Hunting Down the Origin of Neutrino Masses
– from sterile neutrinos to baryon number violation

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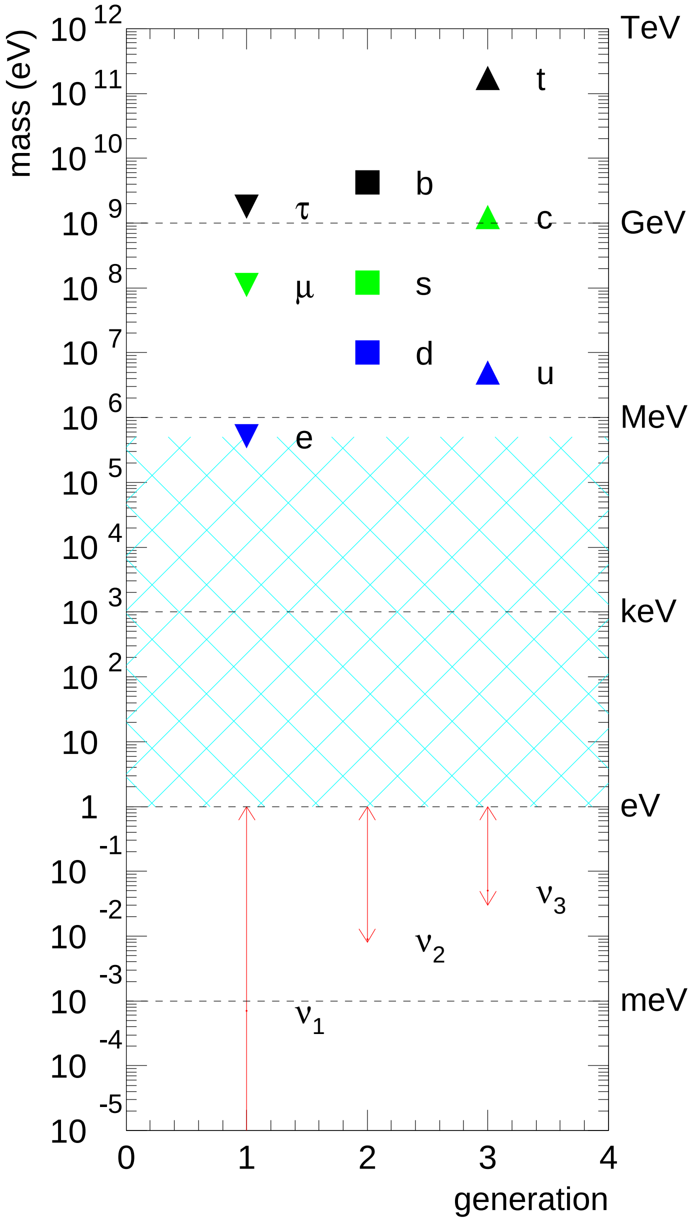
Planck 2014
Paris – May 26–30, 2014



What We Are Trying To Understand:

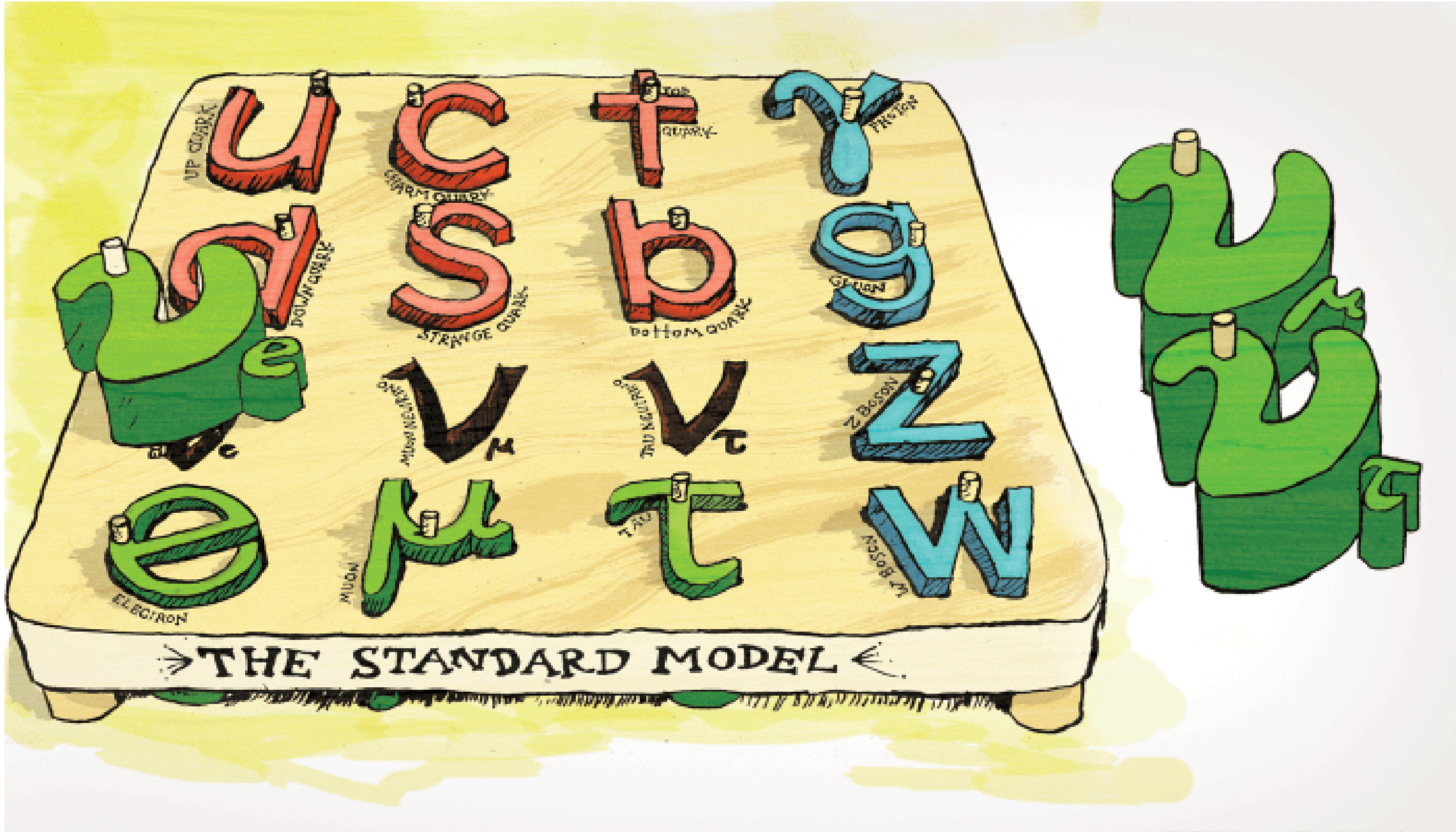
⇐ **NEUTRINOS HAVE TINY MASSES**

⇓ **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?

I Will Concentrate on One of the Questions:



Where do Neutrino Masses Come From?

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).

Neutrino Masses, EWSB, and a New Mass Scale of Nature

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).

Searches for $0\nu\beta\beta$ help tell (1) from (2) and (3), the LHC, charged-lepton flavor violation, *et al* may provide more information.

One Candidate νSM

SM as an effective field theory – non-renormalizable operators

$$\mathcal{L}_{\nu\mathrm{SM}} \supset -y_{ij}\frac{L^i H L^j H}{2\Lambda} + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + H.c.$$

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

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

- Neutrino masses are small: $\Lambda \gg v \to m_\nu \ll m_f$ ($f = e, \mu, u, d$, etc)
- Neutrinos are Majorana fermions – Lepton number is violated!
- νSM effective theory – not valid for energies above *at most* Λ/y.
- Define $y_{\max} \equiv 1 \Rightarrow$ data require $\boxed{\Lambda \sim 10^{14}\ \text{GeV.}}$

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

The Seesaw Lagrangian

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

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

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 $m_{\alpha\beta}=\sum_i \mu_{\alpha i}M_i^{-1}\mu_{\beta i}$ $[m\propto 1/\Lambda \;\Rightarrow\; \Lambda=M/\mu^2]$.

  This the **seesaw mechanism.** Neutrinos are Majorana fermions. Lepton number is not a good symmetry of $\mathcal{L}_\nu$, 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).

- $M\ll\mu$: 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 et al, hep-ph/0410298; Farina et al, ; 1303.7244; AdG et al, 1402.2658):

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

- Leptogenesis! "Vanilla" Leptogenesis requires, very roughly, smallest

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

- Stability of the Higgs potential (e.g., Elias-Miró et al, 1112.3022):

$$M < 10^{13}\ \text{GeV}.$$

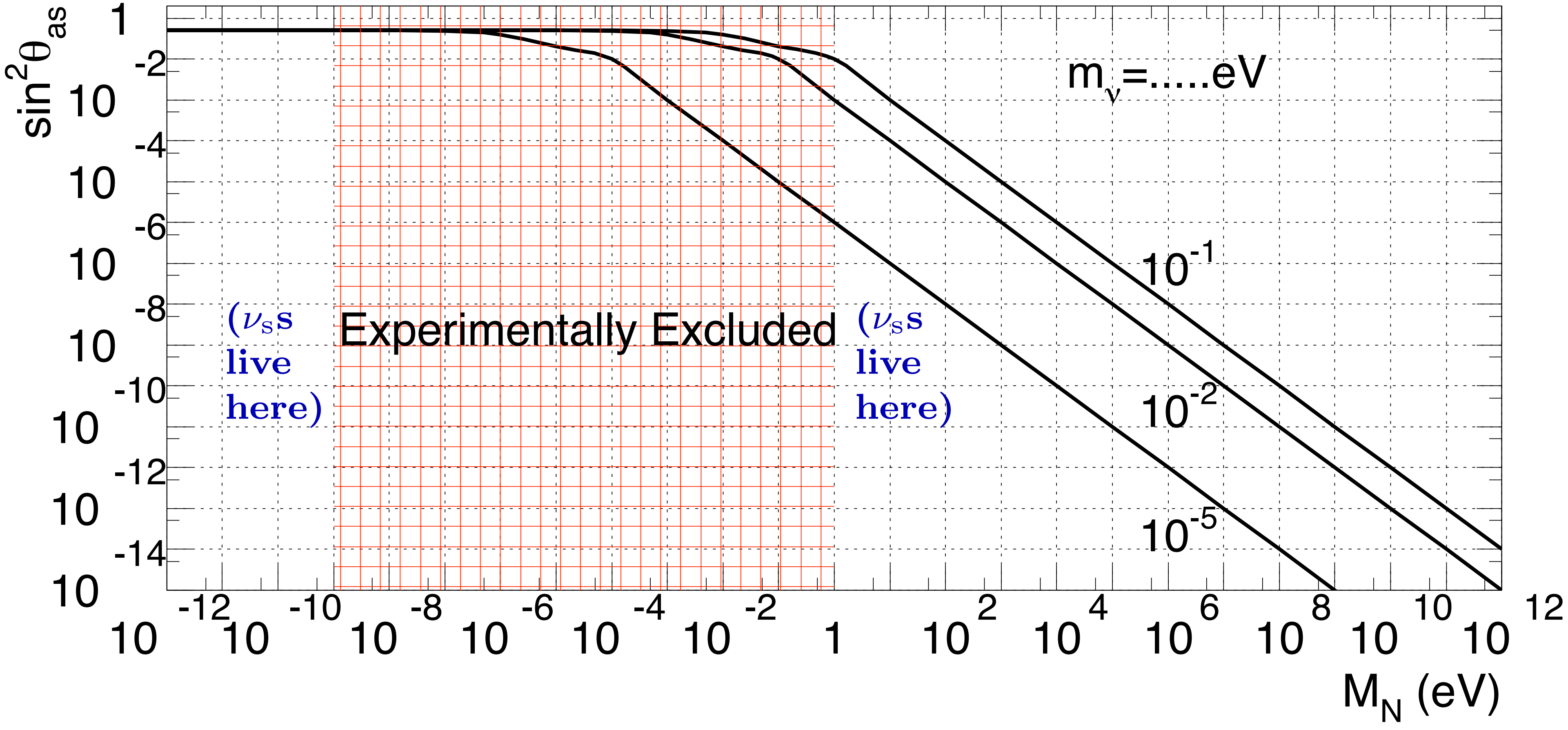
- Physics "too" heavy! No observable consequence other than leptogenesis. Will we ever convince ourselves that this is correct? (Buckley et al, hep-ph/0606088)

Low-Energy Seesaw [AdG PRD72,033005)]

The other end of the M spectrum ($M < 100$ GeV). What do we get?

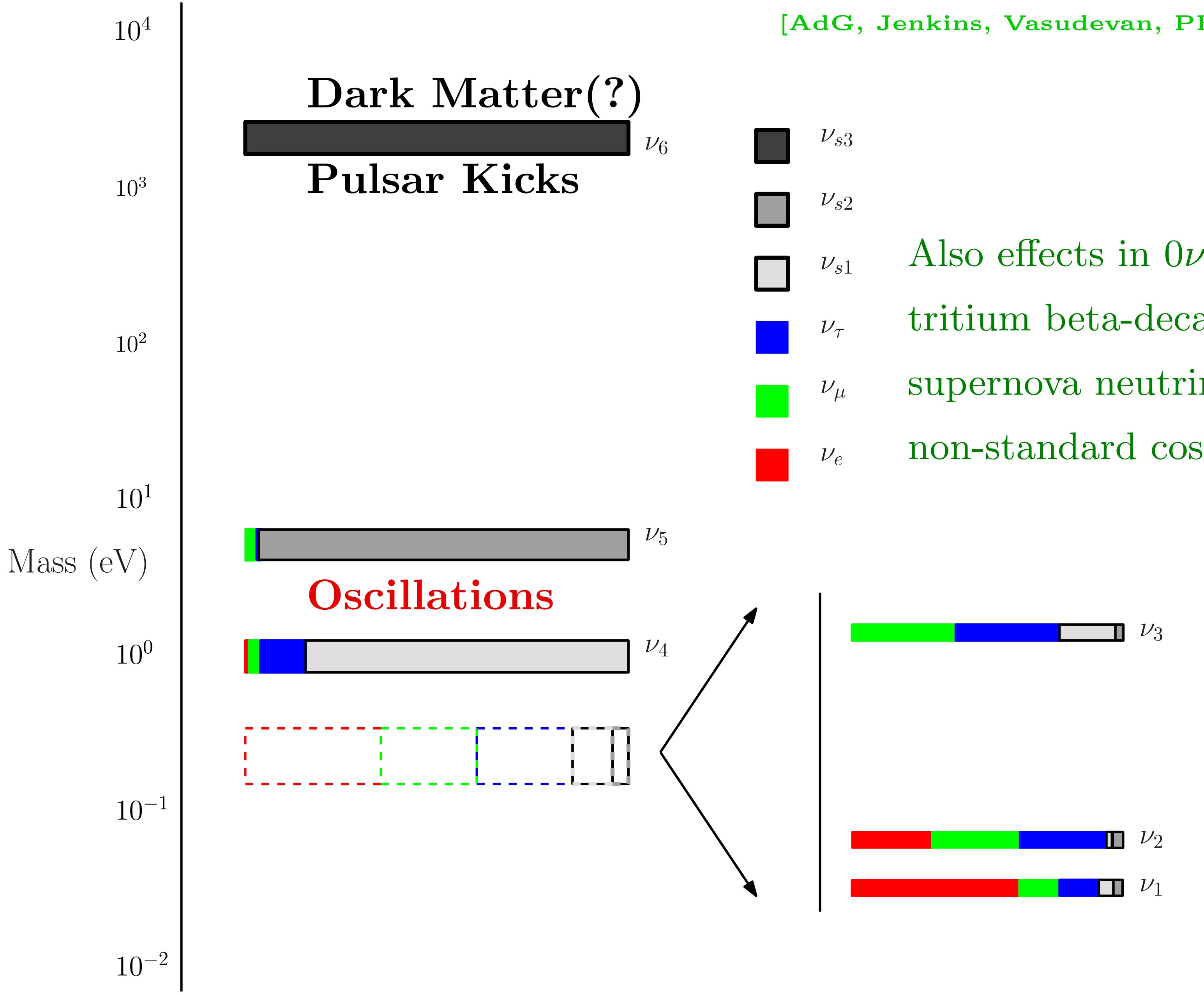
- Neutrino masses are small because the Yukawa couplings are very small $\lambda \in [10^{-6}, 10^{-11}]$;
- No standard thermal leptogenesis – right-handed neutrinos way too light? [For a possible alternative see Canetti, Shaposhnikov, arXiv: 1006.0133 and reference therein.]
- No obvious connection with other energy scales (EWSB, GUTs, etc);
- Right-handed neutrinos are propagating degrees of freedom. They look like sterile neutrinos ⇒ sterile neutrinos associated with the fact that the active neutrinos have mass;
- sterile–active mixing can be predicted – hypothesis is falsifiable!
- Small values of M are natural (in the 'tHooft sense). In fact, theoretically, no value of M should be discriminated against!

Constraining the Seesaw Lagrangian



[AdG, Huang, Jenkins, arXiv:0906.1611]

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



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

tritium beta-decay,

supernova neutrino oscillations,

non-standard cosmology.

Making Predictions, for an inverted mass hierarchy, $m_4 = 1$ eV($\ll m_5$)

- 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 $\nu_\mu \to \nu_\tau$ appearance search sensitive to probabilities larger than 0.1% for a mass-squared difference of 1 eV^2 would definitively rule out $m_4 = 1$ eV if the neutrino mass hierarchy is inverted.

"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!

For example:

- SUSY with trilinear R-parity violation – neutrino masses at one-loop;
- Zee models – neutrino masses at one-loop;
- Babu and Ma – neutrino masses at two loops;
- Chen et al, 0706.1964 – neutrino masses at two loops;
- Angel et al, 1308.0463 – neutrino masses at two loops;
- etc.

AdG, Jenkins, 0708.1344 [hep-ph]

Effective Operator Approach

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

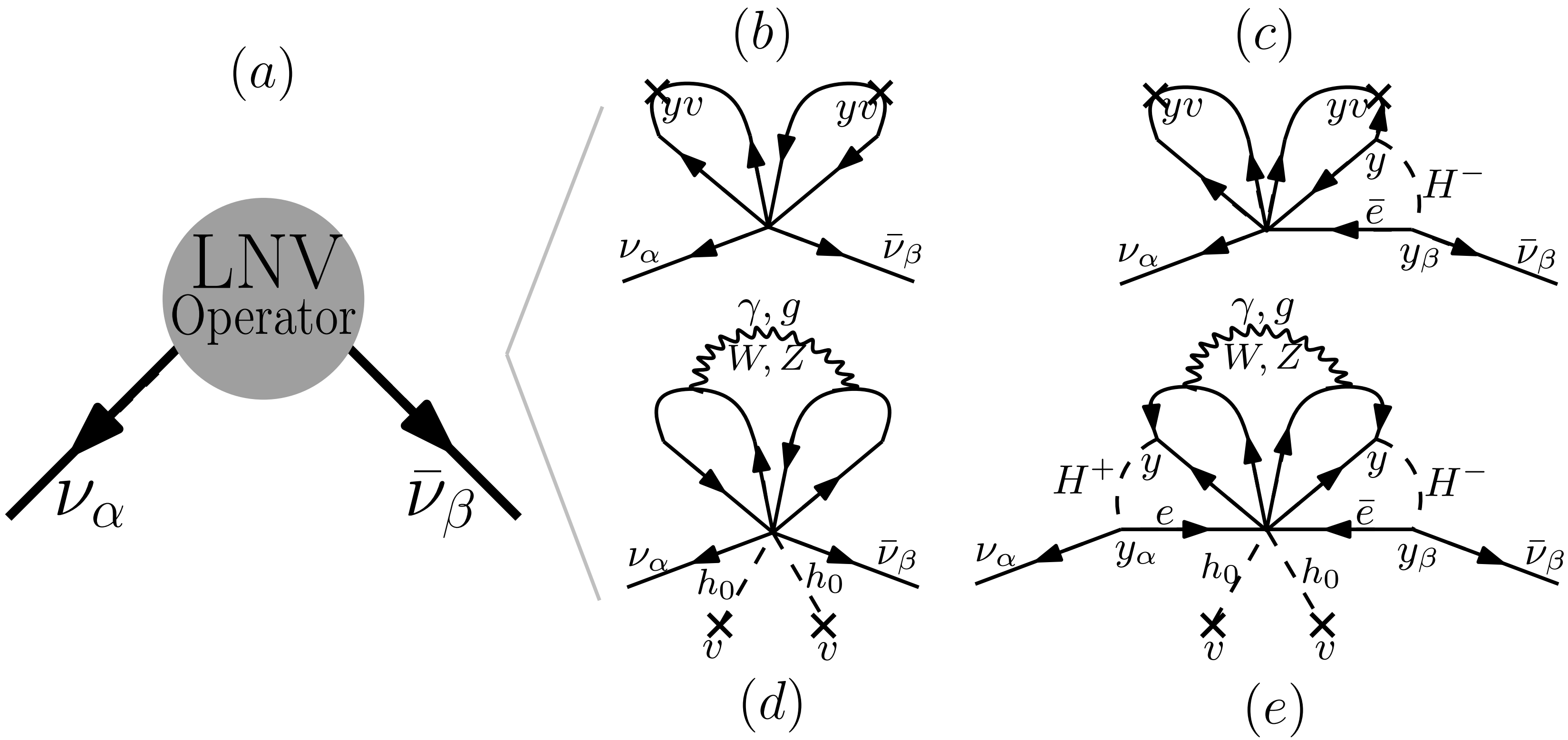
classified by Babu and Leung in NPB**619**,667(2001)

4_a	$L^iL^j\overline{Q}_i\overline{u^c}H^k\epsilon_{jk}$	$\frac{y_u}{16\pi^2}\frac{v^2}{\Lambda}$	4×10^9	$\beta\beta0\nu$
4_b	$L^iL^j\overline{Q}_k\overline{u^c}H^k\epsilon_{ij}$	$\frac{y_u g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^6	$\beta\beta0\nu$
5	$L^iL^jQ^kd^cH^lH^m\overline{H}_i\epsilon_{jl}\epsilon_{km}$	$\frac{y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^5	$\beta\beta0\nu$
6	$L^iL^j\overline{Q}_k\overline{u^c}H^lH^k\overline{H}_i\epsilon_{jl}$	$\frac{y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^7	$\beta\beta0\nu$
7	$L^iQ^j\overline{e^c}\overline{Q}_kH^kH^lH^m\epsilon_{il}\epsilon_{jm}$	$y_{\ell_\beta}\frac{g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	4×10^2	mix
8	$L^i\overline{e^c}\overline{u^c}d^cH^j\epsilon_{ij}$	$y_{\ell_\beta}\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^3	mix
9	$L^iL^jL^ke^cL^le^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_\ell^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	3×10^3	$\beta\beta0\nu$
10	$L^iL^jL^ke^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_\ell y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^3	$\beta\beta0\nu$
11_a	$L^iL^jQ^kd^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_d^2g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	30	$\beta\beta0\nu$
11_b	$L^iL^jQ^kd^cQ^ld^c\epsilon_{ik}\epsilon_{jl}$	$\frac{y_d^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^4	$\beta\beta0\nu$
12_a	$L^iL^j\overline{Q}_i\overline{u^c}\overline{Q}_j\overline{u^c}$	$\frac{y_u^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^7	$\beta\beta0\nu$
12_b	$L^iL^j\overline{Q}_k\overline{u^c}\overline{Q}_l\overline{u^c}\epsilon_{ij}\epsilon^{kl}$	$\frac{y_u^2g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^4	$\beta\beta0\nu$
13	$L^iL^j\overline{Q}_i\overline{u^c}L^le^c\epsilon_{jl}$	$\frac{y_\ell y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^5	$\beta\beta0\nu$
14_a	$L^iL^j\overline{Q}_k\overline{u^c}Q^kd^c\epsilon_{ij}$	$\frac{y_dy_ug^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^3	$\beta\beta0\nu$
14_b	$L^iL^j\overline{Q}_i\overline{u^c}Q^ld^c\epsilon_{jl}$	$\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^5	$\beta\beta0\nu$
15	$L^iL^jL^kd^c\overline{L}_i\overline{u^c}\epsilon_{jk}$	$\frac{y_dy_ug^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^3	$\beta\beta0\nu$
16	$L^iL^je^cd^c\overline{e^c}\overline{u^c}\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	2	$\beta\beta0\nu$, LHC
17	$L^iL^jd^cd^c\overline{d^c}\overline{u^c}\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	2	$\beta\beta0\nu$, LHC
18	$L^iL^jd^cu^c\overline{u^c}\overline{u^c}\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	2	$\beta\beta0\nu$, LHC
19	$L^iQ^jd^cd^c\overline{e^c}\overline{u^c}\epsilon_{ij}$	$y_{\ell_\beta}\frac{y_d^2y_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1	$\beta\beta0\nu$, HElnv, LHC, mix
20	$L^id^c\overline{Q}_i\overline{u^c}\overline{e^c}\overline{u^c}$	$y_{\ell_\beta}\frac{y_dy_u^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	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	$L^iL^jL^ke^c\overline{L}_k\overline{e^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^4	$\beta\beta0\nu$
23	$L^iL^jL^ke^c\overline{Q}_k\overline{d^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{y_\ell y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	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	$\beta\beta0\nu$

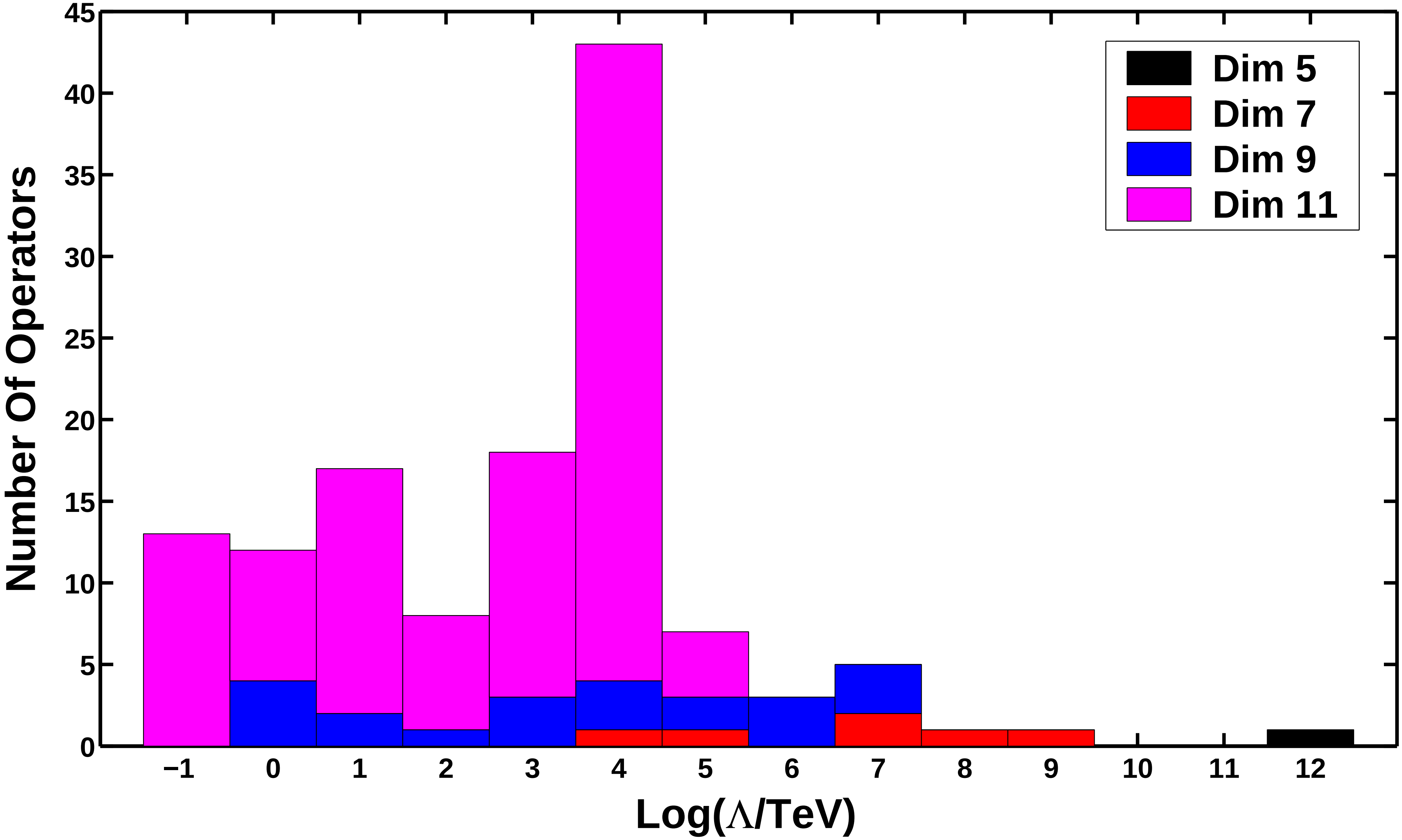
Assumptions:

- Only consider $\Delta L = 2$ operators;
- Operators made up of only standard model fermions and the Higgs doublet (no gauge bosons);
- Electroweak symmetry breaking characterized by SM Higgs doublet field;
- Effective operator couplings assumed to be "flavor indifferent";
- Operators "turned on" one at a time, assumed to be leading order (tree-level) contribution of new lepton number violating physics.
- We can use the effective operator to estimate the coefficient of all other lepton-number violating lower-dimensional effective operators (loop effects, computed with a hard cutoff).

All results presented are order of magnitude *estimates*, not precise quantitative results.



(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
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Dim 11
Number Of Operators
Log(Λ/TeV)
45
40
35
30
25
20
15
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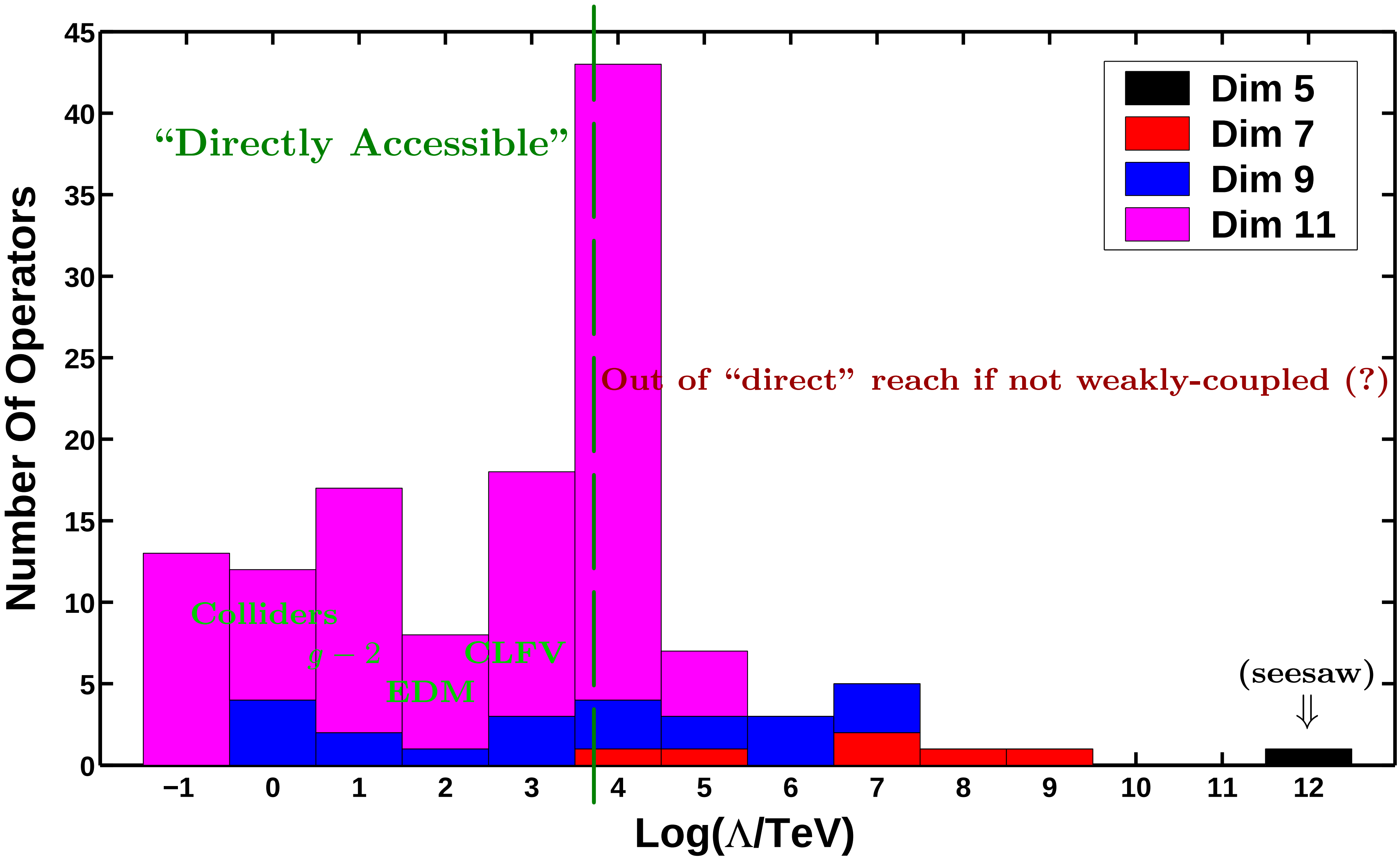
11
12



45
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Number Of Operators
−1
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11
12
Log(Λ/TeV)
Dim 5
Dim 7
Dim 9
Dim 11
"Directly Accessible"
Out of "direct" reach if not weakly-coupled (?)
Colliders
g − 2
EDM
CLFV
(seesaw)
⇓

Neutrino Masses and Baryon Number Violation

(AdG, Herrero-García, Kobach, 1404.4057)

We are exploring whether the following happens:

$$\mathrm{SM} + X$$
$$\downarrow$$
$$\mathrm{SM} + \mathcal{O}_{\mathrm{LNV}}$$

If GUTs are real, lepton-number, baryon-number, and any physics that violates one or the other, are closely related. The X fields also have GUT-partners, i.e., they must also be part of complete representations of the GUT group:

$$X \to X_5$$

The act of integrating out the partners of the X fields will, necessarily, lead to baryon number violating operators of the **same** mass-dimension.

$$\text{GUT SM} + X_5$$

$$\downarrow$$

$$\text{SM} + X_5 \ (+\text{“other” H.D.O.})$$

$$\downarrow$$

$$\text{SM} + \mathcal{O}_{\rm LNV} + \mathcal{O}_{\rm BNV} \ (+\text{“other” H.D.O.})$$

$\mathcal{O}_{\rm LNV} + \mathcal{O}_{\rm BNV}$ are obtained at the tree level and are of the same mass dimension. They arise at the $\Lambda_{\rm LNV,BNV}$ scales after the X_5 particles are integrated out.

On Higher Dimensional Operators (no Gauge Fields)

Very generically, there is relationship between ΔL, the lepton number of a given operator, ΔB, the baryon number of a given operator, and D, the mass-dimension of the operator, assuming only Lorentz and hypercharge invariance.

$$\left|\frac{1}{2}\Delta B + \frac{3}{2}\Delta L\right| \in \mathbb{N} \begin{cases} \text{odd} & \leftrightarrow \quad D \text{ is odd,} \\ \text{even} & \leftrightarrow \quad D \text{ is even.} \end{cases}$$

- Operators with $|\Delta L| = 2$, $\Delta B = 0$ have odd mass dimension. The lowest such operator is dimension five.
- Operators with odd mass-dimension must have non-zero ΔB or ΔL. In more detail, it is easy to show that, for operators with odd mass-dimension, $|\Delta(B-L)|$ is an even number not divisible by four $(2, 6, 10, \ldots)$. All odd-dimensional operators violate $B-L$ by at least two units. For operators with even mass-dimension, $|\Delta(B-L)|$ is a multiple of four, including zero $(0, 4, 8, 12, \ldots)$.

Odd higher-dimensional operator constructed out of $SU(5)$ fields. ψ is a five-bar fermion, χ is a ten fermion, and Φ is the five-bar scalar.

Dimension	J, for $\mathcal{O}_J^{\rm GUT}$	Operator	I, for $\mathcal{O}_I$
5	1	$\psi^i \Phi^\dagger_i \psi^j \Phi^\dagger_j$	$\mathbf{1}$
7	2_a	$\epsilon_{ijklm}\chi^{\dagger ij}\chi^{\dagger kl}\psi^m\psi^n\Phi^\dagger_n$	$\mathbf{4_a}$, 8
7	$2_b^\star$	$\epsilon_{ijklm}\chi^{\dagger ij}\psi^k\psi^l\chi^{\dagger mn}\Phi^\dagger_n$	$\mathbf{4_b}$, 8
7	3	$\chi_{ij}\psi^i\psi^j\psi^k\Phi^\dagger_k$	2, $\mathbf{3_b}$
7	$4^\star$	$\epsilon_{ijklm}\psi^i\psi^j\psi^k\psi^l\Phi^m$	
9	5	$\chi_{ij}\chi_{kl}\psi^i\psi^j\psi^k\psi^l$	9, 10, $\mathbf{11_b}$
9	6_a	$\epsilon_{ijklm}\psi^i\chi^{\dagger jk}\chi^{\dagger lm}\chi_{no}\psi^n\psi^o$	13, $\mathbf{14_b}$, 16, 19
9	6_b	$\epsilon_{ijklm}\psi^i\psi^j\chi^{\dagger kl}\chi^{\dagger mn}\chi_{no}\psi^o$	13, $\mathbf{14_b}$, 16, 18, 19
9	$6_c^\star$	$\epsilon_{ijklm}\psi^i\psi^j\psi^k\chi^{\dagger lm}\chi^{\dagger no}\chi_{no}$	$\mathbf{14_a}$, 16, 18
9	7_a	$\epsilon_{ijklm}\epsilon_{nopqr}\psi^i\chi^{\dagger jk}\chi^{\dagger lm}\psi^n\chi^{\dagger op}\chi^{\dagger qr}$	$\mathbf{12_a}$, 20, singlets
9	$7_b^\star$	$\epsilon_{ijklm}\epsilon_{nopqr}\psi^i\psi^j\chi^{\dagger kl}\chi^{\dagger mn}\chi^{\dagger op}\chi^{\dagger qr}$	$\mathbf{12_b}$, 20, singlets
9	$8_a^\star$	$\epsilon_{ijklm}\psi^i\psi^j\psi^k\psi^l\chi^{\dagger mn}\psi^\dagger_n$	$\mathbf{17}$
9	$8_b^\star$	$\epsilon_{ijklm}\psi^i\psi^j\psi^k\chi^{\dagger lm}\psi^n\psi^\dagger_n$	$\mathbf{15}$, 17
9	9	$\epsilon_{ijklm}\psi^i\Phi^j\chi^{\dagger kl}\chi^{\dagger mn}\Phi^\dagger_n\psi^o\Phi^\dagger_o$	$\mathbf{6}$

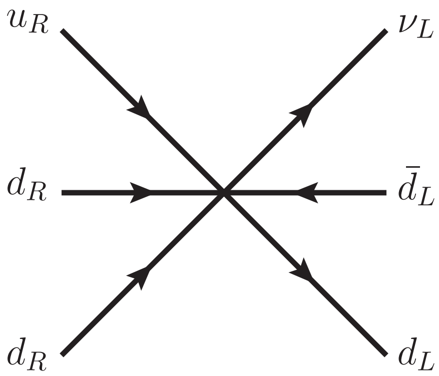
- We use the $\mathcal{O}^{\rm GUT}$ operators to identify which different $\mathcal{O}_{\rm BNV}$ and $\mathcal{O}_{\rm LNV}$ are related to one another.
- If $\Lambda_{LNV,BNL} > \Lambda_{\rm GUT}$, i.e.

$$\text{GUT SM} + X_5$$
$$\downarrow$$
$$\text{GUT SM} + \mathcal{O}_{\rm (B-L)V}$$
$$\downarrow$$
$$\text{SM} + \mathcal{O}_{\rm LNV} + \mathcal{O}_{\rm BNV}\ \ (+\text{“other” H.D.O.})$$

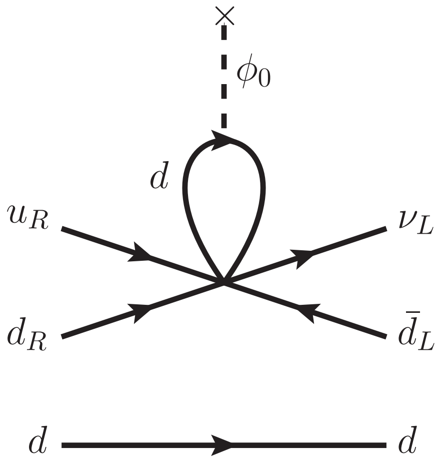
  the coefficients of $\mathcal{O}_{\rm LNV}$ and $\mathcal{O}_{\rm BNV}$ would be the same, modulo quantum effects effects (running between the GUT and the weak scales).
- Since in the real world it must be the other way around, the coefficients are not the same. Nonetheless, we ignore **GUT-breaking** effects in order relate rates of different processes. We don't know how large these are, but it is not unreasonable to assume that they are small (i.e., order one). However, it is known that large effects are possible (most notorious is the “doublet–triple” splitting problem of Φ, the Higgs fiveplet).

$$\frac{1}{\Lambda^3}\epsilon^{ijklm}(\chi_{ij}\chi_{kl})(\psi^\dagger_m\psi^\dagger_n)\Phi^n \supset$$

$$\left\{\frac{\epsilon^{\alpha\beta}}{\Lambda^3}\epsilon_{\delta\gamma}H^*_\alpha(L^\dagger_\beta d^{c\dagger})(Q^\gamma Q^\delta),\ \frac{\epsilon^{\alpha\beta}}{\Lambda^3}H^*_\alpha(L^\dagger_\beta d^{c\dagger})(e^c u^c),\ \frac{\epsilon^{\alpha\beta}}{\Lambda^3}\delta_{\delta\gamma}H^*_\alpha(L^\dagger_\beta L^\dagger_\delta)(Q^\gamma u^c)\right\}$$



$$\Rightarrow \qquad \Gamma(n\to M\nu)\sim\frac{1}{8\pi}\left(\frac{1}{\Lambda^5}\right)^2\Lambda^{11}_{\rm QCD}$$



$$\Rightarrow \qquad \Gamma(n\to M\nu)\sim\frac{1}{8\pi}\left(\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}\right)^2\Lambda^5_{\rm QCD}$$

J for $\mathcal{O}_J^{\rm GUT}$	Operator	$\mathcal{O}_I$	Λ in GeV	Select $\Delta B \neq 0$ Observables
2_a	$\epsilon_{ijklm}\chi^{\dagger ij}\chi^{\dagger kl}\psi^m\psi^n\Phi_n^\dagger$	$\mathcal{O}_{4_a}$	$4\times 10^{11-12}$	$\tau(N\to M\nu)\sim 8\pi\left(\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{37-44}$ years
$2_b^\star$	$\epsilon_{ijklm}\chi^{\dagger ij}\psi^k\psi^l\chi^{\dagger mn}\Phi_n^\dagger$	$\mathcal{O}_{4_b}$	$6\times 10^{8-9}$	$\tau(N\to M\ell)\sim 8\pi\left(\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{20-27}$ years
3	$\chi_{ij}\psi^i\psi^j\psi^k\Phi_k^\dagger$	$\mathcal{O}_{3_b}$	$1\times 10^{10-11}$	$\tau(N\to M\nu)\sim 8\pi\left(\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{28-34}$ years
4	$\epsilon_{ijklm}\psi^i\psi^j\psi^k\psi^l\Phi^m$	none	no estimate	no estimate
5	$\chi_{ij}\chi_{kl}\psi^i\psi^j\psi^k\psi^l$	$\mathcal{O}_{11_b}$	$2\times 10^{6-7}$	$\tau(N\to M\nu)\sim 8\pi\left(\frac{16\pi^2}{y_d}\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{13-20}$ years $\tau(n\to Me)\sim 8\pi\left(\frac{16\pi^2}{y_u}\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{10-16}$ years $\tau(n-\overline{n})\sim\frac{\Lambda^5}{\Lambda_{\rm QCD}^6}\sim 10^{3-8}$ years
6_a	$\epsilon_{ijklm}\psi^i\chi^{\dagger jk}\chi^{\dagger lm}\chi_{no}\psi^n\psi^o$	$\mathcal{O}_{14_b}$	$6\times 10^{7-8}$	$\tau(N\to M\nu)\sim 8\pi\left(\frac{16\pi^2}{y_u}\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{19-25}$ years $\tau(n-\overline{n})\sim\frac{\Lambda^5}{\Lambda_{\rm QCD}^6}\sim 10^{10-16}$ years
6_b	$\epsilon_{ijklm}\psi^i\psi^j\chi^{\dagger kl}\chi^{\dagger mn}\chi_{no}\psi^o$	$\mathcal{O}_{14_b}$	$6\times 10^{7-8}$	$\tau(N\to M\nu)\sim 8\pi\left(\frac{16\pi^2}{y_u}\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{19-25}$ years $\tau(n\to Me)\sim 8\pi\left(\frac{16\pi^2}{y_d}\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{22-28}$ years $\tau(n-\overline{n})\sim\frac{\Lambda^5}{\Lambda_{\rm QCD}^6}\sim 10^{10-16}$ years
$6_c^\star$	$\epsilon_{ijklm}\psi^i\psi^j\psi^k\chi^{\dagger lm}\chi^{\dagger no}\chi_{no}$	$\mathcal{O}_{14_a}$	$1\times 10^{5-6}$	$\tau(N\to M\nu)\sim 8\pi\left(\frac{16\pi^2}{y_u}\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{2-8}$ years $\tau(n\to Me)\sim 8\pi\left(\frac{16\pi^2}{y_d}\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{5-12}$ years
7_a	$\epsilon_{ijklm}\epsilon_{nopqr}\psi^i\chi^{\dagger jk}\chi^{\dagger lm}\psi^n\chi^{\dagger op}\chi^{\dagger qr}$	$\mathcal{O}_{12_a}$	$2\times 10^{9-10}$	$\tau(p\to M\nu)\sim 8\pi\left(\frac{16\pi^2}{y_u}\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{28-34}$ years $\tau(n\to M\ell)\sim 8\pi\left(\frac{16\pi^2}{y_u}\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{28-34}$ years $\tau(n-\overline{n})\sim\frac{\Lambda^5}{\Lambda_{\rm QCD}^6}\sim 10^{18-23}$ years
$7_b^\star$	$\epsilon_{ijklm}\epsilon_{nopqr}\psi^i\psi^j\chi^{\dagger kl}\chi^{\dagger mn}\chi^{\dagger op}\chi^{\dagger qr}$	$\mathcal{O}_{12_b}$	$4\times 10^{6-7}$	$\tau(p\to M\nu)\sim 8\pi\left(\frac{16\pi^2}{y_u}\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{12-18}$ years $\tau(n\to M\ell)\sim 8\pi\left(\frac{16\pi^2}{y_u}\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{12-18}$ years
$8_a^\star$	$\epsilon_{ijklm}\psi^i\psi^j\psi^k\psi^l\chi^{\dagger mn}\psi_n^\dagger$	$\mathcal{O}_{17}$	$2\times 10^{2-3}$	$\tau(p\to M\nu)\sim 8\pi\left(\frac{(16\pi^2)^2}{g^2 y_d}\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{2-8}$ seconds $\tau(n\to Me)\sim 8\pi\left(\frac{16\pi^2}{y_d}\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{(-3)-(+3)}$ seconds
$8_b^\star$	$\epsilon_{ijklm}\psi^i\psi^j\psi^k\chi^{\dagger lm}\psi^n\psi_n^\dagger$	$\mathcal{O}_{15}$	$1\times 10^{5-6}$	$\tau(p\to M\nu)\sim 8\pi\left(\frac{(16\pi^2)^2}{g^2 y_d}\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{11-17}$ years $\tau(n\to Me)\sim 8\pi\left(\frac{16\pi^2}{y_d}\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{5-12}$ years
9	$\epsilon_{ijklm}\psi^i\Phi^j\chi^{\dagger kl}\chi^{\dagger mn}\Phi_n^\dagger\psi^o\Phi_o^\dagger$	$\mathcal{O}_6$	$2\times 10^{9-10}$	$\tau(N\to M\nu)\sim 8\pi\left(16\pi^2\frac{\Lambda^3}{v}\right)^2\frac{1}{\Lambda_{\rm QCD}^5}\sim 10^{28-34}$ years

Piecing the Neutrino Mass Puzzle

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

- understanding the fate of lepton-number. Neutrinoless double beta decay!
- a comprehensive long baseline neutrino program, towards precision oscillation physics.
- other probes of neutrino properties, including neutrino scattering.
- precision studies of charged-lepton properties ($g-2$, edm), and searches for rare processes ($\mu \to e$-conversion the best bet at the moment).
- collider experiments. The LHC and beyond may end up revealing the new physics behind small neutrino masses.
- cosmic surveys. Neutrino properties affect, in a significant way, the history of the universe. Will we learn about neutrinos from cosmology, or about cosmology from neutrinos?
- **searches for baryon-number violating processes.**