All-flavor Neutrino
Point-like Source Search
with the ANTARES Neutrino Telescope
The ANTARES neutrino telescope:
Detector layout

- Largest neutrino telescope in the Northern Hemisphere
- First detection line installed in early 2006
- Completed in 2008
- 2475 m depth in the Mediterranean Sea
- 40 km offshore from Toulon

- Three-dimensional array of 885 PMTs
- 12 vertical lines, 25 storeys
- 3 PMTs per storey
- PMT facing 45° downwards
The ANTARES neutrino telescope: Detection principle

- Earth used as shield for atmospheric muons
- Either CC or NC interaction with a nucleus inside or nearby the detector volume
- Cherenkov radiation detected by the PMTs
- Position, time and charge used to reconstruct direction and energy

Track-like events:
- $\nu_\mu$ ($\nu_\tau$) neutrino
- CC interaction near the detector
  ➔ track

Shower-like events:
- all neutrinos NC
- $\nu_e, \nu_\tau$ CC interaction inside or very close to the detector ➔ shower

• New shower reconstruction mechanism recently released [1]
• Shower-like events included for the first time in a point-like source search with ANTARES

All-flavour neutrino point source analysis:
Data sample

- Jan 29, 2007 to Dec 31, 2015
- 2423.6 days of lifetime
- Track and Shower events

Total number of selected events:
- 7629 tracks
- 180 showers

Probability to obtain a reconstructed angle within $\Delta\Psi$ between the reconstructed direction with respect to the true Monte Carlo neutrino direction. A neutrino flux with an energy spectrum $E^{-2}$ is assumed.

Acceptance as a function of the source declination for an $E^{-2}$ energy spectrum.
Search method: likelihood

$$\log L_{s+b} = \sum_j \sum_{i \in j} \log \left[ \mu_{\text{sig}}^j S_i^j + N_j B_i^j \right] - \mu_{\text{sig}}$$

Track signal PDFs

$$S_i^{tr} = S_{\text{space}}(\alpha_i, \beta_i) \cdot S_{\text{energy}}(E_i, \beta_i | \delta_i)$$

Track background PDFs

$$B_i^{tr} = B_{\text{space}}(\delta_i) \cdot B_{\text{energy}}(E_i, \beta_i | \delta_i)$$

Shower signal PDFs

$$S_i^{sh} = S_{\text{space}}(\alpha_i) \cdot S_{\text{energy}}(E_i)$$

Shower background PDFs

$$B_i^{sh} = B_{\text{space}}(\delta_i) \cdot B_{\text{energy}}(E_i)$$

Test Statistic

$$Q = \log L_{s+b} - \log L_b$$
Search method: likelihood

\[
\log L_{s+b} = \sum_j \sum_{i \in j} \log \left[ \mu_{\text{sig}}^j S_i^j + N_j^i B_i^j \right] - \mu_{\text{sig}}
\]

Signal PDFs

\[
S_i = S_{\text{space}} \cdot S_{\text{energy}}
\]

Background PDFs

\[
B_i = B_{\text{space}} \cdot B_{\text{energy}}
\]
Search method: strategies

- **Full-sky search**
  - TS evaluated in squares of $1^\circ \times 1^\circ$ over the ANTARES visible sky

- **Galactic Centre region search**
  - TS evaluated in squares of $1^\circ \times 1^\circ$ over a restricted region around the GC: ellipse, $15^\circ$ semi-axis in galactic latitude, $20^\circ$ semi-axis in galactic longitude

- **Candidate list searches**
  - 106 known astrophysical objects (Pulsars, SNRs, …)
  - 13 IceCube tracks from the HESE sample [1][2]

- **Sagittarius A* location**
  - Tested as an extended source by assuming a Gaussian emission profile of various widths

**Free parameters:**

- $\mu_{tr}$
- $\mu_{sh}$
- $\alpha_{\text{source}}$
- $\delta_{\text{source}}$

Results: Most significant cluster

Full-sky search

Most significant cluster located at

\((\alpha, \delta) = (343.8^\circ, 23.5^\circ)\)

Post-trial significance:

5.9% or 1.9\(\sigma\) (two-sided convention)

Upper limit on the neutrino flux:

\(E^2d\phi/dE = 3.8 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1}\)
Results: Most significant cluster
Candidate list search – 106 candidates

Most significant cluster located at

**HESSJ0632+057** location
\((\alpha, \delta) = (98.24^\circ, 5.81^\circ)\)

Post-trial significance:

13% or 1.5\(\sigma\) (two-sided convention)

Upper limit on the neutrino flux:

\[E^2d\phi/dE = 2.4 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1}\]
Results: Most significant cluster
Candidate list search – 13 HESE

Most significant cluster located at

\((\alpha, \delta) = (130.1^\circ, -29.8^\circ)\)

at a distance of 1.5° from the HESE track with ID 3

Post-trial significance:

20% or 1.3\(\sigma\) (two-sided convention)

Upper limit on the neutrino flux:

\(E^2d\phi/dE = 2.1 \times 10^{-8}\) GeV cm\(^{-2}\) s\(^{-1}\)
Results: Most significant cluster
Galactic Centre region search

Other spectral indices ($\gamma = 2.1, 2.3, 2.5$) and source extensions ($\sigma = 0.5^\circ, 1.0^\circ, 2.0^\circ$) tested

Most significant clusters located at

- $(\alpha, \delta) = (257.4^\circ, -41.0^\circ)$ for a $E^{-2}$ spectrum and point-like source
  - Post-trial significance: 60% or 0.5$\sigma$ (two-sided convention)

- $(\alpha, \delta) = (273.0^\circ, -42.2^\circ)$ for a $E^{-2.5}$ spectrum and point-like source
  - Post-trial significance: 30% or 1.0$\sigma$ (two-sided convention)
Results: Most significant cluster
Sagittarius A*

Location:

$(\alpha,\delta) = (266.42^\circ, -29.01^\circ)$

Investigated as a point-like source $(\sigma = 0^\circ)$ and as an extended source $(\sigma = 0.5^\circ, 1.0^\circ, 2.0^\circ)$

Largest excess above background found for

- Point-like assumption
- Pre-trial significance: 22% or $1.2\sigma$ (two-sided convention)
Results: Sensitivities and Limits
Full-sky and Candidate list searches

Sensitivities and upper limits at a 90% C.L. on the signal flux from the Full-sky and the Candidate list searches
90% C.L. upper limits of the search restricted to the region around the origin of the galactic coordinates at \((\alpha, \delta) = (266.40^\circ, -28.94^\circ)\) assuming different spectral indices for the neutrino flux (left) and different source extensions for \(\gamma = 2\) (right).
Results: Sensitivities and Limits
Sagittarius A*

Discovery flux (solid red), median sensitivity (dotted blue) and upper limits (solid blue) at 90% C.L. for a search for an extended source at Sagittarius A* at \((\alpha, \delta) = (266.42^\circ, -29.01^\circ)\) assuming different angular extensions \(\sigma\). The dashed lines correspond to the point-like source assumption.
Conclusions

- First all-flavor neutrino point-like source search with the ANTARES neutrino telescope
- No significant evidence of cosmic neutrino sources found
- Full-sky search: largest excess found at $(\alpha, \delta) = (343.8^\circ, 23.5^\circ)$ with $1.9\sigma$ significance
- Candidate list search over 106 candidates: largest excess found for HESSJ0632+057 with $1.5\sigma$ significance
- Candidate list search over 13 IceCube HESE: largest excess found HESE with ID 3 with $1.3\sigma$ significance
- Galactic Centre region search: largest excess found at $(\alpha, \delta) = (257.4^\circ, -41.0^\circ)$ for a $E^{-2}$ spectrum and point-like source with $0.5\sigma$ significance
- Sagittarius A*: largest excess found for a point-like source with $1.2\sigma$ significance
- Most sensitive limits for a large fraction of the Southern Sky set, especially at neutrino energies below 100 TeV.
Backup
### Table 3: List of astrophysical objects used in the candidate list search. Presented are the object’s coordinates in declination (δ) and right-ascension (α). The first column reports the type of source. Binary means X-ray binary, GC means Galactic Centre, Radio means Radio Galaxy, Sog2 means Seyfert 2 Galaxy, UNID means unidentified. The last two columns show the sum of the fitted number of signal track and shower events $\mu_{sig} = \mu_{tr} + \mu_{sh}$ and the 90% C.L. upper limits on the flux normalization factor $\phi_{0}^{lim}$ (in units of 10\(^{-8}\) GeV cm\(^{-2}\) s\(^{-1}\)). Candidates of the same type are sorted by declination.

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>δ(^{\circ})</th>
<th>α(^{\circ})</th>
<th>$\mu_{sig}$</th>
<th>$\phi_{0}^{lim}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL Lac</td>
<td>PKS0205-489</td>
<td>-48.82</td>
<td>302.37</td>
<td>0.3</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>PKS0357-441</td>
<td>-44.08</td>
<td>84.71</td>
<td>0.6</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>PKS1149-502</td>
<td>-14.14</td>
<td>239.40</td>
<td>2.9</td>
<td>1.56</td>
</tr>
<tr>
<td></td>
<td>PKS0246-309</td>
<td>-37.53</td>
<td>67.17</td>
<td>0.7</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>PKS0436-400</td>
<td>-33.67</td>
<td>244.36</td>
<td>1.2</td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td>TXS1714+684</td>
<td>-10.15</td>
<td>249.40</td>
<td>0.8</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td>PKS0548+022</td>
<td>-82.27</td>
<td>67.61</td>
<td>0.8</td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td>HE2206-059</td>
<td>-22.67</td>
<td>50.78</td>
<td>0.7</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>PKS2150-394</td>
<td>-40.53</td>
<td>309.73</td>
<td>0.8</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>PKS1641-25</td>
<td>-33.49</td>
<td>165.51</td>
<td>0.8</td>
<td>0.83</td>
</tr>
</tbody>
</table>

### References

arXiv:1706.01857
Table 4: The 13 IceCube muon track candidates from the IceCube HESE sample [19, 20] that are in the field of view of the ANTARES detector. The table gives the equatorial coordinates, the angular error estimate $\beta_{\text{IC}}$ of the event and the 90\% C.L. upper limits on flux $\Psi_0$ (in units of $10^{-8}$ GeV cm$^{-2}$ s$^{-1}$).

<table>
<thead>
<tr>
<th>HESE ID</th>
<th>$\delta$ [°]</th>
<th>$\alpha$ [°]</th>
<th>$\beta_{\text{IC}}$ [°]</th>
<th>$\Phi_0^{90%}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>-31.2</td>
<td>127.9</td>
<td>1.4</td>
<td>2.1</td>
</tr>
<tr>
<td>5</td>
<td>-0.4</td>
<td>110.6</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td>8</td>
<td>-21.2</td>
<td>182.4</td>
<td>1.3</td>
<td>1.7</td>
</tr>
<tr>
<td>13</td>
<td>-40.3</td>
<td>67.9</td>
<td>1.2</td>
<td>2.4</td>
</tr>
<tr>
<td>18</td>
<td>-24.8</td>
<td>345.6</td>
<td>1.3</td>
<td>2.0</td>
</tr>
<tr>
<td>23</td>
<td>-13.2</td>
<td>208.7</td>
<td>1.9</td>
<td>1.7</td>
</tr>
<tr>
<td>28</td>
<td>-71.5</td>
<td>164.8</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>37</td>
<td>20.7</td>
<td>167.3</td>
<td>1.2</td>
<td>1.7</td>
</tr>
<tr>
<td>38</td>
<td>14.0</td>
<td>93.3</td>
<td>1.2</td>
<td>2.1</td>
</tr>
<tr>
<td>43</td>
<td>-22.0</td>
<td>206.6</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>44</td>
<td>0.0</td>
<td>336.7</td>
<td>1.2</td>
<td>1.8</td>
</tr>
<tr>
<td>45</td>
<td>-86.3</td>
<td>219.0</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>53</td>
<td>-37.7</td>
<td>239.0</td>
<td>1.2</td>
<td>1.6</td>
</tr>
</tbody>
</table>
Selection criteria

Table 1: Selection cuts for the track sample and number of remaining simulated events after each step for atmospheric muons ($n_\mu^{\text{atm}}$), atmospheric neutrinos ($n_\nu^{\text{atm}}$) and cosmic neutrinos ($n_\nu^{E^{-2}}$) reconstructed as a track in the detector. For cosmic neutrinos, a flux according to $d\Phi/dE = 10^{-8} (E/\text{GeV})^{-2} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$ is assumed.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Condition</th>
<th>$n_\mu^{\text{atm}}$</th>
<th>$n_\nu^{\text{atm}}$</th>
<th>$n_\nu^{E^{-2}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td></td>
<td>4.9 x 10^8</td>
<td>6.3 x 10^4</td>
<td>204</td>
</tr>
<tr>
<td>Up-going</td>
<td>$\cos \theta_\nu &gt; -0.1$</td>
<td>4.3 x 10^7</td>
<td>5.0 x 10^4</td>
<td>151</td>
</tr>
<tr>
<td>Angular error estimate</td>
<td>$\beta_\nu &lt; 1^\circ$</td>
<td>2.2 x 10^7</td>
<td>3.3 x 10^4</td>
<td>105</td>
</tr>
<tr>
<td>Track reconstruction quality</td>
<td>$\Lambda &gt; -5.2$</td>
<td>1513</td>
<td>7475</td>
<td>44</td>
</tr>
<tr>
<td>Track length and energy cut</td>
<td>$L_\mu &gt; 380 \text{ m}$, $\log_{10}(\rho) &gt; 1.6$</td>
<td>1117</td>
<td>7086</td>
<td>41</td>
</tr>
</tbody>
</table>

Table 2: Selection cuts for the shower sample and number of remaining simulated events after each step for atmospheric muons ($n_\mu^{\text{atm}}$), atmospheric neutrinos ($n_\nu^{\text{atm}}$) and cosmic neutrinos ($n_\nu^{E^{-2}}$) reconstructed as a shower in the detector. For cosmic neutrinos, a flux according to $d\Phi/dE = 10^{-8} (E/\text{GeV})^{-2} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$ is assumed. Refer to Appendix A for more details.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Condition</th>
<th>$n_\mu^{\text{atm}}$</th>
<th>$n_\nu^{\text{atm}}$</th>
<th>$n_\nu^{E^{-2}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track Veto</td>
<td>not selected as muon track</td>
<td>4.9 x 10^8</td>
<td>5.6 x 10^4</td>
<td>160</td>
</tr>
<tr>
<td>Up-going</td>
<td>$\cos \theta_{sh} &gt; -0.1$</td>
<td>1.5 x 10^8</td>
<td>2.3 x 10^4</td>
<td>90</td>
</tr>
<tr>
<td>Interaction vertex</td>
<td>$R_{sh} &lt; 300 \text{ m}$, $</td>
<td>Z_{sh}</td>
<td>&lt; 250 \text{ m}$</td>
<td>7.7 x 10^7</td>
</tr>
<tr>
<td>M-estimator</td>
<td>$M_{\text{est}} &lt; 1000$</td>
<td>7.2 x 10^7</td>
<td>2.0 x 10^4</td>
<td>80</td>
</tr>
<tr>
<td>RDF</td>
<td>$RDF &gt; 0.3$</td>
<td>8.0 x 10^4</td>
<td>2044</td>
<td>24</td>
</tr>
<tr>
<td>Muon likelihood</td>
<td>$L_\mu &gt; 50$</td>
<td>90</td>
<td>109</td>
<td>12</td>
</tr>
</tbody>
</table>
Selection criteria

Track-like events selection cuts

- Quality parameter: $\Lambda_{tr} > -5.2$
- Estimated angular error: $\beta_{tr} < 1^\circ$
- Up-going: $\cos \theta_{tr} > -0.1$
- Energy estimator: $\log_{10}(\rho) > 1.6$
- Muon track length: $L_\mu > 360$ m

Shower-like events selection cuts

- Track veto: not selected as track
- Estimated angular error: $\beta_{sh} < 1^\circ$
- Up-going: $\cos \theta_{sh} > -0.1$
- Interaction vertex: $R_{sh} < 300$ m, $|Z_{sh}| < 250$ m
- M-estimator: $\text{Mest} < 1000$
- Random Decision Forest: RDF > 0.3
- Muon likelihood: $L_\mu > 50$
Data/MC comparison

Comparison of the data with Monte Carlo simulations as a function of the quality parameter $\Lambda$ (left) and of the zenith $\theta_{sh}$ of the reconstructed shower direction.
Systematic uncertainties

- **Absolute Pointing Accuracy Uncertainty**
  0.13° uncertainty on the horizontal (ϕ) direction
  0.06° uncertainty on the vertical (θ) direction

- **Angular Resolution Uncertainty**
  15% (12%) degradation on the angular resolution in the track (shower) channel

- **Acceptance Uncertainty**
  15% uncertainty

- **Background Uncertainty**
  declination-dependent distribution of background events parameterized as a linear combination of the two different spline functions (the red and blue lines)