Leptogenesis

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- Yuval Grossman *(Technion)*
- Enrico Nardi *(Frascati)*
- Esteban Roulet *(Bariloche)*

Plan of Talk

1. Baryogenesis
2. Basics
3. Implications
4. Recent developements
    - Spectator processes
    - Finite temperature
    - Flavor
    - Variations

$\boxed{\text{Baryogenesis}}$

Sakharov, 1967

Sakharov Conditions

Nucleosynthesis, CMBR $\Longrightarrow$ $\boxed{Y_B \equiv \frac{n_b - n_{\bar{b}}}{s} = \frac{n_b}{s} \sim 10^{-10}}$

The baryon asymmetry can be dynamically generated ('baryogenesis') provided that

1. Baryon number is violated;
2. C and CP are violated;
3. Departure from thermal equilibrium.

SM Baryogenesis

Sakharov conditions are met within the SM:

1. $B - L$ is conserved, but $B + L$ is violated;
2. CP is violated by δ_{KM};
3. Departure from thermal equilibrium at the EWPT.

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The SM fails on two aspects:

1. The Higgs sector does not give a strongly first order PT;
2. KM CP violation is too suppressed.

Alternative Scenarios

MSSM baryogenesis is (hardly) viable:

- New scalars $\Longrightarrow$ first order PT is possible;
- At least two new phases $\Longrightarrow$ diagonal CP violation;
- Pushed to a corner of parameter space:
  $m_h < 115$ GeV, $m_{\tilde{t}_1} < m_t$, $\tan\beta < 6$, $m_\chi < 250$ GeV.

GUT baryogenesis not quite dead:

- Minimal SU(5) is dead (again) because $B - L = 0$;
- Inflation will erase B;
- $T_{RH} \ll M_{\mathrm{GUT}}$ is a problem, but preheating might help.

Basics

Fukugita and Yanagida, 1986

The Seesaw Mechanism

- Atmospheric + Solar Neutrinos $\Longrightarrow$ $\boxed{m_{\nu_3} \gtrsim 0.05\ eV}$

- In the SM: $m_\nu = 0$
- Add SM singlets N: $\mathcal{L}_N = YNHL + MNN$

$\Longrightarrow$ Neutrinos are massive but very light

- "The Seesaw Mechanism:" $\boxed{m_\nu \sim \frac{Y^2 \langle \phi \rangle^2}{M}}$

$(\Longrightarrow M/Y^2 \lesssim 10^{15}\ GeV)$

The Seesaw ⇔ Leptogenesis Relation

$$\mathcal{L}_N = Y N H L + M N N$$

- Implications:

1. Lepton number is violated (M)
2. New sources of CP violation (Y)
3. If $\Gamma_{N_1} < H(T = M_{N_1})$ $(\Longrightarrow M_{N_1}/Y_1^2 \gtrsim 10^{15}\ GeV)$
   $\Longrightarrow N_1$ decays out of equilibrium

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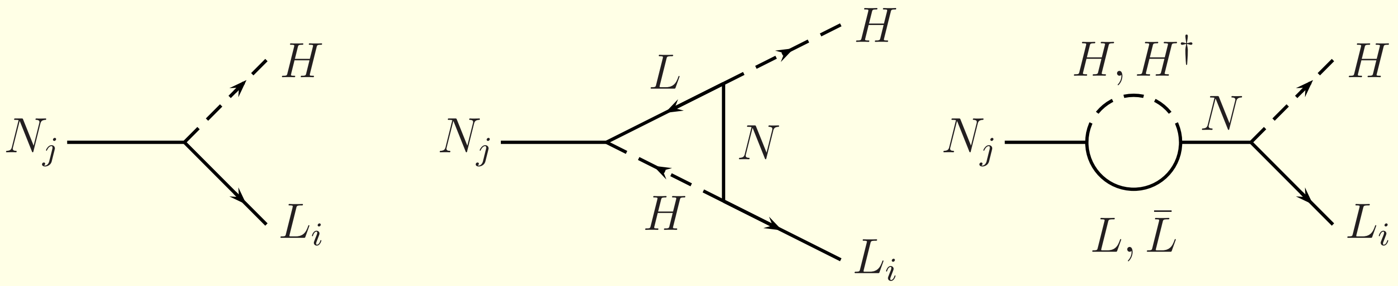
$$\Downarrow$$

$$\boxed{\text{LEPTOGENESIS}}$$

Leptogenesis at Work



- Lepton number violation at tree level,
- Direct CP violation at one loop,
- Requires at least 2 N's.

$$\epsilon \equiv \frac{\Gamma(N \to LH) - \Gamma(N \to \overline{L}H^\dagger)}{\Gamma(N \to LH) + \Gamma(N \to \overline{L}H^\dagger)} = \frac{1}{8\pi}\sum_k \frac{\mathcal{I}m[(Y^\dagger Y)^2_{k1}]}{(Y^\dagger Y)_{11}} \times f\left(\frac{M_k^2}{M_1^2}\right)$$

$$\frac{n_B}{s} = -1.38 \times 10^{-3}\, \eta\, \epsilon.$$

Implications

The relevant parameters

The final Y_B depends on four parameters:

- ϵ, the CP asymmetry;
- M_1, the mass of the lightest N;
- $\tilde{m}_1 \equiv \frac{(Y^\dagger Y)_{11} v^2}{M_1}$, the effective neutrino mass;
- $\bar{m}^2 = m_1^2 + m_2^2 + m_3^2$, the sum of light neutrino mass-squared.

Successful baryogenesis requires

- $M_1 \gtrsim 4 \times 10^8$ GeV ($\Longrightarrow T_{RH} \gtrsim 3 \times 10^9$ GeV)
  With supersymetry: gravitino problem?
- No model-independent bound on low energy phases

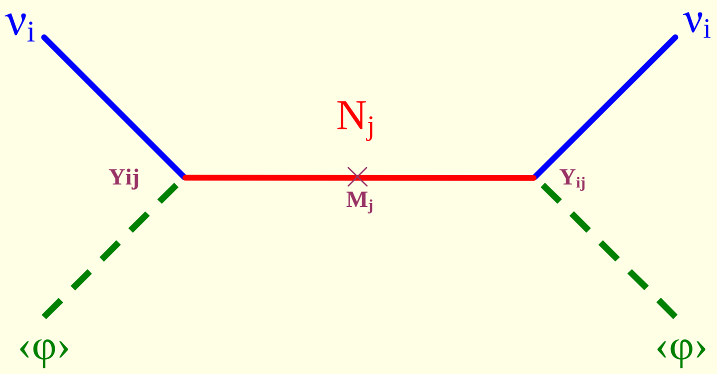
$$\tilde{m}_1 \equiv \frac{(Y^\dagger Y)_{11}\langle\phi\rangle^2}{M_1} \sim 10^{-3}\ eV$$

- N_1 Decay rate: $\Gamma_1 = \frac{M_1 (Y^\dagger Y)_{11}}{8\pi}$
- The expansion rate: $H(T) = 1.66 g_*^{1/2} \frac{T^2}{M_{\rm Pl}}$
- The out of equilibrium decay condition: $\Gamma_1 \lesssim H(T = M_1)$
- Equivalently: $\tilde{m}_1 \equiv \frac{(Y^\dagger Y)_{11}\langle\phi\rangle^2}{M_1} \lesssim 10^{-3}\ eV$
- $\tilde{m}_1$ determines almost all washout effects: $\eta \sim (10^{-3}\ eV/\tilde{m}_1)$
- $\tilde{m}_1$ always larger than the lightest ν mass, $\tilde{m}_1 \geq m_1$

$$\Longrightarrow \boxed{m_1 \leq \tilde{m}_1 \lesssim 10^{-1}\ eV}$$

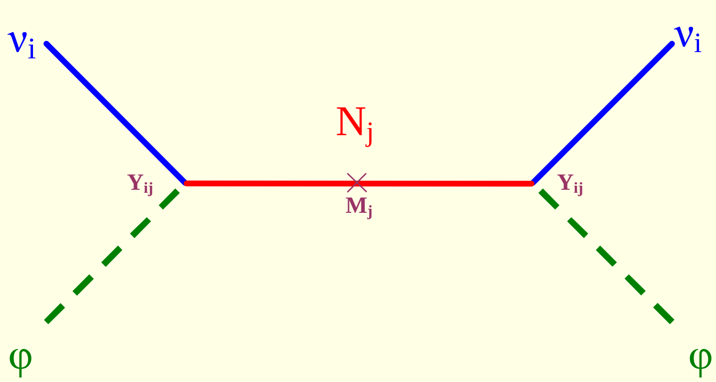
Implications

$$\underline{m_1^2 + m_2^2 + m_3^2 \lesssim (0.15\ eV)^2}$$



Light Neutrino Masses

$$m_i \propto \sum_j Y_{ij}^2/M_j$$



$L-$changing 2→2 Scattering

$$\sigma \propto \sum_i |\sum_j Y_{ij}^2/M_j|^2$$

- Require that $\Delta L = 2$ washout effects are not too strong:

$$\boxed{m_1^2 + m_2^2 + m_3^2 \lesssim (0.15\ eV)^2}$$

Buchmuller, Plumacher; Giudice et al.

- $T_{\rm LG} < 10^{12}\ GeV$ + Flavor effects $\Longrightarrow m_\nu \lesssim 4\ eV\ (10^{10}\ GeV/T_{\rm LG})^{1/2}$

Recent Developments

Spectator Processes

- Fast, $B - L$ conserving processes:

Gauge, (Heavy) Yukawa, Sphaleron

$\Longrightarrow$ T-dependent relations among chemical potentials

- $T > 10^{13}$ GeV:

Higgs asymmetry enhances washout-effects

$\Longrightarrow$ Suppression of Y_{B-L} by $\sim 40\%$

Buchmuller, Plumacher, PLB 511 (2001) 74

- $T < 10^{8}$ GeV:

Lepton asymmetry transferred into baryons and into SU(2)-singlets

$\Longrightarrow$ Enhancement of Y_{B-L} by $\sim 20\%$

Nardi, Nir, Racker, Roulet, JHEP 0601 (2006) 068

Finite Temperature Effects

- Finite temperature effects modify masses and couplings

$\Longrightarrow$ Decay and scattering rates depend on temperature

- The most dramatic effect: $\frac{m_H^2}{T^2} = \frac{3}{16} g_2^2 + \frac{1}{16} g_Y^2 + \frac{1}{4} y_t^2 + \frac{1}{2}\lambda$
  - $N \to LH$ blocked above $T \sim 2m_N$
  - $H \to LN$ opened above $T \sim 7m_N$

$\Longrightarrow$ $\mathcal{O}(1)$ corrections to final asymmetry

Giudice, Notari, Raidal, Riotto, Strumia, NP B685 (2004) 89

Flavor Issues

- $\boxed{\text{See Ibarra's talk}}$
  - $N_1 \to H\ell_1$: Define $K_i = |\langle \ell_i | \ell_1 \rangle|^2$ $(i = e, \mu, \tau)$
  - $\epsilon_i \sim \epsilon K_i^0 + (K_i - \overline{K}_i)$
  - For generic flavor structure $(K_i = \mathcal{O}(1), \neq 0, 1)$
    $\eta_i \sim \eta K_i \quad \Longrightarrow \boxed{Y_{B-L} \propto \sum_{i=1}^{n_f} \eta_i \epsilon_i \sim n_f\ (\eta\epsilon)}$
    $$n_f = \begin{cases} 1 & T > 10^{13}\ GeV, \\ 2 & 10^{11} < T < 10^{13}\ GeV, \\ 3 & T < 10^{11}\ GeV. \end{cases}$$
  - For non-generic flavor structure $(K_i \ll 1, \neq 0)$
    Large (order of magnitude) effects are possible
  - Qualitatively new effects from $K_i \neq \overline{K}_i$

Barbieri et al, NP B575 (2000) 61; Abada et al, JCAP 0604 (2006) 004
Nardi et al, JHEP 0601 (2006) 164; Abada et al, hep-ph/0605281

Resonant Leptogenesis

- The lepton asymmetry is resonantly enhanced for $M_2 - M_1 \sim \Gamma_N$

$\Longrightarrow$ Successful leptogenesis is possible even with $M \sim 1\ TeV$

e.g. Pilaftsis, Underwood, NP B692 (2004) 303

- If, however, $M_2 - M_1 \propto |Y|^2$, the CP asymmetry is, quite generally, high order in Y

$\Longrightarrow$ Successful resonant leptogenesis requires $M \gtrsim 10^{12}\ GeV$.

Cirigliano, Isidori, Poretti, hep-ph/0607068

Soft Leptogenesis

- The framework: $\boxed{\text{Supersymmetric Standard Model + N's}}$
- Soft SUSY breaking terms $(A, B, m_{\tilde{w}})$
  $\Longrightarrow$ New sources of lepton number violation
  $\Longrightarrow$ New sources of CP violation
- The lepton asymmetry is generated by sneutrino decays
- Indirect CP violation can play a major role
  (Similar to ϵ or to $S_{\psi K_S}$)
- Particularly significant for low M
  (No gravitino problem)

Grossman, Kashti, Nir, Roulet, PRL 91 (2003) 251801; JHEP 0411 (2004) 080

D'Ambrosio, Giudice, Raidal, PL B575 (2003) 75

Conclusions

- $m_\nu \neq 0 \Longrightarrow$ See-saw $\Longrightarrow$ leptogenesis
- Quantitative success depends on unknown values of parameters:
  $M \gtrsim 10^9\ GeV$ - gravitino problem?
  $\tilde{m}_1 \sim 0.01\ eV$ - plausible
  $\bar{m} \lesssim 0.12\ eV$ (not valid with flavor effects) - no strong degeneracy
- Various aspects have been explored/improved/corrected:
  Spectator processes, finite-temperature, flavor...
- Additional subtleties are being discovered
- Interesting variations have been proposed:
  Resonant, Soft,...
- Observation of $0\nu2\beta$ decay and/or CPV in ν - further support;
  Direct tests are very unlikley