TWO INTRIGUING COINCIDENCES

- The seesaw scales needed for leptogenesis versus the seesaw scales needed for \( v \) masses.

\( \text{If for a hierarchical spectrum of } N_i: M_{N1} < M_{N2,3} \)

\[
E_{N1} = -\frac{3}{16\pi} \frac{\text{Im} \left[ (Y_{l1}Y_{l1}^*)^2 \right]}{M_{N1}^2} = -\frac{3}{16\pi} \frac{M_{N1} \text{Im} \left[ (Y_{l1}Y_{l1}^*)^2 \right]}{M_{N2}^2} \\
= -\frac{3}{16\pi} \frac{\Sigma m_j^2 \text{Im} \left[ (R_{l1}^2) \right]}{\Sigma m_j^2 M_{N2}^2} \quad Y_{l1} = \frac{\sqrt{2}}{\Sigma m_j^2 M_{N2}^2} \text{Re} \left( M_{l1}^2 \right) \]

\( \Rightarrow E_{N1} \leq \frac{3}{16\pi} \frac{M_{N1} (\Sigma m_j^2 \text{Im} \left[ (R_{l1}^2) \right])}{\Sigma m_j^2 M_{N2}^2} \leq \frac{3}{16\pi} \frac{M_{N1} \sqrt{\Delta m_{12}^2}}{0.05 \text{eV}} \)

\( \Rightarrow \text{requiring } \frac{M_{N1}}{M_{N2}} = \frac{28}{79} \quad \frac{E_{N1}(M_{N1})}{\text{eV}} > \frac{\text{mV}}{\text{eV}} \quad M_{N1} = 9.10^{-11} \)

\( \Rightarrow M_{N1} > 4.708 \text{ GeV} \quad \text{Davidson-Ibarra 02.} \)

- This value (obtained for \( \text{Im} \left( R_{l1}^2 \right) = 1 / M_{N2}^4 \)) or higher values of \( M_{N1} \) (for smaller \( R_{l1}^2 \)) fit very well with seesaw scales needed for \( v \) masses (in particular scales where seesaw mass suppression of \( M_{N2} \) is fully operative).

- N.B.: for \( M_{N2,3} \approx M_{N1} \) for example one can have successful leptogenesis for much smaller values of \( M_{N1} \) (for large entries of \( R \)).

T. H. et al. 03
\( \text{The v mass scale value versus } m_v \text{ and } m_{\text{Planck}} \text{ scales} \)

\[
K_{m} \equiv \frac{\Gamma_{\nu}^{\text{Tot}}}{H_\nu} \geq \frac{m_{\nu}^{\min}}{10^{-3}\text{eV}} \geq 10^{-3}\text{eV} \leq 17.8 \text{eV} \frac{10^{-3}\text{eV}}{m_{\text{Planck}}} \\
\Rightarrow \quad \alpha \leq \frac{1}{2} \frac{\nu \nu_i}{m_{\nu}^2} \quad \alpha \geq \nu_i^T \cdot m_{\nu}^2 \cdot \nu_v.
\]

\( \Rightarrow \) given the \( m_v \leq 1.7 \text{eV} \) bound from KATRIN this means the washout is naturally limited.

\( P_{\nu} / H_\nu \leq 1 \) cannot be much violated.

\( \Rightarrow \) real coincidence because \( 10^{-3}\text{eV} \) scale is determined by \( \nu = 246 \text{eV} \) and \( m_{\text{Planck}} = 10^{16}\text{eV} \).

\( \Rightarrow \) \( m_v \sim \text{keV} \) for example would kill leptogenesis.

\( \bullet \) In fact for \( M_{\nu} \ll \nu_{\nu_i} \) successful leptogenesis requires \( m_v \leq 0.12 \text{eV} \) in this case \( m_{\nu} \sim m_{\nu_2} \sim m_{\nu_3} \sim m_{\nu_1} \).

\( \Rightarrow \) due to 2 effects:

\( \bullet \) \( E_{\nu_1} < \frac{3}{4\pi} \frac{m_{\nu_2}}{\nu_2^2} (m_{\nu_3} - m_{\nu_1}) \) when \( m_v > \)

\( \Rightarrow \) \( m_{\nu_3} - m_{\nu_1} = \frac{3.5 \times 10^{-3}\text{eV}}{2m_{\nu}} \)

\( \bullet \) \( K_{m_1} \geq \frac{m_{\nu_1}^{\min}}{10^{-3}\text{eV}} \) when \( m_v > m_{\nu_1} - m_{\nu_2} \) for \( m_v > 0.05\text{eV} \).

\( \Rightarrow \) however: to get a quasi-degenerate \( m_v \) spectrum from hierarchical \( M_{\nu} \) spectrum implies tuning (cancellation in \( m_{\nu} \cdot \nu_i^T \cdot m_{\nu} \cdot \nu_v \)).

\( \Rightarrow \) more natural is to get it from quasi-
The degenerate spectrum of $M_\nu$ in this case no more relevant upper bound on $m_\nu$ as resonances in $E_\nu$ (see below).

- Flavor effect also relax this bound (see below).

$\Rightarrow$ to sum up so far: the scales ($m_\nu, r, m_{\text{planck}}$) and the $m_\nu$ observed value match very well!!

$\Rightarrow$ it is nevertheless difficult to make any precise prediction:

$$E_{N_1} = -\frac{3}{16 \pi} \frac{M_\nu}{v^2} \frac{3 m_\nu^2}{E m_{\nu_1}} \frac{\text{Im}(R^2)}{E m_{\nu_1} m_{\nu_2}}$$

$E_{N_1}$ depends on low energy $m_\nu$ value but the phases leading to lepto-genesis are the 3 "high-energy" ones

$+ dependence on 3 real parameters in $R$ which are also "high-energy"

$+ dependence in unknown $m_{\nu_1}$
FLAVOR LEPTOGENESIS

So far, all results: counting the # of lepton created and destroyed independently of their \( e, \mu \) or \( \tau \) flavor.

Justified for \( T \gtrsim 10^{12} \text{GeV} \): \( e^-, \mu^-, \tau^- \) indistinguishable in the thermal bath; same gauge inter. and SM charged inter. out of equilibrium.

\( \Rightarrow \) the \( N_1 \) couples to a single \( \sum \nu_e \nu_e + \nu_\mu \nu_\mu + \nu_\tau \tau \) and this combination remains coherent afterwards: one counts # of \( \nu \) created/destroyed \( \Rightarrow \) a single Boltzmann eqn.

\( \Rightarrow \) however, for \( T \lesssim 10^{12} \text{GeV} \): \( \Gamma_\nu^\text{SM} > H \sim SM \times \text{Yukawa} \)

\( \Rightarrow \) thermal bath distinguishes \( \tau \) flavor from \( e + \mu \) flavor.

\( \Rightarrow \) 2 Boltzmann eqns.: \( \Rightarrow \) for # of \( \nu \)

\( \Rightarrow \) for # of \( e + \mu \)

\( \Rightarrow \) a multi-variate distribution for each one with its flavor asym:

\[ E_{\nu_\mu} = \frac{\Gamma_{(N \rightarrow e_\mu H)} - \Gamma_{(N \rightarrow \nu_\mu H)}}{\Gamma_{(N \rightarrow \nu_\mu H)}} \]

For \( T \lesssim 10^{9} \text{GeV} \): \( \Gamma_{\nu_\mu}^\text{SM} > H \)

\( \Rightarrow \) 3 Boltzmann eqns.: \( \Rightarrow \) for # of \( \nu \)

\( \Rightarrow \) for # of \( e + \mu \)

N.B.: in fact, more precisely the \( Y_\nu \) Yukawas interact.

breaks the \( \nu \) coherence: if a \( \nu \) undergoes a \( Y_\nu \) interaction on average before it goes in an inverse decay \( \nu \rightarrow e + H \).
Flavor typical effects:

- Reduction of washout effect: in strong washout case: \( N_{N_1} \gg 1 \)
  - \( \beta \) in one flavor approx.: strong washout
  - \( \beta \) in several flavor case: possibility of less washout: e.g. if \( \Gamma(N_1 \rightarrow \text{lept. } H) \gg \Gamma(N \rightarrow l_x H) \): \( \gamma \) asym, less washed-out
  - \( \beta \) changes result by factor of a few (typically)
  - \( \beta \) does not change on \( N_{N_1} \approx 4 \times 10^8 \text{ GeV bound} \)
    obtained anyway in no washout case.

- \( N_{2,3} \) leptogenesis:
  - \( \beta \) in one flavor approx.: \( \beta \) created by \( N_2, N_3 \) decays washed out by \( N_1 \) interactions
  - \( \beta \) in several flavor case: not so true anymore if \( N_i \)'s couple to 4 flavors

- Initial condition dependence:
  - \( \beta \) in one flavor approx.: any preexisting L asym would be easily washed out by \( N_i \)'s interactions
  - \( \beta \) in several flavor case: not so true anymore

- \( \delta \phi \) phases contributing to leptogenesis
  - \( \beta \) in one flavor approx.: only the 3 high energy phases
  - \( \beta \) in several flavor case: the 3 low energy phases

\( \delta \phi \) = complicated in \( U^\nu \) can also contribute \( \Rightarrow \) in general less low energy combination of 6 high predictive. Possibility to have leptogenesis with only Dirac phase in \( U^\nu \), \( \delta \phi \), but no reason to have only it at all.
Ponely flavored leptogenesis:

\[ \rightarrow \text{for each } L_i \text{ flavor: } \Sigma_j^k = \frac{\Gamma(N \rightarrow L_i \bar{L}_j H^+)}{\Gamma_{tot}} - \frac{\Gamma(N \rightarrow L_i \bar{L}_j H)}{\Gamma_{tot}} \]

\( \Sigma \) in one flavor case: \( \Sigma_j^k = 0 \Rightarrow \) no leptogenesis

\( \Sigma \) in several flavor case: \( \Sigma_j^k = -\Sigma_{\text{washed out}} \neq 0 \)

\( \text{can be not washed out} \)

\( \text{can be washed out} \)

\( \Rightarrow \) leptogenesis

\text{generically subleading because suppressed by } \frac{m_{L_i}^2}{m_{\tilde{e}_{1,2,3}}^2} \) factors but possible
EL QUASI-DEGENERATE $M_{\nu_i}$ SPECTRUM CASE: LOW SCALE LEPTOGENESIS

If at least 2 $\nu_i$ have similar masses $\Rightarrow$ resonance effect!

\[ \text{for } M_{\nu_1} - M_{\nu_2} : \ ]

\[ \Rightarrow E_{\nu_1} = \frac{1}{8\pi} \text{Im} \left[ \left( Y_{\nu_1} Y_{\nu_2}^* \right)^2 \right] \frac{M_{\nu_4}}{M_{\nu_2}} S_{12} \]

\[ S_{12} = \frac{M_{\nu_2}^2}{M_{\nu_4}^2 - M_{\nu_2}^2} \]

\[ \Rightarrow \text{need to include decay width:} \]

\[ M(\nu_1^c\nu_2) \propto \left( \frac{1}{H_{M_1} - H_{M_2} + i \Gamma_{\nu_2} M_{\nu_1}} \right) \]

\[ M(\nu_1\nu_2^c) \propto \left( \frac{1}{H_{M_1} - M_{\nu_1}^2 + i \Gamma_{\nu_2} M_{\nu_1}} \right) \]

\[ \Rightarrow \begin{cases} S_{12} = 1 & \text{if } M_{\nu_2} > M_{\nu_1} \\ S_{12} = \frac{M_{\nu_2}}{\Gamma_{\nu_2} M_{\nu_1}} & \text{if } M_{\nu_2} - M_{\nu_1} = \Gamma_{\nu_2} / 2 \\ S_{12} = 0 & \text{if } M_{\nu_2} = M_{\nu_1} \end{cases} \]

Huge resonant enhancement.
\[ \Rightarrow \text{En}_1 \text{ not bounded anymore by } \frac{M_{\nu_1} (m_{\nu_3} - m_{\nu_4})}{\nu_2} \]

\[ \Rightarrow \frac{\text{En}_1}{2} + \text{En}_1 + \text{En}_2 \leq 1 \]

at the peak

\[ \Rightarrow \text{no more bound on } M_{\nu_1} \text{ from En}_1 \]

\[ \Rightarrow \text{"low scale leptogenesis"} \]

\[ \Rightarrow M_{\mu} \sim M_{\tau} \text{ new perfectly possible} \]

\[ \Rightarrow N \text{ decay to LH only requires } M_{\nu_2} > m_L + m_H \sim 100 \text{ GeV} \]

- No more relevant upper bound on \( m_{\nu} \): \( m_{\nu} \sim 1 \text{ eV perfectly possible} \)

\[ \Rightarrow \text{if } m_{\nu_1} \sim m_{\nu_2} \sim m_{\nu_3} \sim 1 \text{ eV: } \frac{m_{\nu_2} - m_{\nu_1}}{m_{\nu_3}} \sim 10^{-3} \]

\[ \Rightarrow \text{easier to explain if } \frac{m_{\nu_2} - m_{\nu_1}}{M_{\nu_1}} \sim 10^{-3} \text{ too } \Rightarrow \text{resonance!} \]

- A proper treatment of resonant case: quantum Boltzmann equations bringing corrections

- Bochmuller et al. De Simone, Risotto et al. Gann et al.

- Tests of low scale leptogenesis:

\[ \Rightarrow \text{if } M_{\nu_1} \sim 1 \text{ TeV one could naively expect a production of } N_3 \text{ at colliders} \]

\[ \Rightarrow \text{however } m_{\nu} \sim Y_{\nu}^2 \sim 10^{-2} \text{ requires typically by } Y_{\nu} \sim 10^{-2} \Rightarrow \text{too small to produce } N_3 \text{ at colliders } (N_1 \text{ is SU(2)} \times U(1): \text{no gauge interacts}) \]

\[ \Rightarrow 2 \text{ ways out one could think of:} \]
production of $N^*$s from other interactions

- for example: L-R models

$\Rightarrow$ $N^*$s can be produced at LHC via $W^p \bar{q}$, $W^p \bar{N}$, $\bar{q} \bar{N}$

$\Rightarrow$ however: any large interaction of $N$ such as $gg$ ones will deeply thermalize TeV scale $N^*$s:

$$\frac{dY_N}{dz} = \ldots \gamma_D (1 - \frac{Y_N}{Y_N^{eq}}) + \ldots \gamma_{W^p} (1 - \frac{Y_N}{Y_N^{eq}}) + \ldots$$

$\Rightarrow$ since $\gamma_{W^p} \gg \gamma_D = \gamma_{W^p} - Y_N^{eq}$ much more suppressed than with $\gamma_D$ term only

$$\Rightarrow \ldots \frac{dY_N}{dz} = \ldots \gamma_D (1 - \frac{Y_N}{Y_N^{eq}}) E_N + \ldots$$

very suppressed

$\Rightarrow$ not much product of $Y_N$

$\Rightarrow$ this is not a washout effect but a $N$ thermalized effect

$\Rightarrow$ successful leptogenesis requires

$m_{W^p} > 18$ TeV $\Rightarrow$ $N$ production at LHC through $W^p$ hopeless in this case

Fritz, T.M., Vanlangeren, 08.
- approximate L conservation frameworks: if one assumes (just so for the sake of testability) that there exists an extra UNI global symmetry that is broken only by a small amount, one can get small ν masses even though some of the Yukawas are large.

Example: 2N's framework with L(N1) = 1, L(N2) = -1

\[
\begin{pmatrix}
N_1 & N_2 & N_3 \\
Y_{N1} & 0 & Y_{N2} \\
0 & M_N & 0
\end{pmatrix}
\Rightarrow m_\nu = 0 \quad \text{(L conserved)}
\]

\Rightarrow adding & perturbations:

\[
M = \begin{pmatrix}
0 & Y_{N1} & Y_{N2} \\
Y_{N1} & \mu & M_N \\
Y_{N2} & M_N & \mu
\end{pmatrix}
\]

\Rightarrow m_\nu = \frac{1}{M_N} Y_{N1} Y_{N2}^2 - \frac{1}{M_N} Y_{N1} \frac{1}{M_N} M_N  

\Rightarrow testable at LHC for M_N \sim 1 \text{eV}, Y_{N1} \sim 10^{-m} m \sim 0-2

Testable by experiments searching for rare charged lepton flavor violating processes such as \( \mu \to e\nu \), \( \mu \to e\nu \), \( \mu \to e\nu \) conversion in atomic nuclei. Rates are of the order of \( \frac{1}{\text{ dim-6 operat.}} \)

Leptogenesis testable to some extent on parameters in right direction.

Leptogenesis of quasi-degeneracy of M_N: M_N\_1 - M_N\_2 predicted here: M_N\_1 - M_N\_2
LEPTOGENESIS WITH VERY SMALL VALUES OF $M_N$

1. $M_N < m_\nu$, $m_{\nu, \mu, \tau}$ \(\Rightarrow\) no more 2-body $N$ decays

2. $N_i \leftrightarrow N_j$ CP transitions can still be operative together with NLH Yukawa interactions inducing various processes, $H = NL +$ scatterings...

3. Leptogenesis from oscillations: Ahmedov, Rubakov, Smirnov

A purely flavourful framework occurring at

- typically $10^5 \text{ GeV} \Rightarrow T \gg m_{\nu}$: finite temperature effect important.

- generation of $L_i - \bar{L}_i$ asym and $N_i - \bar{N}_i$ asym with $\frac{1}{2} (L_i - \bar{L}_i) = - \frac{1}{2} (N_i - \bar{N}_i)$ until a flavour asym is more washed out than another

- $\varepsilon (L_i - \bar{L}_i) = - \varepsilon (N_i - \bar{N}_i)$ to total lepton asym $= 0$, but total SM lepton asym $\neq 0$

Since this latter one is transferred into $B$

- via sphalerons (at $T > 150 \text{ GeV}$) unlike the $N$ asym

\(\Rightarrow\) baryogenesis.

- Doesn't require huge quasi-degeneracy of $N_i's$

- but some degeneracy is still needed.

4. There is also a $\kappa$ contribution which is suppressed

T.H. Tenasi (T2)

- by $M_i^2$ but involves $2$ powers less of $\kappa \Rightarrow$ can dominate easily for larger quasi-degeneracy of $N$ and occurs just before sphaleron decoupling: $T \approx 200 \text{ GeV}$

- both pure flavour ARS and $\kappa$ contributions can be considered in a density matrix formalism as well as decay/scattering.
III. LEPTOGENESIS IN ALTERNATIVE SCENARIOS

Here will talk mainly about frameworks involving type-II and type-III seesaw.

Type-II leptogenesis:

- Type-II requires only one $\Delta L \Rightarrow \text{no CP asymmetry:}

\[ \Delta L \Rightarrow \text{Im} \ldots J = 0 \]

Type-III leptogenesis:

\[ \begin{align*}
Z_1 & \rightarrow Z_1 H_2 + Z_2 H_1 \\
Z_2 & \rightarrow Z_2 H_2 + Z_1 H_1
\end{align*} \Rightarrow M_{Z_1} > 7.5 \times 10^9 \text{GeV} \quad (M_{Z_2} < M_{H_1}) \]

\[ M_{Z_1} > 1.6 \text{ TeV} \quad (M_{Z_2} > M_{H_1}) \]

Type-I + Type-II leptogenesis:

\[ \begin{align*}
L & \rightarrow L + \Delta L \\
\bar{L} & \rightarrow \bar{L} + \Delta L
\end{align*} \Rightarrow M_L > 3 \times 10^9 \text{ GeV} \]

T.H. Raidal, Strumia 07

TH, Lin, Nolani, Apruzzi, Sinnumia 03

T.H., Senjanovic, 03

T.H., Senjanovic 03

Antusch, Long 04

This framework is very well motivated in So(10).

GUT: all fermion SM generated in a single So(10) representation: 16 representation.

- contains also a $N \Rightarrow$ type-I seesaw!

$\begin{align*}
L & \rightarrow L + \Delta L \\
\bar{L} & \rightarrow \bar{L} + \Delta L
\end{align*}$

- $M_{V_1}$ Majorana mass if generated from renormalizable coupling requires a 126 scalar representation.

This 126 scalar repres. contains a $\Delta L \Rightarrow$ type-II seesaw.
Type-II + Type-II

\[ M_{\Delta_1} > 3 \times 10^{16} \text{GeV} \quad (M_{\Delta_1} \ll M_{\Delta_2}) \]

\[ M_{\Delta_1} > 2.6 \text{ TeV} \quad (M_{\Delta_1} > M_{\Delta_2}) \]

M. Sano, S. Kanam 98

Type-III + Type-III

\[ M_{\Psi} > 3 \times 10^{16} \text{GeV} \quad (M_{\Psi} < M_{\Delta}) \]

\[ M_{\Delta} > 2.5 \times 10^{16} \text{GeV} \quad (M_{\Psi} < M_{\Delta}) \]

Bajc et al. 07

Fileviez-Pérez et al. 07

\[ \text{Bimaximal in SU(5) GUT} \]

\[ \text{with a single 24 fermion} \]

\[ \text{repres., which contains a N and a \Xi} \]

• From decay of a triplet (\Delta_1 or \Xi): lower bounds on decaying triplet mass above are somewhat higher than on \( M_{\Psi} \) in Type-I seesaw.

• Triplets unlike \( N_{\Psi} \) have SU(2)_L gauge interactions:

\[ \text{fast interactions: } g-1 \rightarrow Y_0 \rightarrow Y_{\text{eff.}} \quad \Rightarrow \text{suppresses } Y_0 - Y_{\text{eff.}} \text{ in } dY_0 \quad \text{Bohm-} \text{white eq.} \quad \frac{d\varepsilon}{dz} \]

\[ \Rightarrow \text{suppresses } Y_{\text{asymmetry product}} \quad \text{in } \frac{d\varepsilon}{dz} = \frac{\gamma_{\varepsilon}}{\gamma_{\Psi 0}} Y_{\varepsilon 0} \quad \text{suppressed} \]

\[ \text{such a suppression occurs if gauge interactions are in thermal equlib. } \frac{Y_{\Delta}}{m_{\text{Higgs}}} > 1 \Leftrightarrow T \lesssim 10^{14} \text{GeV} \quad \text{and if } \]

\[ Y_{\Delta} > Y_0 \Leftrightarrow \text{if a } \Delta_1 \text{ undergo on average a gauge inten. before undergoing a decay.} \Rightarrow \text{even on the resonance peak one still needs } M_{\Delta_1}, M_{\Xi} > 1.6 \text{ TeV} \]