ANTARES

recent results

with focus on the multi-messenger and real-time program

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on behalf of the ANTARES collaboration

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Astronomy with a Neutrino Telescope and Abyss environment RESEARCH
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Event topologies

Angular resolution [°]

< 0.4 ° $E_{\nu} > 10$ TeV

$\nu_e$ CC

$\nu_x$ NC

reaches 2deg

Shower-like

Track-like

$\nu$

$\mu$

cascade
Physics with a neutrino telescope

Sources of cosmic rays
- Point sources (steady/transient)
- Diffuse flux, UHE, ...
- CR anisotropies
- **Multi-messenger studies**

High energy physics
- Atmospheric muons
- Atmospheric neutrinos
- Neutrino oscillations
- ...

Indirect detection of dark matter

Exotics (monopoles, nuclearites, ...)

Environmental sciences
- Online measurements
- Long periods: exotic phenomena
- Carbon cycle
- ...

Detection parameters
- $100 \text{ GeV} < E < 1 \text{ PeV}$
- Angular res.: $0.3 \text{ deg}$
- Volume: $20 \text{ Mt}$
ANTARES vs IceCube

Sensitivities to track like events assuming an E^{-2} spectrum within an energy interval

→ focus on Galactic TeV sources (and transients)
Search for a diffuse, high-energy flux

Blinded analyses, optimizing cuts for $\Gamma=2$ and $\Gamma=2.5$ spectra
Checks on 10% burn sample

<table>
<thead>
<tr>
<th>Channel</th>
<th>Period</th>
<th>DATA</th>
<th>Background</th>
<th>IC-flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracks</td>
<td>2007-2015</td>
<td>19</td>
<td>13.5 ± 3</td>
<td>3</td>
</tr>
<tr>
<td>Showers</td>
<td>2007-2013</td>
<td>7</td>
<td>5 ± 2</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Searches for neutrino sources
Searches for point-like neutrino sources

All-Sky + 54 candidate sources + 8 IC HESE-tracks
No significant cluster:
• All-sky: 1.3σ at RA:311.7°, Dec=-48.3°
• Candidates: 0.75σ for HESS J°6302+057

6490 tracks + 172 showers
Searches for point-like neutrino sources

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Nature 531 (2016) 476
Using input from EM observations

- Spatial and temporal information as input to neutrino searches
  - Optimize search windows
  - Reduce backgrounds
  - Increase sensitivity
- Coincident signals ➔ smoking gun for common source, hadronic origin, etc.
Using input from EM observations

**GRBs**


**AGNs**

- Blazars monitored by FERMI-LAT and IACTs (JCAP 1512 (2015), 014)

**Microquasars**

- hard X-ray states + hard to soft transitions (JHEAP 3-4 (2014) 9)
Multimessenger + alert program: TAToO

ANTARES Shore Station:
On-line reconstruction
Trigger: multiplets, close to galaxy or HE event
Alert messages + Online analysis of incoming alerts

~10s

Real time

Follow-up instruments

Follow-up analyses

The ANTARES Telescope Neutrino Alert System
Multimessenger + alert program: TAToO

Multi wavelength follow-up of neutrinos

- **Radio**
  - MWA (Parkes)
- **Visible**
  - TAROT
  - ZADKO
  - MASTER
- **X-ray**
  - Swift
- **GeV-ray**
  - Fermi-LAT
- **TeV-ray**
  - HESS
  - HAWC
- **GW**
  - Ligo
  - Virgo
- **ν**
  - IceCube

**Outgoing alerts**
- 12/yr
- 30/yr
- 6/yr (Offline)
- (1-10/yr) (Offline)
- (joint analyses)

**Incoming alerts**
- FRBs
- GRBs, AGN flares, etc.
- GW events
- HESE + EHE

2016-09-01
Fabian Schüssler
Outgoing: Optical follow-up analysis

- Follow-up optimized for GRBs (min-hours) and SNe (days-weeks)
- Image analysis: search for variable sources

Upper limits compared to the optical GRB afterglow (Kann et al 2010)

Upper limits compared to Swift GRB observations

Optical and X-ray early follow-up of ANTARES neutrino alerts
JCAP 02 (2016) 062, arXiv: 1508.01180
Outgoing: X-ray + VHE follow-up

- September 1st, 2015: TAToO single HE-alert to optical telescopes + Swift
- Unknown, bright and variable X-ray source detected by Swift
- ATEL 7987
  - Extensive follow-up (radio – optical – X – VHE)
  - No gamma-ray source (e.g. HESS-MM talk)
  - Identification as variable star
Incoming: Neutrino follow-up of GW150914

- Size of GW150914: 590 deg$^2$ / ANTARES resolution: <0.5 deg$^2$
- Searches for coincident neutrinos (±500s): compatible with atmo. backgrounds
- Limits from ANTARES dominate below O(100 TeV) (white line)
- Limits on total energy radiated in neutrinos: <10% GW
- Currently commissioning: Receive + analyze GW alerts in real time

Phys.Rev. D93 (2016) no.12, 122010
Summary

- Northern hemisphere detectors mainly sensitive to Galactic TeV sources
- Extensive searches for neutrino sources
  - neutrino sky (still ?) isotropic
- Extensive multi-messenger program
  - Correlation studies with catalogs of source candidates
  - Time domain important
    - enhanced sensitivity due to background reduction
    - online reconstruction ➔ real-time coincidences + alert emission
  - TAToO: online analysis and alert emission
    - Alerts within a few seconds
    - Extensive follow-up program covering all wavelengths
Backup
Neutrino astronomy

Interaction: angle between neutrino and muon

Scattering: angle muon is scattered between interaction point and reaching the detector
Detector operation

since 2008:
12 lines
0.85 duty cycle

cable failure

springs: bio-luminescence
Fermi-Bubbles and diffuse emission

2pt correlations

- Improved auto-correlation analysis
  - Number of event pairs \( \mathcal{N} \) as function of their mutual angular distance \( \Delta \Omega \), weighted with the estimated energy of the events

\[
\mathcal{N}_p(\Delta \Omega) = \sum_{i=1}^{N} \sum_{j=i+1}^{N} w_{ij} \times H(\Delta \Omega_{ij} - \Delta \Omega)
\]
2pt cross-correlations

• Cross-correlation with external messengers
  – High energy gamma-rays (2FGL, Nolan et al. 2012)
  – Matter distribution in the local universe (GWGC, White 2011)
  – Massive black holes (Caramete&Biermann 2010)

• No significant correlation observed

S. Adrian-Martinez, et al., JCAP 05 (2014) 001

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Atmospheric neutrinos

- main background in searches for astrophysical neutrinos
- access to high energy flavor physics (‘prompt’ component)
- soft energy spectrum
  - excess at high $E \rightarrow$ diffuse, astrophysical flux (e.g. Phys. Lett. B 696 (2011) 16)
  - use energy information as discriminant variable in analyses

$$E^2 \frac{dN}{dE} \text{[GeV s}^{-1} \text{sr}^{-1} \text{cm}^{-2}]$$

- ANTARES Unfolding
- AMANDA-II Unfolding
- IceCube40 Unfolding

- Bartol flux
- Bartol uncertainty
- Bartol + Martin flux
- Bartol + Enberg flux

Temporal search windows: Sensitivity gain

$\tilde{n}_s(50\%@5\sigma)$

Flare length (days)