Neutrino Physics Theory

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Outline

1. What We Have Learned About Neutrinos;
2. What We Know We Don't Know;
3. Ideas for Neutrino Masses (and Lepton Mixing), with Consequences;
4. Conclusions.

What We've Learned About Neutrinos – Last 10 Years:

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.

- $\nu_\mu \to \nu_\tau$ and $\bar{\nu}_\mu \to \bar{\nu}_\tau$ — atmospheric experiments ["indisputable"];
- $\nu_e \to \nu_{\mu,\tau}$ — solar experiments ["indisputable"];
- $\bar{\nu}_e \to \bar{\nu}_{\rm other}$ — reactor neutrinos ["indisputable"];
- $\nu_\mu \to \nu_{\rm other}$ — accelerator experiments ["indisputable"].

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

[Maltoni and Schwetz, arXiv: 0812.3161]

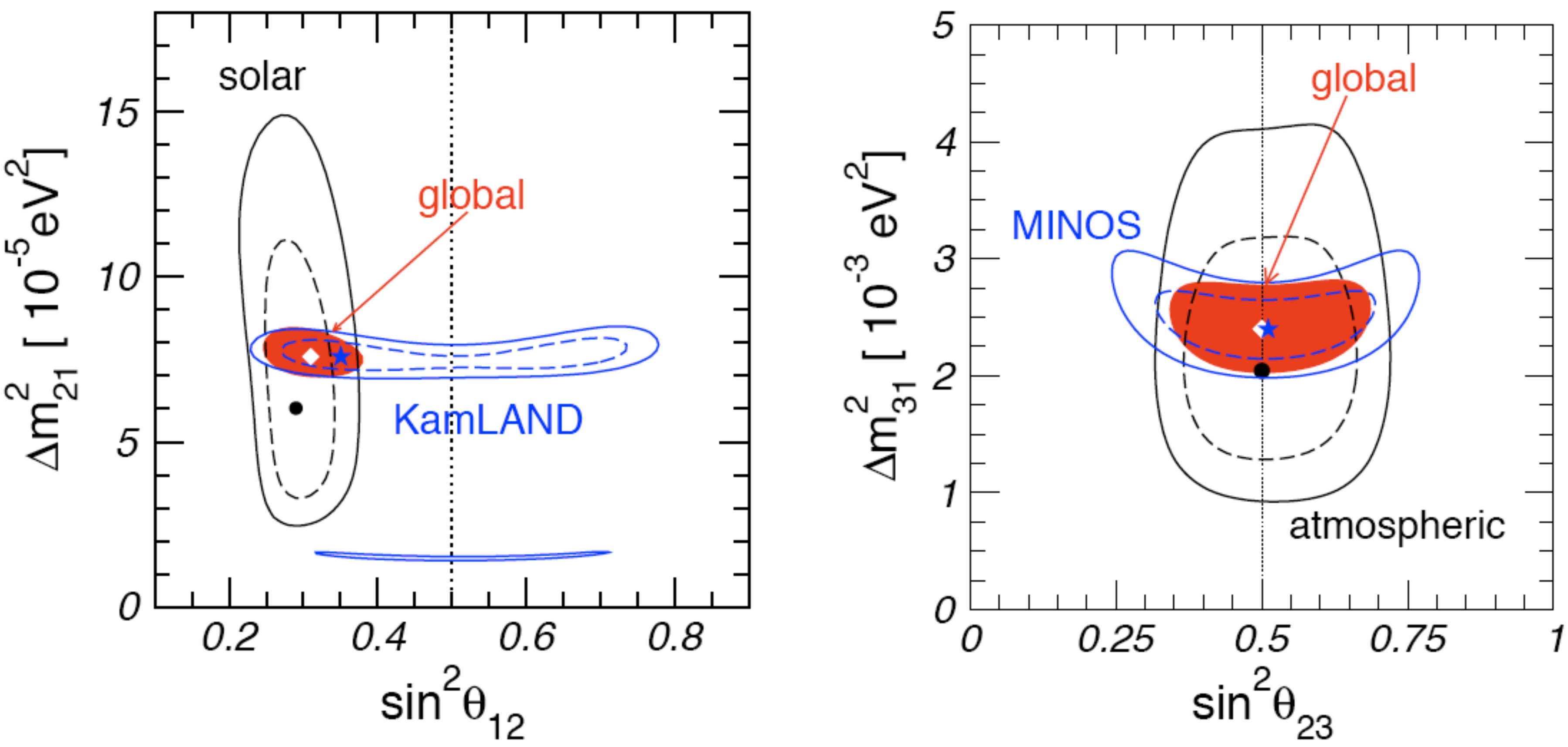


Figure 1: Determination of the leading "solar" and "atmospheric" oscillation parameters [1]. We show allowed regions at 90% and 99.73% CL (2 dof) for solar and KamLAND (left), and atmospheric and MINOS (right), as well as the 99.73% CL regions for the respective combined analyses.

[Also, solar neutrino oscillations very non-trivial (LMA) → See Cristiano Galbiati's talk]

Previous fits shown assuming two-flavor mixing. Of course, there are three neutrinos...

Phenomenological Understanding of Neutrino Masses & Mixing

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

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 AdG, Jenkins, arXiv:0804.3627]

Three Flavor Mixing Hypothesis Fits All Data Really Well.

⇒ Good Measurements of Oscillation Observables

	Ref. [1]		Ref. [2] (MINOS updated)	
parameter	best fit $\pm 1\sigma$	3σ interval	best fit $\pm 1\sigma$	3σ interval
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.05–8.34	$7.67^{+0.22}_{-0.21}$	7.07–8.34
Δm^2_{31} $[10^{-3}\text{eV}^2]$	$\pm 2.40^{+0.12}_{-0.11}$	$\pm(2.07–2.75)$	-2.39 ± 0.12 $+2.49 \pm 0.12$	$-(2.02–2.79)$ $+(2.13–2.88)$
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.25–0.37	$0.321^{+0.023}_{-0.022}$	0.26–0.40
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.36–0.67	$0.47^{+0.07}_{-0.06}$	0.33–0.64
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.056	0.003 ± 0.015	≤ 0.049

Table 1: Determination of three–flavour neutrino oscillation parameters from 2008 global data [1, 2].

[1] Schwetz, Tortola and Valle, arXiv:0808.2016

[2] Gonzalez-Garcia and Maltoni, arXiv:0704.1800

[Maltoni and Schwetz, arXiv: 0812.3161]

[Maltoni and Schwetz, arXiv: 0812.3161]

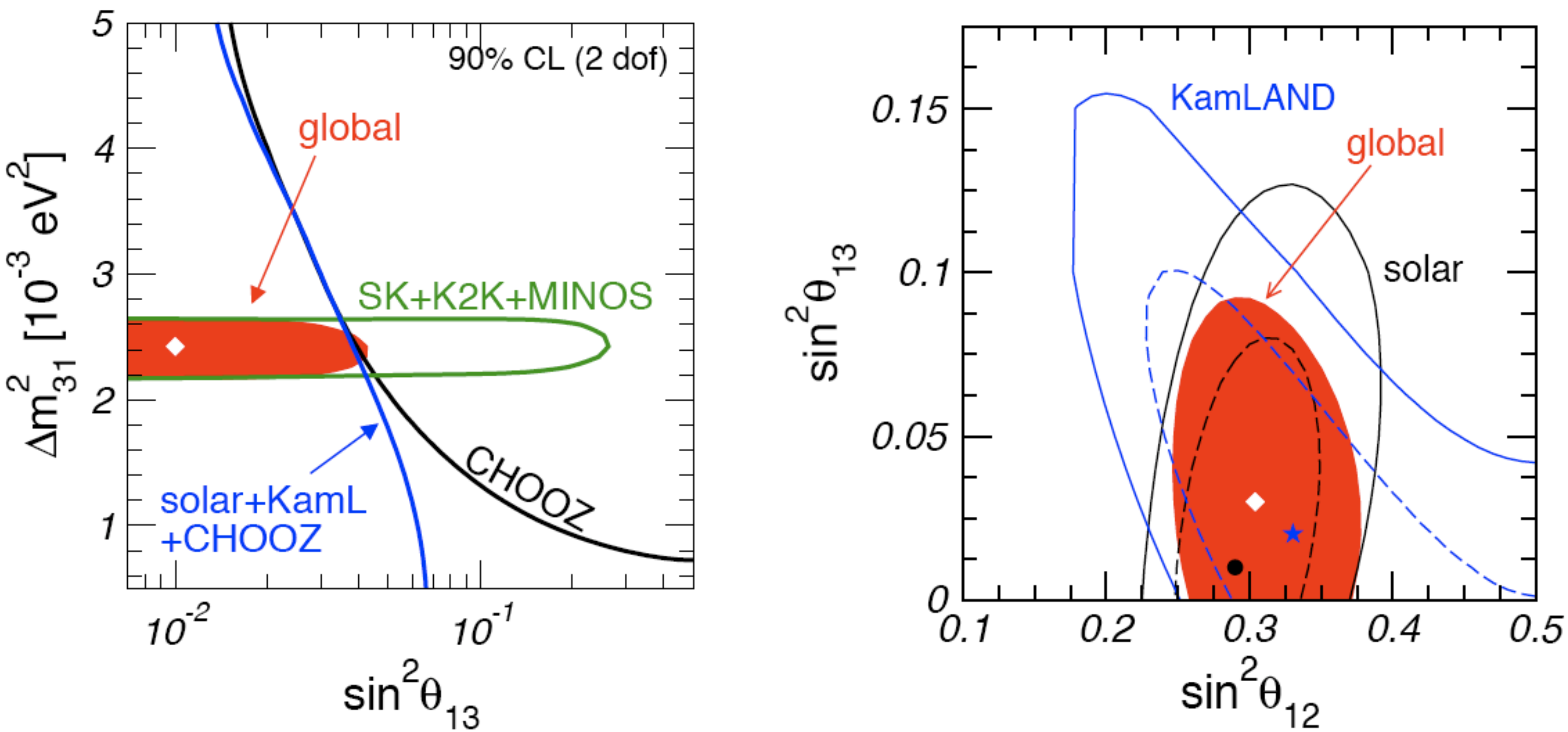
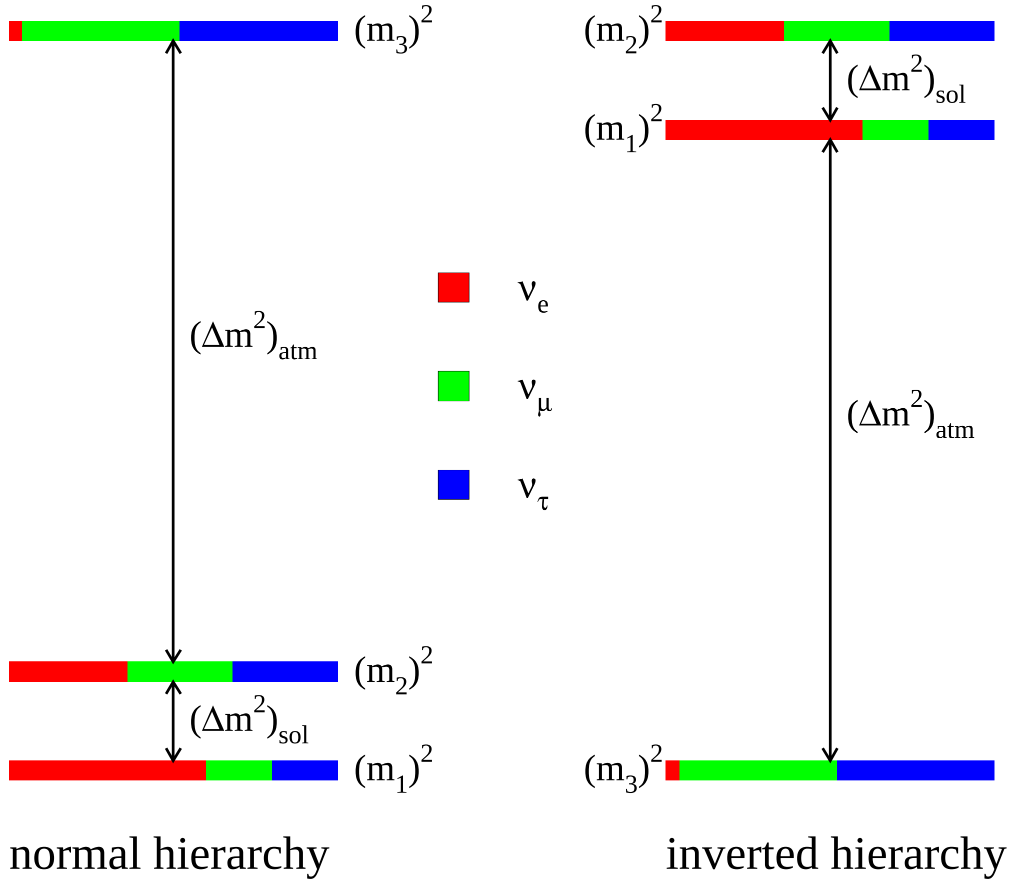


Figure 2: Left: Constraints on $\sin^2\theta_{13}$ from the interplay of different parts of the global data. Right: Allowed regions in the $(\theta_{12}-\theta_{13})$ plane at 90% and 99.73% CL (2 dof) for solar and KamLAND, as well as the 99.73% CL region for the combined analysis. Δm^2_{21} is fixed at its best fit point. The dot, star, and diamond indicate the best fit points of solar, KamLAND, and combined data, respectively.

"Hint" for non-zero $\sin^2\theta_{13}$? You decide. . . (see claim by Fogli et al., arXiv:0806.2649)

What We Know We Don't Know (1): Missing Oscillation Parameters

[see talk by Lindley Winslow]

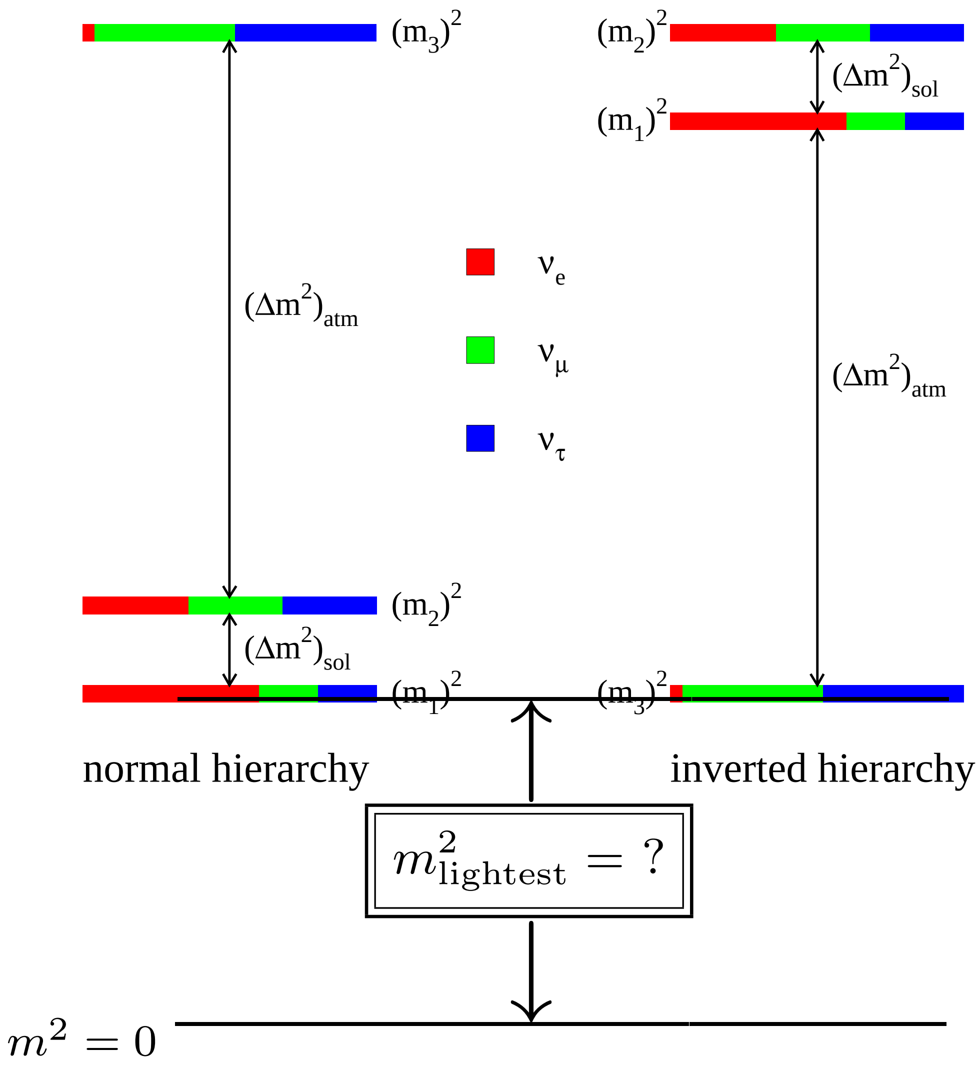


- What is the ν_e component of ν_3? $(\theta_{13} \neq 0?)$
- Is CP-invariance violated in neutrino oscillations? $(\delta \neq 0, \pi?)$
- Is ν_3 mostly ν_μ or ν_τ? $(\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4?)$
- What is the neutrino mass hierarchy? $(\Delta m^2_{13} > 0?)$

$\Rightarrow$ 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 Know We Don't Know (2): 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: $m^2_{\rm lightest} < 1~\text{eV}^2$

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.

Most direct probe of the lightest neutrino mass – β-decay spectrum

Kinemarical Effect of Non-Zero m_ν. In practice sensitive to "electron neutrino mass":

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

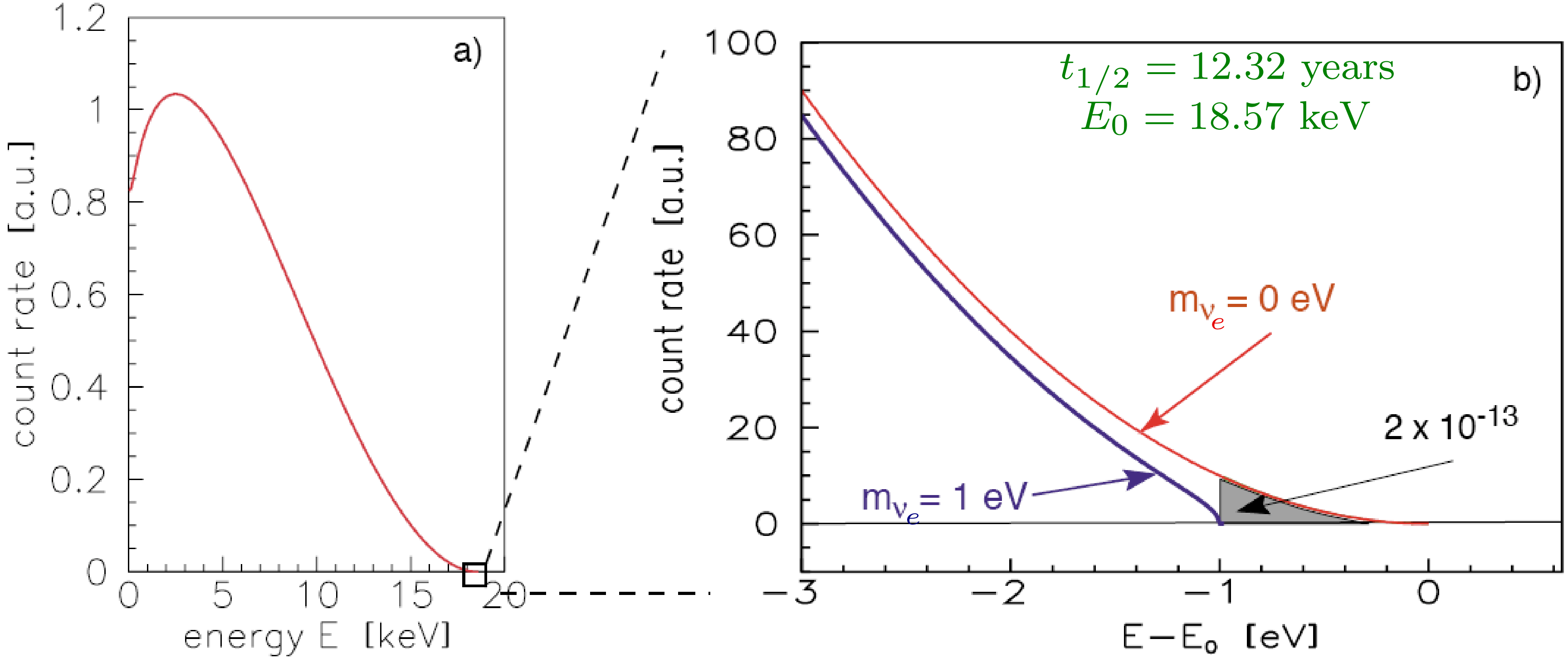


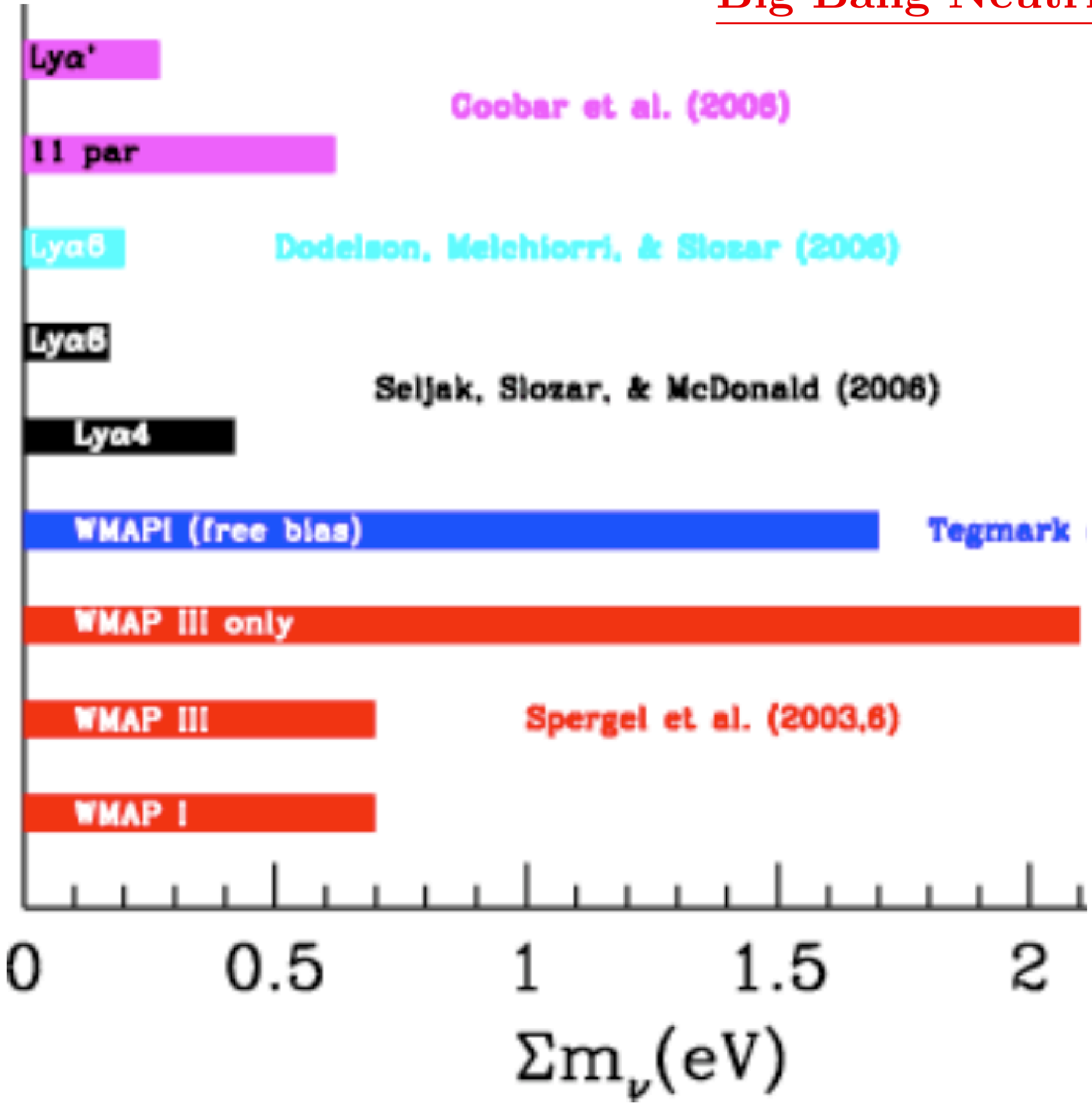
Figure 2: The electron energy spectrum of tritium β decay: (a) complete and (b) narrow region around endpoint E_0. The β spectrum is shown for neutrino masses of 0 and 1 eV.

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



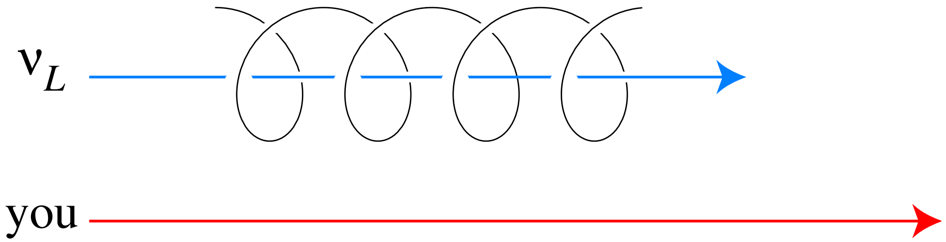
- Constrained by the Large Scale Structure of the Universe.

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?

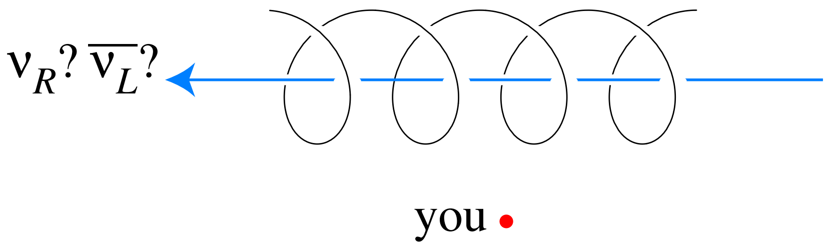
What We Know We Don't Know (3) – Are Neutrinos Majorana Fermions?



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

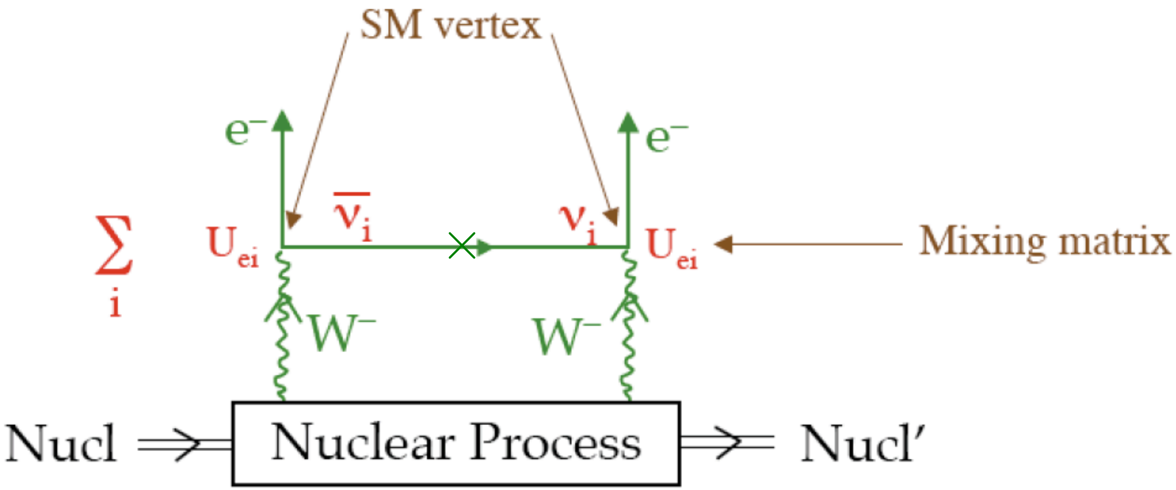
The "smoking gun" signature is the observation of LEPTON NUMBER violation. This is easy to understand: Majorana neutrinos are their own antiparticles and, therefore, cannot carry "any" quantum numbers — including lepton number.

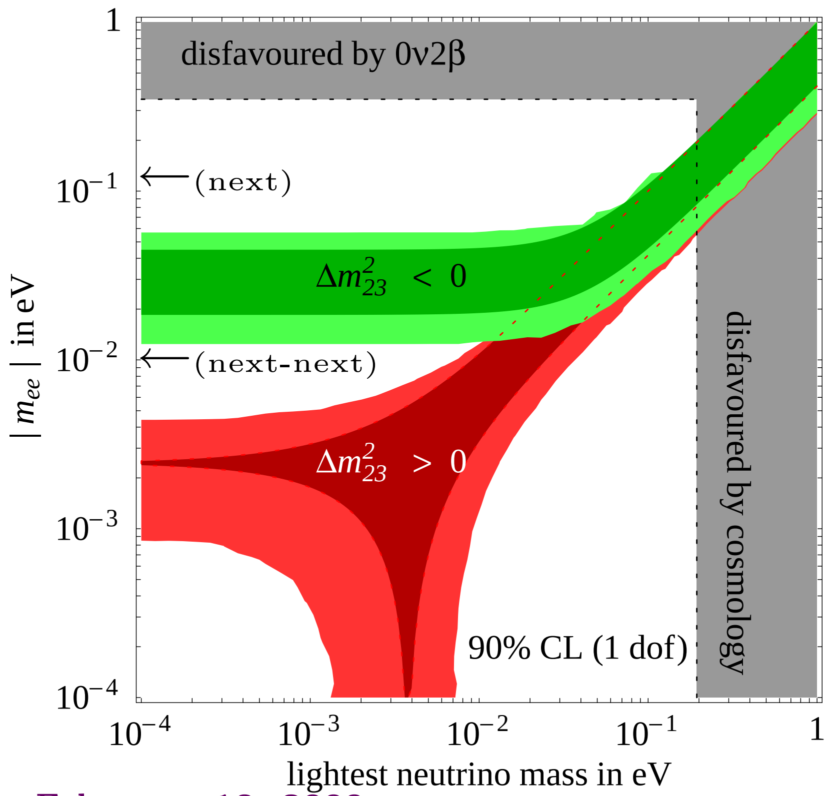
Search for the Violation of Lepton Number (or $B - L$)

Best Bet: search for

Neutrinoless Double-Beta

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

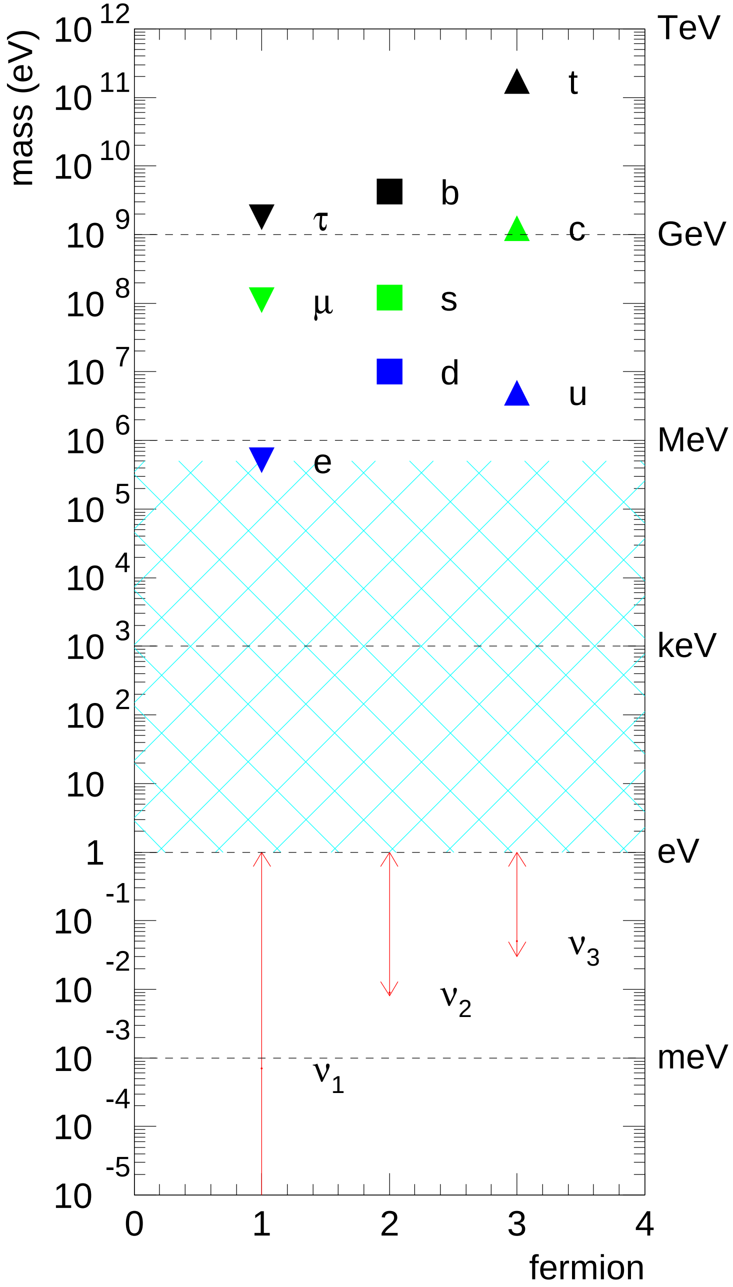




Helicity Suppressed Amplitude $\propto \frac{m_{ee}}{E}$

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

⇐ **no longer lamp-post physics!**



What We Are Trying To Understand:

⇐ **NEUTRINOS HAVE TINY MASSES**

⇓ **LEPTON MIXING IS "WEIRD"** ⇓

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

What Does It Mean?

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!

Options include:

- modify SM Higgs sector (e.g. Higgs triplet) and/or
- modify SM particle content (e.g. $SU(2)_L$ Triplet or Singlet) and/or
- modify SM gauge structure and/or
- supersymmetrize the SM and add R-parity violation and/or
- augment the number of space-time dimensions and/or
- etc

Important: different options → different phenomenological consequences

Candidate νSM

SM as an effective field theory – non-renormalizable operators

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

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

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

- 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!
- νSM effective theory – not valid for energies above *at most* Λ/λ.
- What is Λ? First naive guess is that M is the Planck scale – does not work. Data require $\Lambda \sim 10^{14}$ GeV (anything to do with the GUT scale?).

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

Why are Neutrino Masses Small? – Different Interpretations

Assume the dimension-5 operator is the consequence of integrating out a new massive state with mass M (seesaw mechanism). Below the mass scale M,

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

In the case of the seesaw,

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

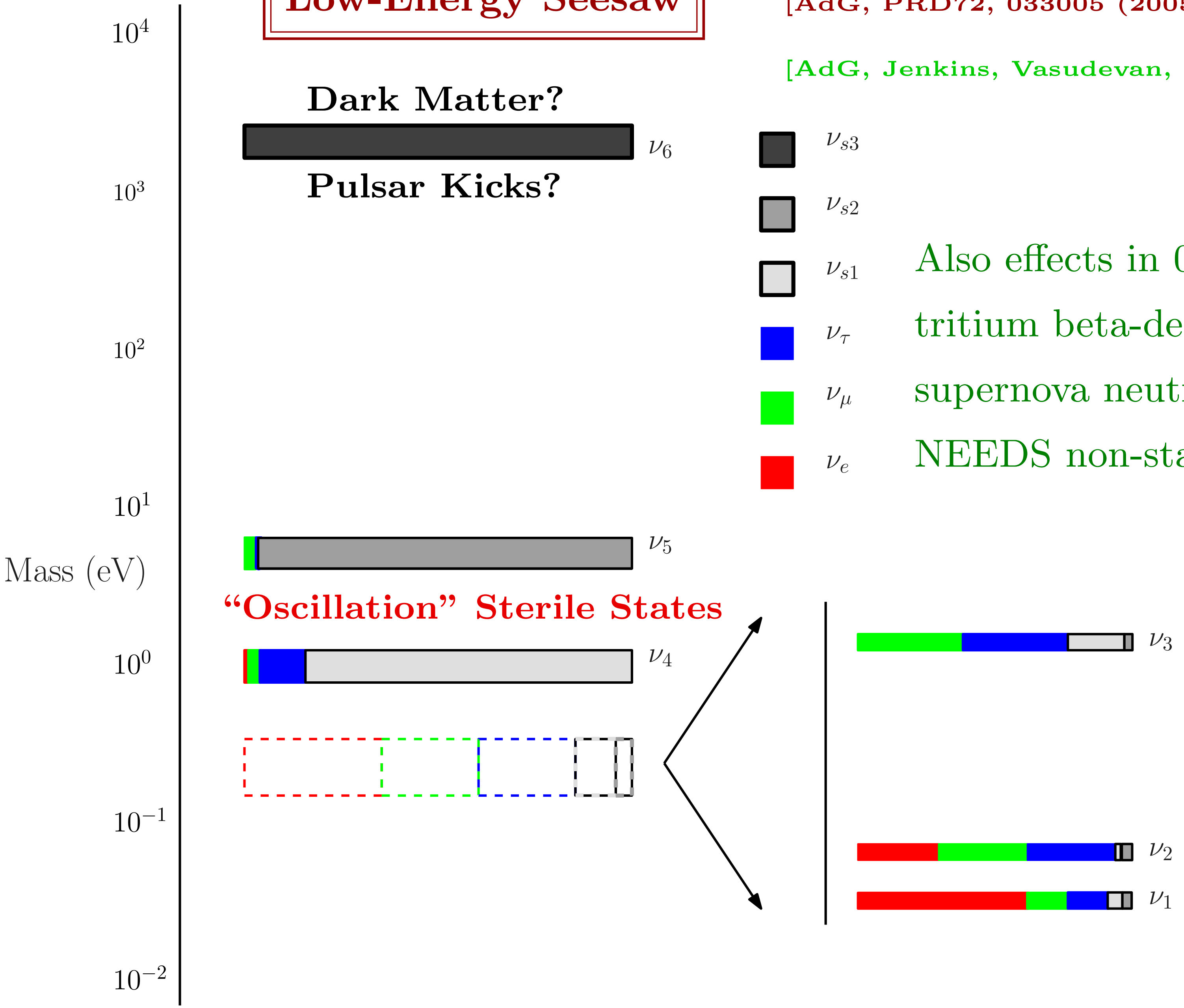
so neutrino masses are small if either

- 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").

Low-Energy Seesaw

[AdG, PRD72, 033005 (2005)]

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



Also effects in $0\nu\beta\beta$,

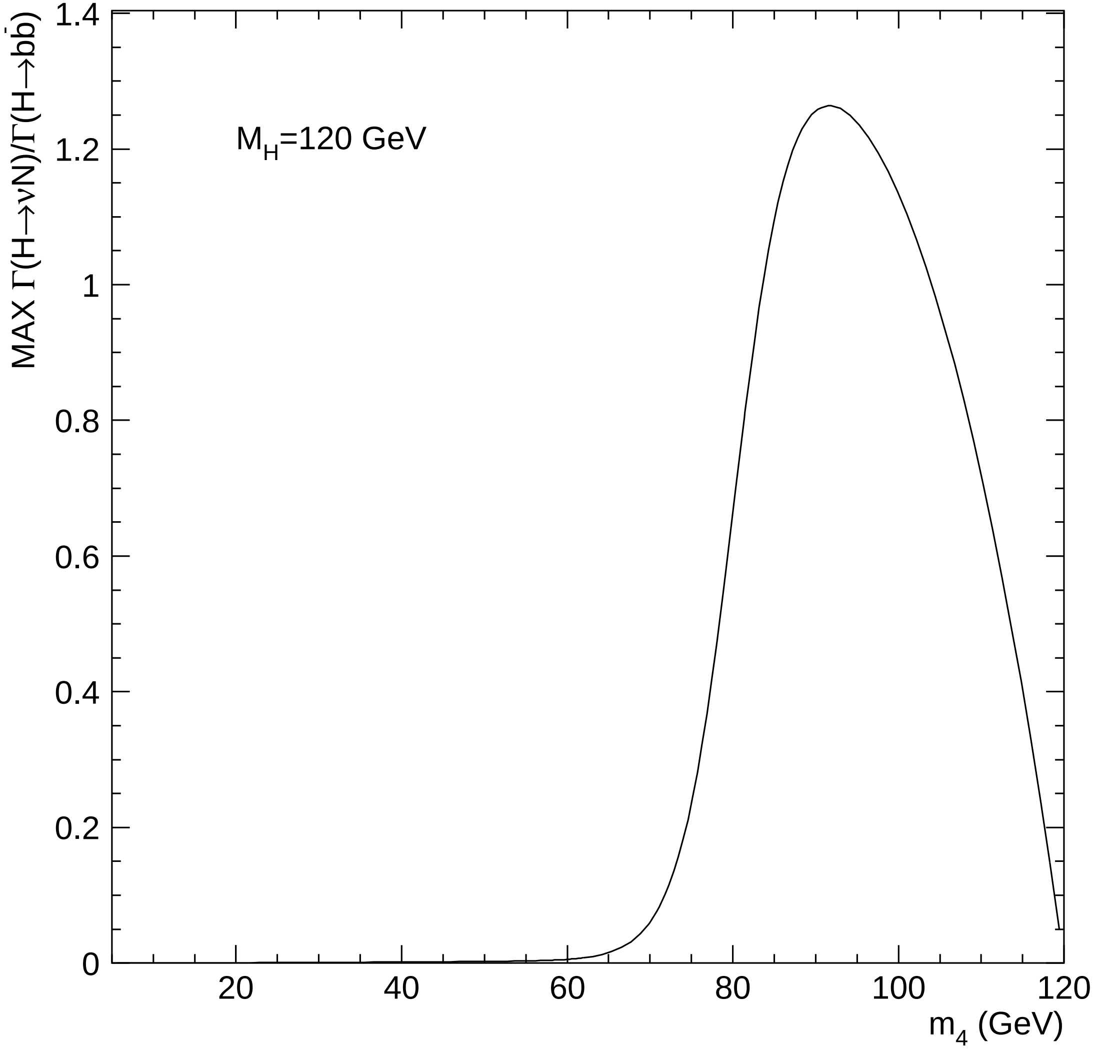
tritium beta-decay,

supernova neutrino oscillations,

NEEDS non-standard cosmology.

Weak Scale Seesaw, and Accidentally Light Neutrino Masses

[AdG arXiv:0706.1732]



What does the seesaw Lagrangian predict for the LHC?

Nothing much, unless…

- $M_N \sim 1 - 100$ GeV,
- Yukawa couplings larger than naive expectations.

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

(NOTE: $N \to \ell q' \bar{q}$ or $\ell \ell' \nu$ (prompt) "Weird" Higgs decay signature!)

ALSO: "Majorana neutrinos at the LHC," see Han, Zhang, hep-ph/0604064

et cetera

Fourth Avenue: Higher Order Neutrino Masses from $\Delta L = 2$ Physics.

Imagine that there is new physics that breaks lepton number by 2 units at some energy scale Λ, but that it does not, in general, lead to neutrino masses at the tree level.

We know that neutrinos will get a mass at some order in perturbation theory – which order is model dependent!

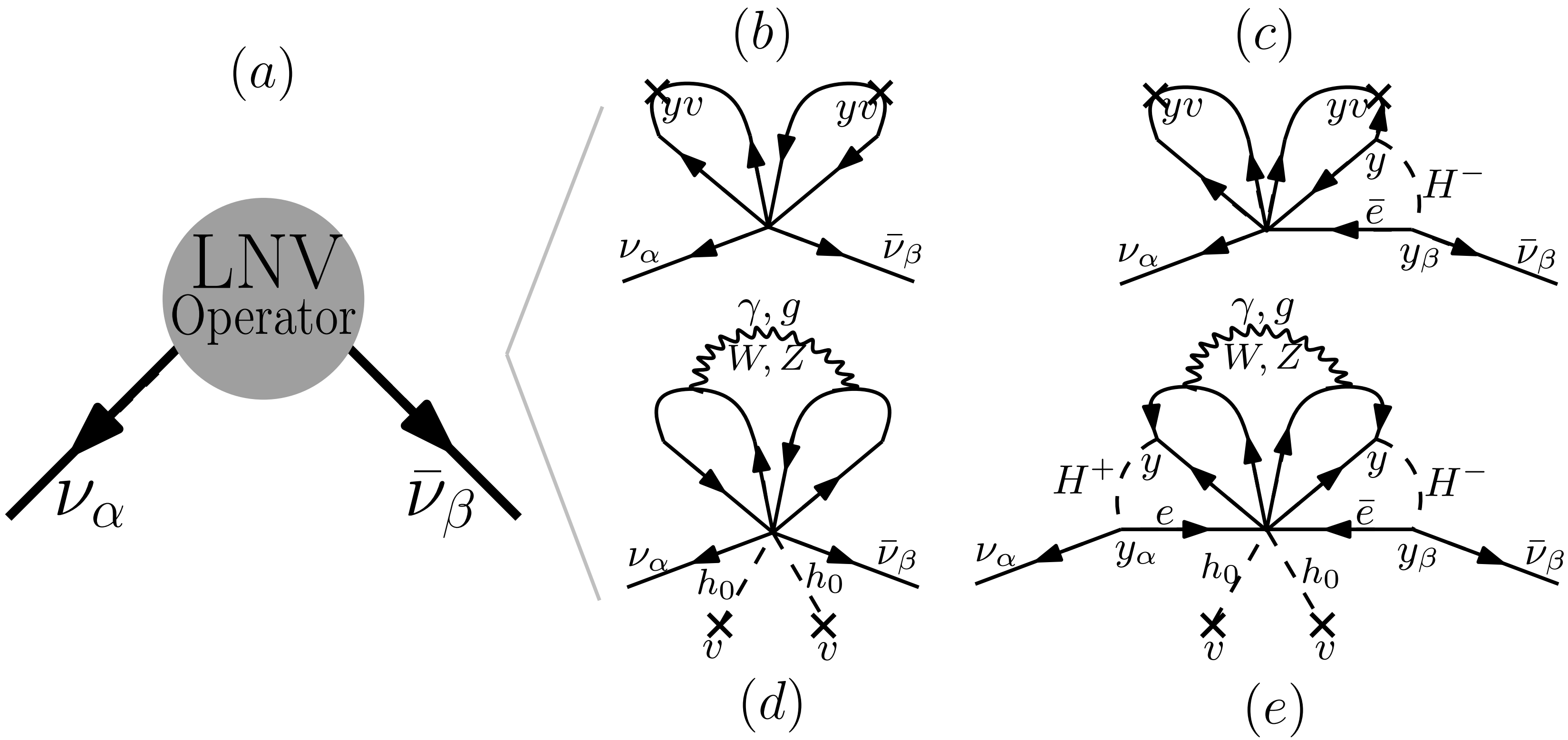
AdG, Jenkins, 0708.1344 [hep-ph]

Effective Operator Approach ($\Delta L = 2$)

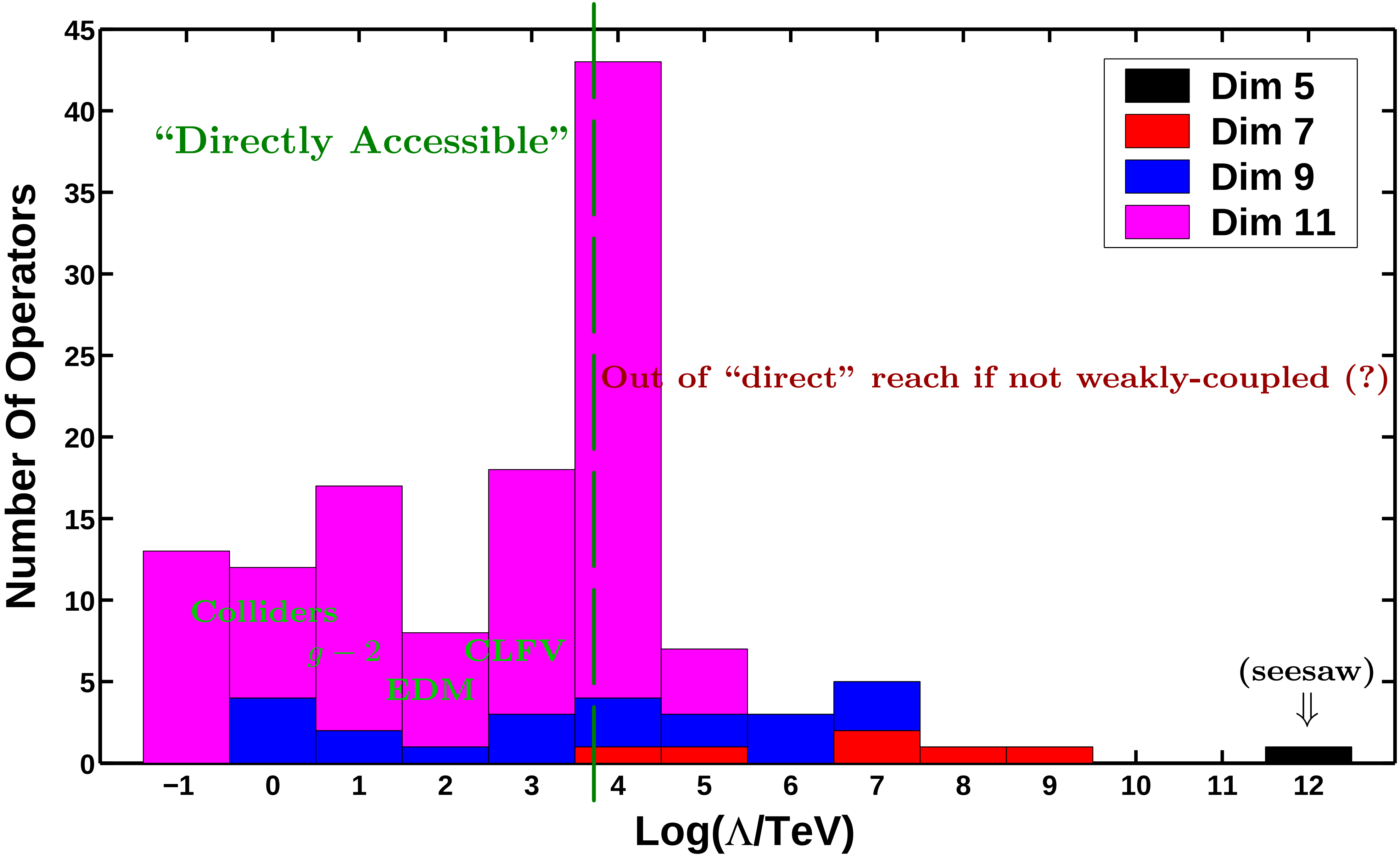
(there are 129 of them if you discount different Lorentz structures!)

classified by Babu and Leung in NPB**619**,667(2001)

13	$L^iL^j\overline{Q}_i\bar{u^c}L^le^c\epsilon_{jl}$	$\frac{y_\ell y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^5	$\beta\beta0\nu$
14_a	$L^iL^j\overline{Q}_k\bar{u^c}Q^kd^c\epsilon_{ij}$	$\frac{y_dy_ug^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^3	$\beta\beta0\nu$
14_b	$L^iL^j\overline{Q}_i\bar{u^c}Q^ld^c\epsilon_{jl}$	$\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^5	$\beta\beta0\nu$
15	$L^iL^jL^kd^c\overline{L}_i\bar{u^c}\epsilon_{jk}$	$\frac{y_dy_ug^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^3	$\beta\beta0\nu$
16	$L^iL^je^cd^c\bar{e^c}\bar{u^c}\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	2	$\beta\beta0\nu$, LHC
17	$L^iL^jd^cd^c\bar{d^c}\bar{u^c}\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	2	$\beta\beta0\nu$, LHC
18	$L^iL^jd^cu^c\bar{u^c}\bar{u^c}\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	2	$\beta\beta0\nu$, LHC
19	$L^iQ^jd^cd^c\bar{e^c}\bar{u^c}\epsilon_{ij}$	$y_{\ell_\beta}\frac{y_d^2y_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1	$\beta\beta0\nu$, HElnv, LHC, m
20	$L^id^c\overline{Q}_i\bar{u^c}\bar{e^c}\bar{u^c}$	$y_{\ell_\beta}\frac{y_dy_u^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	40	$\beta\beta0\nu$, mix
21_a	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{ij}\epsilon_{km}\epsilon_{ln}$	$\frac{y_\ell y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	2×10^3	$\beta\beta0\nu$
21_b	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{il}\epsilon_{jm}\epsilon_{kn}$	$\frac{y_\ell y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	2×10^3	$\beta\beta0\nu$
22	$L^iL^jL^ke^c\overline{L}_k\bar{e^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^4	$\beta\beta0\nu$
23	$L^iL^jL^ke^c\overline{Q}_k\bar{d^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{y_\ell y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	40	$\beta\beta0\nu$
24_a	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jk}\epsilon_{lm}$	$\frac{y_d^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^2	$\beta\beta0\nu$
24_b	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jm}\epsilon_{kl}$	$\frac{y_d^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^2	$\beta\beta0\nu$
25	$L^iL^jQ^kd^cQ^lu^cH^mH^n\epsilon_{im}\epsilon_{jn}\epsilon_{kl}$	$\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	4×10^3	$\beta\beta0\nu$
26_a	$L^iL^jQ^kd^c\overline{L}_i\bar{e^c}H^lH^m\epsilon_{jl}\epsilon_{km}$	$\frac{y_\ell y_d}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	40	$\beta\beta0\nu$
26_b	$L^iL^jQ^kd^c\overline{L}_k\bar{e^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{y_\ell y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	40	$\beta\beta0\nu$
27_a	$L^iL^jQ^kd^c\overline{Q}_i\bar{d^c}H^lH^m\epsilon_{jl}\epsilon_{km}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^4	$\beta\beta0\nu$
27_b	$L^iL^jQ^kd^c\overline{Q}_k\bar{d^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^4	$\beta\beta0\nu$
28_a	$L^iL^jQ^kd^c\overline{Q}_j\bar{u^c}H^l\overline{H}_i\epsilon_{kl}$	$\frac{y_dy_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^3	$\beta\beta0\nu$
28_b	$L^iL^jQ^kd^c\overline{Q}_k\bar{u^c}H^l\overline{H}_i\epsilon_{jl}$	$\frac{y_dy_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^3	$\beta\beta0\nu$
28_c	$L^iL^jQ^kd^c\overline{Q}_l\bar{u^c}H^l\overline{H}_i\epsilon_{jk}$	$\frac{y_dy_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^3	$\beta\beta0\nu$
29_a	$L^iL^jQ^ku^c\overline{Q}_k\bar{u^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{y_u^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	2×10^5	$\beta\beta0\nu$
29_b	$L^iL^jQ^ku^c\overline{Q}_l\bar{u^c}H^lH^m\epsilon_{ik}\epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^4	$\beta\beta0\nu$
30_a	$L^iL^j\overline{L}_i\bar{e^c}\overline{Q}_k\bar{u^c}H^kH^l\epsilon_{jl}$	$\frac{y_\ell y_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	2×10^3	$\beta\beta0\nu$
30_b	$L^iL^j\overline{L}_m\bar{e^c}\overline{Q}_n\bar{u^c}H^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$	$\frac{y_\ell y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	2×10^3	$\beta\beta0\nu$
31_a	$L^iL^j\overline{Q}_i\bar{d^c}\overline{Q}_l\bar{u^c}H^kH^l\epsilon_{jl}$	$\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	4×10^3	$\beta\beta0\nu$

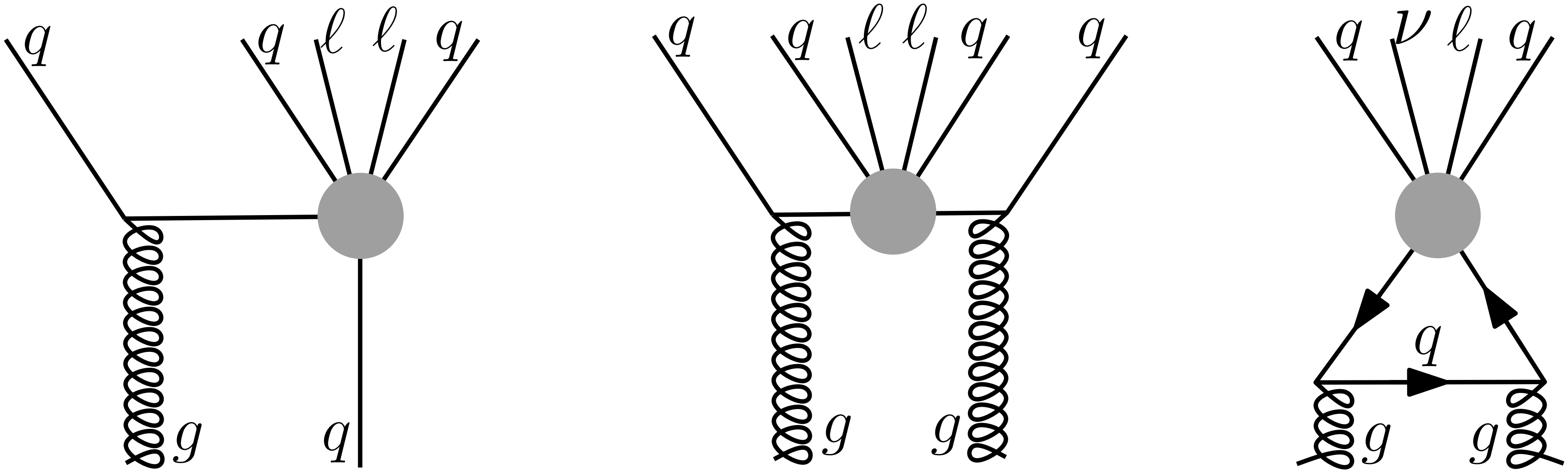


(a)
LNV
Operator
ν_α
$\bar{\nu}_\beta$
(b)
yv
yv
ν_α
$\bar{\nu}_\beta$
(c)
yv
yv
y
H^-
$\bar{e}$
ν_α
y_β
$\bar{\nu}_\beta$
γ, g
W, Z
ν_α
h_0
h_0
$\bar{\nu}_\beta$
v
v
(d)
γ, g
W, Z
H^+
y
y
H^-
e
$\bar{e}$
ν_α
y_α
h_0
h_0
y_β
$\bar{\nu}_\beta$
v
v
(e)



Dim 5
Dim 7
Dim 9
Dim 11
"Directly Accessible"
Out of "direct" reach if not weakly-coupled (?)
Colliders
$g-2$
EDM
CLFV
(seesaw)
⇓
Number Of Operators
Log(Λ/TeV)
0
5
10
15
20
25
30
35
40
45
−1
0
1
2
3
4
5
6
7
8
9
10
11
12

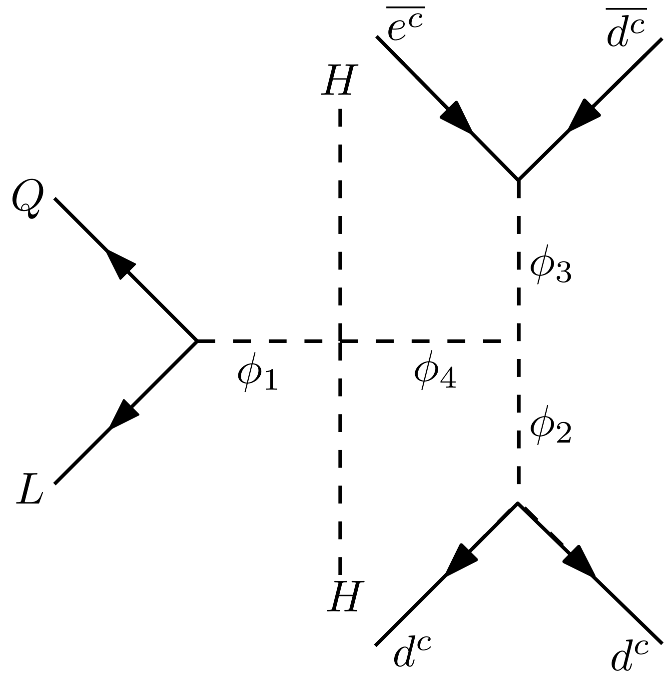
LNV at Colliders ⇒ LHC: $pp \to \ell^\pm \ell^\pm +$ multi-jets



(a) (b) (c)

OK *OK* ν in final state

[arXiv:0708.1344]



Order-One Coupled, Weak Scale Physics Can Also Explain Naturally Small Majorana Neutrino Masses:

Multi-loop neutrino masses from lepton number violating new physics.

$$-\mathcal{L}_{\nu\mathrm{SM}} \supset \sum_{i=1}^{4} M_i \phi_i \bar{\phi}_i + i y_1 Q L \phi_1 + y_2 d^c d^c \phi_2 + y_3 e^c d^c \phi_3 + \lambda_{14} \bar{\phi}_1 \phi_4 H H + \lambda_{234} M \phi_2 \bar{\phi}_3 \phi_4 + h.c.$$

$m_\nu \propto (y_1 y_2 y_3 \lambda_{234}) \lambda_{14}/(16\pi)^4 \ \rightarrow$ neutrino masses at 4 loops, requires $M_i \sim 100$ GeV!

WARNING: For illustrative purposes only. Details still to be worked out. Scenario most likely ruled out by charged-lepton flavor-violation, LEP, Tevatron, and HERA.

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 $\longrightarrow$ Well-defined experimental program.

2. **neutrino masses are very small** – we don't know why, but we think it means something important.

3. we need a minimal νSM 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).

4. We know very little about the new physics uncovered by neutrino oscillations.
   - It could be renormalizable $\rightarrow$ "boring" Dirac neutrinos
   - It could be due to Physics at absurdly high energy scales $M \gg 1$ TeV $\rightarrow$ high energy seesaw. How can we ever convince ourselves that this is correct?
   - It could be due to very light new physics $\rightarrow$ low energy seesaw. Prediction: new light propagating degrees of freedom – sterile neutrinos
   - It could be due to new physics at the TeV scale $\rightarrow$ either weakly coupled, or via a more subtle lepton number breaking sector. Predictions: charged lepton flavor violation, collider signatures!
5. We **need more experimental input** – and more seems to be on the way (this is a data driven field). We only started to figure out what is going on.
6. 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., $\Lambda \simeq 10^{14}$ GeV).

Propagating Neutrinos For Sale – Soon!

ν_1

ν_2

ν_3

20% orange (ν_μ)
60% yellow (ν_e)
20% red (ν_τ)

32% orange (ν_μ)
36% yellow (ν_e)
32% red (ν_τ)

48% orange (ν_μ)
4% yellow (ν_e)
48% red (ν_τ)

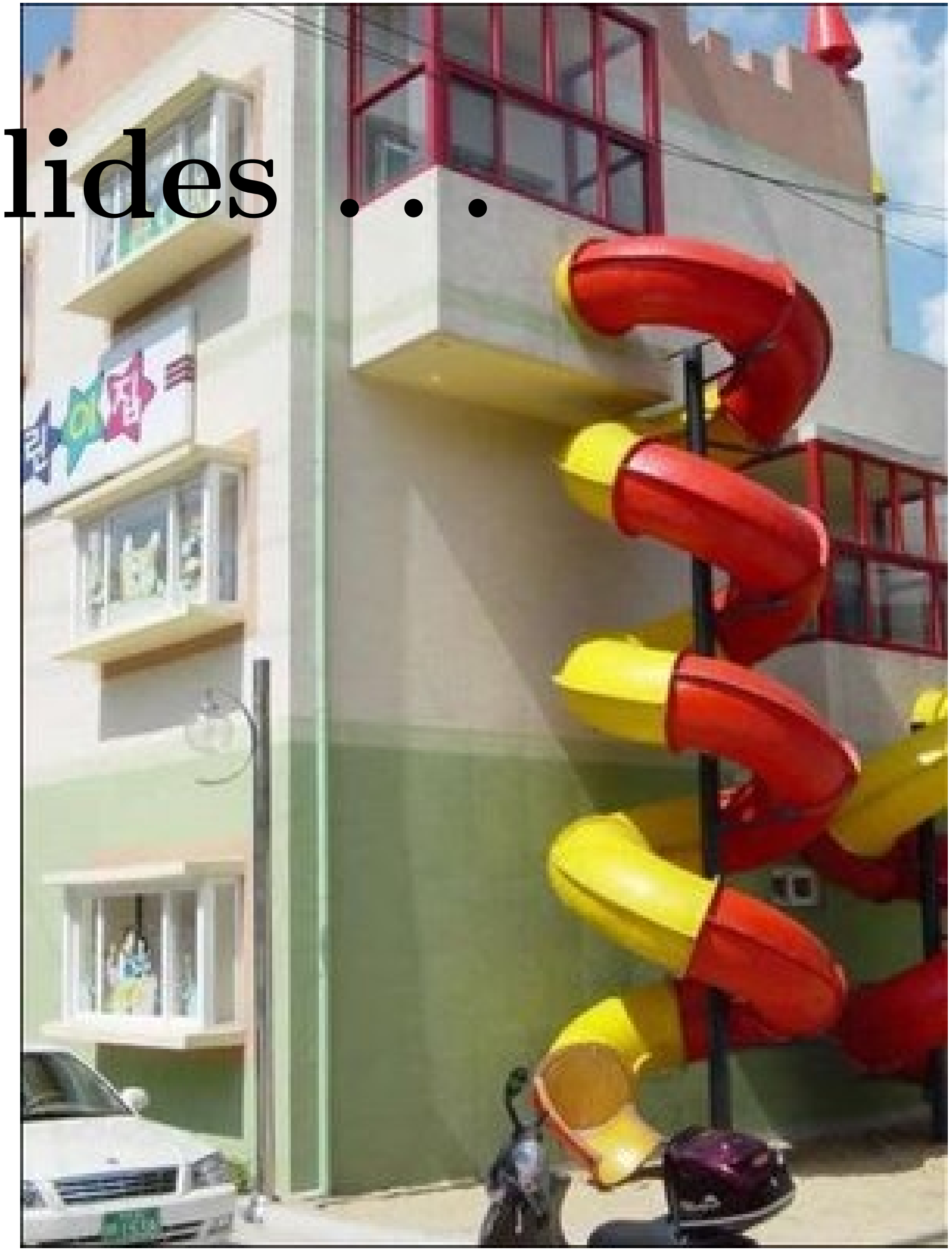
electron-neutrino

muon-neutrino

tau-neutrino

electron-antineutrino

Backup Slides ...



On very small Yukawa couplings

We would like to believe that Yukawa couplings should naturally be of order one.

Nature, on the other hand, seems to have a funny way of showing this. Of all known fermions, only one (1) has a "natural" Yukawa coupling – the top quark!

Regardless there are several very different ways of obtaining "naturally" very small Yukawa couplings. They require more new physics.

"Natural" solutions include flavor symmetries, extra-dimensions of different "warping," . . .

The "Holy Graill" of Neutrino Oscillations – CP Violation

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

$\Rightarrow$ 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.

Neutrino masses and lepton mixing provide strong reason to believe that other sources of CP-invariance violation exist.

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

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

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: $\arg(U_{ei}^* U_{\mu i}) \to \delta \neq 0, \pi$;
- Nontrivial "Strong" Phases: Δ_{12}, $\Delta_{13} \to L \neq 0$;
- Because of Unitarity, we need all $|U_{\alpha i}| \neq 0 \to$ 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!

High-energy seesaw has no observable consequence other than non-zero neutrino masses, 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 the seesaw mechanism contains all necessary ingredients to explain the baryon asymmetry of the Universe as long as the right-handed neutrinos are heavy enough – $M > 10^9$ GeV (with some exceptions that I won't have time to mention).