ANTARES Results

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On behalf of the
ANTARES Collaboration

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First cosmic HE neutrino signal detected by IceCube

After several decades of scientific and technical efforts

What can ANTARES say?
Highlighted topics

• Diffuse fluxes
  – full-sky (tracks and showers)
  – Fermi Bubbles

• Point sources
  – Full-sky and selected candidates
  – near the Galactic Centre

• Multi-messenger searches

• Dark Matter
  – Sun, Galactic Centre

Left out: neutrino oscillations, magnetic monopoles, multi-messenger searches with optical devices, GWHEN (VIRGO/LIGO), dark matter: dwarf galaxies, Earth, secluded DM, nuclearites, associated sciences,…
The ANTARES Telescope

- 12 lines (885 PMTs)
- 25 storeys / line
- 3 PMTs / storey
- 5-line setup in 2007
- Completed in 2008

In the Mediterranean Sea (near Toulon) at 2500 m depth
**Diffuse fluxes – Shower analysis**

- **Good runs**
  
  Period: 29 Jan 2007 to 31 December 2012
  
  Good detector + environmental conditions
  
  Total livetime: 1247 days
  
  Burn sample: 135 days.

- **Shower reconstruction algorithm**

  Good reconstruction efficiency

  Compares well with simulation: ("run-by-run Monte Carlo" with environmental conditions simulated)

- **Selection chain:**

  Muon filter → Hits > 2 lines → No spark events

  Fitted zenith > 94° + \( E_{\text{shower}} > 10 \text{ TeV} \)

- **Sensitivity per neutrino flavour:**

  \[ E^2 \cdot \Phi_{90\%} = 2.21^{+0.87}_{-0.73} \cdot 10^{-8} \text{ GeV/cm}^2 \cdot \text{sr} \cdot \text{s} \]

**EVENT NUMBERS AFTER FINAL OPTIMIZED CUTS**

<table>
<thead>
<tr>
<th>Cosmic signal events</th>
<th>Atmospheric background events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic signal (test flux 1.2 ( \times 10^8 ) per flavour)</td>
<td>1.75</td>
</tr>
<tr>
<td>Conventional atmospheric neutrinos</td>
<td>-</td>
</tr>
<tr>
<td>Prompt atmospheric neutrinos</td>
<td>-</td>
</tr>
<tr>
<td>Tau neutrino estimation</td>
<td>0.78</td>
</tr>
<tr>
<td>Atmospheric muon extrapolation</td>
<td>-</td>
</tr>
<tr>
<td>Correction for missing vertex showers in CC muon simulations</td>
<td>0.26</td>
</tr>
<tr>
<td>High multiplicity muon bundles</td>
<td>-</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>2.79</td>
</tr>
</tbody>
</table>

**Reconstruction efficiency vs MC energy**

*ANTARES Preliminary*
Diffuse flux – Showers

After unblinding

After zenith cut:
Expected background: 82±40
60 events observed

After cut on energy:
Expected background: 4.92^{+2.84}_{-2.95}
8 events observed

Interpreting excess as a background fluctuation:

Limits on normalization of an $E^{-2}$ flux:

$E^2 \Phi_{90\%} < 3.9 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$
(Feldman-Cousins 90% C.L. upper limit)

$E^2 \Phi_{90\%} < 4.9 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$
(systematic uncertainties using Pole 1.0)
**Diffuse flux**

**Showers (all flavours):**

2007-2012 (1247 days)

Expected background: 4.9 events
Observed: 8 events

$E^2 \frac{dN}{dE} < 4.9 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$
(per flavour, 90% CL)

$23 \text{ TeV} < E < 7.8 \text{ PeV}$

**Tracks ($\nu_\mu$):**

2008-2011 (885 days)

Expected background: 8.4 events
Observed: 8 events

$E^2 \frac{dN}{dE} < 5.1 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$
(90% CL)

$45 \text{ TeV} < E < 10 \text{ PeV}$
Diffuse fluxes from special regions

**Fermi Bubbles**

- Excess of $\gamma$- (and X-)rays in extended “bubbles” above and below the Galactic Centre. Homogenous intensity, hard spectrum ($E^{-2}$) probably with cutoff.


- In the field of view of ANTARES background estimated from average of 3 non-overlapping “off-zone” data regions (same size, shape and average detector efficiency)

**Galactic Plane – central region**

- The Galactic Plane is a most populated region.

- Cosmic rays can interact and produce neutrinos.

- $E^{-2.7}$ spectrum expected (due to the low density leptons can decay). Magnetic fields could enhance the neutrino signal.

- In the field of view of ANTARES background estimated from off-zones.
Fermi bubbles

Special regions

Galactic Plane

$N_{\text{obs}} = 16$

$\langle N_{\text{bkg}} \rangle = 11$

$n_b = 165.5 \pm 4.5$

$n_s = 177 \pm 13$

$\Phi_{\nu_\mu + \bar{\nu}_\mu} < 10.18 \times 10^{-27} \text{ GeV}^{-1} \text{ m}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$

$153 \text{ GeV} < E < 52.1 \text{ TeV}$

Higher fluxes expected in ANTARES signal region.
Search for Point Sources

• Good runs
  Period: 29 Jan 2007 to 31 December 2012
  Good detector and environmental conditions
  Total livetime: 1338 days

• Well-reconstructed $\nu_\mu$ events
  Good quality upgoing tracks with low angular error
  ($\Lambda > -5.2$; $\Delta(\text{ang}) < 1^\circ$; $\cos \theta < 0.1$)

• Background from data;
  Performance from simulation
  Scambled data
  MC: Angular resolution, Acceptance

• Likelihood method
  • Full-sky
  • Candidate list
  • Special searches (e.g. Gal. Centre)

• Unblinding
  Analysis optimised on simulation to avoid bias
Point sources

- Years 2007-2012 (1338 days)
  5516 neutrino candidates (90% of which being better reconstructed than 1°)
- All-sky search:
  Most significant cluster, 6 (14) events in 1° (3°): p-value = 2.7% (2.2 σ)
  Compatible with background hypothesis

- Fixed search (50 sources):
  5 most significant:

<table>
<thead>
<tr>
<th>Name</th>
<th>(\alpha) (°)</th>
<th>(\delta) (°)</th>
<th>(n_s)</th>
<th>(p)</th>
<th>(\phi_{90\text{CL}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>HESSJ0632+057</td>
<td>98.24</td>
<td>5.81</td>
<td>1.60</td>
<td>0.0012</td>
<td>4.40</td>
</tr>
<tr>
<td>HESSJ1741-302</td>
<td>-94.75</td>
<td>-30.20</td>
<td>0.99</td>
<td>0.0003</td>
<td>3.23</td>
</tr>
<tr>
<td>3C279</td>
<td>-165.95</td>
<td>-5.79</td>
<td>1.11</td>
<td>0.01</td>
<td>3.45</td>
</tr>
<tr>
<td>HESSJ1023-575</td>
<td>155.83</td>
<td>-57.76</td>
<td>1.98</td>
<td>0.03</td>
<td>2.01</td>
</tr>
<tr>
<td>ESO139-G12</td>
<td>-95.59</td>
<td>-59.94</td>
<td>0.79</td>
<td>0.06</td>
<td>1.82</td>
</tr>
</tbody>
</table>

Limits on normalization factor
\((E/\text{GeV})^{-2} \times 10^{-8} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}\)
(assuming no energy cut-off)
Flux sensitivities and limits (90% C.L.)

ANTARES 2007-2012 (1338 days)  IceCube 2008-2011 (1040 days)

\[ E < 100 \text{ TeV} \]

ANTARES

IceCube

Full-sky limit

1° bands

\[ E < 100 \text{ TeV} \]
Source around the GC?

- What about IC’s cluster near the GC?
  - Shower events have low angular resolution
  - IC does **not** claim a signal.
  - If it were a point source:
    \[(\alpha, \delta) = (−79°, −23°)\]
    \[\phi_0 = 6 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1}\]
    (M. C. Gonzalez-Garcia, F. Halzen and V. Niro, arXiv1310.7194)

- **ANTARES:**
  - Point source search at different \(\delta\)’s
  - Allow for extended sources:
    widths: 0°, 0.5°, 1° and 3°

Recent 3-year IC update does not add more events to the cluster.

ANTARES data excludes a point source as origin of the IceCube’s cluster
The Multi-Messenger Program

Increases chances of detection:
- Common sources for different messengers.
- Limits searches in time and space, Low backgrounds.
- Uncorrelated backgrounds and systematics.
Dark matter searches

- Relic WIMPs (neutralinos, KK particles) captured in celestial bodies.
- $\chi\chi$ self-annihilations produce $\tau$ leptons, $b$, $c$ and $t$ quarks and gauge bosons that in turn give rise to high energy neutrinos.
- Signal less affected by astrophysical uncertainties/backgrounds than other messengers

In the Sun

- Events in the Sun generated in a model independent way
- Annihilations into $b$ quarks (soft spectrum) and $\tau$ leptons $WW/ZZ$ bosons (hard spectrum) used as benchmarks
- $\nu$ interactions in the Sun medium, regeneration of $\nu_\tau$ in the Sun and $\nu$ oscillations taken into account.
- Optimisation of track quality cut and search cone performed

In the Galactic Centre

WIMPs self-annihilate according to $<\sigma_A\nu>$ (halo model-dependent).
Fluxes depend on WIMP density through the J-factor:

$$J(\Delta \Psi) = \int_{\Delta \Psi} \int_{\Delta \Psi} \rho_{\text{int}}^2(l,\Psi)dl\,d\Psi$$

J-factor for a Navarro-Frenk-White profile

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J-factor for a Navarro-Frenk-White profile
Dark matter – Results

From the Sun
- Observed events in the Sun’s direction vs. scrambled data (2007-2012).
- **No excess:** limits on flux from the Sun.

From the GC
- Observed events in the Sun’s direction vs. scrambled data (2007-2012).
- **No excess:** limits on flux from the GC.
Conversion to limits on WIMP-proton SD-x sections assumes equilibrium between capture and annihilation rates inside the Sun.

Much better sensitivity of ν-telescopes on SD cross-section w.r.t. direct detection (due to capture on H in the Sun).

First ANTARES results published in JCAP11 (2013) 032

MSSM-7 and CMSSM predictions take into account recent experimental constraints (Higgs mass, etc...).

There is still room for improvement in ANTARES: better reconstruction at low energies, unbinned method, more data “on tape”, ...
Galactic Centre – Limits on $<\sigma_A v>$

*$(\alpha, \beta, \gamma) = (1, 3, 1.3)$ and $\rho_S = 0.3$ GeV.cm$^{-3}$, and $R_S = 21.7$ kpc.*
Conclusions

• **ANTARES** – the first undersea Neutrino Telescope – is in its seventh year of operation.

• Despite its moderate size, but thanks to its location and excellent angular resolution, it is yielding:
  – Diffuse flux sensitivities in the relevant range;
  – Best limits for Galactic sources in the relevant energy range, with impact on interpretation of IC results;
  – Best limits on dark matter from neutrinos coming from the Sun and the Galactic Centre.

• It will keep producing excellent results until the next generation Mediterranean NT, **KM3NeT**, takes over (just around the corner: cf. de Jong’s talk this conf.).