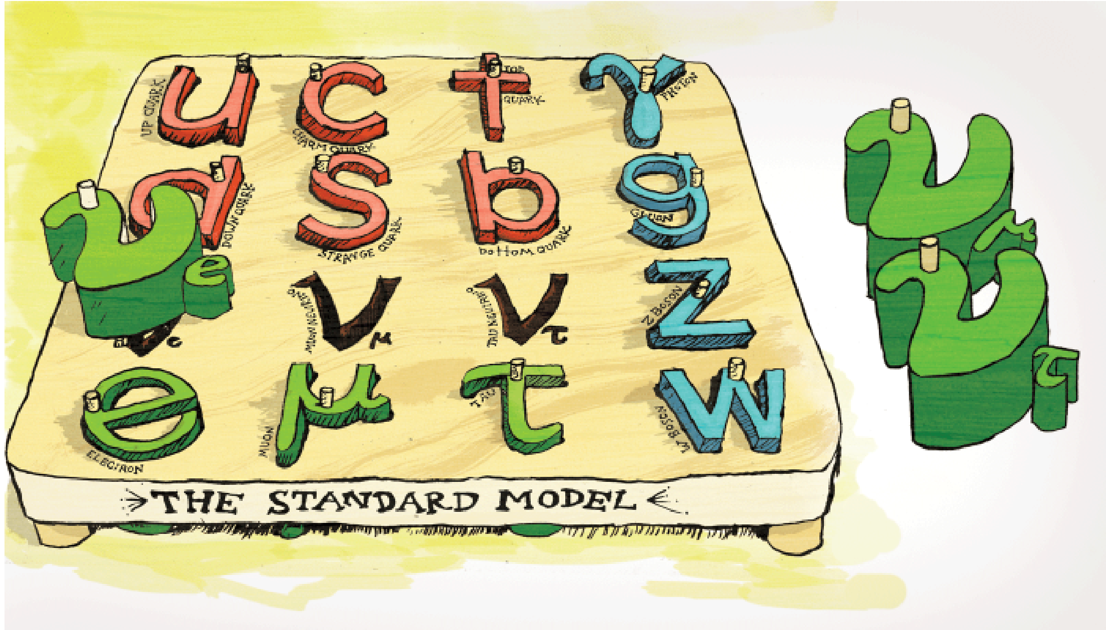
Neutrinos – Interpretations, Outlook, Ideas



André de Gouvêa – Northwestern University

ICHEP 2016 – Chicago

August 3–10, 2016

A Realistic, Reasonable, and Simple Paradigm:

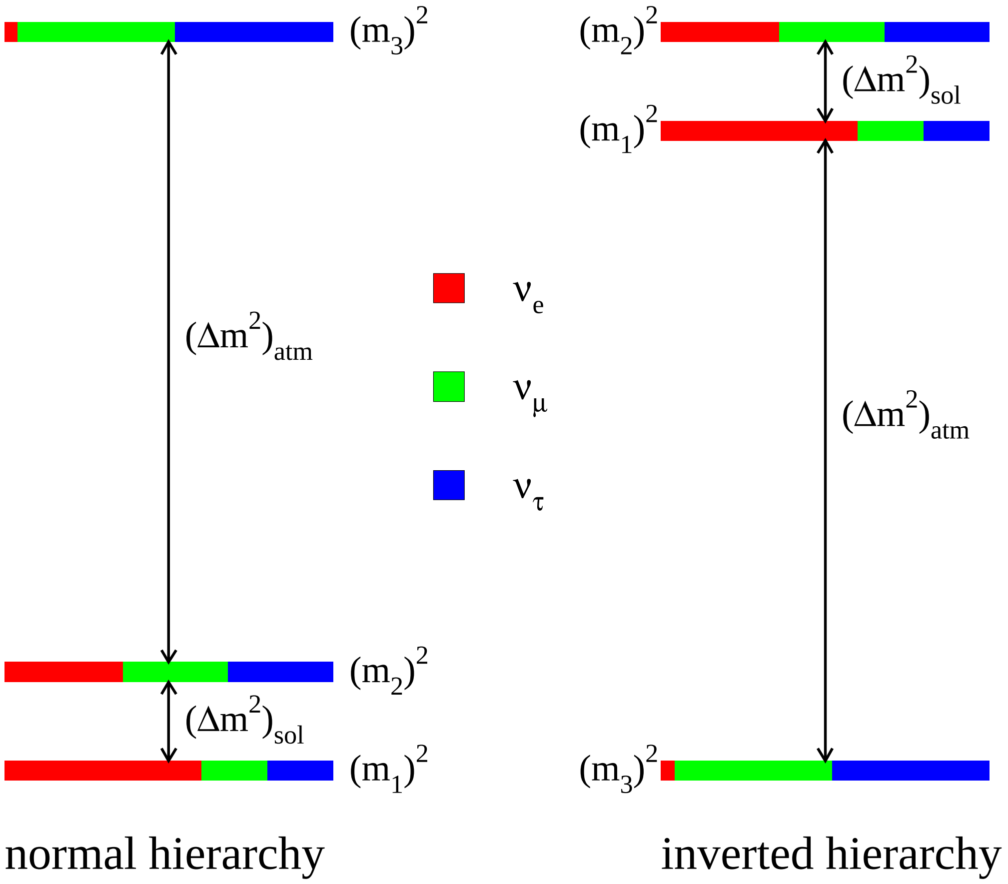
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{e\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

- $m_1^2 < m_2^2$ — $\Delta m^2_{13} < 0$ – Inverted Mass Hierarchy
- $m_2^2 - m_1^2 < |m_3^2 - m_{1,2}^2|$ — $\Delta m^2_{13} > 0$ – Normal Mass Hierarchy

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

Understanding Neutrino Oscillations: Are We There Yet?

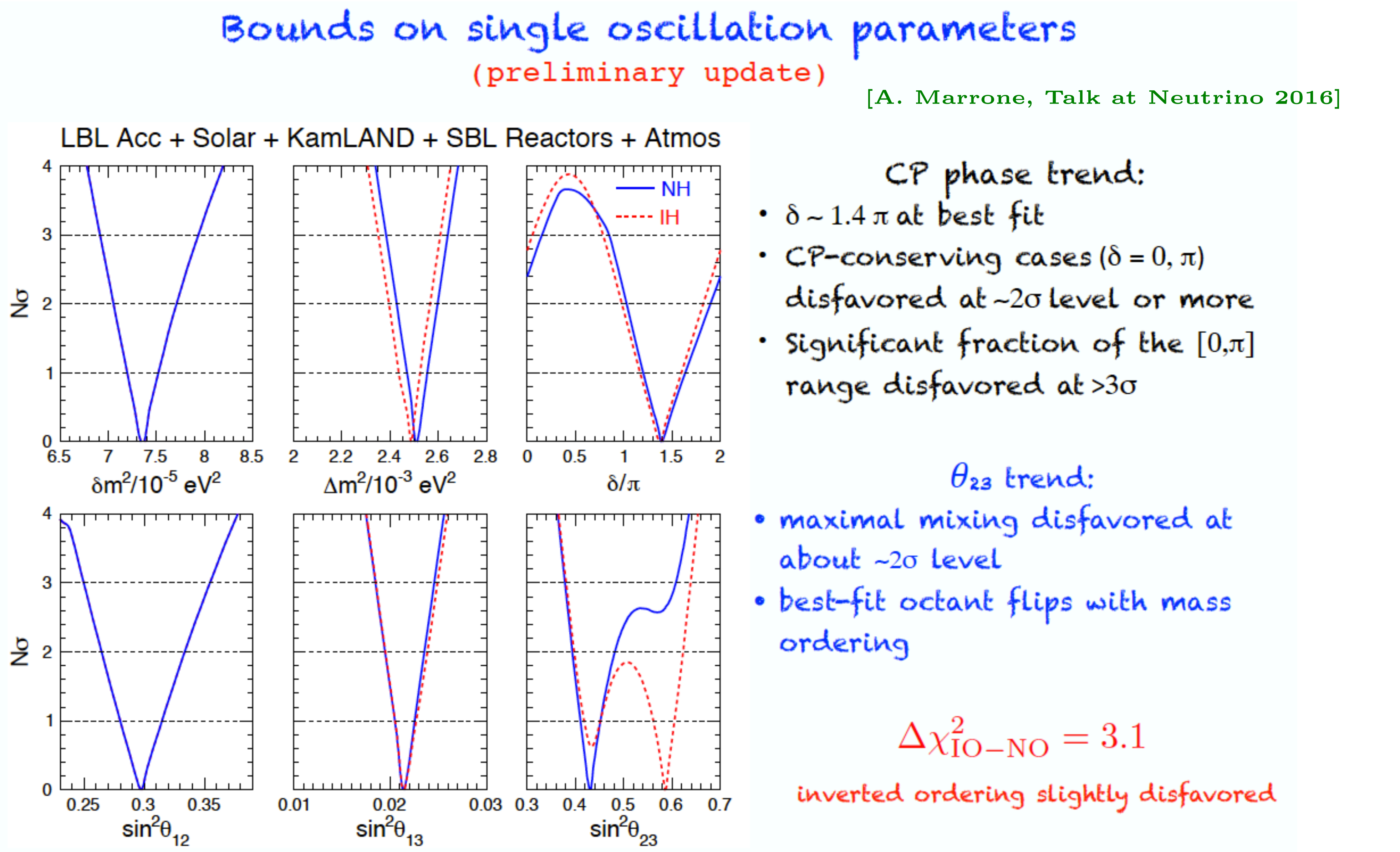


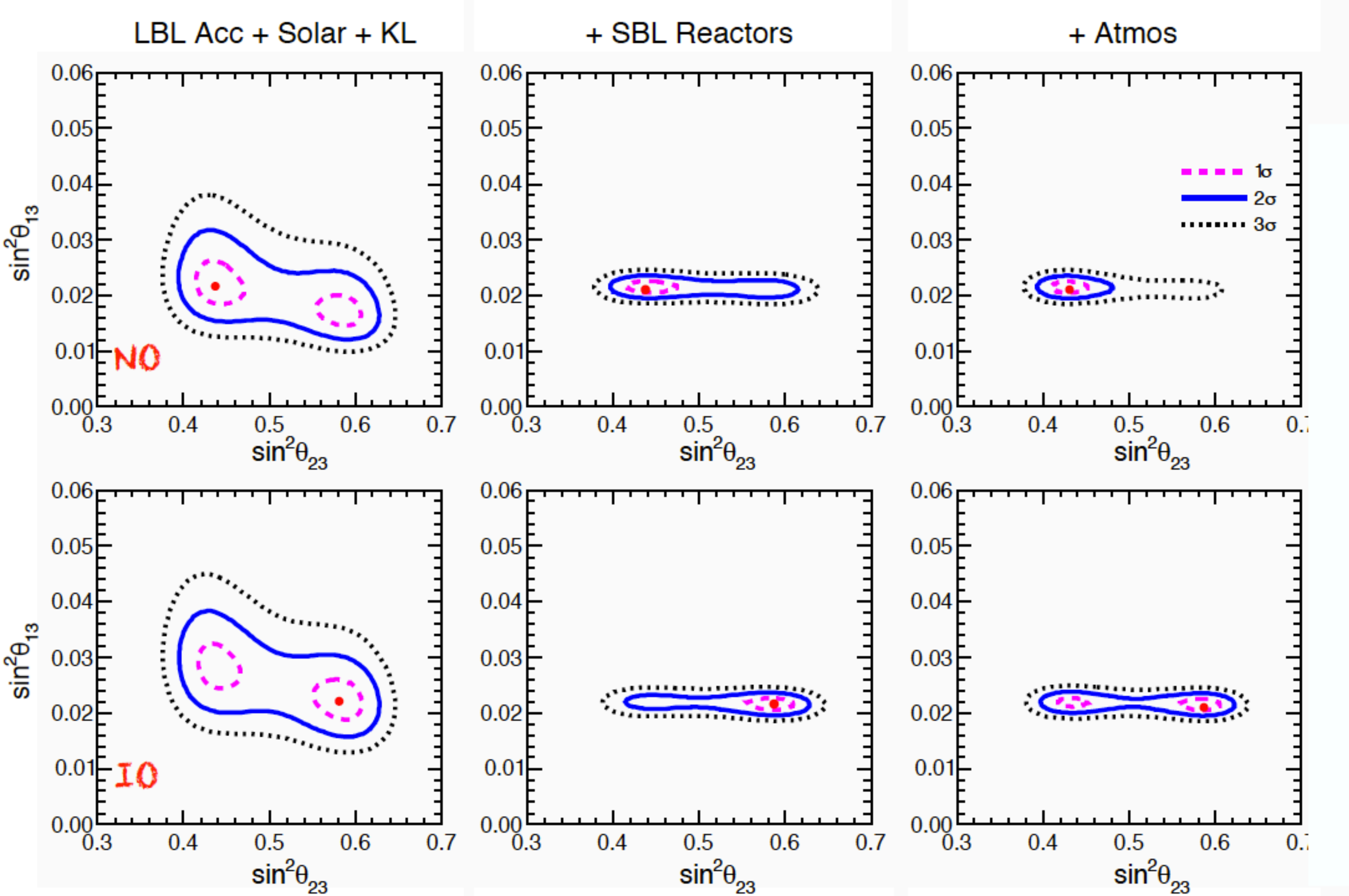
- ~~What is the ν_e component of ν_3?~~ ($\theta_{13} \neq 0$!)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?)

$\Rightarrow$ All of the above can "only" be addressed with new neutrino oscillation experiments

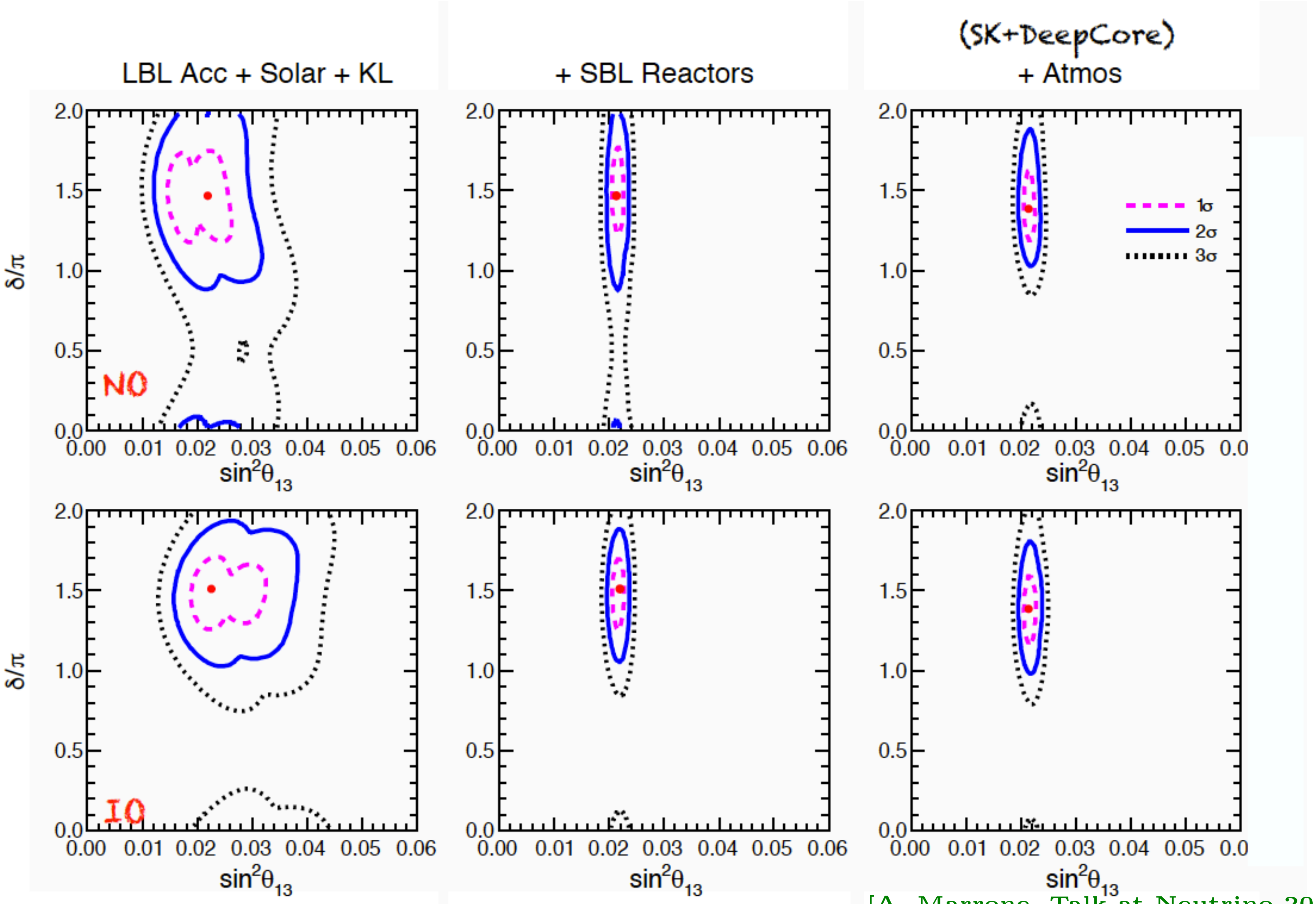
The Three-Flavor Paradigm Fits All* Data Really Well

[*modulo short-baseline anomalies, later]





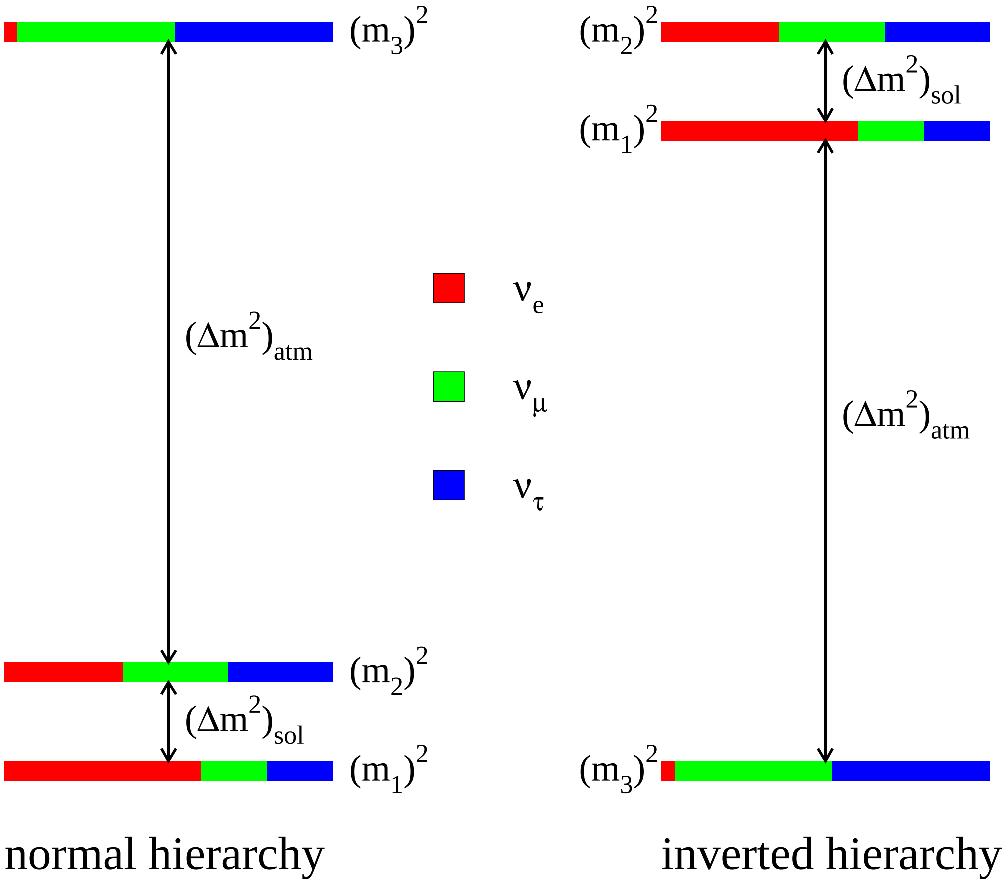
Atmospheric data do not spoil this trend but introduce some differences in the relative likelihood of the two octants in NO and IO. Octant degeneracy may show up in terms of "bumps" or "double bands" when marginalized away –> [A. Marrone, Talk at Neutrino 2016]



[A. Marrone, Talk at Neutrino 2016]

Results in the (δ, θ_{13}) plane corroborated by atmospheric data

Understanding Neutrino Oscillations: Are We There Yet? [NO!]

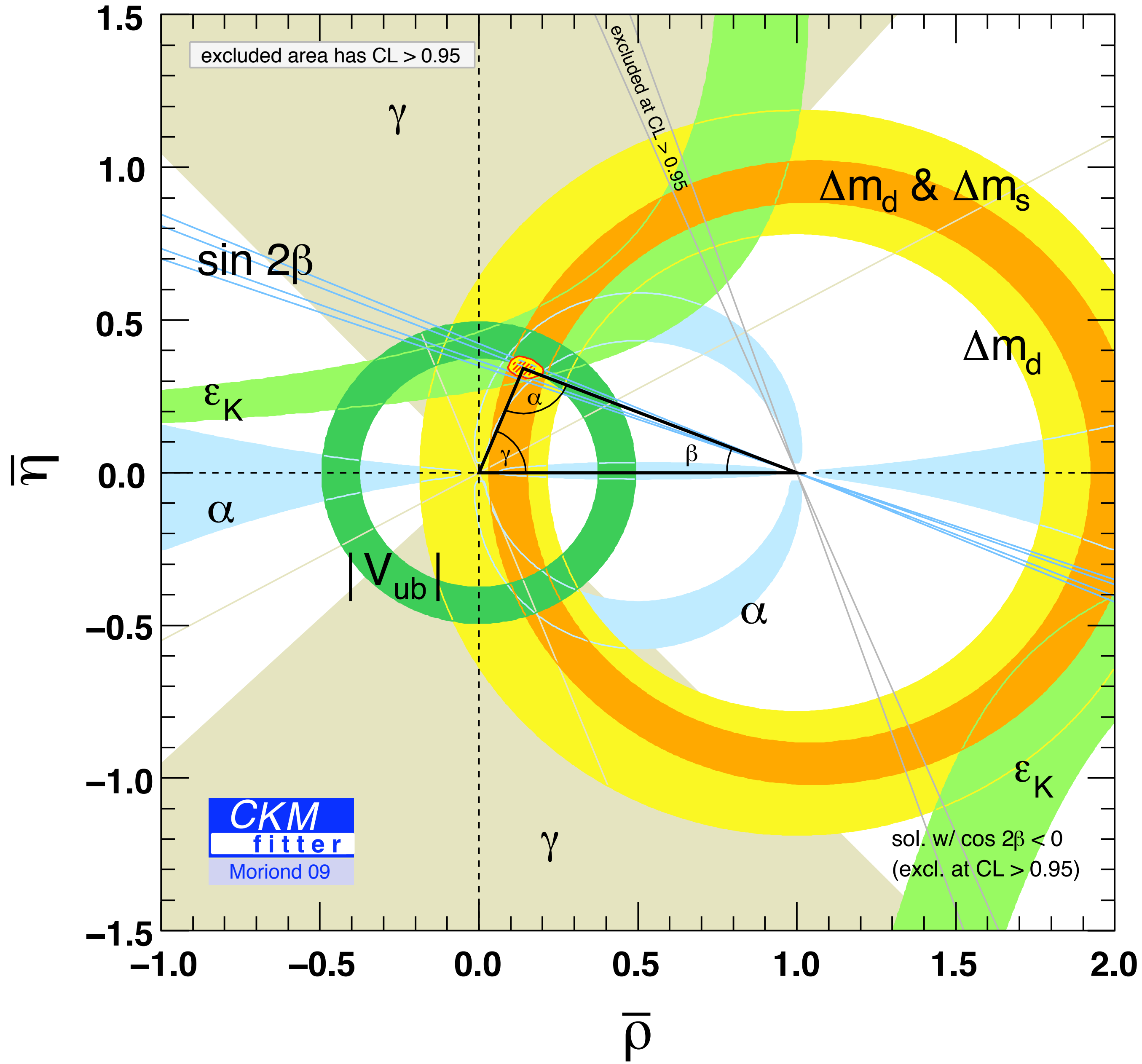


- ~~What is the ν_e component of ν_3?~~ $(\theta_{13} \neq 0!)$
- Is CP-invariance violated in neutrino oscillations? $(\delta \neq 0, \pi?)$ ['yes' hint]
- Is ν_3 mostly ν_μ or ν_τ? [$\theta_{23} \neq \pi/4$ hint]
- What is the neutrino mass hierarchy? $(\Delta m^2_{13} > 0?)$ [NH weak hint]

$\Rightarrow$ All of the above can "only" be addressed with new neutrino oscillation experiments

Ultimate Goal: Not Measure Parameters but Test the Formalism (Over-Constrain Parameter Space)

What we ultimately want to achieve:



We need to do this in the lepton sector!

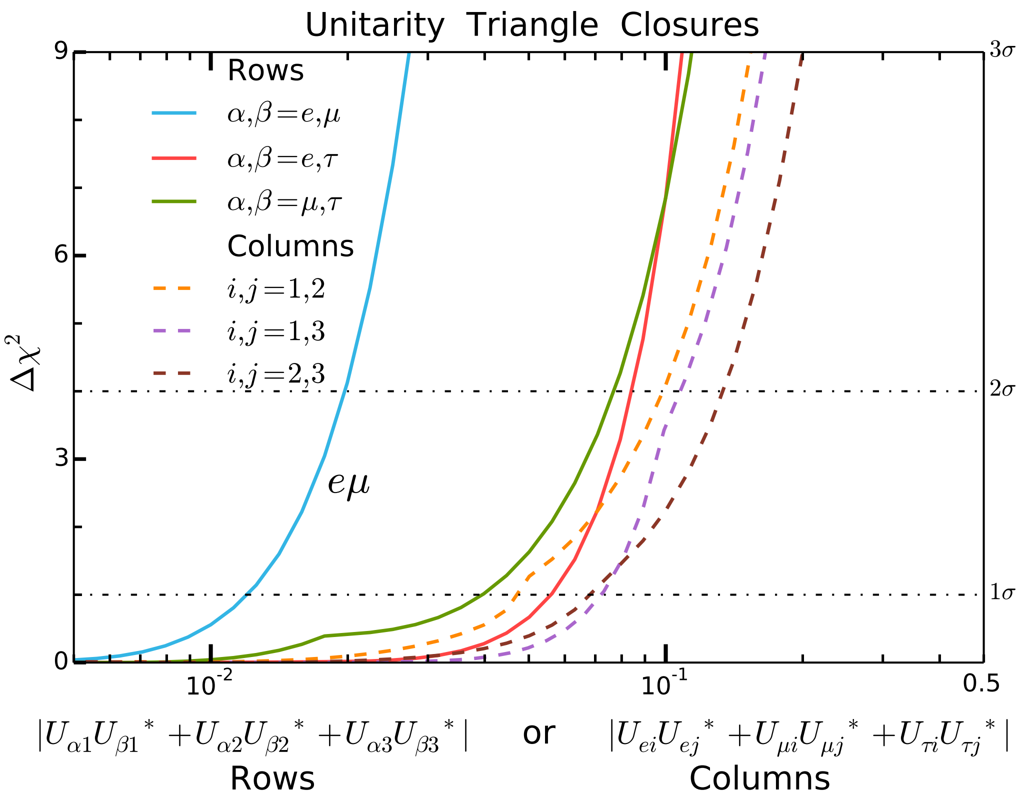
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

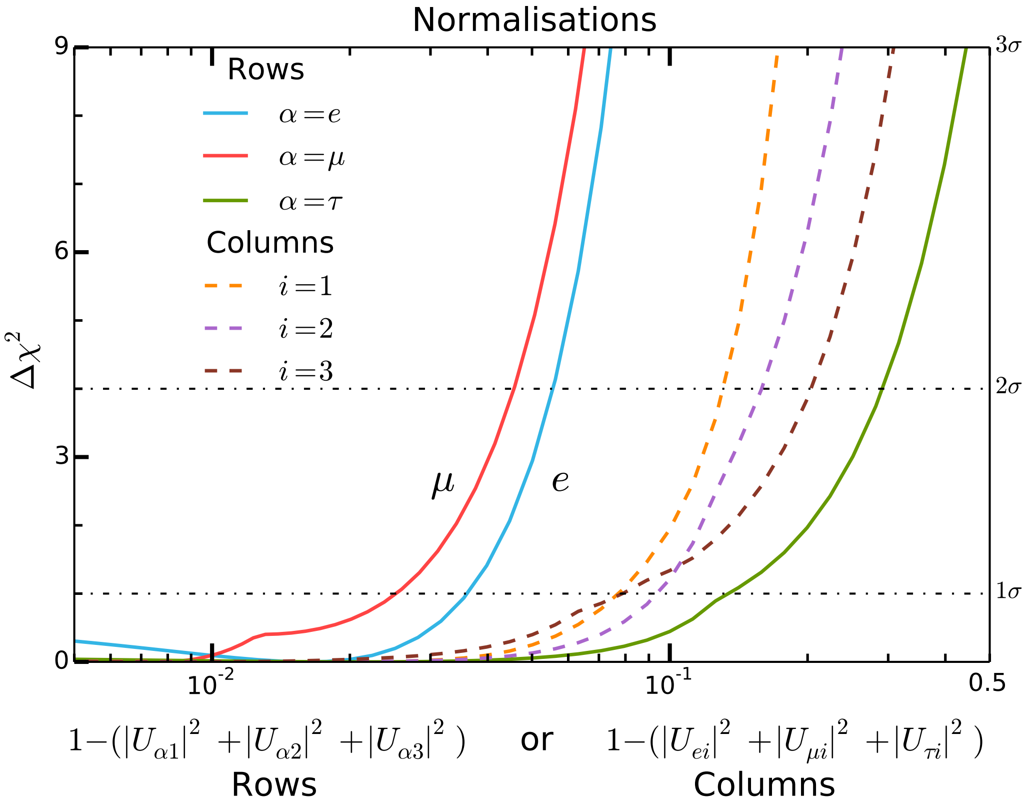
What we have **really measured** (very roughly):

- Two mass-squared differences, at several percent level – many probes;
- $|U_{e2}|^2$ – solar data;
- $|U_{\mu 2}|^2 + |U_{\tau 2}|^2$ – solar data;
- $|U_{e2}|^2|U_{e1}|^2$ – KamLAND;
- $|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)$ – atmospheric data, K2K, MINOS;
- $|U_{e3}|^2(1-|U_{e3}|^2)$ – Double Chooz, Daya Bay, RENO;
- $|U_{e3}|^2|U_{\mu 3}|^2$ (upper bound $\rightarrow$ evidence) – MINOS, T2K.

We still have a ways to go!

A little more quantitative:





[Parke and Ross-Lonergan, arXiv:1508.05095]

New Phenomena? What Could We Run Into?

- New neutrino states. In this case, the 3×3 mixing matrix would not be unitary.
- New short-range neutrino interactions. These lead to, for example, new matter effects.
- New, unexpected neutrino properties. Do they have nonzero magnetic moments? Do they decay? The answer is 'yes' to both, but nature might deviate dramatically from νSM expectations.
- Weird stuff. CPT-violation. Decoherence effects (aka "violations of Quantum Mechanics.")
- etc.

Aside: The Short Baseline Anomalies

Different data sets, sensitive to L/E values small enough that the known oscillation frequencies do not have "time" to operate, point to unexpected neutrino behavior. These include

- $\nu_\mu \to \nu_e$ appearance — LSND, MiniBooNE;
- $\nu_e \to \nu_{\rm other}$ disappearance — radioactive sources;
- $\bar{\nu}_e \to \bar{\nu}_{\rm other}$ disappearance — reactor experiments.

None are entirely convincing, either individually or combined. However, there may be something interesting going on here.

What is Going on Here?

- Are these "anomalies" related?
- Is this neutrino oscillations, other new physics, or something else?
- Are these related to the origin of neutrino masses and lepton mixing?
- How do clear this up **definitively**?

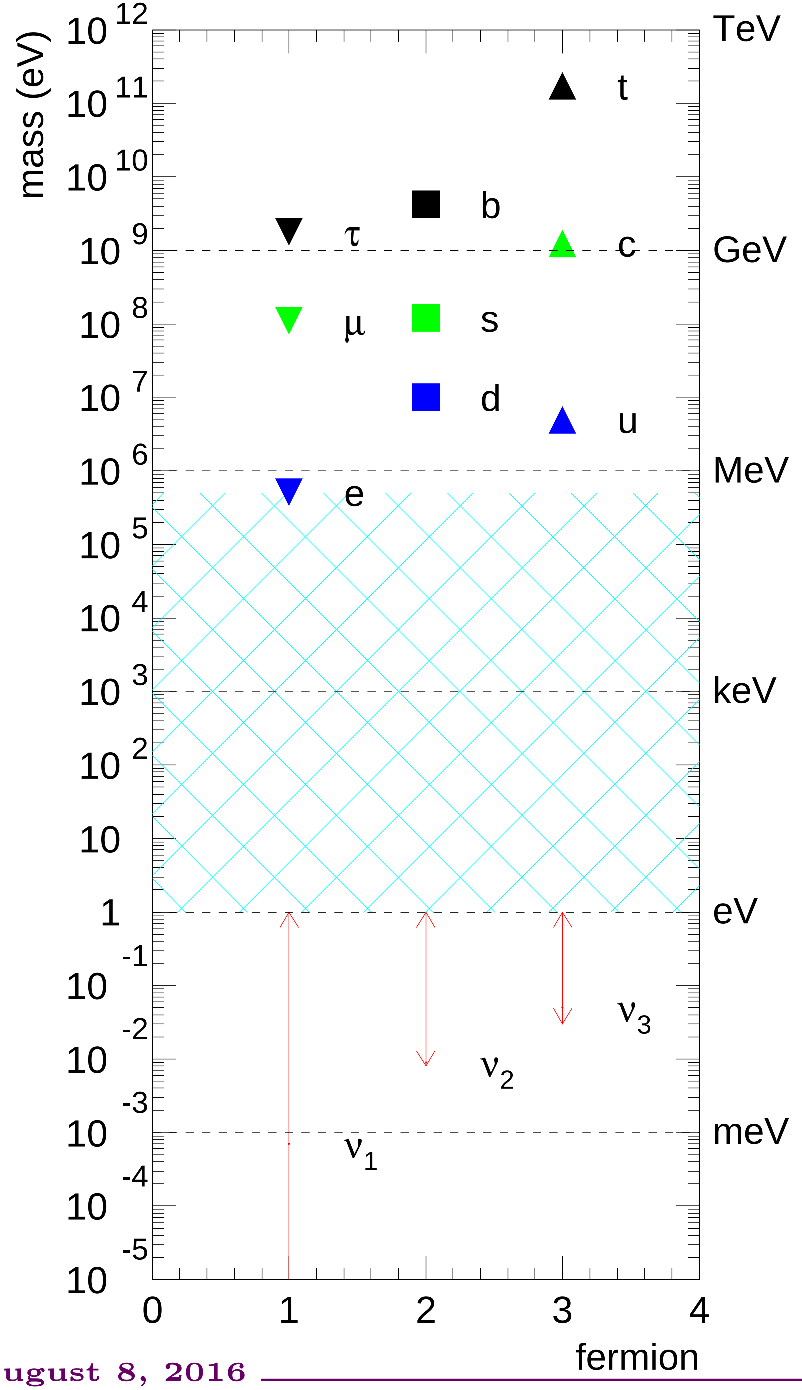
Need new clever experiments, of the short-baseline type (and we are working on it)!

Observable wish list: **[Community working on almost all of these]**

- ν_μ disappearance (and antineutrino);
- ν_e disappearance (and antineutrino);
- $\nu_\mu \leftrightarrow \nu_e$ appearance;
- $\nu_{\mu,e} \to \nu_\tau$ appearance.

If the oscillation interpretation of the short-baseline anomalies turns out to be correct . . .

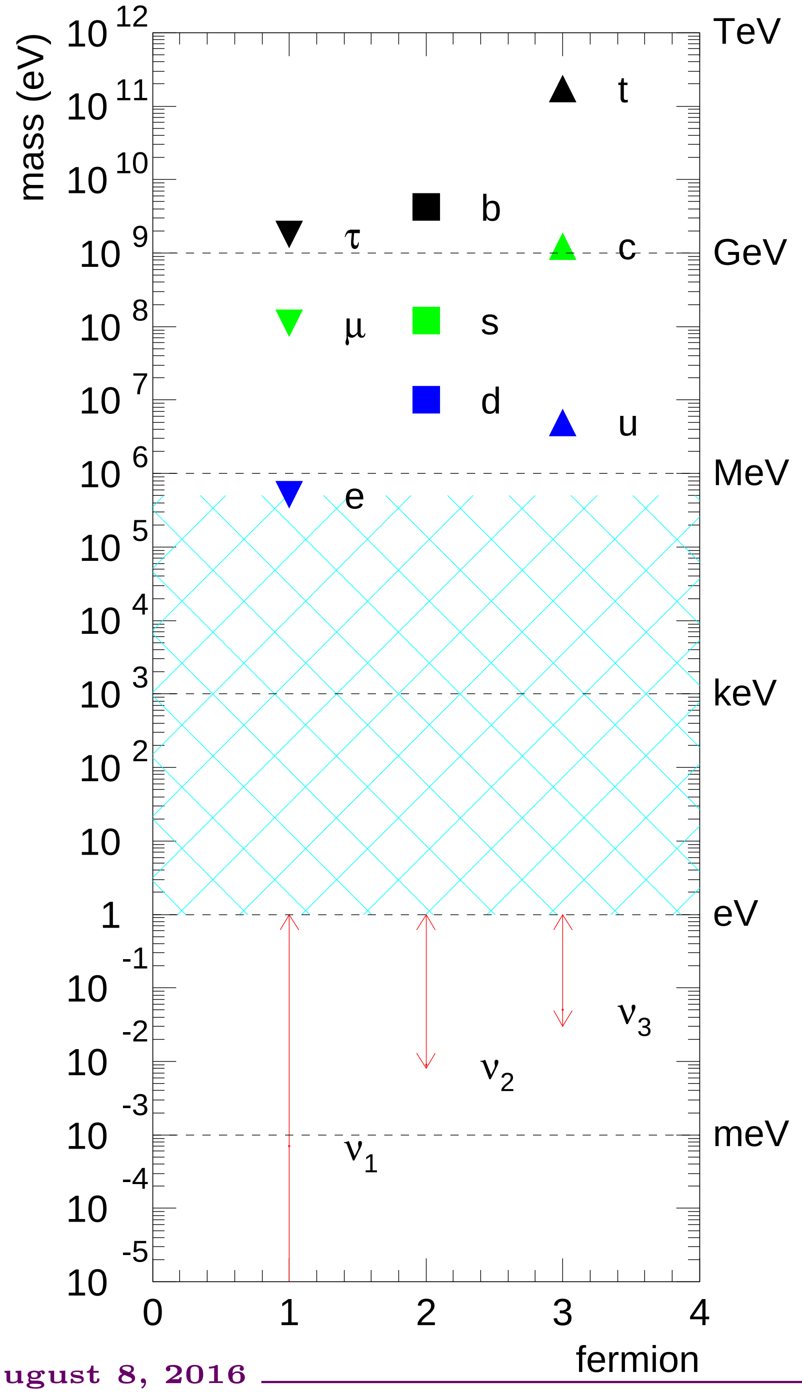
- We would have found new particle(s)!!!!!! [cannot overemphasize this!]
- Lots of Questions! What is it? Who ordered that? Is it related to the origin of neutrino masses? Is it related to dark matter?
- Lots of Work to do! Discovery, beyond reasonable doubt, will be followed by a panacea of new oscillation experiments. If, for example, there were one extra neutrino state the 4×4 mixing matrix would require three more mixing angles and three more CP-odd phases. Incredibly challenging. For example, some of the new CP-odd parameters can only be "seen" in tau-appearance.
- How is any of this consistent with cosmic surveys, big bang nucleosynthesis and other probes of the early universe!?



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?

⇓

NEW PHYSICS

Neutrino Masses: Only* "Palpable" Evidence of Physics Beyond the Standard Model

The SM we all learned in school predicts that neutrinos are strictly massless. Hence, massive neutrinos imply that the the SM is incomplete and needs to be replaced/modified.

Furthermore, the SM has to be replaced by something qualitatively different.

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* There is only a handful of questions our model for fundamental physics cannot explain (my personal list. Feel free to complain).

- What is the physics behind electroweak symmetry breaking? (Higgs ✓).
- What is the dark matter? (not in SM).
- Why is there more matter than antimatter 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 [inflation]? (not in SM).

What is the New Standard Model? [νSM]

The short answer is – WE DON'T KNOW. Not enough available info!

$$\Updownarrow$$

Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the νSM candidates can do. [are they falsifiable?, are they "simple"?, do they address other outstanding problems in physics?, etc]

We need more experimental input.

Neutrino Masses, EWSB, and a New Mass Scale of Nature

The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs double 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** (Dirac neutrinos);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking! (Majorana neutrinos);
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 (Majorana neutrinos).

Searches for $0\nu\beta\beta$ help tell (1) from (2) and (3), the LHC, charged-lepton flavor violation, etc may provide more information.

Fork on the Road: Are Neutrinos Majorana or Dirac Fermions?

Best (Only?) Bet: Neutrinoless Double-Beta Decay.

νSM – An Old Idea

SM as an effective field theory – non-renormalizable operators

$$\mathcal{L}_{\nu\rm SM} \supset -y_{ij}\frac{L^iHL^jH}{2\Lambda} + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + H.c.$$

There is only one dimension five operator [Weinberg, 1979]. If $\Lambda \gg 1$ TeV, it leads to only one observable consequence...

$$\text{after EWSB } \mathcal{L}_{\nu\rm SM} \supset \frac{m_{ij}}{2}\nu^i\nu^j; \quad m_{ij} = y_{ij}\frac{v^2}{\Lambda}.$$

- Neutrino masses are small: $\Lambda \gg v \to m_\nu \ll m_f$ ($f = e, \mu, u, d$, etc)
- Neutrinos are Majorana fermions – Lepton number is violated!
- νSM effective theory – not valid for energies above at most Λ.
- What is Λ? First naive guess is that Λ is the Planck scale – does not work. Data require $\Lambda \sim 10^{14}$ GeV (related to GUT scale?) [note $y^{\rm max} \equiv 1$]

What else is this "good for"? Depends on the ultraviolet completion!

Example: the (Type I) Seesaw Mechanism

A simple[a], renormalizable Lagrangian that allows for neutrino masses is

$$\mathcal{L}_\nu = \mathcal{L}_{\rm old} - \lambda_{\alpha i} L^\alpha H N^i - \sum_{i=1}^{3} \frac{M_i}{2} N^i N^i + H.c.,$$

where N_i ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions. $\mathcal{L}_\nu$ is the most general, renormalizable Lagrangian consistent with the SM gauge group and particle content, plus the addition of the N_i fields.

After electroweak symmetry breaking, $\mathcal{L}_\nu$ describes, besides all other SM degrees of freedom, six Majorana fermions: **six neutrinos.**

[a]Only requires the introduction of three fermionic degrees of freedom, no new interactions or symmetries.

What We Really Know About M and λ:

- $M=0$: the six neutrinos "fuse" into three Dirac states. Neutrino mass matrix given by $\mu_{\alpha i}\equiv\lambda_{\alpha i}v$.

  The symmetry of $\mathcal{L}_\nu$ is enhanced: $U(1)_{B-L}$ is an exact global symmetry of the Lagrangian if all M_i vanish. Small M_i values are 'tHooft natural.

- $M\gg\mu$: the six neutrinos split up into three mostly active, light ones, and three, mostly sterile, heavy ones. The light neutrino mass matrix is given by $m_{\alpha\beta}=\sum_i\mu_{\alpha i}M_i^{-1}\mu_{\beta i}$ $[m\propto 1/\Lambda \ \Rightarrow\ \Lambda=M/\mu^2]$.

  This the **seesaw mechanism.** Neutrinos are Majorana fermions. Lepton number is not a good symmetry of $\mathcal{L}_\nu$, even though L-violating effects are hard to come by.

- $M\sim\mu$: six states have similar masses. Active–sterile mixing is very large. This scenario is (generically) ruled out by active neutrino data (atmospheric, solar, KamLAND, K2K, etc).

- $M\ll\mu$: neutrinos are quasi-Dirac fermions. Active–sterile mixing is maximal, but new oscillation lengths are very long.

Accommodating Small Neutrino Masses

If $\mu = \lambda v \ll M$, below the mass scale M,

$$\mathcal{L}_5 = \frac{LHLH}{\Lambda}.$$

Neutrino masses are small if $\Lambda \gg \langle H \rangle$. Data require $\Lambda \sim 10^{14}$ GeV.

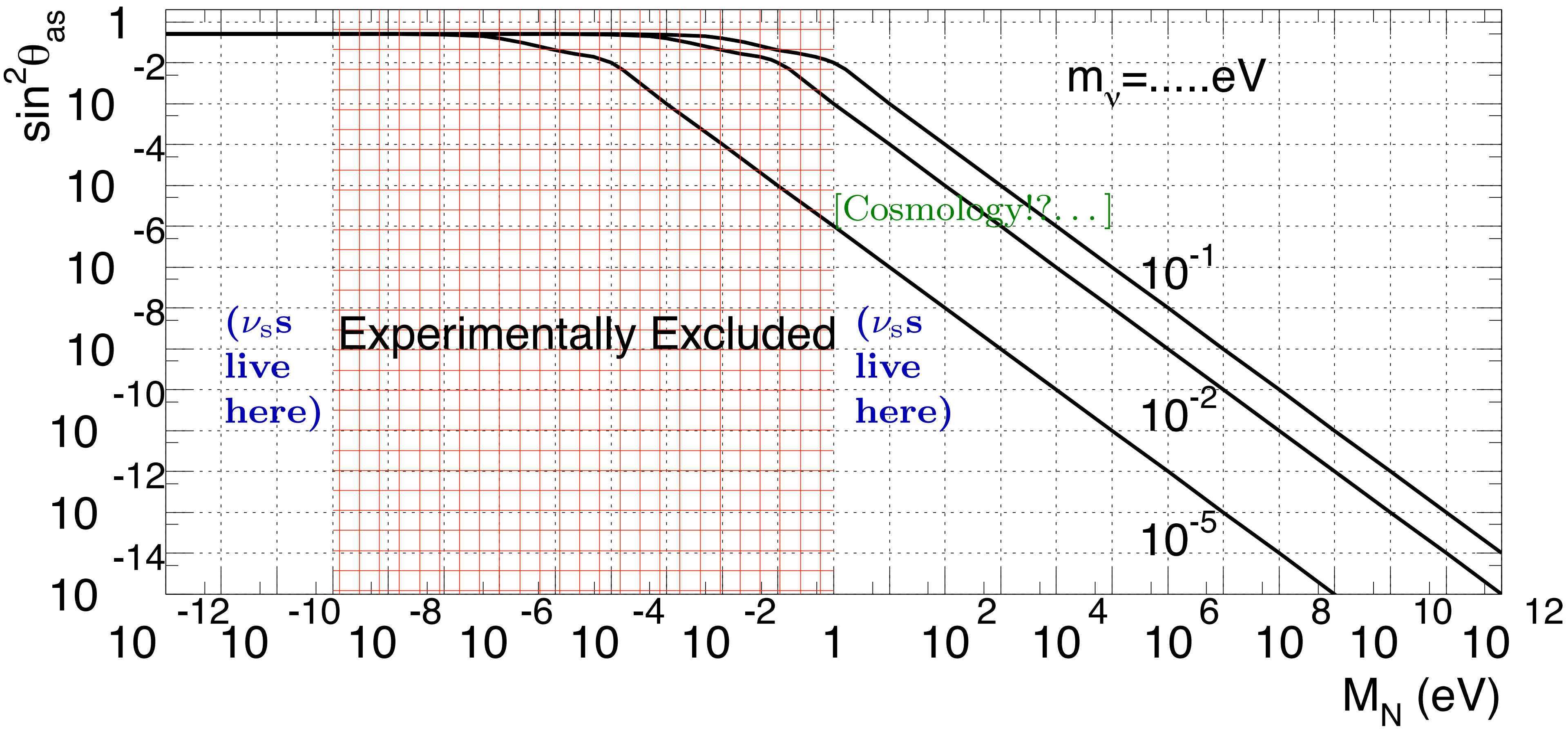
In the case of the seesaw,

$$\Lambda \sim \frac{M}{\lambda^2},$$

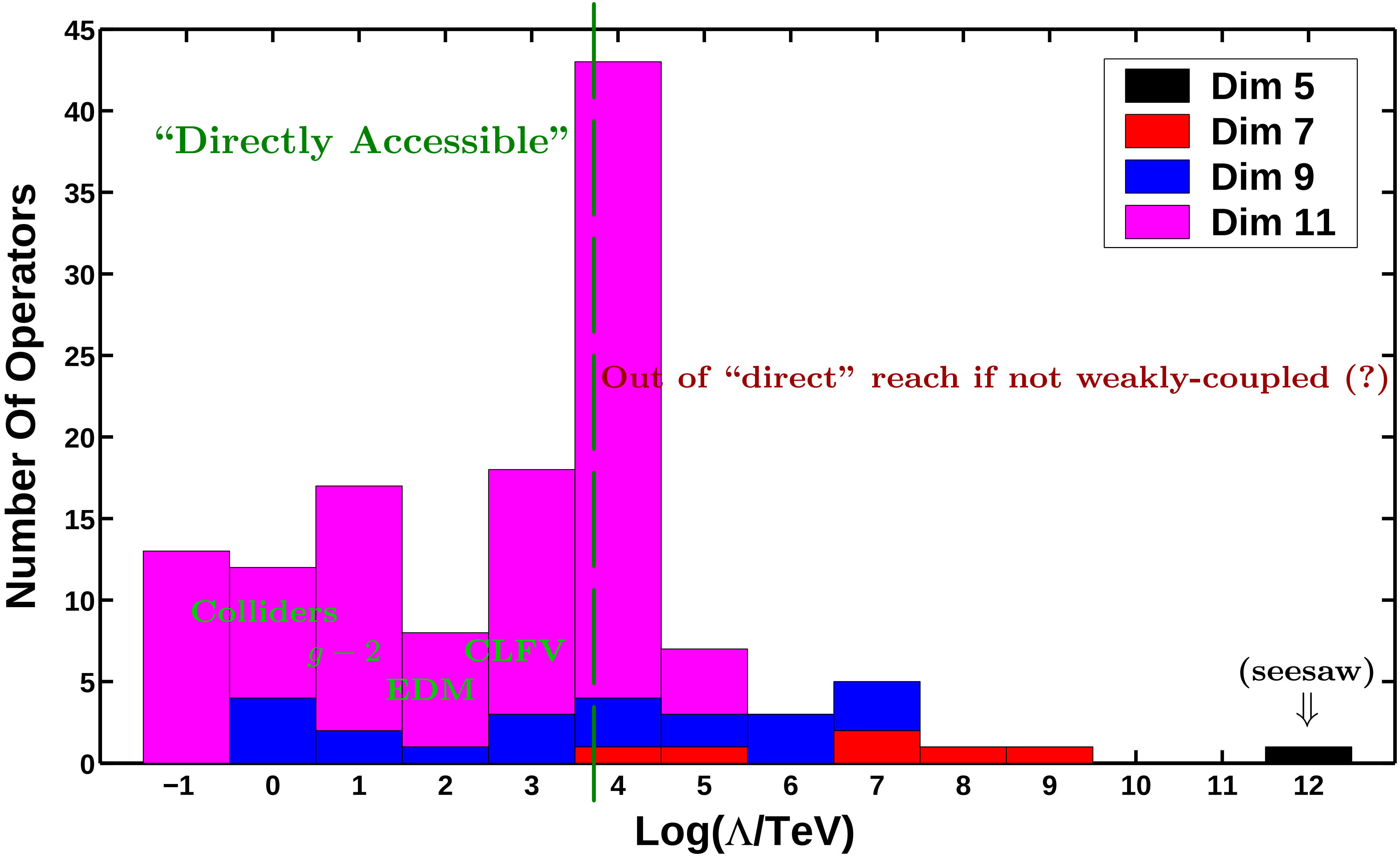
so neutrino masses are small if either

- they are generated by physics at a very high energy scale $M \gg v$ (high-energy seesaw); or
- they arise out of a very weak coupling between the SM and a new, hidden sector (low-energy seesaw); or
- cancellations among different contributions render neutrino masses accidentally small (fine-tuning or symmetry).

Constraining the Seesaw Lagrangian



[AdG, Huang, Jenkins, arXiv:0906.1611]


45
40
35
30
25
20
15
10
5
0
Number Of Operators
"Directly Accessible"
Out of "direct" reach if not weakly-coupled (?)
Colliders
$g-2$
EDM
CLFV
(seesaw)
⇓
Dim 5
Dim 7
Dim 9
Dim 11
−1
0
1
2
3
4
5
6
7
8
9
10
11
12
Log(Λ/TeV)

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, including . . .

- understanding the fate of lepton-number. Neutrinoless double beta decay!
- a comprehensive long baseline neutrino program, towards precision oscillation physics.
- other probes of neutrino properties, including neutrino scattering.
- precision studies 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.
- cosmic surveys. Neutrino properties affect, in a significant way, the history of the universe. Will we learn about neutrinos from cosmology, or about cosmology from neutrinos?
- searches for baryon-number violating processes.

Understanding Fermion Mixing

One of the puzzling phenomena uncovered by the neutrino data is the fact that Neutrino Mixing is Strange. What does this mean?

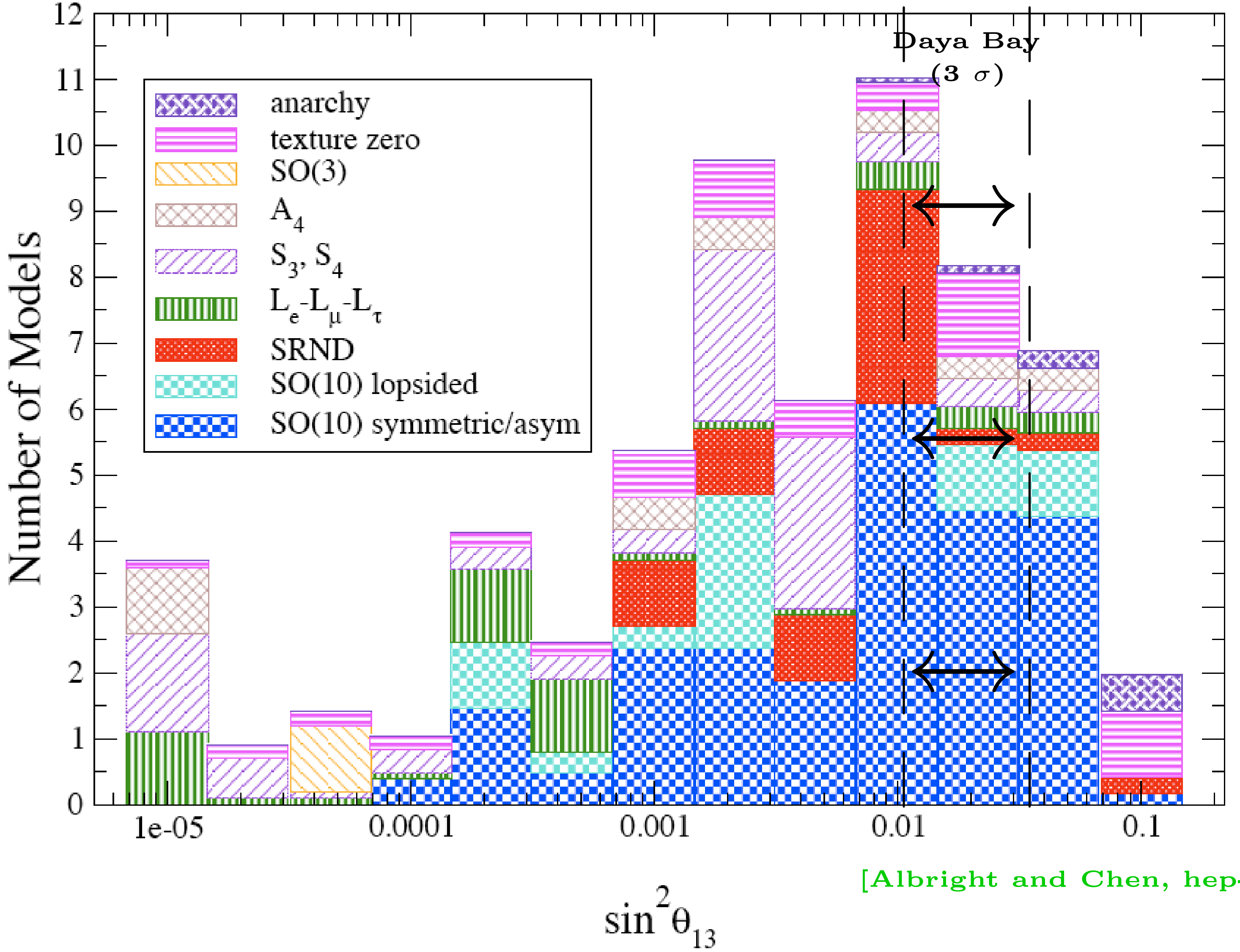
It means that lepton mixing is very different from quark mixing:

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

$[|(V_{MNS})_{e3}| < 0.2]$

WHY?

They certainly look VERY different, but which one would you label as "strange"?



[Albright and Chen, hep-ph/0608137]

"Left-Over" Predictions: δ, mass-hierarchy, $\cos 2\theta_{23}$

10 anarchical mixing matrices, plus the "real" one

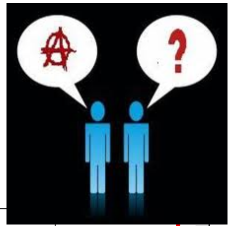
$$\begin{pmatrix} |U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\ \cdots & \cdots & |U_{\mu 3}|^2 \\ \cdots & \cdots & |U_{\tau 3}|^2 \end{pmatrix} = \begin{pmatrix} 0.69 & 0.29 & 0.02 \\ \cdots & \cdots & 0.40 \\ \cdots & \cdots & 0.58 \end{pmatrix}, \begin{pmatrix} 0.36 & 0.35 & 0.29 \\ \cdots & \cdots & 0.68 \\ \cdots & \cdots & 0.03 \end{pmatrix},$$

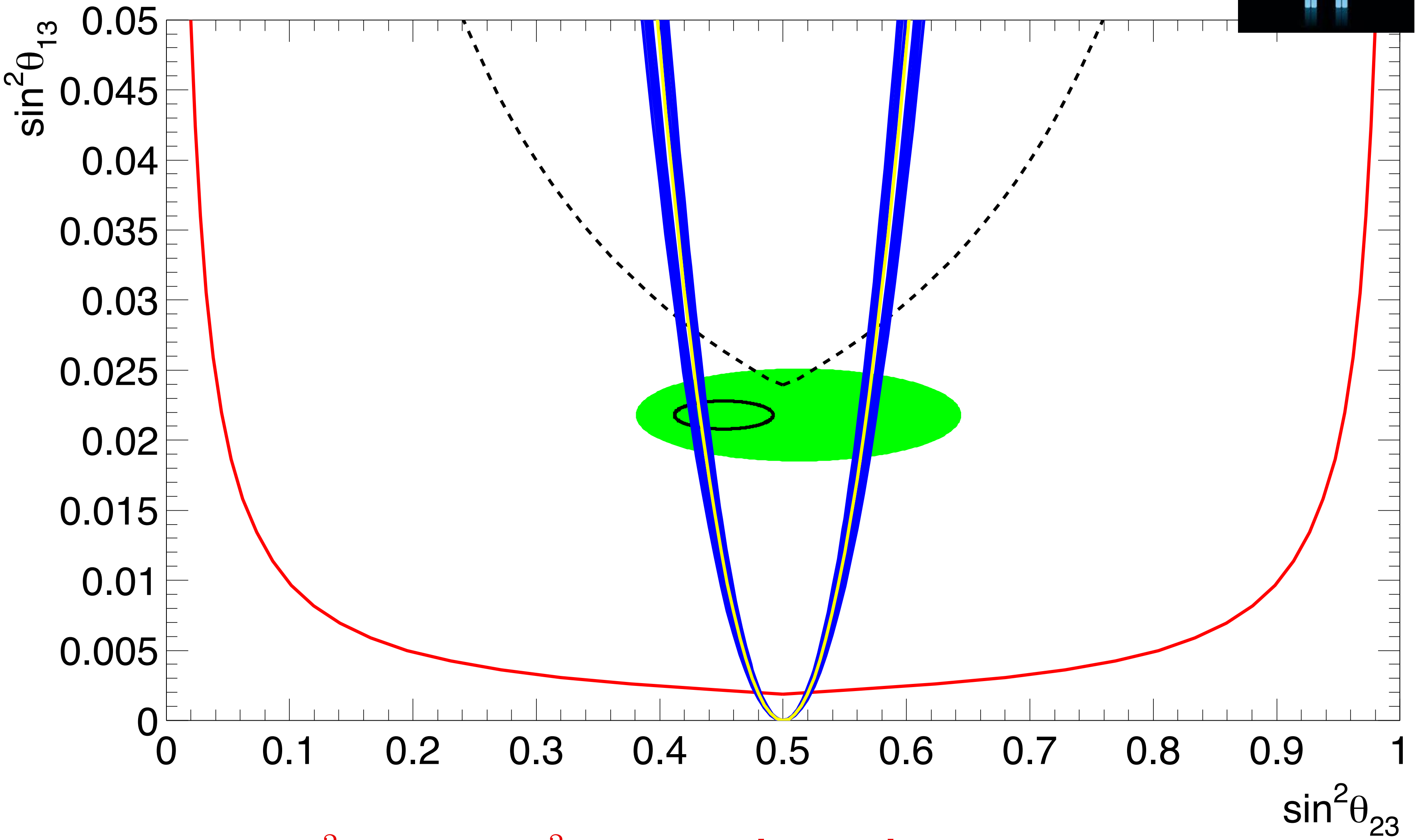
$$\begin{pmatrix} 0.83 & 0.11 & 0.06 \\ \cdots & \cdots & 0.87 \\ \cdots & \cdots & 0.07 \end{pmatrix}, \begin{pmatrix} 0.71 & 0.13 & 0.16 \\ \cdots & \cdots & 0.20 \\ \cdots & \cdots & 0.64 \end{pmatrix}, \begin{pmatrix} 0.24 & 0.47 & 0.29 \\ \cdots & \cdots & 0.58 \\ \cdots & \cdots & 0.13 \end{pmatrix},$$

$$\begin{pmatrix} 0.16 & 0.35 & 0.49 \\ \cdots & \cdots & 0.13 \\ \cdots & \cdots & 0.38 \end{pmatrix}, \begin{pmatrix} 0.63 & 0.24 & 0.13 \\ \cdots & \cdots & 0.73 \\ \cdots & \cdots & 0.14 \end{pmatrix}, \begin{pmatrix} 0.12 & 0.35 & 0.53 \\ \cdots & \cdots & 0.12 \\ \cdots & \cdots & 0.35 \end{pmatrix},$$

$$\begin{pmatrix} 0.22 & 0.55 & 0.23 \\ \cdots & \cdots & 0.12 \\ \cdots & \cdots & 0.65 \end{pmatrix}, \begin{pmatrix} 0.21 & 0.37 & 0.42 \\ \cdots & \cdots & 0.08 \\ \cdots & \cdots & 0.50 \end{pmatrix}, \begin{pmatrix} 0.54 & 0.44 & 0.02 \\ \cdots & \cdots & 0.54 \\ \cdots & \cdots & 0.44 \end{pmatrix}.$$

Anarchy vs. Order — more precision required!





Order: $\sin^2\theta_{13} = C\cos^2 2\theta_{23},\ C \in [0.8, 1.2]$

[AdG, Murayama, 1204.1249]

Summary

The venerable Standard Model sprung a leak in the end of the last century: neutrinos are not massless! [and we are still trying to patch it...]

1. We still **know very little** about the new physics uncovered by neutrino oscillations. In particular, the new physics (broadly defined) can live almost anywhere between sub-eV scales and the GUT scale.

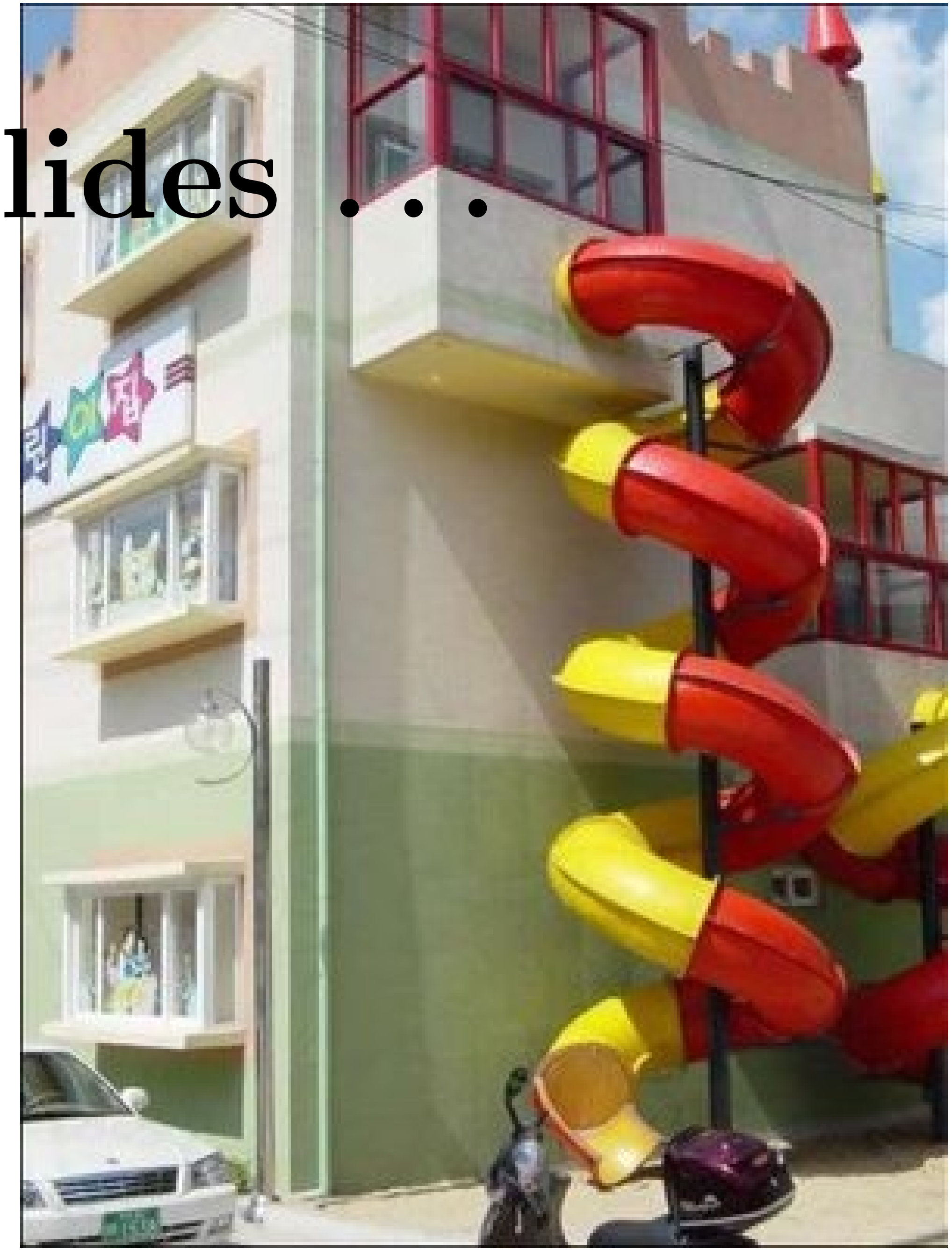
2. **Neutrino masses are very small** – we don't know why, but we think it means something important.

3. **Neutrino mixing is "weird"** – we don't know why, but we think it means something important.

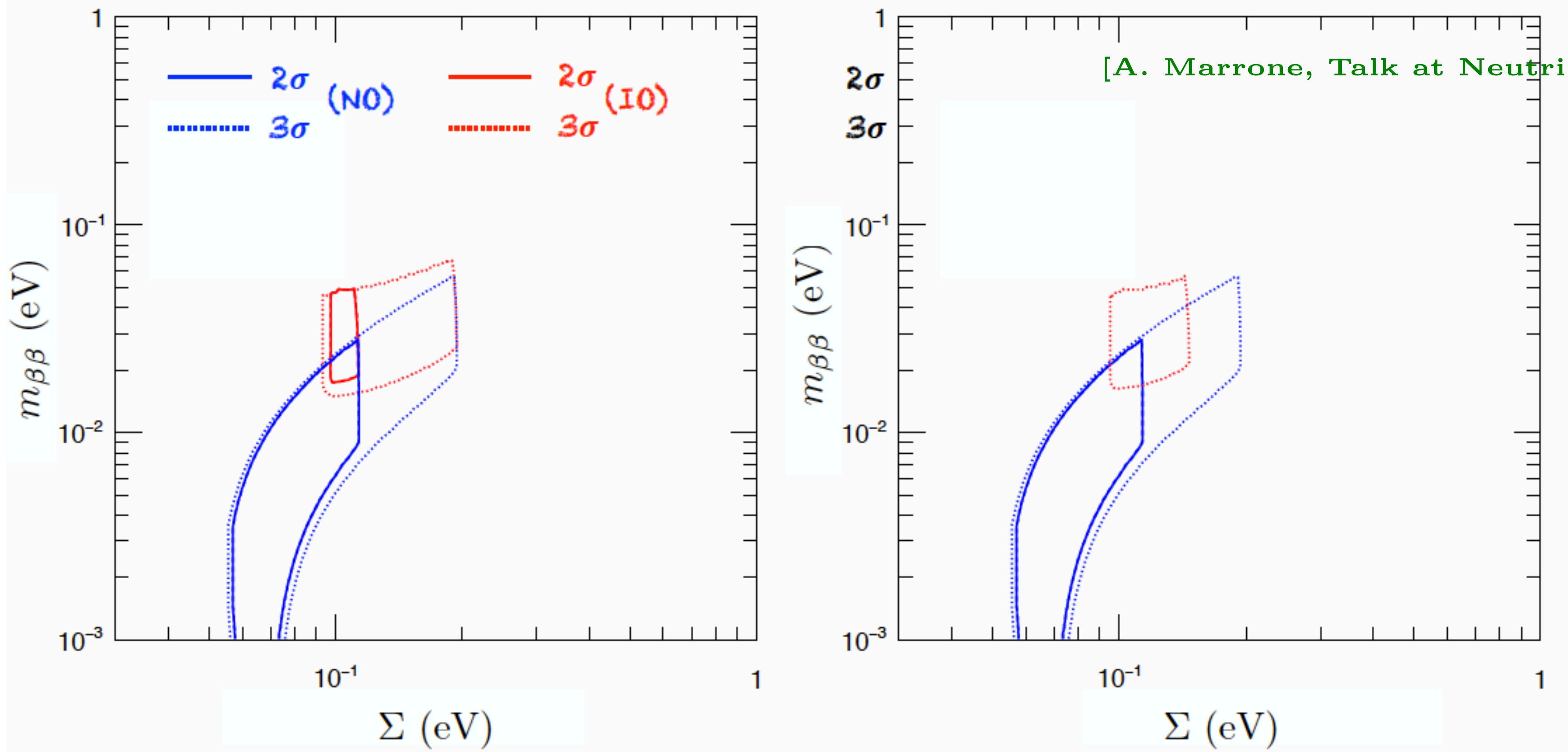
4. What is going on with the **short-baseline anomalies?**

5. There is plenty of **room for surprises**, as neutrinos are very deep probes of all sorts of physical phenomena. Neutrino oscillations are "quantum interference devices," potentially sensitive to whatever else might be out there (keep in mind, neutrino masses might be physics at $\Lambda \simeq 10^{14}$ GeV).

Backup Slides . . .



Oscillations + $0\nu\beta\beta$ + Cosmo "strong" (*)



Normal ordering and inverted ordering separate minima

Absolute minimum in NO, $\Delta\chi^2$(IO−NO) = 4.6

Inverted ordering case "under pressure" if one takes all data at face value. But too early to draw conclusions.

Future oscillation probes —>

(*) $\Delta\chi^2$ taken from "base+BAO+H073p02" scenario in arXiv:1605.04320v1

"Higher Order" Neutrino Masses from $\Delta L = 2$ Physics

Imagine that there is new physics that breaks lepton number by 2 units at some energy scale Λ, but that it does not, in general, lead to neutrino masses at the tree level.

We know that neutrinos will get a mass at some order in perturbation theory – which order is model dependent!

For example:

- SUSY with trilinear R-parity violation – neutrino masses at one-loop;
- Zee models – neutrino masses at one-loop;
- Babu and Ma – neutrino masses at two loops;
- Chen et al, 0706.1964 – neutrino masses at two loops;
- Angel et al, 1308.0463 – neutrino masses at two loops;
- etc.

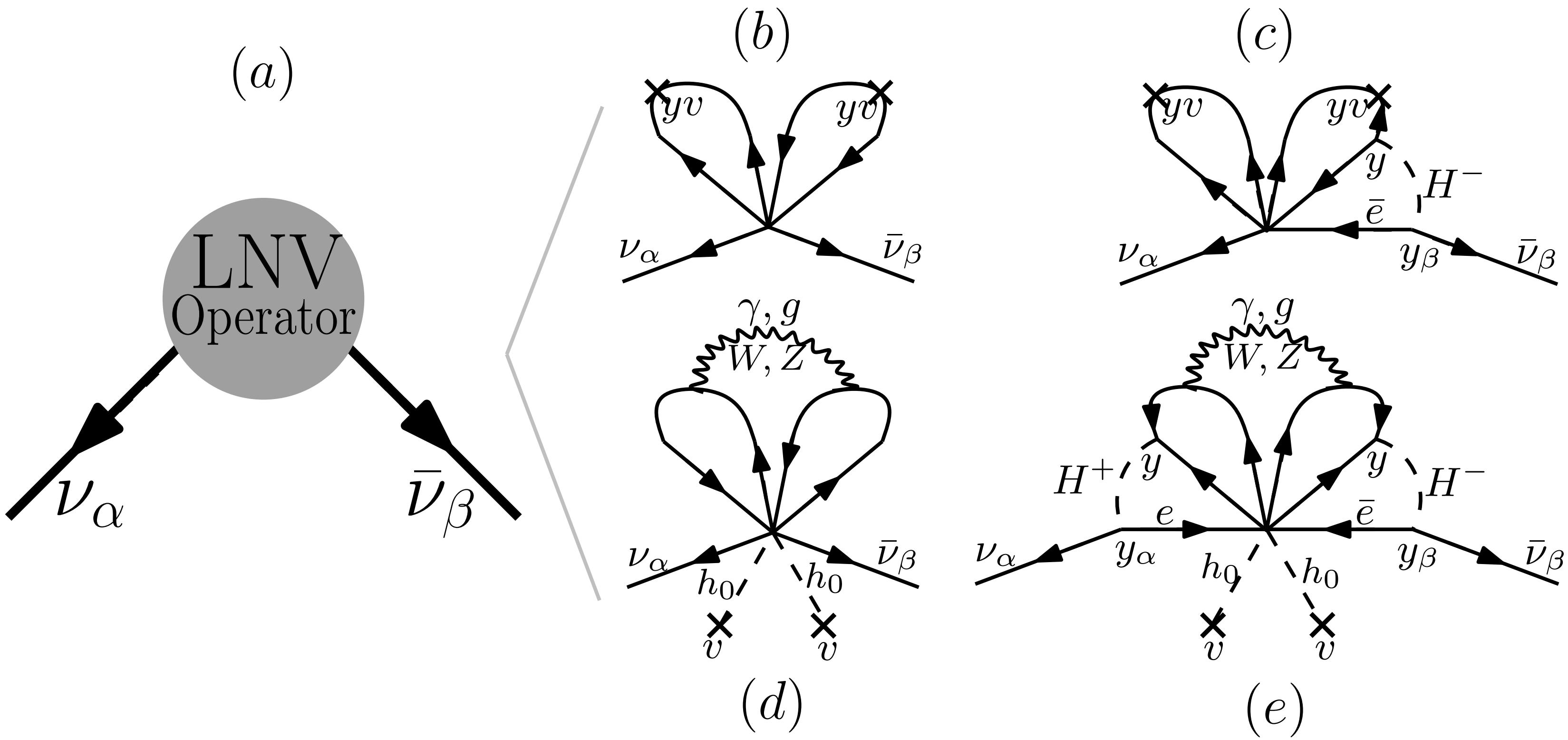
AdG, Jenkins, 0708.1344 [hep-ph]

Effective Operator Approach

(there are 129 of them if you discount different Lorentz structures!)

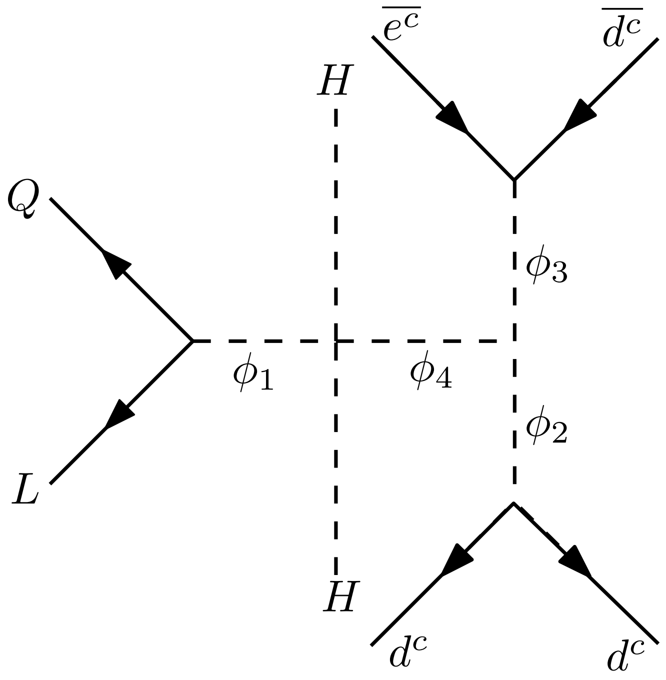
classified by Babu and Leung in NPB**619**,667(2001)

4_a	$L^iL^j\overline{Q}_i\bar{u}^cH^k\epsilon_{jk}$	$\frac{y_u}{16\pi^2}\frac{v^2}{\Lambda}$	4×10^9	$\beta\beta0\nu$
4_b	$L^iL^j\overline{Q}_k\bar{u}^cH^k\epsilon_{ij}$	$\frac{y_u g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^6	$\beta\beta0\nu$
5	$L^iL^jQ^kd^cH^lH^m\overline{H}_i\epsilon_{jl}\epsilon_{km}$	$\frac{y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^5	$\beta\beta0\nu$
6	$L^iL^j\overline{Q}_k\bar{u}^cH^lH^k\overline{H}_i\epsilon_{jl}$	$\frac{y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^7	$\beta\beta0\nu$
7	$L^iQ^j\bar{e}^c\overline{Q}_kH^kH^lH^m\epsilon_{il}\epsilon_{jm}$	$y_{\ell_\beta}\frac{g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	4×10^2	mix
8	$L^i\bar{e}^c\bar{u}^cd^cH^j\epsilon_{ij}$	$y_{\ell_\beta}\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^3	mix
9	$L^iL^jL^ke^cL^le^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_\ell^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	3×10^3	$\beta\beta0\nu$
10	$L^iL^jL^ke^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_\ell y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^3	$\beta\beta0\nu$
11_a	$L^iL^jQ^kd^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_d^2g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	30	$\beta\beta0\nu$
11_b	$L^iL^jQ^kd^cQ^ld^c\epsilon_{ik}\epsilon_{jl}$	$\frac{y_d^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^4	$\beta\beta0\nu$
12_a	$L^iL^j\overline{Q}_i\bar{u}^c\overline{Q}_j\bar{u}^c$	$\frac{y_u^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^7	$\beta\beta0\nu$
12_b	$L^iL^j\overline{Q}_k\bar{u}^c\overline{Q}_l\bar{u}^c\epsilon_{ij}\epsilon^{kl}$	$\frac{y_u^2g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^4	$\beta\beta0\nu$
13	$L^iL^j\overline{Q}_i\bar{u}^cL^le^c\epsilon_{jl}$	$\frac{y_\ell y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^5	$\beta\beta0\nu$
14_a	$L^iL^j\overline{Q}_k\bar{u}^cQ^kd^c\epsilon_{ij}$	$\frac{y_dy_ug^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^3	$\beta\beta0\nu$
14_b	$L^iL^j\overline{Q}_i\bar{u}^cQ^ld^c\epsilon_{jl}$	$\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^5	$\beta\beta0\nu$
15	$L^iL^jL^kd^c\overline{L}_i\bar{u}^c\epsilon_{jk}$	$\frac{y_dy_ug^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^3	$\beta\beta0\nu$
16	$L^iL^je^cd^c\bar{e}^c\bar{u}^c\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	2	$\beta\beta0\nu$, LHC
17	$L^iL^jd^cd^c\bar{d}^c\bar{u}^c\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	2	$\beta\beta0\nu$, LHC
18	$L^iL^jd^cu^c\bar{u}^c\bar{u}^c\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	2	$\beta\beta0\nu$, LHC
19	$L^iQ^jd^cd^c\bar{e}^c\bar{u}^c\epsilon_{ij}$	$y_{\ell_\beta}\frac{y_d^2y_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1	$\beta\beta0\nu$, HElnv, LHC, mix
20	$L^id^c\overline{Q}_i\bar{u}^c\bar{e}^c\bar{u}^c$	$y_{\ell_\beta}\frac{y_dy_u^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	40	$\beta\beta0\nu$, mix
21_a	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{ij}\epsilon_{km}\epsilon_{ln}$	$\frac{y_\ell y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	2×10^3	$\beta\beta0\nu$
21_b	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{il}\epsilon_{jm}\epsilon_{kn}$	$\frac{y_\ell y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	2×10^3	$\beta\beta0\nu$
22	$L^iL^jL^ke^c\overline{L}_k\bar{e}^cH^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^4	$\beta\beta0\nu$
23	$L^iL^jL^ke^c\overline{Q}_k\bar{d}^cH^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{y_\ell y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	40	$\beta\beta0\nu$
24_a	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jk}\epsilon_{lm}$	$\frac{y_d^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^2	$\beta\beta0\nu$
24_b	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jm}\epsilon_{kl}$	$\frac{y_d^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^2	$\beta\beta0\nu$
25	$L^iL^jQ^kd^cQ^lu^cH^mH^n\epsilon_{im}\epsilon_{jn}\epsilon_{kl}$	$\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	4×10^3	$\beta\beta0\nu$



(a)
LNV
Operator
ν_α
$\bar{\nu}_\beta$
(b)
yv
yv
ν_α
$\bar{\nu}_\beta$
(c)
yv
yv
y
H^-
$\bar{e}$
ν_α
y_β
$\bar{\nu}_\beta$
γ, g
W, Z
ν_α
$\bar{\nu}_\beta$
h_0
h_0
v
v
(d)
γ, g
W, Z
H^+
y
y
H^-
e
$\bar{e}$
ν_α
y_α
h_0
h_0
y_β
$\bar{\nu}_\beta$
v
v
(e)

[arXiv:0708.1344 [hep-ph]]



Order-One Coupled, Weak Scale Physics Can Also Explain Naturally Small Majorana Neutrino Masses:

Multi-loop neutrino masses from lepton number violating new physics.

$$-\mathcal{L}_{\nu\text{SM}} \supset \sum_{i=1}^{4} M_i \phi_i \bar{\phi}_i + i y_1 Q L \phi_1 + y_2 d^c d^c \phi_2 + y_3 e^c d^c \phi_3 + \lambda_{14} \bar{\phi}_1 \phi_4 H H + \lambda_{234} M \phi_2 \bar{\phi}_3 \phi_4 + h.c.$$

$m_\nu \propto (y_1 y_2 y_3 \lambda_{234}) \lambda_{14}/(16\pi)^4 \;\rightarrow$ neutrino masses at 4 loops, requires $M_i \sim 100$ GeV!

WARNING: For illustrative purposes only. Scenario almost certainly ruled out by searches for charged-lepton flavor-violation and high-energy collider data.

Dirac Neutrinos – Enhanced Symmetry!(Symmetries?)

Back to

$$\mathcal{L}_\nu = \mathcal{L}_{\rm old} - \lambda_{\alpha i} L^\alpha H N^i - \sum_{i=1}^{3} \frac{M_i}{2} N^i N^i + H.c.,$$

where N_i ($i = 1, 2, 3,$ for concreteness) are SM gauge singlet fermions.

Dirac Neutrinos – Enhanced Symmetry!(Symmetries?)

If all $M_i \equiv 0$, the neutrinos are Dirac fermions.

$$\mathcal{L}_\nu = \mathcal{L}_{\rm old} - \lambda_{\alpha i} L^\alpha H N^i + H.c.,$$

where N_i ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions. In this case, the νSM global symmetry structure is enhanced. For example, $U(1)_{B-L}$ is an exactly conserved, global symmetry. This is new!

Downside: The neutrino Yukawa couplings λ are tiny, less than 10^{-12}. What is wrong with that? We don't like tiny numbers, but Nature seems to not care very much about what we like…

More to the point, the failure here is that it turns out that the neutrino masses are not, trivially, qualitatively different. This seems to be a "missed opportunity."

There are lots of ideas that lead to very small Dirac neutrino masses.

Maybe right-handed neutrinos exist, but neutrino Yukawa couplings are forbidden – hence neutrino masses are tiny.

One possibility is that the N fields are charged under some new symmetry (gauged or global) that is spontaneously broken.

$$\lambda_{\alpha i} L^\alpha H N^i \to \frac{\kappa_{\alpha i}}{\Lambda}(L^\alpha H)(N^i \Phi),$$

where Φ (spontaneously) breaks the new symmetry at some energy scale v_Φ. Hence, $\lambda = \kappa v_\Phi/\Lambda$. How do we test this?

E.g., AdG and D. Hernández, arXiv:1507.00916

Gauged chiral new symmetry for the right-handed neutrinos, no Majorana masses allowed, plus a heavy messenger sector. Predictions: new stable massive states (mass around v_Φ) which look like (i) dark matter, (ii) (Dirac) sterile neutrinos are required. Furthermore, there is a new heavy Z'-like gauge boson.

$\Rightarrow$ Natural Conections to Dark Matter, Sterile Neutrinos, Dark Photons!