Plan of Talks

1. The Standard Model and (a Little) Beyond
2. Neutrinos (Mainly) from Heaven
3. The Numbers and What They Tell Us
4. Flavor Puzzle(s)
5. Leptogenesis

Plan of Talk V

Leptogenesis

1. Baryogenesis
2. Leptogenesis
3. Soft leptogenesis

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.

KM $\leftrightarrow$ Baryogenesis

The SM violates CP if and only if

1. No degeneracy in either quark sector;
2. All mixing angles $\neq 0, \pi/2$;
3. The KM phase $\neq 0, \pi$.

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The baryon asymmetry is proportional to:

$$\begin{aligned}
\epsilon_{\rm CPV} &= \frac{1}{m_W^{12}}(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2) \\
&\times (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) \\
&\times \sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\theta_{13}\cos\theta_{13}\sin\delta_{\rm KM} \\
&\sim 10^{-18}
\end{aligned}$$

SM and Baryogenesis

The SM $B + L$ violating (but $B - L$ conserving) processes are very fast in the Early Universe ($10^{12}\ GeV \gtrsim T \gtrsim 10^{2}\ GeV$)

$$\Downarrow$$

1. If NP processes generate $B + L \neq 0$ but $B - L = 0$, the SM processes will washout a baryon asymmetry $\Longrightarrow B = 0$
2. If NP processes generate $B - L \neq 0$ (even with $B = 0$, that is, only $L \neq 0$), the SM processes will maintain/generate a baryon asymmetry $\Longrightarrow B \neq 0$

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;
- $T_{RH} \ll M_{\rm GUT}$ is a problem, but preheating might help.

Leptogenesis

Fukugita and Yanagida, 1986

Neutrino Masses

- Atmospheric + Solar Neutrinos $\Longrightarrow$ $\boxed{m_{\nu_3} \gtrsim 0.05\ eV}$
- The Seesaw Mechanism $\Longrightarrow$ $\boxed{m_\nu \sim \frac{Y^2 \langle \phi \rangle^2}{M_N}}$

$\Longrightarrow M_{N_3}/Y_3^2 \lesssim 10^{15}\ GeV$

- Implications:

1. Lepton number is violated (M_N)
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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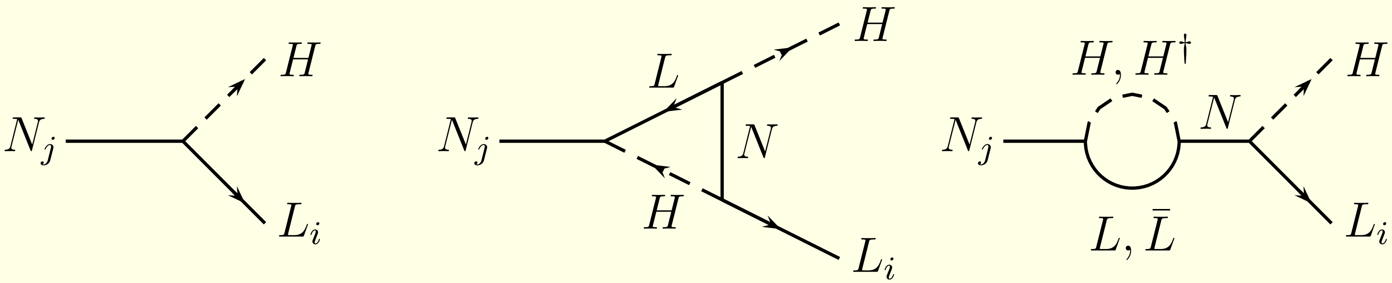
$\Downarrow$

LEPTOGENESIS

Leptogenesis at Work



- Lepton number violation at tree level,
- Direct CP violation at one loop,
- Requires 3 generations + 2 N's.

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

$$Y_L = \frac{2T^3}{\pi^2 s}\, d\, \epsilon_L \sim 0.004\, d\, \epsilon_L, \qquad Y_B = -\frac{28}{79} Y_L.$$

See-saw CPV $\leftrightarrow$ Leptogenesis

- $M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix}$
- $m_D = Y\langle\phi\rangle = 3 \times 3$ matrix
- $M = 3 \times 3$ symmetric matrix

$\Longrightarrow$ $\boxed{M_\nu \text{ has 6 physical phases}}$

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$\Longrightarrow$ M_ν has 6 physical phases

1. It is no problem to have $\epsilon_L \sim 10^{-6}$ with reasonable parameters
2. $M_\nu^{\text{light}} = m_D M^{-1} m_D^T$ has 3 physical phases
3. Neutrino oscillation experiments are sensitive to only one of these three phases
4. It could happen that CPV(leptogenesis)$\neq 0$ while CPV(low-energy)=0

Implications

The final Y_B depends on four parameters:

- ϵ_L, 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 masses-squared.

Successful baryogenesis requires

- $M_1 \gtrsim 4 \times 10^8$ GeV ($\Longrightarrow T_{RH} \gtrsim 3 \times 10^9$ GeV);
- $m_3 \lesssim 0.12$ eV;
- No model-independent bound on low energy phases.

Supersymmetric Leptogenesis

- MSSM+N: $W = MNN + YH_uLN$
- The seesaw mechanism $\Longrightarrow$ $M \gg m_Z$

$\Longrightarrow$ Supersymmetry is strongly motivated

- But the picture is not very different from SM+N:
  - Direct CP violation;
  - N and $\widetilde{N}$ give similar contributions, $\epsilon_L^{\rm MSSM} \approx 2\epsilon_L^{\rm SM}$;
  - $Y_B = -\frac{32}{92} Y_L$;

Supersymmetric Leptogenesis

- $\epsilon_L \gtrsim 10^{-6} \;\Leftrightarrow\; \tilde{m}/M \sim 10^{-8}$

SUSY breaking effects negligible

- $\mathrm{NS}: \; T_{RH} \lesssim 10^9 \; GeV \;\Leftrightarrow\; \mathrm{LG}: \; T_{RH} \gtrsim 3 \times 10^9 \; GeV$

Gravitino problem?

Soft Leptogenesis

Grossman, Kashti, Nir, Roulet, 2003

D'Ambrosio, Giudice, Raidal, 2003

Soft Supersymmetry Breaking

$$\mathcal{L}^N_{\text{soft}} = B\widetilde{N}\widetilde{N} + AH\widetilde{L}\widetilde{N}$$

- A new source of lepton number violation B
- A new source of CP violation $\phi_N = \arg(AMB^*Y^*)$

Soft Leptogenesis?

Highlights

- Indirect CP violation (conceptually interesting!)
- ϵ_L from only $\widetilde{N}$ decays ('sleptogenesis')
- One generation is enough
- Three SUSY-breaking factors, yet significant effects (surprising!)
- $B < \tilde{m}M$
- No gravitino problem

Implications

ϵ_L depends on four parameters:

- M, the mass of the (lightest) $\widetilde{N}$;
- Y, the Yukawa coupling;
- A, the trilinear scalar coupling (we fix $A \sim \tilde{m}Y$)
- B, the bilinear scalar coupling.

Successful soft leptogenesis requires:

- $M \lesssim 5 \times 10^8$ GeV
- $Y \lesssim 10^{-4}$
- $\frac{B}{M} \sim \frac{MY^2}{16\pi} \lesssim$ GeV

Summary

- If the seesaw mechanism is responsible for the light neutrino masses, leptogenesis is unavoidable.
- Whether leptogenesis accounts for the observed baryon asymmetry is a quantitative question and depends on several unknown parameters.
- Parameters related to the light neutrino sector are required to have values within very reasonable ranges.
- Soft supersymmetry breaking terms may have significant effects on leptogenesis.

Conclusions

Conclusions

We have learnt a lot from our search for neutrino masses:

1. SM is not a complete picture of Nature
2. NP at a scale $\Lambda_{\rm NP} \leq 10^{15}$ GeV
3. $SO(10) \Longrightarrow m_\nu \sim 10^{-2}$ eV - confirmed
4. $SU(5) \Longrightarrow |V_{\mu 3} V_{cb}| \sim \frac{m_s}{m_b}$ - confirmed
5. Most of the simplest and most predictive flavor models - excluded
6. Interesting implications for
   (a) Supersymmetry without R-parity
   (b) Extra dimensions
7. Leptogenesis may account for the baryon asymmetry

Conclusions

There is still a lot to be learnt:

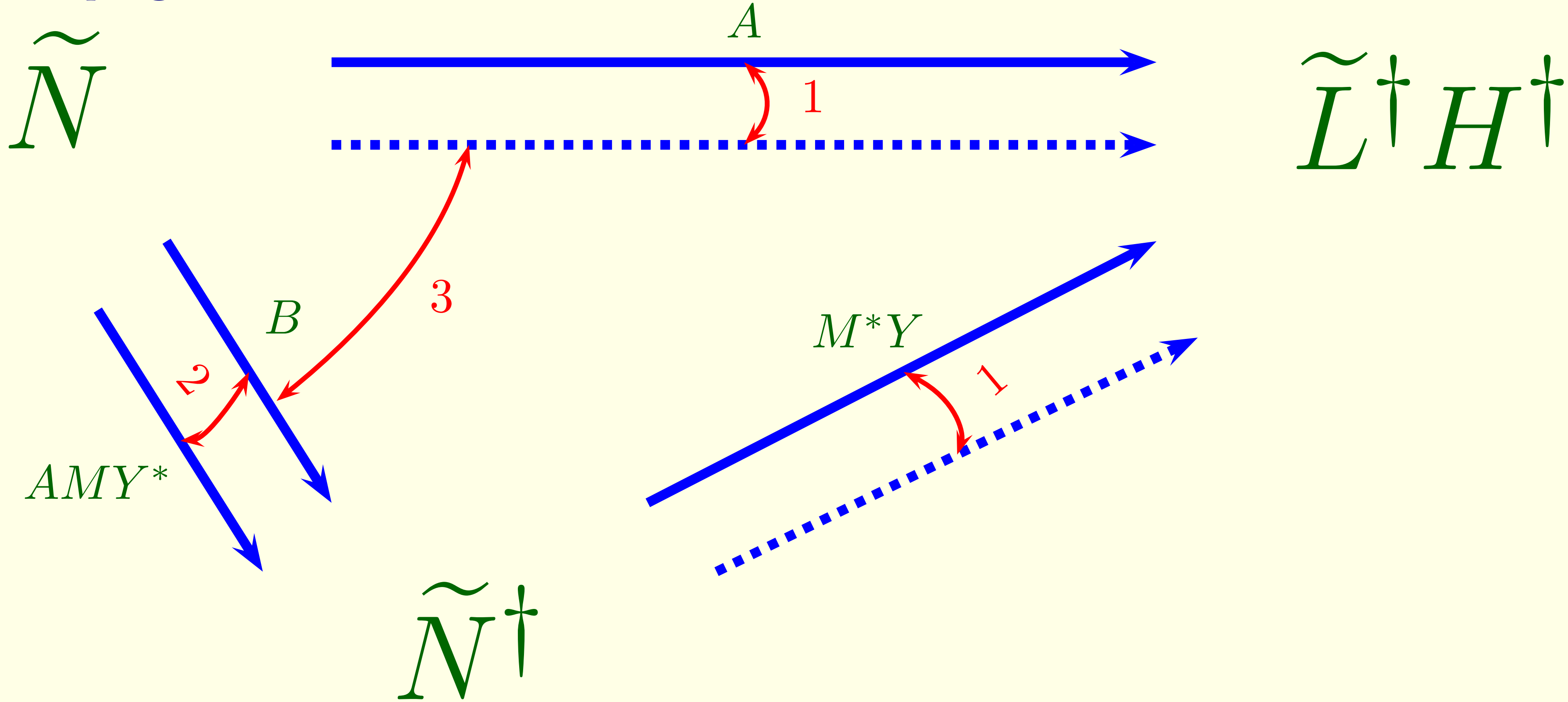
1. Neutrinoless double beta decay: m_{ee}
   Majorana or Dirac?

2. Cosmology, direct searches, $0\nu2\beta$: m_i
   Hierarchical or degenerate?

3. LBL, ν-factory, AN: $\text{sign}(\Delta m^2_{32}), |U_{e3}|, |U_{\mu 3}U_{\tau 3}| - 1/2, \delta_{\text{CPV}}$
   Normal or inverted hierarchy?
   Small or tiny 1-3 mixing?
   Large or maximal 2-3 mixing?
   Leptonic CP violation?

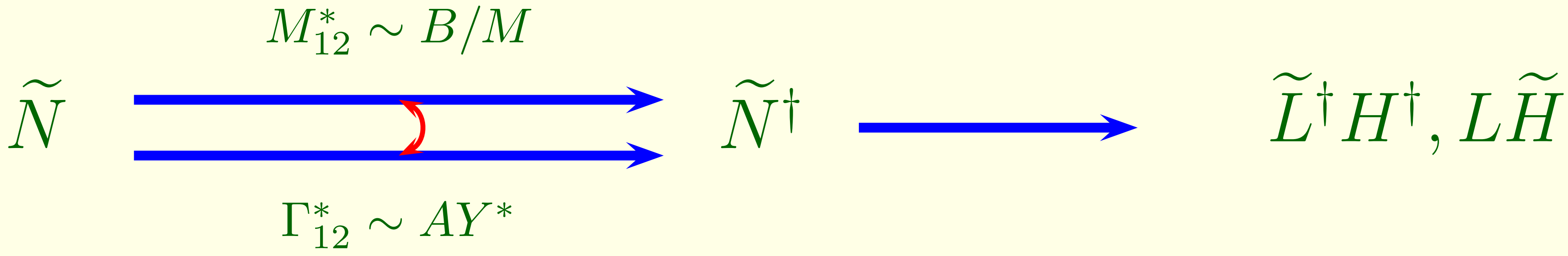
4. Lepton flavor violation: $\mu \to e\gamma, \tau \to \mu\mu\mu, \tilde{\nu} \leftrightarrow \tilde{\nu}^\dagger, ...$
   Solutions to the flavor puzzles?

5. ...



1. In decay: Leptogenesis, $\epsilon'(K \to \pi\pi)$
2. In mixing: Soft leptogenesis, $\epsilon(K \to \pi\ell\nu)$
3. In interference: Soft leptogenesis, $S_{\psi K}(B \to \psi K_S)$

Soft Leptogenesis at Work



$$\epsilon_L \ \sim \ \delta_{\widetilde{L}\bar{L}} \times \mathcal{I}m \frac{\Gamma_{12}}{M_{12}} \times \frac{(\Delta m/\Gamma)^2}{1+(\Delta m/\Gamma)^2}$$

- CP violation is encoded in $\mathcal{I}m \frac{\Gamma_{12}}{M_{12}} \sim \left|\frac{AMY^*}{2\pi B}\right| \sin\phi_N$
- Lepton number violation is encoded in $\frac{\Delta m}{\Gamma} \sim \frac{8\pi|B|}{|MY|^2}$
- $\delta_{\widetilde{L}\bar{L}} = \frac{|A_{\widetilde{L}}|^2 - |A_{\overline{L}}|^2}{|A_{\widetilde{L}}|^2 + |A_{\overline{L}}|^2}$ vanishes in the supersymmetric limit

$$\boxed{\epsilon_L \ \sim \ \frac{32\pi AB\sin\phi_N}{M^3Y^3}\ \delta_{\widetilde{L}\bar{L}}}$$

Finite Temperature Effects

- In the supersymmetric limit,

$\Gamma(\widetilde{N}^\dagger \to \widetilde{L}^\dagger H^\dagger) = \Gamma(\widetilde{N}^\dagger \to L\widetilde{H})$

$\Gamma(\widetilde{N}^\dagger \to \widetilde{L}H) = \Gamma(\widetilde{N}^\dagger \to \overline{L}\overline{\widetilde{H}}) = 0,$

$$\Longrightarrow \ \delta_{\widetilde{L}\bar{L}} = 0$$

- At $T = 0$ the relevant effect is scalar-fermion mass splitting,

$\delta_{\widetilde{L}\bar{L}} \sim \tilde{m}^2_{\widetilde{N}}/M^2$

$$\Longrightarrow \delta_{\widetilde{L}\bar{L}} \text{ is tiny}$$

- At $T \sim M$ Pauli blocking/Bose-Einstein stimulation give

$\delta_{\widetilde{L}\bar{L}} = \frac{(1+n_B)^2-(1-n_F)^2}{(1+n_B)^2+(1-n_F)^2}$ where $n_{F,B} = [\exp(M/2T) \pm 1]^{-1}$

$$\Longrightarrow \boxed{\delta_{\widetilde{L}\bar{L}} = \mathcal{O}(1)} \quad .$$

How can [susy-breaking]^3 be relevant?

- $\epsilon_L \sim \delta_{\widetilde{L}\overline{\widetilde{L}}} \; \frac{A}{MY} \; \frac{32\pi B}{M^2 Y^2}$

  - $\delta_{\widetilde{L}\overline{\widetilde{L}}}$ from finite temperature effects, not a suppression factor;
  - Naively, $A \sim \tilde{m} Y$, $B \sim \tilde{m} M$: $\epsilon_L \sim \left(\frac{\tilde{m}}{M}\right)^2 \frac{1}{Y^2}$
    For example, $M \sim 10^9$ GeV, $Y \sim 10^{-3} \implies \epsilon_L \sim 10^{-6}$;
  - However, for $B/M \gtrsim MY^2 \implies \Delta m/\Gamma \gg 1 \implies$ suppression.