Searches for Dark Matter with the ANTARES and KM3Net neutrino telescopes

S.R. Gozzini for the ANTARES and KM3NeT Collaborations

Dark Ghosts 2018 Bruxelles Belgium

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Overview

Neutrino telescopes have a wide scientific target in *one* data set

- neutrino astronomy
- dark matter
- multi-messengers
- particle physics

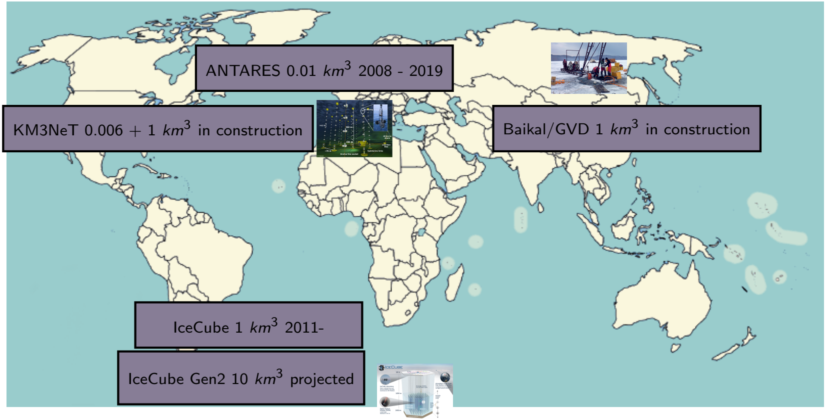
νs travel indisturbed but need large instrumented volume

Water with respect to ice

- more noise: radioactive ^{40}K decays, luminescence in sea
- larger scattering length: better angular resolution
- maintainable (but moving)

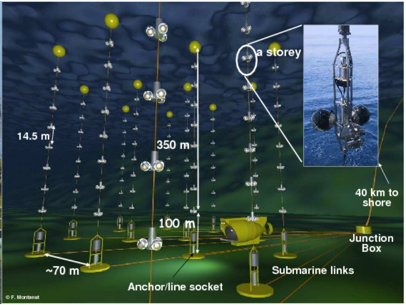
Field of view of ANTARES/KM3NeT complementary to IceCube

Atlas of neutrino telescopes



ANTARES

- 12 lines, 885 PMTs, 25 storeys per line, 3 PMT per storey
- 10 years of operation at 2500 m depth 40 km offshore Toulon



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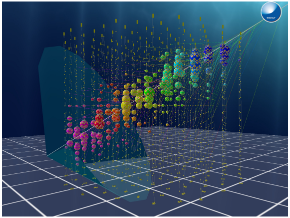
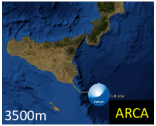
KM3NeT ARCA and ORCA



115 strings, 64000 PMTs (31 PMTs/DOM and 18 DOMs/string)

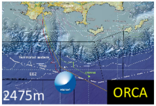
ARCA (2 building blocks)



string spacing: 90 m
DOM spacing: 36 m

Large sparse unit, high energies

ORCA (1 building block)

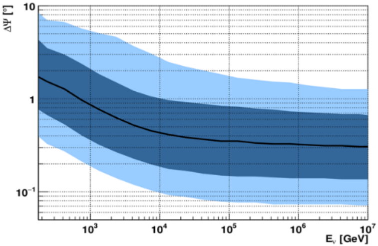


string spacing: 20 m
DOM spacing: 9 m

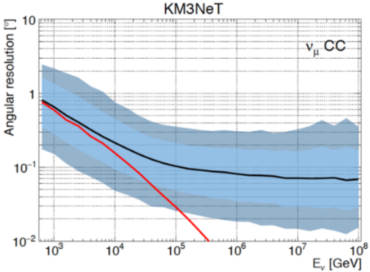
Small dense unit, low energies

Performances

ANTARES tracks ($\nu_\mu CC$)



KM3NeT ARCA tracks ($\nu_\mu CC$)



(red line is median angle between μ and ν direction)

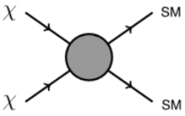
Dark matter: indirect searches with neutrinos

Candidate: WIMPs, for example SUSY neutralino

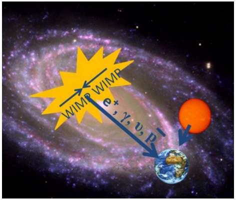
- thermally produced in the early Universe
- relic density is *blocked* at *freeze-out*
- mass $\sim$ electroweak scale: $\sim$ GeV $< M_{WIMP} < \sim$ 100 TeV

Neutrino source in this case is a WIMP pair annihilation process

- can yield significant fluxes of high-energy ν



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



Sources

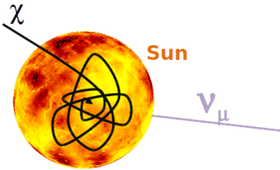
Relic WIMPs accumulate in massive celestial bodies like

The galactic center

- highest signal expectation
- below horizon for detectors in Northern hemisphere

The sun

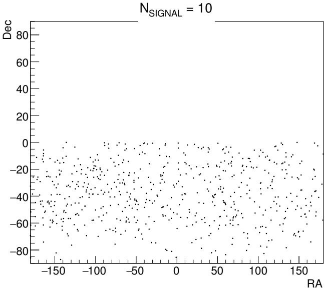
- sensitive to WIMP-nucleon cross-section (spin-dependent and spin-independent)
- clean signal, background well known
- less affected by halo uncertainties



The Earth

Galaxy clusters

Signal: a cluster on the source



Reproduced with pseudoexperiments: variable number of signal events from MC simulations weighted according to DM model, over a number of background events taken from RA-shuffled data

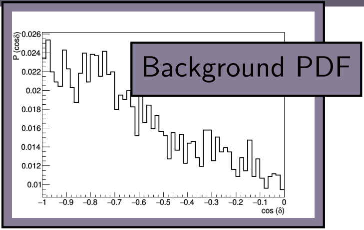
Analysis Method

Unbinned likelihood analysis

$$\log \mathcal{L}(n_s) = \sum_{i=1}^{N} \log \left[n_s \mathcal{S}(\psi_i, E_i, q_i) + n_{bg} \mathcal{B}(\delta_i, E_i, q_i) \right] - n_{bg} - n_s$$

with $\mathcal{S}$, $\mathcal{B}$ describing the signal and background distribution of discriminating variables (angular information ψ, δ, energy estimate E, track reconstruction quality q).
Significance is computed comparing test statistics of data with distribution of pseudo-experiments with injected variable signal

Analysis Method



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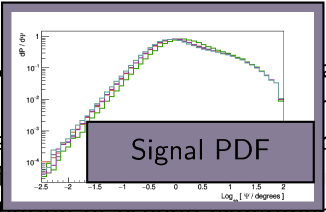
$$\log \mathcal{L}(n_s) = \sum^{N} \log \left[n_s \mathcal{S}(\psi_i, E_i, q_i) + n_{bg} \mathcal{B}(\delta_i, E_i, q_i) \right] - n_{bg} - n_s$$



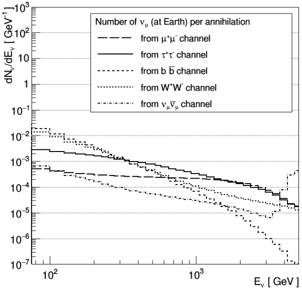
with … and background distribution of discri… information ψ, δ, energy estimate E, tra… q).

Signif… ring test statistics of data with distribution of pseudo-experiments with injected variable signal

Searches towards the Galactic Centre with ANTARES

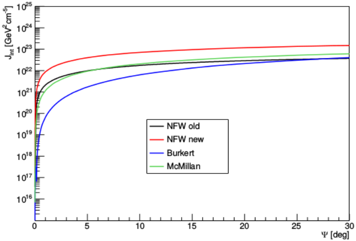
$$\frac{d\Phi_\nu}{dE_\nu} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2M_\chi^2}\frac{dN_\nu}{dE_\nu}\int_0^{\Delta\Omega} d\Omega \int_{los} \rho^2\left(r(s,\theta,\psi)\right) ds$$

Energy distribution from the PPPC tables [arXiv:1012.4515] by Cirelli et al. based on PYTHIA + oscillations



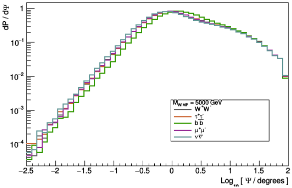
Morphology: *J*-Factor

- NFW, Einasto: cuspy, result from simulations
- Isothermal, Burkert: galactic rotation curves

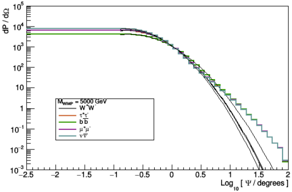


Ingredients - Signal / Background

Spatial: angular offset from GC drawing from J-Factor profile, in equal solid angle bins. For background: $\sin\delta$ (declination)

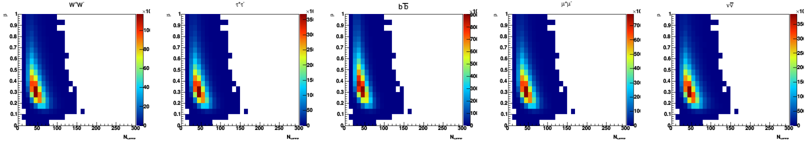


offset, smeared for source profile



$dP/d\Omega$

Energy estimator (N_{HITS}) : angular error estimate β



Analysis procedure and results

Data set: 2007-16 tracks (ν_μ CC events)

Physical background (atmospheric ν, mis-reconstructed atmospheric μ) are included in the likelihood

- spatial distribution: angular offset from source
- distribution of estimated energy
- reconstruction quality

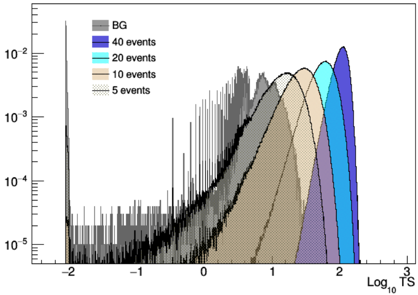
Likelihood ratio as a test statistics

$$\log TS = \log \mathcal{L}(n_s)^{max} - \log \mathcal{L}(n_s = 0)$$

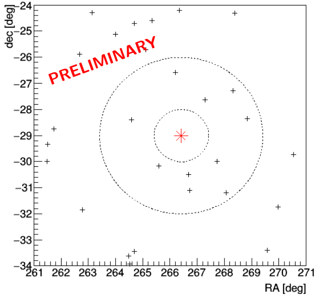
Blind analysis: RA of real data is randomly shuffled until end.

Limits at 90% CL are set after finding no TS compatible with dark matter pseudoexperiment distribution in 10 years ANTARES data

- Sensitvity 90% CL means missing signal *false negative* less than 10% of the times
- Discovery 3σ means excluding *false positive* less than $1\text{-}\mathcal{P}(3\sigma)$



TS distribution for hypothesis test



Unblinding results

Observations, limits etc

Most prominent channels yielding ν (assumed 100% B.R.)
$\chi\bar{\chi} \to W^+W^-, b\bar{b}, \tau^+\tau^-, \mu^+\mu^-, \nu\bar{\nu}$

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

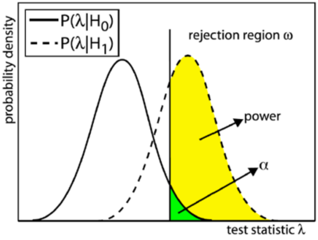
Observation n or limit μ_{90} on integrated flux $\Phi = \mu_{90}/\left(\mathcal{A}cc \cdot t\right)$

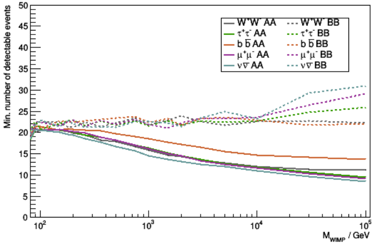
$$\mu_{90} = \frac{\langle\sigma v\rangle}{2}\int_0^M \frac{dN}{dE} dE \, \frac{J}{4\pi}\frac{1}{M_\chi^2}\mathcal{A}cc(M_\chi)\, t$$

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

Sensitivity

Neyman approach: median upper limit at 90% CL = fake negative (signal confused with bg) less than 10% of the times.
Poisson (μ, n_s) accounts for fluctuations





Acceptances

Acceptance is effective area weighted with source spectrum

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

$$\text{WIMP WIMP} \rightarrow \nu\bar{\nu}$$

μ_{90}: median upper limit on number of ν

$$\int_0^M \frac{d\Phi_{\nu+\bar{\nu}}}{dE_\nu} = \frac{\mu_{90}}{\mathcal{A}cc\ t} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2M_\chi^2}\int_0^M \frac{dN_{\nu+\bar{\nu}}}{dE_\nu}dE_\nu\ J_{NFW}$$

$$\frac{\#}{m^2 s} \quad = \quad m^3 s^{-1}\ \ GeV^{-2} \quad \# \quad GeV^2 m^{-5}$$

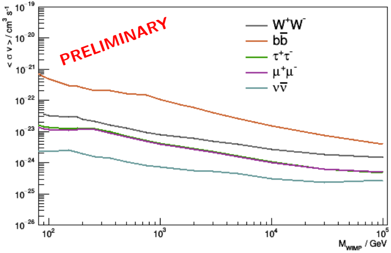
Flux at detector

Nr. of particles per collision

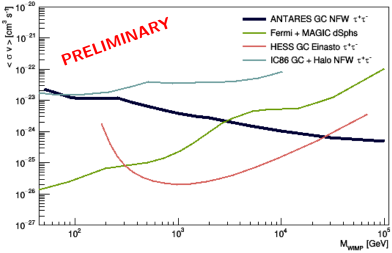
Limits on thermally-averaged annihilation cross-section

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2M_\chi^2}\frac{dN_\nu}{dE_\nu}J$$

ANTARES different channels



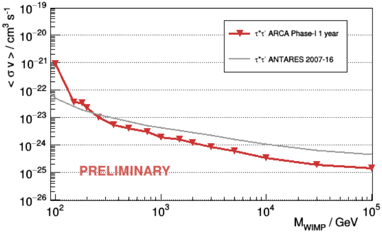
Results from $\tau^+\tau^-$ from different experiments

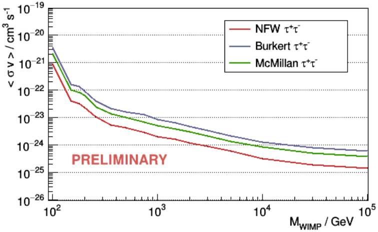


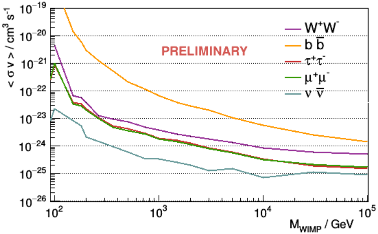
Best limits for high WIMP masses: better angular resolution and higher effective volume (GC is in Southern hemisphere → good visibility without veto)

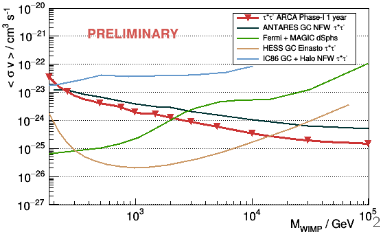
Sensitivity estimated for KM3NeT

Promising chances - KM3NeT ARCA phase I (24 lines) 1 year







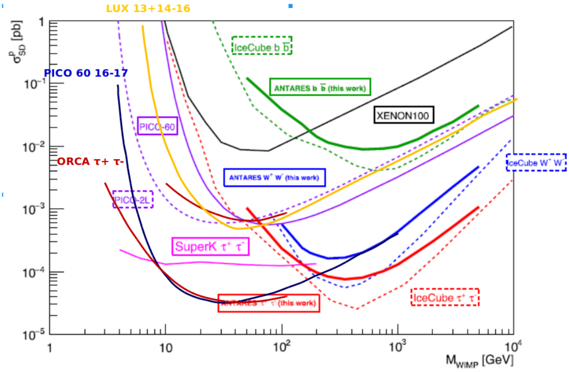


Searches towards the Sun

- Differential neutrino flux is related with the annihilation rate
$$\frac{d\Phi}{dE_\nu} = \frac{\Gamma}{4\pi d^2}\frac{dN_\nu}{dE_\nu}$$
- In equilibrium between capture and annihilation $\Gamma = C/2$ with C capture rate
- Flux only depends on WIMP-nucleon scattering cross section
- Very clean (BG well known); if signal $\rightarrow$ direct interpretation
- Signal from moving source: bias-free
- Searches with neutrino telescopes crucial because sensitive at low velocities (= easier capture)

Searches towards the Sun

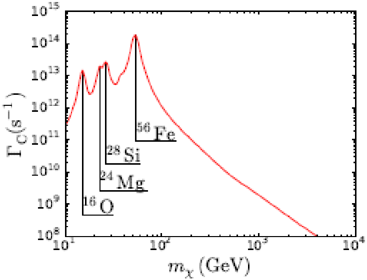
Sensitivities and limits on spin-dependent WIMP-nucleon cross section comparable with those from direct searches

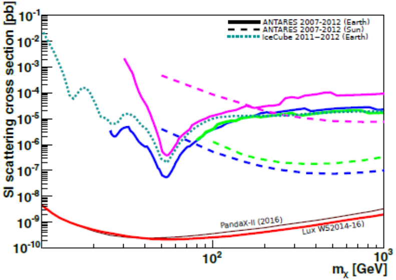


Searches towards the Earth

WIMP capture and subsequent decay, but no equilibrium can be assumed due to low escape velocity

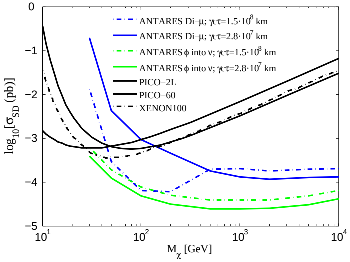
- WIMP scattering on Fe, Ni $\rightarrow$ spin-independent cross section
- Easier capture for WIMPs with mass $\sim$ nucleus
- No easy background; non competitive with direct searches



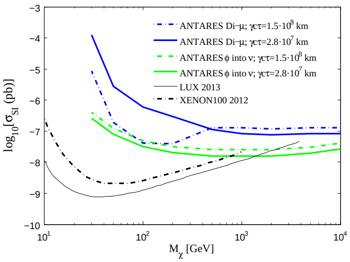


Searches towards the Sun with secluded DM models

DM particle *secluded* from SM matter by a mediator (GUT new gauge boson for instance). Possible signatures: double μ, direct annihilation into ν



Spin-dependent σ



Spin-independent σ

Summary

- Search for dark matter profits from complementary methods: indirect searches crucial
- Limits on cross-section for WIMP pair annihilation with 10 years ANTARES data. Best limits at high WIMP masses
- Limits for spin-dependent cross-section for WIMP-nucleon interaction, complementing with those from direct searches
- New scenarios can be tested: for instance secluded DM models. Wide range of possibilities in reach for KM3NeT.

Activities ongoing in DM group

- searches towards the Sun with ANTARES (update on existing analysis) and ORCA
- searches towards the galactic centre with ORCA
- searches for secluded DM