Prospective IN2P3 GT04 : Multi-messenger neutrino analyses

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I. Context

Time-domain astronomy has received a considerable boost in recent years due to its ability to study extreme physics, to track cataclysmic phenomena like the birth of stellar mass black holes or the mergers of neutron stars, to probe distant regions of the Universe, and to identify candidate sources for multi-messenger astrophysics. These explosive events can release enormous amounts of energy both in electromagnetic radiation and in non-electromagnetic forms such as neutrinos and gravitational waves. They lie at the frontier of our understanding of the laws of physics under the most extreme conditions.

Multi-messenger astronomy – the observation of astrophysical objects and processes using combinations of different messengers such as electromagnetic radiation, neutrinos, cosmic rays and gravitational waves – has emerged as a major new field in astronomy during the last years. Major breakthroughs were the first observed coincidence of gravitational waves and electromagnetic signals over a huge wavelength regime from a merger of two neutron stars [1] and the detection of gamma rays and neutrinos from a flaring blazar [2]. Also, the identification of a PeV accelerator ("PeVatron") in the centre of our Galaxy by the H.E.S.S. gamma-ray telescope [3] is remarkable in this context since it represents a major step forward in linking gamma-ray observations to Galactic cosmic rays. Multi-messenger astronomy employs both spatial and time correlations between different observations and therefore particularly targets transient phenomena; it thus belongs to the field of time-domain astronomy. Significant efforts are dedicated to this domain, with specialised robotic telescopes, instruments with wide fields of view (e.g. neutrino telescopes and cosmic-ray observatories) and satellite-borne instruments scanning large portions of the sky in short cycles. The recent first observation of sub-TeV gamma-rays from a gamma-ray burst (GRB) by MAGIC [4] demonstrates the far-reaching potential of coordinated observations for time-domain astronomy.

Neutrino astronomy allows us to study the most energetic non-thermal sources in the Universe. Despite observations of cosmic rays up to ultra-high energies and observations of γ-rays and astrophysical neutrinos, we do not yet know where or how these particles are accelerated. Neutrino astronomy is clearly a key to directly answer this question. Astrophysical neutrinos provide insight into source characteristics not accessible through the observation of other messengers. Due to their low cross sections, neutrinos can escape dense astrophysical environments that are opaque to photons. In contrast to γ-rays, neutrinos travel through the Universe almost without interactions, allowing direct observation of their sources at high redshifts with sub-degree-scale pointing. Unlike cosmic rays, neutrinos are not deflected in magnetic fields and can be observed in spatial and temporal coincidence with photons and gravitational waves, which is a key prerequisite to reap the scientific rewards of multi-messenger astronomy. In addition, neutrinos come in different flavors: electron, muon, and tau neutrinos (ν_e, ν_μ, & ν_τ), and the flavor ratios observed at Earth give insight into the environment of cosmic-ray sources.

The last decade is marked by the IceCube at the South Pole results in high-energy neutrino astronomy, with the discovery of an astrophysical neutrino flux in the 10 TeV – 10 PeV energy range. Up to now, the arrival directions of the most energetic neutrinos seem to be consistent with a uniform distribution across the sky. Neutrino emission at the observed flux level has been predicted from a variety of source classes, including γ-ray bursts, blazars, starburst galaxies, galaxy clusters, and others. Recently, coincident observations of neutrinos and γ-rays from the blazar TXS 0506+056 present evidence of the first extragalactic neutrino source. However, this cannot be the entire story: multiple independent analyses indicate that only a fraction of the diffuse neutrino flux can come from γ-ray blazars.

In the coming years, a second neutrino telescope with similar sensitivity will be constructed in the Mediterranean Sea: KM3NeT, with one densely instrumented detector for lower neutrino energies (ORCA, neutrino energies ranging from few GeV to ~10 TeV) and one larger detector for higher energies (ARCA, few 100 GeV to beyond PeV). Both detectors are based on the same technology: the Cherenkov light induced by charged secondary particles emerging from neutrino interactions is detected using a three-dimensional deep-sea grid of photo-sensors with single-photon sensitivity and nanosecond time resolution. One building block of KM3NeT will host 115 vertical detection lines with 18 digital optical modules each, where each module is equipped with 31 3-inch photomultiplier tubes. All data above noise threshold are sent to shore via optical fibers and are filtered for event signatures in an online computer cluster (see [6] for more details). ORCA will comprise one building block with an instrumented volume of 8 Mtons of water, ARCA will consist of two building blocks, together covering one cubic kilometer. Both detectors are already collecting data with first detection units and will reach significant sensitivities for the detection of cosmic neutrinos during the project duration, by far surpassing other neutrino telescopes in the Northern hemisphere. We are currently working so that **KM3NeT will enter into the global network of multi-messenger observations by performing analysis with KM3NeT data, in particular targeting transient events such as GRBs, flaring active galactic nuclei (AGN) or mergers of compact objects (black holes, neutron stars).** Due to KM3NeT's geographic location and its excellent pointing resolution [6] these studies will be of unprecedented sensitivity for neutrino signals from a field of view complementing that of IceCube. In particular, KM3NeT has an excellent view of the galactic centre/plane. Partners of KM3NeT in the global multi-messenger network are IceCube, the gravitational wave detectors LIGO/Virgo, and a large set of telescopes, observing electromagnetic radiation from radio to gamma rays.

Real-time multi-messenger campaigns, in collaboration with multi-wavelength (radio to γ-ray) and gravitational wave astronomers, could prove crucial in unveiling the sources of the most energetic particles and the acceleration mechanisms at work. Neutrinos would provide insights into the physics of stellar explosions, compact object mergers, and relativistic jets, as well as particle acceleration processes. The main requirement for these multi-messenger studies is the quasi-online communication of potentially interesting observations to partner instruments ("alerts"), with latencies of a few minutes, at most. Such alerts are the only way to achieve simultaneous observations of transient phenomena by pointing instruments.

In the next decade, the main challenge will be to identify and characterize the population of sources of high-energy neutrinos. To solve this challenge, we will need to work on two main axes: obtaining high statistics to be able to perform precision measurements of the diffuse neutrino spectrum and having high-resolution neutrino data from observatories with deep exposure and wide sky coverage. As said before, introducing time-dependent combined observations of these neutrinos and other cosmic messengers will provide optimal strategies of identifying these sources. Up to now, only one neutrino source candidate has been identified. The current lack of established neutrino point sources — despite a firm detection of a diffuse neutrino flux — indicates a dominant population of low-luminosity extragalactic sources. For example, with the current knowledge of the hadronic interaction models, we can exclude a dominant contribution of highly energetic blazars and gamma-ray bursts. Source populations either with sufficiently large local densities — like starburst galaxies, galaxy clusters, low-luminosity AGN, radio-quiet AGN or star-forming galaxies with AGN outflows — or with high local rate densities — like (extragalactic) jet-powered SNe including hypernovae and interaction-powered SNe — are presently consistent with the observations.

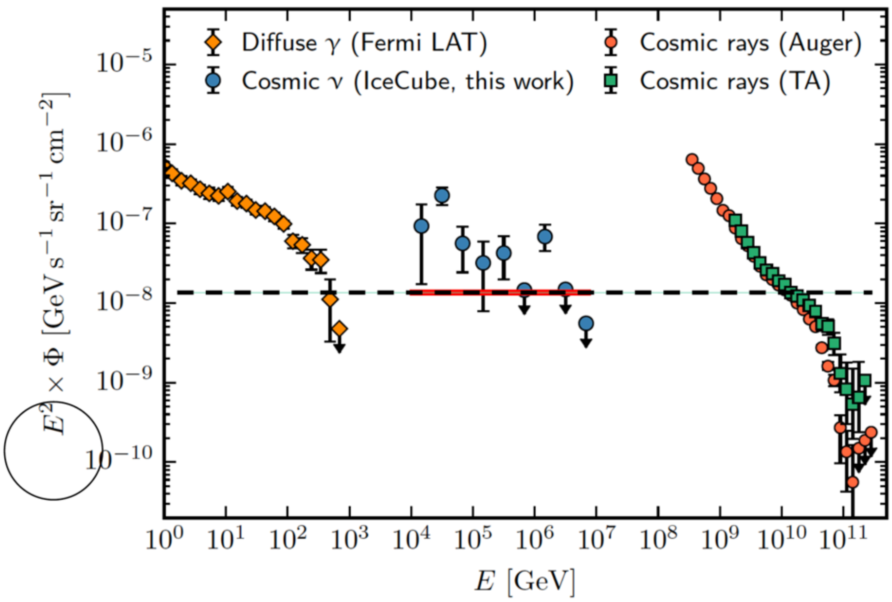

Figure 1: Diffuse gamma, neutrino and UHE cosmic ray fluxes.

Current measurements of the isotropic neutrino flux (Φ) are shown in Fig. 1, along with the observed isotropic γ-ray background (IGB) and the UHE cosmic-ray flux. The correspondence among the energy densities, proportional to $E^2\Phi$, observed in neutrinos, γ-rays, and cosmic rays suggests a strong multi-messenger relationship that offers intriguing prospects for deeper observations with a new generation of instruments. In most of the hadronic models, we can expect a simultaneous production of neutral and charged pions in cosmic-ray interactions that suggests that the sources of high-energy neutrinos may also be strong 10 TeV –10 PeV γ-ray emitters. Only few hints of PeVatron candidates have been detected by the current air shower Cherenkov telescopes, all of them being galactic sources. For extragalactic sources, the γ-ray emission is not directly observable because of the strong absorption of photons by e^-e^+ pair production in extragalactic background photons. But these high-energy γ-rays can initiate electromagnetic cascades of repeated inverse-Compton scattering and pair production that eventually can produce a measurable signal below 100 GeV. The correspondence of the diffuse fluxes of the cosmic messengers explains why we are putting enormous effort to link together in real time observations of multiple messengers. The most successful example so far is the multi-messenger flare of TXS 0506+056, which demonstrated the feasibility of neutrino-triggered follow-up campaigns.

Meeting these science goals requires measurements of the neutrino flux density, the neutrino spatial distribution, neutrino flavor ratios, and requires linking neutrino observations with observations of complementary astrophysical messengers. Measuring neutrino point-source and diffuse energy flux densities will require large detector arrays. As detector effective areas increase, it is imperative to maintain low backgrounds to achieve improved sensitivity.

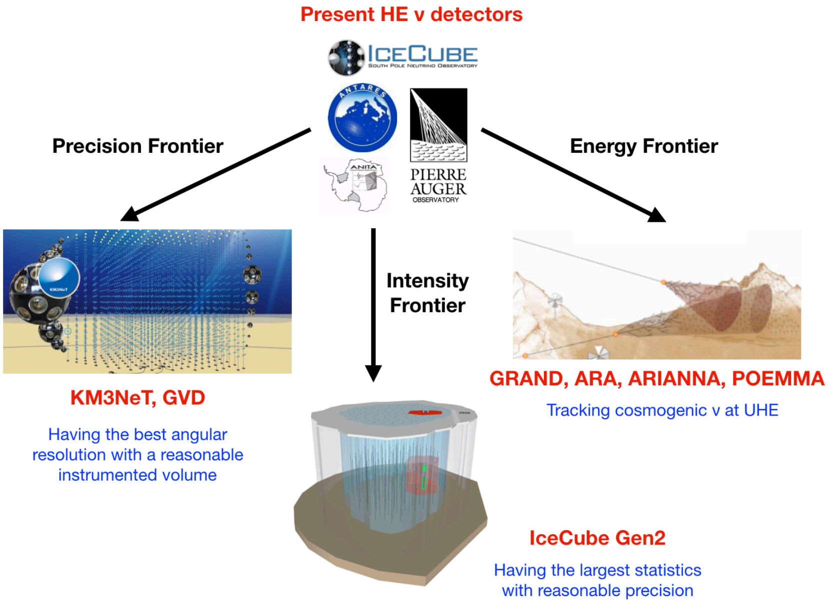

Figure 2: Future of neutrino high-energy telescopes (adapted from M. Ackermann).

Like the particle physics domain, we can define 3 main axes of development: a precision, an intensity and an energy frontiers (Figure 2). To obtain the best angular precision, clear water is the best medium with very low scattering. KM3NeT will achieve a precision of <0.1 degrees for the muon neutrino tracks at very high energies. One of the main expectation is the quite low angular resolution, <1.5°, of the cascade events (ν_e-ν_τ + neutral current interaction of ν_μ). This is a factor ~10 improvements compared to IceCube. With KM3NeT, we will be able to perform a very efficient all-flavour neutrino astronomy.

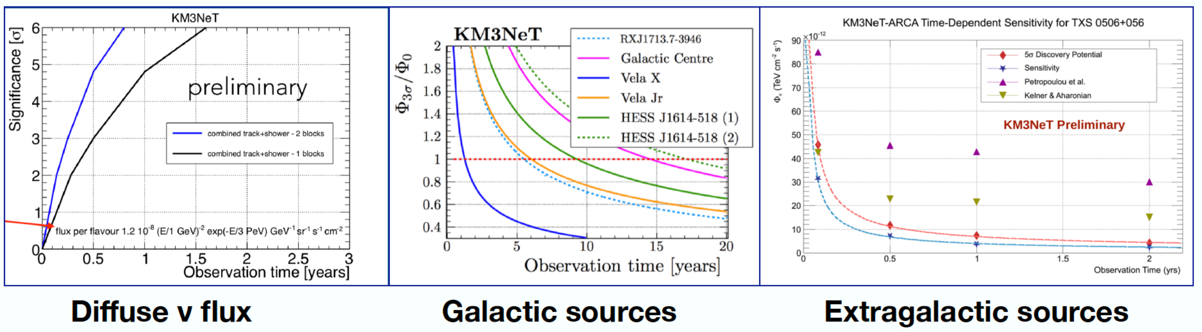

Figure 3: Expected sensitivities for KM3NeT ARCA detector.

The success of building IceCube suggests that this is the best solution to build a very large detector to obtain the largest statistics at TeV-PeV. In the ICeCube Gen2 project, they expect to extend the detector to ~10 km3. To push the energy to ultra-high energies, the best sensitivities are or will be achieved by radio or space missions (ARA, ARIANNA, GRAND, EUSO, POEMMA). With these new generation neutrino telescopes, we can expect to detect a large number of neutrino sources and be able to measure very precisely the neutrino diffuse flux. With an order-of-magnitude improvement at energies between 10 TeV – 10 PeV, we will be able to discover neutrino point sources consistent with the flux discovered by IceCube, and at energies 1 – 100 PeV, to identify a break, a cutoff, or a new component necessary to probe diffuse model predictions. Having multiple neutrino observatories with different detection technics and environments will help in reducing the systematics errors of the measurements.

II. Multi-messenger activities at IN2P3 with KM3NeT

At IN2P3, we are deeply involved in the ANTARES and KM3NeT projects. After more than ten years of operation and more than 50 papers, ANTARES will be decommissioned in 2020. KM3NeT by then will have better sensitivities than ANTARES in the whole energy range. The French groups have been pioneer in the introduction of multi-messenger activities in the Collaborations. Clearly, we want to at least maintain or increase this effort in the future. We have been the first one to do alert sending, time-dependent analysis with major astrophysical sources (AGN, gamma-ray burst, supernova), to perform real-time and offline multi-messenger analyses (correlation with IceCube neutrino and LIGO/VIRGO gravitational wave triggers…). We have clearly obtained a huge expertise in this domain that we hope will be translated in KM3NeT. The multi-messenger studies of the joint GW-neutrino analyses are described in more details in the contribution "GWHEN, Gravitational Waves and High Energy Neutrinos, the next multi-messenger connection" by T. Pradier. Taking advantage of the very large energy range of KM3NeT from MeV to PeV, we want to continue to perform analyses to identify neutrinos from various astrophysical sources such as supernovae, gamma-ray burst, merger of massive objects, active galactic nuclei, etc. In KM3NeT, we have started to explore the energy range 10-40 MeV where we can expect promising results on core-collapse supernova detection, and the 1-20 GeV region where we can try to see for the first-time non-thermal neutrinos from solar flares or merger of massive objects. These low-energy analyses are described in more details in the contribution "Detecting low-energy transient neutrino signals with KM3NeT" by G. de Wasseige.

In France and in particular in our 4 laboratories (APC, CPPM, IPHC, Subatech), we are lucky to have collaborators in all the major experiments such as HESS/CTA, INTEGRAL, Fermi, SVOM, LSST, VIRGO/LIGO, etc. We are already cooperating in multi-messenger campaigns. This axis should be clearly developed in the future. To go further on the multi-messenger analysis, we should organize and develop the cooperation between IN2P3 and INSU, develop common tools to access and provide data in a standard way (VO, broker). For example, the PNHE and, the workshop TS2020 launched in 2017, are good frameworks to develop these collaborations.

IV. Bibliography

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