Beyond the PMNS paradigm with neutrino oscillations

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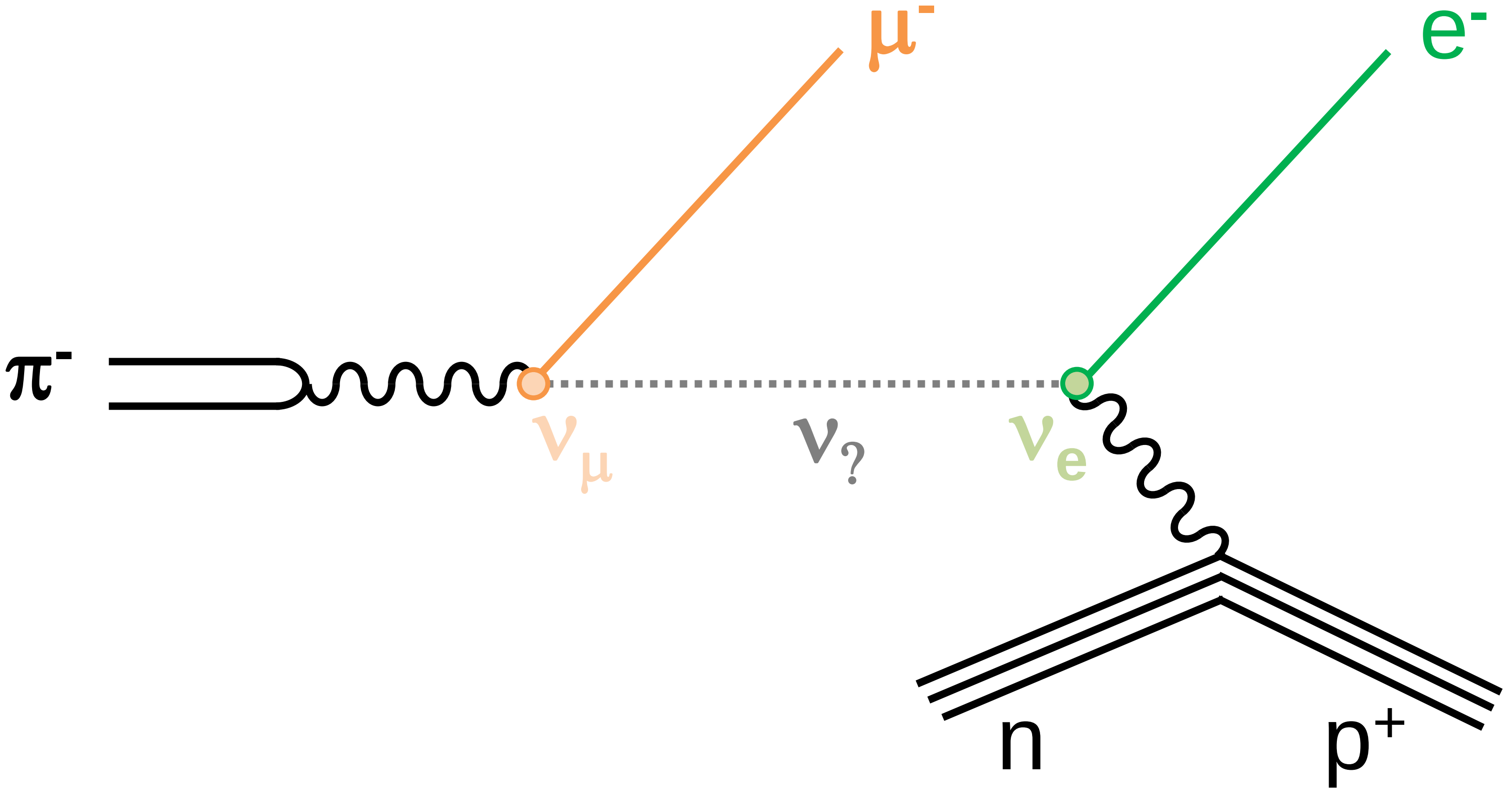
APC Laboratory

04 July 2023

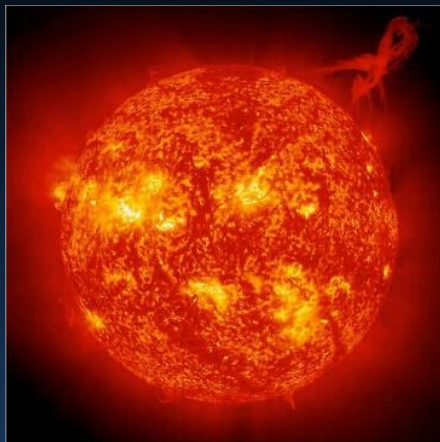
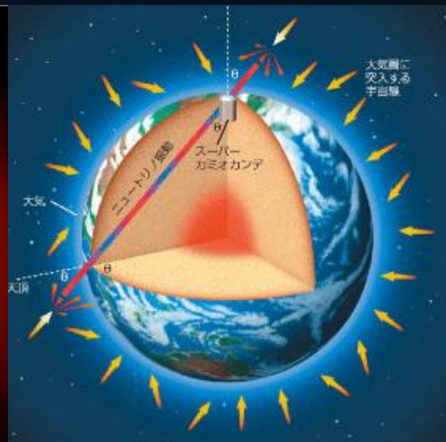
Neutrino Oscillations

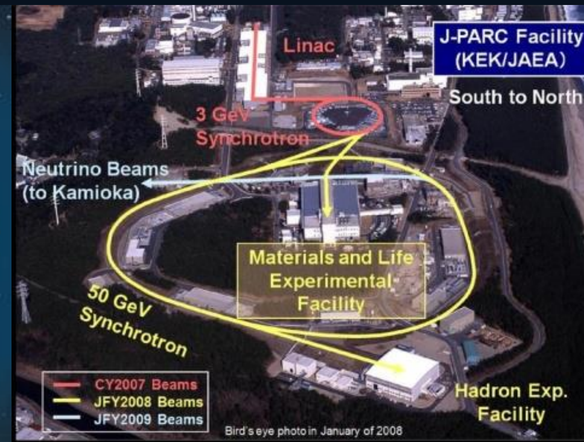


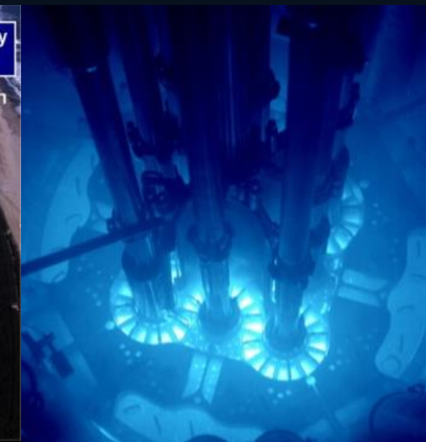
Where we are

Neutrino Experiments

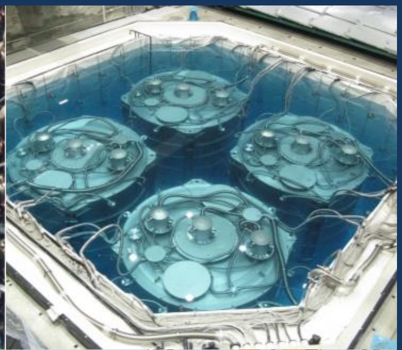
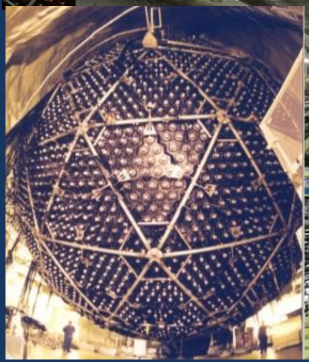
Many neutrino sources



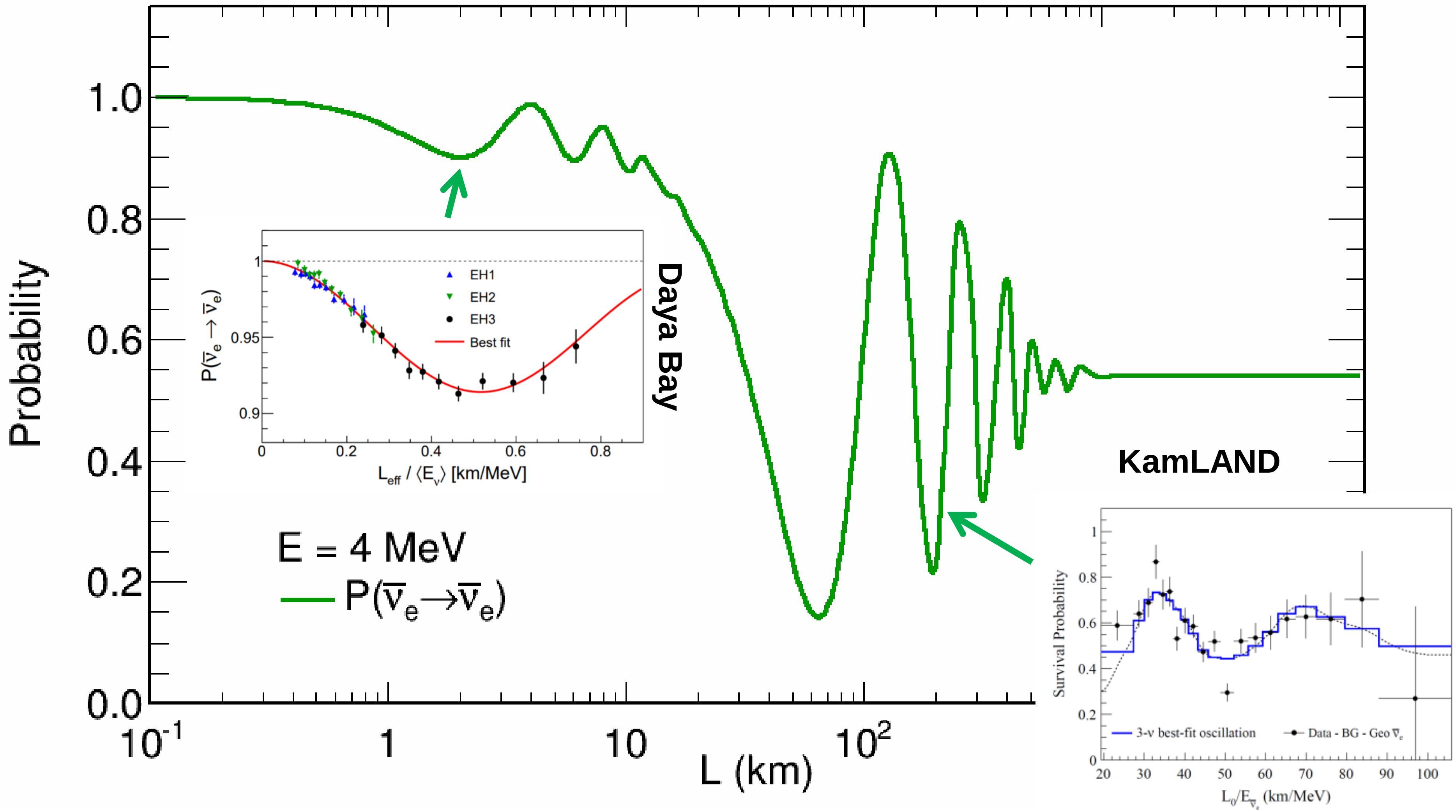




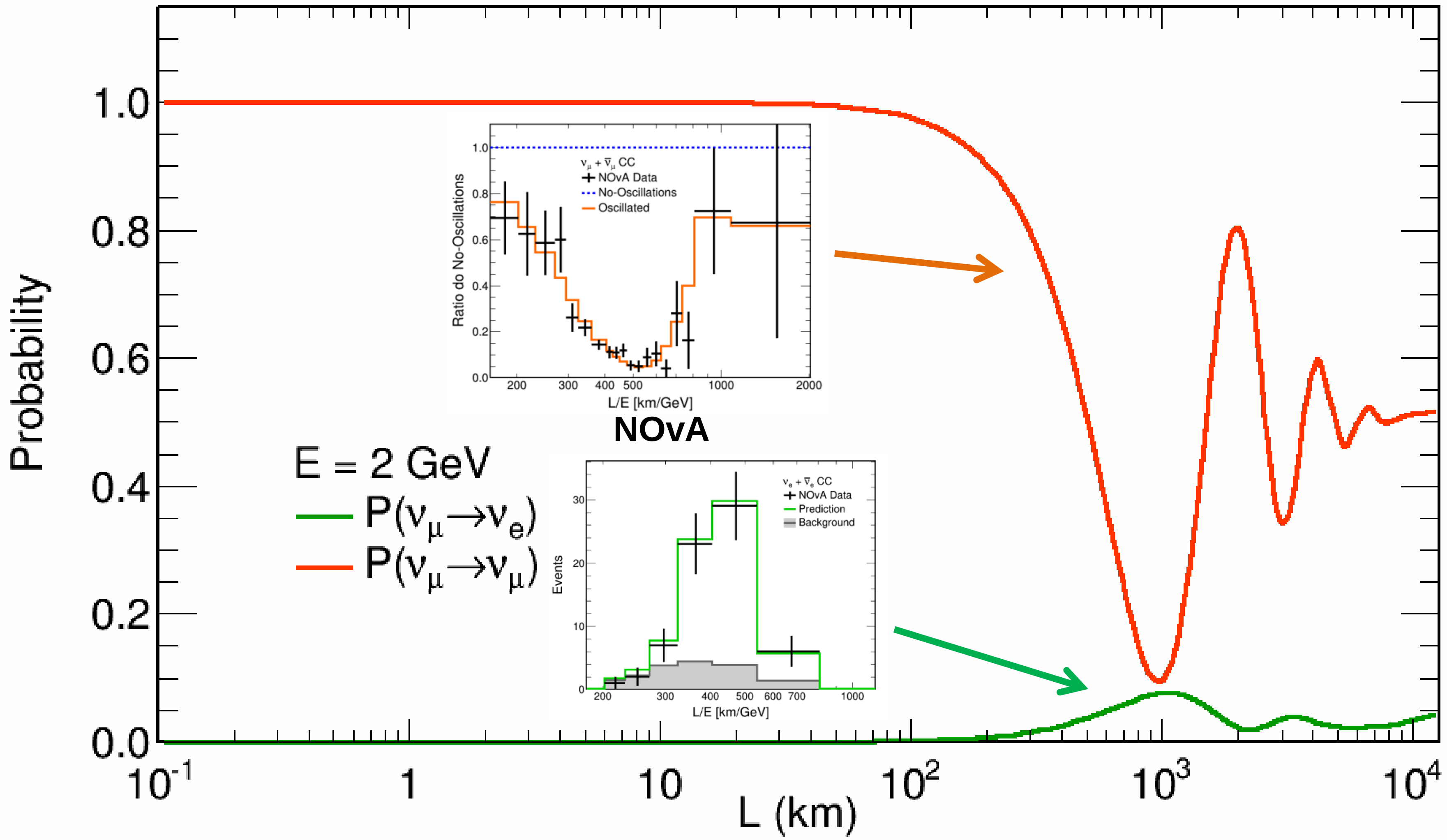



Many neutrino detectors

The Data: Reactor Neutrinos



The Data: Accelerator Neutrinos



Evolution of Knowledge

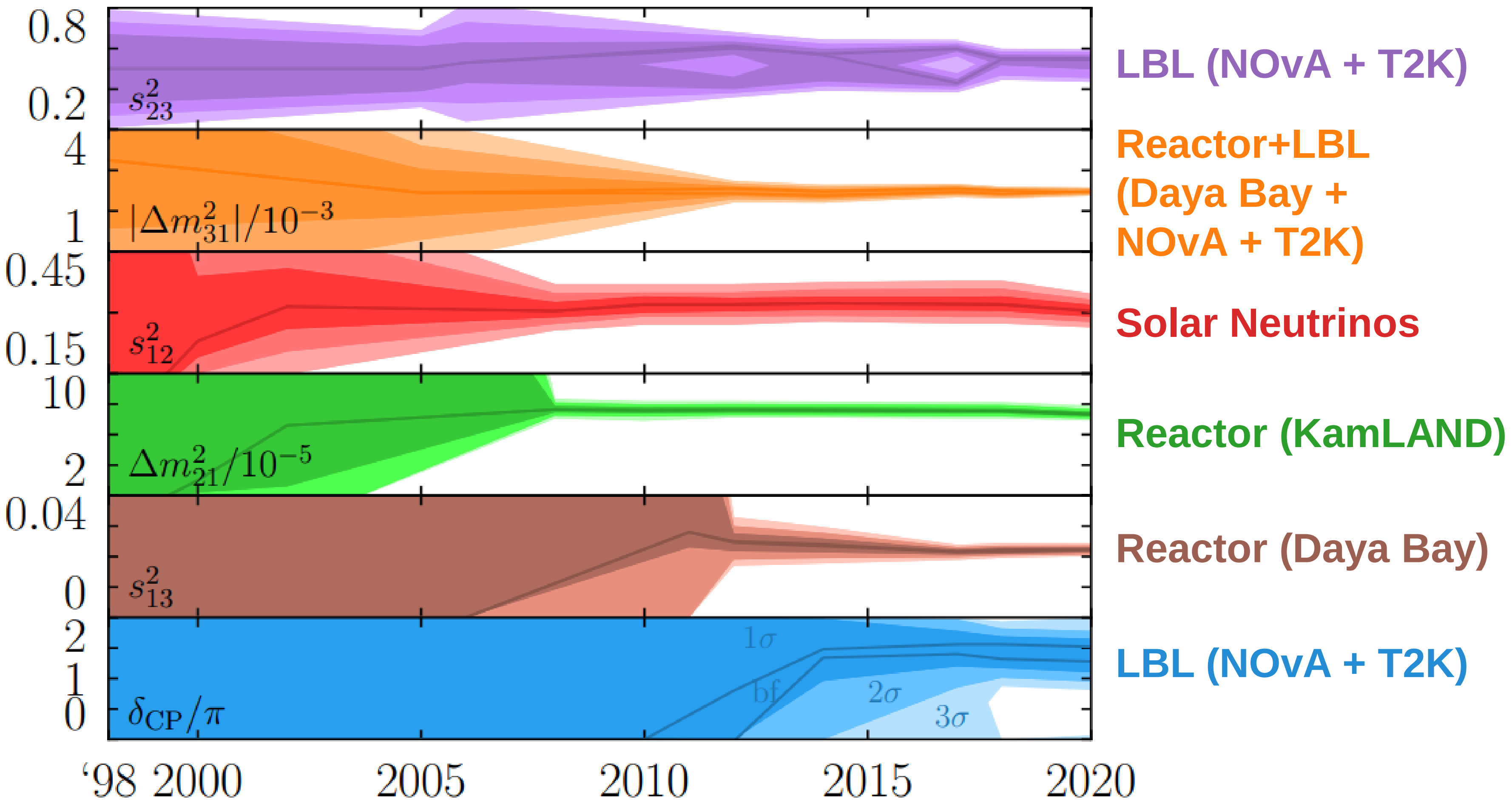
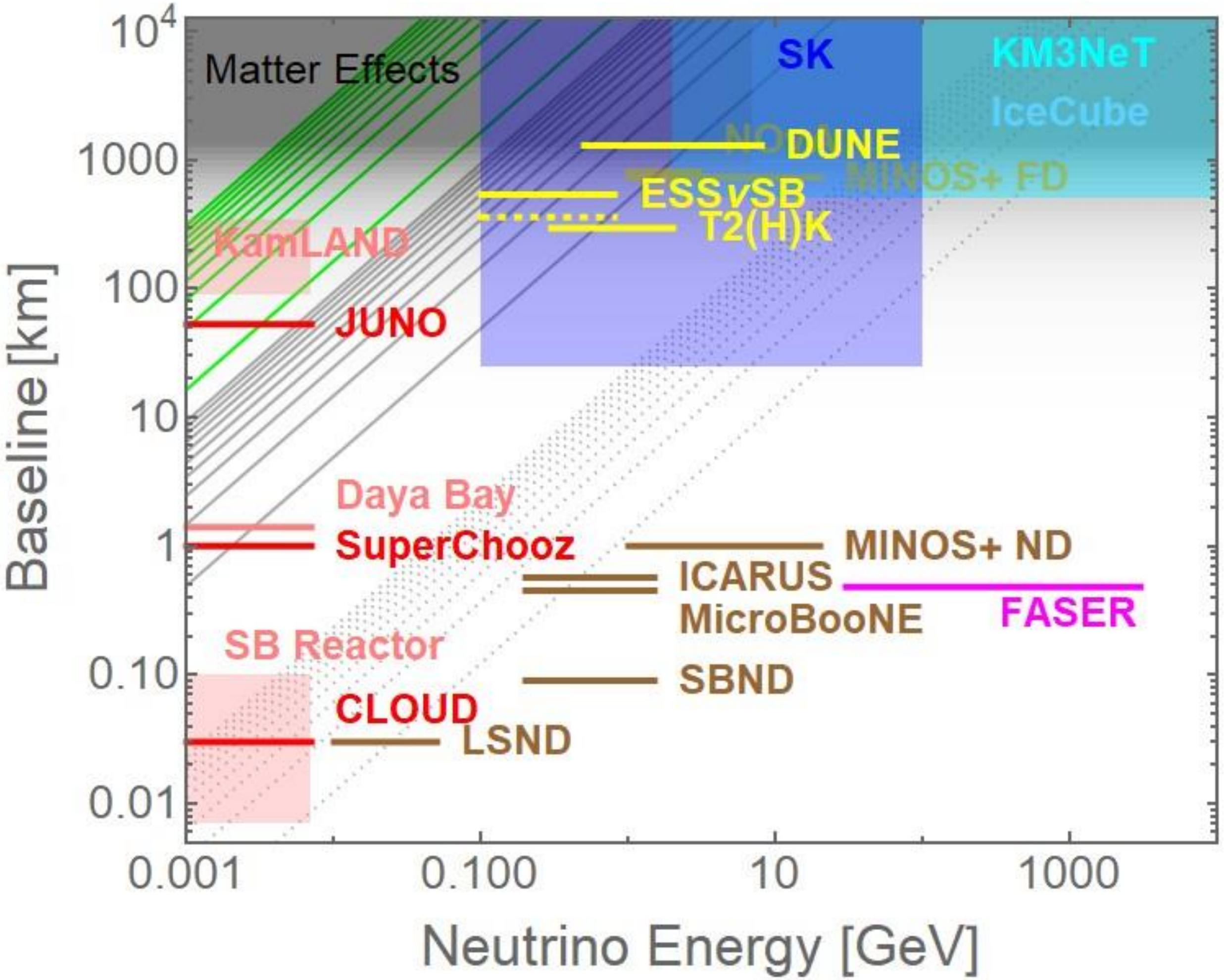


Figure 1: The six oscillation parameters listed in the order they were first measured, and the evolution of our understanding of them. Data comes from [8, 31–40].

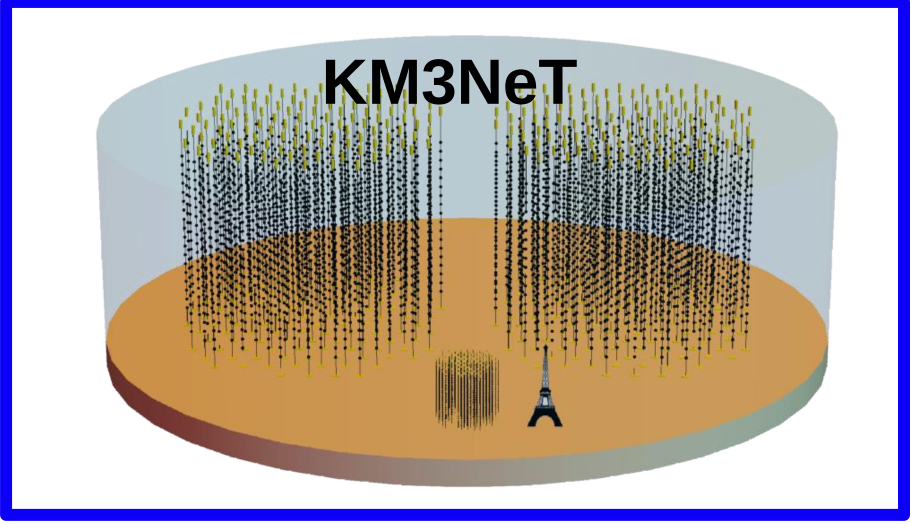
P. B. Denton et al., arXiv:2212.00809

L and E landscape



- L/E is the classic fingerprint of the standard picture oscillations
- Exploring multiple baselines with high precision may potentially unveil BSM effects
- At very long baselines, BSM may also manifest from neutrino-Earth interactions

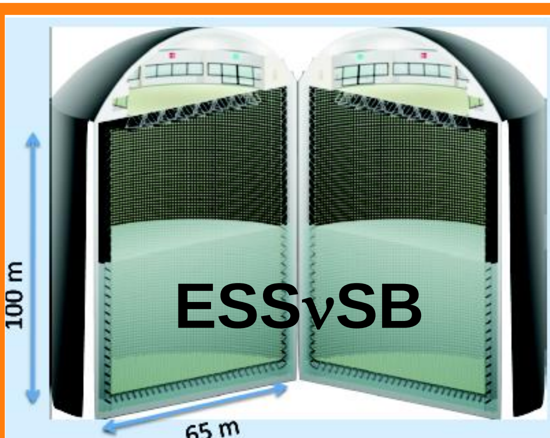
Upcoming Major Players

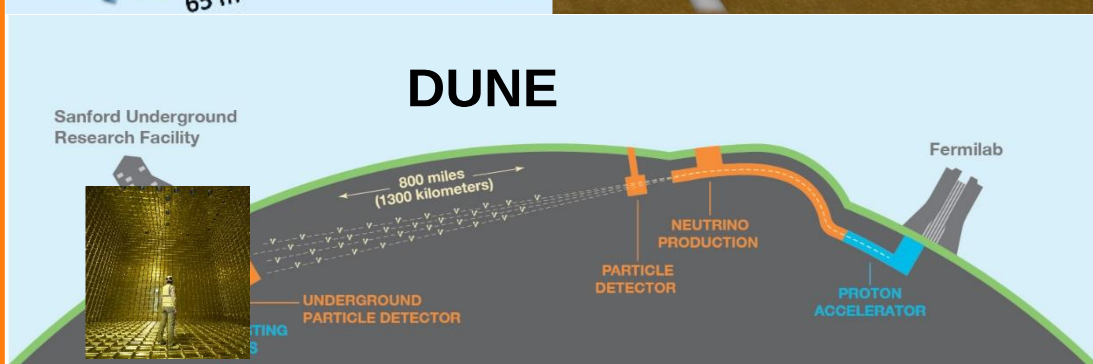


Atmospheric

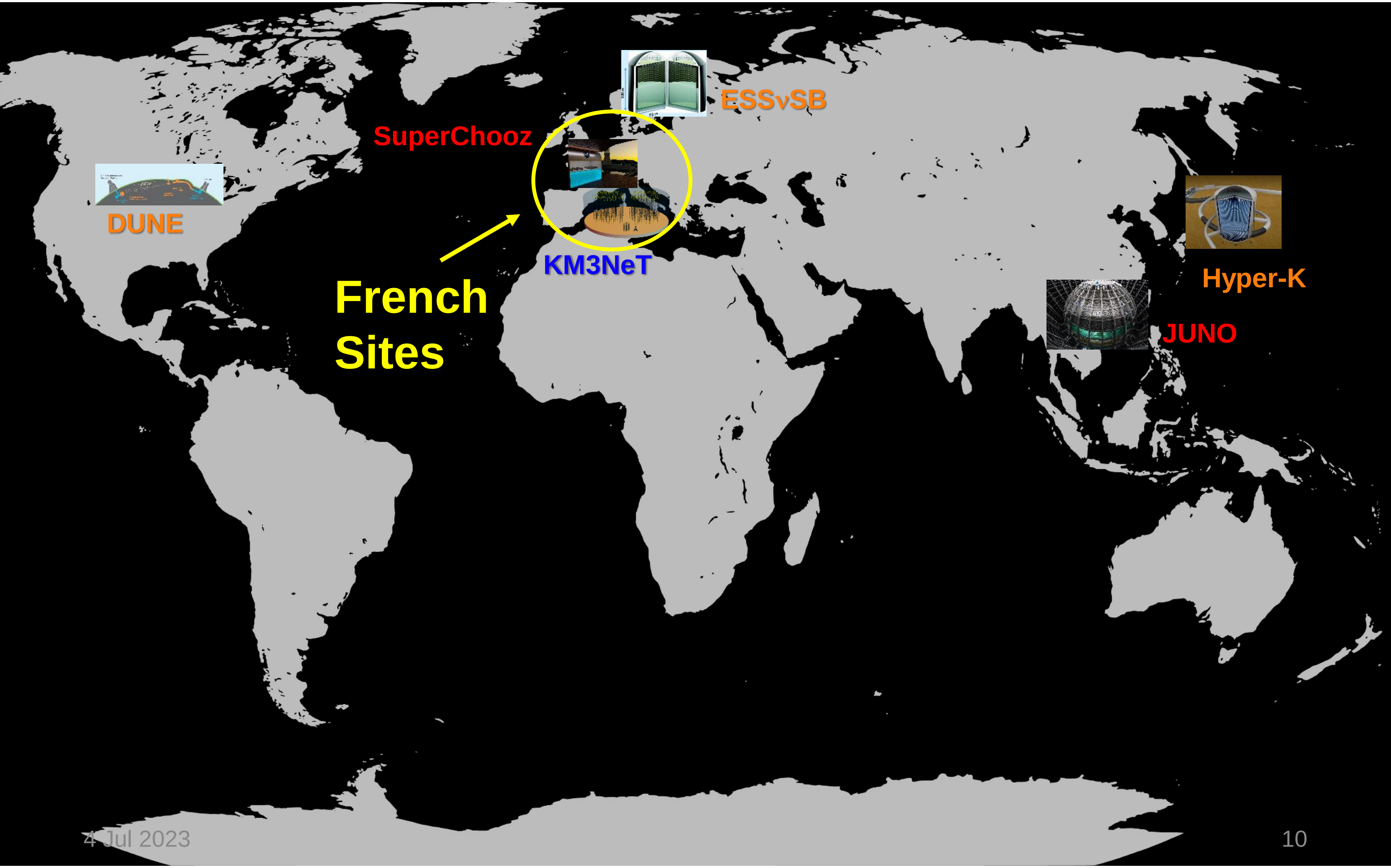
Reactor

Long-Baseline



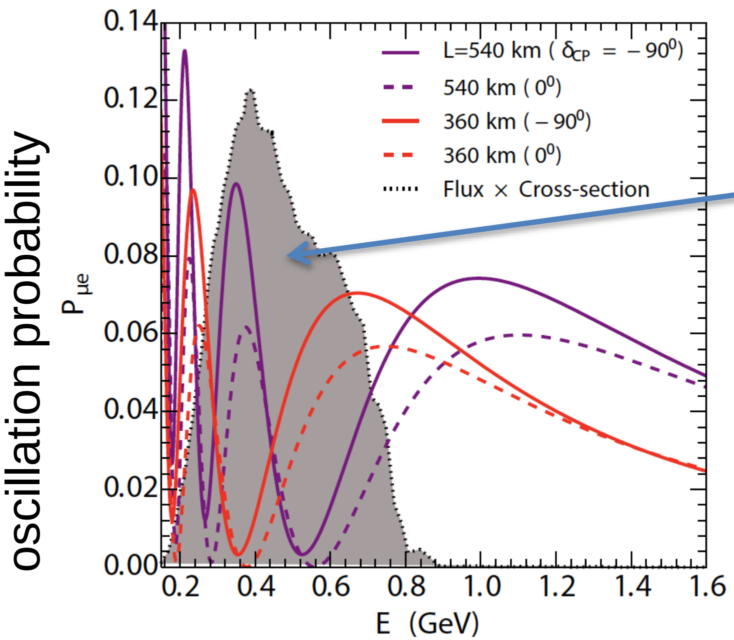


Global Effort

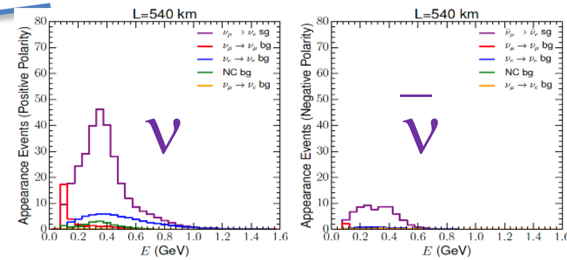


Dracos, NUFACT22

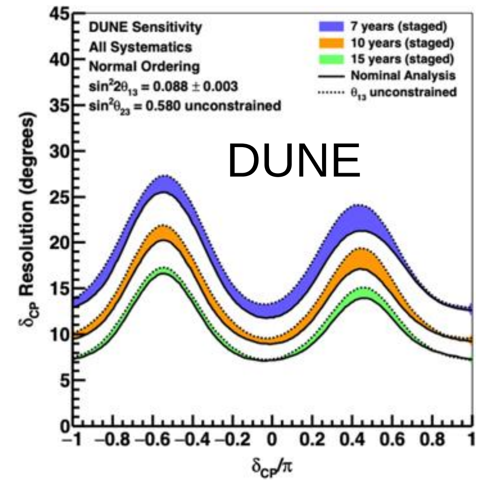
LBL Experiments



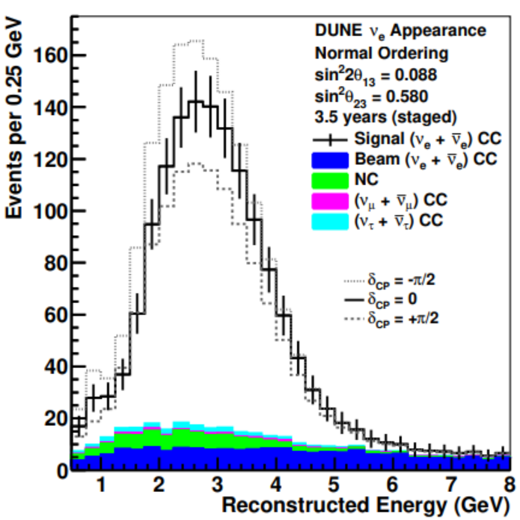
2nd oscillation max. well covered by ESSνSB

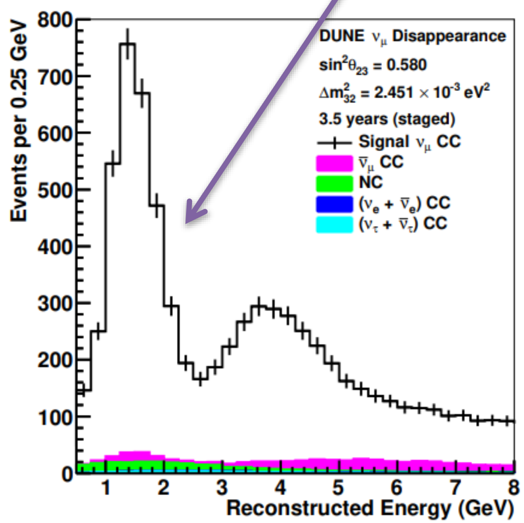


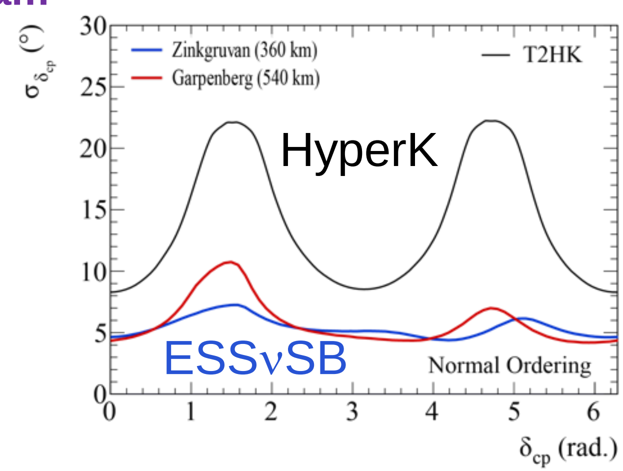
Key Measurement: CP Violation



DUNE also provides good coverage with a wide-band on-axis beam



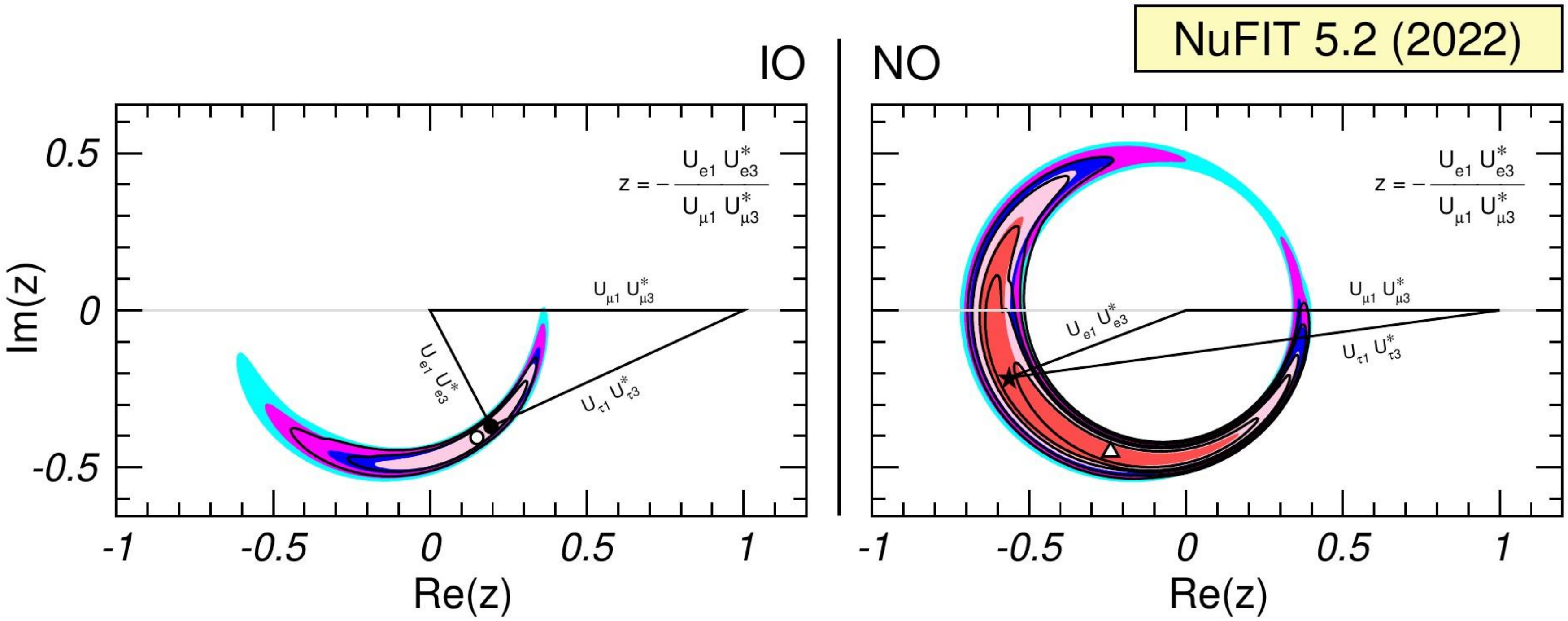




DUNE, EPJC 80 (2020) no.10, 978

Unitarity

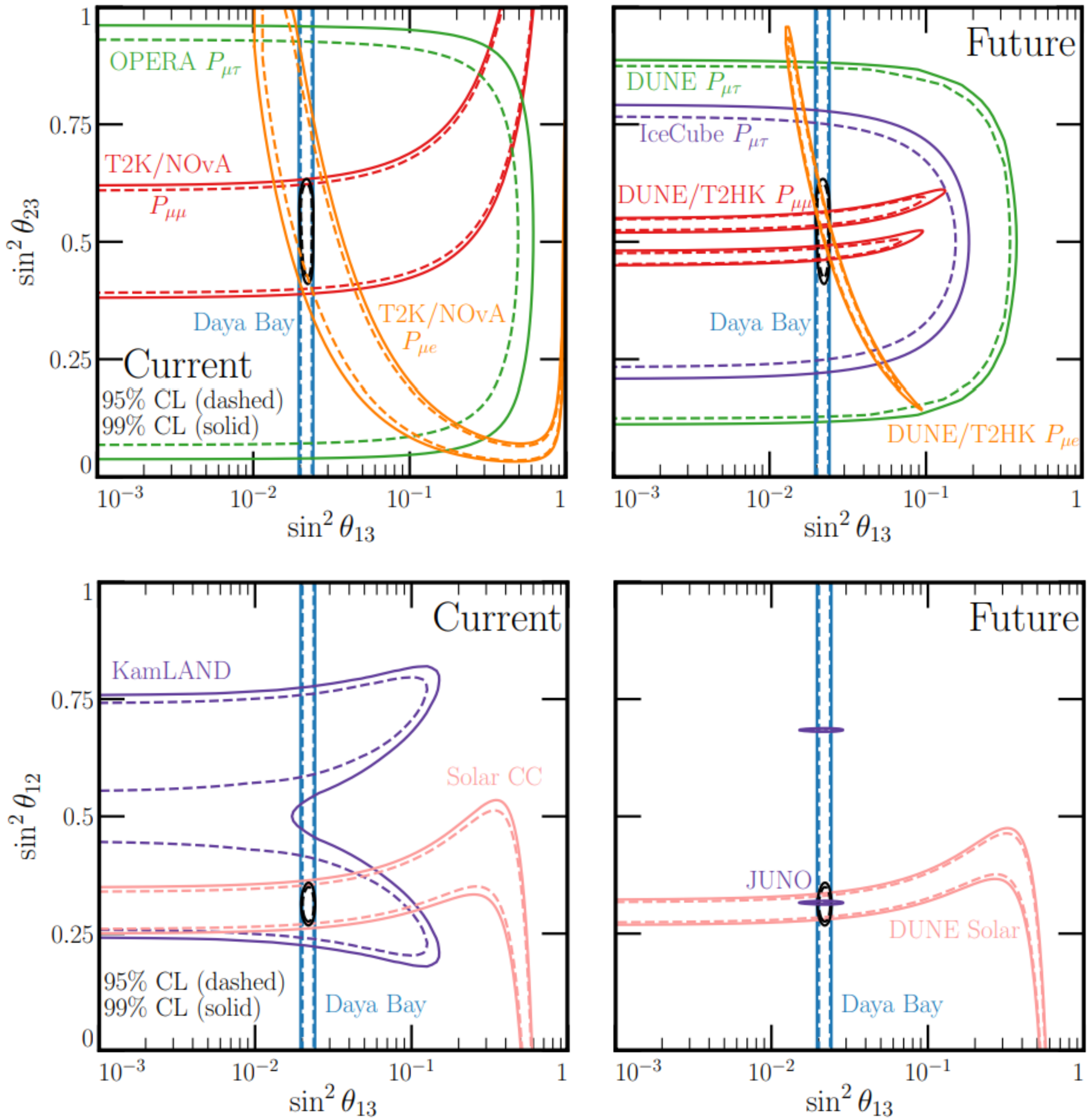
PMNS Triangle



- In analogy to the CKM matrix, neutrino oscillations are now approaching a constraint on the PMNS triangles
- However, oscillations don’t provide as many observables as the quark sector
- These results rely on assumptions of unitarity of the PMNS matrix

Non-Unitarity in General

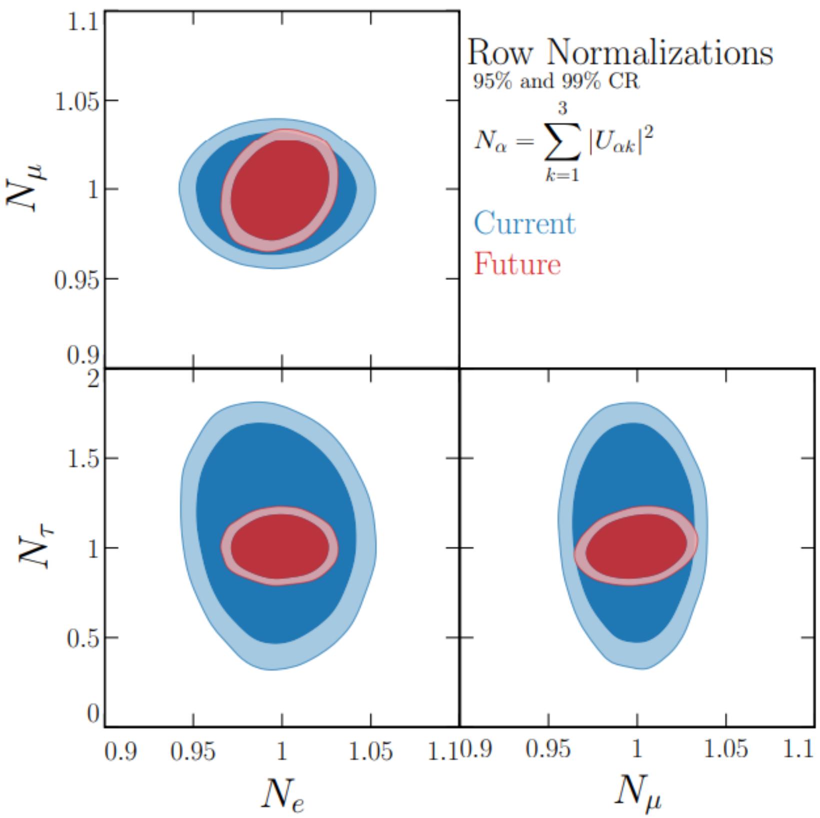
- Current measurements of neutrino mixing are already placing some constraints on unitarity in an agnostic scenario
- The next generation will make significant leaps in precision, testing unitarity at unprecedented levels
- JUNO/SuperChooz, DUNE and IceCube/KM3NeT are expected to drive these improvements

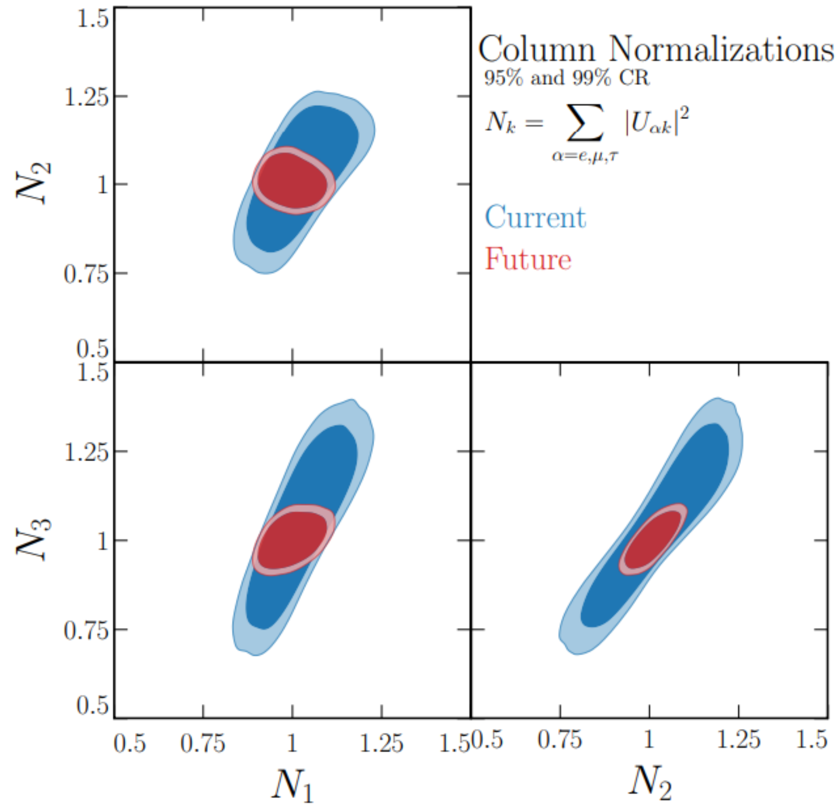


S. Ellis et al., JHEP 12 (2020), 068

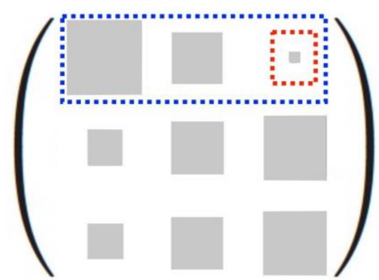
Normalization Constraints

S. Ellis et al., JHEP 12 (2020), 068





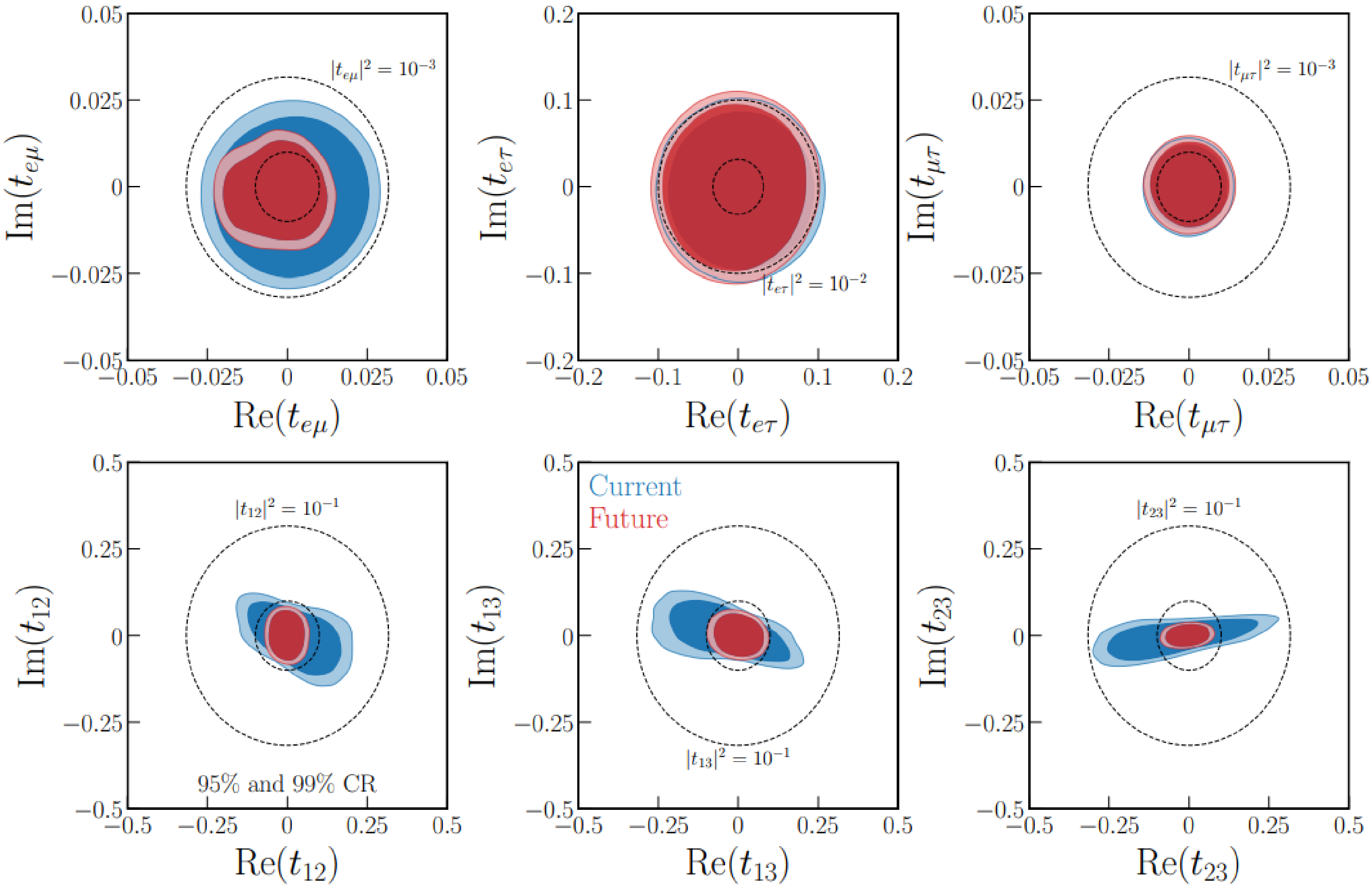
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \approx$$



A. Cabrera, PoS EPS-HEP2019 (2020), 375

electron row unitarity: $|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$

Closure Constraints



$$t_{\alpha\beta} \equiv U^*_{\alpha 1} U_{\beta 1} + U^*_{\alpha 2} U_{\beta 2} + U^*_{\alpha 3} U_{\beta 3} = 0 \quad (\alpha \neq \beta; \quad \alpha,\ \beta = e,\ \mu,\ \tau).$$

[S. Ellis et al., JHEP 12 (2020), 068]

Sub-Matrix Scenario: Sterile Nus

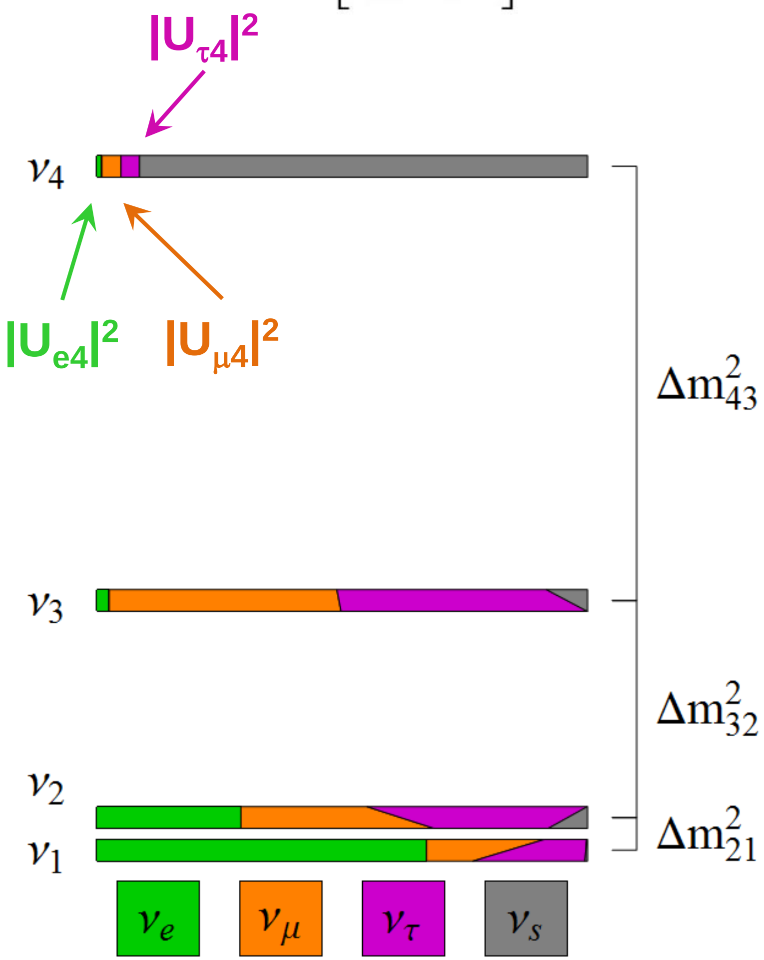
(3+N)x(3+N)

3x3

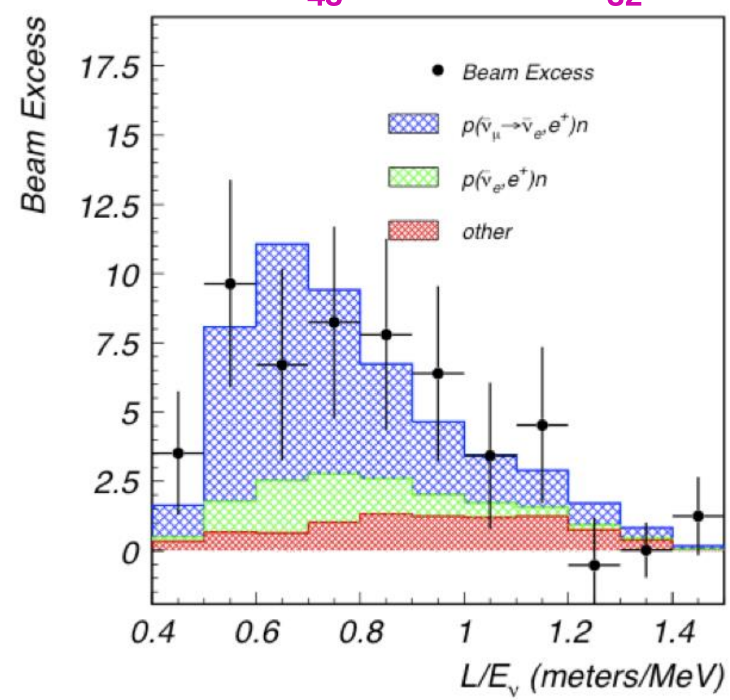
$$\mathbf{U} = \begin{bmatrix} U & W \\ Z & V \end{bmatrix}$$

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

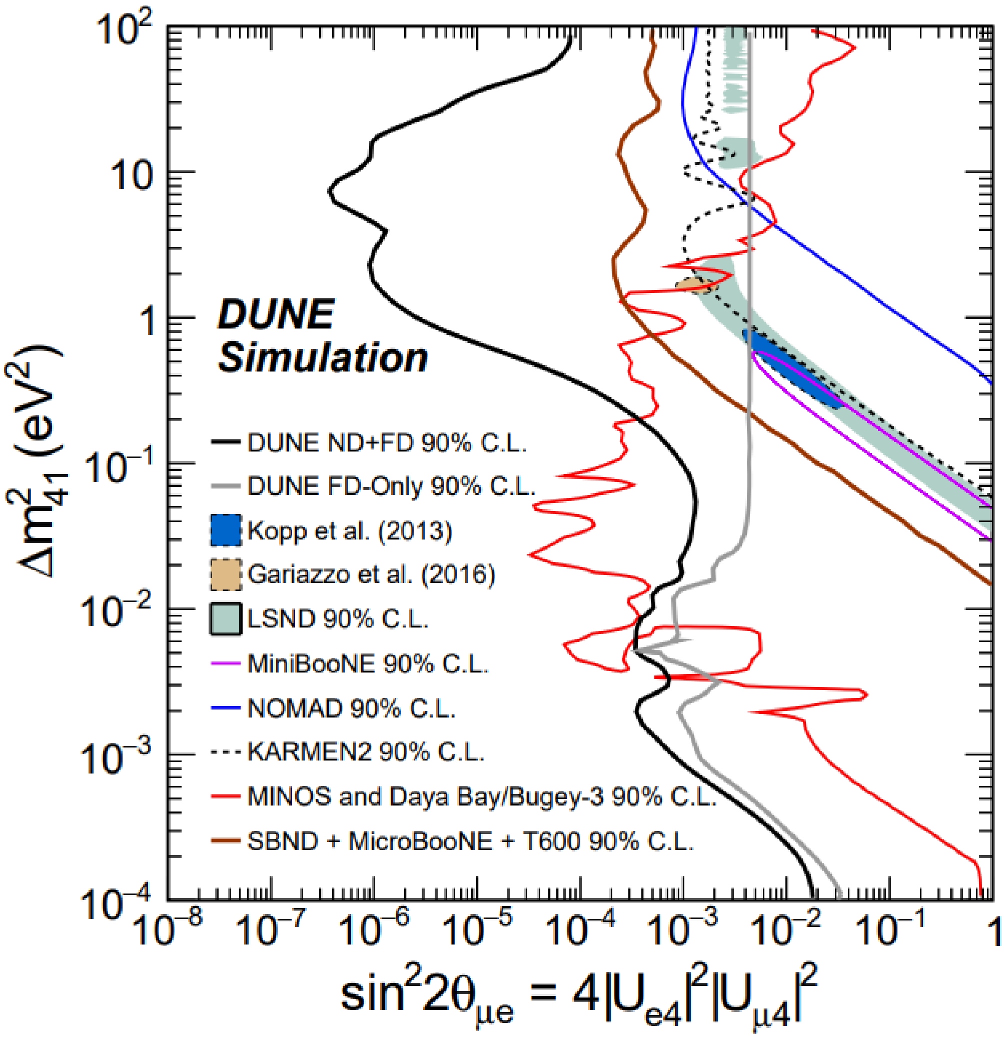
NC Contribution



LSND: $\nu_\mu \rightarrow \nu_e$ at
L/E ~ 1 km/GeV
Δm^2_{43} ~ 100x Δm^2_{32}

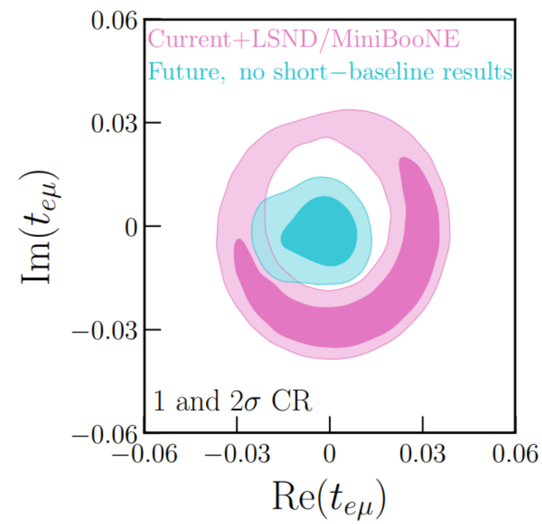


DUNE in Unchartered Waters



[DUNE, EPJC 81 (2021) 4, 322]

- The ability of DUNE to measure multiple channels in a wide range of energies in both near and far detectors will project the sensitive regions to sterile neutrinos way beyond current anomalies
- This is related to the power of unitarity constraint from DUNE and other future experiments

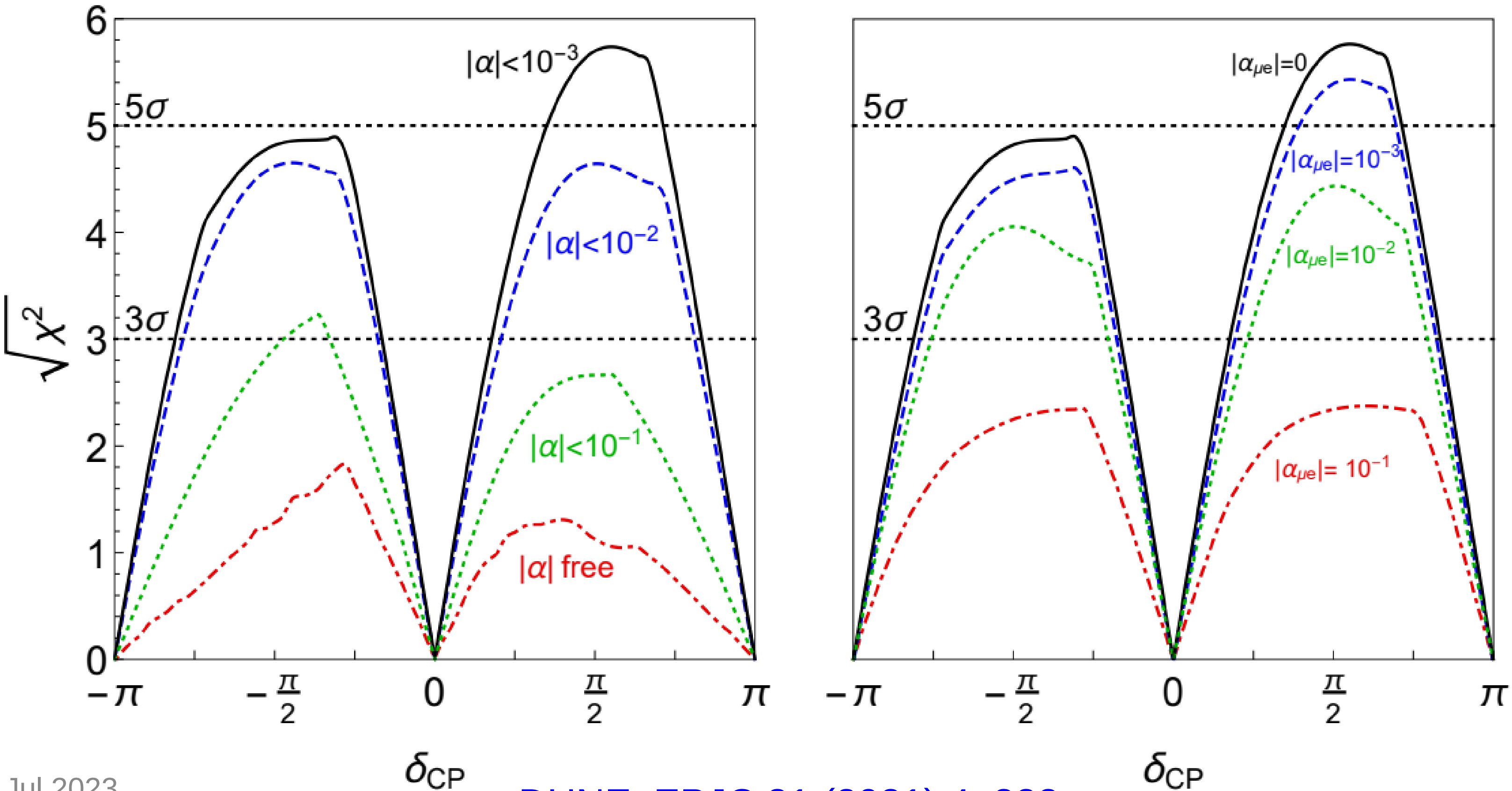


[S. Ellis et al., JHEP 12 (2020), 068]

Unitarity and CPV

- Without assuming unitarity, CPV measurements would be severely degraded
- The degree of impact will depend on assumption on unitarity violation models

DUNE CPV Sensitivity



DUNE, EPJC 81 (2021) 4, 322

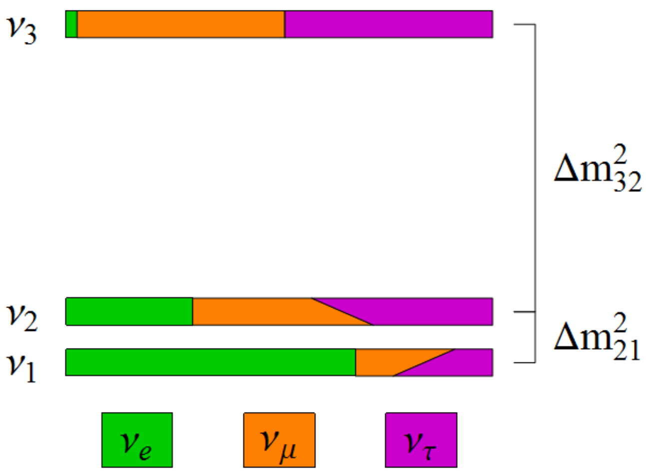
Matter Effects

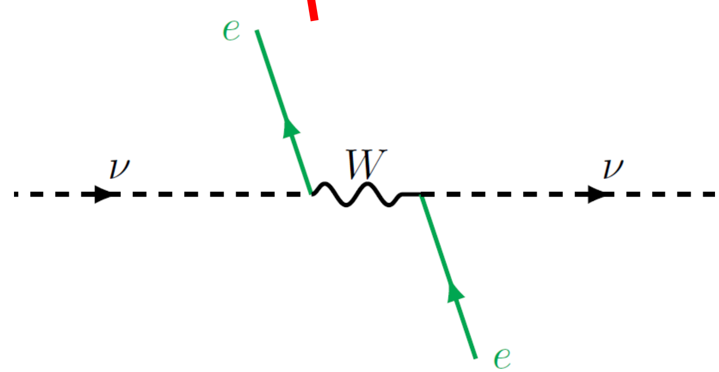
The Standard Picture

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

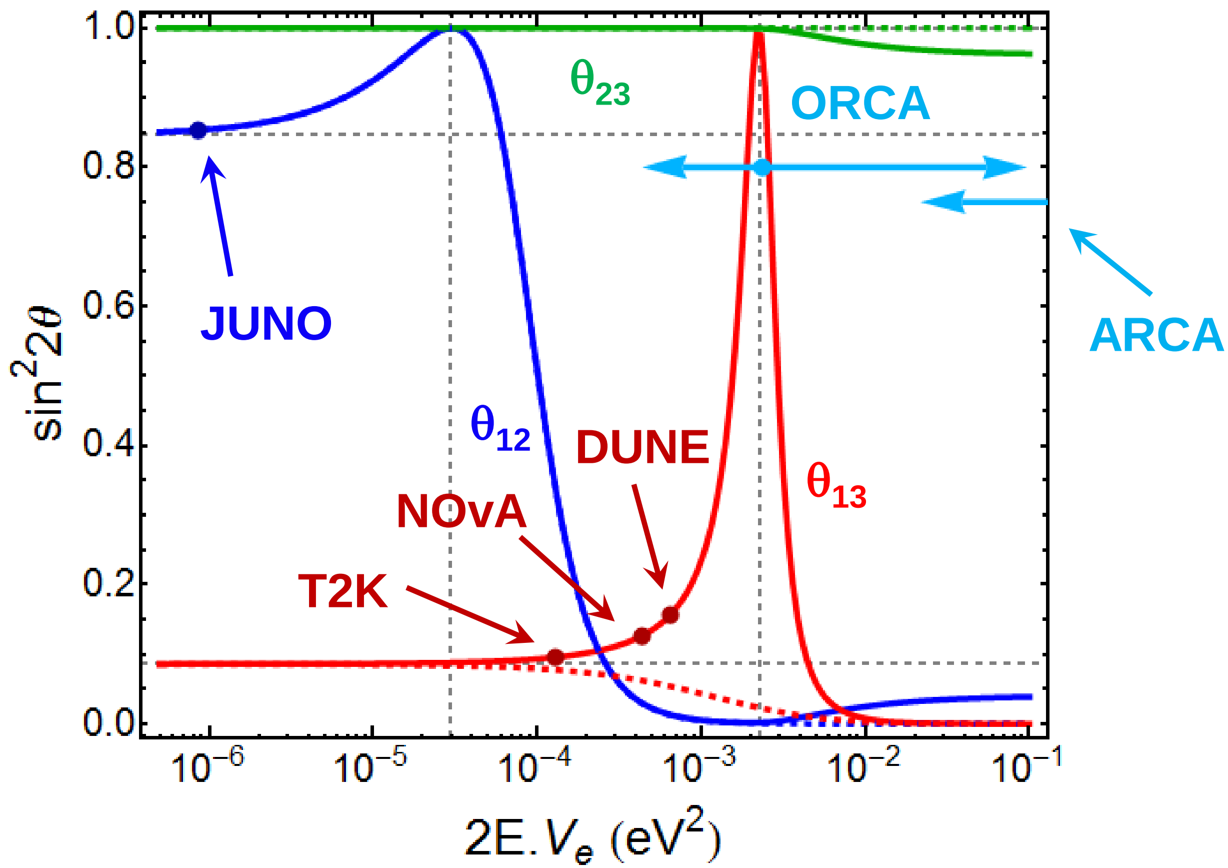
α L/E

α L





Resonances



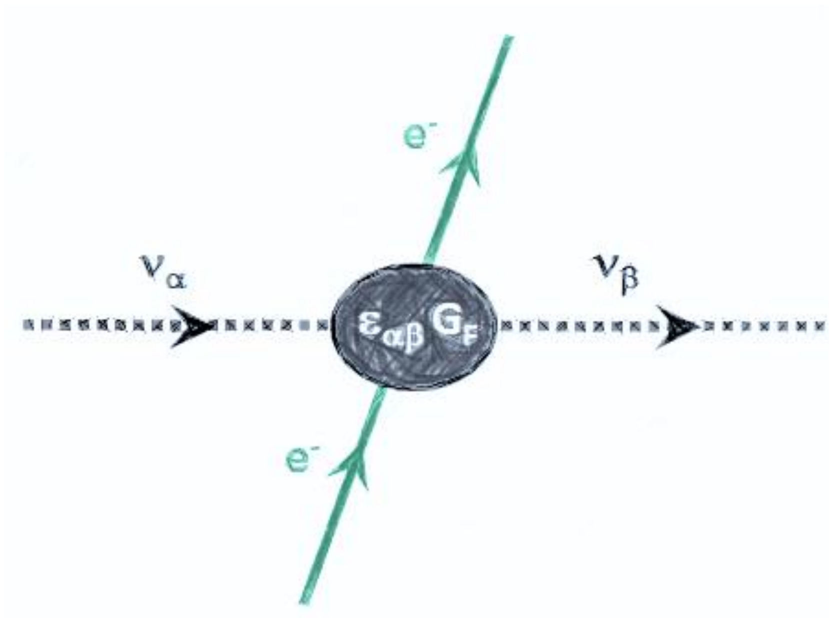
$$H_{eff} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger + V_e \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

NSI Motivation

Non-Standard Interactions (NSI)

Arbitrary Perturbation

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



Dimension-6 + Naturalness

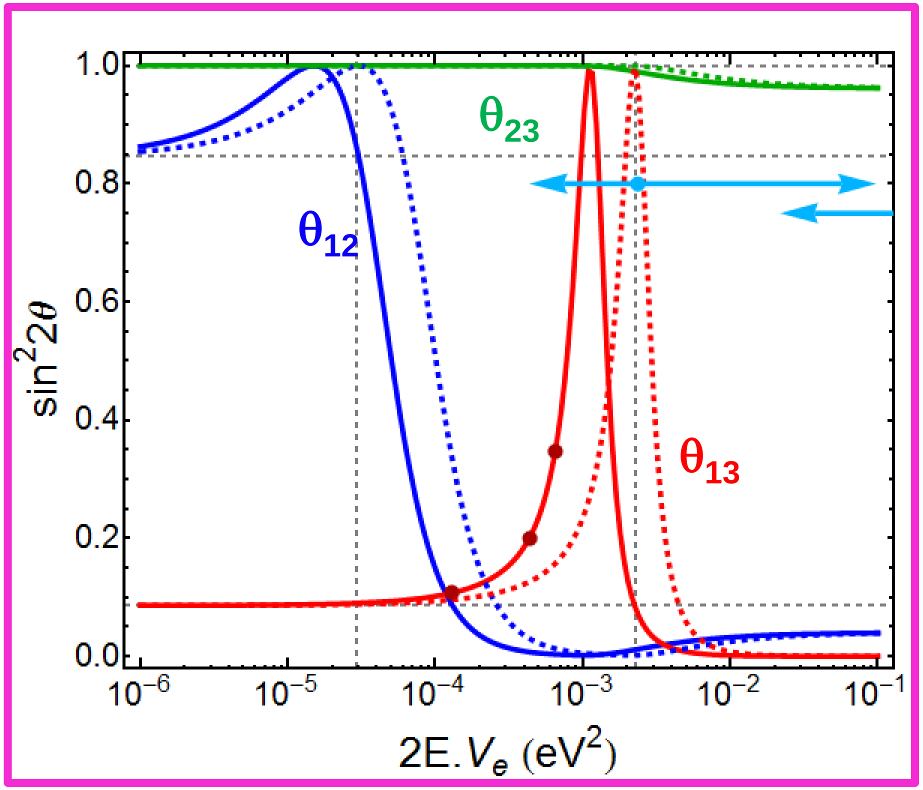
$$\varepsilon \propto \frac{m_W^2}{m_X^2}$$

TeV Scale ~ 10^{-2}

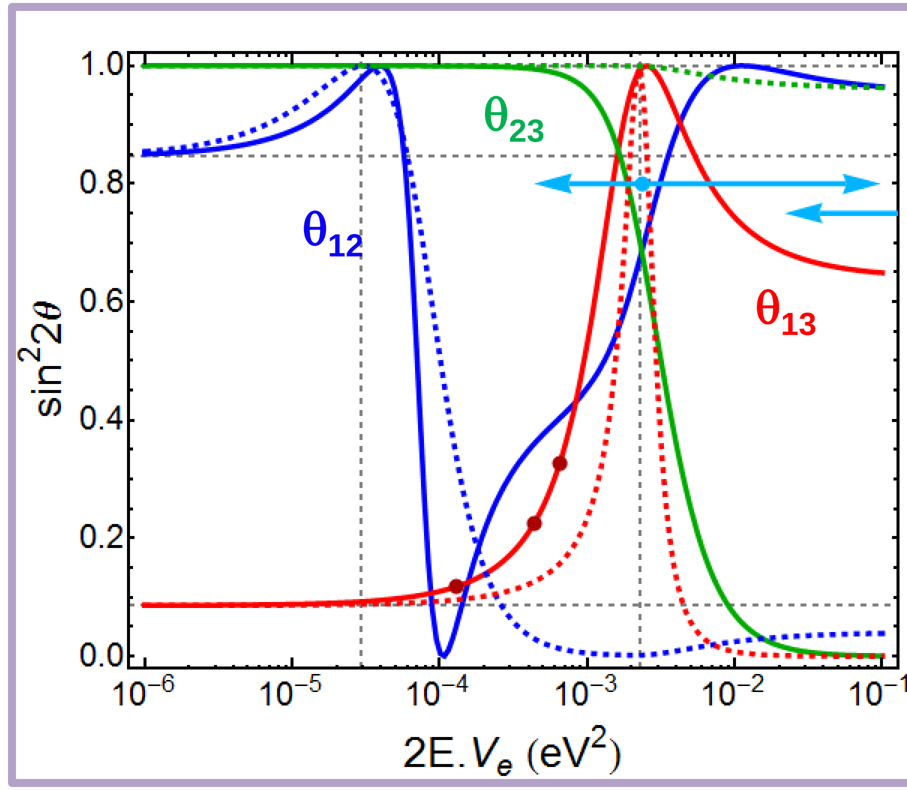
$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{ff'C} \left(\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta\right)\left(\overline{f}\gamma_\mu P_C f'\right)$$

Resonances w/ NSI

$\varepsilon_{ee} = 1$



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

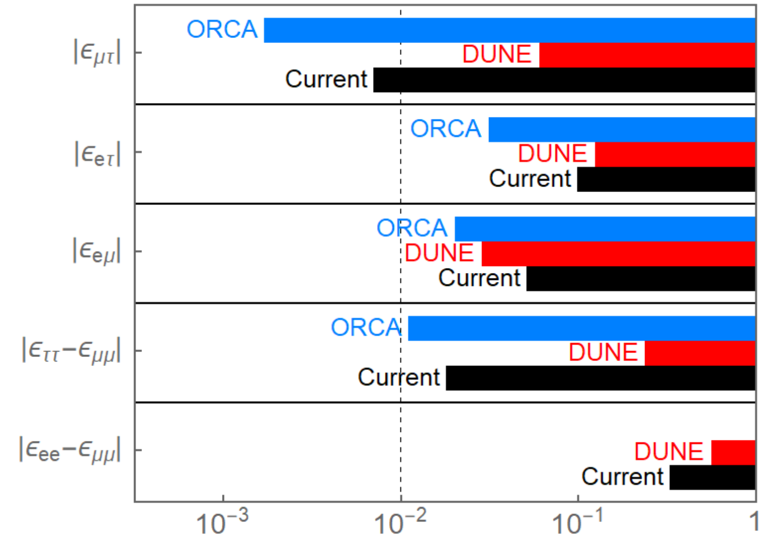


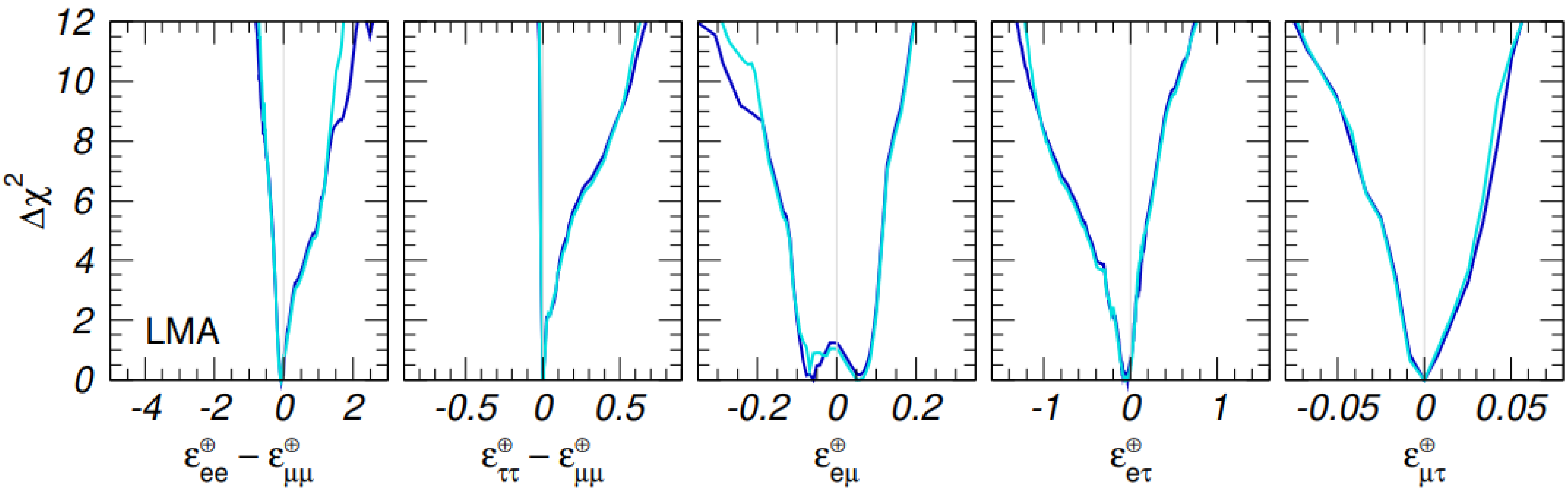
$$H_{eff} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger + V_e \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} &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

NSI Status

Adapted from:
N. Chowdhury, PhD Thesis, IFIC (2021)

- Current bounds are taken from a global analysis of neutrino data
- Upcoming measurements from DUNE may add extra sensitivity
- The new generation of atmospheric neutrino experiments will have a significant impact due to large matter potentials

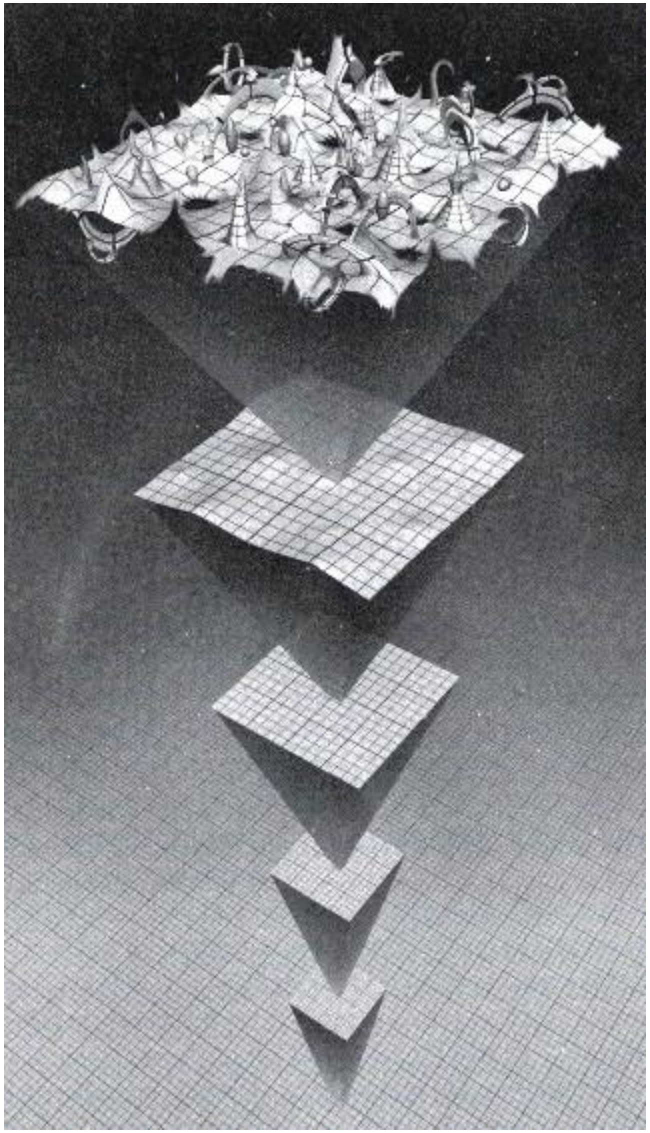




I. Esteban et al., JHEP 08 (2018), 180

Quantum Gravity

QG and Decoherence



- At Planck scales spacetime may be permeated with short-lived horizons
- Could such horizons act as a quantum bath, generating non-unitary quantum evolution?

Unitary **Non-Unitary**

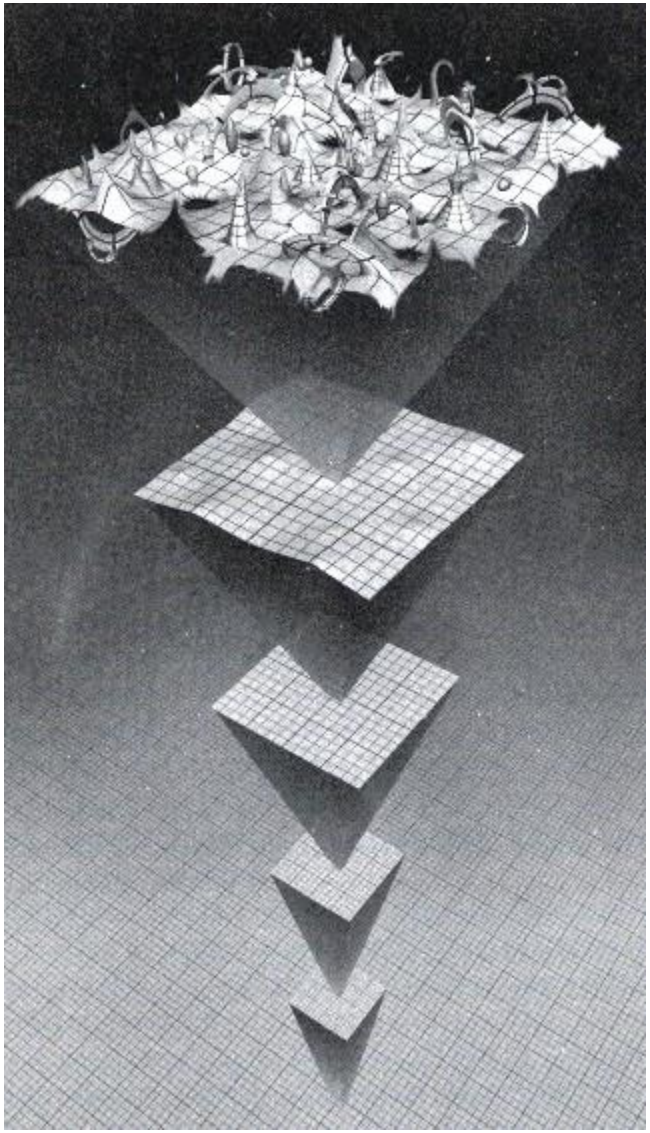
$$\partial_t \rho = -i[H, \rho] + \not{\delta} H(\rho)$$

Dimensional Analysis

$$\not{\delta} H \sim \mu^2 / M_P$$

$$\mu \sim E? \qquad \mu \sim \Delta E?$$

QG and Decoherence



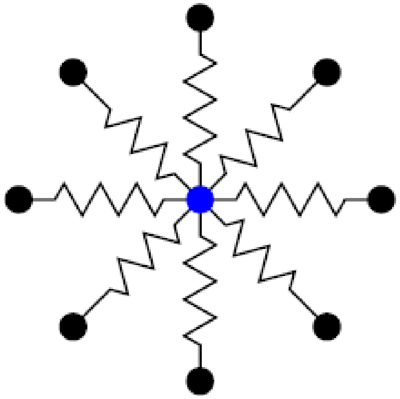
- At Planck scales spacetime may be permeated with short-lived horizons
- Could such horizons act as a quantum bath, generating non-unitary quantum evolution?

Unitary **Non-Unitary**

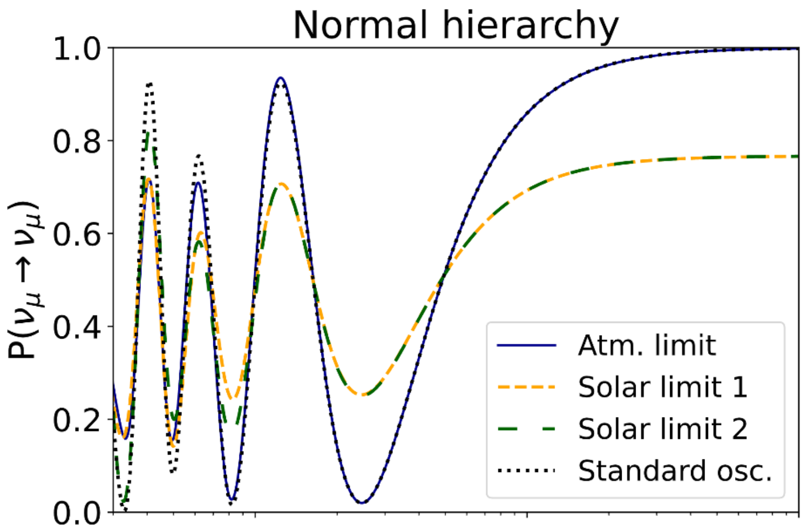
$$\partial_t \rho = -i[H,\rho] + \frac{1}{2}\sum_j 2A_j\rho A_j^\dagger - \{A_j^\dagger A_j, \rho\}$$

Lindblad Equation:

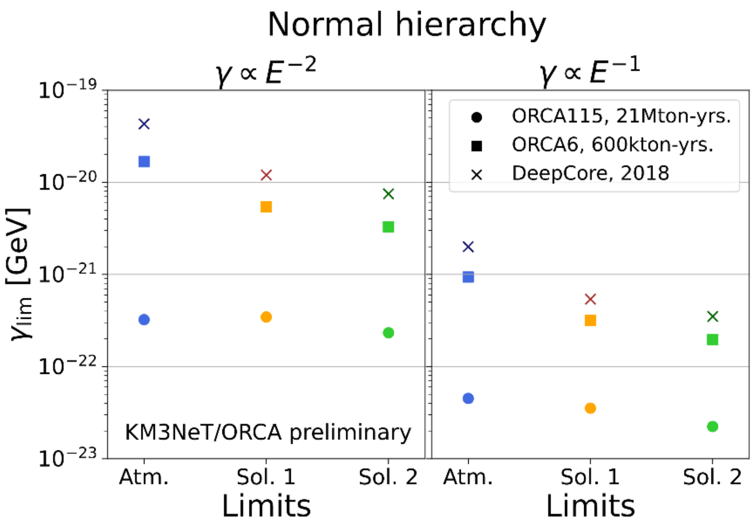
Most general Markovian evolution that preserves probabilities even in the environment system

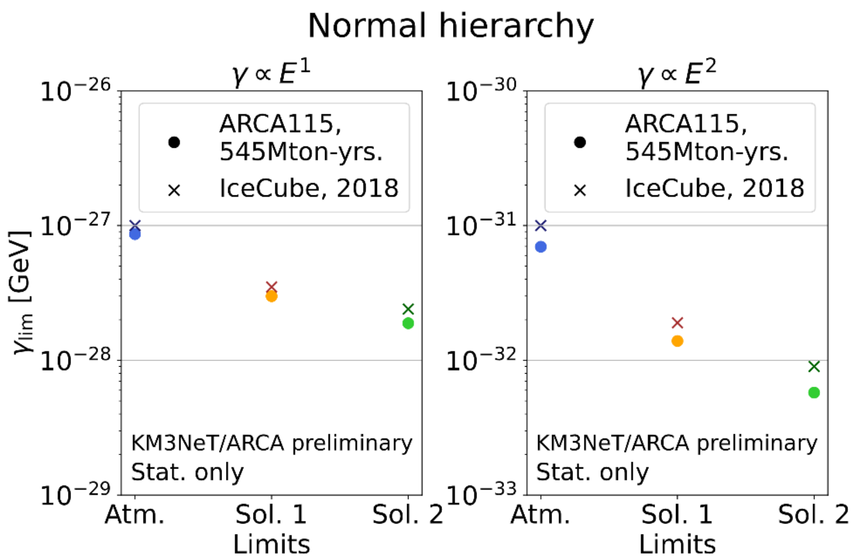


Decoherence Constraints



- IceCube currently puts the strongest limits on environmental decoherence
- New atmospheric oscillation experiments will improve this further for the cases where the energy dependence favours lower energies



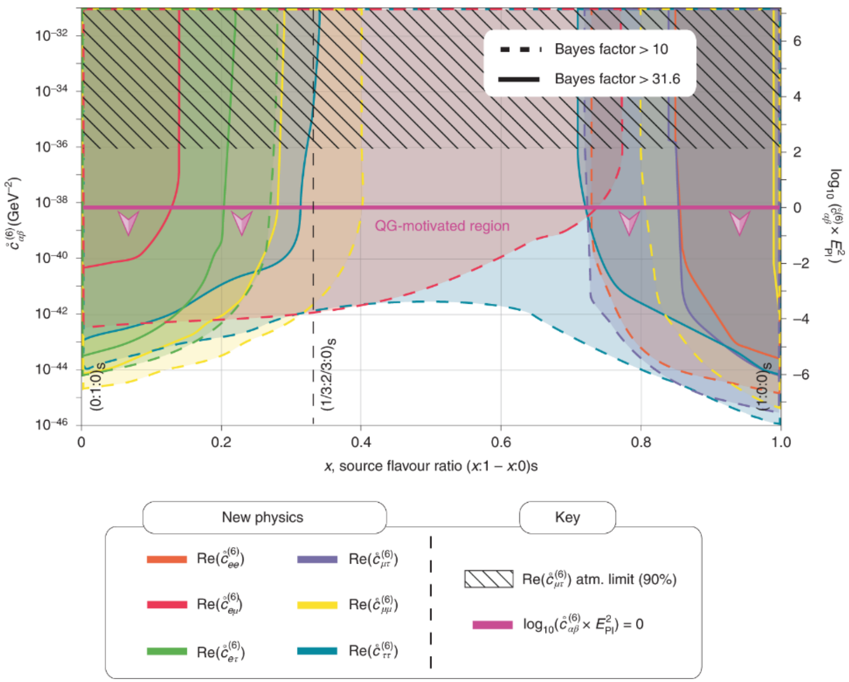


N. Lessing, Ms Thesis (2022)

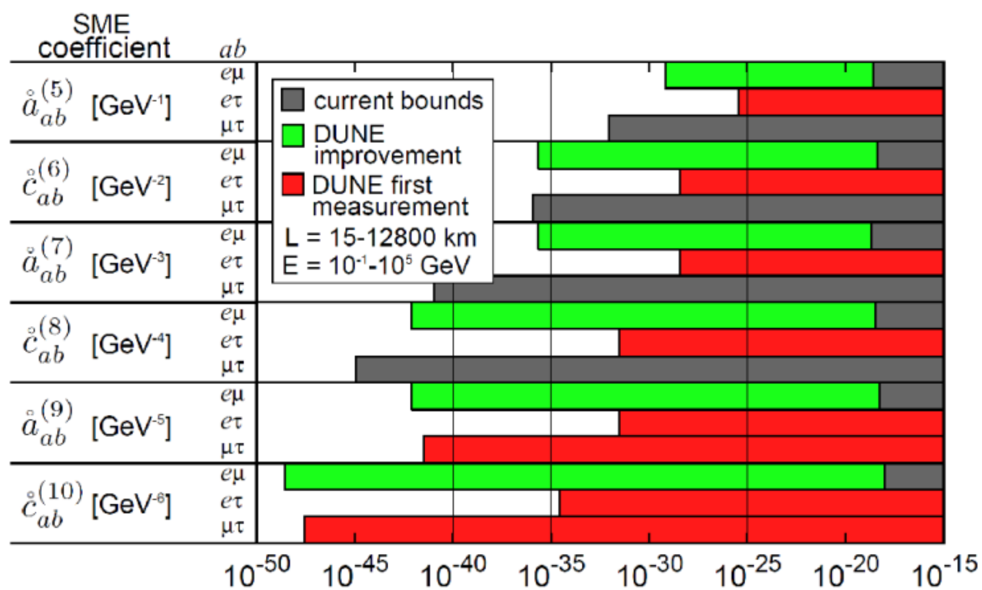
Lorentz Invariance Violation

[IceCube, Nature Phys. 18 (2022) 11, 1287-1292]

$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E\,\mathring{c}^{(4)} + E^2\,\mathring{a}^{(5)} - E^3\,\mathring{c}^{(6)} \cdots .$$



- Similar to NSI, the low-energy effects of QG may be expressed as modified dispersion relations with varying powers of energy
- Under some model assumptions, the flavour content of astrophysical neutrinos sets very stringent constraints



- Atmospheric neutrinos, e.g. in DUNE, can provide complementary constraints without dependence on the astrophysical neutrino flux models

[DUNE, EPJC 81 (2021) 4, 322]

Conclusion

- The **precision era** of neutrino oscillations is arriving

- **Tests of unitarity** are a very general and important tool
- Measure tau neutrinos will remain a challenge despite improvements from the upcoming generation

- Exploring the texture of the **matter potential** may lead to the discovery of non-standard neutrino interactions

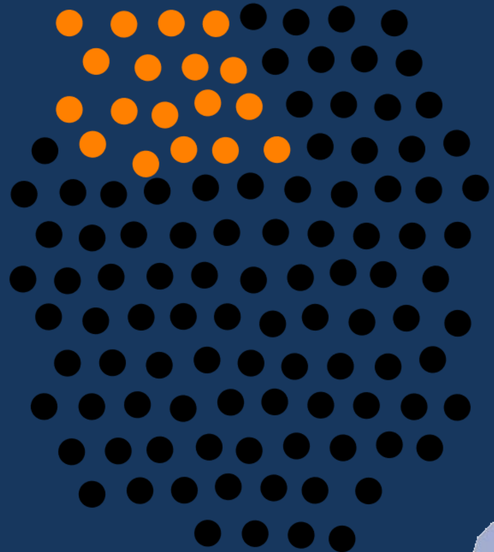
- A full exploration of the L and E spectrum can be an excellent probe of **Quantum Gravity** effects

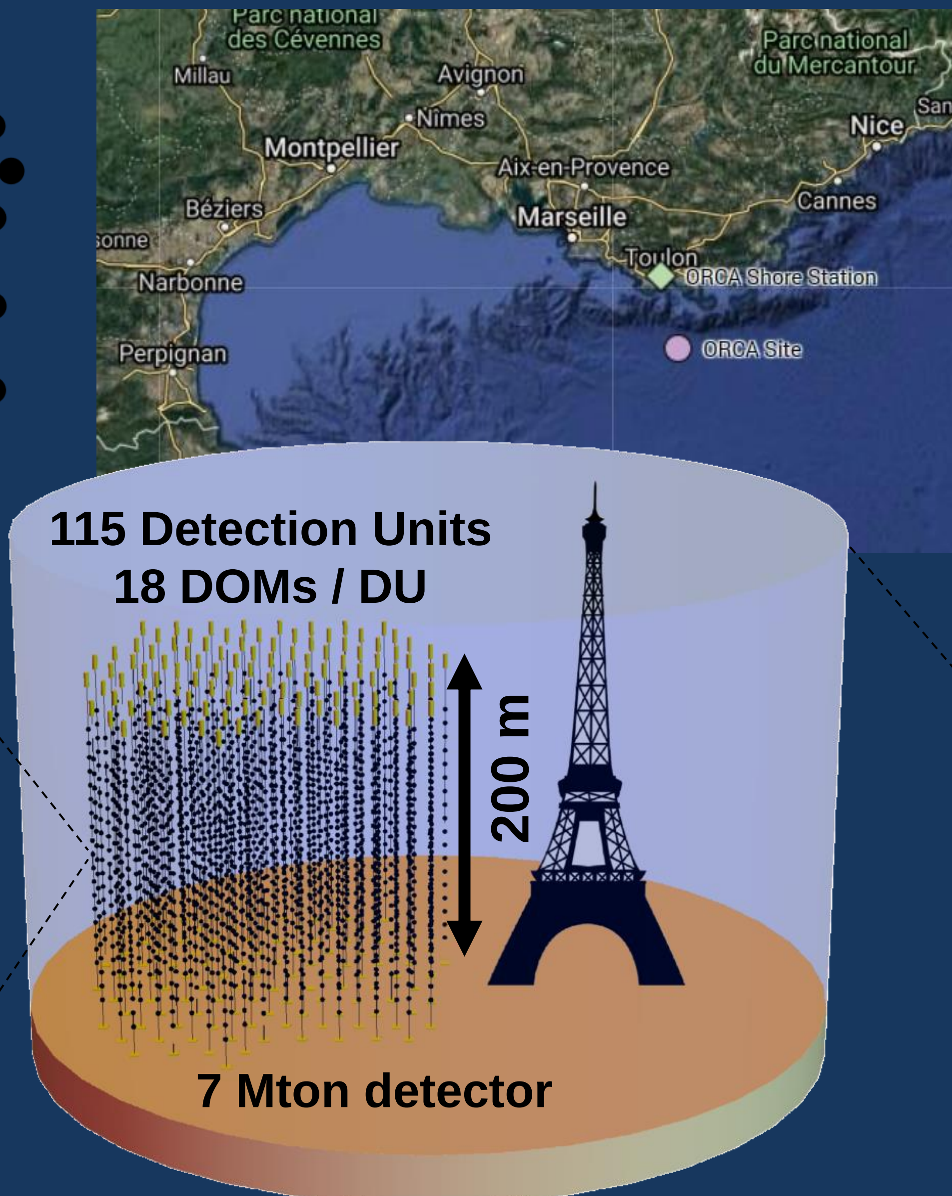
- And much more within and beyond oscillations…

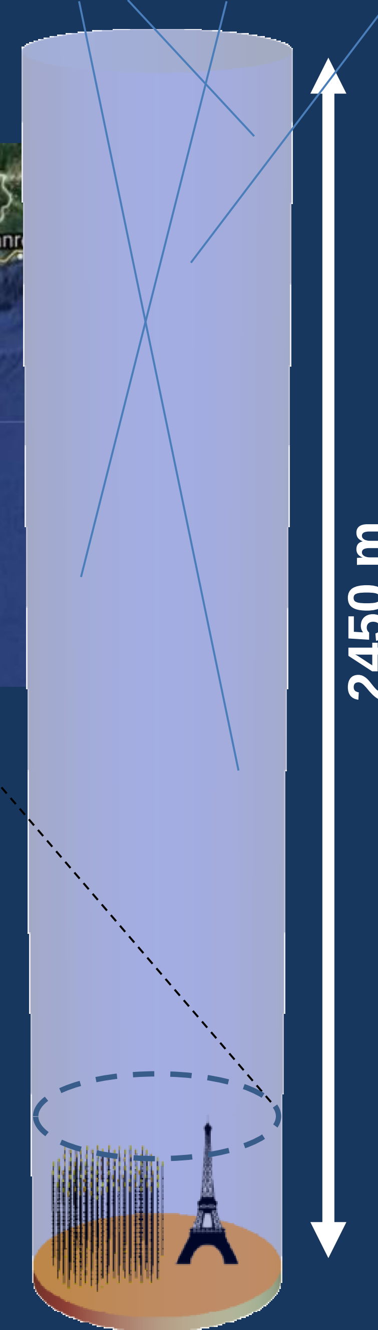
Thank you!

KM3NeT/ORCA

18 DUs Deployed





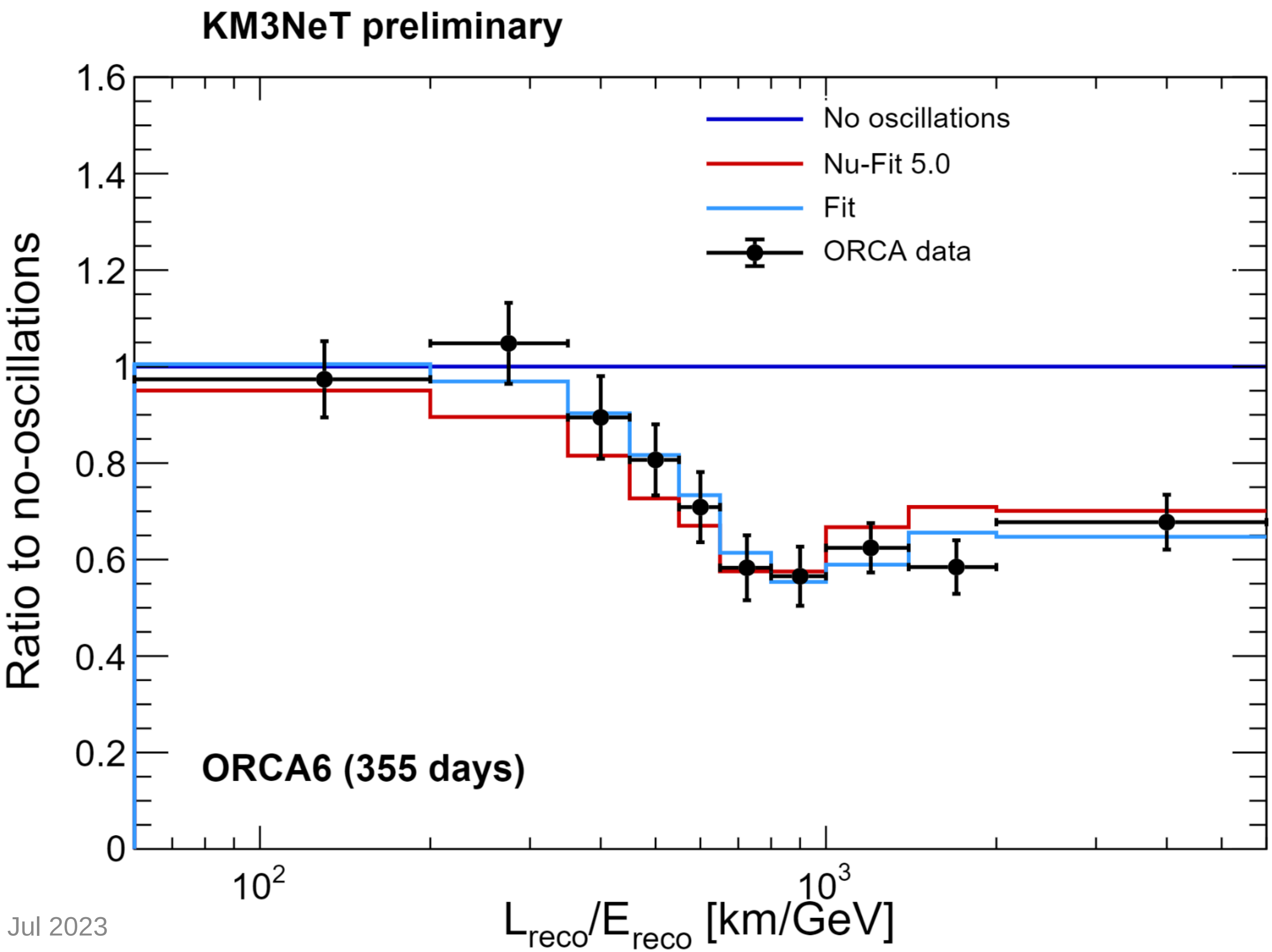


31x 3" PMTs

43 cm

Clear Evidence of Oscillations

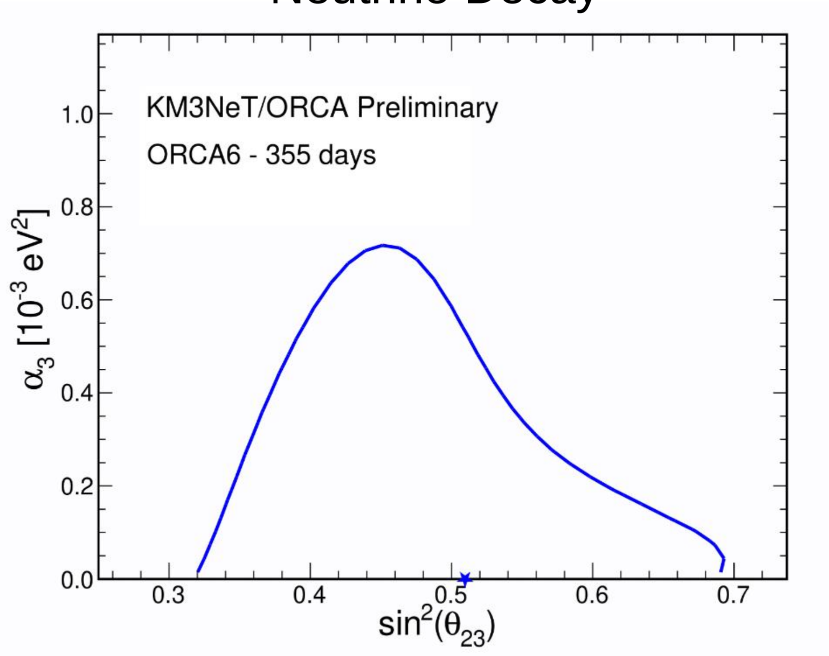
- **First data confirm oscillation hypothesis at 5.9σ**



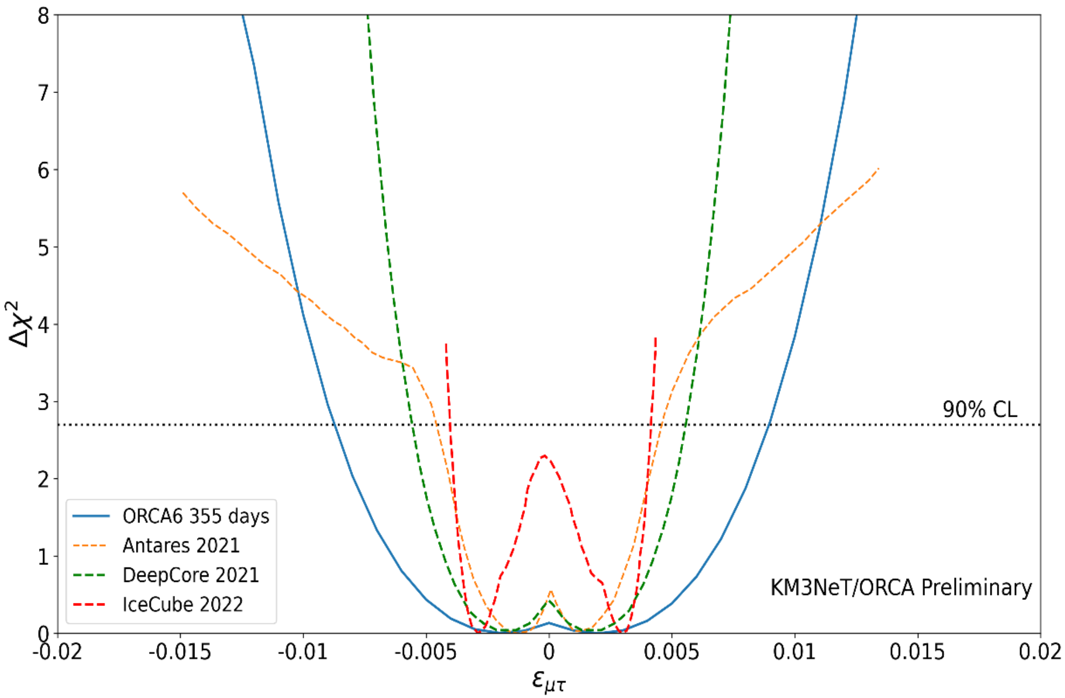
BSM Searches

- First data already constraining some new physics scenarios

Neutrino Decay

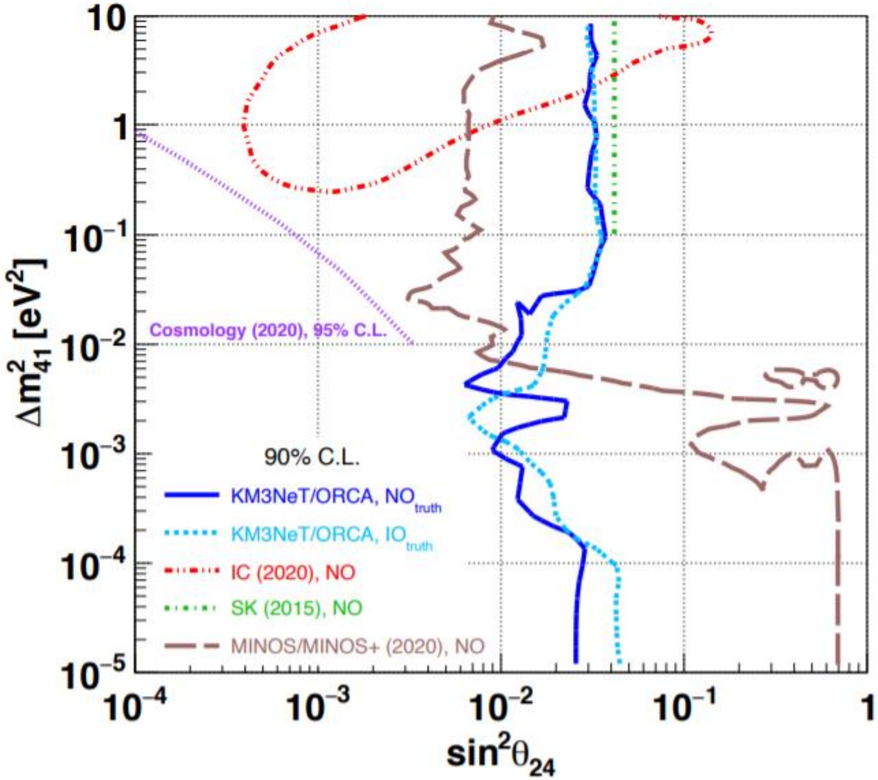


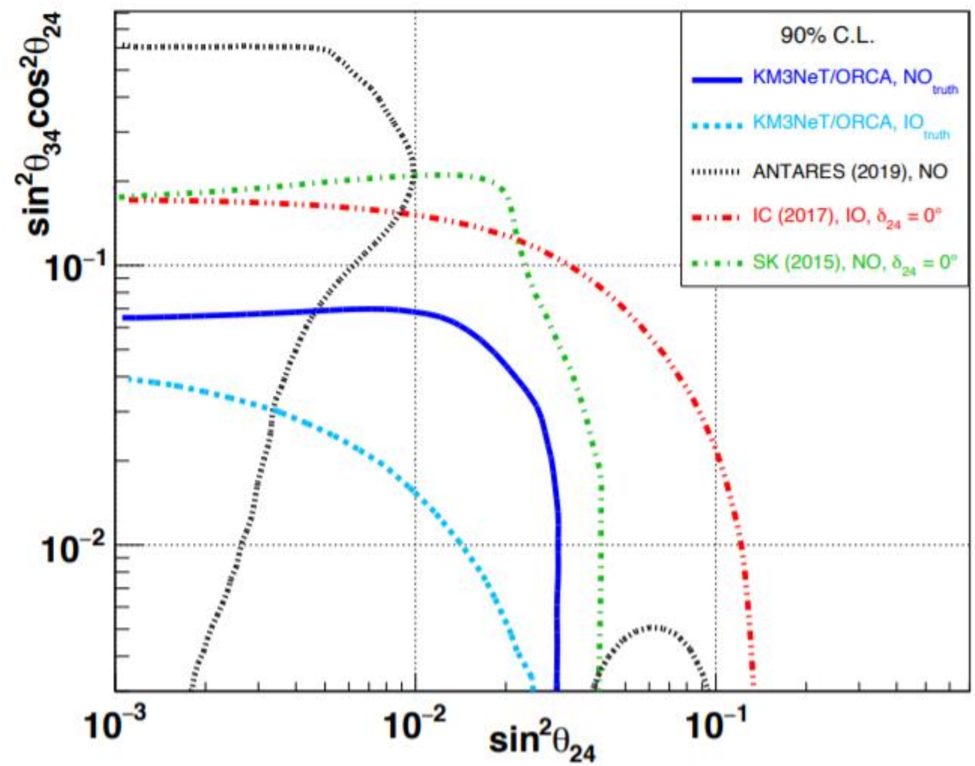
Non-Standard Interactions



Sterile Neutrinos

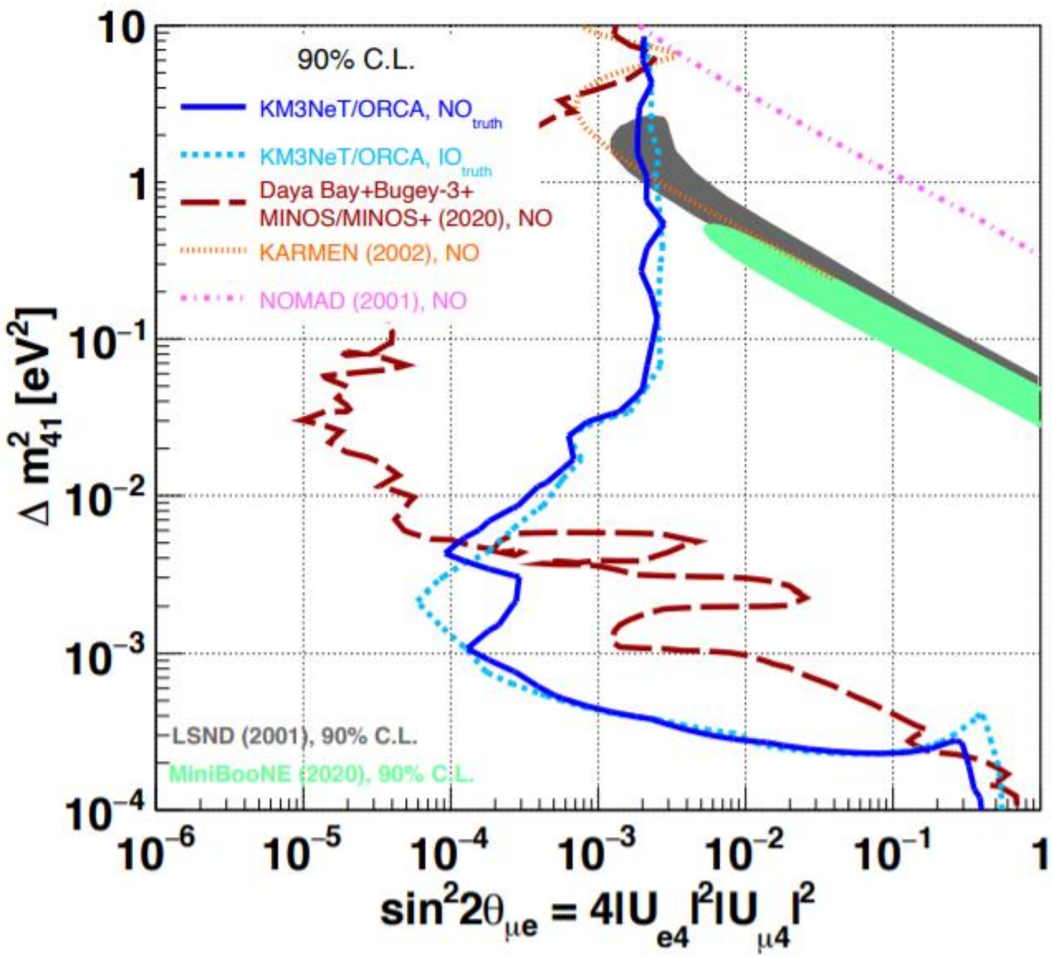
- Explores very low Δm^2_{41} values due to longer baselines
- World leading sensitivity to $U_{\tau 4}$ coupling





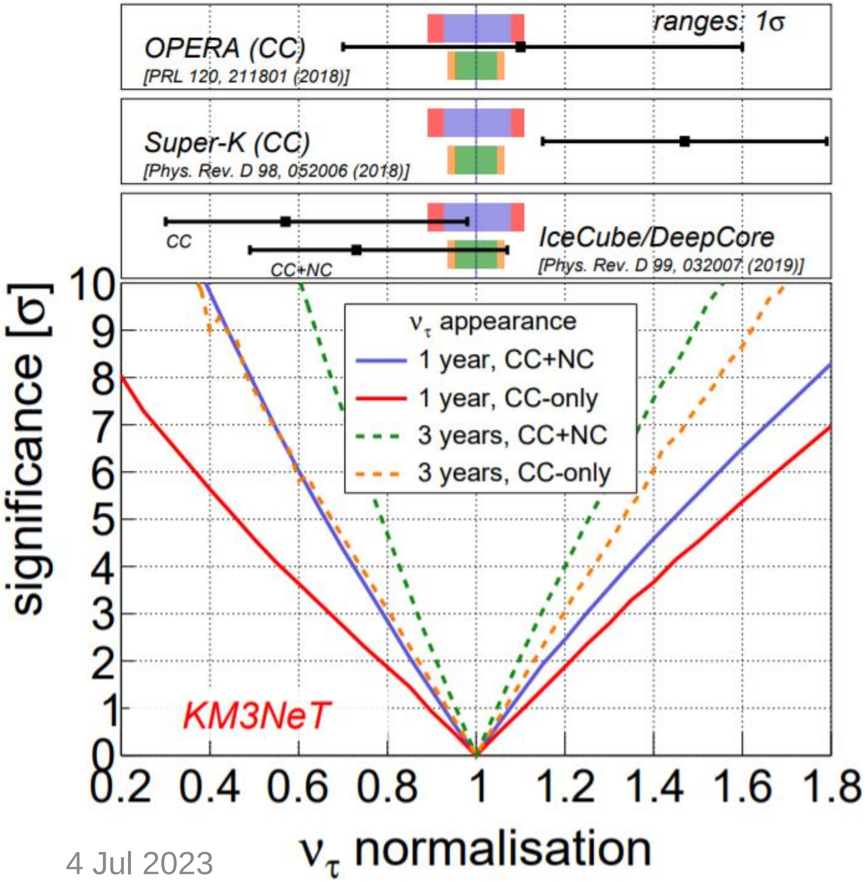
Sterile Neutrinos

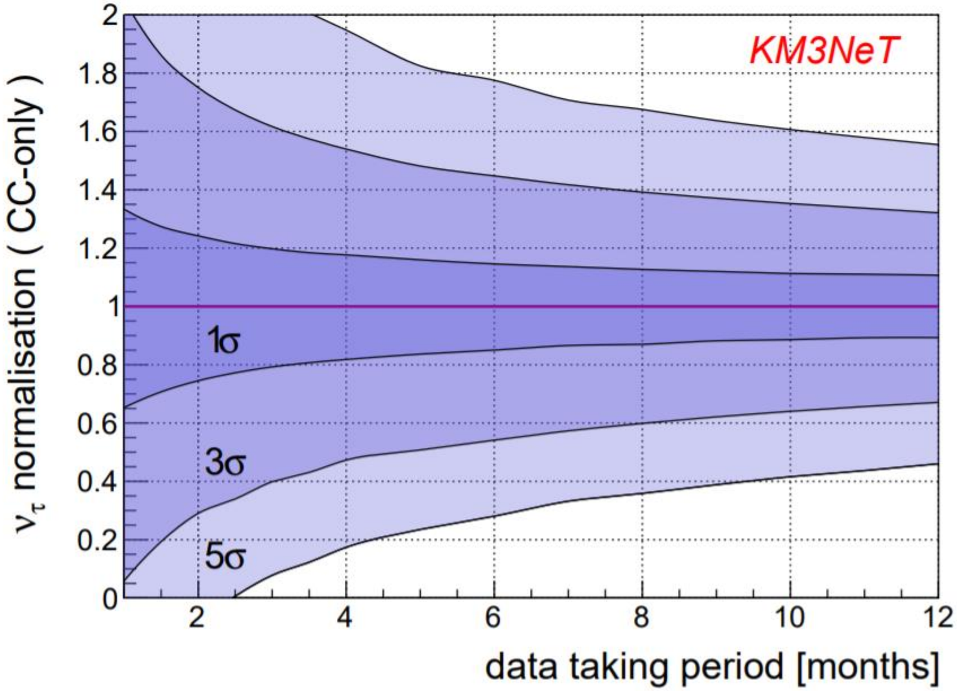
- Explores very low Δm^2_{41} values due to longer baselines
- World leading sensitivity to $U_{\tau 4}$ coupling
- Probing LSND/MiniBooNE anomaly in single experiment



Tau Appearance

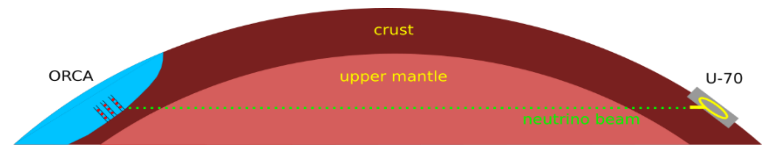
- Atmospheric neutrinos are also an excellent probe of ν_τ appearance
- KM3NeT will be able to constrain the nt component to 7% level in 3 years
- Measurement can be used to probe the unitarity of the PMNS matrix
- Tau appearance can be confirmed with 5σ confidence in 2.5 years



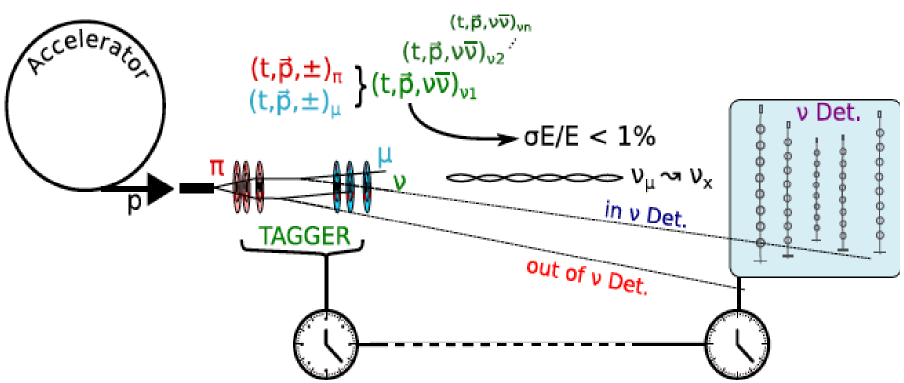


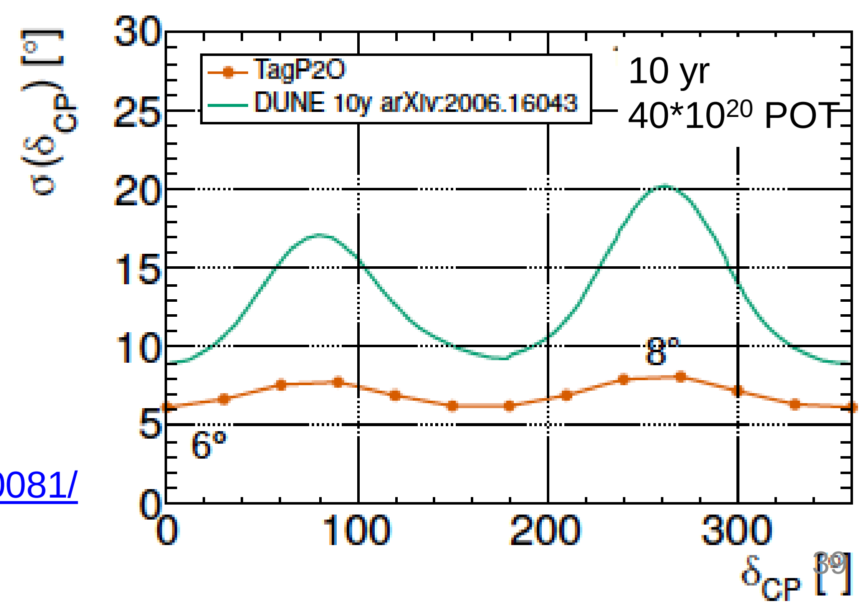
New idea: Tagged Protvino to ORCA

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:

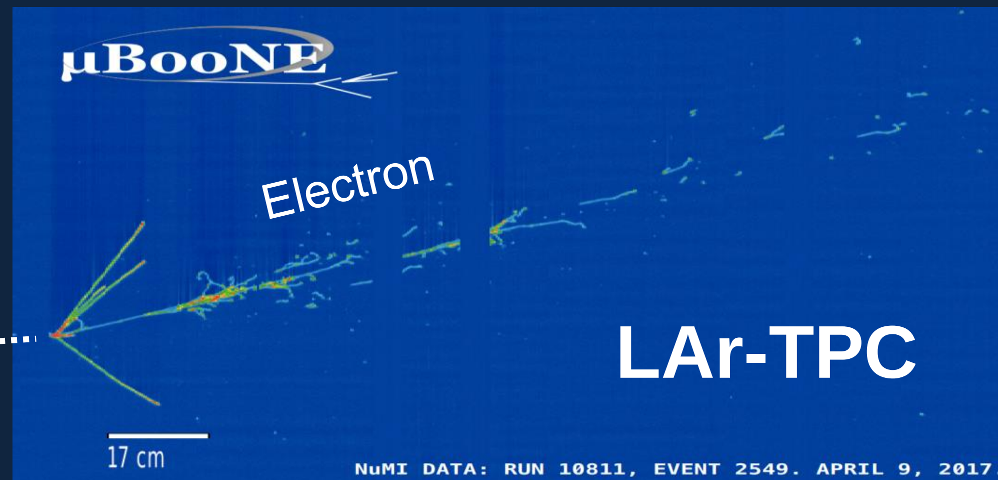




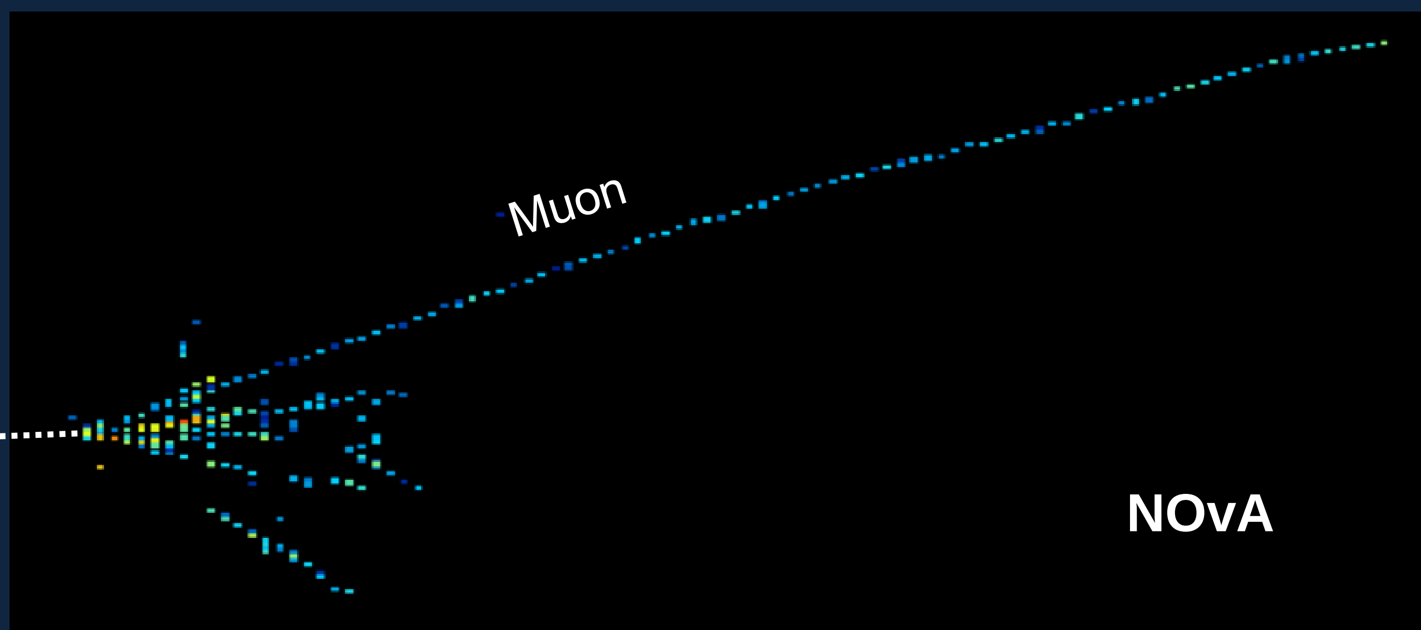
[Mathieu Perrin-Terrin@NuTel2021](https://agenda.infn.it/event/24250/contributions/130081/)
https://agenda.infn.it/event/24250/contributions/130081/

Neutrino Interactions

ν_e



ν_μ

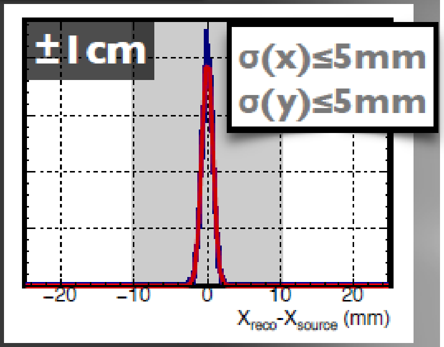


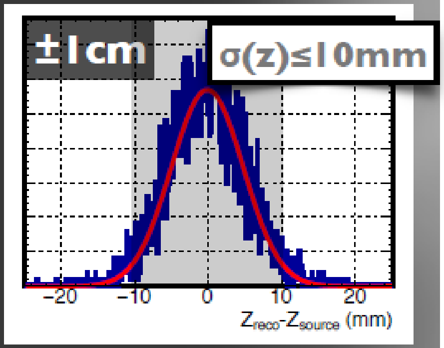
LiquidO ↔ stochastic light confinement

Topology (X,Y) direct & native (PID)→ possible **sub-mm vertex precision**

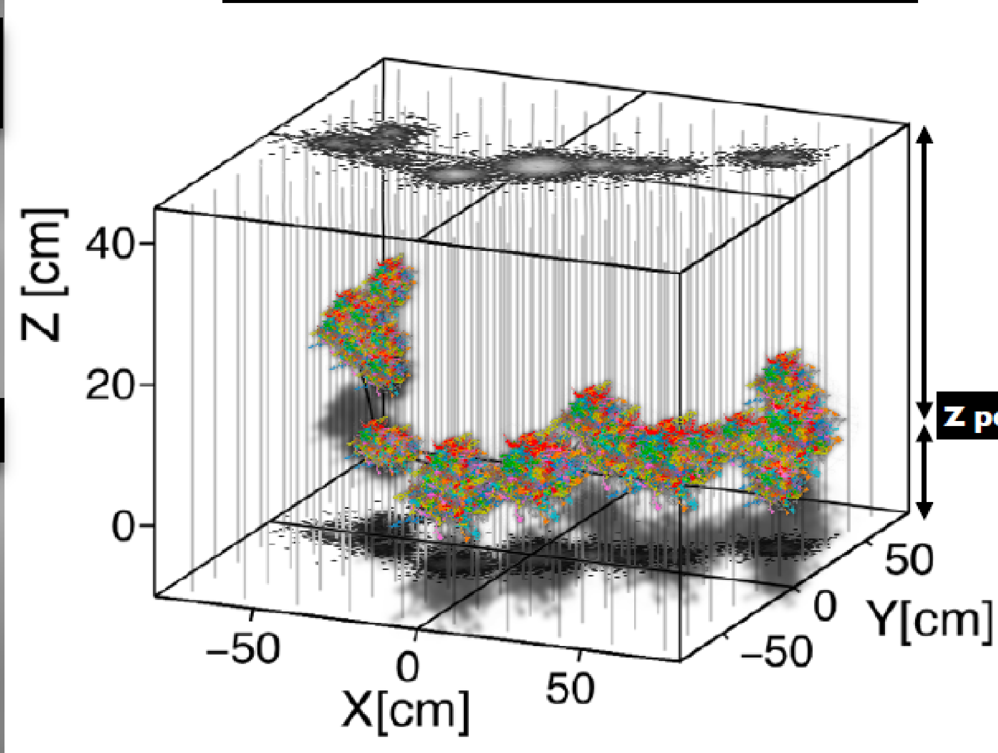
Vanilla LiquidO: 1D lattice (fibres along Z-axis only)

~0.5MeV



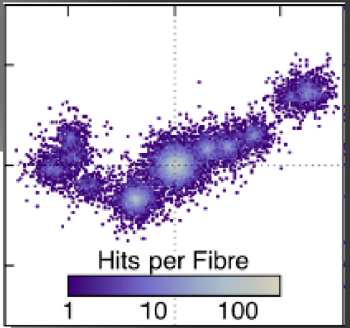


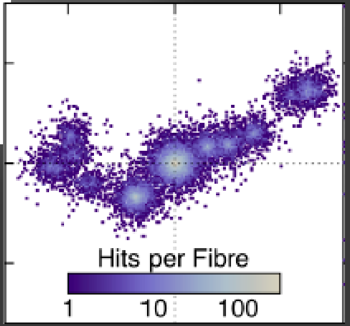
TOP VIEW: (X,Y) Projection→ direct readout



Z position: Δt (time difference)

BOTTOM VIEW: (X,Y) Projection→ direct readout



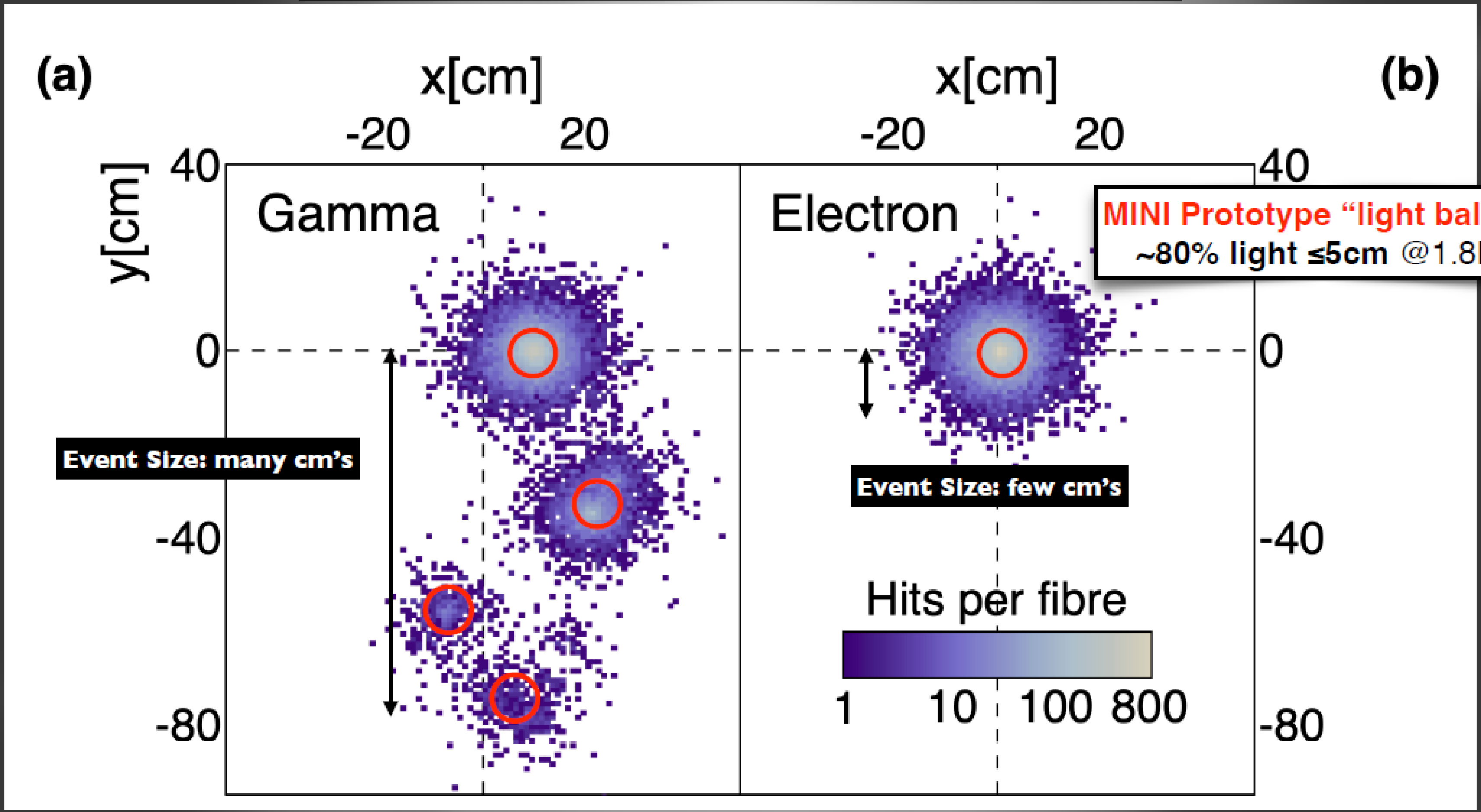


A. Cabrera, CERN EP Seminar (2022)

LiquidO can have up 3 orthogonal fibre lattice orientations (3D)

topology's PID (no timing)...

PID e/γ should be ≥100:1 rejection @ ≥90%
(**γ** resembles more **e+** = **e-** + **2γ**)

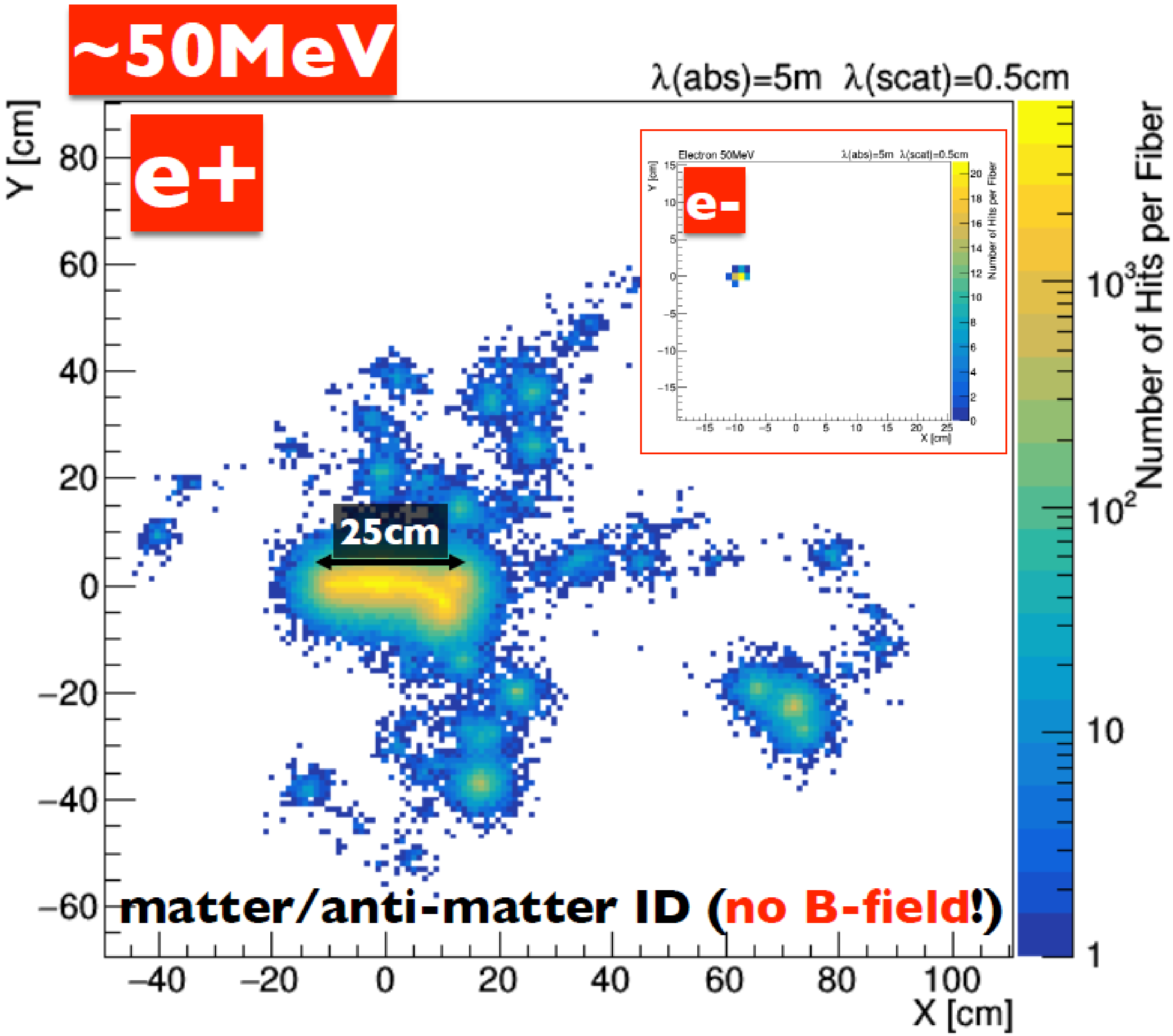


scattered points ($e^+ \approx \gamma$) **point-like** ($e^- = \alpha =$ p-recoil)

Neutrino physics with an opaque detector
LiquidO Consortium
Communications Physics 4, Article number: 273 (2021) | Cite this article

A. Cabrera, CERN EP Seminar (2022)

multi-MeV improves (more light too)...

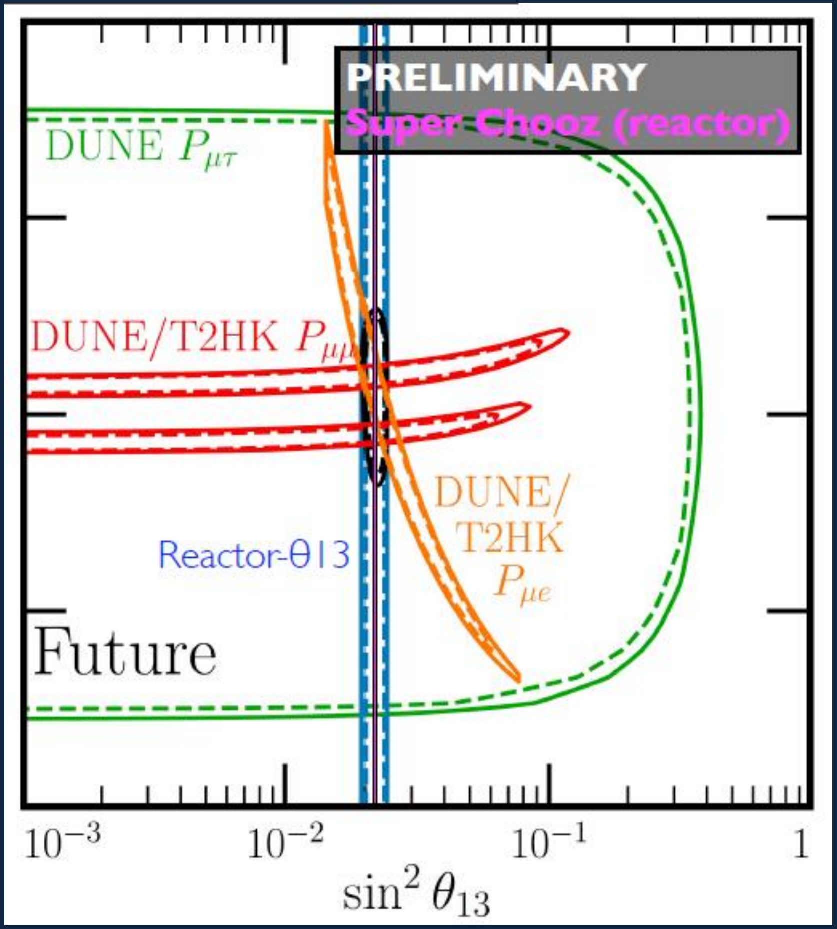


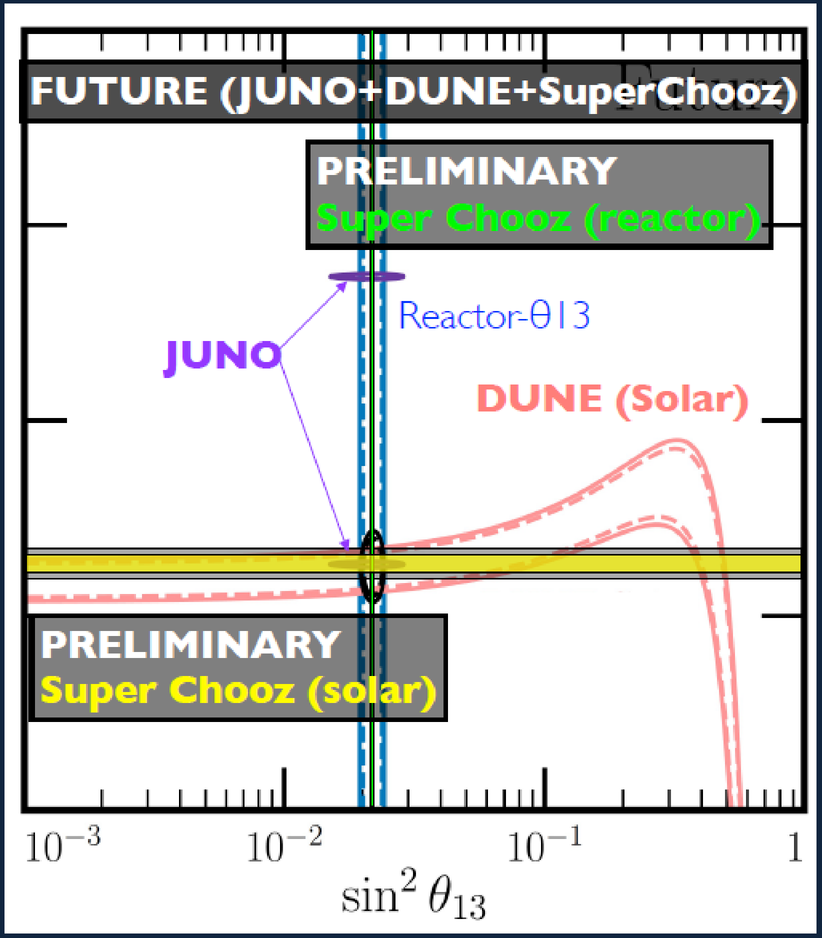
- **powerful PID**
- **energy flow**
- **tracking** (mm)
  →cosmogenic BG tagging
- **directionality**
- **dE/dx** (range)

~10MeV: supernovae (remnant, core-collapse)**, atmospherics, etc**

[A. Cabrera, CERN EP Seminar (2022)]

SuperChooz Precision Measurements

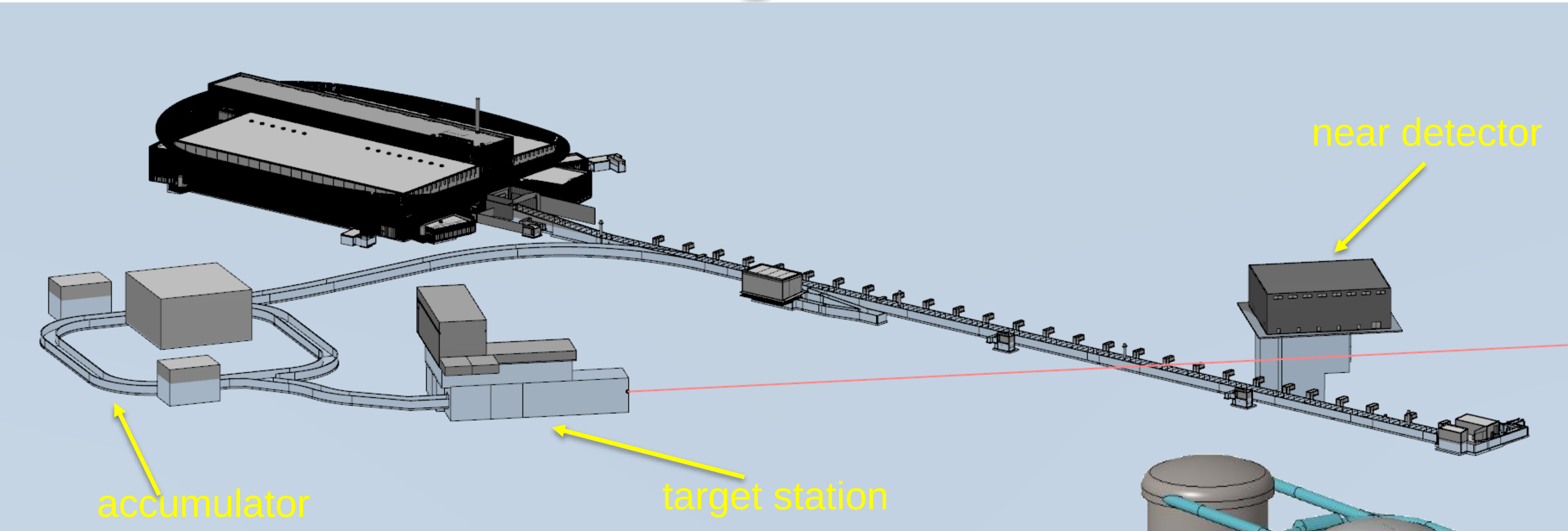


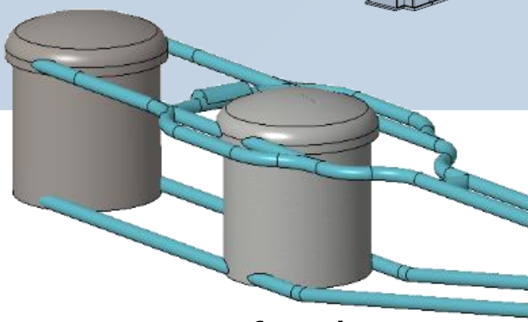


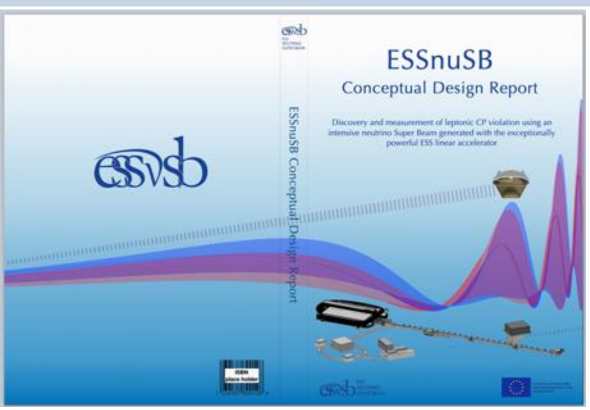
A. Cabrera, CERN EP Seminar (2022)

Final ESSνSB facility configuration

Dracos, NUFACT22







Conceptual Design Report

https://arxiv.org/abs/2206.01208

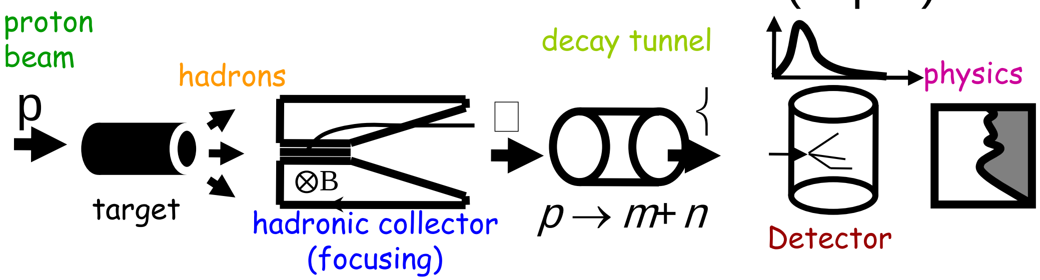
[Dracos, NUFACT22](#)

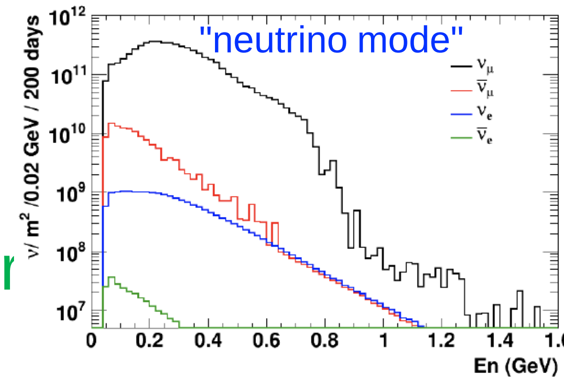
Having access to a powerful proton beam…

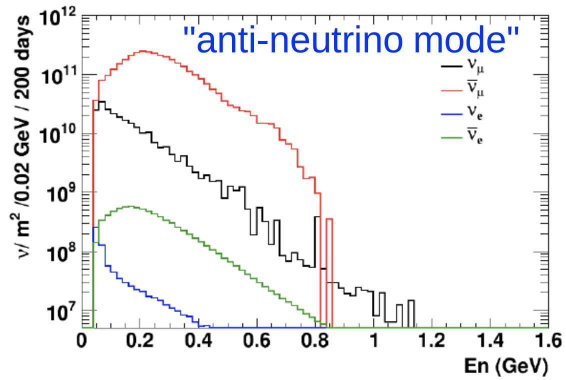
What can we do with:

- 5 MW power
- 2 GeV energy
- 14 Hz repetition rate
- 10^{15} protons/pulse
- $>2.7\times10^{23}$ protons/year

conventional neutrino (super) beam







- almost pure ν_μ beam
- small ν_e contamination which could be used to measure ν_e cross-sections in a near detector

	ν Mode		$\bar{\nu}$ Mode	
	$N_\nu(10^{10}/m^2)$	%	$N_\nu(10^{10}/m^2)$	%
ν_μ	583	97.5	23.9	6.55
$\bar{\nu}_\mu$	12.8	2.1	340	93.2
ν_e	1.93	0.3	0.08	0.02
$\bar{\nu}_e$	0.03	0.01	0.78	0.21

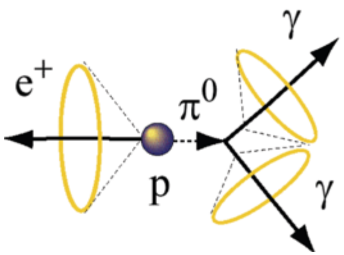
at 100 km from the target, per year (in absence of oscillations)

Dracos, NUFACT22

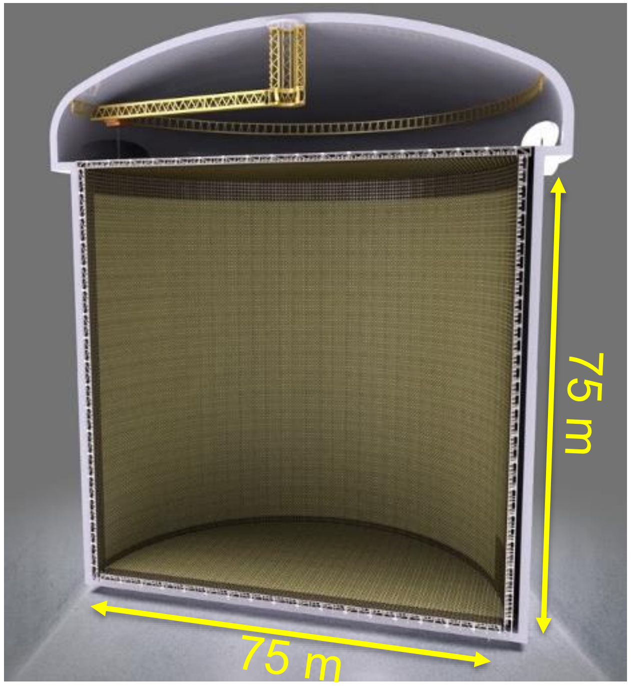
Can we go to the 2^{nd} oscillation maximum using our proton beam?

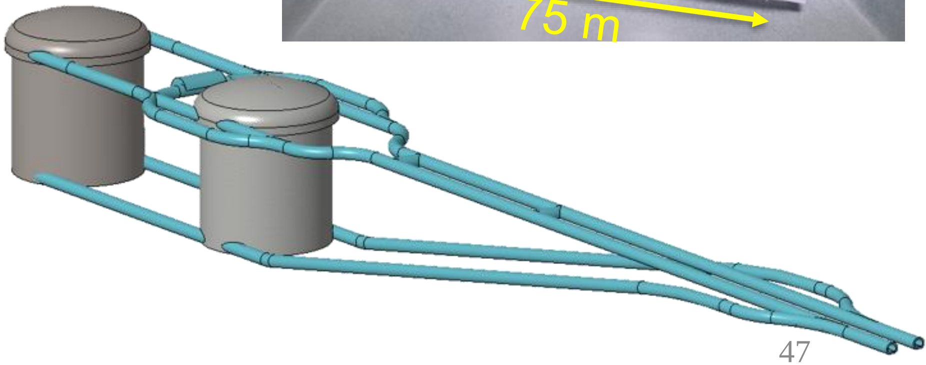
Yes, if we place our far detector at around 500 km from the neutrino source.

Megaton Water Cherenkov detector



- **Neutrino Oscillations**
- **Proton decay**
- **Astroparticles**
- Understand the gravitational collapsing: galactic SN ν
- Supernovae "relics"
- Solar Neutrinos
- Atmospheric Neutrinos

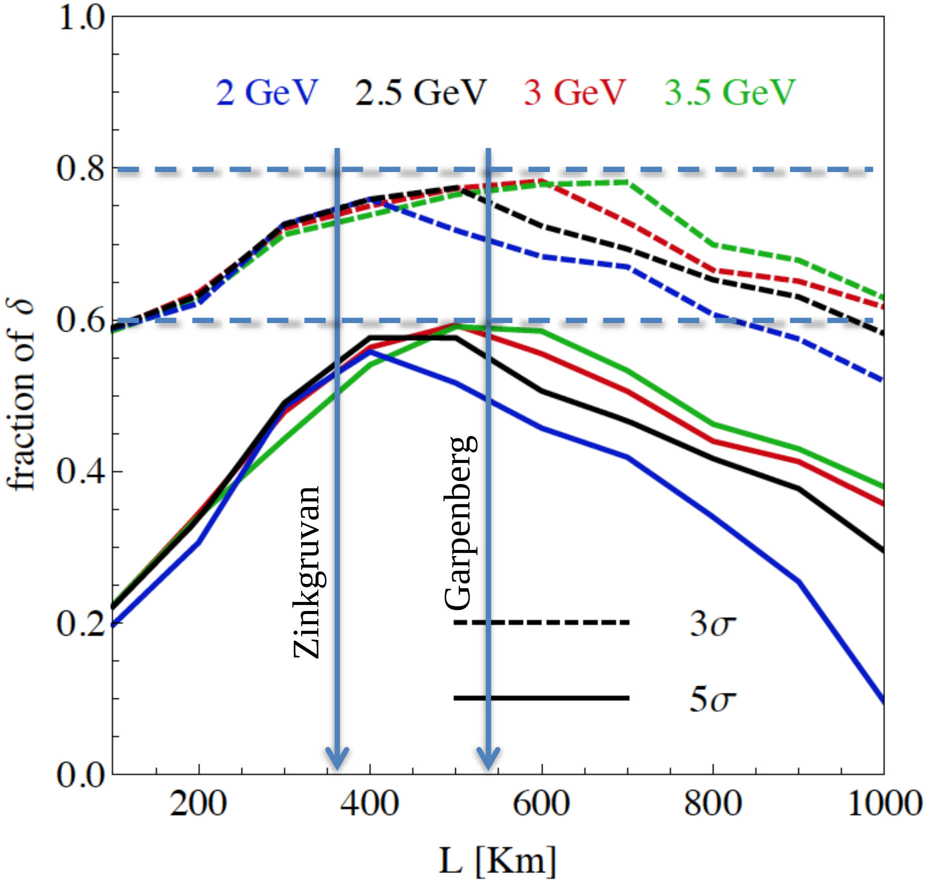




- 500 kt fiducial volume (~20xSuperK)
- Readout: ~20” PMTs
- 30% optical coverage

Which baseline?

CPV (*Nucl. Phys. B 885 (2014) 127*)

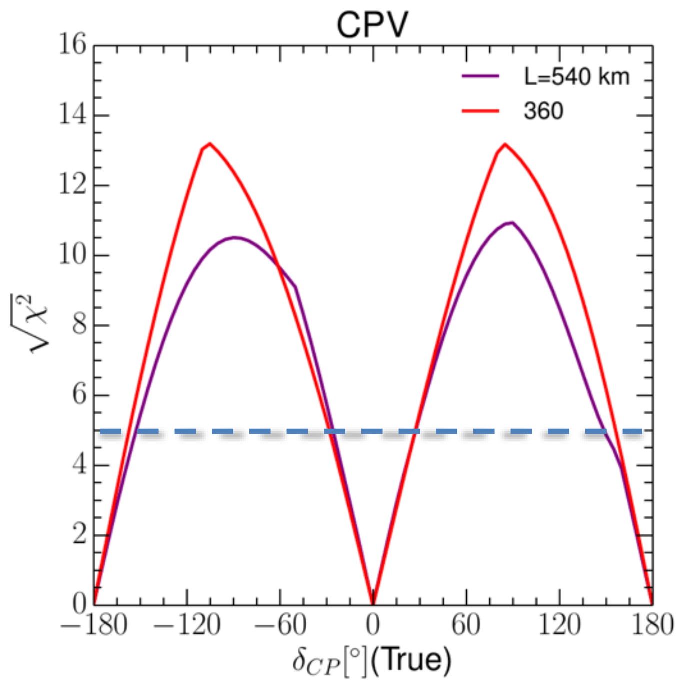


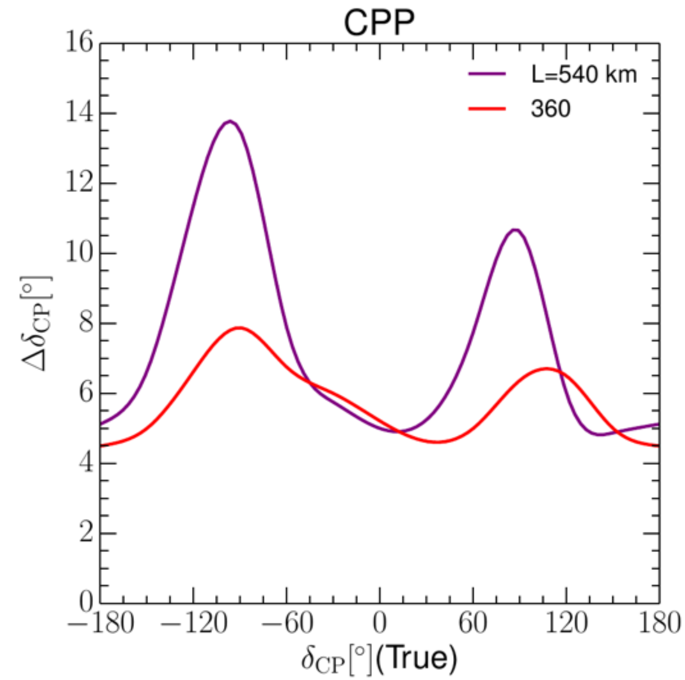
Candidate active mines

- ~60% δ_{CP} coverage at 5 σ C.L.
- >75% δ_{CP} coverage at 3 σ C.L.
- **systematic errors: 5%/10% (signal/backg.)**

Dracos, NUFACT22

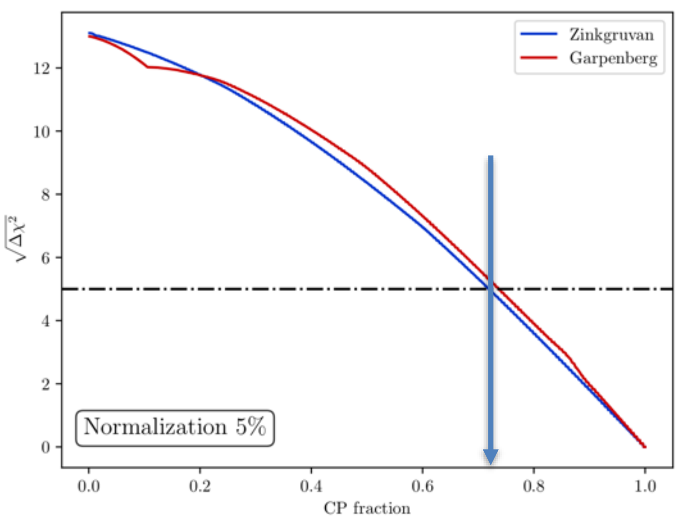
Final results





Precision measurement

$\Delta\delta_{CP}$<8° for all values



>72% after 10 years

equivalent to Neutrino Factory

Dracos, NUFACT22

Possible ESSνSB schedule

(2nd generation neutrino Super Beam)

2012: inception of the project

Nucl. Phys. B 885 (2014) 127

2016-2019: beginning of COST Action EuroNuNet

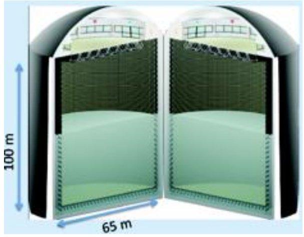
2018: beginning of ESSνSB Design Study (EU-H2020)

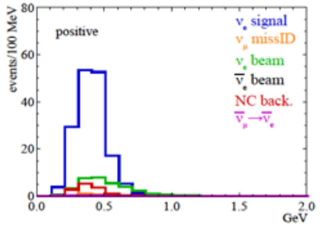
2022: End of ESSνSB **Design Study, CDR and preliminary costing**

arxiv.org/abs/2206.01208

2022-2026: Preparatory Phase, TDR

2026-2028: Preconstruction Phase, International Agreement



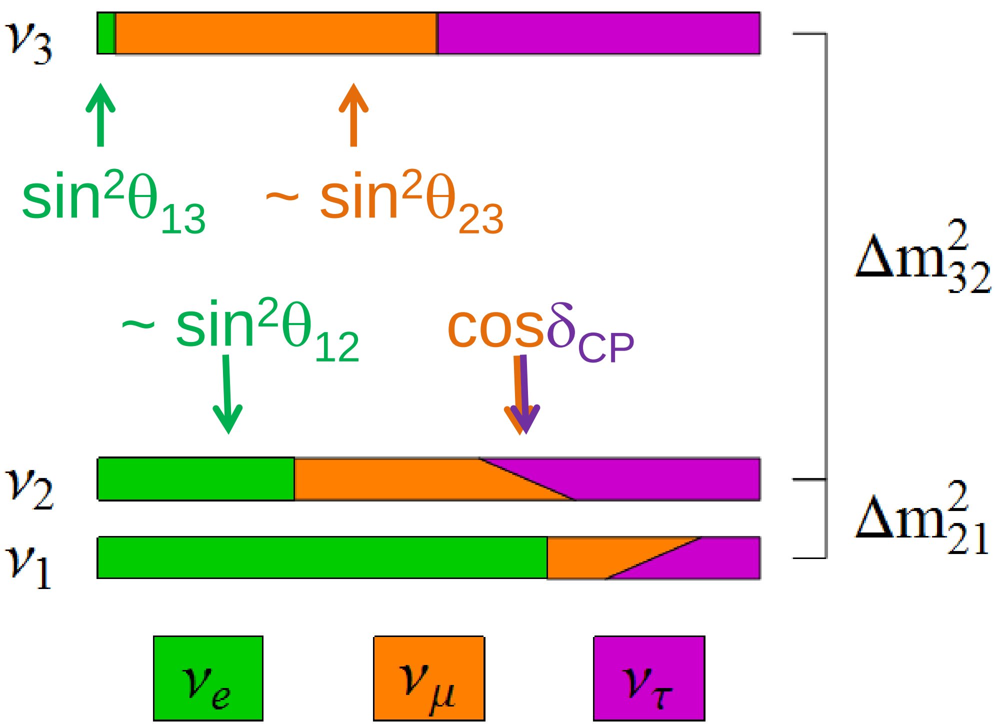


2028-2036: Construction of the facility and detectors, including commissioning

2037-: Data taking

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}



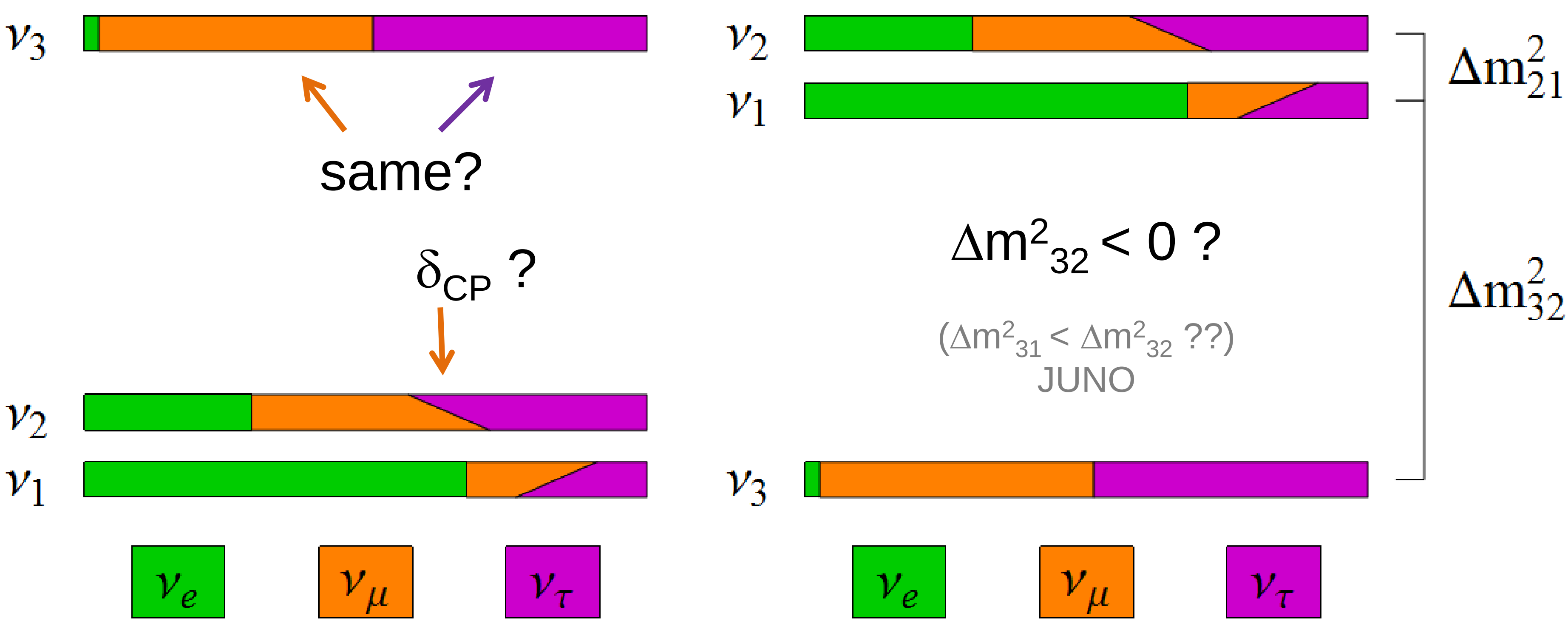
Missing Pieces

symmetries

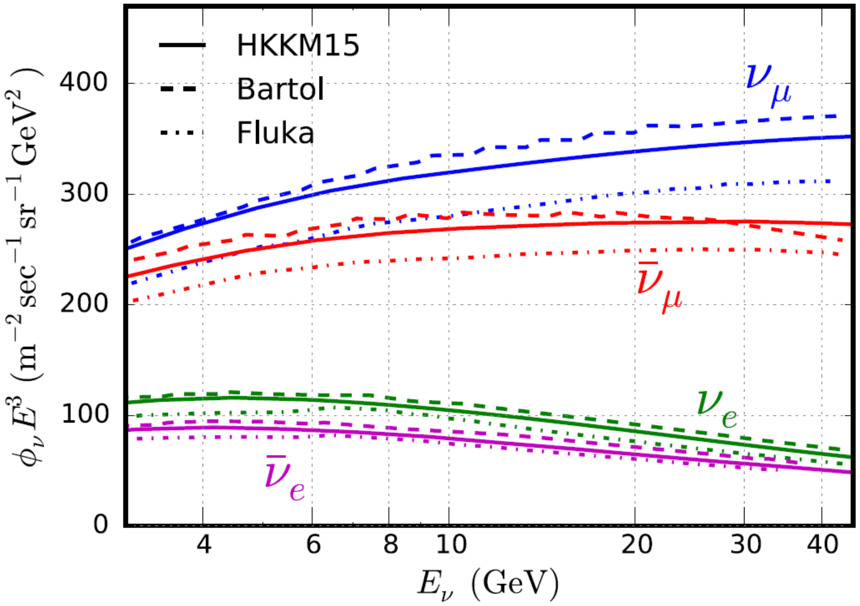
$$\sin^2 2\theta \times \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

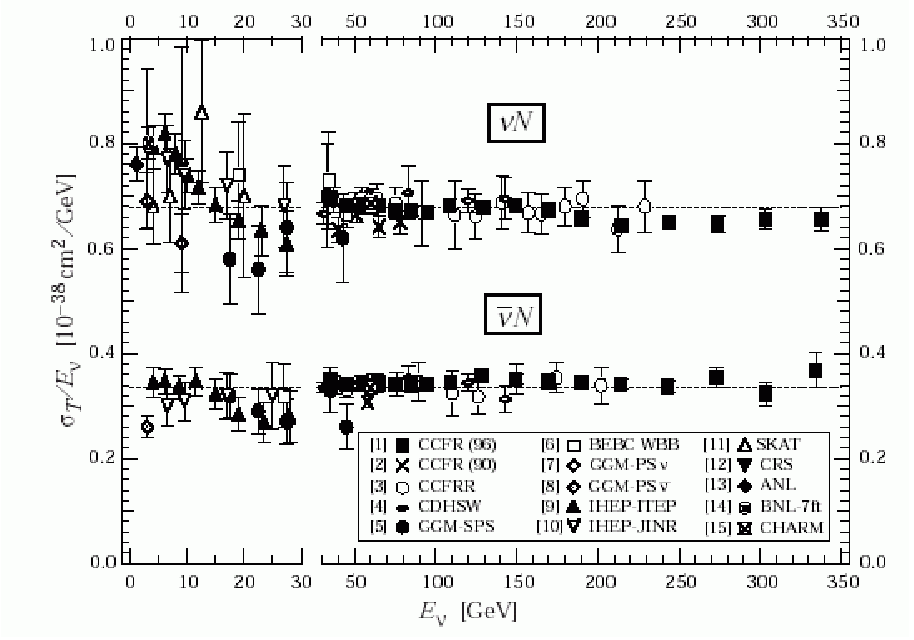
- Is $\theta_{23} = \pi/4$? Underlying symmetry?
- Do neutrinos violate CP? (δ_{CP})
- **What is the mass ordering? (Mass Hierarchy)**

Normal Hierarchy | **Inverted Hierarchy**



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

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

Depends on
sign of Δm^2_{31} (MH)

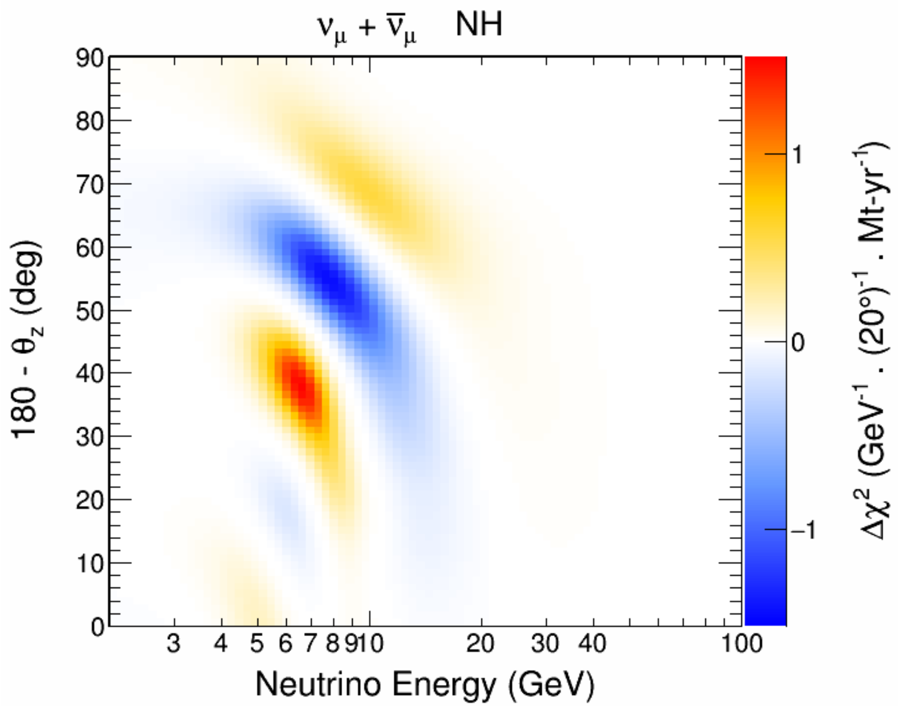
$$\Delta^m m^2 \equiv \sqrt{(\Delta m^2_{31} \cos 2\theta_{13} - 2\,E_\nu\,A)^2 + (\Delta m^2_{31} \sin 2\theta_{13})^2}\,,$$

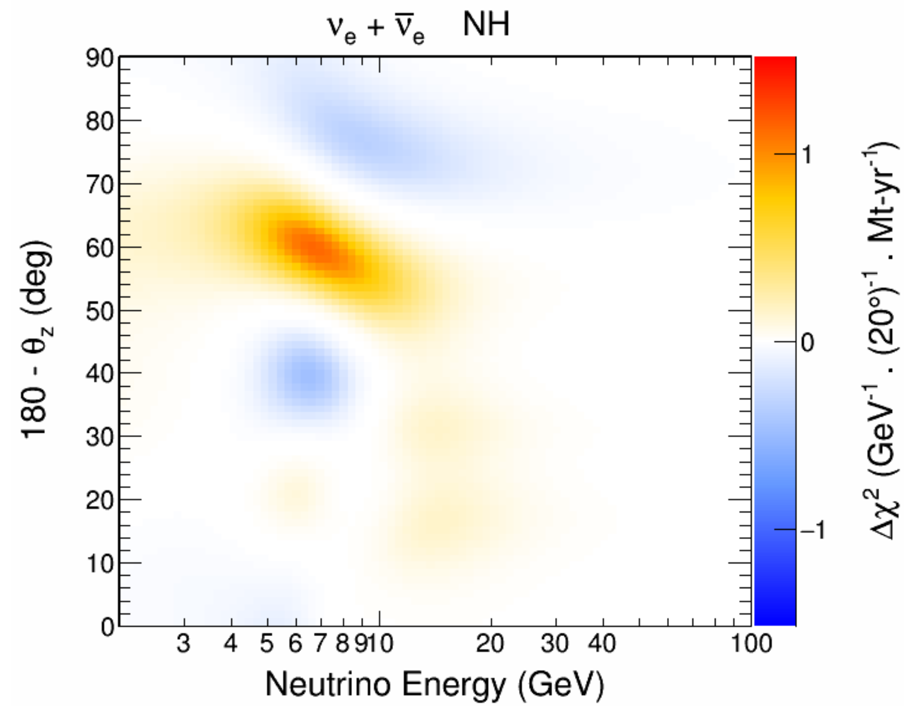
$$E_{\rm res} \equiv \frac{\Delta m^2_{31} \cos 2\theta_{13}}{2\sqrt{2}\,G_F\,N_e} \simeq 7\,\mathrm{GeV} \left(\frac{4.5\,\mathrm{g/cm}^3}{\rho}\right) \left(\frac{\Delta m^2_{31}}{2.4\times 10^{-3}\,\mathrm{eV}^2}\right) \cos 2\theta_{13}\,.$$

NSI Phase Space

- Very different from MH for nue
- Sensitivity in both channels, but numu is correlated with MH
- Still under unrealistic assumptions:
  - Perfect flavour selection
  - No systematics or nuisance pars.

$\varepsilon_{e\tau} = 0.2, \varepsilon_{\tau\tau} = 0.04$





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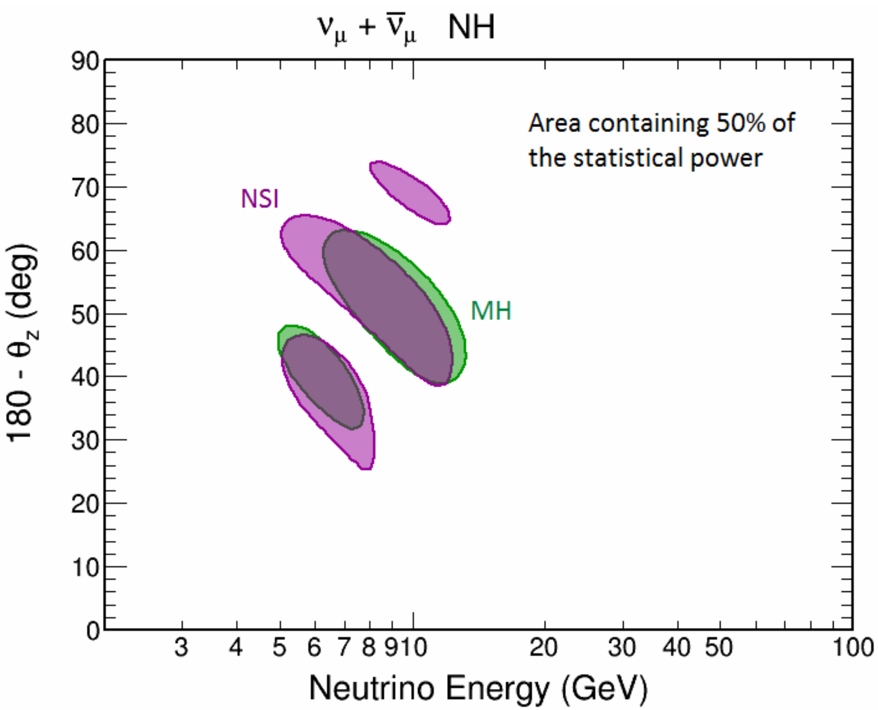
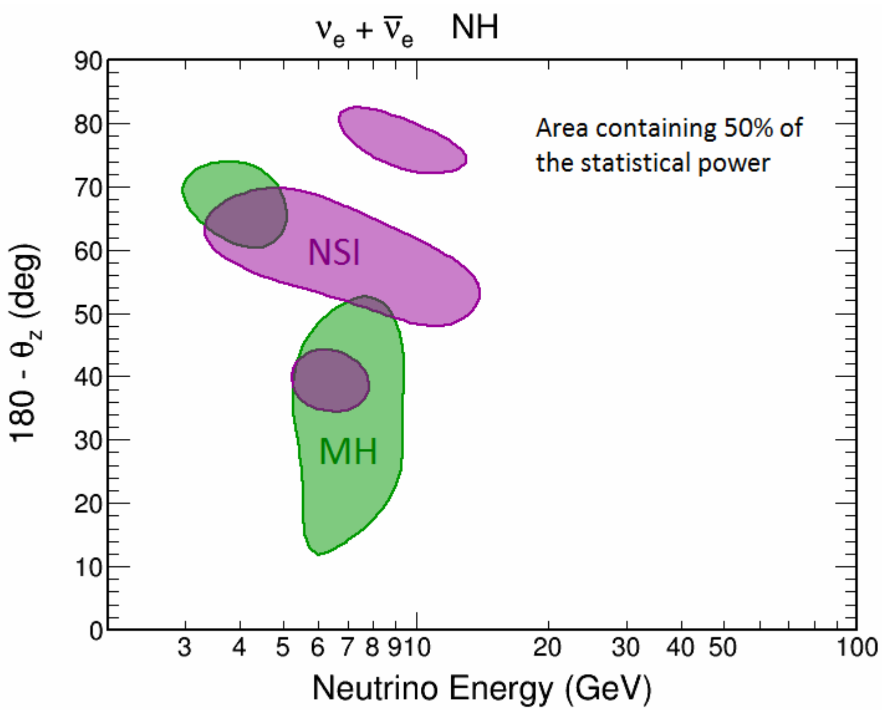
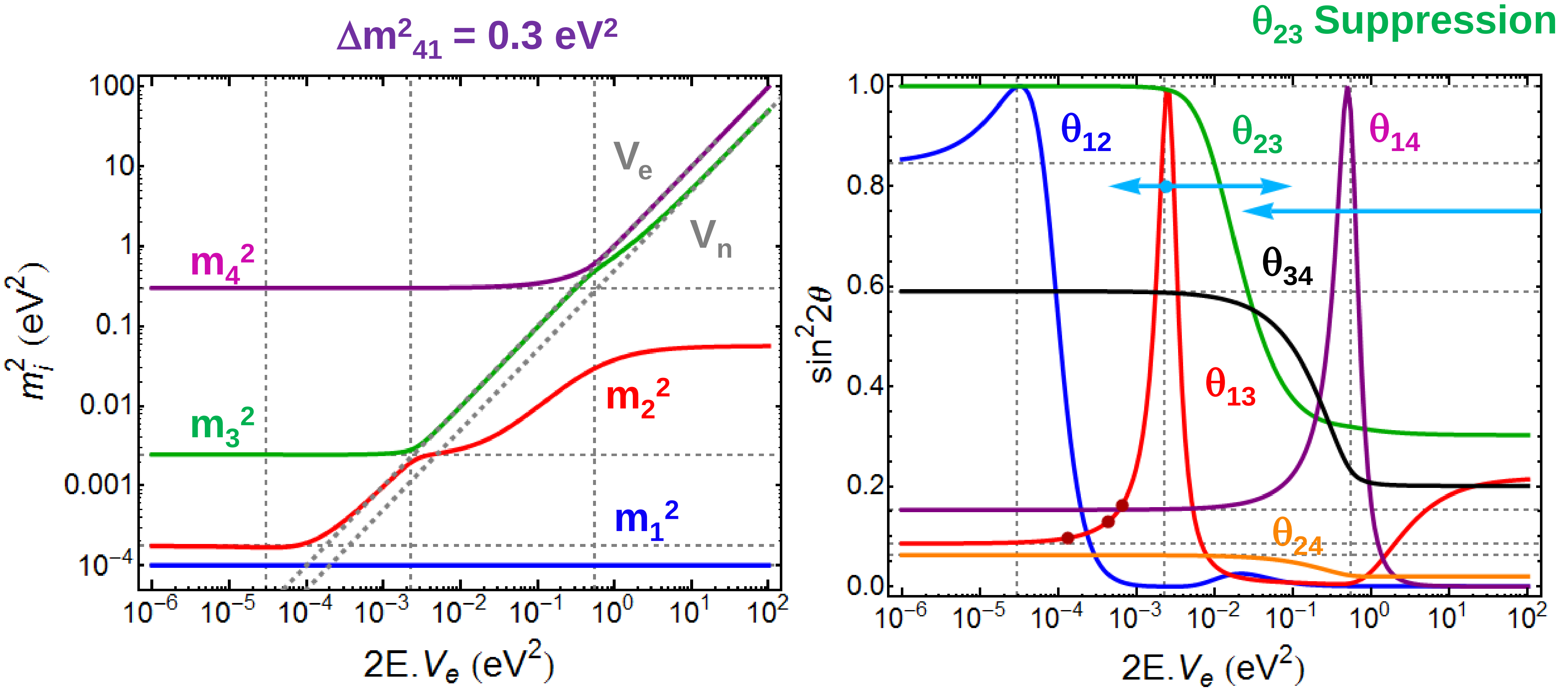




Sterile Neutrinos

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}



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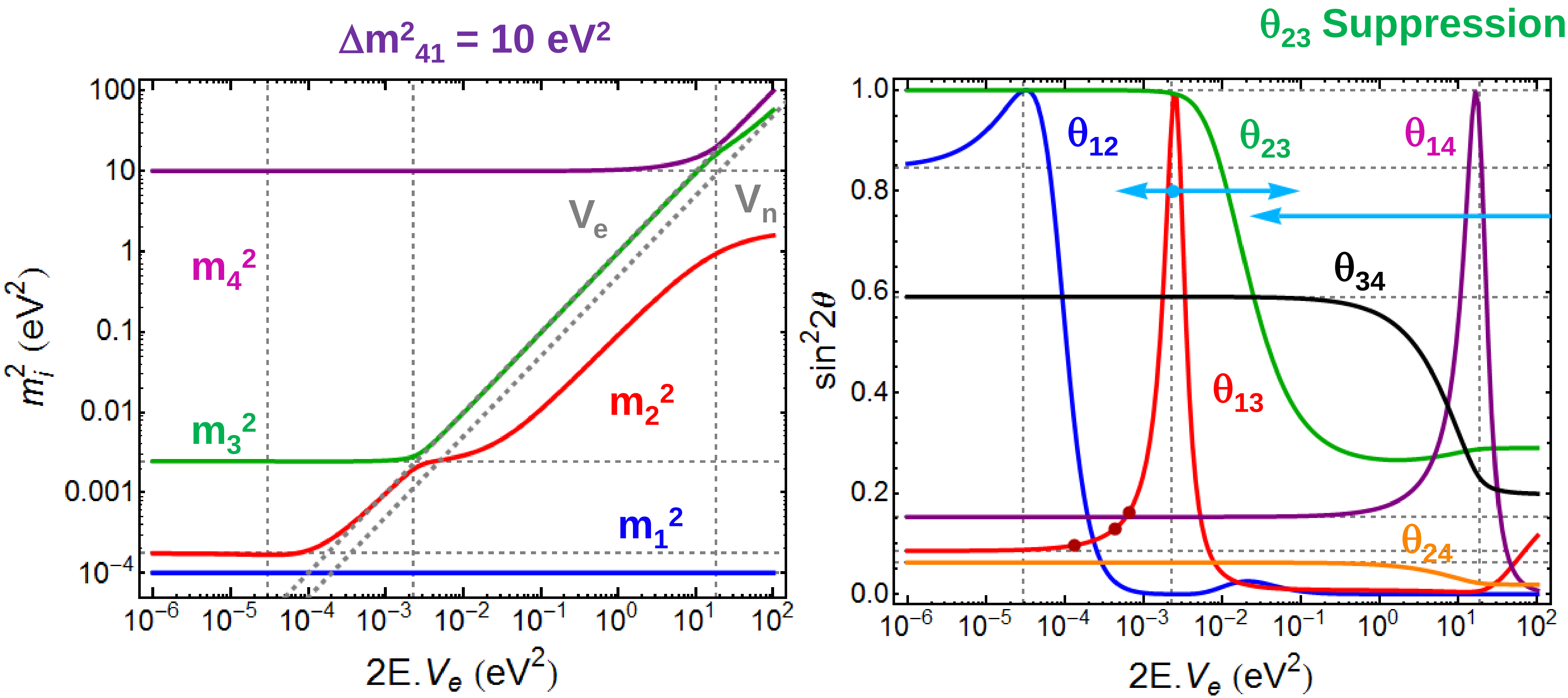
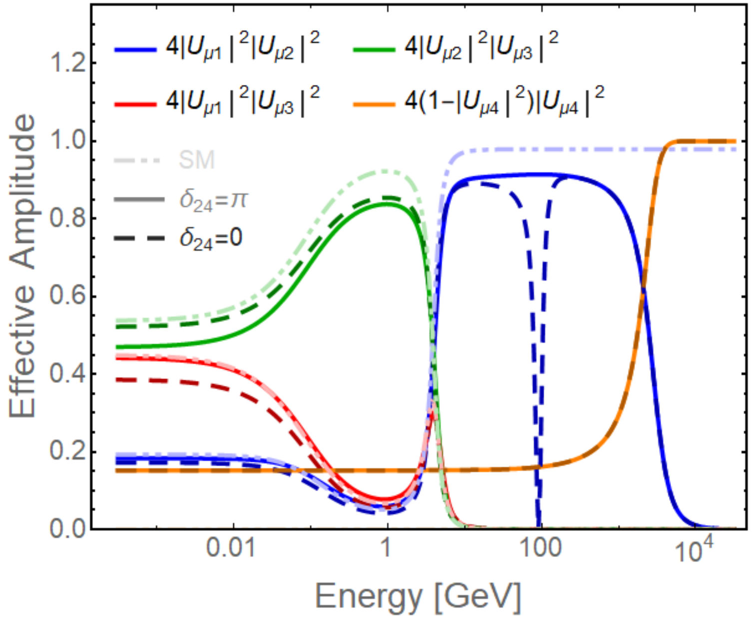
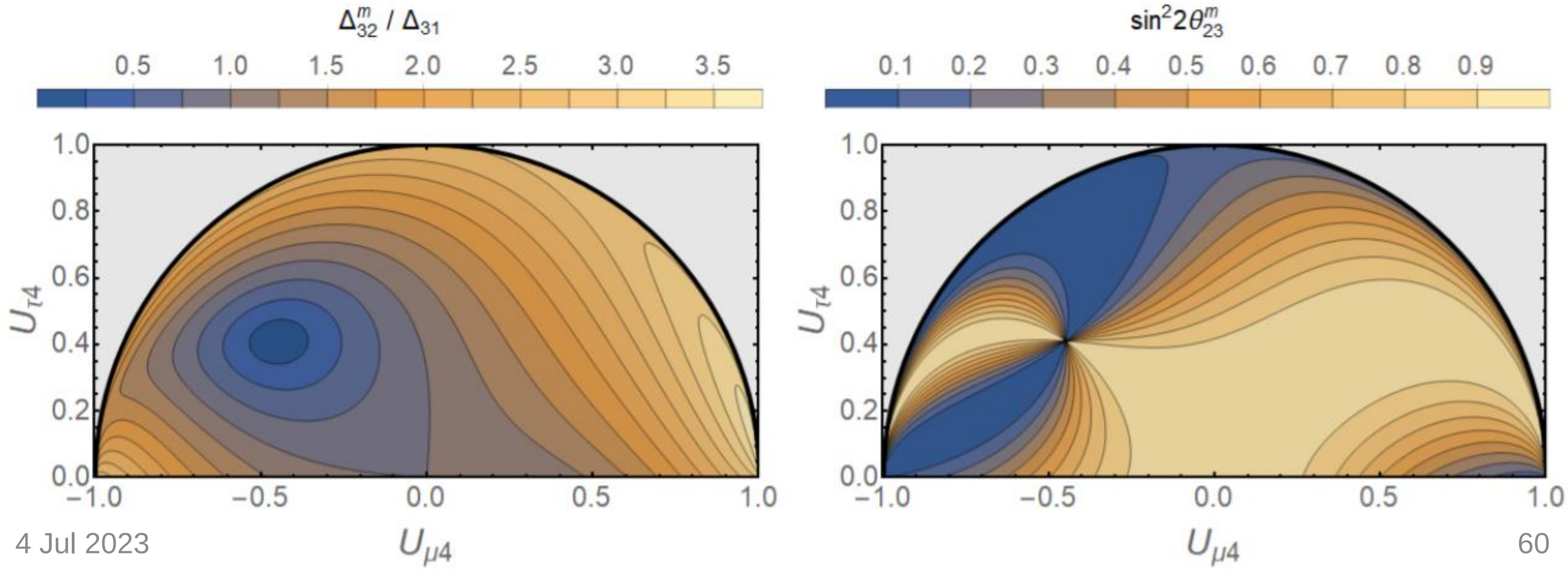


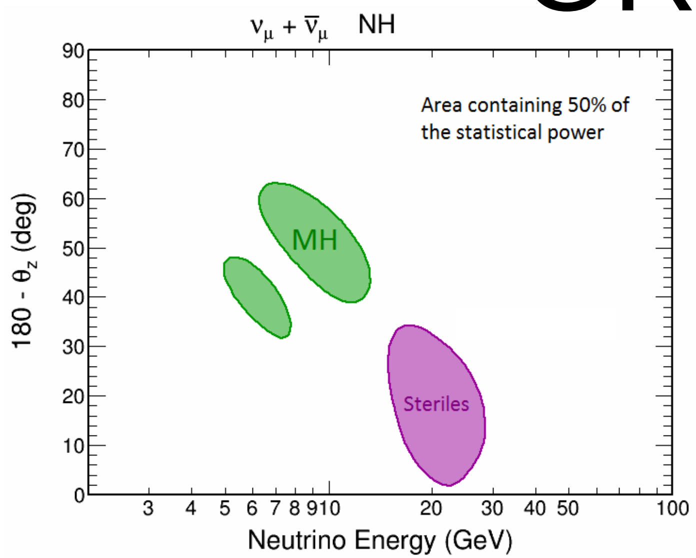
Resonances w/ Steriles

- 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





ORCA Studies



- Strong sensitivity with ν_μ channel
- Very different from 3ν resonance
- Still under unrealistic assumptions:
  - Perfect flavour selection
  - No systematics or nuisance pars.