Lecture 9

→ Recap

→ Baryogenesis

→ Dark Matter
  - → evidence
  - → candidates

Next lectures:

Recap

BBN

- As a result of BBN we get 75% of H, 25% of He and $\sim 2\cdot 10^{-5}$ of D, and comparable amounts of Li, T, other light isotops
- It happens after freeze out of $n \leftrightarrow p$, $T \lesssim 1$ MeV [most important reactions, like $p+n \to D+\gamma$ happen at $T \sim 10$'s keV
- 25% of He is an equilibrium computation [from n/p ratio, sensitive to weak]
- $\sim 10^{-5}$ of D is a non-equilibrium computation, sensitive to η_B

Baryogenesis

- Where did all the baryons in the Universe come from? There is no process that we know happenned for sure (like BBN or recombination), however, there are several conjectures for how it happenned.

- Often people assume an initial state symmetric under Baryon $\leftrightarrow$ anti baryon then evolution produces assymetry:

$$n_B > n_{\bar{B}}$$

$$\left(\frac{\Delta n}{n} \ll 1 \right)$$

this process is called "Baryogenesis"

- Then most B and $\bar{B}$ anihilate living:

$$n_B^{final} = \Delta n$$

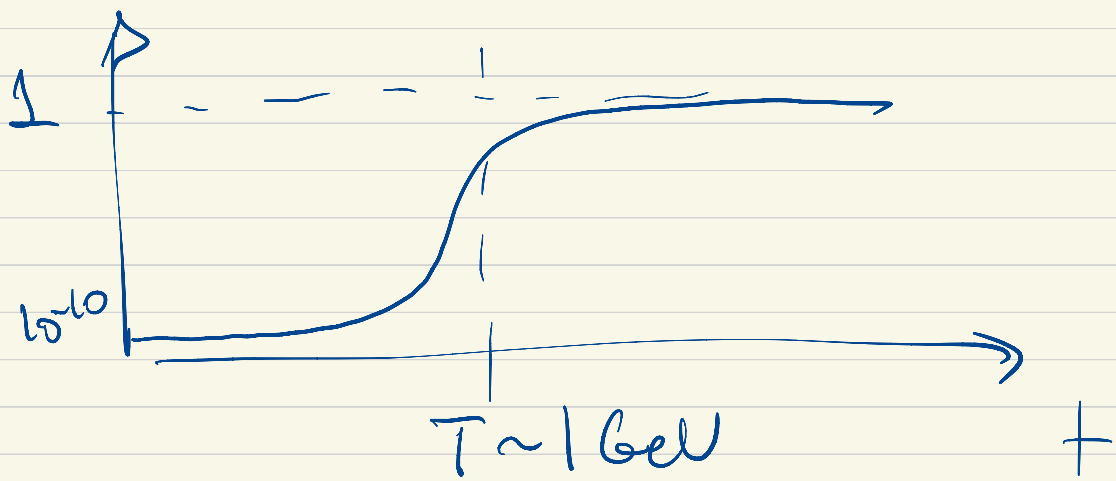
- Since below $T \sim 100$ GeV

Baryon number is a good symmetry (it is conserved), we do not need to worry about n_B changing after that.

At $T \gg 1\,\text{GeV}$

$$n_B \sim n_{\bar{B}} \sim n_\gamma \sim T^3 \Rightarrow$$

$$\frac{\Delta n}{n_B} \sim \eta_B \sim 10^{-10}$$



Sakharov's conditions

P, T and C symmetries:

$$P: \vec{x} \rightarrow -\vec{x}$$

$$T: t \rightarrow -t$$

$$C: B \rightarrow \bar{B}$$

CPT is an exact symmetry, which implies masses of particles and anti-particles (as well as their interactions) are the same.

Individually all C, P, and T are broken, however, breaking of CP is weaker than just of C or P. (first detected in Kaon decays)

For Baryogenesis it is necessary:

1. Baryon number violation
2. Departure from thermal equilibrium
3. Violation of C and CP

→ Standard model of particle physics has all ingredients, but the effect is too small.

Baryon number violation is non-perturbative (like tunnelling in QM)

$$\Gamma \sim e^{-\frac{E_{sph}}{T}}$$

This process is in thermal equilibrium until $T \sim 100$ GeV

→ $B-L$ is exact in SM

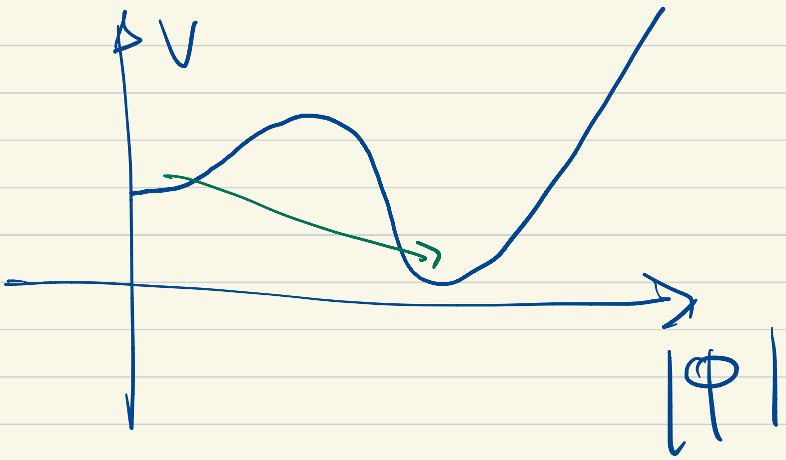
→ Thus, if B-asymmetry is generated at times earlier than 100 GeV, one needs to create a B−L asymmetry, otherwise sphalerons will erase just B asymmetry.

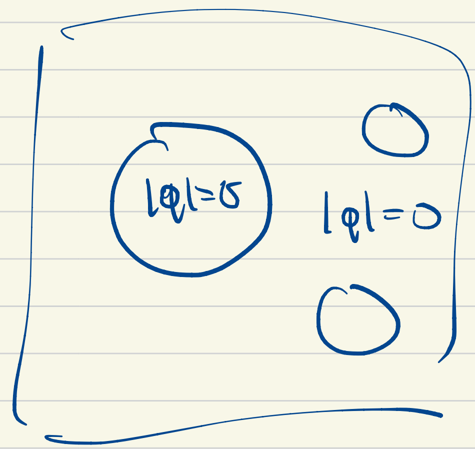
→ Usually this is done by adding heavy particles that decay in B−L non-invariant way.

→ Another way is to generate asymmetry just with SM particles. [this was a very elegant idea that, however, doesn't seem to work]

Electroweak Baryogenesis

main problem is to satisfy Saharov's 2nd condition. If Electroweak phase transition was 1st order, there would be enough deviation from thermal equilibrium:



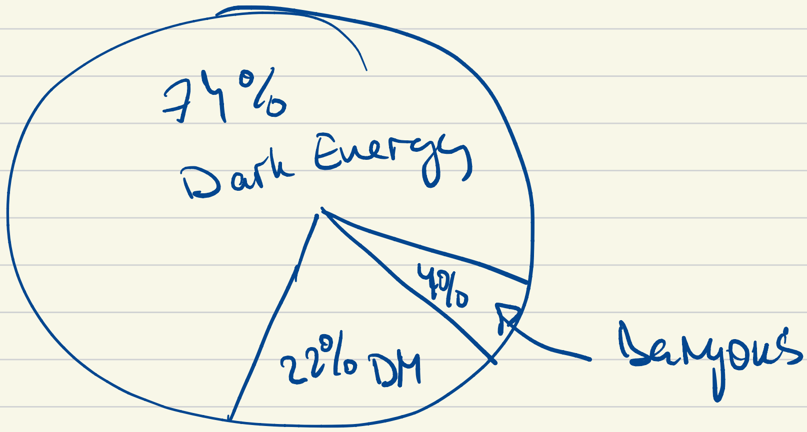


Then sphaleron process (mentioned above) could generate B asymmetry (creating some L asymmetry)

- It appears that $V(\varphi)$ is such that EW phase transition is the second order.

Dark Matter

Evidence for its existence.



→ How do we know there is DM?

- FRW evolution of the U tells us the total amount of matter, and we can also measure the amount of Baryons because the interact.
- A more direct observation comes from rotational curves of the galaxies

Most baryons are in the stars – we see them

$$I_B = I_0 \exp\left(-\frac{r}{r_0}\right)$$

from this $v \sim \frac{1}{\sqrt{r}}$ for $r \gg r_0$:

$$\left(mv^2 = G\frac{Mm}{r} \right)$$

In reality, we see flat profile:

$$v \simeq \text{const}$$

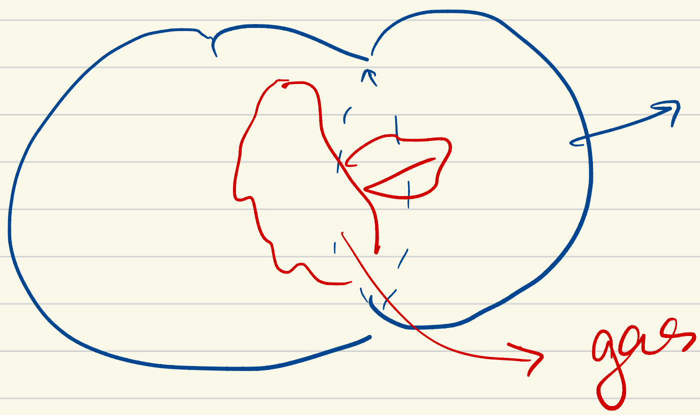
This suggests $M(r) \sim r$, which suggests $\rho_{Dark} \sim \frac{1}{r^2}$

a better fit is given by

$$\rho_{DM}(r) \simeq \frac{r_c^2}{r^2 + r_c^2}$$

- Gravitational lensing allows to measure the total mass of distant galaxy clusters, leading to the same conclusion

- Bullet Cluster ("recently" collided galaxy clusters) mass distribution vs stars distribution.



It is one of the strongest constraints on self interaction of DM.

- Data from BBN, CMB and LSS (to be discussed later) all points to the same approximate amount of DM.

We thus have observational evidence for it coming from very different physical effects and cosmological epochs!

Dark Matter candidates

DM should be stable and very weakly interacting. The only DM particle that roughly satisfy these criteria is neutrino. In fact, for some time people thought that ν's could be DM. This does not work for the following reason:

ν's are fermions, so total number in given volume and with a bound on momentum is given by

$$N_\nu \lesssim \frac{1}{(2\pi)^3} \int d^3p \, d^3x \, n \sim p^3 r^3$$

$$M_\nu \lesssim m_\nu N_\nu \sim m_\nu^4 v^3 r^3$$

$$v^2 \lesssim \frac{GM}{r} \Rightarrow m_\nu \gtrsim \left(\frac{1}{G v r^2} \right)^{1/4} \simeq$$

$$\simeq 120 \left(\frac{100\,\mathrm{km/s}}{v}\right)^{1/4} \left(\frac{1\,\mathrm{kpc}}{r}\right)^{1/2}$$

This is the Tremaine–Gunn limit

- In our Galaxy $v \sim 220\,\mathrm{km/s}$

  $r \sim 10\,\mathrm{kpc}$

gives $m_\nu \gtrsim 30\,\mathrm{eV}$

- Dwarf Galaxies give

  $m_\nu \gtrsim 300\,\mathrm{eV}$

Inconsistent with the bounds.

- More generally, fermionic DM has to be heavier than the bound, bosonic DM can be much lighter!

Bound on bosonic DM mass comes from $\lambda_{\mathrm{compton}} \gtrsim r_{\mathrm{halo}}$

$$\lambda_{compton} \simeq \frac{h}{mc} = \frac{1}{m}$$

$$m \gtrsim 10^{-20}\ eV$$

→ QCD Axion

There is a puzzle with CP violation in SM that we discussed above.

It is present in the EW sector, but absent in strong interactions. An elegant way to explain it is to introduce a particle called "Axion". Due to various experimental constraints axion can have a mass in the range:

$$10^{-11}\ eV \lesssim m_a \lesssim 10^{-2}\ eV \quad \text{(also ADMX)}$$

Axion can also be the DM particle:

If its mass is below $\sim 10^{-5}$ eV

$$V_a\Big|_{T=0} \simeq \Lambda_{QCD}^4 \cos\frac{a}{f_a} \qquad m_a^2 \simeq \frac{\Lambda_{QCD}^4}{f_a^2}$$

$$\rho_a \sim V_a \sim m_a^2 f_a^2 \cos^2\theta_i \sim m_a^2 f_a^2 \theta_i^2$$

$$n_a \sim \frac{\rho_a}{m_a} \qquad H(t_{osc}) \sim m_a$$

(Axion mass has a complicated T-dependence at $T > \Lambda_{QCD}$)

$$\Omega_a \simeq \left(\frac{10^{-6}eV}{m_a}\right) \theta_i^2$$

Ignoring this subtlety we can estimate it.

$$H = \frac{T^2}{M_*} \longrightarrow n_a\Big|_i \simeq \frac{T_{osc}^2}{M_*} f_a^2 \theta_i^2$$

$$n_{a,0} = n_a^i \left(\frac{T_0}{T_{osc.}}\right)^3 \simeq T_0^3 \frac{f_a^2 \theta_i^2}{M_* T_{osc}}$$

$$\rho_{a,0} \simeq m_a T_0^3 \frac{f_a^2}{M_* T_{osc}} \Theta^2 = T_0^3 \frac{\Lambda_{QCD}^4}{M_*^{3/2} m_a^{3/2}} \Theta^2$$

$$T_{osc} = \sqrt{M_* m_a} \qquad f_a^2 = \frac{\Lambda_{QCD}^4}{m_a^2}$$

→ Axion-like particles

→ Other DM:

- WIMP
- Primordial BH (and other macroscopic objects)

Weakly Interacting Massive Particle

"Weakly" is a technical term –
– interacts with Electroweak force →
→ known strength (of course no charge)

[Used to be the most popular DM candidate]

Production by the freeze out mechanism.

Start with heavy particles X and $\bar{X}$

$$X + \bar{X} \rightarrow SM$$

$$X \not\rightarrow SM$$

crossection $\Gamma_X = \langle \sigma n v \rangle \sim H$

$[\sigma \sim \frac{\sigma_0}{v}]$ freeze-out

$$n_X = g_X \left(\frac{M T}{2\pi}\right)^{3/2} e^{-M/T} \, .$$