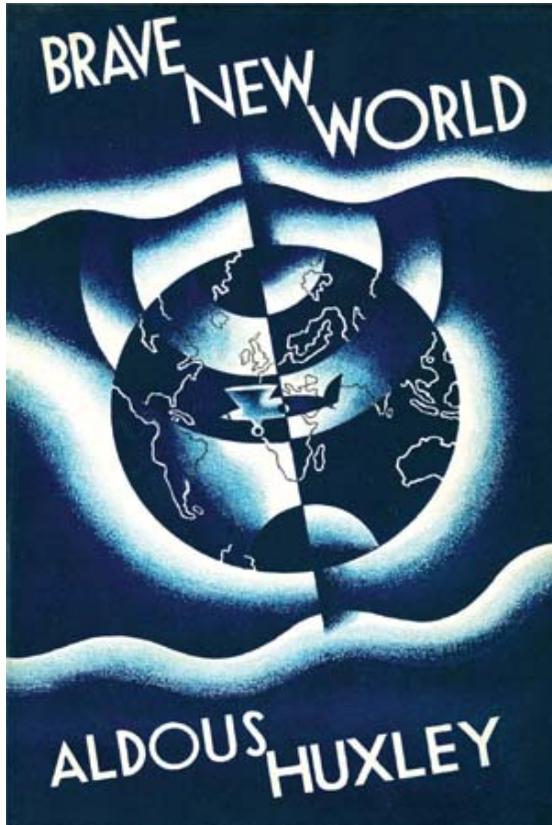
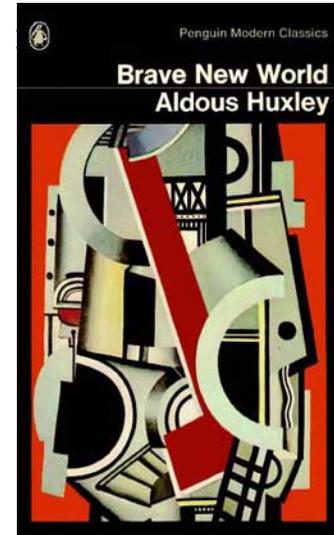


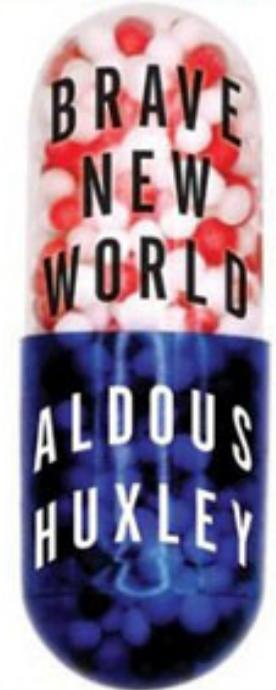
The Brave ν World



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Fermilab Colloquium

April 27, 2016



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.

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

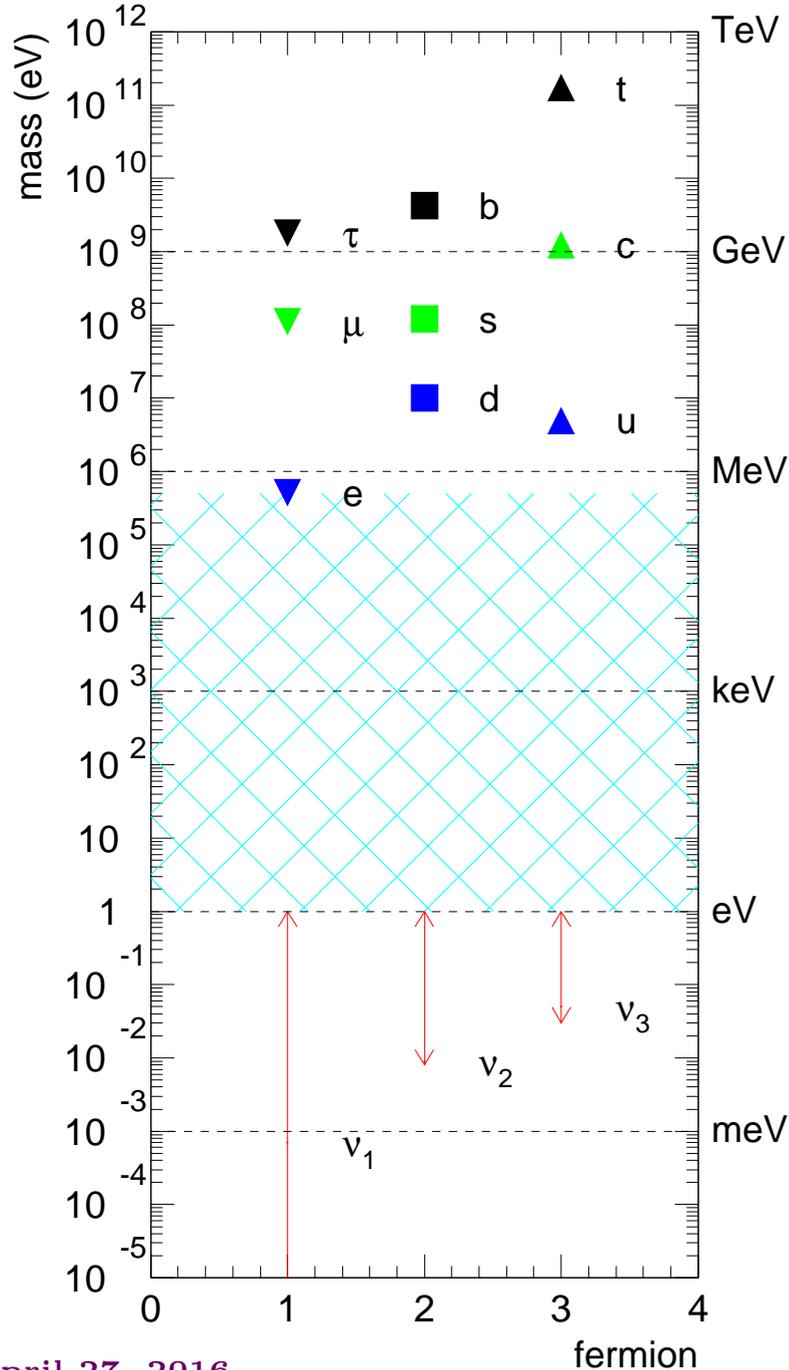
The simplest and **only satisfactory** explanation of **all** these data is that neutrinos have distinct masses, and mix.

Three Flavor Mixing Hypothesis Fits All* Data Really Well.

NuFIT 2.0 (2014)

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2 \theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \rightarrow 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \rightarrow 0.344$	$0.270 \rightarrow 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \rightarrow 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \rightarrow 35.91$	$31.29 \rightarrow 35.91$
$\sin^2 \theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \rightarrow 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \rightarrow 0.644$	$0.385 \rightarrow 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \rightarrow 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \rightarrow 53.3$	$38.3 \rightarrow 53.3$
$\sin^2 \theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \rightarrow 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \rightarrow 0.0251$	$0.0188 \rightarrow 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \rightarrow 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \rightarrow 9.11$	$7.87 \rightarrow 9.11$
$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \rightarrow 360$	254^{+63}_{-62}	$0 \rightarrow 360$	$0 \rightarrow 360$
$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \rightarrow 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \rightarrow 8.09$	$7.02 \rightarrow 8.09$
$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \rightarrow +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \rightarrow -2.307$	$\left[+2.325 \rightarrow +2.599 \right]$ $\left[-2.590 \rightarrow -2.307 \right]$

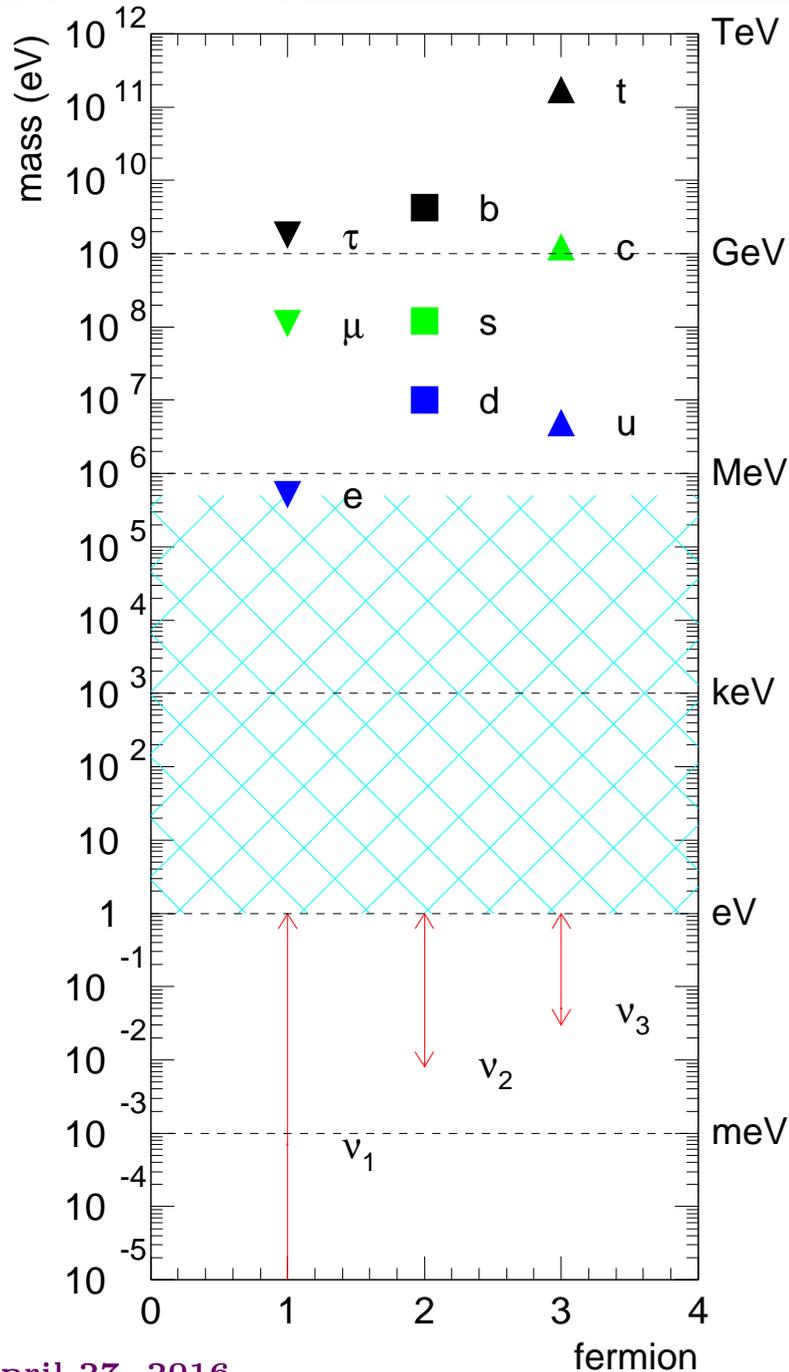
[Gonzalez-Garcia, Maltoni, Schwetz, 1409.5439, <http://www.nu-fit.org>]*Modulo a handful of 2σ to 3σ anomalies.



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?



NEW PHYSICS

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

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

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

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

- What is the physics behind electroweak symmetry breaking? (Higgs ✓).
- What is the dark matter? (not in SM).
- Why is there more matter than antimatter in the Universe? (not in SM).
- Why does the Universe appear to be accelerating? Why does it appear that the Universe underwent rapid acceleration in the past? (not in SM).

What is the New Standard Model? [ν SM]

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



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

We need more experimental input.

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

The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs double model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly** (Dirac neutrinos);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking! (Majorana neutrinos);
3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the seesaw mechanism (Majorana neutrinos).

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

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



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 $m_\nu \rightarrow 0$. Since neutrinos masses are very small, the probability for these to happen is very, very small: $A \propto m_\nu/E$.

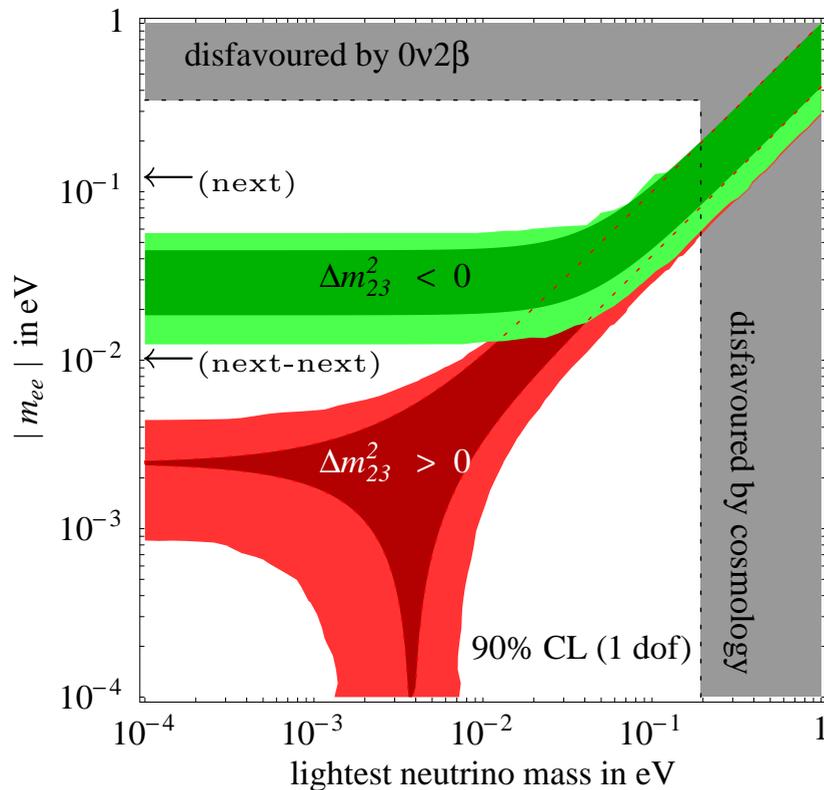
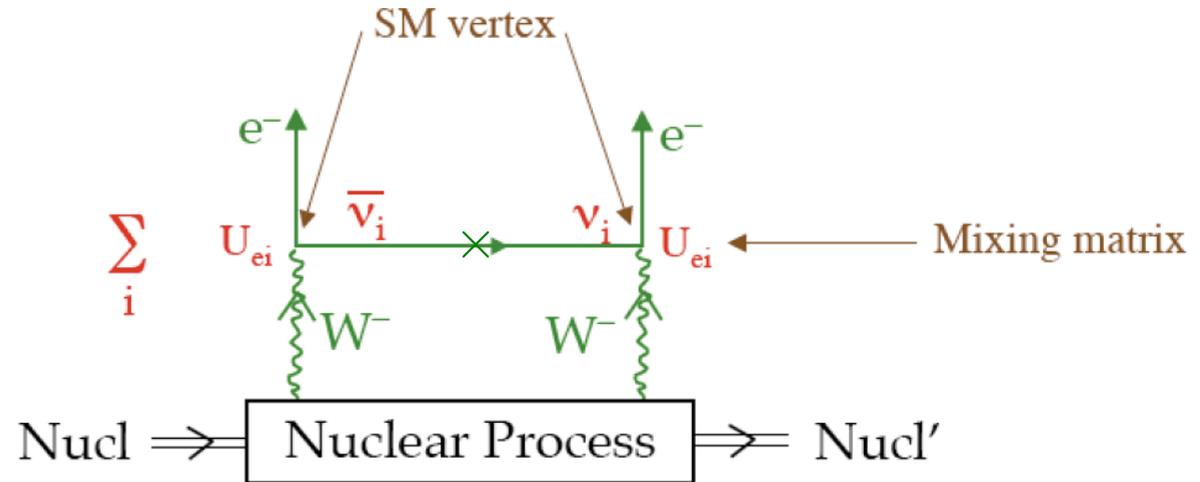
The “smoking gun” signature is the observation of LEPTON NUMBER violation. This is easy to understand: Majorana neutrinos are their own antiparticles and, therefore, cannot carry **any** quantum numbers — including lepton number.

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

Best Bet: search for

Neutrinoless Double-Beta

Decay: $Z \rightarrow (Z + 2)e^- e^-$



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

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

Plus Help from Oscillations (Mass Hierarchy)

We Will Still Need More Help ...



ν SM – One Path

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: $\Lambda \gg v \rightarrow m_\nu \ll m_f$ ($f = e, \mu, u, d$, etc)
- Neutrinos are Majorana fermions – Lepton number is violated!
- ν SM 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 $y^{\text{max}} \equiv 1$]

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

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

where N_i ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions. \mathcal{L}_ν 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}_ν describes, besides all other SM degrees of freedom, six Majorana fermions: **six neutrinos**.

^aOnly requires the introduction of three fermionic degrees of freedom, no new interactions or symmetries.

What We Know About M :

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

The symmetry of \mathcal{L}_ν 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}_ν , 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.).

Accommodating Small Neutrino Masses

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

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

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

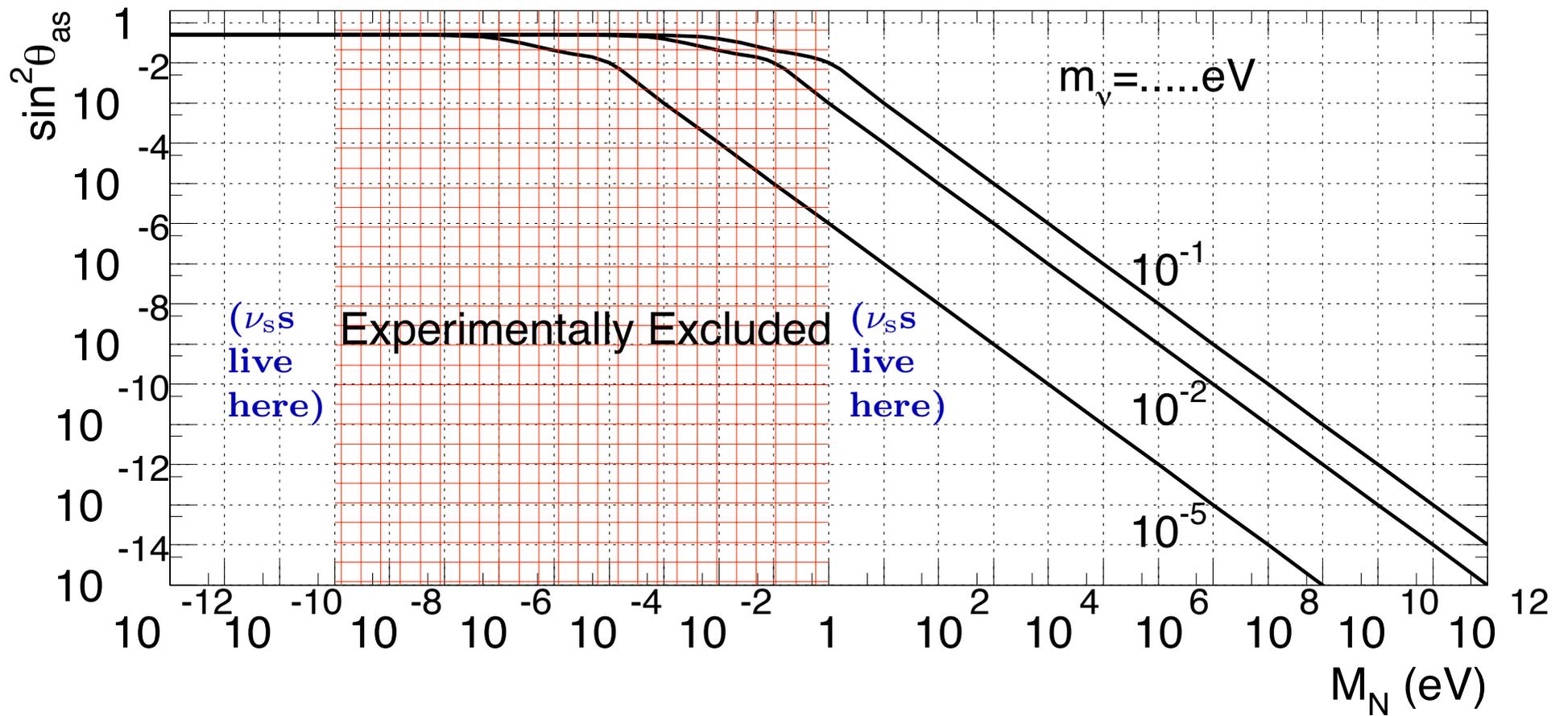
In the case of the seesaw,

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

so neutrino masses are small if either

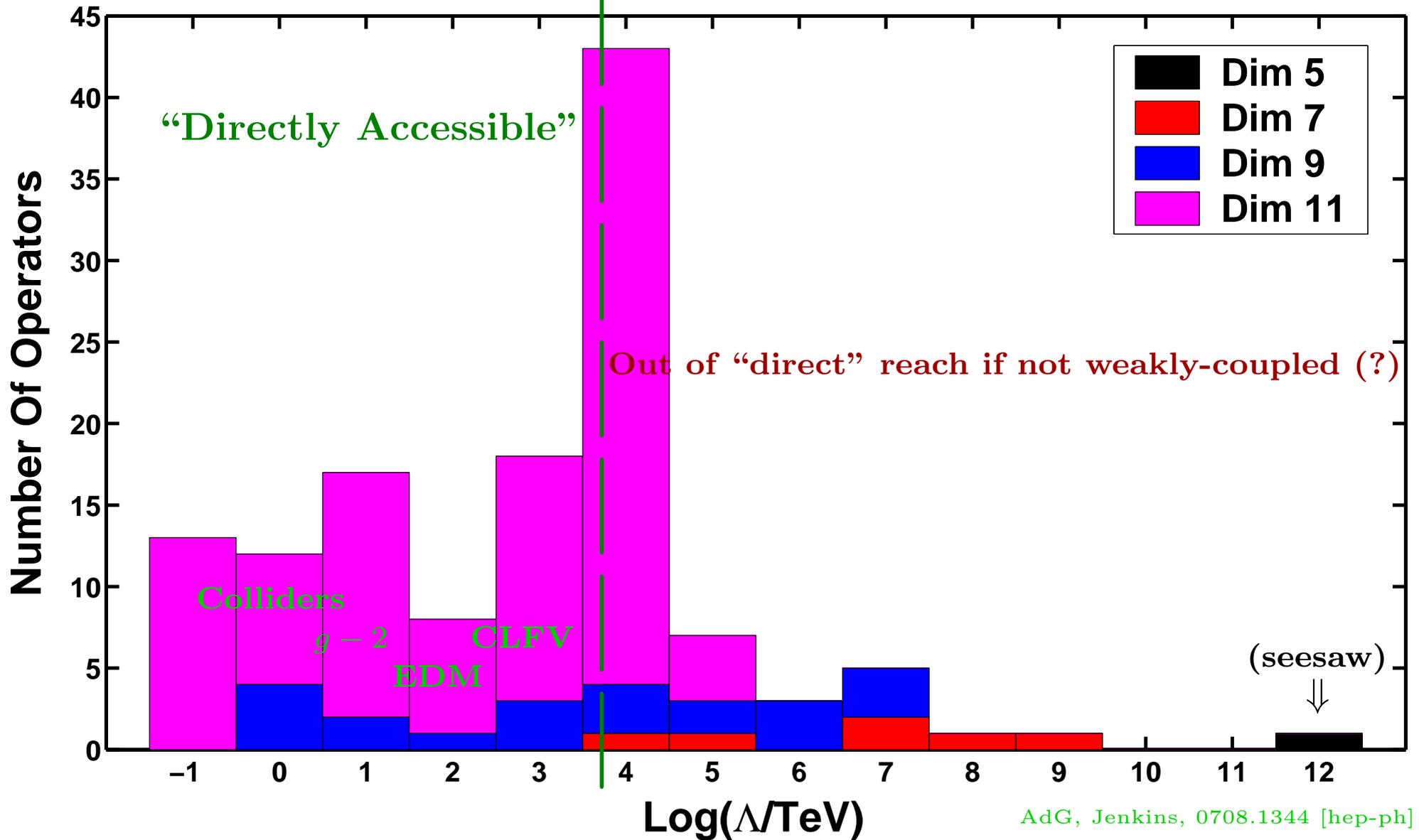
- they are generated by physics at a very high energy scale $M \gg v$ (high-energy seesaw); **or**
- they arise out of a very weak coupling between the SM and a new, hidden sector (low-energy seesaw); **or**
- cancellations among different contributions render neutrino masses accidentally small (“fine-tuning”).

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, including ...

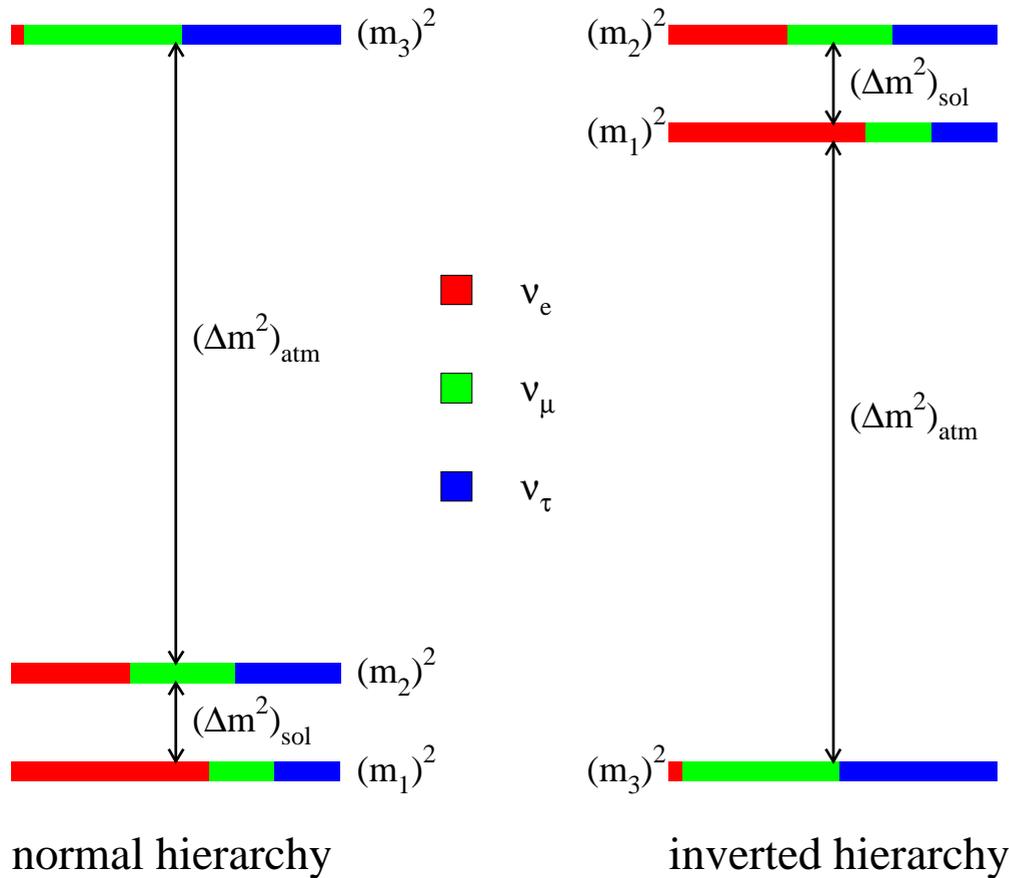
- understanding the fate of lepton-number. Neutrinoless double beta decay!
- a comprehensive long baseline neutrino program, towards precision oscillation physics.
- other probes of neutrino properties, including neutrino scattering.
- precision studies of charged-lepton properties ($g - 2$, edm), and searches for rare processes ($\mu \rightarrow e$ -conversion the best bet at the moment).
- collider experiments. The LHC and beyond may end up revealing the new physics behind small neutrino masses.
- cosmic surveys. Neutrino properties affect, in a significant way, the history of the universe. Will we learn about neutrinos from cosmology, or about cosmology from neutrinos?
- searches for baryon-number violating processes.

HOWEVER...

We have only ever objectively “seen” neutrino masses in long-baseline oscillation experiments. It is the clearest way forward!

Does this mean we will reveal the origin of neutrino masses with oscillation experiments? We don't know, and we won't know until we try!

New Neutrino Oscillation Experiments: Missing Oscillation Parameters

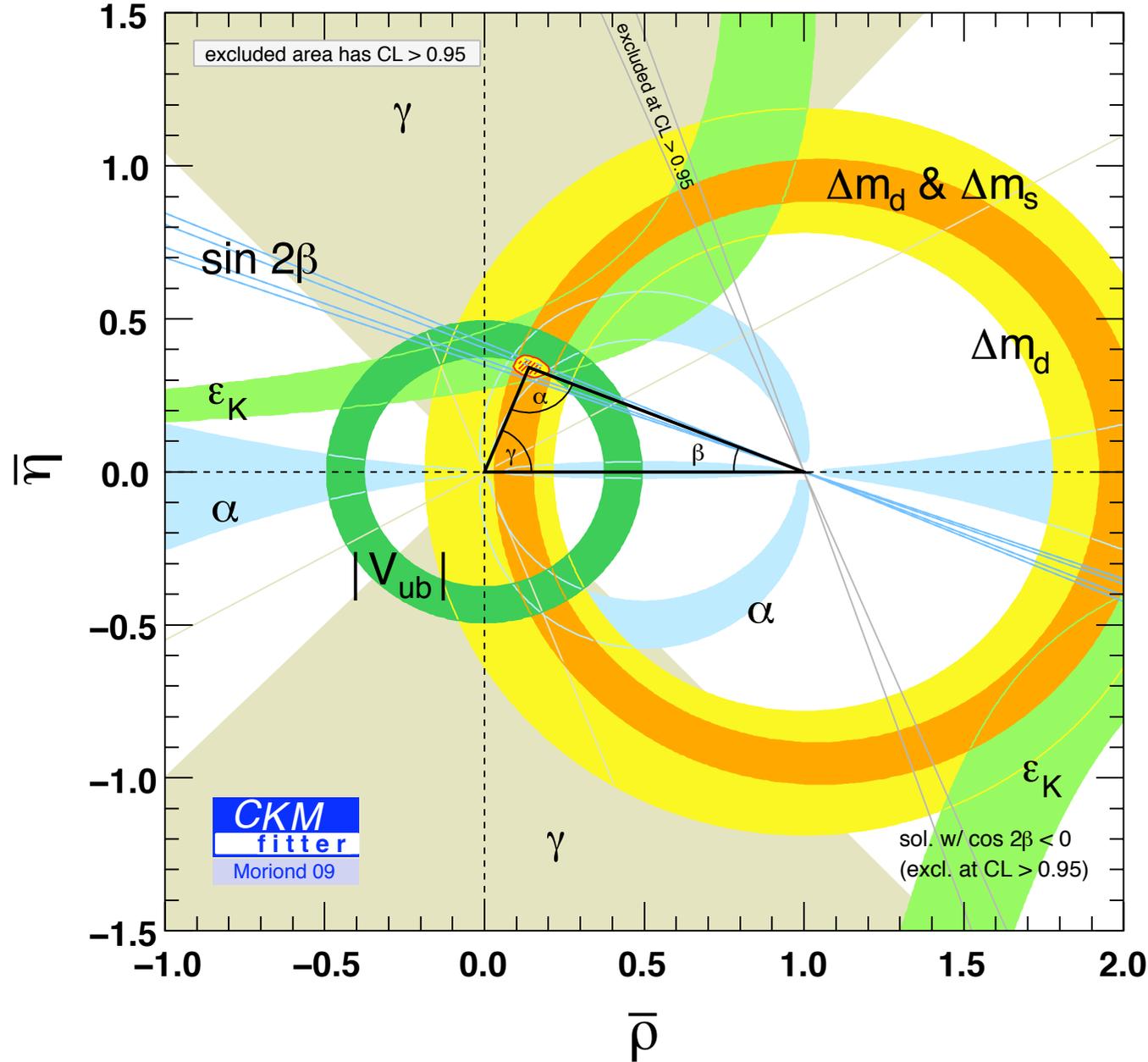


- ~~What is the ν_e component of ν_3 ?~~
($\theta_{13} \neq 0!$)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi?$)
- Is ν_3 mostly ν_μ or ν_τ ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4?$)
- What is the neutrino mass hierarchy? ($\Delta m_{13}^2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

⇒ 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 \rightarrow evidence) – MINOS, T2K.

We still have a ways to go!

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”

CP-invariance Violation in Neutrino Oscillations

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

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

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

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

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

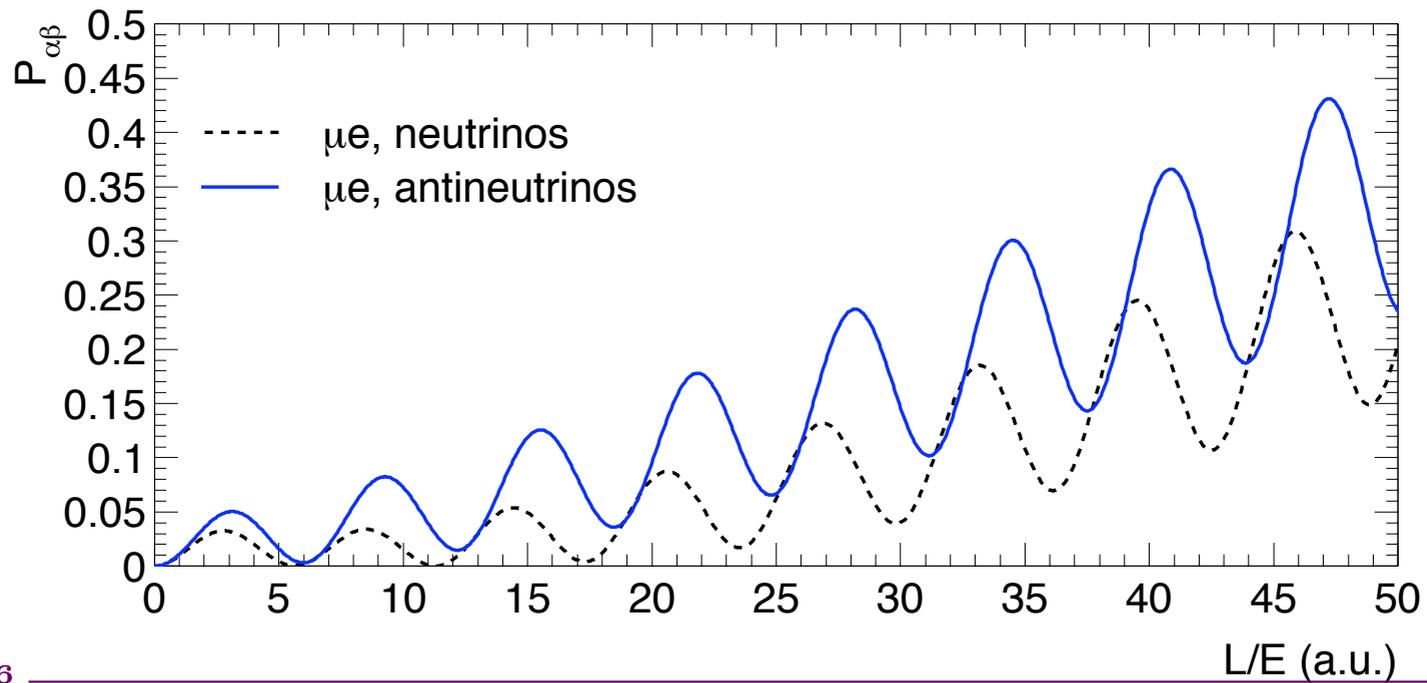
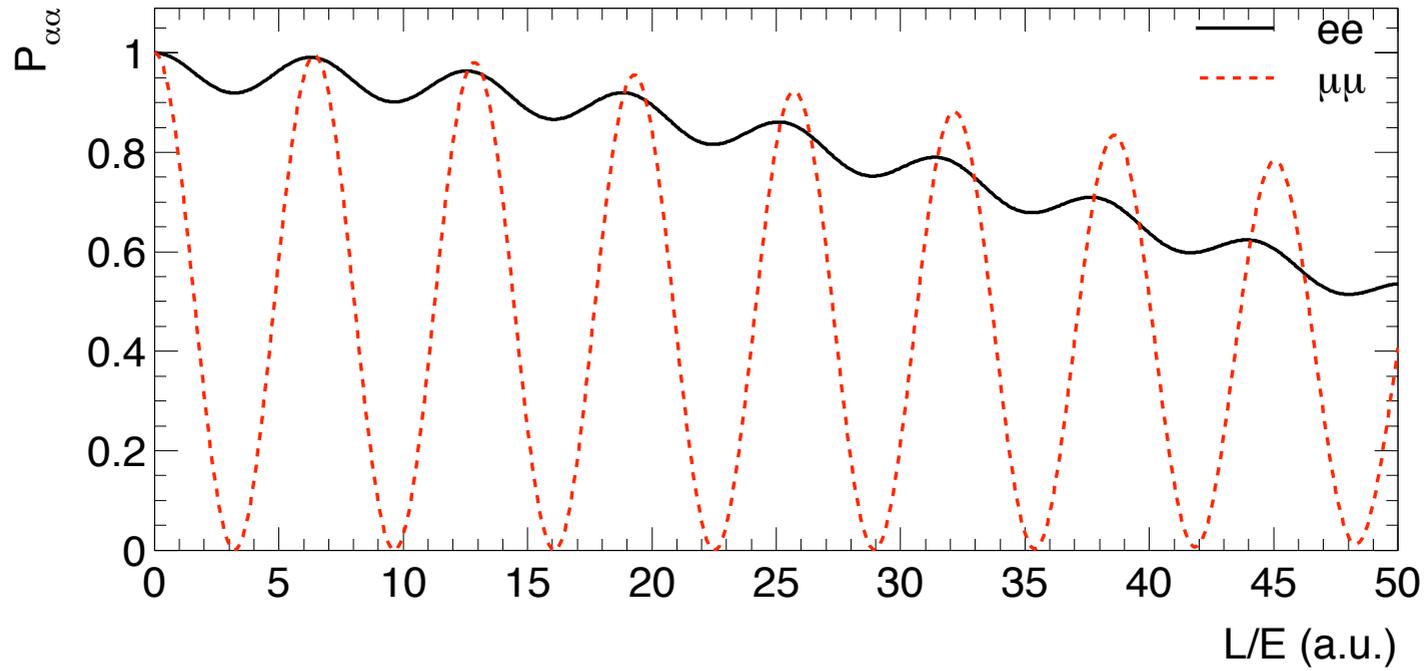
$$\bar{A}_{\mu e} = U_{e2} U_{\mu 2}^* (e^{i\Delta_{12}} - 1) + U_{e3} U_{\mu 3}^* (e^{i\Delta_{13}} - 1).$$

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

All of these can be satisfied, with a little luck: **we needed** $|U_{e3}| \neq 0$. ✓



What Could We Run Into?

- New neutrino states. In this case, the 3×3 mixing matrix would not be unitary.
- New short-range neutrino interactions. These lead to, for example, new matter effects. If we don't take these into account, there is no reason for the three flavor paradigm to “close.”
- New, unexpected neutrino properties. Do they have nonzero magnetic moments? Do they decay? The answer is ‘yes’ to both, but nature might deviate dramatically from ν SM expectations.
- Weird stuff. CPT-violation. Decoherence effects (aka “violations of Quantum Mechanics.”)
- etc.

Case Studies

I will briefly mention two case-studies: the **fourth-neutrino hypothesis** and **non-standard neutral-current neutrino–matter interactions**. In general

- I will mostly discuss, for concreteness, the DUNE setup;
- I don't particularly care about how likely, nice, or contrived the scenarios are. It is useful to consider them as well-defined ways in which the three-flavor paradigm can be violated. They can be used as benchmarks for comparing different efforts, or, perhaps, as proxies for other new phenomena.
- I will mostly be interested in three questions:
 - How sensitive are next-generation long-baseline efforts?;
 - How well they can measure the new-physics parameters, including new sources of CP-invariance violation?;
 - Can they tell different new-physics models apart?

A Fourth Neutrino

(Berryman et al, arXiv:1507.03986)

If there are more neutrinos with a well-defined mass, it is easy to extend the paradigm:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_? \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & \cdots \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & \cdots \\ U_{?1} & U_{?2} & U_{?3} & U_{?4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \vdots \end{pmatrix}$$

- New mass eigenstates easy: ν_4 with mass m_4 , ν_5 with mass m_5 , etc.
- What are these new “flavor” (or weak) eigenstates $\nu_?$? Here, the answer is we don’t care. We only assume there are no new accessible interactions associated to these states.

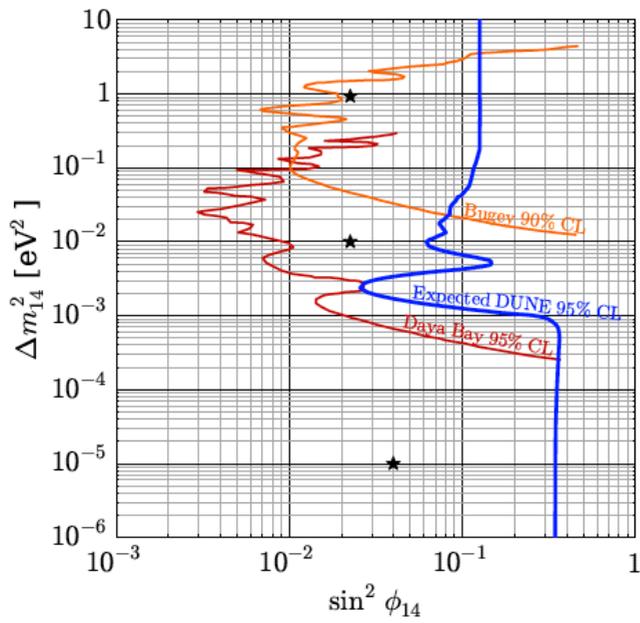
$$\begin{aligned}
U_{e2} &= s_{12}c_{13}c_{14}, \\
U_{e3} &= e^{-i\eta_1} s_{13}c_{14}, \\
U_{e4} &= e^{-i\eta_2} s_{14}, \\
U_{\mu 2} &= c_{24} (c_{12}c_{23} - e^{i\eta_1} s_{12}s_{13}s_{23}) - e^{i(\eta_2-\eta_3)} s_{12}s_{14}s_{24}c_{13}, \\
U_{\mu 3} &= s_{23}c_{13}c_{24} - e^{i(\eta_2-\eta_3-\eta_1)} s_{13}s_{14}s_{24}, \\
U_{\mu 4} &= e^{-i\eta_3} s_{24}c_{14}, \\
U_{\tau 2} &= c_{34} (-c_{12}s_{23} - e^{i\eta_1} s_{12}s_{13}c_{23}) - e^{i\eta_2} c_{13}c_{24}s_{12}s_{14}s_{34} \\
&\quad - e^{i\eta_3} (c_{12}c_{23} - e^{i\eta_1} s_{12}s_{13}s_{23}) s_{24}s_{34}, \\
U_{\tau 3} &= c_{13}c_{23}c_{34} - e^{i(\eta_2-\eta_1)} s_{13}s_{14}s_{34}c_{24} - e^{i\eta_3} s_{23}s_{24}s_{34}c_{13}, \\
U_{\tau 4} &= s_{34}c_{14}c_{24}.
\end{aligned}$$

When the new mixing angles ϕ_{14} , ϕ_{24} , and ϕ_{34} vanish, one encounters oscillations among only three neutrinos, and we can map the remaining parameters $\{\phi_{12}, \phi_{13}, \phi_{23}, \eta_1\} \rightarrow \{\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}\}$.

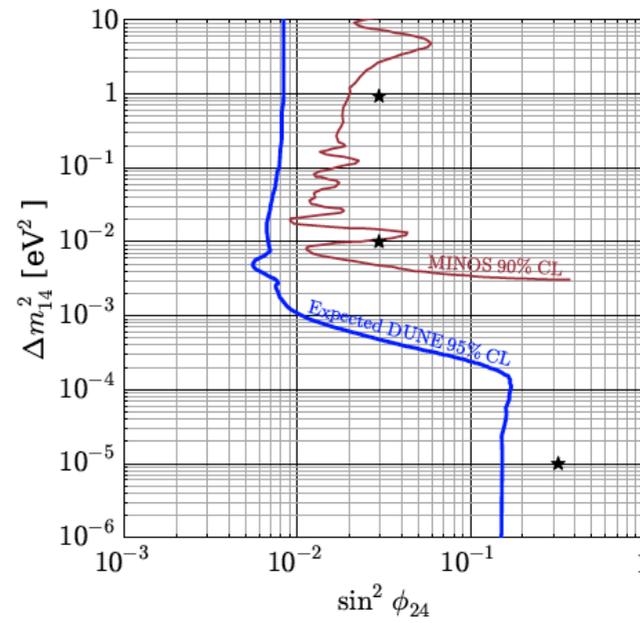
Also

$$\eta_s \equiv \eta_2 - \eta_3,$$

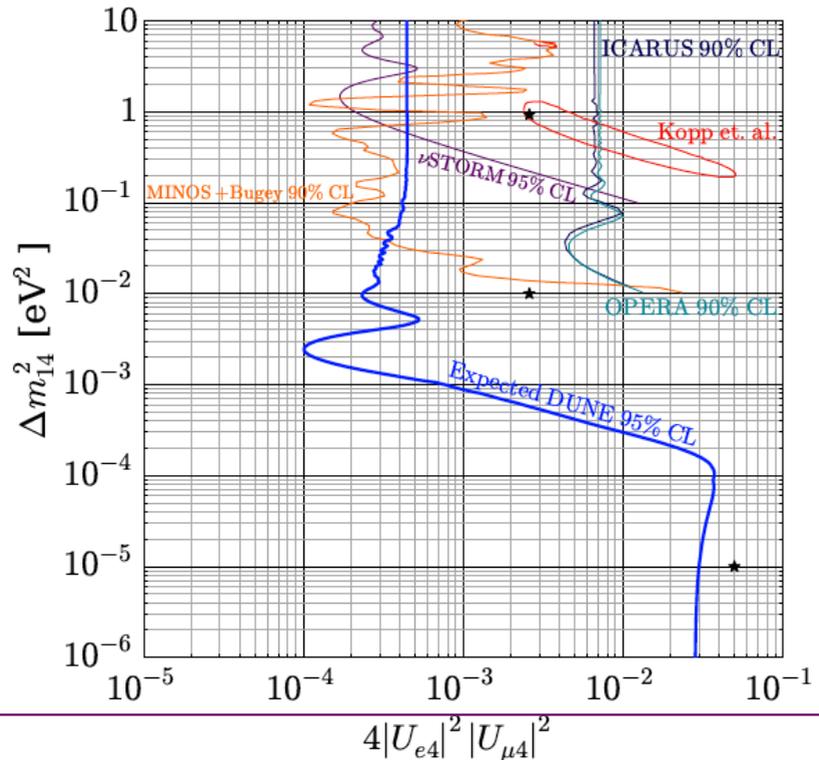
is the only new CP-odd parameter to which oscillations among ν_e and ν_μ are sensitive.



(a)



(b)



[Berryman et al, arXiv:1507.03986]

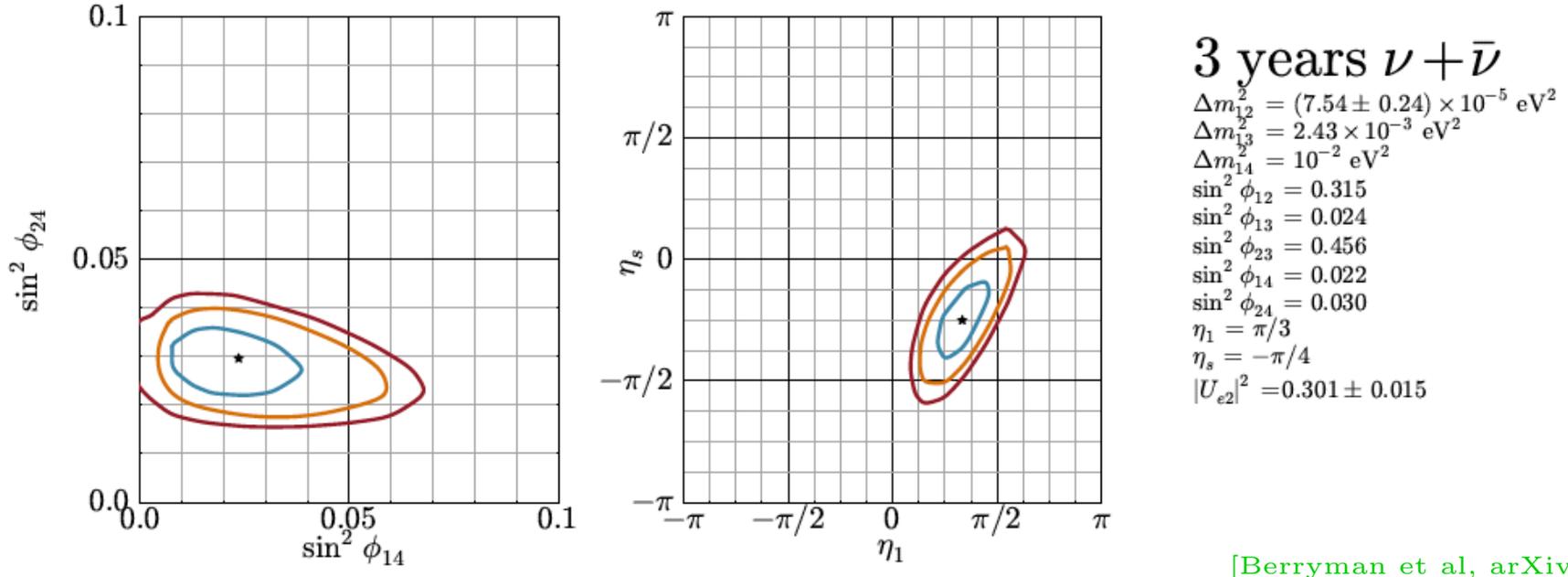


FIG. 5: Expected sensitivity contours at 68.3% (blue), 95% (orange), and 99% (red) CL at DUNE with six years of data collection (3y $\nu + 3y \bar{\nu}$), a 34 kiloton detector, and a 1.2 MW beam given the existence of a fourth neutrino with parameters from Case 2 in Table I. Results from solar neutrino experiments are included here as Gaussian priors for the values of $|U_{e2}|^2 = 0.301 \pm 0.015$ and $\Delta m_{12}^2 = 7.54 \pm 0.24 \times 10^{-5} \text{ eV}^2$ [22].

	$\sin^2 \phi_{14}$	$\sin^2 \phi_{24}$	$\Delta m_{14}^2 \text{ (eV}^2\text{)}$	η_s	$\sin^2 \phi_{12}$	$\sin^2 \phi_{13}$	$\sin^2 \phi_{23}$	$\Delta m_{12}^2 \text{ (eV}^2\text{)}$	$\Delta m_{13}^2 \text{ (eV}^2\text{)}$	η_1
Case 1	0.023	0.030	0.93	$-\pi/4$	0.315	0.0238	0.456	7.54×10^{-5}	2.43×10^{-3}	$\pi/3$
Case 2	0.023	0.030	1.0×10^{-2}	$-\pi/4$	0.315	0.0238	0.456	7.54×10^{-5}	2.43×10^{-3}	$\pi/3$
Case 3	0.040	0.320	1.0×10^{-5}	$-\pi/4$	0.321	0.0244	0.639	7.54×10^{-5}	2.43×10^{-3}	$\pi/3$

TABLE I: Input values of the parameters for the three scenarios considered for the four-neutrino hypothesis. Values of ϕ_{12} , ϕ_{13} , and ϕ_{23} are chosen to be consistent with the best-fit values of $|U_{e2}|^2$, $|U_{e3}|^2$, and $|U_{\mu 3}|^2$, given choices of ϕ_{14} and ϕ_{24} . Here, $\eta_s \equiv \eta_2 - \eta_3$. Note that Δm_{14}^2 is explicitly assumed to be positive, i.e., $m_4^2 > m_1^2$.

Non-Standard Neutrino Interactions (NSI)

(AdG and Kelly, arXiv:1511.05562)

Effective Lagrangian:

$$\mathcal{L}^{\text{NSI}} = -2\sqrt{2}G_F(\bar{\nu}_\alpha\gamma_\rho\nu_\beta) \sum_{f=e,u,d} (\epsilon_{\alpha\beta}^{fL}\bar{f}_L\gamma^\rho f_L + \epsilon_{\alpha\beta}^{fR}\bar{f}_R\gamma^\rho f_R) + h.c.,$$

For oscillations,

$$H_{ij} = \frac{1}{2E_\nu} \text{diag} \{0, \Delta m_{12}^2, \Delta m_{13}^2\} + V_{ij},$$

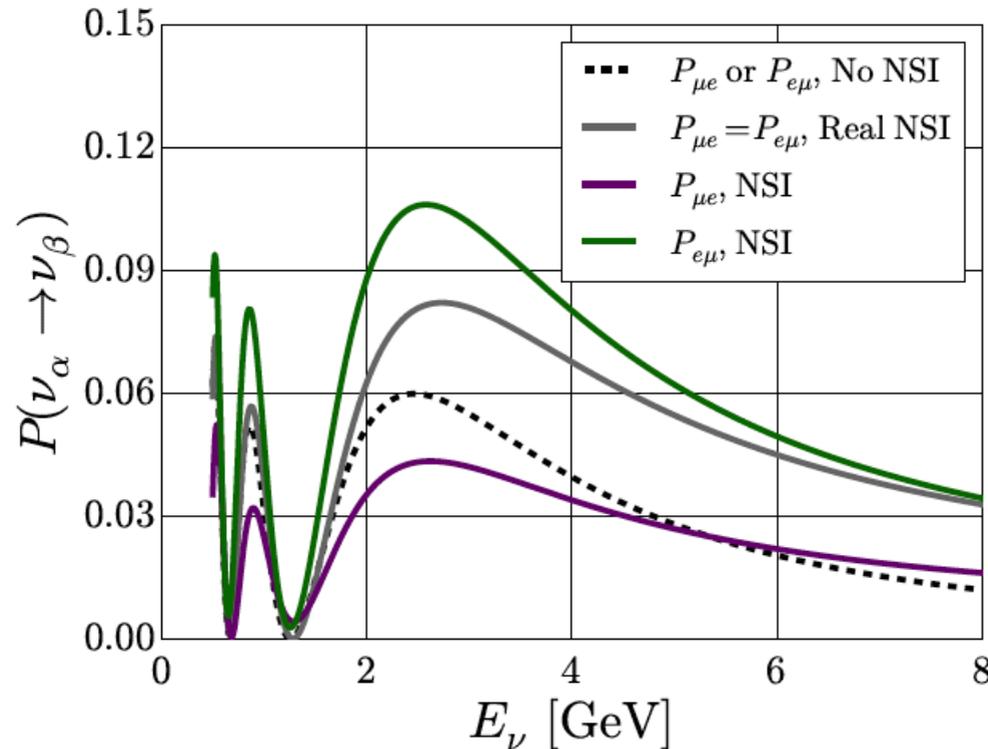
where

$$V_{ij} = U_{i\alpha}^\dagger V_{\alpha\beta} U_{\beta j},$$

$$V_{\alpha\beta} = A \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix},$$

$A = \sqrt{2}G_F n_e$. $\epsilon_{\alpha\beta}$ are linear combinations of the $\epsilon_{\alpha\beta}^{fL,R}$. Important: Propagation effects only. We don't include NSI effects in production or detection.

There are new sources of CP-invariance violation! [easier to see T-invariance violation]



[AdG and Kelly, arXiv:1511.05562]

FIG. 2: T -invariance violating effects of NSI at $L = 1300$ km for $\epsilon_{e\mu} = 0.1e^{i\pi/3}$, $\epsilon_{e\tau} = 0.1e^{-i\pi/4}$, $\epsilon_{\mu\tau} = 0.1$ (all other NSI parameters are set to zero). Here, the three-neutrino oscillation parameters are $\sin^2 \theta_{12} = 0.308$, $\sin^2 \theta_{13} = 0.0234$, $\sin^2 \theta_{23} = 0.437$, $\Delta m_{12}^2 = 7.54 \times 10^{-5}$ eV², $\Delta m_{13}^2 = 2.47 \times 10^{-3}$ eV², and $\delta = 0$, i.e., no “standard” T -invariance violation. The green curve corresponds to $P_{e\mu}$ while the purple curve corresponds to $P_{\mu e}$. If, instead, all non-zero NSI are real ($\epsilon_{e\mu} = 0.1$, $\epsilon_{e\tau} = 0.1$, $\epsilon_{\mu\tau} = 0.1$), $P_{e\mu} = P_{\mu e}$, the grey curve. The dashed line corresponds to the pure three-neutrino oscillation probabilities assuming no T -invariance violation (all $\epsilon_{\alpha\beta} = 0$, $\delta = 0$).

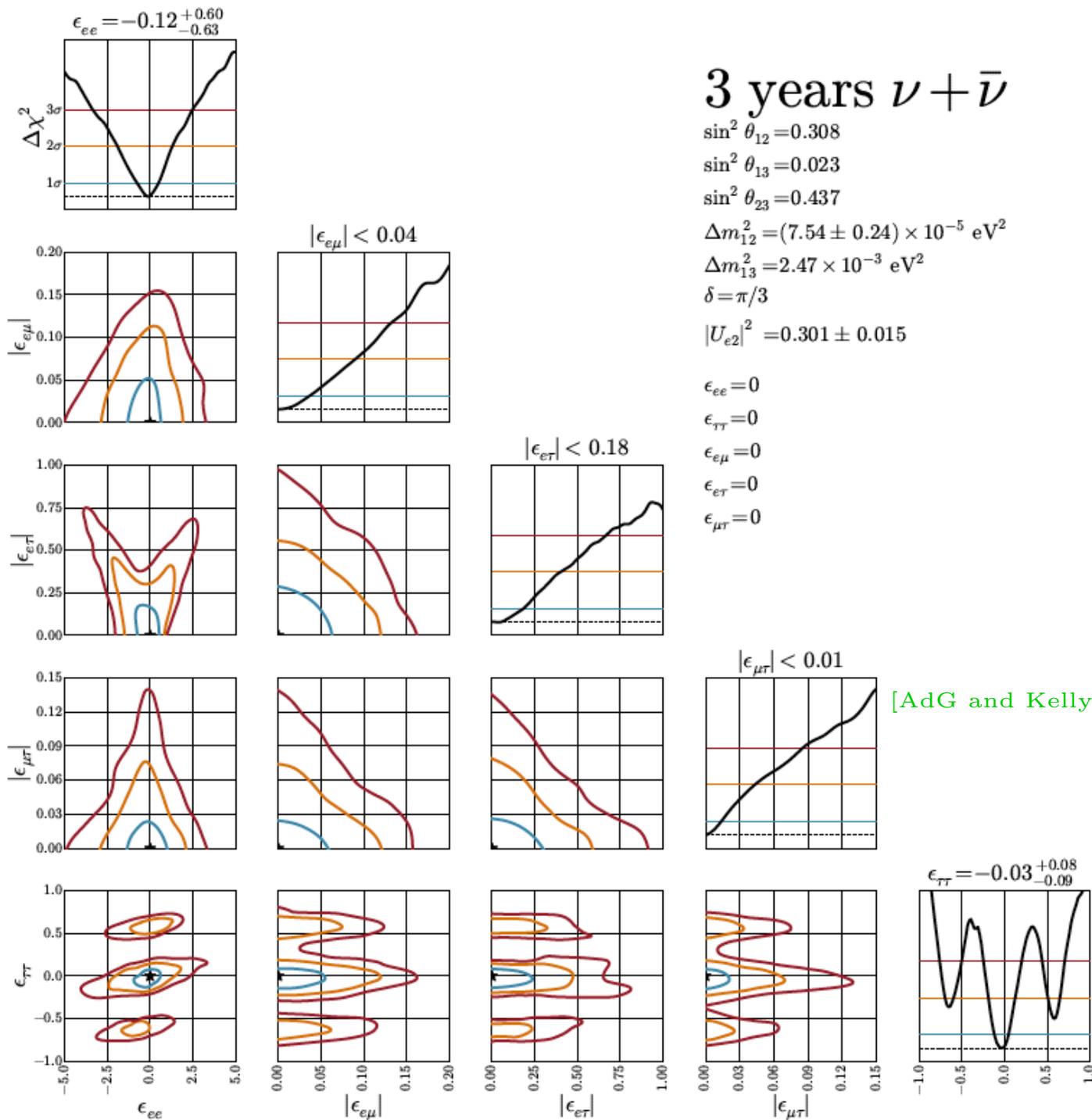


FIG. 4: Expected exclusion limits at 68.3% (red), 95% (orange), and 99% (blue) CL at DUNE assuming data consistent with the global best fit. The CP violation phase is fixed to $\delta = \pi/3$ and the θ_{13} value is fixed to the global best fit value. The $\epsilon_{\tau\tau}$ plot is a 2D projection of the $\epsilon_{\tau\tau}$ vs ϵ_{ee} plane.

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

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

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

What is Going on Here?

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

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

Observable wish list:

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

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

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

For example, if the new neutrino states are the “right-handed neutrinos” from the standard seesaw, independent from the short-baseline anomalies (for an inverted mass hierarchy, $m_4 = 1 \text{ eV} (\ll m_5)$) ...

[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 $\nu_\mu \rightarrow \nu_\tau$ appearance search sensitive to probabilities larger than 0.1% for a mass-squared difference of 1 eV^2 would definitively rule out $m_4 = 1 \text{ eV}$ if the neutrino mass hierarchy is inverted.

Understanding Fermion Mixing

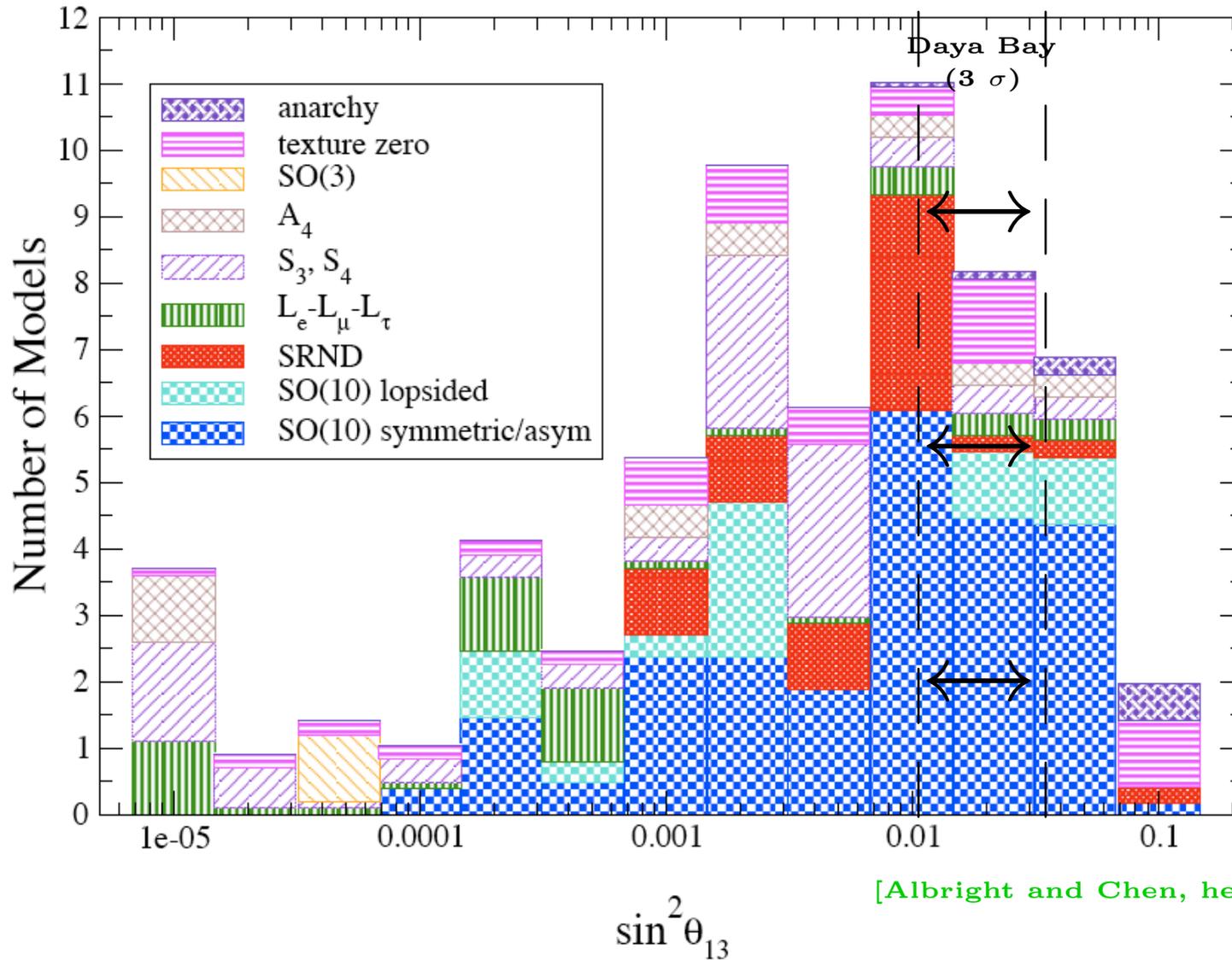
One of the puzzling phenomena uncovered by the neutrino data is the fact that **Neutrino Mixing is Strange**. What does this mean?

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

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

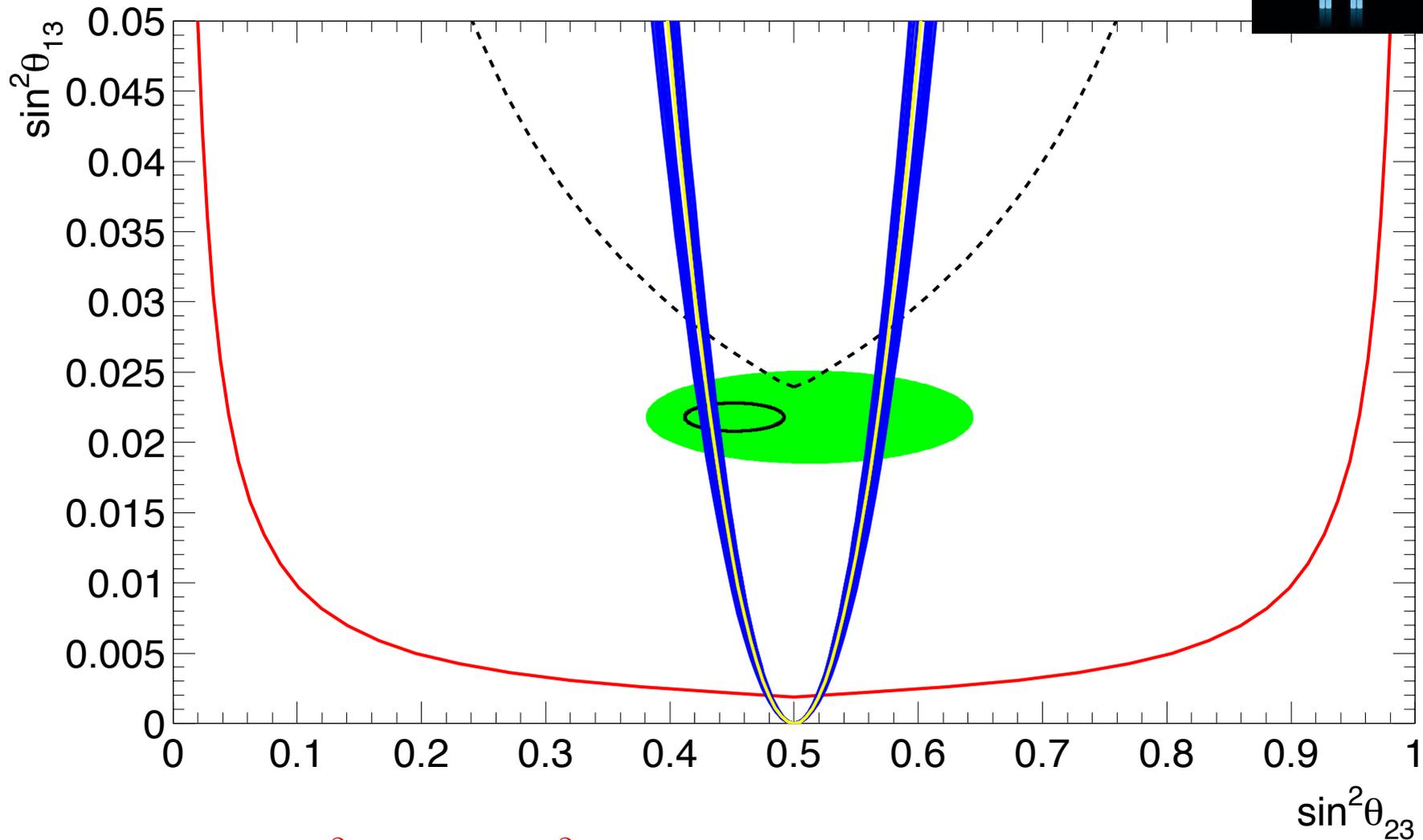
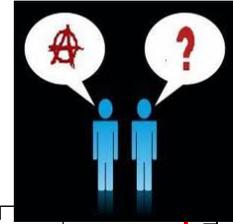
$[|(V_{MNS})_{e3}| < 0.2]$

They certainly look **VERY** different, but which one would you label as “strange”?



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

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]

In Conclusion

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

1. We still **know very little** about the new physics uncovered by neutrino oscillations.
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 ν SM 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).



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

Backup Slides . . .



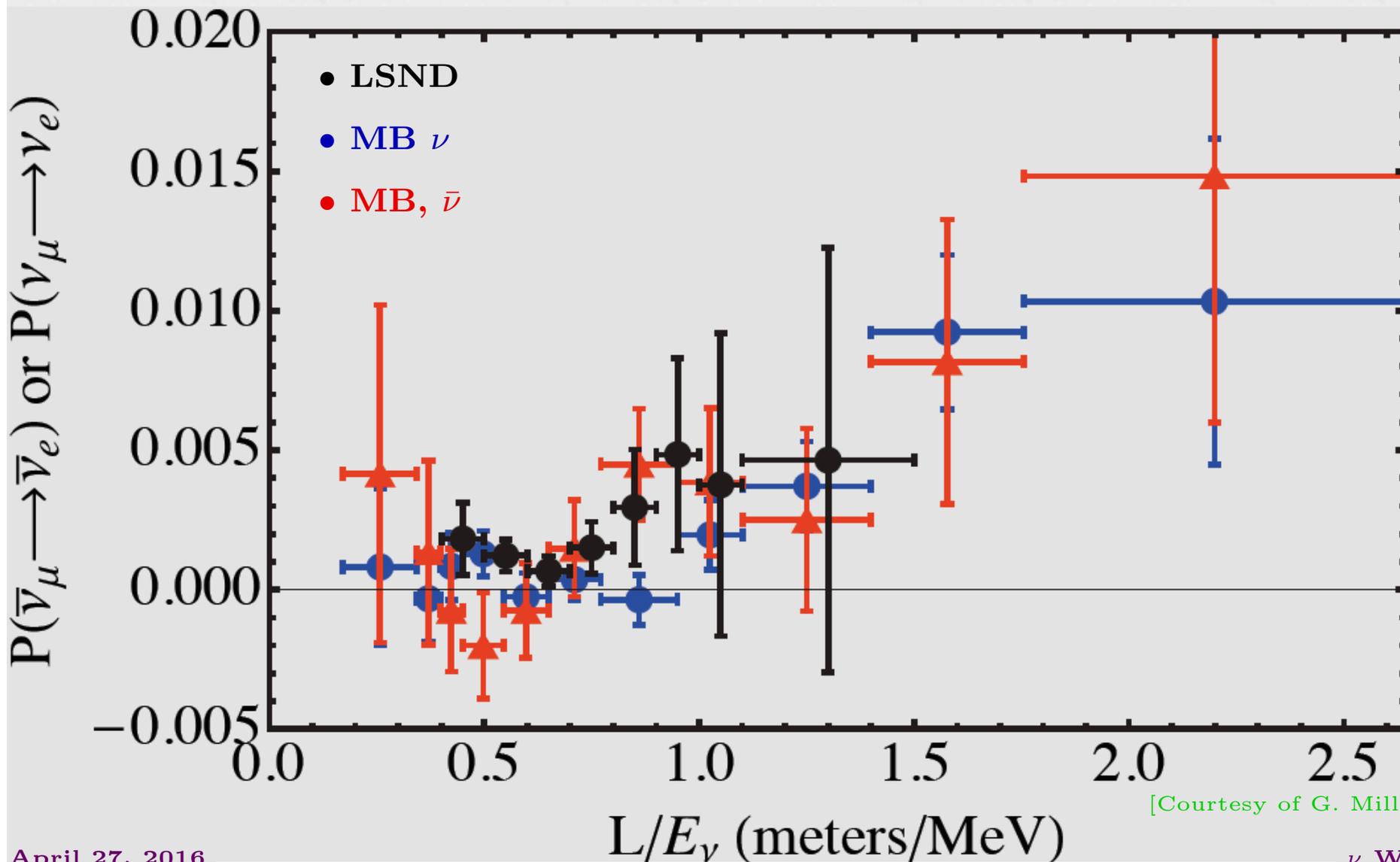
Not all is well(?): The Short Baseline Anomalies

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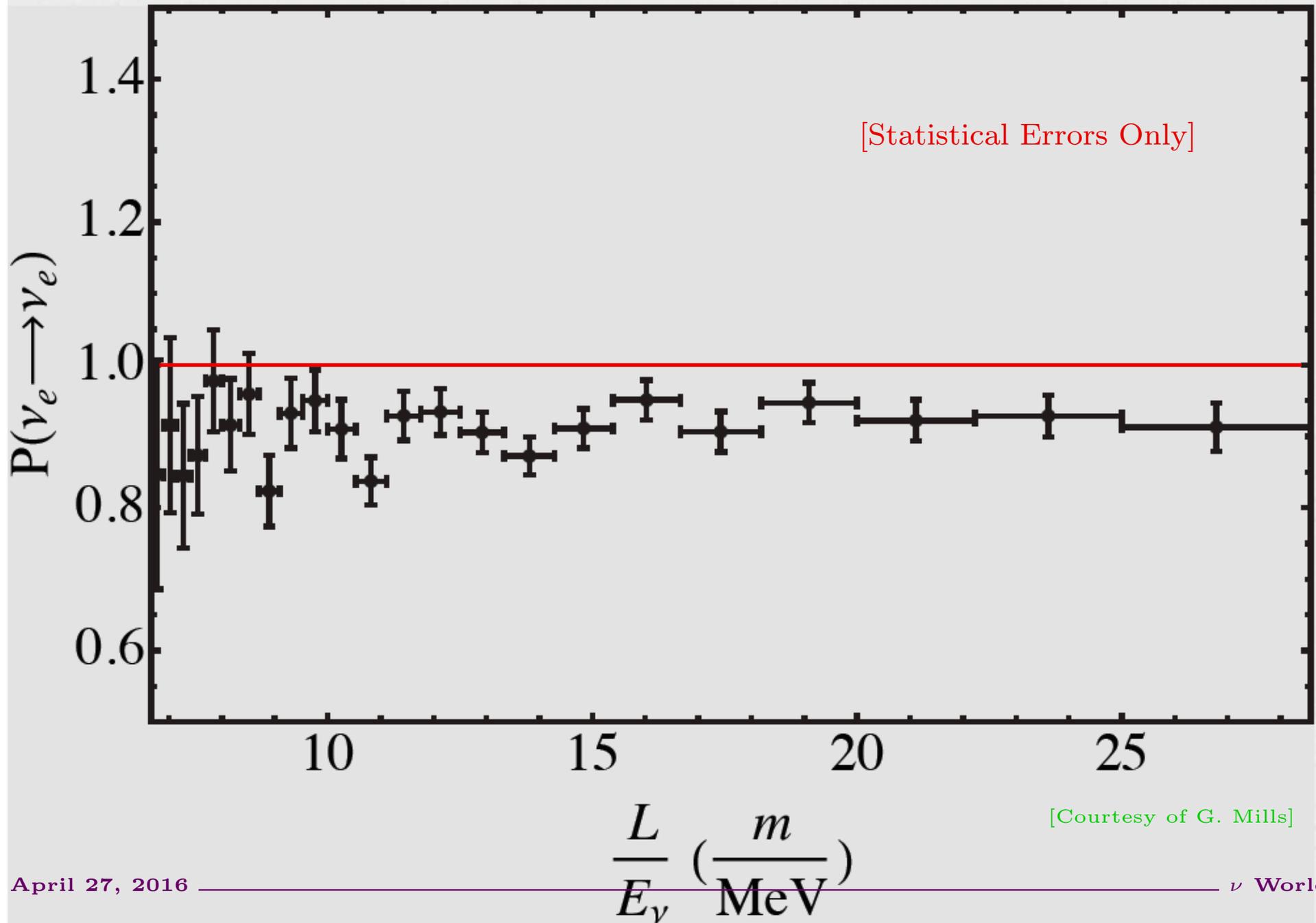
- $\nu_\mu \rightarrow \nu_e$ appearance — LSND, MiniBooNE;
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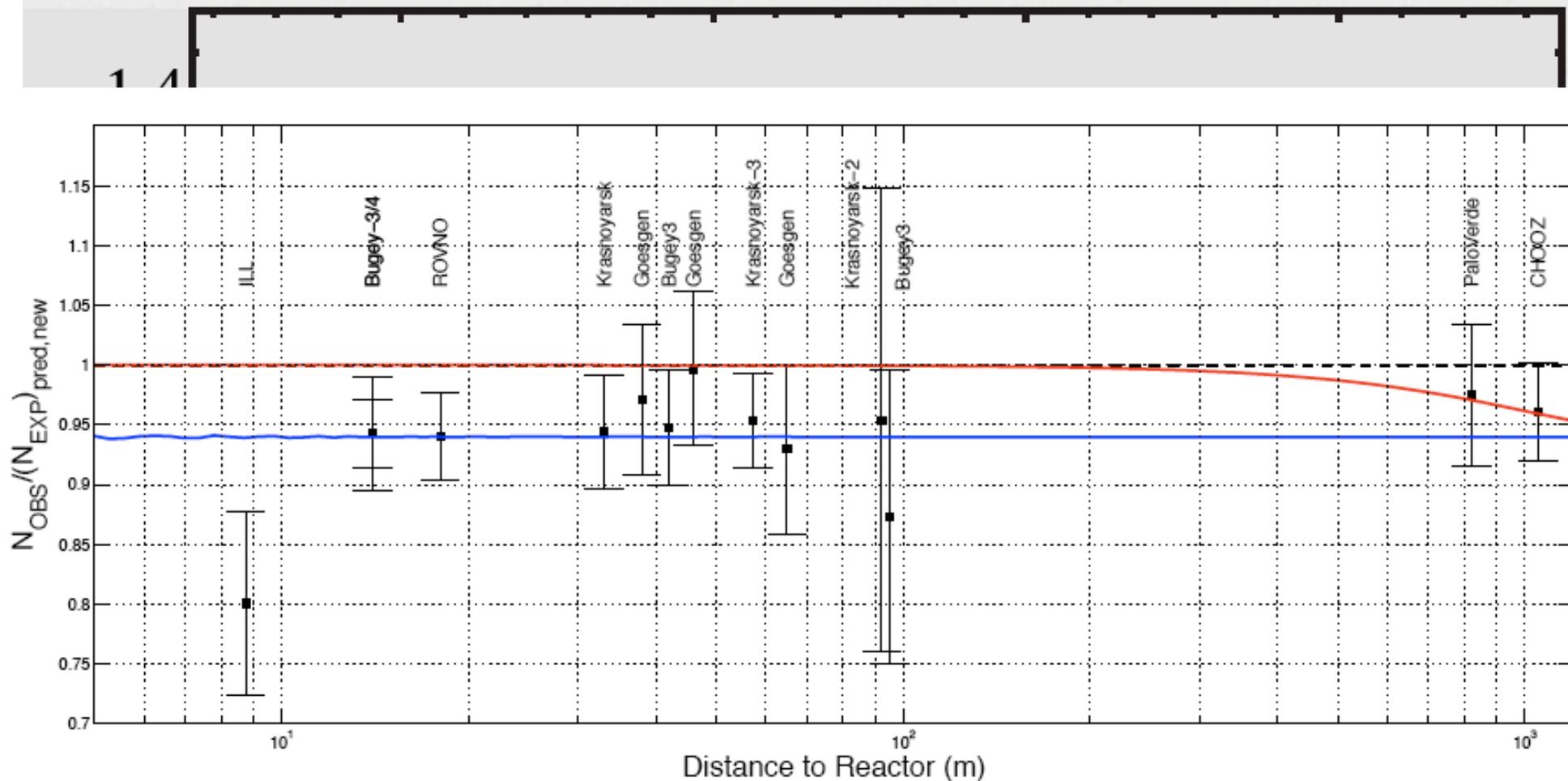
MiniBooNE & LSND



Bugey 40 m



Bugey 40 m



10

15

20

25

$$\frac{L}{E_\nu} \left(\frac{m}{\text{MeV}} \right)$$

What is Going on Here?

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- $\nu_{\mu,e} \rightarrow \nu_\tau$ 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.

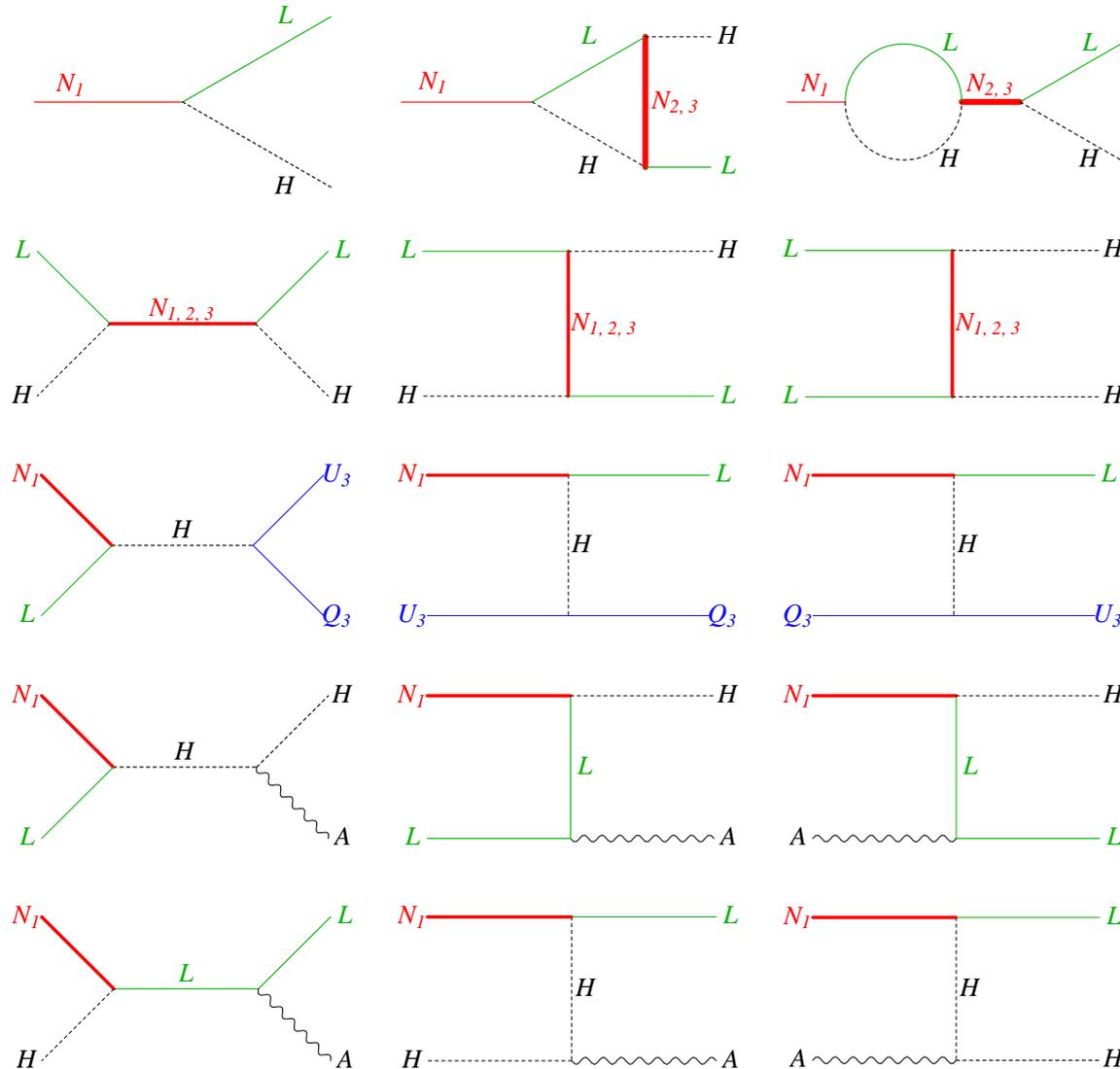
Neutrinos help by providing all the necessary ingredients for successful baryogenesis via leptogenesis.

- Violation of lepton number, which later on is transformed into baryon number by nonperturbative, finite temperature electroweak effects (in one version of the ν SM, 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]



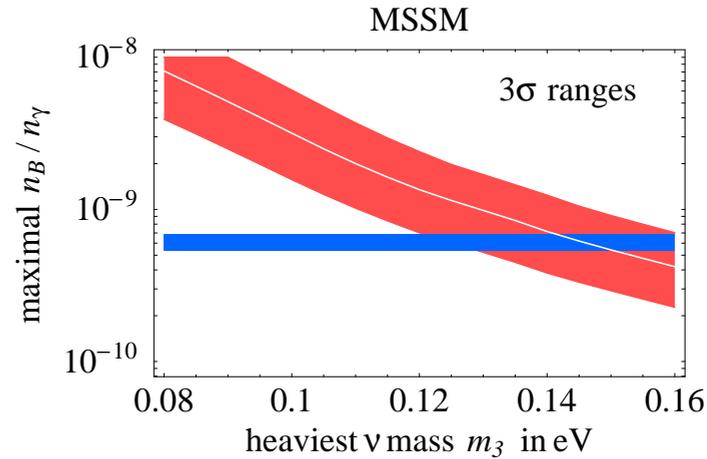
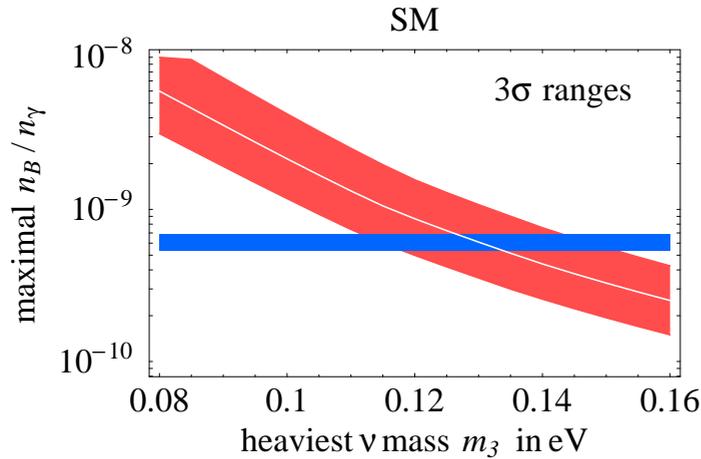
- L-violating processes
- $y \Rightarrow$ CP-violation
- deviation from thermal eq. constrains combinations of M_N and y .
- need to yield correct m_ν

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 $m_\nu = y^\dagger M_N^{-1} y$.

There could be a relationship, but it requires that we know more about the high energy Lagrangian (model dependent). 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).

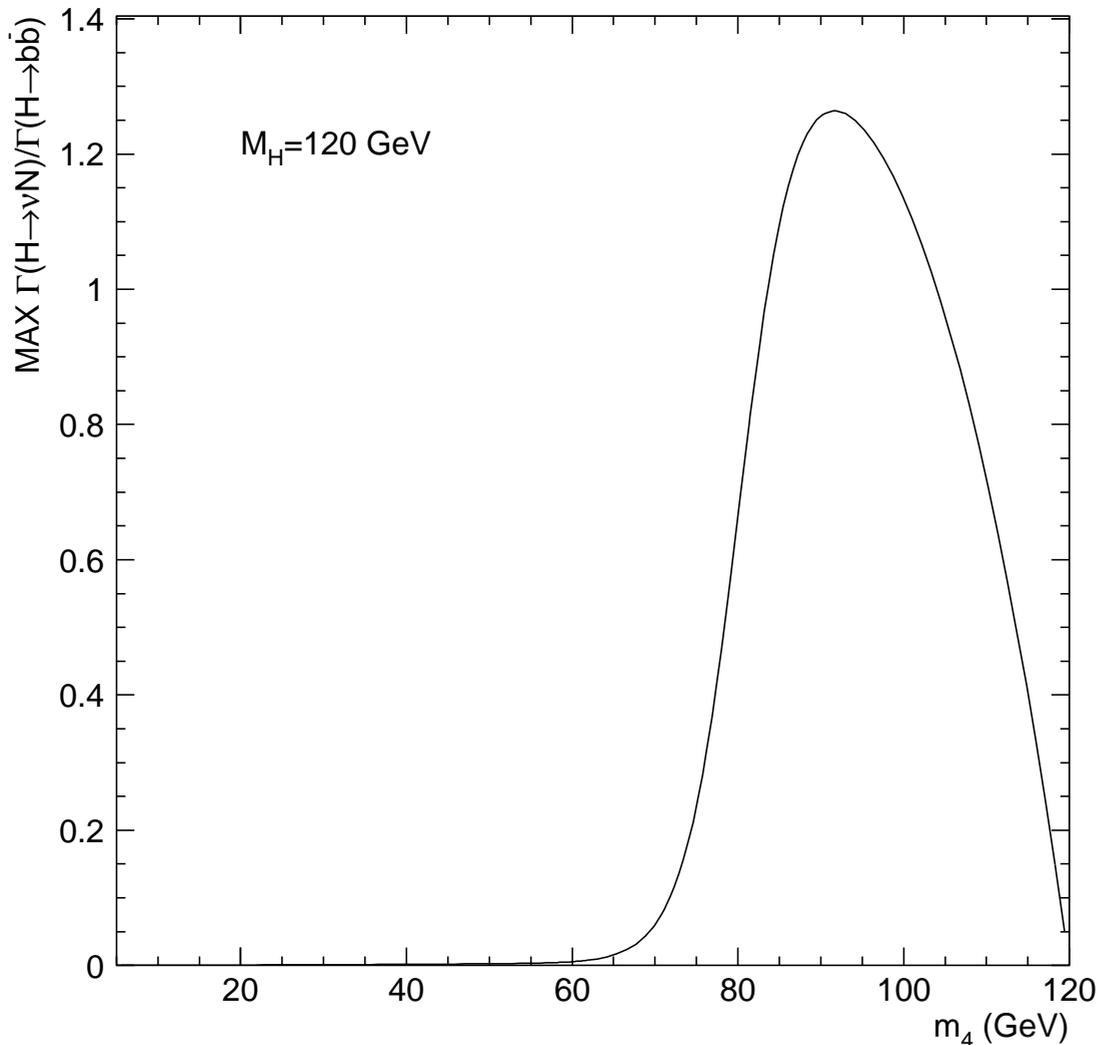
Making Predictions, for an inverted mass hierarchy, $m_4 = 1 \text{ eV} (\ll m_5)$

[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 $\sin^2 2\vartheta_{ee} > 0.04$;
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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.

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

(NOTE: $N \rightarrow \ell q' \bar{q}$ 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.

Big Bang Neutrinos are Warm Dark Matter

Planck Collaboration: Cosmological parameters

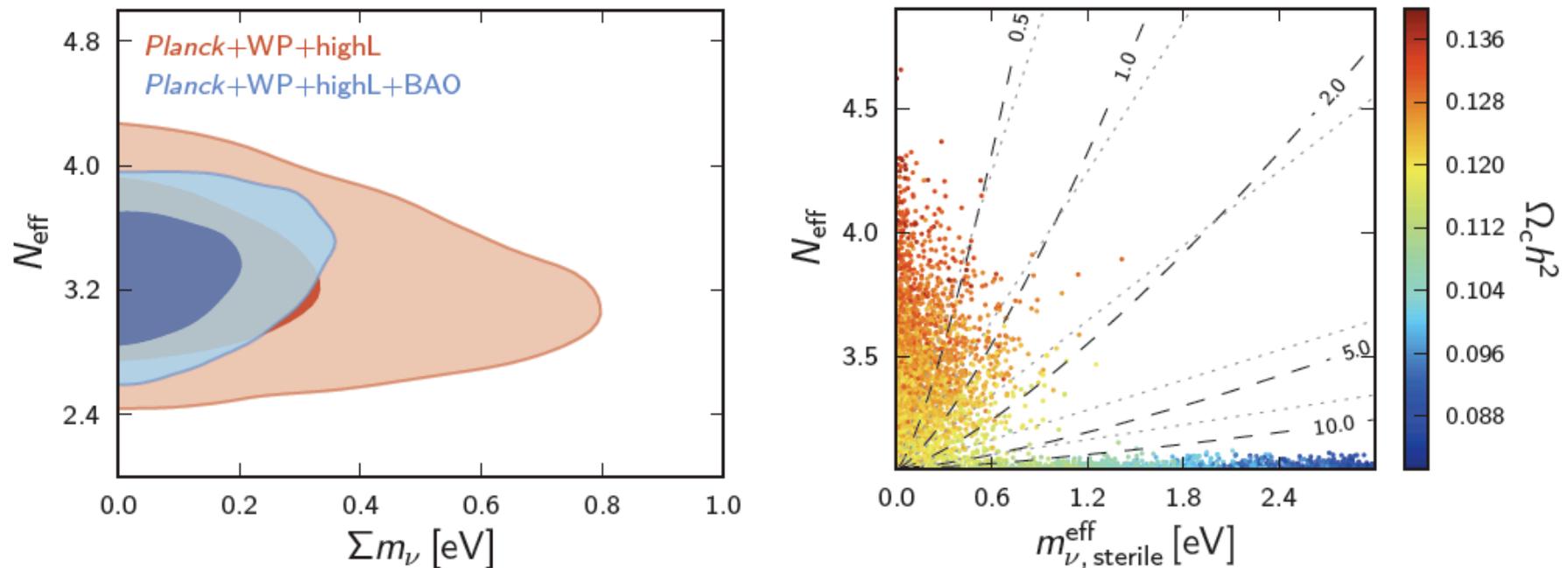
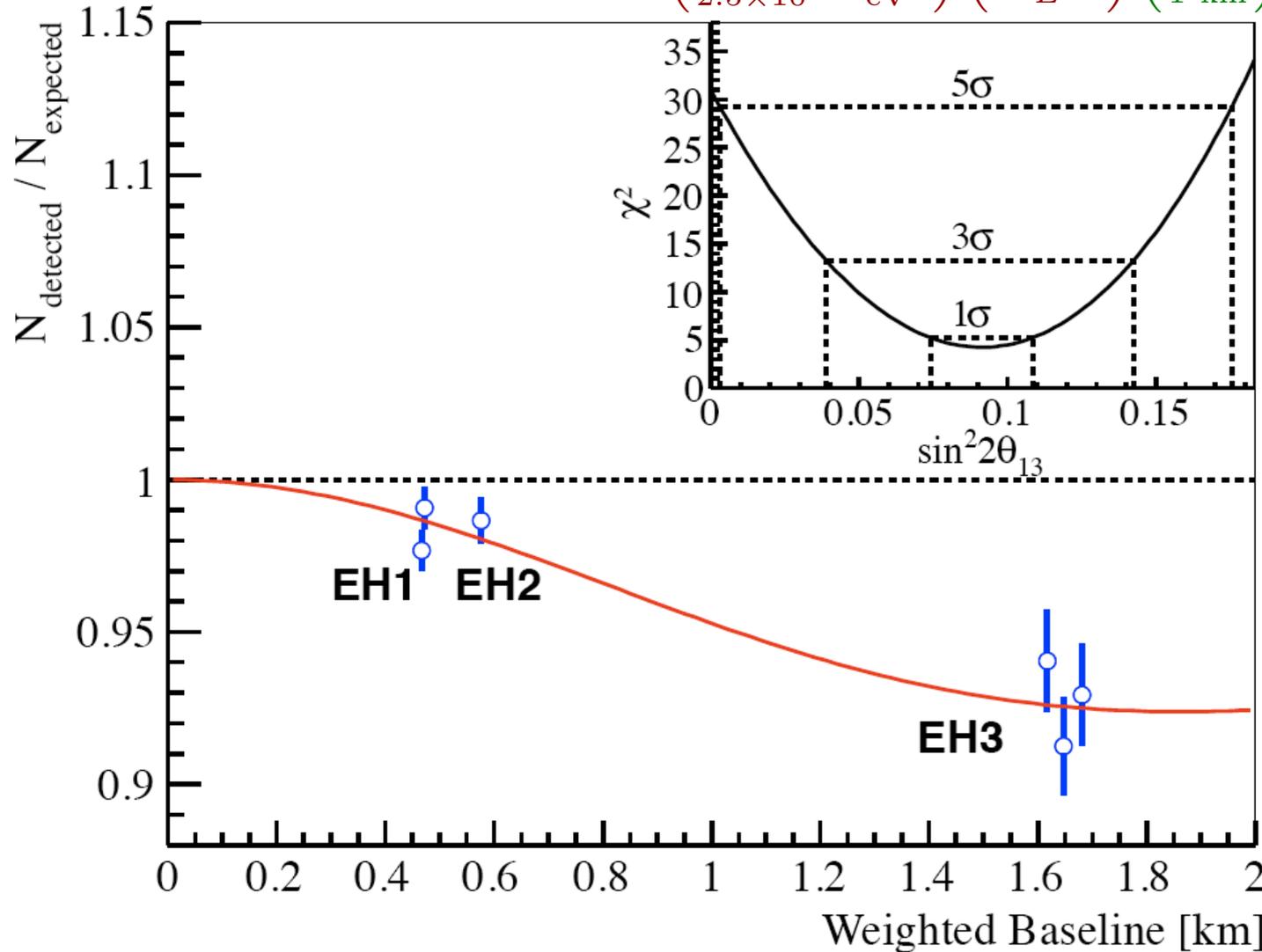


Fig. 28. *Left:* 2D joint posterior distribution between N_{eff} and $\sum m_\nu$ (the summed mass of the three active neutrinos) in models with extra massless neutrino-like species. *Right:* Samples in the $N_{\text{eff}}-m_{\nu, \text{sterile}}^{\text{eff}}$ plane, colour-coded by $\Omega_c h^2$, in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

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

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



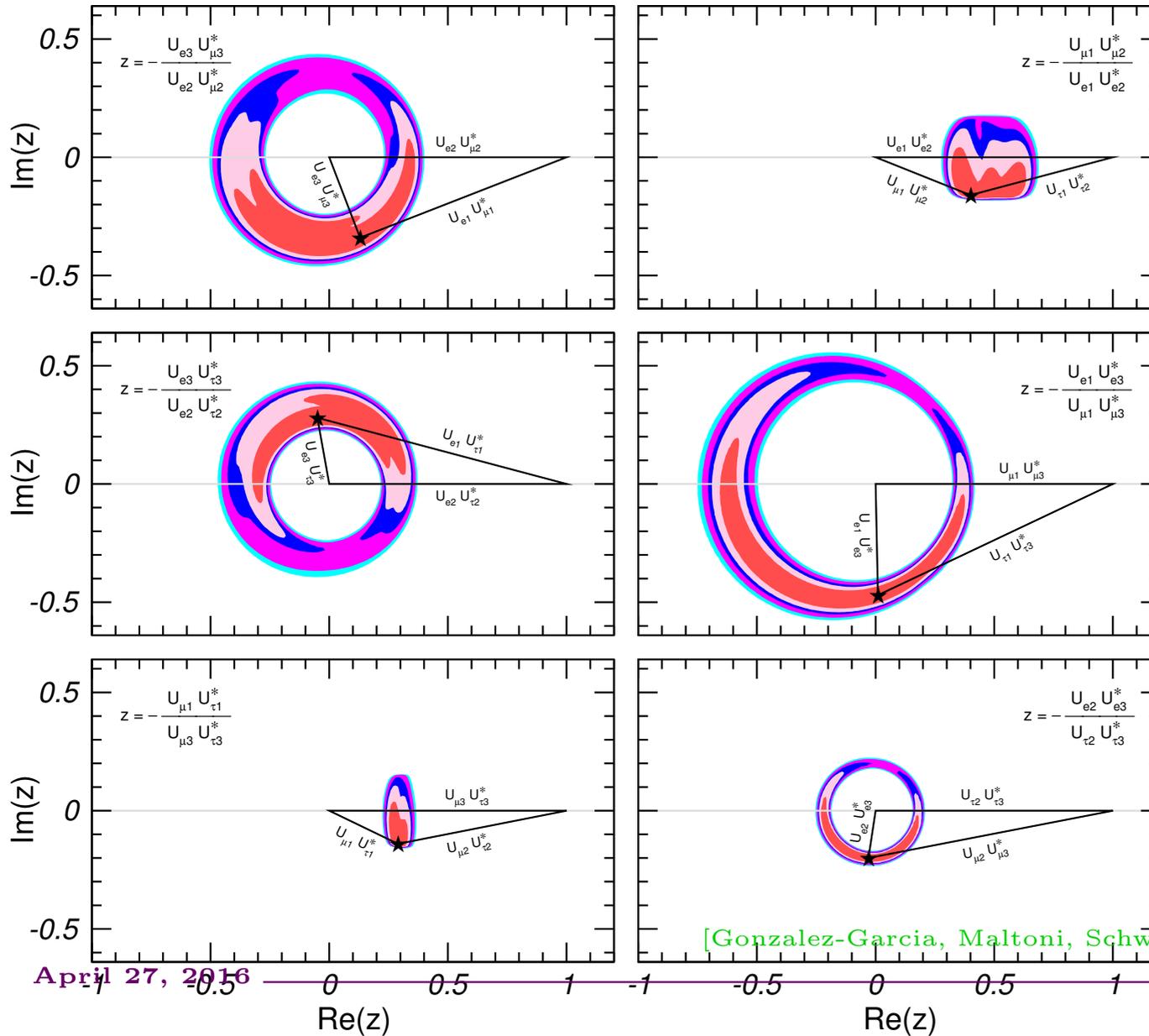
Triumph of the 3 flavor paradigm!

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

[Daya Bay Coll., 1203.1669]

Where We Are (?) [This is Not a Proper Comparison Yet!]

NuFIT 2.0 (2014)



But it is a start...

[Gonzalez-Garcia, Maltoni, Schwetz, 1409.5439, <http://www.nu-fit.org>]

CP-invariance Violation in Neutrino Oscillations

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

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

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

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

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

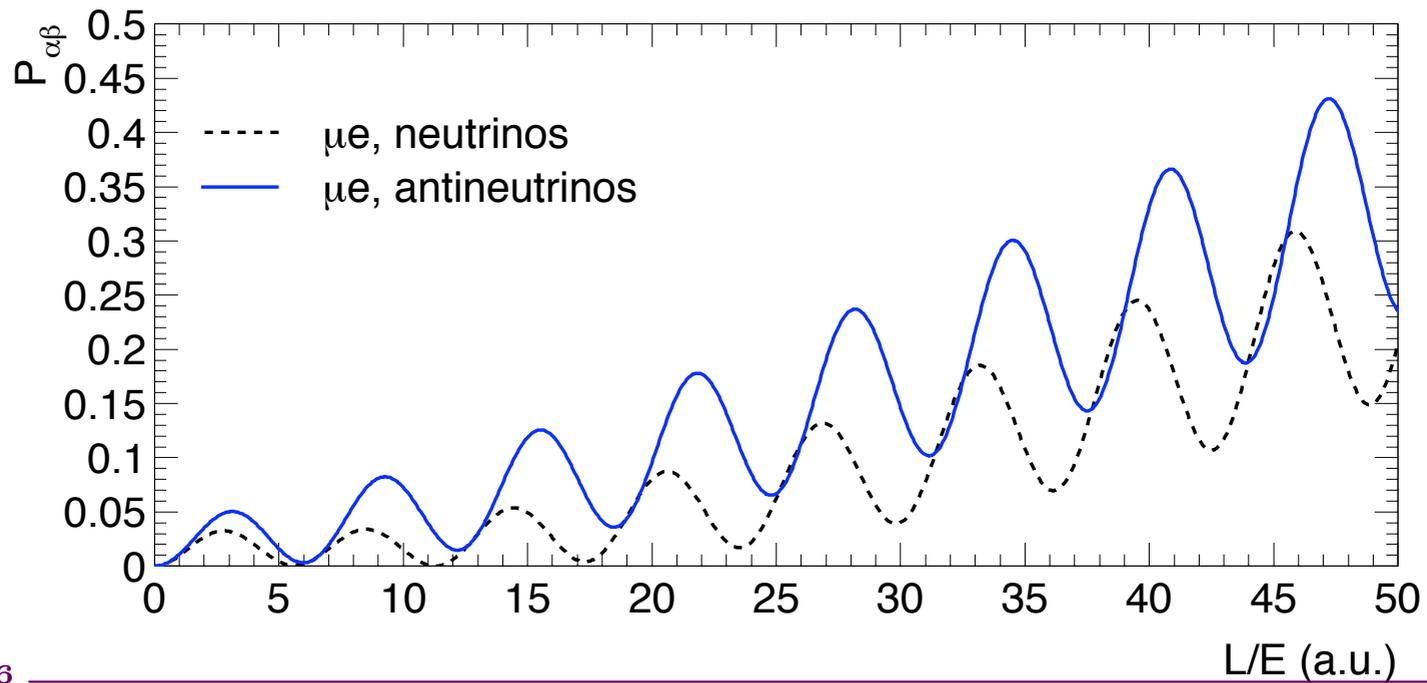
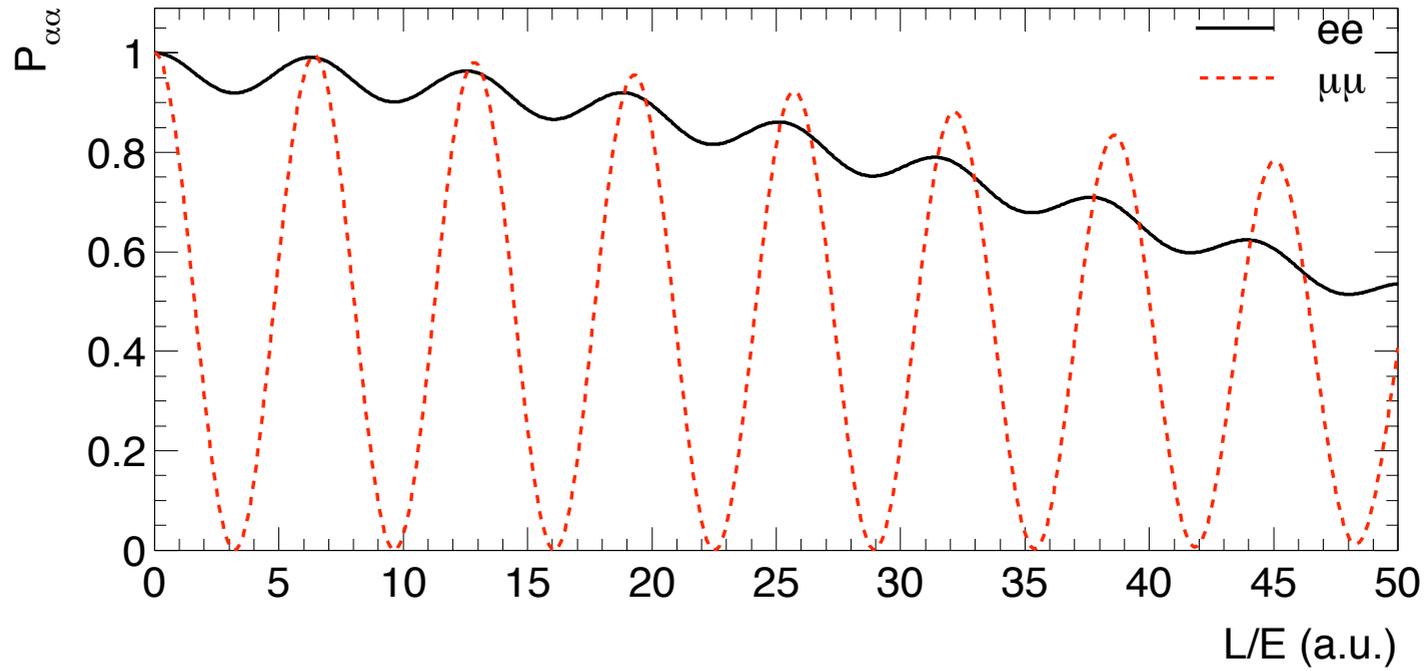
$$\bar{A}_{\mu e} = U_{e2} U_{\mu 2}^* (e^{i\Delta_{12}} - 1) + U_{e3} U_{\mu 3}^* (e^{i\Delta_{13}} - 1).$$

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

All of these can be satisfied, with a little luck: **we needed** $|U_{e3}| \neq 0$. ✓



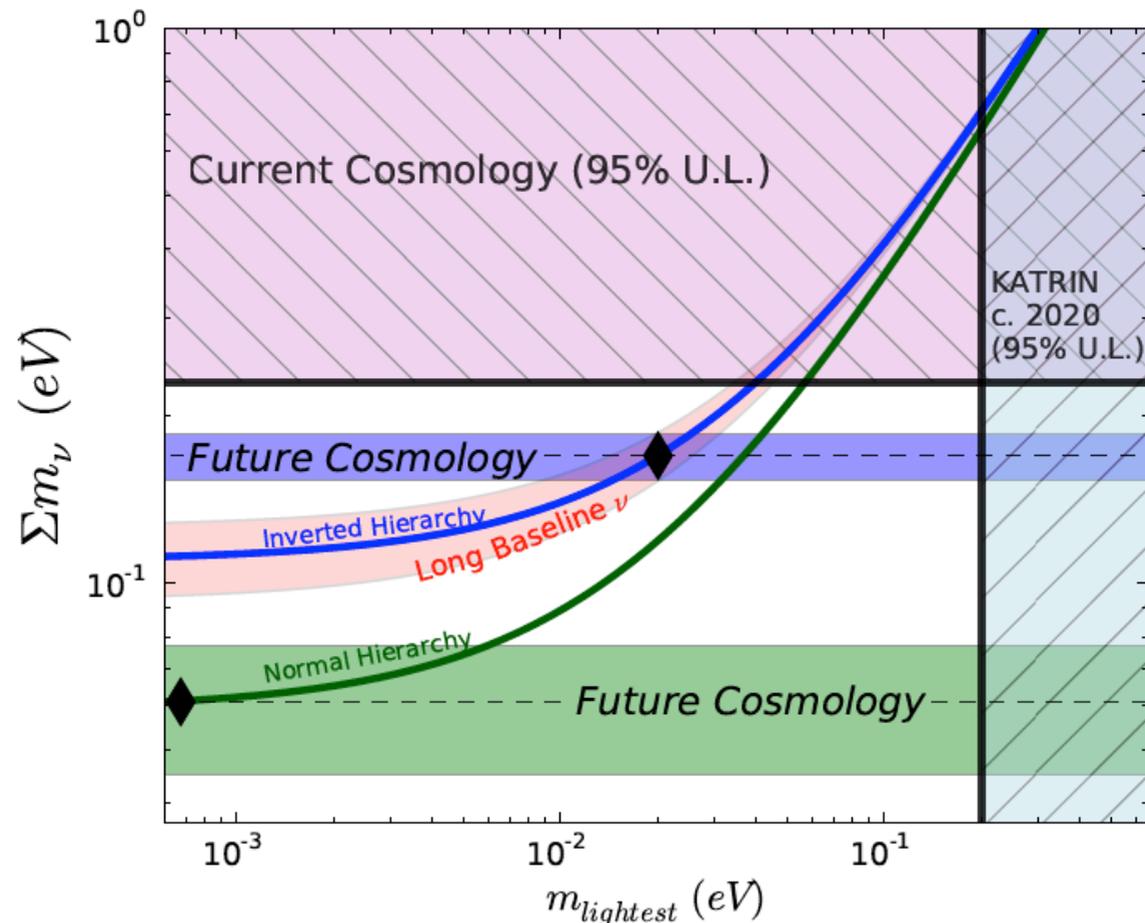
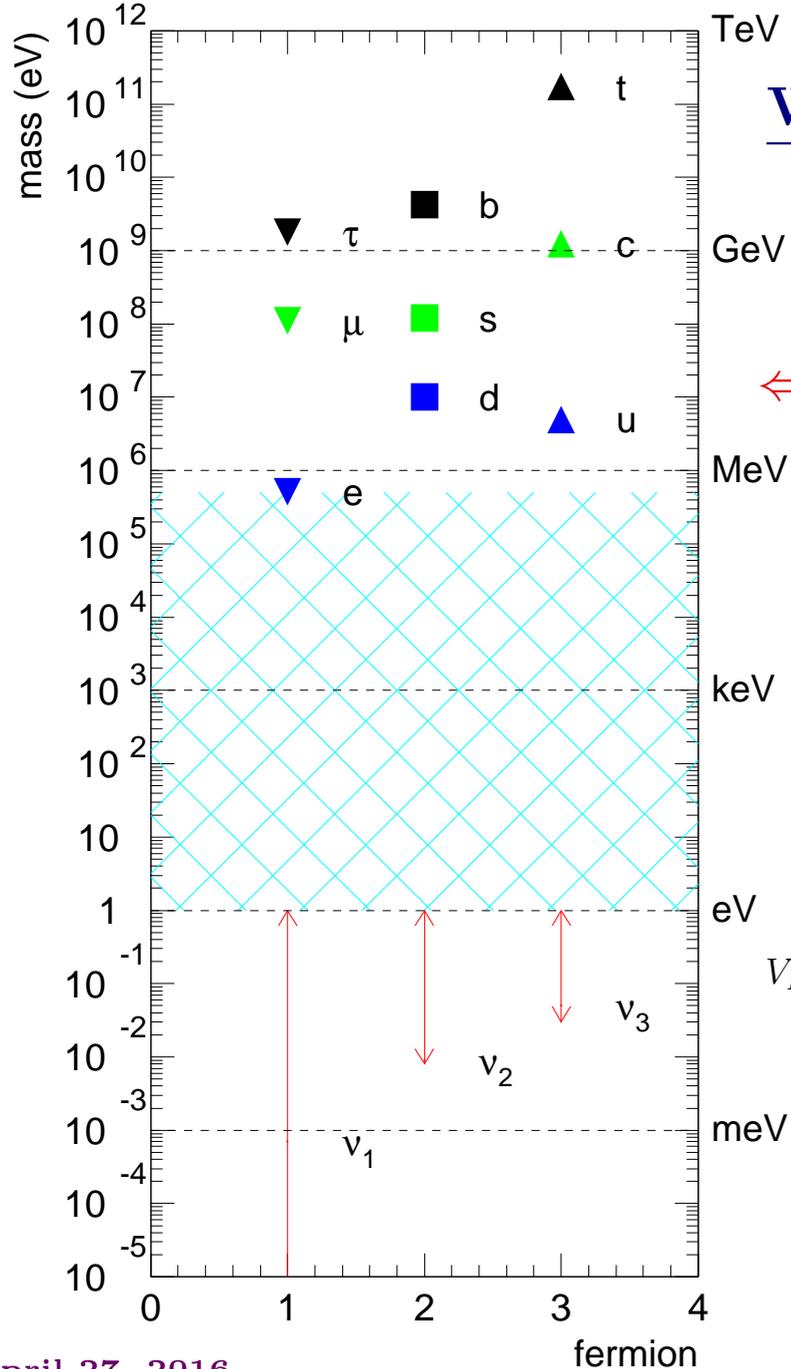


Figure 7. Current constraints and forecast sensitivity of cosmology to the sum of neutrino masses. In the case of an “inverted hierarchy,” with an example case marked as a diamond in the upper curve, future combined cosmological constraints would have a very high-significance detection, with $1\text{-}\sigma$ error shown as a blue band. In the case of a normal neutrino mass hierarchy with an example case marked as diamond on the lower curve, future cosmology would still detect the lowest Σm_ν at greater than $3\text{-}\sigma$.

[K. Abazajian *et al.* arXiv:1309.5386]



What We Are Trying To Understand:

⇐ **NEUTRINOS HAVE TINY MASSES**

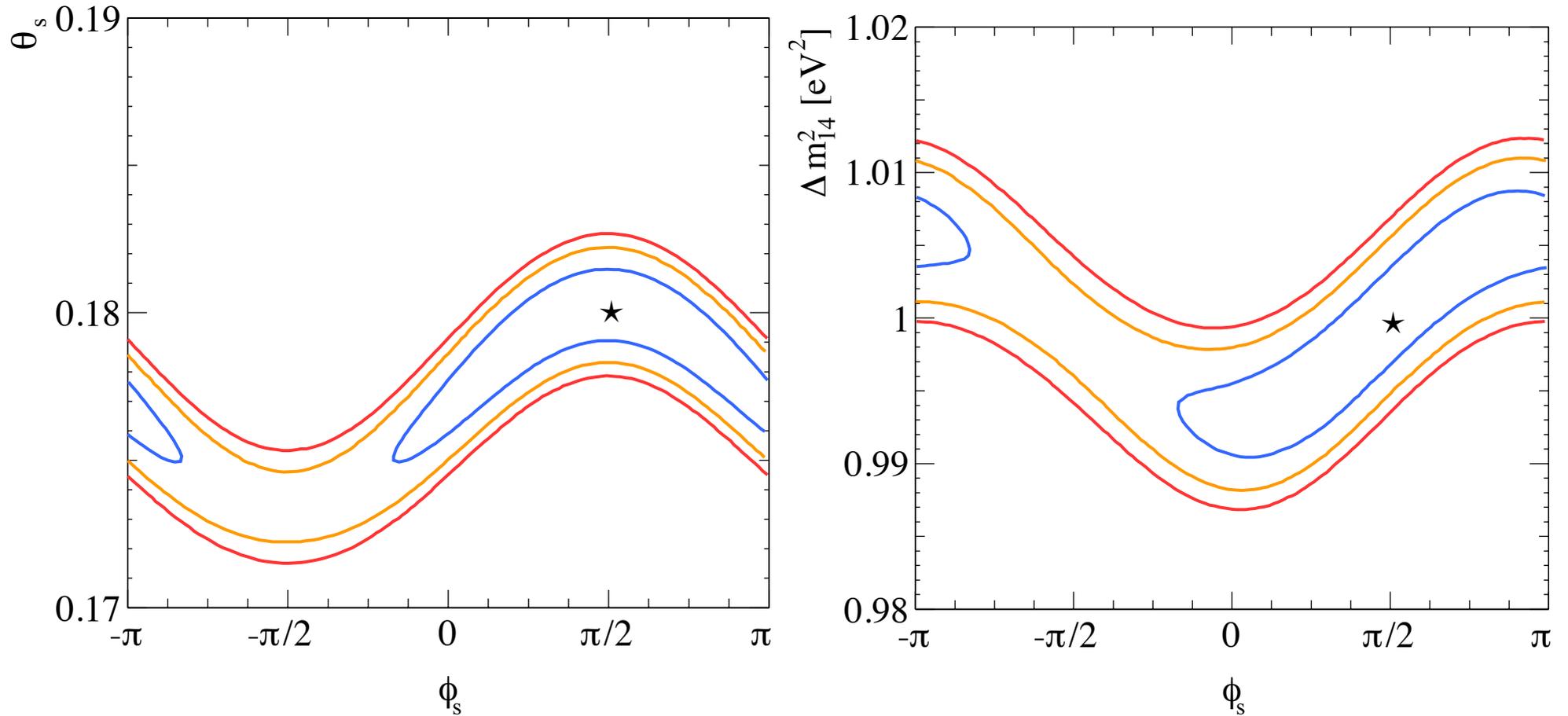
⇓ **LEPTON MIXING IS “WEIRD”** ⇓

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

What Does It Mean?

E.g., CPV in 3+1 Scenarios. ν STORM+, $\nu_e \rightarrow \nu_\mu$ at the “optimal” baseline...



[AdG, Kelly, Kobach, arXiv:1412.1479]

Solar Neutrinos

We are not done yet!

- see “vacuum-matter” transition
- probe for new physics: NSI, pseudo-Dirac, ...
- probe of the solar interior! “solar abundance problem” (see e.g. 1104.1639)
- ‘CNO neutrinos may provide information on planet formation!’

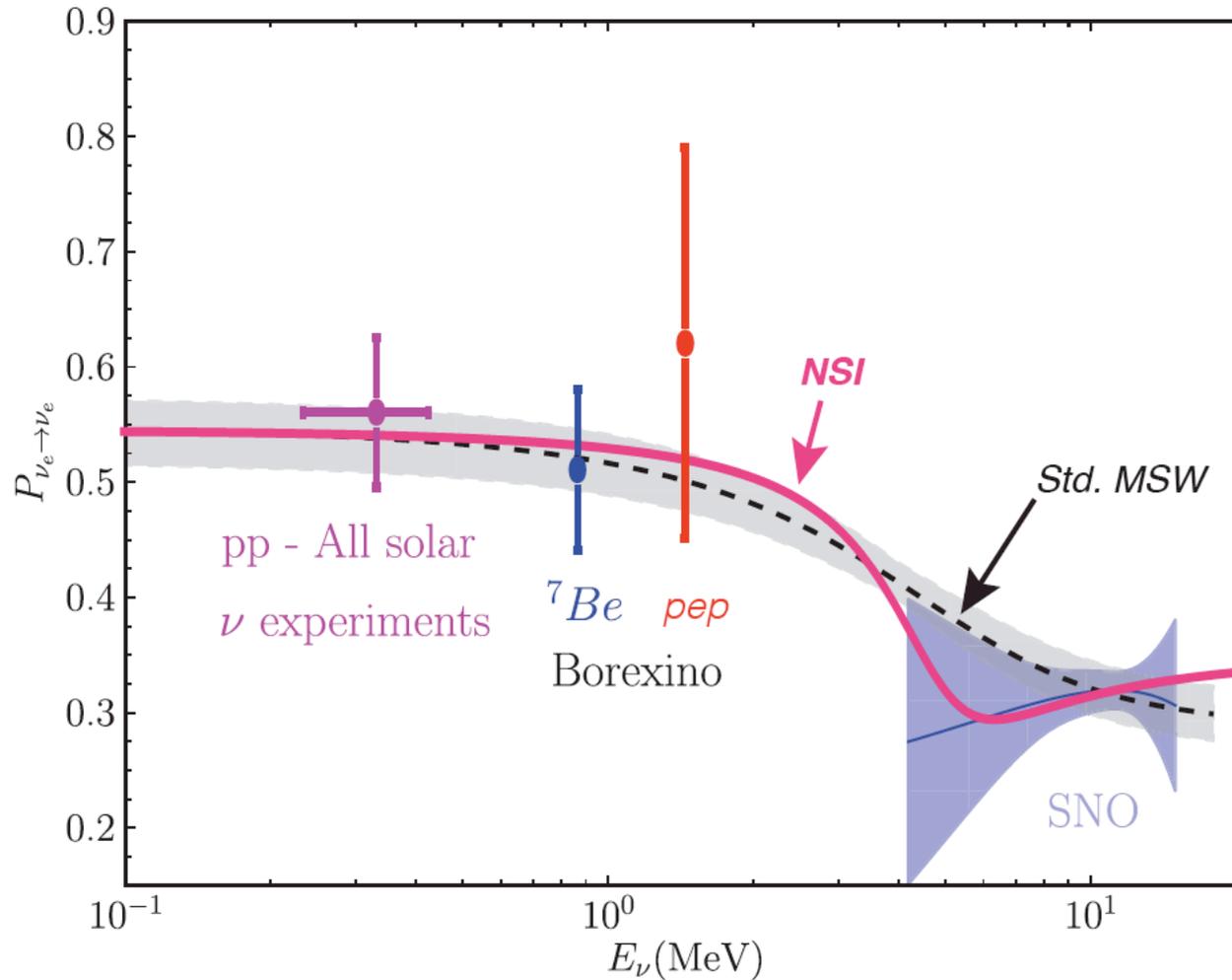
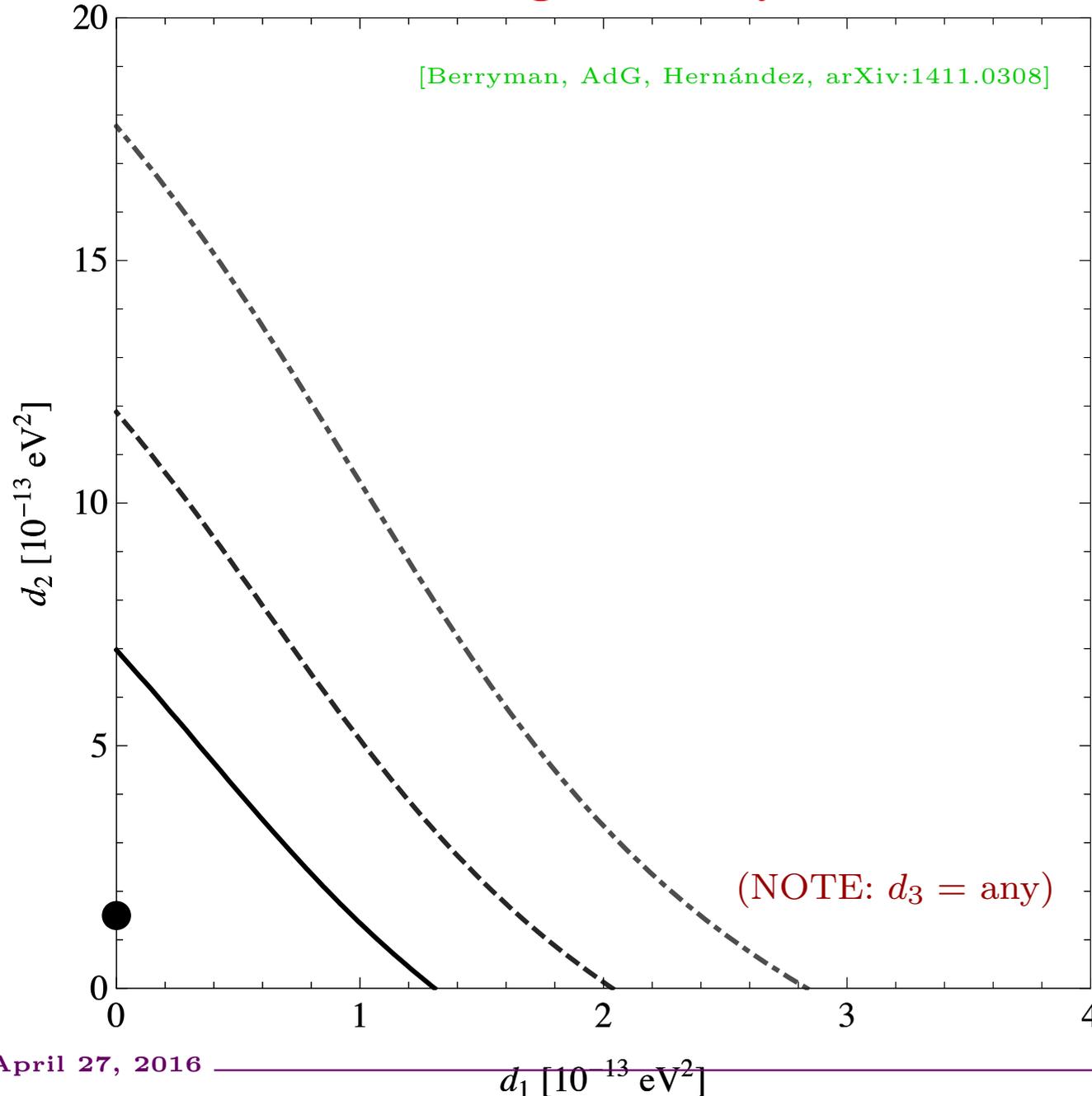


FIG. 1: Recent SNO solar neutrino data [18] on $P(\nu_e \rightarrow \nu_e)$ (blue line with 1σ band). The LMA MSW solution (dashed black curve with gray 1σ band) appears divergent around a few MeV, whereas for NSI with $\epsilon_{e\tau} = 0.4$ (thick magenta), the electron neutrino probability appears to fit the data better. The data points come from the recent Borexino paper [19].

[Friedland, Shoemaker 1207.6642]

Constraining the Decay of Neutrinos – Solar Edition

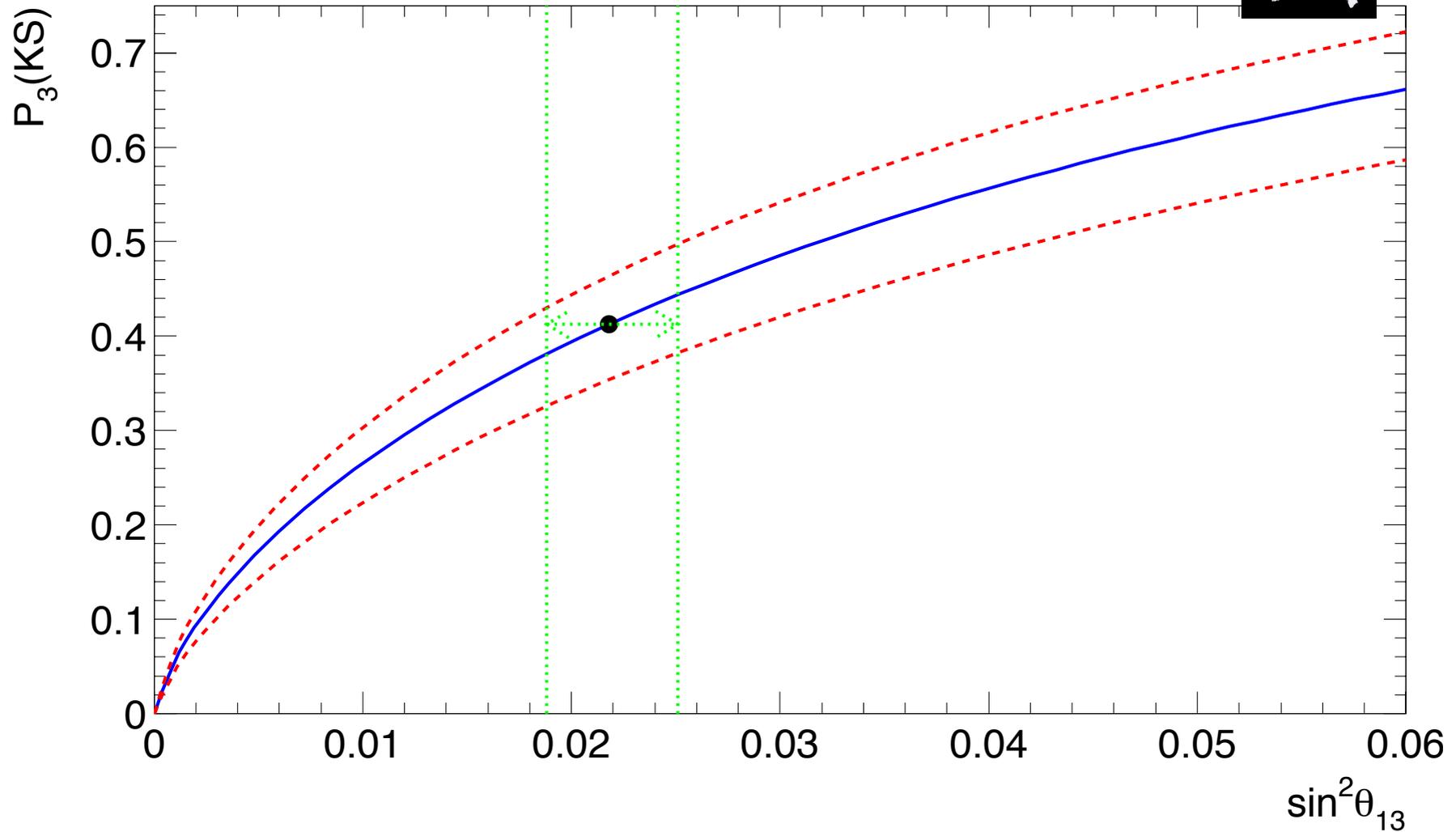
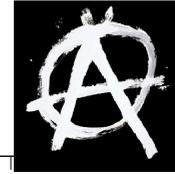


Model-independently,
we know little about
the neutrino lifetime.
 ν SM: $\tau > 10^{37}$ years.

Here, $d_i = m_i/\tau_i$

$$\tau_i = 7 \left(\frac{m_i}{1 \text{ eV}} \frac{10^{-13}}{d_i} \right) \text{ ms}$$

Neutrino Mixing Anarchy: Alive and Kicking!



[AdG, Murayama, 1204.1249]

E.g. 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 ν SM (the old Standard Model plus operators that lead to neutrino masses) $\mu \rightarrow e\gamma$ is allowed (along with all other charged lepton flavor violating processes).

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

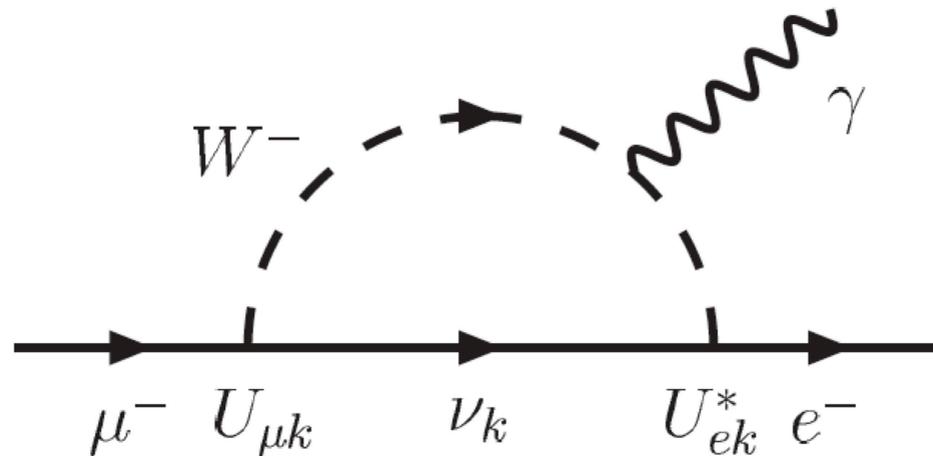
Unfortunately, we do not know the ν SM expectation for charged lepton flavor violating processes → **we don't know the ν SM Lagrangian !**

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...**

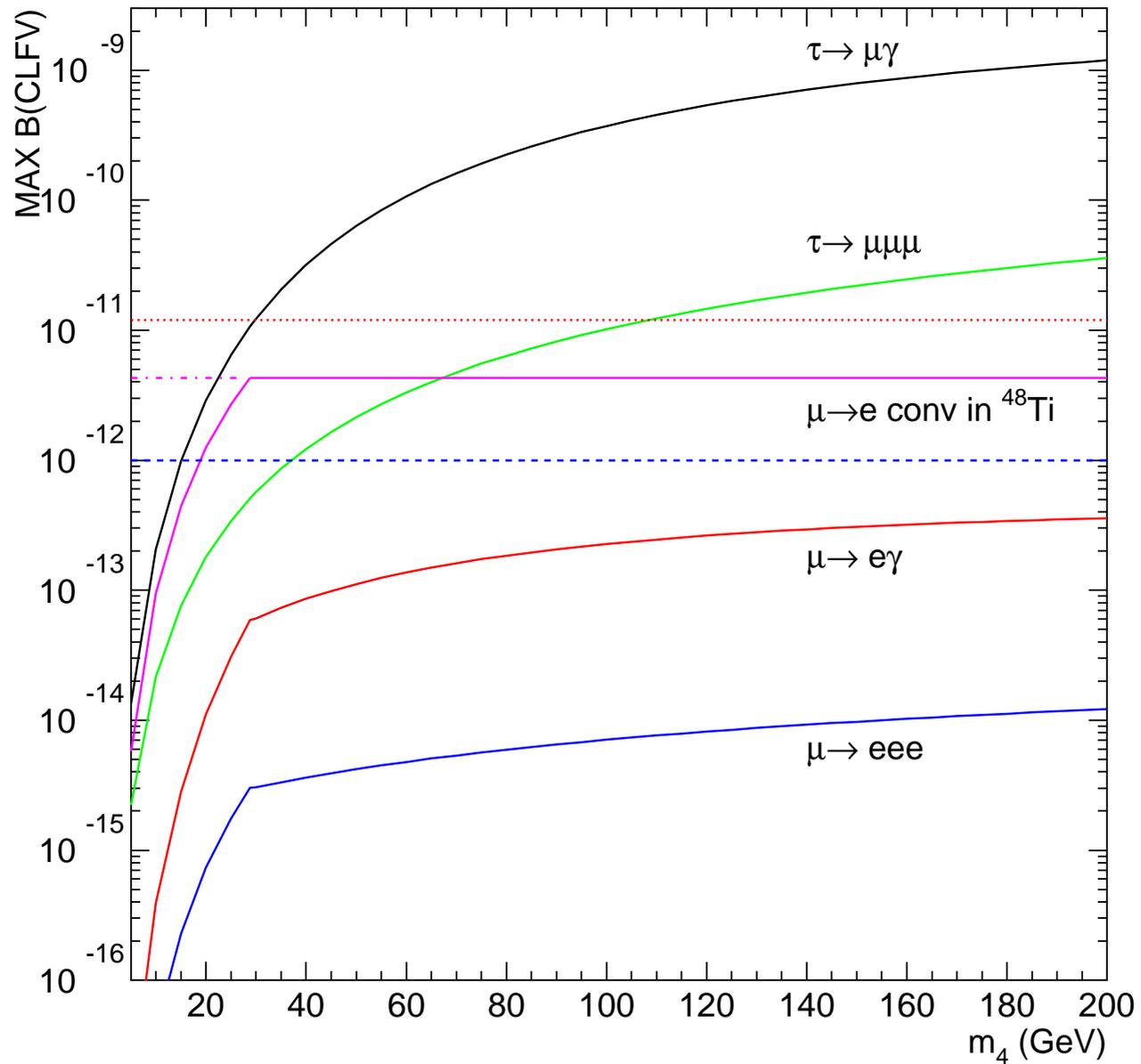
$$\text{e.g.: } Br(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54}$$

[$U_{\alpha i}$ are the elements of the leptonic mixing matrix,

$\Delta m_{1i}^2 \equiv m_i^2 - m_1^2$, $i = 2, 3$ are the neutrino mass-squared differences]



e.g.: SeeSaw Mechanism [minus “Theoretical Prejudice”]



arXiv:0706.1732 [hep-ph]