The "Holy Graill" of Neutrino Oscillations – CP Violation

In the old Standard Model, there is only one[a] source of CP-invariance violation:

⇒ The complex phase in V_{CKM}, the quark mixing matrix.

Indeed, as far as we have been able to test, all CP-invariance violating phenomena agree with the CKM paradigm:

- ϵ_K;
- ϵ'_K;
- $\sin 2\beta$;
- etc.

Recent experimental developments, however, provide strong reason to believe that this is not the case: neutrinos have mass, and leptons mix!

---

[a] modulo the QCD θ-parameter, which will be "willed away" henceforth.

CP-invariance Violation in Neutrino Oscillations

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

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

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

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

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

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

[remember: according to unitarty, $U_{e1}U_{\mu 1}^* = -U_{e2}U_{\mu 2}^* - U_{e3}U_{\mu 3}^*$]

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: Δ_{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: given that two of the three mixing angles are known to be large, **we need** $|U_{e3}| \neq 0$**. (✓)**

The goal of next-generation neutrino experiments is to determine the magnitude of $|U_{e3}|$. We need to know this in order to understand how to study CP-invariance violation in neutrino oscillations!

In the real world, life is much more complicated. The lack of knowledge concerning the mass hierarchy, θ_{13}, θ_{23} leads to several degeneracies.

Note that, in order to see CP-invariance violation, we **need** the "subleading" terms!

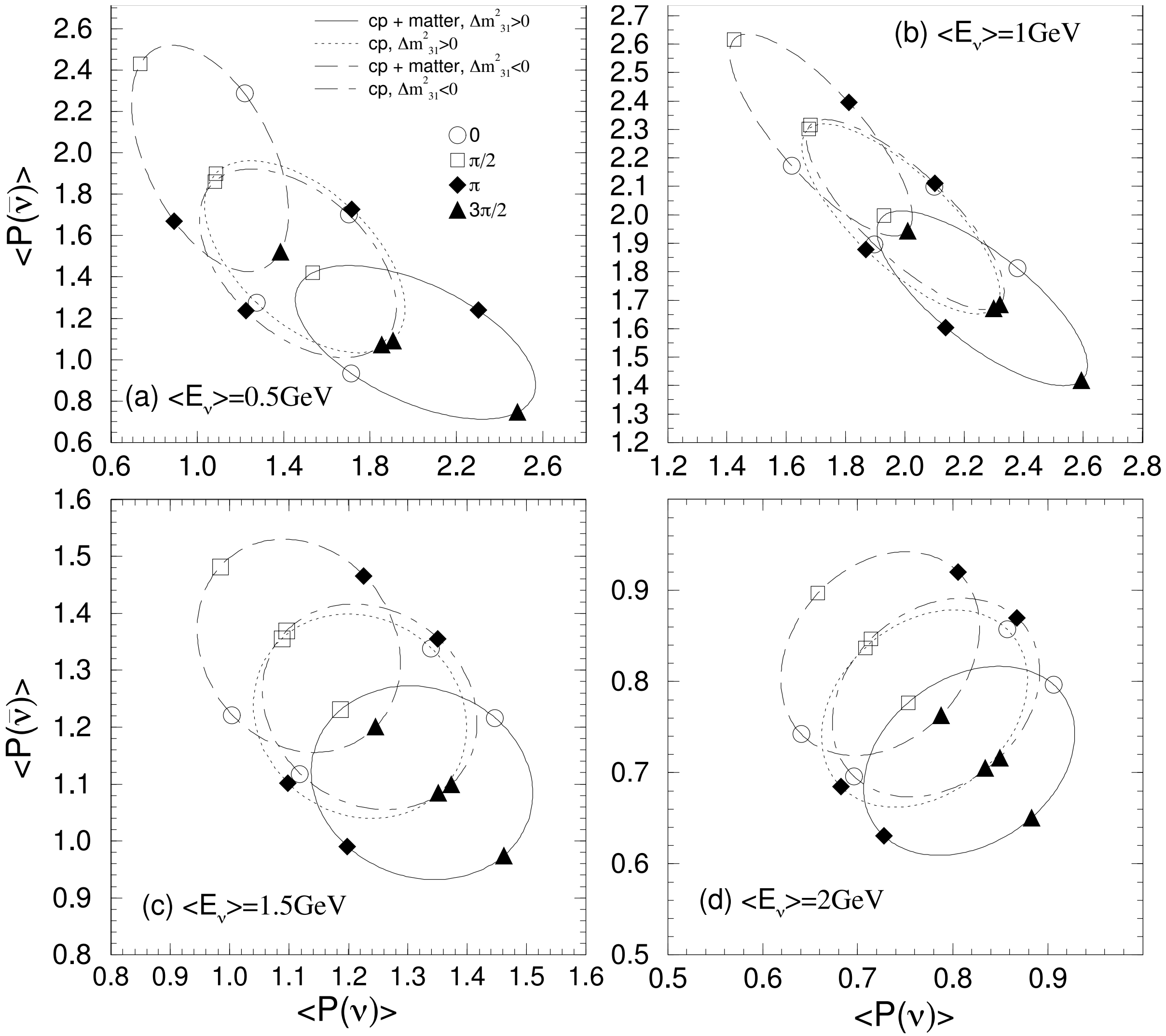
In order to ultimately measure a new source of CP-invariance violation, we will need to combine different measurements:

– oscillation of muon neutrinos and antineutrinos,

– oscillations at accelerator and reactor experiments,

– experiments with different baselines,

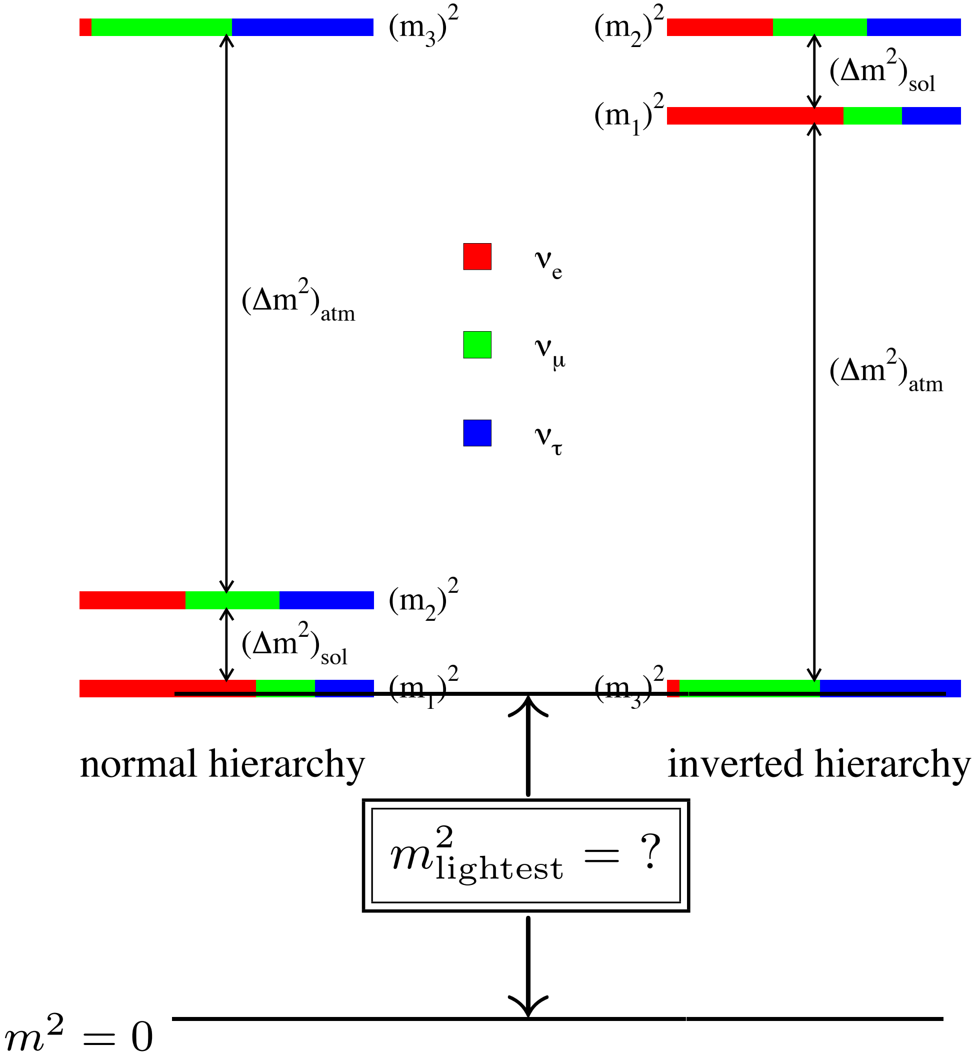
– etc.



Need to determine "other" oscillation parameters in order to realistically study CP-invariance violation.

[Minakata, Nunokawa, hep-ph/0108085]

5– What We Know We Don't Know (ii): 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.

The most direct probe of the lightest neutrino mass – precision measurements of β-decay

Observation of the effect of non-zero neutrino masses **kinematically**.

When a neutrino is produced, some of the energy exchanged in the process should be spent by the non-zero neutrino mass.

Typical effects are very, very small – we've never seen them! The most sensitive observable is the electron energy spectrum from tritium decay.

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

Why tritium? Small Q value, reasonable abundances. Required sensitivity proportional to m^2/Q^2.

In practice, this decay is sensitive to an effective "electron neutrino mass":

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

Experiments measure the **shape** of the end-point of the spectrum, not the value of the end point. This is done by counting events as a function of a low-energy cut-off. note: LOTS of Statistics Needed!

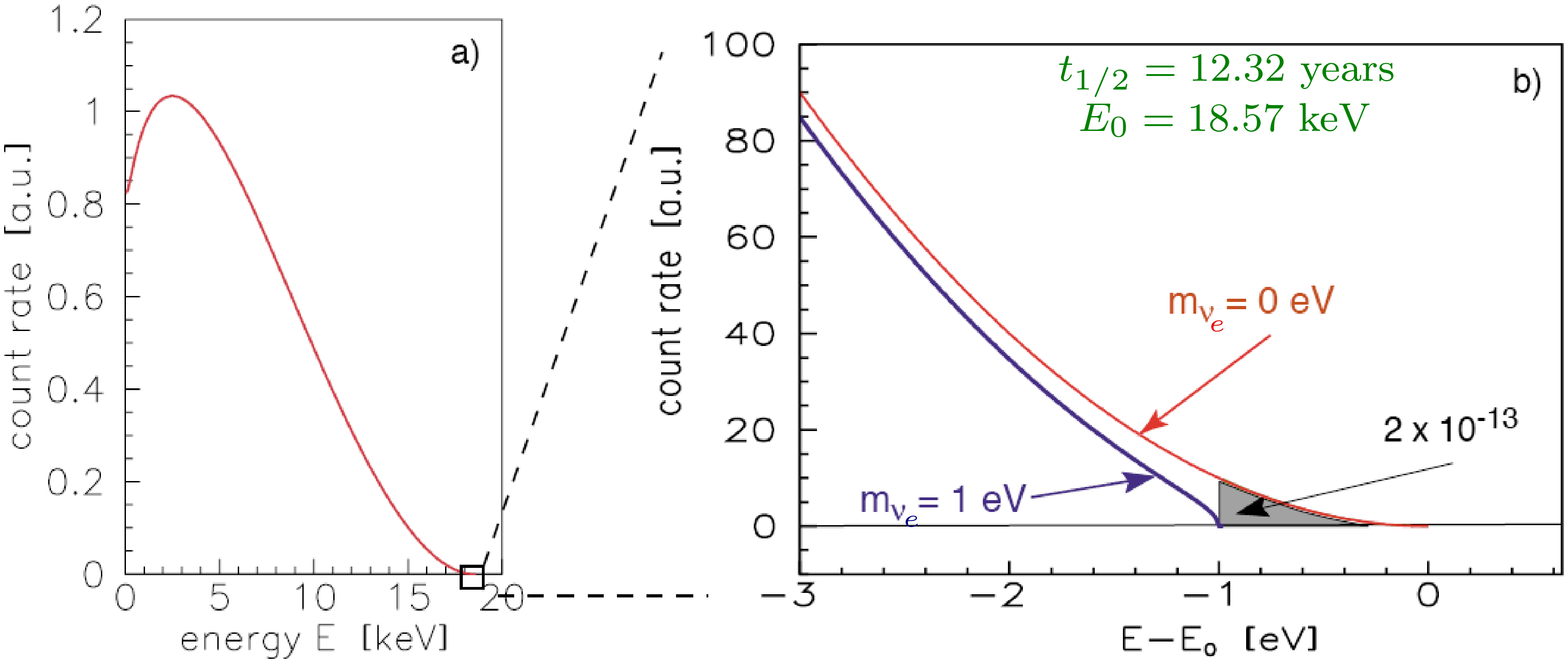


Figure 2: The electron energy spectrum of tritium β decay: (a) complete and (b) narrow region around endpoint E_0. The β spectrum is shown for neutrino masses of 0 and 1 eV.

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

(not your grandmother's table top experiment!)

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

Big Bang Neutrinos are Warm Dark Matter

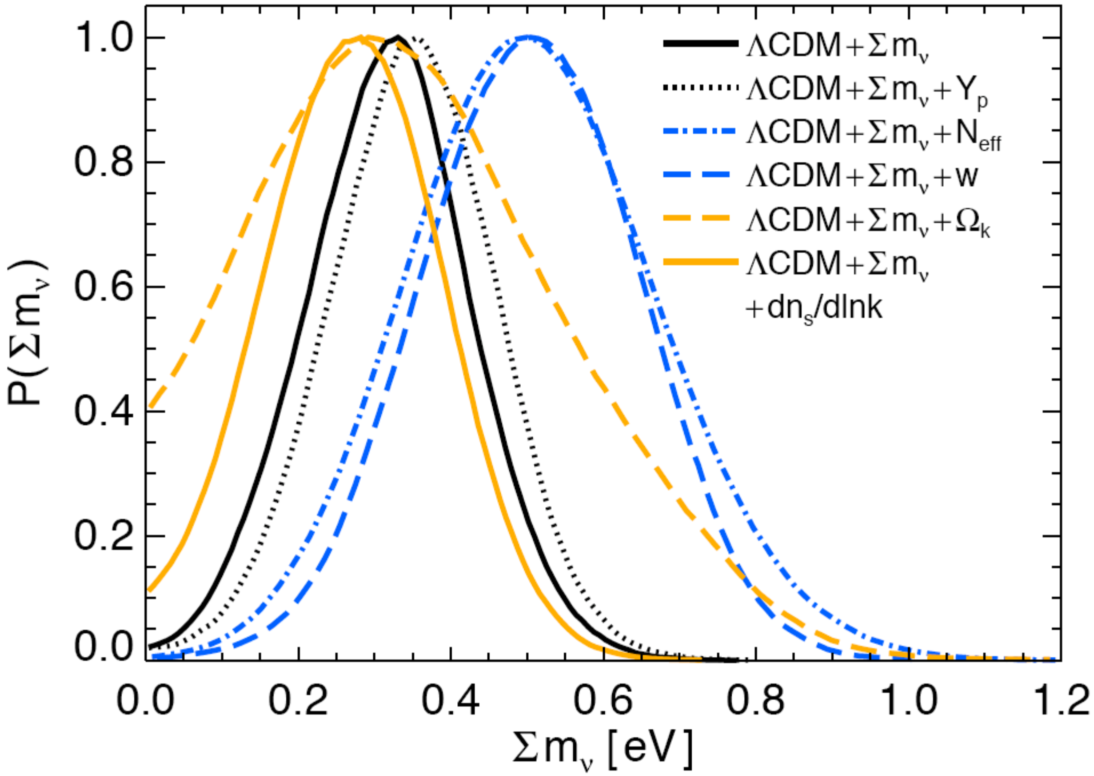


FIG. 10.— This figure illustrates the robustness of the neutrino mass detection to other parameter extensions. The marginalized one-dimensional posteriors for $\sum m_\nu$ are shown for two-parameter extensions to ΛCDM for the combined CMB+BAO+H_0+SPT$_{CL}$ data sets (for w, SNe are used instead of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

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

- Constrained by the Large Scale Structure of the Universe.

Constraints depend on

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

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

Big Bang Neutrinos are Warm Dark Matter

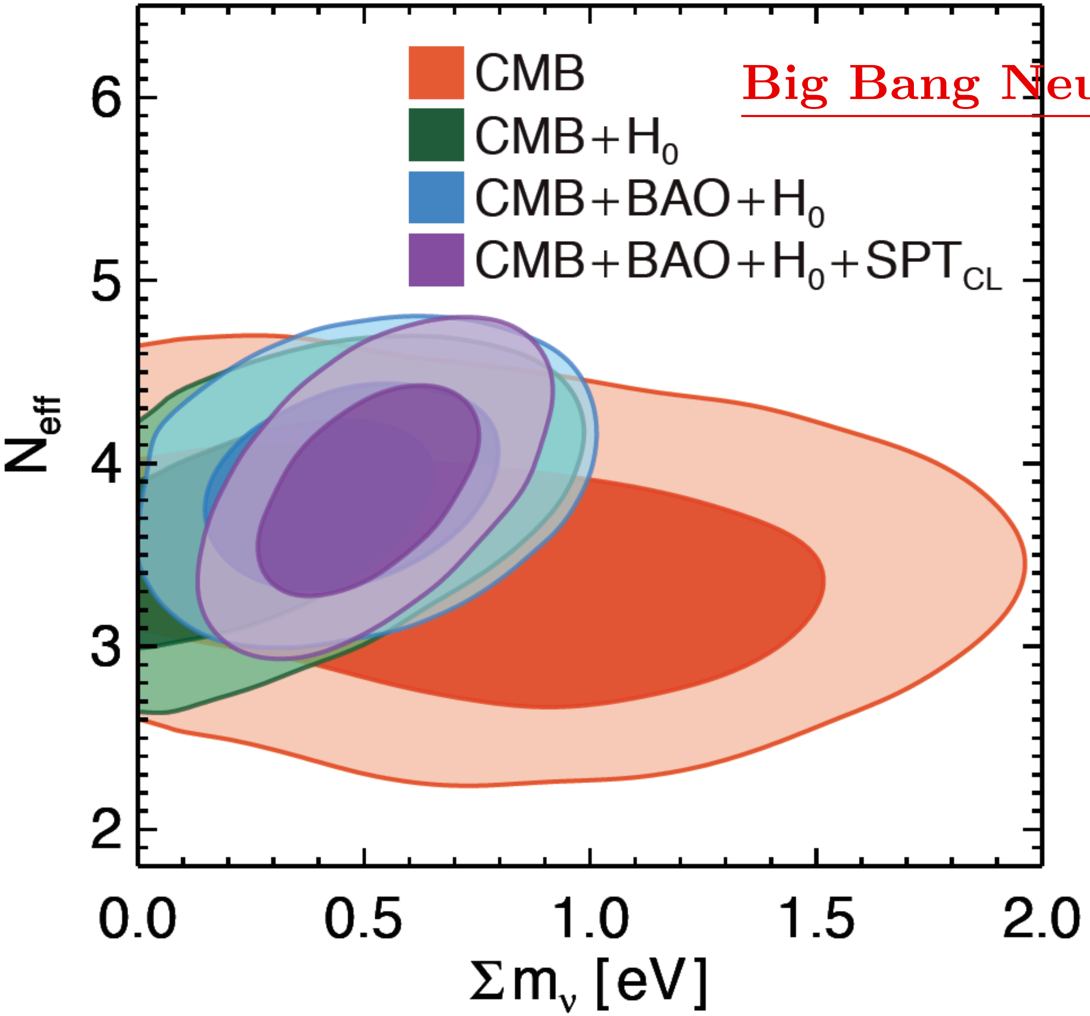


FIG. 18.— This figure demonstrates the impact of each combination of datasets on the constraints on $\sum m_\nu$ and $N_{\rm eff}$. The shaded contours are the 68% and 95% confidence intervals for the following data combinations: SPT+*WMAP7* (CMB; red), CMB+H_0 (green), CMB+H_0+BAO (blue), CMB+H_0+BAO+$\mathrm{SPT}_{\rm CL}$ (purple). The combined data are in $>2\,\sigma$ tension with the ΛCDM assumption of three massless neutrino species.

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

- Constrained by the Large Scale Structure of the Universe.

Constraints depend on

- Data set analysed;
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- . . .

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

Big Bang Neutrinos are Warm Dark Matter

Planck Collaboration: Cosmological parameters

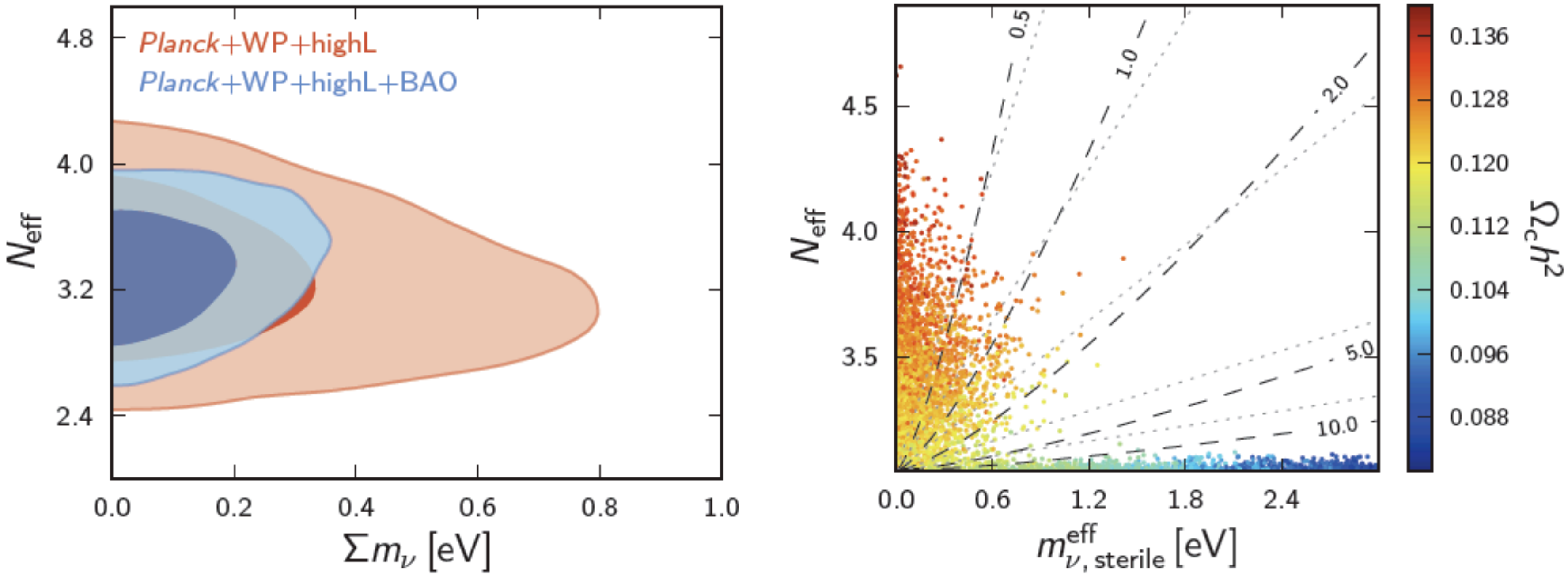
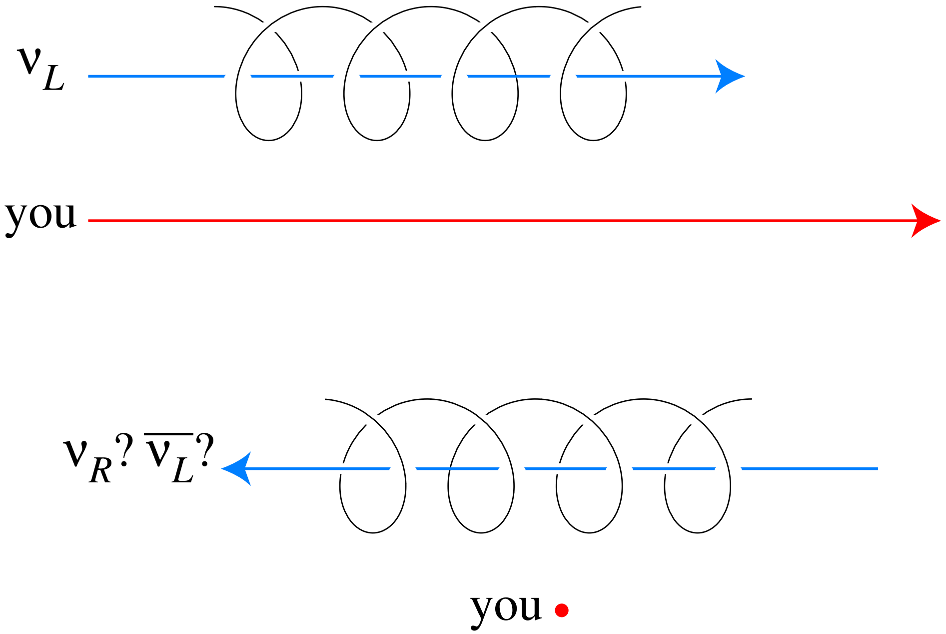


Fig. 28. *Left*: 2D joint posterior distribution between $N_{\rm eff}$ and $\sum m_\nu$ (the summed mass of the three active neutrinos) in models with extra massless neutrino-like species. *Right*: Samples in the $N_{\rm eff}$–$m^{\rm eff}_{\nu,\,\rm sterile}$ plane, colour-coded by $\Omega_c h^2$, in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

5– What We Know We Don't Know (iii) – 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 (Yet)?

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

Processes that are proportional to the Majorana nature of the neutrino vanish in the limit $m_\nu \to 0$. Since neutrinos masses are very small, the probability for these to happen is very, very small: $A \propto m_\nu/E$.

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

Weak Interactions are Purely Left-Handed (Chirality):

For example, in the scattering process $e^- + X \to \nu_e + X$, the electron neutrino is, in a reference frame where $m \ll E$,

$$|\nu_e\rangle \sim |L\rangle + \left(\frac{m}{E}\right)|R\rangle.$$

If the neutrino is a Majorana fermion, $|R\rangle$ behaves mostly like a "$\bar{\nu}_e$," (and $|L\rangle$ mostly like a "ν_e,") such that the following process could happen:

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

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

How many new CP-violating parameters in the neutrino sector?

If the neutrinos are Majorana fermions, there are more physical observables in the leptonic mixing matrix.

Remember the parameter counting in the quark sector:

$$\begin{array}{ll} 9 & (3\times 3 \text{ unitary matrix}) \\ \underline{-5} & (\text{relative phase rotation among six quark fields}) \\ 4 & (\text{3 mixing angles and 1 CP-odd phase}). \end{array}$$

If the neutrinos are Majorana fermions, the parameter counting is quite different: there are no right-handed neutrino fields to "absorb" CP-odd phases:

$$\begin{array}{rl} 9 & (3\times 3 \text{ unitary matrix}) \\ \underline{-3} & (\text{three right-handed charged lepton fields}) \\ 6 & (3 \text{ mixing angles and } 3 \text{ CP-odd phases}). \end{array}$$

There is CP-invariance violating parameters even in the 2 family case: $4-2=2$, one mixing angle, one CP-odd phase.

$$\mathcal{L} \supset \bar{e}_L U W^\mu \gamma_\mu \nu_L - \bar{e}_L (M_e) e_R - \overline{\nu_L^c} (M_\nu) \nu_L + H.c.$$

Write $U = E^{-i\xi/2} U' E^{i\alpha/2}$, where $E^{i\beta/2} \equiv \mathrm{diag}(e^{i\beta_1/2}, e^{i\beta_2/2}, e^{i\beta_3/2})$, $\beta = \alpha, \xi$

$$\mathcal{L} \supset \bar{e}_L U' W^\mu \gamma_\mu \nu_L - \bar{e}_L E^{i\xi/2} (M_e) e_R - \overline{\nu_L^c} (M_\nu) E^{-i\alpha} \nu_L + H.c.$$

ξ phases can be "absorbed" by e_R,

α phases cannot go away!

on the other hand

Dirac Case:

$$\mathcal{L} \supset \bar{e}_L U W^\mu \gamma_\mu \nu_L - \bar{e}_L (M_e) e_R - \bar{\nu}_R (M_\nu) \nu_L + H.c.$$

$$\mathcal{L} \supset \bar{e}_L U' W^\mu \gamma_\mu \nu_L - \bar{e}_L E^{i\xi/2} (M_e) e_R - \bar{\nu}_R (M_\nu) E^{-i\alpha/2} \nu_L + H.c.$$

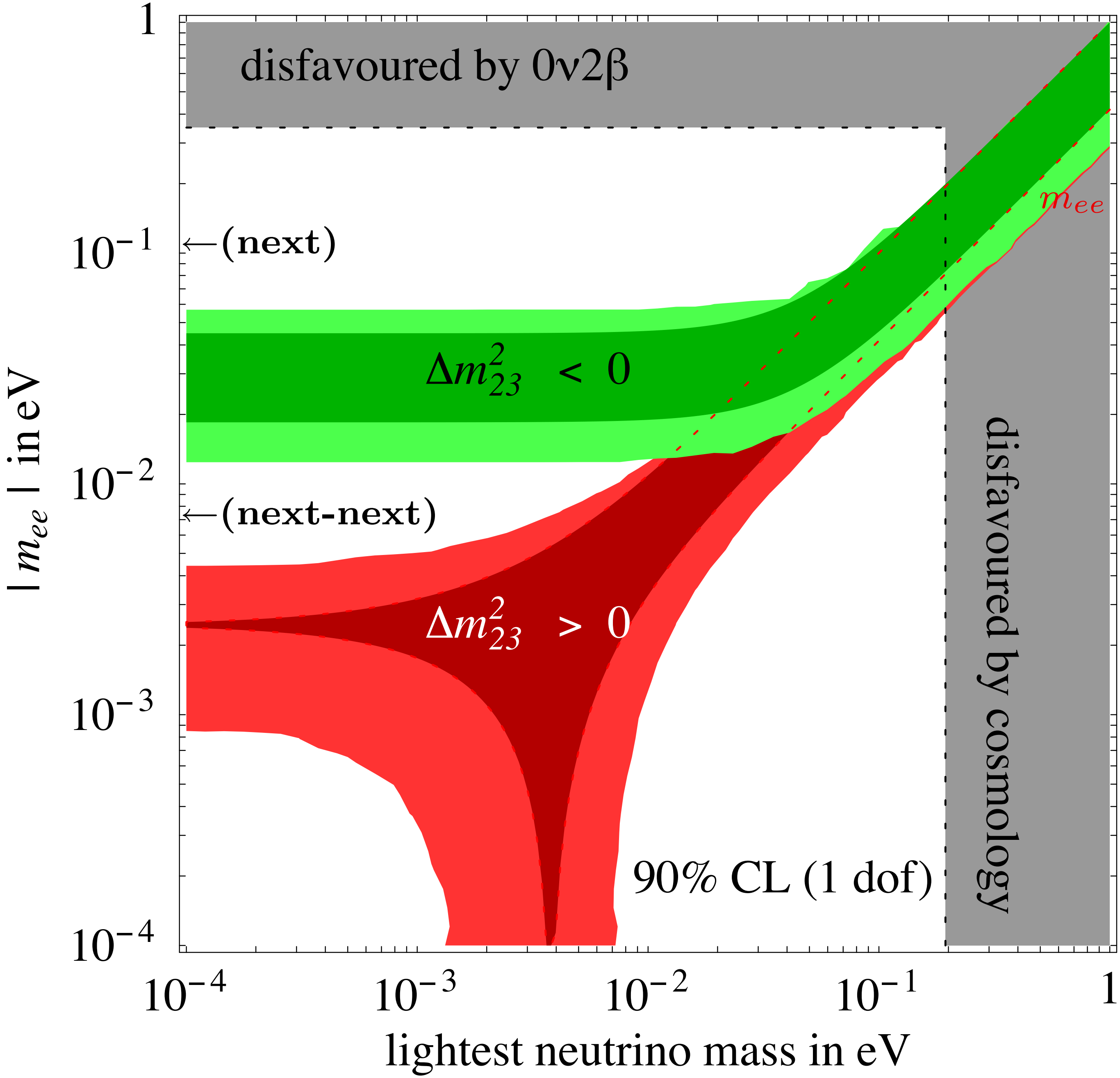
ξ phases can be "absorbed" by e_R, α phases can be "absorbed" by ν_R,

$$V_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix}' \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & e^{i\alpha_3/2} \end{pmatrix}.$$

It is easy to see that the Majorana phases never show up in neutrino oscillations ($A \propto U_{\alpha i} U^*_{\beta_i}$).

Furthermore, they only manifest themselves in phenomena that vanish in the limit $m_i \to 0$ – after all they are only physical if we “know” that lepton number is broken.

$$A(\alpha_i) \propto m_i/E \quad \to \quad \text{tiny!}$$



[U_{ei}^2 complex numbers]

↓

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

Depends on Majorana Phases

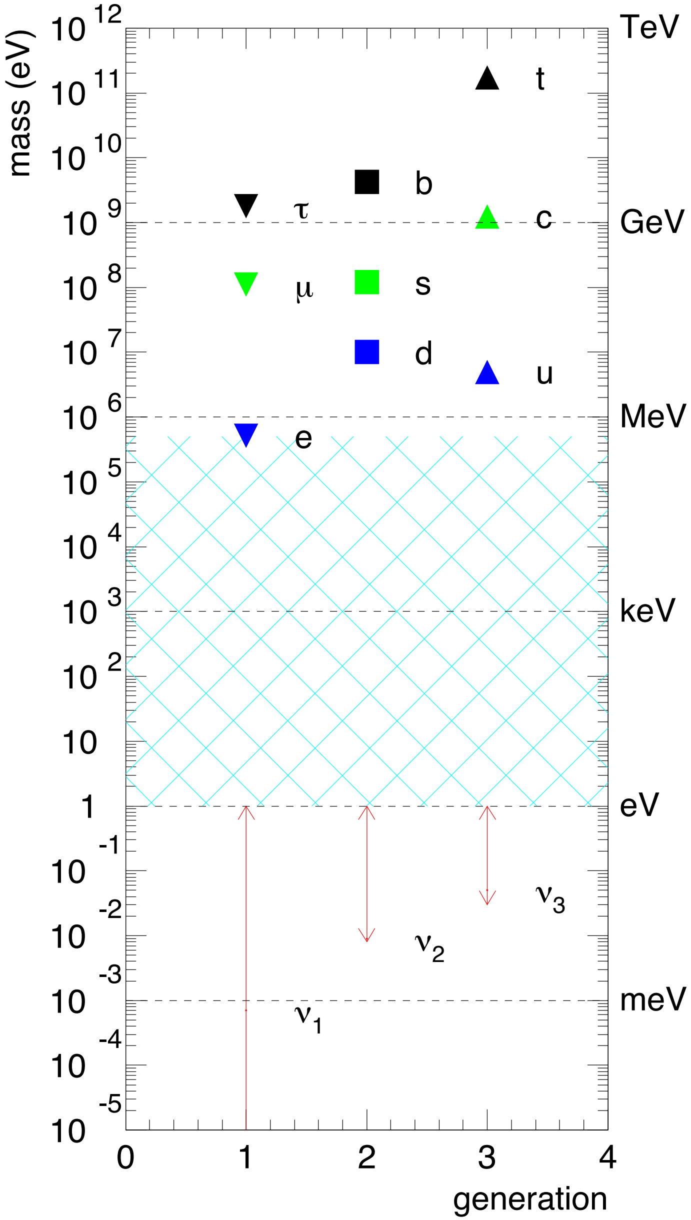
e.g. inverted hierarchy:

$$m_3 \ll m_1 \sim m_2 \sim \sqrt{\Delta m^2_{13}},$$

$$m_{ee} \sim \sqrt{\Delta m^2_{13}} \times$$
$$\times \left(\cos^2\theta_{12} + e^{i\alpha}\sin^2\theta_{12}\right).$$

$$m_{ee} > \sqrt{\Delta m^2_{13}} \cos 2\theta_{12}$$

[W. Rodejohann's talk]



NEUTRINOS HAVE MASS

albeit very tiny ones...

SO WHAT?

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 properly. These are in order of palpabiloity (these are personal. Feel free to complain)

- What is the physics behind electroweak symmetry breaking? (Higgs or not in SM).
- What is the dark matter? (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 – Is this "particle physics?").

Standard Model in One Slide, No Equations

The SM is a quantum field theory with the following defining characteristics:

- Gauge Group $(SU(3)_c \times SU(2)_{\rm L} \times U(1)_{\rm Y})$;
- Particle Content (fermions: Q, u, d, L, e, scalars: H).

Once this is specified, the SM is unambiguously determined:

- Most General Renormalizable Lagrangian;
- Measure All Free Parameters, and You Are Done! (after several decades of hard experimental work…)

If you follow these rules, neutrinos have no mass. Something has to give.

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, and it looks like it may be coming in the near/intermediate future!

The νSM – Everyone's Favorite Scenario

SM as an effective field theory – non-renormalizable operators

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

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

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

- Neutrino masses are small: $M \gg v \longrightarrow m_\nu \ll m_f$ ($f = e, \mu, u, d$, etc)
- Neutrinos are Majorana fermions – Lepton number is violated!
- νSM effective theory – not valid for energies above at most M.
- What is M? First naive guess is that M is the Planck scale – does not work. Data require $M < 10^{15}$ GeV (anything to do with the GUT scale?)

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

Note that this VERY similar to the “discovery” weak interactions. Imagine the following scenario:

$U(1)_{E\&M}\ +\ e(q=-1),\ \mu(q=-1),\ \nu_e(q=0),\ \nu_\mu(q=0).$

The most general renormalizable Lagrangian explains *all* QED phenomena once all couplings are known (α, m_f).

New physics: the muon decays! $\mu^-\to e^-\bar{\nu}_e\nu_\mu$. This can be interpreted as evidence of effective four fermion theory (nonrenormalizable operators):

$$-\frac{4G_F}{\sqrt{2}}\sum_\gamma g_\gamma\left(\bar{e}\Gamma^\gamma\nu\right)\left(\bar{\nu}\Gamma_\gamma\mu\right), \qquad \Gamma_\gamma = 1,\gamma_5,\gamma_\mu,\ldots$$

Prediction: will discover new physics at an energy scale **below** $\sqrt{1/G_F}\simeq 250$ GeV. We know how this turned out $\Rightarrow$ $W^\pm, Z^0$ discovered slightly below 100 GeV!

Full disclosure:

All higher dimensional operators are completely negligible, **except** those that mediate proton decay, like:

$$\frac{\lambda_B}{M^2}QQQL$$

The fact that the proton does not decay forces M/λ_B to be much larger than the energy scale required to explain neutrino masses.

Why is that? We don't know…

Example: the Seesaw Mechanism

A simple[a], renormalizable Lagrangian that allows for neutrino masses is

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

where N_i ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions. $\mathcal{L}_\nu$ is the most general, renormalizable Lagrangian consistent with the SM gauge group and particle content, plus the addition of the N_i fields.

After electroweak symmetry breaking, $\mathcal{L}_\nu$ describes, besides all other SM degrees of freedom, six Majorana fermions: **six neutrinos.**

---

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

To be determined from data: λ and M.

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

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

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

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

we can impose very, very few experimental constraints on M

What We Know About M:

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

  The symmetry of $\mathcal{L}_\nu$ is enhanced: $U(1)_{B-L}$ is an exact global symmetry of the Lagrangian if all M_i vanish. Small M_i values are 'tHooft natural.

- $M \gg \mu$: the six neutrinos split up into three mostly active, light ones, and three, mostly sterile, heavy ones. The light neutrino mass matrix is given by $m_{\alpha\beta} = \sum_i \mu_{\alpha i} M_i^{-1} \mu_{\beta i}$ $[m = 1/\Lambda \ \Rightarrow \ \Lambda = M/\mu^2]$.

  This the **seesaw mechanism.** Neutrinos are Majorana fermions. Lepton number is not a good symmetry of $\mathcal{L}_\nu$, even though L-violating effects are hard to come by.

- $M \sim \mu$: six states have similar masses. Active–sterile mixing is very large. This scenario is (generically) ruled out by active neutrino data (atmospheric, solar, KamLAND, K2K, etc).

[ASIDE: 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.

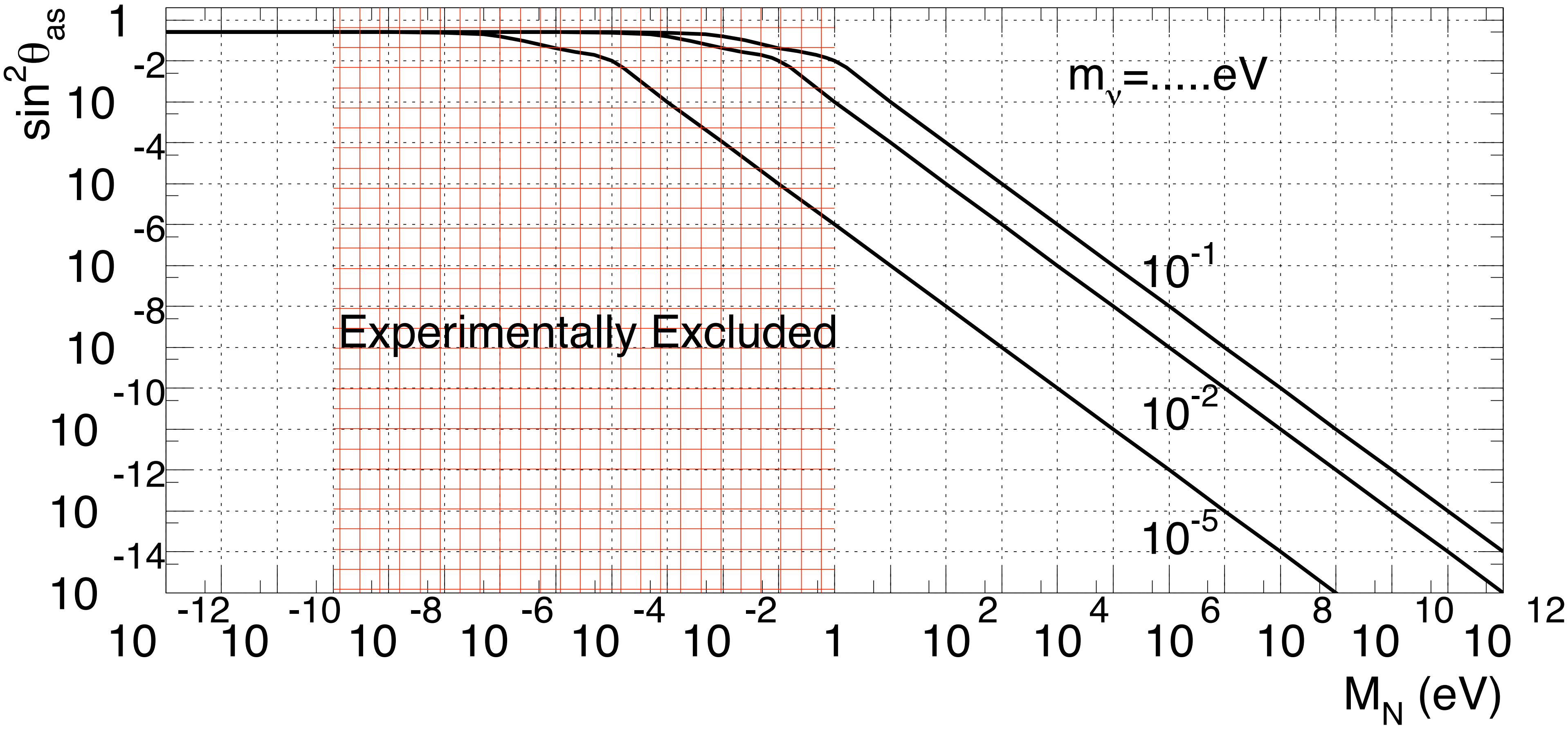
In the case of the seesaw,

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

so neutrino masses are small if either

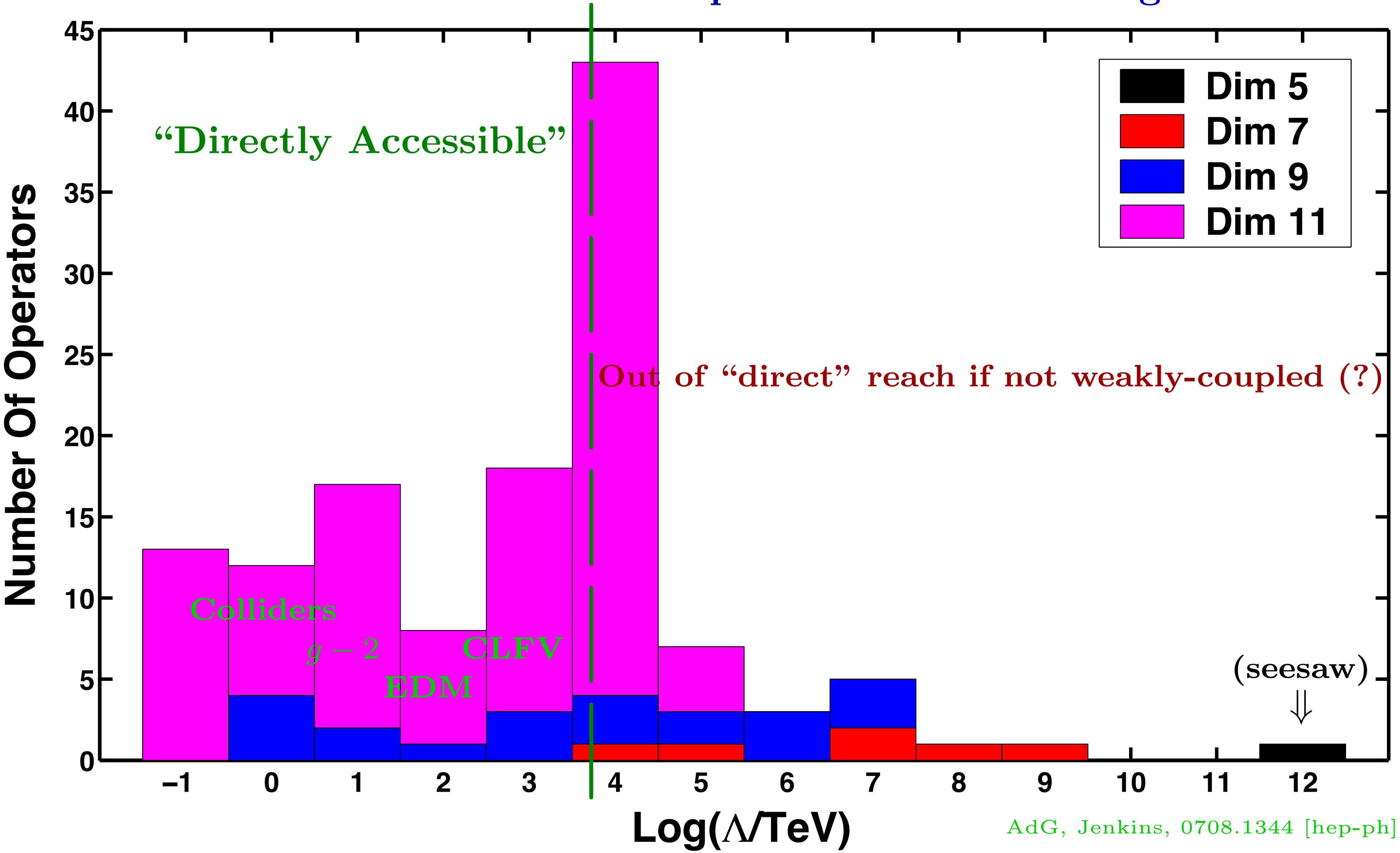
- they are generated by physics at a very high energy scale $M \gg v$ (high-energy seesaw); or
- they arise out of a very weak coupling between the SM and a new, hidden sector (low-energy seesaw); or
- cancellations among different contributions render neutrino masses accidentally small ("fine-tuning").

Constraining the Seesaw Lagrangian



[AdG, Huang, Jenkins, arXiv:0906.1611]

This is Just the Tip of the Model-Iceberg!



AdG, Jenkins, 0708.1344 [hep-ph]

Understanding Fermion Mixing

The other puzzling phenomenon uncovered by the neutrino data is the fact that Neutrino Mixing is Strange. What does this mean?

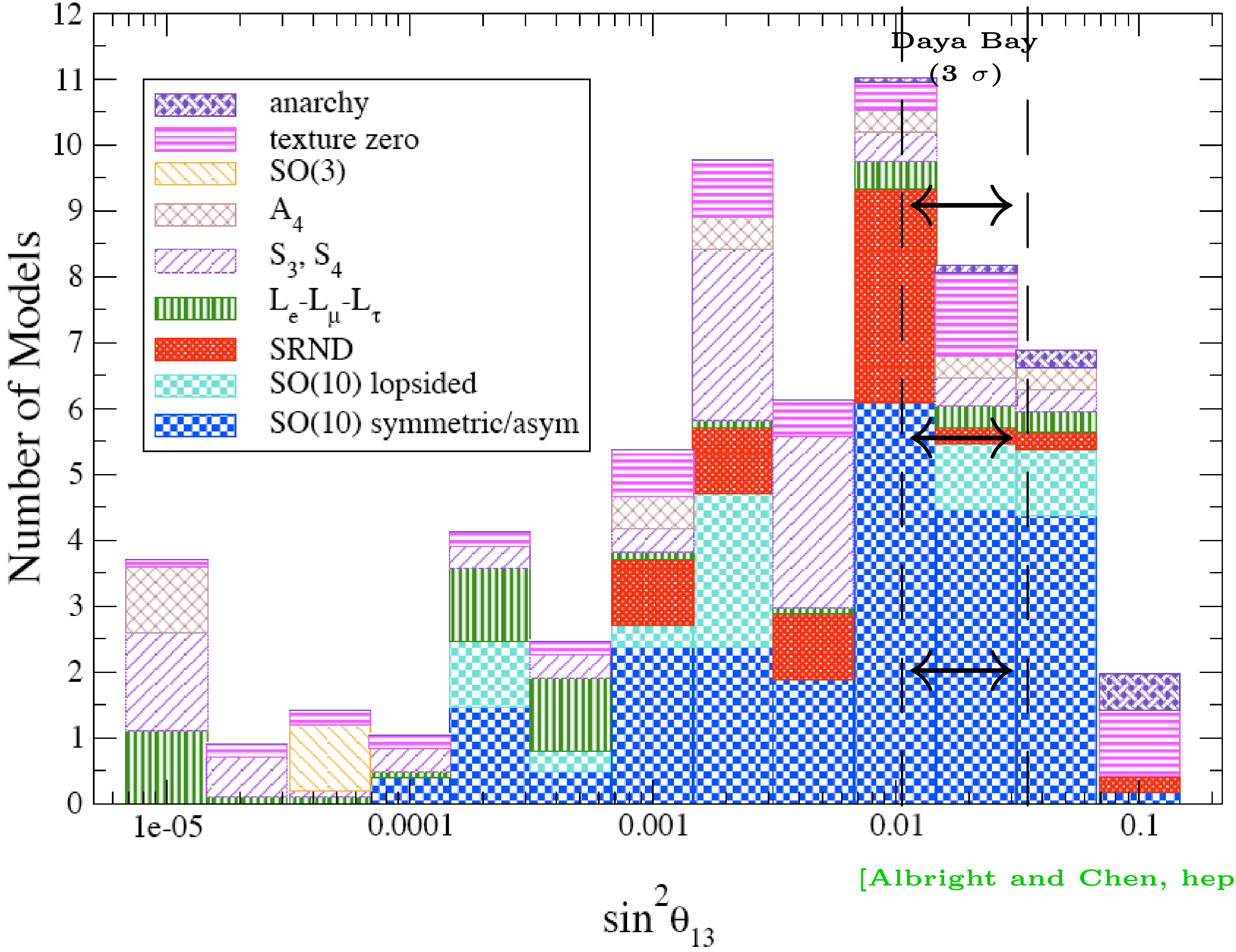
It means that lepton mixing is very different from quark mixing:

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

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

$\boxed{\text{WHY?}}$

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



[Albright and Chen, hep-ph/0608137]

"Left-Over" Predictions: δ, mass-hierarchy, $\cos 2\theta_{23}$. More important: CORRELATIONS!

Lepton Mixing Anarchy is the hypothesis that there is *no symmetry principle* behind the leptonic mixing matrix U.

In more concrete terms, it postulates that the observed leptonic mixing matrix can be described as the result of a *random draw* from an unbiased distribution of unitary 3×3 matrices.

This is *not a very ambitious model.* It does not make predictions for the values of any of the mixing parameters, nor does it predict any correlations among the different mixing parameters. It does not, obviously, allow one to reduce the number of mixing parameters compared to those in the lepton mixing sector of the νSM.

The Anarchy hypothesis, however, *does make some predictions.* It predicts a *probability distribution* for the different parameters that parameterize U. The distributions are parameterization dependent, but unique once a parameterization is fixed.

[Murayama et al, hep-ph/9911341, hep-ph/0009174, hep-ph/0301050, 1204.1249]

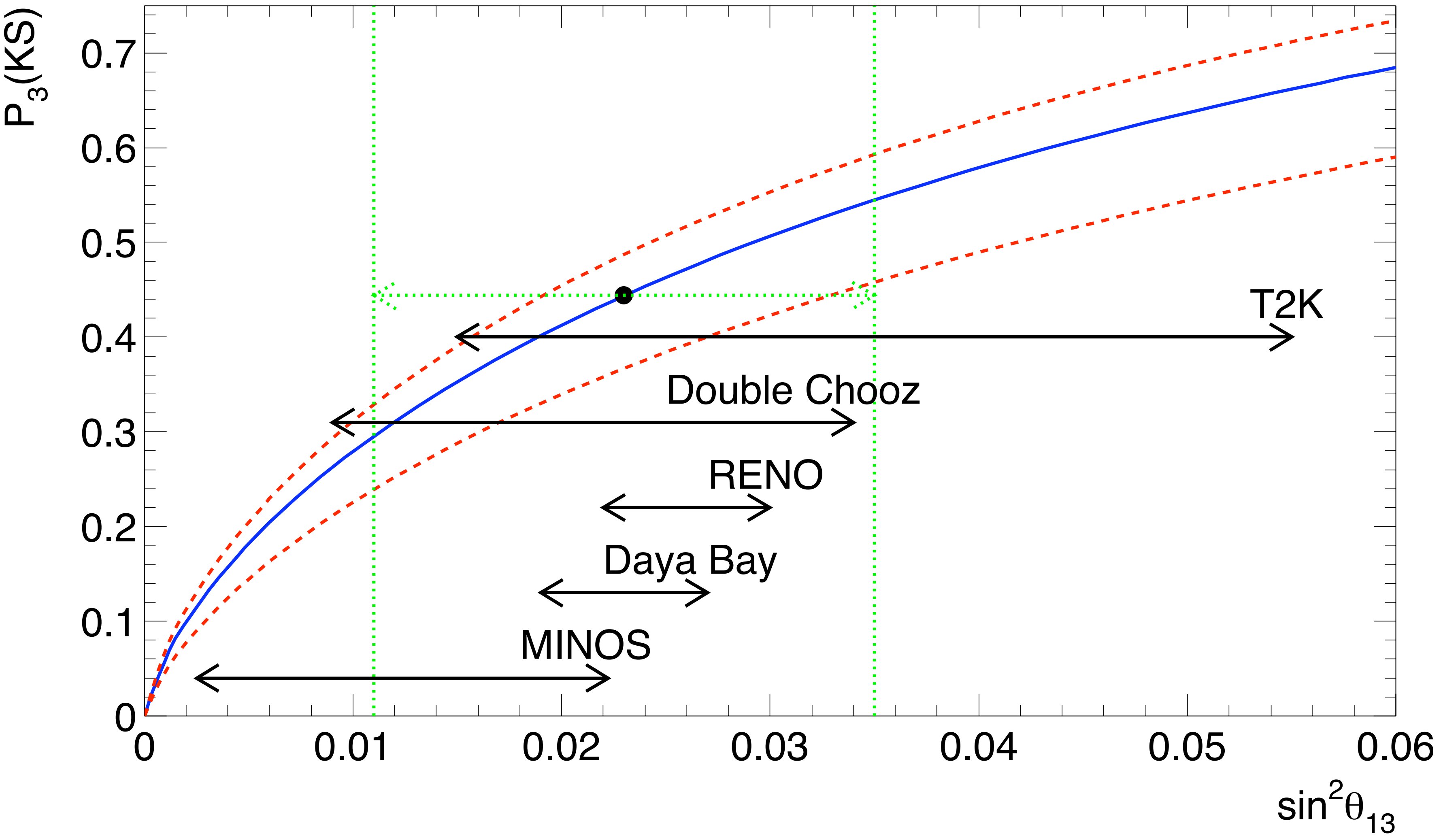
The probability distributions, first derived by Haba and Murayama, hep-ph/0009174, are easy to obtain. The idea is that they are invariant under a basis redefinition of the neutrino weak eigenstates, i.e, weak-basis independent. They are given by the *invariant Haar measure* of $U(3)$ (assuming that U is a 3×3 unitary matrix).

This is similar to obtaining the probability distribution for picking a point on the surface of a sphere from $\mathrm{d}A = \mathrm{d}\cos\theta\mathrm{d}\phi$. The probability density is flat in ϕ and flat in $\cos\theta$.

For unitary 3×3 matrices, using the standard PDG parameterization, one gets that the probability distribution is **flat** in

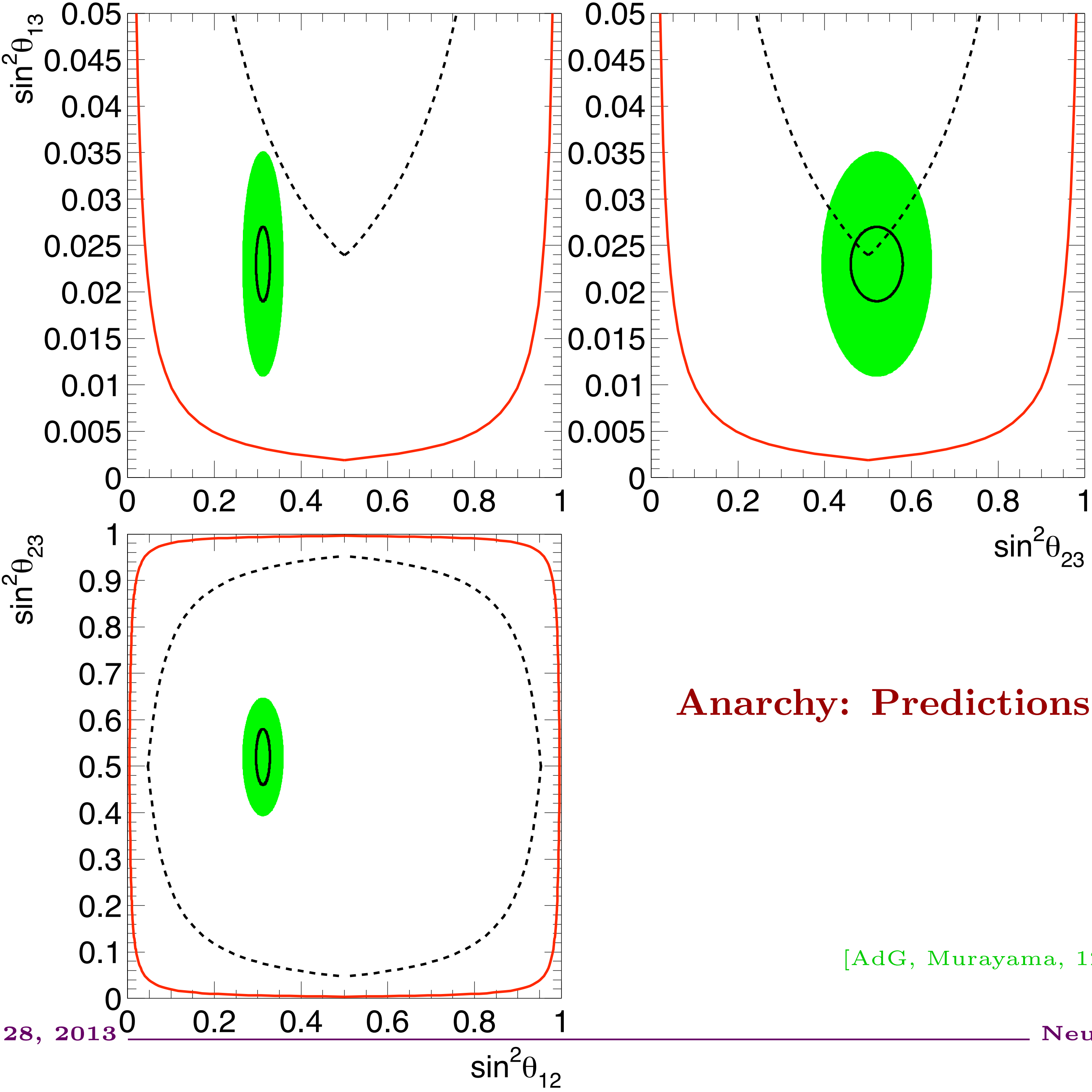
$$\sin^2\theta_{12} \qquad \sin^2\theta_{23} \qquad \cos^4\theta_{13} \qquad \delta \qquad \phi_{1,2} \text{ (Majorana phases).}$$

Neutrino Mixing Anarchy: Alive and Kicking!



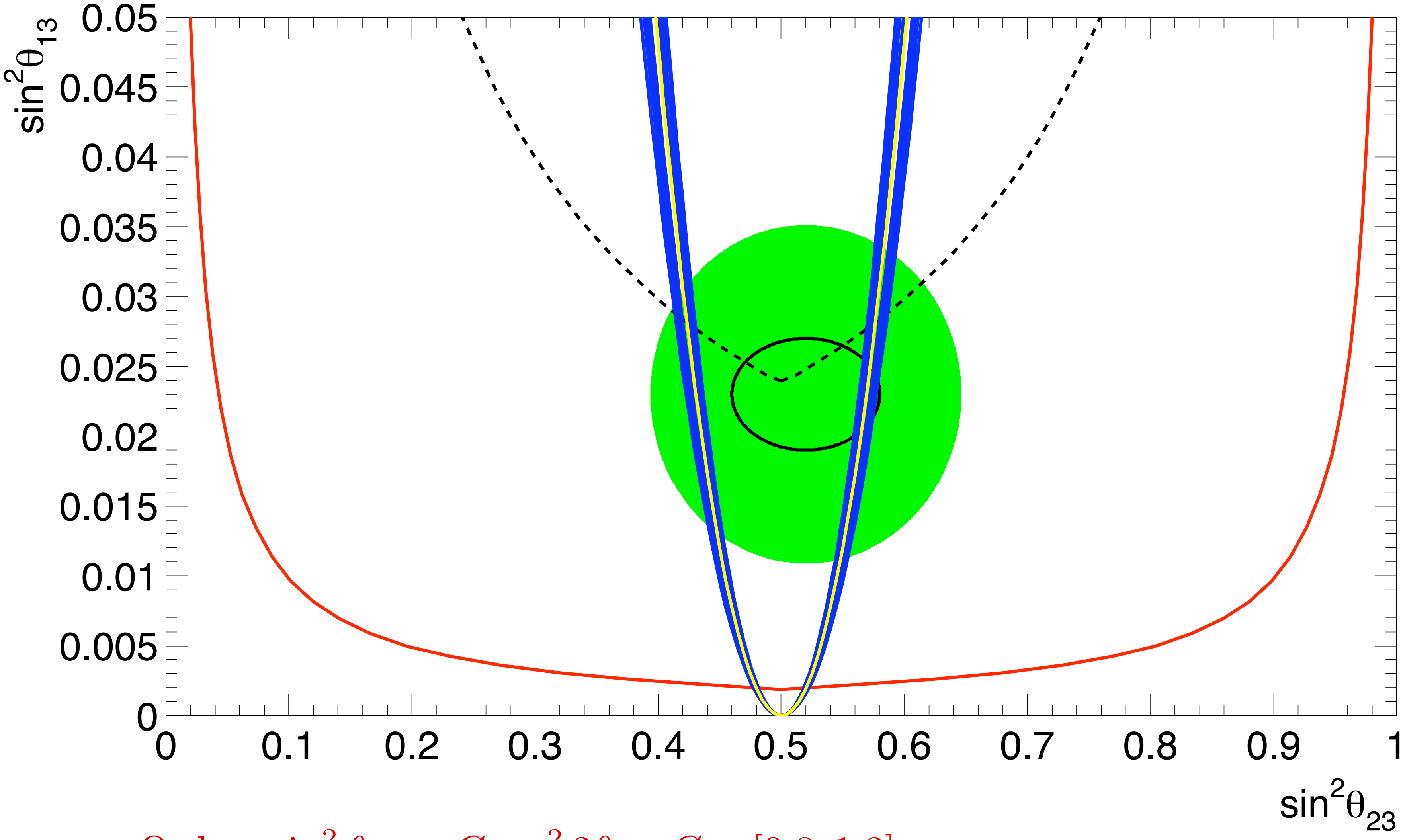
[AdG, Murayama, 1204.1249]

Anarchy: Predictions



[AdG, Murayama, 1204.1249]

Anarchy vs. Order — more precision required!



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

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How Do We Learn More?

In order to learn more, we need more information. Any new data and/or idea is welcome, including

- searches for charged lepton flavor violation;

  ($\mu \to e\gamma$, $\mu \to e$-conversion in nuclei, etc)

- searches for lepton number violation;

  (neutrinoless double beta decay, etc)

- precision measurements of the neutrino oscillation parameters;

  (Daya Bay, NOνA, etc)

- searches for fermion electric/magnetic dipole moments

  (electron edm, muon $g-2$, etc);

- precision studies of neutrino – matter interactions;

  (Minerνa, NuSOnG, etc)

- collider experiments:

  (LHC, etc)

  - *Can* we "see" the physics responsible for neutrino masses at the LHC? – YES!

    Must we see it? – NO, but we won't find out until we try!
  - we need to understand the physics at the TeV scale before we can really understand the physics behind neutrino masses (is there low-energy SUSY?, etc).

CONCLUSIONS

The venerable Standard Model has finally sprung a leak – neutrinos are not massless!

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 νSM Lagrangian. In order to decide which one is "correct" (required in order to attack 2. and 3. above) we must uncover the faith 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? (A. Ibarra's talk)

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., $M_{\rm seesaw} \simeq 10^{14}$ GeV).

8. Finally, we need to resolve the short baseline anomalies (W. Rodejohann's talk). Life could be much more interesting!


"That's all Folks!"