Baryogenesis

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What is the problem?

Open questions

- Why there is basically only matter in the universe?

$$n(\overline{B}) \ll n(B)$$

- Quantitatively, can we explain

$$\eta \equiv \frac{n(B) - n(\overline{B})}{N(\gamma)} \approx 6 \times 10^{-10}$$

B stands for Baryons. γ stands for CMB photons

Remarks

$$n(\overline{B}) \ll n(B) \;\;\&\;\; \eta \equiv \frac{n(B) - n(\overline{B})}{N(\gamma)} \approx 6 \times 10^{-10}$$

- Rather amazing that we can even ask this question
- The SM predicts an hierarchy, but it falls short in getting the numerical value of η
- Many explanations beyond the SM. Nothing confirmed
- Not easy to probe any of these ideas as there is only one number to explain
- The solution must involve interplay of particle physics and cosmology
- Maybe neutrinos are the key to the solution

Some vocabulary

- Bryogenesis: The creation of net baryon number in the universe
- Leptogenesis: A nickname for “baryogenesis via leptogenesis” where lepton number is generated and this what drives baryogenesis

What about the lepton number of the universe?

Outline

- Very basic cosmology
- The Sakharov's conditions
- CPV
- GUT Baryogenesis
- SM Baryogenesis
- Leptogenesis

Very basic cosmology

The very basic of early cosmology

- Recall statistical mechanics
- The early universe was very hot
- While the universe expands it cools down
- While cooling down, when $T < M$ the equilibrium density of particles reduce exponentially

$$n \propto \exp(-T/M)$$

- The actual density does not follow the equilibrium one
- How close it does? It depends on the mass and strength of interactions
- The weaker the interaction, it deviates more from its equilibrium density

The Sakharov's conditions

Sakharov's conditions

Sakharov's conditions for dynamically generated baryon asymmetry

- Baryon number violating process

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

- C and CP violation

$$\Gamma(X \to p^+ e^-) \neq \Gamma(\overline{X} \to p^- e^+)$$

- Deviation from thermal equilibrium

$$\Gamma(X \to p^+ e^-) \neq \Gamma(p^+ e^- \to X)$$

Sakharov’s conditions: Remarks

- B violation requires for microscopic baryogenesis
- C and CP violation and out of equilibrium require for macroscopic baryogenesis
- Out of equilibrium condition: Make sure nothing can bring it back to equilibrium

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Eugene Wigner on Baryon conservation : “I can feel it in my bones”

- It is a proof that Baryon number is a very good symmetry today
- In a way, it is also a proof that Baryon number must be broken

Total asymmetry

Consider decays of particle X that generate baryons

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

- N_I is the initial density of X at $T \gg m_X$
- $\epsilon < 1$ is the CP violation asymmetry. This factor is from particle physics
- $\eta_a < 1$ is an efficiency factor due to “washout” effects. This factor is from cosmology

CPV

What is CP

- A symmetry between a particle and its anti-particle
- CP is violated if we have

$$\Gamma(A \to B) \neq \Gamma(\bar{A} \to \bar{B})$$

- It is not easy to detect CPV
  - Always need interference of two (or more) diagrams
  - These two amplitudes must differ in both their weak and strong phases

All these phases

- Weak phase (CP-odd phase) changes sign under CP. It is a phase in $\mathcal{L}$

$$CP(Ae^{i\phi}) = Ae^{-i\phi}$$

- Strong phase (CP-even phase) is invariant under CP

$$CP(Ae^{i\delta}) = Ae^{i\delta}$$

- Due to time evolution $\psi(t) = e^{-iHt}\psi(0)$ and thus needs intermediate real states
- Check for yourself that to get CPV we need both weak and strong phases

GUT Baryogenesis

GUTs

An example of a way to get Baryogenesis

- 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, $\mathbf{5}$ and $\mathbf{10}$
- 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

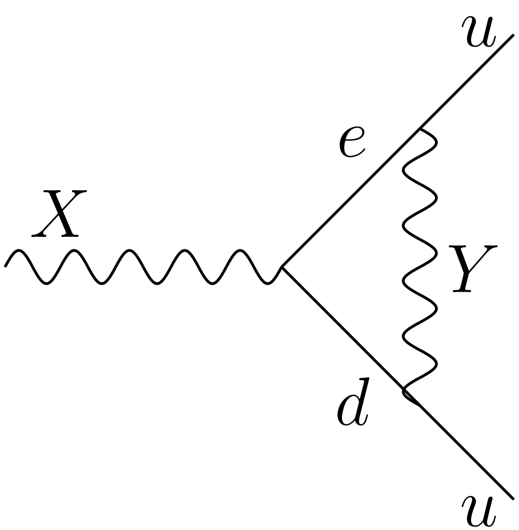
$$X \to u + u \qquad X \to e^+ + \bar{d}$$

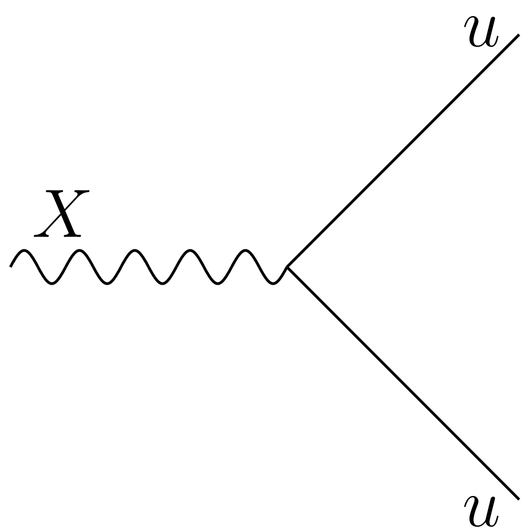
and

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

- 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

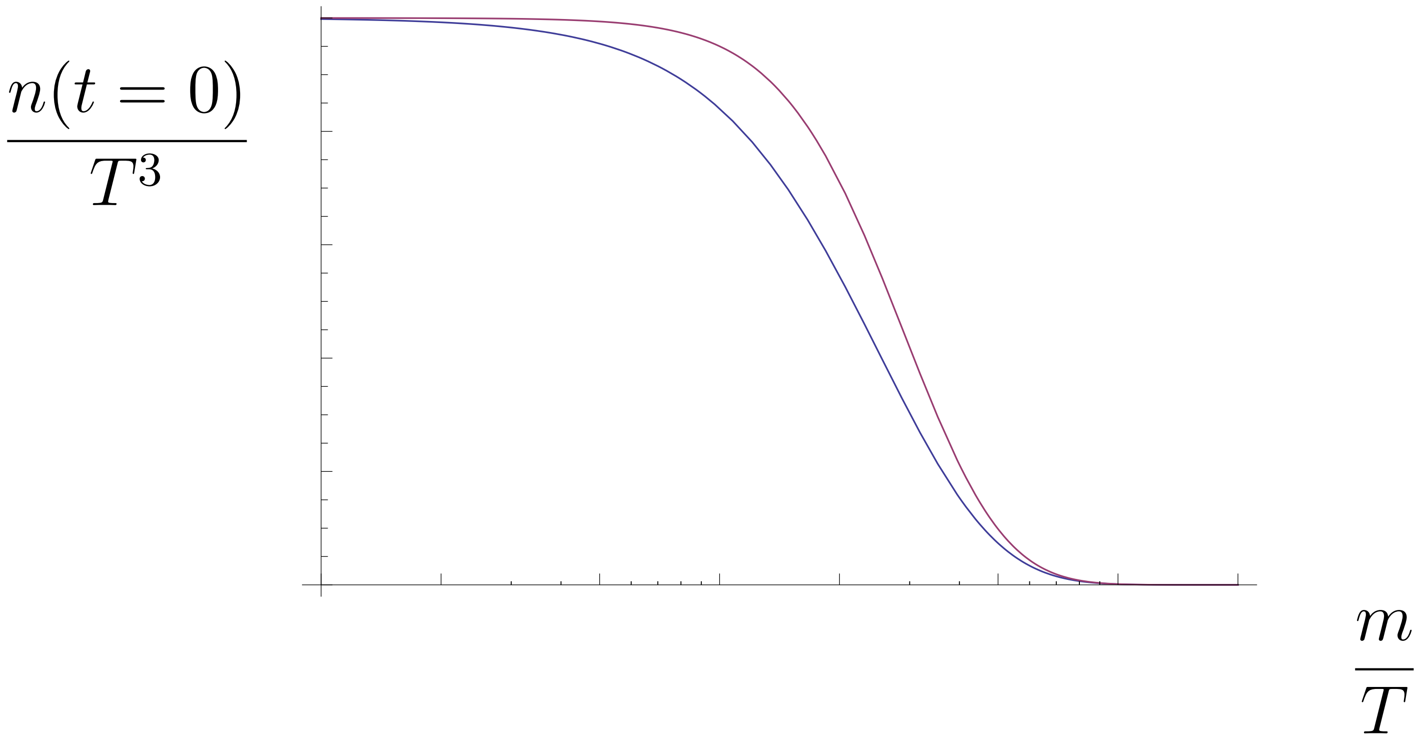
GUT diagrams





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

Out of equilibrium



- Blue: equilibrium, red: actual
- Baryogenesis by decays out of equilibrium

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

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

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
- Sphalerons conserve B$-$L and break B$+$L

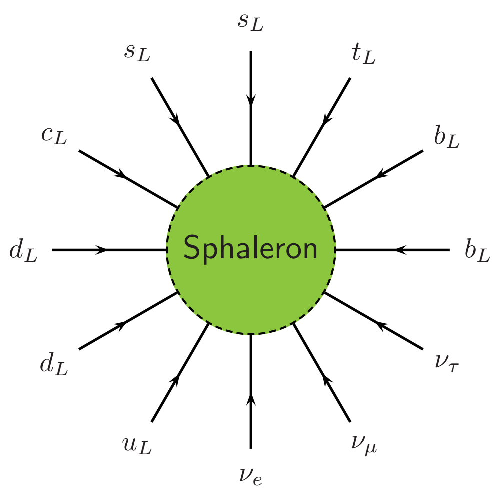
The very basic of sphalerons

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 the temperature, T
- Too small to see it today
- Very important in the early universe
- Conserve B$-$L

Leptogenesis

The SM+N

We know neutrinos have tiny masses

- What is the mechanism that give them mass?
- One option is the see-saw mechanism
- We add to the SM three SM singlets, N_i
- The N_is acquire large Majorana masses
- The neutrinos masses are then

$$m_\nu \sim \frac{m_W^2}{M_N}$$

SM+N leptogenesis

Leptogenesis in decays of heavy singlet neutrino

- Similar to GUT, here N generate lepton asymmetry
- Sakharov's conditions for generating lepton asymmetry
  - Lepton number violating process: $N \to H^+ e^-$
  - C and CP violation

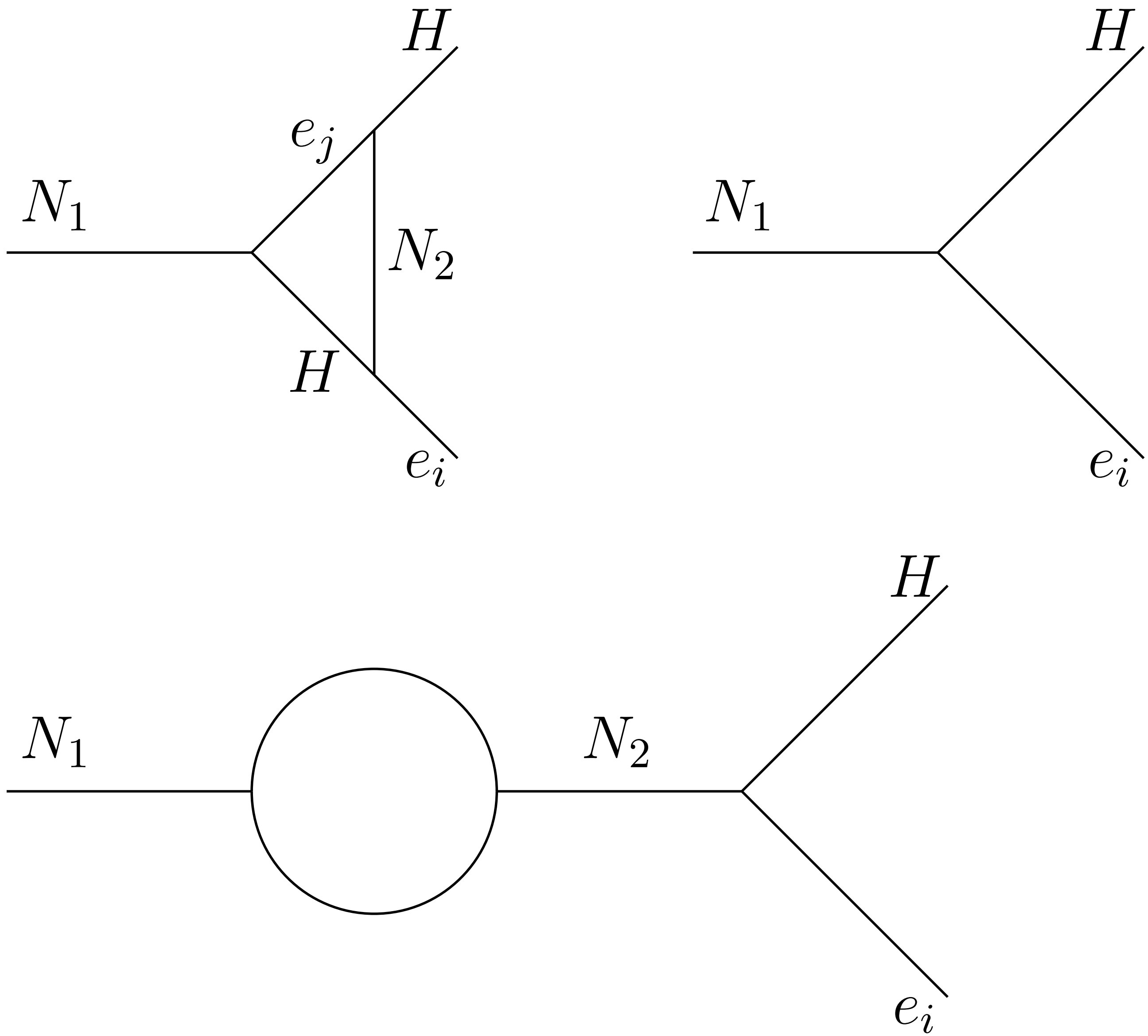
$$\Gamma(N \to H^+ e^-) \neq \Gamma(N \to H^- e^+)$$

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

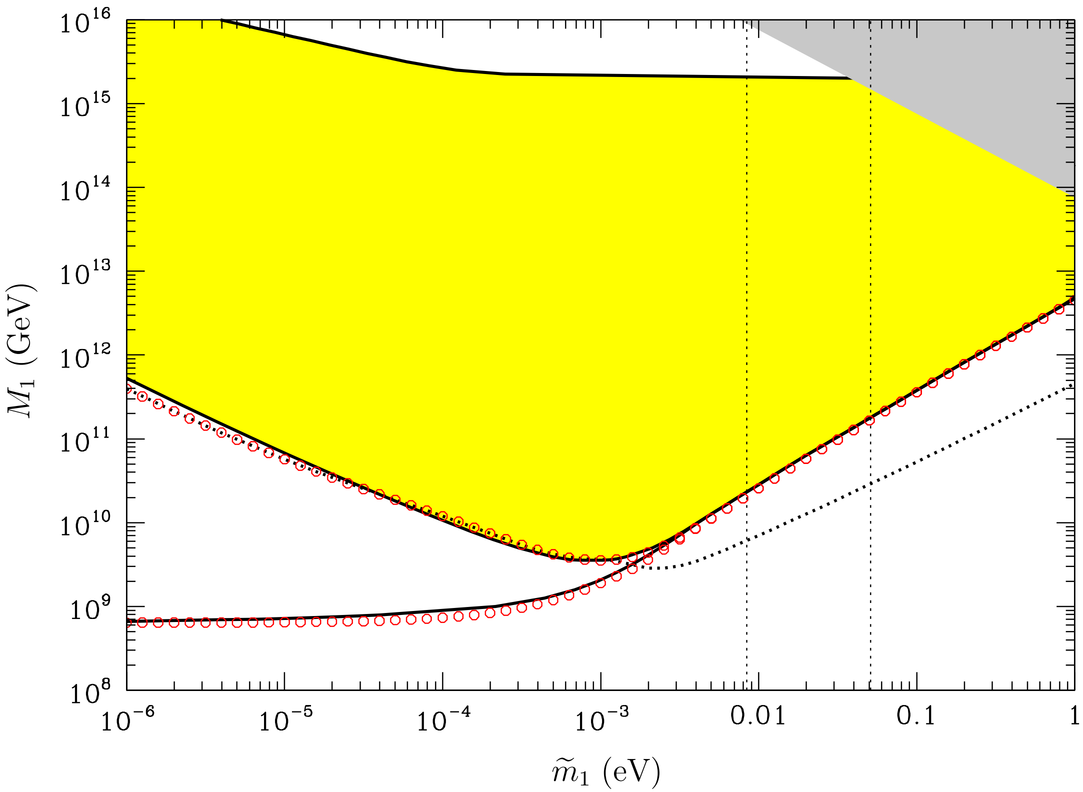
$$\Gamma(N \to H^+ e^-) \neq \Gamma(H^+ e^- \to N)$$

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

Diagrams



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

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 requires 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
- The big “issue” with LG is that it is not easy to test
- Yet it passed one non trivial test!

Conclusions

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- Baryogenesis is an open questin in physics
- Many ideas, but no conclusion yet
- It will be so nice if we find more ways to find the answer