Dark matter and new physics searches in first KM3NeT data

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Intro: physics beyond the Standard Model expectations

Standard Model = gauge (local symmetry) $SU(3) \otimes SU(2) \otimes U(1)$. Realistically an **effective theory**: fine-tuned on a large number of parameters: masses, mixing angles, coupling constants.

Experiments: frontier is being scraped at sight with advancements of technology.
Theory: Standard Model extensions.

Bring in either brand new sector, or new particles or new operators in existing sectors (SM = quark sector + lepton sector + Higgs sector + ...)

1. Direct discovery: produce them
2. Indirect searches for observables that can be measured and tested against theory predictions: look for the impact of new particles on interactions with ordinary matter

Standard Model leaks $\rightarrow$ fix

- Dark matter WIMPs or other candidates from SUSY, grand unified theories
- Matter-antimatter asymmetry: needs CP violation either in strong sector (axions) or in lepton sector (measure CP phase in ν oscillations, NSI)
- Higgs naturalness SUSY, superstrings, extra-dimensions
- Microscopic theory and quantisation of gravity graviton
- Anomalous μ magnetic dipole moment axion-like particles, lepto-quarks, GUT
- Origin of hierarchy in fundamental scales superstrings, extra-dimensions, measure with ν
- Mixing matrix SUSY, superstrings, extra-dimensions, measure with ν

Standard Model leaks → fix: **much in ν sector!**

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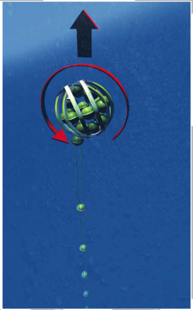
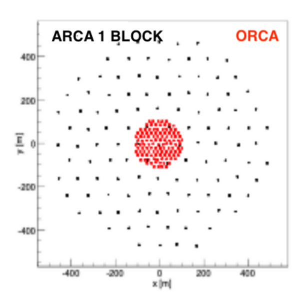
Neutrinos → KM3NeT [*J.Phys.G:Nucl.Part.Phys.* **43** 084001]

Collaboration: 62 institutes, 22 countries, 5 continents [see previous talk by A. Margiotta]

KM3NeT/ORCA



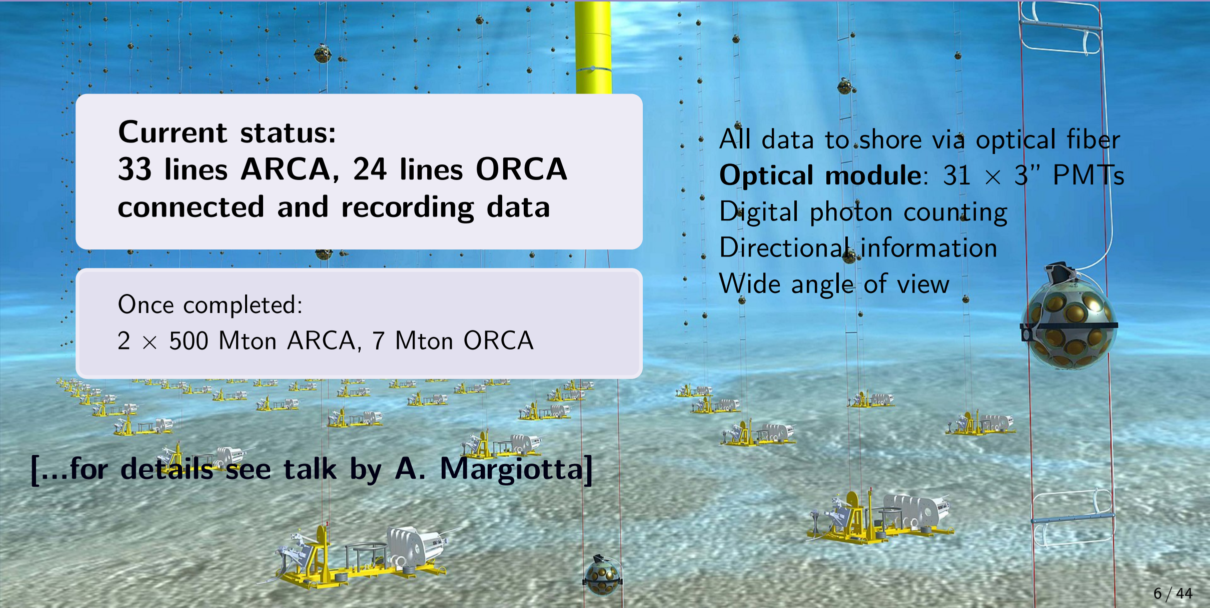


KM3NeT/ARCA

ORCA (spacing 23×9 m): **high statistics** of atmospheric ν

ARCA (spacing 90×36 m): **rare fluxes** of extraterrestrial ν

KM3NeT: layout



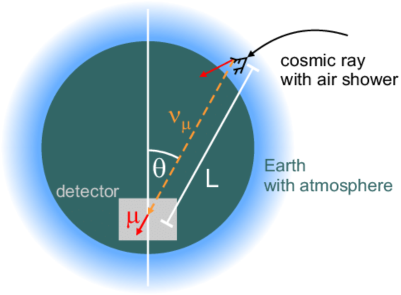
Current status:
33 lines ARCA, 24 lines ORCA connected and recording data

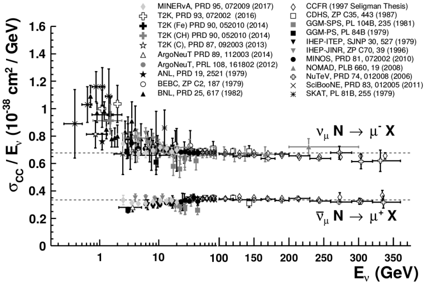
Once completed:
2 × 500 Mton ARCA, 7 Mton ORCA

- All data to shore via optical fiber
- **Optical module**: 31 × 3" PMTs
- Digital photon counting
- Directional information
- Wide angle of view

[...for details see talk by A. Margiotta]

Very-large volume Cherenkov neutrino detector **data**

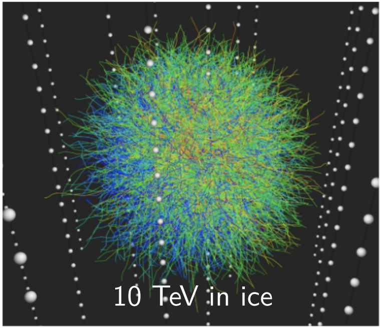


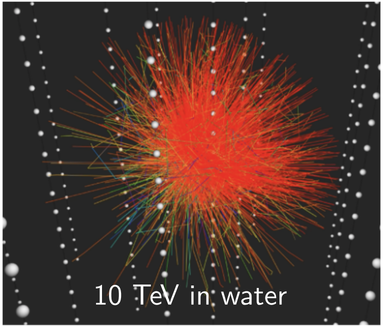


Times and positions of hits	$\rightarrow$	arrival direction coordinates
Number of hits	$\rightarrow$	energy
Shape	$\rightarrow$	flavour of associated lepton

Water over ice?

In water: larger scattering length: direct photons → better **pointing** and **particle identification capability** (despite noise from radioactive ^{40}K decays and natural bioluminescence in the sea, easily identifiable and removable).





Using KM3NeT for *new physics* searches

Neutrino telescopes are versatile instruments! Exploiting two features

1. At 1-100 GeV energies: effects that alter oscillations of atmospheric neutrinos, which are measured with **high statistics**
2. At TeV-PeV energies: limits from cosmic neutrinos: effects that **scale with energy** or **accumulate along large distances**

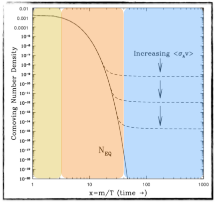
Flavour-related observables (oscillations, mass ordering) require **particle identification** in detector (e, μ, τ lepton?). Ideal region for search is GeV and just above, at the first disappearance peak.

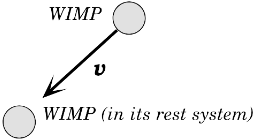
Thermal relic dark matter: WIMPs

σ: annihilation cross section, **inlcusive**; v: relative velocity of projectile, non relativistic
$\langle\rangle$ = thermally averaged = averaged over the dark matter velocity distribution

Freeze-out mechanism:

Equilibrium: **dark matter $\leftrightarrow$ SM**
Cooling: **dark matter $\rightarrow$ SM**
Expansion: **dark matter $\not\leftrightarrow$ SM**

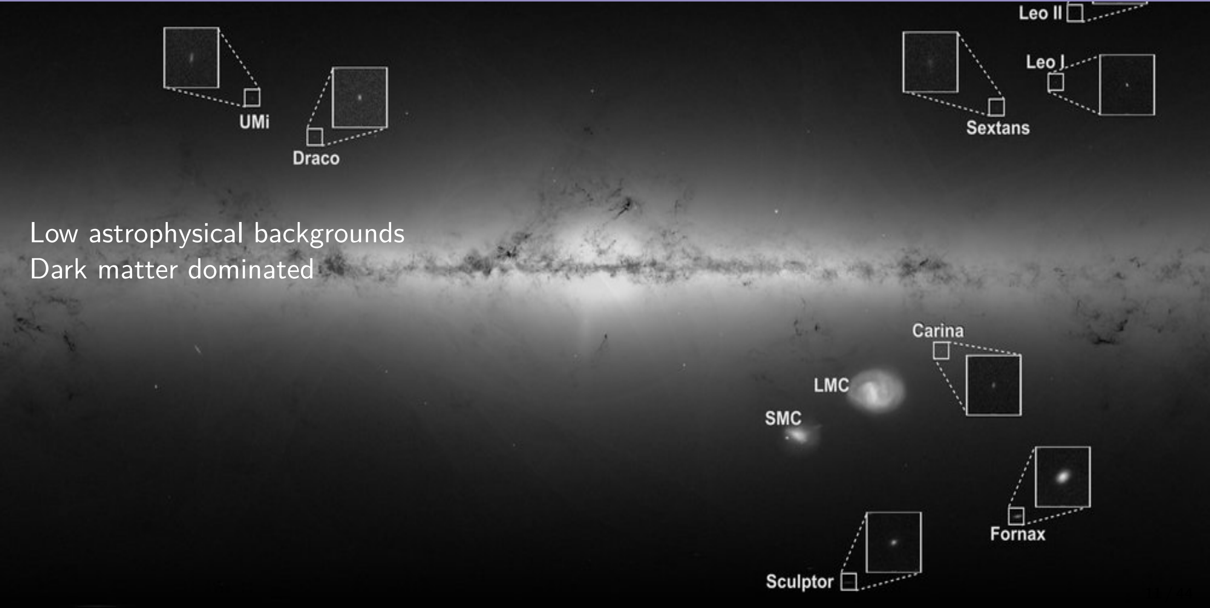




v is the relative velocity

The size of $\langle \sigma v \rangle$ determines the abundance of dark matter nowadays: $\Omega \propto \dfrac{1}{\langle \sigma v \rangle}$

Targeting dark matter sources: Milky Way Halo



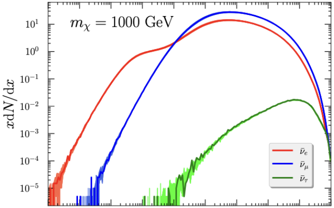
Low astrophysical backgrounds

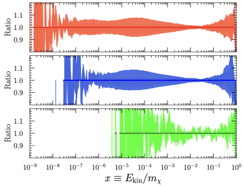
Dark matter dominated

The extra trouble with indirect searches: external input

Indirect searches are unavoidably affected by large uncertainties. This also means that these searches alone can hardly make a univocal claim for detection.

(I) Energy feature

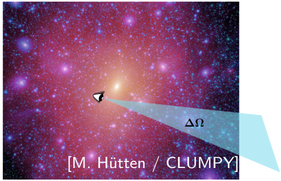




$x = E_{kin}/m_\chi$

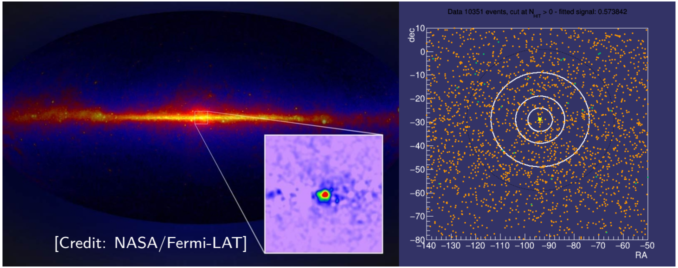
Affected both by energy rec. of the detector (20% – 5%) and by theoretical uncertainties (10% – 30%) mostly on hadronization model [JCAP03(2024)035]

(II) Ambient



Dominated by astrophysical input for modelling haloes

High dark matter content but source confusion (recent excess in gamma rays that neutrinos can start to probe). Major uncertainties from J-factor. Detector sits inside the source.



$$J_{\mathrm{ANN}} = \int_{\Omega} d\Omega \int_{l} \rho^2(r(\theta,\phi))dl$$

$$J_{\mathrm{DEC}} = \int_{\Omega} d\Omega \int_{l} \rho(r(\theta,\phi))dl$$

Signal = a cluster of n ν-induced events produced in dark matter pair-annihilation process.
Measurement = reconstructed arrival directions and energy proxy.

Galactic Centre: $\langle \sigma v \rangle$

Search run with binned or unbinned maximum likelihood method. Number of neutrino-induced events from pair annihilation of dark matter seen with acceptance $\mathcal{A}$ after data taking time t

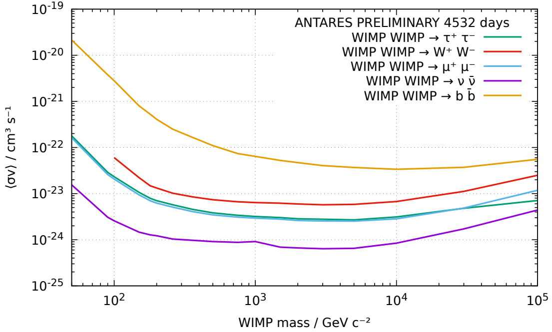
$$n = \frac{1}{2} \langle \sigma v \rangle \int_0^{M_{\mathrm{DM}}} \frac{dN}{dE} dE \, \frac{1}{4\pi} \int_{d\Omega} \int \rho^2 \left(r(\theta, \phi) \right) \frac{1}{M_{\mathrm{DM}}^2} \mathcal{A}(M_{\mathrm{DM}}) \, t$$

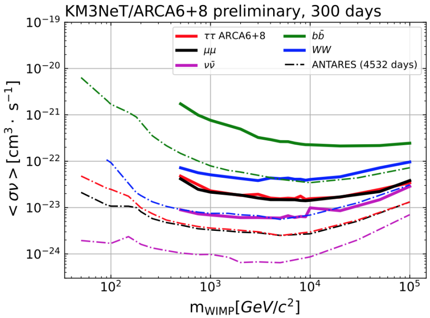
With additional *caveats*

1. A factor 2 according whether dark matter particle corresponds with its own antiparticle
2. A factor 0...100% for the relative branching ratio of annihilation modes. This requires model-dependent amplitudes.

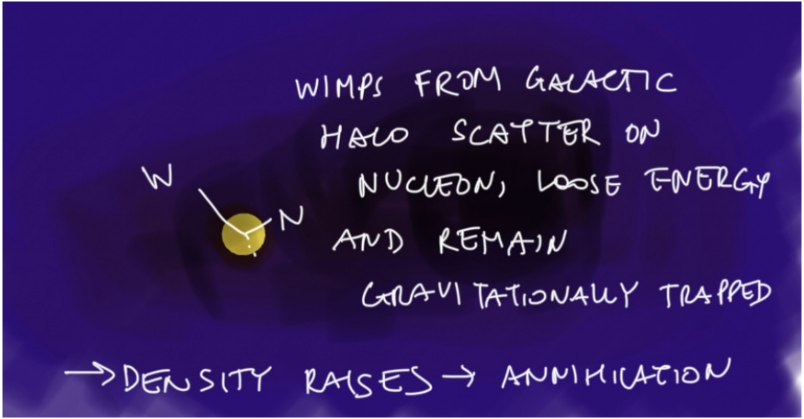
Galactic Centre with ANTARES and KM3NeT

Galactic Centre visible for about 70% of the time in regular data taking mode, using the Earth as a filter. Data from ANTARES 2007 to 2022 + KM3NeT/ARCA6+8 is found consistent with background for all combinations of WIMP parameters **[arXiv:2411.10092]**.

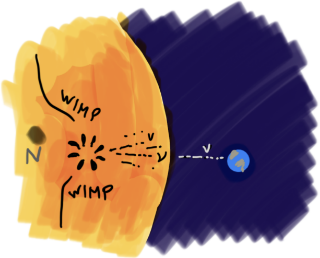




Flux of neutrinos is produced inside the Sun from annihilation of dark matter accumulated because gravitationally trapped. **Special occasion for ν telescopes!**



Searches for dark matter accumulating in the Sun: signal features



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

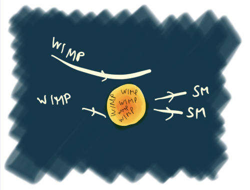
d= distance source-detector

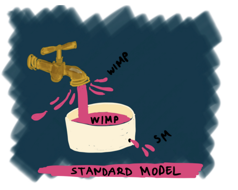
Γ_{ann}= annihilation rate

- Direct interpretation in case of signal (astrophysical background well known)
- Unaffected by halo uncertainties because of point-like extension
- Searches with neutrino telescopes are sensitive at low velocities (= easier capture)
- Given the age of the Sun with respect to the typical time-scale for the competing process "capture/annihilation", the Sun is considered at equilibrium. $\Gamma = C/2$ with C capture rate

Searches for dark matter accumulating in the Sun

Flux only depends on WIMP-nucleon scattering cross section, no longer on WIMP velocity distribution $f(v)$





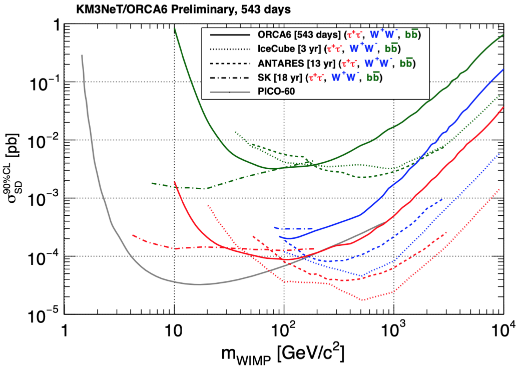
There are two types of interactions of WIMPs with ordinary matter:

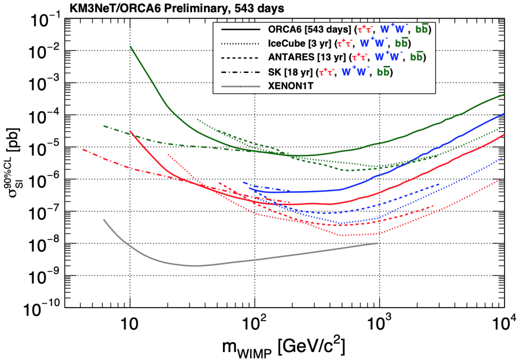
1. spin-dependent, coupling to the spin of the target nucleon
2. spin-independent, coupling to the mass of the target nucleon

The two of them can take place inside the Sun that contains both light elements with an odd number of nucleons, like H, and relatively heavy elements, like He and O.

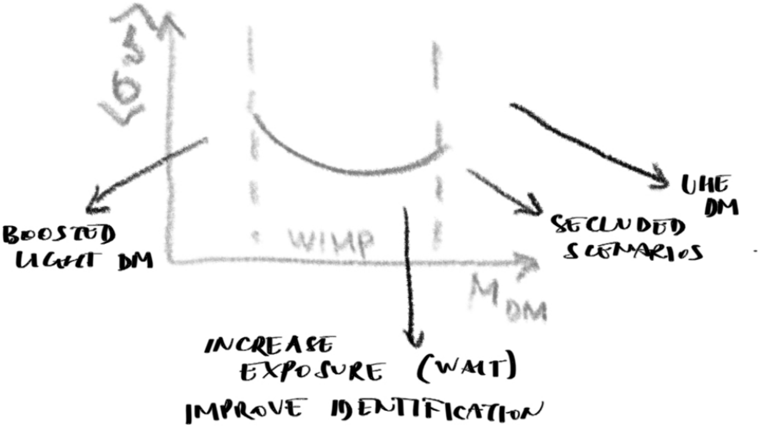
Dark Matter Annihilation in the Sun

Results from data set with partial KM3NeT configuration (6 lines) [PoS(ICRC2023)1406].
Sensitivity estimate with full ORCA detector [PoS(ICRC2019)536]





No evidence for WIMP at the GeV-TeV scale; where to search next?



Neutrino quantum decoherence

Here in the case: non-closed quantum system (ν) in interaction with enviroment.

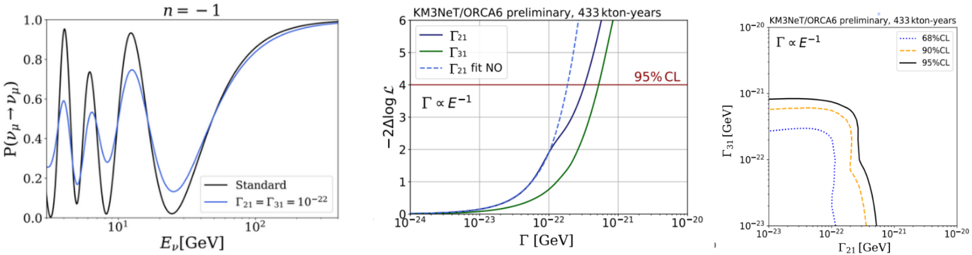
> Neutrino + environment represented as a quantum system (mixture of states, ρ) with *dissipative* term $\mathcal{D}$ (decoherence) that damps the oscillation probabilities.

$$\frac{d\rho(t)}{dt} = -i[H, \rho(t)] + \mathcal{D}[\rho(t)]$$

Example case: loop quantum gravity scenarios: space-time with a *foamy* structure in which Planck length size black holes form and evaporate on the Planck time scale $\rightarrow$ loss of quantum information across their event horizons, providing an *environment* that can induce decoherence of apparently isolated matter systems [Phys.Rev.D 72 (2005)].

Neutrino quantum decoherence

Neutrino mass eigenstates lose their coherent superposition due to interactions with the environment → oscillation amplitude is suppressed [arXiv:2410.01388]



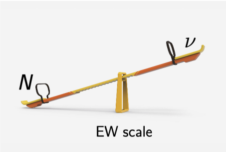
Heavy neutral leptons: context

Problem of hierarchy in fundamental scales → ν **masses are tiny.** How built?

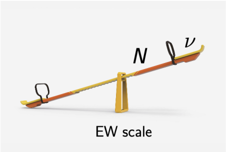
1. Tiny Yukawa couplings. Tuned by hand
2. See-saw mechanism. Masses of active ν are kept small by some large mass M.

$$\mathcal{L}^{\text{mass}}_{\text{see-saw}} = -\frac{1}{2}(\bar{\Phi}_L, \bar{\Phi}_R)\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \Phi_L \\ \Phi_R \end{pmatrix}$$

Diagonalizing mass matrix: $m_{\text{light}} \simeq \frac{m_D^2}{M}$, $m_{heavy} \simeq M$



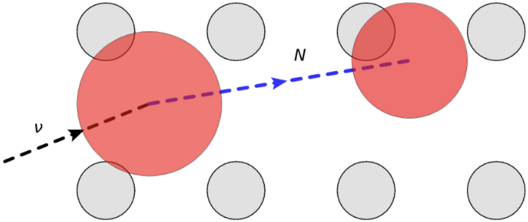
Type-1 see-saw.
Heavy N can hardly be tested



This HNL search.
Light N weakly interacting.

Heavy neutral leptons

Heavy neutral lepton (HNL) such as 4th sterile ν with mass around the GeV could leave a signal in KM3NeT/ORCA [JHEP05(2009)030], [PRL 119, 201804 (2017)].
KM3NeT/ORCA could become competitive with its future larger-volume configurations.

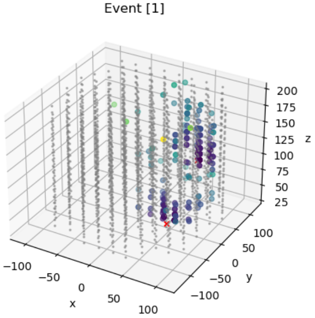


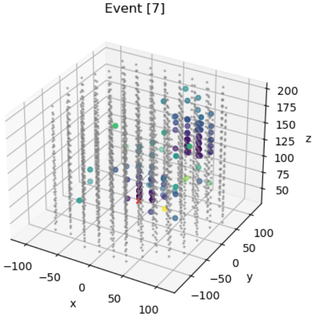
HNL mass: in keV range: dark matter candidate, in $\mathcal{O}(1-100)$ GeV can generate the matter-antimatter asymmetry (*baryogenesis from* ν *oscillations*) [arXiv:1606.06719]

Generation

Toy Monte Carlo events generated adding a second cascade with collinear versor.

Simulation of HNLs with the lepton injector of SIREN [arXiv:2406.01745]. Machine learning regression (dynedge) to discriminate and reconstruct distance and energy.

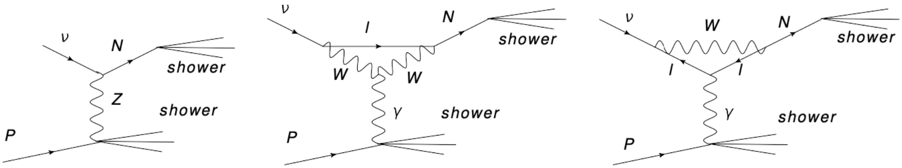




Search for heavy neutral lepton signatures

Signature: double cascade events at low energy. Active ν is atmospheric, after oscillations.

1. HNL production via neutral current + mixing in final state. $|U_{\tau 4}|^2$ is the least constrained. Separation between vertices (decay length) depends on MN and on $|U_{\tau 4}|^2$.
2. HNL production via a transition magnetic moment: NC + W loop + mixing in final state



1) NC scattering with mixing

2) transition magnetic moment: W-loop and mixing in final state

Background

1. Random coincidences of two uncorrelated muons. In full ORCA we expect a rate of 10^{-9} events $/\mu$s. Duration of snapshot in KM3NeT DAQ: 3μs $\Rightarrow$ about $3{\cdot}10^{-9}$ events in same snapshot: negligible probability
2. Stochastic electromagnetic showers along the track: under study but only relevant for μ tracks. Here firstly considering cascades from electrons.
3. ν_τ: completely negligible. At GeV energies the two cascades are of order of micrometres apart: completely overlayed.

> The signature with two cascades separated by a long distance is characteristic fingerprint of something **new** outside the Standard Model

Non-standard interactions of neutrinos (NSI)

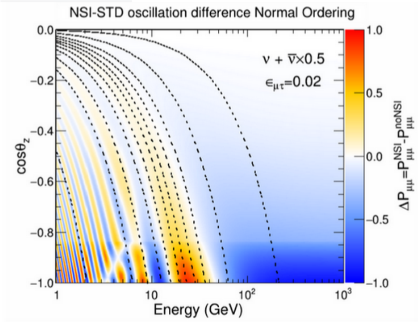
LHC has detected **no new particles** $\Rightarrow$ interest turns towards possible **new operators** that can be constructed: modifications of the Standard Model that manifest themselves indirectly.

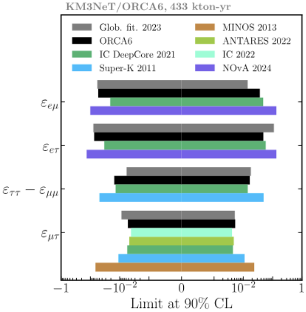
SM effective theory (SMEFT) = SM + dimension 6 operators + ...

All dimension-4 operators that observe Lorenz invariance and gauge symmetry are already contained in the SM. Next possible trial is dimension 6 $\Rightarrow$ this brings in new terms in the Hamiltonian $\Rightarrow$ new vertex $\Rightarrow$ modified interaction.

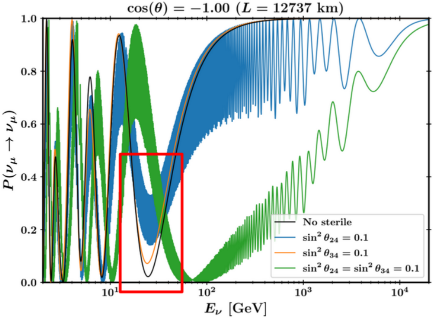
Non-standard interactions of neutrinos (NSI)

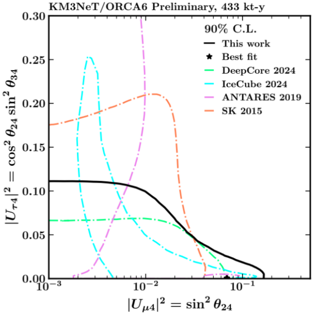
Neutral current forward scattering of neutrinos inside the Earth is modified $\rightarrow$ Flavour-dependent matter effects alter neutrino oscillations inside the Earth. [arXiv:2411.19078]





Motivation: (3+1) models with $\Delta m^2_{41} \sim$1 eV^2 might explain short baseline anomalies.
KM3NeT is sensitive to mixing angles $\Theta_{24} and \Theta_{34}$.





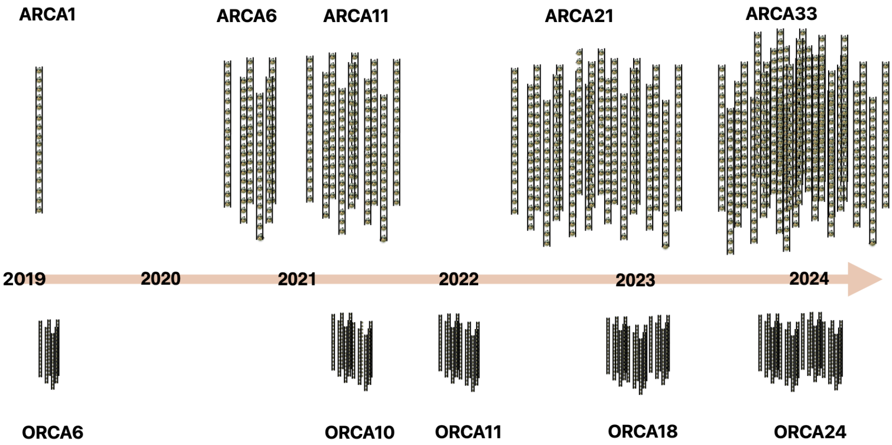
Conclusions

> The most exciting phrase to hear in science [...] is not '*Eureka!*' but 'That's funny...' [Isaac Asimov]

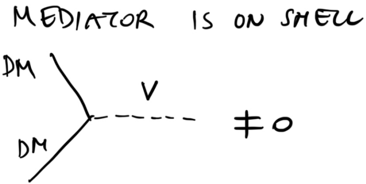
KM3NeT has recorded 715 kton-year (ORCA) and 332 days (ARCA) of **high-quality data**, in continuous growth: a broad physics case is in reach.

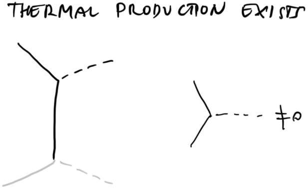
- Indirect dark matter searches towards pushing the thermal relic cross-section;
- Physics beyond the standard model is indirectly accessible through modifications of the oscillation behaviour: non-standard interactions (NSI), ν quantum decoherence, ν decay, sterile νs, violation of Lorentz Invariance with effects on oscillations, heavy neutral leptons via double cascades at low energy.

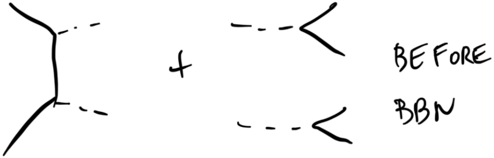
KM3NeT: building roadmap

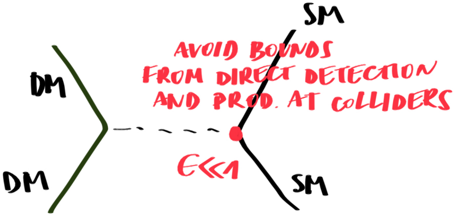


Heavy dark matter in secluded scenarios









Heavy dark matter in secluded scenarios

Above 10-100 TeV, in line with recent interest for BSM physics in heavy sectors at colliders

1. Unitarity bound on the dark matter mass naturally evaded with a modified cosmology.
2. $\mathrm{DM}\,\mathrm{DM} \to 4\mathrm{SM}$ leaving the Galactic Centre as neutrinos. Spectra of relevance for experiments are computed from *boosted* PPPC4DMID [JCAP02(2019)014].

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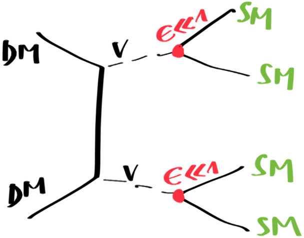

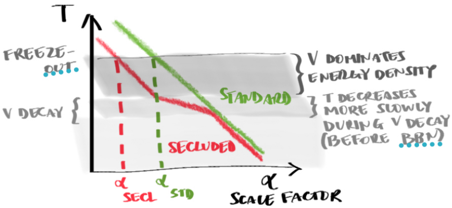

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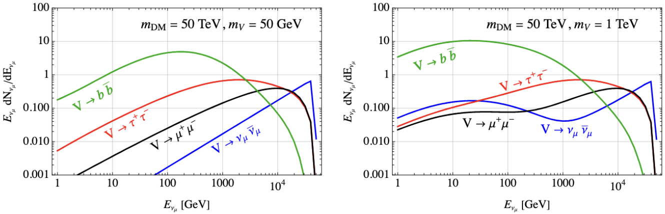

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Above 10-100 TeV, in line with recent interest for BSM physics in heavy sectors at colliders

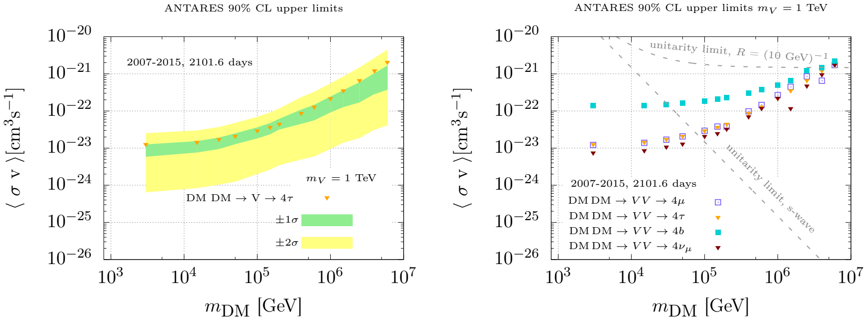
1. Unitarity bound on the dark matter mass naturally evaded with a modified cosmology.
2. $\mathrm{DM\,DM} \to 4\mathrm{SM}$ leaving the Galactic Centre as neutrinos. Spectra of relevance for experiments are computed from *boosted* PPPC4DMID [JCAP02(2019)014].

…*boosted* PPPC4DMID?

The relevant energy scale is not the heavy dark matter mass (that would demand a re-summation of electroweak radiation for $m_{\mathrm{DM}} > 10$ TeV), but rather the sub-TeV mediator mass, where the first order treatment of electroweak corrections included in PPPC4DMID is under control.

Heavy dark matter in secluded scenarios

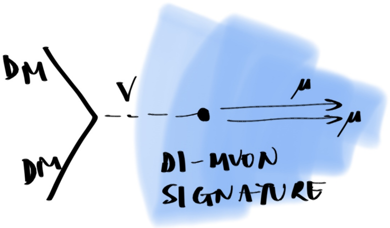
Modified cosmological evolution: universe at freeze-out is smaller ⇒ the same amount of DM is later more diluted ⇒ $\sigma v(\text{DM DM} \to \text{VV})$ smaller ⇒ DM can be **heavier**



Search for signature of secluded dark matter at large masses using high energy ANTARES data **[JCAP06(2022)028]**

Secluded dark matter in close-by sources

Other scenario is the case when the vector mediator V propagates up to the vicinity of the detector. Case of close-by sources like the Sun.

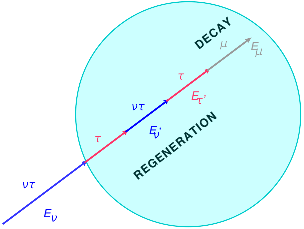


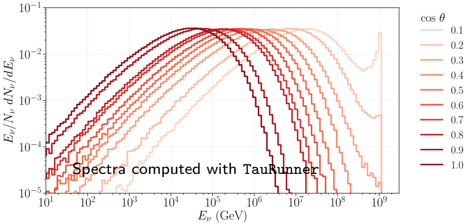
Di-muon signature searched from the direction of the Sun. The mediator V escapes the Sun before producing any neutrinos, avoiding attenuation

Several scenarios propose EeV-scale dark matter. Example: right-handed neutrino $\nu_{R,1}$ in CPT symmetry, that decays into Higgs + a light Majorana ν (two-body therefore monochromatic) [LHEP 01,13(2018)]

$$\nu_{R,1} \rightarrow H + \nu_M$$

Search channel: ν_τ reaching the detector through τ regeneration across the Earth. `TauRunner` to propagate neutrinos from incident high-energy flux (1 to 10^{16} GeV)





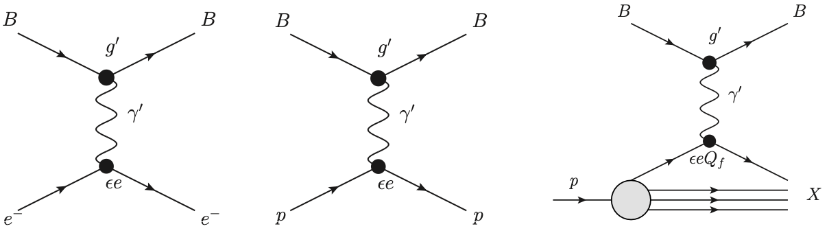
Light boosted dark matter

1. Scenario (1): sub-population of relativistic dark matter produced non-thermally in late-time processes [J. Phys.:Conf.Ser.718 042041]
2. Scenario (2): dark matter up-scattered by cosmic rays [arXiv:2405.00086]

Light boosted dark matter

1. Scenario (1): sub-population of relativistic dark matter produced non-thermally in late-time processes [J. Phys.:Conf.Ser.718 042041]

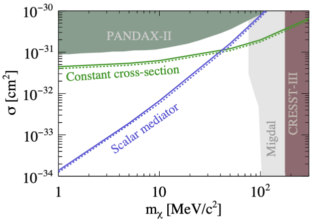
Strategy: detect Cherenkov light from the final state charged particles, above the Cherenkov threshold. No ν yield, rather an unconventional usage of ν detectors [Rev.Mod.Phys.84, 1307].



Light boosted dark matter

2. Scenario (2): dark matter up-scattered by cosmic rays [arXiv:2405.00086]

The upscattering riginates from the same dark matter-nucleus interactions as direct detection experiments search for. Directional preference from the GC. Searched by Super-Kamiokande [Phys.Rev.Lett.130, 031802]

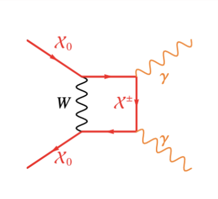


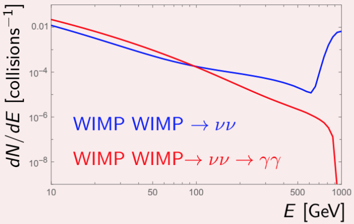
(Conventional direct detection experiments focusing on nuclear recoils are not sensitive to cold sub-GeV dark matter due to insufficient recoil energy).

Current efforts to improve experimental upper limits

1. Combined analyses. ANTARES + IceCube **[Phys.Rev.D 102 (2020)]**, ν and γ-rays with Fermi-LAT,MAGIC, H.E.S.S., VERITAS, HAWC using joint likelihood `glike` **[https://zenodo.org/records/4028908]**

Signal: WIMP WIMP $\to \gamma\gamma$ (primary, from loops) $\to \nu\nu$ (secondary) - [PPPC4DMID]





2. Global fit approach. DarkBit, NeutrinoBit modules as part of GAMBIT