On Neutrino and Nucleon Decay Physics

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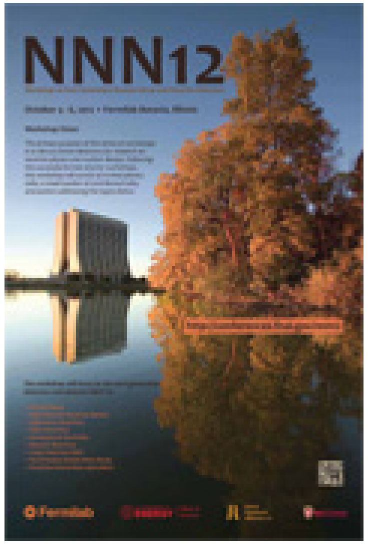


Next-Generation Nucleon Decay and Neutrino Detectors

Fermilab – October 4–6, 2012

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.

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:

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

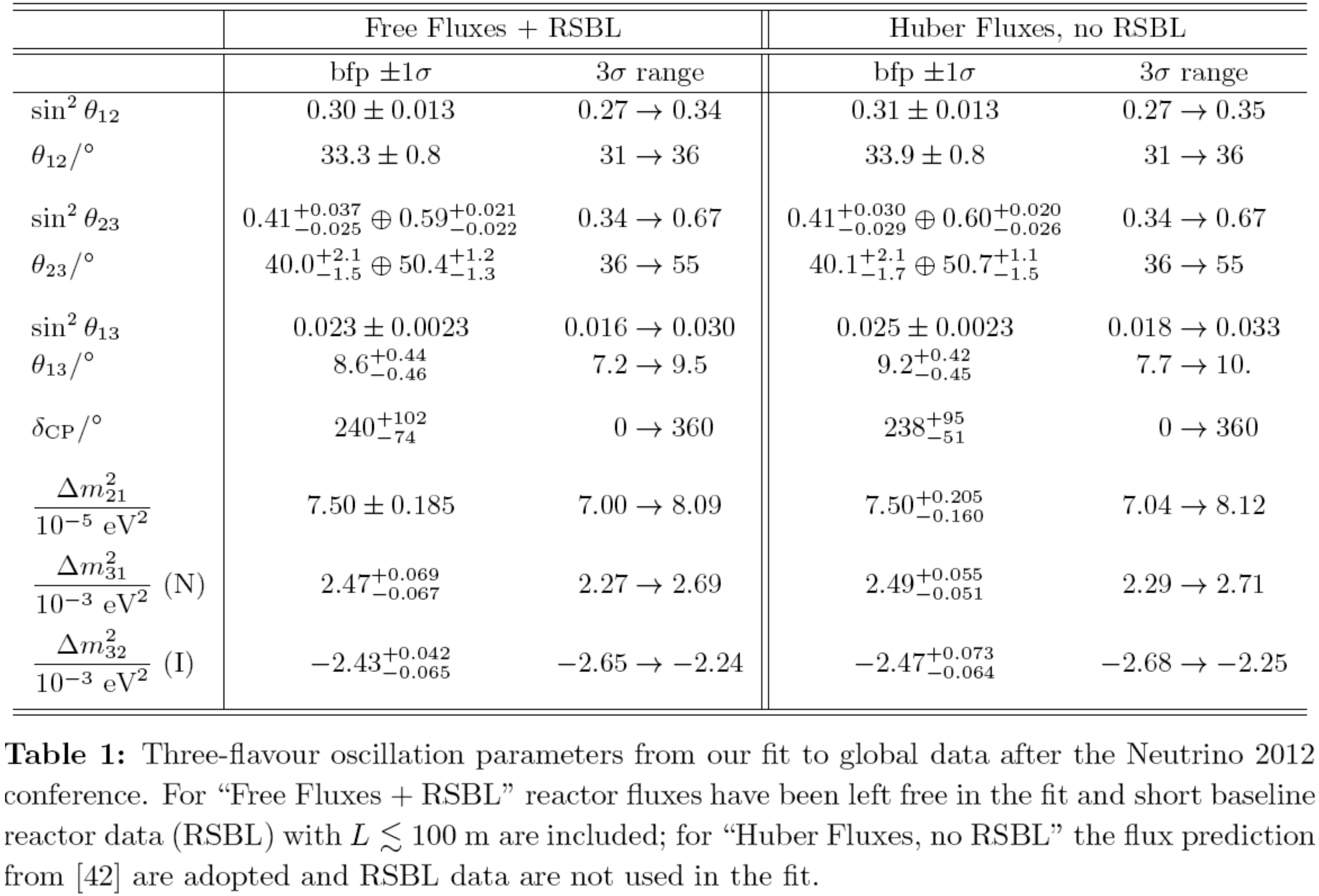
Definition of neutrino mass eigenstates (who are ν_1, ν_2, ν_3?):

- $m_1^2 < m_2^2$ $\Delta m^2_{13} < 0$ – 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 AdG, Jenkins, PRD78, 053003 (2008)]

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

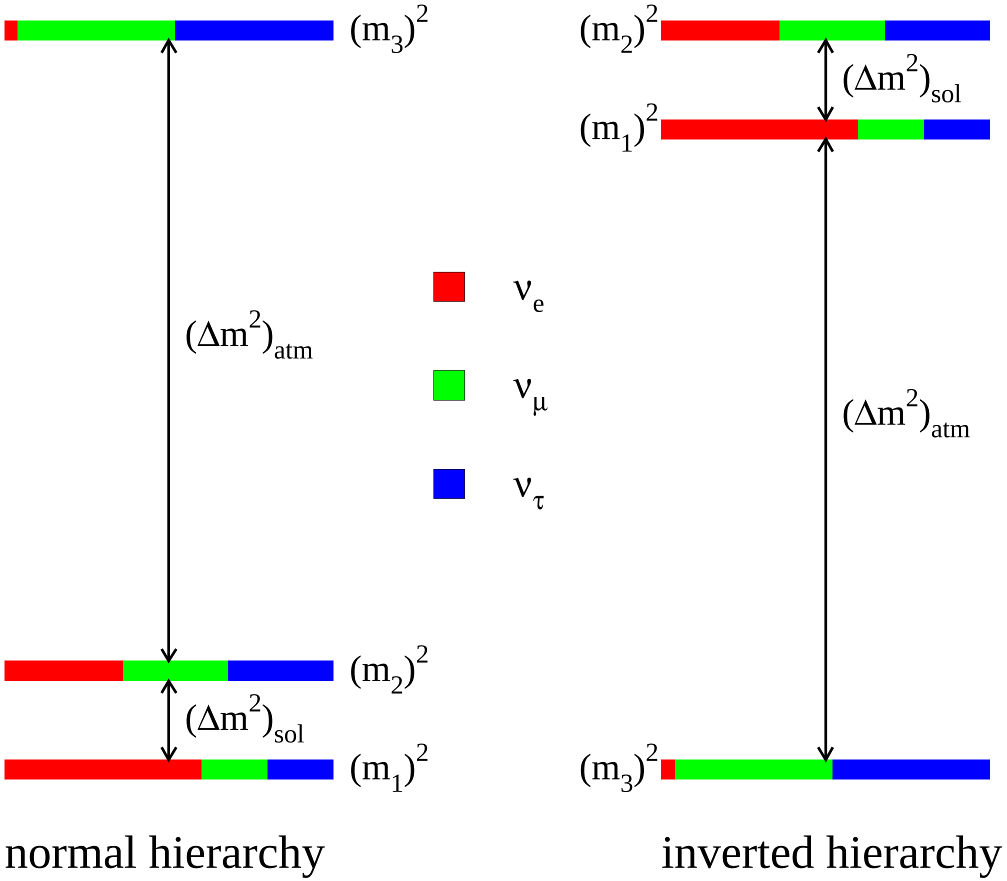


	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	0.30 ± 0.013	$0.27 \to 0.34$	0.31 ± 0.013	$0.27 \to 0.35$
$\theta_{12}/^\circ$	33.3 ± 0.8	$31 \to 36$	33.9 ± 0.8	$31 \to 36$
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.34 \to 0.67$	$0.41^{+0.030}_{-0.029} \oplus 0.60^{+0.020}_{-0.026}$	$0.34 \to 0.67$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.2}_{-1.3}$	$36 \to 55$	$40.1^{+2.1}_{-1.7} \oplus 50.7^{+1.1}_{-1.5}$	$36 \to 55$
$\sin^2\theta_{13}$	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}	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}~{\rm eV}^2}$	7.50 ± 0.185	$7.00 \to 8.09$	$7.50^{+0.205}_{-0.160}$	$7.04 \to 8.12$
$\dfrac{\Delta m^2_{31}}{10^{-3}~{\rm eV}^2}$ (N)	$2.47^{+0.069}_{-0.067}$	$2.27 \to 2.69$	$2.49^{+0.055}_{-0.051}$	$2.29 \to 2.71$
$\dfrac{\Delta m^2_{32}}{10^{-3}~{\rm eV}^2}$ (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

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



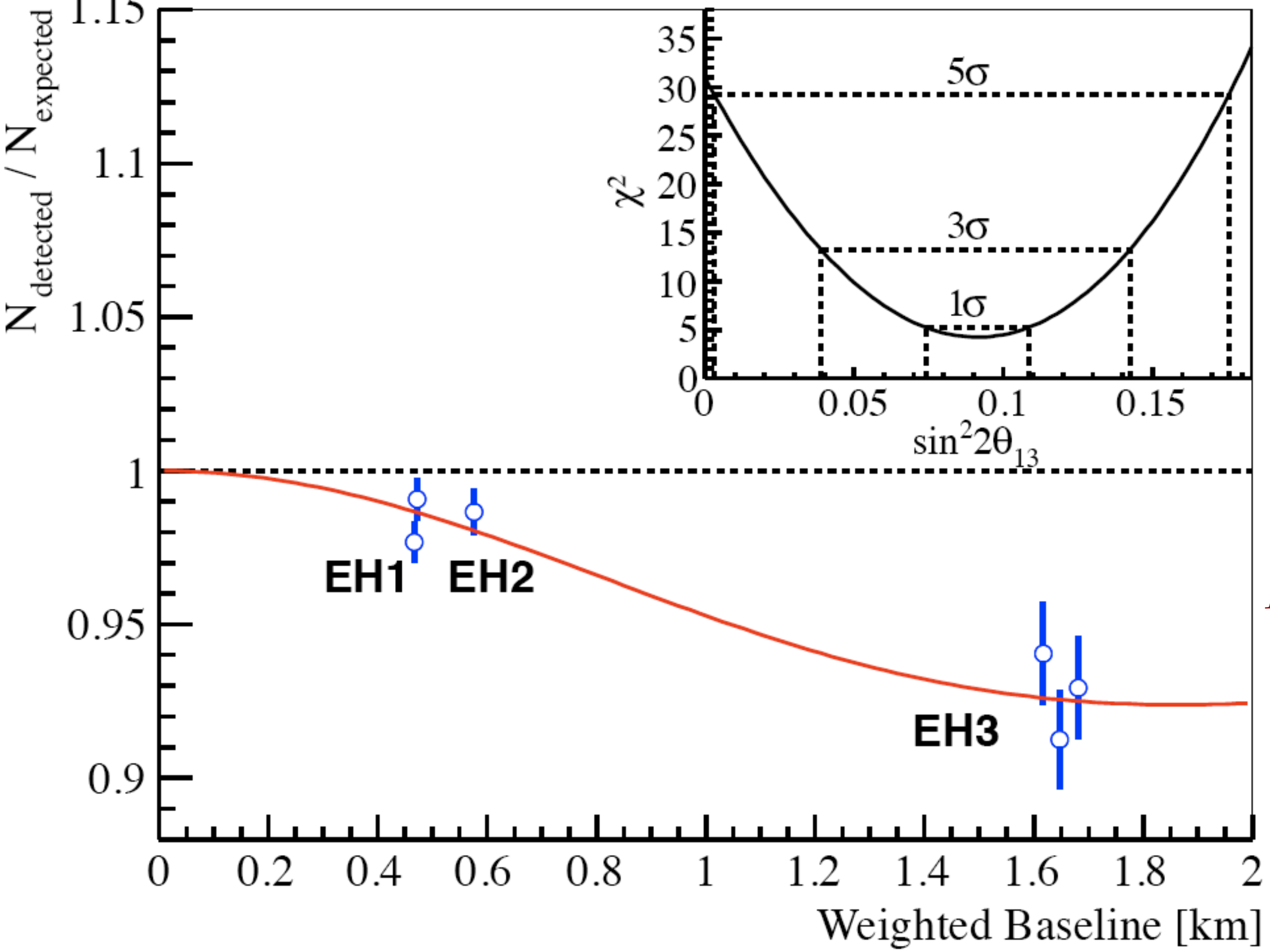
- ~~What is the ν_e component of ν_3?~~ $(\theta_{13} \neq 0!)$
- Is CP-invariance violated in neutrino oscillations? $(\delta \neq 0, \pi?)$
- Is ν_3 mostly ν_μ or ν_τ? $(\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4?)$
- What is the neutrino mass hierarchy? $(\Delta m^2_{13}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

$\Rightarrow$ 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)

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

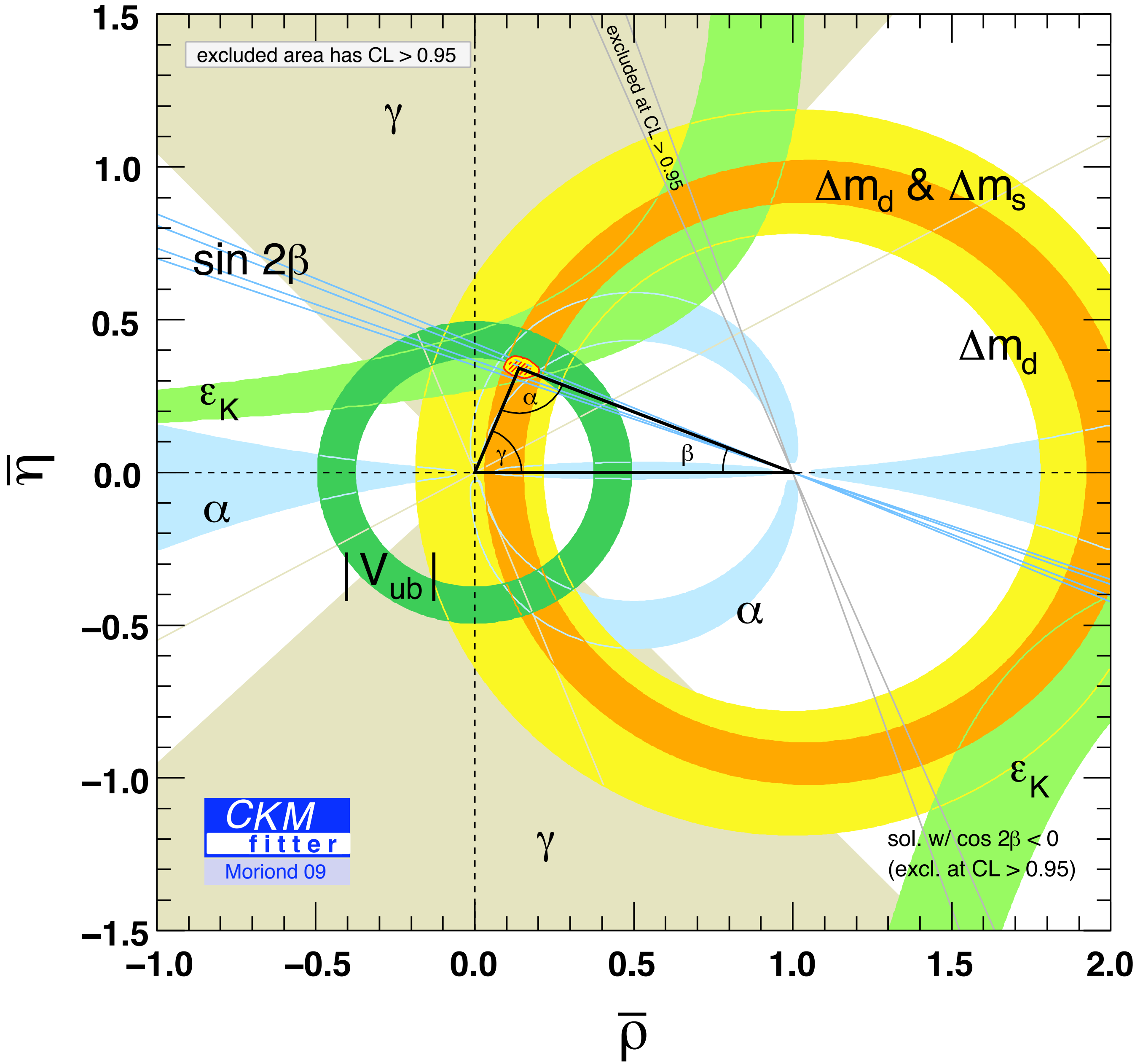
$$\text{phase}= 0.64\left(\frac{\Delta m^2}{2.5\times10^{-3}\ \text{eV}^2}\right)\left(\frac{5\ \text{MeV}}{E}\right)\left(\frac{L}{1\ \text{km}}\right)$$



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 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 → hint) – MINOS, T2K.

We still have a ways to go!

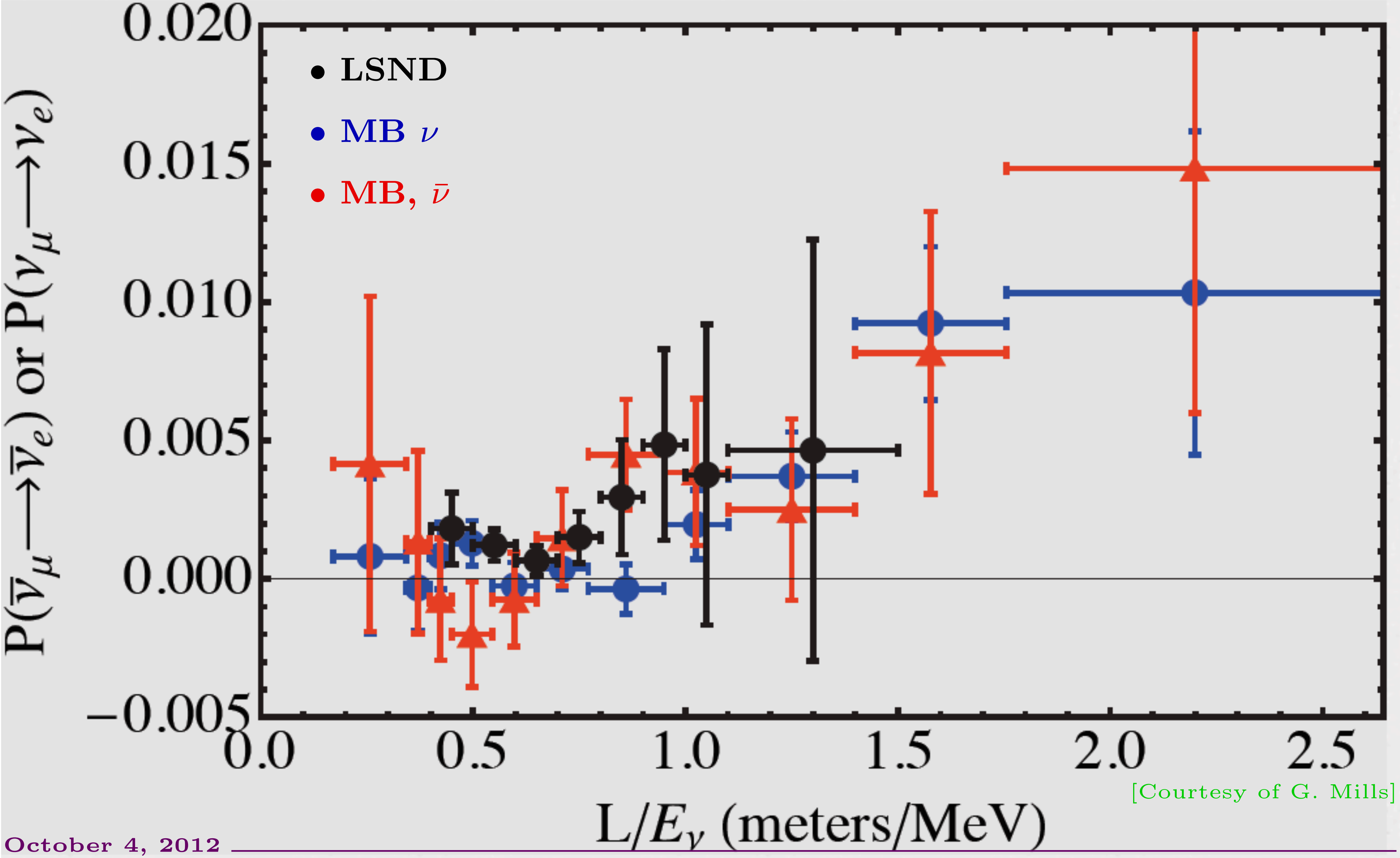
Not all is well(?): The Short Baseline Anomalies

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.

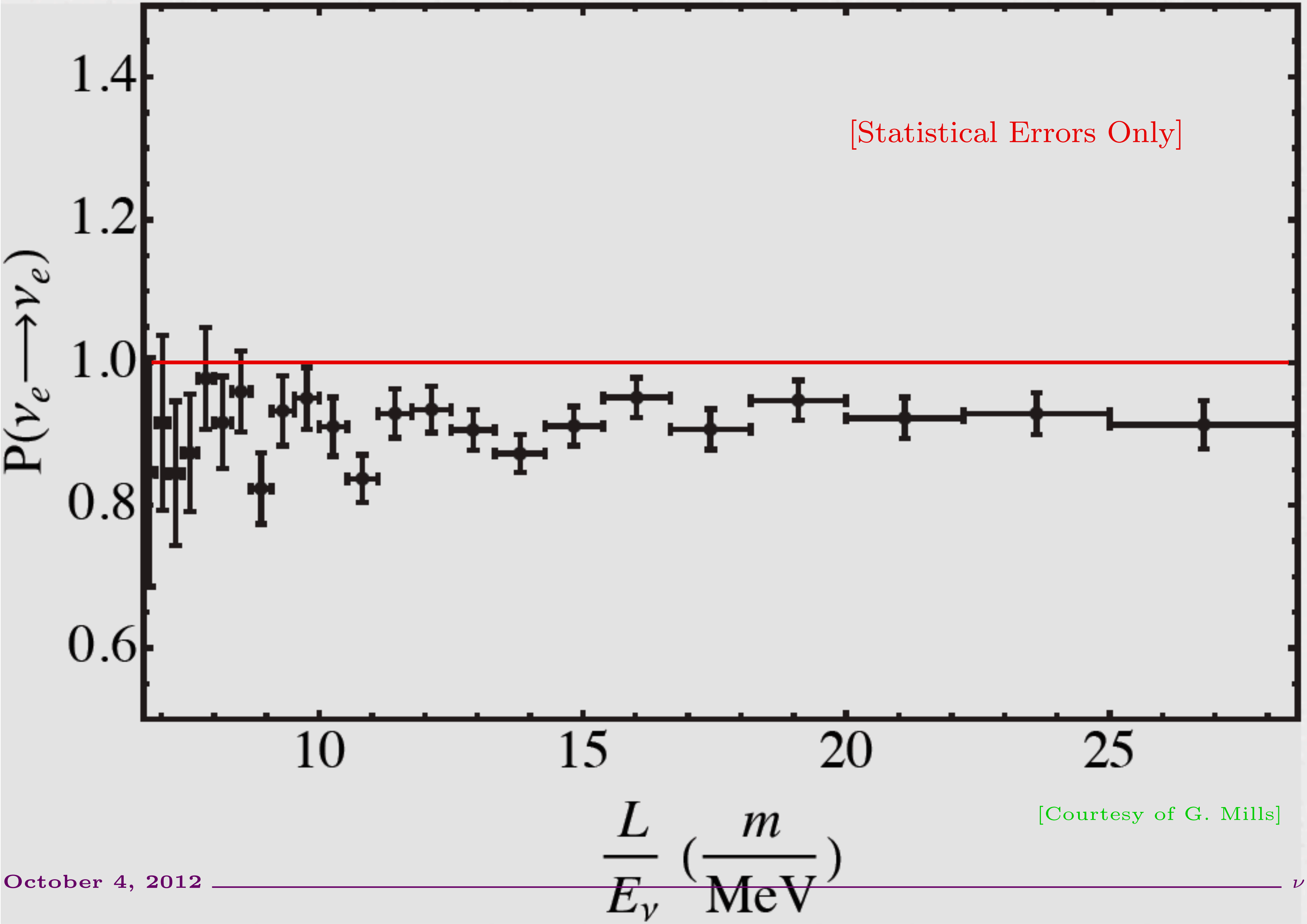
None are entirely convincing, either individually or combined. However, there may be something very very interesting going on here…

MiniBooNE & LSND



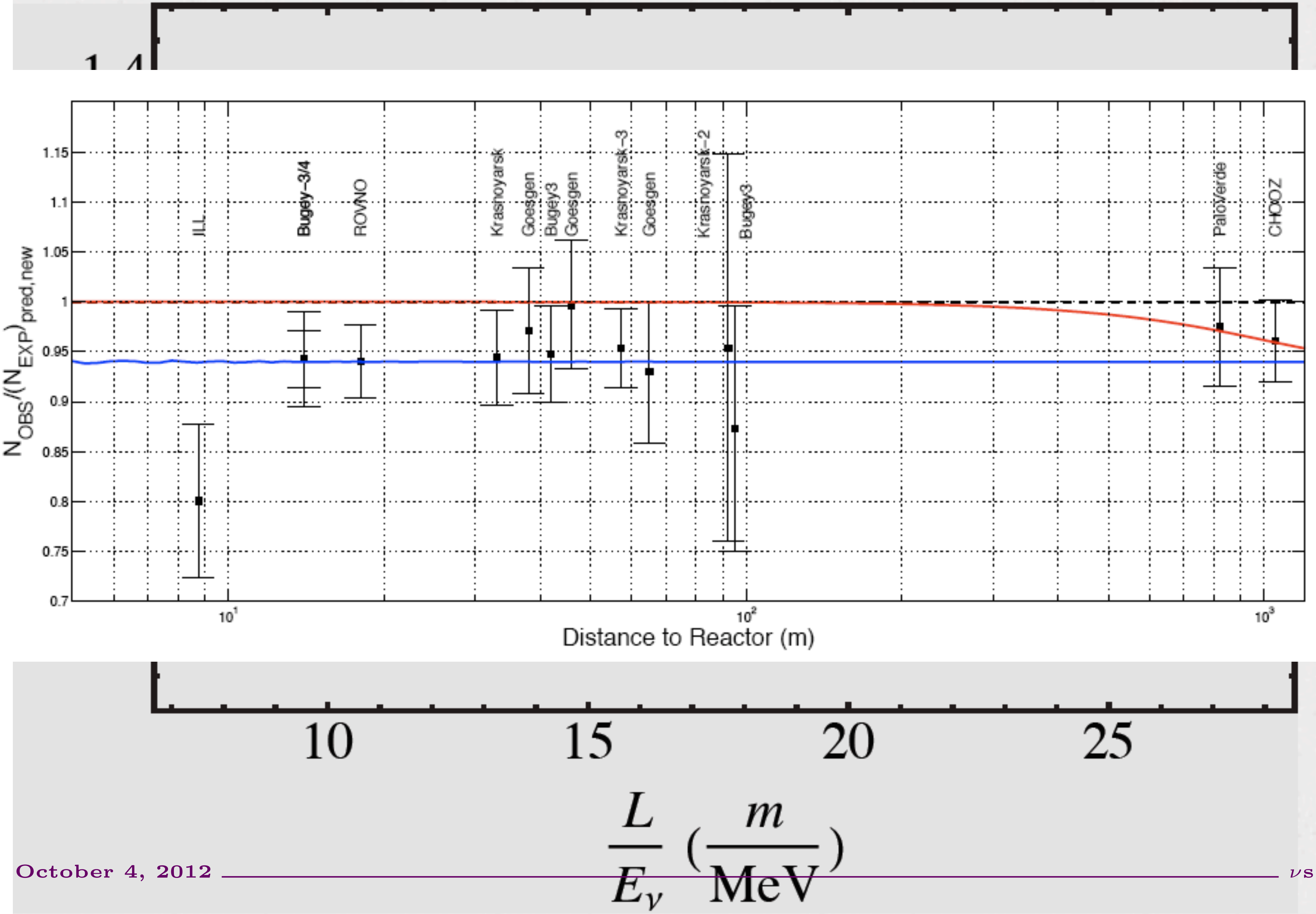
[Courtesy of G. Mills]

Bugey 40 m



[Courtesy of G. Mills]

Bugey 40 m


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

What is Going on Here?

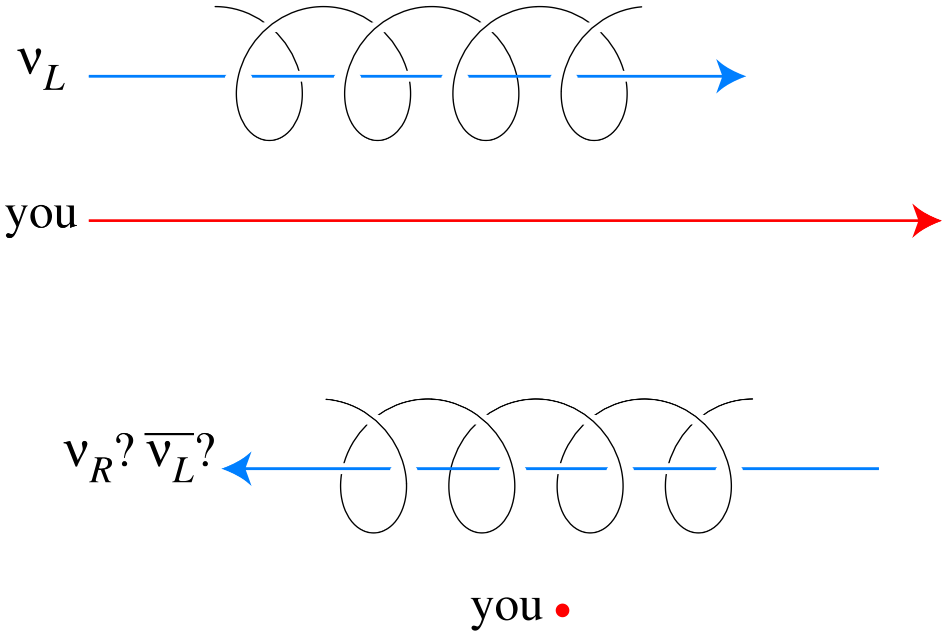
- Are these “anomalies” related?
- Is this neutrino oscillations, other new physics, or something else?
- Are these related to the origin of neutrino masses and lepton mixing?
- How do clear this up **definitively**?

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;
- $\nu_{\mu,e} \to \nu_\tau$ appearance.

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:

$$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$$

$$\updownarrow \text{Lorentz} \qquad \text{“DIRAC”}$$

$$(\nu_R \leftarrow \text{CPT} \rightarrow \bar{\nu}_L)$$

“MAJORANA”

$$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$$

$$\updownarrow \text{Lorentz}$$

$$(\bar{\nu}_R \leftarrow \text{CPT} \rightarrow \nu_L)$$

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

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:

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

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 $(\nu_e \overset{(m.m.)}{\to} \bar{\nu}_\beta \overset{(\mathrm{osc})}{\to} \bar{\nu}_e)$ $\vec{B}$ in the Sun?, how well oscillation parameters are known? (KamLAND!)
- astrophysics red giants, SN1987A, . . .

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

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

Will we ever get to such a tiny effect?

Supernova Neutrinos

[see C. Lunardini's talk]

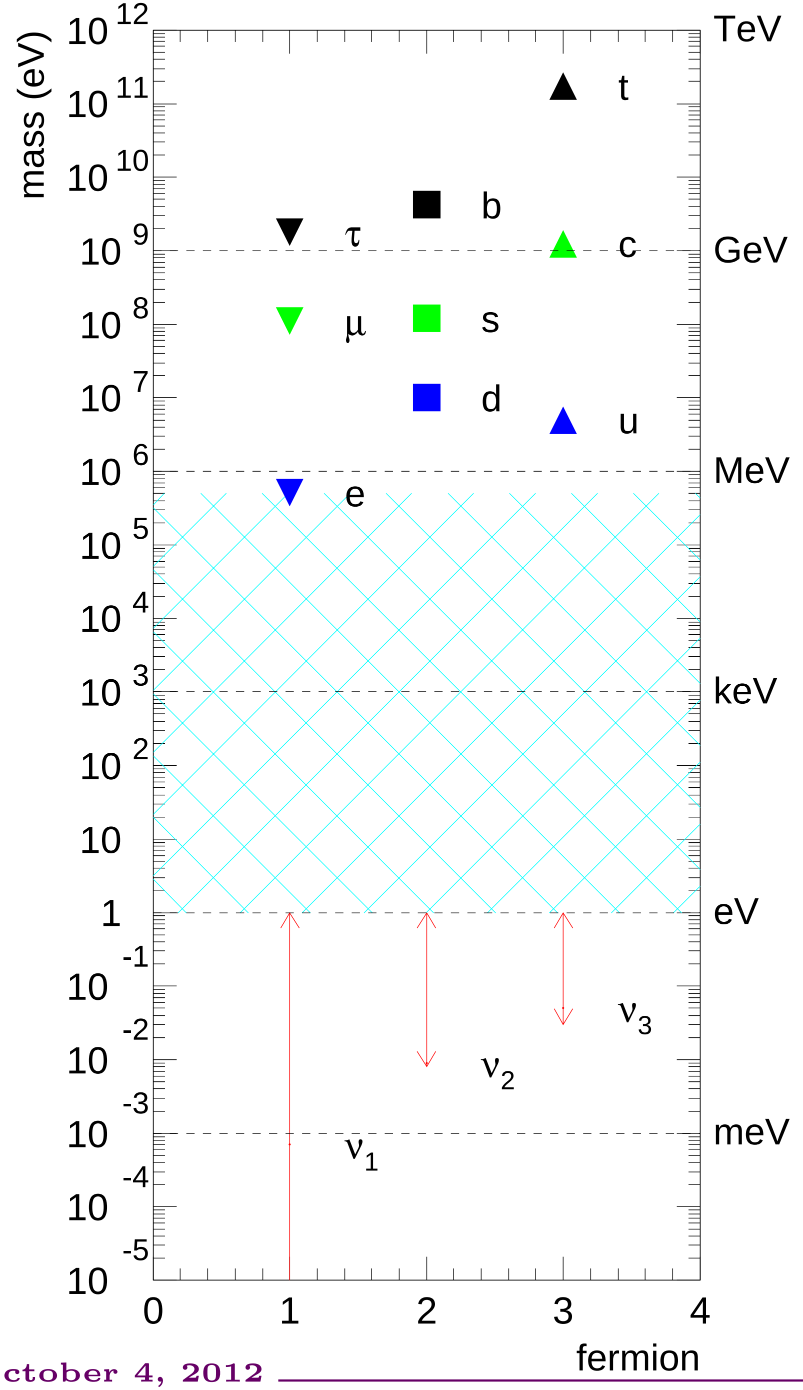
We are in the process of learning that neutrinos produced in supernova explosions oscillate in a very non-trivial way. The bottom line is that the flux of neutrinos from a supernova explosion carries a lot of very nontrivial information:

$\Phi_{\nu_\alpha,\bar{\nu}_\alpha} = f(\mathrm{sign}(\Delta m^2_{13}), \mathrm{astro}, \mathrm{others})$, 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!



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, and How to Learn More – Nucleon Decay

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!

CONCLUSIONNNS: ν 2012 Edition

1. 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).
2. very high priority: test the three flavor paradigm. Requirement: long baseline neutrino experiments. Several observables: neutrinos versus antineutrinos, different flavors, different beams (e.g. don't forget atmospherics)!
3. high priority: test the short-baseline anomalies. Can we "move on" without resolving them? I would rather not.
4. really high priority (for TH): 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).

5. high priority: supernova neutrinos carry a lot of information, some of it quite unique. And I mean particle physics, not "just" astrophysics. Requirement: neutrinos versus antineutrinos, different flavors.
6. 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? Can we find this out via searches for nucleon decay?
7. 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).