Overview of ANTARES neutrino telescope: multimessenger results

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ANTARES and KM3NeT collaborations

* ANTARES
○ KM3NeT

+ Since April 2017: CIRA Perth Australia as observer

Deployment sites: Marrakech, Rabat, Oujda
ANTARES

- Running since 2007
- 885 10” PMTs
- 12 lines
- 25 storeys/line
- 3 PMTs / storey

70 m

40 km to shore

450 m

Junction Box

Interlink cables

Details:

see arXiv 1409.4552
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- see arXiv 1409.4552

- Junction Box

- Interlink cables

- Spurio: ANTARES Multimessenger@NOW2018

Dimensions:

- 2500m
- 45
- 70 m
Detecting **cosmic** neutrinos: a threefold way

(IceCube HESE and IceCube upgoing muons)

I. Point-like events, significant excess in the sky map. Based on measurement of the **v direction**

II. Excess of HE neutrinos over the background of atmospheric events. Based on the estimation of the **v energy**

III. Coincident event in a restricted time/direction windows with EM/γ/GW counterparts. Relaxed **v energy/direction measurement + transient/ multimessenger** information
Sample:
- 2007 – 2015; livetime 2424 days
- Maximum likelihood method used to search for clusters of vs from sources
- Irreducible bck: atmospheric neutrinos
- All-flavour analysis: 7622 track-like, 180 shower-like neutrino candidates

Full-sky search
1°x1° squares over ANTARES visible sky

Candidate list searches
106 known astrophysical objects (Pulsars, SNRs, ...), 13 IceCube HESE tracks
I) ANTARES – Point Sources (Phys. Rev. D 96, 082001)

Most significant cluster of the full-sky search (1.9σ post-trial significance)
\( \alpha = 343.8^\circ \ \delta = 23.5^\circ \)

Sensitivities and upper limits at a 90% C.L.
on the signal flux from the Full-sky and the Candidate list searches (Neyman method)

Sky map in equatorial coordinates of pre-trial p-values

Most sensitive limits for a large fraction of the southern sky, especially at neutrino energies below 100 TeV
Sample:
• 2007 – 2015; livetime 2450 days
• All-flavour analysis (track+showers)

Event selection chain + energy-related cut applied to
• obtain a high-purity neutrino sample
• maximise sensitivity

Signal modeled according to the IceCube flux

Result:
33 events (19 tracks + 14 showers) in data
24 ±7 (stat.+syst.) events background in MC

1.6σ excess, null cosmic rejected at 85% CL
II) CR propagation in the Milky Way: $\gamma$ and $\nu$.

- Neutrinos allow testing CRs propagation
- Dense matter regions boost $\gamma$ and $\nu$ fluxes
- Models can be tuned to $\gamma$ and CR observations
- Northern Hemisphere optimal point of view for galactic CR

Do diffuse Galactic vs contribute to the IceCube astrophysical signal?

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Result: total flux contribution of diffuse Galactic neutrino emission < 8.5% of the total diffuse IC astrophysical signal ($E_\gamma > 30$ TeV) [ApJ 809:98(2015)].
III) ANTARES – Multimessenger

* participation to AMON

Gamma-ray Coordinates Network (GCN) [https://gcn.gsfc.nasa.gov/](https://gcn.gsfc.nasa.gov/)

ANTARES

- GeV-TeV γ-rays
  - Fermi, HESS, HAWC, CTA

- Neutrinos
  - IceCube, GVD, SNEWS

- UHECR
  - Auger, TA

- Only spatial coincidence

Radio/Optic /X-ray
- TAROT, MASTER, Swift, INTEGRAL, MWA

Receive alerts
Generate alerts

Gravitational Waves
- VIRGO, LIGO
### III) ANTARES multimessenger and transients

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<td>FERMI/LAT</td>
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<td>Galactic Plane</td>
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<td>BH/NS mergers</td>
<td>Gravitational waves + EM + $\nu$</td>
<td>Ligo/Virgo (+ IceCube and Pierre Auger Observatory)</td>
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ANTARES neutrino alerts

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<th>Radio</th>
<th>Optical</th>
<th>X-ray</th>
<th>GeV γ-rays</th>
<th>TeV γ-rays</th>
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<tr>
<td>MWA</td>
<td>TAROT, ZADKO MASTER, GWAC</td>
<td>Swift</td>
<td>Fermi</td>
<td>HESS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>INTEGRAL</td>
<td></td>
<td>HAWC</td>
</tr>
</tbody>
</table>

**ANTARES real time alerts:**
- Time to send an alert: ~5 s
- Track median angular resolution: 0.5°
- Doublet of neutrinos: ~0.04 events/yr
- Single neutrino with direction close to local galaxies: ~1 TeV, ~10 events/yr
- Single HE neutrinos: ~5 TeV, 20 ev/yr
- Single VHE neutrinos: ~30 TeV, ~3-4 ev/yr

Sent neutrino alerts (2009-2018)
- 277 to robotic telescopes
  - +15 to Swift
  - +8 to INTEGRAL
  - +22 to MWA (radio)
  - +2 to HESS

- JCAP 02 (2016) 062
ANTARES – external alerts follow up

Offline studies
• Calibrated geometry
• Calibrations
• More refined tracking

Prompt search
• Online tracking
• Default geometry
• Prompt response (minutes)
• (Lower trigger threshold)
Fast Radio Bursts

Petroff E et al., MNRAS, 469 (2017) 4465

- High galactic latitude
- Expected rate: \( \sim 10^3 \text{ FRB/day/all sky} \)

Green bank
Arecibo
GBT
Parkes
UTMOST
ASKAP

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• 16 FRB (Parkes, UTMOST, ASKAP) → 12 in the FoV during the data taking.
• ± 6h search period in 2°.
• Event selection optimization – 1 seen neutrino = 3σ discovery.
• No events found → limits set.
Neutrino emission from TXS 056+056: 
Online follow-up associated with IceCube-170922A

• On September 22, 2017 a high-energy neutrino was observed by IceCube, selected by the Extremely High Energy online filter.

• \( \gamma \)-rays (Fermi-LAT, MAGIC) and other EM observations were reported, indicates that a blazar, **TXS 0506+056**, may be the source of HEN. (Science 361, 137 (2018)).

• IceCube find an excess of HENs at TXS 0506+056 position between 9/2014 and 3/2015 at 3.5\( \sigma \), independent of the 2017 flaring episode. (Science 361, 147-151 (2018)).

• For ANTARES, the direction of IC170922A was 14.2° below horizon.

• Use of a fast online algorithm that selects only upgoing candidates.

• No upgoing \( \nu \) candidate was recorded in a cone of 3° within \( \pm 1 \) h (ATEL #10773, 24/9) and \( \pm 1 \) day by the online reconstruction.

• \( \nu \) fluence upper limit set for \( E^{-2} \) (\( F< 15 \) GeV \( cm^{-2} \) integrated from 3 TeV-3 PeV) and \( E^{-2.5} \) spectra.

**ANTARES visibility map of IC170922A in equatorial coordinates. The sky region below the horizon (=upgoing events) at the alert time is shown in blue.**
Neutrino emission from TXS 056+056: Time-integrated search

- The same maximum likelihood ratio used in PS searches, +2016/17 (PRD96, 082001)
- Expected background from the source in 3136 days livetime:
  - 0.23/deg$^2$ for track-like
  - 0.005/deg$^2$ for shower-like events
- # of events fitting the likelihood signal function for the source: $\mu_{\text{sig}} = 1.03$
- Pre-trial p-value of 3.4% (post-trial 87%)
- 1 track (12/12/2013) 0.3° from the source position
- Flux U.L. (@100 TeV) for $E^{-2}$: $1.6 \times 10^{-18}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ in the range [2 TeV-4 PeV]
- In the list of 107 pre-selected sources, only two have smaller p-value

Distribution of the 13 tracks +1 shower events in the (RA, $\delta$) coordinates around (radius=1° and 5°) the position of TXS 0506+056. The dashed circles around the events indicate the angular error estimate.
Neutrino emission from TXS 056+056: Search for neutrinos in the 2015 bursting period

- The IceCube time-dependent analysis contains a significant excess (two time-window shapes) centered on MJD 57004.

- We use a time-dependent analysis (developed to correlate $\nu$'s to X-rays and $\gamma$-rays as in JCAP04 (2017), 019) that reduces by a factor of 2-3 the signal required for a discovery with respect to a time-integrated search.

- Time window defined by the IceCube Gaussian- and box-shaped flares.

- Relaxed cuts: more low-energy events accepted both in signal and background (background a x4 factor higher).

- Results: no events found during flares. Within 2° from the source, 10 background events expected, 13 events found in data. None of them lies in the flaring period.
Gravitational Waves (GW) + HE Neutrinos (HEN)

Short GRB
(Merger of Black Holes/Neutron Stars)

- GW: 100 Mpc

- HEN: 10 Mpc (ANTARES)
  [ANTARES, JCAP 06 (2013) 006]

Long GRB
(Collapsars - massive star collapse)

- GW: realistically 20 Mpc
  [e.g. Gossan et al., PRD93 042002 (2016)]

- HEN 20 Mpc (ANTARES)
  [ANTARES, JCAP 06 (2013) 006]
Gravitational Waves (GW) + HE Neutrinos (HEN)

Error box of GW170817 reconstructed with two different pipelines (~30°²)
Gravitational Waves (GW) + HE Neutrinos (HEN)

ANTARES (2020)-KM3NeT(>2020)

Field-of-view: $2\pi$ sr

Angular resolution:
- <0.5° (tracks)
- 2°-3° (showers)
Searching for HEN from BBH coalescences (O1-O2)

HEN emission coincident with GW signals expected?
If hadronic/magnetic environment

Different ANTARES analyses, no HEN +GW, Upper Limits produced:

- **GW150914 (with IC)**: HEN emission < 20% of GW energy;  
  PRD93 (2016) 122010
- **GW151226+LVT151012 (with IC)**: upgoing, HEN emission < 1-15% of GW energy;  
  PRD96 (2017) 022005
- **GW170104**: first full sky search, optimization.  
  EPJC 77(2017) 911
Binary NS Mergers and HEN?

GW170817

- Prompt neutrino production on-axis
- Off-axis scenario, neutrino-production related to the extended $\gamma$-ray emission (Kimura et al. 2017).
GW170817 followup: constraints on the source-prompt emission (+ AUGER, IceCube)


GW170817: Neutrino limits (fluence per flavour: $\nu_x + \bar{\nu}_x$)

±500 sec time-window
GW170817 followup: constraints on the source - extended emission (+ AUGER, IceCube)


GW170817: Neutrino limits (fluence per flavour: $\nu_x + \bar{\nu}_x$)

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Next GW + HEN observations

Exciting period ahead for Multi-Messenger Astronomy

- Run O3 will start early 2019. Possibly several alerts/week
- Neutrino follow-ups: ANTARES (up to early 2020), KM3NeT (2020), IceCube + AUGER + BAIKAL
ANTARES can also study (not covered here...)

**Neutrino oscillations and NMH:**
- ... Works on going

**Indirect Dark Matter searches**
- Physics of the Dark Universe 16 (2017) 41
- JCAP05(2016)016

**Magnetic Monopoles:**
- JHEP 07 (2017) 054

**Sea and Earth Science**
- Scientific Reports 7(2017): 45517
- Jou. Geophysical Research 122(2017) 2291
- Ocean Dynamics 64 (2014)507–517
- Deep-Sea Research I 58(2011)875

During operation on the ANTARES/KM3NeT site, last summer
WIMPs accumulate in massive celestial objects (Sun, Galactic Centre, ...)
  • Neutrinos could be produced in WIMP-WIMP annihilation
  • Clean signal and low expected background

**Ingredients** used in the analysis:
  • Signal energy spectra for each considered WIMP mass and annihilation channel:
$$ WIMP + WIMP \rightarrow bbs, W^+W^-, \tau^+\tau^-, \mu^+\mu^-, \nu^- $$
  • Spatial distribution of dark matter in the source:
    • Point-like (Sun)
    • NFW, Burkert, McMillan halos (GC)

  • **No excess** above background observed;
  • Upper limits derived, as a function of the WIMP mass and annihilation channel on
    • spin-(in)dependent WIMP-nucleon scattering cross-section (Sun)
    • thermally averaged annihilation cross-section (Galactic center)
Summary and Perspectives

• ANTARES: more than 10 years of continuous data taking! ... and still stably ongoing!

• ANTARES Data taking continues up to the end of GW O3
  - Then, KM3NeT in the Mediterranean Sea

• Solid results from various searches of astrophysical neutrino emission.
  - (point-like, diffuse, extended regions, dark matter, ...)

• Active multi-messenger program:
  - Neutrino alerts distribution, participation to GCN and AMON
  - External alerts reception, prompt analysis
  - Offline multi-messenger analysis.
  - Combined analyses with IceCube (point sources, galactic plane, time correlation...).

• Best practice and multi-messenger collaborations ported to KM3NeT!
• Neutrino astronomy is on its way to increased sensitivity and full sky coverage
• Neutrinos are an indispensable ingredient of multi-messenger astronomy
• Neutrino telescopes also offer opportunities for precision measurements in neutrino physics
Thank you!
A neutrino telescope

- **Tracks (CC $\nu_\mu$):** Long pattern in the detector
- **Cascades (CC $\nu_e + NC$):** Short pattern (point like)

- **Track/cascade direction** reconstructed from time-space correlation between hits produced by Cherenkov photons
- **Event energy reconstructed** from amplitudes

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Neutrino telescopes. Where ...
ANTARES real time neutrino alerts

Real-time analysis → Alert triggering

Performances:
• Time to send an alert: ~5 s
• Median angular resolution: 0.5°
4 bright GRB selected:
GRB080916C, GRB110918A, GRB130427A and GRB130505A

Upper limits
Two model investigated:
• photospheric
• internal shock

Constraints
on baryonic fraction, $f_p$, and Lorentz factor $\Gamma$
• 90% C.L. (solid line)
• 50% C.L. (dashed line)
ANTARES Alert VHE (Sept. 1, 2015)
E~50 TeV; RA=246.3°; δ=-27.4°

• Sent after 10 s to MASTER, Swift-XRT

• Unknown, relatively bright and variable X-ray source-(0.5-1.4)x10^{-13} erg cm^{-2} s^{-1} detected by Swift XRT 9h after the ATEL

• Great interest in the community (15ATels+6 GCN)

• Later, the X-ray source associated with a young accreting G-K star, or a binary system of active stars undergoing a flaring episode with X-ray emission.

• H.E.S.S.: No VHE transient source \( \Phi(E > 320\text{GeV};99\%\text{C.L.}) < 2.7\times10^{-8}\text{m}^{-2}\text{s}^{-1} \)
Gravitational Waves (GW) + HE Neutrinos (HEN)

Optical robotic telescopes

angular resolution: ~arcsec

field-of-view: ~square degree

1°