Neutrino Mass: a Particle Physics Perspective

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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.

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.

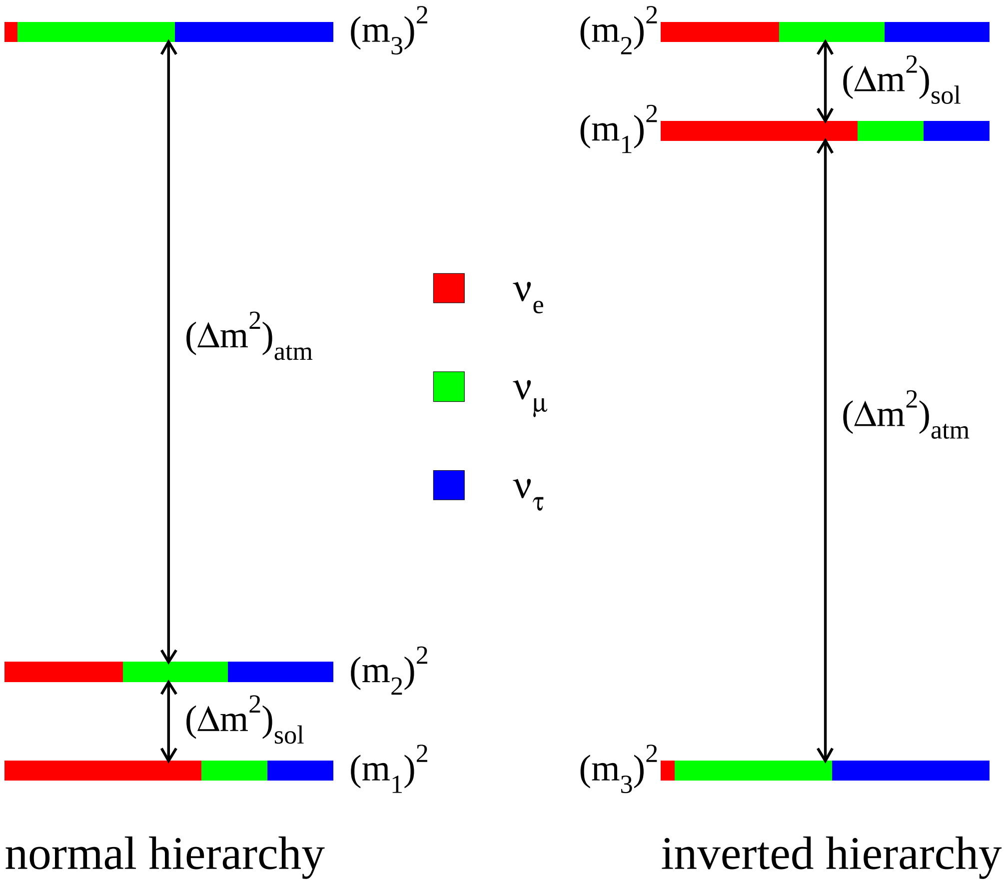
NuFIT 3.2 (2018)

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

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

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

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

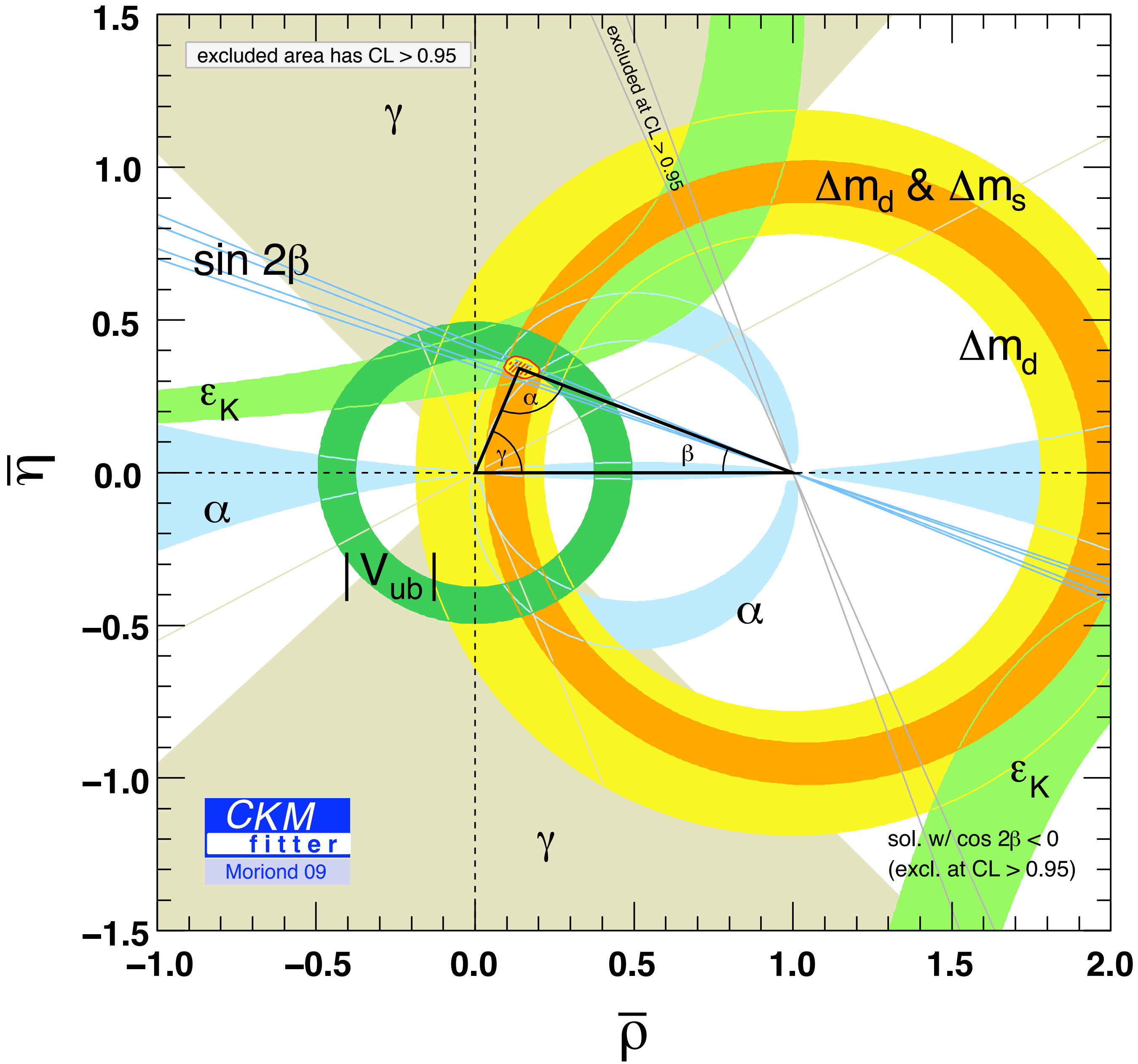


- ~~What is the ν_e component of ν_3?~~ ($\theta_{13} \neq 0$!)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?) ['yes' hint]
- Is ν_3 mostly ν_μ or ν_τ? [$\theta_{23} \neq \pi/4$ hint]
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?) [NH weak hint]

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

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

What we ultimately want to achieve:



We need to do this in the lepton sector!

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

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

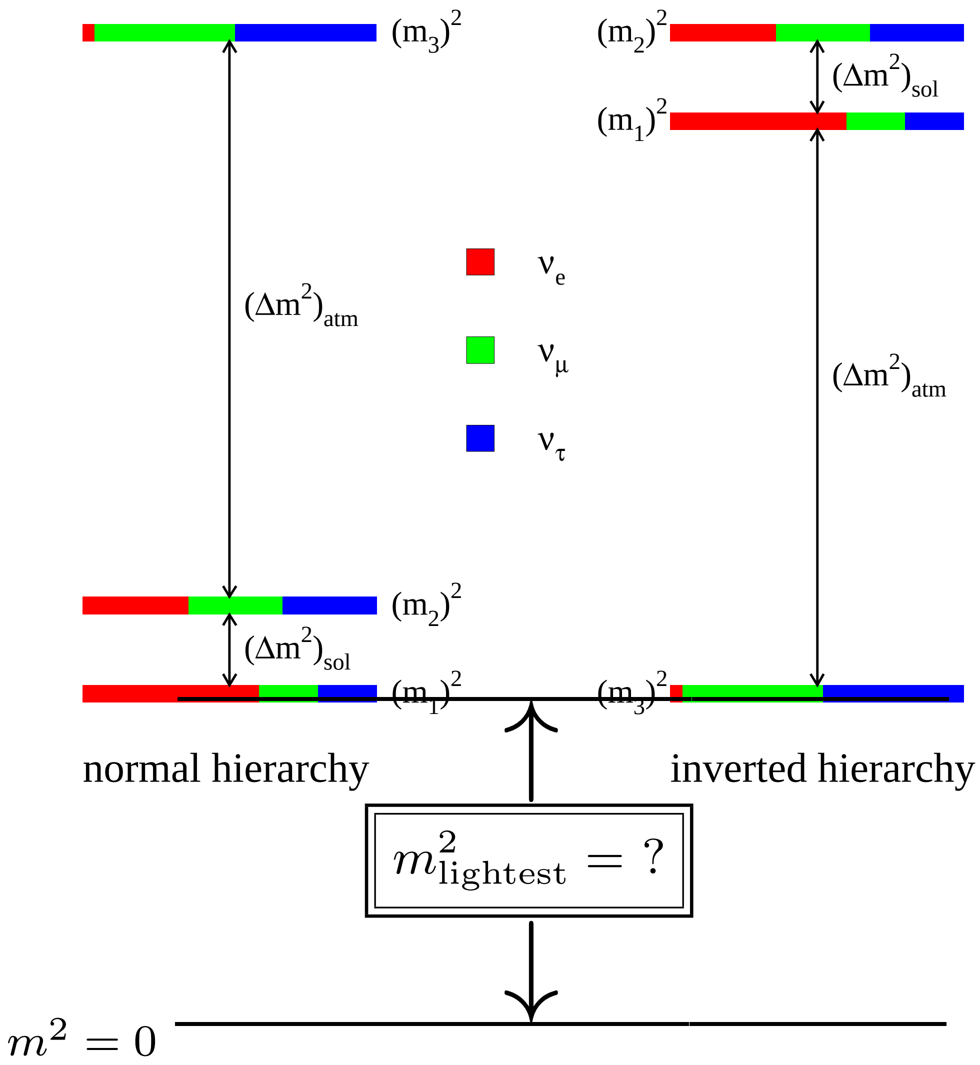
- Two mass-squared differences, at several percent level – many probes;
- $|U_{e2}|^2$ – solar data;
- $|U_{\mu2}|^2 + |U_{\tau2}|^2$ – solar data;
- $|U_{e2}|^2|U_{e1}|^2$ – KamLAND;
- $|U_{\mu3}|^2(1-|U_{\mu3}|^2)$ – atmospheric data, K2K, MINOS;
- $|U_{e3}|^2(1-|U_{e3}|^2)$ – Double Chooz, Daya Bay,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

We still have a ways to go!

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

- [NOW] T2K (Japan), NOνA (USA) – $\nu_\mu \to \nu_e$ appearance, ν_μ disappearance – precision measurements of “atmospheric parameters” ($\Delta m^2_{13}, \sin^2\theta_{23}$). 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” ($\Delta m^2_{12}, \sin^2\theta_{12}$). 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?



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, $0\nu\beta\beta$

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":

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

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!

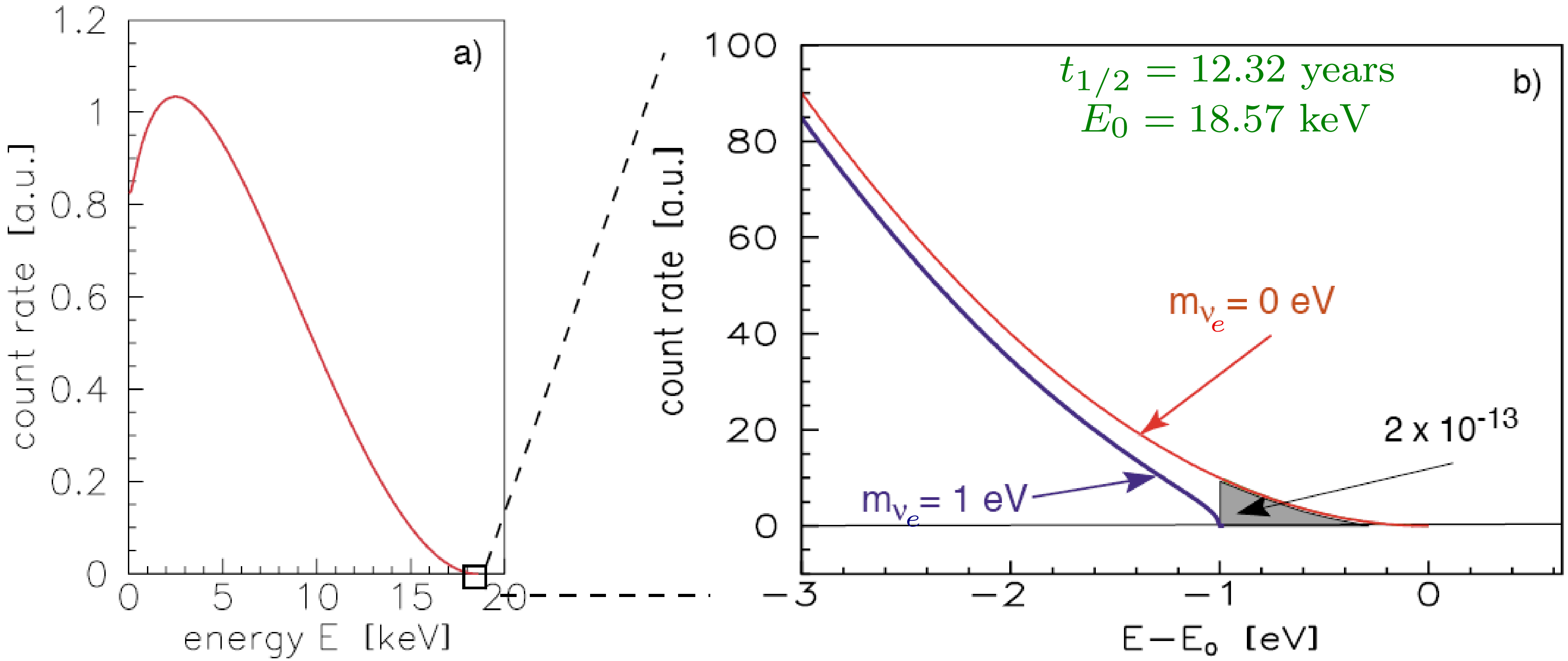


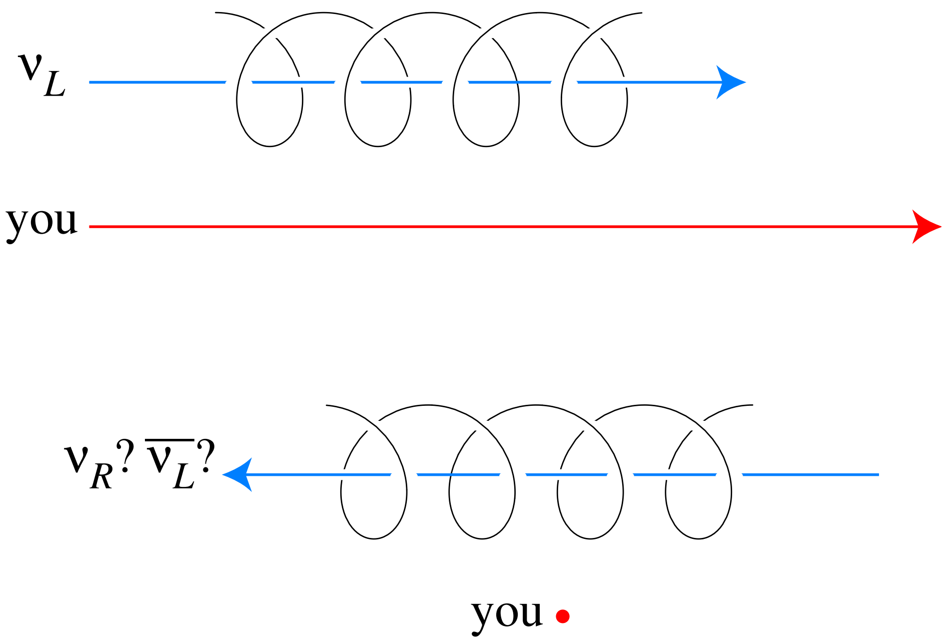
Figure 2: The electron energy spectrum of tritium β decay: (a) complete and (b) narrow region around endpoint E_0. The β spectrum is shown for neutrino masses of 0 and 1 eV.

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

(not your grandmother's table top experiment!)

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

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:

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

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

$$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$$
$$\updownarrow \text{“Lorentz”} \qquad \text{‘DIRAC’}$$
$$(\nu_R \leftarrow \text{CPT} \rightarrow \bar{\nu}_L)$$

‘MAJORANA’

$$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$$
$$\updownarrow \text{“Lorentz”}$$
$$(\bar{\nu}_R \leftarrow \text{CPT} \rightarrow \nu_L)$$

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

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: $A \propto m_\nu/E$.

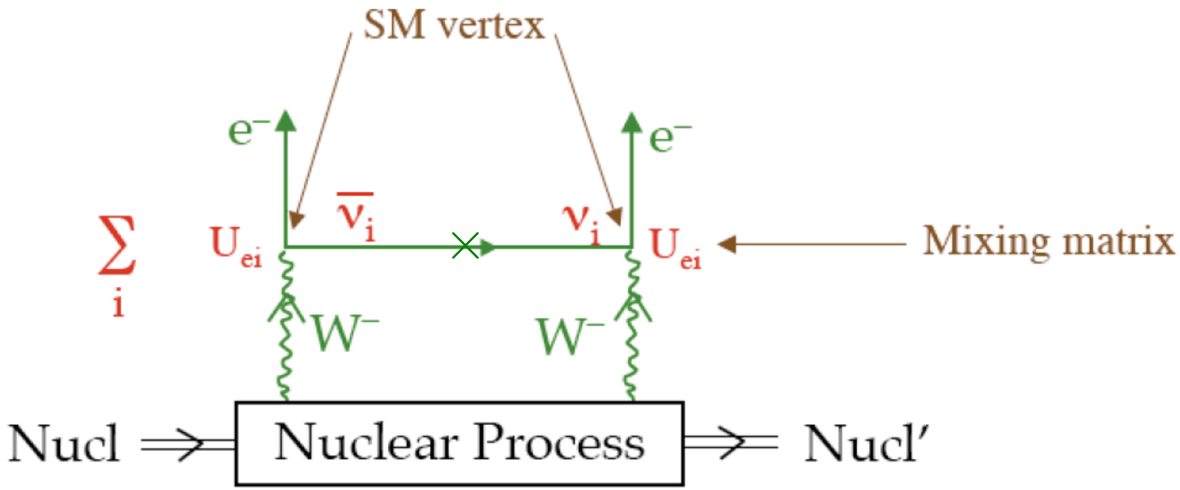
The "smoking gun" signature is the observation of LEPTON NUMBER violation. This is easy to understand: Majorana neutrinos are their own antiparticles and, therefore, cannot carry **any** quantum number — including lepton number.

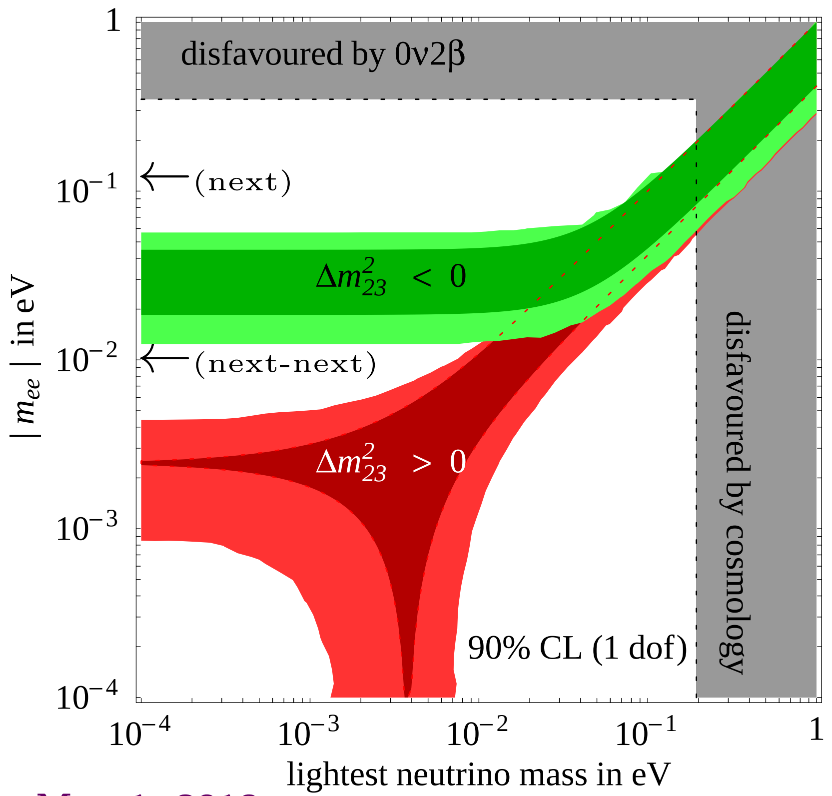
Search for the Violation of Lepton Number (or $B-L$)

Best Bet: search for

Neutrinoless Double-Beta

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





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

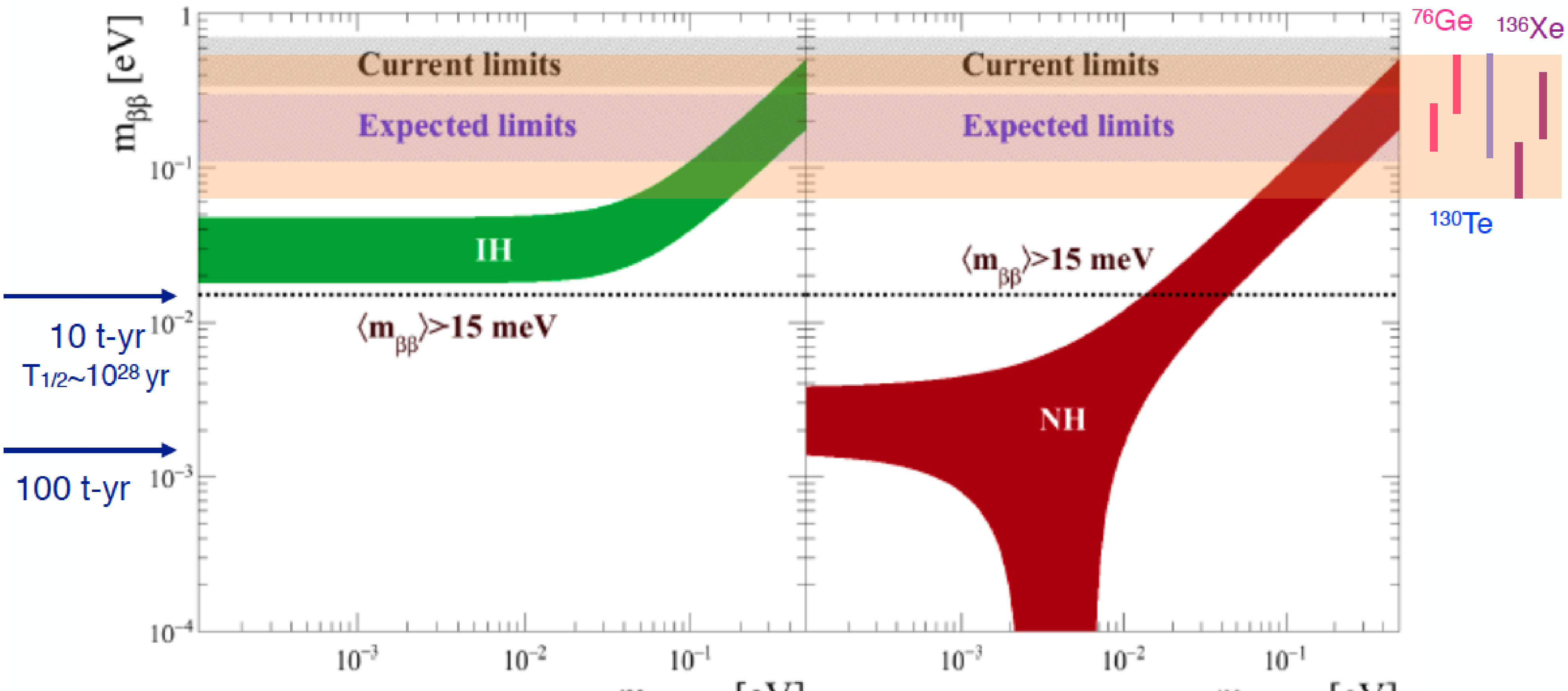
Observable: $m_{ee} \equiv \sum_i U_{ei}^2 m_i$

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

Searching for 0νββ Decay

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

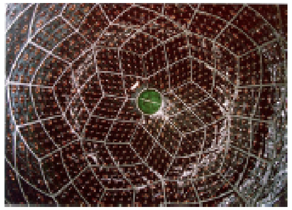
$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2 \qquad m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

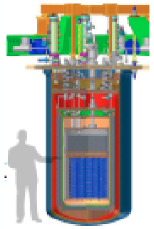


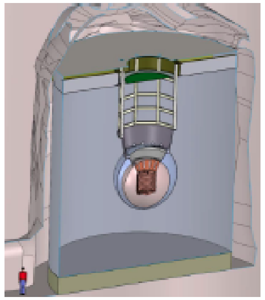
2015 NSAC Long Range Plan for Nuclear Science

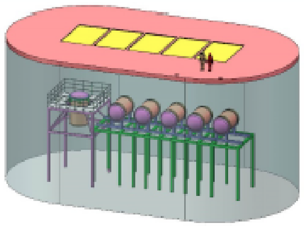
0νββ decay Experiments - ton scale

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**	

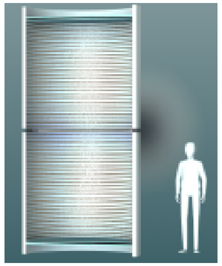

KamLAND Zen

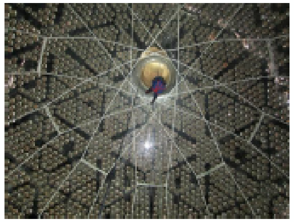

CUPID


nEXO


PandaX-III


LEGEND

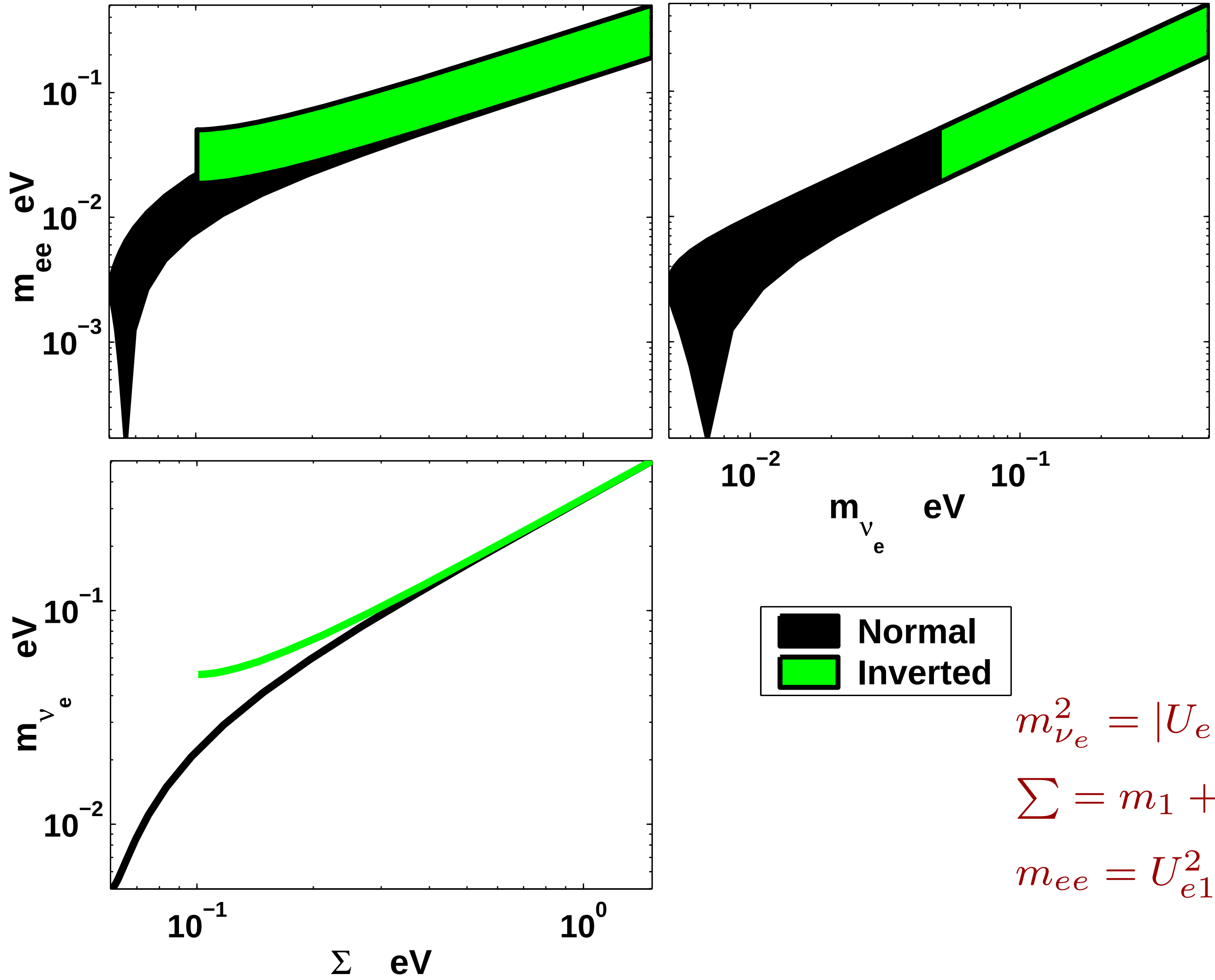

NEXT


SNO+

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

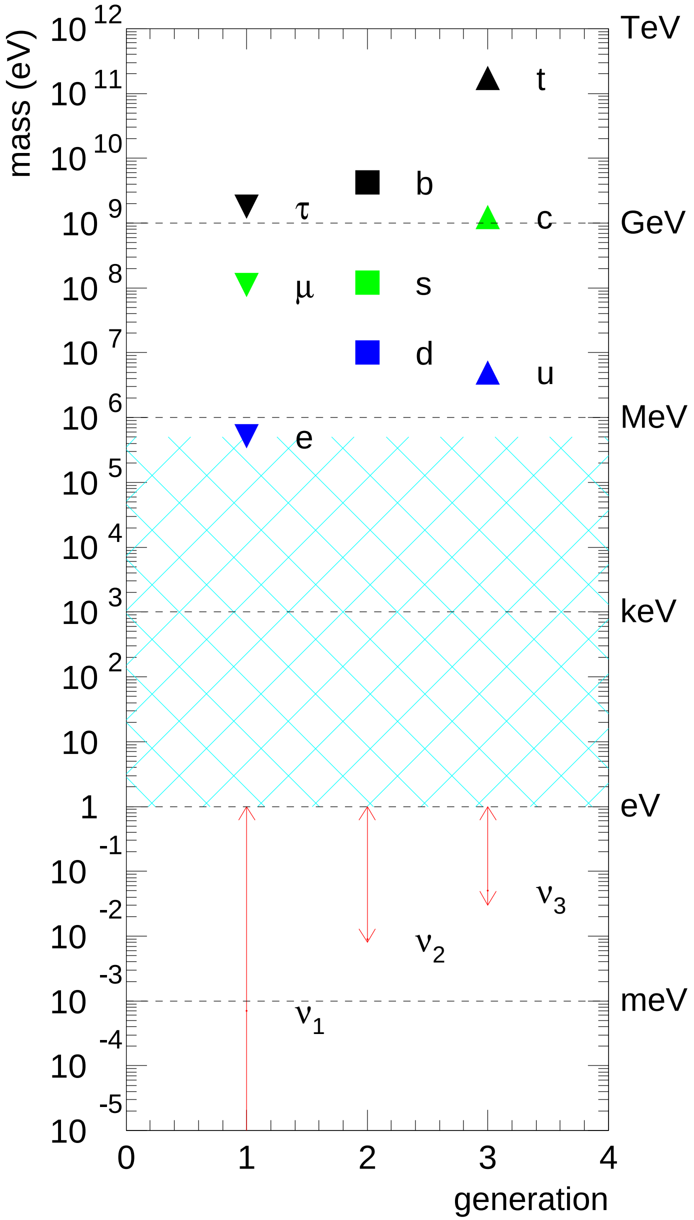


$$m^2_{\nu_e} = |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2$$

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

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

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



What We Are Trying To Understand:

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

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

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

$\boxed{\textbf{What Does It Mean?}}$

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.

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* 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]

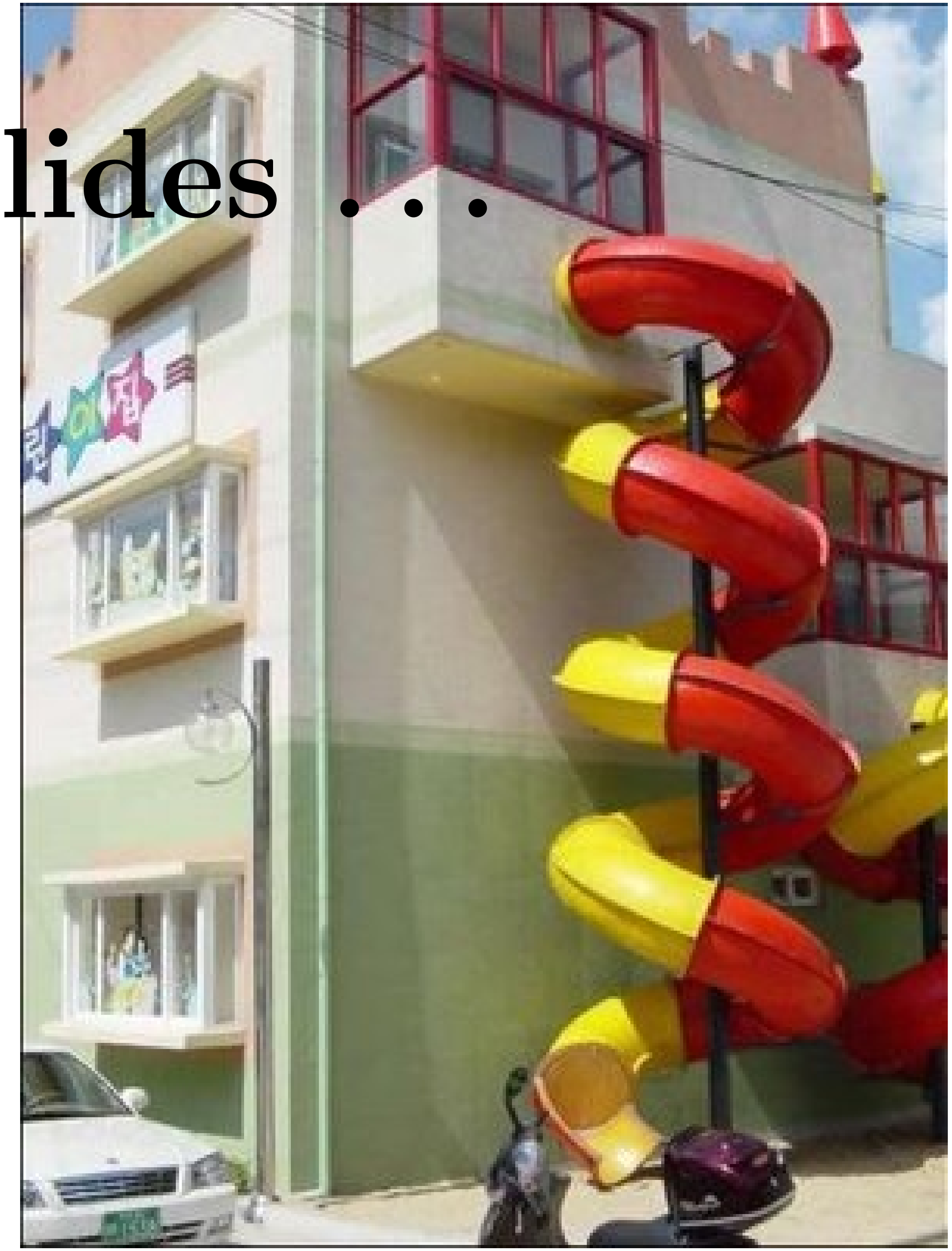
We need more experimental input.

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. (On-going T2K and $NO\nu$A. DUNE and HyperK next 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). Unique access to some neutrino properties!**

Backup Slides . . .



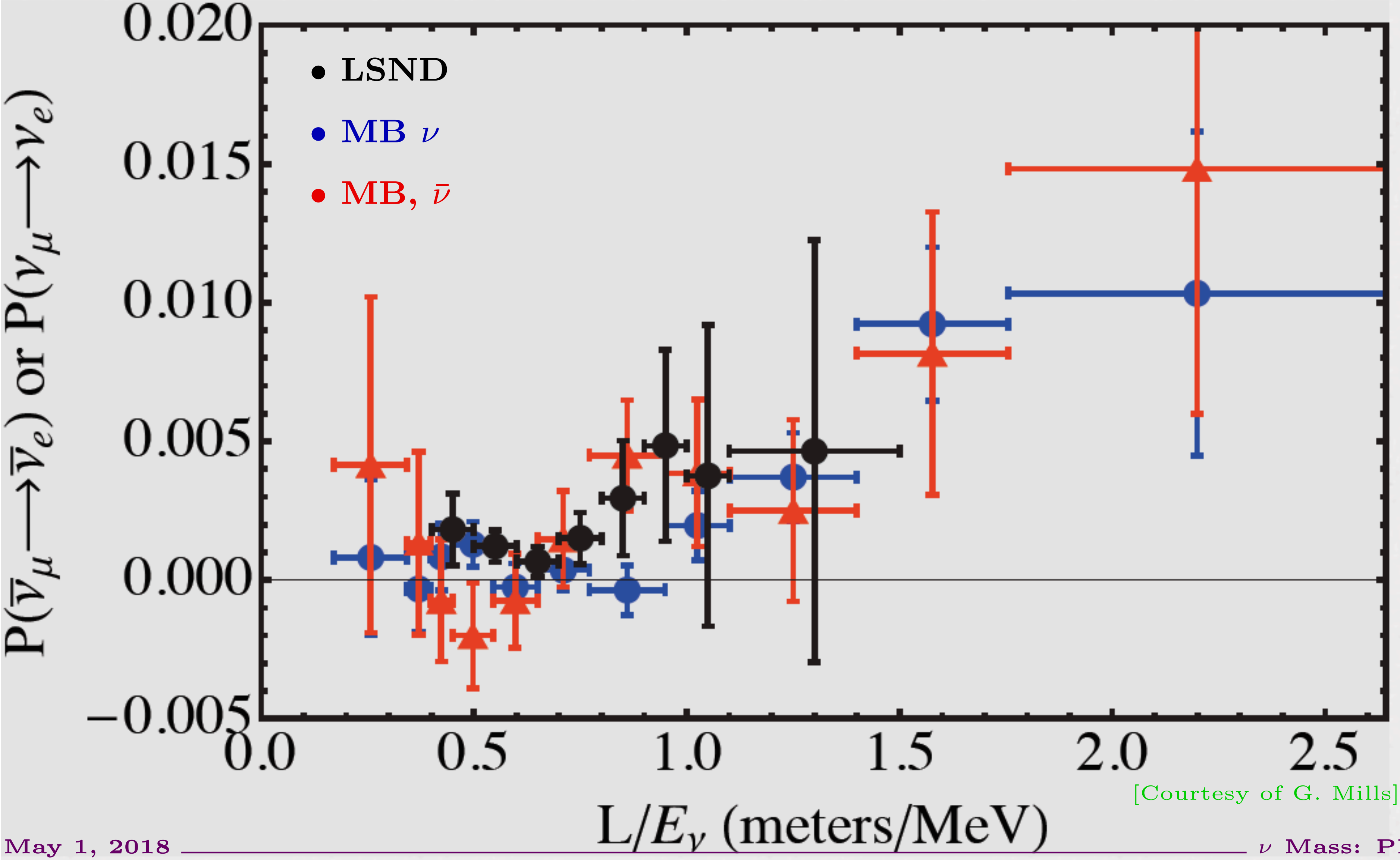
Not all is well(?): The Short Baseline Anomalies

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.

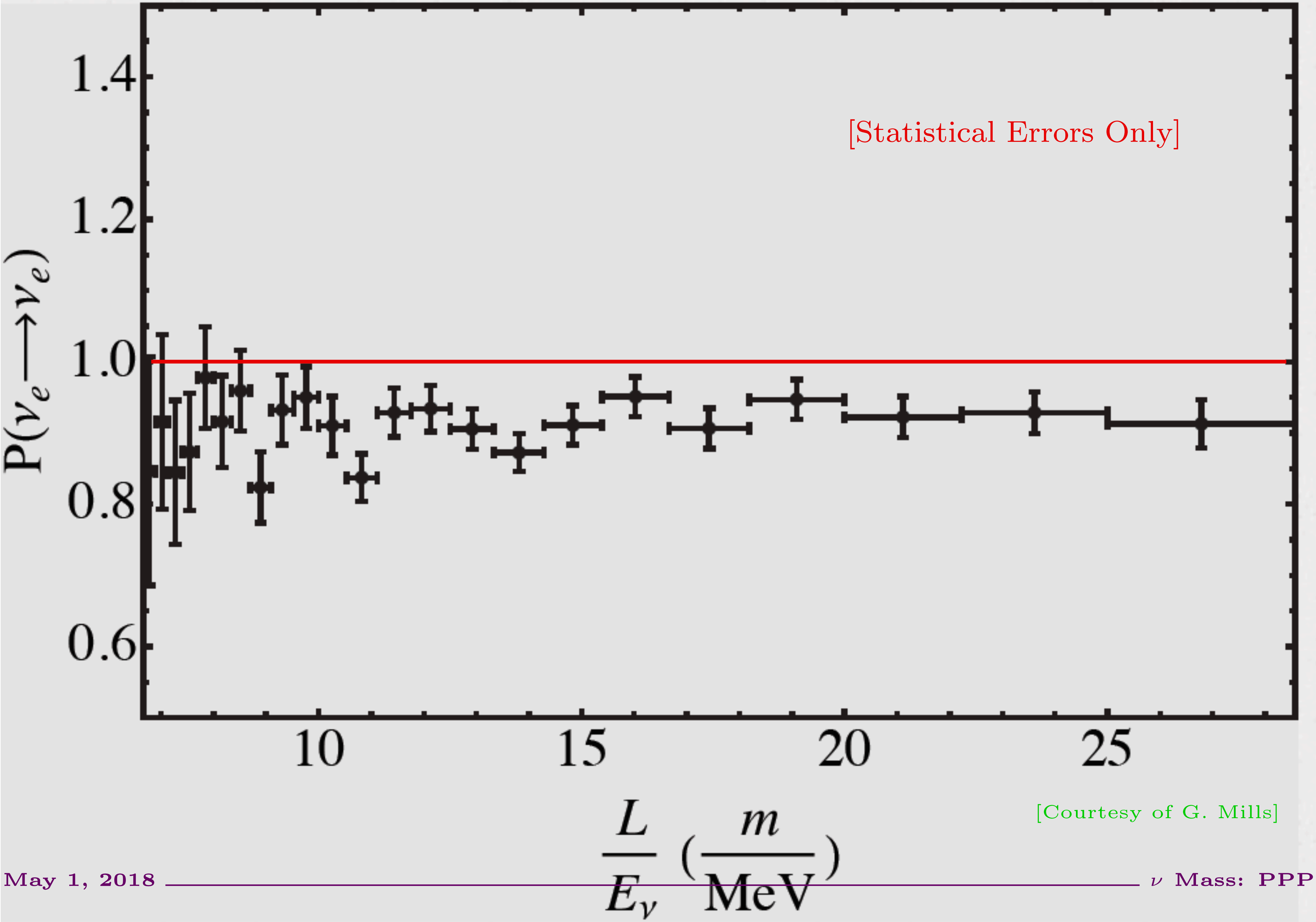
None are entirely convincing, either individually or combined. However, there may be something very very interesting going on here…

MiniBooNE & LSND



[Courtesy of G. Mills]

Bugey 40 m



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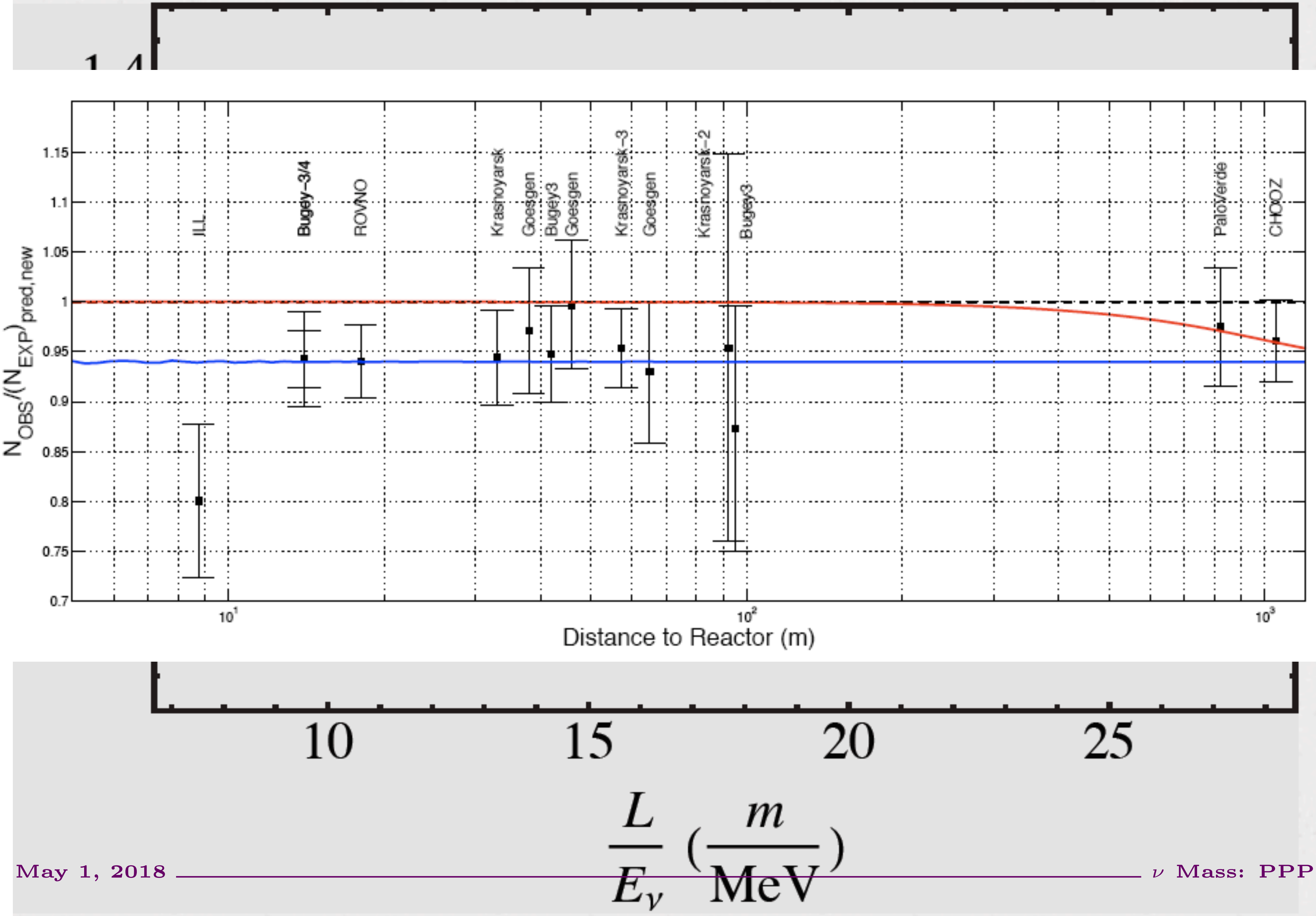


1.4
10
15
20
25
$\frac{L}{E_\nu}\ (\frac{m}{\text{MeV}})$
$N_{OBS}/(N_{EXP})_{pred,new}$
Distance to Reactor (m)
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
10^1
10^2
10^3
ILL
Bugey-3/4
ROVNO
Krasnoyarsk
Goesgen
Bugey3
Goesgen
Krasnoyarsk-3
Goesgen
Krasnoyarsk-2
Bugey3
PaloVerde
CHOOZ

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.

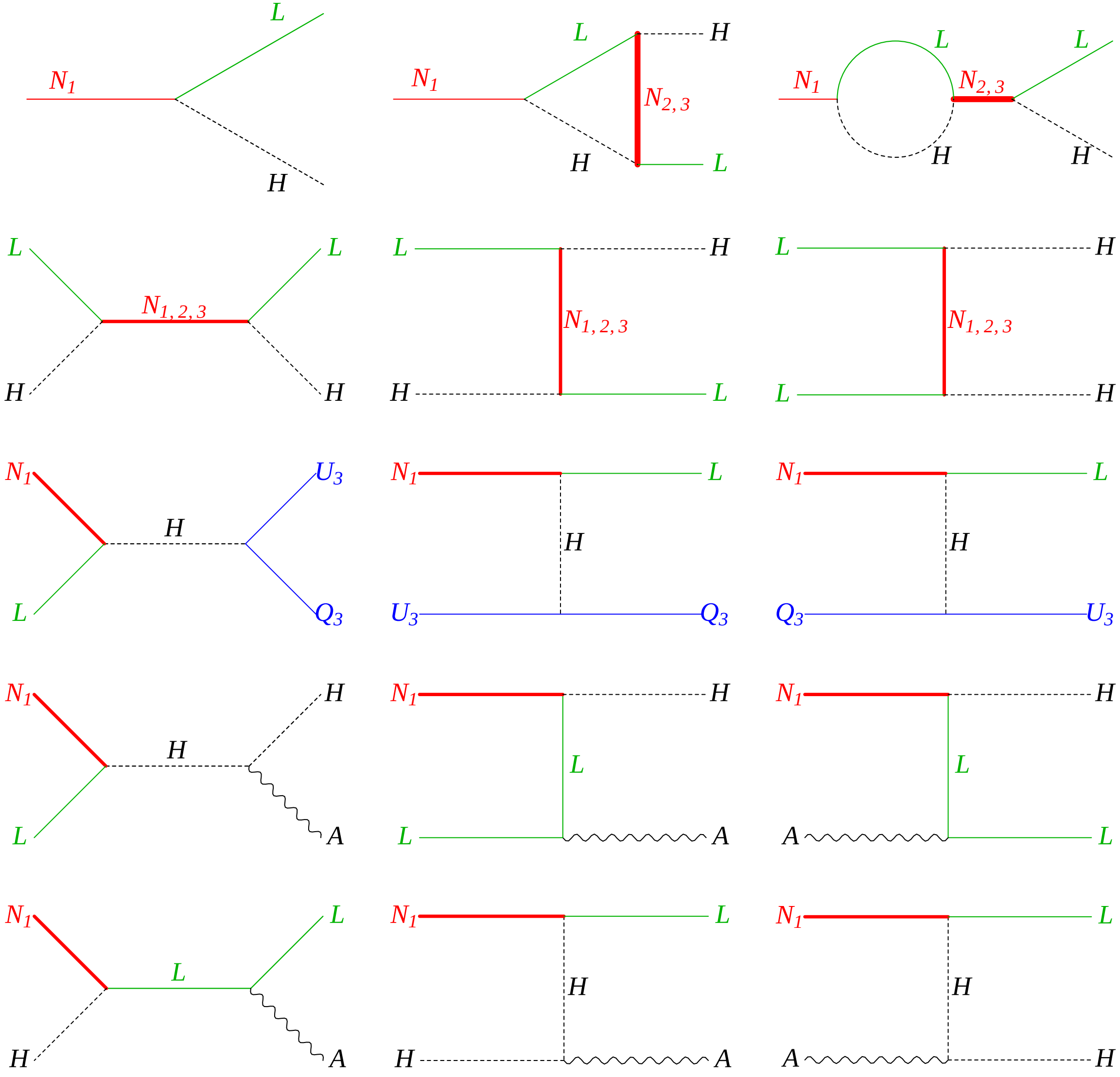
It turns out that massive neutrinos can help solve this puzzle!

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



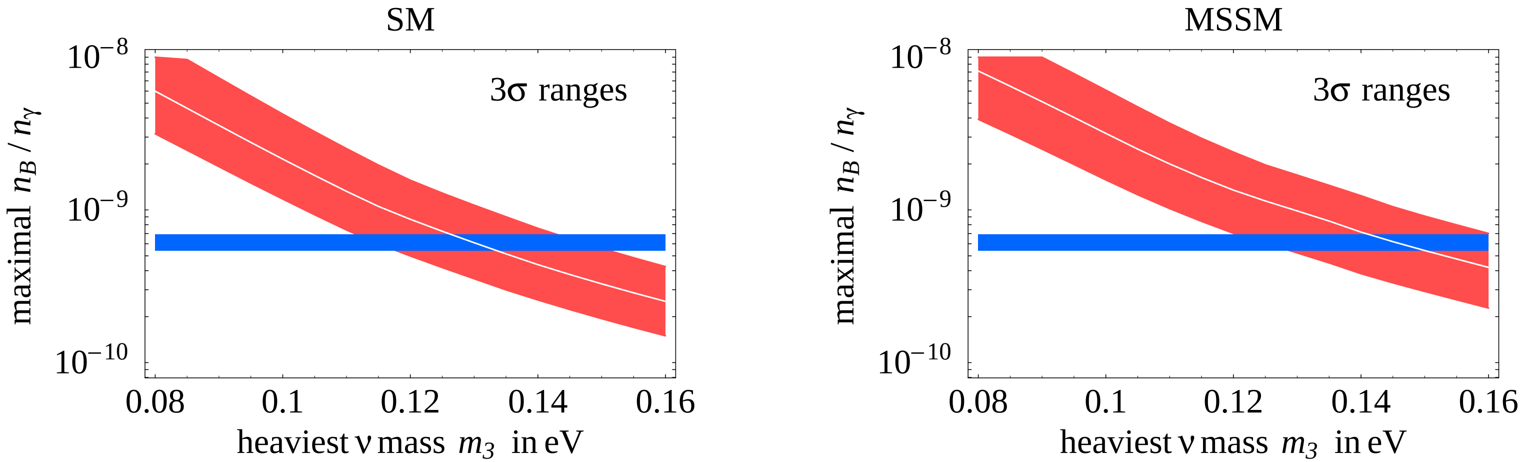
[Fukugita, Yanagida]

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



[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...)