Dark matter searches in the Galactic Centre with KM3NeT/ARCA6+8+19+21

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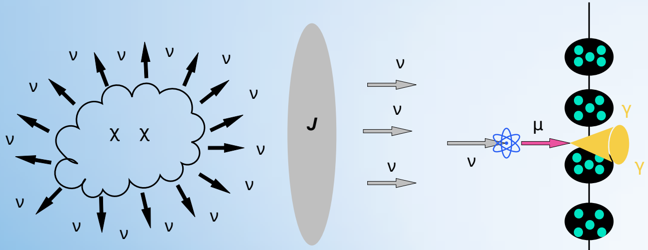
Detection of dark matter with KM3NeT

- Aim: detection of neutrinos produced by WIMP pair-annihilation processes $\rightarrow$ particle physics and astrophysics inputs are required to determine the neutrino flux

astrophysics (J_{int}) — particle physics ($\frac{dN}{dE}$) — NFW (ρ^2)

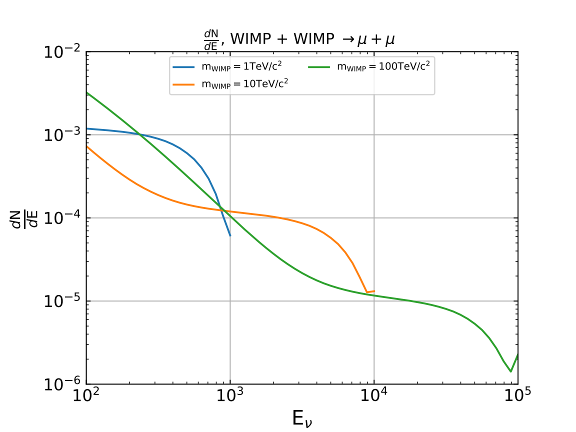
$$\frac{d\Phi}{dE} = J_{\text{int}} \, \frac{1}{4\pi} \, \frac{<\sigma v>}{2m^2_{\text{WIMP}}} \, \frac{dN}{dE} \qquad J_{\text{int}} = \int_{\Delta\Omega} \int_{\text{l.o.s.}} \rho^2 (\theta, l) dl \, d\Omega$$



Particle physics input: $\frac{dN}{dE}$

A model-independent analysis $\rightarrow$ scan of the parameter space

$$\mathrm{WIMP} + \mathrm{WIMP} \rightarrow \mu^-\mu^+, \tau^-\tau^+, b\bar{b}, W^-W^+, \nu\bar{\nu} \rightarrow \nu\bar{\nu}.$$



Detection of dark matter with KM3NeT

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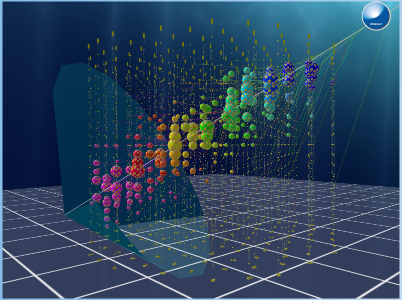
$$\frac{d\Phi}{dE} = \underbrace{J_{\text{int}}}_{\text{astrophysics}} \frac{1}{4\pi} \frac{<\sigma v>}{2m_{\text{WIMP}}^2} \underbrace{\frac{dN}{dE}}_{\text{particle physics}} \qquad J_{\text{int}} = \int_{\Delta\Omega} \int_{\text{l.o.s.}} \underbrace{\rho^2}_{\text{NFW}} (\theta, l) dl\, d\Omega$$

⇒ The aim of this work is to place an upper limit on the thermally-averaged pair-annihilation cross section, $<\sigma v>$.

The KM3NeT detector

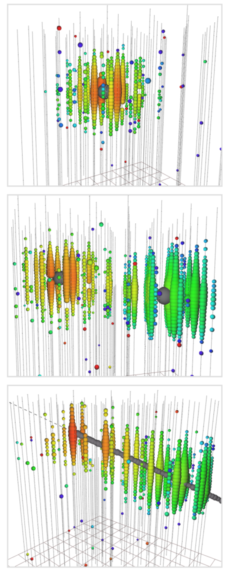


- Underwater Cherenkov neutrino telescopes placed in two sites at the bottom of the Mediterranean Sea: Italy and France.
- The two detectors are each optimised to detect events at different energies: KM3NeT/ORCA $[1 - 100 \text{ GeV}]$ and KM3NeT/ARCA $[> 100 \text{ GeV}]$.
- The Cherenkov light is detected by photomultiplier tubes contained in the Digital Optical Modules (DOMs), which are grouped in vertical Detection Units (DUs).

Current status: KM3NeT/ARCA currently consists of 28 DUs, and KM3NeT/ORCA consists of 18 DUs.

Events in KM3NeT

- The lepton produced by the scattering of the neutrino in or close to the detector stimulates the emission of Cherenkov light, resulting in a track-like or shower-like signature: in this work we focus on track-like events
- This analysis is conducted on the data sets of the KM3NeT/ARCA detector when it was composed of **6**, **8**, **19** and **21** DUs



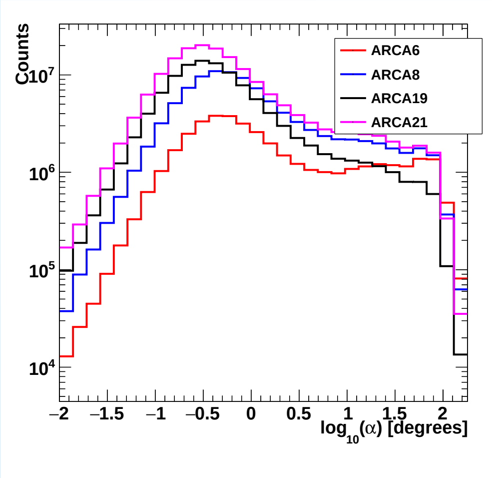
Data sets

Datasets and their associated livetime

- ARCA6: 91.7 days of livetime between May 2021 - September 2021
- ARCA8: 210.1 days of livetime September 2021 - June 2022
- ARCA19: 50.1 days of livetime between June 2022 - September 2022
- ARCA21 68.3 days of livetime between September 2022 - December 2022

Total: **420.6** days of accumulated livetime

Angular response to signal events: bigger is better!



detector	$m_{DM} = 1$ TeV/c^2	10	100
ARCA6	2.13°	1.90°	0.91°
ARCA8	1.52°	0.87°	0.69°
ARCA19	1.33°	0.60°	0.39°
ARCA21	1.38°	0.66°	0.41°

Table: $\bar{\alpha}$, the median of the angular response distribution to signal events at different WIMP masses, at selection level

Data sets: selection

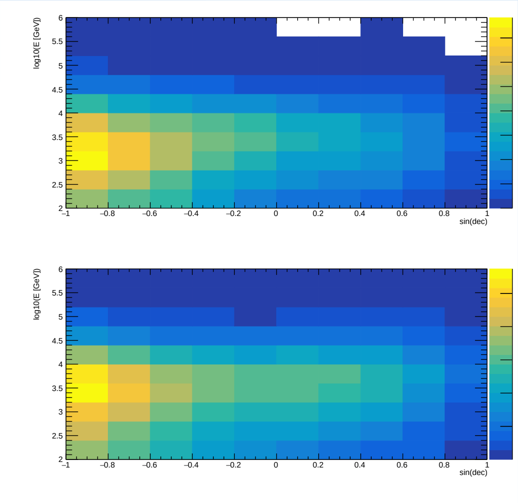
Two different selection methods:

- Initial selection same for both methods, application of conditions on the track likelihood, number of hits in the detector in order to remove noise, and requiring the events to come from below the horizon in order to remove the atmospheric muon background
- ARCA6/8: usage of cuts on reconstruction variables: optimisation performed on the track length and event reconstruction angular error estimate
- ARCA19/21: optimisation on the BDT track score: trained to select well-reconstructed, upgoing tracks

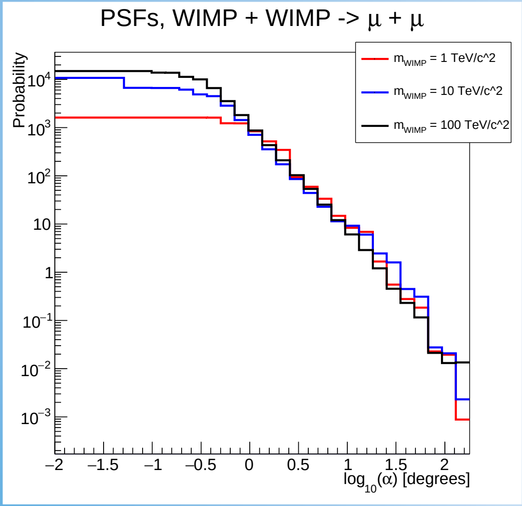
Analysis method

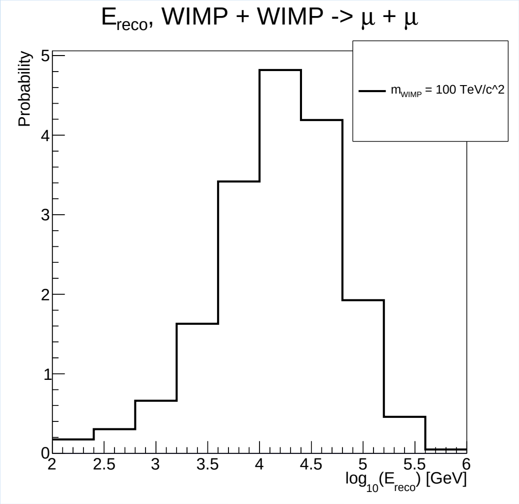
Unbinned likelihood framework used, characterising the signal and background events with two-dimensional probability density functions (PDFs) in angular distance to source centre (declination), and reconstructed energy.

Shown on the right: background PDF obtained from data (top) and MC (bottom)



$m_{WIMP} = 100 TeV/c^2$ signal PDFs, 1D projections





Analysis method

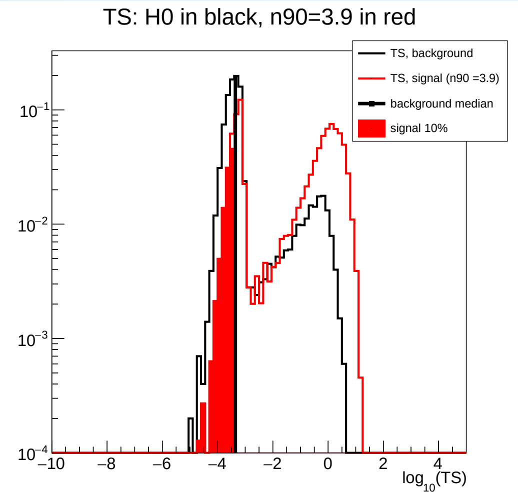
- Perform pseudo-experiments, creating mock data a large number of times (10^4), for a varying number of signal events injected (0-50), repeated for every WIMP mass and annihilation channel combination, by sampling from the PDFs.
- The likelihood function is maximised for each mock data set:

$$\mathcal{L} = \Sigma_{N_{\rm tot}} \log(n_{\rm sg} P_{\rm sg}(\alpha, E) + (N_{\rm tot} - n_{\rm sg}) P_{\rm bg}(\alpha, E)) - N_{\rm tot}.$$

- For each mock data set, the test statistic (TS) is evaluated: $\mathrm{TS} = \frac{\mathcal{L}(n_{\rm sg,max})}{\mathcal{L}(n_{\rm sg}=0)}$.

Analysis method

The average upper limit on the number of signal events at 90% CL, n_{90}, is computed from the $\log_{10}(\mathrm{TS})$ distributions: comparisons of TS distributions with injected signal events to the median of the background-only TS distribution.



Analysis method

- The integrated flux upper limit is then computed from the detector acceptance to signal events, Acc, the data taking livetime, T, and the number of signal events sensitivity, n_{90}:

$$\Phi = \frac{\mathrm{n}_{90}}{Acc \times T}.$$

- The cross section limit is then obtained for each mass / annihilation channel from Equation (1):

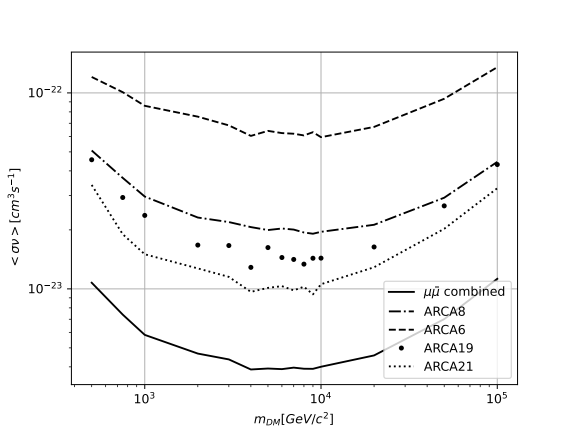
$$\Phi = J_{\mathrm{int}} \frac{1}{4\pi} \frac{< \sigma v >}{2m^2_{\mathrm{WIMP}}} \int_{E_{\mathrm{th}}}^{m_{\mathrm{WIMP}}} \frac{dN}{dE} dE$$

Sensitivities: Galactic Centre, , WIMP + WIMP $\rightarrow \mu + \mu$

$$\Phi_{90\%} = \frac{\Sigma_{\text{det}} f_{\text{det}} \times n_{90\%,\text{det}}}{t_{tot} \times \Sigma_{\text{det}}(f_{\text{det}} \times Acc_{\text{det}})}$$

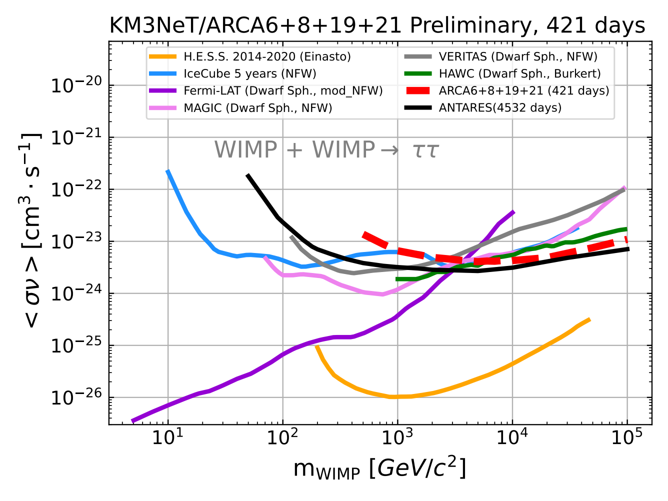
$\text{det} \in \{$ARCA6, ARCA8, ARCA19, ARCA21$\}$

$$f_{\text{det}} = \frac{t_{\text{det}}}{t_{\text{tot}}}$$



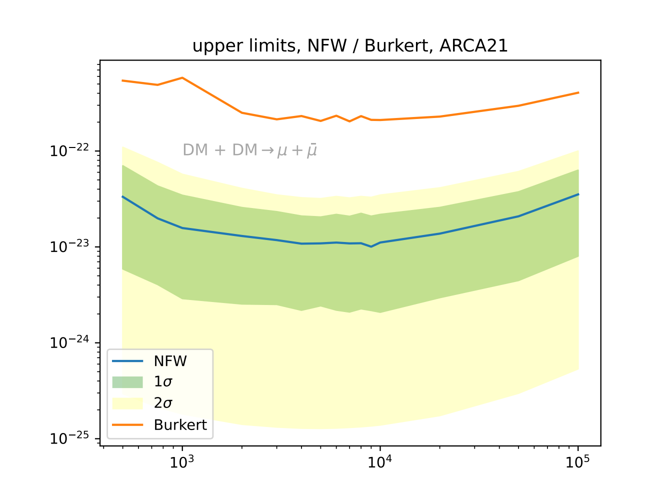
Sensitivity of each configuration & combined.

Sensitivities: Galactic Centre



Comparisons to other experiments.

Caveat: choice of density profile matters!



Limits with NFW (cuspy) / Burkert (cored) profile: factor 10 difference!

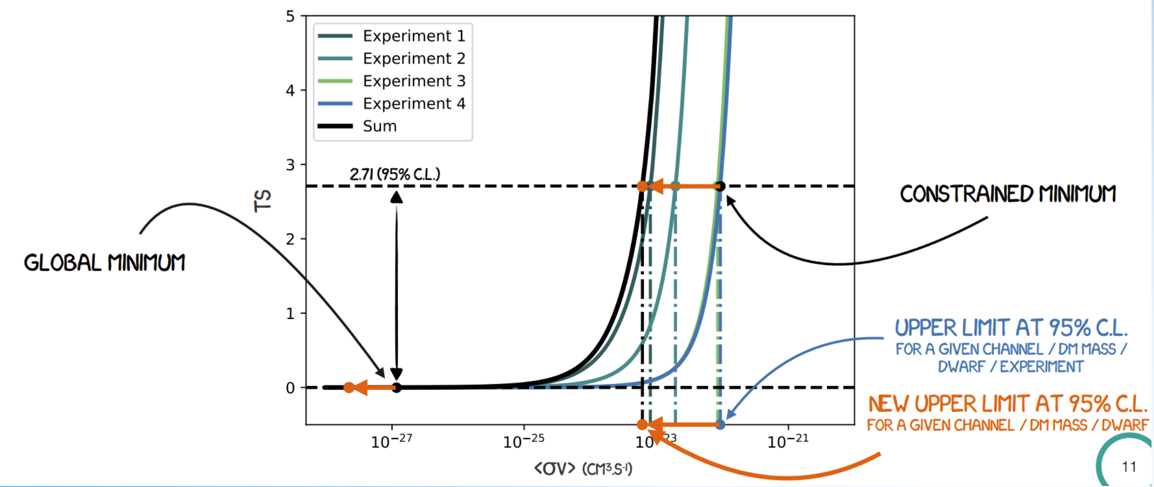
Combined analysis with γ-ray telescopes

- Approach of combining likelihoods that does not require the sharing of event-by-event data.
- In this approach limits are obtained by computing the TS at fixed values of N_{sg} ($< \sigma\nu >$)

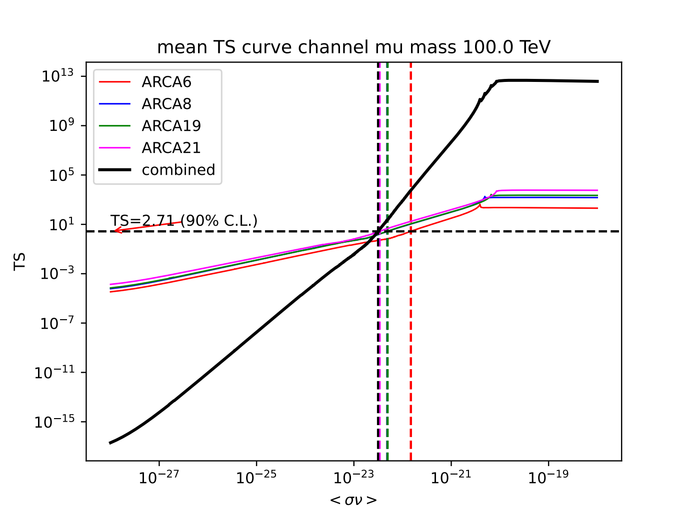
$$\mathcal{L} = \Pi_i \Pi_j \mathcal{L}_{i,j} \times J_i$$

where i denotes the different observation targets (Galactic Centre, dSph), and j the different experiments: MAGIC, Fermi LAT, Veritas, HAWC, H.E.S.S

Combined analysis with γ-ray telescopes: result combination



Combined analysis with γ-ray telescopes: result combination



Thank you!

Hvala!