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The Origin of the Universe as Revealed Through the Polarization of the Cosmic Microwave Background

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Executive Summary

Modern cosmology has sharpened questions posed for millennia about the origin of our cosmic habitat. The age-old questions have been transformed into two pressing issues primed for attack in the coming decade:

- **How did the Universe begin?**

The current cosmological paradigm successfully explains how the majestic structure observed in the Universe today grew out of small ripples in the density of matter. What is the physical origin of the primordial seeds which are ultimately responsible for the existence of galaxies, stars, planets, and people in the Universe? It is natural to expect (and many theories predict) that whatever produced the density ripples also produced gravity waves – undulations in the fabric of space-time which travel at the speed of light. Does the Universe contain a spectrum of primordial gravity waves produced by the same mechanism which produced the ripples in the density?

- **What physical laws govern the Universe at the highest energies?**

All explanations for the seeds of structure rely on physics at energies far beyond those probed by, e.g., CERN's Large Hadron Collider. Experiments probing these seeds therefore may provide information about new particles, forces, or perhaps even extra dimensions of space that are visible only at the highest energies.

The clearest window onto these questions is the pattern of polarization in the Cosmic Microwave Background (CMB), which is uniquely sensitive to primordial gravity waves. A detection of the special pattern produced by gravity waves would be not only an unprecedented discovery, but also a direct probe of physics at the earliest observable instants of our Universe. Experiments which map CMB polarization over the coming decade will lead us on our first steps towards answering these age-old questions.

I. HOW DID THE UNIVERSE BEGIN?

Over the course of billions of years, perturbations in the early Universe were amplified by gravitational instability, transforming an almost perfectly smooth Universe into one with planets, stars, galaxies, and galaxy clusters. This cosmic evolution has been quantitatively confirmed: the small initial perturbations encoded in the CMB have just the right amplitude to produce the structure observed in the Universe today. We are emboldened to seek an understanding not only of the origin of the primordial perturbations which seeded structure in the Universe, but ultimately of the origin of the Universe itself.

Beyond their amplitude, the initial perturbations present several distinctive features [1]. They are nearly *scale-invariant*: perturbations at all wavelengths have nearly the same amplitude. They are almost exactly *Gaussian*, in that their statistical properties conform to a classic Gaussian random field to at least one part in 1000. Most strikingly, measurements of the CMB indicate that the perturbations were *synchronized* at early times: when the perturbations are decomposed into Fourier modes, one finds that every mode began with the same temporal phase.

This early synchronization is particularly puzzling since it was locked in when the relevant spatial scales were apparently larger than the distance light traveled since the beginning of time (the horizon). This discovery of the last decade sharpens the classic horizon problem: why does radiation arriving from opposite ends of the Universe share the same temperature? The problem is now even more profound: how were the initial perturbations, with their puzzling synchronization, produced? What physical mechanism could have possibly planted these primordial seeds?

II. NEW LAWS OF PHYSICS

Over the next decade, the era during which the seeds of structure were produced – perhaps 10^{-35} seconds after the Big Bang – will join nucleosynthesis (3 minutes) and recombination (380,000 years) as windows into the primordial Universe that can be explored via present-day observations. However, recombination and nucleosynthesis depend on the well-tested

details of atomic and nuclear physics respectively, while the energy scale at which the seeds were laid down is likely to be so high that the fundamental constituents of the universe and the laws of nature at that time are currently unknown. Our ability to see through this new window will turn the early universe into a laboratory for ultra-high energy physics [1] at scales entirely inaccessible to conventional terrestrial experimentation.

Is the new physics associated with the Grand Unified Scale at which the three low-energy forces – weak, electromagnetic, and strong – become one? Supersymmetry is a theory of particle physics which explains why the electroweak scale is so different from the scale associated with gravity. Is the new physics part of a supersymmetric theory? Are there other particles or fields that can be discovered which are related to those which generated the primordial perturbations? Almost all models for these seeds predict an epoch of acceleration in the early universe. Did some early form of dark energy drive this acceleration? A number of models rely on extra dimensions. Does the universe have more than three spatial dimensions? Almost all models rely on assumptions about the laws of physics at energies close to the Planck scale, the scale at which quantum-mechanical fluctuations render general relativity unstable. The underlying complete theory that describes physics at the Planck scale – perhaps a string theory, or perhaps some theory not yet conceived – then dictates the amplitude of the gravitational waves produced. In particular, the symmetries of this fundamental theory can leave traces in the primordial gravity wave signal, so that a detection of, or constraints on, primordial gravity waves could provide the first observational clue as to the nature of quantum gravity.

III. INFLATION

The general considerations outlined above are most easily illustrated in the context of the most-studied model of the early Universe: inflation – the idea that the Universe expanded nearly exponentially rapidly very early in its history. Inflation resolved several classical problems in cosmology and correctly predicted the observed features of the primordial perturbations. The early accelerated expansion drove small regions that had been in causal contact far away from one another. Quantum fluctuations, usually observed only on micro-

scopic scales, were stretched to astronomical sizes and promoted to cosmic significance as the seeds of large scale structure. The wavelengths of these fluctuations became so large – larger even than the horizon – that the perturbations froze at a constant amplitude. When they re-entered the horizon much later, all modes were therefore synchronized to have the same temporal phase. Most models of inflation are driven by an almost constant energy density (similar to the models for dark energy today), so perturbations in the small wavelength modes which left the horizon latest were generated under the same conditions that existed when large wavelength modes left the horizon. Hence, the spectrum of perturbations is nearly scale-invariant, in agreement with observations. Additionally, the huge growth eliminated curvature, in full agreement with today’s percent-level measurements that the Universe is flat.

All models of inflation make predictions for the shape of the density spectrum, the amplitude and shape of the gravity wave spectrum, and the level of deviations from Gaussianity. Many of the simplest models predict an appreciable gravity wave signal but no detectable deviations from Gaussianity, while alternatives to inflation seem to predict a Universe with no detectable primordial gravity waves but often appreciable non-Gaussianity. The amplitude of primordial gravity waves therefore provides a way to distinguish between simple models of inflation and alternative proposals for the dynamics of the early Universe.

Moreover, the gravity wave amplitude is directly tied to the energy scale during inflation, so a detection can be translated into clues about the new physics responsible for the origin of structure in the Universe. The amplitude of the gravity wave spectrum is expressed relative to that of the density perturbation spectrum by the parameter r . Current experiments constrain $r < 0.3$, and in the coming decade values of r at least as low as 0.01 will be attainable. This amplitude of gravity waves represents a crucial target: theoretical models with $r > 0.01$ are qualitatively different from those with small r . Particle physicists have recently made progress understanding the symmetries underlying these two classes of theories [1], so detection of or constraints on r will provide information about the underlying principles governing the physics operating at ultra-high energies.

Summarizing the reasons why the hunt for primordial gravity waves is so compelling, a

detection would:

- Rule out alternatives to inflation,
- Pinpoint the energy scale at which inflation took place,
- Provide clues about the symmetries underlying new physics at the highest energies.

IV. CMB POLARIZATION: THE ULTIMATE GRAVITY WAVE DETECTOR

Primordial gravity waves leave a unique imprint on the microwave background as they stretch and squeeze the space in which the electrons and photons interact. A quadrupole intensity anisotropy in the radiation field produces observable polarization in the CMB via Compton scattering. When gravity waves are the source of the anisotropy, the ensuing polarization pattern has a handedness, depicted as the *B-modes* in Figure 1. On the other hand, density perturbations sourcing the anisotropy produce only *E-mode* polarization patterns. On large angular scales, the most plausible cosmological sources of a B-mode signal are primordial gravity waves, so the amplitude of the B-mode signal is a direct measure of the gravity wave background, and thus the energy scale of inflation. A detection would be not only an unprecedented discovery, but also a direct probe of physics at the earliest observable instants of our Universe.

Figure 2 depicts the expected angular spectra of the two modes of CMB polarization. E-modes have been detected and a number of experiments are on the verge of pinning down their spectrum, thereby further constraining cosmological parameters.

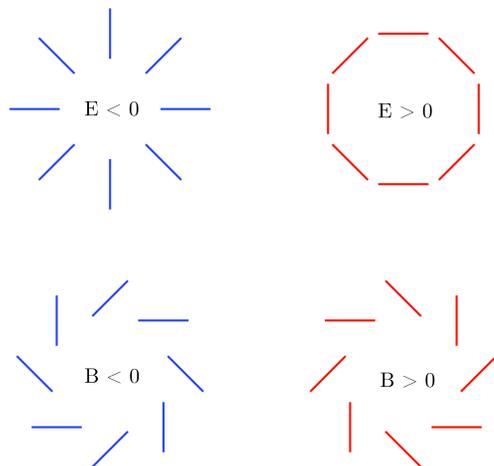


FIG. 1: Any polarization field can be decomposed into two modes. Positive (negative) E-modes surround hot (cold) spots. B-modes cannot be produced by ordinary perturbations to the density but are produced by gravity waves.

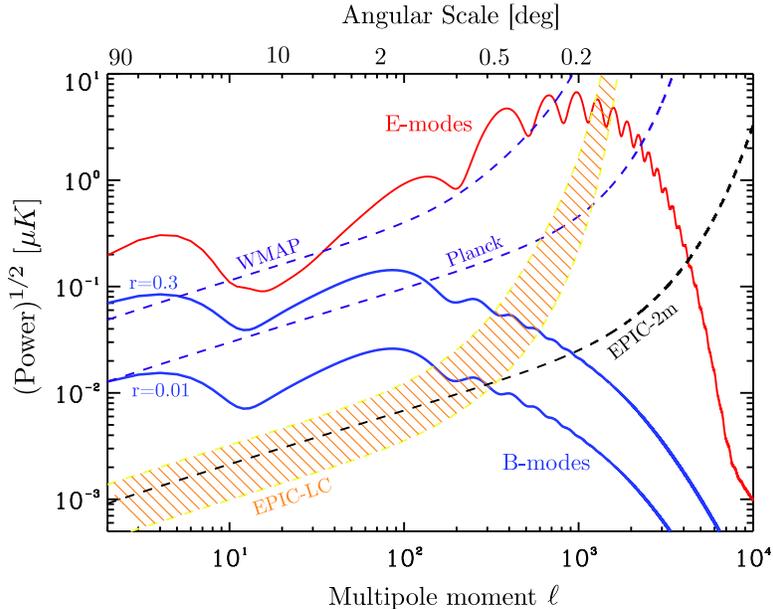


FIG. 2: Predicted spectra of E- and B-modes. The blue solid curves representing B-modes labeled $r=0.3$ and $r=0.01$ correspond to amplitudes just below current limits and within reach of a satellite mission dedicated to polarization, respectively. The hatched region and the dashed curve labeled “EPIC” show the noise levels projected for two possible implementations of this mission [4]. The dashed curves labeled “WMAP” and “Planck” correspond to the statistical noise limits for these satellites after 9 years and 1 year, respectively. All noise curves are averaged over bins of width $\Delta l = 0.3l$.

The primordial B-mode spectrum has a characteristic double-humped shape, the first bump on large angular scales produced at the end of the Dark Ages and the second on degree scales produced during electron-photon decoupling around the time of recombination. The amplitude of the B-mode spectrum is unknown since inflationary models make a range of predictions for the amplitude of the primordial gravity waves. There are no known technical limitations [2] to achieving the sensitivity necessary to detect r down to 10^{-3} . Astrophysical foregrounds will likely degrade this sensitivity, but a variety of simulations using multiple techniques shows that a robust detection of r down to a level of 0.01 – a key threshold delineating the theoretical models – is achievable with a future satellite mission [3].

Beyond this principal science, CMB polarization measurements will also impact upon non-inflationary science. These measurements will determine the gravitational potential along the line of sight to the last scattering surface [5], thereby constraining models of dark energy and possibly detecting the decaying gravitational potentials produced by massive

neutrinos. CMB polarization will also constrain reionization, which heralds the end of the Dark Ages [6], and will provide information about the distribution of magnetic fields in and outside our Galaxy [7].

V. CONCLUSION

Cosmic microwave background polarization offers an extraordinary opportunity to gain a first glimpse into the physics that shaped our Universe. Experimentalists have demonstrated that a coordinated attack on this problem over the coming decade will likely detect primordial gravity waves – thereby providing extensive information about new physics at ultra-high energy scales – or severely constrain the scenario responsible for the origin of the Universe.

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