Combined search for dark matter from the Galactic Center with the ANTARES and IceCube neutrino telescopes

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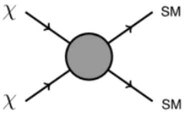
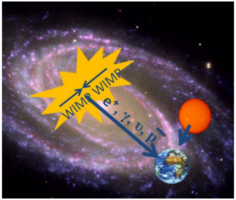
Dark matter: indirect searches with neutrinos

Candidate: WIMPs, for example SUSY neutralino

- thermally produced in the early Universe
- relic density is *blocked* at *freeze-out*
- mass $\sim$ electroweak scale: $\sim$ GeV $< M_{WIMP} < \sim 100$ TeV



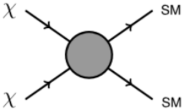
with SM $= f\bar{f}, W^{\pm}, q\bar{q}$



Dark matter: indirect searches with neutrinos

Neutrino source in this case is a WIMP pair annihilation process

- can yield significant fluxes of high-energy ν
- each channel has its own energy distribution
- sensitive to halo profile in spacial distribution



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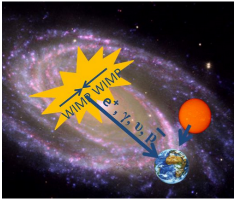
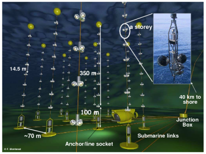


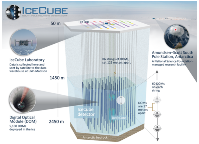
Sources

Relic WIMPs accumulate in massive celestial bodies like the GC

- below horizon for detectors in Northern hemisphere
- IceCube event selection is based on veto techniques

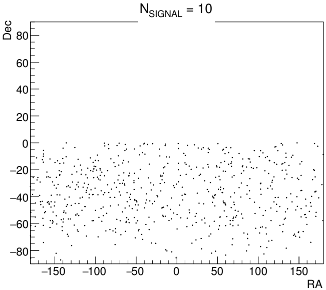


12 lines between 2 and 2.4 km underwater



86 strings between 1.5 and 2.5 km in ice

Signal: a cluster on the source



Reproduced with MC simulations including a variable number of signal events, weighted according to a DM model (energy spectrum + halo profile). Likelihood method returns the number of signal events.

Sensitivities

Average upper limit μ_{90} of events in cluster $\rightarrow$

$$\Phi = \frac{\mu_{90}}{\mathcal{A}cc \cdot t}$$

flux of particles at the detector Φ. Given the energy spectrum of single collision dN/dE and the J-factor

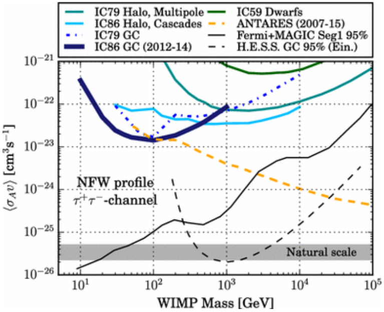
$$\frac{d\Phi_\nu}{dE_\nu} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2M_\chi^2} \frac{dN_\nu}{dE_\nu} \int_0^{\Delta\Omega} d\Omega \int_{los} \rho^2 \left(r(s,\theta,\psi)\right) ds$$

$$\mu_{90} = \frac{\langle \sigma v \rangle}{2} \int_0^M \frac{dN}{dE} dE \, \frac{J}{4\pi} \, \frac{1}{M_\chi^2} \, \mathcal{A}cc(M_\chi) \, t$$

number of events observed = annihilation rate * average number of particles per collision * source geometry * acceptance * time

Goal of combined analysis

- Improve the limit on $\langle \sigma v \rangle$ in the region where ANTARES and IceCube are comparable: between 50 GeV and 1 TeV
- Understand and unify the analysis method of the two collaborations



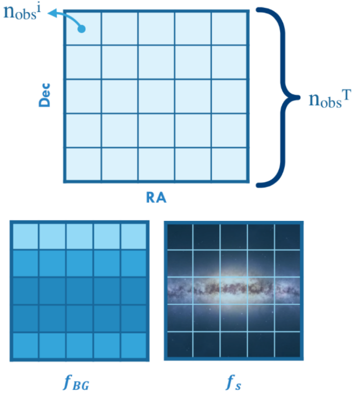
[arXiv:1705.08103]

Data sets

Exchange of following data sets between the collaborations was approved

- ANTARES
  - Lifetime: 2101.6 days from 2007 to 2015
  - Single-line rec. < 250 GeV, multi-line rec. > 250 GeV
- IceCube:
  - Lifetime: 1006 days from May 2012 to May 2015
  - Official IC86 GC WIMP search data set

Binned likelihood method



[Picture from J.A. Aguilar]

Minimise $-\log \mathcal{L}(\mu)$

$$\mathcal{L}(\mu) = \prod_{i}^{Nbins} Poisson\left(n_{obs}^i; n_{obs}^T f^i(\mu)\right)$$

n_{obs}^i = oberved events in bin i
n_{obs}^T = total expected events
$f^i(\mu) = \mu f_s^i + (1-\mu) f_{bg}^i$

Free parameter $\mu = \frac{n_{sig}}{n_{obs}^T}$ in [0,1]

f_s, f_{bg} probability density functions for signal and background

[Main analyser: N. Iovine, UL Brussels]

Combined likelihood

- Two-component mixture model to combine the sensitivities of IceCube and ANTARES
- The two likelihoods are multiplied and optimised with respect to μ

$$\mathcal{L}_{comb}(\mu) = \prod_{k=A,I} \mathcal{L}_k(\mu_k)$$

- μ is the ratio of the number of signal events over the total number of background events in the sample n^T_{obs}
- Upper limit on the signal fraction using the Feldman-Cousins method

Combined likelihood

$$-\log \mathcal{L}_{comb}(\mu) = -\log \mathcal{L}_A(\mu_A) - \log \mathcal{L}_I(\mu_I)$$

Minimize a single parameter $\mu = \frac{n_s}{n_T} = \frac{n_s^A + n_s^I}{n_T^A + n_T^I} = \frac{n_s(f_s^A + f_s^I)}{n_T(f^A + f^I)}$

$$\mu_i = \frac{n_s^i}{n_T^i} = \frac{f_s^i n_s}{f^i n_T} = \frac{f_s^i}{f_i}\mu$$

IceCube: $$n_{sig}^{ICE} = \sum \frac{1}{4\pi m_{WIMP}^2} \frac{\langle \sigma v \rangle}{2} \frac{w_{OW}}{N_{gen}} \frac{dN}{dE} \int \rho^2 ds$$

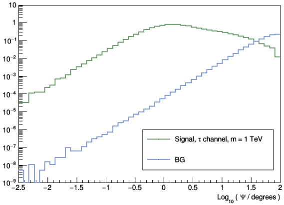
ANTARES: $$n_{sig}^{ANT} = \frac{1}{4\pi m_{WIMP}^2} \frac{\langle \sigma v \rangle}{2} t \langle \mathcal{A}_{eff} \rangle \Phi^{INT} J$$

PDFs ANTARES $\to$ IceCube

WIMP WIMP $\to W^+W^-, \tau^+\tau^-, b\bar{b}, \mu^+\mu^- \to \nu\bar{\nu}$ or $\to \nu\bar{\nu}$

For binned analysis, same variable for signal and BG.

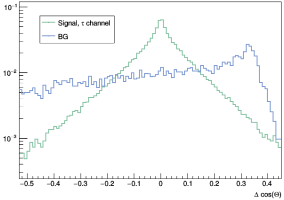
- Spectra: last used by IceCube [arXiv:1705.08103]
- Masses: 50,65,100,130,200,300,400,500,1000 GeV



AAFit

$\log_{10}\left(acos(v_{track} \cdot v_{GC})\right)$

v is direction versor

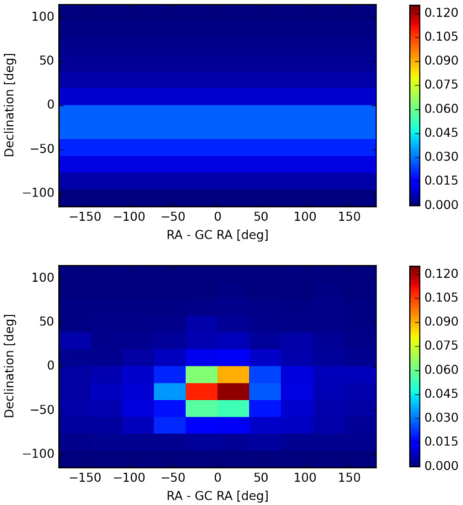


BBFit single line

$\cos(\theta_{track}) - \cos(\theta_{GC})$

θ is zenith

PDFs IceCube



Effective areas and acceptances

Acceptance is average effective area for each WIMP mass.
In this analysis, acceptances are not normalised to the integral of the DM spectra:

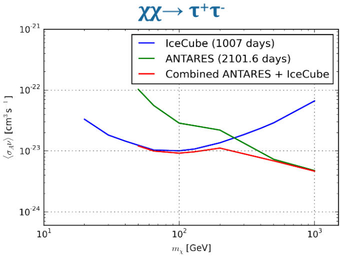
$$\text{combined def.} \quad \mathcal{A}cc(M) = \langle A_{eff} \rangle = \int_0^M A_{eff}(E_\nu) \frac{dN(E_\nu)}{dE_\nu} dE_\nu$$

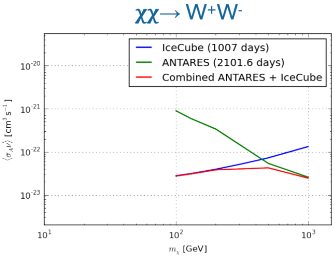
because

$$n_{sig}^{ICE} = \sum \frac{1}{4\pi m_{WIMP}^2} \frac{\langle \sigma v \rangle}{2} \frac{w_{OW}}{N_{gen}} \frac{dN}{dE} \int \rho^2 ds$$

$$n_{sig}^{ANT} = \frac{1}{4\pi m_{WIMP}^2} \frac{\langle \sigma v \rangle}{2} t \langle \mathcal{A}_{eff} \rangle \Phi^{INT} J$$

Results and conclusions





Work in progress for sensitivities with new spectra and masses in order to compare with same analysis parameters

- Between 65 GeV and 1 TeV an improvement was achieved with respect to the sensitivities of ANTARES and IceCube
- Converging on analysis details and procedures of both collaborations: spectra have significant impact