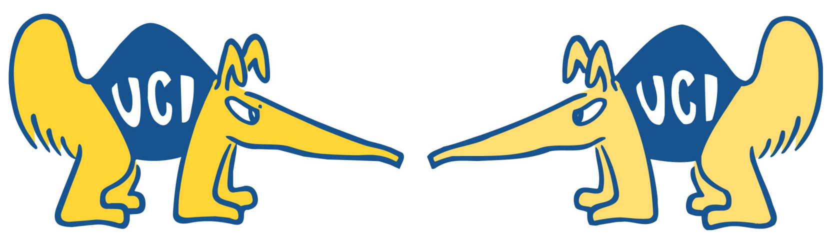
Neutrino Physics Introduction

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 ⇒ Massive Neutrinos

- Neutrino Masses are non-degenerate (at least two are non-zero)
  - mass eigenstates ≠ 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?

MEG II: Toshiyuki Iwamoto

Mu2e: Tamasi Eameshchandra Kar

COMET: Truong Nguyen

Overview by Masato Yamanaka

$$\mu \xrightarrow{?} e$$

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

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

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

$$U_{\mathrm{PMNS}} = V^\dagger_{e,L} V_{\nu,L}$$

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

Leptonic Mixing Matrix

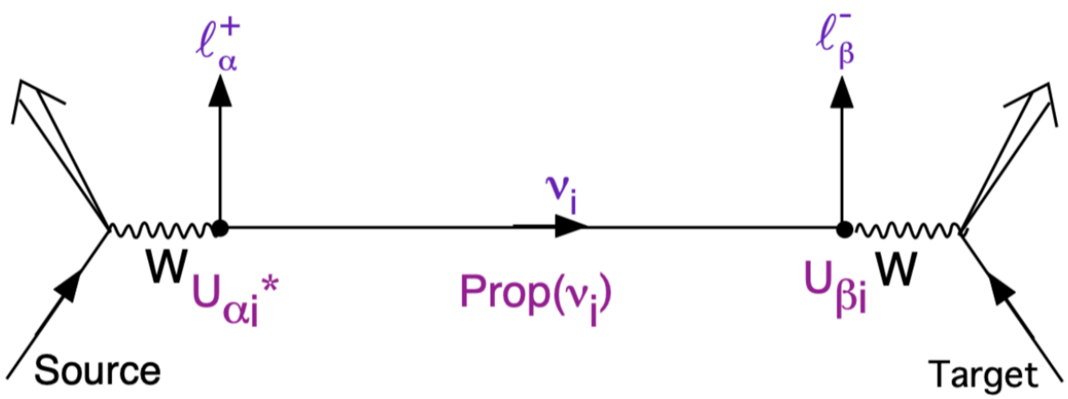
- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix

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

- 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

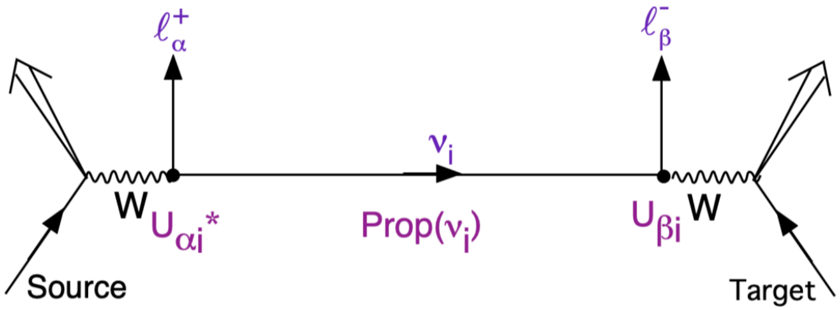


$$P(\nu_\alpha \to \nu_\beta)$$

2 flavor approximation

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

Neutrino Oscillation: General



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

$$\begin{aligned} \mathrm{P}(\nu_\alpha \to \nu_\beta;\, L, E) &= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re\mathrm{e}\,(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j})\, \sin^2(\Delta m^2_{ij} \frac{L}{4E}) \\ &+ 2 \sum_{i>j} \boxed{\Im\mathrm{m}\,(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j})}\, \sin(\Delta m^2_{ij} \frac{L}{2E}) \end{aligned}$$

Leptonic Jarlskog invariant

Classes of Experiments

Oscillation Experiments:

Atmospheric, solar, reactor, accelerator neutrinos

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

Neutrino cross sections, CEνNS:

- 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 phase, precision measurements
- Searches for BSM physics

Neutrino cross sections, CEνNS:

- Interpretation of data
- BSM

Neutrinoless Double Beta Decay:

- Majorana vs Dirac

Weak Decay Kinematics:

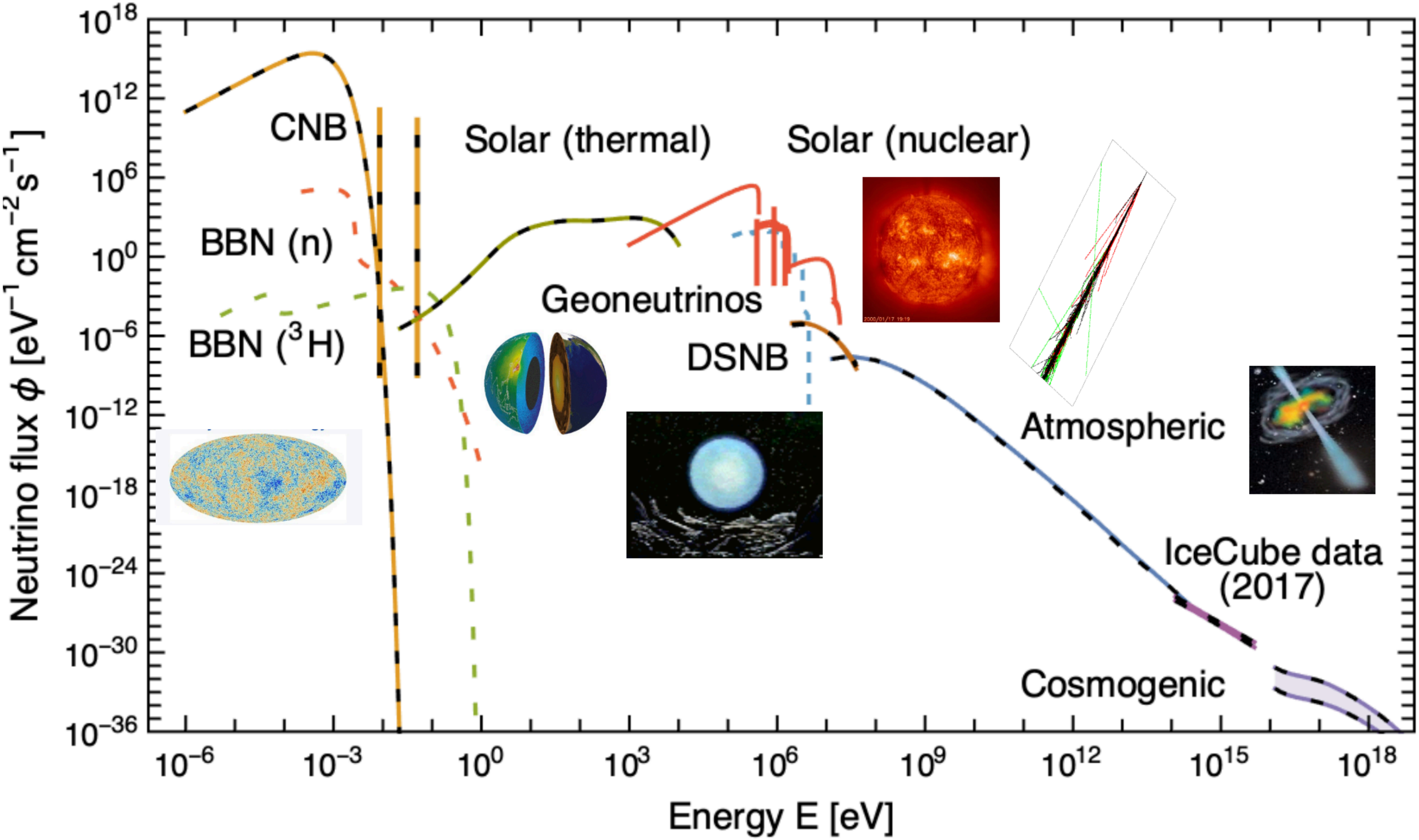
- Absolute mass scale
- Precision cosmology

Astrophysical Neutrinos:

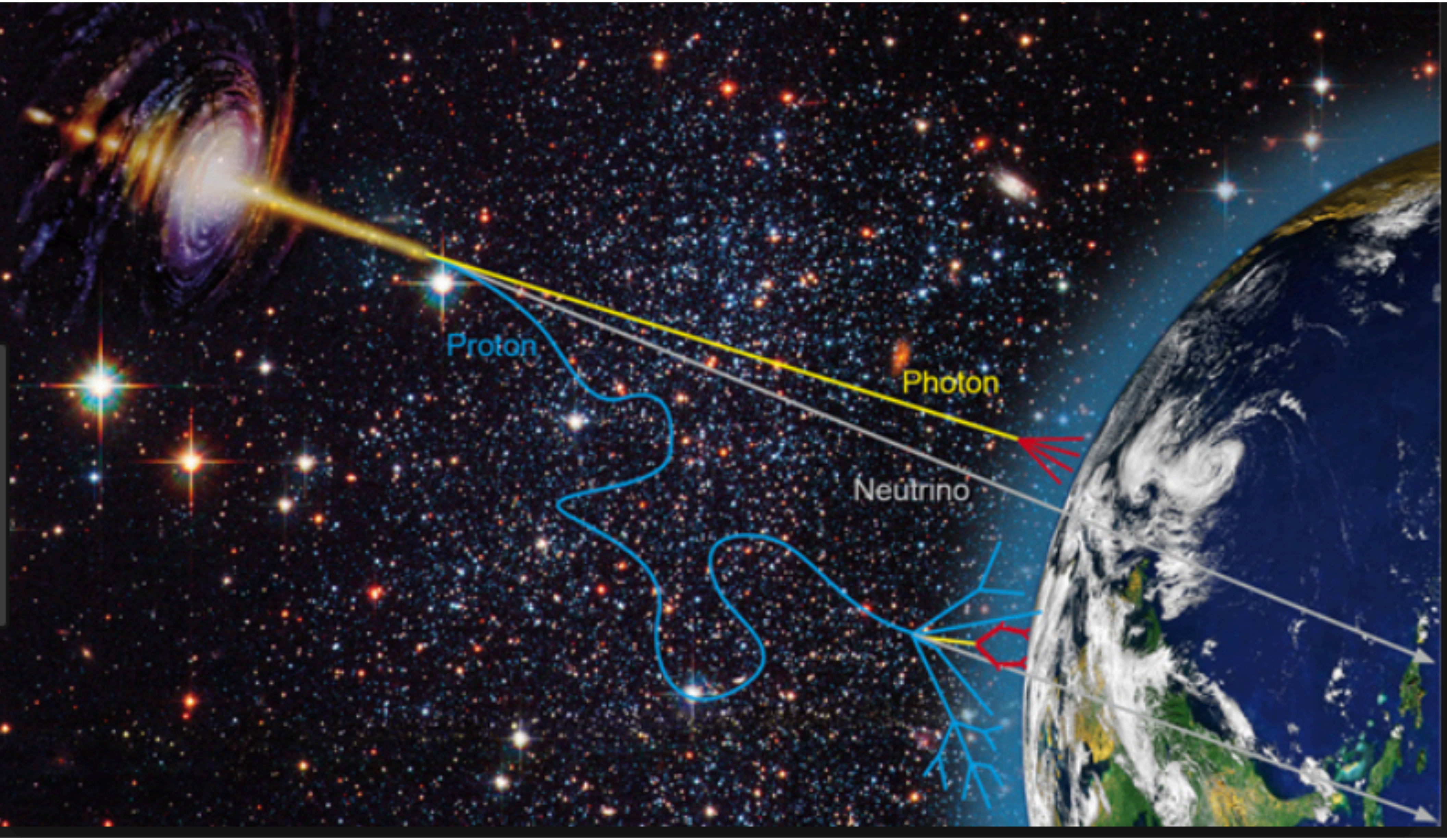
SN, GRBs, AGNs, mergers

- 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 [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 $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.013}$	$0.435 \to 0.585$	$0.550^{+0.012}_{-0.015}$	$0.440 \to 0.584$
$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	$41.3 \to 49.9$	$47.9^{+0.7}_{-0.9}$	$41.5 \to 49.8$
$\sin^2\theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	$0.02030 \to 0.02388$	$0.02231^{+0.00056}_{-0.00056}$	$0.02060 \to 0.02409$
$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.59^{+0.11}_{-0.11}$	$8.25 \to 8.93$
$\delta_{CP}/^\circ$	212^{+26}_{-41}	$124 \to 364$	274^{+22}_{-25}	$201 \to 335$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.513^{+0.021}_{-0.019}$	$+2.451 \to +2.578$	$-2.484^{+0.020}_{-0.020}$	$-2.547 \to -2.421$

Neutrino Mass Measurements

- search for absolute mass scale:
  - end point kinematic of tritium beta decays $\text{Tritium} \to He^3 + e^- + \overline{\nu}_e$

KATRIN: current** limit ~ 0.8 eV
Future sensitivity ~ 0.2 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) eV (KamLAND-Zen, 2024)

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

$\Sigma(m_{\nu_i}) < 0.072$ eV

(DESI BAO + CMB, 2024)

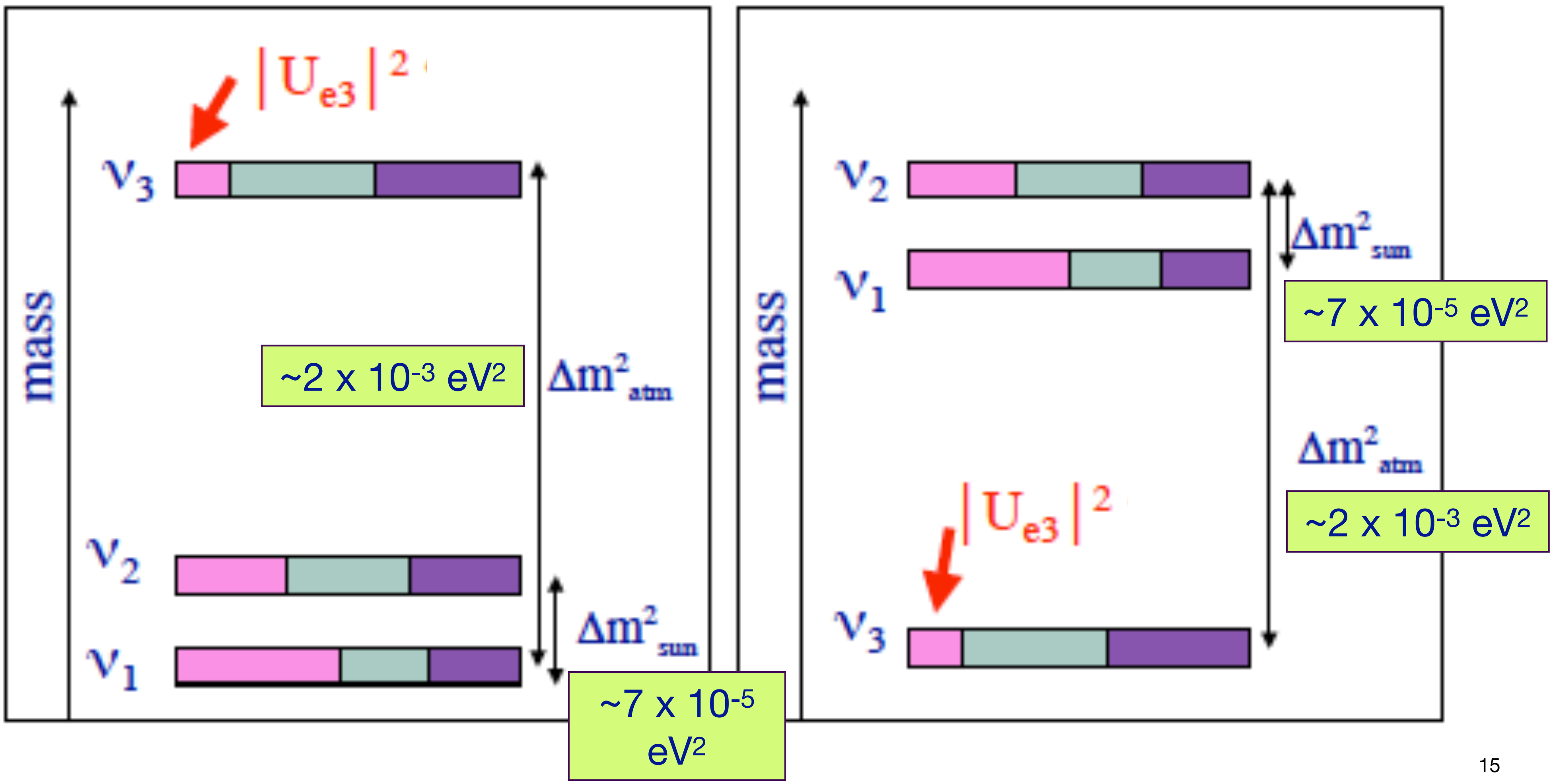
$N_{eff} = 3.0440 \pm 0.0002$ [2008.01074; 2012.02726]

$\Rightarrow$ fully thermalized sterile neutrino disfavored

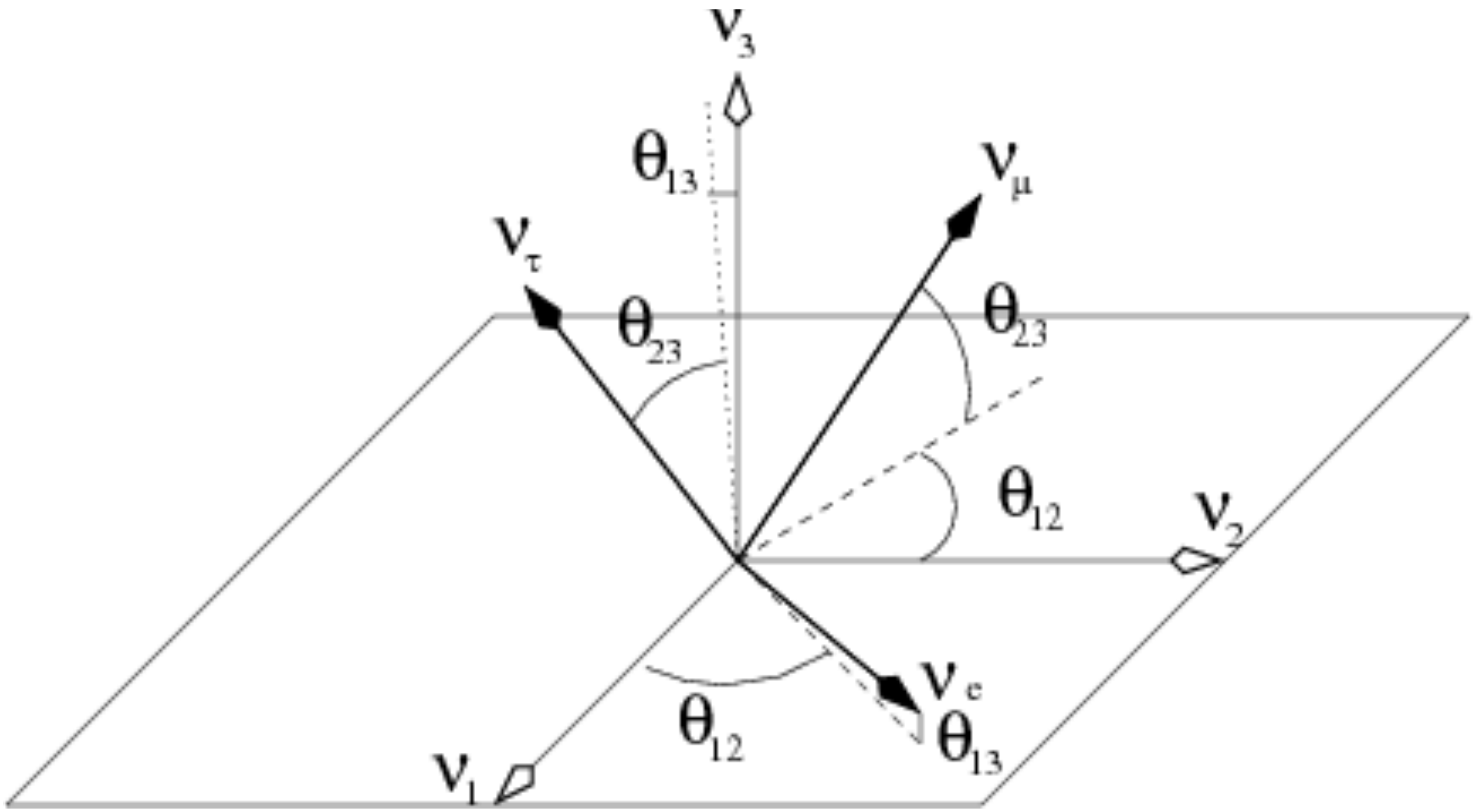
How are masses ordered?

The known knowns:

normal hierarchy: inverted hierarchy:



The Known Knowns



NuFIT (2022)

[θ^{lep}_{23} ~ 42°] [θ^{lep}_{12} ~ 33°] [θ^{lep}_{13} ~ 9°]

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

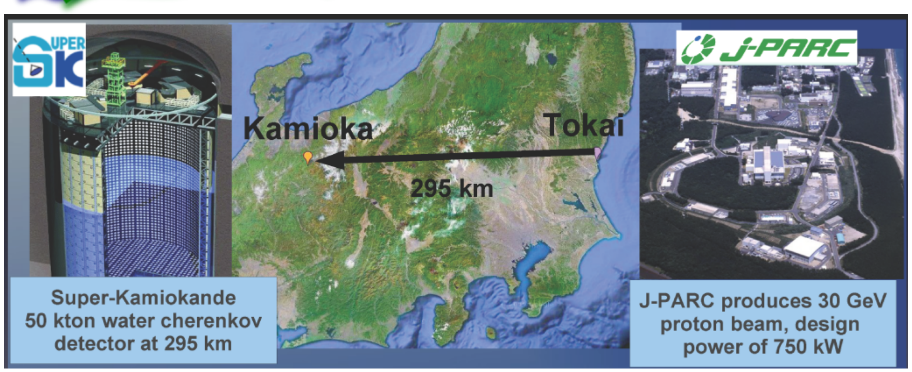
- With leptonic Dirac CP phase δ ≠ 0 ➜ leptonic CP violation
- Predict different transition probabilities for neutrinos and antineutrinos

$$P(\nu_\alpha \to \nu_\beta) \neq P(\overline{\nu_\alpha} \to \overline{\nu_\beta})$$

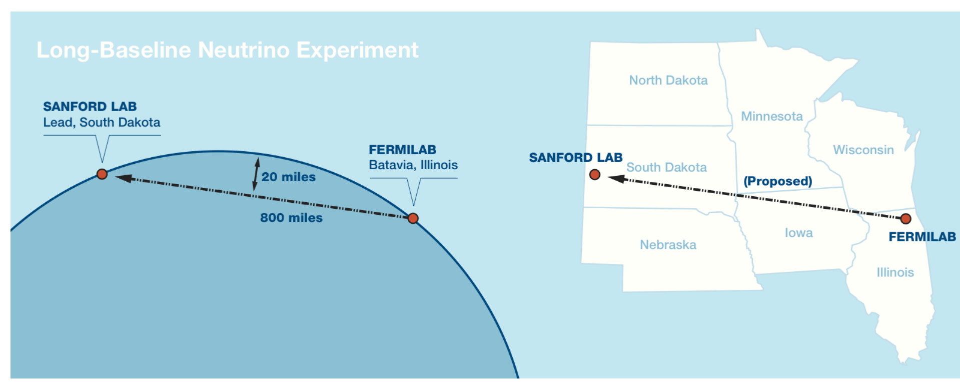
- One of the major scientific goals at current and planned neutrino experiments

T2K

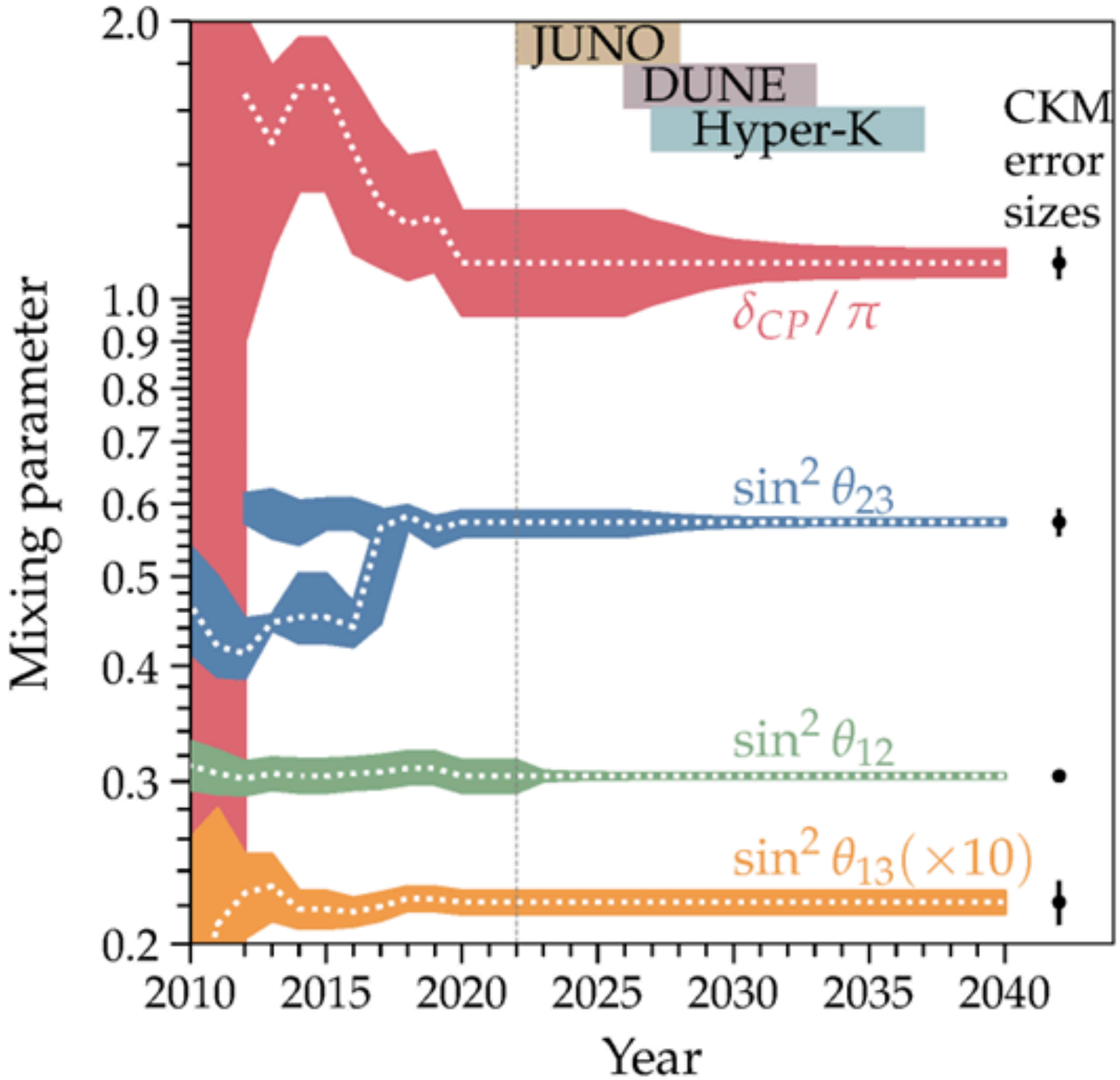
Hyper-Kamiokande



DUNE



Experimental Precision: Oscillation Parameters



T2K: Talks by Joanna Zalipska

NOvA: Talk by Anastasiia Kalitkina

Super-K: Talk by Seungho Han

JUNO: Talk by Achim Stahl

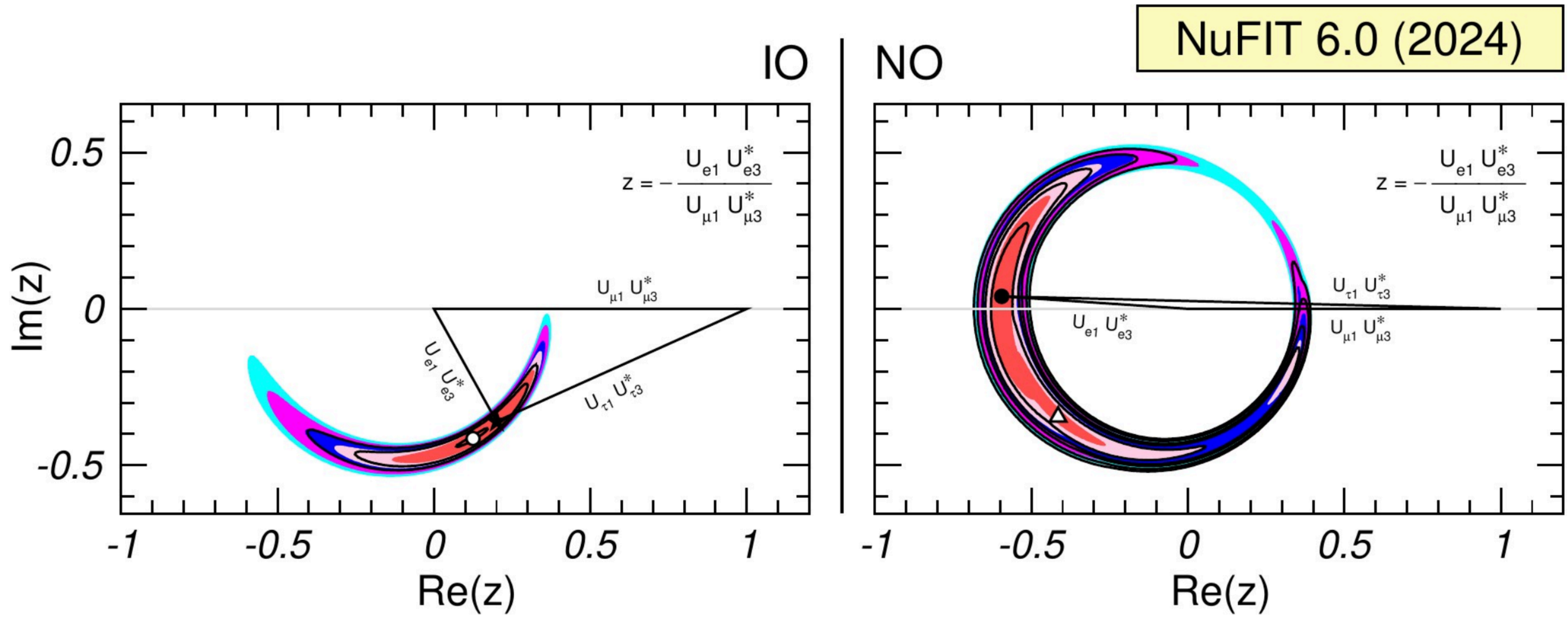
DUNE: Talk by Ioana Caracas

Hyper-K: Talk by Nick Prouse

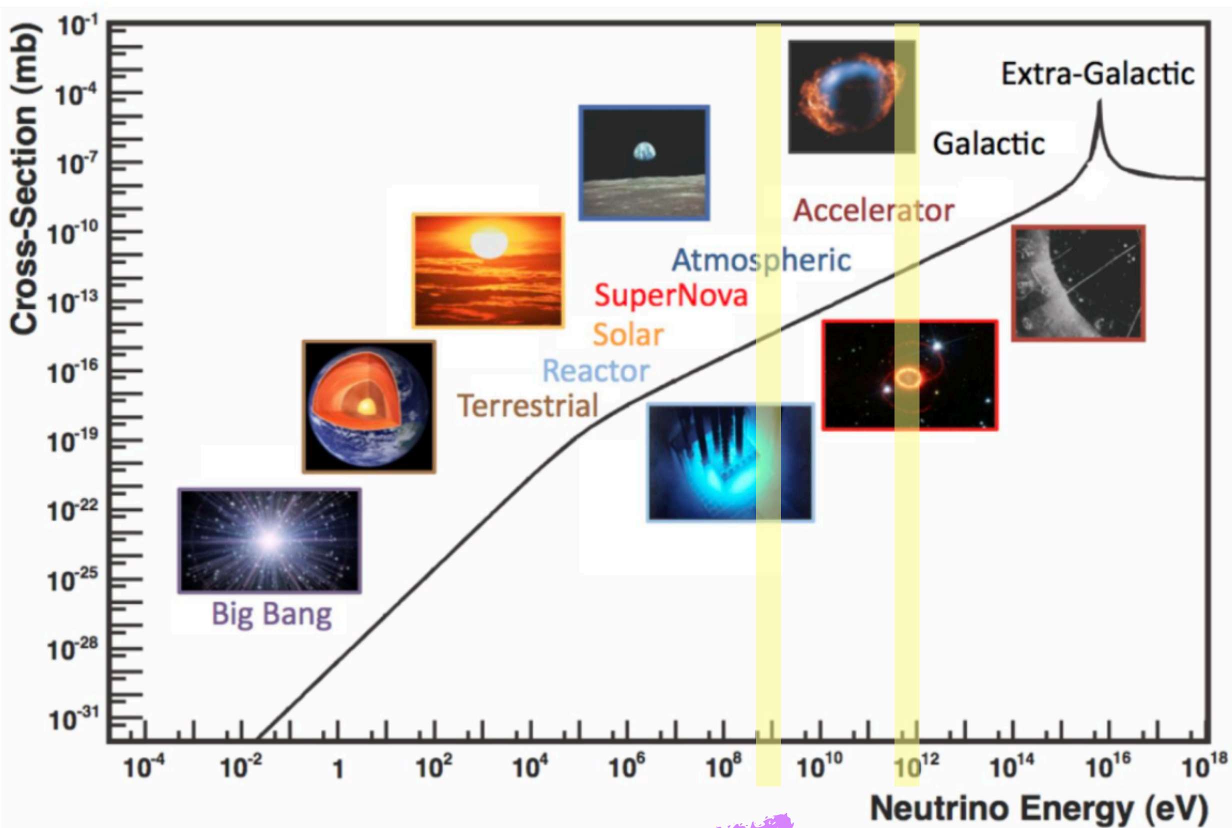
Complementarity among experiments

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

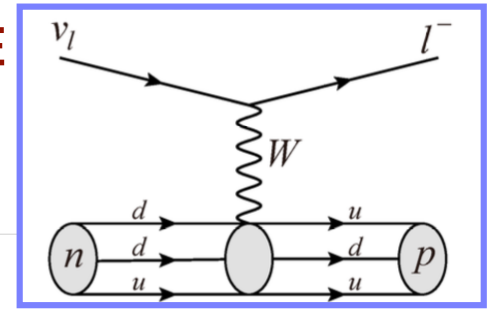
Leptonic Unitarity Triangle



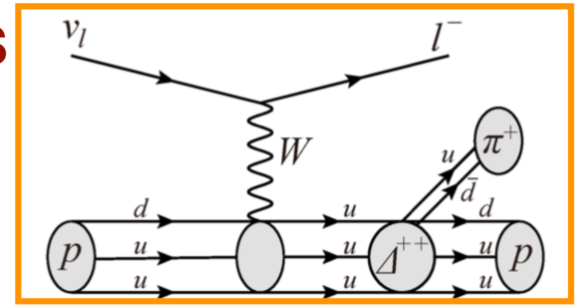
Neutrino Interactions



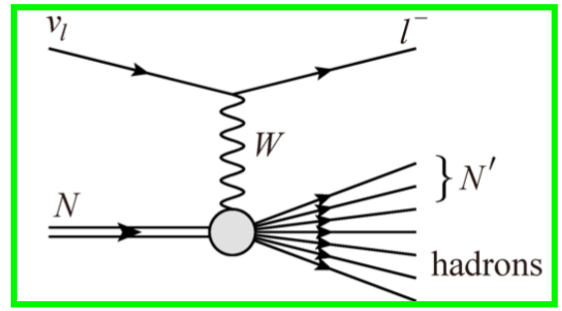
CCQE



CC RES



CC DIS



Neutrino-Nucleus Interactions: Talk by Minoo Kabirmezhad

@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)

Neutrino An...

Common origin of superluminal neutrinos and DAMA annual modulation

Multiple Lorentz Groups - A Toy Model for Superluminal Muon Neutrinos

Superluminal neutri... domain w...

Neut... ...ght, According ... Experiment

Others doubt the mind... would overturn Einstein's theory of special relativity

Superluminal Neutrinos in the Minimal Standard Model Extension

...11 · BY ADRIAN CHO

Superluminal Neutrinos without Revolution

Tachyonic neutrinos and the neutrino mas...s

A model of superluminal neutrinos

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)

Common origin of

Ne

Multipl

N

Superlum

Experiment

Others doubt the mind-b... would overturn Einstein's theory of special relativity

...11 · BY ADRIAN CHO

Superluminal Neutrinos in the Minimal Standard Model Extension

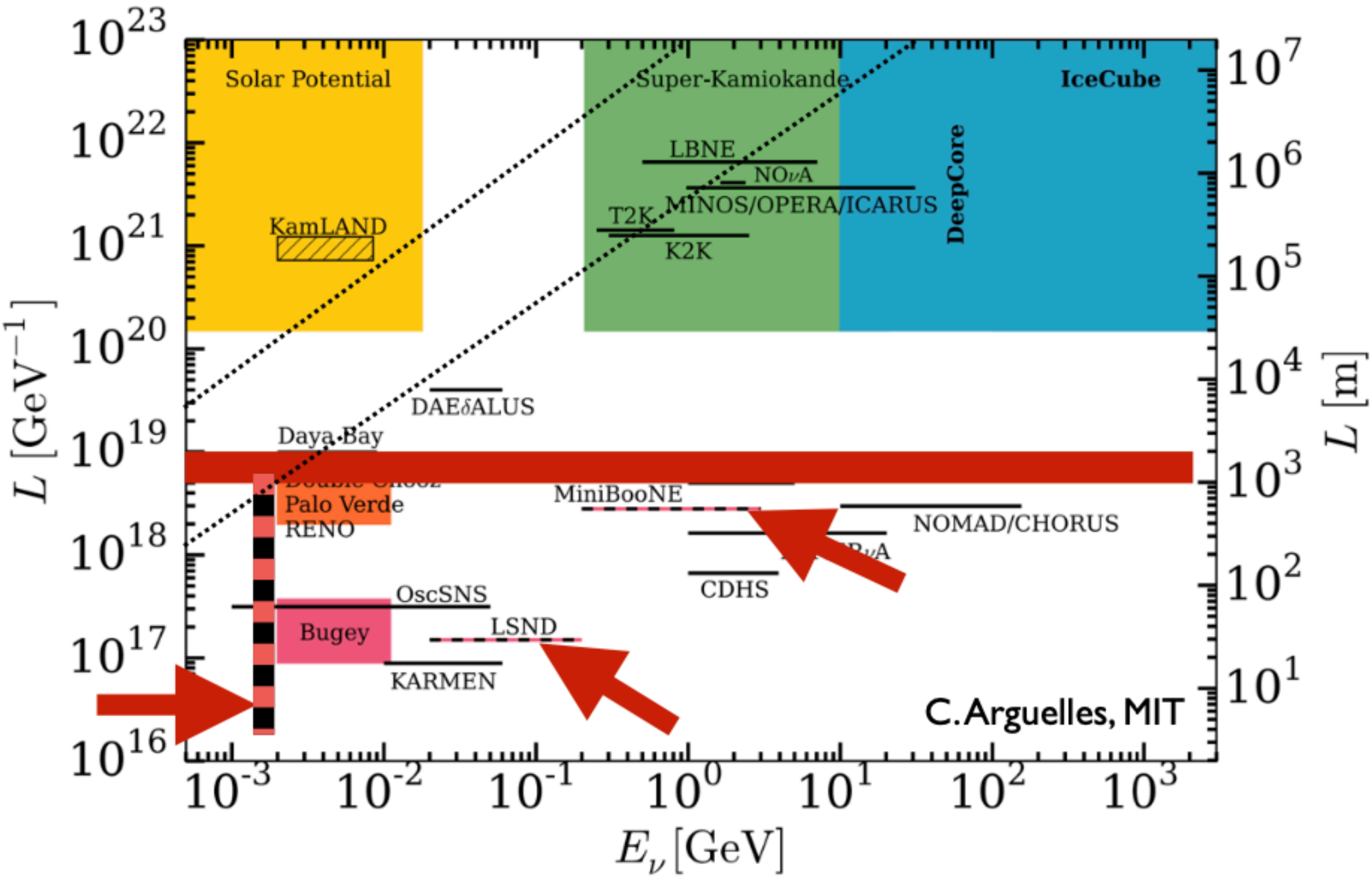
Superluminal Neutrinos without Revolution

Tachyonic neutrinos and the neutrino mass

A model of superluminal neutrinos

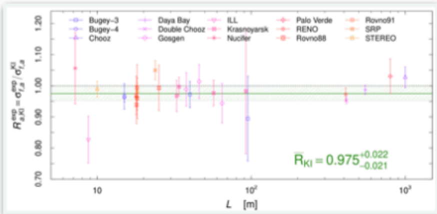
Neutrino Anomalies

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



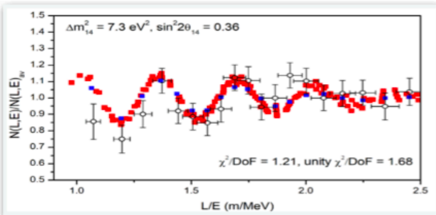
Neutrino Anomalies

✓



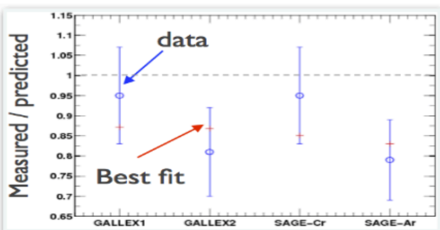
reactor flux anomaly
resolved with new input data
to flux calculation

?



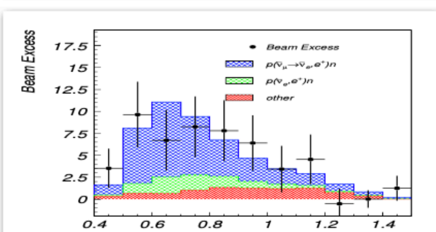
reactor spectra
is there really an anomaly?

?



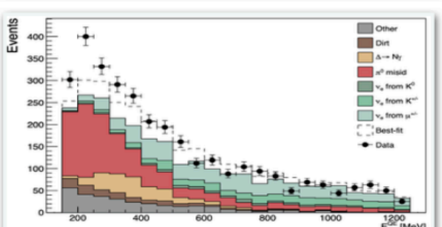
gallium anomaly
unresolved, recently reinforced

?



LSND
unresolved

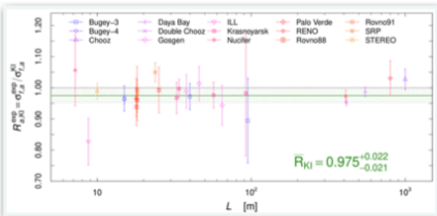
?



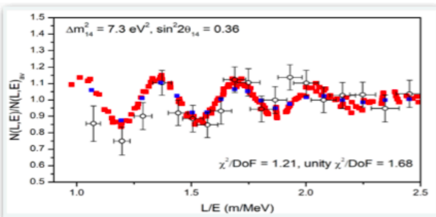
MiniBooNE
unresolved

[Slide from
Joachim Kopp @
Neutrino 2022]

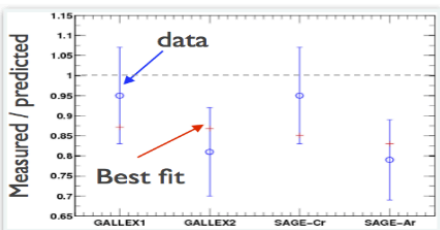
Neutrino Anomalies



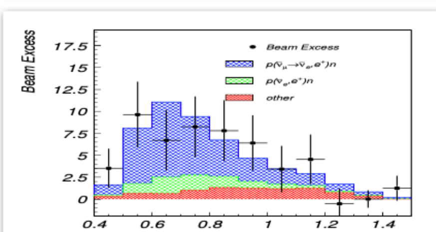
reactor flux anomaly
resolved with new input data
to flux calculation



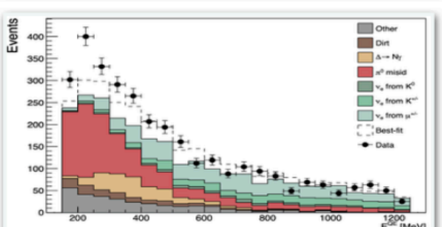
reactor spectra
is there really an anomaly?



gallium anomaly
unresolved, recently reinforced



LSND
unresolved

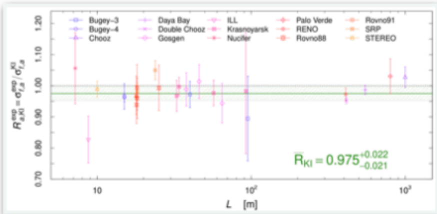


MiniBooNE
unresolved

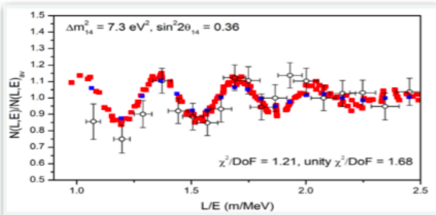
[Slide from Joachim Kopp @ Neutrino 2022]

Not much progress since Vietnam Flavour Conference 2022

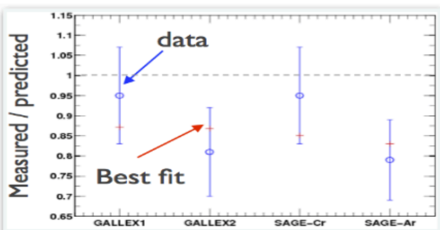
Are there sterile neutrinos?



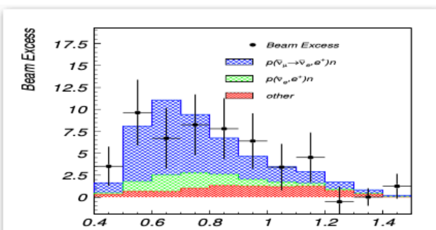
reactor flux anomaly
resolved with new input data to flux calculation



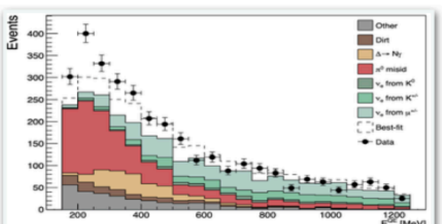
reactor spectra
is there really an anomaly?



gallium anomaly
unresolved, recently reinforced



LSND
unresolved



MiniBooNE
unresolved

[Slide from Joachim Kopp @ Neutrino 2022]

New neutrino mass states (eV)?

Sterile neutrinos

ICAUS: Talk by Alice Campani

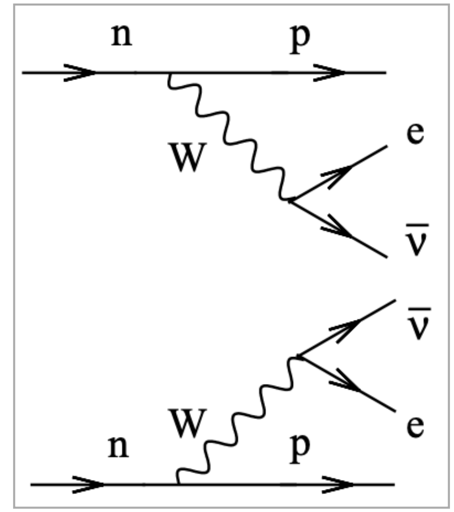
SBND: Talk by Supraja Balasubramanian

NOvA: Talk by Anastasiia Kalitkina

Are Neutrinos their Own Antiparticles?

Two-neutrino double-β decay

Maria Goeppert-Mayer, 1935



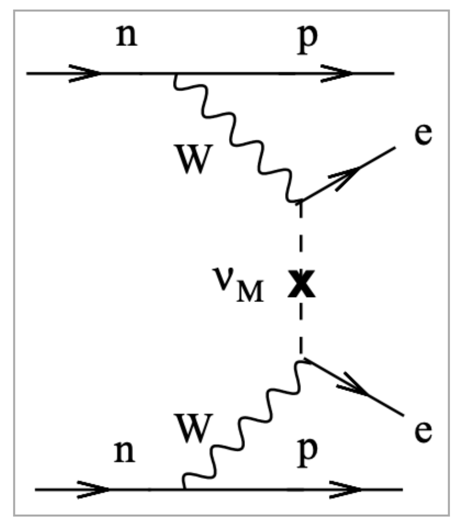
LN conserved

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

First observed in 1987

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

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

phase space dependence

Nuclear matrix element

effective Majorana mass

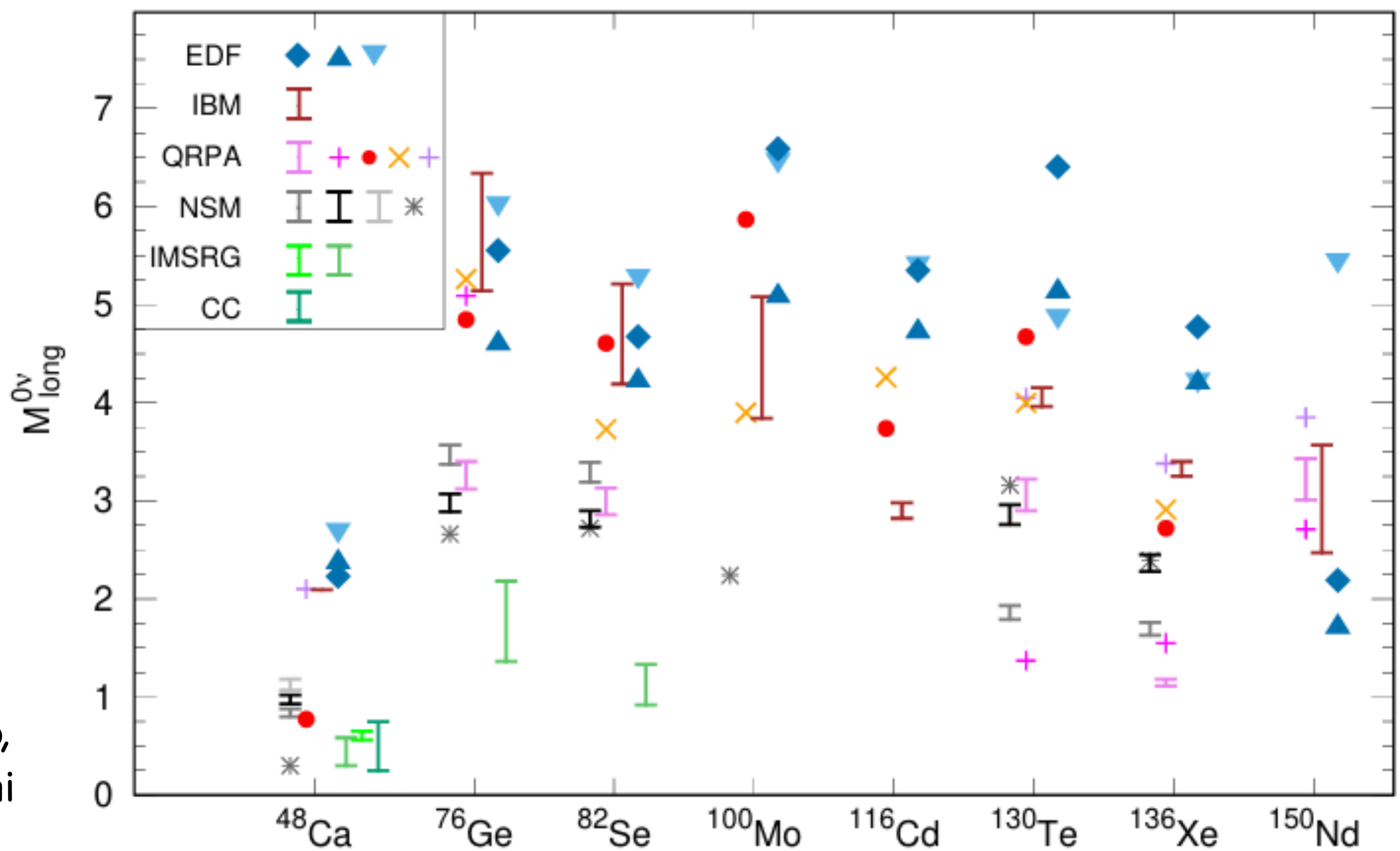
$$m_{ee}^2 = |\sum_i U_{ei}^2 m_{\nu_i}|^2$$

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



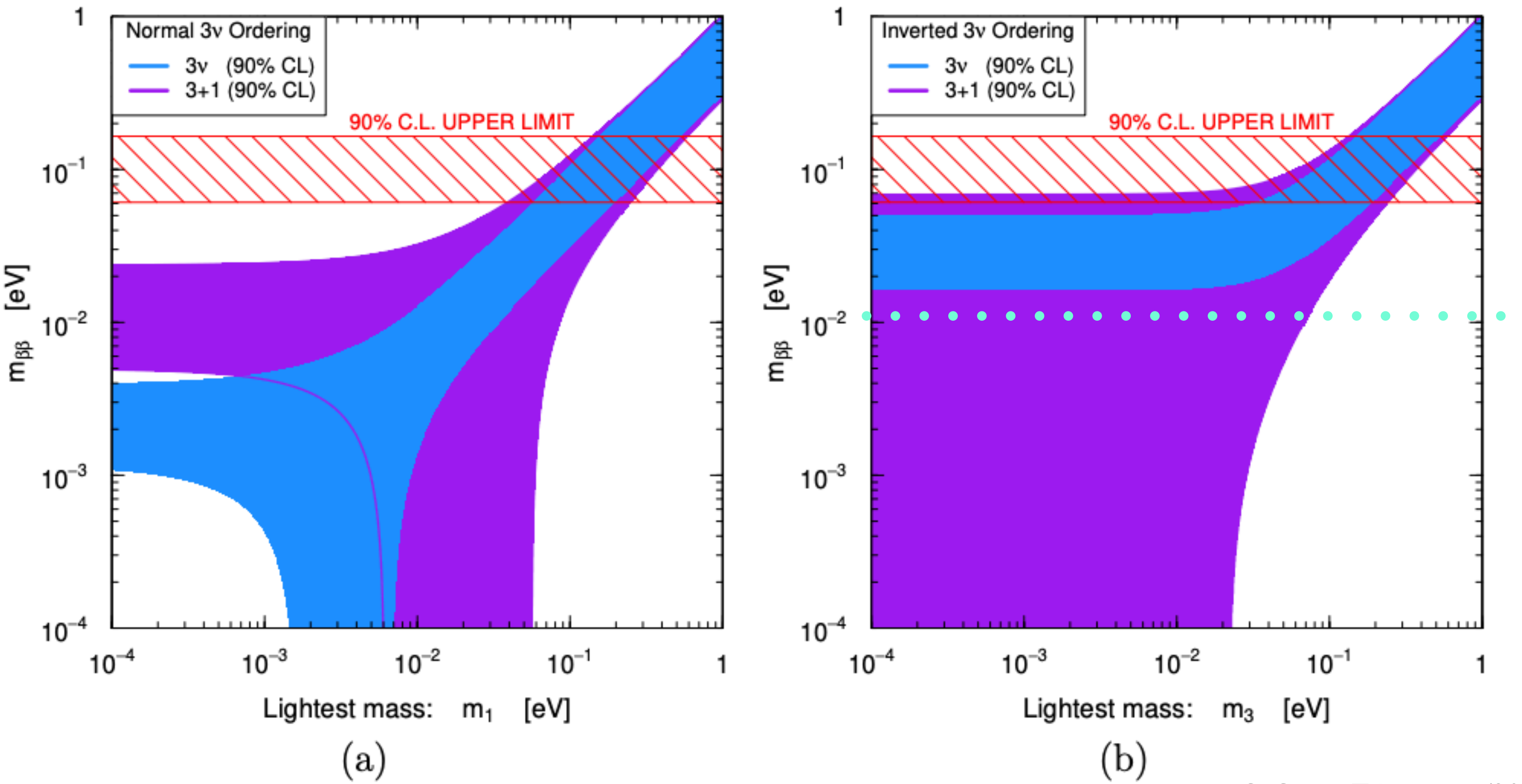
Review by Agostini, Benato, Detwiler, Menéndez, Vissani (2202.01787)

Neutrinoless Double Beta Decay

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

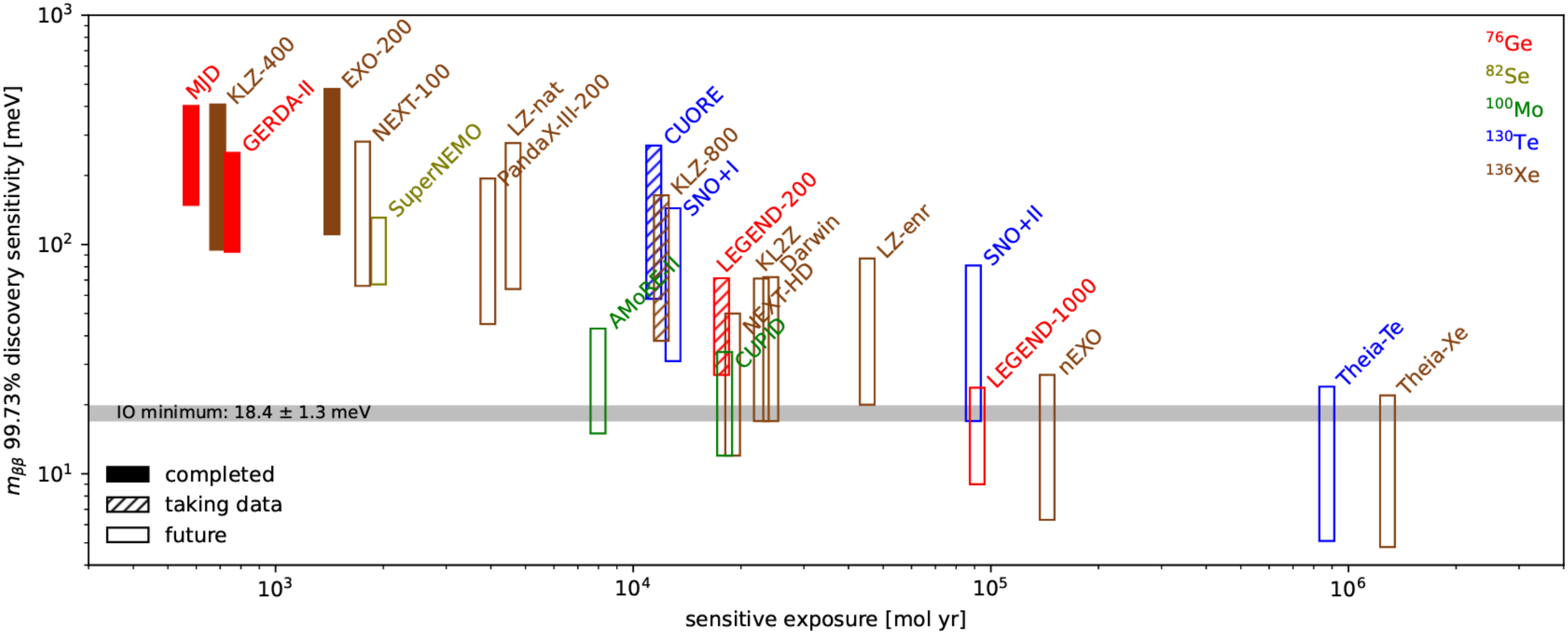
4ν: NO can be probed

3ν: IO fully covered by 2035



C. Giunti, T. Lasserre (2019)

Neutrinoless Double Beta Decay



LEGEND: Talk by
David Hervas Aguilar

[From Snowmass White Paper 2212.11099]

Open Questions - Neutrino Properties

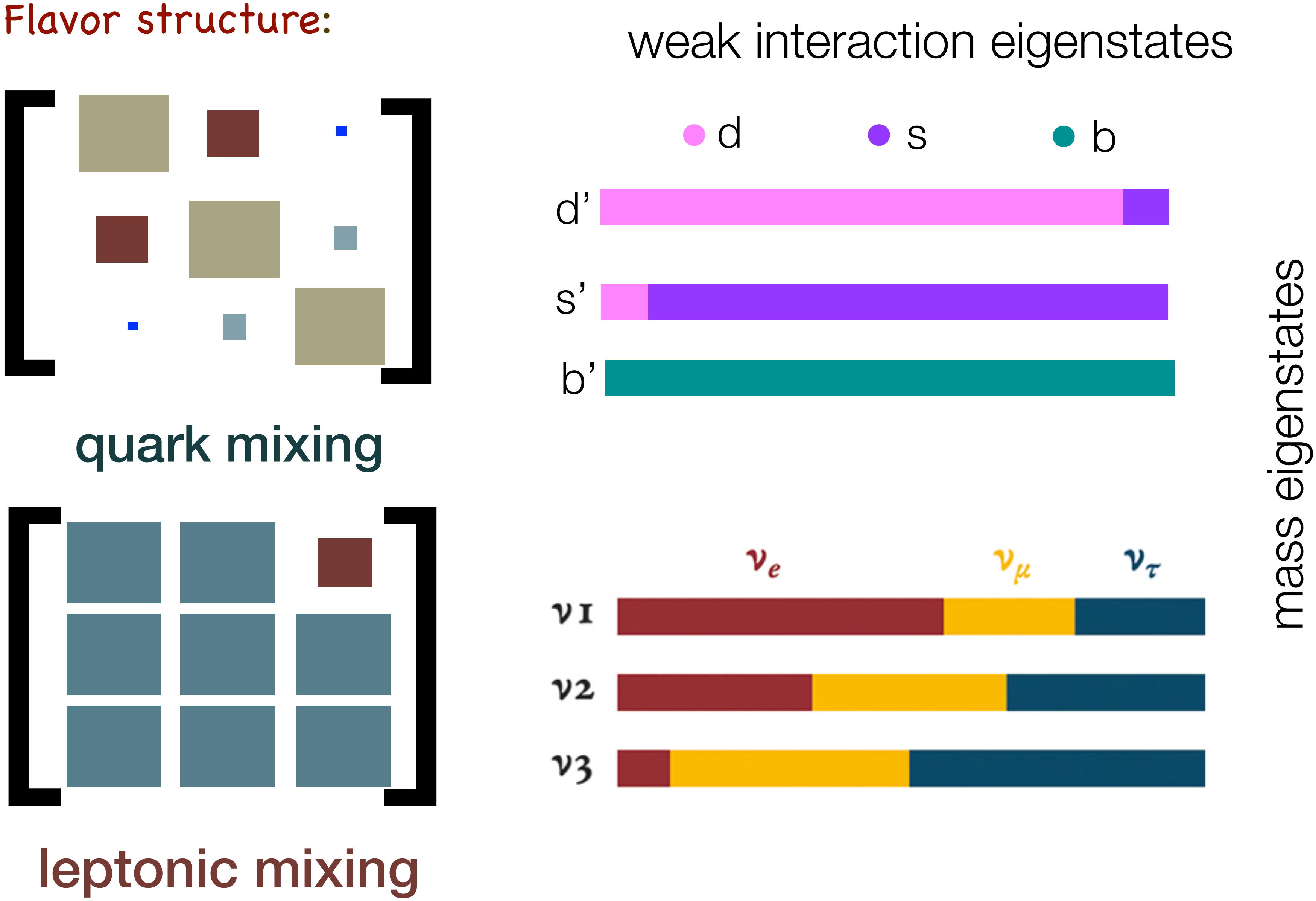
- ☞ Majorana vs Dirac?
- ☞ CP violation in lepton sector?
- ☞ Absolute mass scale of neutrinos?
- ☞ Mass ordering: sign of (Δm_{13}^2)?
- ☞ Sterile neutrino(s)?
- ☞ Precision: $\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, $\theta_{23} = \pi/4$?
- ☞ Additional Neutrino Interactions?

To understand some of these properties
$\Rightarrow$ BSM Physics

a suite of current and upcoming experiments to address these puzzles

Open Questions - Theoretical

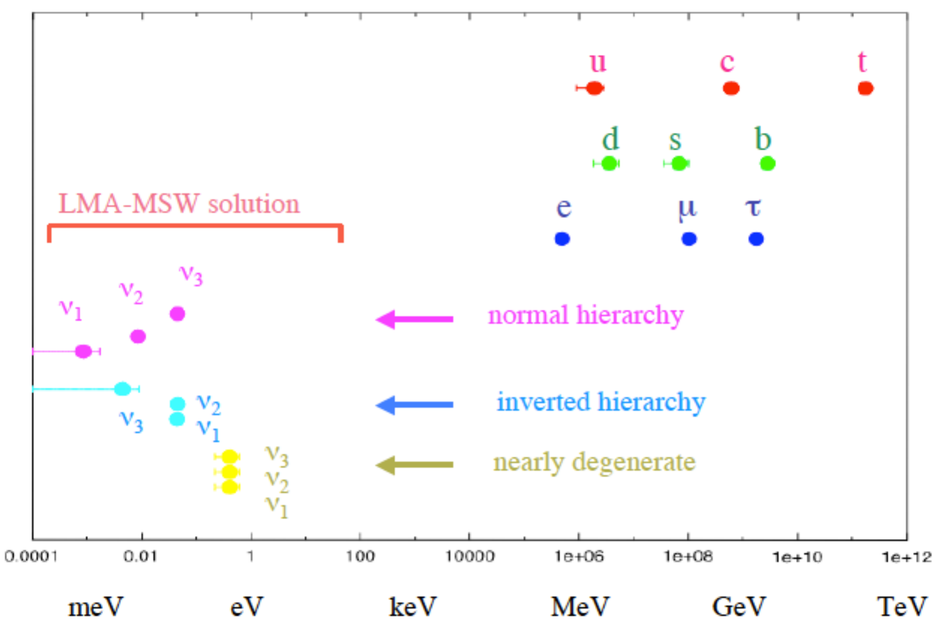
☞ Flavor structure:



Open Questions - Theoretical

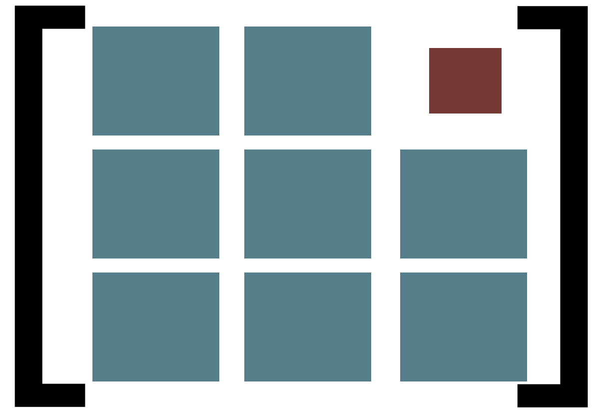
☞ Smallness of neutrino mass:

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

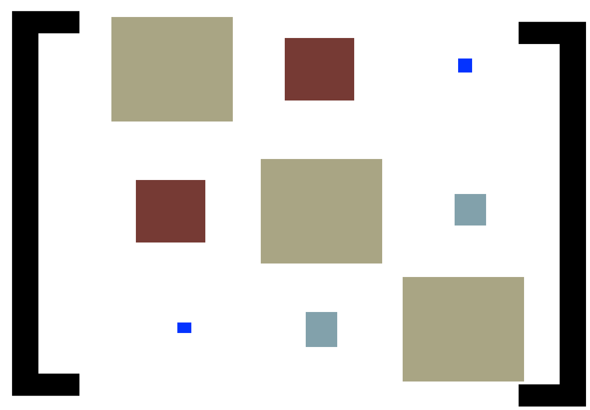


Fermion mass and hierarchy problem ➟ Many free parameters in the Yukawa sector of SM

☞ 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

co-Chairs: Mu-Chun Chen, Michael Smy | E-Mail: neutrino2026uci@gmail.com

https://sites.uci.edu/neutrino2026/