Aim: to explain baryogenesis

\[ \eta = \frac{n_B}{s} \approx 0.6-1 \times 10^{-10} \]

required in nucleosynthesis (and for our existence!)

Several Candidates

but first an interlude
Sketch of B+L violation by Strong W fields

Strong W fields distort the normal Dirac sea structure, causing fermions charged under $SU(2)_W$ to go in and out of the positive energy region.

$W = 0$

\[ ud, cs, tb, \ell^c, \nu, \mu, \nu_\tau \]

\[ W = \frac{1}{9} \]

and go back for $W$ reversed.
But during phase transition, energy has other avenues (bubble formation, etc).

So can be left with net $B+L$.

Salient fact: fluctuations above Ten wipe out any pre-existing $B+L$. 
(A) Out-of-equilibrium decays of GUT leptoquarks

Problem: too heavy to be regenerated after inflation

(B) sphaleron processes before and during EW phase transition - strong \( O(\frac{1}{g}) \)

EW fields violate B+L, preserve B-L

Problem: required \( \eta \) achieved only for small \( m_{+} \) (<70 GeV) or small \( m_{\tau} \).
(c) **Affleck-Dine mechanism** -
generation of B during evolution of classical squark field to equilibrium value (zero)

\[ n_B \sim \phi \]

Problem: complicated interplay with inflaton dynamics;

no B-L asymmetry \( \Rightarrow \) reheat must

\[ T_{re} < T_{EW} \]

(d) **Murayama-Yanagida** variant:

Leptogenesis via evolution of classical sneutrino/higgs field

Generates B-L, so can have

\[ T_{R} > T_{EW} \]

Still some complex interplay w/ inflation dynamics.
(E) Out of equilibrium decays of Heavy right-handed singlet neutrinos. Fukujita + Yanagida

\[ N \rightarrow \ell \phi \neq N \rightarrow \ell^c \phi^c \]

Fast sphaleron processes convert

\[ \Delta B \approx \frac{1}{3} (B-L) \]
\[ \Delta B \approx -\frac{1}{3} \Delta L \]

Problems: later
Heavy Leptons: Intermediaries in see-saw mechanism

\[ Z = -N^T \lambda L H - \frac{1}{2} N^T M N \]

\[ m_\nu \approx -m_0^T M^{-1} m_0 \]

\[ m_0 = \lambda \langle H \rangle = \lambda v \]

- Small \( m_\nu \)'s \( \rightarrow \) large \( M \)
  \[ \sim 10^{10-15} \text{ GeV} \]

- \( N \)'s appear in GUTs (SO(10), E(6)) and 4-D string constructions

- Produced as a result of reheating after inflation, or preheating for heavy \( N \)'s

Giudice, Peloso, Riotto, Tkatchev hep-ph/9905242
Muroyama et al (SUSY)
Sekharov Criteria

- $\Delta L \neq 0$ in decay
- CP violation
- Non-equilibrium during decay

First and Second

$$\varepsilon_i = \frac{\Gamma(N_i \to lH) - \Gamma(N_i \to l^cH^c)}{\Gamma(N_i \to lH) + \Gamma(N_i \to l^cH^c)}$$
Results (for decay of lightest $N_i$)

\[ \epsilon_i = \frac{-3}{16\pi} \frac{1}{(x^+/\lambda)_{ii}} \sum_{j \neq i} \text{Im} \left[ (x^+/\lambda)_{ij}^2 \right] \frac{M_i}{M_j} \]

\[ \chi_L = \frac{n_i}{5} = k \frac{\epsilon_i}{g^*} = k \cdot 10^{-2} \epsilon_i \]
\[ = 2 \frac{n_0}{5} \]

- $k$ represents suppression because out of equilibrium condition violated

M.A. Luty
Liu + Segrè
M. Plümacher
Covi, Roulet + Vissani
Campbell et al. (SUSY)
Out of Equilibrium:

Must insure that

\[ \Gamma (eH \rightarrow N) < H \text{ at } T = M_i \]

same as

\[ \Gamma_{N_i} < H(M_i) \]

\[ \tilde{m}_i \equiv \frac{(\lambda^+ \lambda)_{i0} v^2}{M_i} < 2 \times 10^{-3} \text{ eV} \]

- If \( \tilde{m}_i > 2 \times 10^{-3} \text{ eV} \), \( \kappa \) gets smaller
- \( \tilde{m}_i \) is not necessarily \( = m_i \)
So... restrictions on $\lambda$

- But $\lambda$ defined in basis where $M$ and $\ell^c$ mass matrices are diagonal. So only indirect info on yukawa textures.

Present simple model with direct information on neutrino masses as input.
Simple Model

Adopt:

1. Maximal $\mu-\tau$ mixing
2. Small angle MSW - $\theta = 0$

$\rightarrow e$ decouples

\[ U^T m_\nu U = m_{\text{diag}} = \begin{pmatrix} m_2 & 0 \\ 0 & m_3 \end{pmatrix} \]

$m_2$ complex

\[ U = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \]

\[ m_\nu = \frac{1}{2} \begin{pmatrix} m_2 + m_3 & -m_2 + m_3 \\ -m_2 + m_3 & m_2 + m_3 \end{pmatrix} \]

\[ = -\nu^2 \lambda^T M^{-1} \lambda \]
Work in basis where $M$ is real, negative, diagonal

$$(m_{ij})_{ij} = v^2 \sum_k \lambda_{ki} \lambda_{kj} / M_k$$

Because of symmetric nature, 3 eqn in 4 complex $\lambda$'s

$$\lambda = \begin{pmatrix} a & d \\ c & b \end{pmatrix}$$

Look at two scenarios:
(I) \( \mathbf{d} = 0 \quad \lambda = \begin{pmatrix} a & 0 \\ c & b \end{pmatrix} \)

\[ a = \left( \frac{2m_2}{v^2} \frac{m_2 m_3}{m_2 + m_3} \right)^{1/2} \]

\[ b = \left( \frac{M_3}{2v^2} \left( m_2 + m_3 \right) \right)^{1/2} \]

\[ c = b \left( \frac{m_3 - m_2}{m_3 + m_2} \right) \]

Easy description of near-degeneracy \( c \ll b \)

\[ m_3 = m_2 \left( 1 - \delta \right) |\delta| \ll 1 \]
To lowest order in $\delta$

$$m_3^2 \equiv \frac{(\lambda^+ \lambda)_{33} v^2}{M_3^2} = m_3$$

Out of Equ.

$$\tilde{m}_3 < 2 \times 10^{-3} \text{ eV} \Rightarrow m_3 < 2 \times 10^{-3} \text{ eV}$$

Not compatible with $m_2 = m_3$ and atmospheric data even if we allow $\tilde{m}_3 \approx 5 \times 10^{-2} \text{ eV}$.
(II) \[ d = c \quad \lambda = \begin{pmatrix} a & c \\ c & b \end{pmatrix} \]

(like \( \lambda \) in \( SO(10) \))

Interesting solution for

\[ c = a - \delta \]
\[ b = a - \delta + \kappa \]

\( |\delta|, |\kappa| \ll a \)

\[ a = \left( \frac{m_3 M_3}{2 V^2} \right)^{1/2} \]
\[ \delta = \left( \frac{2 m_2 M_2}{V^2} \right)^{1/2} \]
\[ \kappa = \left( \frac{2 m_2 M_3}{V^2} \right)^{1/2} \]
For consistency, require
\[ |m_2| \ll m_3 \left( \frac{M_3}{4M_2} \right) \]

Again, find
\[ \tilde{m}_3 \approx m_3 \]
But now \( m_3 = 5 \times 10^{-2} \text{ eV} \)
\[ Y_L = 10^{-4} \epsilon_3 \]

(Extra suppression by factor of \( 10^{-2} \))

Faridmani et al. hep-ph 9804261
\[ \epsilon_3 = \frac{3}{8\pi} \left( \frac{\text{Im} m_2 m_3 M_2 M_3}{\sqrt{\eta}} \right)^{\frac{1}{2}} \]

\[ \times \left( \frac{M_3}{M_2} \right) \sin \frac{1}{2} \phi \]

Take

\[ M_3 = 10^{12} \text{ GeV} \]
\[ M_2 = 5 \times 10^{12} \text{ GeV} \]
\[ m_2 = 2 \times 10^{-3} \text{ eV} \]
\[ m_3 = 5 \times 10^{-2} \text{ eV} \]
\[ \epsilon_3 = 2 \times 10^{-4} \sin \frac{1}{2} \phi \]

\[ \frac{n_0}{5} \approx 0.5 \gamma_\phi = 5 \times 10^{-10} \phi_{\text{CP}} \]

OK for \( \phi_{\text{CP}} \approx 0.20 \)
Summary

(1) Out of Equ decay of heavy $\nu$s ($N$s) provides very attractive scenario for $\Delta B \neq 0$
   • ties in with see-saw
   • parameters required are completely compatible with present neutrino spectrum

(2) A simple model presented in which $\frac{m_3}{5}$ written directly in terms of neutrino masses +
    mixing. Agreement with BBN for $m_3 \sim 5 \times 10^{-2}$ eV.
Problems:

- Need to produce N's.
  In SUSY $T_RH \leq 10^8$ GeV
  Need parametric resonance
- Need other reactions $(SU(2)_R)$ to thermalize N's