Tema 5

Nucleosíntesis primordial

Asignatura de Física Nuclear

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Universidad de Santiago de Compostela

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Big Bang cosmology

1.1 The Universe today

The present state of the Universe is characterized by few large-scale observables and some basic physical laws.

Large-scale observables:
- expansion of .the Universe (red shift)
- background radiation at 2.76 K
- 10^{-9} asymmetry between density of baryons and photons
- universal abundance of about 75% H and 25% He

Physical laws:
- General Theory of Relativity provides a relation between the elapsed time and temperature of the Universe

$$T = \frac{1.5 \cdot 10^{10}}{\sqrt{t}}$$

- Statistical Mechanics (Stefan-Boltzman law) provides a relation for the energy density of radiation (photon gas)

$$u_{\gamma}(E)dE = \frac{8\pi E^3}{(hc)^3} \frac{1}{e^{E/kT} - 1} dE$$

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Big Bang cosmology

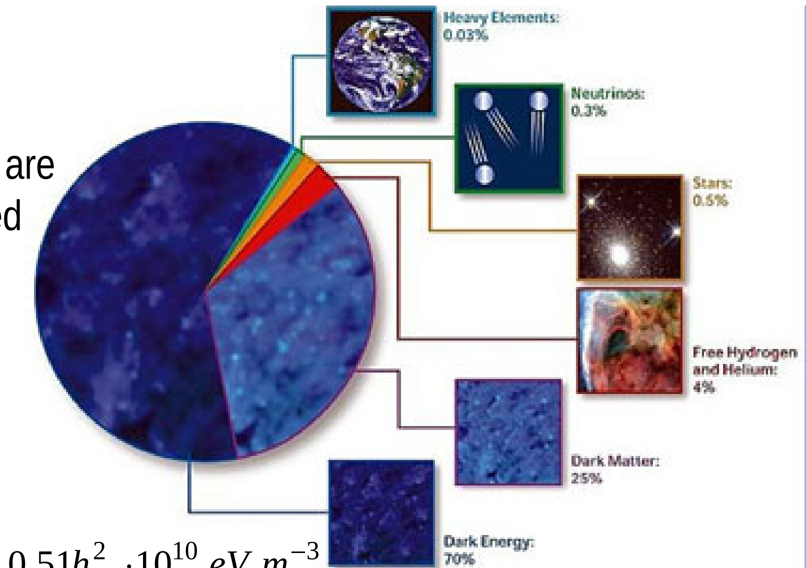
1.2 The Universe composition

The visible Universe:

The building blocks of the visible Universe are galaxies which are themselves composed of stars, interstellar gas and unidentified dark matter. The density of visible matter is:

$$\rho_{vis} \sim 0.2 \cdot 10^{-31}\ g / cm^3$$
$$\sim 0.4\ nucleons / m^3$$

$$\Omega_{vis} = \frac{\rho_{vis}}{\rho_c} = 0.002$$



where ρ_c represents the *critical density*:

$$\rho_c = \frac{3H_0^2}{8\pi G} = 0.92 h_{70}^2 \cdot 10^{-26}\ kg\ m^{-3} = 1.4 h_{70}^2 \cdot 10^{11}\ M_{\odot}\ Mpc^{-3} = 0.51 h_{70}^2 \cdot 10^{10}\ eV\ m^{-3}$$

Being $H_0=70\ km\ s^{-1}\ Mpc^{-1}$ the *Hubble constant* and $h_{70}=H_0/70\ km\ s^{-1}\ Mpc^{-1}$ the *reduced Hubble constant*

Baryons:

In order to reproduce the relative abundances of light nuclei produced in the primordial nucleosynthesis the required density of baryons (protons, nuclei and electrons) is estimated to be one order of magnitude greater than that of visible baryions:

$$\Omega_b = 0.044 \pm 0.004$$

The missing dark baryons are though to be in the intergalactic medium in the form of ionized gas, dark compact objects sush as dead stars (neutron stars or white dwarfs) or stars too light to burn hydrogen (brown dwarfs).

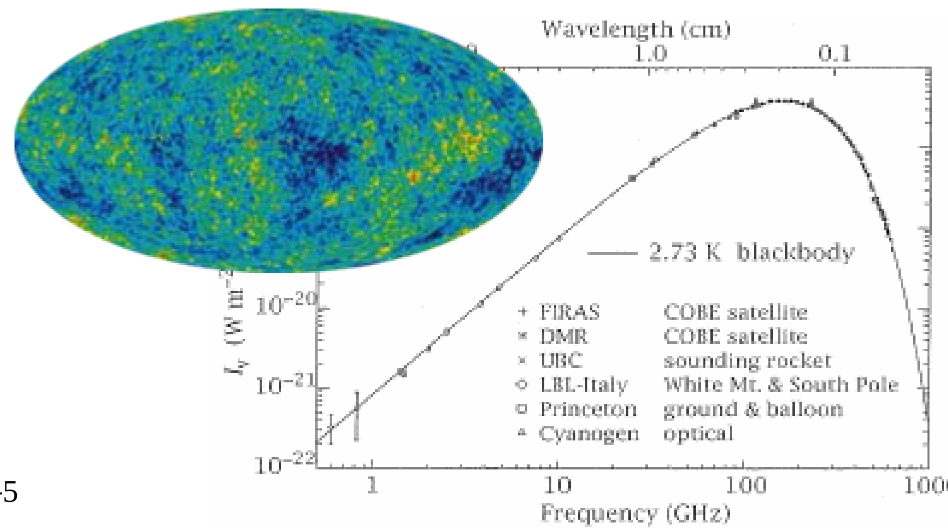
Big Bang cosmology

1.2 The Universe composition

Cold dark matter:

90% of the matter in galaxies and clusters of galaxies is not visible. Some theories suggest that this *cold dark matter* is made of nonbaryonic weakly interacting massive particles called *wimps*. The present density of CDM is estimated to be an order of magnitude greater than that of baryons.

$$\Omega_{CDM} = 0.226 \pm 0.04$$



Photons:

The most abundant particles in the Universe are the photons of the cosmic background radiation. this photons have a thermal spectrum being the present temperature T=2.7 K. Despite their great Abundance, the low temperature results in a small photon density.

$$\Omega_\gamma = (5.06 \pm 0.4) \cdot 10^{-5}$$

$$u(E)dE = \frac{8\pi E^3}{(hc)^3} \frac{1}{e^{E/kT} - 1} dE \quad \Rightarrow \quad \rho_\gamma = 4.7 \cdot 10^3 T^4 \ \text{eV/m}^3 \quad \text{T} = 2.7\text{K} \rightarrow 250\ \text{keV/m}^3$$

$$n(E)dE = \frac{u(E)}{E} dE = \frac{8\pi E^2}{(hc)^3} \frac{1}{e^{E/kT} - 1} dE \quad \Rightarrow \quad N_\gamma = 2.0 \cdot 10^7 T^3 \ \gamma/\text{m}^3 \quad \text{T} = 2.7\text{K} \rightarrow 4 \cdot 10^8 \ \gamma/\text{m}^3$$

There is a strong asymmetry between matter and radiation: $\rho_\gamma / \rho_{nuc} \sim 10^8 - 10^9$

Big Bang cosmology

1.2 The Universe composition

Neutrinos:

In addition to thermal photons it is believed that the Universe is filled with neutrinos and the corresponding anti-neutrinos. However, because of their extremely weak interactions, there is little hope of directly detecting the cosmic neutrino background. Their energy density depends on its mass, the present estimates provide the following range:

$$0.0006 < \Omega_{\nu} < 0.015$$

The vacuum:

One of the most surprising recent discoveries is that the Universe appears ti be dominated by and apparent vacuum energy or cosmological. This energy is a consequence of the quantum field theory and can be understood as due to the zero-point energy of the oscillators describing a given field or the virtual particle-antiparticle pairs generated by the field. The density energy associate to vacuum is estimated to be:

$$\Omega_{\Lambda} \approx 0.7$$

Anti-matter:

Our Universe is composed mostly by matter otherwise the effects of annihilation between matter and anti-matter should be observed.

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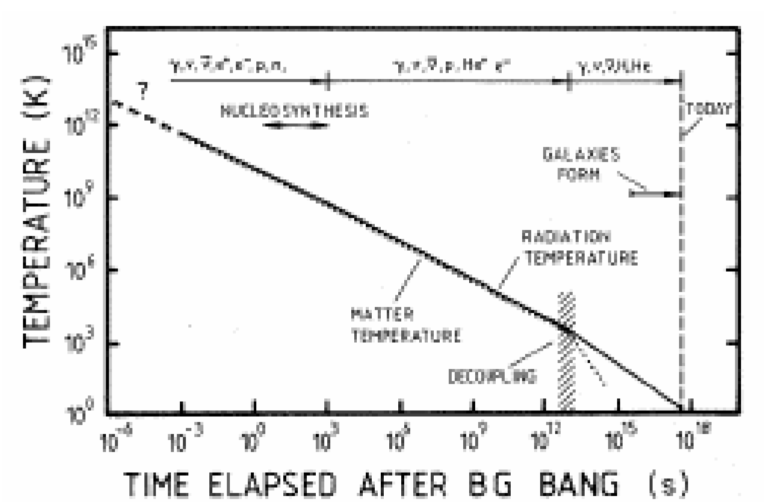
Big Bang cosmology

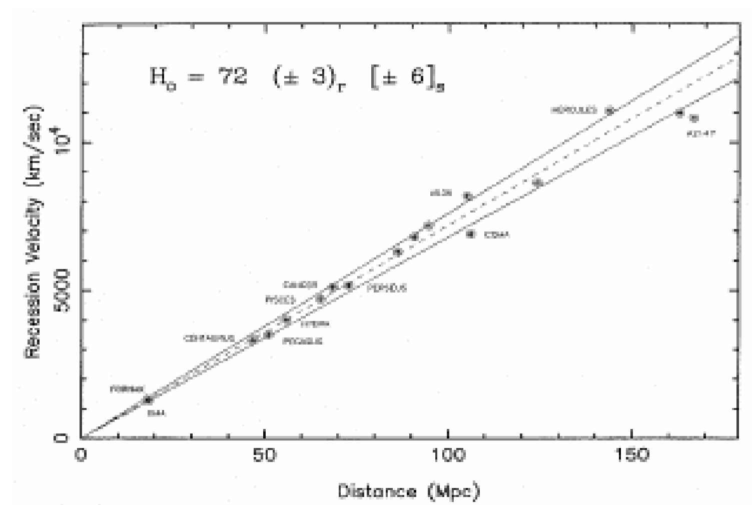
1.2 Big Bang and first moments

Universe expansion, background radiation and the abundance of light elements, are considered as evidences for the Big Bang theory.

- Moving back in time one would reach infinity density and energy as initial stage.
- The expansion and cooling of the initial Universe would progressively break the equilibrium between different particle species and radiation.
- Gamma probes, as the microwave background radiation allow us to explore the Universe back until the moment at which radiation and matter decoupled (~10^5 y)

$$T = \frac{1.5\cdot 10^{10}}{\sqrt{t}}$$





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2.1 Particle physics era

First moments:

- t=10^{-12} s, T=10^{16} K (E~1000 GeV)
  At this temperature matter and radiation is in equilibrium, all species of particles and anti-particles are created but also annihilated.

$$\gamma + \gamma \leftrightarrow e^{+} + e^{-}$$

$$\gamma + \gamma \leftrightarrow p + \overline{p}, n + \overline{n}$$

$$\vdots$$

$$\gamma + \gamma \leftrightarrow q + \overline{q}\,?$$

- t=10^{-6} s, T=10^{13} K (E~1000 MeV)
  Nucleons and anti-nucleons annihilate but are not created any more
  leptons are neutrinos made possible the conversion between protons and neutrons via weak interactions.

$$p + \overline{\nu}_e \leftrightarrow n + e^{+}$$

$$n + \nu_e \leftrightarrow p + e^{-}$$

A mechanism should account for the present imbalance between matter and radiation (~10^{-9}) and between matter and anti-matter → CP violating decays.

2.1 Particle physics era

- $t=10^{-2}$ s, $T=10^{11}$ K (E~10 MeV)

Electrons are the only remaining leptons, μ (mc^2=105 MeV) and τ (mc^2=1784 MeV) are no longer produced and they decay to electrons or annihilate but neutrinos are produced in neutral weak interactions.

$$e^+ + e^- \leftrightarrow Z^o \leftrightarrow \nu_e + \bar{\nu}_e$$

$$e^+ + e^- \leftrightarrow Z^o \leftrightarrow \nu_\mu + \bar{\nu}_\mu$$

$$e^+ + e^- \leftrightarrow Z^o \leftrightarrow \nu_\tau + \bar{\nu}_\tau$$

Proton and neutron concentrations are in equilibrium being more abundant protons because they are lighter than neutrons.

$$\frac{N_n}{N_p} = e^{-(m_n - m_p)c^2/kT}$$

- $t=1$ s, $T=10^{10}$ K (E~1 MeV)

Neutrino interactions are no longer important and they expand freely.

2.2 Nuclear physics era

- t=190 s, T=10^9 K (E<0.5 MeV)
  Positrons were no longer produced and they annihilated, then the proportion of protons and neutrons was fixed.

$$N_n / N_p = 13/87 \sim 1/7$$

At this moment, protons and neutrons underwent a series of nuclear reactions leading to the transformation of protons and neutrons in ^{4}He with no free neutrons surviving. After this process The Universe was composed of protons, helium, electrons, photons and neutrinos.

- t~500000 y, T=5 10^3 K (E~0.43 eV)
  Under these conditions, ions and electrons combined forming a neutral gas From this moment on the Universe changed from being radiation dominated to be matter dominated. The consequence is that the previously opaque Universe became transparent since radiation could travel unscattered through space. Indeed, the background radiation we observe now was produced at that time.

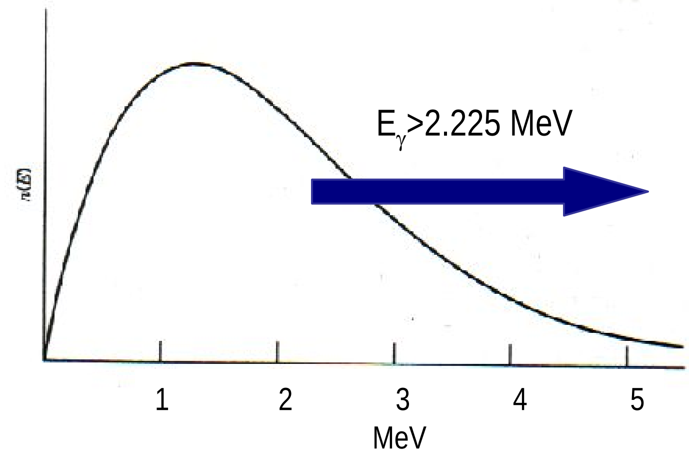
Big Bang nucleosynthesis

3.1 First nuclear reactions

The first nuclear reaction that took place in the Universe was the production of deuterium in the proton and neutron fusion reaction.

$$p + n \rightarrow d + \gamma$$

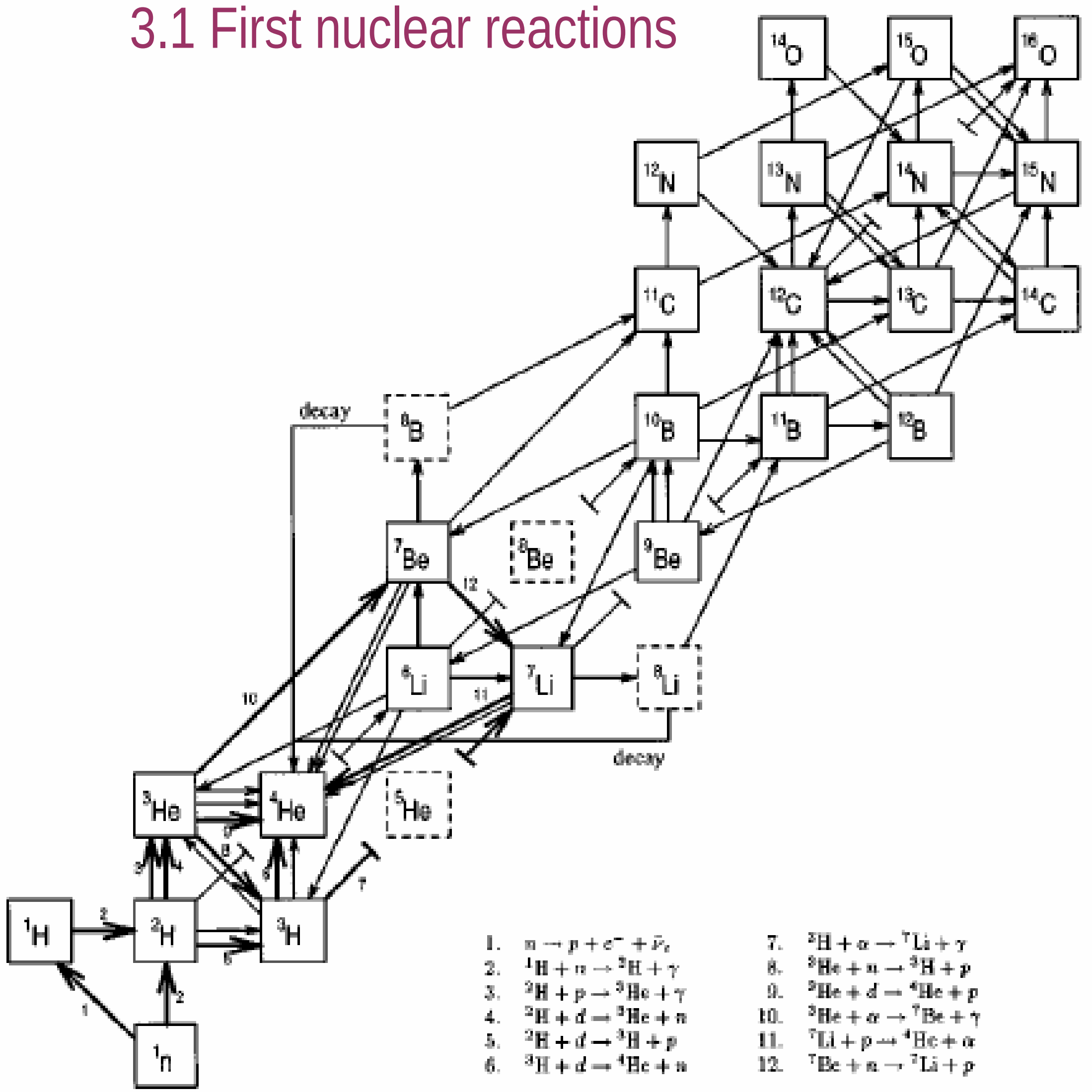
At high temperatures, the reverse reaction occurs as quickly as deuterium production, and there is no effective accumulation of deuterium nuclei. Taking into account that the photon energy necessary for photodissociation is 2.225 MeV one can obtain that deuterium production is effective at temperatures below T=9 10^8 K and thus, for a time t=250 s.



The final abundance of deuterium will depend on the neutron half life but also on the ratio between photons and baryons densities at the early Universe. The comparison between calculated and measured abundances allow to determine one of the main cosmological parameters, the baryon density of the Universe.

Primordial nucleosynthesis

3.1 First nuclear reactions

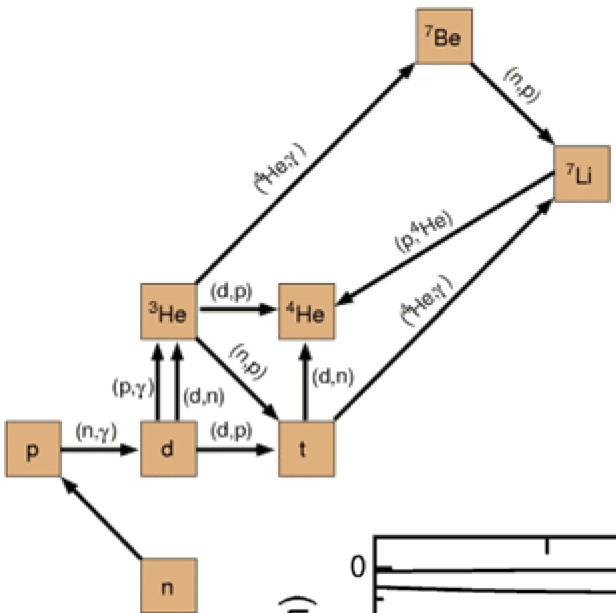


The initial proton and neutron concentrations in a Universe at some 10^9 K and a baryon density around 3.6 10^{-31} g/cm^3 are though to produce around 40 different nuclear reactions Leading to the production of nuclei up to the mass number 16.

However, the non existence of stable nuclei with mass numbers 5 and 8 limits the main reactions to those leading to the production of nuclei until the mass number 8.

Primordial nucleosynthesis

3.1 First nuclear reactions



The main reactions in the Big Bang nucleosynthesis process leads mostly to the transformation of the existing neutrons in the early Universe into ^{4}He nuclei. Additionally, some deuterium ^{3}He, ^{3}H and heavier species as ^{7}Be, ^{7}Li and ^{6}Li are also produced.

$d+n \rightarrow {}^3H+\gamma$

$d+d \rightarrow {}^3H+p$

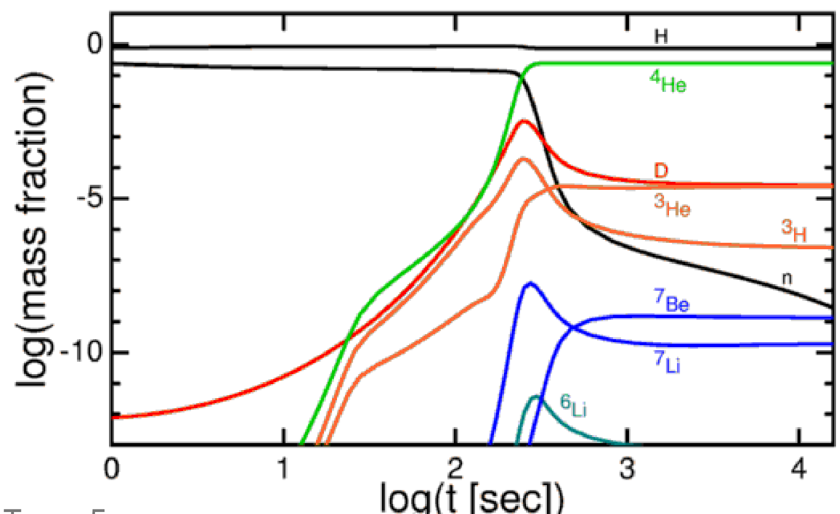
$d+p \rightarrow {}^3He+\gamma$

$d+d \rightarrow {}^3He+n$

$n+{}^3He \rightarrow {}^3H+p$

$d+{}^3H \rightarrow {}^4He+n$

$d+{}^3He \rightarrow {}^4He+p$



${}^3H+{}^4He \rightarrow {}^7Li+\gamma$

${}^3He+{}^4He \rightarrow {}^7Be+\gamma$

$n+{}^7Be \rightarrow {}^7Li+p$

${}^7Be \rightarrow {}^7Li+e^-+\nu$

$p+{}^7Li \rightarrow {}^8Be \rightarrow {}^4He+{}^4He$

Primordial nucleosynthesis

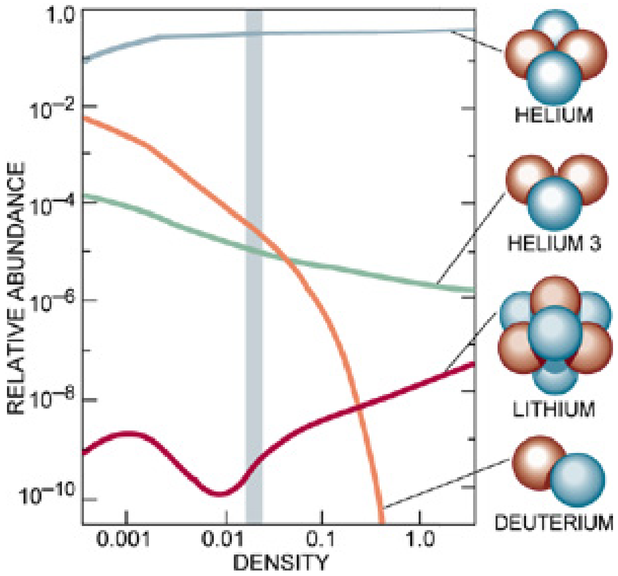
3.2 Big Bang nucleosynthesis and cosmology

The final abundances of different nuclear species produced during the Big Bang nucleosynthesys process are very much dependent on some fundamental cosmological parameters such as the baryon density of the Universe.

Nuclear models allow to determine the expected abundances of light nuclei produced after the Big Bang as a function of the Universe baryon density with high accuracy.

Primordial abundances obtained from astronomic abundances or detailed characterizations of the temperature fluctuations in the Cosmic background radiation (CBR) together with Big Bang nucleosynthesis models help in putting some light in fundamental questions such as:

- the baryon density of the Universe
- galactic chemical evolution
- particle physics standard model

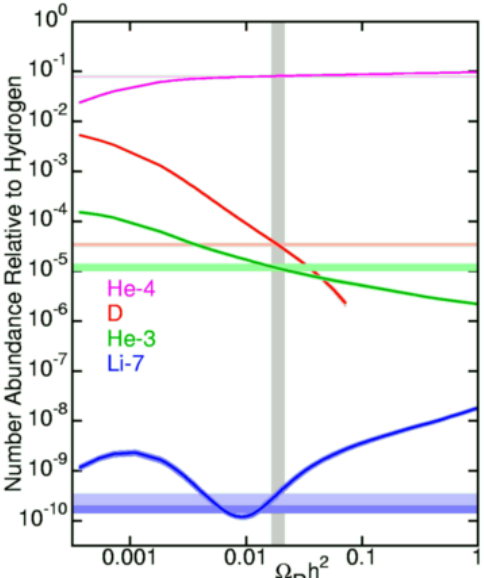


Primordial nucleosynthesis

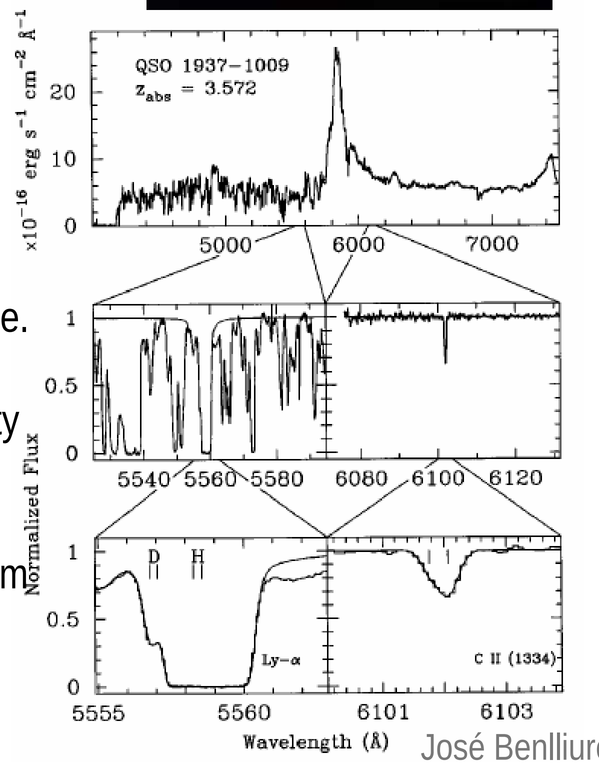
3.2 Big Bang nucleosynthesis and cosmology

Deuterium is the primeral nucleus whose abundance present the larger sensitivity to the Universe baryon density. Primeral deuterium Abundance can be determined in the analysis of the wing of the hydrogen Lyman spectrum obtained from high-redshift hydrogen clouds.

Clouds at z>3 redshift represent nearly virgin samples of cosmic material. For z>3, Ly-a is shifted into the visible part of the spectrum And thus can be observed from Earth-based telescopes as the 10 m Keck telescope in Hawai.



The astronomic determination of the primeral nuclei abundances shows that ^{4}He in rather insensitive to the baryon density of the Universe. Deuterium and ^{3}He are more sensitive being both abundances described by a baryon density around Ω_B~$0.03h^2$. However, the observed primeral abundance of ^{7}Li does not fit with the same baryon density determined from deuterium and ^{3}He abundances.

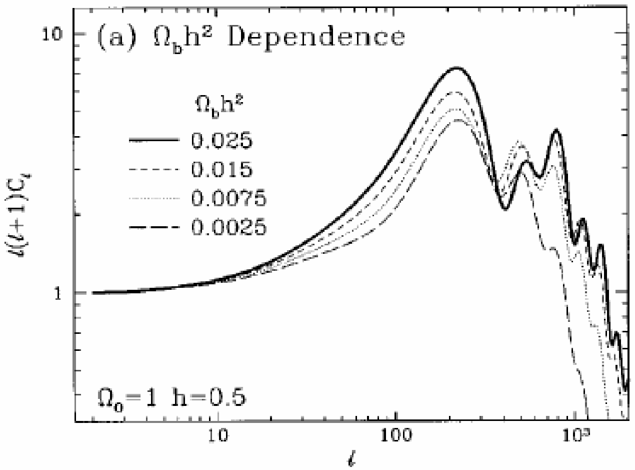


3.2 Big Bang nucleosynthesis and cosmology

Photon detectors on board of satellite missions such as COBE, WMAP and more recently Planck allow for a detailed characterization of the cosmic background radiation (CBR) in our Universe. The CBR temperature fluctuations are usually described by their multipole decomposition:

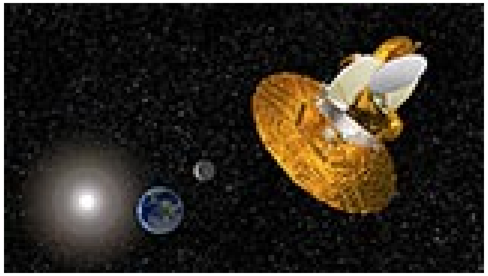
$$\frac{\delta T(\theta,\phi)}{T} = \sum_{lm} a_{lm} Y_{lm}(\theta,\phi)$$

The multipoles are Gaussian distributed with zero mean and with the rms temperature difference between directions on the sky separated with angle θ given roughly by $[l(l+1)C_l/2\pi]^{1/2}$ with $l \sim 180°/\theta$.

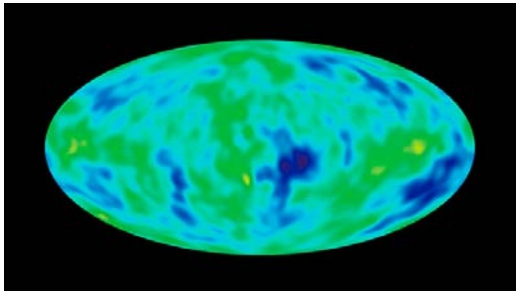


The agulat power spectrum, $C_l = \langle |a_{lm}|^2 \rangle$, depends not only on the spectrum of density perturbations, but also upon cosmological parameters, including the baryon density. According to these data the baryon density of the Universe is $\Omega_B \sim 0.0224h^2$

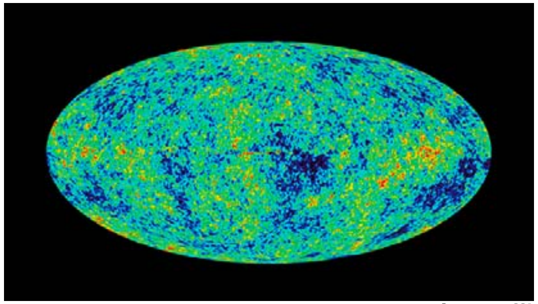
WMAP space mission



CBR Universe map from COBE



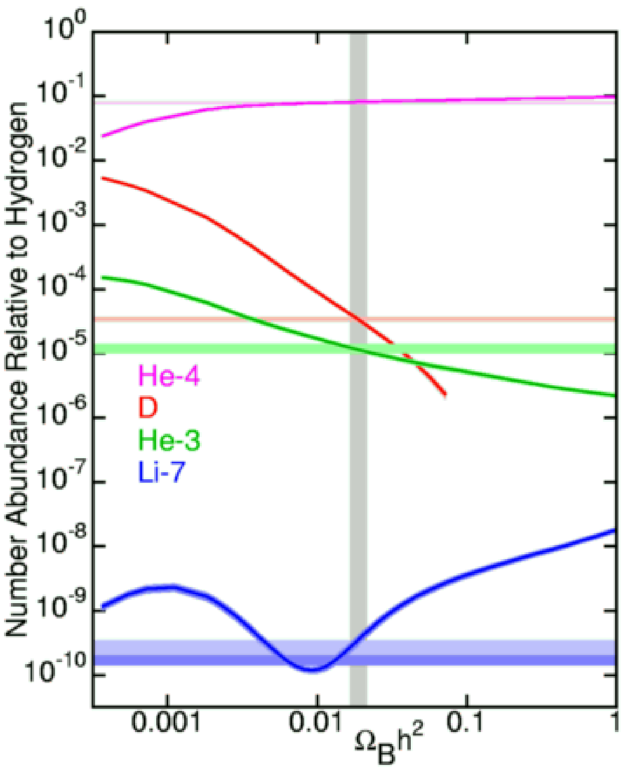
CBR Universe map from WMAP



3.2 Big Bang nucleosynthesis and cosmology

The joint interpretation of Big Bang nucleosynthesis models (BBN), astronomically determined primeral abundances of different nuclear species and the baryon density of the Universe obtained from CBR anisotropies leads to the following conclusions:

- BBN and the CBR baryon densities perfectly describe the observed abundances of deuterium and ^{3}He.
- ^{4}He concentrations are rather insensitive to BBN calculations and baryon density dependences.
- Measured primeral abundance of ^{7}Li do not agree with BBN calculations and CBR baryon density. This discrepancy could be due to the difficulties in determining ^{7}Li concentrations in stellar halos or inter-stellar gas.



Primordial nucleosynthesis

Exercise 1.
Determine at which moment the ratio between protons and neutrons was frozen in the early Universe and the ratio between protons and neutrons at that moment.

Exercise 2.
Calculate the time at which the production of deuterium started to be effective in the early Universe. Remember that this process will depend on the temperature, the photon to baryon density, the deuterium binding energy and the half life of the neutron.