Highlights of the ANTARES Neutrino Telescope

Annarita Margiotta
Dipartimento di Fisica e Astronomia dell’Università and INFN Bologna
on behalf of the ANTARES collaboration

HEP-EPS 2017, 6 Jul 2017 - Venezia
ANTARES: the largest neutrino telescope in the Northern hemisphere

Scientific goals

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

Not discussed today

2006 PARTIAL CONFIGURATION
2008 COMPLETED
How does a $\nu$ telescope work?

Neutrino detection principle

$\nu_{\mu} \rightarrow \mu^{-}$

3D PMT array

Cherenkov light from $\mu$

$2500 \text{ m depth}$

$43^\circ$

Measurement:
Time & position of hits

$\langle \theta_{\mu-\nu} \rangle = \frac{1.5^\circ}{\sqrt{E_\nu[\text{TeV}]}}$

$\mu (~ \nu)$ trajectory
Event topology

- **μ±**
- **neutrino or charged lepton**
- **atmospheric muon**

**Background** strongly reduced with geometrical cuts and quality requirements on reconstruction.

**Ideal tool for astronomy**
- Angular resolution <0.4°
- @E_ν > 10 TeV; 90% purity

**Angular resolution < 3°**
- Shower within ≈ 10 m → contained events
- ν energy estimate better than 10%

**μ±**

**(−) ν_μ**
- muon neutrino, CC only (track reconstruction)

**ν_x**
- all neutrino flavours, CC & NC (shower reconstruction)
The ANTARES site

Institut M. Pacha
control room

La Seyne-sur-Mer

Electro-optical Cable of 40 km

depth ~ 2500 m

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

ALL-DATA-TO-SHORE:
computer farm @ the shore station: data filtering, processing and storage.

14.5 m
350 m
~70 m
40 km to shore

Submarine links
Neutrino astrophysics

Search for fluxes of high energy cosmic neutrinos

- Individual sources (point-like and extended sources)
- Diffuse flux (not identifiable single source)

**Galactic sources:** near objects
lower luminosity requirements
- Micro-quasars
- Supernova remnants
- Magnetars
- Galactic Centre and Galactic ridge

**Extra-galactic sources:**
most powerful accelerators in the Universe
- AGNs
- GRBs

ANTARES visible sky
ANTARES search for point-like sources of cosmic $\nu$s

9 years of ANTARES data – all neutrino flavours:
7629 track-like + 180 shower-like events
2007-2015 – Total livetime = 2423.6 d

arXiv:1706.01857
Full sky search

Search for an excess of signal events located anywhere in the ANTARES visible sky without any assumption about the source position $\rightarrow$ ANTARES visible sky divided in $1^\circ \times 1^\circ$ (r.a $\times$ decl.) boxes. $\rightarrow$ Maximum Likelihood analysis searching for clusters

decl. $\delta = 23.50$, r.a. $\alpha = 343.80$ = most significant cluster ($\approx 1.9 \sigma$)

arXiv:1706.01857  
equatorial coordinates
Candidate list search

Red: cascades
Blue: tracks

IC HESE – 13 track-like events

candidate sources – 106 known astrophysical sources

No significant excess found so far

arXiv:1706.01857
Sensitivity and upper limits
Diffuse flux search

vs from unresolved sources, GZK, Z-jets...

Search for excess of HE events over the expected atmospheric background (softer spectrum ~ 3.7)
Diffuse flux search

vs from unresolved sources, GZK, Z-jets...

Search for excess of HE events over the expected atmospheric background
(softer spectrum ~ 3.7)
Diffuse flux

**TRACKS**
Data: 2007-2015 (2450 livedays)

Above $E_{\text{cut}}$: Bkg: 13.5 ± 4 evts
IC-like signal: 3 evts
Observed: **19 evts**

**SHOWERS**
Data: 2007-2015 (2450 livedays)

Above $E_{\text{cut}}$: Bkg: 10.5± 4 evts
IC-like signal: 4 evts
Observed: **14 evts**

Reliable energy estimate required
Upper limit at 90% C.L. 68% confidence interval for the combined track and shower analysis (systematics included)
The Galactic ridge - 1

- \( \nu \)'s and \( \gamma \)-rays produced by CR propagation

\[
p_{\text{CR}} + p_{\text{ISM}} \rightarrow \pi^0 \pi^+ \pi^- \ldots
\]

\[
\pi^0 \rightarrow \gamma \gamma \text{ (EM cascade)}
\]

\[
\pi^\pm \rightarrow \nu_\mu \nu_e \ldots
\]

- Search for \( \nu_\mu \), data 2007-2013
- Search region \(|l|<30^\circ, |b|<4^\circ\)
- Cuts optimized for \( \Gamma=2.4-2.5 \)
- Counts in the signal/off zones
- No excess in the HE neutrinos
- 90% c.l. upper limits: \(3<E_\nu<300 \text{ TeV}\)

The Galactic ridge – 2 → new analysis

Tracks + showers 2007-2015 → LT = 2423.6 d
Maximum Likelihood analysis

KRAγ - radially dependent model for CR transport in the Galaxy: δ(R)~1/R
arxiv:1702.01124

Enhanced production of γs and νs

Probability density function of the signal for shower and track-like events (5PeV cutoff model)
Background extracted from data

arXiv:1705.00497
Multimessenger program

Intense effort in working with other collaborations

- better understanding of the sources and of the physics mechanisms
- increase detector sensitivity (uncorrelated backgrounds)

**Multi wavelength follow-up of neutrinos**

<table>
<thead>
<tr>
<th>Radio</th>
<th>Visible</th>
<th>X-ray</th>
<th>GeV-ray</th>
<th>TeV-ray</th>
<th>GW</th>
<th>ν</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWA</td>
<td>TAROT</td>
<td>Swift</td>
<td>Fermi-LAT</td>
<td>HESS</td>
<td>Ligo</td>
<td>IC</td>
</tr>
<tr>
<td>ZADKO</td>
<td></td>
<td></td>
<td></td>
<td>HAWC</td>
<td>Virgo</td>
<td></td>
</tr>
<tr>
<td>MASTER</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Alerts**

- Radio: MWA 12/yr, ZADKO 30/yr, MASTER 6/yr
- Visible: TAROT 30/yr
- X-ray: Swift 6/yr
- GeV-ray: Fermi-LAT (Offline)
- TeV-ray: HESS (1-10/yr), HAWC (Offline)
- GW: Ligo
- ν: IC, Virgo
Real-time (follow-up of the selected neutrino events):

- optical telescopes [TAROT, ROTSE, ZADKO, MASTER]
- X-ray telescope [Swift/XRT]
- GeV-TeV γ-ray telescopes [HESS, HAWC]
- radio telescope [MWA]
- Online search of fast transient sources [GCN, Parkes]

Multi-messenger correlation with:

- Gravitational wave [Virgo/Ligo]
- UHE events [Auger]

Time-dependent searches:

- GRB [Swift, Fermi, IPN]
- Micro-quasar and X-ray binaries [Fermi/LAT, Swift, RXTE]
- Gamma-ray binaries [Fermi/LAT, IACT]
- Blazars [Fermi/LAT, IACT, TANAMI…]
- Crab [Fermi/LAT]
- Fast radio burst [radio telescopes]
Real-time follow-up (TAToO)

- M. Ageron et al., The ANTARES telescope neutrino alert system, APP 35 (2012) 530 (method)
- Adrián-Martínez et al., Optical and X-ray early follow-up of ANTARES neutrino alerts, JCAP02(2016)062

**ANTARES trigger**
- single HE ν (~10 TeV)
- single ν correlated to local galaxies for SNe (~1 TeV)
- doublet of ν’s

**Performances:**
- Time to send an alert: ~ 5 s
- Median angular resolution: 0.3° - 0.4°
- First image of the follow-up: <20 s
- Dedicated optical image analysis
GW observation neutrino follow-up
joint analyses ANTARES/IceCube/LigoSC/Virgo

GW150914

- No ANTARES events in ±500 s around event time
- ANTARES limits dominates for $E_{\nu} < 100$ TeV
- Size of GW150914: 590 deg$^2$
- ANTARES resolution: <0.5 deg$^2$
- < 10% GW total energy radiated in $\nu$

GW151226

LVT151012

$\nu_\mu$ associated with GeV and TeV $\gamma$-ray flaring blazars and X-ray binaries

- Search for $\nu$’s (2008-2012) correlated with high activity state
- **Blazars** monitored by FERMI-LAT and IACTs (JCAP 1512 (2015), 014)
- 40 blazars + 33 X-ray binaries during flares observed by Swift-BAT, RXTE-ASM and MAXI. Transition states from telegram alerts
- No significant excess
- Upper limits on $\nu$ fluence and model parameters constrain
DM $\rightarrow \nu$
Dark Matter from the Sun the Earth and the Galactic Centre

- Gravitational trapping and accumulation of DM particles in the centre of astrophysical objects like the Sun, the Galactic centre and also the Earth
- DM annihilation would produce eventually a HE neutrino flux with no significant astrophysical backgrounds
- $\nu_\mu$ spectrum $\rightarrow$ WIMPSIM [Blennow, Edsjö, Ohlsson, arXiv:0709.3898]
- Bkg estimated from time scrambled data. No excess observed
The Galactic Center

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

3 DM halo models in the Milky Way

effect on the thermally averaged cross section

good visibility of the GC
only muon like events considered
\[ \rightarrow \text{angular resolution } <0.4^\circ \]

J-factor \( \rightarrow \rho^2_{\text{DM}} \) integrated over a line of sight at an angular separation \( \Psi \) from the center of the source, depends on the halo model

JCAP, 10 (2015) 068

5 annihilation channels
Dark Matter annihilation in the Earth and the Sun

data collected between 2007-2012
3 channels: $\tau^+ \tau^-, W^+ W^-, b\bar{b}$

Limits on the SI WIMP-nucleon scattering cross-section

Limits on the SD WIMP-nucleon scattering cross-section

Physics of the Dark Universe, 16 (2017) 41

Summary

• **ANTARES** → the largest underwater neutrino telescope
• Search for a neutrino flux from the Southern sky
• Huge *multimessenger* effort
  – EM radiation: radio (MWA), optical, X-ray, γ-rays (LAT, IACTs)
  – Gravitational Wave observatories and IceCube
• Important contribution to the indirect searches for *Dark Matter*
• competitive sensitivities and excellent angular resolution in both *track* and *cascade* events because of
  – OPTICAL PROPERTIES OF THE SEAWATER
  – LOCATION → Northern Hemisphere
  – DEPTH
• main limitation → reduced size

The future: **KM3NeT/ARCA**
(talk C. Distefano, on Sat morning)