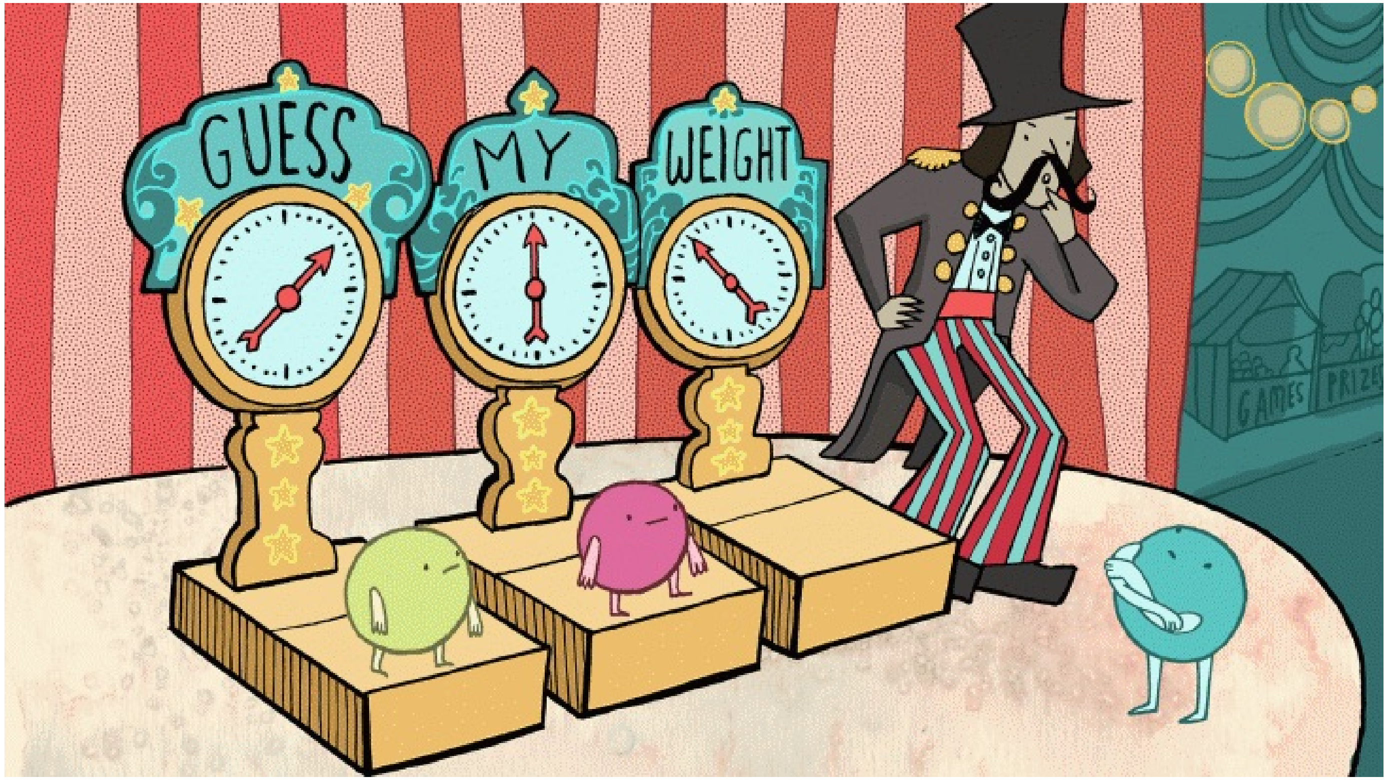
Neutrino Masses & the Nature of Neutrinos



NPC Neutrino University – First Lecture

André de Gouvêa – Northwestern University

Outline

- What Do We Know About Neutrino Masses?;
- Since Neutrino Masses are Not Zero: Are Neutrinos Majorana or Dirac Fermions?;
- Why Do We Care About Neutrino Masses?

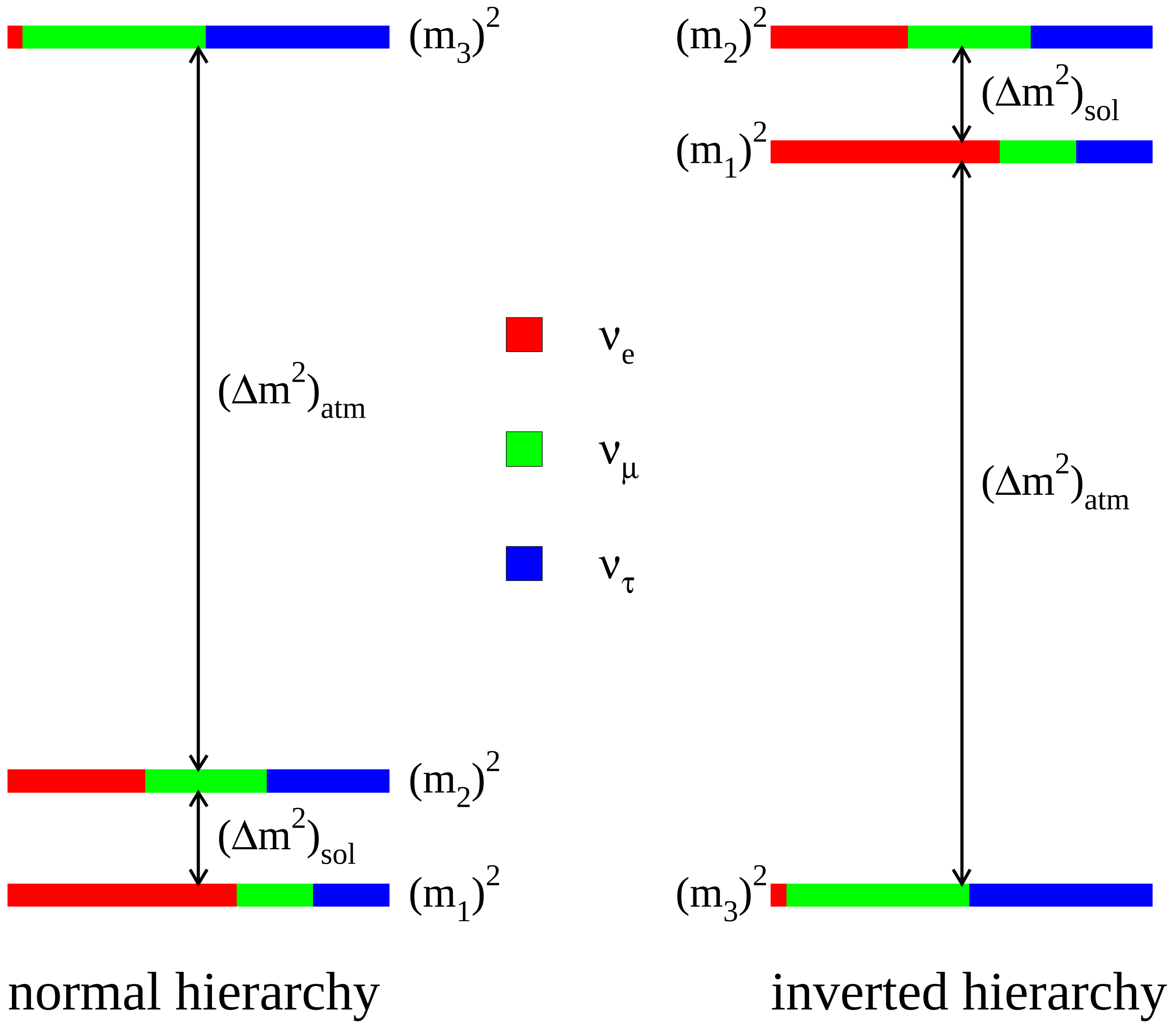
Neutrino Oscillations: Everything We Know About Neutrino Masses Other Than "They Are Very Small"

$$\left(\begin{array}{c}\nu_e\\ \nu_\mu\\ \nu_\tau\end{array}\right)=\left(\begin{array}{ccc}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{e\tau2} & U_{\tau3}\end{array}\right)\left(\begin{array}{c}\nu_1\\ \nu_2\\ \nu_3\end{array}\right)$$

Definition of neutrino mass eigenstates (who are ν_1, ν_2, ν_3?):

- $m_1^2 < m_2^2$ — $\Delta m^2_{31} < 0$ – Inverted Mass Hierarchy
- $m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$ — $\Delta m^2_{31} > 0$ – Normal Mass Hierarchy

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu3}|^2}{|U_{\tau3}|^2}; \quad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$$



(m3)2
(Δm2)atm
(m2)2
(Δm2)sol
(m1)2
normal hierarchy
νe
νμ
ντ
(m2)2
(Δm2)sol
(m1)2
(Δm2)atm
(m3)2
inverted hierarchy

Three Flavor Mixing Hypothesis Fits All* Data Really Well.

NuFIT 6.0 (2024)

	Normal Ordering ($\Delta\chi^2 = 0.6$)		Inverted Ordering (best fit)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
$\sin^2\theta_{23}$	$0.561^{+0.012}_{-0.015}$	$0.430 \to 0.596$	$0.562^{+0.012}_{-0.015}$	$0.437 \to 0.597$
$\theta_{23}/^\circ$	$48.5^{+0.7}_{-0.9}$	$41.0 \to 50.5$	$48.6^{+0.7}_{-0.9}$	$41.4 \to 50.6$
$\sin^2\theta_{13}$	$0.02195^{+0.00054}_{-0.00058}$	$0.02023 \to 0.02376$	$0.02224^{+0.00056}_{-0.00057}$	$0.02053 \to 0.02397$
$\theta_{13}/^\circ$	$8.52^{+0.11}_{-0.11}$	$8.18 \to 8.87$	$8.58^{+0.11}_{-0.11}$	$8.24 \to 8.91$
$\delta_{CP}/^\circ$	177^{+19}_{-20}	$96 \to 422$	285^{+25}_{-28}	$201 \to 348$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.534^{+0.025}_{-0.023}$	$+2.463 \to +2.606$	$-2.510^{+0.024}_{-0.025}$	$-2.584 \to -2.438$

*Modulo short-baseline anomalies.

http://www.nu-fit.org

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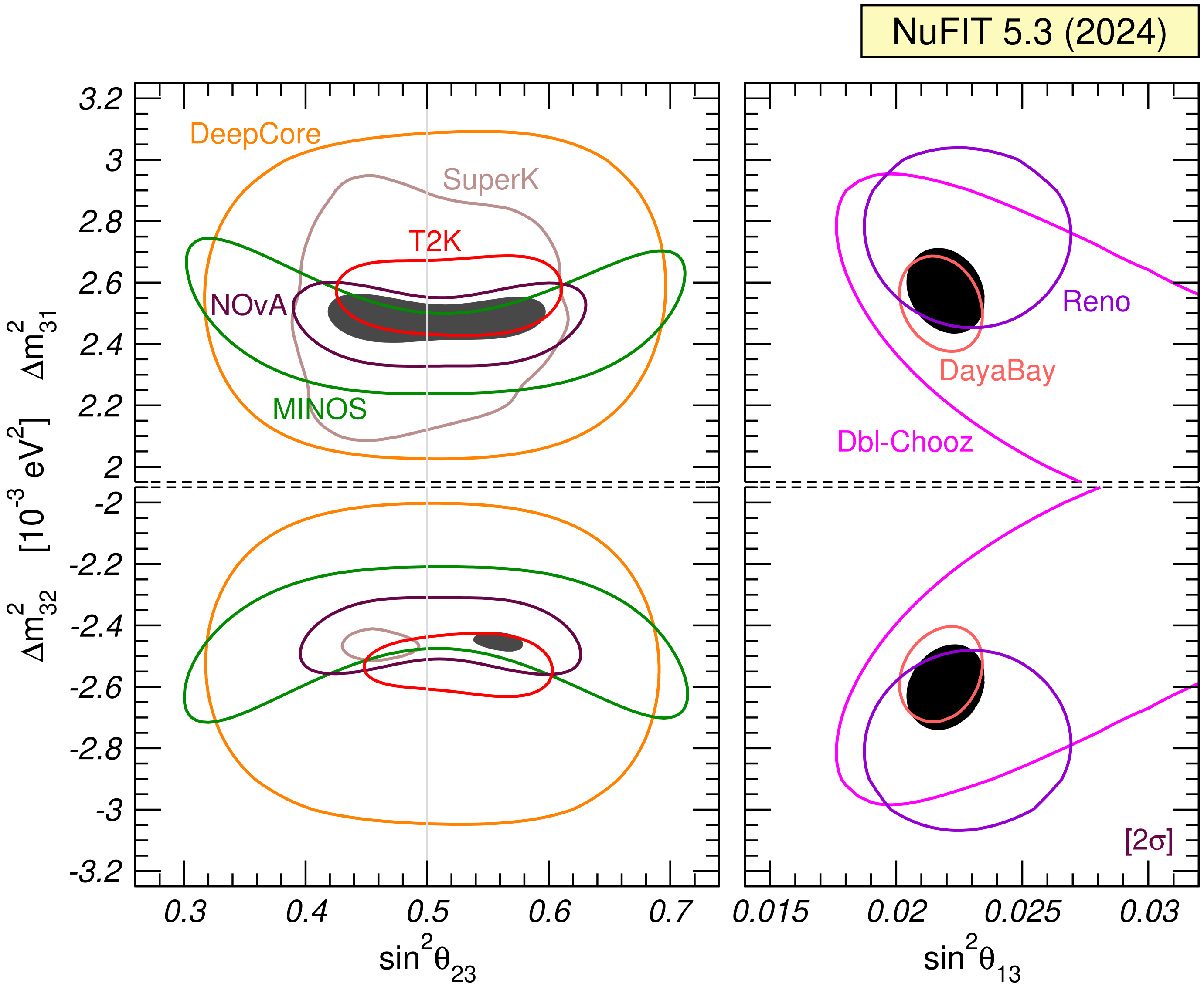
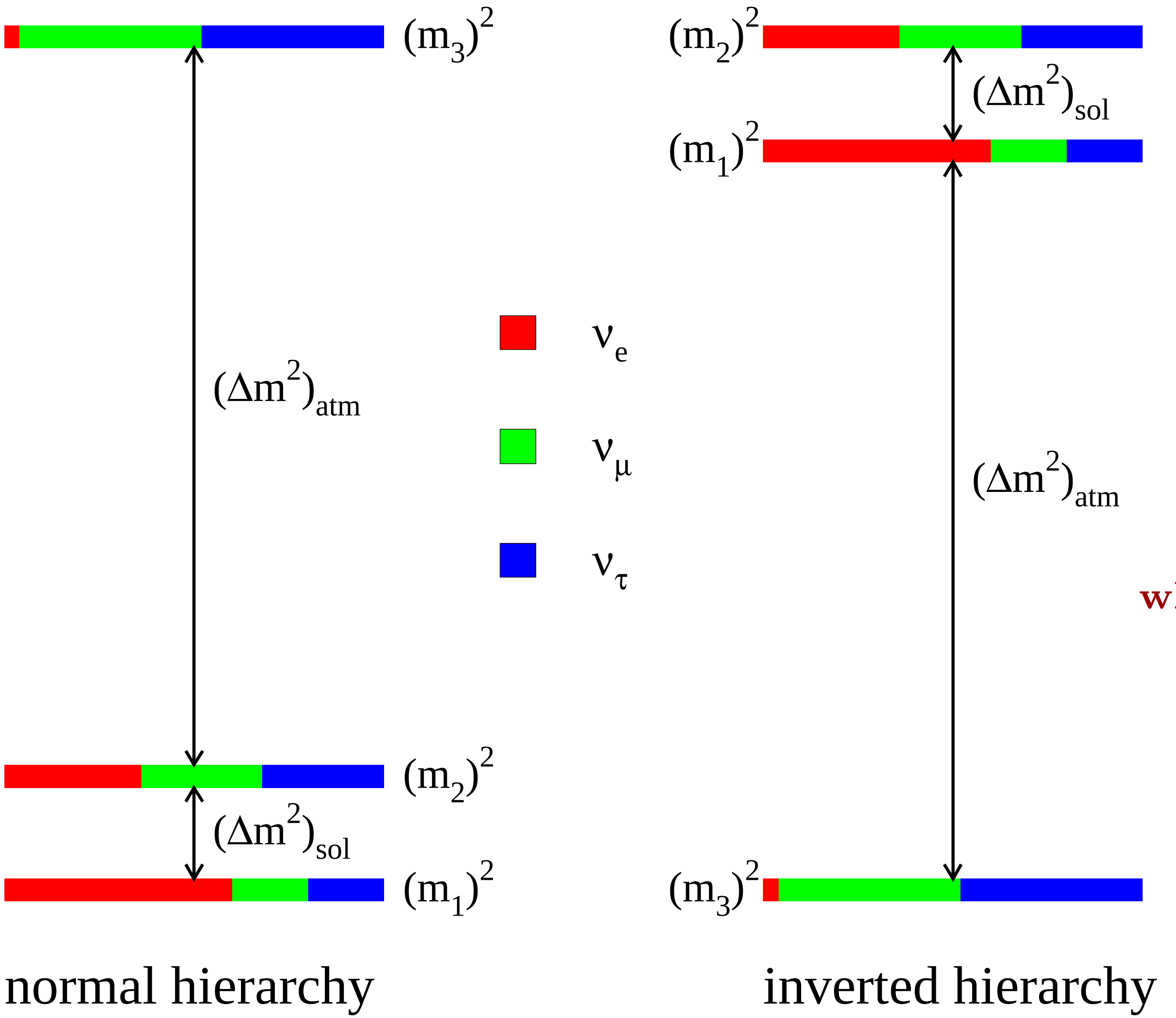


http://www.nu-fit.org

The Neutrino Mass Hierarchy



which is the right picture?

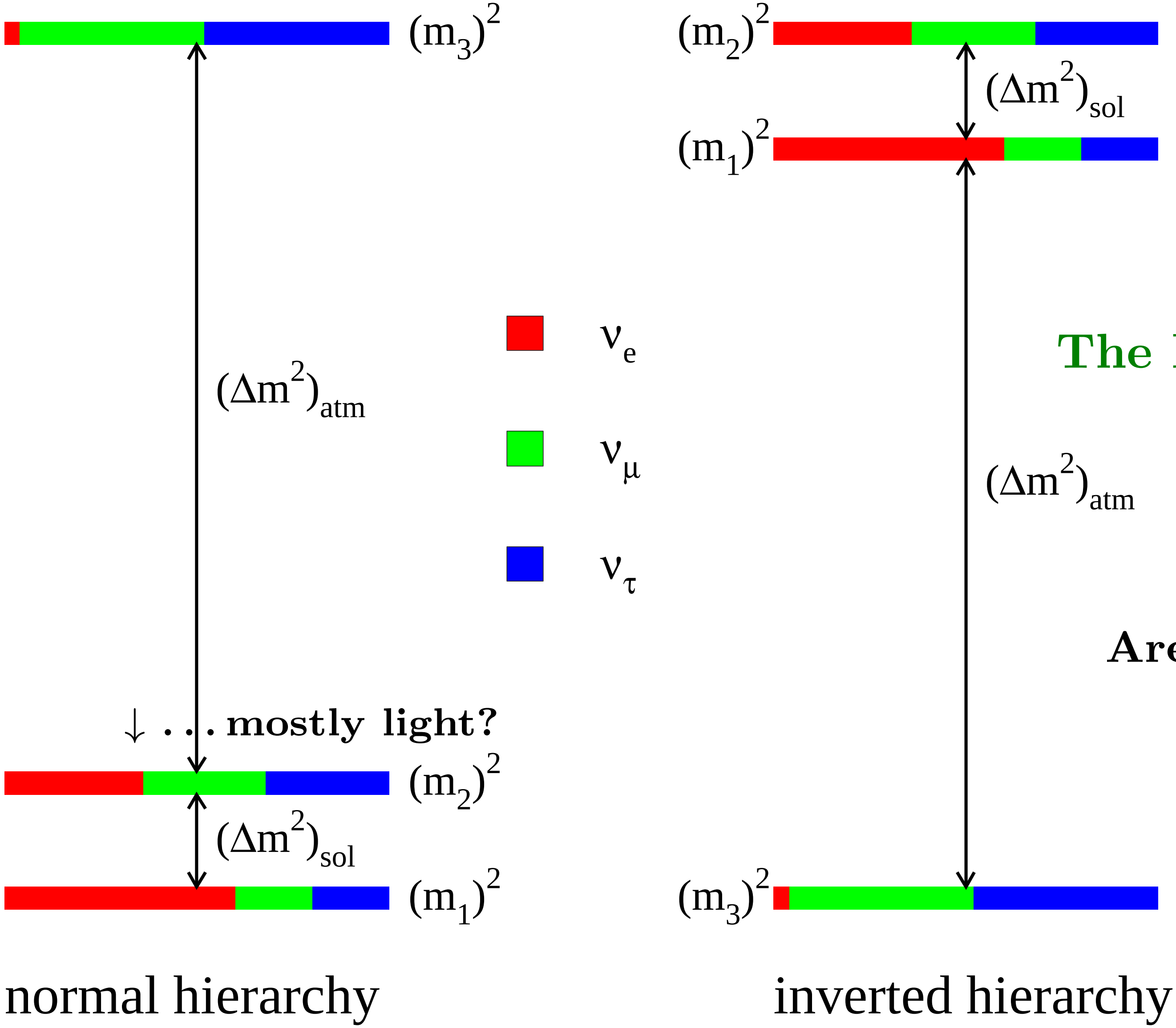
Why Don't We Know the Neutrino Mass Hierarchy?

We usually only get to see one oscillation frequency at a time. For example, most of the information we have regarding θ_{23} and Δm^2_{13} comes muon-neutrino disappearance from atmospheric neutrino experiments (Super-K) and long-baseline oscillation experiments (NOνA, T2K). Typically, they measure

$$P_{\mu\mu} \sim 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{13} L}{4E}\right) + \text{ subleading.}$$

It is easy to see from the expression above that the leading term is simply not sensitive to the sign of Δm^2_{13}.

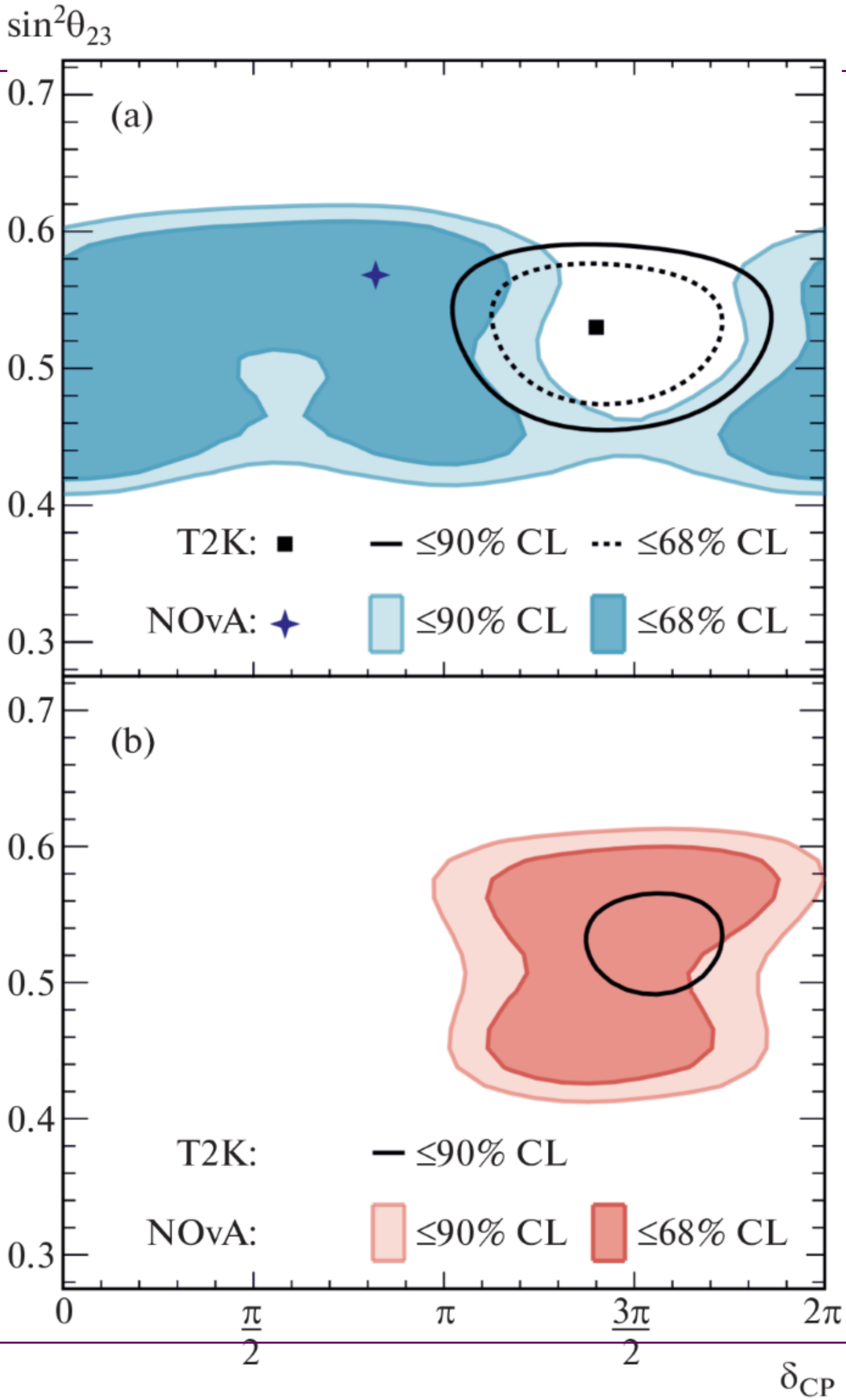
On the other hand, because $|U_{e3}|^2 \sim 0.02$ and $\frac{\Delta m^2_{12}}{\Delta m^2_{13}} \sim 0.03$ are both small, we are yet to observe the subleading effects.



← . . . **mostly heavy?**

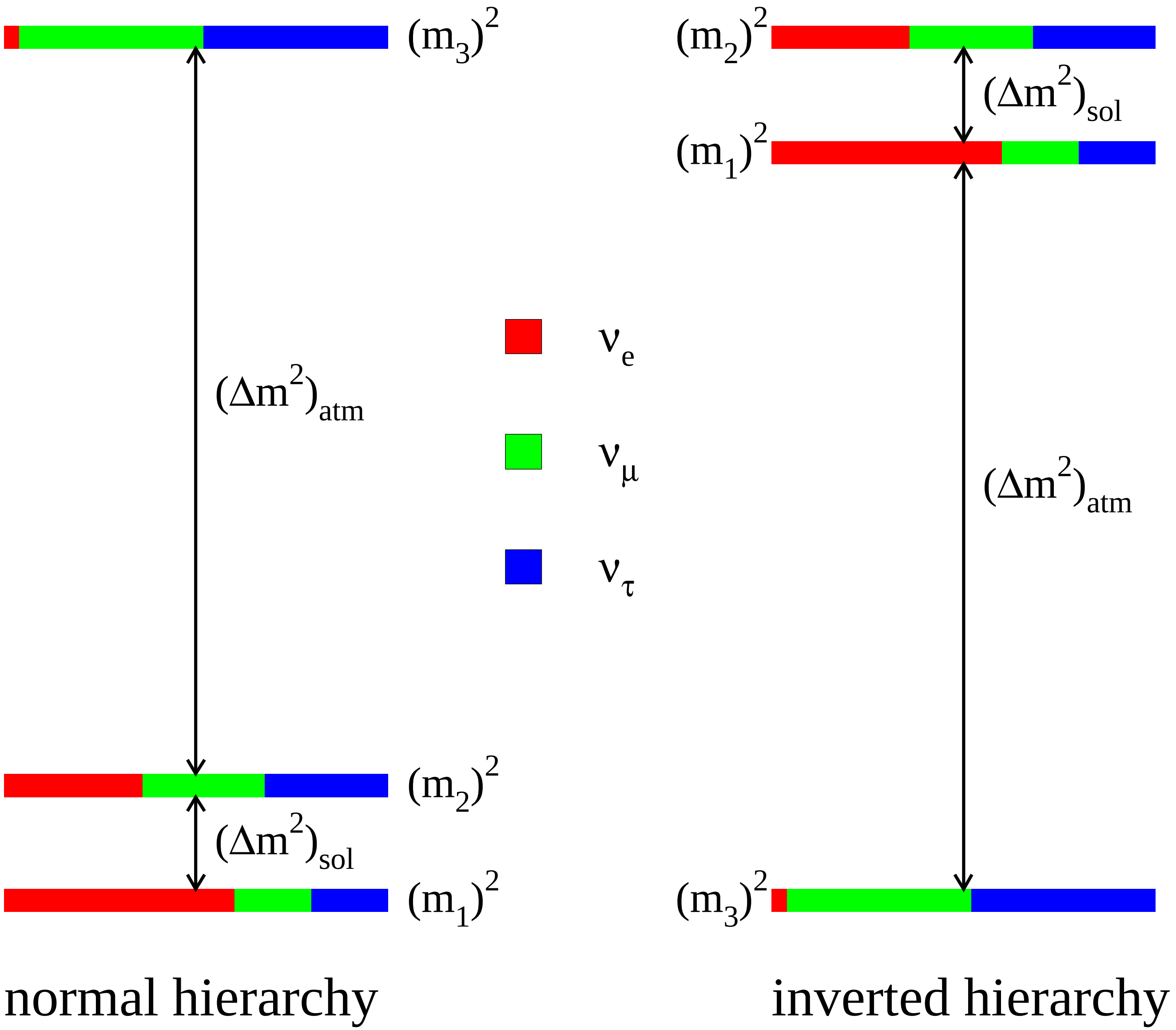
The Matter Effect way:

Are electon neutrinos . . .



Normal Ordering

Inverted Ordering

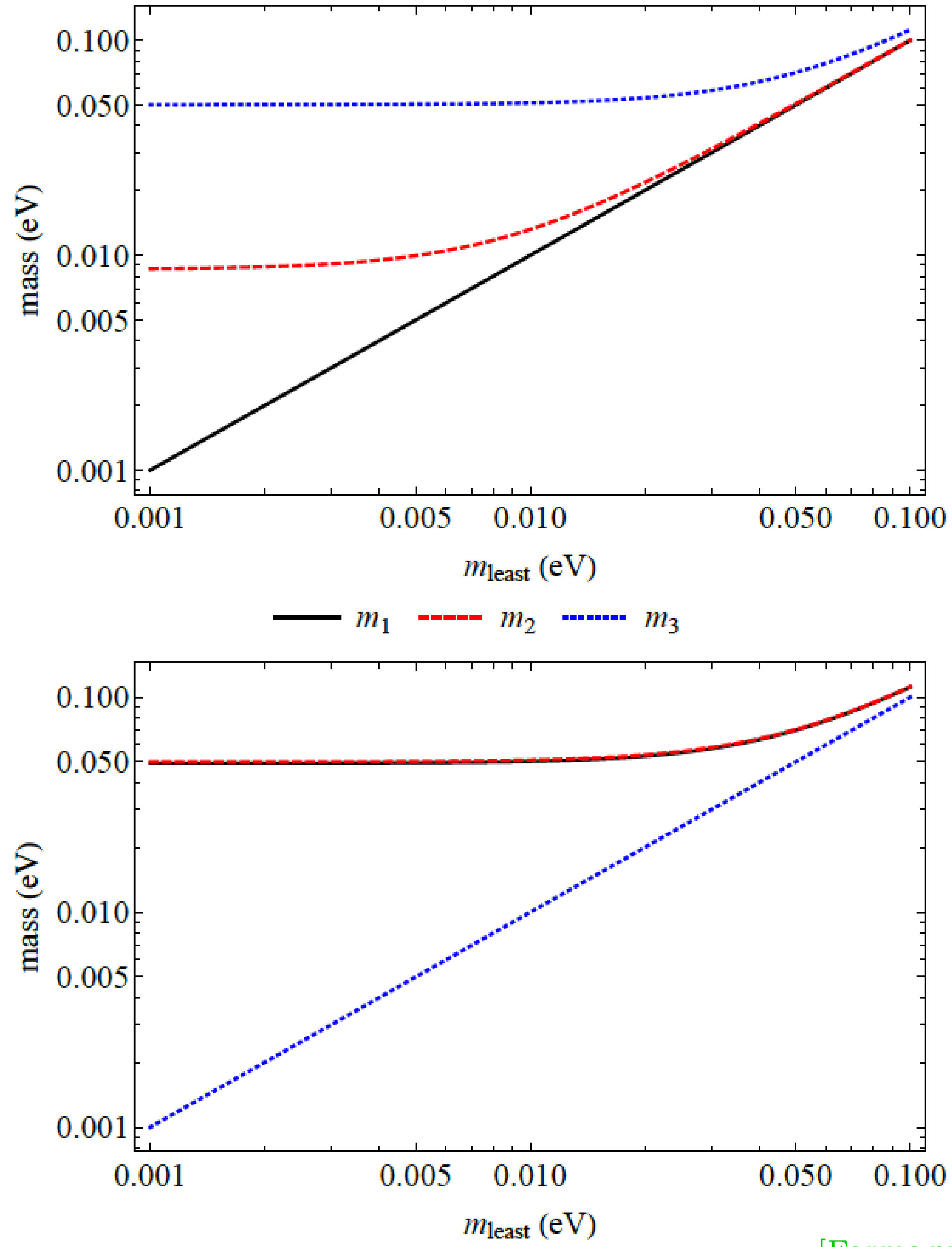


The JUNO way:

What is largest,

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

Need to resolve all three oscillation lengths.



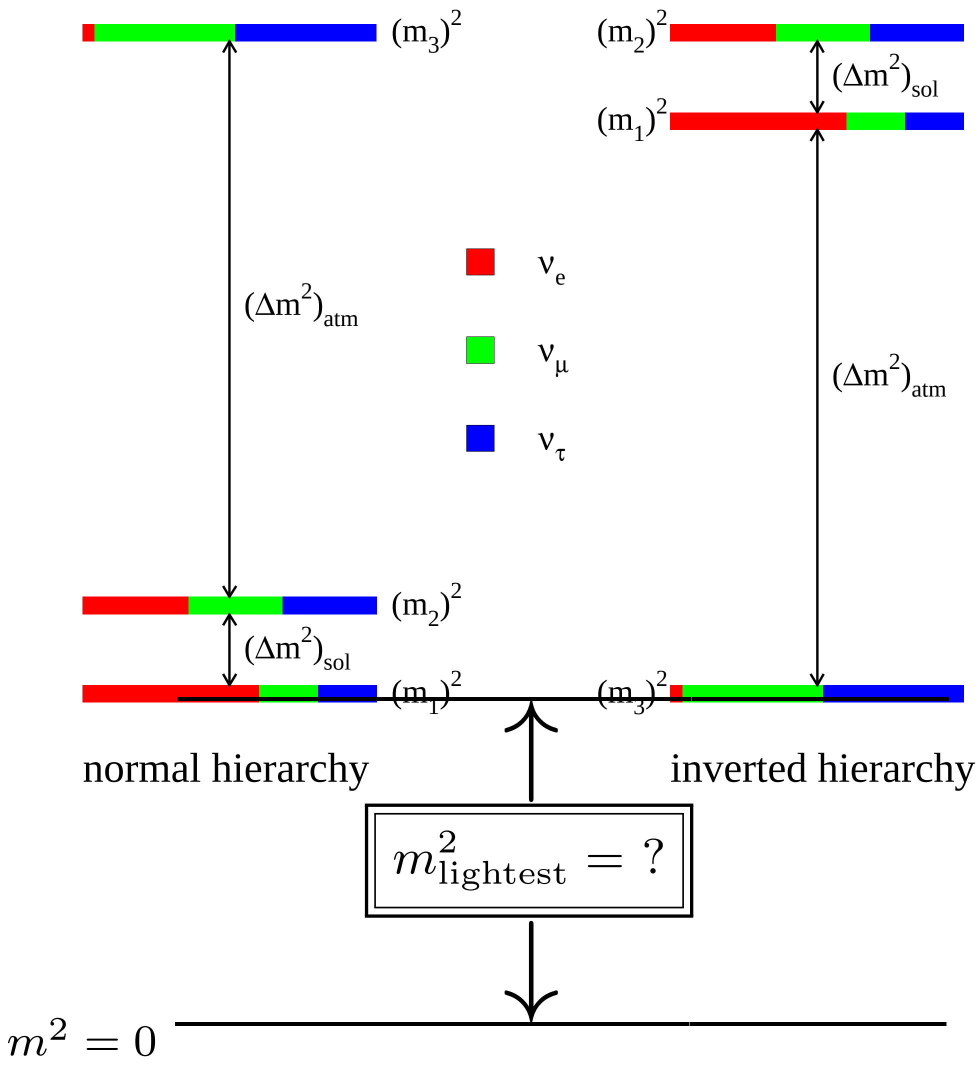
Normal Ordering

Inverted Ordering

[Formaggio, AdG, Robertson, Phys.Rept. 914 (2021)]

FIG. 4: Current best-fit values of the neutrino masses m_1, m_2, m_3 as a function of the lightest neutrino mass, for the normal mass-ordering (top) and the inverted mass ordering (bottom).

How Light is the Lightest Neutrino?



So far, we've only been able to measure neutrino mass-squared differences.

The lightest neutrino mass is only relatively poorly constrained.

qualitatively different scenarios allowed:

- $m^2_{\rm lightest} \equiv 0$;
- $m^2_{\rm lightest} \ll \Delta m^2_{12,13}$;
- $m^2_{\rm lightest} \gg \Delta m^2_{12,13}$.

Need information outside of neutrino oscillations.

The most direct probe of the lightest neutrino mass – precision measurements of β-decay

Observation of the effect of non-zero neutrino masses **kinematically**.

When a neutrino is produced, some of the energy exchanged in the process should be spent by the non-zero neutrino mass.

Typical effects are very, very small – we've never seen them! The most sensitive observable is the electron energy spectrum from tritium decay.

$$^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu}$$

Why tritium? Small Q value, reasonable abundances. Required sensitivity proportional to m^2/Q^2.

In practice, this decay is sensitive to an effective "electron neutrino mass":

$$m^2_{\nu_e} \equiv \sum_i |U_{ei}|^2 m_i^2$$

Experiments measure the **shape** of the end-point of the spectrum, not the value of the end point. This is done by counting events as a function of a (lowest) energy cut-off. note: LOTS of Statistics Needed!

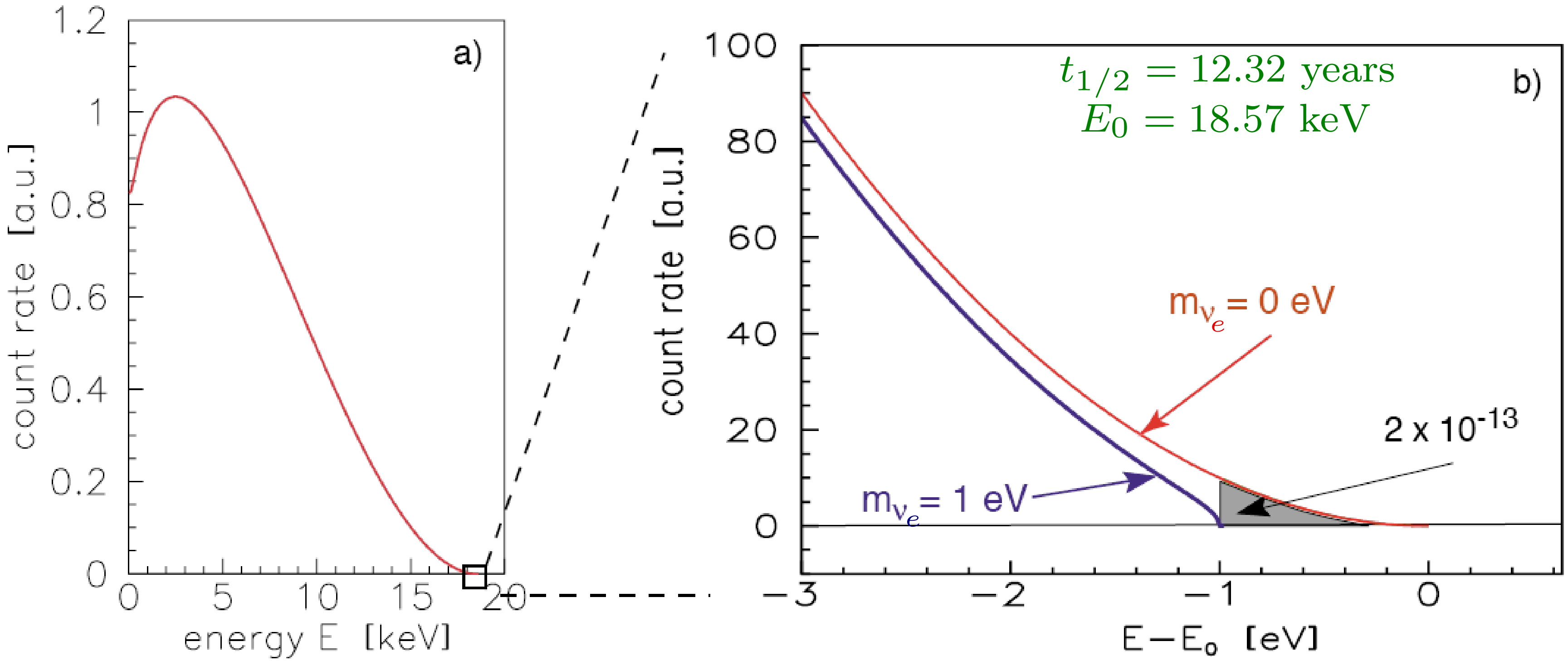
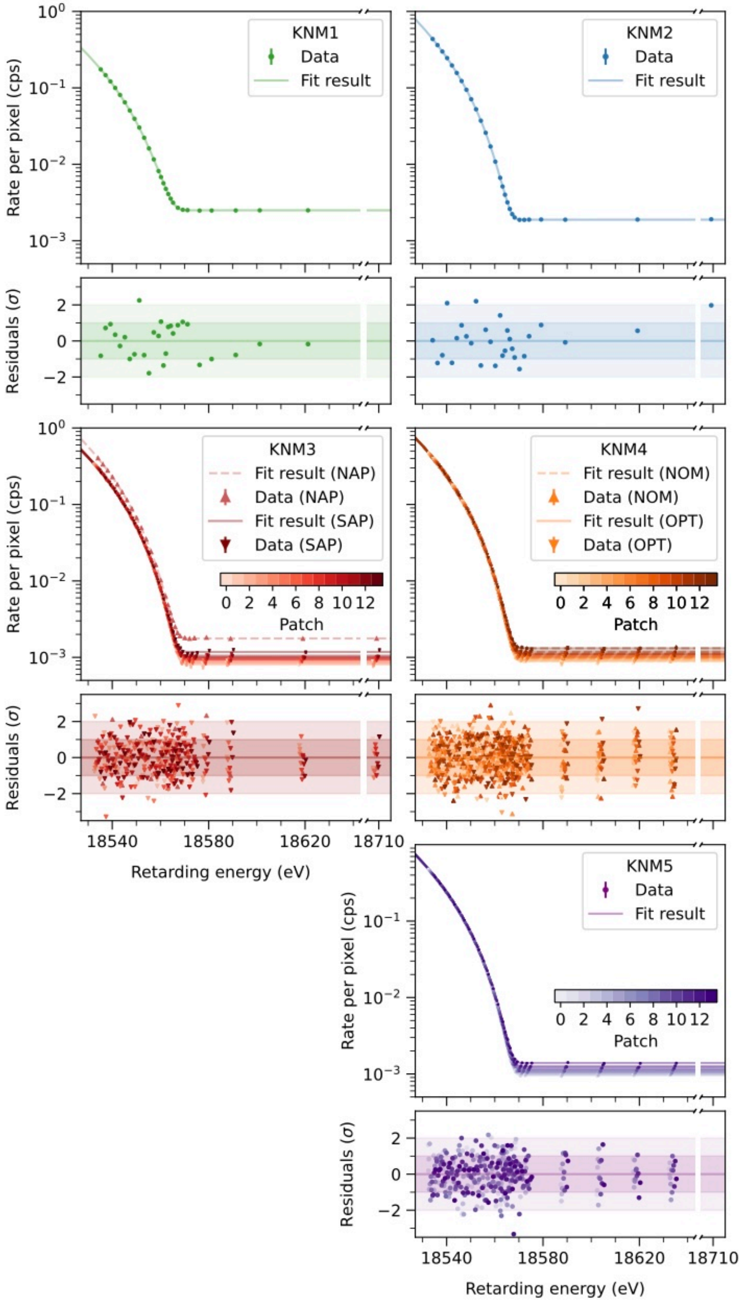


Figure 2: The electron energy spectrum of tritium β decay: (a) complete and (b) narrow region around endpoint E_0. The β spectrum is shown for neutrino masses of 0 and 1 eV.



[KATRIN Collabortation, Science 388 (2025) 6743]

Figure 2: Spectra, fit models and normalized residuals of each measurement campaign. The KNM3-SAP, KNM4-NOM, and KNM4-OPT, and KNM5 data are subdivided into 14 detector patches. The squared neutrino mass is a common fit parameter over all data sets.

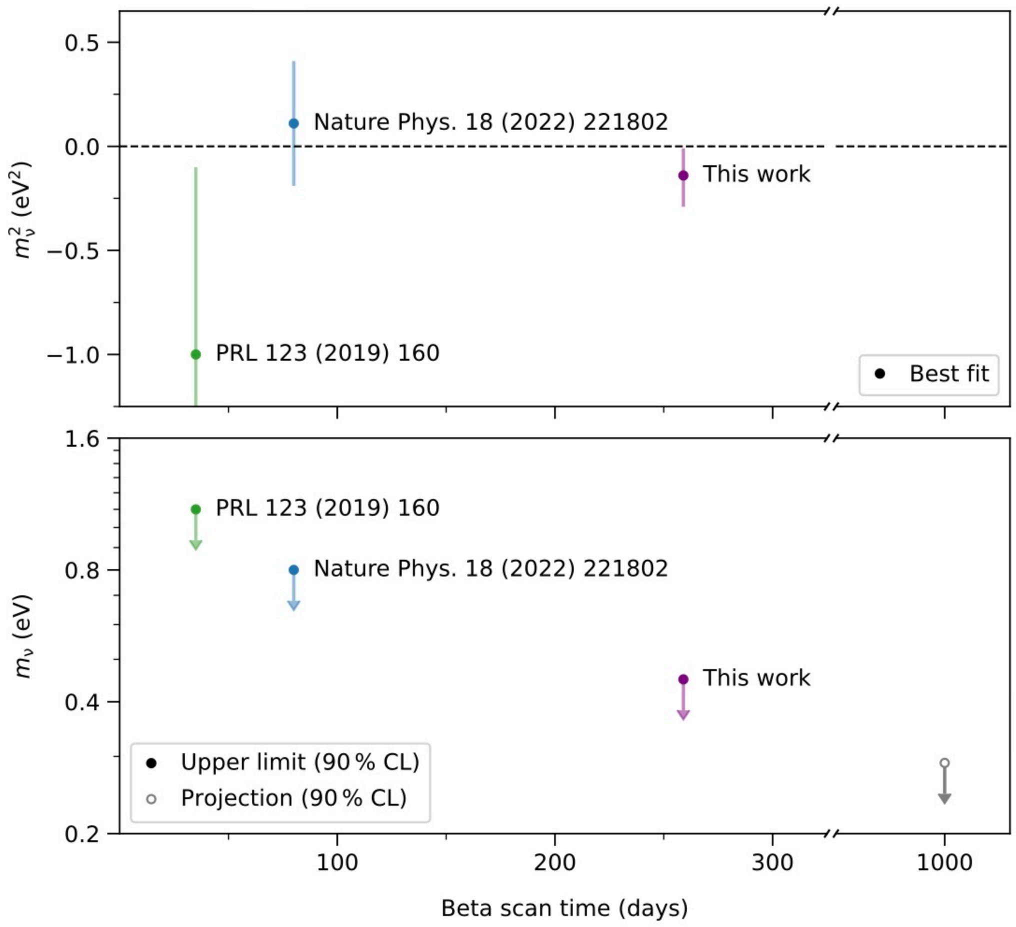


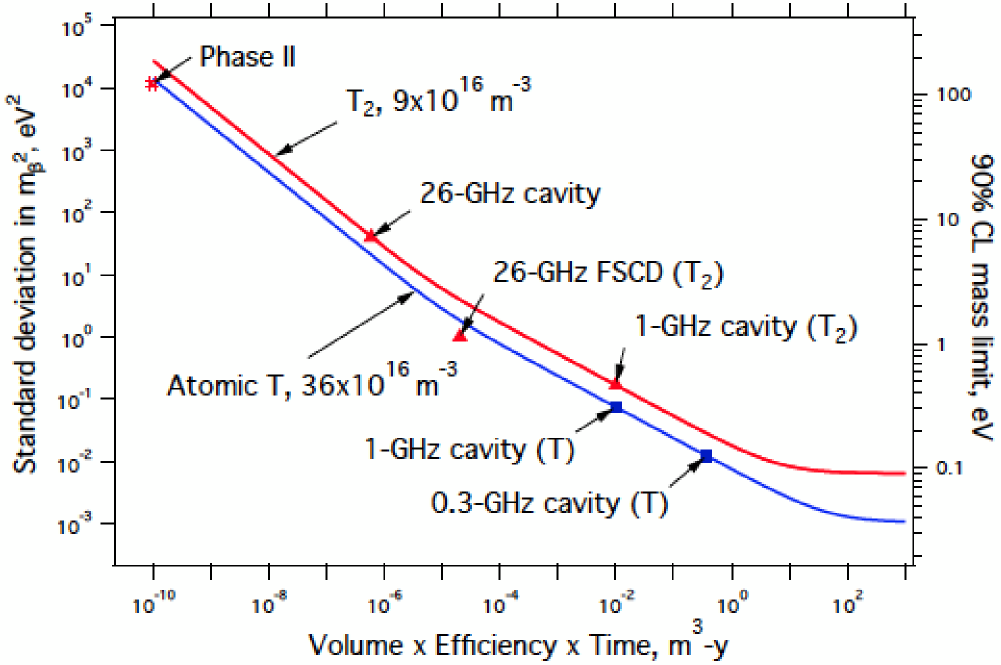
Figure 3: KATRIN neutrino-mass result obtained in this work (five measurement campaigns, purple) compared to previous KATRIN results (first campaign, green, and combined first and second campaigns, blue).

[KATRIN Collabortation, Science 388 (2025) 6743]

Any experiment with a molecular tritium (T_2) source will have a systematic penalty associated with uncertainty from rotational and vibrational states of the daughter $^3HeT^+$ populated in the decay.

In order to push to the inverted ordering scale, future experiments will need to switch from molecular to atomic sources.

Project 8 aims to evolve to atomic tritium target to overcome this obstacle and push to the inverted ordering scale



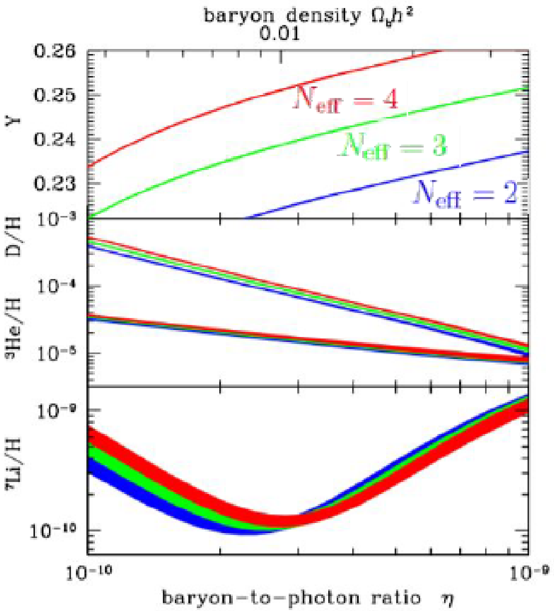
See Snowmass contribution arXiv:2203.07349 for more details

[Formaggio at APS 2022]

Cosmic Neutrinos are Measured through BBN and CMB

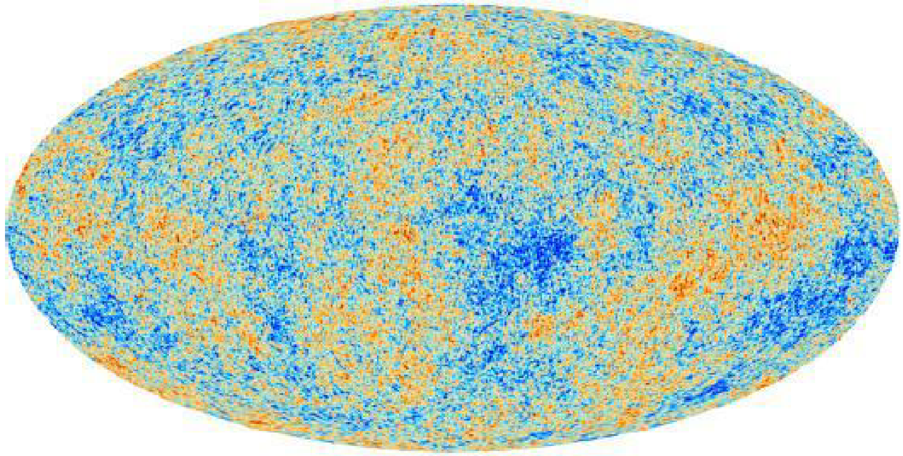
Primordial Abundances

$N_{\rm eff}^{\rm BBN} = 2.95 \pm 0.54$ (95% CL)



CMB Measurements

$N_{\rm eff}^{\rm CMB} = 2.99 \pm 0.34$ (95% CL)



Cyburt, et al. (2015); Cooke, et al. (2018); Planck (2018)

[Meyers at APS 2022]

Currents bounds on the neutrino mass sum...

There is **no** cosmological measurement of the neutrino mass sum yet.

- Current constraints on $\sum m_\nu$ are typically $O(0.1 - 0.3)$ eV, depending on exactly how you do the analysis → Model dependence.

6+1 fit parameters (→ Baseline row)

Model	Degenerate	Normal	Inverted
Baseline ΛCDM+Σm_ν	**0.121**	**0.146**	**0.172**
+ r	0.115	0.142	0.167
+ w	0.186	0.215	0.230
+ $w_0 w_a$	0.249	0.256	0.276
+ $w_0 w_a$, $w(z) > -1$	0.096	0.129	0.157
+ Ω_k	0.150	0.173	0.198

Primordial tensors (+ r)

Dynamical dark energy (+ w; + $w_0 w_a$; + $w_0 w_a$, $w(z) > -1$)

Spatial curvature (+ Ω_k)

Factor of 3 variation between min and max.

Roy Choudhury & Hannestad 2019

[Y. Wong, early 2025]

Caveats for Cosmic Surveys as input for neutrino masses

- Indirect probe of neutrino mass. What we are really measuring are properties of the universe at very large scales as a function of red-shift.
- Degeneracies with other parameters. Lots of quantities are fit for at once. Model dependency. Current bounds can be loosened if there is new particle physics or new ingredients in the early universe.
- Imagine a positive claim from cosmic surveys that neutrino masses are not zero. Would you believe it if you did not know, from oscillations, neutrinos were massive?

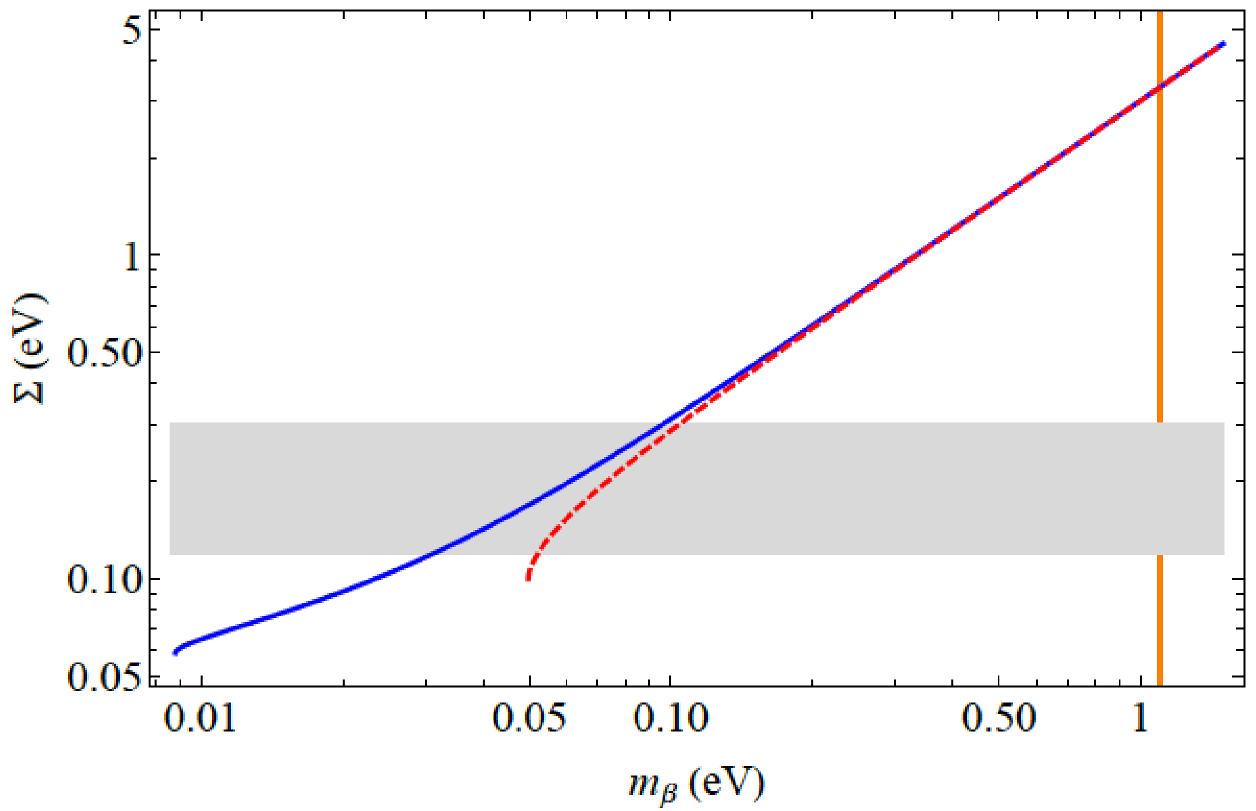
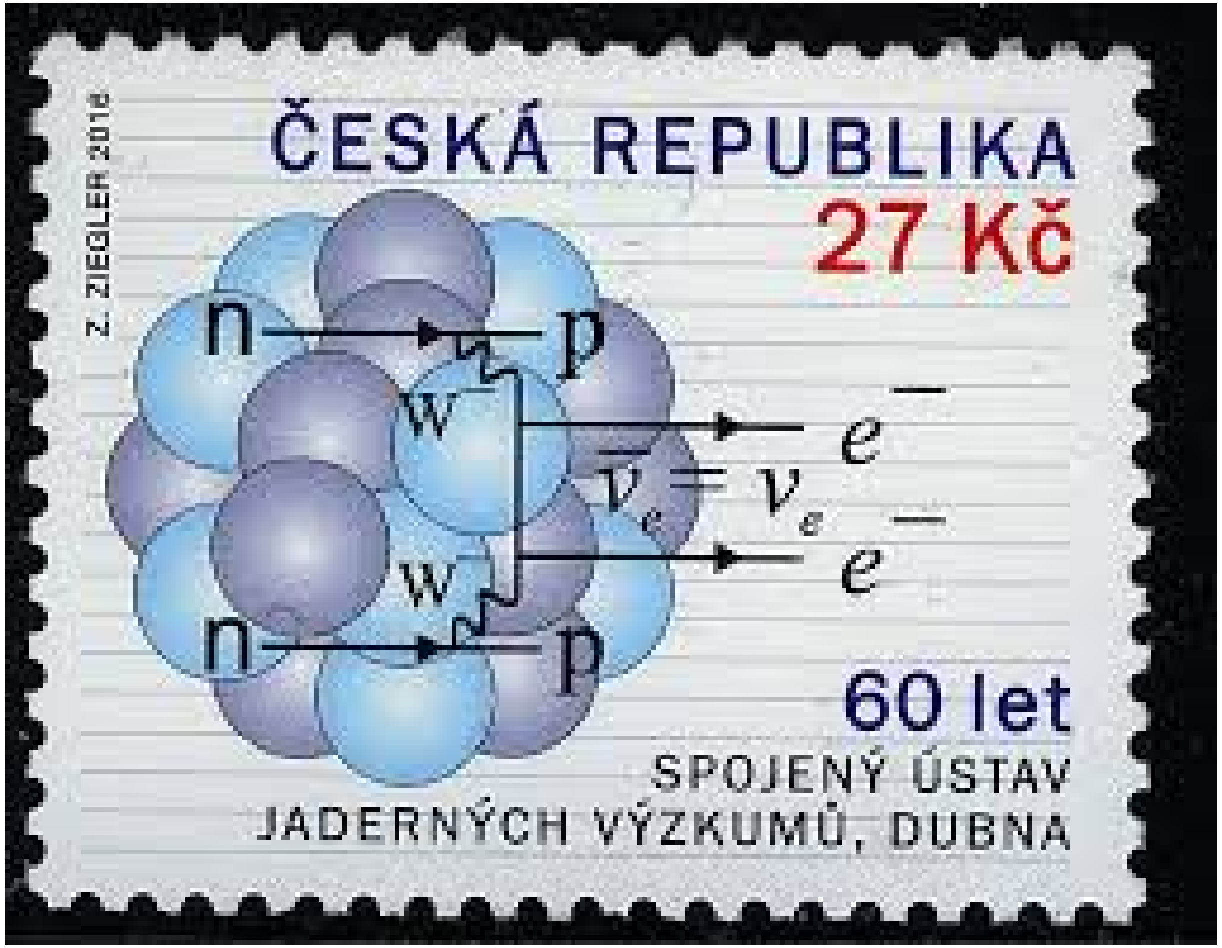


FIG. 6: Σ as a function of m_β, for both the normal (blue,solid) and inverted (red,dashed) mass orderings. We use the current best-fit values of the oscillation parameters from [29]. The, horizontal band corresponds to the range of 95% CL upper bounds on Σ discussed in [60]. Different upper bounds correspond to different ingredients added to the Standard Model of cosmology. The vertical line corresponds to the current 90% upper bound on m_β [56].

[Formaggio, AdG, Robertson, Phys.Rept. 914 (2021)]

Majorana versus Dirac



How Many Degrees of Freedom are There in a Massive* Neutrino? (2 versus 4)

Warm-up:

A massive charged fermion (s=1/2) is described by 4 degrees of freedom:

$$e^-_L \leftarrow \text{CP} \rightarrow e^+_R$$

$$\updownarrow \text{“Lorentz”}$$

$$e^-_R \leftarrow \text{CP} \rightarrow e^+_L$$

This is referred to as a Dirac fermion. Here, we can talk about

$$\text{Parity: relates } e^\pm_R \text{ with } e^\pm_L$$

$$\text{Charge-Conjugation: relates } e^\pm_R \text{ with } e^\mp_R$$

* Massless fermions are weird. We can make do with only “half” of them, even if they are charged.

How Many Degrees of Freedom are There in a Massive Neutrino? (2 versus 4)

For a massive neutral fermion (s=1/2), there are two choices: Dirac ...

$$\nu_L \leftarrow \mathrm{CP} \rightarrow \bar{\nu}_R$$

$$\updownarrow \text{“Lorentz”}$$

$$\nu_R \leftarrow \mathrm{CP} \rightarrow \bar{\nu}_L$$

or Majorana ...

$$\nu_L \leftarrow \mathrm{CP} \rightarrow \nu_R$$

$$\updownarrow \text{“Lorentz”}$$

$$\nu_R \leftarrow \mathrm{CP} \rightarrow \nu_L$$

In the Majorana case, neutrinos are their own antiparticles. This means $\nu_L = \bar{\nu}_L$ and $\nu_R = \bar{\nu}_R$. (Helicity matters!)

Why Don't We Know the Answer to 4 versus 2?

If neutrino masses were indeed zero, this is a nonquestion: there is no distinction between a massless Dirac and Majorana fermion.

Processes that are sensitive to the Majorana versus Dirac nature of the neutrino vanish in the limit $m_\nu \to 0$. Since neutrinos masses are very small, the probability for these to happen is very, very small: $A \propto m_\nu/E$.

Charged-Current Weak Interactions are Chiral ("Left-Handed")

What does this mean? For example, In the decay of a muon at rest,

$$\mu^- \to e^- \nu_\mu \bar{\nu}_e,$$

the electrons come out almost 100% polarized:

$$|e^-\rangle \sim |L\rangle + \left(\frac{m_e}{m_\mu}\right)|R\rangle.$$

For the CP-conjugated process, we get the CP-conjugated answer: In the process

$$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e,$$

the positrons come out almost 100% polarized:

$$|e^+\rangle \sim |R\rangle + \left(\frac{m_e}{m_\mu}\right)|L\rangle.$$

Charged-Current Weak Interactions are Chiral ("Left-Handed")

When it comes to neutrino production, for example, in pion-decay at rest

$$\pi^+ \to \mu^+ \nu$$

$$|\nu\rangle \sim |L\rangle + \left(\frac{m_\nu}{m_\pi}\right)|R\rangle.$$

For the CP-conjugated process, we get the CP-conjugated answer:

$$\pi^- \to \mu^- + \mathrm{CP}(\nu)$$

the CP-conjugated neutrino state comes out almost 100% polarized:

$$|\mathrm{CP}(\nu)\rangle \sim |R\rangle + \left(\frac{m_\nu}{m_\pi}\right)|L\rangle.$$

(Remember: $m_\nu/m_\pi < 10^{-9}$)

Charged-Current Weak Interactions are Chiral ("Left-Handed")

The same goes for neutrino detection. Ignoring neutrino-mass effects

$$\nu_L + X \to e^- + Y$$

and the CP conjugate channel is

$$\mathrm{CP}(\nu_L) + \mathrm{CP}(X) \to e^+ + \mathrm{CP}(Y)$$

So, if we can ignore neutrino masses, left-handed neutrinos are produced together with positively-charged leptons and, when they are detected, they only know how to produce negatively-charged leptons. The opposite goes for the CP-conjugate of the neutrino: these are produced with negatively-charged leptons and, when they are detected, they only know how to produce positively-charged leptons. It does not matter if they are Dirac fermions or Majorana fermions!

Gedanken Experiment, remembering that $m_\nu \neq 0$:

In the scattering process $e^- + X \to \nu_e + X$, the electron neutrino is, in a reference frame where $m \ll E$,

$$|\nu_e\rangle \sim |L\rangle + \left(\frac{m}{E}\right)|R\rangle.$$

If the neutrino is a Majorana fermion, $|R\rangle$ behaves mostly like a "$\bar{\nu}_e$," (and $|L\rangle$ mostly like a "ν_e,") such that the following process could happen:

$$e^- + X \to \nu_e + X, \quad \text{followed by} \quad \nu_e + X \to e^+ + X, \qquad P \simeq \left(\frac{m}{E}\right)^2$$

Lepton number can be violated by 2 units with small probability. Typical numbers: $P \simeq (0.1~\text{eV}/100~\text{MeV})^2 = 10^{-18}$. VERY Challenging!

Global Lepton Number Symmetry

In the massless-neutrino limit, there is a conserved global symmetry we call **Lepton Number**. If we assign the following charges to the leptons

$$L(e^-) = L(\mu^-) = L(\tau^-) = 1 = L(\nu),$$

$$L(e^+) = L(\mu^+) = L(\tau^+) = -1 = L(\mathrm{CP}(\nu)),$$

the total lepton number is always conserved.

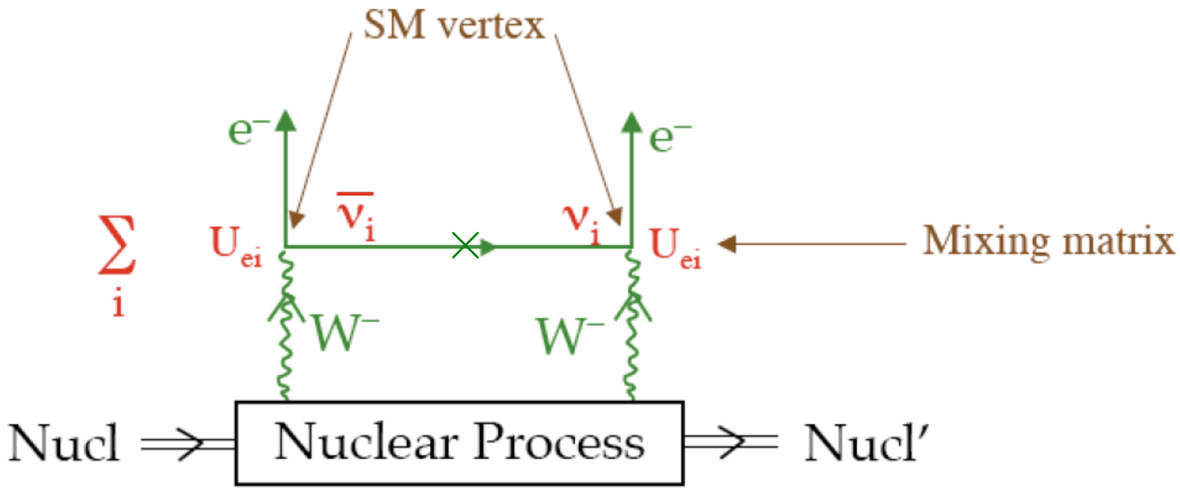
If neutrinos are massive Majorana fermions, we can't assign them ANY quantum number, including lepton number. Hence, lepton number cannot be exactly conserved. If neutrinos are Majorana fermions, lepton number is only approximately conserved. Hence, the "smoking gun" signature of Majorana neutrinos is the observation of LEPTON NUMBER violation.

Search for the Violation of Lepton Number (or $B - L$)

Best Bet: search for

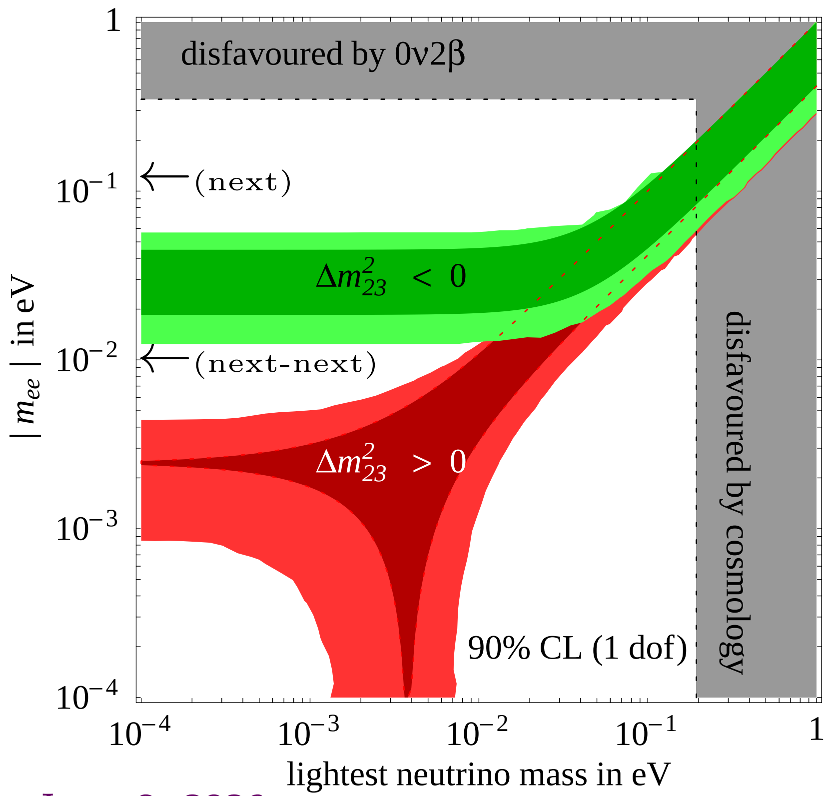
Neutrinoless Double-Beta

Decay: $Z \to (Z+2)e^- e^-$



Helicity Suppressed Amplitude $\propto \frac{m_{ee}}{E}$

Observable: $m_{ee} \equiv \sum_i U_{ei}^2 m_i$



$\Leftarrow$ **information even if the answer is no**

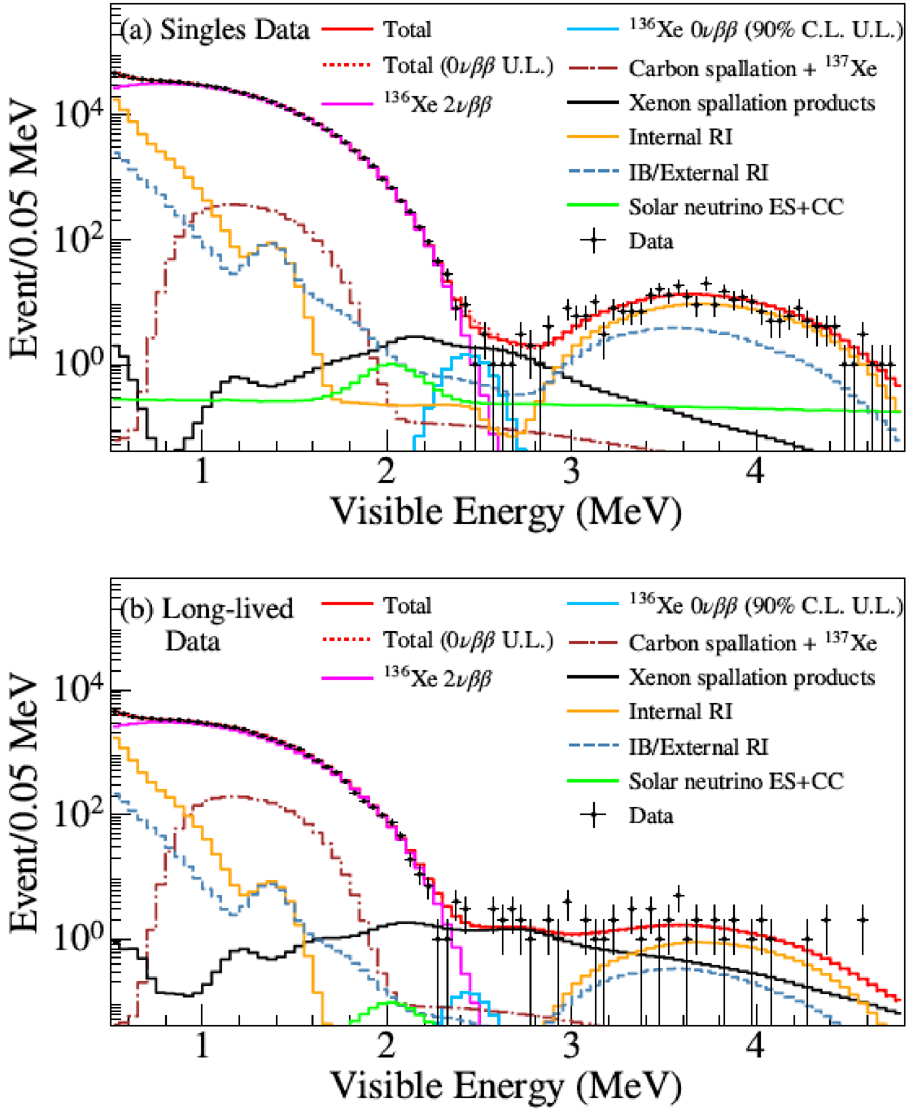


FIG. 2: Energy spectra of selected $\beta\beta$ candidates within a 1.57-m-radius spherical volume drawn together with best-fit backgrounds, the $2\nu\beta\beta$ decay spectrum, and the 90% C.L. upper limit for $0\nu\beta\beta$ decay of (a) singles data (SD), and (b) long-lived data (LD). The LD exposure is about 10% of the SD exposure.

Lots of Experimental Activity!

Moving Towards Ton-Scale Expts.

(LEGEND, CUPID, nEXO, etc)

[KamLAND-Zen Coll. (Abe *et al*), 2203.02139 [hep-ex]]

Limits on Majorana mass $m_{\beta\beta}$

- Assuming light neutrino exchange:
- Use phenomenological NME range to convert to limits on $m_{\beta\beta}$ for ^{76}Ge combined result

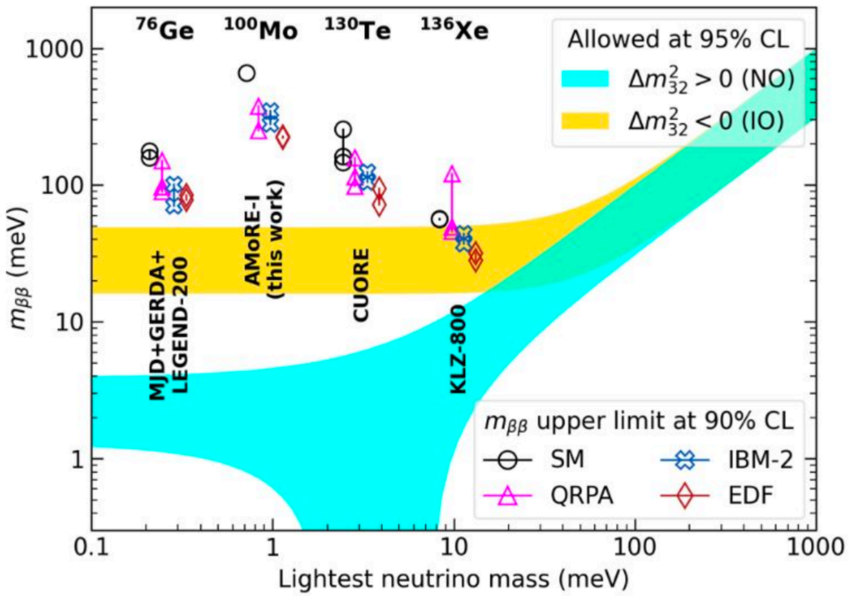
$$s \propto \epsilon\, \mathcal{E}\, \underbrace{\mathcal{G}^{0\nu} g_A^4 \left|\mathcal{M}^{0\nu}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2}_{\Gamma_{1/2} = (T_{1/2}^{0\nu})^{-1}}$$

phenom. NME: $2.35 - 6.34$

$$m_{\beta\beta} < 70 - 200\,\mathrm{meV}$$

PRELIMINARY

(Plot shows result prior to new unblinding but only minor difference.)



A. Agrawal et al., Eur. Phys. J. C **85**, 9 (2025).

- **KLZ-800 leading charge into ν mass IO**
  → other experiments to follow in next few years!

Louis Varriano | 0νββ experiments | 18 March 2025

24

[L. Varriano at 2025 APS Meeting]

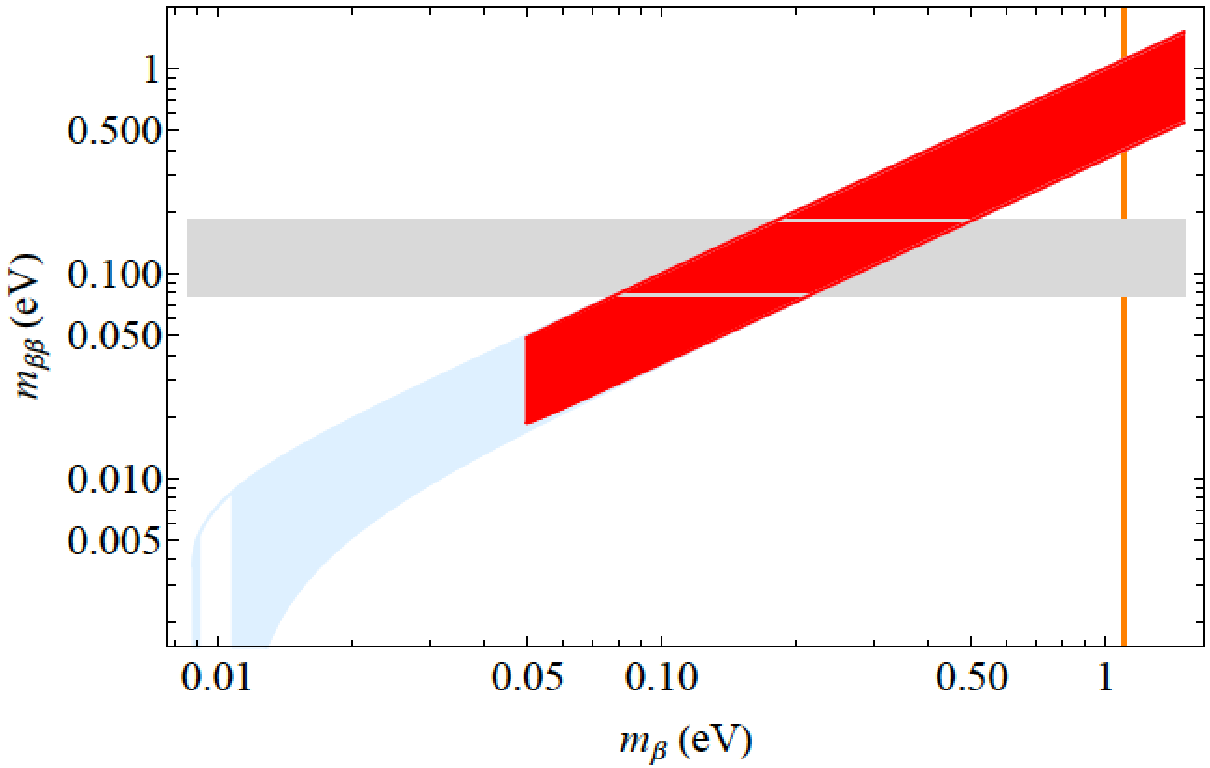


FIG. 5: $m_{\beta\beta}$ as a function of m_β, for both the normal (lighter, blue) and inverted (darker, red) mass orderings. The bands are a consequence of allowing for all possible values of the relative Majorana phases. For everything else, we use the current best-fit values of the oscillation parameters from [29]. The whited-out region inside the light-blue contour is meant to highlight the values of m_β for which $m_{\beta\beta}$ can vanish exactly. We assume the neutrinos are Majorana fermions. If neutrinos are Dirac fermions, $m_{\beta\beta} = 0$. The grey, horizontal band corresponds to the 95% CL upper bound on $m_{\beta\beta}$ from GERDA [37]. The width of the band is a consequence of uncertainties in the nuclear matrix element for the neutrinoless double-beta decay of ^{76}Ge. The vertical line corresponds to the current 90% upper bound on m_β [56].

[Formaggio, AdG, Robertson, Phys.Rept. 914 (2021)]

Caveats for $0\nu\beta\beta$ as input for neutrino masses

- Indirect probe of neutrino mass;
- Only works if the neutrinos are Majorana fermions;
- Model dependent. While a nonzero rate for $0\nu\beta\beta$ implies neutrinos are (massive) Majorana fermions, the connection to nonzero neutrino masses can be very indirect. How do we learn that we are measuring what we think we are measuring?
- Real life is hard. Large uncertainties in translating the half-life to the effective neutrino mass (nuclear matrix elements).

What Else is There?

1. How about other searches for lepton number violation? Can they ever be competitive? How?

2. Are there other ways to tell whether the neutrinos are Majorana or Dirac fermions?

How about other searches for lepton number violation? Can they ever be competitive? How?

There are two major challenges one must face before embracing other searches for lepton number violation (LNV).

1. **Constraints from searches for $0\nu\beta\beta$ are too strong.** There is an "easy" way out: play with the flavor structure of the LNV physics.
2. **Neutrino masses are very small. Majorana neutrino masses are a consequence of LNV physics.** The relation between the LNV physics and the neutrino masses, however, is indirect so the real question is whether there are scenarios where LNV is accessible to laboratory experiments while, at the same time, the neutrino masses are tiny.

TOTAL LEPTON NUMBER

Violation of total lepton number conservation also implies violation of lepton family number conservation.

$\Gamma(Z \to pe)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to p\mu)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 95%
limit on $\mu^- \to e^+$ conversion		
$\sigma(\mu^- \, ^{32}\mathrm{S} \to e^+ \, ^{32}\mathrm{Si}^*)$ / $\sigma(\mu^- \, ^{32}\mathrm{S} \to \nu_\mu \, ^{32}\mathrm{P}^*)$		$<9 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- \, ^{127}\mathrm{I} \to e^+ \, ^{127}\mathrm{Sb}^*)$ / $\sigma(\mu^- \, ^{127}\mathrm{I} \to$ anything)		$<3 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- \mathrm{Ti} \to e^+ \mathrm{Ca})$ / $\sigma(\mu^- \mathrm{Ti} \to$ capture)		$<3.6 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \to e^+ \pi^- \pi^-)/\Gamma_{total}$		$<2.0 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \mu^+ \pi^- \pi^-)/\Gamma_{total}$		$<3.9 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to e^+ \pi^- K^-)/\Gamma_{total}$		$<3.2 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to e^+ K^- K^-)/\Gamma_{total}$		$<3.3 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \mu^+ \pi^- K^-)/\Gamma_{total}$		$<4.8 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \mu^+ K^- K^-)/\Gamma_{total}$		$<4.7 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to p \mu^- \mu^-)/\Gamma_{total}$		$<4.4 \times 10^{-7}$, CL = 90%
$\Gamma(\tau^- \to \overline{p} \mu^+ \mu^-)/\Gamma_{total}$		$<3.3 \times 10^{-7}$, CL = 90%
$\Gamma(\tau^- \to \overline{p} \gamma)/\Gamma_{total}$		$<3.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p} \pi^0)/\Gamma_{total}$		$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p} 2\pi^0)/\Gamma_{total}$		$<3.3 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p} \eta)/\Gamma_{total}$		$<8.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p} \pi^0 \eta)/\Gamma_{total}$		$<2.7 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \Lambda \pi^-)/\Gamma_{total}$		$<7.2 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \overline{\Lambda} \pi^-)/\Gamma_{total}$		$<1.4 \times 10^{-7}$, CL = 90%
$t_{1/2}(\, ^{76}\mathrm{Ge} \to \, ^{76}\mathrm{Se} + 2\, e^-)$		$>1.9 \times 10^{25}$ yr, CL = 90%
$\Gamma(\pi^+ \to \mu^+ \overline{\nu}_e)/\Gamma_{total}$	[q]	$<1.5 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^- \mu^+ e^+)/\Gamma_{total}$		$<5.0 \times 10^{-10}$, CL = 90%
$\Gamma(K^+ \to \pi^- e^+ e^+)/\Gamma_{total}$		$<6.4 \times 10^{-10}$, CL = 90%
$\Gamma(K^+ \to \pi^- \mu^+ \mu^+)/\Gamma_{total}$	[q]	$<1.1 \times 10^{-9}$, CL = 90%
$\Gamma(K^+ \to \mu^+ \overline{\nu}_e)/\Gamma_{total}$	[q]	$<3.3 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^0 e^+ \overline{\nu}_e)/\Gamma_{total}$		$<3 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to \pi^- 2e^+)/\Gamma_{total}$		$<1.1 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to \pi^- 2\mu^+)/\Gamma_{total}$		$<2.2 \times 10^{-8}$, CL = 90%
$\Gamma(D^+ \to \pi^- e^+ \mu^+)/\Gamma_{total}$		$<2.0 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to \rho^- 2\mu^+)/\Gamma_{total}$		$<5.6 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^- 2e^+)/\Gamma_{total}$		$<9 \times 10^{-7}$, CL = 90%
$\Gamma(D^+ \to K^- 2\mu^+)/\Gamma_{total}$		$<1.0 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to K^- e^+ \mu^+)/\Gamma_{total}$		$<1.9 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to K^*(892)^- 2\mu^+)/\Gamma_{total}$		$<8.5 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2\pi^- 2e^+ + \text{c.c.})/\Gamma_{total}$		$<1.12 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2\pi^- 2\mu^+ + \text{c.c.})/\Gamma_{total}$		$<2.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to K^- \pi^- 2e^+ + \text{c.c.})/\Gamma_{total}$		$<2.06 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to K^- \pi^- 2\mu^+ + \text{c.c.})/\Gamma_{total}$		$<3.9 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^- 2e^+ + \text{c.c.})/\Gamma_{total}$		$<1.52 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^- 2\mu^+ + \text{c.c.})/\Gamma_{total}$		$<9.4 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \pi^- \pi^- e^+ \mu^+ + \text{c.c.})/\Gamma_{total}$		$<7.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to K^- \pi^- e^+ \mu^+ + \text{c.c.})/\Gamma_{total}$		$<2.18 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^- e^+ \mu^+ + \text{c.c.})/\Gamma_{total}$		$<5.7 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to p e^-)/\Gamma_{total}$	[r]	$<1.0 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \overline{p} e^+)/\Gamma_{total}$	[s]	$<1.1 \times 10^{-5}$, CL = 90%
$\Gamma(D_s^+ \to \pi^- 2e^+)/\Gamma_{total}$		$<4.1 \times 10^{-6}$, CL = 90%
$\Gamma(D_s^+ \to \pi^- 2\mu^+)/\Gamma_{total}$		$<1.2 \times 10^{-7}$, CL = 90%
$\Gamma(D_s^+ \to \pi^- e^+ \mu^+)/\Gamma_{total}$		$<8.4 \times 10^{-6}$, CL = 90%
$\Gamma(D_s^+ \to K^- 2e^+)/\Gamma_{total}$		$<5.2 \times 10^{-6}$, CL = 90%
$\Gamma(D_s^+ \to K^- 2\mu^+)/\Gamma_{total}$		$<1.3 \times 10^{-5}$, CL = 90%
$\Gamma(D_s^+ \to K^- e^+ \mu^+)/\Gamma_{total}$		$<6.1 \times 10^{-6}$, CL = 90%
$\Gamma(D_s^+ \to K^*(892)^- 2\mu^+)/\Gamma_{total}$		$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to \pi^- e^+ e^+)/\Gamma_{total}$		$<2.3 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \pi^- \mu^+ \mu^+)/\Gamma_{total}$		$<4.0 \times 10^{-9}$, CL = 95%
$\Gamma(B^+ \to \pi^- e^+ \mu^+)/\Gamma_{total}$		$<1.5 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to \rho^- e^+ e^+)/\Gamma_{total}$		$<1.7 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to \rho^- \mu^+ \mu^+)/\Gamma_{total}$		$<4.2 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to \rho^- e^+ \mu^+)/\Gamma_{total}$		$<4.7 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to K^- e^+ e^+)/\Gamma_{total}$		$<3.0 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to K^- \mu^+ \mu^+)/\Gamma_{total}$		$<4.1 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to K^- e^+ \mu^+)/\Gamma_{total}$		$<1.6 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to K^*(892)^- e^+ e^+)/\Gamma_{total}$		$<4.0 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to K^*(892)^- \mu^+ \mu^+)/\Gamma_{total}$		$<5.9 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to K^*(892)^- e^+ \mu^+)/\Gamma_{total}$		$<3.0 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to D^- e^+ e^+)/\Gamma_{total}$		$<2.6 \times 10^{-6}$, CL = 90%
$\Gamma(B^+ \to D^- e^+ \mu^+)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 90%
$\Gamma(B^+ \to D^- \mu^+ \mu^+)/\Gamma_{total}$		$<6.9 \times 10^{-7}$, CL = 95%
$\Gamma(B^+ \to D^{*-} \mu^+ \mu^+)/\Gamma_{total}$		$<2.4 \times 10^{-6}$, CL = 95%
$\Gamma(B^+ \to D_s^- \mu^+ \mu^+)/\Gamma_{total}$		$<5.8 \times 10^{-7}$, CL = 95%
$\Gamma(B^+ \to \overline{D}^0 \pi^- \mu^+ \mu^+)/\Gamma_{total}$		$<1.5 \times 10^{-6}$, CL = 95%
$\Gamma(B^+ \to \Lambda^0 \mu^+)/\Gamma_{total}$		$<6 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \Lambda^0 e^+)/\Gamma_{total}$		$<3.2 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \overline{\Lambda}^0 \mu^+)/\Gamma_{total}$		$<6 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \overline{\Lambda}^0 e^+)/\Gamma_{total}$		$<8 \times 10^{-8}$, CL = 90%

TOTAL LEPTON NUMBER

Violation of total lepton number conservation also implies violation of lepton family number conservation.

$\Gamma(Z \to pe)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to p\mu)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 95%
limit on $\mu^- \to e^+$ conversion		
$\sigma(\mu^- \, {}^{32}S \to e^+ \, {}^{32}Si^*)$ / $\sigma(\mu^- \, {}^{32}S \to \nu_\mu \, {}^{32}P^*)$		$<9 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- \, {}^{127}I \to e^+ \, {}^{127}Sb^*)$ / $\sigma(\mu^- \, {}^{127}I \to$ anything)		$<3 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- Ti \to e^+ Ca)$ / $\sigma(\mu^- Ti \to$ capture)		$<3.6 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \to e^+\pi^-\pi^-)/\Gamma_{total}$		$<2.0 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \mu^+\pi^-\pi^-)/\Gamma_{total}$		$<3.9 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to e^+\pi^-K^-)/\Gamma_{total}$		$<3.2 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to e^+K^-K^-)/\Gamma_{total}$		$<3.3 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \mu^+\pi^-K^-)/\Gamma_{total}$		$<4.8 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \mu^+K^-K^-)/\Gamma_{total}$		$<4.7 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to p\mu^-\mu^-)/\Gamma_{total}$		$<4.4 \times 10^{-7}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\mu^+\mu^-)/\Gamma_{total}$		$<3.3 \times 10^{-7}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\gamma)/\Gamma_{total}$		$<3.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\pi^0)/\Gamma_{total}$		$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}2\pi^0)/\Gamma_{total}$		$<3.3 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\eta)/\Gamma_{total}$		$<8.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\pi^0\eta)/\Gamma_{total}$		$<2.7 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \Lambda\pi^-)/\Gamma_{total}$		$<7.2 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \Lambda\pi^-)/\Gamma_{total}$		$<1.4 \times 10^{-7}$, CL = 90%
$t_{1/2}({}^{76}Ge \to {}^{76}Se + 2\,e^-)$ $\Leftarrow$ $0\nu\beta\beta$		$>1.9 \times 10^{25}$ yr, CL = 90%
$\Gamma(\pi^+ \to \mu^+\overline{\nu}_e)/\Gamma_{total}$	[q]	$<1.5 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^-\mu^+e^+)/\Gamma_{total}$		$<5.0 \times 10^{-10}$, CL = 90%
$\Gamma(K^+ \to \pi^-e^+e^+)/\Gamma_{total}$		$<6.4 \times 10^{-10}$, CL = 90%
$\Gamma(K^+ \to \pi^-\mu^+\mu^+)/\Gamma_{total}$	[q]	$<1.1 \times 10^{-9}$, CL = 90%
$\Gamma(K^+ \to \mu^+\overline{\nu}_e)/\Gamma_{total}$	[q]	$<3.3 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^0e^+\overline{\nu}_e)/\Gamma_{total}$		$<3 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to \pi^-2e^+)/\Gamma_{total}$		$<1.1 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to \pi^-2\mu^+)/\Gamma_{total}$		$<2.2 \times 10^{-8}$, CL = 90%
$\Gamma(D^+ \to \pi^-e^+\mu^+)/\Gamma_{total}$		$<2.0 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to \rho^-2\mu^+)/\Gamma_{total}$		$<5.6 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^-2e^+)/\Gamma_{total}$		$<9 \times 10^{-7}$, CL = 90%
$\Gamma(D^+ \to K^-2\mu^+)/\Gamma_{total}$		$<1.0 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to K^-e^+\mu^+)/\Gamma_{total}$		$<1.9 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to K^*(892)^-2\mu^+)/\Gamma_{total}$		$<8.5 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2\pi^-2e^+ + c.c.)/\Gamma_{total}$		$<1.12 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2\pi^-2\mu^+ + c.c.)/\Gamma_{total}$		$<2.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to K^-\pi^-2e^+ + c.c.)/\Gamma_{total}$		$<2.06 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to K^-\pi^-2\mu^+ + c.c.)/\Gamma_{total}$		$<3.9 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^-2e^+ + c.c.)/\Gamma_{total}$		$<1.52 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^-2\mu^+ + c.c.)/\Gamma_{total}$		$<9.4 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \pi^-\pi^-e^+\mu^+ + c.c.)/\Gamma_{total}$		$<7.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to K^-\pi^-e^+\mu^+ + c.c.)/\Gamma_{total}$		$<2.18 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^-e^+\mu^+ + c.c.)/\Gamma_{total}$		$<5.7 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to pe^-)/\Gamma_{total}$	[r]	$<1.0 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \overline{p}e^+)/\Gamma_{total}$	[s]	$<1.1 \times 10^{-5}$, CL = 90%
$\Gamma(D_s^+ \to \pi^-2e^+)/\Gamma_{total}$		$<4.1 \times 10^{-6}$, CL = 90%
$\Gamma(D_s^+ \to \pi^-2\mu^+)/\Gamma_{total}$		$<1.2 \times 10^{-7}$, CL = 90%
$\Gamma(D_s^+ \to \pi^-e^+\mu^+)/\Gamma_{total}$		$<8.4 \times 10^{-6}$, CL = 90%
$\Gamma(D_s^+ \to K^-2e^+)/\Gamma_{total}$		$<5.2 \times 10^{-6}$, CL = 90%
$\Gamma(D_s^+ \to K^-2\mu^+)/\Gamma_{total}$		$<1.3 \times 10^{-5}$, CL = 90%
$\Gamma(D_s^+ \to K^-e^+\mu^+)/\Gamma_{total}$		$<6.1 \times 10^{-6}$, CL = 90%
$\Gamma(D_s^+ \to K^*(892)^-2\mu^+)/\Gamma_{total}$		$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to \pi^-e^+e^+)/\Gamma_{total}$		$<2.3 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \pi^-\mu^+\mu^+)/\Gamma_{total}$		$<4.0 \times 10^{-9}$, CL = 95%
$\Gamma(B^+ \to \pi^-e^+\mu^+)/\Gamma_{total}$		$<1.5 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to \rho^-e^+e^+)/\Gamma_{total}$		$<1.7 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to \rho^-\mu^+\mu^+)/\Gamma_{total}$		$<4.2 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to \rho^-e^+\mu^+)/\Gamma_{total}$		$<4.7 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to K^-e^+e^+)/\Gamma_{total}$		$<3.0 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to K^-\mu^+\mu^+)/\Gamma_{total}$		$<4.1 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to K^-e^+\mu^+)/\Gamma_{total}$		$<1.6 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to K^*(892)^-e^+e^+)/\Gamma_{total}$		$<4.0 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to K^*(892)^-\mu^+\mu^+)/\Gamma_{total}$		$<5.9 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to K^*(892)^-e^+\mu^+)/\Gamma_{total}$		$<3.0 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to D^-e^+e^+)/\Gamma_{total}$		$<2.6 \times 10^{-6}$, CL = 90%
$\Gamma(B^+ \to D^-e^+\mu^+)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 90%
$\Gamma(B^+ \to D^-\mu^+\mu^+)/\Gamma_{total}$		$<6.9 \times 10^{-7}$, CL = 95%
$\Gamma(B^+ \to D^{*-}\mu^+\mu^+)/\Gamma_{total}$		$<2.4 \times 10^{-6}$, CL = 95%
$\Gamma(B^+ \to D_s^-\mu^+\mu^+)/\Gamma_{total}$		$<5.8 \times 10^{-7}$, CL = 95%
$\Gamma(B^+ \to \overline{D}^0\pi^-\mu^+\mu^+)/\Gamma_{total}$		$<1.5 \times 10^{-6}$, CL = 95%
$\Gamma(B^+ \to \Lambda^0\mu^+)/\Gamma_{total}$		$<6 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \Lambda^0e^+)/\Gamma_{total}$		$<3.2 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \overline{\Lambda}^0\mu^+)/\Gamma_{total}$		$<6 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \overline{\Lambda}^0e^+)/\Gamma_{total}$		$<8 \times 10^{-8}$, CL = 90%

TOTAL LEPTON NUMBER

Violation of total lepton number conservation also implies violation of lepton family number conservation.

$\Gamma(Z \to pe)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to p\mu)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 95%
limit on $\mu^- \to e^+$ conversion		
$\sigma(\mu^- {}^{32}S \to e^+ {}^{32}Si^*)$ / $\sigma(\mu^- {}^{32}S \to \nu_\mu {}^{32}P^*)$		$<9 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- {}^{127}I \to e^+ {}^{127}Sb^*)$ / $\sigma(\mu^- {}^{127}I \to$ anything)		$<3 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- Ti \to e^+ Ca)$ / $\sigma(\mu^- Ti \to$ capture)		$<3.6 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \to e^+\pi^-\pi^-)/\Gamma_{total}$		$<2.0 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \mu^+\pi^-\pi^-)/\Gamma_{total}$		
$\Gamma(\tau^- \to e^+\pi^-K^-)/\Gamma_{total}$		
$\Gamma(\tau^- \to e^+K^-K^-)/\Gamma_{total}$		
$\Gamma(\tau^- \to \mu^+\pi^-K^-)/\Gamma_{total}$		
$\Gamma(\tau^- \to \mu^+K^-K^-)/\Gamma_{total}$		
$\Gamma(\tau^- \to p\mu^-\mu^-)/\Gamma_{total}$		
$\Gamma(\tau^- \to \overline{p}\mu^+\mu^-)/\Gamma_{total}$		
$\Gamma(\tau^- \to \overline{p}\gamma)/\Gamma_{total}$		
$\Gamma(\tau^- \to \overline{p}\pi^0)/\Gamma_{total}$		
$\Gamma(\tau^- \to \overline{p}2\pi^0)/\Gamma_{total}$		
$\Gamma(\tau^- \to \overline{p}\eta)/\Gamma_{total}$		
$\Gamma(\tau^- \to \overline{p}\pi^0\eta)/\Gamma_{total}$		
$\Gamma(\tau^- \to \Lambda\pi^-)/\Gamma_{total}$		
$\Gamma(\tau^- \to \overline{\Lambda}\pi^-)/\Gamma_{total}$		
$t_{1/2}({}^{76}Ge \to {}^{76}Se + 2e^-)$		
$\Gamma(\pi^+ \to \mu^+\overline{\nu}_e)/\Gamma_{total}$		
$\Gamma(K^+ \to \pi^-\mu^+e^+)/\Gamma_{total}$		
$\Gamma(K^+ \to \pi^-e^+e^+)/\Gamma_{total}$		
$\Gamma(K^+ \to \pi^-\mu^+\mu^+)/\Gamma_{total}$	[q]	$<1.1 \times 10^{-9}$, CL = 90%
$\Gamma(K^+ \to \mu^+\overline{\nu}_e)/\Gamma_{total}$	[q]	$<3.3 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^0e^+\overline{\nu}_e)/\Gamma_{total}$		$<3 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to \pi^-2e^+)/\Gamma_{total}$		$<1.1 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to \pi^-2\mu^+)/\Gamma_{total}$		$<2.2 \times 10^{-8}$, CL = 90%
$\Gamma(D^+ \to \pi^-e^+\mu^+)/\Gamma_{total}$		$<2.0 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to \rho^-2\mu^+)/\Gamma_{total}$		$<5.6 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^-2e^+)/\Gamma_{total}$		$<9 \times 10^{-7}$, CL = 90%
$\Gamma(D^+ \to K^-2\mu^+)/\Gamma_{total}$		$<1.0 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to K^-e^+\mu^+)/\Gamma_{total}$		$<1.9 \times 10^{-6}$, CL = 90%

$\Gamma(B^0 \to \Lambda_c^+\mu^-)/\Gamma_{total}$	$<1.4 \times 10^{-6}$, CL = 90%
$\Gamma(B^0 \to \Lambda_c^+e^-)/\Gamma_{total}$	$<4 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to \pi^+e^-)/\Gamma_{total}$	$<6 \times 10^{-7}$, CL = 90%
$\Gamma(\Lambda \to \pi^+\mu^-)/\Gamma_{total}$	$<6 \times 10^{-7}$, CL = 90%
$\Gamma(\Lambda \to \pi^-e^+)/\Gamma_{total}$	$<4 \times 10^{-7}$, CL = 90%
$\Gamma(\Lambda \to \pi^-\mu^+)/\Gamma_{total}$	$<6 \times 10^{-7}$, CL = 90%
$\Gamma(\Lambda \to K^+e^-)/\Gamma_{total}$	$<2 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to K^+\mu^-)/\Gamma_{total}$	$<3 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to K^-e^+)/\Gamma_{total}$	$<2 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to K^-\mu^+)/\Gamma_{total}$	$<3 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to K_S^0\nu)/\Gamma_{total}$	$<2 \times 10^{-5}$, CL = 90%
$\Gamma(\Xi^- \to p\mu^-\mu^-)/\Gamma_{total}$	$<4 \times 10^{-8}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \overline{p}2e^+)/\Gamma_{total}$	$<2.7 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \overline{p}2\mu^+)/\Gamma_{total}$	$<9.4 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \overline{p}e^+\mu^+)/\Gamma_{total}$	$<1.6 \times 10^{-5}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \Sigma^-\mu^+\mu^+)/\Gamma_{total}$	$<7.0 \times 10^{-4}$, CL = 90%

$\Gamma(D^+ \to K^*(892)^-2\mu^+)/\Gamma_{total}$		$<8.5 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2\pi^-2e^+ + c.c.)/\Gamma_{total}$		$<1.12 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2\pi^-2\mu^+ + c.c.)/\Gamma_{total}$		$<2.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to K^-\pi^-2e^+ + c.c.)/\Gamma_{total}$		$<2.06 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to K^-\pi^-2\mu^+ + c.c.)/\Gamma_{total}$		$<3.9 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^-2e^+ + c.c.)/\Gamma_{total}$		$<1.52 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^-2\mu^+ + c.c.)/\Gamma_{total}$		$<9.4 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \pi^-\pi^-e^+\mu^+ + c.c.)/\Gamma_{total}$		$<7.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to K^-\pi^-e^+\mu^+ + c.c.)/\Gamma_{total}$		$<2.18 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^-e^+\mu^+ + c.c.)/\Gamma_{total}$		$<5.7 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to pe^-)/\Gamma_{total}$	[r]	$<1.0 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \overline{p}e^+)/\Gamma_{total}$	[s]	$<1.1 \times 10^{-5}$, CL = 90%
$\Gamma(D_s^+ \to \pi^-2e^+)/\Gamma_{total}$		$<4.1 \times 10^{-6}$, CL = 90%
		$<1.2 \times 10^{-7}$, CL = 90%
		$<8.4 \times 10^{-6}$, CL = 90%
		$<5.2 \times 10^{-6}$, CL = 90%
		$<1.3 \times 10^{-5}$, CL = 90%
		$<6.1 \times 10^{-6}$, CL = 90%
		$<1.4 \times 10^{-3}$, CL = 90%
		$<2.3 \times 10^{-8}$, CL = 90%
		$<4.0 \times 10^{-9}$, CL = 95%
		$<1.5 \times 10^{-7}$, CL = 90%
		$<1.7 \times 10^{-7}$, CL = 90%
		$<4.2 \times 10^{-7}$, CL = 90%
		$<4.7 \times 10^{-7}$, CL = 90%
		$<3.0 \times 10^{-8}$, CL = 90%
		$<4.1 \times 10^{-8}$, CL = 90%
		$<1.6 \times 10^{-7}$, CL = 90%
		$<4.0 \times 10^{-7}$, CL = 90%
		$<5.9 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to K^*(892)^-e^+\mu^+)/\Gamma_{total}$		$<3.0 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to D^-e^+e^+)/\Gamma_{total}$		$<2.6 \times 10^{-6}$, CL = 90%
$\Gamma(B^+ \to D^-e^+\mu^+)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 90%
$\Gamma(B^+ \to D^-\mu^+\mu^+)/\Gamma_{total}$		$<6.9 \times 10^{-7}$, CL = 95%
$\Gamma(B^+ \to D^{*-}\mu^+\mu^+)/\Gamma_{total}$		$<2.4 \times 10^{-6}$, CL = 95%
$\Gamma(B^+ \to D_s^-\mu^+\mu^+)/\Gamma_{total}$		$<5.8 \times 10^{-7}$, CL = 95%
$\Gamma(B^+ \to \overline{D}^0\pi^-\mu^+\mu^+)/\Gamma_{total}$		$<1.5 \times 10^{-6}$, CL = 95%
$\Gamma(B^+ \to \Lambda^0\mu^+)/\Gamma_{total}$		$<6 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \Lambda^0e^+)/\Gamma_{total}$		$<3.2 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \overline{\Lambda}^0\mu^+)/\Gamma_{total}$		$<6 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \overline{\Lambda}^0e^+)/\Gamma_{total}$		$<8 \times 10^{-8}$, CL = 90%

TOTAL LEPTON NUMBER

Violation of total lepton number conservation also implies violation of lepton family number conservation.

$\Gamma(Z \to pe)/\Gamma_{total}$	$<1.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to p\mu)/\Gamma_{total}$	$<1.8 \times 10^{-6}$, CL = 95%
⇒ limit on $\mu^- \to e^+$ conversion ⇐ (Next Best Thing)	
$\sigma(\mu^- {}^{32}\text{S} \to e^+ {}^{32}\text{Si}^*)$ / $\sigma(\mu^- {}^{32}\text{S} \to \nu_\mu {}^{32}\text{P}^*)$	$<9 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- {}^{127}\text{I} \to e^+ {}^{127}\text{Sb}^*)$ / $\sigma(\mu^- {}^{127}\text{I} \to$ anything)	$<3 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- \text{Ti} \to e^+ \text{Ca})$ / $\sigma(\mu^- \text{Ti} \to$ capture)	$<3.6 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \to e^+\pi^-\pi^-)/\Gamma_{total}$	$<2.0 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \mu^+\pi^-\pi^-)/\Gamma_{total}$	$<3.9 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to e^+\pi^-K^-)/\Gamma_{total}$	$<3.2 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to e^+K^-K^-)/\Gamma_{total}$	$<3.3 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \mu^+\pi^-K^-)/\Gamma_{total}$	$<4.8 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \mu^+K^-K^-)/\Gamma_{total}$	$<4.7 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to p\mu^-\mu^-)/\Gamma_{total}$	$<4.4 \times 10^{-7}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\mu^+\mu^-)/\Gamma_{total}$	$<3.3 \times 10^{-7}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\gamma)/\Gamma_{total}$	$<3.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\pi^0)/\Gamma_{total}$	$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}2\pi^0)/\Gamma_{total}$	$<3.3 \times 10^{-5}$, CL = 90%

Are there other ways to tell whether the neutrinos are Majorana or Dirac fermions?

The answer is a qualified 'yes.'

The qualification is that we have to know the relevant physics – new physics may spoil everything! There are no "theorems" as far as I know. . .

Again: Why Don't We Know the Answer?

Neutrino Masses are Very Small!*

In fact, except for neutrino oscillation experiments, no consequence of a nonzero neutrino mass has ever been observed in any experiment. As far as all non-oscillation neutrino experiments are concerned, neutrinos are massless fermions.

*Very small compared to what? Compared to the typical energies and momentum transfers in your experiment. Another way to think about this: neutrinos are always **ultrarelativistic** in the lab frame.

There are two ways around it:

1. Find something that only Majorana fermions know how to do [e.g. violate lepton number] or
2. **find some non-ultrarelativistic neutrinos to work with!**

The Burden of Working with Non-Ultrarelativistic Neutrinos

In a nutshell: there aren't too many of them, and the weak interactions are weak. Remember, at low energies

$$\sigma \propto E \quad \text{(or worse)}$$

On the other hand, telling Majorana From Dirac neutrinos is "trivial." Indeed, it is an order one effect.

Example: The Cosmic Neutrino Background

[see, e.g., Long, Lunardini, Sabancilar, arXiv:1405.7654]

Assuming the Standard Model of Cosmology, at least two of the three neutrinos are mostly non-relativistic today:

$$T_\nu \sim 2\text{K} \sim 2 \times 10^{-4}~\text{eV}.$$

Furthermore, it turns out that hitting a Majorana CνB with a charged-current process is easier than hitting a Dirac CνB, assuming the weak interactions. All of this is assuming one is measuring the CνB via neutrino-capture on nuclei, $\nu(Z, A) \to e^-(Z + 1, A)$ (charged-current weak interaction on matter)

When you interact with a polarized (anti)neutrino at rest, it will either choose to behave like the left-chiral component or the right-chiral component, with the same probability.

In the Dirac case, the right-chiral component of the neutrino is sterile, i.e., it does not participate in the weak interactions and you can't interact with it. Furthermore, the antineutrinos have the opposite lepton number and can't be detected via $\nu(Z, A) \to e^-(Z+1, A)$.

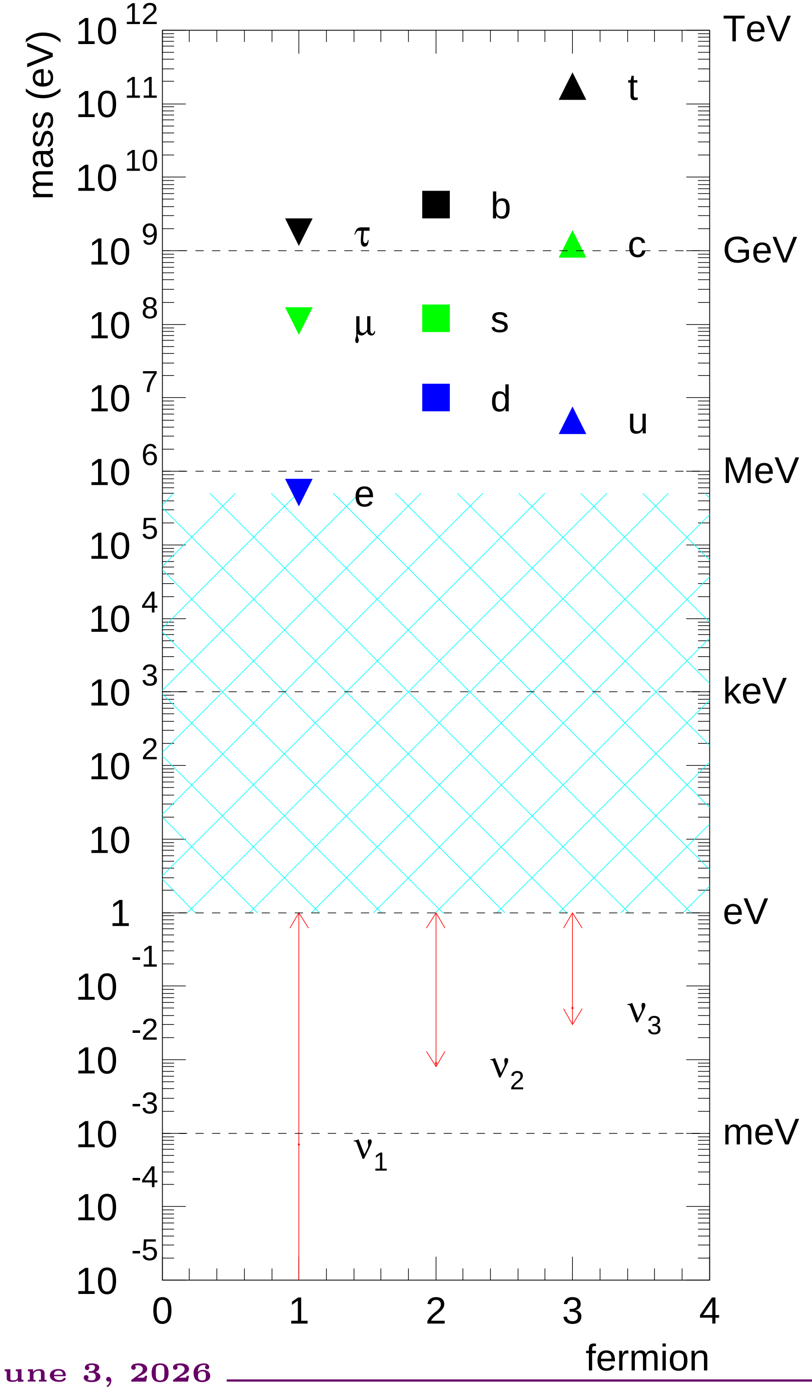
In the Majorana case, the right-chiral component knows how to produce positrons (the "antineutrino") so both can interact via the weak interactions.

When it comes to the cosmic neutrino background detected via $\nu(Z, A) \to e^-(Z+1, A)$, we get a hit from the neutrinos – just like in the Dirac case – but we also get a hit from the "antineutrino," with the same rate, since the left-chiral component of the other polarization-state knows how to produce electrons!

This means that if we ever observe the cosmic neutrino background, we can determine the nature of the neutrino. If all neutrinos were at rest, for the same neutrino (+ "antineutrino") flux, we expect twice as many events in the experiment if the neutrinos are Majorana fermions. One can easily include finite temperature effects, effects related to the neutrino mass ordering, a potential primordial lepton asymmetry, etc.

Some challenges:

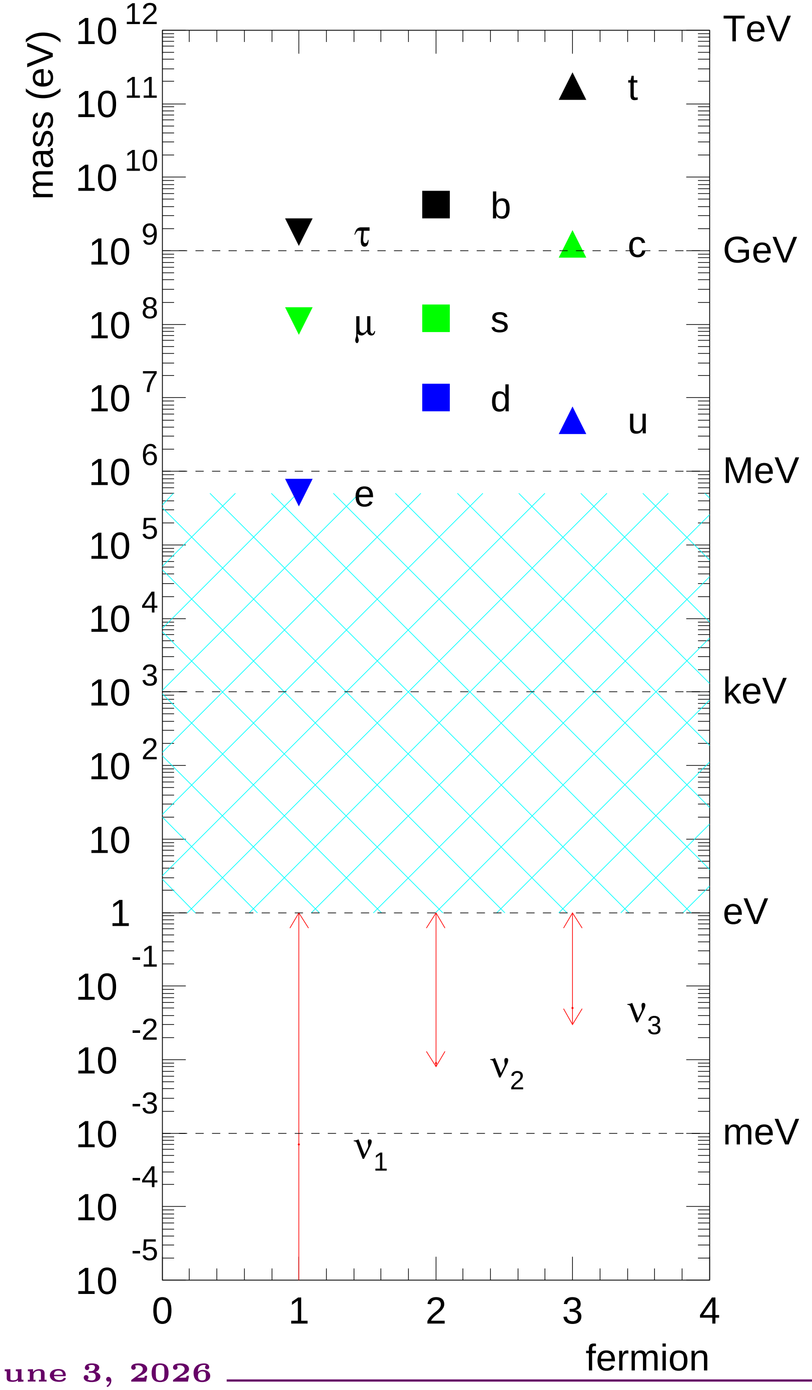
- We have never detected the cosmic neutrino background! (see, however, PTOLEMY [arXiv:1808.01892 and many uddates] for an idea that may work one day?);
- We measure flux times cross-section. While we know the average neutrino number density of the universe very well from the Standard Model of Cosmology, we don't know the number density of neutrinos *here* very well [Uncertainty around 10% so likely ok?].



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?

New Physics!

Nonzero neutrino masses imply the existence of new fundamental fields ⇒ New Particles

We know nothing about these new particles. They can be bosons or fermions, very light or very heavy, they can be charged or neutral, experimentally accessible or hopelessly out of reach…

There is only a handful of questions the standard model for particle physics cannot explain (these are personal. Feel free to complain).

- What is the physics behind electroweak symmetry breaking? (Higgs ✓).
- What is the dark matter? (not in SM).
- Why is there so much ordinary matter in the Universe? (not in SM).
- Why does the Universe appear to be accelerating? Why does it appear that the Universe underwent rapid acceleration in the past? (not in SM).

Neutrino Masses, Higgs Mechanism, and New Mass Scale of Nature

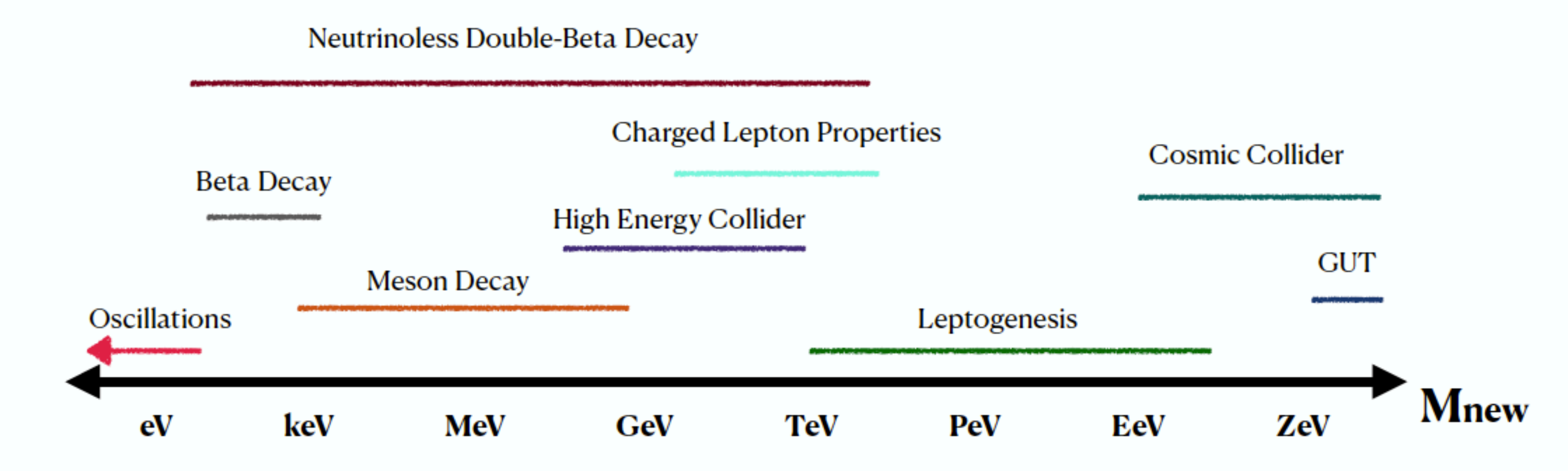
The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs doublet model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly**. And **lepton-number must be an exact symmetry** of nature (or broken very, very weakly);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking!;
3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the **seesaw mechanism**.

We are going to need a lot of experimental information from all areas of particle physics in order to figure out what is really going on!

What Is the ν Physics Scale? We Have No Idea!



Different Mass Scales Are Probed in Different Ways, Lead to Different Consequences, and Connect to Different Outstanding Issues in Fundamental Physics.

Piecing the Neutrino Mass Puzzle

Understanding the origin of neutrino masses and exploring the new physics in the lepton sector will require unique **theoretical** and **experimental** efforts ...

- understanding the fate of lepton-number. Neutrinoless double-beta decay.
- A comprehensive long-baseline neutrino program.
- Probes of neutrino properties, including neutrino scattering experiments. And what are the neutrino masses anyway? Kinematical probes.
- Precision measurements of charged-lepton properties ($g-2$, edm) and searches for rare processes ($\mu \to e$-conversion the best bet at the moment).
- Collider experiments. The LHC and beyond may end up revealing the new physics behind small neutrino masses.
- Neutrino properties affect, in a significant way, the history of the universe. These can be "seen" in cosmic surveys of all types.
- Astrophysical Neutrinos – Supernovae and other Galaxy-shattering phenomena. Ultra-high energy neutrinos and correlations with not-neutrino messengers.
- etc

Concluding Remarks

- We still **know very little** about the new physics uncovered by neutrino oscillations.

- We have only seen the impact of nonzero neutrino masses in **neutrino oscillation experiments**. These, in turn, only measure **neutrino mass-squared differences**.

- More information expected from high-precision measurements of weak decays, especially **tritium β-decay**, searches for **neutrinoless double-beta decays**, and **cosmic surveys**.

- These are **strongly complementary**. Neutrinoless double-beta decays only translated into neutrino masses if neutrinos are Majorana fermions and if there are no other sources of lepton-number violation. Cosmic surveys depend on the different ingredients that make up the universe and on neutrino properties.

- **Massive Majorana and Dirac Fermions are Qualitatively Different.** However, massless Majorana and Dirac fermions are "the same:" Majorana-versus-Dirac is a nonquestion! Since neutrinos are always ultra-relativistic, it is very difficult to address whether they are Majorana or Dirac. Neutrinos are massless as far as most experiments are concerned.

- One solution is to look for phenomena that can only occur if the neutrino is a Majorana fermion (e.g., **lepton number violation**). Even for very rare phenomena, any positive result establishes that neutrinos are Majorana fermions.

- The other way is to find **circumstances where the neutrinos are not ultra-relativistic**. In this case, the Majorana versus Dirac differences are large. The rates, on the other hand…

Backup Slides . . .