Neutrinos: Overview and the Snowmass Process

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Intensity Frontier Neutrino Subgroup Workshop
SLAC – March 6 and 7, 2013

Organization

Neutrinos are a subgroup of the Intensity Frontier Working Group for the 2013 Community Summer Study, "Snowmass on the Mississippi" (conveners: André de Gouvêa, Kevin Pitts, Kate Scholberg, Sam Zeller)

We are organized into seven subsubgroups:

- Nu1: Neutrino Oscillations and the Three-Flavor Paradigm (Mary Bishai, Karsten Heeger, Patrick Huber);
- Nu2: The Nature of the Neutrino: Majorana vs. Dirac (Steve Elliott, Lisa Kaufman);
- Nu3: Absolute Neutrino Mass (Hamish Robertson, Ben Monreal);
- Nu4: Neutrino Interactions (Jorge Morfin, Rex Tayloe);
- Nu5: Anomalies and New New Physics (Boris Kayser, Jon Link);
- Nu6: Astrophysical and Cosmological Neutrinos (Kara Hoffman, Cecilia Lunardini, Nikolai Tolich);
- Nu7: Neutrinos and Society (José Alonso, Adam Bernstein).

ASIDE: Neutrino Particle and Nuclear Theory

We recently assembled a small "Neutrino Phenomenology" task force – André de Gouvêa, Patrick Huber, Jonathan Link, Cecilia Lunardini, Jorge Morfin

- Do we need more neutrino theorists?
- What do we need them for?
- What can we do about it?

We have already received some informal input from part of the experimental community (special need for neutrino/nuclear theorist for neutrino scattering computations) and from the DOE.

A more broad version of the same question applies to the *Intensity Frontier* as whole.

Snowmass Process – We are in the Midst of It!

Deliverables:

1. 60–100 pages writeup with contributions from all working groups. To be written by the subsubgroup (Nu's) conveners.
2. 6–8 page summary, part of the Intensity Frontier $\sim$30 page document. To be written by the Neutrino conveners.

Input:

- Intensity Frontier 2011 Rockville Workshop, and 2012 Intensity Frontier Report,
- 83 one-page white papers received from the community,
- Workshops (like this one).

Snowmass Process – We are in the Midst of It!

- 01/31 Collection of White Papers from the community
- 03/06&07 SLAC Meeting $\longleftarrow$ [we are here]
- 03/31 First draft of neutrino working group document circulated to the community for feedback
- 04/24 Deadline for first round of community feedback
- 04/25–27 Intensity Frontier Workshop at ANL
- 05/21 Second draft of neutrino working group document circulated to the community for feedback
- 06/15 Deadline for second round of community feedback
- 07/01 Third draft of neutrino working group document circulated to the community for feedback

[Yes, prompt feeback from everyone is essential!]

Our Job

Describe the Research Opportunities in Neutrino Physics for This and the Coming Decade.

This is aimed at the neutrino community, the intensity frontier community, the particle physics community at large, the funding agencies, and, ideally, society as a whole. (We clearly won't achieve this, but it is important to worry about it)

Very important: make the **physics case** for a broad, comprehensive neutrino research program. How does it fit within the Intensity Frontier, and how does it fit in the overall goals of nuclear and particle physics?


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[H. Murayama]

Lots of Examples... a somewhat personal list

Neutrinos are unique probes of several different physics phenomena from vastly different scales, including...

- Dark Matter;
- Weak Interactions;
- Nucleons;
- Nuclei;
- the Earth;
- the Sun;
- Supernova explosions;
- The Origin of Ultra-High Energy Cosmic Rays;
- The Universe.

...and we aren't even talking about the neutrinos proper!

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):

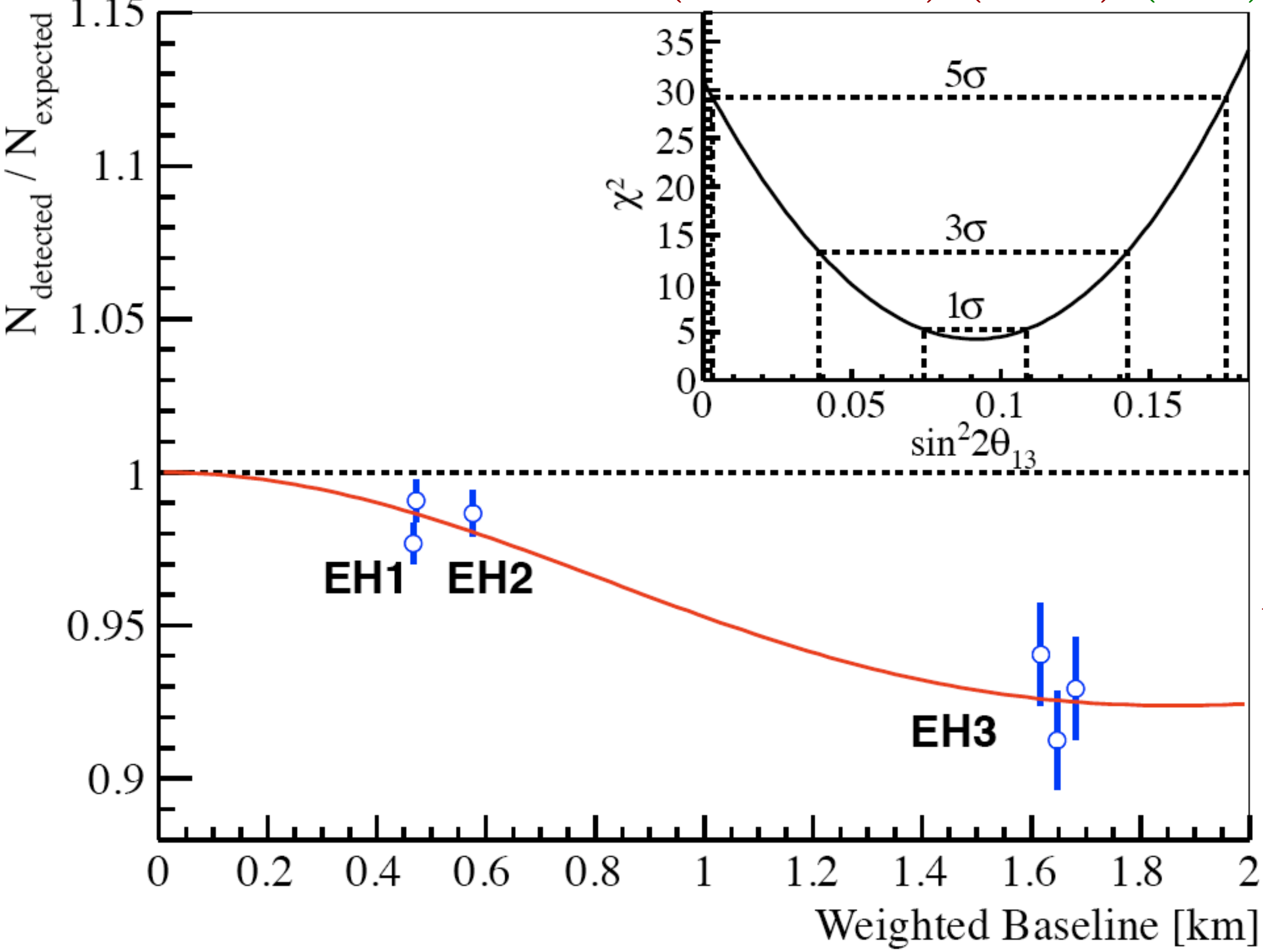
	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}$	0.30 ± 0.013	$0.27 \to 0.34$	0.31 ± 0.013	$0.27 \to 0.35$
$\theta_{12}/^\circ$	33.3 ± 0.8	$31 \to 36$	33.9 ± 0.8	$31 \to 36$
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.34 \to 0.67$	$0.41^{+0.030}_{-0.029} \oplus 0.60^{+0.020}_{-0.026}$	$0.34 \to 0.67$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.2}_{-1.3}$	$36 \to 55$	$40.1^{+2.1}_{-1.7} \oplus 50.7^{+1.1}_{-1.5}$	$36 \to 55$
$\sin^2\theta_{13}$	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}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	7.50 ± 0.185	$7.00 \to 8.09$	$7.50^{+0.205}_{-0.160}$	$7.04 \to 8.12$
$\frac{\Delta m^2_{31}}{10^{-3}\ \rm eV^2}$ (N)	$2.47^{+0.069}_{-0.067}$	$2.27 \to 2.69$	$2.49^{+0.055}_{-0.051}$	$2.29 \to 2.71$
$\frac{\Delta m^2_{32}}{10^{-3}\ \rm eV^2}$ (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

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

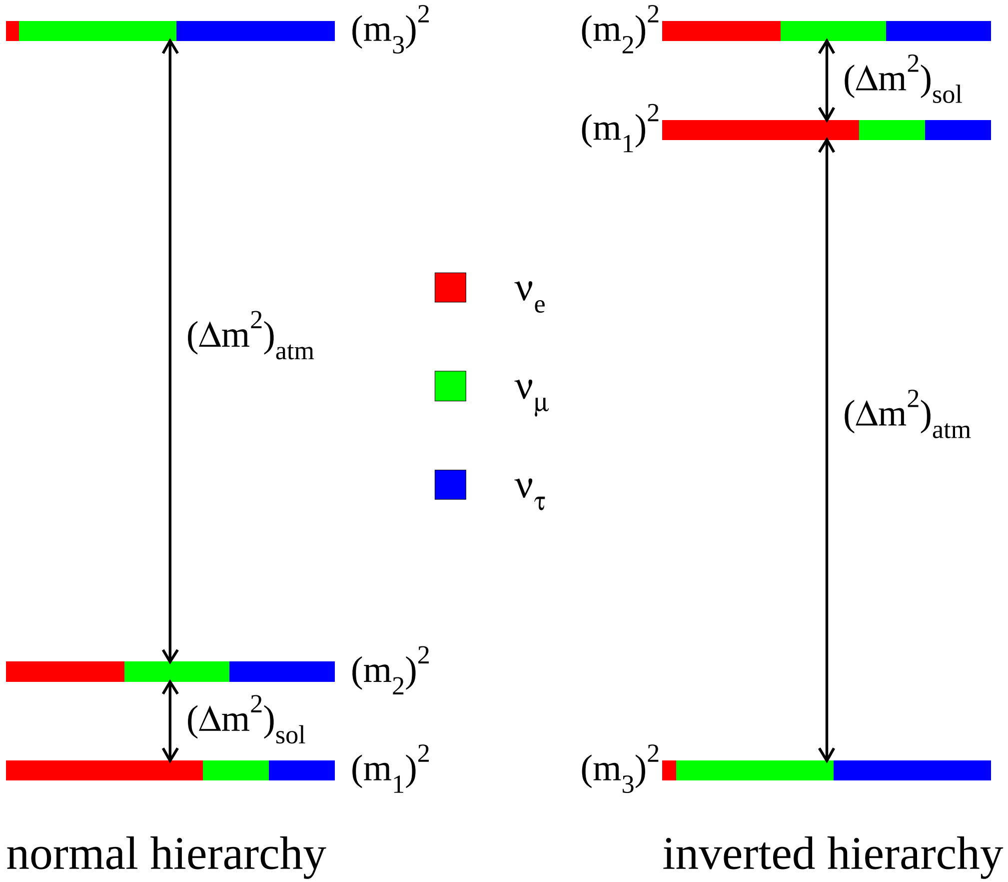
phase$= 0.64\left(\frac{\Delta m^2}{2.5\times10^{-3}\ \mathrm{eV}^2}\right)\left(\frac{5\ \mathrm{MeV}}{E}\right)\left(\frac{L}{1\ \mathrm{km}}\right)$



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

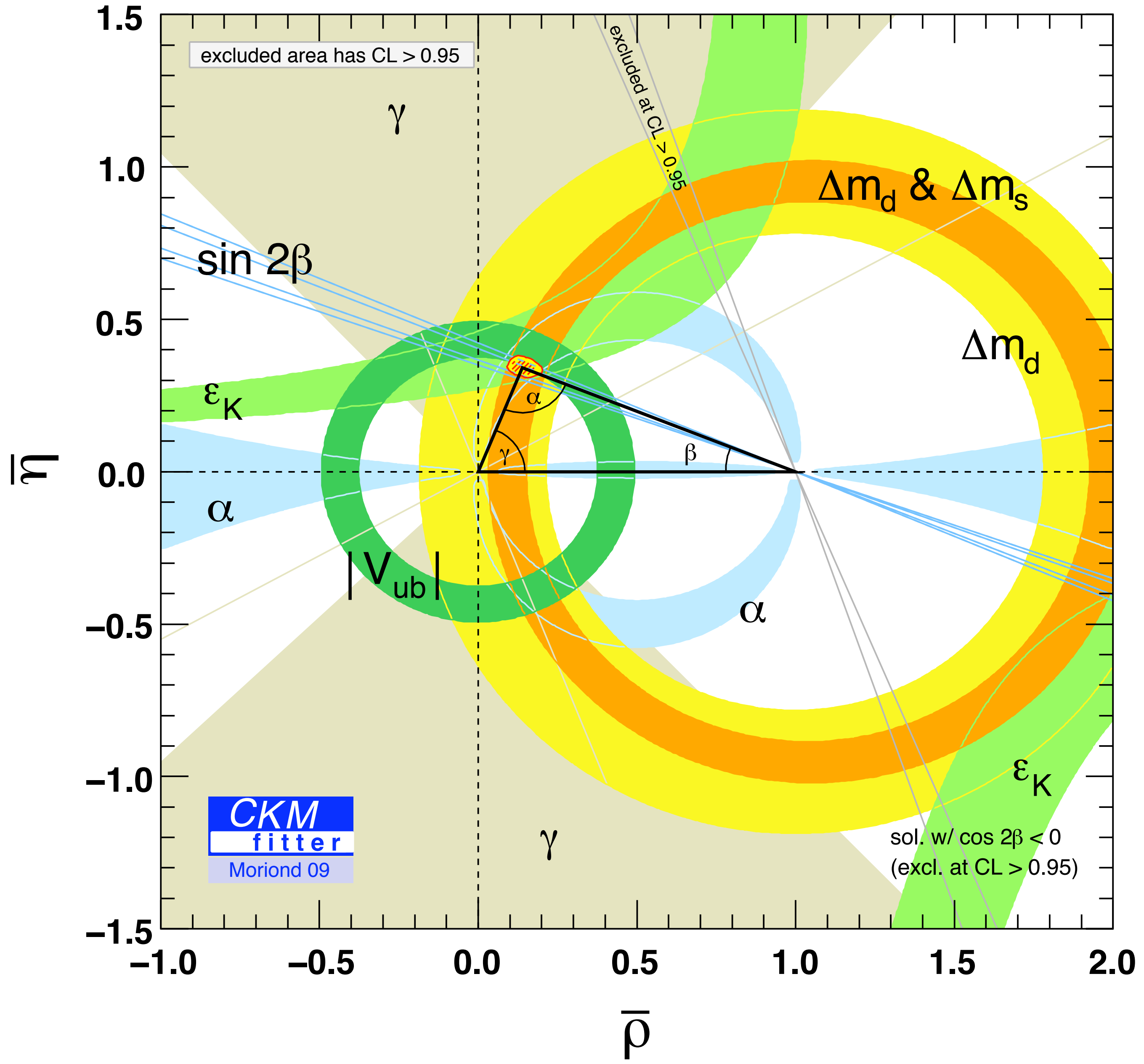


- ~~What is the ν_e component of ν_3?~~ ($\theta_{13} \neq 0$!)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m^2_{13}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

$\Rightarrow$ 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:



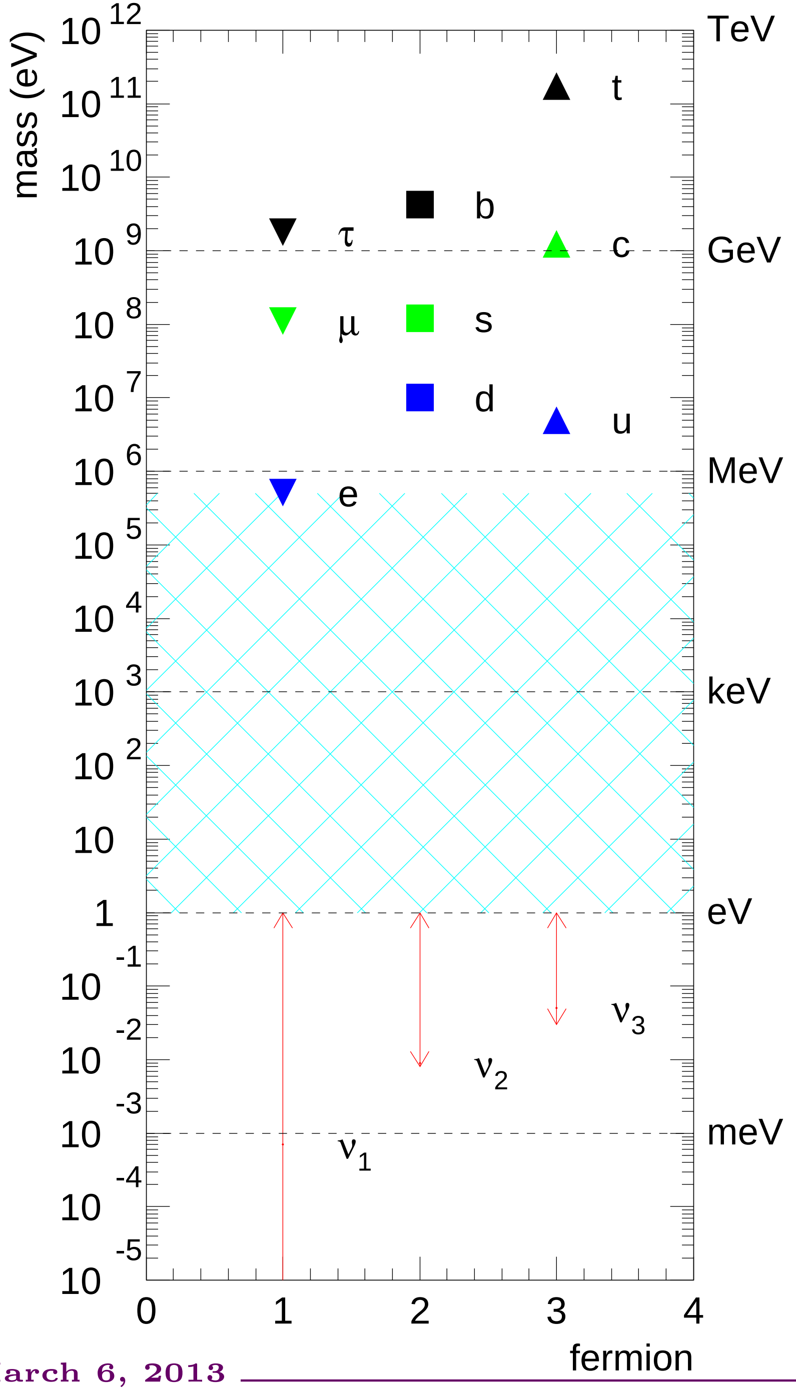
We need to do this in the lepton sector!

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

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!

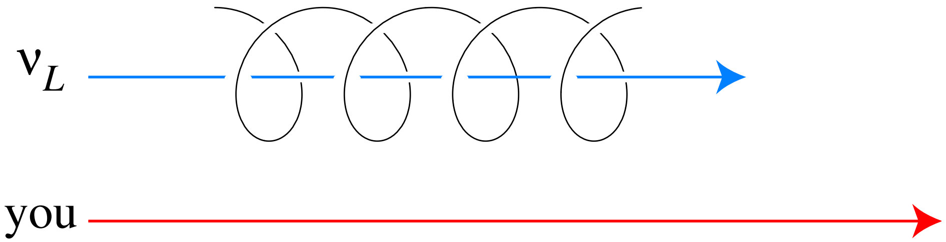


NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?

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

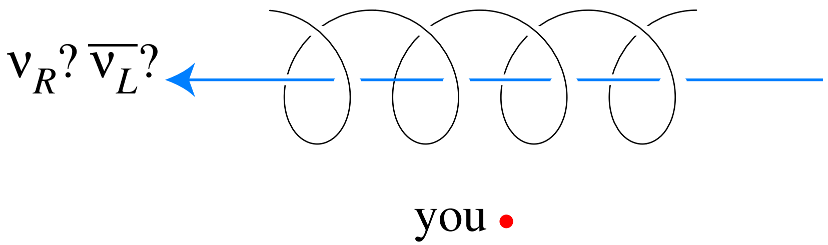


A massive charged fermion (s=1/2) is described by 4 degrees of freedom:

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

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?

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!

Understanding Fermion Mixing – Precision

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

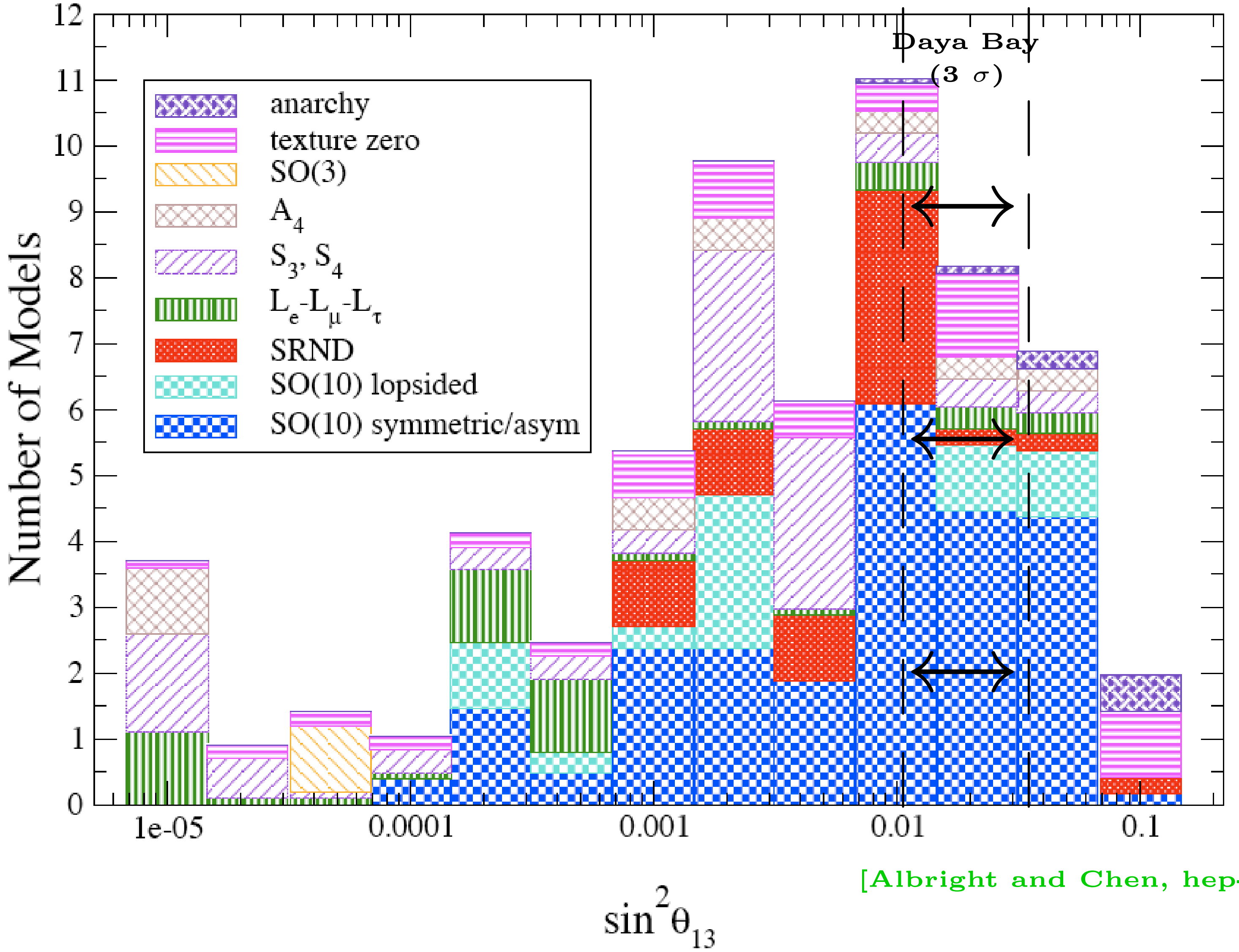
It means that lepton mixing is very different from quark mixing:

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

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

WHY?

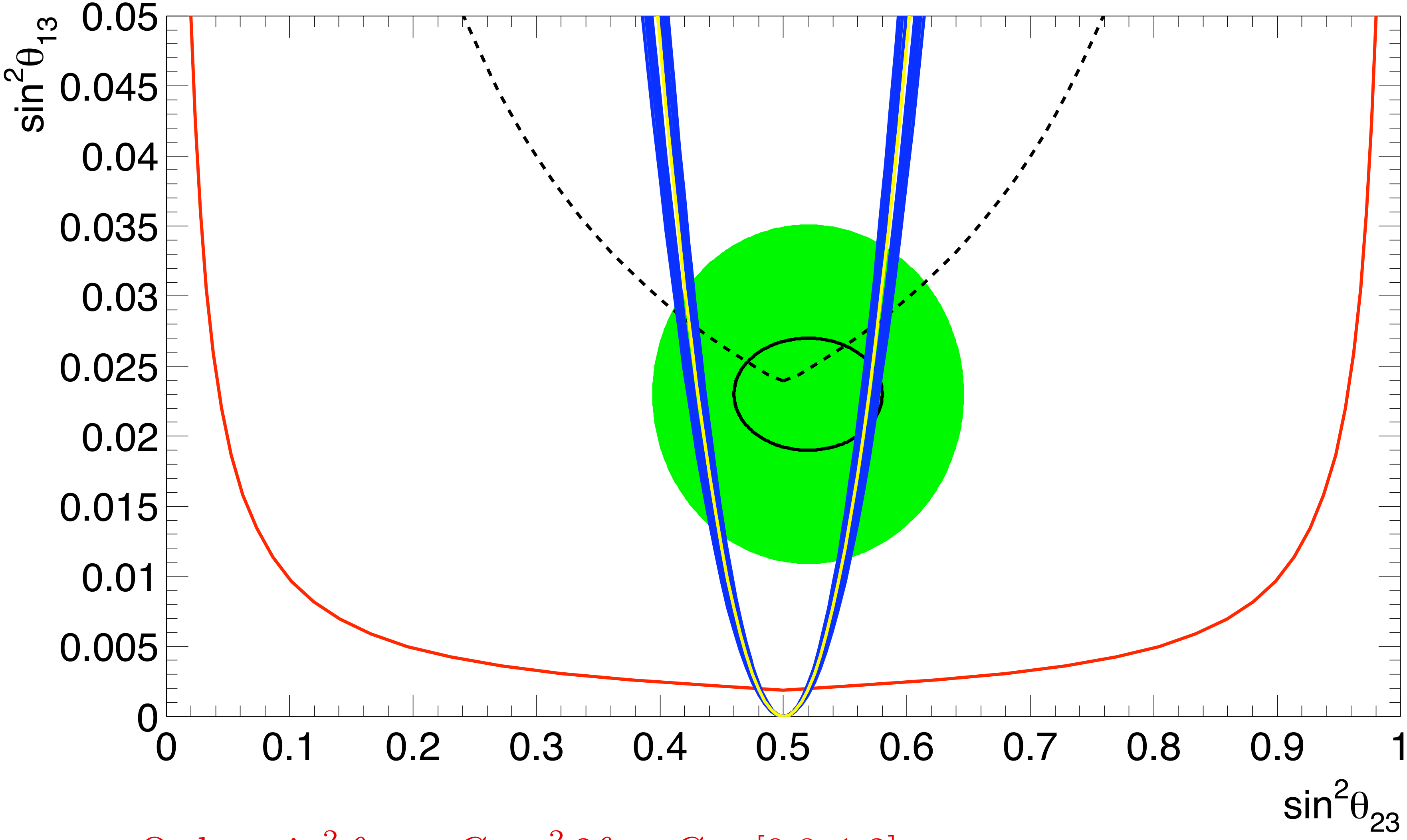
They certainly look VERY different, but which one would you label as "strange"?



[Albright and Chen, hep-ph/0608137]

"Left-Over" Predictions: δ, mass-hierarchy, $\cos 2\theta_{23}$. More important: CORRELATIONS!

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]

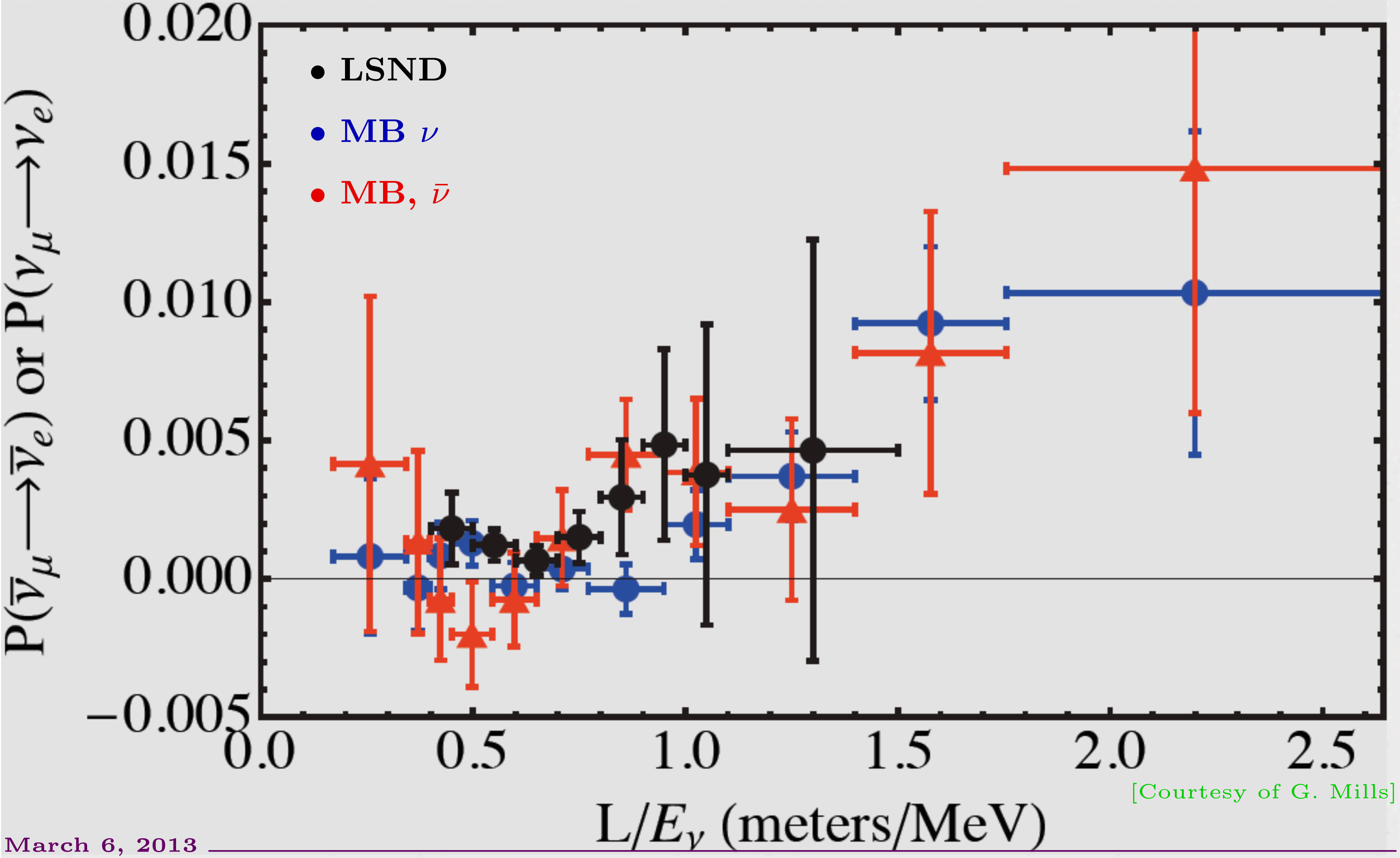
Not all is well(?): The Short Baseline Anomalies

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

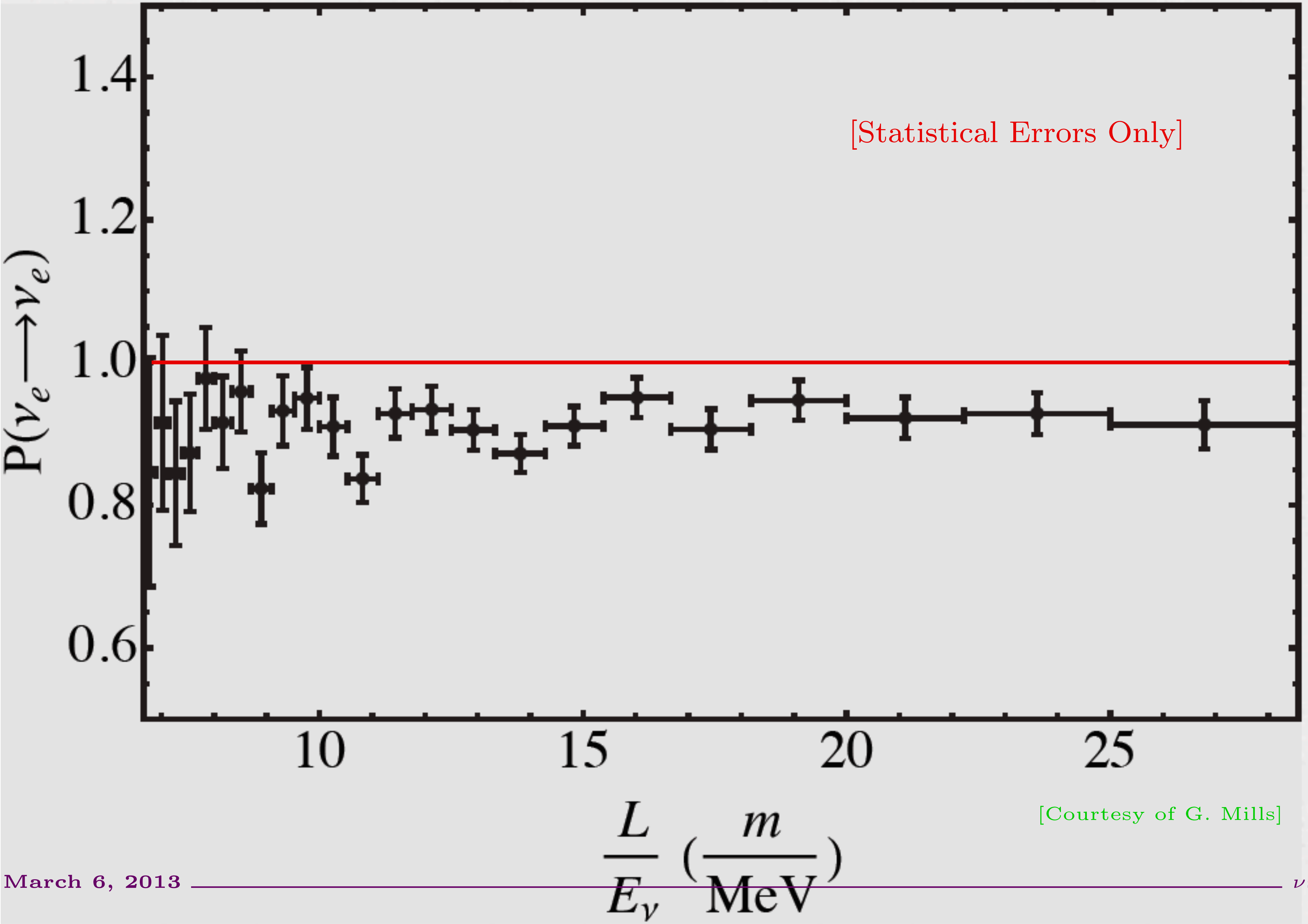
- $\nu_\mu \to \nu_e$ appearance — LSND, MiniBooNE;
- $\nu_e \to \nu_{\rm other}$ disappearance — radioactive sources;
- $\bar{\nu}_e \to \bar{\nu}_{\rm other}$ disappearance — reactor experiments.

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

MiniBooNE & LSND

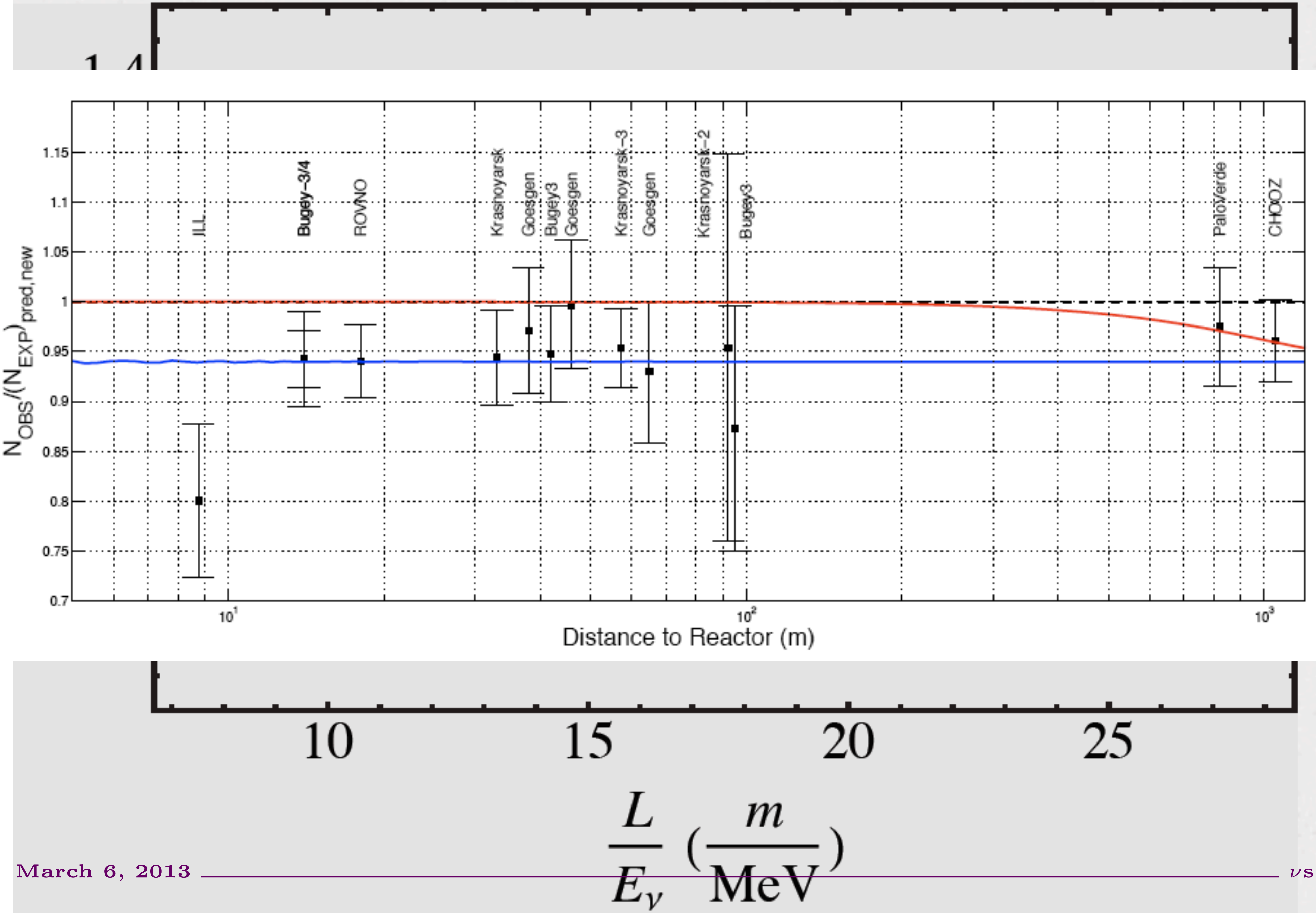


Bugey 40 m



[Courtesy of G. Mills]

Bugey 40 m



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
$\frac{L}{E_\nu}\ (\frac{m}{\mathrm{MeV}})$

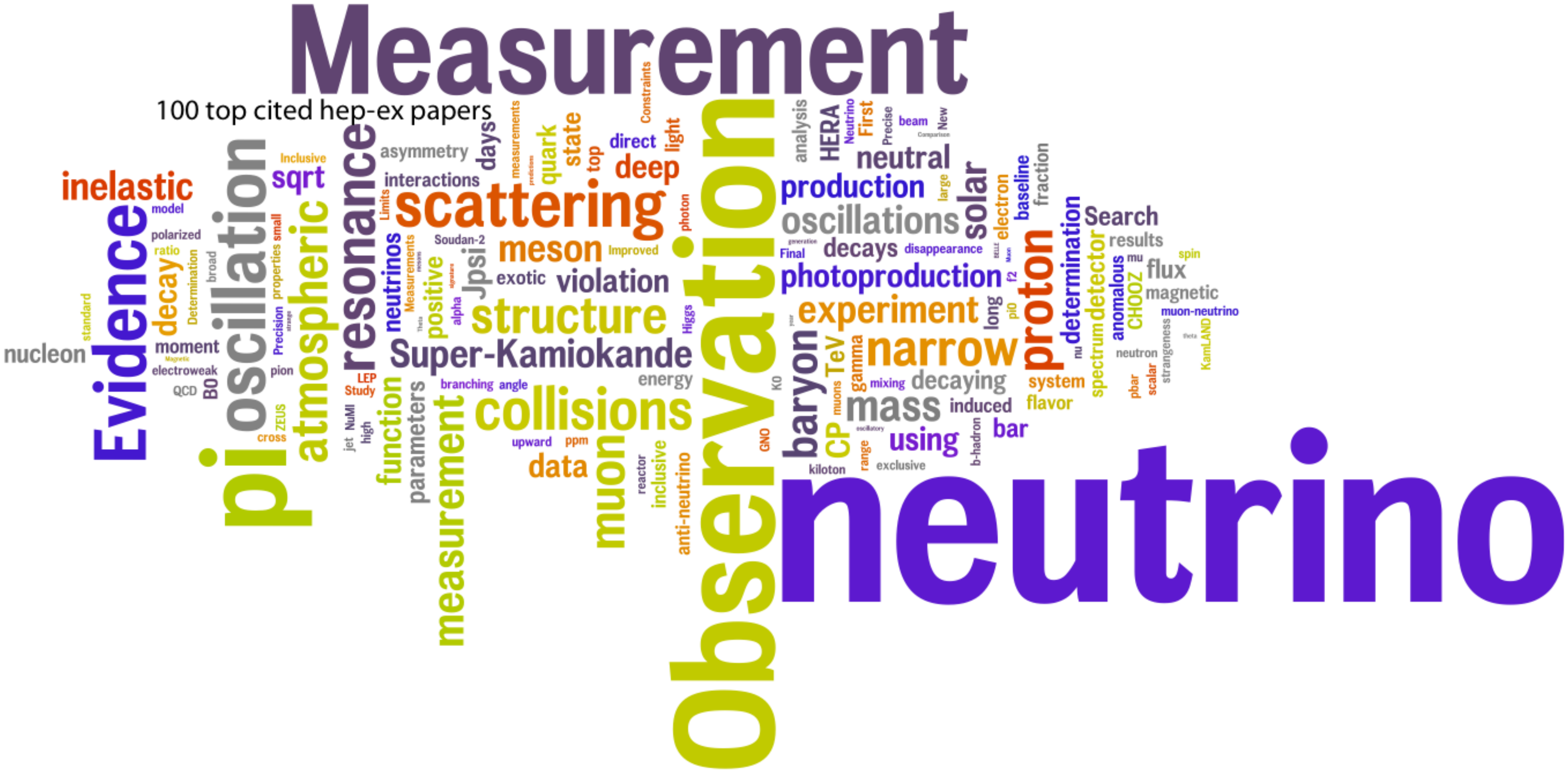
What is Going on Here?

- 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;
- $\nu_{\mu,e} \to \nu_\tau$ appearance.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neutrino
Observation
Evidence
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oscillation
atmospheric
resonance
scattering
inelastic
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asymmetry
interactions
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light
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days
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production
oscillations
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disappearance
photoproduction
proton
determination
detector
spectrum
anomalous
CHOOZ
experiment
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Jpsi
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Soudan-2
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K0
muons
standard
Determination
broad
Inclusive
Constraints