Recent results of ANTARES

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(for the ANTARES Collaboration)
Neutrino Telescopes in a nutshell

- Use Earth as a shield. Look for **upgoing muons** (coming from ν’s crossing the Earth). **Muon neutrinos** are well suited for HE detection since cross-section and muon range increase with energy.
- Muons emit **Cherenkov light** collected by a lattice of PMTs in a natural medium. Other signatures ($\nu_e$, $\nu_\tau$) can also be detected.
- Position and arrival time of photons enable track reconstruction.

- **IceCube and ANTARES** cover the whole sky (and 0.5π sr instantaneous common view).
- ν-telescopes in the **northern hemisphere**, as ANTARES, observe mostly the **southern sky**, where the Galactic Centre and a variety of HE gamma sources are located.
- The natural energy range of detection is **1 TeV to 100 TeV** (but can be extended for some specific studies).
- **Sea water** has relative little scattering, thus angular resolution is very good (~0.5°)
ANTARES

- 12 lines (885 PMTs)
- 25 storeys / line
- 3 PMTs / storey

- In the Mediterranean Sea (near Toulon) at 2500 m depth

- 5-line setup in 2007
- Completed in 2008

- 40 km to shore
- 350 m
- 100 m
- 14.5 m
**Diffuse $\nu_\mu$ flux**

- **Goal:** Look for an overall excess of neutrinos above the $\nu$ atmospheric background.
- **Data:** 2008-2009 data (334 days).
- **Selection guidelines:**
  - **Basic selection:**
    - Good quality runs are selected.
      (i.e. most of the detector running, low bioluminescence)
    - A trigger based on minimum number of causally related hits.
      (all data to shore → on-shore event filtering)
  - **1st Level cuts:**
    Upgoing reconstructed tracks of fair enough quality:
    \[ \cos \theta_{\text{rec}} < 80^\circ \ ; \ \Lambda > -6 \ ; \ N_{\text{hits}} > 60 \]
    According to MC this removes all atm muons with $E < 1$ TeV and reduces misreconstructed events by almost 3 orders of magnitude.
    (more about $\Lambda$ later).
  - **2nd Level cuts:**
    Combined selection based on $N_{\text{hits}}$ and track quality, $\Lambda$.
    MC: $< 1$ misreconstructed muon /year in the final sample
  - **Energy estimator:**
    Use hit repetition rate per OM as energy estimator to reduce atmospheric $\nu$ background.
Diffuse $\nu_\mu$ flux - Energy estimator

$$R = \frac{\sum R_i}{N_{OM}}$$

$N_{OM} =$ Number of OMs used in the event reconstruction.

$R_i =$ Number of hits in $i$-th OM.

$R =$ Mean number of repetitions in the event

$R$ correlates with the energy of the event

Good MC/agreement for the $R$ variable (20 days of data unblinded of atm $\mu$’s). Normalization factor 1.12

$R$ cut determined by optimizing the Model Rejection Factor. After unblinding (2nd level candidates) events above $R$ cut are compatible with background expectation.
Diffuse $\nu_\mu$ flux – Upper limits ($E^{-2}$)

$$E^2 \Phi(E)_{90\%} = 4.7 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

$20 \text{ TeV} < E < 2.5 \text{ PeV}$
Search for point sources of HE cosmic $\nu$’s

- **Goal:** using the good pointing capabilities of ANTARES ($< 0.5^\circ$) look for event clusters.

- **Data:** 2007-2010 data (813 days). Preliminary results. Previous results for 2007-2008 data (304 days) can be found in arXiv:1108.0292 (submitted to *ApJL*).

- **Selection guidelines:**
  - Good quality runs are selected (i.e. most of the detector running, low bioluminescence)
  - A trigger based on minimum number of causally related hits (all data to shore → on-shore event filtering)
  - Keep events reconstructed as upgoing.
  - Events are accepted if the angular error estimate is $< 1^\circ$ (misreconstruted muons have a much larger error estimate)
  - A cut on track quality is chosen to optimize the sensitivity to an $E^{-2}$ flux.

Data/MC ratio $\approx$1 $\rightarrow$ simulation describes data fairly well.
Integrated live time: 813 days

<table>
<thead>
<tr>
<th># of Lines</th>
<th>Year</th>
<th>Livetime (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2007</td>
<td>183</td>
</tr>
<tr>
<td>9-10-12</td>
<td>2008</td>
<td>189</td>
</tr>
<tr>
<td>12</td>
<td>2009</td>
<td>209</td>
</tr>
<tr>
<td>12</td>
<td>2010</td>
<td>232</td>
</tr>
</tbody>
</table>

Final selected sample: 3058 events

Cut on $\Lambda$ optimizes discovery potential
- quality: $\Lambda > -5.2$
- angular error: $\beta < 1^\circ$
- upgoing: $\cos(\text{zenith}) > 0$

$N_{\text{hits}}$ used in search algorithm as energy proxy to further improve background rejection (see later)

Final sample contains $\sim 15\%$ atmospheric muons
Detector Performance

Cumulative angular resolution

Angle between true neutrino direction and reconstructed track for selected muons
Assuming an $E^{-2}$ flux for the signal
Median is $0.46^0$; 83% of events have $< 1^0$

Event acceptance

Number of events for a reference flux
$\Phi = 10^{-8} (E / \text{GeV})^{-2} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$
Everything included, i.e.: reconstruction, event selection and visibility.
Unbinned algorithm:

\[
\log \mathcal{L}_{s+b} = \sum_i \log[\mu_{\text{sig}} \times F(\beta_i, \delta_i, \alpha_i)] \times \mathcal{N}(N_{\text{hit}_i}^{\text{sig}}) + B_i \times \mathcal{N}(N_{\text{hit}_i}^{\text{bkg}}) + \mu_{\text{tot}}
\]

Compare expectation for background vs. signal (position and energy) and maximize likelihood ratio.

**Ingredients:**
- Angular resolution (point spread function)
- Distribution of background in sky
- Bck/signal expected energy difference

**Outcome:**
- Full-sky search: \( \mu_{\text{sig}}, \delta_s \) and \( \alpha_s \)
  amount of signal (or limit) and position
- List of candidate sources: \( \mu_{\text{sig}} \)
  Signal (positions fixed)

**Significance:** \( Q = \log \mathcal{L}_{s+b}^{\text{max}} - \log \mathcal{L}_b \)

From distributions of \( \mathcal{L} \) ratio at minimum
Full-sky search

Sky map in **Galactic Coordinates**
Background colour indicates **visibility**

- Blue points: selected events (3058)
- Red stars: candidate source list

**Most significant cluster at:**
\[ \text{RA} = -46.5^\circ, \]
\[ \delta = -65.0^\circ \]

**\( N_{\text{sig}} = 5 \)**
**\( Q = 13.02 \)**
**p-value = 0.026**
**Significance = 2.2 \( \sigma \)**

Result **compatible with the background hypothesis**
Source candidate list

Look in the direction of a list of 51 predefined candidate sources
(selection of sources mostly based in γ-ray flux and visibility)

First eleven sources sorted by Q-value.
Last column shows the 90% CL upper limit on
the flux \((E / \text{GeV})^{-2} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1}\)

<table>
<thead>
<tr>
<th>name</th>
<th>ra</th>
<th>decl</th>
<th>Nsigfit</th>
<th>Q</th>
<th>p-value</th>
<th>nsigma</th>
<th>lim_Nsig</th>
<th>lim_flux</th>
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<tbody>
<tr>
<td>HESS J1023-575</td>
<td>155.83</td>
<td>-57.76</td>
<td>1.97</td>
<td>2.35</td>
<td>0.41</td>
<td>0.82</td>
<td>5.62</td>
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<td>3C 279</td>
<td>-165.95</td>
<td>-5.79</td>
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<td>2.15</td>
<td>0.48</td>
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<td>GX 339-4</td>
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<td>-48.79</td>
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<td>1.49</td>
<td>0.72</td>
<td>0.36</td>
<td>5.10</td>
<td>5.8e-08</td>
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<td>Cir X-1</td>
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<td>-57.17</td>
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<td>1.31</td>
<td>0.79</td>
<td>0.27</td>
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<td>5.8e-08</td>
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<td>MGRO J1908+06</td>
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<td>0.90</td>
<td>1.22</td>
<td>0.82</td>
<td>0.23</td>
<td>4.59</td>
<td>1.1e-07</td>
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<tr>
<td>ESO 139-G12</td>
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<td>-59.94</td>
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<td>0.76</td>
<td>0.94</td>
<td>0.08</td>
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<td>HESS J1356-645</td>
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<td>-64.50</td>
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<td>0.49</td>
<td>0.98</td>
<td>0.03</td>
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<tr>
<td>PKS 0548-322</td>
<td>87.67</td>
<td>-32.27</td>
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<td>0.39</td>
<td>0.99</td>
<td>0.02</td>
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<td>7.1e-08</td>
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<tr>
<td>HESS J1837-069</td>
<td>-80.59</td>
<td>-6.95</td>
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<td>0.99</td>
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<tr>
<td>PKS 0454-234</td>
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<td>0.39</td>
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<td>ICECUBE</td>
<td>75.45</td>
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<td>0.34</td>
<td>0.07</td>
<td>1.00</td>
<td>0.00</td>
<td>3.83</td>
<td>7.0e-08</td>
</tr>
</tbody>
</table>

**HESS J1023−575** most signal-like, \( p \)-value 40\% (post trial)

Compatible with the background hypothesis.
Candidate list search – Flux limits

Assuming an $E^{-2}$ flux for a possible signal

- ANTARES 2007-2010
  - 813 days
  - $\times 2.5$ improvement w.r.t. previous analysis (304 days)

For most of the sources ANTARES gives the most stringent limits.
(IceCube requires very high energy component ($E > 1$ PeV) for Southern Sky).
Neutrino search from $\gamma$-ray flaring blazars

- **Goal**: using the information from $\gamma$-ray detectors (Swift, Fermi, HESS) increase discovery potential.

- **Data**: 2008 data (61 days) 
  LBAS Catalog (Fermi LAT Bright AGN Sample).

- **Selection guidelines**:
  - Similar to previous analyses for runs and event selection ($\Lambda > -5.4 + \beta < 1^\circ$)
  - Include space-time information in likelihood ratio to reduce background and increase discovery potential.
  - Flare (HE state) period identification:
    - Extraction of a baseline + error
    - Prior: $(\text{flux-erflux}) > (\text{baseline} + 2*\text{sigma}) + \text{flux} > (\text{baseline} + 3*\text{sigma})$
    - Duration: add consecutive points to the prior $(\text{flux-erflux}) > (\text{baseline} + \text{sigma})$
    - Add +/- 0.5 day to each flare (1-day binned LC + uncertainties models)
Neutrinos from γ-ray flaring blazars. Results.

10 flaring sources in selected period:
PKS0208-512, AO0235+164, PKS1510-089, 3C273, 3C279, 3C454.3, OJ287, PKS0454-234, Wcomae, PKS2155-304

For 9 sources: 0 events ⇒ upper-limit on the neutrino fluence

3C279: 1 event compatible with the source direction (Δα=0.56º) and time distribution
⇒ pre trial p-value = 1.1%
post trial p-value ~10%
not significant
No time to report on...

Optical Follow-up +
coincidence with Gravitational wave signals
Alerts sent by ANTARES to robotic telescope systems such as TAROT and ROTSE.(HE ν’s or doublets in space-time window).
Common data analysis with VIRGO/LIGO

Indirect search for dark matter
See V. Bertin’s talk in this conference

Neutrinos from GRBs

Search for magnetic monopoles
Best limit at present
...plus a variety of other scientific activities.

Acoustic detection studies

Marine Biology

Sea Sciences

Geoscience

The Economist

Hang on, that's not a neutrino

Dec 1st 2010, 16:19 by J.P.

PHYSICISTS are often accused by the public and other scientists of spending inordinate sums on fancy kit that does little apart from merely satisfying human curiosity. Besides stressing that there is nothing more about knowledge, the boffins will typically respond by trotting out a long list of blue-sky projects that yielded serendipitous results, from microwave ovens to the internet. They can also offer plenty of examples of how their own research has aided colleagues in other fields, from climate science to, somewhat more improbably, marine biology.
Conclusions

- ANTARES has more than 4 years of data on tape (since 2008 in its final configuration).
- The expected performances have been reached, in particular ANTARES has an excellent angular resolution.
- The physics program is very broad. We have shown the latest results on some of the analyses:
  - Point sources (2007-2010).
  - Neutrinos from flaring blazars (2008)
- No cosmic neutrino sources found yet, but more data to come. Other interesting results are being released on GRBs, monopoles, etc. plus a lively program in sea and geo-sciences.
- The success of ANTARES underlines the feasibility of a much larger detector (KM3NeT).