PROCEEDINGS OF SCIENCE

Highlights of the ANTARES neutrino telescope results

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The ANTARES neutrino telescope is located in the Mediterranean Sea, at a depth of about 2500 m under the sea level, 40 km off-shore from Toulon. The long attenuation length of the sea water allows for the reconstruction of neutrino direction with an excellent angular resolution. This feature, together with the location of the telescope in the Northern hemisphere, results in competitive sensitivity for neutrino source searches in the Southern Sky at TeV energies. The latest results of the ANTARES analyses for neutrino point sources and for diffuse neutrino emission from the entire sky as well as from several interesting regions such as the Galactic Plane are presented here. An overview of the multi-messenger activities of ANTARES will be given. The results of a search for neutrinos produced in the annihilation of dark matter accumulated in massive objects like the Sun and the Galactic Centre are also presented.

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1. Introduction

ANTARES [1] is a three-dimensional array of about 900 Optical Modules (OMs), distributed on 12 strings, about 400 m long, anchored at the sea bottom, at 2475 m, at 40 km off-shore the Southern French coast. It has been taking data in its complete configuration since 2008. The Cherenkov photons emitted along the path of the relativistic particles in the final state of the neutrino interactions are collected by the OMs and the relevant information about their position and arrival time is used to reconstruct the direction of the tracks. No data filtering is applied off-shore and the all-data-to-shore approach is used. In the shore station, a farm of computer filters the data stream and all potentially interesting events are finally stored and analyzed by dedicated tracking and reconstruction programs. In order to reduce the overwhelming background due to high energy atmospheric muons, relics of the atmospheric showers, only events are considered whose reconstructed direction is "upward-going", exploiting the shielding effect of the Earth. Two categories of events are reconstructed: i)"track-like" events, due to charged current (CC) interactions of muon neutrinos in proximity of the detector: a long track of a muon, almost collinear to the parent neutrino, whose direction can be inferred with a precision better than 1°, is present; ii) "shower-like" events, produced by all-flavour neutral current interactions and by electron neutrino CC inside the active volume of the detector. The angular resolution for the reconstruction of the shower event direction is ~3°. The data set used in the analyses discussed hereafter has been collected between early 2007 and the end of 2015, for a total livetime of more than 2400 days.

2.Search for neutrino sources

Cosmic neutrino sources have been searched for using both track-like and shower-like events. Different strategies have been followed: i) full-sky search, where the whole visible sky of ANTARES is scanned to find a statistically significant cluster of events; ii) investigations of the directions of a pre-defined list of known sources, potential neutrino emitters; iii) search for an excess of events around the Galactic Centre; iv) exploration of the Sagittarius A* location, assuming an extended source with a Gaussian emission profile of different widths.

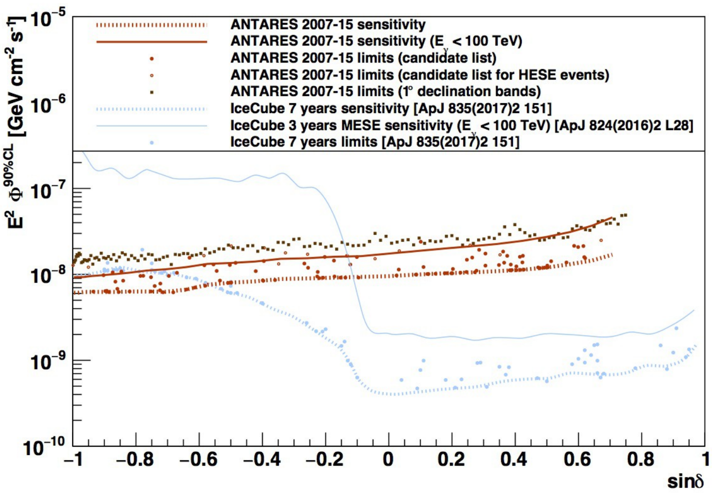

Fig. 1: Summary of the results of the point sources search. Details are in the main text. Results of the IceCube experiment are also shown for comparison.

PoS(EPS-HEP2017)018

No evidence of neutrino sources has been found, but the best world limits have been provided for a large fraction of the Southern Sky, particularly at energies below 100 TeV. In fig.1, 90% C.L. upper limits on the total signal flux (sum of the three neutrinos flavours), assuming an E^{-2} spectrum, are shown (red circles). The dashed red and blue lines are the ANTARES and the IceCube sensitivities [2]. The curves for the sensitivity to neutrino energies under 100 TeV are also included (solid lines).

3. Neutrinos from the Galactic Centre

The IceCube Collaboration measured an excess of high energy neutrinos over the expected atmospheric background [3]. Some tension exists between the spectral index of the neutrino fluxes from the Northern and the Southern hemispheres. The central Galactic plane might host an enhanced neutrino production, thus leading to anisotropies in the extraterrestrial neutrino signal and explaining this so-called "spectral anomaly". The expected diffuse Galactic neutrino emission can be obtained adopting a model of generation and propagation of cosmic rays with the morphology of the gas distribution in the Milky Way. In this analysis the "Gamma model" [4] is assumed as a reference. The data set of ANTARES collected between 2007 and 2015 has been used, considering all flavour neutrino interactions. No excess of events has been observed and an upper limit on the neutrino flux has been set that excludes the diffuse Galactic neutrino emission as the major cause of the "spectral anomaly". Fig. 2 shows the ANTARES upper limit at 90% C.L., on the three-flavour neutrino flux (black line), on the "Gamma" model. Two different energy cut-offs for the primary protons producing neutrinos when interacting with the gas are considered. Only the results concerning the inner Galactic plane region are shown in the plot, though all-sky data have been used for the analysis [5].

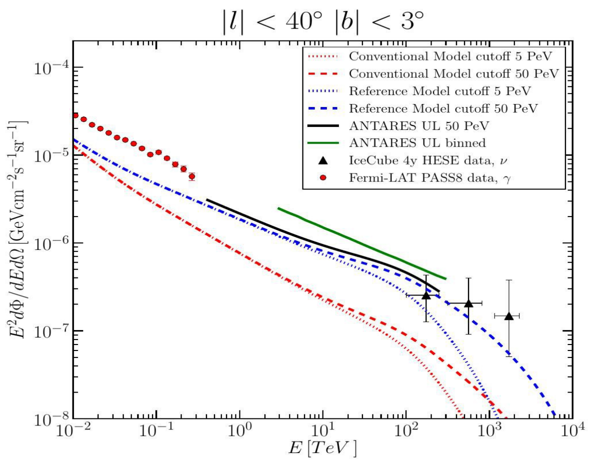

Fig. 2: Results of the analysis on the neutrino emission from the Galactic plane. Details are in the text.

4. Diffuse neutrino flux

A diffuse flux of cosmic neutrinos may be due to the ensemble of unresolved individual sources or to the interactions of high energy cosmic rays during their propagation through the Universe. The features of a diffuse flux of cosmic neutrinos, in particular the spectrum and the flavour composition, could provide information on the cosmic rays production mechanisms. In this analysis the 9-years data sample has been used and events from interactions of all neutrino flavours considered. An excess of events over the expected atmospheric backgrounds is observed at high energy, which is compatible with the background within its uncertainties, but it is also of the same order of magnitude of the expectations from a cosmic contribution to the overall event rate. Fig. 3 (left – tracks, right – showers) shows the distribution of the energy estimator for data (black crosses) and Monte Carlo. The arrow in the two plots indicates the optimal selection cut obtained with a Model Rejection Factor [6] procedure based on the Feldman and Cousins upper limit estimation [7].

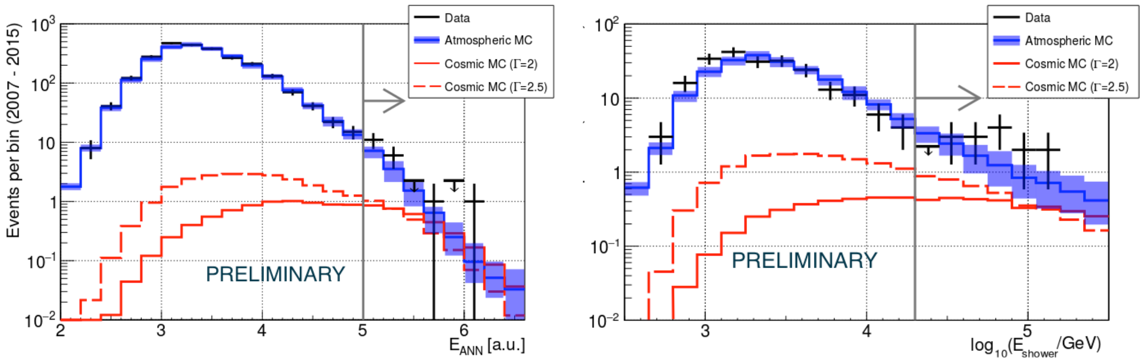

Fig. 3: Distribution of the energy estimator for data (black crosses) and Monte Carlo, before applying the energy-related selection shown as an arrow. Left panel for tracks, right for showers.

5. Multi-messenger

High-energy neutrinos could be produced in the interaction of charged cosmic rays with matter or radiation surrounding astrophysical sources. This means that transient phenomena might happen in coincidence with the emission of high-energy neutrinos. Since 2009 the ANTARES Collaboration has started a follow-up program of neutrino alerts to search for coincidences between a transient event and a neutrino emission. This program triggers a network of robotic optical telescopes immediately after the detection of a neutrino event and schedule several observations in the following weeks. The most interesting neutrino candidates are also followed by the Swift XRT telescope and the Murchison Widefield Array radio telescope and the H.E.S.S. very high-energy gamma-ray telescope. The multi-messenger approach combines information provided by the ANTARES neutrino telescope and information from other observatories. This enhances the probability of detecting a source, allowing the possibility of identifying a neutrino progenitor from a single detected event and reducing the background. No significant counterpart associated with a neutrino emission has been identified so far.

Recently, also a search for neutrinos in coincidence with gravitational wave (GW) events has been performed. The ANTARES Collaboration has joined the follow-up effort of LIGO/Virgo detections and has been receiving GW alerts. An updated high-energy neutrino follow-up of the GW170104 event produced no evidence of a spatially and temporally coincident neutrino production. The non-detection of joint GW and neutrino signals is used to constrain neutrino emission from the GW source. An upper limit of ~ 4 x 10^{54} erg to the total neutrino emission, for a generic E^{-2} neutrino spectrum and for a spectrum with a high-energy cut off, has been obtained. This result is in agreement with what already derived for the previous events GW150914, LVT151012 and GW151226 [8,9].

6. Dark matter

A neutrino telescope like ANTARES can search for neutrinos due to the annihilation of weakly interacting massive particles (WIMPs), generally considered the most likely dark matter candidates. WIMPs can accumulate inside massive astrophysical objects, being gravitationally trapped. This would produce a clean signals and low expected background. Dark matter signals from the Sun, the Galactic Center and the Earth core have been searched for with different analysis methods. No significant excess has been found, but the upper limits for the Galactic Center are the most stringent among all indirect detection experiments for WIMP masses above 30 TeV. In fig. 4 the comparison between the results of different experiments is shown. The decay chain selected for the comparison is the $\tau^+\tau^-$ [10].

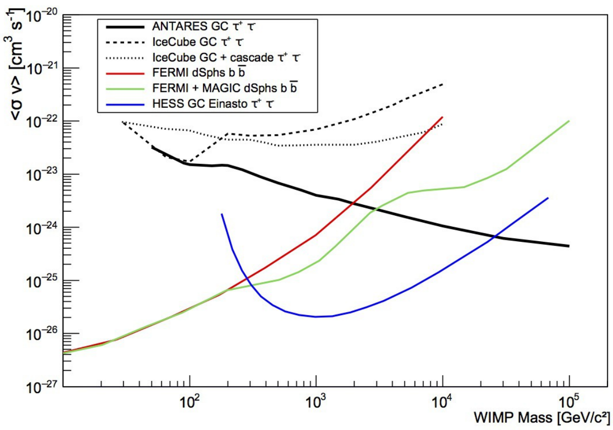

Fig. 4 - 90% C.L. limits on the thermally averaged annihilation cross-section, σv, as a function of the WIMP mass in comparison to the limits from other experiments.

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