Neutrino Mass – Origins

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NEUTRINOS HAVE MASS
[albeit very tiny ones...]

So What?
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[albeit very tiny ones...]

So What?

NEW PHYSICS
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 (my personal list. 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 [inflation]? (not in SM).
What is the New Standard Model? \([\nu\text{SM}]\)

The short answer is – WE DON’T KNOW. Not enough available info!

\[\uparrow\]

Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the \(\nu\text{SM}\) candidates can do. [are they falsifiable?, are they “simple”?; do they address other outstanding problems in physics?, etc]

We need more experimental input.
What is the $\nu$SM?

My goal here is not to provide a comprehensive list of the different ways of rendering the neutrinos massive. Instead, I plan to discuss a few “big picture” ideas and a select few examples [a.k.a. a biased sample I happen to like for apparently random reasons. Apologies if your favorite model is not mentioned or when I don’t properly cite the relevant literature].

The main goals are

- To illustrate the broad range of possibilities;
- To point out that, while we have found something new and exciting, we don’t know where it is. I.e., we don’t know at what energy scale we are supposed to see the new physics behind non-zero neutrino masses;
- To highlight where we hope to learn more about the neutrino mass puzzle.

P3.039 – Small Neutrino Masses from Gravitational $\theta$-Term (Lena Funcke)
**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 doublet 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, etc may provide more information.
Fork on the Road: Are Neutrinos Majorana or Dirac Fermions?

Best (Only?) Bet: Neutrinoless Double-Beta Decay.
We Will Still Need More Help . . .
**νSM – One Path**

SM as an effective field theory – non-renormalizable operators

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

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

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

- Neutrino masses are small: \( \Lambda \gg v \rightarrow m_\nu \ll m_f \) \( (f = e, \mu, u, d, \text{etc}) \)

- Neutrinos are Majorana fermions – Lepton number is violated!

- \( \nu \)SM effective theory – not valid for energies above at most \( \Lambda \).

- What is \( \Lambda \)? First naive guess is that \( \Lambda \) is the Planck scale – does not work.

  Data require \( \Lambda \sim 10^{14} \) GeV (related to GUT scale?) \[ \text{[note } y^{\text{max}} \equiv 1] \]

What else is this “good for”? Depends on the ultraviolet completion!
Example: the (Type I) Seesaw Mechanism

A simple\(^a\), renormalizable Lagrangian that allows for neutrino masses is

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

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.

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\(^a\)Only requires the introduction of three fermionic degrees of freedom, no new interactions or symmetries.
What We Really Know About $M$ and $\lambda$:

- $M = 0$: 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 $m_{\alpha \beta} = \sum_i \mu_{\alpha i} M_i^{-1} \mu_{\beta i}$.
  This is 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.
Accommodating Small Neutrino Masses

If $\mu = \lambda v \ll M$, 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

\begin{align*}
\sin^2 \theta_{as} & \quad m_{\nu} = \ldots \text{eV} \\
M_N (\text{eV}) & \\
\end{align*}

Experimentally Excluded

$\nu_s$s live here

$\nu_s$s live here

[AdG, Huang, Jenkins, arXiv:0906.1611]

July 6, 2016
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): $M < 10^7$ GeV.
- Leptogenesis! “Vanilla” Leptogenesis requires, very roughly, smallest $M > 10^9$ GeV.
- Stability of the Higgs potential (e.g., Elias-Miró et al, 1112.3022): $M < 10^{13}$ 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)

[See Pasquale Di Bari’s Talk.]
“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 $\Lambda$, 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.
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Effective Operator Approach

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

classified by Babu and Leung in NPB619,667(2001)
LNV Operator

(a) \( \nu_\alpha \rightarrow \bar{\nu}_\beta \)

(b) \( \gamma, g \)

(c) \( W, Z \)

(d) \( yv \)

(e) \( y H^- \)

Mass Origins
André de Gouvêa

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Log($\Lambda$/TeV)
Number Of Operators

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Number Of Operators

Log(Λ/TeV)

“Directly Accessible”

Out of “direct” reach if not weakly-coupled (?)

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ν Mass Origins
Dirac Neutrinos – Enhanced Symmetry!(Symmetries?)

Back to

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

where \( N_i \ (i = 1, 2, 3, \) for concreteness) are SM gauge singlet fermions.
Dirac Neutrinos – Enhanced Symmetry!(Symmetries?)

If all $M_i \equiv 0$, the neutrinos are Dirac fermions.

$$\mathcal{L}_\nu = \mathcal{L}_{\text{old}} - \lambda_{\alpha i} L^\alpha H N^i + H.\text{c.},$$

where $N_i$ ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions. In this case, the $\nu$SM global symmetry structure is enhanced. For example, $U(1)_{B-L}$ is an exactly conserved, global symmetry. This is new!

Downside: The neutrino Yukawa couplings $\lambda$ are tiny, less than $10^{-12}$.

What is wrong with that? We don’t like tiny numbers, but Nature seems to not care very much about what we like…

More to the point, the failure here is that it turns out that the neutrino masses are not, trivially, qualitatively different. This seems to be a “missed opportunity.”
There are lots of ideas that lead to very small Dirac neutrino masses. Maybe right-handed neutrinos exist, but neutrino Yukawa couplings are forbidden – hence neutrino masses are tiny.

One possibility is that the $N$ fields are charged under some new symmetry (gauged or global) that is spontaneously broken.

$$\lambda_{\alpha i} L^\alpha H N^i \rightarrow \frac{\kappa_{\alpha i}}{\Lambda} (L^\alpha H)(N^i \Phi),$$

where $\Phi$ (spontaneously) breaks the new symmetry at some energy scale $v_\Phi$. Hence, $\lambda = \kappa v_\Phi / \Lambda$. How do we test this?

E.g., AdG and D. Hernández, arXiv:1507.00916

Gauged chiral new symmetry for the right-handed neutrinos, no Majorana masses allowed, plus a heavy messenger sector. Predictions: new stable massive states (mass around $v_\Phi$) which look like (i) dark matter, (ii) (Dirac) sterile neutrinos are required. Furthermore, there is a new heavy $Z'$-like gauge boson.

⇒ Natural Conections to Dark Matter, Sterile Neutrinos, Dark Photons!
Summary

The venerable Standard Model sprung a leak in the end of the last century: neutrinos are not massless! [and we are still trying to patch it…]

1. We still **know very little** about the new physics uncovered by neutrino oscillations. In particular, the new physics (broadly defined) can live almost anywhere between sub-eV scales and the GUT scale.

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

3. **neutrino mixing is “weird”** – we don’t know why, but we think it means something important. [⇒ next couple of talks]
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 ($\mu \rightarrow e$-conversion the best bet at the moment).
- collider experiments. The LHC and beyond may end up revealing the new physics behind small neutrino masses.
- 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.
O, wonder!

How many goodly creatures are there here!

How beauteous mankind is! O brave new world,

That has such people in’t!

W. Shakespeare, “The Tempest,” Act V, Scene 1
Backup Slides . . .
Weak Scale Seesaw, and Accidentally Light Neutrino Masses

What does the seesaw Lagrangian predict for the LHC?

Nothing much, unless...

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

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

(Note: $N \to \ell q' \bar{q}$ or $\ell \ell' \nu$ (prompt)

“Weird” Higgs decay signature!)
E.g. Charged-Lepton Flavor Violation

In the old SM, the rate for charged lepton flavor violating processes is trivial to predict. It vanishes because individual lepton-flavor number is conserved:

- $N_\alpha(\text{in}) = N_\alpha(\text{out})$, for $\alpha = e, \mu, \tau$.

But individual lepton-flavor number are NOT conserved—\(\nu\) oscillations!

Hence, in the \(\nu\)SM (the old Standard Model plus operators that lead to neutrino masses) $\mu \to e\gamma$ is allowed (along with all other charged lepton flavor violating processes).

These are Flavor Changing Neutral Current processes, observed in the quark sector ($b \to s\gamma$, $K^0 \leftrightarrow \bar{K}^0$, etc).

Unfortunately, we do not know the \(\nu\)SM expectation for charged lepton flavor violating processes $\to$ we don’t know the \(\nu\)SM Lagrangian!
One contribution known to be there: active neutrino loops (same as quark sector).

In the case of charged leptons, the **GIM suppression is very efficient**...

e.g.: \[ Br(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i} U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54} \]

\[ [U_{\alpha i} \text{ are the elements of the leptonic mixing matrix,} \]
\[ \Delta m_{1i}^2 \equiv m_i^2 - m_1^2, \ i = 2, 3 \text{ are the neutrino mass-squared differences} ] \]
e.g.: SeeSaw Mechanism [minus “Theoretical Prejudice”]

\[ \tau \rightarrow \mu \gamma \]
\[ \tau \rightarrow \mu \mu \mu \]
\[ \mu \rightarrow e \gamma \]
\[ \mu \rightarrow eee \]
\[ \mu \rightarrow e \text{ conv in } ^{48}\text{Ti} \]

\[ m_4 \text{ (GeV)} \]

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.