Recent results from the ANTARES neutrino telescope

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**UHE neutrinos**

**Bottom-Up Models**
( Acceleration): **galactic**
(supernova remnants, pulsars, microquasars) and **extra-galactic** (active galactic nuclei, gamma ray bursts) **sources**.

\[
p + \gamma \text{ or } p + p \rightarrow \pi^\pm + \pi^0 + X
\]

**Top-Down Models**
(Annihilation/Decay): Topological Defects, Z-burst, WIMPs.

**GZK neutrinos**

\[
p + \gamma \rightarrow \gamma + \gamma
\]

\[
p + \pi^0 \rightarrow \Delta^+
\]

\[
\rightarrow n + \pi^+
\]

\[
\rightarrow \mu^+ + \nu_\mu
\]

\[
\rightarrow e^+ + \nu_e + \bar{\nu}_\mu
\]

\[
\pi^0 \rightarrow \gamma \gamma
\]
Neutrino Astronomy: why?

Neutrinos: the optimal choice

- weakly interacting (propagate through regions opaque to photons);
- electrically neutral (not deflected by magnetic fields like protons → point back to their source);
- stable (can travel along big distances).

Photoons abundant and easy to detect but:
- hot and dense regions opaque to γ;
- high energy γ interact with the CMB radiation producing e⁺e⁻ pairs.

Protons at high energy (> 10¹⁹ eV) interact with the CMBR, at lower energy deviated by galactic magnetic fields.

Signature of hadronic processes in the high-energy universe.
Neutrino Astronomy: how?

- $\nu$ can be detected collecting the visible **Cherenkov radiation** emitted as the high-energy **charged particles** produced in $\nu$ interaction with the medium propagate through a transparent medium with superluminal velocity.

- Since $\nu$ are weakly interacting and their fluxes from astrophysical sources are expected to be faint, a **large target/detection volume (~ km$^3$)** is required.

Main detection channel:

**Track-like events:**

$\nu_\mu$ CC-interaction giving a relativistic $\mu$

Other detection channels:

**Shower-like events:**

$\nu_e$ & $\nu_\tau$ CC-interaction and $\nu_\mu$, $\nu_e$, $\nu_\tau$ NC-interaction

Detection principle

“We propose getting up an apparatus in an underground lake or deep in the ocean in order to determine the location of charged particles with the help of Cherenkov radiation” M. Markov, 1960

$$\theta_{\mu\nu} = \frac{0.7^\circ}{(E\nu[TeV])^{0.6}}$$

Detector:

matrix of photomultipliers (PMTs)

Earth’s crust

interaction

$\nu_\mu$

$\mu$

time, position & amplitude of hits

energy & arrival direction of $\nu$

C. Perrina for ANTARES
**Signal vs. background**

**SIGNAL** → Neutrinos from cosmic sources

**BACKGROUND** → Two types of physics bkg:
- **atmospheric muons** induced by CR interactions in atmosphere;
- **muons** by atmospheric neutrinos interactions.

- To reject atmospheric $\mu$, only **up-going** events considered.
- To discriminate atmospheric neutrinos (irreducible bkg):
  → energy reconstruction:
  - Atmo. $\nu$ flux $\sim E^{-3.5}_\nu$
  - Astro. $\nu$ flux $\sim E^{-2}_\nu$
  → event clustering (search for point sources).
Astronomy with a Neutrino Telescope and Abyss environmental RESearch.

- Located at a depth of ~2475 m in the Mediterranean Sea, ~40 km South-East off the coast from Toulon, France;
- The 1\textsuperscript{st} undersea \( \nu \) telescope, completed in May 2008;
- The largest \( \nu \) telescope in the Northern Hemisphere: instrumented volume \( \sim 0.02 \text{ km}^3 \);
- The only one undersea neutrino telescope currently operating.

**Diagram:**
- 12 lines
- 25 floors / line
- 3 PMTs / floor
- 885 PMTs
- PMTs oriented at 45° downwards to maximize the sensitivity to up-going \( \mu \)
✓ ~ 85 % physics duty cycle

✓ $3.5\pi$ sr annual sky coverage, most of the Galactic Plane

✓ Galactic Centre (GC) coverage

✓ $1.5\pi$ sr annually integrated common view with IceCube (IC)

✓ ~ 20 atmospheric muons per second

✓ ~ 5 atmospheric neutrinos per day

✓ real time data processing

✓ ~1 m$^2$ effective area for $\nu$ at 30 TeV

Visibility (galactic coordinates)

Complementary to IceCube
ANTARES performance: two event classes

**Track-like** event signatures  
(CC interactions of $\nu_\mu$)  
- $\mu$ travels up to several km $\rightarrow$ interactions outside the instrumented volume  
- Angular resolution $< 1^\circ$  
- Energy resolution: factor 2-3 in $E_{\text{reco}}/E_{\text{MC}}$

**Shower-like** event signatures  
(CC interactions of $\nu_e$ & $\nu_\tau$, NC interactions)  
- Only interactions inside/close to the instrumented volume  
- (Worse) angular resolution $> 10^\circ$  
- (Better) energy resolution: factor $< 1.4$ in $E_{\text{reco}}/E_{\text{MC}}$
Highlighted topics

- Search for **diffuse** neutrino fluxes
  - Measurement of the atmospheric $\nu_\mu$ spectrum
  - Search for a diffuse neutrino flux of astrophysical origin
  - Search for neutrinos from Fermi bubbles

- Search for neutrino fluxes from **point-like** astrophysical sources
  - Full-sky search
  - Candidate list search
  - The Galactic Centre region

- Overview of the **Multi-messenger** neutrino search

- **Dark matter** search from the Sun and the Galactic Centre

Not covered in this talk: neutrino oscillation, magnetic monopoles, GWHEN (VIRGO/LIGO), multi-messenger searches with optical devices, dark matter from dwarf galaxies and Earth, nuclearites, associated sciences.
Measurement of the atmospheric $\nu_\mu$ spectrum

A precise measurement of the atmospheric $\nu$ flux (irreducible bkg in the search of cosmic neutrinos) is important
✓ as a test of the good behaviour of the detector
✓ as a source of information on the physics of atmospheric showers

- Data set: Dec 2007 – Dec 2011 (livetime = 885 days), up-going $\nu_\mu$
- Optimisation tuned on a burn sample of 10% data
- Reconstruction of the energy spectrum with unfolding procedure

 Zenith-averaged atmo. $\nu_\mu$ spectrum multiplied by $E_\nu^{3.5}$.

- for $E_\nu < 10^5$ GeV, $\nu_\mu$ from $\pi^\pm$ and $K^\pm$ decays $\Rightarrow$ spectrum $\propto E_\nu^{-3.7}$;
- for $E_\nu > 10^5$ GeV, in addition $\nu_\mu$ from prompt decay of charmed and bottomed mesons $\Rightarrow$ spectrum $\propto E_\nu^{-2.7}$.

Once the atmo. $\nu$ flux has been measured, one can look for an excess of events, that would reflect the existence of a diffuse neutrino flux from **unresolved astrophysical sources**. This excess would appear above an energy threshold.

**Track events**

- Data set: Dec 2007 – Dec 2011 (*livetime* = 885 days), **up-going $\nu_\mu$**
- Optimisation tuned on a burn sample of 10% data, based on the Model Rejection Factor (MRF) approach.
- $E_\nu$ estimation based on the $E_\mu$ loss along its path ($dE/dx$), evaluated from the total collected charge of the hits selected for the track reconstruction fit.
Shower events

- Data set: Feb 2007 – Dec 2012 (*livetime* = 1247 days), **up-going** $\nu_\mu, \nu_e, \nu_\tau$
- Optimisation tuned on a burn sample of 10% data based on the Model Rejection Factor (MRF) approach.
## Search for a diffuse astrophysical \( \nu \) flux (3/4)

<table>
<thead>
<tr>
<th></th>
<th>Track</th>
<th>Shower</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu ) flavours</td>
<td>muonic</td>
<td>all</td>
</tr>
<tr>
<td>Data set</td>
<td>2007-2011 (885 days)</td>
<td>2007-2012 (1247 days)</td>
</tr>
<tr>
<td>Expected bkg events</td>
<td>8.4</td>
<td>4.9</td>
</tr>
<tr>
<td>Observed signal events</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Upper limit ( E^2 \frac{dN}{dE} \ [\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}] ) (per flavour, 90% CL, systematic included)</td>
<td>( 5.1 \times 10^{-8} )</td>
<td>( 4.9 \times 10^{-8} )</td>
</tr>
<tr>
<td>Energy range</td>
<td>45 TeV &lt; ( E &lt; 10 ) PeV</td>
<td>23 TeV &lt; ( E &lt; 7.8 ) PeV</td>
</tr>
</tbody>
</table>

Upper limit for the previous analysis: \( E^2 \frac{dN}{dE} = 5.3 \times 10^{-8} \) GeV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) (20 TeV < \( E < 2.5 \) PeV)
Search for a diffuse astrophysical $\nu$ flux (4/4)
Search for neutrinos from Fermi bubbles (1/3)

- Excess of γ-(X-) rays, observed by Fermi-LAT, from two extended “bubble”-like regions above and below the Galactic Plane.
- The signal is characterized by:
  - a homogeneous intensity over the whole bubble regions
  - a hard ($\propto E^{-2}$) spectrum with a probable cutoff at energies > 100 GeV.

- The origin is still debated. Some models propose hadronic mechanisms in which accelerated cosmic rays interact with the interstellar medium producing $\pi$ decaying in $\gamma$ and $\nu$.

References:
- astro-ph 1402.0403
- PRL 106 (2011)
Data set: May 2008 – Dec 2011 (livetime = 806 days), up-going $\nu_\mu$

Background (atmospheric $\nu$) estimated from average of three non-overlapping “off-zone” with same size, shape and average detector efficiency of the “on zone” region

(galactic coordinates)
Search for neutrinos from Fermi bubbles (3/3)

Distribution of the reconstructed energy of the events.

N_{obs} = 16
<N_{bkg}> = 11

- On-zone
- Off-zones average
- 68% confidence area giving by the total background simulation

No significant excess (1.2 \sigma)

- Upper limits (lines) on the neutrino flux from Fermi bubbles;
- theoretical prediction (filled areas) for the case of a purely hadronic model for different cutoffs.

Expected signal no cutoff

Expected signal 50 TeV cutoff

50 TeV cutoff
100 TeV cutoff
500 TeV cutoff
no cutoff
Search for neutrinos from point-like sources

The aim of this search is to detect significant excesses of events from particular regions of the sky. The search can be performed

- over the full sky
- in the direction of a priori selected candidate source locations that correspond e.g. to known γ-ray emitters.

- Data set: Feb 2007 (5 lines) – Dec 2012 (livetime = 1339 days), up-going νμ
- 5516 neutrino candidates
- 90% predicted atmo. ν purity
- 0.4° ± 0.1° median uncertainty on reconstructed neutrino direction (assuming $E^{-2}_ν$ energy spectrum)

Cumulative distribution of the angle between the reconstructed μ and the true ν direction.
1) **Time-integrated full-sky search**: looking for an excess of events over the atmospheric neutrino background in the declination range $[-90^\circ, 48^\circ]$.

Most significant cluster: 6 (14) events in $1^\circ$ ($3^\circ$), $p$-value = 2.7% (2.2 $\sigma$)

*Compatible with bkg hypothesis*
2) **Candidate-list search**: looking for events in the directions of a predefined list of 51 candidate sources of interest.

No significant excess was found in any of these 51 directions → upper limits derived

<table>
<thead>
<tr>
<th>Name</th>
<th>$\alpha$ (°)</th>
<th>$\delta$ (°)</th>
<th>$n_s$</th>
<th>$p$</th>
<th>$\phi^{90\text{CL}}$</th>
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</thead>
<tbody>
<tr>
<td>HESSJ0632+057</td>
<td>98.24</td>
<td>5.81</td>
<td>1.60</td>
<td>0.0012</td>
<td>4.40</td>
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<tr>
<td>HESSJ1741-302</td>
<td>-94.75</td>
<td>-30.20</td>
<td>0.99</td>
<td>0.003</td>
<td>3.23</td>
</tr>
<tr>
<td>3C279</td>
<td>-165.95</td>
<td>-5.79</td>
<td>1.11</td>
<td>0.01</td>
<td>3.45</td>
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<tr>
<td>HESSJ1023-575</td>
<td>155.83</td>
<td>-57.76</td>
<td>1.98</td>
<td>0.03</td>
<td>2.01</td>
</tr>
<tr>
<td>ESO139-G12</td>
<td>-95.59</td>
<td>-59.94</td>
<td>0.79</td>
<td>0.06</td>
<td>1.82</td>
</tr>
<tr>
<td>CirX-1</td>
<td>-129.83</td>
<td>-57.17</td>
<td>0.96</td>
<td>0.11</td>
<td>1.62</td>
</tr>
</tbody>
</table>

“Top 5”
Pre-trial p-value < 0.1

**Flux upper limits** \((10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1})\)
assuming an $E_{\nu}^{-2}$ spectrum (no energy cut-off hypothesis)

Best candidate source:
- Post-trial p-value = 6.1%
- Signal significance = 1.9 $\sigma$
Point-like sources: flux sensitivities and limits (90 % C.L.)

ANTARES 2007-2012 (1338 days)

IceCube 2008-2011 (1040 days)

ANTARES has the best limits in the world for many (galactic) sources in the Southern Hemisphere, especially for $E_\nu < 100$ TeV

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What about accumulation of 7 events near the GC detected by IceCube?

- Shower events have low angular resolution
- IC does not claim a signal
- If due to a point source at \((\alpha, \delta) = (-79^\circ, -23^\circ)\), the expected flux would be \(\phi = 6 \times 10^{-8} \text{ GeV cm}^{-2} \text{s}^{-1}\).

The full-sky algorithm is applied at a region of 20° around the proposed location. Point-like source hypothesis (width = 0°) and three Gaussian-like extended source hypotheses are tested (width = 0.5°, 1°, 3°). No significant cluster has been found \(\rightarrow\) upper limits derived.

Presence of a point-like or extended source anywhere in the region excluded.
Overview of ANTARES Multi-messenger searches

We expect very faint $\nu$ fluxes from astrophysical sources. The multi-messenger approach can increase the discovery potential by observing different probes, the significance by coincident detection and by reducing the time/region observation, and the efficiency by relaxing cuts.

Gravitational waves
VIRGO/LIGO

Common working group
GWHEN

GeV/TeV $\gamma$-rays
FERMI, HESS

Optic/X-rays
TAROT, ROTSE/Swift, ZADKO

UHECRs
Auger

Gravitational waves

GeV/TeV $\gamma$-rays

Optic/X-rays

UHECRs

Common working group

APP 36 (2012) 204

JCAP 05 (2014) 001

JCAP 03 (2013) 006

APJ 774 (2013) 19
Indirect search for Dark Matter

• Relic WIMPs (e.g. neutralinos $\chi$, KK particles) gravitationally captured in massive celestial bodies like the Sun, the Earth, the Galactic Centre.
• $\chi\chi$ self-annihilate in SM particles ($\tau$ leptons, b, c, t quarks, $W^{\pm}$, Z, H bosons) that eventually decay producing high energy neutrinos, $E_\nu \sim O(10-100)$ GeV.
• The $\nu$ signal is less subjected to astrophysical uncertainties than $\gamma$-rays or CR.
• Annihilations into $bb$, $\tau^+\tau^-$, $W^+W^-$, $\mu^+\mu^-$, $\nu\bar{\nu}$ used as benchmarks.

In the Sun
• WIMPSIM neutrino spectra are used.
• Data set: 2007-2012 (livetime = 1321 days).

No observed excess → Flux limits

In the Galactic Centre
• Cirelli neutrino spectra are used.
• Data set: 2007-2012 (livetime = 1321 days).

Limits on WIMP-proton cross section.

Limits on the velocity-averaged WIMP self-annihilation cross section.
ANTARES - the first undersea Neutrino Telescope - is in its 7th year of operation.

Despite its limited size, but thanks to its location and to its excellent angular resolution, it is complementary to IceCube and it is yielding:

- diffuse flux sensitivities in the relevant energy range;
- best limits for Galactic sources in part of the southern hemisphere in the relevant energy range, with impact on interpretation of IC results;
- competitive limits on dark matter for neutrinos coming from the Sun and the Galactic Centre.

It is working within design specifications, DAQ ongoing.

Data analysis ongoing and extended results forthcoming.