

Neutrino Theory

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Very Quick Reminder: 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 .

- $\nu_\mu \rightarrow \nu_\tau$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$ — atmospheric experiments [“indisputable”];
- $\nu_e \rightarrow \nu_{\mu,\tau}$ — solar experiments [“indisputable”];
- $\bar{\nu}_e \rightarrow \bar{\nu}_{\text{other}}$ — reactor neutrinos [“indisputable”];
- $\nu_\mu \rightarrow \nu_{\text{other}}$ — accelerator experiments [“indisputable”].
- $\nu_\mu \rightarrow \nu_e$ — accelerator experiments [“very strong”];

{talks by K. Scholberg, K.-B. Luk}

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

Phenomenological Understanding of Neutrino Masses & Mixing

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

Definition of neutrino mass eigenstates (who are ν_1, ν_2, ν_3):

- $m_1^2 < m_2^2$ $\Delta m_{31}^2 < 0$ – Inverted Mass Hierarchy
- $m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$ $\Delta m_{31}^2 > 0$ – 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 AdG, Jenkins, arXiv:0804.3627]

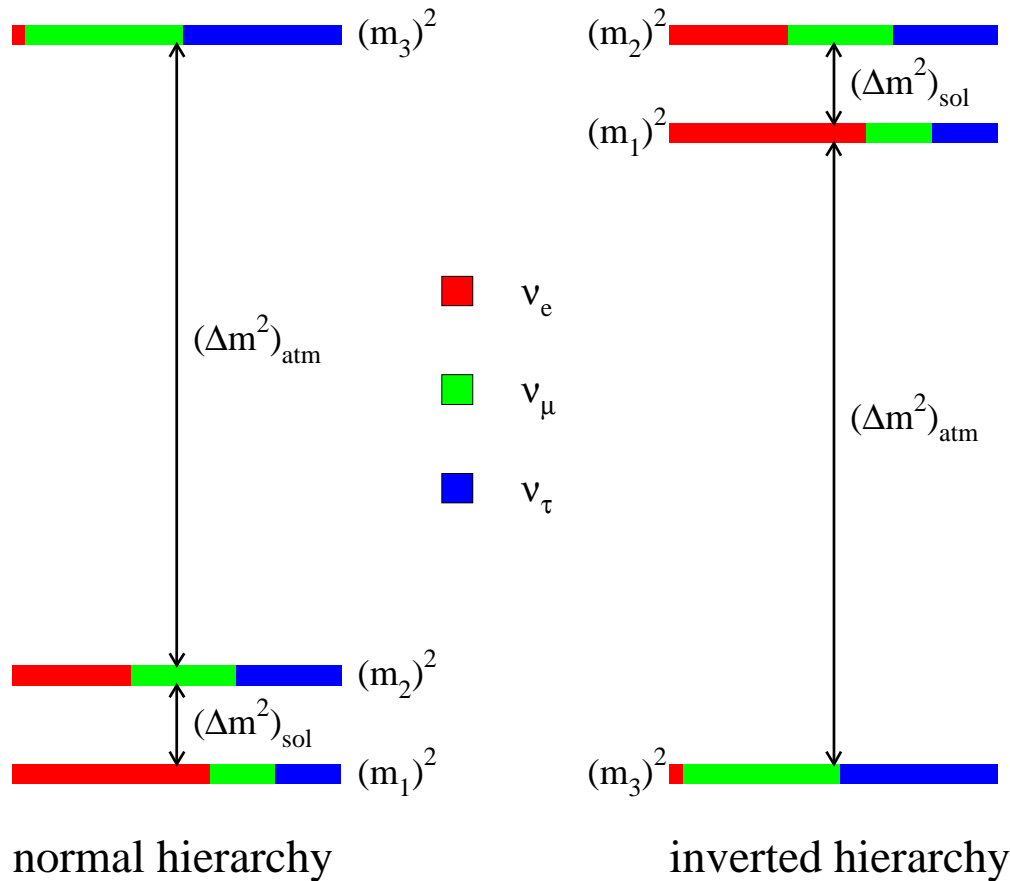
Three Flavor Mixing Hypothesis Fits All* Data Really Well.

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

* Modulo short-baseline anomalies.

[Forero, Tórtola, Valle, 1205.4018]

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

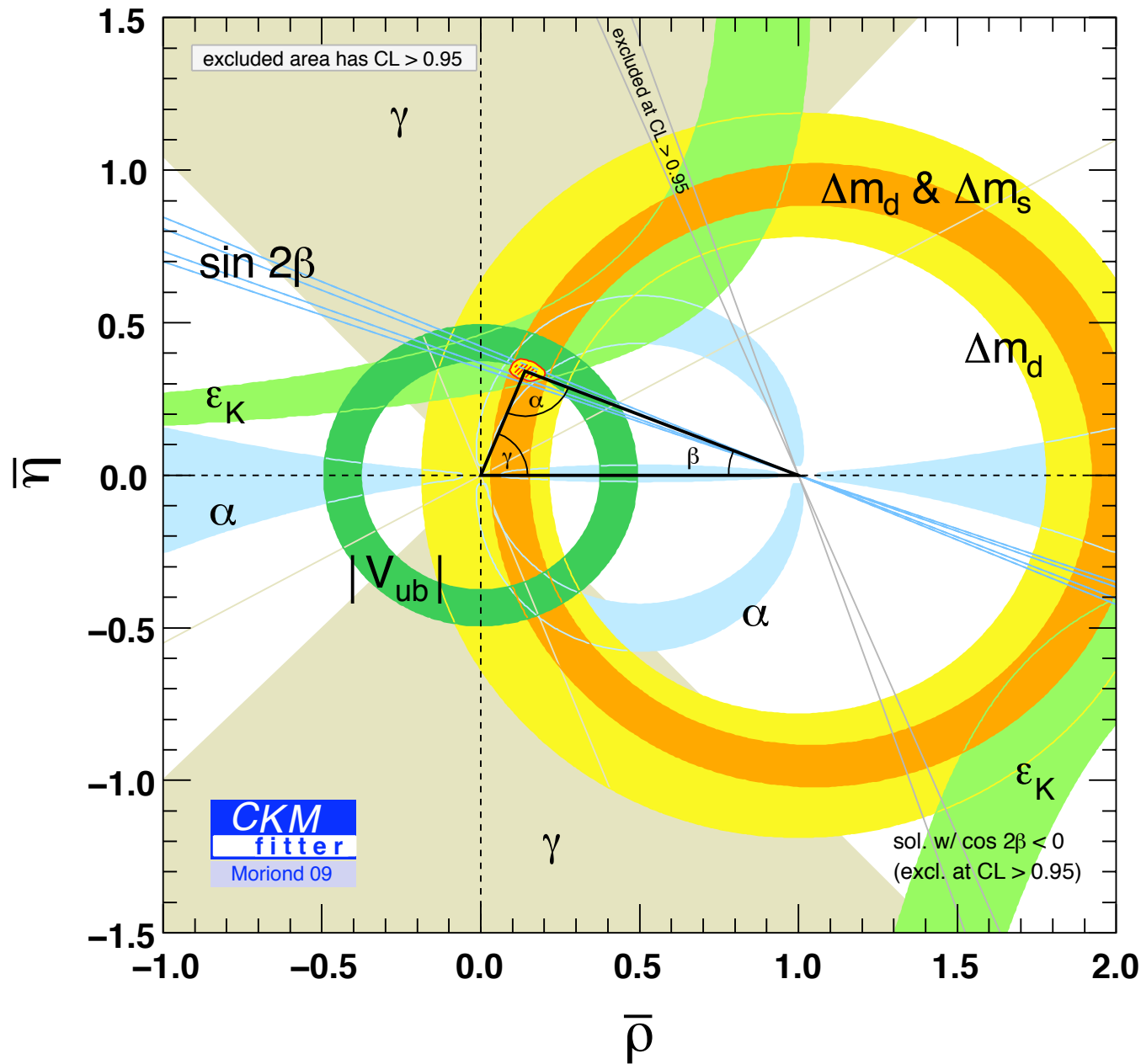


- What is the ν_e component of ν_3 ? ($\theta_{13} \neq 0!$)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi?$)
- Is ν_3 mostly ν_μ or ν_τ ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4?$)
- What is the neutrino mass hierarchy? ($\Delta m_{13}^2 >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

⇒ 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): [see, e.g., Antusch et al, hep-ph/0607020]

- 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!

CP-Violation in the Lepton Sector – Why Bother?

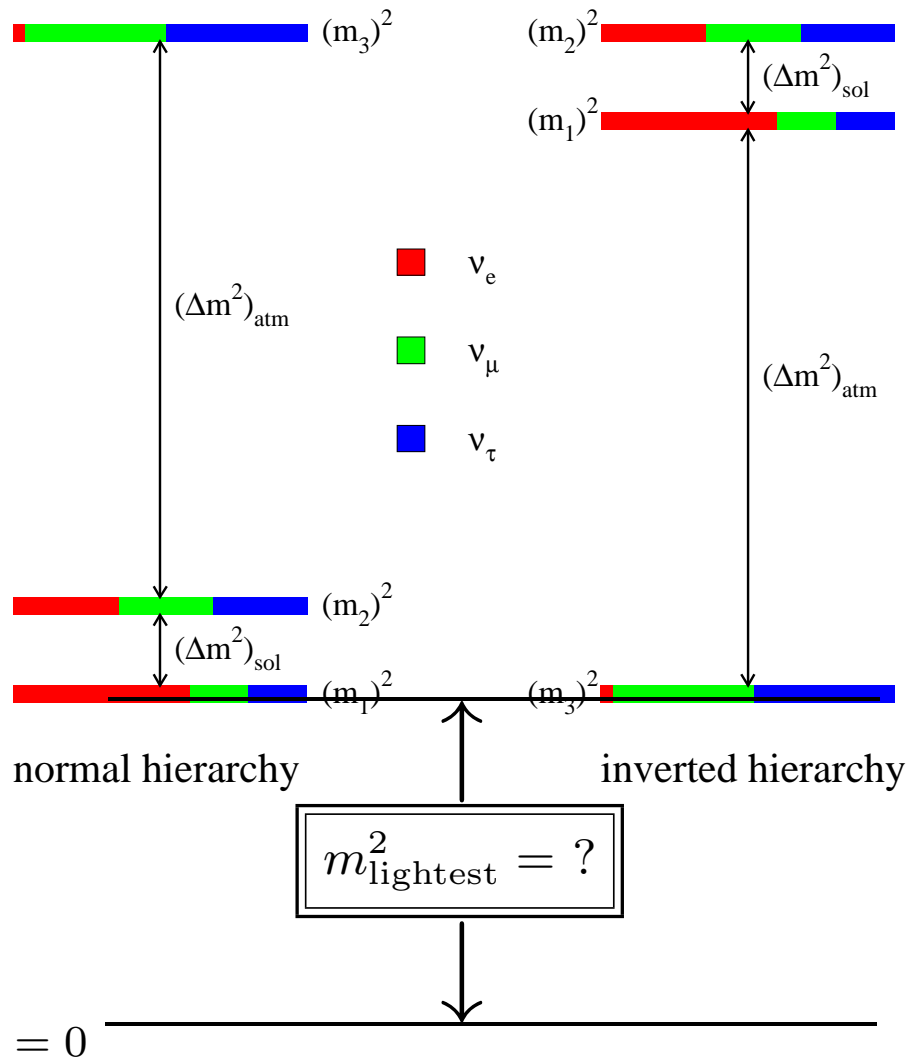
The SM with massive Majorana neutrinos accommodates **five** irreducible CP-invariance violating phases.

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

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

Cautionary tale: “Mixing angles are small”

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



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

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

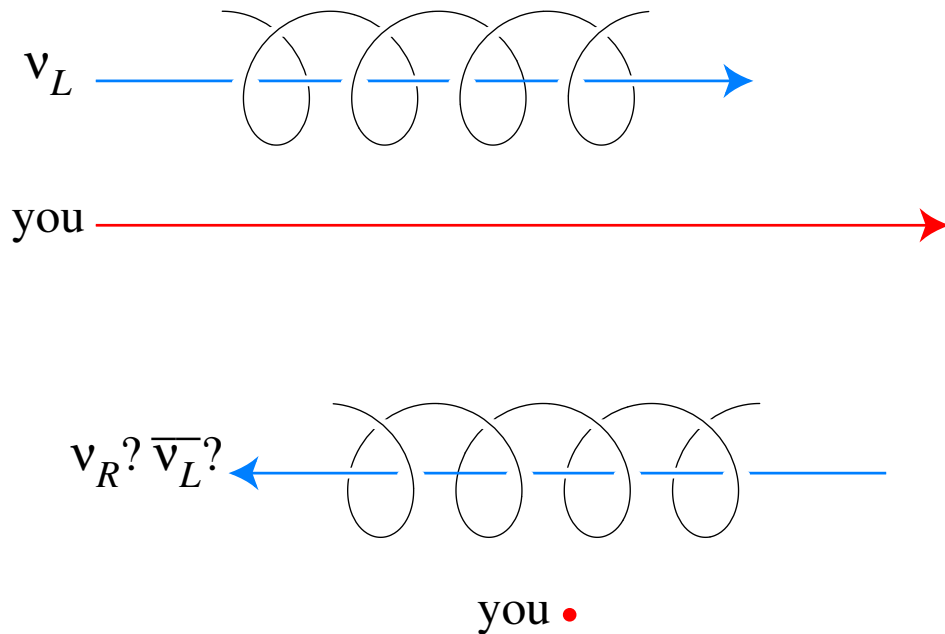
qualitatively different scenarios allowed:

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

Need information outside of neutrino oscillations:

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

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:

$$\begin{aligned}
 &(e_L^- \leftarrow \text{CPT} \rightarrow e_R^+) \\
 &\quad \updownarrow \text{“Lorentz”} \\
 &(e_R^- \leftarrow \text{CPT} \rightarrow e_L^+)
 \end{aligned}$$

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

$$\begin{aligned}
 &(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R) \\
 &\quad \updownarrow \text{“Lorentz”} \quad \text{‘DIRAC’} \\
 &(\nu_R \leftarrow \text{CPT} \rightarrow \bar{\nu}_L)
 \end{aligned}$$

$$\begin{aligned}
 &(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R) \\
 &\quad \updownarrow \text{“Lorentz”} \\
 &(\bar{\nu}_R \leftarrow \text{CPT} \rightarrow \nu_L)
 \end{aligned}$$

‘MAJORANA’

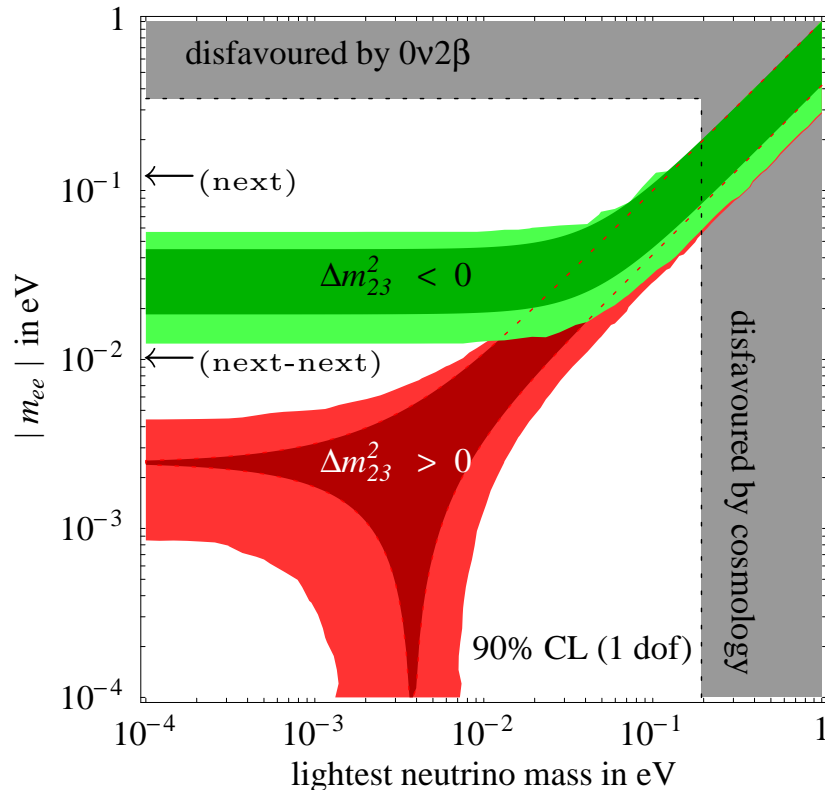
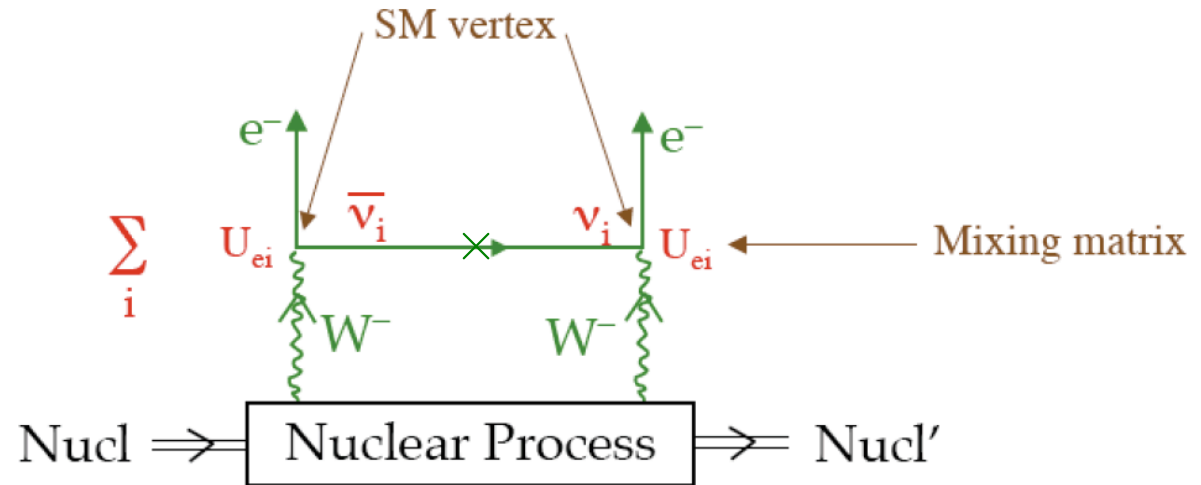
How many degrees of freedom are required to describe massive neutrinos?

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

Best Bet: search for

Neutrinoless Double-Beta

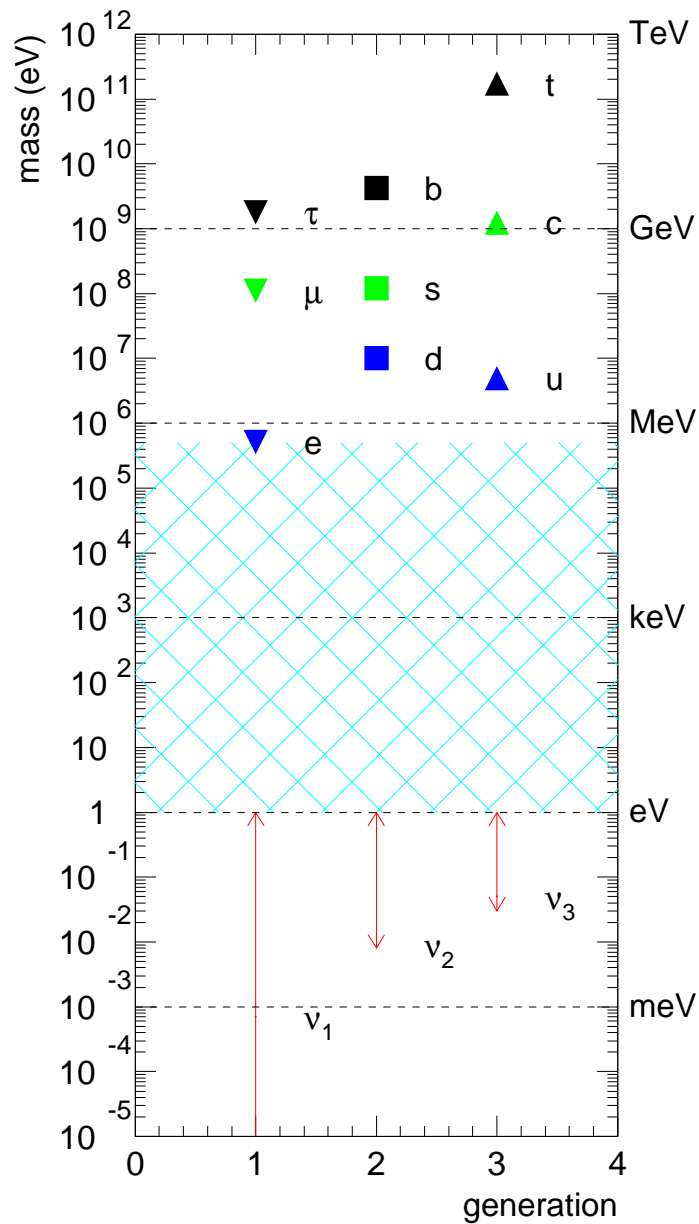
Decay: $Z \rightarrow (Z + 2)e^- e^-$



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

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

⇐ **no longer lamp-post physics!**



What We Are Trying To Understand:

⇐ **NEUTRINOS HAVE TINY MASSES**

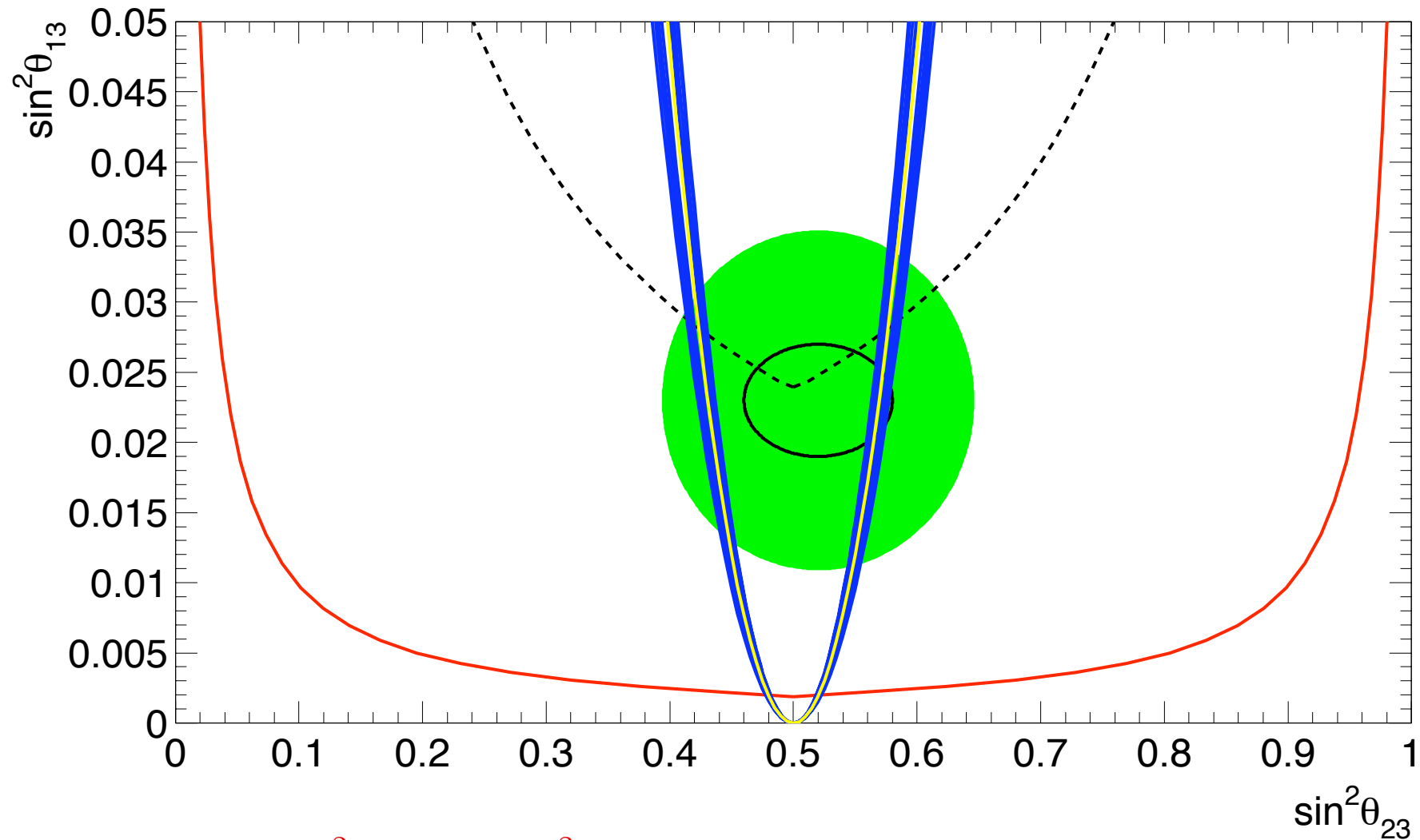
⇓ **LEPTON MIXING IS “WEIRD”** ⇓

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

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

What Does It Mean?

Anarchy vs. Order — more precision required!



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

[AdG, Murayama, 1204.1249]

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

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

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

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

- What is the physics behind electroweak symmetry breaking? (Higgs ✓).
- What is the dark matter? (not in SM).
- Why is there more matter than antimatter? (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, Electroweak Symmetry Breaking, and a New Scale

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

The tiny neutrino masses point to three different possibilities.

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

One Candidate ν 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!
- ν SM effective theory – not valid for energies above *at most* Λ/y .
- Define $y_{\text{max}} \equiv 1 \Rightarrow$ data require $\Lambda \sim 10^{14}$ 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}_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.

To be determined from data: λ and M .

The data can be summarized as follows: there is evidence for three neutrinos, mostly “active” (linear combinations of ν_e , ν_μ , and ν_τ). At least two of them are massive and, if there are other neutrinos, they have to be “sterile.”

This provides very little information concerning the magnitude of M_i (assume $M_1 \sim M_2 \sim M_3$).

Theoretically, there is prejudice in favor of very large M : $M \gg v$. Popular examples include $M \sim M_{\text{GUT}}$ (GUT scale), or $M \sim 1 \text{ TeV}$ (EWSB scale).

Furthermore, $\lambda \sim 1$ translates into $M \sim 10^{14} \text{ GeV}$, while thermal leptogenesis requires the lightest M_i to be around 10^{10} GeV .

we can impose very, very few experimental constraints on M

What We Know About M :

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

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.).

(**Why are Neutrino Masses Small in the $M \neq 0$ Case?**

If $\mu \ll M$, below the mass scale M ,

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

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

In the case of the seesaw,

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

so neutrino masses are small if either

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

)

High-Energy Seesaw: Brief Comments

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

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

- Hierarchy problem hint (e.g., Casas, Espinosa, Hidalgo, hep-ph/0410298):

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

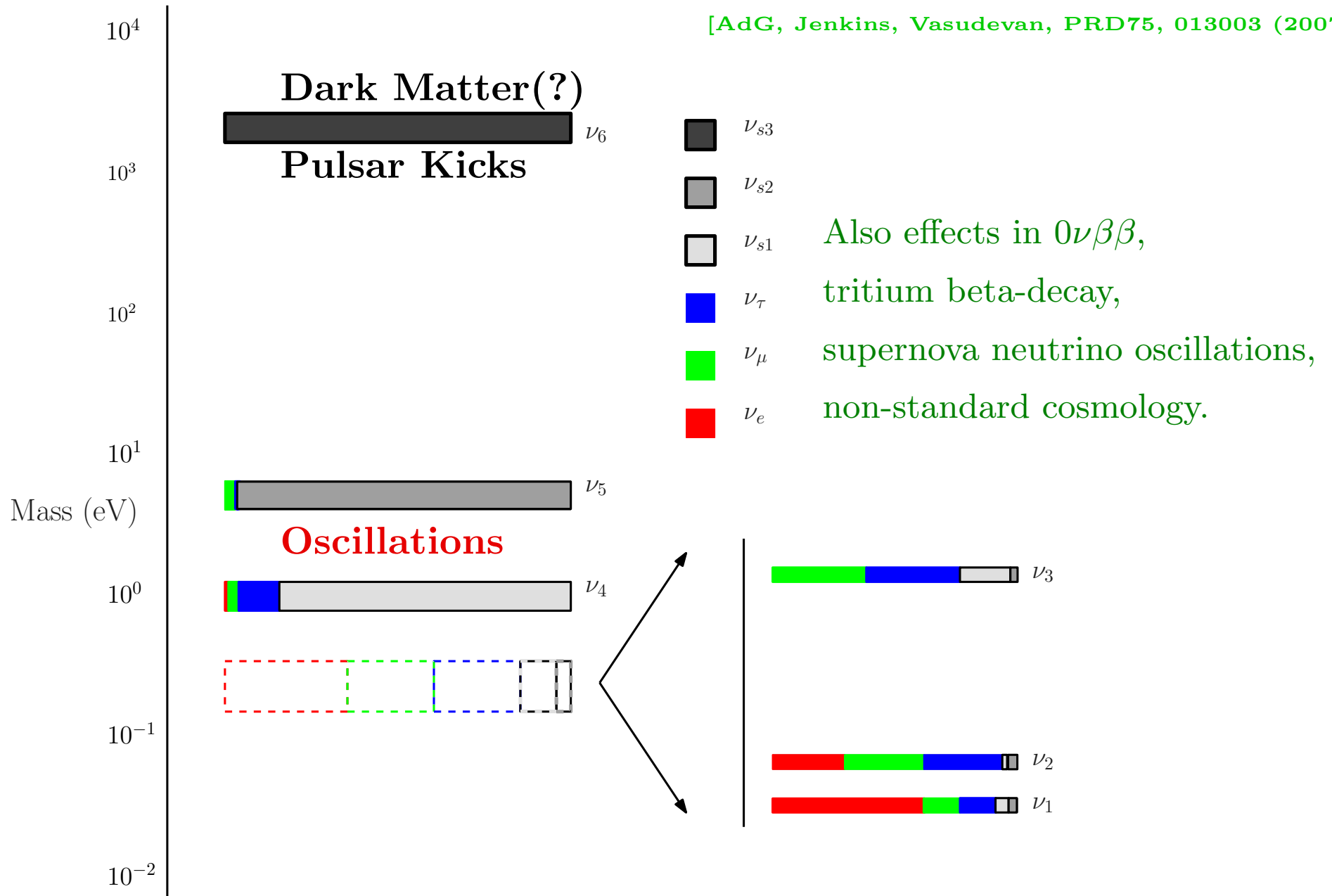
- Leptogenesis! “Vanilla” Leptogenesis requires, roughly, smallest

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

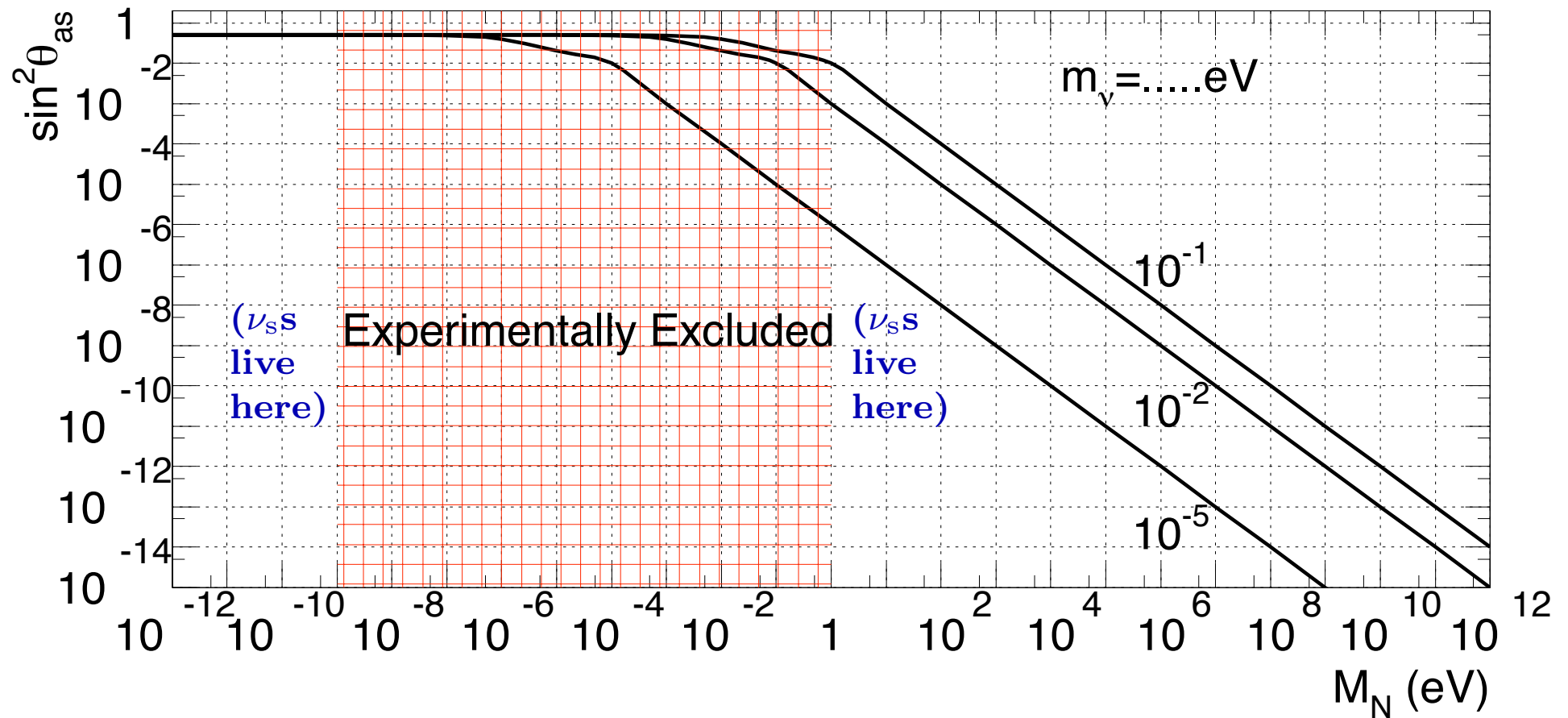
- Physics “too” heavy! No observable consequence other than leptogenesis. Will we ever convince ourselves that this is correct?

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

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



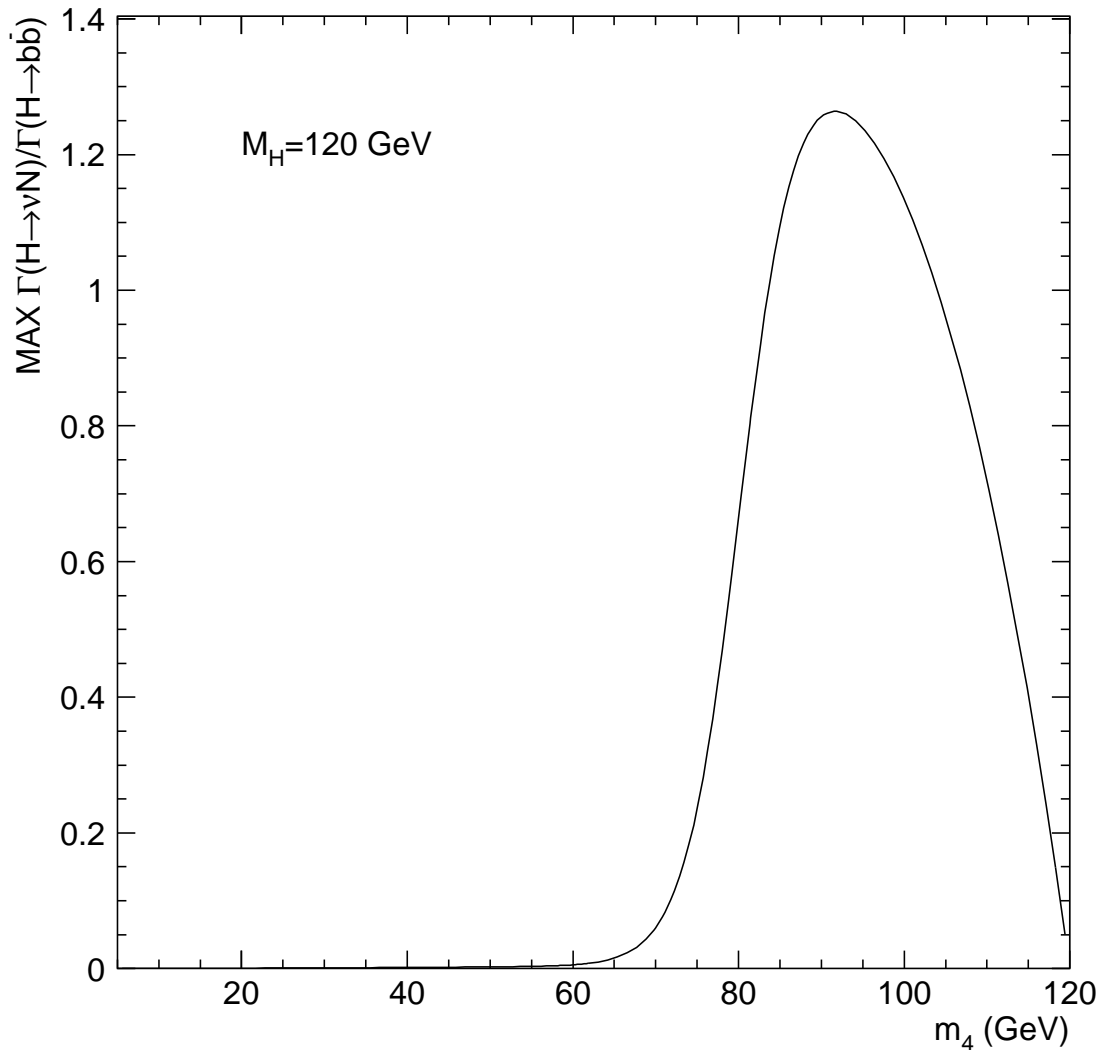
Constraining the Seesaw Lagrangian



[AdG, Huang, Jenkins, arXiv:0906.1611]

Weak Scale Seesaw, and Accidentally Light Neutrino Masses

[AdG arXiv:0706.1732 [hep-ph]]



What does the seesaw Lagrangian predict for the LHC?

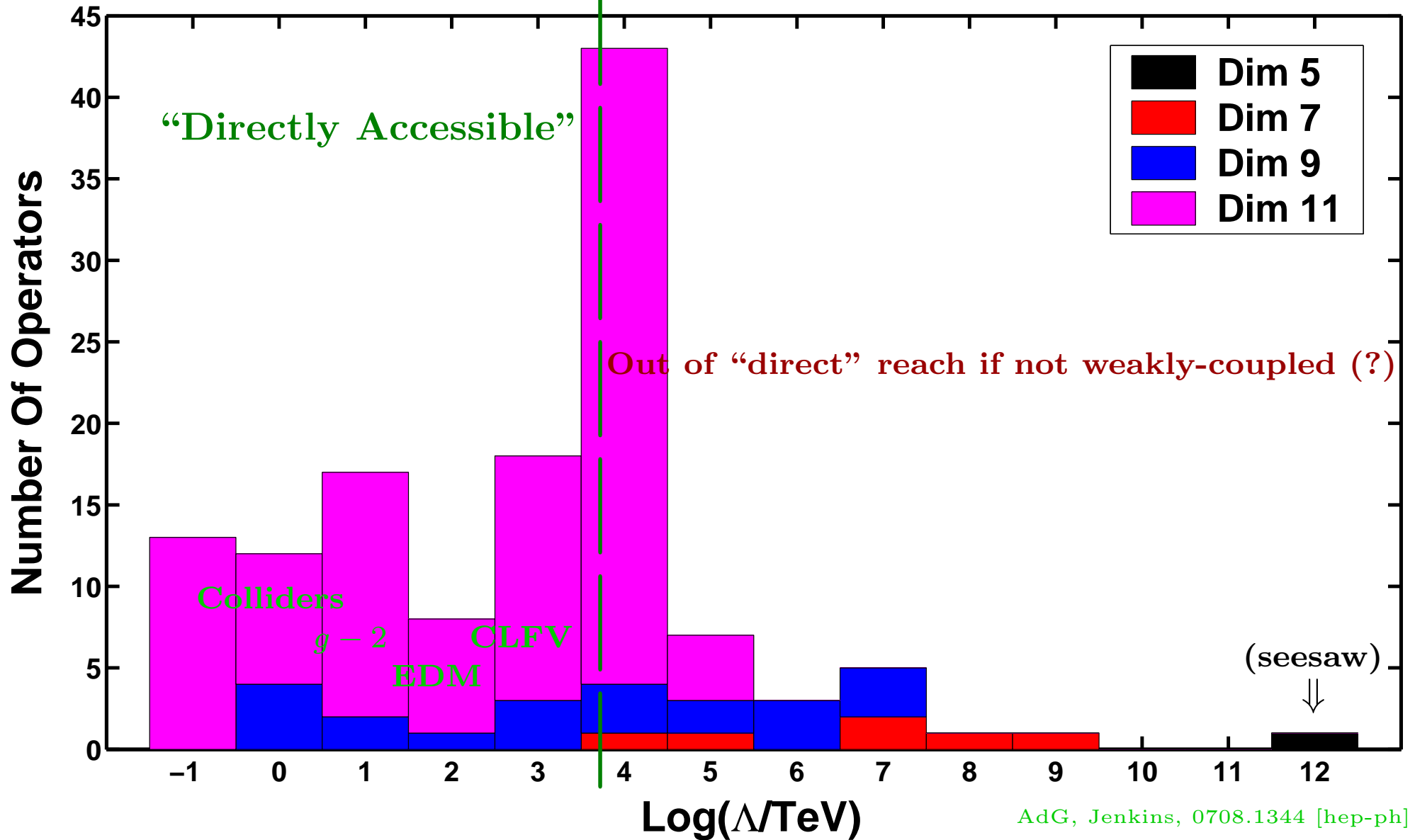
Nothing much, unless...

- $M_N \sim 1 - 100$ 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!)

This is Just the Tip of the Model-Iceberg!



AdG, Jenkins, 0708.1344 [hep-ph]

Piecing the Neutrino Mass Puzzle

Understanding the origin of neutrino masses and exploring the new physics in the lepton sector will require unique **theoretical** and **experimental** efforts ...

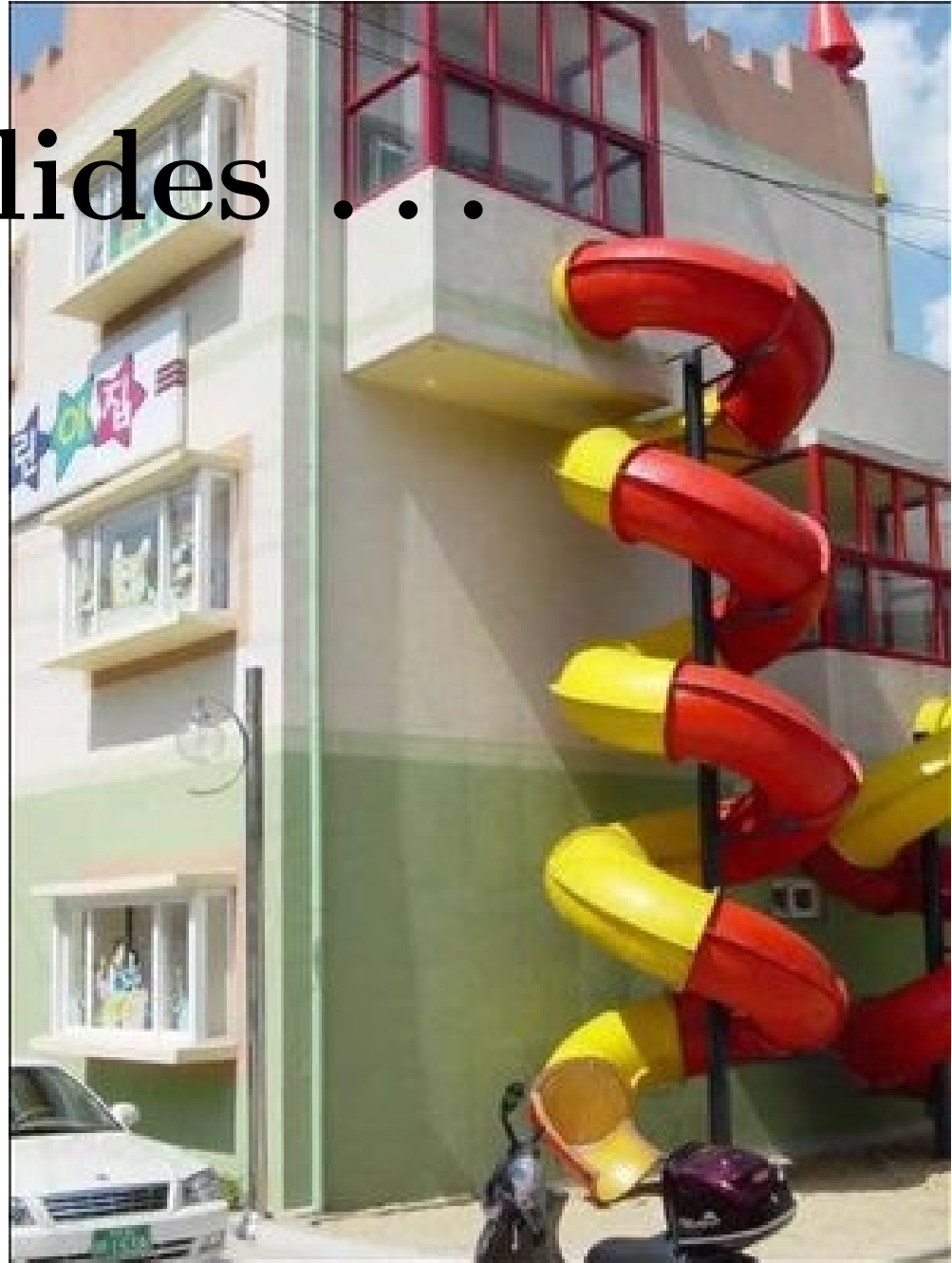
- understanding the fate of lepton-number. Neutrinoless double beta decay!
- A comprehensive long baseline neutrino program. LBNE and HyperK first steps towards the ultimate “superbeam” experiment.
- The next-step is to develop a qualitatively better neutrino beam – e.g. muon storage rings (neutrino factories).
- Different baselines and detector technologies a must for both over-constraining the system and looking for new phenomena.
- Probes of neutrino properties, including neutrino scattering experiments.
- Precision measurements of charged-lepton properties ($g - 2$, edm) and searches for rare processes ($\mu \rightarrow e$ -conversion the best bet at the moment).
- Collider experiments. The LHC and beyond may end up revealing the new physics behind small neutrino masses.
- Neutrino properties affect, in a significant way, the history of the universe (Cosmology). Will we learn about neutrinos from cosmology, or about cosmology from neutrinos?

CONCLUSIONS

1. we have a very successful parametrization of the neutrino sector, and we have identified what we know we don't know.
2. neutrino masses are very small – we don't know why, but we think it means something important.
3. lepton mixing is very different from quark mixing – 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” (required in order to attack 2. and 3. above) we must uncover the fate of baryon number minus lepton number ($0\nu\beta\beta$ is the best [only?] bet).
5. We need more experimental input – and more seems to be on the way (this is a truly data driven field right now). We only started to figure out what is going on.

6. The fact that neutrinos have mass may be intimately connected to the fact that there are more baryons than antibaryons in the Universe. How do we test whether this is correct?
7. There is plenty of room for surprises, as neutrinos are very narrow but 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., $M_{\text{seesaw}} \simeq 10^{14}$ GeV).
8. Finally, we need to resolve the short baseline anomalies (which I did not have time to discuss). Life could be much more interesting!

Backup Slides . . .



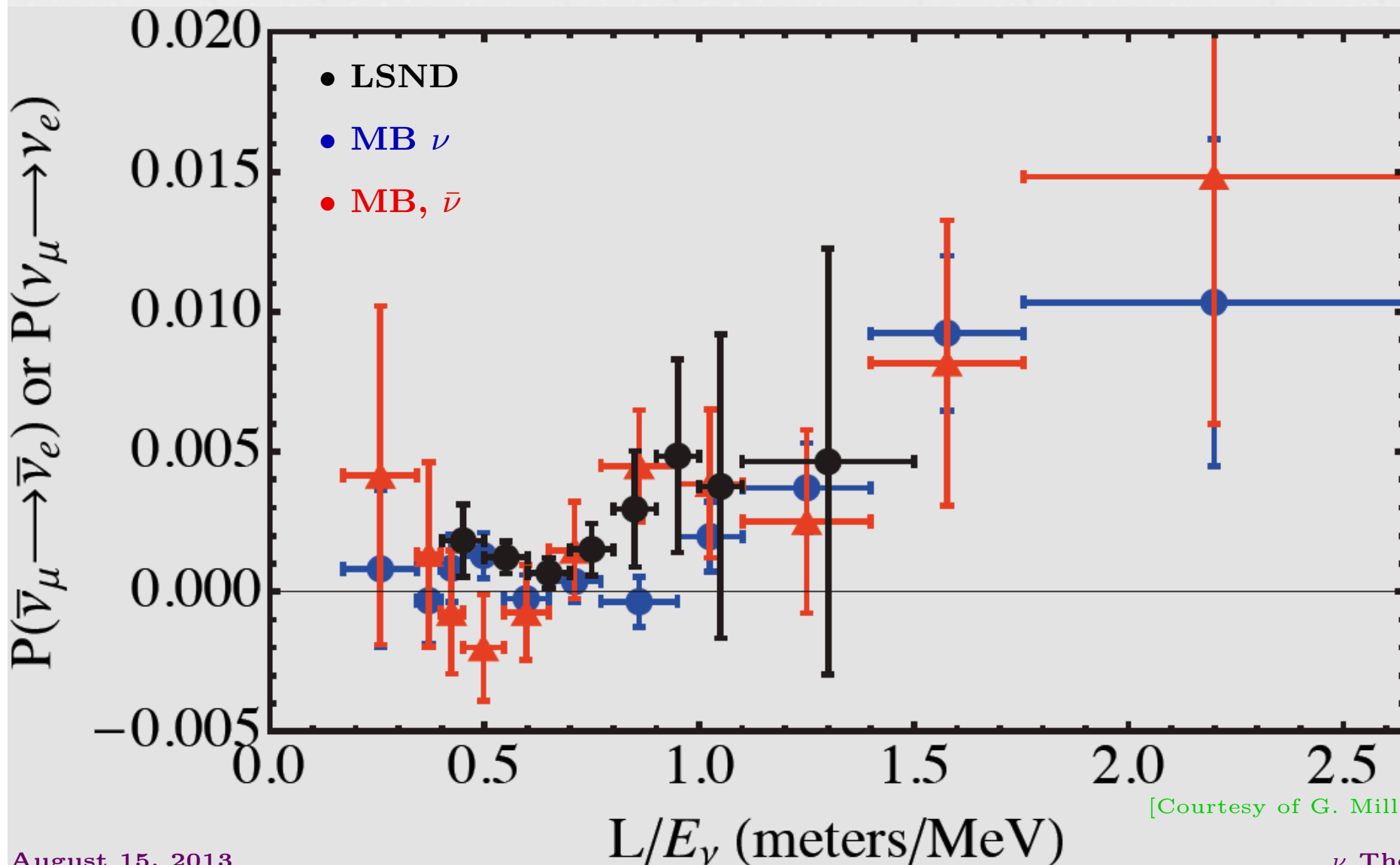
Not all is well(?): The Short Baseline Anomalies

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

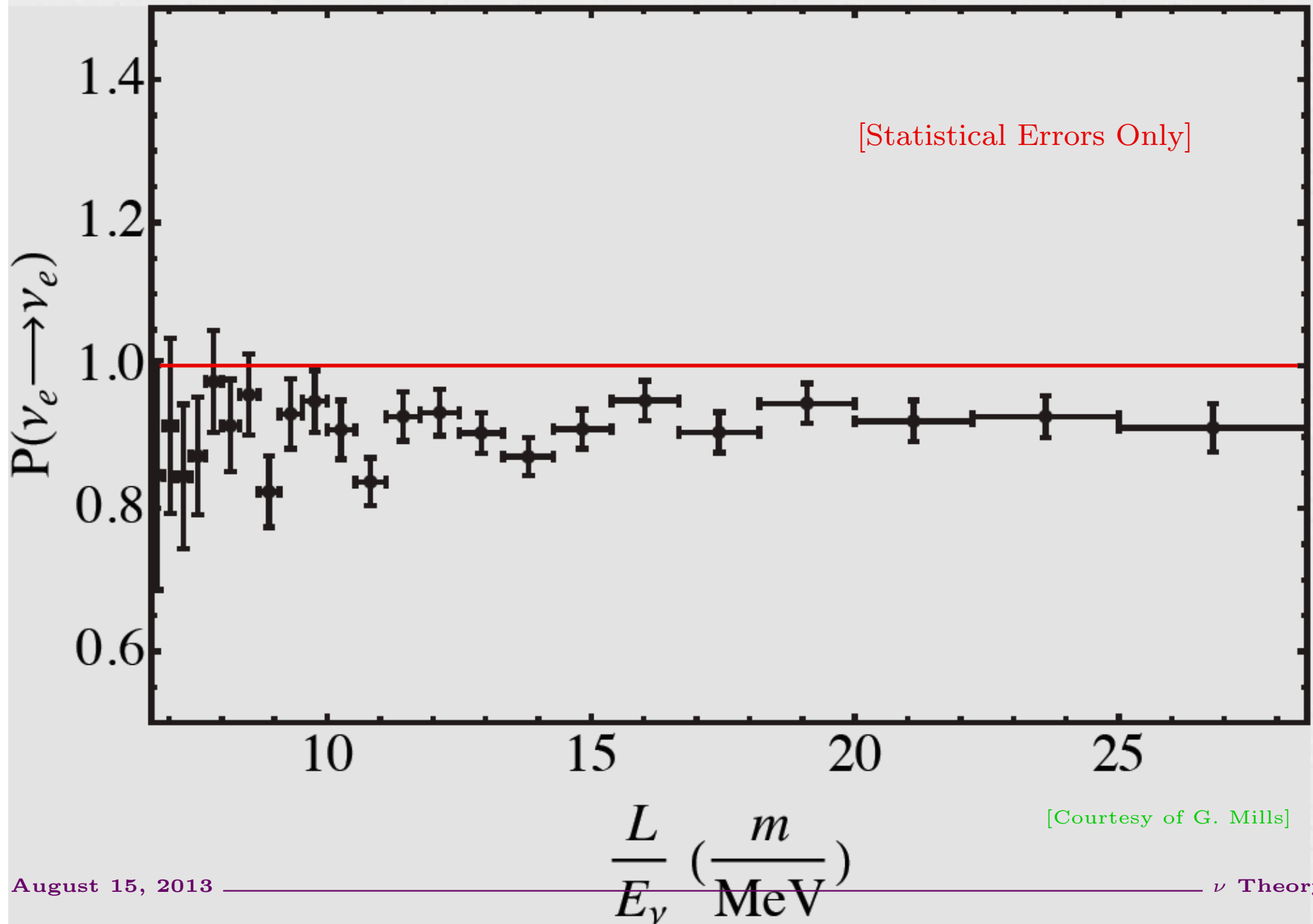
- $\nu_\mu \rightarrow \nu_e$ appearance — LSND, MiniBooNE;
- $\nu_e \rightarrow \nu_{\text{other}}$ disappearance — radioactive sources;
- $\bar{\nu}_e \rightarrow \bar{\nu}_{\text{other}}$ disappearance — reactor experiments.

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

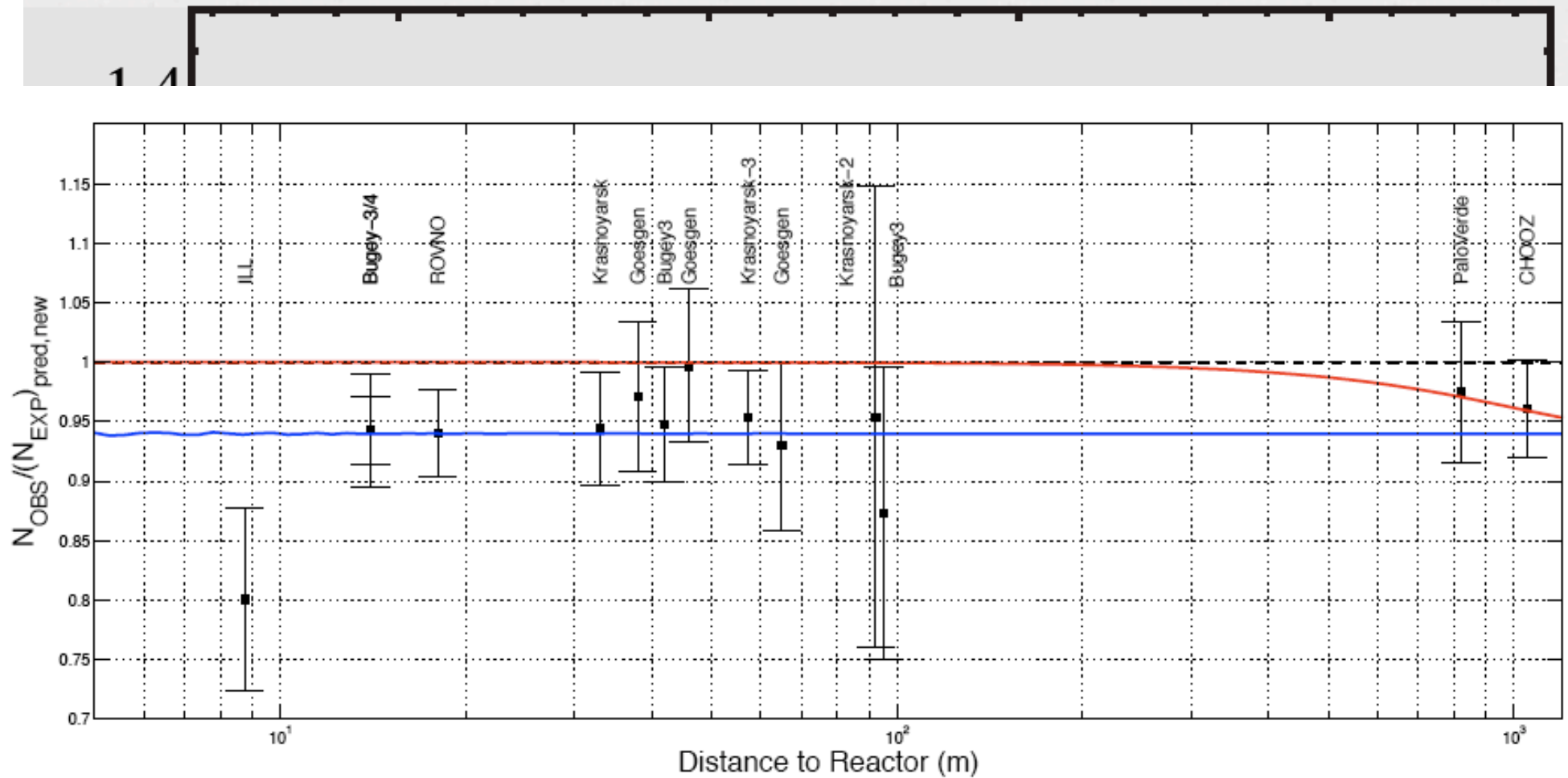
MiniBooNE & LSND



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?

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

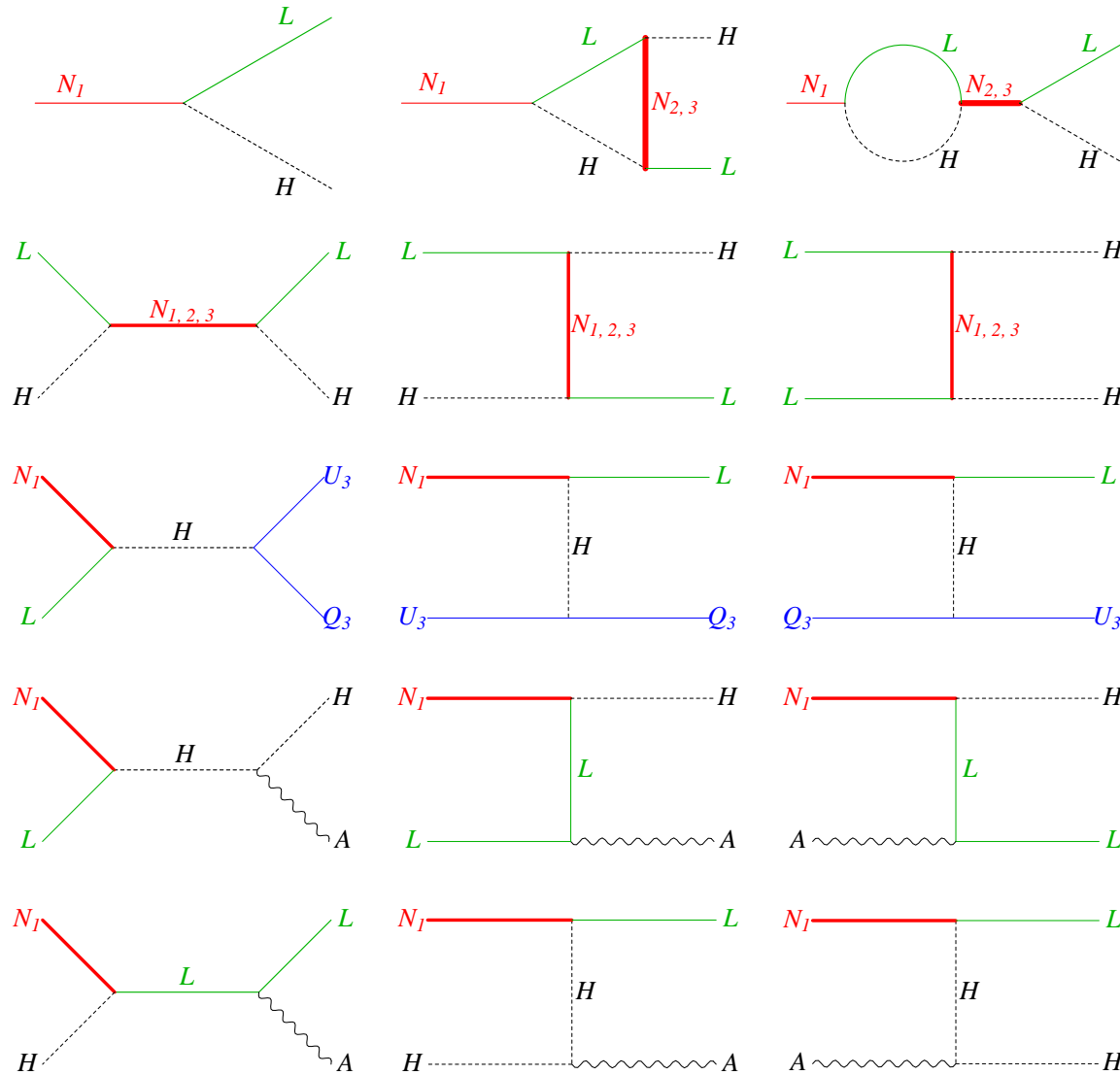
Neutrinos help by providing all the necessary ingredients for successful baryogenesis via leptogenesis.

- 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]



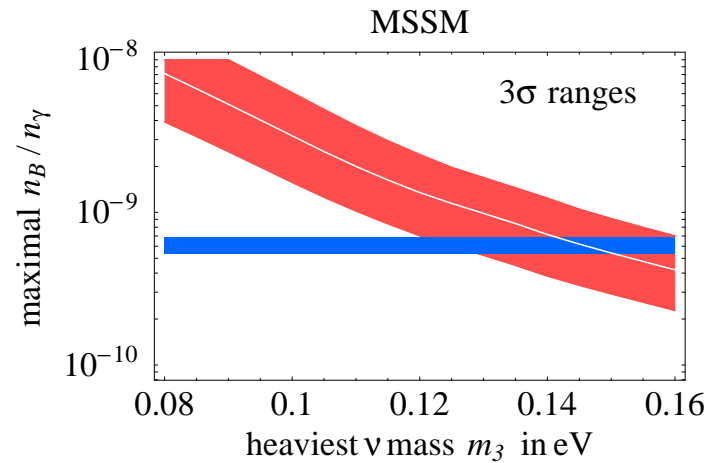
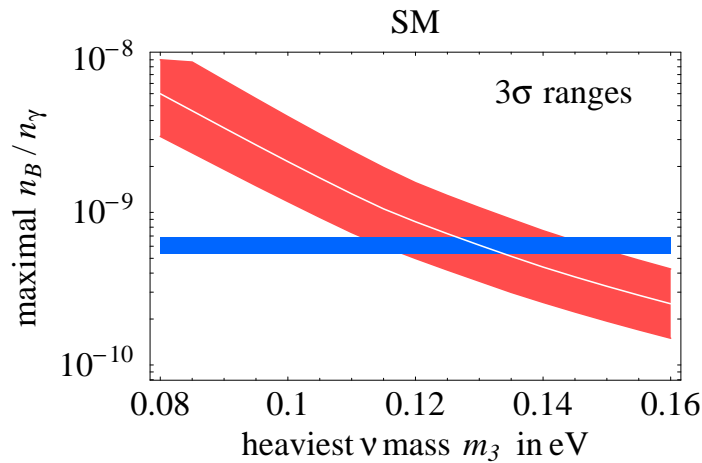
- L-violating processes
- $y \Rightarrow$ CP-violation
- deviation from thermal eq. constrains combinations of M_N and y .
- need to yield correct m_ν

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).

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.



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!

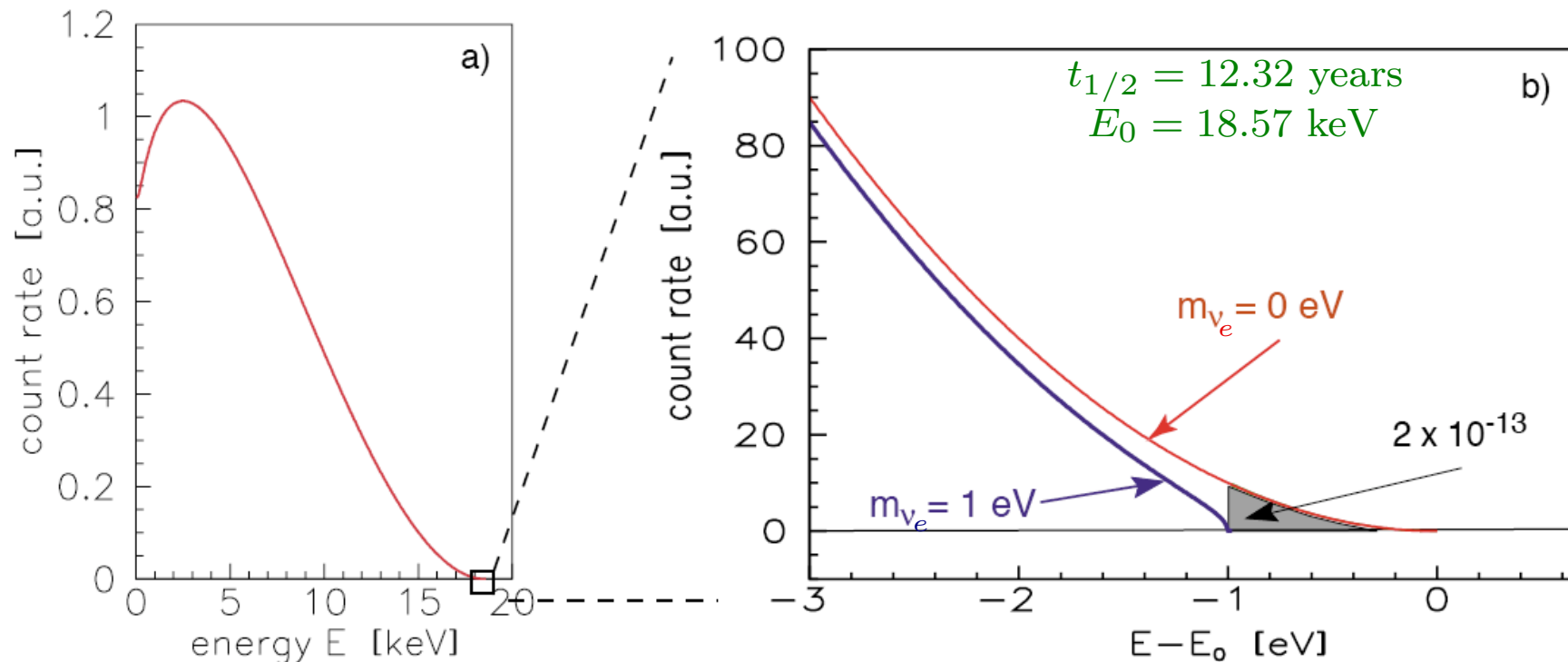


Figure 2: The electron energy spectrum of tritium β decay: (a) complete and (b) narrow region around endpoint E_0 . The β spectrum is shown for neutrino masses of 0 and 1 eV.

NEXT GENERATION: The Karlsruhe Tritium Neutrino (KATRIN) Experiment:
(not your grandmother's table top experiment!)



Big Bang Neutrinos are Warm Dark Matter

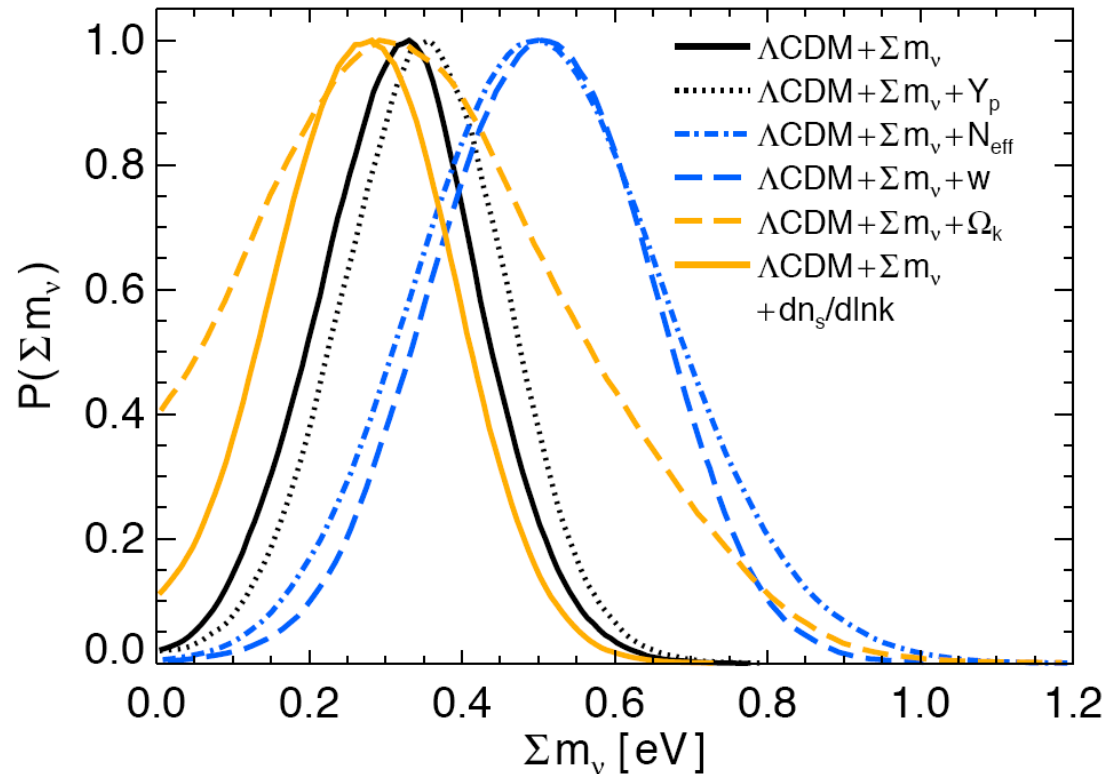


FIG. 10.— This figure illustrates the robustness of the neutrino mass detection to other parameter extensions. The marginalized one-dimensional posteriors for $\sum m_\nu$ are shown for two-parameter extensions to Λ CDM for the combined CMB+BAO+ H_0 +SPT_{CL} data sets (for w , SNe are used instead of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

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

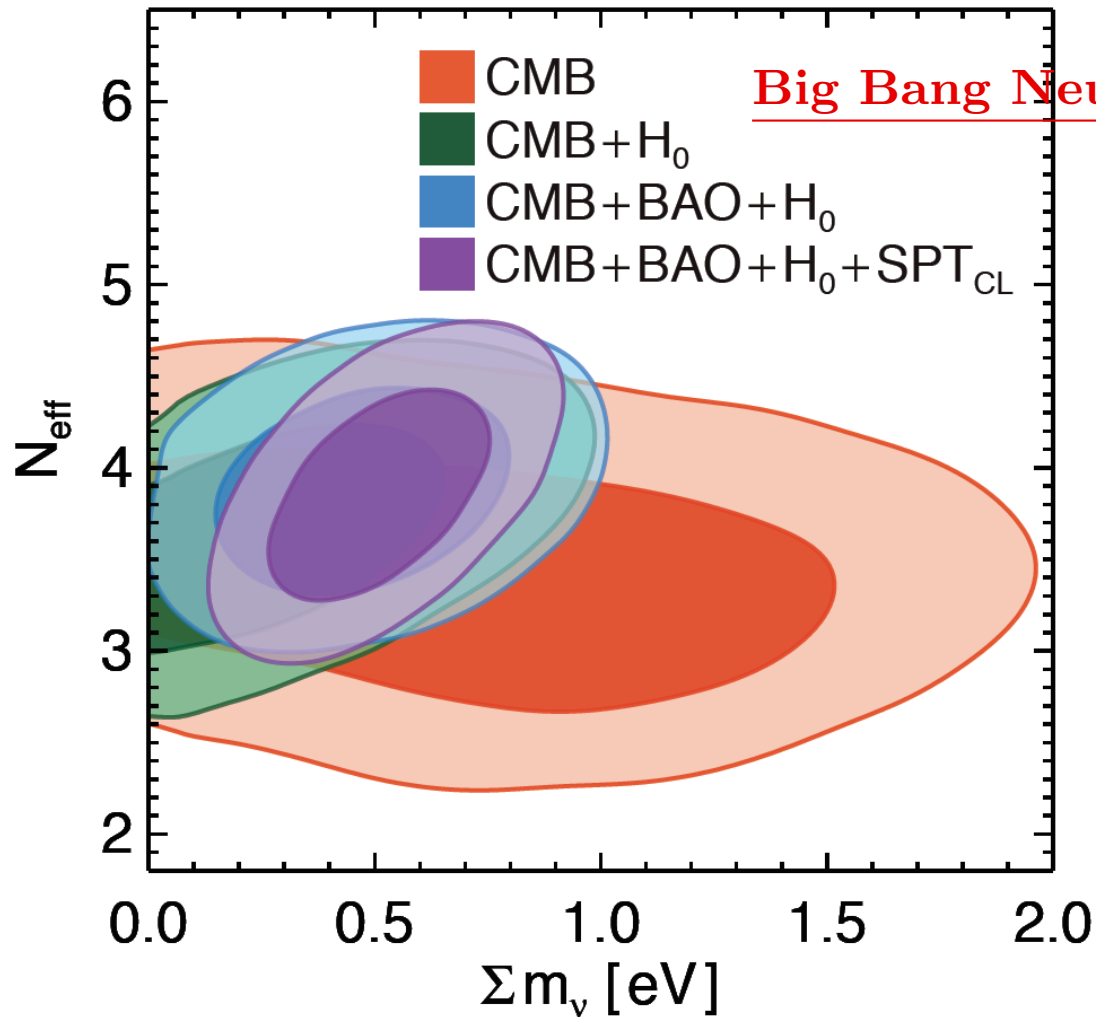
- Constrained by the Large Scale Structure of the Universe.

Constraints depend on

- Data set analysed;
- “Bias” on other parameters;
- ...

Bounds can be evaded with non-standard cosmology. Will we learn about [neutrinos from cosmology](#) or about [cosmology from neutrinos](#)?

Big Bang Neutrinos are Warm Dark Matter



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FIG. 18.— This figure demonstrates the impact of each combination of datasets on the constraints on $\sum m_\nu$ and N_{eff} . The shaded contours are the 68% and 95% confidence intervals for the following data combinations: SPT+*WMAP*7 (CMB; red), CMB+ H_0 (green), CMB+ H_0 +BAO (blue), CMB+ H_0 +BAO+SPT_{CL} (purple). The combined data are in $>2\sigma$ tension with the Λ CDM assumption of three massless neutrino species.

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

Big Bang Neutrinos are Warm Dark Matter

Planck Collaboration: Cosmological parameters

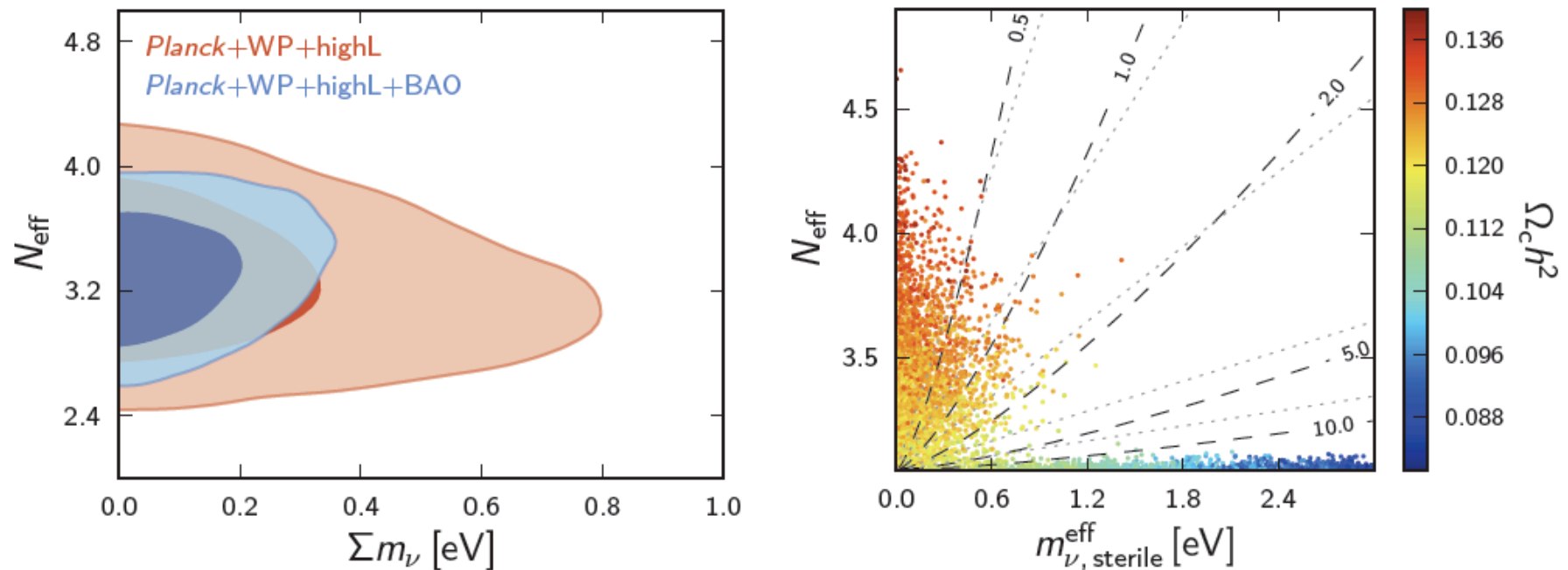


Fig. 28. *Left:* 2D joint posterior distribution between N_{eff} and $\sum m_\nu$ (the summed mass of the three active neutrinos) in models with extra massless neutrino-like species. *Right:* Samples in the $N_{\text{eff}}-m_{\nu, \text{sterile}}^{\text{eff}}$ plane, colour-coded by $\Omega_c h^2$, in 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).

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