Beyond 3 massive active $\nu$
Beyond 3 (slightly) massive active $\nu$

How: add new light particles (need models) $M \lesssim 10$ GeV
add new heavy particles (can do EFT) $M \gg 10$ GeV

Why: explain some data (osc. anomalies (light $\nu_S$ ?), leptogen...)
address a theory problem (majorana operator non-renorm.,
small masses, large angles...)
predict new observables: LeptonFlavour Violation
— distinguish models

Outline:
1. some seesaw models (make majorana masses)
   (renormalisable, minimal, can be natural, leptogenesis)
2. leptogenesis
   (heavy singlets, $\nu$MSM)
(3. EFT + (Charged)Lepton Flavour Violation)
Things I am unlikely to talk about...

1. not light steriles (I am not expert) 
   various oscillation anomalies can be fit by sterile, $\Delta m^2 \gtrsim eV^2$ fits several, but global fit not improved?

2. not models/symmetries that explain small couplings, large angles...(I am not a model builder)

3. probably not NonStandardInteractions $= \text{NSI}$ (offend my EFT preconceptions)
   dim 8 operators with $\Lambda_{NP} \sim \text{few TeV}$, gives $\nu$-LFV, but no dim6 Charged LFV.

4. Lepton Universality Violation exists in SM...
Two simple ways to add $m_\nu$ to the SM

1. add $\{\nu_R\}$ + Yukawa couplings: $\mathcal{L}_{SM} \rightarrow \mathcal{L}_{SM} + \lambda \bar{\ell} \tilde{H} \nu_R + h.c.$
   - renormalisable, $L$-conserving-$m_\nu \equiv \text{“Dirac”}$
   - $\mathcal{A}_{LFV} \propto \frac{m_\nu^2}{m_W^2}$, multiplicative GIM suppression

2. add “Weinberg operator”: $\mathcal{L}_{SM} \rightarrow \mathcal{L}_{SM} + \frac{\ell H \ell H}{\Lambda} + h.c.$
   - non-renormalisable (dim 5), $\mathcal{L}$ -$m_\nu \equiv \text{“Majorana”}$
   - $\mathcal{A}_{LFV}$ diverges...(need maaaaany counterterms; not predictive)

3. could add non-renormalisable but $L$-conserving, or higher-dim $\mathcal{L}$.

Since “Dirac” masses are boring (suppressed LFV), lets consider case of heavy NP in the lepton sector.
Assume heavy NP in lepton sector; to calculate something?

1 replace non-renorm operator by a renorm. model
   • predict all observables
   • identify correlations ↔ distinguish models?
     + ≈ scientific method = construct hypothesis then test
     − much pursued: invent models faster than exclude

2 add the counterterms.
   ⇒ add dim 6 LFV operators to $\mathcal{L}_{SM}$, with arbitrary coefficients ↔ EFT
      (can subtract divs, impose exptal constraints on coeffs)
     + separate known (SM + data), from not (BSM)
     − less predictive? What to do?

⇒ measure/constain coefficients, translate to $\Lambda_{NP}$, then try to build model indicated by the data
( parenthesis about EFT
What is EFT?

- EFT = recipe to study observables at scale $\ell$
  1. choose *appropriate* variables to describe *relevant* dynamics (*eg* use $\vec{E}, \vec{B}$ and currents for radio waves, electrons and photons at LEP)
  2. $O(0)$ interactions: send parameters $\left\{ \begin{array}{c} L \gg \ell \rightarrow \infty \\ \delta \ll \ell \rightarrow 0 \end{array} \right.$
  3. then perturb in $\ell/L$ and $\delta/\ell$

For LFV, take scale to be energy $E: \text{GeV} \rightarrow \Lambda_{NP}(\sim \text{few TeV})$
(then do pert. theory in $E/\Lambda_{NP}, m/E$ for $m \ll E \ll \Lambda_{NP}$)
EFT $\Leftrightarrow$ add (yet another) perturbative expansion, in scale ratios,
to SM calns. *If* $E/\Lambda_{NP}$ “small”, lowest order (dim 6) ok.
Ummm....renormalisation and EFT

- EFT an expansion in scale ratios, eg $E/M_{NP}$
- But...ummm...in QFT are loops, $p_{\text{loop}} \to \infty$, $p_{\text{loop}} \gg M_{NP}$?
- theorists disturbed by loops : \[
\begin{aligned}
\text{usually diverge on paper} \\
\text{usually finite tiny effects in real world}
\end{aligned}
\]
  ⇒ machinery to regularise (loops) and renormalise (cplg cts)
- can extend regularis./renormalisation to dim > 4 ops of EFT
  … but EFT depends on details of how (eg put, or not, $M \gg E$ particles in loops?)
  ⋆ I use dimensional regularisation; restricts the EFT I construct.

⇒ EFT as well-behaved a QFT as renormalisable models!
but (less arrogant =) less predictive, because knows only true things = what data and SM say...
parenthesis about EFT

Models
for small Majorana masses
Tree-level Majorana mass models (*minimal*)

Heavy new particles (mass $M$) induce dimension 5 operator in $\mathcal{L}$:

$$\frac{K}{4M} [\ell H][\ell H] \rightarrow \nu \nu \frac{K \langle H_0 \rangle^2}{4M}$$

Three possibilities at tree level:

- **SU(2) singlet fermions**
- **triplet fermions**
- **triplet scalars**

**Type I**          **Type III**          **Type II**
Type 1 seesaw, one generation

Add to SM a singlet $N$ with all renorm. interactions:

$$\mathcal{L}_{Yuk}^{\text{lep}} = h_e(\bar{\nu}_L, \bar{e}_L) \left( \begin{array}{c} -H^+ \\ H_0^* \end{array} \right) e_R + \lambda(\bar{\nu}_L, \bar{e}_L) \left( \begin{array}{c} H^0 \\ H^- \end{array} \right) N + \frac{M}{2} \overline{N^c} N + h.c.$$ 

$$m_e \bar{e}_L e_R + m_D \bar{\nu}_L N + \frac{M}{2} \overline{N^c} N + h.c.$$ 

$\Rightarrow$ neutrino mass matrix:

$$\left( \begin{array}{cc} 0 & m_D \\ m_D & M \end{array} \right) \left( \begin{array}{c} \nu_L^c \\ N \end{array} \right)$$

$\Rightarrow$ eigenvectors $\sim$: $\nu_L$ with $m_\nu \sim \frac{m_D^2}{M}$, $N$ with mass $\sim M$
A 2-chasing exercise

Majorana mass $m_\nu$ appears in low-E $\mathcal{L}$ as

$$\frac{m_\nu}{2} \nu_L \nu_L + h.c.$$ 

In type-1 seesaw, $m_\nu = \frac{m_D^2}{M}$

In SU(2)-invariant version, $(\frac{K}{M})$ is the 2H-2$\ell$ Feynman rule)

\[ \mathcal{L} \ni \frac{K}{4M} (\ell H)(\ell H) + h.c. \Leftrightarrow m_\nu = \frac{K\langle H\rangle^2}{2M} \]

So need $\frac{K\langle H\rangle^2}{2M} = \frac{\lambda_D^2\langle H\rangle^2}{M}$ in type 1. But:

\[ \nu_L \xrightarrow{\mathcal{M}} \nu_L = \nu_L \xrightarrow{\lambda_D} \nu_L \xrightarrow{\lambda_D} \nu_L \]

\[ \frac{K}{M} = \frac{\lambda_D^2}{M} \]

ACK
A 2-chasing exercise

Majorana mass \( m_\nu \) appears in low-E \( \mathcal{L} \) as

\[
\frac{m_\nu}{2} \nu_L \nu_L + h.c.
\]

In type-1 seesaw, \( m_\nu = \frac{m_D^2}{M} \)

In SU(2)-invariant version, \( (\frac{K}{M}) \) is the 2H-2ℓ Feynman rule

\[
\mathcal{L} \supset \frac{K}{4M} (\ell H)(\ell H) + h.c. \iff m_\nu = \frac{K \langle H \rangle^2}{2M}
\]

So need \( \frac{K \langle H \rangle^2}{2M} = \frac{\lambda_D^2 \langle H \rangle^2}{M} \) in type 1. But:

\[
\nu_L = \frac{K}{M} \nu_L = \frac{\lambda_D^2}{M} \nu_L + \frac{2\lambda_D^2}{M} \nu_L \quad \text{yippee!}
\]
The type I seesaw

- add 3 singlet $N$ to the SM in charged lepton and $N$ mass bases:
  \[ \mathcal{L} = \mathcal{L}_{SM} + \lambda_{\alpha j} \overline{N}_j \ell_\alpha \cdot H - \frac{1}{2} \overline{N}_j M_j N_j^c \]
  add 18 parameters: $M_1, M_2, M_3$

- at low scale, for $M \gg m_D = \lambda v$, light $\nu$ mass diagram

\[
\begin{align*}
\nu_{L\alpha} & \xrightarrow{\nu \lambda^{\alpha A}} N_A \xrightarrow{M_A \nu \lambda^{\beta A}} \nu_{L\beta} \\
\end{align*}
\]
18 - 3 ($\ell$ phases) in $\lambda$

- 9 parameters: $m_1, m_2, m_3$
- 6 in $U_{MNS}$

\[
[m_\nu] = \lambda M^{-1} \lambda^T v^2
\]

for $\lambda \sim h_t$, $M \sim 10^{15} \text{ GeV}$

$\lambda \sim 10^{-6}$, $M \sim \text{ TeV}$

$\sim .05 \text{ eV}$

“natural” $m_\nu \ll m_f$, but $N$ hard to detect?
The type I seesaw + Higgs mass

- add 3 singlet $N$ to the SM in charged lepton and $N$ mass bases:
  \[ \mathcal{L} = \mathcal{L}_{SM} + \lambda_{\alpha j} \bar{N}_j \ell_\alpha \cdot H - \frac{1}{2} \bar{N}_j M_j N_j^c \]
- at low scale, Higgs mass contribution

\[ \delta m_H^2 \simeq - \sum_I \frac{[\lambda^\dagger \lambda]_{II}}{8\pi^2} M_I^2 \simeq \frac{m_\nu M_I^3}{8\pi^2 v^4} v^2 \]

for $M \gtrsim 10^7$ GeV $> v^2$ tuning problem

(adding particles to cancel 1 loop? Need symmetry to cancel $\geq 2$ loop?)
⇒ do seesaw with $M_I \lesssim 10^8$ GeV?
a low-scale tree model detectable at the LHC: the inverse seesaw

- add two singlets $N, S$ per generation to the SM:

$$\mathcal{L} = \mathcal{L}_{SM} + \lambda \bar{N} \ell \cdot H - \bar{N} MS - \frac{1}{2} \bar{S} \mu S^c$$

Dirac mass between $N$ and $S$, small Majorana mass for $S$.

For $\mu = 0$, lepton number conserved, $L=1$ for $\ell, N, S^c$, and $m_{\nu} = 0$.

To check in 1-gen: mass matrix is

$$\begin{pmatrix}
\nu_L & \bar{N}^c & \bar{S} \\
\end{pmatrix}
\begin{bmatrix}
0 & m_D & 0 \\
m_D & 0 & M \\
0 & M & 0 \\
\end{bmatrix}
\begin{pmatrix}
\nu_L^c \\
\bar{N} \\
\bar{S}^c \\
\end{pmatrix}$$

determinant vanishes.
massive $\nu_L$ in inverse seesaw

- add two singlets $N, S$ per generation to the SM:
  $$\mathcal{L} = \mathcal{L}_{SM} + \chi \bar{N} \ell \cdot H - \bar{N} MS - \frac{1}{2} \bar{S} \mu S^c$$

Dirac mass between $N$ and $S$, small Majorana mass for $S$.

For $\mu \neq 0 \ll m_D \lesssim M$,

$$\begin{pmatrix}
\bar{\nu}_L & \bar{N}^c & \bar{S}
\end{pmatrix}
\begin{bmatrix}
0 & m_D & 0 \\
m_D & 0 & M \\
0 & M & \mu
\end{bmatrix}
\begin{pmatrix}
\nu_L^c \\
N \\
S^c
\end{pmatrix}$$

determinant $= \mu m_D^2 \Rightarrow$ masses $M, M, m_D^2 \mu / M^2$
diagrammatic $\nu_L$ mass in inverse seesaw

- add two singlets $N, S$ per generation to the SM:
  \[ \mathcal{L} = \mathcal{L}_{SM} + \lambda \overline{N} \ell \cdot H - \overline{N} MS - \frac{1}{2} \overline{S} \mu S^c \]

  Dirac mass between $N$ and $S$, small Majorana mass for $S$.

- at low scale, light $\nu$ mass matrix

\[
\begin{bmatrix}
\nu_L \\
N \\
S \\
N \\
\nu_L
\end{bmatrix}
\]

\[
[m_\nu] = \lambda M^{-1} \mu M^{-1} \lambda^T \nu^2 \sim 0.05 \text{ eV}
\]

for $\lambda \sim 0.01$, $M \sim \text{TeV}$, $\Rightarrow \mu \sim 10 \text{ keV}$

Naturally small $m_\nu$, and $N \cong \text{TeV}$ with $O(1)$ yukawas.
Can neutrinos make the Universe we see?

Leptogenesis

*Leptogenesis* is a class of recipes, that use majorana neutrino mass models to generate the matter excess. The model generates a lepton asymmetry (before the Electroweak Phase Transition), and the non-perturbative SM B+L violn reprocesses it to a baryon excess.
Preambule

1. about “What the stars (and us) are made of” (5% of U)
   \[ \approx H \approx \text{baryons} \]
   not worry about lepton asymmetry : is \text{(undetected)}
   Cosmic Neutrino Background ...so how to measure asym? ? ?

2. I am made of baryons\text{(defn)} ... observation... all matter
   we see is made of baryons (not anti-baryons)

3. quantify as \( (s_0 \approx 7n_{\gamma,0}) \)

\[
Y_B \equiv \left. \frac{n_B - n_{\bar{B}}}{s} \right|_0 = 3.86 \times 10^{-9} \Omega_B h^2 \approx (8.53 \pm 0.11) \times 10^{-11}
\]

\[\Rightarrow\] Question : where did that excess come from?

\text{PLANCK}
Where did the matter excess come from?

1. the U(niverse) is matter-anti-matter symmetric?
   = islands of particles and anti-particles
   ✗ no! not see $\gamma$s from annihilation

2. U was born that way...
   ✗ no! After birth of U, there was “inflation”
   ▶ (only theory explaining coherent temperature fluctuations in microwave background that arrive from causally disconnected regions today...)
   ▶ “60 e-folds” inflation $\equiv V_U \rightarrow > 10^{90} V_U$

   $$(n_B - n_{\overline{B}}) \rightarrow 10^{-90}(n_B - n_{\overline{B}}), s \text{ from } \rho \text{ of inflation...}$$

3. created/generated/cooked after inflation...
Three ingredients to prepare in the early U (old Russian recipe)

1. **B violation**: if Universe starts in state of \( n_B - n_{\bar{B}} = 0 \), need \( \mathcal{B} \) to evolve to \( n_B - n_{\bar{B}} \neq 0 \)

2. **C and CP violation**: ...particles need to behave differently from anti-particles. Present in the SM quarks, observed in Kaons and Bs, searched for in leptons (...T2K, future expts)

3. **out-of-thermal-equilibrium**...equilibrium = static. “generation” = dynamical process
   No asym.s in un-conserved quantum #s in equilibrium
From end inflation \( \rightarrow \) BBN, Universe is an expanding, cooling thermal bath, so non-equilibrium from:
   - slow interactions: \( \tau_{int} \gg \tau_U = \text{age of Universe} \)
     \( (\Gamma_{int} \ll H) \)
   - phase transitions:
ingredient 1: Does the SM conserve $B$?

$B, L$ are global symmetries of the SM Lagrangian ($q, \ell$ doublets, $e, u, d$ singlets)

$$\mathcal{L}_{SM} \supset \bar{q} D q, \quad \bar{\ell} D \ell, \quad \bar{\ell} H e, \quad \bar{q} \tilde{H} u, \quad \bar{q} H d$$

so, classically, there are conserved currents, and $B$ and $L$ are conserved. (So $B + L$ and $B - L$ are conserved.)

Good—proton appears stable: $\tau_p \gtrsim 10^{33}$ yrs ($\tau_U \sim 10^{10}$ yrs).

But the SM does not conserve $B + L$...

In QFT, there is the axial anomaly...

...anomalously, the fermion current associated to a classical symmetry is not conserved.

see Polyakov, “Gauge Fields + Strings,” 6.3=qualitative effects of instantons
ingredient 1: the SM does not conserve $B + L$

$B + L$ is anomalous. Formally, for one generation ($\alpha$ colour):

$$\sum_{\text{singlets}} \partial^\mu (\bar{\psi} \gamma_\mu \psi) + \partial^\mu (\bar{\ell} \gamma_\mu \ell) + \partial^\mu (\bar{q}^\alpha \gamma_\mu q_\alpha) \propto \frac{1}{64\pi^2} W^A_{\mu\nu} \tilde{W}^{\mu\nu A}.$$ 

where integrating the RHS over space-time counts “winding number” of the SU(2) gauge field configuration.

$\Rightarrow$ Field configurations of non-zero winding number are sources of a doublet lepton and three (for colour) doublet quarks for each generation.

thanks to V Rubakov
SM B+L violation: rates

At $T = 0$ is tunneling process (from winding # to next, "instanton"): $\Gamma \propto e^{-8\pi/g^2}$

At $0 < T < m_W$, can climb over the barrier:

$$\Gamma_{B+L} \sim e^{-m_W/T} \quad T < m_W$$

$$\Gamma_{B+L} \sim \alpha^5 T \quad T > m_W$$

$\Rightarrow$ fast SM B+L at $T > m_W$

$$\Gamma_{B+L} > H \text{ for } m_W < T < 10^{12} \text{ GeV}$$

SM B+L called "sphalerons"

$\Rightarrow$ if produce a lepton asym, "sphalerons" partially transform to a baryon asym. !!

★★★ SM B+L is $\Delta B = \Delta L = 3 (= N_f)$. No proton decay! ★★★
Summary of preliminaries: A Baryon excess today:

- Want to make a baryon excess $\equiv Y_B$ after inflation, that corresponds today to $\sim 1$ baryon per $10^{10}$ $\gamma$s.
- Three required ingredients: $B$, $\mathcal{CP}$, $\mathcal{T}$.
  Present in SM, but hard to combine to give big enough asym $Y_B$.

\[ \text{Cold EW baryogen? ? Tranberg et al...} \]

\[ \Rightarrow \text{evidence for physics Beyond the Standard Model (BSM)} \]

One observation to fit, many new parameters...

\[ \Rightarrow \text{prefer BSM motivated by other data} \Leftrightarrow m_\nu \Leftrightarrow \text{seesaw!} \quad \text{(uses non-pert. SM $B\mathcal{L}$)} \]
Recall...the type I seesaw

- add 3 singlet $N$ to the SM in charged lepton and $N$ mass bases, at scale $M_i > M_i$

\[ \mathcal{L} = \mathcal{L}_{SM} + \lambda_{\alpha J} \bar{N}_J \ell_{\alpha} \cdot H - \frac{1}{2} \bar{N}_J M_J N_J^c \]

$M_i$ few GeV $\rightarrow 10^{15}$ GeV, $\not\! \mathcal{L}$ $\not\! \mathcal{P}$ in $\lambda_{\alpha J} \in \mathcal{C}$. 
Leptogenesis in the type 1 seesaw: usually a Fairy Tale

Once upon a time, a Universe was born.
Leptogenesis in the type 1 seesaw: usually a Fairy Tale

Once upon a time, a Universe was born. At the christening of the Universe, the fairies give the Standard Model and the Seesaw (heavy sterile $N_j$ with $L$ masses and $\mathcal{CP}$ interactions) to the Universe.

The adventure begins after inflationary expansion of the Universe:
1. If it’s hot enough, a population of $N$s appear (they like heat).
2. The temperature drops below $M$, $N$ population decays away.
3. In the $\mathcal{CP}$ and $L$ interactions of the $N$, an asymmetry in SM leptons is created.
Leptogenesis in the type 1 seesaw: usually a Fairy Tale

If this asymmetry can escape the big bad wolf of thermal equilibrium...
Leptogenesis in the type 1 seesaw: usually a Fairy Tale

Once upon a time, a Universe was born.
At the christening of the Universe, the fairies give the Standard Model and the Seesaw (heavy sterile $N_j$ with $\mathcal{L}$ masses and $\mathcal{CP}$ interactions) to the Universe.
The adventure begins after inflationary expansion of the Universe:
1. If its hot enough, a population of $N$s appear (they like heat).
2. The temperature drops below $M$, $N$ population decays away.
3. In the $\mathcal{CP}$ and $\mathcal{L}$ interactions of the $N$, an asymmetry in SM leptons is created.
4. If asymmetry escapes the wolf of thermal equilibrium...
5. the lepton asym gets partially reprocessed to a baryon asym by non-perturbative $B + L$ -violating SM processes (“sphalerons”)
And the Universe lived happily ever after, containing many photons. And for every $10^{10}$ photons, there were 6 extra baryons (wrt anti-baryons).
Does it work? Calculate something?

Recipe: calculate suppression factor for each Sakharov condition, multiply together to get $Y_B$:

$$\frac{n_B - n_{\bar{B}}}{s} \sim \frac{1}{3g_*} \epsilon_{L,CP}\eta_{TE} \sim 10^{-3}\epsilon\eta$$

(want $10^{-10}$)

$s \sim g_* n_\gamma$, $\epsilon = \text{lepton asym in decay}$, $\eta = \text{TE process}/\gamma$

$\text{TE + dynamics:}$

Suppose at $T \gtrsim M_1$, a density $\sim T^3$ is produced.

Later, Lepton asym produced in $CP$ $N$ decays, survives if not washed out by Inverse Decays = survives after ID out of equil:

$$\Gamma_{ID}(\phi \ell \rightarrow N) \sim \Gamma_{decay}e^{-M_1/T} = \frac{[\lambda \lambda^\dagger]_{11} M_1}{8\pi}e^{-M_1/T} < \frac{10T^2}{m_{pl}}$$

Fraction $N$ remaining at $T_{ID}$ when ID turn off:

$$\frac{n_N}{n_\gamma}(T_{ID}) \sim e^{-M_1/T_\alpha} \sim \frac{H}{\Gamma(N \rightarrow \ell_\alpha \phi)} \equiv \eta$$
Estimate $\epsilon$, the CP asymmetry in decays

Recall (in S-matrix) $CP : \langle \phi_\ell | S | N \rangle \rightarrow \langle \bar{\phi}_\ell | S | \bar{N} \rangle = \langle \bar{\phi}_\ell | S | N \rangle, (\bar{\eta} = \text{anti-}\eta)$

In leptogenesis, need $CP, \mathcal{L}$ interactions of $N_I$...for instance:

$$\epsilon_I^\alpha = \frac{\Gamma(N_I \rightarrow \phi_\ell \alpha) - \Gamma(\bar{N}_I \rightarrow \bar{\phi}_\ell \bar{\alpha})}{\Gamma(N_I \rightarrow \phi_\ell) + \Gamma(\bar{N}_I \rightarrow \bar{\phi}_\ell)} \quad \text{(recall } N_I = \bar{N}_I)$$

$$\sim \text{ fraction } N \text{ decays producing excess lepton}$$

Just try to calculate $\epsilon_1$?

- asym at tree $\times$ loop, if $CP$ from complex cpling and on-shell particles in the loop (divergences cancel in diff, need Im part of Feynman param integrtn)
Can use unitarity and CPT invariance of S-matrix to estimate $\epsilon$ from tree amplitudes.
Consider $M_1 \ll M_{2,3}$, asym from $\mathcal{CP}$, $\mathcal{L}$ decays of $N_1$:

$$
\epsilon_1^\alpha = \frac{\Gamma(N_1 \rightarrow \phi \ell_\alpha) - \Gamma(\bar{N}_1 \rightarrow \bar{\phi} \bar{\ell}_\alpha)}{\Gamma(N_1 \rightarrow \phi \ell) + \Gamma(\bar{N}_1 \rightarrow \bar{\phi} \bar{\ell})} \quad \text{(recall } N_1 = \bar{N}_1) \n$$

$$
\kappa_{\alpha \beta} \sim \frac{[m_\nu]_{\alpha \beta}}{v^2} \n$$

$$
\epsilon_1 \sim \frac{1}{8\pi} \frac{\lambda^2 \kappa}{\lambda^2} M < \frac{3}{8\pi} \frac{m_\nu^{\text{max}} M_1}{v^2} \sim 10^{-6} \frac{M_1}{10^9 \text{GeV}} \n$$
Estimate $Y_B$

Recall($s \sim g_* n_\gamma$, $\epsilon =$ lepton asym in decay $\eta = \text{TE process/}\gamma$):

$$\frac{n_B - n_{\bar{B}}}{s} \sim \frac{1}{3g_*} \epsilon_{L,CP} \eta_{TE} \sim 10^{-3} \epsilon \eta \quad \text{(want } 10^{-10})$$

$$\sim 10^{-3} \frac{H}{\Gamma} 10^{-6} \frac{M_1}{10^9 \text{GeV}}$$

for $M_1 \ll M_{2,3}$, need $M_1 \gtrsim 10^9$ GeV to obtain sufficient $\epsilon$

?but give $\delta m_H^2 \gg m_H^2$?
do leptogenesis with $M_K < 10^7$ GeV?

For $M_I \sim M_J \Leftrightarrow$ resonantly enhance $\epsilon$ ... up to $\epsilon \lesssim 1/8\pi$! but need decays before Electroweak PT (to profit from sphalerons)... and ID out-of-equil:

$$\Gamma_{ID} \sim e^{-M/T} \Gamma(N \rightarrow \phi \ell) < H \implies M \gtrsim 10T_c$$

Fairy tale works for degen $N_I$ for $M_I \gtrsim$ TeV

(but are $M_I \sim$ TeV any more detectable than $M_I \sim 10^9$ GeV?)
νMSM : type 1 seesaw below 100 GeV gives BAU and DM

**ingredients :** SM +

\[ N_{2,3} : 100 \text{ MeV} \lesssim M_{2,3} \lesssim 10 \text{ GeV}, \Delta M \lesssim \begin{cases} 10^{-6} \text{ eV} & Y_B, \Omega_{DM} \\ \text{keV} & Y_B, \text{NOT} \Omega_{DM} \end{cases} \]

Yukawas \( \ni \) give 2 light SM neutrinos via seesaw

\( N_1 : M_1 \sim \text{keV}. \) WDM candidate.

feebly coupled (negligible contribution \( m_{\nu,SM} \))

**scenario :**

Population of \( N_{2,3} \) produced via Yukawas before EPT

Produce \( \Delta L \to Y_B \) via oscillations of \( N_{2,3}, \nu_{SM} \) before EPT

Produce \( \Delta L \gtrsim 10^{-5} \) via osc. and decay of \( N_{2,3} \) after EPT

Can produce sufficient distribution of \( N_1 \) via osc.

**tests :**

\( N_{2,3} : \) beam dump, SHIP

\( N_1 \) as DM : X-rays from DM decay, WDM bounds (depend on momentum distribution)
How does asym generation work? (very simplified!)

1. at $T \lesssim \text{TeV}$ (recall $\lambda \lesssim 10^{-7}$), produce $N_2, N_3$ via Yukawa interaction $\lambda \bar{N} \ell \cdot \phi$

2. $N_2, N_3$ oscillate (almost degenerate)

3. back to $\nu_L$ via $\lambda$

at $\tau_U \sim \tau_{\text{osc}}$, 1,2,3 are coherent, so CPV from $\lambda-\Delta M^2-\lambda$ gives flavour asyms in $\nu_{L\alpha}$ (to small)

*lepton number in $\ell_L + N_R$ is conserved* (actually, $L_{SM} +$ helicity of $N_i$)

from $\tau_{\text{osc}} \rightarrow \tau_{\text{EWPT}}$, asyms in $\nu_{L\alpha}$ seed asyms in $N \rightarrow$ asyms in $\nu_{L\alpha}$ (enough asym)

...works also in detailed calculations with all available technology...

(eg also include lepton number violating interactions)

Teresi Hambye
Eijima + Shaposhnikov
Ghiglieri+ Laine
$$U^2 = \text{Tr}[\lambda M^{-2} \lambda^\dagger]$$
Summary

*Leptogenesis* is a class of recipes, that use majorana neutrino mass models to generate the matter excess. The model generates a lepton asymmetry (before the Electroweak Phase Transition), and the non-perturbative SM B+L violn reprocesses it to a baryon excess.

⋆ efficient, to use the BSM for $m_\nu$ to generate the Baryon Asym.
⋆ using SM B+L violn ($\Delta B = \Delta L = 3$) avoids proton lifetime bound
⋆ *it works* ...rather well, for a wide range of parameters