The KM3NeT neutrino telescope: indirect searches for new physics

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KM3NeT

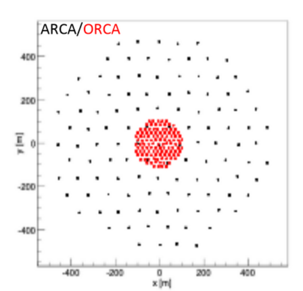
Underwater astronomy and high-exposure accumulator of atmospheric neutrinos using an instrumented portion of the Mediterranean Sea as a detector medium.

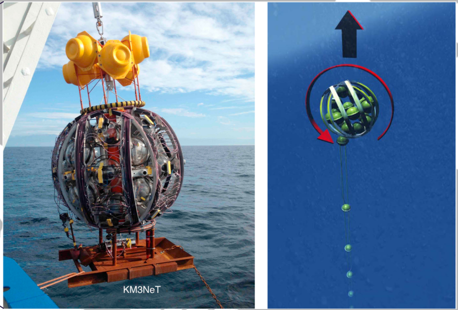
[*J.Phys.G:Nucl.Part.Phys.* **43** 084001 (2016)]

KM3NeT: layout

KM3NeT/ORCA

ex ANTARES site



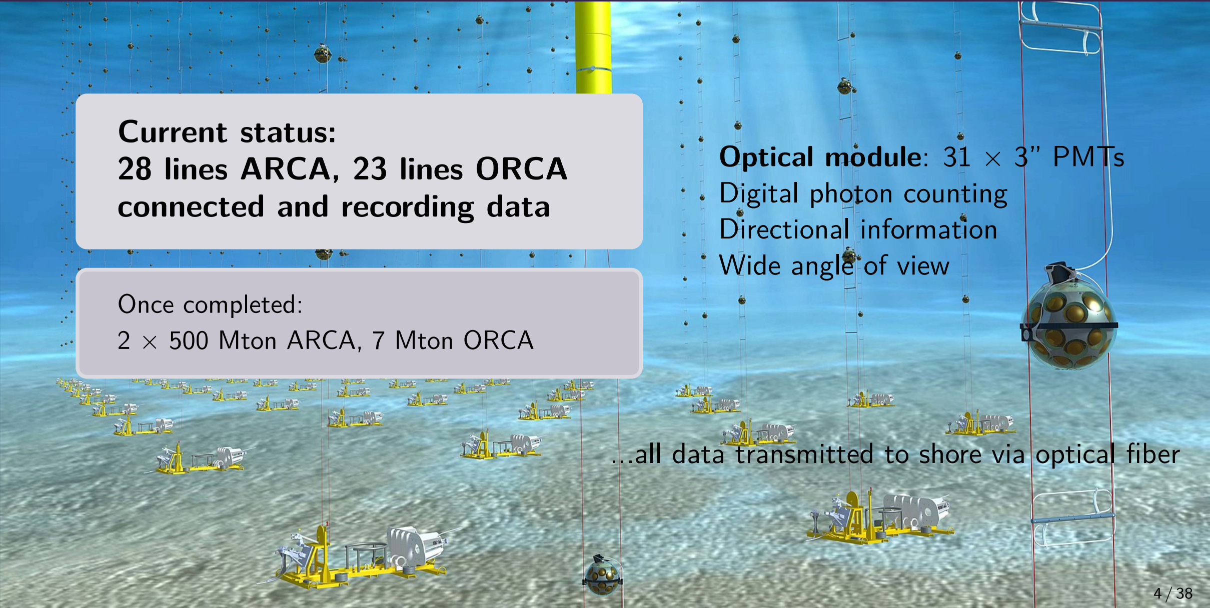


KM3NeT/ARCA

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

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

KM3NeT: layout



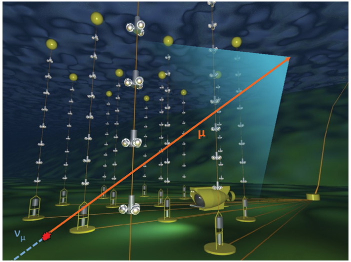
Current status:
28 lines ARCA, 23 lines ORCA connected and recording data

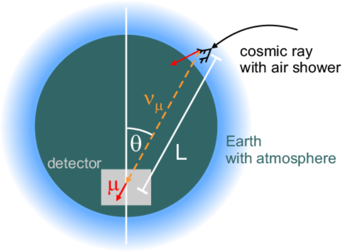
Once completed:
2×500 Mton ARCA, 7 Mton ORCA

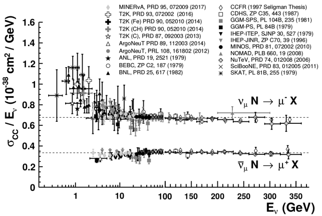
Optical module: $31 \times 3''$ PMTs
- Digital photon counting
- Directional information
- Wide angle of view

...all data transmitted to shore via optical fiber

Very-large volume Cherenkov neutrino detector

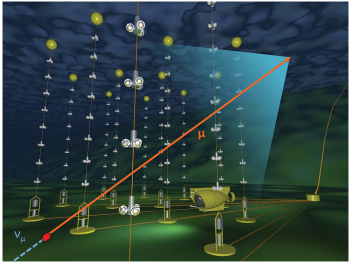


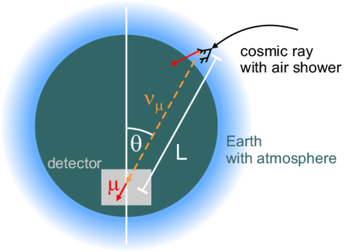


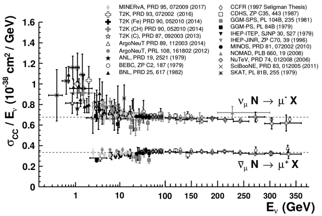


Look through the Earth for leptons from $\nu \to$ lepton conversion.
$\sigma_{\nu \to l} \sim 10^{-38}$ cm^2 at 1 GeV! Low rate $\to$ very large (natural) reservoirs of transparent medium. Scattering length influences pointing precision.

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

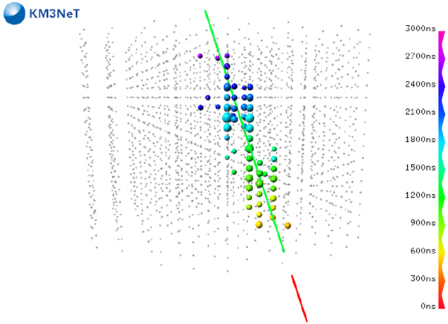


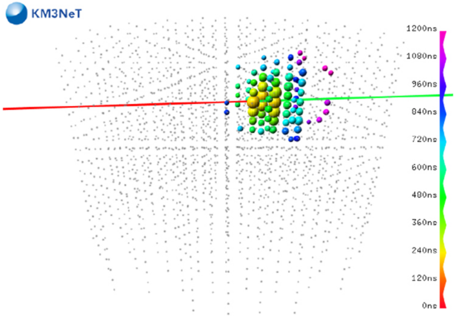




Times, positions of hit PMTs	$\rightarrow$	arrival direction coordinates
Number of hit PMTs	$\rightarrow$	energy
Shape	$\rightarrow$	flavour of associated lepton

Performance: pointing





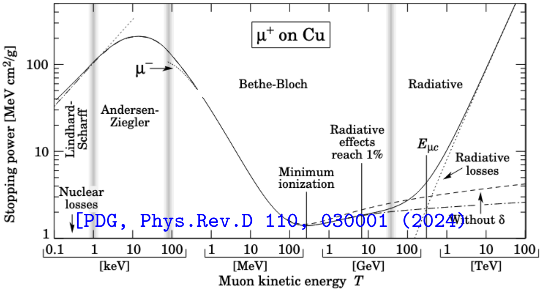
KM3NeT reconstructs two classes of events:

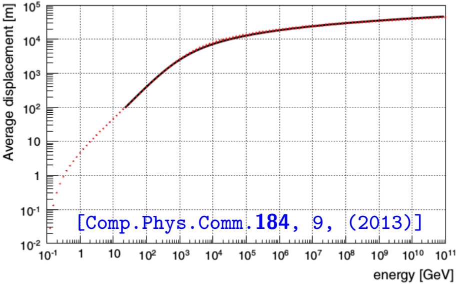
Tracks: predominantly $\nu_\mu CC$; angular resolution down to 0.1° at 1 PeV - fly-through

Showers: predominantly ν_e CC or any NC; angular resolution 1° at 1 PeV - contained

Performance: particle identification

Tracks and showers are not univocally discriminated depending on their energy





Example: 1 GeV muon leaves a track of a few metres in water. ORCA granularity: 23×9 m

Water over ice?

Larger scattering length: direct photons → better **pointing** and **particle identification capability**. Noise from radioactive ^{40}K decays, natural luminescence in sea easily identifiable.

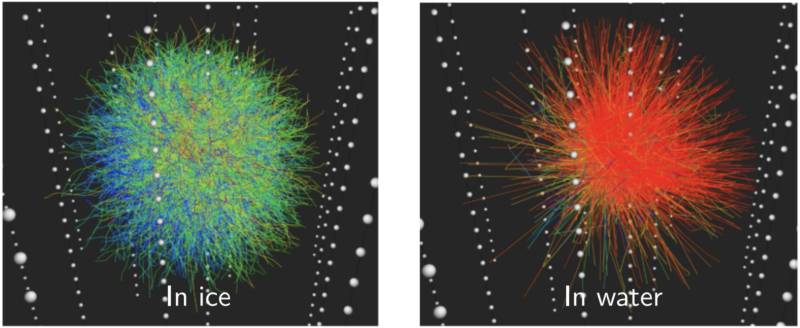
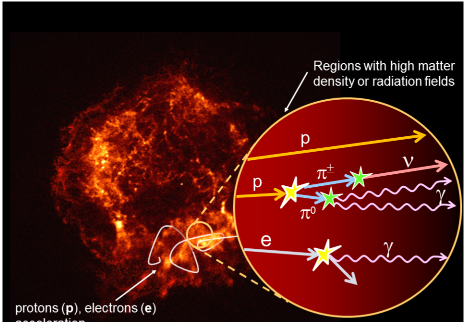


Figure: Simulation of light from a 10 TeV cascade in ice (left) and water (right).

Physics Case I: Measurement of extraterrestrial neutrinos

Measurement of extraterrestrial neutrinos

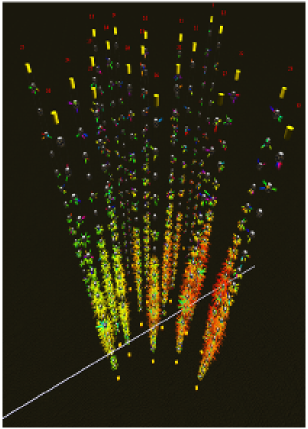
High-energy cosmic ν are expected from collisions yielding particles such as $\pi^{\pm}$ and $\mu^{\pm}$, through pp and $p\gamma$ scattering, taking place in different environments, steady or with flares



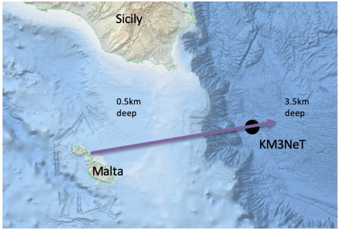
[Fig. from Universe 2020, 6(2), 30]

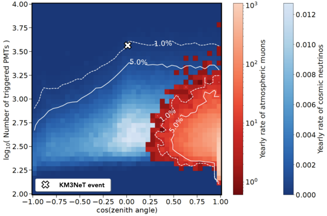
- Neutrino astronomy: backtracking sources
  1. As a **correlation** with underlying catalogue
     1. Jets of active galactic nuclei (AGNs)
     2. Starburst galaxies, star-forming galaxies
     3. Expanding front of supernova remnants
     4. Gamma-ray bursts
     5. IceCube HE events
  2. As **autocorrelation** or clusters in space (-time)
- Search for a diffuse excess and measurement of its energy spectrum. Accelerator properties.
- Search for prompt multimessenger coincidences

Observation of an ultra-high-energy cosmic ν with KM3NeT

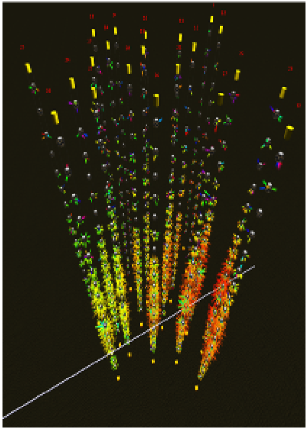


- Observed with 21-line configuration of KM3NeT/ARCA
- Horizontally crossing the detector traversing continental shelf: not an atmospheric muon
- 35% of the detector (3672 photomultipliers) triggered





Observation of an ultra-high-energy cosmic ν with KM3NeT

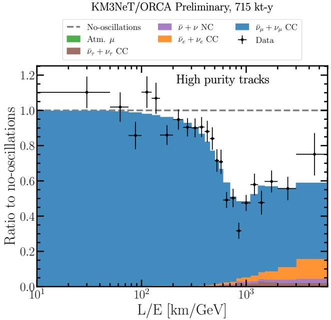


Physics Case II: Fundamental properties of atmospheric ν

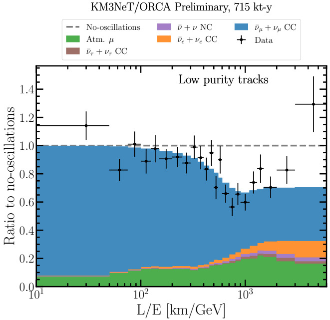
Flavour-related observables (oscillations, mass ordering) require particle identification in detector (e, μ, τ lepton?). Ideal region for search is GeV and just above, at the first disappearance peak.

Evidence for atmospheric neutrino oscillations

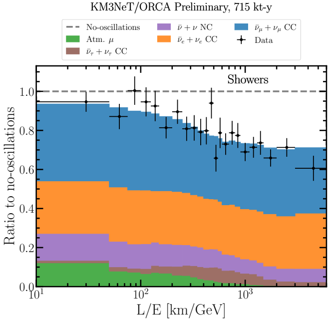
Oscillations are seen with significance $> 6\sigma$ in L/E distributions through ν_μ **disappearance** with KM3NeT/ORCA 715 kton-years data set (6+10+11 detector lines).



High-purity tracks



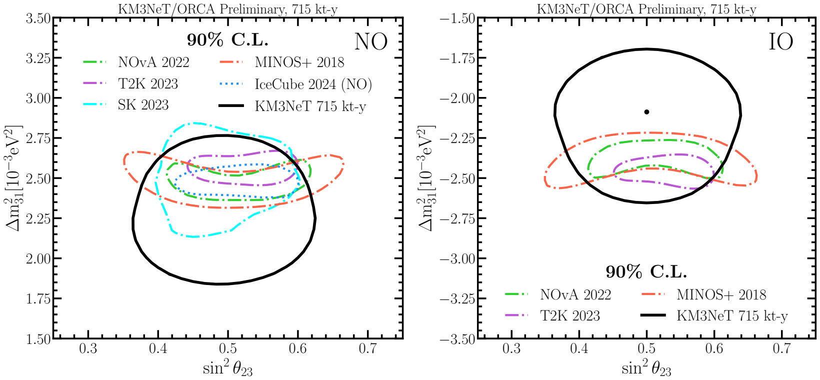
Low-purity tracks



Showers

Measurement of atmospheric oscillation parameters

Best fit: $\sin^2\theta_{23} = 0.50^{+0.07}_{-0.07}$ $\Delta m^2_{31} = -2.09^{+0.17}_{-0.21} \cdot 10^{-3}\text{eV}^2$. Data display a slight preference for inverted ordering. 1.6 Mton-y of data awaiting.



Physics Case III: Indirect searches for *new physics*

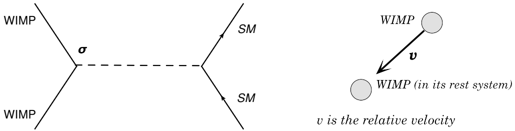
Physics case 3: indirect searches for *new physics* signatures

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**

- Non-standard interactions (NSI)
- Neutrino quantum decoherence
- Neutrino decay
- Sterile neutrinos
- Violation of Lorentz Invariance with effects on oscillations
- Neutrinos from annihilation of dark matter particles
- Heavy Neutral Leptons via double cascades at low energy

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



Rate of outcoming particles = velocity of incident particle $\times\, \sigma \,\times$ number of targets.

The probability for **one** process to happen is $\propto$ velocity of projectile $\times\, \sigma$.

Bonus: no pointing

Data are recorded over 4π at once. Source information is only necessary to discriminate signal from background **at analysis level**. No need to choose at DAQ level.

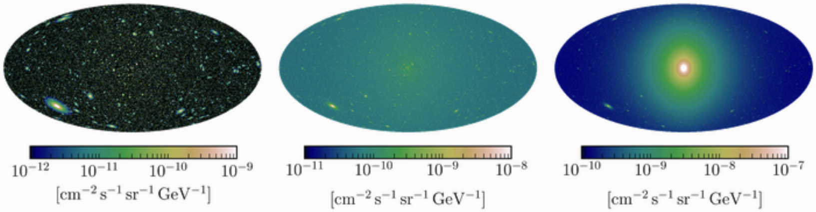
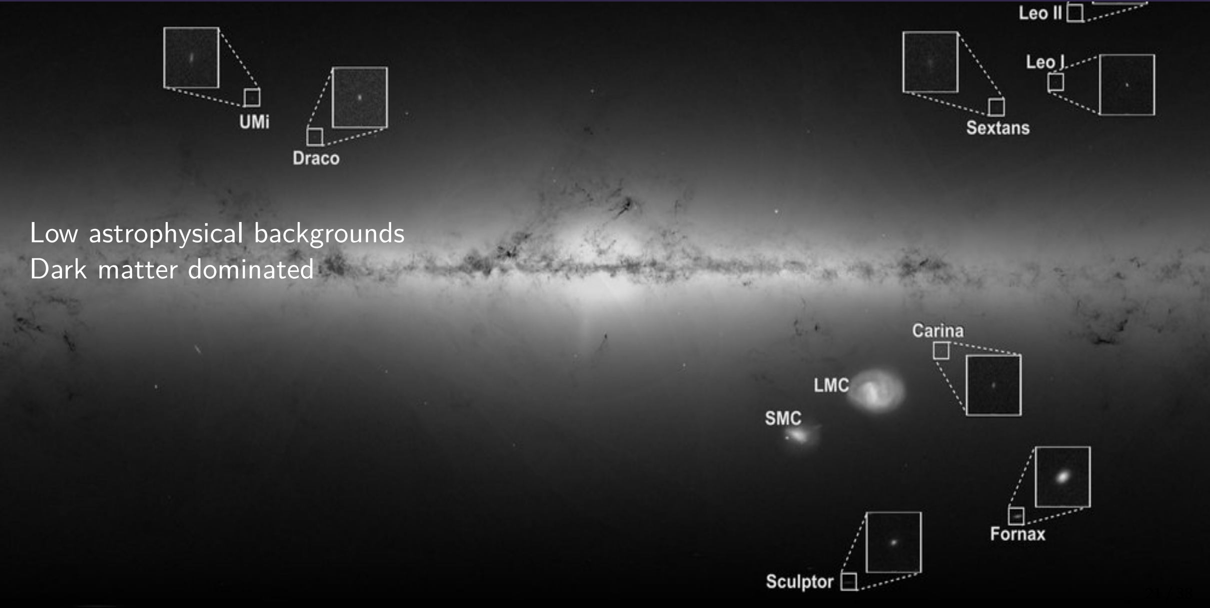


Fig. 2.4 Full-sky maps of the γ-ray emission from Galactic DM (resolved substructures, resolved + unresolved substructures, and total emission). Figure published in Hütten et al. (2016).

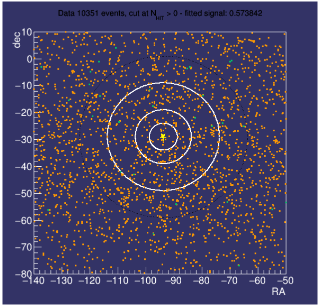
Targeting dark matter sources: Dwarf Spheroidal Galaxies

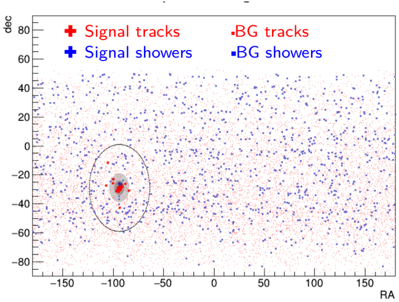


Low astrophysical backgrounds
Dark matter dominated

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

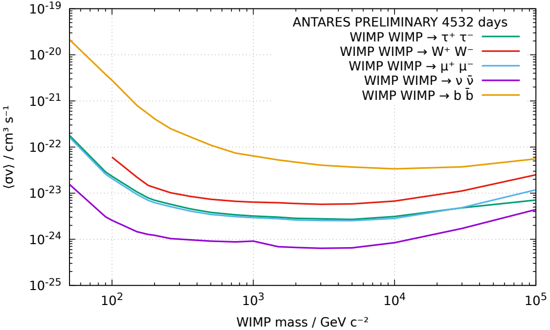
Signal = a cluster of n ν-induced events produced in dark matter pair-annihilation process.
Measurement = reconstructed arrival directions and energy proxy.
Search run with unbinned maximum likelihood method.

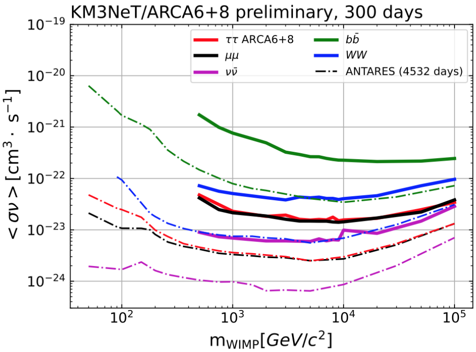




Galactic Centre - ANTARES 2007 to 2022 data + KM3NeT

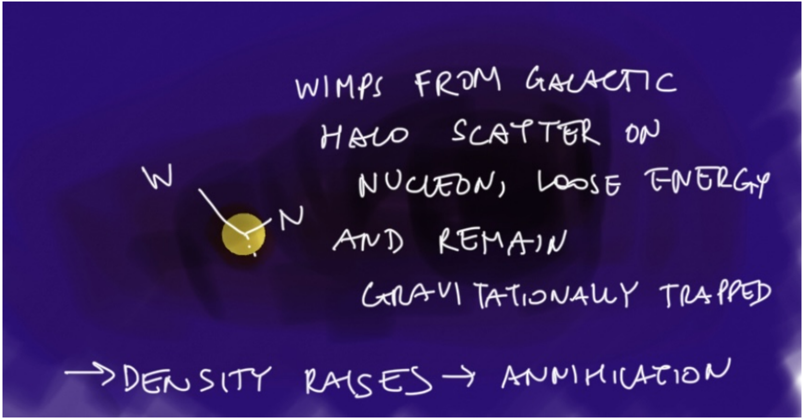
Lifetime 4532.16 days = 12.41 years. Tracks + cascades. Galactic Centre: favourable spot (in Southern sky) = visible for about 70% of the time in regular data taking mode, using Earth filter. Data TS is found consistent with background for all combinations of WIMP parameters.



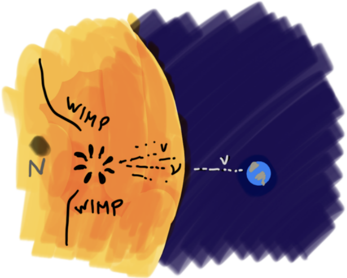


Searches for dark matter accumulating in the Sun

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

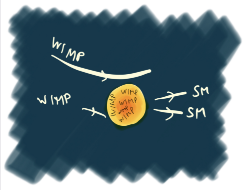
Γ_{ann}= annihilation rate

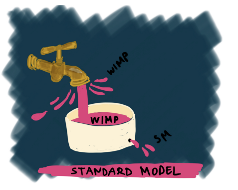
- Direct interpretation in case of signal (astrophysical background well known)
- Unaffected by halo uncertainties because of point-like extension
- Searches with neutrino telescopes are sensitive at low velocities (= easier capture)
- Given the age of the Sun with respect to the typical time-scale for 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: signal features (cont.)

Searches for dark matter accumulating in the Sun

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





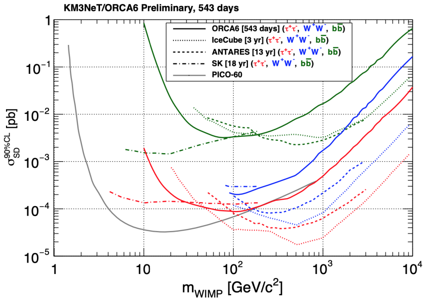
There are two types of interactions of WIMPs with ordinary matter:

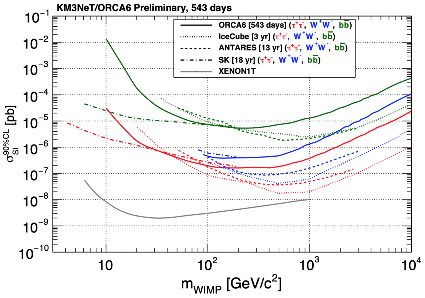
1. spin-dependent, coupling to the spin of the target nucleon
2. spin-independent, coupling to the mass of the target nucleon

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.

KM3NeT - Sun

Unblinded: data set with partial configuration ORCA6 [PoS(ICRC2023)1406]



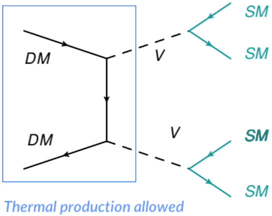


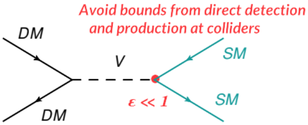
Sensitivity estimate with full ORCA detector [PoS(ICRC2019)536]
Legacy ANTARES limits in preparation for Neutrino 2024.

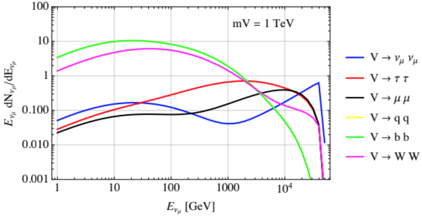
No evidence for WIMP at the GeV-TeV scale; where to search next?

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. Spectra of relevance for experiments computed from 'boosted' PPPC [JCAP 2019 014]



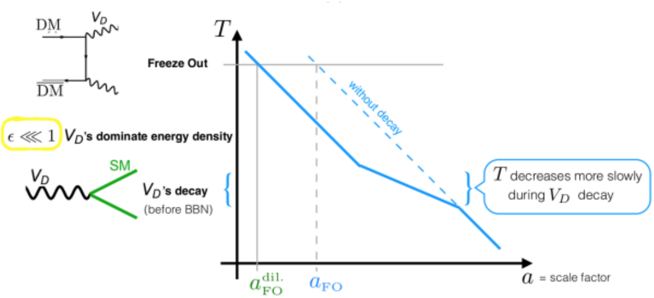


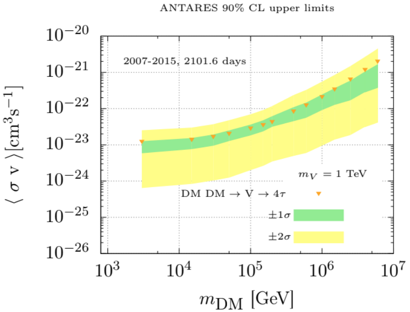


Modified cosmological evolution: universe at freeze-out is smaller $\Rightarrow$ the same amount of DM is later more diluted $\Rightarrow$ $\sigma v(\mathrm{DM\ DM} \to \mathrm{VV})$ smaller $\Rightarrow$ DM can be heavier

ANTARES - Heavy secluded dark matter

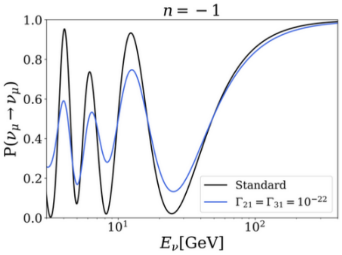
Search for secluded dark matter towards the Galactic Centre with the ANTARES neutrino telescope **[JCAP06(2022)028]**

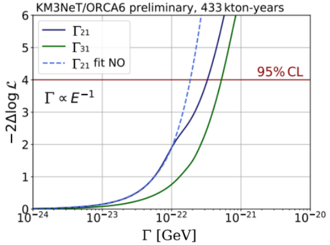


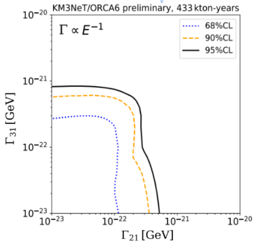


Neutrino quantum decoherence

Neutrino mass eigenstates lose their coherent superposition due to interactions with the environment $\rightarrow$ oscillation amplitude is suppressed [https://doi.org/10.22323/1.444.1025]







Non-standard interactions of neutrinos (NSI)

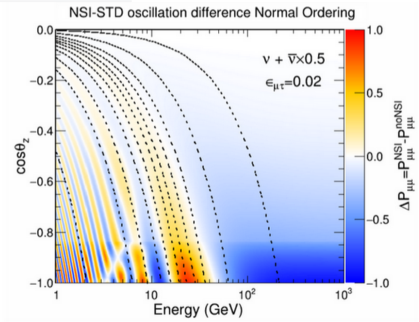
LHC has detected **no new particles** $\Rightarrow$ interest turns towards possible **new operators** that can be constructed: modifications of the Standard Model that manifest themselves indirectly.

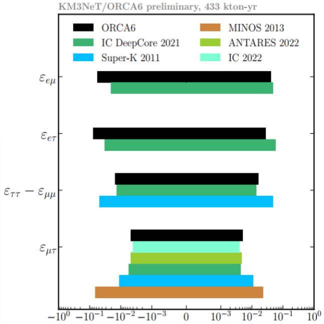
SM effective theory (SMEFT) = SM + dimension 6 operators + ...

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)

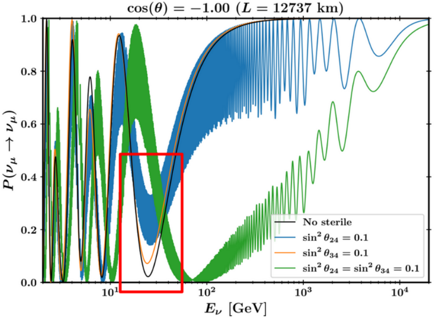
Neutral current forward scattering of neutrinos inside the Earth is modified $\rightarrow$ Flavour-dependent matter effects alter neutrino oscillations inside the Earth. [https://doi.org/10.22323/1.444.0998]

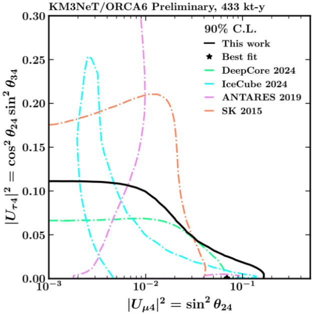




Sterile neutrinos

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

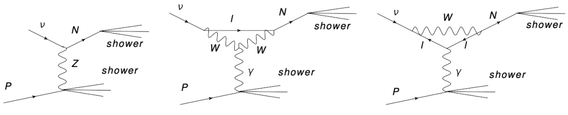




Search for heavy neutral lepton signatures

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



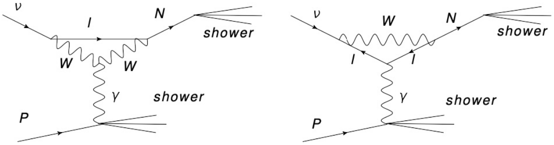
1) NC scattering with mixing
2) transition magnetic moment: W-loop and mixing in final state

Nick Kamp (Harvard U.): simulation of HNLs with the lepton injector of SIREN. Jorge Prado (IFIC): studying machine learning reconstruction to discriminate double cascades in ORCA and estimate distance and energy. Case investigated: **transition magnetic moment**.

Transition magnetic moment

Conservation of lepton number holds in the Standard Model. There is no transition of neutrino to other flavour in interactions. Note: transition instead occurs in propagation (oscillations).

A magnetic moment for neutrino is allowed in the Standard Model [arXiv:2411.03122], however not-flavour-changing, and through **loops** $\rightarrow$ small effects. In in a BSM scenario with new interactions from higher dimension operators, 4th fermion can be produced in this transition.



Wrapping up

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 with the next generation of neutrino observatories
- Physics beyond the standard model is indirectly accessible through modifications of the oscillation behaviour

KM3NeT: building roadmap