Dark Matter searches with KM3NeT

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What do we search for?

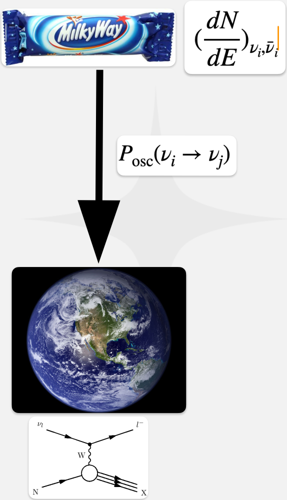
- (In)direct detection experiments attempt to detect interactions of dark matter particles with the Standard Model, along with attempts of production at colliders.
- Searches focus on WIMPs: particles in $GeV/c^2 - TeV/c^2$ mass range with self-interactions at the electroweak scale, thermal relics that produce the observed abundance in the late Universe via the freeze-out scenario.
- Neutrino telescopes search for neutrinos produced by the WIMP pair-annihilation process.

Where do we search for WIMPs?

- The searches focus on astrophysical objects with a large accumulation of dark matter particles.
- These objects include the Galactic Centre and the Sun.
- Galactic Centre: dark matter halos necessary for large scale structure formation, produced from primordial density fluctuations.
- The Sun: capture of local halo WIMPs by scatterings with nuclei of the solar medium.
- Produce many flux expectations, varying the WIMP mass and primary annihilation channel and assuming a 100% branching ratio:

$$M_{WIMP} = [1\,GeV/c^2 - 100\,TeV/c^2]$$
$$WIMP + WIMP \to \mu^+\mu^-, \tau^+\tau^-, b\bar{b}, W^+W^-, \nu\bar{\nu}.$$

Galactic Centre WIMPs



- Galactic Centre halo density inferred from observations of stellar rotation curves and numerical simulations of dark matter halos: NFW profile with $\rho_0 = 0.471 \mathrm{GeV}/cm^3$, $r_{\mathrm{scale}} = 19.1 \mathrm{kpc}$.
- Spectra at production site travel through vacuum to the detector, modulation due to neutrino oscillations, averaged out over the large distance.
- Neutrino flux:

$$\Phi = \frac{1}{4\pi} \frac{<\sigma\upsilon>}{2m^2_{WIMP}} \int_{E_{th}}^{m_{WIMP}} \frac{dN}{dE} dE \int_{d\Omega} \int_{\mathrm{l.o.s}} \rho(\theta, l)^2 dl d\Omega.$$

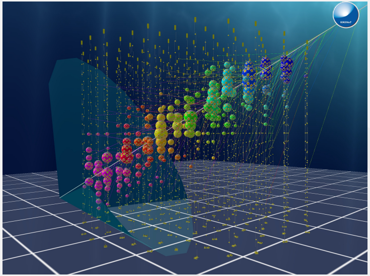
Solar WIMPs

- Capture of WIMPs surrounding the Sun by scatterings with solar nuclei.
- Equilibrium between capture and annihilation processes is reached: $\rightarrow$ neutrino flux rate determined by process governing the capture, the WIMP-nucleon scattering cross section.
- Scattering assumed to be either entirely spin-dependent or independent.
- Neutrinos traverse the solar medium before travelling through vacuum to reach the Earth, resulting flux:

$$\Phi = \frac{C_r}{8\pi d^2} \int_{E_{th}}^{m_{WIMP}} \frac{dN}{dE} dE$$

$$C_r = \mathcal{F}(\upsilon_0, \rho_0, f(H, He, O, C, N, ...)).$$

The KM3NeT detector



- Underwater Cherenkov neutrino telescopes placed in two sites at the bottom of the Mediterranean Sea: Italy and France.
- The Cherenkov light is detected by photomultiplier tubes contained in the Digital Optical Modules (DOMs), which are grouped in vertical Detection Units (DUs).
- KM3NeT/ORCA energy range: [1 – 100 GeV] and KM3NeT/ARCA: $[100\mathrm{GeV} - \mathrm{PeV}]$.
- Current status: KM3NeT/ARCA currently consists of 28 DUs (out of 230), and KM3NeT/ORCA consists of 23 DUs (out of 115).

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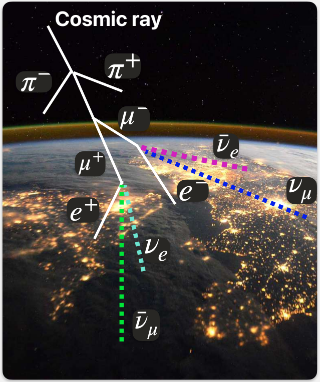
Search method: event selection

2 Method



- Optical background from ^{40}K decays and bioluminescence removed by looking at DOM coincidences.
- Second most dominant source of background: atmospheric muons, produced by cosmic ray interactions in the atmosphere $\rightarrow$ select events traversing the Earth.
- Atmospheric neutrinos remain a source of irreducible background.
- Further requirements on reconstruction quality in order to improve purity of event sample (event likelihood, angular error estimate / BDT selection).

Search method: signal & background probability densities

- Dark matter signal, derived from MC simulation of muon neutrino events:
  - energy expectation: MC event reweighting to the WIMP pair-annihilation flux.
  - angular expectation: angular response of the detector, convolved with source extension (Galactic Centre analysis).
  - 2D function of $\alpha - E_{\mathrm{reco}}$.
- Background expectation:
  - Uniform in right ascension
  - Declination dependence, due to varying visibility at different declinations.
  - Derived from data, by scrambling in right ascension in order to smear out possible signal events.
  - 2D function of $\sin(\delta) - E_{\mathrm{reco}}$.

Search method: statistical analysis

2 Method

- Unbinned likelihood analysis, using the PDFs described in previous slides in order to create mock data and evaluate the signal / background likelihood of events.

- Negative log-likelihood is minimised:

$$\log(\mathcal{L}) = \sum_{i=0}^{N_t} -\log[n^*_{\mathrm{sg}}\mathcal{S}(\alpha_i, E_i) + (N_t - n_{\mathrm{sg}})\mathcal{B}(\alpha_i, E_i)] - N_t.$$

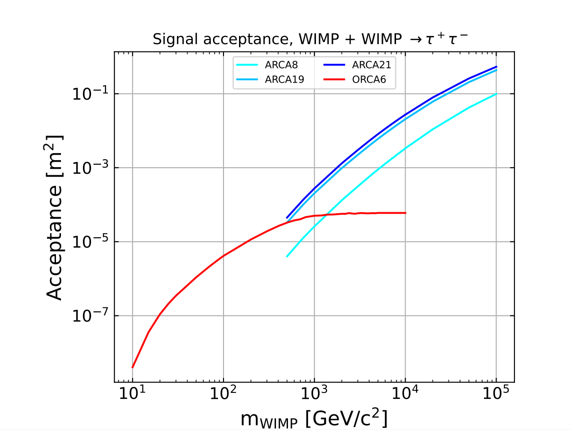
- TS evaluation:

$$\mathrm{TS} = \frac{\mathcal{L}_{\mathrm{min}}}{\mathcal{L}_{\mathrm{bg}}}.$$

- Limit evaluation: large number of mock samples varying the number of signal events, number of events limit at 90% C.L. is obtained from the TS distribution for which the integral at the data TS is equal to 10% .

Search method: flux limit computation

2 Method



- Limit on flux from the number of events limit:

$$\Phi = \frac{n_{90}}{T \int_{E_{\rm th}}^{M_{\rm WIMP}} A_{\rm eff}(E_\nu) \frac{dN}{dE} dE_\nu}.$$

- Effective area: computed from simulations from the ratio of detected and generated number of events in particular energy bin.

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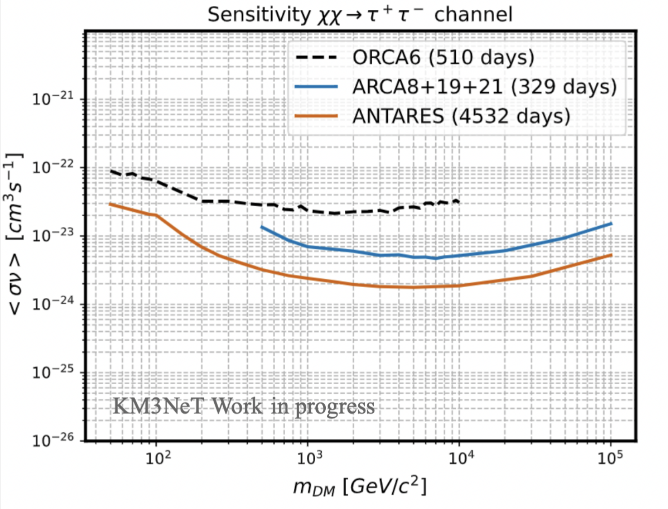
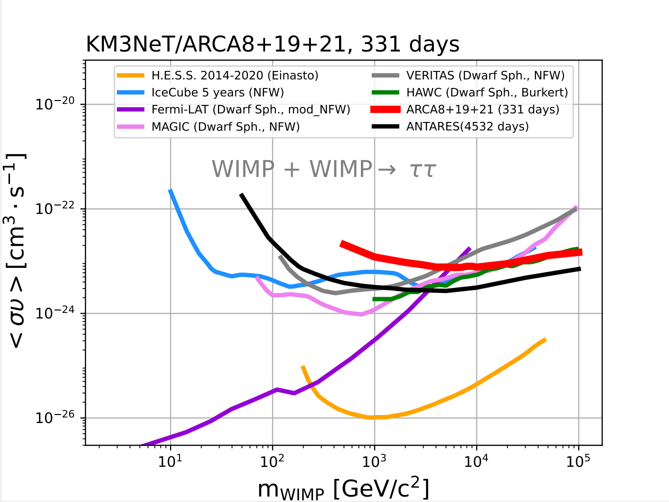
Results: Galactic Centre searches

3 Results



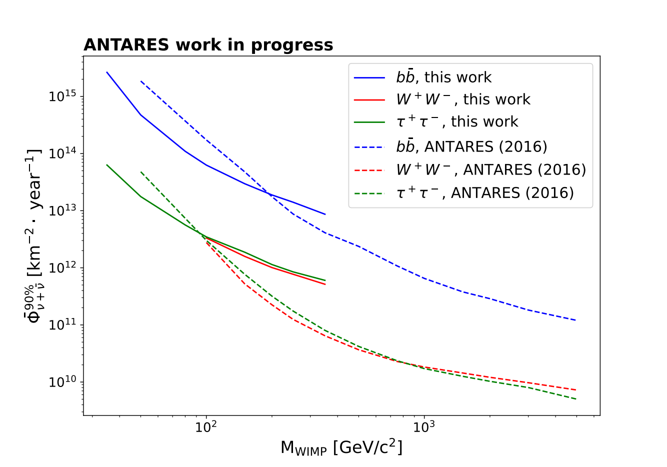
Annihilation cross section upper limits as a function of WIMP mass, for ARCA8+19+21, ORCA6, and the predecessor, ANTARES [1], $\mathrm{WIMP} + \mathrm{WIMP} \to \tau^+\tau^-$

Results: Galactic Centre searches



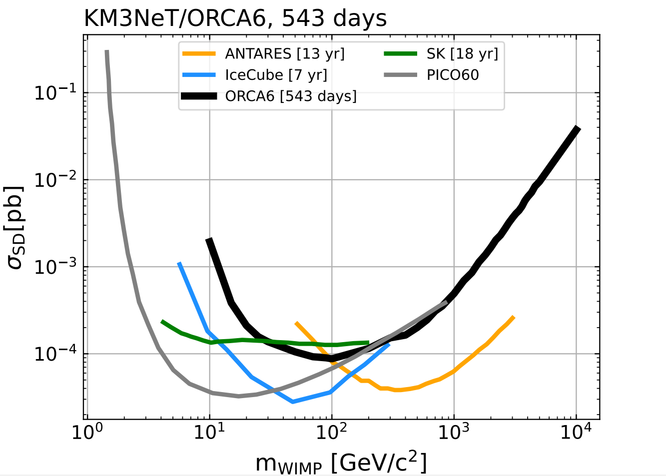
Annihilation cross section upper limits from ARCA8+19+21 and ANTARES compared to other experiments in the field: see refs. [2, 3, 4, 5, 6, 7].

Results: searches in the Sun with ANTARES



Flux sensitivities for DM in the Sun obtained with the full ANTARES dataset, extending the mass range to lower masses with NN single-line reconstruction, compared to previous results [9].

Results: searches in the Sun with KM3NeT



Spin-dependent cross section upper limit for DM in the Sun obtained with the KM3NeT/ORCA6 dataset, compared to other experiments in the field, see refs. [8, 9, 10, 11].

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Conclusions

- First results on dark matter searches with KM3NeT in the Sun and Galactic Centre.
- Utilise both KM3NeT/ARCA and ORCA to search in a very wide range of the mass parameter space.
- Ongoing efforts to improve the sensitivity at lower masses with novel reconstruction methods for single-line events.
- Sensitivities are expected to improve further with accumulated livetime and growing size of detectors.

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Thank you for listening !

Any Questions ?