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High-energy neutrino searches in the Mediterranean Sea: The ANTARES results

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Summary. — The antares Collaboration is operating the first neutrino telescope (NT) ever built in the deep sea. The detector was gradually deployed between 2006 and 2008 and is, as of today, the largest NT in the Northern Hemisphere. It is anchored 2475 m below the surface of the Mediterranean Sea and 40 km offshore from Toulon (France). The detector is contributing significantly in the new endeavor of multimessenger astrophysics thanks to its excellent angular resolution in both the ν_μ channel and the cascade channel (induced by all neutrino flavours). The Southern sky (in particular central regions of our Galaxy) is studied searching for extended regions of emission as well as for point-like objects. By adopting a multimessenger approach, based on time and/or space coincidences with other cosmic probes, the sensitivity can be considerably augmented. antares provides also various constraints on Dark Matter through indirect searches for WIMP annihilation, with limits that are the most restrictive in some WIMP mass intervals.

1. – Searches for neutrino sources

The antares detector consists of 12 detection lines 450 m long with 25 storeys per line and 3 optical modules with 10-inch photomultipliers per storey. The scientific landscape of high-energy neutrino astrophysics has significantly changed after the IceCube evidences for cosmic high-energy neutrinos [1]. As discussed by many authors (see *e.g.* [2] and references therein), there are arguments for the presence of a Galactic component in the cosmic neutrino flux below 100 TeV. The detector acceptance for neutrinos in this energy range and its location makes antares perfectly suited for: disentangling the nature of the astrophysical neutrinos; the follow-up studies of astrophysical transients; and for indirect searches for Dark Matter candidates.

Point-like sources can be identified by looking for an excess of muons from ν_μ charged-current (CC) interactions. Cascade-like events (or *showers*), that are induced by ν_e (and ν_τ) CC interactions, and by all flavor neutrino neutral-current (NC) interactions, contribute to about 25% to the sensitivity in the search for a E^{-2} cosmic signal.

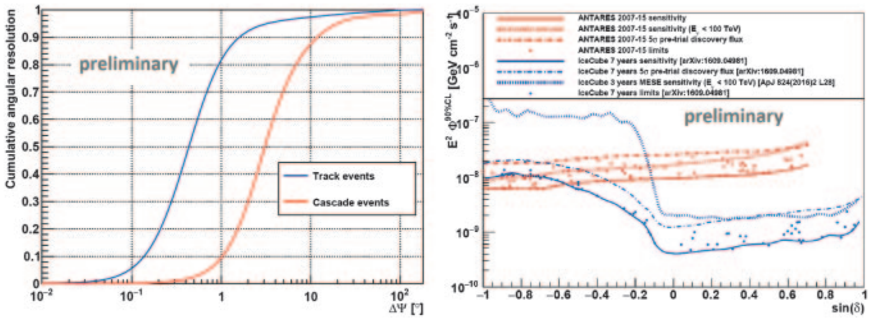

Fig. 1. – Left: cumulative distribution of the angle between the reconstructed direction of tracks (blue) and cascades (red) with respect to the neutrino direction, for an E^{-2} spectrum. Right: upper limits at a 90% C.L. on the signal flux (E^{-2}) from the investigated candidates. The continuous red line shows the ANTARES sensitivity, the blue line the sensitivity of the 7 years analysis of IceCube. The discovery flux and the sensitivity for $E_\nu < 100\,\text{TeV}$ are also shown.

Figure 1 (left) shows the cumulative distributions of the angular distance between the reconstructed and true neutrino direction for tracks and showers. In cascade events, the energy deposited in the detector is more strongly correlated with the energy of the primary neutrino. The background is due to atmospheric neutrinos and those few atmospheric muons mis-reconstructed as up-going.

The latest search has used data collected between early 2007 and the end of 2015, with a livetime of 2424 days. A total of 7629 tracks and 180 cascades have been selected. Four different approaches have been used: i) An unbinned search for an excess of events in the full visible sky; ii) A search from the directions of a pre-defined list of 90 galactic and extragalactic objects emitting γ-rays; iii) A search restricted to a $\sim 20°$ region around the Galactic Center (GC); iv) A study of Sagittarius A* as an extended source by assuming a Gaussian emission profile of various widths. In all searches, no significant excess over background has been found. In the full-sky search, the most signal-like cluster of events is located at $(\alpha, \delta) = (-16.2°, 23.5°)$ with a significance of 1.9σ. The neutrino flux sensitivity of the search is $\sim 6 \times 10^{-9}\,\text{GeV cm}^{-2}\,\text{s}^{-1}$ for declinations from $-90°$ up to $-42°$. The limits on the neutrino flux obtained for pre-selected sources is shown in fig. 1 (right). The most signal-like cluster (1.6σ) is found at the location of HESSJ0632 + 057 at $(\alpha, \delta) = (-98.2°, 5.8°)$. Based on muon tracks only, a joint ANTARES and IceCube search for a neutrino excess from selected sources in the Southern hemisphere [3] shows that ANTARES is dominant for declinations $\delta < -15°$.

2. – Diffuse fluxes and extended source searches

A cosmic diffuse ν flux in ANTARES is searched for looking to an excess of high-energy (HE) events with respect to the background in the track and shower channels separately. Energy estimators (particularly efficient for cascades) allow rejecting most of the atmospheric events with a cut on the reconstructed energy. The procedure is optimized to obtain the best upper limits. In showers (data collected from 2007 to 2013), 7 HE events have been observed, while 5 ± 2 are expected from backgrounds and ~ 1.5 events from the cosmic signal observed by IceCube. In tracks (using data form 2007 to 2015), there were 19 HE events for an expected background of 13^{+3}_{-4} events and ~ 3 signal events assuming the IceCube flux (see fig. 2, left). In this search, the shower channel

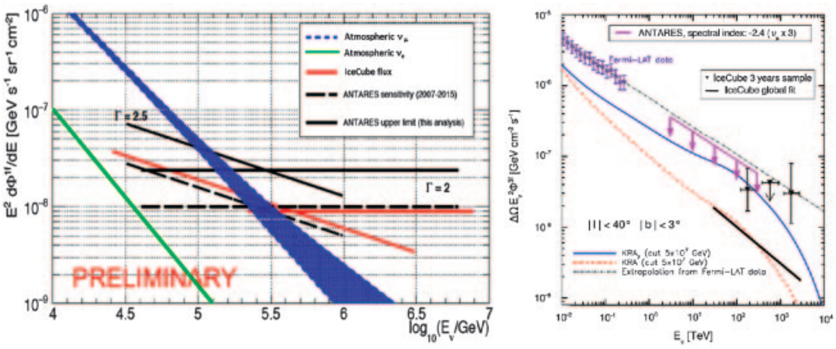

Fig. 2. – Left: upper limits (90% C.L.) on the diffuse neutrino fluxes (black thick lines) for E_ν^{-2} and $E_\nu^{-2.5}$ spectra, combining tracks and showers. The sensitivity achievable with the entire ANTARES 2007–2015 data set (dashed lines) and the IceCube measured flux (red) are also shown as well as the expected flux of atmospheric ν_μ (blue line) and ν_e (green line). Right: 90% C.L upper limit (magenta) for the search for an excess of events from the central Galactic region, compared to expectations [4].

is more powerful than the muon channel because the atmospheric ν_e flux (green line) is about a factor of 20 smaller than the atmospheric ν_μ (blue line), see fig. 2 (left). The small excesses (not significant by their own) observed so far are rather compatible with the IceCube signal. In any case, a final analysis is expected once the detector is decommissioned.

Within the direction uncertainty of cosmic IceCube events, several extended regions have been proposed as hadronic acceleration sites. Our searches from these regions rely on binned and unbinned (on-going) techniques. The first method uses "on-zones" defined by specific templates, which are compared to "off-zones" of exactly the same size and shape, but offset in right ascension. The method has been used for the Fermi bubbles and a search for muon neutrinos from the Galactic Ridge. In the latter, the search [4] has been optimized in the region $|l| < 40°$ and $|b| < 3°$. No excess has been found in track events using data from 2007 to 2013. The resulting limits shown in fig. 2 (right) exclude the simplistic hypothesis of a one-to-one relation between γ-rays (*Fermi* LAT) and neutrinos from the inner galactic plane. Fainter predictions [5] are tackled with more sophistical approaches.

3. – Multimessenger astrophysics and transient phenomena

Transient phenomena are particularly promising, since observations in γ-rays (*e.g.* *Fermi* LAT and IACTs) have shown that the HE Universe is extremely variable. ANTARES is well designed to look for ν's emitted by transient sources, because of its large field of view (2π sr) and high duty cycle. Restricting the searches to well-defined space-time windows decreases considerably the background, so that only one event may be enough to claim a discovery. These multimessenger searches are performed in a twofold way: by triggering radio, optical, X-ray and γ-ray observations immediately after the detection of an interesting neutrino candidate; or searching for neutrinos spatially and temporally coincident with transient events detected across the electromagnetic spectrum or via gravitational waves. Since 2009, more than 200 alerts have been sent to optical robotic telescopes (TAROT, ROTSE and MASTER) while 12 X-ray targets of opportunity have been sent to the XRT (Swift satellite) since mid-2013. From January 2010 to January 2016, 93 alerts with early optical follow-up have been analyzed. No optical counterparts have been found [6].

Specific strategies are also developed to look for neutrino events in both time and space coincidence with transient events (mainly, Gamma-ray Bursts, GRBs) announced by an alert distributed through the Gamma-ray Coordinated Network (GCN). A stacking approach [7] has been used to analyze possible neutrino events correlated with GRBs outside the electromagnetic prompt-emission time window, due to Lorentz Invariance Violation effects or other astrophysical models. No significant excess over the expected accidental coincidence rate has been found. A dedicated study has been done on four very bright GRBs (080916C, 110918A, 130427A and 130505A). They have been investigated assuming two scenarios of the fireball model: the internal shock scenario, leading to the production of neutrinos with energies mainly above 100 TeV, and the photospheric scenario, characterized by a low-energy component. With non-detection, upper limits at 90% C.L. on the neutrino fluences have been derived, as well as constraints on the bulk Lorentz factor of the jet and the baryon loading parameters [8].

Cataclysmic cosmic events (long and short GRBs, the merger of neutron stars, ...) can be plausible sources of both gravitational waves (GWs) and high-energy neutrinos (HEN). Combining directional and timing information on HEN events and GW bursts provides a novel way of constraining the processes at play in the sources. A real breakthrough for astrophysics occurred on September 14th, 2015 with the first GW event observed by LIGO. ANTARES and IceCube searched for HE neutrino follow-up of GW150914. The non-detection has been used to constrain neutrino emission from the GW transient event and ANTARES provided the most stringent limit up to 100 TeV [9]. For the second scientific run of LIGO (started at the end of November 2016), soon joined also by VIRGO, ANTARES is receiving triggers in real-time, offering the possibility to drastically reduce the size of the region of interest in case of a matching neutrino detection.

4. – Dark matter searches

ANTARES is contributing to the worldwide efforts to search for Dark Matter (DM). Scenarios for the production of HE neutrinos involve dense sources in the Universe, such as the Sun, the Centre of the Earth, the Galactic Centre, dwarf galaxies and galaxy clusters. Since the expected DM density tends to be strongly peaked near the centers of these objects, and ANTARES has an excellent angular resolution, competitive limits can be set for $E_{\mathrm{WIMP}} > 50\,\mathrm{GeV}$. The geographical location of the detector is also an advantage compared to IceCube, since it allows a better visibility of the Galactic Center, and an observation of the Sun with less atmospheric background, being at intermediate latitude (and therefore observing the Sun less close to the horizon).

Neutrinos from DM annihilations in the Sun have been searched for assuming 15 WIMP masses ranging from $50\,\mathrm{GeV/c^2}$ to $5\,\mathrm{TeV/c^2}$ and three annihilation channels (WIMP+WIMP $\rightarrow b\bar{b},\ \tau^+\tau^-,\ W^+W^-$) and assuming a branching ratio of 100% for each channel. No excess of events has been observed (fig. 3, left). Due to the solar composition rich of hydrogen nuclei, neutrino telescopes produce the more stringent limits in the spin-dependent channel and for $M_{\mathrm{WIMP}} > 200\,\mathrm{GeV/c^2}$, surpassing even the direct-detection experiments. Null excess has been found (fig. 3, right) in a similar search for DM annihilation in the Milky Way. Three halo models and five annihilation channels, (WIMP + WIMP$\rightarrow b\bar{b},\ \tau^+\tau^-,\ W^+W^-,\ \mu^+\mu^-$ and $\nu\bar{\nu}$) with M_{WIMP} ranging from $50\,\mathrm{GeV/c^2}$ to $100\,\mathrm{TeV/c^2}$ have been considered. These results are the most competitive

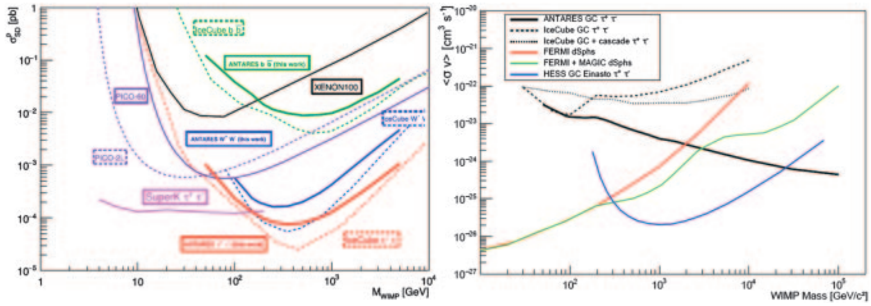

Fig. 3. – Left: search for DM annihilation in the Sun: limits on the spin-dependent WIMP-nucleon scattering cross-section as a function of WIMP mass for the $b\bar{b}$, $\tau^+\tau^-$, W^+W^- channels [10]. Right: search for DM annihilation in the Galactic Center: 90% C.L. upper limits on $\langle\sigma v\rangle$ as a function of the WIMP mass [11]. The ANTARES and IceCube limits have been obtained with the Navarro-Frenk-White (NFW) halo profile and the same values of the parameters.

ones for neutrino telescopes. The search from the Earth core has used dedicated event reconstruction to select almost vertical tracks (difficult to reconstruct with more than one detection string). No significant excess of neutrinos over the expected background has been observed. For M_{WIMP} close to the mass of iron nuclei (50 GeV/c^2), our limits are more stringent than those obtained by other indirect searches.

5. – Conclusions

The high quality of ANTARES data and the competitiveness of the results achieved, despite the modest size of the detector, demonstrate the tremendous potential of deep sea neutrino telescopes for HE neutrino astronomy. 2017 will be the last year of data taking of ANTARES, with KM3NeT [12] taking up the torch in monitoring the Southern Sky from the Mediterranean Sea. The amount and quality of the data collected, together with the rich multimessenger program setup, naturally call for great expectations. The hope for discoveries is also enhanced by the perspective of several combined searches.

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