Weak Interactions and Neutrinos
7-12 June 2021

Searches for NSI and Sterile Neutrinos with ANTARES and KM3NeT

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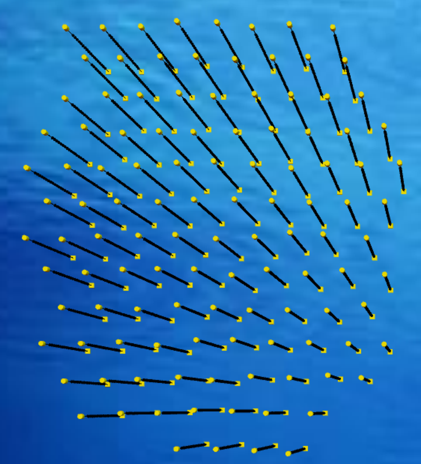
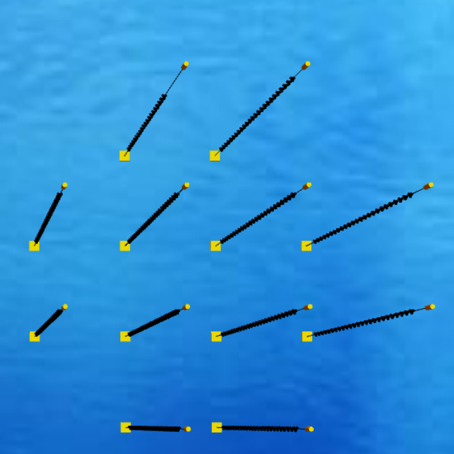
- ~7 Mton detector
- 115 lines
- 18 DOMs per line
- 31 PMTs per DOM
- ~20m horiz. spacing
- 9m vert. spacing

KM3Net DOM 31x3'' PMTs

KM3NeT/ORCA



ANTARES



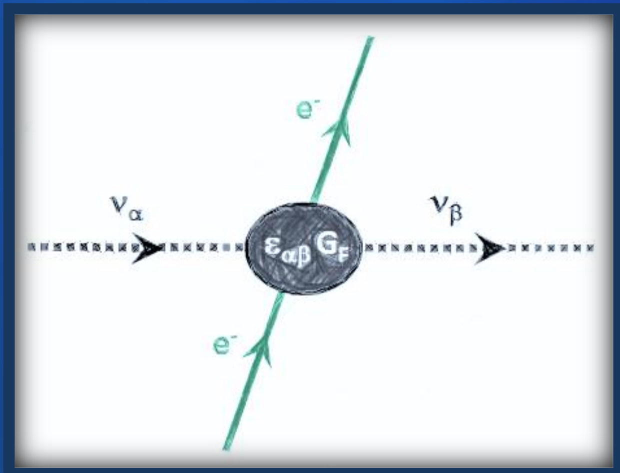
ANTARES Storey 3x10'' PMTs

- ~10 Mton detector
- 12 lines
- 25 Storeys per line
- 3 PMTs per Storey
- ~60m horiz. spacing
- 14.5m vert. spacing

Scan for animations
https://tinyurl.com/4ckwj8h6

Non-Standard Interactions

- Matter effects arise from coherent CC forward scattering of neutrinos on electrons in the earth's interior, introducing a flavour imbalance.
- If additional neutrino-electron interactions exist beyond the Standard Model, they may modify the neutrino effective propagation Hamiltonian.



- Strong bounds exist on some NSI couplings, but limits on ε_{ee}, $\varepsilon_{e\tau}$ and $\varepsilon_{\tau\tau}$ are currently larger than 10% of G_F [4].

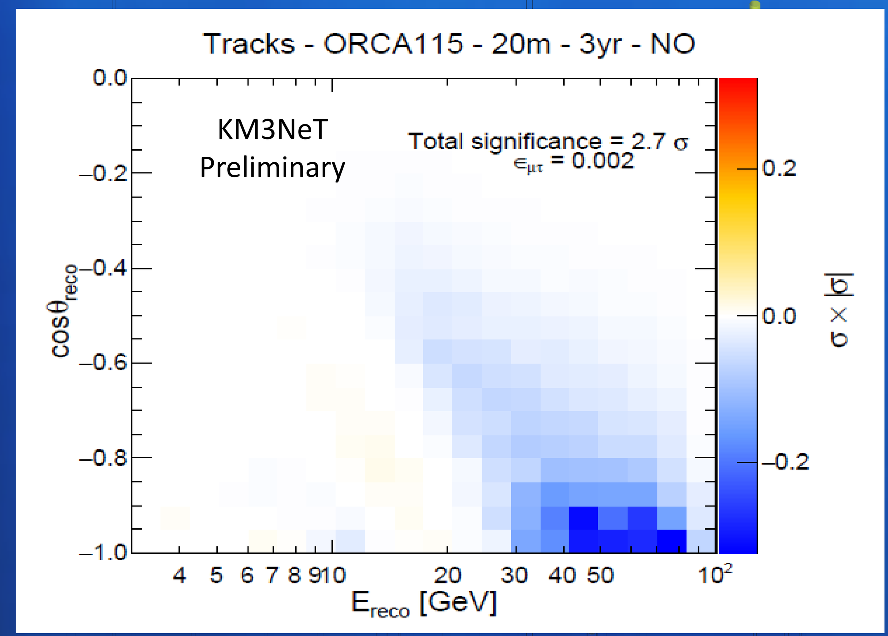
$$\begin{pmatrix} |\epsilon_{ee}| < 0.5 & |\epsilon_{e\mu}| < 0.05 & |\epsilon_{e\tau}| < 0.1 \\ & |\epsilon_{\mu\mu}| < 0.4 & |\epsilon_{\mu\tau}| < 0.007 \\ & & |\epsilon_{\tau\tau}| < 0.4 \end{pmatrix}$$

- Atmospheric neutrinos provide an excellent probe of these NSI, since strong matter effects are expected to occur at the scale of the Fermi interaction.

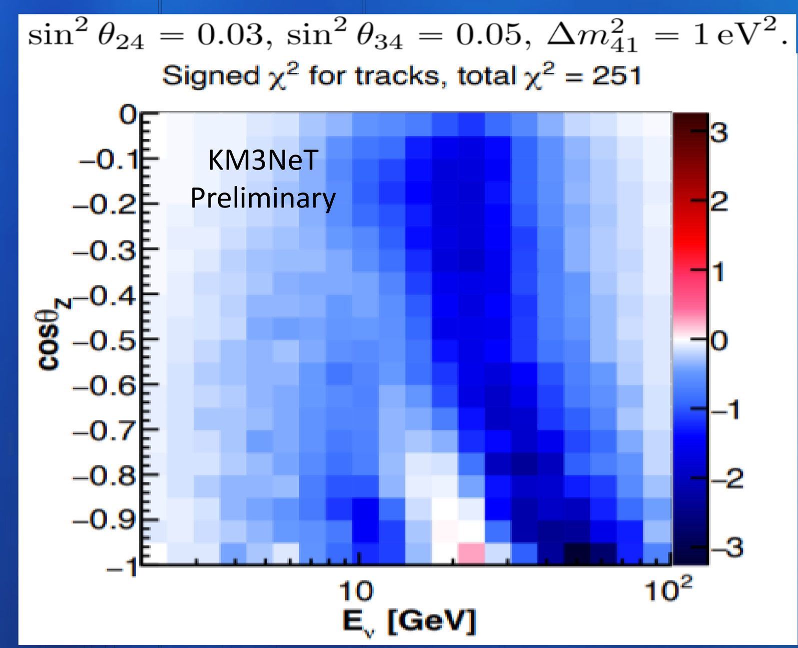
$$H_{eff} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger + V_e \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{bmatrix}$$

[4] JHEP 08 (2018) 180, 12 (2020) 152

Measurement Principle



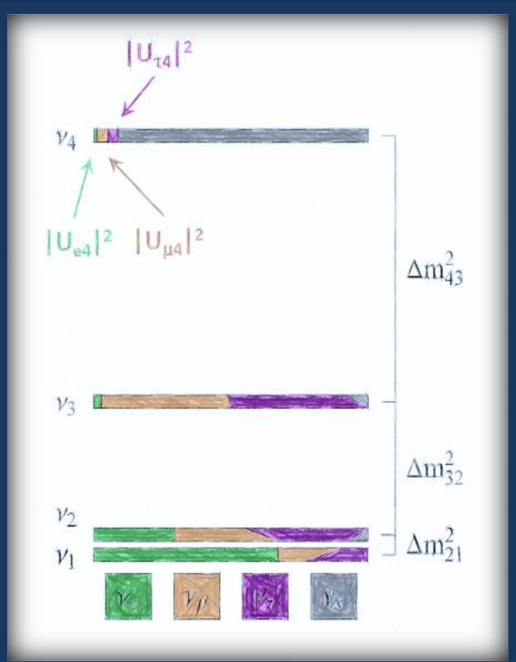
NSI Effect Illustration



Sterile ν Effect Illustration

- We can probe NSI and active-sterile neutrino mixing by searching for changes in the oscillation pattern due to resonant transitions in both the ν_μ and ν_e channels.
- Strong matter effects mean the difference in pattern expected is heavily dependent in both energy and zenith angle of the neutrino. This provides many control regions mitigating systematic uncertainties.
- The richness of patterns in the oscillation spectra allows neutrino telescopes to probe many BSM parameters simultaneously. Many parameter degeneracies present in fixed baselines can be resolved by observing the full range of neutrino paths through the earth.

Sterile Neutrinos



- Almost all neutrino oscillation data can be well described by a set of 3 neutrino mass eigenstates coupling to the 3 charged leptons according to the PMNS matrix.
- Some hints of a 4th neutrino mass eigenstate, with very weak coupling to the charged leptons have been found, most notably by the LSND [1] and MiniBooNE [2] collaborations.
- This new, eV scale, mass eigenstate changes the effective oscillation Hamiltonian and generates new resonant transition effects due to propagation in matter [3].

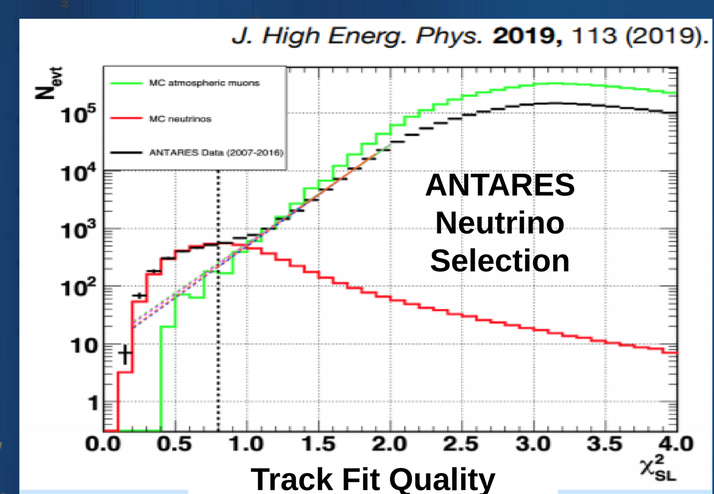
$$H_{eff} = U_S \begin{bmatrix} 0 & 0 & 0 & 0 & \cdots \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 & 0 & \cdots \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} & 0 & \cdots \\ 0 & 0 & 0 & \frac{\Delta m^2_{41}}{2E} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} U_S^\dagger + \begin{bmatrix} V_e & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & V_n/2 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

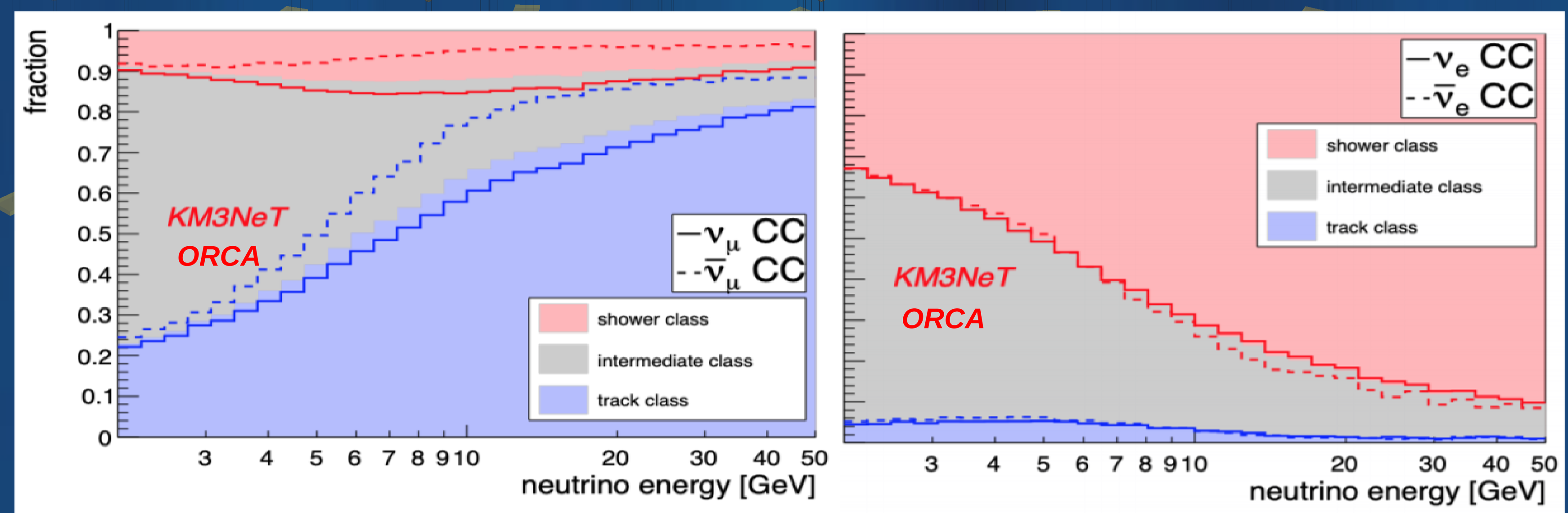
$$U_S = U_{N-1,N} \cdots U_{34} U^{(c)}_{24} U^{(c)}_{14} U_{23} U^{(c)}_{13} U_{12}$$

[1] Phys. Rev. D 64, 112007 (2001)
[2] Phys. Rev. Lett. 110, 161801 (2013)
[3] JHEP 0712, 014 (2007)

Methods

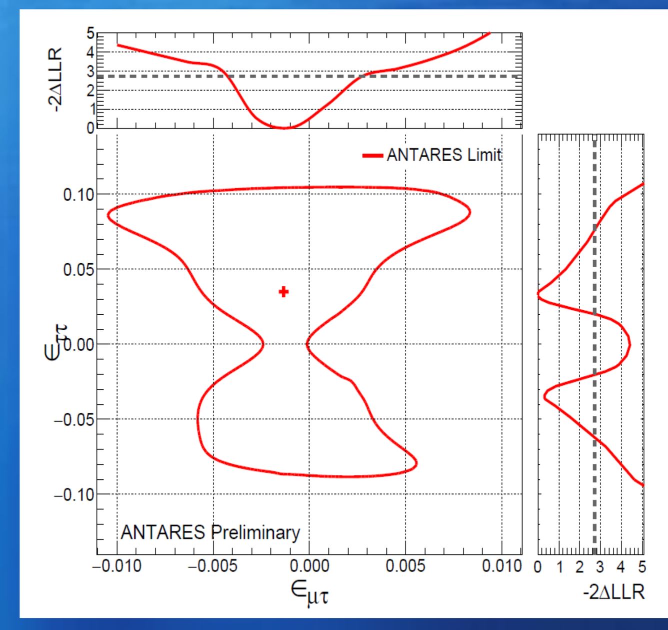
- ANTARES has focused on track-like topologies. The sparse detector is sensitive mostly to neutrino energies above 20 GeV
- ORCA's dense instrumentation provides not only a much lower energy threshold ~3 GeV, but also the ability to identify shower-like topologies. The analysis is performed in 3 bins of track score.



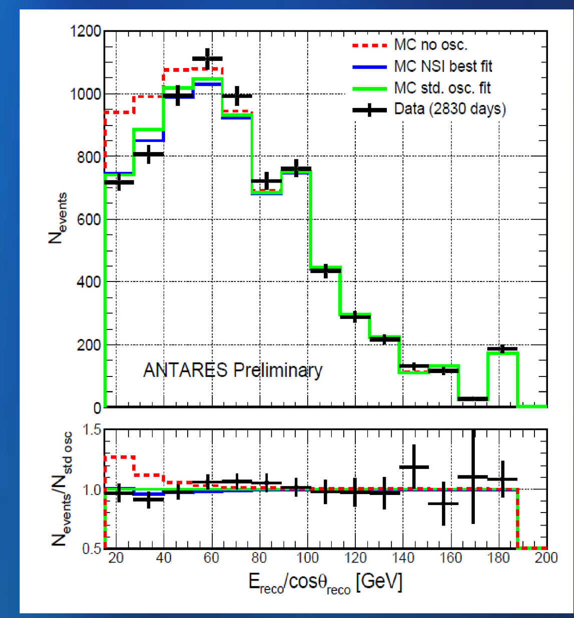


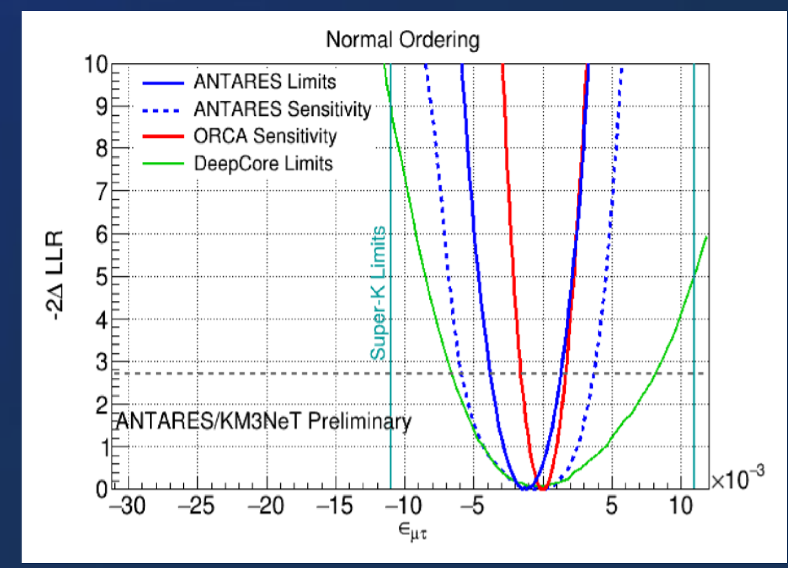
NSI Results

$$-4.2\times10^{-3} < \epsilon_{\mu\tau} < 2.7\times10^{-3} \quad \text{(at 90\% C.L.)},$$
$$-6.1\times10^{-2} < \epsilon_{\tau\tau} < -2.1\times10^{-2} \quad \text{and} \quad 2.1\times10^{-2} < \epsilon_{\tau\tau} < 7.3\times10^{-2} \quad \text{(at 90\% C.L.)}$$



- With 10 years of data, ANTARES has set the world's strongest limits on the $\varepsilon_{\mu\tau}$ NSI parameter.
- A mild preference for non-zero NSI is observed due to a small deficit of upgoing events at low energies.
- ORCA is expected to improve this result, with a factor of 3 stronger sensitivity.
- Using track and shower topologies, ORCA will also constrain the full NSI Hamiltonian with ~1% precision



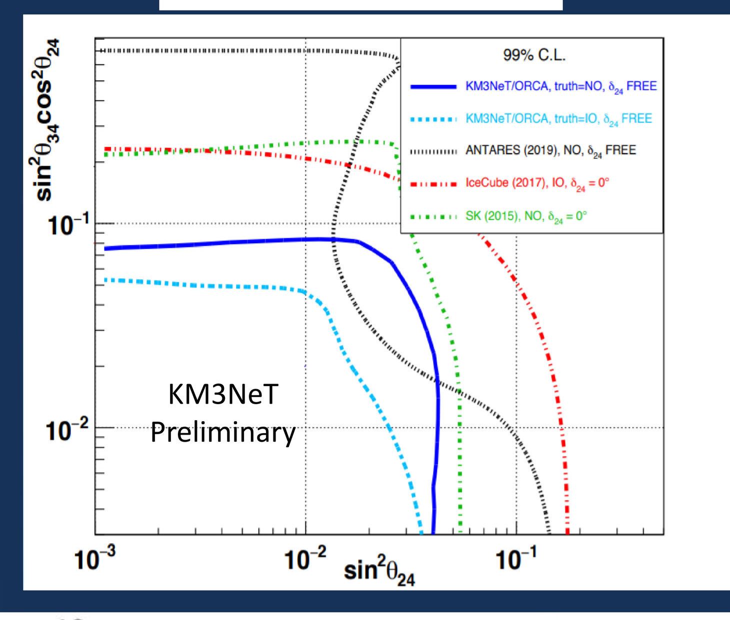


Sterile Neutrino Results

- Analysis of 10 years of ANTARES data has yielded no evidence of active-sterile mixing in atmospheric neutrinos with a track topology.

$$|U_{\mu4}|^2 < 0.007\ (0.13) \text{ at } 90\%\ (99\%) \text{ CL},$$
$$|U_{\tau4}|^2 < 0.40\ (0.68) \text{ at } 90\%\ (99\%) \text{ CL}.$$

- This result adds to the strong tension between null results in muon disapp. searches and excesses of ν_e events observed by LSND and MiniBooNE.



- Significant improvements are expected with ORCA, probing $|U_{\tau4}|^2$ mixing with world leading sensitivity.
- ORCA will also test the largely unexplored region of very low Δm^2_{41} with a few % precision on $|U_{\mu4}|^2$.