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Chapter 1

Standard Model of Cosmology

Contents

Introduction

Cosmology is the study of the Universe, aiming to understand its origin and evolution. Within the broader landscape of science and physics, it occupies a unique position: it is one of the few fields where phenomena cannot be reproduced to directly test theoretical predictions. We have access to a single realization of the Universe, cannot replicate its underlying mechanisms, and can only observe a limited portion of its information.

This thesis aims to contribute to our understanding of the earliest moments of the Universe. This first chapter provides a structured overview of the standard cosmological model, known as ΛCDM, guiding the reader from its fundamental principles to its current limitations. The chapter is organized into five sections. The first introduces the key components of the model, including its foundations, assumptions, and limitations, while the second presents a qualitative overview of the thermal history of the Universe. The third focuses on the Cosmic Microwave Background (CMB), one of the most powerful probes of the early Universe. The fourth section presents the main sources of contamination affecting CMB observations. Finally, the fifth section reviews past CMB experiments and their major results, before discussing upcoming missions.

1.1 The Standard Model of Cosmology

Modern cosmology is built upon a set of simple but powerful principles that allow us to describe the large-scale behaviour of the Universe. Observations reveal that the Universe is expanding and appears remarkably homogeneous and isotropic on large scales. These properties provide the foundation for the standard cosmological model, known as ΛCDM.

In this section, we introduce the key elements of this framework. We begin with the observational evidence for the expansion of the Universe, then present the assumptions underlying its large-scale description. We subsequently describe the main components of the Universe, before discussing the limitations of this model and the role of inflation as a possible resolution.

1.1.1 Expanding universe

A major milestone in modern cosmology was the discovery that the Universe is expanding, independently established by Lemaître in 1927 [1] and Hubble in 1929 [2]. Their observations showed that distant galaxies recede from each other, with a velocity proportional to their distance. This relation, now known as Hubble-Lemaître law, provided the first evidence that the Universe is not static but evolving.

This expansion is described by the *scale factor* $a(t)$, which quantifies how distances between comoving points evolve with time. By convention, the scale factor is normalized to $a(t_0) = 1$ today. As the Universe expands, the scale factor increases, implying that physical distances between distant, gravitationally unbound objects grow proportionally with time, as illustrated in Figure 1.1.

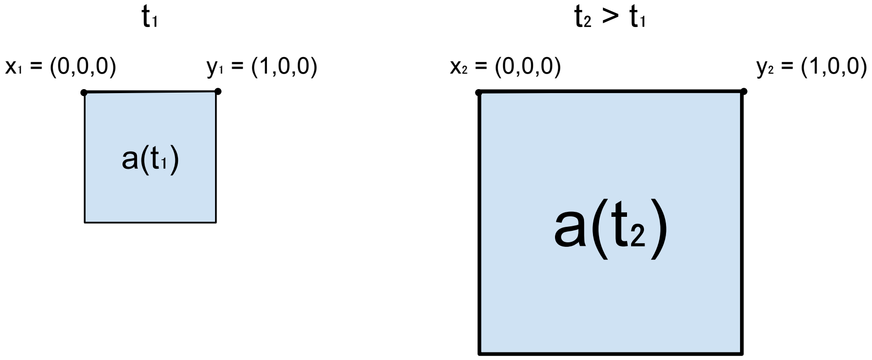

Figure 1.1: Illustration showing the difference between comoving and physical distances. At a time t_1, two points x_1 and y_1 are separated by a distance 1. After some time, at t_2, the Universe has expanded: the scale factor increased and the physical distance between x and y is larger proportionally to the scale factor. In comoving coordinates, however, the distance between x_2 and y_2 remains unchanged.

An observable consequence of this expansion is the *cosmological redshift* z. As light propagates through an expanding Universe, its wavelength is stretched along with space. This effect is not a simple Doppler redshift [3], but rather a consequence of the expansion of spacetime, hence the name of cosmological redshift, illustrated in Figure 1.2.

The redshift is defined as:

$$1 + z \equiv \frac{\lambda_{\text{obs}}}{\lambda_{\text{emit}}} \equiv \frac{a_{\text{obs}}}{a_{\text{emit}}} = \frac{1}{a_{\text{emit}}} \tag{1.1}$$

This relation allows us to infer distances and the expansion history of the Universe from observations of spectral lines. In his original work, Hubble measured the redshift of galaxies and compared it to their distances, establishing the linear relation between velocity and distance shown in Figure 1.3. This observation demonstrates that the expansion of the Universe is uni-

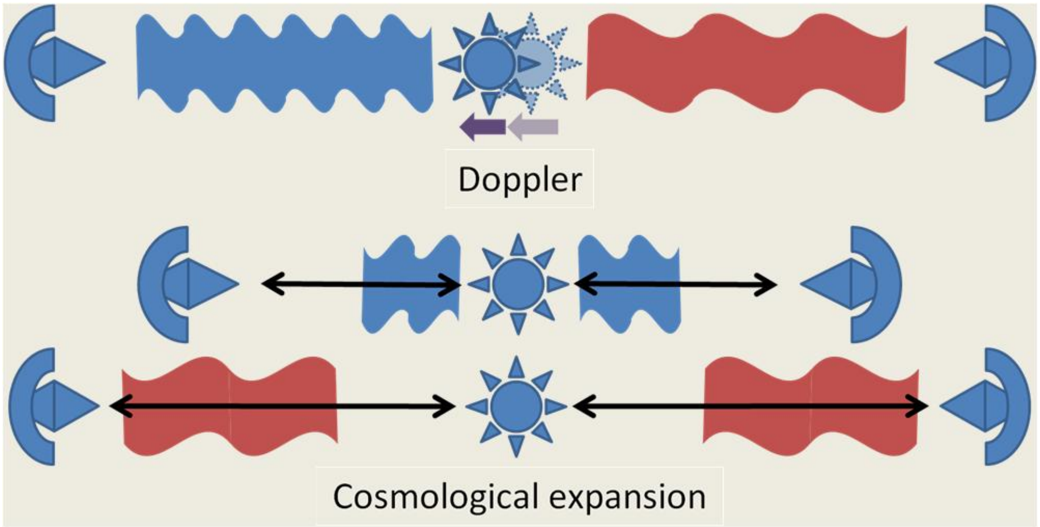

Figure 1.2: Illustration, from [4], showing the difference between Doppler redshift and cosmological redshift. Doppler's redshift [3], on top, is the decrease in wavelength of an object approaching us, and the broadening of an object moving away from us. Cosmological's redshift [2] is the broadening of the wavelength in all directions due to the expansion of the universe.

form on large scales: every observer sees distant galaxies receding, without implying a special position in space.

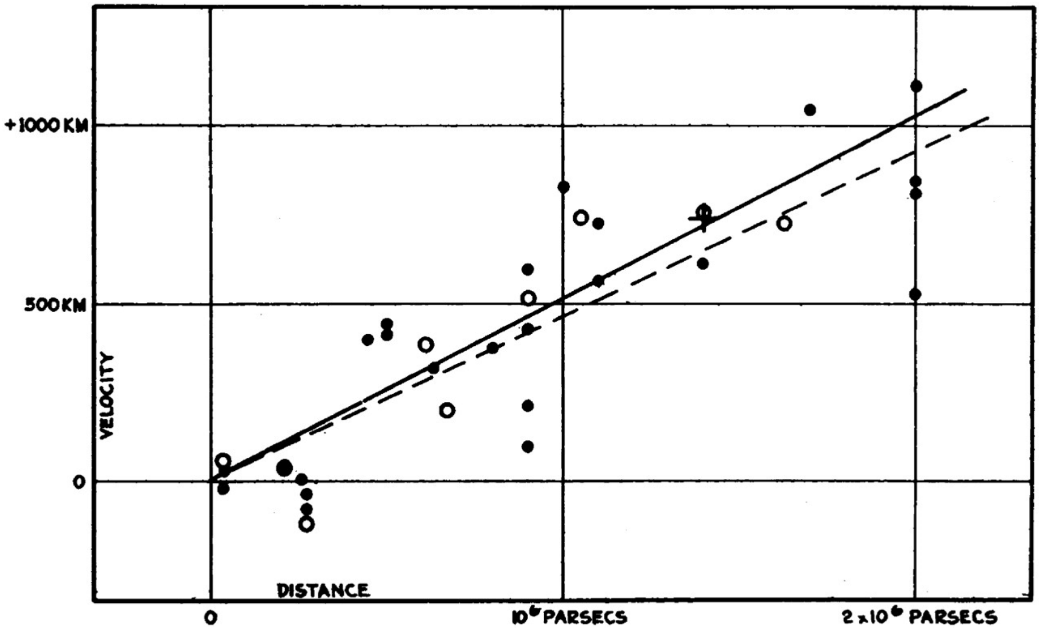

Figure 1.3: Historical velocity-distance diagram from Edwin Hubble [2]. It shows the recession velocity of galaxies as a function of their distance, illustrating the linear relation now known as Hubble's law.

1.1.2 Cosmological principle

The fundamental concept of the cosmological principle states that the universe is homogeneous and isotropic at large scales. This idea was introduced as a simplification to solve the general relativity equations [5]. It was done by Einstein in 1917 in the case of a static universe [6], but as we saw in previous subsection 1.1.1, it was not relevant any more to assume a static universe after Lemaître and Hubble's works. In 1922, Friedmann showed that a non-static solution for a homogeneous universe is possible [7], quickly followed by evidences of universe expansion in 1927 by Lemaître [1]. Building on these results, Robertson [8] and Walker [9] formulated the general relativistic metric for a homogeneous and isotropic expanding universe. This metric forms the cornerstone of the ΛCDM model. The veracity of this principle is much debated, but latest result from Planck Satellite suggest that the universe is homogeneous and isotropic at 10^{-5} (= 0.001%) at scale above 6° on the sky [10].

1.1.3 Content of the Universe

In the two previous subsections 1.1.1 and 1.1.2, we introduced the standard assumptions about the universe : it is homogeneous, isotropic and expanding. Now, we now provide a brief overview of its contents. These contents can be classified into three categories: radiation, matter, and the cosmological constant. Each of these components evolves differently with the scale factor and, consequently, with the expansion of the universe. Moreover, each component dominated the universe at different epochs in its history. The evolution of each density is shown in Figure 1.4.

At early times of the universe, the radiation was dominating. This radiation consisted of the relativistic particles : photons and neutrinos, the main contribution being the Cosmic Microwave Background (detailed in Section 1.3). The density of radiation and matter were equal at $z \approx 3408$ according to DESI [11] and $z \approx 3387$ according to Planck [12], which correspond to approximatively 80000 years after first times of the universe.

Today, radiation contributes about 0.008% of the total energy density, as inferred from Planck 2018 data [12].

As the Universe expanded, non-relativistic matter came to dominate the energy density. This matter is composed of baryonic matter and dark matter. The term "baryonic matter" is misleading, as it designates all non-relativistic particles of the Standard Model; however, its energy density is overwhelmingly dominated by protons and neutrons, hence the terminology. On the other hand, dark matter is a hypothetical form of matter, which only (or mostly) interact through gravitational force, and thus, which does not emit light. It was first suggested by comparing "seen mass" computed from galaxies light and "unseen mass" computed from galaxies velocity in the Coma Galaxies Cluster by Zwicky in 1933 [13]. The mass computed from galaxies velocity was much higher than the luminous mass, suggesting the presence of massive matter that does not emit light.

Since then, multiple independent observations have provided strong evidence for dark matter : galaxy rotation curves [14], the Bullet Cluster through gravitational lensing [15], Baryon Acoustic Oscillations pics observed in CMB [12], formation rate of Large Scale Structures [16], and many oth-

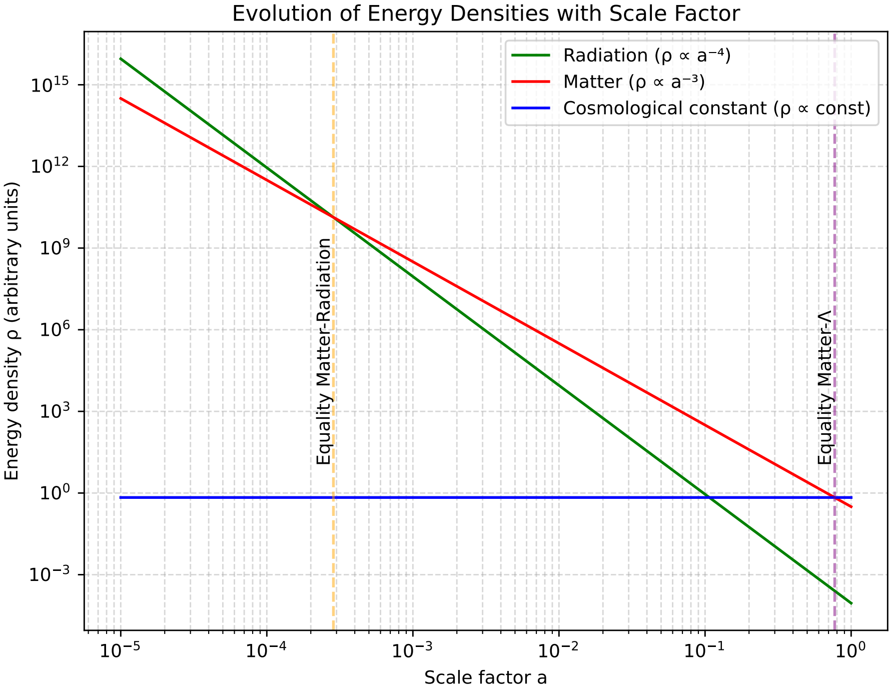

Figure 1.4: Energy density of the Universe's components as a function of the scale factor, highlighting the epochs when matter equals radiation and when matter equals the cosmological constant.

ers. While we still don't know its nature from the particle point of view, its cosmological properties are well constrained. It is commonly divided into three categories : cold, warm and hot dark matters, which refer to their velocity(or equivalently, whether it was relativistic in the early Universe). This classification determines how far dark matter can propagate (free-stream) and thus influences the formation of structures at different scales. Observations strongly favor the Cold Dark Matter (CDM) scenario [17], in which dark matter is non-relativistic.

Today, Cold Dark Matter (CDM) represents about 26.5% [12] of total energy density, and plays a central role in Standard Model of Cosmology, ΛCDM. The ordinary matter is responsible for 4.5% [12] of the energy density budget, meaning that the energy density of matter occupies 31% of the energy density of the universe, and that 85% of matter in the universe is composes of dark matter.

At $z \approx 0.3$, corresponding to an age of about 10 Gyr, the Universe transitions from matter domination to dark energy domination, as the cosmological constant becomes the dominant component. The concept of dark energy was first introduced to explain the acceleration of the expansion in the late universe from distant Type Ia supernovae in 1999 [18]. To account for this acceleration, the introduction of a cosmological constant Λ, corresponding to an energy density which does not depend on the scale factor, was needed. Today, dark energy remains one of the greatest unkown in cosmology and in fundamental physics in general.

Dark energy is responsible for 69% of the total energy dansity today, and is by far the main constituent of our universe.

1.1.4 Problems of the Standard Model

From the previous subsection, the Standard Model of cosmology describes the universe as homogeneous, isotropic, expanding, and composed of radiation, matter and dark energy. It is enough to describe the evolution of the universe, and match remarkably well with observations. However, fundamental questions remain unanswered, and in particular three issues cannot be explained within this framework: the horizon problem, the flatness problem, and the monopole problem.

Horizon problem : Why is the CMB temperature so uniform ? As discussed previously, at the time of recombination the Universe was extremely homogeneous, with density fluctuations of order 10^{-5}, and consequently the cosmic microwave background (CMB) exhibits an almost perfectly uniform temperature. This uniformity is naturally explained if the early Universe was in thermal equilibrium, consistent with the fact that the CMB spectrum is an almost perfect blackbody [19]. However, within the standard cosmological model, regions of the CMB that are widely separated on the sky were never in causal contact: light signals would not have had enough time to travel between them since the beginning of the expansion. These regions therefore lie outside each other's particle horizon and cannot have exchanged information or thermalised. This raises a fundamental question: why do causally disconnected regions have the same temperature?

Flatness problem : Why is the universe flat ? In general relativity [5], the geometry of spacetime is determined by its energy content. In a homogeneous and isotropic Universe, this relation is encoded in the Friedmann equations [7], which relate the expansion rate to the total energy density and spatial curvature. From these equations, one defines the critical density, ρ_c, which corresponds to a spatially flat Universe. Depending on the ratio $\Omega = \rho/\rho_c$, the Universe can be:

$$\begin{aligned} \Omega &= 1 \quad \text{flat (Euclidean geometry)}, \\ \Omega &> 1 \quad \text{closed (positive curvature)}, \\ \Omega &< 1 \quad \text{open (negative curvature)}. \end{aligned}$$

Current measurements, notably from the Planck mission [12], indicate that Ω differs from unity by less than about one percent, implying that the Universe is extremely close to spatial flatness. However, within the standard Friedmann evolution, flatness is not a stable state: any small deviation from $\Omega = 1$ grows with time. Consequently, evolving backward in time implies an extreme fine-tuning of the initial condition. For example, a deviation of order $|\Omega_0 - 1| \sim 10^{-3}$ today corresponds to an initial deviation of order 10^{-60} near the Planck epoch. This extraordinary sensitivity suggests an apparent fine-tuning problem: why was the early Universe so precisely close to flatness?

Monopole problem : Why are magnetic monopoles not observed ? Grand unified theories (GUTs), which attempt to unify the electromagnetic, weak, and strong interactions at high energy scales, generically predict the existence of topological defects formed during phase transitions in the early Universe. Among these relics are magnetic monopoles, hypothetical particles carrying an isolated magnetic charge, whose existence was first proposed by Dirac in 1931 [20]. In standard cosmology, such monopoles should be efficiently produced during the spontaneous symmetry breaking associated with the GUT phase transition. Causally disconnected regions of space choose different vacuum states, leading to the formation of stable topological defects. As a consequence, one expects a large relic abundance of monopoles. However, monopoles are not observed in the present Universe, despite extensive experimental searches. This discrepancy constitutes the monopole problem: standard cosmology predicts a relic density of monopoles that is many orders of magnitude larger than observational bounds. should I talk about higher order topological defects ? Like cosmic cords, walls, ...

Finally, an additional issue remains throughout the Standard Model of Cosmology's equations. As with any set of equations describing the evolution of a physical system, the dynamics are only fully specified once appropriate initial conditions are given. This naturally raises the question: how can the initial conditions of our Universe be determined or constrained observationally? An answer to the three problems and to this issue was proposed by Alan Guth in 1981, through the idea of an exponential expansion phase at the very beginning of the Universe [21]. The model was then developed by Andrei Linde in 1983 [22], and has since given rise to a wide variety of models. We will explain in the following subsection the idea behind this theory and how it can solve the issues discussed previously.

1.1.5 Inflation theory

I have the feeling that I should talk about the Inflation scale ($\exp -N$, with $N \sim 60$), to make more understandable that it solves all the problems

The theory of Inflation postulates that in the very early universe, all regions were causally connected. These regions were then disconnected due to an exponentially expanded phase. This theory was developed to solve the various problems presented previously 1.1.4. **Horizon Problem.** Indeed, if all regions were connected in the very early universe, they could have thermalised, explaining why the CMB temperature is uniform at a very large scale. **Flatness Problem.** As we said, a nearly flat universe is an unstable solution, meaning that it is very unlikely to happen. But, Inflation suggests that they do not care about the curvature before it occurs, as an exponential expansion will make all local curvatures negligible. We can understand this argument with the analogy of a sphere: if we zoom enough on a sphere, its surface will be flat. This mechanism explains why the universe is flat today, independently of its initial conditions. **Monopole Problem.** The GUT theories predict the formation of monopoles, but the exponential expansion dilutes their density to the point where they become unobservable today.

Additionally, we talked about all the properties of the universe for the Λ-CDM model: homogeneity, isotropy, and flat geometry. These initial conditions seem too "fine-tuned." Inflation also solves this issue by making any specific initial condition negligible due to the exponential expansion. To go even further, Inflation would have expanded quantum fluctuations to a macroscopic scale, responsible for the inhomogeneity of density observed in the temperature fluctuations in the CMB, which led to the large-scale structures under gravitational effects today.

1.2 Thermal history of the universe

1.3 Cosmic Microwave Background

1.4 CMB contaminations

1.5 Past & Future Experiment

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