Indirect Dark Matter Search with ANTARES towards the Galactic Center

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Neutrinos experiments

Dark Matter in the Earth
- Mechanism of capture favors low mass WIMPs (<50 GeV)
- Annihilation and capture rates are not supposed to be in equilibrium, inducing large uncertainties on the $\nu$ flux

Dark Matter in the Sun
- Clean channel in neutrinos
- Annihilation and capture rates expected to be in equilibrium
- Expected signal <300 GeV due to the neutrinos absorption in the Sun medium

Dark Matter in the Galactic Center, Galactic halo, dSph galaxies, cluters of galaxies, …
- Neutrino telescopes are the most competitive for high mass WIMPs (>1 TeV)
- Highly dependent on the dark matter halo model (NFW, Einasto, Moore, …)
- Necessary cross-check to the highly competitive $\gamma$-rays experiments
Largest undersea neutrino telescope in the Northern hemisphere located at 40 km offshore from Toulon, France, (at 2475 m of depth) in the Mediterranean Sea

- 885 10” PMTs distributed over 12 lines (25 floors per line, 3 PMTs per floor)
- Fully completed in May 2008
- Data taking started in 2007 with 5 detection lines

\[ E^\text{th}_\nu \sim 15 \text{ GeV} \]

\[ \text{atm. } \mu \text{ 3-10 Hz} \]
\[ \text{atm. } \nu \sim 50 \text{ } \mu\text{Hz} \]

\[ \text{Good candidate for dark matter search} \]
- Sun visibility ~50 %
- GC visibility ~60%
General detection principle

- Main detection channel: $\nu_\mu$ interaction giving an ultra-relativistic $\mu$ ($\nu_e$ and $\nu_\tau$ also)
- Energy threshold $\sim 15$ GeV
- 24hr operation, more than half sky coverage

The reconstruction is based on local coincidences compatible with the Cherenkov light front

Sea floor

Down-going events (atm. $\mu$)

Up-going events (atm. $\nu$)

Cosmic $\nu$ (astrophysical sources, dark matter, ...)

3D PMT array

Cherenkov light from $\mu$

42°
Example of reconstructed events

reconstructed up-going neutrino
detected in 6/12 detector lines

reconstructed down-going muon
detected in all 12 detector lines
Dark Matter Search in the Galactic Center

- WIMPs self-annihilate according to $\langle \sigma_A v \rangle$ (halo model-dependent)

\[
\frac{d\phi_v}{dE_v} = \frac{\langle \sigma_A v \rangle}{2} \frac{J(\psi)}{4\pi m_*^2} R_{sc} \rho_{sc}^2 \frac{dN_v}{dE_v}
\]

- $\rho_{sc} = 0.3 \text{ GeV cm}^{-3}$
- $R_{sc} = 8.5 \text{ kpc}$

\[
J(\psi) = \int_0^{l_{max}} \rho^2 \left( \sqrt{R_{sc}^2 - 2lR_{sc} \cos \psi + l^2} \right) dl
\]

- $\nu$ can propagate with a minimum of astrophysical uncertainties

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Neutrino energy spectrum at the surface of the Earth

- **DM energy spectra** for GC from Cirelli et al. production including EW corrections as computed in arXiv:1009.0224 (www.marcocirelli.net/PPPC4DMID.html)

![Graph showing neutrino energy spectrum](image)
Method to derive limits for a dark matter signal

- First analysis based on 2007 (5 lines) and 2008 (9, 10 and 12 lines) data ~ 295 days for the Sun (arXiv:1302.6516)

- Second analysis based on 2007-2012 data ~ 1321 days (in publication process…)

- General aspect of the analysis:
  - Two reconstruction algorithms: $\chi^2$-like (QFit), M-L ratio ($\Lambda$Fit)
  - Binned search in the direction of the GC
  - Basic selections:
    - Reconstructed events with nline > 1 (high E) with $\Lambda$Fit
    - (for 2007-2012) nline = 1 (low E) with Qfit
  - Chosen Elevation
    - Track quality Q and $\Lambda$
    - Optimise sensitivities in $\nu$-flux

- Optimization on the solid angle $\psi$ around the GC following the Model Rejection Factor (MRF) method with:
  - Neutrino background from the data scrambled in time for $\psi$ around the GC
  - Visibility of the Source
  - Derived limits:

For a given channel ($W^+W^-, bb, \ldots$)

$$\phi_{v+\bar{v}}^{90} = \sum_i A_{\text{eff}}^{v+\bar{v}}(M_{\text{wimp}}) \times T_{\text{eff}}^i$$

Period $i = 5, 10, 9$ and $12$ lines
~1321 days
Expected angular resolutions
(from MC simulations)

\[ (\Lambda\text{Fit}) \tilde{\alpha} = \text{med}[|\arccos(\tilde{d}_{\text{rec}} \cdot \tilde{d}_{\text{pr}})|] \]

\[ (Q\text{Fit}) \tilde{\alpha} = \text{med}[|\theta_{\text{rec}} - \theta_{\text{pr}}|] \]

\[
\begin{align*}
\alpha (\circ) & \quad \text{vs.} \quad \text{Log}_{10}(E_{\nu} \text{ (GeV)}) \\
0 & \quad 1 \quad 1.5 \quad 2 \quad 2.5 \quad 3 \quad 3.5 \quad 4
\end{align*}
\]

kinematic counter-part at ν-μ vertex
Expected effective areas
(from MC simulations)

For a full detector (12 lines)

- Improvement of the efficiency in low mass regime with QFit
- Particularly interesting for soft channels
QFit parameter distribution

69% of purity in atm. $\nu$

Robustness in the rejection of atm. $\mu$

Events reconstructed under the horizon ($\cos(\theta) > 0$)
Fit parameter distribution

Events reconstructed with $\cos(\theta) > -0.1$

72% of purity in atm. $\nu$

Data $+$

Atm. $\nu$ ---

Atm. $\mu$ ----
QFit elevation distribution

- QFit is dedicated to single-line events
- Most of reconstructed events are vertical

Events reconstructed with $Q < 0.8$

### Graph

- Data: +
- Atmos. $\nu$: --
- Atmos. $\mu$: ---

69% of purity in atm. $\nu$
Λfit elevation distribution

Events reconstructed with Λ > -5.7

72% of purity in atm. ν

data + 
avt. ν -- 
avt. μ ---

N_{events}
Elements to derive limits for a dark matter signal

ANTARES data 2007-2012 with respect to the GC

- No significant excess 😞
- Estimated background and data are in good agreement 😊 😞

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Elements to derive limits for a dark matter signal

Acceptance to be estimated for different angular separation $\psi$ to the GC

\[
A_{\text{eff}}(M_{\text{WIMP}}) \times T_{\text{eff}} (\text{m}^2 \cdot \text{yr}) \]

- $bb$
- $\mu^+\mu^-$
- $W^+W^-$
- $\nu\nu$
- $\tau^+\tau^-$

$\Psi < 10^\circ$ (QFit)
$\Psi < 2^\circ$ ($\Lambda$Fit)
Derived neutrino flux upper limits for a dark matter signal

\[
\Phi_{\nu_e,\mu,\tau} (\text{km}^2 \cdot \text{yr}^{-1})
\]

- \(b\bar{b}\)
- \(\mu^+\mu^-\)
- W^+W^-
- \(\tau^+\tau^-\)

\(\Psi < 10^\circ \) (QFit)
\(\Psi < 2^\circ \) (\(\Lambda\)Fit)
Sensitive to the dark matter halo profile in the Milky-Way.

\[ \rho_{sc} \approx 0.4 \text{ GeV cm}^{-3} \]

\[ R_{sc} \approx 8.5 \text{ kpc} \]

- **CLUMPY** version 2011.09_corr2

Made for:
- Experimentalists – \( \gamma \)-ray skymaps for sensitivity expectations or model analyses
- Astrophysicists – computation of J factor
- Theoreticians – Compute expected \( \gamma \)-ray flux from the Milky-way/dSphs

\[ \frac{d\Phi_\gamma}{dE_\gamma} (E_\gamma, \Delta \Omega) = \Phi^{pp}(E_\gamma) \times J(\Delta \Omega) \]

\[ J(\Delta \Omega) = \int_{\Delta \Omega} \int \rho_{DM}^2(l, \Omega) \, dl \, d\Omega \]

\[ \Phi^{pp}(E_\gamma) = \frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi} \frac{dN_\gamma}{dE_\gamma} \cdot \langle \sigma_{\text{ann}} v \rangle \]

\( \langle \sigma_{\text{ann}} v \rangle \)

Totally equivalent for the \( \nu \) flux expectations

Cirelli et al.
Averaged J-Factor for a given solid angle, or angular separation, to the GC

\[ J = \int_0^{\Delta \Omega} \int_{l_{\text{min}}}^{l_{\text{max}}} \frac{1}{l^2} \left( \rho_{\text{sm}} + \sum_i \rho_{\text{cl}}^i \right)^2 l^2 dl d\Omega \]
GC $<\sigma v>$ limits from ANTARES 2007-2012

$M_{\text{WIMP}}$ (GeV) vs. $<\sigma_A v>$ (cm$^3$s$^{-1}$)

- bb
- $\mu^+\mu^-$
- QFit
- $W^+W^-$
- $\tau^+\tau^-$
- $\nu\nu$
- $\Lambda$Fit

$10^{-24}$ to $10^{-17}$ $<\sigma_A v>$ vs. $10^2$ to $10^4$ $M_{\text{WIMP}}$
GC $\langle \sigma v \rangle_{\tau^+\tau^-}$ channel sensitivities from ANTARES 2007-2012
GC $<\sigma v>$ $\tau^+\tau^-$ channel sensitivities from ANTARES 2007-2012 (Astrophys. syst.)

$<\sigma_A v>$ (cm$^3$.s$^{-1}$)

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

$DMDM \rightarrow \tau^+\tau^-$

- Iso
- NFW
- Einasto
- contr. NFW
Summary & Conclusions

• Neutrino signals can be used to set a conservative limit on the total dark matter self-annihilation cross section (Galactic Center)

• Neutrino signals are able to test claims from other indirect channels or direct detection Positron excess

• New limits will soon be stated from an un-binned method (MultiDark Valencia)

• Data integration and upgrade of the experiments in the future are expected to gain more than a factor 10-100 in sensitivity for $M_{\text{WIMP}} = 1 \text{ GeV} - 10 \text{ TeV}$ with KM3NeT, Hyper-Kamiokande, PINGU, ORCA, …
Minimization of the Neutrino + anti-neutrino flux sensitivities

- Sensitivities/Limits in neutrinos+anti-neutrinos flux:
  For 5 channels
  \( bb, W^+W^-, \tau^+\tau^-, \mu^+\mu^- \) and \( \nu\nu \)
  times \( 17 \, M_{\text{wimp}} \)

\[ (-)^{90} \phi_{\nu^+\nu^-} = \mu_{90} \sum_i \bar{A}_{\text{eff}}^{E_{\nu^+\nu^-}}(M_{\text{wimp}}) \times T_{\text{eff}_i} \]

Where,

\[ \bar{A}_{\text{eff}}^{E_{\nu^+\nu^-}}(M_{\text{wimp}}) = \frac{\int_{T_{\text{th}}}^{M_{\text{wimp}}} A_{\text{eff}}(E_{\nu}) \frac{dN}{dE_{\nu}} \, dE_{\nu} + A_{\text{eff}}^{\bar{E}_{\nu}}(E_{\bar{\nu}}) \frac{dN}{dE_{\bar{\nu}}} \, dE_{\bar{\nu}}}{\int_{0}^{M_{\text{wimp}}} \frac{dN}{dE_{\nu}} \, dE_{\nu} + \frac{dN}{dE_{\bar{\nu}}} \, dE_{\bar{\nu}}} \]

\( T_{\text{th}} \sim 15 \, \text{GeV} \)

With:
- \( A_{\text{eff}}_{\nu(\bar{\nu})} \) the neutrino (anti-neutrino) effective area weighted by the GC visibility (~60%)
- \( dN/dE \) typical energy spectra from dark matter self-annihilation channels propagated until the Earth surface (three-flavor oscillations in vacuum)

Convolution \( \bar{A}_{\text{eff}}(M_{\text{wimp}}) \)

Period \( i = 5, 10, 9 \) and 12 lines
~1321 days

\( 13/10/2014 \)

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e⁻/e⁺ excess: a try of interpretation

- P. Meade, M. Papucci, A. Strumia, T. Volansky, Dark Matter Interpretations of the e⁻/e⁺ Excesses after FERMI, arXiv: 0905.0480
- CRs excesses observed by PAMELA in e⁺ fraction, and by FERMI and HESS in e⁻ + e⁺
- Interpreted as DM self-annihilations or decays into leptonic final states
- Final states into tau leptons (from DMDM --> 2 SM particles) give the best fit to the excess

DM with $M = 3$. TeV that annihilates into $\tau^+\tau^-$ with $\sigma v = 1.8 \times 10^{-22}$ cm³/s
$e^-/e^+$ excess: 
a try of interpretation

Can neutrino telescopes rule this interpretation out?
Cross-section sensitivities from ANTARES 2007-2012

Spin-dependent cross-section limit for ANTARES 2007-2012 in MSSM-7
Cross-section sensitivities from ANTARES 2007-2012

Spin-independent cross-section limit for ANTARES 2007-2012 in MSSM-7

![Graph showing spin-independent cross-section limits for different experiments including IceCube-79, ANTARES 2007-2008, SUPER-K, W+W-, T+T-, XENON-100, MSSM-7, and CMSSM.](image)