Neutrino Masses and Mixing: Current Status and Open Questions

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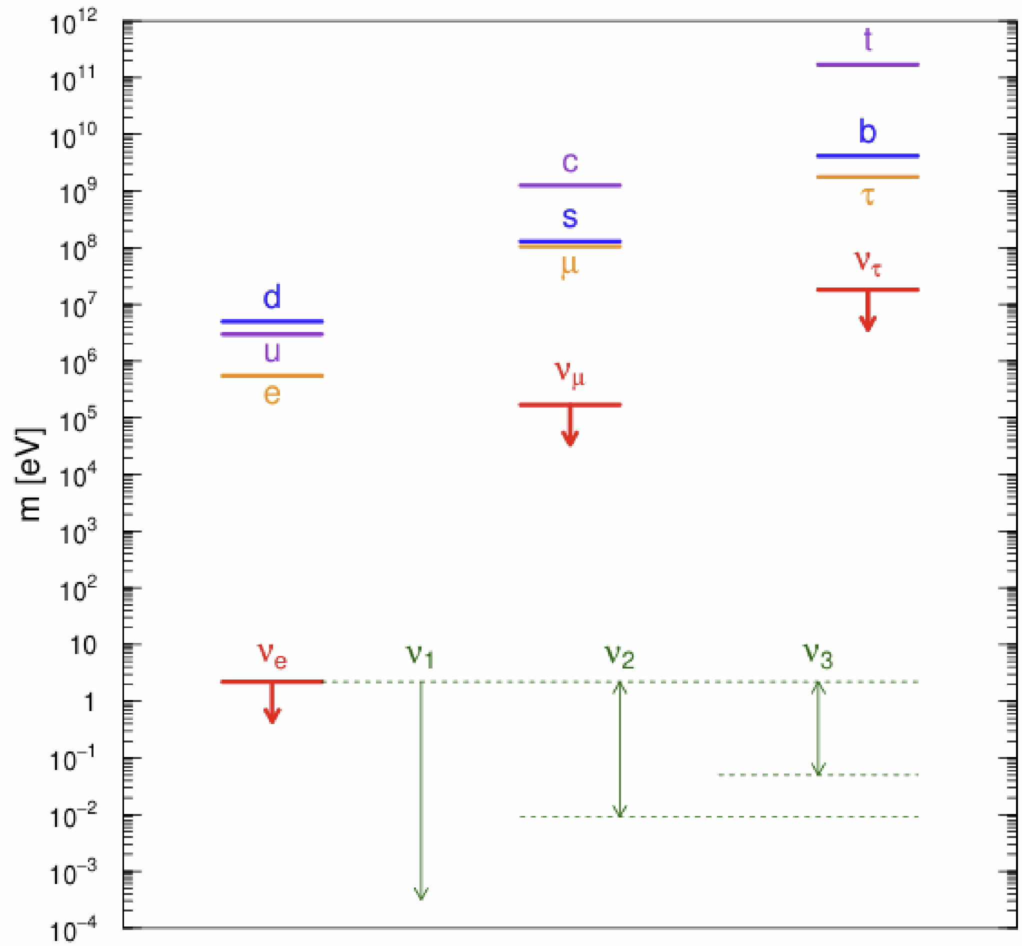
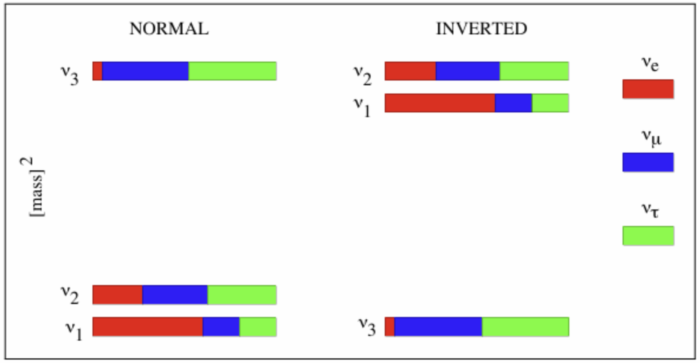
2025/9/15-2025/9/19

Neutrino mass and mixing

Neutrino mass and mixing: truly new physics beyond the standard model

Tiny neutrino mass and large mixing!





Leptons	Quarks
$\theta_{12} \approx 33^\circ$	$\theta_{12} \approx 13^\circ$
$\theta_{23} \approx 45^\circ$	$\theta_{23} \approx 2^\circ$
$\theta_{13} \approx 9^\circ$	$\theta_{13} \approx 0.2^\circ$

$$U_{PMNS} = \frac{1}{\sqrt{3}} \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(1) & \epsilon \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix} \qquad U_{CKM} = \begin{pmatrix} 1 & \epsilon & \epsilon \\ \epsilon & 1 & \epsilon \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

Three-neutrino mixing

- Flavor Neutrinos: ν_e, ν_μ, ν_τ produced in Weak Interactions
- Massive Neutrinos: ν_1, ν_2, ν_3 propagate from Source to Detector
- Neutrino Mixing:

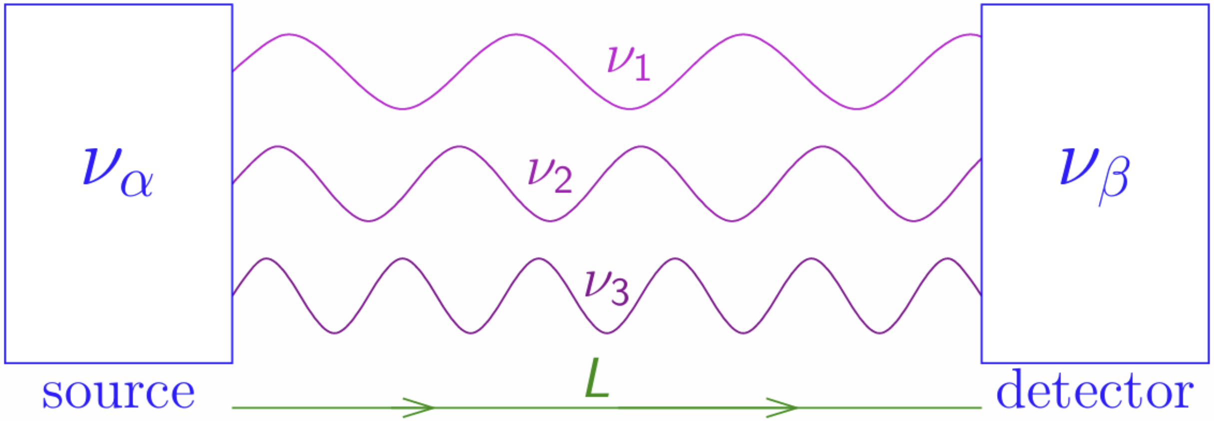
  Flavor Neutrinos are superpositions of Massive Neutrinos

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- U is the 3×3 unitary Neutrino Mixing Matrix

Neutrino oscillations

$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = U_{\alpha 1}\,|\nu_1\rangle + U_{\alpha 2}\,|\nu_2\rangle + U_{\alpha 3}\,|\nu_3\rangle$$



$$|\nu(t>0)\rangle = U_{\alpha 1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{\alpha 2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{\alpha 3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_\alpha\rangle$$

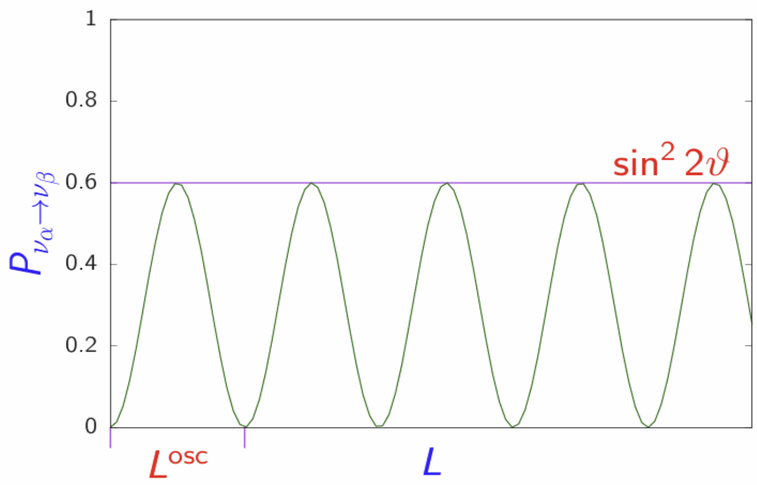
$$E_k^2 = p^2 + m_k^2 \qquad\qquad t = L$$

$$P_{\nu_\alpha\to\nu_\beta}(L) = |\langle\nu_\beta|\nu(L)\rangle|^2 = \sum_{k,j} U_{\beta k} U_{\alpha k}^{*} U_{\beta j}^{*} U_{\alpha j} \exp\left(-i\frac{\Delta m_{kj}^2 L}{2E}\right)$$

The oscillation probabilities depend on U and $\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$

Neutrino oscillations

2ν-mixing: $P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\vartheta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \implies \boxed{L^{\text{osc}} = \frac{4\pi E}{\Delta m^2}}$



Tiny neutrino masses lead to observable macroscopic oscillation distances!

$$\frac{L}{E} \lesssim \begin{cases} 10 \, \frac{\text{m}}{\text{MeV}} \; \left(\frac{\text{km}}{\text{GeV}}\right) & \text{short-baseline experiments} & \Delta m^2 \gtrsim 10^{-1}\,\text{eV}^2 \\ 10^3 \, \frac{\text{m}}{\text{MeV}} \; \left(\frac{\text{km}}{\text{GeV}}\right) & \text{long-baseline experiments} & \Delta m^2 \gtrsim 10^{-3}\,\text{eV}^2 \\ 10^4 \, \frac{\text{km}}{\text{GeV}} & \text{atmospheric neutrino experiments} & \Delta m^2 \gtrsim 10^{-4}\,\text{eV}^2 \\ 10^{11} \, \frac{\text{m}}{\text{MeV}} & \text{solar neutrino experiments} & \Delta m^2 \gtrsim 10^{-11}\,\text{eV}^2 \end{cases}$$

Neutrino oscillations are the optimal tool to reveal tiny neutrino masses!

Three-neutrino mixing matrix

Standard Parameterization of Mixing Matrix (as CKM)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$c_{ab} \equiv \cos\vartheta_{ab} \qquad s_{ab} \equiv \sin\vartheta_{ab} \qquad 0 \leq \vartheta_{ab} \leq \frac{\pi}{2} \qquad 0 \leq \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$

OSCILLATION PARAMETERS
- 3 Mixing Angles: ϑ_{12}, ϑ_{23}, ϑ_{13}
- 1 CPV Dirac Phase: δ_{13}
- 2 independent $\Delta m^2_{kj} \equiv m^2_k - m^2_j$: Δm^2_{21}, Δm^2_{31}

2 CPV Majorana Phases: λ_{21}, λ_{31} $\Longleftrightarrow$ $|\Delta L| = 2$ processes

Mixing parameters: the solar sector

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

Solar

$\nu_e \to \nu_\mu, \nu_\tau$

(SNO, Borexino; Super-Kamiokande; GALLEX/GNO, SAGE; Homestake, Kamiokande)

VLBL Reactor

$\bar{\nu}_e$ disappearance

(KamLAND)

$\to$

$$\Delta m^2_S = \Delta m^2_{21} = (7.36 \pm 0.155) \times 10^{-5}\ \text{eV}^2$$

($\sim$ 2.3% accuracy)

$$\sin^2\vartheta_S = \sin^2\vartheta_{12} = 0.303 \pm 0.013$$

($\sim$ 4.5% accuracy)

[A. Marrone, talk at NeuTel 2021]

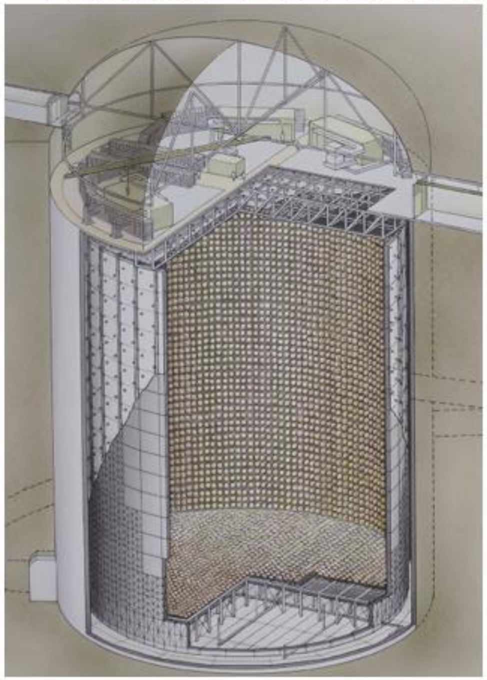
[Capozzi, Di Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2003.08511]

[de Salas, Forero, Gariazzo, Martinez-Mirave, Mena, Ternes, Tortola, Valle, arXiv:2006.11237]

[Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, arXiv:2007.14792]

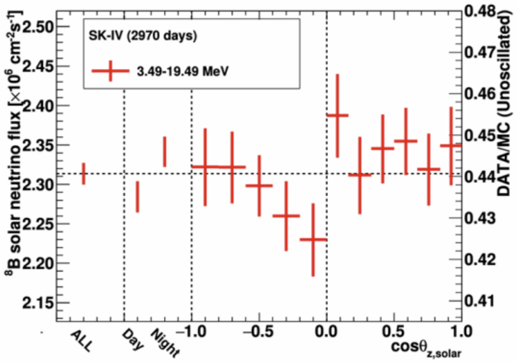
Mixing parameters: the solar sector

Solar neutrino measurements using the full data period of Super-Kamiokande-IV
Phys. Rev. D 109, 092001 (2024)



Phase	SK-I	SK-II	SK-III	SK-IV
Period (Start)	Apr. '96	Oct. '02	Jul. '06	Sep. '08
Period (End)	Jul. '01	Oct. '05	Aug. '08	May '18
Livetime [days]	1,496	791	548	2,970
ID PMTs	11,146	5,182	11,129	11,129
OD PMTs	1,885	1,885	1,885	1,885
PMT coverage [%]	40	19	40	40
Energy thr. [MeV]	4.49	6.49	3.99	3.49

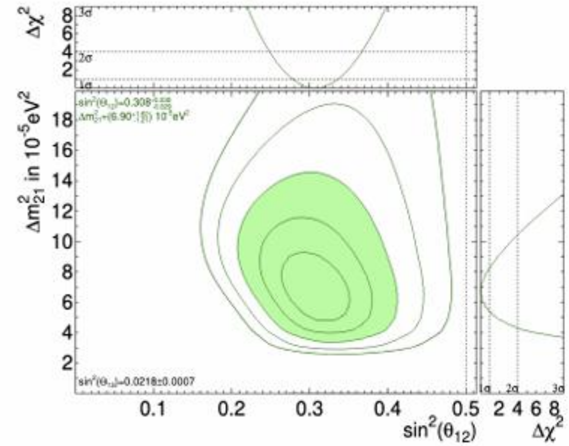
^{8}B



SK IV: $A_{D/N}^{SK-IV,fit} = -0.0262 \pm 0.0107(\text{stat.}) \pm 0.0030(\text{syst})$

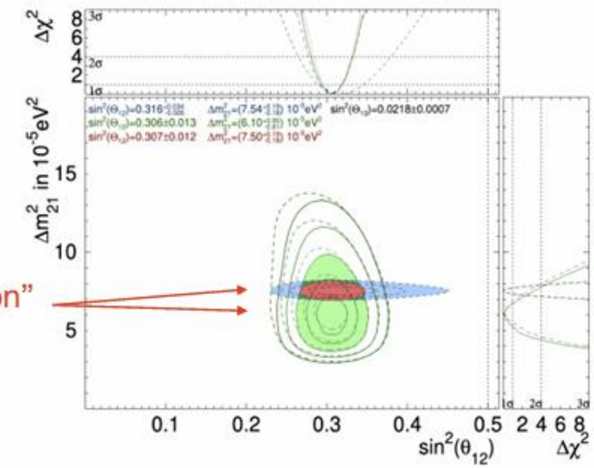
SK I-IV: $A_{D/N}^{SK,fit} = -0.0286 \pm 0.0085(\text{stat.}) \pm 0.0032(\text{syst})$ → 3.36σ

Best fit oscillation parameters from SK-IV



Combined SK I-IV and with SNO (dotted) compared with KamLAND (blue)

1.5σ "tension"



Mixing parameters: the atmospheric sector

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

Atmospheric $\nu_\mu \to \nu_\tau$	(Super-Kamiokande, Kamiokande, IMB, MACRO, Soudan-2)
LBL Accelerator ν_μ disappearance	(K2K, MINOS, T2K, NOνA)
LBL Accelerator $\nu_\mu \to \nu_\tau$	(OPERA)

$\to$

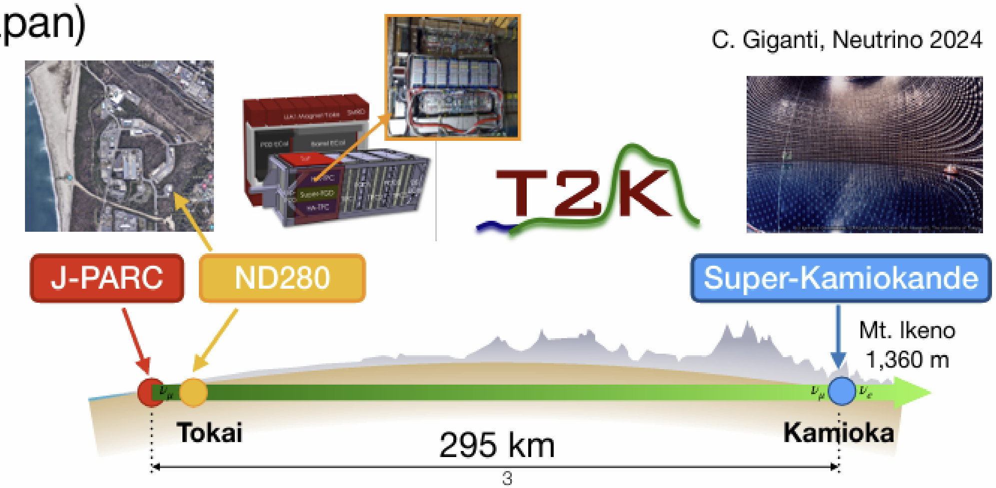
$$\begin{aligned} \Delta m^2_{\rm A} &= |\Delta m^2_{31} + \Delta m^2_{32}|/2 \\ &= (2.475 \pm 0.028) \times 10^{-3}\ {\rm eV}^2 \\ &\quad (\sim 1.1\%\ \text{accuracy}) \quad \text{(NO)} \\ &= (2.455 \pm 0.028) \times 10^{-3}\ {\rm eV}^2 \\ &\quad (\sim 1.2\%\ \text{accuracy}) \quad \text{(IO)} \end{aligned}$$

$$\begin{aligned} \sin^2\vartheta_{\rm A} &= \sin^2\vartheta_{23} \\ &= 0.569 \pm 0.017 \\ &\quad (\sim 5.4\%\ \text{accuracy}) \end{aligned}$$

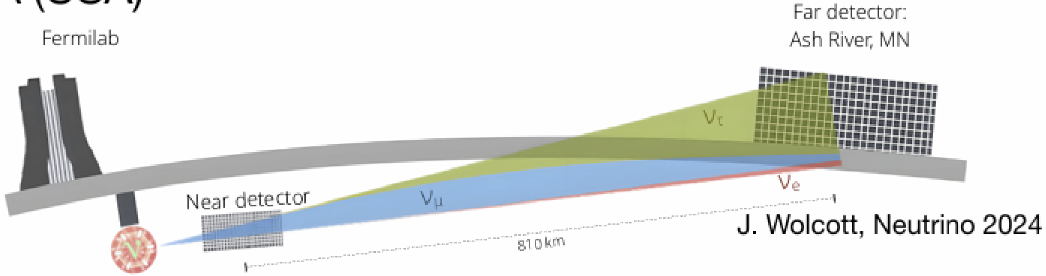
[A. Marrone, talk at NeuTel 2021]
[Capozzi, Di Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2003.08511]
[de Salas, Forero, Gariazzo, Martinez-Mirave, Mena, Ternes, Tortola, Valle, arXiv:2006.11237]
[Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, arXiv:2007.14792]

Mixing parameters: the atmospheric sector

T2K (Japan)



NOvA (USA)



$\nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu$ —Neutrino mode→ $\nu_\mu, \nu_\mu, \nu_e, \nu_e, \nu_\tau, \nu_\tau, \nu_\tau$

$\bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu$ —Anti-neutrino mode→ $\bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_e, \bar{\nu}_\tau, \bar{\nu}_\tau, \bar{\nu}_\tau, \bar{\nu}_\tau$

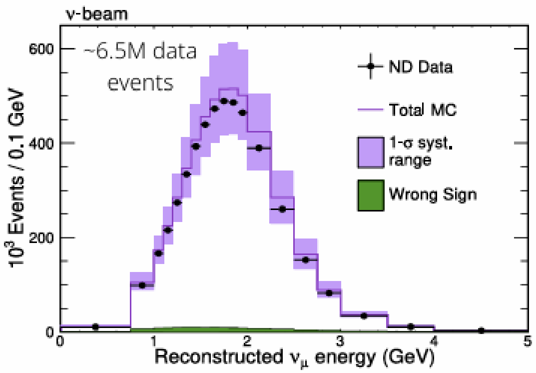
- Selectable ν_μ or $\bar{\nu}_\mu$ beams by focusing $\pi^\pm$ produced by p beam on fixed target
- Precision study of $\nu_\mu \to \nu_{e,\mu}$ oscillations near first oscillation maximum
- Low $\nu_e/\bar{\nu}_e$ contamination allows study of $\nu_\mu \to \nu_e$ oscillations for both $\nu/\bar{\nu}$
- Near detectors to measure neutrinos before oscillations
  ↓
  constrain flux × interaction systematics

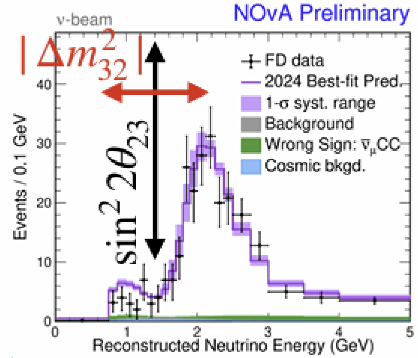
Mixing parameters: the atmospheric sector

Neutrino 2024 Preliminary

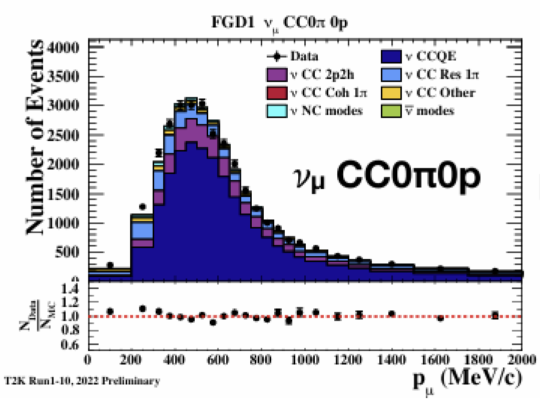
ν_μ disappearance

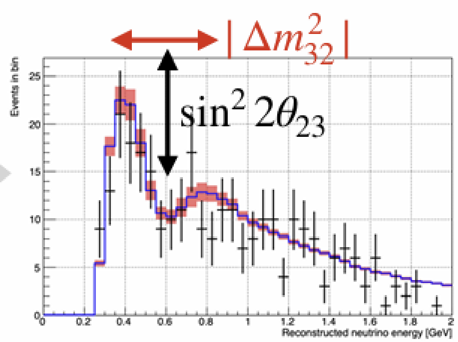
ND | **FD**





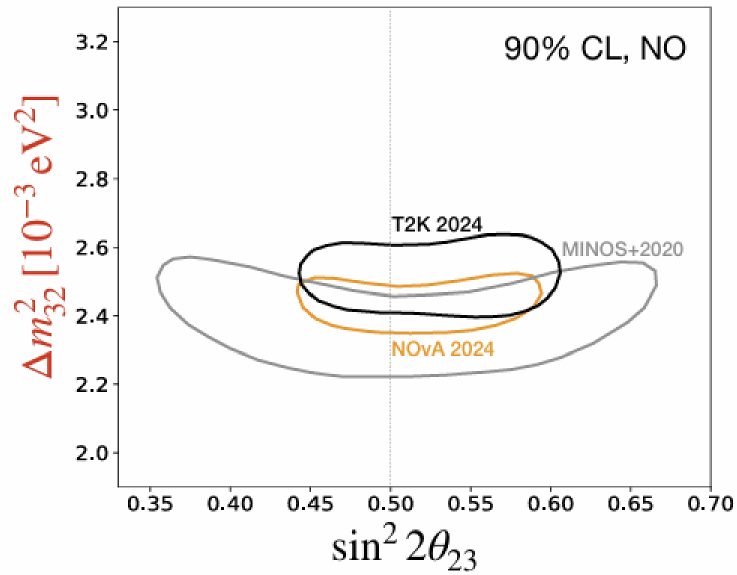
384 ν_μ data candidates
(11.3 background)





NOvA doubled ν-mode statistics → leading

T2K 10% more ν-mode compared to 2022 and reduced FD detector systematics



Consistent with maximal mixing

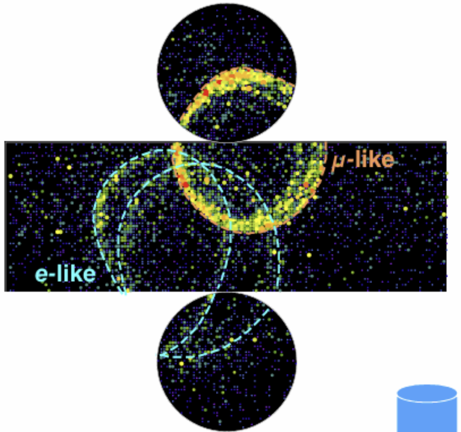
T2K has been upgrading beam-line and ND.
→ expect improvement in future.

Mixing parameters: the atmospheric sector

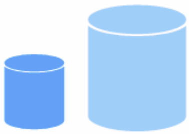
Atmospheric ν detectors

detectors drawn roughly to scale

Surface covering



PhysRevD.109.072014

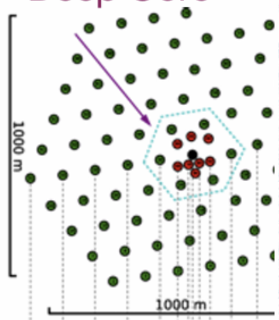


SuperK

HyperK

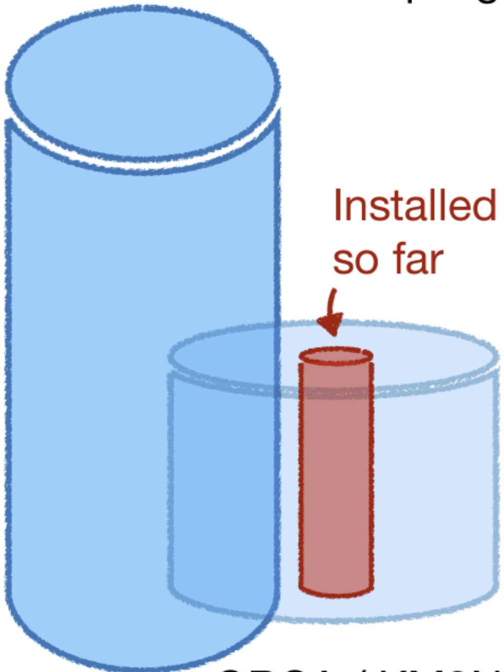
Detailed event reconstruction over wide E_ν down to sub-GeV

3D sampling



IceCube (South Pole)

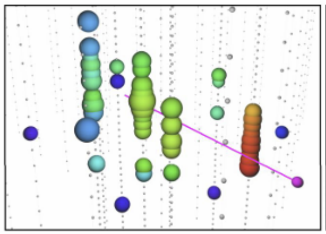
DeepCore 10 Mton

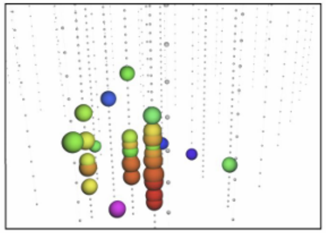


Installed so far

ORCA / KM3Net (Mediterranean Sea) 7 Mt

Track-like (ν_μ)



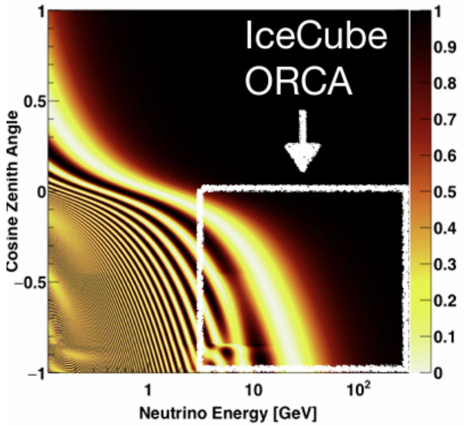


Shower-like (ν_e, NC, …)

Ice Cube, Neutrino 2024

Mixing parameters: the atmospheric sector

ν_μ disappearance



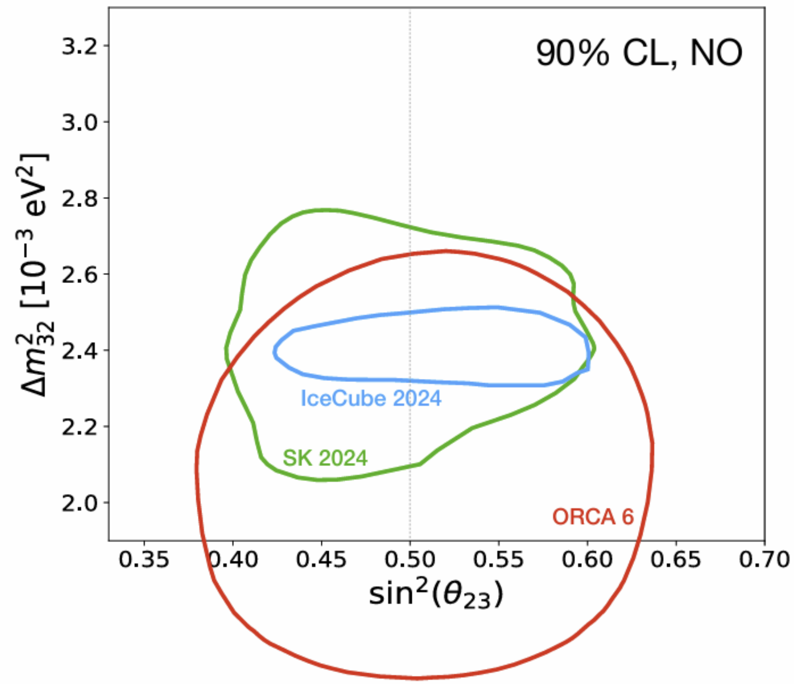
SuperK

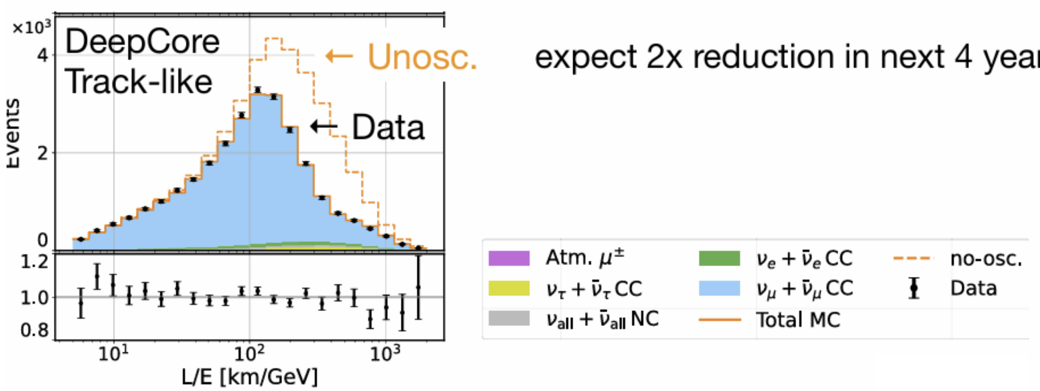
- **SuperK:** 20% expansion of fiducial volume + additional years.
  `PRD 109, 072014 (2024)`

  In total 48% statistics increase over previous publication

- **DeepCore** moved to CNN-based reconstruction + 2 years
  ↓
  7x increase in statistics
  `arXiv:2405.02163`

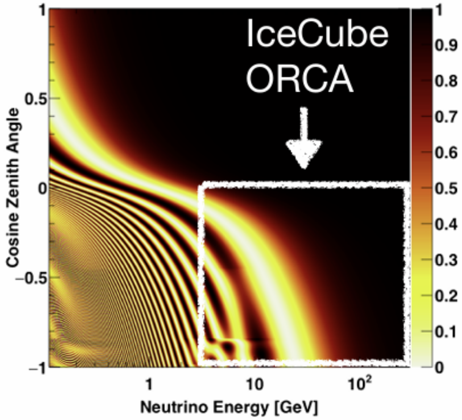
  expect 2x reduction in next 4 years



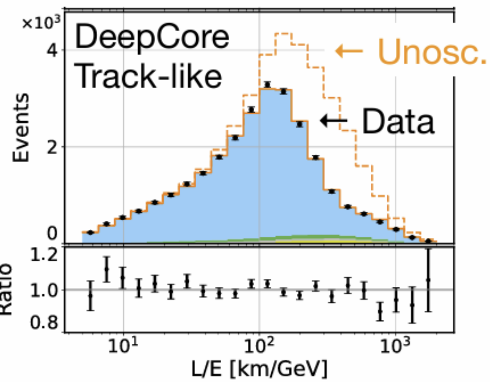


Mixing parameters: the atmospheric sector

ν_μ disappearance



SuperK



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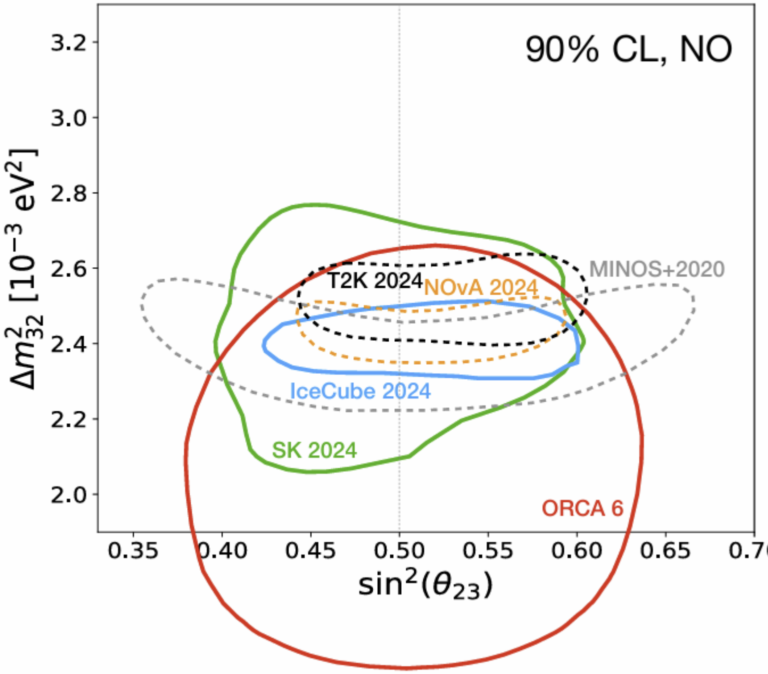


Consistent results, and now competitive (IC) with accelerator measurements

note: 20~50x longer baselines and energies

Mixing parameters: the θ_{13} sector

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

LBL Accelerator (T2K, MINOS, NOνA)
$\nu_\mu \to \nu_e$

LBL Reactor (Daya Bay, RENO, Double Chooz)
$\bar{\nu}_e$ disappearance

$\rightarrow$

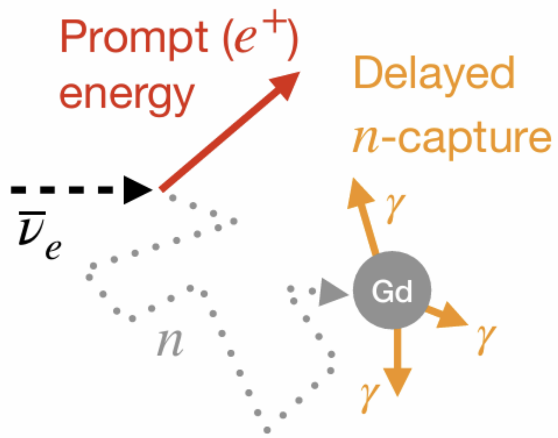
$$\Delta m^2_A = |\Delta m^2_{31} + \Delta m^2_{32}|/2$$

$$\sin^2 \vartheta_A = \sin^2 \vartheta_{13} = 0.0223 \pm 0.0006$$

($\sim$ 2.9% accuracy)

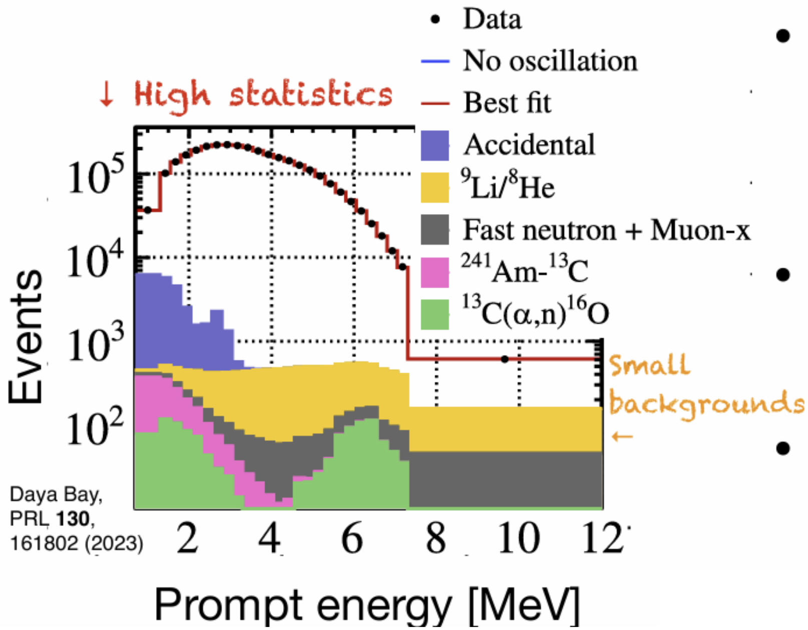
[A. Marrone, talk at NeuTel 2021]
[Capozzi, Di Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2003.08511]
[de Salas, Forero, Gariazzo, Martinez-Mirave, Mena, Ternes, Tortola, Valle, arXiv:2006.11237]
[Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, arXiv:2007.14792]

Mixing parameters: the θ_{13} sector



Medium Baseline (km) Reactor Experiments

- Intense anti-neutrino flux from reactor beta decay chain
- Detection in liquid scintillator via inverse-beta decay with delayed coincidence $\overline{\nu}_e + p \rightarrow e^+ + n$
- Neutrino energy inferred from e^+ energy deposit in LS
- Delayed γ from neutron capture on Gd (main) or H (sub) for significant background reduction



Daya Bay, PRL **130**, 161802 (2023)

Mixing parameters: the θ_{13} sector

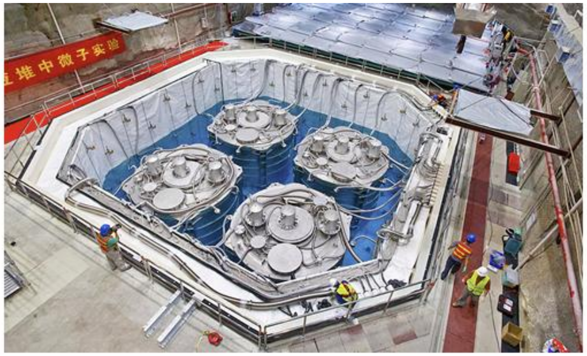
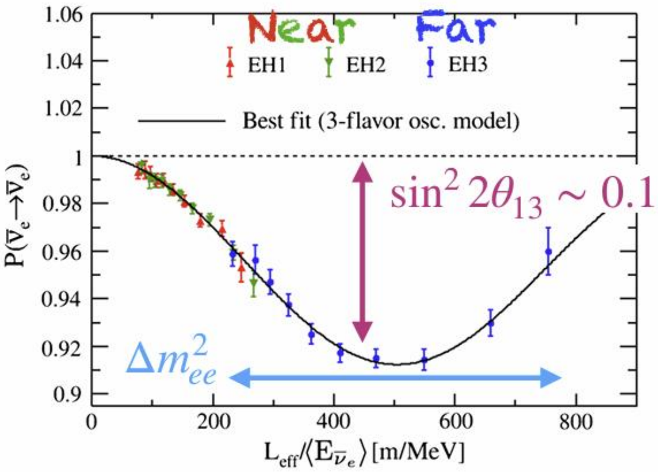


Photo: Roy Kaltschmidt, Berkeley Lab

DayaBay (PRL.130.161802)



Very clear oscillation signature

Medium Baseline (km) Reactor Experiments

- 3 experiments with similar design
  Double Chooz (France),
  Daya Bay (China),
  RENO (Korea)

  All have completed data taking

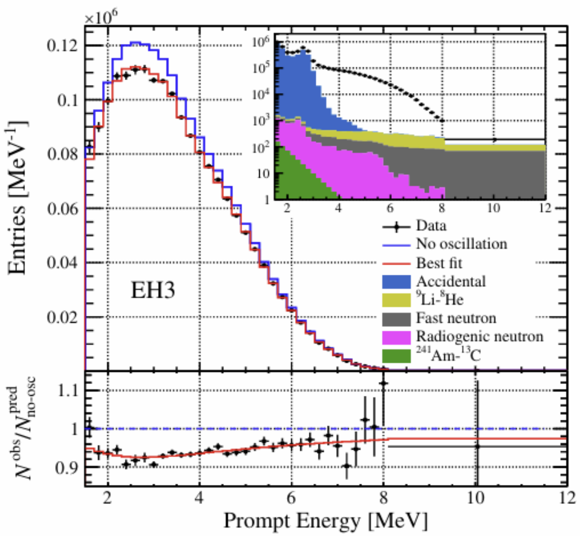
- Identical detectors near and far (~ 1 km) from reactor allows cancellation of many systematic effects

- Oscillation of $\bar{\nu}_e \to \bar{\nu}_e$ at first osc. max.

  Approximately 2-flavor osc. with amplitude $\sin^2 2\theta_{13}$ and frequency $|\Delta m^2_{ee}| \approx |\Delta m^2_{31}|$

θ_{13} constraints

Daya Bay nH analysis
PRL **133**, 151801 (2024)



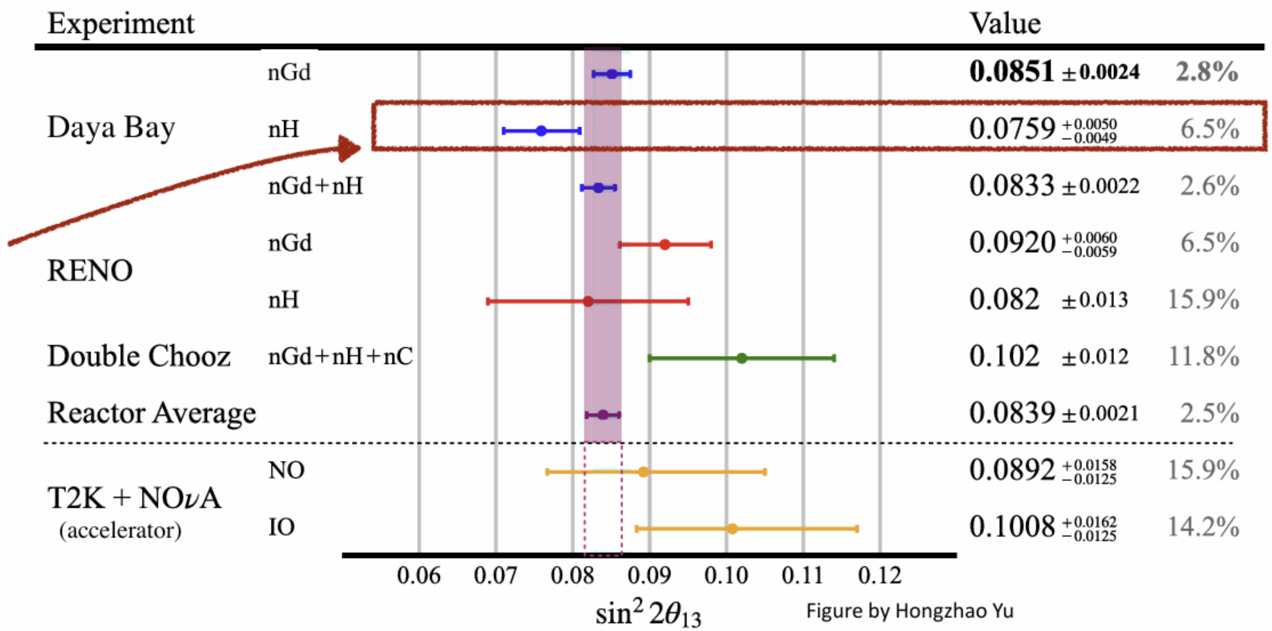
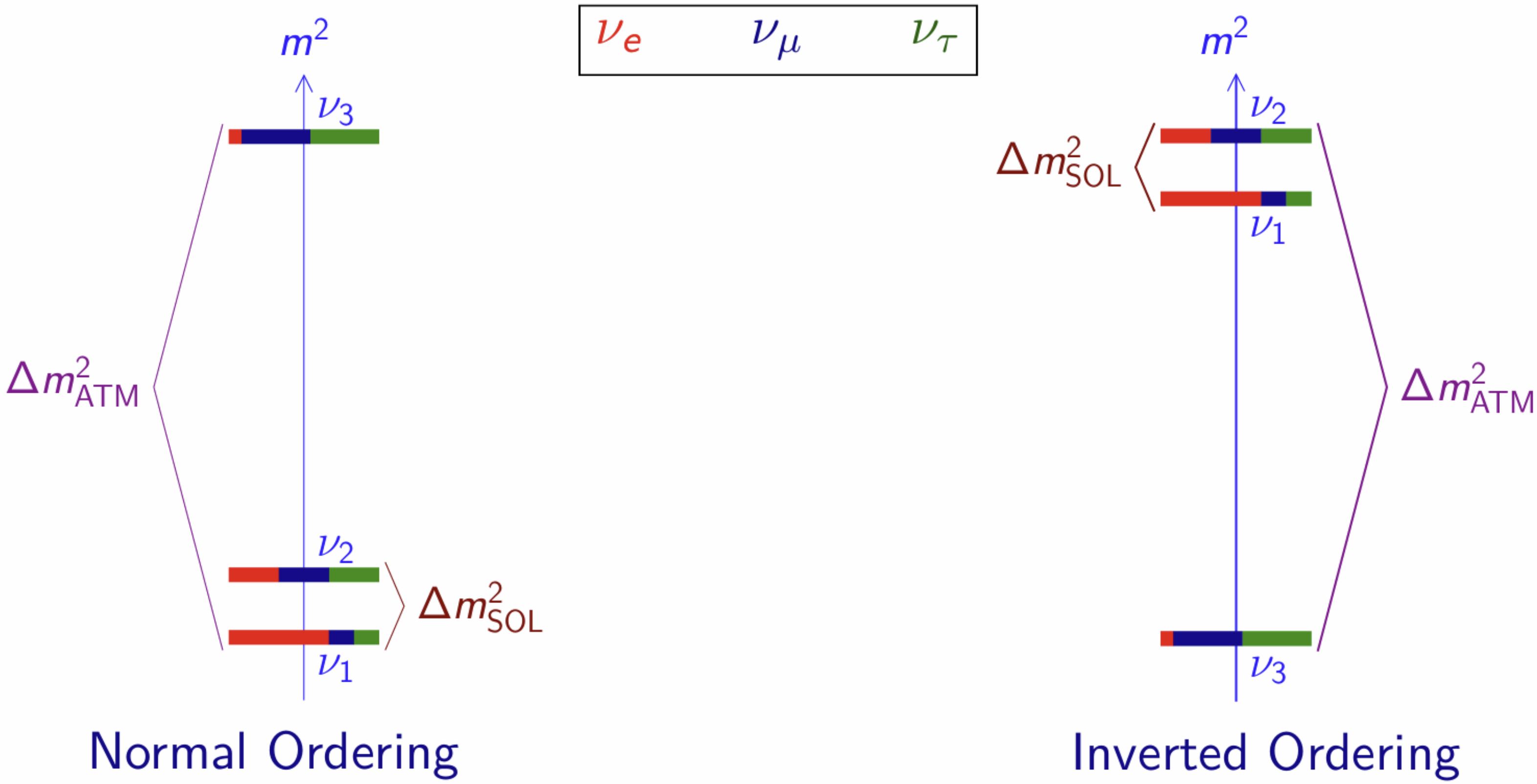


Figure by Hongzhao Yu

Slightly modified emphasis

Note: average is error weighted average assuming no correlation

Unknowns: mass ordering and CP violation



$\Delta m^2_{31} > \Delta m^2_{32} > 0$

$\Delta m^2_{32} < \Delta m^2_{31} < 0$

absolute scale is not determined by neutrino oscillation data

Unknowns: mass ordering and CP violation

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\alpha\beta} - 4 \underbrace{\sum_{k>j} \mathrm{Re}\left[U_{\alpha k}^* \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^*\right] \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right)}_{\text{CP conserving}}$$

$$+ 2 \underbrace{\sum_{k>j} \mathrm{Im}\left[U_{\alpha k}^* \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^*\right] \sin\left(\frac{\Delta m_{kj}^2 L}{2E}\right)}_{\text{CP violating}}$$

- The oscillation probabilities depend on the quartic rephasing invariants

$$U_{\alpha k}^* \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^*$$

- CP violation depends on the Jarlskog invariant

$$J_{\mathrm{CP}} = \pm \, \mathrm{Im}\left[U_{\alpha k}^* \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^*\right] = c_{12} s_{12} c_{23} s_{23} c_{13}^2 s_{13} \sin\delta_{13}$$

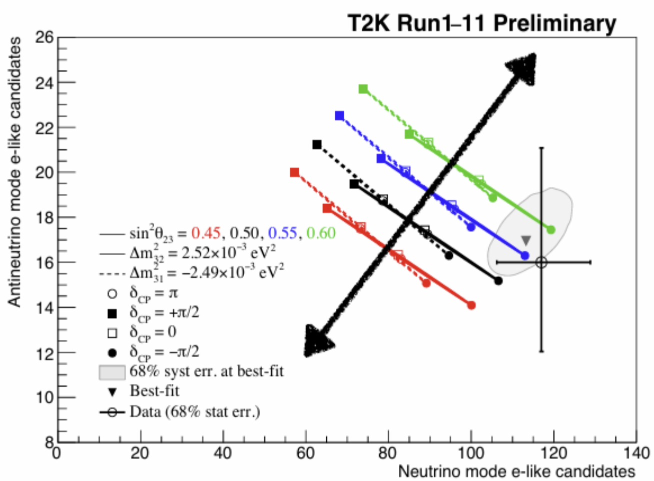
Unknowns: from accelerator neutrinos

$\nu_e/\overline{\nu}_e$ appearance

Currently mostly a rate measurement

T2K

$\#\overline{\nu}_e$

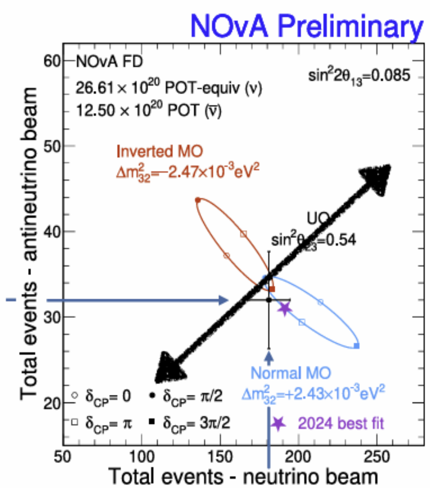


$\#\nu_e$

NOvA

$\#\overline{\nu}_e$

32 $\overline{\nu}_e$ data candidates



181 ν_e data candidates

$\#\nu_e$

Correlated change

Accelerator only: θ_{13}

With reactor θ_{13} :

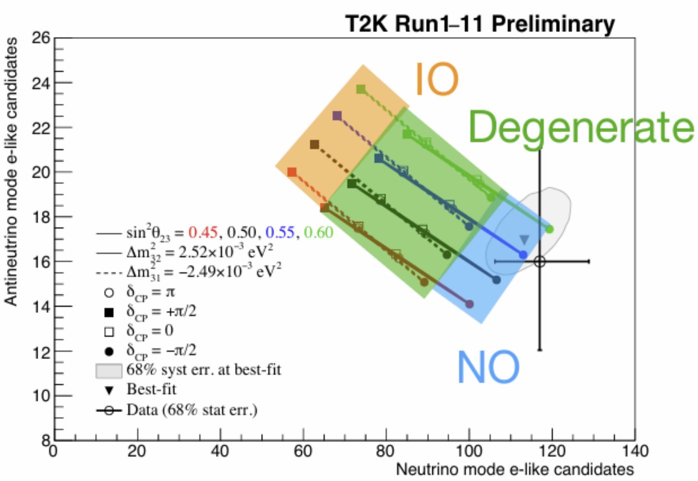
θ_{23} octant, $\cos\delta_{CP}$

Unknowns: Mass ordering and CP

$\nu_e/\overline{\nu}_e$ appearance

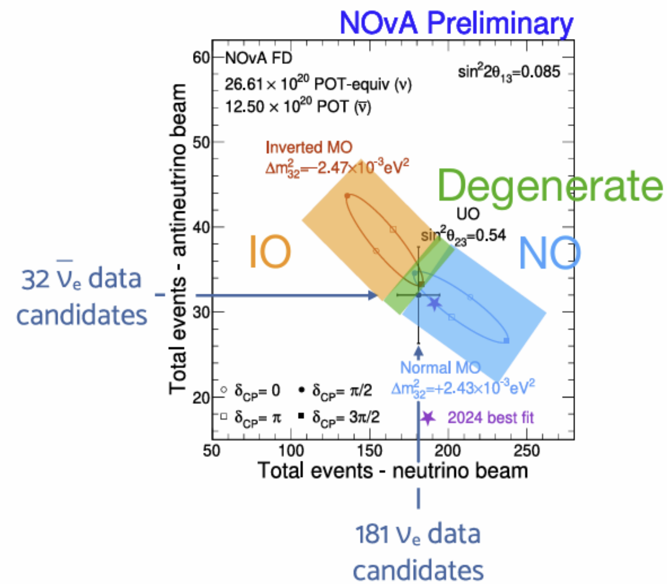
Currently mostly a rate measurement

T2K



Preference for NO

NOvA



More sensitivity to MO than T2K due to higher energy (longer baseline).

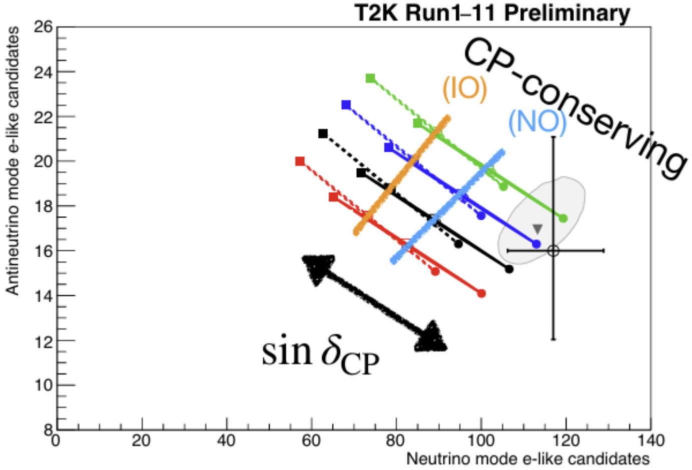
But data prefers MO-degenerate region

Unknowns: mass ordering and CP

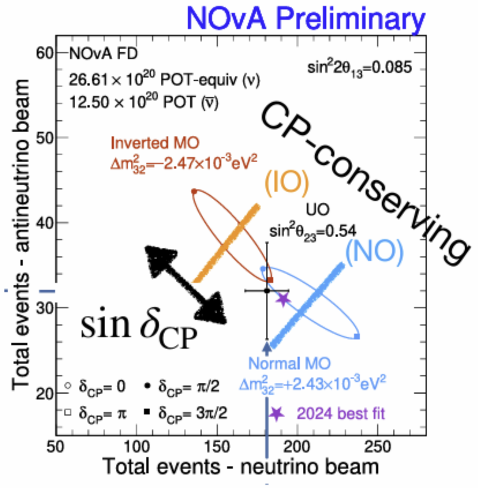
$\nu_e/\bar{\nu}_e$ appearance

Currently mostly a rate measurement

T2K



NOvA



Preference for $\delta_{CP} \approx -\pi/2$

Data outside of MO-degeneracy = stronger CP constraint

δ_{CP} preference depends on MO

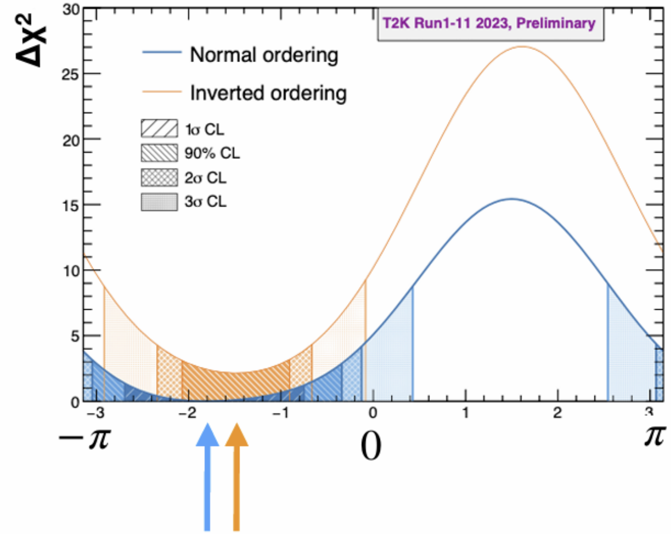
Unknowns: mass ordering and CP

Using reactor θ_{13} constraint
(different values are used)

warn: difference in freq vs. bayesian

T2K

Smaller = more favored

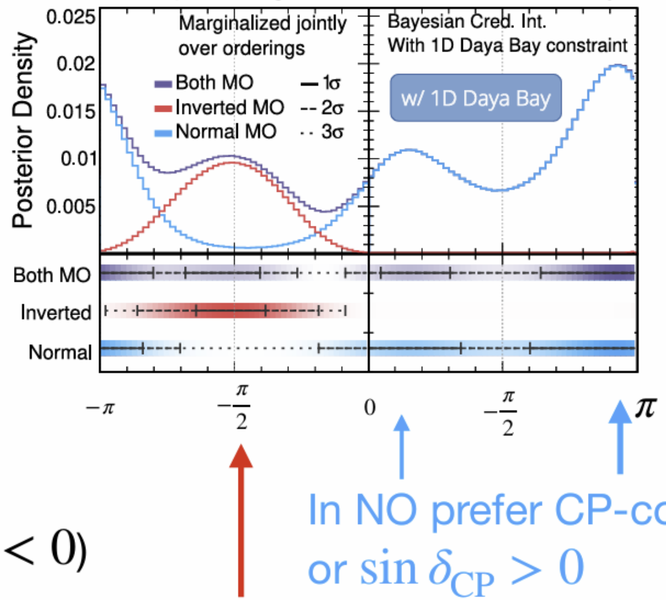


Preference for CP violation ($\sin\delta_{CP} < 0$)

Mild NO preference* (1.7σ_{freq})

NOvA

NOvA Preliminary (Neutrino 2024)
note: plot range modified for consistency



Larger = more favored

In NO prefer CP-conserving or $\sin\delta_{CP} > 0$

In IO prefer CP-violation ($\sin\delta_{CP} < 0$)

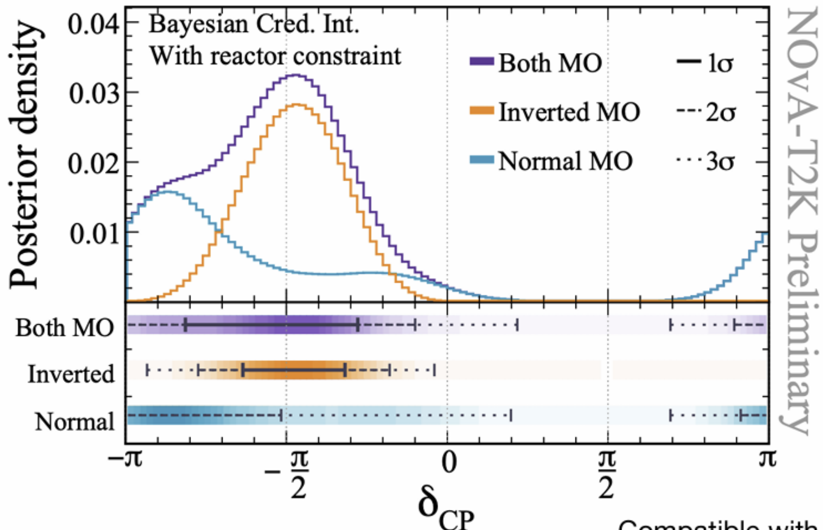
Mild NO preference (1.4σ_{freq})

Neutrino 2024, Preliminary
* Carabadjac Denis, ICHEP 2024, T2K Preliminary

Unknowns: mass ordering and CP

T2K + NOvA

NOvA only: Phys. Rev. D106, 032004 (2022)
T2K only: Eur. Phys. J. C83, 782 (2023)
Input analyses are not latest results, but first shown in 2020



- If IO, CP violated at 3σ
  (Above plot is normalized over both MO, but conclusion also holds when conditioned on IO)
- If NO, consistent with CP conservation

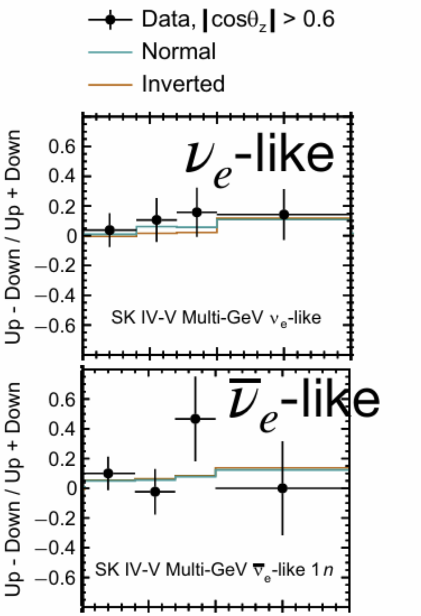
Compatible with both MO, posterior influenced by reactor constraint

NOVA+T2K only : IO (71%)
+ 1D θ_{13} : IO (57%)
+ 2D $\left(\theta_{13}, \Delta m^2_{32}\right)$: NO (59%)

- Different degeneracy of δ_{CP}, MO, and θ_{23} octant → synergy
- A first joint fit was performed using the analyses first shown in 2020
  (publication in preparation)
- Candidate for systematic correlations: ν interactions
  - No trivial mapping between parameters
    (except $\nu_e/\overline{\nu}_e$ systematics which were correlated)
  - At current statistics omitting correlations found to not affect result
  - Studied impact of interaction model differences, all tests pass pre-set criteria

Mass ordering

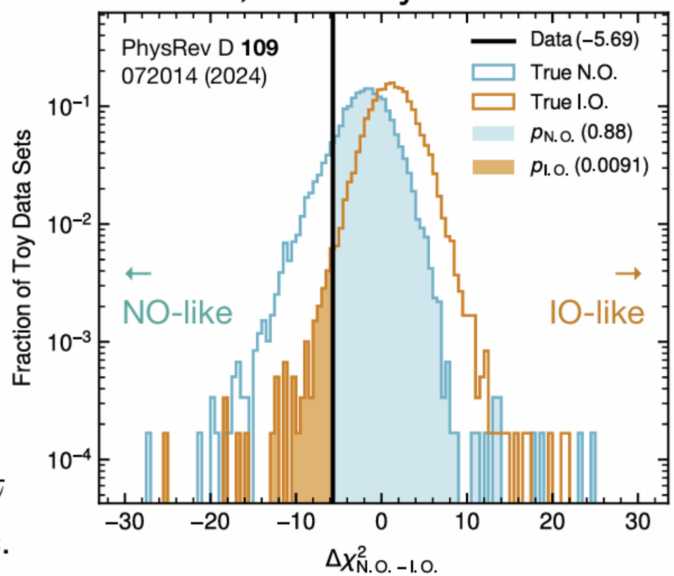
From matter resonance



(subset of sensitive samples shown)

- SK performs statistical $\nu/\overline{\nu}$ separation using # of π etc. to enhance purity
- Updates to selection
  Multi-Ring: likelihood → BDT
  Single-Ring: + neutron tag

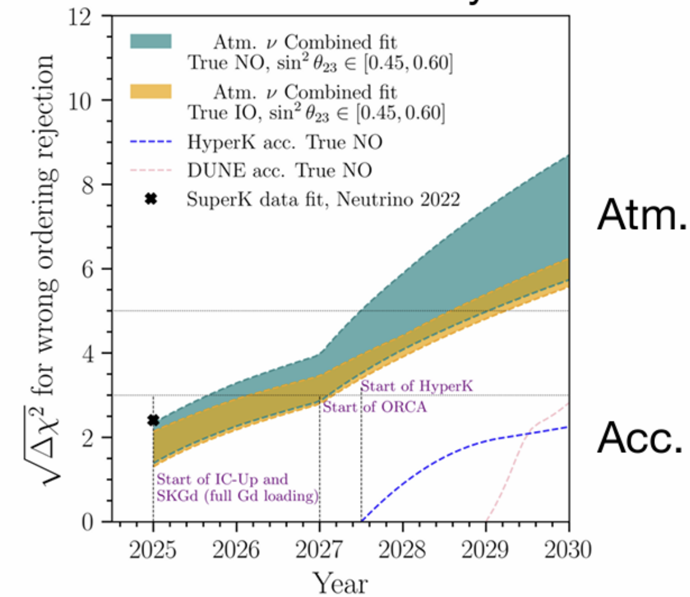
SK, 484 kt years



Indication of NO.
Rejection of IO at 92.3% CL_s.

Dominated by stats, then xsec

Future sensitivity



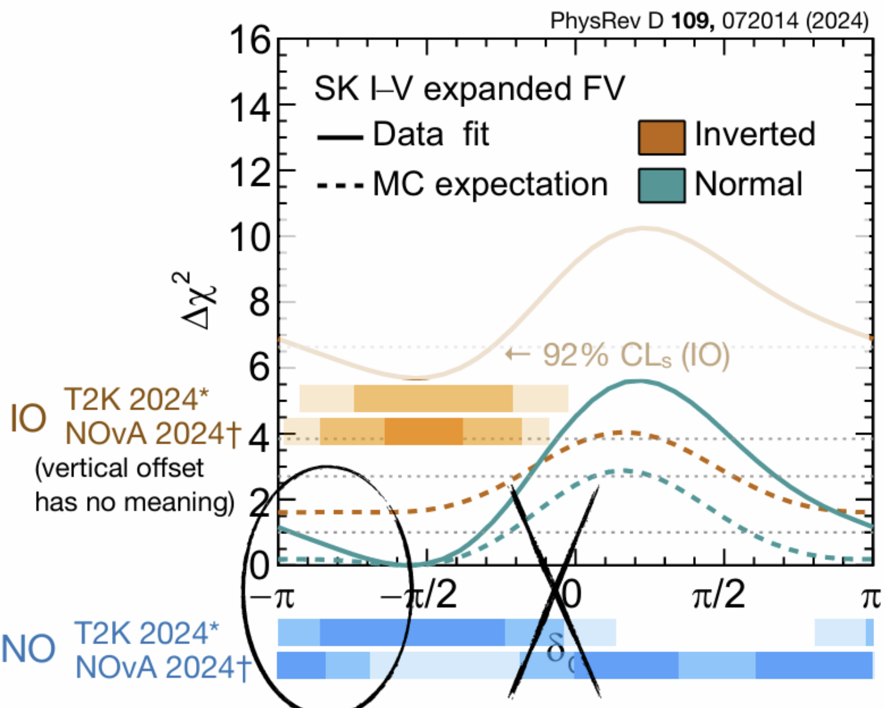
IceCube upgrade, ORCA, and HyperK expected to measure MO in the next few years. PRX 13, 041055 (2023)

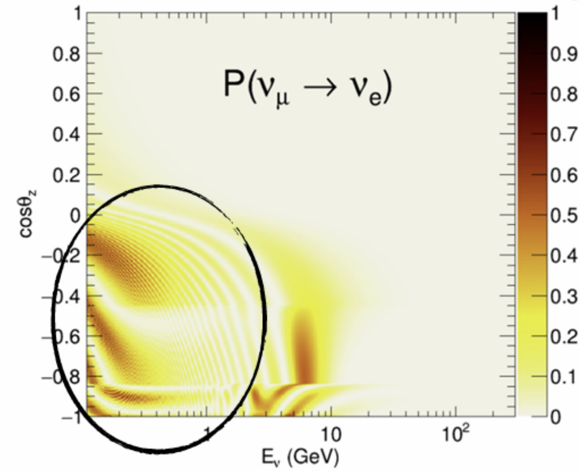
Unknowns: from atmospheric neutrinos

Using θ_{13} constraint from reactors

* Feldman-Cousins
† Bayesian

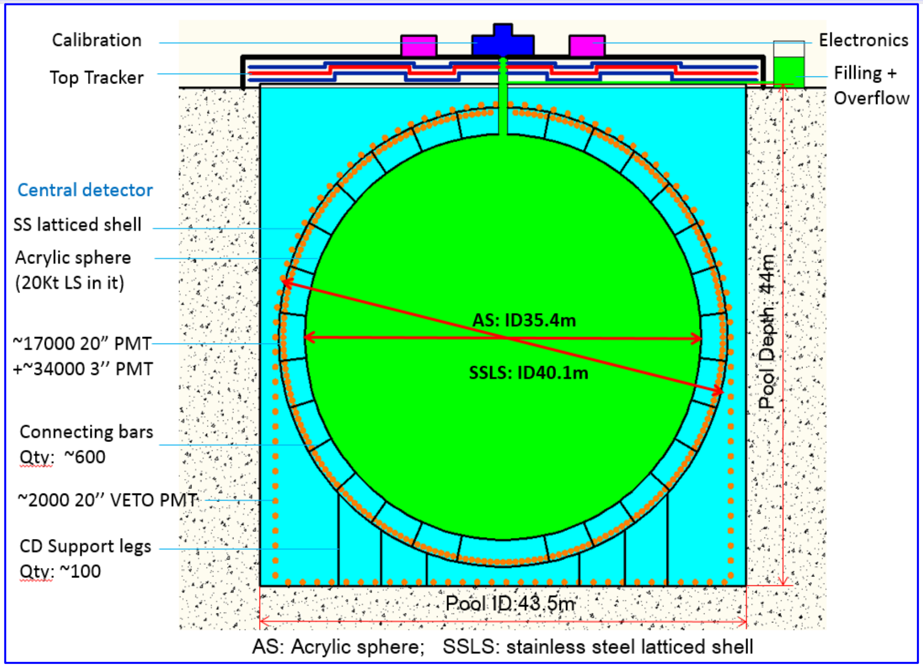
CP phase

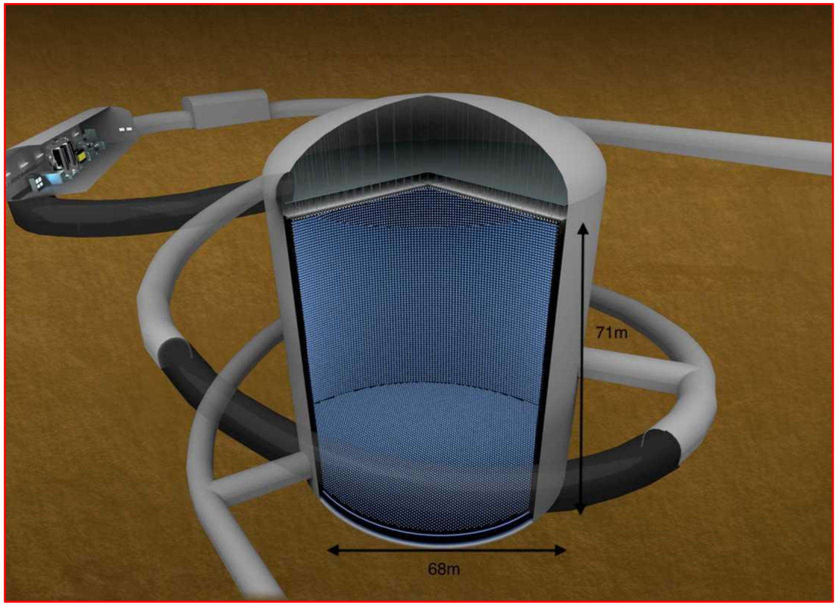




- SK also constrains δ_{CP} from normalization of sub-GeV e-like events. Unlike accelerators, decoupled from MO.
  Interplay of $\Delta m^2_{32} - \Delta m^2_{21}$ interference phase-shift and flux/xsec shape, fully smeared due to resolution.
- Weak indication of maximal CP violation but CP conservation still allowed
  Caveat: somewhat stronger exclusion than sensitivity. Due to parameter boundaries and degeneracies cannot take $\sqrt{\Delta\chi^2}$ as sigmas.
- Prefer $\delta_{CP} = \pi$ over 0.
  Interesting contribution to NOvA and T2K's NO constraints.

Future prosects

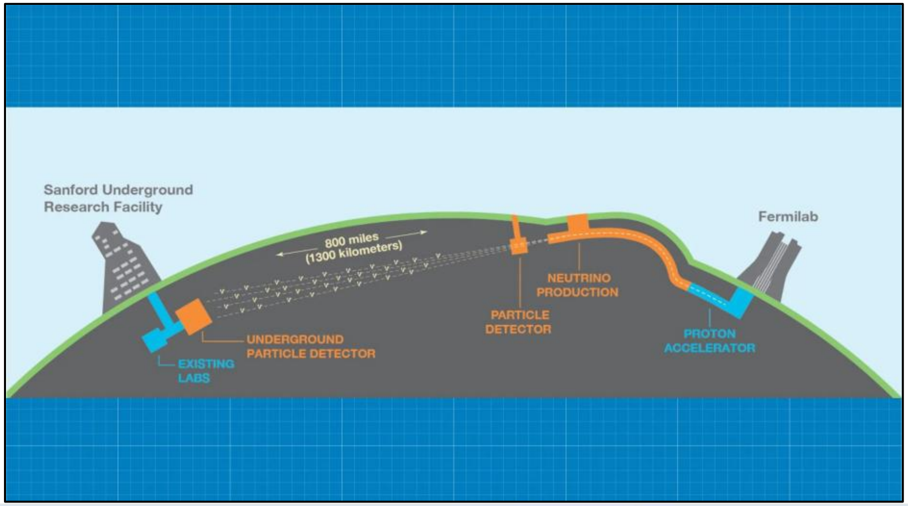




JUNO: 2025 (running) Jie Zhao's talk
Reactor neutrinos for mass ordering

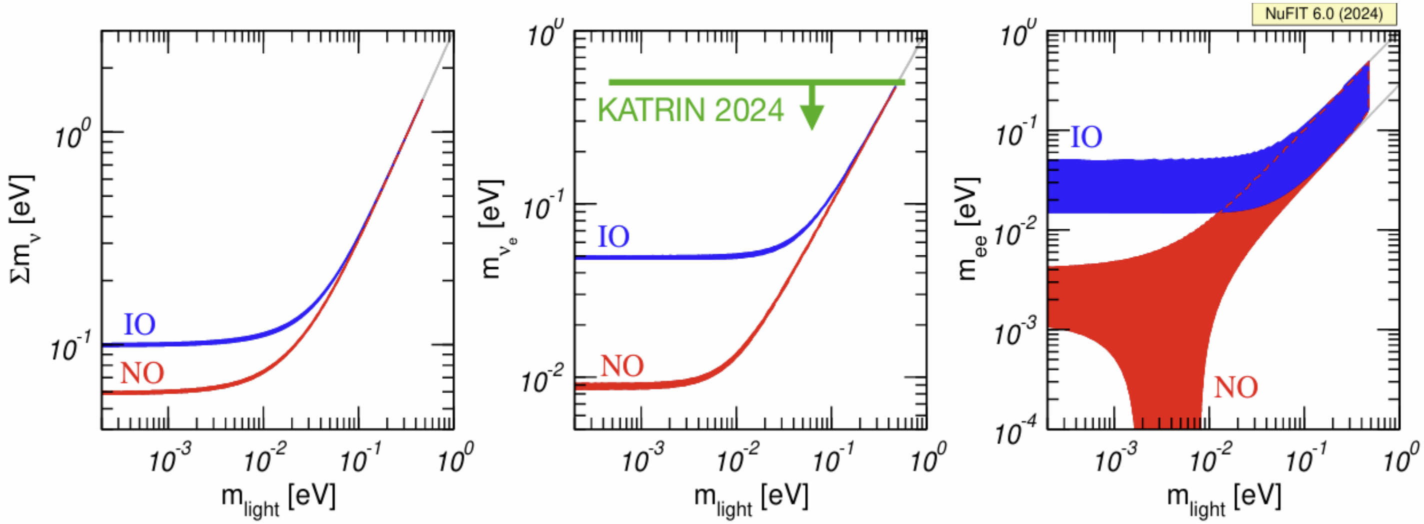
HyperK: 2028, Jan Kisiel' talk
Acc. & Atm. neutrinos, MO & CP

DUNE: 2029-2031, Jianming Bian' talk
Acc. & Atm. neutrinos, MO & CP



Unknowns: absolute neutrino mass

cosmology | beta-decay spectrum (KATRIN) | neutrinoless double-beta decay (assuming Majorana neutrinos)



Unknowns: absolute neutrino mass

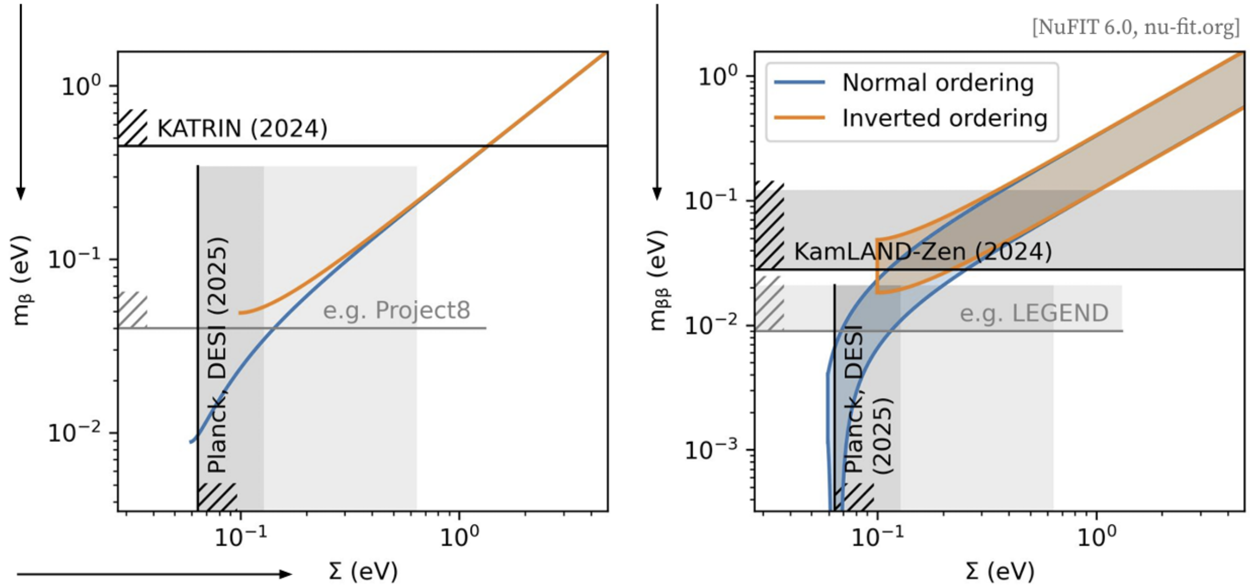
- Strong **complementarity**, also with cosmology

➔ Interplay allows to **test underlying models**

- Many **new constraints** and **powerful tools online**, e.g. LEGEND-200

Energy conservation

Light **Majorana neutrino** exchange



Standard **cosmology**

Cosmology (**Planck, DESI**)
[Abdul Karim et al., arXiv:2503.14738]

Σ **< 0.06 eV** (95% CI)

Neutrinoless ββ decay (**KamLAND-Zen**, ^{136}Xe)
[Abe et al., arXiv:2406.11438]

$m_{\beta\beta}$ **< [0.03, 0.12] eV** (90% CL)

β decay kinematics (**KATRIN**)
[Aker et al., Science 388 (2025) 6743]

m_β **< 0.45 eV** (90% CL)

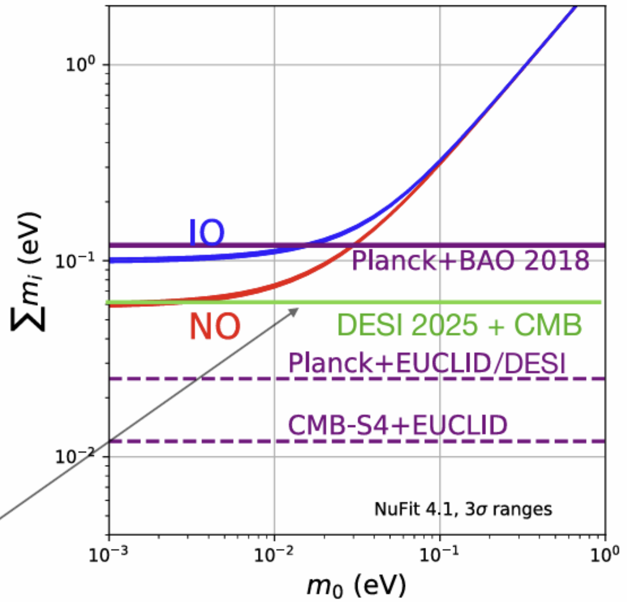
Unknowns: absolute neutrino mass

$$\Sigma \equiv \sum_{i=1}^{3} m_i = \begin{cases} m_0 + \sqrt{\Delta m_{21}^2 + m_0^2} + \sqrt{\Delta m_{31}^2 + m_0^2} & \text{(NO)} \\ m_0 + \sqrt{|\Delta m_{32}^2| + m_0^2} + \sqrt{|\Delta m_{32}^2| - \Delta m_{21}^2 + m_0^2} & \text{(IO)} \end{cases}$$

- minimal values predicted from oscillation data for $m_0 = 0$:

$$\Sigma_{\min} = \begin{cases} 98.6 \pm 0.85\,\text{meV} & \text{(IO)} \\ 58.5 \pm 0.48\,\text{meV} & \text{(NO)} \end{cases}$$

- **Upper bounds from current data:**
  - $\Sigma m_\nu < 0.12\,\text{eV}\ (95\,\%\ \text{CL})$ Planck CMB+BAO 2018
  - $\Sigma m_\nu < 0.064\,\text{eV}\ (95\,\%\ \text{CL})$ DESI 2025 + CMB



Unkowns: Neutrino mass nature

The simplest and most natural way to accommodate tiny neutrino masses

- Massive Majorana Neutrinos

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \overline{\nu_{\rm R}} {\rm i}\partial\!\!\!/ \nu_{\rm R} - \left[\overline{\ell_{\rm L}} Y_\nu \tilde{H} \nu_{\rm R} + {\rm h.c.}\right] - \left[\frac{1}{2}\overline{\nu^{\rm C}_{\rm R}} M_{\rm R} \nu_{\rm R} + {\rm h.c.}\right]$$

Generate tiny Majorana ν masses via the so-called seesaw mechanism

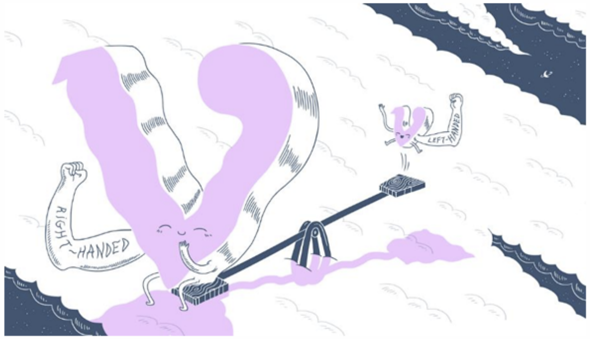
- Retain SM gauge symmetries
- Well motivated by the GUTs

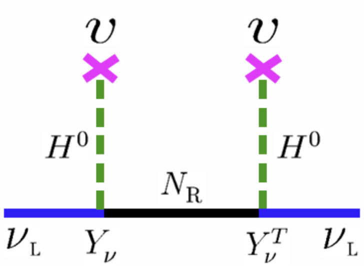
$$M_\nu = v^2 Y_\nu M_{\rm R}^{-1} Y_\nu^{\rm T}$$

M_ν: $\boldsymbol{O}(0.1\ \mathrm{eV})$ $\quad$ $M_{\rm R}$: $\boldsymbol{O}(10^{14}\ \mathrm{GeV})$

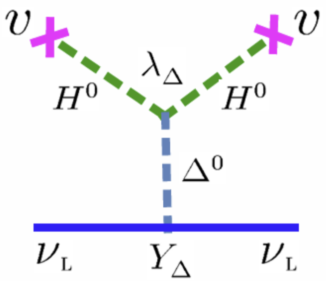
Introduce all terms allowed by the SM gauge symmetries

Canonical Seesaw Mechanism

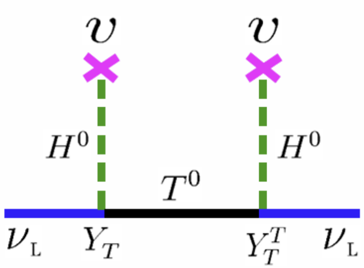




$$M_\nu \approx -v^2 Y_\nu \frac{1}{M_{\rm R}} Y_\nu^T$$



$$M_\nu \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}$$

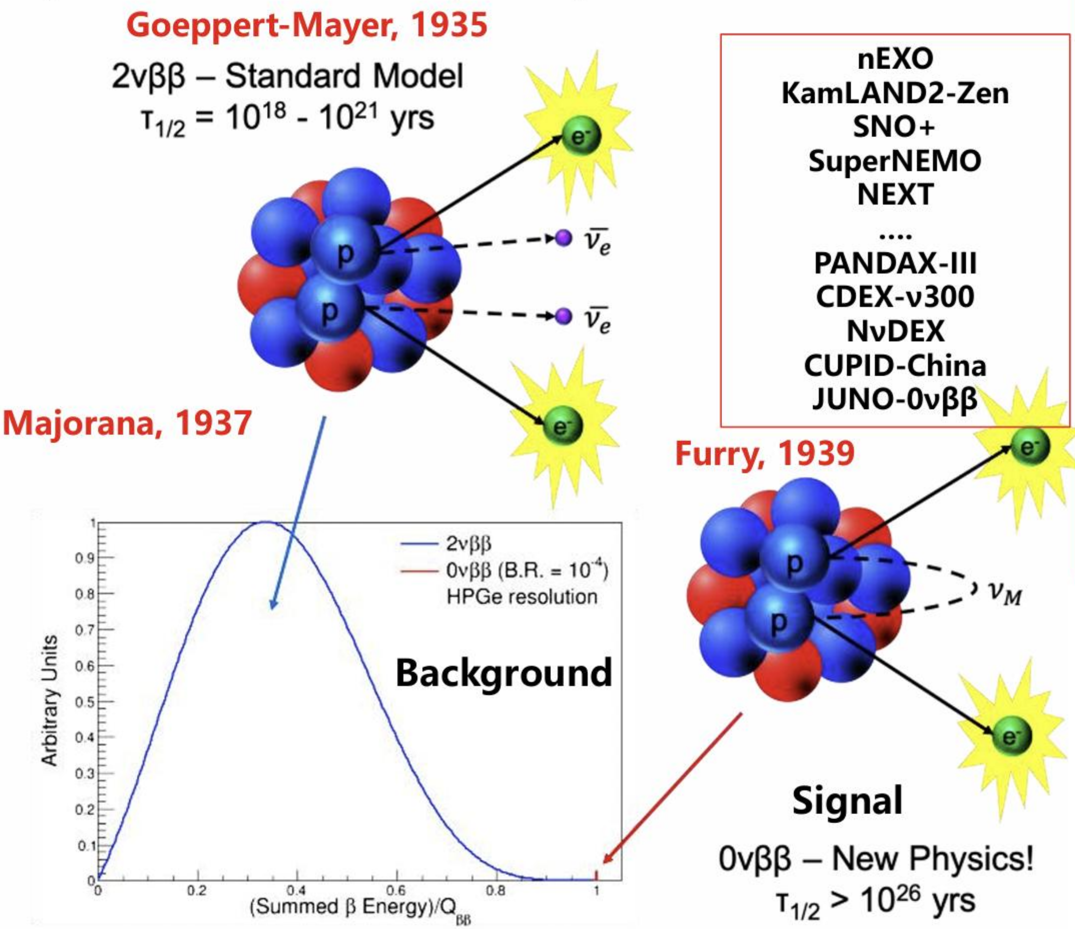


$$M_\nu \approx -v^2 Y_T \frac{1}{M_T} Y_T^T$$

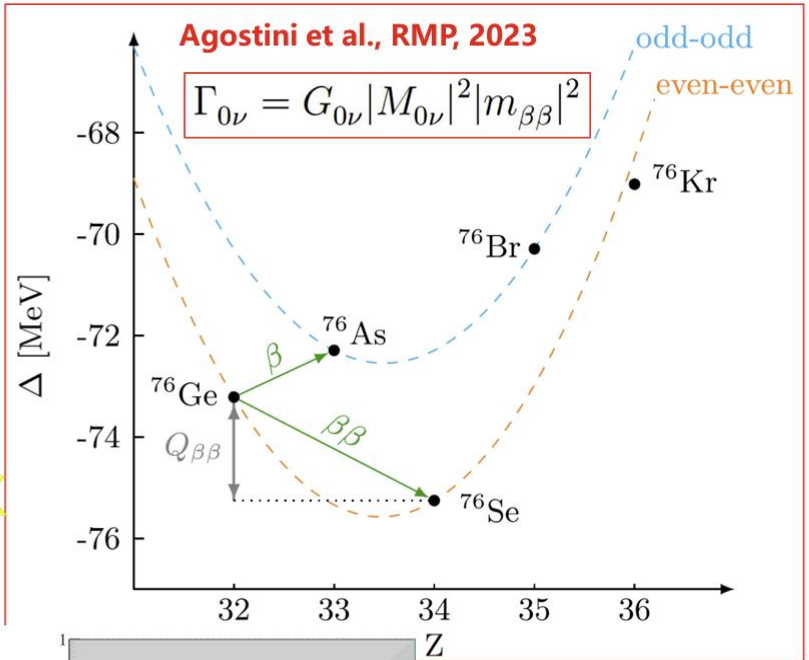
Dirac v.s. Majorana masses

Neutrinoless double beta decay: talk by Pin-Jung Chiu

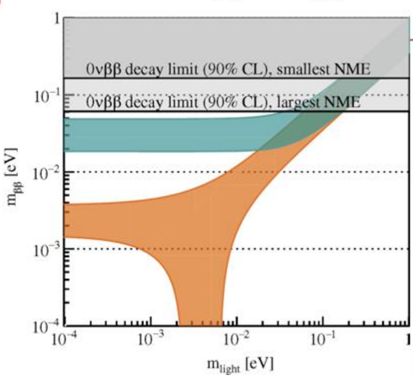
Lepton-flavor-violating rare processes



nEXO
KamLAND2-Zen
SNO+
SuperNEMO
NEXT
....
PANDAX-III
CDEX-ν300
NνDEX
CUPID-China
JUNO-0νββ



$$\Gamma_{0\nu} = G_{0\nu}|M_{0\nu}|^2|m_{\beta\beta}|^2$$



$$m_{\beta\beta} = \left|\Sigma_i U_{ei}^2 m_i\right| \text{ [eV]}$$

Key observations to probe the Majorana nature of massive neutrinos and origin of neutrino masses

The most promising way to test the lepton number violation and Majorana nature of neutrinos.

Summary & Outlook

Neutrino mass and mixing: truly new physics beyond the standard model

Robust 3ν-Mixing Paradigm

$$\Delta m^2_{\rm S} \simeq 7.4 \times 10^{-5}\,{\rm eV}^2 \qquad \Delta m^2_{\rm A} \simeq 2.5 \times 10^{-3}\,{\rm eV}^2$$

$$\sin^2\vartheta_{12} \simeq 0.3 \qquad \sin^2\vartheta_{23} \simeq 0.5 \qquad \sin^2\vartheta_{13} \simeq 0.02$$

$$\beta \text{ and } \beta\beta_{0\nu} \text{ Decay} \Longrightarrow m_1, m_2, m_3 \lesssim 1\,{\rm eV}$$

To Do

Theory: Why lepton mixing $\neq$ quark mixing?
(Due to Majorana nature of ν's?)
Why $0 < \sin^2\vartheta_{13} \ll \sin^2\vartheta_{12} < \sin^2\vartheta_{23} \simeq 0.5$?

Experiments: Measure mass ordering and CP violation.
Find absolute mass scale and Majorana or Dirac.

Summary & Outlook

- Important first determination: neutrino mass ordering.
- Neutrinos can be powerful messengers of the physics beyond the SM.
- The discovery of L violation through $\beta\beta_{0\nu}$ decay is of paramount importance $\Longrightarrow$ Majorana neutrinos.
- The additional discovery of CP violation in the lepton sector in LBL neutrino oscillation experiments will represent a strong indication in favor of leptogenesis as the origin of the matter-antimatter asymmetry in the Universe.
- The search for sterile neutrinos may open a cornucopia of new phenomena.

See talk by Michele Lucente

- Look out for Non-Unitary Mixing neutrino Non-Standard Interactions, and Electromagnetic Interactions.

Thanks!

谢谢!

Extras

Borexino: CNO cycle

Article | Published: 25 November 2020

Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun

The Borexino Collaboration

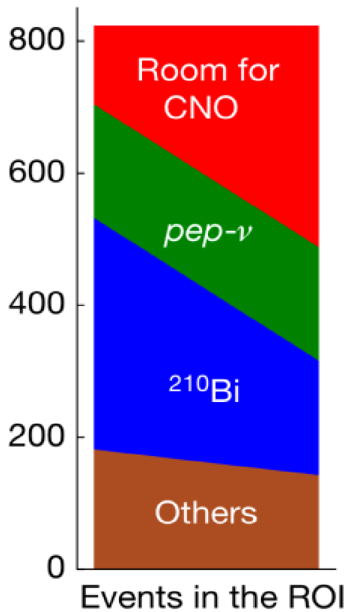
Nature **587**, 577–582 (2020) | Cite this article

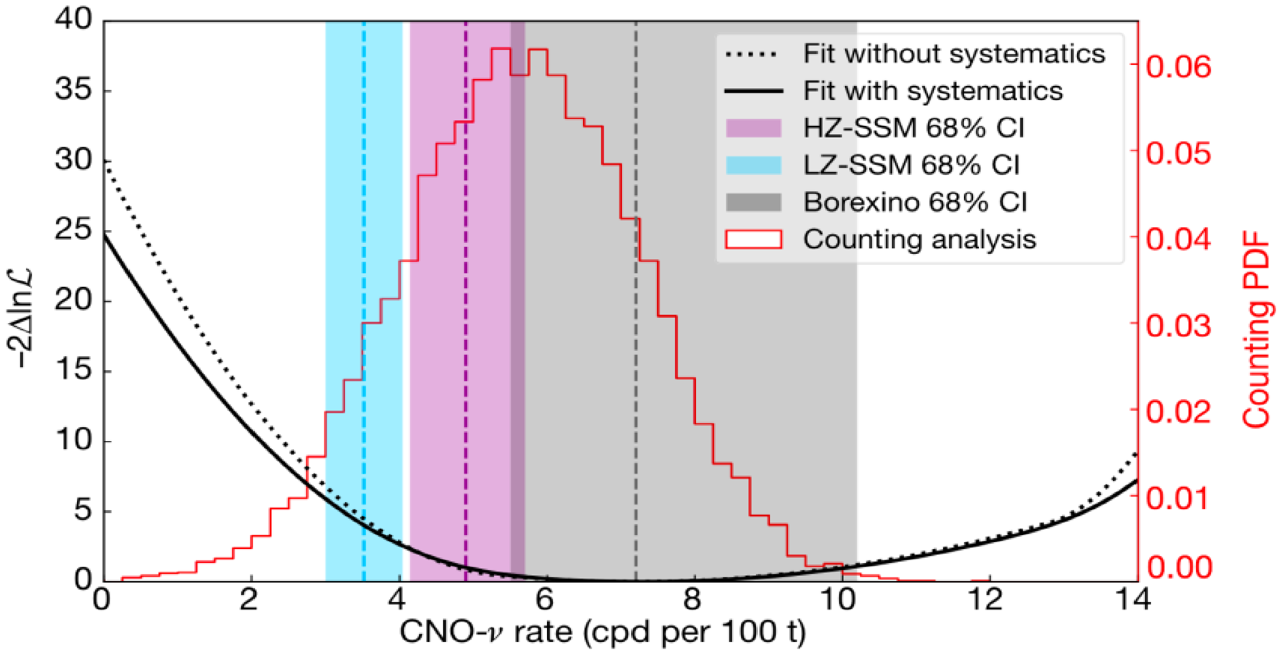
14k Accesses | **137** Citations | **902** Altmetric | Metrics

$6.6^{+2.0}_{-0.9} \times 10^8\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Phys.Rev.D 108 (2023) 102005

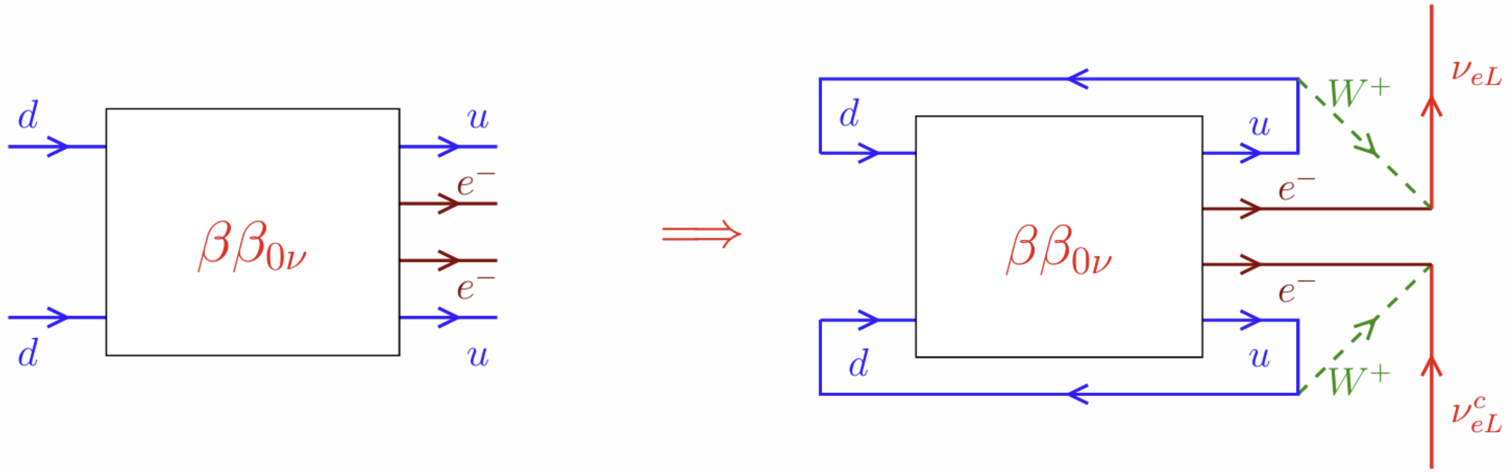
→ $6.7^{+1.2}_{-0.8} \times 10^8\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$





Neutrinoless double beta decay

- $|m_{\beta\beta}|$ can vanish because of unfortunate cancellations among the ν_1, ν_2, ν_3 contributions or because neutrinos are Dirac particles.
- However, $\beta\beta_{0\nu}$ decay can be generated by another mechanism beyond the Standard Model.
- In this case, a Majorana mass for ν_e is generated by radiative corrections:

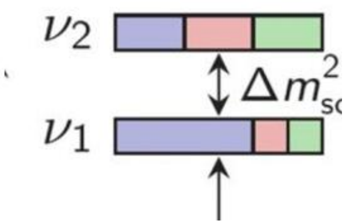


[Schechter, Valle, PRD 25 (1982) 2951; Takasugi, PLB 149 (1984) 372]

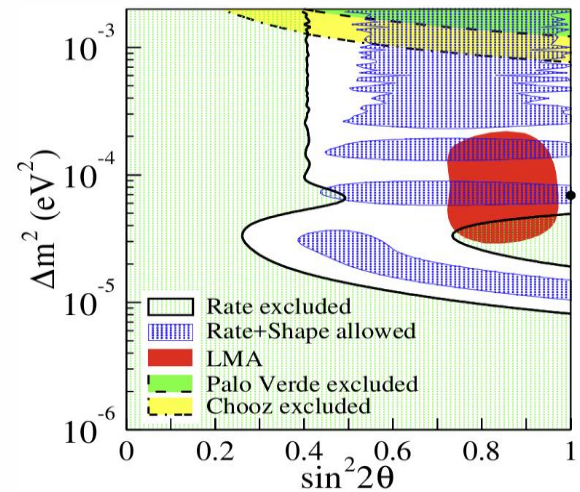
- Majorana Mass Term: $\mathcal{L}^{\mathrm{M}}_{eL} = -\frac{1}{2}\, m_{ee} \left(\overline{\nu^c_{eL}}\, \nu_{eL} + \overline{\nu_{eL}}\, \nu^c_{eL} \right)$
- Very small four-loop diagram contribution: $m_{ee} \sim 10^{-24}$ eV

[Duerr, Lindner, Merle, JHEP 06 (2011) 091 (arXiv:1105.0901)]

What is mass ordering: 2 flavors



$$\begin{pmatrix}\nu_a \\ \nu_b\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}$$



95% C.L.

[KamLAND, PRL 90 (2003) 021802, hep-ex/0212021]

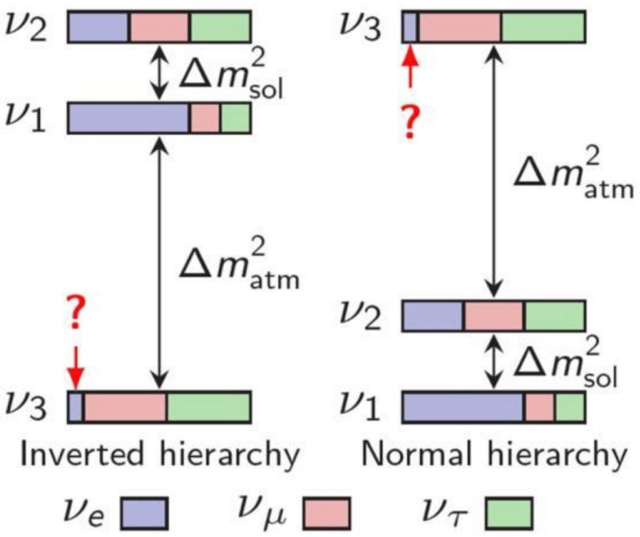
$$P(\nu_e \rightarrow \nu_\mu) = sin^2(2\theta) sin^2(1.27\Delta m^2 \frac{L}{E_\nu})$$

With ν_1←→ν_2, and θ ←→ π/2 - θ, complete degenerate!

We can either choose $m_2 > m_1$ → determine if θ < or > π/4?
or choose θ< π/4, → determine if $m_2 > m_1$ or $m_2 < m_1$?

Solar neutrino flavor conversion (matter effects) tell us $\cos 2\theta * \Delta m^2_{21} > 0$

What is mass ordering? 3 flavors



Atmospheric neutrino (vacuum) oscillation: $\Delta m^2_{31}>0$ or $\Delta m^2_{31}<0$?

The mass ordering is only relevant, after we intrinsically define what are the mass eigenstates: ν_1 ν_2 ν_3.

One definition: decreasing ν_e components of these mass eigenstates

Hierarchical mass spectrum v.s. quasi degenerate mass pairs

Methods to determine MO

Matter Effects: **Accelerator, atmospheric, supernova neutrinos**

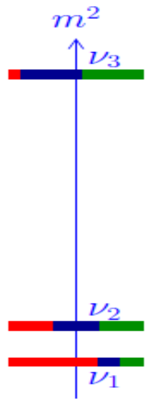
- $\nu_e \leftrightarrows \nu_\mu$ MSW resonance: $V = \dfrac{\Delta m^2_{13} \cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m^2_{13} > 0$ NH
- $\bar\nu_e \leftrightarrows \bar\nu_\mu$ MSW resonance: $V = -\dfrac{\Delta m^2_{13} \cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m^2_{13} < 0$ IH

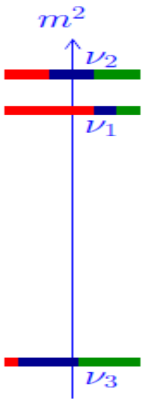
Vacuum oscillations: **Reactor neutrinos, Petcov et al., PLB 533, 94 (2002)**

Normal Hierarchy

$|\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$

$|\Delta m^2_{31}| > |\Delta m^2_{32}|$





Inverted Hierarchy

$|\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$

$|\Delta m^2_{31}| < |\Delta m^2_{32}|$

SURVIVAL PROBABILITY

$$P_{\bar\nu_e \to \bar\nu_e} = 1 - \sin^2 2\vartheta_{13} \times \left(\cos^2\vartheta_{12} \sin^2\Delta_{31} + \sin^2\vartheta_{12} \sin^2\Delta_{32}\right)$$ FAST Δm^2_{ATM}

$$- \sin^2 2\vartheta_{12} \cos^4\vartheta_{13} \sin^2\Delta_{21}$$ SLOW Δm^2_{SOL}