Highlights of the ANTARES Neutrino Telescope

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ANTARES: the largest Northern neutrino telescope

Scientific goals

- Neutrino astrophysics – (1)
- Multi-messenger studies – (2)
- Dark matter searches – (3)
- Atmospheric neutrinos
- Exotic particles search: nuclearites, monopoles
- Acoustic neutrino detection
- Earth and Sea sciences
How does a telescope work?

Neutrino detection principle

3D PMT array

Cherenkov light from μ

γ_c

2500 m depth

43°

Interaction

μ

ν

μ (~ ν) trajectory

\( \langle \theta_{\mu-\nu} \rangle = \frac{1.5^\circ}{\sqrt{E_\nu \,[\text{TeV}]} } \)
Event topology

- Muon neutrino, CC only (track reconstruction)
- Neutrino or charged lepton
- Atmospheric muon
- All neutrino flavours, CC & NC (shower reconstruction)
The ANTARES site

- **The ANTARES site**
- **Institut M. Pacha** control room
- **Electro-optical Cable of 40 km**
- **La Seyne-sur-Mer**
- **Toulon**
- **depth ~ 2500 m**
- **Site ANTARES**
  - 42° 50' N, 6° 10' E
  - 2500 m under s.l.
The ANTARES telescope

- 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.

Submarine links
Junction Box
40 km to shore

~70 m
14.5 m
350 m

4-08-2010
ANTARES performance

ANTARES angular resolution vs $E_{\parallel}$

Tracks ($\mu$CC) ideal tool for astronomy
Angular resolution $< 0.4^\circ$ above 10 TeV
90% purity

FAVOURABLE OPTICAL PROPERTIES

Upgoing cascade events ($e$CC, NC)
Angular resolution $< 3^\circ$
Shower confined within $\approx 10$ m $\rightarrow$ contained events

Good estimate of the energy, better than 10%
1 - Neutrino astrophysics

Search for fluxes of high energy cosmic neutrinos

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

**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
1 - Neutrino astrophysics

**Search for fluxes of high energy cosmic neutrinos**

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Diffuse flux search

- Search for excess of reconstructed HE events over the expected atmospheric background
**Diffuse flux**

**TRACKS**
- Data: 2007-2015 (2451 livedays)
- **Above $E_{\text{cut}}$:** Bkg: $13.5 \pm 3$ evts
- IC-like signal: 3 evts
- **Observed:** 19 evts

**SHOWERS**
- Data: 2007-2013 (1405 livedays)
- **Above $E_{\text{cut}}$:** Bkg: $5 \pm 2$ evts
- IC-like signal: 1.5 evts
- **Observed:** 7 evts
Highlights of ANTARES

**A. Margiotta**

Above $E_{\text{cut}}$: Bkg: $13.5 \pm 3$ evts

IC-like signal: 3 evts

**TRACKS**

Data: 2007-2015 (2451 livedays)

**Above $E_{\text{cut}}$**: Bkg: $13.5 \pm 3$ evts

IC-like signal: 3 evts

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**PRELIMINARY**

ANTARES combined upper limits and sensitivities

(2007-2015) tracks + showers
Point sources

- 92 candidate sources
  + 13 HESE
- 2007-2015 data:
  2424 days
  7269 tracks
  180 cascades
- Unbinned all-sky search
“Enhanced” diffuse flux

ICECUBE PRELIMINARY

\( TS = 2 \log(L/L_0) \)

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The Galactic ridge

• ν’s and γ-rays produced by CR propagation
  \( p_{CR} + p_{ISM} \rightarrow \pi^0\pi^\pm \ldots \)
  \( \pi^0 \rightarrow \gamma\gamma (EM \text{ cascade}) \)
  \( \pi^\pm \rightarrow \nu_\mu, \nu_e \ldots \)
• 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: \( 3<E_\nu<300 \text{ TeV} \)

PLB 760(2016)143
Simple extrapolation of the *Fermi*-LAT $\gamma$-ray measurement to the IC $\nu$ flux in the Galactic Plane area excluded

$\geq 3$ HESE originating in this region excluded at 90% c.l. for $\Gamma = 2.4$-2.5

Improvements expected considering showers and extending the data sample
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>
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<tr>
<td>MWA</td>
<td>TAROT</td>
<td>Swift</td>
<td>Fermi-LAT</td>
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<td>HAWC</td>
<td>IC</td>
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<td>MASTER</td>
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Alerts:
- Radio: 12/yr
- Visible: 30/yr
- X-ray: 6/yr
- GeV-ray: (Offline)
- TeV-ray: (1-10/yr)
- GW: (Offline)
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]
• Supernovae Ib,c [Optical telescopes]
• 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 $\nu$ (~10 TeV)
- single $\nu$ correlated to local galaxies for SNe (~1 TeV)
- doublet of $\nu$’s

**Performances:**
- Time to send an alert: ~ 5 s
- Median angular resolution: $0.3^\circ$ - $0.4^\circ$
- First image of the follow-up: <20 s
- Dedicated optical image analysis
Neutrino follow-up of GW150914

- No ANTARES events in ±500 s from the GW time (0.015 expected)
- Limits from ANTARES dominates for $E \nu < 100$ TeV
- U.L. from IC dominated above 100 TeV
- Size of GW150914: 590 deg$^2$ ANTARES resolution: <0.5 deg$^2$
- Limits on total energy radiated in neutrinos: <10% GW
- Future: Receive / send alerts in real time
Neutrino follow-up of GWs

3 alerts sent by LIGO during the run 01 (2015/09 → 2016/01):

- GW150914: merging of 2 BHs (M= 36/29 $M_\odot$ - 410 Mpc - 5.1 $\sigma$)  
  
- LVT151012: merging of 2 BHs (M= 23/13 $M_\odot$ - 1000 Mpc - 1.7 $\sigma$)  
  
- GW151226: merging of 2 BHs (M= 14/7 $M_\odot$ - 440 Mpc - >5 $\sigma$)
associated with GeV and TeV $\gamma$-ray flaring blazars and X-ray binaries

- Search for $\gamma$'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
Dark Matter searches

$\text{DM} \rightarrow \nu$
Gravitational trapping and accumulation of DM particles in the centre of astrophysical objects like the Sun and the Galactic centre

DM annihilation would produce a HE neutrino flux with no significant astrophysical backgrounds


\[ \nu_\mu \text{ spectrum } \rightarrow \text{WIMPSIM [Blennow,Edsjö,Ohlsson,arXiv:0709.3898]} \]

Bkg estimated from time scrambled data.

No excess observed
The Galactic Center

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

5 annihilation channels

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

\[ \text{angular resolution } < 0.4^\circ \]

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

\[ \frac{d\Phi_{\nu_\mu+\bar{\nu}_\mu}}{dE_{\nu_\mu+\bar{\nu}_\mu}} = \frac{<\sigma v>}{8\pi M^2_{\text{WIMP}}} \cdot \frac{dN_{\nu_\mu+\bar{\nu}_\mu}}{dE_{\nu_\mu+\bar{\nu}_\mu}} \cdot J_{\text{int}}(\Delta \Omega). \]

\[ J_{\text{int}}(\Delta \Omega) = \int_{\Delta \Omega} \int_{\rho^2_{\text{DM}}} \cdot dl \cdot d\Omega. \]
Summary

- **ANTARES** → the largest Northern 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. James, on Thu)
• Combined 90% CL sensitivities (green line) and limits (points) for $E^{-2}$ spectrum.
• Blue (Red) curves/points indicate ANTARES (IceCube) sensitivities/limits

Highlights of ANTARES-IceCube PS searches

Effective areas (IC, ANTARES)

Angular resolution (IC, ANTARES)

$A_{\text{eff}} [m^2]$

$E [GeV]$

$\sin(\delta)$

$E^2 d\psi/dE [GeV cm^{-2} s^{-1}]$

$\log_{10}(E [GeV])$

[$\Delta_\gamma = -30^\circ$]