Executive Summary

Modern cosmology has sharpened questions posed for millenia about the origin of humanity and its cosmic habitat. The age-old questions have been transformed into two pressing issues ripe 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. A key question which remains unresolved is: What is the physical origin of these primordial seeds which are ultimately responsible for the existence of galaxies, stars, planets, and people in the Universe? Were gravity waves – undulations in the fabric of space-time which travel at the speed of light – also produced at the same time?

- **What physical laws govern the Universe at the highest energies?**
  The most plausible explanation for the seeds of structure is that in its earliest moments, the universe underwent a tremendous burst of expansion, known as inflation. What is the underlying physical cause of inflation and how is it related to the other laws of nature? The physical processes responsible for inflation – or even more revolutionary alternatives – probably involved energies billions of times larger than will be probed at CERN's Large Hadron Collider. Cosmological observations thus provide a unique probe of physics at the highest imaginable energies.

The clearest window onto these questions is the pattern of polarization in the Cosmic Microwave Background (CMB), and experiments which map this polarization over the coming decade will lead us on our first steps towards answering these newly-formed, yet 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 obtain an understanding of the origin of the primordial perturbations which seeded structure in the universe.

Beyond their amplitude, the initial perturbations present several distinctive features [1]. They are nearly *scale-invariant*: fluctuations have equal amplitudes at all wavelengths. They are almost exactly *Gaussian*, in that their statistical properties conform to a classical Gaussian distribution to at least one part in 100. Most strikingly, measurements of the CMB indicate that the perturbations were *synchronized* at early times: when the perturbations are decomposed into Fourier modes, every mode began with the same temporal phase.

This early synchronization is particularly puzzling since it was generated when the relevant wavelengths 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 either ends of the visible universe share the same temperature? The problem is now even more profound: how were the early perturbations, with their baffling synchronized temporal phases, produced? An explanation of these distinctive features is tantamount to answering an even more profound question: What physical mechanism planted the primordial seeds?

The new physics responsible for seed production likely lies at energies around one trillion times greater than those which will be studied at the Large Hadron Collider. 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.

II. INFLATION

The idea that the universe expanded exponentially rapidly very early in its history for a short time – *inflation* – resolves several classical problems in cosmology and correctly predicts the observed features of the primordial perturbations. The early accelerated expansion drove regions that had been in causal contact – and hence equilibrated to the same temperature

– far away from one another. Quantum fluctuations, usually observed only on microscopic scales, were blown up to astronomical sizes and promoted to cosmic significance, as they are the seeds of large scale structure. The wavelengths of these fluctuations became so large – larger even than the horizon – that the perturbations froze at 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 the small wavelength modes which left the horizon latest were generated under the same conditions as existed when large wavelength modes left the horizon. Hence, the spectrum of perturbations is nearly scale invariant. This 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 non-gaussianity. Measurements which accurately determine these properties of the primordial perturbations will differentiate among competing models of inflation or falsify the theory in favor of alternatives.

The gravity wave amplitude is likely to be the most powerful probe of the physics driving inflation. Many models predict a large amplitude that can be detected in the coming decade. Alternatives to inflation uniformly predict a universe with no detectable primordial gravity waves. Moreover, the gravity wave amplitude is directly tied to the energy scale during inflation, so a detection or constraint on this quantity can be translated into limits on the precise energy scale 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: so-called *large field models* – those in which the field driving inflation changes considerably in Planck units – predict values of r above this, while small field models predict lower values of r. Particle physicists have recently made progress understanding the symmetries of the underlying theories that might lead to these two classes of models [1], so there is the real hope that detection or constraints on r will provide information about the underlying principles governing the physics operating at ultra-high energies.

III. CMB POLARIZATION: THE ULTIMATE GRAVITY WAVE DETECTOR

Primordial gravitational waves leave a unique imprint on the microwave background as they deform 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 “handed-ness”, depicted as the *B-modes* in Fig. 1. On the other hand, density perturbations sourcing the anisotropy produce only *E-mode*, or rotationally invariant, polarization patterns. On large angular scales, the only possible sources of a B-mode signal are primordial gravitational waves, so the amplitude of the B-mode signal is a direct measure of the gravitational 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 very instant our universe was formed.

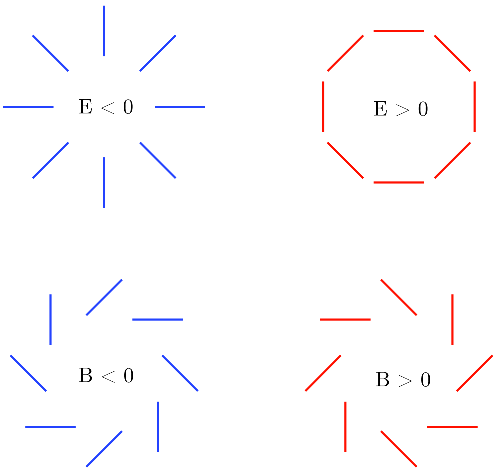

FIG. 1: Any polarization field can be decomposed into two modes. Positive (negative) E-modes surround hot (cold) spots. B-modes cannot be produced by ordinary perturbations to the density but are produced by gravity waves.

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. 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 to achieving the sensitivity necessary to detect r down to 10^{-3}. Simulations confirm that a 10-σ detection of $r = 10^{-2}$ – a key threshold delineating the theoretical models – is achievable with a future satellite mission, even after accounting for foregrounds [2].

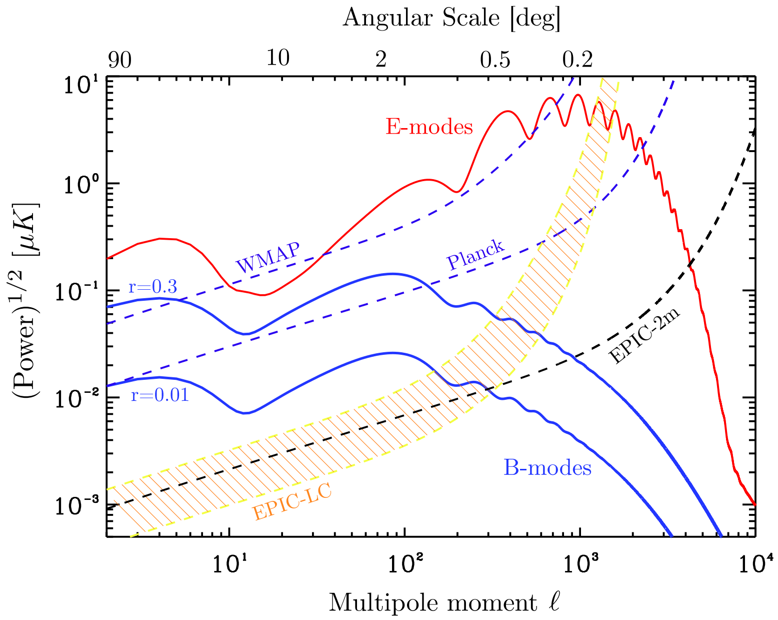

FIG. 2: Predicted spectra of E- and B-modes. The two curves representing B-modes labeled r=0.3 and r=0.01 correspond to amplitudes just below current limits and within reach of a satellite mission dedicated to polarization. The curves labeled EPIC show the noise levels projected for two possible implementations of this mission. The dashed curves labeled "WMAP" and "Planck" correspond to the statistical noise limits for these satellites after 9 years and 1 year respectively.

Beyond this principal science, CMB polarization measurements will also determine the gravitational potential along the line of sight to the last scattering surface [3], 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 [4] and magnetic fields in and outside our Galaxy [5].

IV. 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 gravitational waves if they exist – thereby providing extensive information about this primordial physics – or severely constrain the scenario responsible for the seeds of structure in the universe.

---

[1] D. Baumann *et al.*, (2008), astro-ph/0811.3919.

[2] J. Dunkley *et al.* (2008), astro-ph/0811.3915.

[3] K. Smith *et al.*, (2008), astro-ph/0811.3916.

[4] M. Zaldarriaga *et al.*, (2008), astro-ph/0811.3918.

[5] A. Fraisse *et al.*, (2008), astro-ph/0811.3920.