ANTARES Neutrino Telescope
Recents results
1. ANTARES telescope
2. Relativistic magnetic monopoles
3. Neutrino oscillations
4. Dark matter
5. Outlook
Why neutrino astronomy
• neutrinos point back to the source
• neutrinos travel cosmological distances
• neutrinos escape optically thick sources
• neutrinos are a clear sign of hadron acceleration
⇒ complementary to gamma and cosmic rays

Some source candidates
• Galactic sources: supernova remnants, microquasars
• Extra-galactic sources: active galactic nuclei, gamma ray bursts
• Dark matter
Neutrino telescope: detection principle

Reconstruction of $\mu$ trajectory ($\sim \nu$) from timing and position PMT hits

Cherenkov light from $\mu$

Sea floor

43°
Background rates

Event rates:
- $\sim 10^6$ atmospheric muons per day
- $\sim 5$ atmospheric neutrinos per day
- ??? cosmic neutrinos

$\Rightarrow$ Selecting only well reconstructed upgoing particles
Neutrino telescopes

Angular resolution (Ice: $\sim 2^\circ/0.6^\circ$)

Galactic centre: not seen

Angular resolution (water: $\sim 0.2^\circ/0.1^\circ$)

galactic centre: 2/3 of the time
ANTARES Detector

- 12 lines
- 25 storeys / line
- 3 PMs / storey
- 885 PMs

Depth: 2500m

- Deployment finished: 2008
- Detection lines: 12
- Horizontal spacing between lines: ~ 70 m
- Storeys per line: 25
- Vertical spacing between storeys: 14.5 m
- Optical modules per storey: 3
- Total optical modules: 885
Some analysis topics

**Cosmic neutrinos**
- Steady sources
  - full sky search
  - candidate list
- Transient sources – multi-messenger
  - flare analysis (GRBs, microquasars, etc.)
  - triggered search, optical follow-up
  - gravitational waves
  - Diffuse flux

**Particle physics and exotic phenomena**
- super-heavy particles
- neutrino oscillations
- indirect search of dark matter

**Environmental and marine science**
- seismology
- marine biology
- in situ oxygen consumption

---

**Search for Point Sources**

90% CL upper limits for neutrinos flux with an $E^{-2}$ spectrum for 51 candidates sources (blue points), sensitivity in blue

---

P. Gay
ANTARES Results

LI012 Lyon
Relativistic Magnetic Monopoles

Magnetic monopoles

required in many models via SSB [‘t Hooft, Polyakov]

\[ g_{MM} = k \frac{e}{2 \alpha} \]

light yield

Cerenkov regime \( \beta > \beta_{th} = 0.75 \)

via \( \delta \)-rays \( 0.5 < \beta < 0.75 \)

knock off electrons (\( \delta \)-rays) produced along its path

\begin{align*}
\gamma \text{ Cherenkov from MM with } g = g_0 & \\
\gamma \text{ Cherenkov from } \delta \text{-rays} & \\
\gamma \text{ Cherenkov from } \mu &
\end{align*}

*8500

\begin{align*}
\text{Monopole light yield}
\end{align*}
Relativistic Magnetic Monopoles

Reconstruction algorithm developed for magnetic monopole, also below Cerenkov threshold, $\beta$ free parameter

$\beta \in [0.825, 0.875]$ \[ \Delta \beta / \beta \approx 0.002 \]

$\beta \in [0.625, 0.675]$ \[ \Delta \beta / \beta \approx 0.012 \]
Relativistic Magnetic Monopoles

Discriminante variables
- cut on numbers of hits
- cut on the ratio of reconstruction qualities $\lambda$

$\lambda = \log\left[ \frac{Q_{\beta=1}}{Q_{\beta=\text{free}}} \right]$

$\beta < \beta_{th}$

$\beta \in [0.775, 0.825]$

15% of data used here
# Relativistic Magnetic Monopoles

## 2007-2008

116 days

<table>
<thead>
<tr>
<th>$\beta_{rec}$ range</th>
<th>Selection cuts (nhit ; $\lambda$)</th>
<th>cuts</th>
<th>backg</th>
<th>observed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10-line</td>
<td>9-line</td>
<td>12-line</td>
<td>Number of expected background events</td>
</tr>
<tr>
<td>[0.625, 0.675]</td>
<td>(27; 0.6)</td>
<td>(28; 0.5)</td>
<td>(36; 0.7)</td>
<td>$2.2 \times 10^{-2}$</td>
</tr>
<tr>
<td>[0.675, 0.725]</td>
<td>(34; 0.4)</td>
<td>(35; 0.2)</td>
<td>(47; 0.0)</td>
<td>$1.3 \times 10^{-1}$</td>
</tr>
<tr>
<td>[0.725, 0.775]</td>
<td>(43; 0.2)</td>
<td>(57; 0.4)</td>
<td>(53; −2.1)</td>
<td>$4.6 \times 10^{-2}$</td>
</tr>
<tr>
<td>[0.775, 0.825]</td>
<td>(77; 0.9)</td>
<td>(64; 0.7)</td>
<td>(81; 0.8)</td>
<td>$1.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>[0.825, 0.875]</td>
<td>(93; 0.4)</td>
<td>(79; 0.3)</td>
<td>(93; 0.4)</td>
<td>$8.2 \times 10^{-7}$</td>
</tr>
<tr>
<td>[0.875, 0.925]</td>
<td>(118; 0.1)</td>
<td>(99; 0.2)</td>
<td>(85; 0.7)</td>
<td>$6.9 \times 10^{-7}$</td>
</tr>
<tr>
<td>[0.925, 0.975]</td>
<td>(114; 0.2)</td>
<td>(108; 0.1)</td>
<td>(84; 0.0)</td>
<td>$2.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>[0.975, 1.025]</td>
<td>(85; 0.0)</td>
<td>(110; −2.1)</td>
<td>(92; 0.0)</td>
<td>$1.3 \times 10^{-2}$</td>
</tr>
</tbody>
</table>
Relativistic Magnetic Monopoles

Limits

90% confidence level limit on upgoing magnetic monopole flux, ANTARES 2008 (116 days)

Neutrino oscillations

oscillations w/ atmospheric neutrinos

- \[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2 \left( \frac{1.27 \Delta m_{32}^2 L}{E_\nu} \right) \]
- where \( L = D_{\text{Earth}} \cdot \cos \Theta \)
- \( \Rightarrow P(\nu_\mu \rightarrow \nu_\mu) \) function of \( E_\nu / \cos \Theta \)

\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2 \left( \frac{16200 \Delta m_{32}^2 \cos \Theta}{E_\nu} \right) \]

vertical \( \uparrow \) \( \nu_\mu \) expected to be completely suppressed at \( E_\nu = 25 \text{ GeV} \)

(muon range~120m)

Larger effect on single-line events (low energy) than multi-line events (higher energy)
Neutrino oscillations

**track selection**

Special low energy fit for single-line events (>7 storeys, do not fit azimuth)

- **Multi-line**
  - Red: atm. neutrino w/ oscill.
  - Green: w/o oscill.
  - Blue: atmo. muons

- **Single-line**
  - 0.8° for multi-line events
  - 3° for single-line events

Select pure sample of atmospheric neutrinos (<5% muon contamination)

Red: atm. neutrino w/ oscill.
Green: w/o oscill.
Blue: atmo. muons

zenith angle resolution
Neutrino oscillations

Analysis, low energy
not easy!

$E_\nu > 50$ GeV : multi-lines (65 m between lines)
$E_\nu \geq 20$ GeV : single-line

![Graph showing multi-line and single-line events with and without oscillations.]

Blue: multi-line events
Red: single-line events
Solid line: no oscill.
Dashed line: w/ oscill.
Neutrino oscillations

Observable $E_{\nu}/\cos\Theta$

Energy estimator using approximate $\mu$ range $S = (z_{\text{max}} - z_{\text{min}})/\cos\Theta_R$

$E_R = 0.2(z_{\text{max}} - z_{\text{min}})/\cos\Theta_R$

Ionisation energy loss 0.2GeV/m for $\mu$
@ mip in sea water

$E_{\nu} < 100$ GeV

$<E_R> \sim 0.45$

$E_{\nu}$ from muon range $\Rightarrow$
Neutrino oscillations

Test the distribution of \( \frac{E_R}{\cos \Theta_R} \)

2008-2010 data (863 days):

- No oscillation: \( \chi^2/\text{NDF} = 40/24 \) (2.1%)
- Best fit: \( \chi^2/\text{NDF} = 17.1/21 \)
  \[ \Delta m^2 = 3.1 \times 10^{-3} \text{ eV}^2 \]
  \[ \sin^2 2\theta = 1.00 \]

Absolute normalisation free
(absorbs dominant uncertainties)

Systematics:

- (Absolute normalisation free)
- Absorption length: ±10%
- Detector efficiency: ±10%
- Spectral index of \( \nu \) flux: ±0.03

Red: best fit w/ oscill. blue: atm. neutrinos w/o oscill. + atm. muons
Neutrino oscillations

Assuming maximal mixing: $\Delta m^2 = (3.1 \pm 0.9) \times 10^{-3}$ eV$^2$

Search for Dark Matter in the Sun

- WIMPs (neutralinos, Kuluza Klein particles) are among the most popular explanations for Dark Matter
- They would accumulate in massive objects like the Sun, the Galactic Center, dwarf galaxies...

The products of such annihilations would yield “high energy” neutrinos, which can be detected by neutrino telescopes.

In the Sun a signal would be very clean (compared with gammas from the Galactic Centre, for instance)
Neutralino annihilations in the Sun in CMSSM

Study of neutralino DM sensitivity within SUSY CMSSM framework

Random scan within CMSSM parameter space

\[
0 < m_{1/2} < 2000 \text{ GeV} \\
0 < m_0 < 8000 \text{ GeV} \\
0 < \tan\beta < 60 \\
-3 m_0 < A_0 < 3 m_0
\]

Integrated neutrino flux for \( E_\nu > 10 \text{ GeV} \)

DarkSUSY & ISASUGRA (RGE code)
w/ \( m_{\text{top}} = 172.5 \text{ GeV/c}^2 \)
Including \( \nu \) oscillation effects in the Sun and in vacuum

Local \( \rho_\chi : 0.3 \text{ GeV/cm}^3 \)
\(<v_\chi> = 220 \text{ km/s}\)

V. Bertin E. Nazri J. Orloff

Bulk low \( m_0 \) and \( m_{1/2} \)
Neutralino annihilations in the Sun in CMSSM

10 < tan β < 20

Bulk

Higgs funnel

Focus points

Higgs funnel

Bulk
Neutralino annihilations in the Sun in CMSSM

Detection rate with ANTARES in 3 years

Sensitivity calculated for 3 years of data taking

“Excludable” = Signal is distinguishable from the background at 90% C.L. (Feldman-Cousins scheme)

Background from atmospheric neutrinos and misreconstructed atmospheric muons within 3° radius search cone around the Sun

Model with relic density within $2\sigma$ of WMAP constraint are highlighted ($0.094 < \Omega \chi h^2 < 0.129$)

mSugra models favoured by WMAP
- 90% CL excludable by ANTARES
- not excludable

mSugra models disfavoured by WMAP
- 90% CL excludable by ANTARES
- not excludable

\[
\text{Detection rate (t)} = \nu_\mu + \bar{\nu}_\mu \text{ flux} \left( E_{\nu}, \theta_{\nu}, t \right) \cdot \text{Effective Area} \left( E_{\nu}, \theta_{\nu}\right) \cdot \text{Sun's } \theta_{\nu} \text{ distribution}
\]
Search for neutralino annihilations in the Sun

Exclusion capabilities of ANTARES for the CMSSM parameter space: mainly Focus Point region (good complementarity to direct search at LHC)

Excludable in 3 years at 90% CL: all, some, none

(A_0 varied between -3m_0 and +3m_0 and tan(β) within indicated slice)

Ωh^2 > 1
No EWSB
X≠LSP

excluded by accelerator (LEP)
neutrino signal from WIMP annihilation

**Signal energy spectrum** derived from **WIMPSIM** simulation package for different **WIMP masses**

- The **WIMPSIM package** (Blennow, Edsjö, Ohlsson, 03/2008) is used to generate events in the Sun in a model-independent way
- Great statistics: with $3 \times 10^6$ WIMPs annihilations
- Capture rate and annihilations in equilibrium at the Sun core
- Annihilations in c, b and t quarks, $\tau$ leptons and direct channels
- Interactions taken into account in the Sun medium
- Three flavors oscillations, regeneration of $\tau$ leptons in the Sun medium (Bahcall et al.)
- Available parameters: WIMPs mass, oscillations parameters...
Neutrino spectra from neutralino annihilations

"hard" annihilation: $\chi\chi \rightarrow W^+W^-$

- $M_\chi = 100 \text{ GeV}$

"soft" annihilation: $\chi\chi \rightarrow b\bar{b}$

- Solid: including neutrino oscillation
- Dotted: without neutrino oscillation

$M_\chi = 100 \text{ GeV}$

Neutrinos from $\chi\chi \rightarrow WW$ (hard spectrum) are more energetic and easier to detect
Main annihilation channels

\[ M_{\text{WIMP}} = 350 \text{ GeV} \]

Important contributions from \( \tau \) leptons regeneration in the Sun \( \rightarrow \) visible neutrinos oscillations
Dark Matter Sun analysis

New results with Sun analysis, 200-2008 data, ~ 295 days

2007-2011 analysis ongoing, ~400 effective days

Search strategy

Binned search towards the direction of the Sun (visibility below horizon)

Background from atm. neutrinos and muons estimated from MC simulation and scrambled data

Signal energy spectrum from WIMPSIM

Sensitivity optimised using Feldman-cousins method, scanning track quality cut and cone opening angle
Dark Matter Sun analysis

Event selection

Quality parameter of the track reconstruction for upgoing events
- very good agreement data vs. Monte Carlo events
- good separation between neutrino and muon events

Zenith distribution of selected events (Tchi2 < 1.6)
strong reduction of the atmospheric muon background
Signal and cut optimization

Neutrino flux at the earth, from the Dark Matter coannihilation, are convoluted with the efficiency of the detector for a cuts parameter space (track fit quality cut, cone).

Neutrino background from the scrambled data in the Sun direction is evaluated in the same space.

Minimize this quantity:

$$\Phi^{90\%}_\nu = \frac{\bar{\mu}_{90}}{A_{eff}(M_{WIMP}) T_{eff}}$$

- $A_{eff}$ effective area
- $T_{eff}$ active time

Average upper limit (Feldman-Cousins)

Acceptance to be estimated for different sets (Track quaklity cut, cone)
Dark Matter Sun analysis

cone angle cut ~3°

comparison of the number of events observed in a cone around the Sun direction with the excepted background
**background in the sun direction**

- Background estimated from data scrambled in time and \((\theta, \Phi)\) using the Sun visibility at the ANTARES location
- 2007-2008 period, ~295 days

- Background from CR interactions in the Sun corona much lower (<1% of atmospheric neutrinos)

---

**All upward-going events from 2007-2008 data**

**Example of Sun tracking in horizontal coordinates**
Neutrino flux sensitivity @ 90% CL for 2007-2008 data

Neutrino flux sensitivity

Preliminary
Muon flux sensitivity

Muon flux sensitivity @ 90% CL for ANTARES 2007-2008

Preliminary
CMSSM cross-section sensitivity

Spin-dependent cross-section flux sensitivity @ 90% CL for ANTARES 2007-2008

Preliminary

Log$_{10}$[\(\sigma_{H,SD}\) (pb)]

m$_{\chi}$ (GeV)

Flux \(\Phi_\mu\)

Annihilation rate \(\Gamma\)

Capture rate \(C\)

Cross-section \(\sigma_{SD}\)

Compare SUSY predictions to observables as sparticles masses, collider observables, dark matter relic density, direct detection cross-sections, …

SuperBayes
(arXiv:1101.3296)
mUED cross-section sensitivity

Spin-dependent cross-section flux sensitivity @ 90% CL for ANTARES 2007-2008

Cross-section $\sigma_{SD}$

Capture rate C

Annihilation rate $\Gamma$

Flux $\Phi_\mu$

Flux $\Phi_\nu$

SuperBayes modified version

Physical Review D 83, 036008 (2011)

Compare mUED predictions to observables as KK masses, collider observables, relic density, direct detection cross-sections, ...

P. Gay

ANTARES Results

LIO'12 Lyon
ANTARES complete and running since 2008

Physics analysis ongoing
  take advantage of
    low energy threshold
    low diffusion of deep sea water

Exotic massive particles
  as magnetic monopoles, stringent limits
  also below Cerenkov threshold

Oscillation analysis
  2007-2010 data analysed
  measurement compatible with world data
  low energy is reliable and systematics under control

Dark matter
  2007-2008 data analysis completed
  2007-2011 analysis on track