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PhD in Physics

Follow-up of the neutrino emission from known gamma-ray celestial sources

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Doctoral programme
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Programa de doctorado en Física código 3126

May 2026

Abstract

Astroparticle physics originated in 1912 with the discovery of cosmic rays, when particles of extraterrestrial origin were first observed traversing the Earth's atmosphere. This discovery opened up the possibility of studying the Universe and astrophysical objects not only through optical telescopes, but also using instruments developed for particle physics, thereby providing complementary information to traditional astrophysics.

Today, the composition of cosmic rays is well understood, being primarily made of nuclei (mostly protons), yet their origin remains an open question. Identifying their sources is particularly challenging: as charged particles, cosmic rays are deflected by electromagnetic fields, making it difficult to trace back their trajectories.

For this reason, the search for their sources relies on other electrically neutral messengers produced in the same acceleration and propagation processes, namely gamma rays and neutrinos. Gamma rays, i.e. high-energy photons, are observed with techniques similar to those used for cosmic rays, and several very-high-energy sources are now known. However, distinguishing the origin of gamma-ray emission is not straightforward, as it can arise from both leptonic and hadronic processes; moreover, gamma rays may be absorbed during propagation.

Neutrinos, on the other hand, interact only weakly with matter and can therefore carry information about their production mechanisms almost unaltered. In addition, unlike gamma rays, neutrinos are produced exclusively in hadronic processes, making them a unique probe of cosmic-ray acceleration. However, their weak interaction also makes them extremely difficult to detect, requiring large detection volumes such as water or ice.

Neutrino telescopes are based on the detection of Cherenkov radiation emitted by charged particles produced in neutrino interactions. In 2013, the IceCube experiment, located at the South Pole with an instrumented volume of about 1 km³, reported the first observation of a flux of astrophysical neutrinos; in 2017, it also identified a source candidate, the blazar TXS 0506+056.

These discoveries highlighted the need for cubic-kilometer-scale detectors and motivated the construction of new neutrino telescopes, including KM3NeT, currently under construction in the Mediterranean Sea. KM3NeT consists of two detectors: ORCA, dedicated to atmospheric neutrino studies, and ARCA, designed for high-energy neutrino astronomy.

In its final configuration, ARCA will comprise 230 detection lines equipped with photomultiplier tubes to measure Cherenkov light, instrumenting a volume of about 1 km^3 . At present, about 20% of the detector is deployed and taking data. In 2023, with 21 active lines, ARCA detected the highest-energy neutrino ever observed (KM3-230212A), highlighting the experiment's scientific potential. This PhD work, carried out within the KM3NeT Collaboration, focuses on the search for neutrino emission from point-like sources. The results presented are based on data collected by ARCA between May 2021 and September 2023, spanning detector configurations from 6 lines (ARCA6) up to 21 lines (ARCA21). The event selection procedure developed for the ARCA19 and ARCA21 datasets is also discussed, as neutrino telescopes are affected by a significant background of atmospheric neutrinos and muons.

Finally, a likelihood-based method used for the data analysis is described. In addition to the KM3NeT/ARCA Point Source results, three complementary studies are presented: a follow-up analysis of the KM3-230212A event, a joint point source search analysis combining ARCA and ANTARES (the predecessor of KM3NeT), and a study of Galactic sources in which gamma-ray observations are used to model the expected neutrino signal.

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Chapter 1

Astro-particle physics and multi-messengers astronomy

Astroparticle physics is a research field that applies detection techniques developed within particle physics to the study of astrophysical objects. The main messengers investigated in this domain are cosmic rays, gamma rays, and high-energy neutrinos. In this chapter, the three messengers will be introduced, the most relevant experimental observations will be summarized, and finally their interconnections will be described.

Cosmic rays, high-energy gamma rays, and high-energy neutrinos are the three main messengers studied in astroparticle physics. However, one more messenger is used for multi-messenger astronomy: gravitational waves.

This work is primarily focused on neutrino astronomy and its connection with cosmic-ray physics and gamma-ray astronomy.

1.1 Cosmic Rays

In the early 1900s, scientists knew that some kind of ionisation effect was present in the air and associated this phenomenon with the passage of charged particles emitted by the natural radioactivity of elements present in the Earth's crust.

Several experiments were conducted to study this ionisation. For example, the Italian Domenico Pacini observed, by diving in underwater, that ionisation decreases with increasing depth [1].

Among these experiments, the most significant contribution was made by Victor Hess (Figure 1.1 right) [2]. In 1912, he studied how air ionisation varied with altitude by taking measurements aboard aerostatic balloons. He found that ionization first decreased, but then increased again at higher altitudes. If the origin had been solely terrestrial, the radiation should have decreased; on the contrary, Hess's measurements proved an extraterrestrial origin ¹. In 1920,

¹Hess also proved that such radiation is not solar through experiments performed at night

Robert Millikan coined the term “cosmic rays” [3].

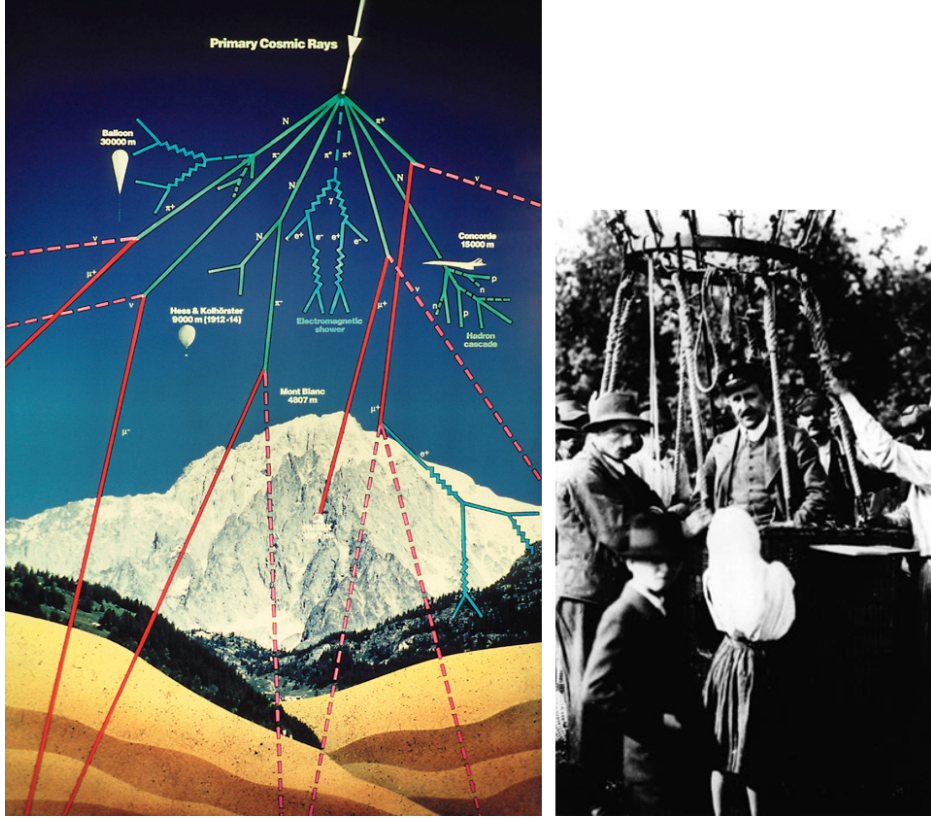


Figure 1.1: On the left, illustration of the particles produced through the interaction of a primary cosmic ray with the Earth atmosphere. On the right, Victor Hess (center) on the return from his balloon flight, 1912.

Today (in 2026, more than a century after Hess’s discovery), we know that cosmic rays are ionised particles and nuclei produced in astrophysical sources that collide with the Earth’s atmosphere, producing swarms of secondary particles, hence the phenomenon of air ionisation (Figure 1.1 left). At present, the sources of cosmic rays and the mechanisms that accelerate them to extremely high energies remain the subject of scientific debate.

With the discovery of cosmic rays, astroparticle physics began, i.e. the branch of physics that studies cosmic objects using high-energy particle detection techniques [4]. During the study of cosmic rays, several particles were discovered, such as the positron, discovered by Carl Anderson in 1932 [5], the muon, discovered by Anderson and Neddermeyer in 1936 [6], the pion, first observed by Lattes, Occhialini and Powell [7] in 1947, and the kaon, by Rochester and Butler, and during eclipses

in 1947 [8]. All of this took place before the advent of particle accelerators in 1950.

The following sections describe the properties of cosmic rays (energy spectrum, chemical composition and arrival direction) together with a brief description of the techniques used to observe them. In addition, the theoretical model used to explain how they are accelerated, even to very high energies (less 10^{20} eV), in astrophysical sources will be illustrated. Finally, the link between cosmic rays and gamma rays and neutrinos, on which multi-messenger astronomy is based, will be described.

1.1.1 Cosmic rays: detection technique

Figure 1.2 shows the energy spectrum of cosmic rays: the total contribution is shown in black, while the various elements that compose it are shown in different colors. The same graph also shows the spectra of the diffuse gamma-ray and cosmic neutrino backgrounds, which will be discussed in the following sections.

Note that the spectrum extends over an energy range from less than 1 GeV up to hundreds of EeV ².

By observing the spectrum, it can be understood that cosmic rays are a non-thermal population of particles, as they do not follow a Maxwellian distribution. The spectrum depends on energy E according to a power law $E^{-\gamma}$, which implies that as energy increases, the flux decreases: from ~ 1 particle/m²/sec at $E \sim 1$ TeV, ~ 1 particle/m²/day at $E \sim 1$ PeV, to ~ 1 particle/km²/year at $E \gtrsim 1$ EeV.

Before discussing the spectrum details, it is useful to contextualise how measurements are performed. Following Victor Hess's method, direct observations of primary cosmic rays are made at high altitudes using balloons or even in space using satellites. Balloon-borne detectors include CREAM [15], HEAT [16], TRACER [17] and JACEE [18], while satellite-based detectors include PAMELA [19], DAMPE [20], CALET [21] and AMS [22], the latter two, in particular, are installed on the International Space Station.

Figure 1.3 shows the diagrams of the AMS experiment structures (top), and for comparison, the structure of the CMS experiment at CERN (bottom). Note that both detectors use alternating layers of trackers and calorimeters to detect, identify and study particles. As mentioned at the beginning of this section, astroparticle physics uses technologies similar to those used for high-energy particle physics in accelerators to identify particles coming from space.

Through direct measurements, it is possible to identify the composition of the particles and nuclei that contribute to the spectrum. Given that solar particles dominate at energies between 1 MeV and 1 GeV [24], cosmic rays consist mainly of hydrogen nuclei protons (approximately 85% to 90%), helium nuclei (10%-12%), Heavier nuclei ($\sim 1\%$ carbon, oxygen, neon, magnesium, silicon, and

²In particle physics, the electronvolt (eV) and gigaelectronvolt (GeV = 10^9 eV) energy scales are used, therefore 1 TeV = 10^{12} eV = 10^3 GeV, 1 PeV = 10^{15} eV = 10^6 GeV and 1 EeV = 10^{18} eV = 10^9 GeV

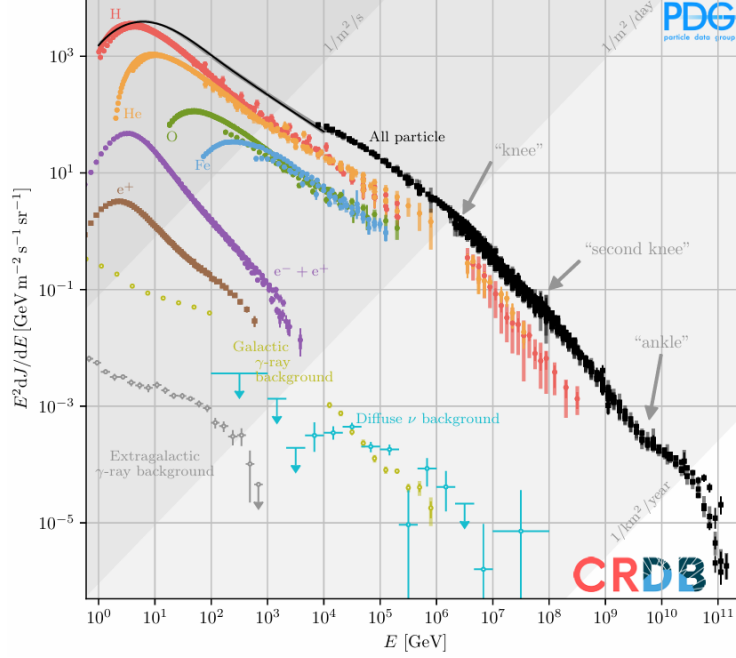


Figure 1.2: Measurements of the flux of charged CRs, multiplied by energy squared, reported in the 2024 review of the Particle Data Group [9]. For the charged CRs, the data from the Cosmic Ray Database (CRDB) [10] have been used, while measurements from Fermi-LAT and LHAASO [11, 12, 13] are used for γ -ray fluxes and results from the IceCube collaboration [14] for diffuse neutrino background.

iron are among the most represented) and electrons ($\sim 1\%$), with a small contribution (estimated to be less than 0.1%) from antiparticles: positrons and antiprotons. As energy increases, there is a gradual decrease in the fraction of light nuclei and a relative increase in heavy nuclei. Figure 1.4 shows the energy spectra for different nuclear species.

At energies larger than 100 TeV (i.e., 10^{14} eV), the intensity of cosmic rays falls below one particle per square meter per day. In this regime, to collect statistically relevant samples, the surface area that the detector would need to cover is too large for satellites or balloons. Therefore, at such high energies, cosmic rays are studied indirectly by ground-based experiments that observe extended air showers (EASs), i.e. cascades of secondary particles produced by the collision of primary cosmic rays with the Earth's atmosphere.

When a very high energy ($E \gtrsim 1\text{PeV}$) cosmic proton or nucleus interacts with a nucleus of air, it generates between a few and hundreds of secondary particles, depending on its energy. Between 30% and 40% of the energy is transferred to the main baryons or nuclei, while the rest is used in the production of charged

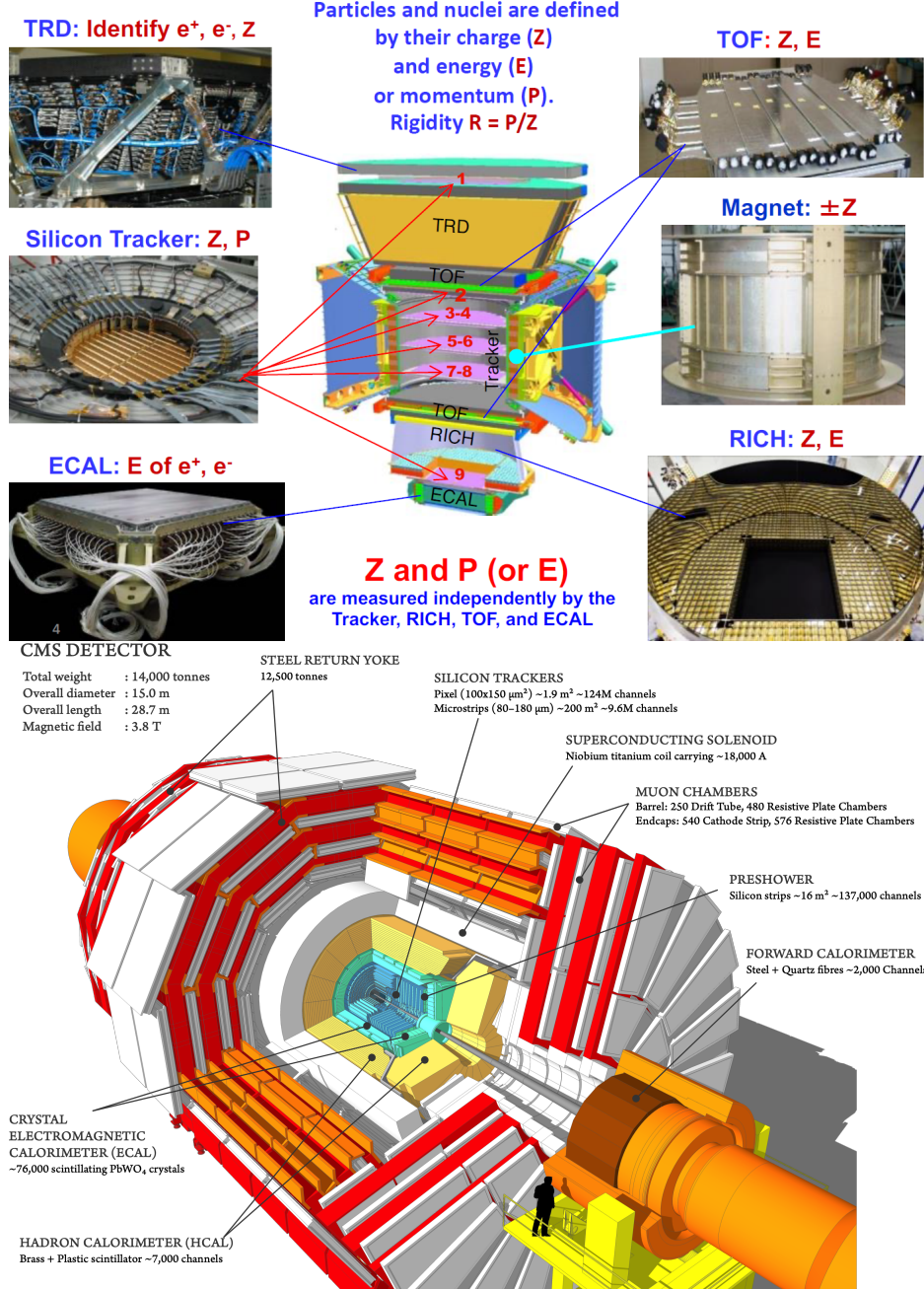


Figure 1.3: Top: diagram of the structure of the AMS [22]. Bottom: diagram of the CMS experiment [23], shown for comparison. Both experiments employ similar techniques to detect particles, using silicon trackers to identify charged particles and measure their momentum, and electromagnetic (ECAL) and hadronic (HCAL) calorimeters to determine the particle energy.

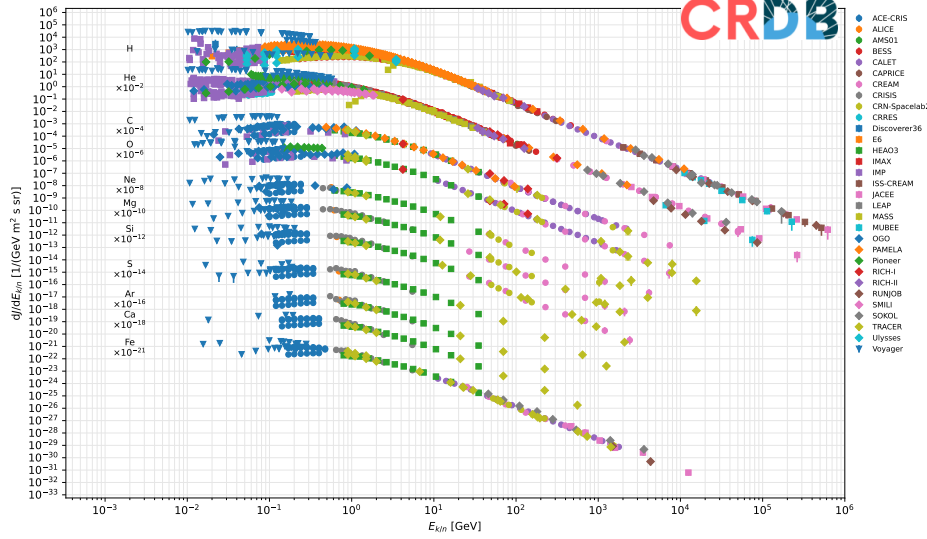


Figure 1.4: Direct measurements of the energy spectrum as a function of energy per nucleon ($E_{k/N} = E_k/A$ with A mass number) for different nuclei in cosmic rays: hydrogen, helium, carbon, oxygen, neon, magnesium, silicon, sulphur, argon, calcium and iron. The plot was done using the data and tools from the Cosmic Ray Database (CRDB) [10].

and neutral mesons, mainly pions: charged ($\pi^\pm$) and neutral (π^0). The primary particle rapidly dissipates its energy in the production of secondary particles. These secondaries may then interact or decay depending on their nature, their energy, and the density of the medium, further sustaining the development of the shower.

A sufficiently energetic charged pion can interact with an air nucleus before decaying. Other hadrons can thus be produced and contribute to the development of the air shower; these constitute the *hadronic component* of the EAS (see Figure 1.5 left).

The muons that constitute the *muonic component* (see Figure 1.5 left) originate from the decay of charged pions ($\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$) and other hadrons. This is also referred to as the penetrating component of the shower, since if the muons have sufficient energy, they can pass through the entire atmosphere and penetrate deep into the sea (as will be explained in the chapter on neutrino telescopes) and even into rock. Several experiments are conducted underground to reduce the background of muons from cosmic rays.

On the other hand, most neutral pions, continuously produced in the hadronic core of the shower, do not travel long enough distances to interact with an air nucleus unless their energy is well above 1 EeV. Instead, they decay almost immediately $\pi_0 \rightarrow \gamma + \gamma$, initiating electromagnetic showers. Neutral pions play a significant role in generating the electromagnetic component (see Figure 1.5

left) that forms the majority of the shower.

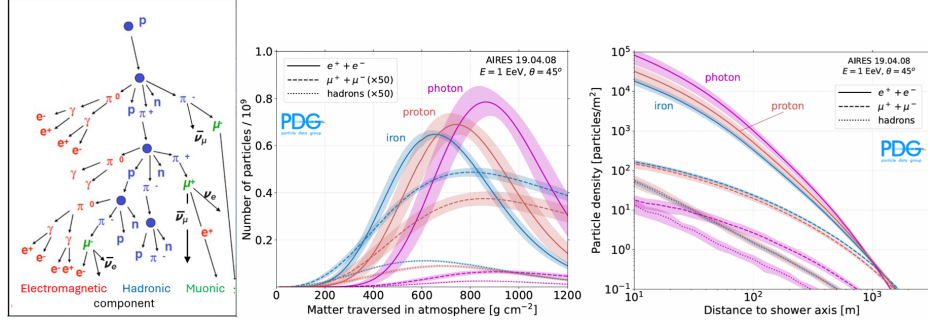


Figure 1.5: Left: diagram of the three components of an extended air shower: hadronic, electromagnetic and muonic. Center: average number of electron/positron, muons and hadrons (lines), and their $\pm\sigma$ deviation (bands), as a function of matter (in $\text{g}\times\text{cm}^{-2}$) crossed in the atmosphere along the shower axis. The longitudinal profiles are obtained with AIRES simulations [25] of proton, iron and photon-induced EASs of energy $E = 1 \text{ EeV} = 10^{18} \text{ eV}$ and zenith angle $\theta = 45^\circ$ w.r.t. the vertical to ground (at depth 870 gcm^{-2}). Right: lateral development (perpendicular to shower axis) at ground level of the same components as in the left panel as a function of distance to shower axis. The center and right figure are taken from the 2024 Particle Data Group Review [9].

Figure 1.5 (left) shows a diagram of the development of the EAS. In Figure 1.5 (center), the number of particles (electrons/positrons, muons and hadrons) in the shower, as a function of the matter traversed in the atmosphere is reported, considering various primary particles: protons, iron nuclei and photons. The graph shows that most of the particles that make up the shower are electron/positron pairs that constitute the electromagnetic component. They originate from the pair production mechanism of photons ($\gamma + \gamma \rightarrow e^+ + e^-$) and from muon decay ($\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ and $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$). Figure 1.5 (right) shows the density as a function of the distance from the centre of the shower.

Muons can generally be identified by the Cherenkov light they induce in water tanks, which is collected by the PMTs installed in tanks, or by the signal they produce in scintillators when they pass through them. These two technologies can also be used to detect electrons and positrons from EAS.

Electrons and positrons are responsible for the radio signature of EAS through two processes: synchrotron emission following their movement in the Earth's geomagnetic field, in this case indicated as coherent radio emission, and in the annihilation of the shower's positrons with electrons in the air, whereby the shower is not electrically neutral, in this other case indicated as Cherenkov Radio Emission or the Askaryan effect.

In general, relativistic charged particles moving through air can induce Cherenkov emission. The refractive index of air is not exactly 1 (its value is approximately

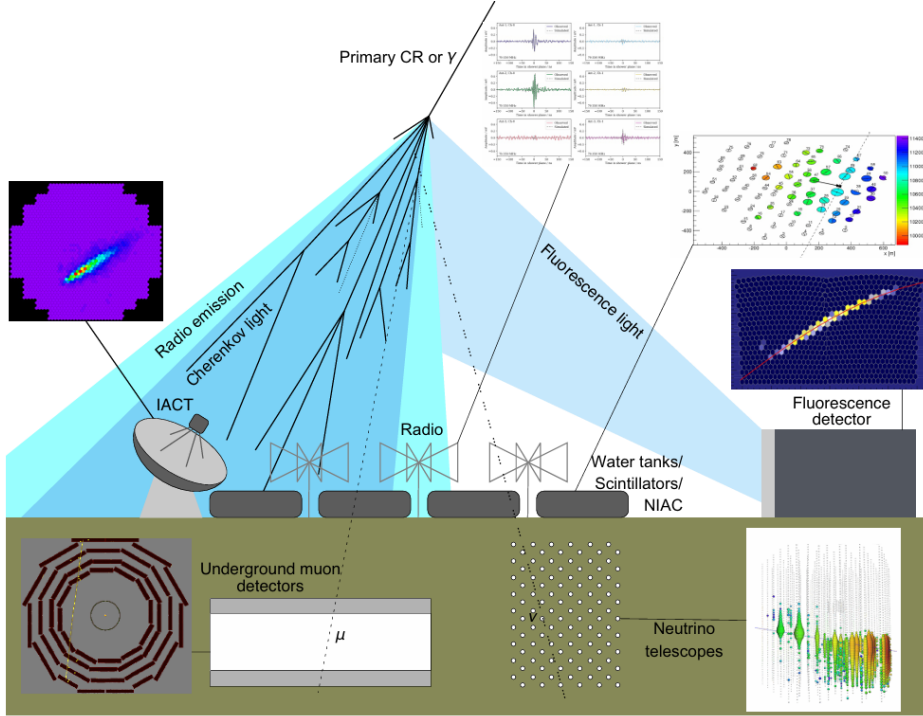


Figure 1.6: Schematic overview of the various techniques used to study the different components of an extensive air shower [26].

1.00029), therefore very energetic particles can travel faster than light in air and induce Cherenkov radiation. The detection principle of Imaging Atmospheric Cherenkov Telescopes (IACTs) is based on this concept.

In addition, EAS can also be studied by collecting the fluorescence light emitted by nitrogen molecules N_2 in the air, excited by the passage of shower particles.

All these detection techniques are summarised in Figure 1.6. Detectors are typically distributed over large areas to increase the effective collection area and, therefore, the exposure to the low primary particle flux. In such a way, cosmic rays can be studied at energies above 100 TeV. Figure 1.6 also shows neutrino telescopes, which will be described in detail in the next chapter. Typically, experiments studying EAS tend to combine one or more of the techniques described above. Table 1.1 lists the experiments and methods used to study very high-energy cosmic rays.

Altitude plays an important role in the study of EAS. As shown in Figure 1.5 the number of EAS particles does not increase steadily with the amount of matter traversed, but at a certain point reaches a maximum value (shower maximum) and then decreases as the particles are absorbed by the atmosphere. The crucial point is to place the detector as close as possible to the shower maximum, where

the particle density is highest, so that a large number of particles (electrons, positrons, photons, and muons) can be detected. This improves not only the reconstruction of the energy and composition of the primary particle, but also the estimated arrival direction.

Experiment	Detection techniques
GRAPES-3 [27]	Surface scintillator array + underground muon detector
H.E.S.S. [28]	Imaging Atmospheric Cherenkov Telescopes (IACT)
VERITAS [29]	Imaging Atmospheric Cherenkov Telescopes (IACT)
MAGIC [30]	Imaging Atmospheric Cherenkov Telescopes (IACT)
HAWC [31]	Water Cherenkov detectors (surface array)
LHAASO [32]	Hybrid: water Cherenkov array, scintillators, muon detectors, wide-field Cherenkov and fluorescence telescopes
IceCube/IceTop [33]	In-ice Neutrino Telescope + surface ice-Cherenkov tanks
TUNKA [34]	Atmospheric Cherenkov light detectors + radio antennas (Tunka-Rex) + surface and underground scintillators (Tunka-Grande)
KASCADE-Grande [35]	Surface scintillator array + shielded muon detectors
Telescope Array [36]	Surface scintillators + fluorescence telescopes
Pierre Auger Observatory [37]	Water Cherenkov detectors (surface) + fluorescence telescopes

Table 1.1: Major cosmic-ray and gamma-ray observatories and their detection techniques.

Regarding the experiments reported in Table 1.1, it is important to mention that observations of cosmic rays with energies greater than 100 PeV are mainly carried out by the Pierre Auger Observatory [37] and Telescope Array [36] collaborations. Covering vast areas ($\sim 3000 \text{ km}^2$ Auger, $\sim 700 \text{ km}^2$ TA), these collaborations have collected enough data to study the highest-energy particles, known as “ultra-high-energy cosmic rays” ³.

³i.e. CRs with energies greater than 100 PeV, as mentioned above.

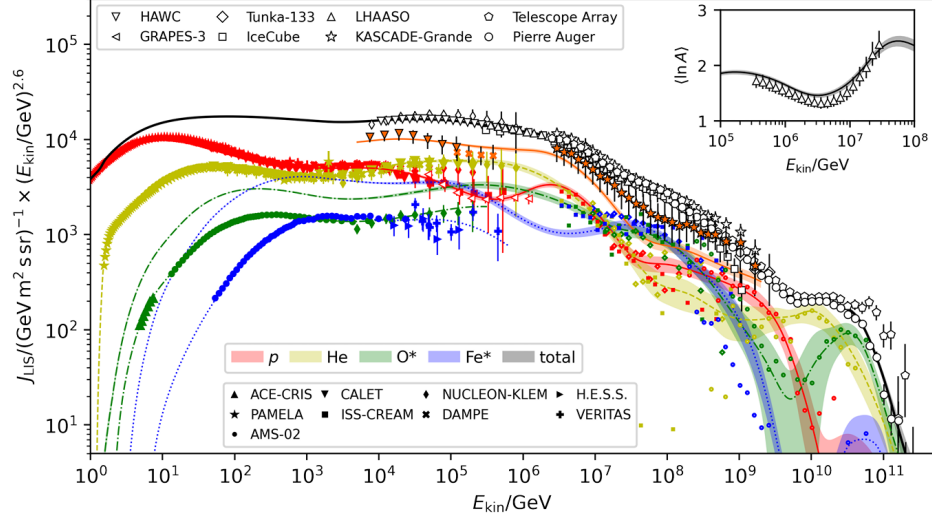


Figure 1.7: All-particle flux (black thick solid line), proton flux (red solid line), helium flux (yellow dashed line), oxygen group flux (green dash-dotted line), and iron group flux (blue dotted line). The orange solid line represents the flux from the combination of proton and helium. The bands around the lines indicate one standard deviation regions. The elemental fluxes of oxygen and iron are also shown. Plot taken from the proceedings on ‘Global Spline Fit (GSF) 2024’ by Kozo Fujisue [38].

1.1.2 Cosmic Rays: energy spectra, mass composition and arrival directions

Energy Spectrum Figure 1.7 collects measurements from satellite/balloon instruments and from ground-based observatories, together with extrapolations for different species [38], providing a near-complete representation of the cosmic-ray energy distribution. At energies below roughly 10 GeV the heliospheric environment (solar wind and heliospheric magnetic field) significantly reduces the flux of incoming charged particles; consequently the measured spectrum flattens and exhibits a turnover at a few hundred MeV. For $E \gtrsim 10$ GeV solar modulation becomes negligible and the all-particle spectrum is, at first approximation, a power law $E^{-\gamma}$ with $\gamma \approx 2.6$ – 2.7 . Near $\sim 3 \times 10^{15}$ eV the spectrum undergoes a pronounced steepening (the **first knee**), after which the slope is roughly $E^{-3.0}$. The latest measurement from LHAASO [39] would support the hypothesis that this is due to a concrete Galactic population, for instance, micro-quasars. A second steepening (the **second knee**) is observed at higher energies; in scenarios where spectral breaks scale with particle rigidity this feature naturally corresponds to the energy where the heaviest Galactic nuclei are depleted. At a few EeV the spectrum shows a relative flattening known as the **ankle**, interpreted as the transition from a predominantly Galactic to an extragalactic population.

Finally, above several 10^{19} eV a marked suppression of the flux is seen, which could be due to the maximum energy achievable in the sources and/or energy losses during propagation (the GZK cutoff). These spectral features, succinctly, are the macroscopic imprint of source spectra, maximum attainable energies, and propagation effects.

Mass composition Direct measurements from satellite and balloon experiments show that at GeV–TeV energies cosmic rays are dominated by protons with a substantial helium component; helium becomes comparable to (and in some measurements exceeds) the proton flux around $\sim 10^5$ GeV (~ 100 TeV).⁴ Approaching the knee (around 3×10^{15} eV) the spectrum steepens first for the light elements, producing a progressive shift toward a heavier composition above the knee. This scenario would appear to be consistent with the latest proton spectrum measurements done by LHAASO[39]. Ground-based air-shower arrays (KASCADE / KASCADE-Grande and successors) report this “light-to-heavy” trend and identify an additional steepening at higher energies often associated with an iron-like break (the so-called “second knee” or “iron knee”) near $\sim 10^{17}$ – $10^{17.5}$ eV. At energies around the ankle (a few 10^{18} eV) and above, composition results are more model and experiment dependent: some measurements indicate a predominantly light composition near the ankle, while others (notably some analyses by the Pierre Auger Collaboration) report a trend toward heavier primaries at the highest energies. Finally, all composition inferences obtained from extensive air showers rely on hadronic interaction models to relate observables (e.g. X_{max} , muon content) to primary mass; accordingly, systematic uncertainties related to these models remain an important caveat.

Arrival directions Cosmic rays, as charged particles, are subject to the Lorentz force and are therefore deflected by electromagnetic fields. The Lorentz force $\vec{F}$ is the force acting on a charge q with velocity $\vec{v}$ in the presence of an electric field $\vec{E}$ and a magnetic field $\vec{B}$ [40]. Such force is described by the following Equation:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \quad (1.1)$$

Deflection consists of a shift in the trajectory of the charge by an angle θ . For a charged particle with momentum p (in absolute value) travelling a distance L in a magnetic field with intensity B , the deflection angle θ can be expressed as in the following equation :

$$\theta = \frac{qBL}{p} \approx \frac{ZeBL}{E} = \Re BL \quad (1.2)$$

Here Ze denotes the charge of a nucleus with atomic number Z , with e the elementary charge ($e \simeq 1.6 \times 10^{-19}$ C). In the final step, the approximation valid for relativistic particles has been used, namely that their momentum p is approximately equal to their energy E .

⁴See e.g. direct measurements and reviews.

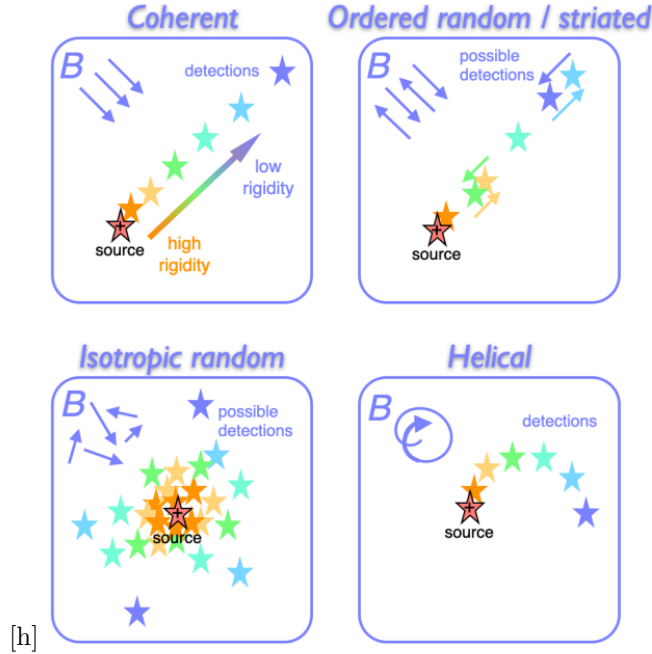


Figure 1.8: Illustration of the effects of different magnetic field components on the observed directions of CR [26]. For a source position (red star) emitting positively charged CRs, the coherent component (upper left) causes a systematic shift in the arrival direction as a decreasing function of rigidity (orange to blue). The striated component (upper right) mixes these deflections along the same line on the sky. The isotropic random component (lower left) causes a scatter in all directions, and the helicity (lower right) produces a curved set of deflections

Note that the deflection is proportional to the rigidity $\mathfrak{R}$, defined as the ratio between the energy and the charge of a particle. Therefore, for nuclei with the same charge, those with higher energy are less deflected, while for nuclei with the same energy, those with higher charge (i.e. the heavier ones) are more deflected.

Figure 1.8 shows a representation of the effect of deflection by magnetic fields. Various field models are considered. Ideally, if there were no deflection, the reconstructed direction of the cosmic rays should point to the source that produced them, whose position is indicated as the red star in the figure. The presence of magnetic deflection means that the original position of the source does not coincide with the reconstructed position assuming a straight trajectory (ballistic trajectory) of the cosmic ray [26]. The reconstructed positions are indicated according to their rigidity using a colour scale ranging from orange to blue. A lower cosmic-ray rigidity corresponds to a larger deviation between the reconstructed arrival direction and the true position of the source.

Due to magnetic deflection, it is almost impossible to identify point sources of cosmic rays. Therefore, the study of their arrival directions is mainly aimed

at observing medium-to-large scale anisotropies. The simplest case of deviation of the arrival directions of CRs from an isotropic distribution is that of a pure dipole, characterised by amplitude and phase.

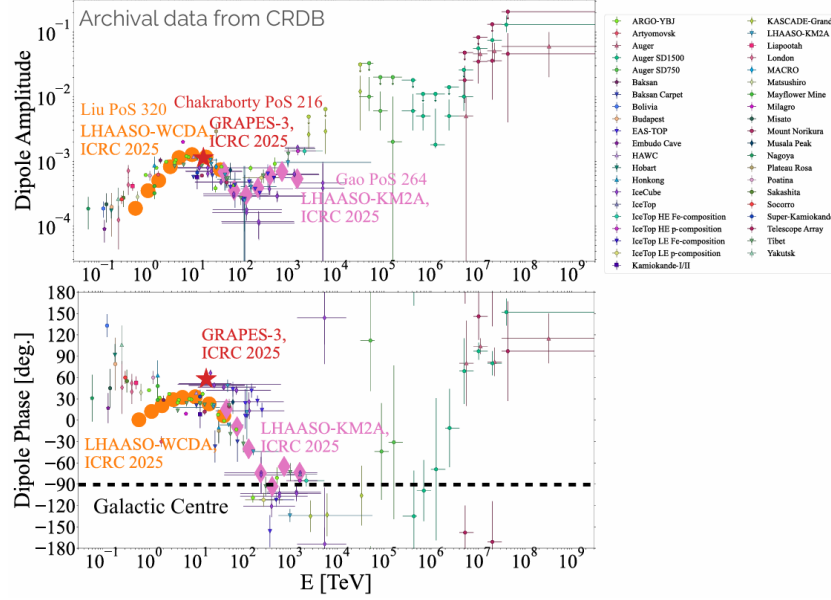


Figure 1.9: Phase and amplitude of the dipole anisotropy in CRs [41, 10, 42, 43, 44].

Figure 1.9 shows the measurements of the phase and amplitude of the dipole anisotropy in CRs [10, 42, 43, 44]. At energies higher than 8 EeV (8×10^{16} TeV), the Pierre Auger Observatory has measured a dipole anisotropy with a statistical significance of 6.9σ [45]. The amplitude of the dipolar anisotropy is $d \sim 0.073$. The dipole points in a direction that is $\sim 115^\circ$ away from the Galactic Center (GC). The dipole direction is not aligned with any obvious individual source.

At energies lower than EeV, the distribution of cosmic ray directions appears mostly isotropic, since the dipole amplitude is less than 10^{-2} . However, measurements of the phase indicate a trend for the dipole direction to change from pointing close to the Galactic Center at low energy towards a direction away from the GC in the EeV energy range.

These experimental observations favour the scenario in which cosmic rays up to the knee energy are mainly produced within our Galaxy (the Milky Way), while from the ankle energy onwards most CRs are of extragalactic origin, with the transition region between the two populations lying between the knee and ankle.

At even higher energies, it is possible to study anisotropies on smaller scales. PAO collaboration found a 4σ excess of events above 38 EeV in a region of angular radius $\approx 27^\circ$ centered on the radio galaxy Centaurus A (CenA) [45]. The

Telescope Array Collaboration has also reported an excess of events with energies above 57 EeV (the so-called hot spot) in the northern sky in the direction with right ascension $RA = 144.0^\circ$ and declination $\delta = 40.5^\circ$, with a 2.8σ significance and in an angular window of 25° [46].

1.1.3 Cosmic-ray origin: acceleration mechanisms

The origin of cosmic rays (CRs) has been one of the fundamental open questions in astrophysics since their discovery. In 1934, Baade and Zwicky first proposed that supernova explosions could be the sources of cosmic rays [47]. A few years later, in 1949, Enrico Fermi introduced a quantitative model of particle acceleration [48], establishing the theoretical foundation for what would become the modern theory of cosmic-ray acceleration.

The general idea behind these models is that charged particles can gain energy through repeated interactions with moving magnetic fields, or by repeatedly crossing shock fronts in astrophysical plasmas.⁵ Such mechanisms can operate in various astrophysical environments, from supernova remnants to active galactic nuclei.

Second-order (stochastic) acceleration. Fermi’s original proposal described a stochastic process in which charged particles are elastically scattered by randomly moving magnetized clouds (Figure 1.10 left), acting as “magnetic mirrors”. At each interaction, a particle can gain or lose energy depending on the relative motion of the cloud. On average, the fractional energy gain per scattering is proportional to the square of the velocity of the cloud:

$$\frac{\Delta E}{E} \propto \beta^2, \quad (1.3)$$

where $\beta = v_m/c$ and v_m is the velocity of the magnetic clouds. Because the energy gain scales as β^2 , this mechanism is relatively inefficient and cannot explain the observed cosmic-ray spectra alone.

First-order (Diffusive Shock Acceleration). A major theoretical breakthrough occurred in the late 1970s, when Krymsky [49], Axford, Leer, and Skadron [50], Bell [51] independently developed the theory of **Diffusive Shock Acceleration** (DSA). In this model, a shock front separates two regions of plasma moving at different velocities (upstream and downstream) (Figure 1.10 right). Charged particles diffusing across the shock experience repeated head-on scatterings with magnetic irregularities, systematically gaining energy with each crossing.

The average fractional energy gain per cycle is given by

$$\frac{\Delta E}{E} \simeq \frac{4}{3} \frac{u_1 - u_2}{c}, \quad (1.4)$$

⁵Plasma consists of ionised gases (electrons and ions) embedded in magnetic and electric fields.

where u_1 and u_2 are the plasma velocities upstream and downstream of the shock, respectively.

The compression ratio of the shock is defined as

$$r = \frac{u_1}{u_2}, \quad (1.5)$$

which for strong non-relativistic shocks is approximately $r \approx 4$.

Combining the mean energy gain with the probability of escape per cycle leads to a power-law spectrum of accelerated particles:

$$N(E) \propto E^{-p}, \quad p = \frac{r+2}{r-1}. \quad (1.6)$$

For $r = 4$, this gives $p = 2$, remarkably consistent with the observed energy spectrum of Galactic cosmic rays after propagation effects are considered.

Injection problem. Despite its success, the DSA mechanism still faces the so-called **injection problem**: how do particles transit from the thermal plasma to the non-thermal population involved in the acceleration process? Several pre-acceleration mechanisms have been proposed, such as turbulence-induced energisation or magnetic reconnection, but a complete picture remains an active area of research.

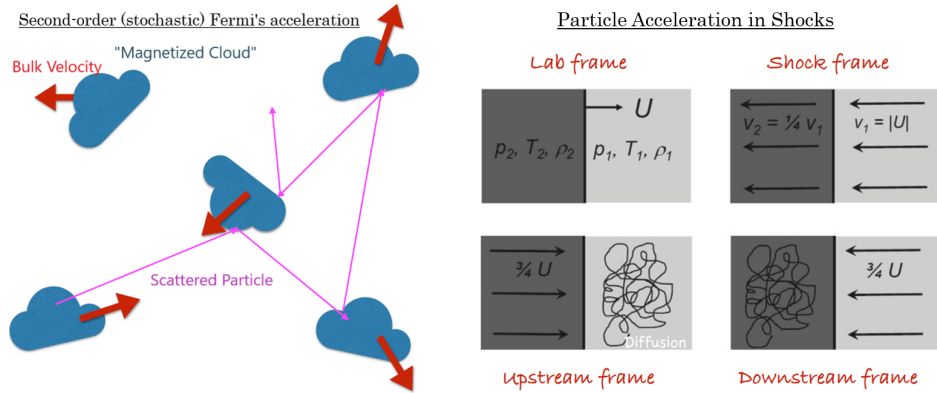


Figure 1.10: Schematic illustration of cosmic-ray acceleration mechanisms: stochastic (second-order) magnetic scattering (left) and diffusive shock acceleration (right).

The Hillas criterion. While diffusive shock acceleration provides a general mechanism for particle energisation, not all astrophysical sources can accelerate particles to the highest observed cosmic-ray energies. Hillas [52] proposed a simple yet powerful condition that relates the maximum achievable particle energy

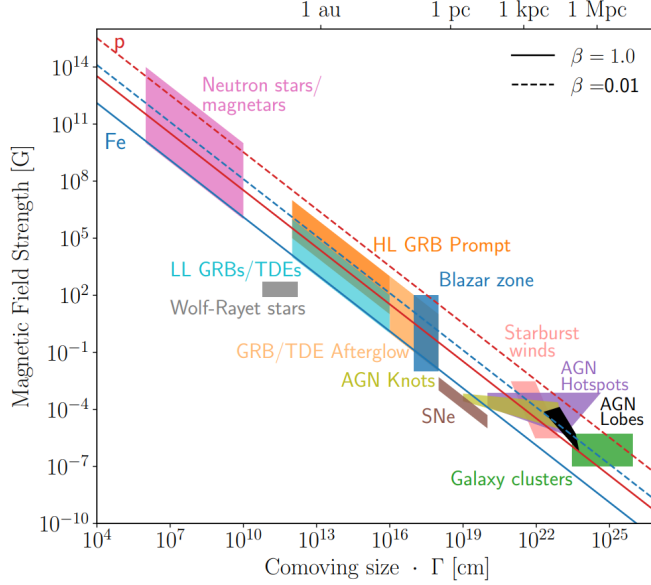


Figure 1.11: Figure taken from [26]. Hillas Plot: source classes are shown as a function of their characteristic size and magnetic field strength. Classes located to the right of the solid diagonal lines can confine 10^{20} eV iron (blue) and proton (red) nuclei, assuming bulk outflows with velocities close to the speed of light. Dashed lines illustrate the condition for sources with lower expansion velocity.

to the size and magnetic field strength of the accelerator:

$$E_{\max} \simeq Z e B R \beta, \quad (1.7)$$

where Z is the charge of the particle, B is the magnetic field strength, R the characteristic size of the acceleration region, and $\beta = v/c$ the velocity of the scattering centres. Only sources that can confine particles with Larmor radii smaller than the physical size of the astrophysical object can effectively accelerate them to ultra-high energies. This relation is often represented in the *Hillas diagram*, which maps potential astrophysical accelerators—such as supernova remnants, pulsar wind nebulae, active galactic nuclei, and gamma-ray bursts—according to their size and magnetic field strength (Figure 1.11). This criterion remains a key tool for identifying candidate sources of Galactic and extragalactic cosmic rays.

The GZK cutoff. The suppression of the cosmic-ray flux at the highest energies is commonly attributed to the Greisen–Zatsepin–Kuzmin (GZK) effect [53, 54]. Ultra-high-energy protons propagating through the cosmic microwave background (CMB) interact with CMB photons and lose energy primarily via

photo-pion production,

$$p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases} . \quad (1.8)$$

The threshold for this process corresponds to proton energies of the order of

$$E_{\text{th}} \sim 5 \times 10^{19} \text{ eV},$$

for typical CMB photon energies $\varepsilon \sim k_B T_{\text{CMB}} \simeq 6 \times 10^{-4} \text{ eV}$. Above this energy protons suffer severe energy losses over cosmological distances: the energy-loss length due to photo-pion production is of order tens of Mpc (depending on energy), so only sources located within a relatively local volume (of order $\mathcal{O}(10\text{--}100 \text{ Mpc})$) can contribute significantly to the observed flux above the GZK threshold.

For heavy nuclei, an analogous suppression arises from photodisintegration on the CMB and the extragalactic background light (EBL), which effectively reduces the energy per nucleon and leads to a depletion of the highest-energy nuclear components at distances comparable to or smaller than the proton attenuation length.

Observationally, the pronounced flux suppression above several 10^{19} eV reported by large experiments (e.g. Pierre Auger Observatory, Telescope Array) could be consistent with the expected GZK attenuation and/or with source maximum-energy limits; discerning the relative contribution of propagation losses and intrinsic source cutoffs remains an active topic of research [55, 56].

1.1.4 Cosmic Rays origin: candidate sources

Before introducing additional cosmic messengers (gamma rays and neutrinos), this section provides a concise overview of the main classes of candidate sources proposed as potential accelerators of cosmic rays. The discussion begins with Galactic candidates, including supernova remnants, the Galactic Center, neutron stars, and microquasars.

Shell-type Supernova Remnants Shell-type supernova remnants (SNRs) are the expanding shock fronts produced by supernova explosions [57]. They emit strongly in radio and X-rays due to synchrotron and thermal bremsstrahlung radiation from accelerated particles and hot plasma. Typical physical size: a few to tens of parsecs (young SNRs $\sim 1\text{--}5 \text{ pc}$; evolved SNRs up to $\sim 10\text{--}100 \text{ pc}$). Estimated magnetic field intensity: shell/shock regions $\sim 10\text{--}10^3 \mu\text{G}$ (i.e., $\sim 0.01\text{--}1 \text{ mG}$) with strong local amplification close to the shock. Origin of the field: compression of the ambient interstellar field plus shock-driven and turbulence-driven amplification (including cosmic-ray-driven instabilities) at the shock front.

Galactic Center The Galactic Center is the rotational center of the Milky Way, hosting a dense stellar environment and the supermassive black hole Sagittarius A* [58]. It is a rich source of high-energy radiation, non-thermal radio

emission, and variable infrared and X-ray activity. Beginning with the innermost region, the area dominated by Sagittarius A* and the nuclear star cluster extends over approximately one parsec. At larger radii lies the Central Molecular Zone (CMZ), which spans several hundred parsecs and is characterized by high densities of molecular gas. Estimated magnetic field intensity: on CMZ / few-hundred-pc scales the field is relatively strong compared to the Galactic disk, with lower limits $\gtrsim$ tens of μG (studies frequently quote values of order $\sim 50 \mu\text{G}$ and higher on 100s-pc scales; smaller-scale fields near dense clouds can be larger). Origin of the field: large-scale Galactic field shaped/compressed by the dense central environment, with additional amplification and ordering by shearing, turbulence and feedback from star formation and accretion activity. H.E.S.S. observations have shown that the Galactic Center is a PeVatron source [59].

Neutron Stars Neutron stars are the compact remnants of massive stars that have undergone supernova explosions. Composed primarily of neutrons, they possess extremely strong magnetic fields and rapid rotation, often observed as pulsars emitting periodic radiation [60, 61]. Typical physical size: radius $\sim 10\text{--}15 \text{ km}$ (which is $\approx 3.2 \times 10^{-13} \text{ pc}$ for a 10 km radius). Estimated magnetic field intensity: surface fields range broadly from $\sim 10^8$ to $\sim 10^{15} \text{ G}$ (ordinary pulsars $\sim 10^8\text{--}10^{13} \text{ G}$; magnetars up to $\sim 10^{14}\text{--}10^{15} \text{ G}$). Origin of the field: mostly inherited/concentrated from the progenitor (flux freezing) and further amplified/organized during collapse and early proto-neutron-star dynamo processes; subsequent evolution (decay, burial by accretion) modifies the observable field.

Microquasars Microquasars are X-ray binary systems in which a stellar-mass black hole or neutron star accretes matter from a companion star. They exhibit relativistic jets and strong variability across the electromagnetic spectrum, analogous to scaled-down active galactic nuclei [61]. Typical physical size: the accretion/ejection region is sub-parsec, but jets can extend from sub-parsec scales out to tens of parsecs in the surrounding medium (some systems such as SS 433 produce jet-inflated lobes extending $\sim 10\text{--}50 \text{ pc}$). Estimated magnetic field intensity: near the compact object / jet base fields can be very large (estimates for inner-disk/jet-launch regions range over many orders of magnitude depending on model; values $\sim 10^6\text{--}10^9 \text{ G}$ are quoted in some cases), while extended jet lobes and termination regions have much lower fields (order $\sim 1\text{--}100 \mu\text{G}$). Origin of the field: magnetic flux advected from the accretion flow plus local disk dynamos and field amplification in shocks and turbulence along the jet. Recently, both HAWC and LHAASO have observed gamma-ray emissions with energies greater than 0.1 PeV from several microquasars [62, 63].

Moving beyond the Milky Way, the classes of extragalactic sources capable of accelerating cosmic rays comprise active galactic nuclei, gamma-ray bursts, and starburst galaxies.

Active Galactic Nuclei Active galactic nuclei (AGN) are extremely luminous regions at the centers of some galaxies, powered by accretion of matter onto a supermassive black hole (SMBH) [64]. They emit across all wavelengths and can produce powerful relativistic jets and broad emission lines. Typical physical scales: the accretion disk/broad-line region is ~ 0.01 – 1 pc, the narrow-line region up to ~ 10 – 1000 pc, and jets can extend to kpc–Mpc scales (1 kpc = 10^3 pc, so jets often reach 10^3 – 10^6 pc). Estimated magnetic field intensity: very strong near the SMBH/jet base (estimates of $\sim 10^3$ – 10^4 G in some models), dropping to ~ 0.1 – 1 G on parsec scales and to μ G levels in large-scale radio lobes. Origin of the field: accretion-disk dynamos, advection of magnetic flux into the inner disk, and processes that extract rotational energy from disk/black hole (e.g., Blandford–Znajek / Blandford–Payne–type mechanisms), with further amplification/error shaping in shocks and turbulence along the jet. As it will be discussed in Section 1.3, AGNs are a class of sources from which neutrino emission has been observed.

Gamma-Ray Bursts Gamma-ray bursts (GRBs) are short-lived but extremely intense flashes of gamma radiation and represent one of the most energetic transient phenomena in the Universe [65]. GRBs are commonly divided into two main classes according to their duration: long GRBs (lasting $\gtrsim 2$ s) and short GRBs (lasting $\lesssim 2$ s) [66]. Long GRBs are generally associated with the collapse of massive, rapidly rotating stars forming a black hole and launching relativistic jets (the collapsar scenario) [67]. Short GRBs are believed to originate from mergers of compact objects such as binary neutron stars or neutron star–black hole systems. This interpretation was strongly supported by the joint detection of gravitational waves from the binary neutron star merger GW170817 and the associated short GRB 170817A [68, 69]. The prompt emission region is typically located at radii of $\sim 10^{12}$ – 10^{15} cm ($\sim 3 \times 10^{-7}$ – 3×10^{-4} pc). Magnetic field strengths in the emitting region depend on the jet magnetization and radiation model, with typical estimates of $\sim 10^3$ – 10^6 G in internal shock regions, while stronger fields may exist near the central engine. These magnetic fields may be advected from the central engine or generated locally through plasma instabilities and turbulence within the relativistic outflow.

Starburst Galaxies Starburst galaxies are characterized by exceptionally high rates of star formation, often triggered by galactic interactions or mergers. They emit strongly in infrared and radio bands due to dust heating and massive stellar activity [70]. Typical physical size: the starburst nucleus or active star-forming region is often concentrated in the central ~ 100 – 500 pc (varies by galaxy; e.g., M82 has a compact starburst of a few 100 pc). Estimated magnetic field intensity: substantially stronger than in normal galaxy disks, with typical mean fields of order ~ 50 – 500 μ G in the central starburst regions (local peaks can be larger). Origin of the field: intensive supernova-driven turbulence and strong small-scale dynamo action amplify the ambient galactic field; large-scale flows and winds can order and advect the fields. They can emit across all wavelengths and can

produce powerful relativistic jets and broad emission lines.

1.2 Gamma Rays

Gamma rays are the highest energetic form of electromagnetic radiation, consisting of photons with energies greater than 10 keV. They are emitted during nuclear processes and radioactive decay. They were first observed by Paul Ulrich Villard in 1900, while he was studying nuclear reactions [71].

Initially, gamma rays of extraterrestrial origin were detected using detectors on atmospheric balloons [72] or satellites [73], as the Earth's atmosphere absorbs most photon wavelengths, allowing only visible light and radio waves to pass through (Figure 1.12). Historically, the evolution of gamma-ray astronomy developed in parallel with the study of cosmic rays, as will be described in the next sections.

The first detection took place in 1958, through an experiment on an atmospheric balloon, by Peterson and Winckler [72]. Since then, the technology for studying gamma astronomy has continued to evolve, and today astrophysical gamma-ray sources are observed both in space via satellites and on Earth through the extensive air showers that the most energetic events produce in the atmosphere.

High-energy astrophysical gamma rays are very important because they allow us to identify the source that produced them and because they are a signature of the lepton-hadron acceleration processes of cosmic rays.

1.2.1 Gamma-ray measurements

Concerning detection methods, gamma-ray observations rely on techniques that are essentially similar to those employed in cosmic-ray studies. Measurements can be performed either directly, using detectors on board balloons or satellites, or indirectly from the ground by observing the Extensive Air Showers generated in the atmosphere. The technologies involved are therefore closely related, and most of the experiments mentioned in the previous chapter also contribute to gamma-ray detection. Figure 1.13 shows a schematic overview of the main experimental techniques used in this field, and Table 1.2 (adapted from [10]) summarizes the main characteristics of each detector.

At high energies (HE, $E > 0.1$ GeV), gamma rays are detected by satellite-based instruments such as *AGILE* [75], *EGRET* [76], *Fermi-LAT* [77], and *DAMPE* [78]. Typically, these detectors feature a large field of view (FOV), a moderate angular resolution (0.1° – 5°), and a high duty cycle (around 80%). This combination allows continuous all-sky monitoring of steady gamma-ray sources as well as the detection of transient phenomena. To date, more than 600 sources of high-energy gamma rays have been observed or discovered by these space missions [75, 76, 77, 78].

At energies above 0.1 TeV, the gamma-ray flux becomes too low to be efficiently measured in space. For this reason, ground-based detectors are employed, in which the primary gamma rays are reconstructed indirectly from the Extensive Air Showers they produce in the atmosphere. Very-high-energy (VHE, $E > 0.1$ TeV) gamma rays were initially studied using Imaging Atmospheric

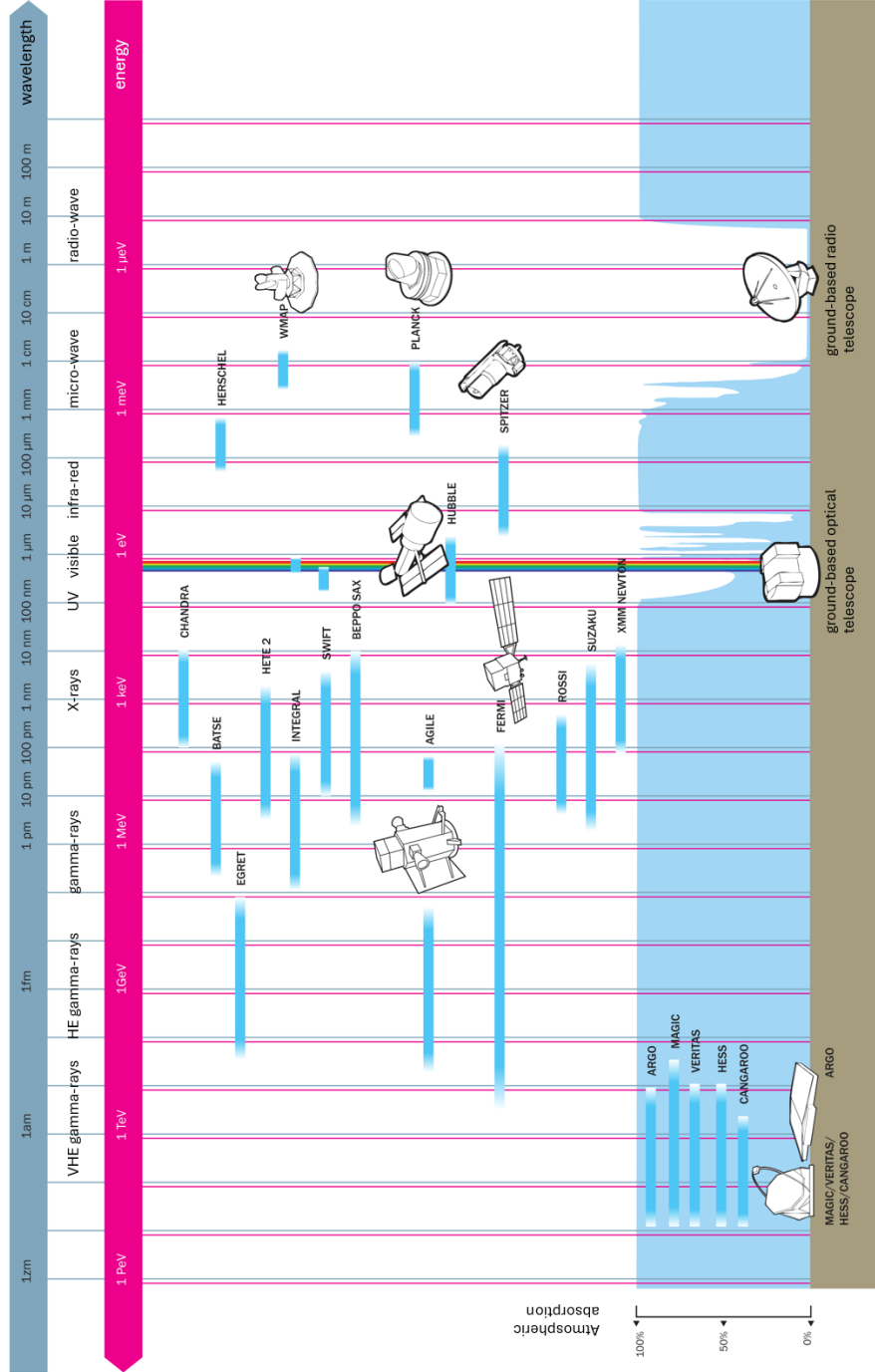


Figure 1.12: Diagram of detectors/telescopes for different wavelengths/photon energies [74]. At the top is the energy scale for electromagnetic radiation: starting from the lowest energies, there are radio waves, followed by microwaves, the infrared region, visible light, ultraviolet, X-rays and finally gamma rays. For each detector, the bright blue line indicates the energy range of the photons they observe. The light blue region represents the absorption of electromagnetic radiation in the atmosphere for different energies; the absorption scale is shown on the left-hand side.

Cherenkov Telescopes (IACTs) such as *H.E.S.S.* [79], *VERITAS* [80], *MAGIC* [81] and *CTA* [82]. The main advantage of these instruments lies in their excellent angular resolution (0.06° – 0.17°) and energy reconstruction capabilities, which enable highly precise spectral and morphological studies of astrophysical sources. On the other hand, their limited field of view (3° – 5°) and relatively low duty cycle make full-sky surveys challenging. Nevertheless, IACTs have detected gamma-ray emission above 100 GeV from over 200 sources, most of which were initially identified through observations at lower energies.

To achieve unbiased observations of very-high-energy gamma-ray emitters and perform large-scale sky surveys, instruments with a wide field of view and an almost continuous duty cycle ($\gtrsim 90\%$) are required. Ground-based extensive-air-shower arrays satisfy these conditions thanks to their large FoV and high uptime. Among them, one of the most notable results comes from the *Tibet AS γ* experiment, which first reported the detection of an ultra-high-energy (UHE, $E > 0.1$ PeV) gamma-ray source — the Crab Nebula [83]; previously, Milagro had observed a very high-energy gamma-ray emission from the Crab Nebula, reaching up to 0.1 PeV [84].

Experiment	energy range	Effective area (m ²)	sensitivity (milli-CU [†])	
Fermi-LAT ^{a)}	20 MeV - 300 GeV	~ 0.95	10 - 30	
H.E.S.S. ^{b)}	10 GeV - 50 TeV	~ 10 ⁵	~ 5	
MAGIC ^{c)}	≥ 30 GeV	~ 10 ⁵	~ 7	
VERITAS ^{d)}	50 GeV - 50 TeV	~ 10 ⁵	~ 5	
CTA-LST1 ^{e)}	20 GeV - 300 GeV	~ 10 ⁴	~ 10	
ASγ ^{f)}	10 TeV - 1 PeV	~ 7 × 10 ⁴	~ 200	
ARGO-YBJ ^{g)}	50 GeV - 10 TeV	~ 0.8 × 10 ⁴	~ 300	
HAWC ^{h)}	100 GeV - 100 TeV	~ 3 × 10 ⁴	~ 50	
LHAASO-WCDA ⁱ⁾	100 GeV - 20 TeV	~ 0.8 × 10 ⁵	~ 12	
LHAASO-KM2A ⁱ⁾	10 TeV - 4 PeV	~ 10 ⁶	~ 12	

Experiment	energy resolution (%)	PSF (°)	FoV (sr)	duty cycle (%)
Fermi-LAT ^{a)}	8 - 18	0.15 - 3.5	~ 2.4	~ 60
H.E.S.S. ^{b)}	15	< 0.1	~ 0.03	~ 10
MAGIC ^{c)}	16	≤ 0.07	0.02	~ 18
VERITAS ^{d)}	10 - 15	0.08 - 0.13	0.02	10 - 14
CTA-LST1 ^{e)}	10 - 30	0.05 - 0.1	0.02	~ 10
ASγ ^{f)}	20 - 40	~ 0.8	~ 2.0	90
ARGO-YBJ ^{g)}	> 13	~ 0.5	~ 2.0	86
HAWC ^{h)}	20 - 50	~ 0.69	> 1.5	95
LHAASO-WCDA ⁱ⁾	~ 33	0.2 - 0.84	~ 2.0	95
LHAASO-KM2A ⁱ⁾	15 - 40	0.2 - 0.6	~ 2.0	95

Table 1.2: the main characteristics of astrophysical gamma-ray observatories [85, 86, 30, 87, 88].

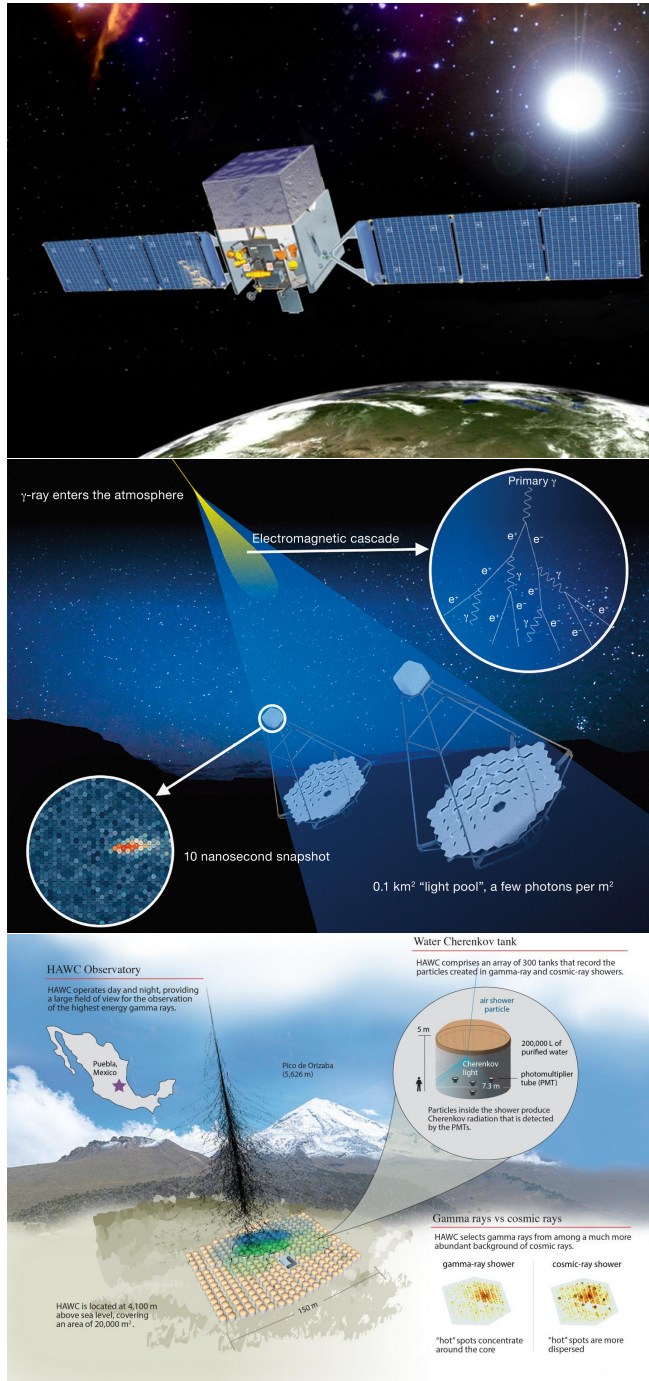


Figure 1.13: Diagram showing the main experimental techniques used in gamma-ray astronomy: a space-based detector (Fermi-LAT [85]), an IACT telescope (MAGIC [30]), and a ground-based EAS array (HAWC).

More recently, the *HAWC* observatory has detected UHE gamma-ray emission from three distinct sources [89, 90], while the *LHAASO* collaboration has reported 43 UHE gamma-ray sources, including several emitting photons up to PeV energies [91]. These results mark a new era in gamma-ray astronomy, extending the observable energy range and providing key constraints on particle acceleration mechanisms in extreme astrophysical environments.

1.2.2 Production mechanisms: leptonic scenario vs. hadronic scenario

There are two possible ways in which astrophysical gamma rays are produced from cosmic rays: mechanisms involving mainly electrons, which make up the leptonic scenario, or through the decay of mesons and baryons, in this case referred to as the hadronic scenario.

Synchrotron emission Charged particles undergoing acceleration or deceleration emit electromagnetic radiation, as predicted by Maxwell's equations and later verified experimentally by Heinrich Hertz. The instantaneous power radiated by a charged particle is given by

$$P = \frac{2}{3} \frac{q^2 a^2}{c^3},$$

where q is the particle charge, a its acceleration, and c the speed of light.

In the case of a particle moving within a magnetic field, it follows a helical trajectory under the action of the Lorentz force, thus experiencing a centripetal acceleration. In this situation, as described in [92], the emitted power can be expressed as

$$P = \frac{2}{3} \frac{q^4 B^2 \gamma^2 \sin^2 \alpha}{m^2 c^3},$$

where B is the magnetic field strength, m the particle mass, α the pitch angle between the particle's velocity and the magnetic field, and γ the Lorentz factor.

When the particle is in a relativistic regime, the emitted radiation becomes strongly beamed in the direction of motion — a phenomenon known as *relativistic beaming* (Figure 1.14). Under these conditions, the process is referred to as *synchrotron emission*. This mechanism allows electrons to emit photons with energies extending up to the X-ray band. Note that since power is inversely proportional to the square of mass, synchrotron radiation mainly comes from electrons, as they are lighter⁶.

The synchrotron emission spectrum depends on both the energy distribution of the particles and the magnetic field intensity. If the electrons follow a power-law energy distribution $N(E) \propto E^{-p}$, the observed frequency spectrum also follows a power law of the form

$$I_\nu \propto \nu^{-\alpha},$$

⁶For comparison, the mass of an electron is $0.511 \text{ MeV}/c^2$, while the mass of a proton is $938.28 \text{ MeV}/c^2$, thus protons are ~ 2000 times heavier than electrons

where the spectral index α is related to the particle distribution index p through $\alpha = (p - 1)/2$. This spectral behavior is a distinctive signature of non-thermal processes dominating many astrophysical systems, such as SNRs, quasar jets, and radio galaxies.

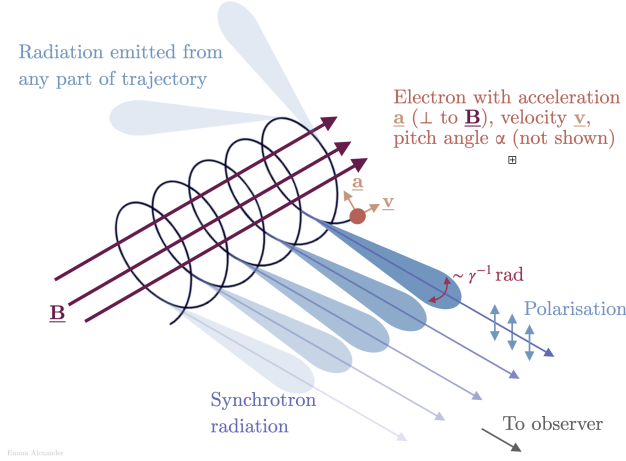


Figure 1.14: Diagram of synchrotron emission, arising from an electron moving along a helical path around an ordered magnetic field [93]. The Lorentz force causing the acceleration a is perpendicular to the magnetic field vector B , and both are also perpendicular to the tangent component of the electron's velocity v . The radiation is concentrated in a beamwidth of $\sim 1/\gamma$ radians.

These synchrotron photons could interact again with the electrons, by the Inverse Compton process.

Inverse Compton scattering The process whereby an electron collides with a photon, with energy $E_{\text{ph}, i}$, results in an electron and a photon, with energy $E_{\text{ph}, f}$, which is equal to

$$E_{\text{ph}, f} = \frac{E_{\text{ph}, i}}{1 + \frac{E_{\text{ph}, i}}{m_e c^2} (1 - \cos \theta)} \quad (1.9)$$

where θ is the angle between the incoming and outgoing photon directions and $m_e c^2$ the rest energy of the electron, which is approximately 511 keV

When the initial energy of the photon is small with respect to the electron rest mass-energy, the process can be described in terms of classical electro-dynamics, therefore, the probability of this process occurring is given by the Thomson scattering cross section [40]:

$$\sigma_T = \frac{8\pi}{3} \left(\frac{e^2}{4\pi\epsilon_0 m_e c^2} \right)^2 \quad (1.10)$$

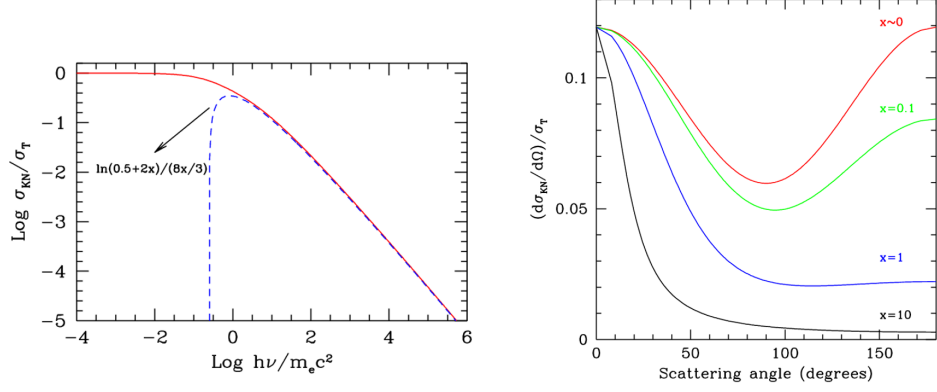


Figure 1.15: Left: the total Klein–Nishina cross section as a function of energy. The dashed line is the approximation at high energies as given in Eq. 5.13 [92]. Right: the differential Klein–Nishina cross section (in units of σ_T), for different incoming photon energies[92].

The Thomson cross section is the classical limit of the more general Klein–Nishina cross section, which is used to compute the interaction probability as the initial photon energy increases and becomes comparable or greater than electron rest mass–energy:

$$\sigma_{\text{KN}} = \frac{3}{4} \sigma_T \left\{ \frac{1+x}{x^3} \left[\frac{2x(1+x)}{1+2x} - \ln(1+2x) \right] + \frac{1}{2x} \ln(1+2x) - \frac{1+3x}{(1+2x)^2} \right\} \quad (1.11)$$

where $x = E_{\text{ph}, i}/m_e c^2$

Figure 1.15 (left) shows the trend of the Klein-Nishina cross section as a function of the initial photon energy. As mentioned above, at low energies the cross section is approximately equal to the Thomson cross section, while at high energies it has an asymptotic trend

$$\sigma_{\text{KN}} \simeq \frac{3}{8} \frac{\sigma_T}{x} \left[\ln(2x) + \frac{1}{2} \right]$$

Therefore, the probability of interaction tends to decrease as energy increases. As for the direction of scattering, Figure 1.15 (right) show the trend of the differential cross section with respect to the scattering angle. The scattering becomes preferentially forward as the energy of the photon increases.

Together, synchrotron and inverse Compton processes constitute the lepton process of gamma ray production and acceleration. The alternative mechanism, the hadronic scenario, predicts that gamma rays derive from meson decay.

Hadron decay It is known from particle physics experiments with accelerators that large quantities of π mesons (pions) are produced in collisions between protons (or between protons and nuclei). In particular, neutral pions decay with an extremely short half-life (8.5×10^{-17} seconds) into two gamma-rays, as first observed by Oreste Piccioni and his colleagues in 1950 [94]. Therefore, gamma rays can be produced in hadronic collisions:

$$p + p \rightarrow p + p + \pi^0 \rightarrow p + p + 2\gamma$$

In this case, the gamma ray spectrum Φ_γ is related to the pion spectrum Φ_π according to the relationship [95]:

$$\Phi_\gamma(E_\gamma) = 2 \int_{E_\gamma}^{\infty} \Phi_\pi(E) \frac{dE}{E} \quad (1.12)$$

As the energy of protons increase, other mesons could be produced, which could contribute to the gamma-ray flux, as the η^0 meson which also decay in two gamma-rays. In this case, the equation 1.12 can be rewritten to take into account the contributions from these reactions, [96].

In addition to interactions between protons alone, gamma rays can be produced by collisions between protons and radiation. Protons and photons can produce a Δ^+ resonance, which in turn can decay into a proton and a neutral pion, as in the following reaction:

$$p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow p + 2\gamma$$

Comparing the two mechanisms Gamma rays play a crucial role in identifying the sources of cosmic rays, as they are a direct signature of both leptonic and hadronic acceleration processes.

Figure 1.16 shows a qualitative representation of the distribution of photons emitted by different mechanisms. At energies above several tens of TeV, the leptonic scenario becomes less efficient for gamma-ray production, since the cross section of inverse Compton scattering decreases with increasing energy, as shown in Figure 1.15 (left). In this regime, the hadronic mechanism is generally considered more plausible. However, distinguishing unambiguously between leptonic and hadronic origins remains challenging, as both can produce similar gamma-ray spectra under certain conditions.

1.2.3 Gamma-ray propagation and absorption effect

Gamma rays produced in a source γ_{src} could interact with other photons γ_{target} , resulting in the process of pair production:

$$\gamma_{\text{src}} + \gamma_{\text{target}} \rightarrow e^+ + e^- \quad (1.13)$$

This would correspond to an attenuation of the flux coming from a source $\Phi_{\gamma, \text{src}}$.

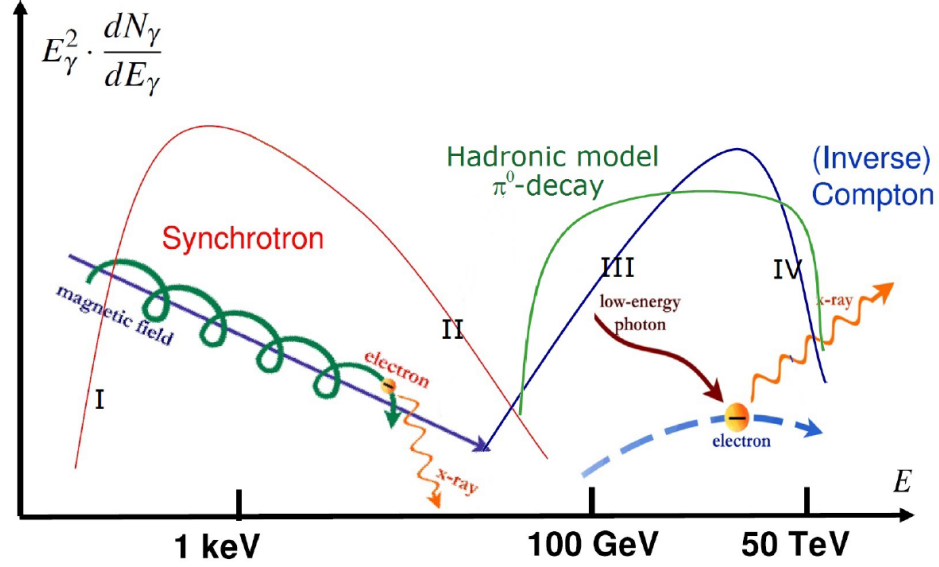


Figure 1.16: Spectral energy distribution of photons produced in leptonic/hadronic models. Synchrotron radiation is caused by relativistic electrons accelerated in a magnetic field. Photons from synchrotron emission represent also the target for inverse Compton scattering of the parent electrons. When hadrons interact with matter or ambient photons, a distribution of γ -rays from π^0 decays as indicated by the green curve could be obtained.

In this case, the relation between $\Phi_{\gamma, \text{src}}$ and $\Phi_{\gamma, \text{obs}}$, the flux observed on the Earth, can be written using the radiative transport equation as following

$$\Phi_{\text{obs}} = \Phi_{\text{src}} \times e^{-\tau_{\gamma\gamma}} \quad (1.14)$$

where $e^{-\tau_{\gamma\gamma}}$ is the so called absorption factor (or survival probability) and $\tau_{\gamma\gamma}$ is the optical depth.

In the most general form, the optical depth $\tau_{\gamma\gamma}$ between two points in the space $(\vec{x}_1, \vec{x}_2)$, for photons γ_{src} with energy E_γ , is given by the following equation

$$\tau_{\gamma\gamma}(E_\gamma, \vec{x}_1, \vec{x}_2) = \int_{t=0}^{t=\|\vec{x}_2-\vec{x}_1\|} \int \int (1-\cos(\theta)) n_\gamma(\epsilon, \Omega, \vec{x}+\vec{u}t) \sigma_{\gamma\gamma}(E_\gamma, \epsilon, \theta) d\Omega d\epsilon dt \quad (1.15)$$

i.e. $\tau_{\gamma\gamma}$ is given by the integral of the product between the process cross section $\sigma_{\gamma\gamma}$ and the targeting photon density $n_{\gamma\gamma}$, integrated over the trajectory t , over the energy ϵ and the direction Ω of the targeting photon⁷. The factor $1 - \cos(\theta)$ accounts for the relative velocity of the interacting particles.

⁷In the equation 1.15, θ is the angle between the direction of γ_{src} and γ_{target} and $\vec{u}$ is the versor of the trajectory $\vec{u} = (\vec{x}_2 - \vec{x}_1)/\|\vec{x}_2 - \vec{x}_1\|$.

The cross section for the pair production process just depends only on the interaction kinematics, not on the origins of the two photons, and can be computed using the quantum-electrodynamics theory; on the other hand, the photon density n_γ depends on the nature of the target photons. Actually, there are three main sources of photons γ_{target} : the cosmic microwave background, the inter stellar radiation field (ISRF) and the extra-galactic background light.

The largest component (in terms of number of photons per unit volume) of the target radiation field is the CMB. The CMB is the relic radiation from the early Universe, released approximately 380,000 years after the Big Bang during the epoch of recombination. At that time, the Universe had cooled to about 3000 K, allowing protons and electrons to combine into hydrogen atoms. As a result, photons decoupled from matter and began to travel freely through space; these photons form the CMB we observe today. Such radiation was discovered in 1965 by Arno Allan Penzias and Robert Woodrow Wilson [97]; its spectral distribution is well described by a blackbody function with $T = 2.7255$ K [98] and its angular distribution is highly isotropic.

The ISRF is the infrared emission of dust, heated by stellar light. This is main source of target photons for the propagation of gamma rays in the Galaxy (together with the CMB) [99, 100].

The EBL [101, 102, 103] refers to the accumulated electromagnetic radiation from all extragalactic sources—primarily stars and galaxies—emitted throughout the history of the universe.

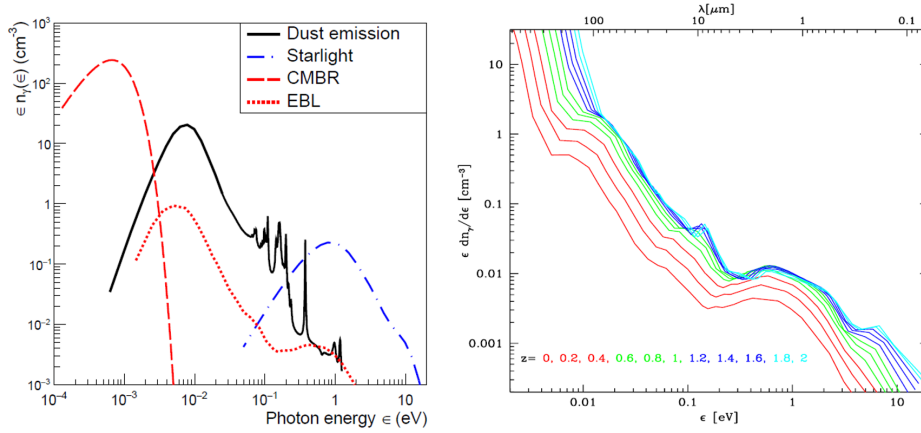


Figure 1.17: Left: number density of the different radiation components in the Solar neighborhood [100]. Right: number density of EBL photons for different redshifts [104].

Figure 1.17 shows the photon distributions for the different components (CMB, EBL, ISRF) [100]. On the left, the distributions are presented within our Galaxy (solar neighbourhood), while on the right they refer to extragalactic regions corresponding to increasing values of redshift [104].

1.3 Neutrino Astronomy

Neutrino astronomy is the main focus of this work. The following chapter will be entirely devoted to neutrino physics and to the detection techniques employed to search for astrophysical neutrino signals. In this section, the main results obtained in this field will be summarized, and the origin of neutrinos, together with their connection to the other cosmic messengers discussed in this chapter, will be outlined.

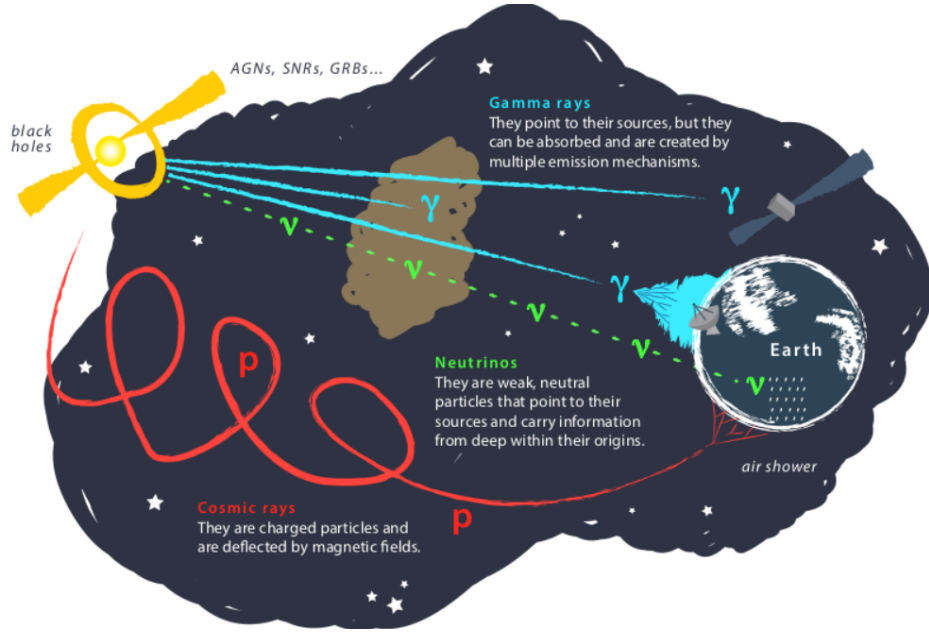


Figure 1.18: Schematic view of the astroparticle probes: cosmic rays, gamma-rays and neutrino

The neutrino is one of the fundamental particles of the Standard Model. Its existence was first hypothesized by Wolfgang Pauli in 1930 and later confirmed experimentally by Clyde Cowan and Frederick Reines in 1956. It is a neutral lepton, and for each of the three lepton flavors—electron, muon, and tau—there exists a corresponding neutrino, denoted respectively as ν_e , ν_μ , and ν_τ .

The main property of the neutrino is that it interacts solely through the weak force. As a consequence, its interactions with matter are extremely rare. This makes neutrinos challenging to detect but, at the same time, ideal cosmic messengers: being electrically neutral, they are not deflected by magnetic fields, and since they are only weakly absorbed, they can traverse vast cosmic distances while preserving the information about their sources almost unaltered (Figure 1.18)

In order to illustrate the extremely weak interaction of neutrinos with mat-

ter, Figure 1.19 compares their penetration depth with other types of radiation. Whereas conventional radiation (α , β , γ , and neutrons) is effectively stopped or absorbed by different materials, a 1 MeV neutrino can pass through virtually all matter.

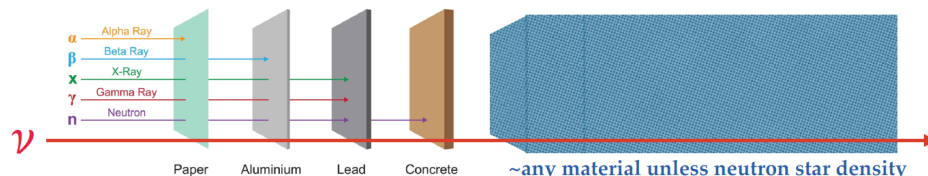


Figure 1.19: Illustration of the penetrating power of neutrinos and other particles. An alpha-ray (i.e. a helium nucleus ${}^4_2\text{He}$) can be stopped by a sheet of paper, a beta-ray (i.e. an electron e^-) can be stopped by an aluminium foil, X-ray and gamma-ray (i.e. photons with energies between 100 eV and 100 keV, X-rays, and energies greater than 100 keV, gamma rays) can be stopped by a lead layer and a neutron can be stopped by a concrete wall. Finally a MeV energetic neutrino is able to pass every material except a neutron star [105].

Neutrinos have never been directly detected; rather, they are investigated through the secondary particles generated in their rare interactions with matter. For astrophysical neutrinos, one of the most established detection techniques involves measuring the Cherenkov light produced by charged secondary particles. Accordingly, neutrino observatories are composed of arrays of PMTs deployed within transparent media such as water or ice.

The detector dimensions are determined by the expected neutrino flux: the lower the flux, the larger the instrumented volume required to collect a statistically meaningful sample of events. Typically, these telescopes are constructed at great depths—either underground or underwater—to reduce the background noise induced by atmospheric muons. Additional technical details regarding the design and operation of neutrino telescopes will be discussed in the following chapter.

One of the first and most significant observations in the field of neutrino astronomy was made in 1987, when the Kamiokande II experiment detected neutrinos originating from Supernova 1987A. The remarkable feature of this observation was that the neutrino signal arrived at Earth several hours before the optical detection of the supernova, providing unique insight into the dynamics of stellar collapse and confirming the role of neutrinos as early messengers of cosmic events.

The neutrinos detected by the Kamiokande experiment originated from nuclear reactions and had energies of the order of a few MeV. The detector consisted of a tank filled with ultra-pure water, located underground, with a total volume of about 1000 m^3 .

To investigate higher-energy events ($E > 100 \text{ GeV} = 10^5 \text{ MeV}$), such as those associated with cosmic-ray production, detectors with instrumented volumes of

the order of one cubic kilometre are required—roughly one million times larger than Kamiokande. Because of the enormous volumes needed, such experiments cannot be constructed underground; instead, they must be deployed in naturally transparent environments such as deep-sea water or large natural lakes or ice.

Starting from the late 1990s, the construction of the first neutrino telescopes meeting the necessary scale and sensitivity requirements began. Among such experiments, two of the most notable were *Baikal NT* and *ANTARES*.

Baikal NT, located in Lake Baikal, Siberia (Russia), and *ANTARES*, deployed in the Mediterranean Sea at a depth of about 2.5 km and 40 km off the coast of Toulon (France), represented the first-generation underwater neutrino detectors. Both instruments had relatively modest instrumented volumes compared to the cubic-kilometre scale later achieved—approximately 10^{-4} km³ for *Baikal NT* and 0.01 km³ for *ANTARES*.

Since 2015, the Baikal experiment has undergone several major upgrades, eventually evolving into *Baikal-GVD* (Gigaton Volume Detector), which has recently reached an instrumented volume of about 0.7 km³. *ANTARES*, on the other hand, concluded its data-taking operations in 2022, after more than fifteen years of continuous activity.

At the South Pole, the construction of the *IceCube Neutrino Observatory* began in the early 2000s. By 2010, *IceCube* achieved an instrumented volume of approximately 1 km³, marking the first detector of true cubic-kilometre scale and inaugurating the era of high-energy neutrino astronomy.

More recently, in 2016, construction of *KM3NeT*, the successor to *ANTARES*, began. The experiment comprises two distinct detectors:

- **KM3NeT/ARCA** (*Astroparticle Research with Cosmics in the Abyss*), designed for high-energy neutrino astronomy and targeting an instrumented volume of about 1 km³;
- **KM3NeT/ORCA** (*Oscillation Research with Cosmics in the Abyss*), optimized for studying the properties of atmospheric neutrinos with a denser, smaller array.

Both detectors are currently under construction and have already begun data collection. Such large-scale instruments mark a new generation of neutrino telescopes, combining unprecedented detection volumes with improved angular and energy resolutions. They will be discussed in detail in the following sections.

1.3.1 Search for cosmic neutrino signal

Diffuse neutrino flux. In 2013, the *IceCube* collaboration reported an excess of events over the expected background from atmospheric neutrinos and misreconstructed atmospheric muons. This observation provided the first evidence of a cosmic neutrino signal, in this case originating from a diffuse emission that could not be resolved into individual sources.

Subsequent analyses performed by the *IceCube* collaboration, using different event samples and selection criteria, confirmed the presence of this diffuse flux

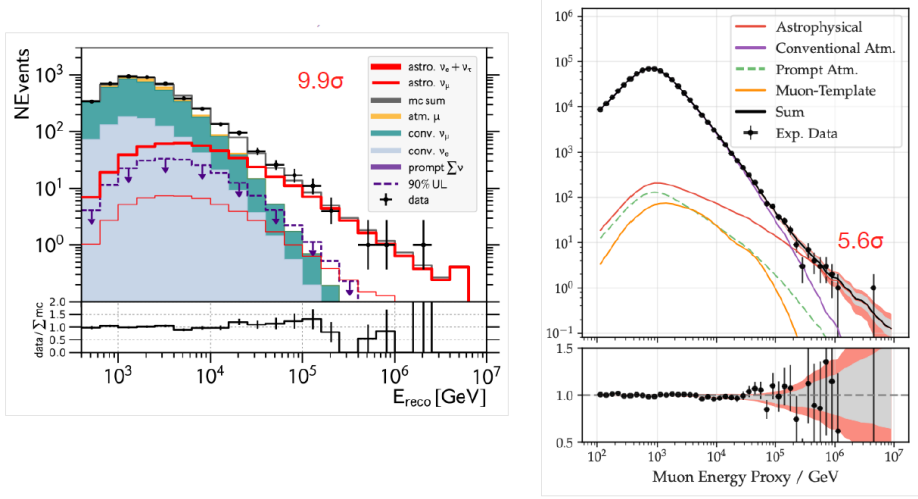


Figure 1.20: IceCube measurement of the diffuse astrophysical neutrino flux over the background of atmospheric neutrino and mis-reconstructed atmospheric muons. The plots show the energy distribution for data and simulated events for the analysis which use shower-like events (left) [106] and the one using track-like events (right) [107]

with a significance exceeding 5σ . Cosmic neutrino interactions predominantly give rise to two classes of event signatures: shower-like and track-like. The origin and underlying mechanisms of these two categories will be discussed in the next chapter. Figure 1.20 illustrates the excess of cosmic neutrinos observed by the IceCube experiment for shower-like (left) [106] and track-like (right) events [107].

In 2025, the *Baikal-GVD* collaboration also reported the observation of a diffuse astrophysical neutrino flux with a significance exceeding 5σ [108]. Both the *IceCube* and *Baikal-GVD* experiments assume a power-law distribution for the diffuse neutrino energy spectrum, expressed as

$$\Phi_{\nu,\text{diff}} = \Phi_{\text{astro}} \left(\frac{E}{100 \text{ TeV}} \right)^{-\gamma_{\text{astro}}}. \quad (1.16)$$

Figure 1.21 shows the best-fit values of the power-law parameters, together with the corresponding confidence-level contour plots. Both the IceCube and Baikal data sets are consistent with a spectral index of

$$\gamma_{\text{astro}} \sim 2.0\text{--}2.5.$$

The two experiments also agree on the normalization scale,

$$\Phi_{\text{astro}} \sim 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.$$

However, the Baikal-GVD data favour a somewhat higher flux compared to IceCube measurements.

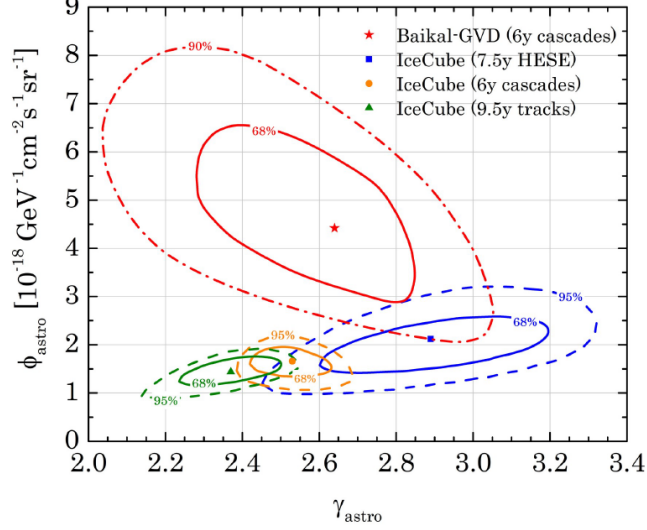


Figure 1.21: The best fit parameters (red star) and the contours at 68% confidence region (red solid curve) and 90% one (red dot-dashed) for the single power law hypothesis obtained in the upward-going cascade analysis of the Baikal-GVD data [108]. Other best fits and the confidence level contours of the 68% (solid) and 95% (dashed) are shown for studies based on high-energy starting events (blue) [109], track-like events (green)[107] and cascade-like events (light orange) by IceCube [106].

Neutrino point source search. Approximately four years after the discovery of the diffuse component, *IceCube* detected the first high-energy neutrino signal associated with an astrophysical source. The neutrino detection was followed by the observation of high-energy photons from the same direction by the *MAGIC* telescope. The gamma-ray emission detected by *MAGIC* was traced back to a flaring blazar, *TXS 0506+056*. This event represented the first identified case of a high-energy neutrino emission coincident with a transient astrophysical object.

In a subsequent analysis, the *IceCube* collaboration identified another excess of neutrino events spatially correlated with the position of the active galactic nucleus *NGC 1068* (also known as the starburst galaxy *Messier 77*). In this case, the observed emission was found to be more consistent with a steady-emission model rather than a flaring scenario.

Neutrino from the Galactic Plane. First indications of TeV-scale neutrino emission from the Galactic Ridge were reported by the *ANTARES* collaboration [110]. More recently, the *IceCube* collaboration measured a flux of Galactic neutrinos with a significance of 4.5σ with respect to the background-only hypothesis [111].

Figure 1.22 shows a map of the Galactic plane, illustrating the point-by-point pre-trial significance of the *IceCube* neutrino observations. While the overall signal is consistent with the modeled diffuse emission expected from the Galactic Plane, a substantial fraction of the observed excess could also originate from a population of unresolved point sources. However, all individual “hot spots” remain statistically compatible with background fluctuations.

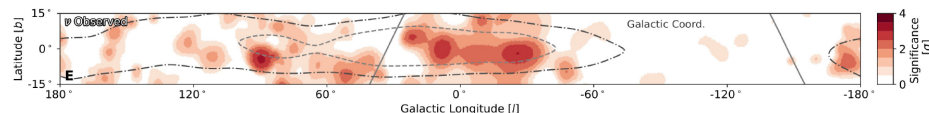


Figure 1.22: The Milky Way plane in neutrinos (Galactic coordinates, with the origin being at the Galactic Center). Pre-trial significance of the IceCube observations using a cascade neutrino event sample, calculated from an all-sky scan for point-like sources [111]. Contours indicate the regions that contain 20% and 50% of the predicted diffuse neutrino emission based on gamma-ray observations by Fermi-LAT. Grey lines indicate the Northern-Southern sky horizon line.

1.3.2 Neutrino origin

High-energy astrophysical neutrinos are produced through interactions between cosmic rays and either ambient matter or radiation fields, arising from highly energetic astrophysical environments such as supernova explosions and active galactic nuclei.

In the case of SNR, neutrino production can occur when the hot material from the inner stellar layers is ejected and collides with the cooler, outer regions of the expanding envelope. In AGN, on the other hand, interactions take place within the accretion disk or in the relativistic jets launched along the rotation axis of the central supermassive black hole, where collisions predominantly occur within the jet plasma itself.

In both scenarios, the accelerated or ejected material (i.e., high-energy protons) may interact not only with photons from the intrinsic radiation field of the source, but also with external photon backgrounds such as the cosmic microwave background, the interstellar radiation field, and the extragalactic background light.

When high-energy protons collide with ambient matter or photon fields, pions are produced through hadronic interactions. Each charged pion subsequently decays into a muon and a muon neutrino. The muon then decays into an electron, an electron neutrino, and another muon neutrino. This decay chain constitutes the primary mechanism responsible for the production of high-energy astrophysical neutrino fluxes, while neutral pion decay leads to the emission of high-energy gamma rays.

Two main channels are typically considered, depending on whether cosmic rays interact with matter or with radiation fields.

Interactions with matter. In collisions of cosmic rays with ambient matter, the dominant processes involve proton–proton or proton–neutron interactions, leading to the production of charged pions:

$$p + p \rightarrow p + n + \pi^+ \quad \text{or} \quad p + n \rightarrow p + p + \pi^- . \quad (1.17)$$

Each charged pion decays as:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu , \quad (1.18)$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu ,$$

followed by the muon decay:

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu . \quad (1.19)$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu .$$

Interactions with radiation. When cosmic rays interact with photon fields, the dominant process proceeds through the photohadronic (or $p\gamma$) channel:

$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ . \quad (1.20)$$

The subsequent pion and muon decays follow the same sequence described above, ultimately leading to the production of neutrinos with comparable energy distributions.

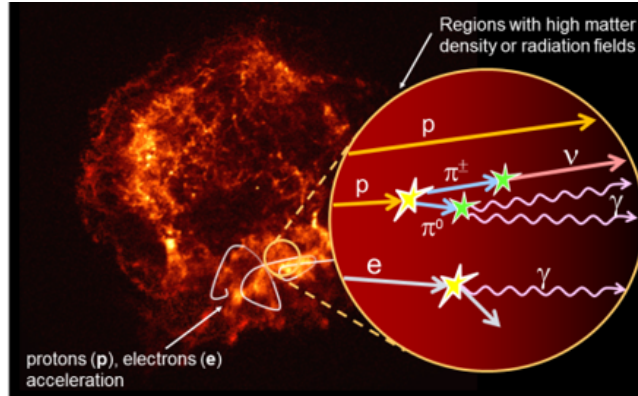


Figure 1.23: Scheme of neutrinos/photons production through the propagation of cosmic rays [112].

1.3.3 Modelling the neutrino signal using information from gamma-ray observations

In the previous section, the main production mechanisms of astrophysical neutrinos were described, highlighting their close connection with high-energy gamma rays and their common origin in the propagation of cosmic rays.

In this context, a theoretical framework has been developed to describe the relationship between the emissions of these messengers. As discussed previously, in the case of proton–proton collisions, the photon spectrum can be expressed as a function of the pion spectrum. Analogously, the neutrino spectrum can be written as

$$\Phi_\nu(E_\nu) = \int_{E_\nu}^{\infty} f_\nu\left(\frac{E_\nu}{E}\right) \Phi_\pi(E) \frac{dE}{E}, \quad (1.21)$$

where f_ν is the neutrino spectrum in the pion rest frame, expressed as a function of the fraction of the pion energy transferred to the neutrino. This function accounts for both the two-body pion decay ($\pi^\pm \rightarrow \mu^\pm + \nu_\mu$) and the subsequent three-body muon decay ($\mu^\pm \rightarrow e^\pm + \nu_e + \nu_\mu$), and depends solely on the intrinsic kinematics of these processes.

The first parametrizations of photon and neutrino fluxes in terms of the pion spectrum were presented in 2006 by **S.R. Kelner**, **F.A. Aharonian**, and **V.V. Bugayov** [95]. Building upon this work, **F. Villante** and **F. Vissani** further developed the Kelner–Aharonian–Bugayov models by including the contributions to the fluxes from the decay of other mesons produced in proton–proton interactions, such as the η meson and kaons (K) [96]. These mesons exhibit decay channels analogous to those of pions but with different branching ratios: for instance, the η meson predominantly decays into two photons ($\eta \rightarrow 2\gamma$) with a branching ratio of approximately 39%, while charged kaons ($K^\pm$) decay mainly into a muon and a neutrino ($K^\pm \rightarrow \mu^\pm + \nu_\mu$) with a branching ratio of about 63%.

In their 2008 paper, Villante and Vissani provided the first formulation of the neutrino spectrum directly in terms of the gamma-ray spectrum, using the most updated parametrizations of the decay functions f_ν . Finally, this framework was refined in 2019 by **C. Mascaretti** and **F. Vissani** [113], who incorporated the latest measurements of neutrino oscillation parameters into the model.

1.4 Gravitational Waves

General Relativity states that a perturbation in a gravitational field propagates as a wave at the speed of light c . All astrophysical phenomena produce oscillations of spacetime which, due to their extremely weak interaction with matter, can propagate across the entire Universe, ideally allowing a probe of the processes taking place in the innermost regions.

However, the effects of these perturbations are extremely small and become significant only when they are produced by large-scale motions of very massive astrophysical objects. A typical example is the merger of a binary system, i.e., the process in which two massive objects (neutron stars or black holes) undergo an inspiral phase, progressively approaching each other until they collide and merge into a single object (Figure 1.24).

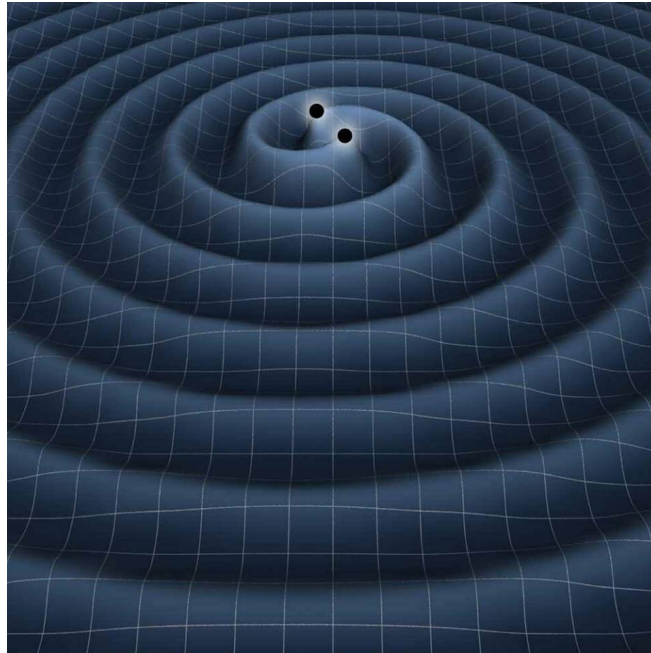


Figure 1.24: A schematic representation of gravitational waves produced by the collapse of a binary system. In this image, the disturbance is illustrated as ripples in space-time, the intensity and frequency of which depend on the mass of the two objects and their rotational speed.

1.4.1 Detection technique

The extremely weak nature of the gravitational interaction makes the detection of such signals very challenging. Gravitational waves are detected and studied using laser interferometers, whose operating principle combines a Michelson

interferometer configuration with Fabry–Perot cavities (Figure 1.25). In this framework, gravitational perturbations are measured as relative variations in the arm lengths, encoded as phase differences between laser beams propagating along the two arms of the detector. These variations are typically expressed in terms of the dimensionless strain. Upon interacting with the detector, the wave momentarily modifies the lengths of the perpendicular arms, leading to corresponding alterations in the path length traveled by the laser beam. Interferometric detectors such as LIGO (Hanford and Livingston, United States) [114](Figure 1.25) and VIRGO (Pisa, Italy) [115] have been developed for this purpose.

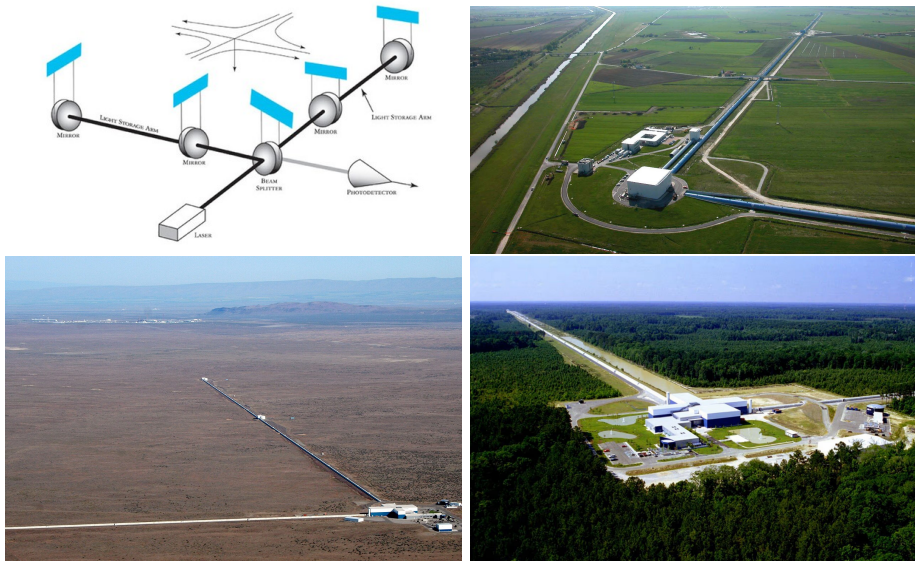


Figure 1.25: On the top left, interferometer diagram; the presence of a gravitational wave is detected as a noticeable shift in the interference pattern. On the top right, the Virgo interferometer, located in Italy. On the bottom left, LIGO LA interferometer in Livingston, Louisiana. On the bottom right, LIGO WA Interferometer in Hanford, Washington.

On September 14, 2015, the first gravitational wave signal (GW150914) was observed [114] (Figure 1.26). The event was found to be consistent with a phenomenon predicted by General Relativity and never observed before: the inspiral and subsequent merger of two black holes, leading to the formation of a single remnant black hole.

Figure 1.27 shows the expected strain curve for this phenomenon. The rotation of the two black holes is responsible for the oscillations; as the two objects approach each other, the period of the oscillations decreases, with a corresponding increase in the frequency and amplitude of the oscillations. These two parameters reach their maximum at the moment the two bodies begin to merge and then decrease considerably once they become a single black hole.

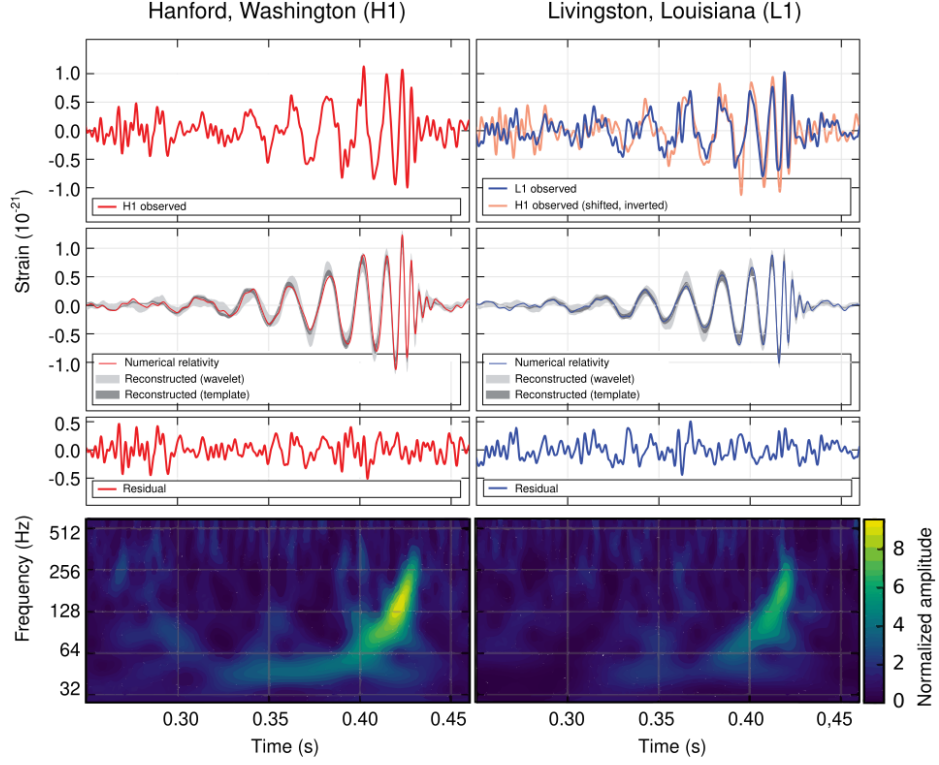


Figure 1.26: LIGO measurement of the gravitational waves at the Hanford (left) and Livingston (right) detectors, compared to the theoretical expected values [114].

At the time of GW150914, the VIRGO detector was not yet operational, and the signal was observed only by the two LIGO interferometers. As a consequence, the localization of the source in the sky was relatively poor.

A major step forward was achieved with the detection of GW170817 on August 17, 2017 [116], when the global network of interferometers, including VIRGO, was operational. This signal was associated with the inspiral and merger of a binary neutron star system and was observed by the LIGO and VIRGO interferometers. Remarkably, the gravitational wave detection was followed by the observation of a short gamma-ray burst (GRB 170817A) by the *Fermi* and *INTEGRAL* satellites, as well as by a broad electromagnetic counterpart across multiple wavelengths. This event provided the first direct evidence of a binary neutron star merger as the progenitor of short gamma-ray bursts and marked the beginning of the multimessenger astronomy era, demonstrating the complementarity between gravitational wave and electromagnetic observations.

To conclude the discussion on gravitational-wave detection, it is worth noting

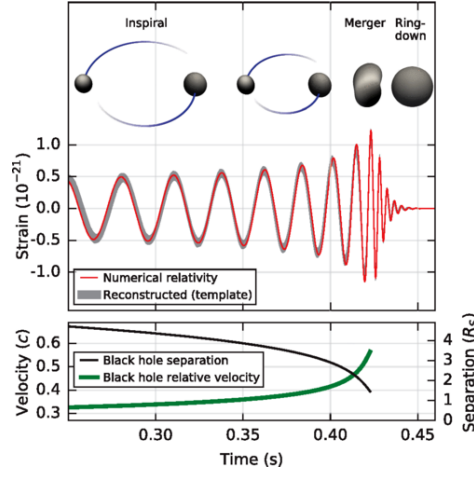


Figure 1.27: Estimated gravitational-wave strain amplitude from GW150914 [114].

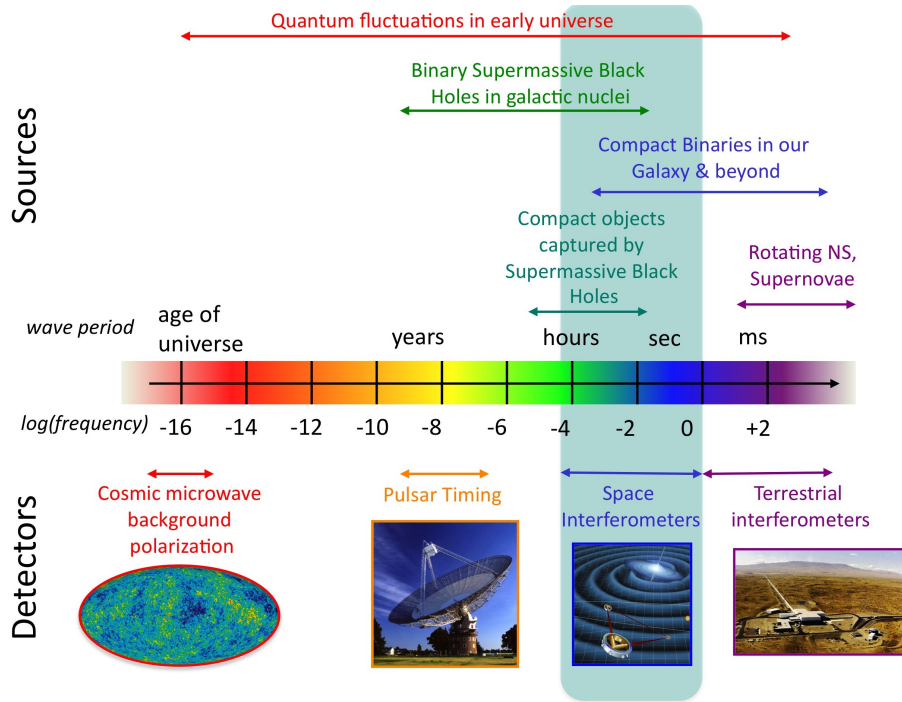


Figure 1.28: Gravitational waves range of frequency [117] for different sources and different detectors.

that in recent years several alternative techniques to ground-based interferometers have been under development. These include the design of space-based interferometers, such as LISA [118] and the use of pulsar timing arrays [119]. In the latter case, gravitational waves are studied by monitoring the arrival times of pulses from multiple pulsars distributed across the Galaxy. Minute variations in these arrival times, induced by the passage of gravitational waves, can be detected thanks to the extraordinary regularity of pulsar emission.

The development of these techniques will make it possible to observe gravitational waves at frequencies much lower than those accessible to current ground-based interferometers, thereby opening access to different regions of the gravitational wave spectrum, as illustrated in Figure 1.28.

1.4.2 Gravitational waves origin and combined search with neutrinos

Gravitational wave sources can be classified into two main categories [120]: the first related to a cosmological origin, and the second to a relativistic-astrophysical origin. In cosmological models, gravitational waves would have been produced during the earliest phases of the Universe and are referred to as primordial gravitational waves [121].

Concerning the relativistic-astrophysical origin, gravitational waves can arise from the following processes: rotation of a non-axisymmetric neutron star; supernova explosions; and inspiral, merger, and ringdown of compact binary systems involving white dwarfs, neutron stars, and/or black holes. Compact binary systems are the dominant observed sources [120].

As mentioned at the beginning of this work, the focus is placed on the connection between cosmic rays, gamma rays, and neutrinos, rather than on their relation to gravitational waves. Nevertheless, it is worth noting the interest in searching for coincidences between neutrino signals and gravitational-wave events, particularly following the observation of gravitational waves accompanied by electromagnetic emission in the case of GW170817.

Both IceCube and KM3NeT have performed joint analyses with the LIGO–Virgo collaboration to investigate such coincidences [122, 123]. However, no direct evidence for an association between neutrinos and gravitational-wave events has been found so far.

1.5 Summary: Cosmic Rays, Gamma Rays, and Neutrinos

Cosmic rays (CRs), gamma rays, and neutrinos are the three principal messengers used to probe the high-energy Universe. Together with GWs, they provide a complementary view of the most extreme astrophysical environments and of the

mechanisms responsible for particle acceleration beyond the reach of terrestrial experiments.

Because of magnetic deflection by the interstellar and intergalactic magnetic fields, cosmic rays lose directional information during propagation, making it extremely difficult to identify their sources. The study of cosmic rays is therefore focused on energy spectra, composition, and large-scale anisotropies. Measurements from the Pierre Auger Observatory have revealed a significant dipole anisotropy at energies above 8 EeV, pointing about 115° away from the Galactic Centre, consistent with an extragalactic origin of ultra-high-energy cosmic rays. At lower energies, the nearly isotropic arrival directions indicate that most CRs up to the *knee* are produced within the Milky Way, with a gradual transition to extragalactic sources around the *ankle* region.

Unlike cosmic rays, gamma rays are neutral and thus travel in straight lines from their production sites, providing direct information about their sources. High-energy (HE) and very-high-energy (VHE) gamma rays are produced through both leptonic and hadronic processes, the latter being directly connected to the acceleration of CRs. Space-based telescopes such as *Fermi-LAT*, *AGILE*, and *DAMPE* have mapped hundreds of sources up to hundreds of GeV, while ground-based instruments such as *H.E.S.S.*, *MAGIC*, and *VERITAS* have extended these observations into the TeV regime. More recently, extensive air-shower arrays like *HAWC*, *LHAASO*, and *Tibet AS γ* have discovered sources emitting photons up to PeV energies, marking the beginning of ultra-high-energy (UHE) gamma-ray astronomy and offering key insights into Galactic particle accelerators or “PeVatrons”.

Neutrinos, on the other hand, interact only through the weak force, which makes them exceptionally difficult to detect but ideal for carrying unaltered information from the most obscured regions of the Universe. The detection of a diffuse flux of astrophysical neutrinos by the *IceCube* Collaboration in 2013 marked the beginning of neutrino astronomy. Later, the association of a high-energy neutrino with the flaring blazar TXS 0506+056, and the steady emission from NGC 1068, confirmed neutrinos as unique probes of non-thermal processes in astrophysical sources.

Most recently, the *KM3NeT* Collaboration has reported the detection of an ultra-high-energy neutrino event [124]. Preliminary studies indicate an estimated energy in the hundreds of PeV range, highlighting the potential of next-generation detectors to probe extreme acceleration regimes and to search for cosmogenic neutrinos.

Together, these observations establish the foundation of multi-messenger astronomy. By correlating charged cosmic rays, neutral gamma rays, and weakly interacting neutrinos, it becomes possible to constrain the origin of cosmic accelerators and to explore the physical mechanisms that govern the most energetic phenomena in the Universe.

Chapter 2

Neutrino physics and neutrino telescope

In the previous chapter, neutrino astronomy and its principal experimental results were introduced. This chapter examines neutrino physics in detail, beginning with the discovery of the particle and fundamental interaction mechanism. Subsequently, the main natural sources of neutrinos are described, including the cosmic neutrino background ($C\nu B$), thermal and nuclear processes in the Sun, core-collapse supernovae, radioactive materials in the Earth's crust.

The final sections focus on the experiments employed to observe neutrinos produced during the acceleration and propagation of cosmic rays: neutrino telescopes (neutrino observatories). Although these detectors were introduced in the previous chapter, their operating principles and detection techniques are presented here.

Finally, two experiments of this class that are central to this work are described in detail: ANTARES and KM3NeT

2.1 Properties of the Neutrino

Particle physics describes the fundamental constituents of the Universe, the elementary particles, in terms of their individual properties and of the interactions among them, the forces. By individual properties, one refers to quantities such as mass, charge, and spin. The four fundamental forces through which particles interact are the gravitational force, the electromagnetic force, the strong force, and the weak force. However, since the gravitational interaction between two particles is exceedingly small compared to the others, it is usually neglected in particle physics.

This description is used here to outline the basic idea underlying the Standard Model; a complete and accurate treatment lies beyond the scope of this work.

In such a picture, the neutrino is a fundamental particle within the Standard

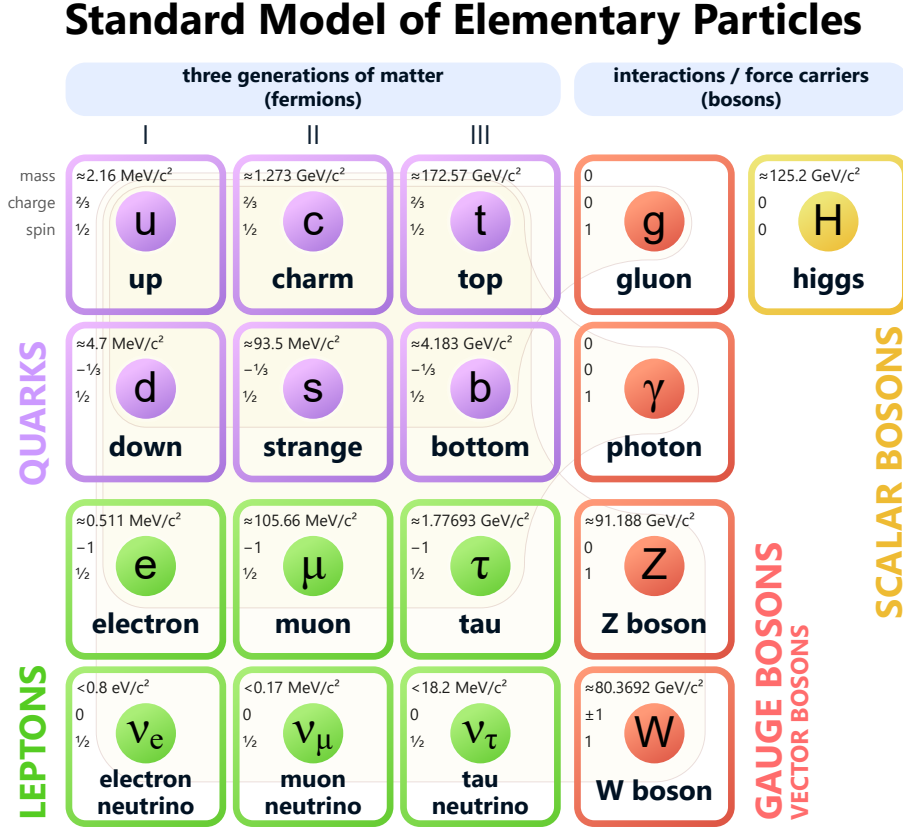


Figure 2.1: Scheme of the elementary particle of the Standard Model [125]. On the left are the fermions, particles with half-integer spin, and on the right are the bosons, particles with integer spin. Fermions can be divided into two families: quarks, which are subject to the strong interaction, and leptons, which are not. Finally, leptons are divided into those with charge and those that are neutral, the neutrinos. As for bosons, we can distinguish between vector bosons, which have spin 1, and the Higgs boson, which has spin 0. The four vector bosons are the mediators of the three fundamental forces: the gluon, mediator of the strong interaction; the photon, mediator of the electromagnetic interaction; and the W and Z bosons, both mediators of the weak interaction. In particular, the W boson is the mediator of charged current processes and the Z boson is the mediator of neutral current processes.

Model and is uniquely characterized by interacting solely through the weak force. Neutrinos are fermions with spin $1/2$ and belong to the lepton family—particles that do not experience the strong interaction. As their name suggests, neutrinos carry no electric charge and therefore do not participate in electromagnetic interactions.

Three neutrino flavours are known, each associated with a corresponding charged lepton: the electron (e), the muon (μ), and the tau (τ).

Neutrinos are massive particles and are commonly regarded as the lightest known particles (with the exception of photons and gluons, which are massless). For many calculations in particle physics, it is therefore convenient to approximate neutrinos as massless. At present, the exact values of the neutrino masses are not known, and only upper limits have been established.

This section provides a brief account of the historical discovery of the neutrino. It then discusses the mechanisms through which neutrinos interact, as well as the phenomenon of flavour oscillations that occurs during their propagation.

2.1.1 History of neutrino physics

From a historical perspective, the discovery and study of neutrinos is closely linked with the study of weak interaction. The weak interaction is responsible for beta decay of nuclei, the process in which, initially, a nucleus (Z, A) was observed to decay into a nucleus ($Z+1, A$) with the emission of an electron. If this had been a two-body decay the energy spectrum of the electron should have appeared as a narrow line. Surprisingly, in 1927, Charles Drummond Ellis and William Alfred Wooster found that the spectrum is continuous as in the case of a three-body decay [126]. To explain this, in 1930, Wolfgang Pauli hypothesised that another particle was emitted in the process together with the electron and, to be consistent with the experimental observations at the time, this particle had to be a neutral particle with a mass so light that its interaction with the rest of matter was effectively zero [127].

For these reasons, Pauli called this particle a “neutron”. The name was later changed when the true neutron was discovered by James Chadwick in 1932 [128] and it was observed that it also underwent beta decay. Influenced by Chadwick’s discovery, Enrico Fermi developed the first theoretical model of beta decay in 1934 [129], where the term “neutrino” was used for the first time.

Fermi’s theory was a reference point for Clyde Cowan and Frederick Reines, who in 1956 finally succeeded in revealing the existence of the neutrino by observing electron antineutrinos produced in nuclear reactors [130]. Furthermore, it was in these processes that the charge-current mechanism through which neutrinos interact was observed for the first time. A detailed description of neutrino interaction processes will be provided in the next section.

Following the discovery of the electron neutrino, several crucial experimental and theoretical breakthroughs helped shape our modern understanding of neutrinos and of the weak interaction. Between 1956 and 1957, Chien-Shiung Wu and collaborators performed a landmark experiment on the beta decay of ^{60}Co ,

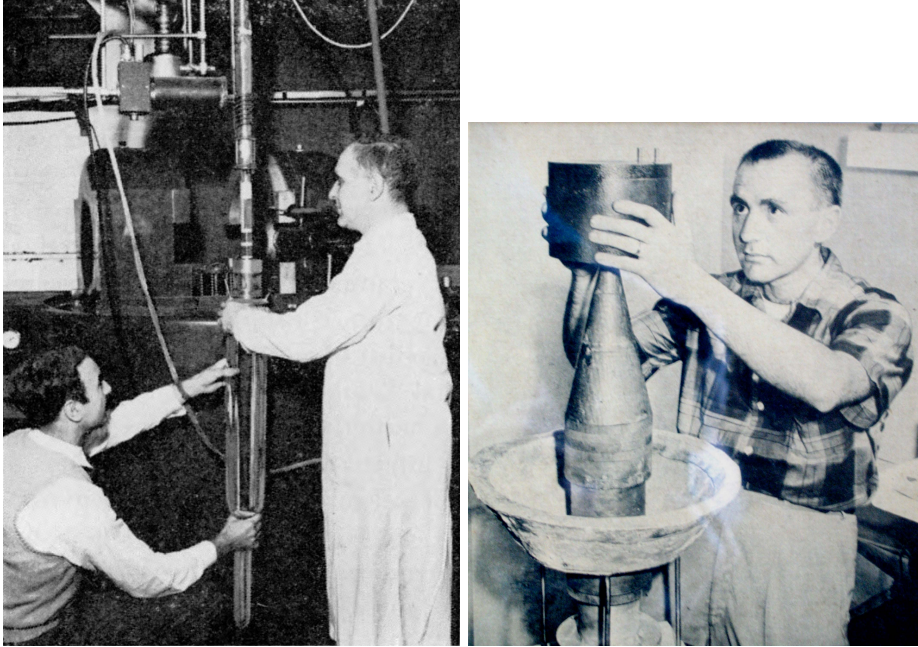


Figure 2.2: On the left, the Wu experiment performed at the Bureau of Standards low temperature laboratory, Washington DC, in 1956. The vertical vacuum chamber, containing the cobalt-60, detectors, and field coil, is being placed into a Dewar before being inserted into the large electromagnet in the background, which will cool the radioisotope near absolute zero by adiabatic demagnetization. On the right, Apparatus of the Goldhaber, Grodzins, Sunyar experiment 1957. This experiment was made at Brookhaven. It used the electron capture by the nucleus of Europium 152 which produces a ν_e and a nucleus of Samarium 152, which emits a gamma ray whose helicity is the same as the neutrino one if they are emitted back to back. A NaI photomultiplier placed below a lead shield allowed to detect the gamma ray and to measure its polarization. The result showed without ambiguity that neutrinos have always a negative helicity

demonstrating for the first time that the weak interaction violates parity symmetry [131] (Figure 2.2 left). Shortly afterwards, in 1957, Maurice Goldhaber, Lee Grodzins, and Andrew W. Sunyar measured the polarization of neutrinos emitted in electron capture and showed that interacting neutrinos are essentially left-handed (negative helicity) [132] (Figure 2.2 right).

These two key experimental results provided the empirical foundation for refining Fermi's original model: they directly inspired the formulation of the vector-minus-axial (V-A) structure of the weak interaction, developed independently by Sudarshan & Marshak and by Feynman & Gell-Mann. [133, 134] The V-A theory successfully incorporated parity violation and became the conceptual

backbone for the subsequent electroweak theory.

A further major step came with the identification of additional neutrino flavours. The first high-energy neutrino experiment at Brookhaven (1962) demonstrated interactions of the muon neutrino, establishing experimentally that ν_e and ν_μ are distinct particles [135], Lederman, Schwartz and Steinberger were central members of this collaboration. Over a decade later, in 1975, Martin Perl and collaborators discovered the tau lepton, which implied the existence of a third neutrino flavour, ν_τ . [136]

In the 1970s and 1980s the observation of neutral current processes mediated by the Z^0 boson confirmed essential aspects of electroweak unification, consolidating the role of neutrinos in the Standard Model. On 19 July 1973, the Gargamelle group, at CERN, announced that they had found evidence of weak neutral currents [137]. In 1983, two CERN experiments, UA1 and UA2, discovered the W and Z particles [138], which are, respectively, the mediators of the positive current and neutral current processes.

Finally, the study of solar neutrinos was crucial in the discovery of the phenomenon of flavour oscillations. Electron neutrinos are produced in the Sun, in large quantities, through the nuclear processes that lead to the formation of nuclei. The solar neutrino flux was first observed in 1968 by the Homestake experiment [139]. The Homestake results showed a deficit between the expected and the observed number of events, the “solar neutrino puzzle” [140]. This deficit was later confirmed by the data of the Super-Kamiokande experiment in 1998 [141] (Figure 2.3 left). In 2002, the SNO experiment (Figure 2.3 right) demonstrated that this discrepancy was due to flavour oscillations by measuring the flux of electron, muon, and tau neutrinos [142]. Such observations demonstrated that neutrinos have non-zero mass.

2.1.2 Neutrino interaction with matter

The three forces acting on elementary particles, excluding gravity, are the strong force, the electromagnetic force, and the weak force. The strong force acts only on quarks, the electromagnetic force acts on charged particles, namely quarks and charged leptons, while the weak force acts on all elementary particles. Consequently, through the weak interaction, neutrinos can interact with all other particles, either with leptons or with the hadronic constituents of nuclei.

The strength of the interaction is characterised by the cross section, which determines the interaction rate for a given incident flux and number of targets (see Sect. 2.1.3). The probability for a neutrino to interact in matter is much larger when nucleons are present than when only electrons are available, simply because a nucleus contains many nucleons and thus provides a far greater number of scattering centers per atom.

One usually distinguishes three principal interaction regimes depending on the neutrino energy:

- **Quasi-elastic scattering (QE):** dominant at low energies, typically $E_\nu \lesssim 1$ GeV. In this regime the neutrino scatters coherently off a nucleon produc-

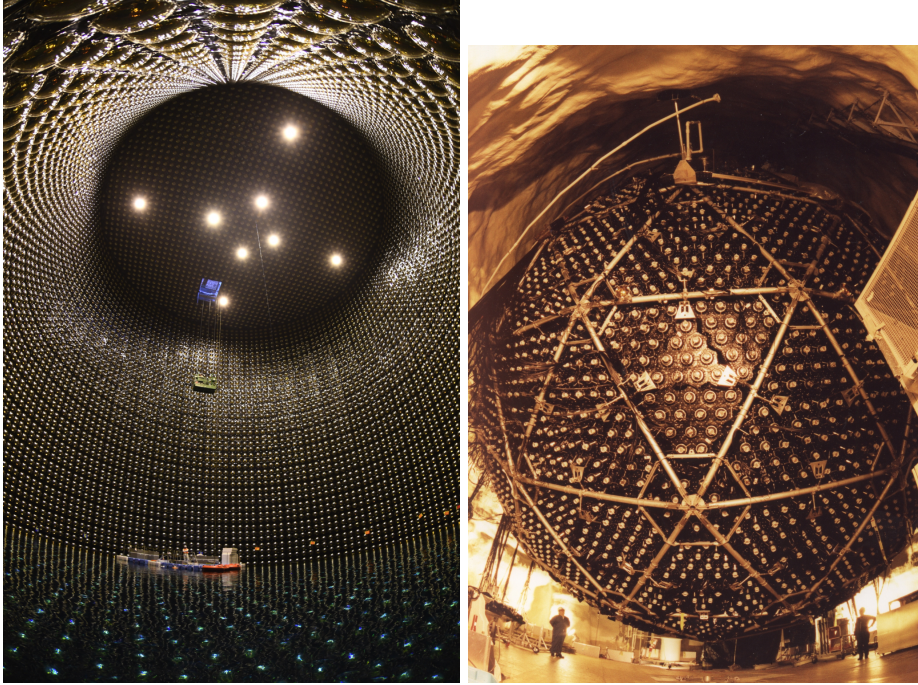


Figure 2.3: On the left, Inside view of the Super - Kamiokande experiment. It is located 1,000 m underground in the Mozumi Mine in Hida's Kamioka area. It consists of a cylindrical stainless steel tank that is 41.4 m tall and 39.3 m in diameter holding 50,220 tonnes of ultrapure water. The tank volume is divided by a stainless steel superstructure into an inner detector region and outer detector. Mounted on the superstructure are 11,146 photomultiplier tubes 50 cm in diameter that face the inner detector and 1,885 20 cm PMTs that face the outer detector. On the right, Outside view of the Sudbury Neutrino Observatory detector. The SNO detector target consisted of 1,000 tonnes of heavy water contained in a 6-metre-radius acrylic vessel. The detector cavity outside the vessel was filled with normal water to provide both buoyancy for the vessel and radiation shielding. The heavy water was viewed by approximately 9,600 PMTs mounted on a geodesic sphere at a radius of about 850 cm.

ing a single outgoing lepton and a recoiling nucleon (or an excited nucleon that subsequently de-excites).

- **Resonance production (RES):** for intermediate energies (around 1 GeV), resonant excitation of nucleon resonances (e.g. Δ) contributes significantly to the cross section.
- **Deep inelastic scattering (DIS):** at higher energies (tens of GeV and above) the neutrino resolves the nucleon's partonic structure and scatters

off individual quarks, producing multi-particle hadronic final states. This is the regime most relevant for high-energy astrophysical neutrinos.

The mediators of the weak interaction are the charged bosons $W^\pm$ and the neutral boson Z^0 . Unlike the photon and the gluons, these bosons are massive: $M_W \simeq 80.38 \text{ GeV}/c^2$ and $M_Z \simeq 91.19 \text{ GeV}/c^2$ (PDG values [9]). The mediator charge determines the interaction channel and the apparent final state.

Charged-current (CC) interactions. A neutrino of flavour ν_ℓ ($\ell = e, \mu, \tau$) interacting via charged-current exchange converts into the corresponding charged lepton ℓ^- and produces a hadronic final state X when the target is a nucleon:

$$\nu_\ell + N \rightarrow \ell^- + X. \quad (2.1)$$

For antineutrinos the analogue process is

$$\bar{\nu}_\ell + N \rightarrow \ell^+ + X'. \quad (2.2)$$

In the CC channel a substantial fraction of the neutrino energy is transferred to the charged lepton, which typically provides an experimentally distinctive signature (an electromagnetic shower for ν_e CC, a long muon track for ν_μ CC, and a short-lived τ with its characteristic decay products for ν_τ CC), while the hadronic system X develops a hadronic shower.

Neutral-current (NC) interactions. Neutral-current exchange leaves the neutrino flavour unchanged:

$$\nu_\ell + N \rightarrow \nu_\ell + Y, \quad (2.3)$$

where Y denotes the hadronic final state. NC interactions typically deposit only a fraction of the primary neutrino energy in the visible detector through the hadronic shower; the outgoing neutrino escapes undetected.

For high-energy astrophysical neutrinos (conventionally $E_\nu \gtrsim 100 \text{ GeV}$), DIS dominates and the interaction almost invariably results in the development of hadronic cascades. Thus, irrespective of whether the process is CC or NC, the collision produces an observable hadronic shower: in CC events that shower is accompanied by the charged-lepton signature, whereas in NC events the hadronic cascade is the primary visible imprint. The detailed partitioning of energy between the hadronic system and the outgoing lepton (or neutrino in the NC case) is determined by the inelasticity distribution of the process and by the neutrino flavour and energy.

2.1.3 Interaction cross section

The interaction of a particle with matter is commonly quantified in terms of its cross section σ . Given an incident flux Φ_b and a number of target centers N_t , the interaction rate dN_i/dt is defined as [143]

$$\frac{dN_i}{dt} = \sigma \Phi_b N_t, \quad (2.4)$$

which expresses the proportionality between the measurable rate of interactions and the underlying microscopic probability encoded in σ .

Figure 2.4 shows the charged-current neutrino–nucleon cross section as a function of the neutrino energy E_ν (the corresponding center-of-mass energy $\sqrt{s}$ is indicated on the top axis). At neutrino energies below roughly 10^3 GeV, the cross section grows nearly linearly with E_ν . This behavior derive from the kinematics of deep inelastic scattering in the low-momentum-transfer regime, where the dominant factor is the increase in center-of-mass energy, $s \simeq 2m_N E_\nu$.

$$\sigma_{\nu N}(E_\nu) \propto G_F^2 s \sim G_F^2 m_N E_\nu \quad (2.5)$$

where G_F is the Fermi’s constant and m_N is the nucleon mass.

Around 10^3 – 10^4 GeV, the growth of the cross section changes behavior as the center-of-mass energy becomes comparable to the mass of the charged weak boson, $\sqrt{s} \gtrsim M_W \simeq 80$ GeV. Beyond this threshold, the weak-boson propagator introduces a suppression factor of the form $(Q^2 + M_W^2)^{-2}$, which reduces the efficiency with which higher momentum transfers contribute to the scattering amplitude. Simultaneously, the interaction begins to probe the nucleon at small Bjorken- x , where the parton distribution functions rise only moderately, approximately as $x^{-\lambda}$ with a small positive exponent λ .

The combined effect of weak-boson propagation and small- x QCD dynamics leads to a slower-than-linear increase of the neutrino–nucleon cross section at high energies. The dependence can be approximated by a power law,

$$\sigma_{\nu N}(E_\nu) \propto E_\nu^\alpha, \quad (2.6)$$

with an effective exponent $\alpha \simeq 0.2$ – 0.4 , depending on the choice of parton distribution function set and the details of QCD evolution. Classic calculations [144, 145, 146] and more recent updates consistently find $\alpha \approx 0.3$ – 0.4 across the multi-TeV to ultra-high-energy range.

Therefore, while at sub-TeV energies the cross section scales nearly linearly with the neutrino energy, above a few TeV the increase becomes significantly more gradual, reflecting the onset of propagator suppression and the increasingly important role of the nucleon’s partonic structure at small x .

2.1.4 Neutrino oscillations

One of the most striking properties of neutrinos is their ability to change flavour during propagation. This phenomenon — neutrino oscillation — can only occur if neutrinos possess non-zero masses, a situation not accommodated in the original formulation of the Standard Model. The possibility of flavour conversion was first proposed by Bruno Pontecorvo in 1967 [158] and was experimentally established by the results of Super-Kamiokande collaboration in 1998 [141] and of the SNO collaboration in 2002 [142].

The theoretical description establish that the three flavour eigenstates $\{\nu_e, \nu_\mu, \nu_\tau\}$, in which neutrinos are produced and detected, are coherent superpositions of the three mass eigenstates $\{\nu_1, \nu_2, \nu_3\}$ with definite masses m_1, m_2, m_3 . The relation

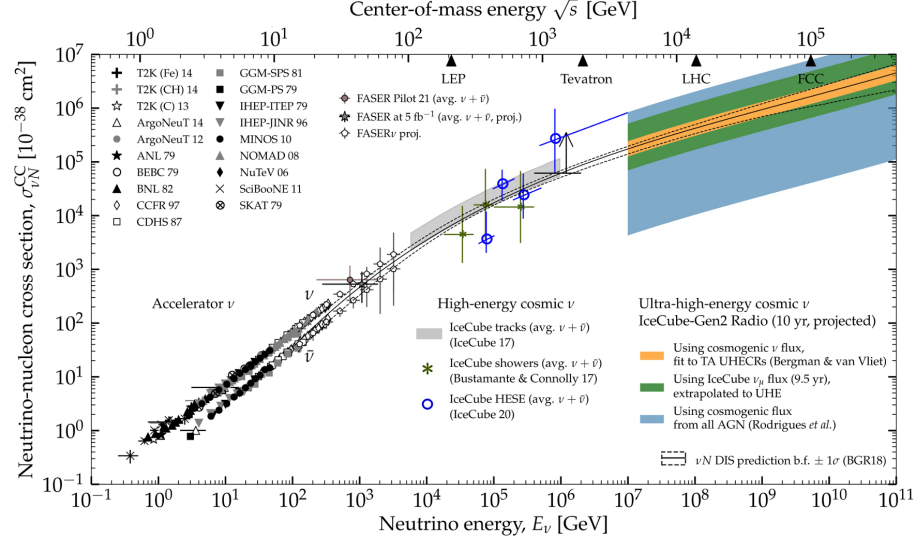


Figure 2.4: Neutrino–nucleon charged-current (CC) cross section [147, 148]: measurements and predictions. Sub-TeV measurements come from accelerator-based experiments [149, 150, 151, 152, 153]; few-TeV measurements from the FASER ν experiment [154]; TeV–PeV measurements from IceCube astrophysical neutrino data [155, 156, 157].

between flavour and mass states is encoded in the unitary Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix U :

$$|\nu_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i}^* |\nu_i\rangle \quad (\alpha = e, \mu, \tau). \quad (2.7)$$

A neutrino produced as a flavour eigenstate $|\nu_\alpha\rangle$ propagates as a superposition of mass eigenstates; after a distance L (or time t), interference among the mass components produces a non-zero probability to observe a different flavour β . The exact transition probability in vacuum is

$$P_{\alpha \rightarrow \beta}(L, E) = \left| \sum_{i=1}^3 U_{\beta i} e^{-i \frac{m_i^2}{2E} L} U_{\alpha i}^* \right|^2, \quad (2.8)$$

where E is the neutrino energy and we used the relativistic approximation $E_i \simeq E + m_i^2/(2E)$. Oscillations are governed by the mass-squared differences $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$ and by the mixing angles and phases contained in U . In many practical situations a two-flavour approximation suffices and the transition probability reduces to the form

$$P_{\alpha \rightarrow \beta} \simeq \sin^2(2\theta) \sin^2 \left(1.27 \frac{\Delta m^2 [\text{eV}^2] L [\text{km}]}{E [\text{GeV}]} \right), \quad (2.9)$$

where θ is the effective mixing angle and Δm^2 the relevant mass-splitting.

A few important points follow directly from this formalism:

- Oscillation experiments are sensitive only to mass-squared differences Δm_{ij}^2 and to the elements of the mixing matrix U ; they do not determine the absolute neutrino masses m_i . Independent probes (kinematic beta-decay experiments such as KATRIN [159] and cosmological observations) set upper bounds on the absolute scale of neutrino masses.
- Several parameters remain to be fully determined: the sign of Δm_{31}^2 (mass ordering, normal versus inverted), the octant of θ_{23} , and the possible CP-violating phase δ_{CP} in the PMNS matrix.
- For astrophysical neutrinos that travel astronomical distances, oscillations average out because the oscillation phases become extremely large. In this averaged regime, the flavour transition probabilities become time and distance independent and are determined by the moduli squared of the mixing matrix elements,

$$\langle P_{\alpha \rightarrow \beta} \rangle = \sum_{i=1}^3 |U_{\alpha i}|^2 |U_{\beta i}|^2.$$

Consequently, a commonly quoted example is the pion-decay source flavour composition $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ which, after long-baseline averaging, is converted to approximately $1 : 1 : 1$ at Earth (up to small deviations due to the precise values of the mixing parameters).

In summary, neutrino oscillations provide direct evidence of physics beyond the minimal Standard Model by demonstrating that neutrinos have mass. The phenomenon is quantitatively described by the PMNS framework and has been confirmed by a wealth of solar, atmospheric, reactor and accelerator experiments; further precision measurements are focused on resolving the mass ordering, measuring δ_{CP} , and pinning down the remaining parameter uncertainties.

2.2 Neutrino sources and neutrino fluxes

The overall spectrum of neutrinos produced by all existing sources, known as the Grand Unified Neutrino Spectrum (GUNS), is expected to extend over 24 orders of magnitude, from 10^{-6} eV up to 10^{18} eV. Figure 2.5 shows the Grand Unified Neutrino Spectrum presented [160]. According to this framework, up to energies of order meV, neutrinos originate predominantly from primordial processes in the early Universe, namely the Cosmic Neutrino Background (CNB) and neutrinos produced shortly after the Big Bang (BBN). The former represents a relic background of neutrinos [161], analogous to the photon CMB, while the latter originates from weak decays of neutrons and light nuclei formed during Big Bang nucleosynthesis, such as neutron beta decay (BBH(n): $n \rightarrow p + e^- + \bar{\nu}_e$) and tritium decay (BBH(^3H): $^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e$) [162].

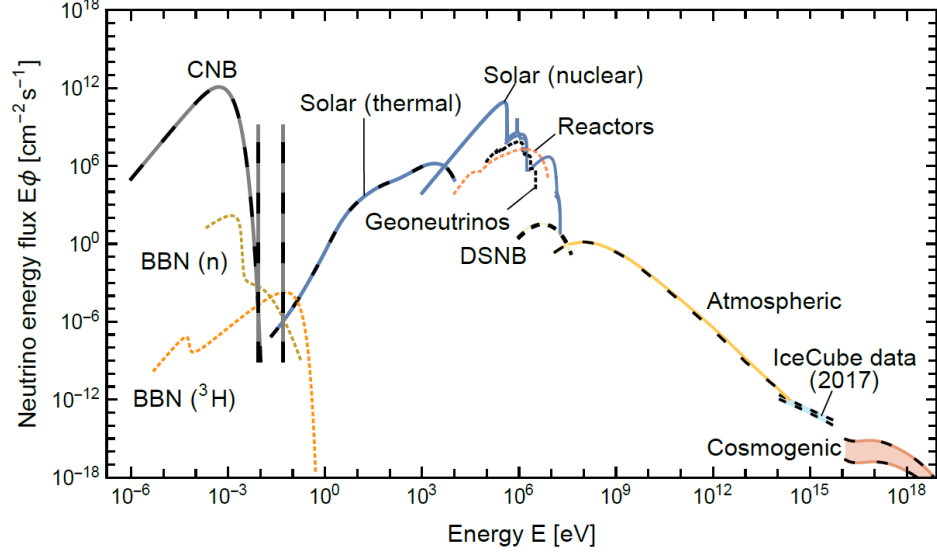


Figure 2.5: Grand Unified Neutrino Spectrum at Earth, integrated over all directions and summed over flavors [160]. Solid lines refer to neutrinos, while dashed or dotted lines refer to antineutrinos.

Between meV and keV energies, the dominant contribution arises from solar thermal neutrinos [163, 164]. These are produced through several plasma processes such as plasmon decay ($\gamma \rightarrow \nu + \bar{\nu}$), Compton scattering ($\gamma + e^- \rightarrow e^- + \nu + \bar{\nu}$), and Bremsstrahlung ($Ze + e^- \rightarrow e^- + Ze + \nu + \bar{\nu}$). As in the primordial case, these fluxes have not yet been observed directly and current predictions rely entirely on theoretical models of stellar interiors.

In the energy range between keV and MeV, the main contribution comes from neutrinos produced by nuclear fusion processes occurring in the Sun, starting from hydrogen burning into helium, and continuing with helium fusion and the subsequent reactions of the carbon–nitrogen–oxygen (CNO) cycle [163, 164].

From MeV to GeV energies, natural neutrinos originate from nuclear fission in reactors [165] and from the radioactive decay of isotopes within the Earth’s crust, such as ^{238}U , ^{235}U , and ^{40}K . These neutrinos are collectively known as geoneutrinos [166]. In the same energy range, a significant contribution comes from core-collapse supernovae and the diffuse supernova neutrino background (DSNB) [167].

At higher energies, the dominant contribution arises from the processes described in the previous chapter. Beginning at GeV energies, atmospheric neutrinos are produced by collisions of primary cosmic rays with Earth’s atmosphere. Their spectrum is determined mainly by the propagation and decay chains of pions and kaons. The expected flux is approximately related to the primary cosmic-ray spectrum by an additional factor of $1/E$ due to meson decay kin-

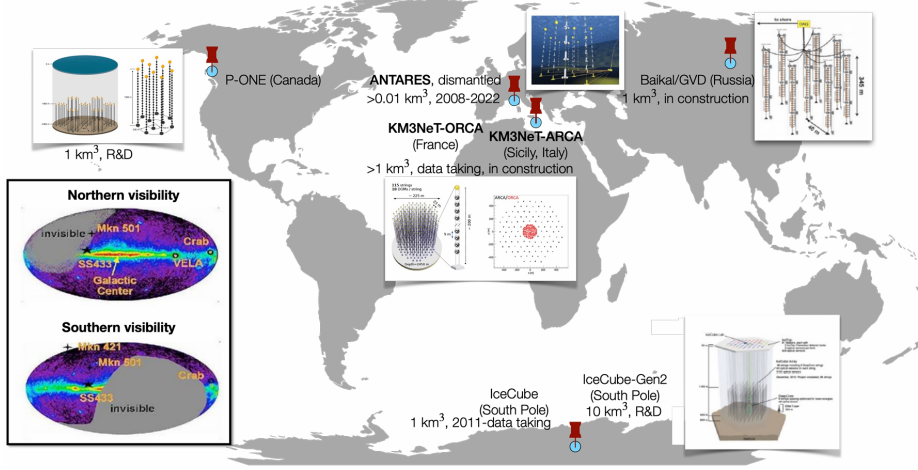


Figure 2.6: Map and diagrams of the main neutrino telescopes around the world [168]. On the bottom left, a sketch of their visibilities is reported.

matics [113]. Therefore, assuming a primary spectrum $\propto E^{-\gamma_{\text{CR}}} \simeq E^{-2.7}$, the atmospheric neutrino spectrum follows approximately $E^{-(\gamma_{\text{CR}}+1)} \simeq E^{-3.7}$.

Above TeV energies, the flux of astrophysical neutrinos becomes increasingly relevant and is expected to dominate over the atmospheric component at energies above ~ 100 TeV. In this regime, the event rate is extremely low, of order one event per square kilometer per day.

Finally, in the ultra-high-energy regime, neutrinos, with energy above 100 PeV, are produced through interactions of cosmic rays with the cosmic microwave background and the extragalactic background light, according to the Greisen – Zatsepin – Kuzmin mechanism described in the previous chapter.

2.3 Neutrino Telescopes

Neutrino telescopes consist of arrays of photomultiplier tubes deployed in transparent media such as water or ice, designed to detect Cherenkov light induced by charged secondary particles generated in neutrino interactions occurring inside or near the instrumented volume. The concept of such detectors was first proposed by M. Markov in 1960.

As discussed in the previous section, the expected event rate for high energy astrophysical neutrinos is extremely low, of order one event per square kilometer per day. For this reason, neutrino telescopes must instrument very large detection volumes to collect sufficient statistics for studying these rare events. Consequently, large-scale experiments have been constructed in deep lakes (Baikal-GVD), in the sea (ANTARES, KM3NeT), and within the Antarctic ice (IceCube), a map of the main experiments is reported in Figure 2.6.

In the previous chapter, the main scientific results of these experiments were presented. In the present chapter, the detection principle and the different classes of observable neutrino-induced signals will be discussed in detail.

2.3.1 Detection Principle: Cherenkov Radiation

Cherenkov radiation is a physical process first observed in 1934 by Pavel Alekseyevich Cherenkov [169], and later explained theoretically in 1937 by Ilya Mikhailovich Frank and Igor Yevgenyevich Tamm [170]¹. The phenomenon consists of electromagnetic emission produced when a charged particle travels through a dielectric medium with refractive index η at a velocity greater than the phase velocity of light in that medium (i.e., $v > c/\eta$, where c is the speed of light in vacuum). As the particle moves through the medium, it perturbs the local electromagnetic field, inducing a polarization of the surrounding atoms. When this polarization relaxes, coherent radiation is emitted. Due to the particle's superluminal velocity in the medium, constructive interference occurs, giving rise to the characteristic observable light emission (Figure 2.7, left and center).

A distinctive feature of Cherenkov radiation is that it is emitted along the surface of a cone whose axis coincides with the particle's trajectory. The Cherenkov angle θ is given by:

$$\cos \theta = \frac{c}{\eta v}, \quad (2.10)$$

where v is the particle's velocity.

Cherenkov radiation is also characterized by its bright bluish color (Figure 2.7, right), which arises from its emission spectrum peaking in the near-ultraviolet and visible regions [170]. According to the Frank–Tamm theory, the number of emitted photons N per unit wavelength λ and per unit path length x is:

$$\frac{dN}{d\lambda dx} = \frac{2\pi\alpha q^2}{\lambda^2} \left(1 - \frac{c^2}{n^2 v^2} \right), \quad (2.11)$$

where α is the fine-structure constant and q the charge of the particle.

For a charged particle travelling in seawater, the Cherenkov angle is approximately 42° , and the energy threshold for emission is about 0.761 MeV for electrons and 157.3 MeV for muons.

When light from the Cherenkov radiation hits a PMT, the photon is converted into an electrical signal through the photo electric effect. This means that a photon is converted to an electron which is amplified by several orders of magnitude over different stages. This signal is collected up by the discriminator which converts it into a digital signal resulting in what is called a hit.

2.3.2 Neutrino signatures: tracks and showers

Depending on the neutrino flavour (electron e , muon μ , or tau τ) and the interaction channel (charged current, CC, or neutral current, NC), events recorded

¹For this work, the three scientists were awarded the Nobel Prize in Physics in 1958.

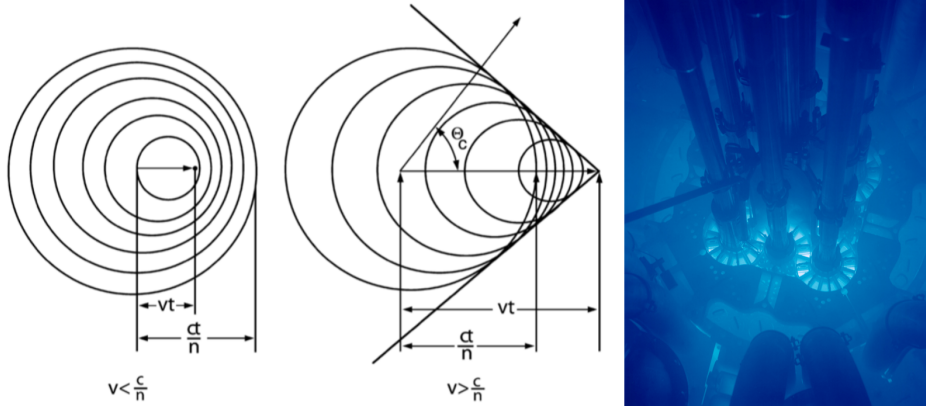


Figure 2.7: Cherenkov emission. Left: schematic representation of light emission for a charged particle traveling slower than the speed of light in the medium; the wavefronts do not produce constructive interference. Center: when the particle travels faster than the speed of light in the medium, constructive interference is established along the Cherenkov cone. Right: photograph of Cherenkov radiation induced by charged particles produced in the Advanced Test Reactor in Arco (United States).

in a neutrino telescope are commonly classified into three main topologies (see Figure 2.8):

- (i) ν_μ CC: a muon neutrino charged-current interaction produces a muon in the final state accompanied by a hadronic shower. This yields *track-like* events.
- (ii) ν_e CC: an electron neutrino charged-current interaction produces an electron that initiates an electromagnetic shower, superimposed on the hadronic shower from the interaction vertex. This produces *shower-like* (cascade) events.
- (iii) ν_τ CC: a tau neutrino charged-current interaction produces a τ lepton that decays promptly; the observed topology depends on the τ energy and decay channel (point-like cascades, double-pulse or “double-bang” signatures, etc.).
- (iv) ν_ℓ NC: Neutral current interactions of any flavour produce primarily hadronic showers and therefore are observed as shower-like events, since only a fraction of the neutrino energy is transferred to the target.

Track-like events If a relativistic muon is present in the final state, it can traverse distances of several kilometers in transparent media, water or ice (Figure 2.9), and induce Cherenkov light along its path. At the energies relevant

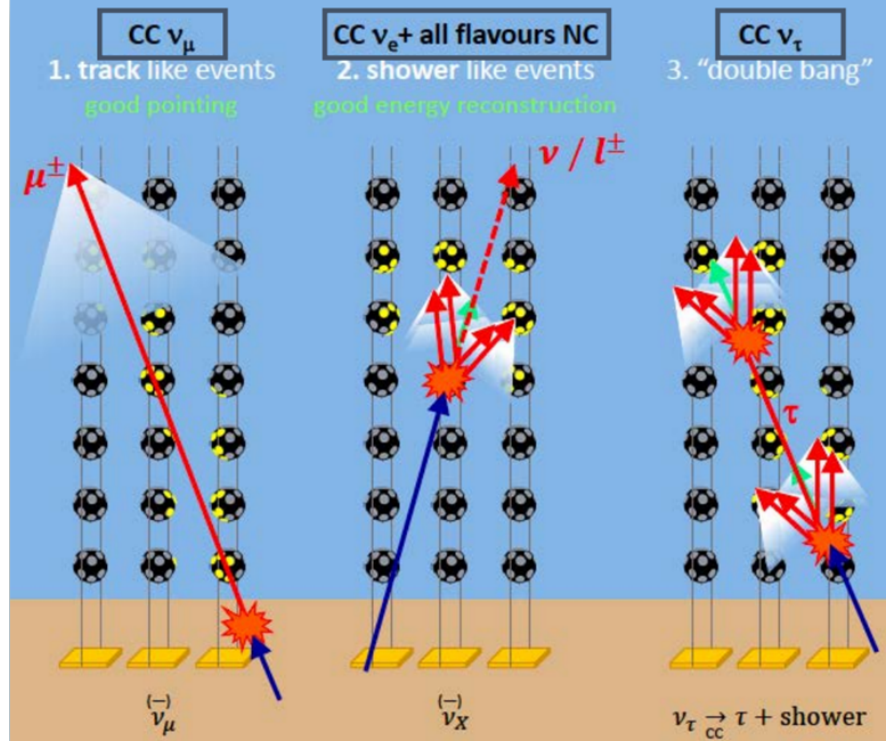


Figure 2.8: Schematic view of the neutrino signature and different event topologies in a neutrino telescope: charged current interaction of muon neutrino creates track-like events, while charged current interaction of electron neutrino (and neutral current of all neutrino flavors) produce shower like events. Finally CC interaction of tau-neutrino can produce double-bang events if the energy of the decaying tau-lepton is enough.

for astrophysical neutrino telescopes, muon angular scattering is small, so the muon direction can be reconstructed with high precision; for $E_\nu \gtrsim 1$ TeV the muon direction is nearly aligned with the incident neutrino. A commonly used approximation for the angle between the muon and neutrino directions $\alpha_{\mu\nu}$ is

$$\alpha_{\mu\nu} \lesssim \frac{0.6^\circ}{\sqrt{E_\nu/1 \text{ TeV}}}.$$

Energy estimation is more challenging: since muons may traverse the entire volume, the detector typically measures only the portion of energy lost inside the instrumented region. For fully contained events (muon produced and stopped inside the volume) a more accurate energy reconstruction is possible; for through-going muons the reconstructed energy represents typically a lower bound.

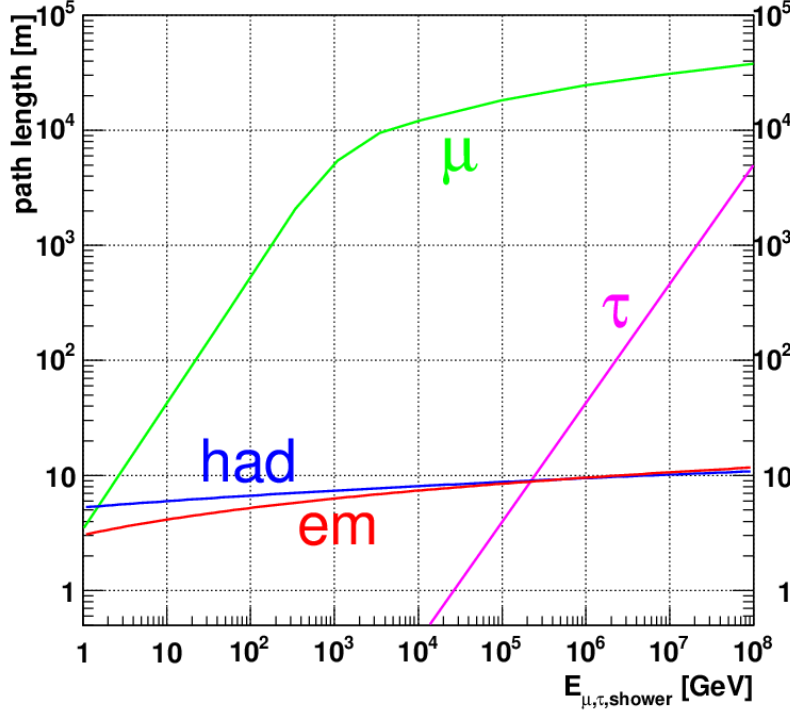


Figure 2.9: Path length of particles produced by neutrino interactions in water: muons (μ), taus (τ), electromagnetic (em) and hadronic (had) showers, as a function of their energy [171].

Shower-like events Electromagnetic and hadronic showers (produced by ν_e CC or by NC interactions) deposit their energy in a relatively compact volume compared to the spacing of optical sensors [171]. The path length is estimated to be less than 10 m for this kind of events (Figure 2.9). These events appear as approximately point-like sources of Cherenkov light for a sparse detector like a neutrino telescope. They allow good energy resolution (most of the visible energy is locally deposited) but generally worse angular resolution than tracks (angular uncertainties of several degrees to tens of degrees, depending on energy and detector geometry). Because particle cascades contain a large number of secondary charged particles, they produce many overlapping Cherenkov emission fronts. As a consequence, the detected light appears spatially diffuse and temporally smeared, resulting in a more compact and less directional signal compared to track-like events.

Tau topologies and double-bang The event topology depends on the energy and on the decay channel of the tau lepton. The mean lifetime of the tau is

2×10^{-13} s. At low energies, ($E_\tau \lesssim 1$ PeV, Figure 2.9) the charged lepton does not travel far enough to produce a significant Cherenkov signal, and the observed light originates mainly from the decay products. The tau decay channels yield charged hadrons in 64.8% of the cases, an electron ($\tau \rightarrow e \nu_e \nu_\tau$) in 17.4%, and a muon ($\tau \rightarrow \mu \nu_\mu \nu_\tau$) in 17.8%. The first two channels lead to a shower-like signature, whereas the muonic decay results in a track-like event. At very high energies, a tau lepton produced in a ν_τ CC interaction may decay at a macroscopic distance from the interaction vertex, producing the characteristic “double-bang” topology: a first pulse from the initial hadronic shower and a second pulse from the τ decay. The mean decay length of the τ is

$$L_\tau \simeq \gamma c\tau = \frac{E_\tau}{m_\tau} c\tau \approx 50 \text{ m} \times \left(\frac{E_\tau}{1 \text{ PeV}} \right),$$

so the two pulses become experimentally resolvable at PeV energies and above.

2.3.3 Signal and background events in a neutrino telescope

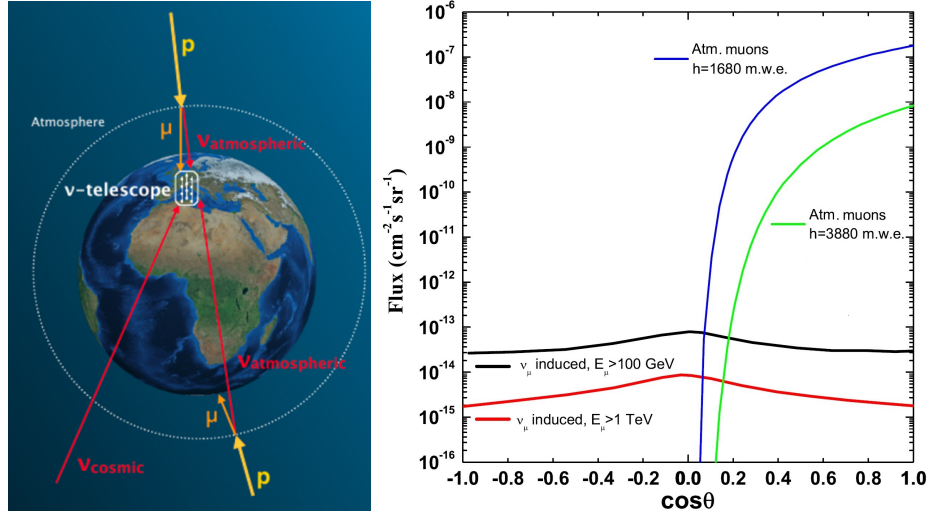


Figure 2.10: On the left: schematic view of the three main event topologies in a neutrino telescope: cosmic neutrinos, atmospheric neutrinos, and atmospheric muons. On the right: flux of atmospheric muons and muons induced by atmospheric neutrinos as a function of the zenith angle θ [172, 173].

The dominant background in neutrino telescopes consists of neutrinos and muons produced in the Earth’s atmosphere as a consequence of interactions of primary cosmic rays (Figure 2.10, left).

Muon-induced events constitute the overwhelming majority of the signals recorded by a neutrino telescope. High-energy muons immediately emit Cherenkov

light upon entering the water or ice, and their large penetration power—second only to that of neutrinos—allows them to reach the detector even when produced far above it. Being charged leptons, they interact mainly via the electromagnetic and weak forces; they primarily lose energy through ionization and therefore cannot traverse the Earth. For this reason, neutrino telescopes are installed at great depths underwater or under ice, where the overburden significantly attenuates the atmospheric muon flux [174]. The right panel of Figure 2.11 shows measurements and predictions of the muon flux as a function of depth in water [174]. Beyond a depth of 2000 meters, the flux of atmospheric muons is reduced by a factor of $\sim 10^3$, and by $\sim 10^4$ at depths greater than 3000 meters.

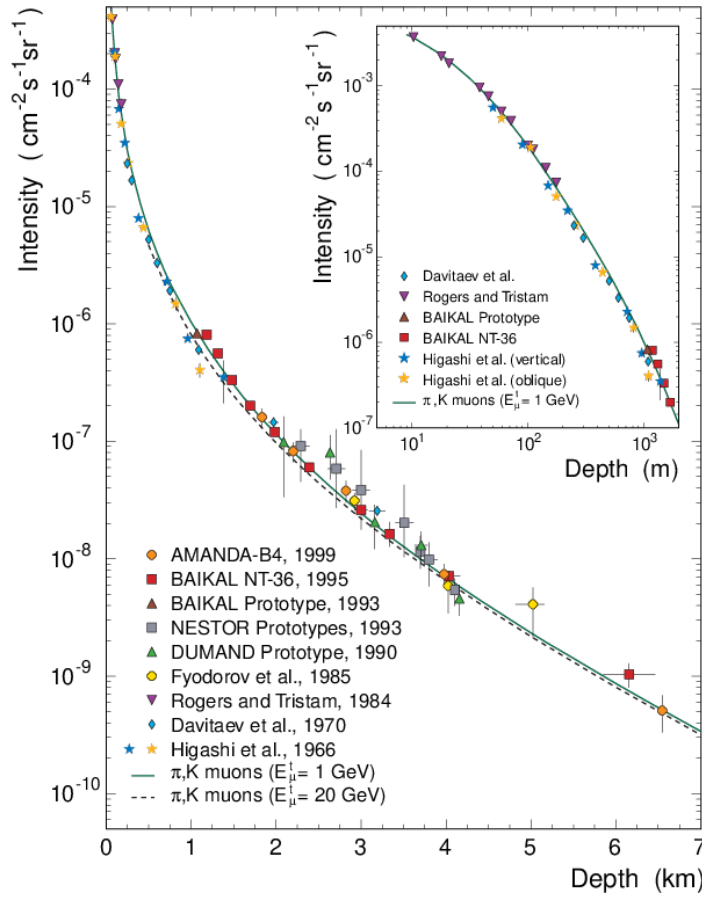


Figure 2.11: Muon intensity as a function of water depth [174]. The small panel shows the same picture using a scale for depth values.

The primary method for discriminating neutrinos from atmospheric muons relies on selecting track-like events originating from below the horizon, referred to as *up-going tracks*. Since muons cannot cross the Earth, such events can only

be induced by neutrinos.

Discriminating between atmospheric and cosmic neutrinos is more challenging, as they are the same particles and differ only in their origin. Their discrimination from cosmic neutrinos is achieved statistically, exploiting the fact that the flux of astrophysical neutrinos is expected to dominate at energies above ~ 100 TeV. In the context of point-source searches, an additional discrimination method can be employed: while the atmospheric background is generally assumed to be uniformly spatial - distributed, the signal from cosmic neutrinos is expected to cluster around the position of a candidate source.

The methods used to separate these event categories will be discussed in detail in Chapter 4.

In order to observe an astrophysical source effectively via the up-going track channel, the source must occupy sky coordinates for which the atmospheric muon background is suppressed. We define the visibility of a neutrino telescope as the fraction of time (per sidereal day) during which a source lies below the local horizon and is therefore observable as an up-going event. This is the reason why the Northern sky is visible for neutrino telescopes located in the southern hemisphere of the Earth while astrophysical sources in the southern sky are mainly observed by experiments in Northern Hemisphere.

Visibility can be increased by considering events in which the Cherenkov light is produced inside the detector volume. Atmospheric muons, being charged particles, emit Cherenkov radiation as soon as they enter the water, and their tracks are therefore always observed as entering the neutrino telescope. Neutrinos, on the other hand, may also interact within the detector itself; in such cases, the resulting Cherenkov light originates from inside the instrumented volume. These events are commonly referred to as starting events.

Very pure samples can thus be obtained by excluding events whose earliest reconstructed hits occur in the outer layers of the detector. In this way, even downgoing events can be used. This type of selection, however, significantly reduces the available statistics and is therefore typically employed by large-volume experiments such as IceCube [106].

2.3.4 Optical background

In addition to the background caused by high-energy particles produced in the atmosphere, neutrino telescopes are subject to another type of background, namely optical background. This refers to phenomena in which photons are emitted that can reach the detectors' PMTs. There are two main sources of optical background. First of all the almost constant potassium-40 decay (^{40}K) and secondly biological activity that mainly depend on sea currents and seasonal behaviour [175]. This type of background has a greater impact on underwater neutrino telescopes than on ice-based detectors, where bioluminescence is practically non-existent

Potassium-40 decay ^{40}K isotopes are naturally abundant in sea salt. The main decay channels are β -decay (89.3%):

$$^{40}\text{K} \rightarrow ^{40}\text{Ca} + e^- + \bar{\nu}_e$$

or via electron capture (10.7 %):

$$^{40}\text{K} + e^- \rightarrow ^{40}\text{Ar} + \gamma + \bar{\nu}_e$$

In the main decay, $\sim 21\%$ of the emitted e^- have enough kinetic energy to produce Cherenkov radiation, and the produced photon in the subdominant decay channel may free an electron from water molecules through Compton scattering, subsequently also producing Cherenkov light. The KM3NeT/ARCA experiment observed this phenomenon, resulting in a constant background rate of approximately 4.7 kHz per photomultiplier tube.

Bioluminescence Bioluminescence is the emission of visible light organisms as a result of a chemical reaction. It is found in most of the major marine phyla, from bacteria to fish. The light signals, typically lasting up to several seconds, are used for a wide range of interactions, permitting the organisms to find or avoid each other and defence, offence, and reproduce [176, 175]. The amount of light observed in KM3NeT depends on sea current and follows seasonal behaviour [177].

2.4 ANTARES

ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RE-Search) was the first successfully operating undersea Cherenkov detector. It was deployed at a depth of 2475 meters in the Mediterranean Sea, approximately 40 km off the coast of Toulon, France. The first detection line of ANTARES was installed on 14 February 2006. The full detector, consisting of 12 lines, was completed in May 2008. After 15 years of continuous operation, ANTARES was decommissioned in February 2022 and subsequently dismantled, paving the way for the construction of its successor, KM3NeT.

2.4.1 Experiment Design

The ANTARES detector consisted of 12 vertical detection lines anchored to the seabed in an octagonal configuration, each stabilized by a buoy at its upper end. The inter-line spacing was approximately 60 m, and each line reached a height of nearly 480 m. Beginning 100 m above the seafloor, each line featured 25 storeys, spaced 12 m apart (Figure 2.12), resulting in an instrumented volume of approximately 0.01 km^3 [178, 179].

Each storey served as a titanium support structure for the optical and electronic components. Three optical modules (OMs) were mounted on each storey, arranged 120° apart and inclined 45° downward, with a total of 885 OMs across

the detector. The local control module (LCM), housing the electronics for data acquisition and operation, was also embedded within each storey. The storeys were interconnected by electro-optical mechanical cables (EMCs), which transmitted optical signals, distributed electrical power, and provided structural integrity to the lines [179].

Additional devices were located on specific storeys depending on their depth. These included LED optical beacons for time calibration and hydrophones for acoustic positioning, ensuring precise alignment of the array.

ANTARES operated under an “all data to shore” philosophy. All detected signals were transmitted from the seabed to a shore-based station for processing, filtering, and storage. This was enabled by the main electro-optical cable (MEOC), which provided power, data transfer, and a master clock signal for synchronization. A junction box connected the MEOC to the individual detection lines via link cables terminating at string power/control modules (SPM/SCM) at the base of each line. The SPM delivered electrical power (400 V per line), while the SCM monitored temperature, voltage, and current.

Each optical module housed a 10-inch Hamamatsu R7081-20 photomultiplier tube (PMT) enclosed in a pressure-resistant glass sphere with high optical transparency in the 450–500 nm wavelength range. The lower hemisphere contained the PMT and was shielded from the Earth’s magnetic field using a μ -metal cage. The upper hemisphere was coated black to reduce internal light scattering and accommodated the PMT base.

Every OM featured an internal pulsed LED, affixed behind the PMT. Emitting blue light at approximately 470 nm, this LED was used for internal calibration, particularly to measure the PMT transit time.

2.5 KM3NeT

KM3NeT (Cubic Kilometre Neutrino Telescope) is an infrastructure network currently under construction in the Mediterranean Sea. It comprises two complementary neutrino telescopes (Figure 2.13): ARCA (Astroparticle Research with Cosmics in the Abyss), dedicated to neutrino astronomy, and ORCA (Oscillation Research with Cosmics in the Abyss), dedicated to the study of neutrino oscillations [181].

Both detectors exploit the same detection principle—the indirect observation of neutrinos through the Cherenkov light induced by secondary charged particles produced in neutrino interactions—and both are built as arrays of pressure-resistant optical modules. Each KM3NeT Digital Optical Module (DOM) houses 31, 3-inch diameter, photomultiplier tubes (PMTs) [182] (Figure 2.14). The final design foresees three *building blocks*, each composed of 115 detection lines, also called detection unit (DU), with 18 DOMs installed along each line at equal spacing. It is worth noting that, while ANTARES employed a multi-OM per storey architecture (several separate optical modules per storey), KM3NeT uses a multi-PMT approach in which a single DOM contains multiple small PMTs (Figure 2.15).

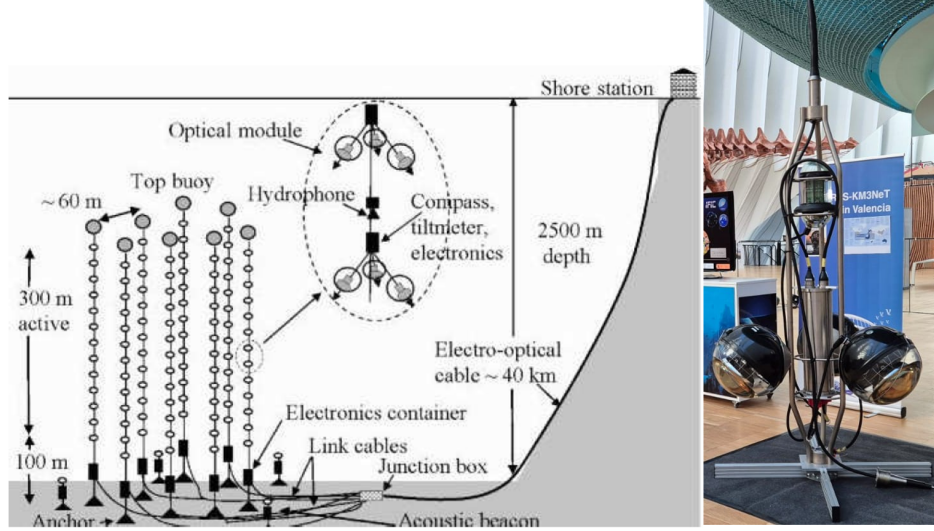


Figure 2.12: On the left, sketch of the ANTARES detector [178]. On the right, photo of one the ANTARES DOM at an exposition in Valencia (Spain).

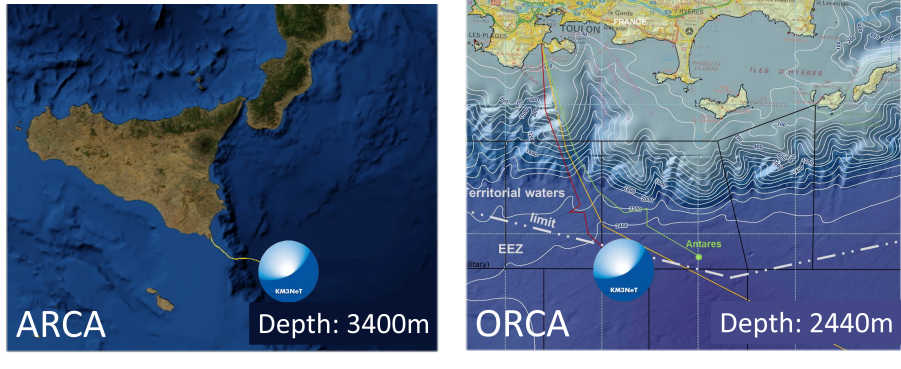


Figure 2.13: On the left, site location of KM3NeT/ARCA, at a depth of ~ 3500 meters and 100 km offshore from Capo Passero (Sicily, Italy). On the right, site location of KM3NeT/ORCA, at a depth of ~ 2500 meters and 40 km offshore from Toulon (France) [180]. Both detectors are connected to their respective shore stations via electro-optical cables, as is the case with ANTARES. In particular, ANTARES was located near KM3NeT/ORCA, and the experiment site is shown in the figure on the right.

Besides the PMTs, each DOM houses calibration instruments and electronics for power, as well as a central logic board (CLB) which collects all information produced by the PMTs and the other instruments (like a piezo sensor, compass/tiltmeter, nanobeacon, humidity sensor and temperature sensors) and



Figure 2.14: Photo of a selection of components of an optical module [182].

forwards it to the control station [183].

The position of each DOM (relative to the others) is determined by triangulation, based on acoustic information from emitters and receivers as well as compass and tilt measurements. For this purpose autonomous acoustic beacons are placed around the detector and on some DU bases, each with a characteristic emission pattern (in the 20-40 kHz range). Every DOM contains a piezo sensor, while a hydrophone is installed on the DU bases to detect the emitted acoustic signals. Furthermore, on each CLB a compass chip is mounted to measure the orientation of each individual DOM

The DOMs in the arrays are integrated into detection units, vertical structures anchored to the seabed, featuring an electro-optical backbone cable that runs along their full length. At the anchor of a detection unit a base module provides the interconnection with the seafloor electro-optical cable network. The network connects the detection units with control stations onshore for data transfer and detector control [184].

For precise timing of photon detection, the White Rabbit time-synchronisation system [185] is used—an Ethernet-based network that timestamps all signals with

respect to a GPS-referenced clock. The uncertainty on the absolute timing originating from the GPS is well within the requirements for neutrino astronomy [186]. In order to calibrate the detector elements in time, in addition to lab measurements, in-situ light information from nanobeacons, ^{40}K decay, and light from atmospheric muons are used [181, 187].

Of the three building blocks under construction, two will constitute KM3NeT/ARCA (Figure 2.15) and one will constitute KM3NeT/ORCA (Figure 2.16). The two detectors are optimized for different neutrino fluxes: ORCA targets atmospheric neutrinos produced by cosmic-ray interactions in the atmosphere, whereas ARCA targets high-energy astrophysical neutrinos originating from cosmic sources. Consequently, their geometrical layouts differ: in KM3NeT/ARCA the inter-line spacing is approximately 90 m and the spacing between DOMs along a line is 36 m; conversely, KM3NeT/ORCA features a denser geometry with roughly 20 m between lines and 9 m between DOMs. In its final configuration KM3NeT/ARCA will instrument on the order of 1 km^3 , while KM3NeT/ORCA will have an instrumented volume of approximately 0.007 km^3 .

The two detectors are deployed at different sites: KM3NeT/ORCA is being constructed in the Mediterranean Sea about 40 km off the coast of Toulon (France), at a depth of roughly 2500 m, near the former ANTARES site; KM3NeT/ARCA is sited 100 km offshore from Capo Passero (Sicily, Italy) at a depth of approximately 3500 m below sea level.

KM3NeT/ARCA. In July 2025, 51 out of the 230 detection units were deployed on the seabed. The corresponding footprint is shown in Figure 2.17. Since each DU is capable of detecting Cherenkov light independently of the others, the detector has already begun data acquisition. This is illustrated in Figure 2.18 (right), which shows the detector exposure as a function of time, starting from the configuration with six installed DUs—referred to as ARCA6—up to the configuration with 30 DUs.

The following chapters describe how the data collected so far can be analysed to search for a cosmic neutrino signal.

2.6 Summary and Outlook

This chapter has provided a compact overview of neutrino properties, interaction mechanisms, natural neutrino sources, and the detection principles underlying large-scale Cherenkov neutrino telescopes. We reviewed the principal classes of neutrino fluxes spanning many decades in energy—from the Cosmic Neutrino Background and Big-Bang nucleosynthesis relics, through solar, geoneutrino and reactor contributions, to atmospheric and ultra-high-energy astrophysical components—and we discussed the characteristic energy ranges, production channels, and observational challenges associated with each class.

The operational principles of neutrino telescopes were presented in detail, including the topology-based event classification into track-like and shower-like

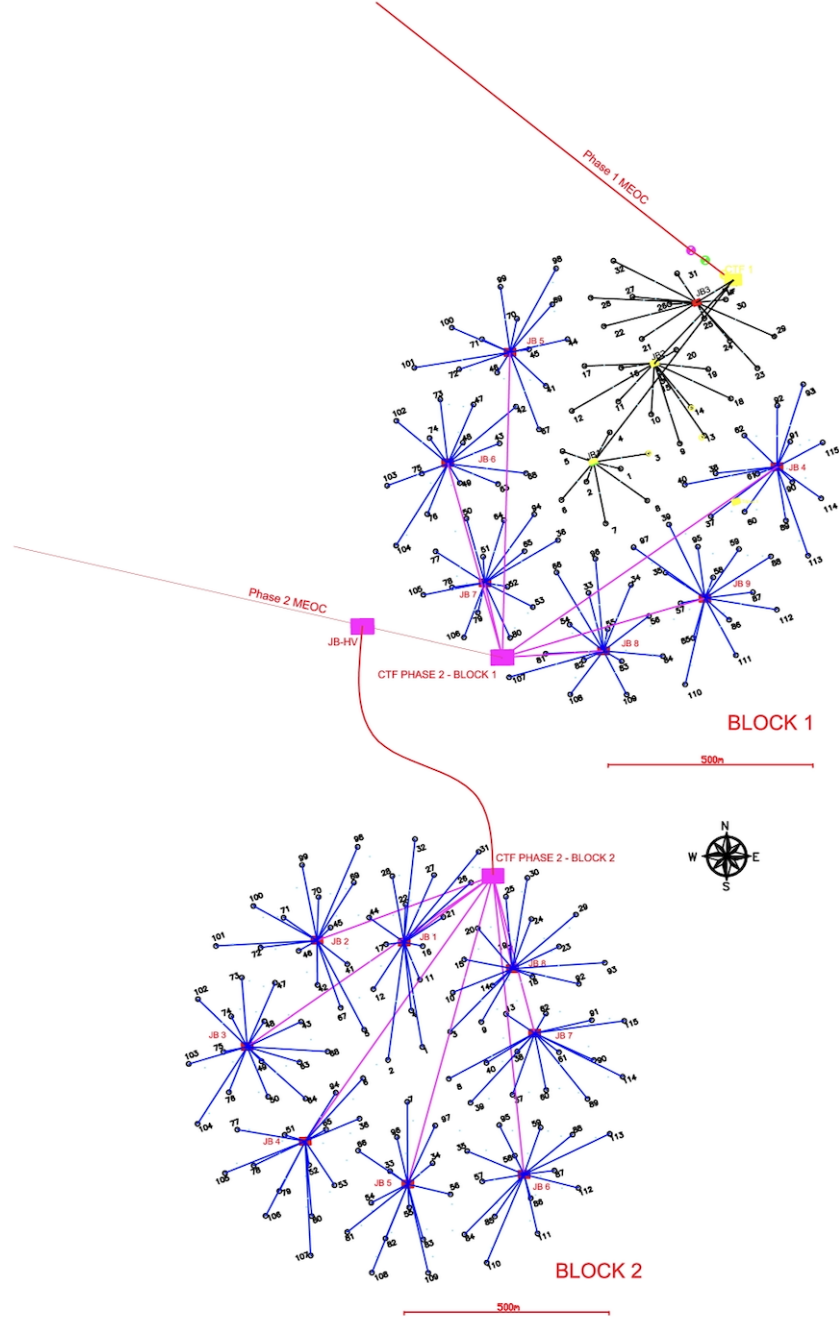


Figure 2.15: Layout of the ARCA network [184]. Boxes represent the junction boxes; Dots indicate the detection units connected to the junction boxes. The junction boxes are connected to the cable termination frames of the Main Electro-Optical Cables (MEOCs) to shore (red lines to the pink boxes).

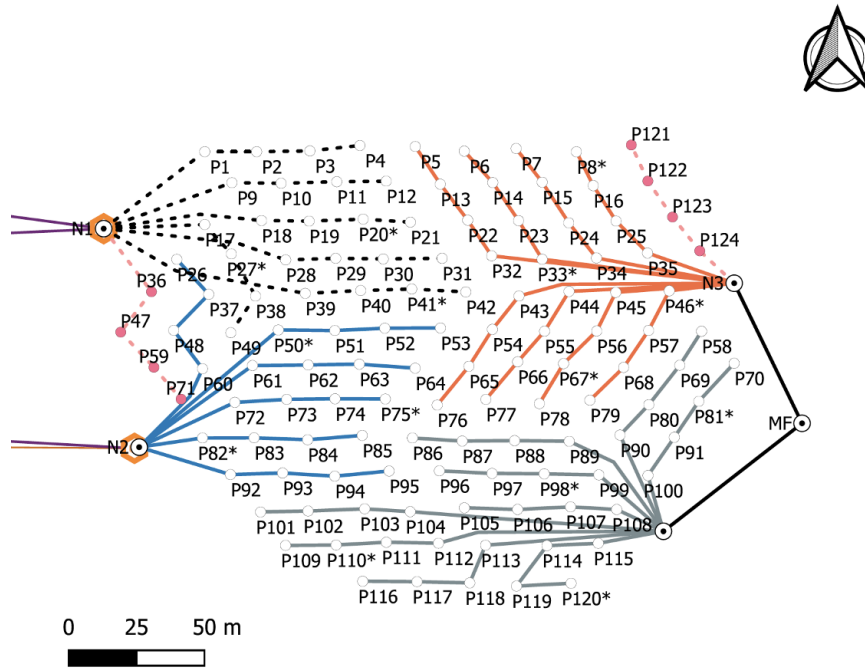


Figure 2.16: Layout of the ORCA network [184]. The node N1 and N2 are daisy-chained in the main electro-optical cable and reflect the implementation of the network in the first phase of KM3NeT. Dots are detection units daisy-chained to a node.

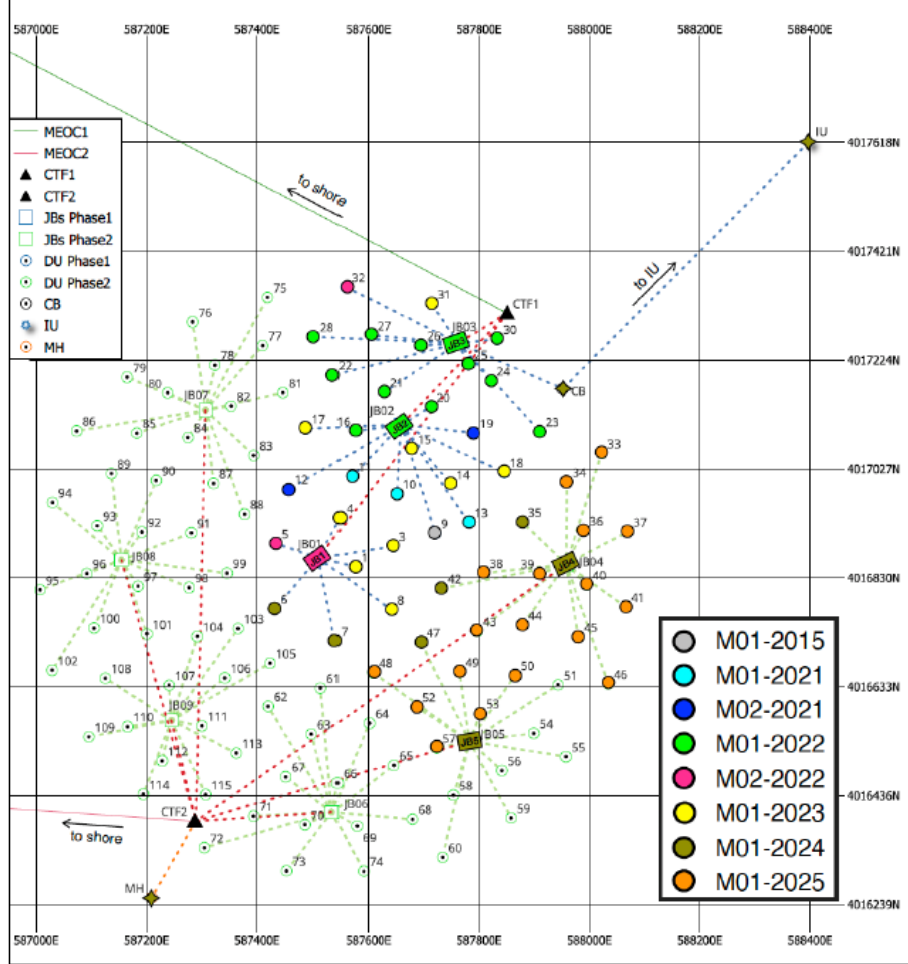


Figure 2.17: Footprint of the KM3NeT/ARCA installed detector lines until July 2025; different colors indicate different period of sea-campaign for the line installation.

signatures, the role of background (atmospheric muons and atmospheric neutrinos), and the concept of detector visibility. Practical implications for detector design and analysis were illustrated with two flagship Mediterranean projects: ANTARES, whose long operation pioneered the undersea approach, and KM3NeT, whose modular ARCA and ORCA configurations are optimized respectively for high-energy astrophysical searches and precision oscillation measurements. The chapter also highlighted key experimental issues—large instrumented volumes, background suppression via depth and up-going selection, and the trade-offs be-

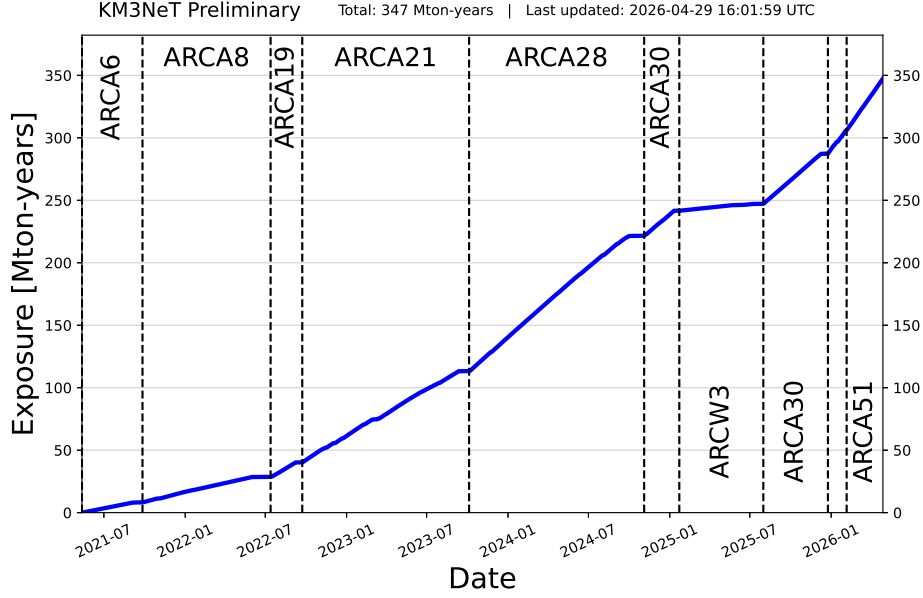


Figure 2.18: Exposure of the partial detector configuration as a function of the time from March 2021 to April 2026.

tween angular and energy resolution for different event classes.

Looking forward, the ongoing deployment and commissioning of KM3NeT, together with synergies among global neutrino observatories and multi-messenger facilities, will substantially improve sensitivity to cosmic neutrino sources and enable more precise studies of neutrino properties. The subsequent chapters describe the data analysis methods and statistical techniques employed to discriminate signal from background, reconstruct event kinematics, and perform searches for both point-like and diffuse astrophysical neutrino emission.

Chapter 3

Event Selection for KM3NeT/ARCA

One of the main achievements of this work is the development of the event selection for data samples collected with the partial configurations of the KM3NeT/ARCA detector, namely ARCA19 and ARCA21.

These datasets were used in a combined point-source search with data collected by the earlier configurations ARCA6 and ARCA8, thus exploiting the full KM3NeT/ARCA dataset recorded up to September 2023.

The event selection developed for ARCA21 is based on the selection previously adopted for the earlier configurations, which is used as a baseline. Additional selection criteria, based on reconstructed variables and on a Boosted Decision Tree (BDT) algorithm, are then applied. Several combinations of quality cuts were investigated in order to reduce the atmospheric muon background. The optimisation of the final selection was guided by sensitivity and discovery potential considerations.

3.1 Data samples

The data samples considered in this work were collected between May 2021 and September 2023, corresponding to a total livetime of approximately 640 days. During this period, KM3NeT/ARCA operated in several partial configurations, as detection units (DUs) were progressively installed on the seabed. The configurations considered are ARCA6, ARCA8, ARCA19 and ARCA21, corresponding respectively to 6, 8, 19 and 21 operational DUs.

The cumulative exposure as a function of time is shown in Figure 3.1. The data-taking period and the individual livetimes for each configuration are listed in Tab. 3.1.

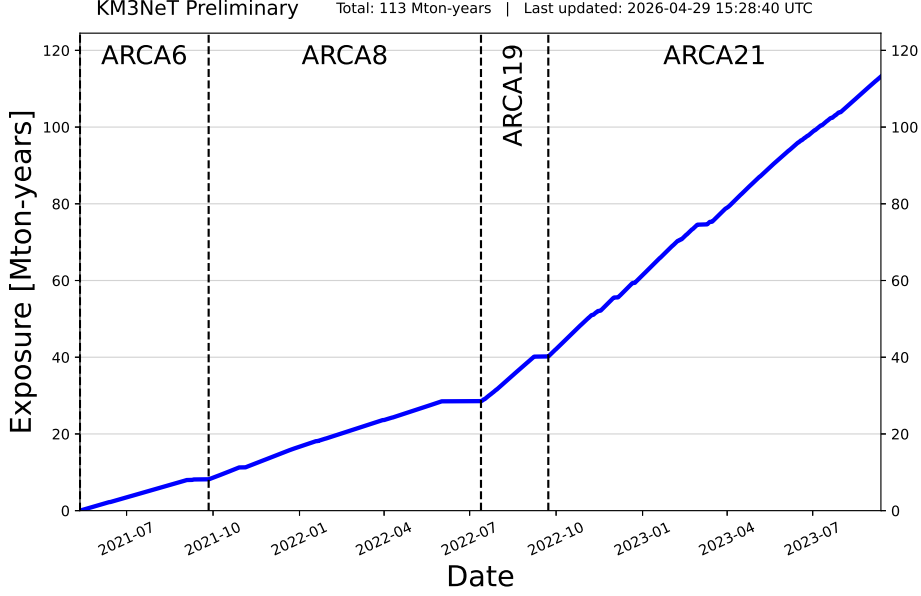


Figure 3.1: Exposure as a function of time for the partial configurations of KM3NeT/ARCA, from May 2021 to September 2023.

Configuration	Period	Livetime[days]
ARCA6	May 2021- September 2021	92
ARCA8	September 2021- June 2022	210
ARCA19	June 2022- September 2022	48
ARCA21	September 2022- September 2023	287

Table 3.1: Effective data taking time for different ARCA configurations

3.2 Simulations and event reconstruction

The simulation chain of KM3NeT events is described in detail in [188] and consists of four main stages: particle generation, particle propagation and light emission, trigger simulation, and event reconstruction.

The simulation for a specific dataset, is performed following a *run-by-run* approach. All simulated events are generated for a predefined data-taking period, typically corresponding to acquisition intervals of 3 to 6 hours, commonly referred to as runs. In the simulation framework, a cylindrical volume, referred to as the *can*, is defined around the instrumented detector volume (Figure 3.2). The can extends several light absorption lengths beyond the detector (typically four) and is bounded at the bottom by the seabed. Within this volume, the emission of Cherenkov light and the detector response are simulated.

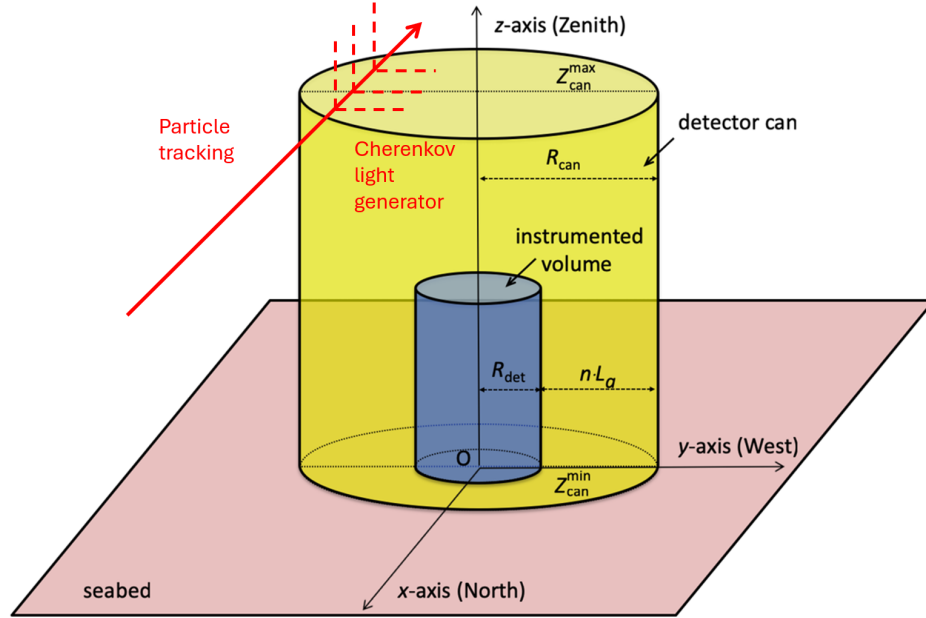


Figure 3.2: Overview of the detector geometry used in the event simulation. Neutrino interactions are generated in a large volume surrounding the detector [189]. The resulting muons are propagated to the can (yellow), inside which the Cherenkov light production and detector response are simulated. The volume of sea water instrumented with optical sensors, usually indicated as instrumented volume, is shown as the blue cylinder.

In addition, a larger interaction volume is defined, representing the region in which neutrino interactions may produce detectable secondary particles. This distinction accounts for the fact that muons produced in neutrino interactions can propagate over kilometre-scale distances in rock and water before reaching the detector.

3.2.1 Event generation

Neutrino events are generated with interaction vertices distributed throughout the interaction volume. Each event is assigned an initial position, direction, and energy. The neutrino propagation and interaction, including the production of secondary charged particles, are simulated according to the relevant cross-section models using the GENIE software package [190, 188].

The distributions used to generate the initial neutrino direction, position, and energy are employed to compute an event weight for each simulated event. These weights allow the effective number of expected events to be recalculated for a given neutrino flux and for specific regions of solid angle and direction.

Atmospheric muons produced by the interaction of primary cosmic rays with the Earth's atmosphere are simulated using the MUPAGE generator [191]. MUPAGE is based on parametric formulas describing the muon flux at detector depth as a function of particle energy, zenith angle, and bundle parameters such as multiplicity and lateral distance from the bundle axis.

3.2.2 Particle propagation and light emission

Until particles reach the boundary of the can, no Cherenkov light emission is simulated and only energy losses are taken into account. As described in Chapter 2, muons lose energy through ionisation, bremsstrahlung, pair production, and photonuclear interactions. These processes are modelled using the PROPOSAL[192] software package.

Once a particle enters the can volume, the emission of Cherenkov light is simulated using probability density functions describing the photon arrival times at the PMTs. Light propagation effects such as absorption, scattering, and chromatic dispersion in seawater are taken into account to model the transmission of light to the detector.

3.2.3 Trigger and detector response

Following light generation, the PMT response and the front-end electronics are simulated [193]. In addition, random optical background is added according to *in situ* measurements, in order to account for noise contributions from ^{40}K decays and bioluminescence.

After this stage, the format of the simulated events is identical to the experimental data, allowing simulated and real events to be processed by the same reconstruction and analysis chain.

3.2.4 Event reconstruction

Event reconstruction aims to determine the physical properties of the detected particles, such as direction and energy, starting from the set of triggered hits in the detector. Reconstruction algorithms are based on fitting physical models to the observed hit times and positions. For track-like events, the dominant hypothesis is the Cherenkov light emission from a relativistic muon, while shower-like events are described by an expanding point-like light source.

3.2.5 Track reconstruction

The track reconstruction procedure consists of two main steps [195]. First, a directional pre-fit is performed by scanning a predefined set of approximately 20 000 directions uniformly covering the full sky. This pre-fit is applied to clusters of hits that satisfy causality criteria, indicating that they may originate from the same particle track. For each tested direction, the track position and the time at which the track crosses a reference plane perpendicular to the assumed direction

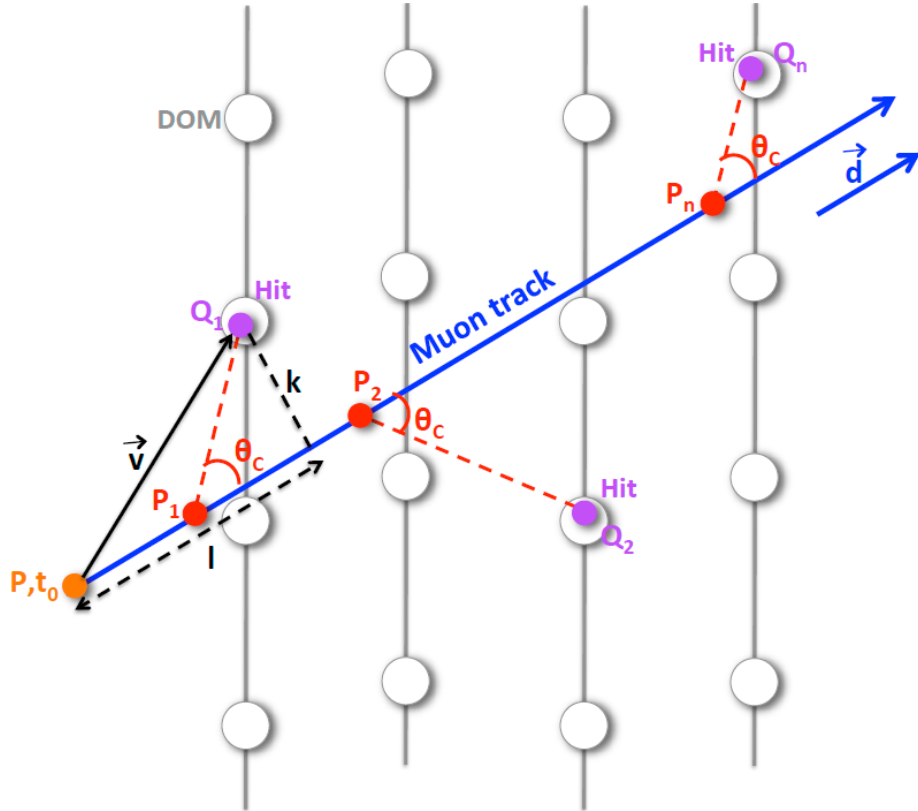


Figure 3.3: Description of the geometry for the detection of the Cerenkov light emitted by a muon (blue line) that goes through the point P (orange point) in direction $\vec{d}$ [194]. The Cerenkov light (red dashed lines) reaches the PMTs located in positions Q_i (lilac points). The vector $\vec{v}$ is defined as the vector that goes from the point P to the hit position Q_i , l and k are the components of $\vec{v}$ parallel and perpendicular to the muon direction.

are iteratively fitted. A χ^2 estimator, based on the difference between observed and expected photon arrival times under the Cherenkov hypothesis, is used to evaluate the fit quality.

In the second step, a maximum-likelihood fit is performed to determine the five parameters describing the muon trajectory, namely the direction, position, and time along the track. The likelihood function is constructed from the hit-time distributions, taking into account the distance and orientation of each PMT with respect to the reconstructed track. The resulting quantity, referred to as the track likelihood, represents the ratio between the likelihood that a given cluster of hits is produced by a track-like signal on top of background and the likelihood that it originates from background only.

Once the track direction and position are reconstructed, the muon energy is estimated. A cylindrical volume around the reconstructed track is defined, and for the PMTs within this volume the expected number of hits is computed as a function of energy. The energy estimate is obtained by maximising a likelihood function comparing the expected and observed number of hits (hit/no-hit likelihood).

In addition to the reconstructed direction, position, energy, and track length, several other reconstruction variables are stored and used for subsequent physics analyses.

3.2.6 Shower reconstruction

The reconstruction of shower-like events is performed with a designated algorithm, indicated as AAshowerfit [195]. The reconstruction is performed in two steps. First, the vertex position and time are fitted using both the timing and spatial distribution of the hits. Subsequently, the direction and energy are reconstructed, again exploiting the full space-time information provided by which PMTs register hits and which do not.

For the vertex position determination, hits are only used if at least two hits occurred on a single DOM within 20 ns, reducing the contribution of random background (like ^{40}K decay). The centre of gravity of the selected hits serves as a first estimation of the vertex. The vertex fit is done minimising the M-estimator which is based on the time difference between the measured time of the hit t_i and its expectation value t_i^* according to the assumption that a light shell spherically expands from a single point:

$$M = \sum_{\text{hits}} \sqrt{1 + (t_i - t_i^*)^2}$$

After measuring the time and position of the shower using the hit times, the energy and direction are estimated from the pattern of the light intensity. The Poisson probability of a PMT to be hit by a photon strongly depends on these quantities. Such probability is used in the likelihood function, which also includes the terms for the PMTs that did not observe any light from the shower. The maximisation of the likelihood function yields the energy and direction estimates.

3.3 Methods for event selection: quality cuts and boosted decision trees

Before discussing the event selection applied to KM3NeT/ARCA data, it is useful to introduce some of the statistical techniques commonly employed in this type of analysis. All the methods rely on the availability of Monte Carlo simulations for both signal and background events. In real data, signal and background cannot be distinguished on an event-by-event basis, and therefore simulated samples are required to model their expected distributions.

The cuts approach and boosted decision trees are two widely used strategies for event classification. Both methods are based on the same underlying principle: selecting events in a multidimensional parameter space and evaluating the number of signal and background events that survive the selection. In this sense, boosted decision trees can be regarded as a more advanced and performant extension of the traditional cuts approach.

3.3.1 Cuts

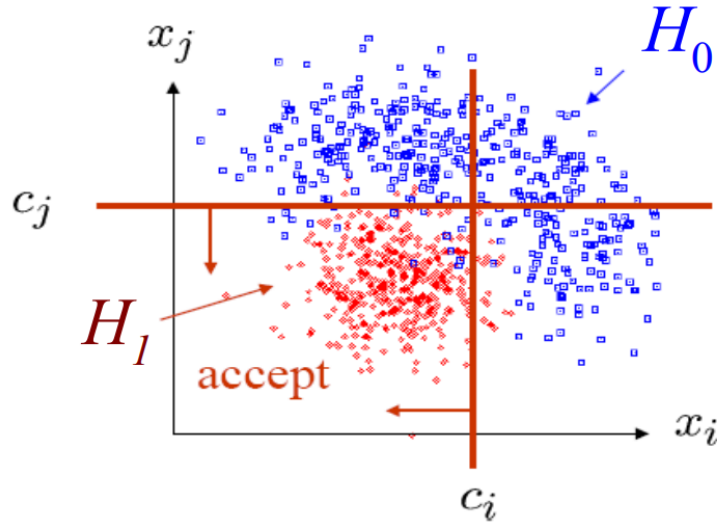


Figure 3.4: Schematic example of a Cut&Count [196]: background and signal events (respectively the blue and red points) are distributed with respect to two variables (x_i , x_j). The selection $x_i < c_i$ and $x_j < c_j$ is used to reject the background.

The Cuts method is the most straightforward and intuitive approach to apply a selection. Given the distribution of events as a function of a variable x , a threshold value x_0 is defined, and only events with values of x larger (or smaller)

than the threshold are retained. This procedure can be extended to multiple variables by applying several cuts simultaneously (Figure 3.4).

The optimization of the selection consists in choosing the set of thresholds that maximizes a given figure of merit, typically balancing background suppression against signal retention. Although simple and transparent, this approach becomes increasingly inefficient when dealing with a large number of correlated variables.

3.3.2 Boosted Decision Trees

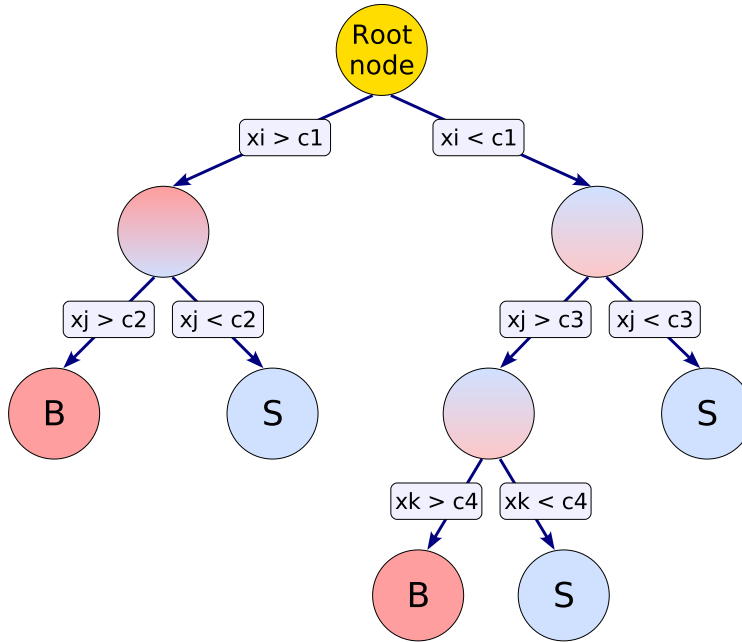


Figure 3.5: Scheme of a decision tree algorithm [197]. Starting from the root node, a sequence of binary splits using the discriminating variables x_i is applied to the data. Each split uses the variable that at this node gives the best separation between signal and background when being cut on. The same variable may thus be used at several nodes, while others might not be used at all. The leaf nodes at the bottom end of the tree are labeled “S” for signal and “B” for background depending on the majority of events that end up in the respective nodes.

When many variables are available for the event selection, it is more efficient to use a boosted decision trees to derive a single discriminating variable that exploits all correlations among them, and then apply the selection on this combined output. BDTs are multivariate classifiers based on an ensemble of decision trees combined through a boosting algorithm. The trees are trained sequentially, such

that each subsequent tree focuses on events that were misclassified by the previous ones (Figure 3.5). The final classifier output is obtained as a weighted sum of the individual trees, resulting in a powerful nonlinear discriminant between signal and background.

A decision tree partitions the feature space into disjoint regions by applying a sequence of binary splits on the input variables. Each terminal node (leaf) is associated with a classification score, determined by the relative abundance of signal and background events in that region. The splitting criteria are determined during the training phase and are then fixed when the classifier is applied to data on an event-by-event basis.

Compared to simple cut-based methods, BDTs are able to exploit correlations among input variables and generally provide superior discrimination power, especially in complex, high-dimensional parameter spaces.

3.3.3 Trade-off between Signal Efficiency and Background Rejection

Applying increasingly selective cuts on reconstruction parameters allows for a strong reduction of the background event rate. However, this typically comes at the cost of a reduced fraction of signal events passing the selection. One of the central aspects of event selection is therefore the optimization of the trade-off between background rejection and signal efficiency, the latter being defined as the ratio between selected events and total number of events in the sample.

Several figures of merit are commonly used to characterize and compare different selections. Receiver Operating Characteristic (ROC) curves provide a visual representation of the trade-off between signal efficiency and background rejection, while the statistical significance, approximated as $S/\sqrt{B}$, offers a simple quantitative estimate of the discrimination power.

In neutrino telescope analyses, however, the optimization is usually performed using more physically meaningful quantities, such as the sensitivity and the discovery potential. These quantities are discussed in the following section.

3.4 Sensitivity and Discovery Potential

The sensitivity of a neutrino telescope is defined as the average upper limit that would be obtained in the absence of a true signal, typically at a given confidence level (e.g. 90%). It represents the weakest signal flux that the detector is expected to constrain.

The discovery potential, on the other hand, is defined as the signal flux required to claim a discovery with a given statistical significance (commonly 3σ or 5σ) in a specified fraction of experiments, indicated as statistical power (commonly 50 %). Both quantities depend on the detector performance, the background level, and the analysis strategy. Considered together, they provide complementary information: the sensitivity characterizes the experiment's ability to

set limits, while the discovery potential quantifies the conditions under which a signal can be claimed.

Both sensitivity $\phi_{90\%}$ and discovery potential $\phi_{\{3\sigma,5\sigma\}}$ can be expressed as functions of the expected signal flux ϕ_s and the expected number of signal events n_s :

$$\phi_{90\%} = \frac{n_{90\%}}{n_s} \phi_s = \xi_{90\%} \phi_s \quad (3.1)$$

$$\phi_{\{3\sigma,5\sigma\}} = \frac{n_{\{3\sigma,5\sigma\}}}{n_s} \phi_s = \xi_{\{3\sigma,5\sigma\}} \phi_s \quad (3.2)$$

where $n_{90\%}$ is the median upper limit and $n_{\{3\sigma,5\sigma\}}$ is the least detectable signal i.e. the minimal number of signal events which would lead to a detection (with significance 3σ or 5σ) in 50% of the trials (according to the statistical power). On the other hand, when a known source is undetected at some statistical significance during an observation, it is customary to state the upper limit on its intensity. This limit is taken to mean the largest intrinsic intensity that the source can have and yet have a given probability of remaining undetected.

The two quantities $\xi_{90\%}$ and $\xi_{\{3\sigma,5\sigma\}}$ can be computed using a likelihood approach as it is described in the next chapter. These two quantities are often referred to as the model rejection factor (MRF) and the model discovery factor (MDF) [198].

3.5 Event selection for ARCA6 and ARCA8

The data collected with the ARCA6 and ARCA8 configurations have already been used in a previous point-source analysis. In this work, for these two samples, we restrict ourselves to the event selection developed for that analysis.

The event selection adopted for the ARCA6 and ARCA8 datasets is described in detail in [180, 199] and is briefly summarised here. The selection aims at isolating track-like cosmic neutrino events from charged-current muon neutrino interactions, while suppressing the atmospheric muon background.

Atmospheric muons are simulated as described in the previous section. The background from atmospheric neutrinos is estimated starting from the same muon neutrino and antineutrino charged-current simulations, weighted according to an atmospheric neutrino flux model. For the atmospheric conventional neutrino flux, the Honda2006 model is used [200]. For the atmospheric prompt neutrino flux, the ERS model is used [201]. Simulated samples are used to optimise the selection by maximising the signal efficiency while reducing the background contamination.

For the ARCA6 and ARCA8 datasets, the track selection does not rely on a BDT and is defined by the following requirements:

- Track reconstruction zenith angle: $\cos \theta_{\text{track}} < 0.1$ ($\theta_{\text{track}} > 84.26^\circ$);
- Shower reconstruction zenith angle: $\theta_{\text{shower}} > 84.26^\circ$ ($\cos \theta_{\text{shower}} < 0.1$);
- Track reconstruction likelihood: $L_{\text{track}} > 50$;

- Number of hits used in the reconstruction of the track: $N_{\text{hits}} > 20$.

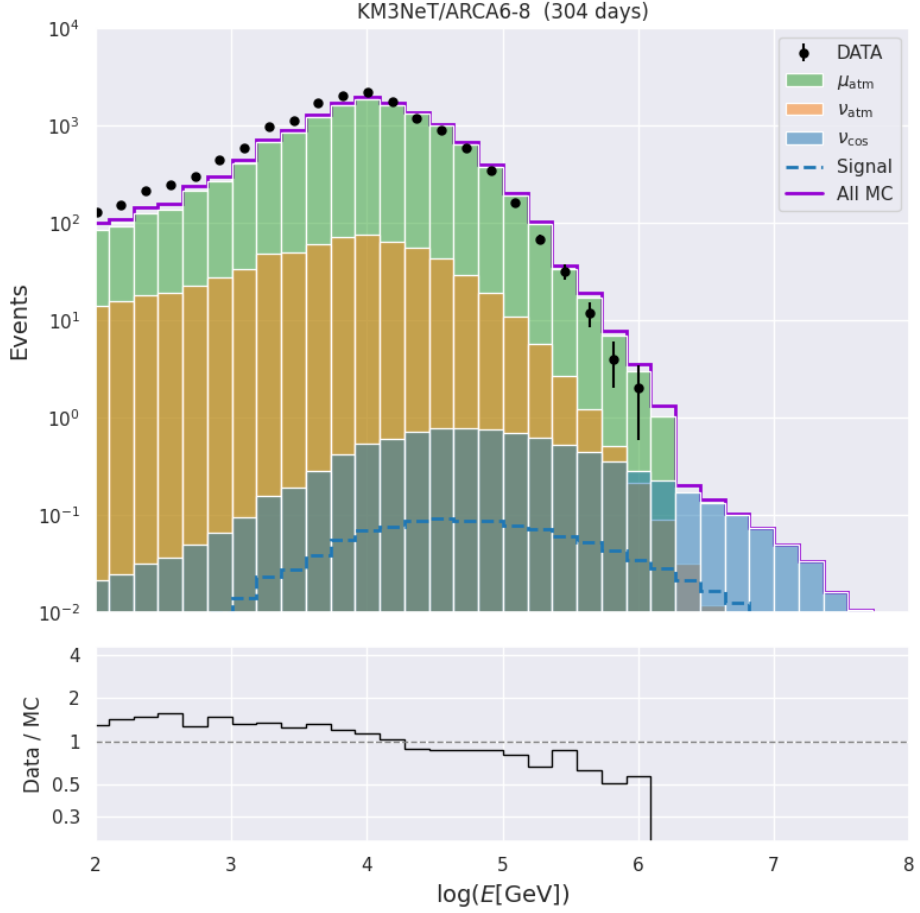


Figure 3.6: Energy distribution of ARCA6-8 events. Data distributions are shown as points, while histograms represent the simulated contributions from cosmic neutrinos (blue), atmospheric neutrinos (orange), and atmospheric muons (green). The sum of all simulated components is shown by the purple curve.

The reconstructed energy distribution of selected ARCA6 and ARCA8 events is shown in Figure 3.6, and the number of events from data and different Monte Carlo (MC) contributions are presented in Tab.3.2. For the distribution of cosmic neutrinos, a power-law flux was assumed:

$$\phi_{\nu+\bar{\nu}} = 1.2 \times 10^{-8} \left(\frac{E_{\nu}}{\text{GeV}} \right)^{-2} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}. \quad (3.3)$$

This is a reference flux, whose normalisation factor and spectral index values are

taken from those measured by IceCube for the diffuse cosmic neutrino flux (see Chapter 1.3)

For atmospheric neutrinos the expected flux is parametrized as done in [202].

Dataset	ARCA6	ARCA8
Atmospheric muons	5020	8260
Atmospheric neutrinos	240	510
Cosmic neutrinos (E^{-2})	1.79	4.14
Data	4205	11537
Data/MC	0.80	1.32

Table 3.2: Total number of events for the track selection of the ARCA6 and ARCA8 datasets.

The event selection for the ARCA6-8 samples was primarily designed to achieve a good signal efficiency. As noted by R. Müller, who developed the selection, the fraction of signal events that pass the cuts is about 81%, while the surviving fraction for atmospheric muons is around 3%. However, due to the large number of atmospheric muons, they still constitute the majority of the expected events. For ARCA6-8 samples, the muon contamination is around 94.75%. The muon contamination is defined as the ratio between the number of weighted atmospheric-muon events and the total number of weighted Monte Carlo events (atmospheric muons, atmospheric neutrinos, and cosmic neutrinos), all evaluated after the selection cuts. The muon-to-total event ratio is computed using event weights. Since muons and neutrinos have different weights, this ratio is not equal to the fraction of simulated events, but reflects their relative weighted contributions.

3.6 Event selection for ARCA21

The main goal of the ARCA21 event selection is to achieve an atmospheric muon contamination close (or even below) to 20%, while ensuring that the contamination is strongly suppressed at high energies.

As a first step, a preselection is applied to both data and Monte Carlo samples. This preselection closely follows the criteria adopted for the ARCA6 and ARCA8 analyses. The basic requirements are:

- Track reconstruction zenith angle: $\cos \theta_{\text{track}} < 0.1$ ($\theta_{\text{track}} > 84.26^\circ$);
- Track reconstruction likelihood: $L_{\text{track}} > 50$;
- Reconstructed energy: $E_{\text{reco}} > 10$ GeV ($\log_{10}(E_{\text{reco}} [\text{GeV}]) > 1$);
- Number of hits used in the track reconstruction: $N_{\text{hits}} > 20$.

Additional selection criteria are then considered in order to further reduce the atmospheric muon background. The variables used in this stage are the

reconstructed energy, the angular uncertainty on the reconstructed direction β_0 , as estimated by the event-reconstruction algorithm, the estimated track length, and the likelihood of the track reconstruction.

Figures 3.7 and 3.8 show the distributions of ARCA21 events as a function of these variables. Regarding the energy distribution, a deficit of events is observed in the data for energies below 10^4 GeV, while an excess appears at higher energies. The data–MC agreement is worse for the reconstruction likelihood: for values of $\log_{10}(\text{Lik}) > 2.5$, the data events populate only a few bins. Among the considered variables, the track length shows the best agreement between data and MC.

In addition to the reconstructed variables, a Boosted Decision Tree (BDT) classifier is evaluated for each event. This BDT was originally developed and used for the point-source analysis of the first three months of ARCA21 data. The distribution of the BDT output for the complete ARCA21 dataset is shown in Figure 3.9 (top). The atmospheric muon contamination at high BDT scores highlights the difficulty of discriminating signal from background in this dataset. Since atmospheric muons are present up to the last bin, the distribution of events as a function of $-\log_{10}(1 - \text{BDT})$ is shown in Figure 3.9 (bottom panel) to provide a more detailed view of the event population in the highest-score region. The contribution of atmospheric muons ceases to be dominant for values of $-\log_{10}(1 - \text{BDT}) \sim 3\text{--}4$, corresponding to BDT scores in the range 0.9990–0.9999. For this reason, a cut of BDT score > 0.9996 was adopted in the final selection.

To suppress the contribution of high-energy atmospheric muons, selection cuts on the track reconstruction likelihood and on the estimated track length are first considered. The cut values are determined by inspecting Monte Carlo distributions for events with reconstructed energies above 100 TeV. The corresponding distributions are shown in Figure 3.10. As can be observed, most high-energy atmospheric muons are reconstructed with track lengths around 100 m and values of $\log_{10}(\text{likelihood})$ between 1.7 and 2.2.

The atmospheric muon contamination can be further reduced by applying an additional cut on the angular uncertainty β_0 . The cut value is determined by studying the two-dimensional distributions of reconstructed energy versus β_0 for atmospheric muons and cosmic neutrinos, shown in Figure 3.11. Atmospheric muons are predominantly located at $\log_{10}(\beta_0) > -2.5$, with a maximum above -2.0 , whereas cosmic neutrinos extend down to $\log_{10}(\beta_0) \sim -3.5$, with a maximum between -2.5 and -2.0 .

Several combinations of selection cuts on the track length, $\log_{10}(\text{Lik})$, and $\log_{10}(\beta_0)$ variables were investigated. For each combination, an additional cut on the reconstructed energy ($E_{\text{reco}} > 100$ GeV) was applied in order to exclude the low-energy region, where the background rate is expected to largely dominate over the signal contribution.

As mentioned before, to finalize the selection, a cut on the BDT score ($\text{BDT} > 0.9996$) was applied, ensuring a strong suppression of atmospheric muons. In particular, in the two-dimensional space defined by the track length and $\log_{10}(\text{Lik})$, an elliptical cut was introduced to improve the discrimination between signal events and atmospheric muons, motivated by the shape of the corresponding

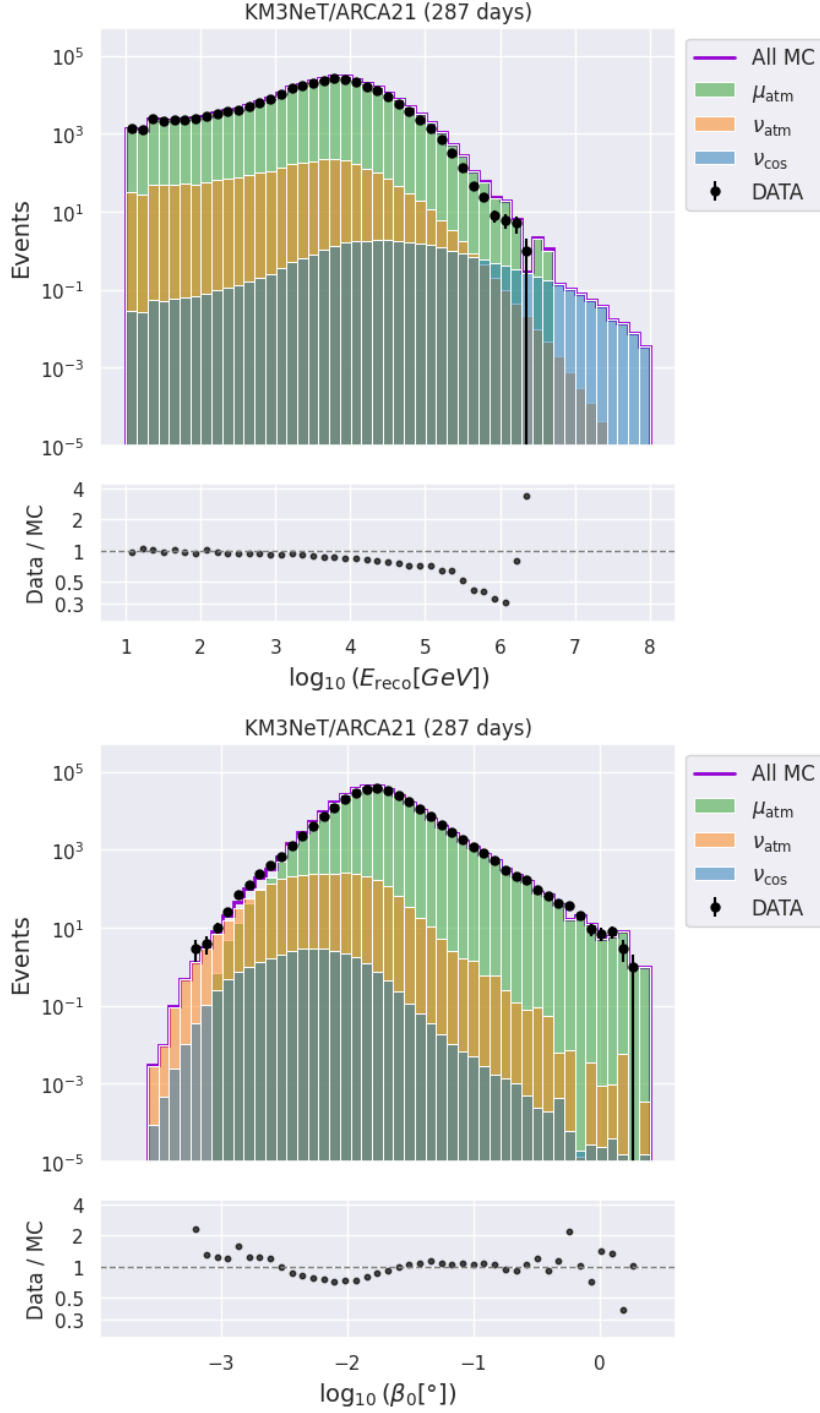


Figure 3.7: ARCA21: Energy distribution $\log_{10}(E_{\text{reco}} [\text{GeV}])$ (top) and direction error $\log_{10}(\beta_0)$ (bottom) for data and MC events passing the pre-cut level.

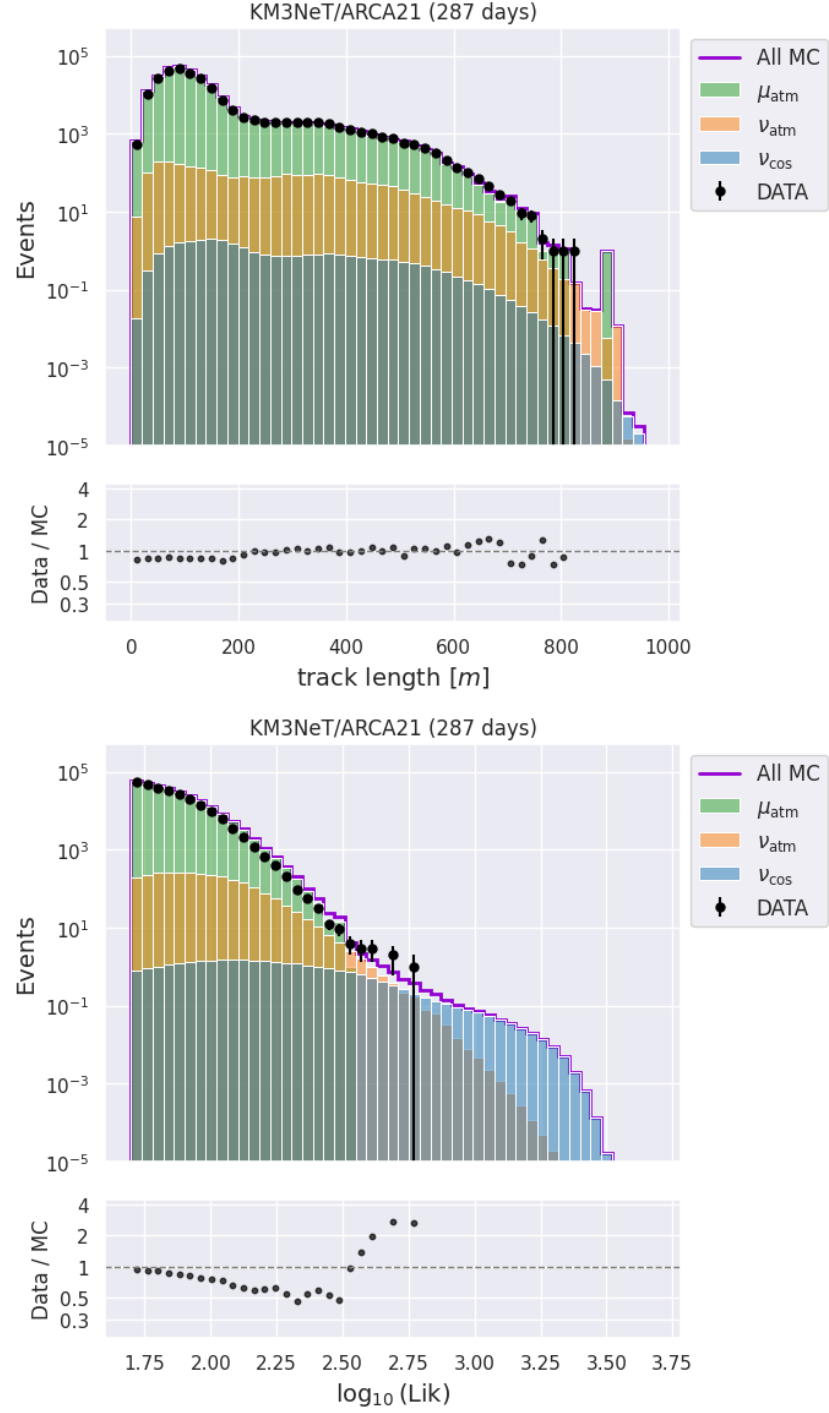


Figure 3.8: ARCA21: Fitted track length (top) and track likelihood (bottom) for data and MC events passing the precut level.

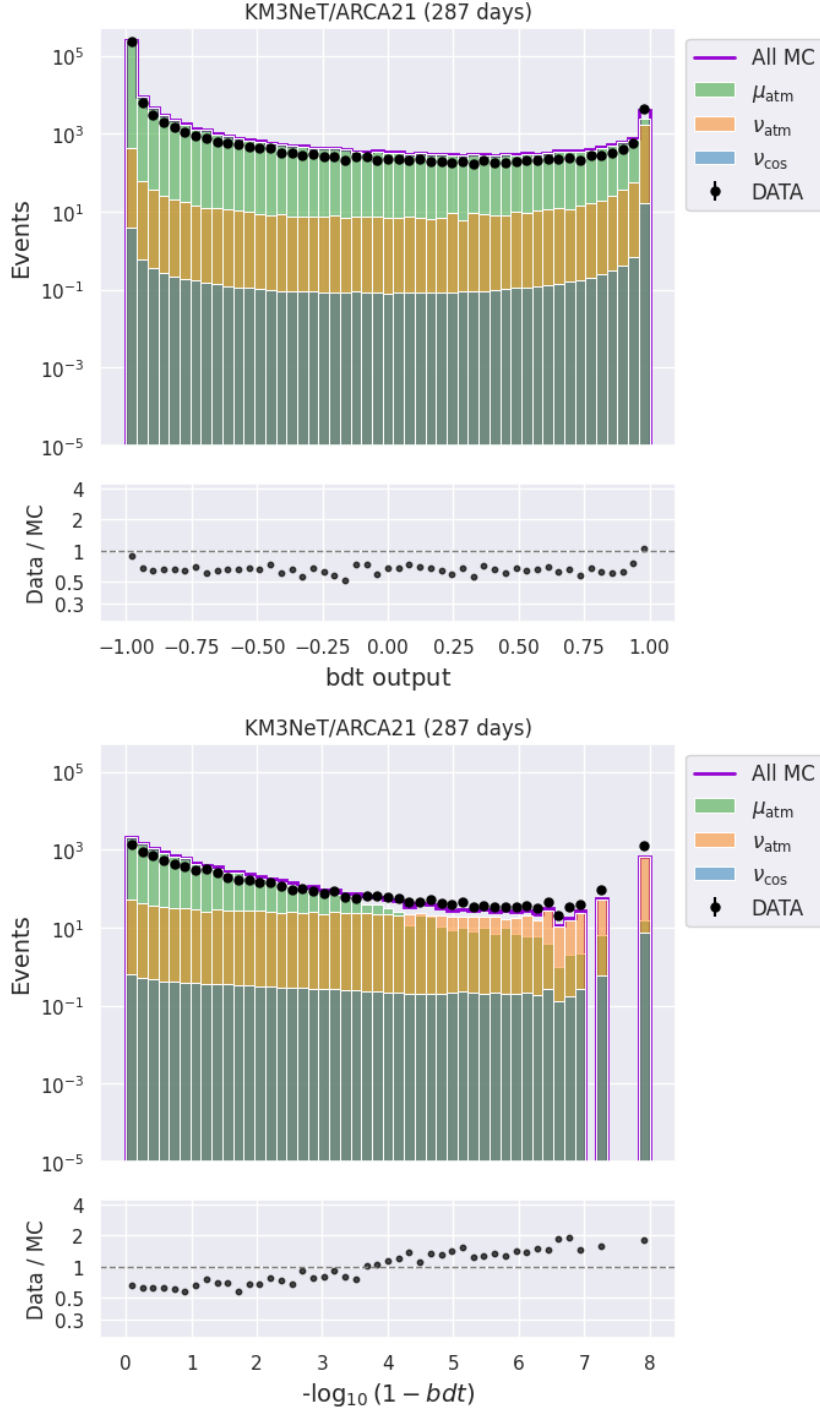


Figure 3.9: BDT output distribution for the ARCA21 data and MC events passing the precut level(top). Distribution of $-\log_{10}(1 - \text{bdt})$ for events with bdt output > 0 (bottom).

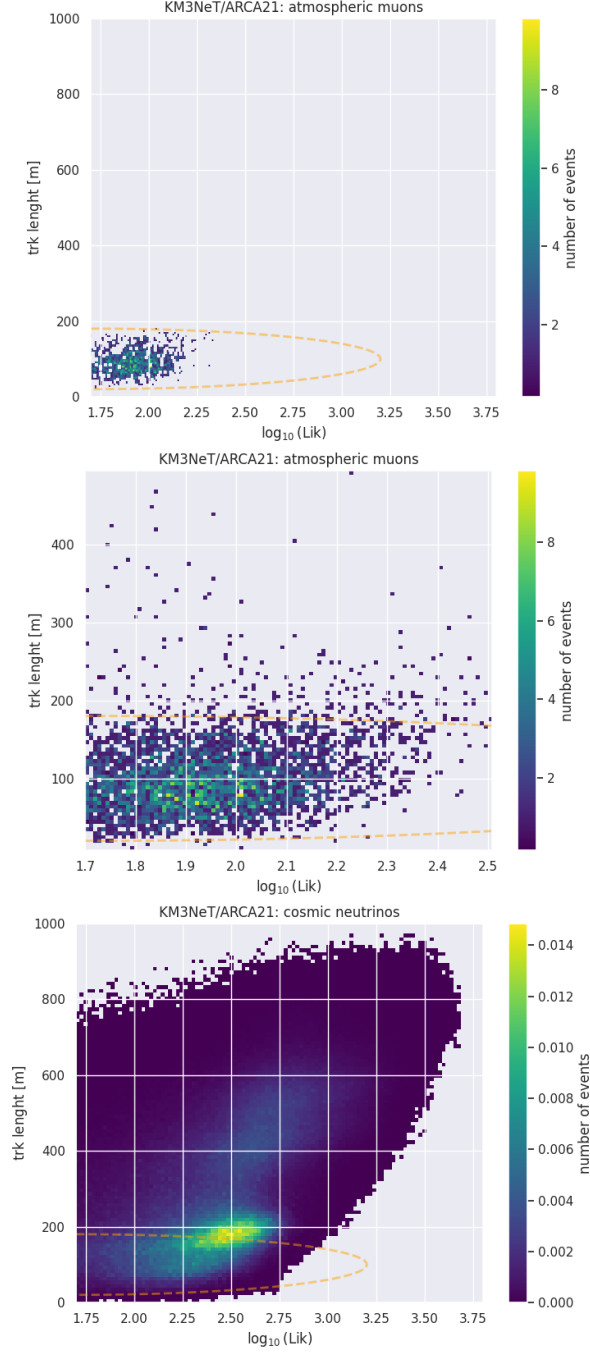


Figure 3.10: ARCA21: 2D distributions of the MC atmospheric muons (top) and cosmic neutrinos (bottom) with respect to the track length and the likelihood of the reconstruction, for events with $\log_{10}(E_{\text{reco}} [\text{GeV}]) > 5$. The orange dashed line indicates the region rejected by the elliptical selection. Center: zoom of muons distribution

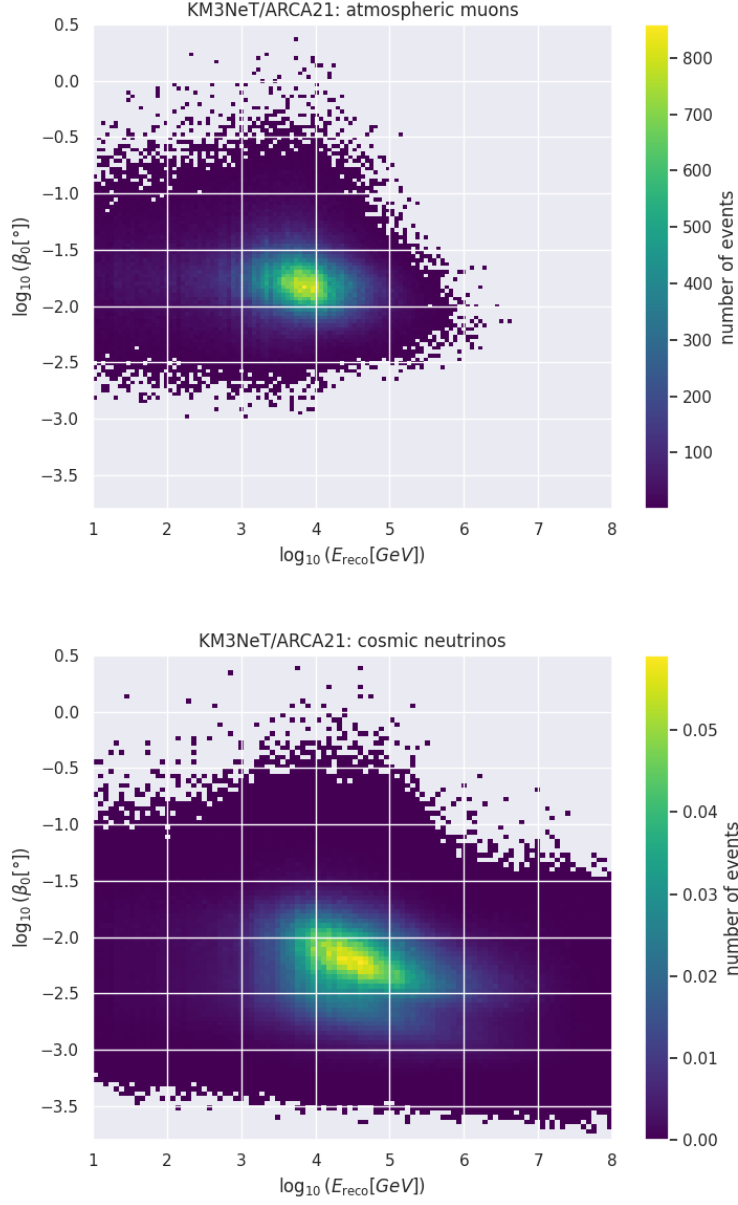


Figure 3.11: 2D distributions of the MC atmospheric muons (top) and cosmic neutrinos (bottom) with respect to the reconstructed energy and the angular error β_0 , for events with $\log_{10}(E_{\text{reco}} [\text{GeV}]) > 1$.

distributions. The elliptical selection is defined as:

$$\left(\frac{\log_{10}(\text{Lik}) - 1.7}{1.5}\right)^2 + \left(\frac{\text{track length} - 100 \text{ m}}{80 \text{ m}}\right)^2 > 1. \quad (3.4)$$

For the angular uncertainty variable β_0 , two alternative cuts were considered:

$$\log_{10}(\beta_0) < -2.20 \text{ and } \log_{10}(\beta_0) < -2.25.$$

These cuts aim at excluding the region populated by the majority of atmospheric muons, while retaining a sufficiently large fraction of cosmic neutrino events.

The following selections are considered:

- **Selection 1:** $\text{BDT} > 0.9996 + \text{elliptical selection} + E_{\text{reco}} > 100 \text{ GeV}$;
- **Selection 2:** $\text{BDT} > 0.9996 + \log_{10}(\beta_0) < -2.20 + E_{\text{reco}} > 100 \text{ GeV}$;
- **Selection 3:** $\text{BDT} > 0.9996 + \log_{10}(\beta_0) < -2.25 + \text{track length} > 100 \text{ m} + \log_{10}(\text{Lik}) > 1.8 + E_{\text{reco}} > 100 \text{ GeV}$;
- **Selection 4:** $\text{BDT} > 0.9996 + \text{elliptical selection} + \log_{10}(\beta_0) < -2.25 + E_{\text{reco}} > 100 \text{ GeV}$.

A summary of the event rates, data-to-MC comparison, atmospheric muon contamination, and signal efficiency for several combinations of selection criteria is reported in Table 3.3.

Selections	bdt>0.95	selection 1	selection 2	selection 3	selection 4
Atmospheric muons	2578	301.8	205.1	146.2	146.1
Atmospheric neutrinos	1720	1048.6	891.8	753.9	796.8
Cosmic neutrinos (E^{-2})	17	12.08	11.37	10.63	10.43
Data	4479	2088	1671	1361	1437
Data/MC	1.042	1.533	1.508	1.494	1.507
Muon contamination	59.95%	22.15%	18.51%	16.05%	15.3%
Signal efficiency	60.93%	43.31%	40.75%	38.11%	37.39%

Table 3.3: Summary of event rates, data-to-MC comparison, muon contamination and signal efficiency for different selection criteria. Signal efficiency is the fraction of signal events that pass selection using the number of events after precuts as a reference value.

In order to determine the optimal event selection for the ARCA21 dataset, the sensitivity and the 5σ discovery potential were evaluated for several declination values spanning a wide range, using the binned likelihood method which will be described in the next chapter. Each declination value was treated as a potential neutrino point-source candidate, and the corresponding sensitivity and discovery potential were computed for each of the proposed selection criteria.

The signal and background histograms entering the likelihood calculation were constructed as follows. For the signal, a power-law neutrino flux was assumed,

described by:

$$\phi_{\nu+\bar{\nu}} = 1 \times 10^{-8} \left(\frac{E_{\nu}}{\text{GeV}} \right)^{-2} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}. \quad (3.5)$$

The signal expectation was obtained by convolving this flux with the detector effective area and the point spread function. The background contribution was estimated using a data-driven approach, which is described in detail in the next chapter.

Plots in Figure 3.12 show the sensitivity and the 5σ discovery potential, respectively, as a function of the sine of the declination for the different selection criteria considered. For comparison, each plot includes a ratio panel at the bottom, where the values obtained for each selection are divided by those corresponding to the reference selection based on a BDT > 0.95 cut.

Compared to the BDT > 0.95 selection, all four selections show a degradation in sensitivity and an improvement in discovery potential, with the magnitude of the effect correlated with the atmospheric muon contamination:

- Selection 1 (22.15% muon contamination): sensitivity worsens by 4.96%, while the discovery potential improves by 17.94%.
- Selection 2 (18.51% muon contamination): worsening of 16.93% in sensitivity and improvement of 11.30% in discovery potential.
- Selection 3 (16.05% muon contamination): 21.50% sensitivity change and a 15.46% improvement in discovery potential.
- Selection 4 (15.30% muon contamination): 20.85% sensitivity variation and a 10.83% improvement in discovery potential.

The estimates of sensitivity worsening and discovery improvement reported above are averaged over the considered declination values.

From these results it can be observed that selections characterised by a lower atmospheric muon contamination and lower signal efficiency, generally exhibit a degradation in sensitivity, while the discovery potential shows a less regular behaviour and does not monotonically follow the same trend.

Based on this comparison, selection 3 was chosen as the final event selection for the ARCA21 dataset. This selection provides a favourable compromise between a low level of atmospheric muon contamination and a significant improvement in the discovery potential while maintaining an acceptable sensitivity performance.

3.7 ARCA19-21 samples after event selection

The event selection developed for the ARCA21 sample was subsequently also applied to the ARCA19 event sample. The final statistics of the ARCA19-21 sample are shown in table 3.4 and figure 3.13 shows the energy distribution of the ARCA19-21 events. With the selection developed, the muon contamination was reduced to 14.76 %.

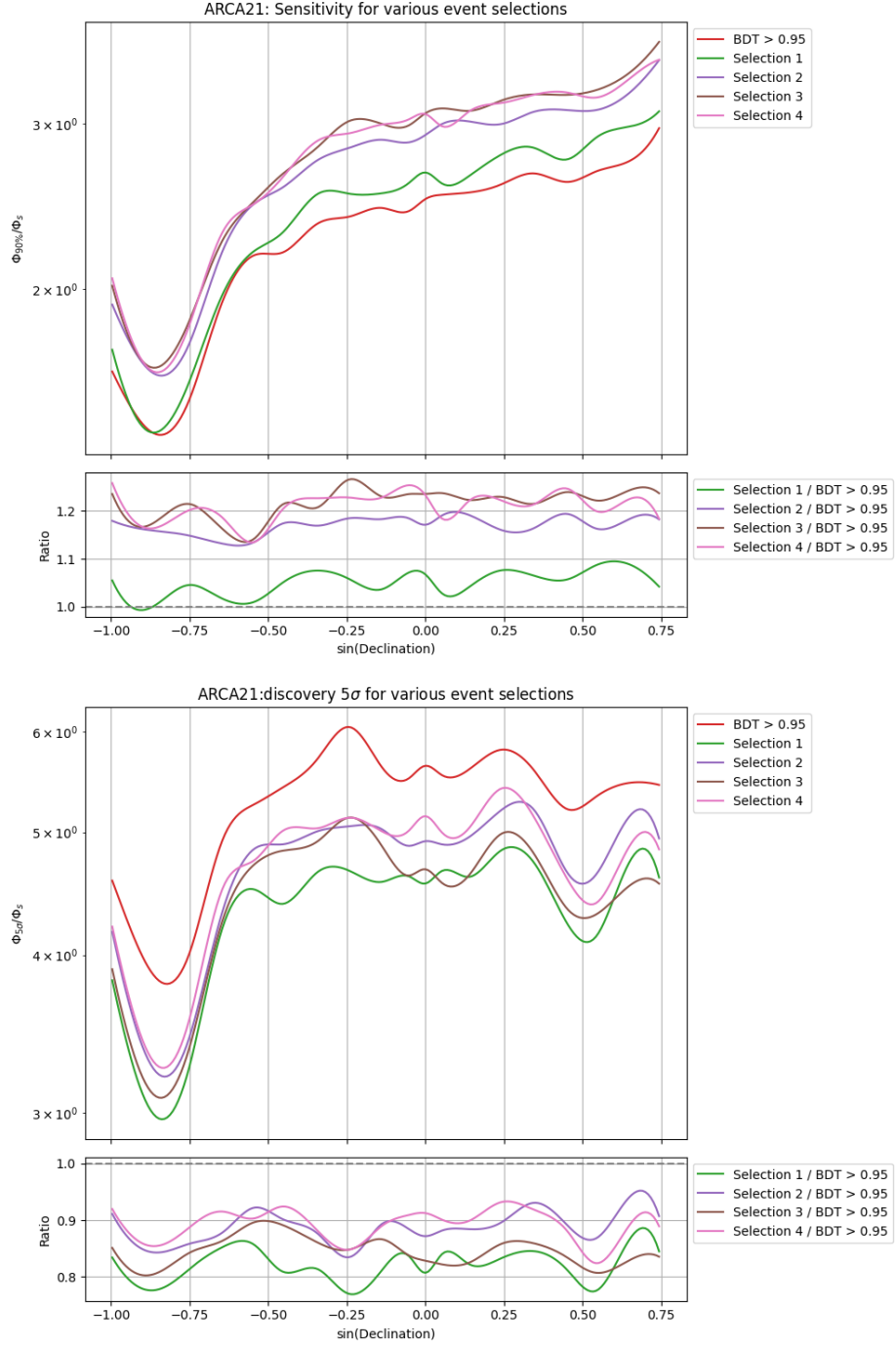


Figure 3.12: Sensitivity (top) and discovery potential (bottom) as a function of the sine of the declination for the event selections in Tab. 3.3.

Dataset	ARCA6-8	ARCA19-21
Atmospheric muons	13280	151
Atmospheric neutrinos	750	860
Cosmic neutrinos (E^{-2})	5.93	12.0
Data	15742	1543
Data/MC	1.12	1.51

Table 3.4: Total number of events for the track selection of the ARCA6-8 and ARCA19-21 datasets.

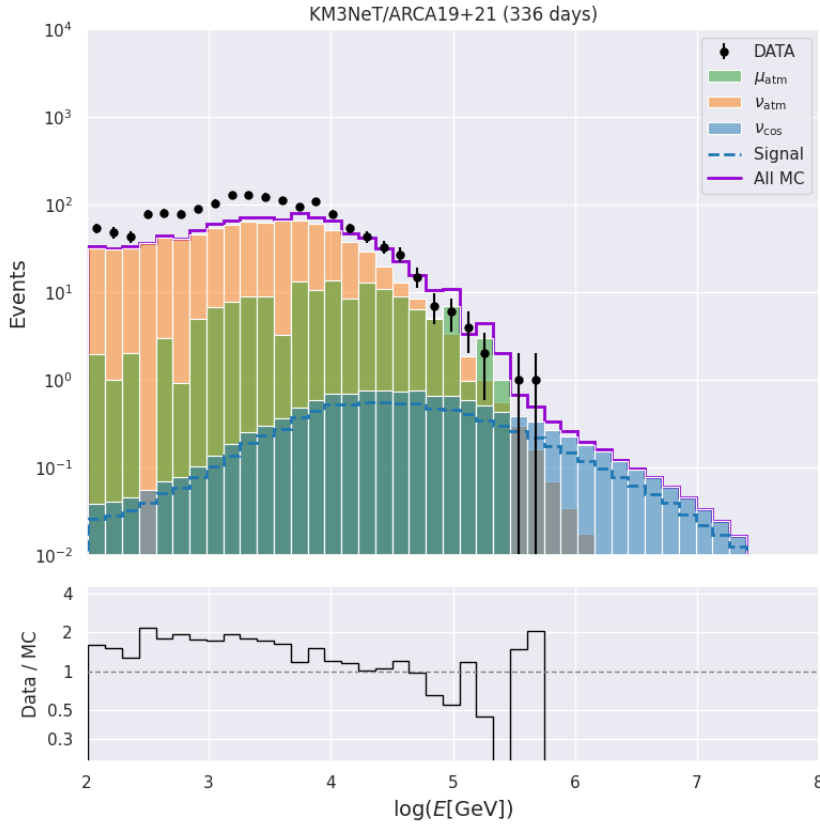


Figure 3.13: Energy distribution of ARCA19-21 selected events

3.8 Detector performance

In addition to sensitivity and discovery potential, two other quantities are commonly used to characterize the performance of a neutrino telescope: the effective area (A_{eff}) and the point spread function (PSF).

3.8.1 Effective Area and Point Spread Function

The **effective area** is defined as the quantity which, when multiplied by the incident neutrino flux Φ , yields the expected rate of detected events R_{det} ,

$$R_{\text{det}} = A_{\text{eff}} \times \Phi. \quad (3.6)$$

The effective area depends on several factors, including the neutrino energy, arrival direction, interaction cross section, detector geometry, and event selection criteria.

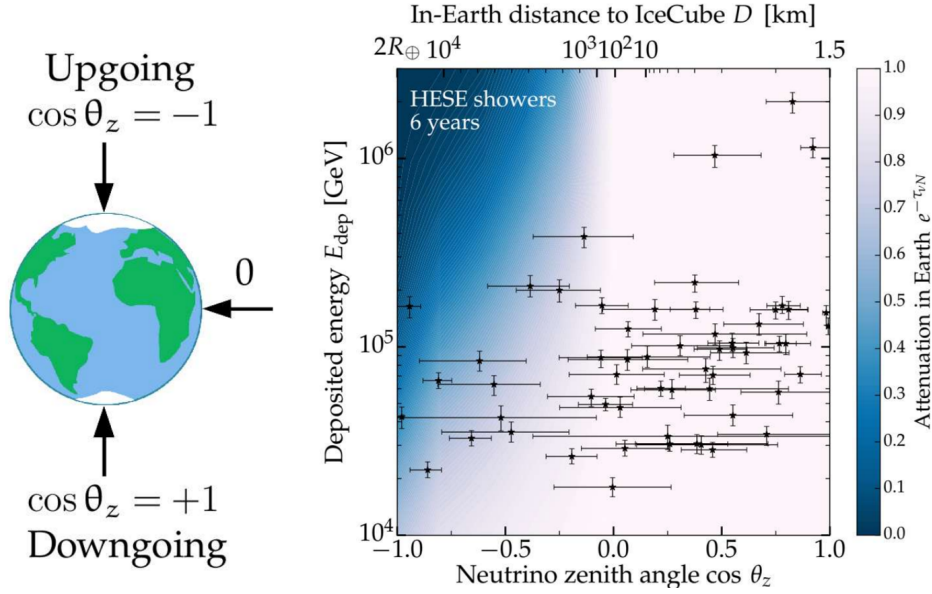


Figure 3.14: Neutrino attenuation in the Earth as a function of neutrino energy and zenith angle, which is related to the length of the neutrino path in the Earth. This estimation was done for shower-like neutrino events in the IceCube detector and the data point refer to the neutrino-induced showers from the IceCube 6-year HESE sample [156].

In fact, in order to detect neutrinos, several conditions must be met:

- the neutrino must survive the Earth absorption and interact sufficiently near to the detector;
- the produced muon must reach the instrumented volume;
- the muon must produce enough light to trigger the detector and to allow the track reconstruction.

Thus, effective area can be expressed as

$$A_{\text{eff}}(E_\nu, \theta_\nu) = A \times \varepsilon \times P_{\nu\mu}(E_\nu, E_\mu^{\text{thr}}) \times e^{-\sigma(E_\nu)\rho N_A Z(\theta_\nu)} \quad (3.7)$$

where E_ν and θ_ν are respectively the neutrino energy and the zenith angle of the direction of arrival. Briefly, the terms in the equation indicate:

- $e^{-\sigma(E_\nu)\rho N_A Z(\theta_\nu)}$ is the survival probability for a neutrino passing through the Earth, along a path $Z(\theta_\nu)$, where $\sigma(E_\nu)$ is the neutrino-nucleon cross section, ρN_A is the nucleon density along the path Z . Figure 3.14 shows the neutrino attenuation in the Earth as a function of E_ν and θ_ν . Upgoing neutrinos with $\cos\theta \sim -1$ traverse the largest amount of material, as they cross the entire Earth. As the neutrino energy increases, the interaction cross section grows, and therefore the probability of interacting along the path becomes higher. For energies above the PeV scale, the attenuation is essentially complete. For directions with $\cos\theta > -1$, the amount of material crossed decreases, resulting in a correspondingly higher survival probability.
- $P_{\nu\mu}(E_\nu, E_\mu^{\text{thr}})$ is the probability that a neutrino with energy E_ν interact and produce a muon with sufficient energy E_μ^{thr} to induce Cherenkov emission.
- ε is the fraction of muon with energy E_μ^{thr} that are detected.
- A is the geometrical projected detector surface.

Figure 3.15 shows the effective area for the complete KM3NeT/ARCA detector. In general the effective area increases with energy due to the rise of the neutrino cross section and increased detector efficiency for high-energy muons, however for high-energy neutrinos the Earth becomes less transparent (as shown in Figure 3.14) resulting in a lower effective area for straight upgoing events.

The point spread function describes the angular reconstruction performance of the detector. It is defined as the probability density of reconstructing an event at an angular deviation ψ from its true direction, per unit solid angle Ω . It can be expressed as

$$\frac{dP}{d\Omega} = \frac{d\log_{10}(\psi)}{d\Omega} \frac{dP}{d\log_{10}(\psi)} = \frac{1}{2\pi \ln(10)\psi \sin(\psi)} \frac{dP}{d\log_{10}(\psi)}. \quad (3.8)$$

The angular deviation ψ is defined as the angle between the true neutrino direction and the reconstructed direction. This angle is partly determined by the kinematic angle between the parent neutrino and the produced muon (as described in Chapter 2), which is energy dependent, but more importantly by the track reconstruction, which is affected by the scattering of light in the medium, and detector geometry.

The effective area and the point spread function fully determine the expected number of detected events N_{ν_ℓ} from a certain direction θ_{ν_ℓ} in a given observation time T and within a given solid angle Ω^* . The event rate is obtained by convolving the incident neutrino flux with the effective area and the angular response of the detector as described by the PSF:

$$\frac{N_{\nu_\ell}}{T} = \int \phi_{\nu_\ell}(E_{\nu_\ell}) \times A_{\text{eff}}^{\nu_\ell}(E_{\nu_\ell}, \theta_{\nu_\ell}) \times \frac{dP}{d\Omega}(E_{\nu_\ell}, \theta_{\nu_\ell}) dE_{\nu_\ell} d\Omega_{\nu_\ell} \quad (3.9)$$

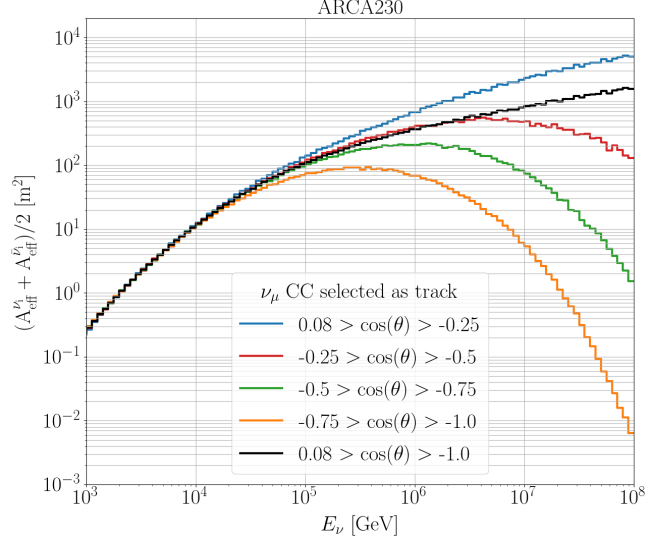


Figure 3.15: The full ARCA effective area for $\nu_\mu CC$ events selected as track for different $\cos(\theta)$ [203].

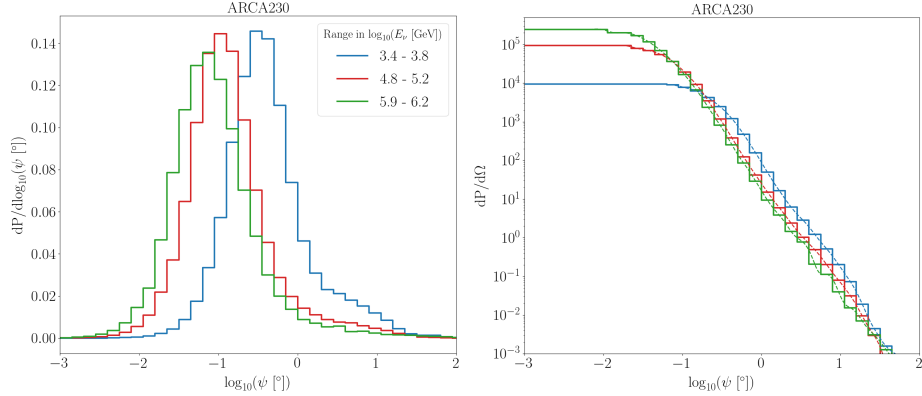


Figure 3.16: The full ARCA $dP/d\log_{10}(\psi)$ (left) and PSF $dP/d\Omega$ (right) for $\nu_\mu CC$ events selected as track [203], considering various energy ranges.

3.8.2 ARCA6-21 detector response

The response of the detector to a possible signal is modeled via detector response functions (acceptance and resolutions), which are based on Monte Carlo simulations [188, 204, 205]. The effective area of ARCA6-21 compared with ANTARES is shown in Figure 3.17 (top). The selections differ among the various detector configurations in terms of efficiency and muon contamination. For selected track events from $\nu_\mu CC + \bar{\nu}_\mu CC$ interactions the difference between the true neutrino

and reconstructed muon direction for the ARCA6-8 and ARCA19-21 periods is shown in Figure 3.17 (bottom). At high energies (100 PeV), this angular deviation from the true neutrino direction improves from $\sim 1^\circ$ (ARCA6-8) to $\sim 0.15^\circ$ (ARCA19-21), and is expected to reach $\sim 0.06^\circ$ in the complete ARCA configuration [203]. The PSFs of all detector periods are compared in Figure 3.18.

In addition to the effective area and the PSF, the detector performance can also be described in terms of the energy resolution, defined as the discrepancy between the true and reconstructed energy of the events. Figure 3.19 shows the 2D distributions of true versus reconstructed energy for $\nu_\mu \text{CC} + \bar{\nu}_\mu \text{CC}$ events in the ARCA6-21 samples. For comparison, the figure also includes the distributions of $\log_{10}(E_{\text{true}}/E_{\text{reco}})$ as a function of the reconstructed energy.

As already mentioned in Chapter 2, the energy resolution for track-like events is quite poor, since only a fraction of the Cherenkov light emitted along the muon track is observed by the detector. However, the resolution improves with increasing energy: above ~ 100 PeV, most events lie close to the bisector $E_{\text{reco}} \sim E_{\text{true}}$.

The $E_{\text{reco}} - E_{\text{true}}$ distributions can be integrated into Eq. 3.9, thereby yielding the expected event rate within a given solid angle and energy interval.

3.9 Summary

In this chapter, the development and optimisation of the event selection for the KM3NeT/ARCA datasets have been presented, with a particular focus on the ARCA21 configuration. Starting from the baseline selection adopted for the earlier ARCA6 and ARCA8 datasets, additional selection criteria based on reconstructed variables and on a multivariate BDT classifier were introduced in order to further suppress the atmospheric muon background.

Several combinations of selection cuts were investigated and their performances were evaluated in terms of sensitivity and 5σ discovery potential for a wide range of source declinations. This comparison highlights the intrinsic trade-off between background suppression and signal efficiency, with increasingly stringent selections leading to lower atmospheric muon contamination at the cost of a reduced sensitivity.

Based on these studies, the final selection adopted for the ARCA21 dataset was chosen as an optimal compromise between these competing effects, providing a significantly reduced atmospheric muon contamination while yielding an improved discovery potential with respect to the baseline selection.

The same selection was subsequently applied to the ARCA19 dataset. With this approach, a final sample characterised by an atmospheric muon contamination below 15% was obtained, while preserving a substantial contribution from cosmic neutrino candidates. This combined ARCA19-21 dataset, together with the earlier ARCA6 and ARCA8 samples, constitutes the full event sample used for the point-source analysis presented in the following chapters.

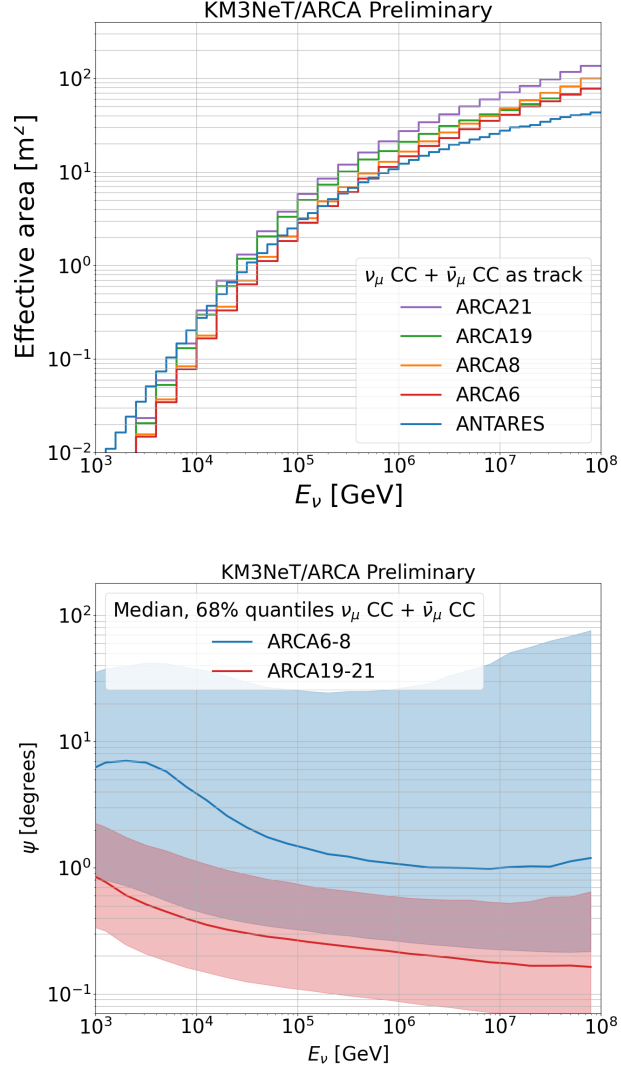


Figure 3.17: Effective area at selection level (top) for the different ARCA detector geometries for a flux of $\nu_\mu + \bar{\nu}_\mu$ that interact via CC interaction. The effective areas are compared with the ANTARES effective area for upgoing events. The difference between the true neutrino and reconstructed muon direction (bottom) for the ARCA6-8 and ARCA19-21 periods with their corresponding 68% quantiles.

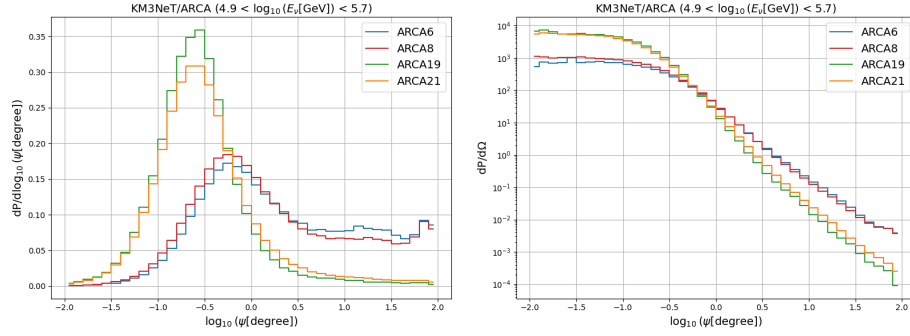


Figure 3.18: Comparison of distributions of $dP/d\log_{10}(\psi)$ (left) and PSF $dP/d\Omega$ (right) for the different ARCA configurations, for $\nu_\mu CC + \bar{\nu}_\mu CC$ events.

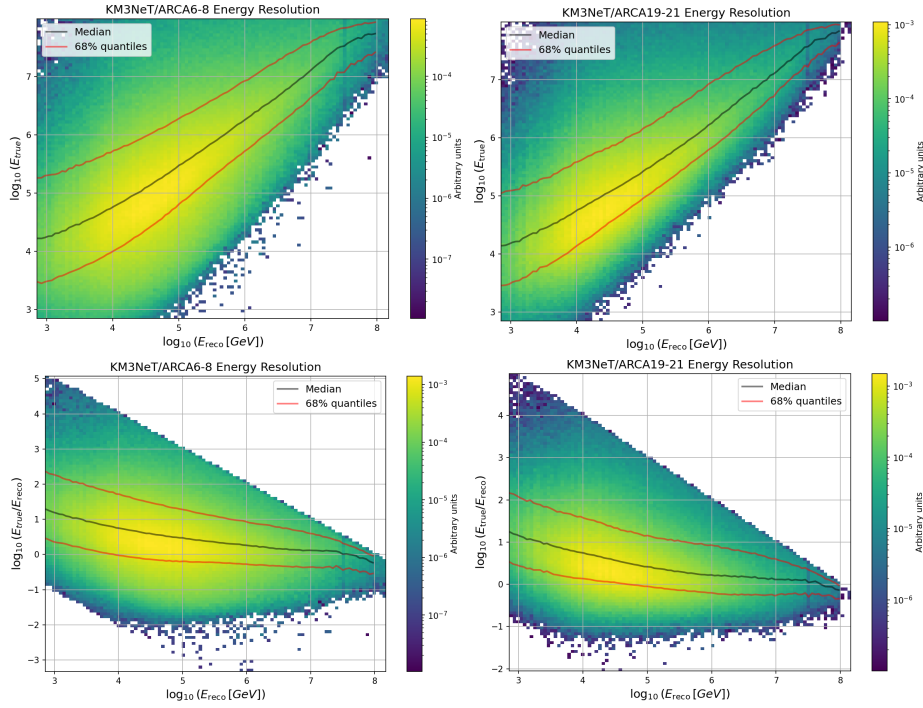


Figure 3.19: On the top: $\nu_\mu CC + \bar{\nu}_\mu CC$ events distribution with respect to the true energy and the reconstructed one, for ARCA6-8 samples (left) and ARCA19-21 (right). On the bottom: the same distribution as a function of $\log_{10}(E_{\text{true}}/E_{\text{reco}})$ and reconstructed energy.

Chapter 4

Search for cosmic neutrino sources with 6-21 lines of KM3NeT/ARCA

Starting from July 2024, I became responsible for conducting the KM3NeT/ARCA point source search. The aim of this work is to analyse KM3NeT/ARCA data to test their compatibility with neutrino signal from point-like sources.

As mentioned in the first chapter, the identification of cosmic objects emitting high-energy neutrinos provides new insights about the Universe and its active sources. The existence of cosmic neutrinos has been confirmed by the IceCube Neutrino Observatory, however the big question of where these neutrinos originate from remains largely unanswered.

As described in the second chapter, KM3NeT/ARCA will have an instrumented volume of a cubic kilometre, and will excel at identifying cosmic neutrino sources due to its unprecedented angular resolution ($< 0.1^\circ$ for muon neutrinos with $E > 300$ TeV). KM3NeT has a view of the sky complementary to IceCube, and is sensitive to neutrinos across a wide range of energies. Currently more than 20% of the detector is installed in the deep sea.

This chapter presents the results of a search for a selected list of point sources and extended sources, as well as an unbiased all-sky scan looking for potential neutrino sources, with KM3NeT/ARCA data taken between May 2021 and September 2023 with an evolving detector geometry up to 21 lines, for a total of 640 days of lifetime. The analysis relies on binned likelihood techniques and employs Monte Carlo-based statistical inference to separate potential cosmic signals from the dominant atmospheric background. The sensitivity estimates, analysis methods, and key results are presented in the following sections.

4.1 Likelihood Formalism

In particle and astroparticle physics, the statistical significance of an excess of signal events over the background expectation is commonly quantified using a likelihood ratio test.

Given a dataset $\{\mathbf{x}_I\}$ and two hypotheses H_0 and H_1 , referred to as the null and alternative hypotheses, respectively, the likelihood ratio is defined as

$$\Lambda(\mathbf{x}) = \prod_{I=1}^N \frac{\mathcal{L}(\mathbf{x}_I|H_1)}{\mathcal{L}(\mathbf{x}_I|H_0)}, \quad (4.1)$$

where $\mathcal{L}(\mathbf{x}_I|H_0)$ and $\mathcal{L}(\mathbf{x}_I|H_1)$ are the probability density functions (likelihoods) of the data under the two hypotheses. The vector $\mathbf{x}_I = \{x_{I,1}, x_{I,2}, \dots, x_{I,m}\}$ represents the set of reconstructed observables characterizing the I -th event, such as reconstructed energy and direction, number of detected hits, or estimated track length.

The importance of the likelihood ratio test lies in the Neyman–Pearson lemma, which states that it provides the most powerful test for discriminating between two simple hypotheses. Large values of Λ indicate that the observed data are more compatible with the alternative hypothesis than with the null hypothesis.

In the specific case considered here, the null hypothesis $H_0 \equiv H_b$ corresponds to the background-only scenario, while the alternative hypothesis $H_1 \equiv H_{b+s}$ includes the presence of a signal contribution.

It is convenient to work with the logarithm of the likelihood ratio, since it transforms the product into a sum:

$$\lambda = \log \Lambda = \sum_{I=1}^N [\log \mathcal{L}(\mathbf{x}_I|H_{b+s}) - \log \mathcal{L}(\mathbf{x}_I|H_b)]. \quad (4.2)$$

The likelihood method is widely used in many areas of physics, often in different formulations. For this reason, this section provided a general description of the approach.

In the analysis presented in this chapter, a specific case of likelihood is employed, in which the probability density functions are represented by two histograms defined in the event-variable space. This formulation is referred to as a binned likelihood, since the product (or sum) is evaluated over the histogram bins.

4.1.1 Binned likelihood approach

For a given neutrino source candidate, identified by its right ascension and declination, a circular region of interest around the source position is defined, and only events within this region are considered. A possible excess of signal over background is quantified using a likelihood-ratio test statistic defined as

$$\lambda = \log \mathcal{L}(\xi = \hat{\xi}) - \log \mathcal{L}(\xi = 0), \quad (4.3)$$

where ξ is the signal strength parameter. The value $\xi = 0$ corresponds to the background-only hypothesis, while $\hat{\xi}$ is the value that maximizes the likelihood for a given dataset and signal/background model.

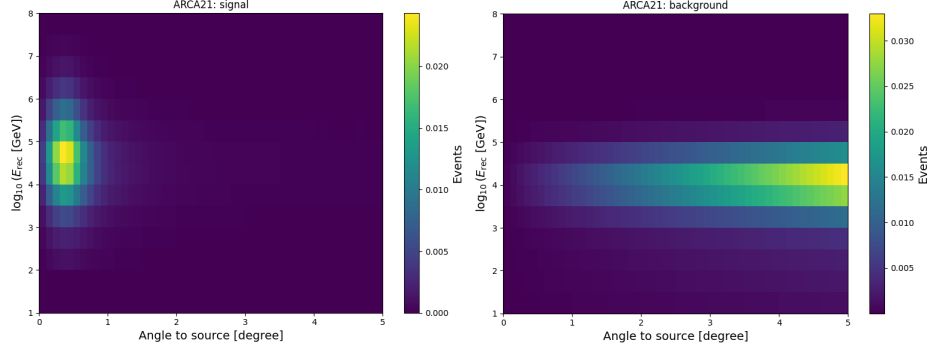


Figure 4.1: ARCA21 (287 days): expected signal (left) and background (right) distributions as a function of reconstructed energy and angular distance to the source for a point source at declination of -14° .

The signal and background expectations are described by two-dimensional histograms as functions of the reconstructed energy (in logarithmic scale) and the angular distance from the source direction (Figure 4.1). In standard KM3NeT/ARCA point source search, it is considered a maximum cone radius of 5° around the source position. The optimization of the cone size will be discussed later, such as the way in which the two histograms are produced.

The likelihood function $\mathcal{L}$ is defined assuming Poissonian statistics in each analysis bin as

$$\mathcal{L} = \prod_{i \in \text{bins}} \frac{x_i^{N_i} e^{-x_i}}{N_i!}, \quad (4.4)$$

where N_i is the observed number of events in bin i , and the expected number of events is given by

$$x_i = B_i + \xi S_i. \quad (4.5)$$

Here, B_i and S_i denote the expected background and signal contributions in bin i , respectively.

The logarithm of the likelihood can thus be written as

$$\log \mathcal{L} = \sum_{i \in \text{bins}} \log \left(\frac{(B_i + \xi S_i)^{N_i} e^{-(B_i + \xi S_i)}}{N_i!} \right). \quad (4.6)$$

By omitting terms that do not depend on the signal strength, the relevant expression becomes

$$\log \mathcal{L}(\xi) = \sum_{i \in \text{bins}} [N_i \log(B_i + \xi S_i) - B_i - \xi S_i]. \quad (4.7)$$

4.1.2 Pseudo-experiments

For a given true value of the signal strength ξ_{true} , pseudo-experiments (PEs) are generated by randomly drawing the number of events N_i in each bin from a Poisson distribution with mean $B_i + \xi_{\text{true}} S_i$. Each pseudo-experiment is then analysed following the procedure described above: a maximum-likelihood fit is performed to determine $\hat{\xi}$, and the corresponding test statistic λ is computed.

By repeating this procedure for a large number of pseudo-experiments, distributions of the test statistic $\lambda(\xi_{\text{true}})$ are obtained. Repeating the process for different values of ξ_{true} yields test statistic distributions under both the background-only hypothesis and signal-plus-background hypotheses.

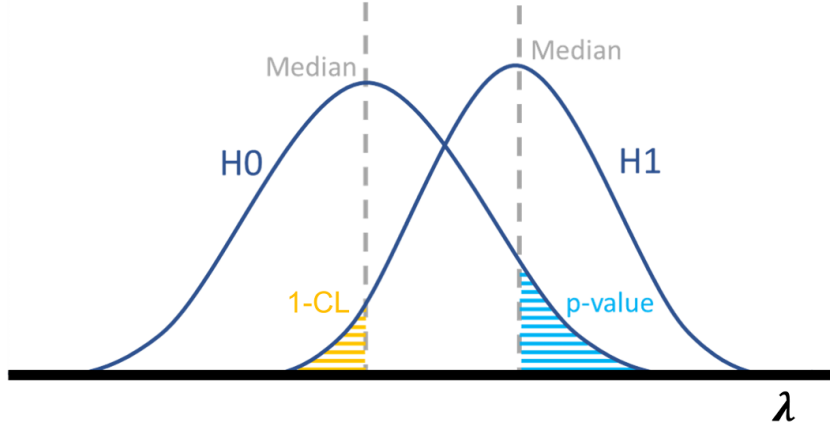


Figure 4.2: Illustration of the areas determining the p -value and the confidence level (CL) in two hypothetical Gaussian test statistic distributions corresponding to the background-only (H_0) and signal-plus-background (H_1) hypotheses.

4.1.3 Confidence interval and p -value determination

The sensitivity and discovery potential are derived from the distributions of the test statistic using the Neyman construction [206, 207]. In this framework, the p -value and the confidence level quantify the probability of observing a given dataset, or a more extreme one, assuming the background-only or signal-plus-background hypothesis to be true, respectively.

For the expected performance of the analysis, these probabilities are evaluated with respect to the median value of the test statistic under the opposite hypothesis. The corresponding integration regions are illustrated in Fig. 4.2.

The confidence level for a given signal strength ξ is computed as the integral of the test statistic distribution obtained for that value of ξ , starting from the median of the background-only distribution and extending to infinity. This procedure yields a confidence level as a function of the signal strength. The sen-

sitivity is defined as the value of ξ for which the median upper limit reaches a given confidence level, typically 90%.

The p -value is computed as the integral of the background-only test statistic distribution above the median of the distribution obtained for $\xi \neq 0$. By evaluating this quantity for different values of ξ , the p -value is obtained as a function of the signal strength. The discovery potential, corresponds to the signal strength for which the median p -value reaches a predefined significance threshold, such as 3σ or 5σ .

4.2 KM3NeT/ARCA6-21 dataset

4.2.1 Data sample

Data are used from a period when KM3NeT/ARCA was running with 6 - 21 detector lines between May 2021 and September 2023. The dataset spans 640 days of live time: 92.0 days with 6 lines (ARCA6), 212.3 days with 7–8 lines (ARCA8), 48.4 days with 19 lines (ARCA19), and 287.4 days with 21 lines (ARCA21). This represents a nearly twofold increase in exposure compared to the previous KM3NeT analysis at ICRC 2023 [208].

In the previous chapter, the event selection applied to each dataset, has been described. In this section, the estimation of the number of background events will be addressed.

4.2.2 Background expectation from scrambled data and signal expectation from MC

In order to create the PEs we perform a scrambling of the data by assigning a different timestamp to each data event. Background rates as functions of reconstructed energy and declination (δ) are derived from scrambled data. A spline fit $F(\delta)$ is used for the declination dependency and a double-Gaussian for modeling the energy distribution $F(\log_{10}(E))$. For each source, the expected background density is calculated as

$$N_{\text{bkg}}(\delta, E) = n \times F(\delta) \times F(\log_{10}(E)) \quad (4.8)$$

where the normalization n ensures consistency with the observed event rate. The data and the background model for the ARCA21 dataset is shown in Figure 4.3. Similar models are made for the other datasets.

In order to obtain the background 2D histogram, the number of background events in a given bin $(\psi_{\text{bin}}, E_{\text{bin}})$ is calculated as:

$$N_{\text{bkg}}(\psi_{\text{bin}}, E_{\text{bin}}) = N_{\text{bkg}}(\delta, E) \times 2\pi(\cos \psi_{\text{bin, min}} - \cos \psi_{\text{bin, max}}) \times (E_{\text{bin, max}} - E_{\text{bin, min}})$$

In this way, the background histogram is produced, as shown in Figure 4.1.

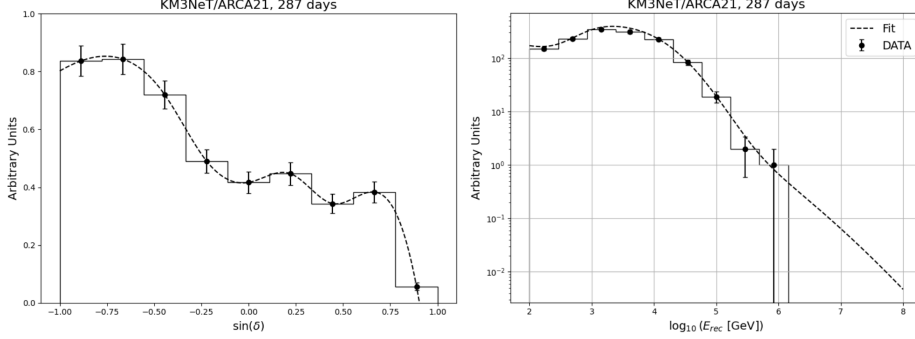


Figure 4.3: The background model for ARCA21. Distributions of events that are selected as track are shown as a function of $\sin(\delta)$ (left) and reconstructed energy (right).

The signal histogram is obtained with the computation described in Chapter 3, using the effective area A_{eff} , the PSF $dP/d\psi$ and the energy resolution dP/dE_{reco} , for a given flux ϕ :

$$N_{\text{sig}}(\psi_{\text{bin}}, E_{\text{bin}}) = \int \phi(E_\nu) \times A_{\text{eff}}(E_\nu, \delta) \times I_{\psi_{\text{bin}}}(E_\nu) \times I_{E_{\text{bin}}}(E_\nu) dE_\nu$$

where $I_{\psi_{\text{bin}}}$ is the fraction of expected signal events with angle ψ between $\psi_{\text{bin, min}}$ and $\psi_{\text{bin, max}}$:

$$I_{\psi_{\text{bin}}}(E) = \int_{\psi_{\text{bin, min}}}^{\psi_{\text{bin, max}}} \frac{dP}{d\psi}(\psi, E) d\psi$$

while $I_{E_{\text{bin}}}$ is the fraction of signal events with reconstructed energy E_{reco} in the range $[E_{\text{bin, min}}, E_{\text{bin, max}}]$:

$$I_{E_{\text{bin}}}(E) = \int_{E_{\text{bin, min}}}^{E_{\text{bin, max}}} \frac{dP}{dE_{\text{reco}}}(E_{\text{reco}}, E) dE_{\text{reco}}$$

Both $I_{\psi_{\text{bin}}}$ and $I_{E_{\text{bin}}}$ are function of the true neutrino energy E_ν .

4.3 Analysis features

4.3.1 Candidate sources

Neutrino source candidates are selected on the following grounds:

- First of all, two **”astrophysical neutrino” sources** were selected: The blazar TXS 0506+056 [209, 210] and NGC 1068 [211], that are interesting because a (possible) association has been made between an astrophysical source and a high-energy neutrino observed by IceCube.

- **The historically famous and interesting source** RX J1713.7-3946 [212], being the brightest SNR seen in TeV γ -rays. These sources have been extensively studied at multiple wavelengths providing chances for comparison with previous results.
- **Marked by other neutrino telescopes.** The most significant sources from source searches by the IceCube and ANTARES collaborations were selected [213, 214, 215, 216]. This includes the time-integrated discovery of NGC 1068 [211], the association of TXS 0506+056 with a high energy neutrino [210], and the observation of the Galactic plane with neutrinos [217]
- **Real time alerts.** IceCube alert locations were compared to the 4FGL-DL3 Fermi-LAT catalogue and sources were selected based on their proximity and luminosity [218].
- **High-energy γ ray sources.** Sources from the LHAASO collaboration [219] and the TeVCat catalogue [220] were selected based on evidence of a hadronic component in cosmic ray production, which is necessary for neutrino production.
- **Extra galactic active galactic nuclei.** High energy neutrinos should be accompanied by γ rays, but the production regions could be opaque to high energy photons [221, 222]. Therefore it is believed that sources that are bright radio emitters could be marked as potential neutrino emitters. Sources were selected from the Radio Fundamental Catalog [223] with the brightest radio component.

In total 106 astrophysical candidates are considered. The list of sources is reported in Table 4.5 at the end of this chapter. Approximately 10% of the selected sources are spatially extended in the sky. This is taken into account in the analysis by smearing the point spread function with a 2D Gaussian where the standard deviation is equal to the source extension. The extended sources are shown in Figure 4.4 by an additional blue circle around the points, and with their names labelled.

4.3.2 All sky scan

In addition to a candidate search, an all-sky scan is performed to search for clusters of neutrinos by testing $2.6 \cdot 10^6$ bins across the sky where KM3NeT has $> 35\%$ visibility for the selected upgoing and horizontal events ($\cos(\theta) > -0.1$). The bins coordinates are determined using the HEALPix software [224], with N_{side} of 512, in this way the distributions of point on the sky map, has a resolution of $0.1^\circ \times 0.1^\circ$.

For both the candidate search and the all sky scan the same binned likelihood method is used.

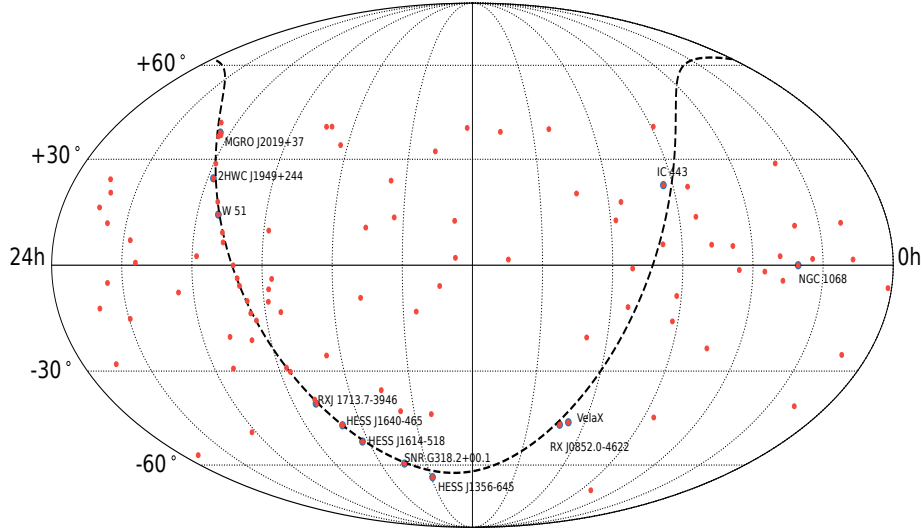


Figure 4.4: Equatorial sky-map of the candidate sources. The Galactic plane is indicated with the dotted line. The extended candidate sources are indicated by name, and with an extra blue ring around the red dot

4.3.3 Analysis method

A binned formalism is used where the compatibility of the data with a point source hypothesis is tested by means of 2D histograms of distance to the candidate source in the range $[0 - 5]$ in degrees, versus $\log_{10}(E_{\text{rec}})$ in the range $[1 - 8]$, in $\log_{10}(\text{GeV})$. For each bin i , there is an estimate of the number of signal events, $\mathcal{S}_i$, expected for a reference flux ϕ_{ref} and the number of background events, $\mathcal{B}_i$. The analysis is done for spectral index $\gamma = 2$ and 2.5 . Furthermore, a spectrum in line with the most recent NGC 1068 IceCube observation [211] ($\gamma = 3.2$) is tested for this particular source only.

4.3.4 Systematic uncertainties

Systematic uncertainties are taken into account for two main parameters describing the detector performance: the angular resolution (0.5° Gaussian smearing) and the acceptance (30% Gaussian spread). The systematic uncertainty on the estimated angular deviation comes from the uncertainty on the absolute orientation of the detector around its z-axis and the uncertainty on the tilts of the lines. The uncertainty on the acceptance also takes into account the uncertainties on the water and PMT properties. The latter have been studied in detail in [225, 226].

4.3.5 Sensitivity and discovery potential

The sensitivity and discovery potential are obtained for a range of declinations with 50,000 PEs for the H0 distribution, and 5,000 PEs for each H1 distribution. Table 4.1 summarises the results for the E^{-2} and $E^{-2.5}$ spectra. For each of the candidate sources, the sensitivity and discovery potential are calculated with 30,000 PEs for the H0 distribution, and 3,000 PEs for each H1 distribution. Depending on the declination, the sensitivity is at a flux level that would produce 2.1 – 2.6 (for an E^{-2} spectrum), 2.4 – 2.8 (for an $E^{-2.5}$ spectrum) signal events per source in the full data taking period. A 3σ discovery would require 1.96 – 3.1 (for an E^{-2} spectrum), 2.5 – 3.8 (for an $E^{-2.5}$ spectrum) signal events per source in the full data taking period.

δ (deg)	N_{sig} $E^{-2.0}$	ref.flux $E^{-2.5}$	N_{bg}	med. $E^{-2.0}$	λ_{H0} $E^{-2.5}$	sens. $E^{-2.0}$	(N_{sig}) $E^{-2.5}$	disc. $E^{-2.0}$	(N_{sig}) $E^{-2.5}$
-85	1.74	16.15	52.36	-0.010	-0.082	2.62	2.87	3.14	3.71
-58	2.02	16.45	53.43	-0.012	-0.085	2.50	2.75	2.83	3.62
-40	1.45	12.56	47.68	-0.009	-0.064	2.43	2.79	2.85	3.81
-33	1.31	11.54	36.16	-0.008	-0.059	2.44	2.73	2.74	3.69
-14	1.14	9.80	25.98	-0.007	-0.054	2.35	2.62	2.45	3.14
0	1.08	8.61	27.12	-0.007	-0.050	2.38	2.55	2.27	2.92
14	1.04	7.60	28.54	-0.007	-0.044	2.34	2.50	2.29	3.00
33	0.99	6.14	30.37	-0.007	-0.038	2.29	2.42	1.96	2.54
40	0.96	5.52	32.43	-0.007	-0.034	2.30	2.42	1.96	2.63

Table 4.1: Summary of the discovery potential and sensitivity for the reference fluxes: $\phi_{\nu_i+\bar{\nu}_i}^{\text{cos}} = 1.2 \cdot 10^{-4} \left(\frac{E}{\text{GeV}}\right)^{-2}$, $1.8 \cdot 10^{-1} \cdot \left(\frac{E}{\text{GeV}}\right)^{-2.5}$, in $\text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$. Total number of signal events for the concerned reference flux and the number of background events inside the 5° cone represented by the analysed 2D histograms, and the medians of the H0 test statistic (λ) distribution with the resulting number of events needed for a 90% confidence level exclusion or a 3σ discovery.

4.3.6 Cone size optimization

The signal and background histograms are computed for a circular region around the position of each candidate, where the radius corresponds to 5° . To verify whether this value is optimal for the analysis, the performance was evaluated for different cone sizes. In Figure 4.5, the discovery potential for the ARCA6-21 sample is shown for cone radii of 5° , 10° , 15° , and 20° . The figure also includes a ratio plot comparing the discovery potential obtained with cones larger than 5° to the one obtained with the 5° cone.

Across the considered declination range, with the exception of the last point, the 5° cone yields the lowest discovery potential, and is therefore the best choice for this analysis.

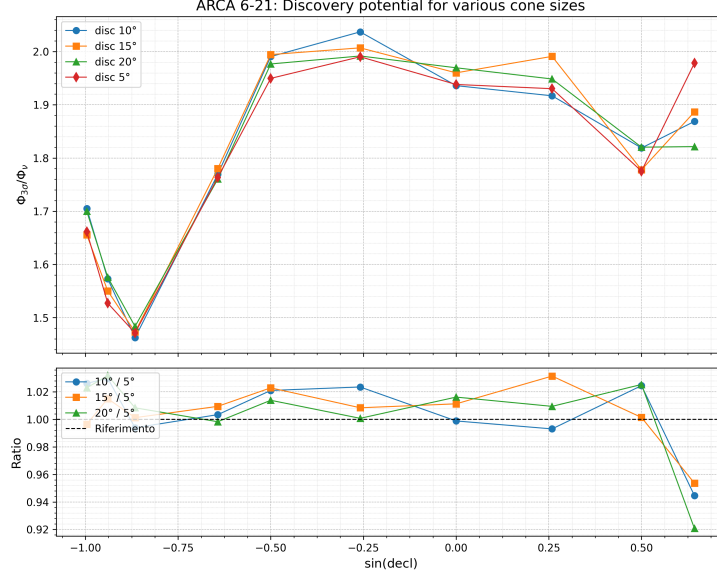


Figure 4.5: Discovery potential for ARCA6-21 samples, for a 3σ significance level. Discovery potential is computed for different values of the sine of the declination and for different cone extensions (5° , 10° , 15° , 20°).

4.4 Results

Following the likelihood formalism described in the previous section, data were analyzed to check for a compatibility of a neutrino signal from each source in the candidate list. Nevertheless, all candidate sources are found consistent with a background-only hypothesis, i.e. no candidate source is significantly observed. The most significant source for the $E^{-2.0}$ spectrum is the Seyfert Galaxy CGCG 420-015 at right ascension 73.35° , declination 4.06° with a pre-trial p-value of $6.37 \cdot 10^{-3}$, which corresponds to a pre-trial significance of 2.49σ .

Name	Declination	Fitted N_{sig}	Flux limit [$\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$]	P-value
CGCG 420-015	$4^\circ 3' 36.00''$	1.4	$5.4 \cdot 10^{-8}$	0.0064
Mkn 421	$38^\circ 12' 36.00''$	2.8	$5.2 \cdot 10^{-8}$	0.0096
J0339-0146	$-1^\circ 46' 48.00''$	1.7	$4.9 \cdot 10^{-8}$	0.0123
HESSJ1848-018	$-1^\circ 45' 0.00''$	1.2	$4.4 \cdot 10^{-5}$	0.0211
J1833-210A	$-21^\circ 3' 36.00''$	1.8	$4.6 \cdot 10^{-8}$	0.0224

Table 4.2: Summary of the top five sources with the largest deviation from the background-only hypothesis for an $E^{-2.0}$ spectrum.

For an $E^{-2.5}$ spectrum, the lowest pre-trial p-value (3.8×10^{-3} , i.e 2.67σ) was found for the blazar Mkn 421 at right ascension 166.11° and declination 38.21° .

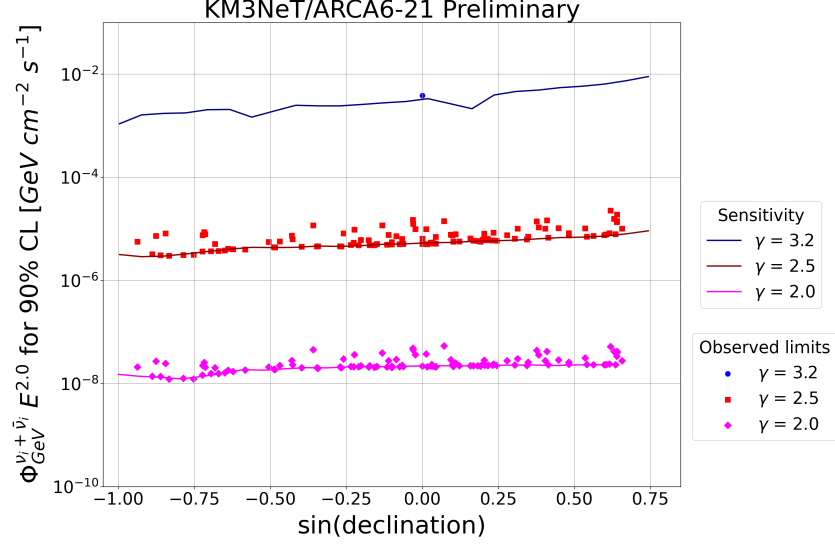


Figure 4.6: Sensitivity and observed limits on the flux as a function of $\sin(\delta)$ for ARCA6-21 using 640 days of data. The results for the 106 sources are shown for $\gamma = 2.0$ and 2.5 , and for NGC1068 the result is also shown for $\gamma = 3.2$.

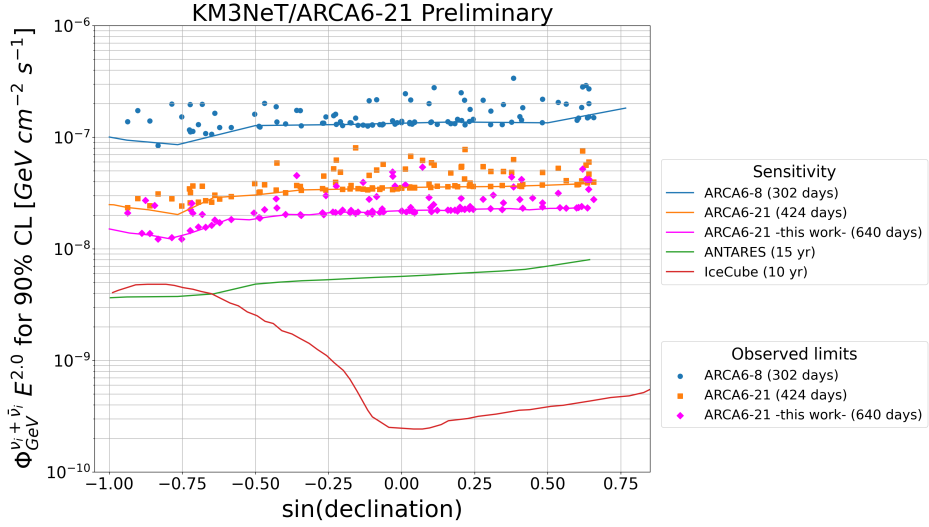


Figure 4.7: Sensitivity and observed limits on the flux as a function of $\sin(\delta)$ for ARCA6-21 using 640 days of data. The results are shown in comparison with earlier presented results of ANTARES 15 years [227] and IceCube [228, 229], assuming an E^{-2} source spectrum.

A summary of the top five sources is shown in Table 4.4.

Name	Declination	Fitted N_{sig}	Flux limit [$\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$]	P-value
Mkn 421	38°12'36.00"	3.7	$2.3 \cdot 10^{-5}$	0.0038
J0339-0146	-1°46'48.00"	2.4	$1.5 \cdot 10^{-5}$	0.0045
CGCG 420-015	4°3'36.00"	1.7	$1.4 \cdot 10^{-5}$	0.0087
HESS J1848-018	-1°45'0.00"	1.3	$1.3 \cdot 10^{-5}$	0.0131
J0555+3948	39°48'36.00"	3.0	$1.9 \cdot 10^{-5}$	0.0132

Table 4.3: Summary of the top five sources with the largest deviation from the background-only hypothesis for an $E^{-2.5}$ spectrum.

The softer $E^{-3.2}$ spectrum was only used to study NGC 1068. This active galactic nucleus is located at right ascension 40.7° and declination -0.01° with a pre-trial p-value of 0.98. The post-trial p-value is identical because it was the only source studied for this flux model.

Name	Declination	Fitted N_{sig}	Flux limit [$\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$]	P-value
NGC 1068	0°0'36.00"	0.05	$3.86 \cdot 10^{-3}$	0.329

Table 4.4: Summary of NGC 1068 study using an $E^{-3.2}$ spectrum.

Sensitivity and observed limits are shown as a function of $\sin(\delta)$ in Figure 4.6. Values are shown for the 106 sources for $\gamma = 2.0$ and 2.5, and for NGC1068 the result is also reported for $\gamma = 3.2$.

In Figure 4.7 the final ARCA6-21 E^{-2} point source results are compared with the IceCube and ANTARES experiments [227, 228, 229]. In terms of sensitivity, the performance of the analysis using the ARCA6-21 data is improved by a factor of about 7 compared to the previous search based only on the ARCA6-8 data [180], while it is worse than the ANTARES point-source[227] analysis by approximately a factor of 3.

For the all sky scan, the p-values in each bin are computed assuming an E^{-2} neutrino spectrum. The results are reported in the sky-map in Figure 4.8. The most significant pixel is found in equatorial coordinates (J2000) for a declination of -71.3° and a right ascension of 310.4° (indicated by a blue circle in the sky-map), for which the local p-value corresponds to $6.69 \cdot 10^{-5}$.

Post-trial p-value computation. To evaluate the post-trial significance, the procedure is repeated 200 times for each candidate source. In each iteration, the events in the dataset are scrambled by randomizing their coordinates, and pseudo-experiments are generated under the null (background-only) hypothesis. In each iteration, the smallest p-value among all sources is recorded.

The post-trial significance is then obtained as the fraction of pseudo-experiments whose minimum p-value is smaller than the best pre-trial p-value observed in the

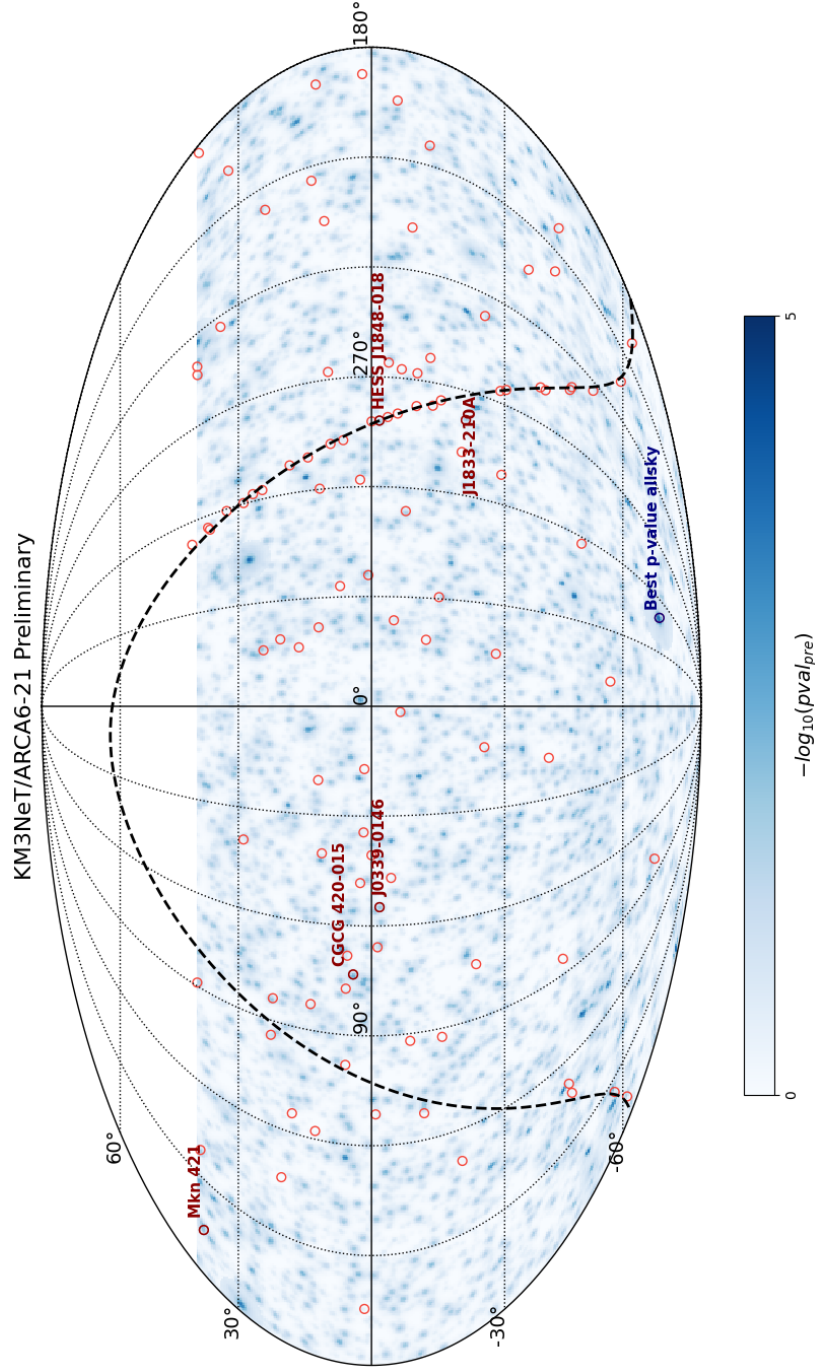


Figure 4.8: Sky map in equatorial coordinates of the local p-values from the sky scan for $-90^\circ < \delta < 40^\circ$ (where KM3NeT has $> 35\%$ visibility for the selected upgoing and horizontal events $\cos(\theta) > -0.1$). Candidate sources are visualized in the sky map by red circles. The five most significant sources from the candidate search are indicated with dark red. The blue circle indicates the position of the best pre-trial p-value.

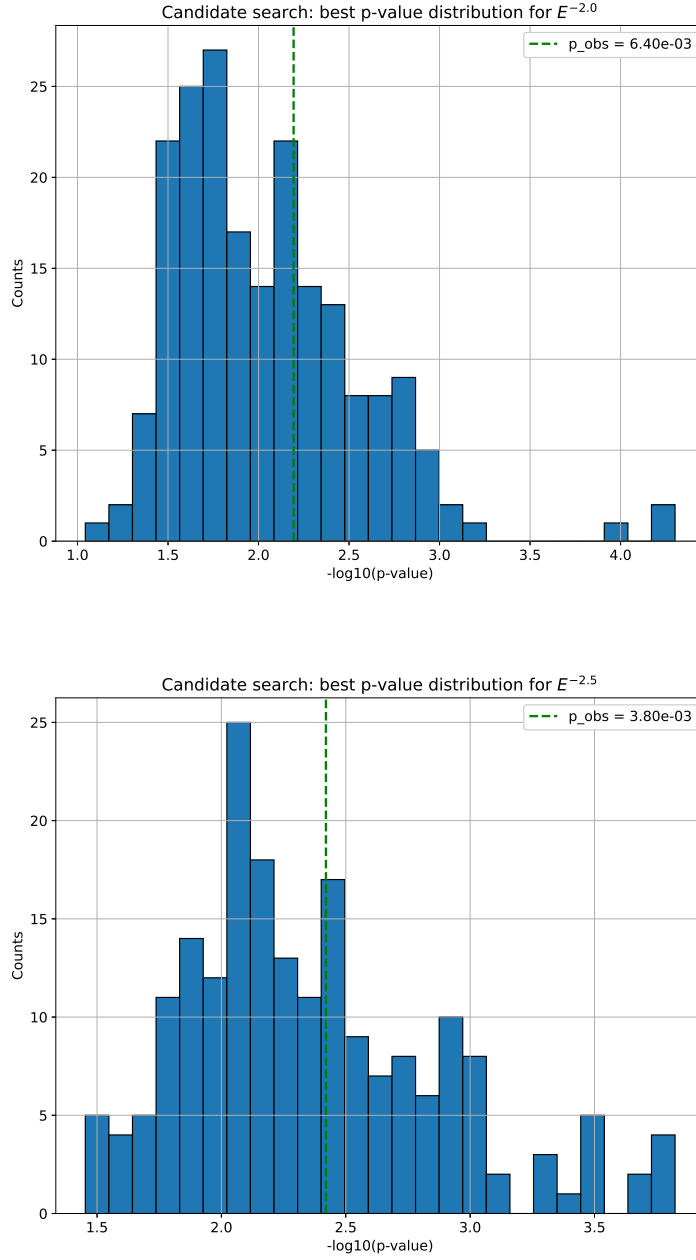


Figure 4.9: Best p-value distribution for background only hypothesis for the candidate search. Distributions are estimated for a $E^{-2.0}$ spectrum (top) and for $E^{-2.5}$ spectrum (bottom).

real data. This distribution quantifies the probability that the observed result at unblinding could be produced by a background fluctuation alone.

Figure 4.9 shows the distributions of the smallest p-values obtained among the source candidate list. For $\Phi_S \propto E_\nu^{-2.0}$ the post trial p-value is 0.325 corresponding to a significance of 0.45σ , while for $\Phi_S \propto E_\nu^{-2.5}$ the post trial p-value is 0.405 corresponding to a significance of 0.2σ .

For the all sky scan, the post-trial p-value is estimated to be 0.88 and is therefore not statistically significant.

4.5 Conclusions

A search for cosmic neutrino point-like and extended sources was performed with 640 days of KM3NeT/ARCA data (6-21 lines). No significant signal was observed from 106 candidates or in the all-sky scan, hence flux upper limits were set. Although the results are compatible with background expectations, the most significant sources from the candidate source list were CGCG 420-015 (for an $E^{-2.0}$ spectrum) and Mkn 421 (for an $E^{-2.5}$ spectrum). The most significant sky excess is found on the Southern hemisphere at declination -71.3° , right ascension 310.4° . As ARCA approaches full deployment, its larger exposure and improved resolution will considerably enhance the prospects for discovering cosmic neutrino sources.

name	source	ra	decl	size [°]	comment
LMC N132D	SNR/Molec.Cl.	5h 24m 48.00s	-69°39'0.00"	0	TeVCaT+hadronic [220]
HESS J1356-645	PWN	13h 56m 0.00s	-64°30'0.00"	0.2	> 0 events in ANTARES [213]
Danks 1	open cluster	13h 12m 28.80s	-62°41'24.00"	0.58	possible Galactic PeVatron [230]
NGC 3603	unknown	11h 15m 9.60s	-61°15'36.00"	0	possible Galactic PeVatron [230]
SNR G318.2+00.1	SNR/Molec.Cl.	14h 57m 40.80s	-59°27'36.00"	0.31	TeVCaT+hadronic [220]
Westerlund 2	unknown	10h 23m 57.60s	-57°41'60.00"	0.75	possible Galactic PeVatron [230]
IC-hotspot S.Hemisph.	Unknown	23h 20m 48.00s	-56°30'0.00"	0	IC most significant Southern h... [216]
HESS J1614-518	Shell	16h 14m 9.60s	-51°52'12.00"	0.23	TeVCaT+hadronic [220]
PKS 2005-489	BLL	20h 9m 28.80s	-48°49'12.00"	0	> 0 events in ANTARES [213]
HESS J1640-465	Composite SNR	16h 40m 38.40s	-46°34'12.00"	0.11	TeVCaT+hadronic [220]
RX J0852.0-4622	Shell	8h 52m 0.00s	-46°22'12.00"	1	TeVCaT+hadronic [220]
HESS J1641-463	Unknown	16h 41m 2.40s	-46°17'60.00"	0	> 0 events in ANTARES [213]
VelaX	PWN	8h 35m 0.00s	-45°36'0.00"	0.42	> 0 events in ANTARES [213]
PKS 0537-441	BLL	5h 38m 50.40s	-44°4'48.00"	0	> 0 events in ANTARES and High .. [213]
Centaurus A	Radio galaxy	13h 25m 26.40s	-43°1'12.00"	0	> 0 events in ANTARES [213]
PKS 1424-418	FSRQ	14h 27m 57.60s	-42°6'36.00"	0	active PKS in gamma and radio .. [231]
J0106-4034	AGN	1h 6m 45.60s	-40°34'12.00"	0	High radio VLBI max flux [223]
RX J1713.7-3946	Shell / SNR	17h 13m 26.40s	-39°46'12.00"	0.65	TeVCaT+hadronic [220]
CTB 37A	SNR/Molec.Cl.	17h 14m 14.40s	-38°31'12.00"	0	TeVCaT+hadronic [220]
PKS 1454-354	BLL	14h 57m 26.40s	-35°40'12.00"	0	> 0 events in ANTARES [213]
HESS J1741-302	Unknown	17h 41m 0.00s	-30°11'60.00"	0	> 0 events in ANTARES [213]
J1924-2914	AGN	19h 24m 50.40s	-29°14'24.00"	0	High radio VLBI max flux [223]
Galactic center	Galactic center	17h 45m 40.80s	-29°0'36.00"	0	Historical + Highest for ANTAR... [213]
J2258-2758	AGN	22h 58m 4.80s	-27°58'12.00"	0	High radio VLBI max flux [223]
J1625-2527	AGN	16h 25m 48.00s	-25°27'36.00"	0	High radio VLBI max flux [223]
NGC 253	Starburst	0h 47m 31.20s	-25°17'24.00"	0	TeVCaT+hadronic [220]
J0457-2324	AGN	4h 57m 2.40s	-23°24'36.00"	0	High radio VLBI max flux [223]
J1833-210A	AGN	18h 33m 40.80s	-21°3'36.00"	0	High radio VLBI max flux [223]
J0836-2016	AGN	8h 36m 38.40s	-20°16'48.00"	0	High radio VLBI max flux [223]
J1911-2006	AGN	19h 11m 9.60s	-20°7'12.00"	0	High radio VLBI max flux [223]
J0609-1542	AGN	6h 9m 40.80s	-15°42'36.00"	0	High radio VLBI max flux [223]
SNR G015.4+00.1	Composite SNR	18h 18m 4.80s	-15°28'12.00"	0	TeVCaT+hadronic [220]
J2158-1501	AGN	21h 58m 7.20s	-15°1'12.00"	0	High radio VLBI max flux [223]
LHAASO J1825-1326	Unknown	18h 25m 48.00s	-13°26'60.00"	0	Latest LHAASO observation [219]
QSO 1730-130	Quasar	17h 33m 12.00s	-13°5'60.00"	0	> 0 events in ANTARES and High .. [213]
J1337-1257	AGN	13h 37m 40.80s	-12°57'36.00"	0	High radio VLBI max flux [223]
J2246-1206	AGN	22h 46m 19.20s	-12°6'36.00"	0	High radio VLBI max flux [223]

Table 4.5: Candidate source list for which results will be obtained. Table continues on the next two pages.

name	source	ra	decl	size [°]	comment
PKS 0727-11	Quasar	7h 30m 19.20s	-11°41'60.00"	0	> 0 events in ANTARES and High .. [213]
TXS 1749-101	Radio blazar	17h 52m 36.00s	-10°11'60.00"	0	Relevant alert in data taking p.. [232]
HESS J1828-099	Unknown	18h 28m 57.60s	-9°59'24.00"	0	> 0 events in ANTARES [213]
J1512-0905	AGN	15h 12m 50.40s	-9°5'60.00"	0	High radio VLBI max flux [223]
J0607-0834	AGN	6h 7m 60.00s	-8°34'48.00"	0	High radio VLBI max flux [223]
QSO 2022-077	BLL	20h 25m 36.00s	-7°35'60.00"	0	> 0 events in ANTARES [213]
RS Ophiuchi	Nova	17h 50m 12.00s	-6°42'36.00"	0	TeVCaT+hadronic [220]
J0006-0623	AGN	0h 6m 14.40s	-6°23'24.00"	0	High radio VLBI max flux [223]
3C279	Blazar	12h 56m 12.00s	-5°47'24.00"	0	> 0 events in ANTARES and High .. [213]
LHAASO J1839-0545	Unknown	18h 39m 48.00s	-5°44'60.00"	0	Latest LHAASO observation
J2225-0457	AGN	22h 25m 48.00s	-4°57'0.00"	0	High radio VLBI max flux [223]
4FGL J0307.8-0419	Blazar	3h 7m 48.00s	-4°19'48.00"	0	IC alert [232]
PKS 1741-038	radio Blazar	17h 44m 0.00s	-3°49'48.00"	0	IC alert + High radio VLBI max.. [223, 232]
LHAASO J1843-0338	Unknown	18h 42m 60.00s	-3°38'60.00"	0	Latest LHAASO observation [219]
J0339-0146	AGN	3h 39m 31.20s	-1°46'48.00"	0	High radio VLBI max flux [223]
HESSJ1848-018	star cluster	18h 47m 48.00s	-1°45'0.00"	0	from the H.E.S.S. Galactic plane survey (2018)
J0423-0120	AGN	4h 23m 16.80s	-1°20'24.00"	0	High radio VLBI max flux [223]
J0725-0054	AGN	7h 25m 50.40s	0°55'12.00"	0	High radio VLBI max flux [223]
LHAASO J1849-0003	Unknown	18h 49m 24.00s	0°3'0.00"	0	Latest LHAASO observation [219]
NGC 1068	Seyfert 2	2h 42m 40.80s	0°0'36.00"	0.12	Interesting for Ice cube [211, 216]
J2136+0041	AGN	21h 36m 38.40s	0°42'0.00"	0	High radio VLBI max flux [223]
J1058+0133	AGN	10h 58m 28.80s	1°34'12.00"	0	High radio VLBI max flux [223]
J0108+0135	AGN	1h 8m 38.40s	1°34'48.00"	0	High radio VLBI max flux [223]
PKS 0215+015	Blazar	2h 17m 48.00s	1°45'0.00"	0	IC alert [232]
J1229+0203	AGN	12h 29m 7.20s	2°2'60.00"	0	High radio VLBI max flux [223]
TXS 0310+022	Blazar	3h 13m 12.00s	2°30'0.00"	0	IC alert [232]
3C403	Radio galaxy	19h 52m 16.80s	2°30'36.00"	0	Promising from ANTARES [215]
CGCG420-015	Seyfert galaxy	4°3'36.00"	4h 53m 24.00s	0	Seyfert candidate pointed by IC [209, 210, 216, 213]
J0433+0521	AGN	4h 33m 12.00s	5°20'60.00"	0	High radio VLBI max flux [223]
TXS 0506+056	BLL	5h 9m 24.00s	5°42'0.00"	0	promising from IC, ANTA.. [209, 210, 216, 213]
HESS J0632+057	Binary	6h 32m 57.60s	5°48'36.00"	0	promising from IC ANTARES comb.. [214]
LHAASO J1908+0621	Unknown	19h 8m 12.00s	6°20'60.00"	0	Latest LHAASO observation [219]
PKS 2145+067	Blazar	21h 48m 4.80s	6°57'36.00"	0	High radio VLBI max flux [223]
W 49B	SNR/Molec.Cl.	19h 11m 7.20s	9°5'24.00"	0	TeVCaT+hadronic [220]
OT 081	BLL	17h 51m 33.60s	9°39'0.00"	0	> 0 events in ANTARES and High .. [213, 232]

name	source	ra	decl	size [°]	comment
PKS 1502+106	Blazar	15h 4m 24.00s	10°29'24.00"	0	brightest flare coincident wit.. [233]
J0242+1101	Blazar	2h 42m 28.80s	11°1'12.00"	0	promising from ANTARES [213]
1LHAASO J1959+1129u	unknown	19h 59m 16.80s	11°29'24.00"	0	Latest LHAASO observation [91]
J2232+1143	AGN	22h 32m 36.00s	11°43'48.00"	0	High radio VLBI max flux [223]
J0121+1149	AGN	1h 21m 40.80s	11°49'48.00"	0	High radio VLBI max flux [223]
J1230+1223	AGN	12h 30m 50.40s	12°23'24.00"	0	High radio VLBI max flux [223]
J0750+1231	AGN	7h 50m 52.80s	12°31'12.00"	0	High radio VLBI max flux [223]
PKS 1413+135	Blazar	14h 16m 7.20s	13°20'60.00"	0	IC alert [232]
J0530+1331	AGN	5h 30m 57.60s	13°31'48.00"	0	High radio VLBI max flux [223]
W 51	SNR/Molec. Cl.	19h 22m 60.00s	14°8'24.00"	0.12	TeVCaT+hadronic [220]
J2253+1608	AGN	22h 53m 57.60s	16°8'60.00"	0	High radio VLBI max flux [223]
PKS 0735+178	Blazar	7h 38m 7.20s	17°42'36.00"	0	IC alert [BAI21, 232]
LHAASO J1929+1745	Unknown	19h 29m 0.00s	17°45'0.00"	0	Latest LHAASO observation [219]
J0854+2006	AGN	8h 54m 48.00s	20°6'36.00"	0	High radio VLBI max flux [223]
RGB J2243+203	BLL	22h 43m 55.20s	20°21'0.00"	0	> 0 events in ANTARES [213]
LHAASO J0534+2202	PWN	5h 34m 12.00s	22°3'0.00"	0	Latest LHAASO observation [219]
IC 443	Shell	6h 16m 50.40s	22°30'0.00"	0.16	TeVCaT+hadronic [220]
PKS 1424+240	BLL	14h 27m 2.40s	23°47'60.00"	0	promising from IC [216]
MG3 J225517+240	Blazar/BLL	22h 55m 16.80s	24°11'24.00"	0	promising from ANTARES [215]
2HWC J1949+244	Unknown	19h 49m 40.80s	24°27'36.00"	1	> 0 events in ANTARES [213]
LHAASO J1956+2845	Unknown	19h 56m 12.00s	28°45'0.00"	0	Latest LHAASO observation [219]
J0237+2848	AGN	2h 37m 52.80s	28°48'0.00"	0	High radio VLBI max flux [223]
J1310+3220	AGN	13h 10m 28.80s	32°21'0.00"	0	High radio VLBI max flux [223]
1LHAASO J2002+3244u	unknown	20h 2m 33.60s	3°2'44'24.00"	0	Latest LHAASO observation [91]
J1613+3412	AGN	16h 13m 40.80s	34°12'36.00"	0	High radio VLBI max flux [223]
LHAASO J2018+3651	Unknown	20h 18m 60.00s	36°51'0.00"	0	Latest LHAASO observation [213, 219]
J2015+3710	AGN	20h 15m 28.80s	37°10'48.00"	0	High radio VLBI max flux [223]
MGRO J2019+37	Unknown	20h 19m 60.00s	37°59'60.00"	0.75	> 0 events in ANTARES [213]
Mkn 421	Superbright blazar	11h 4m 26.40s	38°12'36.00"	0	nearby γ -ray emitters [234]
J0927+3902	AGN	9h 27m 2.40s	39°2'24.00"	0	High radio VLBI max flux [223]
NGC 4151	Seyfert 1	12h 10m 31.20s	39°24'36.00"	0	promising from IC [211]
Mkn 501	Superbright blazar	16h 53m 52.80s	39°45'36.00"	0	nearby γ -ray emitters [234]
J1642+3948	AGN	16h 42m 60.00s	39°48'36.00"	0	High radio VLBI max flux [223]
J0555+3948	AGN	5h 55m 31.20s	39°48'36.00"	0	High radio VLBI max flux [223]
LHAASO J2032+4102	Unknown	20h 32m 12.00s	41°2'60.00"	0	Latest LHAASO observation / > 0.. [213, 219]

Chapter 5

Further research based on point source analysis

This chapter collects a set of analyses derived from the KM3NeT/ARCA search for the neutrino emission from point-like sources. These analyses build on the event selections and data-analysis methods developed for the point source analysis presented in the previous chapters, and are therefore referred to as derived analyses. The collection includes

- the search for a cosmic point-like neutrino source from the direction of the KM3-230213A event,
- Combined search for cosmic neutrino sources with KM3NeT/ARCA and ANTARES,
- the investigation of the neutrino emission from galactic gamma-ray sources with KM3NeT/ARCA.

The **search for a cosmic point-like neutrino source from the direction of the KM3-230213A event** consists of a follow-up study of the ultra-high-energy neutrino observed by KM3NeT/ARCA21. On this occasion, the complete ARCA21 dataset was used for the first time. Moreover, this analysis represents the first application of the all-sky analysis framework to a restricted subset of sky coordinates. The goal of this follow-up analysis is to scan a region around the reconstructed sky direction of the ultra-high-energy event in order to search for a possible excess of lower-energy neutrinos compatible with the same emission.

The **Combined search for cosmic neutrino sources with KM3NeT/ARCA and ANTARES** presents a combined analysis based on the full ANTARES dataset and KM3NeT/ARCA data recorded between May 2021 and September 2023, with an evolving detector geometry up to 21 detection lines. Searches for neutrino emissions from both point-like and extended sources are performed, using a comprehensive catalog of gamma-ray emitters, including Galactic sources

(from TeVCat), extragalactic AGNs detected by VLBI, and candidates previously highlighted by IceCube.

Finally, the **investigation of the neutrino emission from Gamma-Ray (Galactic) Sources with KM3NeT/ARCA** is based on combining information from gamma-ray observatories with KM3NeT/ARCA data. As discussed in Chapter 1, when neutrinos and photons originate from hadronic interactions of cosmic rays, the spectra of the two messengers can be directly related. In this analysis, the neutrino spectrum is therefore inferred from the measured gamma-ray spectrum of several sources, and the resulting prediction is used both to search for a corresponding signal in the data and to estimate the performance of the full detector.

5.1 Search for a cosmic point-like neutrino source from the direction of KM3-230213A

5.1.1 Introduction

On February 13 2023, at 01:16:47 UTC, an extremely high-energy muon was observed by the ARCA detector. This observation was presented and published in Nature [235], where the event is referred to as KM3-230213A. At the time of the observation, KM3NeT/ARCA consisted of 21 detection units.

The direction of KM3-230213A is reconstructed as nearly horizontal, originating 0.6° above the horizon at an azimuth of 259.8° (azimuth angles increase clockwise, with North at 0°). The angular uncertainty on the reconstructed direction is estimated to be 1.5° . This direction intersects the Earth's crust, as shown in Fig. 5.2.

The muon energy at the detector is estimated by counting the number of PMTs participating in the event trigger. The reconstructed muon energy is 120^{+110}_{-60} PeV.

As discussed in [235], for an event with such energy and direction, the probability of originating from atmospheric muons or atmospheric neutrinos is essentially negligible. Therefore, the most likely interpretation is that the event was produced by the interaction of a neutrino of cosmic origin.

The estimated neutrino energy is 220^{+570}_{-110} PeV, making it the highest-energy neutrino observed to date. The equatorial coordinates (J2000) and detection time of KM3-230213A are: $RA = 94.3^\circ$, $Dec = -7.8^\circ$, $MJD = 59988.0533299$. The containment radii are $R(50\%) = 1.2^\circ$, $R(68\%) = 1.5^\circ$, $R(90\%) = 2.2^\circ$, and $R(99\%) = 3.0^\circ$.

5.1.2 Analysis method

The binned-likelihood method described in the previous sections was employed to scan a sky region of size $\pm 3^\circ$ centered on the coordinates of KM3-230213A. The coordinate grid was generated using the HEALPix software [224], providing

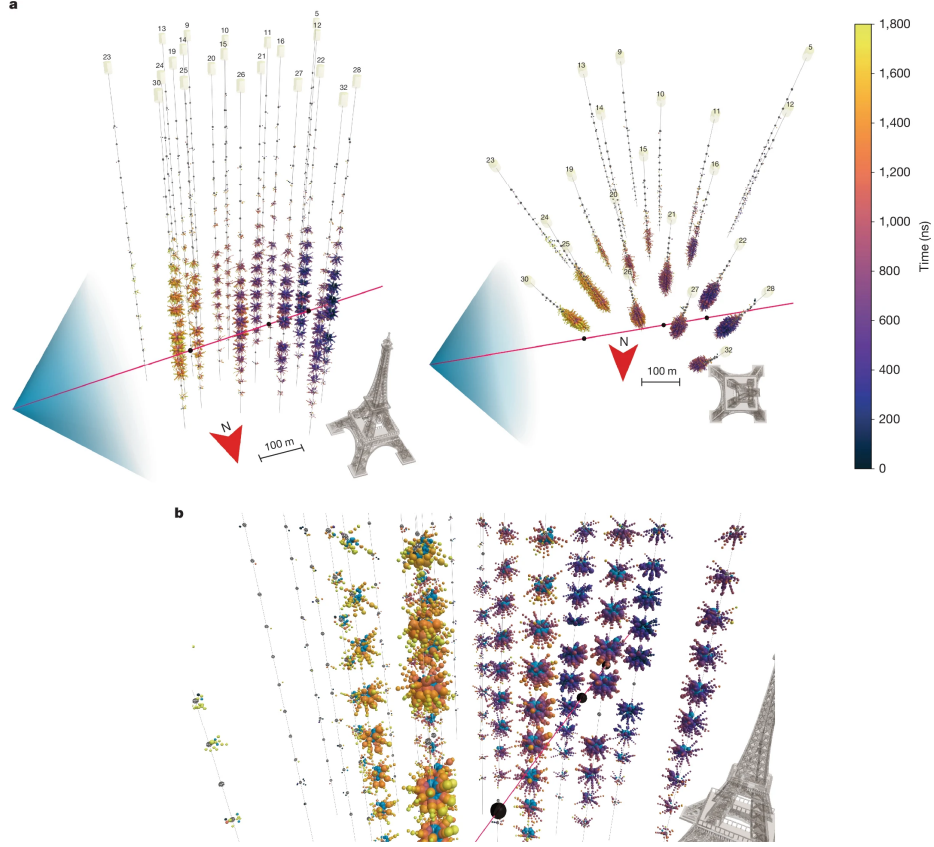


Figure 5.1: On the top, illustration of the UHE event signature in the KM3NeT/ARCA21 detector [235]. The reconstructed trajectory of the muon is shown as a red line, along with an artist's representation of the Cherenkov light cone. The hits of individual PMTs are represented by spheres stacked along the direction of the PMT orientations. On the bottom, zoomed-in view of the optical modules that are close to the first two observed secondary showers in the event. Light-blue spheres represent hits arriving within -5 to 25 ns of the expected Cherenkov arrival times.

a resolution of $0.1^\circ \times 0.1^\circ$, corresponding to a total of 80×34 values in declination and right ascension.

As in the all-sky analysis, the underlying idea is to use the likelihood method to quantify a possible excess of lower-energy cosmic neutrinos within the region. In order to perform an unbiased search, the KM3-230213A event itself was removed from the dataset.

For this analysis, the full KM3NeT/ARCA dataset (640 days of livetime, see previous chapter) was considered. Furthermore, an E^{-2} spectrum was assumed

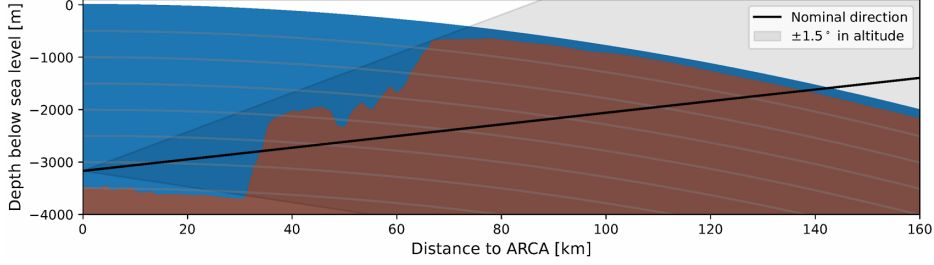


Figure 5.2: Illustration of the event direction through the Earth’s crust [235], with the sea displayed in blue and the seabed and underlying rock in brown. The x-axis indicates the distance from the ARCA site, while the y-axis and grey lines represent the depth relative to sea level. The shaded region illustrates the effect of a $\pm 1.5^\circ$ variation in the reconstructed direction, corresponding to the 68% confidence region obtained from the evaluation of systematic uncertainties.

event selection	sensitivity ($\phi_{90\%}/\phi_s$)		discovery ($\phi_{3\sigma}/\phi_s$)	
	2° cone	5° cone	2° cone	5° cone
track length > 200 m	1.944	1.862	2.051	2.033
ARCA6-8 like	2.643	2.562	3.907	3.910

Table 5.1: Sensitivity and discovery values for a point source at a declination $\delta = -7.8^\circ$ with expected neutrino flux $\phi_s = 10^{-8} \times E_\nu^{-2} [\text{GeV} \times \text{cm}^{-2} \times \text{sec}^{-1}]$. Values are computed for two event selections (“track length > 200 m” and “ARCA6-8 like”) and for two different cone maximum extensions (2° and 5°).

for the signal

$$\phi_s = \frac{1}{10^8} \times \left(\frac{E_\nu}{1 \text{ GeV}} \right)^{-2} \times \frac{1}{\text{GeV} \times \text{cm}^2 \times \text{sec}}$$

5.1.3 Event selection

At the time this analysis was performed, a Boosted Decision Tree (BDT) selection was not yet available for the ARCA19 and ARCA21 datasets. Therefore, in addition to the baseline event selection (see the chapter on event selection), an additional cut on the reconstructed track length was applied: track length > 200 m.

At the beginning of the study, the possibility of applying the same selection used for the ARCA6–8 samples (described in Chapter 3) was also considered. Furthermore, a smaller search-cone radius of 2° was tested to calculate the test statistic.

To fix the final selection, the sensitivity and discovery potential were computed using the scrambled ARCA21 data, assuming a point-like source located at the reconstructed declination of the event (-7.8°). The resulting values are

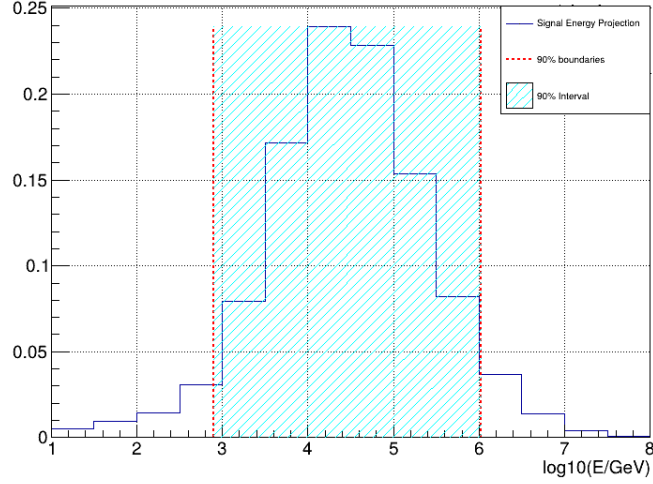


Figure 5.3: ARCA6-21, energy distribution of expected signal, from a point source located at the declination -7.8° . The shaded area in blue, indicates the energy range where 90% of the signal is expected.

reported in Table 5.1 for two cone sizes: 2° and the standard 5° used in point-source analyses.

It was found that both the sensitivity and the discovery potential are optimized (i.e. minimized) for the selection criterion *track length* > 200 m and for a cone radius of 5° .

With this configuration, it is estimated the energy range $\Delta E_{90\%}$ within which 90% of the signal is expected from the direction of the UHE event, for the full ARCA6-21 sample. The range is found to be $2.895 - 6.027$ in $\log_{10}$ scale which corresponds to 785 GeV - 1.064 PeV. To illustrate this, Figure 5.3 shows the distribution of the signal as a function of energy; the shaded area indicates the range $\Delta E_{90\%}$.

5.1.4 Results

Applying the binned-likelihood method to KM3NeT/ARCA data produced the p-value distribution shown in Fig. 5.4. No significant excess of signal events was observed.

Over the entire scanned region, the smallest pre-trial p-value, equal to 2.19 in $-\log_{10}$ scale, was found at coordinates ($\delta = -9.3^\circ$, $RA = 97.3^\circ$), indicated by a red star in the figure. Restricting the search to coordinates within 3° of the KM3-230213A reconstructed direction, the minimum value, 1.3, was found at ($\delta = -6.8^\circ$, $RA = 96.7^\circ$), indicated by a yellow star. For this location, a post-trial p-value of 0.44 was obtained, which corresponds to a significance of 0.15σ .

The location in the sky with lowest p-value, do not correspond to any of the

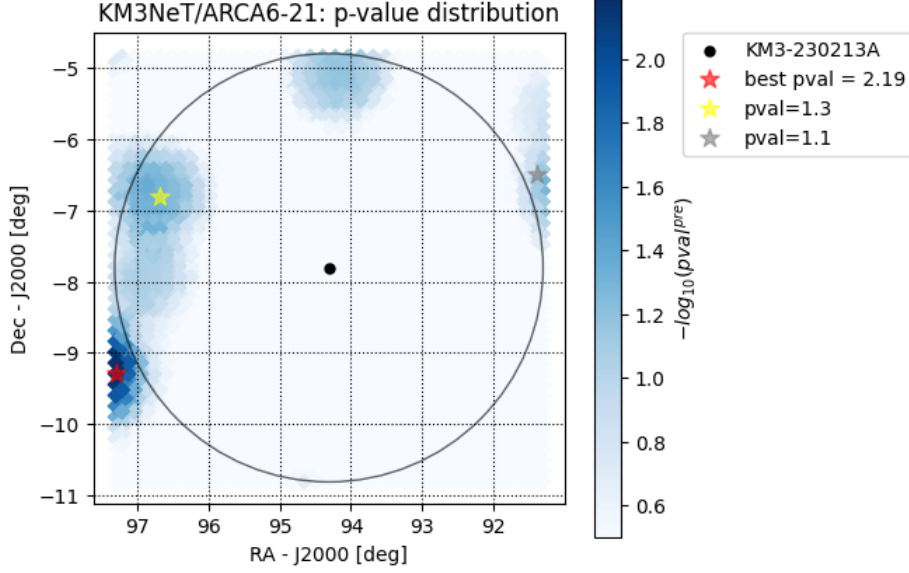


Figure 5.4: Distribution of the p-value for declination values $\delta \in [-10.8^\circ, -4.8^\circ]$ and right ascension values $RA \in [91.3^\circ, 97.3^\circ]$. The black circle encloses all coordinates within a distance of three degrees from the reconstructed direction of KM3-230213A (black dot).

sources listed in Table 4.5. Of these, only the active galactic nucleus J0607-0834 lies within 3° of the reconstructed direction. However, its coordinates ($RA=92^\circ$, $\delta=-8.58$) do not correspond to any p-value hotspot.

5.1.5 Analysis summary

This follow-up analysis searched for additional neutrino emission associated with the ultra-high-energy event KM3-230213A using the KM3NeT/ARCA dataset. A dedicated likelihood scan was performed in a $6^\circ \times 6^\circ$ sky region centered on the reconstructed event direction. No statistically significant clustering of lower-energy neutrinos was observed compatible with a neutrino point-source emission.

In addition to this work, further point-source analyses were carried out using data from ANTARES, ORCA and the IceCube public data set [124, 236]; the lowest p-value was found for the IceCube data set, but even in this case it was not statistically significant. Furthermore, the KM3NeT collaboration presented several follow-up analyses to search for a match between the direction of the event and the location of known sources [124]. Some of these follow-up analyses are also dedicated to investigating whether the event is consistent with a cosmogenic origin, namely neutrinos produced by the photodisintegration of ultra-high-energy cosmic rays.

5.2 Combined search for cosmic neutrino sources with KM3NeT/ARCA and ANTARES

5.2.1 Introduction

The detection of high-energy astrophysical neutrinos represents one of the main challenges in modern astroparticle physics. Neutrinos are unique cosmic messengers: their weakly interacting nature allows them to travel across vast cosmic distances, carrying unaltered information about the most energetic processes in the Universe. However, the same property makes their detection extremely difficult, requiring large and sensitive neutrino telescopes.

Since 2017, the IceCube Neutrino Observatory at the South Pole has reported the observation of high-energy neutrino events associated with astrophysical sources, such as the blazar TXS 0506+056 [237] and the galaxy Messier 77 [238].

In parallel, in the Northern Hemisphere, the ANTARES detector carried out a large effort in searching for neutrino signals from point-like sources, providing complementary coverage of the sky [239]. This effort is now being continued and significantly expanded by the KM3NeT/ARCA experiment [181], which will further enhance sensitivity to cosmic neutrino sources.

5.2.2 Datasets and event topology

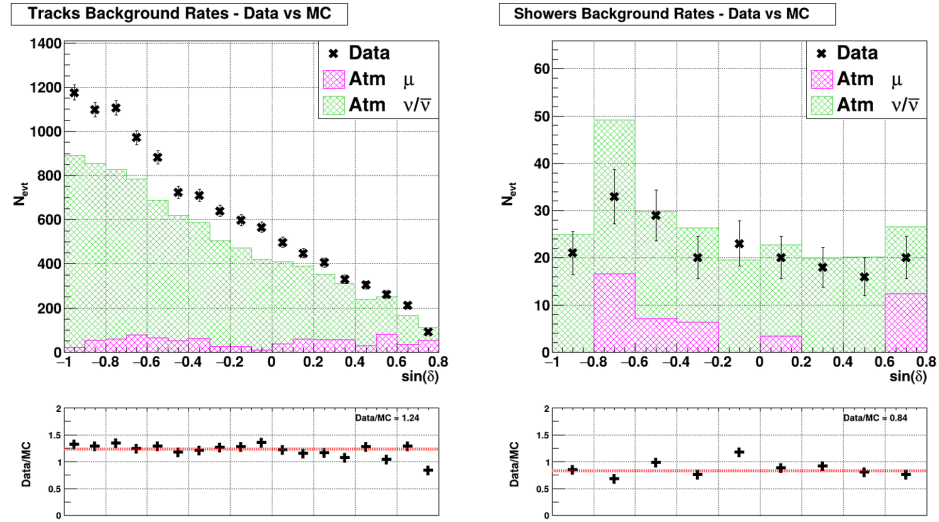


Figure 5.5: ANTARES: DATA and MC events as function of the declination for the track-like events sample (left) and for the shower-like events sample (right) [240].

This analysis combines datasets from both detectors. For ANTARES, the full dataset is used, corresponding to a total livetime of 4541 days and including both track-like and shower-like events.

For KM3NeT/ARCA, each dataset corresponds to a distinct detector configuration and an independent event selection. Four configurations are considered in this work: ARCA6tracks (6 active detection lines, 92 days of livetime), ARCA8tracks (8 lines, 212 days), ARCA19tracks (19 lines, 48.4 days), and ARCA21tracks (21 lines, 287.4 days). The combined livetime amounts to approximately 640 days, and only track-like events are included in the analysis.

For KM3NeT/ARCA data, the event selection is the one described in Chapter 3 and used for the KM3NeT/ARCA stand alone point-source search, Chapter 4.

With regard to the ANTARES data sample, the selection applied is the same as that used in the official analysis for point sources by the ANTARES collaboration [241]. Figure 5.5 shows the distribution for ANTARES track and shower samples.

5.2.3 Likelihood method for point source search

The compatibility of the data with a point-like or extended source hypothesis is evaluated using a binned likelihood method, described in Chapter 4. This procedure, developed for KM3NeT point-source analyses [208, 242, 243], uses a test statistic λ defined as the logarithm of the likelihood ratio between the signal-plus-background and background-only hypotheses:

$$\lambda = \log L(\zeta = \hat{\zeta}) - \log L(\zeta = 0) \quad (5.1)$$

The likelihood function is defined as:

$$\log L(\zeta) = \sum_{\text{bins}} \log(B_i + \zeta S_i) - (B_i + \zeta S_i) \quad (5.2)$$

where S_i is the expected number of signal events in bin i , obtained by convolving the predicted neutrino spectrum with the detector's effective area. In this work, it is assumed a power-law neutrino spectrum:

$$\Phi_{\nu+\bar{\nu}} = \frac{1}{10^8} \left(\frac{E}{1\text{GeV}} \right)^{-2} \times \frac{1}{\text{GeV} \times \text{cm}^2 \times \text{sec}} \quad (5.3)$$

The background histogram B_i is estimated from data using a data-driven technique (as described in Ref. [208, 243]). The signal strength (ζ) is varied to obtain test statistic distributions for statistical analysis. For a fixed value of the signal strength ($\hat{\zeta}$), pseudo-experiments are generated by randomly drawing each N_i from a Poisson distribution with mean $B_i + \hat{\zeta}S_i$.

Figure 5.6 shows the acceptance multiplied by the flux normalization, for the various dataset used in the analysis.

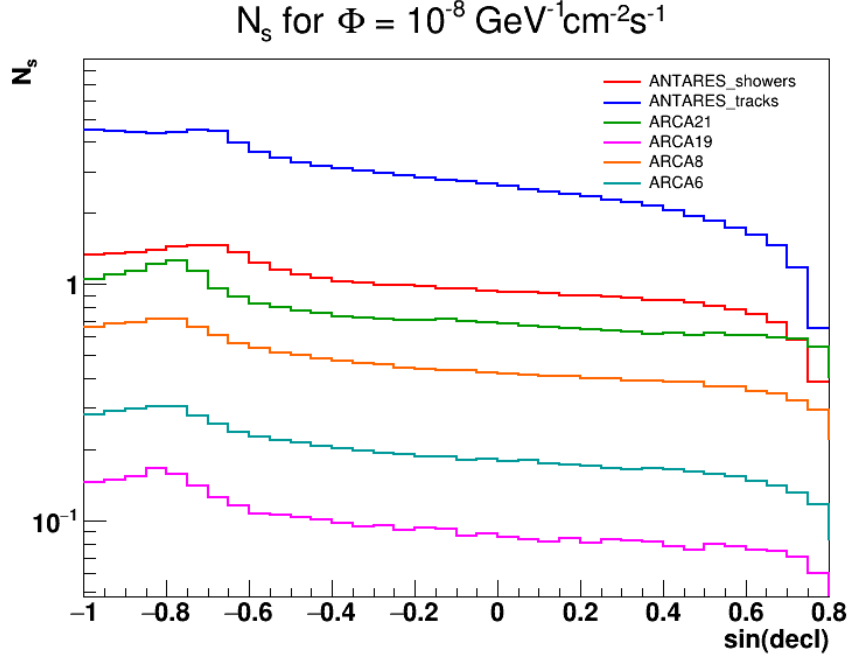


Figure 5.6: Number of expected signal events as function of the declination for ANTARES (track and shower) and KM3NeT/ARCA, from the ARCA6 configuration up to the ARCA21 configuration, (only track-like events). It is assumed a neutrino energy spectra $\Phi_{\nu+\bar{\nu}} = 10^{-8} \times E_{\nu}^{-2} [GeV \times cm^{-2} \times s^{-1}]$

5.2.4 Results

Applying the likelihood framework to the combined sample, the median 90% C.L. upper limits and the 5σ discovery fluxes are computed.

The results are shown in Figure 5.7 (left and right panels) as black lines. For comparison, the corresponding results from the ANTARES standalone point-source analysis [241] and the KM3NeT/ARCA standalone analysis [242] are also reported.

The performance of the combined analysis improves by a factor of almost 10 compared to KM3NeT/ARCA standalone and by about 20% compared to ANTARES standalone, which is to be expected due to the different lifetimes of the detectors.

The analytical framework was applied to search for signals from candidate neutrino-emitting sources. For this analysis, the list of candidate sources is the same as that used in the standalone KM3NeT/ARCA analysis. The 90% C.L. upper limits for each source are shown in Fig. 5.8 for the combined KM3NeT/ARCA + ANTARES sample.

The most significant candidates largely coincide with those identified in the

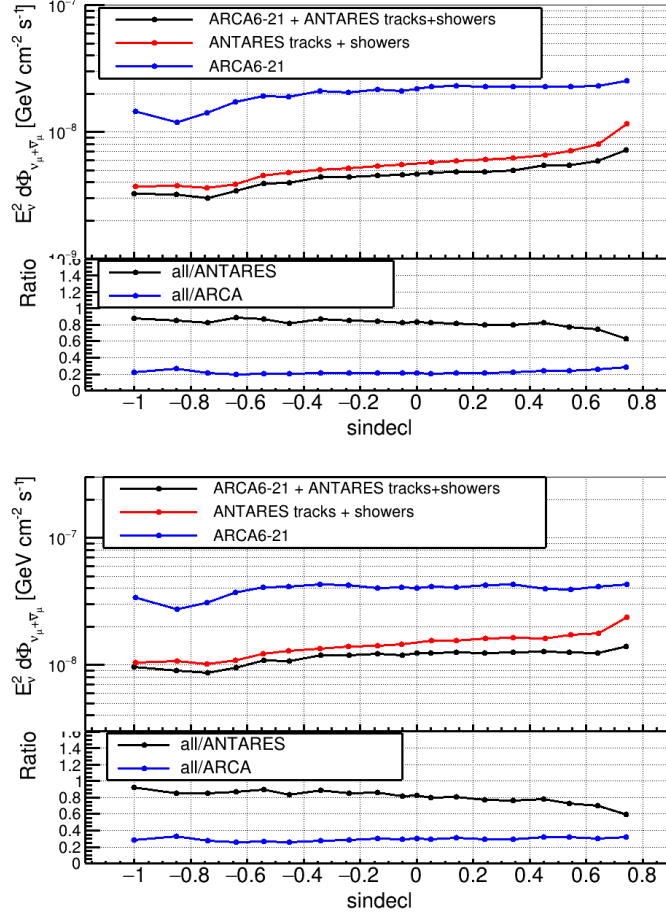


Figure 5.7: On the top, median 90% C.L. upper limits on the one-flavour neutrino flux as a function of declination. On the bottom, 50% probability 5σ discovery flux for the one-flavour neutrino flux as a function of declination.

standalone ANTARES search, as expected given the modest contribution of the current ARCA dataset. The most significant source is the gamma-ray blazar MG3 J225517+2409, with a pre-trial p -value of 4×10^{-5} , corresponding to a pre-trial significance of 3.9σ . Other noteworthy candidates include the blazar J0242+1101 (3.12σ pre-trial), the radio galaxy 3C 403 (3.02σ), and the blazar TXS 0506+056 (associated with the IceCube event IC-170922A), with a pre-trial significance of 2.43σ .

These sources were already identified in the ANTARES stand alone analysis, however the combination with the ARCA samples results in a improvement the source significance, which is estimated to be around 12% for MG3 J225517+2409,

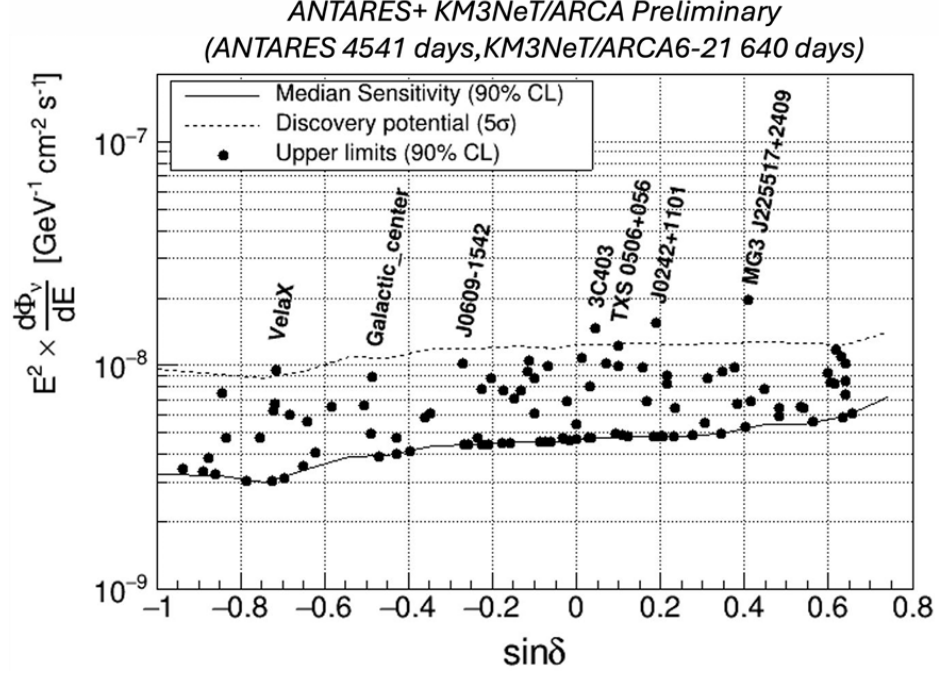


Figure 5.8: 90% C.L. upper limits (dots) on the one-flavour neutrino flux normalization for the investigated astrophysical candidates as a function of the source declination, assuming an E^{-2} spectrum. The names of the sources for which a pre-trial significance greater than 2 has been obtained are reported next to the corresponding upper limits. The solid (dashed) line represents the 90% C.L. median upper limit (50% 5σ discovery flux)

30% for J0242+1101 and 20% for TXS 0506+056.

5.2.5 Analysis summary

A combined point-source analysis using data from ANTARES and KM3NeT/ARCA has been presented. The joint likelihood approach improves the overall sensitivity to astrophysical neutrino sources across the entire declination range. The combined dataset achieves a performance enhancement of nearly one order of magnitude with respect to the current KM3NeT/ARCA standalone configuration, and about a 20% improvement compared to ANTARES alone.

This work demonstrates the feasibility and benefits of combining data from different-generation detectors, providing the most sensitive search to date for neutrino point sources in the Southern sky. With the ongoing expansion of KM3NeT/ARCA, future analyses are expected to further improve sensitivity and enhance the potential for the discovery of a cosmic neutrino source.

5.3 Investigation of the neutrino emission from gamma-ray Galactic sources with KM3NeT/ARCA

5.3.1 Introduction

High-energy neutrinos and photons provide a distinctive signature of cosmic-ray acceleration processes. Collisions of high-energy hadrons in or near astrophysical accelerators produce both neutrinos and gamma rays through the decay of secondary mesons. However, since high-energy gamma rays can also be produced through inverse Compton scattering by relativistic electrons, the detection of neutrinos provides a clear signature - "smoking gun" - for the hadronic origin of cosmic rays.

Since the early 2000s, significant progress has been made in the experimental study of these particles. On one side, the construction of gamma-ray observatories such as HAWC [89] and LHAASO [91] enabled measurements at energies of the order of one PeV. In particular, these two experiments detected very-high-energy gamma-ray emission from tens of sources, reporting the measured energy spectrum for each of them.

On the other hand, experiments capable of detecting high-energy neutrinos were developed. Among these, IceCube has achieved remarkable results, including the detection of a diffuse flux of astrophysical neutrinos and the identification of neutrino events from specific sources such as the blazar TXS 0506+056 [237] and the galaxy Messier 77 [238]. It is also worth mentioning the contribution of KM3NeT/ARCA, which has detected the highest energy neutrino observed to date [235].

5.3.2 KM3NeT/ARCA datasets and MC samples

In this analysis, the DATA collected by KM3NeT/ARCA are considered, starting from the configuration with 6 installed detection lines (ARCA6) up to the configuration with 21 lines (ARCA21). For these samples the event selection is the one discussed in Chapter 3.

In addition, this work also presents a study of the performance of the full detector configuration (ARCA230), based on the most up-to-date ARCA230 simulation [203].

5.3.3 Modelling the neutrino signal using information from gamma-ray observatories

In cosmic-ray acceleration regions, collisions of high-energy hadrons with surrounding matter lead to the production of pions. The subsequent decay of neutral pions results in gamma-ray emission, while the decay chain of charged pions consists of charged leptons and neutrinos.

In this hadronic scenario, the energy spectra of the emitted neutrinos ϕ_ν and photons ϕ_γ can be derived from that of the parent pions. In this way, the neutrino

and photon spectra can be related, as shown by Villante and Vissani (2008) [96], updated by Mascaretti and Vissani (2019) [113].

Following this approach the relation can be written explicitly for the flux of muon neutrinos and antineutrinos:

$$\Phi_{\nu_\mu}(E) = 0.3935\Phi_\gamma(E/(1-r_\pi)) + 0.013455\Phi_\gamma(E/(1-r_K)) + \int_0^1 \frac{dx}{x} k_{\nu_\mu}(x)\Phi_\gamma(E/x)$$

$$\Phi_{\bar{\nu}_\mu}(E) = 0.2879\Phi_\gamma(E/(1-r_\pi)) + 0.009345\Phi_\gamma(E/(1-r_K)) + \int_0^1 \frac{dx}{x} k_{\bar{\nu}_\mu}(x)\Phi_\gamma(E/x)$$

where r_π and r_K are the squares of the ratio between the muon mass and the charged pion and kaon mass:

$$r_\pi = (m_\mu/m_\pi)^2 = 0.573 \quad \text{and} \quad r_K = (m_\mu/m_K)^2 = 0.0458$$

The kernels $k_{\nu_\mu}(x)$ and $k_{\bar{\nu}_\mu}(x)$ are given by:

$$k_{\nu_\mu}(x) = \begin{cases} x^2(22.405 - 59.43x) & \text{if } x \leq r_K = 0.0458 \\ 0.0146 + 0.2838x + 6.89x^2 - 8.117x^3 & \text{if } r_K < x < r_\pi \\ (1-x)^2(-2.693 + 13.436x) & \text{if } x \geq r_\pi = 0.573 \end{cases}$$

$$k_{\bar{\nu}_\mu}(x) = \begin{cases} x^2(23.791 - 46.799x) & \text{if } x \leq r_K = 0.0458 \\ 0.0244 + 0.1965x + 6.042x^2 - 6.602x^3 & \text{if } r_K < x < r_\pi \\ (1-x)^2(-1.4267 + 10.904x) & \text{if } x \geq r_\pi = 0.573 \end{cases}$$

In the paper from Villante-Vissani, it was considered the gamma-ray-neutrino conversion in the special case of a power law spectra for the cosmic rays. They found that the neutrino spectra is proportional to the gamma-ray one times a proportionality coefficient: $Z = Z(\Gamma)$ which depends by the value of spectral index Γ . Such Z coefficient decreases for higher value of the spectral index.

Figure 5.9 shows the neutrino flux computed using the Mascaretti-Vissani method for a power law gamma-ray flux for different values of spectral index. The converted neutrino spectrum is proportional to the gamma-ray spectrum, as their ratio is constant with respect to energy. As the spectral index increase, the ratio between neutrino and gamma decrease: it is around 0.6 for $\Gamma = 2.0$, and it is around 0.25 at $\Gamma = 3.5$.

The observed photon flux may differ from that produced at the source due to attenuation caused by pair-production processes between source photons and those from the cosmic background radiation or the interstellar radiation field.

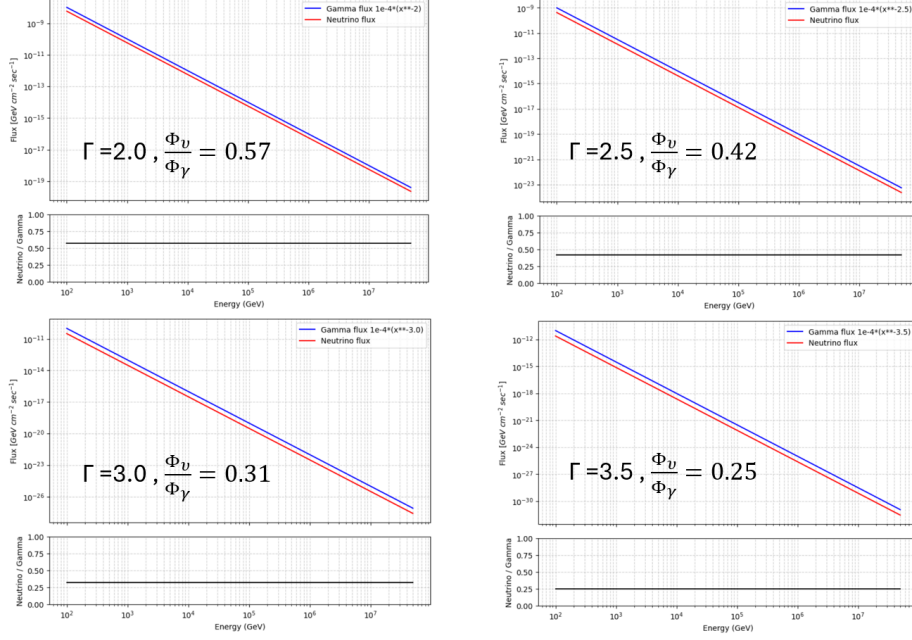


Figure 5.9: Neutrino flux (red line) computed using the Mascaretti-Vissani method for a power law gamma-ray flux (blue line) with spectral index $\Gamma = 2.0, 2.5, 3.0, 3.5$. For each plot is indicated the ratio ϕ_ν/ϕ_γ , it is 0.57 for $\Gamma = 2.0$, 0.42 for $\Gamma = 2.5$, 0.31 for $\Gamma = 3.0$ and 0.25 for $\Gamma = 3.5$

The method developed by Villante and Vissani, later updated in [113], has the advantage of being conceptually and computationally simple, allowing for straightforward modifications to account for gamma-ray absorption effects.

As described in Chapter 1, the observed gamma-ray spectra ϕ_γ^{obs} and the one in the production situ ϕ_γ^{src} are related as $\phi_\gamma^{\text{obs}} = \phi_\gamma^{\text{src}} \times e^{-\tau_{\gamma\gamma}}$, where the attenuation factor $e^{-\tau_{\gamma\gamma}}$ (or survival probability) is a function of the optical depth $\tau_{\gamma\gamma}$. The optical depth is a function of the energy of the gamma-ray, the distance from the source and its position. In this work $\tau_{\gamma\gamma}$ is estimated according to the model of Lipari and Vernetto (2016)[100].

5.3.4 Application to sources observed by LHAASO and HAWC

This approach is applied to estimate the expected neutrino flux from the sources included in the first LHAASO catalog [91] and the third HAWC catalog [89]. The initial sample is built from the LHAASO catalog by selecting sources whose gamma-ray spectra have been reconstructed using both the Water Cherenkov Detector Array (WCDA) and the Kilometer Square Array (KM2A) (Table 1).

Additional sources are then included from the HAWC catalog, selecting only those not associated with any LHAASO source (Table 2).

Both experiments estimate the gamma-ray fluxes by means of spectral fits. In the case of LHAASO, a broken power-law function is adopted:

$$\Phi(E) = \begin{cases} \Phi_{\text{low}} \left(\frac{E}{3\text{TeV}} \right)^{-\alpha_{\text{low}}}, & E < 25 \text{ TeV} \\ \Phi_{\text{high}} \left(\frac{E}{50\text{TeV}} \right)^{-\alpha_{\text{high}}}, & E \geq 25 \text{ TeV} \end{cases} \quad (5.4)$$

For energies below 25 TeV, the spectral parameters (normalization factor and spectral index) are estimated using WCDA data, while for energies above this threshold a fit is performed using KM2A data.

As an indicative estimate, averaging over the sources in the catalog, $\Phi_{\text{low}} \approx 10^{-13} (\text{TeV cm}^2 \text{s})^{-1}$ and $\alpha_{\text{low}} \approx 2.5$, while $\Phi_{\text{high}} \approx 10^{-16} (\text{TeV cm}^2 \text{s})^{-1}$ and $\alpha_{\text{high}} \approx 3.5$.

Regarding the sources from the HAWC catalog, their spectra are modeled using a single power-law function:

$$\Phi(E) = \Phi_0 \left(\frac{E}{7 \text{ TeV}} \right)^{-\alpha} \quad (5.5)$$

In this case, the average parameter values are $\Phi_0 \approx 10^{-13} (\text{TeV cm}^2 \text{s})^{-1}$ and $\alpha \approx 2.5$.

For comparison, the two spectral shapes are shown in Fig. 5.10 (left): the LHAASO spectrum is reported in blue and the HAWC spectrum in green. The corresponding neutrino spectra derived from the two gamma-ray spectral shapes are also shown, in purple for LHAASO and in orange for HAWC.

For each selected source, the neutrino flux is estimated following the method proposed by Villante and Vissani, with a correction for gamma-ray absorption. The absorption is parametrized according to the model by Lipari and Vernetto (2016) [100] and is evaluated only for sources with known distances. Since neither LHAASO nor HAWC provide direct distance estimates, the adopted distances correspond to those of their identified astrophysical counterparts.

For instance, in figure 5.10 (right) the distribution of the optical depth $\tau_{\gamma\gamma}$, computed using the Lipari-Vernetto parameterization, is reported with respect to the energy and to the distance between the source and the hypothetical observer for a fixed position.

5.3.5 Likelihood Formalism

To assess the compatibility of the observed data with the expected neutrino signal from candidate sources, a binned likelihood method is employed. This

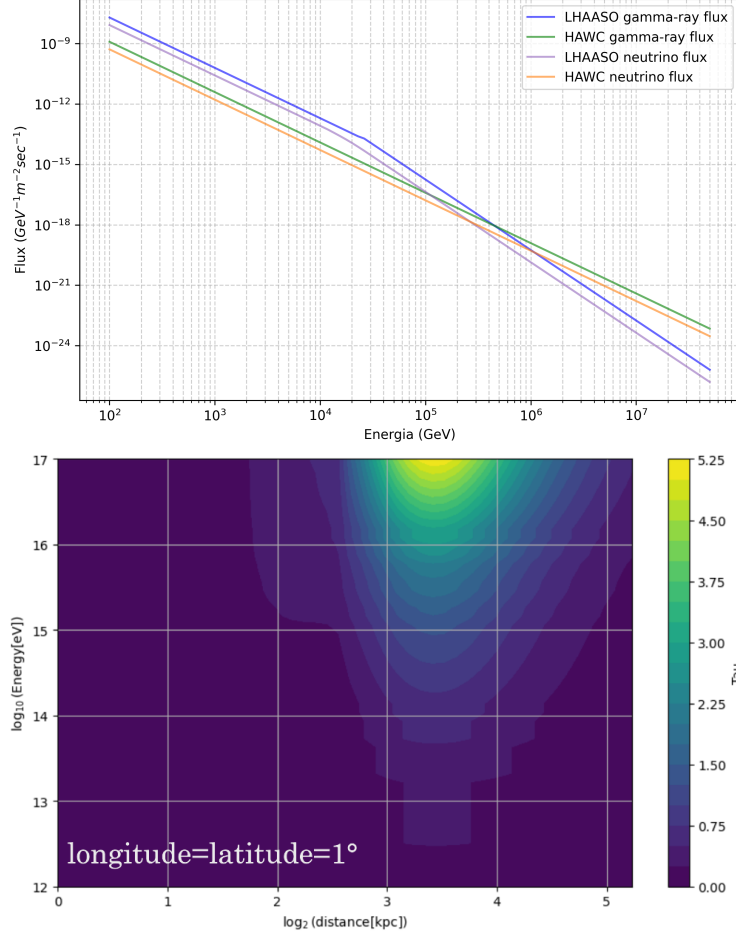


Figure 5.10: On the top, gamma-ray and neutrino fluxes as a function of the energy. On the bottom, optical depth $\tau_{\gamma\gamma}$ distribution with respect to energy and distance for a fixed position (latitude=longitude=1°).

procedure, developed for KM3NeT point-source analyses [203, 208], uses a test statistic λ defined as the logarithm of the likelihood ratio between the signal-plus-background and background-only hypotheses:

$$\lambda = \log L(\xi = \hat{\xi}) - \log L(\xi = 0) \quad (5.6)$$

The likelihood function is defined as:

$$\log L(\xi) = \sum_{\text{bins}} \log(B_i + \xi S_i) - (B_i + \xi S_i) \quad (5.7)$$

where S_i is the expected number of signal events in bin i , obtained by convolving

Table 5.2: List of selected sources from the LHAASO catalogue [91]; for each source, the coordinates (right ascension RA and declination Decl) are reported

#	Source Name	RA (°)	Decl (°)	#	Source Name	RA (°)	Decl (°)
1	1LHAASOJ1809-1918u	272.38	-19.30	14	1LHAASOJ1850-0004u*	282.89	-0.07
2	1LHAASOJ1814-1719u*	273.27	-17.89	15	1LHAASOJ1852+0050u*	283.10	0.84
3	1LHAASOJ1825-1418	276.25	-14.00	16	1LHAASOJ1857+0203u	284.38	2.06
4	1LHAASOJ1825-1337u	276.45	-13.63	17	1LHAASOJ1910+0516*	287.55	5.28
5	1LHAASOJ1825-1256u	276.44	-12.94	18	1LHAASOJ1908+0615u	287.05	6.26
6	1LHAASOJ1813-1245	273.36	-12.75	19	1LHAASOJ1912+1014u	288.38	10.50
7	1LHAASOJ1831-1007u*	277.81	-9.83	20	1LHAASOJ1914+1150u	288.73	11.84
8	1LHAASOJ1834-0831	278.44	-8.38	21	1LHAASOJ0703+1405	105.83	14.10
9	1LHAASOJ1837-0654u	279.31	-6.86	22	1LHAASOJ1922+140	290.73	14.11
10	1LHAASOJ1839-0548u	279.79	-5.81	23	1LHAASOJ0634+1741u	98.57	17.69
11	1LHAASOJ1841-0519	280.21	-5.23	24	1LHAASOJ0534+2200u	83.61	22.04
12	1LHAASOJ1843-0335u	280.91	-3.60	25	1LHAASOJ0542+2311u	85.71	23.20
13	1LHAASOJ1848-0153u	282.02	-1.78	26	1LHAASOJ0622+3754	95.50	37.90

Table 5.3: List of selected sources from the third HAWC catalogue [89]; for each source, the coordinates (right ascension RA and declination Decl) are reported.

#	Source Name	RA (°)	Decl (°)	#	Source Name	RA (°)	Decl (°)
1	3HWCJ1757-240	269.30	-24.09	4	3HWCJ1857+027	284.33	2.80
2	3HWCJ1803-211	270.97	-21.18	5	3HWCJ0634+067	98.66	6.73
3	3HWCJ1849+001	282.35	0.15	6	3HWCJ0617+224	94.39	22.47

the predicted neutrino flux with the detector's effective area. The background histogram B_i is estimated either from data using a data-driven technique (as described in Ref. [208]), or from Monte Carlo simulations for projections involving the full detector configuration [203]. The signal strength (ξ) is varied to obtain test statistic distributions for statistical analysis. For a fixed value of the signal strength ($\hat{\xi}$), pseudo-experiments (PE) are generated by randomly drawing each N_i from a Poisson distribution with mean $B_i + \hat{\xi}S_i$.

5.3.6 Results

The likelihood framework described above is applied to each astronomical source in Table 1 and Table 2 to estimate its significance for both the KM3NeT/ARCA data and the full detector simulation.

From the analysis of the collected data, no evidence was found for the assumed signal from any source, and therefore the upper limits of the spectrum were calculated. Figure 5.11 (top) shows the top ten upper limit values for sources observed by LHAASO, while Figure 5.11 (bottom) shows flux limit values for sources observed by HAWC. In both figures, the horizontal lines correspond to the energy range in which 90% of the signal is expected.

For each source, the upper limit was calculated once considering a neutrino signal estimated from the gamma flux with attenuation correction and once without the correction. Comparing the values obtained in the two cases, absorption

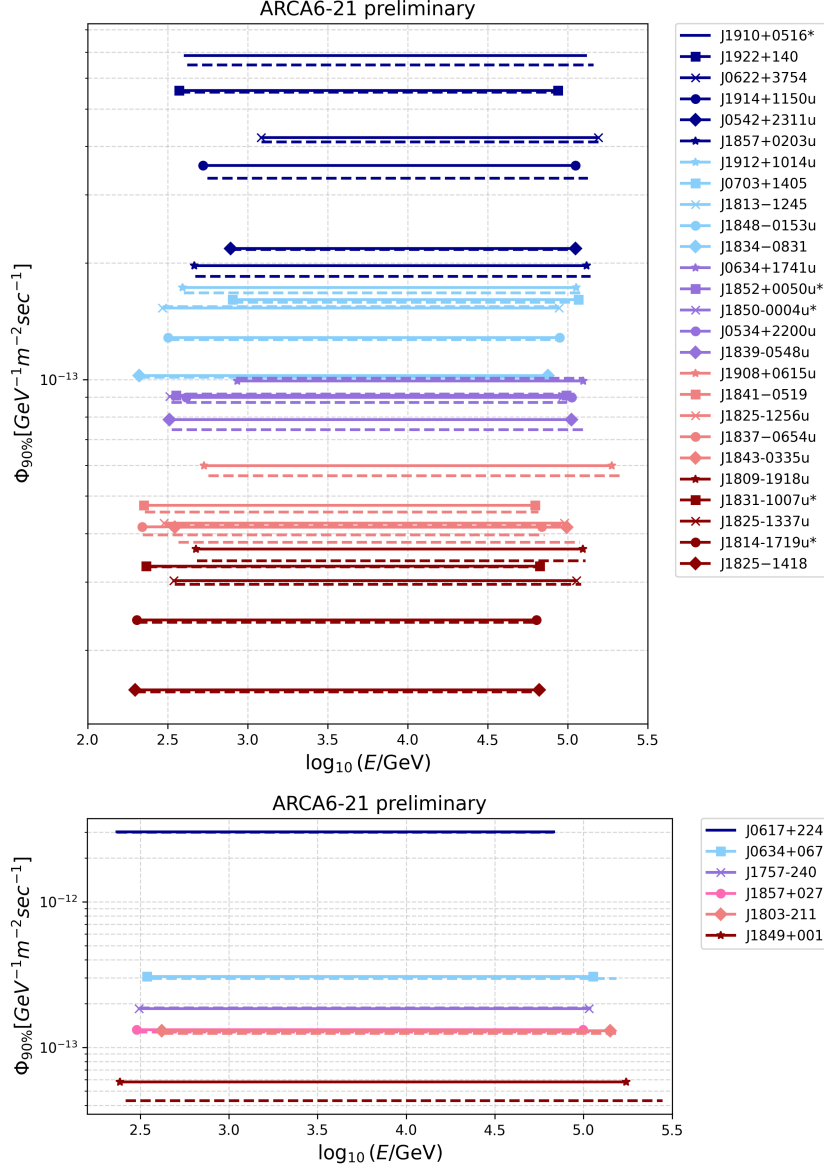


Figure 5.11: Flux upper limits for sources selected from the first LHAASO catalog (top) and from the third HAWC catalog (bottom). The line indicates the energy range where 90% of the signal is expected. The solid lines are the values calculated without considering gamma ray absorption, while the dotted lines correspond to the values calculated considering such absorption.

has a greater impact on the upper limit estimate for source 3HWCJ1849+001, with a 25% variation between the values in the two hypotheses; for all others, the variation is approximately of 10%.

In terms of the upper-limit values:

- The 3 sources from the LHAASO catalog, with lowest upper-limit: 1LHAASOJ1825-1418, 1LHAASOJ1814-1719u* and 1LHAASOJ1825-1337.
- The 3 sources from the HAWC catalog, with lowest upper-limit: 3HWCJ1849+001, 3HWCJ1803-211 and 3HWCJ1857+027.

Regarding the full detector, for each source, the 3σ discovery potential was computed as a function of the observation time. From this, it is estimated the amount of time for a 3σ observation. As shown in figure 5.12, in 5 years KM3NeT/ARCA230 will be able to make a 3σ observation for 5 sources, for 10 sources in 10 years and for 16 sources in 20 years of observation.

More in detail:

- Sources with $T_{3\sigma} \leq 5$ years: 1LHAASO J1825-1418, 1LHAASO J1825-1337u, 1LHAASO J1814-1719u*, 3HWC J1849 + 001 and 1LHAASOJ1809-1918u.
- Sources with $5 \text{ years} < T_{3\sigma} \leq 10$ years: 1LHAASOJ1908+0615u, 1LHAASOJ0534+2200u, 1LHAASOJ1843-0335u, 1LHAASOJ1831-1007u* and 1LHAASOJ1825-1256u.
- Sources with $10 \text{ years} < T_{3\sigma} \leq 15$ years: 1LHAASOJ1837-0654u, 1LHAASOJ0703+1405 and 1LHAASOJ1841-0519.
- Sources with $15 \text{ years} < T_{3\sigma} \leq 20$ years: 1LHAASOJ1848-0153u, 1LHAASOJ0634+1741u and 1LHAASOJ1839-0548u

In this list, an observation time of 20 years is assumed to be a reasonable estimate for the full detector, considering that IceCube has been operating for almost 16 years. Under this assumption, the sources highlighted above would be the most promising among those listed in Table 5.2-5.3, for which KM3NeT/ARCA230 could achieve a significant observation. Naturally, the most favourable candidates are those with the smallest values of $T_{3\sigma}$, which correspond to the sources with the lowest upper limits in the ARCA6-21 data analysis: 1LHAASOJ1825-1418, 1LHAASOJ1825-1337u, 1LHAASOJ1814-1719u*, 3HWCJ1849+001 and 1LHAASOJ1809-1918u.

5.3.7 Analysis summary

This work implements a parameterization of the expected neutrino flux starting from gamma-ray observations, allowing straightforward inclusion of gamma-ray absorption and source-distance information in the neutrino predictions. Based on these expected signals, a likelihood analysis was performed for the selected

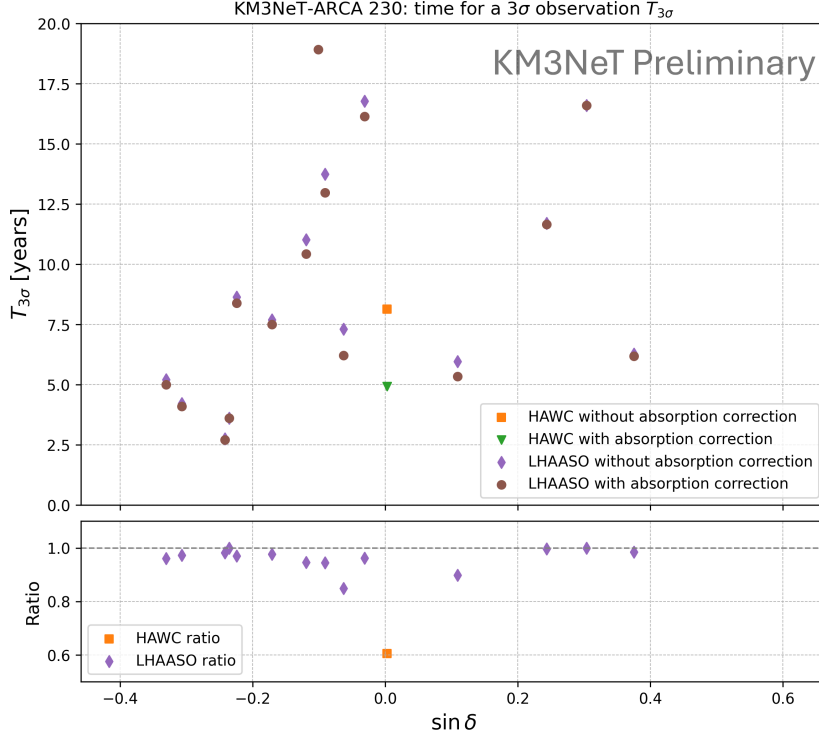


Figure 5.12: Time for a 3σ reported as a function of the sine of the declination. Different markers are used to indicate sources from different catalogues (HAWC and LHAASO) and to distinguish between values calculated without assuming gamma absorption and those in which absorption is taken into account. Below, ratio plot between $T_{3\sigma}$ values with absorption correction and values without correction.

LHAASO and HAWC sources using both KM3NeT/ARCA data and full-detector simulations.

No significant neutrino excess was observed for any selected source; therefore, flux upper limits were derived for each source. Gamma-ray attenuation was included, and its effect on the limits is typically $\approx 10\%$, reaching $\approx 25\%$ for 3HWC J1849+001. The 3σ discovery potential for the full detector indicates potential detections of 5, 10 and 16 sources after 5, 10 and 20 years respectively.

Overall, these results demonstrate KM3NeT/ARCA's increasing sensitivity to Galactic gamma-ray sources and its potential to provide the first statistically significant detections of neutrino emission from such sources in the coming years.

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Summary

Astro-particle physics and multi-messengers astronomy

Astroparticle physics originated in 1912 with the discovery of cosmic rays, when the passage of extraterrestrial particles through the atmosphere was first observed. Since then, the study of the Universe has no longer relied exclusively on traditional electromagnetic observations, but also on instruments and techniques developed in particle physics. Today, cosmic rays, gamma rays, and neutrinos constitute the main high-energy messengers of the Universe and, together with gravitational waves, provide a complementary view of the most extreme astrophysical phenomena and of particle acceleration mechanisms beyond the energies accessible in terrestrial accelerators.

Today, the composition of cosmic rays is well understood, being primarily made of nuclei (mostly protons), but their origin is still under debate. The identification of their sources is particularly challenging due to their charged nature: during propagation through galactic and intergalactic magnetic fields, their trajectories are deflected, resulting in the loss of directional information. For this reason, the study of cosmic rays focuses primarily on energy spectra, composition, and large-scale anisotropies. Cosmic rays with energies below approximately 10 TeV can be directly detected through experiments carried by stratospheric balloons or satellites, such as PAMELA, CALET, AMS, and DAMPE. At higher energies, however, the particle flux becomes too low for efficient direct measurements, and cosmic rays are studied indirectly through ground-based extensive air shower array experiments, which observe the atmospheric cascades produced by the interaction of the primary cosmic ray with the Earth's atmosphere. These detectors reconstruct the properties of the primary particle by observing the different components of the shower, in particular the hadronic, electromagnetic, and muonic ones. Examples of extensive air shower arrays include Tunka, GRAPES, HAWC, and LHAASO. As the energy increases, the cosmic-ray flux decreases drastically, requiring detectors with very large surface coverage to study ultra-high-energy cosmic rays (above 100 PeV), such as the Pierre Auger Observatory and the Telescope Array.

Measurements performed by the Pierre Auger Observatory have revealed a

significant dipole anisotropy for energies above 8 EeV, oriented approximately 115° away from the Galactic Centre and consistent with an extragalactic origin of ultra-high-energy cosmic rays. At lower energies, instead, the nearly isotropic distribution suggests that most cosmic rays up to the “knee” region are produced within the Milky Way, with a gradual transition toward extragalactic sources in the “ankle” region.

To identify the sources of cosmic rays, it is therefore necessary to rely on other electrically neutral astrophysical messengers produced during acceleration and propagation processes: gamma rays and neutrinos. Unlike cosmic rays, gamma rays are not deflected by magnetic fields and travel in straight lines from their production sites, allowing direct source localization. High- and very-high-energy gamma rays can be produced through both leptonic and hadronic processes; the latter are directly associated with cosmic-ray acceleration. In particular, the observation of photons at increasingly higher energies tends to favor hadronic scenarios. However, gamma-ray observations alone do not always allow for an unambiguous discrimination between different production mechanisms, and very-high-energy photons may also be absorbed during propagation.

In recent decades, space-based telescopes such as Fermi-LAT, AGILE, and DAMPE have observed hundreds of sources up to energies of the order of hundreds of GeV, while ground-based instruments such as H.E.S.S., MAGIC, and VERITAS have extended these measurements into the TeV regime. More recently, extensive air shower arrays such as HAWC, LHAASO, and Tibet AS-gamma have identified sources emitting photons up to PeV energies, inaugurating ultra-high-energy gamma-ray astronomy and providing key evidence for the existence of extreme Galactic accelerators, the so-called “PeVatrons”.

On the other hand, neutrinos, interacting only through the weak interaction, can traverse matter and magnetic fields almost undisturbed, carrying information essentially unchanged from the most dense and remote regions of the Universe. Moreover, unlike gamma rays, high-energy neutrinos are produced exclusively in hadronic processes and therefore provide a direct signature of hadron acceleration in astrophysical sources. However, their extremely low interaction probability makes their detection very challenging, requiring kilometer-scale detectors installed in transparent media such as ice or water: neutrino telescopes.

Neutrino telescopes rely on the observation of Cherenkov radiation induced by charged particles produced in neutrino interactions with the surrounding medium. In 2013, the IceCube experiment, located in the Antarctic ice and instrumenting a volume of approximately 1 km^3 , observed for the first time a diffuse flux of astrophysical neutrinos, marking the beginning of high-energy neutrino astronomy. Subsequently, the association of a high-energy neutrino with the blazar TXS 0506+056 and the identification of a persistent emission from the active galaxy NGC 1068 confirmed neutrinos as probes of hadronic processes in cosmic sources.

In this context, KM3NeT is a neutrino telescope currently under construction in the depths of the Mediterranean Sea. The project consists of two complementary detectors: KM3NeT/ORCA, dedicated to the study of atmospheric

neutrinos and fundamental neutrino properties, and KM3NeT/ARCA, designed for high-energy neutrino astronomy.

More recently, the KM3NeT Collaboration reported the detection of an ultra-high-energy neutrino event, with a preliminary estimated energy in the range of hundreds of PeV, highlighting the potential of the next-generation detectors to explore the most extreme acceleration regimes and to search for cosmogenic neutrinos.

Taken together, all these observations constitute the foundation of multi-messenger astronomy, completed by the study of gravitational waves. The combination of information from cosmic rays, gamma rays, and neutrinos makes it possible to investigate the origin of cosmic accelerators and to understand the physical mechanisms responsible for the most energetic phenomena in the Universe.

The KM3NeT/ARCA neutrino telescope

This thesis is focused on neutrino astronomy and is developed within the framework of the KM3NeT experiment, in particular of the KM3NeT/ARCA detector, currently under construction at a depth of approximately 3500 m in the Mediterranean Sea, about 100 km off the coast of Capo Passero (Sicily, Italy) .

In its final configuration, KM3NeT/ARCA will instrument a volume of approximately one cubic kilometer of water using two large arrays of photomultiplier tubes, called building blocks. Each building block will consist of 115 detection lines, each equipped with 18 optical modules. Each optical module is a glass sphere resistant to deep-sea pressure, containing 31 photomultiplier tubes designed to detect the Cherenkov light induced by secondary particles generated in neutrino interactions with matter.

A muon neutrino interacting through charged-current processes inside or near the detector produces a high-energy muon, which can travel distances of the order of a few kilometers, emitting Cherenkov radiation along their trajectory. For this type of event, the Cherenkov signal reconstructed by the PMTs appears as a track due to its elongated topology. Track-like events allow a precise reconstruction of the incoming direction, achieving angular resolutions of the order of 0.1° or better. This property is crucial for identifying neutrino sources, which are accelerators of cosmic rays.

The other type of Cherenkov signal observed in neutrino telescopes is induced by hadronic and electromagnetic showers. These events are mainly produced in charged-current interactions of electron neutrinos and in neutral-current interactions of all neutrino flavours. Since the spatial extension of a shower (typically less than 10 m) is smaller than the spacing between optical modules, the resulting Cherenkov signal appears point-like, and its angular resolution is worse than that achieved for tracks. For this reason, the track channel represents the primary channel for neutrino astronomy studies. However, shower events allow a more precise reconstruction of the event energy, since the Cherenkov light is fully contained within the detector.

Currently, about 20% of the KM3NeT/ARCA detector is installed and operational on the seabed. In particular, in this PhD work the first 640 days of data collected by the experiment have been analysed in order to investigate their compatibility with point-source neutrino emission. The analysed data correspond to track-like events recorded by KM3NeT/ARCA between May 2021 and September 2023, from the 6-line configuration (ARCA6) up to the 21-lines configuration (ARCA21). In this work, the event selection procedure developed for the datasets acquired with the 19-21 lines configurations (ARCA19 and ARCA21) is presented.

In general, the majority of events detected by neutrino telescopes consist of atmospheric muons and atmospheric neutrinos. These events are produced in the interactions of cosmic rays with the Earth's atmosphere and therefore constitute a background in the search for high-energy astrophysical neutrinos.

In particular, high-energy muons immediately emit Cherenkov light upon entering water or ice, and their large penetration power, second only to that of neutrinos, allows them to reach the detector even when produced far from it. Muons therefore account for the overwhelming majority of events recorded by a neutrino telescope. However, being charged particles, they are subject to energy losses mainly due to ionization processes (with additional radiative contributions at higher energies). As a result, there is a limit to the distance they can propagate in matter, whereas neutrinos can traverse the entire Earth without significant attenuation. Muons, instead, gradually lose energy along their path and may decay before reaching the detector.

For this reason, in the analysis of track-like events, a selection based on the reconstructed direction is applied in order to get a sample of particles that have traversed the Earth or part of its crust. Typically, this criterion selects events with zenith angles close to or below the horizon (up-going events), usually up to about 10° above the horizon. However, misreconstructed muons can pass this selection and, due to their very large abundance, may still constitute a significant background.

Regarding atmospheric neutrino background, discrimination with respect to high-energy astrophysical neutrinos is based on probabilistic and statistical methods. Astrophysical events are expected to dominate at high energies (typically ≥ 100 TeV). Moreover, for point-source emission, the reconstructed directions of astrophysical events are expected to be spatially clustered around the source position, whereas the distribution of atmospheric events is approximately isotropic, and therefore uniform with respect to direction.

Event selection for KM3NeT/ARCA

The event selection presented in this thesis is aimed to reduce the contamination due to atmospheric muons, in ARCA19-21 samples; for this purpose, additional quality cuts have been applied to the reconstructed events. In particular, the variables used for the selection include the reconstructed energy, the track angular error, the track length, and the likelihood value obtained from the event

reconstruction. In addition to these variables, a boosted decision tree (BDT) algorithm has also been employed. Different selection configurations have been considered, with the goal of reducing the atmospheric muon contribution, especially at high energies.

In general, the estimation of the atmospheric muon contamination is performed using Monte Carlo simulations. Such contamination is defined as the ratio between the number of weighted atmospheric-muon events and the total number of weighted Monte Carlo events (atmospheric muons, atmospheric neutrinos, and cosmic neutrinos), all evaluated after the event-selection cuts. The muon-to-total event ratio is computed using event weights. Since muons and neutrinos are characterized by different weights, this ratio does not correspond to the simple fraction of simulated events, but rather reflects the relative weighted contribution of the different components.

To determine the optimal event selection for the analysis, the sensitivity and discovery potential have been evaluated for each of the considered selections. The discovery potential represents the minimum flux capable of producing a statistically significant observation in a specified fraction of experiments, indicated as statistical power (fixed to 50% in this work), while the sensitivity corresponds to the flux that can be excluded at a given confidence level (90% in this work) in the absence of a significant signal. These quantities have been calculated for different declination values, assuming for the astrophysical signal a power-law spectrum with spectral index equal to 2.0. Among the considered configurations, the selection, which provides the best compromise between low atmospheric muon contamination and a discovery potential improvement, has been chosen.

For the final event selection, the atmospheric muon contamination in the ARCA19-21 dataset is estimated to be 14.76%. For this configuration, the detector performance has also been evaluated in terms of effective area, point spread function, and energy resolution. The effective area is defined as the quantity which, when multiplied by the incident neutrino flux, yields the expected number of detected events, while the point spread function describes the angular reconstruction performance of the detector. It is defined as the probability density of reconstructing an event at a given angular distance from the true direction of the incoming particle, per solid angle.

Search for cosmic neutrino sources with 6-21 lines of KM3NeT/ARCA

The complete ARCA6-21 dataset has been analysed in order to investigate a possible neutrino emission from point-like sources. While for events collected in the ARCA19-21 configurations the selection developed in this work has been applied, the data recorded in the ARCA6 and ARCA8 configurations had already been analysed in a previous similar study. Therefore, for these samples the selection used in the previous analysis has been retained.

The search for an astrophysical neutrino signal is based on a binned likelihood

method. For each candidate neutrino source, identified by its right ascension and declination, a circular region of interest is defined around the source position, and only events within this region are considered. In this work, a circular region with a radius of 5° is used for each source candidate. A likelihood-ratio test statistic is computed to quantify a possible excess of cosmic neutrino signal over the background, assuming Poissonian statistics. This test statistic is evaluated using the expected signal and background distributions. The signal and background expectations are described by two-dimensional histograms as functions of the reconstructed energy and the angular distance from the source direction.

The background histogram is obtained using a data-driven approach, in which the background distributions in energy and declination are estimated directly from the data. The signal histogram, instead, is computed assuming a given neutrino energy spectrum and by convolving it with the detector effective area, the point spread function (PSF), and the energy resolution. The neutrino emission is modelled using a power-law spectrum, considering three values of the spectral index: 2.0, 2.5, and 3.2.

The full ARCA6-21 dataset (640 days) has been analysed searching for a possible signal from 106 astrophysical neutrino source candidates. These sources have been selected among the most promising candidates considered in previous neutrino telescope analyses (IceCube, ANTARES) and from gamma-ray observatory catalogues reporting very high-energy and/or high-intensity emission.

In addition to the candidate source search, the binned likelihood method has also been applied to an all-sky scan analysis, in which a large set of sky coordinates covering a wide region of the celestial sphere is considered. The coordinate grid consists of about 2 million points, with declination ranging from 90° to 40° , where KM3NeT/ARCA has an estimated visibility above 35%. The coordinates have been generated using the HEALPix software, with an angular resolution of $0.1^\circ \times 0.1^\circ$.

No statistically significant excess has been observed for any of the considered sources; therefore, upper limits on the neutrino fluxes and corresponding p-values have been derived.

For a signal spectrum with spectral index equal to 2.0, the most significant source is the Seyfert galaxy CGCG 420-015, with a pre-trial p-value of 0.0064 and a post-trial p-value of 0.325, corresponding to a significance of 0.45σ . For this source, the flux upper limit is estimated to be $5.4 \times 10^{-8}, \text{GeV}^{-1}, \text{cm}^{-2}, \text{s}^{-1}$.

For a spectral index of 2.5, the lowest pre-trial p-value (0.0038) is obtained for the blazar Mkn 421, for which the post-trial p-value is 0.4, corresponding to a significance of 0.2σ . The flux upper limit is estimated to be $2.3 \times 10^{-5}, \text{GeV}^{-1}, \text{cm}^{-2}, \text{s}^{-1}$.

For a spectral index of 3.2, only the source NGC 1068 is considered, as it is the only source for which IceCube has observed a spectrum compatible with such assumption. For this candidate, the obtained p-value is 0.98, which is not significant; in this case, pre-trial and post-trial p-values coincide since a single source is considered. The flux upper limit is $3.86 \times 10^{-3}, \text{GeV}^{-1}, \text{cm}^{-2}, \text{s}^{-1}$.

Regarding the all-sky analysis, no evidence of neutrino emission has been

found. The coordinates yielding the lowest p-value correspond to a declination of -71.3° and a right ascension of 310.4° . For these coordinates, a pre-trial p-value of 0.0000669 is obtained, while the post-trial p-value is estimated to be 0.88, consistent with a statistical fluctuation of the background.

Further research based on point source analysis

In addition to the search for point-like sources, this thesis describes three further analyses developed within the framework of the PhD project. All three studies are based on the ARCA6-21 dataset, corresponding to 640 days of data taking. Moreover, the analysis methods employed in these studies are directly derived from the binned likelihood approach used for the point-source analysis.

Search for a cosmic point-like neutrino source from the direction of KM3-230213A

On February 13, 2023, an extremely high-energy muon was observed by the KM3NeT/ARCA detector, with 21 operative lines. The reconstructed energy and direction of the event, indicated as KM3-230213A, are such that the probability of originating from the atmospheric muon and neutrino background is negligible. Therefore, the most likely interpretation is that the event was produced by an ultra-high-energy astrophysical neutrino.

Several analyses have been conducted by the KM3NeT Collaboration to investigate the possible origin of the event. As part of this doctoral research, a dedicated analysis has been developed, based on a scan of a limited sky region around the reconstructed direction of the event with the aim of searching for possible evidence of point-like neutrino emission.

Starting from the reconstructed coordinates of the event, corresponding to a declination of -7.8° and a right ascension of 94.3° , a sky region with declination ranging from -10.8° to -4.8° and right ascension between 91.3° and 97.3° has been defined. In this way, a square window with a side length of 6° centred around the direction of the KM3-230213A event has been obtained. The set of points used for the scan was generated using the HEALPix software, adopting an angular resolution of $0.1^\circ \times 0.1^\circ$.

The full ARCA6-21 dataset has been analysed using the binned likelihood method in order to search for a possible excess of signal events at energies lower than that of KM3-230213A. In order to ensure an unbiased search, the KM3-230213A event was removed from the ARCA21 sample used in the analysis. For the signal modelling, a power-law spectrum with spectral index equal to 2.0 has been assumed.

For the ARCA19-21 samples, since a BDT variable was not yet available, the event selection was performed by applying a cut on the reconstructed track length.

For the complete dataset, the energy interval containing 90% of the expected signal is estimated to range from 785 GeV to 1.064 PeV. These values are obtained

assuming a point-like source located at the reconstructed declination of the KM3-230213A event and the considered energy spectrum.

Within the analysed sky region, the most significant pixel was found at a declination of -9.3° and a right ascension of 97.3° , with a pre-trial p-value of 0.0064. Restricting the analysis to pixels within an angular distance of 3° from the reconstructed direction of KM3-230213A, the most significant point (with a pre-trial p-value of 0.05) corresponds to a declination of -6.8° and a right ascension of 96.7° . For this point, the post-trial p-value is estimated to be 0.44, corresponding to a significance of approximately 0.15σ .

Therefore, no significant evidence of point-like neutrino emission has been observed in the considered sky region.

Combined search for cosmic neutrino sources with KM3NeT/ARCA and ANTARES

Part of this PhD work has been dedicated to the search for cosmic neutrino emission through a combined analysis of data collected by KM3NeT/ARCA and ANTARES experiments.

ANTARES was the predecessor of KM3NeT. It was a neutrino telescope installed in the Mediterranean Sea at a depth of approximately 2500 m and located about 40 km off the coast of Toulon (France), close to the site where KM3NeT/ORCA is currently under construction. The detector consisted of 12 detection lines; each line hosted 25 storeys, each equipped with 3 optical modules containing a single photomultiplier tube (PMT). The total instrumented volume of the experiment was approximately 0.01 km^3 .

ANTARES operated for about 16 years, from 2006 to 2022, when the experiment was decommissioned, collecting a total of about 4541 days of data taking. During its operation, ANTARES performed several studies of the atmospheric neutrino flux and conducted numerous searches for high-energy astrophysical neutrino emission.

The goal of this study is to combine ANTARES and KM3NeT/ARCA data in order to improve the performance with respect to the standalone analyses of the individual experiments and obtain more significant results in the search for cosmic neutrino sources.

In this analysis, the full ARCA6-21 dataset has been used, applying to the ARCA19-21 samples the event selection developed in this PhD work. For the ANTARES dataset, which includes both track-like and shower-like events, the selection adopted in the latest ANTARES point-source neutrino search has been used. The combined datasets have been analysed using the binned likelihood method implemented for the analogous search performed with KM3NeT/ARCA data alone.

In terms of performance, the ANTARES dataset provides the dominant contribution, as expected due to its significantly longer exposure time, approximately seven times larger than that of the considered KM3NeT/ARCA dataset. Nevertheless, the combination of the datasets leads to an improvement in both

sensitivity and results of about 20% with respect to the standalone ANTARES analysis.

The compatibility with a neutrino emission has been investigated for 107 candidate sources, corresponding to those considered in the KM3NeT/ARCA analysis, assuming for the signal a power-law energy spectrum with spectral index equal to 2.0.

The most significant source is the gamma-ray blazar MG3 J225517+2409, with a pre-trial p-value of 4×10^{-5} , corresponding to a pre-trial significance of 3.9σ . Other noteworthy candidates include the blazar J0242+1101 (3.12σ pre-trial), the radio galaxy 3C 403 (3.02σ), and the blazar TXS 0506+056, associated with the IceCube event IC-170922A, with a pre-trial significance of 2.43σ .

All these sources had already been identified in the standalone ANTARES analysis; however, the combination with the ARCA samples leads to a further increase in source significance. In particular, the improvement is estimated to be about 12% for MG3 J225517+2409, 30% for J0242+1101, and 20% for TXS 0506+056.

Investigating neutrino emission from gamma-ray Galactic sources with KM3NeT/ARCA

Part of this thesis work has been dedicated to the estimation of neutrino emission using information from gamma-ray observatories. Neutrinos and gamma rays are both produced in cosmic-ray collisions through the decay of pions and kaons. In particular, neutral mesons contribute to the gamma-ray flux, while charged mesons give rise to the neutrino flux. Therefore, a relation between the neutrino and gamma-ray spectra is expected.

To derive the neutrino spectrum from the observed gamma-ray spectrum of a given source, the theoretical model developed by Villante and Vissani (2008), later updated by Mascaretti and Vissani (2019), has been used. According to this approach, the neutrino spectrum can be obtained as a convolution of the gamma-ray spectrum with appropriate kernel functions derived from the neutrino energy spectra of meson decays in the center-of-mass frame. This model assumes proton-proton interactions as origin for both the two messengers.

The main advantage of this model is its conceptual simplicity and straightforward computational implementation. This approach assumes that the observed gamma-ray flux corresponds to the flux emitted at the source. In this analysis, this theoretical model has been refined by introducing a correction for photon absorption. The observed gamma-ray flux may differ from the emitted one due to attenuation processes caused by electron-positron pair production between source photons and the cosmic background radiation or the interstellar radiation field.

The observed gamma-ray spectrum and the one in the production situ, are therefore related through an attenuation factor depending on photon energy, source distance, and source position. In this work, this factor has been modeled using the parametrization proposed by Lipari and Vernetto (2016).

For this analysis, sources from the first LHAASO catalog and the third HAWC catalog have been considered, since these observatories provide estimations of the gamma-ray spectrum as a function of energy. LHAASO uses a broken power-law model, while HAWC adopts a simple power-law description. In both cases, the model parameters are obtained from fits to the observational data. In particular, LHAASO uses WCDA data for the low-energy part and KM2A data for the high-energy component.

The source list used in this work was obtained from the LHAASO first catalog by selecting sources detected by both WCDA and KM2A. Additional sources from the HAWC third catalog were also included. Since absorption modelling requires knowledge of the source distance, and neither LHAASO nor HAWC provide this directly, only sources associated with counterparts of known distance were selected.

In total, 26 sources from LHAASO and 6 sources from HAWC were considered. For each of them, the neutrino spectrum as a function of energy was estimated using the Villante and Vissani model, including absorption effects via the Lipari and Vernetto parametrization.

The ARCA6-21 dataset (with the selection developed in this PhD work) was analysed using the binned likelihood method to test compatibility with the derived neutrino signal.

No statistically significant excess was observed for any source, and therefore upper limits on the flux were derived. The most constraining sources are 1LHAASO J1825-1418, 1LHAASO J1814-1719u*, 1LHAASO J1825-1337, and 3HWC J1849+001.

For each source, in addition to the analysis of the ARCA6-21 data, the performance of the complete KM3NeT/ARCA230 detector was estimated using its most recent simulation.

Performance is expressed in terms of the observation time required for the detector to achieve a 3σ discovery significance. The most promising sources are those for which the estimated observation time is less than 20 years, value considered realistic in comparison with the IceCube experiment (which has collected around 16 years of data). The most interesting sources are those for which KM3NeT/ARCA can achieve a significant detection within 5 years: 1LHAASO J1825-1418, 1LHAASO J1825-1337u, 1LHAASO J1814-1719u*, 3HWC J1849+001, and 1LHAASO J1809-1918u.

Final thoughts

The results of the point-source search with ARCA6-21 data show a significant improvement in performance with respect to the previous analysis based on the ARCA6-8 dataset. Therefore, a further enhancement is expected as additional detection lines are installed and become operational in KM3NeT/ARCA.

Moreover, thanks to the combined analysis, it is now possible to use ARCA and ANTARES data jointly, improving the performance over the standalone

ANTARES analysis and increasing the possibility of achieving a significant detection.

Finally, the results of the study on gamma-ray source emission indicate that the full KM3NeT/ARCA detector will be able to perform significant observations of hadronic emission mechanisms in the most promising sources.

With the continued expansion of the detector and the progressive accumulation of data, KM3NeT/ARCA is expected to make a substantial contribution to the development of astroparticle physics in the coming years.

Summary

Riepilogo

Fisica astroparticellare e astronomia multi-messaggera

La fisica astroparticellare nasce nel 1912 con la scoperta dei raggi cosmici, quando fu osservato il passaggio in atmosfera di particelle di origine extraterrestre. Da allora, lo studio dell'Universo non si basa più esclusivamente sull'osservazione elettromagnetica tradizionale, ma anche sull'utilizzo di strumenti e tecniche sviluppati nella fisica delle particelle. Oggi, raggi cosmici, raggi gamma e neutrini costituiscono i principali messaggeri dell'Universo ad alta energia e, insieme alle onde gravitazionali, forniscono una visione complementare dei fenomeni astrofisici più estremi e dei meccanismi di accelerazione delle particelle oltre le energie raggiungibili negli acceleratori terrestri.

I raggi cosmici sono costituiti principalmente da nuclei atomici, in prevalenza protoni, ma la loro origine è ancora oggetto di dibattito. L'identificazione delle sorgenti è resa particolarmente complessa dal fatto che si tratta di particelle cariche: durante la propagazione attraverso i campi magnetici galattici e intergalattici, la loro traiettoria viene deflessa, causando la perdita dell'informazione direzionale. Per questo motivo, lo studio dei raggi cosmici si concentra principalmente sugli spettri energetici, sulla composizione e sulle anisotropie su larga scala. I raggi cosmici con energie inferiori a circa 10 TeV possono essere rivelati direttamente tramite esperimenti installati su palloni stratosferici o satelliti, come PAMELA, CALET, AMS e DAMPE. A energie superiori, invece, il flusso di particelle diventa troppo basso per consentire misure dirette efficienti e i raggi cosmici vengono studiati indirettamente mediante ground-based extensive air shower arrays, che osservano gli sciami atmosferici prodotti dall'interazione del raggio cosmico primario con l'atmosfera terrestre. Questi rivelatori ricostruiscono le proprietà della particella primaria attraverso l'osservazione delle diverse componenti dello sciame, in particolare quella adronica, elettromagnetica e muonica. Esempi di extensive air shower array sono Tunka, GRAPES, HAWC e LHAASO. All'aumentare dell'energia del raggio cosmico, il flusso diminuisce drasticamente, rendendo necessari rivelatori che coprano superfici molto estese per lo studio dei raggi cosmici di ultra-alta energia (oltre 100 PeV), come il Pierre Auger Observatory e il Telescope Array.

Misure effettuate dal Pierre Auger Observatory hanno evidenziato una significativa anisotropia dipolare per energie superiori a 8 EeV, orientata a circa 115°

dal centro galattico e compatibile con un'origine extragalattica dei raggi cosmici di altissima energia. A energie inferiori, invece, la distribuzione quasi isotropa suggerisce che la maggior parte dei raggi cosmici fino alla regione del “knee” venga prodotta all'interno della Via Lattea, con una transizione graduale verso sorgenti extragalattiche nella regione dell’“ankle”.

Per identificare le sorgenti dei raggi cosmici è quindi necessario ricorrere ad altri messaggeri astrofisici elettricamente neutri, prodotti durante i processi di accelerazione e propagazione: i raggi gamma e i neutrini. A differenza dei raggi cosmici, i raggi gamma non subiscono deflessioni magnetiche e viaggiano in linea retta dal sito di produzione, permettendo di localizzare direttamente le sorgenti. I raggi gamma di alta e altissima energia possono essere prodotti sia tramite processi leptonici sia adronici; questi ultimi sono direttamente associati all'accelerazione dei raggi cosmici. In particolare, l'osservazione di fotoni a energie sempre più elevate tende a favorire interpretazioni di tipo adronico. Tuttavia, la sola osservazione gamma non consente sempre di discriminare univocamente tra i diversi meccanismi di produzione e, inoltre, i fotoni ad altissima energia possono essere assorbiti durante la propagazione.

Negli ultimi decenni, telescopi spaziali come Fermi-LAT, AGILE e DAMPE hanno osservato centinaia di sorgenti fino a energie dell'ordine delle centinaia di GeV, mentre strumenti installati a terra quali H.E.S.S., MAGIC e VERITAS hanno esteso queste misure al regime TeV. Più recentemente, array di sciame atmosferici estesi come HAWC, LHAASO e Tibet AS-gamma hanno identificato sorgenti in grado di emettere fotoni fino a energie del PeV, inaugurando l'astronomia gamma di ultra-alta energia e fornendo importanti indicazioni sull'esistenza di acceleratori galattici estremi, i cosiddetti “PeVatrons”.

D'altra parte i neutrini, interagendo esclusivamente tramite interazione debole, possono attraversare materia e campi magnetici quasi indisturbati, trasportando informazioni praticamente inalterate sulle regioni più dense e remote dell'Universo. Inoltre, a differenza dei raggi gamma, i neutrini di alta energia sono prodotti esclusivamente in processi adronici e costituiscono quindi una prova diretta dell'accelerazione di adroni nelle sorgenti astrofisiche. La loro debolissima probabilità di interazione rende però estremamente difficile la loro osservazione, richiedendo rivelatori di dimensioni chilometriche installati in mezzi trasparenti come ghiaccio o acqua: i telescopi per neutrini.

Questi esperimenti si basano sull'osservazione della radiazione Cherenkov indotta dalle particelle cariche prodotte nell'interazione dei neutrini con la materia circostante. Nel 2013 l'esperimento IceCube, installato nei ghiacci del Polo Sud e caratterizzato da un volume strumentato di circa 1 km^3 , ha osservato per la prima volta un flusso diffuso di neutrini di origine astrofisica, segnando l'inizio dell'astronomia dei neutrini. Successivamente, l'associazione di un neutrino di alta energia con il blazar TXS 0506+056 e l'identificazione di un'emissione persistente dalla galassia attiva NGC 1068 hanno confermato il ruolo dei neutrini come sonde dei processi adronici nelle sorgenti cosmiche.

In questo contesto si inserisce l'esperimento KM3NeT, una rete di telescopi per neutrini attualmente in costruzione nelle profondità del Mar Mediterraneo. Il

progetto è composto da due rivelatori complementari: KM3NeT/ORCA, dedicato allo studio dei neutrini atmosferici e delle proprietà fondamentali del neutrino, e KM3NeT/ARCA, progettato per l'astronomia dei neutrini di alta energia. Più recentemente, la collaborazione KM3NeT ha riportato la rilevazione di un evento di neutrino con un'energia stimata preliminarmente nell'intervallo delle centinaia di PeV, evidenziando il potenziale della nuova generazione di rivelatori nello studio dei regimi di accelerazione più estremi e nella ricerca di neutrini cosmogenici.

Nel loro insieme, tutte queste osservazioni costituiscono il fondamento dell'astronomia multi-messaggera, completata dallo studio delle onde gravitazionali. La combinazione delle informazioni provenienti da raggi cosmici, raggi gamma, neutrini permette infatti di investigare l'origine degli acceleratori cosmici e di comprendere i meccanismi fisici responsabili dei fenomeni più energetici dell'Universo.

Il telescopio per neutrini KM3NeT/ARCA

Questo elaborato è incentrato sull'astronomia del neutrino e si sviluppa nell'ambito dell'esperimento KM3NeT, in particolare del rivelatore KM3NeT/ARCA, attualmente in costruzione ad una profondità di circa 3500 m nel mar Mediterraneo, ad una distanza di 100 km dalla costa di Capo Passero (Sicilia, Italia).

Nella configurazione finale, KM3NeT/ARCA coprirà un volume di circa un chilometro cubo d'acqua attraverso due grandi array di fotomoltiplicatori, denominati building blocks. Ciascun building block sarà composto da 115 linee di rilevazione, ognuna equipaggiata con 18 moduli ottici. Ogni modulo ottico consiste in una sfera di vetro resistente alla pressione marina contenente 31 tubi fotomoltiplicatori, progettati per rivelare la luce Cherenkov indotta dalle particelle secondarie generate nelle interazioni dei neutrini con la materia.

Un neutrino muonico che interagisce mediante un processo di Charged Current, all'interno o in prossimità del rivelatore, produce un muone di alta energia, che può percorrere distanze dell'ordine del kilometro inducendo l'emissione Cherenkov, lungo il suo percorso.

In questo caso, il segnale Cherenkov, ricostruito dai tubi fotomoltiplicatori, è indicato come traccia per via della sua lunghezza. Per questo tipo di segnale si può ricostruire la direzione dell'evento con una buona precisione, arrivando a valori della risoluzione angolare dell'ordine del 0.1° o inferiori. Questa proprietà è molto importante per localizzare le sorgenti dei neutrini, che sono acceleratori di raggi cosmici.

L'altra tipologia di segnale Cherenkov che osservano i telescopi per neutrino, è indotta da sciame adronici ed elettromagnetici. Questi eventi sono principalmente prodotti dalle interazioni Charged Current del neutrino elettronico e dall'interazione Neutral Current di tutti gli altri sapori del neutrino. Dal momento che l'estensione di uno sciame (in genere inferiore a 10 m) è minore della distanza tra i moduli ottici, il segnale Cherenkov associato appare come puntiforme e la sua risoluzione angolare è peggiore di quella stimata per le tracce. Per questo motivo il canale delle tracce è il canale principale per gli studi dell'astronomia del neutrino. Tuttavia gli eventi di tipo sciame consentono

di stimare con maggiore precisione l'energia degli eventi, in quanto il segnale Cherenkov è localizzato interamente nel rivelatore.

Attualmente, circa il 20% del rivelatore KM3NeT/ARCA è installato e operativo sul fondo marino. Nello specifico, in questo lavoro di dottorato sono stati analizzati i primi 640 giorni di dati raccolti dall'esperimento, al fine di investigare la compatibilità con l'emissione di neutrini da sorgenti puntiformi. I dati analizzati corrispondono agli eventi di tipo traccia raccolti da ARCA tra maggio 2021 e settembre 2023, a partire dalla configurazione a 6 linee (ARCA6) fino a quella a 21 linee (ARCA21). In particolare, in questo elaborato è stata descritta la procedura di selezione degli eventi sviluppata per i dataset acquisiti nelle configurazioni a 19 e 21 Detection Units (ARCA19 e ARCA21).

In generale, la maggior parte degli eventi rilevati dai telescopi per neutrini è costituita da muoni e neutrini atmosferici. Questi eventi sono prodotti dalle interazioni dei raggi cosmici con l'atmosfera terrestre e rappresentano quindi un fondo (background) nella ricerca di neutrini astrofisici di alta energia.

In particolare, i muoni di alta energia emettono immediatamente luce Cherenkov al loro ingresso nell'acqua o nel ghiaccio, e la loro elevata capacità di penetrazione—seconda solo a quella dei neutrini—consente loro di raggiungere il rivelatore anche quando prodotti a grande distanza. Pertanto, essi costituiscono la grande maggioranza degli eventi registrati da un telescopio per neutrini. Tuttavia, essendo particelle cariche, sono soggetti a perdite di energia dovute principalmente a processi di ionizzazione (oltre a contributi radiativi alle energie più elevate). Di conseguenza, esiste un limite alla distanza che possono percorrere nel mezzo, mentre i neutrini possono attraversare l'intera Terra senza essere significativamente assorbiti. I muoni, al contrario, tendono a perdere energia lungo il percorso e possono decadere prima di raggiungere il rivelatore.

Per questo motivo, nello studio degli eventi di tipo traccia si applica una selezione sulla direzione ricostruita, al fine di privilegiare particelle che abbiano attraversato la Terra o parte della sua crosta. In genere, tale criterio seleziona eventi con angoli di zenit prossimi o inferiori all'orizzonte (up-going events), tipicamente fino a circa 10° sopra l'orizzonte. Tuttavia, muoni con direzione mal ricostruita possono superare questa selezione e, a causa del loro numero elevatissimo, costituire ancora un fondo rilevante.

Per quanto riguarda invece il fondo derivato dai neutrini atmosferici, la discriminazione rispetto ai neutrini astrofisici di alta energia si basa su metodi probabilistici e statistici. Gli eventi di origine astrofisica sono attesi dominare alle alte energie (tipicamente 100 TeV). Inoltre, nel caso di sorgenti puntiformi, le direzioni ricostruite degli eventi astrofisici tendono a essere correlate spazialmente con la posizione della sorgente, mentre la distribuzione degli eventi atmosferici è approssimativamente isotropa, risultando uniforme rispetto alla direzione.

Selezione degli eventi di KM3NeT/ARCA

La selezione presentata in questo elaborato ha lo scopo di ridurre la contaminazione dovuta ai muoni atmosferici, nei campioni ARCA19-21; a tal fine sono

stati applicati ulteriori criteri di qualità agli eventi ricostruiti. In particolare, le variabili utilizzate per la selezione includono l'energia ricostruita, l'errore angolare della traccia, la lunghezza della traccia e il valore della likelihood ottenuti dalla ricostruzione degli eventi. Oltre a queste variabili, è stato impiegato anche un algoritmo di boosted decision tree (BDT). Diverse configurazioni di selezione sono state considerate, con l'obiettivo di sopprimere il contributo dei muoni atmosferici soprattutto alle alte energie.

In generale, la stima della contaminazione dovuta ai muoni atmosferici viene effettuata mediante simulazioni Monte Carlo. La muon contamination è definita come il rapporto tra il numero di eventi di muoni atmosferici pesati e il numero totale di eventi Monte Carlo pesati (muoni atmosferici, neutrini atmosferici e neutrini astrofisici), entrambi valutati dopo l'applicazione della selezione degli eventi. Il rapporto tra muoni ed eventi totali viene calcolato utilizzando i pesi degli eventi simulati. Poiché muoni e neutrini sono caratterizzati da pesi differenti, questo rapporto non coincide con la semplice frazione di eventi simulati, ma rappresenta il contributo relativo pesato delle diverse componenti.

Per determinare la selezione ottimale da utilizzare nell'analisi sono state calcolate, per ciascuna delle selezioni considerate, la sensitivity e il discovery potential. Il discovery potential rappresenta il flusso minimo in grado di produrre un'osservazione statisticamente significativa in una data frazione di esperimenti, indicata come statistical power (fissata al 50% in questo lavoro), mentre la sensitivity rappresenta il flusso che può essere escluso a un dato livello di confidenza (90% in questo lavoro) in assenza di un segnale significativo. Queste quantità sono state calcolate per diversi valori di declinazione, assumendo per il segnale astrofisico uno spettro di tipo power law con indice spettrale pari a 2.0. Tra le diverse selezioni analizzate, è stata scelta quella che garantisce il miglior compromesso tra una bassa contaminazione da muoni atmosferici e un miglioramento del discovery potential.

Per la selezione finale degli eventi, la contaminazione dei muoni atmosferici nel dataset ARCA19-21 è stimata pari al 14.76%. Con questa selezione sono state inoltre valutate le prestazioni del rivelatore in termini di area efficace, point spread function e risoluzione energetica. L'area efficace è definita come la quantità che, moltiplicata per il flusso incidente di neutrini, fornisce il numero atteso di eventi rilevati, mentre la point spread function descrive le prestazioni di ricostruzione angolare del rivelatore. Essa rappresenta la densità di probabilità di ricostruire un evento a una determinata distanza angolare rispetto alla direzione reale della particella incidente, per unità di angolo solido.

Ricerca per sorgenti astrofisiche di neutrini con KM3NeT/ARCA6-21

Il dataset completo ARCA6-21 è stato analizzato al fine di investigare la possibile presenza di emissione di neutrini da sorgenti puntiformi. Mentre per gli eventi acquisiti nelle configurazioni ARCA19-21 è stata applicata la selezione sviluppata

in questo lavoro, i dati raccolti nelle configurazioni ARCA6 e ARCA8 erano già stati analizzati in precedenza nell'ambito di uno studio analogo. Per tali campioni è stata quindi mantenuta la selezione adottata nell'analisi precedente.

La ricerca di un segnale di neutrini astrofisici è basata su un metodo di binned likelihood. Per ciascuna sorgente candidata, identificata tramite ascensione retta e declinazione, viene definita una regione circolare di interesse attorno alla posizione della sorgente e vengono considerati esclusivamente gli eventi contenuti in tale regione. In questo lavoro è stata utilizzata, per ogni sorgente candidata, una regione circolare con raggio pari a 5° . Per quantificare un eventuale eccesso di segnale cosmico rispetto al fondo atmosferico, viene impiegata una test statistic basata sul likelihood-ratio test, assumendo statistica poissoniana. Tale test statistic viene calcolata utilizzando le distribuzioni attese di segnale e fondo. Le aspettative di segnale e background sono descritte mediante istogrammi bidimensionali in funzione dell'energia ricostruita e della distanza angolare dalla direzione della sorgente.

L'istogramma del fondo è ottenuto attraverso un approccio data-driven, nel quale le distribuzioni del background in energia e declinazione vengono stimate direttamente dai dati sperimentali. L'istogramma del segnale, invece, è costruito assumendo uno specifico spettro energetico dei neutrini e calcolando la convoluzione di tale spettro con l'area efficace del rivelatore, la point spread function e la risoluzione energetica. L'emissione di neutrini è stata modellizzata mediante uno spettro a legge di potenza (power law), considerando tre diversi valori dell'indice spettrale: 2.0, 2.5 e 3.2.

L'intero dataset ARCA6-21, corrispondente a 640 giorni di presa dati, è stato analizzato ricercando un possibile segnale proveniente da 106 sorgenti astrofisiche candidate all'emissione di neutrini. Tali sorgenti sono state selezionate tra i candidati più promettenti individuati in precedenti analisi di telescopi per neutrini, quali IceCube e ANTARES, e nei cataloghi di osservatori gamma che hanno osservato emissioni particolarmente intense e/o ad altissima energia.

Oltre alla ricerca dedicata alle sorgenti candidate, il metodo di binned likelihood è stato impiegato anche per un'analisi di tipo all-sky scan, nella quale è stato considerato un ampio insieme di coordinate distribuite su una vasta regione della sfera celeste. Il set di coordinate è composto da circa 2 milioni di punti, con declinazioni comprese tra 90° e 40° ; in questo intervallo la visibilità di KM3NeT/ARCA è stimata essere superiore al 35%. Le coordinate sono state generate mediante il software HEALPix, adottando una risoluzione angolare di $0.1^\circ \times 0.1^\circ$.

Per nessuna delle sorgenti considerate in questa analisi è stato osservato un eccesso statisticamente significativo; sono stati quindi determinati gli upper limits sui flussi di neutrini e i corrispondenti p-value.

Assumendo uno spettro del segnale con indice spettrale pari a 2.0, la sorgente più significativa risulta essere la galassia di Seyfert CGCG 420-015, con un p-value pre-trial pari a 0.0064 e un p-value post-trial pari a 0.325, corrispondente a una significanza di circa 0.45σ . Per questa sorgente, l'upper limit sul flusso è stimato pari a 5.4×10^{-8} , $\text{GeV}^{-1}, \text{cm}^{-2}, \text{s}^{-1}$.

Per un indice spettrale pari a 2.5, il valore minimo del p-value pre-trial (0.0038) è stato ottenuto per il blazar Mkn 421. In questo caso, il p-value post-trial è pari a 0.4, corrispondente a una significanza di circa 0.2σ . L'upper limit sul flusso è stimato pari a 2.3×10^{-5} , $\text{GeV}^{-1}, \text{cm}^{-2}, \text{s}^{-1}$.

Per un indice spettrale pari a 3.2, è stata considerata esclusivamente la sorgente NGC 1068, essendo l'unica per cui IceCube abbia osservato uno spettro compatibile con tale ipotesi. Per questo candidato il p-value ottenuto è pari a 0.98, quindi non significativo; in questo caso i valori di p-value pre-trial e post-trial coincidono. L'upper limit sul flusso risulta pari a 3.86×10^{-3} , $\text{GeV}^{-1}, \text{cm}^{-2}, \text{s}^{-1}$.

Per quanto riguarda l'analisi all-sky, non è stata osservata alcuna evidenza significativa di emissione di neutrini. Le coordinate che restituiscono il valore minimo del p-value corrispondono a una declinazione di 71.3° e a un'ascensione retta di 310.4° . Per tali coordinate è stato ottenuto un p-value pre-trial pari a 0.0000669, mentre il p-value post-trial è stimato pari a 0.88, risultando quindi compatibile con una fluttuazione statistica del fondo.

Ricerche derivate dall'analisi per sorgenti puntiformi

Oltre alla ricerca di sorgenti puntiformi, in questo elaborato sono descritte tre ulteriori analisi sviluppate nell'ambito del progetto di dottorato. Tutti e tre gli studi sono basati sul dataset ARCA6-21, corrispondente a 640 giorni di presa dati. Inoltre, i metodi di analisi impiegati derivano direttamente dall'approccio di binned likelihood utilizzato per la ricerca di sorgenti puntiformi.

Ricerca per sorgenti puntiformi di neutrini dalla direzione dell'evento KM3-230213A

Il 13 febbraio 2023, un muone di energia estremamente elevata è stato osservato dal rilevatore KM3NeT/ARCA, con 21 linee operative. L'energia e la direzione ricostruite dell'evento, indicato come KM3-230213A, risultano tali che la probabilità di un'origine dovuta al fondo di muoni e neutrini atmosferici sia trascurabile. L'ipotesi più plausibile è quindi che l'evento sia stato prodotto da un neutrino astrofisico di ultra-alta energia.

La collaborazione KM3NeT ha condotto diverse analisi per investigare la possibile origine dell'evento. Nell'ambito di questo lavoro di dottorato è stata sviluppata un'analisi dedicata, basata su uno scan di una regione limitata di cielo attorno alla direzione ricostruita dell'evento, con l'obiettivo di ricercare eventuali evidenze di emissione puntiforme di neutrini.

A partire dalle coordinate ricostruite dell'evento, corrispondenti a una declinazione di -7.8° e un'ascensione retta di 94.3° , è stata definita una regione di cielo con declinazione compresa tra -10.8° e -4.8° e ascensione retta nell'intervallo 91.3° – 97.3° . In questo modo è stata ottenuta una finestra quadrata di lato 6° centrata attorno alla direzione dell'evento KM3-230213A. L'insieme dei punti utilizzati per lo scan è stato generato mediante il software HEALPix, adottando una risoluzione angolare di $0.1^\circ \times 0.1^\circ$.

L'intero dataset ARCA6-21 è stato analizzato mediante il metodo di binned likelihood per ricercare un possibile eccesso di eventi di segnale a energie inferiori rispetto a quella di KM3-230213A. Al fine di garantire una ricerca unbiased, l'evento KM3-230213A è stato rimosso dal campione di ARCA21 utilizzato nell'analisi. Per la modellizzazione del segnale è stato assunto uno spettro di tipo power-law con indice spettrale pari a 2.0.

Per i campioni ARCA19-21, poiché una variabile BDT non era ancora disponibile, la selezione degli eventi è stata effettuata applicando un taglio sulla lunghezza della traccia ricostruita.

Con il dataset completo ARCA6-21, l'intervallo energetico contenente il 90% del segnale atteso è stimato tra 785 GeV e 1.064 PeV. Tali valori sono ottenuti assumendo una sorgente puntiforme localizzata alla declinazione ricostruita per l'evento KM3-230213A e lo spettro energetico considerato.

Nella regione di cielo analizzata, il pixel più significativo è stato trovato alla declinazione di -9.3° e ascensione retta pari a 97.3° , con un p-value pre-trial di 0.0064. Considerando esclusivamente i pixel entro una distanza angolare di 3° dalla direzione ricostruita di KM3-230213A, il punto più significativo (con p-value pre-trial pari a 0.05) corrisponde a una declinazione di -6.8° e a un'ascensione retta di 96.7° . Per questo punto, il p-value post-trial è stimato pari a 0.44, corrispondente a una significanza di circa 0.15σ . Pertanto, non è stata osservata alcuna evidenza significativa di emissione puntiforme nella regione di cielo considerata.

Ricerca combinata delle sorgenti astrofisiche di neutrini con KM3NeT/ARCA e ANTARES

Una parte del lavoro di dottorato è stata dedicata alla ricerca di emissione di neutrini cosmici mediante una combinazione dei dati raccolti dagli esperimenti KM3NeT/ARCA e ANTARES.

ANTARES è il predecessore di KM3NeT. Si trattava di un telescopio per neutrini installato nel Mar Mediterraneo a una profondità di circa 2500 m e situato a circa 40 km dalla costa di Tolone (Francia), in prossimità del sito in cui è attualmente in costruzione KM3NeT/ORCA. Il rivelatore era costituito da 12 linee di rilevazione; su ciascuna linea erano installati 25 storey, ognuno equipaggiato con 3 moduli ottici contenenti un singolo fotomoltiplicatore (PMT). Il volume strumentato complessivo dell'esperimento era pari a circa 0.01 km^3 .

ANTARES è stato operativo per circa 16 anni, dal 2006 al 2022, anno in cui l'esperimento è stato dismesso, accumulando un totale di circa 4541 giorni di presa dati. Nel corso della sua attività, ANTARES ha realizzato diversi studi sul flusso di neutrini atmosferici e numerose ricerche dedicate alle sorgenti emettitrici di neutrini di alta energia.

L'obiettivo di questo studio consiste nel combinare i dati di ANTARES e KM3NeT/ARCA al fine di migliorare le prestazioni rispetto alle analisi standalone dei singoli esperimenti e ottenere risultati più sensibili nella ricerca di sorgenti cosmiche di neutrini.

In questa analisi è stato utilizzato l'intero dataset ARCA6-21, applicando ai campioni ARCA19-21 la selezione sviluppata in questo lavoro di dottorato. Per quanto riguarda il dataset di ANTARES, comprendente sia eventi di tipo traccia sia eventi di tipo sciame, è stata invece adottata la selezione utilizzata nell'ultima analisi per la ricerca di emissione di neutrini da sorgenti puntiformi condotta dalla collaborazione ANTARES. I dati combinati sono stati analizzati mediante il metodo di binned likelihood implementato per l'analoga ricerca effettuata con i soli dati di KM3NeT/ARCA.

Dal punto di vista delle prestazioni, il contributo dominante risulta essere quello di ANTARES, come atteso in virtù del tempo di acquisizione significativamente maggiore, circa sette volte superiore rispetto a quello del dataset KM3NeT/ARCA considerato. Tuttavia, la combinazione dei dati consente di ottenere un miglioramento delle prestazioni e dei risultati di circa il 20% rispetto all'analisi ANTARES standalone.

È stata investigata la compatibilità con un'emissione di neutrini proveniente da 107 sorgenti candidate, corrispondenti a quelle considerate nell'analisi di KM3NeT/ARCA, assumendo per il segnale uno spettro energetico di tipo power law con indice spettrale pari a 2.0.

La sorgente più significativa risulta essere il blazar gamma MG3 J225517+2409, con un p-value pre-trial pari a 0.00004, corrispondente a una significanza pre-trial di 3.9σ . Altri candidati di particolare interesse includono il blazar J0242+1101 (3.12σ pre-trial), la radiogalassia 3C 403 (3.02σ) e il blazar TXS 0506+056, associato all'evento IceCube IC-170922A, con una significanza pre-trial pari a 2.43σ .

Tutte queste sorgenti erano già state identificate nell'analisi standalone di ANTARES; tuttavia, la combinazione con i campioni ARCA porta ad un ulteriore incremento della significanza delle sorgenti. In particolare, il miglioramento è stimato essere dell'ordine del 12% per MG3 J225517+2409, del 30% per J0242+1101 e del 20% per TXS 0506+056.

Studio dell'emissione di neutrini da sorgenti galattiche di raggi gamma

Parte di questo lavoro di tesi è stata dedicata alla stima dell'emissione di neutrini a partire da informazioni provenienti da osservatori gamma.

Neutrini e raggi gamma sono prodotti congiuntamente nelle collisioni tra raggi cosmici, attraverso il decadimento di pioni e kaoni. In particolare, i mesoni neutri contribuiscono al flusso di raggi gamma, mentre quelli carichi danno origine al flusso di neutrini. Di conseguenza, ci si aspetta l'esistenza di una relazione tra lo spettro dei neutrini e quello dei raggi gamma.

Per derivare lo spettro dei neutrini a partire dallo spettro gamma osservato per una sorgente, è stato utilizzato come riferimento il modello teorico sviluppato da Villante e Vissani (2008), successivamente aggiornato da Mascaretti e Vissani (2019), basato su collisioni protone-protone. Secondo tale modello, lo spettro dei neutrini può essere ottenuto mediante una convoluzione dello spettro gamma con opportune funzioni kernel, derivate dagli spettri energetici dei neutrini prodotti

nei decadimenti dei mesoni nel sistema di riferimento del centro di massa.

Il principale vantaggio di questo approccio è la sua semplicità concettuale e la facilità di implementazione numerica. Il modello assume però che il flusso gamma osservato corrisponda al flusso emesso alla sorgente. In questa analisi, tale modello teorico è stato migliorato introducendo una correzione per l'assorbimento dei fotoni. Il flusso gamma osservato può infatti differire da quello emesso a causa dei processi di attenuazione dovuti alla produzione di coppie elettrone-positrone tra i fotoni della sorgente e quelli del fondo cosmico o del campo di radiazione interstellare.

Il flusso gamma osservato e quello alla sorgente sono quindi legati tramite un fattore di attenuazione che dipende dall'energia dei fotoni, dalla distanza della sorgente e dalla sua posizione. In questo lavoro, tale fattore è stato modellizzato utilizzando la parametrizzazione proposta da Lipari e Vernetto (2016).

Per questa analisi sono state considerate sorgenti presenti nel primo catalogo di LHAASO e nel terzo catalogo di HAWC, poiché tali cataloghi forniscono una stima dello spettro gamma in funzione dell'energia. L'esperimento LHAASO utilizza un modello a broken power-law, mentre nel catalogo HAWC gli spettri sono descritti mediante una semplice power-law. In entrambi i casi, i parametri dei modelli sono ottenuti tramite il fit dei dati osservati. In particolare, LHAASO utilizza i dati del WCDA per la parte a basse energie e i dati del KM2A per la componente ad alte energie.

L'elenco delle sorgenti utilizzate in questo lavoro è stato ottenuto a partire dal primo catalogo di LHAASO, selezionando le sorgenti osservate sia dal WCDA sia dal KM2A. Successivamente sono state incluse anche sorgenti dal terzo catalogo di HAWC. Poiché la stima dell'assorbimento richiede una conoscenza della distanza della sorgente, e né LHAASO né HAWC forniscono direttamente tale informazione, sono state selezionate solo sorgenti associate a oggetti astrofisici con distanza nota.

In totale sono state selezionate 26 sorgenti dal catalogo LHAASO e 6 sorgenti dal catalogo HAWC. Per ciascuna di esse, lo spettro dei neutrini in funzione dell'energia è stato stimato utilizzando il modello di Villante e Vissani, includendo la correzione per l'assorbimento tramite la parametrizzazione di Lipari e Vernetto.

Il dataset ARCA6-21 (con la selezione sviluppata in questo lavoro di dottorato) è stato analizzato mediante il metodo di binned likelihood per verificare la compatibilità con il segnale di neutrini derivato.

Per nessuna delle sorgenti è stato osservato un eccesso statisticamente significativo di eventi; sono quindi stati calcolati i limiti superiori dei flussi. Le sorgenti con i limiti più stringenti risultano essere 1LHAASO J1825-1418, 1LHAASO J1814-1719u*, 1LHAASO J1825-1337 e 3HWC J1849+001.

Per ogni sorgente, oltre alla analisi dei dati ARCA6-21, sono state stimate le prestazioni del rivelatore completo KM3NeT/ARCA230, utilizzando la sua simulazione più aggiornata.

Le prestazioni sono espresse in termini del tempo di osservazione necessario affinché il rivelatore possa raggiungere una significatività statistica di 3σ . Le sorgenti più promettenti sono quelle per cui il tempo di osservazione stimato

è inferiore a 20 anni, valore considerato realistico in confronto all'esperienza di IceCube (circa 16 anni di dati acquisiti). Le sorgenti più interessanti sono quelle osservabili in meno di 5 anni: 1LHAASO J1825-1418, 1LHAASO J1825-1337u, 1LHAASO J1814-1719u*, 3HWC J1849+001 e 1LHAASO J1809-1918u.

Commenti finali

I risultati della ricerca di un'emissione puntiforme con i dati ARCA6-21 mostrano un significativo miglioramento delle prestazioni rispetto all'analisi precedente basata sul dataset ARCA6-8. È quindi lecito attendersi un ulteriore incremento delle prestazioni man mano che nuove linee di rivelazione verranno installate e rese operative in KM3NeT/ARCA.

Inoltre, grazie all'analisi combinata, è ora possibile utilizzare congiuntamente i dati di ARCA e ANTARES, migliorando le prestazioni rispetto all'analisi standalone di ANTARES e aumentando la probabilità di ottenere osservazioni significative.

Infine, i risultati dello studio sull'emissione associata alle sorgenti di LHAASO e HAWC indicano che il rivelatore completo KM3NeT/ARCA sarà in grado di effettuare osservazioni significative dei meccanismi di emissione adronica delle sorgenti più promettenti.

In conclusione, con la continua espansione del rivelatore e l'accumulo progressivo di dati, KM3NeT/ARCA è destinato a fornire un contributo sempre più rilevante allo sviluppo della fisica astroparticellare nei prossimi anni.

Resumen

Física de astropartículas y astronomía de multi-mensajero

La física astroparticular nació en 1912 con el descubrimiento de los rayos cósmicos, cuando se observó el paso de partículas de origen extraterrestre a través de la atmósfera. Desde entonces, el estudio del Universo ya no se basa exclusivamente en la observación electromagnética tradicional, sino también en el uso de instrumentos y técnicas desarrollados en la física de partículas. Hoy en día, los rayos cósmicos, los rayos gamma y los neutrinos constituyen los principales mensajeros de alta energía del Universo y, junto con las ondas gravitatorias, proporcionan una visión complementaria de los fenómenos astrofísicos más extremos y de los mecanismos de aceleración de partículas más allá de las energías alcanzables en los aceleradores terrestres.

En la actualidad, se conoce bien la composición de los rayos cósmicos, formados principalmente por núcleos (en su mayoría protones), pero su origen sigue siendo una cuestión abierta. La identificación de sus fuentes es particularmente compleja debido a su naturaleza cargada: durante su propagación a través de los campos magnéticos galácticos e intergalácticos, sus trayectorias se desvían, lo que provoca la pérdida de la información direccional. Por esta razón, el estudio de los rayos cósmicos se centra principalmente en los espectros energéticos, la composición y las anisotropías a gran escala. Los rayos cósmicos con energías inferiores a aproximadamente 10 TeV pueden detectarse directamente mediante experimentos instalados en globos estratosféricos o satélites, como PAMELA, CALET, AMS y DAMPE. A energías superiores, sin embargo, el flujo de partículas es demasiado bajo para permitir mediciones directas eficientes, y los rayos cósmicos se estudian de forma indirecta mediante experimentos terrestres que forman un arreglo de detectores, que observan las cascadas atmosféricas producidas por la interacción del rayo cósmico primario con la atmósfera terrestre. Estos detectores reconstruyen las propiedades de la partícula primaria a partir de la observación de las distintas componentes de la cascada, en particular la hadrónica, electromagnética y muónica. Ejemplos de este tipo de arreglos son Tunka, GRAPES, HAWC y LHAASO. A medida que aumenta la energía, el flujo de rayos cósmicos disminuye drásticamente, lo que hace necesarios detectores que cubran superfi-

cies muy extensas para el estudio de los rayos cósmicos de ultra alta energía (por encima de 100 PeV), como los observatorios Pierre Auger y Telescope Array.

Las mediciones realizadas por el Observatorio Pierre Auger han evidenciado una anisotropía dipolar significativa para energías superiores a 8 EeV, orientada aproximadamente 115° en dirección opuesta al Centro Galáctico y compatible con un origen extragaláctico de los rayos cósmicos de ultra alta energía. A energías más bajas, en cambio, la distribución casi isotrópica sugiere que la mayor parte de los rayos cósmicos hasta la región de la "rodilla" se producen dentro de la Vía Láctea, con una transición progresiva hacia fuentes extragalácticas en la región del "tobillo".

Para identificar las fuentes de los rayos cósmicos es, por tanto, necesario recurrir a otros mensajeros astrofísicos eléctricamente neutros, producidos durante los procesos de aceleración y propagación: los rayos gamma y los neutrinos. A diferencia de los rayos cósmicos, los rayos gamma no sufren desviaciones magnéticas y viajan en línea recta desde su lugar de producción, lo que permite localizar directamente sus fuentes. Los rayos gamma de alta y muy alta energía pueden producirse tanto mediante procesos leptónicos como hadrónicos; estos últimos están directamente asociados a la aceleración de rayos cósmicos. En particular, la observación de fotones a energías cada vez más altas tiende a favorecer escenarios de producción hadrónica. Sin embargo, la observación gamma por sí sola no siempre permite discriminar de forma unívoca entre los distintos mecanismos de producción y, además, los fotones de muy alta energía pueden ser absorbidos durante su propagación.

En las últimas décadas, los satélites como Fermi-LAT, AGILE y DAMPE han observado cientos de fuentes hasta energías del orden de cientos de GeV, mientras que instrumentos terrestres como H.E.S.S., MAGIC y VERITAS han extendido estas mediciones al régimen de los TeVs. Más recientemente, arreglos de detectores como HAWC, LHAASO y Tibet AS-gamma han identificado fuentes capaces de emitir fotones hasta energías del orden del PeV, inaugurando la astronomía gamma de ultra alta energía y proporcionando evidencias clave de la existencia de aceleradores galácticos extremos, los denominados "PeVatrones".

Los neutrinos representan un mensajero complementario y único. Al interactuar únicamente mediante la interacción débil, pueden atravesar materia y campos magnéticos casi sin perturbación, transportando información desde las regiones más densas y remotas del Universo prácticamente sin alterar. Además, a diferencia de los rayos gamma, los neutrinos de alta energía se producen exclusivamente en procesos hadrónicos, constituyendo así una prueba directa de la aceleración de hadrones en las fuentes astrofísicas. Sin embargo, su extremadamente baja probabilidad de interacción hace que su detección sea muy difícil, requiriendo detectores de escala kilométrica instalados en medios transparentes como el hielo o el agua, como es el caso de los telescopios de neutrinos.

Los telescopios de neutrinos se basan en la observación de la radiación Cherenkov inducida por las partículas cargadas producidas en las interacciones de los neutrinos con el medio circundante. En 2013, el experimento IceCube, instalado en el hielo del Polo Sur y con un volumen instrumentado de aproximadamente

1 km³, observó por primera vez un flujo difuso de neutrinos de origen astrofísico, marcando el inicio de la astronomía de neutrinos. Posteriormente, la asociación de un neutrino de alta energía con el blazar TXS 0506+056 y la identificación de una emisión persistente de la galaxia activa NGC 1068 confirmaron el papel de los neutrinos como sondas únicas de procesos hadrónicos en fuentes cósmicas.

Más recientemente, la colaboración KM3NeT ha reportado la detección de un evento de neutrino de ultra alta energía, con una energía estimada preliminarmente en el rango de cientos de PeV, lo que destaca el potencial de la nueva generación de detectores para explorar los regímenes de aceleración más extremos y buscar neutrinos cosmogénicos. En este contexto se sitúa KM3NeT, un telescopio de neutrinos actualmente en construcción en las profundidades del mar Mediterráneo. El proyecto está compuesto por dos detectores complementarios: ORCA, dedicado al estudio de neutrinos atmosféricos y de las propiedades fundamentales del neutrino, y ARCA, diseñado para la astronomía de neutrinos de alta energía.

En conjunto, todas estas observaciones constituyen el fundamento de la astronomía de multimensajero, complementada por el estudio de las ondas gravitatorias. La combinación de la información proveniente de los rayos cósmicos, los rayos gamma y los neutrinos permite investigar el origen de los aceleradores cósmicos y comprender los mecanismos físicos responsables de los fenómenos más energéticos del Universo.

Telescopio de neutrinos y KM3NeT/ARCA

Esta tesis se centra en la astronomía de neutrinos y se desarrolla en el marco del experimento KM3NeT, en particular del detector KM3NeT/ARCA, actualmente en construcción a una profundidad de aproximadamente 3500 m en el mar Mediterráneo, a unos 100 km de la costa de Capo Passero (Sicilia, Italia) .

En su configuración final, KM3NeT/ARCA instrumentará un volumen de aproximadamente un kilómetro cúbico de agua mediante dos grandes matrices de fotomultiplicadores, denominadas "bloques de construcción". Cada bloque estará compuesto por 115 líneas de detección, cada una equipada con 18 módulos ópticos. Cada módulo óptico consiste en una esfera de vidrio resistente a la presión de las profundidades marinas que contiene 31 tubos fotomultiplicadores, diseñados para detectar la luz Cherenkov inducida por las partículas secundarias generadas en las interacciones de los neutrinos.

Un neutrino muónico que interactúa mediante un proceso de corriente cargada (Charged Current) dentro o cerca del detector produce muones de alta energía, capaces de recorrer distancias del orden del kilómetro e inducir la emisión de luz Cherenkov a lo largo de su trayectoria. Para este tipo de evento, la señal Cherenkov reconstruida por los fotomultiplicadores aparece como una traza debido a su geometría alargada. Este tipo de eventos permite reconstruir la dirección de llegada con alta precisión, alcanzando resoluciones angulares del orden de 0.1° o incluso menores. Esta propiedad es fundamental para la localización de fuentes de neutrinos y, en consecuencia, para la identificación de fuentes de rayos

cósmicos.

El otro tipo de señal Cherenkov observada en telescopios de neutrinos es inducida por cascadas hadrónicas y electromagnéticas. Estos eventos se producen principalmente en interacciones de corriente cargada de neutrinos electrónicos y en interacciones de corriente neutra de todos los sabores de neutrinos. Dado que la extensión espacial de una cascada (generalmente inferior a 10 m) es menor que la distancia entre los módulos ópticos, la señal Cherenkov asociada aparece como puntual, y su resolución angular es peor que la de los eventos tipo traza. Por este motivo, el canal de trazas constituye el principal canal para los estudios de astronomía de neutrinos. Sin embargo, los eventos tipo cascada permiten una reconstrucción más precisa de la energía del evento, ya que la luz Cherenkov está completamente contenida dentro del detector.

Actualmente, aproximadamente el 20% del detector KM3NeT/ARCA está instalado y operativo en el fondo marino. En este trabajo de tesis se han analizado los primeros 640 días de datos recogidos por el experimento con el objetivo de investigar su compatibilidad con la emisión de neutrinos provenientes de fuentes puntuales. Los datos analizados corresponden a eventos tipo traza registrados por ARCA entre mayo de 2021 y septiembre de 2023, desde la configuración de 6 líneas (ARCA6) hasta la de 21 líneas (ARCA21). En particular, en este trabajo se describe el procedimiento de selección de eventos desarrollado para los conjuntos de datos adquiridos en las configuraciones de 19 y 21 unidades de detección (ARCA19 y ARCA21).

En general, la mayoría de los eventos detectados por los telescopios de neutrinos está constituida por muones y neutrinos atmosféricos. Estos eventos se producen en las interacciones de los rayos cósmicos con la atmósfera terrestre y constituyen, por tanto, un fondo en la búsqueda de neutrinos astrofísicos de alta energía.

En particular, los muones de alta energía emiten inmediatamente luz Cherenkov al entrar en el agua o el hielo, y su gran poder de penetración—solo superado por el de los neutrinos—les permite alcanzar el detector incluso cuando se producen a gran distancia por encima de él. Los muones constituyen así la gran mayoría de los eventos registrados por un telescopio de neutrinos. Sin embargo, al ser partículas cargadas, están sujetos a pérdidas de energía debidas principalmente a procesos de ionización (con contribuciones radiativas adicionales a energías más altas). Como consecuencia, existe un límite en la distancia que pueden recorrer en el medio, mientras que los neutrinos pueden atravesar la Tierra completamente sin una atenuación significativa. Los muones, en cambio, pierden energía a lo largo de su trayectoria y pueden decaer antes de alcanzar el detector.

Por este motivo, en el análisis de eventos tipo traza se aplica una selección basada en la dirección reconstruida, con el fin de favorecer partículas que hayan atravesado la Tierra o parte de su corteza. En general, este criterio selecciona eventos con ángulos cenitales próximos o inferiores al horizonte (eventos up-going), típicamente hasta unos 10° por encima del horizonte. Sin embargo, muones mal reconstruidos pueden superar esta selección y, debido a su gran abundancia, seguir constituyendo un fondo relevante.

En cuanto al fondo de neutrinos atmosféricos, la discriminación respecto a los neutrinos astrofísicos de alta energía se basa en métodos probabilísticos y estadísticos. Se espera que los eventos astrofísicos dominen a altas energías (típicamente ≥ 100 TeV). Además, en el caso de fuentes puntuales, las direcciones reconstruidas de los eventos astrofísicos tienden a estar espacialmente correlacionadas con la posición de la fuente, mientras que la distribución de los eventos atmosféricos es aproximadamente isotrópica, es decir, uniforme respecto a la dirección.

Selección de eventos para KM3NeT/ARCA

La selección de eventos presentada en esta tesis tiene como objetivo reducir la contaminación debida a los muones atmosféricos, en muestras de ARCA19-21; con este fin, se han aplicado criterios adicionales de calidad a los eventos reconstruidos. En particular, las variables utilizadas para la selección incluyen la energía reconstruida, el error angular de la traza, la longitud de la traza y el valor de la likelihood obtenidos de la reconstrucción de los eventos. Además de estas variables, también se ha empleado un algoritmo de boosted decision tree (BDT). Se han considerado diferentes configuraciones de selección con el objetivo de suprimir la contribución de los muones atmosféricos, especialmente a altas energías.

En general, la estimación de la contaminación de muones atmosféricos se realiza mediante simulaciones Monte Carlo. Esta contaminación se define como la razón entre el número de muones atmosféricos simulados y el número total de eventos Monte Carlo ponderados que sobreviven a los criterios de selección, asegurando al mismo tiempo que la contribución de los muones esté fuertemente suprimida a altas energías. La razón entre muones y eventos totales se calcula utilizando los pesos de los eventos. Dado que muones y neutrinos están caracterizados por pesos diferentes, esta razón no corresponde a la simple fracción de eventos simulados, sino que representa la contribución relativa ponderada de las distintas componentes.

Para determinar la selección óptima de eventos para el análisis, se han calculado la sensibilidad y el potencial de descubrimiento para cada una de las selecciones consideradas. El potencial de descubrimiento representa el flujo mínimo capaz de producir una observación estadísticamente significativa con una determinada probabilidad de éxito (fijada en el 50% en este trabajo), mientras que la sensibilidad corresponde al flujo que puede excluirse a un determinado nivel de confianza (90% en este trabajo) en ausencia de una señal significativa. Estas cantidades se han calculado para distintos valores de declinación, asumiendo para la señal astrofísica un espectro tipo ley de potencias con índice espectral igual a 2.0. Entre las configuraciones analizadas, se ha seleccionado aquella que proporciona el mejor compromiso entre una baja contaminación de muones atmosféricos y una mejora en el potencial de descubrimiento.

Para la selección final de eventos, la contaminación de muones atmosféricos en el conjunto de datos ARCA19-21 se estima en un 15%. Para esta configuración

también se han evaluado las prestaciones del detector en términos de área efectiva, point spread function y resolución energética. El área efectiva se define como la cantidad que, multiplicada por el flujo incidente de neutrinos, proporciona el número esperado de eventos detectados, mientras que la función de dispersión de punto (PSF, por sus siglas en inglés) describe el rendimiento de reconstrucción angular del detector. Esta se define como la densidad de probabilidad de reconstruir un evento a una determinada distancia angular respecto a la dirección real de la partícula incidente, por unidad de ángulo sólido.

Búsqueda de fuentes de neutrinos cósmicos con 6-21 líneas de KM3NeT/ARCA

El conjunto de datos completo ARCA6-21 ha sido analizado con el objetivo de investigar la posible emisión de neutrinos procedentes de fuentes puntuales. Mientras que para los eventos registrados en las configuraciones ARCA19-21 se ha aplicado la selección desarrollada en este trabajo, los datos adquiridos en las configuraciones ARCA6 y ARCA8 ya habían sido analizados previamente en un estudio de naturaleza similar. Por lo tanto, para estas muestras se ha mantenido la selección utilizada en el análisis anterior.

La búsqueda de una señal de neutrinos astrofísicos se basa en un método de máxima verosimilitud. Para cada fuente candidata, identificada por su ascensión recta y declinación, se define una región circular de interés alrededor de la posición de la fuente y se consideran únicamente los eventos contenidos en dicha región. En este trabajo se utiliza una región circular con un radio de 5° para cada fuente candidata. Se calcula un test estadístico basado en la prueba de razón de verosimilitud para cuantificar un posible exceso de señal de neutrinos cósmicos sobre el fondo, asumiendo estadística de Poisson. Este test estadístico se evalúa a partir de las distribuciones esperadas de señal y fondo. Las expectativas de señal y fondo se describen mediante histogramas bidimensionales en función de la energía reconstruida y de la distancia angular respecto a la dirección de la fuente.

El histograma de fondo se obtiene mediante un enfoque basado en datos, en el cual las distribuciones del fondo en energía y declinación se estiman directamente a partir de los datos. El histograma de señal, en cambio, se calcula suponiendo un espectro energético de neutrinos dado y convolucionándolo con el área efectiva del detector, la PSF y la resolución energética. La emisión de neutrinos se modela mediante un espectro de ley de potencias, considerando tres valores del índice espectral: 2.0, 2.5 y 3.2.

El conjunto completo de datos ARCA6-21 (640 días) ha sido analizado en la búsqueda de una posible señal procedente de 106 fuentes astrofísicas candidatas a la emisión de neutrinos. Estas fuentes han sido seleccionadas entre los candidatos más prometedores considerados en análisis previos de telescopios de neutrinos (IceCube, ANTARES) y de catálogos de observatorios gamma que reportan emisiones de muy alta energía y/o alta intensidad.

Además de la búsqueda dirigida a fuentes candidatas, el método de verosimilitud también se ha aplicado a un análisis de todo el cielo, en el que se considera un gran conjunto de coordenadas que cubre una amplia región de la esfera celeste. La cuadrícula de coordenadas está compuesta por aproximadamente 2 millones de puntos, con declinaciones entre -90° y 40° , rango en el cual la visibilidad de KM3NeT/ARCA se estima superior al 35%. Las coordenadas han sido generadas mediante el *software* HEALPix, con una resolución angular de $0.1^\circ \times 0.1^\circ$.

No se ha observado ningún exceso estadísticamente significativo para ninguna de las fuentes consideradas; por lo tanto, se han determinado límites superiores sobre los flujos de neutrinos y los correspondientes p-values.

Para un espectro de señal con índice espectral igual a 2.0, la fuente más significativa es la galaxia Seyfert CGCG 420-015, con un p-value local de 0.0064 y un p-value global de 0.325, correspondiente a una significancia de 0.45σ . Para esta fuente, el límite superior del flujo se estima en $5.4 \times 10^{-8}, \text{GeV}^{-1}, \text{cm}^{-2}, \text{s}^{-1}$.

Para un índice espectral de 2.5, el valor mínimo del p-value local (0.0038) se obtiene para el blázar Mkn 421, para el cual el p-value global es 0.4, correspondiente a una significancia de 0.2σ . El límite superior del flujo se estima en $2.3 \times 10^{-5}, \text{GeV}^{-1}, \text{cm}^{-2}, \text{s}^{-1}$.

Para un índice espectral de 3.2, se considera únicamente la fuente NGC 1068, ya que es la única para la cual IceCube ha observado un espectro compatible con esta hipótesis. Para este candidato, el p-value obtenido es 0.98, no significativo; en este caso, los p-values local y global coinciden, ya que se considera una única fuente. El límite superior del flujo es $3.86 \times 10^{-3}, \text{GeV}^{-1}, \text{cm}^{-2}, \text{s}^{-1}$.

En cuanto al análisis all-sky, no se ha encontrado evidencia significativa de emisión de neutrinos. Las coordenadas que presentan el menor p-value corresponden a una declinación de -71.3° y una ascensión recta de 310.4° . Para estas coordenadas se obtiene un p-value local de 0.0000669, mientras que el p-value global se estima en 0.88, consistente con una fluctuación estadística del fondo.

Investigaciones adicionales basadas en el análisis de fuentes puntuales

Además de la búsqueda de fuentes puntuales, en esta tesis se describen tres análisis adicionales desarrollados en el marco del proyecto de doctorado. Los tres estudios se basan en el conjunto de datos ARCA6-21, correspondiente a 640 días de toma de datos. Además, los métodos de análisis empleados derivan directamente del enfoque de verosimilitud utilizado en el análisis de fuentes puntuales.

La búsqueda de una fuente cósmica puntual de neutrinos procedente de la dirección del evento KM3-230213A

El 13 de febrero de 2023, un muón de muy alta energía fue observado por el detector KM3NeT/ARCA, con 21 líneas operativas. La energía y la dirección reconstruidas del evento, denominado KM3-230213A, son tales que la probabilidad

de que su origen esté asociado al fondo de muones y neutrinos atmosféricos es despreciable. Por lo tanto, la hipótesis más plausible es que el evento haya sido producido por un neutrino astrofísico de ultra alta energía.

La colaboración KM3NeT ha llevado a cabo varios análisis para investigar el posible origen del evento. En el marco de este trabajo de doctorado, se ha desarrollado un análisis dedicado basado en un escaneo de una región limitada del cielo alrededor de la dirección reconstruida del evento, con el objetivo de buscar posibles evidencias de emisión puntual de neutrinos.

A partir de las coordenadas reconstruidas del evento, correspondientes a una declinación de -7.8° y una ascensión recta de 94.3° , se ha definido una región celeste con declinación comprendida entre -10.8° y -4.8° y ascensión recta entre 91.3° y 97.3° . De esta manera, se obtiene una ventana cuadrada de lado 6° centrada alrededor de la dirección del evento KM3-230213A. El conjunto de puntos utilizado para el escaneo fue generado mediante el software HEALPix, adoptando una resolución angular de $0.1^\circ \times 0.1^\circ$.

El conjunto completo de datos ARCA6-21 ha sido analizado mediante el método de verosimilitud con el fin de buscar un posible exceso de eventos de señal a energías inferiores a la de KM3-230213A. Para garantizar una búsqueda unbiased, el evento KM3-230213A fue eliminado de la muestra ARCA21 utilizada en el análisis. Para la modelización de la señal se asumió un espectro de tipo ley de potencias con índice espectral igual a 2.0.

Para las muestras ARCA19-21, dado que todavía no estaba disponible una variable BDT, la selección de eventos se realizó aplicando un corte sobre la longitud de la traza reconstruida.

Para el conjunto completo de datos, el intervalo energético que contiene el 90% de la señal esperada se estima entre 785 GeV y 1.064 PeV. Estos valores se obtienen asumiendo una fuente puntual localizada en la declinación reconstruida del evento KM3-230213A y el espectro energético considerado.

Dentro de la región del cielo analizada, el píxel más significativo se encontró en una declinación de -9.3° y una ascensión recta de 97.3° , con un p-value local de 0.0064. Restringiendo el análisis a los píxeles situados dentro de una distancia angular de 3° respecto a la dirección reconstruida de KM3-230213A, el punto más significativo (con un p-value local de 0.05) corresponde a una declinación de -6.8° y una ascensión recta de 96.7° . Para este punto, el p-value global se estima en 0.44, correspondiente a una significancia de aproximadamente 0.15σ . Por lo tanto, no se ha observado ninguna evidencia significativa de emisión puntual de neutrinos en la región celeste considerada.

Búsqueda conjunta de fuentes de neutrinos cósmicos con KM3NeT/ARCA y ANTARES

Parte de este trabajo de doctorado ha estado dedicada a la búsqueda de emisión de neutrinos cósmicos mediante un análisis combinado de los datos recopilados por los experimentos KM3NeT/ARCA y ANTARES.

ANTARES fue el predecesor de KM3NeT. Se trataba de un telescopio de neu-

trinos instalado en el mar Mediterráneo a una profundidad de aproximadamente 2500 m y situado a unos 40 km de la costa de Tolón (Francia), cerca del sitio donde actualmente se está construyendo KM3NeT/ORCA. El detector estaba compuesto por 12 líneas de detección; cada línea contenía 25 storeys, cada uno equipado con 3 módulos ópticos con un único tubo fotomultiplicador (PMT). El volumen instrumentado total del experimento era de aproximadamente 0.01 km³.

ANTARES estuvo operativo durante aproximadamente 16 años, desde 2006 hasta 2022, año en el que el experimento fue desmantelado, acumulando alrededor de 4541 días de toma de datos. Durante su funcionamiento, ANTARES llevó a cabo diversos estudios sobre el flujo de neutrinos atmosféricos y numerosas búsquedas de emisión de neutrinos astrofísicos de alta energía.

El objetivo de este estudio consiste en combinar los datos de ANTARES y KM3NeT/ARCA con el fin de mejorar las prestaciones respecto a los análisis independiente de cada experimento y obtener resultados más sensibles en la búsqueda de fuentes cósmicas de neutrinos.

En este análisis se ha utilizado el conjunto completo de datos ARCA6-21, aplicando a las muestras ARCA19-21 la selección de eventos desarrollada en este trabajo de doctorado. Para el conjunto de datos de ANTARES, que incluye tanto eventos de tipo traza como eventos de tipo cascada, se ha utilizado la selección adoptada en la última búsqueda de emisión de neutrinos de fuentes puntuales realizada por la colaboración ANTARES. Los datos combinados se han analizado mediante el método de verosimilitud implementado para la búsqueda análoga realizada únicamente con datos de KM3NeT/ARCA.

Desde el punto de vista de las prestaciones, la contribución dominante corresponde al conjunto de datos de ANTARES, como era esperado debido a su tiempo de adquisición significativamente mayor, aproximadamente siete veces superior al del conjunto de datos de KM3NeT/ARCA considerado. Sin embargo, la combinación de los datos permite obtener una mejora en las prestaciones y en los resultados de aproximadamente un 20% respecto al análisis independiente de ANTARES.

Se ha investigado la compatibilidad con una emisión de neutrinos procedente de 107 fuentes candidatas, correspondientes a las consideradas en el análisis de KM3NeT/ARCA, asumiendo para la señal un espectro energético de tipo power law con índice espectral igual a 2.0.

La fuente más significativa resulta ser el blázar gamma MG3 J225517+2409, con un p-value local de 4×10^{-5} , correspondiente a una significancia local de 3.9σ . Otros candidatos de especial interés incluyen el blázar J0242+1101 (3.12σ local), la radiogalaxia 3C 403 (3.02σ) y el blázar TXS 0506+056, asociado al evento de IceCube IC-170922A, con una significancia local de 2.43σ .

Todas estas fuentes ya habían sido identificadas en el análisis independiente de ANTARES; sin embargo, la combinación con las muestras ARCA conduce a un incremento adicional de la significancia de las fuentes. En particular, la mejora se estima en aproximadamente un 12% para MG3 J225517+2409, un 30% para J0242+1101 y un 20% para TXS 0506+056.

Estudio de la emisión de neutrinos procedente de fuentes galácticas de rayos gamma con KM3NeT/ARCA

Parte de este trabajo de tesis ha estado dedicada a la estimación de la emisión de neutrinos utilizando información procedente de observatorios gamma. Los neutrinos y los rayos gamma se producen conjuntamente en las colisiones de rayos cósmicos mediante el decaimiento de piones y kaones. En particular, los mesones neutros contribuyen al flujo de rayos gamma, mientras que los mesones cargados dan lugar al flujo de neutrinos. Por lo tanto, se espera una relación entre los espectros de neutrinos y de rayos gamma.

Para derivar el espectro de neutrinos a partir del espectro gamma observado de una fuente, se ha utilizado el modelo teórico desarrollado por Villante y Vissani (2008), posteriormente actualizado por Mascaretti y Vissani (2019), basado en interacciones protón-protón. Según este modelo, el espectro de neutrinos puede obtenerse como una convolución del espectro gamma con funciones kernel derivadas de los espectros energéticos de neutrinos producidos en los decaimientos de mesones en el sistema de referencia del centro de masas.

La principal ventaja de este modelo es su simplicidad conceptual y su fácil implementación computacional. El modelo asume que el flujo gamma observado corresponde al flujo emitido en la fuente. En este análisis, esta hipótesis se ha extendido incorporando una corrección por absorción de fotones. El flujo gamma observado puede diferir del emitido debido a procesos de atenuación por producción de pares electrón-positrón entre los fotones de la fuente y la radiación de fondo cósmico o el campo de radiación interestelar.

El espectro gamma observado y el intrínseco están relacionados mediante un factor de atenuación que depende de la energía de los fotones, la distancia de la fuente y su posición. En este trabajo, dicho factor se ha modelado utilizando la parametrización propuesta por Lipari y Vernetto (2016).

Para este análisis se han considerado fuentes del primer catálogo de LHAASO y del tercer catálogo de HAWC, ya que proporcionan estimaciones del espectro gamma en función de la energía. LHAASO utiliza un modelo de ley de potencias quebrada, mientras que HAWC adopta un modelo de ley de potencias simple. En ambos casos, los parámetros se obtienen mediante ajustes a los datos observacionales. En particular, LHAASO utiliza datos del WCDA para la parte de bajas energías y del KM2A para la componente de altas energías.

La lista de fuentes utilizada en este trabajo se ha obtenido a partir del primer catálogo de LHAASO, seleccionando fuentes detectadas tanto por WCDA como por KM2A. Además, se han incluido fuentes del tercer catálogo de HAWC. Dado que la modelización de la absorción requiere conocer la distancia de la fuente, y ni LHAASO ni HAWC proporcionan esta información directamente, solo se han seleccionado fuentes asociadas a objetos con distancia conocida.

En total se han seleccionado 26 fuentes de LHAASO y 6 de HAWC. Para cada una de ellas, el espectro de neutrinos en función de la energía ha sido estimado utilizando el modelo de Villante y Vissani, incluyendo la corrección por absorción mediante la parametrización de Lipari y Vernetto.

El conjunto de datos ARCA6-21 (con la selección desarrollada en este trabajo de doctorado) ha sido analizado mediante el método de verosimilitud para comprobar la compatibilidad con la señal de neutrinos derivada.

No se ha observado ningún exceso estadísticamente significativo para ninguna fuente, por lo que se han derivado límites superiores del flujo. Las fuentes más restrictivas son 1LHAASO J1825-1418, 1LHAASO J1814-1719u*, 1LHAASO J1825-1337 y 3HWC J1849+001.

Para cada fuente, además del análisis de los datos ARCA6-21, se estimó el rendimiento del detector completo KM3NeT/ARCA230 utilizando su simulación más reciente.

El rendimiento se expresa en términos del tiempo de observación necesario para alcanzar una significancia de descubrimiento de 3σ . Las fuentes más prometedoras para el detector completo son aquellas con un tiempo de observación inferior a 20 años, un valor realista considerando los aproximadamente 16 años de exposición de IceCube. Las fuentes más interesantes son aquellas para las que KM3NeT/ARCA puede lograr una detección significativa en menos de 5 años: 1LHAASO J1825-1418, 1LHAASO J1825-1337u, 1LHAASO J1814-1719u*, 3HWC J1849+001 y 1LHAASO J1809-1918u.

Reflexiones finales

Los resultados de la búsqueda de fuentes puntuales con los datos ARCA6-21 muestran una mejora significativa del rendimiento respecto al análisis anterior basado en el conjunto ARCA6-8. Por lo tanto, se espera una mejora adicional a medida que se instalen y entren en operación nuevas líneas de detección en KM3NeT/ARCA.

Además, gracias al análisis combinado, ahora es posible utilizar conjuntamente los datos de ARCA y ANTARES, mejorando el rendimiento respecto al análisis independiente de ANTARES y aumentando la probabilidad de obtener una detección significativa.

Finalmente, los resultados del estudio sobre la emisión de fuentes gamma indican que el detector completo KM3NeT/ARCA será capaz de realizar observaciones significativas de los mecanismos de emisión hadrónica en las fuentes más prometedoras.

En conclusión, con la expansión continua del detector y la acumulación progresiva de datos, KM3NeT/ARCA está destinado a realizar una contribución importante al desarrollo de la física de astropartículas en los próximos años.