

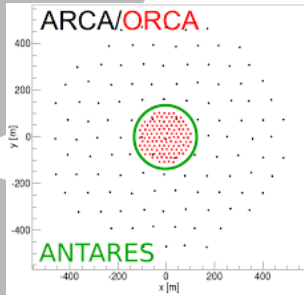
# The usual suspect: has a heavy dark matter particle decayed to KM3-230213A?

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XIX International Conference on Interconnections between Particle Physics and Cosmology  
The University of New South Wales, Sydney, Australia

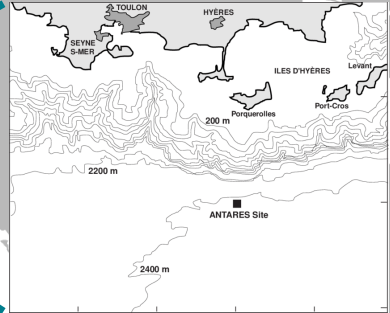
September 3rd, 2026





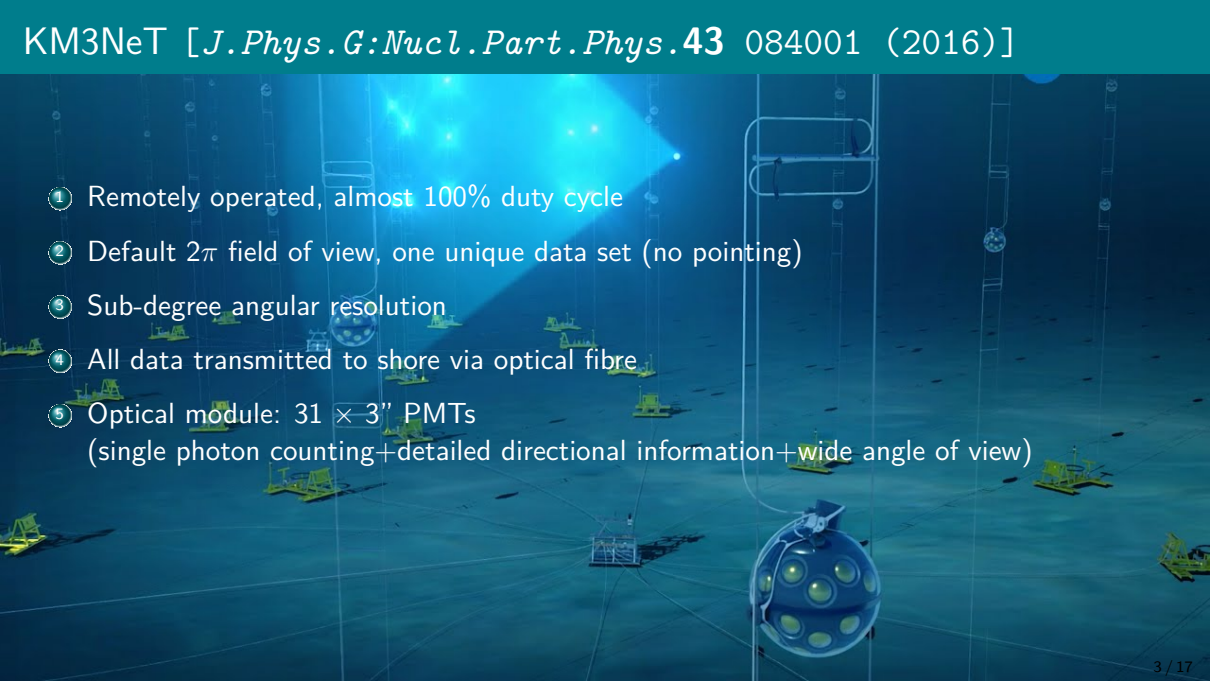
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KM3NeT / ORCA

KM3NeT / ARCA

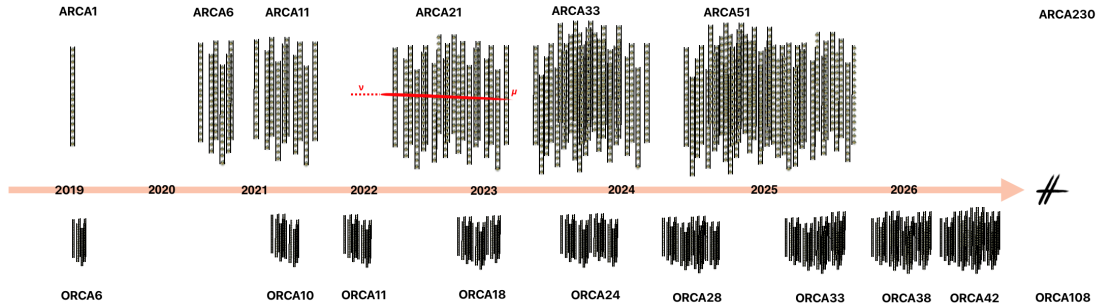


ORCA (spacing  $23 \times 9$  m): very high statistics of atmospheric  $\nu$

ARCA (spacing  $90 \times 36$  m): very rare fluxes of extraterrestrial  $\nu$

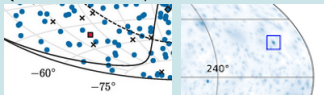
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- The background image shows the KM3NeT detector, a large-scale neutrino observatory. It features a deep-sea environment with several yellow support vessels and a central blue structure. A large, glowing blue beam of light emanates from the top center, illuminating the scene. In the bottom right corner, there is a detailed view of a spherical optical module with multiple yellow PMTs (Photomultiplier Tubes) arranged in a circular pattern.
- ① Remotely operated, almost 100% duty cycle
  - ② Default  $2\pi$  field of view, one unique data set (no pointing)
  - ③ Sub-degree angular resolution
  - ④ All data transmitted to shore via optical fibre
  - ⑤ Optical module:  $31 \times 3''$  PMTs  
(single photon counting+detailed directional information+wide angle of view)

# KM3NeT: construction timeline

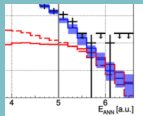


# KM3NeT physics case

## Astrophysical $\nu$ sources (correlation/autocorrelation)



## Diffuse excess (high energy spectral component)

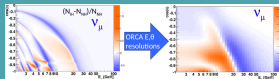


## Low-energy $\nu$ preceding core-collapse SNs

## Multimessenger prompt alert network



## Flavour oscillations Atmospheric oscillation parameters, mass ordering



## Novel signatures

(Sterile  $\nu$ , heavy neutral leptons,  $\nu$  decay, quantum decoherence, NSI)

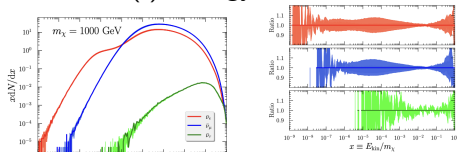
## Dark matter searches – see following

# Indirect searches for dark matter

Particularly symptomatic candidates (WIMP relic density in a freeze-out scenario) give rise to sizeable fluxes of high-energy  $\nu$ .

Unavoidably affected by **large uncertainties**. Indirect searches alone cannot provide conclusive evidence of detection.

(I) Energy feature



$$x = E_{kin}/m_\chi$$

Affected by both detector energy resolution (5% – 20%) and by theoretical uncertainties (10% – 30%) mostly on hadronization model [\[JCAP03\(2024\)035\]](#)

(II) Ambient



Dominated by astrophysical input for modelling haloes, much larger than typical PSF

# Indirect searches for dark matter: targets

Milky Way centre (maximum J-factor: large overdensity and close-by), dense celestial bodies (work as accumulators of dark matter from Galactic haloes, not affected by halo uncertainties).

## Galactic Centre

$$n = \frac{1}{2} \langle \sigma v \rangle \int_0^{M_{\text{DM}}} \frac{dN}{dE} dE \frac{1}{4\pi} \int_{d\Omega} \int \rho^2(r(\theta, \phi)) \frac{1}{M_{\text{DM}}^2} \mathcal{A}(M_{\text{DM}}) t$$

## Massive celestial body at equilibrium

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma_{\text{ann}}}{4\pi d^2} \frac{dN_\nu}{dE_\nu}$$

At equilibrium if age is large with respect to the typical time-scale for the competing process “capture/annihilation”  $\Rightarrow$  flux depends solely on capture rate C:  $\Gamma_{\text{ann}} = C/2$

# Dark matter scenarios

## WIMPs

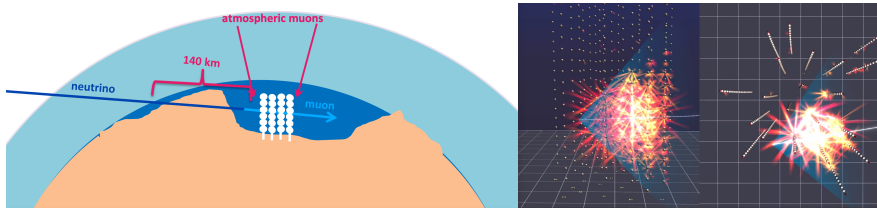
- ① WIMP annihilation Galactic Centre
- ② WIMP-nucleon scattering in the Sun

## Beyond WIMPs

- ① Light boosted dark matter (population of relativistic dark matter aside usual WIMPs)
- ② Dark matter upscattered by cosmic rays
- ③ Non-particle candidates: primordial black holes
- ④ Heavy dark matter in secluded scenarios
- ⑤ '*Agnostic-scenario*' heavy dark matter – see following

# Context: observation of an ultra-high-energy cosmic $\nu$ with KM3NeT

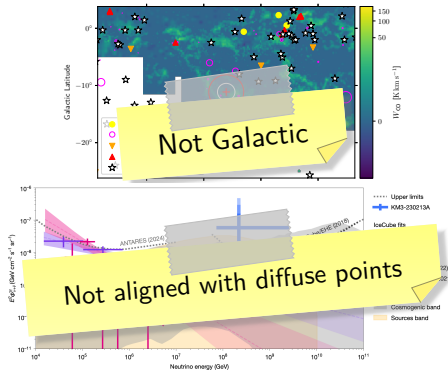
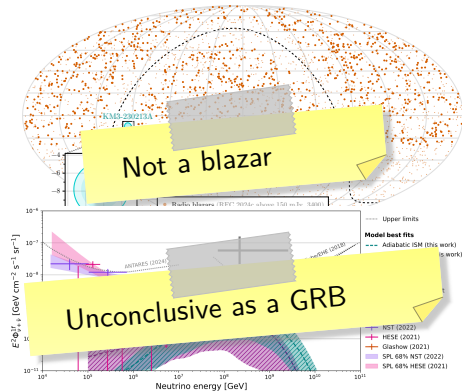
- Horizontally traversing the detector from the continental shelf: not an atmospheric muon
- Very bright: 35% of the detector (3672 photomultipliers) triggered



Actual water equivalent distance even larger due to continental shelf  $\rightarrow$  not an atmospheric  $\mu$ .  
Muon energy:  $120_{-60}^{+110}$  PeV, neutrino energy:  $220_{-100}^{+570}$  PeV assuming a  $E^{-2}$  spectrum.

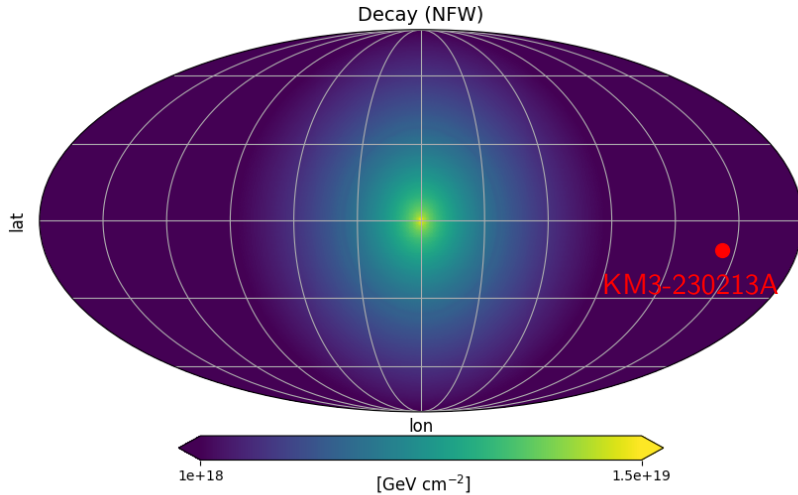
A very high energy astrophysical neutrino [[Nature 638, 376–382 \(2025\)](#)]

# KM3-230213A: origin?



...or any other traceless transient that conveniently disappears?

# Decay of heavy dark matter



# Decay of heavy dark matter

KM3-230213A could owe its energy to a large progenitor mass, rather than an astrophysical acceleration mechanism.

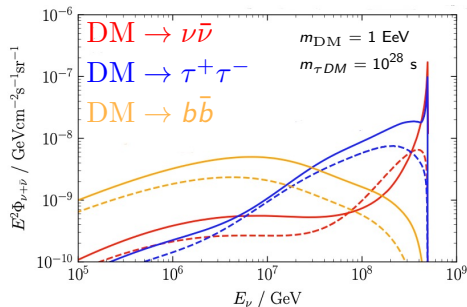
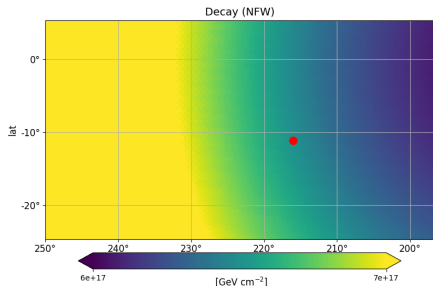
- Energy distributions of decaying dark matter are computed with HDM Spectra [\[JHEP06\(2021\)121\]](#). Relevant role of electroweak interactions at such large energies.
- Halo profiles: NFW and Burkert. Caveat: KM3-230213A is almost perfectly opposed to the Milky Way Centre... unlikely, not impossible.

Discriminating features: angle from Galactic Centre and energy proxy.

Data: KM3NeT/ARCA21 286 days. Cuts: same as Nature publ. + 30 km overburden.

Ref: *Testing Heavy Dark Matter Decay as the Origin of KM3-230213A* [\[arXiv:2606.09986\]](#)

# Decay of heavy dark matter

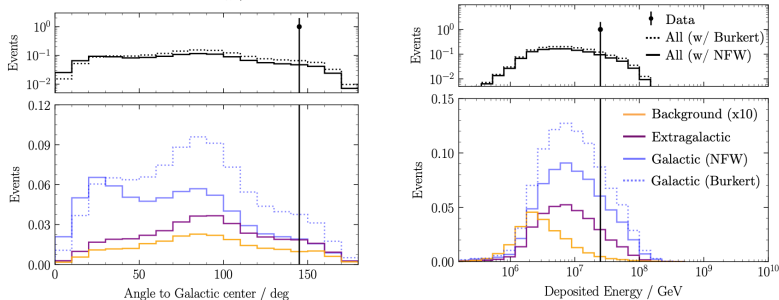


$$\frac{d\Phi^{\text{Gal}}}{dE_\nu d\Omega} = \frac{1}{4\pi m_{\text{DM}} \tau_{\text{DM}}} \frac{dN_\alpha}{dE_\nu} \int_0^\infty ds \rho_{\text{DM}}(r)$$

$$\frac{d\Phi^{\text{egal}}}{dE_\nu d\Omega} = \frac{\Omega_{\text{DM}} \rho_{\text{crit}}}{4\pi m_{\text{DM}} \tau_{\text{DM}}} \int_0^\infty \frac{dz}{H(z)} \frac{dN_\alpha}{dE_\nu} \bigg|_{E'_\nu = E_\nu(1+z)}$$

Probing super-heavy dark matter with ultra-high-energy gamma rays [\[arXiv:2601.11703\]](#)  
 Dark Matter Spectra from the Electroweak to the Planck Scale (HDM) [\[J.HEP. 2021, 121\]](#)

# Decay of heavy dark matter



Signal (I): Galactic dark matter (— NFW - - Burkert)

Signal (II): Extragalactic dark matter

Background: atmospheric<sup>1</sup> + cosmic  $\nu$ , here amplified 10x. Shown here: IceCube Northern Sky Tracks (NST) [ApJ. 928, 50 (2022)]. Also considered: high-energy starting events (HESE) [Phys. Rev. D 104 (2021)], and no cosmic component at all (i.e. spectral cut-off)

<sup>1</sup>conventional + prompt [Phys.Rev.D 78 (2008)]

# Test method

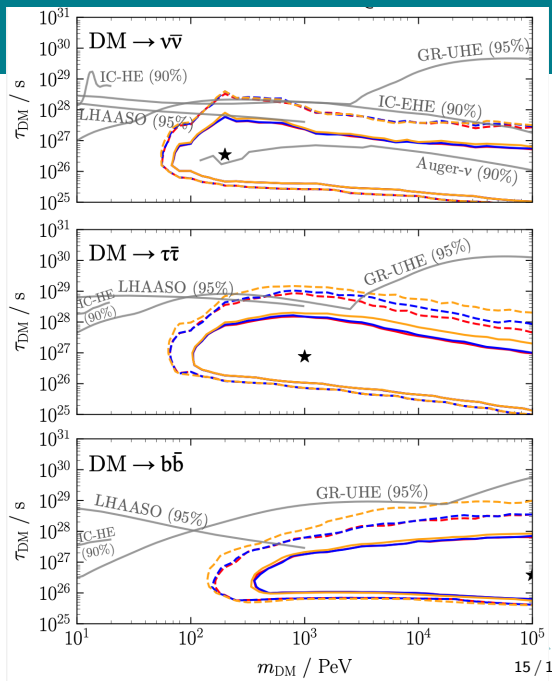
Frequentist analysis: binned likelihood +  
Feldman-Cousins intervals —95% - - 99%.

atmospheric + NST ( $24 \cdot 10^{-3}$  events)

atmospheric + HESE ( $4 \cdot 10^{-3}$  events)

atmospheric ( $0.3 \cdot 10^{-3}$  events)

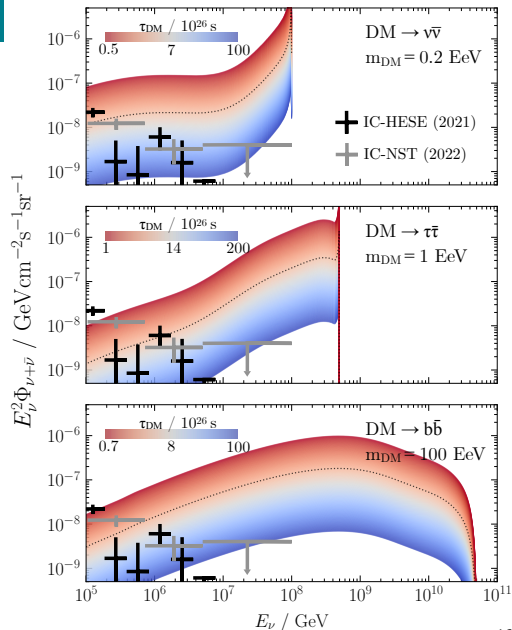
| Decay channel                        | Best fit                   |                             |
|--------------------------------------|----------------------------|-----------------------------|
|                                      | $m_{\text{DM}}/\text{EeV}$ | $\tau_{\text{DM}}/\text{s}$ |
| $\text{DM} \rightarrow \nu\bar{\nu}$ | 0.2                        | $4 \cdot 10^{26}$           |
| $\text{DM} \rightarrow \tau^+\tau^-$ | 1                          | $7 \cdot 10^{26}$           |
| $\text{DM} \rightarrow b\bar{b}$     | 100                        | $4 \cdot 10^{26}$           |



# Results

Test of scenario where heavy dark matter decays yielding KM3-230213A, applying a weight to simulated data for the correct energy distribution.

- 1 Dark matter heavier than 100 PeV is a candidate for the origin of KM3-230213A
- 2 Limited parameter space left, when considering  $\gamma$ -ray constraints
- 3 Given the coordinates of KM3-230213A, Galactic and extragalactic contributions are too similar to disentangle



# Wrap-up

Particle candidates for dark matter can be tested indirectly through the final states of their interactions

- ① upper limits on **WIMP annihilation rate** in the Galactic Centre
- ② upper limits on **WIMP-nucleon scattering** cross section

More scenarios beyond WIMPs are an opportunity for neutrino telescopes!

- ① parameter space regions not yet fully explored (i.e. very heavy dark matter)
- ② non-particle dark matter such as primordial black holes
- ③ test of **dark matter decay at the origin of very-high energy neutrino KM3-230213A**, still orphan of a conclusive source