Dean&Francis
ISSN 2959-6157

# From Inflation to Structure Formation: The Universe's Evolutionary Path

**Siyi Du**[1]

[1]Department of Physics, University of California, Davis, California, USA

*Corresponding author: syidu@ucdavis.edu

**Abstract:**

This paper examines the evolutionary path of the universe from the period of cosmic inflation to the large-scale structures formation, such as clusters and galaxies. The inflationary model, which proposes a rapid exponential expansion shortly after the Big Bang, is explored in detail to explain the uniformity of the Cosmic Microwave Background (CMB) and the large-scale isotropy observed today. Key phases, such as the Recombination Era and Structure Formation, are analyzed, highlighting the role of dark matter in the gravitational collapse of baryonic matter and the formation of cosmic structures. The findings confirm that inflation is a crucial framework for understanding the universe's large-scale properties, although challenges remain in explaining early galaxy formation and the nature of dark energy. Observational evidence from missions like WMAP and Planck provides strong support for the inflationary model, yet new discoveries from the James Webb Space Telescope prompt a reconsideration of early cosmic evolution models.

**Keywords:** Cosmic inflation; Cosmic Microwave Background (CMB); Early universe

## 1. Introduction

The universe's evolution is a complex process. It is commonly considered to begin with a rapid expansion known as cosmic inflation occurring in the first millisecond after the Big Bang. The inflation is important for explaining several fundamental observations in cosmology, such as the uniform cosmic microwave background (CMB) radiation and the displacement of large-scale structures in the universe. Inflation theory proposes that during this period, the universe expanded exponentially, eliminate out irregularities and effectively set the initial conditions for the cosmic structures to develop. After inflation, the universe went through a series of crucial phases, including reheating, recombination, and the formation of the first stars and galaxies. The interaction between dark matter, dark energy, and baryonic matter shaped the formation and gathering of galaxies, creating to the large-scale structures we observe today. Understanding this evolutionary path from inflation to the complex cosmic structures formation is essential for advancing our knowledge of the universe's origins and ultimate fate. The primary objective of this review is to trace the evolutionary path from cosmic inflation to the beginning of all the large-scale

ISSN 2959-6157

structures in the universe. This involves examining key theoretical frameworks, such as the inflationary model, and the subsequent stages of cosmic evolution that lead to structure formation. By exploring both observational evidence and simulation techniques, this review aims to provide a comprehensive overview of the processes that underpin the formation of structures, while also discussing current challenges and future prospects in the field of cosmology[1].

# 2. Theoretical Framework

## 2.1 Cosmic Inflation

Cosmological inflation proposes a period of rapid exponential expansion in the newborn universe, occurring between $10^{-36}$ and $10^{-32}$ seconds after the so-called Big Bang. This theory addresses several basic cosmological questions such as the horizon, flatness, and monopole. The mechanism involves a scalar field famously known as inflation, which drives the universe's accelerated expansion through its potential energy. During inflation, the inflation field undergoes slow-roll conditions where its potential energy significantly exceeds its kinetic energy, allowing for continued exponential growth. Quantum fluctuations in the inflation field during this phase are stretched to cosmic scales, seeding the large-scale structure of the universe, including galaxies and clusters. At the end of inflation, the universe transitions to a radiation-dominated state through a process called reheating, where the inflation field drops into small particles that heat the universe. Observational evidence supporting inflation includes the uniformity of the cosmic microwave background (CMB), the flatness of the universe, and the distribution of large-scale structures, all of which are consistent with inflationary predictions and have been confirmed by experiments like Planck and BICEP2.

## 2.2 Post-Inflationary Universe

Inflation is a expansion period of supercooled. By a factor of about 100,000, the temperature drops. The exact factor depends on the model. This low temperature is conserved during the inflation era. When the inflation era ends, the temperature goes back to pre-inflationary status. When the Inflation era comes to an end, the universe starts reheating. This stage is believed to generate matter and radiation when it transits from the high-speed inflationary expansion to slower expansion, dominated by radiation. The potential energy of the inflation field becomes particles. It fulfills the complete universe with particles of Standard Model. Such as electromagnetic radiation. It starts with the radiation-dominated phase. The baryon overload might be a phenomenon during this process. However, the inflation field's nature is still unknown, and makes the epoch poorly understood. Developing a convincing and numerically satisfying model of this stage is still an continuing area of research [2].

## 2.3 Structure Formation

Most scientists in this area firmly believe that observations indicate the domination of dark matter and dark energy. Yet none of those two have been verified in the lab. Baryonic matter makes up planets, stars and all visible matters, but it is only a small part of our big universe. Electromagnetic radiation contributes even less. Groups of galaxies are not uniformly distributed in local regions, but on sufficiently large scales, the distribution is close to isotropic. This isotropy is supported by electromagnetic distributions, such as X-rays and the cosmic microwave background, which are almost isotropic. When people look further out into space, they can only see objects in their early states because of the limited speed of light. There is clear observational evidence that the distribution of objects such as galaxies changes over time.

# 3. Key Stages of Evolution

## 3.1 Inflationary Era

The inflationary epoch represents the fast exponential expansion in the infant universe, which begins after $10^{-32}$ seconds of the big bang. It is driven by inflation field. During this period, the universe expanded by a factor of at least 1026. This big expansion smoothed out initial irregularities. It explains why the universe today appears homogeneous and isotropic (looks the same in every direction). Inflation also solved the horizon problem by allowing distant regions of the universe to be close enough in the past to interact before the expansion separated them. The rapid growth also flattened the universe, which suggests the universe is geometrically flat and not curved. It could have been curved without inflation. Also, inflation stretched small quantum fluctuations in the early universe to astronomical scales, which provides the seeds for the formation of galaxies and large-scale cosmic structures. These fluctuations are magnified during inflation first, and then evolved under gravity to form the galaxies, clusters, and the intricate cosmic web we observe today. The Inflationary Era explains the large-scale structure of the universe and is now a key component of modern cosmological theory.

### 3.2 Recombination Era

When the universe cooled below 3000 K and the redshift was about $z \sim 10^3$, the radiation and baryon decoupled. At temperature lower than this, proton nuclei can catch and store free electrons to generate hydrogen atoms that is electrically neutral. This is a process also known as "recombination." This is because there are fewer high-energy photons capable of separating hydrogen atoms. In 1968, Peebles [3] analyzed the cosmological recombination. They found that even after the recombination era, enough charged particles were still enough present to keep the universe being a good conductor today. The recombination process takes a limited amount of time, resulting in a surface of non-zero thickness. On this surface, neutral baryons and photons are decoupled. Once decoupling occurs, the mean free path of the photons expands rapidly, allowing them to move almost freely with no restriction. This "last scattering surface" became the original source of the cosmic microwave background (CMB) that we observe today. It is like an electromagnetic opaque "cosmic ball of light."

### 3.3 Formation of the First Structures

Once the initial material condenses, radiation disperses, resulting in a somewhat uneven distribution of dark matter that interacts with gravitational forces. This interaction leads to the formation of a "halo" as dark matter collapses. Subsequently, it attracts ordinary or baryonic matter, predominantly hydrogen. As gravitational forces increase the density of hydrogen, stars begin to form and emit ultraviolet light, which reionizes the surrounding atoms. Gravitational interactions unfold in a hierarchical manner, starting with the emergence of the first stars and clusters, followed by the formation of galaxies, clusters, and superclusters. Dark matter is crucial in this process, as it interacts solely through gravity. The gravitational instability that facilitated structure formation was not mitigated by opposing forces such as radiation pressure. Consequently, dark matter disperses into a complex network of halos prior to the dispersal of ordinary matter. In the absence of dark matter, the formation of galaxies would have occurred significantly later than what is currently observed. The physics governing structure formation during this epoch is relatively straightforward: dark matter perturbations of varying wavelengths evolve independently. As the universe expands, the Hubble radius encompasses increasingly larger perturbations. Throughout the matter-dominated era, all dark matter perturbations experience growth through gravitational clustering, although the short-wavelength perturbations from the radiation-dominated period hinder their growth until matter begins to prevail. During this phase, the evolution of luminous baryonic matter closely mirrors that of dark matter, with their distributions being intricately linked[1].

## 4. Observational Evidence

### 4.1 Techniques and instruments

CMB observations, especially through missions like WMAP and Planck, have been fundamental in exploring the early universe. Launched in 2001, WMAP project provided measurements of temperature fluctuations in the CMB detailed, solidified the inflationary model and offered thoughts into the universe's age and composition. Planck, launched in 2009, further improved these observations by enhancing the precision of temperature and polarization measurements. It allows a more accurate understanding of cosmic inflation and key cosmological parameters.

In addition to CMB observations, large-scale structure surveys like the Dark Energy Survey and the Sloan Digital Sky Survey have mapped the distribution of galaxies and cosmic structures across vast distances. These surveys provide crucial data on galaxy clustering and cosmic evolution, helping constrain cosmological models and refine our understanding of dark energy and structure formation. Upcoming missions like Euclid are set to further expand our knowledge by mapping billions of galaxies, offering deeper insights into the large-scale geometry of the universe [5].

### 4.2 Key Observations

The Planck spacecraft's measurements show that the universe is flat and homogenous by low error, consistent with inflation's explanation. BICEP2 provided direct evidence for gravitational waves produced during the inflationary era by the detection of B-mode polarization in the CMB. This swirling pattern in the polarization of light is a unique prediction of inflation. The initial findings were rechecked because of potential galactic dust contamination. However, the data still supports inflation, supported by newer experiments like BICEP3. Inflation predicts that cosmic structures rose up from early universe quantum fluctuations. It result in a spectrum of perturbations that is nearly invariant of scale. The Planck satellite observations confirm this spectrum with a spectral index very close to predicted values. These fluctuations provided the seeds for the galaxies and clusters we observe today, consistent with inflation's predictions. Additionally, ongoing studies of gravitational waves and B-mode polarization continue to refine our understanding of the energy scale and early

ISSN 2959-6157

dynamics of inflation(SLAC National Accelerator Laboratory)[6].

# 5. Analytical Methods

## 5.1 Simulation Techniques

Modeling cosmic inflation and structure formation requires a combination of simulation techniques to capture the universe's early and later evolution dynamics accurately. N-body simulations play a big role in studying the behavior of dark matter. It treats dark matter as a collection of particles that interact gravitationally. These simulations track the growth of dark matter structures from the initial small perturbations during the inflationary era to the formation of galaxies and galaxy clusters. Hydrodynamical simulations are built on this foundation. It considers baryonic matter, gas dynamics, star formation. These are crucial for understanding galaxy evolution. One of the leading examples of simulations is the IllustrisTNG project [7]. It provides scientists with a model of both dark matter and, baryonic physics as well. IllustrisTNG not only simulates the relatively large structure of the universe, but also allows researchers to study galaxy formation, supermassive black hole activity, and the interaction between dark matter and baryons. By initializing these simulations with data from the cosmic microwave background (CMB) and large-scale surveys, IllustrisTNG is able to copy the observed universe and understand how the universe developed into today's world by time.

## 5.2 Data Analysis

Power spectrum analysis is one of the most important tools to analyze the distribution of fluctuations in the CMB and the matter distribution across the universe. The power spectrum provides a statistical description of cosmic structures. It is used to compare simulations with observational data. Researchers can use it to test and refine models of cosmic inflation. Another method is called Cosmic Web Analysis. Cosmic web analysis focuses on identifying and characterizing large-scale structures. For example, filaments, voids, and galaxy clusters. This helps researchers trace the formation of the cosmic web. It shows how the dark matter framework turned to the network of structures we see today. Besides, Markov Chain Monte Carlo (MCMC) methods are widely used to fit cosmological models to data[8]. These methods provide precise estimates for critical parameters: the Hubble constant, dark matter density, and the amplitude of primordial fluctuations. This leads to a deeper understanding of the early universe, the inflationary period, and the cosmic structures formation.

# 6. Insights into inflation

Recent findings mainly from the CMB from the Planck and WMAP missions provided strong evidence that support the theory of inflation. These observations confirm several predictions of inflationary models[9]. For instance, the near-flatness of the universe and the scale-invariant nature of the initial density perturbations. The high precision CMB temperature fluctuations offers scientists a peak of the universe 380,000 years after the Big Bang. It gives scientists important ideas into the early universe's conditions. Also, inflation explains the uniformity of the CMB in big regions of space. Observational data also support inflation's explanation of the flatness problem. This is because the universe's curvature is very close to zero, according to measured data. It is perfectly predicted by inflationary theory. Another key finding is the detection of the primordial fluctuations in the density of matter. This laid the foundation for the development of galaxies and large-scale structures. What is more, non-Gaussianity constraints from CMB data suggest that single-field inflation models remain viable because they predict the Gaussian distribution of initial fluctuations observed in the CMB.

# 7. Discussion

## 7.1 Interpretation of Findings

The findings from CMB observations and large-scale structure surveys gives important insights into cosmic evolution. They enhance the belief that inflation played a important role in shaping the universe. Evidence that supports it, such as the near-flatness of the universe, and initial density fluctuations suggests that inflation explains the homogeneity and isotropy of the universe. Just like what we see in galaxy surveys and simulations, the formation of cosmic structures directly links primordial density perturbations to the structures we observe today. These results show how important dark matter and dark energy are in cosmic evolution. Dark matter influenced the early formation of galaxies and clusters through gravity. Dark energy pushes the accelerating expansion of the universe present days. Simulations like IllustrisTNG have been successful in replicating cosmic structures. They show how crucial dark matter and baryonic feedback are to galaxy formation. In summary, these observations improve our understanding of how the universe evolved. They help explain the transition from singularity to the complex cosmic structures we see now.

### 7.2 Comparison with Theoretical Models

Recently, there are many challenges to theories of universe evolution, mostly about early galaxy formation. One of the most famous findings comes from observations of giant galaxies in the early universe. For example, the galaxy HFLS3, discovered by the Herschel Space Observatory. It was found to be forming stars 2,000 times faster than the Milky Way when the universe wasn't even a billion years old [10]. According to current galaxy evolution theories, galaxies at this mass and star-forming rate won't exist so early after the Big Bang. This discovery gives a challenge to the "bottom-up" model, which predicts that galaxies grow slowly by merging smaller galaxies and accumulating gas. Also, the James Webb Space Telescope noticed six big galaxies that formed at about 600 million years after the Big Bang, some of them are as large as the Milky Way [11]. These fast galaxies' formation contradicts old models that suggest early galaxies should be small and evolve gradually. The discovery shows that galaxies in the early universe reached its maximum much faster than expected. This presents a significant puzzle for cosmologists.

### 7.3 lmplications for Cosmology

The universe's evolution impacts cosmology in many ways. It provides insights into its origins, structure, and future. The theory of inflation explains the universe's large-scale uniformity. And the cosmic microwave background offers a shot into its early state, which confirms the Big Bang theory. Also it refines models of dark matter and dark energy. These elements are crucial for understanding the formation of galaxies and the universe's accelerating expansion driven by dark energy. Additionally, cosmological constants and fine-tuning suggest a universe balanced for the development of complex structures. It raises questions about the multiverse and the anthropic principle[12].

## 8. Summary

The universe's evolution began with the super-fast expansion during the Inflationary Era, which smoothed out irregularities and stretched quantum fluctuations, setting the stage for the development of large-scale structures such as the galaxies and clusters. After inflation, the universe transitioned into the Recombination Era, where the cooling allowed protons and electrons to combine into neutral hydrogen atoms, leading to the decoupling of photons and the creation of the Cosmic Microwave Background (CMB). Following this, dark matter played a critical role in Structure Formation, as its gravitational interactions led to the formation of halos, which attracted baryonic matter, eventually forming the first stars, galaxies, and the cosmic web. Observational evidence from missions such as WMAP and Planck has confirmed many predictions of the inflationary model, providing insights into the universe's age, composition, and structure distribution. However, challenges remain, such as the discovery of massive galaxies early in the universe's history, which contradicts current models of galaxy formation. This, alongside unresolved questions about dark energy's nature and behavior, presents ongoing puzzles in cosmology. Overall, these findings significantly enhance our understanding of how the universe evolved from its early moments to its present complexity.

## References

[1] Liddle A R, Lyth D H. Cosmological inflation and large-scale structure. 2000.
[2] Ratra B, Vogeley M S. The beginning and evolution of the universe. Publications of the Astronomical Society of the Pacific, 2008, 120(865): 235.
[3] Peebles P J E. Recombination of the primeval plasma. Astrophysical Journal, vol. 153, p. 1, 1968, 153: 1.
[4] Dayal P, Ferrara A. Early galaxy formation and its large-scale effects. Physics Reports, 2018, 780: 1-64.
[5] Martin J, Ringeval C, Vennin V. How well can future CMB missions constrain cosmic inflation?. Journal of Cosmology and Astroparticle Physics, 2014, 2014(10): 038.
[6] Ade P A R, Aghanim N, Ahmed Z, et al. Joint analysis of BICEP2/Keck Array and Planck data. Physical review letters, 2015, 114(10): 101301.
[7] Pillepich A, Springel V, Nelson D, et al. Simulating galaxy formation with the IllustrisTNG model. Monthly Notices of the Royal Astronomical Society, 2018, 473(3): 4077-4106.
[8] Geyer C J. Introduction to markov chain monte carlo. Handbook of markov chain monte carlo, 2011, 20116022(45): 22.
[9] Hinshaw G, Larson D, Komatsu E, et al. Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: cosmological parameter results. The Astrophysical Journal Supplement Series, 2013, 208(2): 19.
[10] Riechers D A, Bradford C M, Clements D L, et al. A dust-obscured massive maximum-starburst galaxy at a redshift of 6.34. Nature, 2013, 496(7445): 329-333.
[11] Labbé I, van Dokkum P, Nelson E, et al. A population of red candidate massive galaxies~ 600 Myr after the Big Bang. Nature, 2023, 616(7956): 266-269.
[12] Bahr-Kalus B, Parkinson D, Easther R. Constraining cosmic inflation with observations: Prospects for 2030. Monthly Notices of the Royal Astronomical Society, 2023, 520(2): 2405-2416.