Baryogenesis and Leptogenesis

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General remarks

- Please ask questions
- I will tell you things that you know. But if you do not know them, ask...
- I will cover only the main ideas. For details look at reviews and books
  - “The early universe,” by Kolb and Turner
  - “Leptogenesis,” by Davidson, Nardi and Nir, arxiv:0802.2962
  - “EW Bryogenesis,” by Cohen, Kaplan and Neslon, hep-ph/9302210
  - “Baryogenesis,” by Dolgov, arXiv:0901.2100

Outline

1. The setup: The problem and the tools
2. The SM and beyond: CPV and other symmetries
3. Ideas for Baryogenesis: GUT and EW
4. Ideas for Leptogenesis: νSM, MSSM, soft LG and Dirac LG

What is the problem?

Open questions

- Why there is only matter around us?

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

- Quantitatively, can we explain

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

B stands for Baryon. γ stand 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
- It is an open question
  - The SM explains the hierarchy, but not the value of η
  - Many explanations beyond the SM. Nothing confirmed
  - Not easy to confirm. Basically, only one number to explain
- The solution must involve interplay of particle physics and cosmology

Ways to baryogenesis

There are several logical possibilities

- Initial conditions are such that $n(B) - n(\overline{B}) \neq 0$
- Separation: we are here, they are there
- Dynamical generation of baryons in the early universe $\equiv$ Baryogenesis

The third possibility looks much more attractive

Baryogenesis

Why do we think that baryogenesis is the answer

- Initial conditions are such that $n(B) - n(\overline{B}) \neq 0$
  - Fine tuning
  - Inflation
- Separation: we are here, they are there
  - Thermodynamic
- Dynamical generation of baryons in the early universe
  - Need to find a mechanism for that

How baryons are generated dynamically?

How the baryon density is measured?

Antibaryons

How do we know that other stars are made of matter?

- Gamma rays from the domain boundaries
- The assumption is that anti-baryons are those we know about
- We do see some positrons and anti-proton, but they are mainly “new”
- From now on we assume that indeed the primordial amount of anti-baryons is negligible

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
- The actual density does not follow the equilibrium one
- How close it does? It depends on the mass and strength of interactions

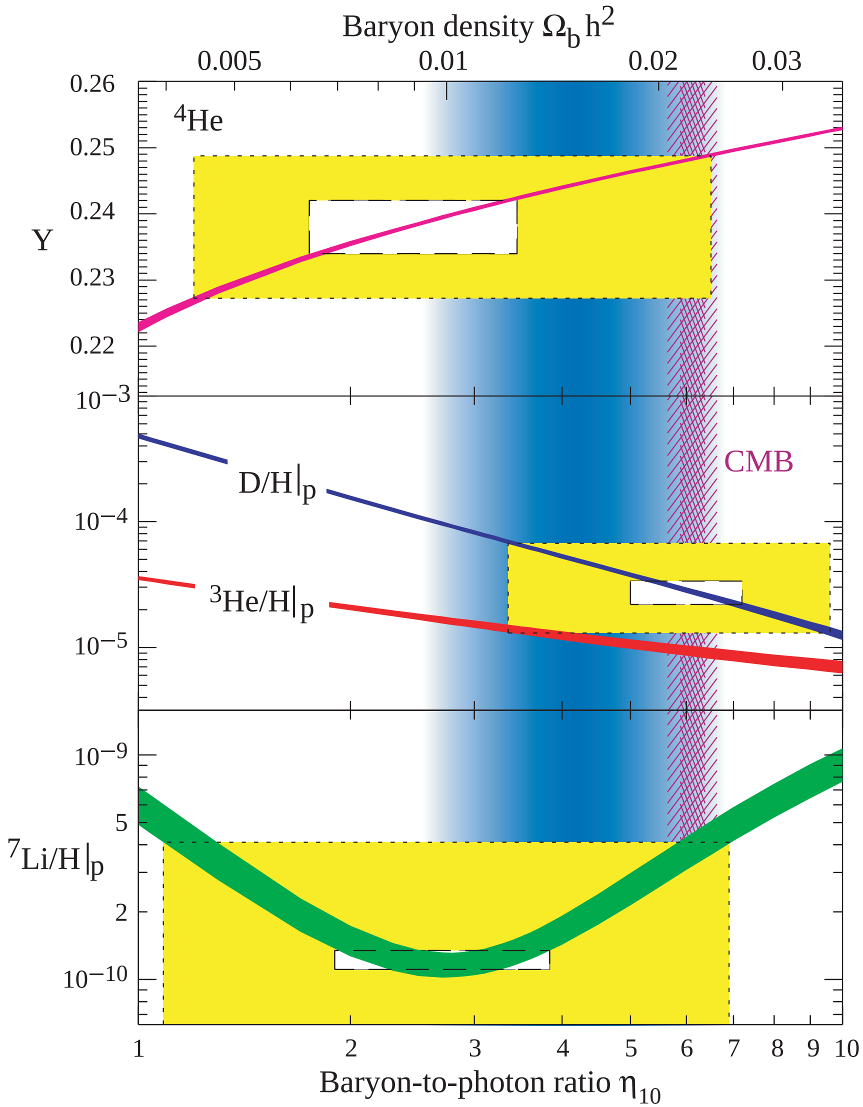
BBN

- At high temperature baryons are not binded
- When the universe cooled below about 1 MeV

$$n + p \to {}^2\mathrm{H} \qquad {}^2\mathrm{H} + {}^2\mathrm{H} \to {}^4\mathrm{He}$$

- The ratio of ${}^4\mathrm{He}$ to H depends on
  - Neutron life time (Which we can measure)
  - The baryon to photon ratio (What we are after)
  - The rate of expansion (Depend on the number of fields)
- Few other elements are also produced, like ${}^3\mathrm{He}$, ${}^7\mathrm{Li}$
- More predictions than parameters, we can test the idea!

Data



- Rather old plot, the data shifted a bit
- Nice agreement

CMB

The CMB spectrum is sensitive to the baryon density

- The physics affects the temperature fluctuation $\Theta \equiv \Delta T/T$
- To leading order

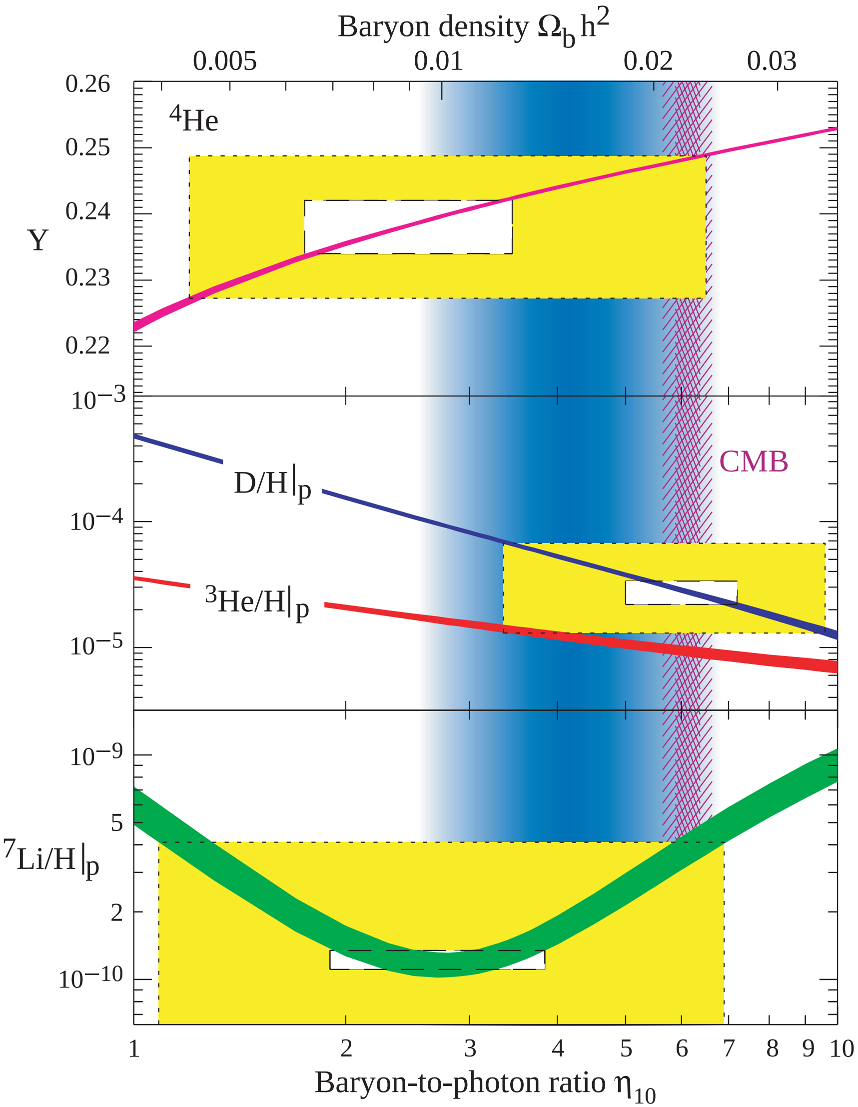
$$\ddot{\Theta} + c_s^2 k^2 \Theta = 0 \qquad c_s = \frac{1}{3}$$

- Baryons affect it in two ways

$$\ddot{\Theta} + c_s^2 k^2 \Theta = F_G \qquad c_s = \frac{1}{\sqrt{3(1+3\rho_B/\rho_\gamma)}}$$

"external gravitational force" F_G and modification of c_s

Data



- BBN and CMB combined

$$\eta = \frac{n(B)}{n(\gamma)} \sim 6 \times 10^{-10}$$

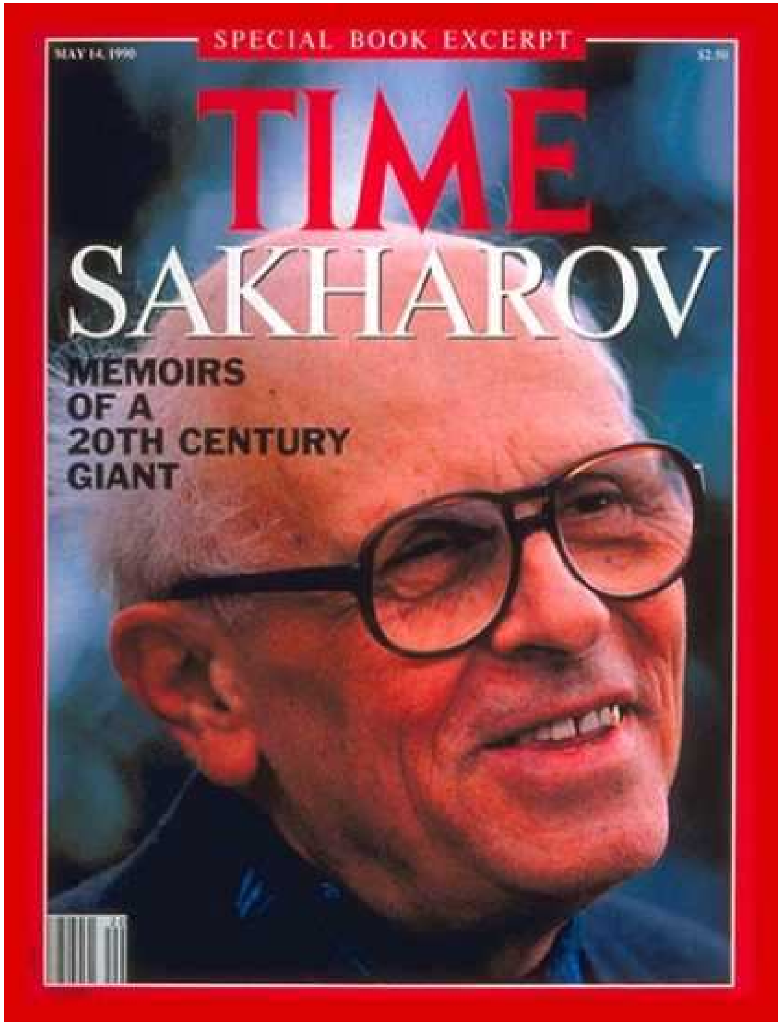
Lepton asymmetry

Q: What do we know about the lepton number of the universe?

- We know the universe is almost charged neutral as at long distance all we have is gravity
- Electron asymmetry is similar to the baryon asymmetry
- We do not know about the neutrinos, and thus we do not know the total lepton number
- Moreover, if neutrinos have Majorana mass, the lepton number of the universe is not well defined

The Sakharov's conditions

Andrey Sakharov



- Nobel Peace Prize in 1975
- CMB oscillations
- Baryogenesis

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

Baryogenesis and HEP

A little bit of model building

We need to understand how to incorporate the needed ingredients of baryogenesis into our theory

- Understand the physics of baryon and lepton numbers
- Understand CP violation

What is HEP

Very simple question

$$\mathcal{L} = ?$$

What is HEP

Very simple question

$$\mathcal{L} = ?$$

Not a very simple answer

Basics of model building

$$\mathcal{L} = ?$$

Axioms of physics

1. Gauge symmetry
2. representations of the fermions and scalars (irreps)
3. SSB (relations between parameters)

Then $\mathcal{L}$ is the most general renormalizable one

Remarks

- We impose Lorentz symmetry (in a way it is a local symmetry)
- We assume QFT (that is, quantum mechanics is also an axiom)
- We do not impose global symmetries. They are “accidental,” that is, they are there only because we do not write NR terms
- The basic fields are two components Weyl spinors
- A model has a finite number of parameters. In principle, they need to be measured and only after that the model can be tested