The KM3NeT neutrino telescope: indirect searches for dark matter and new physics

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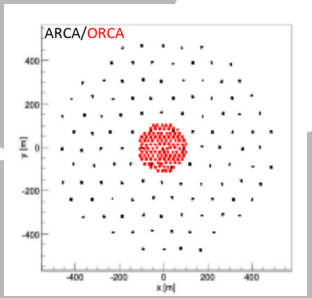
DSU 2024

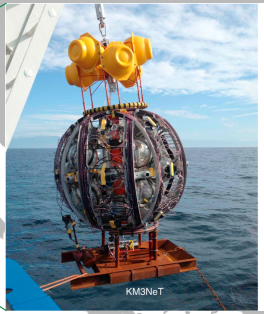
September 14, 2024

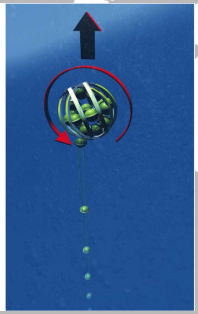
KM3NeT: neutrino detectors in the Mediterranean Sea

KM3NeT/ORCA

ex ANTARES site







KM3NeT/ARCA

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

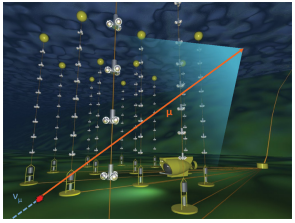
ARCA (spacing 90×36 m): rare fluxes of extraterrestrial ν

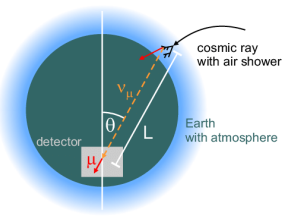
Layout: currently taking data with 28 lines ARCA + 23 lines ORCA

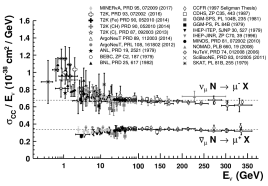
Optical module: 31 3" PMTs
Digital photon counting
Directional information
Wide angle of view

Working principle and data of a neutrino detector

Look through the Earth for leptons from $\nu \to$ lepton conversion. Low rate $\to$ very large (natural) reservoirs of transparent medium. Scattering length influences pointing precision.







Neutrino telescopes reconstruct two kind of events

1. tracks: fly-through, angular resolution down to 0.1°, ν_μ CC
2. cascades: contained, angular resolution $\sim 1 - 10^\circ$, ν_e CC or ν_e NC or ν_μ NC

KM3NeT: physics case

Primary

1. Astronomy: catch extraterrestrial neutrinos, identify sources.
2. Precision measurement of oscillation parameters, determine the mass ordering.

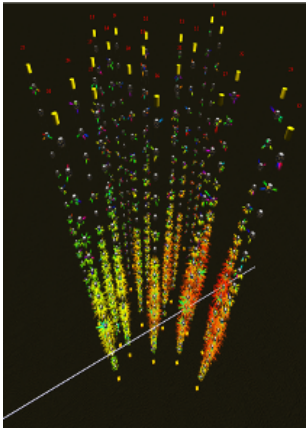
...but neutrino telescopes are versatile instruments!

KM3NeT: physics case (cont.)

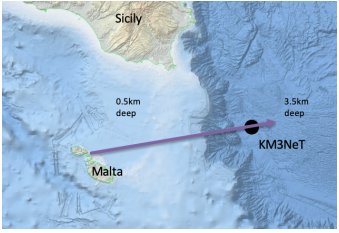
Other: indirect searches for new physics

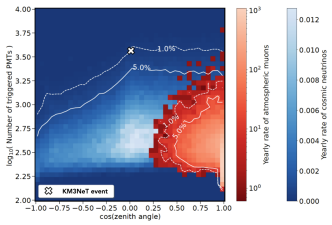
- Indirect searches for dark matter annihilating to neutrinos
- Non-standard oscillations (NSI)
- Neutrino quantum decoherence
- Neutrino decay
- Sterile neutrinos
- Violation of Lorentz invariance with effects on oscillations
- Heavy neutral leptons

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

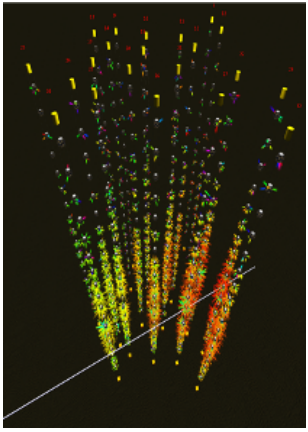


- Observed with 21-line configuration of KM3NeT/ARCA
- Horizontally crossing the detector traversing continental shelf: not an atmospheric muon
- 35% of the detector (3672 photomultipliers) triggered





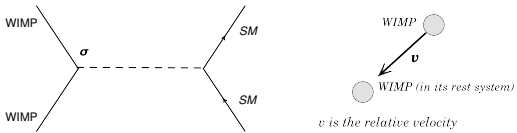
Observation of an ultra-high-energy cosmic ν with KM3NeT



Indirect searches for dark matter annihilating to neutrinos

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

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

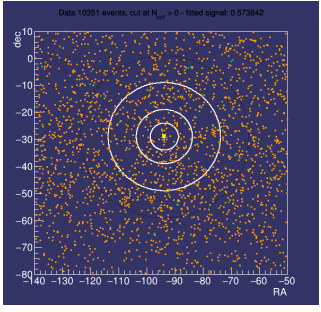


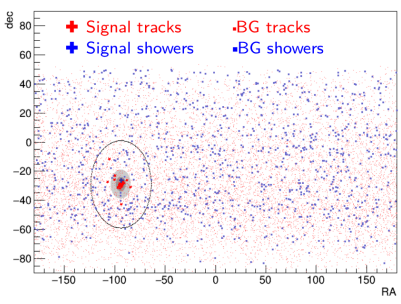
Rate of outcoming particles = velocity of incident particle $\times \sigma \times$ number of targets.

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

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

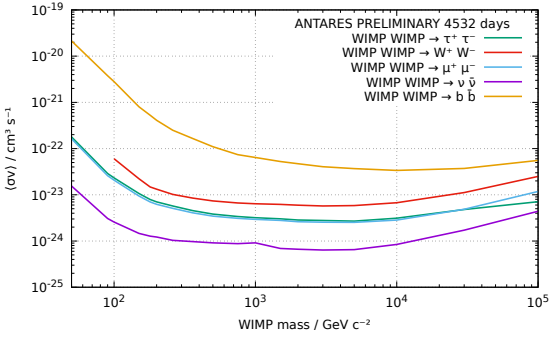
Signal = a cluster of n ν-induced events produced in dark matter pair-annihilation process.
Measurement = reconstructed arrival directions and energy proxy.
Search run with unbinned maximum likelihood method.

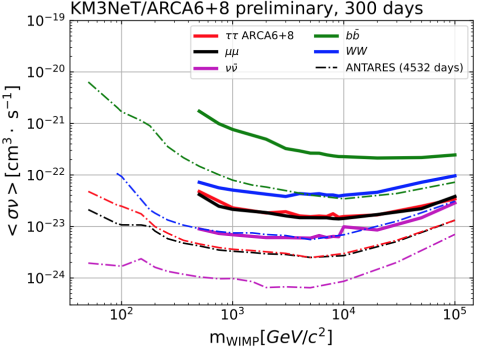




Galactic Centre - ANTARES 2007 to 2022 data + KM3NeT

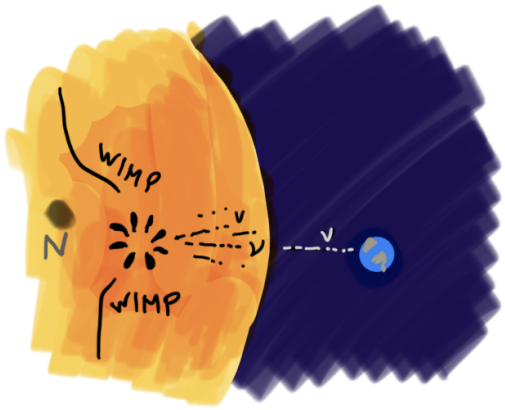
Lifetime 4532.16 days = 12.41 years. Tracks + cascades. Galactic Centre: favourable spot (in Southern sky) = visible for about 70% of the time in regular data taking mode, using Earth filter. Data TS is found consistent with background for all combinations of WIMP parameters.





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!**



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

d= distance source-detector

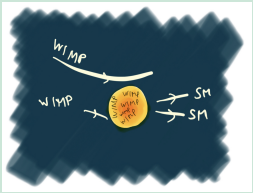
Γ_{ann}= annihilation rate

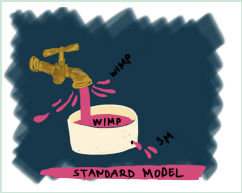
Searches for dark matter accumulating in the Sun: signal features

- 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
- Very clean: if signal $\rightarrow$ direct interpretation(astrophysical background well known)
- Less affected by halo uncertainties because point-like extension
- Signal from moving source: bias-free
- Searches with neutrino telescopes are sensitive at low velocities (= easier capture)

Searches for dark matter accumulating in the Sun

Flux of outcoming particles only depends on WIMP-nucleon scattering cross section, no longer on WIMP velocity distribution.





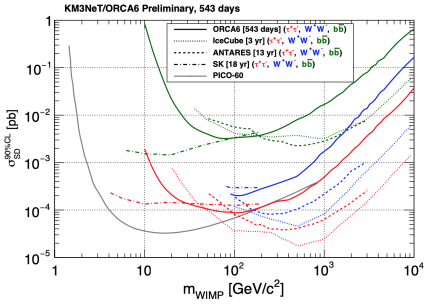
There are two types of interactions of WIMPs with ordinary matter:

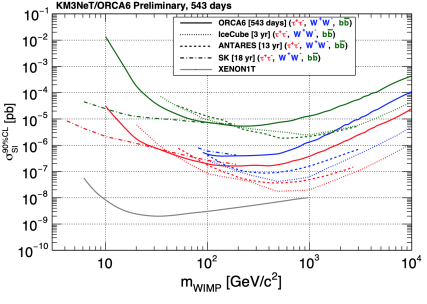
1. spin-dependent, coupling to the spin of the target nucleon
2. spin-independent, coupling to the mass of the target nucleon

Both 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]



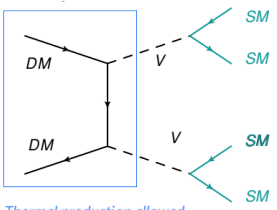


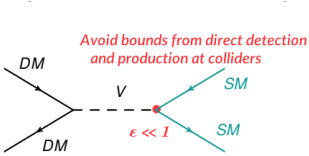
Sensitivity estimate with full ORCA detector [PoS(ICRC2019)536]
Legacy ANTARES limits in preparation for Neutrino 2024.

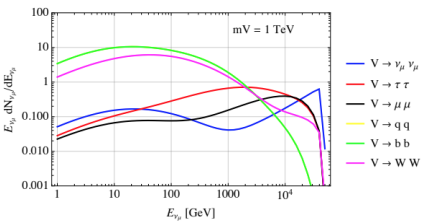
No evidence for WIMP at the GeV-TeV scale; where to search next?

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]



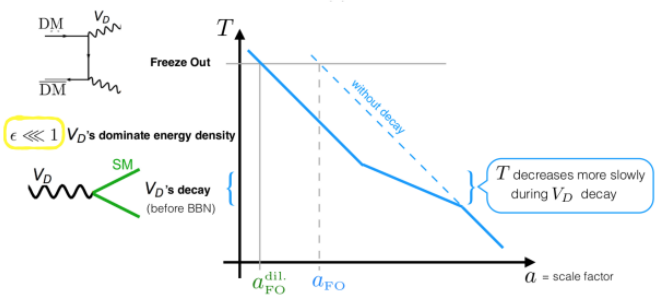


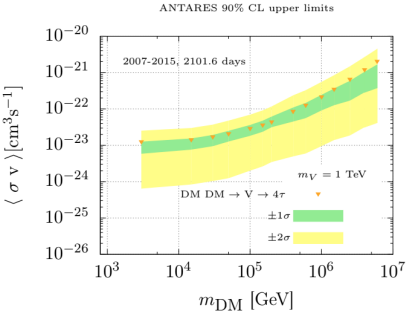


Modified cosmological evolution: universe at freeze-out is smaller $\Rightarrow$ the same amount of DM is later more diluted $\Rightarrow$ σv(DM DM $\rightarrow$ VV) smaller $\Rightarrow$ DM can be heavier

ANTARES - Heavy secluded dark matter

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





Indirect search for *new physics* signatures

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**

Neutrino oscillations as in standard scenario

Oscillations are seen with significance $> 6\sigma$ in L/E distributions through ν_μ disappearance with ORCA-6/11 data set 715 kton-years

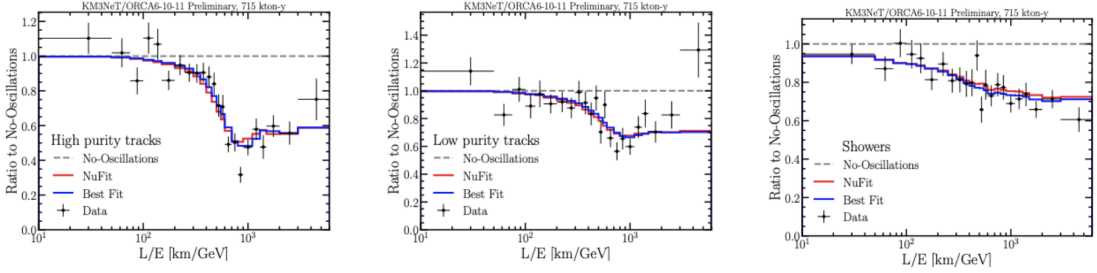
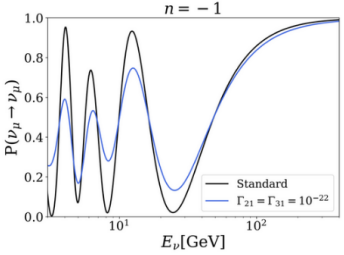
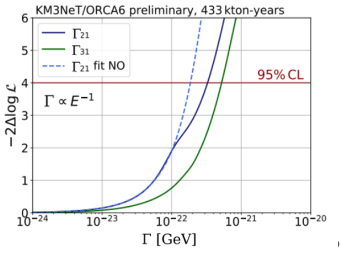


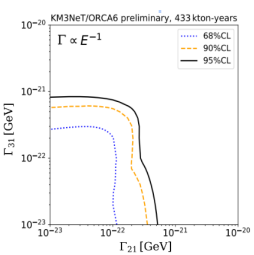
Figure: L/E distributions. Left: high-purity tracks; middle: low purity tracks; right: showers.

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)

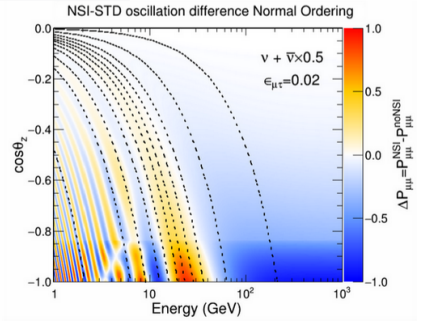
LHC has detected **no new particles** $\Rightarrow$ interest turns towards possible **new operators** that can be constructed: modifications of the Standard Model that manifest themselves indirectly.

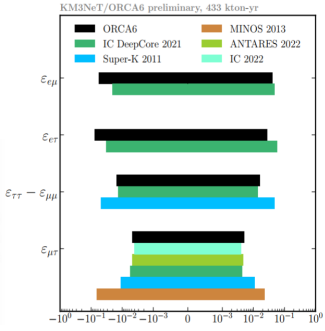
SM effective theory (SMEFT) = SM + dimension 6 operators + ...

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)

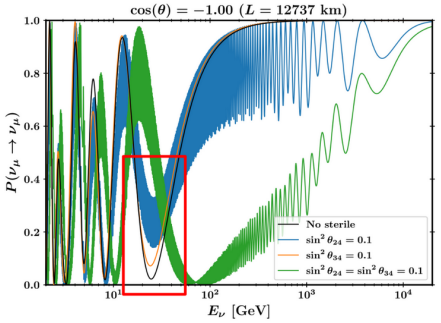
Neutral current forward scattering of neutrinos inside the Earth is modified → Flavour-dependent matter effects alter neutrino oscillations inside the Earth. [https://doi.org/10.22323/1.444.0998]

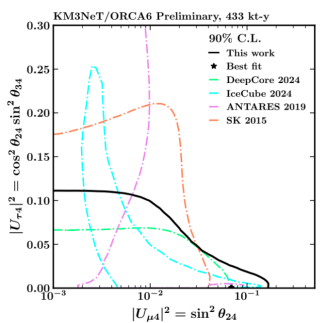




Sterile neutrinos

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





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