Neutrino Oscillation Studies with KM3NeT/ORCA

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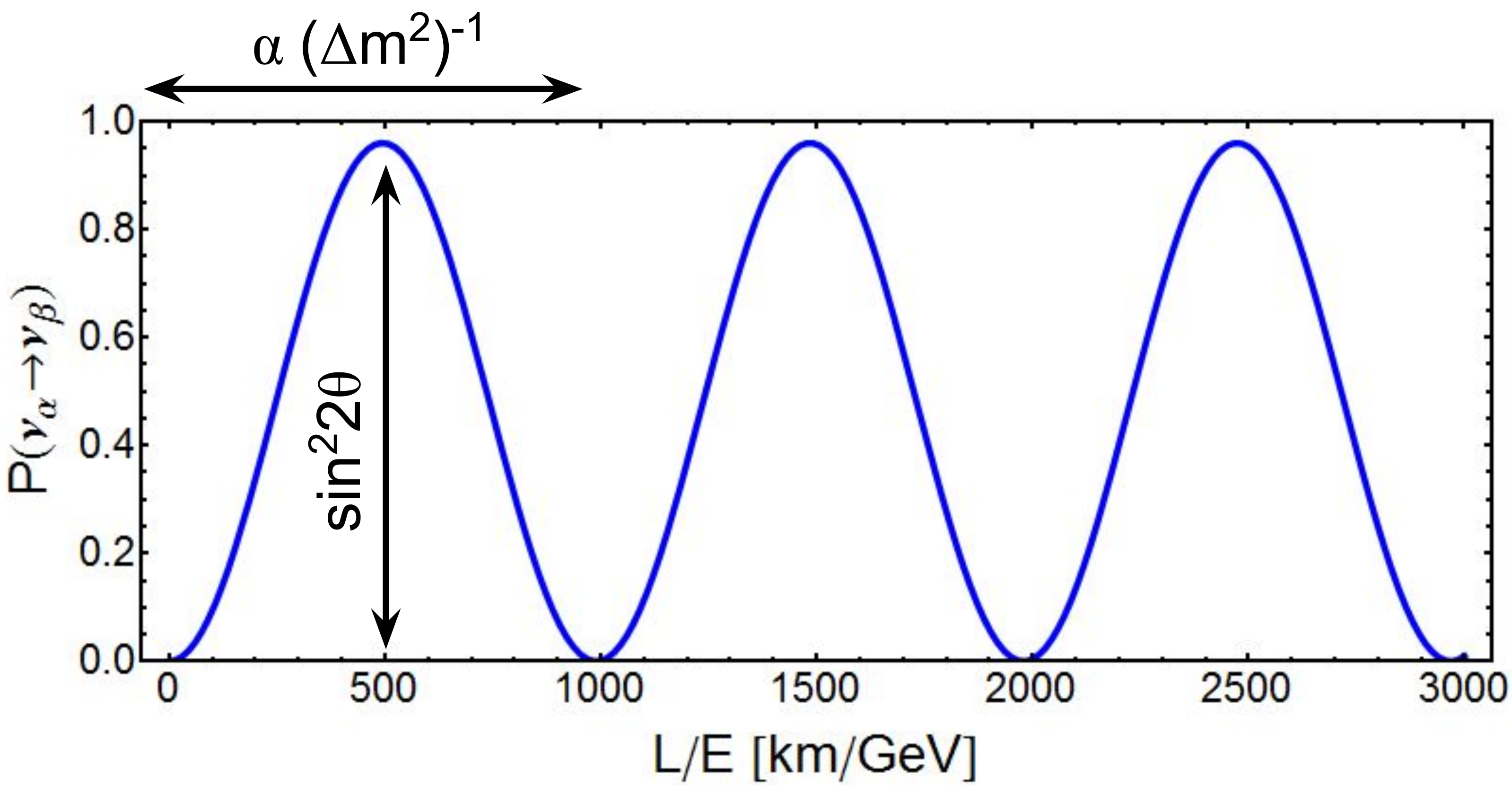
16 November 2022

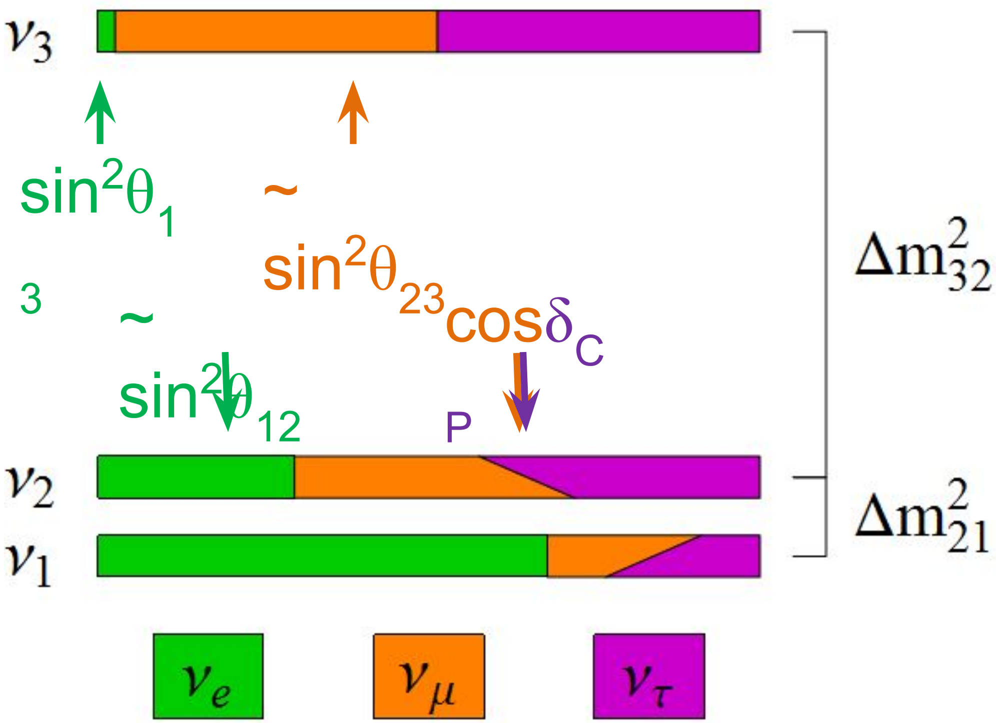
Neutrino Oscillations

$$P(\nu_\alpha \to \nu_\beta) \approx \sin^2 2\theta \times \sin^2\left(1.27 \times \Delta m^2\ [\mathrm{eV}^2] \times L/E\ [\mathrm{km/GeV}]\right)$$



Neutrino Oscillations

- There are 3 neutrinos, so things are a bit more complicated
- Two independent differences in mass-squared (Δm^2_{21}, Δm^2_{32})
- 3 mixing angles (θ_{12}, θ_{13}, θ_{23}) and 1 CPV phase δ_{CP}



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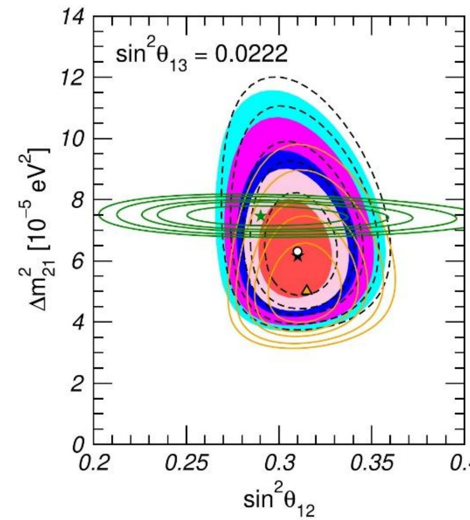
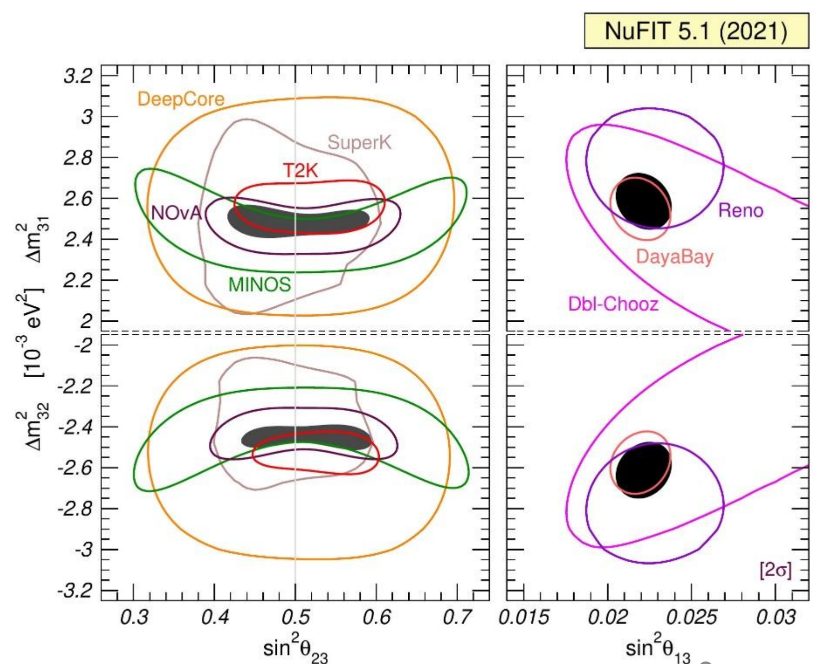


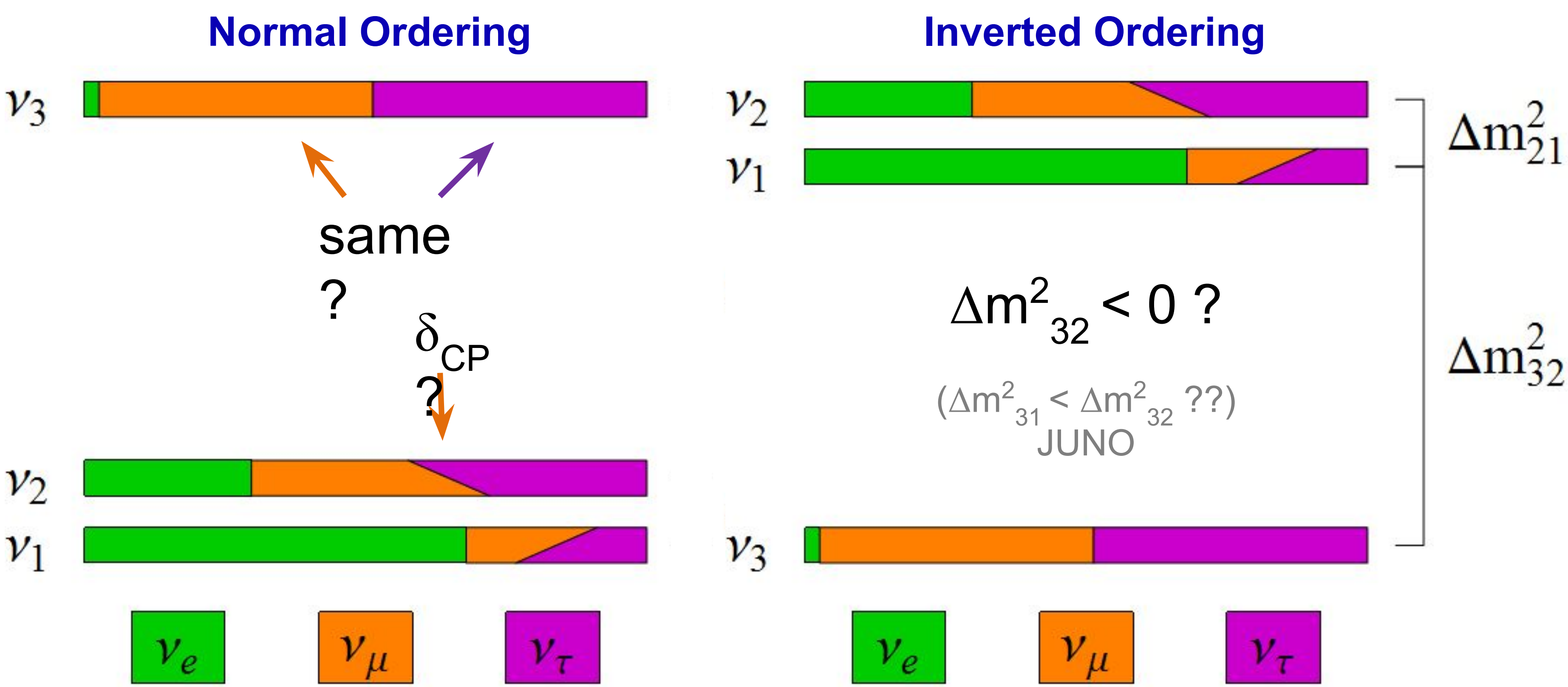


Missing Pieces

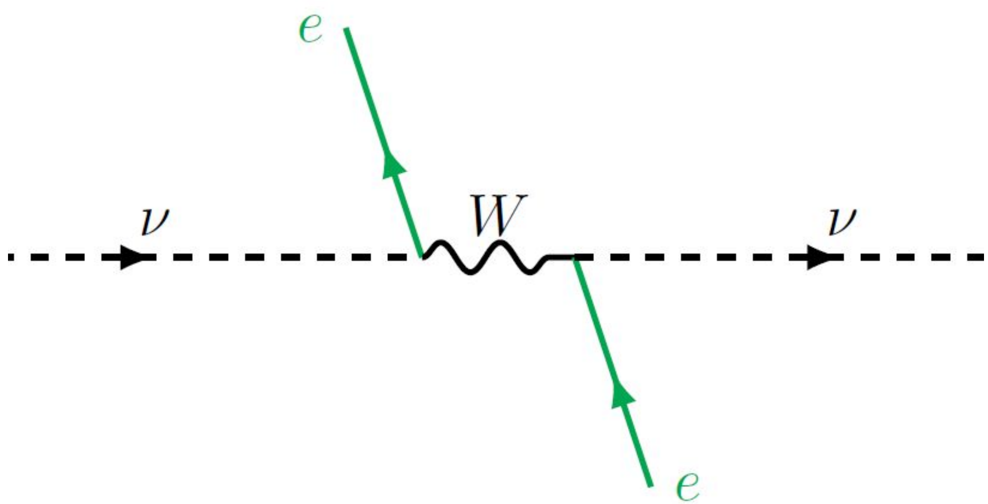
symmetries

$$\sin^2 2\theta \times \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- Is $\theta_{23} = \pi/4$? Underlying symmetry?
- Do neutrinos violate CP? (δ_{CP})
- **What is the mass ordering? (Mass Hierarchy)**

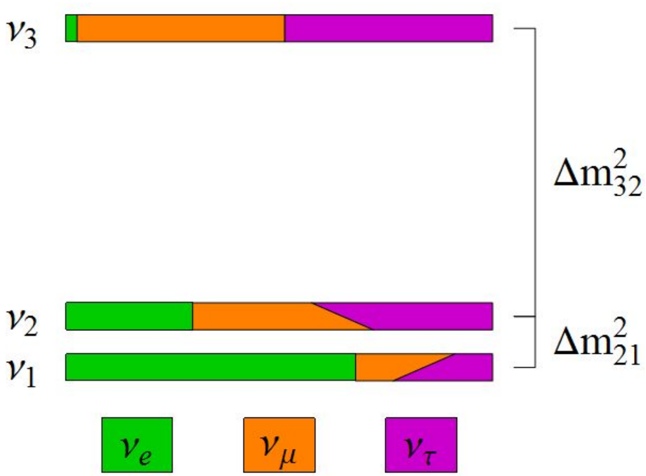


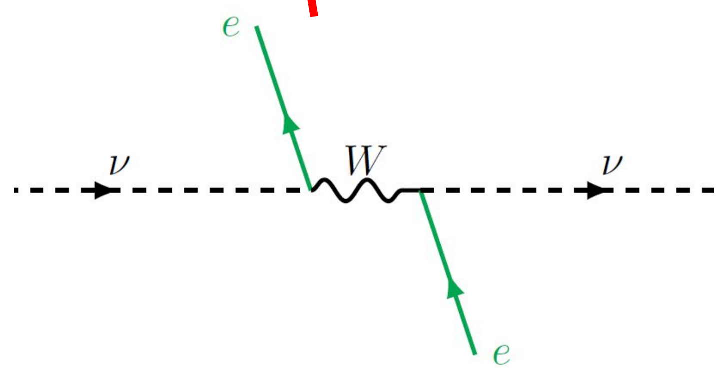
One weird trick to measure the Mass Ordering…



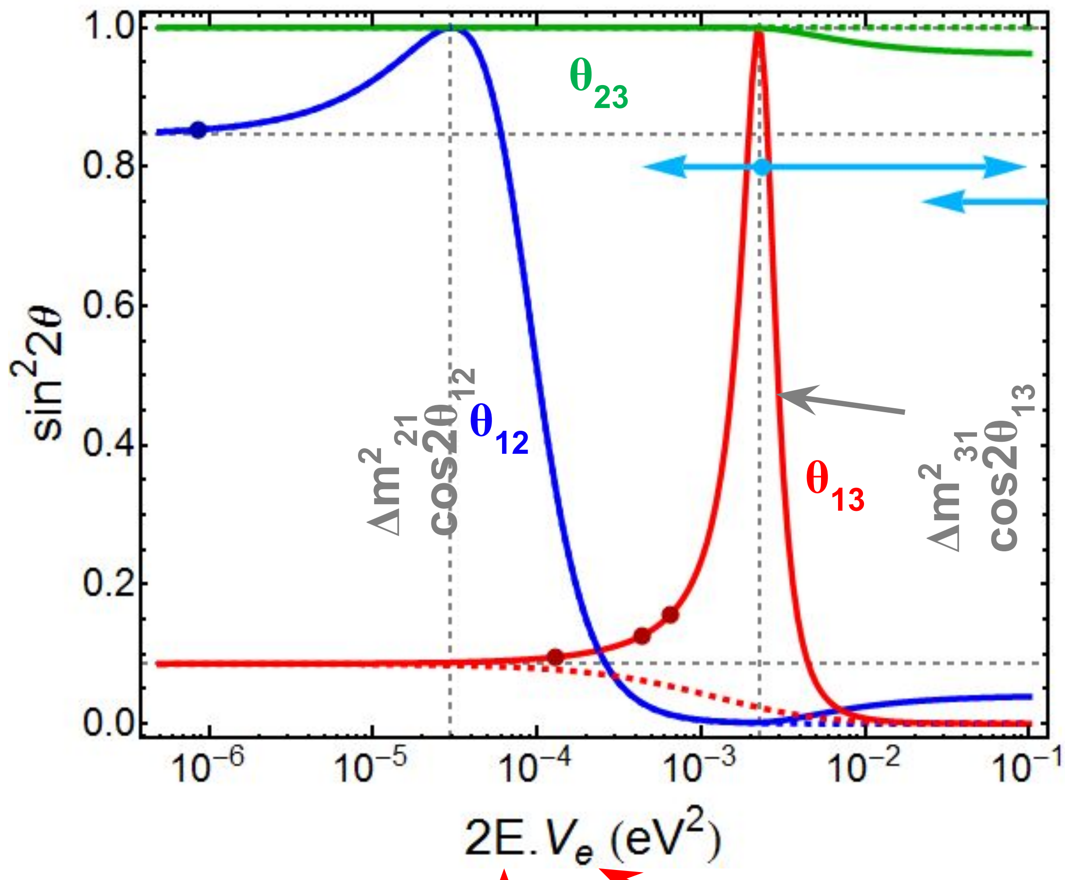
Matter Effects

$$H_{eff} = \overbrace{U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger}^{H_0} + \overbrace{V_e \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}}^{V}$$



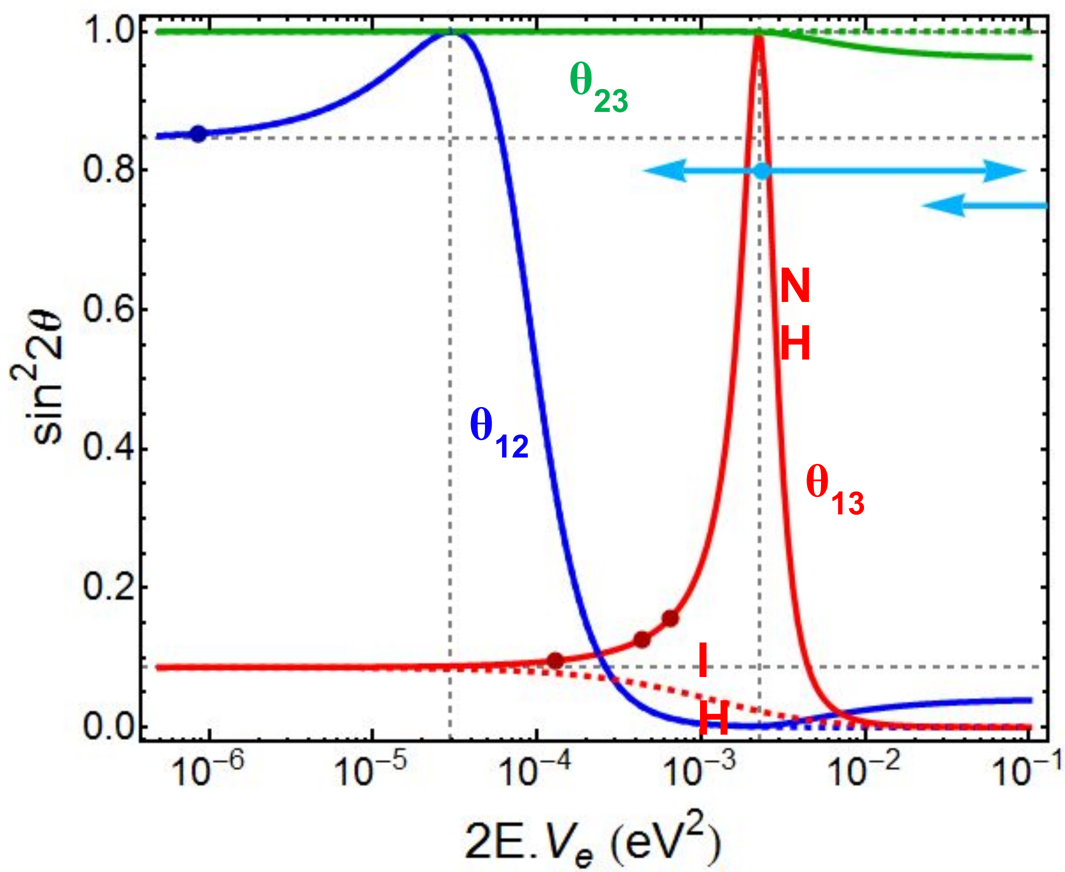


Resonances



$$H_{eff} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger + V_e \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Resonances



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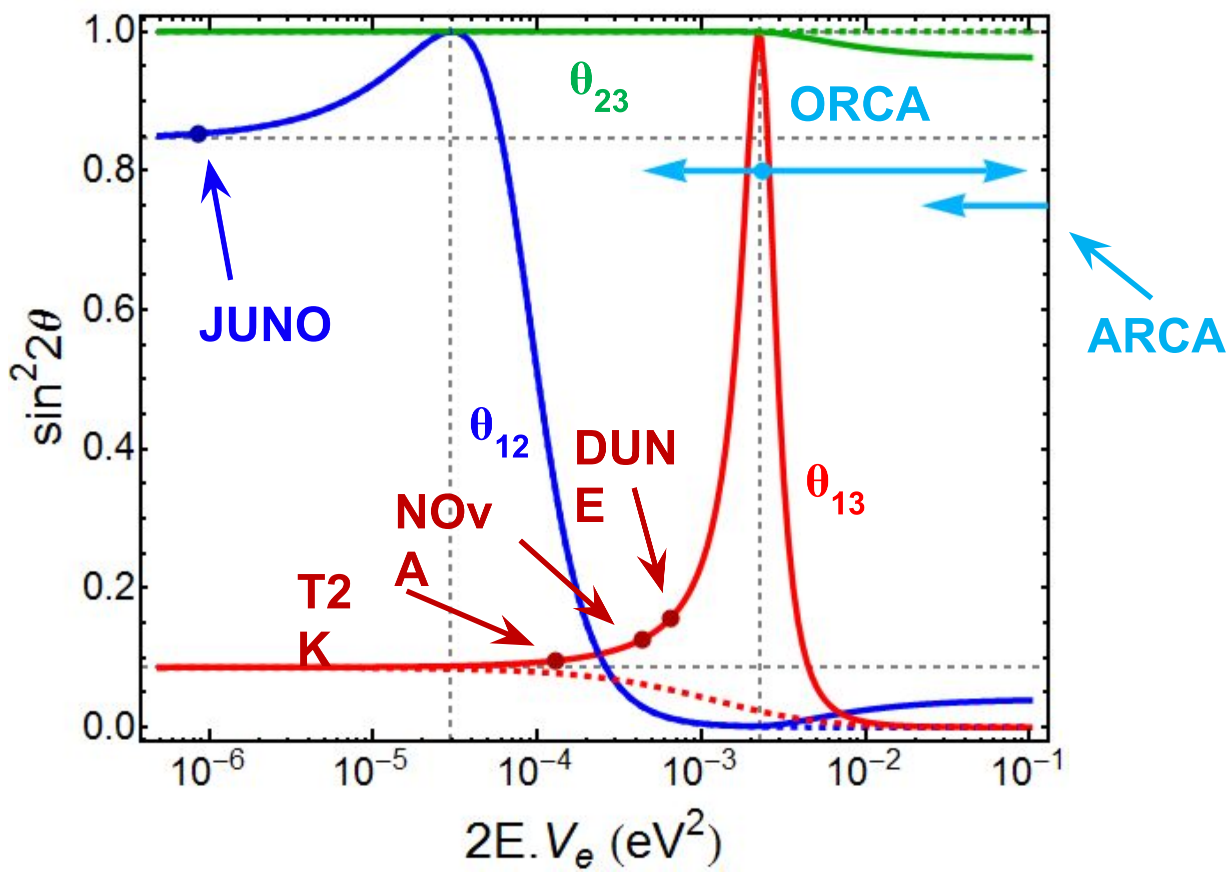
Resonances



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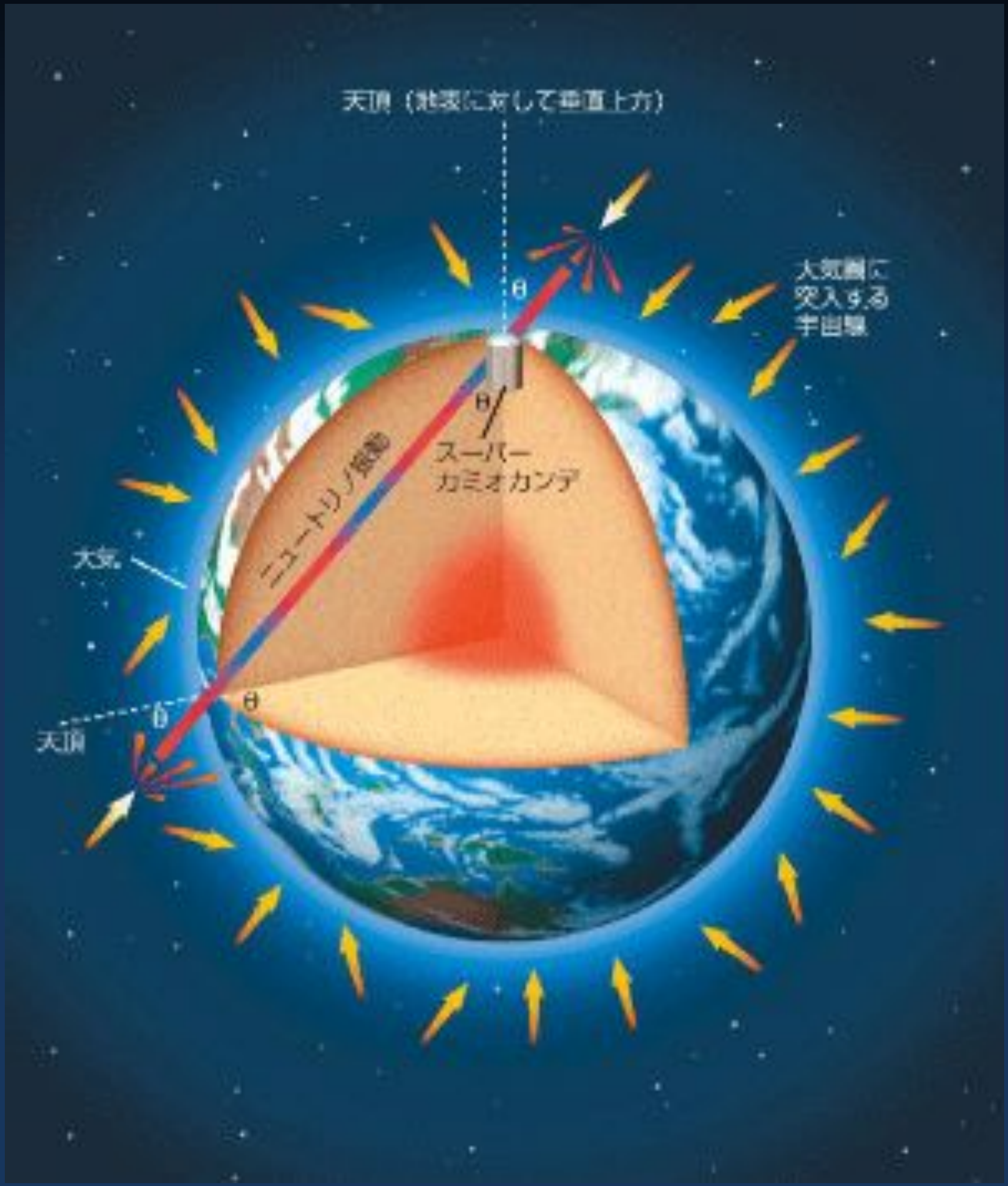
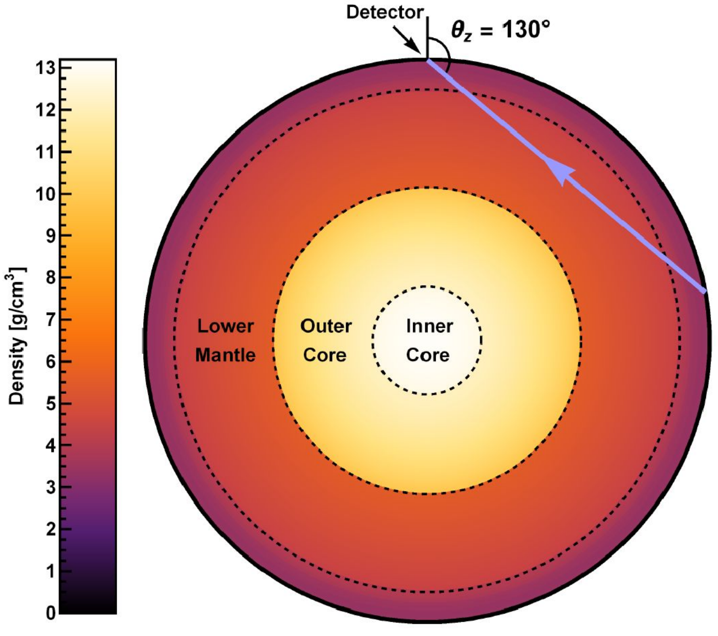
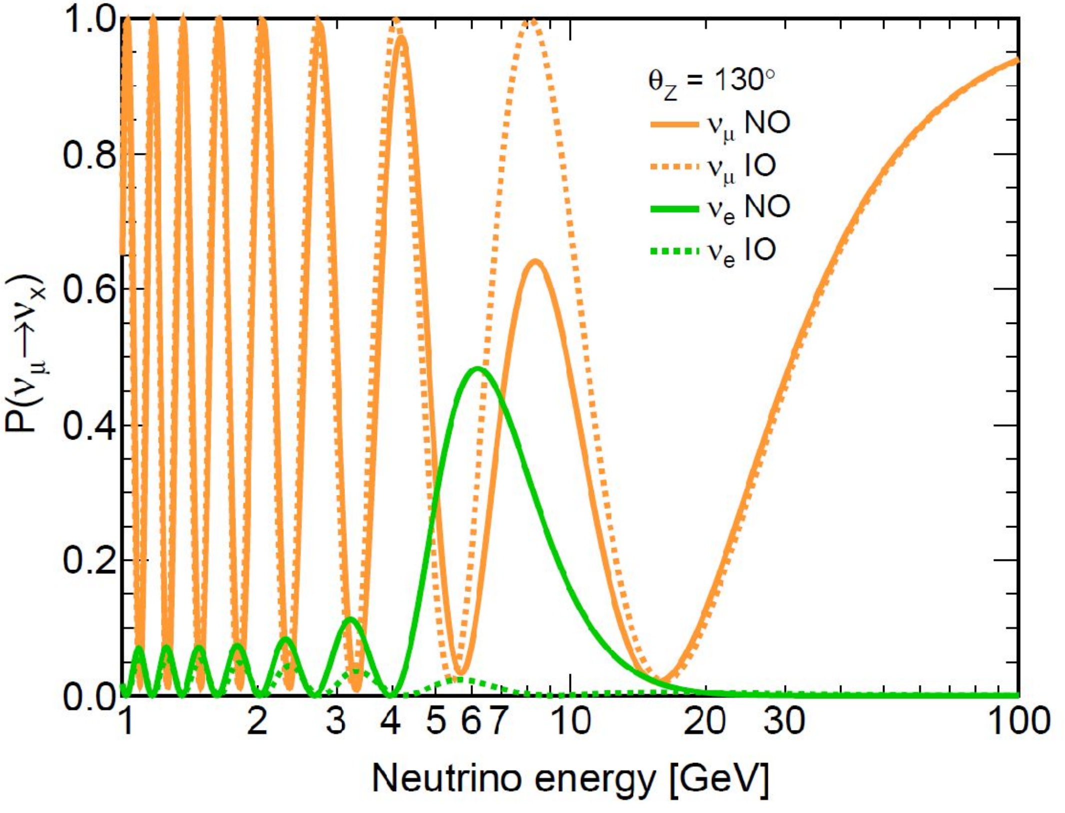
Atmospheric Neutrinos



Sensitive to Mass Ordering at resonance energies

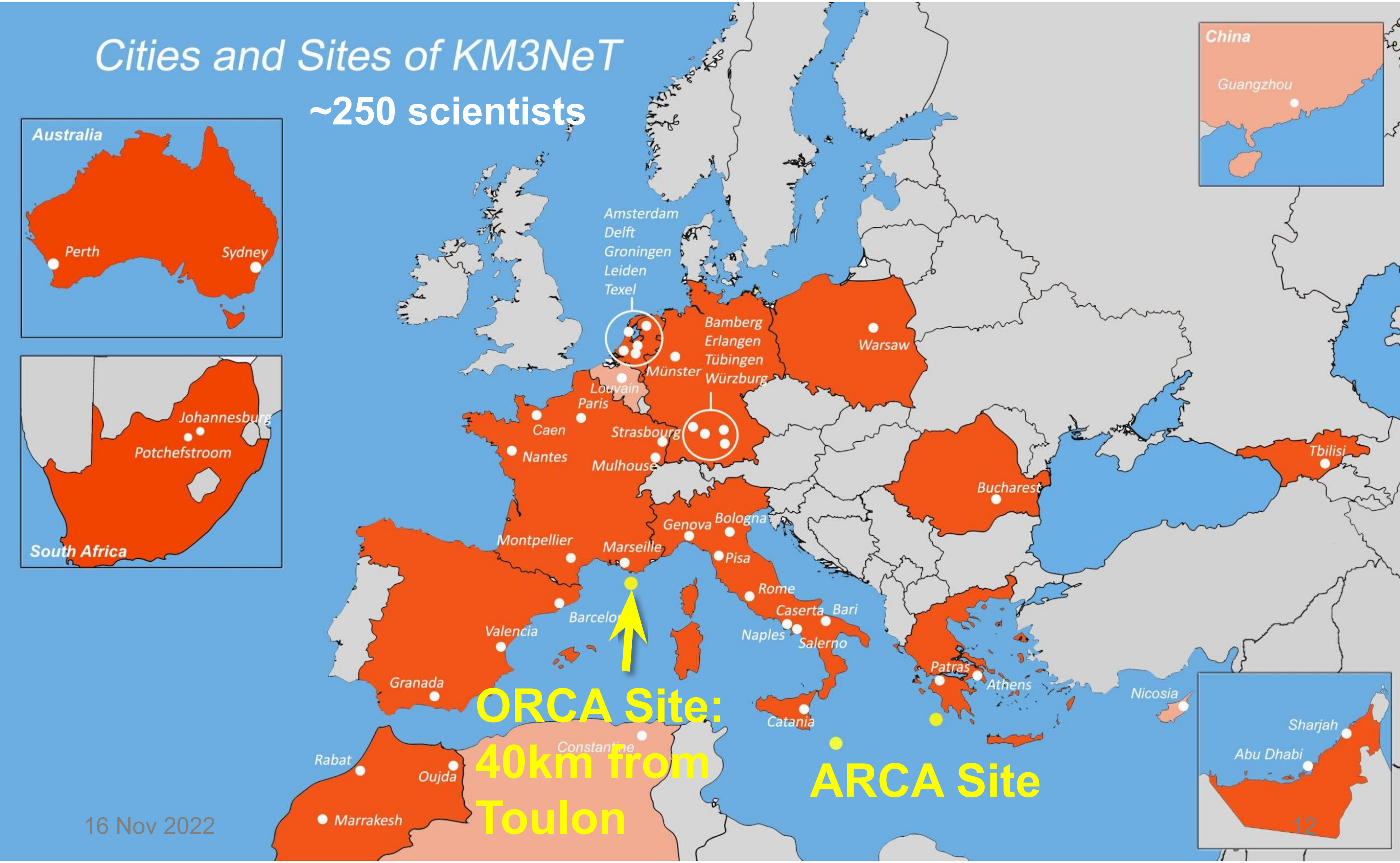




www.km3net.org

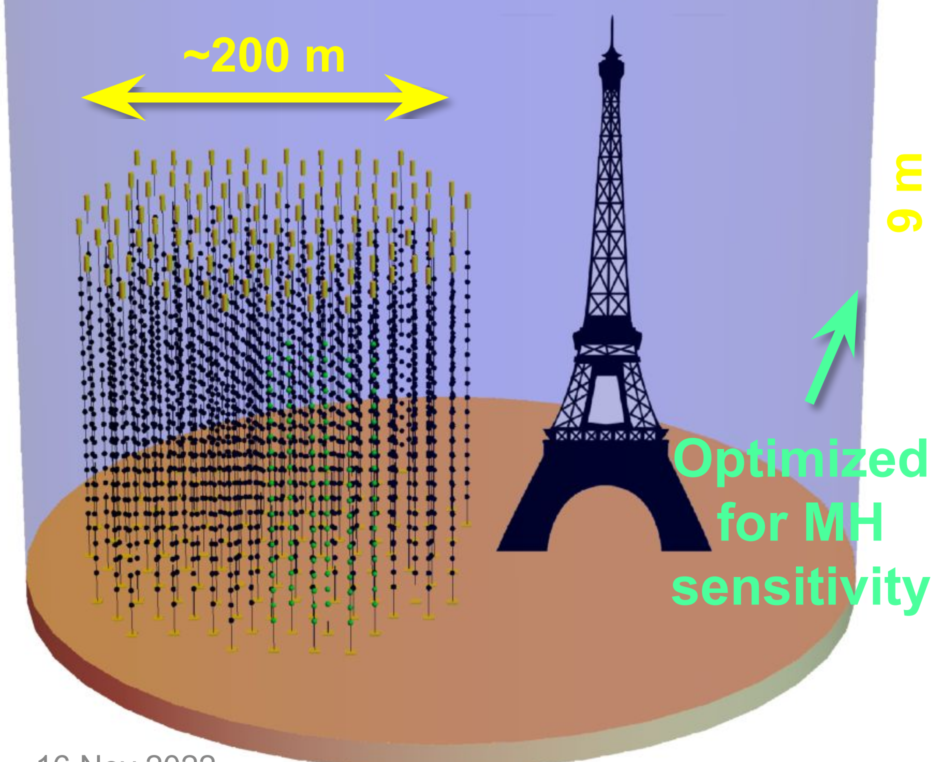
KM3NeT Collaboration

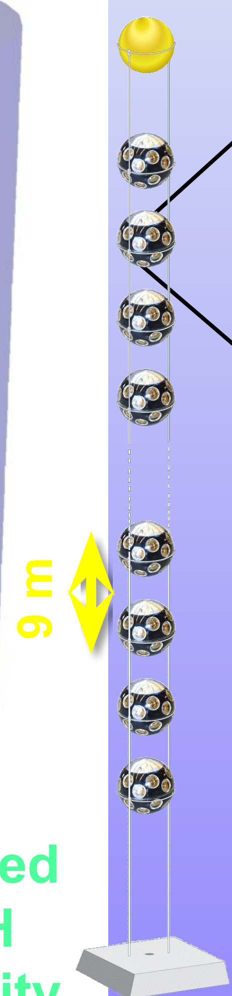
Letter of Intent: J.Phys.G 43 (2016) 8, 084001

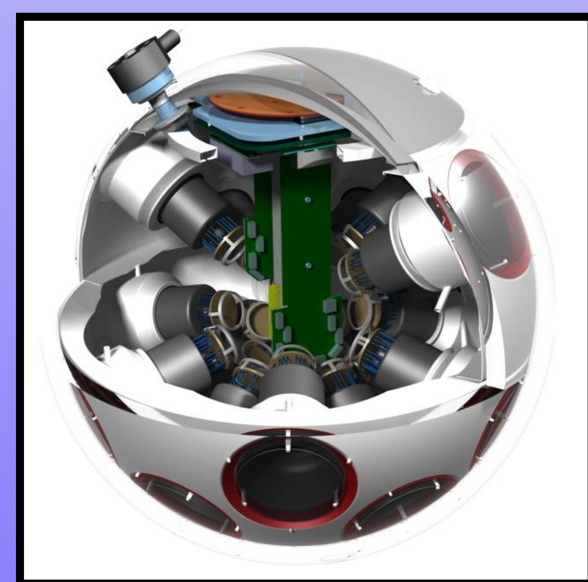


The ORCA Detector

- **~7 Mt** instrumented
- **115** strings
- **18** DOMs / str
- **31** PMTs / DOM
- Total: **64k PMTs**







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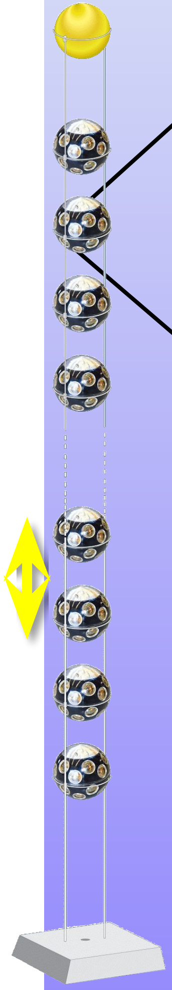
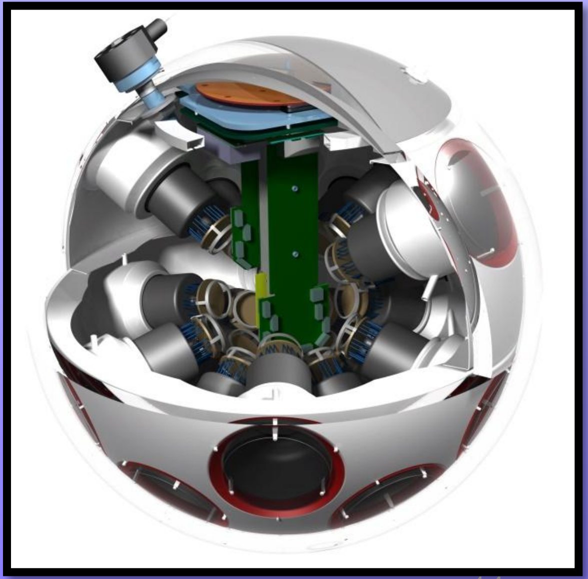
http://www.cherenkov.nl/

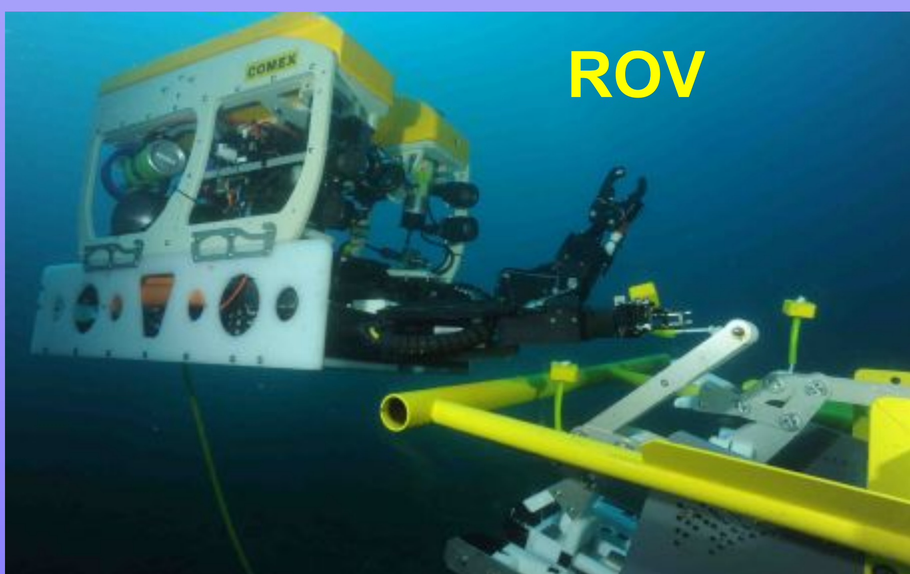


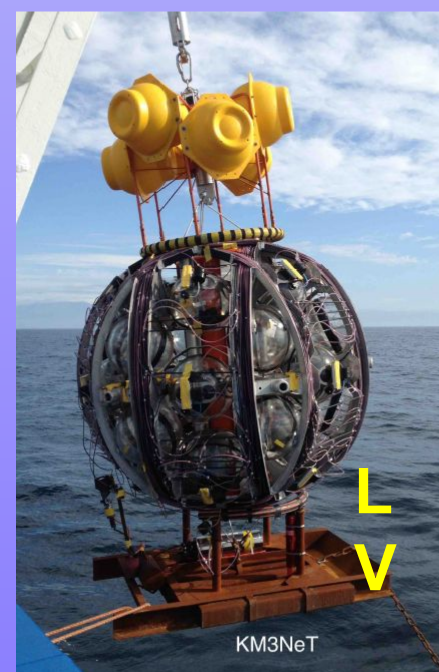


Deployment

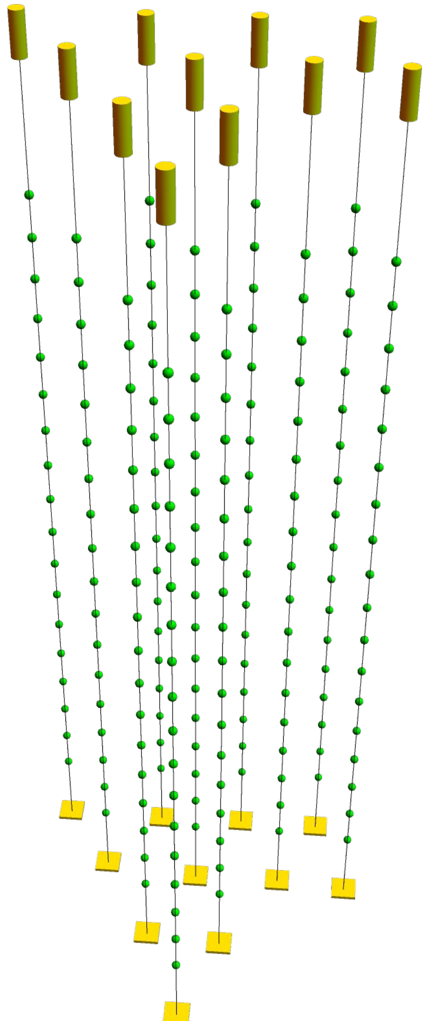
- String fitted to Launcher Vehicle
- Delivered at a **depth of 2450m**
- ROV connects cable to junction box
- Boat triggers unfurling of the string
- Many nice videos on youtube channel:

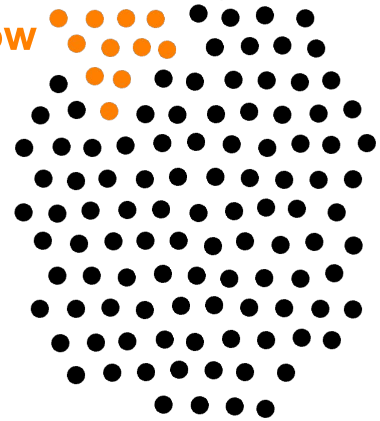
https://www.youtube.com/user/KM3NeTneutrino



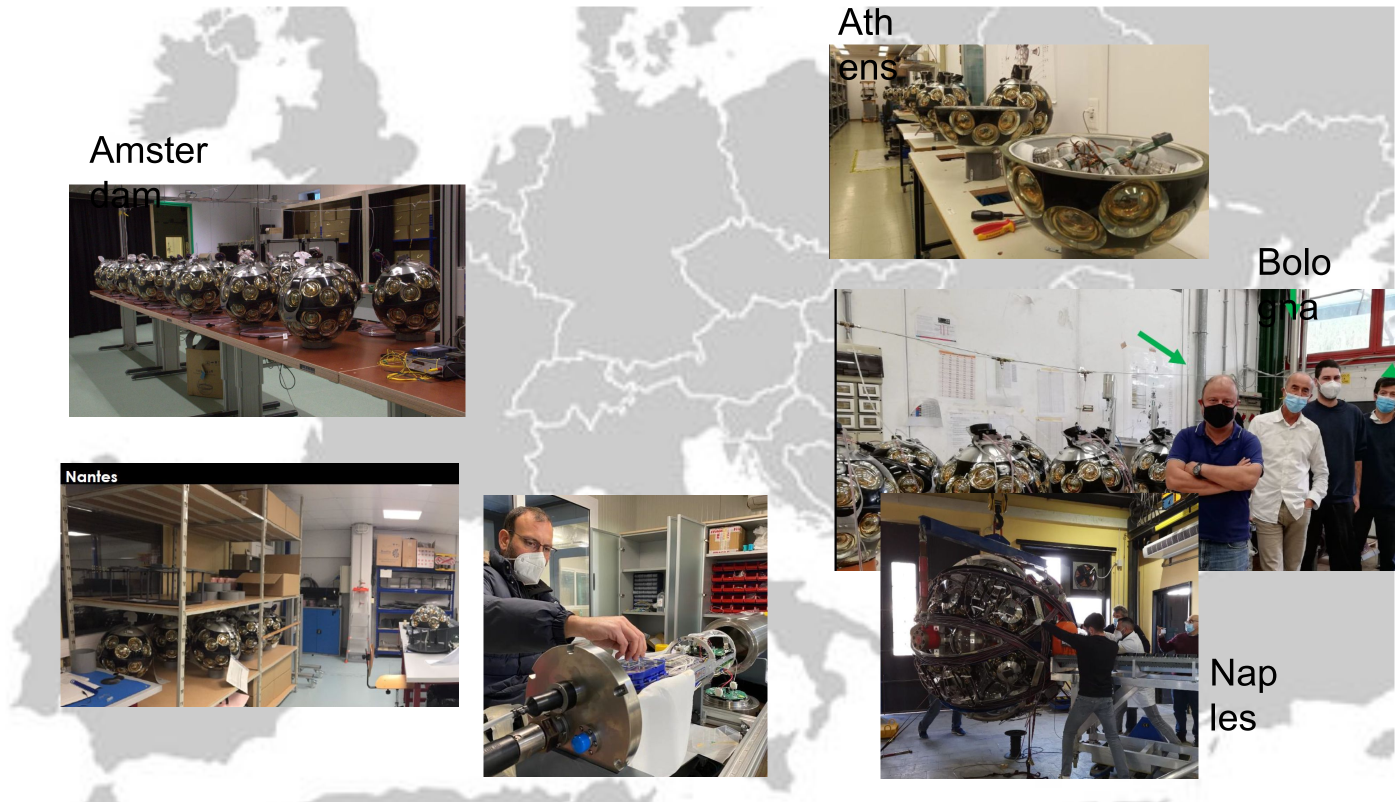


Production ongoing around the world



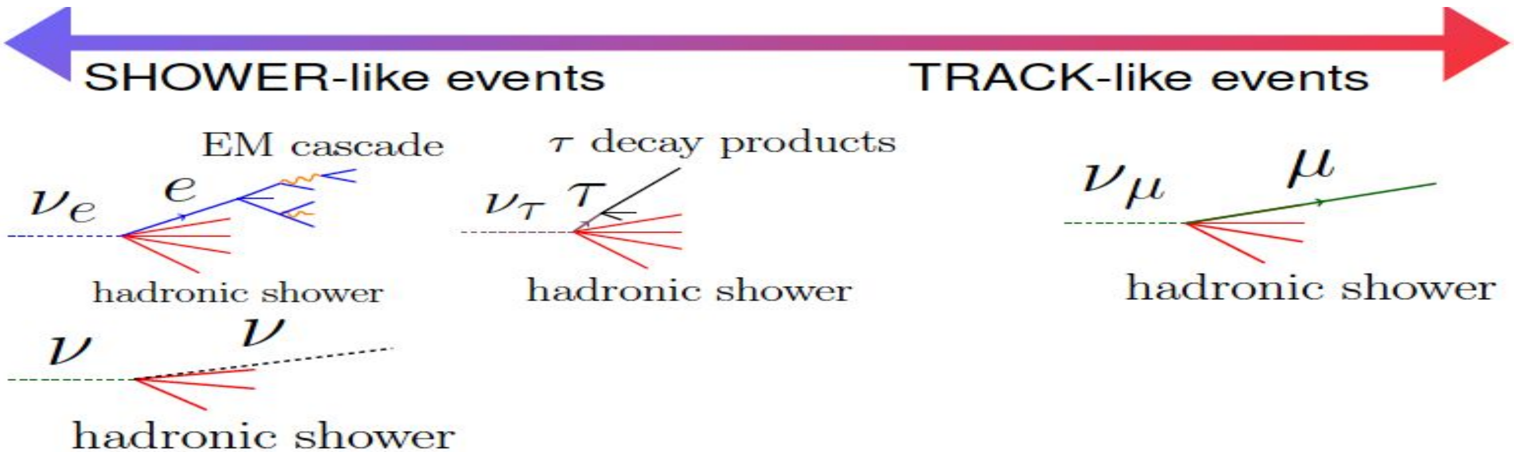


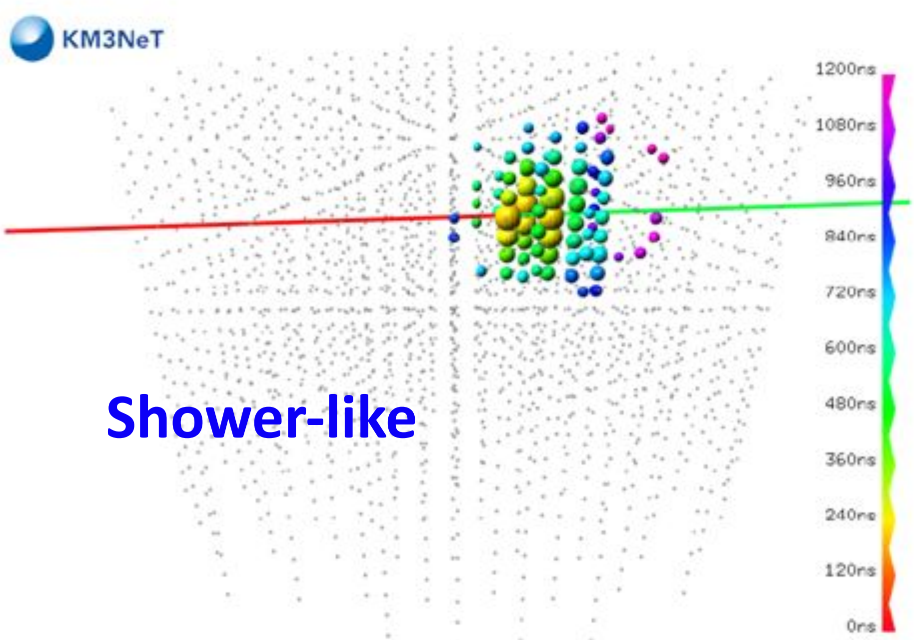
- **ORCA: 11 lines in the water since September 2022**
- **~20 more lines expected by end of 2023** to be deployed

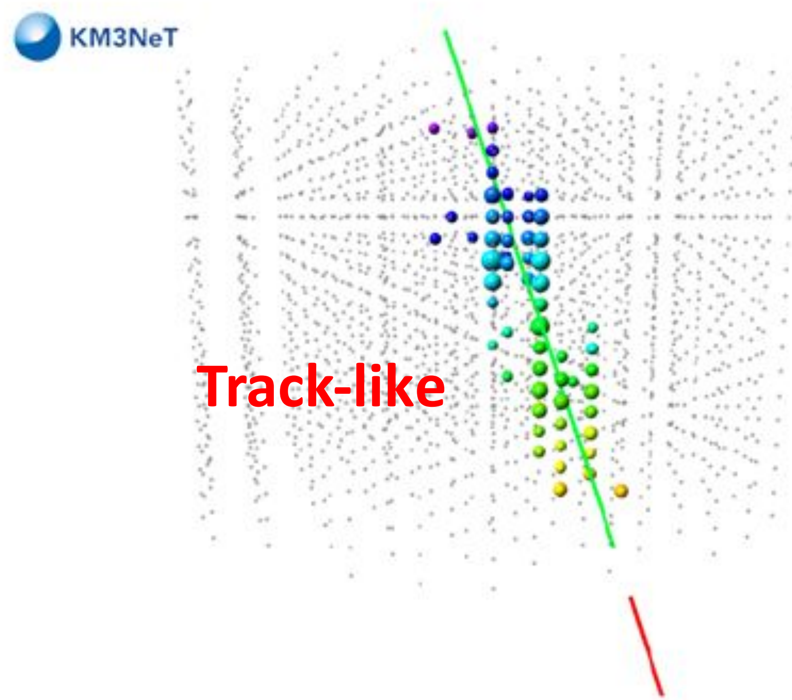


Sensitivities

Measuring Neutrinos

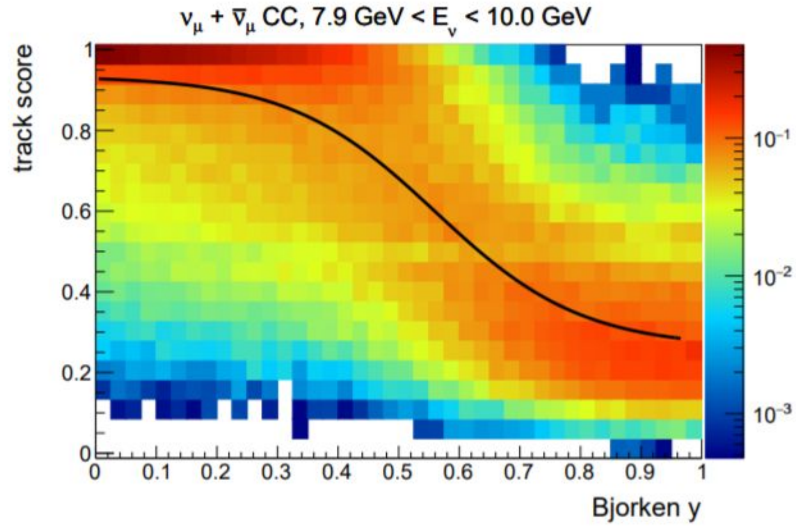


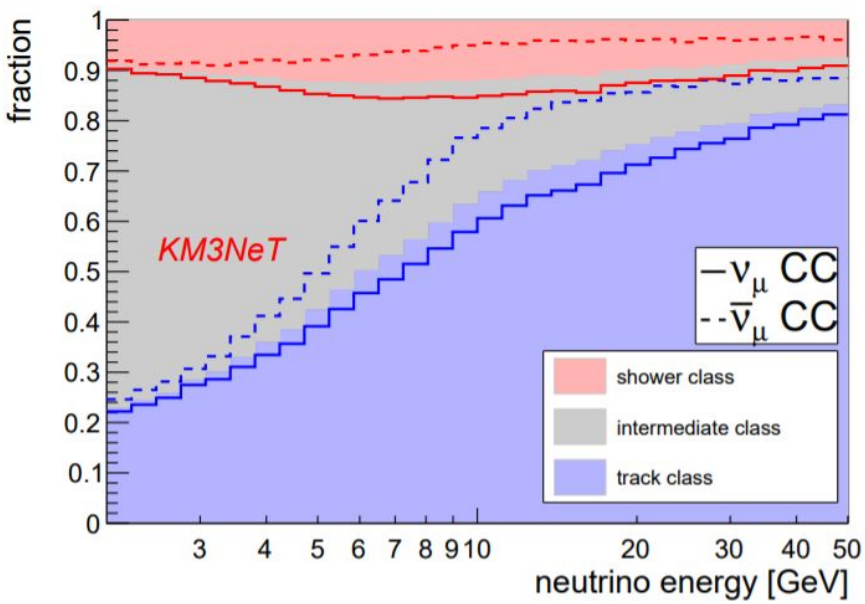


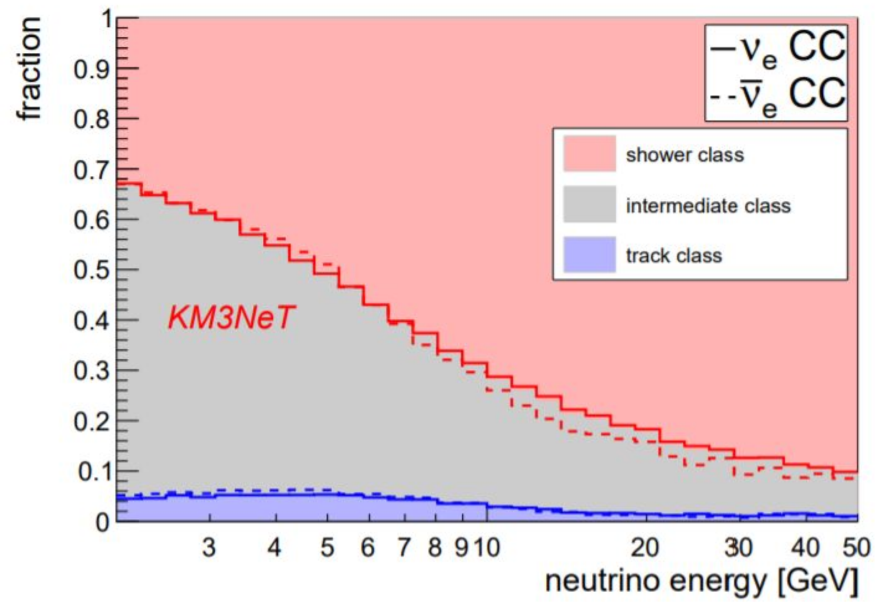


Event Selection

- Split non-track events into shower class (track score < 0.3) and intermediate class (0.3 < track score < 0.7)
- Increases purity in shower class but keeps low purity intermediate sample for control
- ν_μ-CC contamination mostly from highly inelastic interactions







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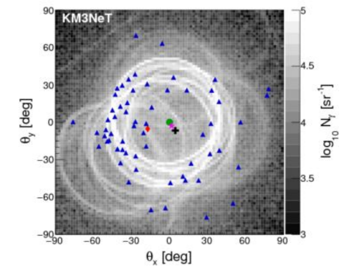
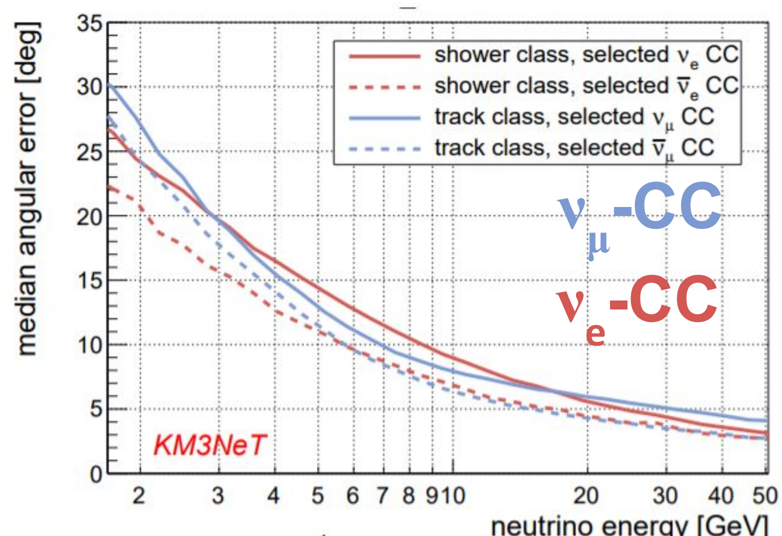
Reco Performance

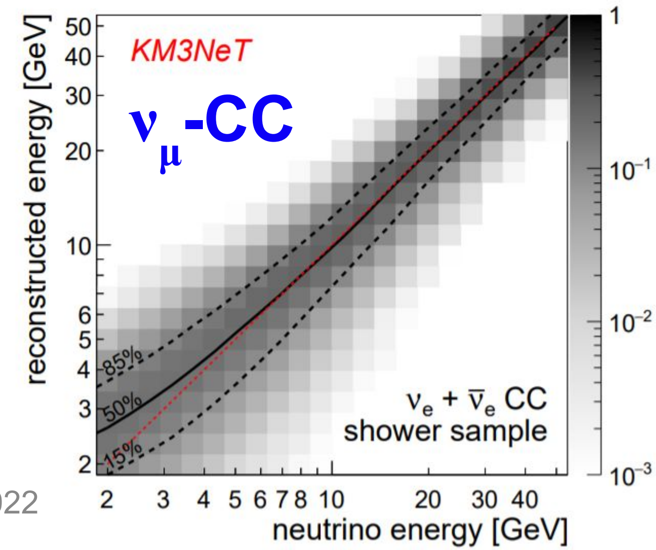
- Energy resolution: ~25% (Close to limit arXiv:1612.05621)
- Angular resolution: Better than 15 degrees at relevant energies



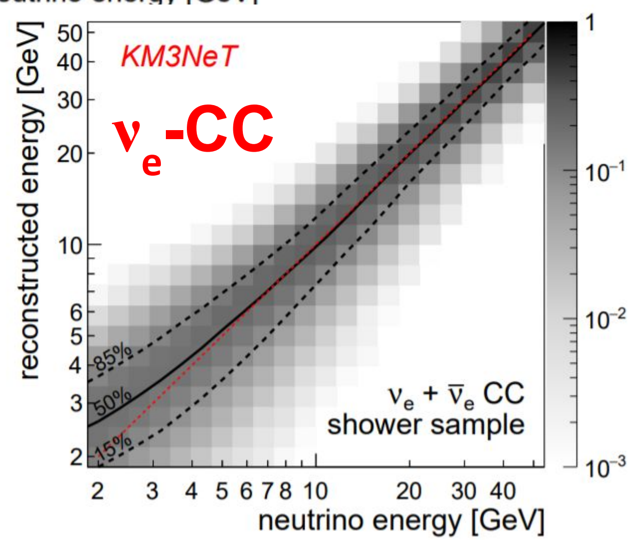
θ Res.



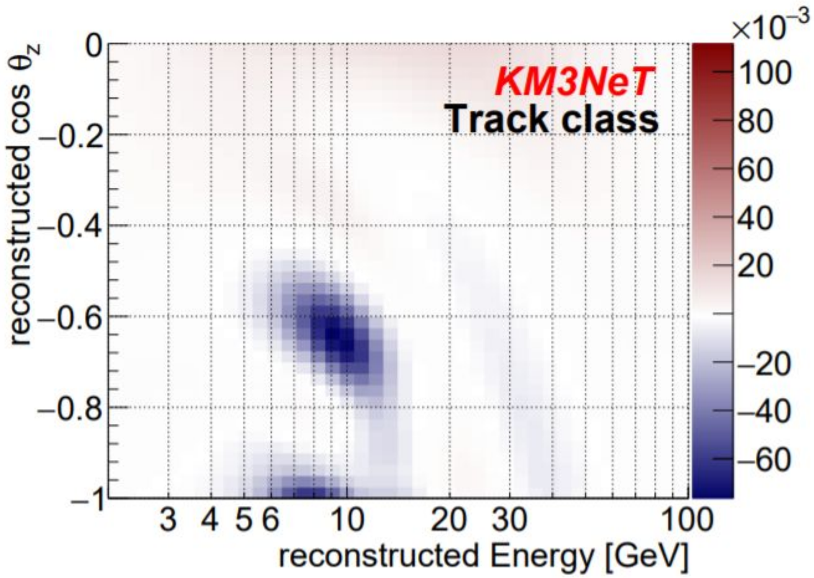
E Res.



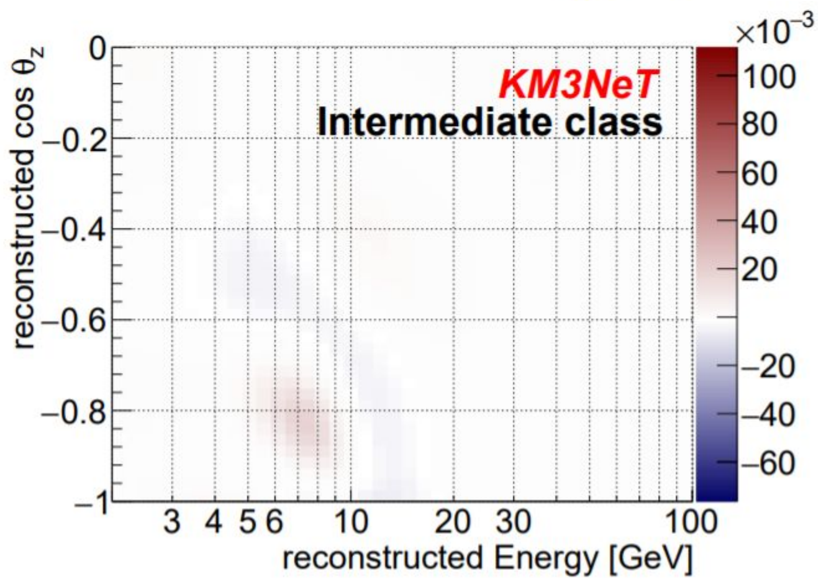
E Res.

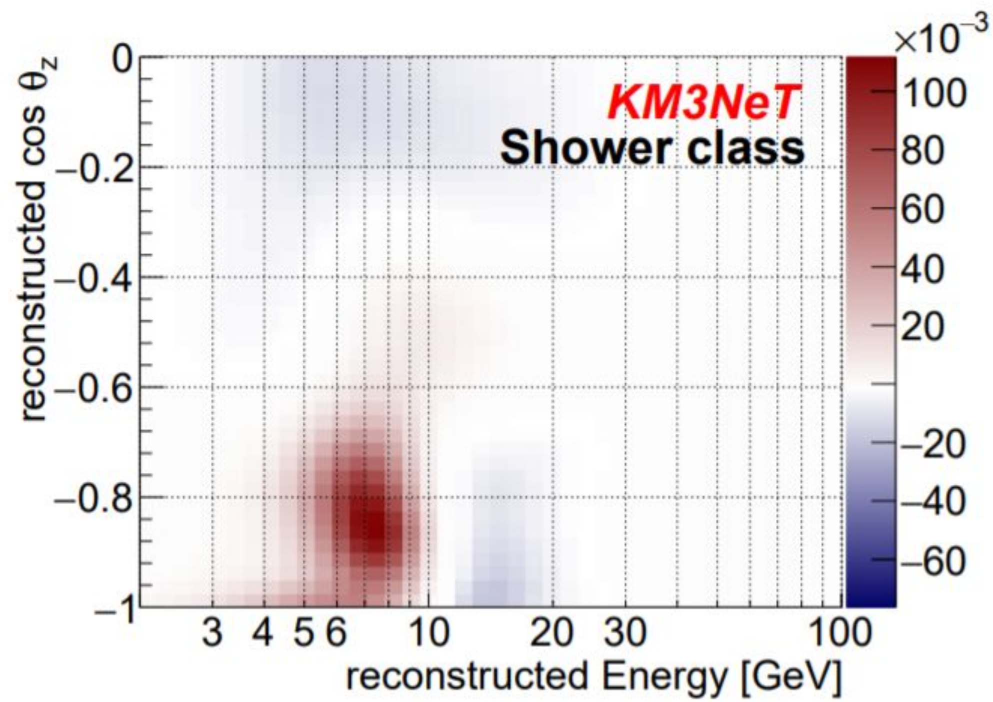


NMO Sensitive Regions



- Matter effects means NMO will impact very specific regions in L and E space
- Sensitivity dominated by shower class, but non-negligible contribution from track class
- Intermediate class has little sensitivity but helps constraint systematics





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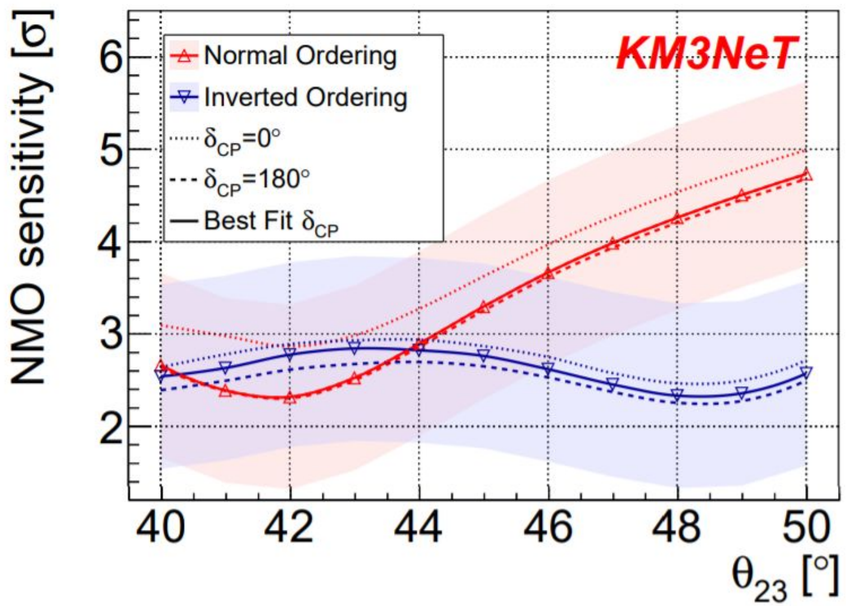
Systematics

- A total of 12 parameters are included in the analysis to account for shape and normalization uncertainties due to a combination of flux, cross-section and detector systematics
- Many systematics can be left free with no priors and will be constrained by our own data in different regions of L and E

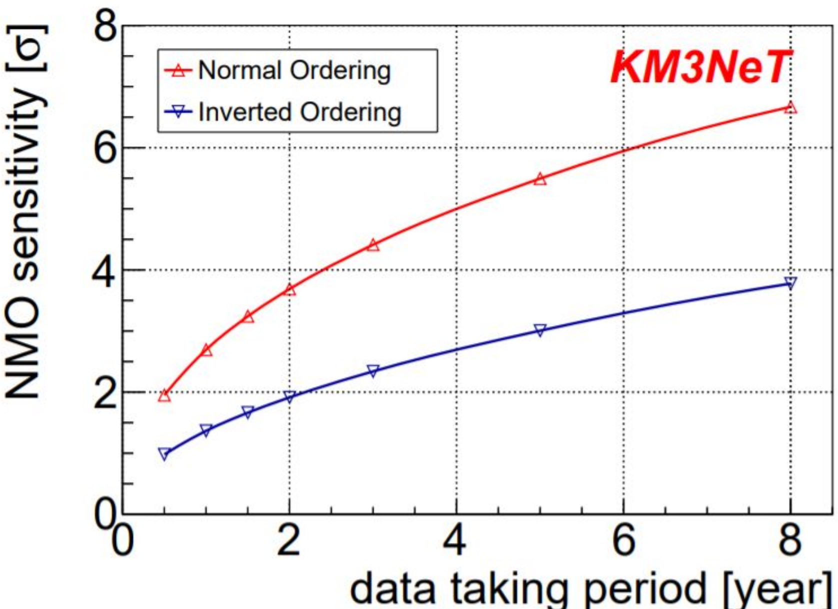
- Ratios between samples:
  - ν_e/anti-ν_e: 7%
  - ν_μ/anti-ν_μ: 5%
  - ν_e/ν_μ: 2%
- Shape uncertainty:
  - Energy scale: 6%
  - Had. energy scale: 5%
  - Directional skew: 2%
  - Spectral index: Free
- Normalization components:
  - NC component: Free
  - ν_τ component : Free
  - Overall norm. of each class: Free
- Plus 4 oscillation parameters:
  - Δm^2_{31}: Free
  - δ_{CP}: Free
  - $\sin^2\theta_{23}$: Free
  - $\sin^2\theta_{13}$: 3%

Sensitivity Results



- **In 3 years** expect to achieve **4.4σ** (2.3σ) if truth is NO (IO) at current best fit oscillation parameters
- **NO and upper octant** of θ_{23} significantly enhances sensitivity (**5σ in ~4 years**)

- In the IO, sensitivity is less dependent on octant of θ_{23}
- **Worst case** scenarios should reach **3σ in ~5 years**
- The value of δ_{cp} has small but non-negligible impact on sensitivity



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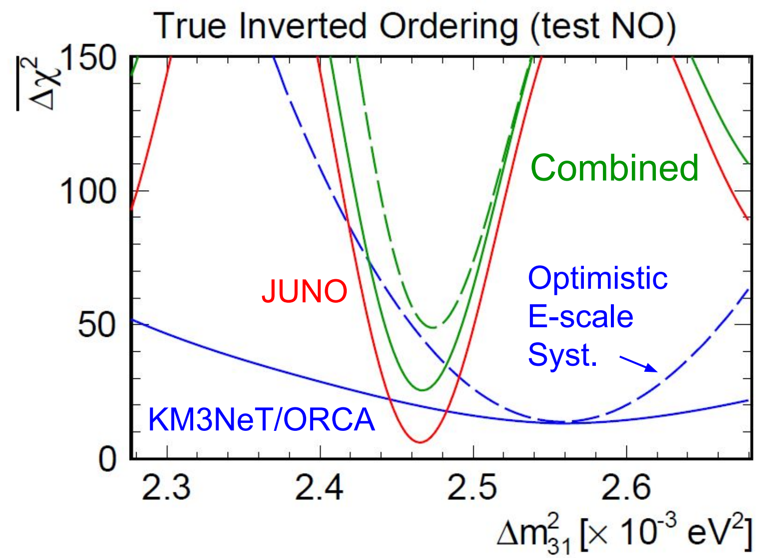
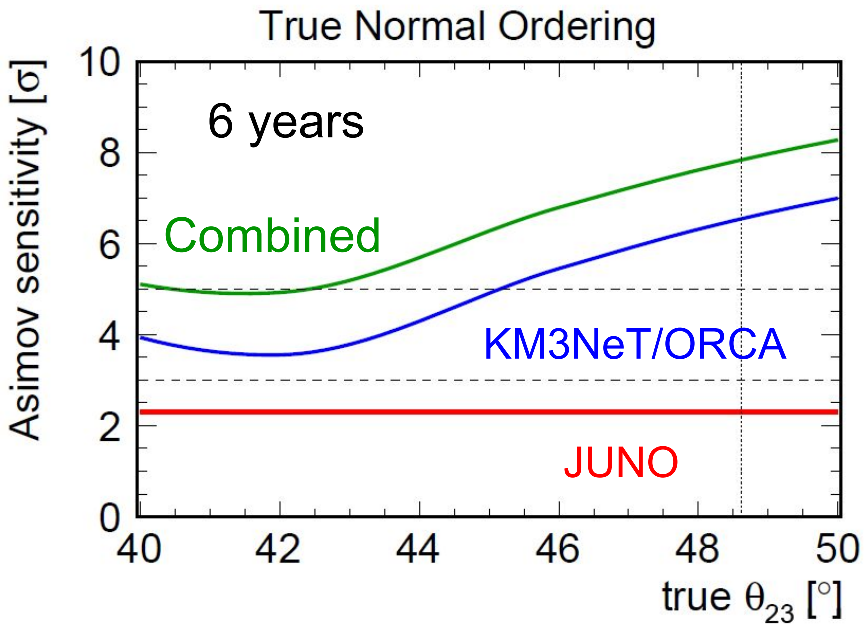
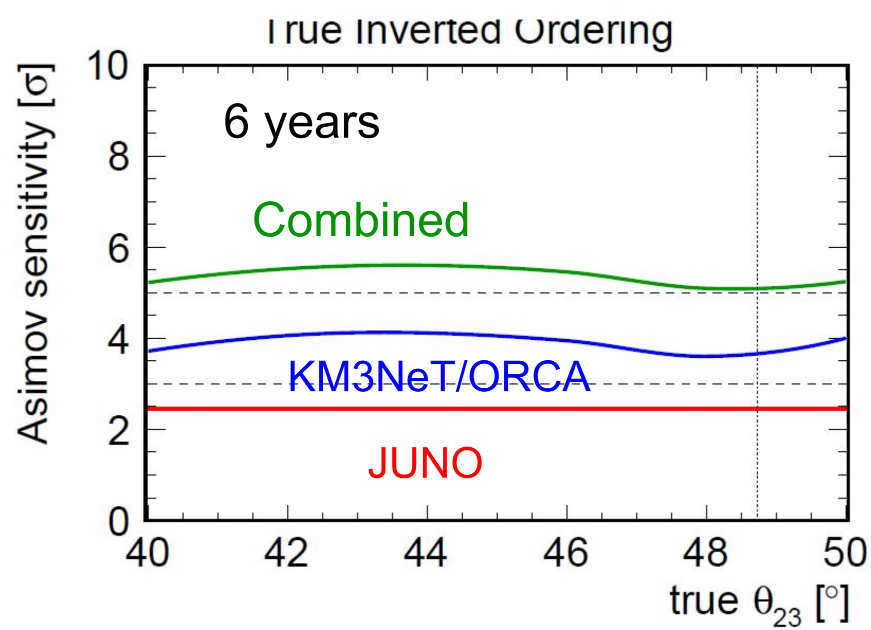
Synergy with JUNO

- Before 2030, JUNO and KM3NeT may be able to **definitively measure the NMO at 5σ** by exploiting a synergy between measurements of Δm^2_{31}
- Combined sensitivity is better than the simple sum of their $\Delta\chi^2$







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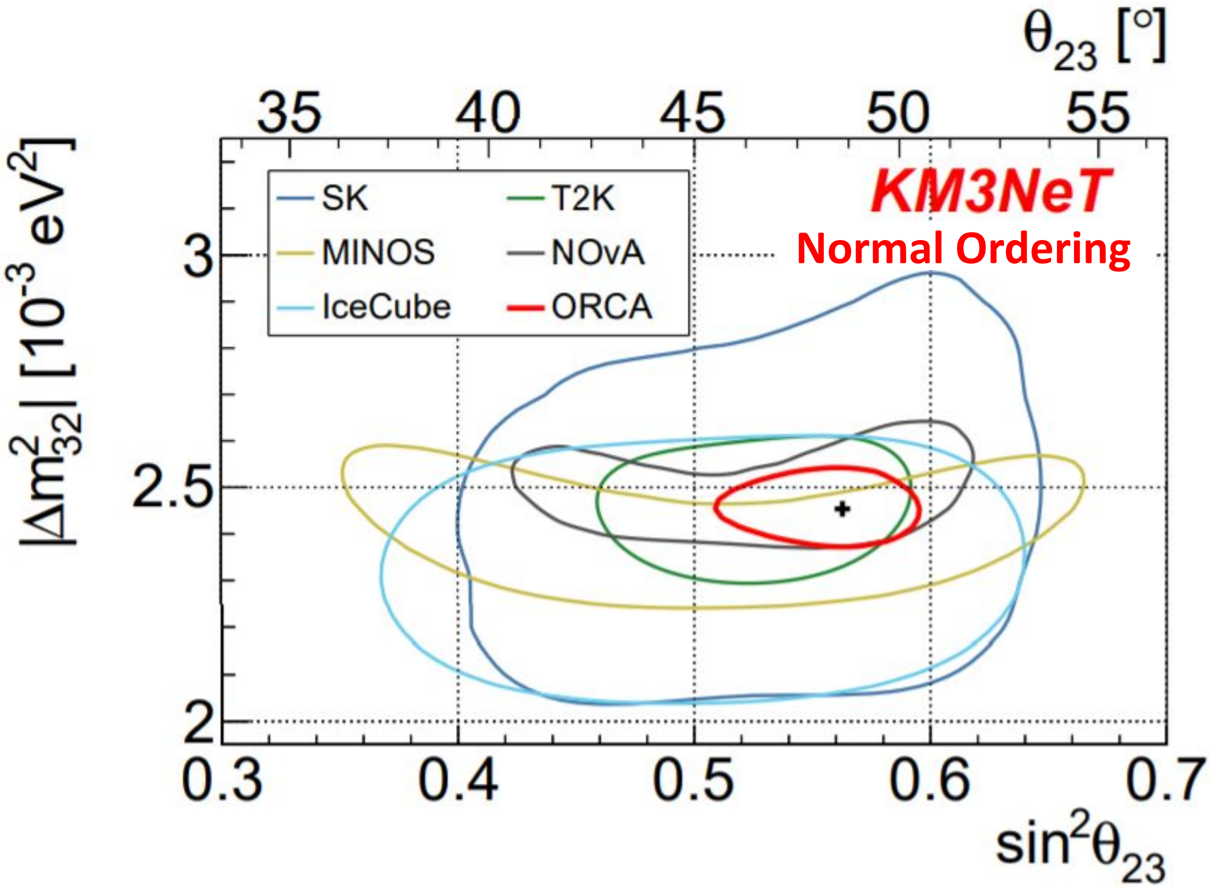
Other Parameters

- High statistics and excellent resolution → Measure Δm^2_{32} and $\sin^2\theta_{23}$
- **Competitive sensitivity with LBL experiments**
- Achieve **4.5%** prec. in $\mathbf{\Delta m^2_{32}}$ and **~10%** in $\mathbf{\sin^2\theta_{23}}$



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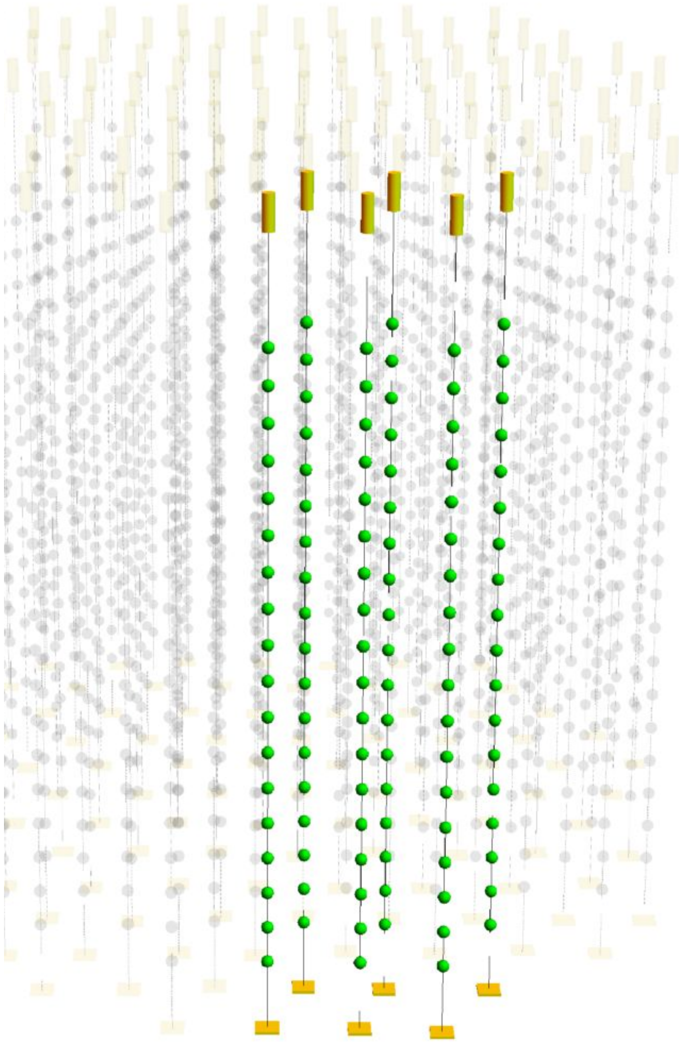
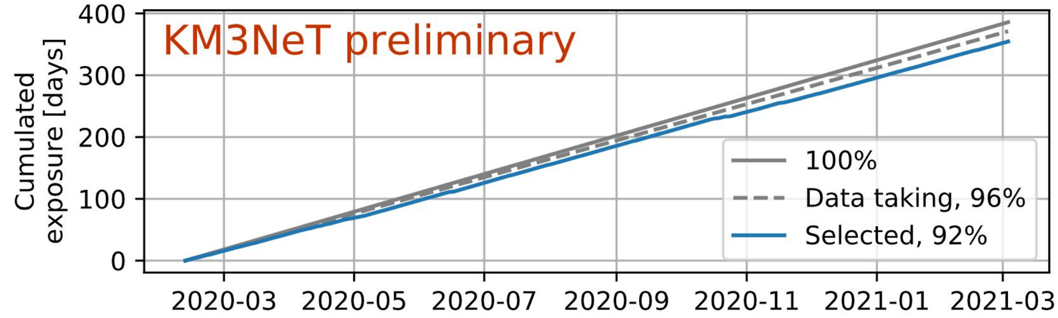
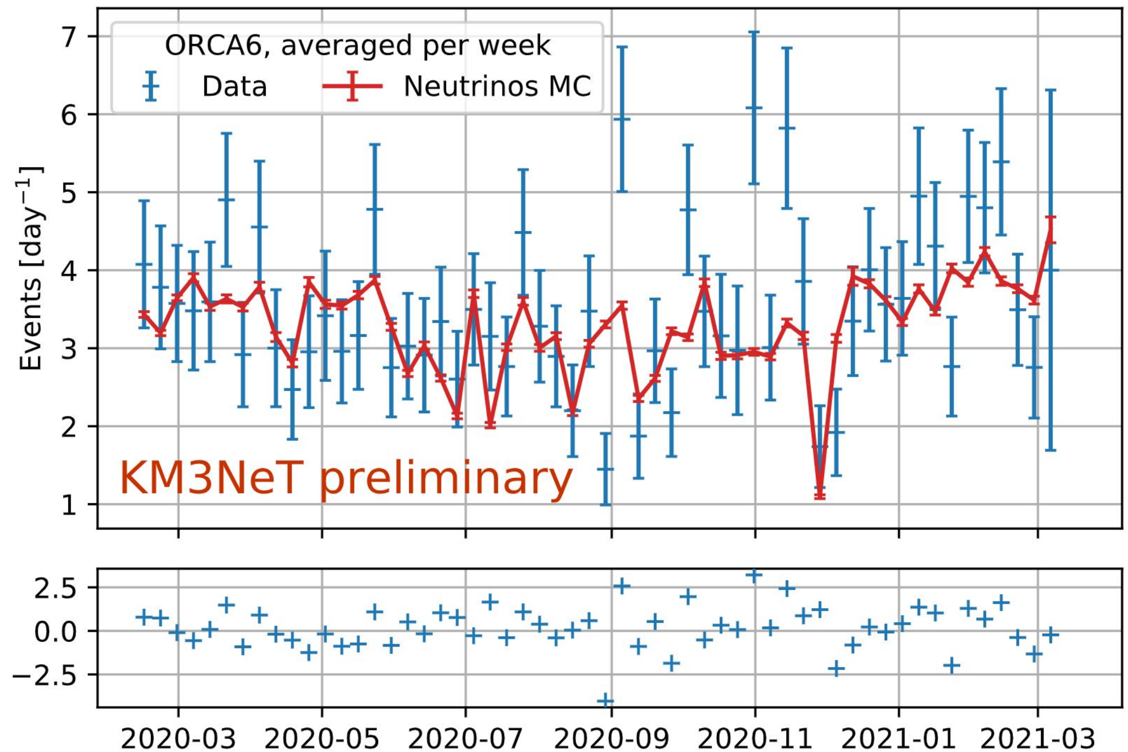
First Results

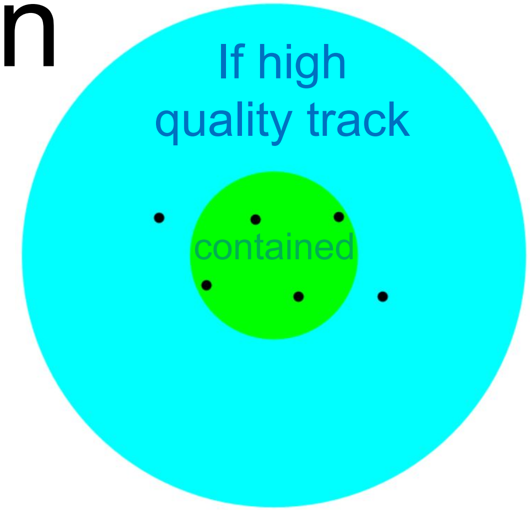
Over 90% up time for 1 year



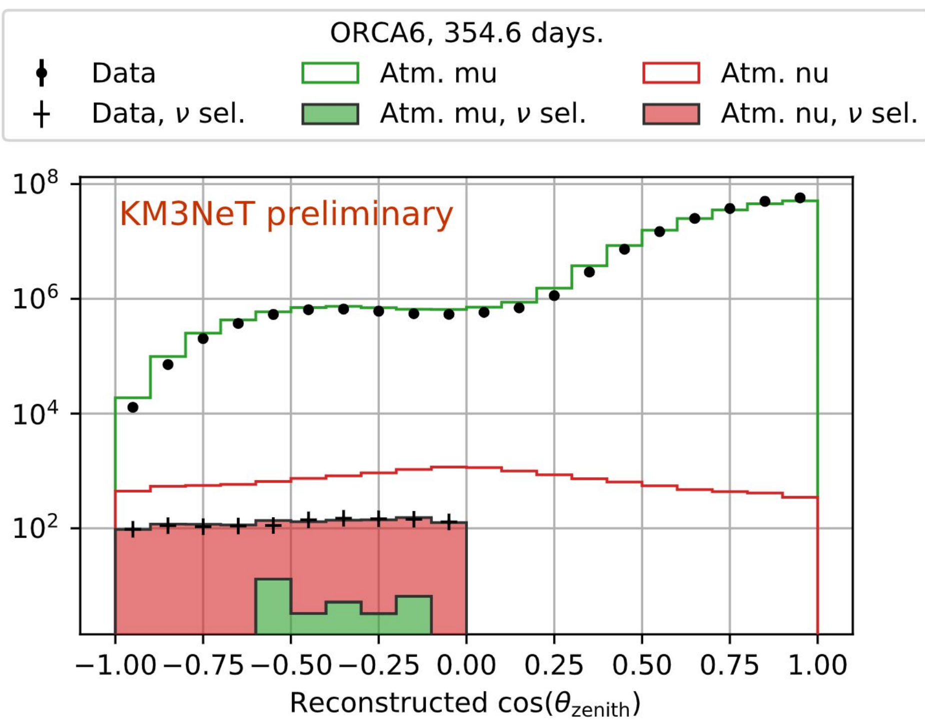


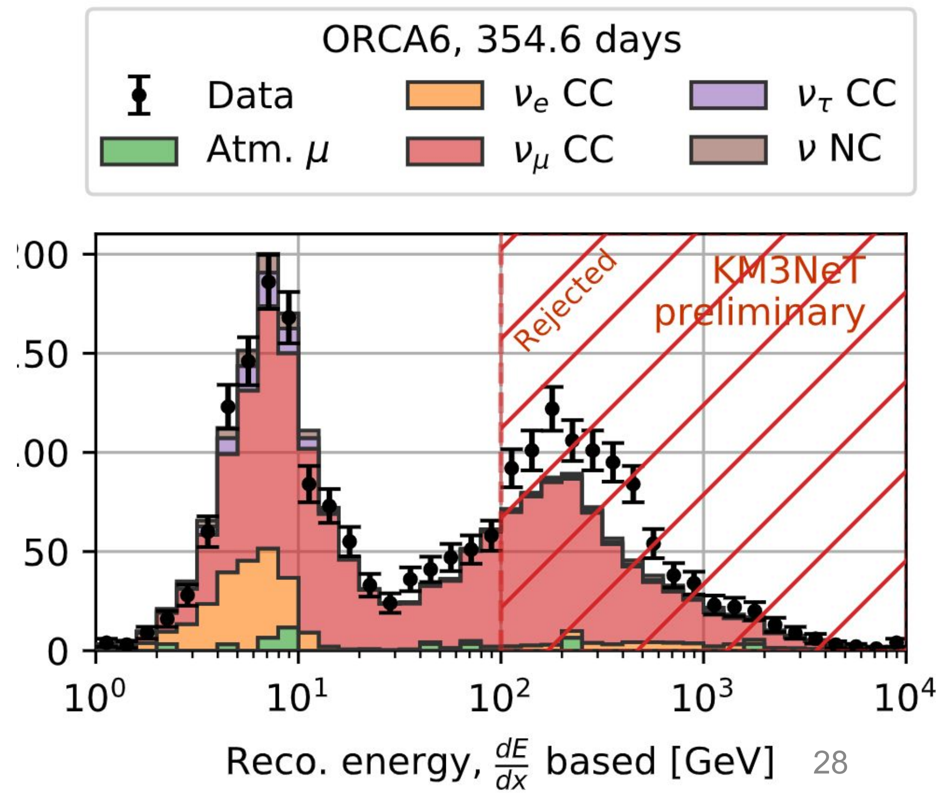


Neutrino Selection



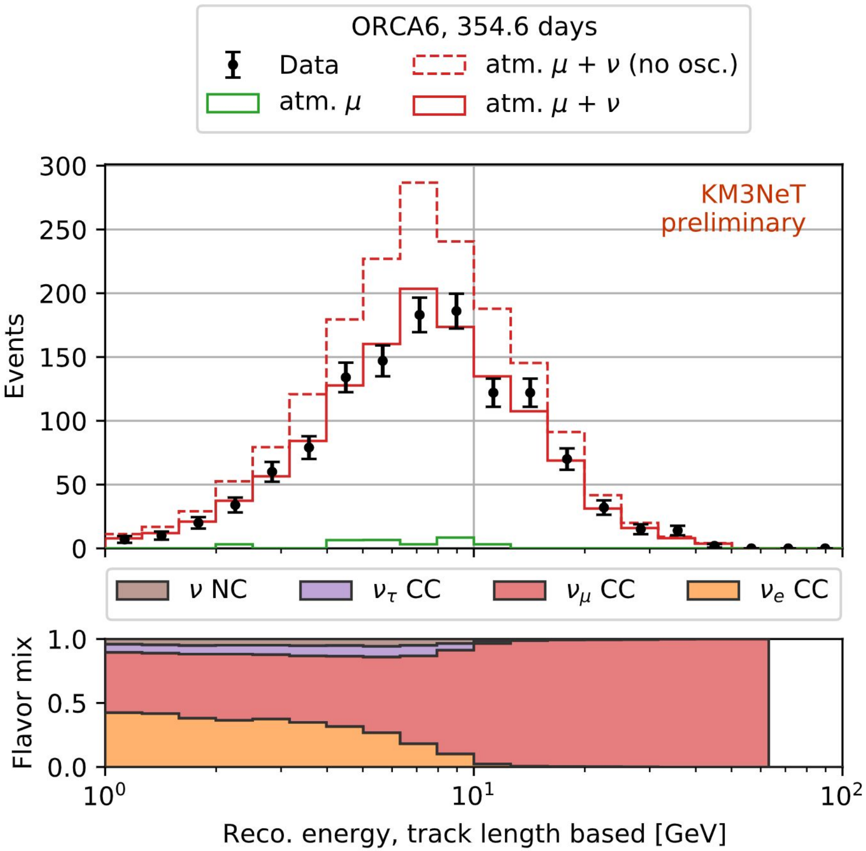
- Simplified selection for track-like events only
- Minimum number of hits matching Cherenkov angle
- Vertex contained in fiducial volume
- High quality track reconstruction, increasing with radius
- Reject poorly understood high energy tail (dE/dx based)

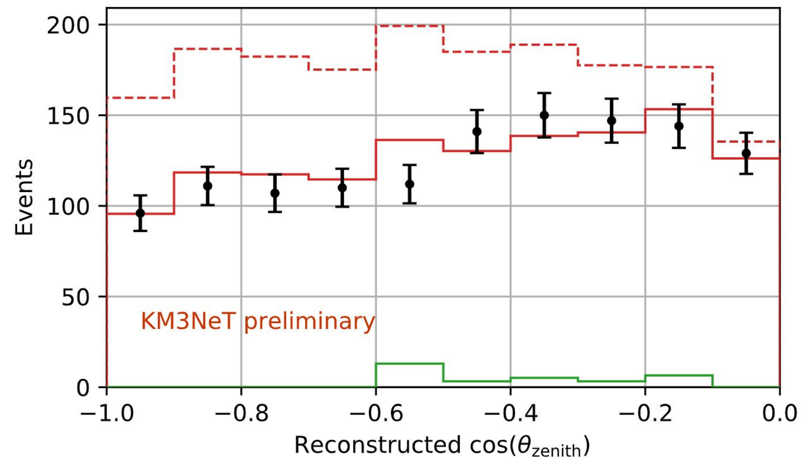


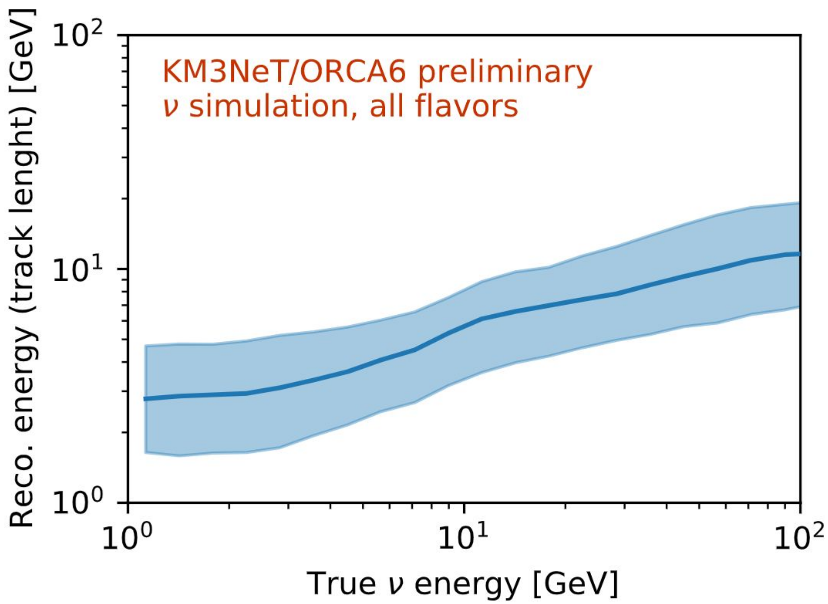


ORCA6 Data

- Energy estimate based on track length
- Poor energy resolution, but robust
- Good agreement with oscillated MC





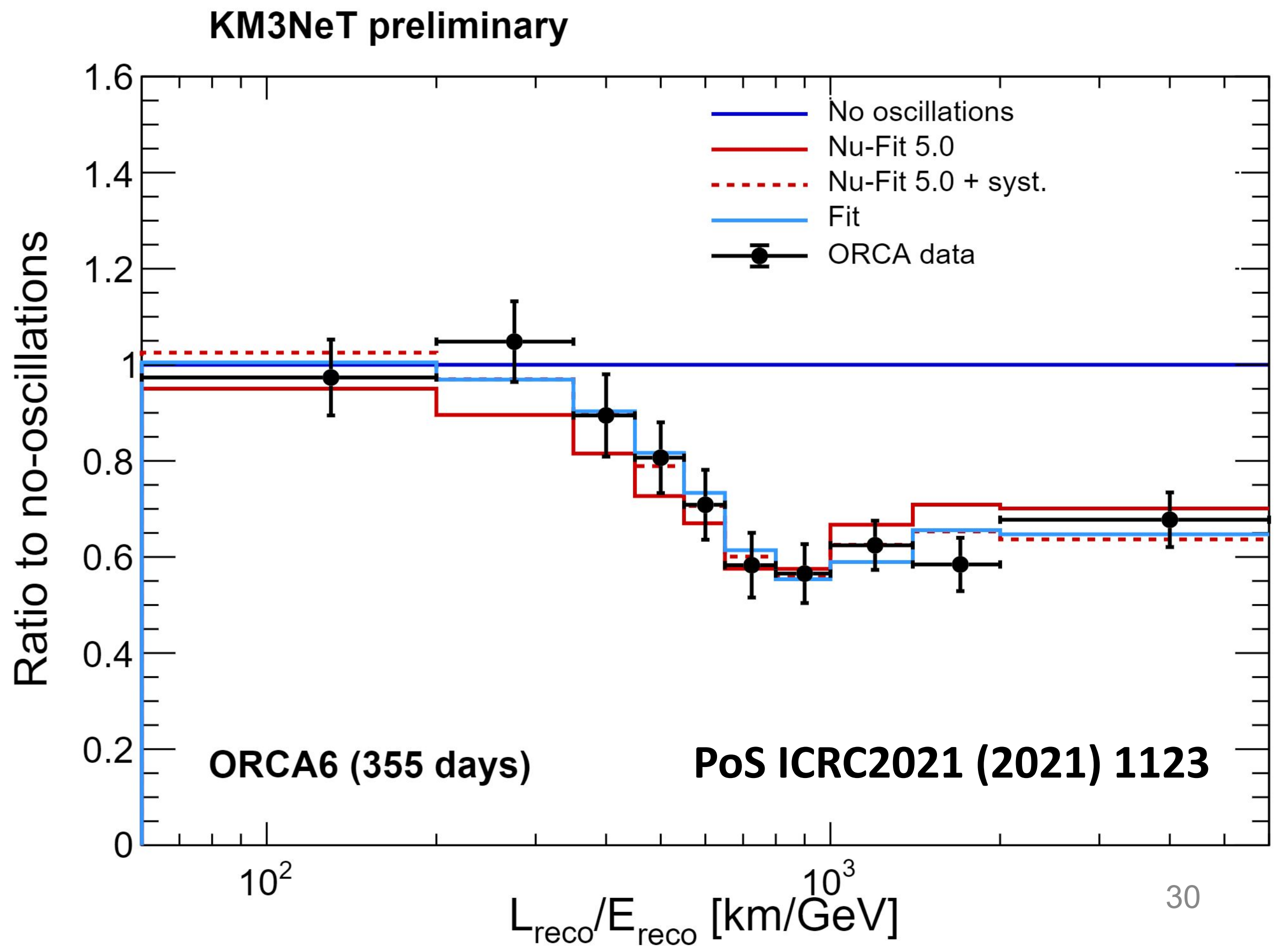


Clear Evidence of Oscillations

- First oscillation dip already visible even with suboptimal resolution
- **Oscillation hypothesis confirmed at 5.9σ**
- Data prefers oscillation minimum at higher L/E than expected from global fits
- Our systematics do cover this effect however, so results are consistent (1.9σ)

Systematics

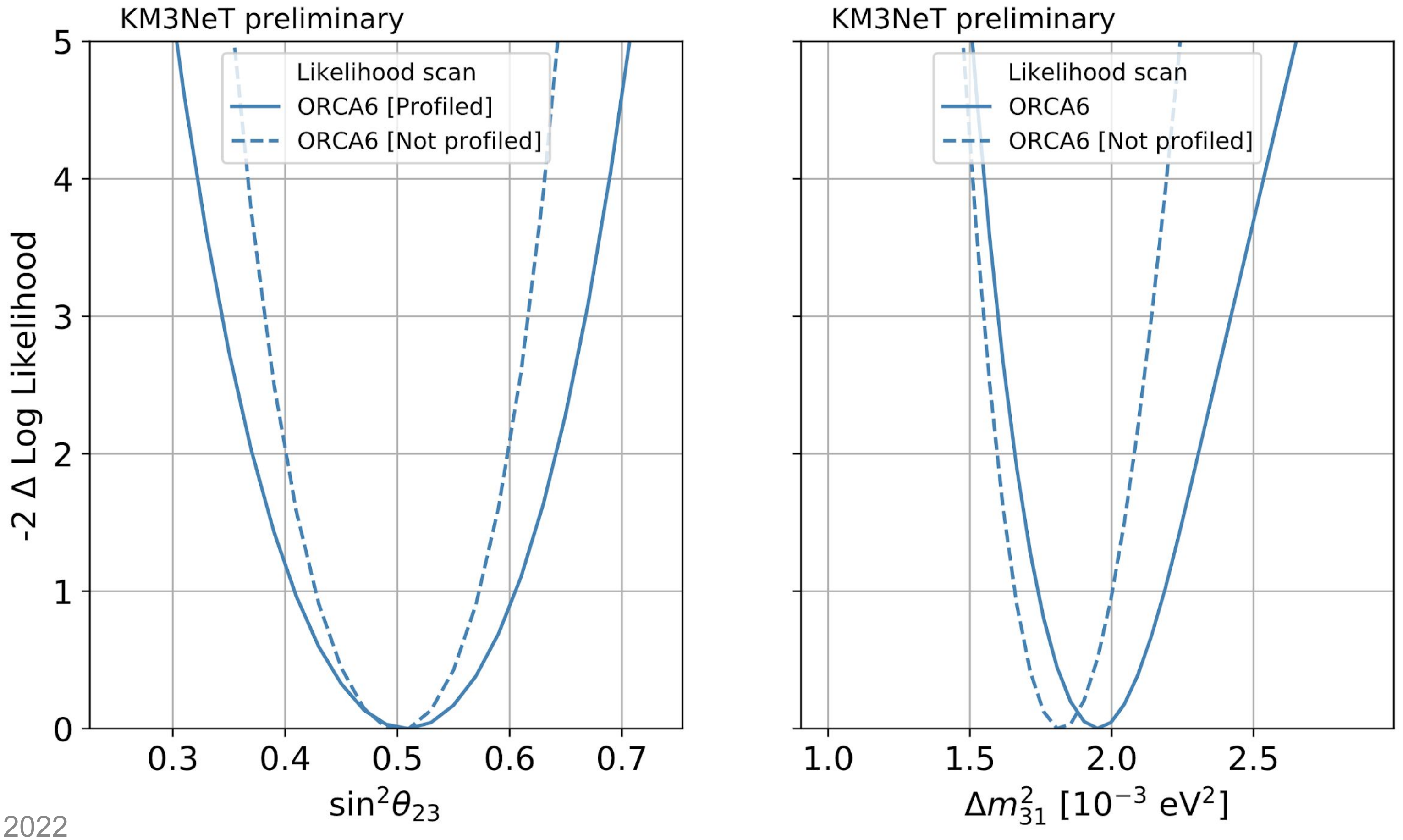
Parameter	Treatment Free/Fixed/Prior
θ_{12} [deg]	Fixed
θ_{13} [deg]	Fixed
θ_{23} [deg]	Free
Δm^2_{31} [10^{-3} GeV^2]	Free
Δm^2_{21} [10^{-5} GeV^2]	Fixed
δ_{CP} [deg]	Fixed
Normalisation	Free
Spectral index	Prior: 10%
$n_{\nu_{up}}/n_{\nu_{horiz}}$	Prior: 7%
$n_{\nu_\mu}/n_{\overline{\nu_\mu}}$	Prior: 10%
$n_{\nu_e}/n_{\overline{\nu_e}}$	Prior: 10%
n_{ν_μ}/n_{ν_e}	Prior: 3%
n^{NC}	Prior: 10%
n_τ^{CC}	Prior: 20%
Energy scale	Prior: 10%



First Oscillation Measurement

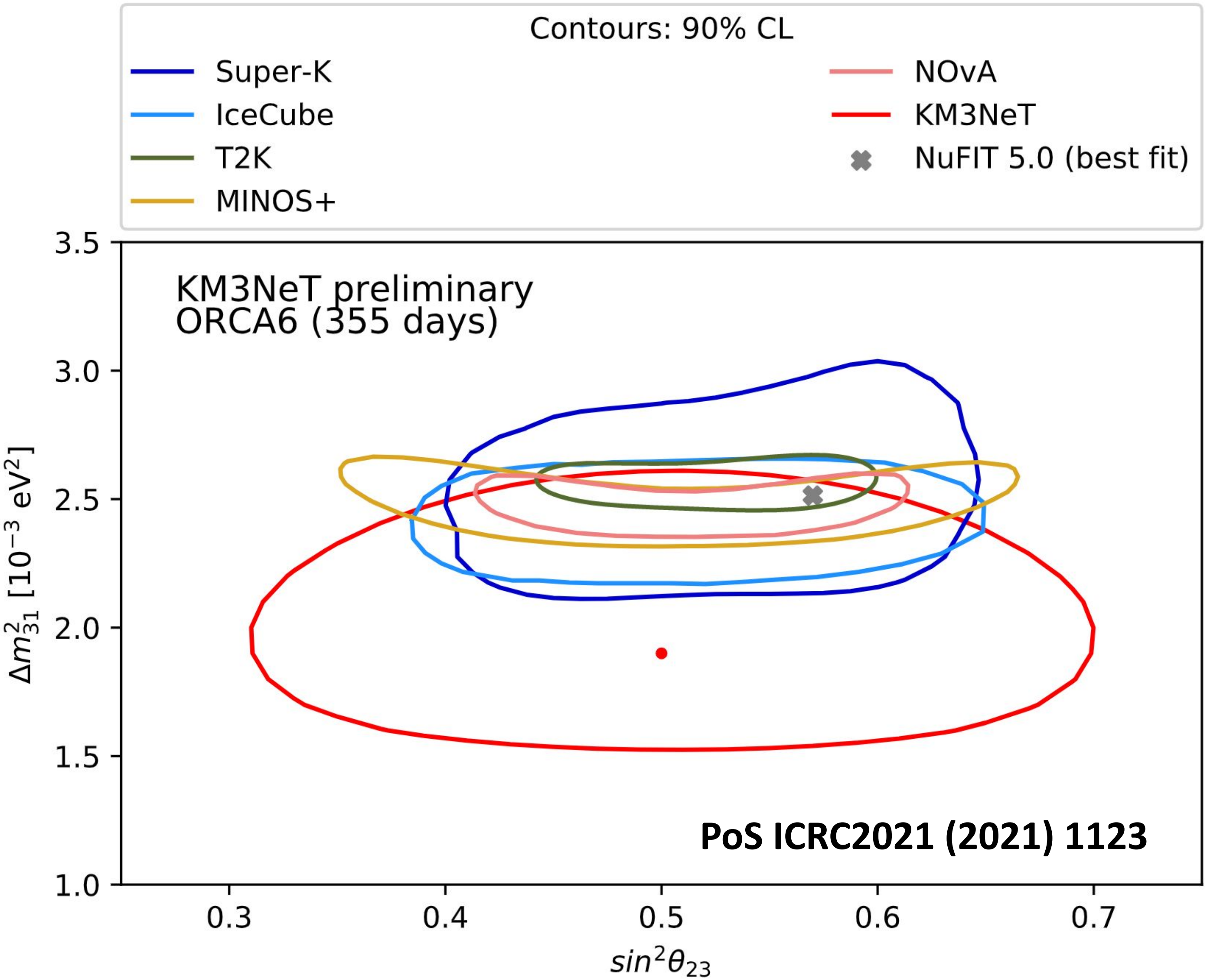
$$\Delta m^2_{31} = 1.95^{+0.24}_{-0.21} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.50 \pm 0.10$$



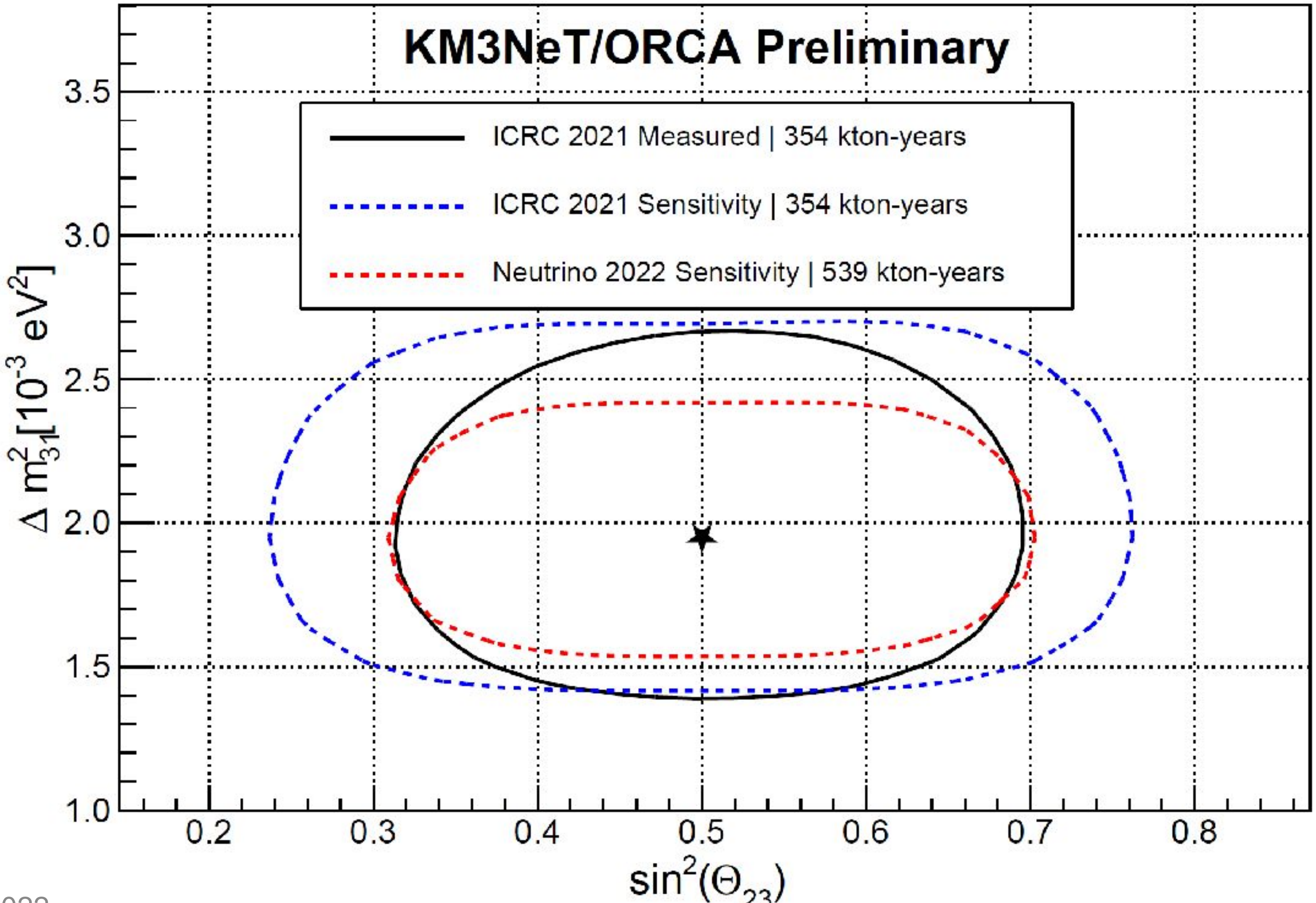
KM3NeT is in the game!

- First oscillation results already interesting with only 5% of the detector in 1 year



Updated Results Soon!

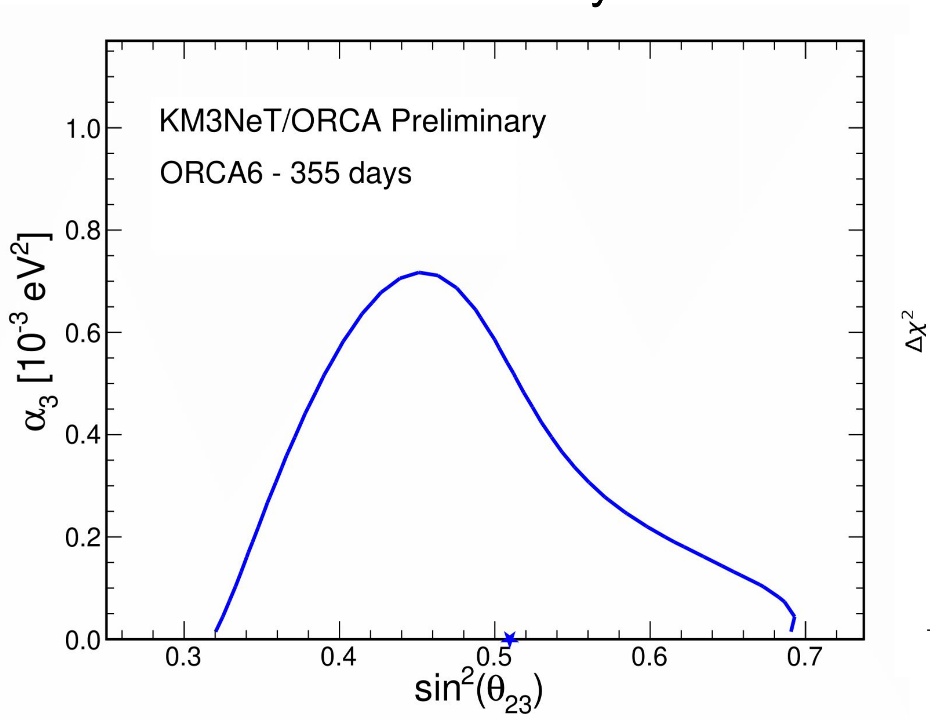
- 50% more data
- 4x more statistical power from analysis improvements



BSM Searches

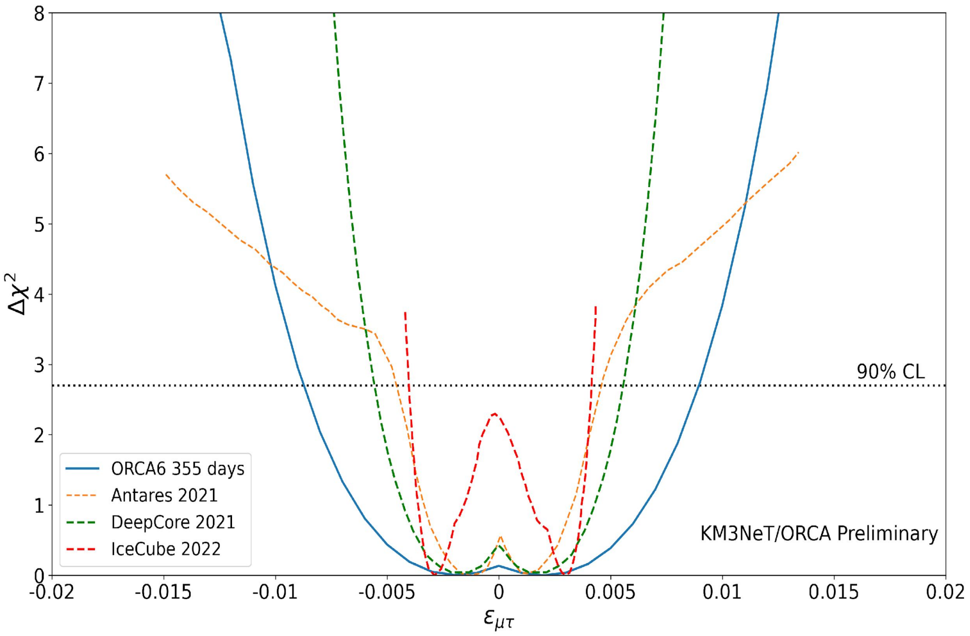
- First data already constraining some new physics scenarios
- Neutrino lifetime $\tau_3/m_3 \equiv 1/\alpha_3 > 2.4$ ps/eV (comparable to LBL limits)
- NSI parameter $|\varepsilon_{\mu\tau}| < 0.009$ (comparable to world best limits)

Neutrino Decay



https://zenodo.org/record/6758959

Non-Standard Interactions



https://zenodo.org/record/6785232

Summary

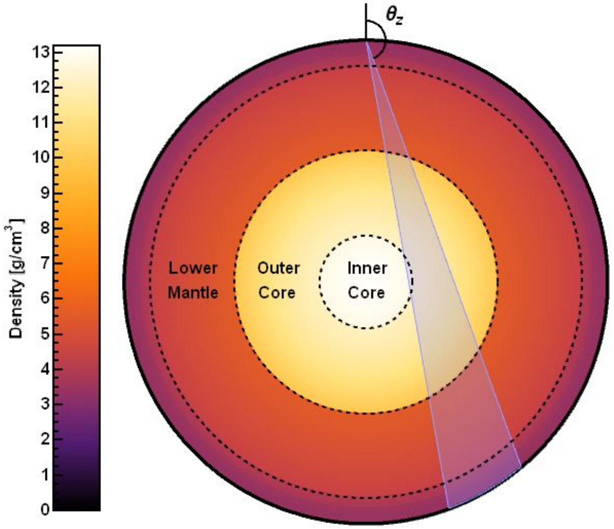
- **ORCA is here and taking data!**
- Main goal is to determine the **Neutrino Mass Ordering**
- Will also improve measurements of Δm^2_{32} and θ_{23}
- First results:

$$\Delta m^2_{31} = 1.95^{+0.24}_{-0.21} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.50 \pm 0.10$$

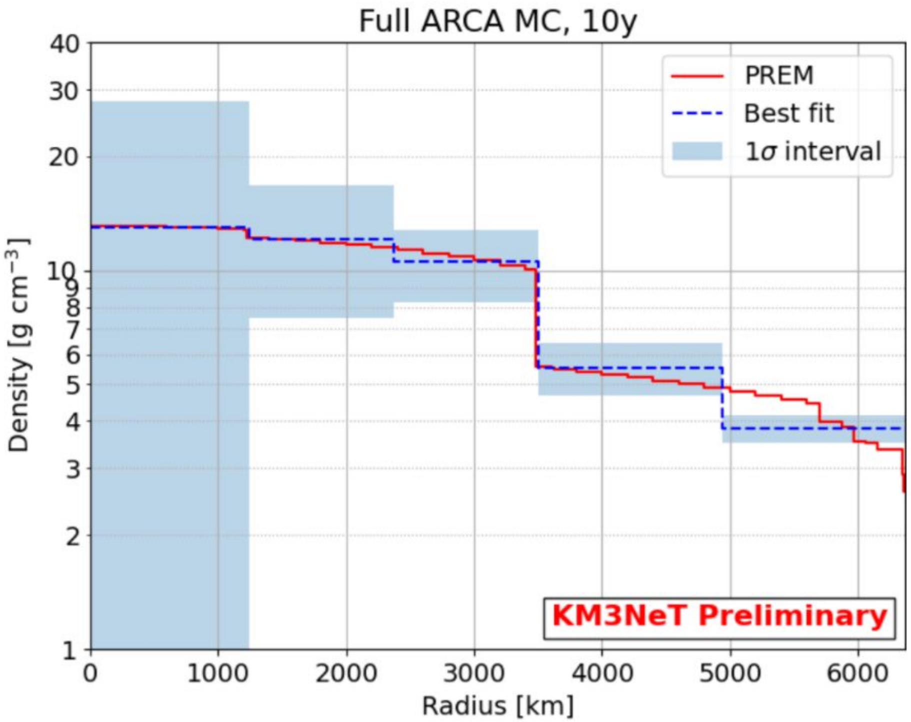
- Lots of potential for other searches: sterile neutrinos, NSI, earth tomography, tau neutrinos, etc.
- Stay tuned for more results soon

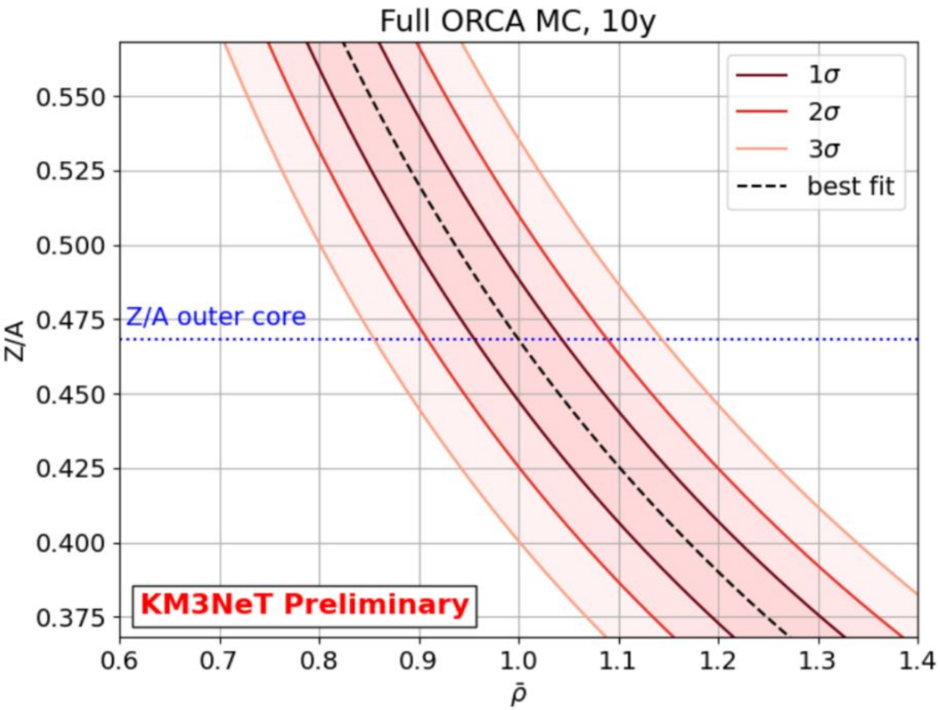
Thank you!



Earth Tomography

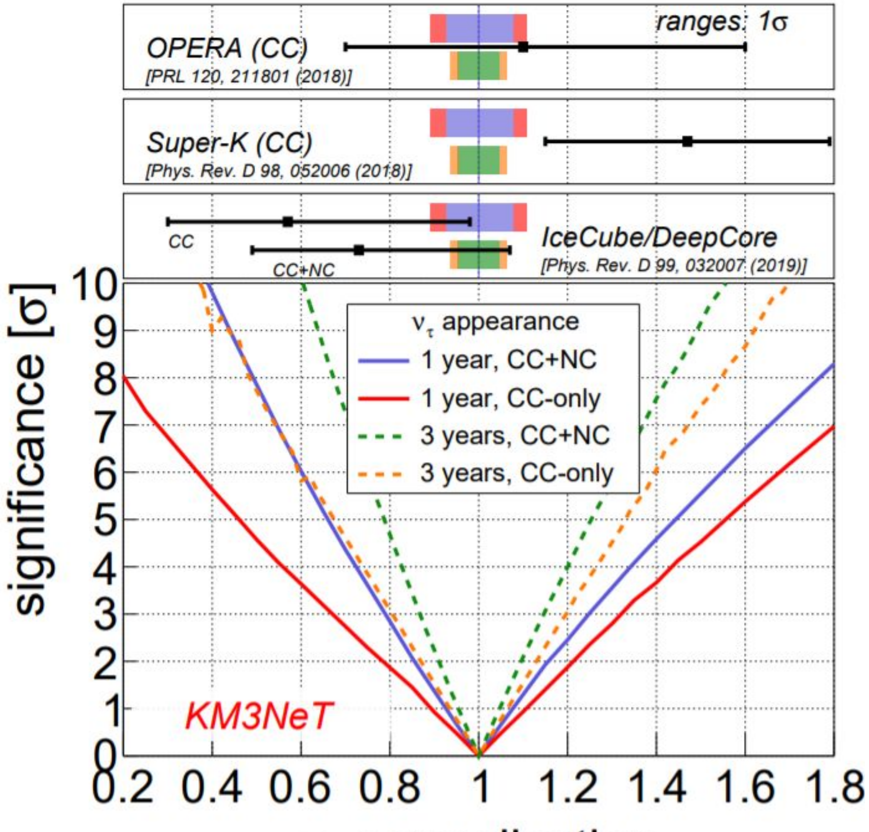
- Use both absorption and oscillations to measure the density and composition of the deep Earth
- The sensitivity to the chemical composition is particularly interesting as there is no other known method to probe it directly

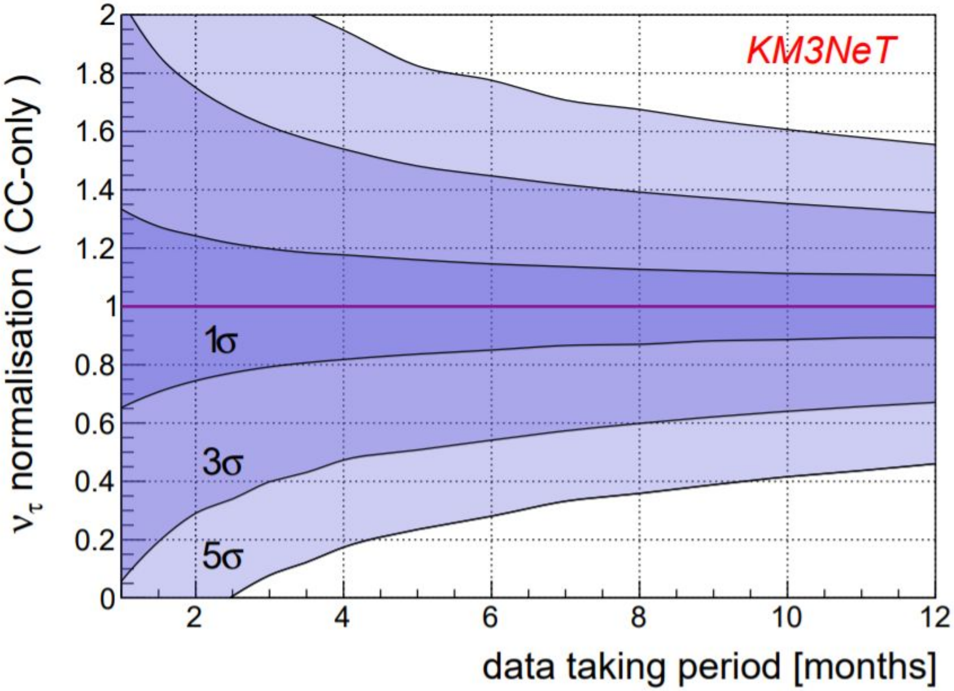




Tau Appearance

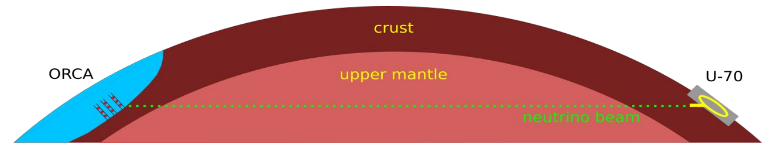
- Atmospheric neutrinos are also an excellent probe of ν_τ appearance
- KM3NeT will be able to constrain the nt component to 7% level in 3 years
- Measurement can be used to probe the unitarity of the PMNS matrix
- Tau appearance can be confirmed with 5σ confidence in 2.5 years



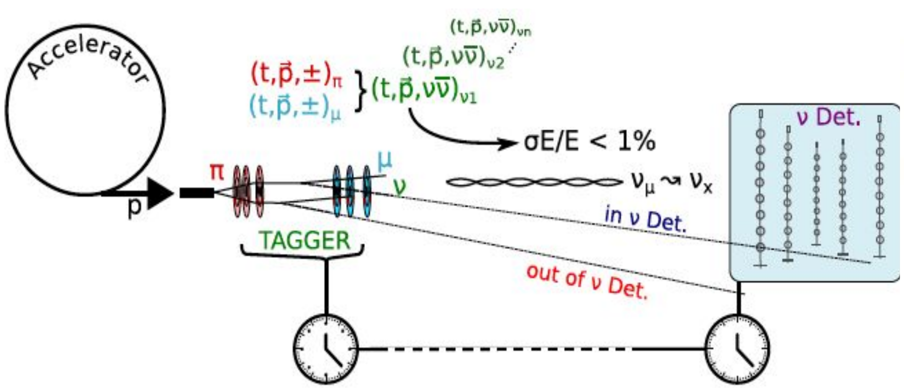


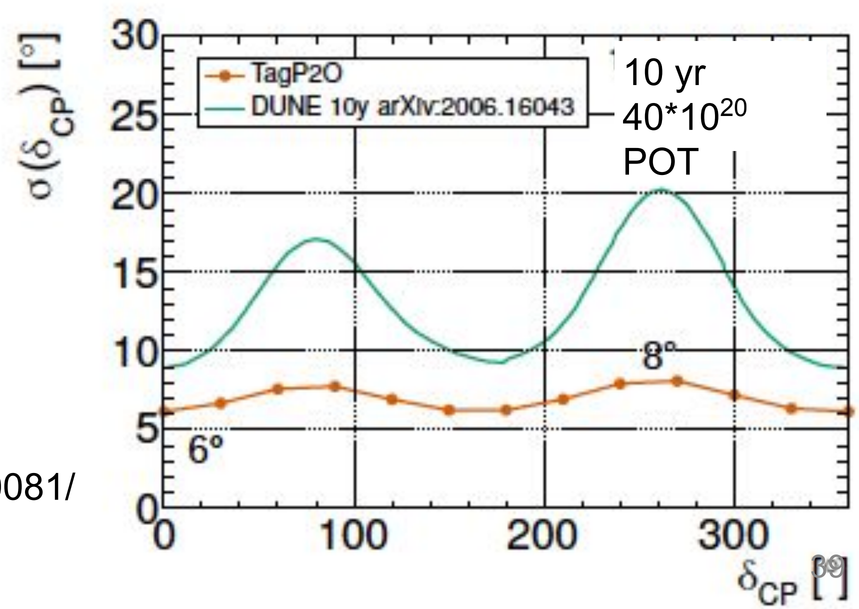
New idea: Tagged Protvino to ORCA

A. V. Akindinov et al.,
“Letter of Interest for a Neutrino Beam from Protvino to KM3NeT/ORCA"
https://arxiv.org/abs/1902.06083



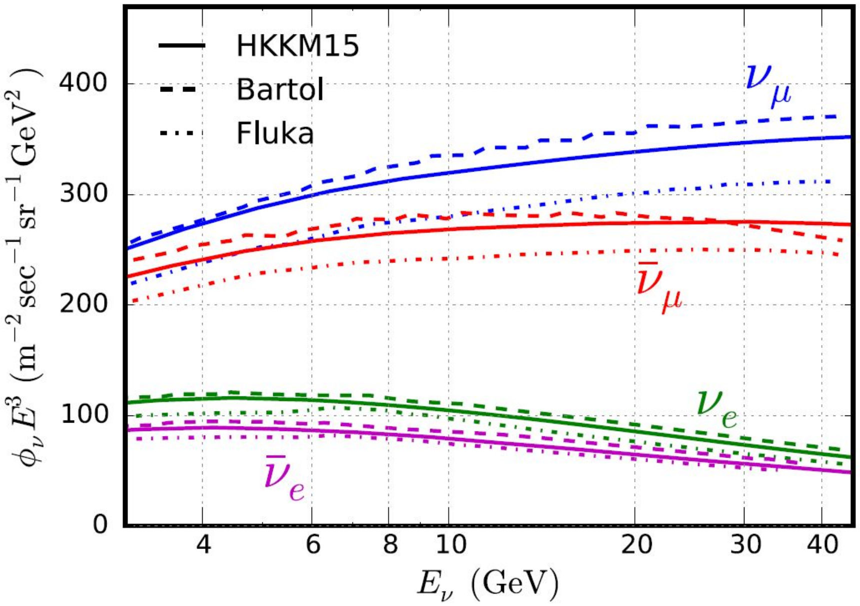
- Neutrino Beam from Protvino to ORCA
- Baseline 2590 km
- First oscillation maximum 5.1 GeV
- Sensitivity to mass hierarchy and CPV
- Huge detector -> relax beam power
- New idea - ν tagging at source:

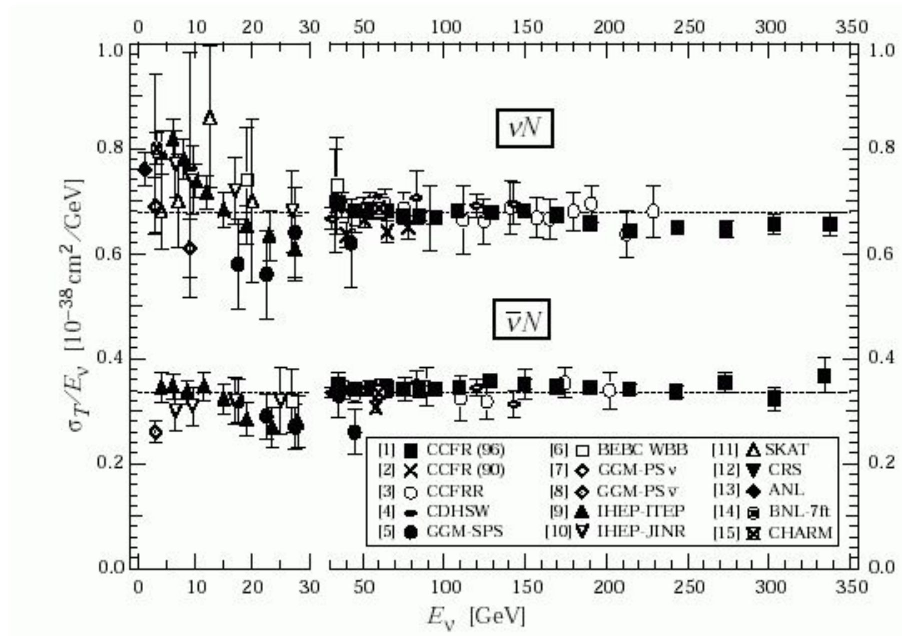




Mathieu Perrin-Terrin@NuTel2021
https://agenda.infn.it/event/24250/contributions/130081/

Atmospheric Neutrinos





- Factor of ~2 between nue and numu
- Factor of ~2 between nu and nubar
- ν_μ + anti-ν_μ = (ν_μ + anti-ν_μ + ν_e + anti-ν_e) -> (ν_μ + anti-ν_μ)

Resonance Formulas

$$\sin^2 2\theta_{13}^m \equiv \sin^2 2\theta_{13} \left(\frac{\Delta m_{31}^2}{\Delta^m m^2} \right)^2$$

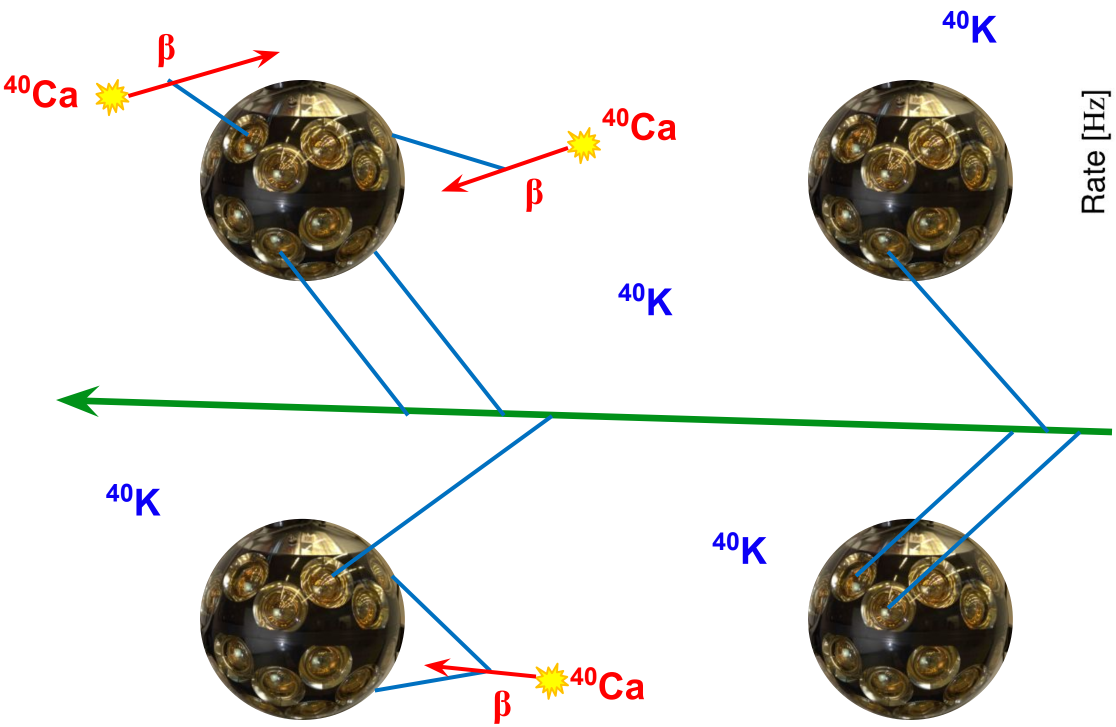
Depends on
sign of Δm^2_{31} (MH)

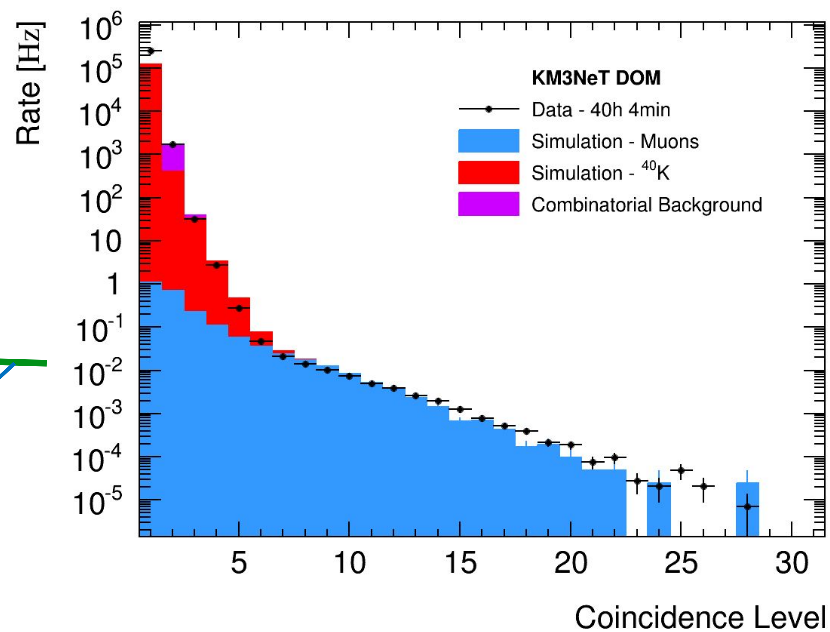
$$\Delta^m m^2 \equiv \sqrt{(\Delta m_{31}^2 \cos 2\theta_{13} - 2 E_\nu A)^2 + (\Delta m_{31}^2 \sin 2\theta_{13})^2}\,,$$

$$E_{\text{res}} \equiv \frac{\Delta m_{31}^2 \cos 2\theta_{13}}{2\sqrt{2}\, G_F N_e} \simeq 7\,\text{GeV} \left(\frac{4.5\,\text{g}/\text{cm}^3}{\rho} \right) \left(\frac{\Delta m_{31}^2}{2.4 \times 10^{-3}\,\text{eV}^2} \right) \cos 2\theta_{13}\,.$$

Trigger

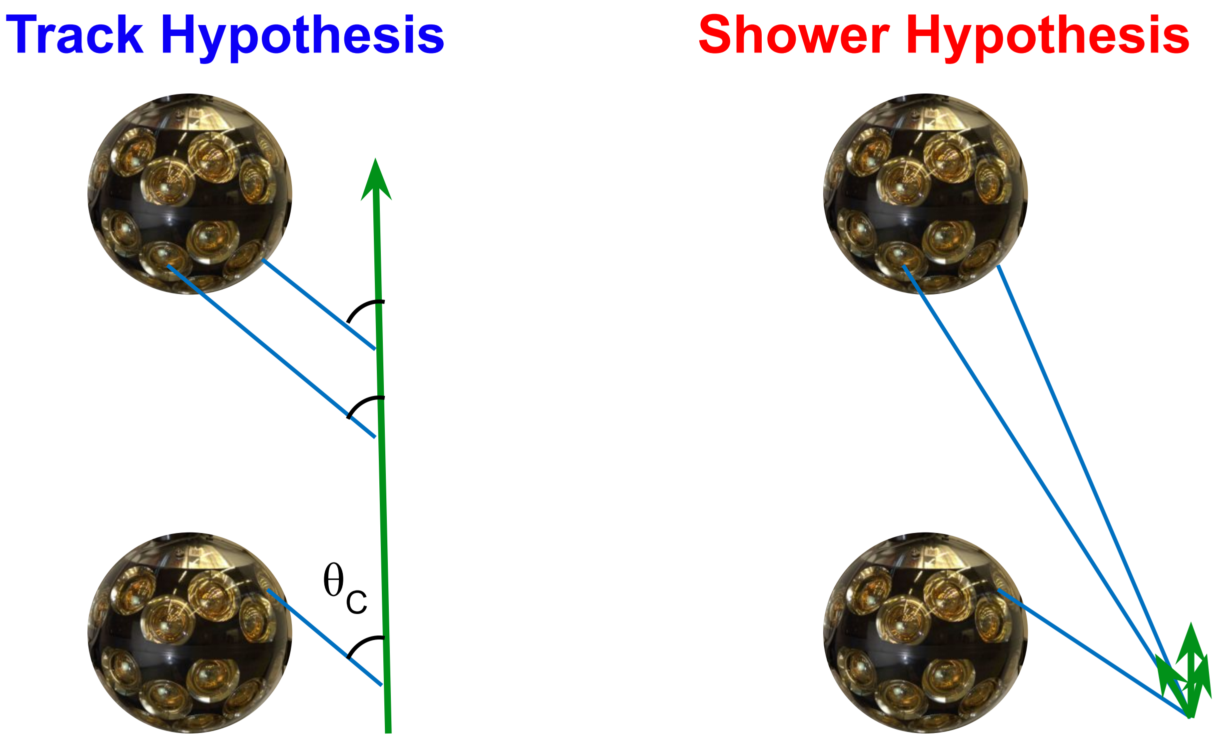
- Optical background mostly from ^{40}K decays in the water
- Measured: **8 kHz** uncorr., **340 Hz** level-two coinc. / PMT **[Eur. Phys. J. C 74, 3056 (2014)]**
- Look for coincidences in time and PMT direction to reduce trigger rate.
- Causality further restricts space and time correlations for extra power.
- Final trigger rate **~59 Hz**, with **70%** of events containing a cosmic ray **muon**.





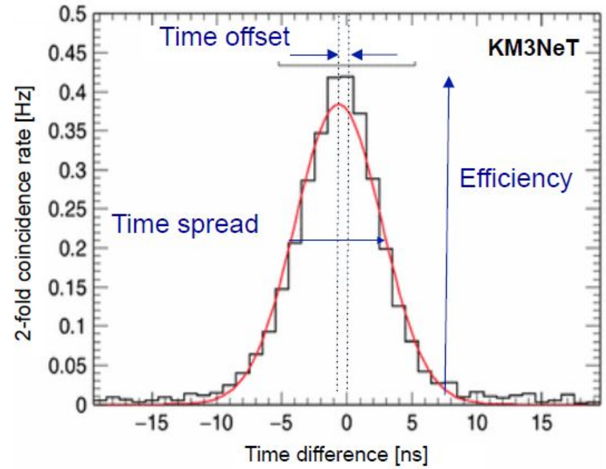
Reconstruction

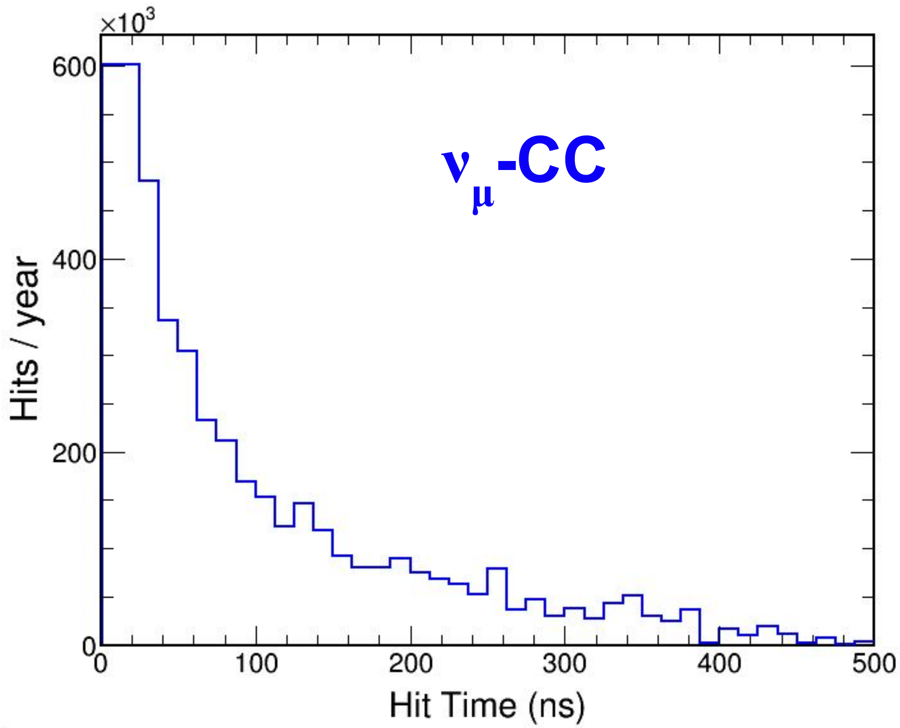
1) Start with a track or shower hypothesis
2) Use **causality** to perform a robust **hit selection**
3) Find **vertex** and **direction** that best match hit pattern
4) Estimate track range for computing **track energy** (0.24 GeV / m)
5) Estimate **Shower energy** and direction from hit distribution after initial fit to the vertex position and time

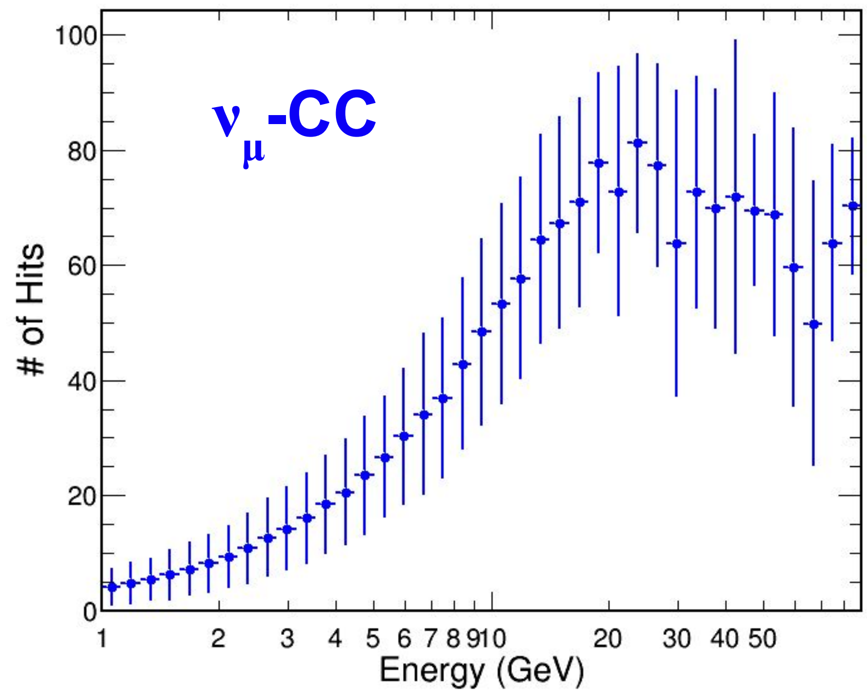


Optical Noise

- Optical background in full detector **~500 MHz**.
- Neutrino events ~40 hits in a **~500 ns** window
- Expect **250 noise hits** (~15% purity)
- Trigger approach **~5 ns time residuals**
- Calibrated using 2-fold coincidences
- Can achieve **~3 noise hits** per trigger (>90% purity)



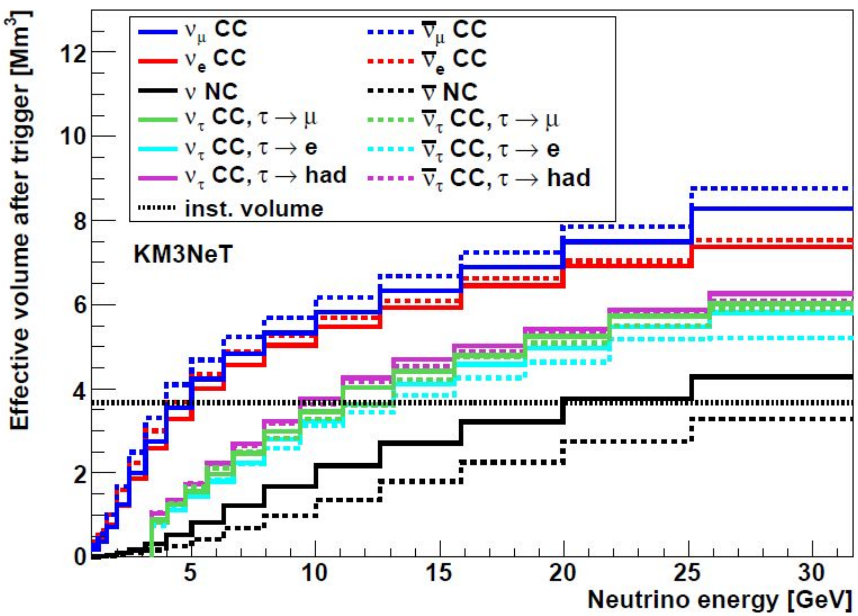




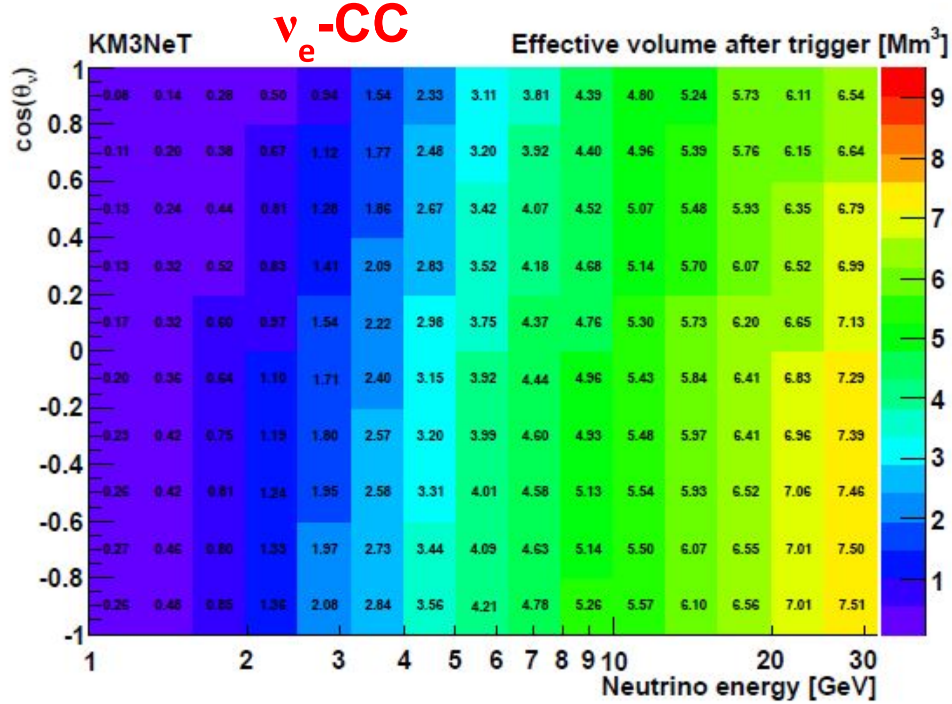
Trigger Performance

- Input a **conservative** noise rate of **10 kHz** uncorr. (**500Hz** level-two coinc.)
- Achieve a total triggered rate of **59 Hz**
- About **70%** of events contain a **muon** (41 Hz)
- High efficiency for ν_μ and ν_e above 4 GeV
- Slightly more efficient for up-going neutrinos (Larger PMT coverage)

Neutrino Rate:
~ 1 ν / 10 min

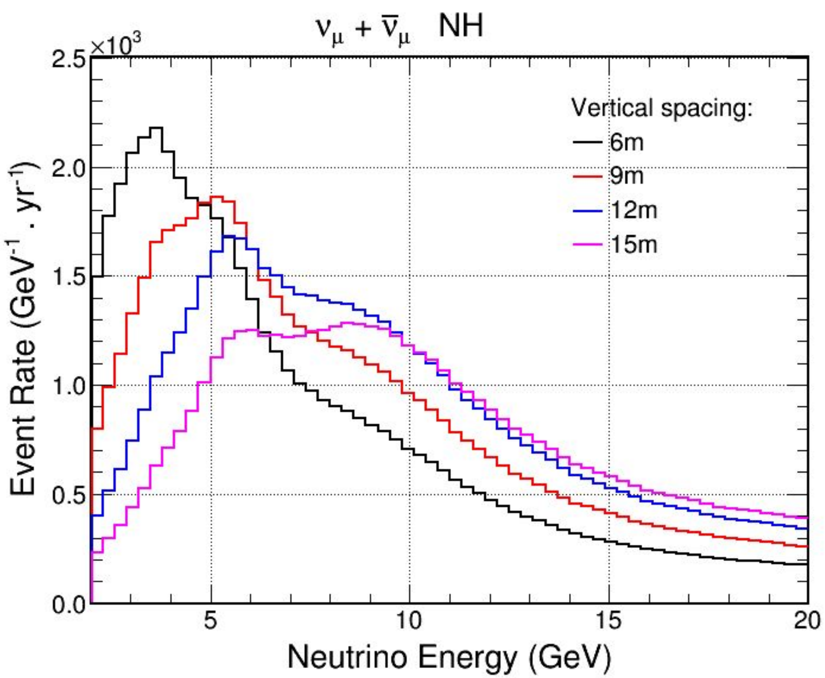


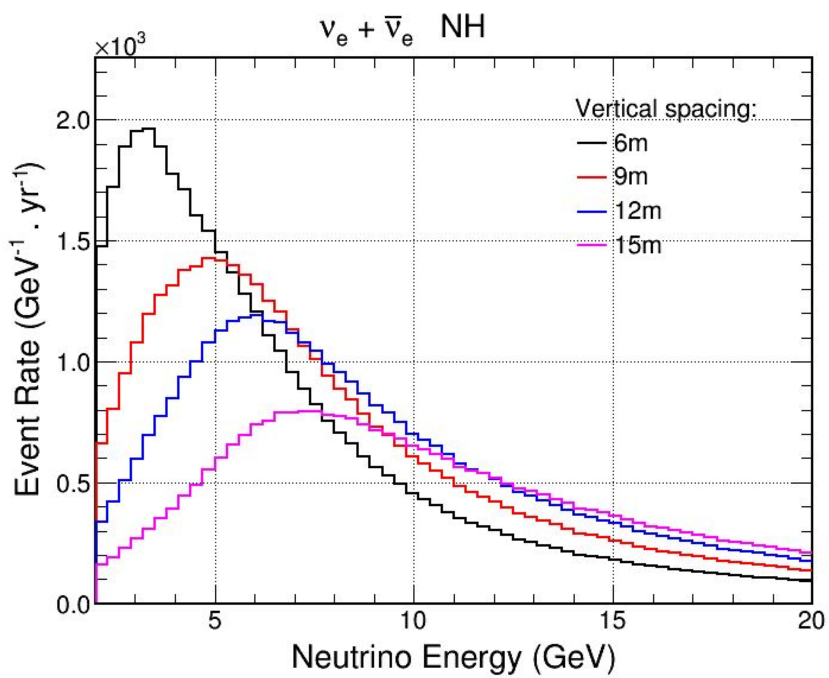
ν_e-CC



Optimizing DOM Spacing

- Simulated small (6m) vertical spacing detector
- Mask off 1/3, 1/2 or 2/3 of DOMs to emulate larger spacing
- **Smaller spacing** enables measurement at **lower energies**
- **Larger spacing improves statistics** due to larger volume
- **Tune spacing** to obtain maximum sensitivity to **Mass Hierarchy**

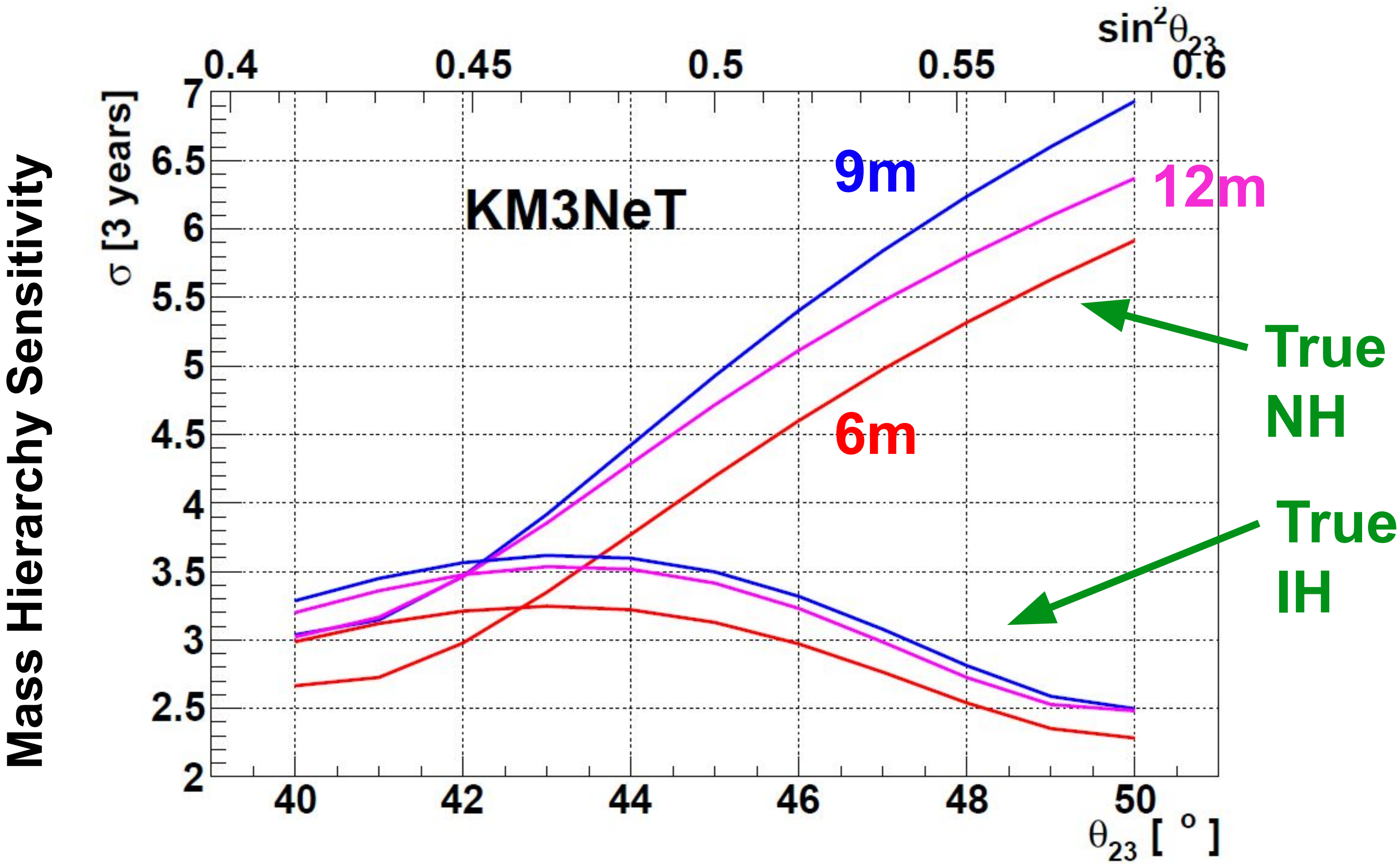




Derived from data in the KM3NeT 2.0 LoI: https://arxiv.org/abs/1601.07459

Simple χ^2 Analysis

- **9m spacing achieves best sensitivity**



Beyond the Standard Model

Extended Models

Arbitrary Perturbation

Non-Standard Interactions (NSI)

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

Sterile Neutrinos (3+N Flavours)

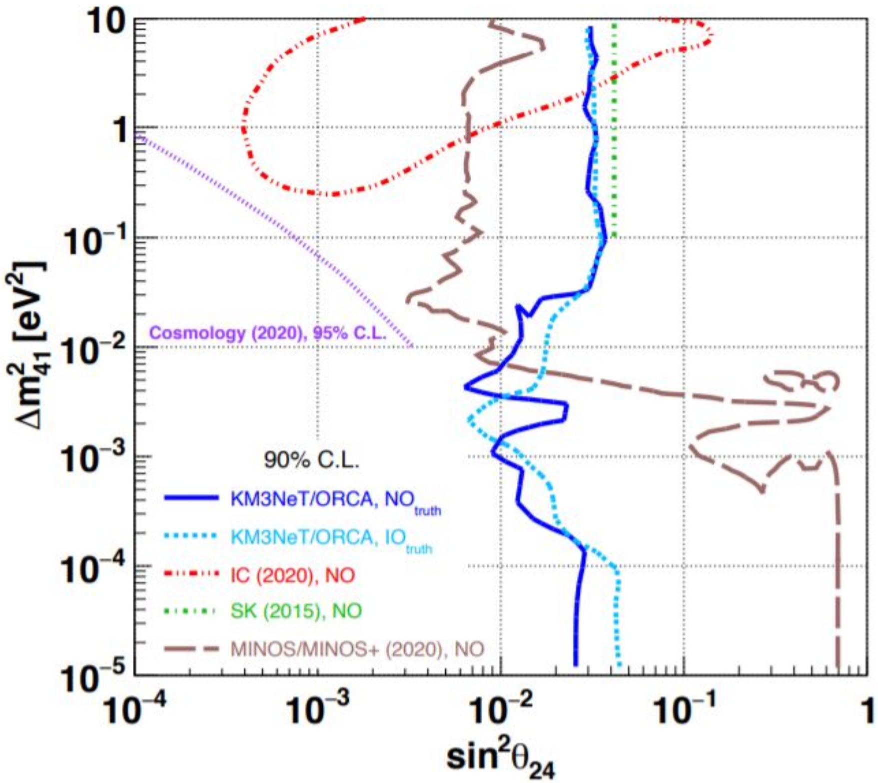
$$H_{eff} = U_S \begin{bmatrix} 0 & 0 & 0 & 0 & \cdots \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 & 0 & \cdots \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} & 0 & \cdots \\ 0 & 0 & 0 & \frac{\Delta m^2_{41}}{2E} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} U_S^\dagger + \begin{bmatrix} V_e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

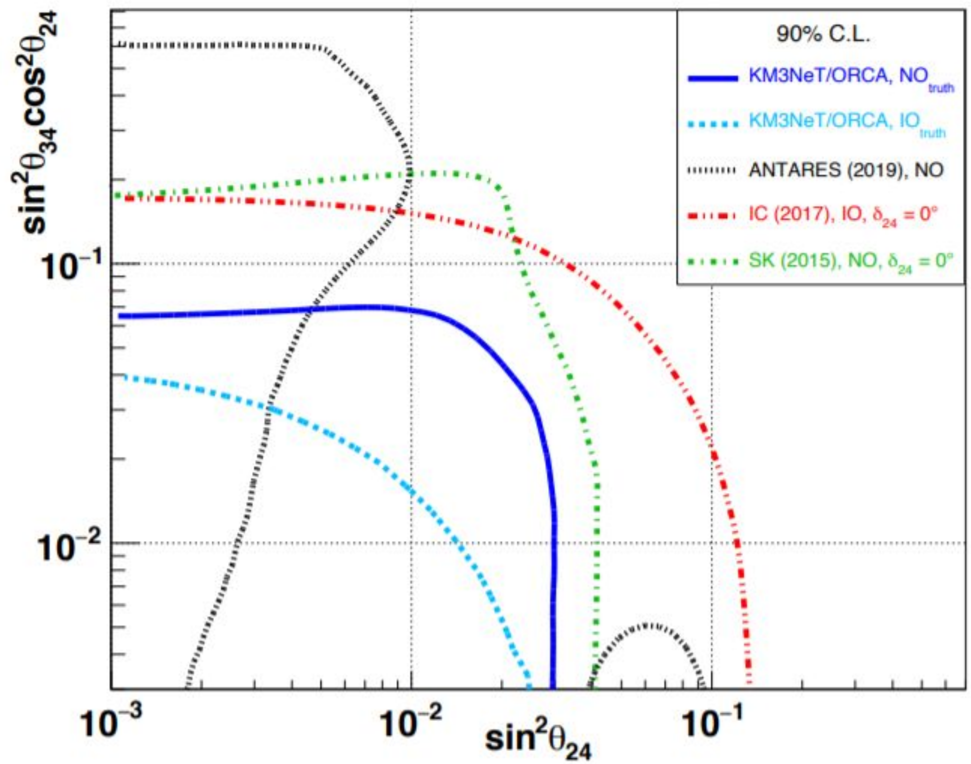
NC Contribution

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

Sterile Neutrinos

- Explores very low Δm^2_{41} values due to longer baselines
- World leading sensitivity to $U_{\tau 4}$ coupling





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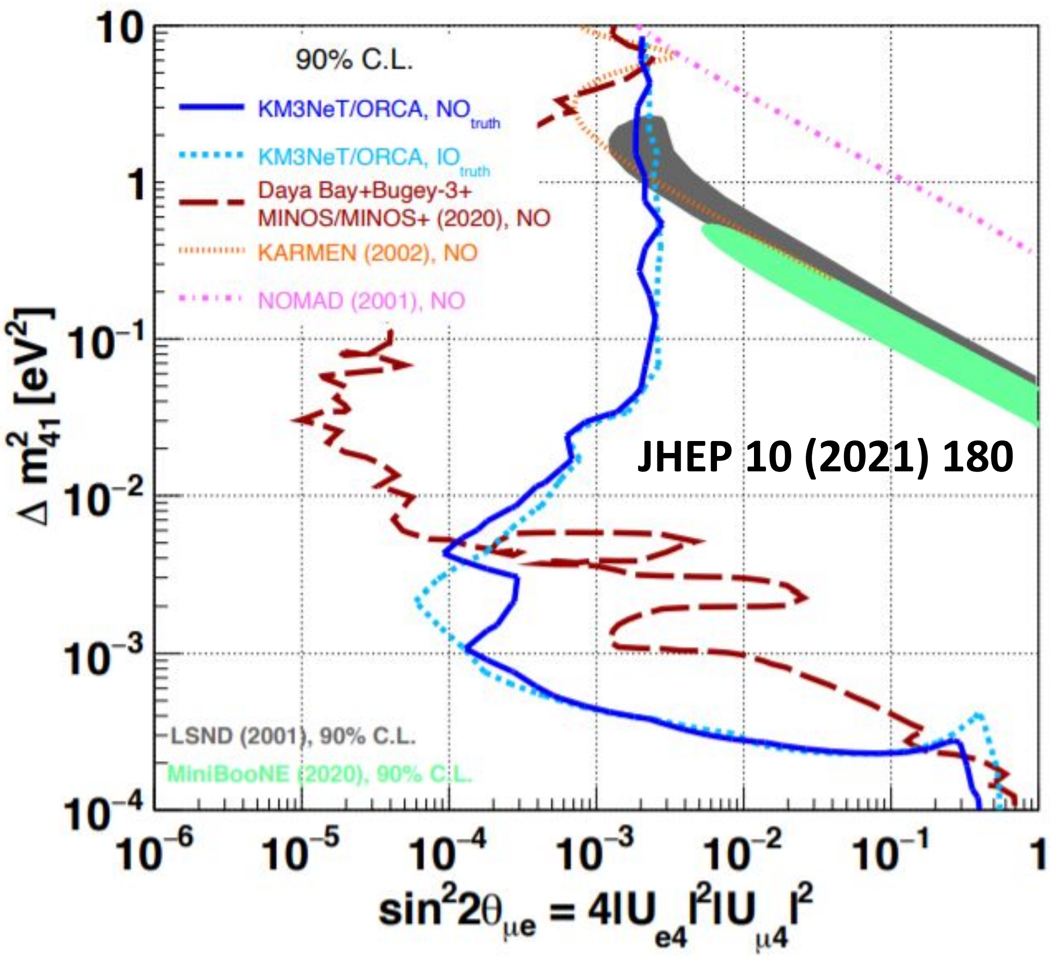
Sterile Neutrinos

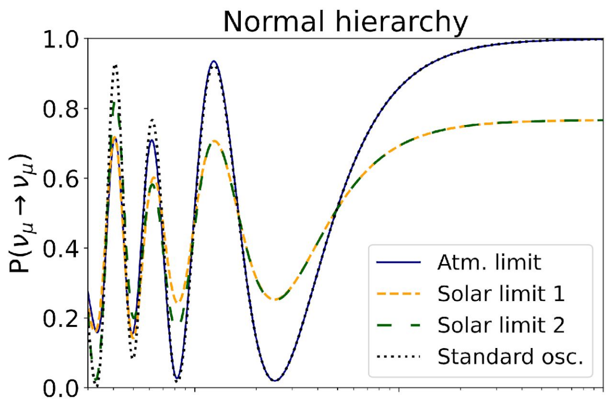
- Explores very low Δm^2_{41} values due to longer baselines
- World leading sensitivity to $U_{\tau 4}$ coupling
- Probing LSND/MiniBooNE anomaly in single experiment

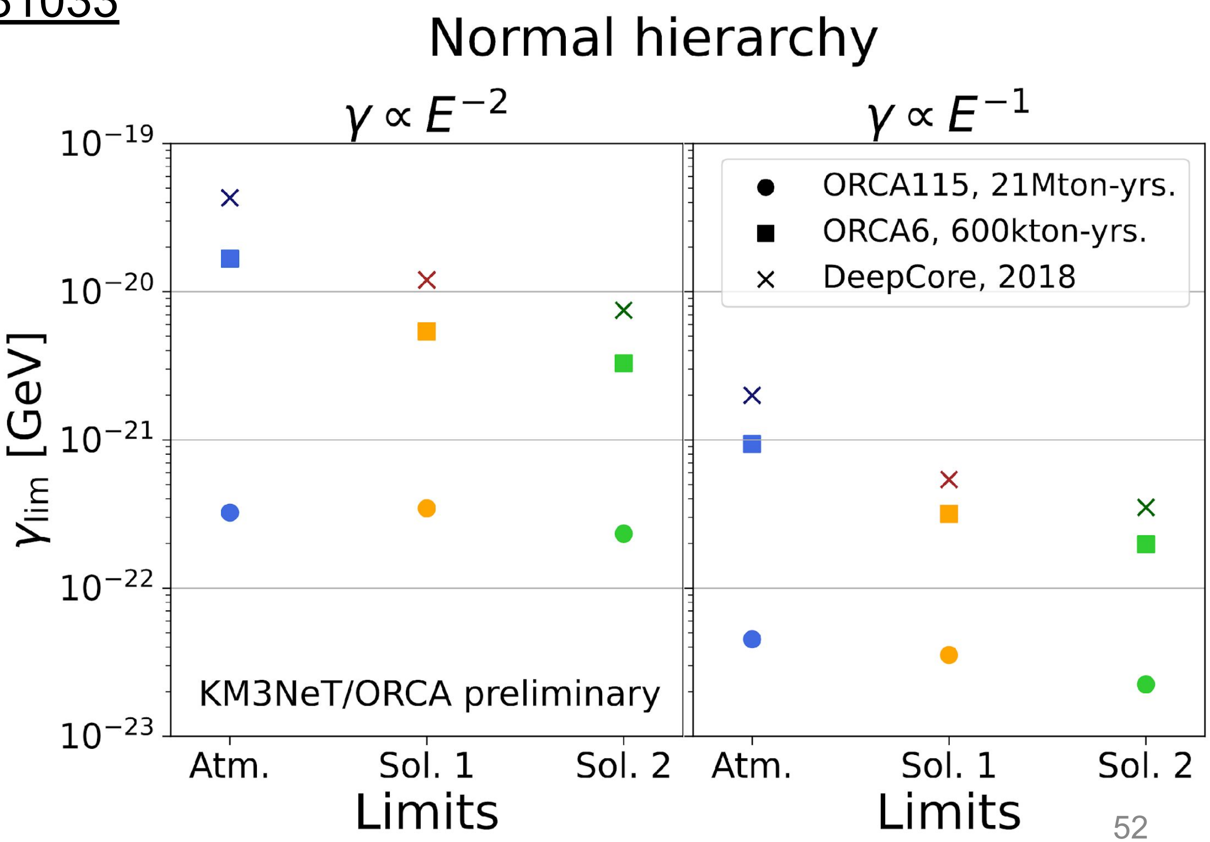


Decoherence

- Measures possible loss of coherence of neutrinos due to interactions with the environment around it
- Proposed as a possible signal of Quantum Gravity
- World leading sensitivity to some decoherence modes

https://zenodo.org/record/6781033





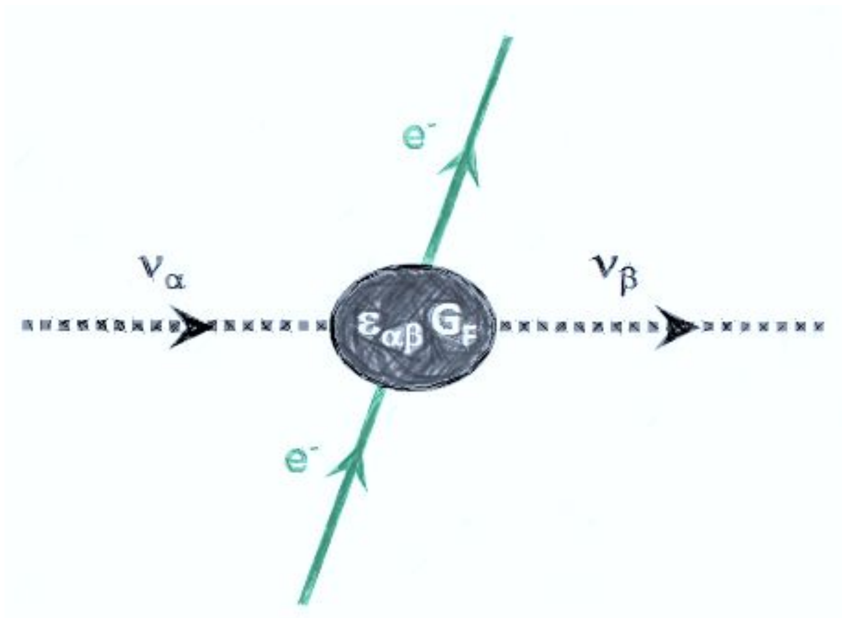
Non-Standard Interactions

NSI Motivation

Non-Standard Interactions (NSI)

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

Arbitrary Perturbation



Dimension-6 + Naturalness

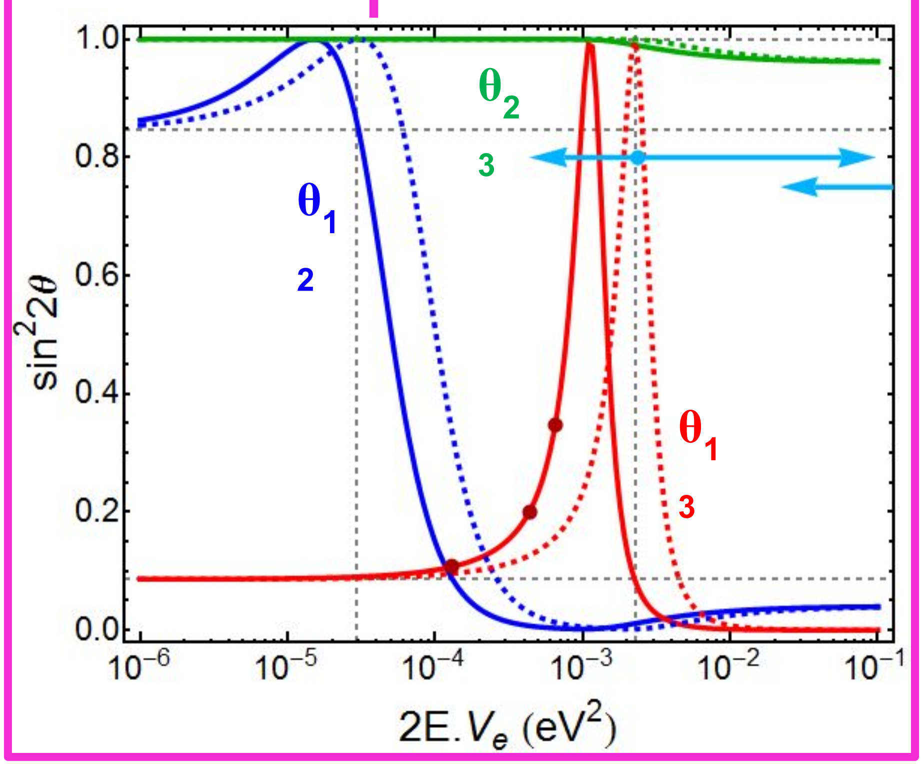
$$\varepsilon \propto \frac{m_W^2}{m_X^2}$$

TeV Scale ~ 10^{-2}

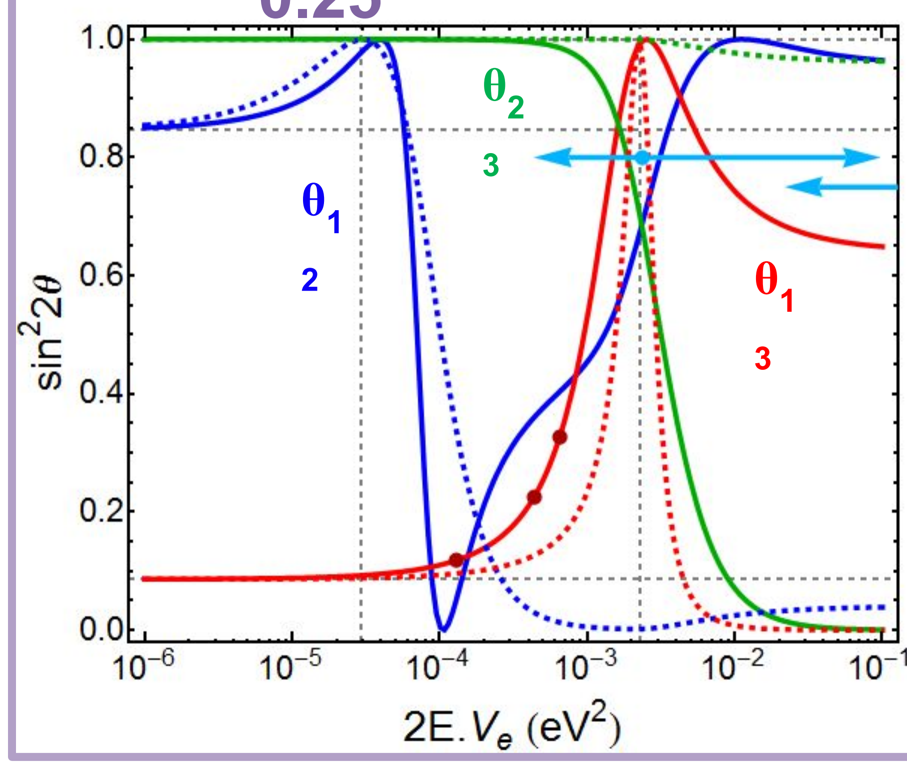
$$\mathcal{L}_{\rm NSI} = -2\sqrt{2} G_F \varepsilon^{ff'C}_{\alpha\beta} \left(\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta\right)\left(\overline{f}\gamma_\mu P_C f'\right)$$

Resonances w/ NSI

$\varepsilon_{ee} = 1$



$\varepsilon_{e\tau} = 0.5$, $\varepsilon_{\tau\tau} = 0.25$



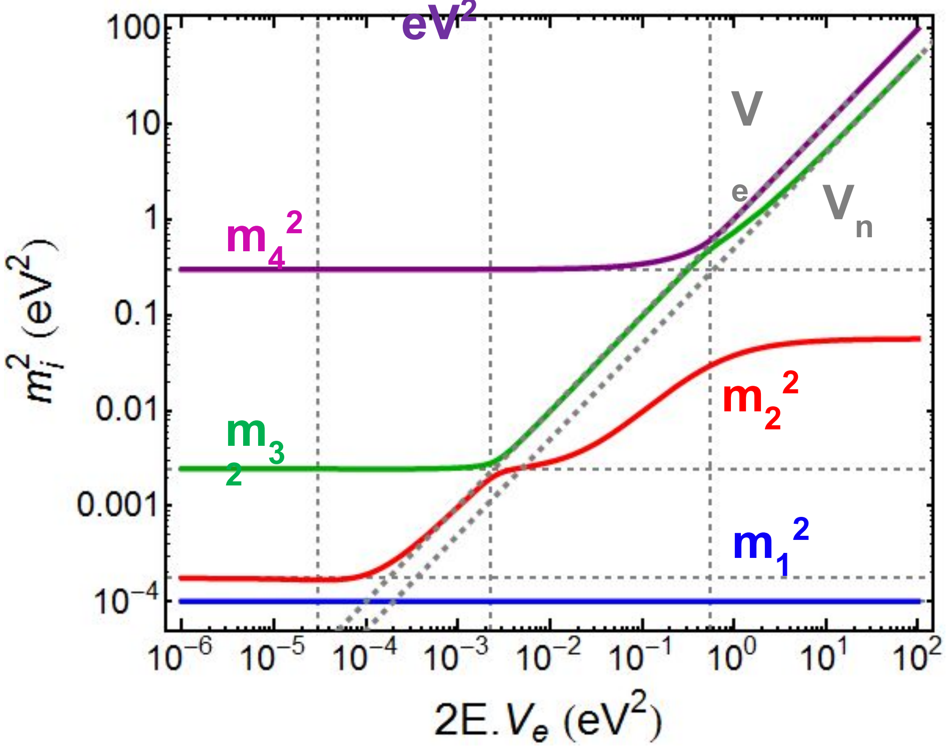
$$H_{eff} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{bmatrix} U^\dagger + V_e \begin{bmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^*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

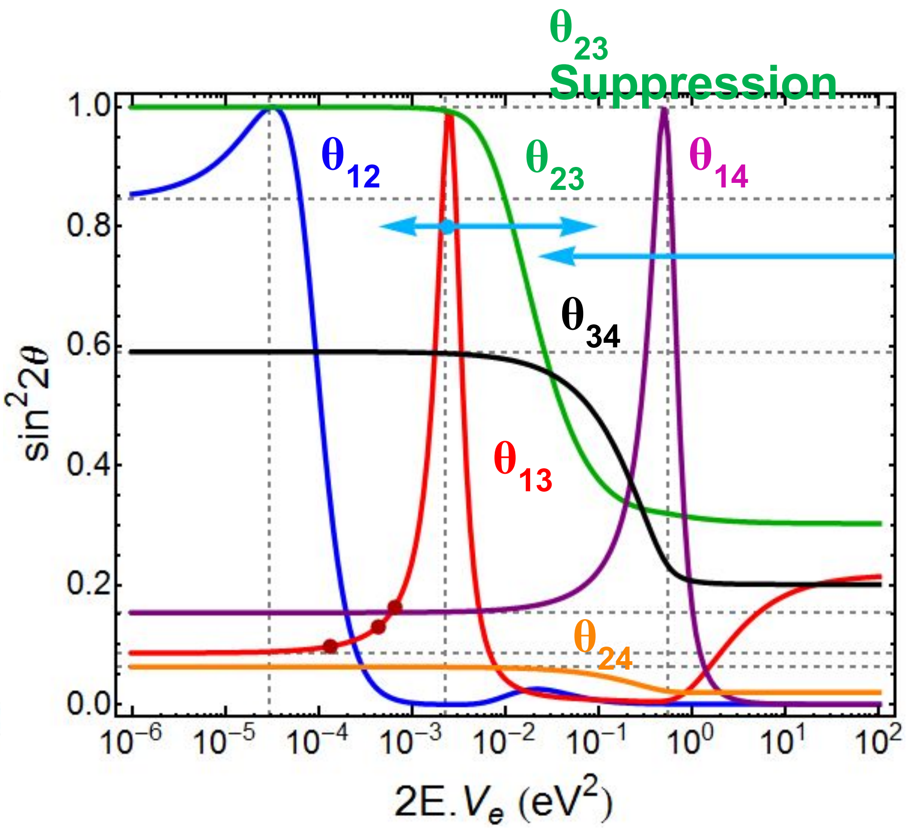
Sterile Neutrinos

Resonances w/ Steriles

- New resonant peak due to Δm^2_{41}
- Some intermediate behaviour between θ_{13} and θ_{14} resonances
- θ_{23} suppression seems to be fairly independent of Δm^2_{41}

$\Delta m^2_{41} = 0.3$ eV^2





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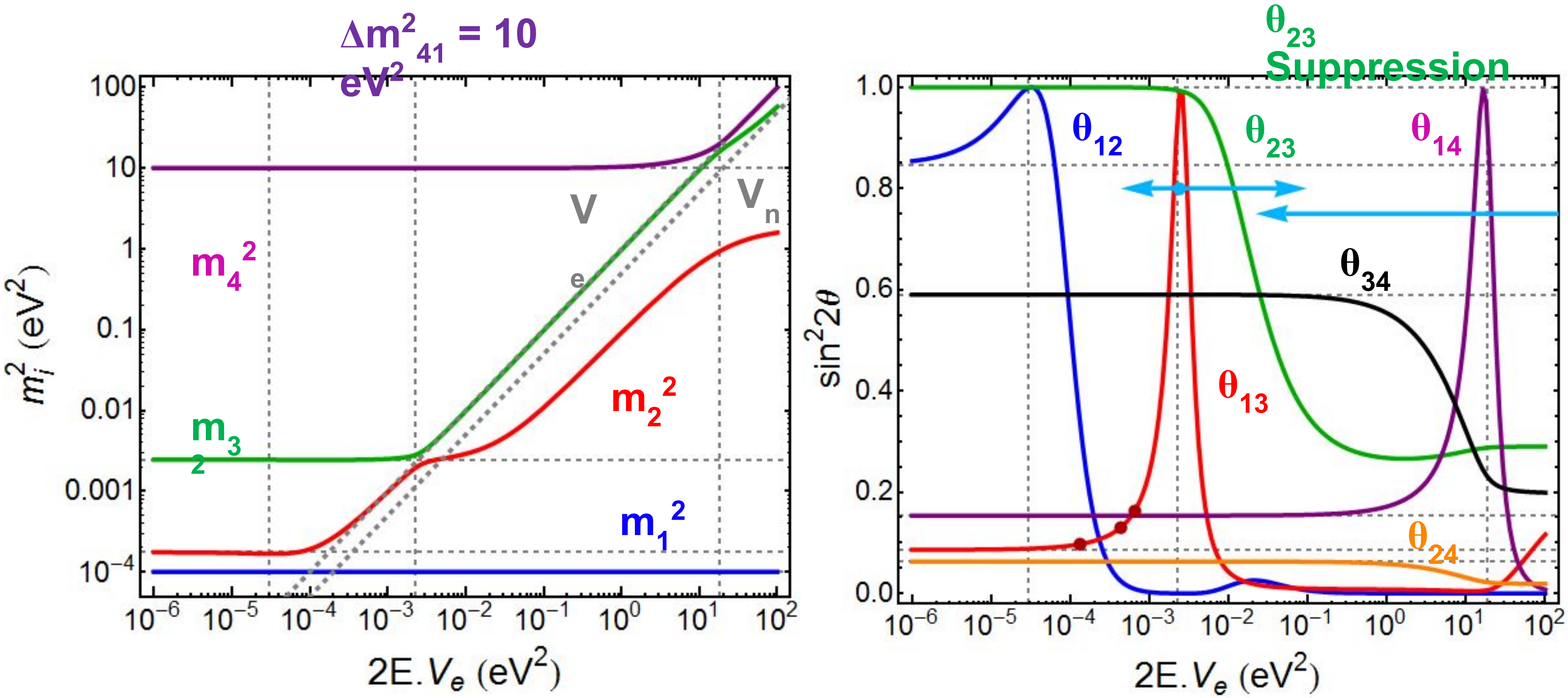

Resonances w/ Steriles

- New second order resonance also depends on CP phases
- Very rich structure with interplays between $U_{\mu 4}$ and $U_{\tau 4}$
- New paper out: https://arxiv.org/abs/2107.00344