ASTERICS Policy Forum

Science cases : KM3NeT

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High-energy photons and neutrinos are produced in the astrophysical beam dump of the primary cosmic ray particles interacting with the ambient matter or photon fields at the source. High-energy gamma-rays are also produced by leptonic processes which involve high-energy electron acceleration (synchrotron/Inverse-Compton). The limited statistics at very high energies and the uncertainties in the source modeling prevent from distinguishing hadronic vs leptonic models when relying only on gamma-ray observations. The detection of high-energy neutrinos would be a smoking gun for the presence of accelerated hadrons in the sources.

With the identification of a diffuse flux of astrophysical (cosmic) neutrinos in the TeV-PeV energy range, IceCube has opened a new window to the Universe. However, the origin of the neutrinos is still undetermined: the observing neutrino flux does not show clear association with known source classses and no individual neutrino sources have been detected yet. With a few years of data, much has been learnt on the shape of the energy spectrum. Important questions remain: what is the exact form of the energy spectrum? What is the flavour composition? Is there a contribution from Galactic sources? Can we identify individual sources?

KM3NeT is the second-generation neutrino telescope in the Mediterranean Sea. It has two main independent objectives: the discovery and subsequent observation of high-energy cosmic neutrino sources and the precise measurements of neutrino oscillations, in particular the determination of the mass hierarchy of neutrinos. For these purposes, the KM3NeT Collaboration is currently building two detectors: ARCA for the high-energy (300 GeV-10 PeV) neutrino detection, closed to Capo Passero (Italy) and ORCA, sensitive to lower-energy (3 GeV-1 TeV) neutrinos offshore Toulon (France). The deployment of the lines in the two sites has already started and the rest of the detector will be deployed in stages allowing scientific analyses during the construction phase.

There is an intimate link between high-energy gamma rays and high-energy neutrinos in their production and therefore also a natural science case to combine CTA and KM3NeT. However, depending on the source optical depth and the distance, high-energy γ-rays may escape or further cascade, complicating time and energy correlation between neutrinos and γ-ray counterparts. **In this context, broadband electromagnetic data (in particular in optical, infrared and radio domains) will be crucial to complement the multi-messenger picture** and further understand hadronic processes occurring in high-energy sources.

The discovery of individual neutrino sources with KM3NeT is likely, especially for the brightest sources in our Galaxy. **The most promising chance will come from transient events** correlated to electromagnetic or gravitational wave signals, since time-dependent analyses have much reduced atmospheric neutrino background. This point is at the basis of the multi-messenger analyses that we have performed in ANTARES and IceCube and are developing in KM3NeT. They are based either on the search for time and/or space correlations with already detected transients (gamma-ray bursts, flares of active galactic nuclei or outbursting gamma-ray binaries) or on the electromagnetic follow-up observations subsequent to neutrino alerts.

Neutrino data rights will be defined on a case-by-case basis. **In the current version of the data management plan of KM3NeT, the neutrino events are public but after a latency of two years.** However, significant events might automatically trigger **public alerts** that will be distributed to the community through several forms of automatic communication, including **VO Events**, within ~10 s following the neutrino detection. **Subthreshold alerts and multiplets will be distributed through a private channel to observing teams upon MoU agreement.**

In this document, we will report two promising science cases on X-ray or gamma ray binaries (Galactic transients) and gamma-ray bursts / blazars (extragalactic sources).

1. Galactic transients: X-ray or gamma-ray binaries

Recent results from ground-based γ-ray Cherenkov telescopes have shown that Galactic sources are able to accelerate particles above TeV energies. The H.E.S.S. telescope has identified a PeVatron source (able to accelerate cosmic rays above PeV) near to the Galactic Center. While the acceleration of leptons is limited by the relatively short cooling timescales, hadrons can be accelerated at higher energy (beyond TeV/PeV energy ranges).

At the moment, the IceCube dataset cannot exclude a subdominant neutrino flux originating from Galactic sources. Identifying them would provide unique constraints into both the long-standing problem of the origin of (Galactic) high-energy cosmic rays and the particle acceleration mechanisms at work in high-energy sources. Thanks to their location in the Northern Hemisphere**, KM3NeT ARCA and ORCA neutrino telescopes will be suitable to look for Galactic sources**. In the KM3NeT analysis pipelines, directional, energy and time information are used to distinguish signal neutrino emission from the background of atmospheric muons and neutrinos. In particular, searching for transient and variable sources in a multi-messenger approach will enable to increase both the sensitivity of KM3NeT and the significance of a potential discovery by requiring a simultaneous detection with several telescopes/messengers.

KM3NeT will operate extensive programs of real-time multi-wavelength follow-up to search for an electromagnetic counterpart to neutrino candidates originating from Galactic sources by generating alerts whenever an interesting neutrino event is detected. Target-of-Opportunity (ToO) observations will be requested to high-energy γ-ray (CTA), optical (ELT) and radio (SKA) observatories together with robotic telescopes located all around the world and γ -ray satellite such as SVOM. As many types of potential source can be at the origin of neutrinos, ToO should be performed with low latency especially for very high-energy γ-rays (typically within a few hours). For this purpose, some joint neutrino-EM observing programs will be requested in the observatories Time Allocated Committee (TAC) in advance and MoU agreements will be discussed.

KM3NeT will also routinely perform real-time and offline analyses looking for space and time neutrino emission correlated with electromagnetic emission of transient or flaring sources detected by external facilities (microquasars, gamma-ray binaries, fast radio bursts, GRBs, gravitational wave counterparts, etc.). CTA, SKA, LSST and SVOM will be the key partners. In general, these electromagnetic triggers are distributed publicly to the community via Astronomer's telegrams. **It will be important to develop a standard VO Event format to disseminate the triggers in a more systematic way to a very wide community** and also to have a same network as the Gamma ray Coordinates Network (GCN) that ensures archive and communication tools. Access to archive data are also important to perform dedicated offline correlation analyses. Source classification, astronomical coordinates, spectral information and light curve are important parameters to be accessed. Selecting only neutrino events coincident with the observed electromagnetic flares allows for a much better background rejection, and thus a better sensitivity. Such studies generally assume a correlation between the γ-ray or radio emission and the neutrino flux. **Consequently, synergies with CTA and SKA will be considered in this topic together with theoretical works that will enable to address the temporal correlation (or shift) between neutrino and electromagnetic emission at different wavelengths.**

Galactic plane surveys in both γ-rays and radio domains will discover new faint variable or transient sources. These observations will pinpoint several new X-ray and gamma-ray binaries that can be promising sources of high-energy neutrinos. The multi-wavelength and multi-messenger observations are crucial to understand the nature of particle acceleration in relativistic jets or strong magnetic winds, etc. Combined observations between SKA, CTA, ELT and KM3NeT can help to solve this puzzle with multiple unknowns: SKA can directly image the jets and determine their properties such as the Lorentz factor, the ELT will be able to study in detail the environment of the system (presence of black-hole, properties of the corona, presence of an accretion disc, etc.) by completing the Spectral Energy Distribution, while CTA can probe the acceleration of high energy particles to very high energies (> TeV-PeV). KM3NeT will test the nature of the high-energy particles; either find a hadronic component or put strong constrains on the baryon load.

These studies will benefit from new theoretical and modeling work using state-of-the-art numerical simulations to interpret multi-messenger data. In particular, there is a need of relativistic outflow dynamical models accounting for hadronic emission in order to accurately estimate the γ-ray and neutrino emission originating from X-ray and gamma-ray binaries. **This multi-messenger program will benefit from the feedback of the multi-messenger programs currently ongoing jointly with the ANTARES neutrino telescopes, gravitational wave and electromagnetic observatories.**

2. Extragalactic sources: GRB and blazars

Gamma ray bursts are bursts of highly energetic γ-rays lasting less than a second to several minutes coming from the most energetic explosions observed in the Universe. They are known to occur at cosmological distance, towards the limits of the observable Universe. **Gamma-ray bursts offer also nice opportunities to detect a signal of high-energy neutrinos.** GRBs have been studied in details thanks to the CGRO, Swift and Fermi missions. A lot has been learned on the distance distribution, the properties of the prompt and afterglow phases. But, several questions are still to be answered: what is the nature of the long GRB progenitors and central engines? What is the physical origin of the prompt emission and the afterglow phase? What are the acceleration mechanisms and the composition of the relativistic ejecta? Are GRB very efficient cosmic accelerators? **Only a complete multi-wavelength and multi-messenger approach can help to solve these long lasting questions.** The recent discovery of a short GRB associated with the gravitational wave signal GW170817 has provided a direct proof that binary neutron star mergers are the sources of this phenomenon through the simultaneous detection of gravitational wave and electromagnetic signals. **To complete the broad picture and unveil the physical mechanisms at work during the merging of the two compact objects, the high-energy neutrino detection is the missing piece of the puzzle**. The physical understanding of GRBs is especially challenging, due to their extreme properties. This quest is however highly motivating as it offers the possibility to improve our knowledge of the final state of massive stars, to understand astrophysical relativistic jets from GRBs and other sources such as microquasars or blazars, and to study an extreme case of cosmic accelerator.

GRBs are detected in the very large field of view gamma-ray instruments such as Swift, Integral and Fermi satellites. In 2022, SVOM will be one of the main providers of GRB triggers. The GRB community is well organized and the alerts are transmitted in real-time to all the telescopes via standard VO Event or socket using the GCN (GRB Central Network) tools. It provides also an archive and a communication channel between the different observers.

Most of the GRB models rely on a population of accelerated electrons radiated in an intense magnetic field. Gamma-ray photons up to ~100 GeV have been detected by Fermi/LAT in several GRBs. However, no TeV γ-ray and no high-energy neutrino signals have been detected. KM3NeT with an unprecedented instantaneous sensitivity can probe the presence of cosmic rays acceleration inside the relativistic jets. CTA will probably unveil for the first time the acceleration of particles to very high energy in the GRB afterglow. This is one of the next challenges of both CTA and KM3NeT. For this purpose, **it is crucial to receive the GRB triggers from gamma-ray satellites with the minimum delay** (typically less than 30 seconds) and to have prompt pointing of the detectors and fast data analysis. **Even a neutrino non-detection starts to put strong constraints on the baryon load and the bulk Lorentz factor of the relativistic jets.**

Being the most energetic phenomena in the Universe, GRBs allow to study the furthest objects almost never observed (redshift 9.3 for the most distant GRB observed so far). The sensitivity of the ELT will take scientists into the largely unknown epoch of the reionization of the Universe and the formation of the first stars (population III). Infrared observations will allow for a detailed study of distant GRB environment. SKA observations of GRBs will also play a key role in determining the physical properties of the jets. **In case of a successful association of a neutrino signal with a gamma ray burst, a ToO can be submitted to ELT to have a very detailed characterization of the local environment of the host galaxy (in particular for the redshift).** For obscured GRBs, the optical/X-ray emission can be fainter if the burst occurred in a very dense region (shock GRB, orphan afterglow) so that we can expect higher p-p interactions and therefore a higher flux of neutrinos. In this last case, KM3NeT will perform, with high priority, follow-up searches of neutrino countererts to orphan afterglows detected by SKA.

The synergies of multi-messenger facilities in the search for transient sources is well illustrated by the ANTARES alert program. In particular, ANTARES sent an alert to the observing community (ANT150901) to have a complete follow-up after having found an association between one very high-energy neutrino and a very bright X-ray flare detected in time/space coincidence by Swift. **The combination of radio (VLA) and NIR observations yielding an unambiguous identification of the nature of the transient** X-ray source: a young accreting G-K star or a binary system of chromospheric active stars (RS CVn), undergoing a flaring episode that produced the X-ray emission. This crucial dataset definitely ruled out the association between the neutrino event and the X-ray flare. **In the future, follow-up observations with SKA and the ELT will be essential to characterize potential (faint) transient sources associated with neutrino events and assess the probability of mis-association.**

Blazars may also emit high-energy neutrinos through lepto-hadronic processes occurring in the relativistic jets. These neutrinos could be emitted during flaring events, making (quasi-) simultaneous observation of neutrino and γ-ray signals a smoking gun of hadronic processes. The contribution of the blazar population detected by Fermi has been constrained to be less than 27% of the total cosmic neutrino flux observed by the IceCube Collaboration. However, although no association has been confirmed so far, a few potentially interesting evidences arise: one PeV neutrino (Big Bird) of IceCube is correlated with a very bright flare of the blazar PKS B1424-418 in 2012-13 or one other neutrino event detected by IceCube in September 2017 has been shown to be positionally consistent with the blazar TXS 0506+056 currently undergoing a flaring episode detected by both Fermi/LAT and MAGIC. The first correlation has been found offline using archive data while the second example illustrates well the result of a real-time follow-up of a neutrino alert by MAGIC and Fermi/LAT. **Taking advantage of its higher sensitivity and better angular resolution, KM3NeT will also look for time/space correlation with blazars.** Up to now, due to its optical and IR spectral energy distribution dominated by non-thermal emission, the redshift of TXS 0506+056 is unknown despite VLT observations performed with the X-Shooter spectrograph. **ELT will certainly help to constrain the redshift of a larger population of blazars. This will be an important asset to compare the data with theoretical models of particle acceleration.**

For the science case of blazars, KM3NeT will need access to the archive data for offline individual correlation analysis or population studies, to the blazar outburst information (source, time, energy spectrum, time variability) for time-dependent point-source analysis. Having a more uniform way to receive the blazar triggers via VO Events, better than astronomer's telegram or private wiki should also be an improvement. At least, the source name, the classification, the coordinates, the flux and the light curve will be needed in the VO Event format.

KM3NeT will also distribute its neutrino alerts to CTA, the ELT and SKA to allow for an efficient electromagnetic follow-up. This will enable to further assess the lepto-hadronic nature of AGN relativistic jets. In case of a simultaneous detection, the broadband spectral energy distribution (from the radio to the very-high energy γ-rays) will be fitted by phenomenological models accounting for particle acceleration at a shock front in the jet. For this purpose, joint neutrino-electromagnetic proposals will be submitted to the appropriated TACs or working groups.