DM searches with the ANTARES neutrino telescope

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Scientific scope

- Origin of cosmic rays
- Hadronic vs. leptonic signatures
- Dark matter

Limitation at low energies:
- Short muon range
- Low light yield
- $^{40}$K (in water)

Limitation at high energies:
Fast decreasing fluxes $E^{-2}$, $E^{-3}$

Detector density

Detector size

- Supernovae
- Oscillations
- Astrophysical neutrinos
- Dark matter (neutralinos, KK)
- GZK

Other physics: monopoles, nuclearites, Lorentz invariance, etc...
The ANTARES detector

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

Detector completed in 2008
Detection of DM

- WIMPs (neutralinos, KK 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 GC, for instance)
- Sun travel in the Galaxy makes it less sensitive to non-uniformities
Detection principle

- The neutrino is detected by the Cherenkov light emitted by the muon produced in the CC interaction.
Signal simulation: WIMPSIM

- Blennow, Edsjö, Ohlsson (03/2008): “WIMPSIM” model-independent production
- Great statistics with $12 \times 10^6$ 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...)

$\nu_e, \nu_\mu, \nu_\tau$
Main channels

$\nu_\mu \bar{\nu}_\mu$ from the $W\bar{W}$ channel (at Earth)

$\nu_\mu \bar{\nu}_\mu$ from the $b\bar{b}$ channel (at Earth)

$\nu_\mu \bar{\nu}_\mu$ from the $\tau\bar{\tau}$ channel (at Earth)

$\nu_\mu \bar{\nu}_\mu$ from all channels (at Earth)

Entries: 400
Mean: 0.1962

Entries: 400
Mean: 0.04645

Entries: 400
Mean: 0.16081

Entries: 400
Mean: 0.07591

$M_{\text{WIMP}} = 350$ GeV

Important contributions from leptons regeneration in the Sun -> visible neutrinos oscillations

mUED particular case...
Averaged Effective area

Define an Averaged Effective Area per channel per WIMP mass

\[ A_{\text{eff}}(M_{\text{WIMP}}) \quad (\text{m}^2) \]

\[ M_{\text{WIMP}} \quad (\text{GeV}) \]

- \( W^+W^- \)
- \( \text{b}\bar{b} \)
- \( \text{mUED} \)

ANTARES 2007-2008
Background estimation

- The background is estimated by scrambling the data in time
- A fast algorithm is used for muon track reconstruction (Astrop. Phys. 34 (2011) 652-662)
- The effect of the visibility of the Sun is taken into account

All upward-going events from 2007-2008 data

Example of Sun tracking in horizontal coordinates
Cut optimization

- Neutrino flux at the Earth $\times$ Detector Efficiency $\times$ Visibility $\rightarrow$ Signal
- Data in the Sun direction time scrambled $\rightarrow$ Background
- Cuts on the angular window size and on the track quality cut are chosen to optimize the flux sensitivity

$$\text{Limit} = \frac{90}{A_{\text{eff}}(M_{\text{wimp}}) \times T_{\text{eff}}}$$

Once the optimum quality cuts are chosen we proceed to unblind...
After unblinding

...no excess $\rightarrow$ data comparable to background

(keep searching)
Neutrino flux limit

Neutrino + anti-neutrino flux limit ANTARES 2007-2008

![Graph showing antineutrino flux limit](image-url)
CMSSM: Muon flux

Muon flux limit for ANTARES 2007-2008 in the CMSSM framework
mUED: Muon flux

Muon flux limit for ANTARES 2007-2008 in the mUED framework

BRs: 0.23(τ), 0.077(c, t), 0.005(b), 0.014(ν)

mUED framework
Stable in (R, Δ, m̅)
Cross section calculation

Differential neutrino flux is related with the annihilation rate as:

\[
\frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma}{4\pi d^2} \frac{dN_\nu}{dE_\nu},
\]

If we assume equilibrium between capture and annihilation in the Sun:

\[
\Gamma \approx \frac{C_\odot}{2}.
\]

where the capture rate can be expressed as:

\[
C_\odot \approx 3.35 \times 10^{18} \text{s}^{-1} \times \left(\frac{\rho_{\text{local}}}{0.3 \text{ GeV} \cdot \text{cm}^{-3}}\right) \times \left(\frac{\sigma_{H,SD}}{10^{-6} \text{ pb}}\right) \times \left(\frac{\text{Tev}}{M_{\text{WIMP}}}\right)^2,
\]
CMSSM: SD cross section limit

Spin-dependent cross-section limit for ANTARES 2007-2008 in CMSSM

G. Lambard

Compare SUSY predictions to observables as sparticles masses, collider observables, dark matter relic density, direct detection cross-sections, … SuperBayes (arXiv:1101.3296)
CMSSM: SI cross section limits

Spin-independent cross-section limit for ANTARES 2007-2008 in CMSSM
mUED: SD cross section limits

Spin-dependent cross-section limit for ANTARES 2007-2008 in mUED

Compare mUED predictions to observables as KK masses, collider observables, relic density, direct detection cross-sections, \ldots \textbf{SuperBayes modified version} (Physical Review D 83, 036008 (2011))
Prospects with 2007-2010 data: muon flux limit

-90% (km$^2$.yr$^{-1}$)

$M_{\text{WIMP}}$ (GeV)

Factor 3-4 wrt present
Summary

- Dark matter is a major goal for neutrino telescopes (and an important complement to direct detection experiments)
- Computed the detector efficiency for two common dark matter models (CMSSM, mUED)
- First analysis done by looking at Sun. Limits for the CMSSM and mUED, in muon flux and SD cross-section calculated
- Analysis on 2007-2010 data in progress...
- Other sources (GC, dwarf galaxies...) also in the scope
Neutrino candidate with 12-line detector
Backup
The interaction of cosmic rays in the Sun (p-p) produces “atmospheric solar neutrinos”, after the decay of the products (pions and muons). Only $10^{-3}$ events per year in ANTARES (0.4% of total atmospheric background).
SD cross section calculation

Conservative view on the local region:
- Jupiter Effect
- w/o additional disk in the dark matter halo
- local density 0.3 GeV.cm$^{-3}$

(arxiv:0903.2986v2)
SI cross section calculation

Conservative view on the local region:
- Jupiter Effect
- w/o additional disk in the dark matter halo
- local density 0.3 GeV.cm⁻³

(arxiv:0903.2986v2)
Signal computation

- Usually, we need:
  - Flux (example: WW) at the surface of the Earth
  - Capture rate into the Sun, dependent on the SD, SI cross-section
  - Annihilation rate $\Gamma \sim 0.5 \times C$ (equilibrium condition)

$$\frac{d}{d\theta d\phi} = \frac{d}{d\theta d\phi} \sum_{i} \frac{d}{d\theta}$$

$$C_{\odot} \simeq 3.35 \times 10^{18} s^{-1} \times \left( \frac{\rho_{local}}{0.3 \text{GeV.cm}^{-3}} \right) \times \left( \frac{270 \text{km.s}^{-1}}{v_{local}} \right) \times \left( \frac{\sigma_{H,SD}}{10^{-6} \text{pb}} \right) \times \left( \frac{\text{TeV}}{M_{WIMP}} \right)^2$$

- Flux from WIMPSIM
- Cross-section from Analytic computation, or simulation in the parameter space of the models
- For Kaluza-Klein, Branching ratio not so dependent on the location in the parameter space ($R$, $\Delta$, and SM Higgs mass $m_h$)
- For CMSSM, it’s different... Equilibrium in the Sun well/not reached, SD/SI very dependent on the parameter space, branching ratios very dependent, main channel chosen is not so obvious -> large systematic from the sensitivity computed
- Need a simulation, and fast one, to compute the cross-sections, the capture rate, etc, for the allowed parameter space
SuperBayes

- Supersymmetry Parameters Extraction Routines for Bayesian Statistics
- Multidimensional SUSY parameter space scanning
- Compare SUSY predictions to collider observables, dark matter relic density, direct detection cross-sections, ...
- Using a new generation Markov Chain Monte Carlo for a full 8-dim scan of CMSSM
- Using PISTOO farm at CC-Lyon to run it
- Well documented (articles, Website), as DarkSUSY package
- Parameter set of CMSSM \((m_0, m_{1/2}, A_0, \tan\beta)\)
- « Nuisance parameters » from SM \((m_t, m_b, \alpha_{em}, \alpha_s)\)
Prospects: muon flux limit

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Prospects: SD cross section
Prospects: SI cross section

\[ \sigma_{h,SI} \] (pB)

\[ M_{WIMP} \] (GeV)

\[ 10^{-9}, 10^{-8}, 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3} \]

Preliminary