What is the Cosmic Microwave Background and what does it tell us about the initial conditions of the universe?

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Abstract:
The aim of this paper is to look at the early Universe, using the theory of cosmic inflation and observations of the Cosmic Microwave Background (CMB). Inflation is a short but very rapid expansion that resolves many of the problems associated with the Universe, such as the uniformity on its large scales, the near-flatness and the absence of the magnetic monopoles predicted by theories of physics. The CMB, formed about 380,000 years after the big bang, carries the imprint of the physics of the early Universe in the form of its temperature anisotropies and polarization patterns. This paper covers the CMB blackbody spectrum, temperature fluctuations, density perturbations, power spectrum and E-mode and B-mode polarization. Particular focus is placed on primordial B-modes, which would be strong evidence for gravitational waves produced by inflation.

1. Introduction:

One of the key objectives of contemporary cosmology is to comprehend the conditions that existed in the initial moments of the Universe. The theory of cosmic inflation suggests the Universe expanded very quickly immediately after the Big Bang [1]. Inflation is a continuation of the Hot Big Bang model, and offers answers to some key questions about the large-scale structure of the Universe, such as why it is near-flat and near-uniform.

The oldest light in the universe that can be detected today is the Cosmic Microwave Background (CMB), and is one of the most significant sources of evidence concerning the early Universe. The CMB was formed around 380,000 years after the Big Bang, thus offering a snapshot of the infant Universe [2] . Its almost uniform temperature combined with the small temperature variations and polarization patterns holds information about the physical conditions and density variations of the early Universe that became the seeds that ultimately produced galaxies and galaxy clusters [3].

The observations of such CMB features have been crucial for testing cosmological models and helped to link observation and theory of the early Universe. In particular, the measurements of CMB anisotropies and polarization can be used to study the refute or prove the theory of cosmic inflation, as the detection of primordial B-mode polarization in the CMB can be used to look for primordial gravitational waves produced during the cosmological inflation.

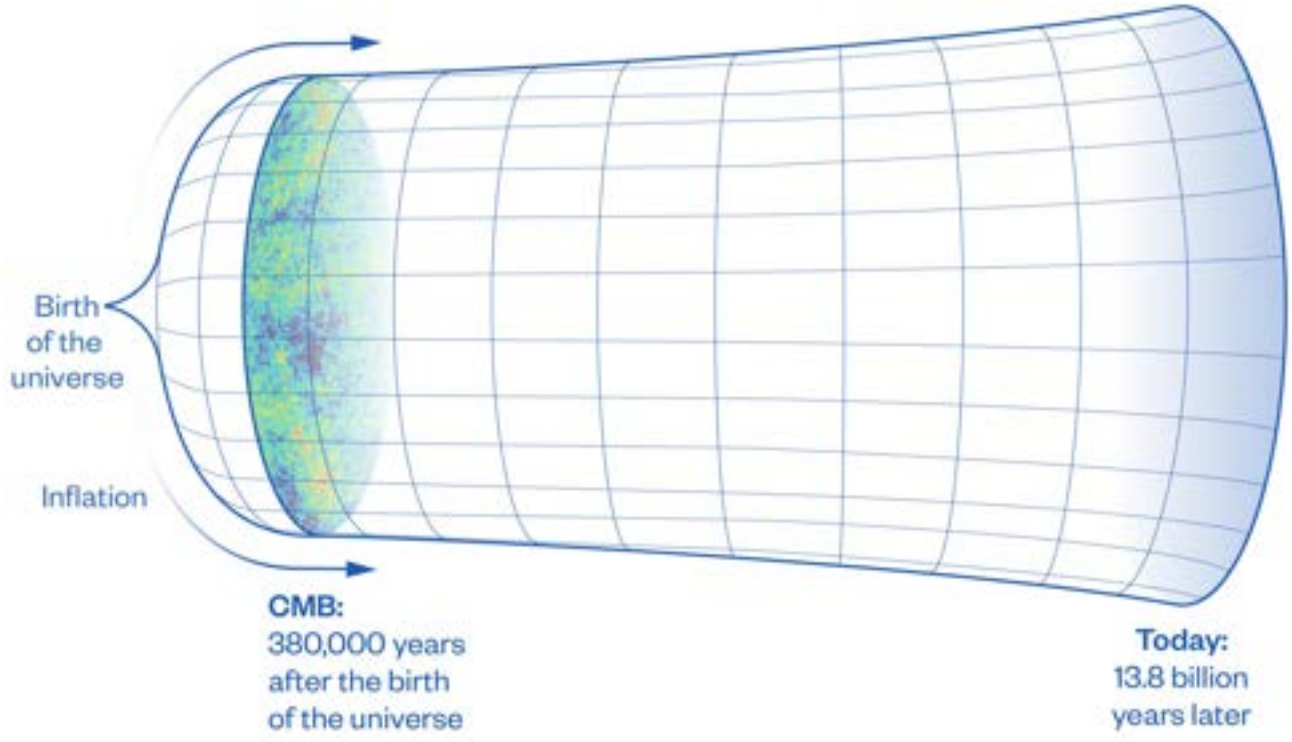


Fig. 1 The Cosmic Microwave Background (CMB) is the oldest light we can see in the Universe, and reveals a snapshot of the Universe at about 380,000 years old. The study of its temperature changes and polarization enables scientists to study the conditions in the early Universe and to understand how the structures we observe today formed. Image from [3]

2. Theory of Inflation:

The theory of cosmic inflation suggests that the Universe expanded at an extremely rapid rate of 10^{-36} to 10^{-32} seconds [4]. In this short period the universe expanded at least 10^{26} times. The Hot Big Bang model is not being superseded by inflation, rather inflation is an extension of the hot, dense phase of the Universe and describes what occurred just before the hot, dense phase started [5]. The Hot Big Bang model is able to account for the expansion of the Universe, the creation of light elements, and the Cosmic Microwave Background. But it alone will not account for several crucial observations. Inflation offers answers to the three key difficulties of the Hot Big Bang: the Horizon Problem, the Monopole Problem and the Flatness Problem. These solutions have rendered inflation a fundamental aspect of today's knowledge of the early Universe.

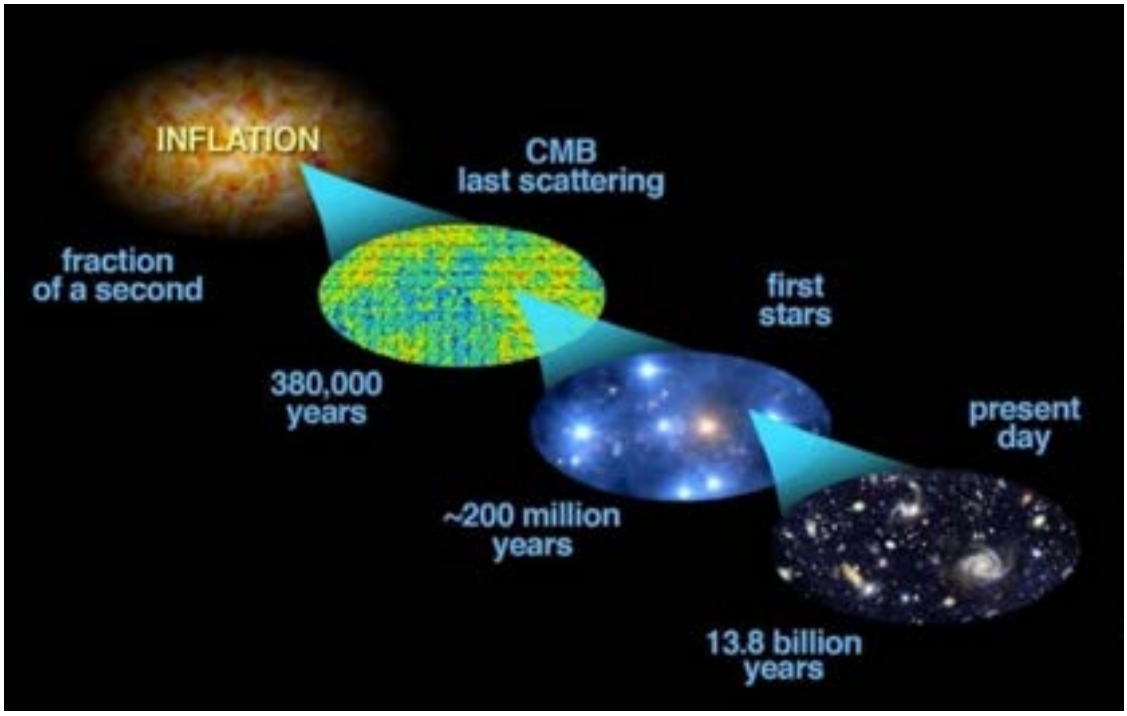


Fig. 2 The Theory of Inflation suggests that shortly after the creation of the Universe, it went through a short, but very fast, period of exponential growth. This expansion is responsible for some of the most important features of the Universe, such as the large-scale flatness, the uniformity of the CMB and the origin of the small density fluctuation that eventually became galaxies. Image from [6]

2.1 Horizon Problem:

As the universe continues to expand we observe there is a constant temperature that is the same in all directions, that temperature is observed by leftover radiation left over from the birth of the universe which is called the cosmic microwave background (see Section 3 for more details).This isotropic temperature implies that regions in space today that are really far away are somehow in causal contact with each other [8]. Causal contact, in this context, means that two regions of the Universe are close enough to exchange energy and come into thermal equilibrium.

However, distant regions in the universe today could not have had time to communicate with each other, and therefore should not exhibit causal contact behavior. This implies that causal contact must have occurred in the early universe, and evidence of that is somehow being seen today.

Inflation solves the horizon problem by suggesting that these regions were once in close proximity to each other and were in thermal equilibrium before they were stretched far apart.

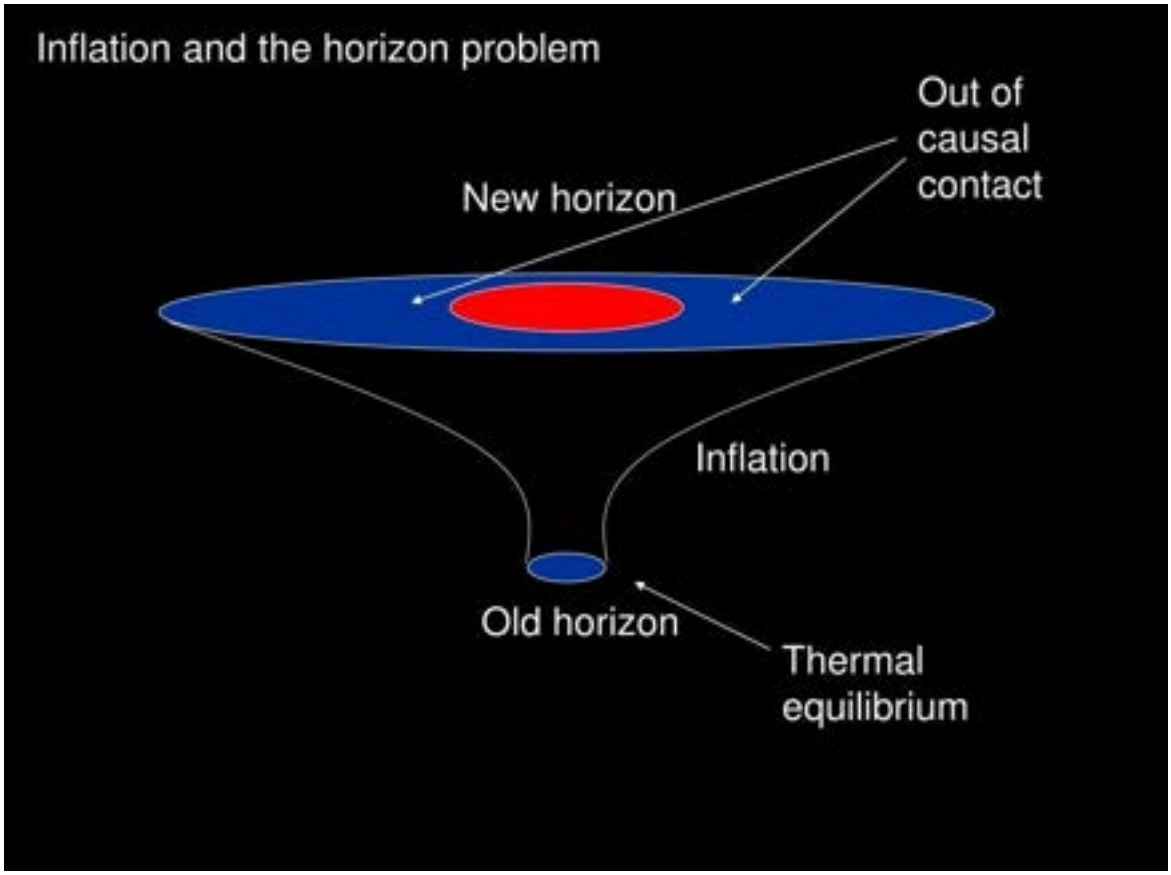


Fig. 3 The Horizon Problem is: How is it that distant parts of the CMB feel almost the same as if they were communicating with each other, yet the temperature difference means that they were never in direct contact? This can be understood from the phenomena of inflation which argue that these regions existed in close proximity and could achieve thermal equilibrium before the space between them was rapidly expanded. Image from [7]

2.2 Monopole Problem:

In the early universe, at extremely high temperatures, the Grand Unified Theories (GUTs) predict a copious production of hypothetical particles called magnetic monopoles. A magnetic monopole is different from ordinary magnets, which always have both a north and a south pole. These long-lasting monopoles should still be found today if they were produced in the numbers forecasted, but large-scale experiments have not detected them.

Cosmic inflation solves this problem. The universe was born expanding at an extremely fast rate and almost instantly. If magnetic monopoles existed at all, they were spread out over a much greater volume of space, reducing the density of magnetic monopoles by many orders of magnitude. Consequently, the monopoles that may have existed in large numbers prior to the inflation, are now further apart than they can be detected.

2.3 Flatness Problem:

Observations show that the geometry of the observable Universe is extremely close to being flat. In a flat Universe, parallel lines remain parallel, and the rules of Euclidean geometry apply on very large scales. However, according to the original Big Bang model, even a very small amount of curvature in the early Universe should have become much larger over time. This means that the Universe would need to have started with a density extremely close to the critical density, with even a tiny initial deviation growing significantly over time. [8]

With cosmic inflation, however, any initial curvature would have been stretched over an enormous distance, making the observable Universe appear nearly flat today.

A useful comparison is the surface of the Earth. Although the Earth is curved, a small region appears flat because its curvature is spread over such a large distance. In the same way, inflation stretched the curvature of the early Universe so much that it now appears almost perfectly flat within the region we observe.

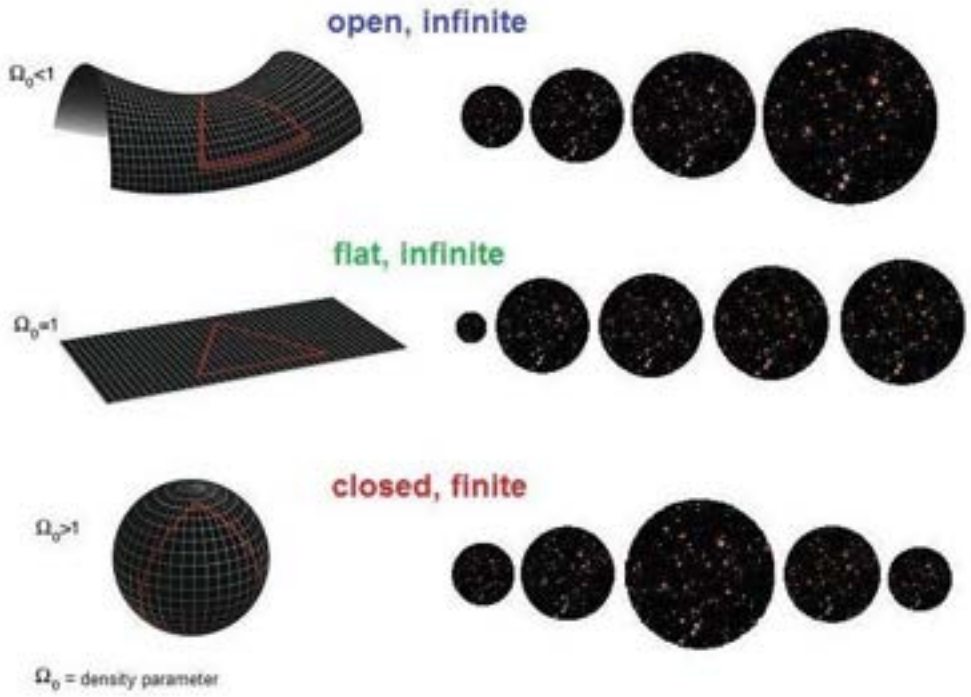


Fig. 4 The Flatness Problem is a question about why the Universe is so flat, given that it could have been curved in response to small differences in the material content of the Universe during its birth. The problem is addressed by cosmic inflation, which expands space far more than it is curved, and makes the initial curvature very small, so that the Universe is forced to assume a flat geometry. Image from [9]

Here is where you should note that the theory of inflation provides great explanations for 3 major discrepancies in the universe but we have not yet proven that this event has occurred. The only way to find evidence for inflation is to try to probe the CMB to uncover whether any evidence from an inflationary event could have embedded itself into the CMB and what that type of signal would like. This way, that provides a transition from inflation section to introducing the CMB

3. Cosmic Microwave Background (CMB)

The Cosmic Microwave Background (CMB) is the oldest light that can be seen in the Universe. It has been termed the "afterglow" of the Big Bang, since it originated about 380,000 years after the Universe was born. Prior to the release of the CMB, the Universe was filled with a hot dense plasma which blocked the passage of light/photons. As the Universe continued to expand, the plasma cooled enough such that free electrons that were colliding into the photons were able to slow down enough to form neutral hydrogen atoms by combining with protons. This allowed the photons to travel through space without being quickly scattered for the first time , allowing light to be transparent for the first time in the Universe, and ultimately becoming the radiation we see today, billions of years later, as the Cosmic Microwave Background.

The Universe was very hot immediately after the Big Bang, and was filled with photons, electrons and atomic nuclei. At these high temperatures, electrons would not be able to bind to the nuclei and become neutral atoms. Rather, photons are continually scattered by free electrons, in what is referred to as Thomson scattering, and the Universe is opaque. Light would not be able to move freely, since it would be continuously scattered by the surrounding plasma.

As the Universe expanded it cooled. After about 380,000 years since the Big Bang, the temperature dropped sufficiently to allow the electrons and protons to recombine to create neutral hydrogen atoms. So, with much less free electrons left to scatter the photons, they were free to travel through space. These photons have been travelling through the Universe ever since, and are seen today as the Cosmic Microwave Background. They give a first-hand account of the Universe at the time it became transparent.

The CMB permeates the entire Universe, and can be seen in all directions of the sky. Its average temperature is 2.725K, however, it has a record of all the conditions of the early Universe. The CMB has remained essentially unchanged for billions of years and therefore is one of the best sources of information for astronomers on the origin, composition and evolution of the Universe.

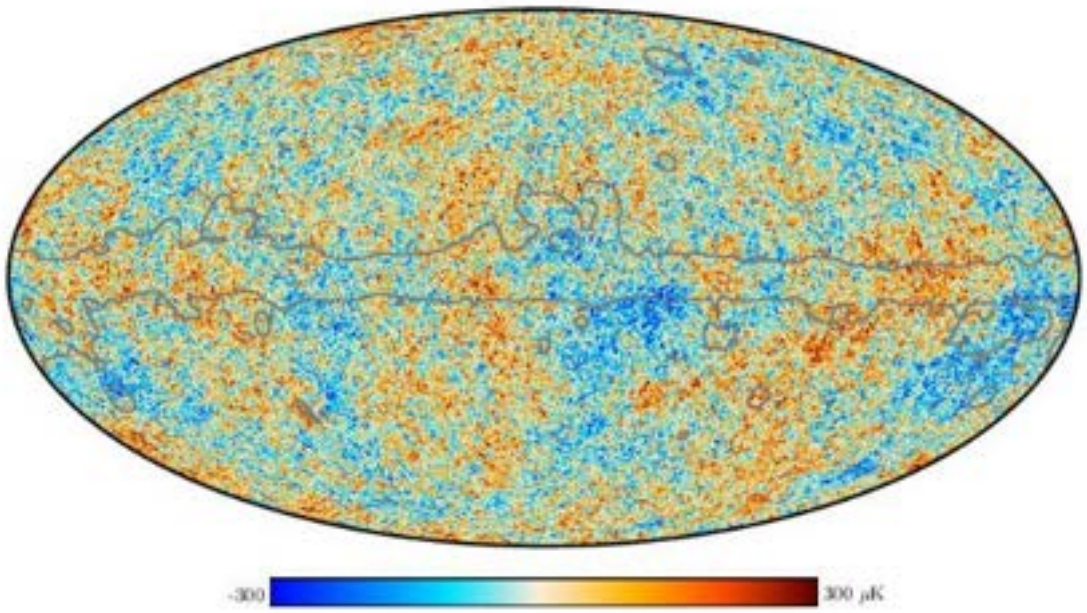


Fig. 5 After the Big Bang the Universe was very hot, but cooled sufficiently after ~380,000 years for neutral atoms to form and free photons to travel through space, forming the CMB that is observed today. Image from [10]

3.1 Blackbody Spectrum:

The CMB is an almost perfect blackbody in nature. A blackbody is an object that absorbs all radiation incident on it, and then emits light solely according to its temperature [5]. Because the early Universe was very hot, dense, and small ,the photons came into constant interaction with matter, so that they eventually reached thermal equilibrium with the surrounding plasma. This balance resulted in a nearly blackbody distribution of the radiation.

During the expansion of the Universe, this radiation was stretched due to cosmological redshift. When first released, the radiation temperature was 3000K, but over time, as the temperature of the radiation decreased, so did its energy and frequency, causing it to redshift to the microwave region of the electromagnetic spectrum, emitting at the 2.7K temperature we see today.

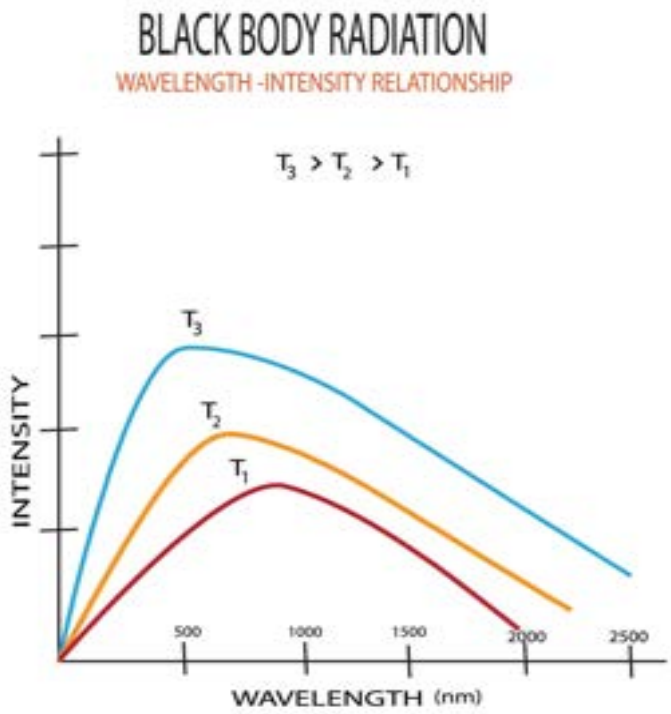


Fig 6. The radiation emitted by an object as a result of its temperature is called Blackbody radiation. The object's radiation increases with rise in temperature and the peak radiation moves towards shorter wavelengths. Image from [5].

4.CMB Temperature Anisotropies:

A detailed inspection of the CMB reveals that there are small differences in temperature, known as temperature anisotropies, throughout the sky. The differences are very small (1 in 100,000) and amount to only a few millionths of a degree.

The early Universe had deeper gravitational potential wells in the overdense regions that pulled matter inwards. The Universe was filled with a hot plasma of atomic nuclei, free electrons and photons at that time. The photons were often scattered off the free electrons, tightly coupling radiation and ordinary matter into a photon–baryon fluid. This fluid was pulled by gravity towards overdense areas, compressing them and heating them. The more the fluid was compressed, the more it radiated pressure, which pushed it outwards. The gravitational attraction and radiation pressure set up acoustic oscillations in the early plasma, which are analogous to sound waves. These variations in density have since been imprinted on the Cosmic Microwave Background (CMB) as small temperature fluctuations that can be seen today. The study of these hot and cold regions allows scientists to study the physical conditions of the Universe a few hundred thousand years after the Big Bang and to learn about the origin, composition and evolution of the Universe.

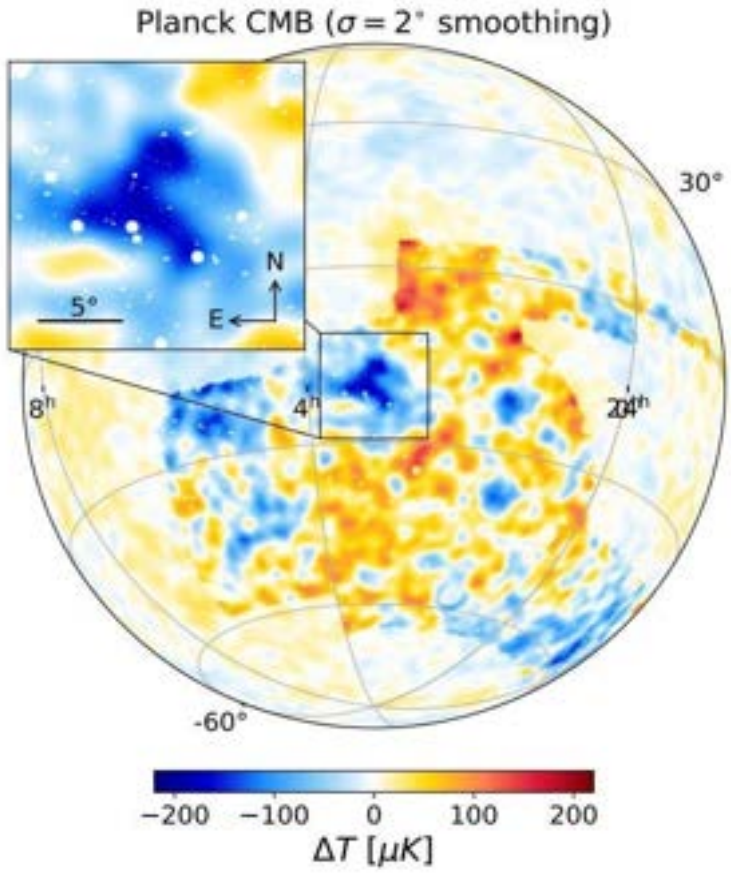


Fig 7. CMB temperature anisotropies are tiny differences in temperature across the Cosmic Microwave Background. These variations reflect small density fluctuations in the early Universe that later developed into galaxies and large-scale cosmic structures. Image from [11]

Gravity was able to concentrate the material and make the densest areas even denser. Eventually they gave rise to the first stars, galaxies, galaxy clusters and the large-scale structure of the Universe that we see today. The less dense regions were allowed to be the large empty spaces— cosmic voids. This link gives the CMB an image of the initial pattern of matter before galaxies had formed [12].

These initial density perturbations manifest themselves as hot and cold spots in the Cosmic Microwave Background radiation and are directly observed by astronomers. The size and distribution of the temperature fluctuations can be compared with theoretical predictions and thus the distribution of matter shortly. The patterns of temperature fluctuations revealed by satellites like WMAP and Planck are very similar to those predicted by the standard cosmological model.

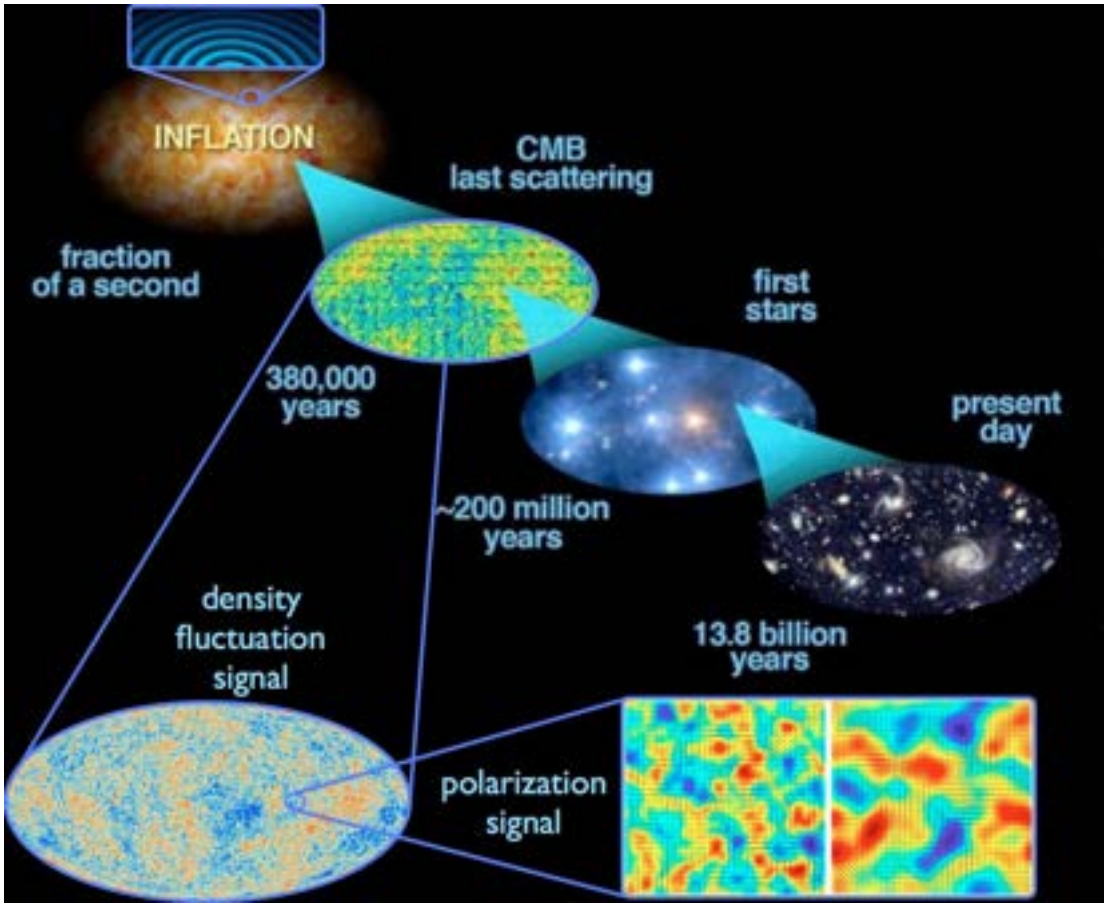


Fig 8. The density perturbations are small variations in the density of matter in the early Universe caused and magnified by the cosmological inflation. These slight variations then expanded under gravity, eventually giving rise to galaxies, galaxy clusters and large-scale structure of the Universe. Image from [13]

4.1 Power Spectrum:

The temperature power spectrum is a summary of the numerous temperature fluctuations in the Cosmic Microwave Background. The power spectrum provides information on how the sky's temperature fluctuates at various angular scales, rather than analyzing each hot and cold spot separately. Sound waves, or acoustic oscillations, in the hot plasma formed the peaks in the power spectrum before photons were emitted. The position and height of these peaks depend on properties of the early Universe such as its age, composition, geometry and expansion rate.

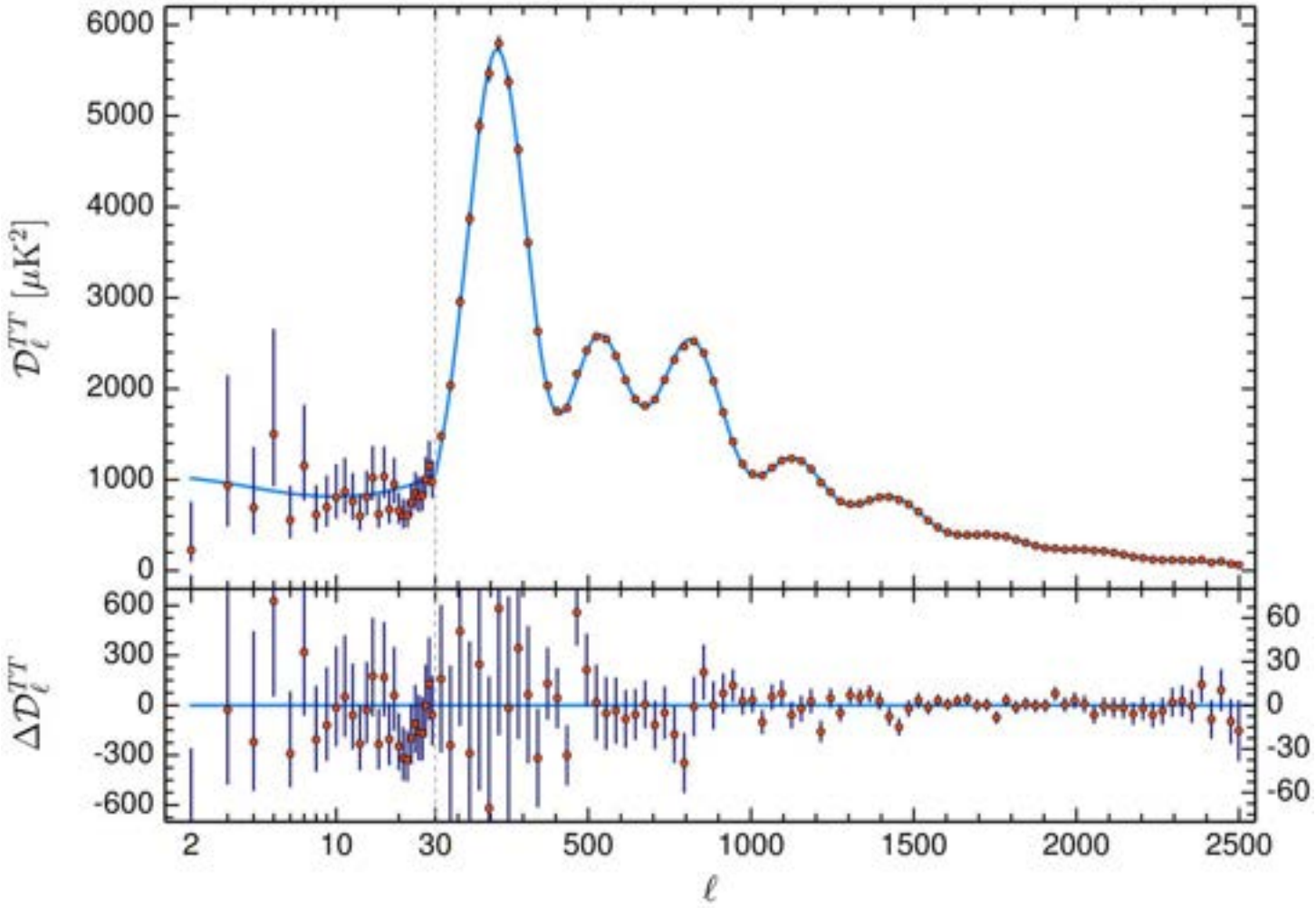


Fig. 9 The CMB temperature power spectrum shows the amplitude of the temperature fluctuations on various angular scales. It produces the peaks which can tell us about the composition, geometry and evolution of the early Universe. Image from [14]

The position of the first peak of the power spectrum on the x-axis gives the overall geometry of the universe, and from direct observation we know that the geometry of our universe is flat. The second peak gives a vital clue about the composition of the universe, while the third peak gives a vital clue about the amount of dark matter in the universe, in comparison to ordinary matter (also known as baryonic matter) that forms stars and planets.

5. CMB Polarization patterns:

The direction of vibration of the electric field of a light wave is known as its polarization. The polarization of the CMB can be used to highlight the patterns formed during the compression and stretching of the early universe by sound waves, which can give insights into the density of matter and gravitational waves.

5.1 E-modes:

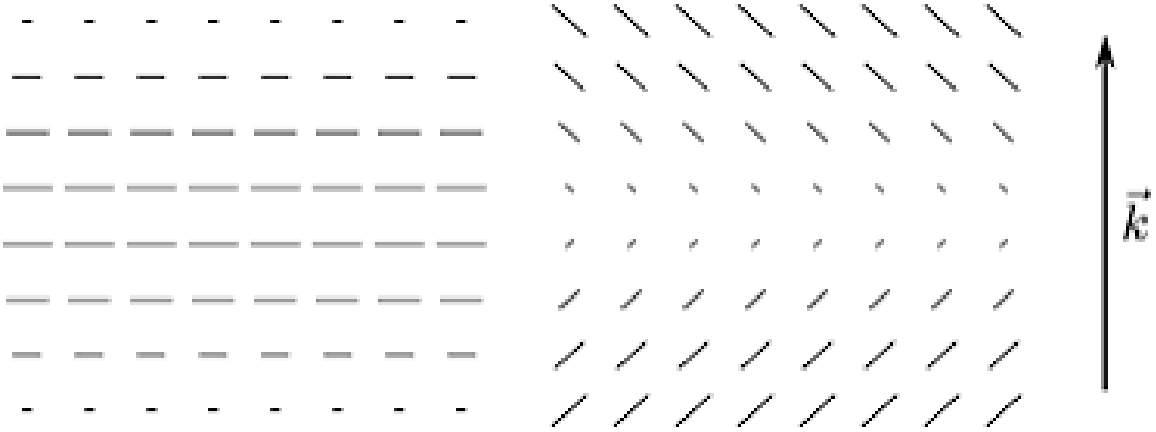


Fig. 10 The E-mode polarization of the CMB creates a sequence of patterns, which are aligned with or perpendicular to the direction of the temperature fluctuations. These patterns are primarily created by Thomson scattering of CMB photons and can yield insights into the density fluctuations and conditions in the early Universe.
Image from [15]

The E-mode polarization patterns in the CMB are a result of Thomson scattering of CMB photons from free electrons in the hot dense plasma.

The polarization of CMB can be split into two types, E-modes and B-modes. The e-mode polarization creates smooth patterns that are oriented towards or away from a central point, or in circular patterns around it (see Figure 12). These patterns are generated when photons scatter from free electrons when they recombine, under the influence of temperature and density variations.

They carry important clues to how matter was distributed in the early Universe, and they are another way of verifying cosmological models. The great accuracy of the measurements of the E-modes are useful for refining estimates of quantities of importance like the density of ordinary matter, dark matter and the age of the Universe.

The patterns are generated by scattering of photons by free electrons in the recombination process in the presence of temperature and density variations. These variations also resulted in temperature anisotropies, which are linked closely to the same density variations that created the early Universe.

Light was polarized due to scattering by free electrons, and local radiation anisotropies were generated by temperature and density fluctuations, needed for E-mode polarization. The relationship is shown in Figure 11, in which both black temperature power spectrum and red E-mode power spectrum exhibit a set of peaks and valleys corresponding to acoustics. The peaks of the E-mode spectrum are centered around the peaks of the temperature spectrum, that is, the two spectra are mostly out of phase, which is indicative of the common acoustic oscillations of the early photon-baryon fluid.

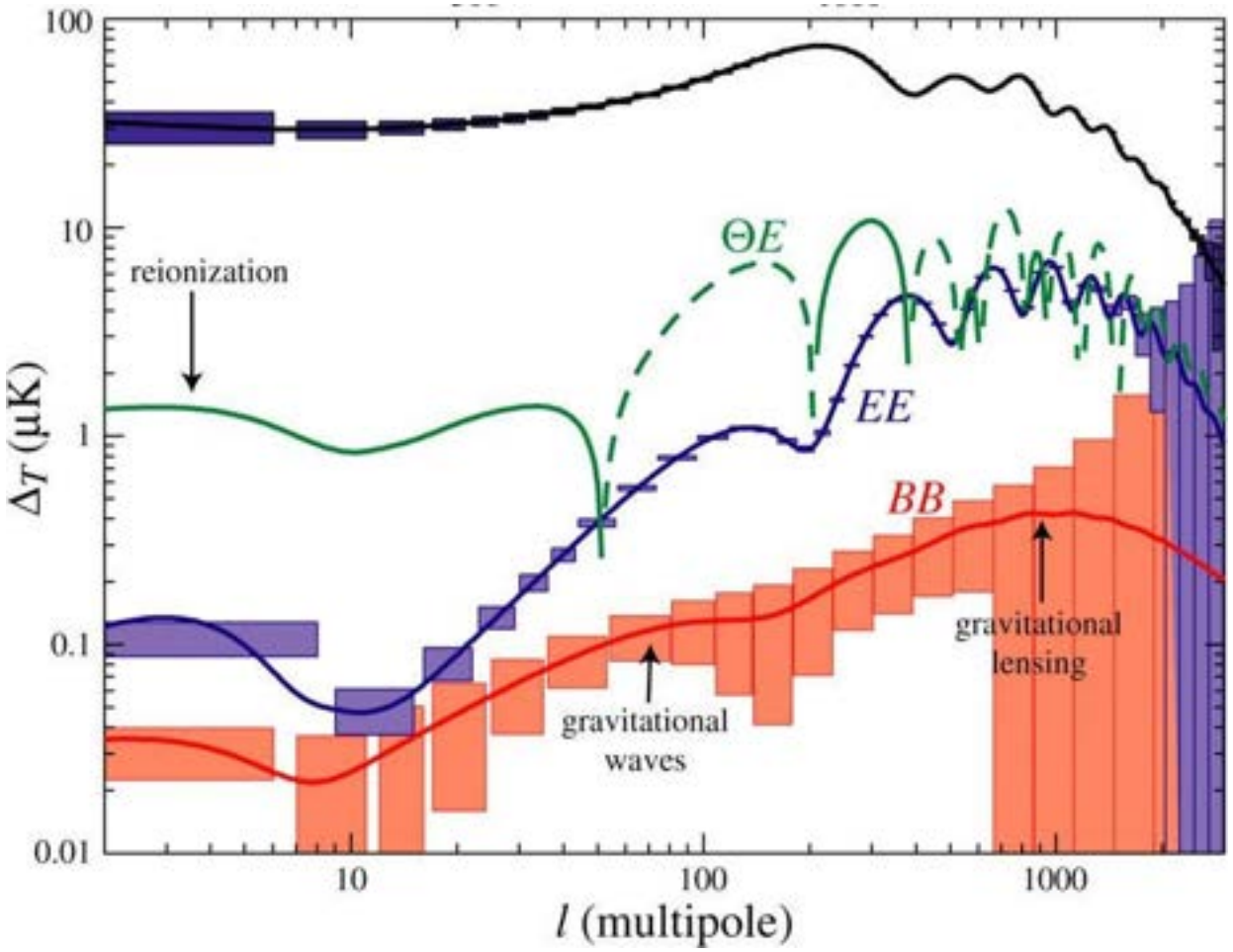


Fig. 11 The temperature (black) and E-mode (red) power spectra both show a clear series of alternating peaks and troughs, produced by acoustic oscillations in the early photon-baryon fluid. The E-mode peaks are approximately shifted relative to the temperature peaks, appearing close to the temperature troughs and reflecting the different phases of the underlying oscillations. Image from [8]

5.2 B-modes:

Primordial gravitational waves from inflation:
B-mode polarization does not have the same sky pattern as E-modes, but instead appears as a swirling or curlicue across the sky (see Figure 12). This pattern is much less evident and much harder to identify. A candidate for B-modes is primordial gravitational waves, which would have been generated during cosmic inflation.The presence of these primordial B-modes would be one of the strongest pieces of evidence for the existence of inflation. But the signal is very weak (see Figure 13) and can easily be drowned out by dust in our own Galaxy, and other sources of noise. This is why modern experiments are equipped with detectors that are extremely sensitive and with powerful techniques of analysis to look for this weak pattern. While the primordial B-modes have not been detected yet, it is one of the most important objectives of modern cosmology.

5.3 Gravitational lensing:

As the CMB travels toward us from the early Universe, its path is slightly deflected by the gravity of intervening matter, including galaxies, galaxy clusters, and dark matter. This effect is called gravitational lensing.

Gravitational lensing distorts the CMB's temperature and polarization patterns. In particular, it converts some of the CMB's E-mode polarization into B-mode polarization. These lensing B-modes complicate searches for primordial B-modes produced in the early Universe, but they also contain valuable information. By measuring the lensing signal, astronomers can map the distribution of matter, including dark matter, and study how cosmic structure formed and evolved over billions of years.

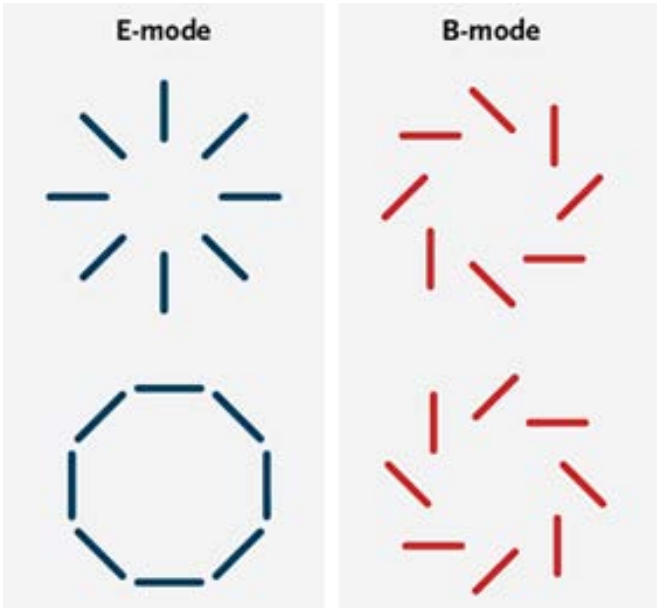


Fig. 12 E-mode polarization produces smooth radial or tangential patterns in the CMB, and is created by density fluctuations via photon scattering. The pattern of B-mode polarization is unique, and can be created by primordial gravitational waves created during cosmic inflation, which would be strong evidence for cosmic inflation. Image from [16]

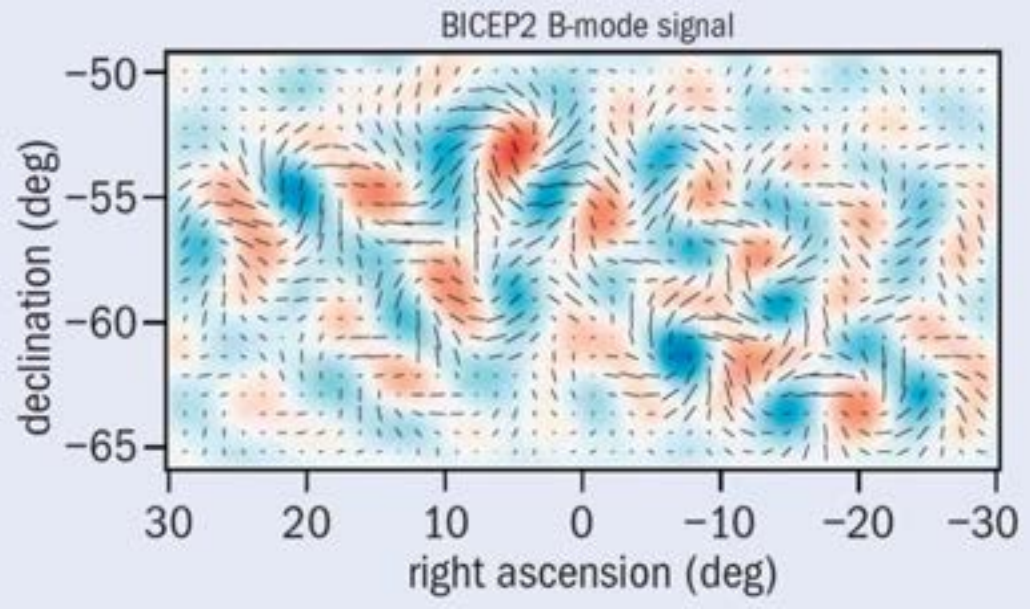


Fig. 13 CMB B-modes are a particular form of polarization pattern that is characterized by a “swirling” or “curl” structure. They can be detected and yield evidence of primordial gravitational waves, which can test theories of cosmic inflation. Image from [17]

6. Conclusion

The Cosmic Microwave Background (CMB) is one of the most compelling observational indications that supports the Big Bang theory since it gives a direct snapshot of the Universe at about 380,000 years after the Big Bang. It is almost uniformly hot with only extremely small temperature anisotropies and polarization patterns, which allow for the retention of valuable information about the physical conditions of the early Universe. These small variations are the primordial density variations that developed into galaxies, the clusters of galaxies and the large-scale structure of the Universe.

The analysis of the CMB has also given support to the theory of cosmic inflation, which is the solution to the Horizon, Flatness and Monopole problems. The CMB has helped scientists to accurately measure the age, composition, expansion, and geometry of the Universe. E-mode polarization has already settled many questions that were predicted by the standard cosmological model, but the detection of primordial B-mode polarization is one of the most important priorities in modern cosmology as it could constitute direct evidence for the existence of inflation soon after the Big Bang.

CMB experiments such as the Simons Observatory and the South Pole Telescope-3G (SPT-3G), measure the Cosmic Microwave Background at a higher sensitivity and angular resolution than ever before. They will also lead to better measurements of CMB temperature and polarization, a decrease in observational uncertainties and improved separation of the CMB signal from foreground emissions like Galactic dust.

One of the primary goals of these experiments is the lookout for the signature of gravitational waves created during the early universe, called primordial B-mode polarization. If successful, the detection would offer one of the biggest checks on inflation, and give us a better understanding of the earliest moments of the Universe, making the next few years one of the most exciting in observational cosmology.

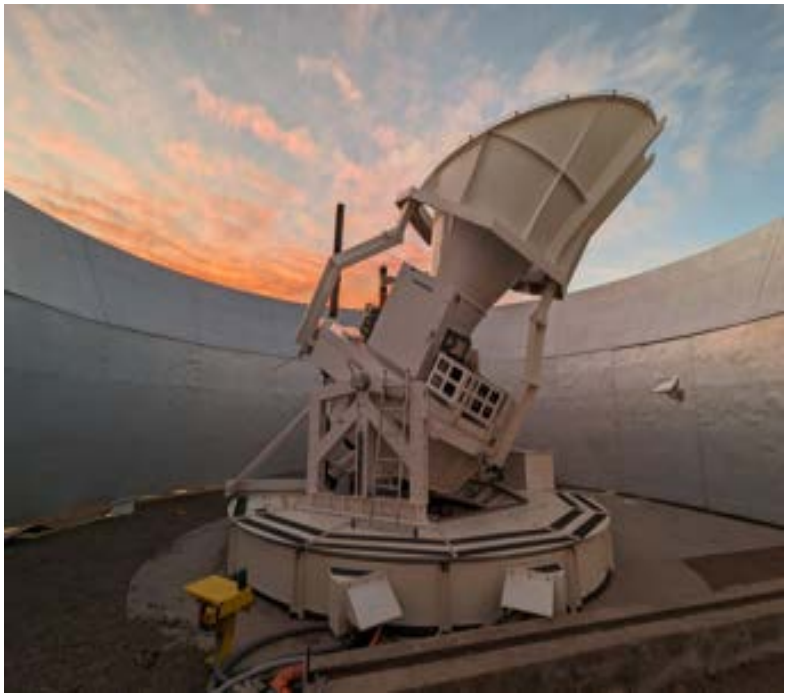


Fig. 14 Other CMB experiments will also feature more accurate measurements of temperature and polarization, and be useful in studying the early Universe in the future, including the Simons Observatory (SO). They are primarily looking for primordial B-mode polarization which would be strong evidence for gravitational waves generated in cosmic inflation. This is an example of one [1]of SO's 3 small aperture telescopes, which are designed for the primary goal of detecting primordial gravitational waves from inflation. [18]

[1] Image from
https://news.yale.edu/2024/07/22/new-observatory-yale-expertise-helps-probe-infant-universe

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