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Recent results with ANTARES, the first undersea neutrino telescope in the Mediterranean Sea

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Abstract. The ANTARES detector is the largest undersea neutrino telescope. It is located at about 2500 m under the sea level in front of the Southern French coast, 40 km from Toulon. Its location in the Mediterranean Sea and the good optical properties of the sea water makes it an excellent tool to search for possible sources of neutrinos in the sky region of the Galactic Plane. Its angular resolution, $\sim 0.4^o$, and the effective area for neutrinos coming from the Southern sky allow to put constraints on the possible interpretation of the recent IceCube cosmic neutrino signal. The ANTARES collaboration has developed a rich program of multi-messenger searches together with experiments sensitive to other cosmic messengers. ANTARES has also produced results on neutrinos coming from the annihilation of Dark Matter particles. In particular, the limits obtained for the spin-dependent WIMP-nucleon cross section overcome the existing direct-detection experiments. An overview of the most interesting and recent results obtained with ANTARES are discussed, together with the future perspectives of analyses.

1. Introduction

The ANTARES detector, the largest neutrino telescope in the Northern hemisphere, has been taking data in its final configuration since May 2008. Anchored to the seabed, at a depth of 2500 m, 40 km off the coast of Toulon (France), it consists of a three dimensional array of 10" photomultipliers, hosted in pressure resistant glass spheres, distributed along 12 strings. The detector design is optimized for the detection of muons with energy larger than 100 GeV emerging from charged current interactions of ν_μ in the vicinity of the detector.
Details on the technical aspects of the detector can be found here [1]. Some of the most recent results obtained with ANTARES are presented in this contribution. They include measurements constraining a neutrino flux from point-like Galactic sources, multimessenger studies of the sky in combination with other experiments, searches for neutrinos due to Dark Matter (DM) particles annihilation. An important contribution is given by ANTARES analyses to the comprehension of the IceCube (IC) signal origin [2].

2. Search for neutrino point-like sources

Only neutrinos can traverse the Earth and produce muons in the vicinity of the detector. To study astrophysical point-like sources of neutrinos, a search for an excess of upgoing signal events over an irreducible background of atmospheric neutrinos is performed. Thanks to the long scattering length of blue light in seawater, an excellent angular resolution, $\sim 0.4^o$, can be obtained. No significant excess has been found in six years of ANTARES data, between 2007

and 2012, [3]. The most signal-like accumulation of events, located at equatorial coordinates R.A. = -46.8^o and δ = -64.9^o, corresponds to a 2.2 σ fluctuation over the background.
Also, a search for an excess of events from a pre-selected list of 50 sources has been performed assuming an E^{-2} spectrum. Upper limits were set. Results are shown in fig.1.

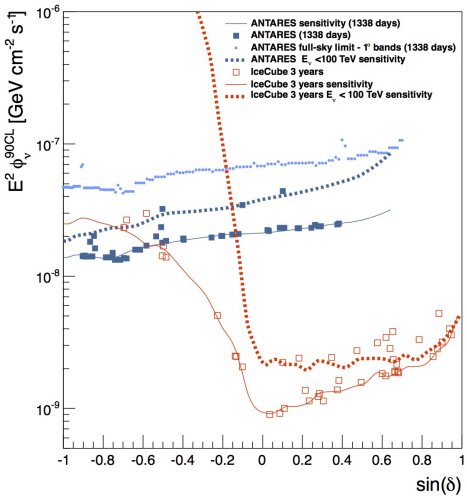

Figure 1. 90 % C.L. flux upper limits and sensitivities on the muon neutrino flux for six years of ANTARES data. The light-blue markers show the upper limit for any point source located in the ANTARES visible sky in declination bands of 1°. The solid lines indicates the sensitivity for a point-source with an E^{-2} spectrum. The squares represent the upper limits for the candidate sources. Finally, the dashed lines indicate the sensitivity for a point-source and for neutrino energies lower than 100 TeV.

Recently, a joint analysis with IC has been performed and results are being published, [4]. Assuming an $E^{-2.5}$ spectrum, the fractional contribution of each data set to the total number of signal events is shown in fig. 2 as a function of the declination. The fraction of events contributed by ANTARES is larger for $\delta < 15^o$, due to the greater sensitivities to low energy upcoming muon tracks. On the contrary, IC requires high-energy events in order to get a good discrimination of the down-going muon background. The results of the joint search are shown

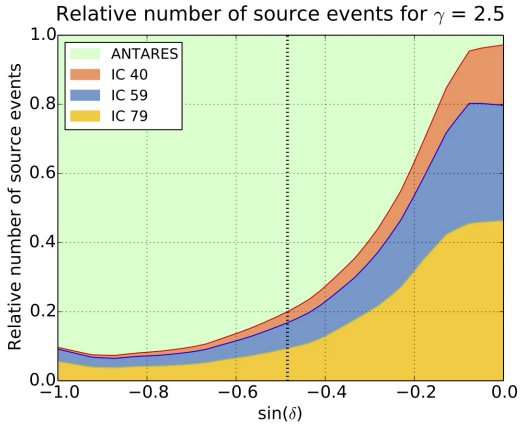

Figure 2. Fractional contributions of each data set to the total number of signal events in the joint ANTARES-IceCube analysis, for point sources with an $E^{-2.5}$ spectrum, as a function of the declination δ

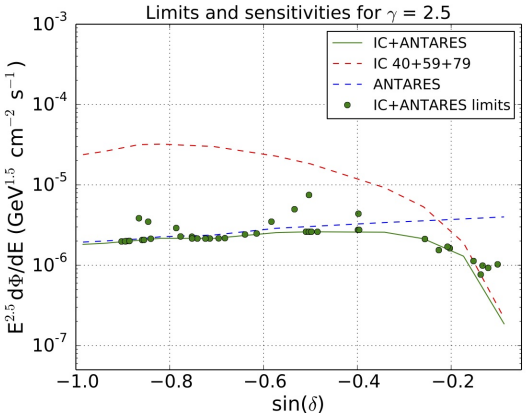

Figure 3. Sensitivities (lines) and point sources limits (dots) to an $E^{-2.5}$ flux with no cutoff, using ANTARES (blue), IC (red) and combined (green) data, as a function of δ.

in the fig. 3. No significant excess was found, but an improvement on the results from both

experiments indicates the complementarity of the two detectors.
Thanks to its good angular resolution, the ANTARES detector can be used to test the hypothesis of a single point-like source as origin of the cluster in the IceCube events. A point-like source with an E^{-2} spectrum has been excluded, but, due to the uncertainty on the index, a further analysis of ANTARES data has been done, considering different energy spectra for a source in the Galactic centre. Different source extensions have been considered (0.5^o, 1^o, 2^o) in a region of 20^o around the location (α, δ) = (- 79 ^{o}, -23^o). No significant cluster has been found in the considered area.

3. Extended source searches

Extended regions of the sky have been proposed as possible sites of cosmic rays acceleration. A search for an excess of neutrinos from these regions has been performed comparing "on-zones" defined according to specific templates, to "off-zones" of same size, extension and exposure.
On-zones corresponding to the region of the Fermi bubbles, of the Galactic plane and to the IceCube hot spot have been considered.

3.1. Fermi bubbles

The Fermi bubbles [5] are regions of enhanced γ-ray emission extending out of the Galactic centre. They are proposed hadronic acceleration sites, with possible neutrino emission. ANTARES data collected in 2008-2013 were used [6]. The on- and off-zones for the Fermi bubble analysis are shown in fig. 4. Two flavour-uniform neutrino fluxes are considered. Also exponential cut-offs at 500, 100 and 50 TeV have been tested. A slight excess corresponding to 1.9 σ significance was found. Results are shown in fig. 5.

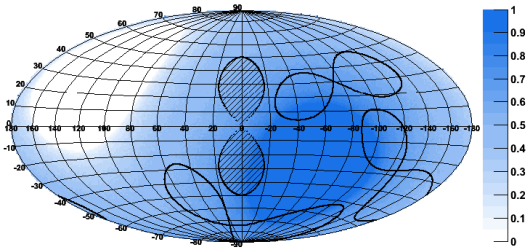

Figure 4. On- and off-zone search regions for the Fermi bubble search. The blue shading shows the ANTARES visibility.

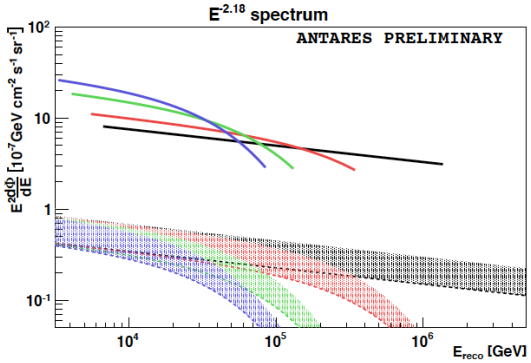

Figure 5. 90% C.L. upper limits (lines) on the neutrino flux from the FB, compared to expectations for different spectral shapes [7].

3.2. Galactic plane

ANTARES location in the Northern hemisphere is suited to searching for possible neutrino flux from the inner Galactic plane. This is a particularly interesting region, as comes out from the Fermi LAT observations of a diffuse galactic γ-ray background. An on-zone defined as the region of galactic longitude $|l| < 40^o$ and latitude $|b| < 3^o$ has been considered and compared to nine off-zones. No excess was found in the on-zone region. Results are shown in fig. 6.

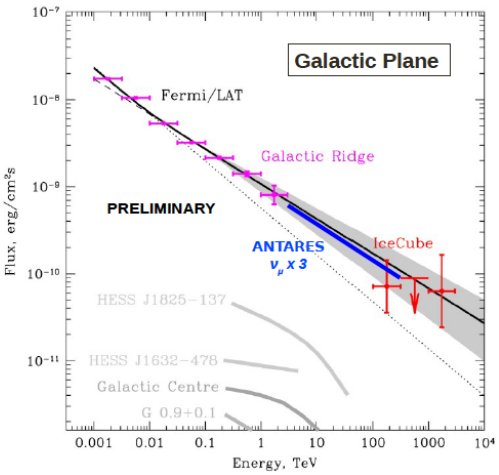

Figure 6. Fermi-LAT-detected gamma-ray flux from the Galactic Ridge (pink), and IC events consistent with this region (red), as in [8], compared to the ANTARES all-flavour flux limit (blue), [9], and γ-ray fluxes from various other galactic sources (grey) [10].

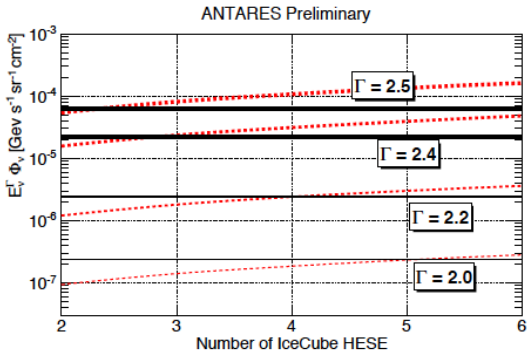

Figure 7. ANTARES upper limits at 90% C.L. (black) on a flavour-uniform neutrino flux from the IC cluster region as a function of the spectral index Γ, compared to (red) the flux required to produce an expected number of events in the IC HESE analysis. See [9] for details.

3.3. IceCube hot spot

A dedicated search for neutrinos coming from the direction of the IC hot spot has been performed. The on-zone corresponding to the excess measured by IC has been compared to twelve off-zones. No excess was observed and resulting limits on the maximum number of HESE produced with different spectral indices are shown in fig. 7. This result extends the result obtained in [3] that puts limits on the possibility of a point-like and mildly extended sources in this region.

4. Multimessenger analyses

A rich program of collaborations with other experiments has been carrying on by ANTARES, particularly dedicated to the search for neutrino emissions in transient phenomena. Searching for events in restricted space-time regions decreases significantly the background. A search for neutrino emission in coincidence with 296 γ-ray bursts detected by Fermi, SWIFT and the GCN for a total prompt emission time of 6.6 hours has been performed. No events have been identified in a window of 10^o around the GRB, [11]. An optical follow-up is also continuously active. ANTARES sends out alerts to a network of optical robotic telescopes [12]. The present telescope network includes TAROT, ZADKO, IRiS and five MASTER telescopes, four located in Russia and one in South Africa. As GRBs and other catastrophic events can be sources of gravitational waves and high energy neutrinos as well, a joint analysis ANTARES and LIGO/Virgo collaborations was performed, using data collected in a partial configuration, [13]. A new analysis is in progress that will use a larger sample of data as starting events to look for possible GW counterparts.

5. Dark matter and exotic particles

Weakly Interacting Massive Particles (WIMPs) are usually considered good candidates to constitute a halo of DM around the visible part of the galaxies. In the framework of SUSY theories the lightest particle, the neutralino, is a stable particle that can annihilate in pair

giving, as final product, a flux of neutrinos. DM particles would accumulate in the core of massive objects (like the Sun and the Galactic centre). A search for high energy neutrinos from the direction of the Sun and of the Galactic centre has been performed. The sensitivity of neutrino telescopes to check the spin-dependent cross section of WIMP-proton is much better than for direct search experiments. No significant excess is observed and upper limits on the neutrino flux have been set. A summary of the results is shown in figs. 8 and 9.

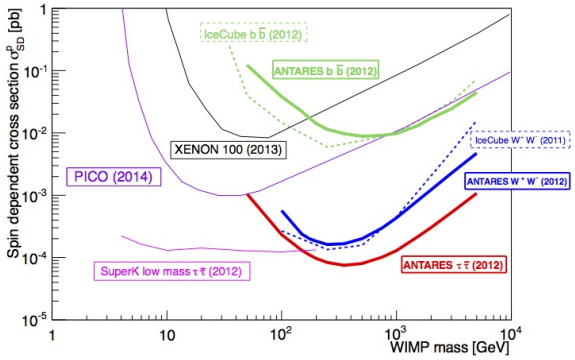

Figure 8. ANTARES limits σ^p_{SD} from the Sun as a function of the WIMP mass. Legenda and references are in [15].

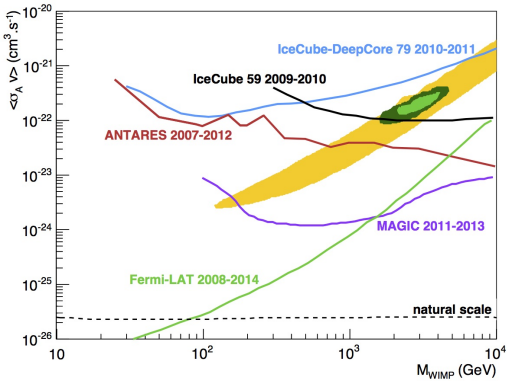

Figure 9. ANTARES limits $\langle\sigma_A\nu\rangle$ from the Galactic Centre as a function of the WIMP mass. Legenda and references are in [15].

6. Conclusions

A short overview of the most recent ANTARES results is given in this contribution. In the next future, analyses of the full data sample are expected to provide improved results, thanks to the increased statistics.

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