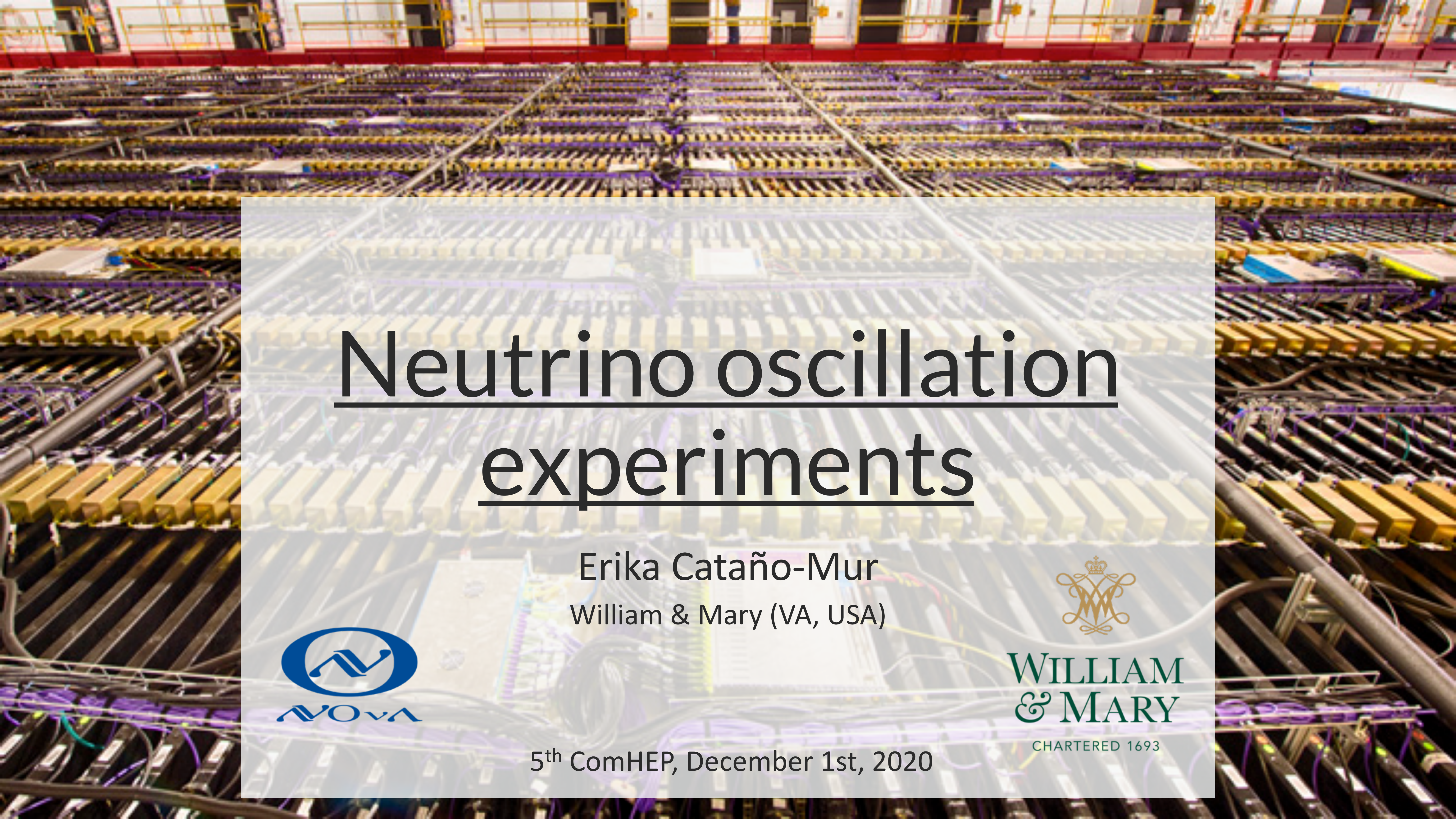


Neutrino oscillation experiments

Erika Cataño-Mur

William & Mary (VA, USA)

5th ComHEP, December 1st, 2020

Neutrino oscillations

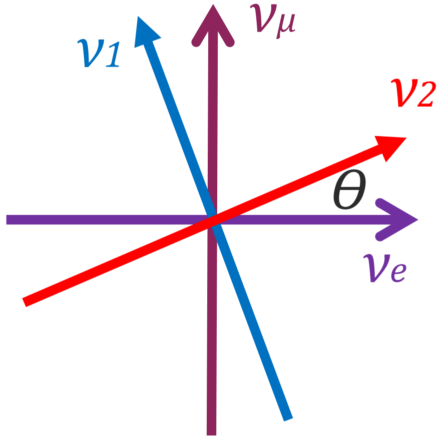
- The "active" neutrinos are produced and detected as one of three definite weak eigenstates: $\boldsymbol{\nu_e, \nu_\mu, \nu_\tau}$
- **"Neutrino oscillations"** refers to the phenomenon where lepton flavor is not conserved in neutrino propagation
- Ex.: neutrinos created in one flavor (ν_μ), travel a distance L, and are detected in another flavor (ν_e)

- Each **flavor** (**e**, **μ**) is a superposition of different **masses** (**1**, **2**)

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

"Mixing matrix"

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



Oscillations require two essential ingredients:

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_i U^*_{\alpha i} e^{-i\frac{m_i^2 L}{2E}} U_{\beta i} \right|^2$$

(1) The PMNS matrix ("mixing" matrix: connects flavor to mass states) must have off-diagonal elements

(2) The neutrino mass states must have differing mass eigenvalues

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

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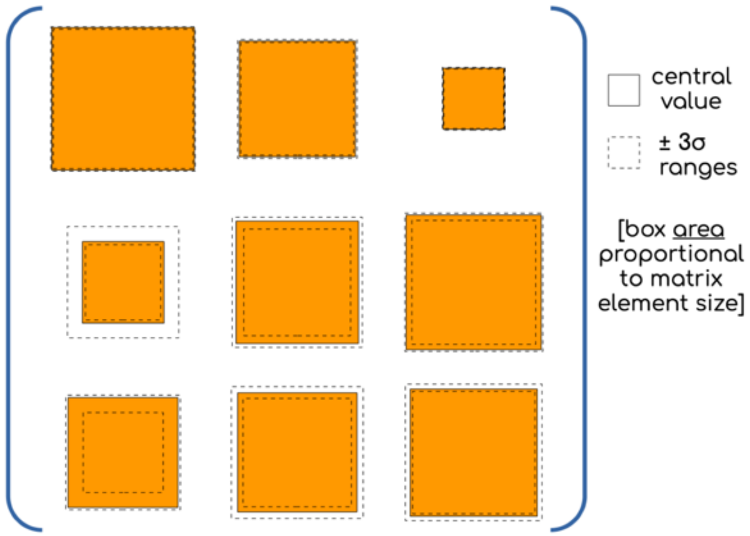
... and it does!
(We know some of the elements much better than others)

[Values from NuFIT 5.0, arXiv:2007.14792]



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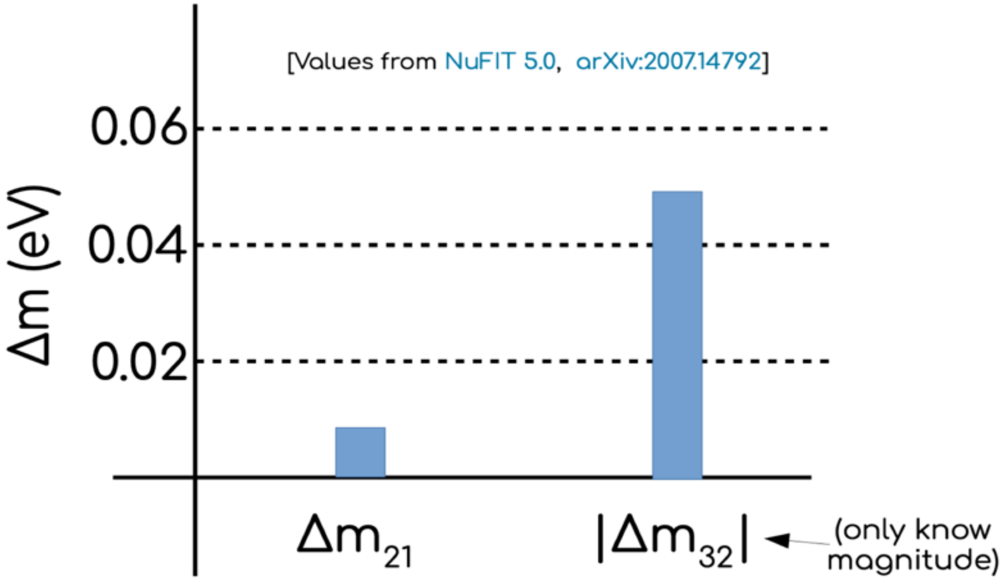


... and they do!
(These differences are known quite well, ~2-3%.)

J Wolcott JETP2020
NuFIT arXiv:2007.14792

3-flavor oscillation probabilities

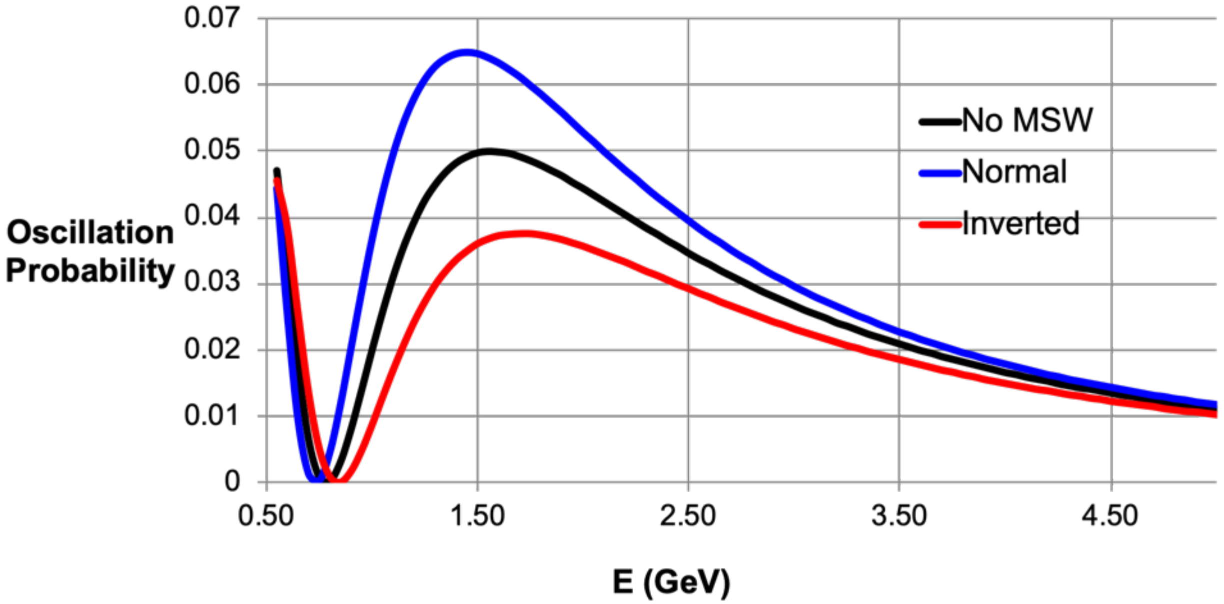
- We need mixing of at least 3 neutrino states to fully describe current experimental results
    - Additional mass eigenstates: 3+1, 3+N models → "sterile" neutrino searches
- In some limits, the observed results can be understood in terms of oscillations driven by one Δm^2

Neutrino appearance

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Neutrino disappearance

$$P(\nu_\alpha \to \nu_\alpha) \simeq 1 - P(\nu_\alpha \to \nu_\beta)$$



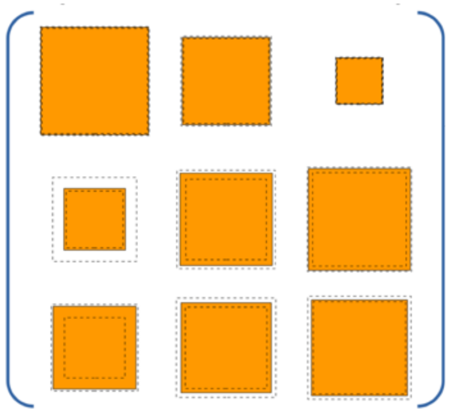
- In matter, ν_e's act differently from ν_μ's and ν_τ's: they obtain a phase shift from coherent charged current forward scattering → possible resonant enhancement

Parametrization of the mixing matrix

- The mixing matrix can be written in terms of 3 angles and 1 phase. Usually factorized into components directly related to the experiments:

$c_{ij} = \cos\theta_{ij}\,, s_{ij} = \sin\theta_{ij}$

$U =$



$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

The (23) sector:
Atmospheric
and accelerator

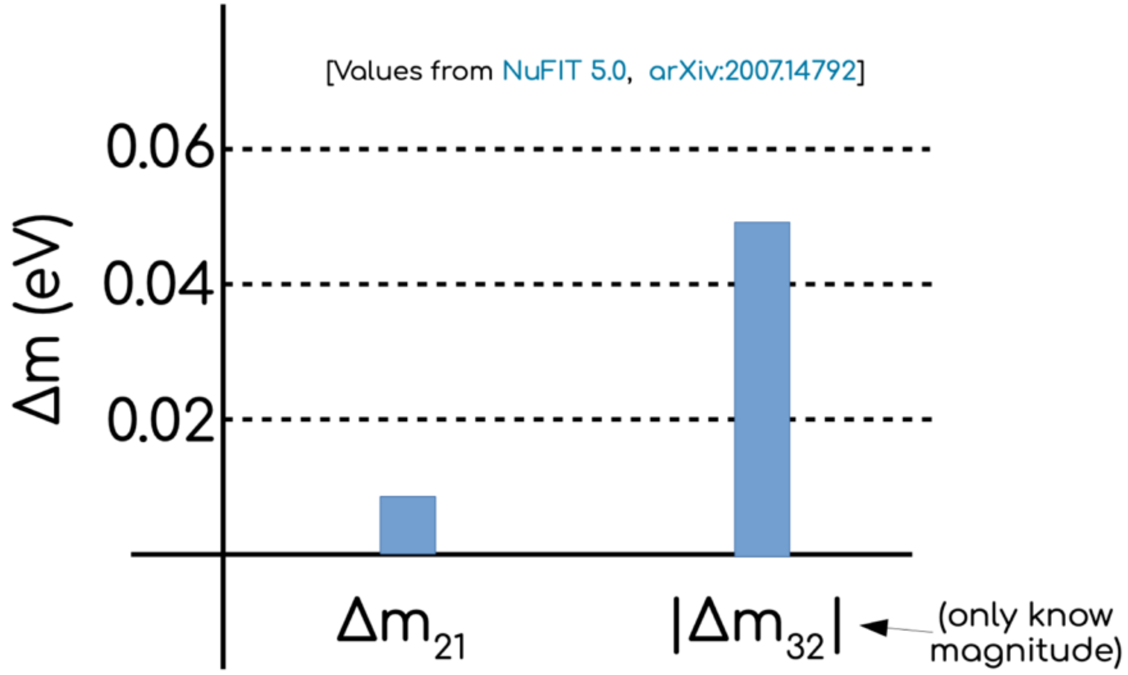
The (13) sector:
Reactor and
accelerator

The (12) sector:
Solar and
reactor

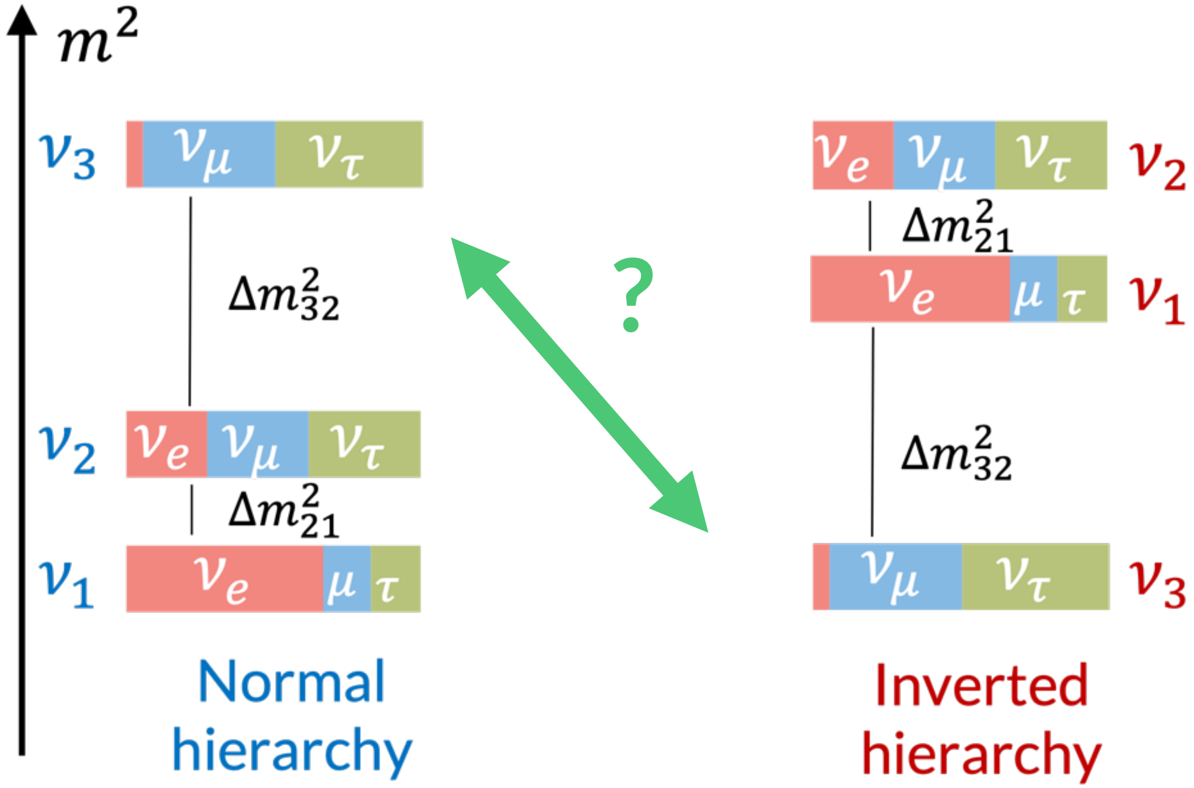
- Current experiments → precision measurements of the angles
- Poorly known: θ_{23} (~5%), δ_{CP} (~unconstrained)
  - Q: is θ_{23} maximal? i.e. is there symmetry in ν_μ, ν_τ mixing to ν_2, ν_3 ? If not, what is the octant?
  - Q: is $\delta_{CP} \neq 0, \pi$? i.e. is CP violated in the neutrino sector?

Squared mass differences and hierarchy

- Neutrino oscillation experiments can access the mass differences squared
- By convention, we denote the mass eigenstate with the largest fraction of ν_e as ν_1
- Q: mass eigenstate is the lightest? → "hierarchy"
  - Normal: ν_1 is the lightest, just like the electron is the lightest charged lepton
  - Inverted: ν_3 is the lightest

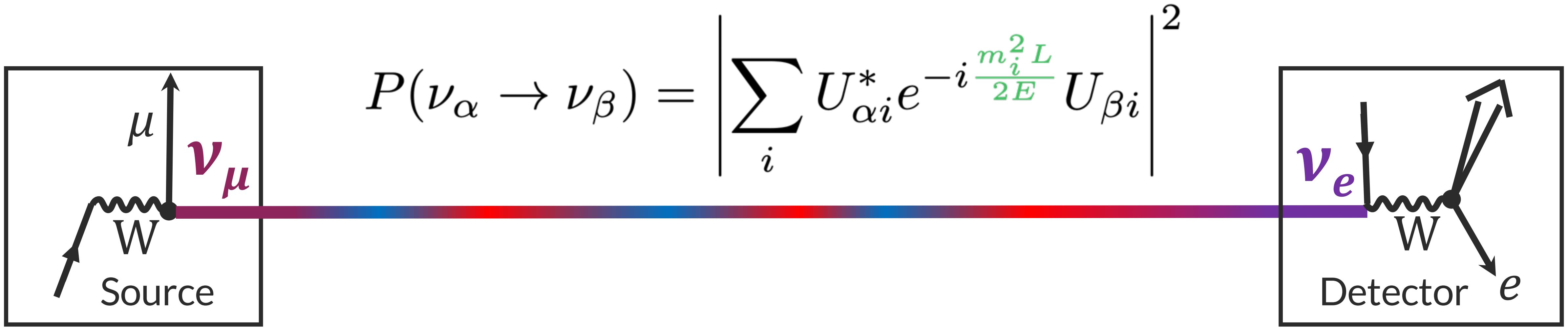

[Values from NuFIT 5.0, arXiv:2007.14792]

(only know magnitude)



Neutrino oscillation experiments at a glance

Experimental study of neutrino oscillations

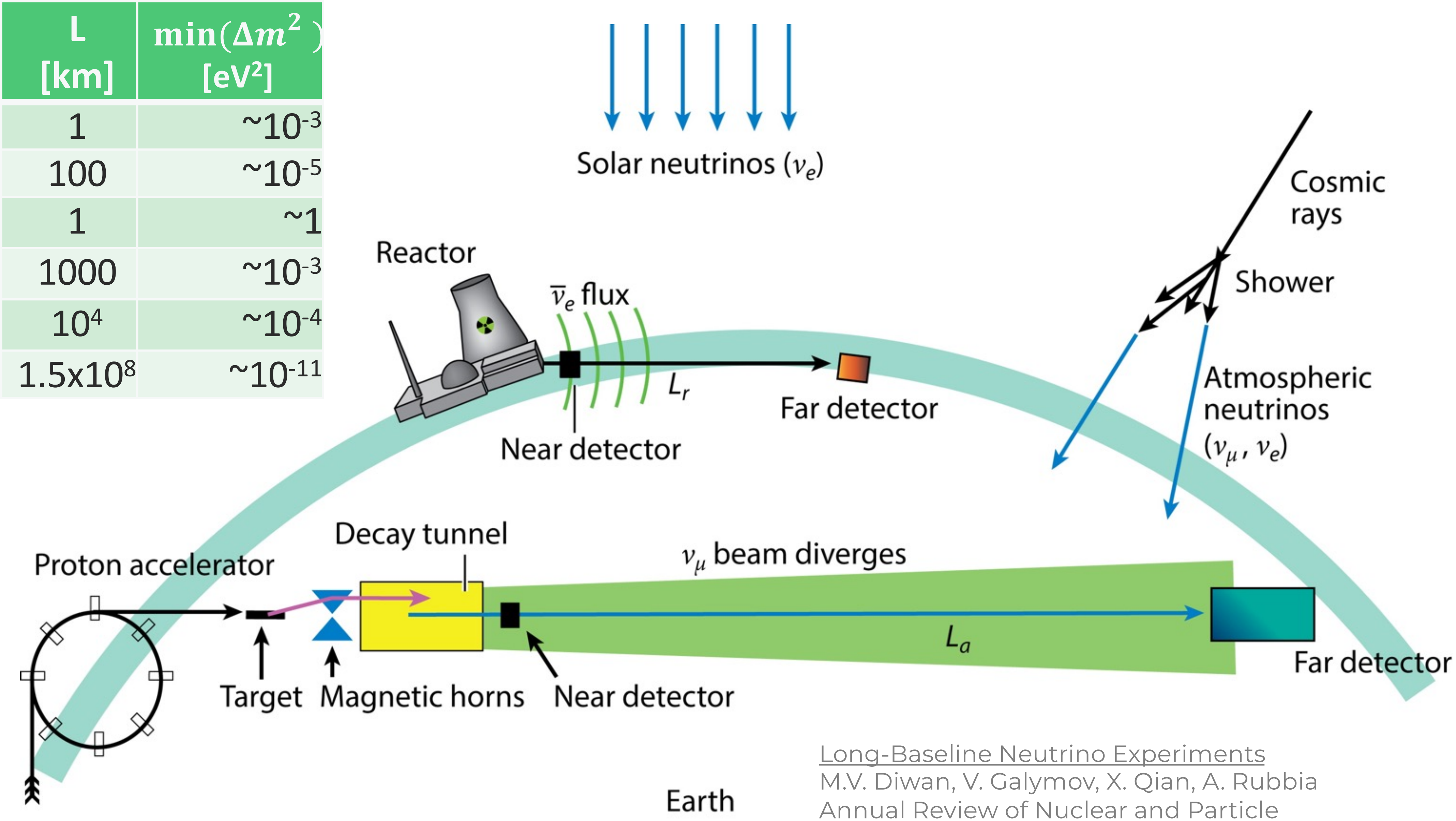


$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_i U^*_{\alpha i} e^{-i\frac{m_i^2 L}{2E}} U_{\beta i} \right|^2$$

- Neutrino oscillations have been experimentally studied using various neutrino sources and detection techniques.
- Considerations:
  - **Large distances** may be necessary for observable oscillation effects
  - Neutrino interactions have **small cross-sections**
  - → Need **intense sources** and **large detectors**
  - Need to know the **neutrino flux** before oscillations with sufficient precision for a definitive measurement

Sources of ν’s for oscillation studies

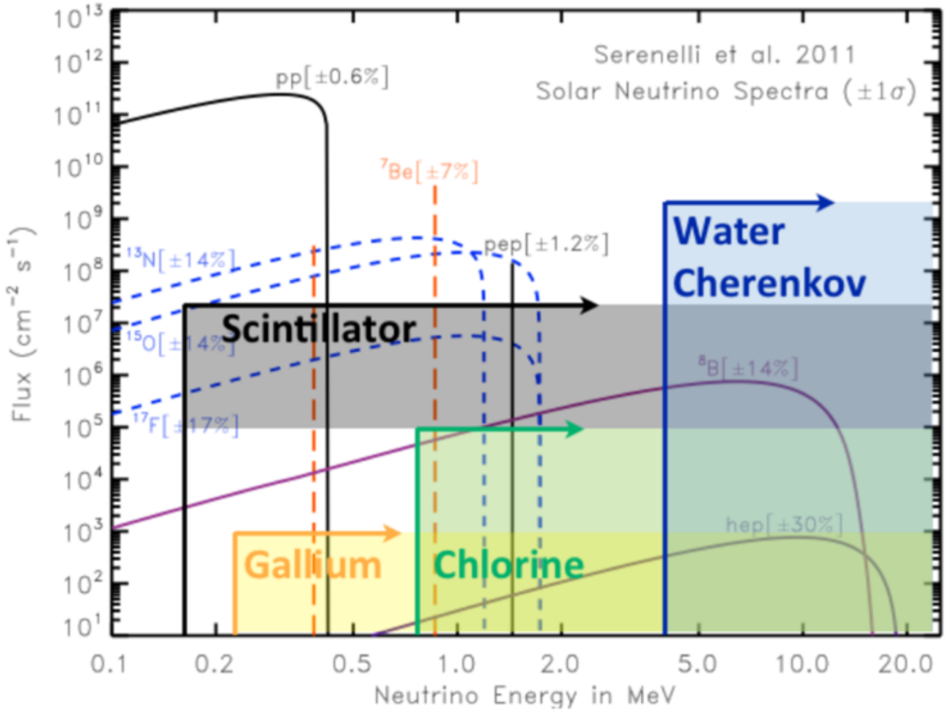
Source	Type of ν	E [MeV]	L [km]	$\min(\Delta m^2)$ [eV^2]
Reactor	$\bar{\nu}_e$	~1	1	~10^{-3}
Reactor	$\bar{\nu}_e$	~1	100	~10^{-5}
Accelerator	$\nu_\mu, \bar{\nu}_\mu$	~10^3	1	~1
Accelerator	$\nu_\mu, \bar{\nu}_\mu$	~10^3	1000	~10^{-3}
Atmospheric	$\nu_{\mu,e}, \bar{\nu}_{\mu,e}$	~10^3	10^4	~10^{-4}
Solar	ν_e	~1	1.5x10^8	~10^{-11}

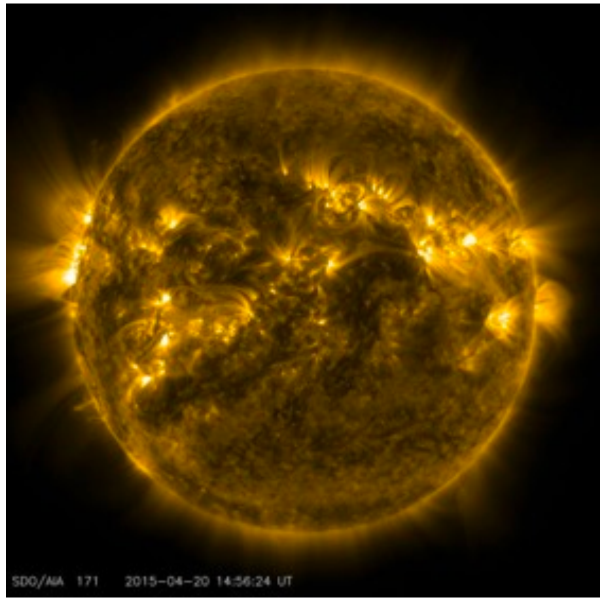


Long-Baseline Neutrino Experiments
M.V. Diwan, V. Galymov, X. Qian, A. Rubbia
Annual Review of Nuclear and Particle Science 2016 66:1, 47-71

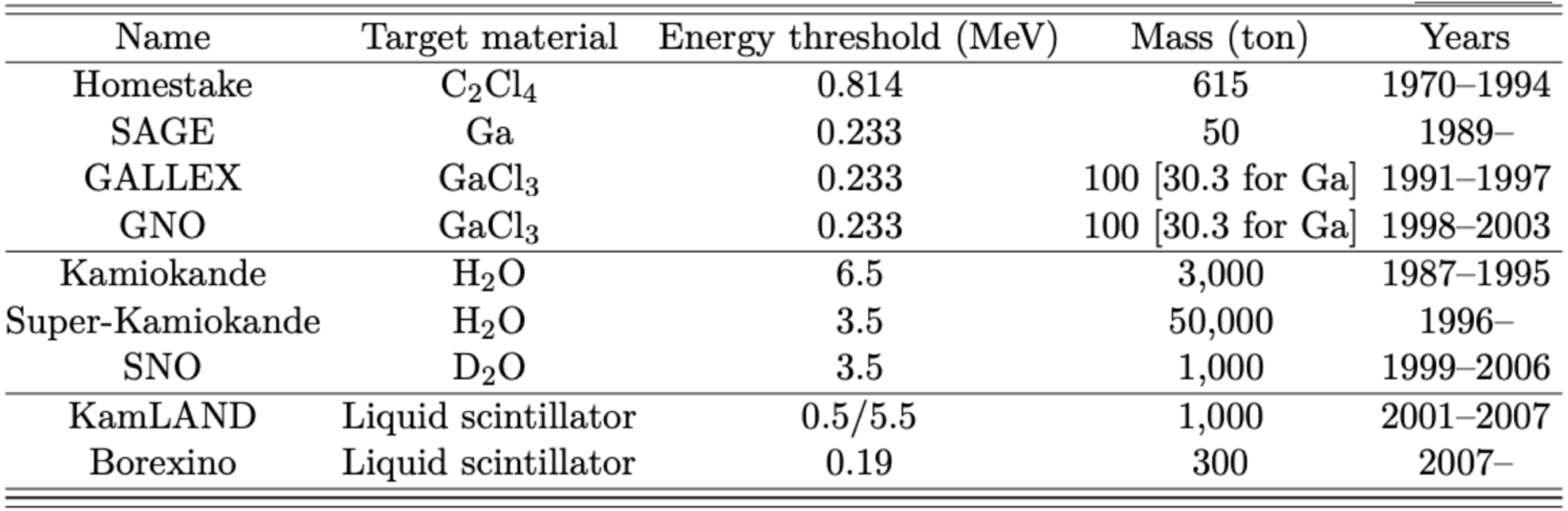
Solar neutrinos

- Electron neutrinos are produced in the thermonuclear reactions which generate the solar energy
- Neutrinos are produced in different reactions with energies ranging from 0.1 to 20 MeV
- Detailed calculation of the solar neutrino fluxes based on the Standard Solar Model





PDG2020

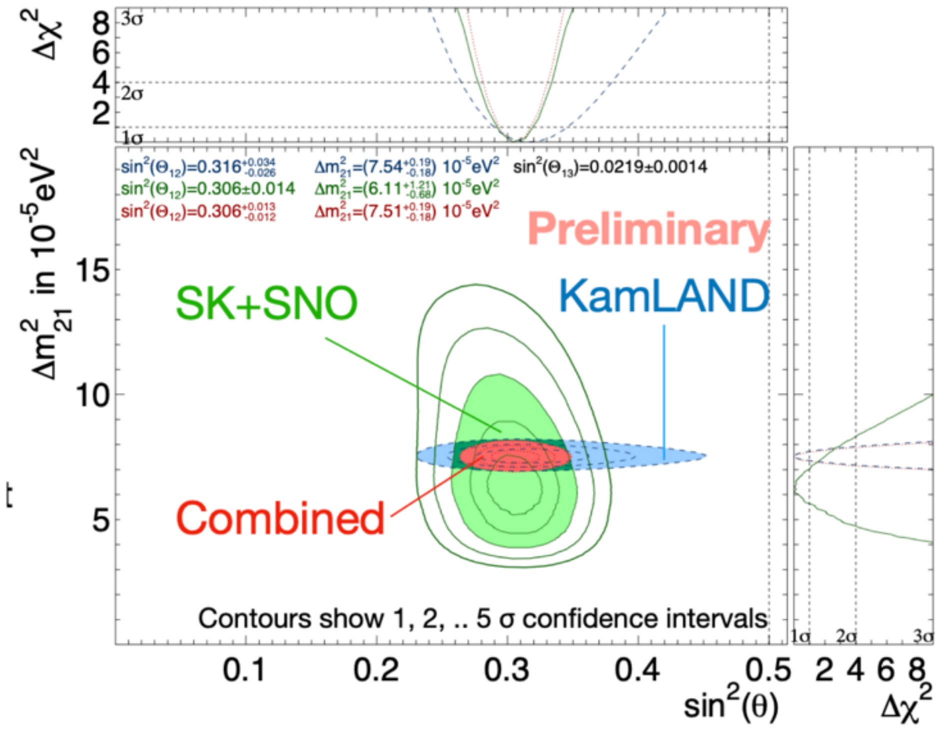


Name	Target material	Energy threshold (MeV)	Mass (ton)	Years
Homestake	C_2Cl_4	0.814	615	1970–1994
SAGE	Ga	0.233	50	1989–
GALLEX	$GaCl_3$	0.233	100 [30.3 for Ga]	1991–1997
GNO	$GaCl_3$	0.233	100 [30.3 for Ga]	1998–2003
Kamiokande	H_2O	6.5	3,000	1987–1995
Super-Kamiokande	H_2O	3.5	50,000	1996–
SNO	D_2O	3.5	1,000	1999–2006
KamLAND	Liquid scintillator	0.5/5.5	1,000	2001–2007
Borexino	Liquid scintillator	0.19	300	2007–

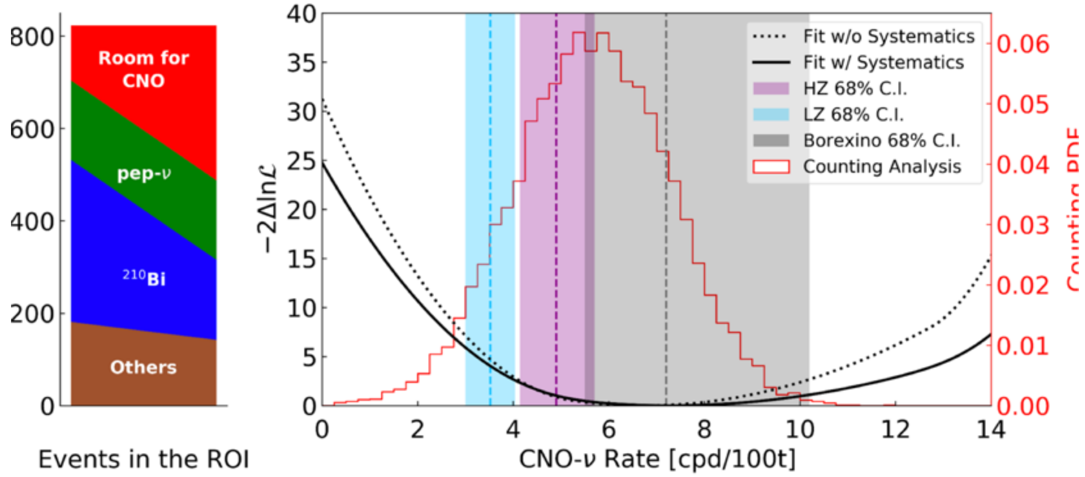
Solar news

- Super-Kamiokande:
  - Added statistics
  - Solar neutrino measurements: New spectrum and Day/Night asymmetry measurements to test MSW
  - SK+SNO fit disfavors the KamLAND best fit value at ~1.4σ (was ~2σ)
- Borexino:
  - Borexino now has observed the neutrino spectrum from the CNO cycle (at 5 **σ**)
  - After a long effort to better understand their Po background
  - Expectation: better understanding of the solar metallicity

Nakajima Nu2020



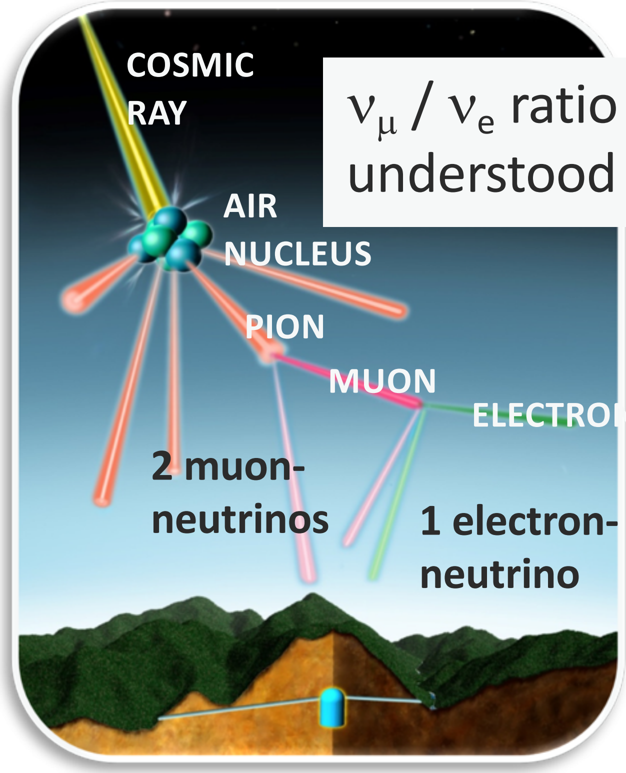
Ranucci Nu2020



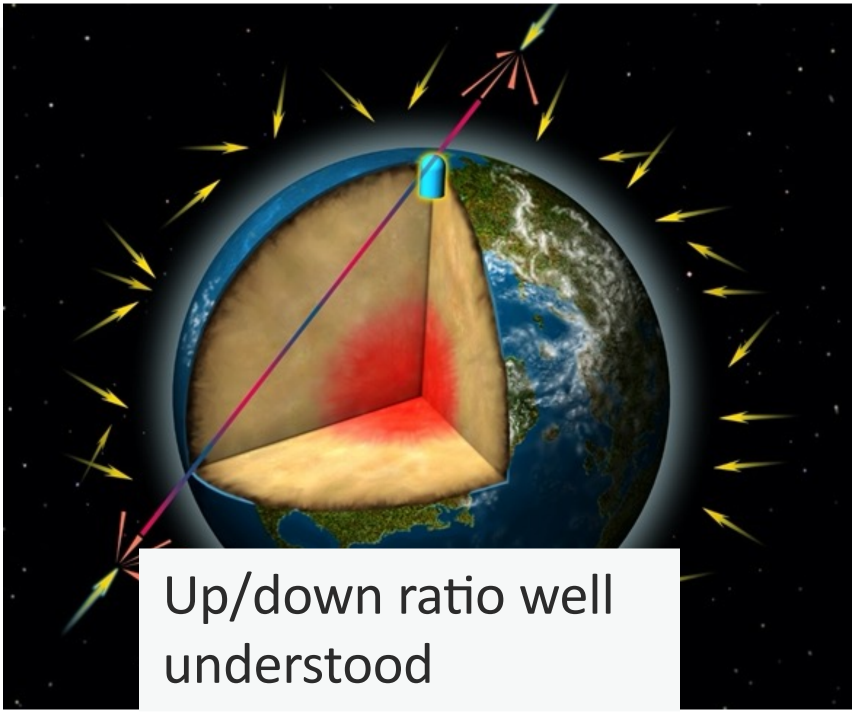
The enduring Borexino quest of the CNO neutrinos has finally produced the first observation of the signal

Atmospheric neutrinos

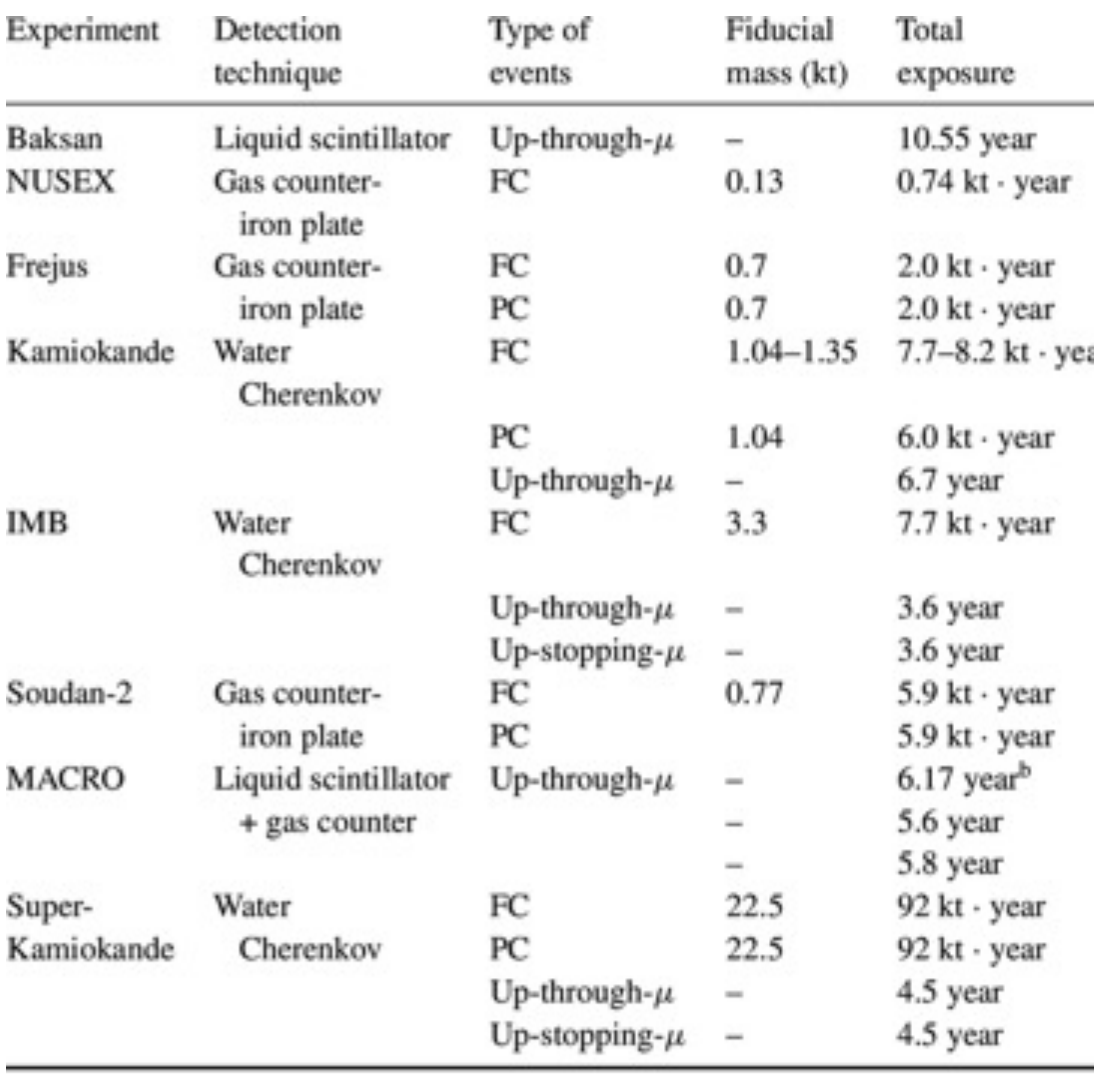
- Atmospheric neutrinos are produced by the decays of pions and kaons generated in the interaction of cosmic rays and nucleons in the Earth's atmosphere.
- Broad range of energy (~0.1 GeV to >TeV)
- Long travel distances (~10 to 1.3×10^4 km)
- Neutrino telescopes (ANTARES, IceCube) can also measure oscillations with atmospheric neutrinos.



ν_μ / ν_e ratio wel understood



Up/down ratio well understood

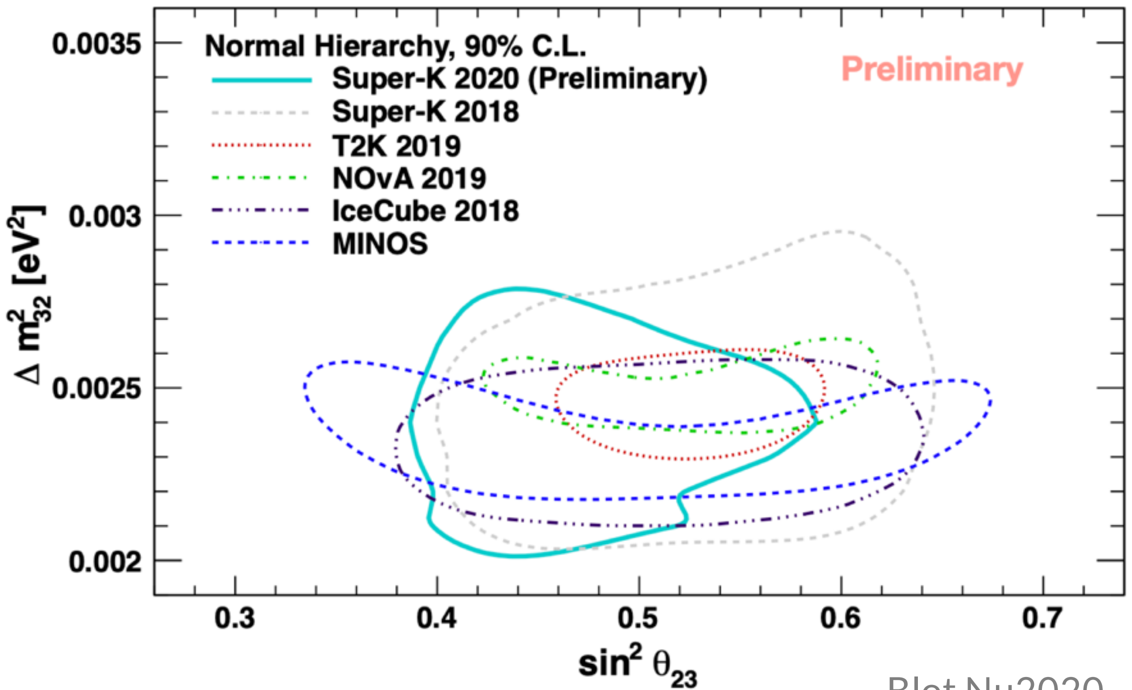


Experiment	Detection technique	Type of events	Fiducial mass (kt)	Total exposure
Baksan	Liquid scintillator	Up-through-μ	–	10.55 year
NUSEX	Gas counter-iron plate	FC	0.13	0.74 kt · year
Frejus	Gas counter-iron plate	FC	0.7	2.0 kt · year
		PC	0.7	2.0 kt · year
Kamiokande	Water Cherenkov	FC	1.04–1.35	7.7–8.2 kt · yea
		PC	1.04	6.0 kt · year
		Up-through-μ	–	6.7 year
IMB	Water Cherenkov	FC	3.3	7.7 kt · year
		Up-through-μ	–	3.6 year
		Up-stopping-μ	–	3.6 year
Soudan-2	Gas counter-iron plate	FC	0.77	5.9 kt · year
		PC		5.9 kt · year
MACRO	Liquid scintillator + gas counter	Up-through-μ	–	6.17 year[b]
			–	5.6 year
			–	5.8 year
Super-Kamiokande	Water Cherenkov	FC	22.5	92 kt · year
		PC	22.5	92 kt · year
		Up-through-μ	–	4.5 year
		Up-stopping-μ	–	4.5 year

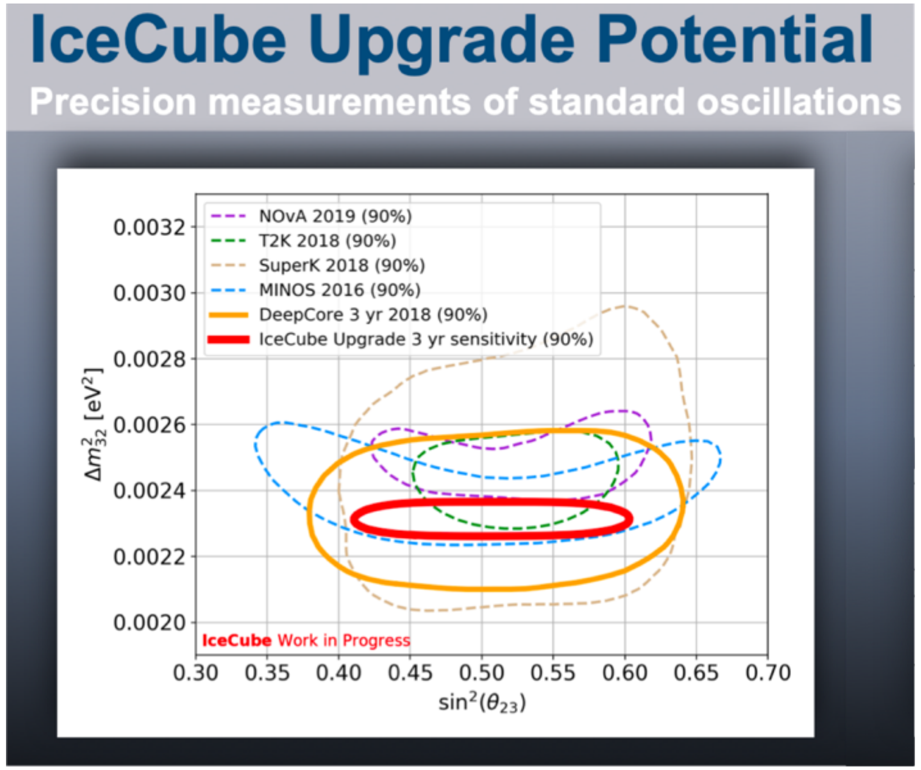
Atmospheric news

- Super-Kamiokande:
  - SK-Gd era is about to start (Neutrino/anti-neutrino discrimination)
  - New results using the full data sets from SK-I to SK-IV
  - Analysis improvements include: neutron tagging, new event selection
  - SK data disfavors Inverted Hierarchy at 71.4-90.3% CLs (was 81.9-96.1% in 2018)
  - Also prefers: 1st θ_{23} octant and δ_{CP}~3/2π
- IceCube
  - New oscillation measurements from IceCube DeepCore with 8 y live time are coming soon
  - IceCube Upgrade will enable more precise measurements of low energy neutrino properties, and better calibrations will benefit entire IceCube science program

Nakajima Nu2020



Blot Nu2020

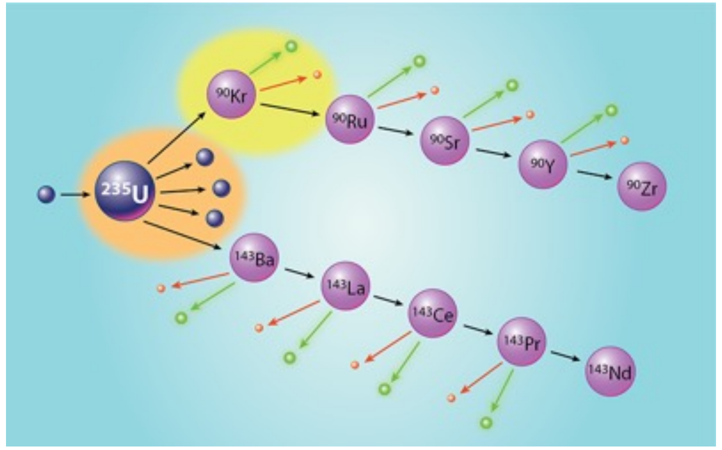


IceCube Upgrade Potential

Precision measurements of standard oscillations

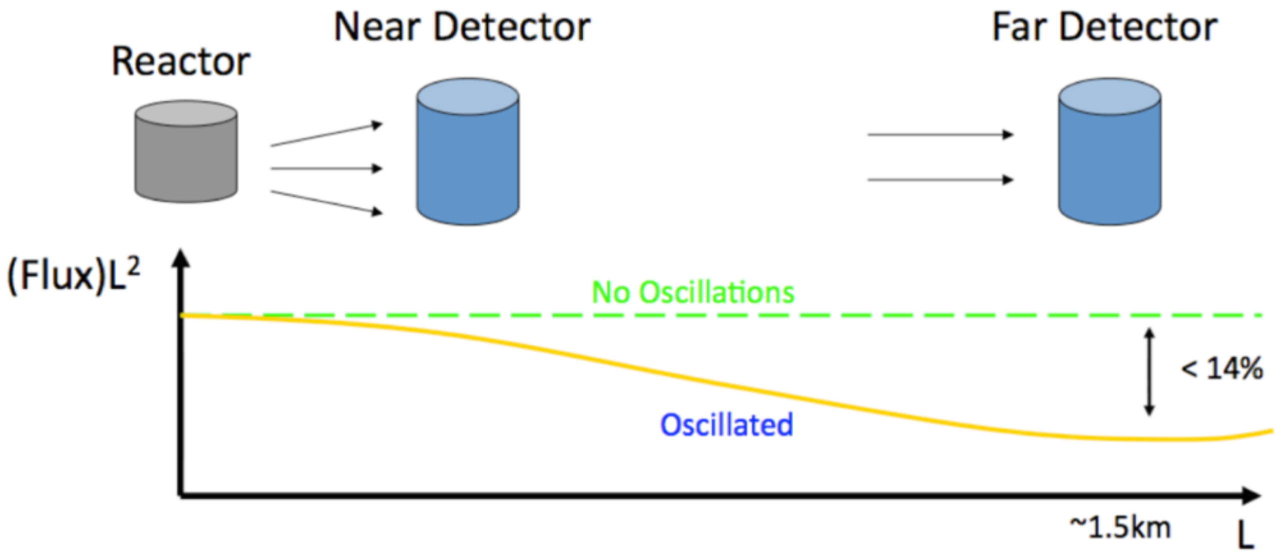
Reactor antineutrinos

- Nuclear reactors are very intense sources of $\overline{\nu}_e$'s in the MeV energy region; generated in nuclear fission of heavy isotopes
- $\overline{\nu}_e$ disappearance is the only channel available (low energy → cannot produce heavier charged leptons)
- O(100) km baseline → sensitive to Δm^2 of 10^{-4}–10^{-5} eV^2
- O(1) km baseline → sensitive to Δm^2 of 10^{-2}–10^{-3} eV^2
- Inverse beta decay → detection



PDG2020

Name	Reactor power (GW$_{\text{th}}$)	Baseline (km)	Detector mass (t)	Year
KamLAND	various	180 (ave.)	1,000	2001–
Double Chooz	4.25×2	1.05	8.3	2011–2018
Daya Bay	2.9×6	1.65	20×4	2011–
RENO	2.8×6	1.38	16	2011–
JUNO	26.6 (total)	53	20,000	

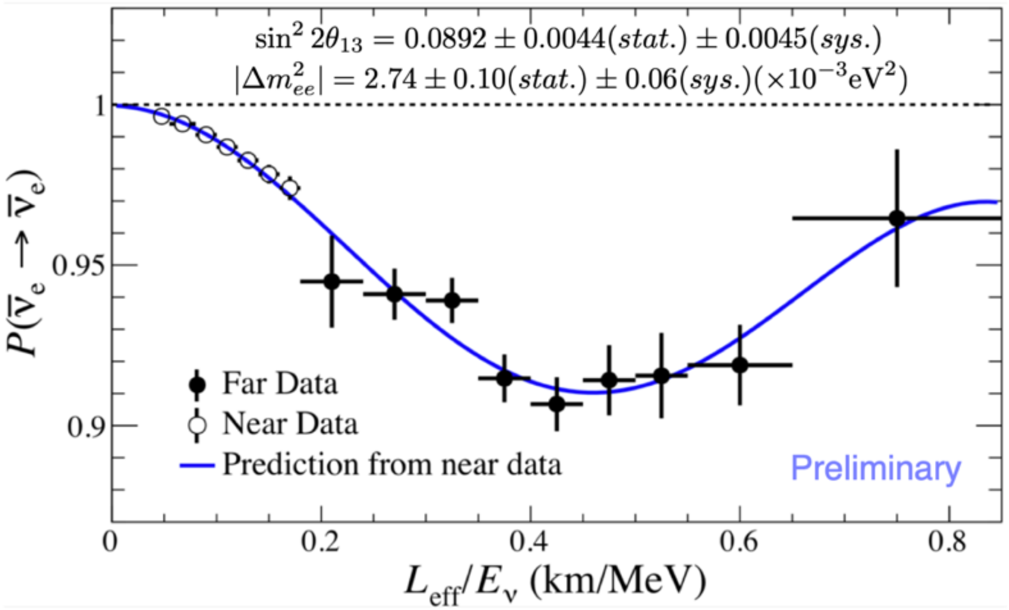


Reactor news

Yoo Nu2020

- RENO

$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2 \left(1.27\Delta m^2_{ee} \frac{L}{E_\nu}\right)$



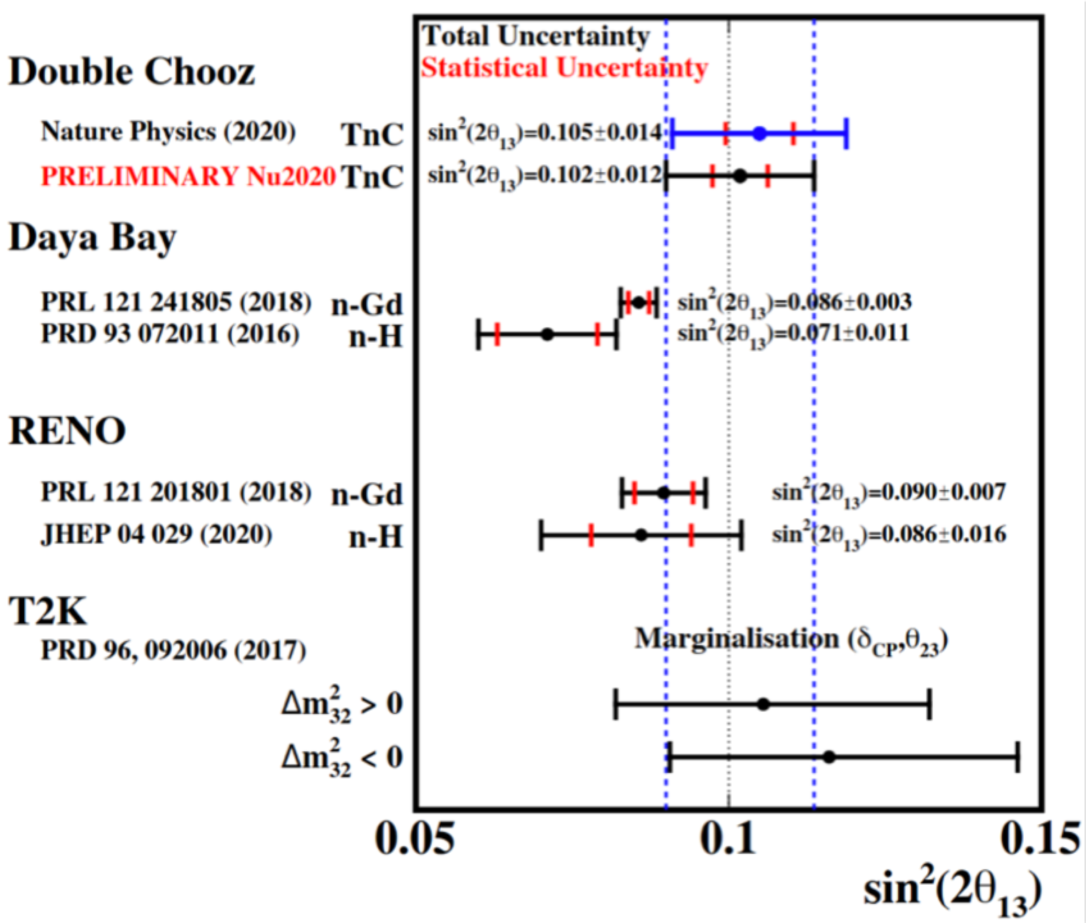
$$\sin^2 2\theta_{13} = 0.0892 \pm 0.0044(stat.) \pm 0.0045(sys.)$$ **± 7.0%**

$$|\Delta m^2_{ee}| = 2.74 \pm 0.10(stat.) \pm 0.06(sys.)(\times 10^{-3}\text{eV}^2)$$ **± 4.4%**

- Daya Bay:
  - Still has the most precise measurements of $\sin^2 2\theta_{13}$
  - Final results expected by Neutrino 2022

Ling Nu2020

- Double Chooz
  - Increased statistics
  - New result: $\sin^2 2\theta_{13}$ = **0.102 ± 0.012** (w/ full two detectors data)
  - Still room for improvement in the precision
  - Double Chooz reaching its life-cycle end



Bezerra Nu2020

Bonus: more reactor experiments

- Recent reactor experiments searching for ~1 eV^2 oscillations
- Distance of ~10 m from the core
- Detectors are based on organic scintillators (liquid = LS, plastic =PS)

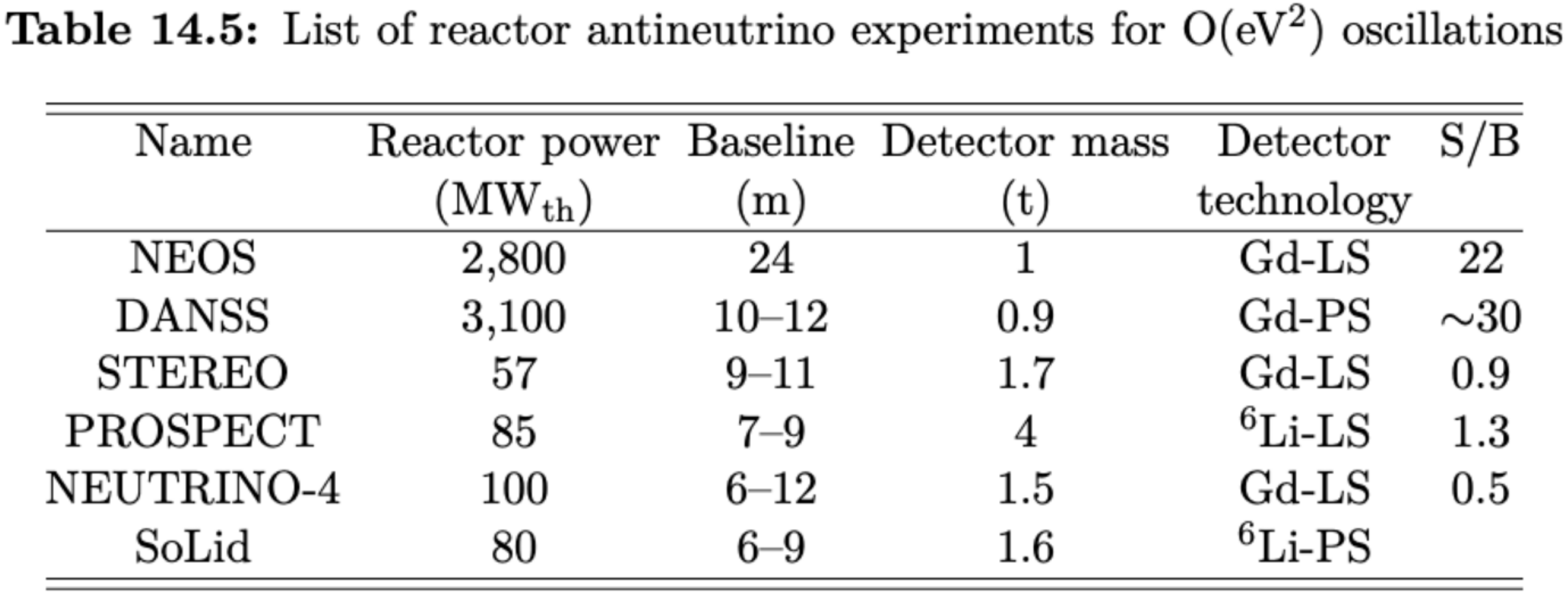
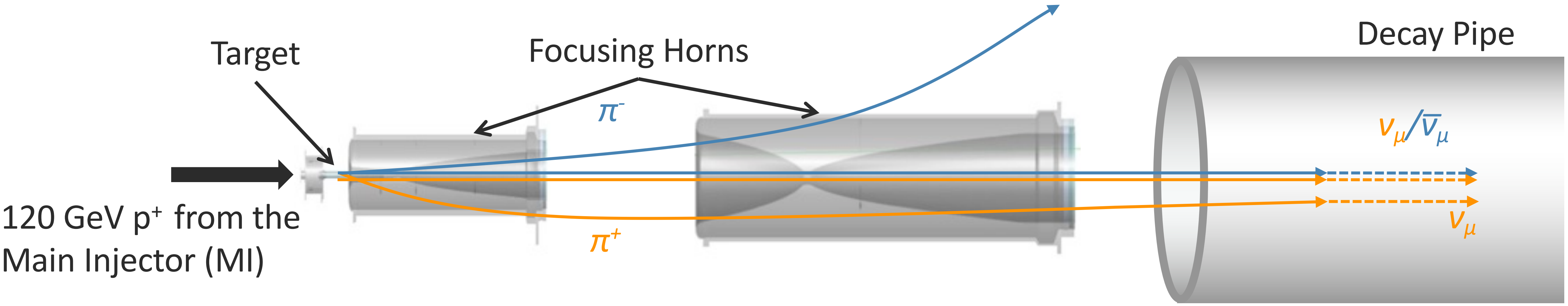


Table 14.5: List of reactor antineutrino experiments for O(eV^2) oscillations

Name	Reactor power ($\mathrm{MW_{th}}$)	Baseline (m)	Detector mass (t)	Detector technology	S/B
NEOS	2,800	24	1	Gd-LS	22
DANSS	3,100	10–12	0.9	Gd-PS	∼30
STEREO	57	9–11	1.7	Gd-LS	0.9
PROSPECT	85	7–9	4	^{6}Li-LS	1.3
NEUTRINO-4	100	6–12	1.5	Gd-LS	0.5
SoLid	80	6–9	1.6	^{6}Li-PS	

PDG2020

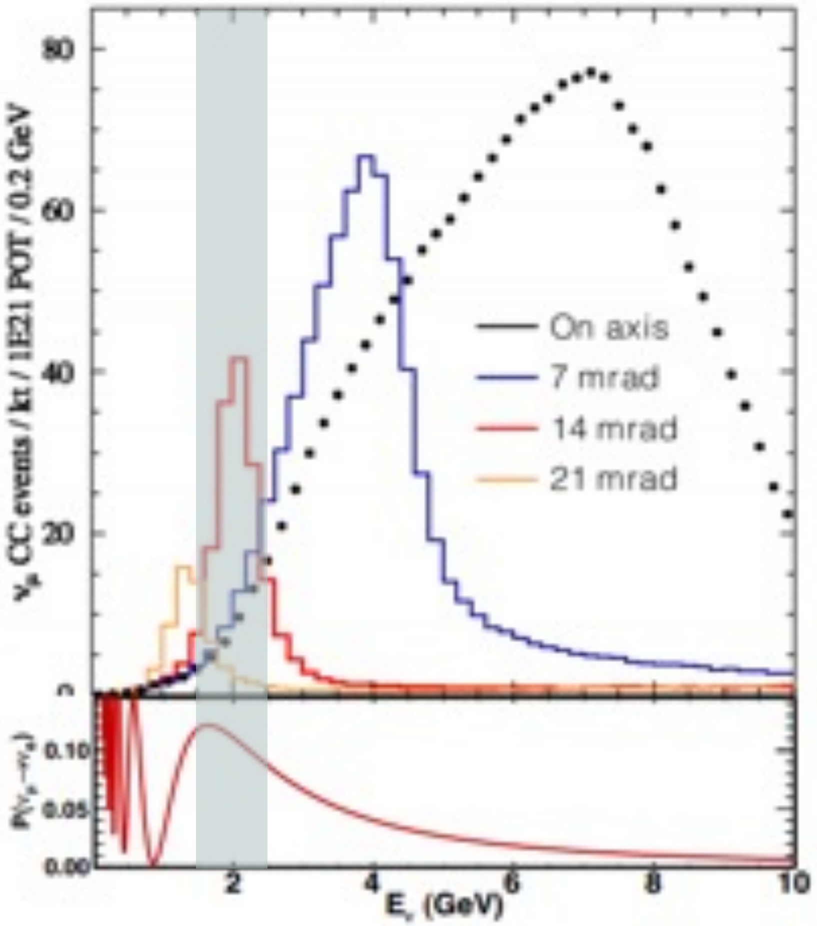
Accelerator neutrinos



- Proton beam is steered onto a target
- Produced hadrons are focused in and charge-sign-selected by two magnetic horns, then go into a decay pipe
- Predominantly pions and kaons, decay modes:

$$\left.\begin{aligned}&\pi^+ \to \mu^+ + \nu_\mu,\\ &K^+ \to \mu^+ + \nu_\mu\end{aligned}\right. \quad \Longrightarrow \boldsymbol{\nu_\mu} \text{ beam}$$

- Small contamination: $\nu_e, \overline{\nu}$
- Reverse the horn current $\Longrightarrow \overline{\nu}_\mu$ beam
- Here: NuMI beam (Fermilab). Equivalent designs at CERN, JPARC



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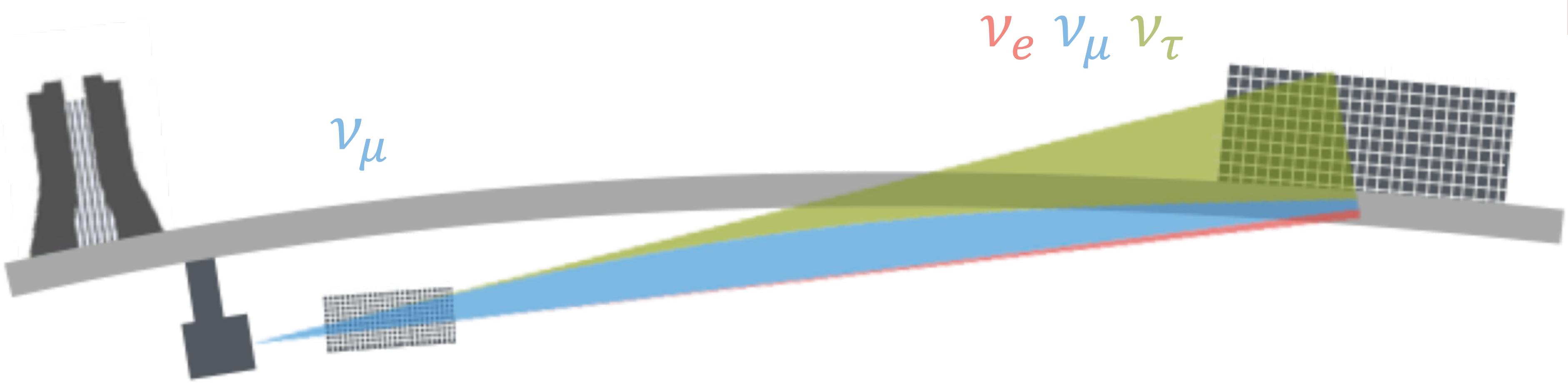
Long baseline experiments

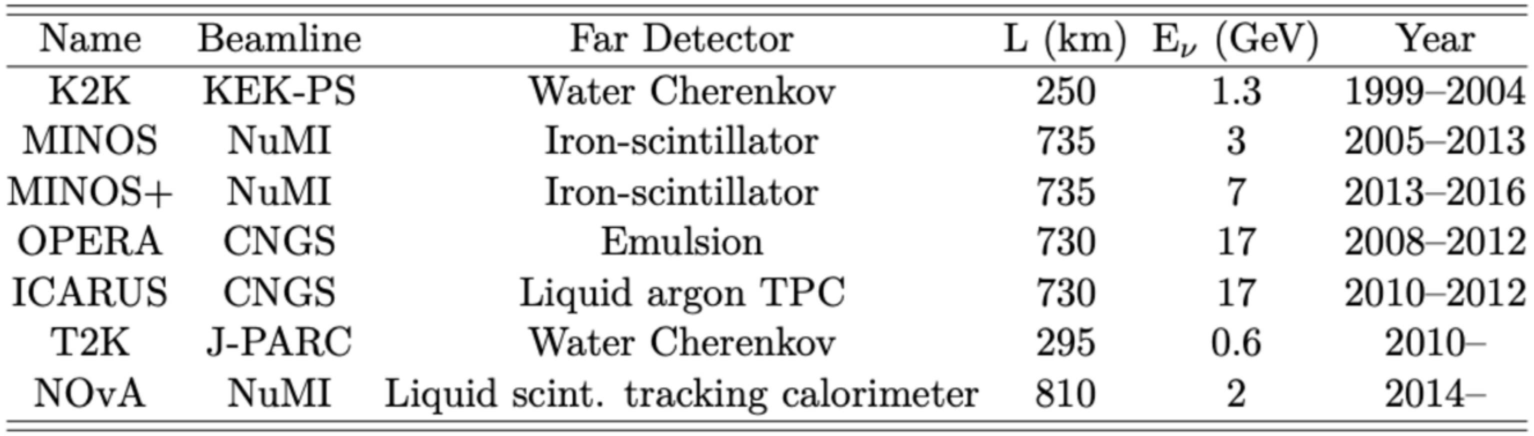


Far Detector

- Measure the oscillated spectrum
- Compare to the prediction without oscillations
- Channels: $\nu_\mu \rightarrow \nu_\mu,\ \nu_\mu \rightarrow \nu_e,$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu,\ \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Near Detector

- Measurements of the unoscillated beam → improve the predictions
- Sources of uncertainty include
  - **Flux**: number of neutrinos produced
  - **Cross section**: how often they interact
- ND/FD same type of detector (NOvA, MINOS)
- FD off-axis (NOVA, T2K); On-axis (MINOS)



Name	Beamline	Far Detector	L (km)	E_ν (GeV)	Year
K2K	KEK-PS	Water Cherenkov	250	1.3	1999–2004
MINOS	NuMI	Iron-scintillator	735	3	2005–2013
MINOS+	NuMI	Iron-scintillator	735	7	2013–2016
OPERA	CNGS	Emulsion	730	17	2008–2012
ICARUS	CNGS	Liquid argon TPC	730	17	2010–2012
T2K	J-PARC	Water Cherenkov	295	0.6	2010–
NOvA	NuMI	Liquid scint. tracking calorimeter	810	2	2014–

PDG2020

Long baseline news (1)

- MINOS/MINOS +
  - Final long-baseline results presented at Neutrino 2020

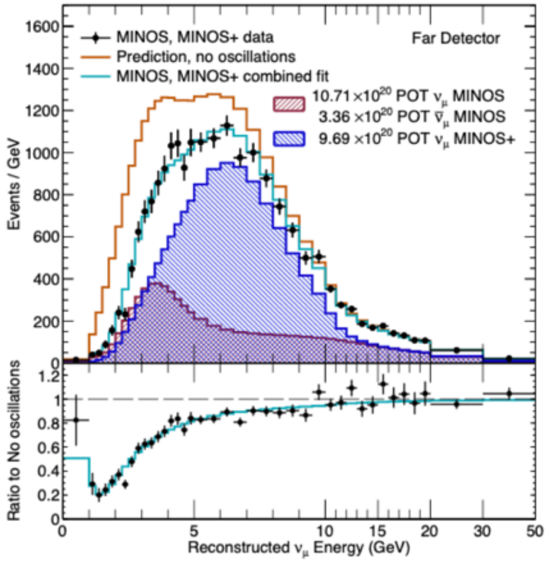
Normal hierarchy, non-maximal mixing

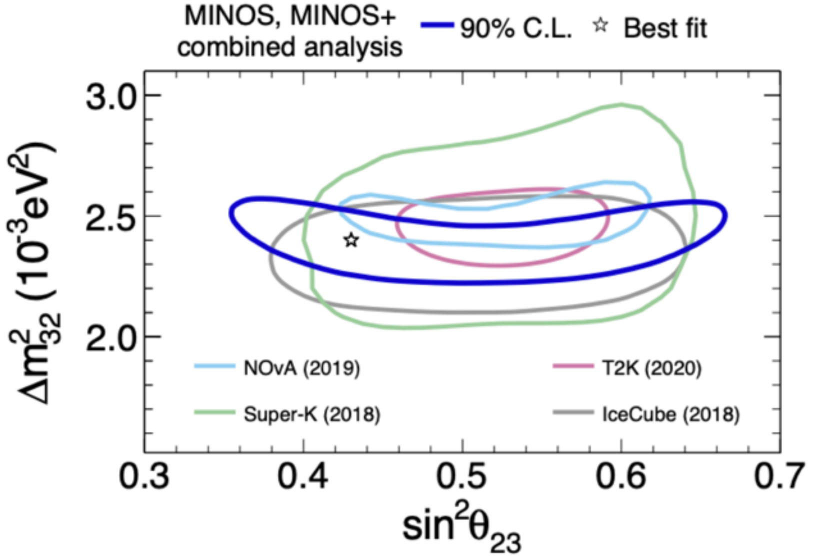
$$\Delta m^2_{32} = 2.40^{+0.08}_{-0.09} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.43\ (0.39 \leftrightarrow 0.63)\ 68\,\%\ \mathrm{C.L.}$$

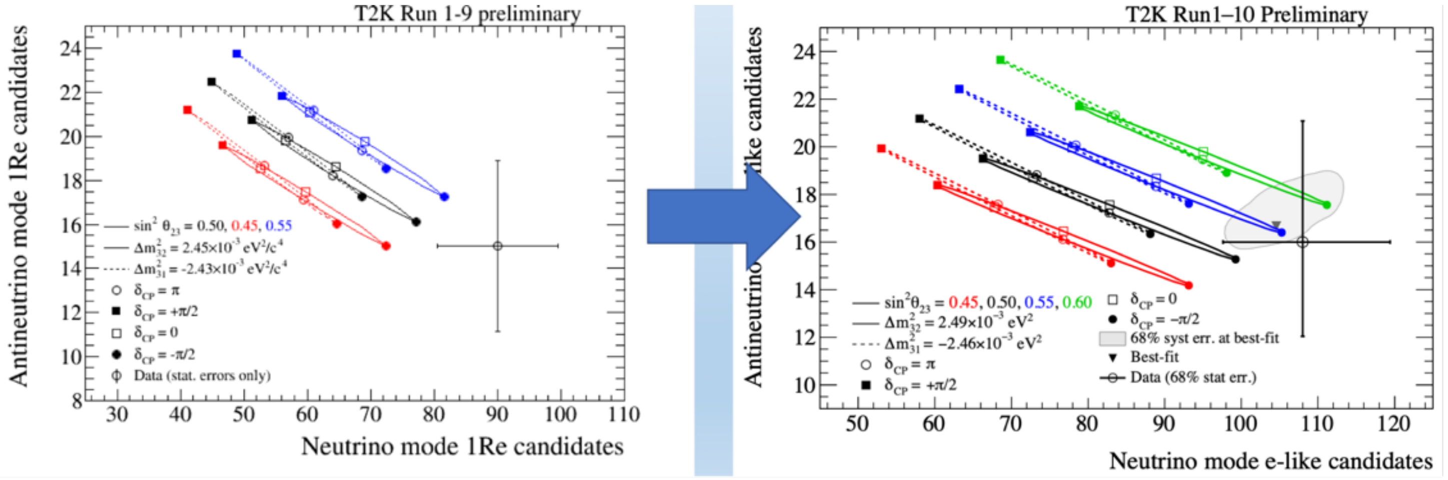
- T2K:
  - Results with 33% more ν-mode data.
  - Upgrades to the interaction and flux modeling
  - Coming soon:
  - Power upgrade 515kW->810kW by FY2022
  - ND280 upgraded in 2022 with a new higher angular coverage TPC and 3D Super-FGD subdetector
  - SK-Gd loading for neutron tagging imminent

Carroll Nu2020





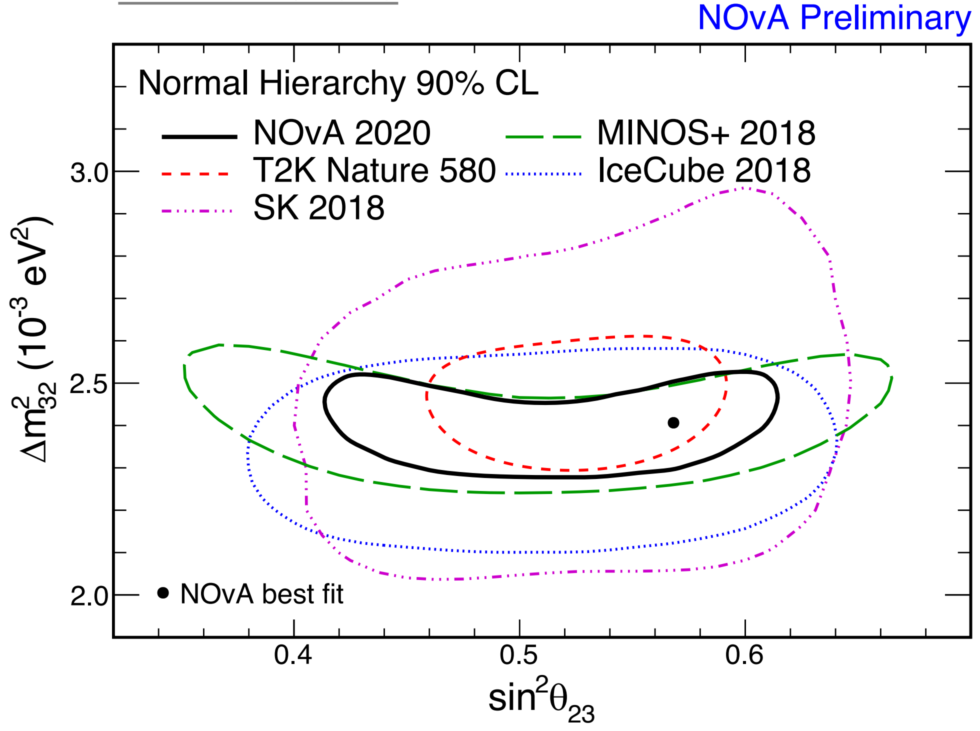
Dunne Nu2020

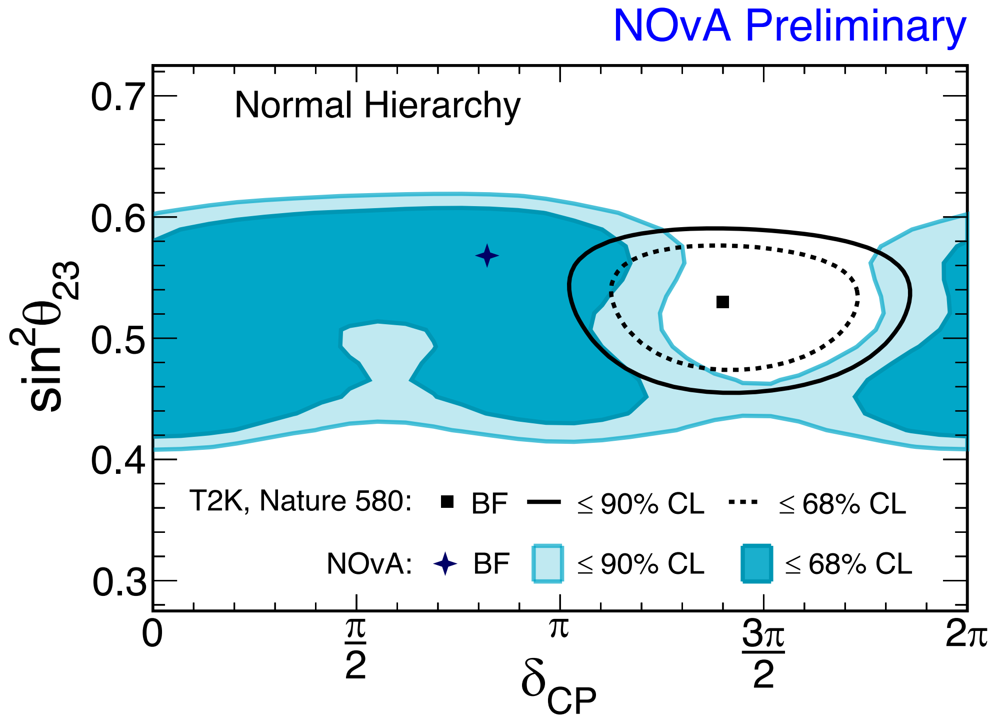


Long baseline news (2)

- NOvA
  - Results with 50% more neutrino beam data
  - Updated simulation and reconstruction, including a new GENIE 3 cross-section model
  - Anticipate running until 2025.
    - **New 3-flavor oscillation results:**
      - $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}$ eV^2
      - $\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$
      - exclude IH, $\delta = \pi/2$ at > 3σ,
      - disfavor NH, $\delta = 3\pi/2$ at ~2σ.
- NOvA + T2K
  - Combined analysis of data allows degeneracies to be broken and maximizes impact of data
  - Work towards T2K+NOvA is underway

Himmel Nu2020





Putting it all together

3- ν oscillation analysis

- The determination of the leptonic parameters requires global analysis of the data from the different experiments

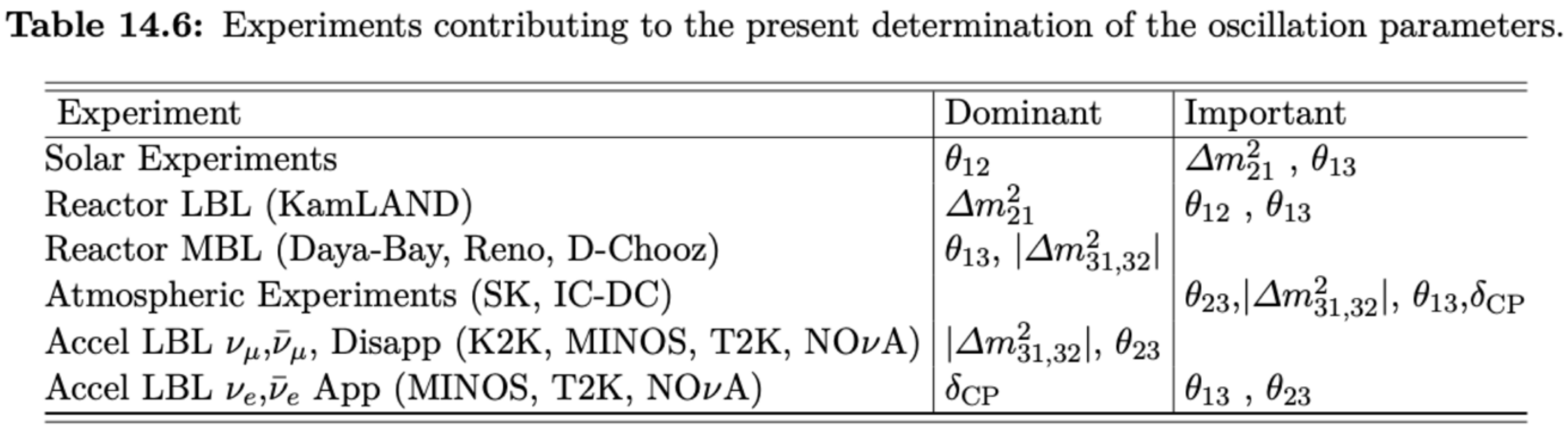


Table 14.6: Experiments contributing to the present determination of the oscillation parameters.

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}, $\|\Delta m^2_{31,32}\|$	
Atmospheric Experiments (SK, IC-DC)		θ_{23},$\|\Delta m^2_{31,32}\|$, θ_{13},δ_{CP}
Accel LBL ν_μ,$\bar{\nu}_\mu$, Disapp (K2K, MINOS, T2K, NOνA)	$\|\Delta m^2_{31,32}\|$, θ_{23}	
Accel LBL ν_e,$\bar{\nu}_e$ App (MINOS, T2K, NOνA)	δ_{CP}	θ_{13} , θ_{23}

PDG2020

- Recent references: (pre/post Neutrino 2020)
  - **2020 Global reassessment of the neutrino oscillation picture** arXiv:2006.11237 [hep-ph]
    P. F. de Salas, D. V. Forero, S. Gariazzo, P. Martínez-Miravé, O. Mena, C. A. Ternes, M. Tórtola, J. W. F. Valle
  - **The fate of hints: updated global analysis of three-flavor neutrino oscillations** arXiv:2007.14792 [hep-ph]
    I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, A. Zhou

3- ν oscillation analysis

- Updates since Neutrino 2020: (arXiv:2007.14792)
  - Long baseline accelerator:
    - NOvA added stats to neutrino sample, changes to antineutrino analysis
    - T2K added stats to neutrino sample, changes to antineutrino analysis
  - Reactor experiments:
    - DoubleChooz from 818/258 to 1276/587 days of far/near detector data
    - RENO from 2200 to 2908 days of exposure
  - Solar experiments:
    - Super-Kamiokande: total energy spectrum and the day-night asymmetry of the 2970-day sample
    - Note: reduced tension between KamLAND and solar

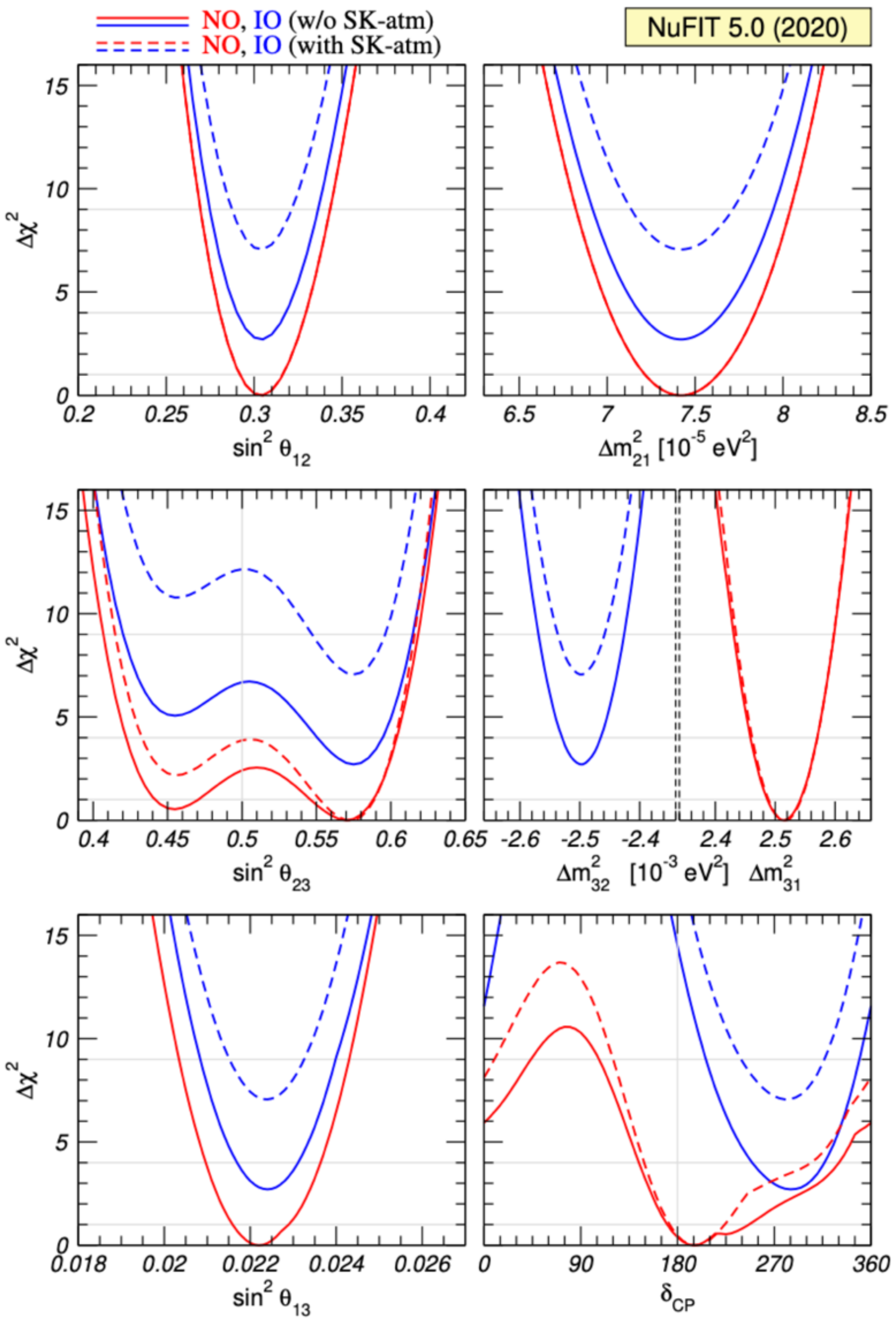
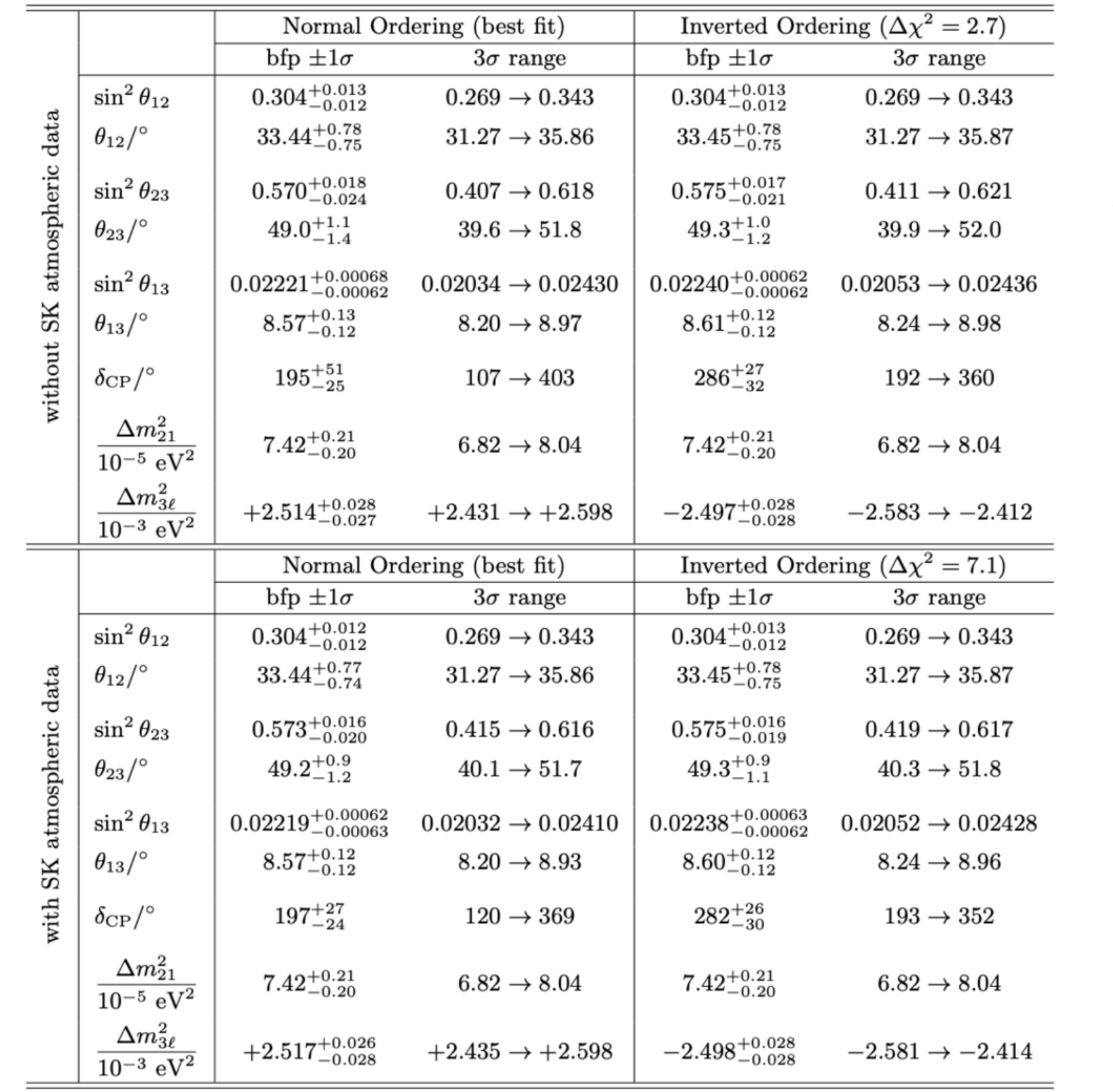


Figure 6. Global 3ν oscillation analysis. We show $\Delta\chi^2$ profiles minimized with respect to all undisplayed parameters. The red (blue) curves correspond to Normal (Inverted) Ordering. Solid (dashed) curves are without (with) adding the tabulated SK-atm $\Delta\chi^2$. Note that as atmospheric mass-squared splitting we use Δm^2_{31} for NO and Δm^2_{32} for IO.

- Best fit in the global analysis remains for the normal mass ordering with reduced significance
- T2K + NOvA LBL results favor inverted mass ordering
- Mild preference for non-maximal mixing, upper octant
- Best fit for the CP phase close to CP-conserving in the NH

NuFIT arXiv:2007.14792



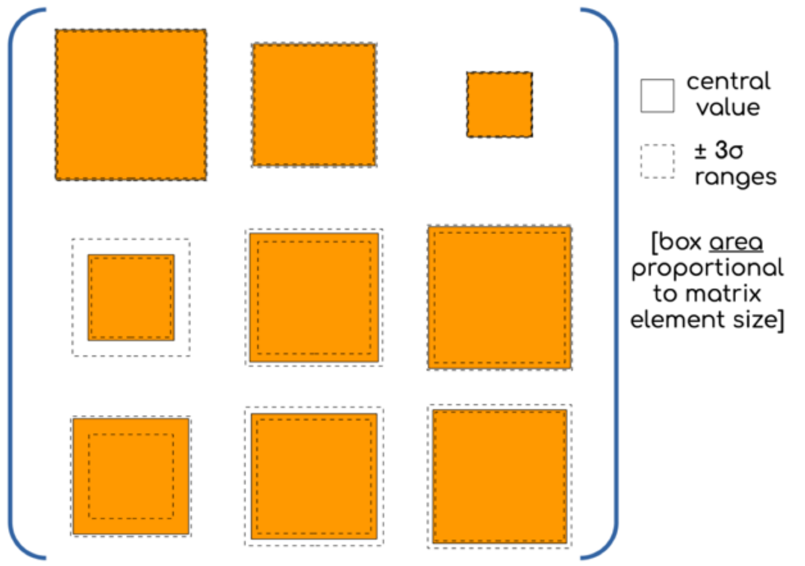
without SK atmospheric data		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
	$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
	$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{\rm CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
	$\dfrac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$

with SK atmospheric data		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{\rm CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\dfrac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

Table 3. Three-flavor oscillation parameters from our fit to global data. The numbers in the 1st (2nd) column are obtained assuming NO (IO), *i.e.*, relative to the respective local minimum. Note that $\Delta m^2_{3\ell} \equiv \Delta m^2_{31} > 0$ for NO and $\Delta m^2_{3\ell} \equiv \Delta m^2_{32} < 0$ for IO. The results shown in the upper (lower) table are without (with) adding the tabulated SK-atm $\Delta\chi^2$.

NuFIT arXiv:2007.14792

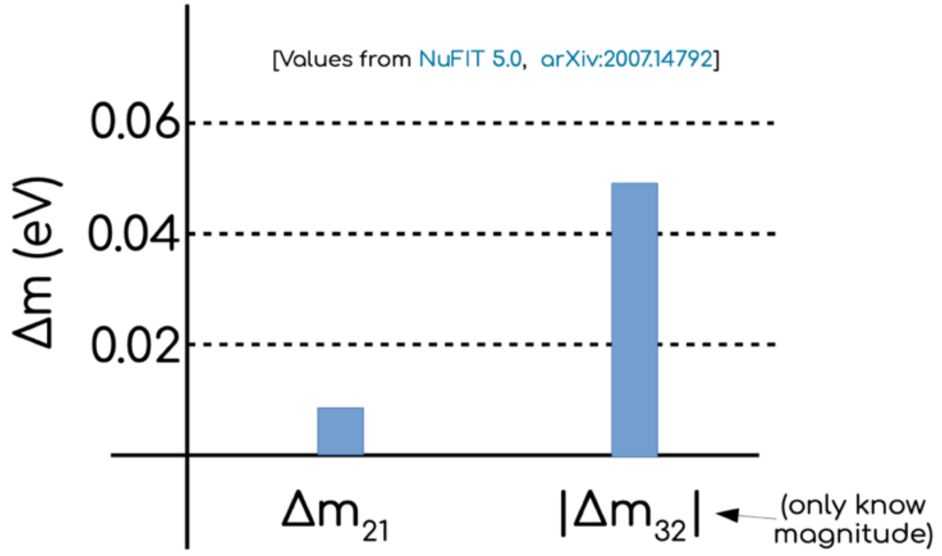
[Values from NuFIT 5.0, arXiv:2007.14792]



(3σ)

$$\theta_{12} : 14\% , \quad \theta_{13} : 9.0\% , \quad \theta_{23} : 27\% \; [25\%] ,$$
$$\Delta m^2_{21} : 16\% , \quad |\Delta m^2_{3\ell}| : 6.7\% \; [6.5\%] , \quad \delta_{\rm CP} : 100\% \; [100\%] ,$$

[Values from NuFIT 5.0, arXiv:2007.14792]



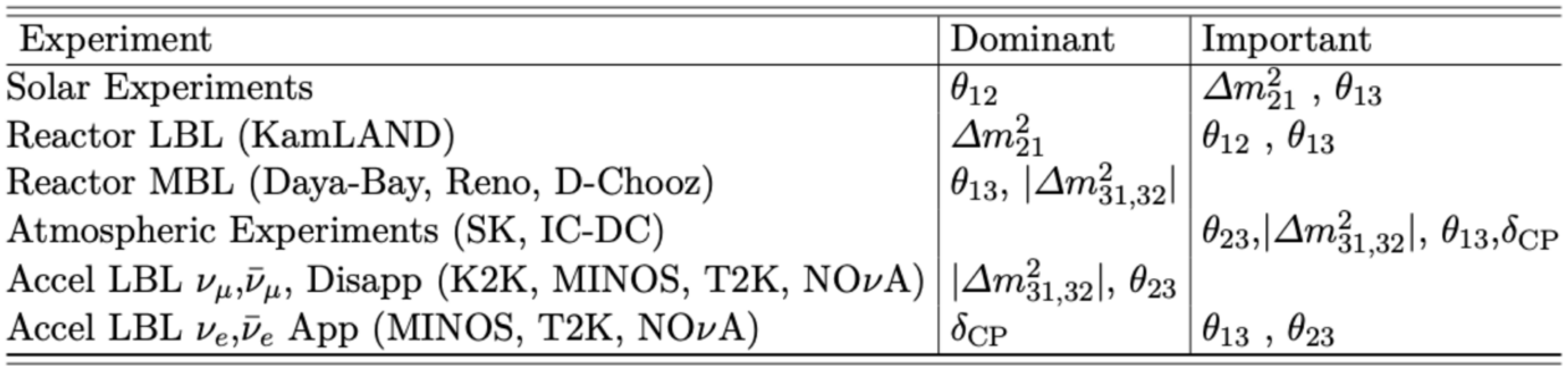
Conclusion


Solar


Reactor


Accelerator

- Neutrinos oscillate!
- Wide range of combinations of neutrino sources / detection techniques
- The determination of the leptonic parameters requires global analysis of the data from the different experiments



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},δ_{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)	δ_{CP}	θ_{13} , θ_{23}

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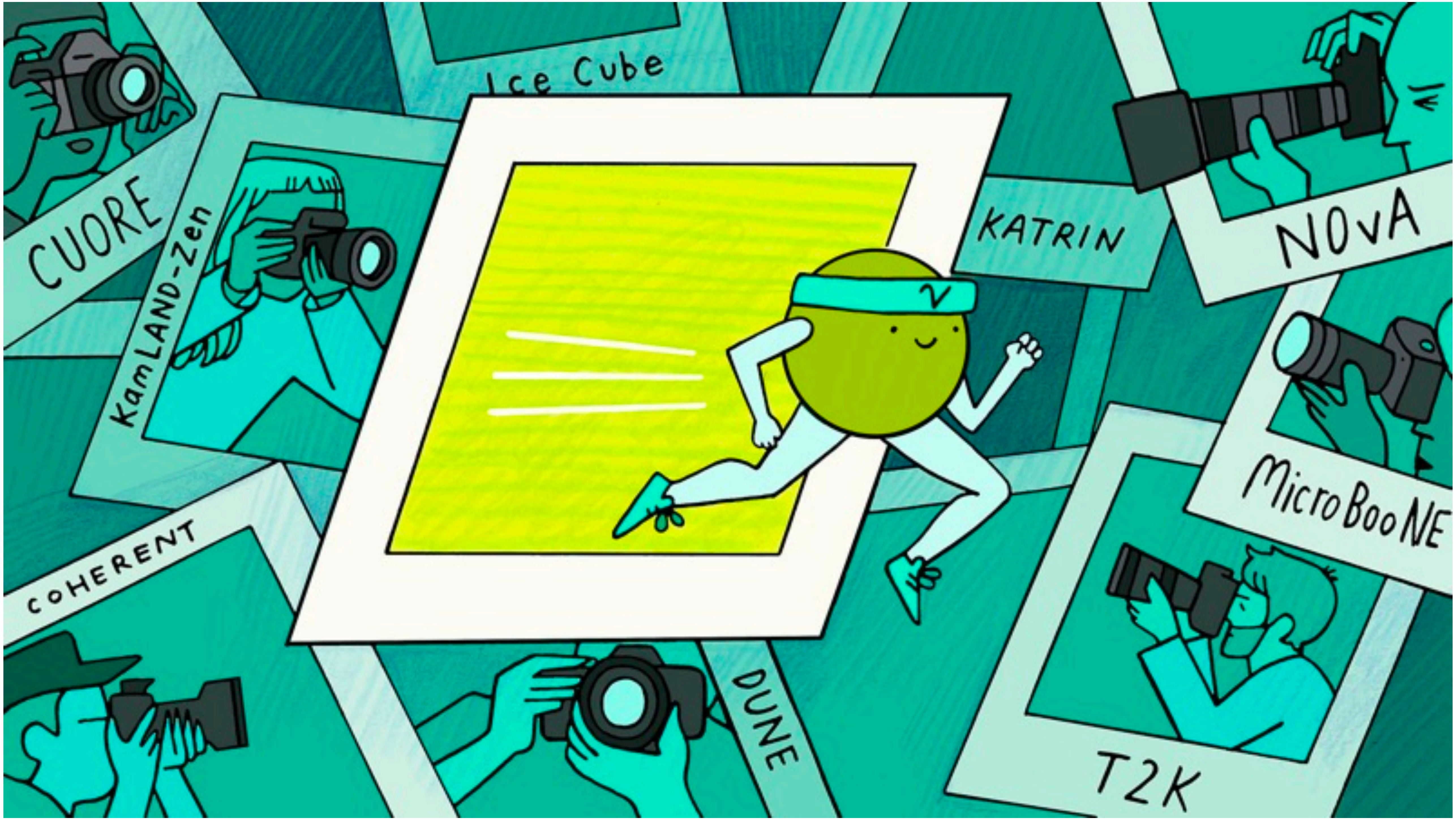
- Progressively increasing the precision of angles and mass squared differences; with more stats agreement between experiments tends to improve
- Still unknown: CP phase and neutrino mass hierarchy. It might be possible to achieve 2-3 σ, higher at very favorable true parameters, by the end of current experiments' lifetime. The next generation (e.g. HyperK, DUNE) will likely do better, ~5 σ within a few years of running.
- Many more exciting ν news to come!



Artwork by Sandbox Studio, Chicago with Corinne Mucha