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# Dark Matter Searches with KM3NeT

Adrian Šaina, on behalf of KM3NeT

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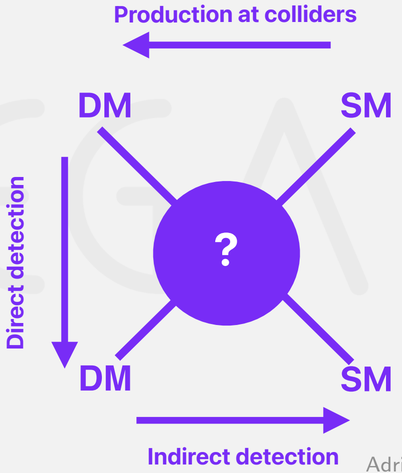
# Searching for WIMPs



- Production from SM particle collisions at colliders: missing momentum, resonance searches, displaced vertices → no significant detection
- Direct detection- scattering of DM with the detector medium, recoil energy detected as scintillation, ionisation, phonons: liquid Xe, Ar TPCs, crystals (Ge, Na/I) → no conclusive evidence
- Indirect detection experiments: detect the SM products of self-interactions of dark matter particles



# WIMP searches with neutrino telescopes

## 1 Introduction

- Detection of neutrinos produced in dark matter annihilations
- Focus on astrophysical objects with a large accumulation of dark matter particles
- Galactic Centre: annihilation in DM halo
- Model-agnostic approach: produce many flux expectations, varying the WIMP mass and primary annihilation channel (100% B.R.):

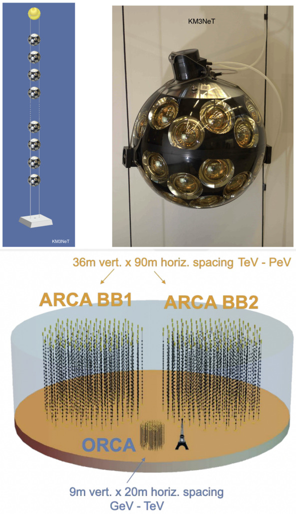
$$M_{WIMP} = [50\,GeV/c^2 - 100\,TeV/c^2]$$
$$WIMP + WIMP \rightarrow \mu^+\mu^-, \tau^+\tau^-, b\bar{b}, W^+W^-, \nu\bar{\nu}.$$

- Neutrino flux:

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

# The KM3NeT detector

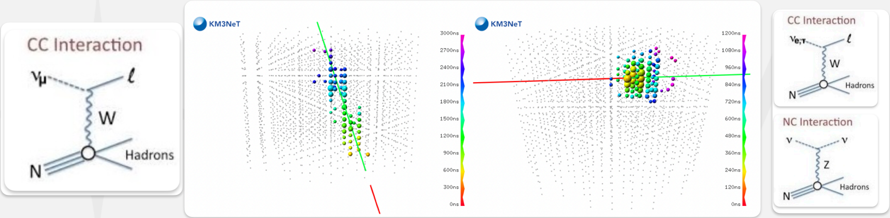





- Underwater Čerenkov neutrino detectors in construction at two sites at the bottom of the Mediterranean: Italy and France.
- Čerenkov light is detected by PMTs contained in the Digital Optical Modules (DOMs), which are grouped in vertical Detection Units (DUs).
- KM3NeT/ORCA energy range: $[1 - 100 \text{ GeV}]$ and KM3NeT/ARCA: $[100\text{GeV} - \text{PeV}]$.
- KM3NeT/ARCA currently consists of 51 DUs (out of 230), and KM3NeT/ORCA consists of 33 DUs (out of 115).

# Event topologies in neutrino telescopes






E $>$ few GeV $\rightarrow$ DIS dominant interaction

# Doing science with KM3NeT

## 1 Introduction

Sources of neutrinos at energies detected by KM3NeT:

- Atmospheric neutrinos: produced in interactions of cosmic rays with the atmosphere $\rightarrow$ studies of neutrino oscillation patterns allows for measurements of $\theta_{23}, \Delta m^2_{31}$ and NMO determination with ORCA
- Astrophysical neutrinos: produced by some of the same sources producing cosmic rays and $\gamma$-rays: SNRs, PWNs (Galactic), blazars, $\gamma$-ray bursts, Seyfert galaxies $\rightarrow$ ARCA
- Cosmogenic neutrinos: produced by cosmic ray scatterings with CMB
- Neutrinos from dark matter annihilations: from the Sun, Galactic Centre $\rightarrow$ ARCA and ORCA

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# Search method: outline

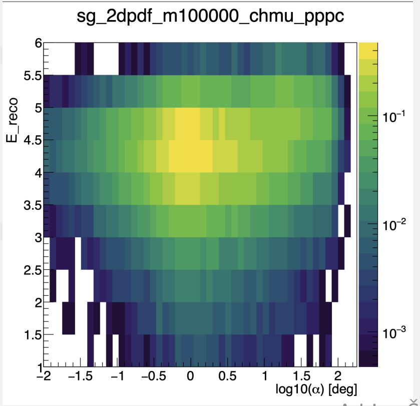
1. Obtain a data and MC event sample of well-reconstructed tracks using some optimised event selection
2. Create expectations of our signal and background in spatial/energy space
3. Create many mock data sets from signal and background models, $n_s = \{0, 1, 2, .., 49, 50\}$
4. Compute likelihood and test statistic of each sample
5. Obtain limit on number of signal events we can reject with 90% confidence $\rightarrow$ limit on neutrino flux $\rightarrow$ annihilation cross section limit

$$n_s \propto \Phi \qquad \Phi \propto \langle \sigma \nu \rangle$$

# Search method: signal & background probability densities



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



# Search method: statistical analysis



- 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:

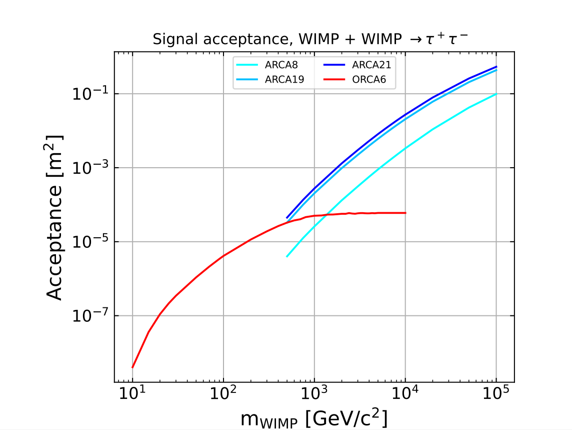
$$\log(\mathcal{L}) = \sum_{i=0}^{N_t} -\log[n_{\mathrm{sg}}^{*}\mathcal{S}(\alpha_i, E_i) + (N_t - n_{\mathrm{sg}})\mathcal{B}(\alpha_i, E_i)] - N_t.$$

- TS evaluation:

$$\log_{10}(\mathrm{TS}) = \log_{10}\left(\frac{\mathcal{L}_{\mathrm{min}}}{\mathcal{L}_{\mathrm{bg}}}\right).$$

# Search method: flux limit computation






- Limit on flux from the number of events limit:

$$\Phi_{90} = \frac{n_{90}}{T \int_{E_{\mathrm{th}}}^{m_{\mathrm{WIMP}}} A_{\mathrm{eff}}(E_\nu) \frac{dN}{dE} dE_\nu}.$$

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

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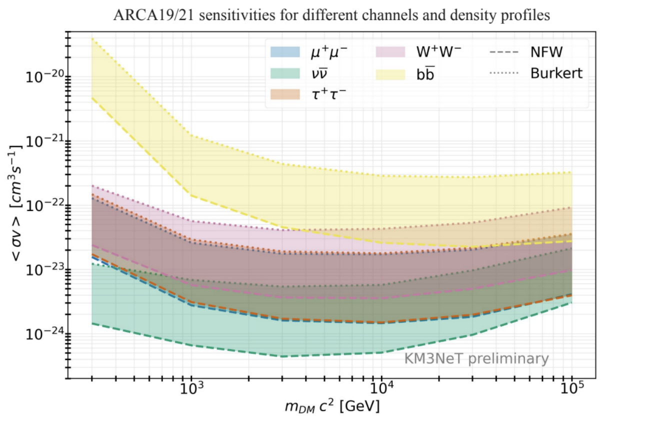
# Results: Galactic Centre searches with ARCA

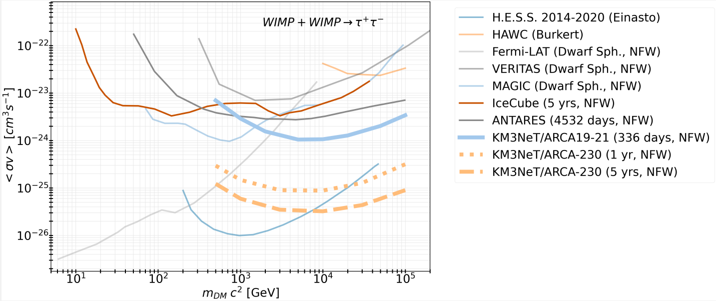





Annihilation cross section sensitivities as a function of WIMP mass, for ARCA19+21; bands defined by sensitivities computed with different density profiles

# Results: Galactic Centre searches with ARCA

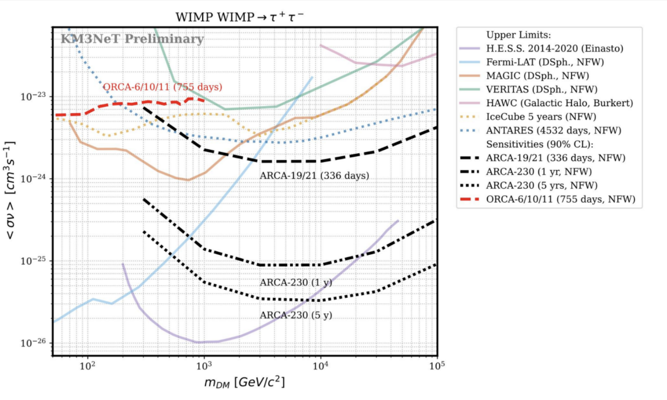





Annihilation cross section sensitivities as a function of WIMP mass, for ARCA19+21 and full ARCA projections

# Results: Galactic Centre searches with ORCA

*3 Results*




Annihilation cross section sensitivities as a function of WIMP mass, for ARCA19+21, full ARCA, and for ORCA6+10+11

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# Conclusions and outlook



- First results on dark matter searches with KM3NeT in the Galactic Centre
- Constraints are valid for a range of models where annihilation to investigated channels is allowed, and there is no late time suppression of annihilations
- Competitive limits on pair-annihilation in the $\sim TeV$ mass range, promising full detector sensitivities
- Constraints expected to surpass ANTARES soon: improved detection technology, event selection methodology and improved efficiency across the parameter space using a combination of two detectors

# References I




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# Dark Matter Searches with KM3NeT

Thank you for listening !

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# Backup



Adrian Šaina, on
behalf of KM3NeT

# Event generation

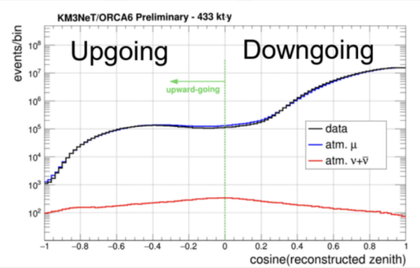


**Non-particle background**:

- $^{40}K$ decays: simulated by adding random hits at 8kHz
- Dark currents / electrical discharges, bioluminescence

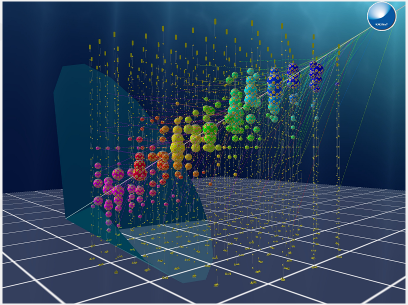
**Particle background**:

- Atmospheric muons:
  - Simulated with parametric flux formulas on can surface
  - Simulated for a portion of the livetime
- Atmospheric neutrinos:
  - Generate outgoing scattering products on same surface
  - $w_{\rm gen}$ computed from the generation spectrum, $P_{\rm int}$, $P_{\rm abs}$: reweighted



# Light propagation, triggering and reconstruction

- **Light propagation**:
  - GEANT4 propagation of particles through detectors ($E < 100$ GeV)
  - Pre-computed light yield tables (high energies)
  - Account for absorption/scattering
  - Light reaching a PMT → hit response
- **Triggering**: minimum light yield on a PMT, multiple coincidences, triggers based on track/shower emission profiles
- **Reconstruction**: maximum likelihood fit based on emission profiles of tracks / showers to determine event direction, vertex and energy

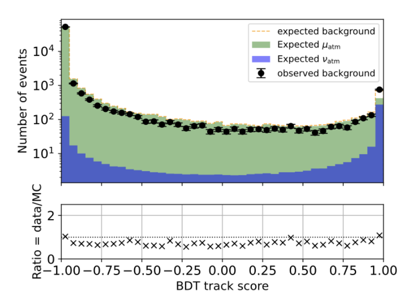


# Calibrating the real data



- **Time calibration**:
  - Intra-DOM: use $^{40}$K decays to calibrate PMTs on same DOM
  - Inter-DOM: optical beacons used for the calibration between DOMs on same DU
  - Inter-DU: usage of a White Rabbit clock broadcast system, measure the RTT
- **Position calibration**:
  - Piezo-electric acoustic sensors detect signals from acoustic beacons on the seabed
  - Measure time of arrival → estimate time of emission → distance estimate
  - Fit of detector geometry: minimise the differences between measured and expected times
- **Orientation calibration**:
  - Relative orientation of DOMs with accelerometers and magnetometers
  - Fit procedure to determine DU twist
- **Validation of the calibration**:
  - Reconstruction of atmospheric muon tracks → likelihood maximisation varying the calibration parameters

# Search method: run and event selection




- Removal of runs with processing issues, unfavourable environmental conditions, etc.
- Background from $^{40}$K decays and bioluminescence removed by looking at DOM coincidences.
- Second most dominant background are atmospheric muons $\rightarrow$ select events traversing the Earth.
- Atmospheric neutrinos: irreducible background.
- Further requirements on reconstruction quality in order to improve purity of event sample (event likelihood, angular error estimate / BDT selection).

# Search method: statistical analysis



- Limit evaluation: 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%.
- A 30% uncertainty on the detected signal is added by smearing the number of injected signal events, or by smearing the TS distributions