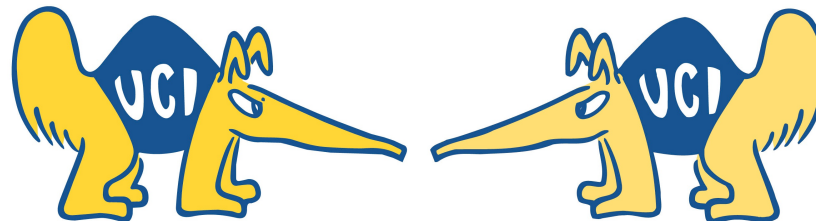


Neutrino Physics Introduction

Mu-Chun Chen, University of California at Irvine



Flavor Physics Conference, ICISE, Quy Nhon, Vietnam, August 21, 2025

Neutrino Physics Post-1998

1998: evidence for neutrino mass from SuperK ($\nu_\mu \rightarrow \nu_\tau$)

first solid evidence of beyond the Standard Model Physics

Massive
Neutrinos

2002: evidence for neutrino mass from SNO ($\nu_e \rightarrow \nu_{\mu,\tau}$)

2003: KamLand confirmed Large Mixing Angle solution to solar ν problem

2011: hints for non-zero θ_{13} from T2K, MINOS, and Double Chooz

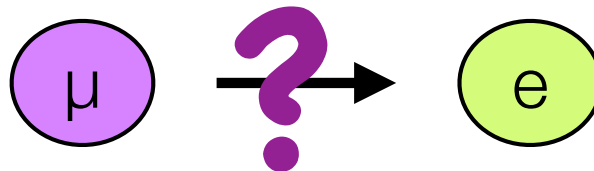
2012: evidences of non-zero θ_{13} from Daya Bay and RENO

for some parameters: discovery phase into precision phase;
and yet, many great discoveries to come

Neutrino Oscillation $\Rightarrow$ Massive Neutrinos

- Neutrino Masses are non-degenerate (at least two are non-zero)
 - mass eigenstates $\neq$ weak eigenstates
- Accidental symmetries in SM
 - Broken lepton flavor numbers: L_e, L_μ, L_τ
 - Processes cross family lines in lepton sector now possible
 - As a result
 - neutrino oscillation ✓
 - lepton flavor violation decays?

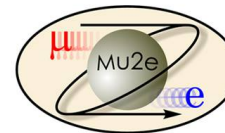
Overview by
Masato
Yamanaka



MEG II: Toshiyuki Iwamoto

Mu2e: Tamasi Eameschandra Kar

COMET: Truong Nguyen

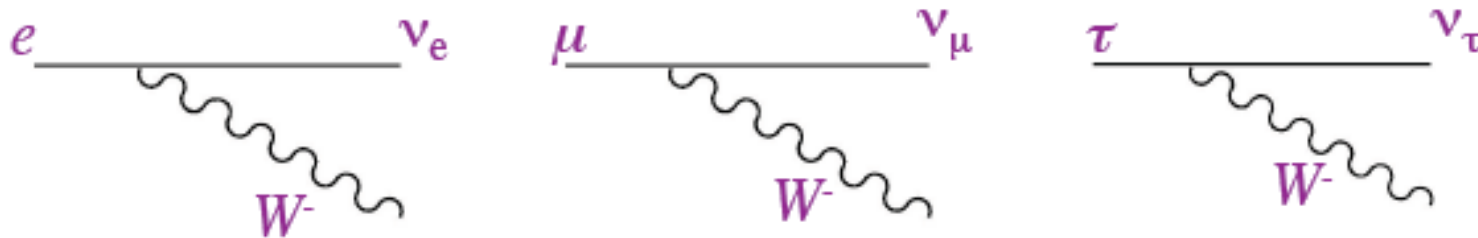


- total lepton number? $L \stackrel{?}{=} L_e + L_\mu + L_\tau$ $\leftrightarrow$

ARE NEUTRINOS
THEIR OWN?
ANTIPARTICLES?

What if Neutrinos Have Mass?

- Similar to the quark sector, there can be a mismatch between mass eigenstates and weak eigenstates
- weak interactions eigenstates: ν_e, ν_μ, ν_τ



- mass eigenstates: ν_1, ν_2, ν_3
- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix

Maki, Nakagawa, Sakata, 1962 ; Pontecorvo, 1967

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{\text{PMNS}} = V_{e,L}^\dagger V_{\nu,L}$$

3 mixing angles
+ 1 (3) phase(s) for
Dirac (Majorana)
neutrinos

Leptonic Mixing Matrix

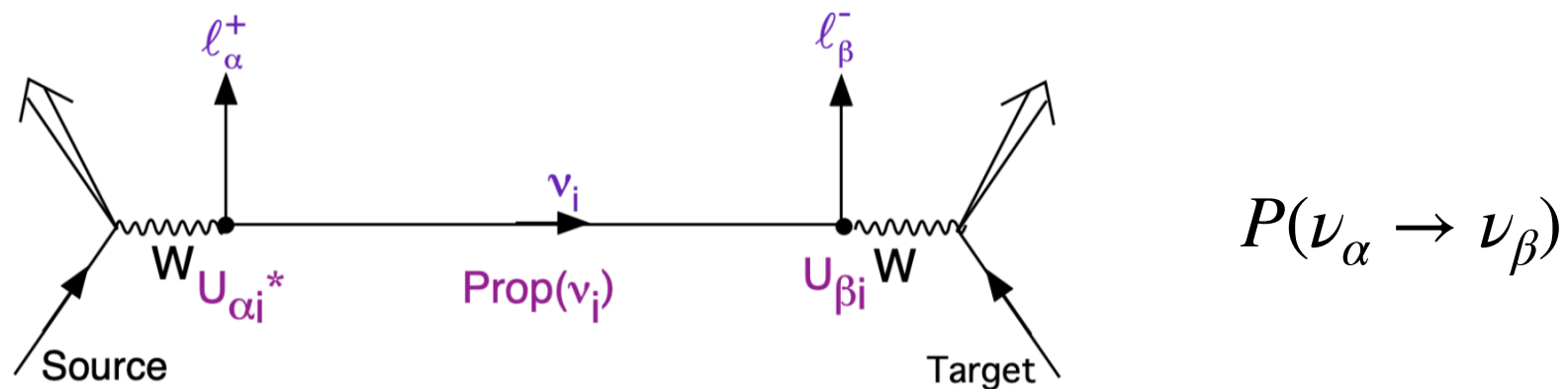
- Pontecorvo–Maki–Nakagawa–Sakata (PMNS) Matrix

$$U_{MNS} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_a & s_a \\ 0 & -s_a & c_a \end{bmatrix}}_{\text{PMNS atm}} \underbrace{\begin{bmatrix} c_x & 0 & s_x e^{-i\delta} \\ 0 & 1 & 0 \\ -s_x e^{i\delta} & 0 & c_x \end{bmatrix}}_{\text{reactor}} \underbrace{\begin{bmatrix} c_s & s_s & 0 \\ -s_s & c_s & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{solar}} \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i(\frac{1}{2}\phi_{12})} & 0 \\ 0 & 0 & e^{i(\frac{1}{2}\phi_{13} + \delta)} \end{bmatrix}}_{\text{Majorana phases}}$$

- Three mass eigenvalues $m_1, m_2, m_3 \Rightarrow$ two $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$
- three mixing angles: c_a, c_s, c_x
- three CP phases (if Majorana): $\delta, \phi_{12}, \phi_{13}$
 - 1 CP phase (if Dirac): δ
- Oscillation experiments: sensitive only to δ
- Neutrinoless double beta decay: sensitive only to Majorana phases: ϕ_{12}, ϕ_{13}

Neutrino Oscillation: Macroscopic Quantum Mechanics

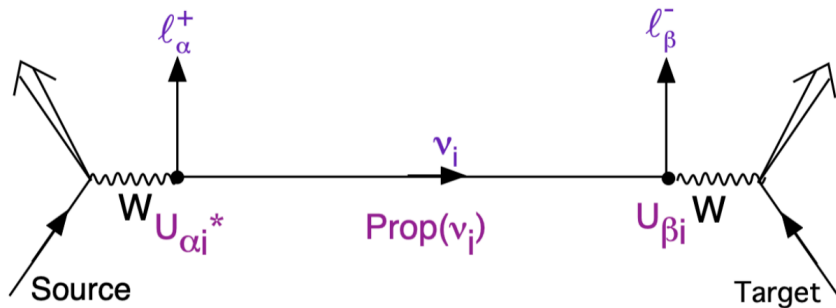
- **production**: neutrinos of a definite **flavor** produced by weak interaction
- **propagation**: neutrinos evolve according to their **masses**
- **detection**: neutrinos of a different **flavor** composition detected



2 flavor
approximation

$$P[\nu_\mu \rightarrow \nu_e] = \sin^2 2\theta \sin^2 \left[1.27 \Delta m_{32}^2 \left(\frac{(\text{eV})^2}{c^2} \right) \frac{L(\text{km})}{E(\text{GeV})} \right]$$

Neutrino Oscillation: General



$$P(\nu_\alpha \rightarrow \nu_\beta)$$

$$P(\nu_\alpha \rightarrow \nu_\beta; L, E) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2(\Delta m_{ij}^2 \frac{L}{4E})$$

$$+ 2 \sum_{i>j} \Im(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin(\Delta m_{ij}^2 \frac{L}{2E})$$



Leptonic Jarlskog invariant

Classes of Experiments

Oscillation Experiments:

Atmospheric, solar, reactor, accelerator neutrinos

- mass ordering, CP phases, precision measurements
- Searches for BSM physics

Neutrino cross sections, CE ν NS:

- Interpretation of data
- BSM

Neutrinoless Double Beta Decay:

- Majorana vs Dirac

Weak Decay Kinematics:

- Absolute mass scale
- Precision cosmology

Neutrino Physics in Vietnam



IFIRSE, ICISE:

T2K, Super-K

beam monitor

flux simulation

cross-section measurement

neutrino oscillation analysis

VAST, IOP: T2K

Classes of Experiments

Oscillation Experiments:

Atmospheric, solar, reactor, accelerator neutrinos

- mass ordering, CP phases, precision measurements
- Searches for BSM physics

Neutrino cross sections, CE ν NS:

- Interpretation of data
- BSM

Neutrinoless Double Beta Decay:

- Majorana vs Dirac

Weak Decay Kinematics:

- Absolute mass scale
- Precision cosmology

Astrophysical Neutrinos:

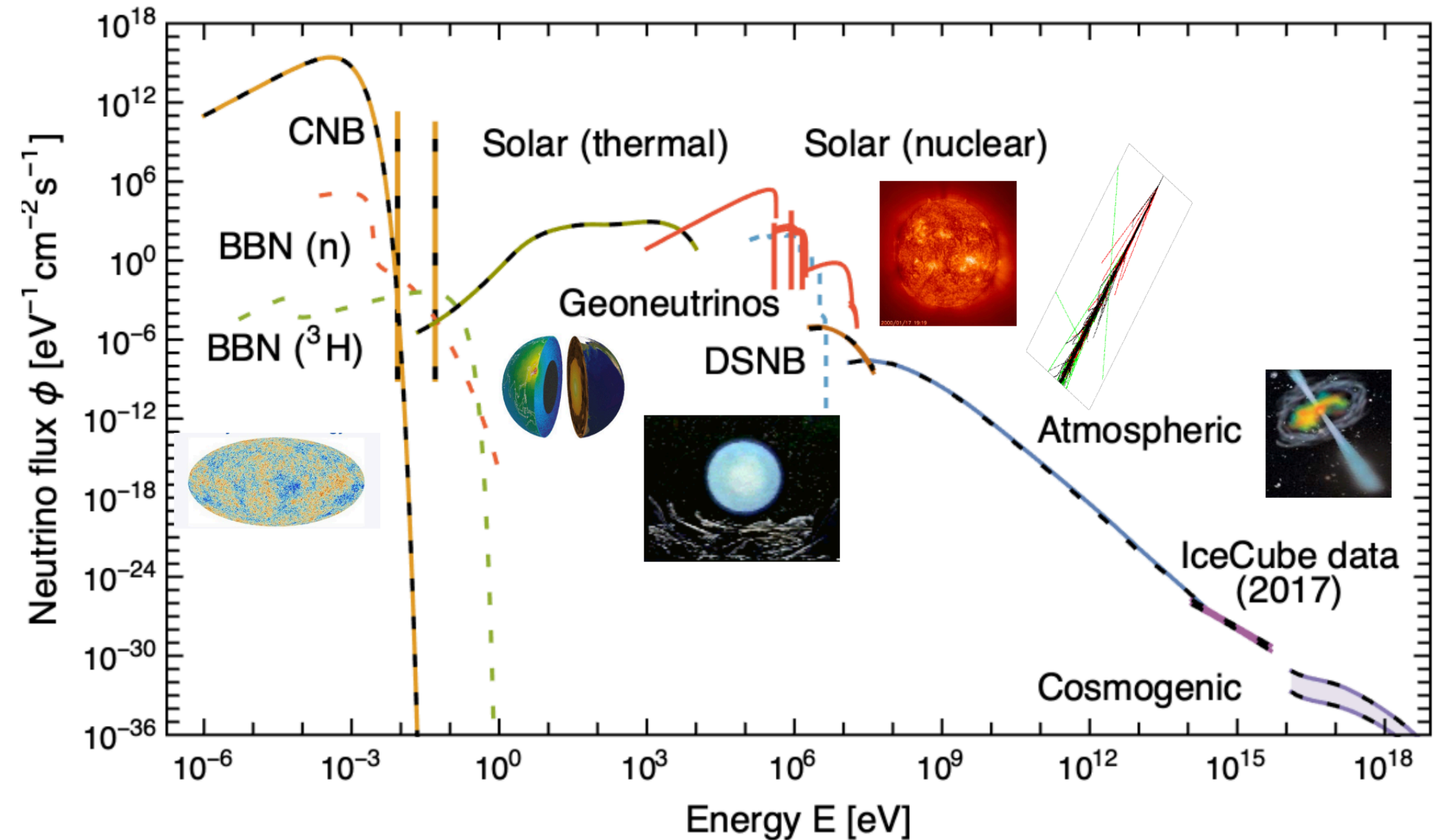
- SN, GRBs, AGNs, mergers
- Possible BSM physics

Grand Unified Neutrino Spectrum at Earth

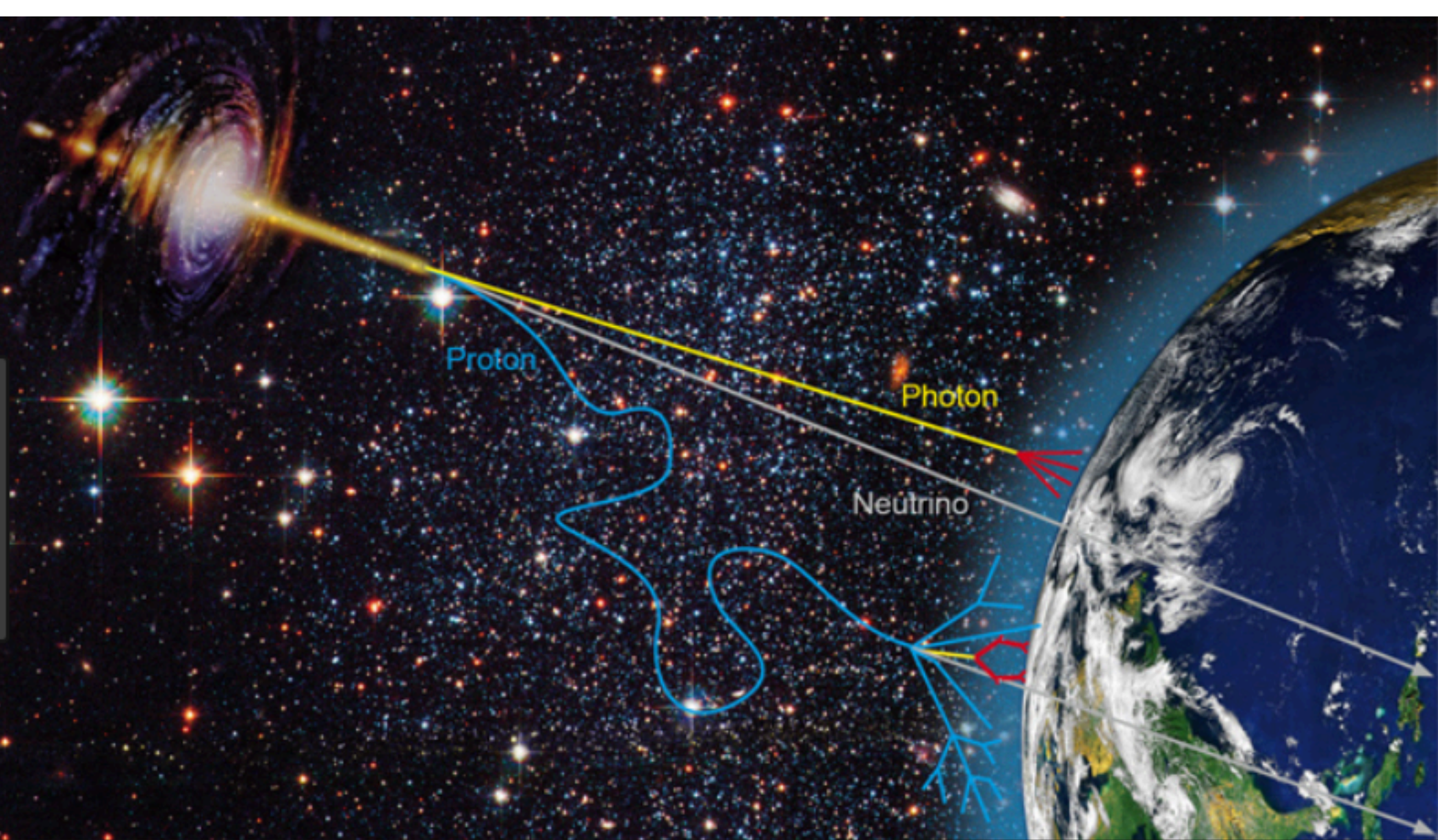
Edoardo Vitagliano, Irene Tamborra, Georg Raffelt. Oct 25, 2019. 54 pp.

MPP-2019-205

e-Print: [arXiv:1910.11878](https://arxiv.org/abs/1910.11878) [astro-ph.HE] | [PDF](#)



[Slide from: Kate Scholberg, Snowmass CSS 2022]



[Photo credit: Astroparticle Physics - DESY]

Neutrinos as
messengers

KM3NeT: Talk by
Gogita Papalashvili

Where Do We Stand?

NuFit-6.0 (2024)

IC24 with SK atmospheric data		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2 \theta_{12}$	$0.308^{+0.012}_{-0.011}$	$0.275 \rightarrow 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \rightarrow 0.345$
	$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \rightarrow 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \rightarrow 35.95$
	$\sin^2 \theta_{23}$	$0.470^{+0.017}_{-0.013}$	$0.435 \rightarrow 0.585$	$0.550^{+0.012}_{-0.015}$	$0.440 \rightarrow 0.584$
	$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	$41.3 \rightarrow 49.9$	$47.9^{+0.7}_{-0.9}$	$41.5 \rightarrow 49.8$
	$\sin^2 \theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	$0.02030 \rightarrow 0.02388$	$0.02231^{+0.00056}_{-0.00056}$	$0.02060 \rightarrow 0.02409$
	$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	$8.19 \rightarrow 8.89$	$8.59^{+0.11}_{-0.11}$	$8.25 \rightarrow 8.93$
	$\delta_{\text{CP}}/^\circ$	212^{+26}_{-41}	$124 \rightarrow 364$	274^{+22}_{-25}	$201 \rightarrow 335$
	$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \rightarrow 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \rightarrow 8.05$
	$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.513^{+0.021}_{-0.019}$	$+2.451 \rightarrow +2.578$	$-2.484^{+0.020}_{-0.020}$	$-2.547 \rightarrow -2.421$

Neutrino Mass Measurements

- search for absolute mass scale:

- end point kinematic of tritium beta decays $\text{Tritium} \rightarrow \text{He}^3 + e^- + \bar{\nu}_e$

KATRIN: current** limit $\sim 0.8 \text{ eV}$
Future sensitivity $\sim 0.2 \text{ eV}$

KATRIN: Talk by Jakkapat Seeyangnok

** Vietnam Flavour Physics Conference 2022

- neutrinoless double beta decay

LEGEND: Talk by David Hervas Aguilar

current bound: $|\langle m \rangle| \equiv \left| \sum_{i=1,2,3} m_i U_{ie}^2 \right| < (0.025 - 0.122) \text{ eV (KamLAND-Zen, 2024)}$

- Cosmology $\Sigma(m_{\nu_i}) < 0.12 \text{ eV} **$



$\Sigma(m_{\nu_i}) < 0.072 \text{ eV}$
(DESI BAO + CMB, 2024)

$N_{\text{eff}} = 3.0440 \pm 0.0002 [2008.01074; 2012.02726]$

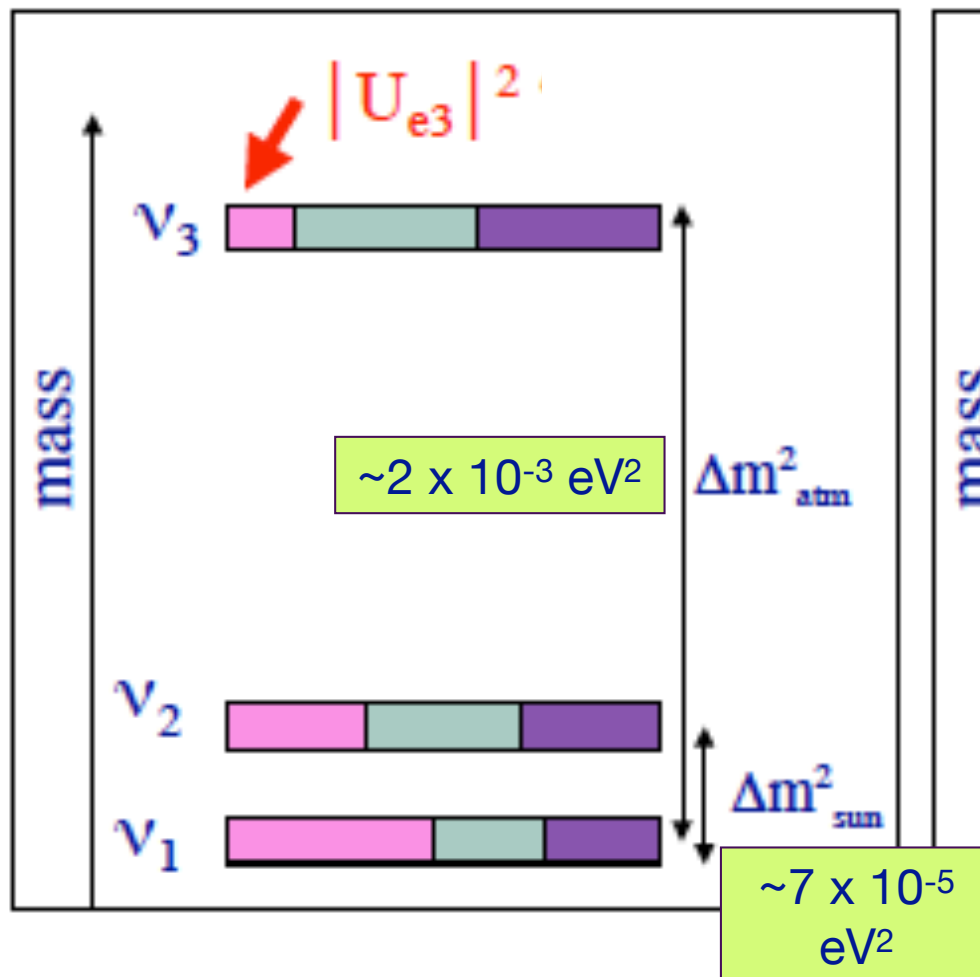
$\Rightarrow$ fully thermalized sterile neutrino disfavored

How are masses ordered?

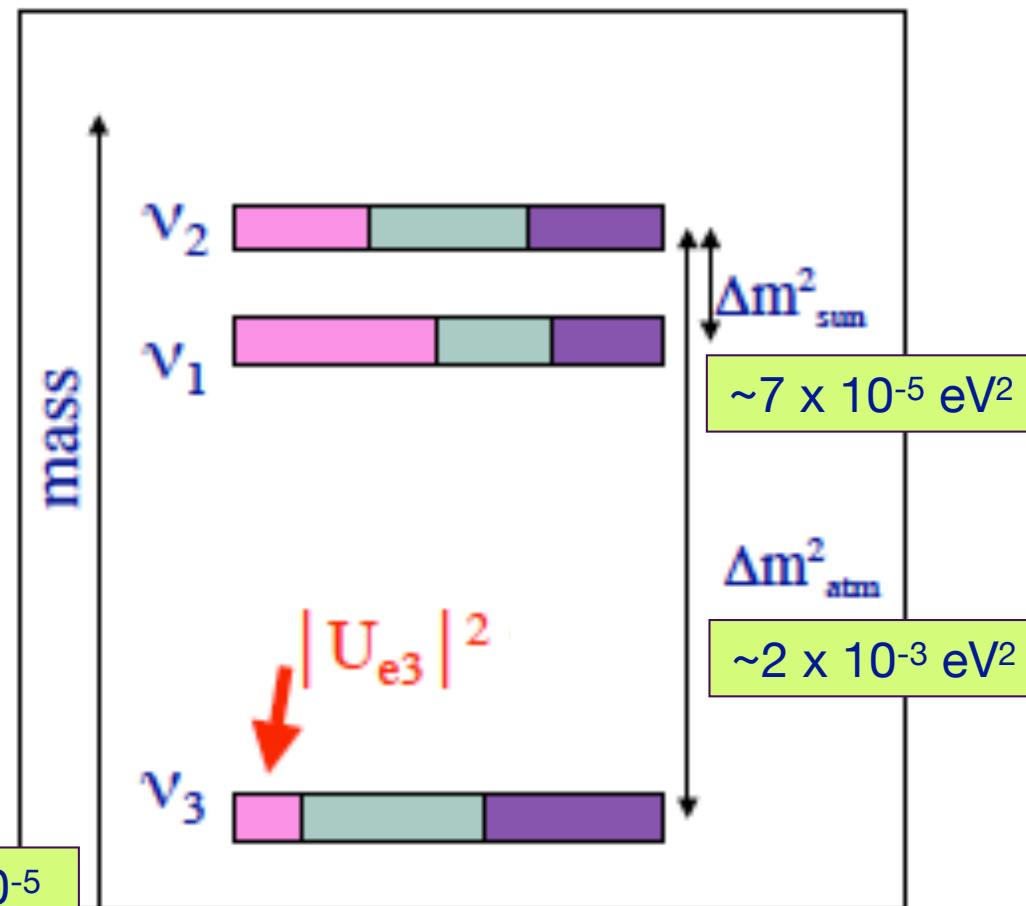


The known knowns:

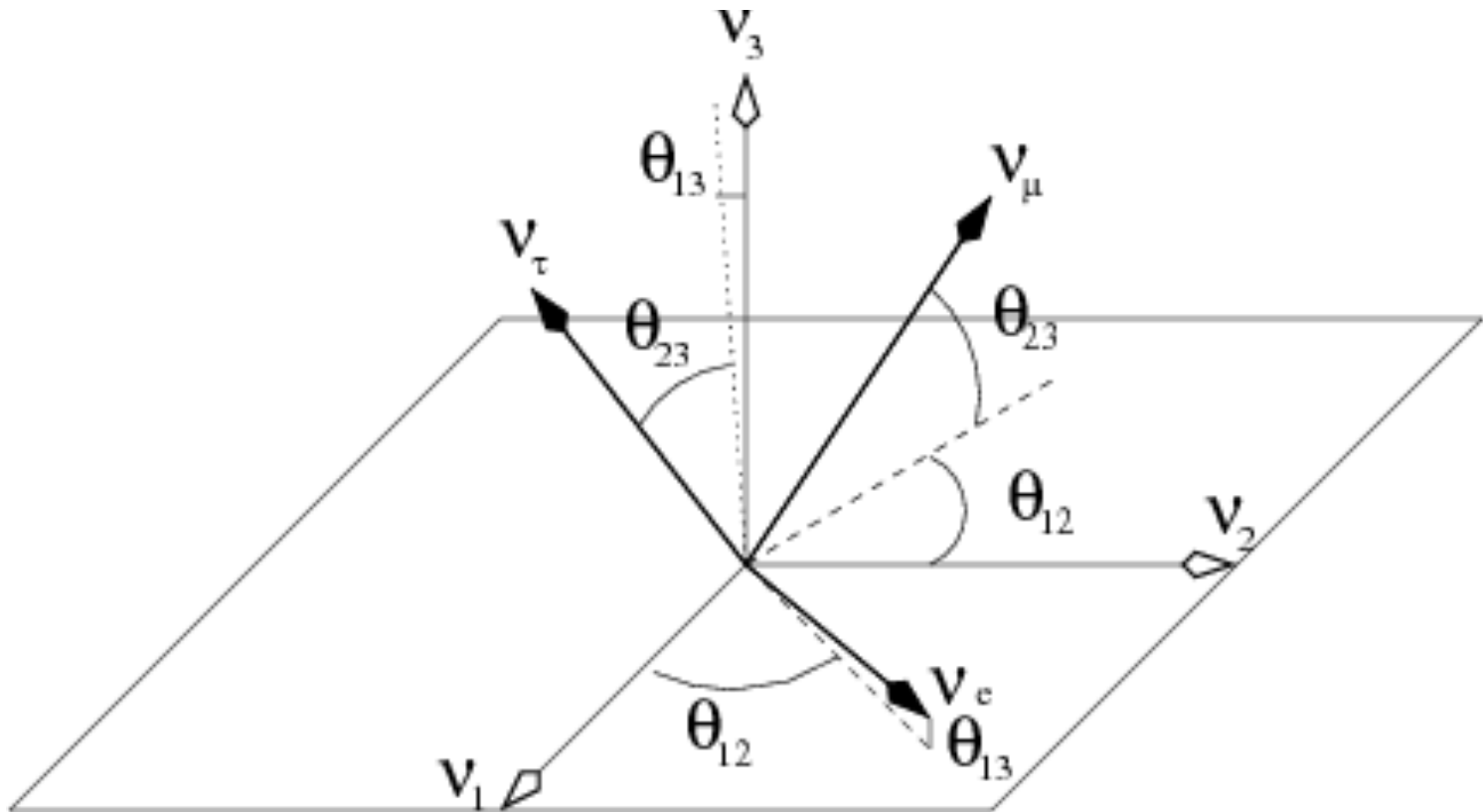
normal hierarchy:



inverted hierarchy:



The Known Knowns



NuFIT (2022)

$$[\theta_{23}^{\text{lep}} \sim 42^\circ]$$

$$[\theta_{12}^{\text{lep}} \sim 33^\circ]$$

$$[\theta_{13}^{\text{lep}} \sim 9^\circ]$$

Open Questions – Neutrino Properties



- ➡ **CP violation** in lepton sector?
- ➡ **Mass ordering:** sign of (Δm_{13}^2) ?
- ➡ **Precision:** $\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, $\theta_{23} = \pi/4$?

CP Violation in Neutrino Oscillation

- With leptonic Dirac CP phase $\delta \neq 0 \rightarrow$ leptonic CP violation
- Predict different transition probabilities for neutrinos and antineutrinos

$$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$$

- One of the major scientific goals at current and planned neutrino experiments

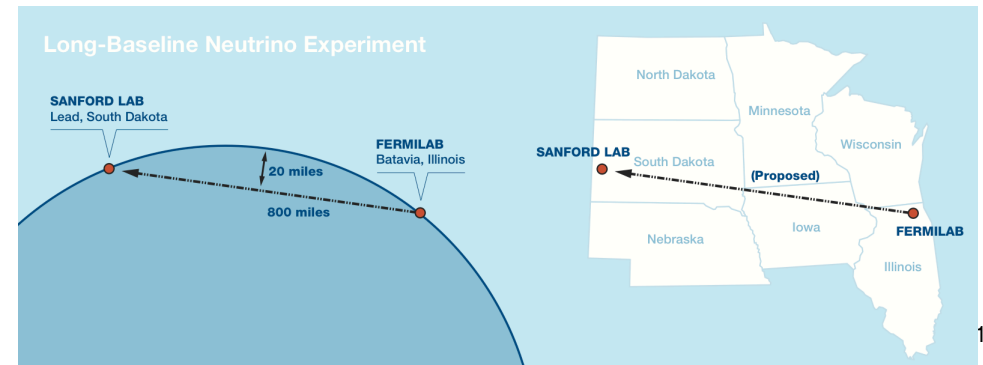


T2K

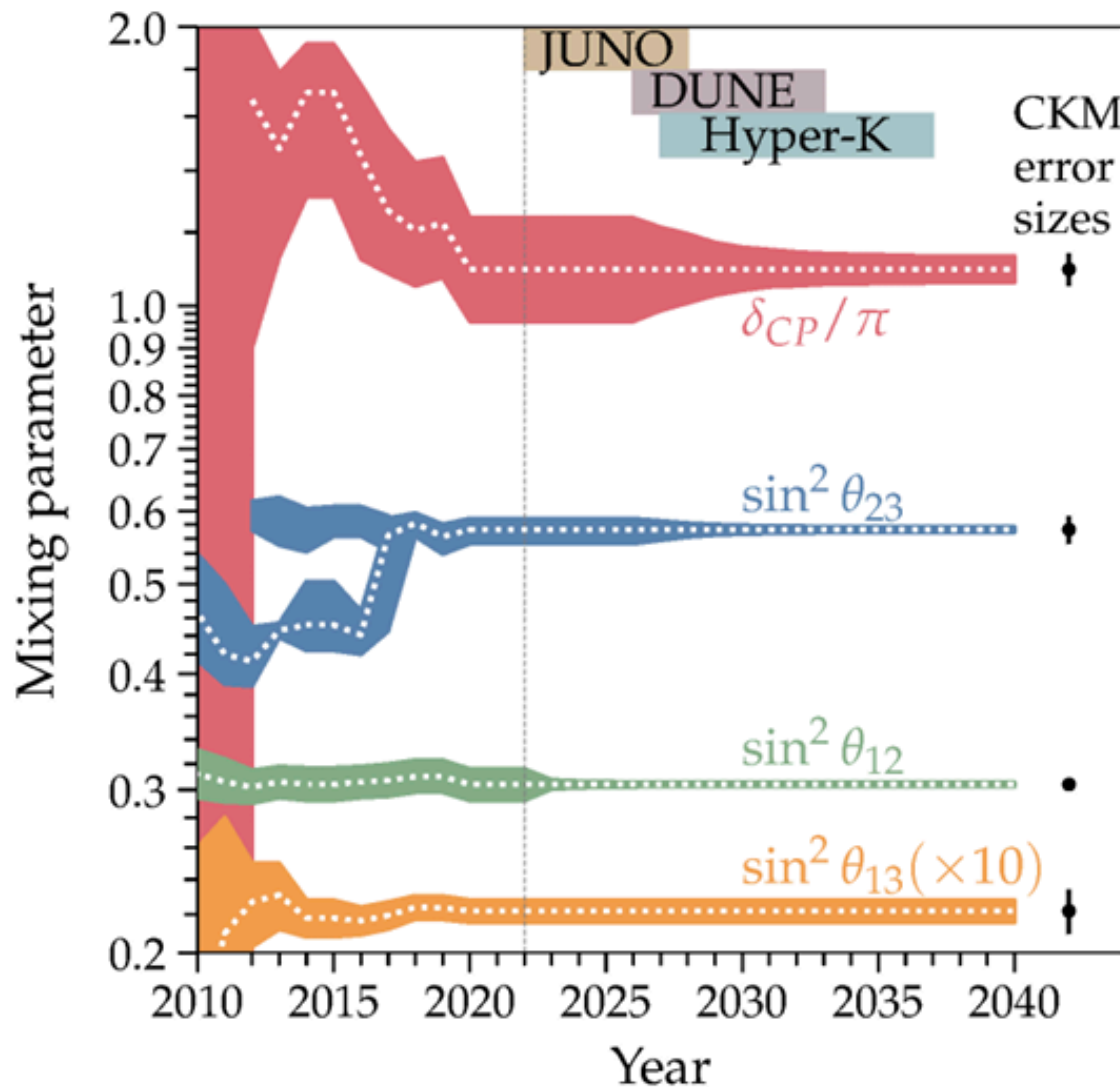
Hyper-Kamiokande



DUNE



Experimental Precision: Oscillation Parameters



T2K: Talks by
Joanna Zalipska

NOvA: Talk by
Anastasiia Kalitkina

Super-K: Talk by
Seungho Han

JUNE: Talk by
Achim Stahl

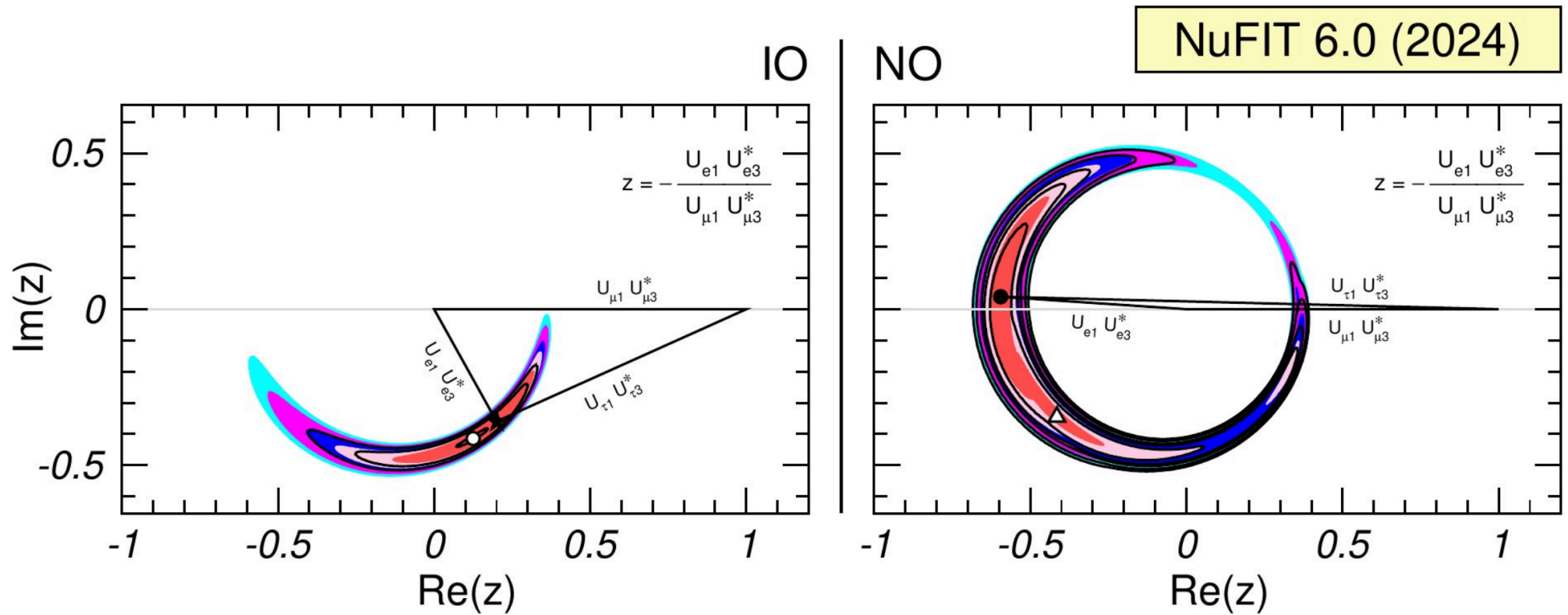
DUNE: Talk by
Ioana Caracas

Hyper-K: Talk by
Nick Prouse

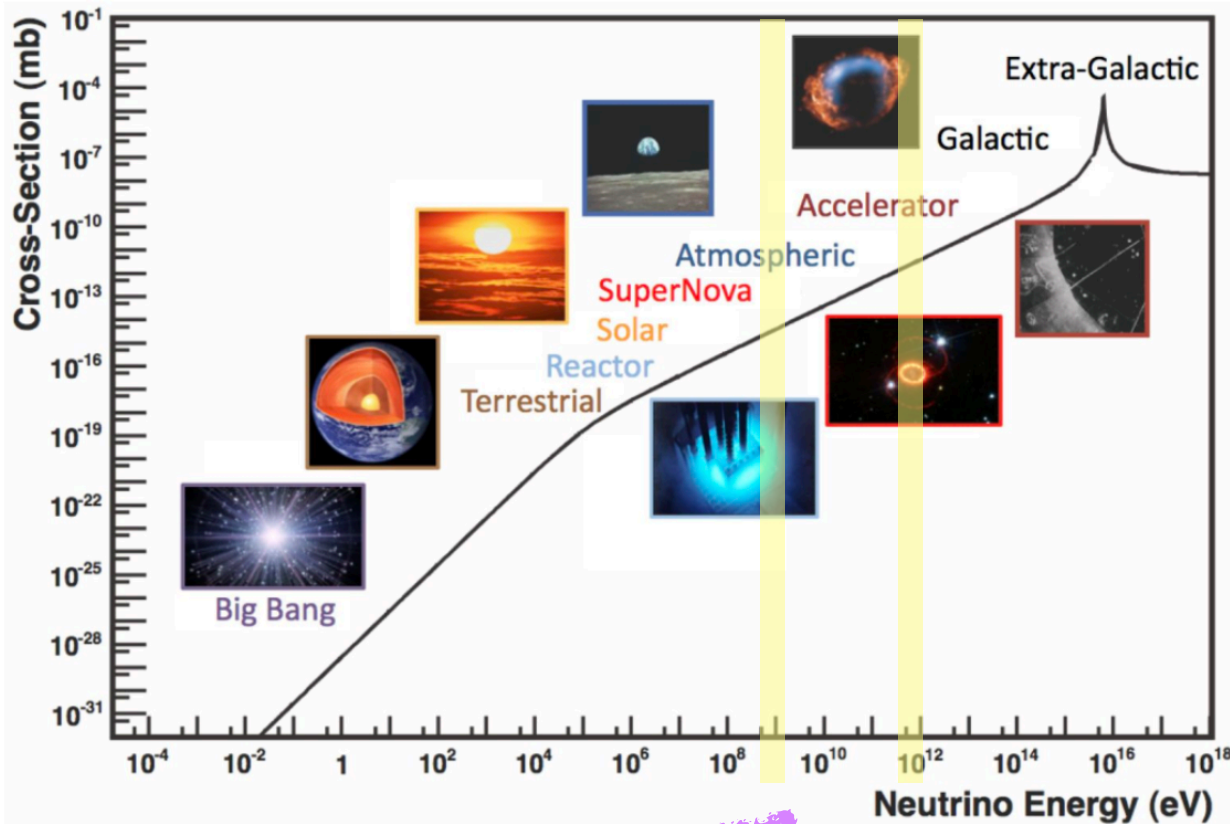
Complementarity
among experiments

Figure Courtesy of Shirley Li (2022), updated from
Song, Li, Argüelles, Bustamante, Vincent (2020)

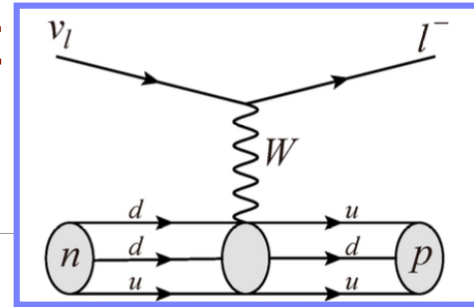
Leptonic Unitarity Triangle



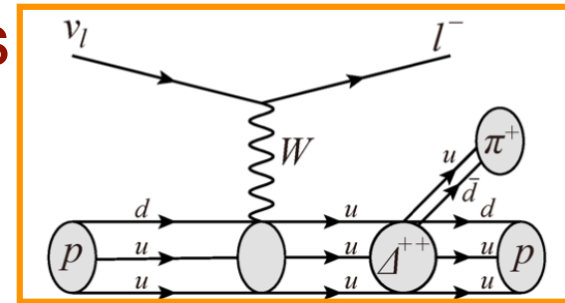
Neutrino Interactions



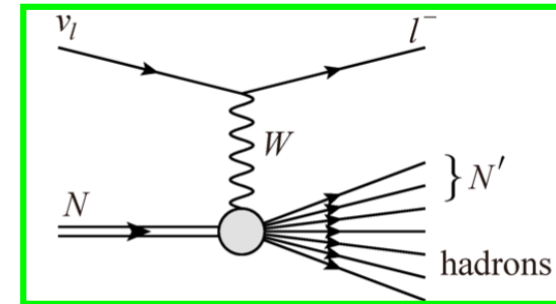
CCQE



CC RES



CC DIS



Neutrino-Nucleus Interactions: Talk by Minoo Kabirmezahad

@GeV: Needed to understand oscillation data

MicroBooNE: Talk by Patrick Green

(TeV) Neutrinos at LHC

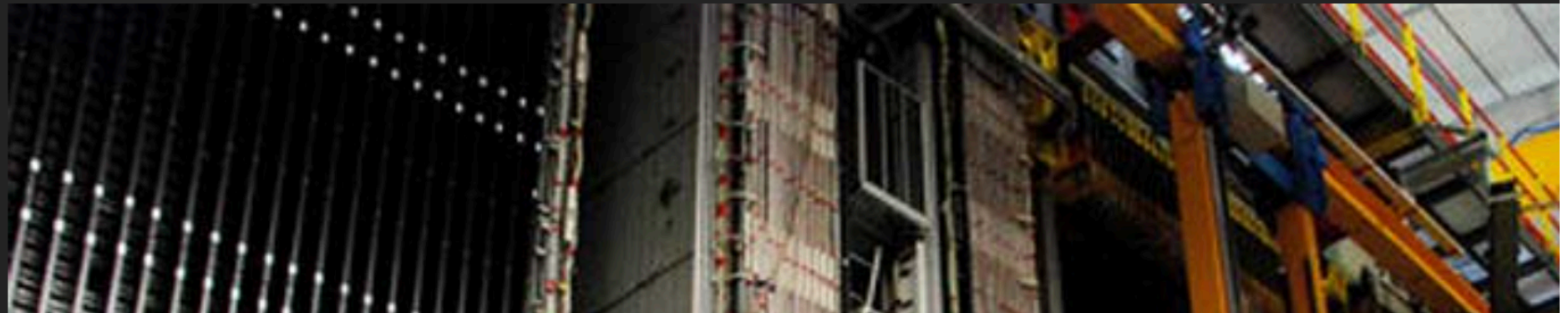
Some Anomalies are
more anomalous
than others.

Neutrino Anomalies

Neutrinos Travel Faster Than Light, According to One Experiment

Others doubt the mind-boggling claim, which would overturn Einstein's theory of special relativity

22 SEP 2011 • BY ADRIAN CHO (Science)



Common origin of superluminal neutrinos and DAMA annual modulation

Neutrino mass domain wall

Multiple Lorentz Groups - A Toy Model for Superluminal Muon Neutrinos

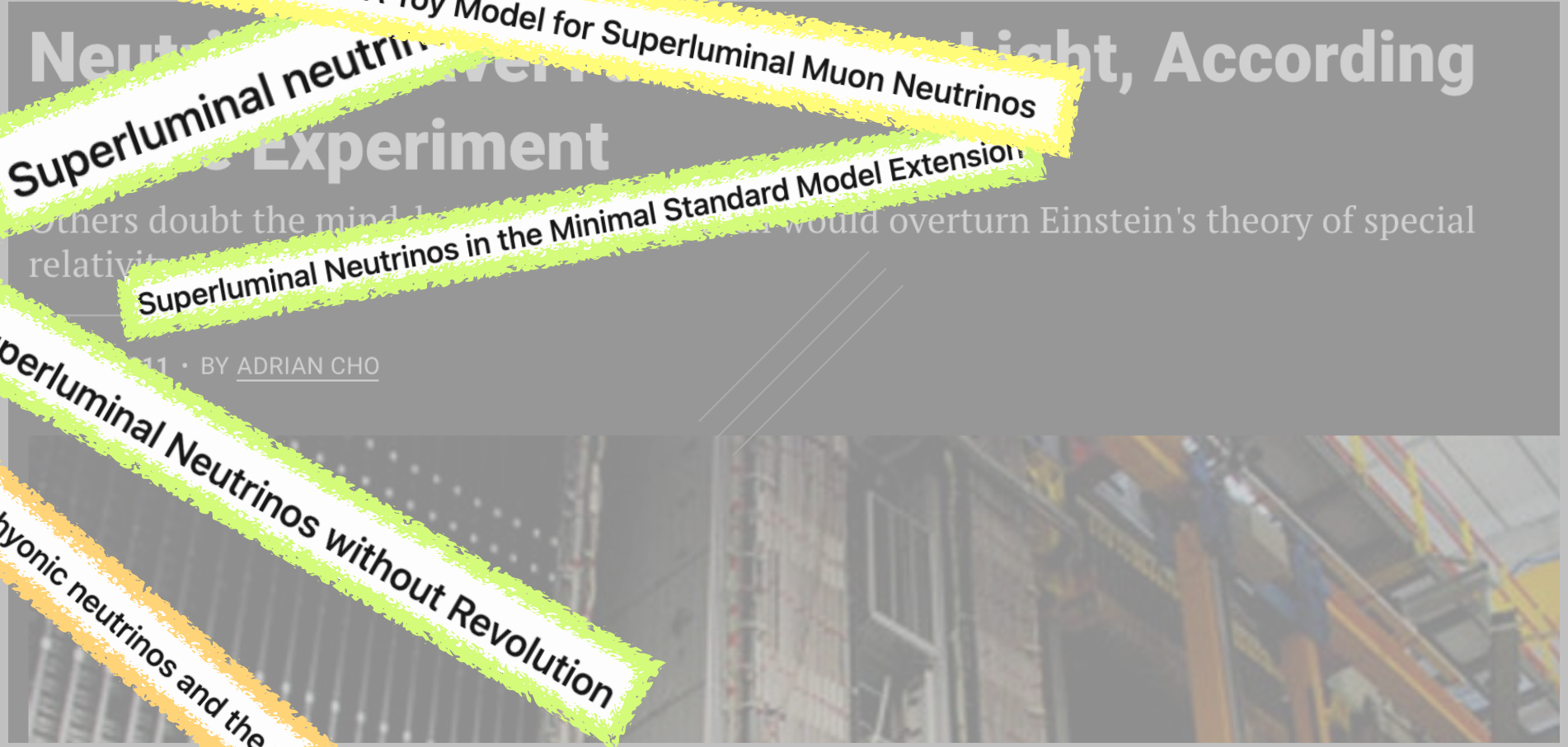
Superluminal neutrinos

Superluminal Neutrinos in the Minimal Standard Model Extension

Superluminal Neutrinos without Revolution

Tachyonic neutrinos and the neutrino mass

A model of superluminal neutrinos



Neutrinos travel faster than light, According
Experiment
Others doubt the mind boggling claim that neutrinos would overturn Einstein's theory of special relativity

11 • BY ADRIAN CHO

Once Again, Physicists Debunk Faster-Than-Light Neutrinos

Five different groups agree that the elusive particles obey Einstein's speed limit after all

8 JUN 2012 • BY ADRIAN CHO (Science)

Superluminal Neutrinos in the Minimal Standard Model Extension

11 • BY ADRIAN CHO

Superluminal Neutrinos without Revolution

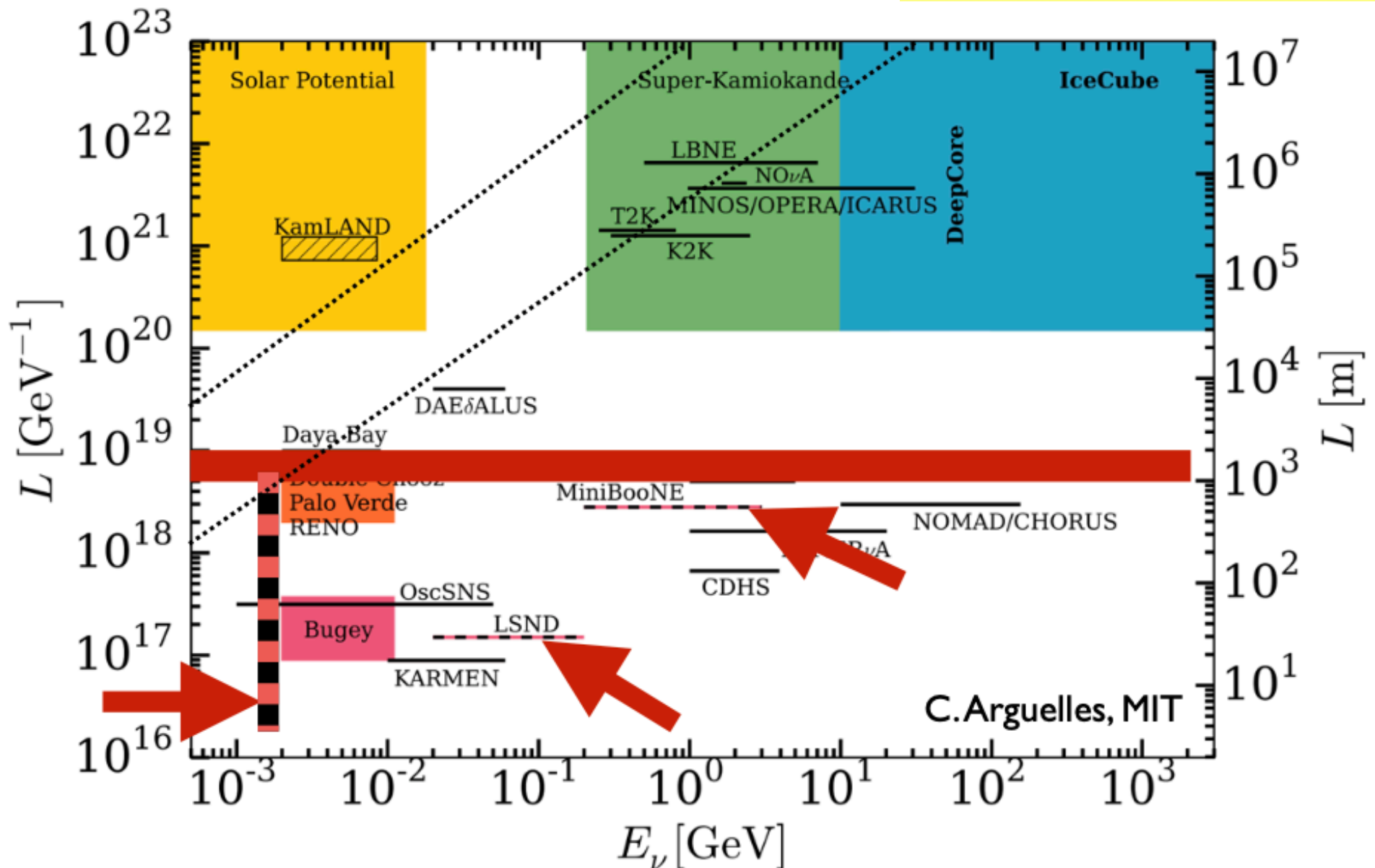
Tachyonic neutrinos and the neutrino mass

A model of superluminal neutrinos

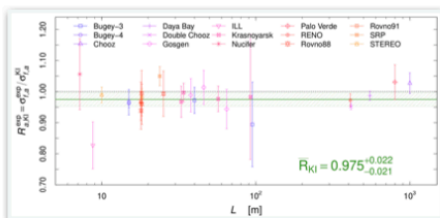


Neutrino Anomalies

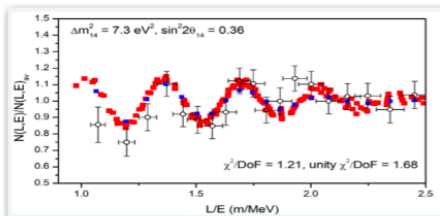
**Measurements at < 1 km
disagree with state-of-
the-art neutrino
predictions**



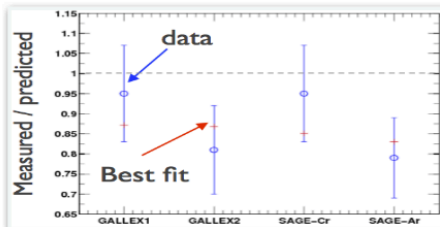
Neutrino Anomalies



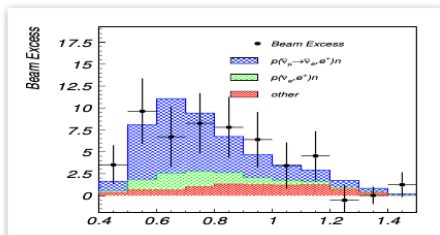
reactor flux anomaly
resolved with new input data
to flux calculation



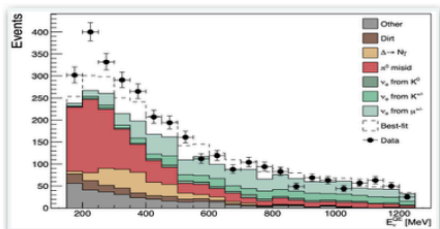
reactor spectra
is there really an anomaly?



gallium anomaly
unresolved, recently reinforced



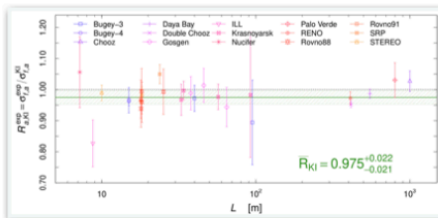
LSND
unresolved



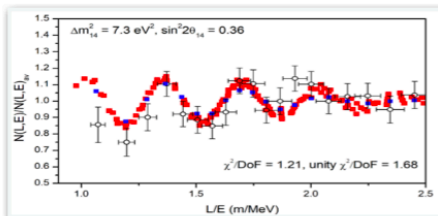
MiniBooNE
unresolved

[Slide Curtesy:
Joachim Kopp @
Neutrino 2022]

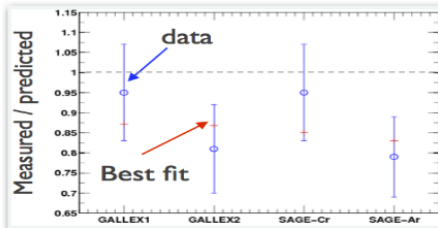
Neutrino Anomalies



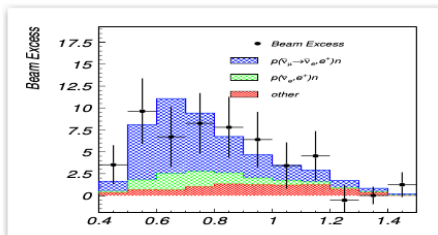
reactor flux anomaly
resolved with new input data
to flux calculation



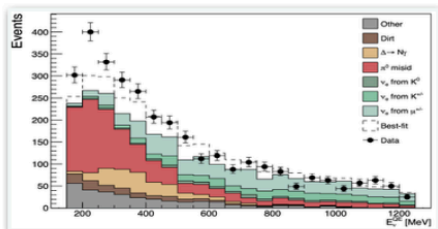
reactor spectra
is there really an anomaly?



gallium anomaly
unresolved, recently reinforced



LSND
unresolved

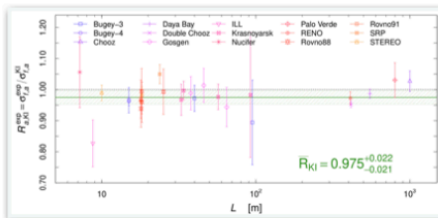


MiniBooNE
unresolved

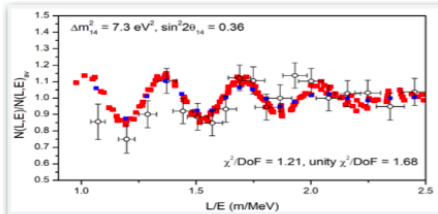
[Slide Curtesy:
Joachim Kopp @
Neutrino 2022]

Not much
progress
since Vietnam
Flavour
Conference
2022

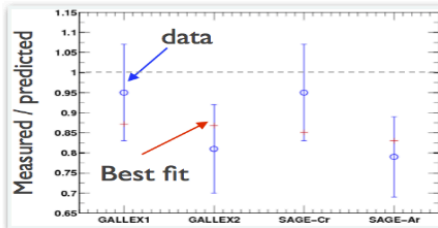
Are there sterile neutrinos?



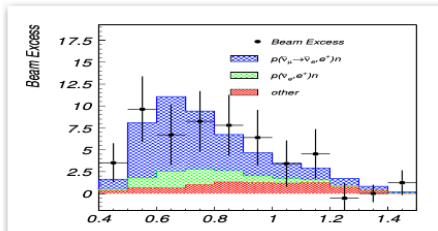
reactor flux anomaly
resolved with new input data
to flux calculation



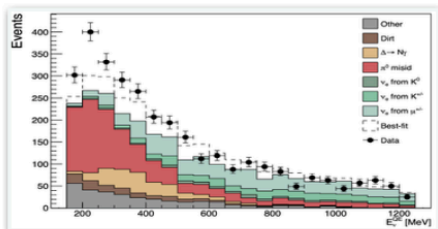
reactor spectra
is there really an anomaly?



gallium anomaly
unresolved, recently reinforced



LSND
unresolved



MiniBooNE
unresolved

[Slide Curtesy:
Joachim Kopp @
Neutrino 2022]

New neutrino
mass states (eV)?



Sterile neutrinos

ICAUS: Talk by
Alice Campani

SBND: Talk by Supraja
Balasubramanian

NOvA: Talk by
Anastasiia Kalitkina

Are Neutrinos their Own Antiparticles?

Two-neutrino double- β decay

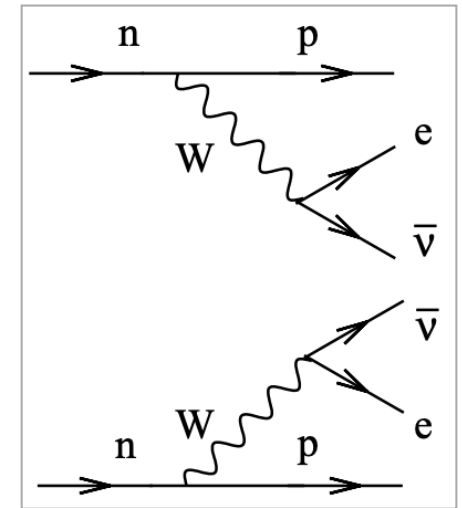
LN conserved

$$(A, Z) \rightarrow (A, Z + 2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

First observed in 1987



Maria Goeppert-Mayer, 1935



Neutrinoless double- β decay



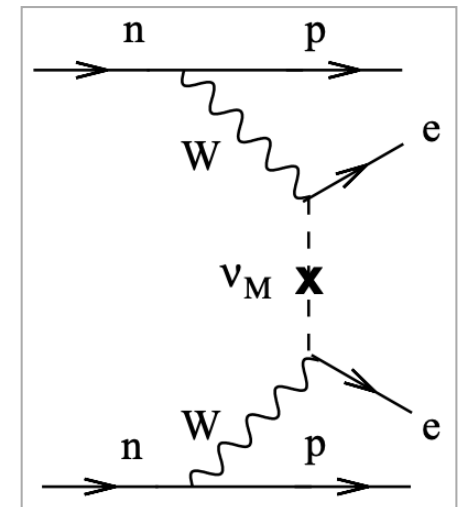
Wendell Furry, 1939

$$\Delta L = 2$$

$$(A, Z) \rightarrow (A, Z + 2) + e^- + e^-$$

Required massive Majorana neutrinos;

Not yet observed



Neutrinoless Double Beta Decay

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot m_{ee}^2$$



phase space
dependence



Nuclear matrix
element



effective
Majorana mass

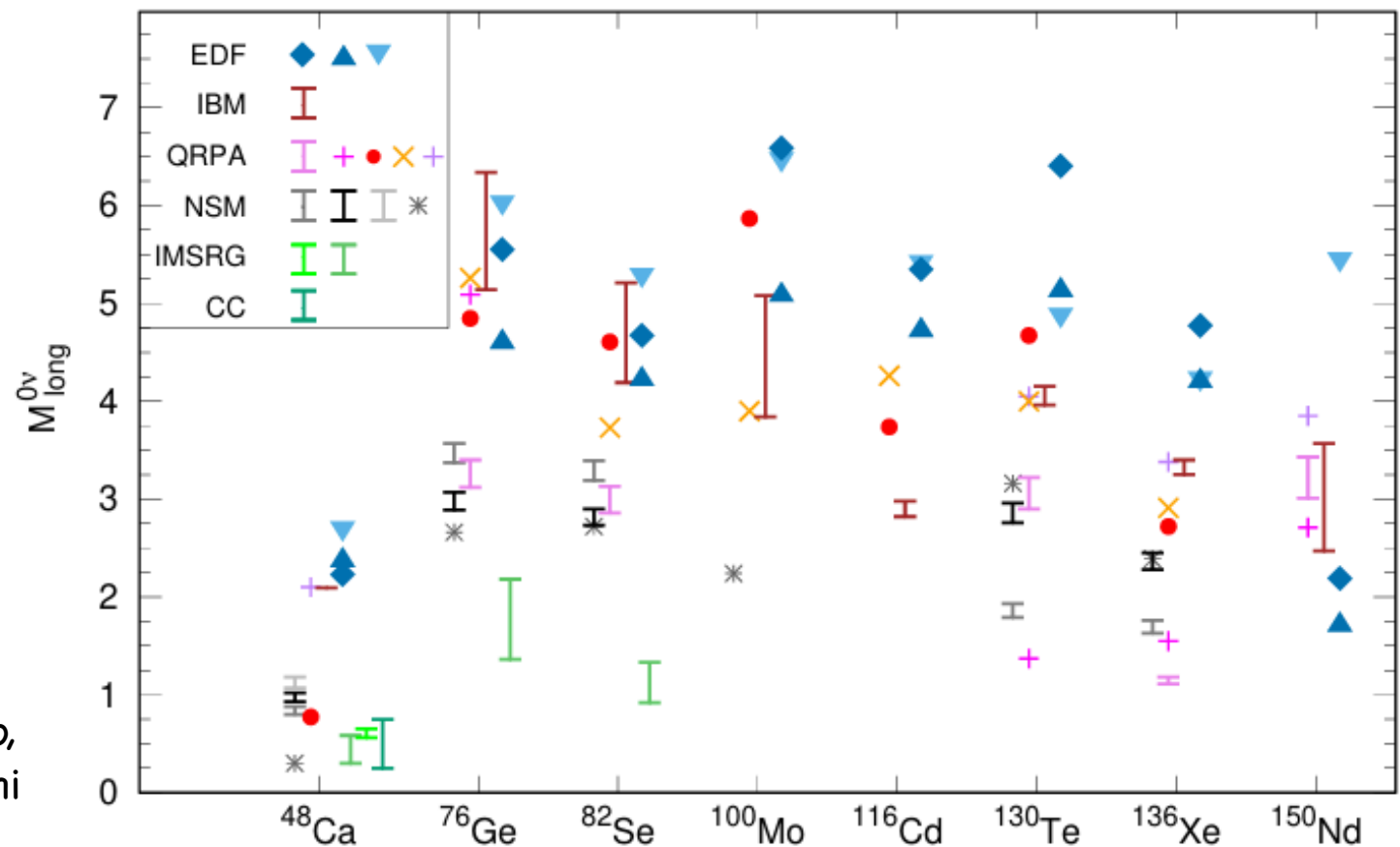
$$m_{ee}^2 = \left| \sum_i U_{ei}^2 m_{\nu_i} \right|^2$$

Neutrinoless Double Beta Decay

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot m_{ee}^2$$

Nuclear Matrix Element:

- Large uncertainty: variation about factor of 3
- Recent Lattice efforts



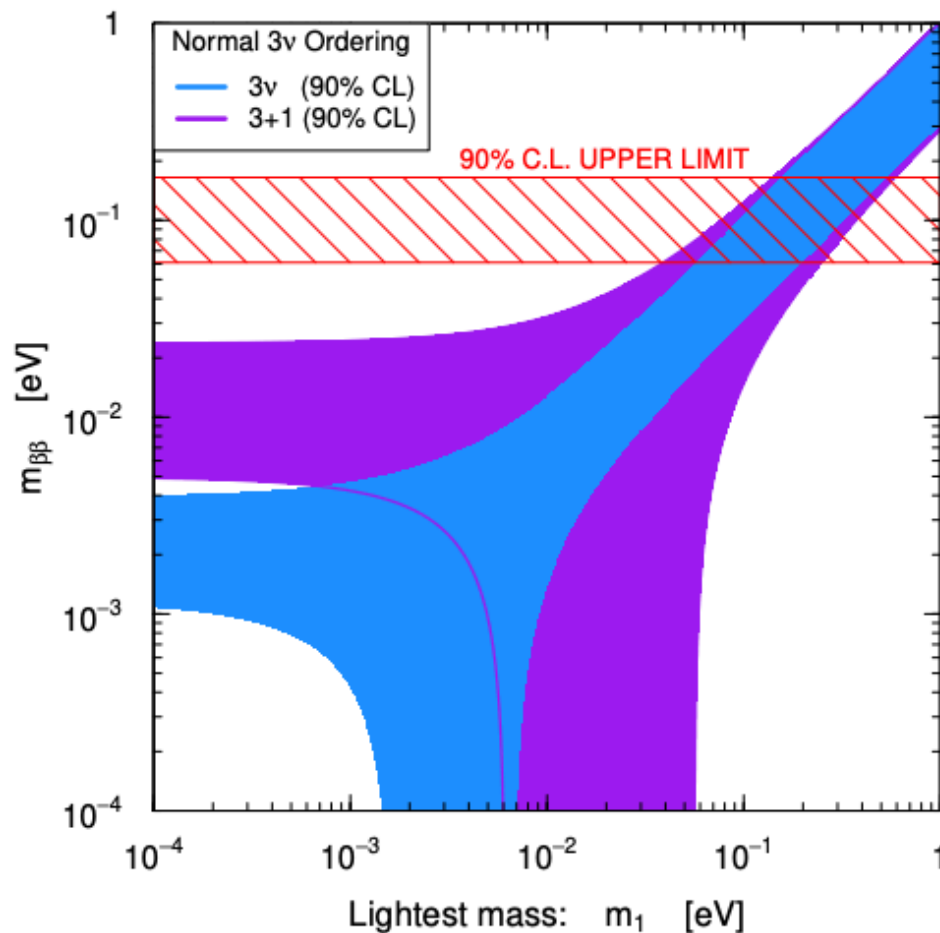
Review by Agostini, Benato,
Detwiler, Menéndez, Vissani
(2202.01787)

Neutrinoless Double Beta Decay

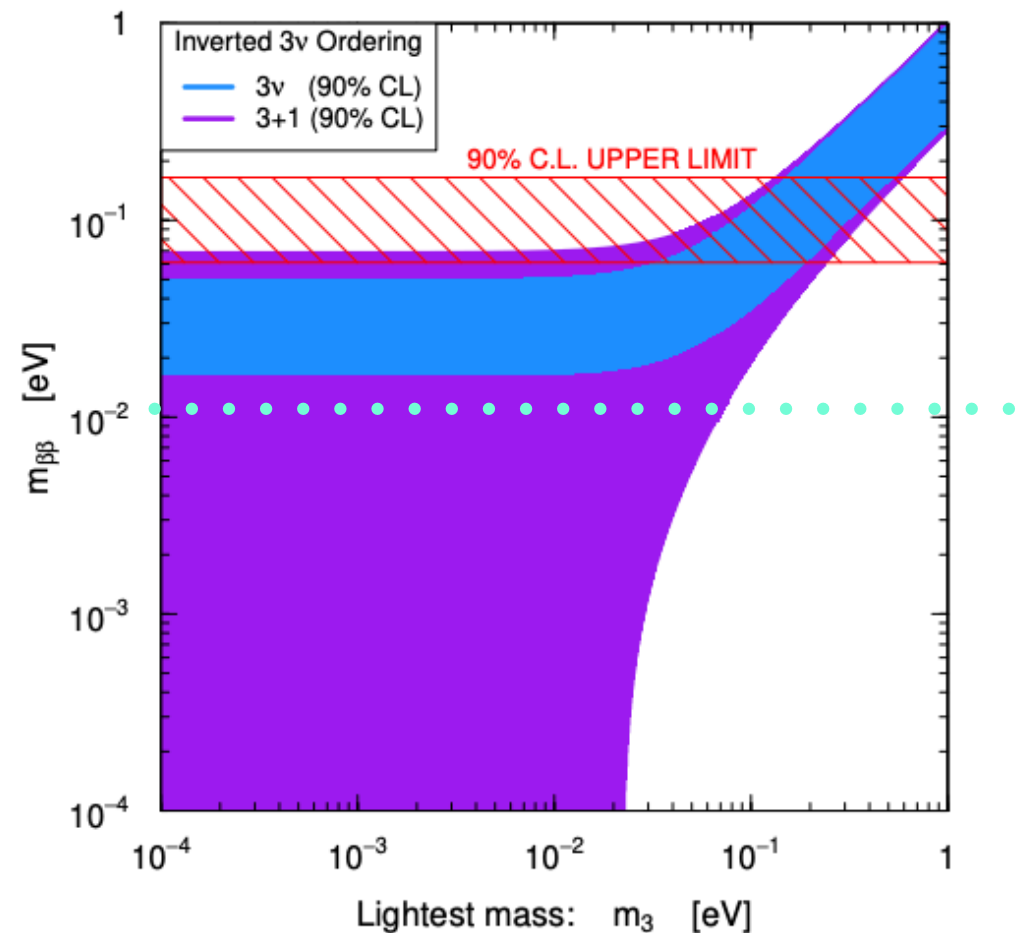
$$|m_{\beta\beta}| = \left| \sum_{k=1}^4 U_{ek}^2 m_k \right|$$

4ν : NO can be probed

3ν : IO fully covered by 2035

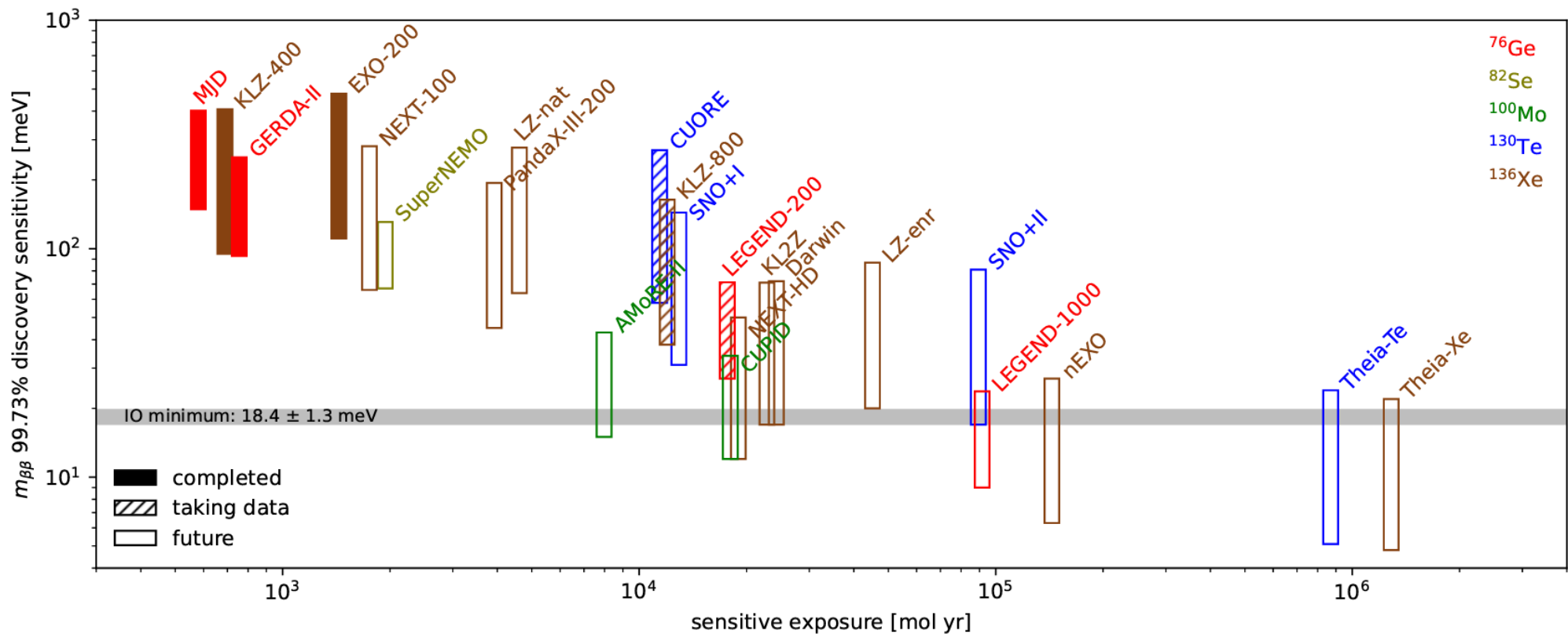


(a)



(b)

Neutrinoless Double Beta Decay



**LEGEND: Talk by
David Hervas Aguilar**

[From Snowmass White Paper 2212.11099]

Open Questions – Neutrino Properties



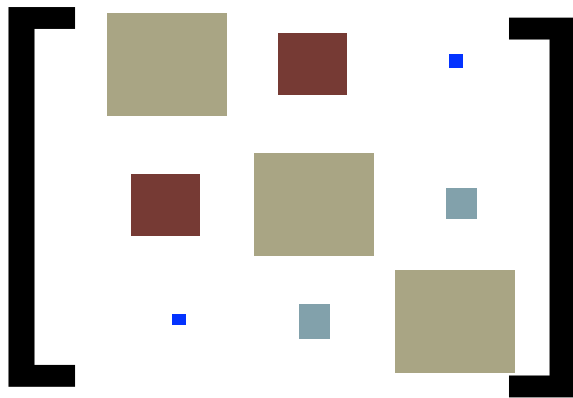
- 👉 **Majorana vs Dirac?**
- 👉 **CP violation in lepton sector?**
- 👉 **Absolute mass scale of neutrinos?**
- 👉 **Mass ordering: sign of (Δm_{13}^2) ?**
- 👉 **Sterile neutrino(s)?**
- 👉 **Precision: $\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, $\theta_{23} = \pi/4$?**
- 👉 **Additional Neutrino Interactions?**

To understand
some of these
properties
⇒ BSM Physics

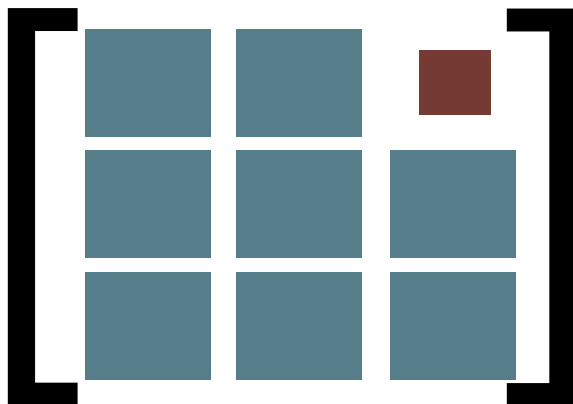
a suite of current and upcoming
experiments to address these puzzles

Open Questions – Theoretical

👉 Flavor structure:

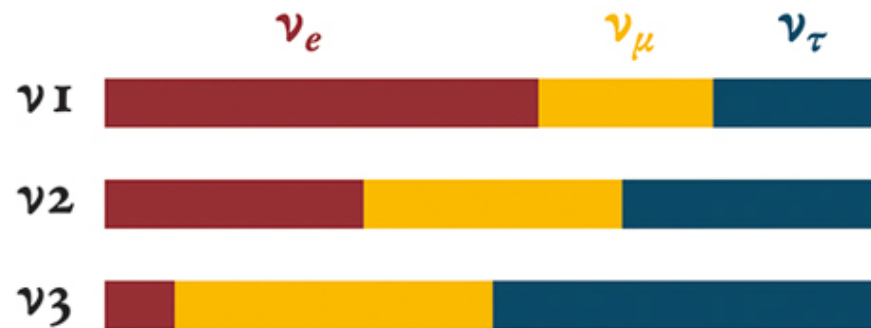
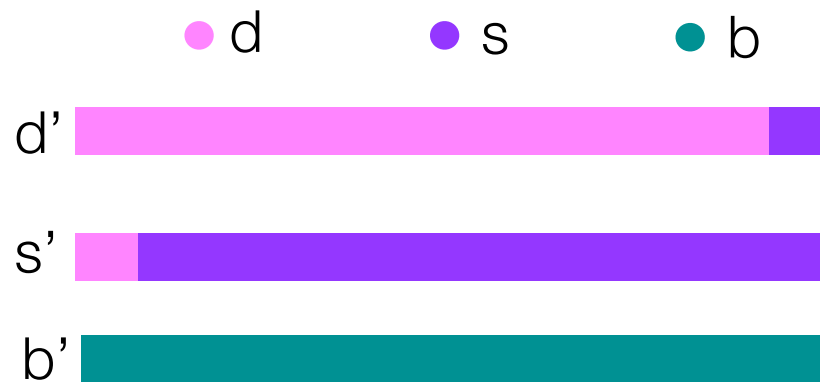


quark mixing



leptonic mixing

weak interaction eigenstates



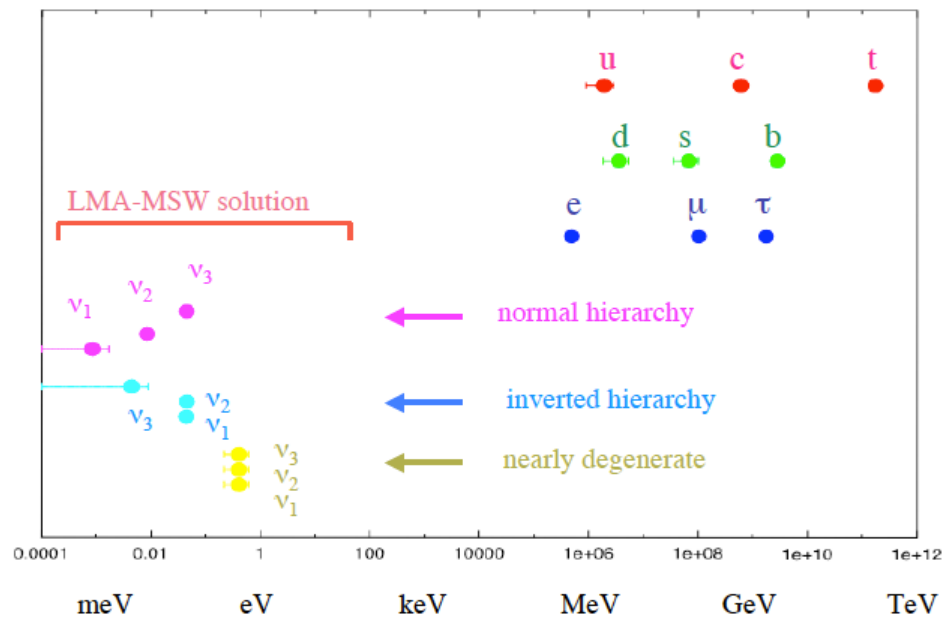
mass eigenstates

Open Questions – Theoretical



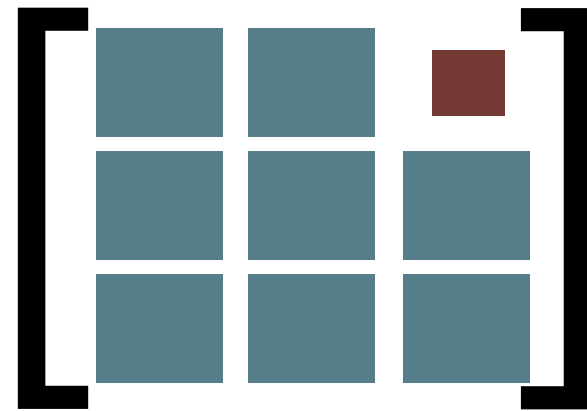
☞ Smallness of neutrino mass:

$$m_\nu \ll m_{e, u, d}$$

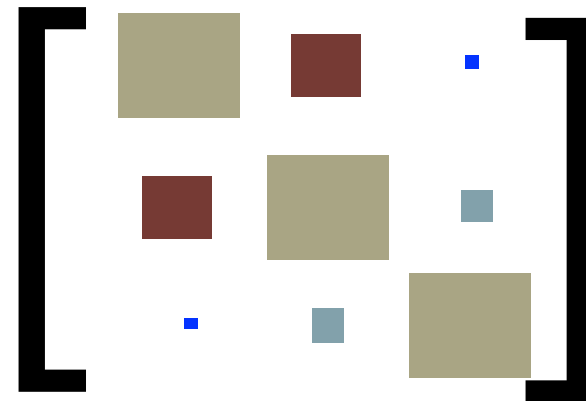


Fermion mass and hierarchy problem $\Rightarrow$ Many free parameters in the Yukawa sector of **SM**

☞ Flavor structure:



leptonic mixing



quark mixing

Why Should We Care?

- Understanding a wealth of data, fundamentally
- **SM flavor sector**: no understanding of significant fraction (22/28) of SM parameters; (c.f. SM gauge sector)
- **Neutrinos as window into BSM physics**
 - neutrino mass generation unknown (suppression mechanism, scale)
 - Uniqueness of neutrino masses → connections w/ NP frameworks
 - New insights on origin of flavor
- **Connection to B/L violation, Dark Sector**
 - Baryogenesis (through Leptogenesis)
 - Dark Matter
 -

Talk by
Yurika Sekikawa

NEUTRINO 2026



**University of California, Irvine,
U.S.A.**

About Irvine, California

a metropolitan city located at about 40 miles (64 km) south of Los Angeles, 70 miles (112 km) north of San Diego, on the beautiful coast of the Pacific Ocean with 11,000 ft (3500 m) towering San Bernadino Mountains in its backdrop.

70th Anniversary of Neutrino Discovery

by George Cowan and Fred Reines.
Fred Reines (1995 Nobel Laureate) was the founding Dean of School of Physical Sciences at UC Irvine.

Contact Us

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