Indirect searches for new physics with the ANTARES and KM3NeT neutrino telescopes

Sara Rebecca Gozzini

on behalf of the ANTARES and KM3NeT Collaborations

Instituto de Física Corpuscular (IFIC), University of Valencia and CSIC

28 January 2022

Contents: physics beyond the Standard Model

1. Standard Model $=$ gauge (local symmetry) $SU(3) \otimes SU(2) \otimes U(1)$.
2. Standard Model could be an effective theory at the energy scales accessible with today's technologies.
3. Hint: Standard Model is fine-tuned on a large number of parameters.
4. Frontier is being scraped at sight: new physics of today is not what it used to be a decade ago.
5. Indirect searches for new physics: observables that can be measured and tested against theory predictions.
6. Neutrino telescopes used for new physics signatures.

Standard Model flaws

- dark matter (strongly suggested by cosmological observation, microscopic theory missing)
- matter-antimatter asymmetry (different abundance of baryons/antibaryons)
- strong CP problem (lack of CP violation in QCD)
- Higgs naturalness (fine-tuning cancelation of quadratic dependence on cutoff)
- microscopic theory and quantisation of gravity (entire missing block in the SM!)
- anomalous μ magnetic dipole moment (deviation from SM prediction, unexplained)
- origin of hierarchy in fundamental scales (bizarre, not elegant, unexplained)
- mixing matrix (untidy!)

Standard Model extensions

Gauge group extensions like grand unified theories (GUT), strings, extra-dimensions, supersymmetry (SUSY)

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

1. graviton
2. axion-like particles
3. WIMPs or other suitable DM candidates
4. 4th neutrino, sterile neutrinos, neutrino decay
5. non-standard interactions of neutrinos (NSI)

Standard Model leaks & cure

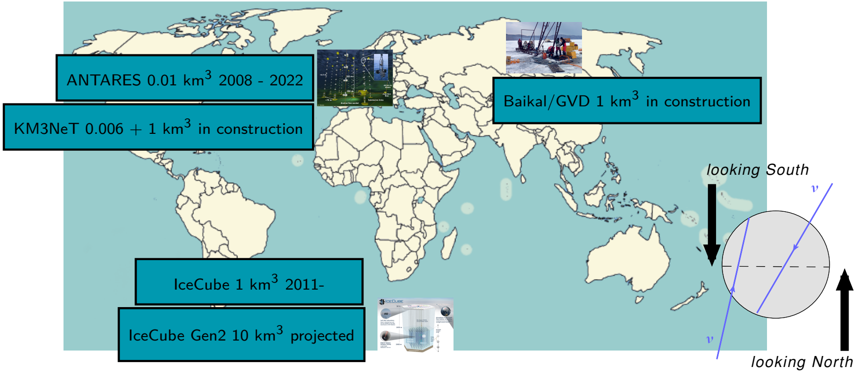
- dark matter (WIMPs or other candidates from SUSY, grand unified theories)
- matter-antimatter asymmetry (requires CP violation)
- CP violation: either in strong sector (axions) or in lepton sector (measure CP phase in ν oscillations, NSI)
- Higgs naturalness (SUSY, superstrings, extra-dimensions)
- 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 & cure: much in ν sector!

- dark matter (WIMPs or other candidates from SUSY, grand unified theories)
- matter-antimatter asymmetry (requires CP violation)
- 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)

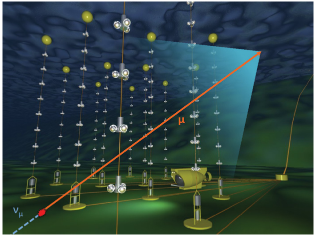
...much in ν sector $\rightarrow$ large-volume ν Cherenkov telescopes

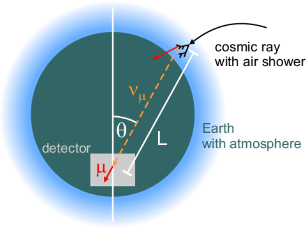
1. Work at very faint signal rates instrumenting large reservoirs of transparent medium
2. Remotely operated, almost 100% duty cycle, one unique data set (broad physics program)

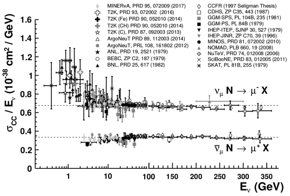


Working principle

Look through the Earth for lepton tracks from $\nu \to l$ conversion. $\sigma_{\nu \to l} \sim 10^{-38}$ cm^2 at 1 GeV!





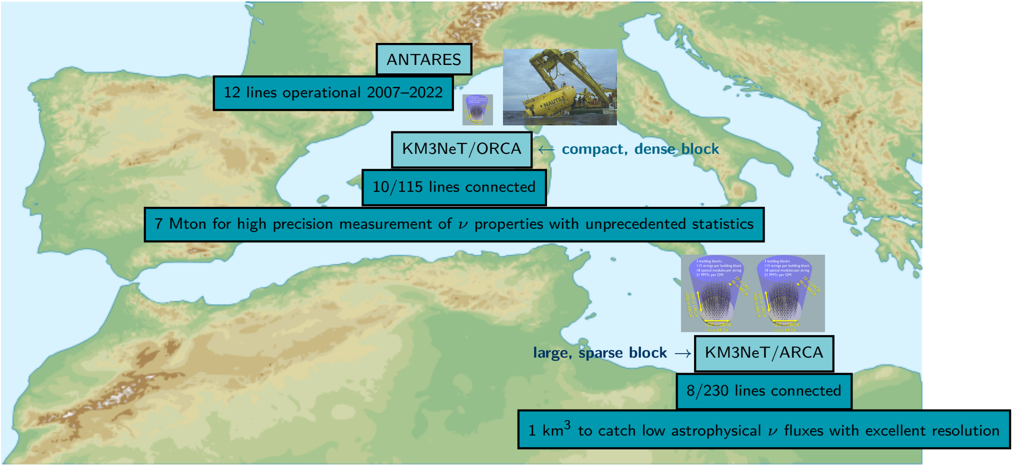


Water or ice? → in Northern Hemisphere only water available.

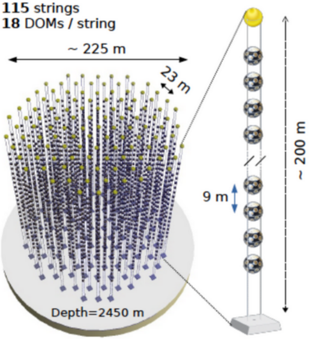
- more noise: radioactive ^{40}K decays, natural luminescence in sea
- larger scattering length: better angular resolution
- maintainable (but moving slowly)

ANTARES and KM3NeT

Cherenkov detectors instrumenting water with a grid of photomultipliers organised in lines

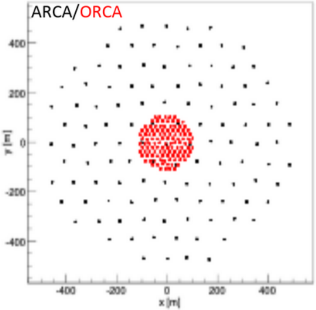


Zoom on the layout of the KM3NeT building block



ORCA and ARCA
same design

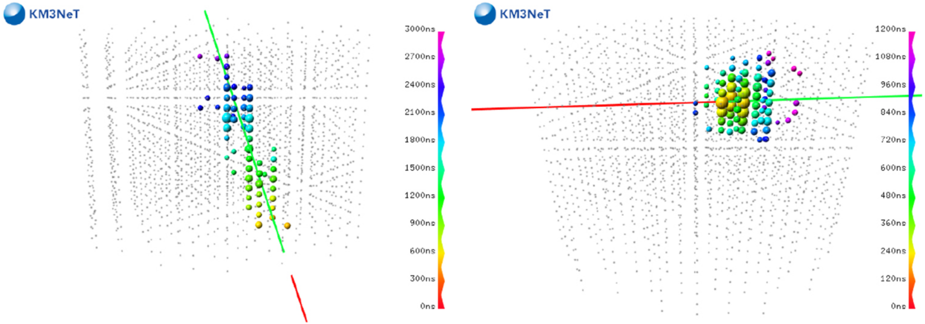
same DOM
holds 31 PMT



ARCA: 90 m inter-string
ARCA: 36 m inter-DOM
ORCA: 23 m inter-string
ORCA: 9 m inter-DOM

Experimental challenge

Astrophysical ν: atmospheric ν: atmospheric μ = 1:10^4 :10^{10}

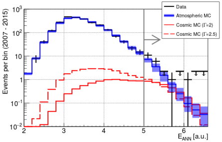


Tracks: predominantly $\nu_\mu CC$; angular resolution < 0.5 degrees (dep. on energy)
Showers: predominantly ν_e CC or any NC; angular resolution 3-10 degrees (dep. on energy)

Typical search modes for astronomy

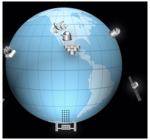
Diffuse search

Excess at high energies without directional information [ApJ Lett. 853, L7 (2018)]



Multimessenger search

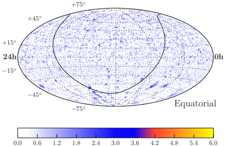
Space-time coincidence upon alert from other experiments



Point source search (all-sky)

Space (-time) clusters of events

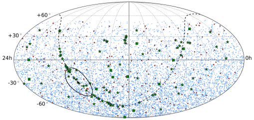
[PoS(ICRC2021)1161 (2021)]



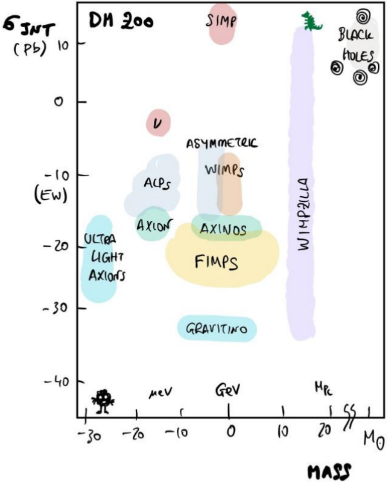
Point source search (catalogue)

Space coincidence with preselected sources

[Phys. Rev. D 96, 082001 (2017)]



Dark Matter



[Sketch by D. Cerdeño]

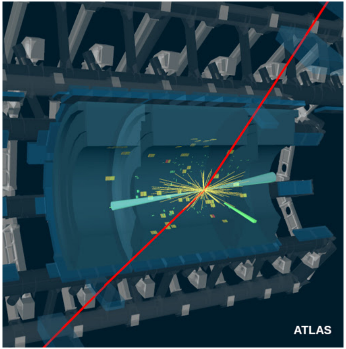
New particle outside the Standard Model, with properties learned from observational evidence

- Neutral
- Stable on cosmological scales
- Reproduces correct relic abundance
- Not excluded by current searches
- No conflicts with BBN or stellar evolution

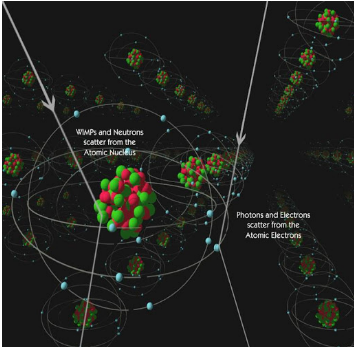
Many candidates in particle physics (WIMPs, axions, gravitino, ...) $\rightarrow$ from here on, for simplicity, WIMP-like candidate

Dark Matter: detection

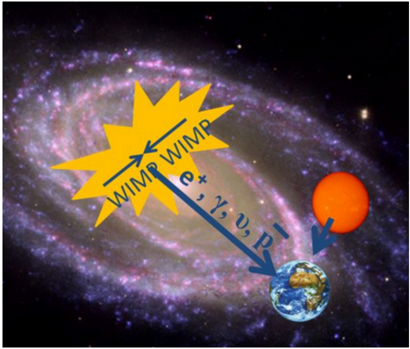
To be detected, weakly interacting dark matter particles could:



Be produced in collisions



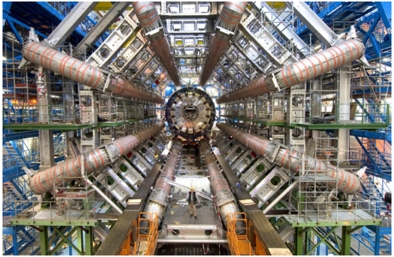
Scatter against SM particle



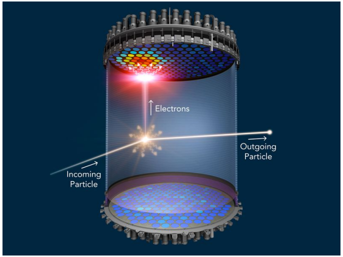
Annihilate into SM particles

Dark Matter: detection

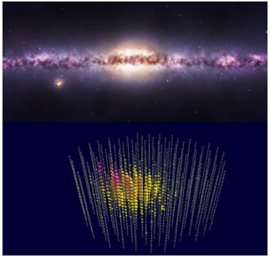
To be detected, weakly interacting dark matter particles could:



Be produced in collisions
Production searches
Colliders



Scatter against SM particle
Direct searches
Underground facilities



Annihilate into SM particles
Indirect searches
Astrophysical sources

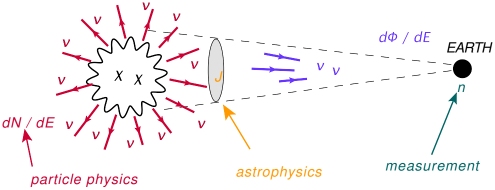
Astrophysical sources: ν (and γ) as dark matter probes

WIMP miracle: required interaction strength is of the same size as the known weak interaction. **Universality**: despite numerous models with differences in the details.$\to$

> It is possible to predict fluxes of SM products from WIMPs decay or pair-annihilation.

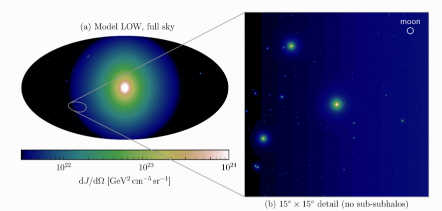
$$\mathrm{WIMP\ WIMP} \to \mathrm{interm.\,channel} \xrightarrow{\text{ANN}} \nu\overline{\nu}+X$$

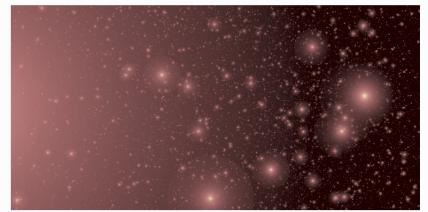
$$\mathrm{WIMP} \to \mathrm{interm.\,channel} \xrightarrow{\text{DEC}} \nu\overline{\nu}+X$$



How much dark matter?

The amount of dark matter and its spacial distribution is described through the J-factor





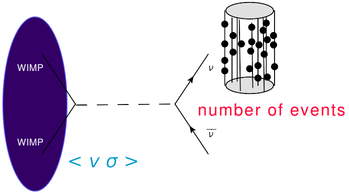
$$J_{\mathrm{ANN}} = \int_{\Omega} d\Omega \int_{l} \rho^2(r(\theta,\phi))dl \quad \text{or} \quad J_{\mathrm{DEC}} = \int_{\Omega} d\Omega \int_{l} \rho(r(\theta,\phi))dl$$

For dark matter density ρ in source at sky coord. (θ, ϕ), seen of size Ω over line of sight l

An instrument like ν telescope does not point to a specific sky direction $\rightarrow$ best dark matter sources are: Galactic Centre (extended and relatively close) or Sun (very close)

Process and measurement

Measurement = number of outcoming events → translates into number of processes.



$$\frac{n}{t} = \frac{1}{2}\langle \sigma v \rangle \int_0^{M_{\mathrm{WIMP}}} \frac{dN}{dE} dE \, \frac{1}{4\pi} \, J \frac{1}{M^2_{\mathrm{WIMP}}} \, \mathcal{A}(M_{\mathrm{WIMP}})$$

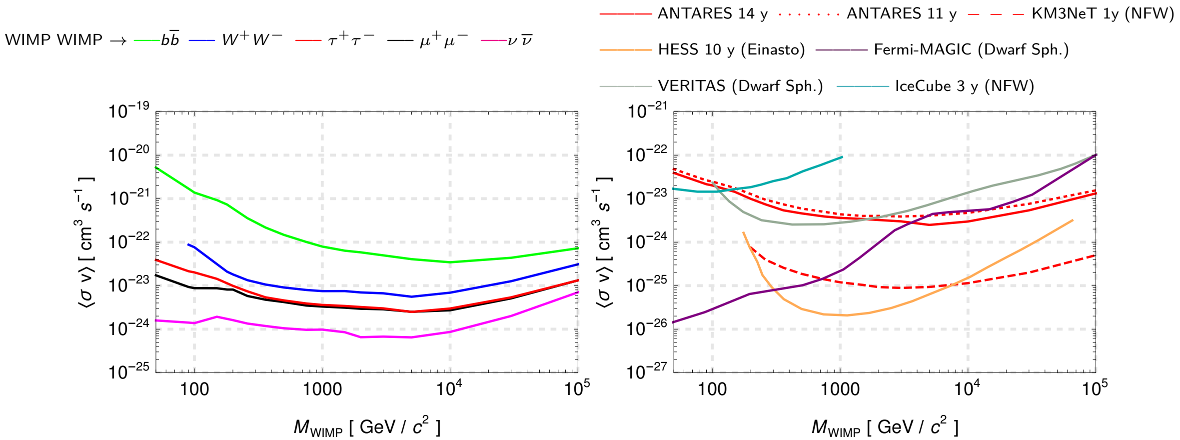
> The probability for **one** process to happen is $\propto$ velocity of projectile $\times\, \sigma$.

But projectile (WIMPs) are non-relativistic → $v \ll c$ ⇒ only know a velocity distribution ⇒ limit on velocity-averaged cross-section $\langle \sigma v \rangle$.

Mass: free to span a wide range: searches performed with ANTARES, ORCA and ARCA.

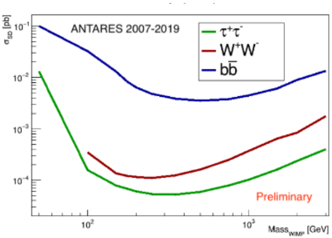
Limits on pair annihilation rate

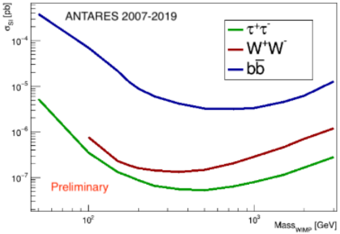
ANTARES data Jan. 2007 - Feb. 2020 (11174 tracks, 225 showers, 3845 days lifetime) is compatible with background [Phys. Lett. B 805, 135439 (2020)] + sensitivity of KM3NeT (1 year).

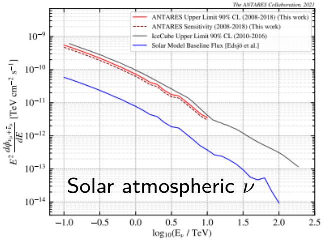


Searches towards the Sun

- In equilibrium between capture and annihilation
- Sensitive at low velocities (= easier capture)
- Clean: if signal $\rightarrow$ direct interpretation (astro bg well known)

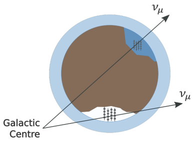


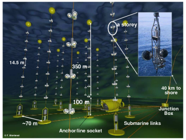




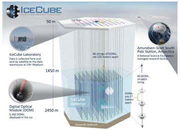
Sun has known isotopic abundance $\Rightarrow$ sensitive to WIMP-nucleon cross section for spin-dependent and spin-independent case (odd or even atomic number)

ANTARES and IceCube have conducted a combined-likelihood search in their joint data set: [Phys. Rev. D 102, 082002 (2020)]

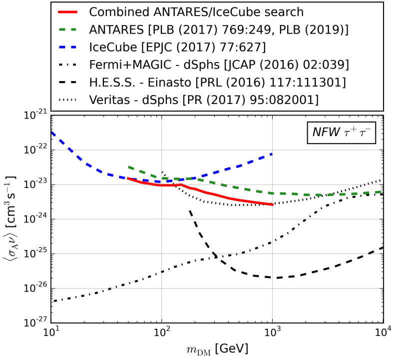




12 lines between 2 and 2.4 km underwater



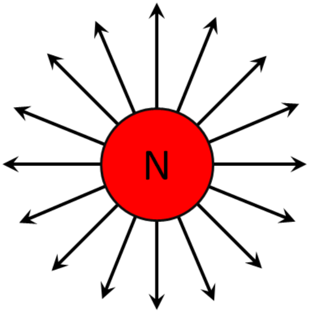
86 strings between 1.5 and 2.5 km in ice

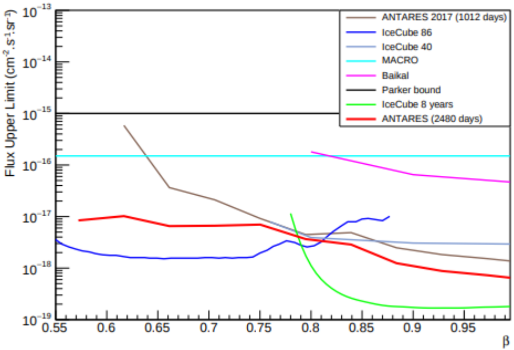


Interest in starting a joint $\gamma + \nu$ analysis, involving MAGIC, HESS, VERITAS, Fermi and ANTARES + IceCube, considering common channels and yield via EW corrections

Exotic particles: magnetic monopoles

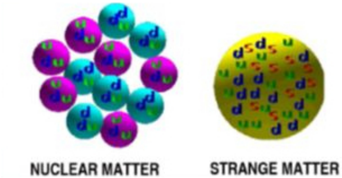
Created during early phase of universe, before symmetry breaking of GUT (+ topological defects) into $SU(3) \otimes SU(2) \otimes U(1)$. Magnetic monopoles with masses $< 10^{14}$ GeV/c^2 would be accelerated by galactic magnetic fields emit a large amount of Cherenkov light.





Exotic particles: very massive nuclearites

Massive strange quark matter, ground state of QCD (aggregates with equal content in u, d, s quarks), produced in violent astrophysical processes, and reaching the Earth in the cosmic radiation. Detectable through black-body radiation (collisional heating)



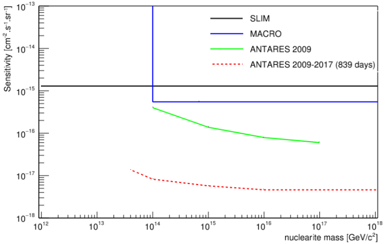


Figure: Sensitivities on the flux of nuclearites with mass $> 10^{13}$ GeV with 9 years of ANTARES data. KM3NeT sensitivity study is ongoing with both ORCA and ARCA [PoS(ICRC2021)532].

Fundamental neutrino properties

Oscillations, mass ordering and related observables

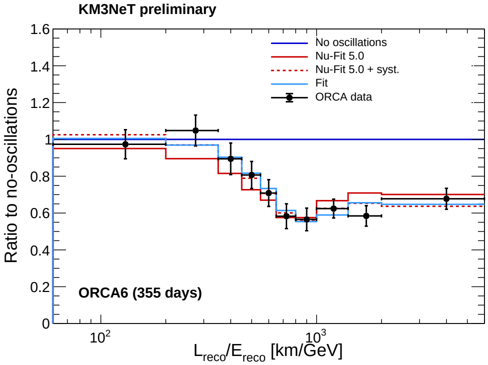
Flavour-related observables require particle identification in detector (e, μ, τ lepton?). Ideal region for search is GeV and just above, at the first disappearance peak.

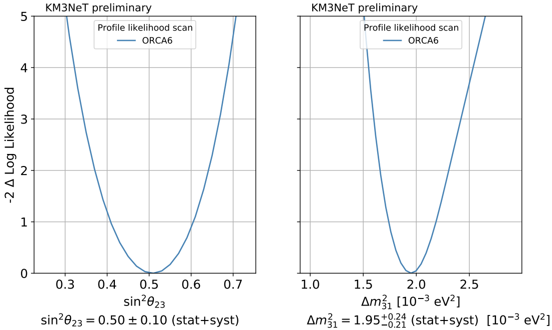
> KM3NeT/ORCA is a **dense** detector unit that can distinguish particle topologies (tracks, showers, double-bang) at GeV energies.

115 optical modules spaced 9 m vertically and 23 horizontally instrument a 7 Mton volume for collection of atmospheric neutrinos with very high statistics.

Neutrino oscillations

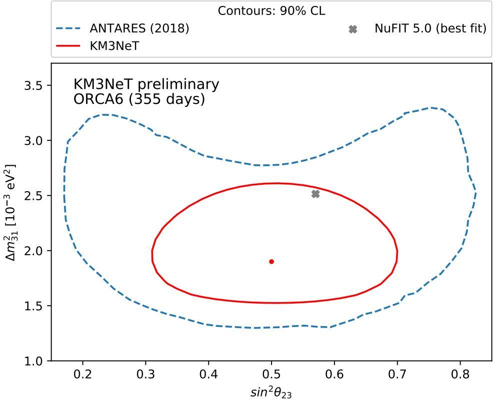
Oscillation parameter θ_{23} and Δm^2_{31} are measured through ν_μ disappearance (muons are seen as tracks from ν_μ CC events). Oscillations seen at $5.9\,\sigma$ with 6 lines of KM3NeT/ORCA [PoS(ICRC2021)1123].

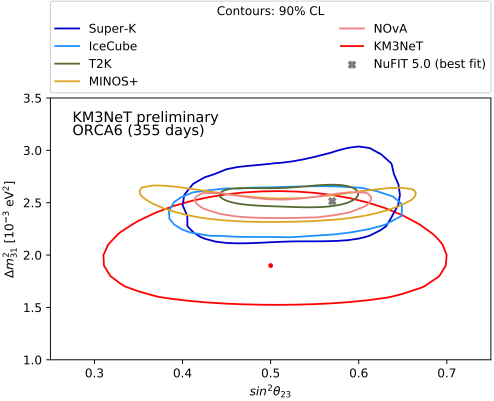




Neutrino oscillations

Best-fit measurements performed from energy 20 GeV with ANTARES, 3 GeV for ORCA.





Neutrino mass ordering

Matter resonance at 5 GeV affects: ν if normal ordering (NO), $\bar{\nu}$ if inverted ordering (IO).

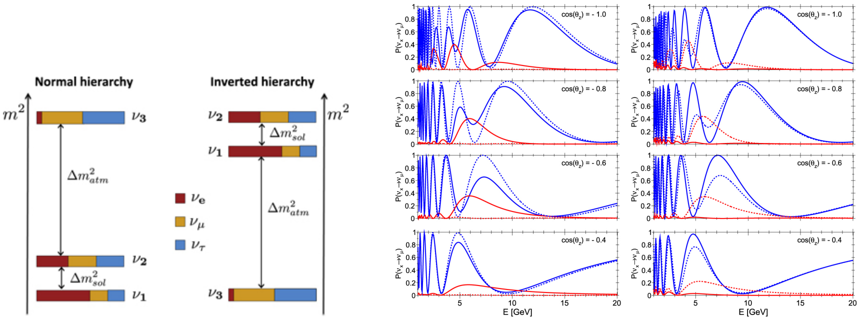
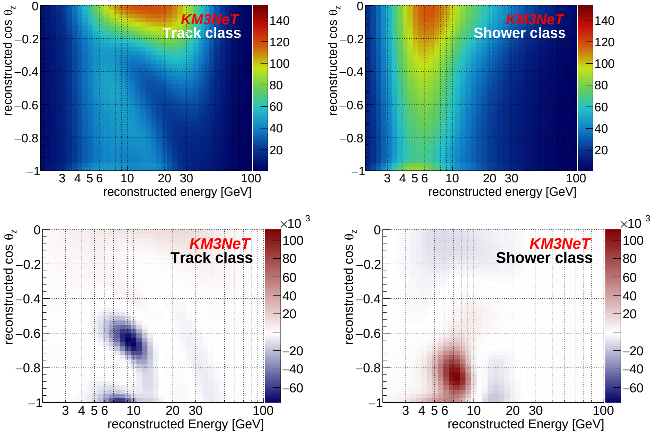


Figure: Right: oscillation probabilities $\nu_\mu \to \nu_\mu$ and $\nu_e \to \nu_\mu$ for different energies and baselines. The solid (dashed) lines are for NO (IO), ν (left) and $\bar{\nu}$ (right).

Neutrino mass ordering

Matter resonance at 5 GeV affects: ν if normal ordering (NO), $\bar{\nu}$ if inverted ordering (IO). Sensitivity due to ν-$\bar{\nu}$ asymmetry in flux and cross-section. Both μ- and e-channels contribute.

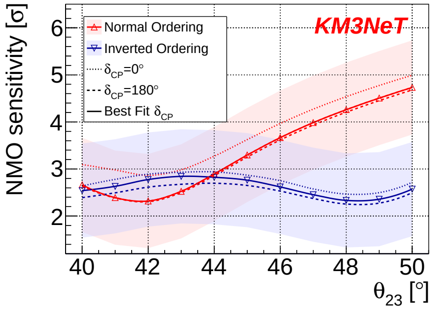


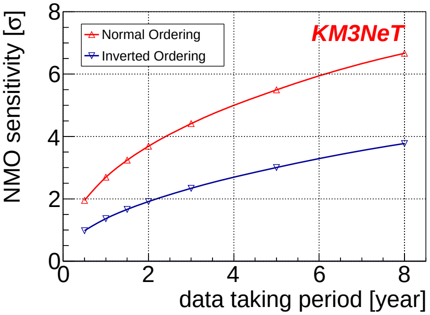
Expected sensitivity: number of expected events with normal/inverted hierarchy $(N_{IH} - N_{NH})/N_{NH}$

and relative χ^2. Left: muons; right: electrons. Electron channel is more robust against detector resolution.

Neutrino mass ordering and CP violation

Number of events also depends on θ_{23} and δ_{CP}. Neutrino mass ordering can be determined with ORCA with 3σ after 3 years of operation [Eur. Phys. J. C 82, 26 (2022)].





Sensitivity to ν_τ appearance

Determined by measuring the normalisation factor n_{ν_τ} of the ν_τ contribution. A measurement in tension with n_{ν_τ}=1 would provide a model-independent test for new physics.

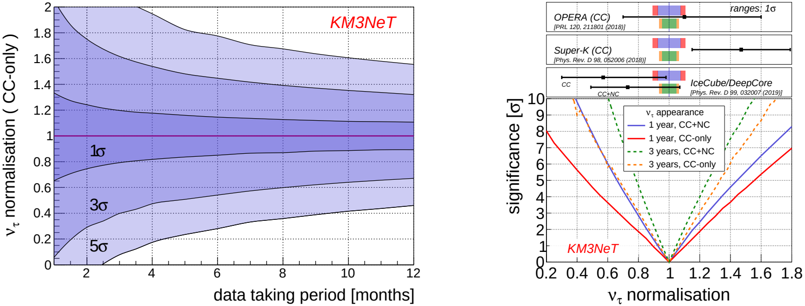


Figure: Left: sensitivity to ν_τ ($\bar{\nu}_\tau$) appearance as a function of time. Right: sensitivity to ν_τ ($\bar{\nu}_\tau$) appearance for CC and CC+NC normalisation scaling after one and three years of operation.

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)

New leptonic currents that imply modifications to the flavour transition probability in matter.
ANTARES and ORCA have sensitivity at higher energies than the first oscillation minimum.
Competitors DUNE, T2HK and JUNO will not issue results for the next 5-10 years.

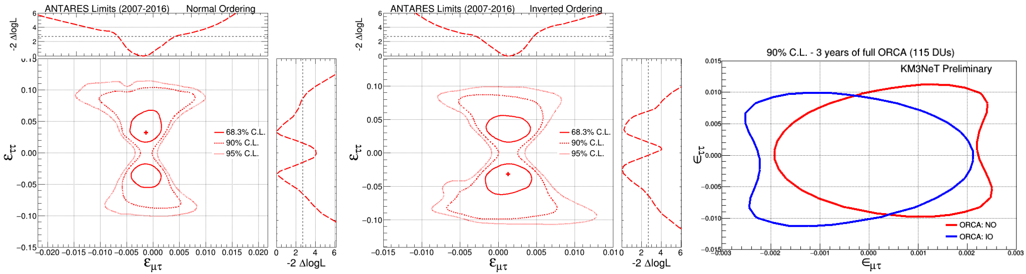
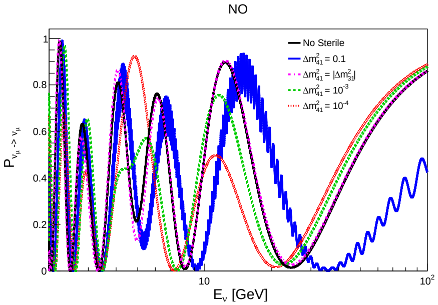
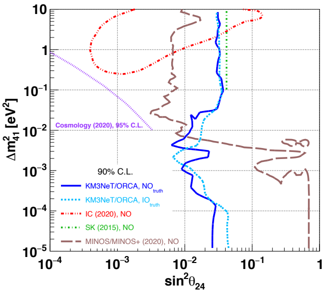


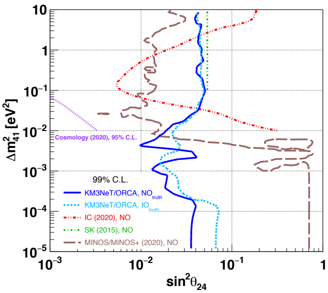
Figure: Upper limits with 10 years of ANTARES data normal ordering (left), inverted ordering (middle) and KM3NeT 3 years predictions.

Sterile neutrinos

Could be at the origin of short-baseline anomalies. Search method: sensitivity to mixing parameters between active and sterile neutrinos. Track (ν_μ) channel more efficient.







Neutrino decay

Scenario: standard oscillation pattern is altered by decay of heaviest ν_3 mass state as $\nu_3 \rightarrow \nu_{\text{sterile}} +$ scalar (or Majoron). This affects atmospheric oscillation parameters.

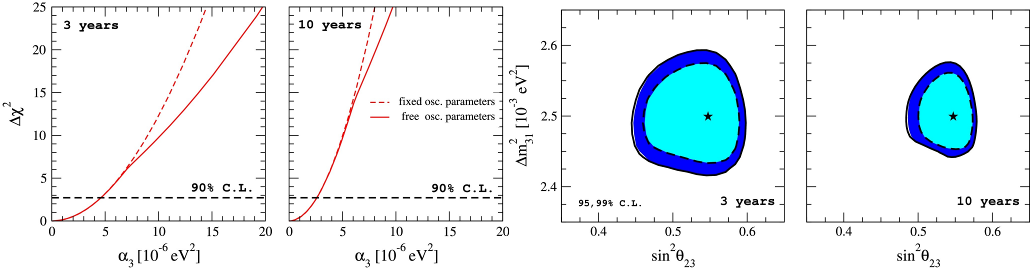
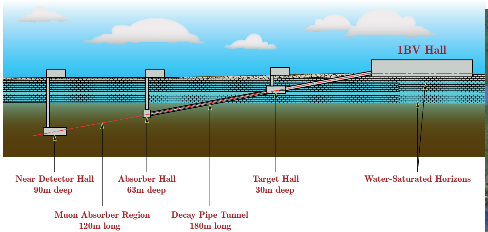
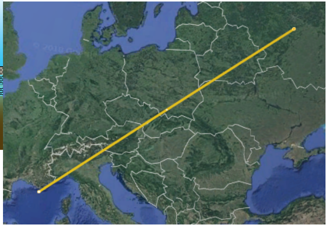


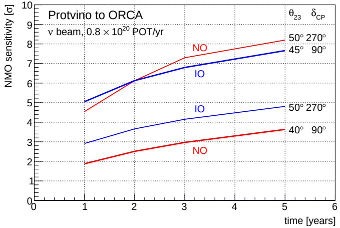
Figure: Left: sensitivity of ORCA to the neutrino decay constant α_3. Right: atmospheric oscillation parameters in the standard picture (filled regions) and with neutrino decay (black lines)

Protvino-to-ORCA P2O

Flavour oscillations of νs over a long baseline (2500 km, first oscillation minimum of ν_μ to ν_e at 5 GeV) with possibility of ν-tagging. Use KM3NeT/ORCA as a far detector; upgrades to the beam production site at Protvino are required. Letter of intent: EPJ 79:758 (2019)







Wrap-up: ANTARES, KM3NeT and indirect searches for new physics

Broad landscape of possibilities to measure new physics obervables with neutrino telescopes, that are very versatile instruments:

1. Searches for WIMP dark-matter pair-annihilation
   - ANTARES (limits on Galactic Centre, Sun competitive with direct searches)
   - KM3NeT ORCA and ARCA (sensitivities on Galactic Centre, Sun. First data under analysis)
   - Combined ANTARES-IceCube search (future: include γ-ray data)
2. Exotic particles: monopoles, nuclearites
3. Measurement of oscillation parameters and hunt for δ_{CP}
   - ANTARES (limits with 10 years of data)
   - KM3NeT/ORCA (limits with ORCA6, sensitivities with full ORCA)
   - P2O (new very long-baseline setup, ambitious project)
4. Sensitivity to sterile neutrinos
5. Sensitivity to contribution of ν_τ appearance
6. Limits on observation of non-standard interactions of neutrinos