Baryogenesis and Leptogenesis

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Last time

Last lecture

- GUT BG: Out of equilibrium decay of a heavy particle
- EW BG: Sphalerons and EW phase transition
- We started to talk about LG

This lecture: Leptogenesis and some specific models

Leptogenesis

νSM

- The model: the SM plus heavy singlets

$$N_i(1,1)_0$$

- We need two or more N to explain the neutrino data
- The interactions

$$W = MNN + YHNL \;\;\Rightarrow\;\; MNN + m_D N\nu$$

$M \gg m_W$ and $m_D \sim m_W$

$$m_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \;\;\Rightarrow\;\; m_{\nu_L} = \frac{m_D^2}{M}$$

- The heavy neutrinos break lepton number

νSM leptogenesis

- Similar to GUT baryogenesis. Here N decays generate lepton asymmetry
- Sakharov's conditions for dynamically generated lepton asymmetry
  - Lepton number violating process: $N \to H^+ e^-$
  - C and CP violation

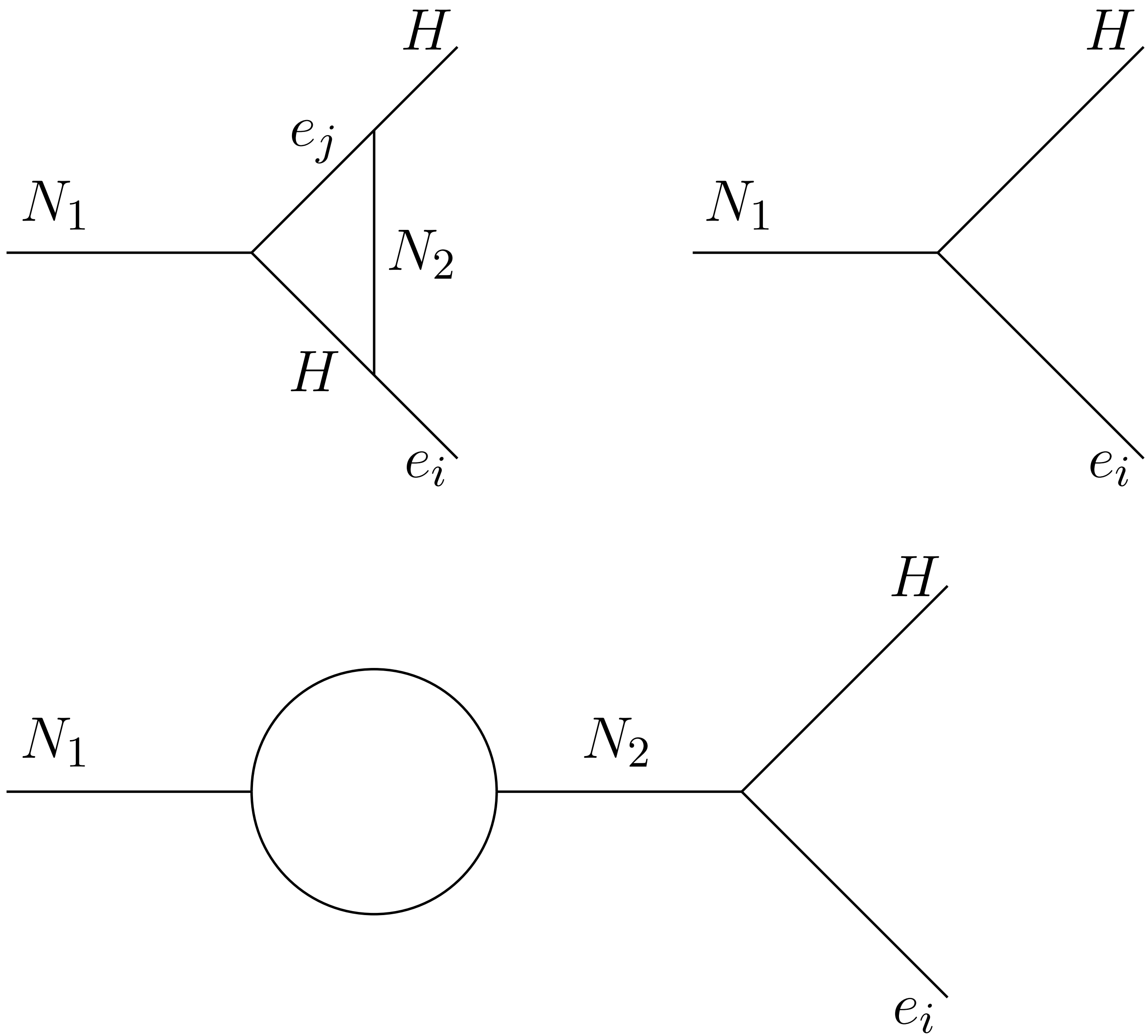
$$\Gamma(N \to H^+ e^-) \neq \Gamma(N \to H^- e^+)$$

  - Deviation from thermal equilibrium. N decays when it is no more in contact with the thermal bath

$$\Gamma(N \to H^+ e^-) \neq \Gamma(H^+ e^- \to N)$$

- Violates B$-$L. Sphalerons convert some L into B

Diagrams



νSM leptogenesis: remarks

The final result is

- Tree

$$T \propto Y_{1\alpha}$$

- Loop

$$L \propto Y_{1\beta} Y^*_{\beta 2} Y_{2\alpha}$$

- Interference

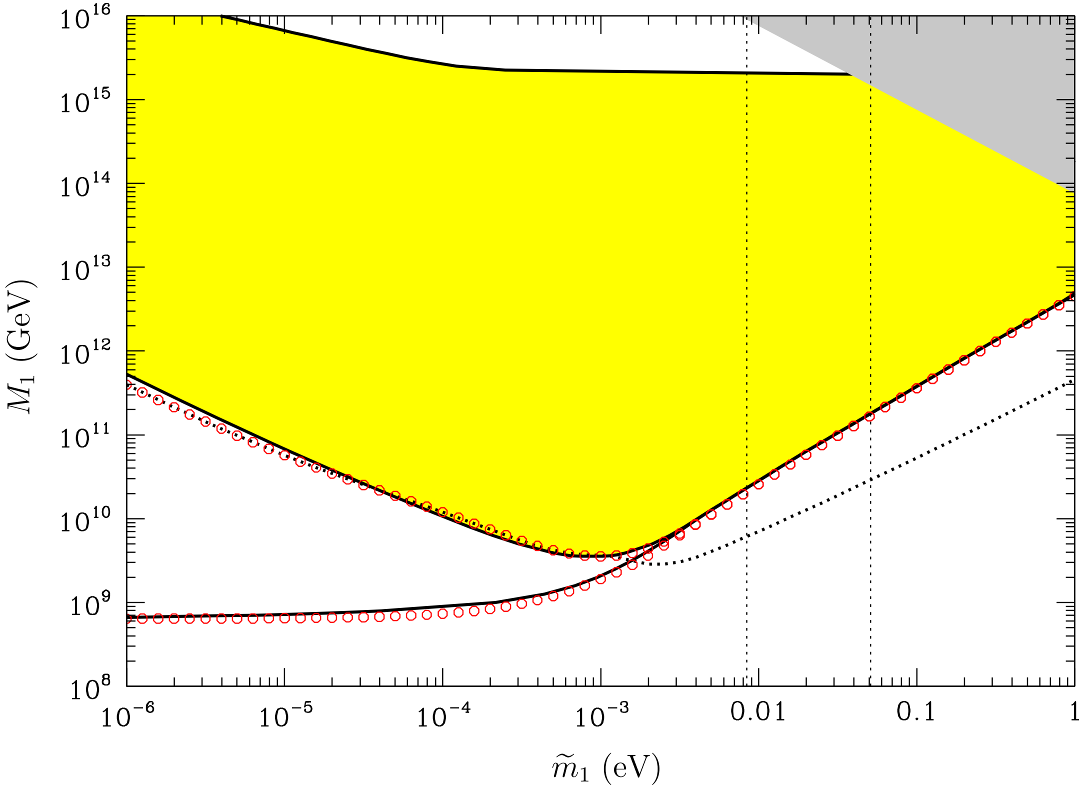
$$\epsilon \propto Im\left[T^* L\right] \sim Im\left[Y^*_{1\alpha} Y_{1\beta} Y^*_{\beta 2} Y_{2\alpha}\right]$$

- We sum over the flavor on the internal and final leptons
- The CP violation depends on the phase in the neutrino Yukawa matrix

LG: all together

- We assume that the heavy neutrinos were in thermal equilibrium to start with
- They decay out of equilibrium to generate lepton asymmetry
- The “washout” factor can be calculated with Boltzmann equations
- Sphalerons convert part of the net lepton number into baryons
- The final result depend on the masses of the heavy particles and their couplings. Can be related to the light neutrino masses

Numerical prediction



- The right side of the plot is "theoretically" motivated
- The fact that both leptogenesis and oscillation data are consistent is not a trivial test

LG: remarks

- What about decays of N_2?
- How the LG parameters related to the ones we measure in low energy neutrinos?
- What about SUSY?
- How can we test LG?

SUSY LG

- We all like SUSY
- We also have sneutrino decay, that double the asymmetry
- Work for $M \gtrsim 10^{10}$ GeV
- Tension with the gravitino problem
- For $M \lesssim 10^{10}$ GeV, we have another mechanism “soft SUSY”. CPV from SUSY breaking and strong phase from sneutrino oscillation

Tests of leptogenesis

- It is not easy to directly test leptogenesis as the heavy neutrino is too heavy, $m_N > 10^{11}$ GeV
- Leptogenesis predicts very small lepton asymmetry in the universe. Very hard to even detect the neutrino background
- Since leptogenesis require CP violation, we like to find CP violation also in neutrino oscillation
- Majorana mass for the neutrinos can be probed with neutrinoless double beta decay
- My big “issue” with LG: Not easy to test

LG: a short summary

- The heavy singlets play a double role
  - They “drive” the seesaw giving small m_ν
  - They decay in the early universe in an L violating way
- With at least two generation of heavy neutrinos we have a CP violation in the decay
- Putting it all together we see it can do the two tasks together!

Dirac Leptogenesis

Dirac Leptogenesis: main idea

Consider a model that conserve lepton number

Q: Can we get leptogenesis?

A1: No! It violate the first Sakharov's condition

A2: Yes! There must be a way...

Dirac Leptogenesis: main idea

Separation

- At high temperature total L$=0$. Yet L for doubles and L for singlet is non zero

$$L_L = C \qquad L_R = -C \qquad L_{\rm total} = 0$$

- At the EW phase transition only the left handed part convert to Baryon number via sphalerons

$$B = \frac{12}{37} C \qquad L_L = \frac{25}{37} C \qquad L_R = -C$$

- For "baryogenesis via leptogenesis" to work all we need is a net lepton number in the left handed fields

Dirac LG from Composite neutrinos

Based on YG and Yuhsin Tsai, 2008; N. Arkani-Hamed and YG, 1998

- Can we get light Dirac neutrinos?
- If the RH neutrino is composite we can have it
- Based on “anomaly matching” that lead to massless composite fermions

Composite fermions

- Consider QCD. It becomes strong at $\Lambda_{QCD} \sim 300$ MeV
- We have composite fields, like protons and pions
- The pions are “massless” since they are Goldstone bosons
- The proton, however, is massive with $m \sim \Lambda_{QCD}$
- The condensate breaks the chiral symmetry of the SM, and the proton is massive

Composite massless fermion

In some cases the fermions, however, can be massless

- Group is SU(6) with fermions. Two **6** (ψ_i) and one **15** (A)
- The theory confines at scale Λ
- After confinement we have fermions

$$B_{ij} = \psi_i A \psi_j \qquad \hat{B}_{ij} = \frac{\psi_i A \psi_j}{\Lambda^3}$$

- These fermions are massless at the renormalizable level

Composite massless fermion

$$B_{ij} = \psi_i A \psi_j \qquad \hat{B}_{ij} = \frac{\psi_i A \psi_j}{\Lambda^3}$$

- They B are SM singlets. Couple to the LH neutrinos

$$Y \bar{L} H B = \frac{Y}{M^3} \bar{L} H \psi_i A \psi_j = \left(\frac{\Lambda}{M}\right)^3 \hat{Y} \bar{L} H \hat{B} \qquad \hat{Y} \sim 1$$

- Small Yukawa couplings because B is composite

$$m_\nu \sim m_W \left(\frac{\Lambda}{M}\right)^3 \qquad \Lambda \ll M$$

- Can also give naturally light sterile neutrinos

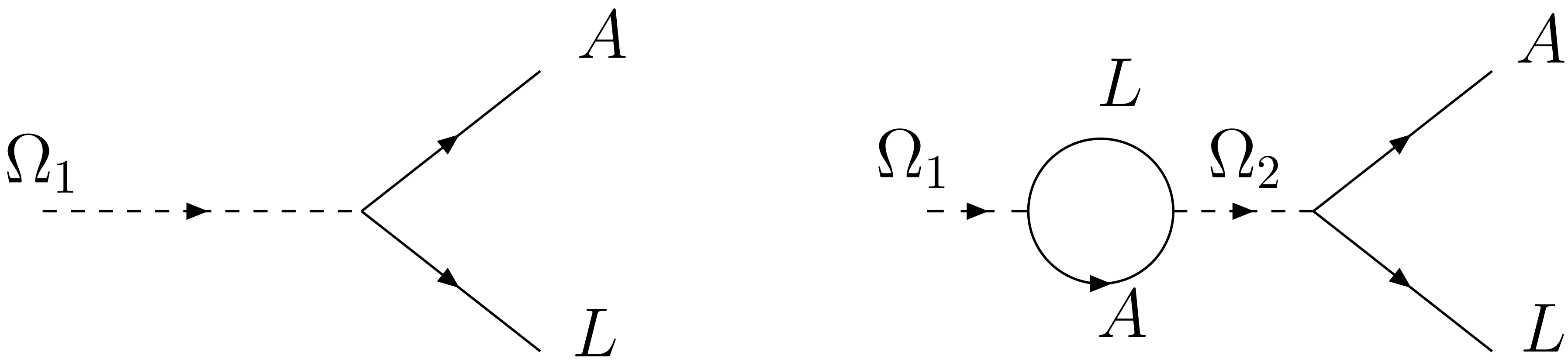
UV completion

- The masses are NR operators
- The are there due to heavy fields. One way to generate them is by adding scalars

$$\Omega(15,2) \qquad \Phi(15,1)$$

- The decay of Ω generates lepton number in the L and A sectors
- Only L participate in the sphalerons

Dirac LG from composite fermions



- Work even for low M
- Give light Dirac neutrinos and leptogenesis

Summary

Baryogenesis

- A very interesting open question in HEP/cosmology
- Leptogenesis is attractive since it come “for free”
- Can you find a way to probe it?

Read more!