Highlights from the ANTARES detector

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ANTARES: the largest Northern neutrino telescope

Scientific goals

• Neutrino astrophysics
• Multi-messenger studies
• Dark matter searches
• Atmospheric neutrinos
• Exotic particles search: nuclearites, monopoles
• Acoustic neutrino detection
• Earth and Sea sciences

The origin of the IceCube signal: what can ANTARES say?
The ANTARES site

Toulon

Institut M. Pacha
control room

La Seyne-sur-Mer

Electro-optical Cable of 40 km

Site ANTARES
42° 50' N, 6° 10' E

2500 m under s.l.
The telescope: full configuration since 2008

- 12 lines of 75 PMTs
- 1 line for Earth and Marine sciences
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

Storey

14.5 m

350 m

40 km to shore

Submarine links

Junction Box

~70 m

10/09/15

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4-08-2010

ECRS10, Turku - Finland
How does a neutrino telescope work?

muon neutrino, CC only
(neutrino or charged lepton)

atmospheric muon

all neutrino flavours, CC & NC
(shower reconstruction)

muon neutrino, CC only (track reconstruction)
muon tracks = golden channel

HE muons from $\nu_\mu$ CC-interaction
Energy threshold $\sim 10$ GeV

$\frac{dN}{dx} = 3.5 \times 10^4 m^{-1}$

$\theta_{\mu\nu} \sim \frac{0.7^\circ}{\sqrt{E_\nu[TeV]}}$

Cherenkov photons $\theta_{ch} \sim 42^\circ$ in water

Array of PMTs

Reconstruction of $\mu$ trajectory ($\sim \nu$) from timing and position of PMT hits

$\nu_\mu \rightarrow \mu$
Point-like sources

5516 events  10% $\mu_{\text{atm}}$ contamination  0.38° angular resolution

Equatorial coordinates

- $\nu_{\mu}$ channel → ANTARES behaves like a telescope
- 50% $\nu_{\mu}$ are reconstructed within 0.4° (for $E^{-2}$)
- ANTARES dedicated study of 50 pre-selected sources using data set 2007-2012 (no significant excess)
- Unbinned searches: no excess (most significant at 2.2$\sigma$)

The Astrophysical Journal Letters, 786:L5 (5pp), 2014 May 1
Joint analysis ANTARES-IC

ANTARES data sample + IceCube (IC-40, IC-59, IC-79) data samples

1) Search for an excess over a BG in the Southern Sky, for E\(^{-2}\) spectrum (unbinned)

2) Search over a pre-selected list of candidate sources with : \(\gamma = 2, 2.5\);
   energy cutoffs at 1 PeV, 300 TeV, 100 TeV

- ANTARES has better angular resolution (less scattering in seawater)
- IceCube has more events with better energy resolution (it's bigger!)
- Different declination dependencies – complementary regions

Combined 90% CL sensitivities (green line) and limits (points) for an E\(^{-2}\) source spectrum. Blue (Red) curves/points indicate ANTARES (IceCube) sensitivities/limits

Paper in preparation
Joint analysis ANTARES-IC

90% CL sensitivities and limits for an $E^{-2}$ source spectrum and exponential cutoff at $E = 300$ TeV.

spectral index $\gamma = 2.5$
Effective areas

evaluated starting from:
IceCube - Science 342, 1242856 (2013)

the HotSpot in HESE: enhanced diffuse flux
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the HotSpot in HESE: enhanced diffuse flux

CR propagating through the Galaxy can produce $\nu$ and $\gamma$-rays

\[
p \downarrow CR + p \downarrow ISM \rightarrow \pi^0 \pi^\pm \ldots
\]

\[
\pi^0 \rightarrow \gamma\gamma, EM cascade
\]

\[
\pi^\pm \rightarrow \nu\mu, \nu\ell \ldots
\]

Fermi-LAT

IceCube

ANTARES

- Search for $\nu_\mu$ using data from 2007-2012
- Search region $|l|<30^\circ$, $|b|<4^\circ$
- Counts in the signal/off zones
- No excess in the HE neutrinos
- 90% cl upper limits in the $3<E_\nu<300$ TeV region

A diffuse flux in the shower channel in IC might appear as an enhanced diffuse emission from a defined region.
ANTARES sensitivity compared with Fermi-LAT and IceCube in the ON region for $\gamma = 2.4$

90% cl limits from the Galactic Plane compared to the expected flux producing a $n_p$ IceCube HESE events vs. $\gamma$. 
Fermi Bubbles

- Hadronic origin for the bubbles?
- $E^{-2}$, $E^{-2.18}$ spectra and different cutoff [Lunardini et al. PRD92 (2015) 2,021301]
- comparison on-zones/off-zones (3) of $\Delta \Omega = 0.66$ sr
- 2008-2013 data analyzed (806+366 days).
- 22 events observed /13 background expected (1.9 $\sigma$)
the HotSpot in HESE: single point-like source

Analysis around the GC for energy spectra between 2.0 and 2.5. The ANTARES 90% C.L. upper limit excludes that a single point-like source produces \( n_p > 6 \) HESE, assuming \( \gamma = 2.0 \).

A search in a region of 20° around the HotSpot: \( \alpha, \delta = (-79°, -23°) \)

A single point-like source yielding \( n_p > 3 \) is excluded for \( \gamma = 2.3 \).

**Solid lines:** 90% c.l. upper limits for source spectra; **Dashed lines:** expected flux normalisation vs the number of HESE events

values above the solid lines disfavoured
Multi-messenger

Common sources for different messengers.
- Limits searches in time and space, low backgrounds.
- Uncorrelated backgrounds and systematics.
  Increased chances of detection
Can blazars produce the HESD PeV events?

A multiwavelength program that monitors extragalactic jets of the Southern Sky.


- Blazars associated with IC14 (Bert) and IC20 (Ernie)
- In the FoV of ANTARES
- Photon flux \( \Phi_\gamma \rightarrow \nu_e \) in IceCube \( \nu_\mu \) ANTARES
- After analysis, one event in the direction of two of the blazars (IC14)
- Consistent with the blazar-origin hypothesis of the IceCube event IC14 for a broad range of blazar spectra, but atmospheric origin cannot be excluded.
- No ANTARES events from BigBird
- PKS B1424–418: A high-fluence blazar in the IC 35 field (BigBird)


<table>
<thead>
<tr>
<th>Source</th>
<th>Cat. Name</th>
<th>( F_\gamma ) [GeV cm(^{-2}) s(^{-1})]</th>
<th>( N_\nu_e ) IceCube</th>
<th>IC</th>
<th>( N_{\text{sig}} )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0235–618</td>
<td>PKS 0235–618</td>
<td>( (6.2^{+3.1}_{-3.1}) \times 10^{-8} )</td>
<td>0.19(^{+0.04}_{-0.04} )</td>
<td>20, 7</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0302–623</td>
<td>PKS 0302–623</td>
<td>( (2.1^{+0.4}_{-0.4}) \times 10^{-8} )</td>
<td>0.06(^{+0.01}_{-0.01} )</td>
<td>20</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0308–611</td>
<td>PKS 0308–611</td>
<td>( (4.7^{+1.8}_{-1.8}) \times 10^{-8} )</td>
<td>0.14(^{+0.05}_{-0.05} )</td>
<td>20</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1653–329</td>
<td>Swift J1656.3–3302</td>
<td>( (2.8^{+0.3}_{-0.3}) \times 10^{-7} )</td>
<td>0.86(^{+0.10}_{-0.10} )</td>
<td>14, 2, 25</td>
<td>1.1</td>
<td>0.10</td>
</tr>
<tr>
<td>1714–336</td>
<td>TXS 1714–336</td>
<td>( (1.5^{+0.3}_{-0.4}) \times 10^{-7} )</td>
<td>0.46(^{+0.10}_{-0.12} )</td>
<td>14, 2, 25</td>
<td>0.9</td>
<td>0.04</td>
</tr>
<tr>
<td>1759–396</td>
<td>MRC 1759–396</td>
<td>( (7.5^{+1.9}_{-1.9}) \times 10^{-8} )</td>
<td>0.23(^{+0.50}_{-0.40} )</td>
<td>14, 2, 15, 25</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

PKS B1424–418 many 35

Indirect Dark Matter searches

\[ X_{\text{WIMP}} \bar{X}_{\text{WIMP}} \rightarrow \nu \bar{\nu}, \ b\bar{b}, \ W^- W^+, \ \tau^- \tau^+, \ \mu^- \mu^+ \]

Searches for a $\nu_\mu$ flux from the Galactic center, the Sun core, the Earth nucleus due to DM annihilation

$\nu_\mu$ spectrum from Earth and Sun $\rightarrow$ WIMPSIM [Blennow, Edsjö, Ohlsson, arXiv:0709.3898]

from GC and galaxy clusters $\rightarrow$ M. Cirelli et al., arXiv:1012.4515

BG estimation from time scrambled data

No excess measured
The Sun

ν telescopes → excellent results for Spin Dependent cross section

Galactic Center

ANTARES: arXiv:1505.04866
IceCube: arXiv:1505.07259
In progress - Cascade analysis

Cascade + muon tracks → sensitivity improved by 30%

Cascade reconstruction: angular resolutions better than 4° from 10 TeV to 1 PeV

\[
\log(E_\nu/\text{GeV})
\]

\[\Phi E^2 / (\text{GeV cm}^2 \text{s}^2)\]

Preliminary
Point source: tracks + showers - New skymap!

2007-2013 sample

6261 muon tracks
156 cascade events (90% purity)
10% atmospheric muons
Summary

- **ANTARES**: the largest underwater neutrino telescope with good angular resolution and Southern Sky direct observation
- Constraints on the possible origin of the IceCube signal
- Several analyses exploiting mainly the track-channel
- Analyses with showers in progress: good angular resolution (better than 4°) but small effective area.
- Data taking until 2016

**THEN**

**KM3NeT**
Backup slides
ANTARES neutrino detection and possible Swift X-ray counterpart

ATel #7987; D. Dornic (CPPM), S. Basa (LAM), P. A. Evans (U. Leicester), J. A. Kennea (PSU), J. P. Osborne (U. Leicester) and V. Lipunov (MSU) on 3 Sep 2015; 12:18 UT
Credential Certification: Phil Evans (pae9@star.le.ac.uk)

Subjects: Optical, X-ray, Neutrinos, Request for Observations

Referred to by ATel #: 7992

On September 1st, 2015, at 07:38:25 UT, ANTARES has detected a bright neutrino at a location of:

RA(J2000) = 16h 25m 42s
DEC (J2000) = -27d 23m 24s
with an uncertainty of 18 arcmin (radius, 50% containment)

A target of opportunity alert has been sent immediately to Swift. The XRT onboard Swift followed the ANTARES error box 10 hours after the neutrino detection. An uncatalogued X-ray source has been detected above the limit of RASS, with the flux varying between 5e-13 and 1.4e-12 erg cm⁻² s⁻¹ (0.3-10 keV), at location:

RA(J2000) = 16h 26m 2.12s
DEC (J2000) = -27d 18m 14.8s
with an uncertainty of 2.4 arcsec (radius, 90% containment).

The detected X-ray source seems to be variable. By contrast no transient source in the visible domain with MASTER SAAO has been observed so far until the magnitude 18.5 with a galactic extinction of 2 (Schlegel et al). Further Swift observations have been planned.

We encourage strongly further multi-wavelength observations to identify this X-ray source.
Field of view of the neutrino alert
Effective areas

Neutrino Effective area (m$^2$)

- IceCube $\nu_e$ (South)
- IceCube $\nu_{\mu}$ (South)
- IceCube $\nu_{\tau}$ (South)
- ANTARES $\nu_\mu$

Neutrino Energy (GeV)

- TeV
- PeV

Angular resolution

1°, 10°-15°, 0.4°

IceCube PRD91 (2015) 2, 022001

10/09/15

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