# Neutrino Physics: Status and Prospects

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## Something Funny Happened on the Way to the 21st Century

### $\nu$ 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 $E_\nu$ 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.

# A Realistic, Reasonable, and Simple Paradigm:

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

Definition of neutrino mass eigenstates (who are $\nu_1$, $\nu_2$, $\nu_3$?):

- $m_1^2 < m_2^2$ $\qquad\qquad\qquad\qquad\qquad$ $\Delta m_{13}^2 < 0$ – Inverted Mass Hierarchy

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

$$
\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu3}|^2}{|U_{\tau3}|^2}; \quad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}
$$

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

# Three Flavor Mixing Hypothesis Fits All* Data Really Well.

|  | Normal Ordering (best fit) | | Inverted Ordering ($\Delta\chi^2 = 4.14$) | | Any Ordering |
|---|---|---|---|---|---|
|  | bfp $\pm 1\sigma$ | $3\sigma$ range | bfp $\pm 1\sigma$ | $3\sigma$ range | $3\sigma$ range |
| $\sin^2\theta_{12}$ | $0.307^{+0.013}_{-0.012}$ | $0.272 \to 0.346$ | $0.307^{+0.013}_{-0.012}$ | $0.272 \to 0.346$ | $0.272 \to 0.346$ |
| $\theta_{12}/°$ | $33.62^{+0.78}_{-0.76}$ | $31.42 \to 36.05$ | $33.62^{+0.78}_{-0.76}$ | $31.43 \to 36.06$ | $31.42 \to 36.05$ |
| $\sin^2\theta_{23}$ | $0.538^{+0.033}_{-0.069}$ | $0.418 \to 0.613$ | $0.554^{+0.023}_{-0.033}$ | $0.435 \to 0.616$ | $0.418 \to 0.613$ |
| $\theta_{23}/°$ | $47.2^{+1.9}_{-3.9}$ | $40.3 \to 51.5$ | $48.1^{+1.4}_{-1.9}$ | $41.3 \to 51.7$ | $40.3 \to 51.5$ |
| $\sin^2\theta_{13}$ | $0.02206^{+0.00075}_{-0.00075}$ | $0.01981 \to 0.02436$ | $0.02227^{+0.00074}_{-0.00074}$ | $0.02006 \to 0.02452$ | $0.01981 \to 0.02436$ |
| $\theta_{13}/°$ | $8.54^{+0.15}_{-0.15}$ | $8.09 \to 8.98$ | $8.58^{+0.14}_{-0.14}$ | $8.14 \to 9.01$ | $8.09 \to 8.98$ |
| $\delta_{\mathrm{CP}}/°$ | $234^{+43}_{-31}$ | $144 \to 374$ | $278^{+26}_{-29}$ | $192 \to 354$ | $144 \to 374$ |
| $\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$ | $7.40^{+0.21}_{-0.20}$ | $6.80 \to 8.02$ | $7.40^{+0.21}_{-0.20}$ | $6.80 \to 8.02$ | $6.80 \to 8.02$ |
| $\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$ | $+2.494^{+0.033}_{-0.031}$ | $+2.399 \to +2.593$ | $-2.465^{+0.032}_{-0.031}$ | $-2.562 \to -2.369$ | $\begin{bmatrix} +2.399 \to +2.593 \\ -2.536 \to -2.395 \end{bmatrix}$ |

[Esteban *et al*, JHEP 01 (2017) 087, http://www.nu-fit.org]

*Modulo a handful of $2\sigma$ to $3\sigma$ anomalies.

# Understanding Neutrino Oscillations: Are We There Yet? [NO!]
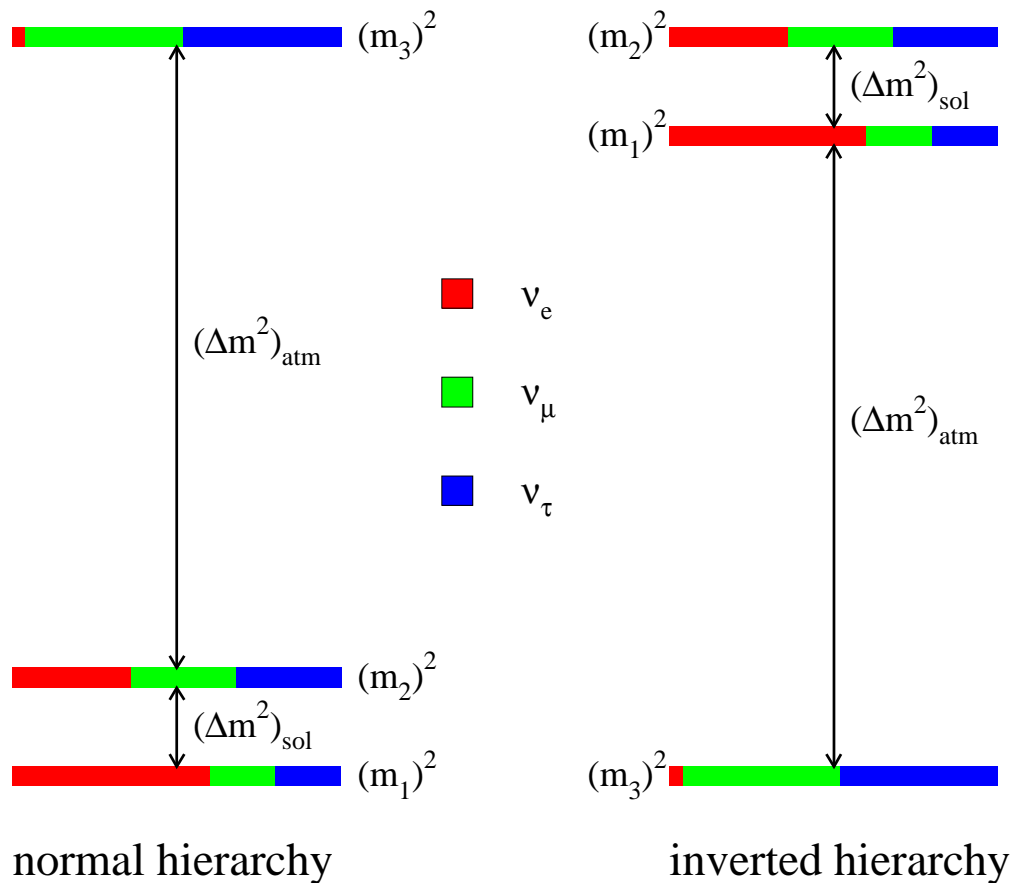


- ~~What is the $\nu_e$ component of $\nu_3$?~~ ($\theta_{13} \neq 0$!)

- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?) ['yes' hint]

- Is $\nu_3$ mostly $\nu_\mu$ or $\nu_\tau$? [$\theta_{23} \neq \pi/4$ hint]

- What is the neutrino mass hierarchy? ($\Delta m_{13}^2 > 0$?) [NH weak hint]

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

(Diagram labels: $(m_3)^2$, $(m_2)^2$, $(m_1)^2$, $(\Delta m^2)_{sol}$, $(\Delta m^2)_{atm}$; legend: $\nu_e$ (red), $\nu_\mu$ (green), $\nu_\tau$ (blue); normal hierarchy, inverted hierarchy)

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

# What we ultimately want to achieve:
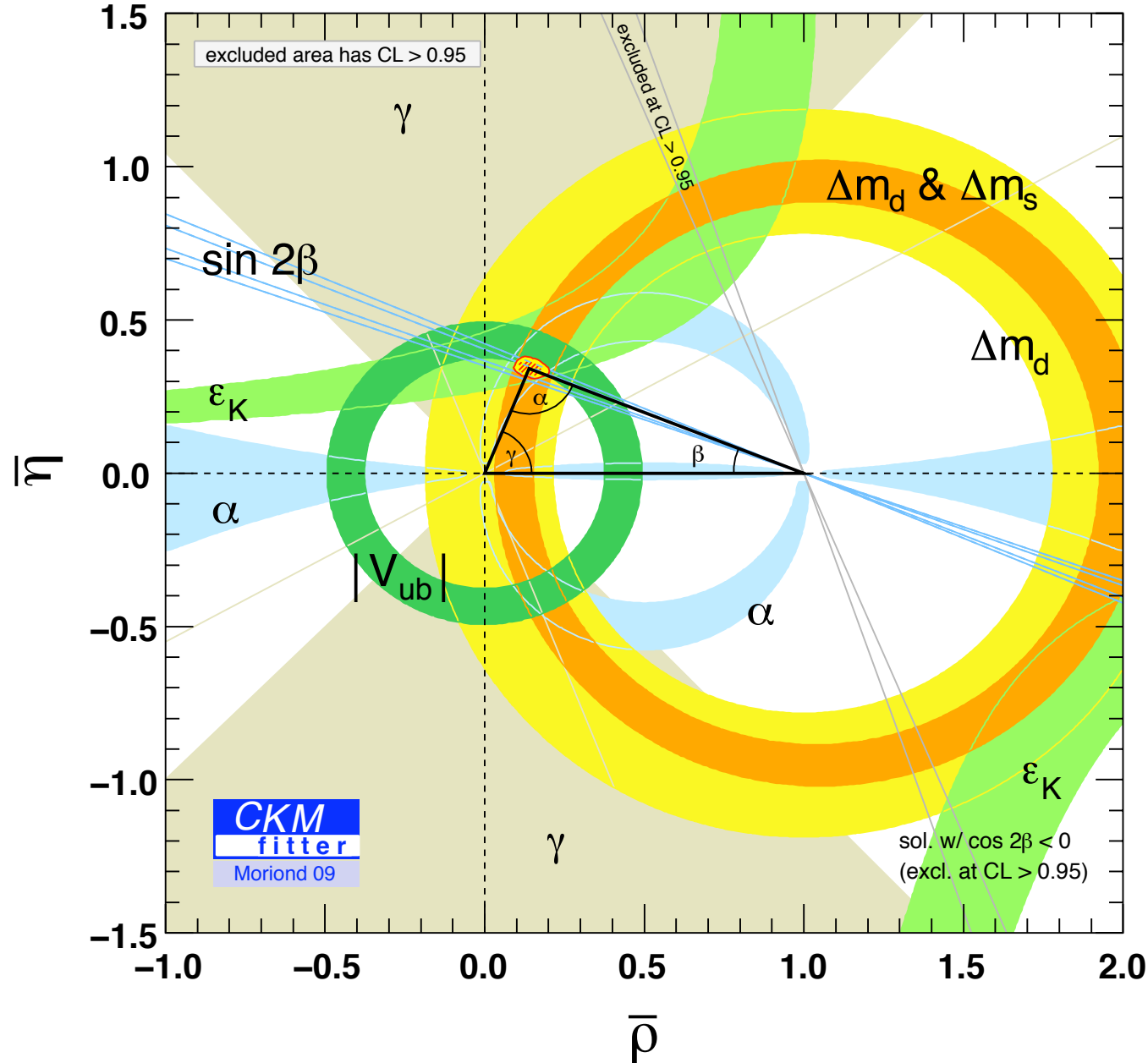


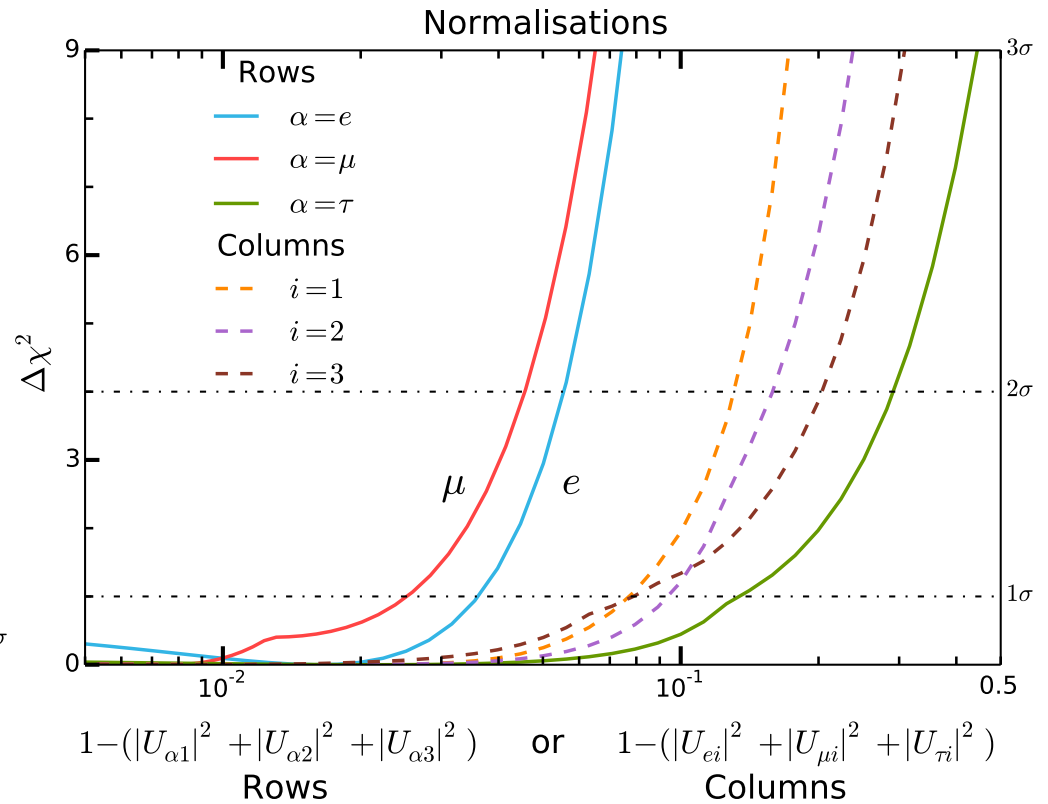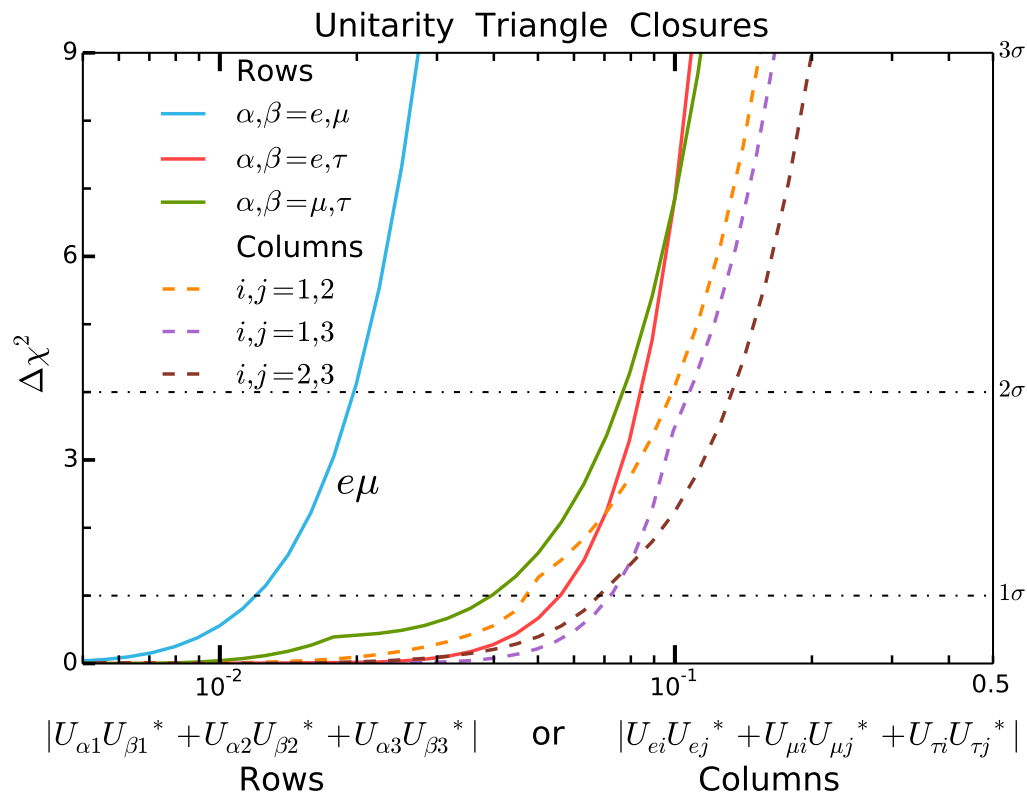We need to do <u>this</u> in the lepton sector!

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

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

- Two mass-squared differences, at several percent level – many probes;

- $\color{red}{|U_{e2}|^2}$ – solar data;

- $\color{red}{|U_{\mu 2}|^2 + |U_{\tau 2}|^2}$ – solar data;

- $\color{red}{|U_{e2}|^2|U_{e1}|^2}$ – KamLAND;

- $\color{green}{|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2)}$ – atmospheric data, K2K, MINOS;

- $\color{blue}{|U_{e3}|^2(1 - |U_{e3}|^2)}$ – Double Chooz, Daya Bay, RENO;

- $\color{blue}{|U_{e3}|^2|U_{\mu 3}|^2}$ (upper bound $\rightarrow$ evidence) – MINOS, T2K.

<div align="right"><span style="color:red">We still have a ways to go!</span></div>

# A little more quantitative:

## Normalisations



Rows
- $\alpha = e$
- $\alpha = \mu$
- $\alpha = \tau$

Columns
- $i = 1$
- $i = 2$
- $i = 3$

$\Delta\chi^2$

$\mu$  $e$

$1 - (|U_{\alpha 1}|^2 + |U_{\alpha 2}|^2 + |U_{\alpha 3}|^2)$  or  $1 - (|U_{ei}|^2 + |U_{\mu i}|^2 + |U_{\tau i}|^2)$
Rows                          Columns

## Unitarity Triangle Closures



Rows
- $\alpha, \beta = e, \mu$
- $\alpha, \beta = e, \tau$
- $\alpha, \beta = \mu, \tau$

Columns
- $i, j = 1, 2$
- $i, j = 1, 3$
- $i, j = 2, 3$

$\Delta\chi^2$

$e\mu$

$|U_{\alpha 1}U_{\beta 1}{}^* + U_{\alpha 2}U_{\beta 2}{}^* + U_{\alpha 3}U_{\beta 3}{}^*|$  or  $|U_{ei}U_{ej}{}^* + U_{\mu i}U_{\mu j}{}^* + U_{\tau i}U_{\tau j}{}^*|$
Rows                          Columns
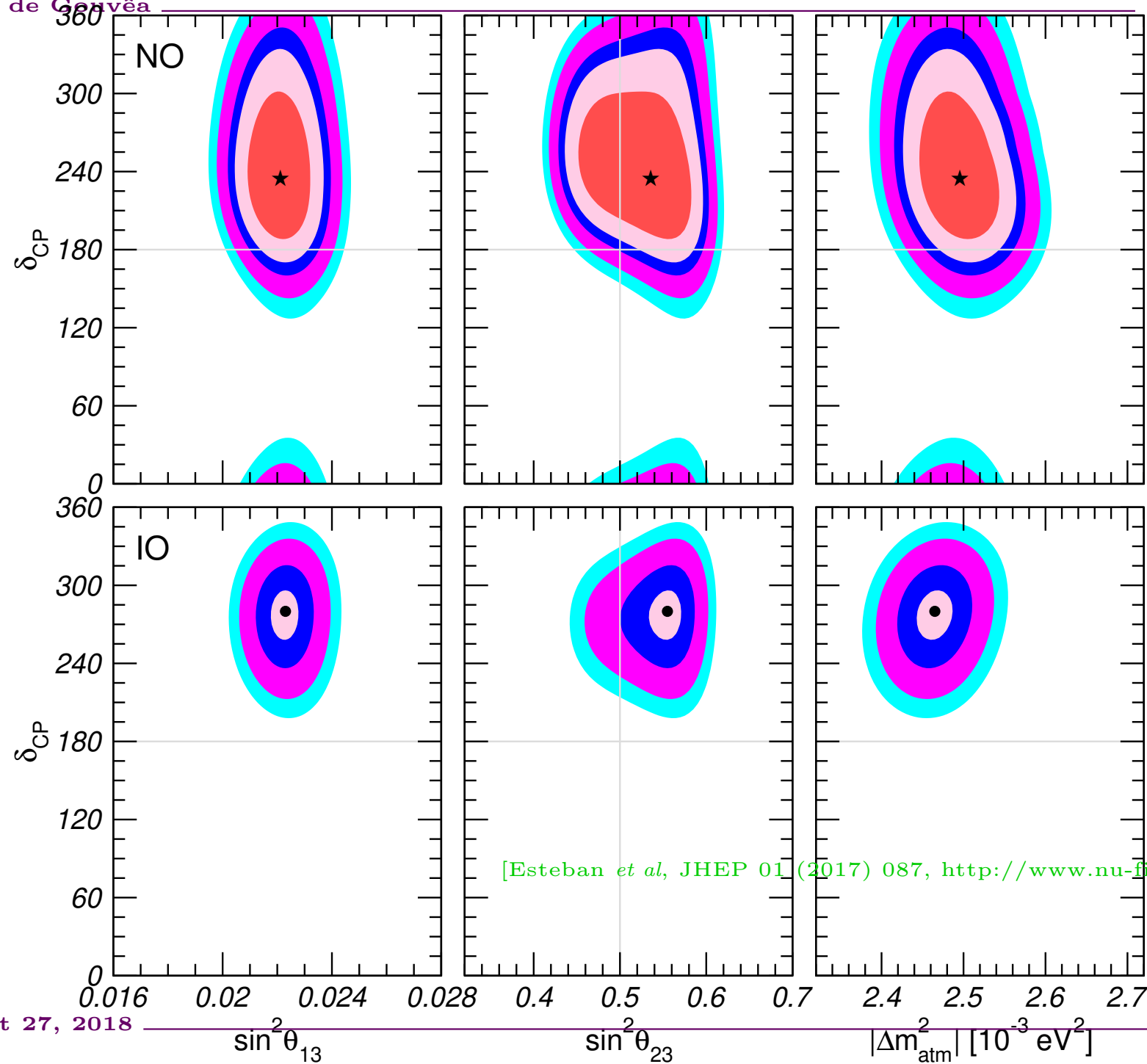
[Parke and Ross-Lonergan, arXiv:1508.05095]

### 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 $\theta_{QCD}$ 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."
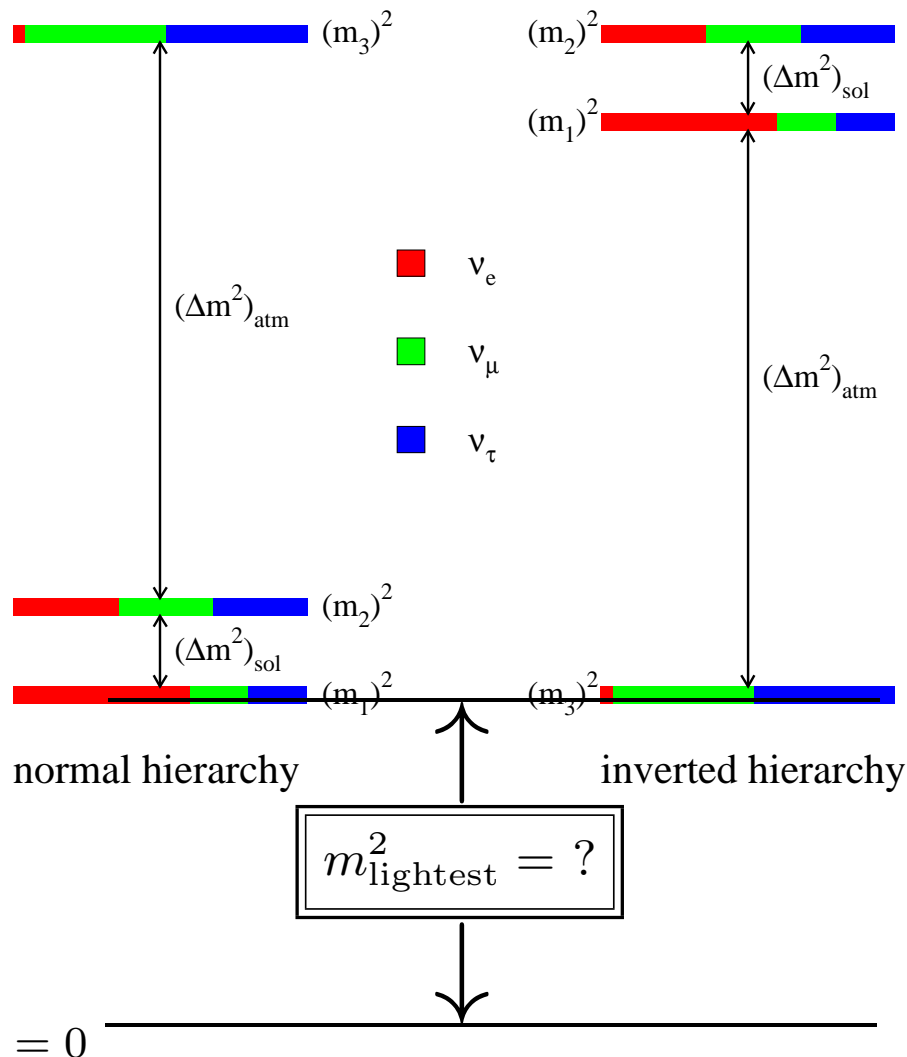
NO

IO

$\delta_{CP}$

$\delta_{CP}$

360

300

240

180

120

60

0

[Esteban *et al*, JHEP 01 (2017) 087, http://www.nu-fit.org]

$\nu$s

$\sin^2\theta_{13}$          $\sin^2\theta_{23}$          $|\Delta m^2_{atm}|$ [$10^{-3}$ eV$^2$]

0.016  0.02  0.024  0.028      0.4  0.5  0.6  0.7      2.4  2.5  2.6  2.7

## Long-Baseline Experiments, Present and Future (Not Exhaustive!)

- [NOW] T2K (Japan), NO$\nu$A (USA) – $\nu_\mu \to \nu_e$ appearance, $\nu_\mu$ disappearance – precision measurements of "atmospheric parameters" ($\Delta m_{13}^2, \sin^2 \theta_{23}$). Pursue mass hierarchy via matter effects. Nontrivial tests of paradigm. First step towards CP-invariance violation.

- [$\sim$2020] JUNO (China) – $\bar{\nu}_e$ disappearance – precision measurements of "solar parameters" ($\Delta m_{12}^2, \sin^2 \theta_{12}$). Pursue the mass hierarchy via precision measurements of oscillations.

- [$\sim$2020] PINGU (South Pole) and ORCA (Mediterranean)– atmospheric neutrinos – pursue mass hierarchy via matter effects.

- [$\sim$2025] HyperK (Japan), DUNE (USA) – Second (real opportunity for discovery!) step towards CP-invariance violation. More nontrivial tests of the paradigm. Ultimate "super-beam" experiments.

- [$>$2030?] Neutrino Factories (?) – Ultimate neutrino oscillation experiment. Test paradigm, precision measurements, solidify CP-violation discovery or improve sensitivity significantly.

# What We Know We Don't Know: How Light is the Lightest Neutrino?

$(m_3)^2$      $(m_2)^2$

$(\Delta m^2)_{sol}$

$(m_1)^2$

$\nu_e$

$\nu_\mu$

$(\Delta m^2)_{atm}$

$\nu_\tau$

$(\Delta m^2)_{atm}$

$(m_2)^2$

$(\Delta m^2)_{sol}$

$(m_1)^2$     $(m_3)^2$

normal hierarchy      inverted hierarchy

$$m^2_{\text{lightest}} = ?$$

$m^2 = 0$

So far, we've only been able to measure neutrino mass-squared differences.

The lightest neutrino mass is only poorly constrained: $m^2_{\text{lightest}} < 1 \text{ eV}^2$

qualitatively different scenarios allowed:

- $m^2_{\text{lightest}} \equiv 0$;
- $m^2_{\text{lightest}} \ll \Delta m^2_{12,13}$;
- $m^2_{\text{lightest}} \gg \Delta m^2_{12,13}$.

Need information outside of neutrino oscillations:

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

# The most direct probe of the lightest neutrino mass – precision measurements of $\beta$-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.

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

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":

$$m_{\nu_e}^2 \equiv \sum_i |U_{ei}|^2 m_i^2$$

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!
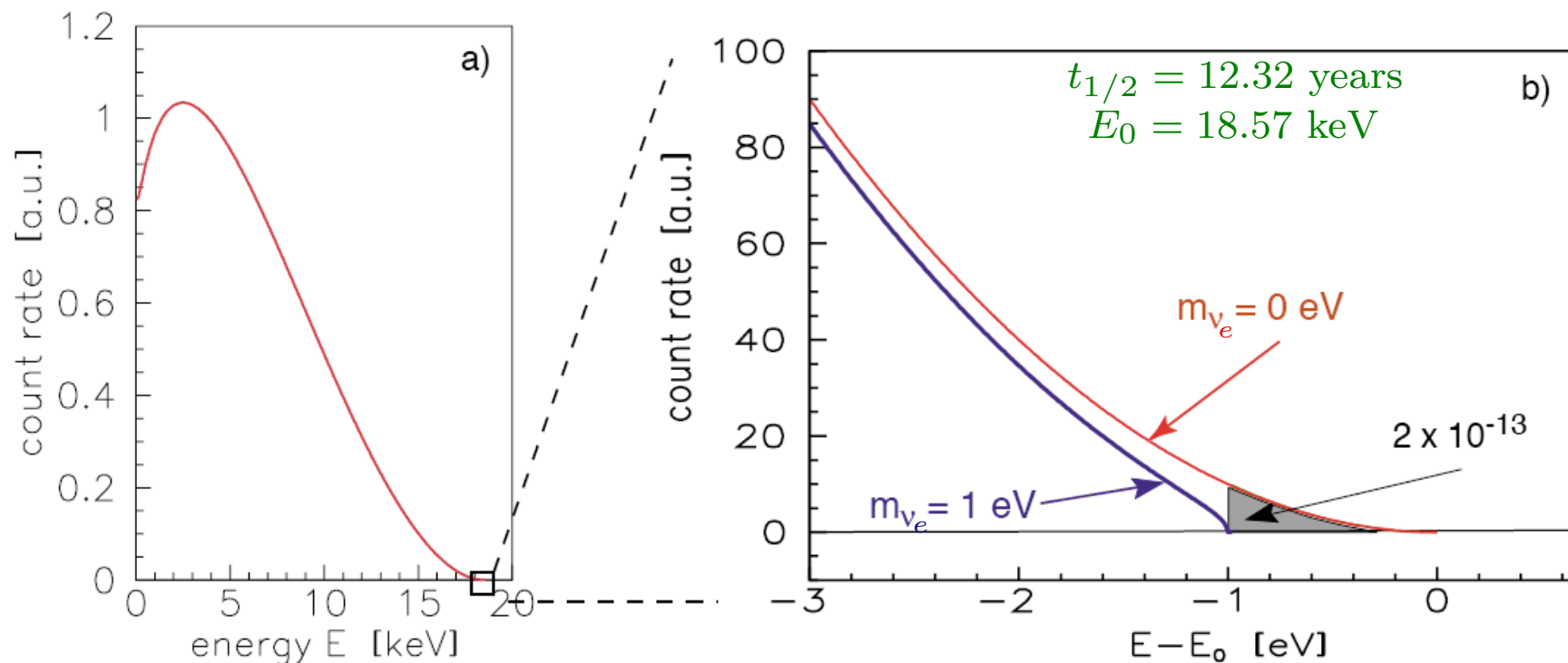


Figure 2: The electron energy spectrum of tritium $\beta$ decay: (a) complete and (b) narrow region around endpoint $E_0$. The $\beta$ spectrum is shown for neutrino masses of 0 and 1 eV.

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

(not your grandmother's table top experiment!)



sensitivity $m_{\nu_e}^2 > (0.2 \text{ eV})^2$

# What We Know We Don't Know: Are Neutrinos Majorana Fermions?
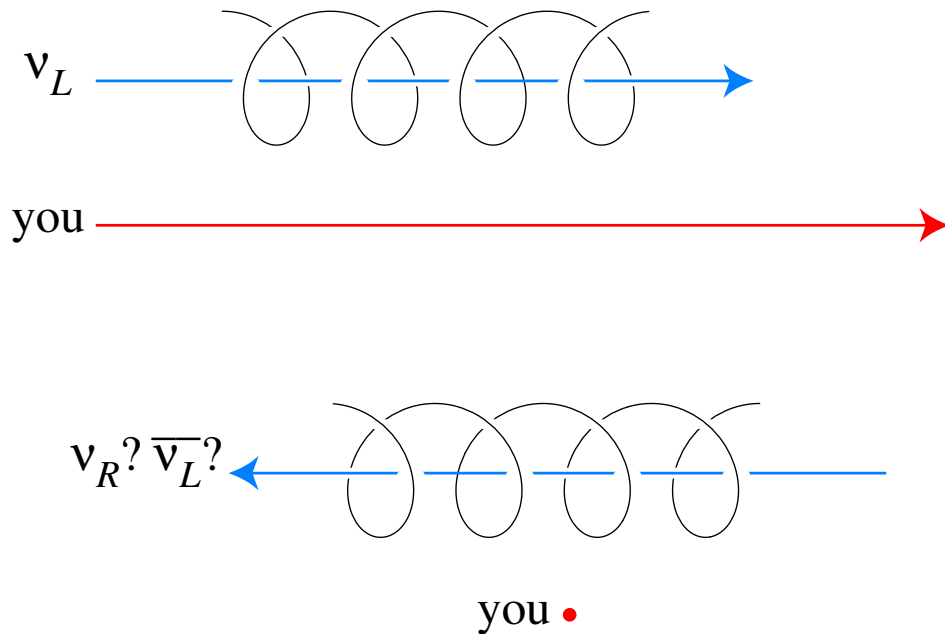
A massive charged fermion (s=1/2) is described by 4 degrees of freedom:

$$(e_L^- \leftarrow \text{CPT} \rightarrow e_R^+)$$

$$\updownarrow \text{"Lorentz"}$$

$$(e_R^- \leftarrow \text{CPT} \rightarrow e_L^+)$$

$\nu_L$ ───────

you ───────────

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

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

$$\updownarrow \text{"Lorentz"} \qquad \text{'DIRAC'}$$

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

$\nu_R? \overline{\nu_L}?$ ◄───────

you •

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

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

'MAJORANA'

$$\updownarrow \text{"Lorentz"}$$

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

# 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 number — including lepton number.

# Searching for 0νββ Decay

Assuming LNV mechanism is light Majorana neutrino exchange and SM interactions (W)

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2 \qquad m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$
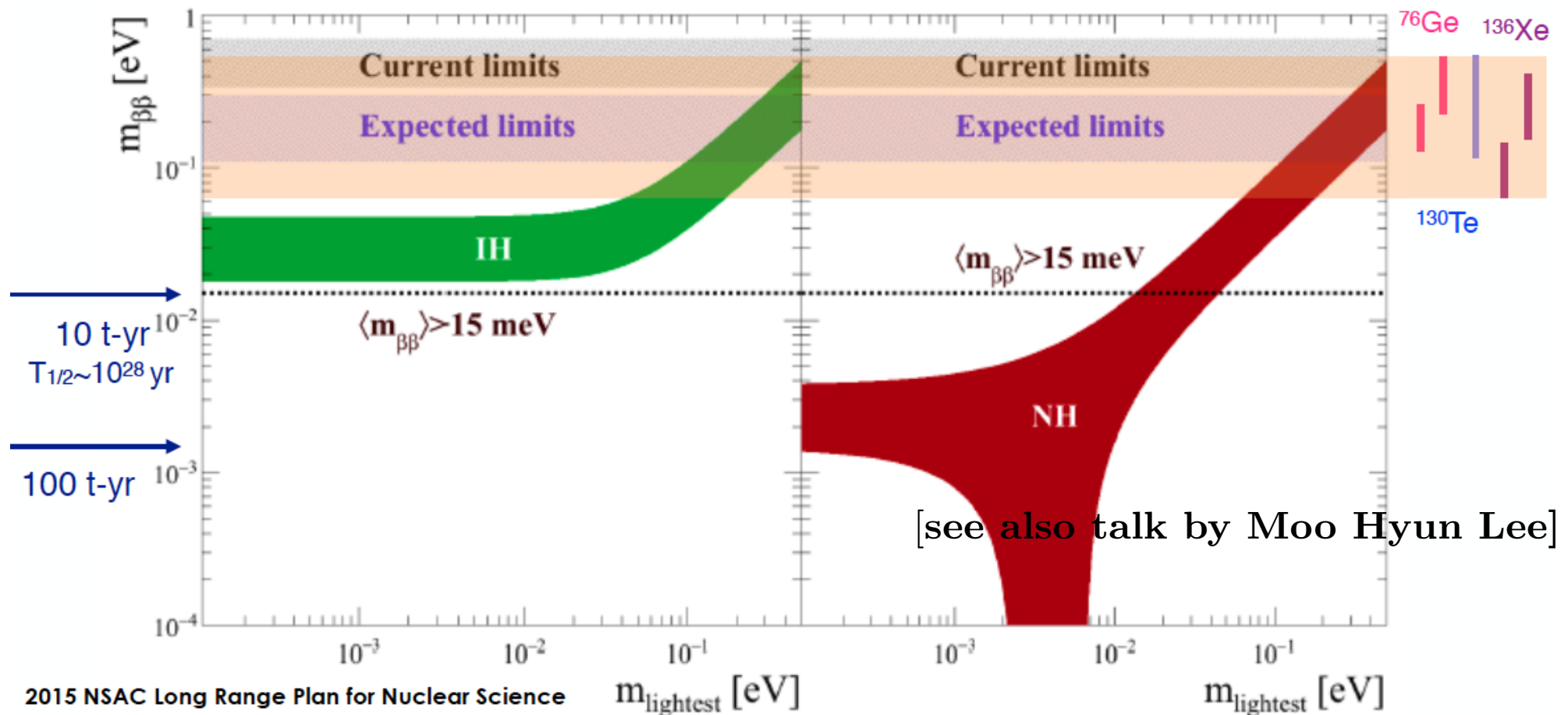


[see also talk by Moo Hyun Lee]

**2015 NSAC Long Range Plan for Nuclear Science**

# 0νββ decay Experiments - ton scale

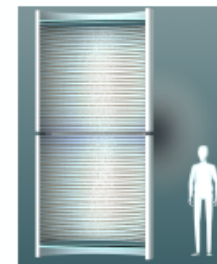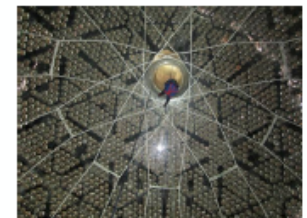| Collaboration | Isotope | Technique | mass (0νββ isotope) | Status |
|---|---|---|---|---|
| GERDA II | Ge-76 | Point contact Ge in LAr | 31 | Operating |
| MAJORANA DEMONSTRATOR | Ge-76 | Point contact Ge | 25 kg | Operating |
| **LEGEND** | Ge-76 | Point contact with active veto | **∼ ton** | R&D |
| | | | | |
| **CUORE** | Te-130 | TeO$_2$ Bolometer | **206 kg** | Operating |
| **CUPID** | Te-130 | TeO$_2$ Bolometer & scint. | **∼ ton** | R&D |
| **SNO+** | Te-130 | 0.3% $^{nat}$Te suspended in Scint | **160 kg** | Constr./Commish |
| | | | | |
| EXO200 | Xe-136 | Xe liquid TPC | 79 kg | Operating |
| **nEXO** | Xe-136 | Xe liquid TPC | **∼ ton** | R&D |
| **KamLAND-Zen (I, II)** | Xe-136 | 2.7% in liquid scint. | **380 kg** | Complete |
| **KamLAND2-Zen** | Xe-136 | 2.7% in liquid scint. | **800 kg** | Upgrade |
| **NEXT** | Xe-136 | High pressure Xe TPC | ∼ton | Const. NEXT-100 |
| **PandaX - III** | Xe-136 | High pressure Xe TPC | ∼ ton | |
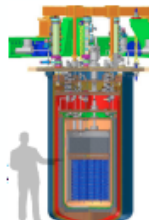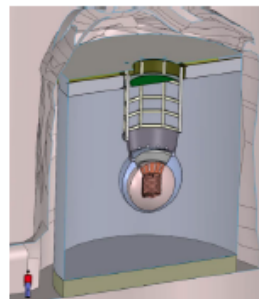


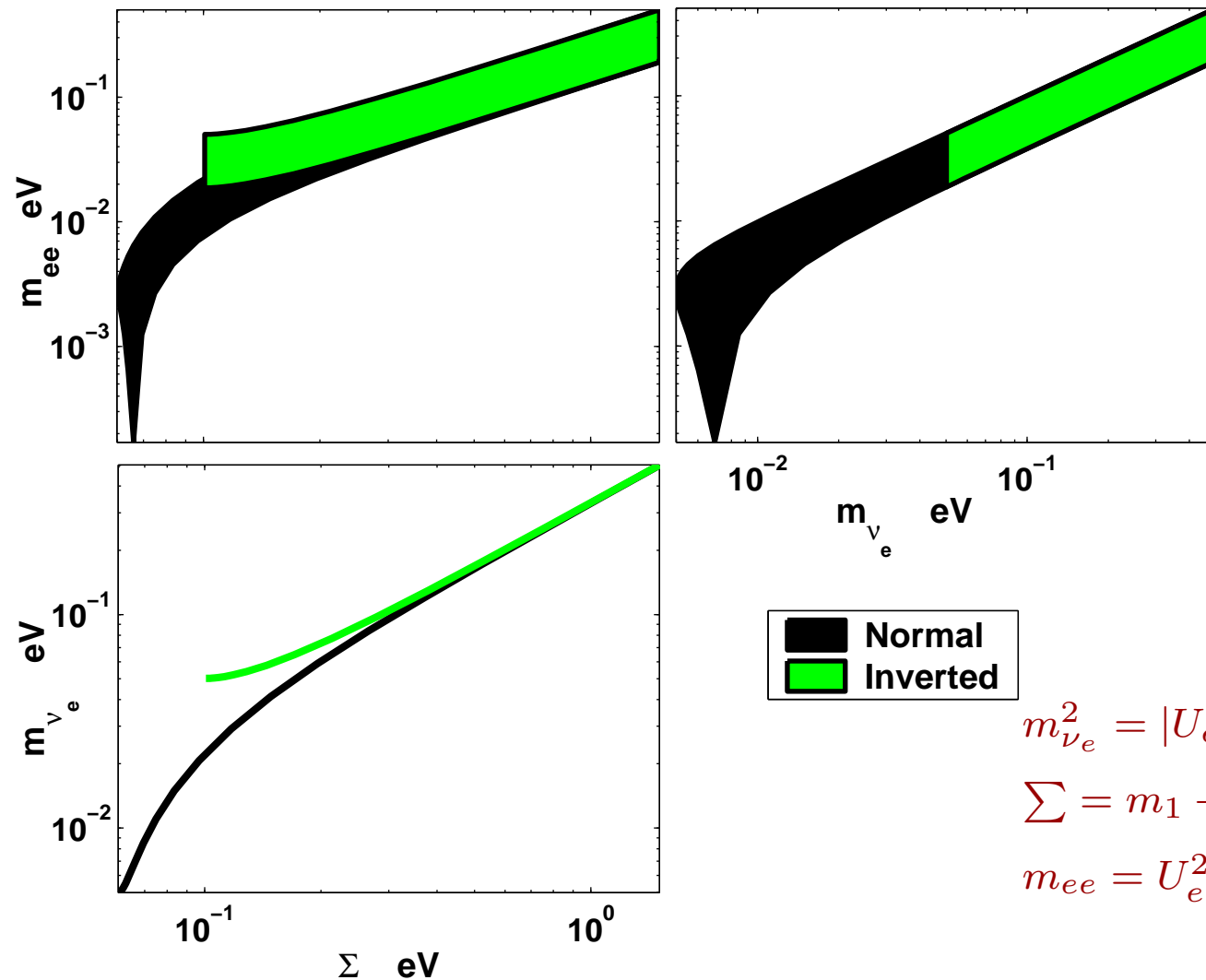KamLAND Zen   CUPID   nEXO   PandaX-III   LEGEND   NEXT   SNO+
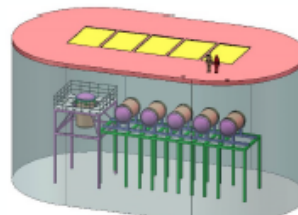
Neutrino Properties and Cosmology – A Few Comments and Questions

- Cosmological observables offer a unique opportunity to learn about neutrino properties. Reach superior to that of lab experiments – but think complementarity!

- Main issue: how do we know we are learning about neutrinos?
  - What if there is something out there mimicking neutrinos?
  - Systematics: results seem to fluctuate depending on which observables are being used, which assumptions are being made.
  - "Robustness" of result. Can we trust a positive result?

- Will we learned about neutrinos from cosmology, or about cosmology from neutrinos?

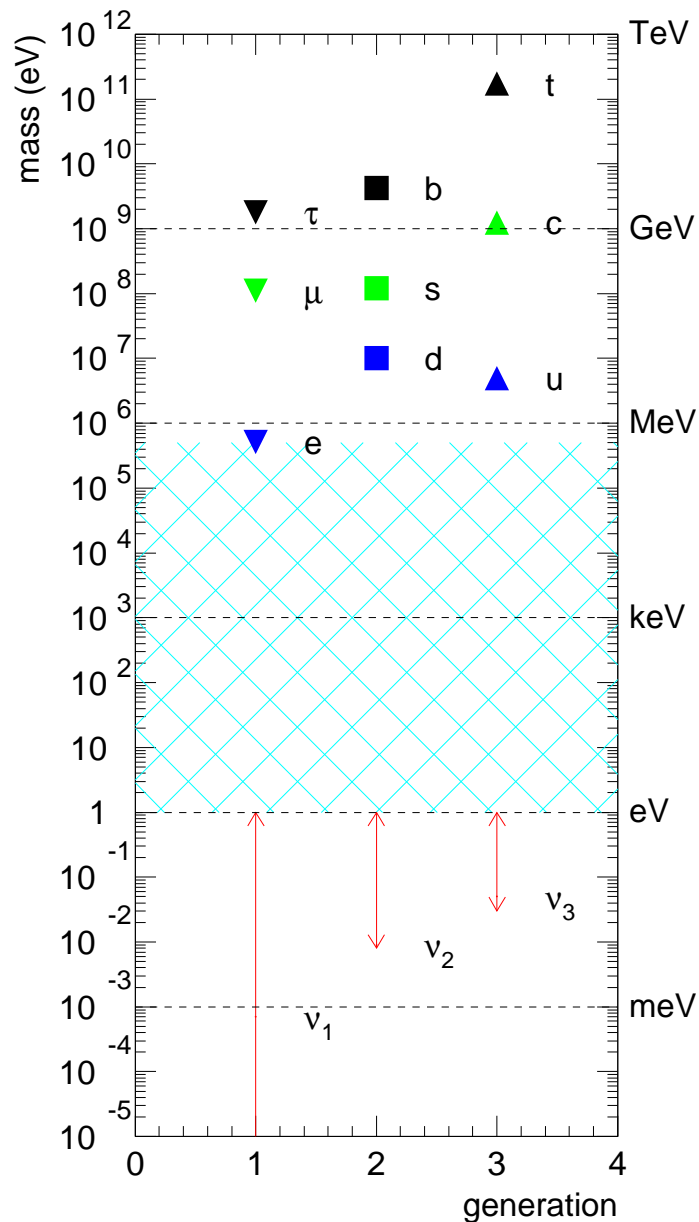# Combining the Different Neutrino Mass Observables – Fundamental



[Illustrative only, for $U_{e3} = 0$, $\Delta m_{13}^{2+} = +2.50 \times 10^{-3}$ eV$^2$, $\Delta m_{13}^{2-} = -2.44 \times 10^{-3}$ eV$^2$]

$$m_{\nu_e}^2 = |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2$$

$$\sum = m_1 + m_2 + m_3$$

$$m_{ee} = U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3$$

## What We Are Trying To Understand:

$\Leftarrow$ **NEUTRINOS HAVE TINY MASSES**

$\Downarrow$ **LEPTON MIXING IS "WEIRD"** $\Downarrow$

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

### What Does It Mean?

# 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? [$\nu$SM]

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 $\nu$SM candidates can do. [are they falsifiable?, are they "simple"?, do they address other outstanding problems in physics?, etc]

We need more experimental input.

# One Candidate $\nu$SM

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!

- $\nu$SM effective theory – not valid for energies above *at most* $\Lambda/y$.

- Define $y_{\text{max}} \equiv 1 \Rightarrow$ 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

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

where $N_i$ ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions.

$\mathcal{L}_\nu$ 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.**

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[a]Only requires the introduction of three fermionic degrees of freedom, no new interactions or symmetries.

<span style="color:red">**To be determined from data: $\lambda$ and $M$.**</span>

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

<span style="color:darkred">This provides very little information concerning the magnitude of $M_i$ (assume $M_1 \sim M_2 \sim M_3$).</span>

<span style="color:green">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).</span>

<span style="color:green">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.</span>

<span style="color:green">**we can impose very, very few experimental constraints on $M$**</span>

# (      **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").

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# Constraining the Seesaw Lagrangian
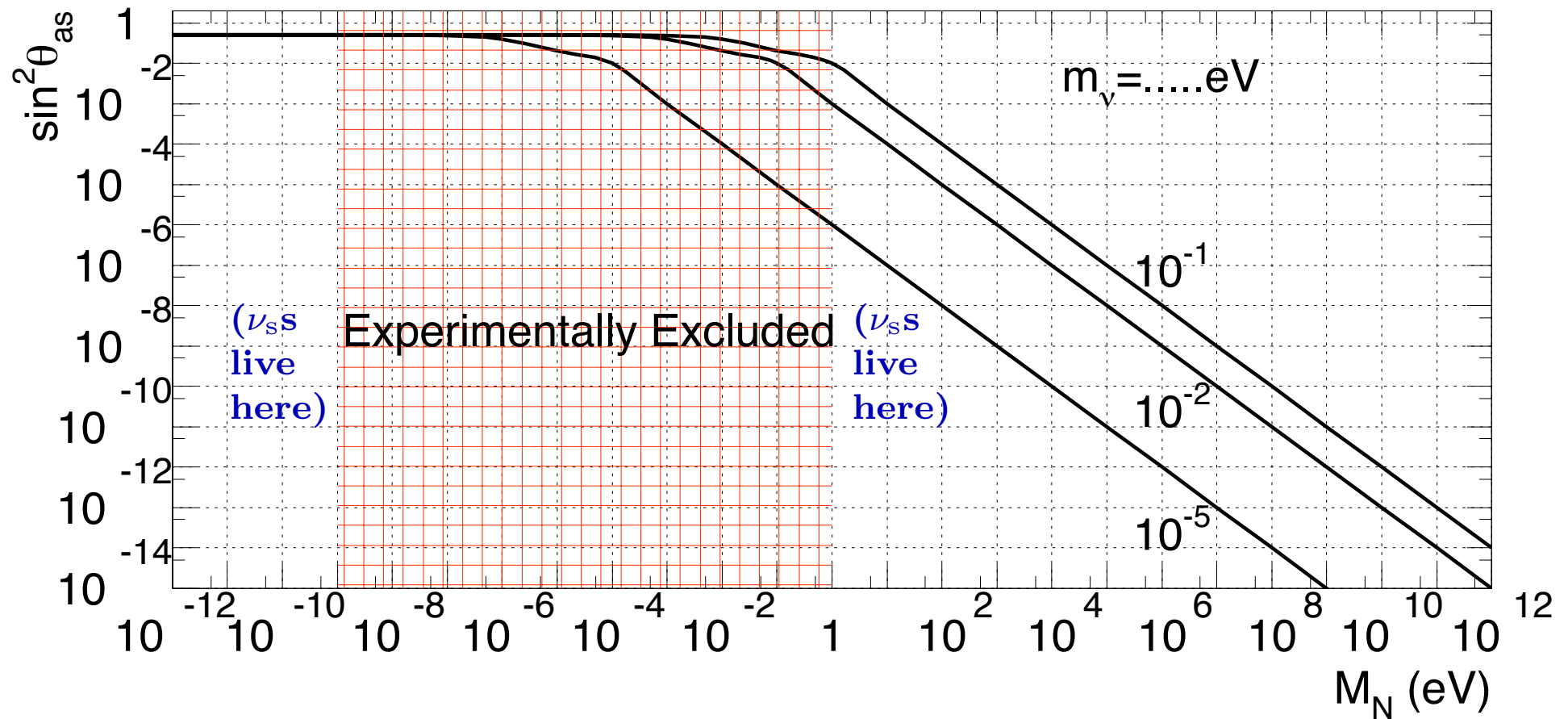


[AdG, Huang, Jenkins, arXiv:0906.1611]

# Dirac Neutrinos – Enhanced Symmetry!(Symmetries?)

If all $M_i \equiv 0$, the neutrinos are Dirac fermions.

$$\mathcal{L}_\nu = \mathcal{L}_{\text{old}} - \lambda_{\alpha i} L^\alpha H N^i + H.c.,$$

where $N_i$ ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions. In this case, the $\nu$SM global symmetry structure is enhanced. For example, $U(1)_{B-L}$ is an exactly conserved, global symmetry. This is new!

Downside: The neutrino Yukawa couplings $\lambda$ are tiny, less than $10^{-12}$. What is wrong with that? We don't like tiny numbers, but Nature seems to not care very much about what we like. . .

More to the point, the failure here is that it turns out that the neutrino masses are not, trivially, qualitatively different. This seems to be a "missed opportunity."

There are lots of ideas that lead to very small Dirac neutrino masses.

Maybe right-handed neutrinos exist, but neutrino Yukawa couplings are forbidden – hence neutrino masses are tiny.

One possibility is that the $N$ fields are charged under some new symmetry (gauged or global) that is spontaneously broken.

$$\lambda_{\alpha i} L^\alpha H N^i \to \frac{\kappa_{\alpha i}}{\Lambda} (L^\alpha H)(N^i \Phi),$$

where $\Phi$ (spontaneously) breaks the new symmetry at some energy scale $v_\Phi$. Hence, $\lambda = \kappa v_\Phi / \Lambda$. How do we test this?

E.g., AdG and D. Hernández, arXiv:1507.00916

Gauged chiral new symmetry for the right-handed neutrinos, no Majorana masses allowed, plus a heavy messenger sector. Predictions: new stable massive states (mass around $v_\Phi$) which look like (i) dark matter, (ii) (Dirac) sterile neutrinos are required. Furthermore, there is a new heavy $Z'$-like gauge boson.

$\Rightarrow$ Natural Conections to Dark Matter, Sterile Neutrinos, Dark Photons!

# 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:

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & {}_{0.001} \\ 0.2 & 1 & {}_{0.01} \\ {}_{0.001} & {}_{0.01} & 1 \end{pmatrix} \qquad \boxed{\text{WHY?}}$$
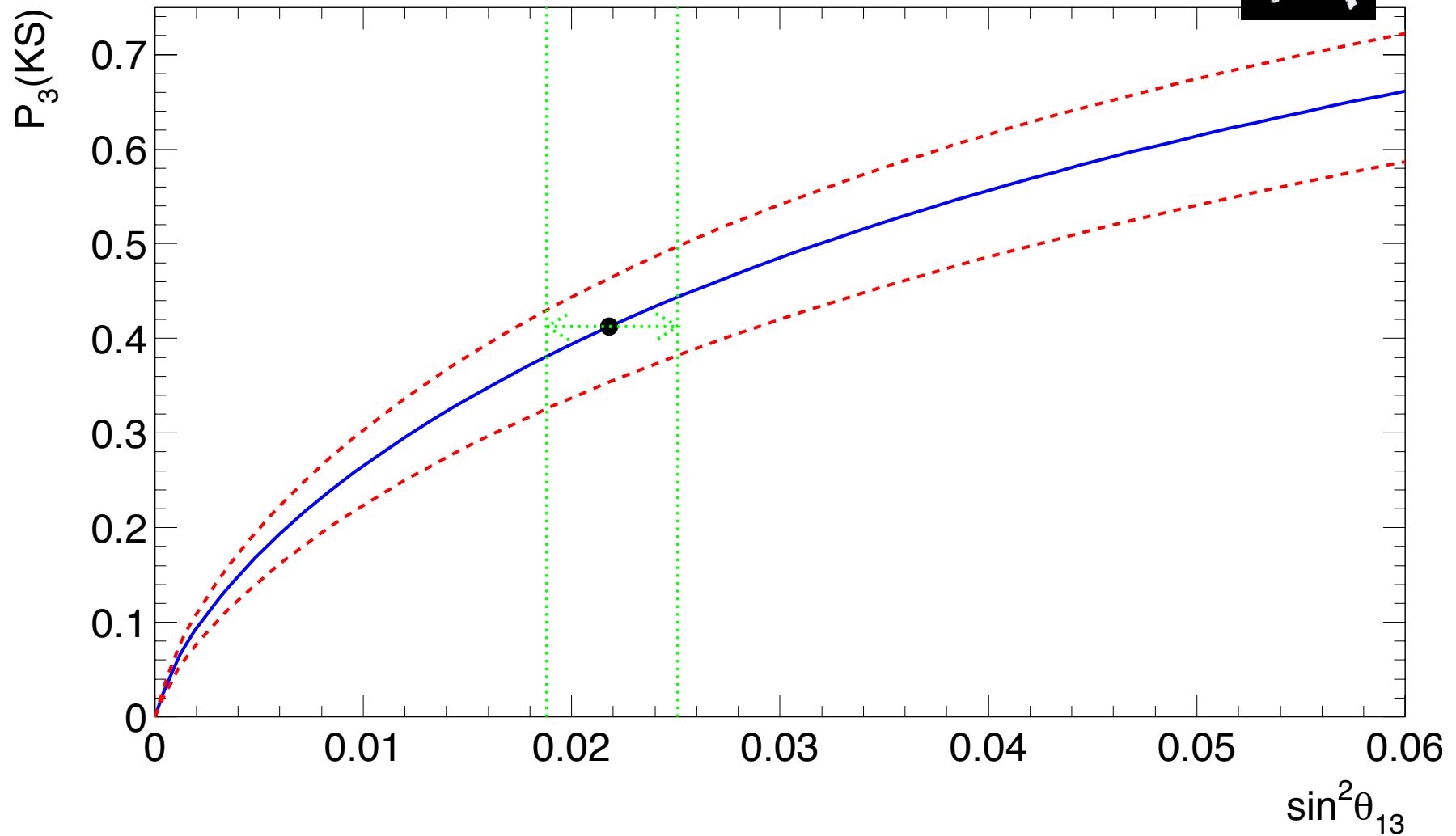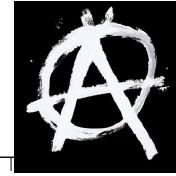
$$[|(V_{MNS})_{e3}| < 0.2]$$

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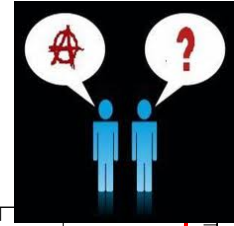
as "strange"?

# Neutrino Mixing Anarchy: Alive and Kicking!

[Hall, Murayama, Weiner hep-ph/9911341]



[AdG, Murayama, 1204.1249]

## Anarchy vs. Order — more precision required!
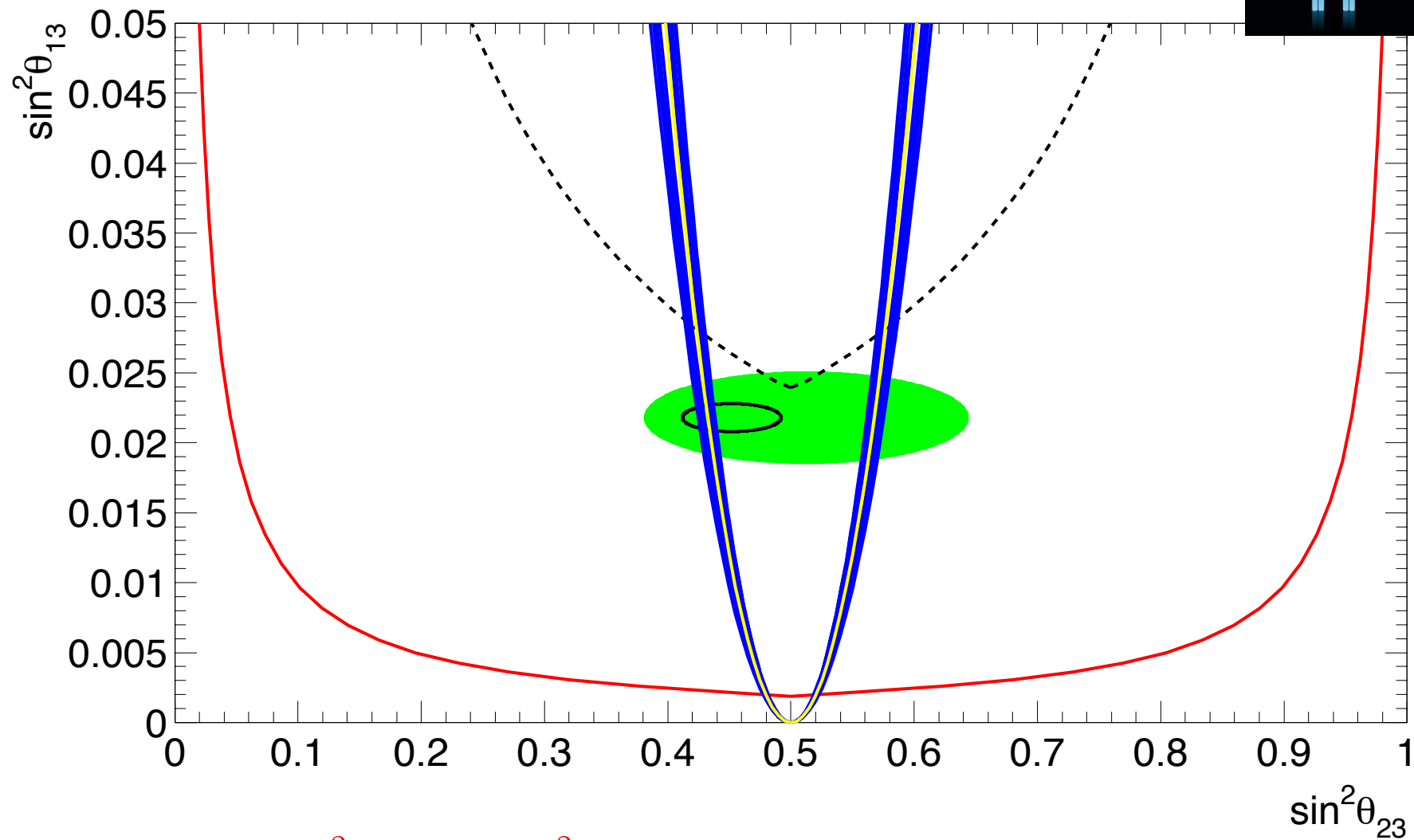


Order: $\sin^2\theta_{13} = C\cos^2 2\theta_{23}$, $C \in [0.8, 1.2]$     [AdG, Murayama, 1204.1249]

The plot axes are $\sin^2\theta_{23}$ (horizontal) and $\sin^2\theta_{13}$ (vertical).

# 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 ($\mu \to e$-conversion the best bet at the moment).

- collider experiments. The LHC and beyond may end up revealing the new physics behind small neutrino masses.

- 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.

# In Conclusion

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

1. We know very little about the new physics uncovered by neutrino oscillations.

   - It could be renormalizable → "boring" (?) Dirac neutrinos.
   - It could be due to Physics at absurdly high energy scales $M \gg 1$ TeV → 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 → 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 $\nu$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).
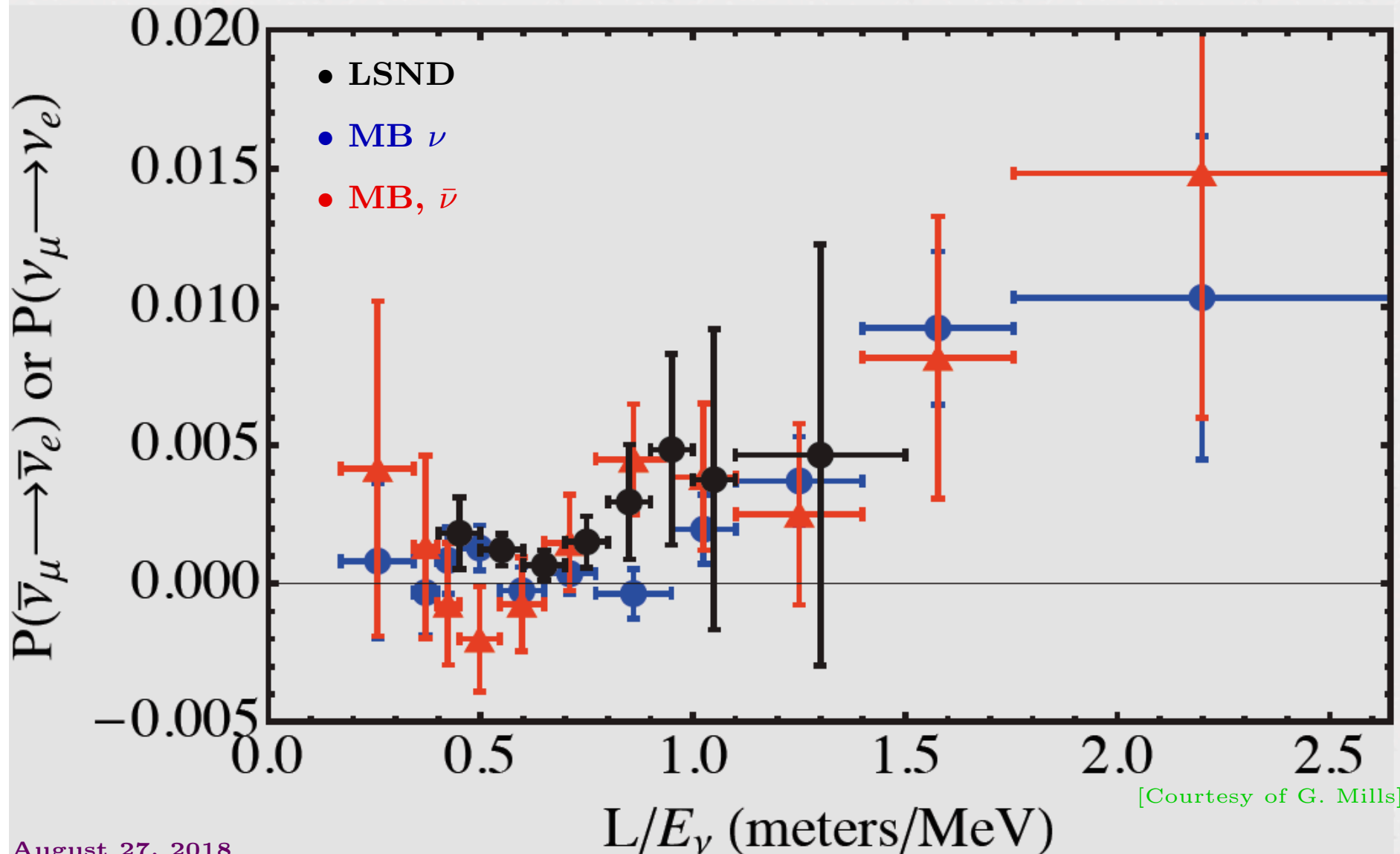
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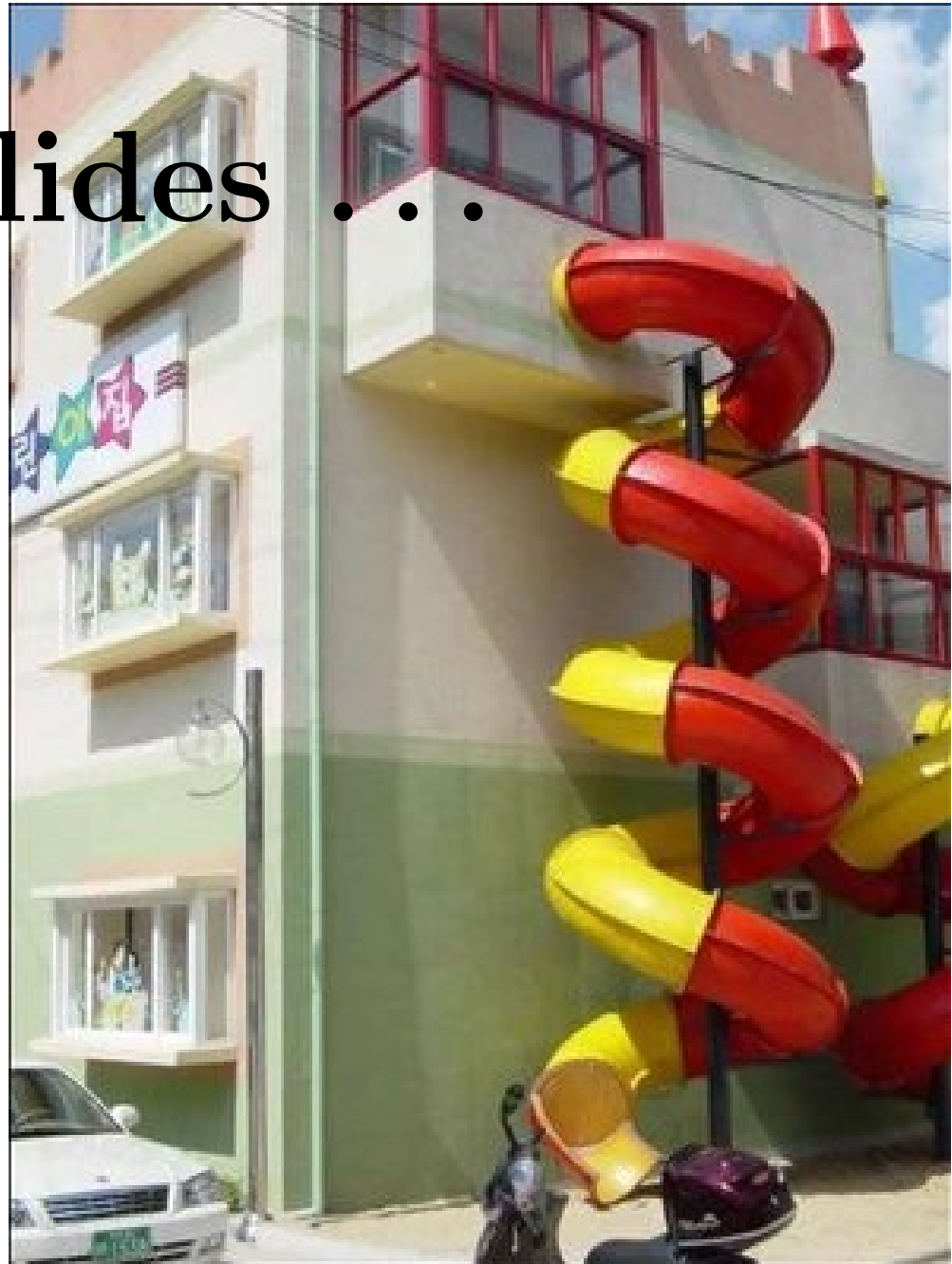
# Not all is well(?): The Short Baseline Anomalies

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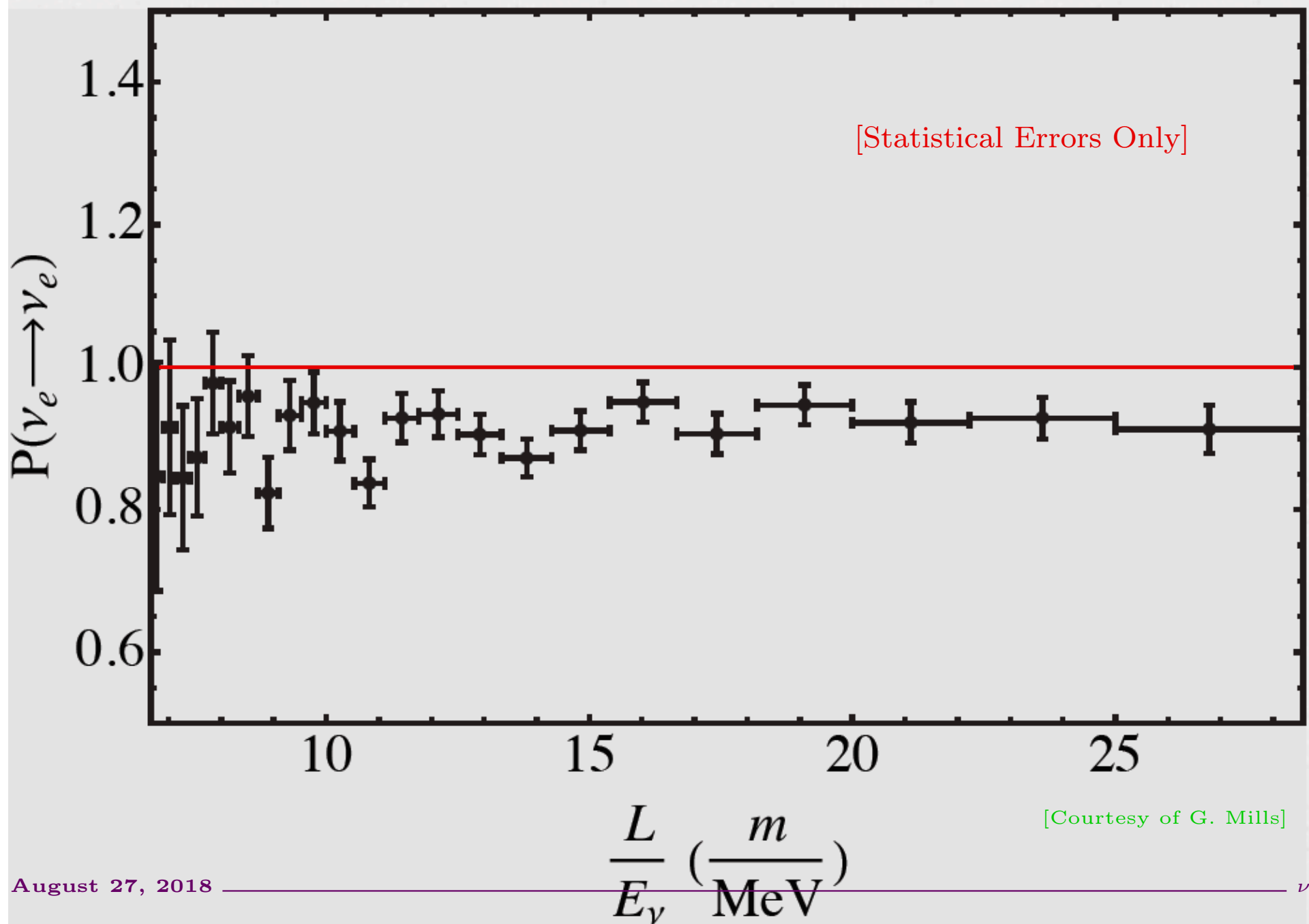
- $\nu_\mu \to \nu_e$ appearance — LSND, MiniBooNE;

- $\nu_e \to \nu_{\text{other}}$ disappearance — radioactive sources;

- $\bar{\nu}_e \to \bar{\nu}_{\text{other}}$ disappearance — reactor experiments.

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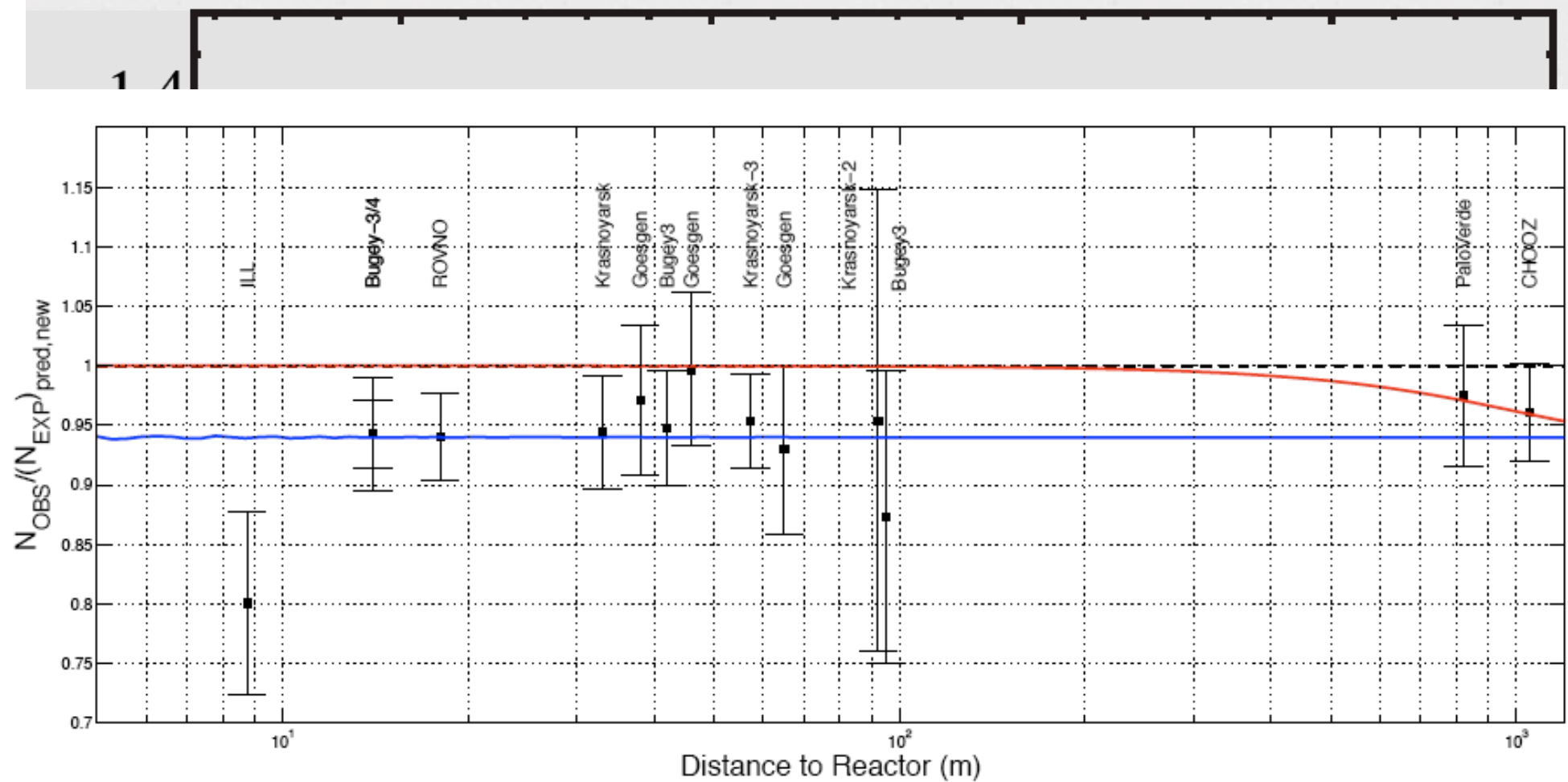
# MiniBooNE & LSND

# Bugey 40 m



[Statistical Errors Only]

$P(\nu_e \longrightarrow \nu_e)$

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

[Courtesy of G. Mills]

August 27, 2018

$\nu$s

# Bugey 40 m



Plot axes: $N_{OBS}/(N_{EXP})_{pred,new}$ versus Distance to Reactor (m), with data points labeled ILL, Bugey-3/4, ROVNO, Krasnoyarsk, Goesgen, Bugey3, Goesgen, Krasnoyarsk-3, Goesgen, Krasnoyarsk-2, Bugey3, PaloVerde, CHOOZ.

Lower axis:

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

with values 10, 15, 20, 25.

# 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:

- $\nu_\mu$ disappearance (and antineutrino);

- $\nu_e$ 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 $\nu$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, $\boxed{\mathcal{L} \supset -y_{i\alpha}L^iHN^\alpha - \frac{M_N^{\alpha\beta}}{2}N_\alpha N_\beta + H.c.}$
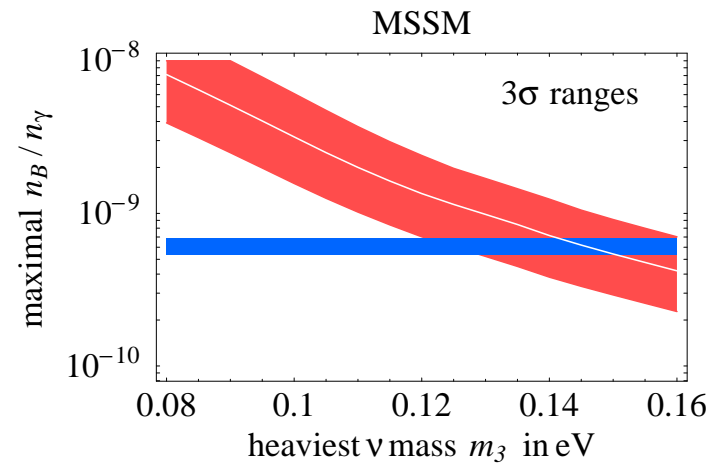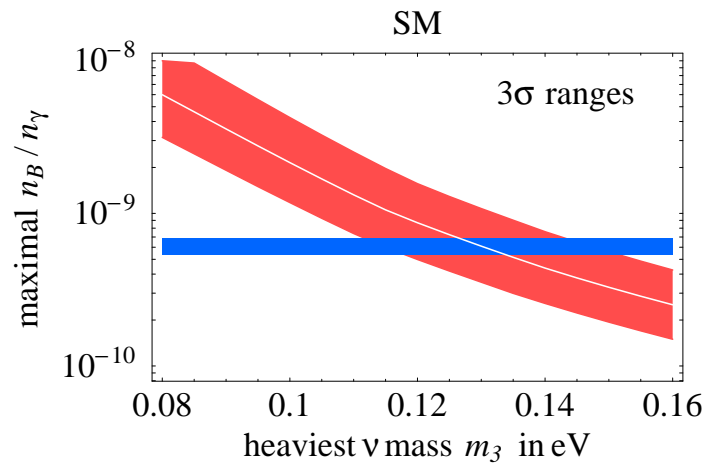
[Fukugita, Yanagida]
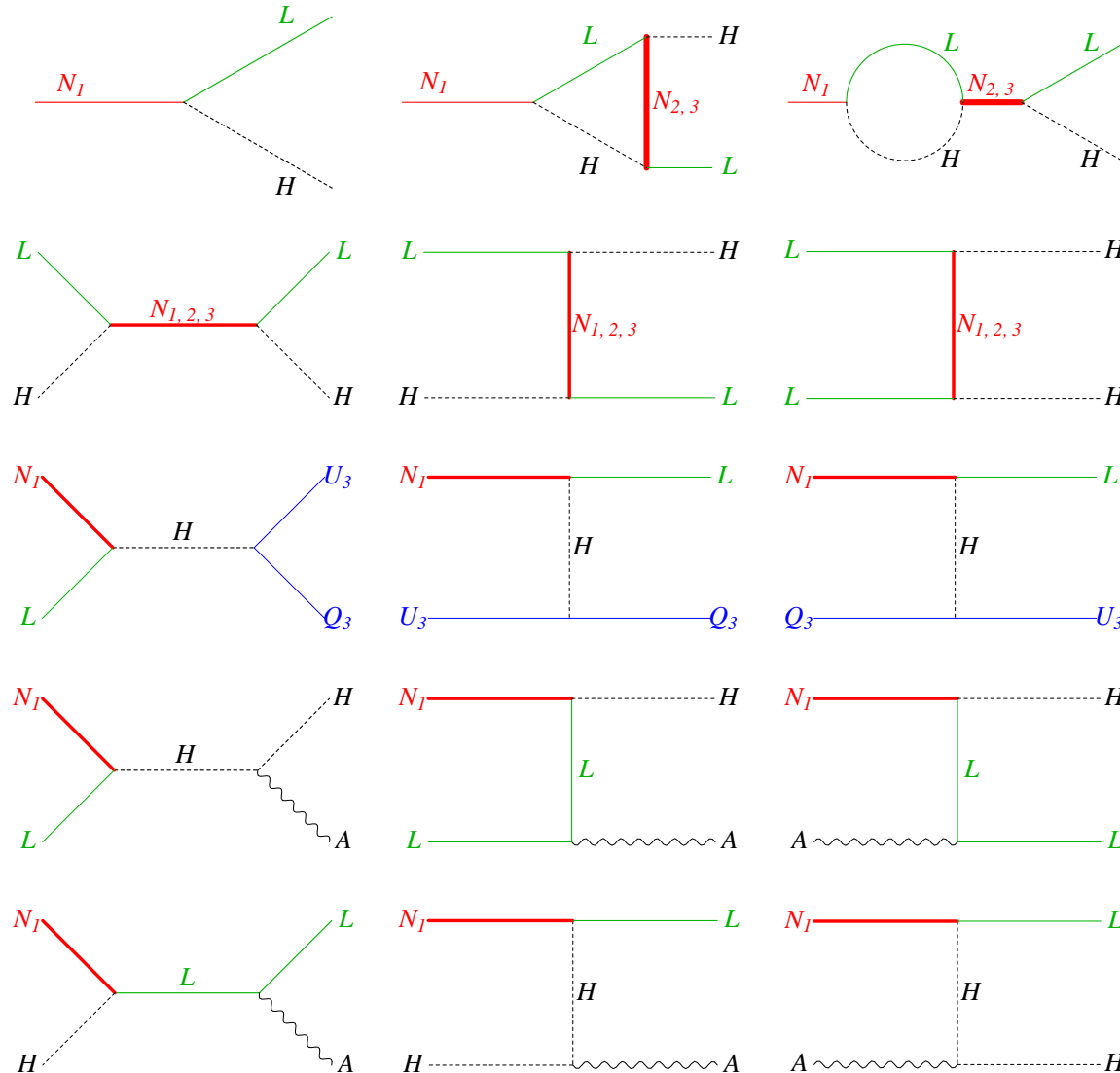
- L-violating processes

- $y \Rightarrow$ CP-violation

- deviation from thermal eq. constrains combinations of $M_N$ and $y$.

- need to yield correct $m_\nu$

not trivial!

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

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



SM

MSSM

[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...)