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The multi-messenger search programme and results of the ANTARES neutrino telescope

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Abstract. The key-word of modern astronomy and astrophysics is multi-messenger: not only photons used as probes for the investigation of the Universe, but also cosmic-rays, neutrinos and gravitational waves. The multi-messenger approach is important in particular for neutrino detectors: potential astrophysical sources are predicted to emit a very faint neutrino signal and the presence of an isotropic flux of atmospheric background requires the development of effective search strategies. The multi-messenger approach can increase the discovery potential, the statistical significance of the observations and the efficiency of the detection. The advantages of the multi-messenger approach are evident, in particular, when looking at transient or flaring sources. In ANTARES, a wide programme of multi-messenger searches is active; the most relevant results will be presented in this contribution.

1. Introduction

In the last decades the community of astronomers and astrophysicists has been witness to an important change in the modalities of observing the Universe. More than an evolution, the revolution of modern astronomy has consisted in moving from traditional astronomy to *multi-wavelength astronomy*, in which observations of light in the visible band are complemented by the information collected in the radio, X-ray and gamma-ray regions of the electromagnetic spectrum. The next step in this mission of exploration of the Cosmos is the progress from *multi-wavelength astronomy* to *multi-messenger astronomy*: no more "only photons", but new "actors" are coming into play in the scene of astronomy and astrophysics. New messengers from the Universe can be added in the list: cosmic rays, gravitational waves and neutrinos, to enrich and complement the information provided by photons at any wavelength. The multi-messenger approach connects astronomy with astrophysics and particle physics, it opens new windows in cosmology and in the theory of gravity and can give some hints of new physics beyond the standard model. The manifesto is completed bearing in mind that it promotes collaborations between different experiments: researchers involved in shared projects join efforts and skills, and can make available additional tools for data analysis.

The multi-messenger approach assumes that the different messengers (all of them or some of them, depending on the model and on the type of source) are expected to be produced in the same astrophysical site. This allows to increase the discovery potential by observing the same source with different probes. Moreover, the statistical significance of the observations can be

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improved by coincident detection (sustained by the development of alert systems between the experiments) and the efficiency of the detection can be refined profiting from relaxed cuts and exploiting the advantages of time-dependent analysis. The advantages of the multi-messenger approach are evident, in particular, when looking at transient or flaring sources.

Dealing with the data analysis in a multi-messenger perspective is crucial for neutrino detectors, since potential astrophysical sources of neutrinos are predicted to emit faint signals and the presence of an isotropic flux of atmospheric background makes the detection challenging and requires the development of effective search strategies. The strongest connection is with gamma-ray and X-ray astronomy, since both high energy photons and neutrinos are expected from cosmic emitters if hadronic processes take place. In the standard picture, known as Fermi acceleration [1], hadrons, confined by magnetic fields inside the astrophysical sites, are accelerated through repeated scattering by plasma shock fronts; collisions of hadrons with ambient plasma produce photons and neutrinos through pion photoproduction mechanisms. In this model, both gammas and neutrinos are linked to cosmic rays; the flux predictions for neutrinos can be computed given the observations of the gamma-ray spectra. Confirmed gamma-ray sources are thus the first target of observations for neutrino telescopes, see for instance the ANTARES results for point-like sources [2], in which the list of candidate sources is a list of gamma-ray emitters, and the ANTARES results for the diffuse neutrino emission from Fermi Bubbles and from the Galactic Plane [3], in which the "on-region" is delimited by gamma-ray observations. The searches included in the ANTARES multi-messenger programme, presented in this contribution after a brief account on the ANTARES detector (Sect. 2), are those that regard specifically the time-dependent analysis: flaring sources, both extragalactic (blazars, Sect. 3) and galactic (micro-quasars, Sect. 4); transient sources, like Gamma-Ray Bursts (GRBs) (Sect. 5); the TAToO project for the optical follow-up (Sect. 6). As examples of looking for coincidences with messengers other than photons, the search for a correlation with Ultra-High-Energy Cosmic Rays (UHECRs) (Sect. 7) and with gravitational waves (GWs) (Sect. 8) is presented. The ANTARES programme includes activities for which other experiments trigger neutrino observations, but also the opposite case, with neutrinos triggering others; the TAToO project and the collaboration with the network of gravitational waves interferometers are examples of this kind.

2. The ANTARES detector

ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) [4], deployed in the Mediterranean Sea, 40 km offshore Toulon, France, at a depth of about 2500 m, is the largest neutrino telescope in operation in the Northern hemisphere. It consists of 12 strings composed of 25 triplets of PMTs (storey), for a total of 885 PMTs; the distance between strings is about 70 m; the distance between storeys along the string is 14.5 m; the total length of the string is 450 m, including the length of 100 m between the bottommost storey and the seabed. The deployment of the telescope started in 2007 with the first 5 lines; the detector has been completed in May 2008. Data taking is continuously on-going since 2007 and it will be on up to end of 2016.

3. Neutrino signal from flaring blazars

The first study of a possible correlation of the ANTARES signal with the enhanced photon emission during AGN flares has been carried on with data collected in 2008 (61 days live time) [5].Ten blazars have been selected from the Fermi/LAT AGN catalog, among those that showed a large variability (flaring state) in the time interval under investigation. A dedicated algorithm has been developed for the identification of flares in the light curve. The idea behind

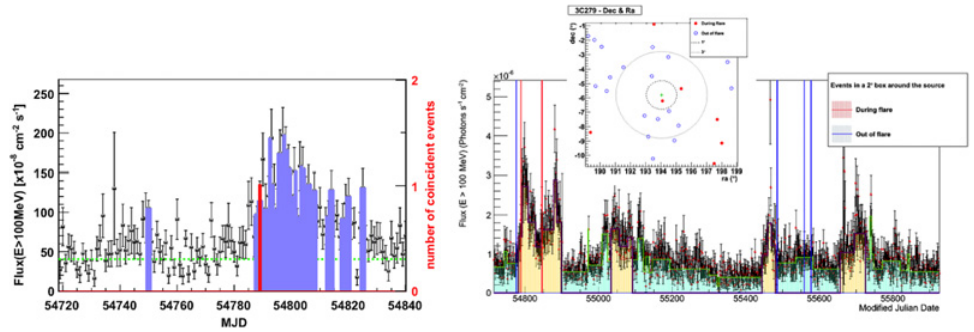

Figure 1. Left: light curve (dots) of the blazar 3C279 measured by Fermi/LAT; the blue (dark grey) shaded histogram indicates the flaring periods selected for the analysis (the dashed line, in green, is the fitted baseline); the red (dark grey) histogram displays the time of the associated ANTARES neutrino event. Right: light curve of 3C279 considering the time interval of the improved analysis; flaring periods are in evidence (in yellow, in the coloured version of this article), the vertical lines identify the time of detected neutrinos around the source; the insert report the position of the candidate neutrino events in a map centred at the source location.

this study is that selecting a narrow time window during which the neutrino signal is expected, in coincidence with the gamma flare, the atmospheric background is cut down. The estimated performance of the method is that the flare timing information yields an improvement of the discovery potential by about a factor 2 (1.3) with respect to a standard time-integrated point source search when looking for a 1 (10) day flare. The outcome of the analysis was one neutrino candidate event compatible in space with source 3C279 and coincident in time with a flaring period (Fig. 1, left); the p-value of the observation was 1% but post-trial probability was 10%; the occurrence is thus not statistically significant and consistent with a background fluctuation. Fluence upper limits have been set for any of the selected sources, with fluence defined as the integral in energy and time of the flux upper limit. Even in absence of a discovery, the method looked very promising and the period under study was extended, considering the interval 2008–2011. The improved analysis is currently in progress and has already selected 40 sources with 86 flaring periods and 6 specially significant flares, among which source 3C279 is still one of the most promising (Fig. 1, right – preliminary). A further extension consists in searching for coincidences not only with FERMI/LAT data, but also with the information provided by IACT telescopes (HESS, MAGIC, VERITAS).

4. Neutrino signal from galactic micro-quasars

Micro-quasars are galactic X-ray binary systems with relativistic jets; several models indicate micro-quasars as possible sources of high-energy neutrinos, with flux expectations depending on the baryonic content of the jets [6]. The analysis has been carried out using the data set collected in the time interval 2007–2010 [7], selecting six sources in the ANTARES visibility and showing an outburst in the period under study. For each source, the data analysis has been restricted to the flaring time periods, selected with a dedicated algorithm in a multi-wavelength approach (X-rays/gamma-rays), using data from RXTE/ASM, Swift/BAT and Fermi/LAT. No statistically significant excess has been found above the expectation of the atmospheric background, thus upper limits have been derived and compared to theoretical predictions, assuming a power-law spectrum (E^{-2}) and considering also the case of an exponential energy cut-off at 100 TeV. The results can be used also to infer information on the jet composition; for some sources, the obtained upper limits already constrain some emission models concerning the ratio of proton to electron luminosity in the jets.

5. Neutrino emission in coincidence with GRBs

The most recent analysis published by ANTARES on the search for neutrino emission in coincidence with detected GRBs has considered data collected in the time interval 2007–2011 and a list of 296 GRBs [8]. The requirement of temporal and spatial coincidence (within 10°) with a GRB reduces the background to $\sim \mathcal{O}(10^{-4})$ per GRB; as a consequence, selection cuts can be loosened. The novelty of the analysis consists also in considering the predictions of the spectra given by the NeuCosmA code [9], based on numerical calculations of the full photohadronic interaction processes. The neutrino flux expected from this model is an order of magnitude below that predicted by previous analytic approaches and can be a key element in the light of the non-observation by IceCube of GRB neutrinos. The analysis has been carried on looking for muon neutrinos; no coincident event was found, 90% C.L. upper limits have been set.

6. TAToO

The TAToO (Telescopes-ANTARES Target of Opportunity) project has established an alert system for sending triggers to a network of optical telescopes, aiming at the optical follow-up of the signal of neutrino candidate events [10]. The opportunity offered by the ANTARES detector is related to the large sky coverage and the high duty cycle of the ANTARES observations; in addition, the pointing accuracy for muon tracks is about 0.5° for energies above the TeV scale. Coincident observations of neutrinos and optical signals are expected from transient sources, like GRBs. A fast online muon track reconstruction algorithm is used to trigger the optical telescopes; the alert criteria include the identification of a multiplet of events within given time and angular window (interpreted as a burst), or the occurrence of an high energy event (signature of energetic processes). The information from the online reconstruction is used for the starting of the follow-up; offline reconstruction is then used for the computation of the refined direction, that is taken into account in the subsequent observations. Several improvements have been introduced since the beginning of the project, the most important being related to the latency of the alert system, that is now reduced to about 15 seconds; data analysis is in progress.

7. Search for correlation with the arrival directions of Auger UHECRs

The arrival directions of 2190 neutrino candidate events (detected by ANTARES in the period 2007–2008, corresponding to an effective live time of 304 days) and 69 UHECRs (detected by the Pierre Auger Observatory in the period 2004–2009, with energy $E > 10^{19.74}$ eV) have been compared, in search for correlations [11]. All the Auger events are in the ANTARES field of view; a light composition has been assumed for this study, so that the magnetic deflection angle could be set at the reasonable value of 3°. A source stacking method has been applied; no significant correlation was observed; the obtained 90% C.L. upper limit on the neutrino flux per source is 5×10^{-8} GeV cm^{-2} s^{-1} (for a E^{-2} energy spectrum).

8. Search for coincidences with the signal of gravitational waves

The GWHEN (Gravitational Wawes + High Energy Neutrinos) working group has been established between the ANTARES and the VIRGO-LIGO Collaborations to set up a common data analysis in search of coincident signals from common astrophysical sources, among which: GRBs, bursting magnetars, topological defects, and also sources with no electro-magnetic counterpart ("hidden sources"). The first study has considered data collected in 2007, when ANTARES construction was in progress and the detector was in a 5-line configuration [12]. The live time of the search was 91 days, during which 216 neutrinos were reconstructed, but only 158 occurred when at least 2 GW detectors were in operation; events reconstructed with less than 2 lines show an azimuthal degeneracy that produces mirror tracks; only 14 candidate neutrinos fulfilled the requirement of at least 3 lines. The result of the search was no gravitational wave burst found associated with any selected neutrinos; all the computed p-values were compatible with the null hypothesis. This outcome can be translated in 90% C.L. limits on the exclusion distances of the sources and on the rate density of common sources (GW+HEN). Work in progress considers an extended data set, collected in 2009 with ANTARES in its final configuration (12 lines), for a total of 129 days of common data taking and an amount of 1989 neutrino candidates. Improved reconstruction algorithms are applied for both neutrinos and gravitational waves, resulting in a factor 7 of improvement in sensitivity and discovery potential.

9. Summary and conclusions

Neutrino astronomy is always carried on in a multi-messenger framework, and given the peculiarity of neutrino interaction properties neutrinos have the ambition of assuming non only a "supporting" role (as complementary source of information for photon astronomy), but a leading role. Astronomy can be done even without photons, with neutrinos offering unique opportunities to look further away and deeper inside astrophysical objects: indeed, in contrast to photons and charged cosmic rays, they can find their way out, without scattering or absorption, from the very inner core of dense astrophysical objects, providing information about sites that are opaque to electromagnetic radiation, revealing the existence of sources so far undetected ("hidden sources") and releasing triggers for other "penetrating" probes (like gravitational waves). Results obtained so far by the ANTARES detector using a multi-messenger approach in data analysis are very competitive; data taking is ongoing and updated results will be soon released.

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