# The indirect search for dark matter with the ANTARES neutrino telescope

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on behalf of the ANTARES Collaboration

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# The ANTARES neutrino telescope

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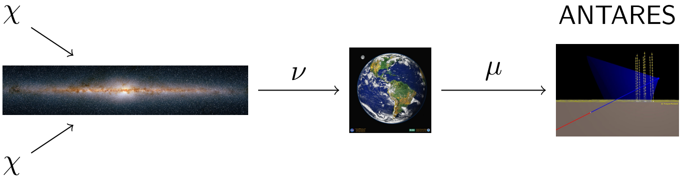
# Indirect detection of dark matter with neutrino telescopes

- Relic WIMPs accumulate in massive celestial bodies like the Sun, the Galactic Center, the Earth (presented as poster) or galaxy clusters
- The annihilation in $W^{\pm}, Z, H$ bosons, $c, b, t$ quarks and $\tau$ leptons can lead to significant neutrino fluxes
- The neutrino signal is less subjected to astrophysical uncertainties than $\gamma$-rays or cosmic rays **and a measured signal will be a smoking gun**



# Dark matter neutrino signal

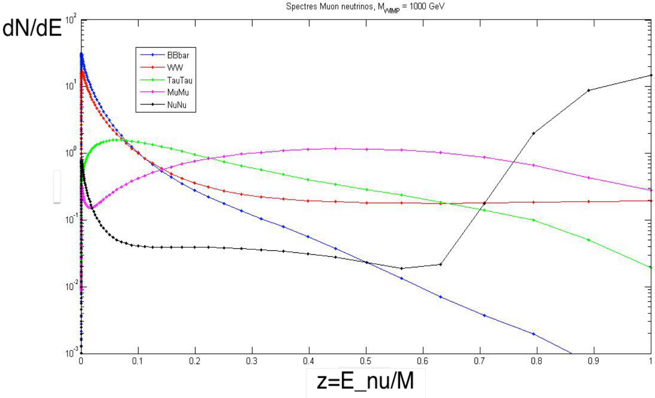
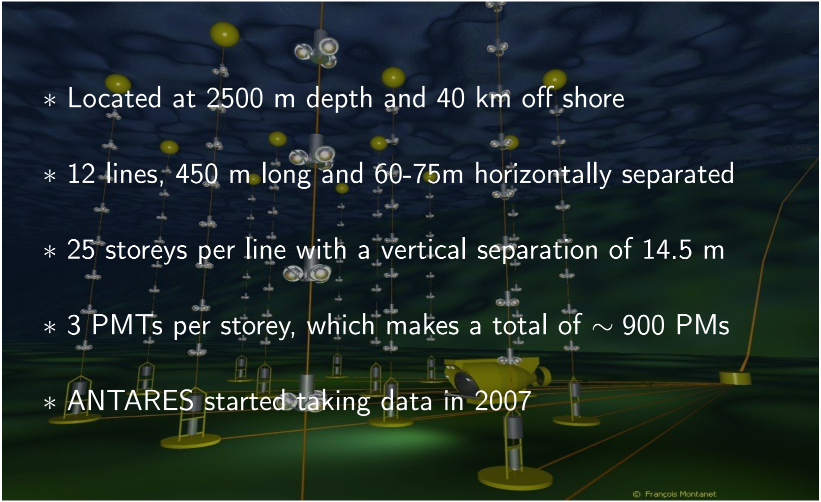



Figure: Neutrino spectra from WIMP annihilations in vacuum, Blue: $b\bar{b}$, Green: $\tau^+\tau^-$, Red: $W^+W^-$, Black: $\nu\bar{\nu}$, Violet: $\mu^+\mu^-$ , used for the Galactic Centre, dwarf galaxies and galaxy clusters

# The ANTARES detector




* Located at 2500 m depth and 40 km off shore
* 12 lines, 450 m long and 60-75m horizontally separated
* 25 storeys per line with a vertical separation of 14.5 m
* 3 PMTs per storey, which makes a total of $\sim$ 900 PMs
* ANTARES started taking data in 2007

# Reconstruction strategies

- AAFit (likelihood based)
  - Better for high energies (>250 GeV)
  - Event selection parameters are $\lambda$ (reconstruction quality) and $\beta$ (angular error estimate)
- BBFit ($\chi^2$ based)
  - Better for low energies (<250 GeV)
  - Can reconstruct single-line events (only zenith angle provided)
  - The main event selection parameter is tchi2 ($\sim \chi^2$)

# Search towards the Galactic Centre

Galactic Centre

# Cone cuts

- In a binned analysis, sensitivities and limits are obtained from a background estimate, that is produced for varying quality cuts and cone cuts around the analyzed source.
- In our analysis this background estimate is generated from time-scrambled data.
- The sensitivities are optimised with respect to the cone and reconstruction quality parameter cut.
- The limits are then generated using the same cone and quality cuts used for the sensitivities.

# Unblinding

Unblinding

# Unblinding

**No observed excess.**

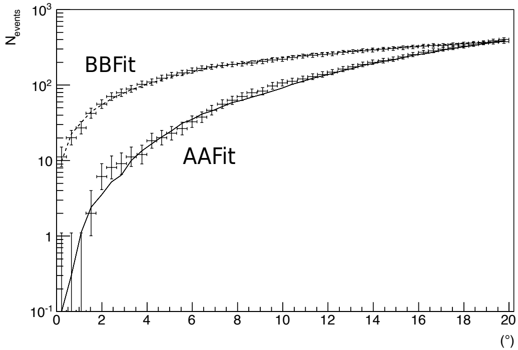



Figure: The cumulative number of events from the 2007-2012 period (crosses) vs. background estimate (line). 1321 days of livetime

# Acceptance

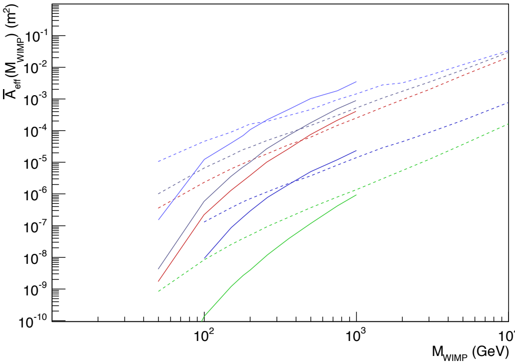



Figure: Acceptance $[m^2]$ per WIMP mass $[GeV]$ for the different channels. Solid lines: AAFit, Dashed lines: BBFit, Green: $b\bar{b}$, Red: $\tau^+\tau^-$,Blue: $W^+W^-$, Gray: $\mu^+\mu^-$, Light blue: $\nu\bar{\nu}$

# Flux limits

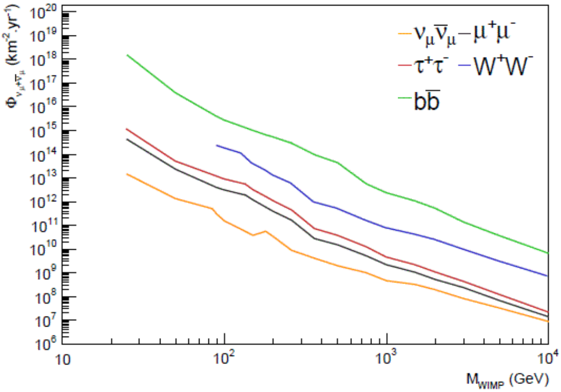



Figure: The neutrino and antineutrino flux limits for the different annihilation channels.

# J-Factor

- The J-Factor is the integral along the line of sight of the dark matter density squared.

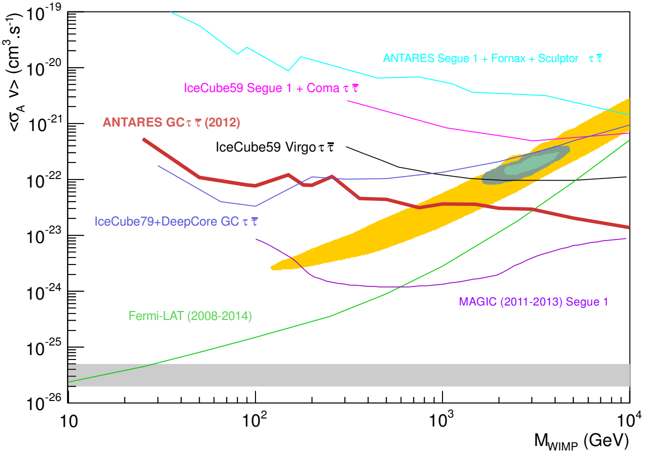
$$J(\theta) = \int_0^{l_{max}} \frac{\rho_{DM}^2 \sqrt{R_{SC}^2 - 2lR_{SC}\cos(\theta) + l^2}}{R_{SC}\rho_{SC,DM}^2} dl$$

- The J-Factor is necessary to convert a flux into a thermally averaged annihilation cross section $<\sigma v>$

$$\frac{d\phi_\nu}{dE} = \frac{<\sigma v>}{2} J_{\Delta\Omega} \frac{R_{SC}\rho_{SC}^2}{4\pi m_\chi^2} \frac{d\ N_\nu}{dE}$$

- The total J-factor for the binned analysis is calculated by integrating the J-factor over solid angle until the cone cut

# Limit comparison



# Search towards the Sun

## The Sun

# Unbinned method

- The used likelihood function is:
  $$\log(L) = \sum_i \log\left(\frac{n_s}{N} S_i(\alpha, N_{hits}, \beta) + \left(1 - \frac{n_s}{N}\right) B_i(dec, N_{hits}, \beta)\right)$$
- $N_{hits}$ is the number of selected hits in the event, $\beta$ the angular error estimate ($\chi^2$ is used for BBFit)
- The test statistics used is:
  $$\log[TS] = \log[L^{max}] - \log[L(n_s = 0)]$$

# Spectra and acceptance

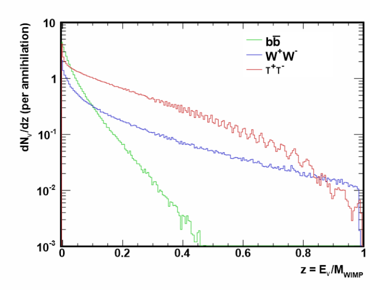



Figure: Neutrino spectra used for the Sun analysis produced with WIMPSIM, taking neutrino oscillations into account.

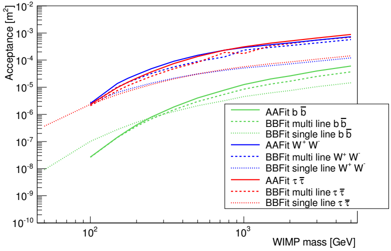



Figure: The acceptance [$m^2$] as a function of the WIMP mass for the different channels

# Conversion to cross sections

- The neutrino fluxes are converted to cross sections assuming an equilibrium between annihilation and capture

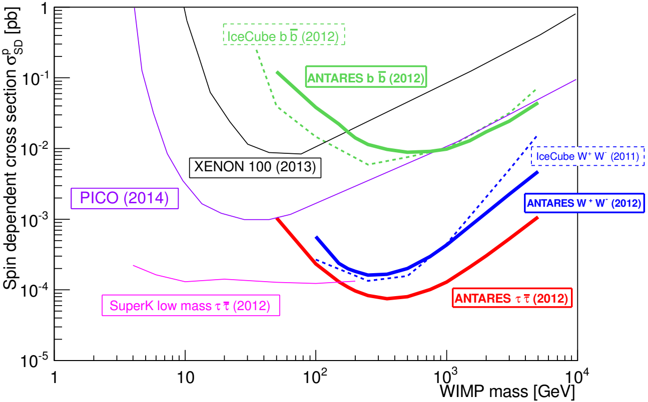
$$C_{cap} = 2C_{ann}$$

- $C_{ann}$ is the annihilation rate, $C_{cap}$ is the capture rate
- The capture rate can be expressed as:

$$C_{cap} = 3.35\frac{1}{s}\left(\frac{\rho_{loc}}{0.3\frac{GeV}{cm^3}}\right)\left(\frac{270\frac{km}{s}}{v_{rms}}\right)^3\left(\frac{\sigma_{H,sd}+\sigma_{H,si}+0.07\sigma_{He,si}}{10^{-6}pb}\right)\left(\frac{100GeV}{m_\chi}\right)^2$$

- $\sigma_{H,sd}$, $\sigma_{H,si}$ and $\sigma_{He,si}$ are the spin-dependent and spin-independent scattering cross-sections with hydrogen and helium, $\rho_{loc}$ is the local DM density, $v_{rms}$ is the mean DM particle velocity and $m_\chi$ is the WIMP mass.

# Limits and results




- The data from the 2007-2012 period has been used (1321 days of livetime)

# Summary

- The searches for dark matter in the Galactic Center and the Sun analysis show **very competitive** results
- The produced limits begin to constrain the SUSY dark matter models
- Further analyses for the Earth and secluded dark matter are also conducted
- ANTARES limits will further improve with new data (and an unbinned GC search is ongoing)

# Flux limits

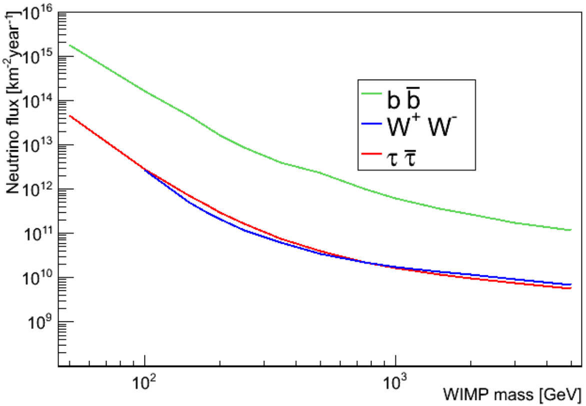
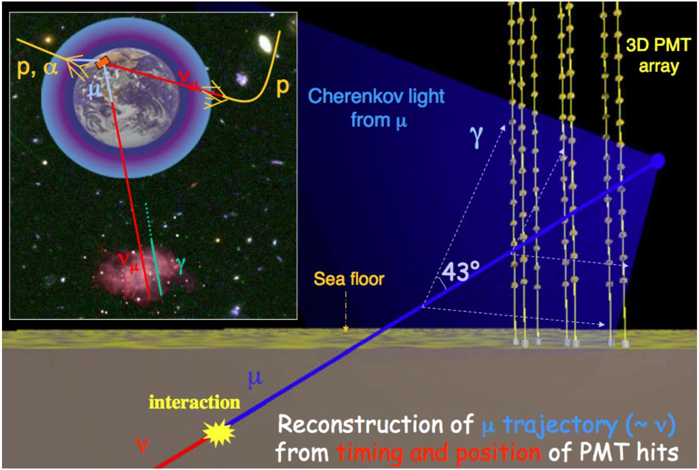



Figure: The neutrino plus antineutrino flux limits for the different annihilation channels.

# Detection principle



# Dark matter neutrino signal

- For the Earth and the Sun analyses the dark matter neutrino spectra have been calculated with the WIMPSIM package (Blennow, Edsjö, Ohlsson, 03/2008)
- For the Galactic Centre and the galaxy cluster analysis the spectra of the Cirelli group are used (M.Cirelli et al., arXiv:1012.4515)
- Annihilations into $b\bar{b}$, $\tau^+\tau^-$, $W^+W^-$, $\mu^+\mu^-$and $\nu_\mu\bar{\nu}_\mu$ are used as benchmark

# Source selection

- An analysis of the 11 most promising sources is in progress
- For now only the binned method has been applied

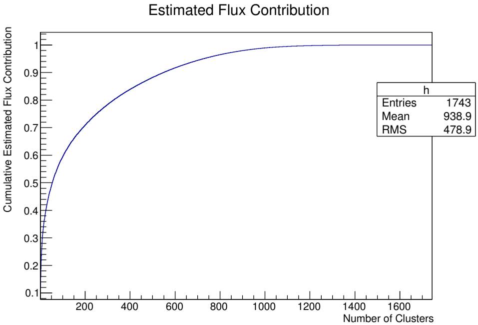



Figure: Cumulative estimated contribution per source sorted by magnitude

# First estimation of sensitivity for the Virgo cluster

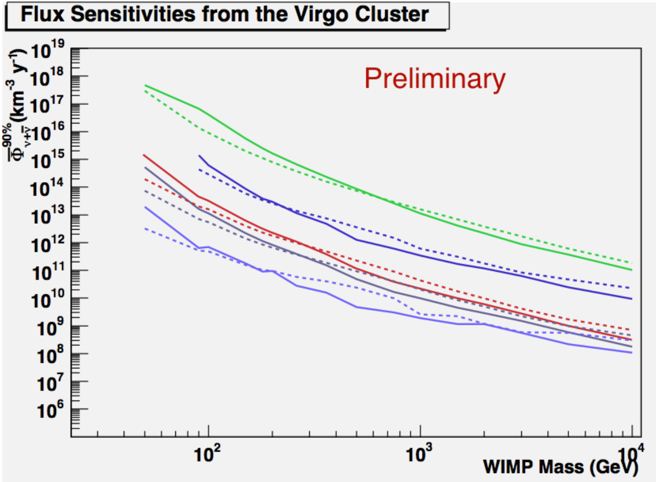
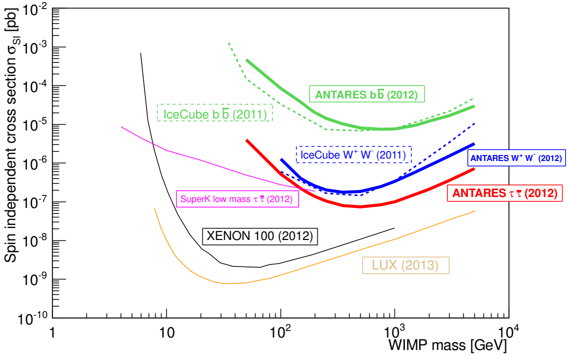


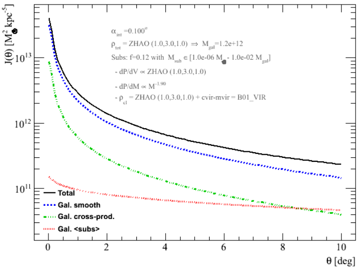

Figure: Solid: AAFit, Dashed: BBFit Colours: $b$,$\tau$, $W$, $\mu$,$\nu_{\mu}$

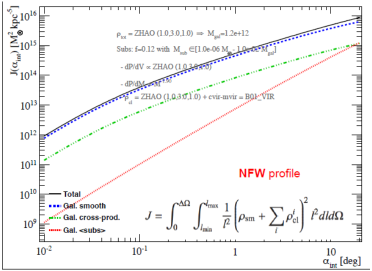
# Limits and results




- The data from the 2007-2012 period has been used
- 1321 days of livetime in this period

# Clumpy Output

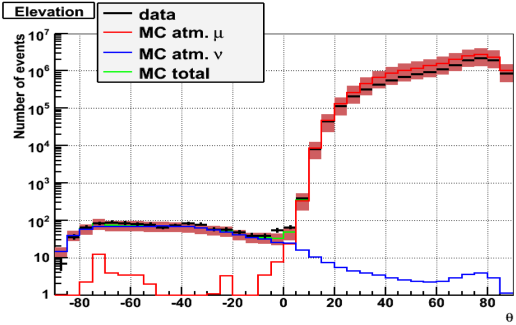



J factor computed for the NFW profile using CLUMPY version 2011.09_corr2 (A. Chardonnier et al., Comp. Phys. Comm. 183, 656 (2012) (http://lpsc.in2p3.fr/clumpy))

# Background rejection

The largest part of the background consists of atmospheric muons




They can be rejected by making a "horizon cut" thereby using the Earth as a shield against these muons

# Visibility

IceCube visibility
without veto
in galactic coordinates
Resolution in ice $\sim 0.6^\circ$

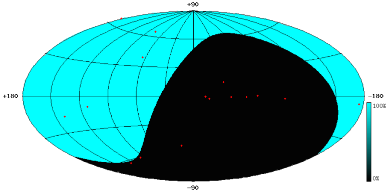



Figure: IceCube visibility increases with the veto at the price effective area

ANTARES visibility
in galactic coordinates
Resolution in water $\sim 0.3^\circ$