Neutrino Physics: Motivation and Update

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ν Flavor Oscillations are a Fact

Neutrino oscillation experiments have revealed that neutrinos change flavor after propagating a finite distance. The rate of change depends on the neutrino energy E_ν and the baseline L. The evidence is overwhelming.

- $\nu_\mu \to \nu_\tau$ and $\bar{\nu}_\mu \to \bar{\nu}_\tau$ — atmospheric and accelerator experiments;
- $\nu_e \to \nu_{\mu,\tau}$ — solar experiments;
- $\bar{\nu}_e \to \bar{\nu}_{\rm other}$ — reactor experiments;
- $\nu_\mu \to \nu_{\rm other}$ and $\bar{\nu}_\mu \to \bar{\nu}_{\rm other}$— atmospheric and accelerator expts;
- $\nu_\mu \to \nu_e$ — accelerator experiments.

The simplest and **only satisfactory** explanation of **all** this data is that neutrinos have distinct masses, and mix.

[Maltoni and Schwetz, arXiv: 0812.3161]

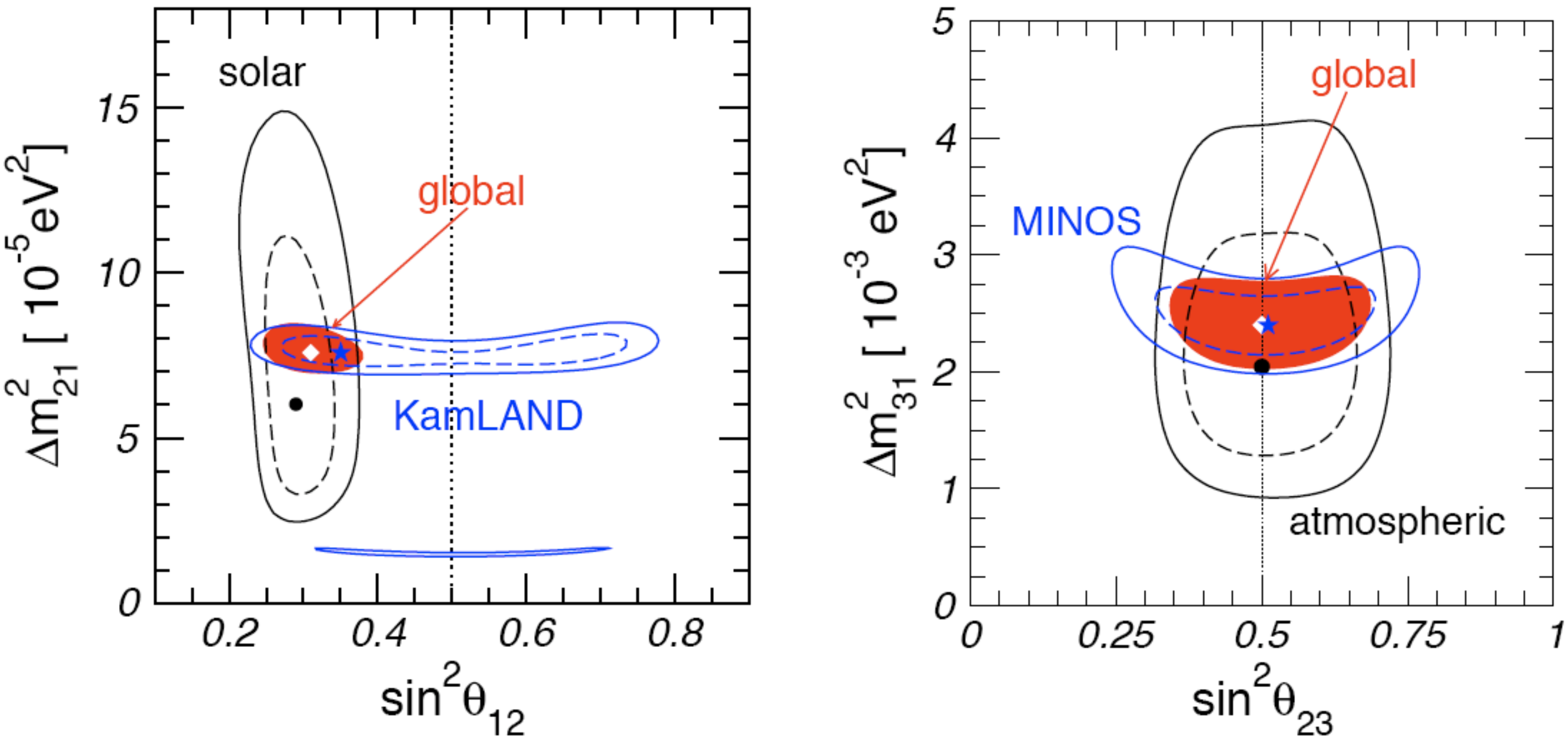


Figure 1: Determination of the leading "solar" and "atmospheric" oscillation parameters [1]. We show allowed regions at 90% and 99.73% CL (2 dof) for solar and KamLAND (left), and atmospheric and MINOS (right), as well as the 99.73% CL regions for the respective combined analyses.

Summarizing:

Both the solar and atmospheric puzzles can be properly explained in terms of two-flavor neutrino oscillations:

- **solar**: $\nu_e \leftrightarrow \nu_a$ (linear combination of ν_μ and ν_τ): $\Delta m^2 \sim 10^{-4}$ eV^2, $\sin^2\theta \sim 0.3$.
- **atmospheric**: $\nu_\mu \leftrightarrow \nu_\tau$: $\Delta m^2 \sim 10^{-3}$ eV^2, $\sin^2\theta \sim 0.5$ ("maximal mixing").
- **short-baseline reactors:** $\nu_e \leftrightarrow \nu_a$ (linear combination of ν_μ and ν_τ): $\Delta m^2 \sim 10^{-3}$ eV^2, $\sin^2\theta \sim 0.02$.

A Really Reasonable, Simple Paradigm:

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

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

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}; \quad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$$

[For a detailed discussion see e.g. AdG, Jenkins, PRD78, 053003 (2008)]

Three-Flavor Paradigm Fits All* Data Really Well (arXiv:1209.3023):

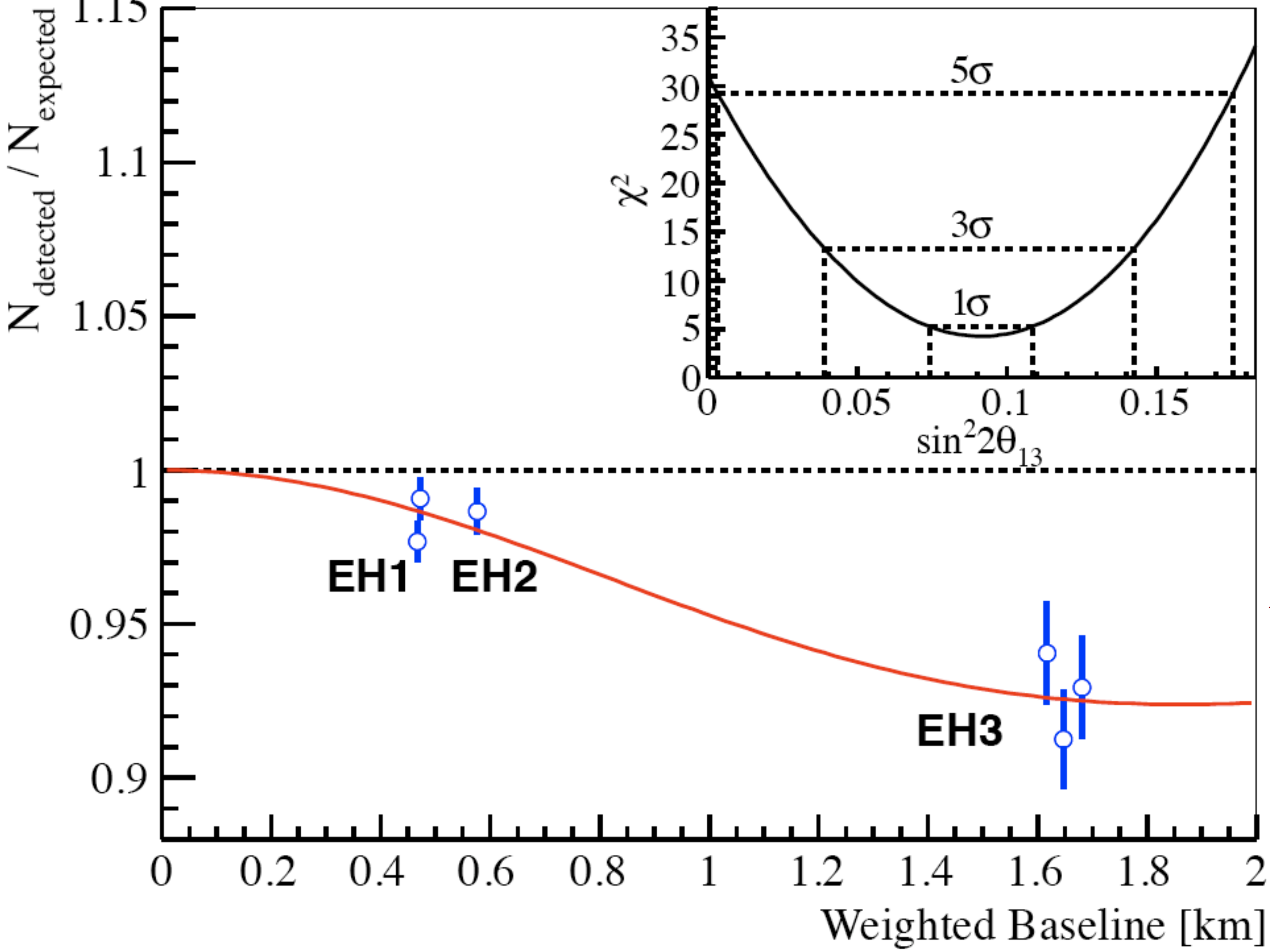
	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	0.30 ± 0.013	$0.27 \to 0.34$	0.31 ± 0.013	$0.27 \to 0.35$
$\theta_{12}/^\circ$	33.3 ± 0.8	$31 \to 36$	33.9 ± 0.8	$31 \to 36$
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.34 \to 0.67$	$0.41^{+0.030}_{-0.029} \oplus 0.60^{+0.020}_{-0.026}$	$0.34 \to 0.67$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.2}_{-1.3}$	$36 \to 55$	$40.1^{+2.1}_{-1.7} \oplus 50.7^{+1.1}_{-1.5}$	$36 \to 55$
$\sin^2\theta_{13}$	0.023 ± 0.0023	$0.016 \to 0.030$	0.025 ± 0.0023	$0.018 \to 0.033$
$\theta_{13}/^\circ$	$8.6^{+0.44}_{-0.46}$	$7.2 \to 9.5$	$9.2^{+0.42}_{-0.45}$	$7.7 \to 10.$
$\delta_{\rm CP}/^\circ$	240^{+102}_{-74}	$0 \to 360$	238^{+95}_{-51}	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	7.50 ± 0.185	$7.00 \to 8.09$	$7.50^{+0.205}_{-0.160}$	$7.04 \to 8.12$
$\dfrac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$2.47^{+0.069}_{-0.067}$	$2.27 \to 2.69$	$2.49^{+0.055}_{-0.051}$	$2.29 \to 2.71$
$\dfrac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.43^{+0.042}_{-0.065}$	$-2.65 \to -2.24$	$-2.47^{+0.073}_{-0.064}$	$-2.68 \to -2.25$

Table 1: Three-flavour oscillation parameters from our fit to global data after the Neutrino 2012 conference. For "Free Fluxes + RSBL" reactor fluxes have been left free in the fit and short baseline reactor data (RSBL) with $L \lesssim 100$ m are included; for "Huber Fluxes, no RSBL" the flux prediction from [42] are adopted and RSBL data are not used in the fit.

* Modulo Short-Baseline Anomalies

Atmospheric Oscillations in the Electron Sector: Daya Bay, RENO, Double Chooz

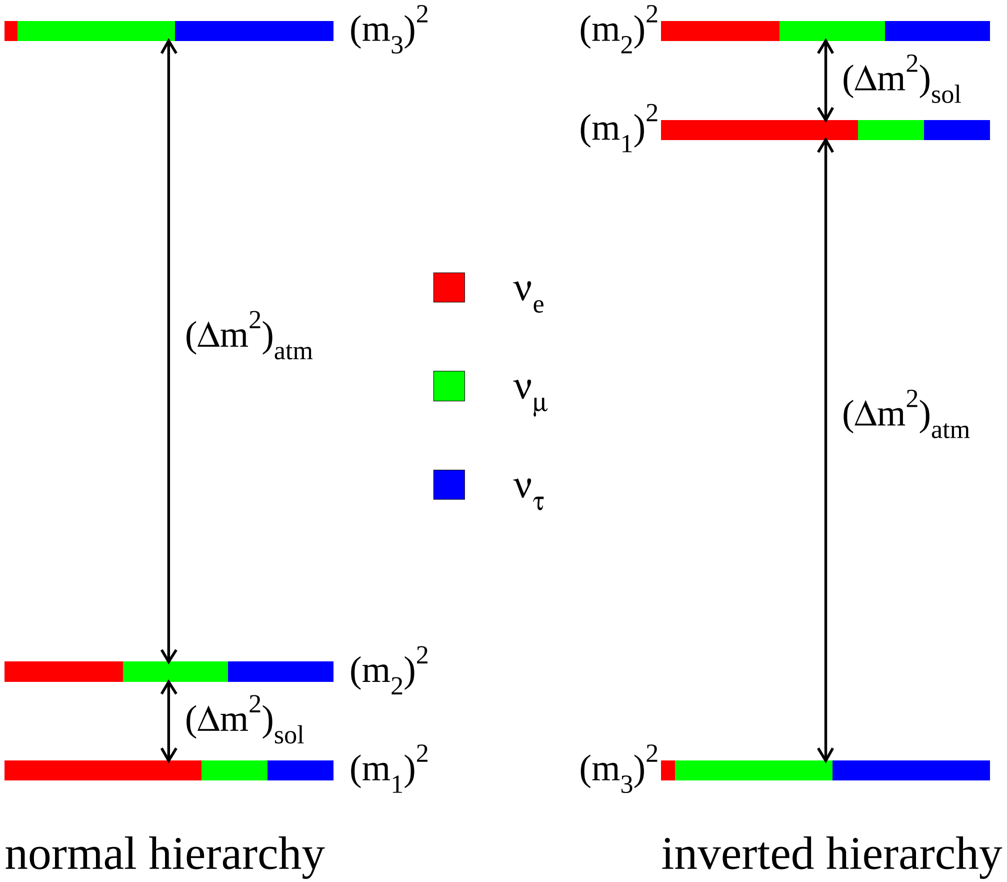
$$\text{phase}= 0.64\left(\frac{\Delta m^2}{2.5\times10^{-3}\ \text{eV}^2}\right)\left(\frac{5\ \text{MeV}}{E}\right)\left(\frac{L}{1\ \text{km}}\right)$$



Triumph of the 3 flavor paradigm!

$$P_{ee} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

What We Know We Don't Know: "Missing" Oscillation Parameters

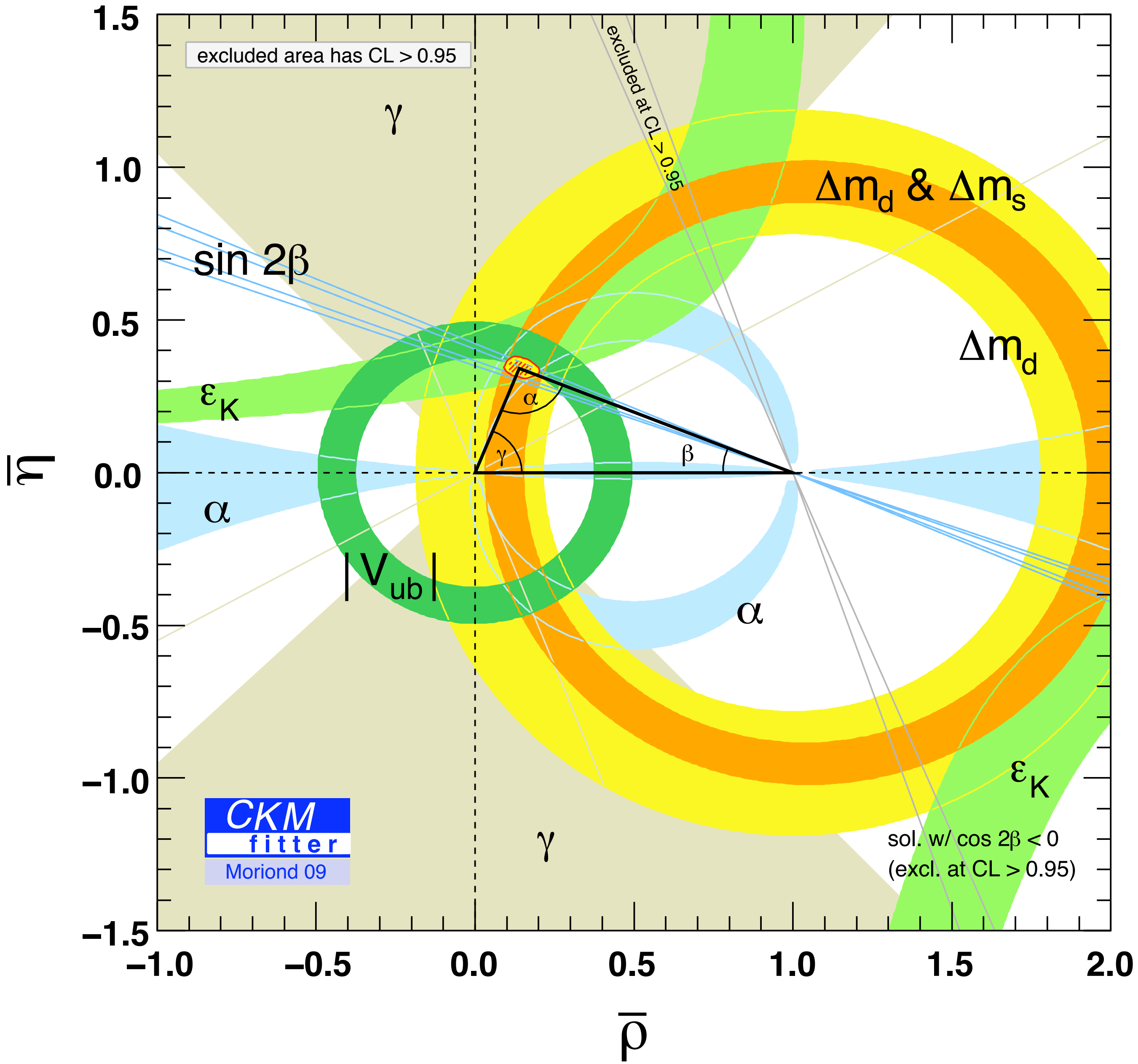


- ~~What is the ν_e component of ν_3?~~ $(\theta_{13} \neq 0!)$
- Is CP-invariance violated in neutrino oscillations? $(\delta \neq 0, \pi?)$
- Is ν_3 mostly ν_μ or ν_τ? $(\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4?)$
- What is the neutrino mass hierarchy? $(\Delta m^2_{13}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

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

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

What we ultimately want to achieve:



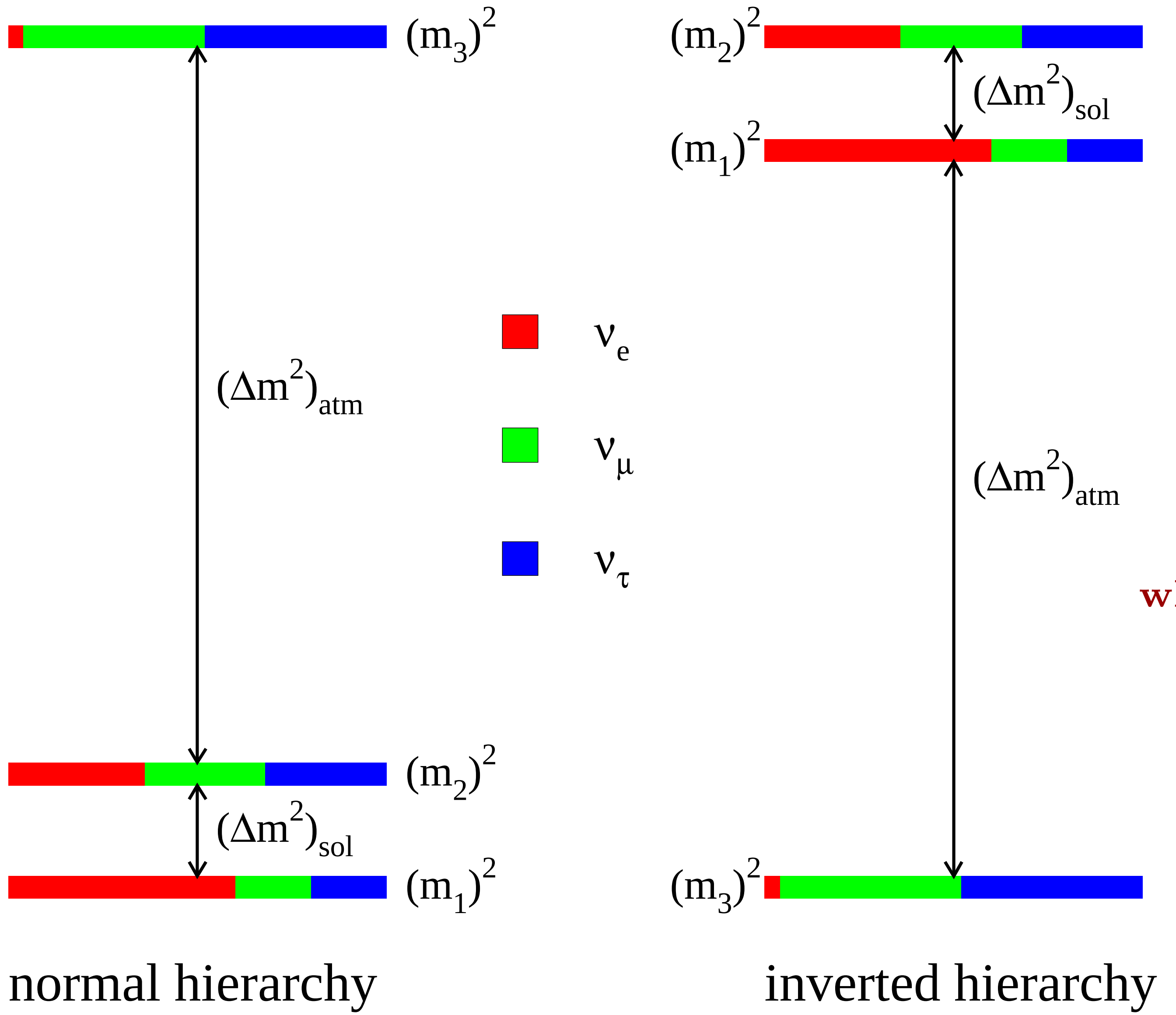
We need to do this in the lepton sector!

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

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 $\rightarrow$ hint) – MINOS, T2K.

We still have a ways to go!



The Neutrino Mass Hierarchy

which is the right picture?

Why Don't We Know the Neutrino Mass Hierarchy?

Most of the information we have regarding θ_{23} and Δm^2_{13} comes from atmospheric neutrino experiments (SuperK). Roughly speaking, they measure

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

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 $\frac{\Delta m^2_{12}}{\Delta m^2_{13}} < 0.06$ are both small, we are yet to observe the subleading effects.

Determining the Mass Hierarchy via Oscillations – the large U_{e3} route ($\checkmark$)

Again, necessary to probe $\nu_\mu \to \nu_e$ oscillations (or vice-versa) governed by Δm^2_{13}. This is the oscillation channel that (almost) all next-generation, accelerator-based experiments are concentrating on, including the next generation experiments T2K and NOνA.

In vaccum

$$P_{\mu e} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{13}L}{4E}\right) + \text{ “subleading”},$$

so that, again, this is insensitive to the sign of Δm^2_{13} at leading order. However, in this case, matter effects may come to the rescue.

In a nutshell, neutrino oscillations get modified when these propagate in the presence of matter. Matter effects are sensitive to the neutrino mass ordering (in a way that I will describe shortly) and different for neutrinos and antineutrinos.

If $\Delta_{12} \equiv \frac{\Delta m^2_{12}}{2E}$ terms are ignored, the $\nu_\mu \to \nu_e$ oscillation probability is described, in constant matter density, by

$$P_{\mu e} \simeq P_{e\mu} \simeq \sin^2\theta_{23}\sin^2 2\theta^{\rm eff}_{13}\sin^2\left(\frac{\Delta^{\rm eff}_{13}L}{2}\right),$$

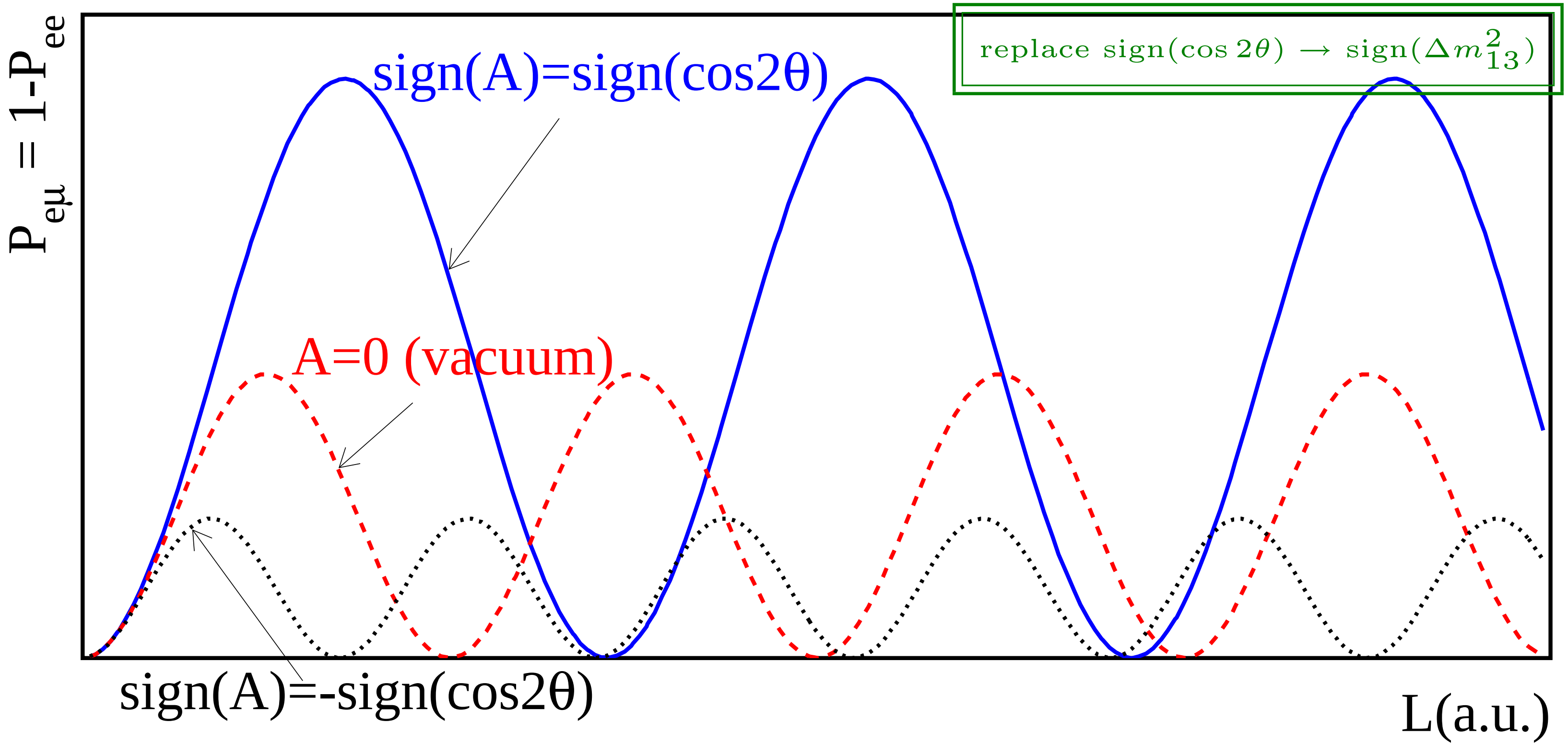
$$\sin^2 2\theta^{\rm eff}_{13} = \frac{\Delta^2_{13}\sin^2 2\theta_{13}}{(\Delta^{\rm eff}_{13})^2},$$

$$\Delta^{\rm eff}_{13} = \sqrt{(\Delta_{13}\cos 2\theta_{13} - A)^2 + \Delta^2_{13}\sin^2 2\theta_{13}},$$

$$\Delta_{13} = \frac{\Delta m^2_{13}}{2E},$$

$A \equiv \pm\sqrt{2}G_F N_e$ is the matter potential. It is positive for neutrinos and negative for antineutrinos.

$P_{\mu e}$ depends on the relative sign between Δ_{13} and A. It is different for the two different mass hierarchies, and different for neutrinos and antineutrinos.



Requirements:

- $\sin^2 2\theta_{13}$ large enough – otherwise there is nothing to see!
- $|\Delta_{13}| \sim |A|$ – matter potential must be significant but not overwhelming.
- $\Delta_{13}^{\rm eff} L$ large enough – matter effects are absent near the origin.

The "Holy Graill" of Neutrino Oscillations – CP Violation

In the old Standard Model, there is only one[a] source of CP-invariance violation:

⇒ The complex phase in V_{CKM}, the quark mixing matrix.

Indeed, as far as we have been able to test, all CP-invariance violating phenomena agree with the CKM paradigm:

- ϵ_K;
- ϵ'_K;
- $\sin 2\beta$;
- etc.

Neutrino masses and lepton mixing provide strong reason to believe that other sources of CP-invariance violation exist.

[a] modulo the QCD θ-parameter, which will be "willed away" as usual.

CP-invariance Violation in Neutrino Oscillations

The most promising approach to studying CP-violation in the leptonic sector seems to be to compare $P(\nu_\mu \to \nu_e)$ versus $P(\bar{\nu}_\mu \to \bar{\nu}_e)$.

The amplitude for $\nu_\mu \to \nu_e$ transitions can be written as

$$A_{\mu e} = U_{e2}^* U_{\mu 2} \left(e^{i\Delta_{12}} - 1\right) + U_{e3}^* U_{\mu 3} \left(e^{i\Delta_{13}} - 1\right)$$

where $\Delta_{1i} = \frac{\Delta m_{1i}^2 L}{2E}$, $i = 2, 3$.

The amplitude for the CP-conjugate process can be written as

$$\bar{A}_{\mu e} = U_{e2} U_{\mu 2}^* \left(e^{i\Delta_{12}} - 1\right) + U_{e3} U_{\mu 3}^* \left(e^{i\Delta_{13}} - 1\right).$$

[remember: according to unitarty, $U_{e1}U_{\mu 1}^* = -U_{e2}U_{\mu 2}^* - U_{e3}U_{\mu 3}^*$]

In general, $|A|^2 \neq |\bar{A}|^2$ (CP-invariance violated) as long as:

- Nontrivial "Weak" Phases: $\arg(U_{ei}^* U_{\mu i}) \to \delta \neq 0, \pi$;
- Nontrivial "Strong" Phases: Δ_{12}, $\Delta_{13} \to L \neq 0$;
- Because of Unitarity, we need all $|U_{\alpha i}| \neq 0 \to$ three generations.

All of these can be satisfied, with a little luck: given that two of the three mixing angles are known to be large, **we need** $|U_{e3}| \neq 0$**.** ✓

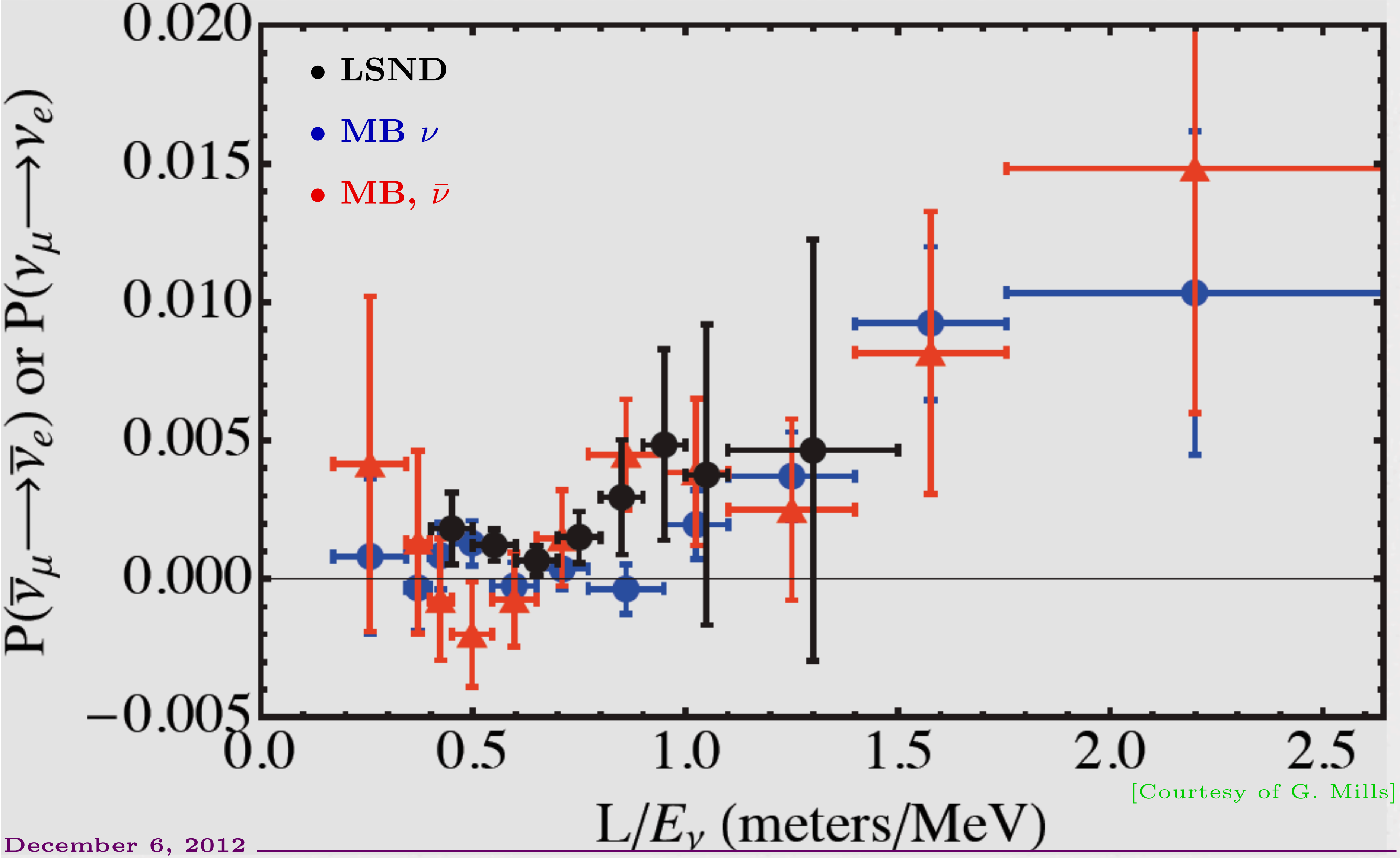
Not all is well(?): The Short Baseline Anomalies

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.

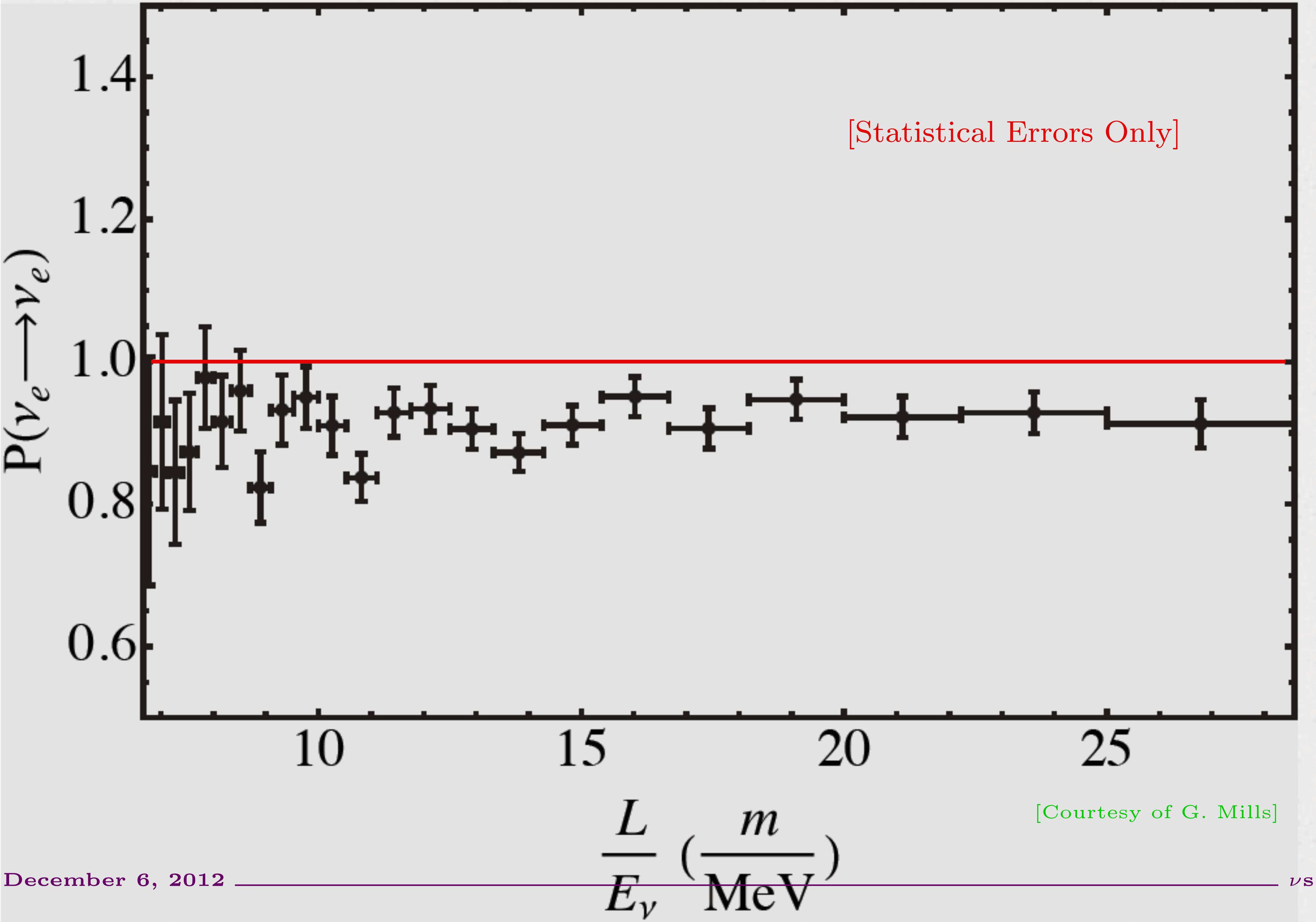
None are entirely convincing, either individually or combined. However, there may be something very very interesting going on here…

MiniBooNE & LSND



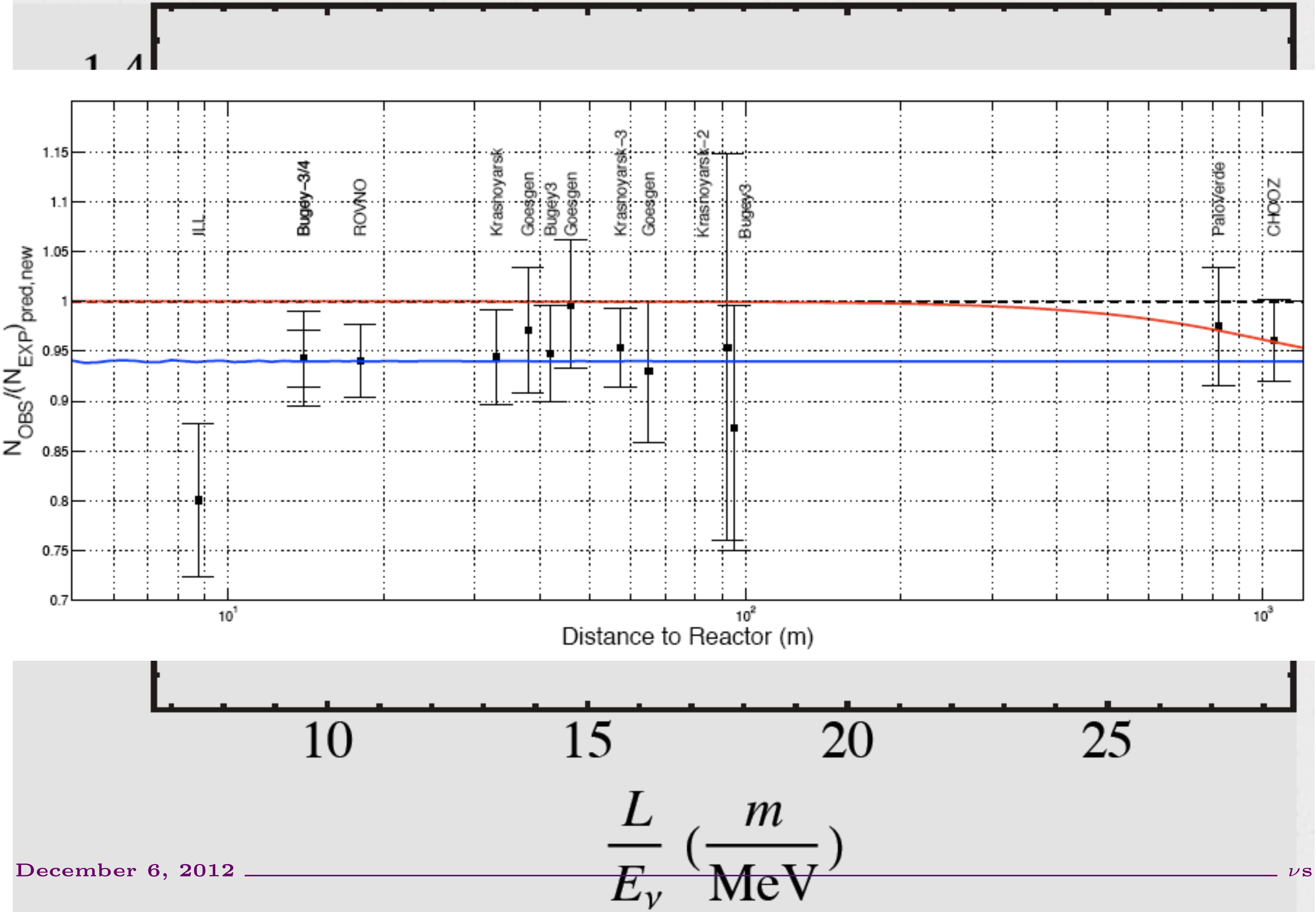
[Courtesy of G. Mills]

Bugey 40 m



1.4
1.2
1.0
0.8
0.6
$P(\nu_e \longrightarrow \nu_e)$
[Statistical Errors Only]
10
15
20
25
$\frac{L}{E_\nu}\left(\frac{m}{\mathrm{MeV}}\right)$
[Courtesy of G. Mills]

Bugey 40 m



1.4
ILL
Bugey-3/4
ROVNO
Krasnoyarsk
Goesgen
Bugey3
Goesgen
Krasnoyarsk-3
Goesgen
Krasnoyarsk-2
Bugey3
PaloVerde
CHOOZ
$N_{OBS}/(N_{EXP})_{pred,new}$
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
10^1
10^2
10^3
Distance to Reactor (m)
10
15
20
25
$\frac{L}{E_\nu}\ (\frac{m}{\mathrm{MeV}})$

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!

Observable wish list:

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

Something Different: Neutrino Magnetic Moments

Now that neutrinos have mass, they **must** also have a nonzero magnetic moment μ_ν.

The nature of μ_ν will depend on whether the neutrino is its own antiparticle:

$$\mathcal{L}_{m.m.} = \mu_\nu^{ij}(\nu_i \sigma_{\mu\nu} \nu_j F^{\mu\nu}) + H.c.,$$

$$\mu_\nu^{ij} = -\mu_\nu^{ji}, \quad i,j = 1,2,3 \ \rightarrow \ \text{Majorana Magnetic Moment}$$

or

$$\mathcal{L}_{m.m.} = \mu_\nu^{ij}(\bar{\nu}_i \sigma_{\mu\nu} N F^{\mu\nu}) + H.c.,$$

$$i,j = 1,2,3 \ \rightarrow \ \text{Dirac Magnetic Moment}$$

This is not exotic physics, nor "optional." The issue is how large the effects are!

In either version of the new SM, μ is really small:

$$\mu \leq \frac{3eG_F}{8\sqrt{2}\pi^2}m_\nu = 3\times 10^{-20}\mu_B\left(\frac{m_\nu}{10^{-1}\text{ eV}}\right); \qquad \mu_B = \frac{e}{2m_e}$$

Transition moments are even smaller, GIM suppressed by $(m_\tau/M_W)^2 \sim 10^{-4}$.

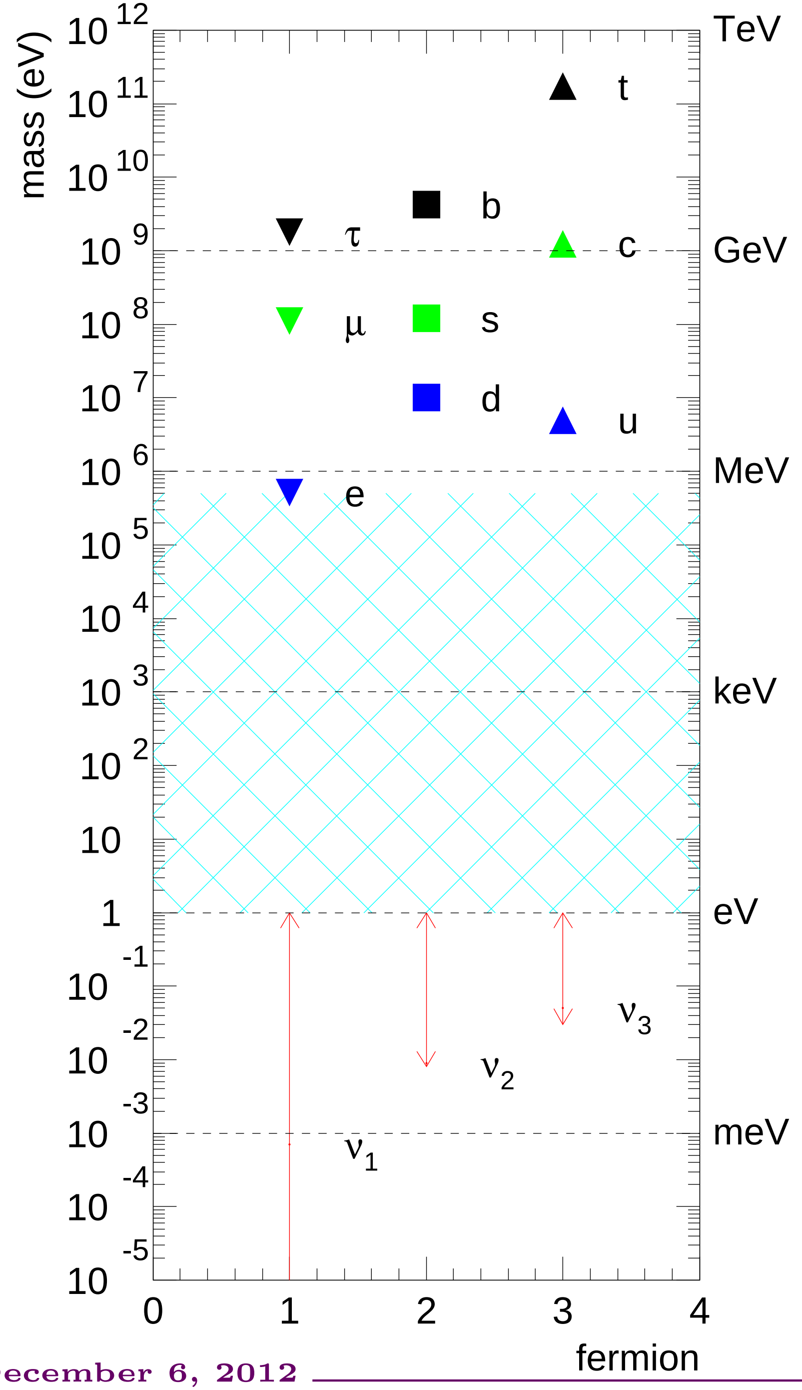
Bounds come from a variety of sources and constrain different linear combination of elements of μ.

- $\bar{\nu}_e e^- \to \nu_\beta\ (\bar{\nu}_\beta)\ e^-$, $\forall\beta\ (\beta = e,\mu,\tau)$ TEXONO, MUNU reactor expt's, SuperK solar
- searches for electron antineutrinos from the Sun $(\nu_e \stackrel{(m.m.)}{\to} \bar{\nu}_\beta \stackrel{(\text{osc})}{\to} \bar{\nu}_e)$ $\vec{B}$ in the Sun?, how well oscillation parameters are known? (KamLAND!)
- astrophysics red giants, SN1987A, ...

$$\Rightarrow \boxed{\boxed{\mu_\nu < 1.5\times 10^{-10}\mu_B}} \quad \text{(PDG accepted bound);}$$

also $O(10^{-[12\div 11]})$ bounds from astrophysics and solar neutrinos.

Will we ever get to such a tiny effect?



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?

Who Cares About Neutrino Masses: “Palpable” Evidence of Physics Beyond the Standard Model*

The SM we all learned in school predicts that neutrinos are strictly massless. 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 understanding of fundamental physics is yet to explain properly. These are in order of palpability (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 does the Universe appear to be accelerating? Why does it appear that the Universe underwent rapid acceleration in the past? (certainly 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]

On Electroweak Symmetry Breaking

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 and charged-lepton flavor violation may provide more information.

Searches for nucleon decay provide the only handle on a new energy scale (3) if that new scale happens to be very small. Unique capability!

νSM – One Possibility

SM as an effective field theory – non-renormalizable operators

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

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

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

- 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 $y^{\max} \equiv 1$]

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

Example: the 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.

To be determined from data: λ and M.

The data can be summarized as follows: there is evidence for three neutrinos, mostly "active" (linear combinations of ν_e, ν_μ, and ν_τ). At least two of them are massive and, if there are other neutrinos, they have to be "sterile."

This provides very little information concerning the magnitude of M_i (assume $M_1 \sim M_2 \sim M_3$)

Theoretically, there is prejudice in favor of very large M: $M \gg v$. Popular examples include $M \sim M_{\rm GUT}$ (GUT scale), or $M \sim 1$ TeV (EWSB scale).

Furthermore, $\lambda \sim 1$ translates into $M \sim 10^{14}$ GeV, while thermal leptogenesis requires the lightest M_i to be around 10^{10} GeV.

we can impose very, very few experimental constraints on M

What We Know About M:

- $M = 0$: 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 $m_{\alpha\beta} = \sum_i \mu_{\alpha i} M_i^{-1} \mu_{\beta i}$ $[m = 1/\Lambda \;\Rightarrow\; \Lambda = M/\mu^2]$.

  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).

[ASIDE: Why are Neutrino Masses Small in the $M \neq 0$ Case?]

If $\mu \ll M$, 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.

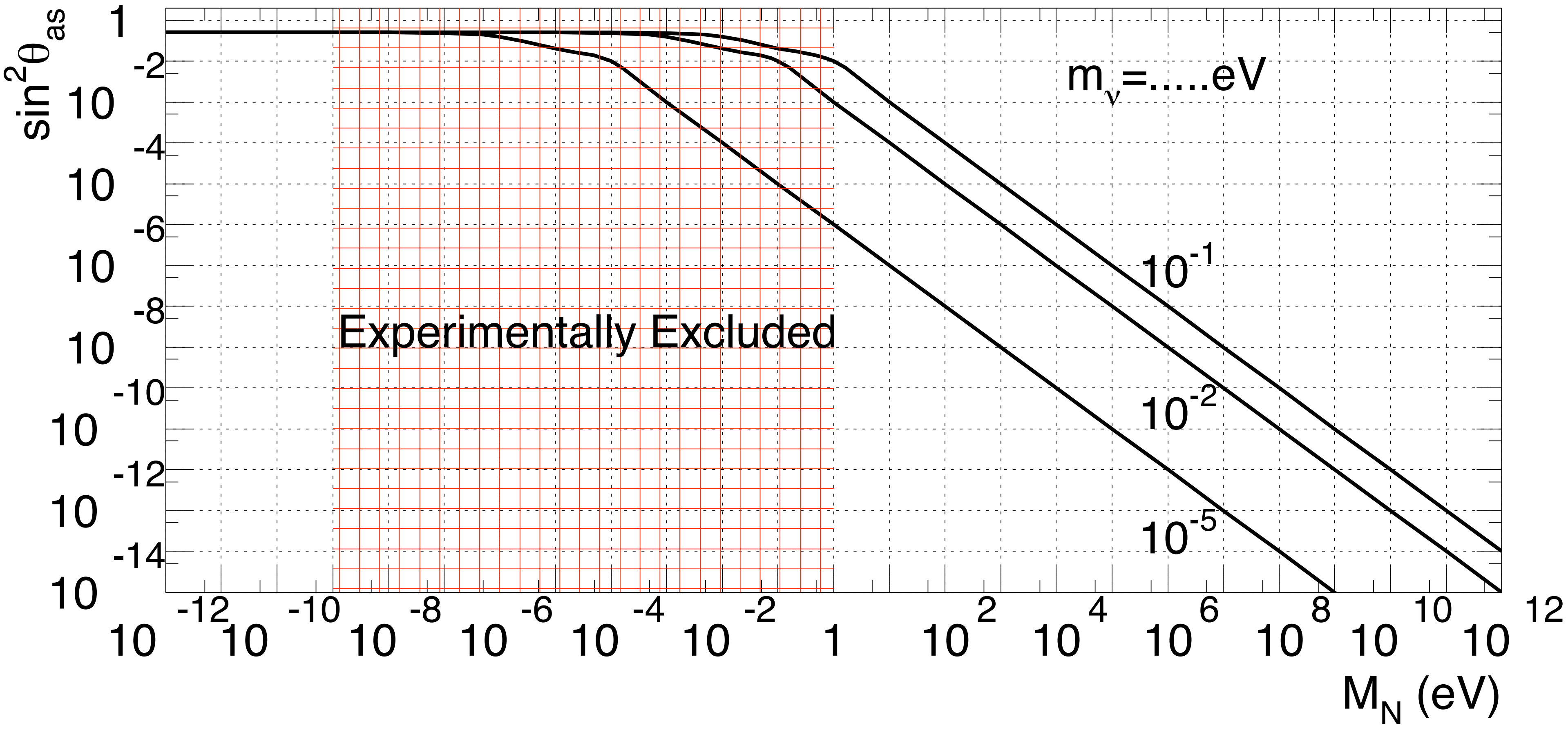
In the case of the seesaw,

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

so neutrino masses are small if either

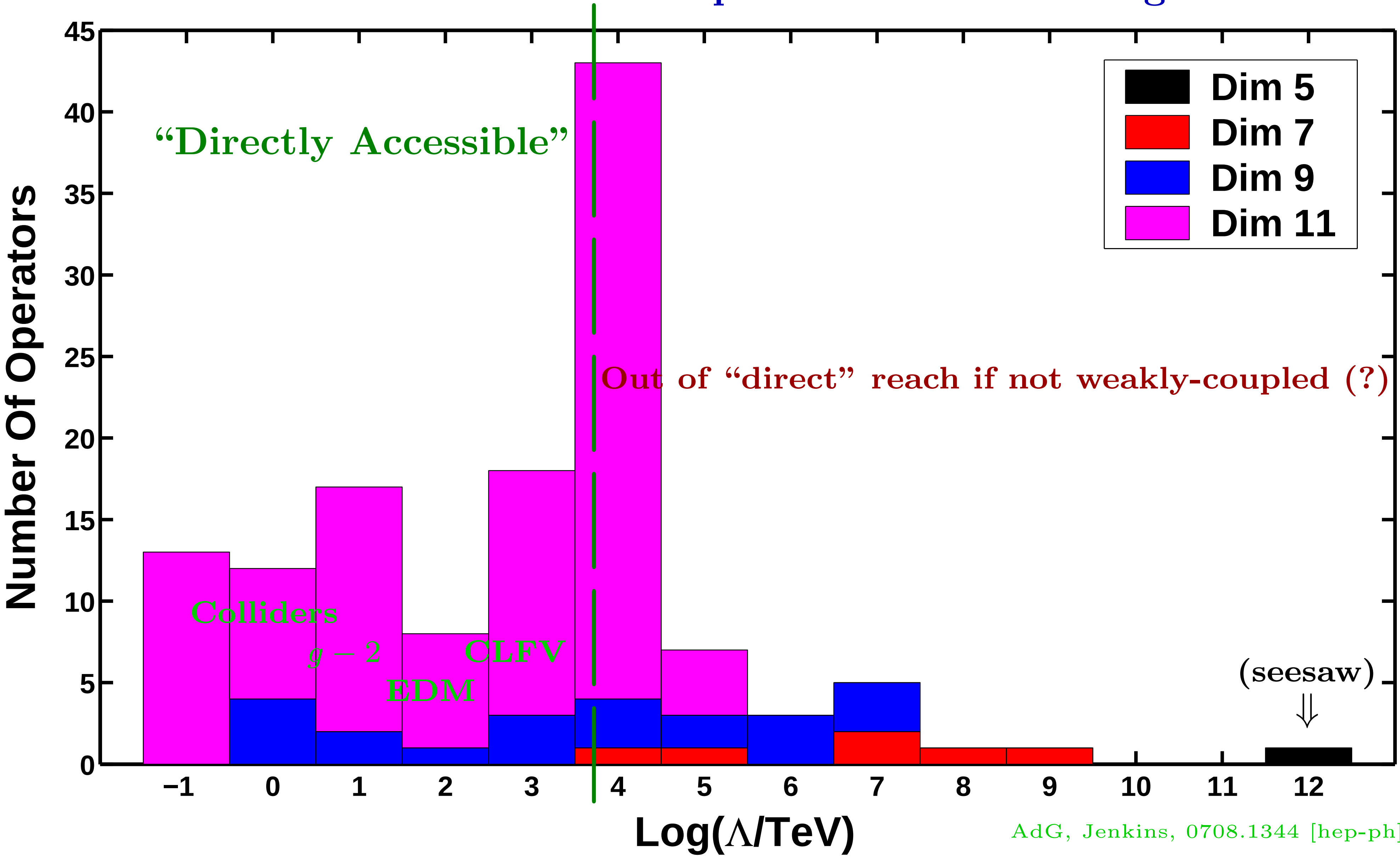
- they are generated by physics at a very high energy scale $M \gg v$ (high-energy seesaw); or
- they arise out of a very weak coupling between the SM and a new, hidden sector (low-energy seesaw); or
- cancellations among different contributions render neutrino masses accidentally small ("fine-tuning").

Constraining the Seesaw Lagrangian



[AdG, Huang, Jenkins, arXiv:0906.1611]

This is Just the Tip of the Model-Iceberg!



AdG, Jenkins, 0708.1344 [hep-ph]

Understanding Fermion Mixing

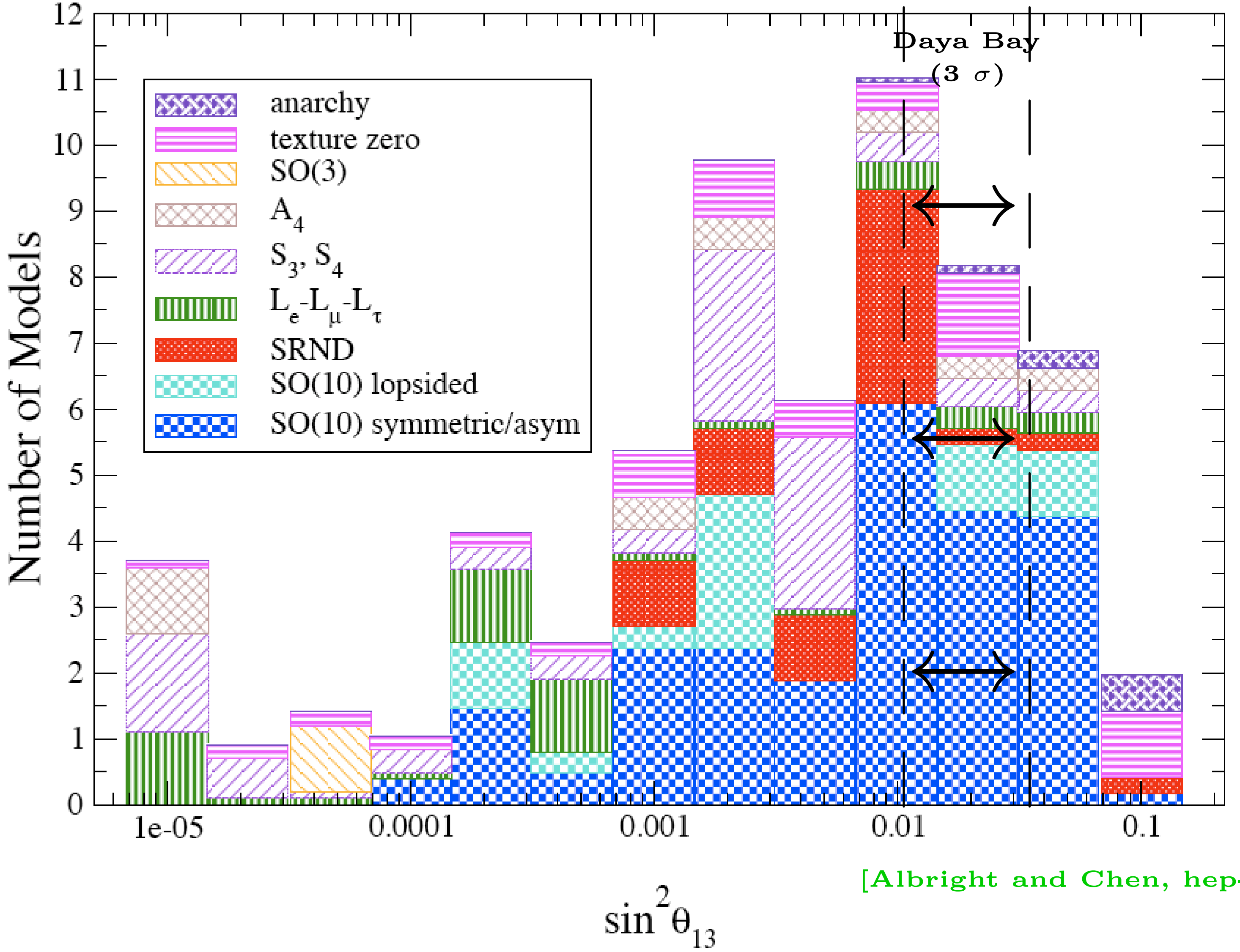
The other puzzling phenomenon uncovered by the neutrino data is the fact that Neutrino Mixing is Strange. What does this mean?

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

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

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

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, $\cos 2\theta_{23}$. More important: CORRELATIONS!

Lepton Mixing Anarchy is the hypothesis that there is *no symmetry principle* behind the leptonic mixing matrix U.

In more concrete terms, it postulates that the observed leptonic mixing matrix can be described as the result of a *random draw* from an unbiased distribution of unitary 3×3 matrices.

This is *not a very ambitious model.* It does not make predictions for the values of any of the mixing parameters, nor does it predict any correlations among the different mixing parameters. It does not, obviously, allow one to reduce the number of mixing parameters compared to those in the lepton mixing sector of the νSM.

The Anarchy hypothesis, however, *does make some predictions*. It predicts a *probability distribution* for the different parameters that parameterize U. The distributions are parameterization dependent, but unique once a parameterization is fixed.

[Murayama et al, hep-ph/9911341, hep-ph/0009174, hep-ph/0301050, 1204.1249]

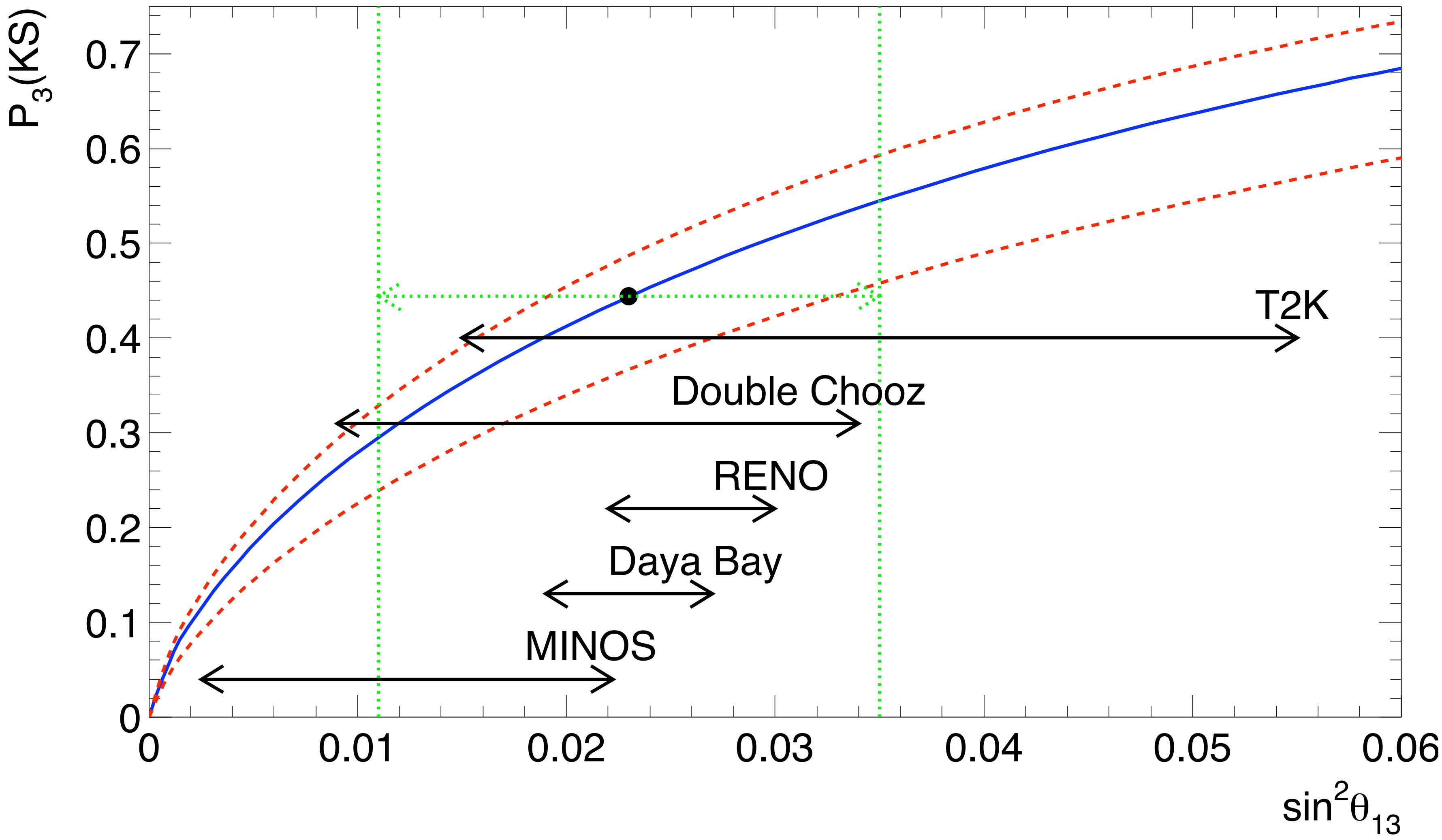
The probability distributions, first derived by Haba and Murayama, hep-ph/0009174, are easy to obtain. The idea is that they are invariant under a basis redefinition of the neutrino weak eigenstates, i.e, weak-basis independent. They are given by the *invariant Haar measure* of $U(3)$ (assuming that U is a 3×3 unitary matrix).

This is similar to obtaining the probability distribution for picking a point on the surface of a sphere from $\mathrm{d}A = \mathrm{d}\cos\theta \mathrm{d}\phi$. The probability density is flat in ϕ and flat in $\cos\theta$.

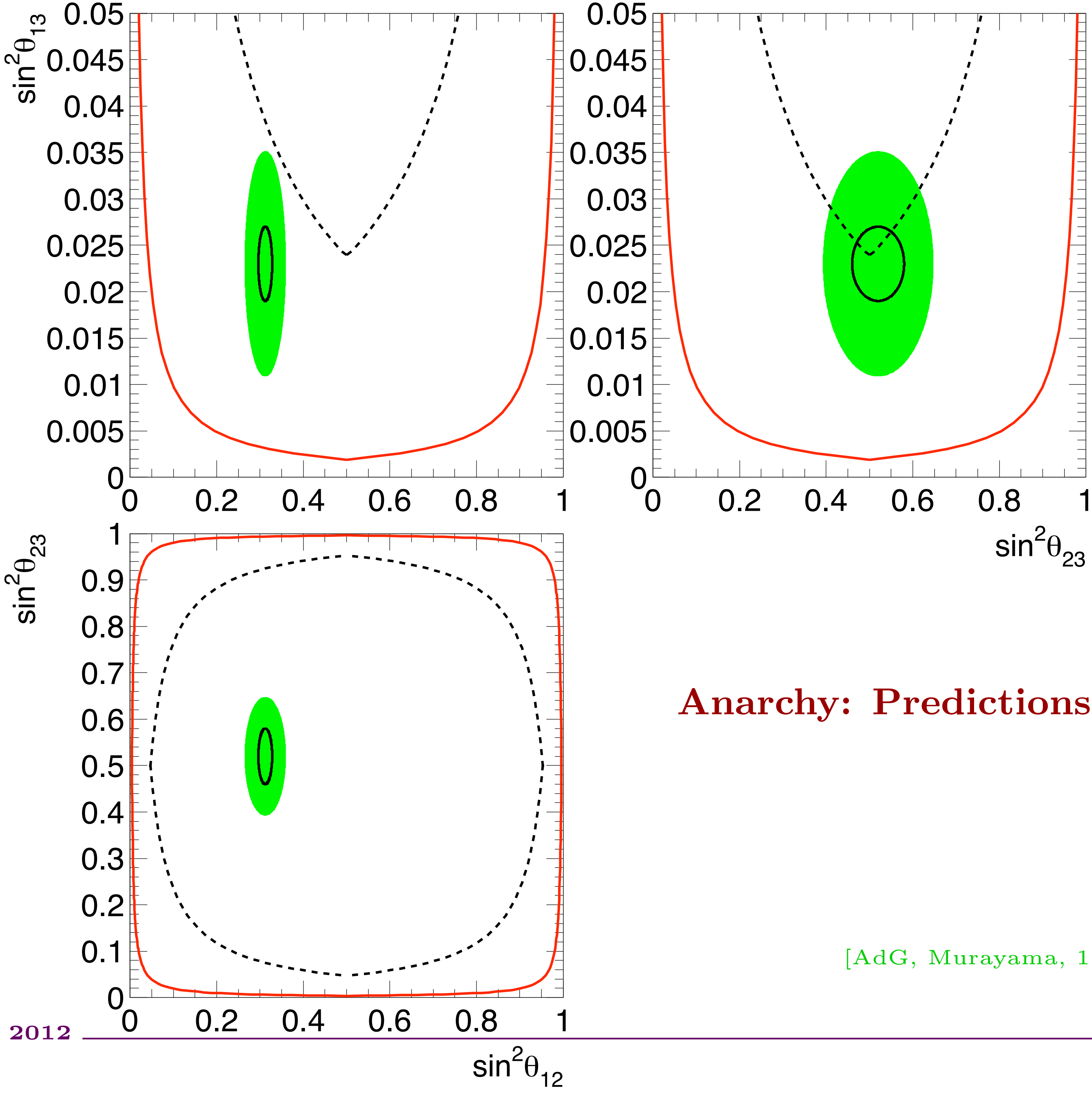
For unitary 3×3 matrices, using the standard PDG parameterization, one gets that the probability distribution is **flat** in

$$\sin^2\theta_{12} \qquad \sin^2\theta_{23} \qquad \cos^4\theta_{13} \qquad \delta \qquad \phi_{1,2} \text{ (Majorana phases).}$$

Neutrino Mixing Anarchy: Alive and Kicking!



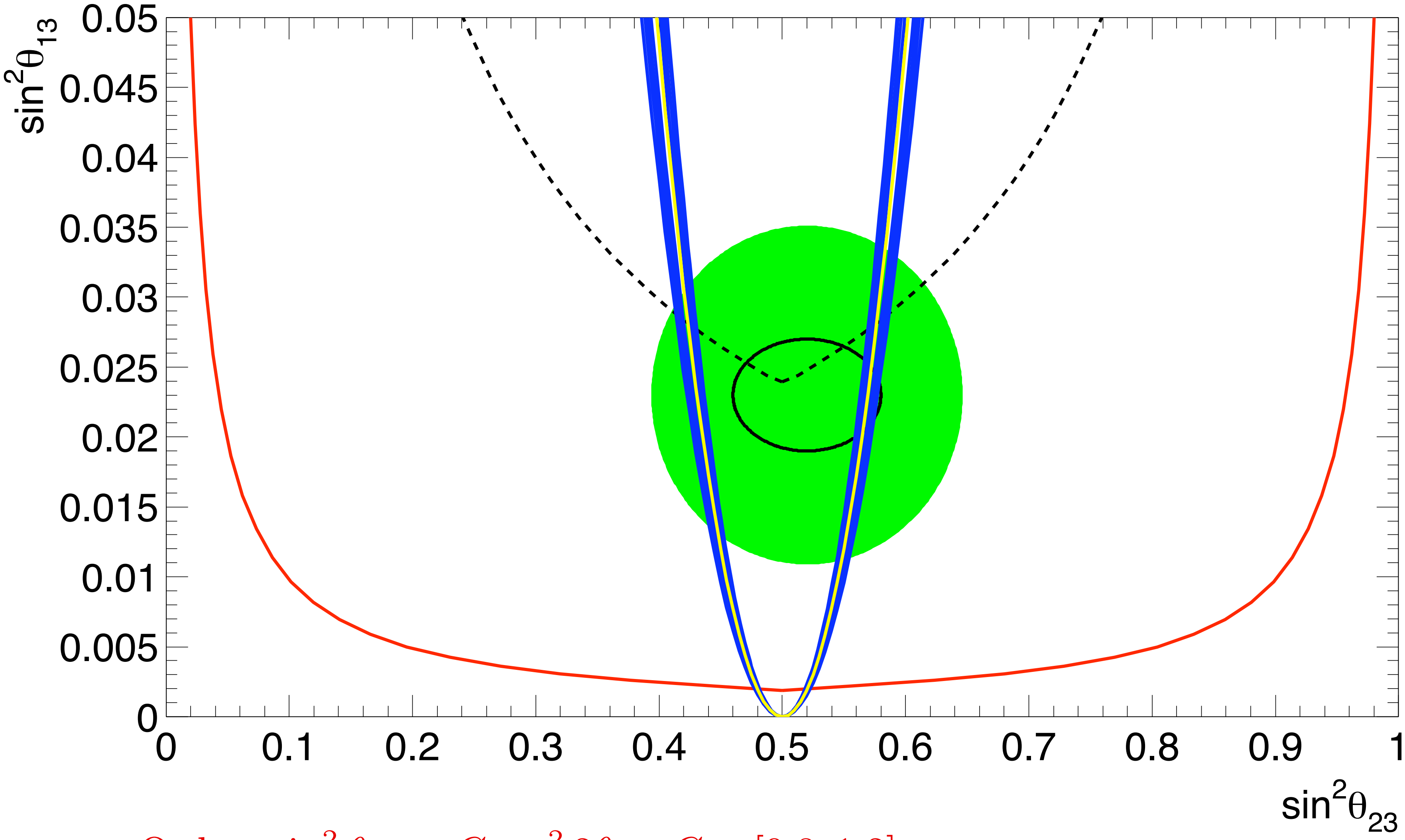
[AdG, Murayama, 1204.1249]



Anarchy: Predictions

[AdG, Murayama, 1204.1249]

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]

How Do We Learn More?

In order to learn more, we need more information. Any new data and/or idea is welcome, including

- searches for charged lepton flavor violation;

  ($\mu \to e\gamma$, $\mu \to e$-conversion in nuclei, etc)

- searches for lepton number violation;

  (neutrinoless double beta decay, etc)

- precision measurements of the neutrino oscillation parameters;

  (Daya Bay, NOνA, etc)

- searches for fermion electric/magnetic dipole moments

  (electron edm, muon $g-2$, etc);

- precision studies of neutrino – matter interactions;

  (Minerνa, NuSOnG, etc)

- collider experiments:

  (LHC, etc)

  – *Can* we "see" the physics responsible for neutrino masses at the LHC? – YES!

    Must we see it? – NO, but we won't find out until we try!

  – we need to understand the physics at the TeV scale before we can really understand the physics behind neutrino masses (is there low-energy SUSY?, etc).

CONCLUSIONS

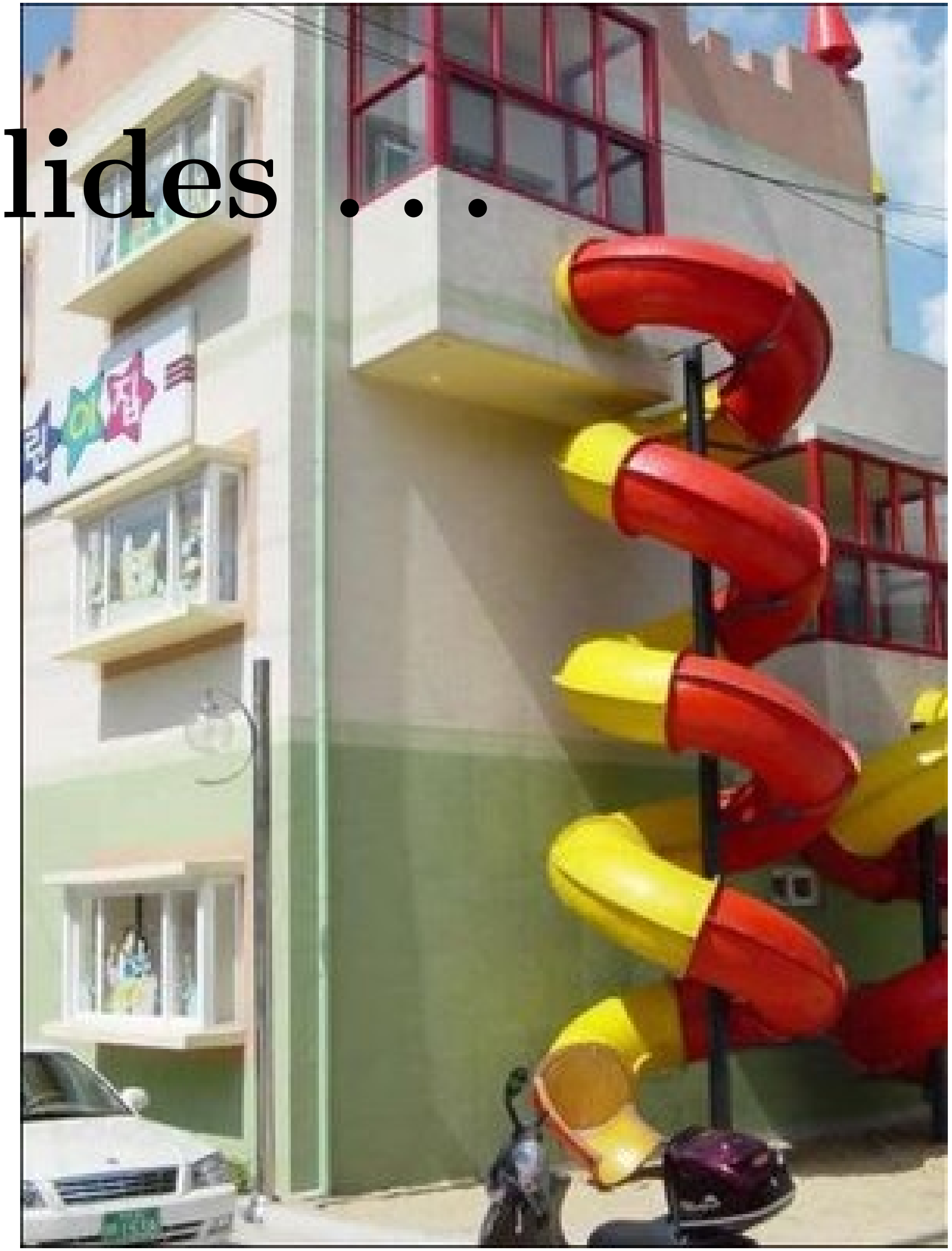
- we have a very successful parametrization of the neutrino sector, and we have identified what we know we don't know. This has been driving the neutrino program for a while now (and it should).
- To-do List (1): test the three flavor paradigm. Requirement: long baseline neutrino experiments. Several observables: neutrinos versus antineutrinos, different flavors, different beams.
- To-do List (2): test the short-baseline anomalies. Can we "move on" without resolving them? I would rather not.
- To-do List (3): we need a minimal νSM Lagrangian. In order to do this we must uncover the faith of baryon number minus lepton number ($0\nu\beta\beta$ is the best [only?] bet).

- To-do List (4): In order to succeed in (1) and (2), we need to understand, with good precision, how neutrinos of different energies interact with matter, and we need to properly characterize, with good precision, all of our neutrino "beams." Remember: CP-violation is a sub-leading (sub-10%) phenomenon!

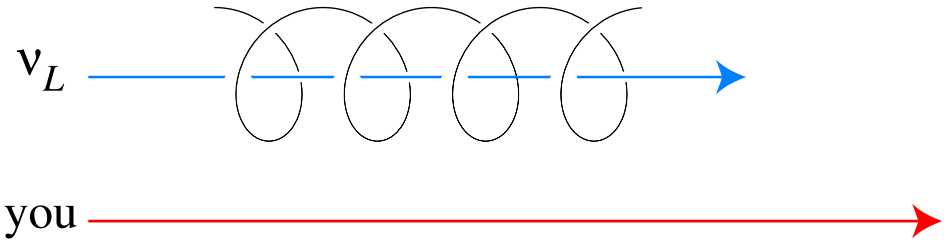
- We still know very little about the origin of neutrino masses. Do neutrinos talk to the Higgs boson? Do they talk to the Higgs boson in a different way? Do they talk to a different Higgs boson? Are neutrino masses evidence for a new mass scale? How do we find this out?

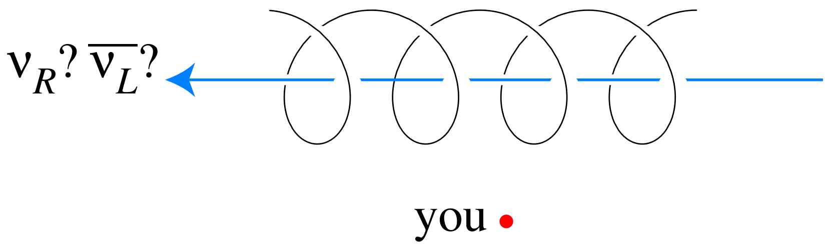
- There is plenty of room for surprises, as neutrinos are very narrow but deep probes of all sorts of physical phenomena. Remember that neutrino oscillations are "quantum interference devices" – potentially very sensitive to whatever else may be out there (e.g., $M_{\rm seesaw} \simeq 10^{14}$ GeV).

Backup Slides . . .



What We Know We Don't Know – Are Neutrinos Majorana Fermions?





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

$$(e^-_L \leftarrow \text{CPT} \rightarrow e^+_R)$$
$$\updownarrow \text{Lorentz}$$
$$(e^-_R \leftarrow \text{CPT} \rightarrow e^+_L)$$

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

$$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$$
$$\updownarrow \text{Lorentz} \qquad \text{“DIRAC”}$$
$$(\nu_R \leftarrow \text{CPT} \rightarrow \bar{\nu}_L)$$

$$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$$
$$\text{“MAJORANA”} \qquad \updownarrow \text{Lorentz}$$
$$(\bar{\nu}_R \leftarrow \text{CPT} \rightarrow \nu_L)$$

How many degrees of freedom are required to describe massive neutrinos?

Supernova Neutrinos

We are in the process of learning that neutrinos produced in supernova explosions oscillate in a very non-trivial way. The bottom line is that the flux of neutrinos from a supernova explosion carries a lot of very nontrivial information:

$\Phi_{\nu_\alpha,\bar{\nu}_\alpha} = f(\text{sign}(\Delta m^2_{13}), \text{astro}, \text{others})$, where others include μ.

We recently reported (AdG, Shalgar arXiv:1207.0516) that $\Phi_{\nu_\alpha,\bar{\nu}_\alpha}$ change qualitatively even for μ values close to the SM expectations, only if the neutrinos are Majorana fermions!

Only one more reason to keep this type of physics in mind!

CHALLENGES: measure ν and $\bar{\nu}$, measure ν_e and not ν_e, energy dependency, time dependency. And it would be nice if the neutrinos from the supernovae that exploded nearby got here already!