Esperimenti con neutrini

Davide Basilico
University of Milano and INFN Milano

Meeting della Commissione Nazionale II INFN
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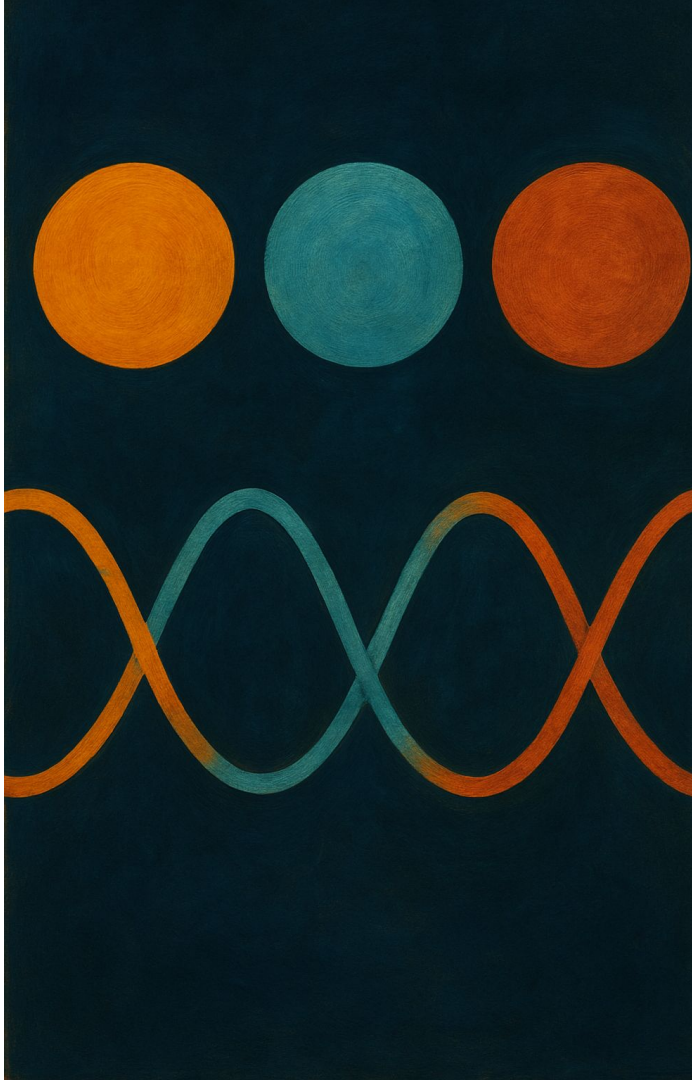
Venezia - 7 Aprile 2025

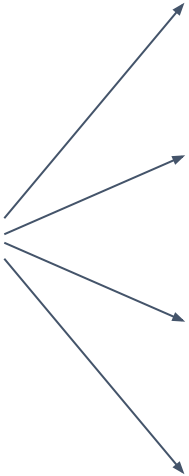
UNIVERSITÀ DEGLI STUDI DI MILANO

INFN
Istituto Nazionale di Fisica Nucleare



Outline

Flavor oscillation physics is entering its precision era



- sub-percentual measurement of mixing angles and mass splittings
- determination of Neutrino Mass Ordering (NMO) with high statistical significance
- is there any CP violation phase in leptonic sector?
- precision testing of 3ν paradigm
  $\rightarrow$ unitarity mixing? sterile ν? dark sector?

Outline

Focus on the **current status** and on challenges to be addressed in the **very next years**

- sub-percentual measurement of mixing angles and mass splittings
- determination of Neutrino Mass Ordering (NMO) with high statistical significance
- is there any CP violation phase in leptonic sector?
- precision testing of 3ν paradigm
  → unitarity mixing? sterile ν? dark sector?

An intense experimental effort

Atmospheric ν

L ~10^3-10^4 km,
E~10^2-10^4 MeV
matter effects

- KM3NeT
- IceCube
- (JUNO)

+

Accelerator ν

L ~10^2-10^3 km
E~10^3 MeV
matter effects

- T2K
- NOvA
- (DUNE, HyperK)

+

Reactor ν

L ~1-10^2 km
E~MeV

- (JUNO)
- KamLAND
- RENO
- + short-baseline

A multi-faceted panorama

Exploring different sectors, based on experimental design

Experiment	Dominant	Important
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}, $\lvert\Delta m^2_{31,32}\rvert$	
Atmospheric Experiments (SK, IC-DC)		θ_{23},$\lvert\Delta m^2_{31,32}\rvert$, θ_{13},$\delta_{\rm CP}$
Accel LBL ν_μ,$\bar{\nu}_\mu$, Disapp (K2K, MINOS, T2K, NOνA)	$\lvert\Delta m^2_{31,32}\rvert$, θ_{23}	
Accel LBL ν_e,$\bar{\nu}_e$ App (MINOS, T2K, NOνA)	$\delta_{\rm CP}$	θ_{13} , θ_{23}

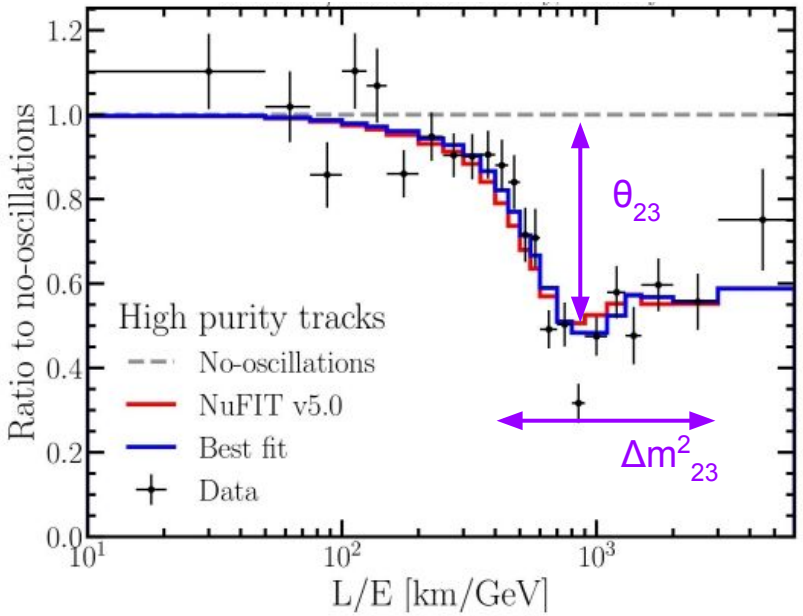
S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)

Several experiments at a maturity stage,
others set to begin or be upgraded

Atmospheric ν experiments

Leading order $\sin^2 2\theta_{23}$ and Δm^2_{32}

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



Atmospheric ν experiments: NMO

ν/anti-ν asymmetry in MSW resonance thanks to matter effects (4-30 GeV):
oscillation probabilities for NO and IO are different due to ν path through the Earth matter.

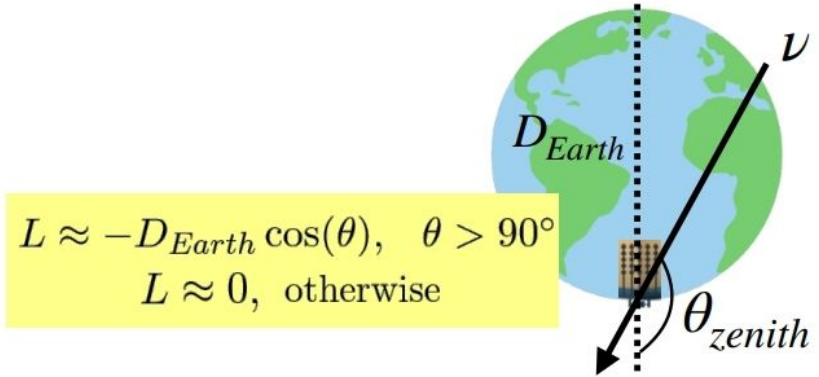
Upgoing muon ν: MSW resonance takes place according to sign($A/\Delta m^2_{3\ell}$), where A = ν-matter potential

$$P(\nu_e \to \nu_e) \approx 1 - \sin^2 2\theta_{13}^m \sin^2\left[1.27\left(\Delta m^2_{31}\right)^m \frac{L}{E_\nu}\right];$$

$$\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{\left(\cos 2\theta_{13} - A/\Delta m^2_{31}\right)^2 + \sin^2 2\theta_{13}}.$$

ν: $A > 0$ $\to$ MSW if $\Delta m^2_{3\ell} > 0$ $\to$ NO

anti-ν: $A < 0$ $\to$ MSW if $\Delta m^2_{3\ell} < 0$ $\to$ IO



$$L \approx -D_{Earth}\cos(\theta), \quad \theta > 90°$$
$$L \approx 0, \quad \text{otherwise}$$

Atmospheric ν : IceCube & DeepCore & Upgrade

IceCube Neutrino Observatory

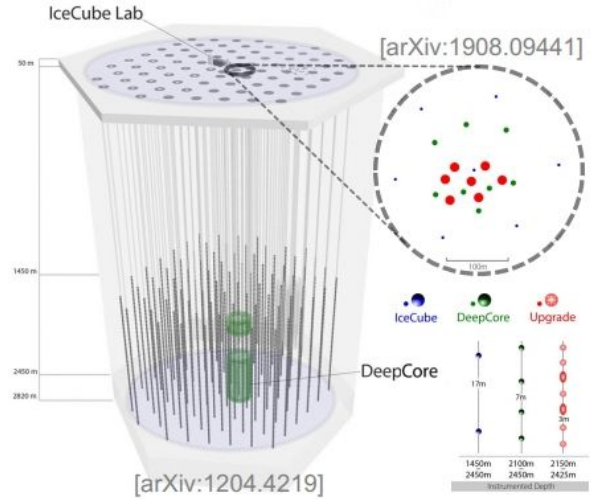
- Products of ν-N interactions radiate Cherenkov photons (no ν/anti-νID)
- 5160 optical sensors on 86 strings embedded within 1 km3 of ice
- Down-facing 10" PMT in pressure sphere at depths 1450 m - 2450 m

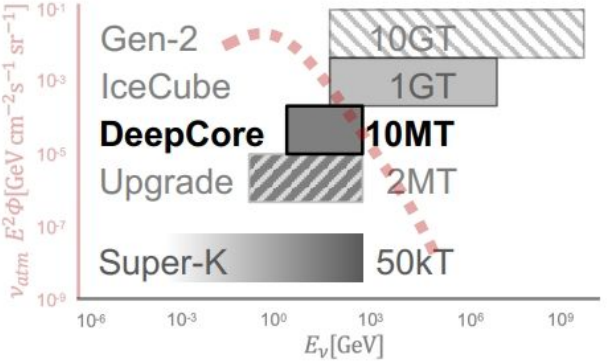
DeepCore: low-energy array

- Low-energy extension at 5x density in the cleanest ice (below 2100 m)
- Higher QE PMTs in digital optical modules (DOMs)
- mHz ν_{atm} rate: neutrino detection every 15 minutes

Upgrade - infill of DeepCore (2025-2026)

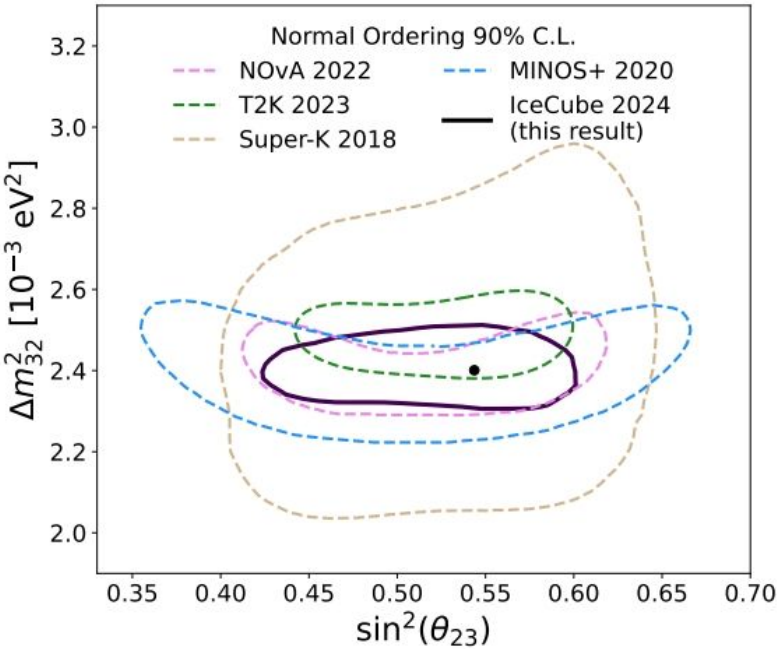
- 700 new DOMs at 10x density on 7 strings in DeepCore region
- New PMTs and first multi-directional modules (D-Eggs, mDOMs)
- Overall 2x ν_{atm} rate and 3x ν_{atm} rate of DeepCore [arXiv:1908.09441]





Atmospheric ν : IceCube & DeepCore & Upgrade

9.3 years of data in IceCube DeepCore



Comparable θ_{23} and mass splitting precision to LBL experiments

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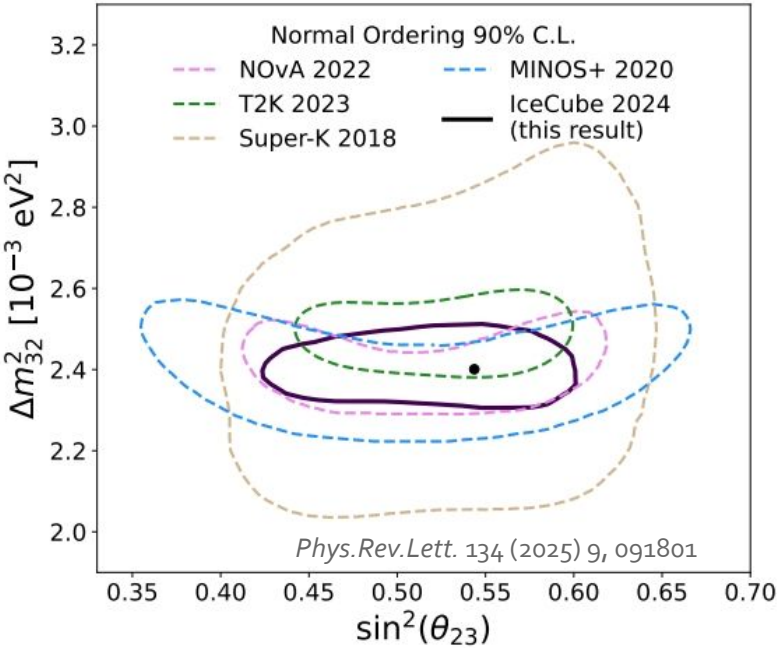
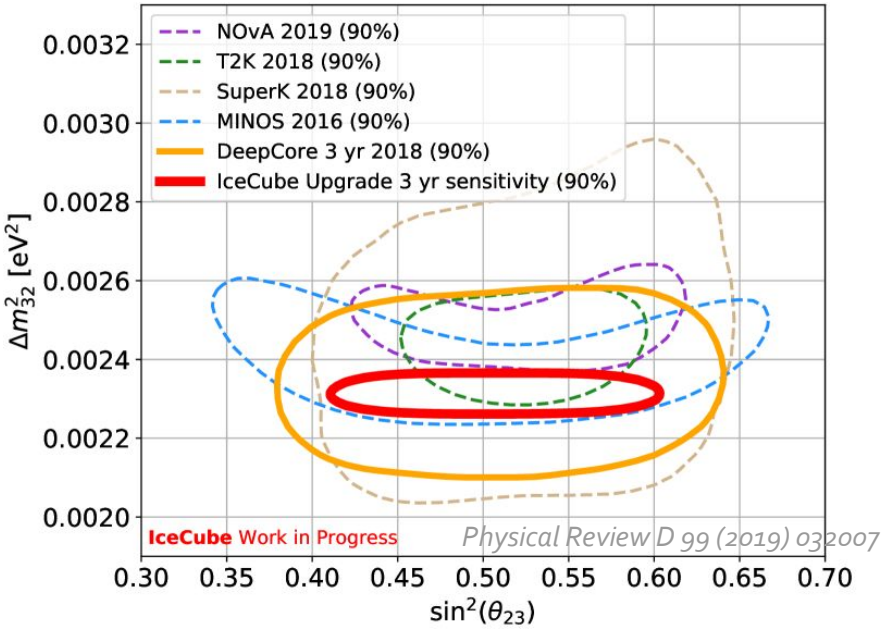


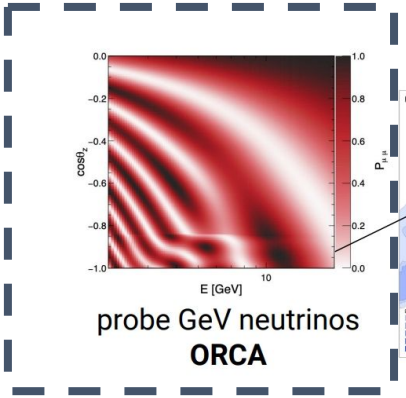
Comparable θ_{23} and mass splitting precision to LBL experiments

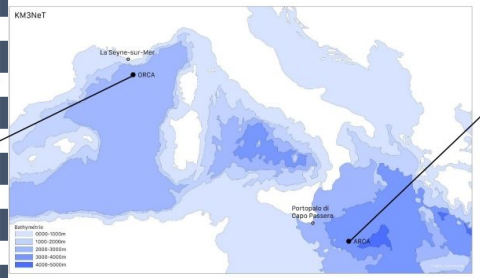
Icecube Upgrade proposal

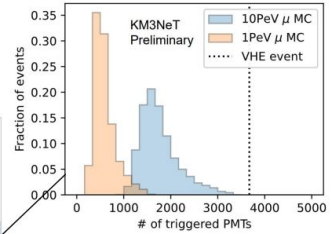


Conservative estimates predict world-leading results within 1 year of data-taking

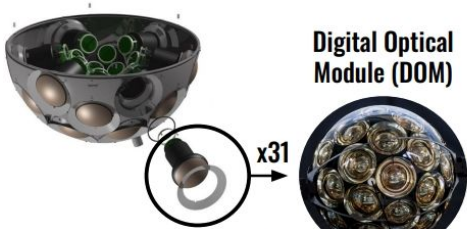
Atmospheric ν : KM3NeT



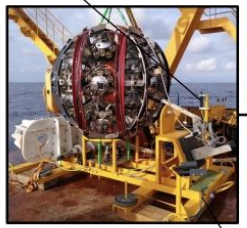


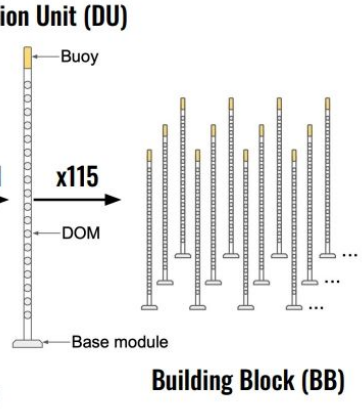


probe TeV-EeV neutrinos
ARCA



detect Cherenkov light from the charged products of neutrino interactions in sea-water





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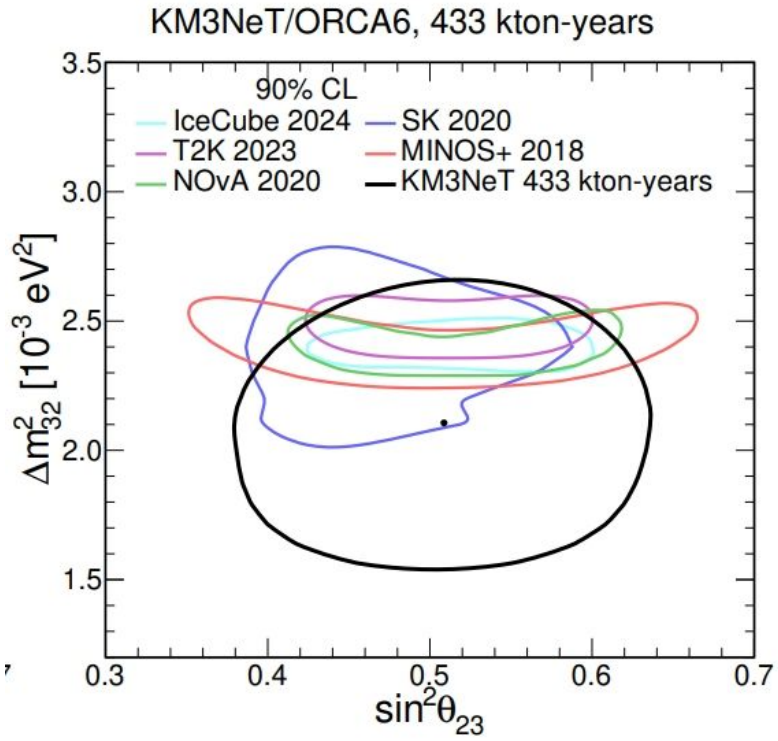
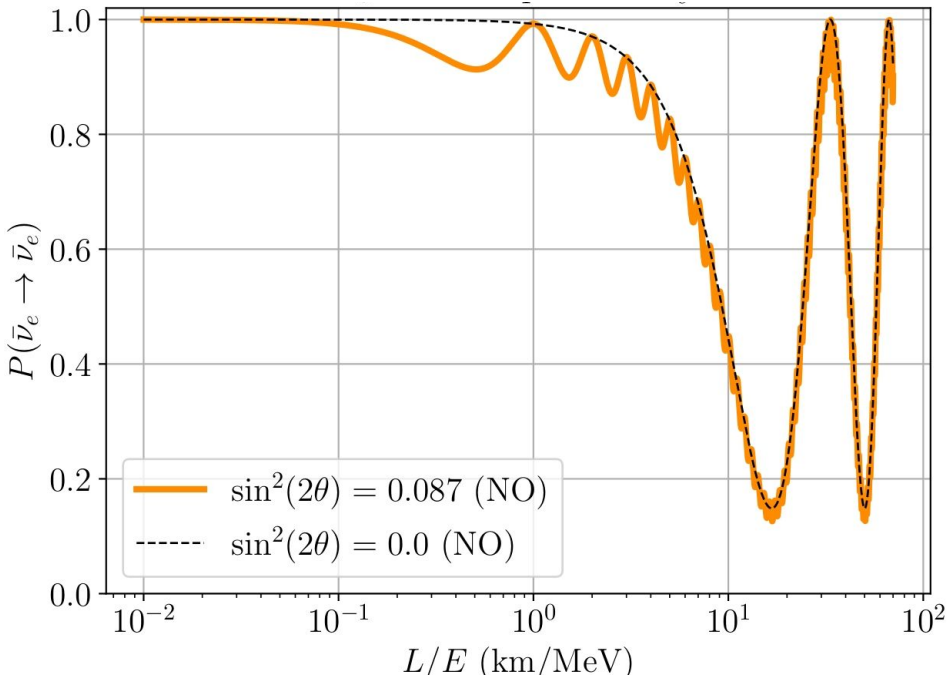


- low preference for IO
- maximum mixing preferred

Measurement of neutrino oscillation parameters with the first six detection units of KM3NeT/ORCA JHEP 10 (2024) 206

Reactor ν

A wide L/E range to explore different oscillation features



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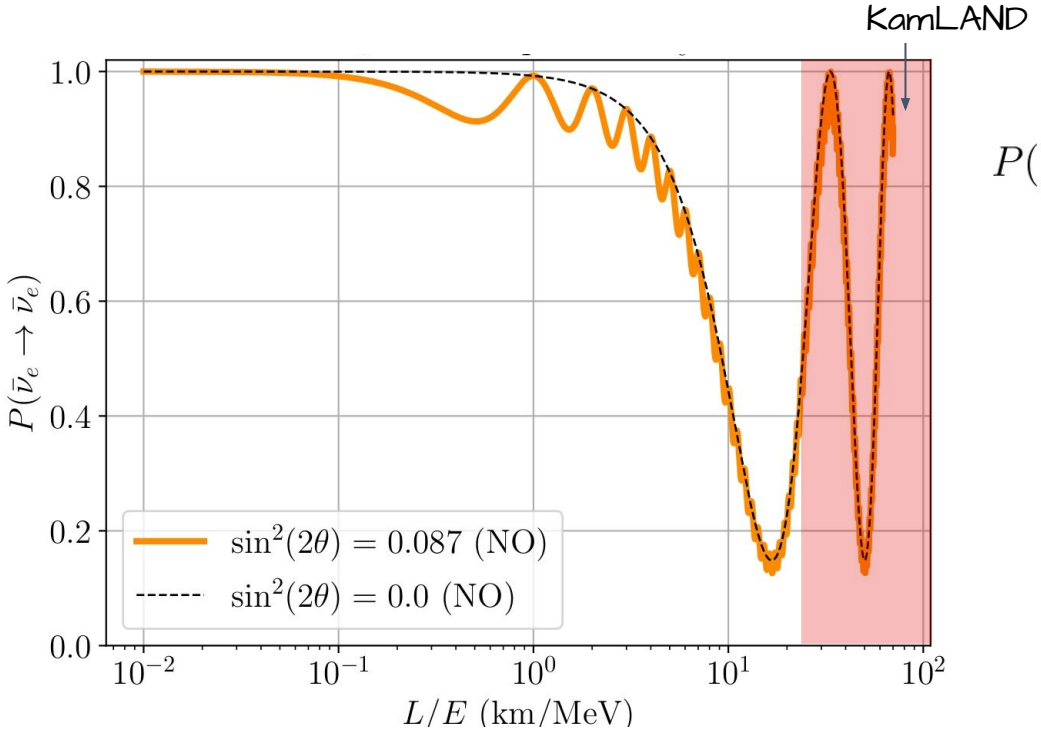

Medium baseline (θ_{12}, Δm^2_{12})

$$P(\nu_e \to \nu_e) = 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) - \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) - \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$

$$\Delta_{kj} = 1.27\Delta m^2_{kj}[\mathrm{eV}^2]\frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}$$

Reactor ν

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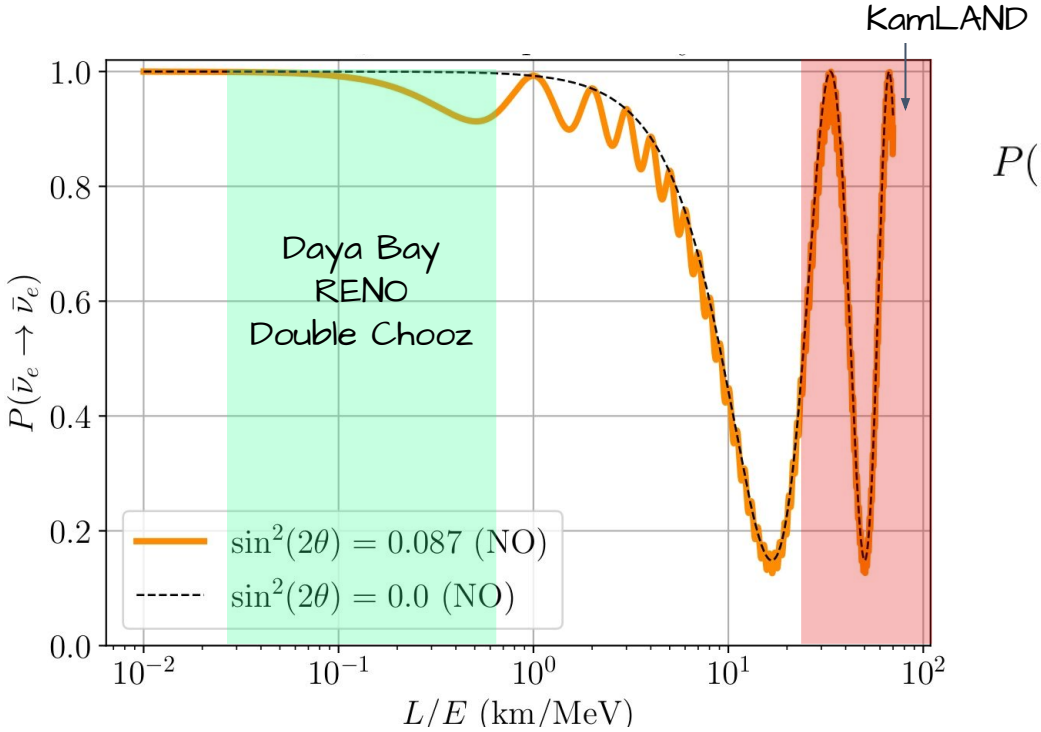

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Short baseline (θ_{13}, Δm^2_{31})

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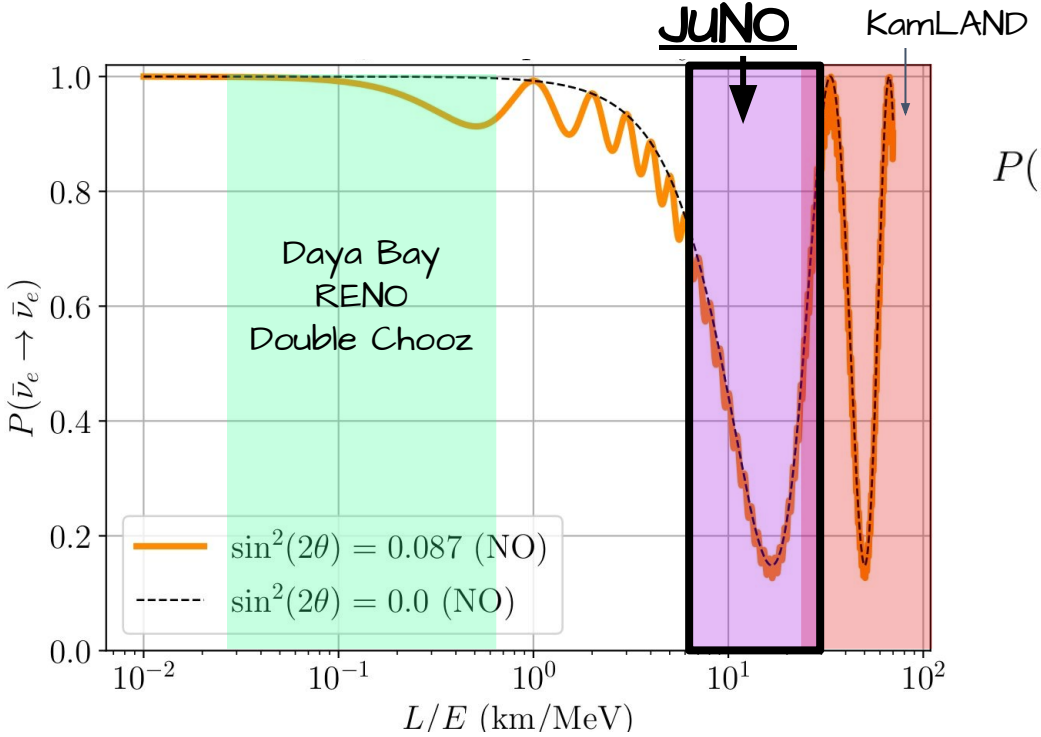
Reactor ν

A wide L/E range to explore different oscillation features



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Short baseline (θ_{13}, Δm^2_{31})

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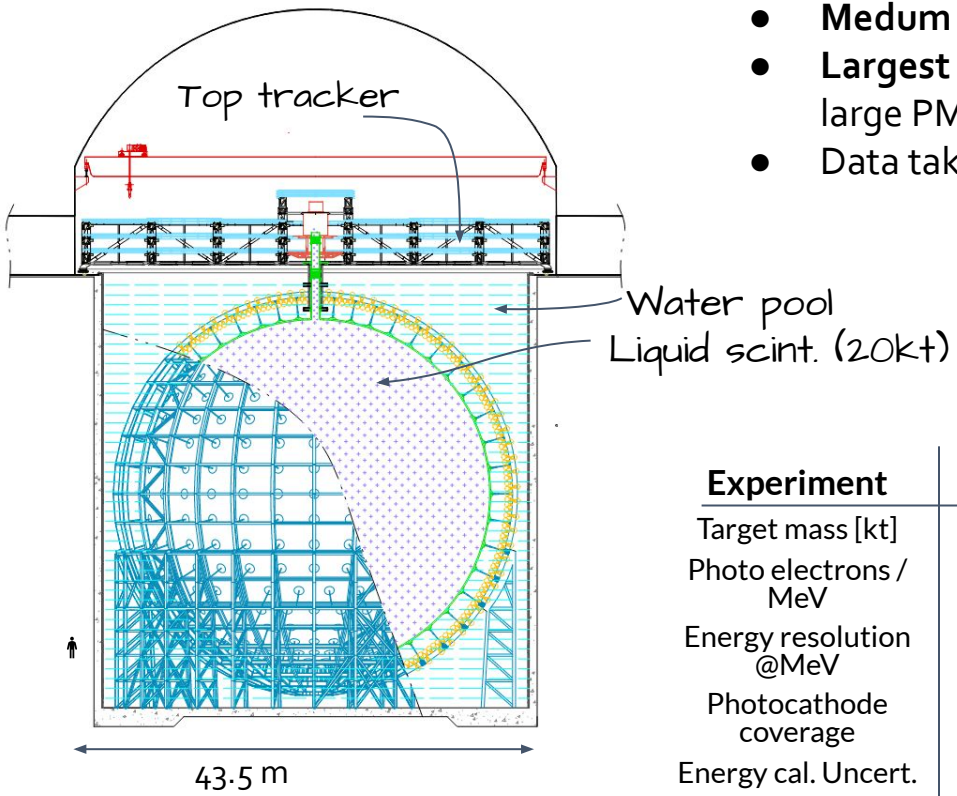
Reactor ν: JUNO



- **Medum baseline,** L = 52 km, E ~ MeV
- **Largest liquid scintillator ever (20 kton),** equipped with 17612 large PMTs + 25600 small PMTs to collect scintillation light
- Data taking started in December 2024

Experiment	Daya Bay	Borexino	KamLAND	JUNO
Target mass [kt]	0.16	~0.3	~1	**~20**
Photo electrons / MeV	~160	~500	~250	**~1600**
Energy resolution @MeV	~8.5%	~5%	~6%	**~3%**
Photocathode coverage	12%	34%	34%	**78%**
Energy cal. Uncert.	0.5%	1.0%	2.0%	**<1%**

Reactor ν: JUNO, experimental challenges

1) Large statistics

⟶ huge scintillator mass, powerful nuclear reactors

2) Energy resolution: 2.95% @ 1MeV + 1% understanding of the intrinsically non-linear energy scale

⟶ LS optical properties + light collection + calibrations

3) Low background

⟶ underground + scintillator purification system + material screening + veto systems

4) Knowledge of reactor spectra at sub-% level

⟶ near detector: Taishan Antineutrino Observatory (TAO) at 44 m from Taishan reactor

⟶ reduce spectral shape systematics

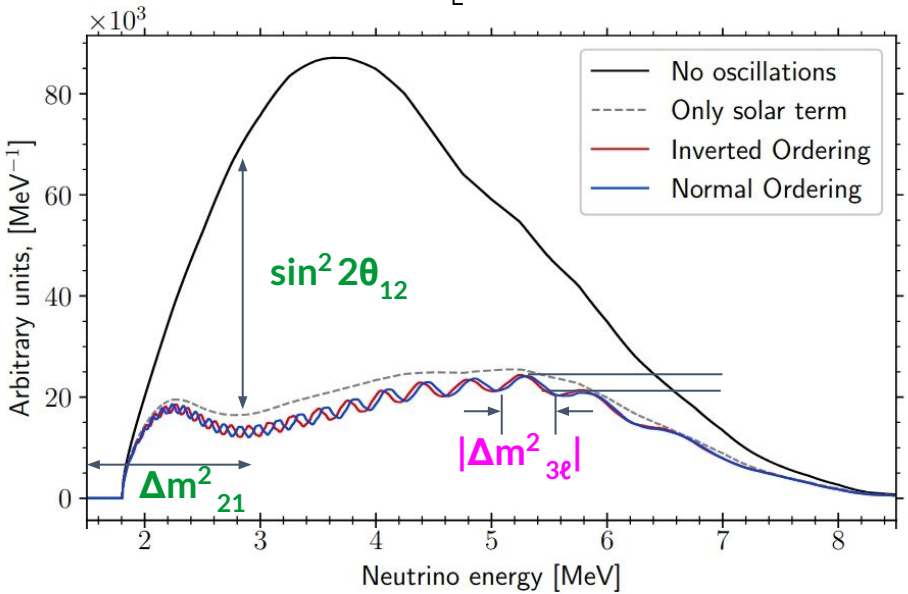
Reactor ν: JUNO analysis

First experiment to observe both **fast** ($\sin^2\theta_{13}$, $|\Delta m^2_{3\ell}|$) and **slow** ($\sin^2\theta_{12}$, Δm^2_{21}) oscillations **in vacuum**

→ **interference pattern depends on NMO**
… no dependence on θ_{23}, δ_{CP}, small dependence on matter effects: **no degeneracies.**

see A. Serafini's talk

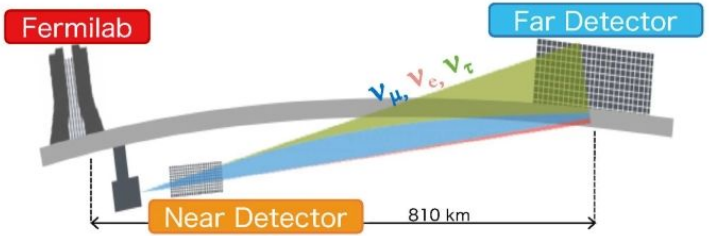
Exemplary spectrum, 6y
(10^5 events, σ_E/E = 2.95% @ 1 MeV)



Chin. Phys. C46 (2022) 12, 123001

	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)

Accelerator ν: NOvA and T2K



L = 295 km, E_{peak} = 0.6 GeV

L = 810 km, E_{peak} = 2 GeV

Accelerator ν: NOvA and T2K

Leading order $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$ and Δm^2_{32} in vacuum

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

$+ \delta_{CP}$ dependent terms CP violating

$+ \delta_{CP}$ dependent terms CP conserving

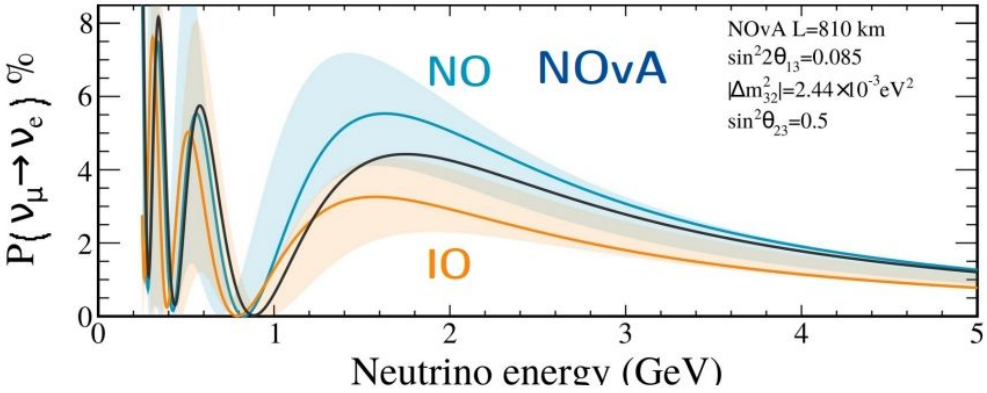
+ other terms

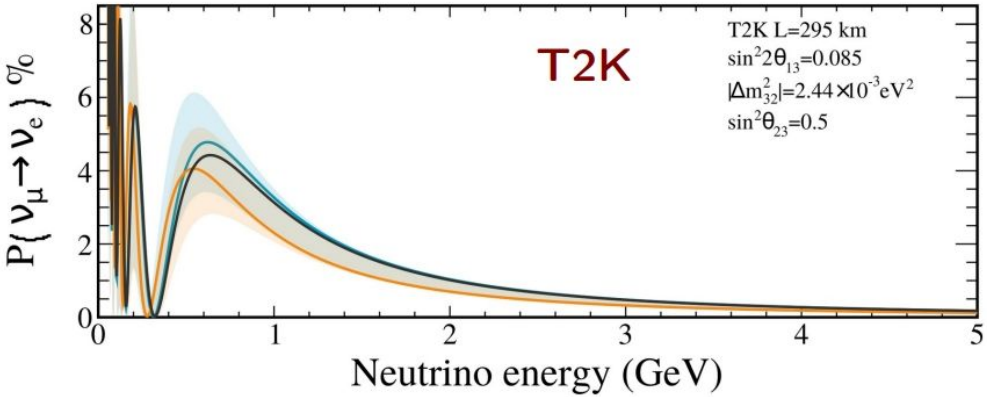
In LBL experiments, matter effects are "degenerate" with NMO and CP violation effects.

L = 295 km, E_{peak} = 0.6 GeV

L = 810 km, E_{peak} = 2 GeV

Accelerator ν: NOvA and T2K





NOvA: lower E and shorter L reduces the matter effects → less degenerate CPV values of δ_{CP}

T2K: higher E and longer L enhances the NMO dependent matter effects

→ impact on P(νμ → νe) and P(anti-νμ → anti-νe) differs for each experiment

NO
IO
Vacuum
$\delta_{CP} = 0$
$\delta_{CP} \in [-\pi/2, \pi/2)$

NOvA and T2K joint analysis

Joint analysis lifts degeneracies of individual experiments. Based on Eur. Phys. J. C (2023) 83: 782 and Phys. Rev. D 110, 012005

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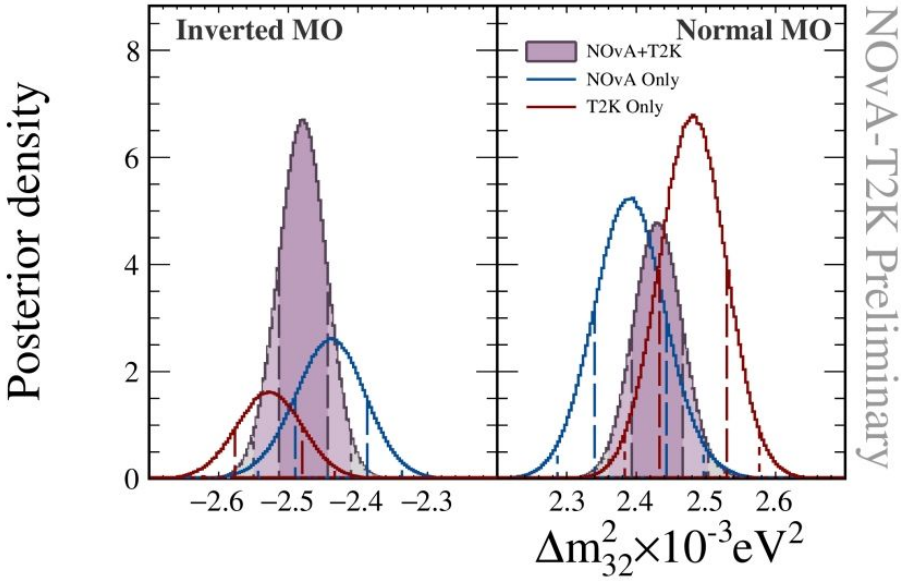
NMO:

- **Joint analysis flips the preference for the IO: T2K and NOvA individually prefer NO**
- Very weak preference for IO, Bayes factor 1.3



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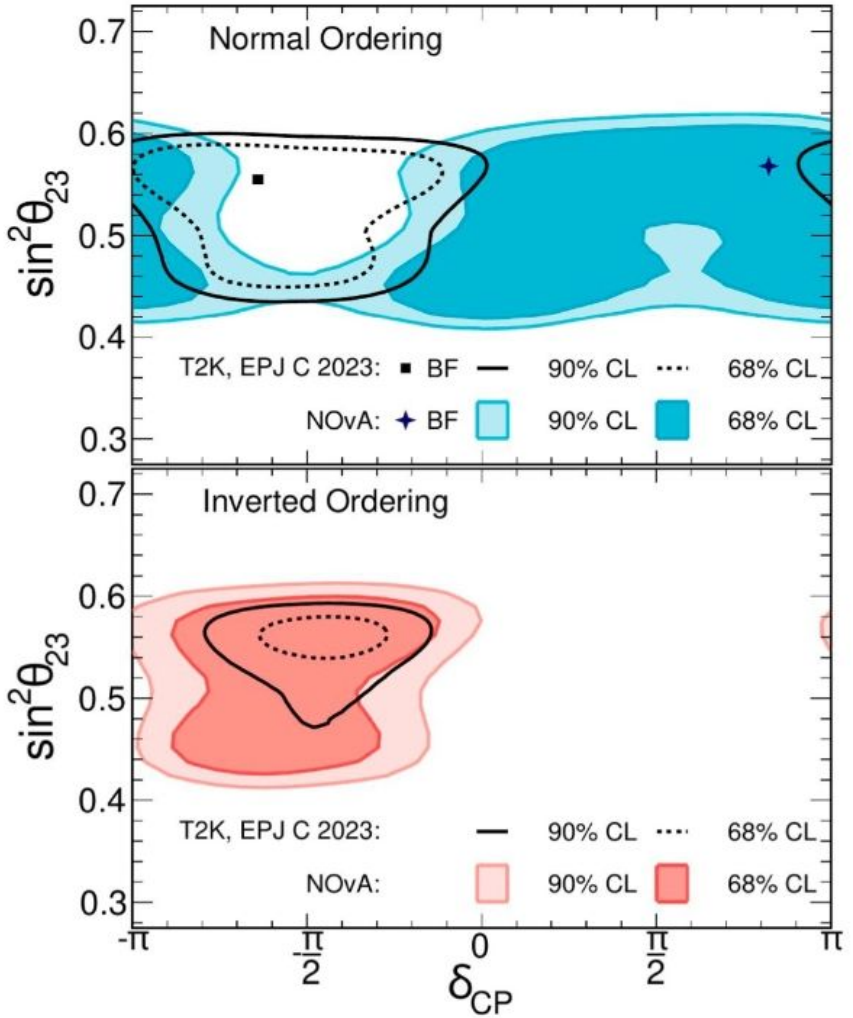

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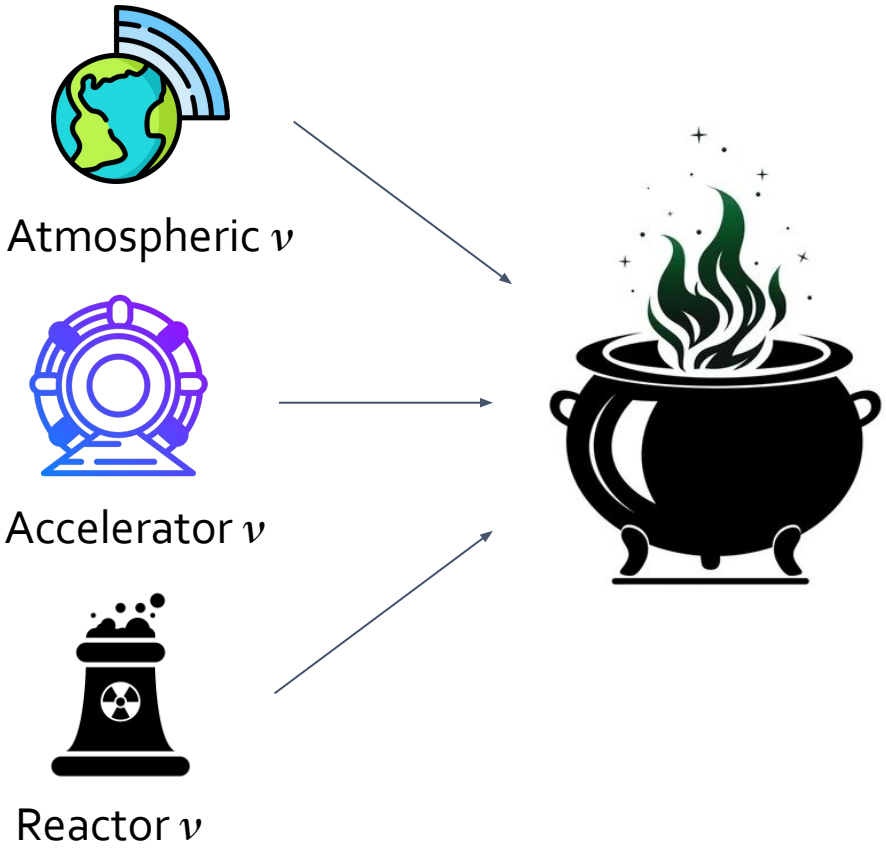
δCP:

- Degeneracy between δCP and MO
- NO: allows for a broad range of possible δCP
- IO: CP-conserving outside 3σ CIs
- Neither NMO points to δCP ~ +π/2 (outside 3σ CI)

An intense experimental effort



Global oscillations analysis of ν experiments

Recipes and Wizards:

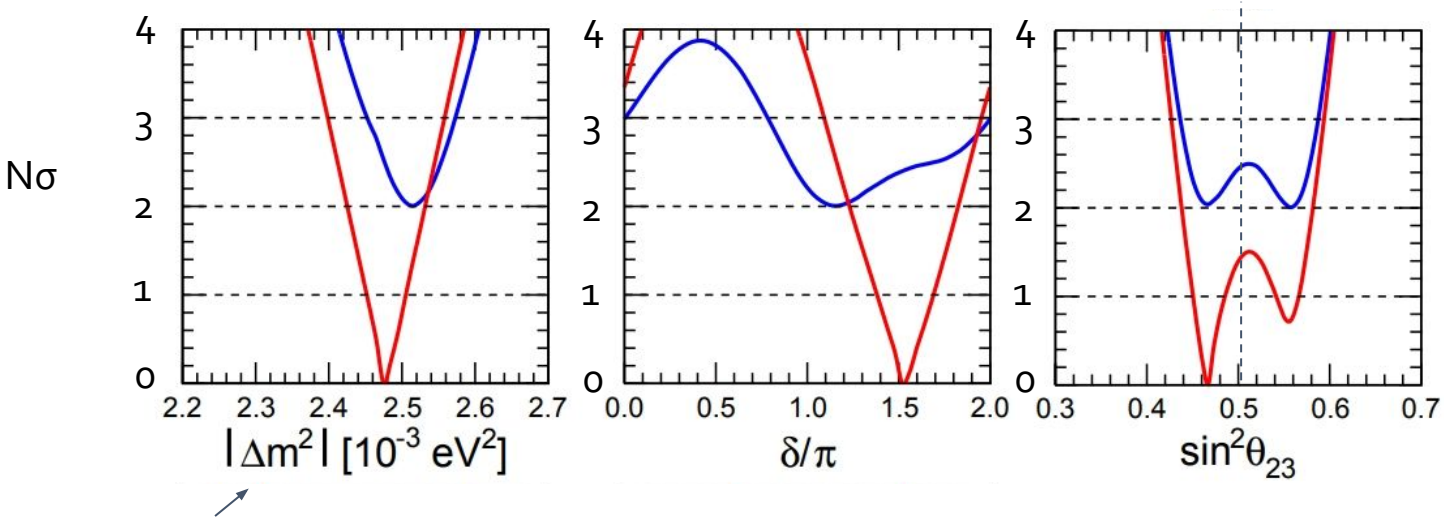
- **Bari)** Capozzi, Lisi et al, *Neutrino masses and mixing: Entering the era of subpercent precision,* https://arxiv.org/pdf/2503.07752
- **NuFit)** Esteban et al., NuFit-6.0: updated global analysis of three-flavor neutrino oscillations, JHEP 12 (2024) 216,
- **Valencia)** de Salas et al, JHEP 02 (2021) 071 https://globalfit.astroparticles.es/

Adding ingredients to the global analysis

LBL Acc + Solar + KamLAND

NO

IO



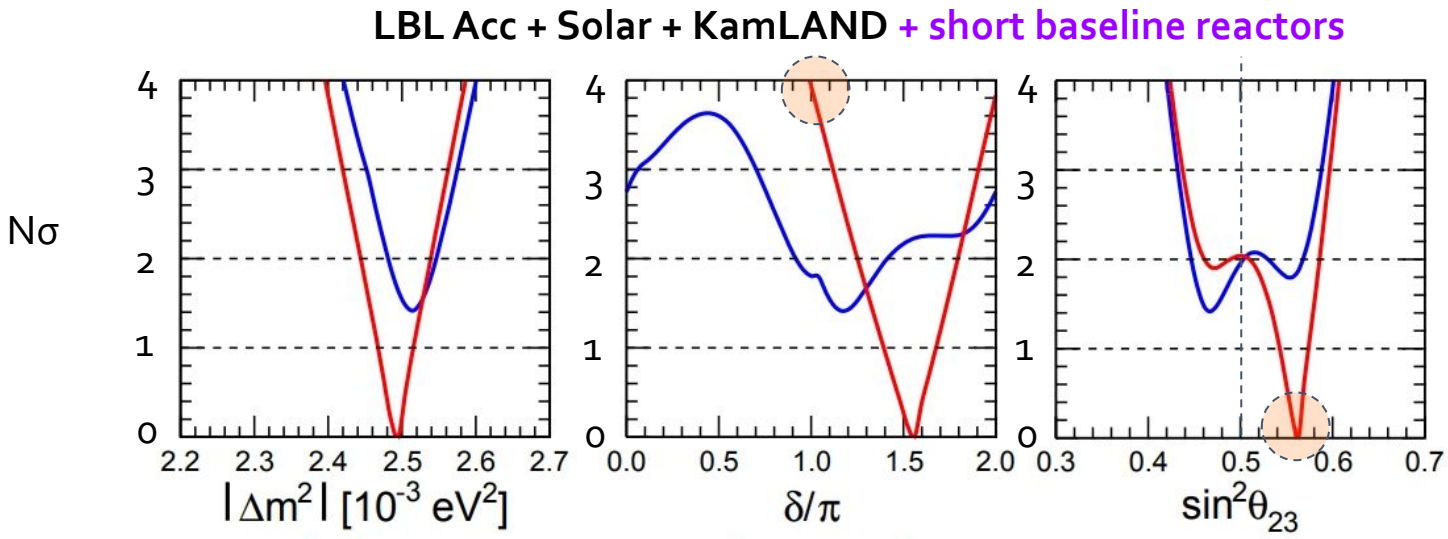
Large ("atmospheric") mass splitting

$$\Delta m^2 = \bar{m}_3^2 - \tfrac{1}{2}(m_1^2 + m_2^2)$$

- IO favored at 2σ level
- θ_{23} octant ambiguity
- CP conservation in NO (δ ≃ nπ), inconsistent with it at > 3σ in IO

Capozzi, Lisi et al, https://arxiv.org/pdf/2503.07752

Adding ingredients to the global analysis

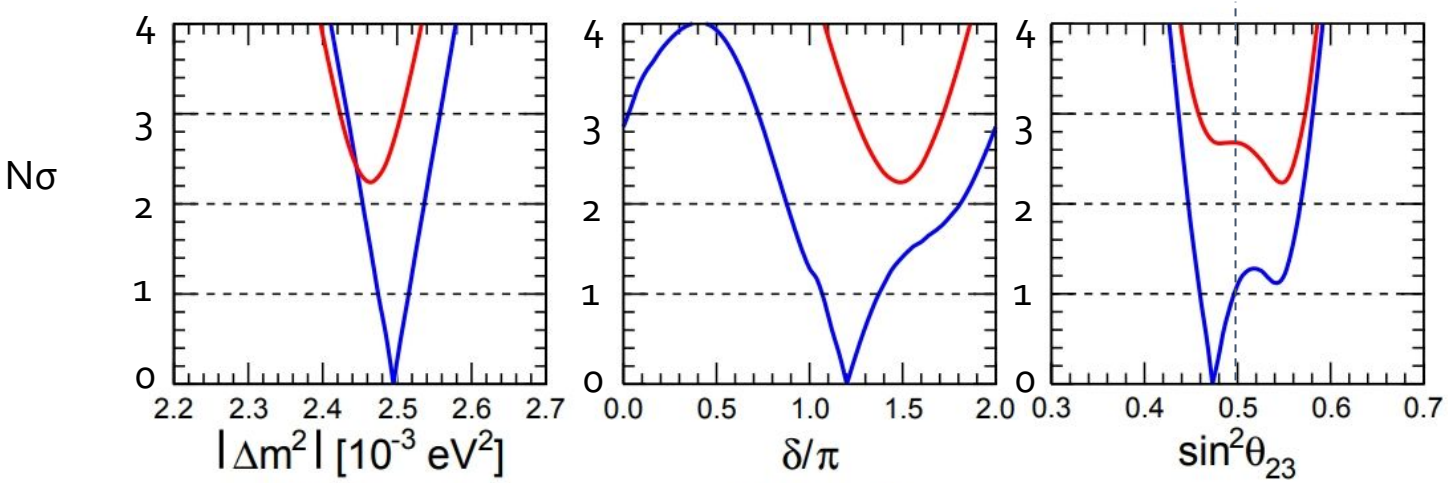


- IO favored at 1.4σ level
- second θ_{23} octant is favored
- a strong indication for CP violation (sin δ < 0 at almost 4σ).

Capozzi, Lisi et al, https://arxiv.org/pdf/2503.07752

Adding ingredients to the global analysis

LBL Acc + Solar + KamLAND + short baseline reactors + SK+IC



NO
IO

- **Different tendencies in global fit!**
- Δm^2 precision 0.8%, sub-percentual for the first time
- Flipped preference for MO: **NO favored at 2.2σ level** (2.5σ in previous analysis)
- Flipped θ_{23} octant: **first octant favored at 1.1σ level**
- **CP conservation disfavored at 1.2σ level** (1.6σ in previous analysis)

Capozzi, Lisi et al, https://arxiv.org/pdf/2503.07752

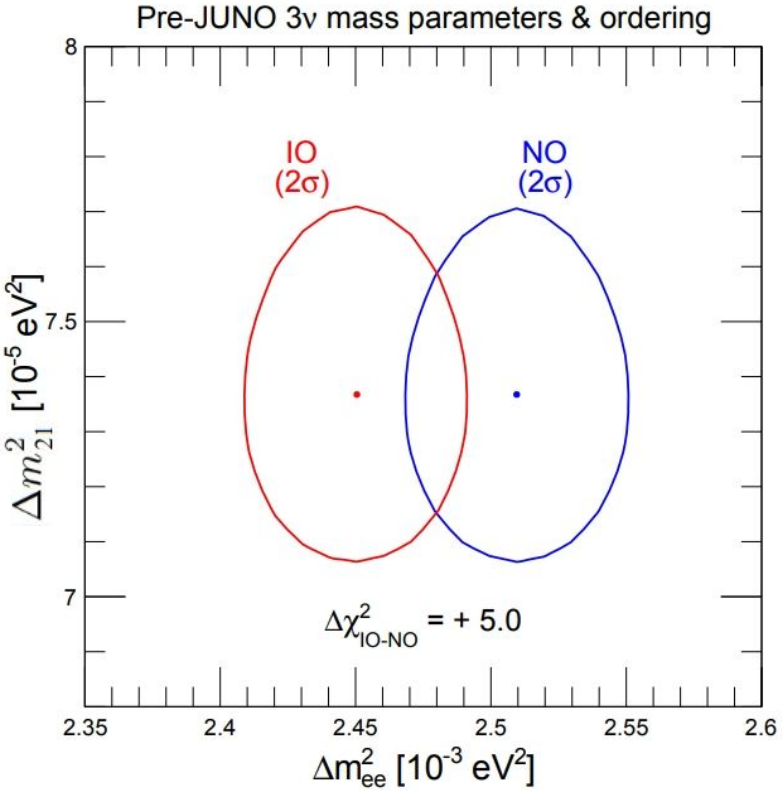
NMO in the next future: synergies with JUNO

+1 for NO, -1 for IO

$$\Delta m^2_{ee} = |\Delta m^2_{3\ell}| + \tfrac{1}{2}\alpha(\cos^2\theta_{12} - \sin^2\theta_{12})\Delta m^2_{21}$$

MBL effective mass splitting for ν_e disappearance, only linear combination of Δm^2_{31} and Δm^2_{32} determined by JUNO

JUNO is expected to measure Δm^2_{ee} and Δm^2_{21} with 2σ errors smaller than in Figure, in few months of operation



Capozzi, Lisi et al, https://arxiv.org/pdf/2503.07752

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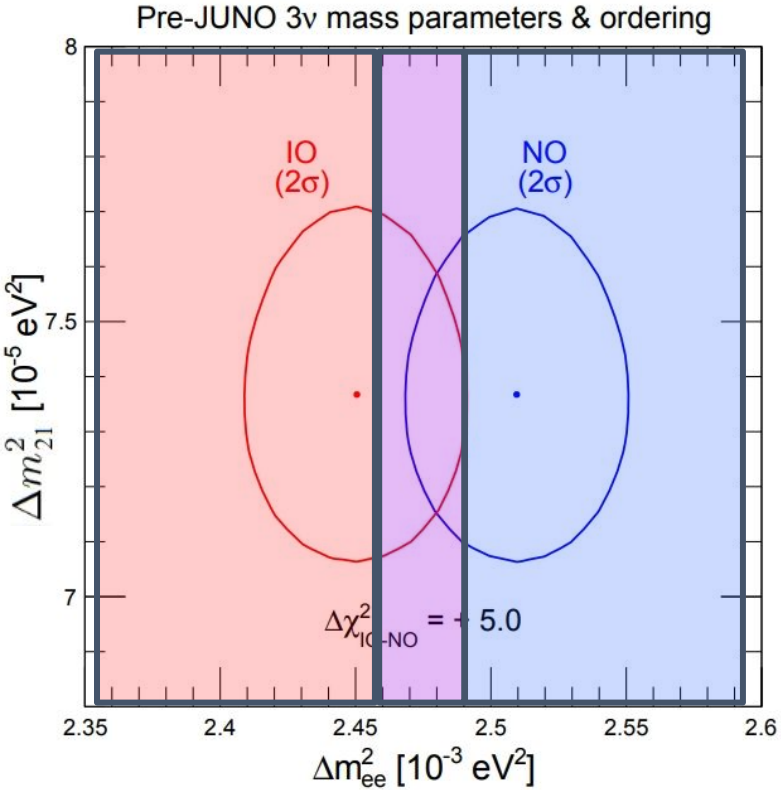
$$\Delta m^2_{ee} = |\Delta m^2_{3\ell}| + \tfrac{1}{2}\alpha(\cos^2\theta_{12} - \sin^2\theta_{12})\Delta m^2_{21}$$

$\Delta m^2_{ee} < 2.47\ 10^{-3}$ eV^2: strong preference for NO (agreement)
$2.47\ 10^{-3}$ eV$^2 < \Delta m^2_{ee} < 2.49\ 10^{-3}$ eV^2: ambiguity
$\Delta m^2_{ee} > 2.47\ 10^{-3}$ eV^2: strong preference for IO (tension)

Central values matters! Δm^2_{ee} central value by JUNO pointing to agreement/tension with pre-JUNO constraints



Capozzi, Lisi et al, https://arxiv.org/pdf/2503.07752

Any anomalies?

New physics from oscillations?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

→ eV-scale sterile ν?

Unitarity of mixing matrix

→ Neutrino masses: ΛCDM tension?

Interplay with cosmology

Sterile neutrinos

Global analyses disfavoured eV sterile neutrino oscillations already 20 years ago

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Nuclear Physics B 643 (2002) 321–338

NUCLEAR PHYSICS B

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Ruling out four-neutrino oscillation interpretations of the LSND anomaly?

M. Maltoni [a], T. Schwetz [b], M.A. Tórtola [a], J.W.F. Valle [a]

[a] *Instituto de Física Corpuscular – C.S.I.C./Universitat de València Edificio Institutos de Paterna, Apt 22085, E-46071 Valencia, Spain*

[b] *Institut für Theoretische Physik, Universität Wien Boltzmanngasse 5, A-1090 Wien, Austria*

Received 22 July 2002; accepted 14 August 2002

Abstract

Prompted by recent solar and atmospheric data, we re-analyze the four-neutrino oscillation description of current neutrino data, including the LSND evidence for oscillations. The higher degree of rejection for non-active solar and atmospheric oscillation solutions implied by the SNO neutral current result as well as by the latest 1489-day Super-K atmospheric neutrino data allows us to rule out $(2+2)$ oscillation schemes proposed to reconcile LSND with the rest of current neutrino oscillation data. Using an improved goodness of fit (g.o.f.) method especially sensitive to the combination of data sets we obtain a g.o.f. of only 1.6×10^{-6} for $(2+2)$ schemes. Further, we re-evaluate the status of $(3+1)$ oscillations using two different analyses of the LSND data sample. We find that also $(3+1)$ schemes are strongly disfavoured by the data. Depending on the LSND analysis we obtain a g.o.f. of 5.6×10^{-3} or 7.6×10^{-5}. This leads to the conclusion that all four-neutrino descriptions of the LSND anomaly, both in $(2+2)$ as well as $(3+1)$ realizations, are highly disfavoured. Our analysis brings the LSND hint to a more puzzling status.

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Sterile neutrinos: fading away?

Global analyses disfavoured eV sterile neutrino oscillations already 20 years ago

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Nuclear Physics B 643 (2002) 321–338

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Ruling out four-neutrino oscillation interpretations of the LSND anomaly?

Tórtola [a], J.W.F. Valle [a]

ncia Edificio Institutos de Paterna, Apt 22085, pain

ltzmanngasse 5, A-1090 Wien, Austria

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In 20 years…

- **reactor anomaly**: came and went away
- **LSND/MiniBoone**: (largely) unsolved
- **Gallium** anomaly: unsolved
- Strong tension with **cosmology**

Sterile neutrinos: fading away?

Unlike a few years ago, sterile ν no longer able to simultaneously explaining anomalies sharing the same channel.

New experimental data required, as upgraded VSBL reactor experiments (KATRIN, PROSPECT-II, JUNO-TAO, DANSS)

If $\nu e \rightarrow \nu e$ and $\nu\mu \rightarrow \nu e$ anomalies confirmed, new physics needed: extra sterile states + *something else* (intense theoretical effort)

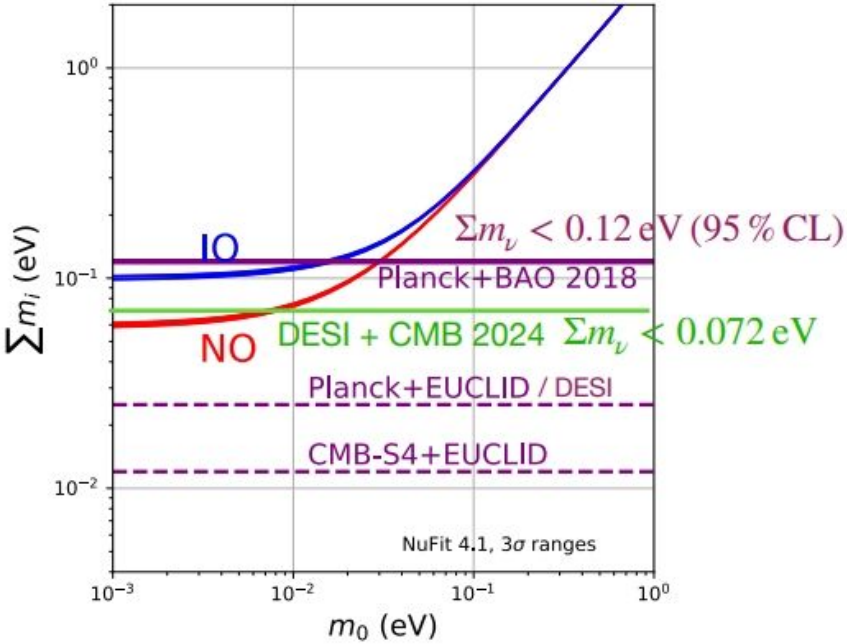
Explanations beyond the Standard Model		
ν_s coupled to ultralight DM (MSW resonance, Sec. 5.1.1)	several exotic ingredients; somewhat tuned MSW resonance; new ν_4 decay channel required for cosmology.	★★★★☆
ν_s coupled to dark energy (MSW resonance, Sec. 5.1.2)	several exotic ingredients; somewhat tuned MSW resonance; cosmology similar to the previous scenario.	★★★☆☆
ν_s coupled to ultralight DM (param. resonance, Sec. 5.1.3)	several exotic ingredients; somewhat tuned parametric resonance; cosmology requires post-BBN DM production via misalignment.	★★★★☆
decaying ν_s (Section 5.2)	difficult to reconcile with reactor and solar data; regeneration of active neutrinos in ν_s decays alleviates tension, but does not resolve it.	★★☆☆☆
vanilla eV-scale ν_s (Refs. [17, 18])	preferred parameter space is strongly disfavored by solar and reactor data.	★☆☆☆☆
ν_s with CPT violation (Refs. [130])	avoids constraints from reactor experiments, but those from solar neutrinos cannot be alleviated.	
extra dimensions (Refs. [131–133])	neutrinos oscillate into sterile Kaluza–Klein modes that propagate in extra dimensions; in tension with reactor data.	
stochastic neutrino mixing (Ref. [134])	based on a difference between sterile neutrino mixing angles at production and detection (see also [135, 136]); fit worse than for vanilla ν_s.	
decoherence (Refs. [137, 138])	non-standard source of decoherence needed; known experimental energy resolutions constrain wave packet length, making an explanation by wave packet separation alone challenging.	
ν_s coupled to ultralight scalar (Ref. [139])	ultralight scalar coupling to ν_s and to ordinary matter affects sterile neutrino parameters; can not avoid reactor constraints	

V. Brdar et al., JHEP 05 (2023) 143 [arXiv:2303.05528]

Neutrino masses: tension with cosmology?

Cosmology provides tight constraints on the sum of neutrino masses Σ in ΛCDM model. Too tight?

DESI (April 2024) + CMB Planck + CMB Atacama Telescope:
- **Best fit value: Σ = 0 , and Σ < 0.072 eV at 95% CL**
- Relaxing the Σ > 0 prior,negative neutrino masses are favored.



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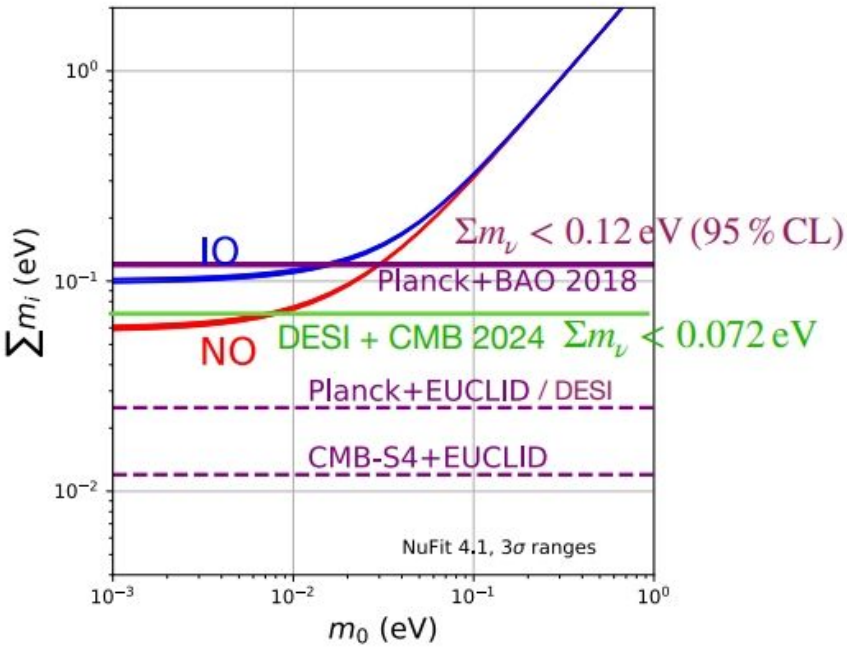
DESI (April 2024) + CMB Planck + CMB Atacama Telescope:
- Best fit value: Σ = 0 , and Σ < 0.072 eV at 95% CL
- Relaxing the Σ > 0 prior,negative neutrino masses are favored.

Long list of possible interpretations:

- Undetected systematics in DESI BAO data?
- Non-standard cosmology?
- New physics beyond the ΛCDM model?
- Exotic neutrino properties?

direct mass determinations crucial ⇒ KATRIN and beyond



Summary & hopes

Neutrino oscillation physics is entering an exciting era

A multi-faceted experimental panorama:
→ several experiments/upgrades starting, other ones reaching maturity levels
→ a variety of designs and expertises required

Near-term hopes (very few years):

- Synergies leading to NMO evidence (JUNO, NOvA+T2K, SK, IC…)
  - Also comparing indications by experiments in the same channel
- Upcoming oscillation parameters measurements to probe mixing unitarity at fine levels
- Interplay with cosmology (DESI, EUCLID?) to highlight possible tensions

Thanks

Backup

Global 3ν oscillation analysis: best-fit values and 1s ranges

Parameter	Ordering	Best fit	1σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.37	7.21 – 7.52	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.91 – 3.17	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.495	2.475 – 2.515	0.8
	IO	2.465	2.444 – 2.485	0.8
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.17 – 2.27	2.4
	IO	2.23	2.19 – 2.30	2.4
$\sin^2\theta_{23}/10^{-1}$	NO	4.73	4.60 – 4.96	5.1
	IO	5.45	5.28 – 5.60	4.3
δ/π	NO	1.20	1.07 – 1.37	18
	IO	1.48	1.36 – 1.61	8
$\Delta\chi^2_{\mathrm{IO-NO}}$	IO−NO	+5.0		

Small ("solar") mass splitting

$$\delta m^2 = m_2^2 - m_1^2 > 0$$

Large ("atmospheric") mass splitting

$$\Delta m^2 = m_3^2 - \tfrac{1}{2}(m_1^2 + m_2^2)$$

Capozzi, Lisi et al, https://arxiv.org/pdf/2503.07752

II. HOW CAN ν_e DISAPPEARANCE MEASUREMENT ALONE SIGNAL THE NEUTRINO MASS HIERARCHY?

The vacuum ν_e survival probability using $\Delta_{ij} \equiv \Delta m^2_{ij} L/4E$ ($\Delta m^2_{ij} \equiv m^2_i - m^2_j$) as shorthand for the kinematical phase, can be written without any approximation as

$$\begin{aligned} P(\nu_e \to \nu_e) &= 1 - 4|U_{e3}|^2|U_{e1}|^2 \sin^2\Delta_{31} - 4|U_{e3}|^2|U_{e2}|^2 \sin^2\Delta_{32} - P_\odot, \\ &= 1 - \frac{1}{2}\sin^2 2\theta_{13}\left[1 - \left(c^2_{12}\cos 2\Delta_{31} + s^2_{12}\cos 2\Delta_{32}\right)\right] - P_\odot, \end{aligned} \tag{1}$$

where the usual parameterization of the mixing matrix [19] is used with the abbreviations $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$. Here E is the neutrino energy and L is the baseline distance. $P_\odot$, as defined by,

$$P_\odot \equiv 4|U_{e2}|^2|U_{e1}|^2 \sin^2\Delta_{21} = \sin^2 2\theta_{12} c^4_{13} \sin^2\Delta_{21}, \tag{2}$$

is the oscillation probability associated with the solar Δm^2 scale. In this paper, we assume the standard three neutrino framework with CPT conservation (except for where we discuss possible CPT violation), which implies that Eq. (1) is also valid for $\bar{\nu}_e$.

The neutrino mass hierarchy can be determined if one knows which kinematical phase, $|\Delta_{31}|$ or $|\Delta_{32}|$, is larger. Namely, if $|\Delta_{31}| > |\Delta_{32}|$ the normal hierarchy is the case, and if $|\Delta_{31}| < |\Delta_{32}|$ the inverted one. How we can know which is larger? When two waves with slight different frequencies travel together there arises the phenomenon of beating. The

Minakata et al, Phys.Rev.D 76 (2007) 053004

Global 3ν oscillation analysis: best-fit values and 1s ranges

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	IO	1.48	1.36 – 1.61	8
$\Delta\chi^2_{\mathrm{IO-NO}}$	IO−NO	+5.0		

sub-percent era

CP violation preference

NO preference

Capozzi, Lisi et al, https://arxiv.org/pdf/2503.07752

NMO hints in JUNO perspective

JUNO will contribute to the NO and IO discrimination in two ways:
1) L/E oscillometry
2) relative difference between Δm^2_{ee} from JUNO and $|\Delta m^2|$ from other non-reactor data

Δm^2_{ee} : short distance effective mass splitting in the ve disappearance channel: only linear combination of Δm^2_{31} and Δm^2_{32} to be determined by JUNO

+1 for NO, -1 for IO

$$\Delta m^2_{ee} = |\Delta m^2| + \tfrac{1}{2}\alpha(\cos^2\theta_{12} - \sin^2\theta_{12})\delta m^2$$

Capozzi, Lisi et al, https://arxiv.org/pdf/2503.07752

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2) relative difference between Δm^2_{ee} from JUNO and $|\Delta m^2|$ from other non-reactor data

Δm^2_{ee} : only linear combination of Δm^2_{31} and Δm^2_{32} that can be determined by a MBL ve disappearance experiment as JUNO

to be measured in JUNO at < % level

+1 for NO, -1 for IO

can be measured in JUNO at < % level

$$\Delta m^2_{ee} = |\Delta m^2| + \underbrace{\frac{1}{2}\alpha(\cos^2\theta_{12} - \sin^2\theta_{12})\delta m^2}_{\pm 0.015\ \text{eV}^2}$$

(0.6% diff. between Δm^2_{ee} and $|\Delta m^2|$)

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to be measured in JUNO at < % level

+1 for NO, -1 for IO

can be measured in JUNO at < % level

$$\Delta m^2_{ee} = |\Delta m^2| + \frac{1}{2}\alpha(\cos^2\theta_{12} - \sin^2\theta_{12})\delta m^2$$

±0.015 eV²
(0.6% diff. between Δm^2_{ee} and $|\Delta m^2|$)

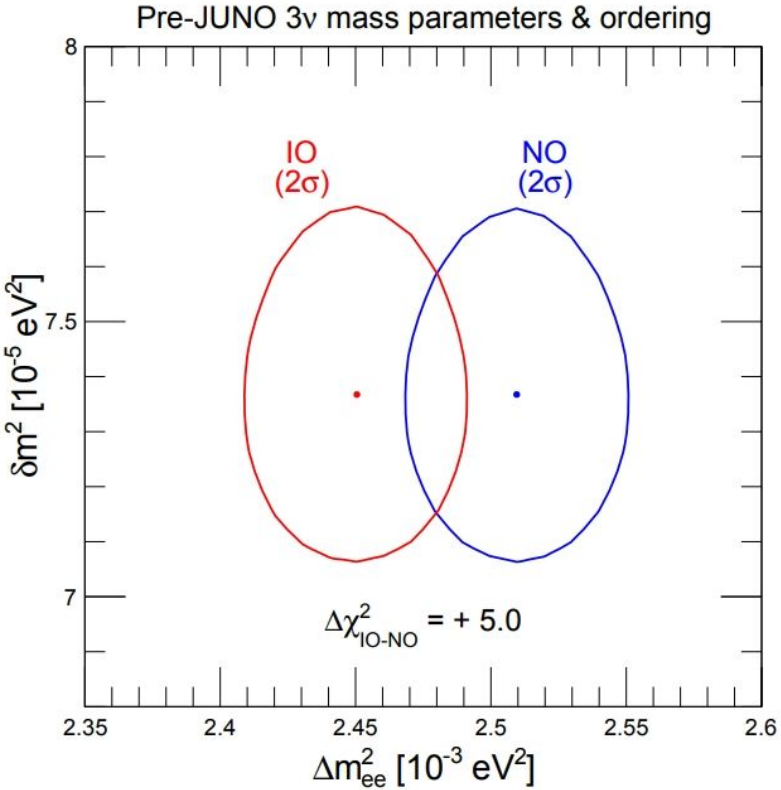
comparable to
- current 1σ of $|\Delta m^2|$ (±0.8%)
- expected 1σ of Δm^2_{ee} in JUNO
(±0.8% after just 100 days of operation)

NMO hints in JUNO perspective

$$\Delta m^2_{ee} = |\Delta m^2| + \tfrac{1}{2}\alpha(\cos^2\theta_{12} - \sin^2\theta_{12})\delta m^2$$

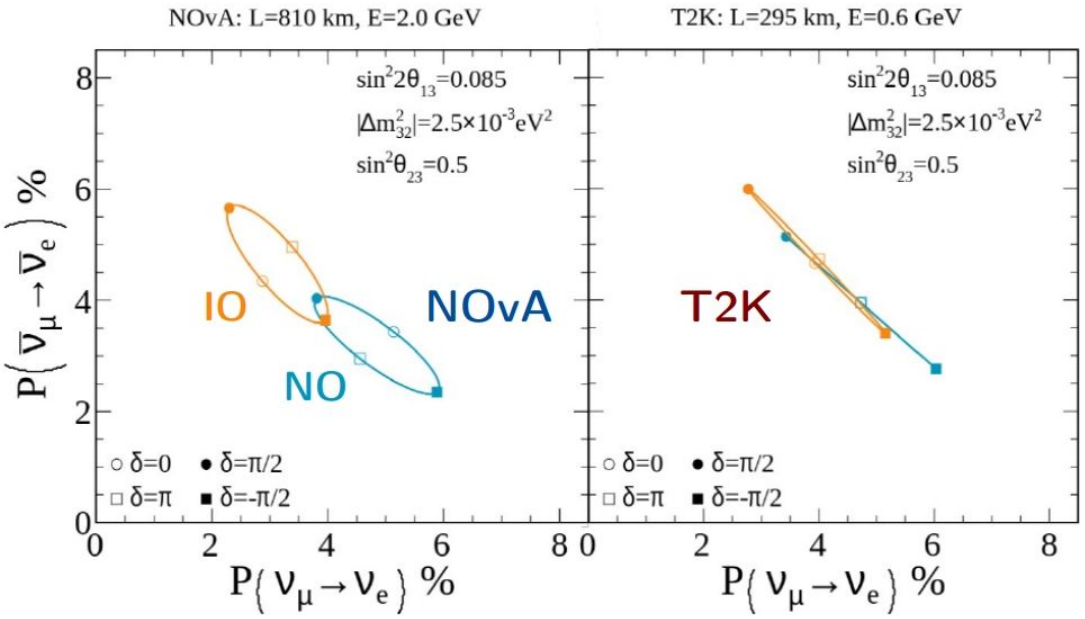
JUNO is expected to measure Δm^2_{ee} and δm^2 with 2σ errors smaller than in Figure, in few months of operation

Central values matters! Δm^2_{ee} central value by JUNO could tell at a glance agreement/tension with rest-of-the-world constraints



Capozzi, Lisi et al, https://arxiv.org/pdf/2503.07752

Accelerator ν: NOvA and T2K



Different E and L give different oscillation probabilities and parameter sensitivity

NOvA:

- Better NMO sensitivity
- Degenerate for δCP ~ π/2 and ~ −π/2 (CPV)

T2K:

- Better δCP sensitivity
- Degenerate for around δCP = 0 and π (no-CPV)

Joint analysis probes both spaces, lifting degeneracies of individual experiments

Based on Eur. Phys. J. C (2023) 83: 782 and Phys. Rev. D 110, 012005

NOvA and T2K joint analysis

Results in a nutshell:

- No strong preference for mass ordering
- New Δm^2_{32} precision < 2 %
- About 1σ (Bayes factor 3.6) preference for $\theta_{23} > 45°$
- CP conserving values of $\delta_{CP} = 0, \pi$ lies outside the 3σ CI in the case of IO

Next steps:

- Expected to double the statistics from both experiments in coming years
- Knowledge sharing and exchange of information resulted in a deeper understanding of each experiment

KATRIN most recent results

A. Tritium β decay and m_β bounds

The KATRIN experiment has recently released the combined results of the first five campaigns of β-decay spectral measurements with tritium [85]. No neutrino mass signal has been found within the uncertainties, and an upper limit on the effective mass parameter $m_\beta < 0.45$ eV has been placed at 90% C.L. (namely, 1.645σ). Upper bounds at different confidence levels, not reported in [85], will appear in supplementary material; relevant ones include $m_\beta < 0.35$, 0.50 and 0.61 eV at 1, 2 and 3σ level, respectively, according to preliminary estimates [86].

To a good approximation, the above $n\sigma$ bounds can be reproduced in terms of a simple empirical function $\Delta\chi^2 = 66.1(m_\beta/\text{eV})^4$ or, equivalently, in terms of an effective 1σ measurement such as $m_\beta^2 = 0 \pm 0.123$ eV^2. With respect to [14] (where KATRIN results were summarized as $m_\beta^2 = 0.1 \pm 0.3$ eV^2), the error is appreciably reduced by a factor > 2, and the m_β^2 best-fit value is pushed at the border of the physical region. [An allowance for $m_\beta^2 < 0$ would provide a slightly negative best fit [85].] For graphical purposes, we shall focus on the corresponding 2σ upper bound, namely,

$$m_\beta < 0.5 \text{ eV } (2\sigma) \, . \tag{2}$$

Cosmology result on sum of masses

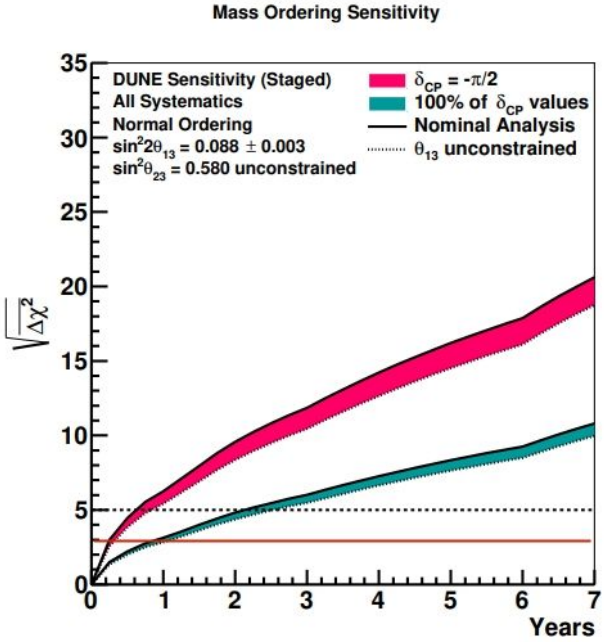
TABLE IV: Results of the cosmological data analysis under three model assumptions: standard cosmology with neutrino masses (ΛCDM+Σ), an extended model accounting for lensing systematics (ΛCDM+Σ+$A_{\rm lens}$), and a nonstandard cosmology with dynamical dark energy and neutrino masses (w_0w_aCDM+Σ). The datasets used are listed in Section III C. For Planck, we consider both Plik and CamSpec likelihoods, which yield very similar results in all cases (shown explicitly only for ΛCDM+Σ). Upper bounds on Σ are reported at the 2σ level.

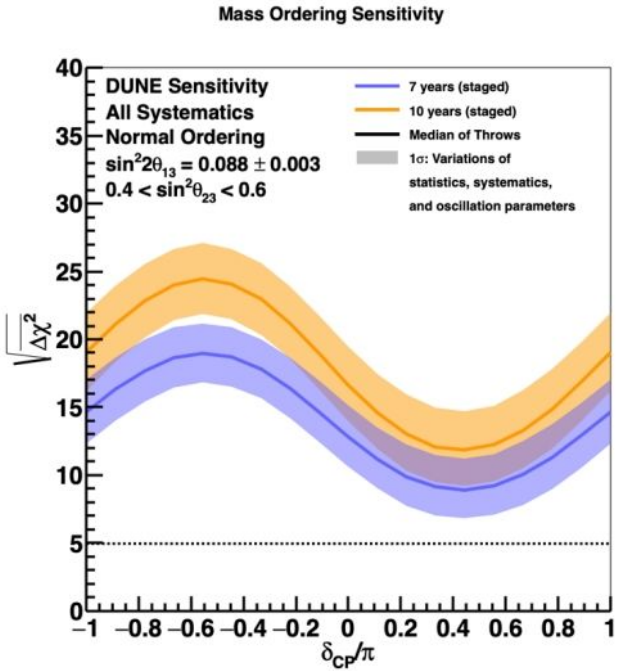
#	Model	Data set	Σ (2σ)
1	ΛCDM + Σ	Plik	< 0.175 eV
2		Plik+DESI	< 0.065 eV
3		Plik+DESI+PP	< 0.073 eV
4		Plik+DESI+DESy5	< 0.091 eV
5		camspec	< 0.193 eV
6		camspec+DESI	< 0.064 eV
7		camspec+DESI+PP	< 0.074 eV
8		camspec+DESI+DESy5	< 0.088 eV
9	ΛCDM+Σ+$A_{\rm lens}$	Plik	< 0.616 eV
10		Plik+DESI	< 0.204 eV
11		Plik+DESI+PP	< 0.255 eV
12		Plik+DESI+DESy5	< 0.287 eV
13	w_0w_aCDM+Σ	Plik	< 0.279 eV
14		Plik+DESI	< 0.211 eV
15		Plik+DESI+PP	< 0.155 eV
16		Plik+DESI+DESy5	< 0.183 eV

Cosmology result on sum of masses

- It appears rather premature to quote a "consensus" upper bound on Σ from cosmological data at present.
- It could be better to quote a "range" of upper bounds, noticing that the 2σ cosmological limits on Σ cluster around a reasonable "geometric average" value of $\Sigma < 0.2$ eV, with variations up to a factor of 3 (upwards or downwards), depending on the specific model and dataset employed.
- It's more conservative stating that $\Sigma < 0.2$ eV at 2σ (within a factor of 3) may be considered as a reasonable summary of acceptable and physically motivated current bounds, ranging from very conservative ($\Sigma < 0.60$ eV) to very aggressive ($\Sigma < 0.07$ eV).
- This interval of limits is essentially supported by Planck data alone within standard cosmology, as well as by both Planck and DESI in nonstandard cases.

DUNE sensitivity to NMO





one (two) year > 3 σ (> 5 σ) for all values of δ_{CP}

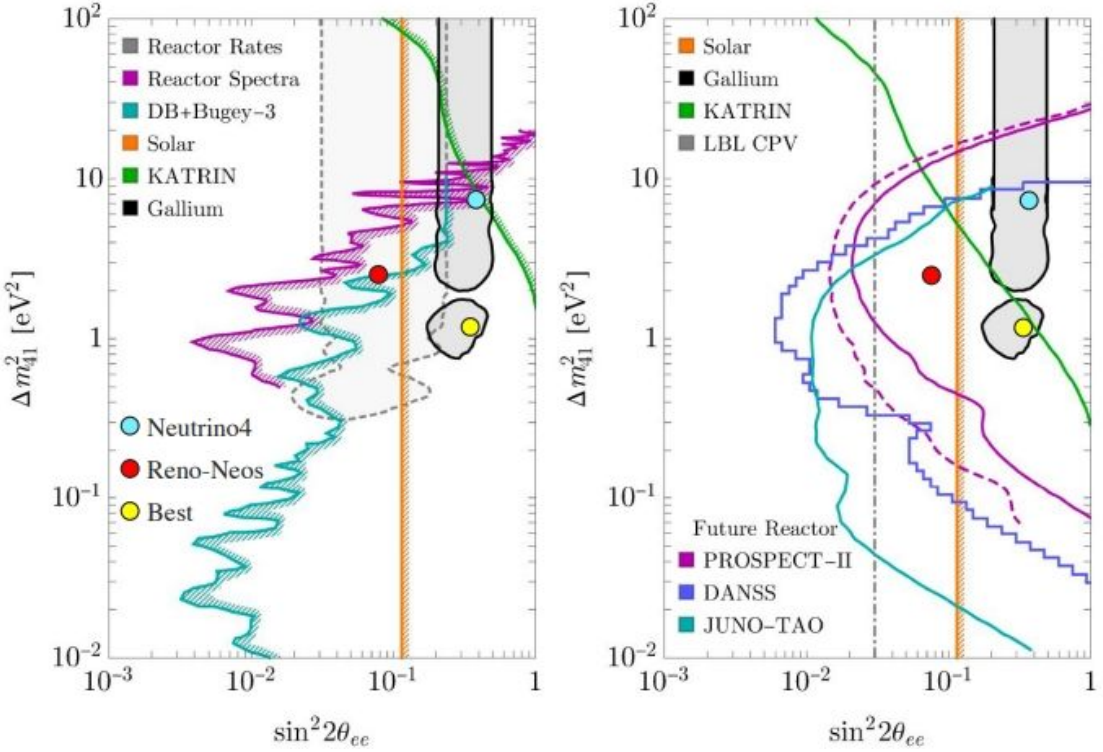
Sterile neutrinos at reactor, worldwide

Research reactors
- Low stat
- Compact core
- Pure ^{235}U

Commercial reactors
- High stat
- Extended core
- Mixed ^{235}U - ^{239}Pu

Θ_{13} measurements at commercial reactors

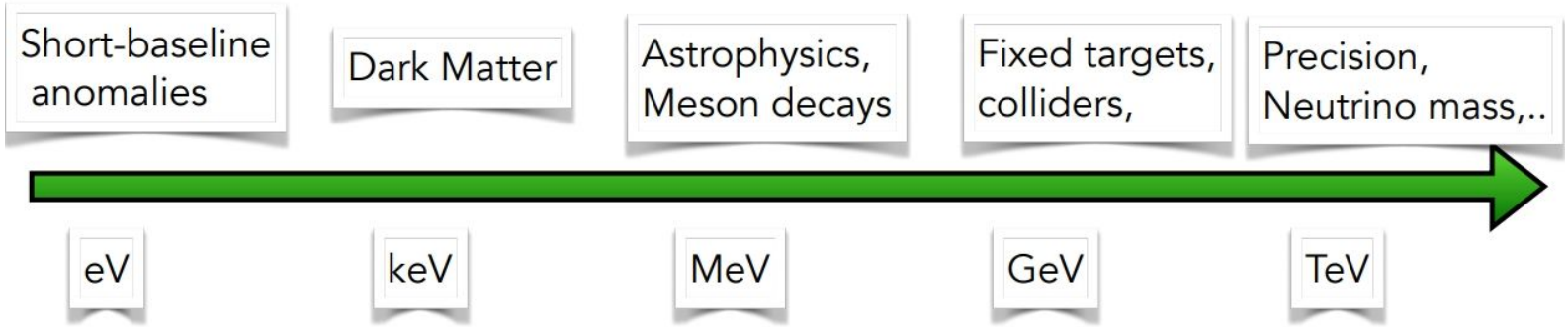
Sterile neutrinos



- Global picture of reactor experiments: rejects the sterile neutrino hypothesis as explanation of the RAA.
- Complementary constraints from Katrin in the high mass range.
- 3σ tension with the Gallium result.
- Full coverage of the BEST and RAA contours by upcoming data from Katrin, Prospect-II, DANSS, JUNO-TAO, …

Sterile neutrinos

1. Neutrino masses (E > TeV)
2. Cosmology. (E > keV)
3. Short baseline anomalies. (m ~ eV)

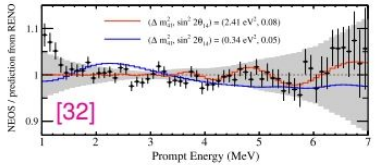


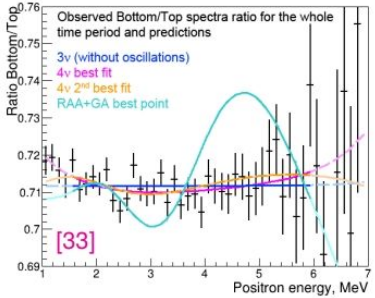
Sterile neutrinos

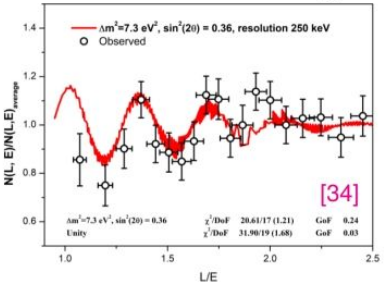
II. Oscillation anomalies: ν_e disappearance

Sterile ν: spectra and baselines

- New detectors with spectral capability and baseline range:
  - NEOS (Korea), commercial, $L = 23.7$ m;
  - STEREO (France), enriched, $L = 9 \to 11$ m;
  - PROSPECT (USA), enriched, $L = 7 \to 12$ m;
  - DANSS (Russia) commercial, $L = 10.9 \to 12.9$ m;
  - SOLID (Belgium), enriched, $L = 5.5 \to 12$ m;
  - Neutrino4 (Russia), enriched, $L = 6 \to 12$ m;
- goals: { – accurate study of reactor ν spectrum; – flux-independent osc. by near/far ratio;
- results: most experiments report no evidence, a few observe wiggles at low significance (DANSS, NEOS); ⇝ [Danilov]
- exception: Neutrino4 reports 3σ signal with $\Delta m^2 \sim 7$ eV^2.





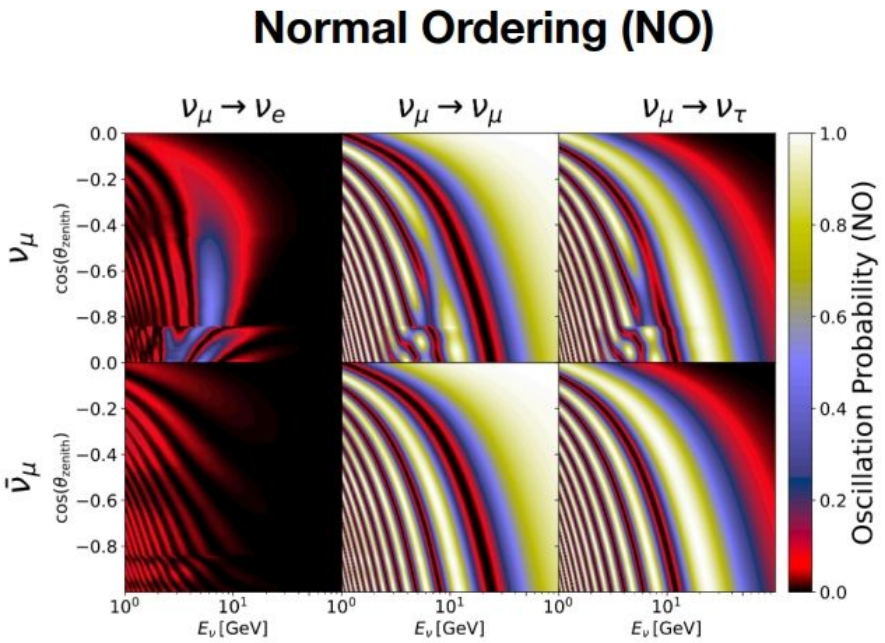


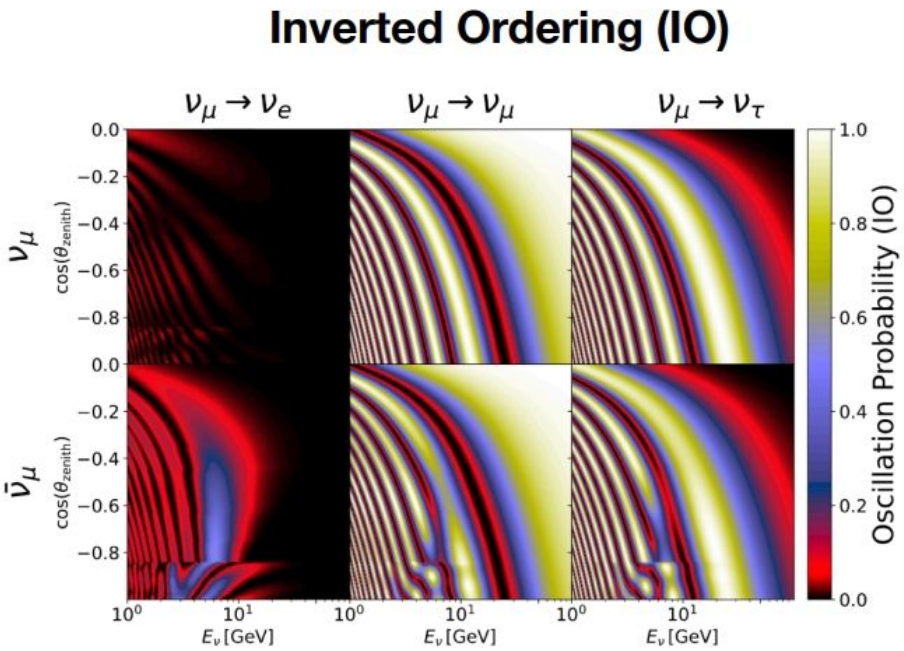
[32] Z. Atif *et al.* [NEOS & RENO], Phys. Rev. D **105** (2022) L111101 [arXiv:2011.00896]

[33] E. Samigullin [DANSS], talk at NuFact 23, Seoul, Korea, 25/08/2023

[34] A.P. Serebrov *et al.* [NEUTRINO4], arXiv:2302.09958

Oscillation patterns for atmospheric exp.

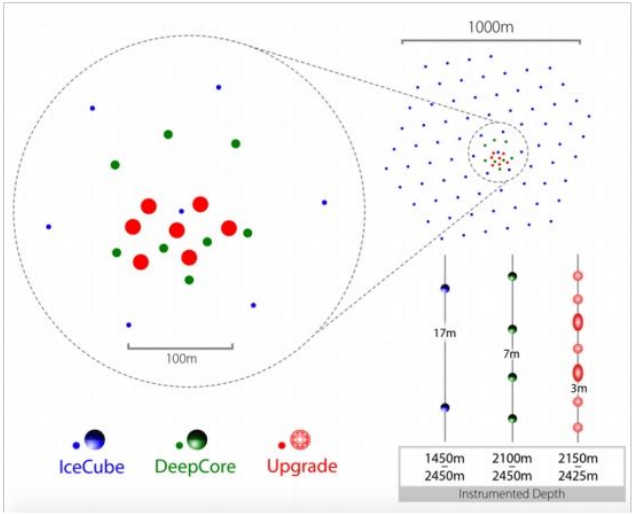


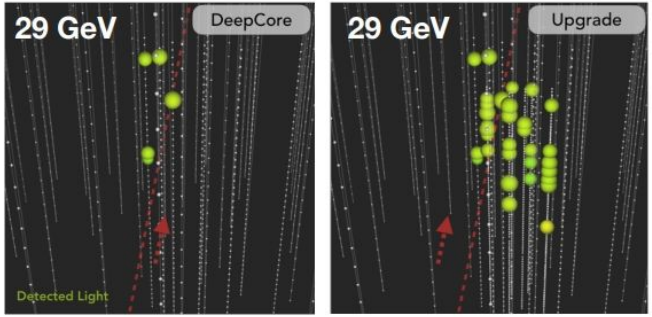


Oscillation patterns for atmospheric exp.

- DeepCore cannot distinguish between neutrinos and antineutrinos
- Flux and cross-section are higher for neutrinos than for antineutrinos at DeepCore energies (3 GeV-100 GeV)
- For a combined neutrino/anti-neutrino sample, matter effects are more pronounced for true NO as compared to true IO

IceCube Upgrade





Seven more strings will be added with smaller optical sensor spacing:
Extend energy range down to 1 GeV

Fully funded — to be deployed in 2025/2026

IceCube Upgrade

- DeepCore: Almost 200k atmospheric neutrino events in 9.28 years
- DeepCore faces limitations due to event quality but the IceCube Upgrade will improve this. Reconstruction capability and PID are still main limiting factors despite the increase in detector livetime
- DeepCore + Upgrade combined sample will have the luxury of high statistics AND improved event quality
- With 5 years of both Upgrade + JUNO data, synergistic effects could enhance NMO signal up to 5σ for both true NO and true IO

NOvA and T2K: design comparison

Experiment	**NOvA**	**T2K**
Country Laboratory Started	USA Fermilab 2014	Japan KEK, J-PARC 2010
Baseline ν energy peak Off angle	810 km 2 GeV 0.84° / 14.6 mrad	295 km 0.6 GeV 2.5° / 43.6 mrad
ν Source $\nu + \bar{\nu}$ POT 2020	120 GeV protons, max 760 kW $(1.36 + 1.25) \times 10^{21}$	30 GeV protons, max 515 kW $(1.97 + 1.63) \times 10^{21}$
Near Detector	**NOvA ND** liquid scintillator tracking calorimeter NO MAGNET	**ND280** TPC trackers targets of pl. scintillator or water magnetized to distinguish $\nu_\mu/\bar{\nu}_\mu$
Far Detector	**NOvA FD** 14 kt liquid scintillator tracking calorimeter	**SuperK** 50 (22.5) kt water Cherenkov 13k (11k) PMTs
ν interactions	QE, 2p2h, RES, DIS mix	Mostly QE, 2p2h and RES bkg
Near-to-far	Direct correction of FD MC based on the ND data (F/N trans.)	Fit to ND data which constrains the interaction and flux parameters
Energy estimator	Lepton and hadronic calorimetry	Lepton kinematics (elastic)