PROCEEDINGS OF SCIENCE

# ANTARES Results

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Neutrino telescopes are powerful tools to study the high energy Universe, since these particles are neutral and weakly interacting. This allows these detectors to explore a wide scientific scope, including the origin of cosmic rays and the nature of dark matter. The ANTARES detector, completed in 2008, has produced a rich sample of results during these years, including search for point sources, transient sources, diffuse fluxes, dark matter, neutrino oscillations and other exotic cases like magnetic monopoles.

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## 1. Introduction

Neutrino astronomy is opening a new window to the Universe, which will help us to understand many relevant issues in a unique and complementary way with respect to other traditional probes like cosmic rays and photons. Neutrinos are neutral and weakly interacting, which allows them to travel cosmic distances without being absorbed or deflected by magnetic fields. These extraordinary characteristics translate into a wide range of scientific goals for neutrino telescopes. One of the main contributions from neutrino astronomy will be to help to understand the origin of cosmic rays. This is a very long question in physics (more than one hundred years old by now) which needs new observational tools to be answered, since the fact that cosmic rays are charged prevent them to keep the directional information needed to identify their sources. Another interesting question to which neutrino telescopes will provide clues is the hadronic versus leptonic origin of the gamma rays observed from many astrophysical sources. Neutrinos are only expected in the former case, so their detection would be a definitive proof of the hadronic contribution. Another outstanding contribution from neutrino telescopes can come from the detection of dark matter. The list of scientific motivations continues and the ANTARES detector has already produced a rich output with the data gathered in the last years, as we will see in this proceeding.

The structure of this paper is as follows. First, the ANTARES neutrino telescope and its the detection principle will be described in section 2. The results of different analyses will follow: time-integrated point sources (section 3), diffuse fluxes (section 4), transient sources (section 5), dark matter (section 6), neutrino oscillations (section 7) and other searches (section 8). Finally, the conclusions will be summarized.

## 2. The ANTARES detector

The operation principle of neutrino telescopes is based on the detection of the Cherenkov light induced by relativistic muons produced in the charged interactions of high energy neutrinos in/around the detector. The time and position information of the detected Cherenkov photons allow for the reconstruction of the muon track, which at high energies (above 1 TeV) points to the direction of the original neutrino. There are also other interesting channels, like the showers produced via neutral currents for all neutrino flavors and via charged current interactions for electronic and tau neutrinos.

For this kind of detectors there are two types of physical background. First, the atmospheric muons produced by the interactions of cosmic rays in the atmosphere. The downgoing flux of these muons is huge, but the upgoing flux is basically null since the Earth filters them out, so the selection of only upgoing events makes this background manageable. However, the downgoing atmospheric muons which are wrongly reconstructed as upgoing (small in fraction but large in number given the huge flux involved) have also to be reduced by selecting only events with a high reconstruction quality. In addition to the atmospheric muons, the other source of background are the atmospheric neutrinos. These ones are also produced in the interactions of cosmic rays in the atmosphere but they are not absorbed by the Earth. The technique to reject such background depends on the analysis, as we will see.

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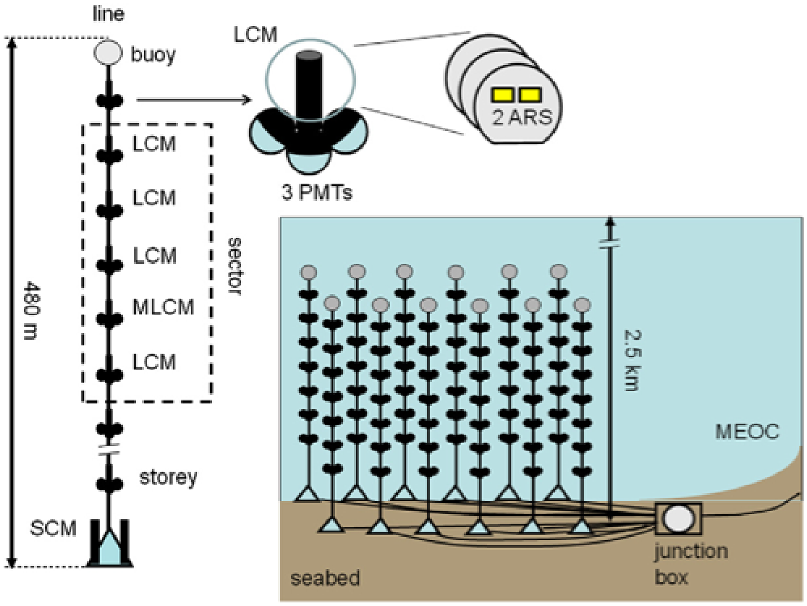


**Figure 1:** Schematic view of the ANTARES detector. 885 PMTs are installed in 12 lines anchored to the sea bottom. An electro-optical cable provides power and signal transmission.

The ANTARES detector [1], completed in 2008, is located 2500 m deep in the Mediterranean Sea, at about 40 km of Toulon, in the French coast. It consists of 885 PMTs distributed along 12 vertical lines anchored to the sea bottom and kept taut by a buoy in the top. The PMTs are grouped in triplets, forming 25 floors in each line, which have a length of about 450 m. The distance between lines is of 60-75 m. A scheme of the detector is shown in figure 1. The lines are connected to a hub called "junction box", where an electro-optical cable is also connected to provide power to the detector and data transmission with the shore station, located in La Seyne sur Mer. A set of hydrophones is used in order to monitor the position of the elements of the lines by acoustic triangulation. An accuracy of 15 cm is reached [2]. Moreover, a system of LED sources and a laser beacon allows for the time calibration of the detector at the level of 1 ns [3, 4].

## 3. Point sources

The search for cosmic neutrino point sources is one of the main goals of the ANTARES detector. The analysis is based on identifying clusters of events with a number of events above what is expected from the background, using a likelihood ratio technique, in which the reconstructed direction and the number of hits of the events are used. Two complementary search strategies have been used: an all-sky scan and a search at the location of 50 neutrino candidate sources. The most recent analysis corresponds to 2007-2012 data. For the all-sky search the most significant cluster, with 6 (14) events within a cone of $1^\circ$ ($3^\circ$), is located at $(\alpha,\delta) = (-47.8^\circ, -64.9^\circ)$, with a post-trial p-value of 2.7% (i.e. $2.2\sigma$ significance). For the list of sources, the best candidate, with a fitted number of signal events of 1.7, is HESS J0632+057. The post-trial p-value is 6.1% ($1.9\sigma$). The pre-trial significance map and the limits for the candidate sources are shown in figure 2. See [5, 6] for more details.

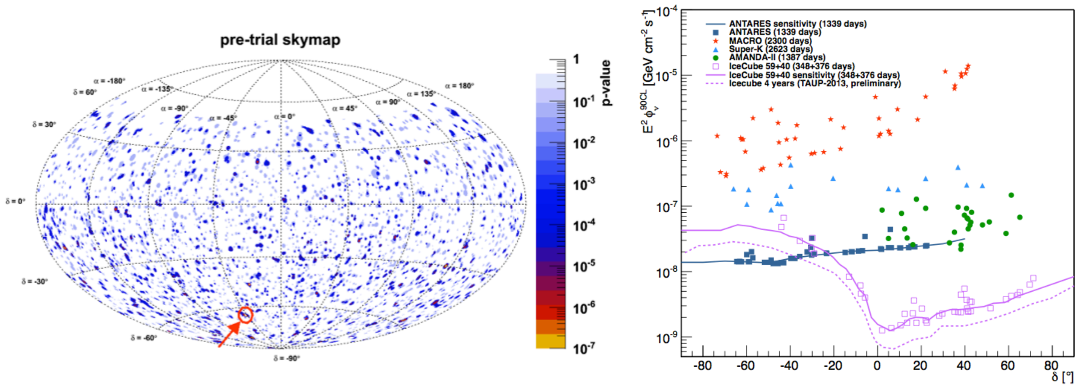


**Figure 2:** Left: Skymap (equatorial coordinates) of pre-trial p-values obtained in the all-sky search. The arrow indicates the location of the most significant cluster. Right: Neutrino flux upper limits (90% c.l.) set by ANTARES with 2007-2012 data. The sensitivity (average upper limit) is also shown. Other limits set by different experiment are also shown for reference. An $E^{-2}$ spectrum is assumed. (Preliminary).

## 4. Diffuse fluxes

As an alternative to the search for point sources, we can also look for an excess in the the diffuse flux produced by unresolved sources. In this his approach, we do not use the event location information but we can integrate the flux of all visible sky. The key of the analysis is to use the fact that the energy spectrum for cosmic signals is expected to be harder than the background, so a selection of the most energetic events is done. No such excess has been found above the background, so upper limits on the cosmic neutrino flux at $E^2\Phi_{90\%} = 4.8 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ in the energy range 45 TeV - 10 PeV have been set (using 2008-2011 data) as indicated in figure 3 (left). A detailed description of the previous analysis (2008-2009 data) can be found in [7]. The atmospheric $\nu_\mu + \bar{\nu}_\mu$ spectrum have also been measured using deconvolution techniques, as shown in figure 3 (right) [8].

## 5. Transient sources

There are many astrophysical sources which show high variability. This includes both cases in which there are flares in the emission (like blazars) as other one-event cases (like gamma ray bursts). The fact that the emission is expected to be concentrated in short time windows allows to reduce the expected background significantly.

### 5.1 Blazars

Blazars are a particular case of active galactic nuclei (AGNs). AGNs are galaxies with a super-massive black hole ($10^{6-8}$ solar masses) towards where is accretion of matter which forms perpendicular jets. When one of these jets points towards the observer, it is called blazar. Protons are expected to be accelerated in the jets and produce high energy neutrinos, in particular during the flaring periods. Data of 2008-2011 have been used in order to look for correlations of neutrino events with the locations and emission times of 40 of the most brilliant flares detected by Fermi [9]

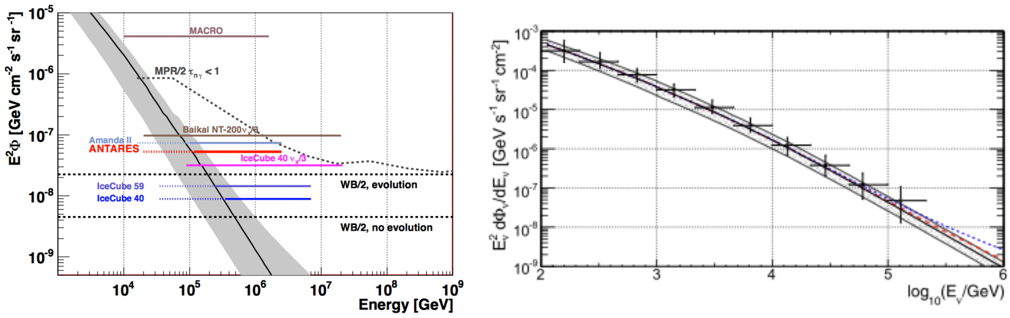


**Figure 3:** Left: ANTARES upper limit (90% C.L.) for a $E^2$ diffuse high energy muon-neutrino flux (red line), compared to 90% CL upper limits from other experiments. The MACRO, Amanda-II, IC40, IC56 limits refer to $\nu_\mu$. The Baikal NT-200 and IceCube 40 $\nu_x$ refer to neutrinos of all-flavors, and are divided by 3. For reference, the W&B (with and without evolution) and the MPR for transparent sources limits are also shown. They are divided by two, to take into account neutrino oscillations. (Preliminary). Right: Atmospheric neutrino energy spectrum obtained with the ANTARES neutrino telescope using 2008-2011 data, compared with theoretical expectations, where the solid line is the conventional atmospheric neutrino flux and the dashed lines are for the contribution from prompt neutrinos. The gray band indicates in the uncertainty in the conventional prediction (see [7, 8] for details about the corresponding references).

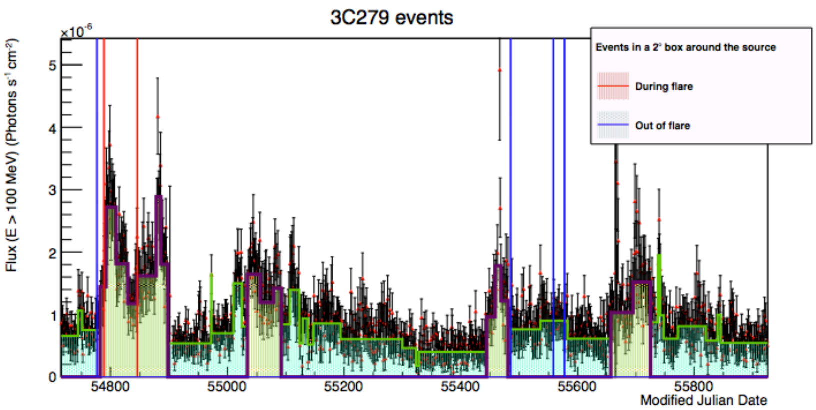


**Figure 4:** Light curve of 3C279 during its brightest flare, as seen by Fermi. The red lines display the time of the two ANTARES events associated with the source. The blue lines show the rest of the events in a two degree box around the source position (more details in [9]. (Preliminary)

(see [10] for a detailed description of the analysis with 2008 data). The lowest pre-trial p-value (0.3%) corresponds to 3C279. The post-trial p-value of the whole analysis is 12%, compatible with background. Figure 4 show the light curve of 3C279.

### 5.2 Gamma Ray Bursts

Gamma ray bursts (GRBs) are the most violent events in the Universe. They are characterized by a short (tenths of second to minutes) explosion in gamma rays, followed by a so-called afterglow in other wavelengths. They are believed to be produced by the collapse of super-massive stars (the long ones) or the merging of compact objects (the short ones). They are among the most favoured candidates to explain the high energy cosmic rays and they are also expected to produce high

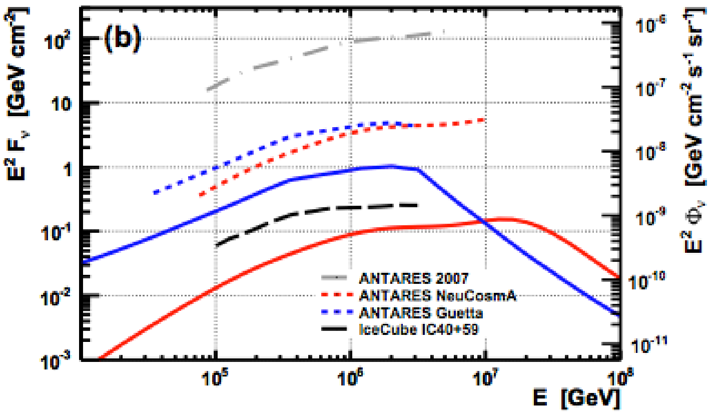


**Figure 5:** Sum of the 296 individual gamma-ray-burst muon neutrino spectra (red and blue solid lines) and limits set by ANTARES (2008-2011 data) on the total flux expected from the sample (red and blue dashed lines). The IceCube IC 40+IC 59 limit on the neutrino emission from 300 GRBs and the first ANTARES limit from 2007 using 40 GRBs are also shown in black (dashed) and grey (dash-dotted), respectively. The right-hand axis represents the inferred quasi-diffuse flux limit $E^2\Phi_\nu$.

energy neutrinos. The most recent analysis with ANTARES data comprises 296 GRB explosions (2008-2011 data). No excess over background has been found and upper flux limits have been set (see figure 5) [11].

## 6. Dark matter

Different experimental data point out towards a picture of the Universe in which about four fifths of the matter is made of a kind of particles not discovered yet. A general candidate fulfilling the required properties are the Weakly Interacting Particles (WIMPs). An example of WIMP realization is the lightest neutralino, which arises as a feasible dark matter candidate in SuperSymmetry models in which the R-parity is conserved. Alternative WIMP possibilites are the lightest Kaluza-Klein particle, from Universal Extra-Dimension theories. If WIMPs exist, they would scatter with nuclei in the Sun or the Earth and could become gravitationally trapped. The increase in the WIMP density in these objects would produce self-annihilations which would subsequently produce high energy neutrinos, detectable by ANTARES. Alternatively, high WIMP densities are also expected in the Galactic Centre, which could also translate into detectable neutrino signals. The most recent results of ANTARES, using 2007-2012 data from the Sun, have constrained the WIMP-nucleus scattering cross-section, as shown in figure 6 for the case of spin-dependent interaction (for which neutrino telescopes are particularly powerful with respect to other searches). See [12, 13] for more details.

## 7. Neutrino oscillations

ANTARES is not designed for a precise measurement of the neutrino oscillation parameters, since the oscillation effect is more evident at energies in the low regime of the ANTARES sensitivity. However, the energy threshold can be lowered up to 20 GeV by using events reconstructed

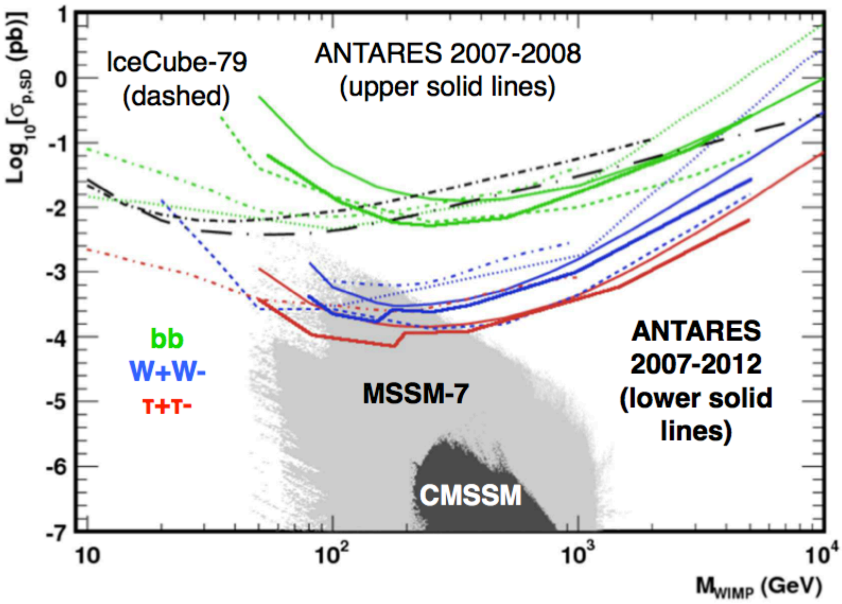


**Figure 6:** 90% CL upper limits on the spin dependent WIMP-proton cross-section as a function of the WIMP mass, for the three self-annihilation channels: $b\bar{b}$ (green), $W^{+}$+$W^{-}$ (blue) and $\tau^{+}$ $\tau^{-}$ (red), for ANTARES (solid line: upper, 2007-2008; lower, 2007-2012) compared to the results of other experiments: Baksan 1978-2009 (dash-dotted), Super-Kamiokande 1996-2008 (dotted), IceCube-79 2010-2011 (dashed), SIMPLE 2004-2011 (short dash-dot), COUPP 2010-2011 (long dash-dot). The results of a grid scan of the CMSSM and MSSM-7 are included (dark and light grey shaded areas respectively) for the sake of comparison. (Preliminary).

with only one line, since the azimuth information is not needed for this analysis and fitting the distribution of the neutrino energy over the zenith angle. With this strategy, the effect of oscillations has been observed for the first time with this kind of detectors, obtaining $\Delta m^2_{32} = (3.1 \pm 0.9)10^{-3}$ eV$^2$, if maximal mixing is imposed, as shown in figure 7. See [14] for more details.

## 8. Other searches

The scientific harvest of ANTARES since the beginning of data acquisition extends beyond the results presented above. In the following, we summarize briefly other results.

### 8.1 Fermi Bubbles

The so-called Fermi Bubbles are two almost spherical structures ($\sim$10 kpc size) located above and below the Galactic Plane next to the Galactic Centre. The data from Fermi-LAT indicate gamma emission with a hard and uniform spectrum. Different theoretical models try to explain these observations through hadronic mechanisms, which infers also neutrino production. The ANTARES location offers a very good visibility of most of these structures. The analysis is based on the comparison of the number of events in the on-source region with three equivalent off-source regions. Using data of 2008-2011, 16 events were found in the on-source region, to be compared with a total of 9+12+12 events in the off-source regions (1.2$\sigma$ excess), so upper limits on this flux have been set, as shown in figure 8, for different energy cut offs.

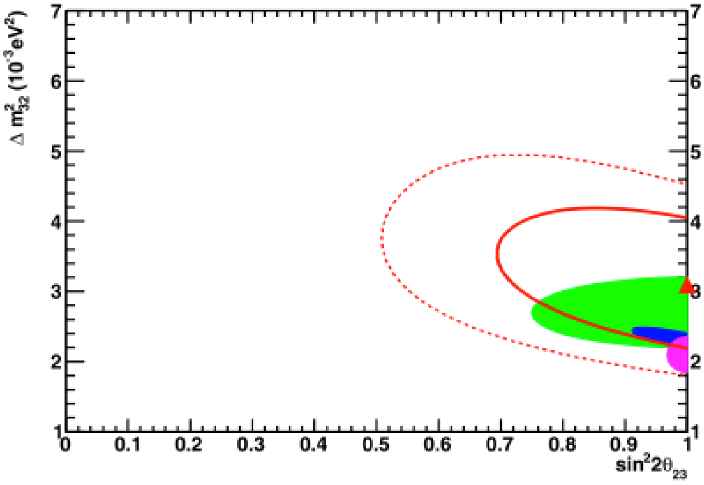


**Figure 7:** 68% and 90% C.L. contours (solid and dashed red lines) of the neutrino oscillation parameters using 2007-2010 data. The best fit point is indicated by the triangle. The solid filled regions show results at 68% C.L. from K2K (green), MINOS (blue) and Super-Kamiokande (magenta) for comparison.

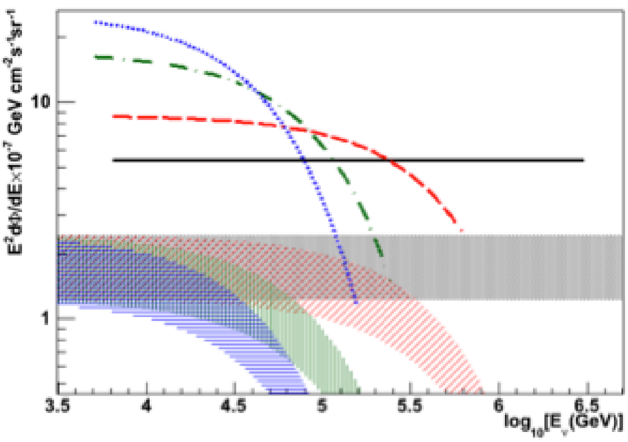


**Figure 8:** Upper limits on the neutrino flux from the Fermi bubbles for different cutoffs: no cutoff (black solid), 500 TeV (red dashed), 100 TeV (green dot-dashed), 50 TeV (blue dotted). These limits are compared with the theoretical predictions for the case of a purely hadronic model (the same colours, areas filled with dots, inclined lines, vertical lines and horizontal lines respectively). (Preliminary).

### 8.2 Gravitational waves

Both high energy neutrino and gravitational wave signal are expected in several catastrophic astrophysical events. In some cases, like chocked GRBs, the signal in other channels could be weak. The chances to detect a signal in these cases can be improved by a joint search of neutrinos and gravitational waves. This has been pursued using data of ANTARES and from detectors like VIRGO and LIGO. The negative results of this analysis allows us, for example, to set distance exclusions for compact object merging, as shown in figure 9 [16].

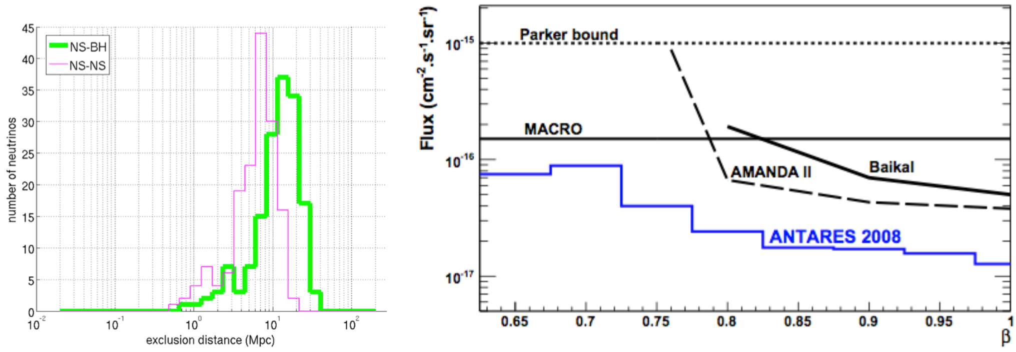


**Figure 9:** Left: Distance exclusions for the two families of binary inspiral models considered: NS-NS and BH-NS (more details in [16]). Right: 90% C.L. upper limit on an upgoing magnetic monopole flux for relativistic velocities $0.625 \leq \beta \leq 0.995$, compared to the theoretical Parker bound, the published upper limits obtained by MACRO (isotropic), Baikal (upgoing) and AMANDA (upgoing) (see [17] for more details).

### 8.3 Magnetic monopoles

Magnetic monopoles are predicted in spontaneously broken gauge theories. The signal in ANTARES would be look like a very bright ($\sim$8500 times more light yield than a muon) and slow event. The lack of positive signal in this analysis has set upper flux limits at 1-9$\times 10^{-17}$cm$^{-2}$ s$^{-1}$ sr$^{-1}$ [17], as shown in figure 9.

## 9. Conclusions

The neutrino astronomy is starting a new, exciting era. The ANTARES neutrino telescope has produced a rich collection of results, showing the wide scientific potential of these kind of detectors. The list is long and includes the search for steady point like sources, diffuse fluxes, blazars, gamma ray bursts, microquasars, correlations with gravitational waves, correlations with UHE cosmic rays, dark matter, oscillations, monopoles, nuclearites... Moreover, the technical success of the experiment also strongly supports the pursuit of the following step, a cubic kilometer detector in the Northern Hemisphere.

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## References

[1] J. A. Aguilar *et al.*, ANTARES Collaboration, *ANTARES: the first undersea neutrino telescope*, Nuclear Instrum. Meth. in Physics Research, **A 656** (2011), 11-38, [arXiv:1104.1607v1].

[2] S. Adrián-Martínez *et al.*, ANTARES Collaboration, *The positioning system of the ANTARES neutrino telescope*, JINST **7** (2012), T08002, [arXiv:astro-ph/1202.3894].

[3] M. Acheron *et al.*, ANTARES Collaboration, *The ANTARES optical beacon system*, Nucl. Instrum. Meth. **A 578** (2007) 498-509, [arXiv:astro-ph/0703355].

[4] J. A. Aguilar *et al.*, ANTARES Collaboration, *Time Calibration of the ANTARES neutrino Telescope*, Astropart. Phys. **34** (2011) 539-549, [arXiv:1012.2204].

[5] S. Adrián-Martínez *et al.*, ANTARES Collaboration, *Search for cosmic neutrino point sources with four year data of the ANTARES telescope*, Astrophysics J., **760** (2012) 53, [arXiv:1207.3105].

[6] S. Schulte, *Update on the ANTARES full-sky neutrino point source search*, Proceedings of the 33rd ICRC (2013), Rio de Janeiro.

[7] J. A. Aguilar *et al.*, ANTARES Collaboration, *Search for a diffuse flux of high-energy $\nu_\mu$ with the ANTARES neutrino telescope* , Phys. Lett. **B696**, (2011), 16-22, [arXiv:1011.3772].

[8] S. Adrián-Martínez *et al.*, ANTARES Collaboration, *Measurement of the atmospheric $\nu_\mu$ energy spectrum from 100 GeV to 200 TeV with the ANTARES telescope*, Eur. Phys. J. C (2013) 73:2606, [arXiv:astro-ph/1308.1599].

[9] D. Dornic *et al.*, *Search for neutrino emission of gamma-ray flaring blazars with the ANTARES telescope*, Proceedings of the 33rd ICRC (2013), Rio de Janeiro.

[10] S. Adrián-Martínez *et al.*, ANTARES Collaboration, *Search for Neutrino Emission from Gamma-Ray Flaring Blazars with the ANTARES Telescope*, Astropart. Phys. **36**, (2012) 204âĂŞ210, [arXiv:1111.3473].

[11] S. Adrián-Martínez *et al.*, ANTARES Collaboration, *Search for muon neutrinos from gamma-ray bursts with the ANTARES neutrino telescope using 2008 to 2011 data*, A&A 559, A9 (2013), [arXiv:astro-ph/1307.0304].

[12] J.J. Hernández and G. Lambard, *Indirect Search for dark matter with the ANTARES neutrino telescope*, Proceedings of the 33rd ICRC (2013), Rio de Janeiro.

[13] S. Adrián-Martínez *et al.*, ANTARES Collaboration, *First Results on Dark Matter Annihilation in the Sun using the ANTARES Neutrino Telescope*, Accepted at JCAP, [arXiv:astro-ph/1302.6516]

[14] S. Adrián-Martínez *et al.*, ANTARES Collaboration, *Measurement of Atmospheric Neutrino Oscillations with the ANTARES Neutrino Telescope*, Phys. Lett. **B714** (2012), 224-230, [arXiv: 1207.3105].

[15] V. Kulikovskiy, *A search for Neutrino Emission from the Fermi Bubbles with the ANTARES Telescope*, Proceedings of 33rd ICRC (2013), Rio de Janeiro.

[16] S. Adrián-Martínez *et al.*, ANTARES, VIRGO and LIGO Collaboration, *A First Search for coincident Gravitational Waves and High Energy Neutrinos using LIGO, Virgo and ANTARES data from 2007*, [arXiv:1205.3018].

[17] S. Adrián-Martínez *et al.*, ANTARES Collaboration, *Search for Relativistic Magnetic Monopoles with the ANTARES Neutrino Telescope*, Astropart. Phys. **35** (2012), 634-640, [arXiv:1110.2656].