Universo Primitivo

2018-2019 (1º Semestre)

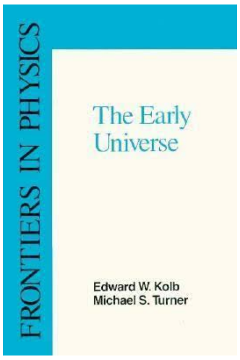
Mestrado em Física - Astronomia

Chapter 8

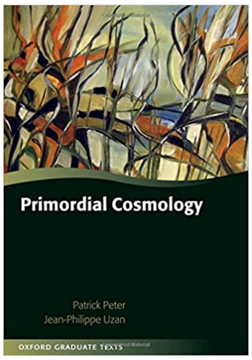
8 Baryogenesis

- Evidences for baryon-anti-baryon asymmetry
- Baryongenesis basic Picture;
- The Sakharov conditions;
- Illustration of a baryogenesis mechanism;

References



Ch. 6



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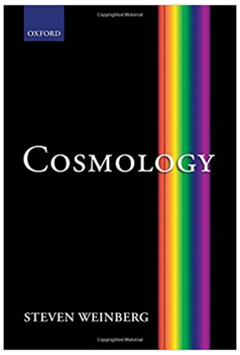

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Additional references (review articles):

- https://arxiv.org/abs/hep-ph/9807454v2
- https://arxiv.org/abs/hep-ph/0609145

Baryogenesis

Evidence for baryon asymmetry

Observational evidences indicate that **our observed universe does not possess significant amounts of anti-matter**. If that was the case, one could in principle observe (very easily) matter / anti-matter annihilations that would produce easy to detect X-ray and γ -ray emission.

Possibility of anti-matter on different scales:

- **Earth-Moon scale**: anti-matter is produced and maintained in particle accelerators; beyond that there's traces of anti-matter in the atmosphere that is easily explained by cosmic ray showers (high energy particles entering the atmosphere)
- **Solar system scale:** Solar cosmic rays fluxes observed on earth are consistent with the sun being made of matter. All our probes to exploring planets didn't "encounter" or observe effects that could be associated with matter annihilations.
- **Galaxy scale**: Cosmic rays provide samples of particles being produced over the galaxy. Their properties are consistent with the existence of no significant amounts of anti-matter
- **Extra-galactic and cosmological scales**: Large scale structure and CMB observations are also consistent with a universe predominantly made of mater.

Baryogenesis

The basic picture

Baryogenesis: is the physical mechanism that attempts to *dynamically describe the observed imbalance between matter (baryons) and anti-matter (anti-baryons), starting from some symmetric state of the primordial Universe*.

The basic idea behind baryogenesis is that matter (quarks and leptons) and anti-matter (anti-quarks and anti-leptons) *result from the decaying of particles, through new type of interactions that do not preserve the net number of baryons* (ie **violate the net baryon number B**). For this to happen, baryons and anti-baryons should have different properties (besides e.g. the electric charge)

All baryogenesis theories should ultimately provide a detailed prediction to the baryon photon ratio,

$$\eta \equiv n_B/n_\gamma$$

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} = 2.74 \times 10^{-8}\, \Omega_B h^2$$

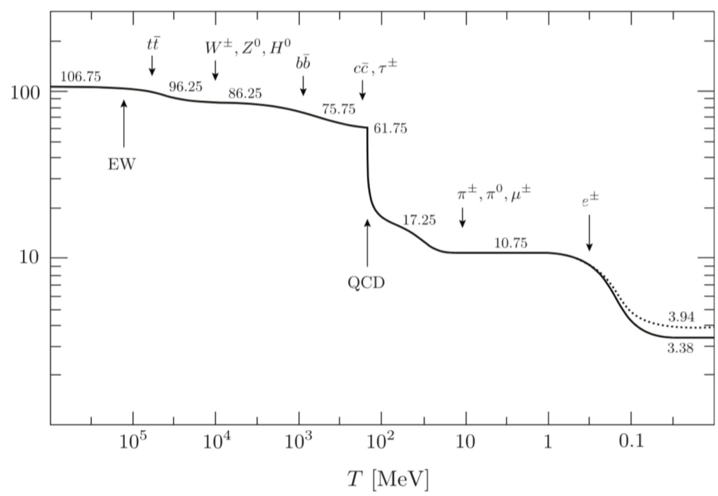
which is an observable that can be use used to impose constraints on these theories.

Baryogenesis

The basic picture

The epoch of baryogenesis is uncertain. Depending on the theory it may have occurred soon after:

- The Planck scale ($< 10^{19}$ GeV, $< 10^{-43}$ s): **Quantum gravity baryogenesis**;
- The Grand Unification Theory scale ($\sim 10^{16}$ GeV, $\sim 10^{-36}$ s): **GUT baryogenesis**
- During the electroweak phase ($> 10^{2}$ GeV, $> 10^{-12}$ s): **electroweak baryogenesis**



Baryogenesis

Sakharov conditions

In 1967 Sakharov formulated the following **set of 3 conditions** for building up baryon-anti-baryon asymmetries in the early Universe:

- **Baryon number violation**: There are interactions that do not preserve the baryon number conservation. In particular these interactions couple quarks with leptons (and their anti-particles) through decays with different channels and branching ratios (see illustrative example bellow).
- **An out of equilibrium condition**: Usually one needs a condition that prevents the reversion of interactions that originate the baryon-anti-baryon asymmetry. Otherwise the baryon-anti-baryon asymmetry wouldn't develop. The Universe expansion can be used as a way to avoid this reversion process.

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Baryogenesis

Sakharov conditions

In 1967 Sakharov formulated the following **set of 3 conditions** for building up baryon-anti-baryon asymmetries in the early Universe:

- **C and CP violations:** In particle physics the **C (charge conjugation)** conservation is a transformation applied to an interaction process that converts particles into their anti-particles keeping the same net charge. **Parity inversion, P**, is a flip of sign in the spatial coordinates of the system.
  CP conservation applied to an interaction, preserves simultaneously the charge conjugation and parity inversion, transformations. **CP violation** in a decaying processes of bosons X and $\bar{X}$, with more than one final state with baryons, **implies** that their decays must have **different branching ratios** (without CP violation, their branching ratios are the same). This implies that baryons and anti-baryons behave differently (have different quantum properties other than their charge eigenstate) in the decaying process.
  Time reversal, T, conservation preserves the physical description of the system with respect to time inversion. The so called **CPT invariance**, is a fundamental symmetry that preserves the C, P, and T transformations when applied to a given a interaction. CPT invariance for the decays of $X, \bar{X}$ bosons above, imply that they **must have the same decaying rates**.
  Violation of C or CP transformations leads to the **violation of the CPT invariance** (which has been already observed for short lived decay interactions involving the K^0 mesons).

Baryogenesis

Baryogenesis mechanism illustration

Consider the ``Leptonquark" boson, X, and its anti-boson, $\bar{X}$, that decay via the processes below, each with a given branching ratio and final baryon number. The decays fail to preserve B, and CP is violated in, at least, one of the decaying channels.

$X, \bar{X}$ branch 1 (rows 1 and 3)

$X, \bar{X}$ branch 2 (rows 2 and 4)

particle		final state	branching ratio	B
X	$\rightarrow$	qq	r	2/3
X	$\rightarrow$	$\bar{q}\bar{l}$	$1-r$	−1/3
$\bar{X}$	$\rightarrow$	$\bar{q}\bar{q}$	$\bar{r}$	−2/3
$\bar{X}$	$\rightarrow$	$q l$	$1-\bar{r}$	1/3

The net Baryon number for the decaying of X and $\bar{X}$ is:

$$B_X = r\left(\frac{2}{3}\right) + (1-r)\left(-\frac{1}{3}\right) = r - \frac{1}{3}$$

$$B_{\bar{X}} = \bar{r}\left(-\frac{2}{3}\right) + (1-\bar{r})\left(\frac{1}{3}\right) = -\bar{r} + \frac{1}{3}$$

So the net baryon number of these decays is:

$$\epsilon = B_X + B_{\bar{X}} = r - \bar{r}$$

This gives zero if there was no CPT violation, which is not the case. Since the above process does not preserve C or CP **the branching ratios are not equal $r \neq \bar{r}$**, and the **net baryon number is not conserved.**