Dark matter sensitivity in ANTARES/KM3NeT

Rebecca Gozzini

on behalf of the ANTARES/KM3NeT Collaborations

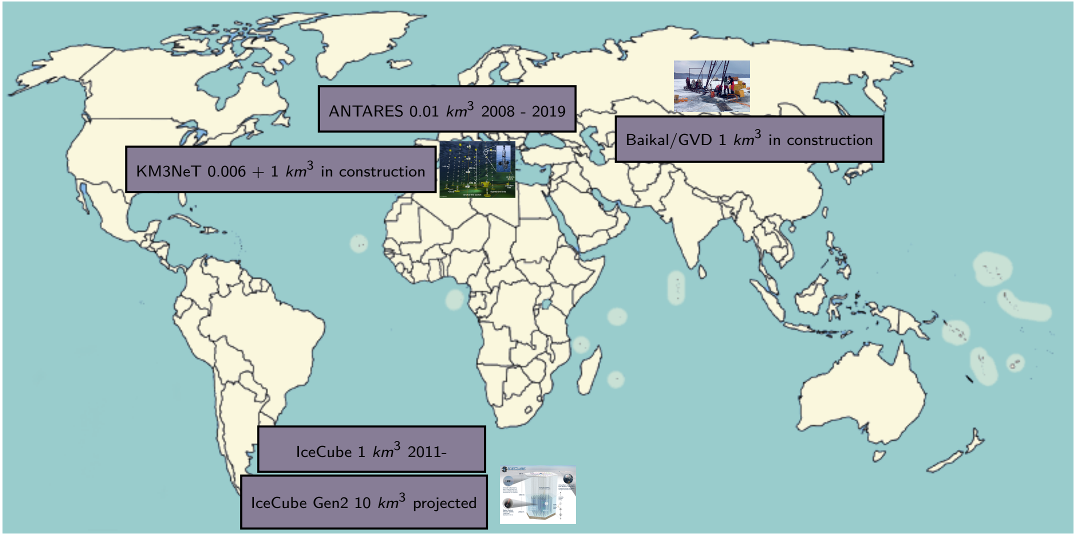
MAGIC Dark Matter Workshop, Barcelona

January 17, 2019

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Atlas of neutrino telescopes



Overview

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

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

Neutrinos travel undisturbed but need *large instrumented volume*

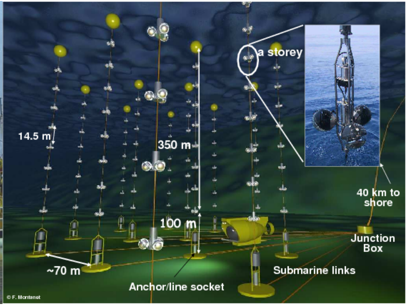
Water with respect to ice

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

Field of view of ANTARES/KM3NeT is complementary to IceCube

ANTARES

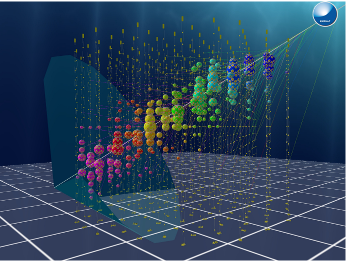
- 12 lines, 885 PMTs, 25 storeys per line, 3 PMT per storey
- 10 years of operation at 2500 m depth 40 km offshore Toulon



ANTARES

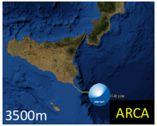
- 12 lines, 885 PMTs, 25 storeys per line, 3 PMT per storey
- 10 years of operation at 2500 m depth 40 km offshore Toulon

KM3NeT ARCA and ORCA



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

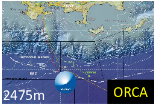
ARCA (2 building blocks)



depth 3500 m
string spacing: 90 m
DOM spacing: 36 m

Large unit, sparse DOMs, high energies

ORCA (1 building block)

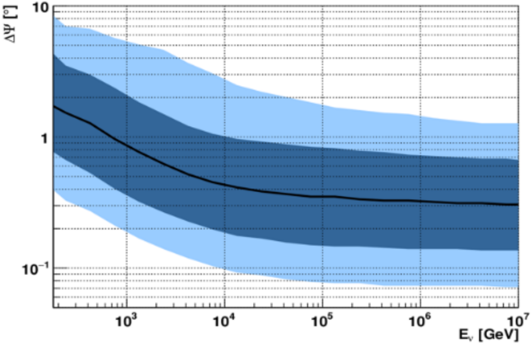


depth 2500 m
string spacing: 20 m
DOM spacing: 9 m

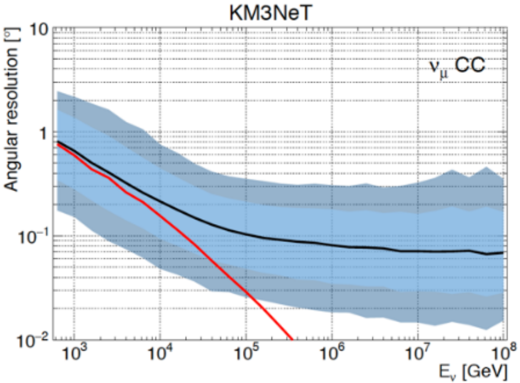
Small Unit, dense DOMs, low energies

Angular resolution

ANTARES tracks ($\nu_\mu CC$)



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



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

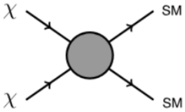
Dark matter: indirect searches (common part with γ-ray astronomy)

Candidate: WIMPs, for example SUSY neutralino

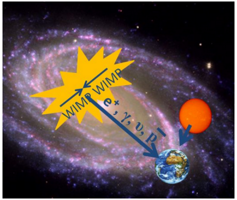
- thermally produced in the early Universe
- relic density is *blocked* at *freeze-out*
- mass $\sim$ electroweak scale: $\sim$ GeV $< M_{WIMP} < \sim$ 100 TeV

Neutrino (photon) source in this case is a WIMP pair annihilation process

- can yield significant fluxes of high-energy ν or γ



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



In short (common part with γ-ray astronomy)

Thermal bath (chemical + thermal equilibrium)

$\downarrow$

Cooling

Production stops

$\downarrow$

Universe expansion

Freeze-out: annihilation stops

$\downarrow$

Thermal equilibrium stops

DM particles created and annihilated in equilibrium with thermal bath

eg. $\gamma\gamma \leftrightarrow$ DM DM

$\downarrow$

Not enough energy to form DM mass

No longer chemical equilibrium

$\downarrow$

Volumes expand, number density decreases, annihilation rate decreases

Only elastic scattering

$\downarrow$

DM in free range propagation

Sources (common part with γ-ray astronomy)

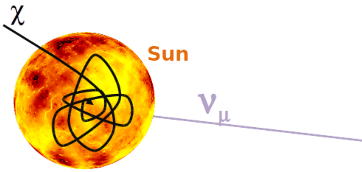
Relic WIMPs are expected to accumulate in massive celestial bodies like

The Galactic Centre

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

The Sun

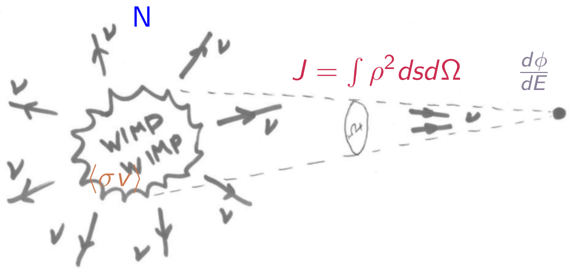
- sensitive to WIMP-nucleon cross-section (spin-dependent and spin-independent)
- clean signal, background well known
- less affected by halo uncertainties
- capture-annihilation in equilibrium



The Earth

Galaxy clusters

Source: a WIMP-WIMP collision



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

flux at Earth = annihilation rate * number of ν per collision * source geometry

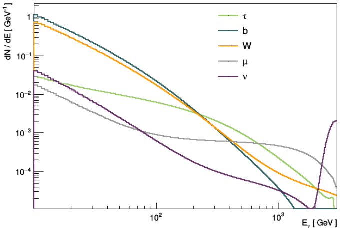
$cm^{-2}s^{-1}GeV^{-1} = cm^3 s^{-1} * GeV^{-1} * GeV^2 cm^{-5} GeV^{-2}$

Searches towards the Galactic Centre with ANTARES

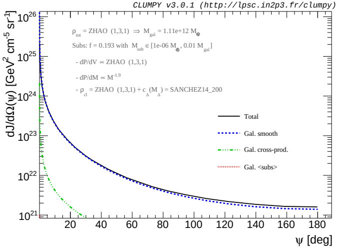
Channels: $\chi\bar{\chi} \to W^+W^-, b\bar{b}, \tau^+\tau^-, \mu^+\mu^-, \nu_\mu\bar{\nu}_\mu$. Masses: M_χ between 10 GeV and 100 TeV

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

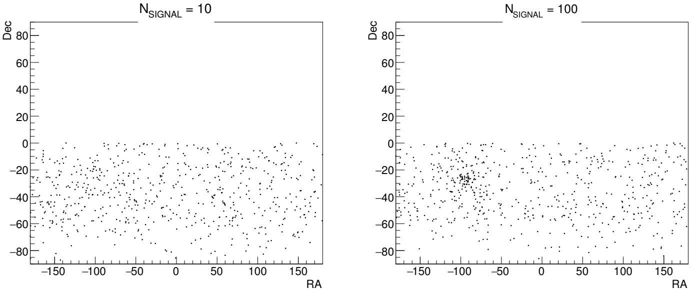
Energy distribution from the PPPC tables [arXiv:1012.4515]



Morphology: *J*-Factor obtained with CLUMPY [arXiv:1806.08639]



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

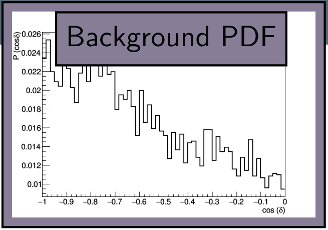
Analysis Method

Unbinned likelihood analysis

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

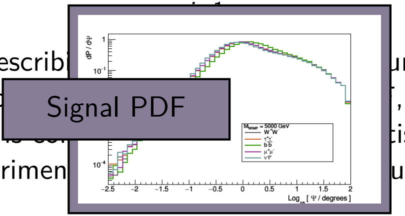
with $\mathcal{S}$, $\mathcal{B}$ describing the signal and background distribution of discriminating variables (angular information ψ, δ, energy estimate E, track reconstruction quality q).
Significance is computed comparing test statistics of data with distribution of pseudo-experiments with injected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

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 $\mathcal{S}$, $\mathcal{B}$ describi … und distribution of discriminating variables (angular info … , track reconstruction quality q).
Significance … tistics of data with distribution of pseudo-experimen … ut known, signal $n_s = N - n_{bg}$

Analysis workflow

PDFs

Signal: $\psi(\nu, GC)$
BG: $\sin\delta$
in equal solid angle bins

Unbinned max likelihood: returns n_s

$$\mathcal{L}(n_s) = \prod_{i}^{Nbins} [n_s \mathcal{S}(\psi_i, E_i, q_i) + n_{bg}\mathcal{B}]$$

Poisson

$\mathcal{P}(n_s, \mu)$

Number of events

Neyman statistics

Acceptances

From PPPC
Integrated

Cross-section sensitivities

Limits on $\langle \sigma v \rangle$

Analysis details

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

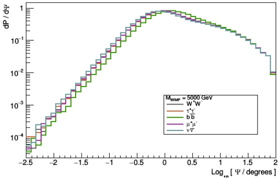
Likelihood ratio as a test statistics

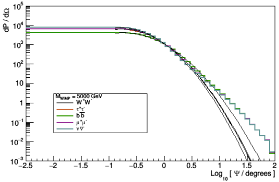
$$\log TS = \log \mathcal{L}(n_s)^{max} - \log \mathcal{L}(n_s = 0)$$

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

Ingredients: signal and background PDFs

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

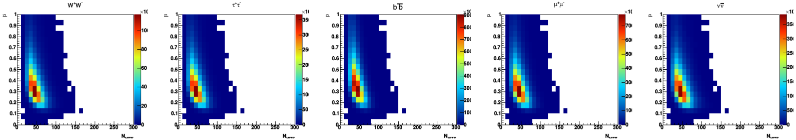




offset, smeared for source profile $\qquad$ $dP/d\Omega$

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

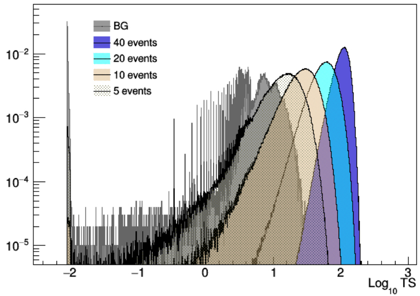
β



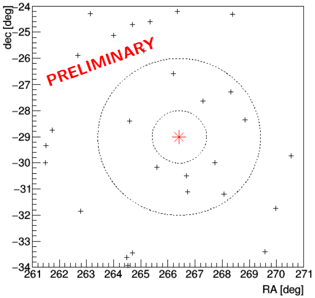
N_{HITS}

Limits at 90% CL are set after finding no TS compatible with dark matter pseudo-experiments 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 $1\text{-}\mathcal{P}(3\sigma)$



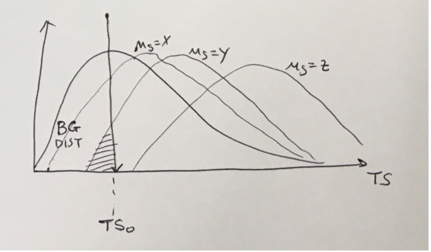
TS distribution for hypothesis test

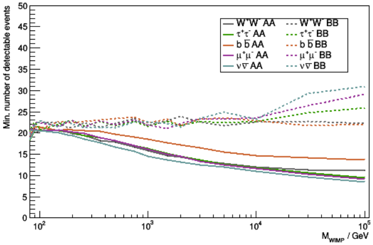


Unblinding results

Sensitivity

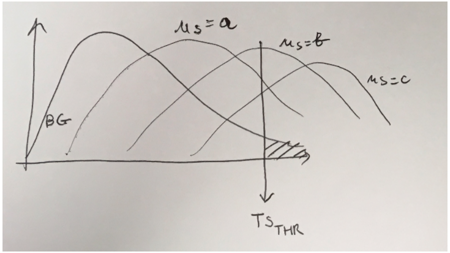
Neyman approach: median upper limit at 90% CL = fake negative (signal confused with bg) less than 10% of the times.
Poisson (μ, n_s) accounts for fluctuations

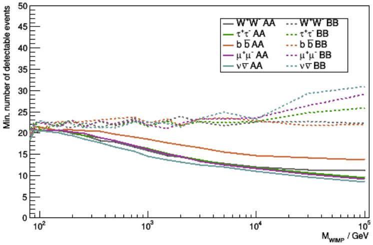




Sensitivity

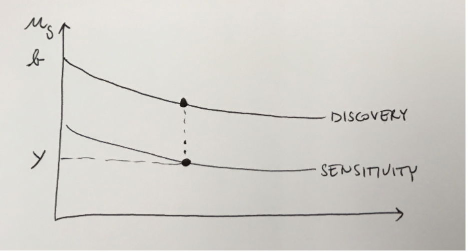
Neyman approach: median upper limit at 90% CL = fake negative (signal confused with bg) less than 10% of the times.
Poisson (μ,n_s) accounts for fluctuations

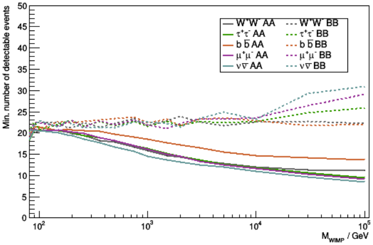




Sensitivity

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



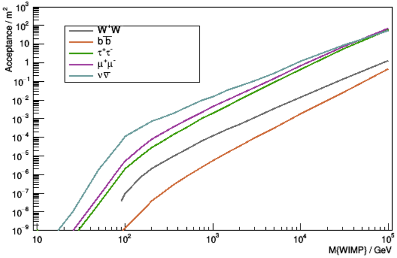


Acceptances

Acceptance is effective area weighted according to source spectrum, for $\nu + \bar{\nu}$

$$\mathcal{A}cc(M) = \int_0^M A_{eff}(E_\nu) \frac{d\bar{N}(E_\nu)}{dE_\nu} dE_\nu$$

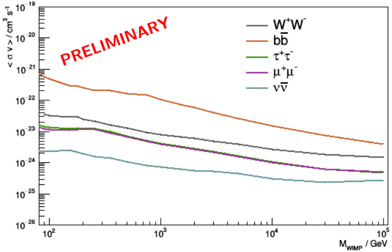
$\Phi_{\nu+\bar{\nu}} = \frac{\mu_{90}}{\mathcal{A}cc\, t}$ is the flux at the detector, t the data taking time



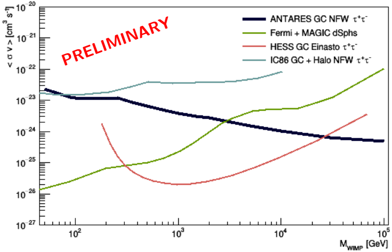
Limits on thermally-averaged annihilation cross-section

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

ANTARES different channels



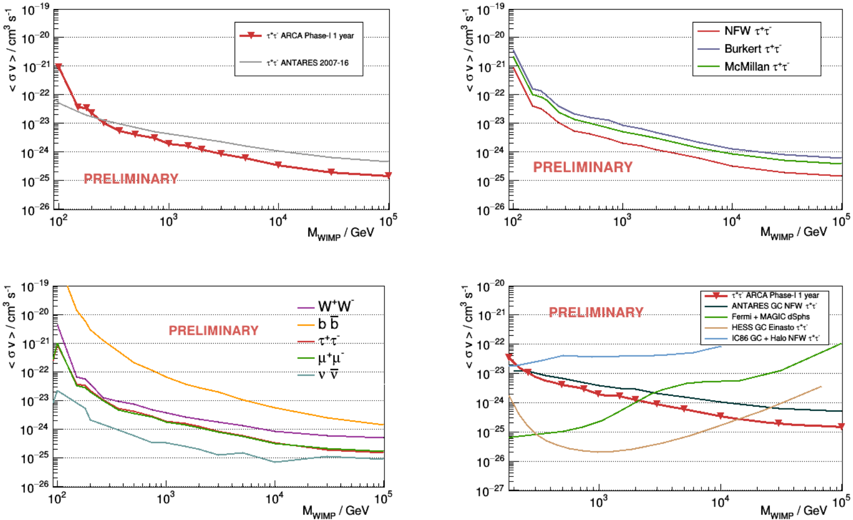
Results from $\tau^+\tau^-$ from different experiments



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

Sensitivity estimated for KM3NeT

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



Summary

- Search for dark matter profits from complementary methods: indirect searches crucial
- Limits on cross-section for WIMP pair annihilation from the Galactic Centre with 10 years ANTARES data. Best limits at high WIMP masses
- Also limits for spin-dependent cross-section for WIMP-nucleon interaction, complementing with those from direct searches (not shown here)
- New scenarios can be tested: for instance secluded dark matter models. Wide range of possibilities in reach for KM3NeT.