Baryogenesis and Leptogenesis

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Last time

Last lecture

- Model building and the SM
- CP and the need for two diagrams with weak and strong phase
- General remarks for BG

$$\eta = N_I \, \epsilon \, \eta_a$$

- Started to talk about BG from decay of a heavy particle

This lecture: GUT BG, EW BG, and start to talk about LG

GUTs

- I will not get into the full story of GUTs
- For our "story" we need to know that the SU(3)$\times$ SU(2)$\times$ U(1) group of the SM is part of a bigger group, say SU(5)
- Baryons and leptons sit in the same representation. In the SU(5) case, **5** and **10**
- Breaking of the GUT group results in heavy particles that "break" baryon and lepton numbers

X and Y

- Heavy spin one doublet

$$q(X) = 4/3 \qquad q(Y) = 1/3$$

- The couplings give rise to

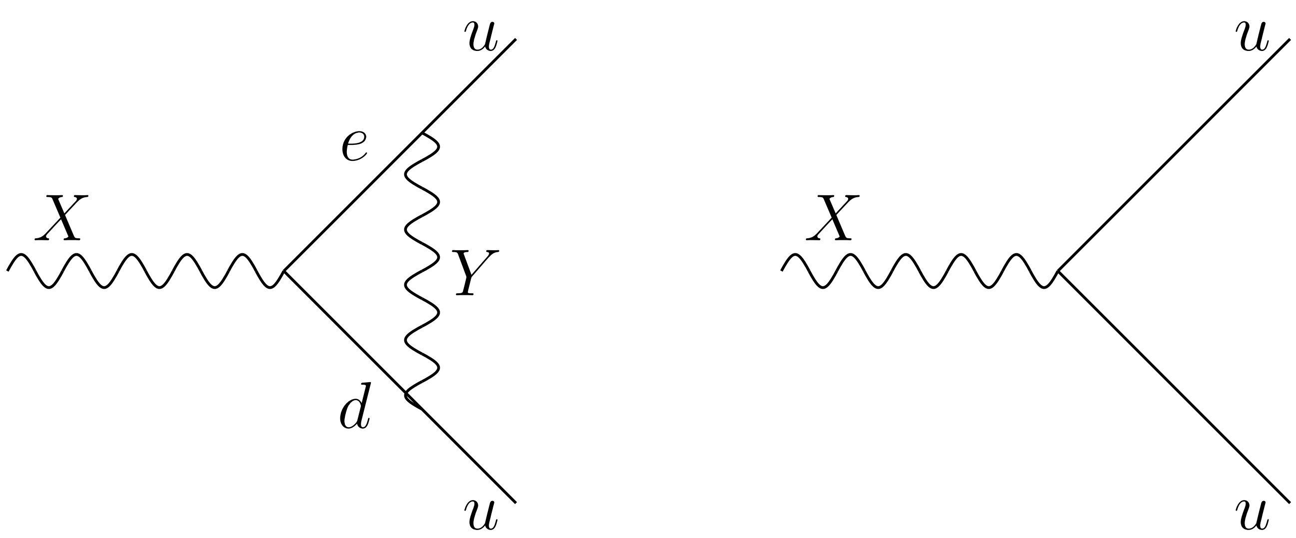
$$X \to u + u \qquad X \to e^+ + \bar{d}$$

and

$$Y \to e^+ + \bar{u} \qquad Y \to d + u \qquad Y \to d + \nu_e$$

- Decays with different final state baryon number $\Rightarrow$ X and Y violate baryon number
- B$-$L is conserved. X and Y have charge $2/3$ under it

GUT diagrams



- e and d can be on shell $\Rightarrow$ strong phase
- Weak phase from the product of the four vertexes
- Similar diagrams for Y decay

CP result

Final “particle physics” asymmetry is

$$\epsilon = \sum_{X,f} \mathrm{BR}(X \to f)\epsilon_f$$

$$\epsilon_f \equiv \frac{\Gamma(X \to f) - \Gamma(\overline{X} \to \overline{f})}{\Gamma(X \to f) + \Gamma(\overline{X} \to \overline{f})} = 2r_f \sin\phi_f \sin\delta_f$$

- r_f is the ratio of loop to tree amplitudes
- ϕ_f is the weak phase difference
- δ_f strong phase difference, that is the phase of the loop diagram the comes from the cut

Out of equilibrium

- Somewhat involves as it requires several processes
- The very rough condition to be in equilibrium is

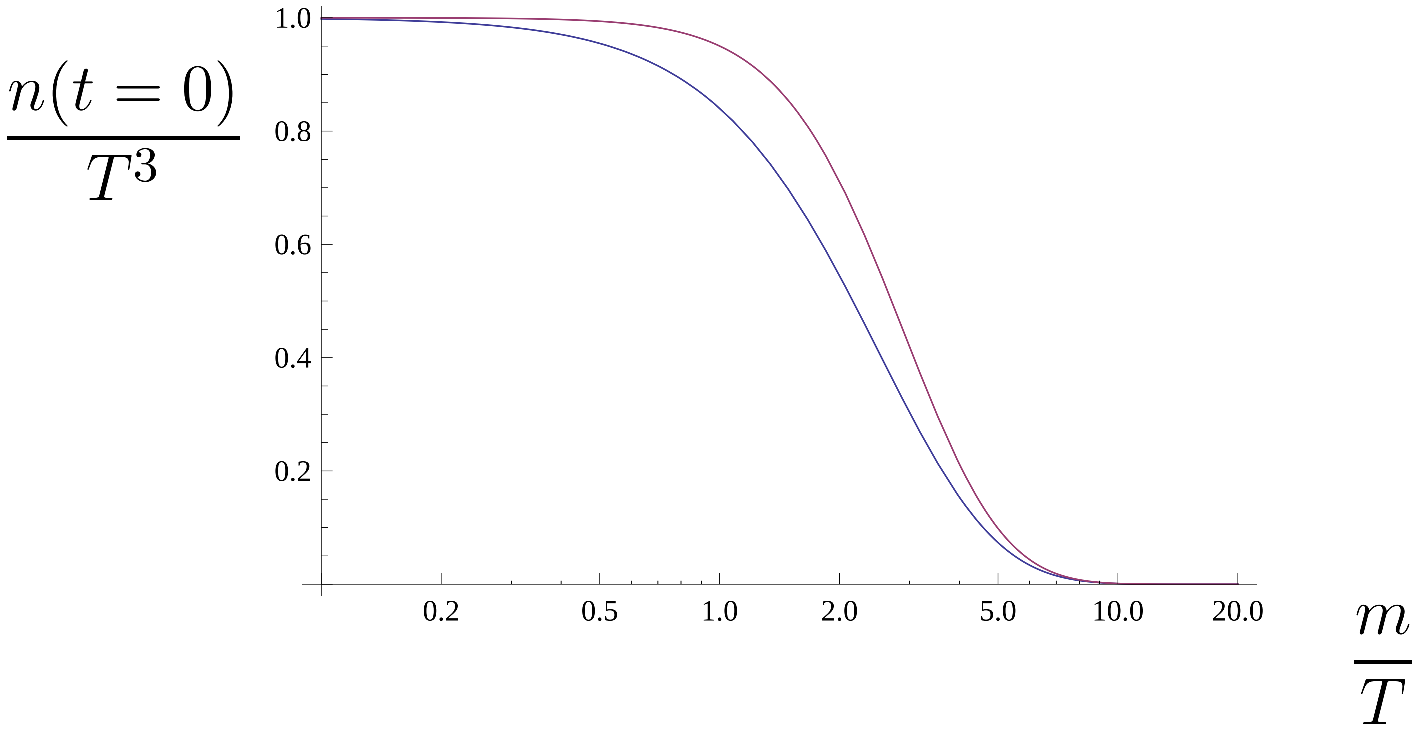
$$\Gamma \gtrsim H\Big|_{T=m}$$

- Not getting into the full details, just give some ideas. To get numbers we need to take all processes into account

Out of equilibrium condition

- When $T < m$ the equilibrium density is dropping as $n \sim \exp(-m/T)$
- The stronger the interaction, the closer the particles follow their equilibrium densities
- When $T < m$ the number of particles decrease due to annihilation and decay
- If the decay is fast enough it follows the equilibrium density
- What is fast enough? Larger than the other time scale, which is H

Plot



- Blue: equilibrium, red: actual for $\Gamma < H$
- Baryogenesis by decays out of equilibrium

Problems with GUT BG

We saw that we get baryogenesis very nicely in GUT, but...

- It requires high reheat temperature that can create monopoles (this is why inflation was invented...)
- In the SUSY version we have a gravitino problem
- Sphalerons (we will get there) erase any GUT asymmetry from models that conserve $B-L$
- With neutrino masses it can still work
- To conclude, nothing is simple, and nothing is ruled out...

SM Baryogenesis

SM baryogenesis

The three Sakharov's conditions are satisfied in the SM

- Baryon number violating process: sphalerons
- The weak interaction violates C and CP
- Out of equilibrium from the electroweak phase transition

The SM, however, is not enough

$$\eta_{\rm SM} \sim 10^{-25} \ll 10^{-10}$$

C and CP violation

- C violation: The SM is chiral, that is E_L and E_R transform differently
- CP violation arises if there are complex couplings in the Lagrangian. We know we have it in the CKM
- Any CPV in the SM must involve the three generation, and thus it involves small CKM elements

Baryon number violation in the SM

- At the classical renormalizable level, baryon and lepton numbers are conserved in the SM
- Non perturbative operators, however, breaks it in a very interesting way
- The processes associate with this breaking are called sphalerons
- Break B$+$L

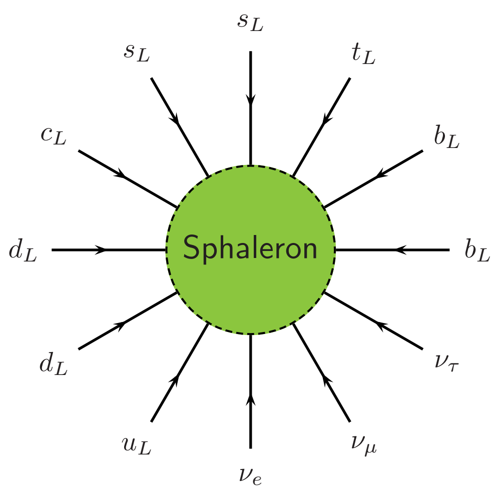
The very basic of sphalerons

Just the very basic...

- Related to the chiral anomaly of a non Abelian gauge group
- In the SM it is the SU(2)
- Non-perturbative effect. Similar to tunneling between different vacuua of the theory
- At $T = 0$, because it is tunneling, it is exponential suppressed and negligible
- At $T \sim v$ no need to tunnel and sphalerons are important
- At $10^2 \lesssim T \lesssim 10^{12}$ GeV the sphalerons are in equilibrium

Sphalerons

Non-perturbative, “tunneling”, effect which involve 3 leptons and 9 quarks



- Can lead to

$$p^+ p^+ \to p^- e^+ e^+ e^+$$

- The rate depend exponentially on T
- No way to see it today
- Very important in the early universe
- Conserve B$-$L

Out of equilibrium

Phase transition

- At high T the EW symmetry is not broken (no need to expand around the minimum)
- When the universe cool down, we have a phase transition.
- Like water, we have bubbles that expand from the “broken phase” into the “unbroken phase”
- This bubble expansion is an out of equilibrium process
- Baryogenesis occurs at the bubble wall
- We need strong (first order) phase transition

Problems with SM BG

Two problems

- The CP violation is too small. The small mixing angles
- The phase transition is too "weak". It has to do with the Higgs mass. The smaller Higgs mass stronger phase transition

EW BG

Still, we can have baryogenesis at the EW phase transition

- Need more scalars to make the phase transition strong
- more sources of CPV
- In the MSSM it can work (marginal)
- Can work in several other models

EM Baryogenesis: summary

- The three Sakharov's conditions are satisfied in the SM
  - Baryon number violating process: sphalerons
  - The weak interaction violates C and CP
  - Out of equilibrium from the electroweak phase transition
- The SM, however, is not enough. too small CPV and the phase transition is not strong enough
- TeV extensions of the SM (say, the MSSM) can produce Baryons at the weak scale

Leptogenesis

Basic idea

The full name: “Baryogenesis via Leptogenesis”

- Generate lepton asymmetry at high temperature
- The Sphalerons convert part of the lepton asymmetry into Baryon asymmetry
- Leptogenesis must be done in a way that breaks B$-$L
- The conversion depends on the number of DOFs

$$B_{SM} = \frac{12}{37}L \qquad B_{MSSM} = \frac{10}{31}L$$

Neutrinos

A short summery

- We know neutrinos are massive
- A nice explanation is the see-saw mechanism

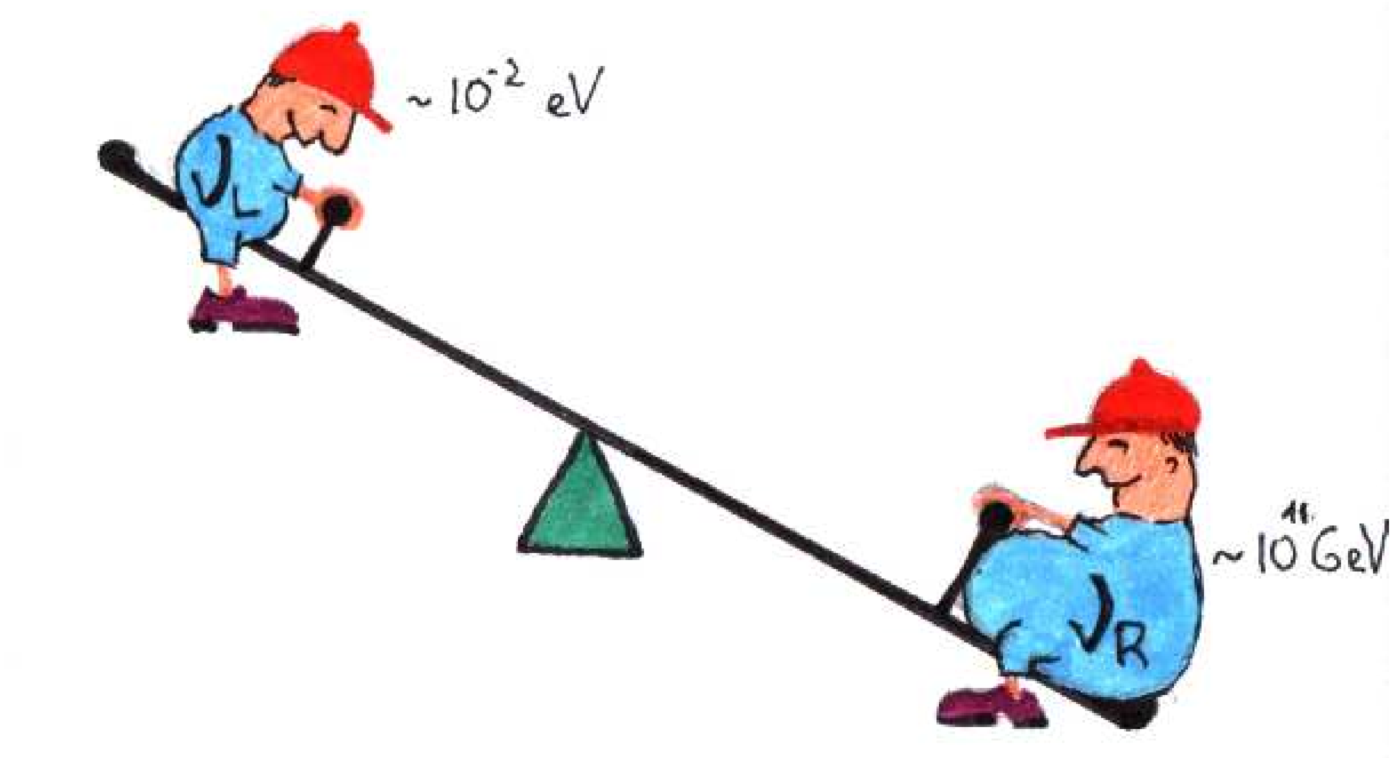
$$W = MNN + YHNL$$

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

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

- The heavy neutrinos break lepton number

The see-saw mechanism



Q: Can the heavy states can do more then give mass to neutrinos?

A: Yes!