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Results from the ANTARES neutrino telescope

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ANTARES is the first and largest undersea neutrino telescope in the Northern Hemisphere. It is located at 2475 m below the Mediterranean Sea level, 40 km offshore from Toulon (France). The telescope consists of 12 detection lines with 25 storeys, each housing a 10-inch photomultiplier and a local control module that contains the electronics. The length of a line is 450 m and the horizontal distance between neighbouring lines is 60-75 m. Data-taking started with the first 5 lines of the detector installed in 2007. The full detector was completed in May 2008 and is operating continuously ever since, except for some short periods in which repair and maintenance operations have taken place.
The ANTARES main scientific target is the search for a cosmic neutrino flux with $E_\nu > 1$ TeV. Its geographical location allows surveying most of the Galactic Plane, including the Galactic Centre, and the search for neutrinos from, e.g., the so-called Fermi Bubbles. Thanks to the sub-degree angular resolution at high energy, the telescope has the possibility to significantly constrain models on the possible origin of the IceCube cosmic neutrinos in the Southern Sky, or on the blazar provenance of the highest-energy neutrinos. Furthermore, the combination of ANTARES and IceCube data allows to enhance the sensitivity of the searches for point-like objects in the Southern Hemisphere.
In addition to standalone point-like and diffuse high energy neutrino signals, ANTARES has developed a range of multi-messenger strategies to exploit the connection between neutrinos and other cosmic messengers: electromagnetic radiation from visible to X- and γ-rays; charged cosmic rays; gravitational waves. This means, e.g., looking for neutrinos in space and time correlation with γ-ray bursts or with flaring blazars, but also looking for optical/X counterparts of neutrino candidates.
Finally, ANTARES can also search for neutrinos produced by the co-annihilation of Dark Matter particles; in the case of spin-dependent WIMP-nucleon cross section, the obtained limits overcome the sensitivity of existing direct detection experiments. The ANTARES experiment offers also a deep-sea cabled observatory for other particle physics studies and for sea and earth sciences, whose results are not covered in this review.

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1. The ANTARES neutrino telescope

The ANTARES detector has been taking data since more than 8 years. During this period, multimessenger astrophysics has made large progresses. Nevertheless, despite theoretical and experimental efforts over several decades, the astrophysical sources of cosmic rays (CRs) have not yet been localized. Many hundreds of γ-ray sources have been detected in the multi-GeV range and over 150 sources in the multi-TeV range. Unfortunately the emission of most of them can be modelled equally well by leptonic as well as hadronic scenarios. In this context, ANTARES in the Mediterranean Sea and IceCube (IC) at the South Pole are the main instruments devoted to provide information on the branch of high-energy neutrinos for the quest for the origin of CRs.

A charged current (CC) interaction of a $\nu_\mu(\overline{\nu}_\mu)$ with the matter below or around a neutrino telescope produces a relativistic muon that can travel $\mathscr{O}(10^2-10^4)$ m and cross the detector. This muon induces Cherenkov light when travels through water/ice, and some of the emitted photons produce a signal in the photomultipliers (PMTs) with the corresponding charge and time information (the *hits*). The signature due to $\nu_e, \nu_\tau(\overline{\nu}_e, \overline{\nu}_\tau)$ CC and to neutral current (NC) interactions inside the instrumented volume are showers yielding more localized hits. Different reconstruction strategies have been developed in ANTARES to reconstruct muons and showers. The hits are used to trace the direction of the event that is well correlated to the neutrino direction in the case of the muon track, and to derive a proxy of the neutrino energy. Detailed information on the detector can be found in [1].

The irreducible background for a cosmic signal consists of atmospheric neutrinos and muons. ANTARES has demonstrated to accurately measure atmospheric ν_μ in the energy range of few tens of GeV, where neutrino oscillations reduce the number of upgoing events [2], up to ~ 200 TeV [3]. The discrimination of cosmic neutrinos from the background is based on three methods: 1) the search for an excess of events in a very small solid angle region over the expected background. 2) The search for an excess of events above a given observed energy, using the fact that the expected cosmic signal is harder than the atmospheric neutrino spectrum. 3) The searches for neutrino candidates correlated in space and/or time with external triggers from other experiments. The first method uses the very good tracking capabilities of the detector, which for the ν_μ channel can act as a telescope, with angular resolution of a fraction of degree for $E_\nu > 1$ TeV. The second method uses the calorimetric capabilities: the energy of neutrino induced events (both track and shower events) is estimated from the hits information. Finally, the third multi-messenger method relies on the time resolution and on the networking with other experiments.

2. ANTARES and the cosmic neutrinos seen by IceCube

The scientific framework of neutrino astrophysics has significantly changed after the IceCube (IC) detection of PeV neutrinos in 2013 [4]. This has been followed by the evidences for extraterrestrial high-energy neutrinos [5] using selection criteria leading to the so-called High Energy Starting Events (HESE) sample. The use of the outer detector layers as veto for atmospheric muons and neutrinos guarantees a high-purity sample of cosmic neutrinos above 60 TeV. By increasing the volume of the detector acting as a veto, neutrino interactions has been detected with an energy threshold down to 1 TeV [6].

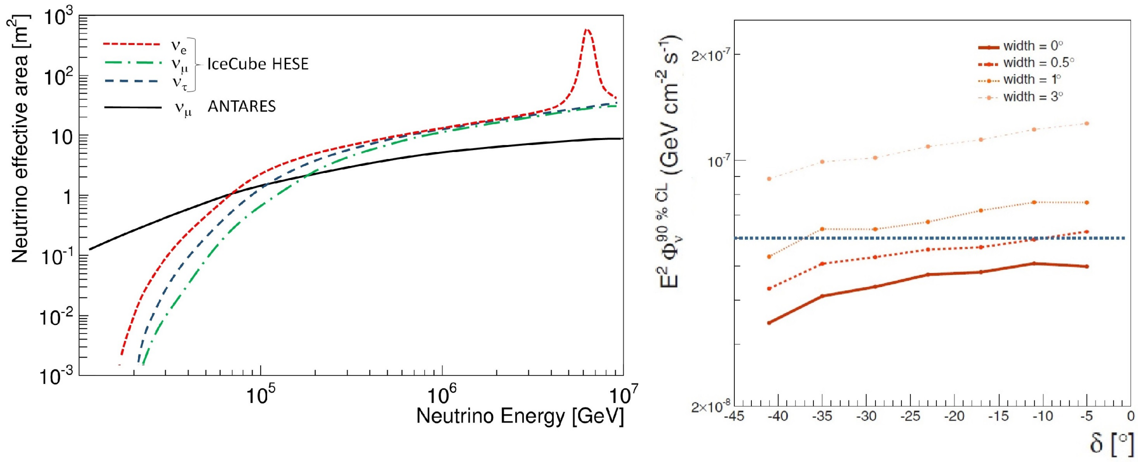

Figure 1: (Left) The red, green and blue lines refer to ν_e, ν_μ and ν_τ neutrino effective area for IC HESE [4]. The black line refers to the ANTARES effective area for the ν_μ flavor obtained in the search for point-like sources [8]. The effective area depends on the cuts of the selection analyses. Event rates can be obtained by folding the assumed ν spectrum with the effective areas. (Right) ANTARES 90% C.L. upper limits for neutrino sources (four different source widths) as a function of the declination [9]. The blue horizontal dashed line corresponds to the signal flux corresponding to a source yielding the seven HESE in the IC hot spot.

Within the present statistics, the IC cosmic neutrino flux is compatible with flavor ratios $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$, as expected from charged meson decays in CR accelerators and neutrino oscillation on their way to the Earth. The non-observation of events beyond 2 PeV suggests a neutrino flux with a power law $\Phi(E) \propto E^{-\Gamma}$ with hard spectral index, e.g. $\Gamma \simeq 2.0$, and an exponential cutoff, or an unbroken power law with a softer spectrum, e.g. $\Gamma \simeq 2.3-2.4$. Different models involving Galactic, extragalactic or exotic origin of the IC signal exist in the literature. Particularly intriguing is the possibility that a sizeable fraction of the cosmic neutrinos observed by IC is originated in our Galaxy [7]. A possible contribution from transient extragalactic objects located in the Southern sky can be considered as well.

The figure-of-merit in the analyses of neutrino telescopes is the quantity called the neutrino effective area, $A_{eff}(E)$, which depends on the neutrino energy. $A_{eff}(E)$ is defined as the ratio between the neutrino event rate in a detector (units: s^{-1}) and the neutrino flux (units: cm^{-2} s^{-1}) at a given energy. It depends on the flavor and cross-section of neutrinos, on their absorption probability during the passage through the Earth, and on detector-dependent efficiencies. Fig. 1 (left) shows the ANTARES effective area, $A^{\nu_\mu}_{ANT}$, for ν_μ emitted by sources located near the declinations of the Galactic Centre, compared with that of IC HESE. $A^{\nu_\mu}_{ANT}$ is larger than that of HESE (irrespectively of the neutrino flavor) at energies below $\sim$ 60 TeV. At the highest energies for the detected neutrinos, 1 PeV, $A^{\nu_\mu}_{ANT}$ is a factor of two larger than that of IC for ν_μ while the total IC effective area $(A^{\nu_e}_{IC} + A^{\nu_\mu}_{IC} + A^{\nu_\tau}_{IC})$ is 7.3 times larger than $A^{\nu_\mu}_{ANT}$.

No hypothesis test on IC cosmic neutrinos yielded statistically significant evidence of clustering or correlations. However, by comparing the number of detected events arising from the Northern and Southern sky regions, taking into account the different effective areas for the two regions, there appears to be an excess of events from the Southern sky [7]. IC is significantly larger than ANTARES in terms of instrumented volume, but the effects of the selection criteria embedded in the event selection reduces its total neutrino effective area. The IC analysis selects a high-purity sample of high-energy neutrinos, with angular resolution of $\sim 1^\circ$ for ν_μ and $\sim 10^\circ \div 15^\circ$ for showering interactions of ν_e, ν_τ. The ANTARES analysis allows a larger contamination of lower-energy atmospheric neutrinos, but enables to reconstruct ν_μ events with superior angular resolution of $\sim 0.4^\circ$. The consequence is that ANTARES has equivalent (or superior, depending on the source spectral index and angular extension) capability to individuate the origin of the possible excess of signal events in the Southern sky, if it is really present. The following considerations rely on the ν_μ sample; the study of neutrino candidates producing showers is currently in progress. At present, the shower reconstruction algorithm reached an angular resolution of $\sim 5^\circ$.

Point-like sources. For a point-like source is intended a source with angular dimension smaller than the detector resolution. The HESE *hot spot* could be originated by a single Galactic point-like source with a normalization factor as large as 6×10^{-8} GeV cm^{-2} s^{-1} for a $E^{-2.0}$ spectrum [10]. ANTARES has considered this hypothesis in [9], where a dedicated study of the Galactic central region was done, producing 90% C.L. upper limits based on a flux spectral index E^{-2} of $\sim 4 \times 10^{-8}$ GeV cm^{-2} s^{-1} (Figure 1, right). This limit excludes that a single point-like source produces the IC hot spot, and can be translated to limits for different spectral indexes [7]. According to this computation, a single point-like source yielding a cluster of more than two HESE is excluded for $\Gamma = 2.3$, while a source producing a cluster of two or more HESE is excluded for $\Gamma > 2.3$.

Enhanced diffuse flux. A second possibility [11] is that the clustering in the HESE *hot spot* originates from a restricted region of the Galaxy, with angular extension smaller or comparable to the IC angular resolution for showering events ($\sim 10^\circ$). As the energy spectrum from a cosmic signal (either point-like or diffuse) is expected to be harder than that of atmospheric neutrinos, the signal should exceed the background above a certain threshold of the reconstructed energy. Thus, the discrimination between signal and diffuse background requires the use of the estimated energy of the event, as ANTARES did for the study of the Fermi Bubble regions [12].

A dedicated search for neutrinos coming from the direction of the IC hot spot is in progress. Fig. 2 (left) shows the expected normalization factors $\Phi_0 = E^{-\Gamma}\Phi_\nu(E)$ for a neutrino spectrum $\Phi_\nu(E)$ necessary to produce from 2 to 6 HESE inside a region of $\theta = 10^\circ$. For different sizes, the normalization factors scale as $\propto \theta^{-2}$. Three spectral indexes ($\Gamma = 2.0, 2.2$ and 2.4) have been considered. The dashed lines represent the ANTARES sensitivities obtained using Monte Carlo simulations for 1250 days. For instance, for $\Gamma = 2.2$ if more than 2 HESE have the same origin in a region of 10°, the expected flux is above the ANTARES sensitivity. The results after unblinding are expected for summer 2015.

The Galactic ridge. A third class of theoretical models for the origin of a Galactic component of the HESE refers to the injection of *fresh* CRs by SNR acceleration followed by escape through the Galactic magnetic field. The induced neutrino flux in a wide region of the Galactic plane has a softer spectral index ($\Gamma \simeq 2.4 - 2.5$) with respect to the Fermi acceleration mechanism ($\Gamma \simeq 2.0$), but harder than the bulk of CRs ($\Gamma \simeq 2.7$). Thus, neutrinos and γ-rays produced by TeV-PeV CRs injected by young (tens of kiloyears old) sources should primarily come from large multi-degrees angular scale regions. The models are constrained by the observed γ-ray flux from Fermi-LAT.

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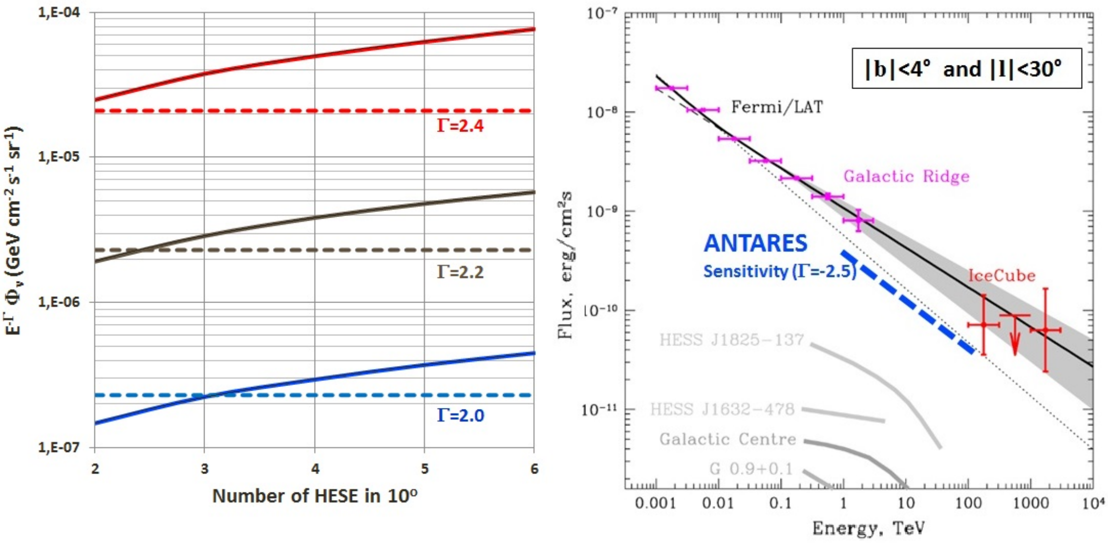

Figure 2: (Left) Normalization factor $\Phi_0 = E^{-\Gamma}\Phi_\nu(E)$ for a neutrino flux yielding from 2 to 6 HESE in a region of 10° radius, computed according to [7]. Three different spectral indexes Γ have been considered. The horizontal dashed lines correspond to the ANTARES sensitivity for 1250 days. (Rigth, adapted from [13]): Comparison of Fermi-LAT and IC spectra in the direction of the inner Galaxy. Magenta data points show the overall γ-ray spectrum in the Galactic Ridge region. Red data points show the estimates of IC neutrino flux > 100 TeV. The ANTARES sensitivity for 1250 days and $\Gamma = 2.5$ is represented by a dashed line.

The right plot of Fig. 2 shows for instance the prediction from the Galactic Ridge region [13] (interval in galactic coordinates $-30^\circ < l < 30^\circ$ and $-4^\circ < b < 4^\circ$, corresponding to a solid angle $\Delta\Omega = 0.15$ sr). The IC neutrino flux compatible to be produced in that region lies right at the power law extrapolation of the γ-ray spectrum measured by Fermi-LAT in the Galactic Ridge. The dashed line represent the evaluated ANTARES sensitivity for $\Gamma = 2.5$ and for 1250 days. Other models [14] give neutrino yields that are also above the ANTARES sensibility. The unblinding of the data (Summer 2015) will enable to confirm or constraint these models.

Transient phenomena in blazars. The three IC PeV neutrino events have stimulated particular interest in the astrophysical community, in particular for possible spatial-temporal coincidences with known blazars. The TANAMI collaboration recently has shown [15] that the first two PeV events detected during the first two years of IC are consistent with the integrated energy output of six blazars that are consistent in direction with these events. The subsequent analysis of ANTARES data shows that each of the two blazars predicted to be the most neutrino-bright in the TANAMI sample (1653-329 and 1714-336) has a signal flux fitted by the likelihood analysis corresponding to approximately one ANTARES event, while the other four have no associated events [16]. This observation is consistent with the blazar-origin hypothesis of the IC event IC14 for a broad range of blazar spectra, although the result is also consistent with random background fluctuations. The TANAMI collaboration searched for spatial correlations with the third PeV IC event and blazars in high state. The search for neutrino candidates in ANTARES in correspondence with the TANAMI selected blazars is in progress.

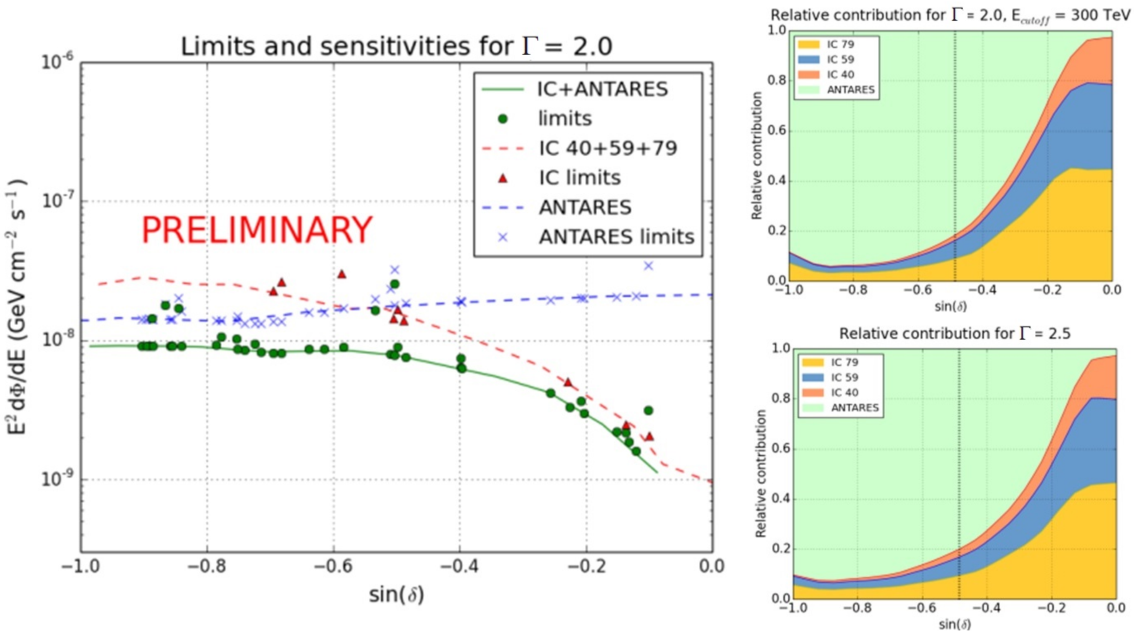

Figure 3: (Left) ANTARES, IC and combined ANTARES+IC sensitivities (continuous lines) and upper limits on some selected sources (points). (Right) Fraction of ANTARES and IC events contributing to a signal for a different spectral index $\Gamma = 2.0$ and energy cutoff at 300 TeV (top) and for $\Gamma = 2.5$ (bottom) of a point-like neutrino source, as a function of the declination. ANTARES sensitivity clearly dominated at low energy (softer spectra) for a large part of the Southern Sky.

Combined searches with IceCube. The ANTARES search for cosmic neutrino sources using six years of data gives no significative excess [9]. The most signal-like accumulation of events at $R.A. = -46^\circ.8$ and declination $= -64^\circ.9$ corresponds to a 2.2σ background fluctuation. In addition, upper limits on the flux normalization of an E^{-2} muon neutrino energy spectrum have been set for 50 pre-selected astrophysical objects. An improved sensitivity was reached by a combined analysis using data from 6 years of ANTARES with 3 years of IceCube (paper in preparation). The ANTARES data complement the IceCube data in the Southern Hemisphere in particular at low energies; thus ANTARES dominates the sensitivity especially for sources with soft energy spectra or energy cut-offs, Fig. 3. No significant excess was found in the analysis and limits on the neutrino flux were set for spectral indices ranging from $\Gamma = 2.0$ to 3.0 and energy cut-offs ranging from 30 TeV to 1 PeV. The combined limits for assumed E^{-2} spectra are in the Southern Hemisphere around a factor 1.5 lower than the ANTARES limits alone.

3. Multimessenger astrophysics and transient phenomena

Transient phenomena are particularly promising, since observations in the high-energy gamma spectrum (e.g. Fermi-LAT experiment in the GeV and IACTs in the TeV energy range) have shown that the high-energy universe is extremely variable. In addition, restricting the searches to well-defined space-time windows decreases considerably the background.

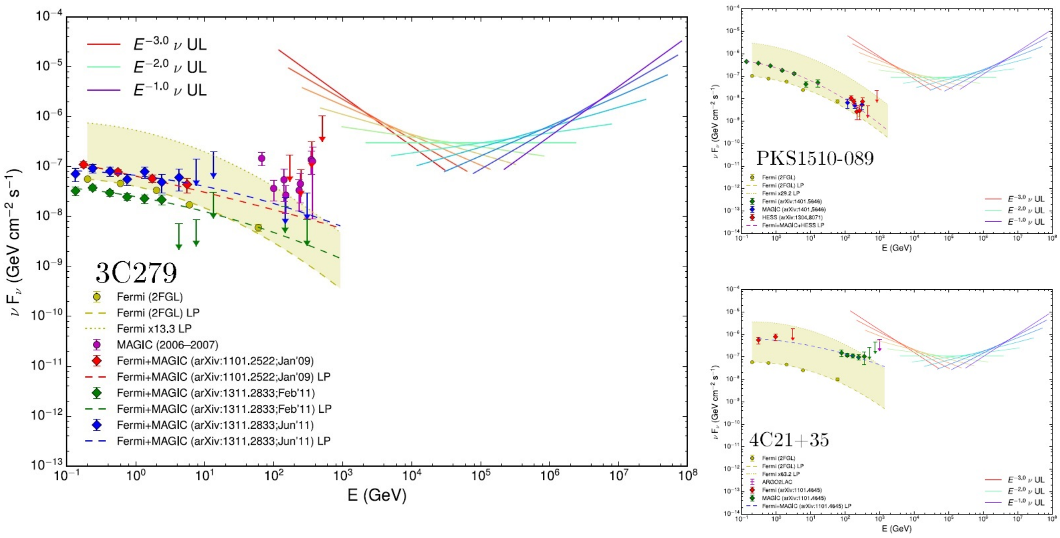

Figure 4: γ-ray SED of blazar 3C279 observed by Fermi-LAT at different epochs. The yellow dots are the average flux with 2008-2010 data (2FGL). The dashed lines represent the fits performed on Fermi data using a log-parabola (LP) and power-law (PL) functions. The shaded area represents an extrapolation of the flux during the studied flares from the average flux observed by LAT. The colored solid lines indicates the ANTARES neutrino upper-limits for different spectral indexes (from E^{-3} in red to E^{-1} in blue).On the right, hybrid SED of two additional very bright Fermi blazars: PKS1510-089 and 4C21+35.

The search for associations in time and direction are particular important for the search for ν_μ signals in coincidence with γ-ray bursts (GRBs) [17]. Here, the selection criteria have been optimized for the NeuCosmA [18] model that provides a more detailed treatment of the particle physics involved in calculating the neutrino spectra. Our search has used 296 long GRBs detected by Fermi, SWIFT and the GCN with a total prompt emission time of 6.6 hours. No events has been found within a 10° window from GRBs. The expectations were 0.48 and 0.061 events for the Guetta and the NeuCosmA models, respectively. A dedicated analysis with negative result has been made for GRB130427, one of the brightest GRB detected so far.

Null results have been also obtained from the search for neutrinos in coincidence with micro-quasars observed by the Rossi RXTE and the Fermi-LAT detectors [19]. In the extension of this analysis, we have found one coincident event with outburst periods of GX 1+4 and IGRJ17091-3624 but these associations are not significant.

An analogous search for neutrinos associated to flares of blazars has selected 41 sources observed by Fermi-LAT and additional 7 TeV sources reported by Air Cherenkov telescopes. The most significant correlation has been found with a flare observed by LAT for the blazar 3C279 for which one neutrino event was detected in time/spatial coincidence with the γ-ray emission. However, this event had a post-trial probability of 67%, and is thus compatible with background fluctuations. Upper-limits were obtained on the neutrino fluence for the selected sources and compared with the high-energy component of the spectral energy distributions (SED) computed with GeV-TeV γ-ray observations (examples in Fig. 4, paper in preparation). These comparisons show that for the brighter blazars, the neutrino flux limits are in the same order of magnitude as the high-energy γ-ray fluxes.

The optical follow-up is operating continuously. ANTARES sends out alerts that are used by optical robotic telescopes in the search for transient phenomena. The robotic telescope systems that are at present receiving alerts from ANTARES are TAROT [20], ZADKO (located in Australia) and IRiS (60 cm telescope in the South of France). Recently, the robotic telescope network has been upgraded with the five MASTER telescopes, four located in Russia and one in South Africa. The main advantages of this network are a very large field-of-view ($2^\circ \times 4^\circ$) and a large availability. ANTARES neutrino alerts can thus be followed by nine robotic telescopes. Since 2009, around 136 alerts have been sent to the telescopes out of which 109 have exploitable optical data. The time delay between the neutrino detection and the first image acquired by the telescope can be as low as 20 s. In Mid 2013, the follow-up program to send alerts to the XRT telescopes (0.2-10 keV) on board the SWIFT satellite has been set and the X-ray telescope has followed six ANTARES alerts. A paper discussing the first results is in preparation.

Long and short GRBs, as well as other cataclysmic cosmic events can be plausible sources of both gravitational waves (GW) and high energy neutrinos (HEN), cosmic messengers carrying information from the innermost regions of the astrophysical engines. In 2013, the ANTARES and LIGO/Virgo collaborations published an article [21] reporting the first GW+HEN joint analysis, presenting limits on the population density of joint emitters. The LIGO/Virgo interferometers used the time and direction of HEN candidates selected by ANTARES in its 5-line configuration to look for possible GW counterparts with an increased sensitivity with respect to an all-sky search. A second paper using data taken by ANTARES 12-line and by the LIGO/Virgo interferometers with enhanced sensitivities in 2009-2010 is in preparation.

4. Search for neutrino from Dark Matter Annihilation

A common assumption is that dark matter is made of Weakly Interacting Massive Particles (WIMPs) that form halos in which the visible baryonic part of galaxies is embedded. There is a variety of candidates for WIMPs, among which those provided by theories based on supersymmetry (SUSY) attract a great deal of interest. In some models, the lightest SUSY particle (LP) is stable thanks to the conservation of a model-dependent conserved quantum number that forbids its decay into standard model particles. Consequently, these LPs can only annihilate in pairs, making them a possible WIMP candidate for dark matter. Dark matter particles would accumulate in massive objects (the Sun, the Galactic centre) and secondary high-energy neutrinos are produced from the decay of the LPs' self-annihilation products.

ANTARES has searched for high-energy neutrinos coming from the direction of the Sun [22] and from the Galactic Centre [23]. The event selection criteria have been chosen to maximise the sensitivity to possible signals produced by the self-annihilation of WIMPs accumulated in the Sun core or around the centre of the Milky Way with respect to the atmospheric background. Compared to direct searches, the sensitivity of neutrino telescopes to probe the spin-dependent cross section of WIMP-proton is unsurpassed. This is due to the high density of hydrogen in astrophysical objects, in particular in the Sun.

The search for an excess of events from the direction of the GC uses data recorded from 2007 to 2012. To compute the initial energy spectra at the GC, five benchmark self-annihilation channels

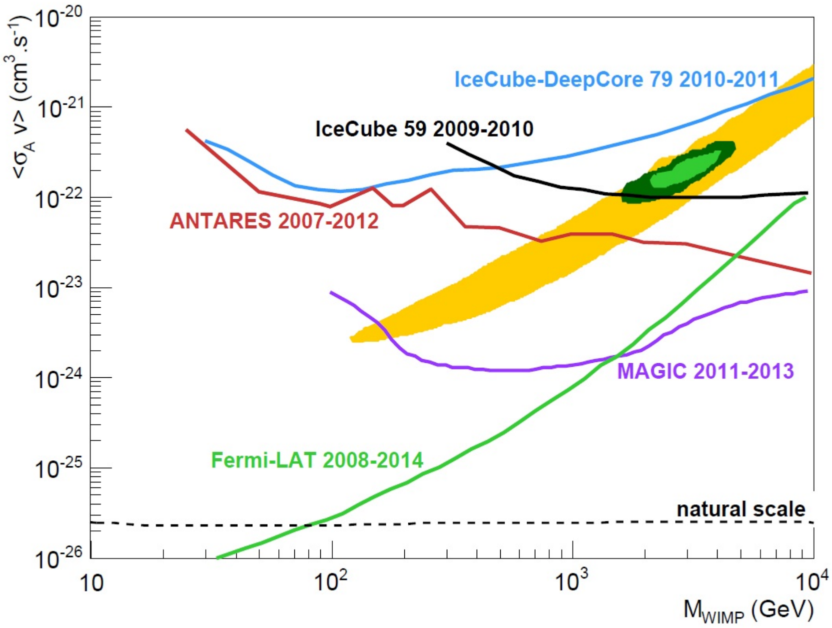

Figure 5: ANTARES 90% C.L. upper limit on the WIMP velocity averaged self-annihilation cross-section, $\langle\sigma v\rangle$, as a function of the WIMP mass in the range 25 GeV $< M_{WIMP} <$ 10 TeV for the WIMP WIMP $\rightarrow \tau^+\tau-$. The results of other experiments are also indicated, see [23].

of WIMP-like dark matter particles into SM particles have been simulated ($b\bar{b}$, W^+W^-, $\tau^+\tau^-$, $\mu^+\mu^-$, $\nu_\alpha\bar{\nu}_\alpha$). The flux of final state neutrino to the Earth includes the effect of oscillation. As no statistically significant excess is observed in the direction of the GC, upper limits on a neutrino flux are set. The upper limit on the neutrino flux are translated into an upper limit on the WIMP velocity averaged self-annihilation cross-section, $\langle\sigma v\rangle$, assuming a given density profile of dark matter and other astrophysical factors. Figure 5 shows the result for the self-annihilation channel WIMP WIMP $\rightarrow \tau^+\tau^-$ compared with other neutrino and γ-ray experiments.

5. Conclusions

The ANTARES neutrino telescope is the first and only deep-sea neutrino telescope currently in operation. Since 2007, it has continuously monitored the declination band $[-90°; +48°]$, which includes the galactic centre, with unprecedented sensitivity. Several searches for neutrinos of astrophysical origin have been performed. An extended multi-messenger program complements and expands its astrophysics reach.

The present focus is to help to understand the origin (galactic, extragalactic, mixed?) of the IC cosmic neutrino signal. ANTARES has already constrained many hypothesis on the origin from point-like objects in the Southern sky of part of the IC signal. With the full data set, at the end of 2016, the sensitivity will be enough to exclude that a single point source produces more than 3 (2) events for spectral index $\Gamma = 2.0$ (≥ 2.2). Particularly intriguing is the hypothesis of an enhanced diffuse flux from small (the IC hot spot, region with solid angle < 0.1 sr) or extended

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(Fermi bubbles, Galactic plane) regions. The neutrino production on extended regions in the recent literature is strongly connected with CR acceleration and diffusion models and constrained by observations of CRs and γ-rays on satellites and ground-based experiments. ANTARES sensitivity will allow (results expected in summer) to confirm or constrain these models. ANTARES can also test the hypothesis that a fraction of the IC signal (namely, the events of the highest energy) is due to specific known sources such as blazars in high state.

ANTARES covers also different particle physics topics, as indirect searches for dark matter, searches for exotic or fossile particles. ANTARES paves the way to a multi-km^3 neutrino telescope in the Northern Hemisphere, KM3NeT [24], to complement IceCube. More competitive results are expected in the future as ANTARES will continue taking data and improving the results at least until the end of 2016.

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