# Leptogenesis in a TeV-scale Supersymmetric Left-Right Model with Inverse Seesaw


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in collaboration with
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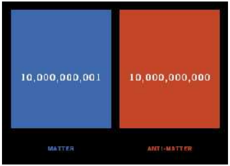
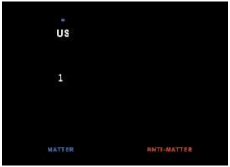
**SUSY 2011**, Fermilab/U. Chicago
(August 31, 2011)

# Outline

# Matter-Antimatter Asymmetry




(H. Murayama)

- BBN + CMB data:

$$\eta_B \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.2 \pm 0.15) \times 10^{-10}$$

- Can be *dynamically* generated provided the Sakharov conditions ($\not{B}$, $\not{C}$ and $\not{C}P$, out of equilibrium) satisfied.
- SM prediction is too small $\sim 10^{-20}$.
- Require new sources of $CP$ and $B - L$ violation.
- From lepton sector??

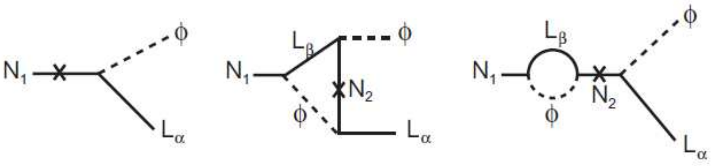
# Leptogenesis

- Lepton asymmetry converted to baryon asymmetry by sphaleron processes. [Fukugita, Yanagida '86]
- Introduce heavy SM singlet sterile neutrinos ($N$):

$$\mathcal{L}_N = (Y_D \bar{L} \Phi N + \mathrm{h.c.}) + M_N N N$$

- $\not{L}$ comes from the Majorana mass term ($M_N$) of these heavy neutrinos.
- Yukawa couplings ($Y_D$) provide new source of $CP$ violation.
- Asymmetry generated in the out-of-equilibrium decay of the heavy sterile neutrino for $\Gamma_N < H(T = M_N)$.
- Also explains the observed small LH neutrino masses via seesaw mechanism.

# $CP$ Asymmetry




[Covi, Roulet, Vissani '96]

$$\epsilon_{i\alpha} = \frac{\Gamma(N_i \to L_\alpha \Phi) - \Gamma(N_i \to \bar{L}_\alpha \Phi^\dagger)}{\Gamma(N_i \to L_\alpha \Phi) + \Gamma(N_i \to \bar{L}_\alpha \Phi^\dagger)} = \frac{1}{8\pi} \sum_{j \neq i} \frac{\mathrm{Im}[(YY^\dagger)^2_{ij}]}{\sum_\beta |Y_{i\beta}|^2} f\left(\frac{M_j^2}{M_i^2}\right)$$

where $f(x) = \sqrt{x}\left[1 - (1+x)\log\left(\frac{1+x}{x}\right)\right]$ is the $L$-violating self-energy and vertex loop factor.

# Scale of RH neutrino mass

- Vanilla Leptogenesis [Davidson, Ibarra '02]
  Hierarchical RH neutrino masses ($M_1 \ll M_2$):
  $$f\left(\frac{M_2^2}{M_1^2}\right) \simeq -\frac{M_1}{2M_2}$$
  - Requires $M_1 \gtrsim 10^9$ GeV for sufficiently large $CP$-asymmetry.
  - Gravitino problem – requires $T_{RH} \lesssim 10^9$ GeV. (see talk by O. Seto)

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- Resonant leptogenesis [Pilaftsis, Underwood '04]

  Quasi-degenerate RH neutrino masses ($M_1 \simeq M_2$):

$$f\left(\frac{M_2^2}{M_1^2}\right) \simeq \frac{(M_2^2 - M_1^2)M_1^2}{(M_2^2 - M_1^2)^2 + (M_2\Gamma_2 - M_1\Gamma_1)^2}$$

  - Possible to have $M_1$ as low as $\sim$ TeV!
  - "Collider-friendly" provided Yukawa couplings are large enough.
  - Interesting effects in flavor sector. (see talk by F. Deppisch)

# Departure from thermal equilibrium

- Effective $B-L$ asymmetry generated by decay of the lightest heavy RH neutrino.
- Solve Boltzmann equations in expanding universe to get the deviation from its equilibrium distribution.

$$\frac{dN_{N_1}}{dz} = -(D+S)(N_{N_1} - N_{N_1}^{\mathrm{eq}}),$$
$$\frac{dN_{B-L}}{dz} = -\epsilon_1 D(N_{N_1} - N_{N_1}^{\mathrm{eq}}) - W N_{B-L}$$

- $D = \Gamma_D/(Hz)$ accounts for decays and inverse decays.
- $S = \Gamma_S/(Hz)$ represents the $\Delta L = 1$ scatterings.
- $W = \Gamma_W/(Hz)$ is the washout term (contributed by inverse decay and $\Delta L = 1, 2$ processes) competing with the decay source term.

# Some Definitions

- Washout parameter

$$K = \frac{\Gamma_D(z=\infty)}{H(z=1)} = \frac{\tilde{m}_1}{m_*}$$

where $\tilde{m}_1 = \frac{(M_D^\dagger M_D)_{11}}{M_1}$ (effective neutrino mass) and $m_* \simeq 1.08 \times 10^{-3}$ eV (equilibrium neutrino mass).

- Efficiency factor

$$\kappa(z) = \int_{z_i}^{z} dz' \frac{dN_{N_1}}{dz'} \frac{D}{D+S} e^{-\int_{z'}^{z''} dz'' W(z'')}$$

$\kappa_f = \kappa(\infty) \to 1$ for $N_{N_1}^1 = N_{N_1}^{\mathrm{eq}}$ and $W = 0$.

- Baryon asymmetry

$$\eta_B = \frac{a_{\mathrm{sph}}}{f} \epsilon_1 \kappa_f \simeq 10^{-2} \epsilon_1 \kappa_1(\infty)$$

# Leptogenesis with Type-I Seesaw

- SM singlet RH Majorana neutrinos ($N$).
  [ Minkowski '77; Yanagida '79; Glashow '79; Gell-Mann, Ramond, Slansky '80; Mohapatra, Senjanović '80]

$$\mathcal{L}_{\rm mass} = (\overline{L} M_D N + {\rm h.c.}) + N M_N N$$
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix}; \qquad m_\nu^{\rm light} = -M_D M_N^{-1} M_D^T$$

- TeV-scale $M_N$ possible only for tiny Yukawas: $M_D \lesssim m_e$.
- Both dilution and washout effects very large: $\frac{D}{D+S} \ll 1$ and $W \gg 1$ – highly suppressed efficiency!
- Not "LHC-friendly" for heavy gauge bosons: $M_{Z'} > 2.5$ TeV for $B-L$ models [Blanchet, Chacko, Granor, Mohapatra '09] and $M_{W_R} > 18$ TeV for LR models [Frere, Hambye, Vertongen '08].

# Inverse Seesaw

- Mostly Dirac $N$. Add another gauge singlet Majorana fermion $S$. [Mohapatra '86; Mohapatra, Valle '86]

$$\begin{aligned}
\mathcal{L}_{\rm mass} &= (\overline{L}M_D N + \overline{N}M_N S + {\rm h.c.}) + S\mu S \\
\mathcal{M}_\nu &= \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M_N \\ 0 & M_N^T & \mu \end{pmatrix}; \\
m_\nu^{\rm light} &\simeq \left(M_D M_N^{-1}\right)\mu\left(M_D M_N^{-1}\right)^T \quad {\rm for}\ \mu \ll M_N
\end{aligned}$$

- TeV scale $M_N$ even with large $M_D \sim m_t$ for $\mu \sim$ keV.
- Smallness of $\mu$ is *natural* in 't Hooft sense.
- Distinct collider phenomenology. [del Aguilla, de Blas '09]
- Also observable effects in the leptonic sector. [BD, Mohapatra '09]

# Leptogenesis in Inverse Seesaw

- Large Yukawa ($\sim 10^{-1} - 10^{-2}$) $\Longrightarrow$ Large $D$.
- The *naive* washout parameter is also very large (due to inverse decay). For TeV RH neutrino mass,

$$K_1 = \frac{(M_D^\dagger M_D)_{11}}{M_1 m_*} \sim 10^{12}$$

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- However, destructive interference within each quasi-Dirac RH neutrino pair in inverse seesaw:

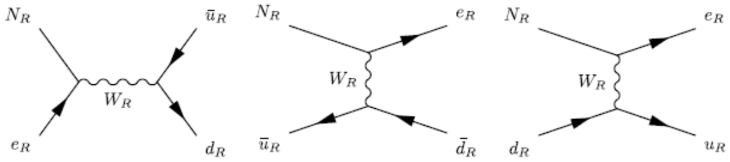
$$\mathcal{M}_{RH} = \begin{pmatrix} 0 & M_N \\ M_N^T & \mu \end{pmatrix}$$

  Mass splitting within $(i,j)$ pair: $M_i - M_j \propto \mu_{ii}$.
- Define effective washout parameter $K_1^{\rm eff} = \delta_1^2 K_1$ where

$$\delta_1 = \frac{|M_1 - M_2|}{\Gamma_1} \simeq \frac{\mu_{11}}{\Gamma_1} \sim 10^{-6}$$

  for $\Delta L = 2$ washout process $\ell\Phi \to \bar{\ell}\Phi^\dagger$. Makes $K_1^{\rm eff} \sim \mathcal{O}(1)$.

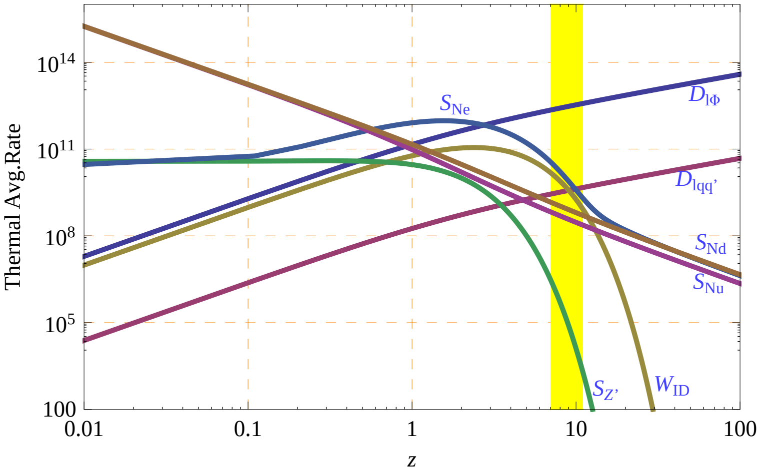
# Gauge Scattering Effects




- Similar destructive interference effects for gauge scatterings (small $S$).
- Processes involving two external heavy-states (e.g. $NN \xrightarrow{Z'} e_R\bar{e}_R, q_R\bar{q}_R$ and $NN \xrightarrow{W_R} e_R\bar{e}_R$) are doubly Boltzmann suppressed.
- Also lepton flavor equilibration ($\ell_\alpha\Phi \leftrightarrow \ell_\beta\Phi$) means flavor effects not important in this case.

(for flavor effects in gauge scatterings, see talk by P. Schwaller)

# Decay and Scattering Rates

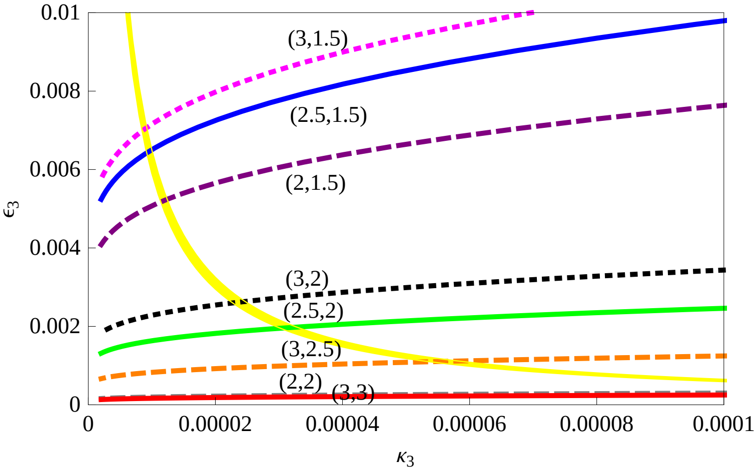


# The Efficiency Factor

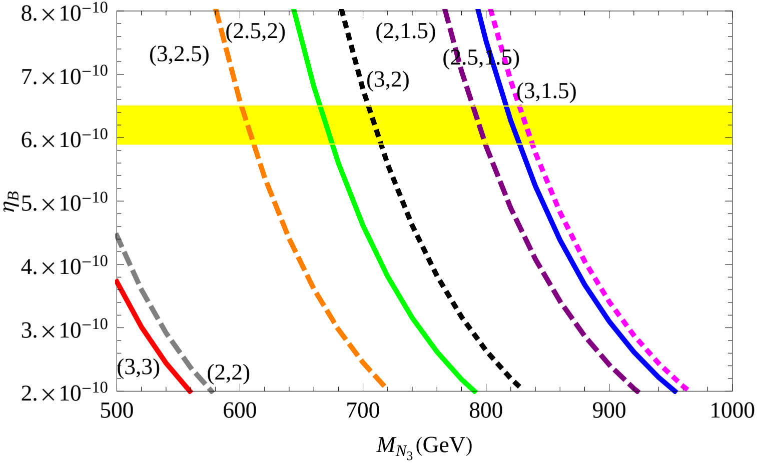
$$\kappa_i(z) \simeq \int_{z_0}^{z} dz' \frac{dN_{N_i}^{\rm eq}(z')}{dz'} \frac{D(K_i, z')}{D(K_i, z') + D_{W_R}(z') + 4S_{Z'} N_{N_i}^{\rm eq}(z') + S_{W_R}(z')}$$
$$\times \exp\left[-\int_{z'}^{z} dz'' \left\{\sum_i W_{\rm ID}(K_i, z'') + W_{W_R}(z'')\right\} \delta_i^2\right]$$

- $D \gg S \Longrightarrow$ Small dilution effect: $\frac{D}{D+S} \sim \mathcal{O}(1)$.
- $\delta_i^2 \ll 1 \Longrightarrow$ Small washout effect: $W\delta^2 \equiv K^{\rm eff} \sim \mathcal{O}(1)$.
- Combination of $\mu^2$ suppression and Yukawa enhancement make the efficiency factor essentially independent of $W_R$ mass.
- Lower bounds on $W_R$ and $Z'$ much weakened (below 1 TeV).

# Efficiency and *CP* Asymmetry



# Baryon Asymmetry



# Summary

- TeV Scale LR symmetry compatible with leptogenesis for inverse seesaw.
- Magnitude of $\not{L}$ Majorana mass is *directly* proportional to the neutrino mass, instead of *inversely* as in usual Type-I case.
- Allows Yukawa couplings to be large (of order 0.1).
- Keeps both washout and dilution in control.
- Lowers the allowed range of $W_R$ and $Z'$ mass to “collider accessible” region.
- Makes leptogenesis *accessible* at LHC.