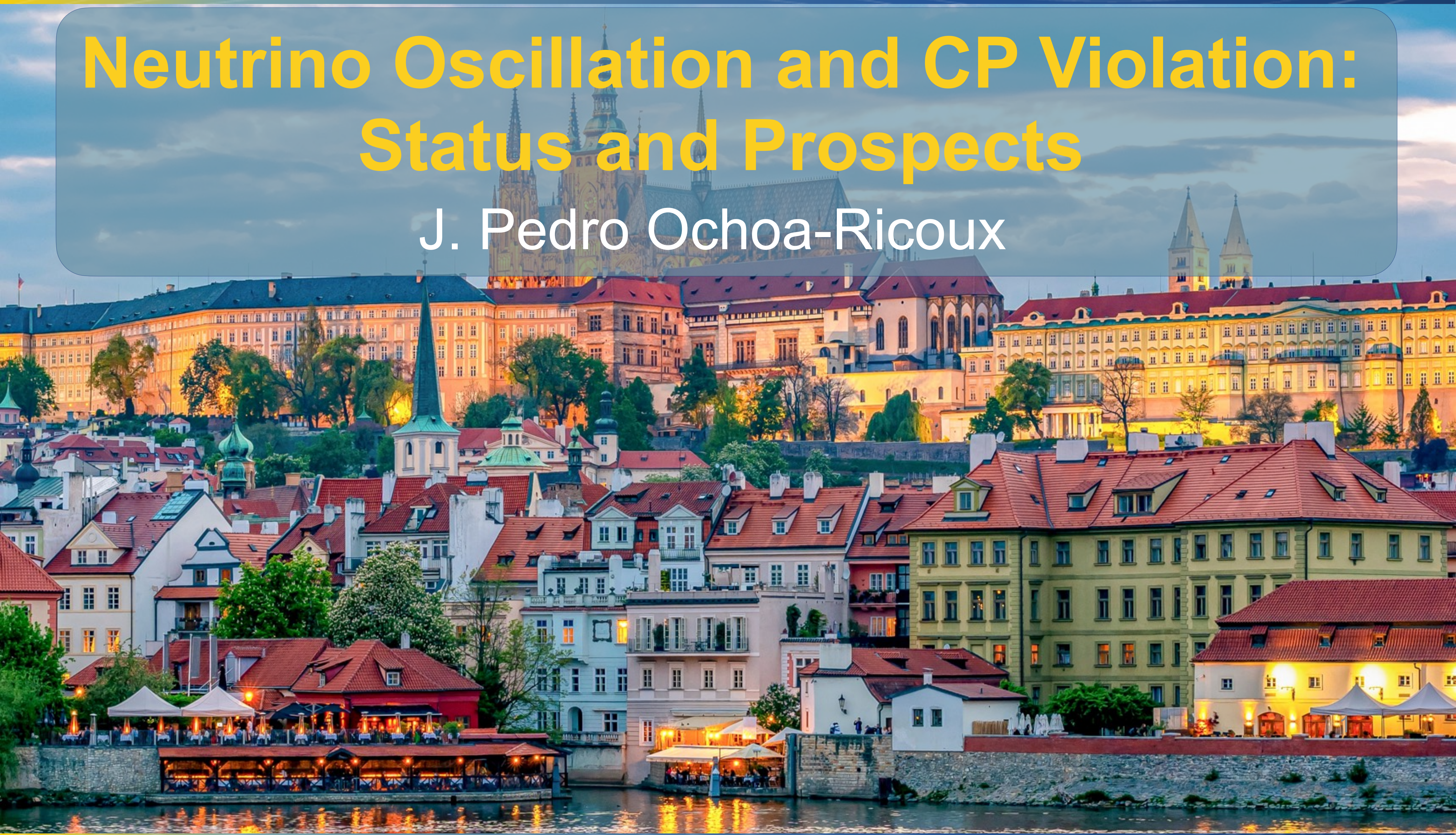
UCI University of California, Irvine

Neutrino Oscillation and CP Violation: Status and Prospects

J. Pedro Ochoa-Ricoux



ICHEP 2024, July 23rd 2024

Disclaimer

The field of neutrino oscillations is broad and extremely active. Apologies that some difficult choices had to be made for this talk to fit within the allotted time

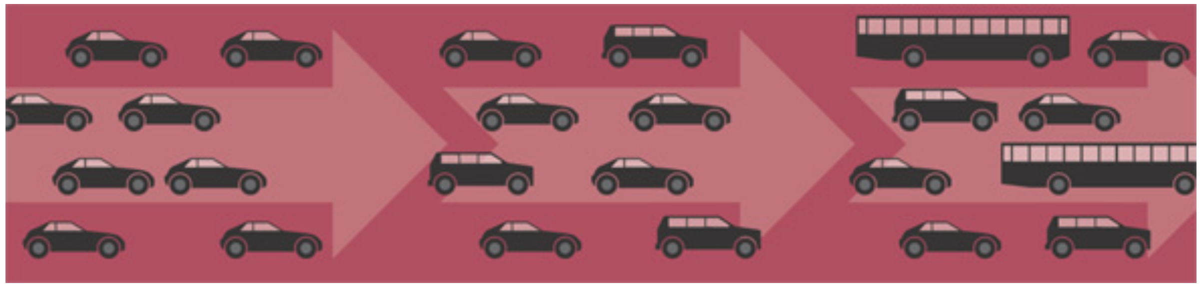
Introduction

to Neutrino Oscillations

Neutrino Oscillation Basics

- The basic principle behind neutrino oscillations: neutrino mixing

Illustration of neutrino oscillation:



$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

How they interact (ν_e, ν_μ, ν_τ)

How they propagate (ν_1, ν_2, ν_3)

where the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix U is parameterized in terms of three mixing angles (θ_{12}, θ_{23}, θ_{13}) and one CP-violating phase δ_{CP}

For example, as a rough approximation at short baselines, the $\bar{\nu}_e$ "survival" probability is:

amplitude

frequency

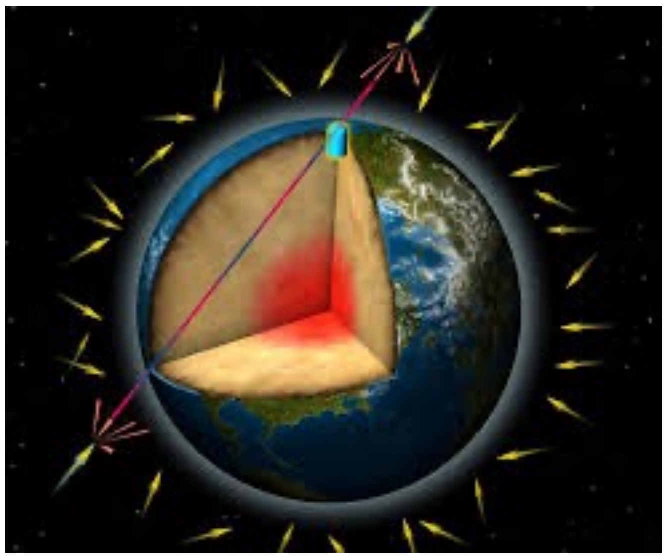
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$

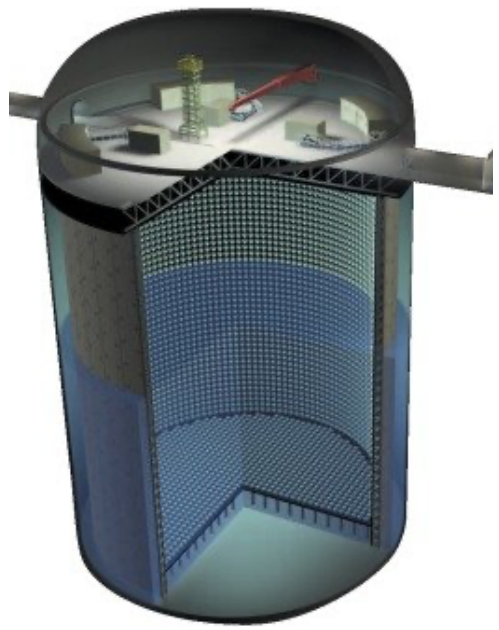
(where $\Delta m^2_{ij} = m^2_i - m^2_j$ are the so-called "mass splittings")

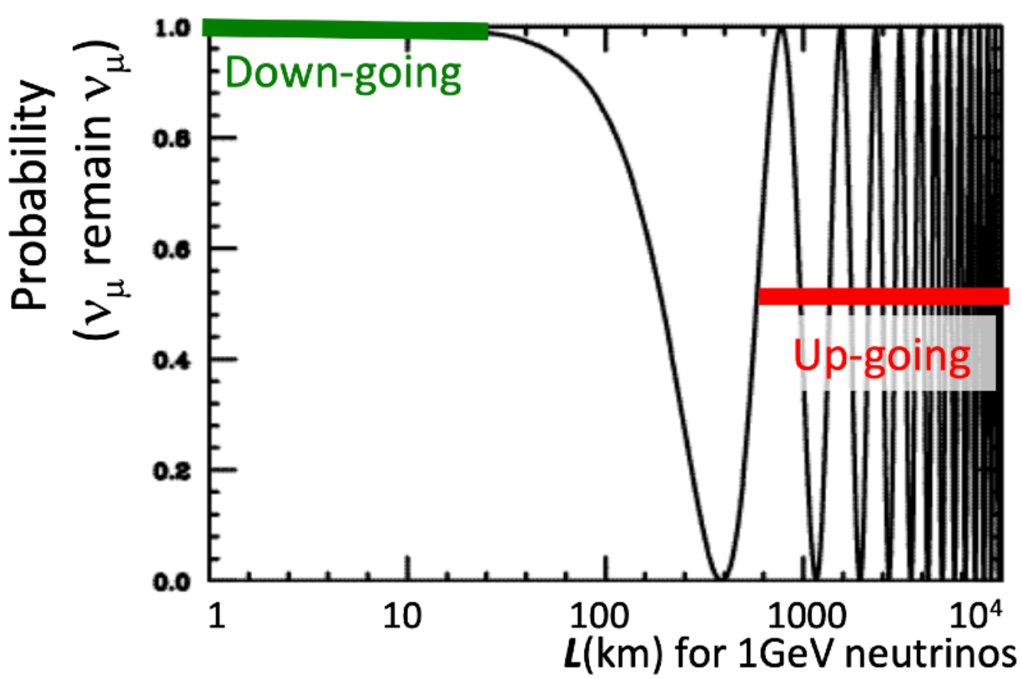
First Unambiguous Evidence

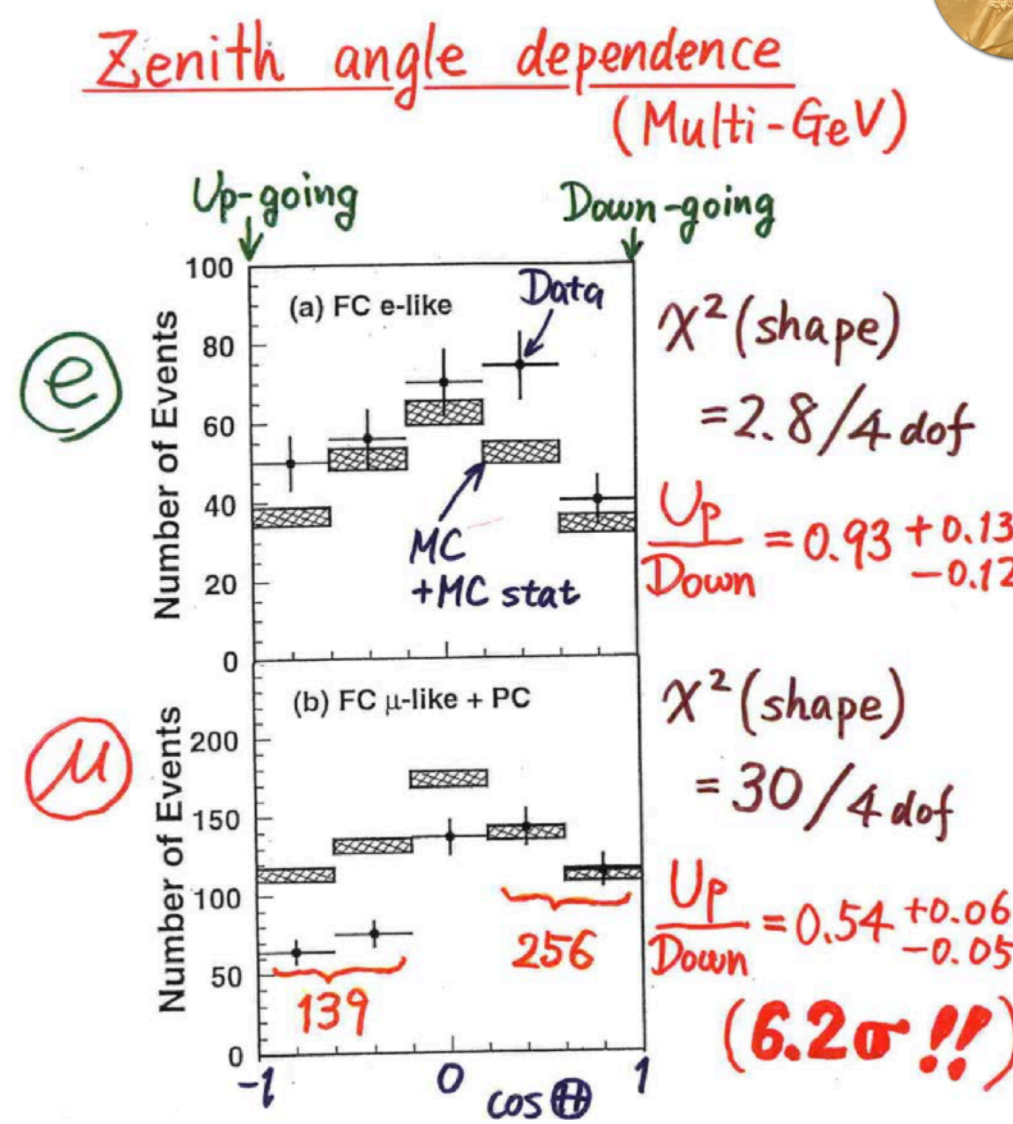
Super-Kamiokande (SK):

- 50 kton water Cherenkov detector
- 1,000 m underground
- Around 11k 20-inch photomultiplier tubes (PMTs)









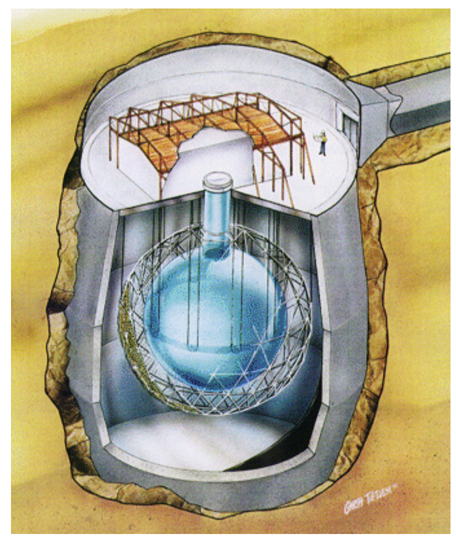
PRL 81, 1562 (1998)

From T. Kajita's Nobel Lecture

First Unambiguous Evidence

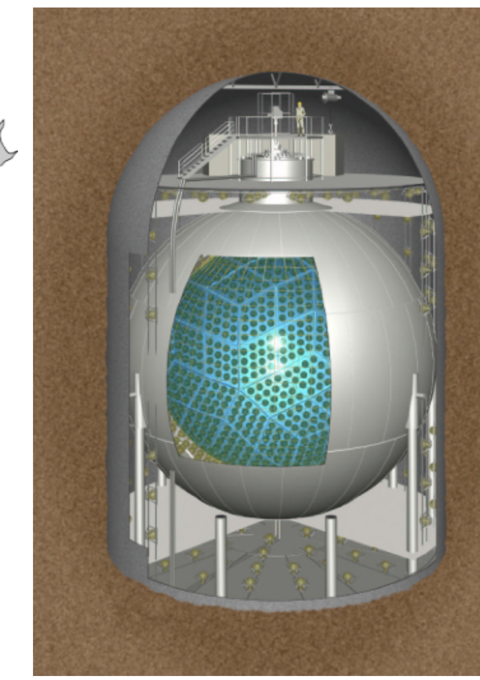
Sudbury Neutrino Observatory (SNO):

- 1 kton of heavy water
- Three complementary interactions (CC, NC and ES) sensitive to different neutrino flavors

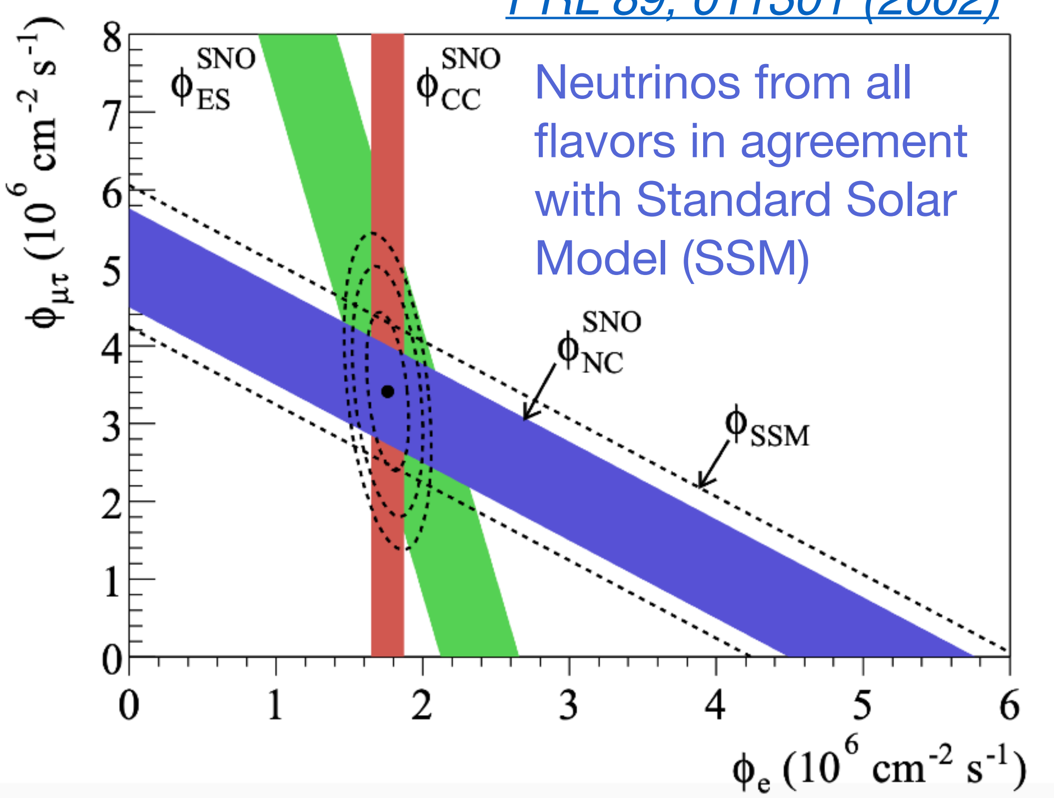


KamLAND:

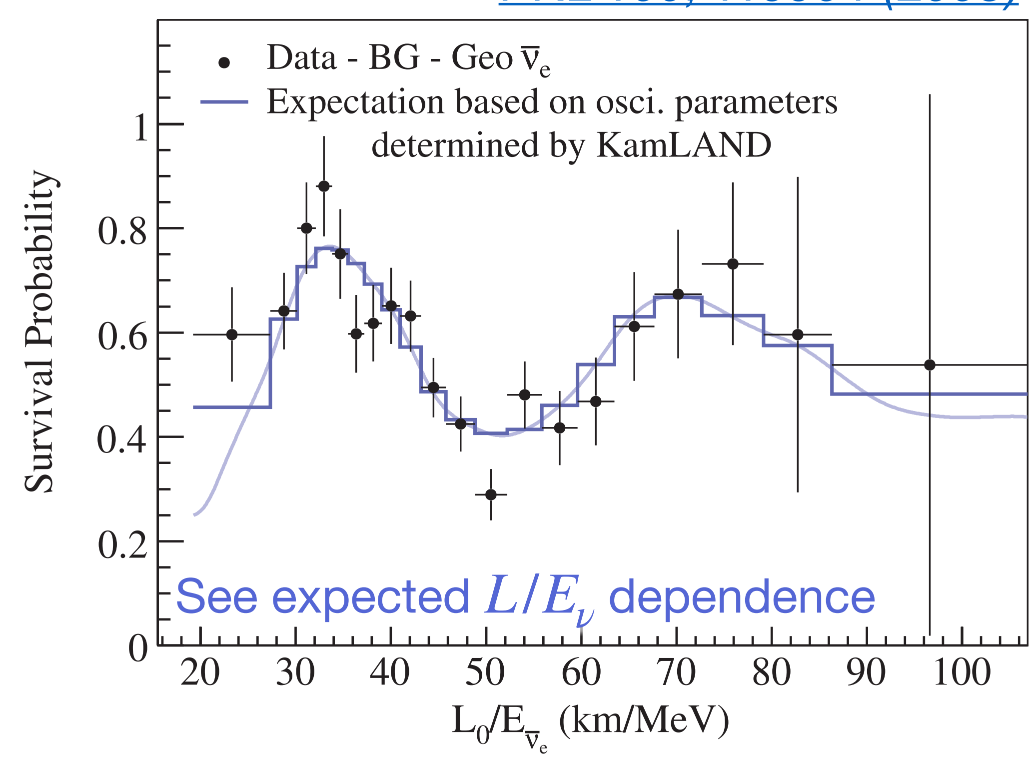
- 1 kton liquid scintillator (LS) detector
- Surrounded by ~50 nuclear reactors at an average baseline of ~180 km



PRL 89, 011301 (2002)



PRL 100, 119904 (2008)



Note: showing more recent results for emphasis

Big Implications!

- Neutrino oscillation implies that neutrinos are massive
  - Vacuum oscillations depend on the mass splittings
- Opened many questions
  - What are the values of the oscillation parameters?

$$\sin^2\theta_{12},\ \Delta m^2_{21}\ \ \sin^2\theta_{23},\ \Delta m^2_{32},\ \sin^2\theta_{13}$$

From PDG 2024

		Precision
$\sin^2(\theta_{12})$	0.307 ± 0.013	4.2 %
Δm^2_{21}	$(7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$	2.4 %
$\sin^2(\theta_{23})$	$0.558^{+0.015}_{-0.021}$	3.2 %
Δm^2_{32}	$(2.455 \pm 0.028) \times 10^{-3}\ \mathrm{eV}^2$	1.1 %
$\sin^2(\theta_{13})$	0.0219 ± 0.0007	3.2 %

All parameters are **known to a few percent**!

But better precision is **important**:
- Constraints for other experiments
- Constraints for flavor and mass models
- Model-independent tests of the 3-neutrino framework (notably PMNS non-unitarity)

Also want to know the octant of θ_{23}

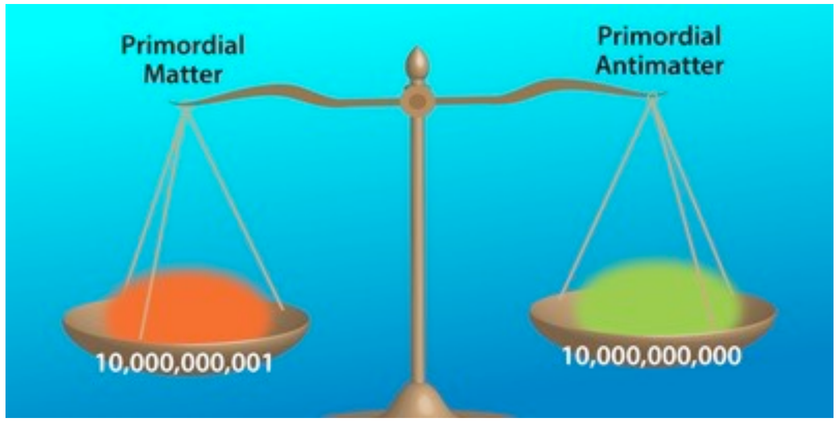
Big Implications!

- Neutrino oscillation implies that neutrinos are massive
  - Vacuum oscillations depend on the mass splittings
- Opened many questions
  - What are the values of the oscillation parameters?

$$\sin^2\theta_{12},\ \Delta m^2_{21}\ \ \sin^2\theta_{23},\ \Delta m^2_{32},\ \ \sin^2\theta_{13}$$

  - Do neutrinos obey the CP symmetry (is $\delta_{CP} = 0$)?

Big implications in cosmology!



Currently, we have some indications of CP violation but none definitive

Big Implications!

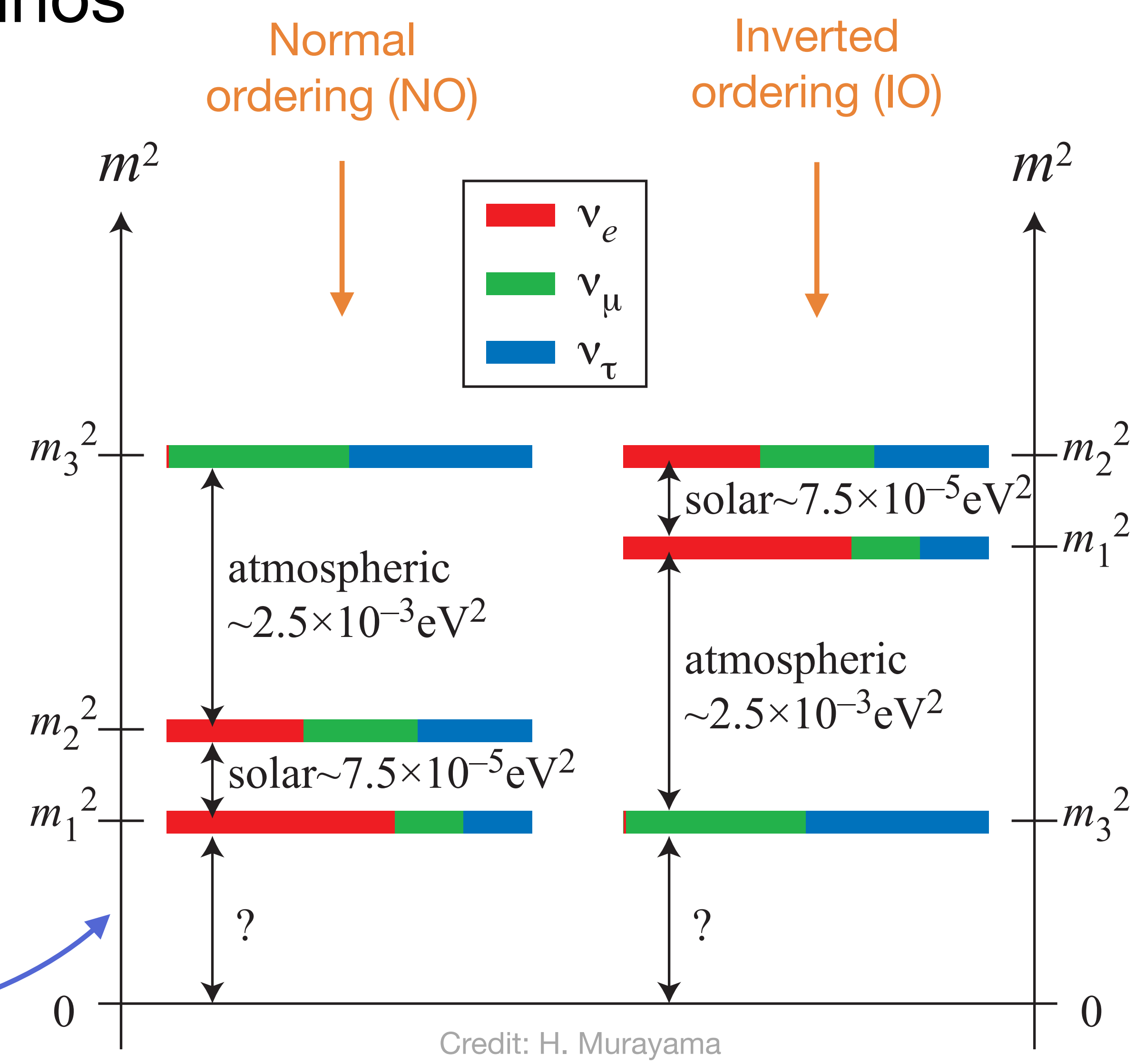
- Neutrino oscillation implies that neutrinos are massive
  - Vacuum oscillations depend on the mass splittings
- Opened many questions
  - What are the values of the oscillation parameters?

$$\sin^2\theta_{12},\ \Delta m^2_{21}\quad \sin^2\theta_{23},\ \Delta m^2_{32},\quad \sin^2\theta_{13}$$

  - Do neutrinos obey the CP symmetry (is $\delta_{CP} = 0$)?
  - What is the ordering of the neutrino masses (i.e. sign of Δm^2_{32})?

Note: Δm^2_{31} can be determined from the other two mass splittings if the mass ordering is known

  - Are there additional neutrino states?



Credit: H. Murayama

Currently, we have some indications of what is the mass ordering but none above 3σ

There are other questions but those require more than oscillation experiments to be answered

Anatomy of a Neutrino Oscillation Experiment

- How do you make a neutrino oscillation experiment?

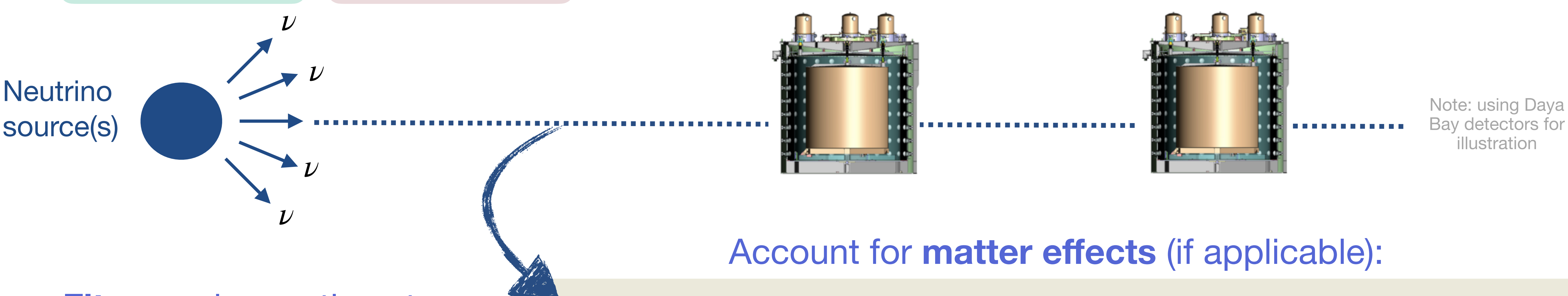
Use a strong neutrino **source(s)**:

Artificial:
- Nuclear reactors
- Accelerators
- Radioactive sources

Natural:
- Sun
- Earth
- Supernovae
- Atmospheric (cosmic rays)

Sample the neutrino flux in at least one location:

- Sampling at multiple baselines → reduce flux uncertainties
- Using identical (or functionally-identical) detectors → reduce correlated detection systematics (e.g. efficiency and cross-section)



Account for **matter effects** (if applicable):

- Oscillation probabilities are modified when propagation occurs in matter
- Arises from ν_e's ability to experience CC scattering with electrons in addition to the NC interactions available to all flavors
- Provides sensitivity to **mass ordering**!

Fit your observations to the model and extract the parameter(s) of interest

Rest of This Talk

- Some types of experiments have traditionally been more effective at probing certain sectors of the PMNS matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric (+Accelerator) | Reactor (+Accelerator) | Solar (+Reactor)

- Great progress has been achieved in the last two decades
  - The great majority of the neutrino oscillation data can be explained with the 3-neutrino framework, but anomalies have arisen
- The rest of this talk will be divided into two general portions:
  - State-of-the-art in accelerator, atmospheric, solar and reactor neutrino oscillations
  - Quick overview of neutrino oscillation anomalies

Accelerator Neutrinos

Status & Prospects

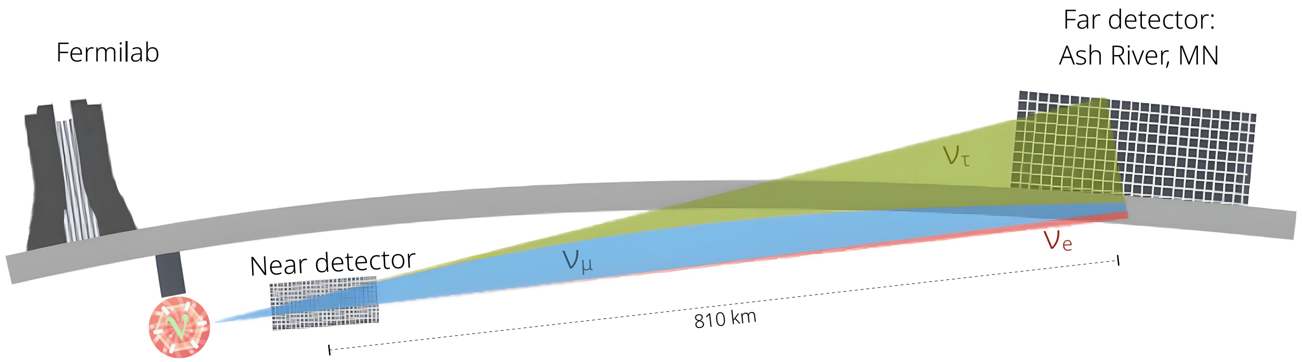
NOvA and T2K

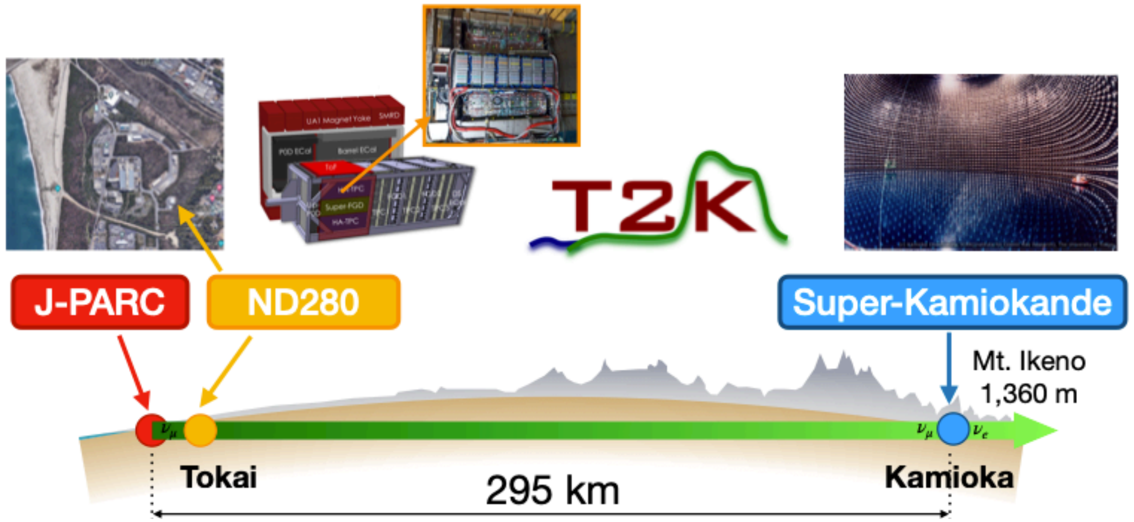
- Two long-baseline neutrino oscillation experiments are currently in operation:

NOvA

T2K

- Both experiments have near and far detectors off-axis
- Both beams can run in ν_μ and $\bar{\nu}_\mu$ mode



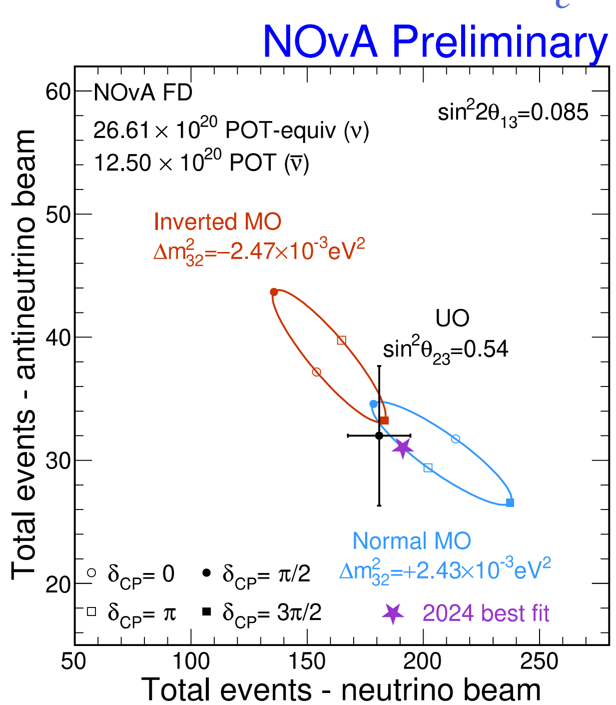


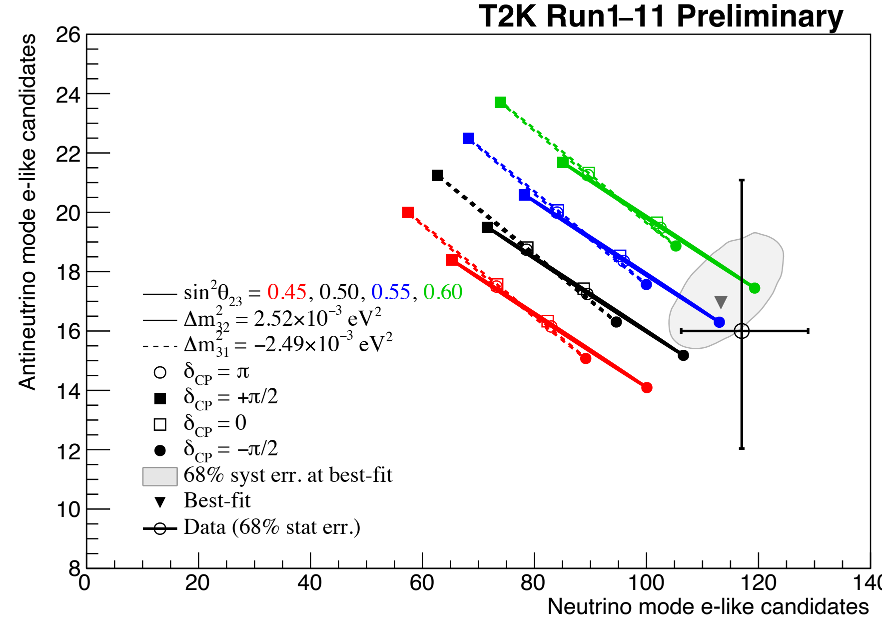
- Similar scope and strategy:

Primary goals: $\sin^2\theta_{23}$, $|\Delta m^2_{32}|$, mass ordering, δ_{CP} (and $\sin^2\theta_{13}$ to a lesser degree)

Strategy: use ν_μ disappearance and ν_e appearance in neutrino and antineutrino beams to disentangle the effects from CP violation, mass ordering, and oscillation parameters

$\bar{\nu}_e$ vs ν_e appearance:





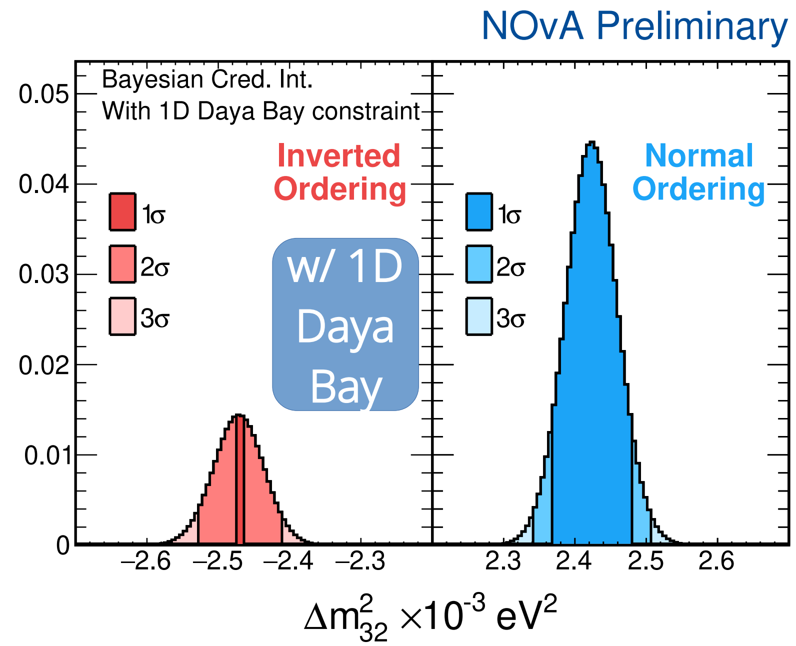
From J. Wolcott's talk and C. Giganti's talk at Neutrino 2024

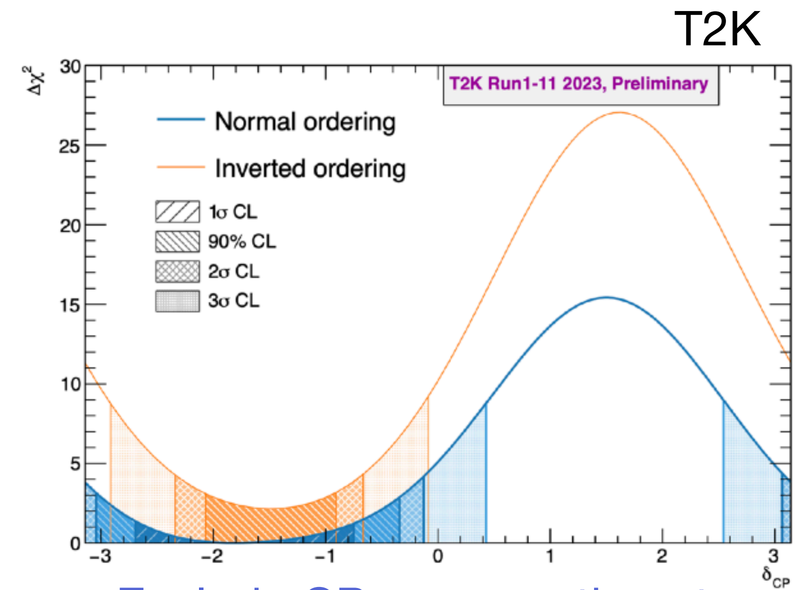
NOvA and T2K

- Individually, both experiments have a slight preference for the upper octant of θ_{23} and the normal mass ordering (NO)

	NO preference Bayes Factor
NOvA-only	3.2
T2K-only	3.3

with reactor constraints on $\sin^2\theta_{13}$

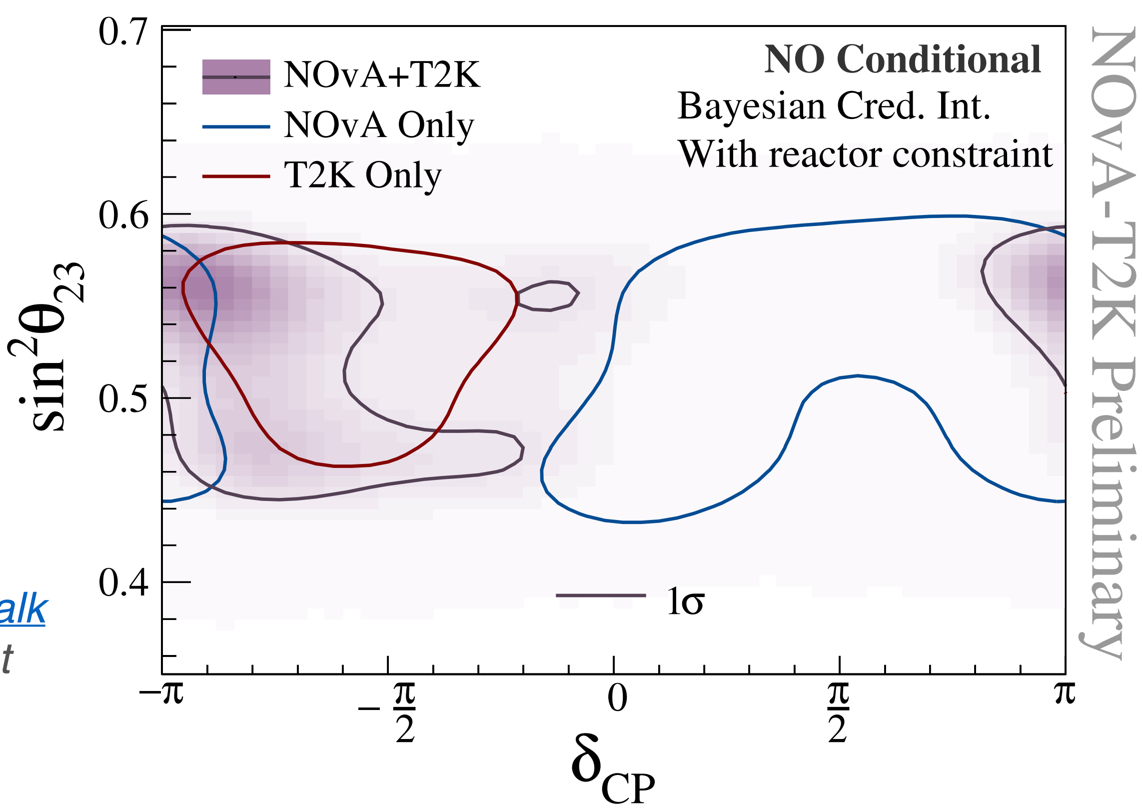


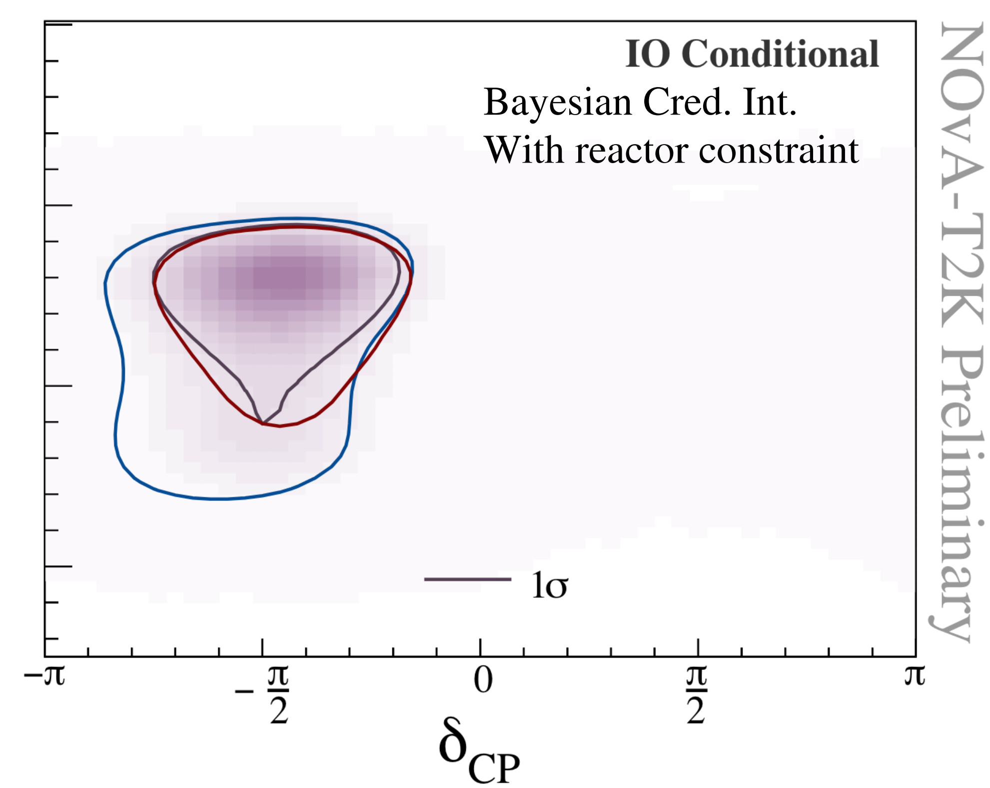


Exclude CP conservation at 90% CL!

  – However, prefer different regions of δ_{CP} in the NO case

Recently completed **joint fit** splits the difference in the NO case, improves constraint in IO case



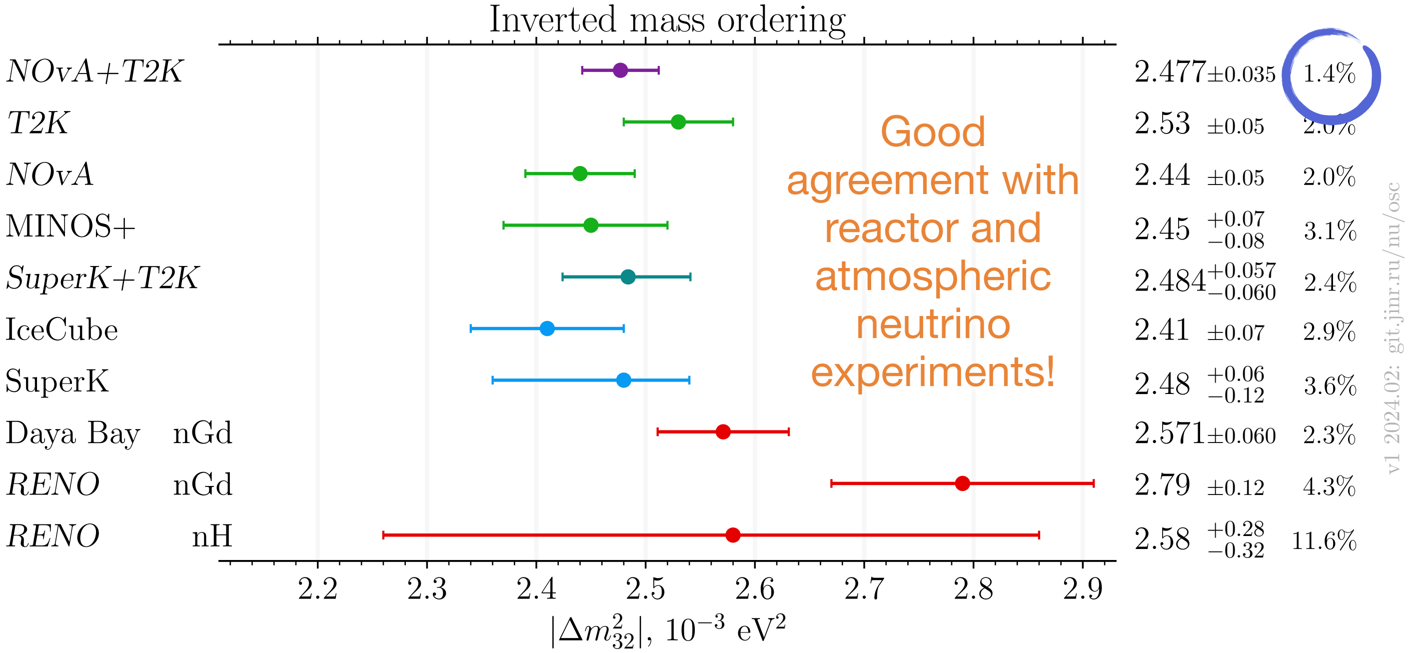


Plots from J. Wolcott's talk and C. Giganti's talk at Neutrino 2024

Joint NOvA+T2K Fit

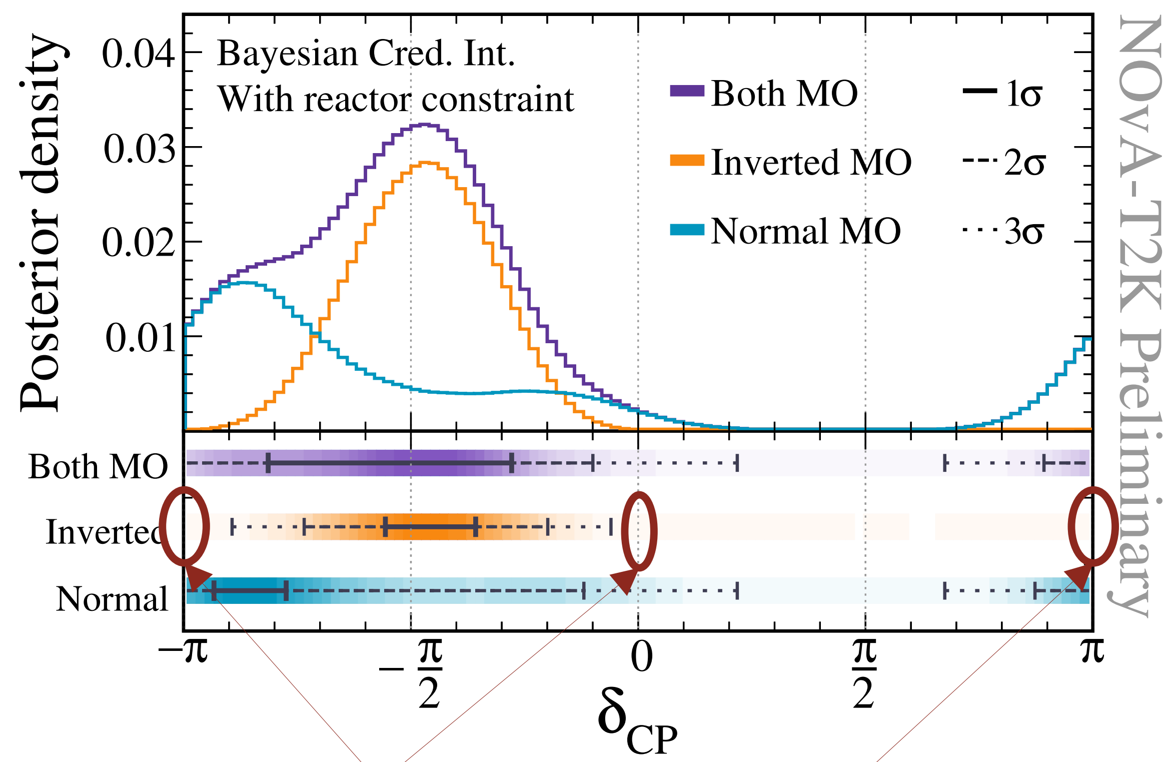
- Main takeaways from joint NOvA+T2K results:

Strong constraint on $|\Delta m^2_{32}|$



Good agreement with reactor and atmospheric neutrino experiments!

Strongly favor CP violation in Inverted Ordering scenario



Mild preference for Inverted Ordering but influenced by θ_{13} constraint

NOvA+T2K only	NOvA+T2K + 1D θ_{13}	NOvA+T2K + 2D (θ_{13}, Δm^2_{32})
IO (71%)	IO (57%)	NO (59%)

CP-conserving points are *outside* 3σ intervals in IO

Expect CPV *if* ordering is inverted

From J. Wolcott's talk at Neutrino 2024

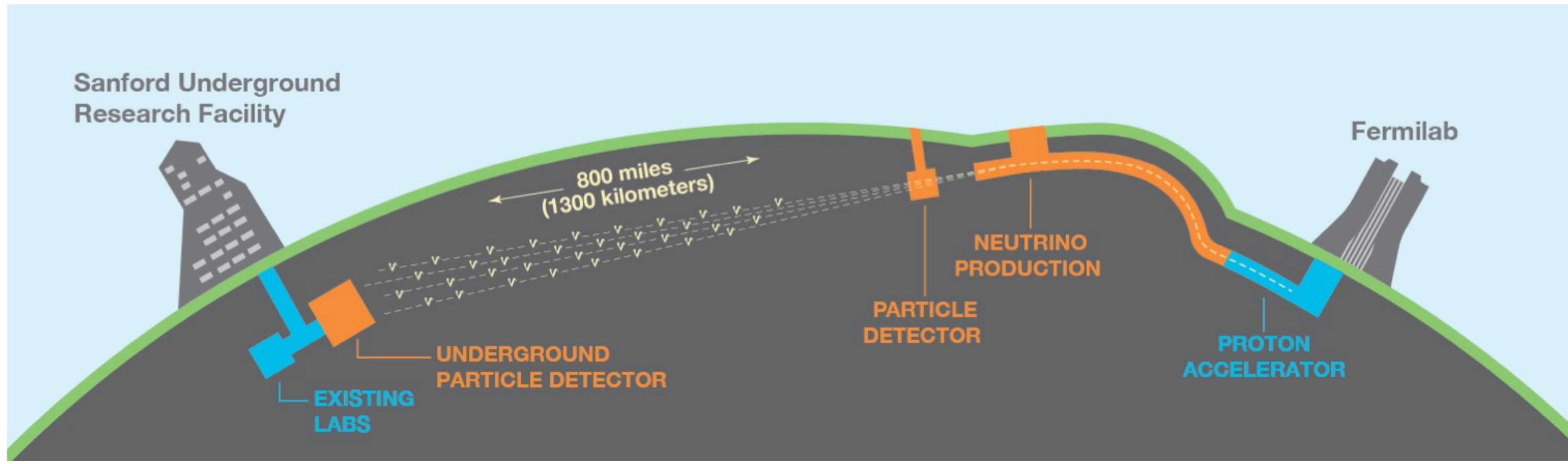
UCI University of California, Irvine

Prospects

- Need definitive measurements! Two large next-generation projects are under preparation:

DUNE:

- > 2 MW beam
- Liquid-Argon TimeProjection Chamber (LArTPC) technology
- ≥ 40 kton far detector fiducial mass
- First physics in ~2029

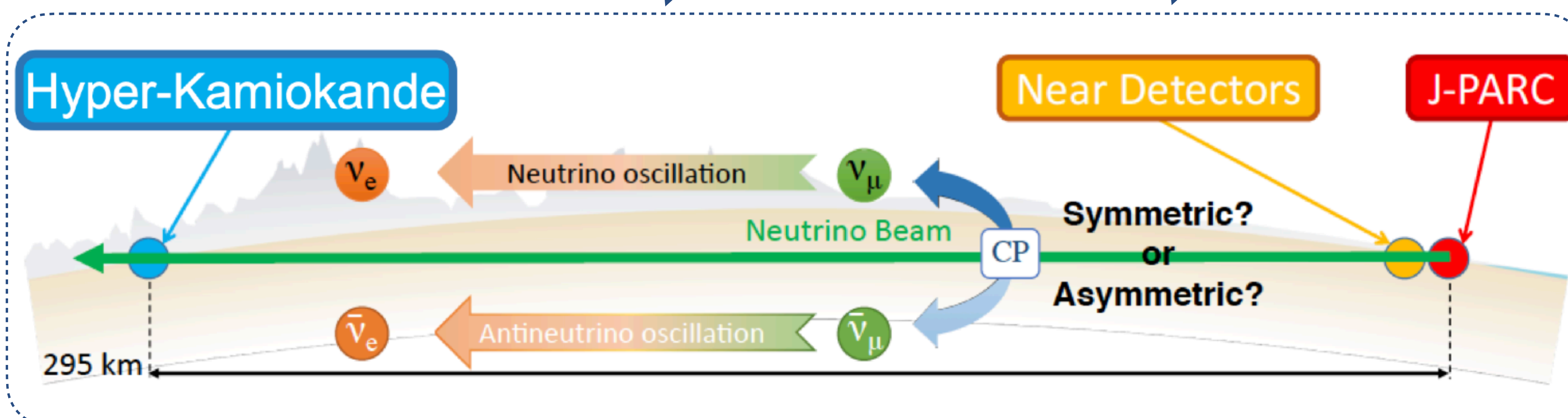


Large degree of complementarity:

DUNE	large	wide band, higher energy	LArTPC
	matter effects	energy spectrum	detection systematics
Hyper-K	small	narrow band, lower energy	Water Cherenkov

Hyper-Kamiokande:

- 1.3 MW beam
- Water Cherenkov far detector
- 190 kton far detector fiducial mass
- First physics in ~2027



From T. Nakadaira's talk at ICHEP 2024

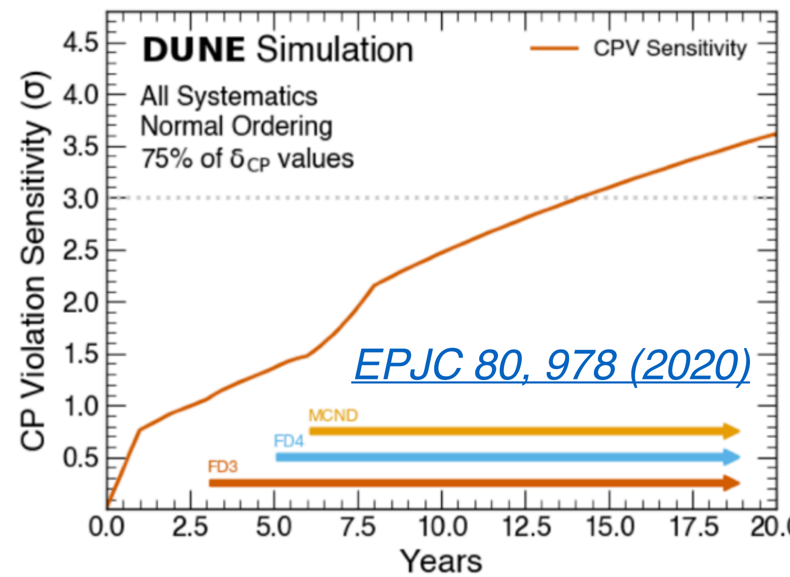
Prospects

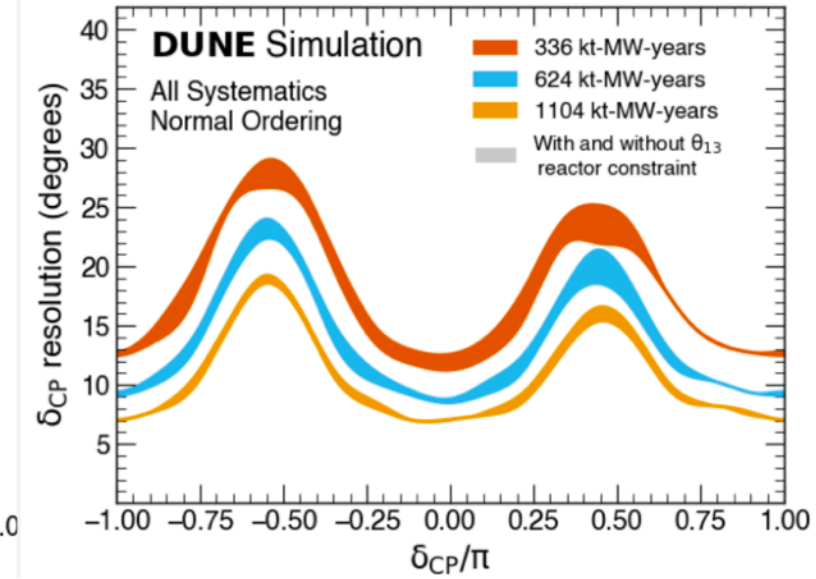
- Mass ordering:
  - DUNE: 5σ between 1 and 3 years (depending on how kind nature is)
- Precision measurement of oscillation parameters:
  - Long term high precision for Δm^2_{31} and θ_{13} sensitive to new physics in comparison with reactor measurements
- CP violation:
  - Long term establishment of CP violation at 3σ over 75% of δ_{CP} values
  - Similar 10-year precision of ~6-18° in δ_{CP} in both experiments

CP violation sensitivity

δ_{CP} resolution

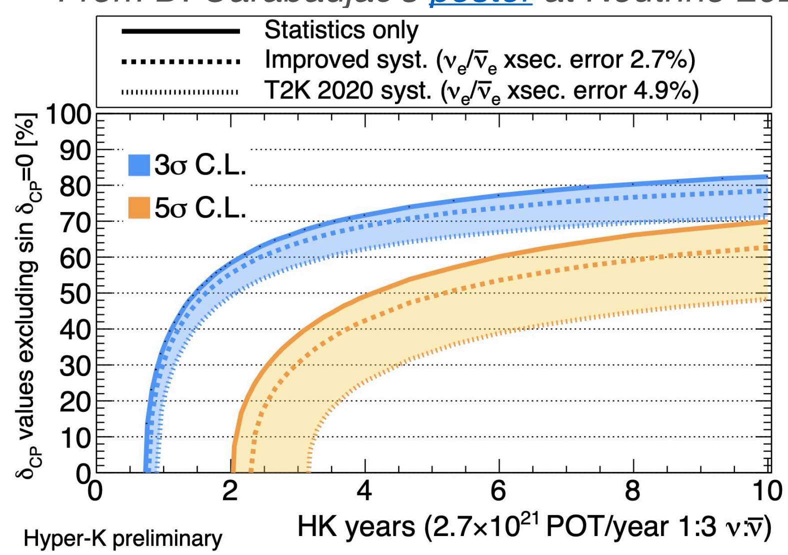
DUNE

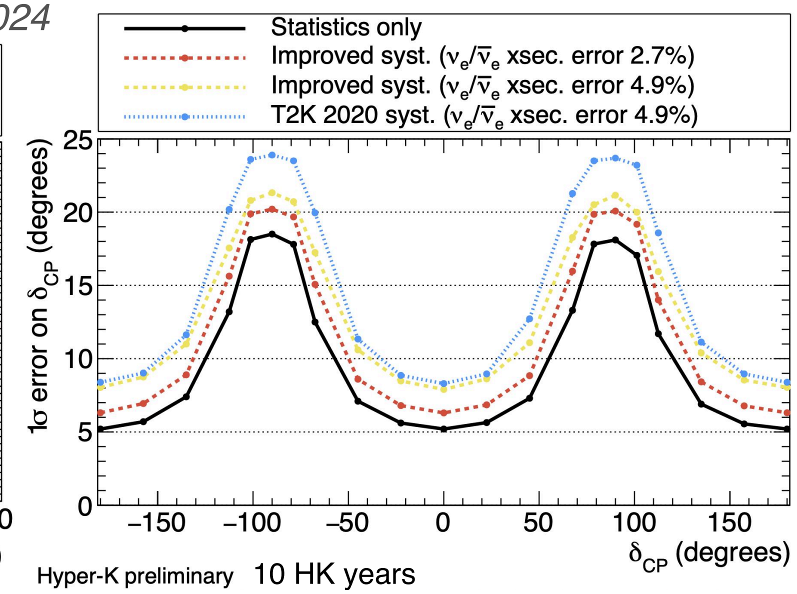




From D. Carabadjac's poster at Neutrino 2024

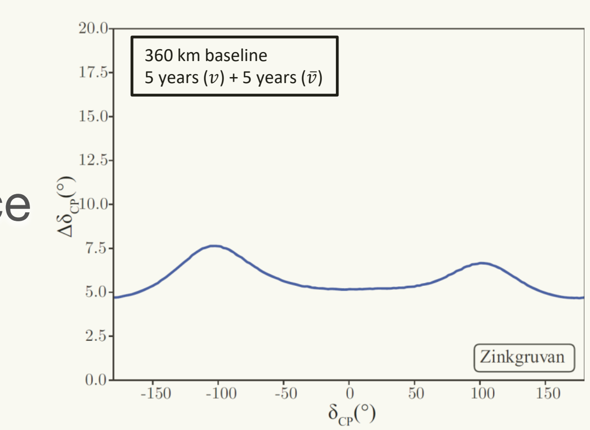
Hyper-K





Also: next-to-next generation experiment (**ESSνSB**) using 5MW European Spallation Neutron Source proton linac under active study

[EPJST 231, 3779-3955 (2022)]



Atmospheric Neutrinos

Status & Prospects

Super-Kamiokande and T2K

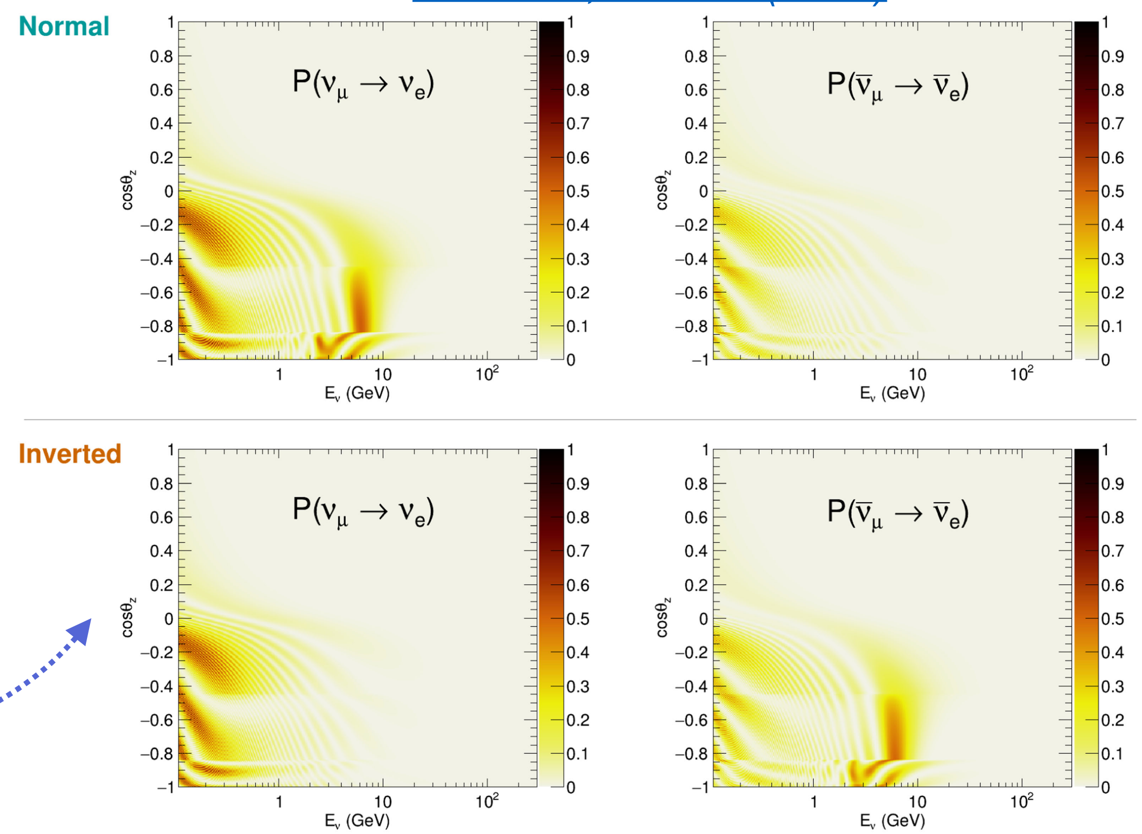
- Access similar space as accelerator experiments but with nice complementarity

Primary goals: $\sin^2\theta_{23}$, $|\Delta m^2_{32}|$, mass ordering, δ_{CP} (and $\sin^2\theta_{13}$ to a lesser degree)

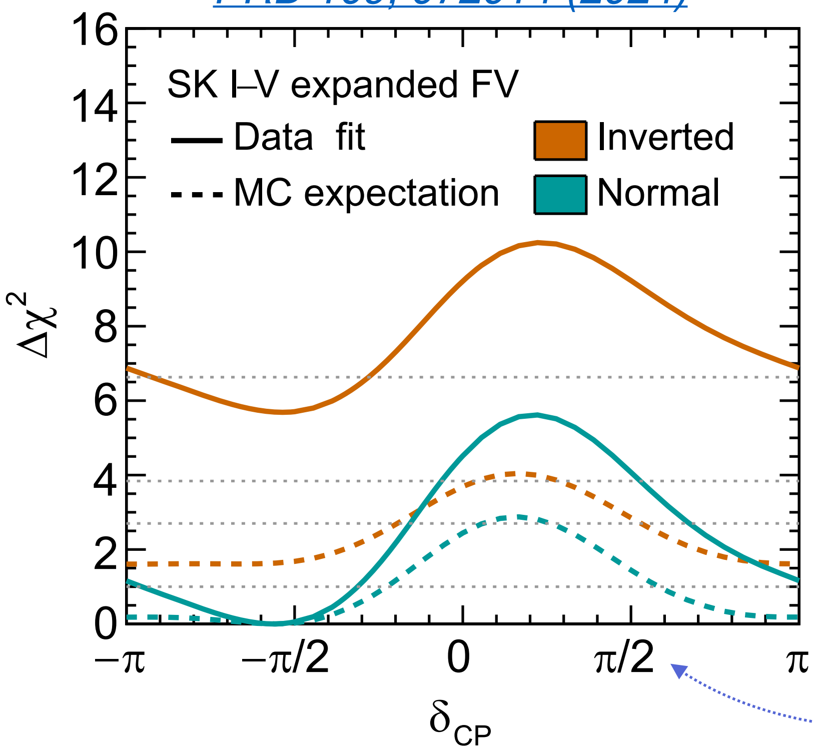
  – Broad energy range
  – Long baselines (<12,000 km)

strong matter effects: enhancement of ν_e ($\bar{\nu}_e$) appearance in the NO (IO) case

PRD 109, 072014 (2024)



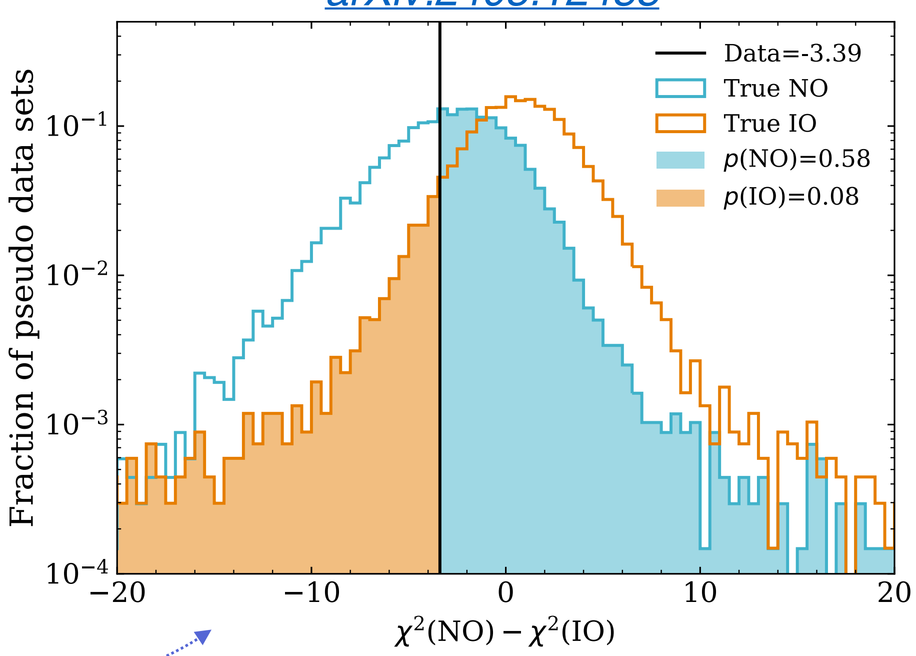
PRD 109, 072014 (2024)



Latest atmospheric neutrino results from Super-Kamiokande **(NO favored at 92.3% level)**

Joint result between SK and T2K **(exclude CP conservation to 1.9σ)**

arXiv:2405.12488

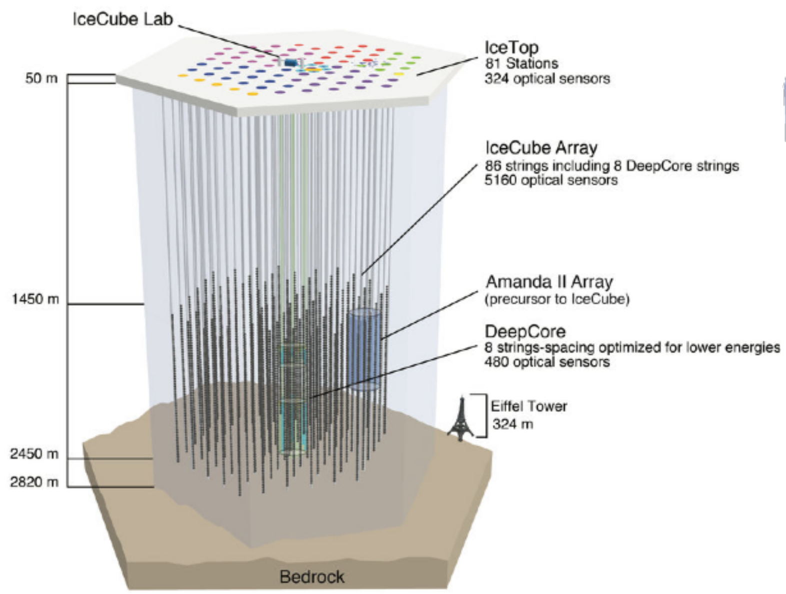


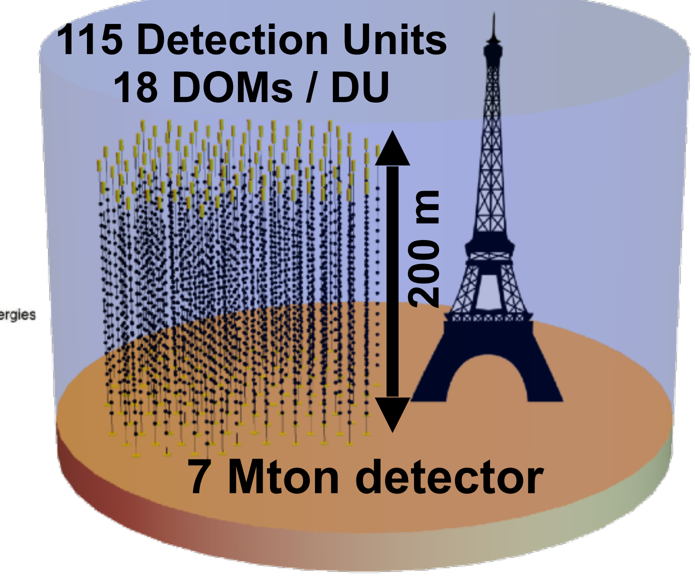
Preference for NO

IceCube and KM3NeT/ORCA

IceCube:

- Around 1 km³ of ice instrumented with strings of Digital Optical Modules (DOMs), each with a PMT
- DeepCore: densely instrumented region at the center (threshold ~8 GeV)

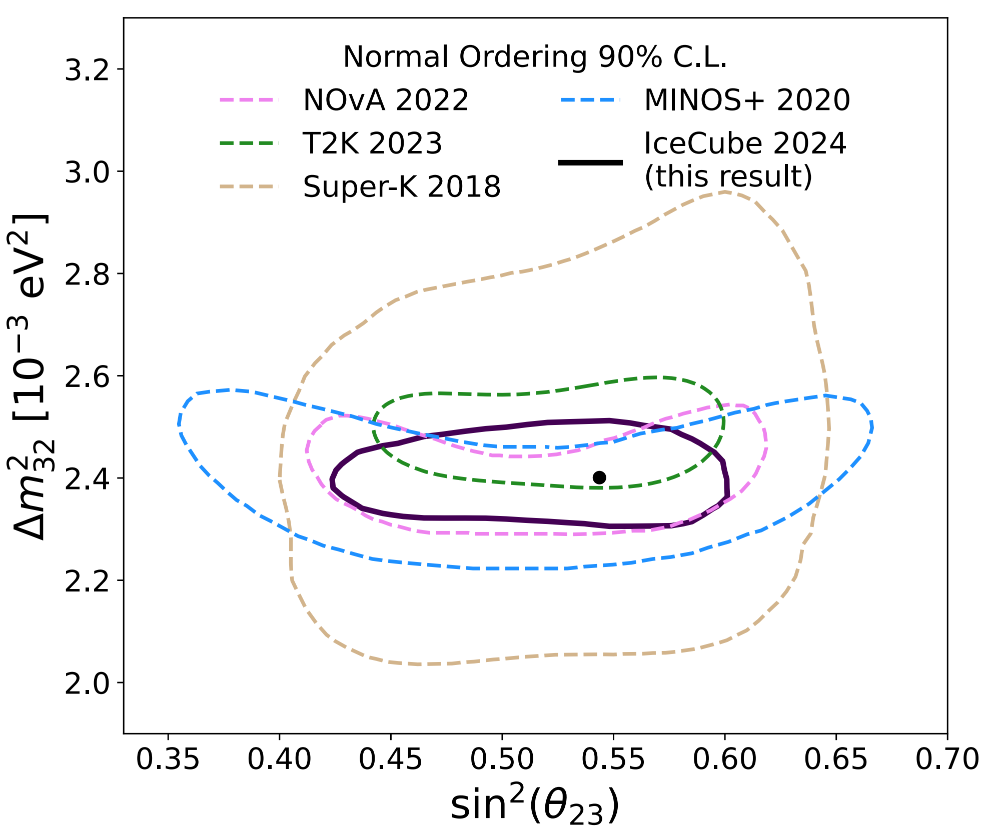




KM3NeT/ORCA:

- 115 strings optimized for neutrino oscillation measurements
- Each DOM has 31 3-inch PMTs
- About 20% of DOMs already installed

arXiv:2405.02163



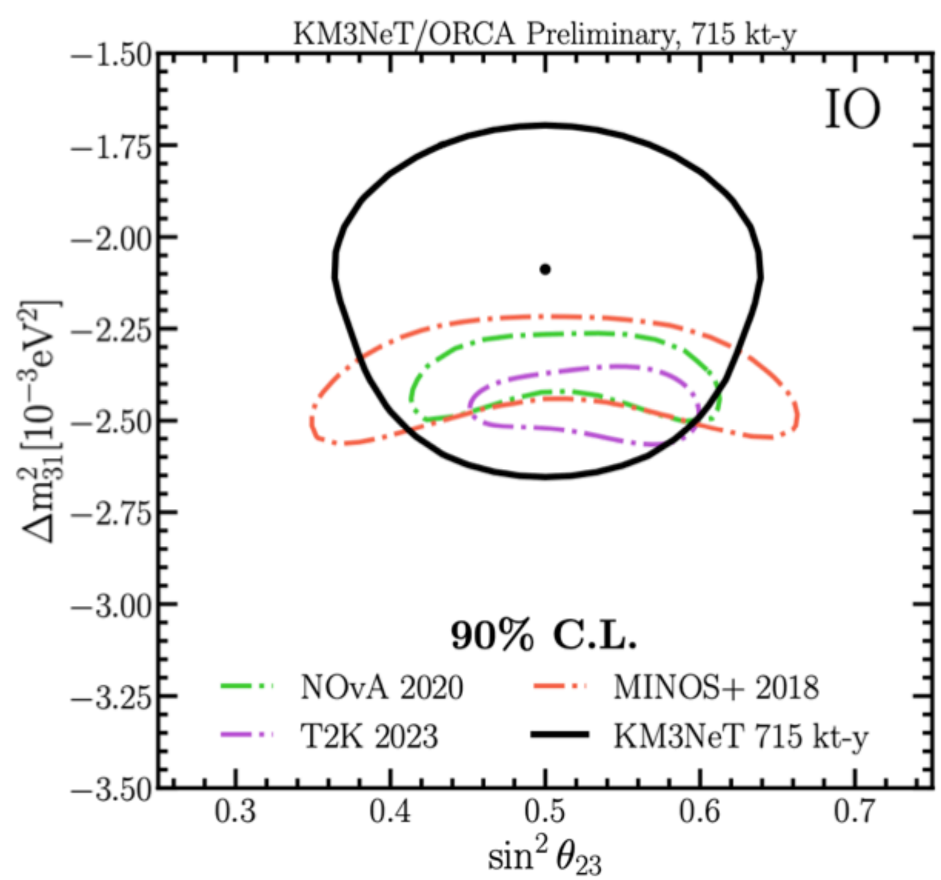
Oscillation results with 9.3 years of DeepCore data

Slight preference for NO reported previously

Oscillation results with data set equivalent to 37 days of full ORCA

Slight preference for IO

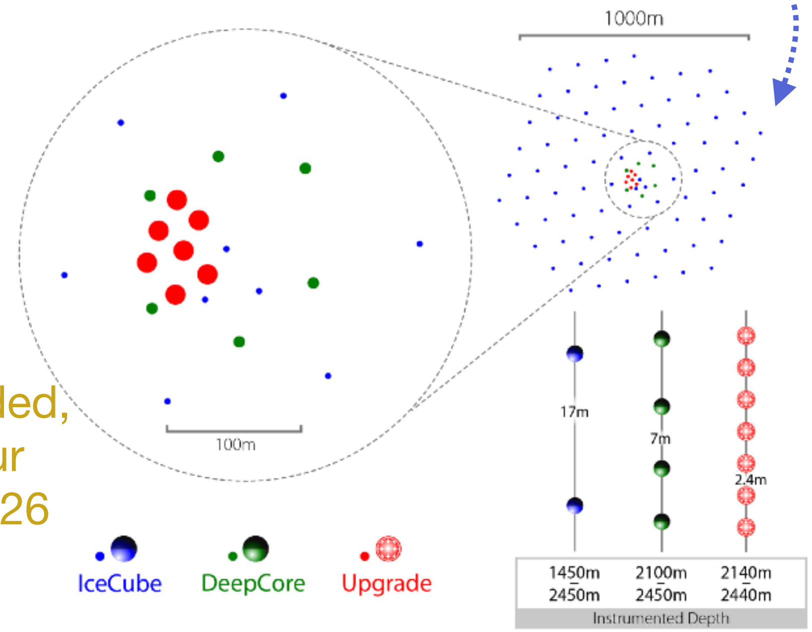
Good agreement and comparable precision with accelerator results



From J. Coelho's talk at Neutrino 2024

Prospects

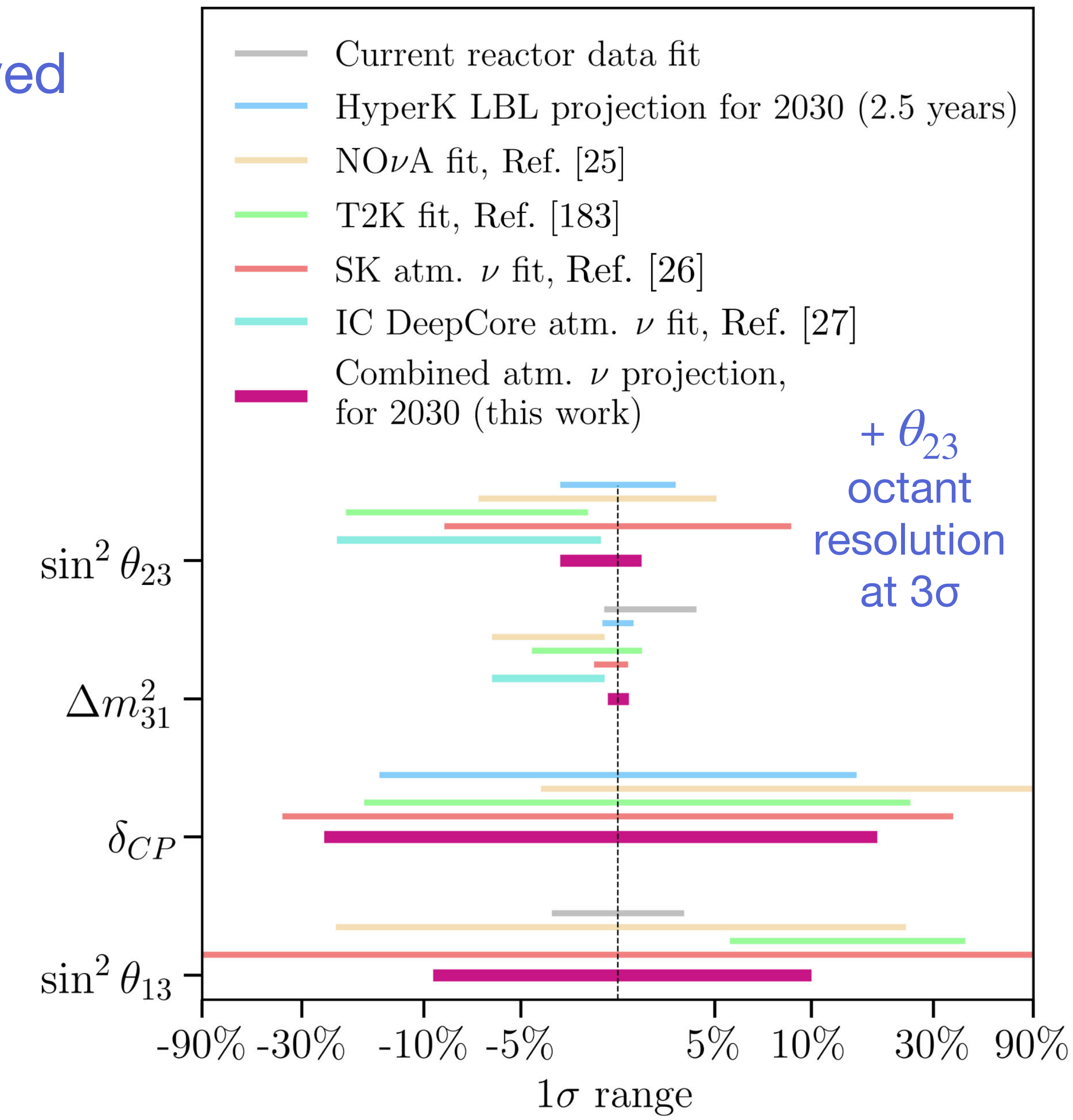
- Bright future with many large projects:
  - In the near future: Super-Kamiokande with improved neutron tagging capabilities (addition of Gd), KM3NeT/ORCA, IceCube Upgrade



Fully funded, to occur 2025-2026

  - In the longer term: Hyper-Kamiokande and DUNE

PRX 13, 041055 (2023)



- Main takeaways:
  - Atmospheric experiments will make very important contributions to the global landscape before 2030
  - In particular, a definite ($> 5\sigma$) mass ordering determination seems within reach by 2030, especially if synergy with JUNO is exploited (JHEP 2022, 55 (2022) and PRD 101, 032006 (2020))

Solar Neutrinos

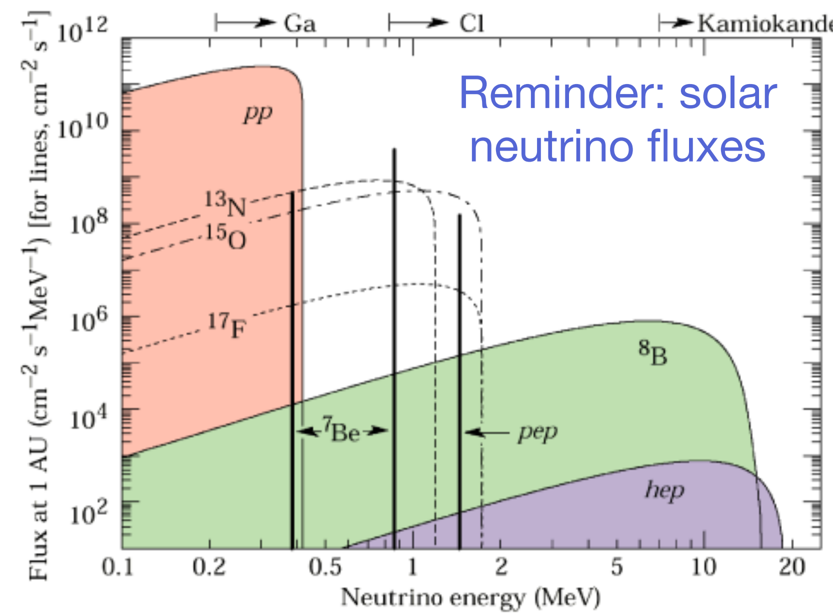
Status & Prospects

Solar Mixing Angle

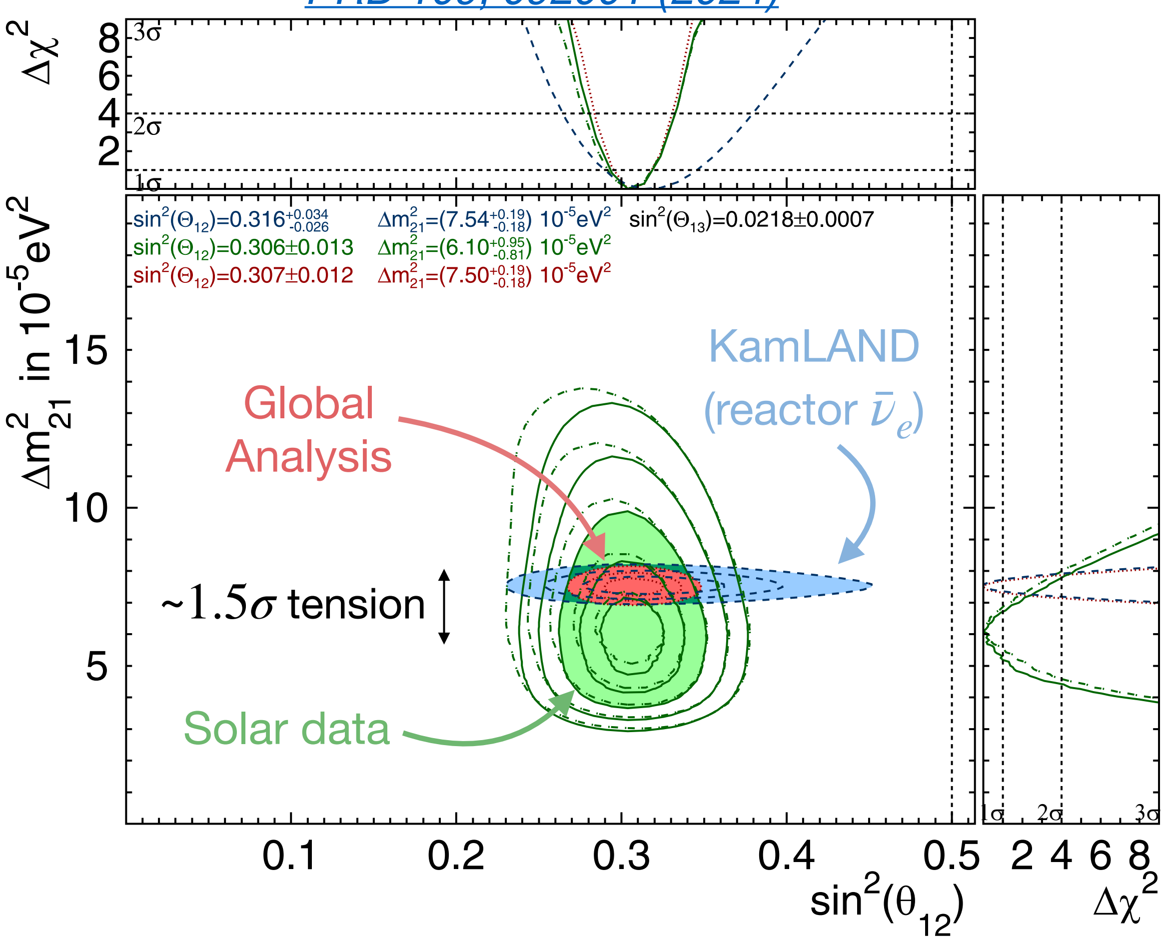
- Best information on $\sin^2\theta_{12}$ comes from solar neutrino measurements
  - Global analysis of solar and KamLAND data

Radiochemical experiments (Homestake, GALLEX/ GNO, and SAGE) SuperKamiokande, SNO, Borexino

Reactor $\bar{\nu}_e$ disappearance

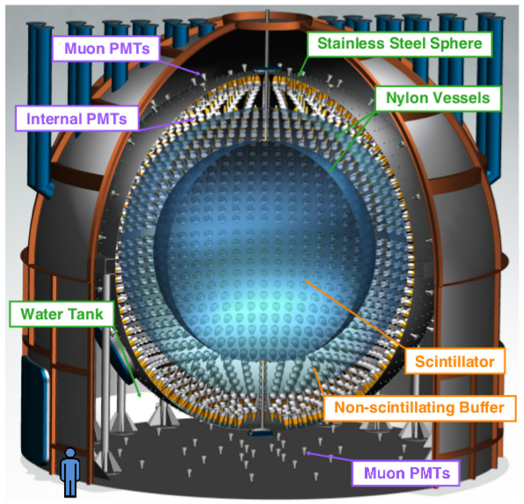


[PRD 109, 092001 (2024)](PRD 109, 092001 (2024))

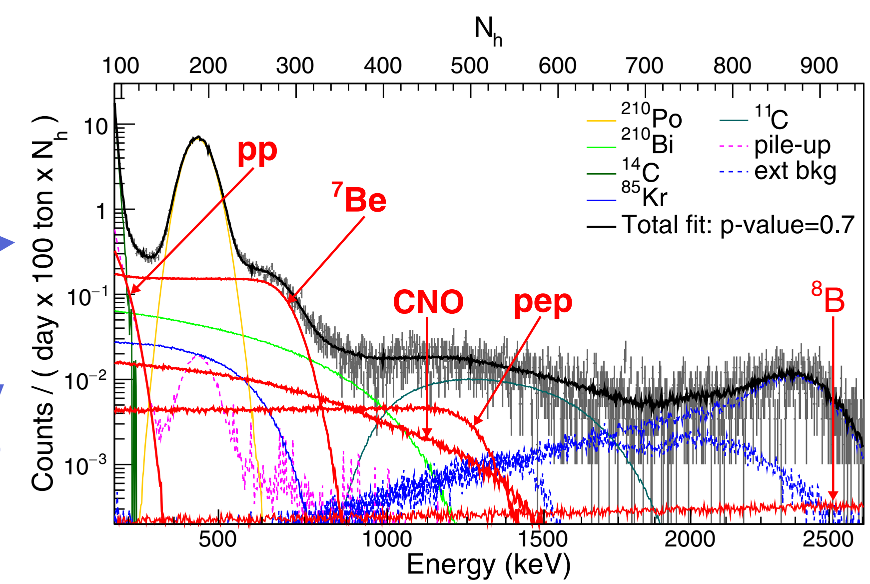


Borexino:

- Liquid scintillator detector in Gran Sasso Laboratory
- Achieved unprecedentedly high radiopurity and low threshold (~100 keV)



Spectroscopy with Borexino



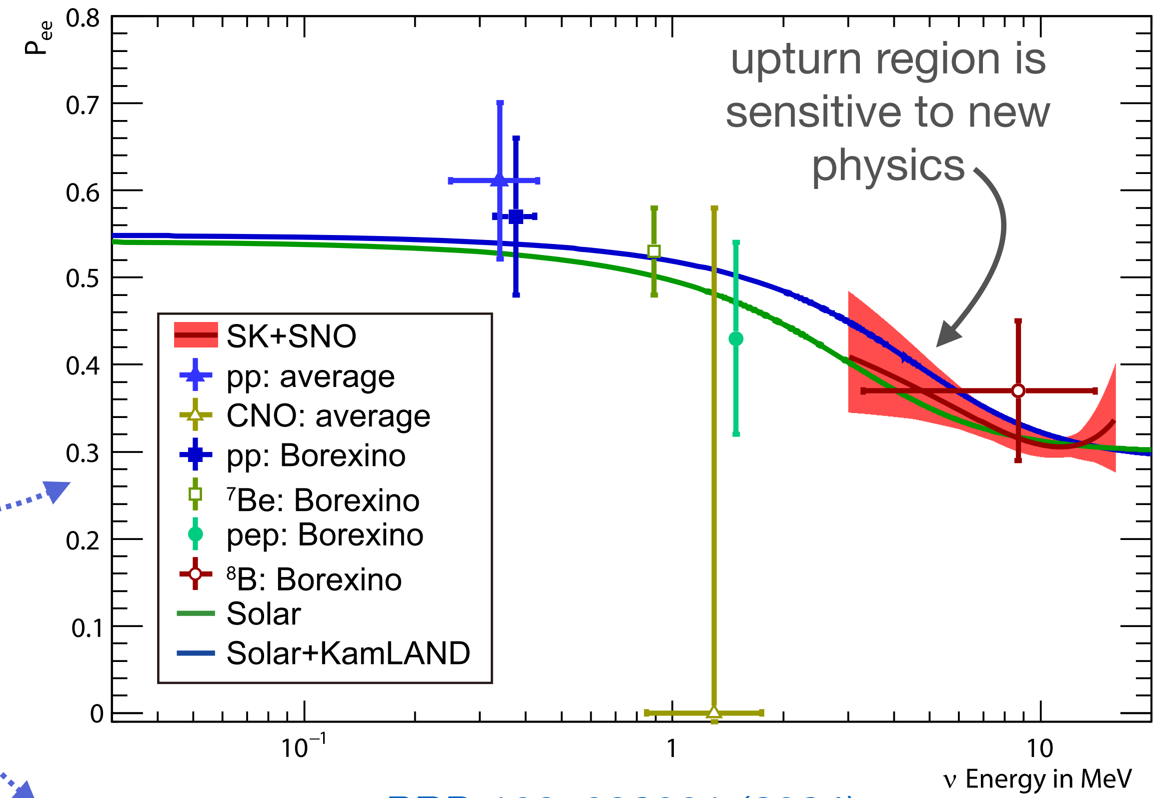
PRD 100, 082004 (2019)

UCI University of California, Irvine

Open Questions

- Solar data in full agreement with 3-neutrino framework, but two predictions remain to be conclusively observed:
  - The “upturn” caused by the transition between vacuum and matter dominance in the Sun
  - The day/night asymmetry induced by matter-effects in the Earth

PRD 109, 092001 (2024)



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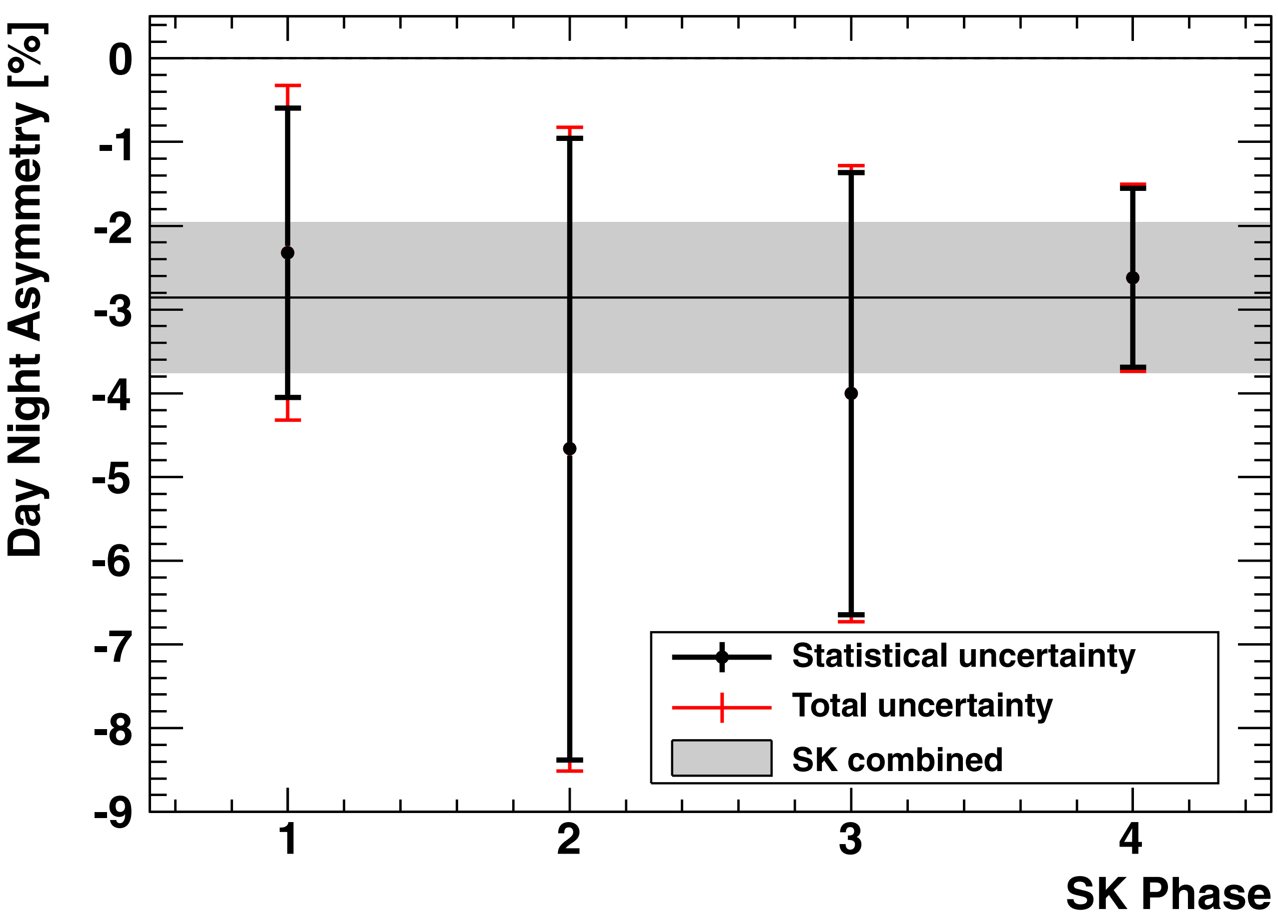
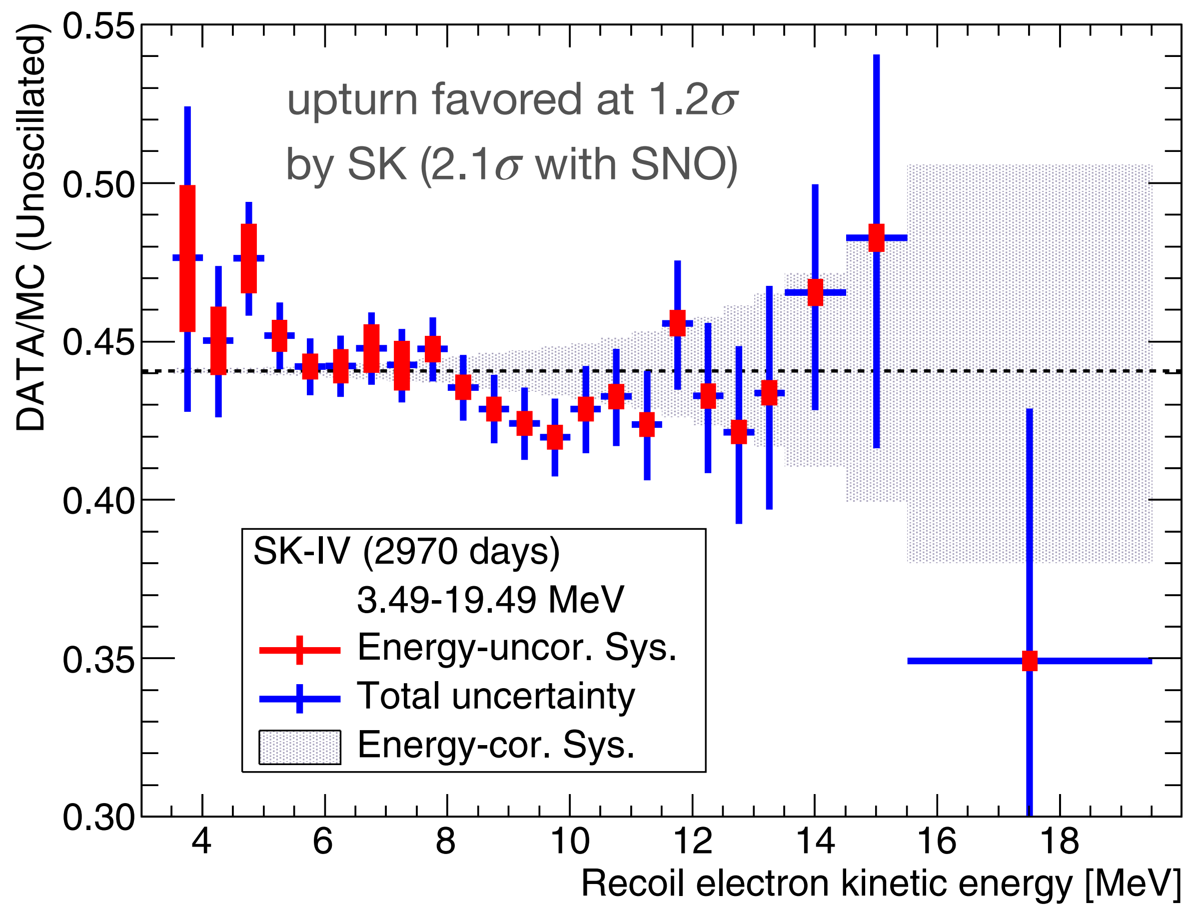
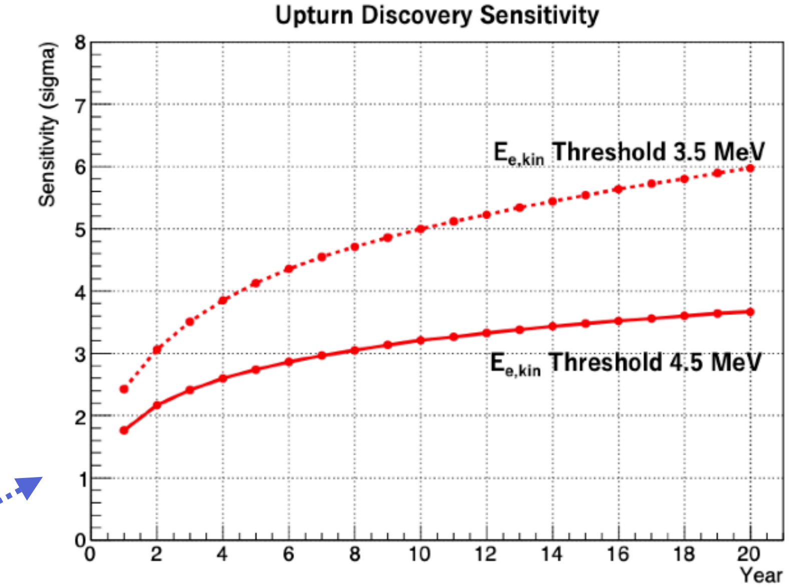


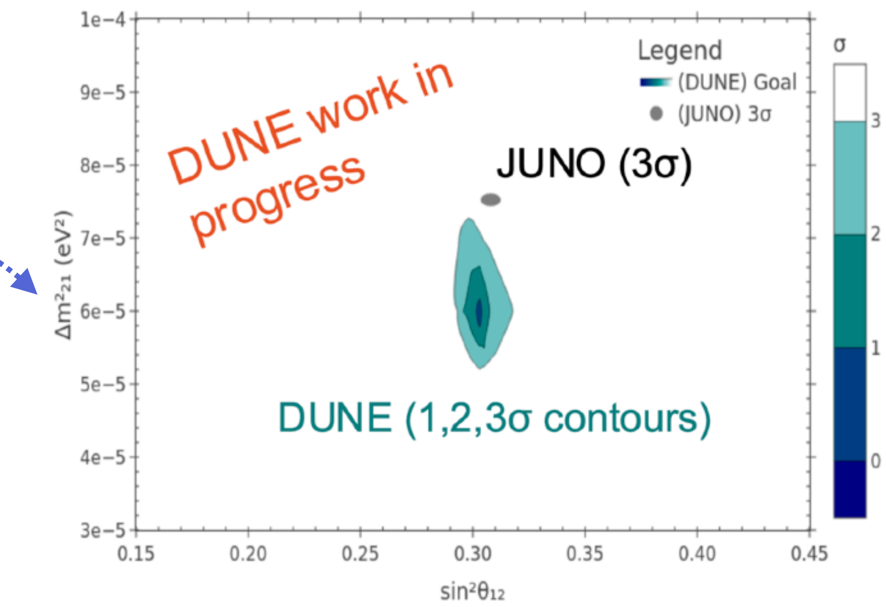
PRD 109, 092001 (2024)

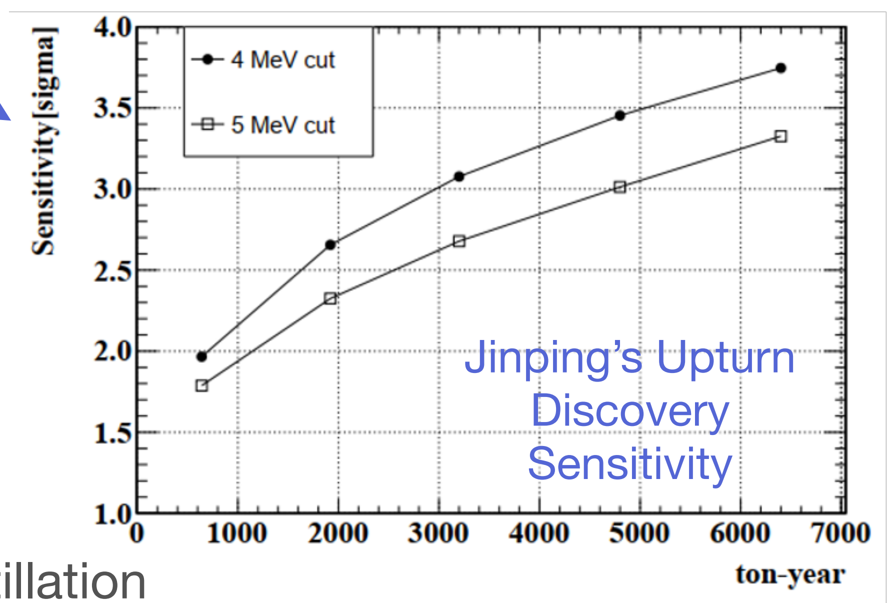


Prospects

- Several projects under preparation will improve on these results:
  - SNO+
    - Scintillator phase just completed, first solar neutrino results already out
  - Hyper-Kamiokande
    - Largest solar detector starting in 2027
  - DUNE
    - Largest LArTPCs ever built starting in 2029
    - Excellent sensitivity to ^{8}B neutrinos $\gtrsim 10$ MeV
  - JUNO
    - Measurement with reactor and solar neutrinos in same detector starting in 2025
    - Potential to improve on some low-energy solar neutrino measurements from Borexino
  - Jingping Neutrino Experiment
    - Big overburden, 500 m^3
    - Possibility of using LiCl as medium
- New detector technologies are also under active R&D that could unlock new opportunities:
  - [THEIA]
    - Hybrid scintillation+Cherenkov detector
  - [LiquidO]
    - Topology discrimination and In doping via opaque scintillation







For more info, please see J. Maneira's talk at Neutrino 2024, Chris Marshall's talk at Neutrino 2024, and W. Luo's talk at ICHEP 2024

Reactor Neutrinos

Status & Prospects

θ_{13} Mixing Angle

- Best information on Δm^2_{21} and $\sin^2\theta_{13}$ comes from reactor experiments
  - For Δm^2_{21} it's KamLAND (see 4 pages ago)
  - For $\sin^2 2\theta_{13}$ it's from short baseline (< 2 km) experiments that access first maximum modulated by $\sin^2 2\theta_{13}$

Reminder: reactor antineutrinos peak around 3.5 MeV

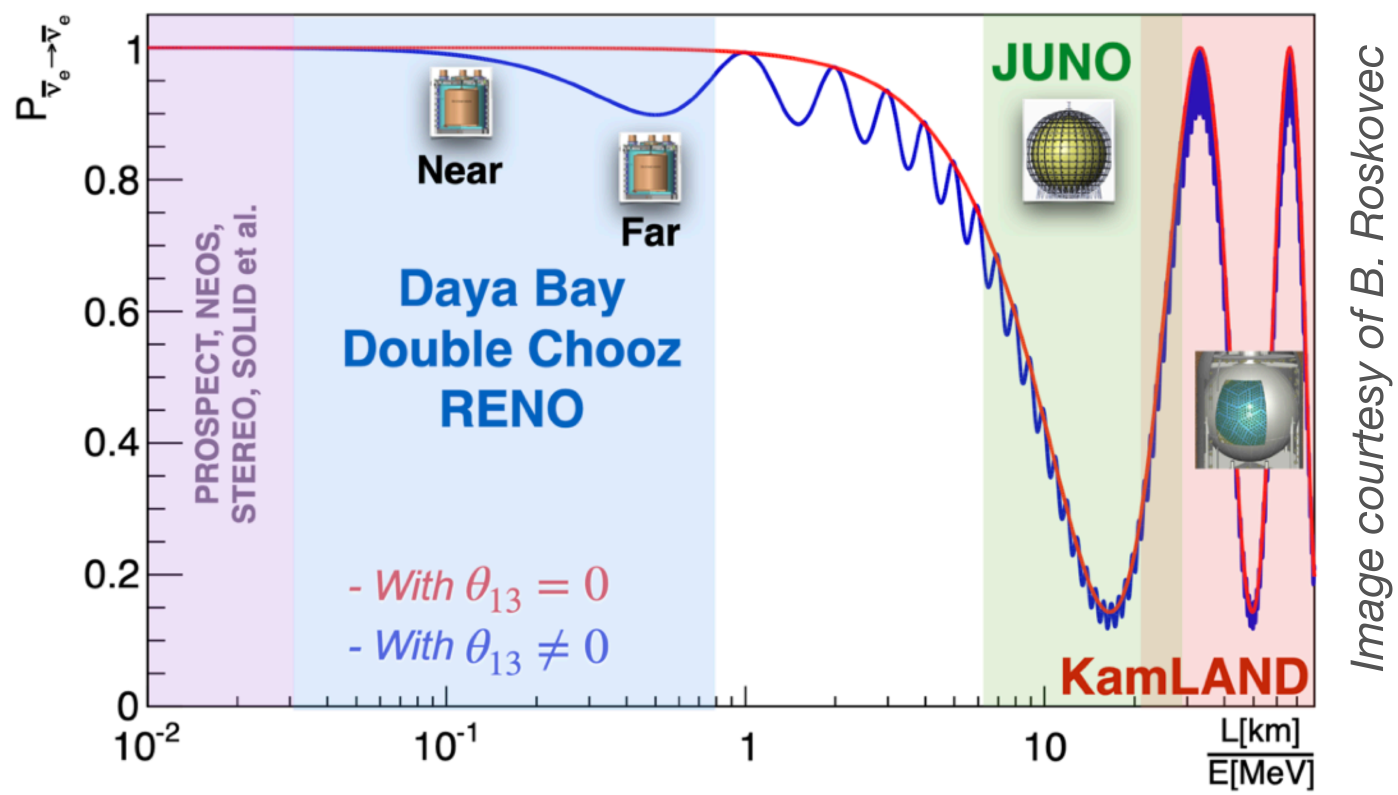
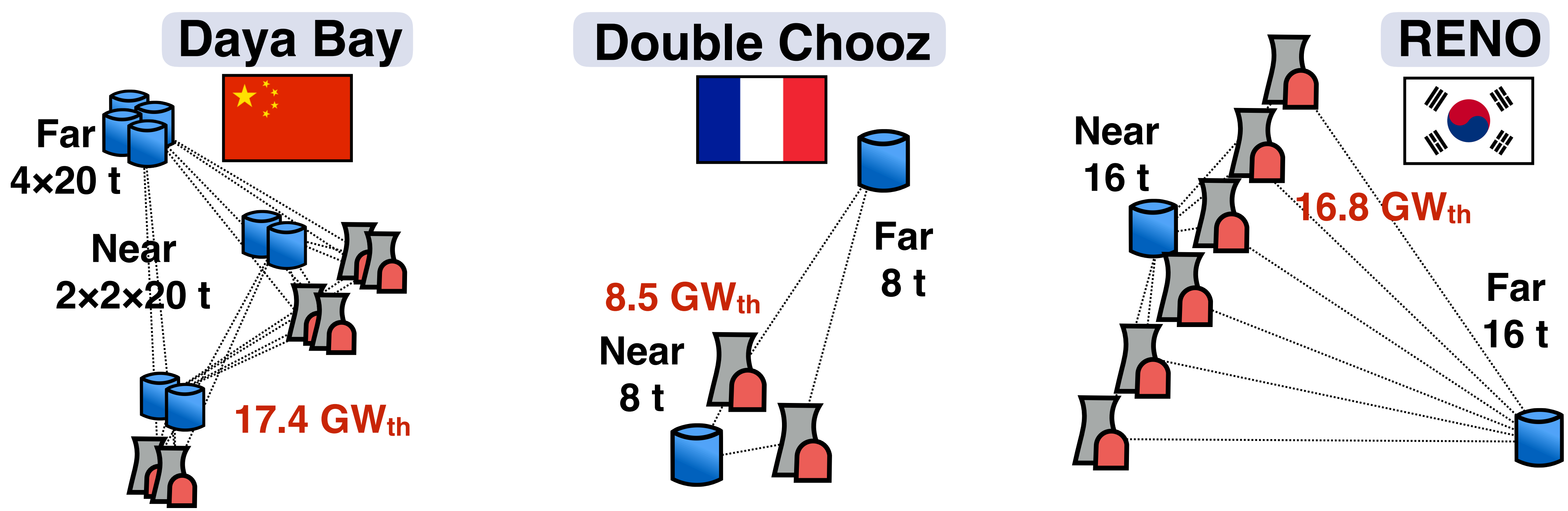


Image courtesy of B. Roskovec



Data taking: 2011 - 2020

Data taking: 2011 - 2017

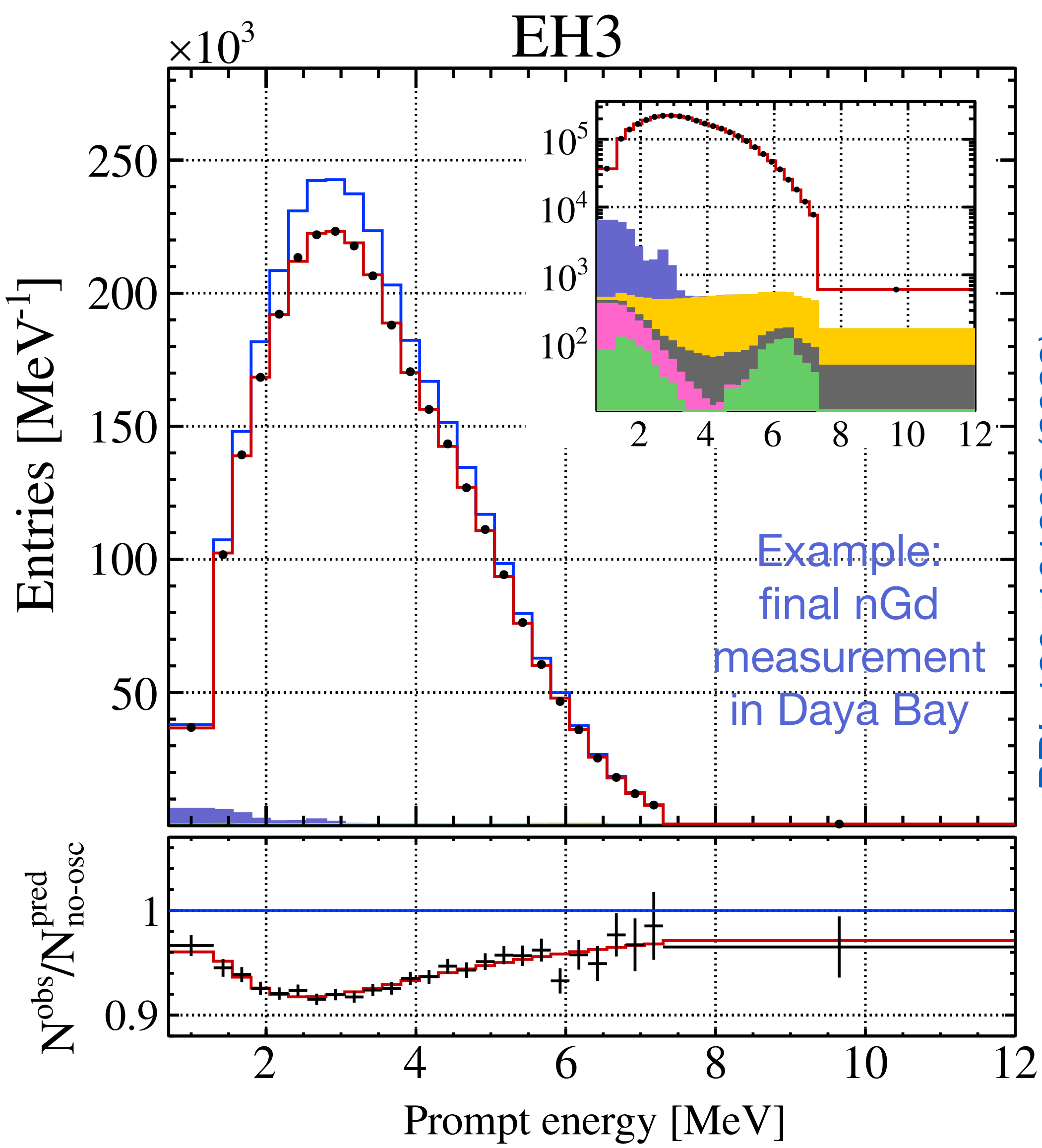
Data taking: 2011 - 2023

Notes: flags indicate location of experiment, not composition of collaboration

θ_{13} Mixing Angle

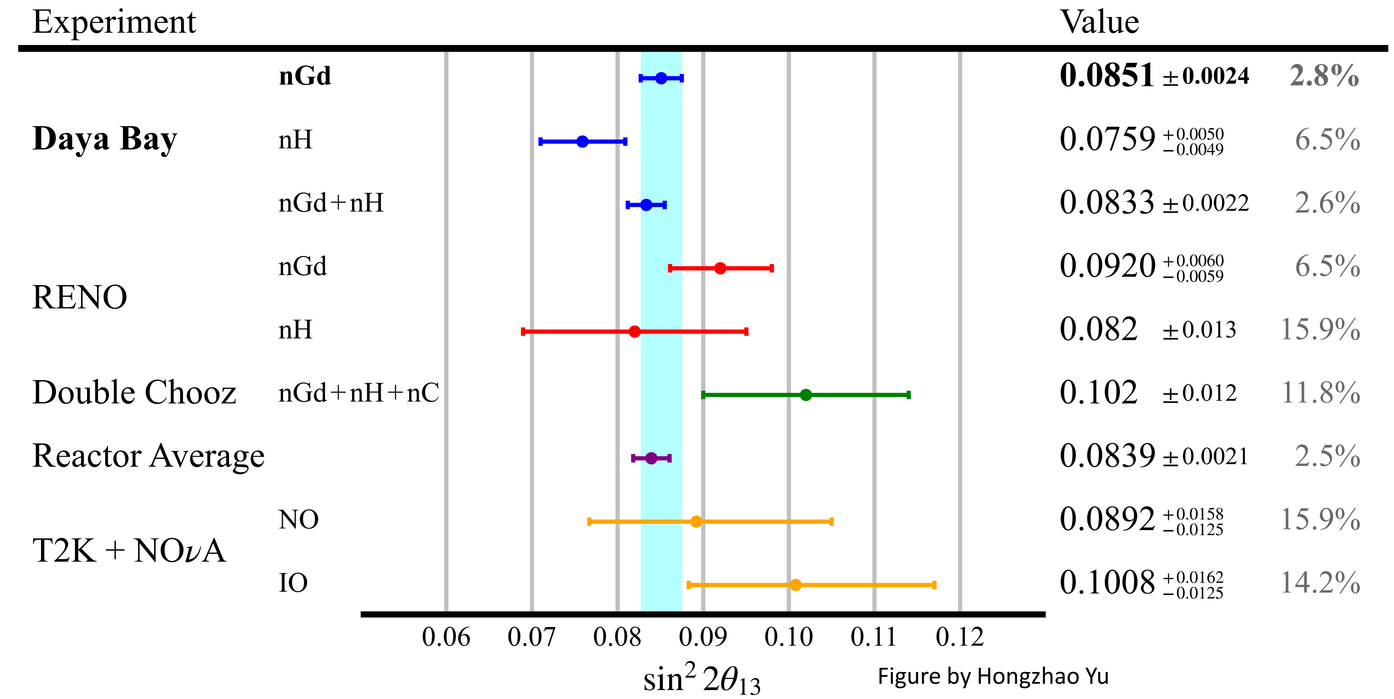
Detection Channel
$\bar{\nu}_e + p \rightarrow e^+ + n$

- These experiments can use neutron capture on Hydrogen (nH) and/or on Gadolinium (nGd) to identify $\bar{\nu}_e$'s, resulting in essentially independent measurements



PRL 130, 161802 (2023)

Plot courtesy of H. Yu, shown in Z. Yu's [talk](#) at Neutrino 2024



Current reactor measurement of θ_{13} likely to remain the world's most precise for a long time

- Proposal for a [Super CHOOZ](#) with LiquidO technology under active exploration
  - Demonstration via the CLOUD experiment

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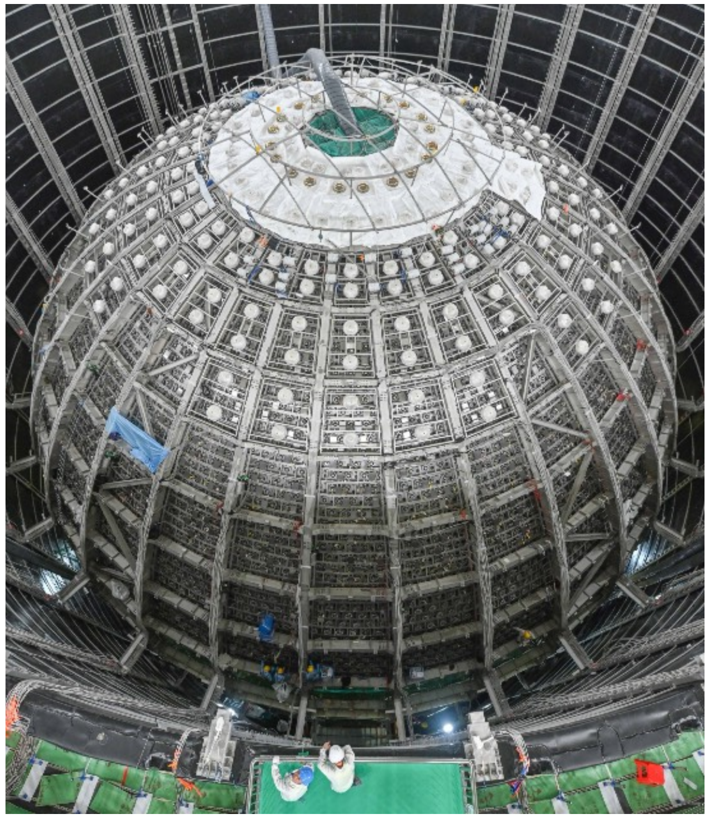
Prospects: JUNO

- JUNO is a next-generation reactor experiment expected to begin data collection within ~1 year

JUNO:
- 20 kton liquid scintillator detector
- Baseline of ~52.5 km from 8 nuclear reactors
- Energy resolution of 3% @ 1 MeV

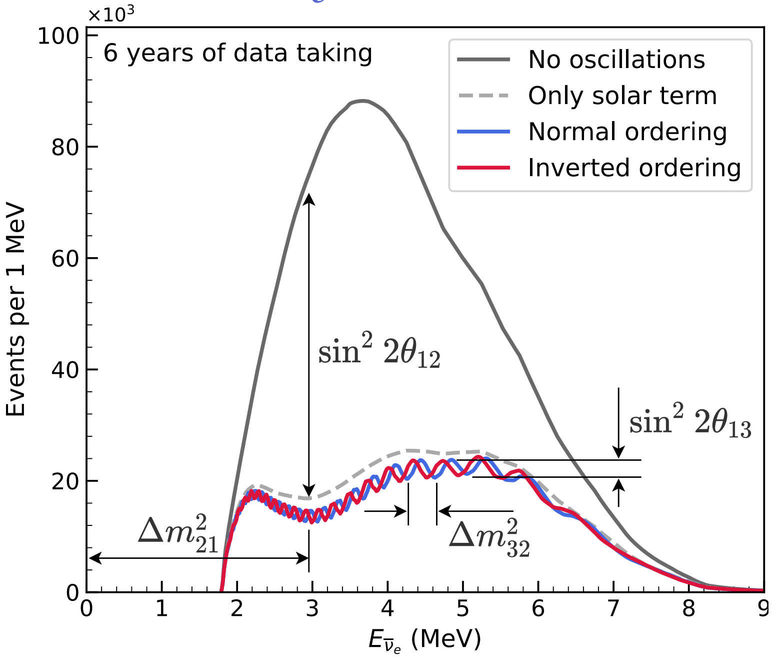


- Sub-percent precision on three oscillation parameters
- Mass ordering determination with unique approach that does not rely on matter effects
- Great complementarity with the global program

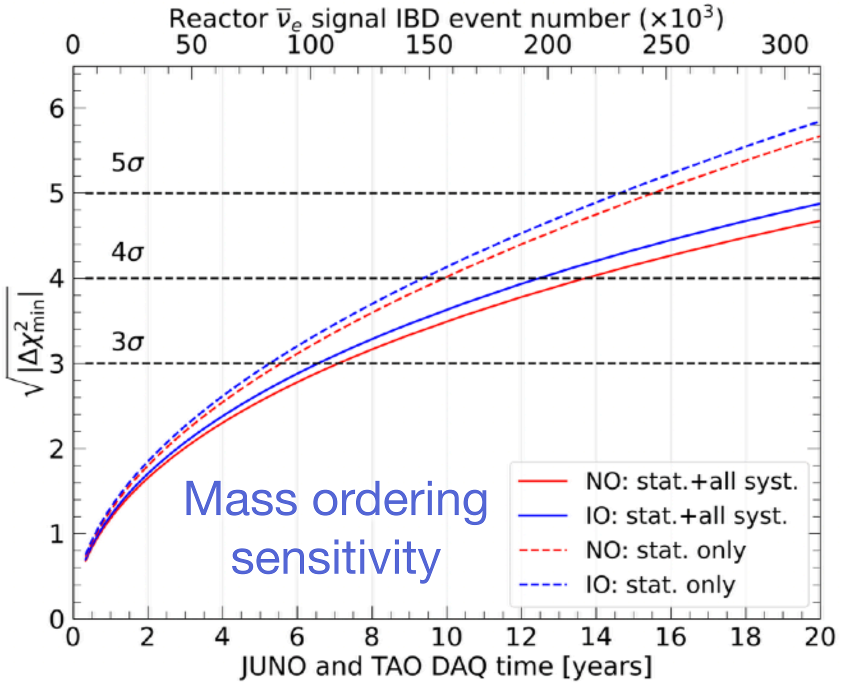
Parameter	$\sin^2\theta_{12}$	Δm^2_{21}	Δm^2_{32}
Current Precision*	4.2%	2.4%	1.1%
JUNO 6 years	0.5%	0.3%	0.2%

* from PDG 2024

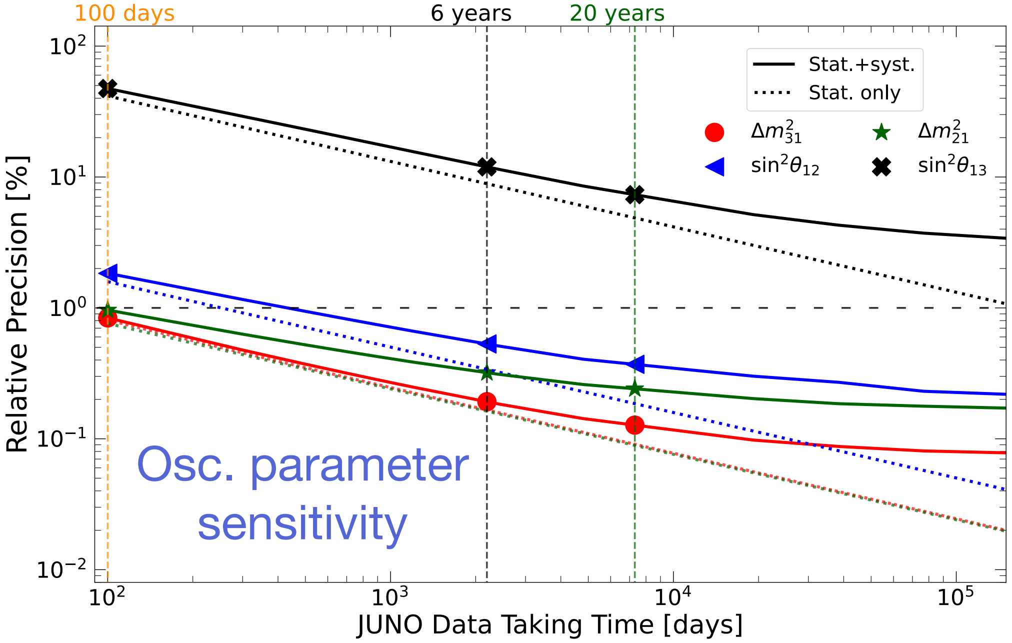
Reactor $\bar{\nu}_e$ Spectrum Cartoon



arXiv:2405.18008



CPC 46, 123001 (2022)



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Oscillation Anomalies

Where do things stand?

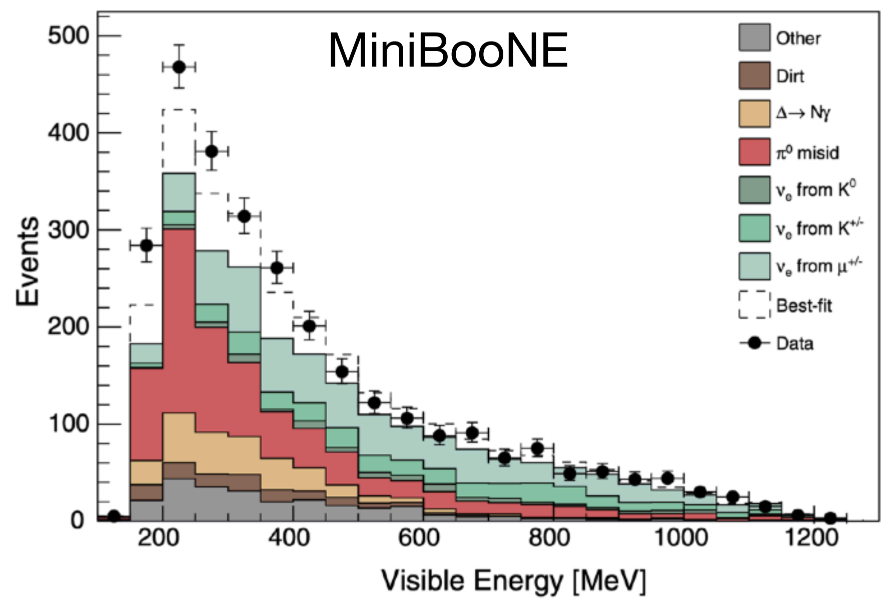
LSND/MiniBooNE

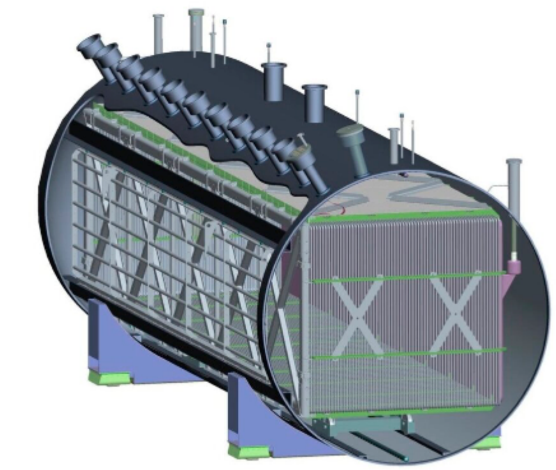
MicroBooNE:

- 170 ton LArTPC
- Same L/E and same beam as MiniBooNE

- LSND and MiniBooNE observed a ~6σ excess of electron (anti)neutrinos in a muon (anti)neutrino beam →
  - Could be explained via eV-scale sterile neutrino oscillations

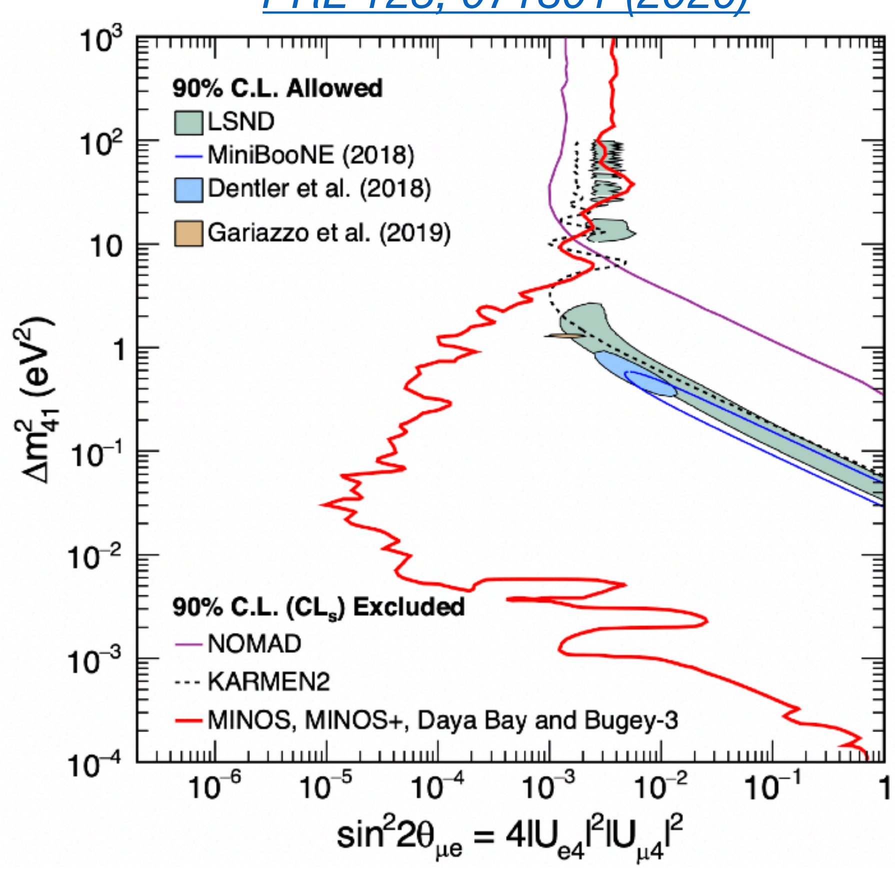
[PRD 64,112007 (2001)](#) and [PRD 103, 052002 (2021)](#)





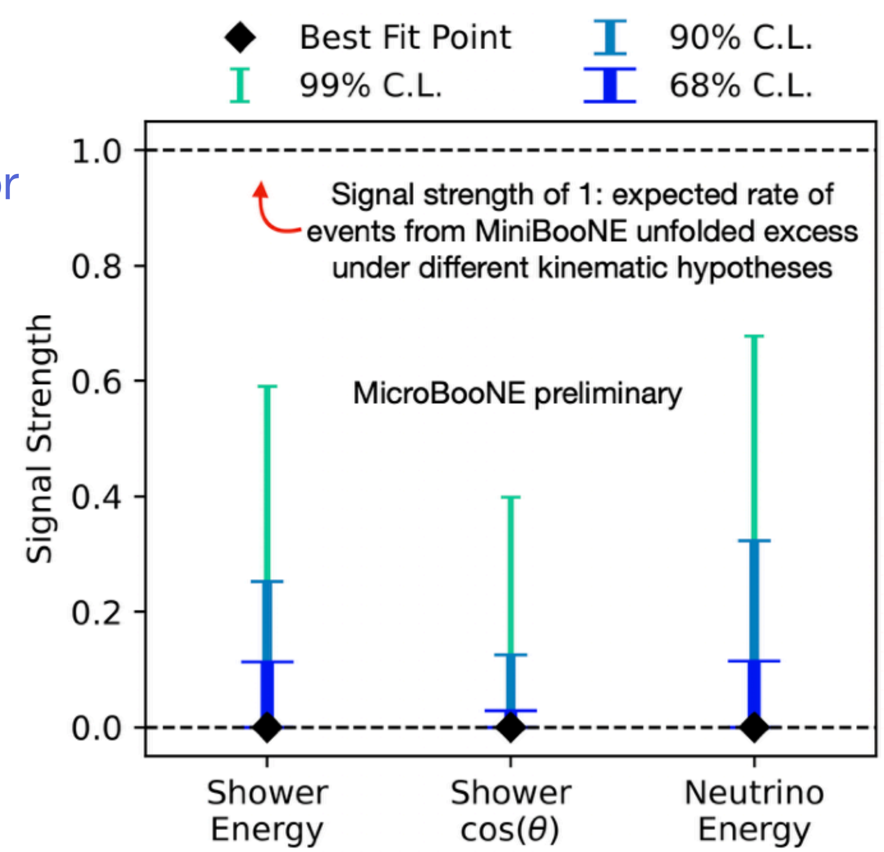
- However:

[PRL 125, 071801 (2020)](#)



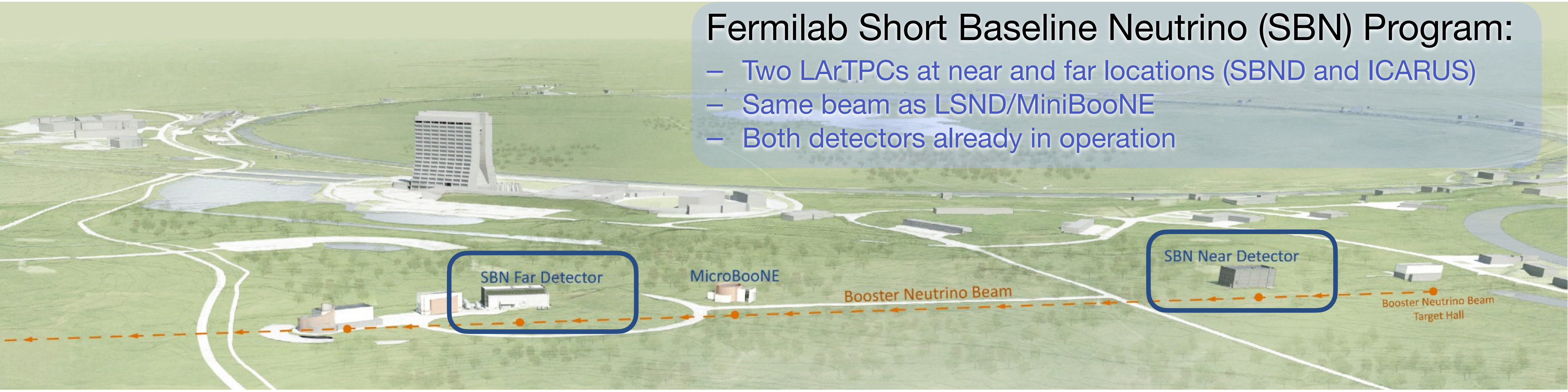
In conflict with accelerator and reactor disappearance measurements

Excess not seen by MicroBooNE experiment as either BSM e^+e^-, single-γ, or ν_e



MicroBooNE public note [1127](#)

Further Tests

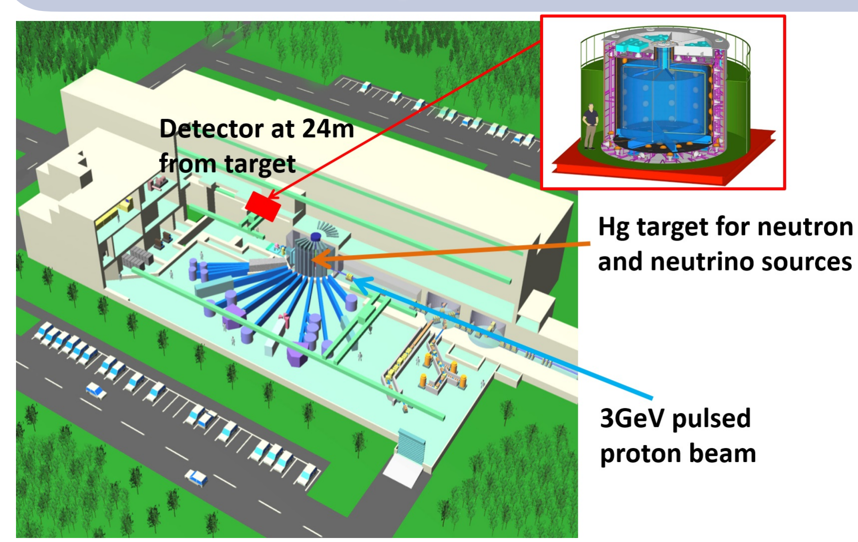


Fermilab Short Baseline Neutrino (SBN) Program:
- Two LArTPCs at near and far locations (SBND and ICARUS)
- Same beam as LSND/MiniBooNE
- Both detectors already in operation

- The Fermilab SBN and JSNS^2 experiments will provide definite tests of the oscillation hypothesis:
  - Fermilab SBN: two functionally identical detectors, very robust against flux and cross-section uncertainties
  - JSNS^2: same type of source (μ decay at rest), neutrino target (proton) and detection principle (inverse beta decay) as LSND, but with better signal-to-noise and two detectors at different baselines

arXiv:2104.13169 and arXiv:2012.10807

JSNS^2:
- Search for ν_e appearance in ν_μ beam from J-PARC's spallation neutron source
- Pulsed neutrino source from pion, muon and kaon decay at rest



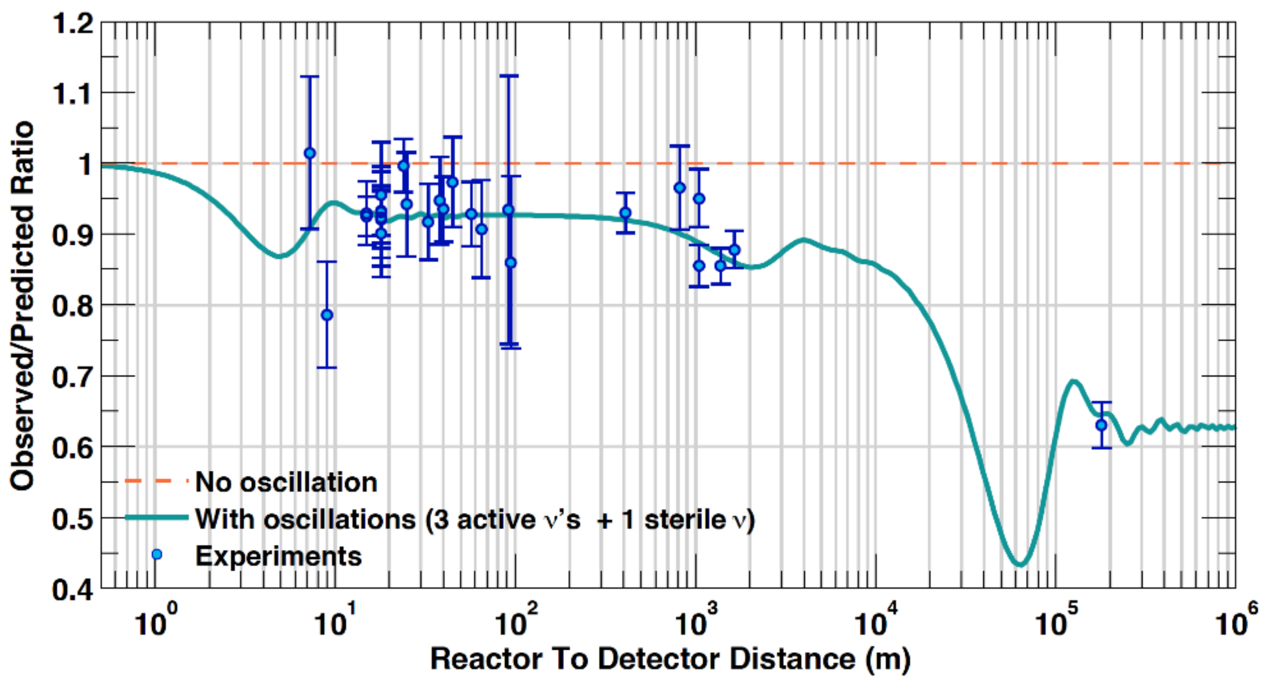
First detector already in operation

Also deploying a second detector at a baseline of 48 m

Reactor Antineutrino Anomaly (RAA)

See [arXiv:2203.07214]() for a detailed description

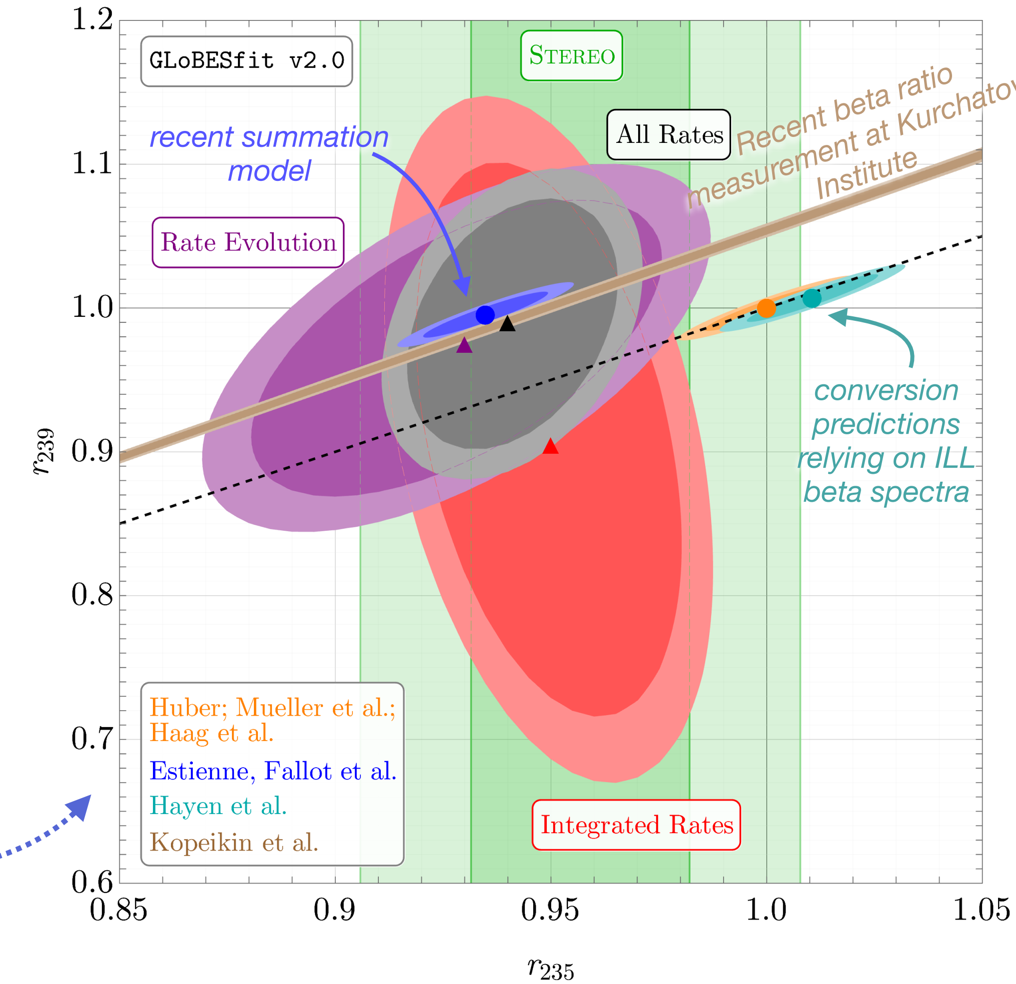
- Description: a ~6% deficit with ~3σ significance in the measured total reactor $\bar{\nu}_e$ flux versus the prediction from the Huber+Mueller (HM) model at short baselines
  - Could also be explained by ~eV sterile neutrino oscillations



  - However, new data* suggests that the HM model overestimates the $\bar{\nu}_e$ flux from ^{235}U fission

… by about the right amount to explain the anomaly!

r_X = ratio of measured over predicted rate for isotope X with respect to the HM prediction



**new data = fuel evolution in LEU experiments, measurements in HEU experiments, measurement of ^{235}U/^{239}Pu beta spectra ratio at Kurchatov Institute*

Note: there is still a discrepancy in the reactor $\bar{\nu}_e$ spectral shape

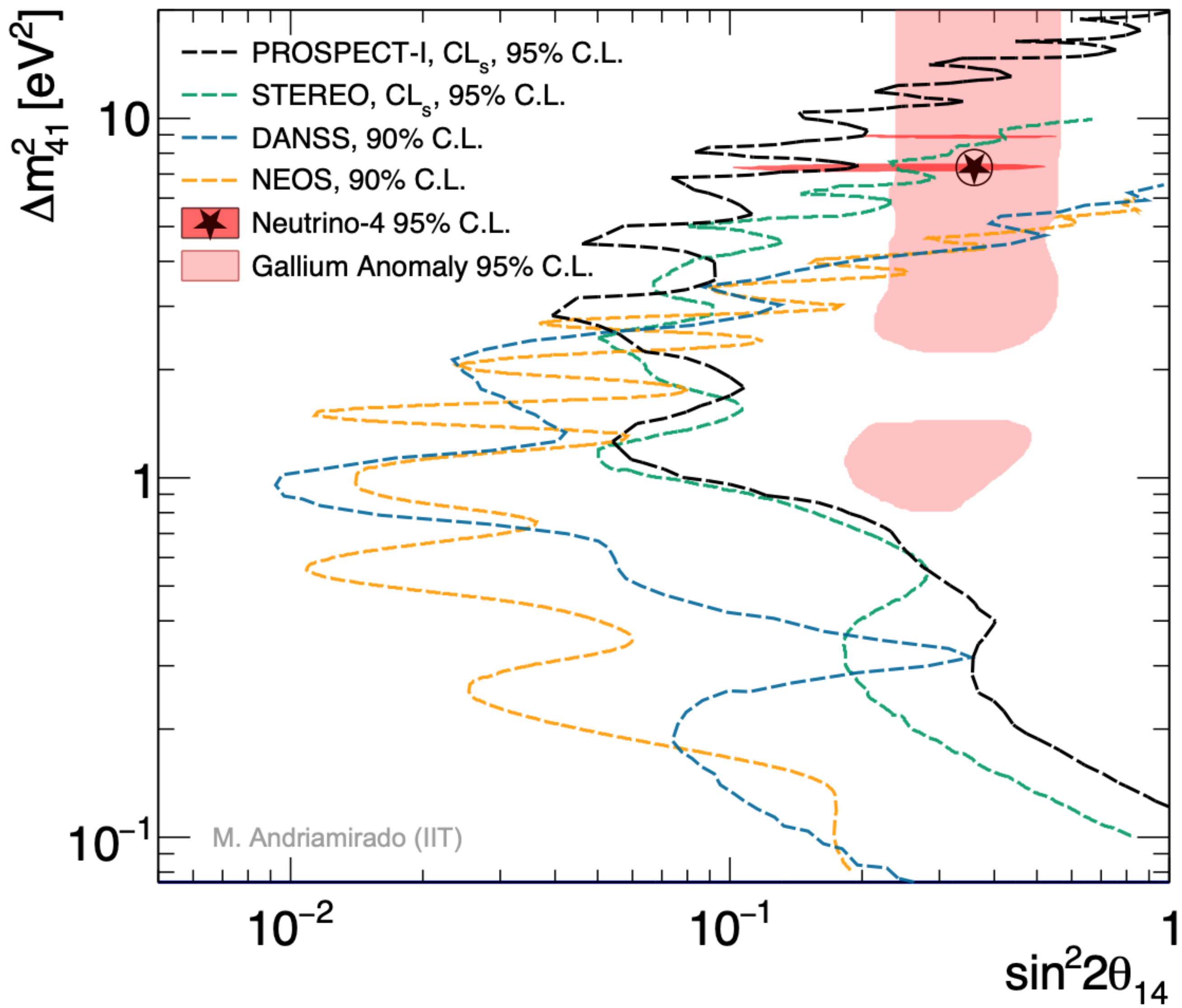
RAA Exclusion Contours and Hint

- Moreover, searches for sterile neutrino oscillations have been performed:

DANSS, NEOS, Neutrino-4, PROSPECT, SoLid, STEREO

Experiments searching for sterile neutrino oscillations at a O(10m) baseline from a nuclear reactor

  – Only one of these experiments has claimed an observation: Neutrino-4 (PRD 104, 032003 (2021))



From D. Lhuillier's talk at Neutrino 2024

- Comments about Neutrino-4's claim:
  – It is 2.7σ
  – It is controversial (e.g. PLB 816, 136214 (2021) and arXiv:2006.13639)
  – It is in strong tension with null results from other experiments (e.g. plot above)
  – It is roughly consistent with the Gallium Anomaly (next slide)

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The Gallium Anomaly

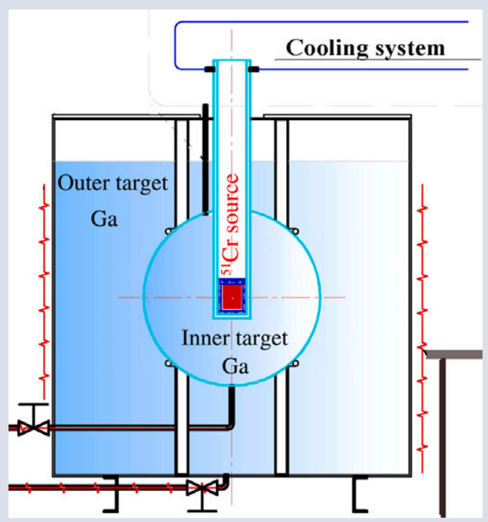
- Description: capture rates of ν_e from calibration sources on ^{71}Ga are below expectation

Gallex and SAGE:

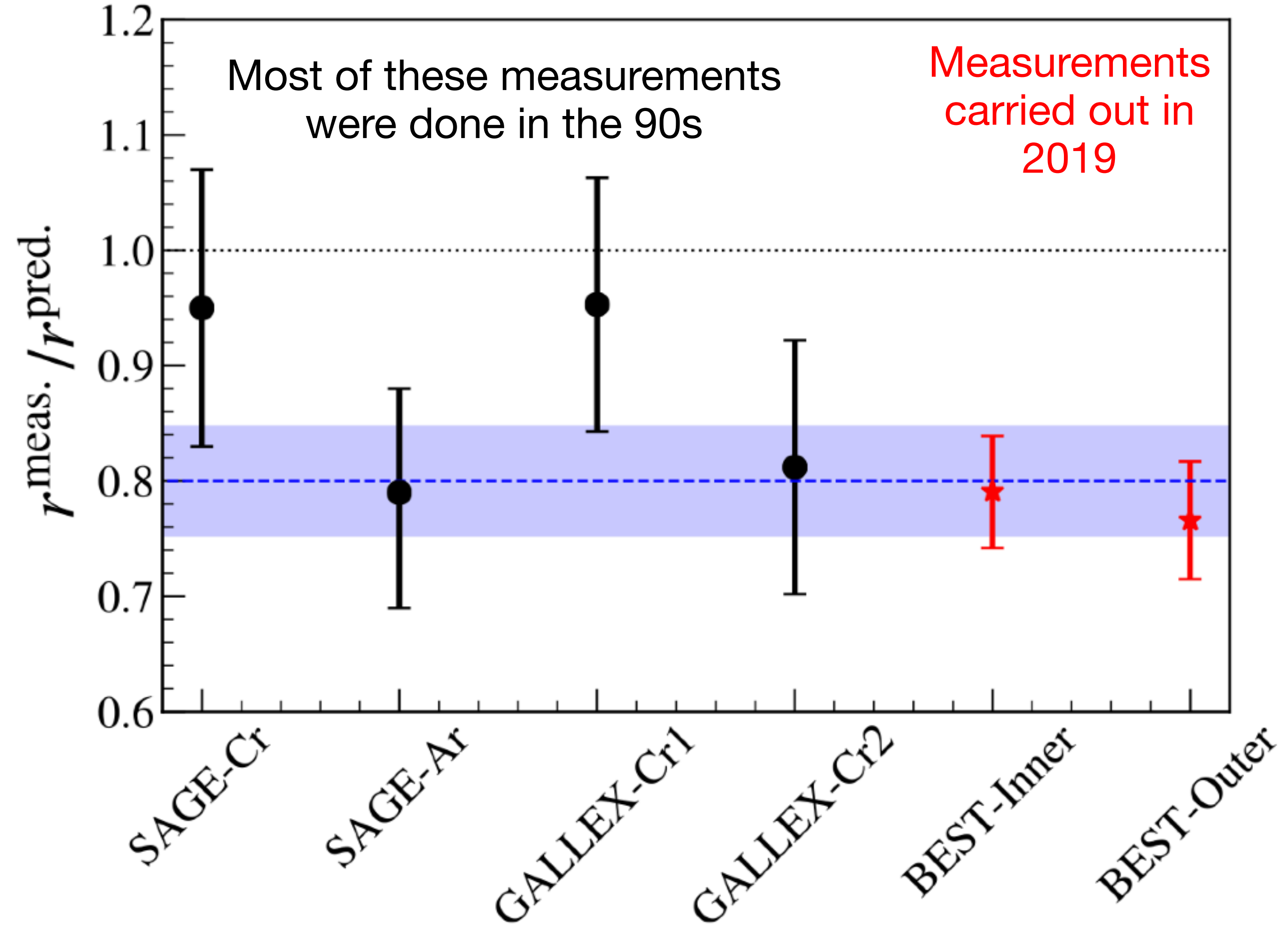
Radiochemical neutrino experiments that detected solar neutrinos via $\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^-$

BEST:

- Independent test of the Gallium Anomaly
- Two-volume design
- High-intensity ^{51}Cr source



PPNP 134, 104082 (2024)



High significance (>5σ), but oscillation interpretation in strong tension with reactor $\bar{\nu}_e$ data and KATRIN exclusion contours

- What next?
  - Several short-baseline reactor $\bar{\nu}_e$ experiments are coming online or working towards an upgrade (DANSS, JUNO-TAO, NEOS, Neutrino-4+ and PROSPECT-II)
  - KATRIN expected to fully cover Neutrino-4 and most of BEST's parameter space
  - Ideas for new tests are under planning & discussion

Summary & Conclusions

Summary & Conclusions

- Neutrino oscillations are a window to physics beyond the Standard Model and an excellent way to measure many properties of these elusive particles
- The field is now in a precision era
- The majority of the data collected to date can be explained with the 3-neutrino model
  - Sterile neutrino oscillations not ruled out, but evidence has weakened
- A global program relying on different sources, baselines and technologies is underway that will explore new territory and test the 3-neutrino model well beyond current limits:
  - We expect the following breakthroughs in rough chronological order:
    - Break the sub-percent precision barrier in some oscillation parameters
    - Make a definite determination of the mass ordering ← hopefully within this decade!
    - Make a definite observation of leptonic CP violation (if nature is kind)
    - Maybe characterize any physics beyond the 3-neutrino framework?

Stay tuned for more exciting results and (hopefully) some surprises!

Thank you for your attention!