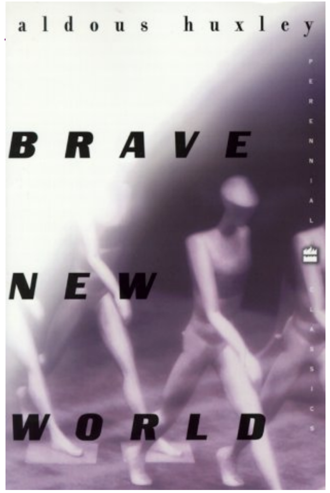
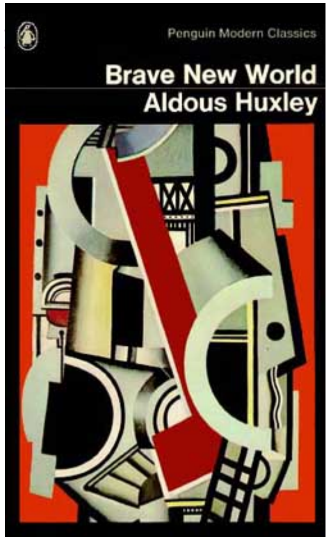
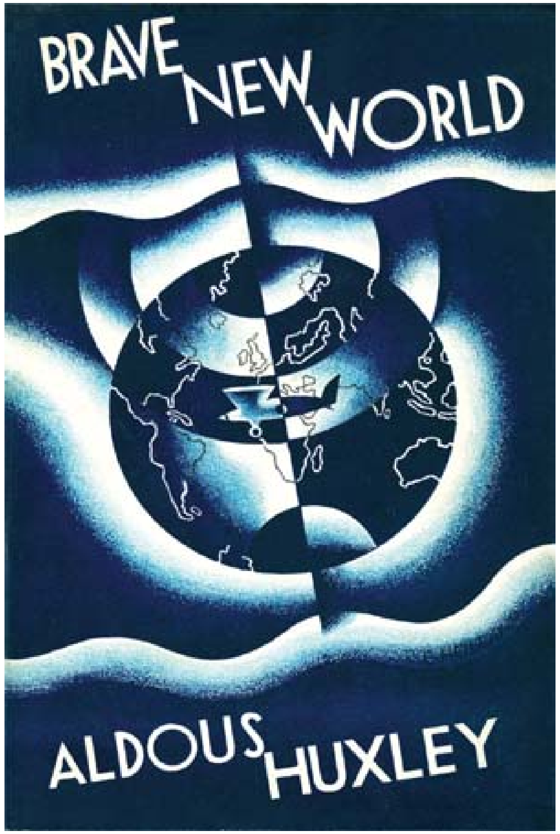


The Brave ν World

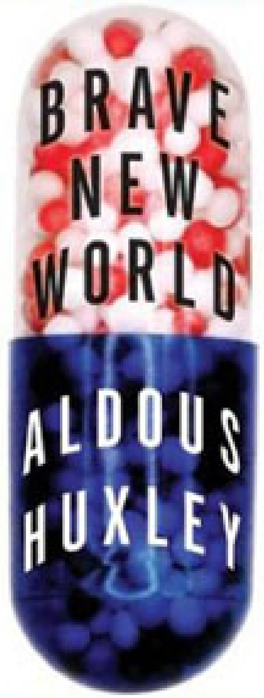




André de Gouvêa
Northwestern University

University of Mississippi – Colloquium

March 18, 2014



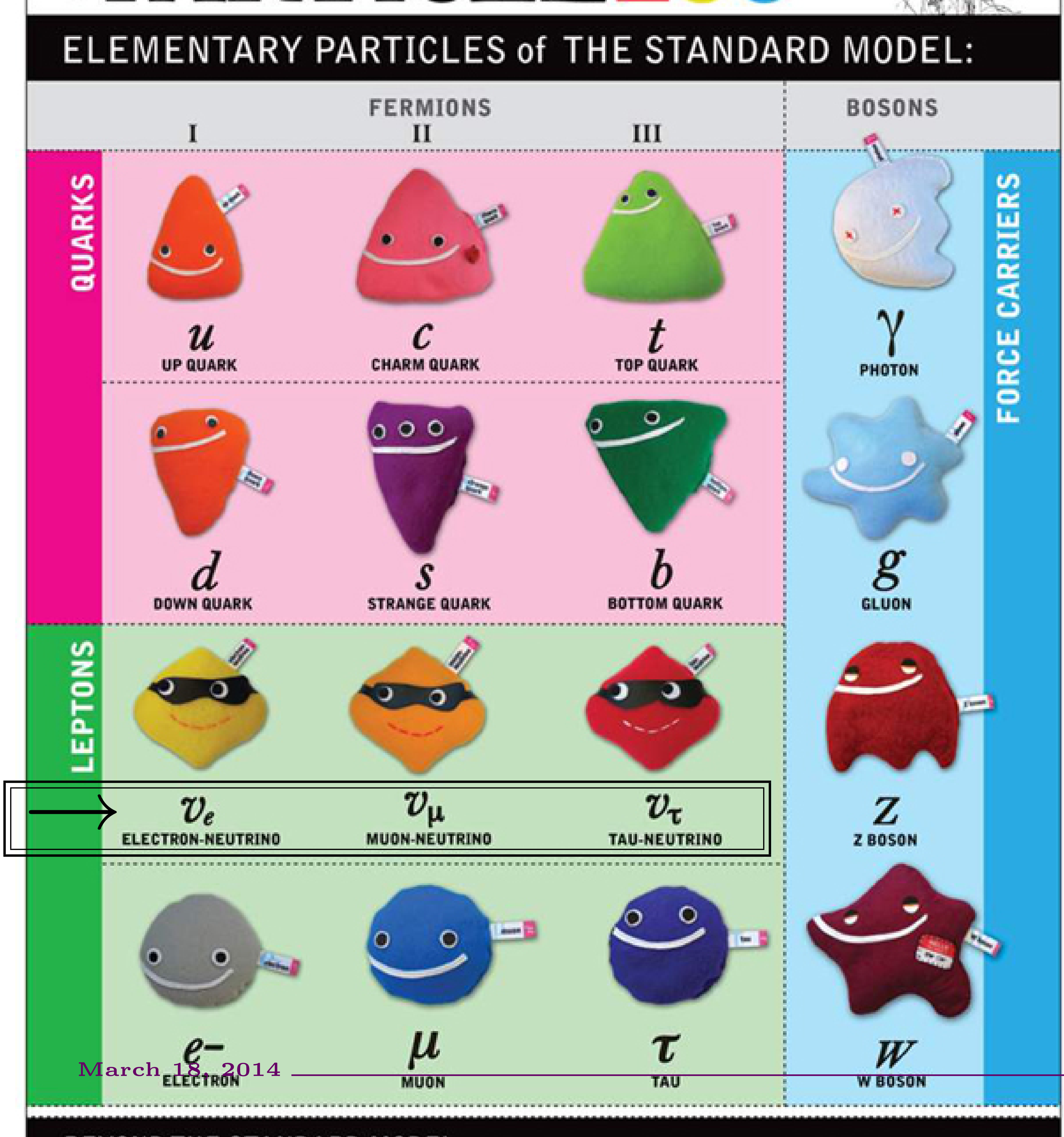
O, wonder!

How many goodly creatures are there here!

How beauteous mankind is! O brave new world,

That has such people in't!

W. Shakespeare, "The Tempest," Act V, Scene 1



Neutrinos are

Among a Handful of

Known Fundamental,

Point-Like Particles.

http://www.particlezoo.net

Neutrino Timeline, abridged:

1. 1930: Postulated by Pauli to (a) resolve the problem of continuous β-ray spectra, and (b) reconcile nuclear model with spin-statistics theorem.

2. 1934: Fermi theory of Weak Interactions – current-current interaction

$$\mathcal{H} \sim G_F \left(\bar{p}\Gamma n\right)\left(\bar{e}\Gamma\nu_e\right), \quad \text{where} \;\; \Gamma = \{1, \gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\}$$

   Way to "see" neutrinos: $\bar{\nu}_e + p \to e^+ + n$. Prediction for the cross-section – too small to ever be observed...

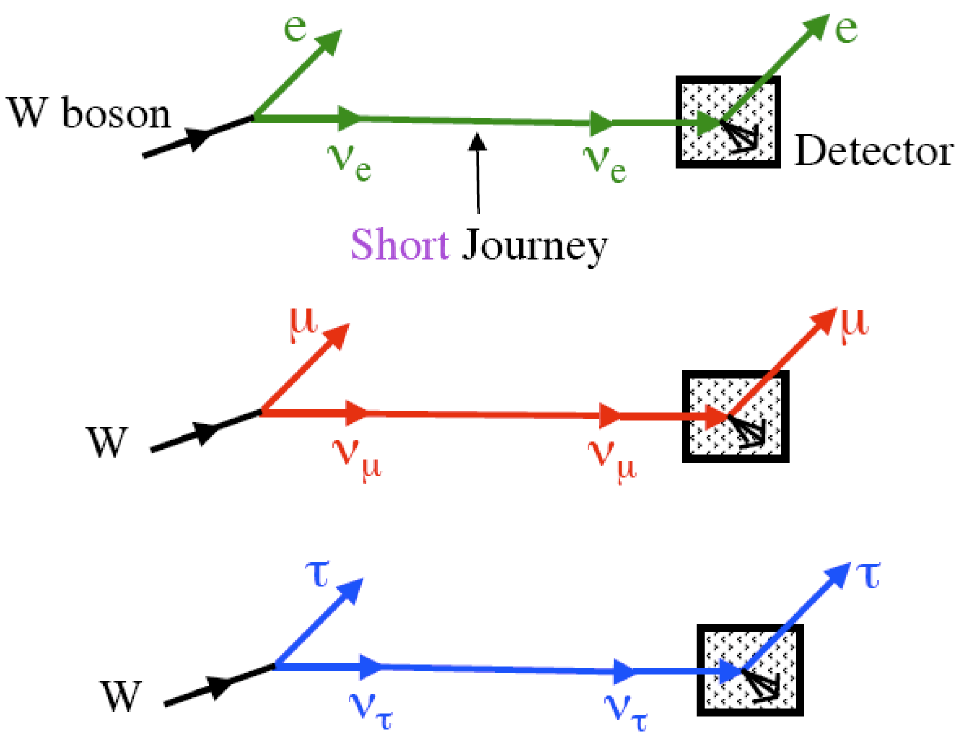
3. 1956: "Discovery" of the neutrino (Reines and Cowan) in the Savannah River Nuclear Reactor site. $\bar{\nu}_e + p \to e^+ + n$.

4. 1962: The second neutrino: $\nu_\mu \neq \nu_e$ (Lederman, Steinberger, Schwartz at BNL). First neutrino beam.

$$p + Z \to \pi^+ X \to \mu^+\nu_\mu \quad \Rightarrow \quad \begin{array}{l} \nu_\mu + Z \to \mu^- + Y \ (\text{“always”}) \\ \nu_\mu + Z \to e^- + Y \ (\text{“never”}) \end{array}$$

5. 2001: ν_τ directly observed (DONUT experiment at FNAL). Same strategy: $\nu_\tau + Z \to \tau^- + Y$. ($\tau$-leptons discovered in the 1970's).

16 years ago, this is how we pictured neutrinos:



- come in three flavors (see figure);
- interact only via weak interactions ($W^{\pm}, Z^0$);
- have ZERO mass – helicity good quantum number;
- ν_L field describes 2 degrees of freedom:
  - left-handed state ν,
  - right-handed state $\bar{\nu}$ (CPT conjugate);
- neutrinos carry lepton number (conserved):
  - $L(\nu) = L(\ell) + 1$,
  - $L(\bar{\nu}) = L(\bar{\ell}) = -1$.

Something Funny Happened on the Way to the 21st Century

ν Flavor Oscillations

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.

Mass-Induced Neutrino Flavor Oscillations

Neutrino Flavor change can arise out of several different mechanisms. The simplest one is to appreciate that, once **neutrinos have mass**, **leptons can mix**. If neutrinos have mass, there are two different ways to define the different neutrino states.

(1) Neutrinos with a well defined mass:

$$\nu_1, \nu_2, \nu_3, \dots \qquad \text{with masses} \;\; m_1, m_2, m_3, \dots$$

(2) Neutrinos with a well defined flavor:

$$\nu_e, \nu_\mu, \nu_\tau$$

These are related by a unitary transformation:

$$\nu_\alpha = U_{\alpha i} \nu_i \qquad \alpha = e, \mu, \tau, \quad i = 1, 2, 3$$

U is a unitary mixing matrix.

The Propagation of Massive Neutrinos

Neutrino mass eigenstates are eigenstates of the free-particle Hamiltonian:

$$|\nu_i\rangle = e^{-i(E_i t - \vec{p_i}\cdot\vec{x})}|\nu_i\rangle, \qquad E_i^2 - |\vec{p}_i|^2 = m_i^2$$

The neutrino flavor eigenstates are linear combinations of ν_i's, say:

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle.$$
$$|\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle.$$

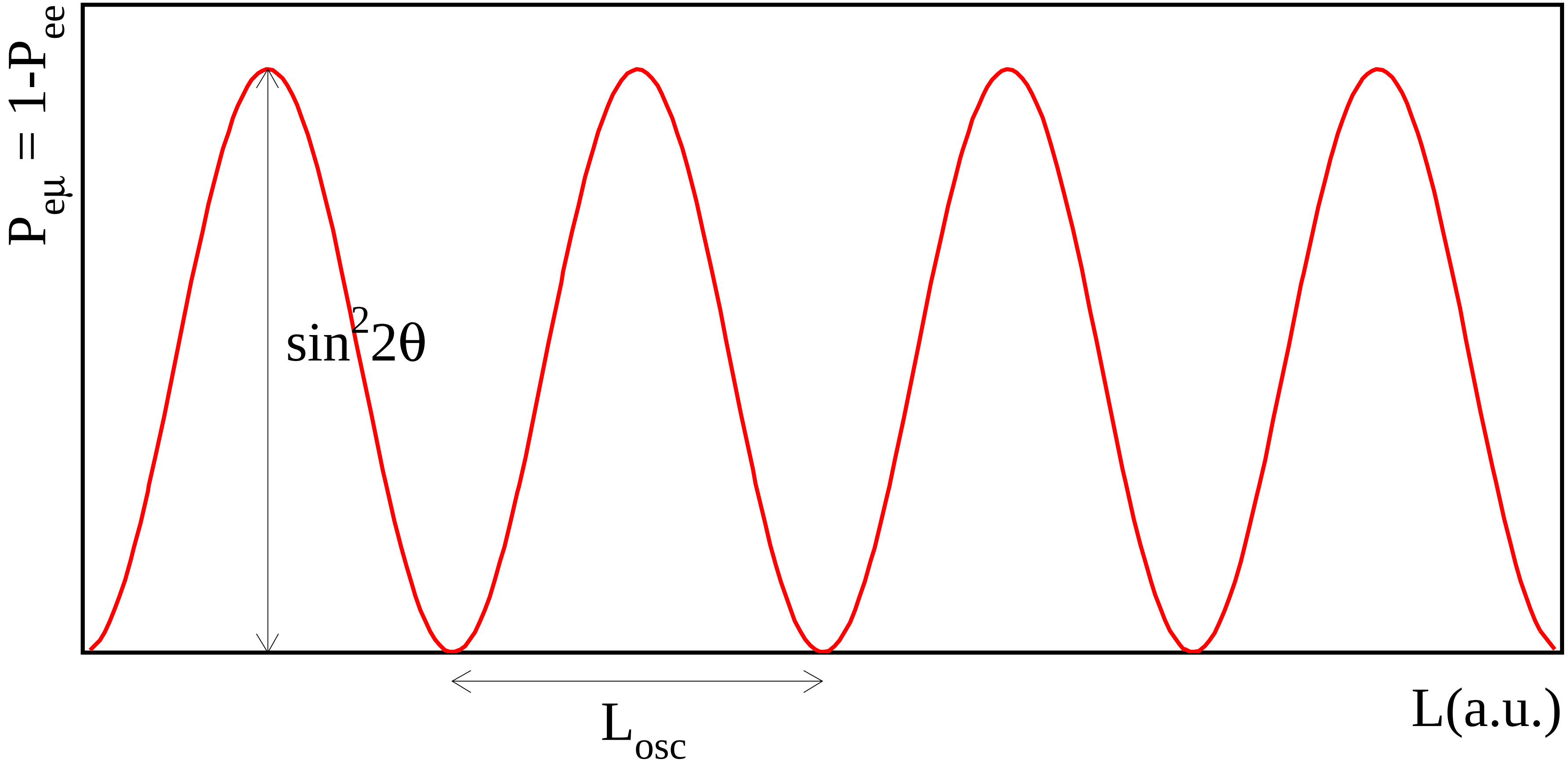
If this is the case, a state produced as a ν_e evolves in vacuum into

$$|\nu(t,\vec{x})\rangle = \cos\theta e^{-ip_1x}|\nu_1\rangle + \sin\theta e^{-ip_2x}|\nu_2\rangle.$$

It is trivial to compute $P_{e\mu}(L) \equiv |\langle\nu_\mu|\nu(t,z=L)\rangle|^2$. It is just like a two-level system from basic undergraduate quantum mechanics! In the ultrarelativistic limit (always a good bet), $t \simeq L$, $E_i - p_{z,i} \simeq (m_i^2)/2E_i$, and

$$\boxed{P_{e\mu}(L) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)}$$

oscillation parameters: $\begin{cases} \pi \frac{L}{L_{\rm osc}} \equiv \frac{\Delta m^2 L}{4E} = 1.267 \left(\frac{L}{\rm km}\right) \left(\frac{\Delta m^2}{\rm eV^2}\right) \left(\frac{\rm GeV}{E}\right) \\ \text{amplitude } \sin^2 2\theta \end{cases}$



A Realistic, Reasonable, and Simple Paradigm:

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

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 Mixing Hypothesis Fits All* Data Really Well.

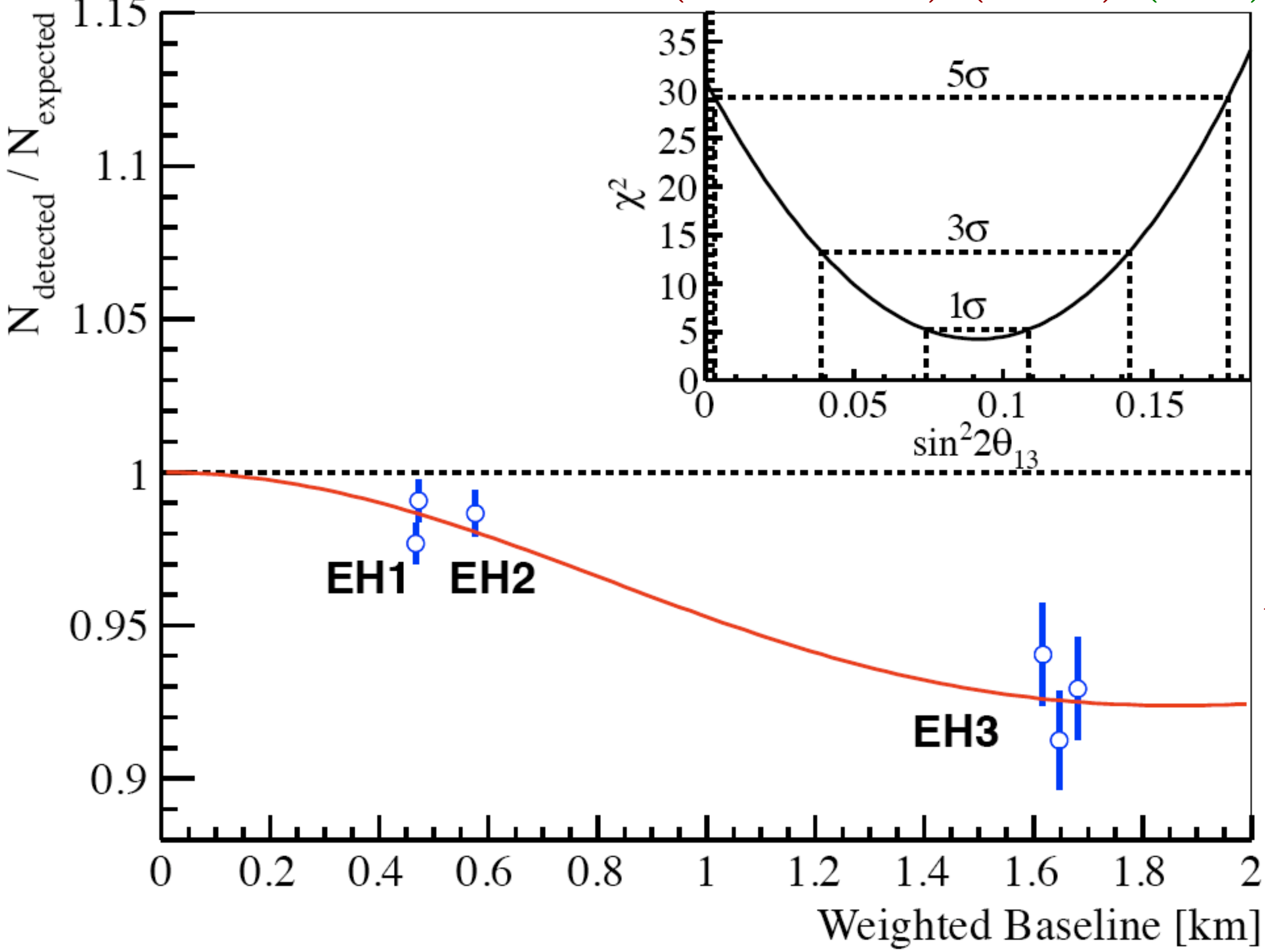
parameter	best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} $[10^{-5}\text{eV}^2]$	7.62 ± 0.19	7.27–8.01	7.12–8.20
Δm^2_{31} $[10^{-3}\text{eV}^2]$	$2.53^{+0.08}_{-0.10}$ $-(2.40^{+0.10}_{-0.07})$	$2.34 - 2.69$ $-(2.25 - 2.59)$	$2.26 - 2.77$ $-(2.15 - 2.68)$
$\sin^2\theta_{12}$	$0.320^{+0.015}_{-0.017}$	0.29–0.35	0.27–0.37
$\sin^2\theta_{23}$	$0.49^{+0.08}_{-0.05}$ $0.53^{+0.05}_{-0.07}$	0.41–0.62 0.42–0.62	0.39–0.64
$\sin^2\theta_{13}$	$0.026^{+0.003}_{-0.004}$ $0.027^{+0.003}_{-0.004}$	0.019–0.033 0.020–0.034	0.015–0.036 0.016–0.037
δ	$\left(0.83^{+0.54}_{-0.64}\right)\pi$ 0.07π [a]	$0 - 2\pi$	$0 - 2\pi$

*Modulo a handful of 2σ to 3σ anomalies.

[Forero, Tórtola, Valle, 1205.4018]

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

$$\text{phase} = 0.64 \left(\frac{\Delta m^2}{2.5\times 10^{-3}\ \text{eV}^2}\right)\left(\frac{5\ \text{MeV}}{E}\right)\left(\frac{L}{1\ \text{km}}\right)$$

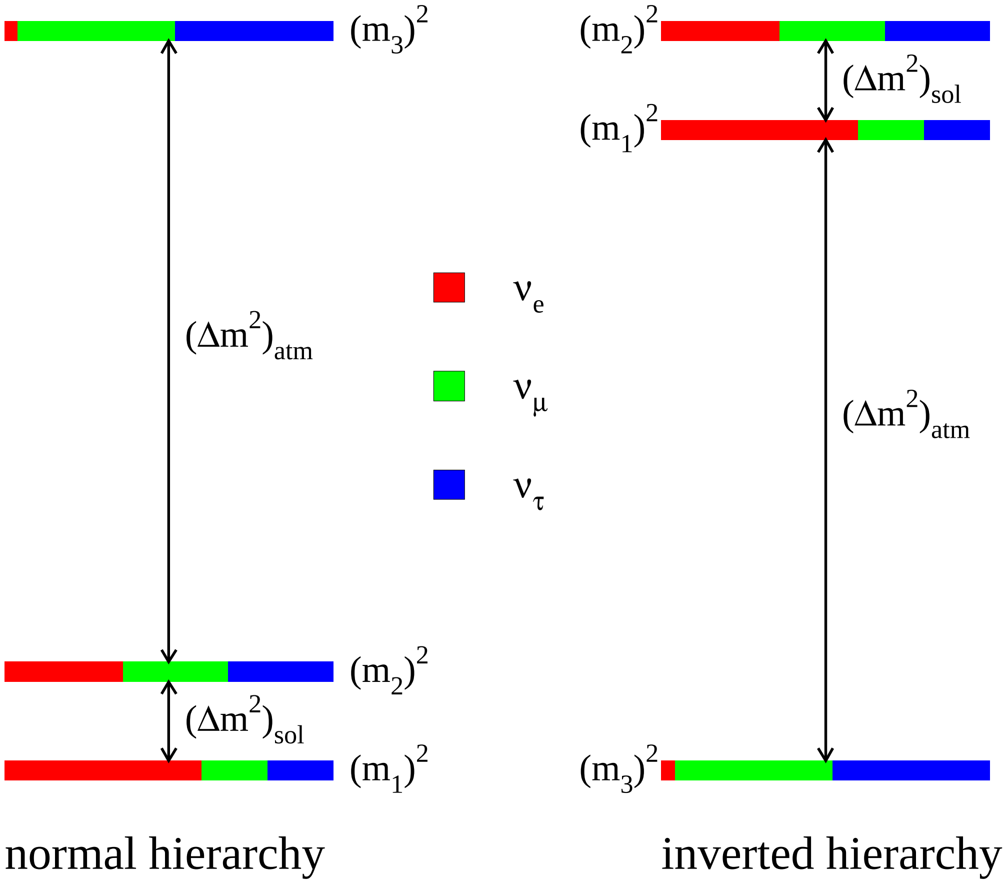


Triumph of the 3 flavor paradigm!

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

[Daya Bay Coll., 1203.1669]

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

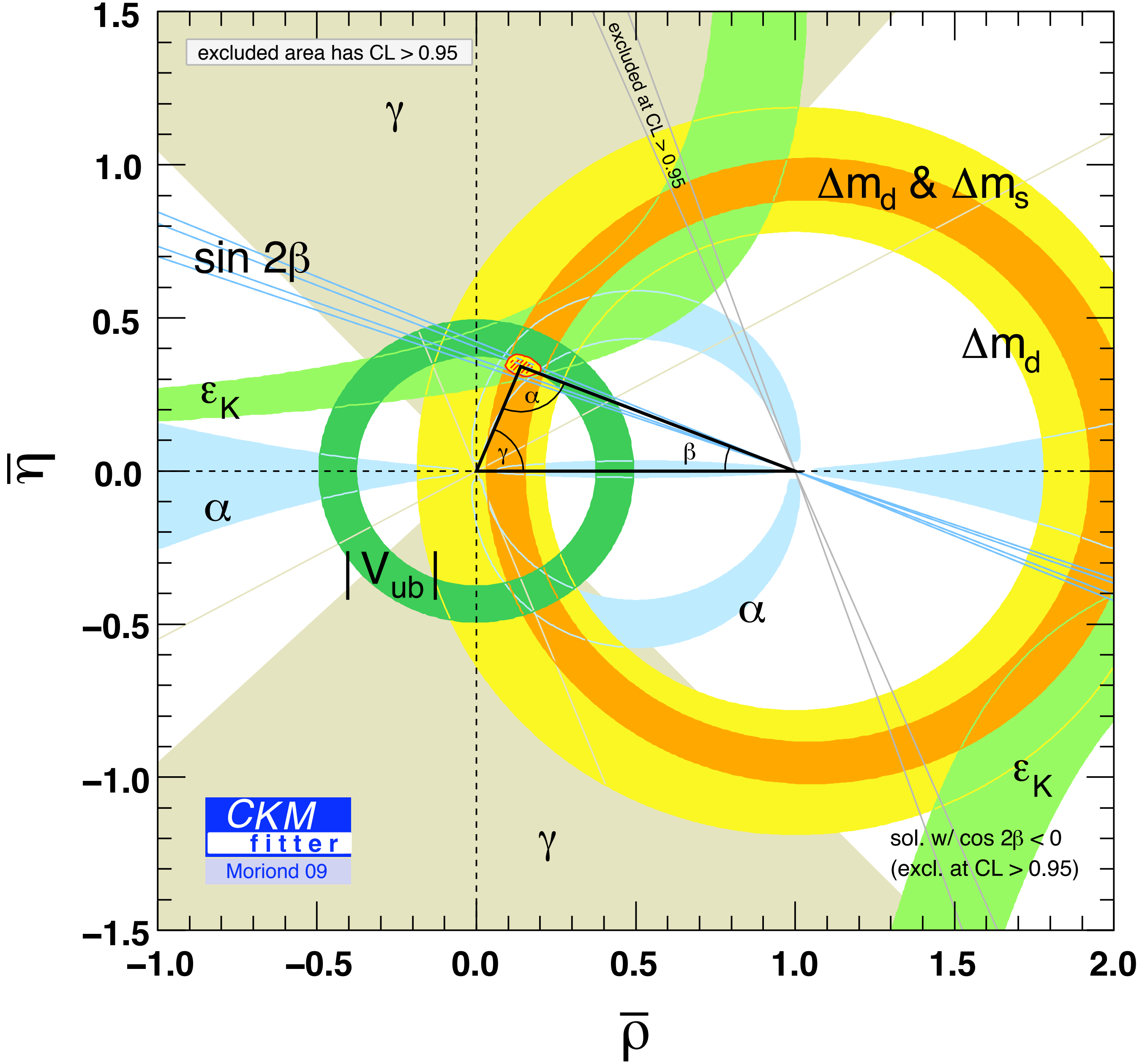


- ~~What is the ν_e component of ν_3?~~ $(\theta_{13} \neq 0!)$
- Is CP-invariance violated in neutrino oscillations? $(\delta \neq 0, \pi?)$
- Is ν_3 mostly ν_μ or ν_τ? $(\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4?)$
- What is the neutrino mass hierarchy? $(\Delta m^2_{13}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

$\Rightarrow$ 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!

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

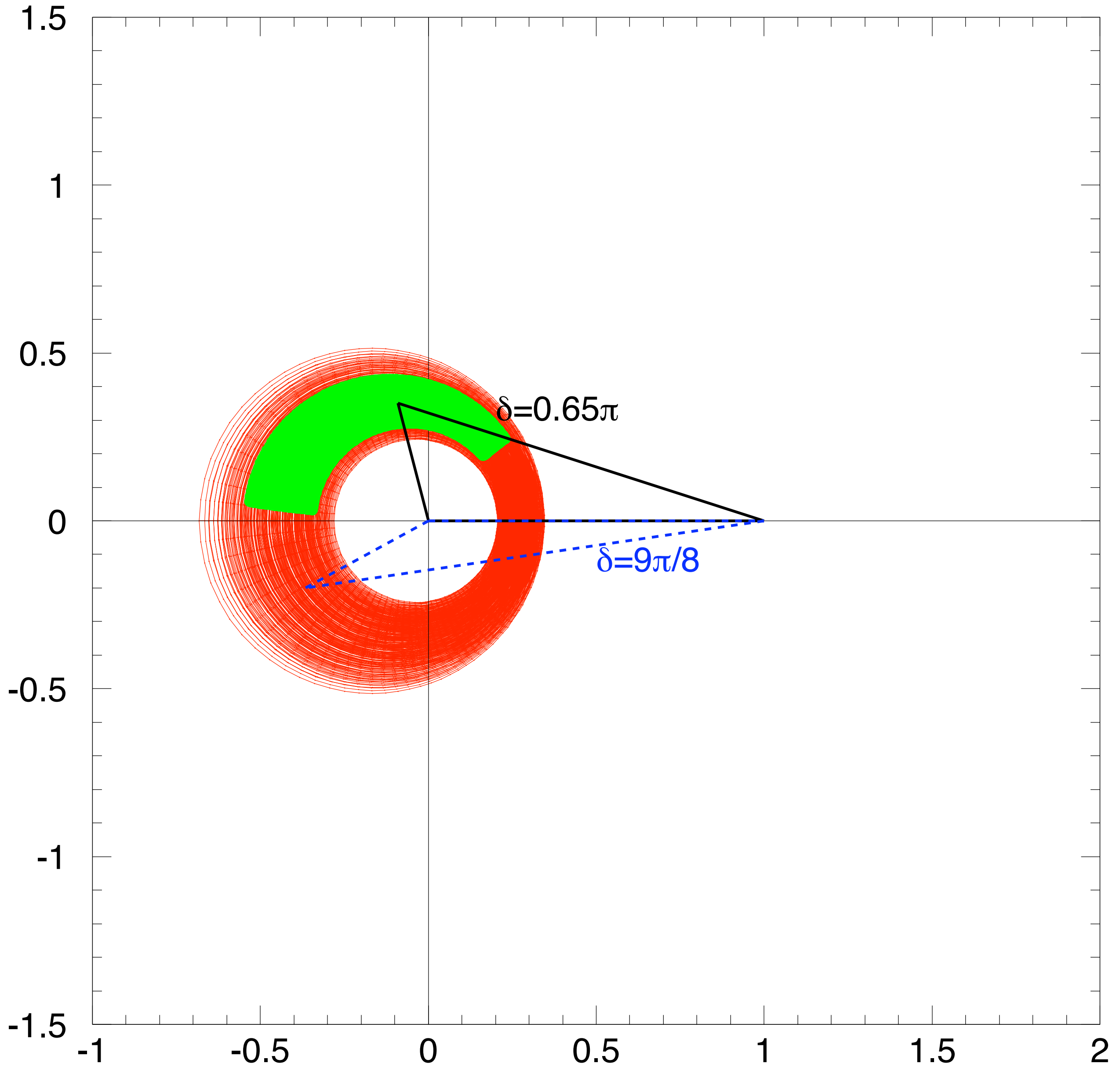
What we have **really measured** (very roughly):

- Two mass-squared differences, at several percent level – many probes;
- $|U_{e2}|^2$ – solar data;
- $|U_{\mu2}|^2 + |U_{\tau2}|^2$ – solar data;
- $|U_{e2}|^2|U_{e1}|^2$ – KamLAND;
- $|U_{\mu3}|^2(1 - |U_{\mu3}|^2)$ – atmospheric data, K2K, MINOS;
- $|U_{e3}|^2(1 - |U_{e3}|^2)$ – Double Chooz, Daya Bay, RENO;
- $|U_{e3}|^2|U_{\mu3}|^2$ (upper bound → evidence) – MINOS, T2K.

We still have a ways to go!

Where We Are (?)

[This is Not a Proper Comparison Yet . . .



. . . but it is a start]

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

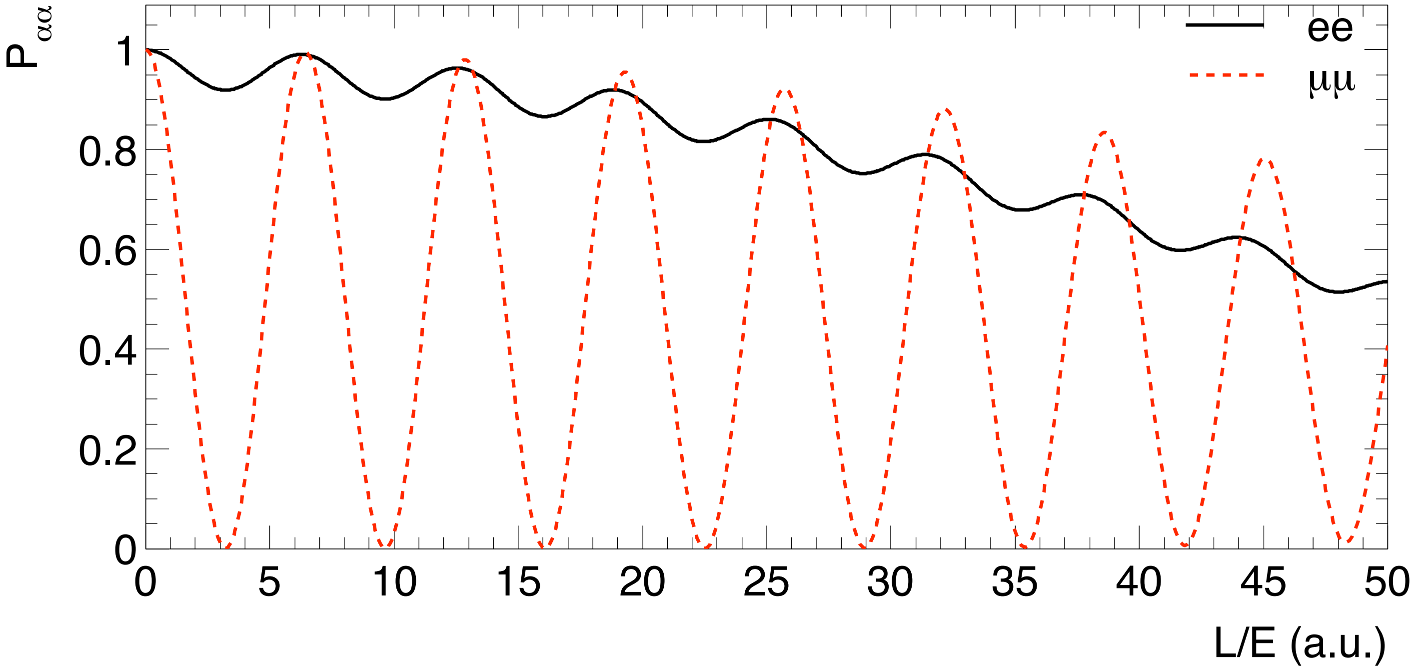
$$\bar{A}_{\mu e} = U_{e2} U_{\mu 2}^* \left(e^{i\Delta_{12}} - 1\right) + U_{e3} U_{\mu 3}^* \left(e^{i\Delta_{13}} - 1\right).$$

[I assume the unitarity of U, $U_{e1}U_{\mu 1}^* = -U_{e2}U_{\mu 2}^* - U_{e3}U_{\mu 3}^*$]

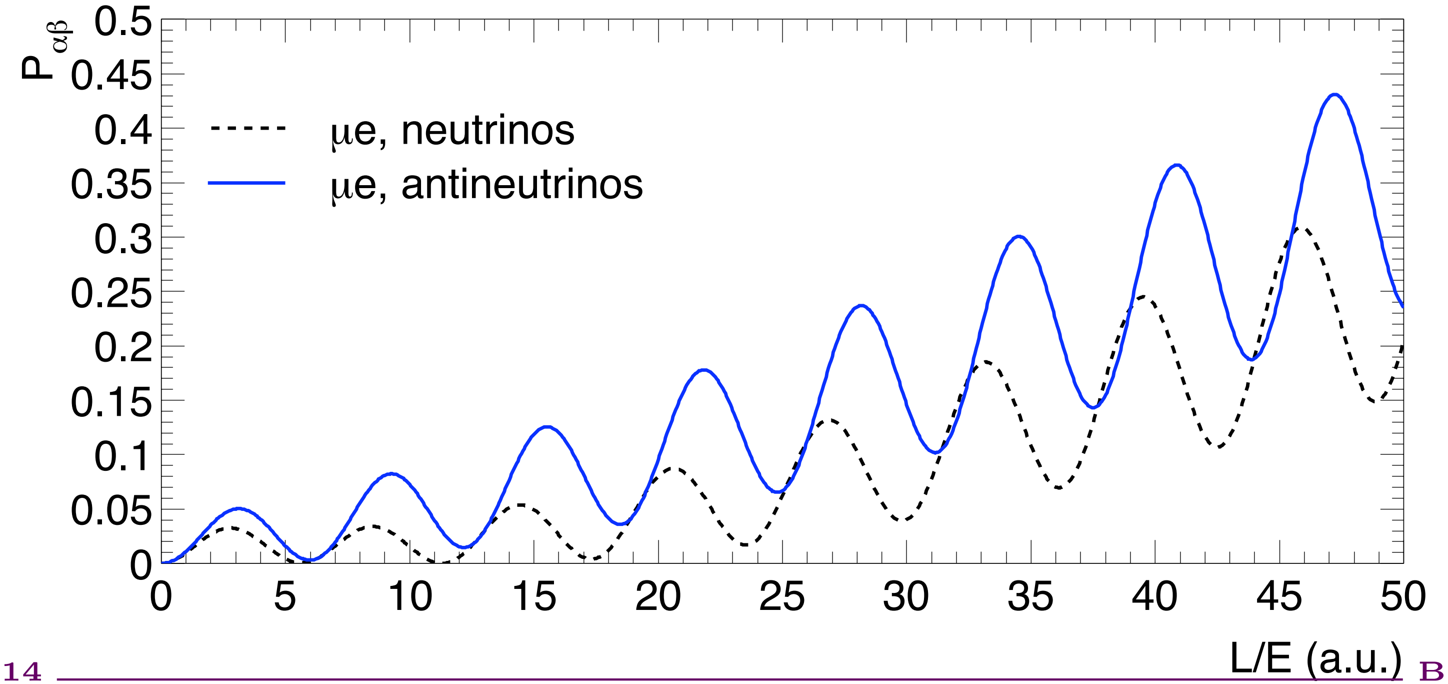
In general, $|A|^2 \neq |\bar{A}|^2$ (CP-invariance violated) as long as:

- Nontrivial "Weak" Phases: $\arg(U_{ei}^* U_{\mu i}) \to \delta \neq 0, \pi$;
- Nontrivial "Strong" Phases: Δ_{12}, Δ_{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: **we needed** $|U_{e3}| \neq 0$**.** ✓



P_αα
ee
μμ
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35
40
45
50
L/E (a.u.)



P_αβ
μe, neutrinos
μe, antineutrinos
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
30
35
40
45
50
L/E (a.u.)

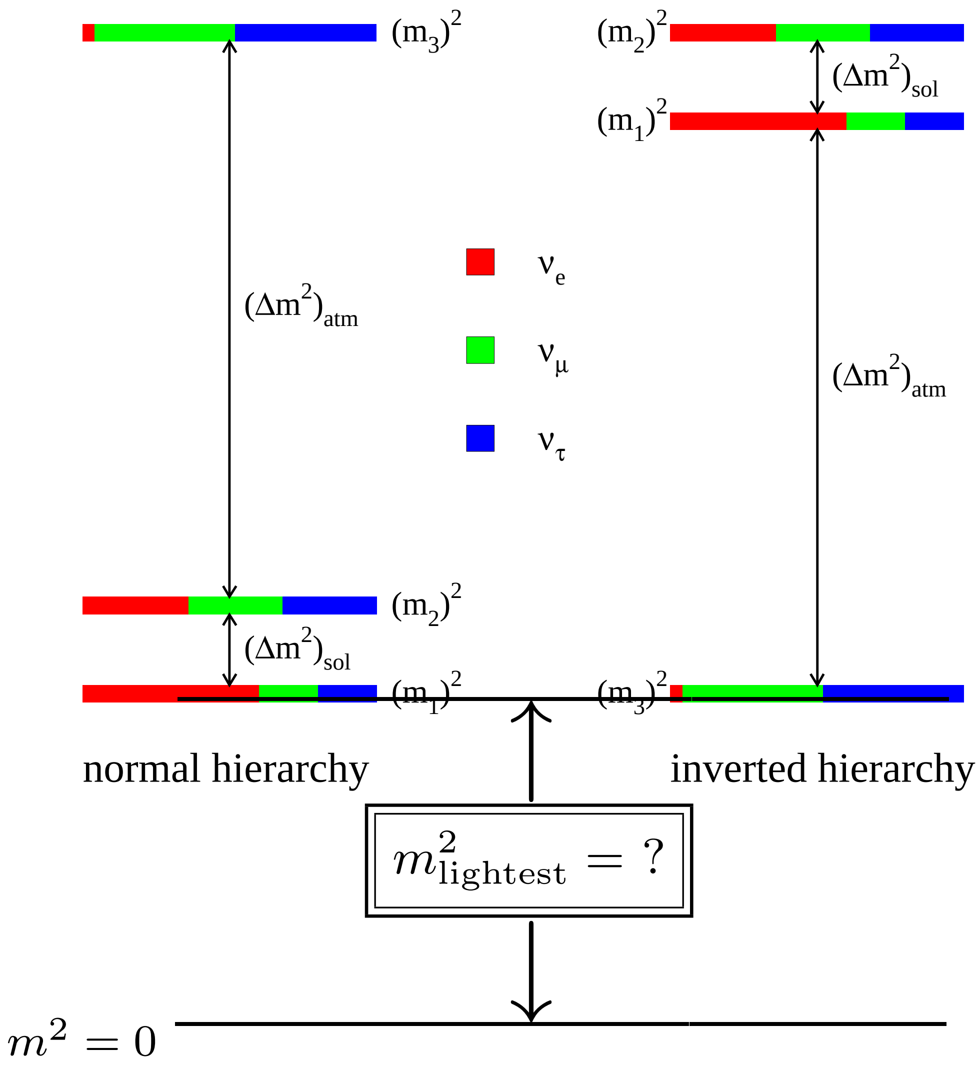
Golden Opportunity to Understand Matter versus Antimatter?

The SM with massive Majorana neutrinos accommodates **five** irreducible CP-invariance violating phases.

- One is the phase in the CKM phase. We have measured it, it is large, and we don't understand its value. At all.
- One is θ_{QCD} term ($\theta G\tilde{G}$). We don't know its value but it is only constrained to be very small. We don't know why (there are some good ideas, however).
- Three are in the neutrino sector. One can be measured via neutrino oscillations. 50% increase on the amount of information.

We don't know much about CP-invariance violation. Is it really fair to presume that CP-invariance is generically violated in the neutrino sector solely based on the fact that it is violated in the quark sector? Why? Cautionary tale: "Mixing angles are small"

What We Know We Don't Know: 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 poorly constrained: $m^2_{\rm lightest} < 1~{\rm eV}^2$

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:

$\rightarrow$ cosmology, β-decay, $0\nu\beta\beta$

Big Bang Neutrinos are Warm Dark Matter

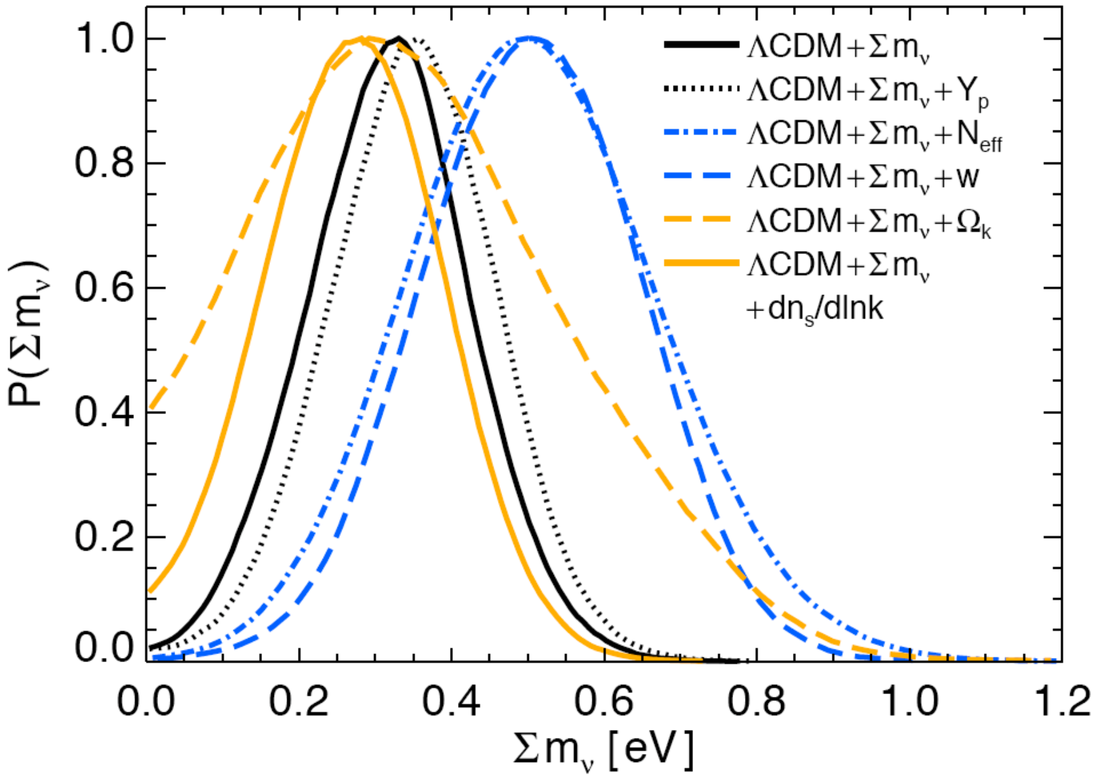


FIG. 10.— This figure illustrates the robustness of the neutrino mass detection to other parameter extensions. The marginalized one-dimensional posteriors for $\sum m_\nu$ are shown for two-parameter extensions to ΛCDM for the combined CMB+BAO+H_0+SPT$_{CL}$ data sets (for w, SNe are used instead of H_0). Allowing significant curvature or running can significantly reduce the preference for nonzero neutrino masses (to 1.7 and 2.4σ respectively). Other extensions increase the preference for positive neutrino masses.

[Z. Hou *et al.* arXiv:1212.6267]

- Constrained by the Large Scale Structure of the Universe.

Constraints depend on

- Data set analysed;
- "Bias" on other parameters;
- ...

Bounds can be evaded with non-standard cosmology. Will we learn about neutrinos from cosmology or about cosmology from neutrinos?

Big Bang Neutrinos are Warm Dark Matter

Planck Collaboration: Cosmological parameters

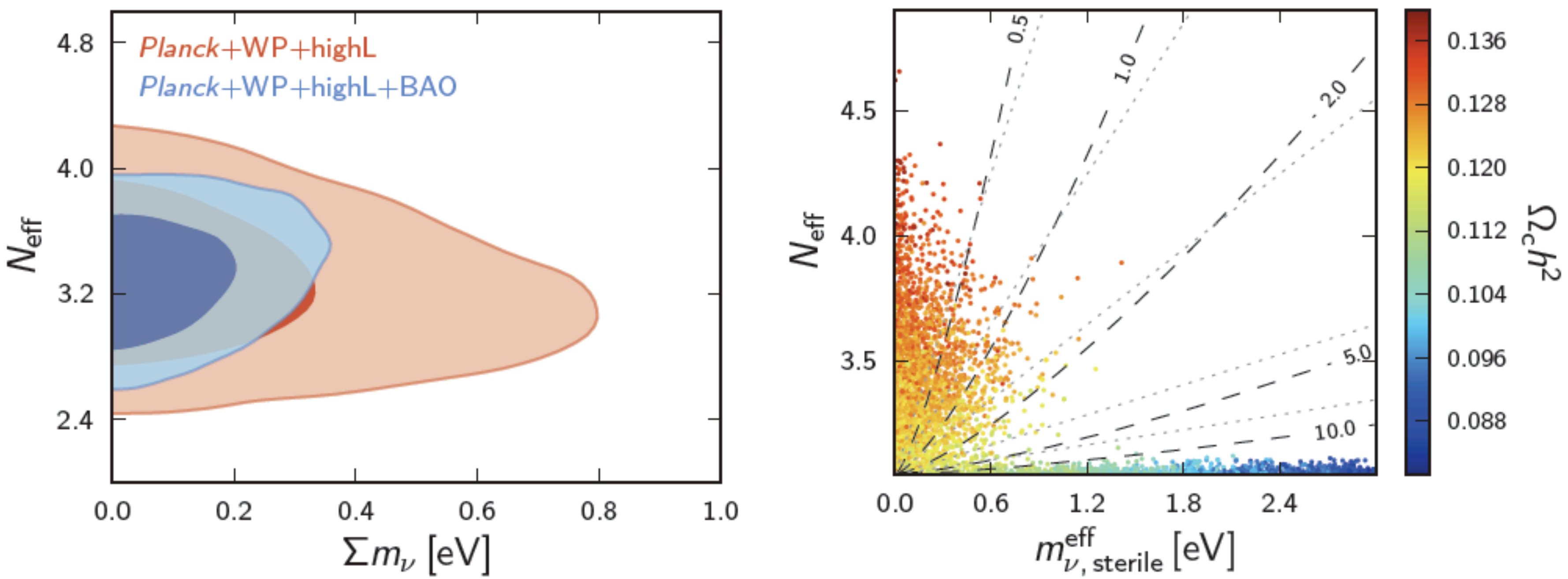
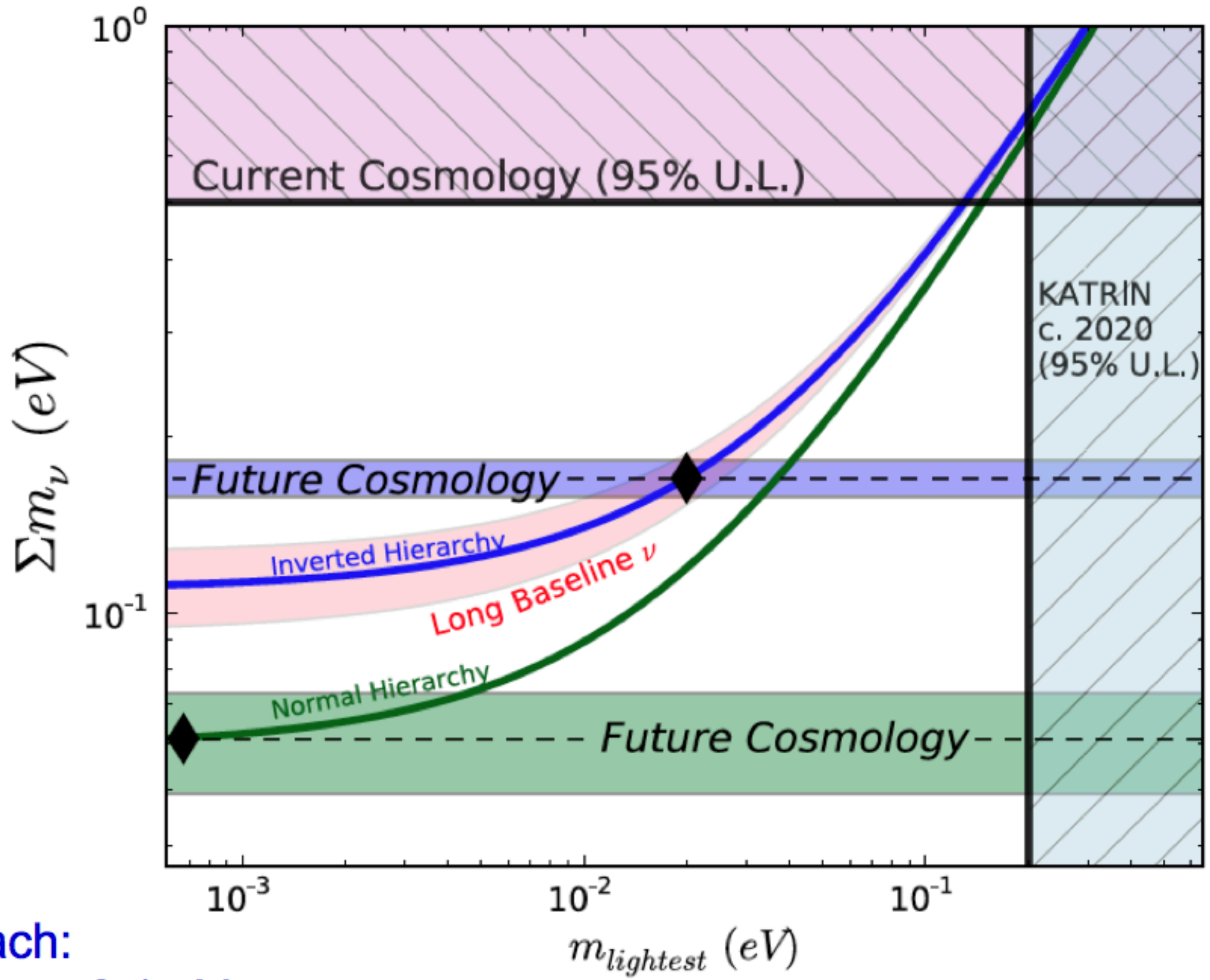


Fig. 28. *Left*: 2D joint posterior distribution between N_{eff} and $\sum m_\nu$ (the summed mass of the three active neutrinos) in models with extra massless neutrino-like species. *Right*: Samples in the N_{eff}–$m^{eff}_{\nu,\,sterile}$ plane, colour-coded by $\Omega_c h^2$, in models with one massive sterile neutrino family, with effective mass $m^{eff}_{\nu,\,sterile}$, and the three active neutrinos as in the base ΛCDM model. The physical mass of the sterile neutrino in the thermal scenario, $m^{thermal}_{sterile}$, is constant along the grey dashed lines, with the indicated mass in eV. The physical mass in the Dodelson-Widrow scenario, $m^{DW}_{sterile}$, is constant along the dotted lines (with the value indicated on the adjacent dashed lines).

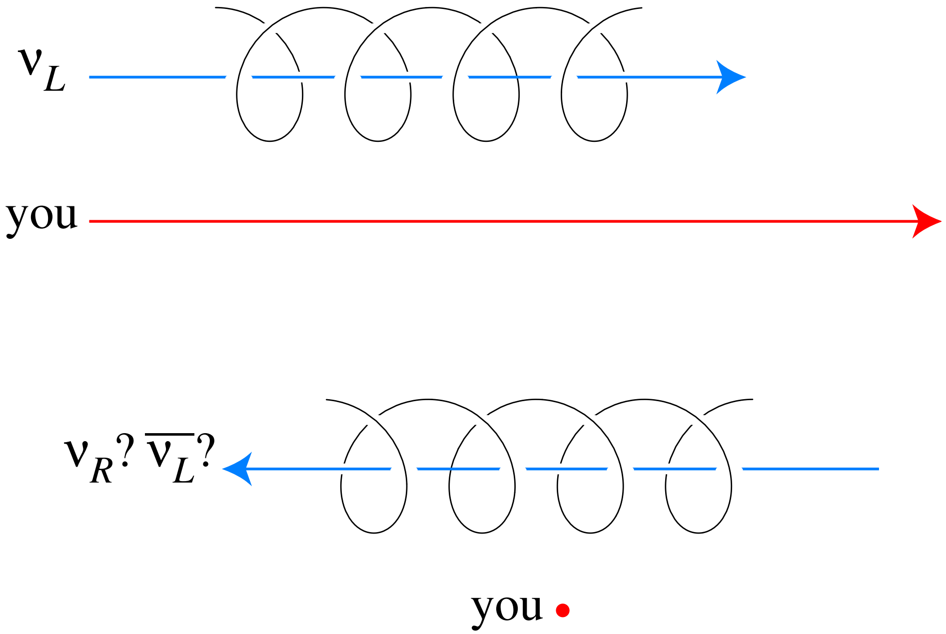
Neutrinos and Cosmology



Projected Reach:
2013-2016: Σm_ν ~0.1 eV
2016-2020: Σm_ν ~ 0.06 eV
2020-2025: Σm_ν ~ 16 meV

(S. Dodelson, Wednesday session)
See talk by S. Ritz [at Snowmass]

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:

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

$\updownarrow$ "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:

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

$\updownarrow$ "Lorentz" 'DIRAC'

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

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

'MAJORANA' $\updownarrow$ "Lorentz"

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

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

Why Don't We Know the Answer?

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

Processes that are proportional to the Majorana 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: $A \propto m_\nu/E$.

The "smoking gun" signature is the observation of LEPTON NUMBER violation. This is easy to understand: Majorana neutrinos are their own antiparticles and, therefore, cannot carry **any** quantum numbers — including lepton number.

Weak Interactions are Purely Left-Handed (Chirality):

For example, 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:

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

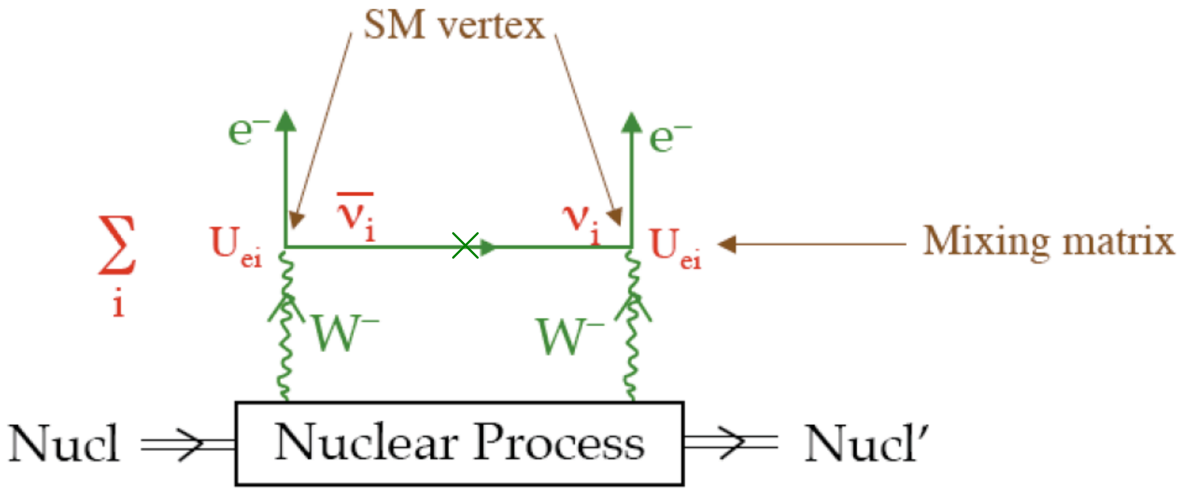
Lepton number can be violated by 2 units with small probability. Typical numbers: $P \simeq (0.1\text{ eV}/100\text{ MeV})^2 = 10^{-18}$. VERY Challenging!

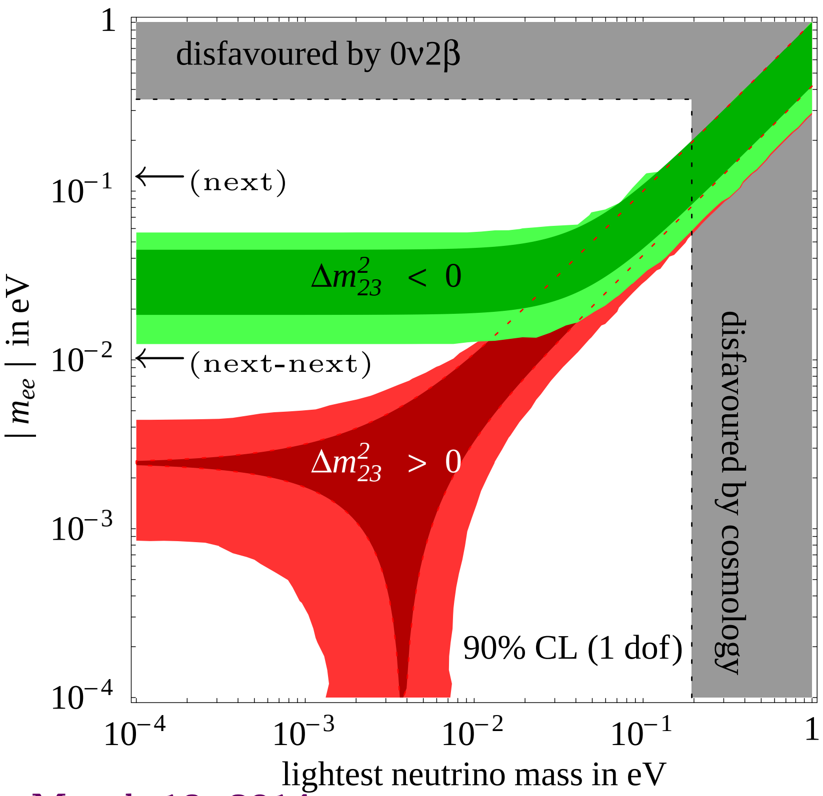
Search for the Violation of Lepton Number (or $B-L$)

Best Bet: search for

Neutrinoless Double-Beta

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

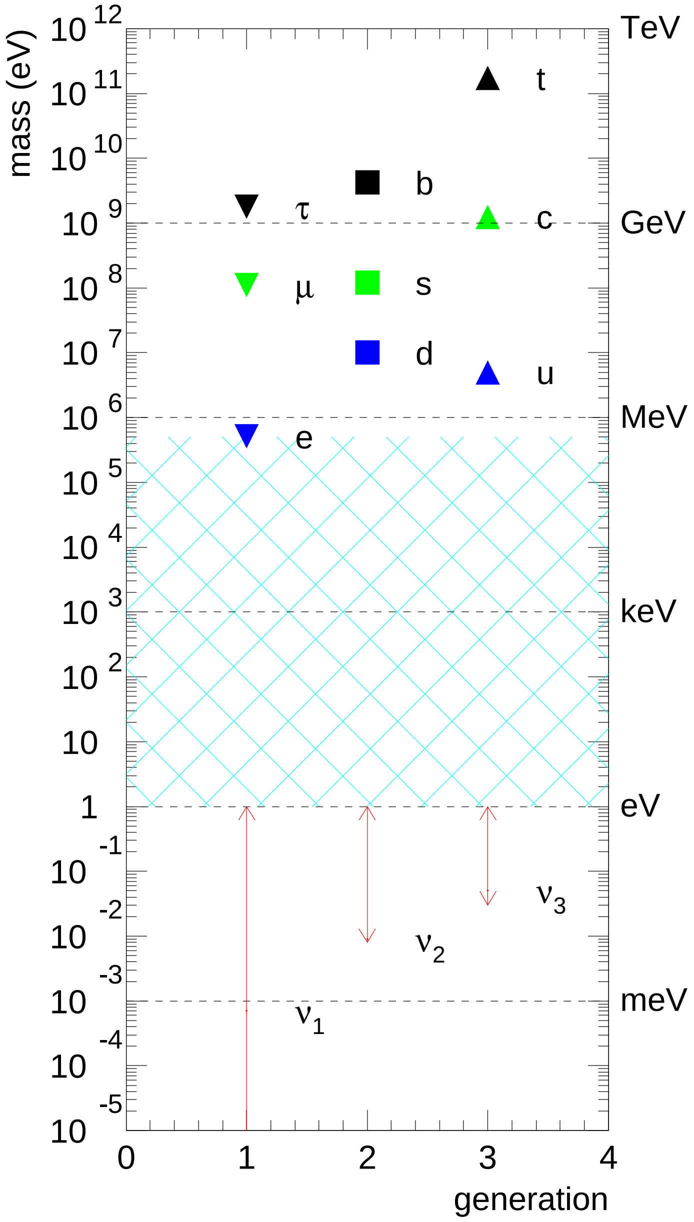




Helicity Suppressed Amplitude $\propto \frac{m_{ee}}{E}$

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

$\Leftarrow$ **no longer lamp-post physics!**



What We Are Trying To Understand:

⇐ NEUTRINOS HAVE TINY MASSES

⇓ LEPTON MIXING IS "WEIRD" ⇓

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

What Does It Mean?

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?

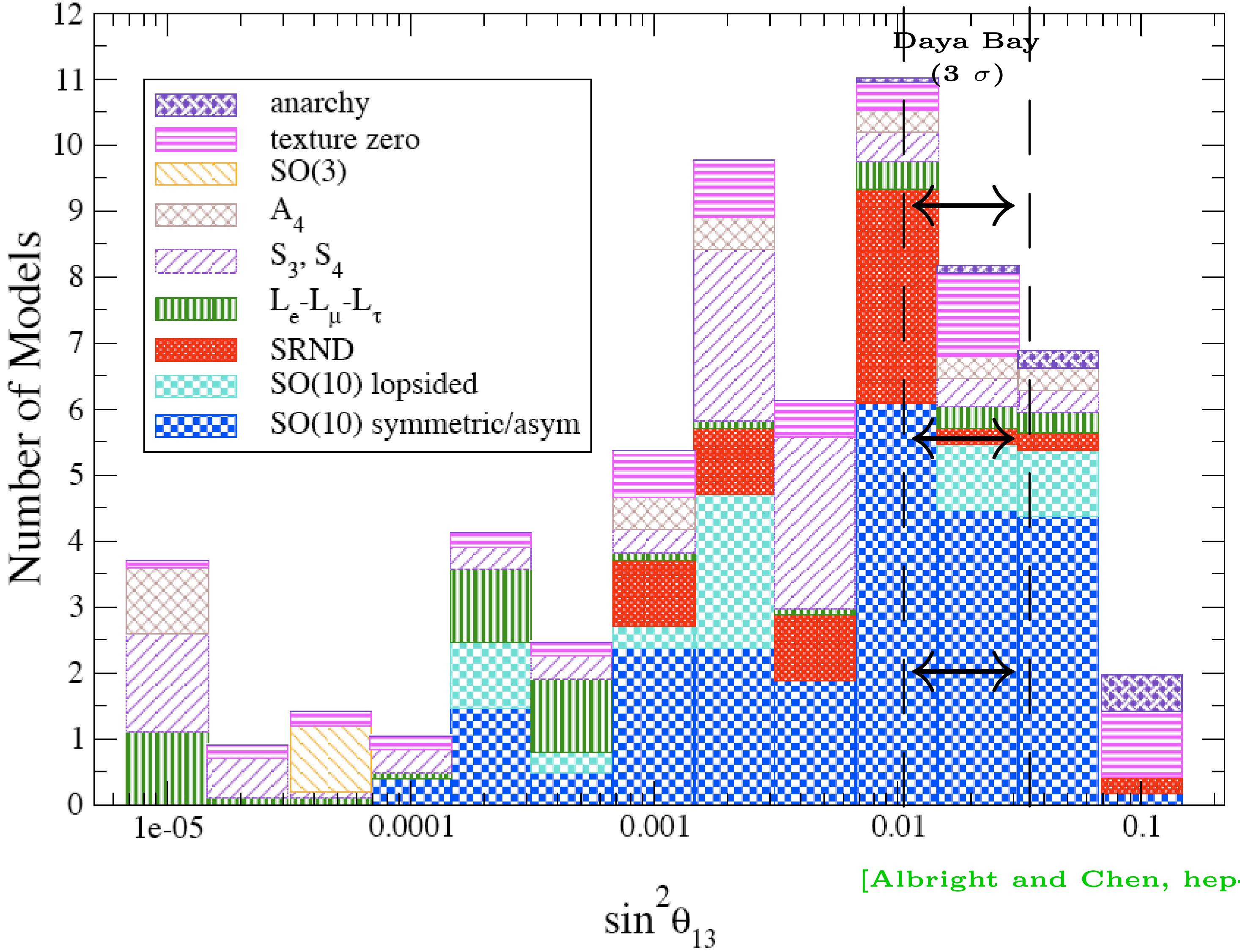
It means that lepton mixing is very different from quark mixing:

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

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

WHY?

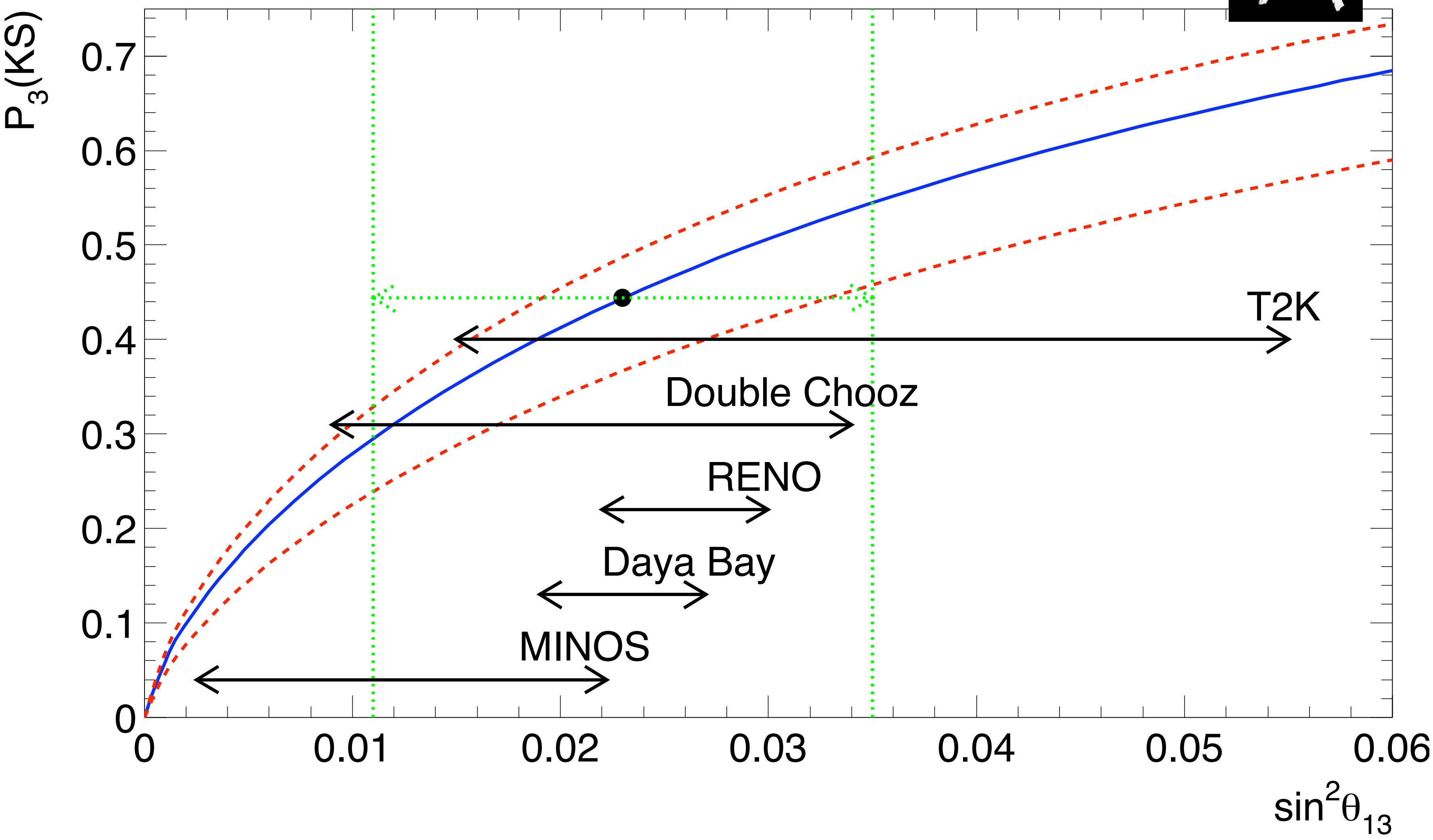
They certainly look VERY different, but which one would you label as "strange"?



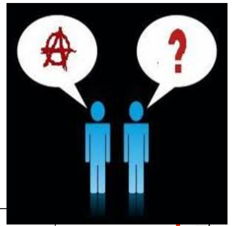
[Albright and Chen, hep-ph/0608137]

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

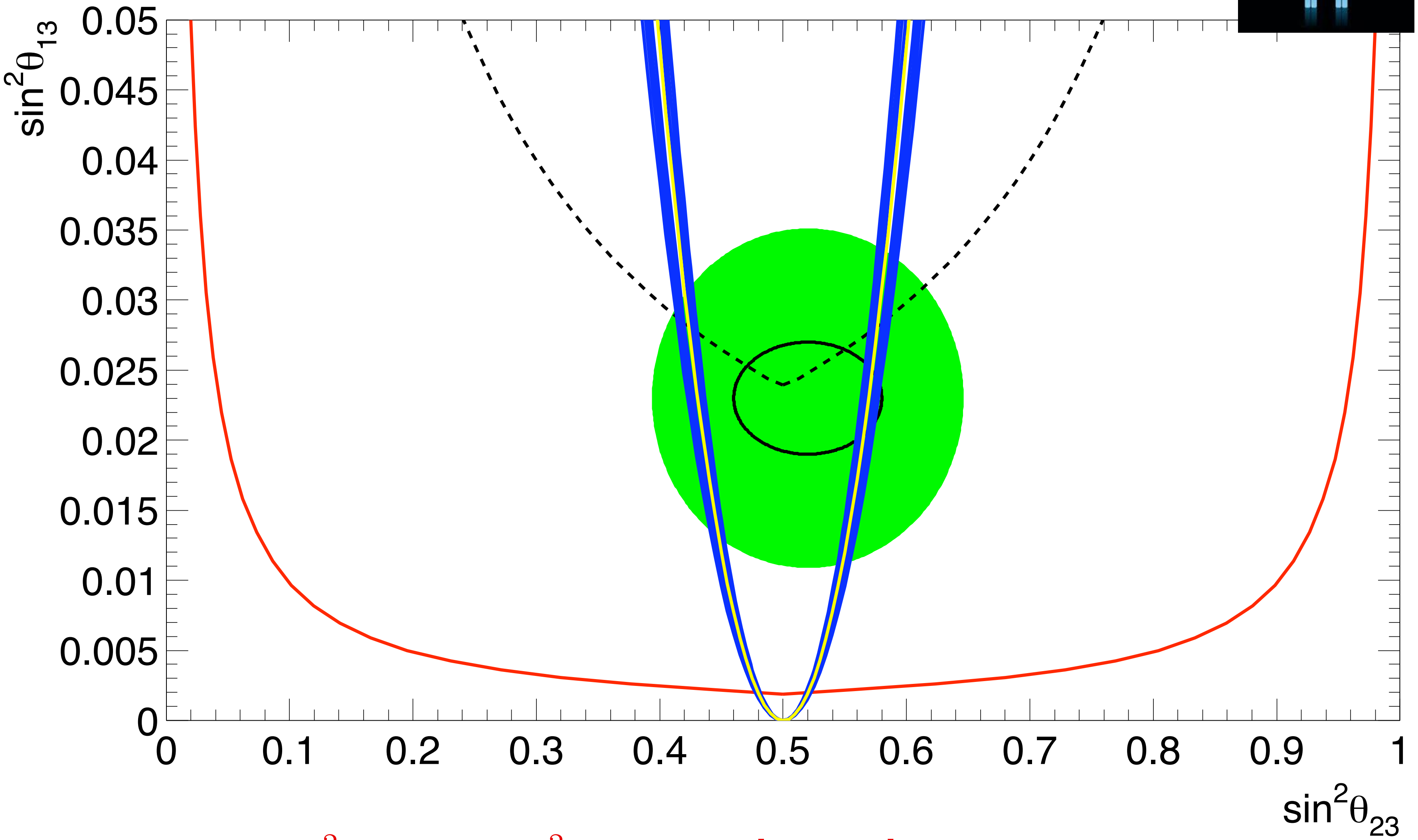
Neutrino Mixing Anarchy: Alive and Kicking!



[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]

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.

---

* There is only a handful of questions our model for fundamental 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 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? (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, Electroweak Symmetry Breaking, and a New Scale

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).

One Candidate νSM

SM as an effective field theory – non-renormalizable operators

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

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

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

- 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/y.
- Define $y_{\max} \equiv 1 \Rightarrow$ data require $\boxed{\Lambda \sim 10^{14}\text{ GeV.}}$

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

The Seesaw Lagrangian

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

  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 (*cf.* 1 A.U.).

(**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").

)

High-Energy Seesaw: Brief Comments

- This is everyone's favorite scenario.
- Upper bound for M (e.g. Maltoni, Niczyporuk, Willenbrock, hep-ph/0006358):

$$M < 7.6 \times 10^{15}\ \mathrm{GeV} \times \left(\frac{0.1\ \mathrm{eV}}{m_\nu}\right).$$

- Hierarchy problem hint (e.g., Casas et al, hep-ph/0410298; AdG et al, 1402.2658):

$$M < 10^7\ \mathrm{GeV}.$$

- Leptogenesis! "Vanilla" Leptogenesis requires, roughly, smallest

$$M > 10^9\ \mathrm{GeV}.$$

- Physics "too" heavy! No observable consequence other than leptogenesis. Will we ever convince ourselves that this is correct?

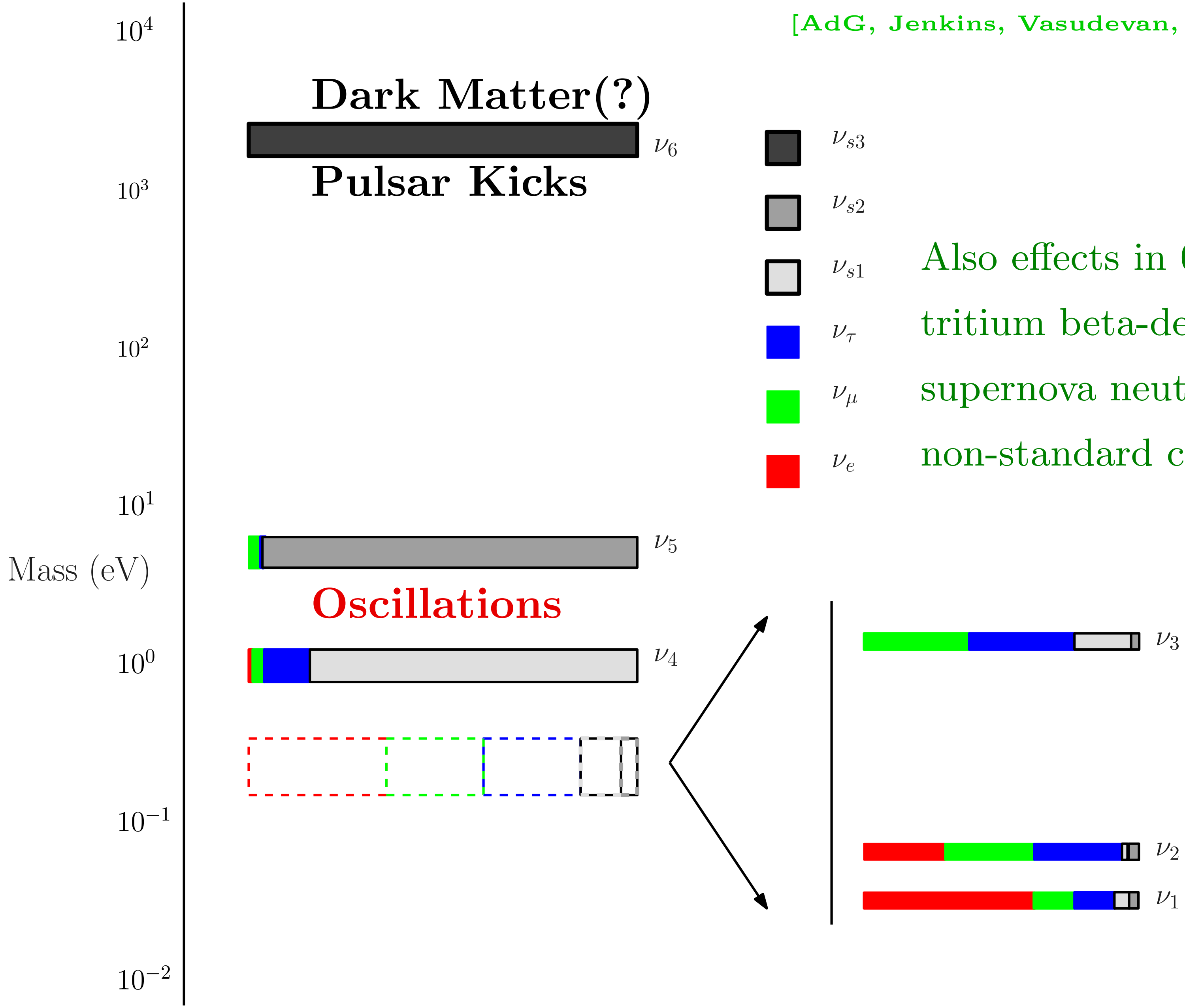
(e.g., Buckley, Murayama, hep-ph/0606088)

Low-Energy Seesaw [AdG PRD72,033005)]

The other end of the M spectrum ($M < 100$ GeV). What do we get?

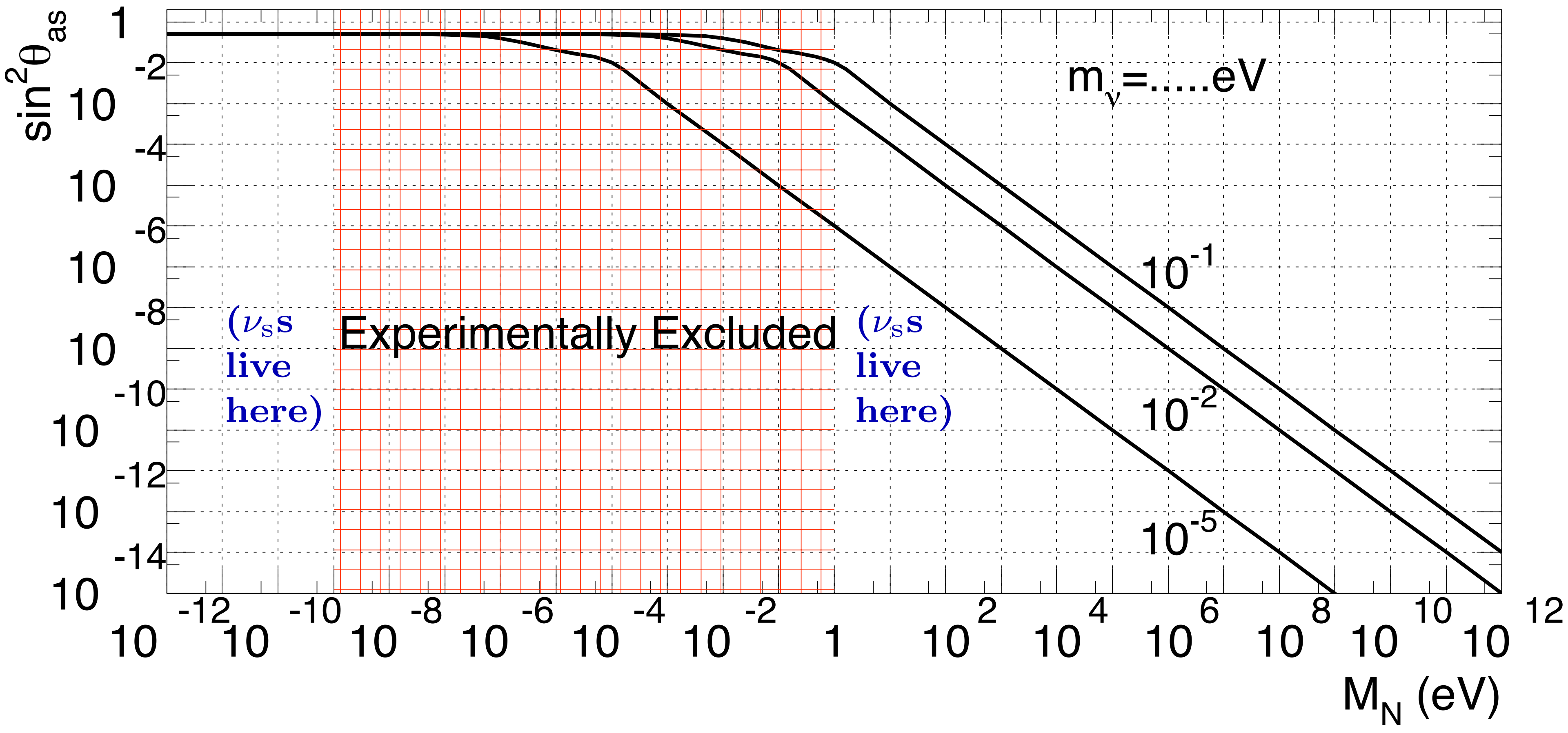
- Neutrino masses are small because the Yukawa couplings are very small $\lambda \in [10^{-6}, 10^{-11}]$;
- No standard thermal leptogenesis – right-handed neutrinos way too light? [For a possible alternative see Canetti, Shaposhnikov, arXiv: 1006.0133 and reference therein.]
- No obvious connection with other energy scales (EWSB, GUTs, etc);
- Right-handed neutrinos are propagating degrees of freedom. They look like sterile neutrinos $\Rightarrow$ sterile neutrinos associated with the fact that the active neutrinos have mass;
- sterile–active mixing can be predicted – hypothesis is falsifiable!
- Small values of M are natural (in the 'tHooft sense). In fact, theoretically, no value of M should be discriminated against!

[AdG, Jenkins, Vasudevan, PRD75, 013003 (2007)]



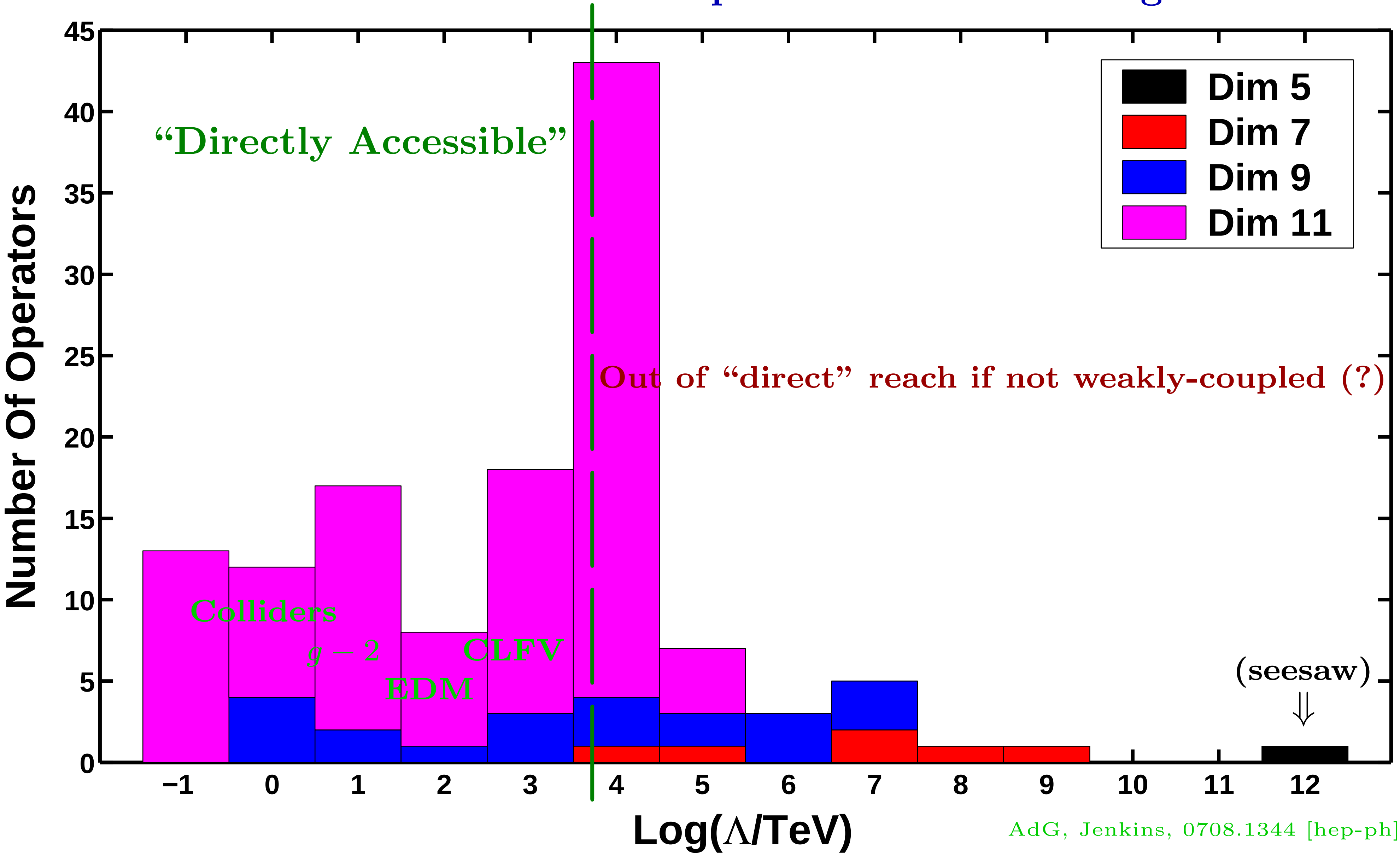
Also effects in $0\nu\beta\beta$,
tritium beta-decay,
supernova neutrino oscillations,
non-standard cosmology.

Constraining the Seesaw Lagrangian



[AdG, Huang, Jenkins, arXiv:0906.1611]

This is Just the Tip of the Model-Iceberg!



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. LBNE and HyperK first steps towards the ultimate "superbeam" experiment.
- The next-step is to develop a qualitatively better neutrino beam – e.g. muon storage rings (neutrino factories).
- Different baselines and detector technologies a must for both over-constraining the system and looking for new phenomena.
- Probes of neutrino properties, including neutrino scattering experiments.
- 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 (Cosmology). Will we learn about neutrinos from cosmology, or about cosmology from neutrinos?

One Very Promising Probe: Charged-Lepton Flavor Violation

In the old SM, the rate for charged lepton flavor violating processes is trivial to predict. It vanishes because individual lepton-flavor number is conserved:

- $N_\alpha(\text{in}) = N_\alpha(\text{out})$, for $\alpha = e, \mu, \tau$.

But individual lepton-flavor number are NOT conserved– ν oscillations!

Hence, in the νSM (the old Standard Model plus operators that lead to neutrino masses) $\mu \to e\gamma$ is allowed (along with all other charged lepton flavor violating processes).

These are Flavor Changing Neutral Current processes, observed in the quark sector ($b \to s\gamma$, $K^0 \leftrightarrow \bar{K}^0$, etc).

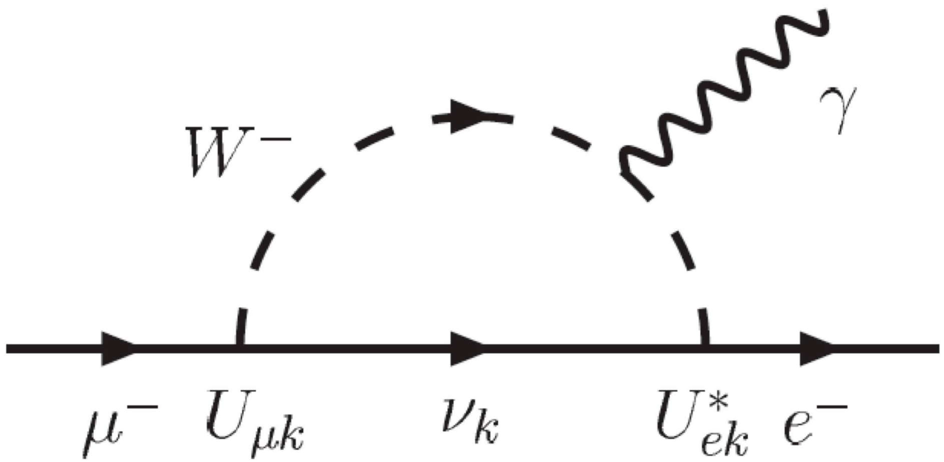
Unfortunately, we do not know the νSM expectation for charged lepton flavor violating processes $\to$ **we don't know the νSM Lagrangian !**

One contribution known to be there: active neutrino loops (same as quark sector).

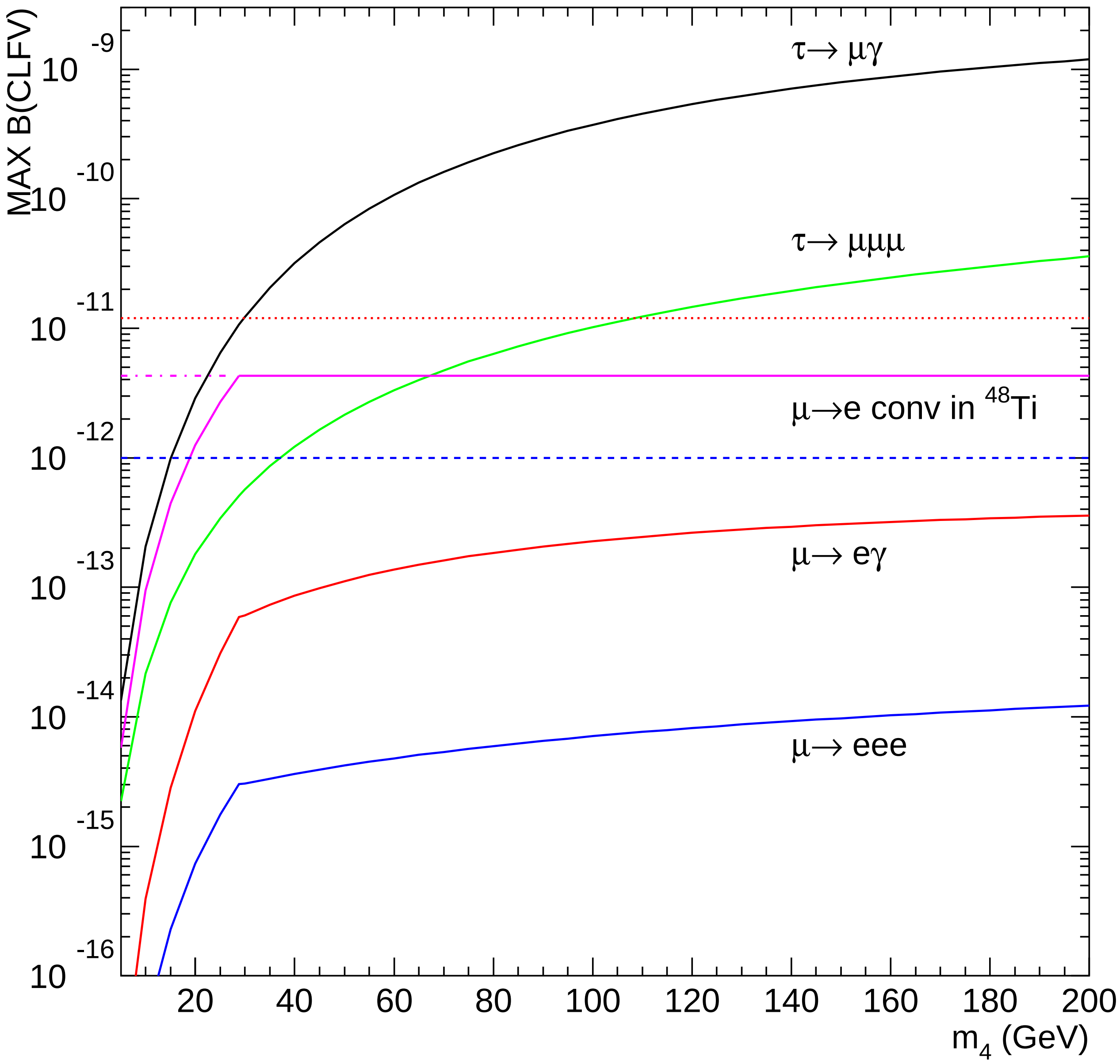
In the case of charged leptons, the **GIM suppression is very efficient**. . .

$$\text{e.g.: } Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

[$U_{\alpha i}$ are the elements of the leptonic mixing matrix,
$\Delta m^2_{1i} \equiv m^2_i - m^2_1$, $i = 2, 3$ are the neutrino mass-squared differences]

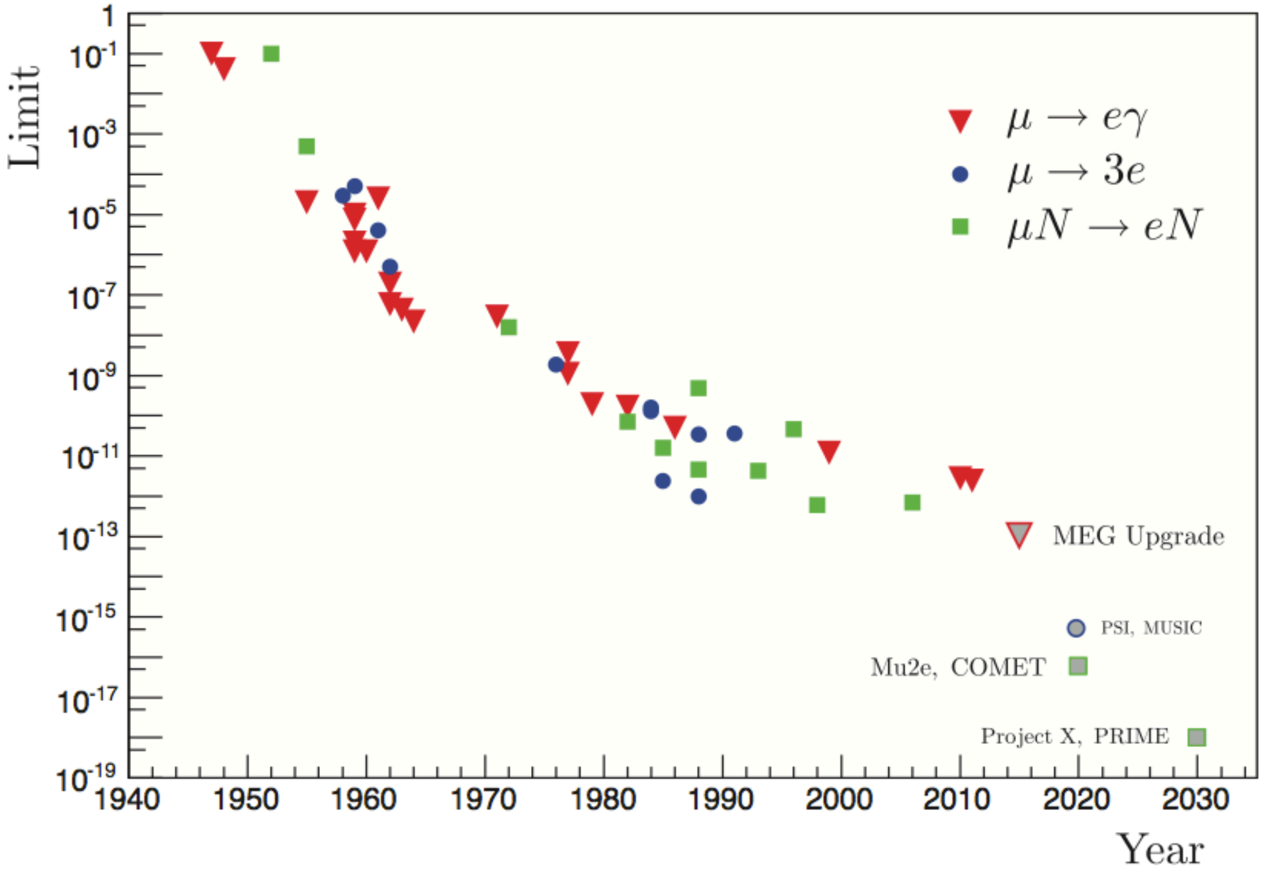


e.g.: SeeSaw Mechanism [minus "Theoretical Prejudice"]



arXiv:0706.1732 [hep-ph]

History of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$

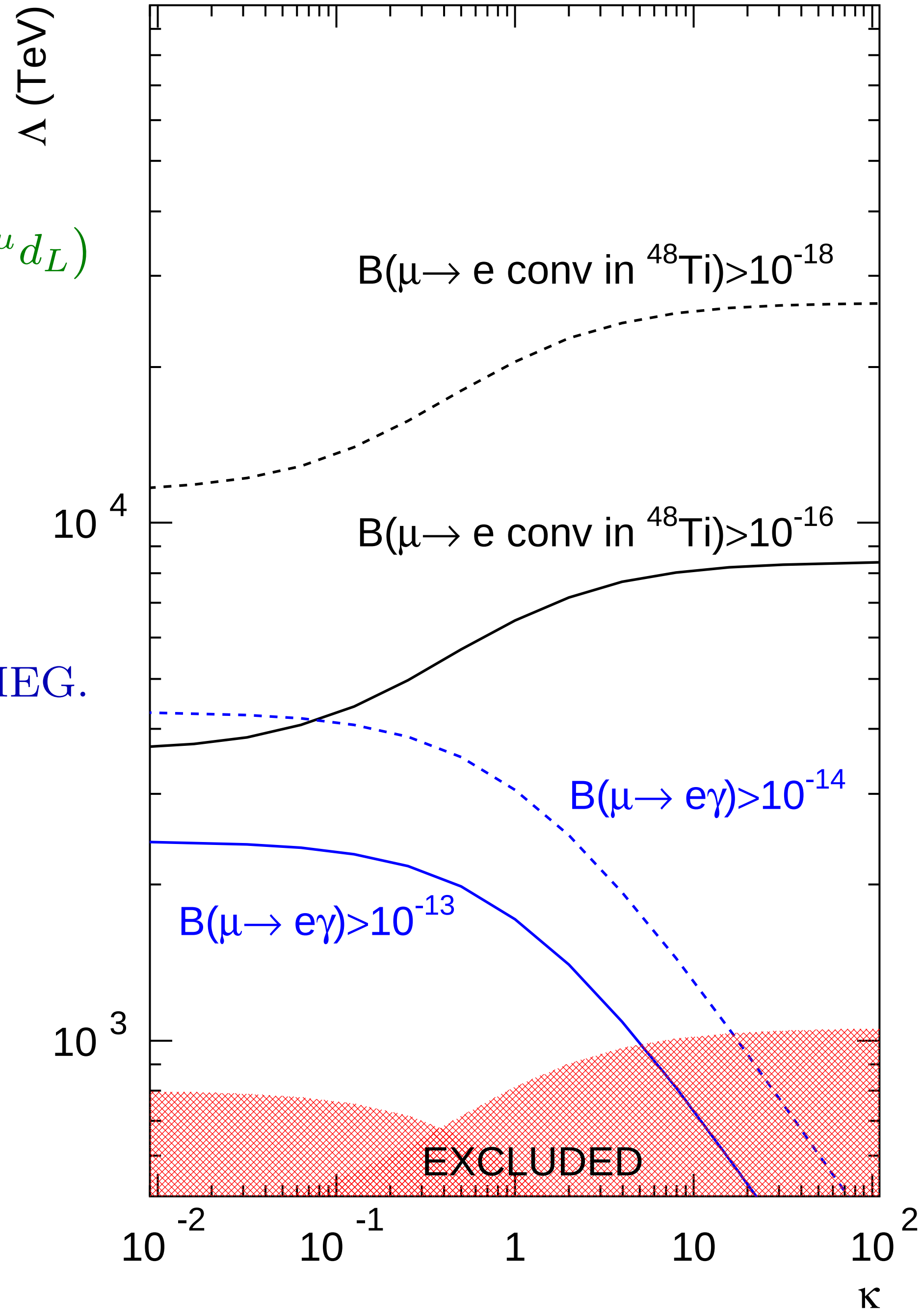


[R. Bernstein, P. Cooper, arXiv 1307.5787]

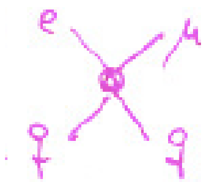
Figure 3: The history of CLFV searches in muons (not including muonium.) One sees a steady improvement in all modes and then a flattening of the rate improvement throughout the 1990s. MEG has upgrade plans for the $\mu \to e\gamma$ search. The two next generations of $\mu N \to eN$, Mu2e/COMET at FNAL and J-PARC are labeled, and possible extensions at Project X and PRIME are shown. Letters-of-intent are in process for $\mu \to 3e$ experiments at PSI and Osaka's MUSIC facility. Individual experiments are discussed in the text.

Model Independent Considerations

$$L_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \\ + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$



- $\mu \to e$-conv at 10^{-17} "guaranteed" deeper probe than $\mu \to e\gamma$ at 10^{-14}.
- We don't think we can do $\mu \to e\gamma$ better than 10^{-14}. $\mu \to e$-conv "only" way forward after MEG.
- If the LHC does not discover new states $\mu \to e$-conv among very few process that can access 1000+ TeV new physics scale: tree-level new physics: $\kappa \gg 1$, $\frac{1}{\Lambda^2} \sim \frac{g^2\theta_{e\mu}}{M^2_{\rm new}}$.

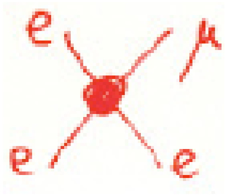


[AdG, Vogel, 1303.4097]

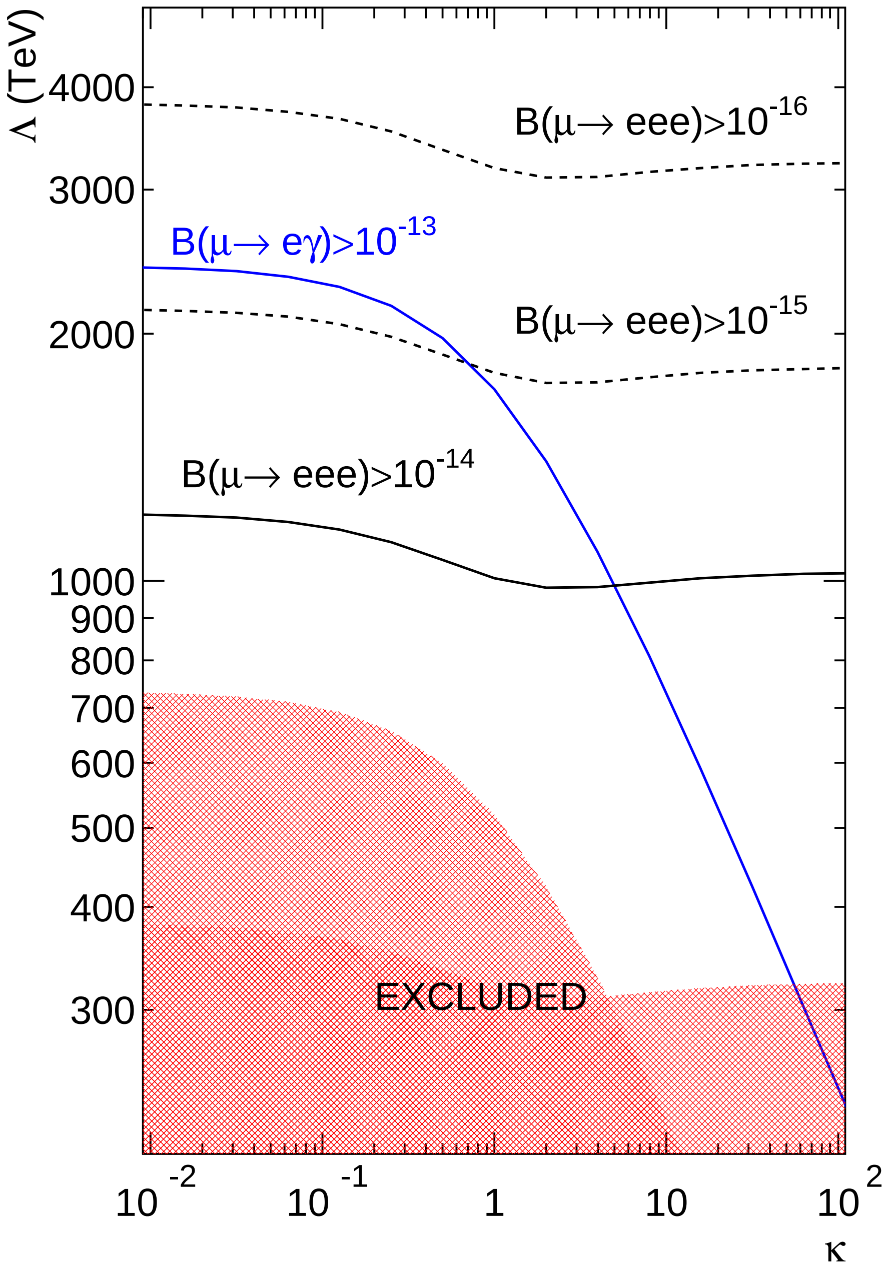
Other Example: $\mu \to e e^+ e^-$

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \bar{e}\gamma^\mu e$$

- $\mu \to eee$-conv at 10^{-16} "guaranteed" deeper probe than $\mu \to e\gamma$ at 10^{-14}.
- $\mu \to eee$ another way forward after MEG?
- If the LHC does not discover new states $\mu \to eee$ among very few process that can access 1,000+ TeV new physics scale: tree-level new physics: $\kappa \gg 1$, $\frac{1}{\Lambda^2} \sim \frac{g^2\theta_{e\mu}}{M^2_{\rm new}}$.



[AdG, Vogel, 1303.4097]



In Conclusion

The venerable Standard Model sprung a leak in the end of the lass century: neutrinos are not massless! (and we are still trying to patch it)

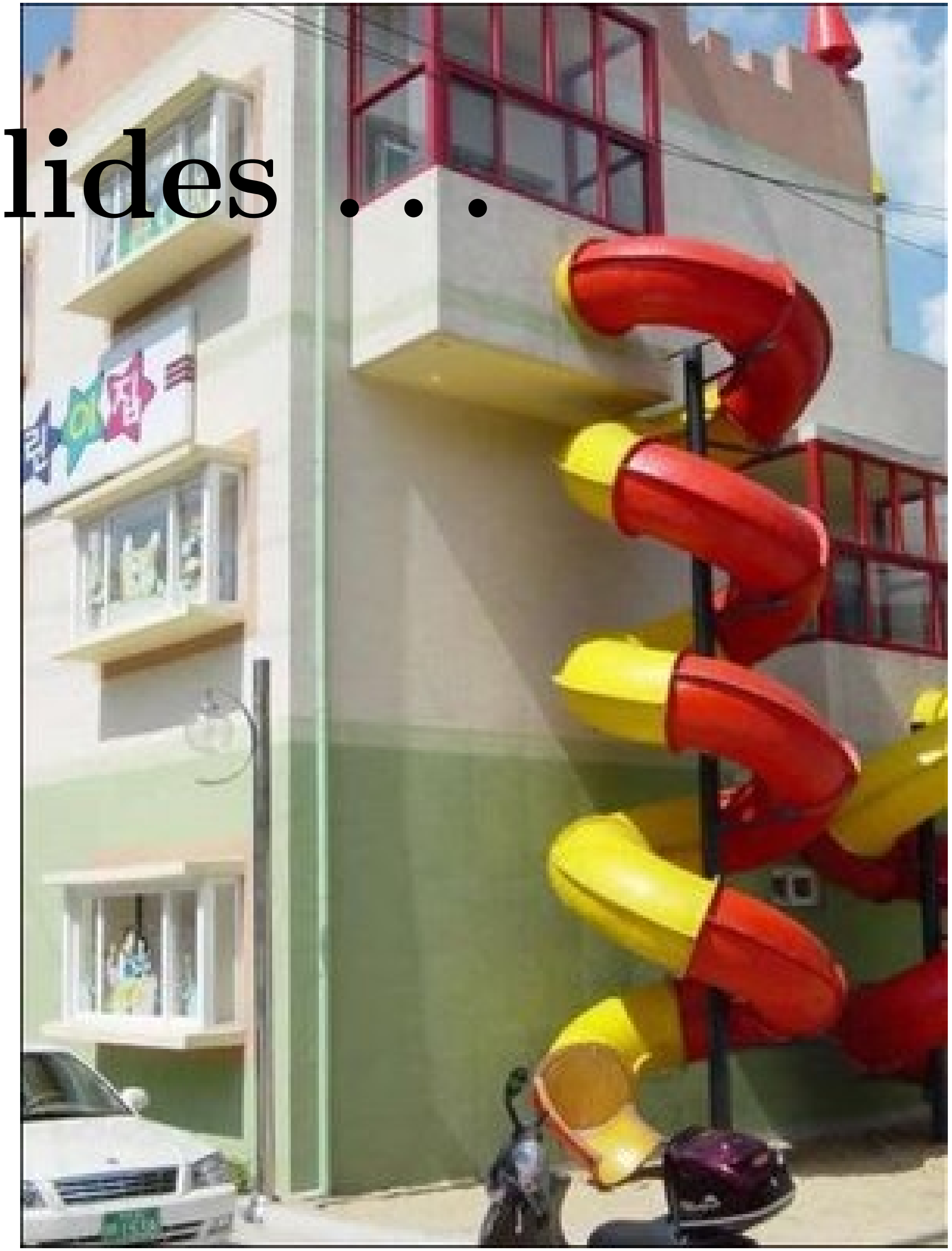
1. We know very little about the new physics uncovered by neutrino oscillations.
   - It could be renormalizable $\rightarrow$ boring (?) Dirac neutrinos.
   - It could be due to Physics at absurdly high energy scales $M \gg 1$ TeV $\rightarrow$ high energy seesaw. How can we convince ourselves that this is correct?
   - It could be due to very light new physics. Prediction: new light propagating degrees of freedom – sterile neutrinos
   - It could be due to new physics at the TeV scale $\rightarrow$ either weakly coupled, or via a more subtle lepton number breaking sector.
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. we need a minimal νSM Lagrangian. In order to decide which one is "correct" we **need to uncover the faith of baryon number minus lepton number** ($0\nu\beta\beta$ is the best [only?] bet).

5. We **need more experimental input** These will come from a rich, diverse experimental program which relies heavily on the existence of underground facilities capable of hosting large detectors (**double-beta decay, precision neutrino oscillations, supernova neutrinos, nucleon decay**). Also "required"
   - Powerful neutrino beam;
   - Precision studies of charged-lepton lepton properties and processes;
   - High energy collider experiments (the LHC will do for now);

6. There is plenty of **room for surprises**, as neutrinos are potentially very 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., $\Lambda \simeq 10^{14}$ GeV).

Backup Slides . . .



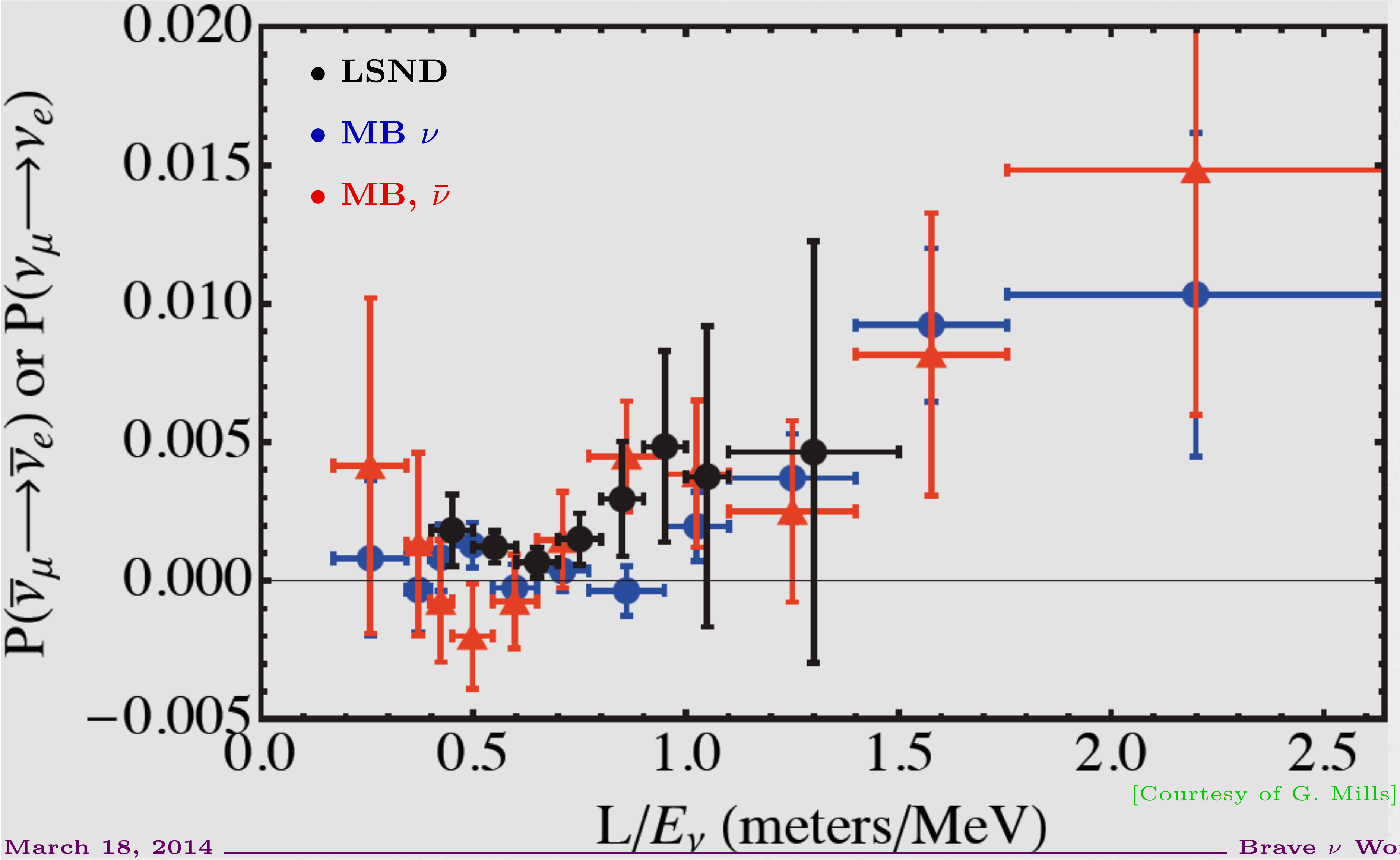
Not all is well(?): The Short Baseline Anomalies

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.

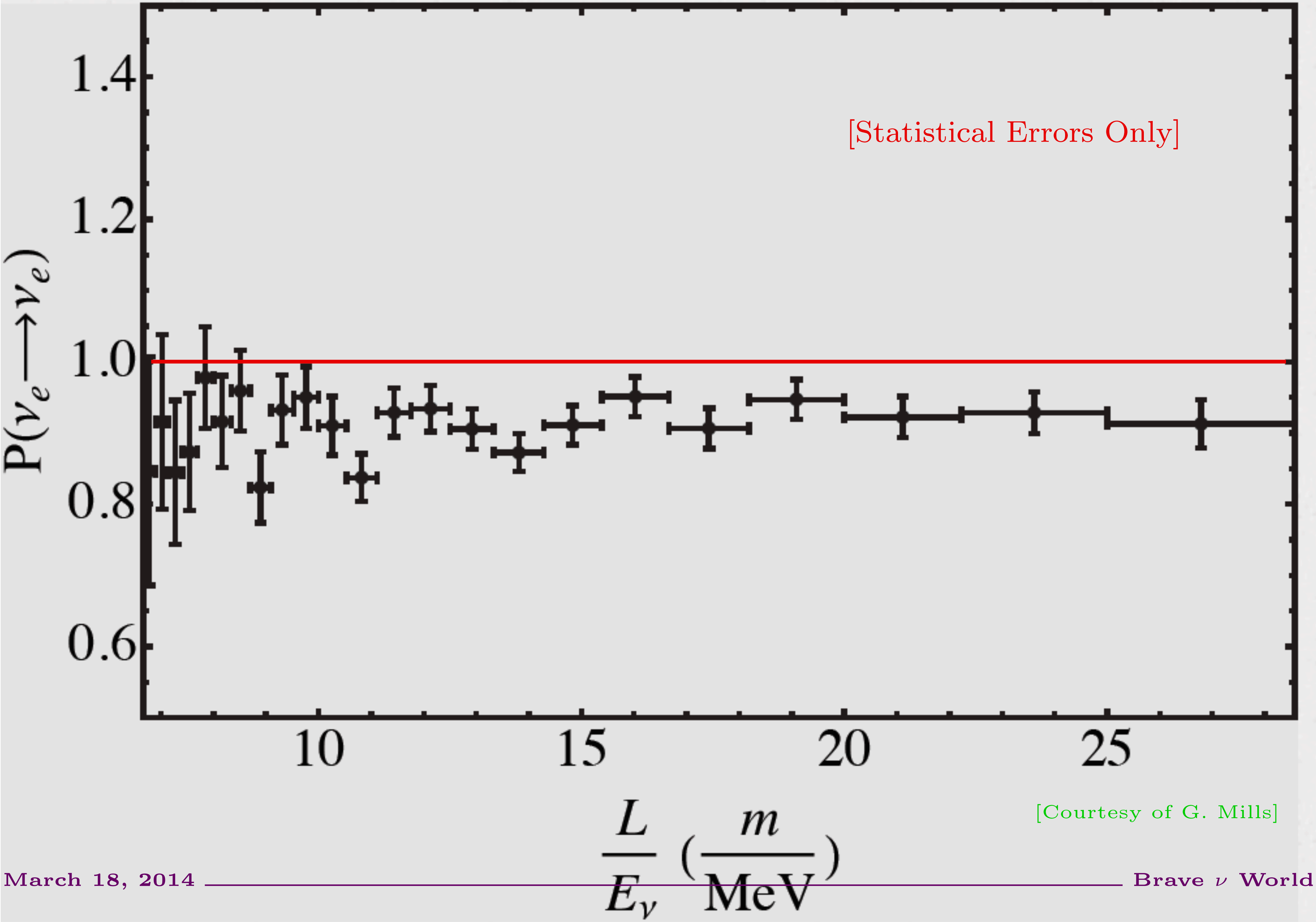
None are entirely convincing, either individually or combined. However, there may be something very very interesting going on here…

MiniBooNE & LSND



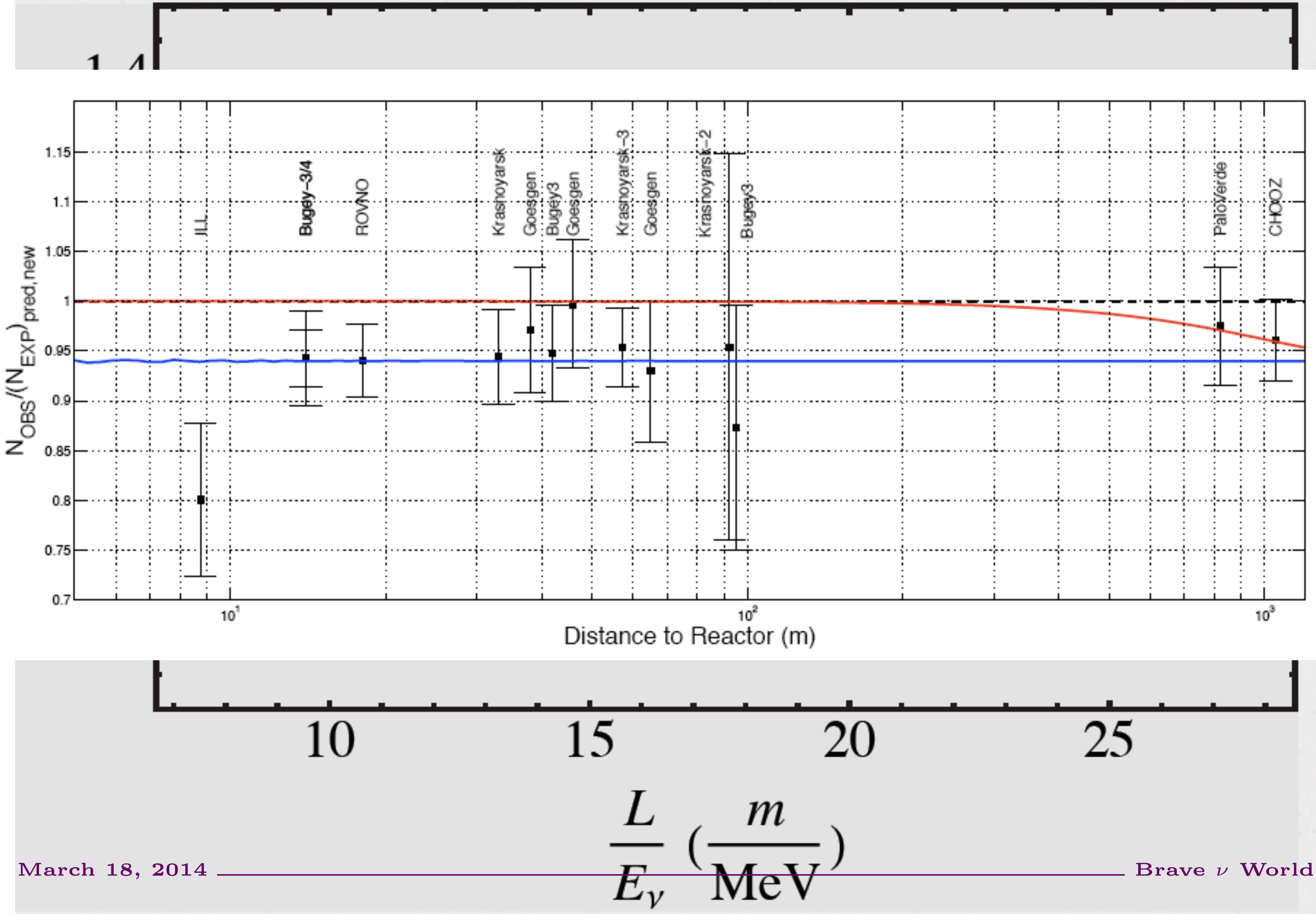
[Courtesy of G. Mills]

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
$\frac{L}{E_\nu}\ (\frac{m}{\text{MeV}})$
[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
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
$N_{OBS}/(N_{EXP})_{pred,new}$
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.

High-energy seesaw has no other observable consequences, except, perhaps, . . .

Baryogenesis via Leptogenesis

One of the most basic questions we are allowed to ask (with any real hope of getting an answer) is whether the observed baryon asymmetry of the Universe can be obtained from a baryon–antibaryon symmetric initial condition plus well understood dynamics. [Baryogenesis]

This isn't just for aesthetic reasons. If the early Universe undergoes a period of inflation, baryogenesis is required, as inflation would wipe out any pre-existing baryon asymmetry.

It turns out that massive neutrinos can help solve this puzzle!

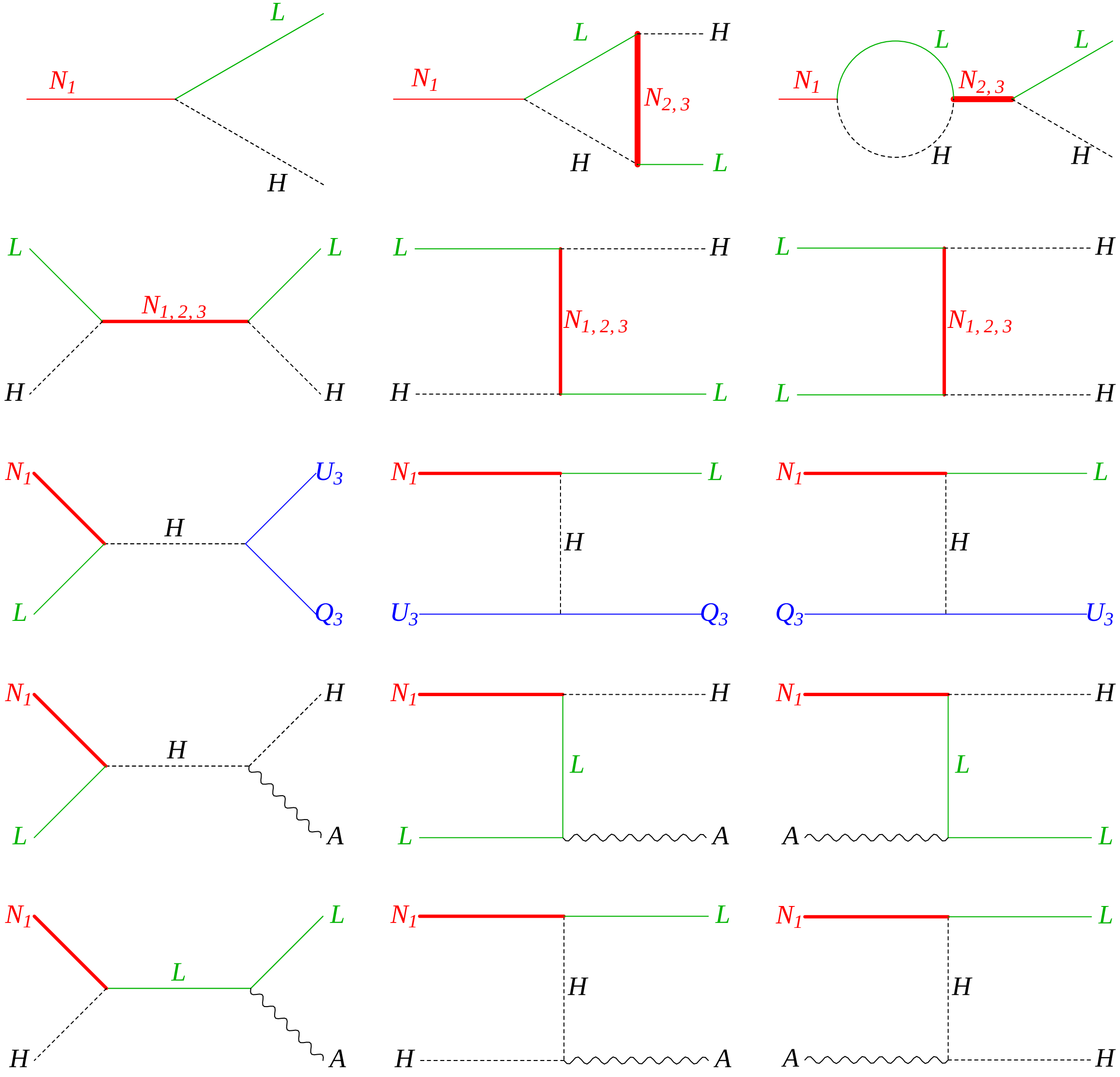
In the old SM, (electroweak) baryogenesis does not work – not enough CP-invariance violation, Higgs boson too light.

Neutrinos help by providing all the necessary ingredients for successful baryogenesis via leptogenesis.

- Violation of lepton number, which later on is transformed into baryon number by nonperturbative, finite temperature electroweak effects (in one version of the νSM, lepton number is broken at a high energy scale M).
- Violation of C-invariance and CP-invariance (weak interactions, plus new CP-odd phases).
- Deviation from thermal equilibrium (depending on the strength of the relevant interactions).

E.g. – thermal, seesaw leptogenesis, $\mathcal{L} \supset -y_{i\alpha} L^i H N^\alpha - \frac{M_N^{\alpha\beta}}{2} N_\alpha N_\beta + H.c.$

[Fukugita, Yanagida]

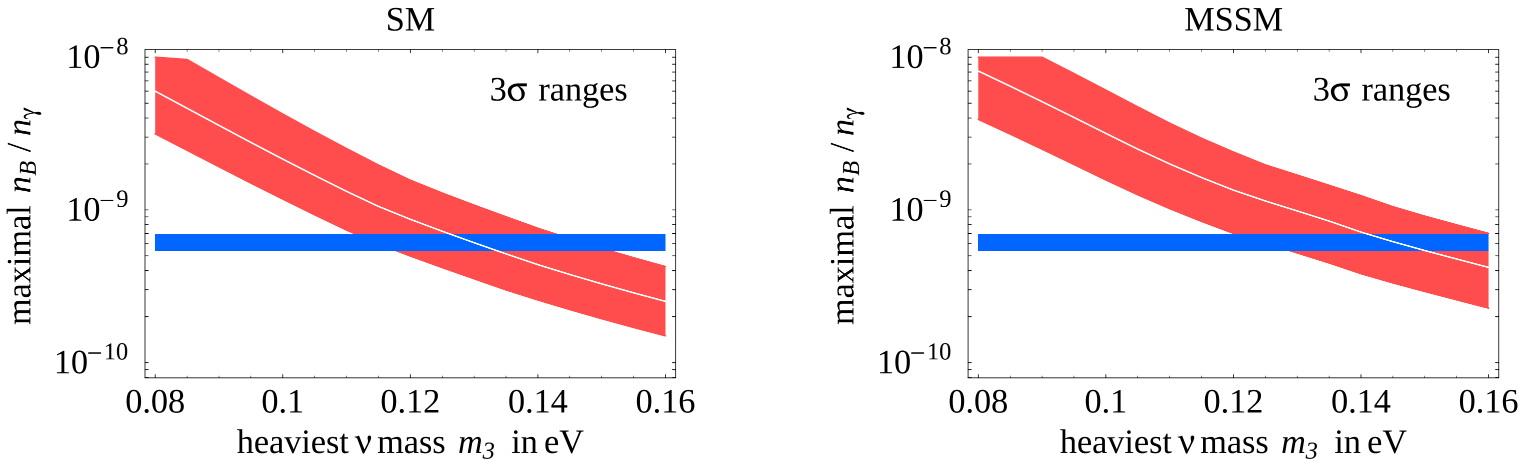


- L-violating processes
- $y \Rightarrow$ CP-violation
- deviation from thermal eq. constrains combinations of M_N and y.
- need to yield correct m_ν

not trivial!

[G. Giudice *et al*, hep-ph/0310123]

E.g. – thermal, seesaw leptogenesis, $\mathcal{L} \supset -y_{i\alpha} L^i H N^\alpha - \frac{M_N^{\alpha\beta}}{2} N_\alpha N_\beta + H.c.$



[G. Giudice *et al*, hep-ph/0310123]

It did not have to work – but it does

MSSM picture does not quite work – gravitino problem

(there are ways around it, of course...)

Relationship to Low Energy Observables?

In general . . . no. This is very easy to understand. The baryon asymmetry depends on the (high energy) physics responsible for lepton-number violation. Neutrino masses are a (small) consequence of this physics, albeit the only observable one at the low-energy experiments we can perform nowadays.

see-saw: y, M_N have more physical parameters than $m_\nu = y^{\rm t} M_N^{-1} y$.

There could be a relationship, but it requires that we know more about the high energy Lagrangian (model depent). The day will come when we have enough evidence to refute leptogenesis (or strongly suspect that it is correct) - but more information of the kind I mentioned earlier is really necessary (charged-lepton flavor violation, collider data on EWSB, lepton-number violation, etc).

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.

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

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 low-energy cut-off.

note: LOTS of Statistics Needed!

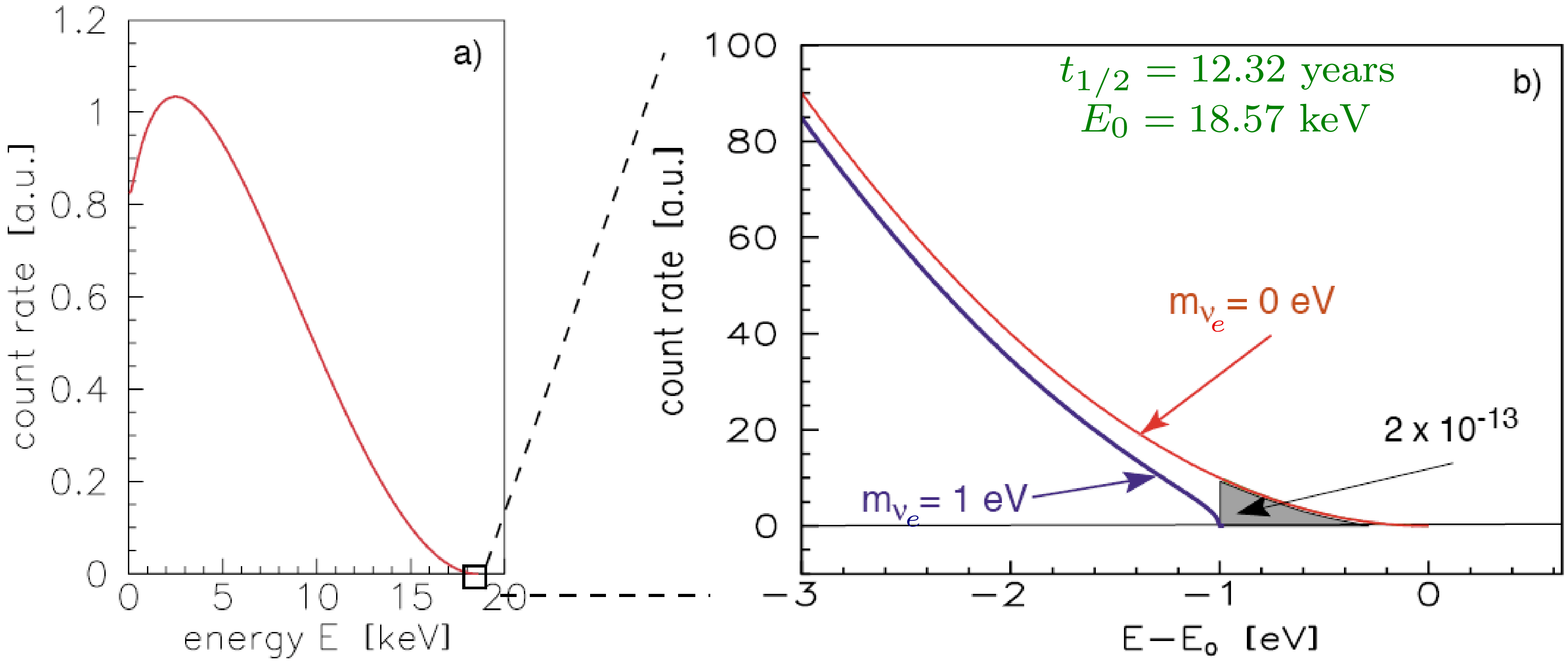


Figure 2: The electron energy spectrum of tritium β decay: (a) complete and (b) narrow region around endpoint E_0. The β spectrum is shown for neutrino masses of 0 and 1 eV.

NEXT GENERATION: The Karlsruhe Tritium Neutrino (KATRIN) Experiment:

(not your grandmother's table top experiment!)

sensitivity $m^2_{\nu_e} > (0.2~\text{eV})^2$

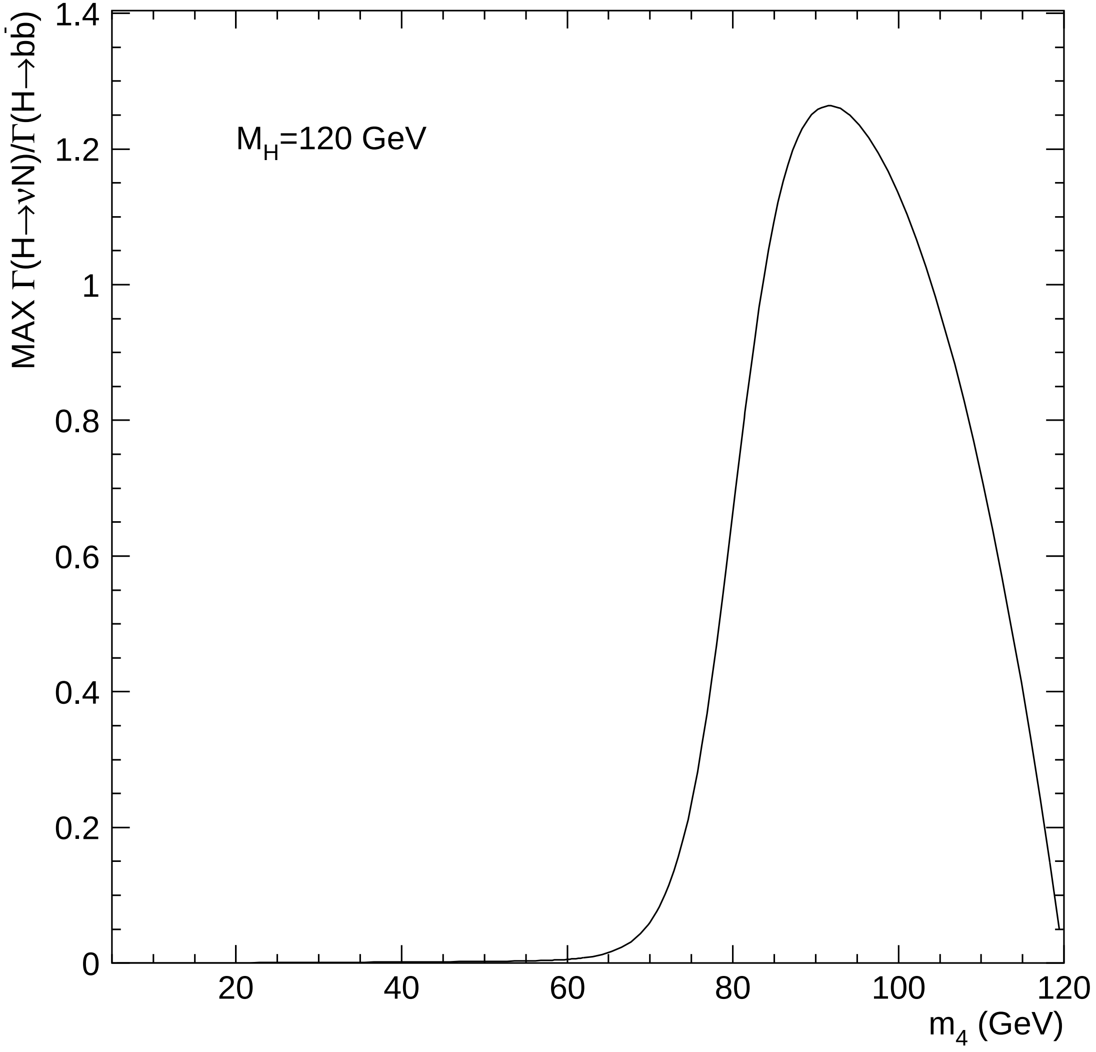
Making Predictions, for an inverted mass hierarchy, $m_4 = 1$ eV$(\ll m_5)$

[AdG, Huang, 1110.6122]

- ν_e disappearance with an associated effective mixing angle $\sin^2 2\vartheta_{ee} > 0.02$. An interesting new proposal to closely expose the Daya Bay detectors to a strong β-emitting source would be sensitive to $\sin^2 2\vartheta_{ee} > 0.04$;
- ν_μ disappearance with an associated effective mixing angle $\sin^2 2\vartheta_{\mu\mu} > 0.07$, very close to the most recent MINOS lower bound;
- $\nu_\mu \leftrightarrow \nu_e$ transitions with an associated effective mixing angle $\sin^2 \vartheta_{e\mu} > 0.0004$;
- $\nu_\mu \leftrightarrow \nu_\tau$ transitions with an associated effective mixing angle $\sin^2 \vartheta_{\mu\tau} > 0.001$. A $\nu_\mu \to \nu_\tau$ appearance search sensitive to probabilities larger than 0.1% for a mass-squared difference of 1 eV^2 would definitively rule out $m_4 = 1$ eV if the neutrino mass hierarchy is inverted.

Weak Scale Seesaw, and Accidentally Light Neutrino Masses

[AdG arXiv:0706.1732 [hep-ph]]



What does the seesaw Lagrangian predict for the LHC?

Nothing much, unless. . .

- $M_N \sim 1 - 100$ GeV,
- Yukawa couplings larger than naive expectations.

$\Leftarrow$ $H \to \nu N$ as likely as $H \to b\bar{b}$!

(NOTE: $N \to \ell q' \bar{q}$ or $\ell \ell' \nu$ (prompt)
"Weird" Higgs decay signature!)

And that is not all! 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.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[H. Murayama]