ISSN: 2834-359X

Research Article

Journal of Plasma Chemistry and Plasma Processing Research

Large-Scale Cosmic Structures and Plasmas: Insights from Dark Matter, Dark Energy, and Field Theory

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Submitted: 2025, July 21; **Accepted:** 2025, Aug 04; **Published:** 2025, Sep 11

Citation: Kardani, S., Pour , M , P., Maleki, M. (2025). Large-Scale Cosmic Structures and Plasmas: Insights from Dark Matter, Dark Energy, and Field Theory. *J Pla Che Pla Pro Res, 6*(1), 01-21.

Abstract
This review paper investigates cosmic plasmas as fundamental constituents of the early universe, highlighting their pivotal role in the formation and evolution of large-scale cosmic structures. The study delves into the intricate interplay between cosmic plasmas, dark matter, dark energy, and field theories, offering a comprehensive review of how these factors contribute to shaping the universe's macroscopic architecture. We examine the early universe and its underlying physical processes, with particular emphasis on nuclear fusion and the theory of cosmological perturbations. By integrating diverse theoretical perspectives, this article aims to present a cohesive understanding of the dynamic mechanisms at work in the early cosmos.

The first section addresses dark energy, focusing on observational evidence from supernovae and a range of theoretical models, including X-matter, Chaplin gas, holographic dark energy, and others. The second section discusses dark matter, elaborating on its various forms and phenomenological implications. The following part explores the significance of cosmic plasmas in cosmological modeling, covering topics such as quark-gluon plasmas and dusty plasmas. Additionally, field theory is reviewed, with attention given to its core equations and cosmological applications. The third section is devoted to the early universe, detailing the formation of the first stars and the evolution of density perturbations into large-scale structures. We further analyze the contribution of primordial black holes to early perturbations, the role of dark matter in structure formation, and discuss key frameworks including weak gravitational lensing, the Fuku Gita model, and the Press–Schechter formalism.

Keywords: Dark Matter, Dark Energy, Cosmic Plasmas, Early Universe, Large-Scale Cosmic Structures, Nuclear Fusion, Effective Field Theory

1. Introduction
The early universe presents a landscape rich with enigmas and profound physical challenges that continue to captivate the scientific community. Through the investigation of dark energy, dark matter, and large-scale cosmic structures, researchers aim to unravel the fundamental mechanisms underlying the universe's origin and evolution. A central aspect of these inquiries is the pivotal role played by cosmic plasmas, which are integral to numerous astrophysical phenomena—including nuclear fusion, the primary mechanism for the synthesis of heavy elements within stars. In recent decades, the advancement of effective field theory and cosmic perturbation theory has provided a robust theoretical framework for probing these complex processes with greater precision. These theoretical tools not only deepen our understanding of the universe's intricate dynamics but also offer predictive insights into phenomena that were once beyond the reach of empirical inquiry. This study focuses on the influence of cosmic plasmas on the formation of large-scale structures, aiming to enhance our comprehension of the early universe's formative stages and its subsequent evolution.

1.1 Part One
1.1.1 Dark Energy
In 1998, results based on observations of Type Ia supernovae (SNe), independently published by two separate groups, dramatically altered our understanding of the current state of the universe. In brief, the Hubble-Sandage diagram, which plots the observed luminosity of these objects as a function of redshift (the increase in wavelength of light due to the recession of light from an object, caused by the Doppler effect), led to an unexpected and striking conclusion. The expansion of the universe is accelerating, not decelerating, as we had believed for several decades. Implicitly, these observations of Type Ia supernovae suggest that the dominant energy density in the universe is repulsive and manifests as a dark energy component.

An unknown form of energy with negative pressure [in addition to ordinary dark matter] that likely originates from the early universe [1]. Observations of SN Ia are one of the key pieces of evidence for cosmic acceleration. When a white dwarf reaches a mass of 4.1 times the mass of the sun (M), gravity overcomes the Fermi pressure and the star explodes. Since SN Ia are produced through this process, we assume that SN Ia always have the same luminosity and can be used as a standard candle. By measuring the apparent magnitude, we can estimate the luminosity distance. A supernova is as bright as an entire galaxy, making the study of SN Ia a powerful and direct method for investigating distant cosmology [2]. However, since the first detections, some scientists have doubted that distant supernovae may appear fainter due to the absorption of light by cosmic dust. Therefore, we have concluded that this faintness is not due to absorption by dust, but rather a result of real cosmic acceleration. Not only SN Ia, but also CMB observations strongly indicate the existence of dark energy. The CMB is an image of the universe when the cosmic structure was still undeveloped and has temperature fluctuations that are influenced by dark energy. This image shows us the history of the universe from the era of photon decoupling to the present [2].

1.1.2 Type Ia Supernovae (SN Ia)

Type Ia Supernovae (SN Ia) observations are one of the key pieces of evidence for cosmic acceleration. When a white dwarf reaches 1.4 times the mass of the Sun (M), gravitational forces exceed the electron degeneracy pressure, causing the star to explode. Since SN Ia originate from this same process, we assume that they always have the same intrinsic luminosity, making them a standard candle. By measuring their apparent magnitude, we can estimate the luminosity distance. A supernova is as bright as an entire galaxy, making SN Ia a highly powerful and direct method for studying the distant universe [2]. However, since the first detections were made, some scientists have questioned whether distant supernovae might appear dimmer due to light absorption by cosmic dust.

We have thus concluded that this dimming is not due to dust absorption but rather the result of true cosmic acceleration. In addition to SN Ia, observations of the Cosmic Microwave Background (CMB) strongly indicate the existence of dark energy. The CMB provides a snapshot of the universe when cosmic structures had not yet formed and shows temperature fluctuations influenced by dark energy. This image offers a history of the universe from the era of photon decoupling to the present day [2]. The angular power spectrum of fluctuations in the Cosmic Microwave Background (CMB) favors the Cold Dark Matter (CDM) model, which predicts a total density parameter of Ω_T=1, a value originally predicted by inflation theory. The density parameter associated with cold dark matter, $\Omega_m \approx 0.3$, a value independently required by the power spectrum of large-scale structure (LSS) and X-ray data from galaxy clusters.

The difference, $\Omega_{DE} = \Omega_T - \Omega_m \approx 0.7$, represents the density parameter of the dark energy component. This model has been further confirmed with greater precision by the Wilkinson Microwave Anisotropy Probe (WMAP), and all these elements collectively support what is commonly referred to as the standard model of cosmological concordance [1]. The existence of an additional component filling the universe has also been indirectly suggested by independent studies based on residual radiation fluctuations of K3. Although dark energy has transformed the traditional view of the universe, the lack of natural guidance from particle physics regarding its nature has sparked intense debates and numerous theoretical speculations. Specifically, a cosmological constant (Λ) is the oldest and by far the simplest model from a mathematical perspective, but it is not the only possible option [1]. The Λ term was originally introduced by Einstein in 1917 to achieve a static model of the universe. This dark component, when spatially uniform and independent over time, can be classically interpreted as a simple perfect relativistic fluid, obeying the equation of state ($\rho_v = -\rho_v$). In the framework of quantum field theory, the existence of Λ is related to the zero-point energy of all particles and fields filling the universe, manifesting in various quantum phenomena such as the Lamb shift and the Casimir effect.

However, a fundamental issue with this theoretical model, commonly referred to as the cosmological constant problem, exists. The current cosmological upper bound on ($\Lambda / 8\pi G \sim 10^{-47}\ GeV^4$) differs by over 100 orders of magnitude from natural theoretical expectations ($\sim 10^{71}\ GeV^4$). Since a key requirement for an accelerating universe is the presence of a dominant component with negative pressure, there are models that address this condition, though they are by no means complete, and other models have been occasionally explored [1]. If "Dark Energy" were uniformly distributed across the universe, it is clear that it could not have any measurable impact on the dynamics of the universe. Consequently, "Dark Energy" must be localized in specific regions where it is needed, which raises skepticism about the hypothesis and underscores the need for alternative models [3].

1.2 Proposed Models: [1]

- **Λ(*t*):** The vacuum energy density decreases over time (time-varying)
- **Scalar Field (SF)**
- **X Matter:** An additional component characterized by the equation of state ($p_x = \omega p_x$) with

$$(-1 \leq \omega < 0)$$

- **Chaplygin Gas:** Its equation of state is ($p = A/\rho^a$), where A is a positive constant and

$$(0 \leq a \leq 1).$$

Also, note that the cosmological constant-dominated model, where (ρ_v = -ρ_v), is a parametric case of X matter with (ω = -1) . Focusing on spacetime through the flat FRW line element, assuming

$$(c = 1) : ds^2 = dt^2 - R^2 (t)[dr^2 + r^2 (d\theta^2 + \sin^2 \theta d\phi^2)]$$

where (R(t)) is the scale factor. Such a background is the same spacetime favored by the cosmic concordance model, as this model is a direct consequence of the Cosmic Microwave Background (CMB) results [1].

1.3 The Term (Λ(t)) Varying with Time

Vacuum-decaying cosmologies, or (Λ(t)) models, are described as a two-phase mixture: a decaying vacuum environment $\rho_v (t) = \Lambda(t) / 8\pi G$, $p_v = -\rho_v$ along with a fluid component (decaying vacuum products) characterized by energy density (ρ) and pressure (p) [1]. The Einstein Field Equations (EFE) and the Energy Conservation Law (ECL) for (Λ(t)) models are given as follows:

$$8\pi G_\rho + \Lambda(t) = 3\frac{\dot{R}^2}{R^2} \quad , \quad 8\pi G_\rho - \Lambda(t) = -2\frac{\ddot{R}}{R}\frac{\dot{R}^2}{R^2}$$

$$\dot{\rho} + 3H(\rho + p) = -\frac{\dot{\Lambda}(t)}{8\pi G}$$

For the entropy production rate in this model, it can be rewritten as:

$$T\frac{ds}{dt} = -\frac{\dot{\Lambda} R^3}{8\pi G}$$

By showing that (Λ) must decrease over time, while energy transfers from the decaying vacuum to the material component, we highlight the difference between models with a cosmological constant and those with a decaying vacuum energy density. In the latter case, it is typically suggested that vacuum energy density is time-dependent as it interacts with other matter fields in the universe. Due to expansion, it can be assumed that the cosmological constant is decreasing towards its natural value (Λ = 0). In general, the main goal of such models is to determine how the energy that drove early inflation and currently accelerates the universe is connected to the present small value of (A) [1].

From an observational perspective, (Λ(t))CDM models have an interesting feature that can distinguish them from (Λ)CDM models. Due to the possibility of adiabatic photon production, the standard temperature-redshift relation may be slightly altered. The temperature is given by the following expression :

$$T(z) = T_0 (1 + z)^{1-\beta}$$

For a given redshift (z), the temperature of the universe is lower than in the standard photon conservation scenario [1] .

1.4 X Matter

In cosmic scenarios driven by Dark Matter X, along with Cold Dark Matter (sometimes referred to as XCDM parameterization), both fluid components are separately conserved. The equation of state for the dark energy component is given by $p_x = w(z)p_x$. Unlike models derived from scalar fields, where $w(z)$is extracted from the field description, the expression $w(z)$ for XCDM scenarios must be assumed a priori. Typically, this parameter changes with a specific power of redshift (e.g. , $w(z)= w_0 (1+z^n)$). Models with constant w are the simplest and their free parameters can be easily constrained through primary cosmic tests [1].

1.5 Chaplygin Gas

It is widely recognized that the main difference between cold dark matter (CDM) and dark energy is that the former clusters on small scales, while dark energy is a uniform component. Such characteristics appear to be directly related to the equation of state for both components. Wetterich suggested that dark matter might consist of dark matter clumps, while Kasuya demonstrated that spin-tension-type scenarios generally lead to instabilities resulting in the formation of Q-balls, which behave as pressureless matter. Padmanabhan and Choudhury explored this through a tachyonic field derived from string theory. Another interesting attempt at unification was proposed by Kamenshchik and colleagues, and later developed by Bilic and Bento. This involves a peculiar fluid known as the Chaplygin gas (Cg), whose equation of state is as follows [1].

$$pc_g = -{}^{A}/_{\rho^\alpha} \quad \alpha = 1, A = const$$

The idea of the Unified Dark Matter-Energy (UDME) scenario, derived from the equation of state of the Chaplygin gas, stems from the fact that this type of gas can naturally transition between non-relativistic matter and dark energy regimes with negative pressure. Since this approach involves only one dark component, along with photons, baryons, and neutrinos, some authors have referred to this UDME scenario as quartessence cosmology [1].

1.6 Holographic Model

The holographic model is a hypothetical attempt to apply the holographic principle to dark energy, and it is considered a promising model of dark energy. It is based on the holographic principle, which represents significant milestones in quantum gravity and reflects many of its characteristics, although no complete theory of quantum gravity has yet been proposed. The holographic principle provides a description that the volume of space can be viewed as encoded on the boundary with a lower dimension. A very simple model for dark energy could be a very small positive value attributed to the cosmological constant. Various dynamic models of dark energy have been introduced, such as quintessence, phantom, k-essence, quintom, hescence, tachyon, and ghostly condensed models. Based on the holographic principle, which is derived from string theory, a local quantum field is not allowed to have more than the permissible degrees of freedom; otherwise, the quantum field theory becomes inapplicable. Therefore, a holographic approach has been proposed as an interesting candidate for describing dark energy and revealing various features of quantum gravity. In this context, the holographic principle allows that any physical quantity within the universe can be described by another quantity on the boundary of the universe. On the other hand, black holes are thermodynamically characterized by maximum entropy; the Bekenstein entropy (SBH) is proportional to the area of a box with size (l) and is associated with its volume. Consequently, the entropy of a black hole is, for example, proportional to the area of its event horizon, which is normalized to the Planck area. Furthermore, the density of dark energy (DE) can be characterized by the reduced Planck mass (M_{pl}) and (l) [4].

$$\rho_\Lambda = c_1 M_{pl}^4 + c_2 L^{-2} M_{pl}^2 + c_3 L^{-4} + \cdots \quad , \; c_1 = c_2 = c_3 = \cdots = const$$

$$\rho_\Lambda = n L^{-2} M_{pl}^2$$

(n) is an arbitrary constant that estimates the possible uncertainties. To prevent the potential collapse of quantum field theory, an additional energy range must be considered. Based on this approach, it is conjectured that the formation of black holes limits the total energy in a box with area (A), such that it does not exceed the mass of a black hole of the same size [4].

$$L^3 \rho_\Lambda \lesssim L M_{pl}^2$$

There are two alternative options to avoid its critical consequences: First, L_Λ describes a particle's life horizon. Second, it must be ensured that the age of the universe is not younger than the age of its components (whether particles or stellar objects) [4].

$$L_{\Lambda \mathrm{H}} = a \int_0^t \frac{d\tilde{a}}{a} = \int_0^a \frac{d\tilde{a}}{H \tilde{a}^2} \quad , \qquad H = \dot{a}/a \; (Hubble\ parameter)$$

1.7 Hořava Model Gravity

A renormalizable quantum gravity model with higher derivatives and Lorentz violation without ghost issues (ghost problem meaning the presence of negative energy values or other theoretical problems) has been proposed. The dark energy based on this model (HDE) naturally explains the non-interactive nature of dark energy and, furthermore, predicts dynamic behavior of dark energy in cosmic evolution, depending on the gravitational action (HDE) that may include Lorentz-violating terms with spatial derivatives up to the sixth order for renormalization and IR Lorentz-violating terms. A peculiar feature of HDE is that a non-flat spatial universe may be "more natural" due to genuine contributions from higher spatial derivatives, since for a flat universe, the standard FLRW cosmological background is akin to that in GR.

In other words, this model can serve as a "natural laboratory" to test a non-flat universe in standard LCDM cosmology. On the other hand, with the increasing precision of cosmological data, some cosmological tensions between different datasets within the standard LCDM cosmology framework and fully resolving them is a challenging problem in current cosmology. In particular, various proposals have been made to address tensions regarding the Hubble constant (H) measured by cosmological experiments, which reveal discrepancies between CMB data and local measurements, indicating inconsistencies between the early universe and the late universe, but there is still no fundamental solution. Furthermore, when considering the possibility of a closed universe, the tensions (inconsistencies) worsen [5].

1.8 Equation of State (EOS) Model

Due to the absence of a preferred dark energy (DE) model capable of fully describing the dynamic phenomena of the universe, several attempts have been made in recent years to model them based on observations. Parameterizing the cosmological or DE parameters is one of the notable efforts. The Hubble parameter, deceleration parameter, or dark energy density can be parameterized. Parameterizing the density parameter of dark energy, for instance, using a simple power expansion where (z) is the redshift, is also a common method. Following this approach, the equation of state (Eos) of dark energy can be parameterized as $\Omega_{DE} = \sum_{i=0}^{N} A_i z^i$, which is a simple EoS parameterization that can describe the dynamic evolutionary behavior for a wide range of dark energy models.

However, this parameterization diverges at high redshifts. Furthermore, since the angular diameter distance depends on the form ($w(z)$ and the angular scale characteristics of the CMB temperature anisotropy vary with peaks, the angular diameter distance constraint to the surface of last scattering by the CMB becomes problematic. Subsequently, a stable parameterization that extends the dark energy parameterization to redshifts ($z > 1$) was proposed, and in addition, a modified model by Jassal and colleagues was suggested. This model can represent a dark energy (DE) component that has the same equation of state (Eos) value at high redshifts. Both models are limited at high redshifts ($z > 1$), but they cannot be distinguished from one another.

The parameterizations proposed in recent years are classified based on the number of parameters that provide the parameter range of the model using numerical analysis. A large number of dark energy (DE) models may exhibit similar evolutionary behaviors and consequently, similar cosmological expansion histories. Therefore, effective model discrimination is very important. Utilizing various types of data to test DE models, select good models, or compare models has become a standard approach in cosmological studies. However, when using only one type of observational data to constrain the models, a specific correlation of cosmological parameters between different models typically occurs.

To break this correlation, common constraints from multiple observational datasets are often employed. In this model, a combination of supernova data, temperature and polarization anisotropy data from the CMB, baryon acoustic oscillation (BAO) data, and observational data of the Hubble parameter ($H(z)$) is used.

For the supernova data, the constraints derived from two samples are compared: the Joint Lightcurve Analysis (JLA) and Pantheon, where the redshift range is expanded in the second sample [6]. As previously stated, various proposals have been made for dark matter, including cold dark matter (CDM), which is composed of heavy particles with a mass ($m_{CDM} \geq 100$) keV, warm dark matter (WDM), which consists of particles with a mass ($m_{WDM} \approx$ 3-30) keV, and hot dark matter (HDM), which is made up of relativistic particles. Assuming that general relativity provides an accurate description of gravity on cosmological scales, approximately 95% of the energy in the universe must be in the "Dark" form, namely in the form of dark energy and dark matter [7] . The energy density of the cosmological constant ρ_Λ can be estimated based on quantum field theory as follows:

$$\rho_\Lambda \sim \mathrm{h} M_{pl}^4 \sim 10^{72}\, Gev^4 \sim 2 \cdot 10^{110}\, erg/cm^3$$

Where $M_{pl} \sim 10^{19}$ GeV is the Planck mass and (h) is the reduced Planck constant. However, cosmological observations of the cosmological constant (such as dark energy) yield a very different result : $\rho_\Lambda^{obs} \sim 10^{-48}\, Gev^4 \sim 2 \cdot 10^{-10}\, erg/cm^3$, This discrepancy of 120 degrees between the predicted and observed energy density of the cosmological constant is referred to as the cosmological constant problem. An alternative viewpoint that is consistent with the equations of general relativity is to abandon attempts to justify the small value of the cosmological constant and consider it purely as a geometric phenomenon. However, the problem with this approach is that, in such a case, spacetime would be without source (a De Sitter universe with internal curvature).

One of the alternatives to the (ΛCDM) model, during the time when the accelerated expansion of the universe is governed by the cosmological constant (Λ), is the dynamic scalar field dark energy models (ϕCDM). In these models, dark energy is described through the equation of state (Eos) and the time-dependent equation of state($w\phi$ (t)), where (w_ϕ (t) = p_ϕ / ρ_ϕ), with (p_ϕ) being the pressure of the scalar field and (ρ_ϕ) being the energy density of the scalar field. In contrast, in the (ΛCDM) model, the state parameter of the equation is constant (w_ϕ (t) < -1) [7].

1.9 Baryon Acoustic Oscillations (BAO)

The study of baryon acoustic oscillations (BAO) is also a significant research area for dark energy. As previously mentioned, after decoupling, baryons remain at the sound horizon, while dark matter is concentrated in the centers of over-dense regions. Baryons attract matter, ultimately leading to the formation of galaxies. Therefore, we expect that a number of galaxies will be separated by the sound horizon distance. This signal is referred to as BAO. It implies that by observing large-scale structure (LSS) of galaxies, we can measure the sound horizon scales and compare them with theoretical predictions. For the analysis of the BAO signal, there is no need to distinguish the luminosity of galaxies or galaxy images.

The only requirement is to determine their three-dimensional positions. From this perspective, BAO observations are less susceptible to astronomical uncertainties compared to other methods of investigating dark energy. The Sloan Digital Sky Survey (SDSS) provides a picture of the distribution of galaxies up to ($z = 0.47$), making the search for the BAO signal feasible. To analyze this image, we utilize the two-point correlation function of galaxies, which gives the probability of finding one galaxy at a certain distance from another galaxy. In the standard cosmological scenario ΛCDM , two epochs of accelerated expansion in the universe are assumed. The first is inflation, which occurs in the very early universe, and the second is the current era dominated by the observed dark energy.

Inflation is a theory of exponential spatial expansion in the early universe that is believed to have lasted from approximately (10^{-32}) to (10^{-32}) seconds after the Big Bang, with the exact duration depending on the microphysics of the inflation model. Inflationary models explain the quantum origin of small initial density fluctuations in the universe, which must have been present in the very early epochs as seeds for both the CMB anisotropies and the formation of structure in the later evolution of the universe. The exponential expansion during inflation ends with a phase transition that converts vacuum energy into radiation and matter, after which the radiation-dominated era begins.

This phase transition is referred to as reheating. As explained, CMB data do not directly determine the Hubble constant; rather, they determine the acoustic scale (θ^*). In models where the contribution of dark energy in the early times is negligible, the sound horizon at the time of recombination (r^*) will be the same, and it can be expected that the measured values of (H^0) can be justified across different redshifts. Simply put, CMB data restrict the matter density, and since IDE models change the matter density in the early times, (h) must also change to meet the CMB constraints [8].

Astronomers conduct several large experiments aimed at using galaxy clustering measurements and supernova observations to measure distances, and gravitational lensing observations to measure the growth rate of structure. This is even more complex than it seems. The first problem arose in 1929 when initial estimates of the expansion rate, known as the Hubble constant (H^0), returned to the singularity of the Big Bang and showed that the universe is younger than the Earth and the Sun. The measurement of the Hubble constant has improved from an uncertainty of 10% in the early 2000s to under 2% by 2019 [9]. Steven Weinberg summarized the state of cosmology in the early universe in his book "The First Three Minutes," describing the early time when the universe was filled with radiation. The gap in our understanding of cosmic history spans the first few seconds, questioning how, in that brief time span, the energy density of the universe was dominated by relativistic particles.

In other words, what determined the initial conditions for Weinberg's analysis? The oldest epoch we can reliably obtain information about is inflation, an early phase of accelerated expansion in the very early universe, which aligns predictions with high-precision measurements of temperature anisotropies in the cosmic microwave background (CMB) . Constraints related to the effects of neutrinos on the CMB, as well as constraints regarding Big Bang nucleosynthesis (BBN), indicate that the universe must have been dominated by relativistic particles at the time of neutrino decoupling from the thermal plasma at MeV energy scales. Although the time between the end of inflation and neutrino decoupling is short (∼1 second), the energy scale can decrease by nearly 20 orders of magnitude during this period, and the universe may have expanded by a factor of 60. The rate at which the universe expands depends on the total energy density (ρ) and the pressure (p) of the fluid components that fill the universe. Specifically, in a flat FLRW universe filled with components that can be modeled as perfect fluids, Einstein's field equations show that the scale factor (a(t)) evolves as a function of time [10].

$$a(t) \propto t^{2/3(1+w)} \quad , \qquad w = \frac{\langle p \rangle}{\langle \rho \rangle}$$

During the inflationary period, the equation of state parameter must satisfy) $w \approx -1$).[10] Nucleosynthesis (BBN) is a cornerstone of the standard cosmological model. Currently, the primordial abundances of helium and deuterium are measured with an accuracy of 1%. This makes BBN a powerful framework for testing non-standard cosmological expansion history. A common belief is that the universe must have been radiation-dominated prior to BBN. To ensure that there is no interference in structure growth, the energy density must evolve more slowly than that of matter, allowing for a prolonged period of matter dominance during which the density inhomogeneities measured by COBE and experiments on cosmic microwave background anisotropy can grow [11].

2 Dark Matter

One of the most important missions of contemporary physics is to understand the nature of dark matter (DM) in the universe. The long-standing paradigm is that most DM is cold (CDM) and consists of some massive particles that interact weakly (WIMPs). In general, any non-baryonic massive particle (even with a very small mass) that interacts through any interaction that is weak or sub-weak (for example, axionic or gravitational) is included. In a more conventional sense, WIMP refers to a particle with a mass ranging from about 2 giga-electron volts (the Lee-Weinberg limit) to about 100 tera-electron volts, whose interactions are essentially determined by the coupling of weak interactions of the standard model.

One of the well-known arguments for the existence of dark matter is based on the rotation curves of galaxies, meaning the relationship between the orbital velocity and the radial distance of stars or gas from the center of the galaxy. It was first observed in the late 1930 that the outer parts of the M31 disk were moving at unexpectedly high speeds. The existence of dark matter is also supported by data from gravitational lensing. Gravitational lensing, or the bending of light in a strong gravitational field, is easily observed when light passes from a very massive and/or dense object, such as a galaxy cluster or the central region of a galaxy. Light rays can bend around the object, or lens, resulting in the inversion of the light source's image, a phenomenon known as strong lensing. The size and shape of the image can be used to determine the mass distribution in the lens, which can then be compared to the observable mass.

A clear conclusion about dark matter (DM) that can be inferred from observational evidence is that DM is composed of particles that must be electrically neutral and must interact with ordinary matter only weakly (or sub-weakly). A simple classification of DM particles based on how relativistic they were at the time of decoupling from thermal equilibrium in the early universe, i.e., when they separated from thermal plasma, is provided. Hot dark matter (HDM) in the mass range of a few tens of electron volts, which was still relativistic at the time of decoupling, did not contribute to the formation of small structures like galaxies due to its large free path, and it does not reproduce the observed universe in large-scale structure (LSS) numerical simulations.This is inconsistent with LSS data and deep field observations that constrain the permissible average velocities of DM particles. Therefore, HDM can only constitute a small component, determined by the properties of the CMB, of the total DM density [12].

One of the remarkable predictions of general relativity is that a region with mass (M) can collapse into a black hole (i.e., a region where the gravitational field is so strong that even light cannot escape). Black holes can exist across a wide range of mass scales. Those that are larger than several solar masses are formed at the end of the evolution of ordinary stars, and there should be billions of such holes even within our own galaxy's disk. In recent years, there has been significant interest in black holes that are not affected by Hawking radiation. These holes may have various astrophysical implications.

They can provide dark matter, which constitutes 25% of the critical density. Wells that form at later times (and certainly exist) cannot account for all dark matter, as they are composed of baryons and are subject to the well-known baryogenesis constraint from Big Bang nucleosynthesis (BBN), which states that baryons cannot exceed 5% of the critical density. An important point is that observations suggest that only a very small fraction of the early universe could have collapsed into primordial black holes. The current density parameter (Ω_{PBH}) associated with primordial black holes formed at a time (t) is related to the initial collapse fraction (β) [13].

$$\Omega_{PBH} = \beta\Omega_R\,(1 + z) \approx 10^6\ \beta\,(t/s)^{-1/2} \approx 10^{18}\beta\,(M/10^{15}g)^{-1/2}$$
$$\Omega_R \approx 10^{-4}$$

The origin of the baryon asymmetry of the universe (BAU) and the nature of dark matter are two challenging problems in cosmology. The conventional assumption is that high-energy physics generates baryon asymmetry everywhere simultaneously through the decay of out-of-equilibrium particles or a first-order phase transition in the very early times. However, there is no direct evidence for this, and even if this process occurs, we cannot be sure that it provides all the required baryon asymmetry. Garcia-Bellido and colleagues have proposed an alternative model in which gravitational collapse into primordial black holes during the QCD era can solve both of these problems.

This collapse is accompanied by the ejection of matter, which may be considered a type of "primordial supernova." Such hot spots with high density create out-of-equilibrium conditions necessary for generating baryon asymmetry through electroweak axion transitions, which are responsible for the twists of the Higgs in the electroweak vacuum. CP violation in the Standard Model is sufficient to create the local baryon-to-photon ratio. The hot spots are separated, but the baryons ejected from them move at the speed of light and become uniformly distributed before Big Bang nucleosynthesis (BBN). Therefore, the large initial baryon asymmetry is diluted into the small observed global baryon asymmetry.

This naturally explains why the observed baryon asymmetry corresponds to the fraction of primordial black hole collapse and why baryons and dark matter have comparable densities. If most dark matter exists in the form of fundamental particles, these particles may cluster around any small mixture of primordial black holes (PBHs) [13]. If primordial black holes (PBHs) leave behind stable remnants with Planck mass after evaporation, these remnants may also contribute to dark matter. If these remnants have a mass such that the survival mass is (κM_{pl}) and reheating occurs at a temperature (T_R), then the condition for them to have a density less than that of dark matter requires that:

$$\beta\,(M) < 5 \times 10^{-29}\,\kappa^{-1}\left(\frac{M}{M_{pl}}\right)^{\frac{3}{2}},\ (\frac{T_{pl}}{T_R})^2 < \frac{M}{M_{pl}} < 10^{11}\kappa^{2/5}$$

The lower mass limit is due to primordial black holes (PBHs) that form before reheating, which dilute exponentially. The upper mass limit arises because black holes larger than this will dominate the total density prior to their evaporation; in this case, the final baryon-to-photon ratio in the universe is determined by the baryonic asymmetry associated with their decay [13]. Almost all current dark matter models utilize the standard concept of quantum field theory to describe the properties of candidate fundamental particles. This implies that they can be characterized by the mass and spin of the dark matter particle. The density of cold dark matter (CDM) is now determined with a precision of a few percent using the Hubble constant (h), expressed in units of kilometers per second per megaparsec [14].

$$\Omega_{CDM}h^2 = 0.1131 \pm 0.0034$$
$$h = 0.705 \pm 0.0134$$

While gravitational evidence for the phenomenon of dark matter (DM) has been continuously gathered through astrophysical and especially cosmological observations, its nature remains an open question. Most efforts to identify massive particles with weak interactions (WIMPs) in the mass range of GeV-TeV have yielded negative results, whether through indirect detection via standard model (SM) observations, direct detection in detectors, or energy losses in colliders. Among the new particles with weak interactions, two dark matter candidates are particularly relevant: axion-like particles (ALPs) and sterile neutrinos. Sterile neutrinos are singlet fermions of the standard model that couple to the visible sector through a mass mixing mechanism, and their nature may be directly linked to the generation of neutrino masses. However, it should be noted that such sterile neutrinos are not in thermal equilibrium in the early universe; therefore, their effects on structure formation must be studied before reaching strong conclusions [15].

In the search for dark matter candidates, several considerations come into play, including that each dark matter candidate must satisfy observational evidence. This begins with the observed density of dark matter, which has been precisely determined during the cosmic microwave background (CMB) era, when the universe was about 380,000 years old and at a redshift of $z \sim 10^3\_10^4$. From the formation of galaxies and galaxy clusters, as well as from galactic rotation curves, it is known that the density of dark matter (ρ) must decrease with the expanding volume of the universe according to ($\rho = \rho^0 (1 + z)^3$) and must have very weak interactions with baryons to avoid disrupting the baryonic acoustic oscillations in the CMB. Additionally, it should remain nearly elliptical in shape (neither perfectly spherical nor disc-like) during the formation of galaxies [16].

On average, dark matter must possess a cold equation of state (w = 0) at least since the universe was approximately 380,000 years old. It should also exhibit sufficiently weak interactions with itself and ordinary matter to allow gravitational forces to control the formation of limited structures, rather than other forces such as baryonic pressure[17]. Despite strong evidence for the effects of dark matter, there is no direct confirmation of the existence of dark matter, such as the discovery of the particle responsible for dark matter. The lack of direct evidence for dark matter has led to the development of alternative models to explain the effects of dark matter, such as Modified Newtonian Dynamics (MOND), introduced by Milgrom in the 1980. According to MOND, Newton's second law of motion must be modified so that for very weak accelerations(a), where ($a \ll a_0$) with (a_0) being a universal acceleration scale parameter), the force (F) associated with (a) is no longer linearly dependent on (a) but instead depends on its square. A narrower formulation of MOND is one in which only Newton's law of gravitation requires modification, as follows:

$$ma = F = \frac{GMm}{\mu(\frac{a}{a_0})\bar{l}^2}, \quad a_0 = 1.2 \times 10^{-10} ms^{-2}$$

where M and m represent the mass of a gravitational body and the mass of a test particle, respectively, which are separated by a distance l and are attracted to each other with a force F. [18] In the ΛCDM cosmological model, based on observations of Type Ia supernovae, the energy density of cosmic dark energy is assumed to be ($\Omega_\Lambda \sim 0.70$), while the density of gravitational mass is assumed to be ($\Omega_\Lambda \sim 0.30$). Assuming that the observed cosmic microwave background is a remnant of the hot early universe, the cosmic plasma density should be small, i.e.,($\Omega_\Lambda \sim 0.05$), otherwise the Sunyaev-Zel'dovich effect would erase the complete blackbody spectrum of the cosmic microwave background. To fill the gap between (Ω_m) and (Ω_b), non-baryonic dark matter ($\Omega_c \sim 0.25$) is added to the ΛCDM model. However, if the cosmic microwave background results from a partial thermal equilibrium between cosmic radiation and cosmic plasma, then a complete blackbody spectrum of the cosmic microwave background can coexist with cosmic plasma. In this case, it is not necessary to include cold non-baryonic dark matter in cosmological models. A better candidate for dark matter is cosmic plasma [19].

Part Two

2.1 Cosmic Plasma

2.1.1 Quarks and Gluons

In the early stages of the universe, approximately one millionth of a second after the Big Bang, the universe was filled with a quark-gluon plasma. Due to the extremely high temperature in this plasma, the strong coupling constant, which dictates the strength of the force acting on quarks and gluons, becomes significantly small. As a result, quarks and gluons within this plasma can be treated as an ideal gas of massless quarks and gluons that interact weakly with each other. Therefore, the properties of this plasma can be described using equations of state that relate the energy density and pressure to the temperature. This has been done in several models within the literature, using recent data on the properties of quark-gluon plasma provided by relativistic heavy-ion collision experiments and certain astrophysical measurements. Quarks and gluons interact weakly at short distances.

Based on this phenomenon, in the mid-1970, quark-gluon plasma (QGP) was proposed as a new state of nuclear matter. QGP can exist at high temperatures and densities, where hadrons decompose into their constituent quarks and gluons. On the other hand, it is believed that one millionth of a second after the Big Bang, the universe was filled with QGP. This plasma can be described by thermodynamic quantities such as energy density, pressure, and temperature, which evolve over time as the universe cools. The study of the time evolution of these thermodynamic quantities can be conducted using cosmological models based on Einstein's theory. These equations are the fundamental field equations of the theory of general relativity. In any system of units, the relativistic formula for the total energy EEE of a particle with mass mmm and momentum p is given by the following [20].

$$E^2 = p^2c^2 + (mc^2)^2$$

The mathematical models used to describe the large-scale features of the universe are commonly referred to as cosmological models. In 1917, Einstein formulated such a model based on Einstein's field equations, which are the fundamental field equations of general relativity. These field equations can be derived from the relation [20]:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = -\kappa T_{\mu\nu}$$

(κ) is a constant, ($R_{\mu\nu}$) is the Ricci tensor, which depends on the metric tensor and its derivatives, (R) is the Ricci scalar, and ($T_{\mu\nu}$) is the energy-momentum tensor [20].

Among the infinite variety of astrophysical objects, some are characterized by extremely intense physical conditions that are not found anywhere else in the universe. There are two classes of such objects: magnetars, whose magnetic activity is manifested through their short but intense gamma-ray bursts, and the central engines of supernovae (SNe) and gamma-ray bursts (GRBs) – the most powerful explosions in the modern universe. Understanding how these complex systems operate requires insight into plasma processes, both small-scale kinetic and large-scale magnetohydrodynamic (MHD), which govern their behavior.

However, the presence of extraordinarily strong magnetic fields alters the fundamental physics to such extremes that reliance on conventional classical plasma physics is often unjustified. Instead, the plasma problems related to these extreme astrophysical environments require the construction of relativistic quantum plasma (RQP) physics based on quantum electrodynamics (QED). In energy transfer processes that control the thermodynamics of extreme plasma environments, small-scale kinetic plasma processes play a critical role in the interaction of intense electric currents that flow through the magnetosphere of the magnetar to the surface of the neutron star.

At the Sandia National Laboratories, MJ-class X-ray sources are provided. This capability enables benchmark experiments on the fundamental properties of materials heated by radiation under conditions previously unattainable in the laboratory. These experiments can produce uniform, long-lasting, large plasmas with volumes of up to 20 cubic centimeters, temperatures ranging from 1 to 200 electron volts, and electron densities from (10^{17}) to (10^{23}) per cubic centimeter. These unique features and the ability to conduct multiple experiments in a single shot with radiative heating have led to a new initiative called the Z Astrophysical Plasma Properties (ZAPP) collaboration. (ZAPP) focuses on producing radiative conditions and astrophysical plasma materials as close as possible to those in the laboratory and using precise spectral measurements to enhance atomic models in plasmas [21, 22].

The charged component of the interstellar medium consists of atomic and molecular ions, electrons, and charged dust grains that are coupled to the local galactic magnetic field. Collisions between neutral particles (often atomic or molecular hydrogen) and charged species, as well as between the charged species themselves, influence the magnetohydrodynamic behavior of the environment and the dissipation of electric currents [23]. A new mechanism for the formation of dense dusty clouds in astrophysical environments is discussed. It is shown that the balance of collective forces acting in dusty plasma can lead to a self-limiting effect of dust, creating stable spherical clusters. The density distribution of dust and plasma within such objects and their stability are examined. Spherical dusty clouds can form over a wide range of plasma parameters, suggesting that this self-organization of dust may be a general phenomenon occurring in various astrophysical media [24].

2.1.2 Faraday Rotation Measurements

The interpretation of Faraday rotation measurements from active galactic nuclei (AGN) in galaxy clusters indicates the presence of ordered or coherent regions filled with large magnetic fields of approximately ~3μG. The magnetic energy in these coherent regions is around L^3_{mag} ($B^2/8\pi$)~10^{59-60}) erg, and the total magnetic energy of the cluster (which has a width of about 1 megaparsec) is expected to be even larger. Understanding the origin and role of these magnetic fields poses a significant challenge for plasma astrophysics. A sequence of physical processes responsible for the generation, redistribution, and diffusion of these magnetic fields has been proposed.

These fields are associated with single AGNs within the cluster and, thus, with all galaxies during the AGN phase (active galactic nucleus or quasar). The supermassive black holes (~10^8 $M_{\odot}$) formed during the AGN phase have an accessible energy formation of ~ 10^{61}, which can supply the energy of the magnetic field; a dynamo process (α-Ω) operates in the accretion disk around the black hole. The rotation of the disk naturally provides a sufficiently large winding number, ~10^{11} turns, to generate both large gain and large flux. The helical dynamo can be produced by differential plasma rotation derived from star-disk collisions. This process of helical generation has been demonstrated in laboratory settings, and dynamo gain has been numerically simulated.

It is hypothesized that the saturated dynamo feedback reaction will lead to the formation of a magnetic helix without a force that removes energy and dynamo flux from the accretion disk, redistributing the field in clusters and galaxy walls. Magnetic reconnection is a small fraction of this energy, which logically serves as a luminous source for AGN (active galactic nucleus or quasar), while the remaining field energy must control the current energy budget of the universe. Reconnection of this intergalactic field over Hubble time is the only sufficient energy source needed to produce the observed ultra-high-energy cosmic ray spectrum in this galaxy and simultaneously allows this spectrum to escape into the cosmic void faster than GZK, loss [25]. In contemporary substellar atmospheric models, dust growth occurs through the surface chemistry of the neutral gas phase. There is growing theoretical and observational evidence that ionization processes may also occur.

Consequently, the atmospheres are filled with regions composed of plasma, gas, and dust, and the impact of plasma processes on dust evolution increases. In dense dust cloud regions, plasma deposition and plasma erosion dominate the surface chemistry of the neutral gas phase if the degree of ionization is $\geq 10^{-4}$. Attached grains with surface bond energies of 0.1-1 electron volt are prone to destruction through plasma erosion for acceptable degrees of ionization and electron temperatures; whereas, robust crystalline grains with bond energies of approximately 10 electron volts are resistant to erosion [26].

Three well-known examples of coherent emission in astrophysical radio sources are examined: plasma emission, electron cyclotron maser emission (ECME), and pulsar radio emission. Plasma emission is a multi-stage mechanism, with the first stage involving the generation of Langmuir waves through current-driven instability [27]. Whether the inflow of interstellar plasma is subsonic or supersonic, the scenario of one or two shock fronts forms, producing a shock [28].

Cosmic rays, scattered throughout interstellar matter, arise through shock waves in supernova remnants. These cosmic rays trigger complex chemistry in molecular clouds and regulate their collapse timescale, determining the efficiency of star and planet formation. However, they cannot penetrate the densest parts of molecular clouds, where star formation is expected, due to energy loss processes and magnetic field deflection. Recently, observations in young protostellar systems have revealed a high ionization rate, a key indicator of cosmic ray presence in molecular clouds. Additionally, synchrotron radiation, a characteristic feature of relativistic electrons, has been detected in the shock wave of a (T) Tauri star. However, the precise origin of these accelerated particles remains puzzling [29].

Cosmic rays (CRs) play various roles in different environments. When, where, and how did cosmic rays originate since the Big Bang? We argue that blast waves from the first cosmic explosions at around z ~ 20 lead to non-relativistic shocks mediated by the Weibel instability, and cosmic rays can be produced through the diffusive shock acceleration mechanism. These cosmic rays could have played multiple roles in the early universe, including ionizing and heating gas, generating magnetic fields, and providing feedback on galaxy formation [30].

2.1.3 Simulations

Particle-in-Cell (PIC) methods have been used to study particle acceleration and magnetic field generation in astrophysical jet flows driven by plasma phase space structures. We discuss astrophysical environments such as jets from compact objects and provide an overview of global PIC simulations of shocks. These simulations reveal several types of phase space structures associated with energy losses. These structures are typically interconnected in shocks, but we consider them here in isolation. Three structures are examined. Simulations of colliding plasma clouds or plasma clouds with thermal anisotropy excite filamentation instabilities.

Both convert a uniform spatial plasma into flow filaments. These filamentary structures generate magnetic fields. By forming electron-saturated phase space holes, the ion beam modulates electron clouds, and a secondary electrostatic instability develops a local space saturated by ion-saturated phase space holes. These holes accelerate electrons to very high velocities. One simulation involves two electron-ion plasma clouds colliding at speeds of 0.9c. The unequal densities of both clouds and a magnetic field that is angled relative to the collision velocity vector give rise to waves with mixed electrostatic and electromagnetic polarization. These waves generate spiral distributions in electrons and ions, establishing an equal energy partition between the electron, ion, and magnetic field energies. In astrophysical plasma, there exists a wide range of scales. Cosmic objects such as supernova remnants can be several light-years in size. Their structure and evolution are shaped by non-thermal particles, whose acceleration and transport are governed by processes occurring at scales down to centimeters or a few milliseconds of light, ten orders of magnitude smaller than the affected object [23].

No technique currently allows for the simultaneous study of processes across all scales, and specific methods are employed for smaller ranges of scales. Here, we review Particle-in-Cell (PIC) simulations designed to describe kinetic processes at the lower end of the scales. Initially conceived over 50 years ago, the development of algorithms and advances in computer hardware have allowed PIC simulations to thrive and become a tool that today enables us to perform precise computational experiments on processes such as magnetic reconnection and particle acceleration in turbulent shocks. This review aims to present the current state of research and recent findings. Kinetic processes in turbulent systems are significant, as they are characterized by low-frequency two-body collisions, through which particles can exchange energy and momentum. In an ionized environment, relevant two-body collisions will involve Coulomb scattering. The mean free path (l_c) and interaction rate (v_{ee}) in a medium with density (n_e) and temperature (T) are expressed as follows [31].

$$l_c \cong \frac{1}{4\pi} (\frac{v}{c})^4 \frac{1}{n_e \sigma_T ln\, \Lambda} \quad , \quad v_{ee} = \frac{v}{l_c}$$

Note: It is often assumed that photons scatter freely in the universe. However, our universe is filled with plasma, a rarefied medium that inhibits the scattering of low-frequency (and small-amplitude) electromagnetic waves [32]. The frequency of ground states, such as the redshifted frequency of free photons, can be utilized in a simple kinetic argument to justify the effects of creation and annihilation (stochastic) [33]. Note: It is important to note that magnetic Langmuir waves can cause disturbances [34]. In relativistic shock waves, the bulk flow speeds are comparable to the speeds of the particles. This leads to highly anisotropic particle distributions in the shock. Unlike the case of non-relativistic shocks, acceleration processes are very sensitive to background conditions, especially the structure of the turbulent magnetic field and the details of particle-wave interactions. However, these aspects are not well understood, and particle acceleration modeling must rely on simplified assumptions about scattering and particle transport.

Efficient transverse particle scattering can occur even in the presence of limited amplitude MHD waves near the shock. These waves may exist in the turbulent upstream environment of the shock, but they can also be generated by the accelerated particles themselves (similar to non-relativistic shocks)[35]. Several mechanisms can be responsible for particle acceleration in the presence of shocks: second-order Fermi acceleration, shear acceleration at the interface between a jet and the outflow of a protostar, acceleration due to background shock turbulence, and acceleration during magnetic reconnection. In this section, we examine the first-order Fermi acceleration mechanism, also known as Diffusive Shock Acceleration (DSA). According to DSA, charged particles gain energy each time they cross a shock, but efficient acceleration occurs only if magnetic field fluctuations exist around the shock.

In fact, these fluctuations ensure angular scattering such that particles can cross the shock multiple times and readily reach relativistic energies, as long as they are downstream of the environment. DSA can convert the thermal particles of a protostar system (a system with specific radiation) into cosmic rays. Thermal electrons can also be accelerated, but due to energy losses and wave damping, they become thermalized. Diffusive Shock Acceleration (DSA) is a well-studied process that occurs in supernova remnants. However, in protostars, the environment is not fully ionized, and friction between ions and neutral particles can significantly reduce DSA acceleration. If ions and neutral particles are coupled, that is, if they move in unison, then the waves produced by ions do not dampen significantly, and particles can accelerate efficiently. The wave damping rate, Γ [29].

$$\Gamma = \frac{\omega^2}{\omega^2 + \omega_i^2}\omega_n \ , \ \omega_i = n_H x \ \langle \sigma v \rangle \ , \ \omega_n = n_H (1 - x) \ \langle \sigma v \rangle$$

$$n_H = n_n + n_i \ , \ \langle \sigma v \rangle = 8.4 \times 10^{-9} T_4^{0.4} \ cm^3 s^{-1}$$

In star-forming cores, which are characterized by the production of new elements through nuclear reactions within stars, several uncertainties persist. Transitioning from the pre-stellar phase to the star-forming phase, it is anticipated that the degree of ionization will be significantly influenced by both short-lived and long-lived radioactive nuclei. This is primarily due to the inability of interstellar cosmic rays to penetrate regions close to active star formation. We term this the "quiet phase," in contrast to the "active phase," during which strong shocks occur, facilitating conditions conducive to the acceleration of local thermal particles to relativistic energies [29].

2.1.4 PIC-MHD-Hybrid

Hybrid models serve as a midpoint between Particle-In-Cell (PIC) models and Magnetohydrodynamics (MHD), where a complete kinetic description is maintained for ions while electrons are treated as a fluid. These models neglect electron scales, as electrons are considered to be magnetic entities that follow magnetic field lines in space. Relevant spatial scales include the radius of ion rotation in stars and the skin depth of ions in gas clouds, with the inverse time scale corresponding to the ion rotation frequency in plasma.

Thus, the evolution of physical systems in the universe can occur over much longer timescales than what is possible with PIC methods. In the simplest implementations, the electron mass is disregarded in the generalized Ohm's law, treating plasma as neutral in stars, while electron pressure is considered a scalar. Advanced hybrid models may include effects of resistivity in gas clouds, electron inertia in plasma, or electron pressure effects in stars. All these models ignore displacement current in Ampère's law (i.e., $\nabla \times B = (4\pi / c)j$), thereby excluding the propagation of light waves in space and aligning with the neglect of high-frequency fluctuations due to electrons in plasma.

However, waves with frequencies around and below the ion rotation frequency in stars are accurately described. A key advantage of the PIC method is its ability to describe plasma from first principles without collision assumptions. Nonetheless, in most implementations, the need for computational stability and accuracy necessitates resolving electron scales down to the smallest scales given by Debye length and electron plasma frequency. Physical systems in space physics and astrophysics typically exhibit multi-scale issues, where physical processes operate not only across a wide range of scales from micro to macro but also where microphysical or kinetic processes significantly influence the macro state of an object. Due to computational limitations, PIC models can provide a description of the system for several thousand proton plasma times or a few hundred proton rotation times, yet they may not cover the spatial scale of the proton rotation radius simultaneously. Therefore, simplifications in kinetic plasma modeling are required to adequately describe larger spatial and temporal scale [31].

2.2 Field Theory

Cosmological observations strongly indicate that our universe has experienced two epochs of accelerated expansion: an initial inflationary phase and a recent ongoing period (dark energy). The exploration of new models and mechanisms for these two phenomena has been the focus of increased theoretical activity over the past decade or two. Although they are characterized by vastly different energy scales, inflation and dark energy share striking similarities. A universal feature of the proposed models is the presence of at least one scalar degree of freedom.

In the case of inflation, it seems unavoidable due to the need for a dynamic mechanism to exit a specific accelerated state and commence the standard phase of large-scale expansion. Regarding the current acceleration, while the cosmological constant remains a strong candidate, it is worth noting that any specific alternative entails a new dynamic scalar degree of freedom. Both early and late-time cosmic acceleration models can now account for all current observations by adjusting a limited number of parameters. The scalar field ($\phi(x)$) invoked by these models has no reason for existence other than being specifically designed to generate acceleration, and it rarely exhibits connections to other aspects of the physical realm that are better known or understood.

For this purpose, the effective field theory (EFT) paradigm seems to be an appropriate tool. First, EFT allows for direct and efficient work with the degrees of freedom of a physical system relevant at the energy scale of a particular experiment. Critically, such degrees of freedom are not necessarily fundamental fields of the theory. A famous example is Quantum Chromodynamics (QCD), a theory of quarks and gluons that, at low energies, only manifests neutrons and pions. They are degrees of freedom that explicitly appear in the effective Lagrangian of the nonlinear sigma model. Furthermore, within the EFT paradigm, all possible theories that are consistent with a particular symmetry are systematically classified [36]. In cosmology, the low-energy degrees of freedom are clearly related to cosmological fluctuations around the homogeneous Friedmann-Robertson-Walker (FRW) background.

Among other aspects, these cosmological fluctuations are responsible for the anisotropies in the cosmic microwave background (CMB) and large-scale structures (LSS) that subsequently evolved from them. According to the standard paradigm, the origin of such fluctuations lies in the early inflation, while their recent evolution is sensitive to the background behavior and possible dynamical features of dark energy. The effective field theory for cosmological fluctuations has a Lagrangian that encompasses all the aforementioned properties. This formulation was first used to study the coupling of ghost condensates to gravity [36].

(Planck mass = $\boldsymbol{M_*}$)

$$S = S_m[g_{\mu\nu},\Psi_i] + \int d^4x\sqrt{-g}[\frac{M_*^2}{2}f(t)R - \Lambda(t) - c(t)g^{00} + \frac{M_2^4(t)}{2}(\delta g^{00})^2$$

$$-\frac{M_3^3(t)}{2}\delta K\,\delta g^{00} - M_2^4(t)\left(\delta K^2 - \delta K_\nu^\mu \delta K_\mu^\nu\right) + \frac{\bar{m}_4^2(t)}{2}R\delta g^{00} - \bar{m}_4^2(t)\delta K^2$$

$$+\frac{\bar{m}_5(t)}{2}R\delta K + \frac{\bar{\lambda}(t)}{2}R^2 + \cdots + \frac{M_3^4(t)}{3!}(\delta g^{00})^3 - \frac{\bar{m}_2^3(t)}{2}(\delta g^{00})^2\delta K + \cdots]$$

$$c = \frac{1}{2}\left(-\ddot{f} + H\dot{f}\right)M_*^2 + \frac{1}{2}(\rho D + pD)$$

$$\Lambda = \frac{1}{2}\left(-\ddot{f} + 5H\dot{f}\right)M_*^2 + \frac{1}{2}(\rho_D + p_D) \quad ,H(t) = \dot{a}(t)/a(t)$$

$$H^2 = \frac{1}{3fM_*^2}(\rho_m + \rho_D) \quad , \quad \dot{H} = -\frac{1}{2fM_*^2}(\rho_m + \rho_D + p_m + p_D)$$

Particle physics can be described using an effective field theory with an ultraviolet (UV) cutoff below the Planck mass (M^*), provided that all momenta and field strengths are smaller than this cutoff to the appropriate power. Calculations carried out within such effective field theories, such as the Standard Model, have proven remarkably successful in describing the properties of fundamental particles. However, studies pertaining to black holes suggest that the fundamental theory of nature is not a local quantum field theory. In the context of an effective quantum field theory confined to a box of size (L) with a UV cutoff, the entropy (S) scales extensively as ($S \sim L^3\Lambda^{3*}$).

Nevertheless, the peculiar thermodynamics of black holes allowed Bekenstein to propose a maximum entropy for a box of volume (L^3) in a non-extensive manner, depending solely on the area of the box. For any (Λ), there exists a sufficiently large volume such that the entropy of an effective field theory surpasses Bekenstein's limit. This finding indicates that conventional (1+3) dimensional quantum field theories significantly overestimate the degrees of freedom; since these field theories are expressed in terms of a Lagrangian density, they inherently exhibit extensive entropy [37].

To construct an Effective Field Theory (EFT) that describes physics at a given energy scale (E), an expansion is made in powers of (E / Λ_i), where (Λ_i) are various scales involved in the problem and are larger than (E). A general effective Lagrangian includes the relevant low-energy degrees of freedom and is consistent with the underlying theory. This Lagrangian can be organized based on powers of momentum or, equivalently, by increasing the number of derivatives. At low energy scales, the lower-dimensional terms will dominate. A simple example of an EFT is provided by Quantum Electrodynamics (QED) at very low energies ($E_\gamma \ll$ me). In this regime, light-light scattering can be described using an effective Lagrangian involving only the electromagnetic field. Lorentz invariance, charge conservation, and parity limit the possible structures in the effective Lagrangian [38].

The study of Quantum Chromodynamics (QCD), a theory about the natural world, is less focused on exact mathematical theorems and more on practical results. From this perspective, the advancement of lattice formulations is that they transform quantum field theory into a well-defined problem in statistical mechanics. Condensed matter theorists and mathematical physicists have developed various methods to solve such problems. In addition to weak perturbation theory, the toolkit includes non-perturbative versions of the renormalization group, strong coupling expansions, and the numerical integration of the functional integral using Monte Carlo methods. The first two approaches were pursued at high energies in the decade following Wilson's seminal paper. Indeed, when most physicists refer to lattice QCD, they generally mean numerical lattice QCD [39].

For example, in the context of strong coupling plasma theory, it describes how many-body physics influenced by correlations affects transport properties. Traditional plasmas are so hot and dilute that the average kinetic energy of each particle significantly exceeds the potential energy of interactions. In this specific weak coupling regime, long-range interactions dominate, and Coulomb collisions are accurately modeled as a series of small-angle dipole scattering events. In contrast, in strongly coupled plasmas, the potential energy of interactions exceeds the average kinetic energy of each particle, necessitating a theory that accounts for both large-angle collisions and many-body correlations. Strongly coupled plasmas in cosmic environments can influence the formation of stars and galaxies [40].

Correlation functions in quantum field theories are useful tools for study. For a field theory in a vacuum or thermal state, Lorentzian correlations can be computed by analytically continuing Euclidean correlation functions. However, for strongly coupled field theories, the direct computation of correlation functions is highly challenging [41].

Quantum cosmology affects the behavior of inhomogeneity related to the form of quantum spacetime structure. In particular, within the framework of theories such as loop quantum gravity, which suggest some form of spatial or spacetime discontinuity, effective field theory is also relevant for conceptual questions. For instance, in mini-superspace models, it is preferable to avoid singularities associated with the Big Bang by modifying classical equations using bounded functions. In mini-superspace equations, the compatibility conditions imposed by the need for covariance of equations regarding inhomogeneity are overlooked. Mini-superspace models used in quantum cosmology eliminate the spatial dependence of all fields by averaging them over a specified region in space.

The resulting model only has temporal dependence, a reality that simplifies many of the compatibility conditions imposed by covariance. However, it has been shown that mini-superspace models still exhibit a covariance problem, which relates to the volume of the coordinate region used to define spatial averaging. This conclusion is demonstrated using a mini-superspace model with a scalar field theory in flat spacetime, with the Lagrangian expressed as follows [42].

$$L = \int d^3x \ (\tfrac{1}{2}\phi^2 \ - \tfrac{1}{2}|\nabla\phi|^2 - W(\phi)$$

Particle physicists, for example, even consider theories that should be fundamental, such as the famous Standard Model of electromagnetic, weak, and strong interactions, as an effective field theory (EFT). Nuclear physicists systematically utilize low-energy effective field theories derived from quantum chromodynamics (which is part of the Standard Model) to explain the dynamics of protons and neutrons in atomic nuclei at low and medium energies. Solid-state theorists reformulate older models, such as the BCS theory of conventional superconductivity, in the language of effective field theories. Even gravitational physicists regard general relativity as a starting point for a power series expansion, to which higher-order terms that remain invariant under general coordinate transformations must be added to explain physics at higher energies. The resulting effective field theories incorporate quantum corrections to Einstein's theory, which are considered as traces of a quantum gravitational theory [43]. In the context of Einstein's theory, we consider an effective theory for the background with leading scalar and gravitational corrections as follows [44].

$$S = \int d^4\, x\sqrt{-g}\ \left\{\frac{M_p^2}{2}R - 1/2(\nabla^2\phi^2) - V(\phi)\right\}$$

$$+ \int d^4\, x\sqrt{-g}\ \{f_{quart}(\phi)\nabla^4\phi^4 + \ f_{curv}(\phi)G^{\mu\nu}\nabla_{\mu\phi}\nabla_{\nu\phi}$$

$$+ f_{GB}(\phi)\ (R^2 - 4R^{\mu\nu}R_{\mu\nu} + R_{\mu\nu\sigma_\rho}R^{\mu\nu\sigma_\rho})\} + \ S_m[\Omega(\phi,\nabla\phi)g_{\mu\nu}\ ,\psi_m]$$

$$\Omega(\phi,\nabla\phi) = \ e^{\alpha(\phi)}(1 + f_{kin}(\phi)(\nabla\phi)^2\ )$$

The power of the effective field theory (EFT) approach lies in its ability to use data obtained from observations to constrain possible parameter values while simultaneously enforcing theoretical consistency, which imposes additional restrictions to eliminate regions of parameter space. For example, it is well known that the radiative stability of the scalar field for quintessence imposes strong constraints on the form of the scalar potential. While the coefficients are practically functions of the scalar field, it is useful to expand these functions in powers of the cutoff scale of the effective theory [44].

A powerful tool for investigating potential signals from the Planck scale in a model-independent way is effective field theory (EFT). Small residual couplings from the underlying theory can appear at the EFT level as correction terms to General Relativity

(GR) combined with the Standard Model (SM), with the magnitude of physical effects controlled by small coefficients that reflect the characteristics of the underlying theory. Each term in the effective Lagrangian density is the product of an operator composed of fields observed in nature with coupling coefficients that determine the scale of interactions. In typical EFT applications, these coupling coefficients are treated as constant scalars, known as coupling constants. However, solutions of the underlying theory that describe our universe might involve non-trivial fields, which could manifest at the EFT level as coupling coefficients that vary with spacetime position and could be tensors instead of scalars.

Tensorial couplings might directly arise from the properties of the underlying theory. Still, even if the underlying theory only produces a non-static scalar field, the final EFT can include vector and tensor coupling coefficients determined by the derivatives of the scalar field. In the Lagrangian density (L) of a general EFT that couples General Relativity to the Standard Model, the product of a field operator (O(x)) with a coupling coefficient (k(x)) or its derivatives appears. Since it acts as a coupling, (k) can be viewed as a field in the theory or equivalently as a non-zero vacuum expectation value of a field. Given that the field operator (O) may behave non-trivially under spacetime transformations and the Lagrangian density is a scalar under general coordinate transformations, the field (k) can have spacetime and local indices. In EFT, the operator (O) is bosonic and thus includes spinor fields only as fermion bilinears, meaning the field (k) has no spinor indices [45].

Part Three

3. Early Universe

3.1 Quantum Chromodynamics (QCD)

This theory predicts that a phase transition from quark-gluon plasma to a hadronic gas occurs in the early universe at a critical temperature of MeV. Only at low net baryon density does lattice theory show a rapid transition from quark-gluon plasma to the hadronic phase. In the standard Big Bang scenario, the baryon asymmetry $\eta B \sim 10^{-10}$ - 10^{-9} exists even before the QCD phase transition, leading to the idea of an initial first-order QCD phase transition in the early universe being largely abandoned. A quantitative model of inflation during the QCD phase transition at high baryon density may exist, which is not in conflict with current cosmological observations [46].

The fluid forces associated with primordial magnetic fields (PMFs) create small-scale density fluctuations that contribute to the linear power spectrum of matter in the ΛCDM model on small scales. These enhanced small-scale fluctuations lead to the earlier formation of galactic halos and stars, thereby affecting cosmic reionization. Radiative feedback from stars not only halts their growth but also inhibits the formation of additional stars within the same pre-galactic object until the first star reaches the end of its life as a supernova [47] .Space telescopes have been used to explore the state of the infant universe, approximately 380,000 years after the Big Bang, through observations of cosmic background radiation.

The precise measurement of Cosmic Microwave Background (CMB) temperature fluctuations has established the current standard cosmological model, which includes the unknown cosmic boundary during the dark ages, a period when the universe was only a few hundred million years old. When the primordial gas became neutral and decoupled from photons, the average energy of CMB photons shifted to infrared, resulting in a complete darkening of the universe. Approximately one hundred million years had to pass before the first generation of stars could be born, illuminating the universe once more and ending the cosmic dark ages. The first stars were the initial sources of light and synthesized heavy elements, enabling the formation of subsequent generations of stellar populations and planets, ultimately leading to the emergence of life.

A model widely accepted as the standard model is consistent with a set of observations of cosmic structure. According to this model, all structures are seeded during a rapid expansion phase known as inflation. Inflationary models of the universe predict that initial density fluctuations have very simple characteristics. The density field is represented by a random Gaussian field, whose power spectrum follows a power law close to $P(k) \propto k_n$ as a function of the wave number k, with n being very close to 1. Such density fluctuations are expected to have larger amplitudes at smaller scales. Consequently, the formation of structures is anticipated to occur hierarchically [48] .

The formation of dark matter halos that host early star-forming gas clouds can be described using fundamental physics. Dense regions in the initial density field grow denser and denser, with each ultimately collapsing under gravity until the average density within surpasses a specific threshold. Such a collapsed object reaches dynamic equilibrium through the process of virialization, subsequently forming a dense clump of dark matter. Due to its hierarchical nature arising from initial random density fluctuations, the formation of dark matter halos occurs similarly, regardless of mass and size. In contrast to dark halo formation, which is driven solely by gravity, star formation involves several physical processes.

First and foremost, a sufficient amount of cold, dense gas must be gathered to initiate star formation in the early universe. Gas within a dark halo can only cool and become dense if radiative cooling operates efficiently [48]. The difference in velocity between dark matter and baryons significantly impacts gas accretion into the first star-forming mini-halos, which have a mass of about (10^6). In fact, the gas halo is often significantly located behind the mini-halos [49].

Computer simulations suggest that stars and galaxies emerged when the universe was around 100 million years old. Prior to that, the universe went through a period known as the "Dark Age," when it was nearly completely dark. Space was filled with a colorless, uniform material composed of dark matter and a fraction of hydrogen and helium, becoming diluted as the universe expanded. Matter was partially inhomogeneous in density, and gravity helped amplify these density fluctuations: denser regions expanded more slowly than less dense areas.

By 100 million years, the densest regions not only expanded at a slower rate but began to collapse. Such regions contained about one million solar masses of matter each. They were the first gravitationally bound objects in the cosmos. Dark matter constituted a significant portion of their mass; however, as its name suggests, it could not emit or absorb light. Therefore, it remained in a vast cloud. Hydrogen and helium gas, on the other hand, emitted light, lost energy, and concentrated in the center of the cloud. Eventually, all collapsed into stars. These first stars were much larger than stars today—hundreds of solar masses[50]. Observations of the existence of massive early stars in the universe's early history indicate that the standard theory for cosmic structure growth predicts that structures grow hierarchically through gravitational instability [51].

3.2 Disturbances and Large Structures

The universe begins with inflation, characterized by density perturbations that are nearly scale-invariant, adiabatic, and of very small (and adjustable) amplitude, with a simple power spectrum given by (P(k) $\propto k^n$), where (n) is less than one. As the universe expands, the growth of these perturbations is initially dominated by radiation and subsequently regulated by dark matter. During the radiation era, the growth of matter perturbations slows down as they are surrounded by the cosmological particle horizon, leading to a specific scale imposed on the power spectrum related to the horizon at the time matter dominated the universe. At smaller scales, the power spectrum bends to (P(k) $\propto k^n$) .

Furthermore, dark matter perturbations are washed out by random thermal motions below the free-streaming scale, which corresponds to the typical comoving distance a particle travels over the age of the universe. This scale varies inversely with the particle mass, (m_X), such that ($\lambda_{fs} \propto m_X^{-1}$). The resulting linear power spectra at late times (e.g., at the time of recombination) can be classified into different states for hot dark matter (HDM), warm dark matter (WDM), and cold dark matter (CDM). For HDM with ($m_X \sim 30$) eV, the characteristic mass associated with the free-streaming length is roughly the mass of a large galaxy cluster; for WDM with ($m_X \sim 2$) keV, it corresponds to the dark halo of a dwarf galaxy; while for CDM with ($m_X \sim 100$) GeV, it is associated with the mass of the Earth.

Consequently, the smallest structures that can directly form fundamentally differ in each case: for HDM, superclusters form first and must fragment to create galaxies; for WDM and CDM, small objects form first and grow by merging and accreting into larger systems. Dark matter objects can be significantly smaller than galaxies in CDM. The proposal for generating inflationary perturbations coincided with increased interest in particle dark matter, marked by the release of the first extensive three-dimensional survey of galaxies, the CfA redshift survey. Although this survey is small by today's standards, it provided the first clear picture of the richness of the large-scale galaxy distribution and offered a glimpse of what would later be termed the "cosmic web". The CfA survey raised questions about the origins of this cosmic web. Ideas derived from particle physics provided an intriguing perspective for understanding large-scale cosmic structure as a result of fundamental physics. All that was needed were tools to calculate how the initial linear conditions reflected in today's observable nonlinear universe [52] .

3.3 The Standard Cosmological Model

This model assumes that the largest structures we observe today—galaxies and galaxy clusters—grew from small initial fluctuations that were seeded during the inflationary phase, approximately (10^{-35}) seconds after the Big Bang. These fluctuations then grew under the influence of gravity. Most growth occurred after the decoupling of photons and electrons, about 350,000 years after the Big Bang, when photons were no longer coupled to baryons and did not exert pressure on them through radiation pressure. In the valid linear theory at early times and large spatial scales, when the fluctuations in the energy density of matter (OL) are less than unity, the density of matter (PM) evolves independently of the spatial scale (k) [53].

We know that significant evolution occurs in galaxies over time, as the density of stellar mass in galaxies evolves rapidly in the range ($1 < z < 3$), with about half of the total stellar mass in galaxies formed by (z = 1). We also know that there are diverse star formation histories for individual galaxies and that the integrated star formation rate density in the history of the universe peaks at (z ~ 2.5) and declines at higher and lower redshifts. However, these observations do not clearly indicate what driving forces create galaxies. We now believe that galaxy formation can occur through several pathways, including star formation in situ within a collapsing galaxy, major and minor mergers, and the accretion of gas from the intergalactic medium. The structure and morphology of galaxies may be the best way to trace these processes [54] .

3.4 Primordial Black Holes and Large Structures

The standard cold dark matter (CDM) scenario is characterized by two assumptions: dark matter consists of massive particles with weak interactions (WIMPs); and cosmic structures evolve from primordial clouds to galaxies and galaxy clusters through a hierarchical structure formation process. Primordial black holes with mass (m) provide a source of fluctuation for objects with mass

($M_\odot$) in two ways: (1) through the seed effect, where the Coulomb effect of a single black hole induces an initial density fluctuation of (m / $M_\odot$); (2) through the Poisson effect, where a fluctuation of (√N) in the number of black holes generates an initial density fluctuation. Both types of fluctuations then grow through gravitational instability to connect regions with mass)$M_\odot$).

It is important to note that the seed does not have to be a black hole; a connected cluster of smaller objects or ultracompact minihalos (UCMHs) would also be equally effective. In fact, the required density fluctuations for forming (UCMHs) would be significantly smaller, so they would typically be more abundant than primordial black holes. Furthermore, the mass of primordial clouds is small enough that the Poisson effect can only connect them if primordial black holes significantly contribute to dark matter. Let us consider the fiducial example where primordial black holes contribute a fraction (f) of dark matter density at (100 $M_\odot$). In the LCDM scenario, Jeans mass fluctuations of about ($10^6\ M_{J6}\ M_\odot$) provide the first dark dwarf galaxies at (z ∼100) .

These dwarfs, which form before ionization, are the building blocks of the next generation of dwarfs, some of which may correspond to the low-metallicity dwarfs observed in recent deep surveys. The proposal that dark matter may consist of primordial black holes (PBHs) in the mass range of intermediate-mass black holes (IMBHs) has recently garnered significant attention due to LIGO's discoveries of binary black holes with masses around (30 $M_\odot$). Since these black holes are larger than expected, it has been suggested that they may represent a new population.

One possibility is that they originated from Population III (i.e., formed between decoupling and galaxies). The suggestion that LIGO might detect gravitational waves from merging intermediate-mass black holes from Population III was first put forth by Band and Kerr (1984) and significantly – Kinugawa et al. (2014) predicted that the Population III merger peak at (30 $M_\odot$) would occur shortly before LIGO's first discovery. Although the origins of black holes associated with LIGO events remain uncertain, LIGO results and data from other gravitational wave detectors – such as eLISA and Pre-DECIGO – may be able to distinguish between binary black holes from Population II, Population III, or primordial origins.

For example, Pre-DECIGO will be capable of measuring the mass spectrum and (z)-dependence of the merger rate. Another important signature may arise from the spin distribution and eccentricity of merging black holes. As Carr first emphasized, a population of primordial black holes with significant mass is also expected to produce a stochastic background of gravitational waves, and it would be interesting if some primordial black holes are in binaries that are converging due to the loss of gravitational radiation in the present era. Sufficiently massive primordial black holes could influence the development of large-scale structures and thus help resolve issues within the cold dark matter scenario.

For instance, primordial black holes might grow through accretion to form supermassive black holes in active galactic nuclei (AGN). Alternatively, if supermassive black holes are themselves primordial, they could play a role in galaxy formation, either through Poisson fluctuations in their number density or due to their gravitational Coulomb effect. They require a minimum initial mass of ($10^6\ M_\odot$), but their contribution to dark matter density is only (10^{-3}). Slightly smaller primordial black holes could allow for the earlier-than-expected connection of baryonic clouds, potentially altering baryonic feedback in dwarf galaxies and producing other domino effects for cosmic structure development [20].

3.5 The Role of Dark Matter in The Growth of Structures

Galaxy redshift maps probe the large-scale structure in the redshift range, and the evolution of clusters in addition to the growth factor (δ(t)) depends on the growth rate ($f = d\ln\delta / H\,dt = d\ln\delta / d\ln a$), which is introduced in redshift-space distortions (RSD). Working with the scale factor (a) or redshift ($z = a^{-1} - 1$), and also normalizing the growth factor to remove the dominant matter behavior ($\delta^{md} \sim a$) in this case using ($g(a) = [\,\delta(a)/\delta(a_i)]/(a/a_i)$) is appropriate, where a_i is the initial scale factor during the matter-dominated era when (g = 1) and (f = 1). The growth evolution equation can then be written as follows [55].

$$0 = a^2 \frac{d^2 g}{da^2} + (5 + \frac{1}{2}\frac{d\ln H^2}{d\ln a})\, a\, \frac{dg}{da}$$
$$+ (3 + \frac{1}{2}\frac{d\ln H^2}{d\ln a} - \frac{3}{2}\,[\Omega_b(a) + F_{cl}(a)\Omega_{dm}(a)]\,)\, g$$

This equation shows that the evolution of large-scale structure in the universe depends on various factors, including the growth factor (δ(t)) and the growth rate (f). Using this equation, we can study the evolution of large-scale structure in the universe and gain a better understanding of cosmic processes. Deviations in cluster power (or in the evolution of dark matter density) can be expressed as follows:

$$f\,\sigma_8(a) = \frac{\sigma_{8,0}^{LCDM}}{g_0^{LDCM}}\, a g\, (1 + \frac{d\ln g}{d\ln a})$$
$$\sigma_{8,0}^{LCDM} = 0.8 \quad , \quad g_0^{LDCM} = 0.779$$

Since growth is a dynamic process, it is expected that growth at a given time is influenced by conditions at all previous times. Therefore, a tomographic survey covering a wide range of redshift transitions will be useful in demonstrating the timing of deviations. Note that (F_{cl}) can be interpreted as all clustered dark matter with a gravitational power (N_G) or just part of the clustered dark matter, for instance, if multiple species of dark matter exist. The evolution of dark matter density affects both the source term and the expansion of the background in the growth equation.

The density evolution can be expressed in terms of the dark matter equation of state parameter (w_{dm}). We allow this parameter to vary independently across four scale factors, similar to before, with standard behavior ($w_{dm} = 0$) for ($a < 0.2$). Clustering is also affected by this parameter. The power in this section is preserved in the standard gravitational coupling (N_G) (which essentially follows the generalized dark matter paradigm), where the properties of dark matter are described by (w_{dm} (a)), the sound speed (c_s (a)), and the viscous sound speed (c_{vis} (a)). To focus on the impact of variations in dark matter density evolution, we fix (c_s (a)) and (c_{vis} (a)). to their standard values of zero. In any case, their effects are generally small, as density evolution is related to the equation of state through the following relationship [55].

$$\rho dm \ = \ \rho dm \ (a = 1) \ c^{3 \int_a^1 (\frac{d\acute{a}}{\acute{a}})[1 + w(\acute{a})]}$$

$$\Omega_{dm\,,0} \ \neq \ \Omega_{dm\,,0}^{LCDM}$$

$$\Omega_{dm\,,0} \ = \ \Omega_{dm\,,0}^{LCDM} \ a_1^{3w_1} a_1^{3(w_2 - w_1)} a_1^{3(w_3 - w_2)} a_1^{3(w_4 - w_3)}$$

In the high redshift transition, the following equation is valid:

$$\frac{H^2(a \ < \ a_1)}{H_0^2} = \Omega_{m\,,0}^{LCDM} \ a^{-3} \ + \ 1 \ - \ \Omega_{b\,,0} \ - \ \Omega_{dm\,,0}$$

Since (H^2(a < a1)) differs from the reference LCDM model by a factor of (a^3) (therefore it is only a small amount at high redshift transition), growth is actually influenced by a small amount even before the first binary. It is straightforward to calculate from the equation that the growth rate (f) and consequently the growth factor (g) differ from the reference model. As (Ω_{dm}, 0) decreases with increasing (w_i), this growth stops for positive (w_i) [55].

3.6 Weak Gravitational Lensing

Weak gravitational lensing refers to subtle changes in the shapes of galaxies due to intervening large-scale structures, serving as a highly powerful tool for studying the growth of cosmic structures. Weak gravitational lensing is sensitive to the presence and distribution of mass along the line of sight between the observer and the source galaxies. This method, proposed in the 1960s and first detected in 2000, has become a flagship in large-scale structure studies. Weak gravitational lensing is also known as cosmic shear because it statistically measures the shear in observed galaxy shapes due to photon deflection, providing information about the projected mass along the line of sight.

The main feature of cosmic shear is the absence of galaxy bias. Although measuring galaxy shapes (for cosmic shear) is more challenging than measuring galaxy positions (for galaxy clustering), the absence of possible transformations between bias and structure growth makes cosmic shear a superior cosmological tool. A key quantity in cosmic shear is the convergence) κ), defined at every point in the sky and proportional to the projected mass density between the observer and the source galaxy. Specifically, the convergence for a single lens and a single source galaxy is given by the following [56].

$$\kappa \ = \ \frac{d_L \, d_{SL}}{d_S} \int_0^{\chi} \nabla^2 \Phi \, d\chi$$

where (d_L), (d_S), and (d_{SL}) are the distances between the observer and the lens, the observer and the source galaxy, and the lens and the source galaxy, respectively. Here, (d) is the angular diameter distance, related to the comoving distance (r) through the relation (d(z) = r(z) / (1 + z)), while (χ) is the comoving coordinate distance, related to (r) by standard relations; in a flat universe, (r = χ). Additionally, (Φ) is the three-dimensional gravitational potential, integrated along the line of sight in the above equation. A quantity closely related to is (γ), which, along with convergence, forms the components of a 2×2 matrix defining the image distortion at any point in the sky. By transforming convergence into harmonic space and assuming statistical isotropy, one obtains the convergence power spectrum (P^{kk}), which is defined as the expected value of the product of two convergence fields at different points in harmonic space [56].

$$\kappa_{\ \ell \mathrm{m}} \kappa_{\ \acute{\ell} \acute{m}} \ = \ \kappa_{\ \ell \acute{\ell}} \kappa_{\ m \acute{m}} \, P^{\kappa\kappa}(\ell)$$

3.7 The Fukugita and Peebles model

Cosmology strongly suggests that galaxies should reside in virial temperature halos. First, standard cosmology predicts that only a minority of baryons are found in stars and cold interstellar gas. In galaxy-rich clusters, the "missing" baryons are directly detected through X-ray emission. In low-density environments, such as the Local Group, the surface brightness of X-ray emission is thought to be too low to be detected by current instruments.

Second, three lines of reasoning suggest that star formation is an inefficient process, where as much gas is ejected from the star-forming system as is converted into stars: 1) We indeed observe winds blowing from star-forming disks; 2) Spectra of some quasars reveal blue-shifted absorption line systems, indicating massive winds flowing from the star-forming host galaxy; 3) In galaxy clusters, about half of the metals synthesized by stars are found in the intergalactic medium. Our assumption is that most of the baryons associated with the dark matter of our galaxy form a virial temperature gas halo, and the gas that supports star formation in the disk is drawn from this halo. The question is, how does gas transfer from a pressure-supported halo to a centrifugally supported disk? [57]

In the Fukugita and Peebles model, the halo density decreases with radius as $r^{-3/2}$, and at 10 kpc, the electron density is 2.6 × 10^{-3} cm^{-3}. The halo is assumed to be isothermal, with T_h = 1.8 × 10^6 K. The cooling time of gas with metallicities [Fe/H] = -1, -0.5, in pressure equilibrium with plasma at this temperature and mean halo density, between 8 and 12 kpc, is shown. At T ~ 2 × 10^6 K, the cooling time is approximately 300 million years. As the temperature decreases to 5 × 10^5 K, the cooling time shortens by about 40%, reaching ~8 million years, which is shorter than the dynamical time at the galactic radius R_0.

As the temperature decreases further to 2.5 K, the cooling time drops by more than an order of magnitude, reaching 0.4 million years. Therefore, although the cooling time of ambient gas in the outer halo is long, any temperature decrease significantly shortens the cooling time. In the Fukugita and Peebles model, plasma flows inward at a rate of $\sim 1 M_\odot\, yr^{-1}$. The work done by compression compensates for X-ray losses, so the plasma temperature remains at 1.8 × 10^8 K. The mass of H_I is uncertain: in an external galaxy, it is unclear where to set the boundary between the disk and H_I for |z|, and a similar issue exists for our own galaxy [57].

The line-of-sight velocity inhomogeneity that separates the halo from the H_I disk (Halo Gas), which exists in intergalactic and galactic environments) is considered. If the disk-halo boundary in NGC 891 is conservatively set at 1.3 kpc, the mass of the H_I halo is approximately ~ 6 × 10^8 $M_\odot$. It is concluded that about 10 percent of the H_I in our galaxy is halo gas, and the total mass of H_I within 12 kpc (the region where most star formation occurs) is about 4.5 ×10^8 $M_\odot$. Therefore, the mass of the H^I halo within 12 kpc is about 4.5 ×10^8 $M_\odot$. The H_I halo is primarily confined to the region |z| < 5 kpc. Thus, we compare the mass of the H_I halo at R < 12 kpc with the mass of the coronal gas in the cylindrical ring where 4 ≤ R / kpc ≤ 12 and |z| < 5 kpc.

The mass of the coronal gas is about ~2 × 10^8 $M_\odot$, indicating that within this volume, there is more than twice the amount of H_I gas compared to coronal gas, even though the coronal gas occupies nearly all the space. The clouds forming the H_I halo typically take about 100 million years to travel from their launch point in the plane through the halo and back to the plane. As a result, over 1 billion years, approximately ~ 4.5 × 10^9 $M_\odot$ of H_I passes through the lower corona, which contains 2 × 10^8 $M_\odot$ of gas. Therefore, if only 4.5 percent of the gas that passes through the corona in one billion years mixes with the coronal gas, the temperature of the coronal gas would decrease by half. This temperature drop reduces the cooling time of the coronal gas to approximately 0.1 billion years, which is the local orbital time [57].

1. A Brief and Different Look at Structure Growth

We begin with the following equation:

$$\ddot{\delta} = 2H\dot{\delta} - 4\pi G\rho_M\,\delta = 0 \qquad (1)$$

This equation can be solved numerically for any arbitrary cosmological model. The required inputs are the Hubble parameter as a function of time, $H(t)$, and the matter density, (ρ_M) (t)). However, in single-component universes, where the expansion is dominated by a single component of matter, radiation, or dark energy, the Hubble parameter is governed by radiation density rather than the prevailing matter density. If

$$(4\pi G\rho M \ll H^2): \ddot{\delta} + 2H\dot{\delta} = 0 \quad , H = 1/2t$$

$$\Rightarrow \delta(t) = A_1 + A_2 \ln t \ , \ A_1, A_2 = const \quad . \quad \text{If } (\delta(t) \propto t^n):$$

Equation (1) will take the form that yields two roots: (n = 3 / 2) and (n = -1). Therefore, in a matter-dominated universe, perturbations grow as a power of time. The growth equation simplifies to (n (n - 1) + 4n / 3 – 2 / 3 = 0). Consequently, in a matter-dominated universe, perturbations grow in two ways: one as a power of time, specifically ($\delta \propto t^{2/3}$), and the other decreases with time, represented as (δ ∝ - t) [56].

$$\delta(t) = B_1 t^{2/3} + B_2 t^{-1} \ , \ B_1, B_2 = const$$

The growth of perturbations scales with the scale factor. This scaling is of paramount importance because the universe spends approximately 10 billion years in a matter-dominated era, from the equality of matter and radiation 50,000 years after the Big Bang to the onset of dark energy a few billion years ago. During that time, structures in the universe grow significantly, all thanks to the scaling ($\delta \propto a$). It is important to note that the linear growth function depends on the Hubble parameter (H (a)) and he matter density (Ω_M). Therefore, the linear growth function is contingent upon fundamental cosmological parameters. Galaxy clustering is one of the primary tools in cosmology, and its measurements provide the main pathway for isolating and constraining the growth of cosmic structure.

Measurements of galaxy clustering limit the power spectrum P (k, z) or, equivalently, the two-point correlation function (ξ (r, z)) over a range of scales. What informs us about the temporal growth of cosmic structure is its dependence on redshift (z). In linear scales, where galaxy bias is expected to be scale-independent, this temporal dependence of bias unfortunately correlates with the temporal growth of cosmic structure. Breaking this correlation requires independent prior information about the bias or combining galaxy clustering with other cosmological measurements [56].

4.1 Nuclear Fusion

The physical representations of high-energy density (HED) plasmas are based on models of plasma properties. For instance, the internal structures of astrophysical plasmas, such as stars, are often inaccessible for direct measurements. In his influential work on the internal structure of stars, Eddington poses this dilemma but continues to assert that we can still construct physical images of the internal functioning of a star, provided we know the properties of the material present. More accurate information may be available for laboratory plasmas, such as inertial confinement fusion explosions and Z-pinches. However, constructing a complete physical description typically requires material property models.

Radiation often plays a fundamental role in astrophysical and laboratory HED plasmas, with opacity being a crucial material property that determines how transparent or opaque the plasma is to radiation. Opacity is generally a rapidly varying function of frequency. In certain applications, knowledge of frequency-dependent opacity is essential, and this is something that must be measured in reference experiments. An example of this is the sinking of "metals" in the cores of stars. Here, "metals" refers to any element other than hydrogen or helium, a definition commonly used in astrophysics. These elements are distributed toward the centers of stars under the influence of gravitational forces. The opposing buoyant force is provided by radiation pressure, which is dependent on frequency-dependent opacity [58].

In other applications, the most important quantity is the average opacity, which considers the mean frequency. An example of this is the transfer of energy by scattering radiation within the cores of stars. Given this simplification, one might ask: why use opacity models? Why not simply measure the required average opacity? The issue is that opacity depends on the plasma, specifically on the density, temperature, and chemical composition of the plasma. Measuring opacity under all plasma conditions is not feasible; thus, opacity models are necessary to predict opacity under various conditions[59].

This issue is of great importance for understanding the structure and evolution of different stars. Despite the considerable efforts of scientists, theoretical reaction rates remain relatively uncertain, especially at high densities, where uncertainties have two aspects: the first aspect relates to nuclear physics and deals with the appropriate resolution of nuclear interaction transitions, which is suitably described by the astrophysical factor (S). The other aspect is associated with plasma physics and pertains to the proper description of Coulomb barrier penetration in a dense many-body system. Carbon burning represents the third stage of stellar evolution for high-mass stars; this phase occurs after helium burning, during which helium is converted into carbon-12 through the triple-alpha process. Carbon burning marks the first stage in stellar evolution governed by processes involving heavy ion fusion. The most significant reaction in the carbon burning stage is the fusion of two carbon-12 nuclei. Additional processes may include carbon-12, carbon-16, and two carbon-16 nuclei. Carbon burning is also crucial for type Ia supernovae. The explosions of these supernovae are driven by carbon fuel in the high-mass white dwarf cores. The burning process progresses from the carbon burning region near the center of a white dwarf through detonation or deflagration throughout the entire white dwarf. The conditions for burning and the timescale are defined by the reaction rate of (C12, C12).

At high densities, reaction cross-sections are significantly influenced by the strong plasma screening, which reduces the Coulomb barrier between (C12) or (O16) nuclei. Explosive carbon burning in the crust of accreting neutron stars has recently been proposed as an energy source and potential trigger for supernova explosions. In this model, small amounts of carbon (3% - 10%) that remain from the preceding process during neutron thermal runaway ignite after the ashes are compressed to an effective density. For this model, carbon burning occurs under specific thermal conditions with strong plasma screening. At high densities or low temperatures, the thermal reaction rate formalism is insufficient, as the fusion process is primarily driven by the high-density conditions present in stellar matter [58].

The nuclear density distribution can be determined through various methods. Density Functional Theories (DFT) provide a successful description of many ground-states nuclear properties, particularly the charge distribution in the known experimental region. Since these theories are valid across the entire periodic table, it is expected that they will also offer reliable predictions for nuclei that are far from stability. Non-relativistic density functionals, such as Skyrme or Gogny functionals, have been widely used. In recent years, relativistic density functionals have played an important role as they provide a fully consistent description of the spin-orbit coupling.

This is particularly crucial for nuclei that are far from stability. The spin-orbit splitting determines the shell structure, which is the most important component in any microscopic theory of finite nuclei. Indeed, the results obtained using relativistic functionals are in very good agreement with experimental data across the entire periodic table, despite having fewer adjustable parameters compared to their non-relativistic counterparts. The most well-known of these is the Relativistic Hartree-Bogoliubov theory, which incorporates pairing correlations with finite-range pairing forces. This theory offers a unified description of mean-field and pairing correlations in nuclei [58].

5. Conclusion

This paper begins with a comprehensive review of the phenomena of dark energy and dark matter, examining various models proposed to explain these cosmic phenomena. Following this, the paper explores the pivotal role of cosmic plasma in various astrophysical processes, analyzing it within the context of effective field theories and the conditions that govern such phenomena. The third section delves into the dynamics of star formation in the early universe, offering a detailed examination of perturbation theory, the growth of large-scale structures, and the models associated with them. The section concludes with a brief yet insightful discussion of nuclear fusion and its crucial role in stellar evolution. The article underscores that a deeper understanding of cosmic plasma, along with its interactions with dark matter, is essential for enhancing our overall comprehension of the universe.

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