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Introduction

"I get wisdom day and night, turning darkness into light."
St. Paul Irish Codex

The cosmological standard model

The current knowledge in Physics allow us to look backwards in the history of the Universe right until the Planck time (when the Universe is 10^{-44} s old). However, without a complete theory of Quantum Gravity, any event before that time is beyond our reach. Yet, the astounding observations made in the 20$^{\text{th}}$ century along with the General Relativity theory have led us to a model that describes well the Universe and its evolution, the ΛCDM **Cosmological Standard model**.

The discovery by Edwin Hubble in 1929 that distant galaxies are receding from us with a velocity that increases with distance is the first empirical evidence that the Universe is expanding and the matter in the Universe is diluting with time. Hubble proposed an empirical law to describe his observations with the linear relation $v = HD$, where v is the recessional speed, H the Hubble parameter (that depends on time) and D the proper distance (that changes with time) from the galaxy to the observer. In this order of ideas, it is natural to ask about the evolution of galaxies in the past, and how everything was formed in the beginning. By reversing Hubble's main conclusion, it is possible to infer that the Universe was hotter and denser at early times.

The best way to describe an expanding Universe is through a comoving system of coordinates. The expansion is introduced with a scale factor $a(t)$, that increases uniformly with time (normalized to $a_0 \equiv 1$, today)[1]. Thus, the proper (physical) coordinate $r(t)$ of an

[1]By convention, in Cosmology the sub index 0 is used to describe observables today.

object in the Hubble flow is defined in terms of the scale factor $a(t)$ and the comoving coordinate x:

$$r(t) \equiv a(t)x, \tag{1.1}$$

where the comoving distance is invariant in time in the reference system that represents the expanding Universe. The evolution of the scale factor in time can be quantified by the Hubble rate (or Hubble parameter mentioned above):

$$H(t) \equiv \frac{da/dt}{a}, \tag{1.2}$$

The Einstein equations describe the interaction of gravity and matter–energy through geometry. Their solution for an expanding Universe takes into account the **Cosmological principle**, the assumption that the Universe is homogeneous and isotropic on large scales (up to $\sim$ 500 Mpc). As a consequence, the spatial components should evolve with the scale factor $a(t)$ to describe the expansion given in eq. (1.1). The formal solution is known as the Friendmann-Lemaitre-Robertson-Walker metric:

$$ds^2 = c^2dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + sin^2\theta d\phi^2)\right], \tag{1.3}$$

being c the speed of light, k the spatial curvature (-1,0,1) for a hyperbolic, flat or spherical Universe, respectively. Introducing the elements of the metric (1.3) in the Einstein equations for a perfect fluid (with density ρ and pressure p), the evolution of the Hubble rate is given by:

$$H^2(t) = \frac{8\pi G}{3}\rho(t) - \frac{kc^2}{a^2(t)}, \tag{1.4}$$

where $\rho(t)$ is the mass density of all the matter–energy components in the Universe as a function of time. The critical mass density $\rho_{\rm cr}$ is the density today for which the spatial geometry of the Universe is flat ($k = 0$),

$$\rho_{\rm cr} \equiv \frac{3H_0^2}{8\pi G}, \tag{1.5}$$

here, H_0 is the current value of the Hubble parameter. Measures of the present Hubble rate value are usually parametrized in terms of h, such that:

$$H_0 = 100h \text{ km / s / Mpc}, \tag{1.6}$$

and $h = 0.6674$ (Planck Collaboration et al., 2015)

The solutions of the Einstein equations describe non-interacting perfect fluids[2]. In the equation (1.4) ρ includes any component of matter–energy in the Universe and each component can be studied as a perfect fluid with an equation of state:

$$p = w\rho c^2, \tag{1.7}$$

where w is the parameter from the state equation, while p and ρ are the pressure and density of the fluid involved, respectively. The evolution of the density of the fluid is given by (eq. 1.1.34 from Weinberg, 2008):

$$\rho \propto a^{-3-3w}. \tag{1.8}$$

However, it is more convenient to define a quantity to weight the density ρ in eq. (1.8) with respect to the critical density today, as $\Omega = \frac{\rho}{\rho_{\rm cr}}$, the density parameter.

The main components in the Universe that contribute to the total density in equation (1.4) are:

- Radiation ($w = \frac{1}{3}$): massless particles with positive pressure and density $\rho \propto a^{-4}$, as photons and massless neutrinos. The density associated with the radiation is expressed in terms of the density parameter Ω_r (the sub index r stands for radiation), the critical density of the Universe and the dependency with a determined by (1.8):

$$\rho_r = \Omega_r \rho_{\rm cr} a^{-4} \tag{1.9}$$

- Matter: particles with mass $m > 0$. Hence, the fluid has a positive density ($\rho \propto a^{-3}$) and null-pressure ($w = 0$). The matter density in this case is given by:

$$\rho_m = \Omega_m \rho_{\rm cr} a^{-3} \tag{1.10}$$

  - Baryonic (ordinary) matter: everything in the visible Universe is made by atoms and responds to the electromagnetic interaction. The radiation–matter interaction allows us to collect photons emitted by distant objects with our telescopes.
  - Dark matter (DM): There is another form of matter, not detected yet, but modelled with very massive particles. The distinctive characteristic of this

[2] If the fluids interchange energy, an additional term should be included in the Einstein equation to account for such energy exchange.

type of matter is that it is completely transparent to light, and indeed any electromagnetic radiation.
Its existence was proposed to solve a problem of the seventies: the rotation curve of disks galaxies. If a galaxy is formed only by baryonic mass, it is expected that the circular velocity of the stars in the disk plane decreases rapidly while moving towards the outskirts of the galaxy. That was not what was observed. Instead, the velocity plateaus at a given radius from the centre of the galaxy. This result indicates that there is an excess of mass in the galaxy, hidden from our instruments. There are now several other indications about the existence of DM. This type of matter can be traced through indirect methods (like gravitational lensing or experiments of dark matter annihilation with gamma-rays production).
The most favoured candidates for dark matter are: sterile neutrinos, axions, supersymmetric particles or WIMPs (weak interacting massive particles), but all of them require energies of the order of GeV − TeV mass to be detected in the large accelerators (not achieved yet).

These matter components satisfy the constraint $\Omega_m = \Omega_b + \Omega_{\mathrm{DM}}$.

- Dark energy: In 1999, different groups found independently an unexpected result. Using distant type Ia supernovae, they discovered that the Universe is speeding up its expansion in the late times. However, any kind of matter has an attractive gravitational charge, therefore an accelerated expansion has to be caused by a completely different component with negative pressure, such that $p = -\rho$.
Although astronomers know the effect of this fluid, there is not a clear idea of how to detect it, mainly because it is a smooth component, dilute throughout all the Universe and the parameter of the equation of state today is most likely $w_0 = -1$, even if $w = w(t)$ in the past. Different models have been proposed in the past 15 years to explain the nature of this component: the cosmological constant Λ that accounts for the quantum vacuum energy, scalar fields with different $w(t)$ or instead, modified gravity models that effectively impose the accelerated expansion through a geometrical contribution, rather than an energy density.
In the context of the standard model, the cosmological constant Λ is assumed to be responsible for the accelerated expansion, with an associated density parameter $\Omega_\Lambda = -\frac{\Lambda c^2}{3H_0^2}$.

Moreover, if the spatial curvature satisfies $k \neq 0$, a density parameter can be associated

with the curvature term $\Omega_k = \frac{3H_0^2}{8\pi G}kc^2$.
The Hubble parameter as a function of the scale factor $a(t)$ and the different components discussed above is given by:

$$H^2 = H_0^2 \left(\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_K a^{-2} + \Omega_\Lambda\right). \tag{1.11}$$

In the context of the Concordance model, $\Omega_{r,0} + \Omega_{m,0} + \Omega_{K,0} + \Omega_{\Lambda,0} = 1$ today. However, the contribution from the radiation at this time is completely negligible, since $\frac{\Omega_{r,0}}{\Omega_{m,0}} \sim 10^{-5}$. On the other hand, the spatial curvature of the Universe does not play a role as a source of matter–energy from the Einstein equations. The density parameter from the curvature $\Omega_k \approx 0$ ($0.0008^{+0.0040}_{-0.0039}$ from the inferred parameters of Planck Collaboration et al. 2015), therefore the spatial curvature of the Universe can be considered flat.

Furthermore, there is great confidence in the measurements of the temperature of the cosmic microwave background (CMB) and its anisotropies with three different missions: COBE (Cosmic Background Explorer), WMAP (Wilkinson Microwave Anisotropy Probe) and PLANCK. The temperature (today) of the CMB photons is $T_0 = 2.728 \pm 0.004$ K (Fixsen et al., 1996; Noterdaeme et al., 2011).
A photon with energy E has a corresponding wavelength λ. In the past, as the scale factor was shorter, so was the wavelength of the signal. The energy of the photon evolves as $E \propto T$, but also $E \propto \lambda^{-1} \propto a^{-1}$, therefore $T \propto a^{-1}$ (*i.e.* as the Universe expands, the temperature of the plasma where the photons are embedded decreases). This can be expressed as:

$$T(t) = \frac{T_0}{a(t)}. \tag{1.12}$$

In addition, the expansion of the Universe has an impact on light signals sent from receding galaxies. A wave emitted at a certain distance will be stretched out and its measured wavelength will be larger $\lambda_{\rm obs} > \lambda_{\rm emi}$. Consequently, the farther away the signal is emitted, the lower its detected frequency (or the longer its wavelength). It is a convention to define the stretching factor as z, the redshift:

$$1 + z = \frac{\lambda_{\rm obs}}{\lambda_{\rm emi}} = \frac{1}{a}. \tag{1.13}$$

For $z << 1$, the classical Doppler effect applies and $z \sim \frac{v}{c}$, being v the velocity of the source and c the speed of light.
Since the first measurement of the redshift of spiral nebulae in 1910, this quantity has been

extensively used in Astronomy to quantify distances, but also, as an indirect indicator of time. The refinement of telescopes in the past century allows us to measure with high precision the wavelength of signals emitted from very far distances.

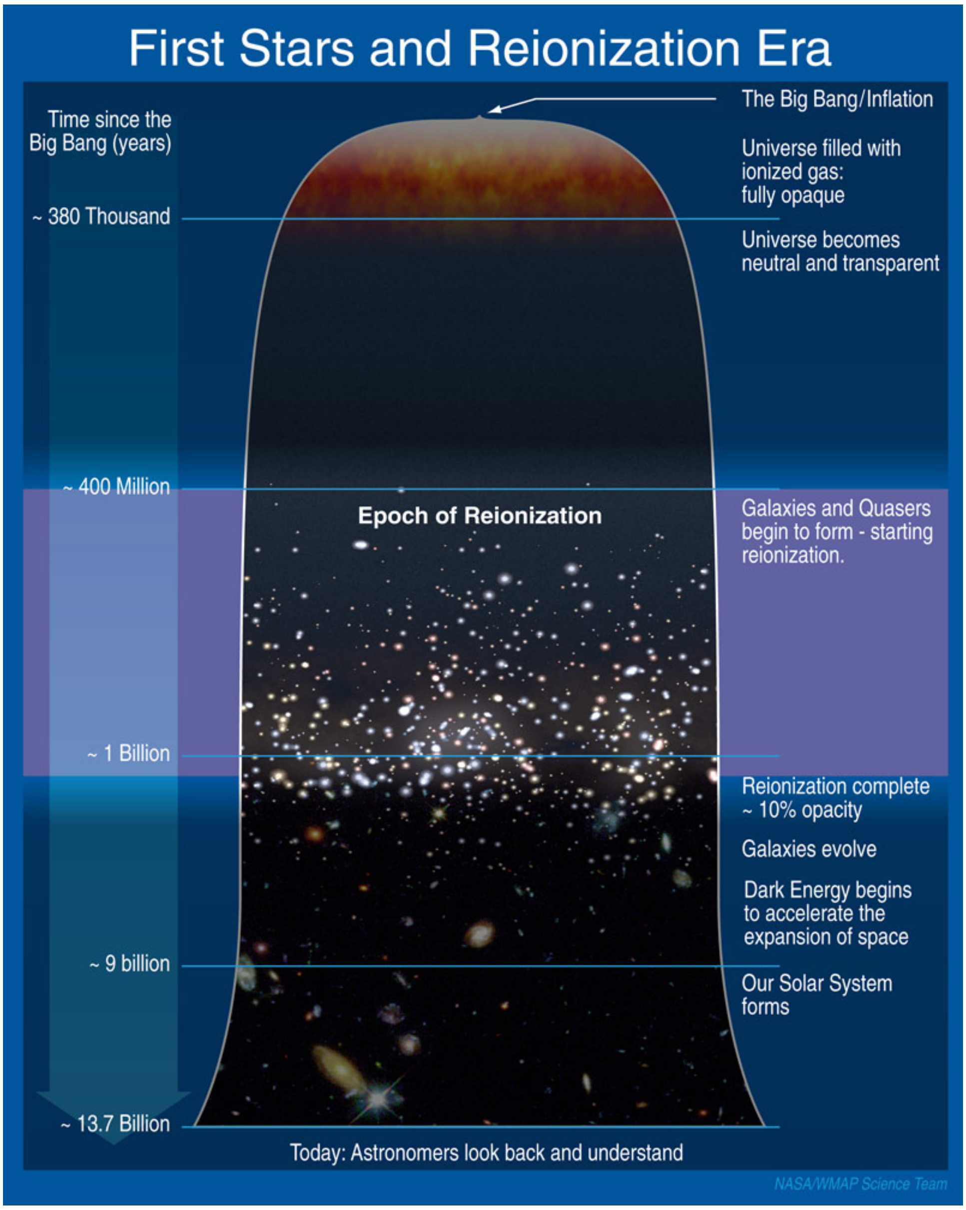

Figure 1.1 Thermal history of the Universe.

1.1 The Early Universe

The first minutes of the Universe were very turbulent. At a short 10^{-35} s, the Universe went through an inflationary period and expanded more than e^{60} times in size. This model, called *Inflation*, was formulated by Andrei Linde (Linde, 1980a,b,c,d) to solve three fundamental issues in the cosmological standard model in the eighties: the horizon, flatness and magnetic–monopole problems. Inflation also explains how the initial conditions of the matter–energy were set up, placing the seeds for the density anisotropies that would lead to the structure formation later on. Once Inflation concluded, the kinetic energy is transferred to the hot plasma. The matter–antimatter asymmetry left enough matter to allow baryogenesis and leptogenesis processes to form the fundamental particles in nature: nucleons, and, electrons and neutrinos, respectively. With these bricks of matter in the hot plasma, Big Bang Nucleosynthesis started: the nuclei of the light elements (Hydrogen, Deuterium, Helium and some traces of the nuclei of Be, Li, C, O, N, etc.) were formed from the free nucleons. Simultaneously, high energy photons (whose wavelength stretches with the expansion of the Universe) interacted via Compton scattering with free electrons. As the Universe expanded, it cooled, then the thermal equilibrium between the matter and radiation (photons and neutrinos) fell out and the Compton interaction among them was less frequent due to the decreasing energy of the radiation. The decoupling between them occurred and left its imprint in the cosmic microwave background. At this time, the mean free path of the photons was close to the horizon size of the Universe.

At $z = 1100$ (the Universe is 380000 years old), the electromagnetic interaction between free electrons and protons was favoured and they were tightly coupled via Coulomb scattering. Photons were not energetic enough to photo-dissociate the Hydrogen atoms. This process is known as Recombination and led to the formation of neutral Hydrogen atoms from the bonding of electrons and protons in thermal equilibrium (Dodelson, 2003).

Overdensities in dark and baryonic matter grew from the primordial density fluctuations set down during Inflation. The dark matter began to collapse into halos, followed by gas, which cooled and set up the temperature and pressure to form the first stars by accretion and subsequently galaxies. This period of the Universe is known as the Dark Ages and there is no observational evidence of the process, but recent detections of early galaxies at redshifts $z \sim$ 9-11 show that galaxies exist at this time and we expect to detect more with future telescopes, such as JWST.

The Epoch of Reionization of Hydrogen (referred to “Reionization” here in), as main era of investigation of this thesis, took place from redshift 15 to 6 and left an imprint in the diffuse gas in between galaxies (the intergalactic medium or IGM). The neutral Hydrogen (HI) formed in the Recombination epoch was turned into its ionized state (HII) due to the energetic UV ionizing fronts produced by the first stars, galaxies, quasars and active galactic nuclei (AGNs).

Once the fraction of HI reached one part in ten thousand with respect to the amount of total Hydrogen ($\frac{n_{\rm HI}}{n_{\rm H}} = 10^{-4}$), the Epoch of Reionization (EoR) has concluded and the only pockets of neutral Hydrogen in the Universe are found in high density regions, where H is self–shielded. These regions are identified as damped Lyman-α systems (DLAs) and they have been observed up to $z \leqslant 5$. Although the ionization state and density of the HI gas may be the same, the physical similarities of the objects associated with $z > 5$ and $z \leq 5$ DLAs are not clear.

1.2 The Dark Ages

The stage of the Universe in between the moment when the CMB was released and the first stars formed is known as the Dark Ages (Loeb, 2006, 2010).

The decoupling of the photons from the plasma at $z = 1100$ leads to a transparent Universe for photons with $E < 13.6$ eV (below the binding energy of the H atom). Dissociations were less and less frequent due to the loss of energy of the photons, favouring the electromagnetic interaction among electrons and protons and, as a consequence, the formation of the Hydrogen atoms. As the CMB photons are decoupled from the matter, they no longer (directly) trace the distribution of baryons, but they still follow the oscillations of the ordinary matter falling into the dark matter potential wells, as perturbations in the speed of sound in the gas. These baryonic oscillations are imprinted in the CMB map.

The only detectable signature of The Dark Ages is the radiation that was emitted by the 21 cm spin-flip line transition by neutral Hydrogen. The occasional collisions of photons with H atoms cause an alignment of the spin of proton and electron in the atom. When the electron flips back the orientation of the spin, it returns to the configuration of minimal energy and the system releases a photon with 21 cm wavelength.
The intensity of the 21 cm photons depends on the spin temperature, $T_{\rm spin}$[3] as:

$$\frac{n_1}{n_0} = 3e^{\left(-\frac{T_*}{T_{\rm spin}}\right)}, \tag{1.14}$$

where n_1 and n_0 are the number densities of electrons in the triplet and singlet states

[3]The temperature/energy gap between the upper 1 (spins aligned) and lower 0 (opposite spins) configurations in the Hydrogen atom. Although there is not an actual definition for the spin temperature, it measures the ratio of level populations 1/0.