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What is the role of the CMB in providing evidence for inflation, and what information can be extracted from doing CMB power spectra analysis?

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ABSTRACT

Cosmic inflation, proposed to resolve the horizon, flatness, and monopole problems of the standard Big Bang model, remains theoretical without direct observational evidence. This paper investigates the role of the CMB in providing evidence for inflation and examines what cosmological information can be extracted through power spectra analysis. We review how the temperature power spectrum encodes the geometry, matter content, and expansion history of the universe through its acoustic peaks and how CMB polarization (specifically B-mode polarization at large angular scales) would constitute evidence of primordial gravitational waves generated during inflation. We then employ the CMB Analysis Summer School notebook pipeline to simulate CMB maps from theoretical spectra, characterize the impact of instrument noise and foregrounds, apply filtering techniques, and recover power spectra with uncertainties. The analysis demonstrates how raw CMB observations produce cosmological constraints, comparing theoretical predictions with observational cosmology.

INTRODUCTION

The Cosmic Microwave Background (CMB) provides an essential window into the early universe. Emitted approximately 380,000 years after the Big Bang during recombination, CMB photons have traveled across expanding space carrying a pristine record of initial conditions.

The CMB is particularly useful for cosmological analysis because density fluctuations in the early universe were still extremely small and evolving within the linear regime. Unlike late-time astrophysical structures (such as galaxies and clusters) that have undergone complex, non-linear gravitational collapse, CMB temperature and polarization anisotropies can be accurately calculated from first principles. Consequently, precise measurements of CMB power spectra allow cosmologists to extract key parameters, including spatial geometry.

SECTION: DEFINING COSMIC INFLATION

Section 1: Introducing Cosmic Inflation

Cosmic inflation is a theory proposing that the universe underwent an extremely rapid, exponential expansion between 10^{-36} and 10^{-32} seconds after the Big Bang, increasing the scale of the universe by a factor of at least 10^{26}.

To understand the scale of cosmic inflation, one must first look at the state of the universe during the Planck epoch ($t < 10^{-43}$ seconds). Before the inflationary event, the entirety of what we now define as our observable universe was compressed into a region of space smaller than the radius of a single proton, approximately 10^{-24} centimeters in diameter.[1] At this stage, the universe was characterized by an extreme energy density and a temperature of roughly 10^{32} Kelvin, where the four fundamental forces of nature (gravity, electromagnetism, and the strong and weak nuclear forces) are theorized to have been unified into a single "superforce."[2] This energy scale is called the Theory of Everything.

The transition into the inflationary epoch occurred between 10^{-36} and 10^{-32} seconds after the birth of the universe, likely triggered by a “phase transition." As the universe cooled to 10^{27} Kelvin, the strong nuclear force separated from the electroweak force. This separation released a colossal amount of energy into a hypothetical scalar field known as the inflation field. During this transition, the inflation field entered a state known as a “false vacuum” (a temporary high-energy state characterized by a non-zero vacuum energy density). In this state, the field’s potential energy density dominated the universe, resulting in a unique condition of negative pressure where pressure is equal to the negative of the energy density. According to Einstein field equations, this negative pressure exerted a massive repulsive gravitational force that drove the metric of space to expand at an accelerating, exponential rate.[3]

During this 10^{-32} second window, the universe expanded by a factor of at least 10^{26} (and in some models, as much as 10^{50} or more). This expansion was governed by an exponential growth law where the scale factor doubled in size every 10^{-37} seconds, effectively smoothing out the fabric of space-time and diluting any pre-existing particle densities.[4] This accelerated growth persisted as long as the inflaton field remained in a "slow-roll" state along the nearly flat plateau of its potential energy curve. Once the field reached the end of this plateau and "rolled" into its global minimum, the period of exponential expansion ceased. This transition resulted in a process known as reheating, where the massive potential energy

[1] Alan H. Guth, "Inflationary Universe: A Possible Solution to the Horizon and Flatness Problems," Physical Review D 23, no. 2 (1981): 347-356, https://journals.aps.org/prd/abstract/10.1103/PhysRevD.23.347.

[2] "Superunification and the Planck Era," Encyclopaedia Britannica, accessed 2026, https://www.britannica.com/science/cosmology-astronomy/Superunification-and-the-Planck-era.

[3] Alan H. Guth, "Inflation and the Very Special Bang," The Encyclopedia of Astronomy and Astrophysics (2005), https://ned.ipac.caltech.edu/level5/March05/Guth/Guth1.html

[4] Francesco Lucchin and Sabino Matarrese, "Power-Law Inflation," Physical Review D 32, no. 6 (1985): 1316-1322, https://journals.aps.org/prd/abstract/10.1103/PhysRevD.32.1316

stored in the inflaton field decayed and was transferred into a hot, dense plasma of relativistic particles.[5] This energy dump essentially initiated the radiation-dominated era of the standard Big Bang model, populating the universe with the matter and energy necessary for the eventual formation of stars and galaxies.

While inflation successfully resolves the horizon, flatness, and monopole problems, these resolutions only demonstrate that our observable universe is consistent with an inflationary past. The temperature anisotropies we observe, while matching inflation's prediction of a nearly scale-invariant spectrum of scalar perturbations, could potentially be produced by alternative theories. Therefore, the temperature power spectrum alone provides support but not definitive proof. To obtain direct evidence, the scientific community must look for a signature unique to the inflationary mechanism: primordial gravitational waves. Inflation predicts that quantum fluctuations in the gravitational field during the exponential expansion produced tensor perturbations. These perturbations would imprint a distinct, parity-odd "B-mode" polarization pattern on the CMB at large angular scales. Because alternative models generally do not predict this specific macroscopic gravitational wave signature, detecting these primordial B-modes is the primary way to confirm inflation as an established physical fact.[6]

Section 2: Addressing the Horizon Problem with Inflation

The horizon problem arises from the observed isotropic temperature of the CMB. Observations from the Planck satellite indicate that the CMB has a nearly uniform temperature of 2.725 K, with fluctuations (anisotropies) of only about one part in 100,000.[7] In a standard Big Bang model without inflation, regions of the sky separated by more than roughly one degree would have been "causally disconnected" at the time of recombination. This means that light would not have had sufficient time to travel between these regions to equalize their temperatures since the birth of the universe. Despite this, we observe a near-perfect thermal equilibrium across the entire celestial sphere. Inflation resolves this by proposing that the entire observable universe was once a subatomic volume in causal contact. This tiny patch had ample time to reach thermal equilibrium before being exponentially stretched to a cosmic scale, thereby "freezing" the uniform temperature into the fabric of space before different regions were pushed beyond each other’s horizons.[8]

Section 3: Addressing the Flatness Problem with Inflation

The flatness problem concerns the extreme precision with which the total energy density of the early universe had to match the "critical density" required for a Euclidean, or flat, geometry. In a standard Big

[5] Andrei D. Linde, "A New Inflationary Universe Scenario: A Possible Solution of the Horizon, Flatness, Homogeneity, Isotropy and Primordial Monopole Problems," Physics Letters B 108, no. 6 (1982): 389-393, https://doi.org/10.1016/0370-2693(82)91219-9

[6] Marc Kamionkowski and Ely D. Kovetz, "The Quest for B Modes from Inflationary Gravitational Waves," Annual Review of Astronomy and Astrophysics 54 (2016): 227-306, https://doi.org/10.1146/annurev-astro-081915-023433

[7] D. J. Fixsen, "The Temperature of the Cosmic Microwave Background," The Astrophysical Journal 707, no. 2 (2009): 916-920, https://doi.org/10.1088/0004-637X/707/2/916.

[8] Guth, "Inflationary Universe," 347.

Bang expansion, any minute deviation from a perfectly flat state would be exponentially amplified over cosmic time, causing the universe to either collapse prematurely or expand too rapidly for galaxy formation to occur. To account for the nearly flat universe observed today, the initial density must have been balanced to within one part in 10^{60} at the moment of the Big Bang. Inflation provides a dynamic solution to this paradox by proposing that the universe underwent an era of exponential expansion, which violently stretched the fabric of space-time and smoothed out any initial curvature. Much like the surface of a sphere appears increasingly flat to a local observer as the sphere's radius grows toward infinity, the inflationary period forced the geometry of our observable volume to appear flat regardless of its starting state.[9] This theoretical prediction is supported by measurements from the Planck satellite, which indicate that the geometry of the observable universe is indeed flat to within a 0.4% margin of error.[10]

Section 4: Addressing the Monopole Problem with Inflation

The monopole problem is a discrepancy between Grand Unified Theories (GUTs) and observational cosmology. GUTs predict that the high-energy phase transitions in the early universe should have produced a high density of stable, extremely massive topological defects known as magnetic monopoles, each possessing a mass of roughly 10^{16} GeV.[11] If the standard Big Bang expansion were the only mechanism at play, these monopoles should be as abundant as protons in the modern universe, creating a density so high that the universe would have collapsed under its own gravity billions of years ago. However, not a single magnetic monopole has ever been detected. Inflation solves this via "dilution." The exponential expansion increased the volume of the universe by such a massive factor (at least 10^{78} in volume) that the density of these pre-existing monopoles dropped to nearly zero within our observable horizon, leaving perhaps only one monopole in a volume far larger than we can ever see.[12]

WHAT IS THE CMB?

Section 1: The Formation of the Cosmic Microwave Background

The CMB is the relic radiation left over from the early universe, originating roughly 380,000 years after the Big Bang. During the universe's earliest epochs, it existed as a hot, opaque, and dense photon-baryon plasma. In this state, photons were constantly colliding with free electrons through a process known as Thomson scattering, which prevented light from traveling any significant distance. As the universe expanded and cooled, it reached a critical temperature that allowed for an event called recombination. During recombination, electrons and protons combine to form neutral hydrogen atoms. This cleared the

[9] Ibid.

[10] Planck Collaboration, "Planck 2018 Results. VI. Cosmological Parameters," Astronomy & Astrophysics 641, A6 (2020), https://doi.org/10.1051/0004-6361/201833910.

[11] Gerard 't Hooft, "Magnetic Monopoles in Unified Gauge Theories," Nuclear Physics B 79, no. 2 (1974): 276-284, https://doi.org/10.1016/0550-3213(74)90486-6

[12] John P. Preskill, "Cosmological Production of Superheavy Magnetic Monopoles," Physical Review Letters 43, no. 19 (1979): 1365–1368, https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.43.1365.

path for photons to travel freely without being scattered, an event known as decoupling. These "first photons" have been traveling through space ever since, stretching into the microwave range as the universe continued to expand.

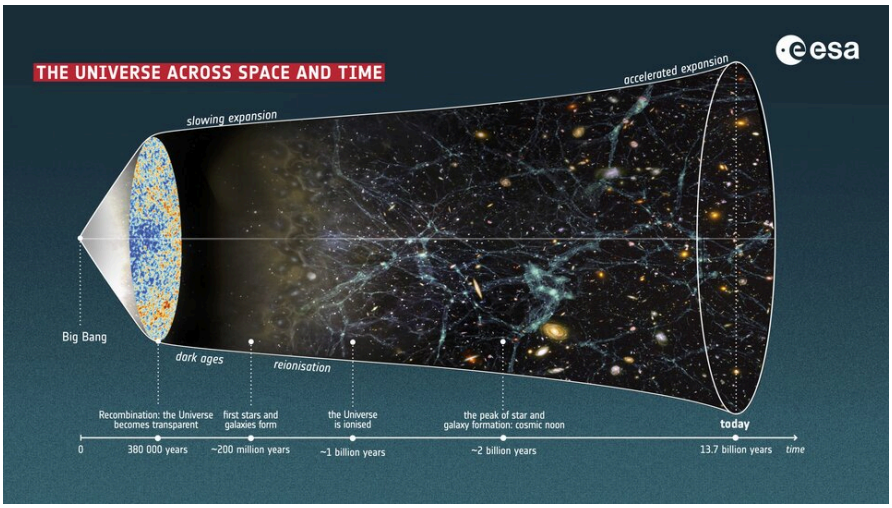


Figure 1: Timeline of cosmic expansion from the Big Bang to the present day, illustrating key cosmological milestones, including the recombination epoch, the cosmic dark ages, reionization, and galaxy formation.[13]

Section 2: The CMB in the Modern Universe

Today, the CMB is observed as a nearly uniform bath of microwave radiation filling the entire sky. It maintains a remarkably precise average temperature of 2.72548 K ± 0.00057 K.[14] While it appears uniform at first glance, high-resolution maps reveal tiny temperature fluctuations at the microkelvin level, which are referred to as anisotropies. These anisotropies are essential to our understanding of the cosmos because they are the "seeds" of all cosmic structure, representing the variations in density of matter that would eventually grow into galaxies and clusters.

Section 3: Defining the Blackbody and Its Spectrum

The CMB is recognized as the most perfect blackbody measured in nature. A blackbody is an idealized physical object that absorbs all incident electromagnetic radiation, regardless of frequency or angle of incidence, and re-emits that energy in a specific, characteristic pattern. This pattern is known as a blackbody spectrum, which is a curve that represents how much energy is emitted at different frequencies,

[13] "Cosmic Eras," European Space Agency, accessed 2026, https://www.esa.int/Science_Exploration/Space_Science/Cosmic_eras.

[14] Fixsen, "Temperature of the Cosmic Microwave Background," 916.

depending solely on the object's temperature. The fact that the CMB follows this theoretical curve so precisely indicates that the early universe was in a state of nearly perfect thermal equilibrium before the photons began their long journey toward us.

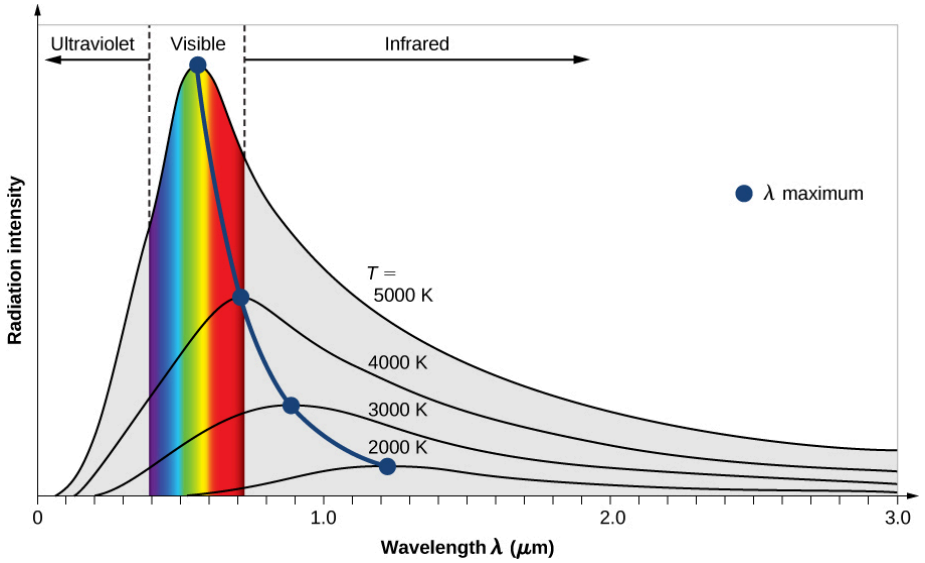


Figure 2: Blackbody Radiation Power Spectrum[15]

Section 4: The Temperature-Power Spectrum and Density Perturbations

To analyze the information hidden within the CMB, cosmologists use the temperature-power spectrum. This is a statistical graph where the x-axis represents the multipole moment, ℓ (essentially the angular scale or "size" of the spots in the sky), and the y-axis represents the power or variance of the temperature fluctuations at those scales.[16] The acoustic peaks in this spectrum reflect the frozen states of gravitational compression and radiation pressure oscillations in the primordial plasma. Temperature anisotropies in the map correspond directly to density perturbations in the early universe where cold spots represent over-dense regions where gravity began pulling matter together and hot spots represent under-dense regions.

[15] "Black-Body Radiation," MIT OpenCourseWare, accessed 2026, https://www.mit.edu/~ashrstnv/black-body-radiation.html.
[16] Wayne Hu and Scott Dodelson, "Cosmic Microwave Background Anisotropies," Annual Review of Astronomy and Astrophysics 40 (2002): 171-216, https://doi.org/10.1146/annurev.astro.40.060401.093926.

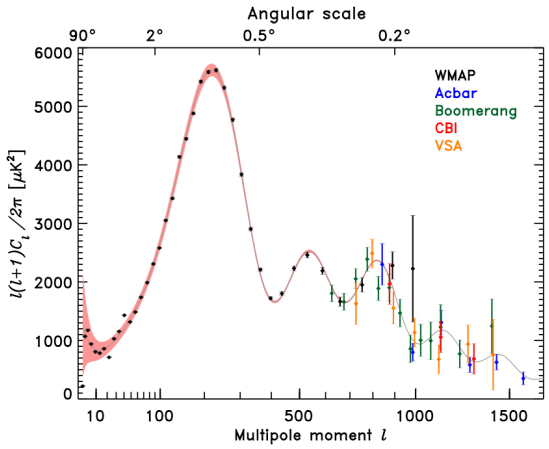


Figure 3: CMB Temperature-Power Spectrum[17]

Section 5: Decoding the First Three Peaks

The specific peaks within the power spectrum serve as a cosmic ledger for the composition and shape of our universe. The first peak is a direct indicator of the universe's geometry; its position on the x-axis confirms that the universe is flat, meaning the total energy density is equal to the critical density required for a Euclidean space.[18] The second peak provides a measurement of the baryon density, as ordinary matter adds inertia to the fluid that enhances compression peaks over rarefaction peaks. Finally, the third peak is used to determine the abundance of dark matter, as dark matter creates gravitational potential wells that resist radiation pressure decay and boost peak amplitude. By comparing the heights of the 2nd and 3rd peaks, scientists can calculate the energy density of dark matter and conclude that 85% of all matter in the universe is dark matter.[19]

SECTION 3: CMB POLARIZATION

Section 1: The Origin of E-mode Polarization

Cosmic Microwave Background (CMB) polarization originates from Thomson scattering of CMB photons off free electrons during recombination. Scattering produces linear polarization only when the

[17] "What Is the Physical Reason That the Universe Is spatially Flat?," Physics Stack Exchange, accessed 2026, https://physics.stackexchange.com/q/155508.
[18] P. de Bernardis et al., "A Flat Universe from High-Resolution Maps of the Cosmic Microwave Background Radiation," Nature 404, no. 6781 (2000): 955-959, https://doi.org/10.1038/35010035.
[19] Wayne Hu, Masataka Fukugita, Matias Zaldarriaga, and Max Tegmark, "CMB Observables and Their Cosmological Implications," The Astrophysical Journal 549, no. 2 (2001): 669-680, https://doi.org/10.1086/319449.

local radiation field around an electron possesses a quadrupole anisotropy, meaning the intensity of incident radiation varies with direction.[20]

The dominant patterns generated are E-modes, characterized by gradient-like spatial distributions that radiate toward or away from density fluctuations.[21] Because scalar (density) perturbations generate local quadrupole fields through acoustic velocity gradients in the photon-baryon plasma, E-modes naturally reflect the same underlying physics as the temperature (TT) spectrum. Consequently, the EE power spectrum features acoustic peaks that are out of phase with TT, serving as a crucial cross-check for the standard cosmological model.

Section 2: B-modes and the Two Sources of Curl Patterns

Unlike E-modes, B-modes represent a much fainter polarization pattern characterized by a parity-odd "curl" or twisting structure. Scalar density perturbations cannot generate B-modes at linear order. Instead, B-modes are produced by two distinct physical mechanisms operating at different angular scales.

The first is gravitational lensing B-modes (small angular scales). As CMB E-mode photons travel across the universe, their trajectories are physically distorted by the gravitational pull of massive large-scale structures like galaxy clusters.[22] This lensing process converts a fraction of the E-mode signal into a B-mode pattern that dominates at small angular scales. The second is primordial B-modes (large angular scales): tensor perturbations (primordial gravitational waves) generated during cosmic inflation stretch and squeeze space-time, leaving a unique, swirling fingerprint on the CMB polarization at recombination.

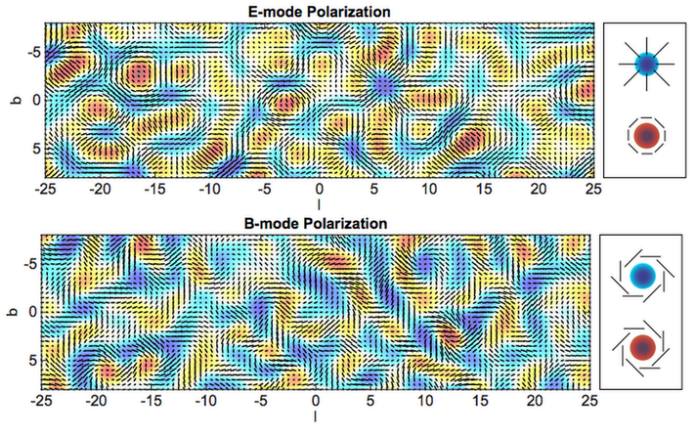


Figure 4: E-mode and B-mode Polarization Models[23]

[20] Wayne Hu and Martin White, "A CMB Polarization Primer," New Astronomy 2, no. 4 (1997): 323-344, https://doi.org/10.1016/S1384-1076(97)00022-5.

[21] Ibid.

[22] Matias Zaldarriaga and Uroš Seljak, "All-Sky Analysis of Polarization in the Microwave Background," Physical Review D 55, no. 4 (1997): 1830-1840, https://doi.org/10.1103/PhysRevD.55.1830.

[23] "Cosmic Microwave Background," Astrowiki, Obsidian, accessed 2026, https://publish.obsidian.md/astrowiki/H.+Cosmology/Cosmic+Microwave+Background.

Section 3: The Tensor-to-Scalar Ratio and the Energy Scale of Inflation

In the study of B-modes, the most critical parameter is the tensor-to-scalar ratio, denoted as r. This value represents the ratio between the amplitude of the tensor perturbations (the gravitational waves) and the amplitude of the scalar perturbations (the density fluctuations that created the temperature spots).[24] Mathematically, r is a direct probe of the energy scale at which inflation occurred; a larger value of r indicates a more violent inflationary expansion and a higher energy level for the inflaton field. Because the amplitude of the primordial B-mode signal is directly proportional to r,[25] detecting this signal would not only confirm the theory of inflation but also provide a specific "thermometer" for the energy of the universe just moments after its birth.

Section 4: Power Spectra of Polarization Signals

Cosmologists evaluate four specific spectra to extract early universe physics: TT, EE, TE, and BB. The TT spectrum measures pure temperature fluctuations driven by scalar density perturbations. The EE spectrum measures gradient-like E-mode polarization from Thomson scattering; its acoustic peaks are out of phase with TT because plasma velocity peaks when density compression is zero. The TE spectrum measures the cross-correlation between temperature and E-modes, oscillating around zero to trace the phase relationship between fluid density and velocity. The BB spectrum measures curl-like polarization and receives no contribution from scalar density perturbations. Instead, BB isolates two distinct phenomena: a small-scale peak ($l \approx 1000$) created when gravitational lensing twists E-modes into B-modes, and a large-scale recombination peak ($l < 100$) generated exclusively by tensor perturbations from primordial gravitational waves.

[24] Kamionkowski and Kovetz, "Quest for B Modes from Inflationary Gravitational Waves."
[25] Ibid.

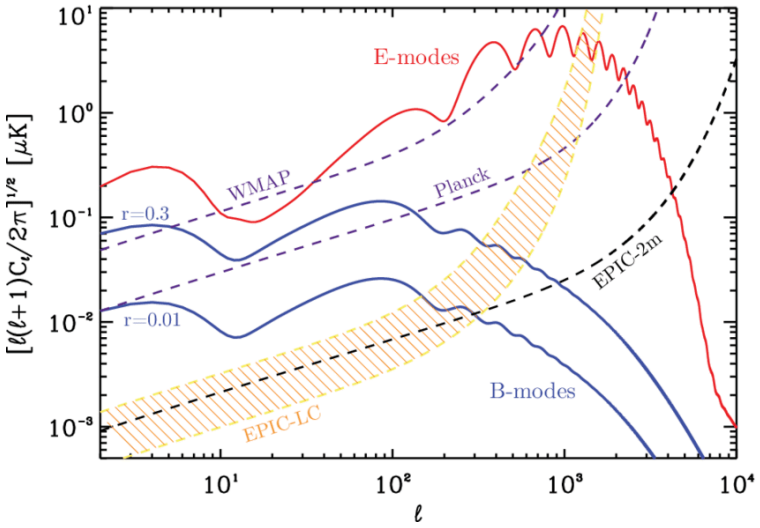


Figure 5: B-mode and E-mode Power Spectra Plots[26]

Gravitational lensing of the CMB converts E-mode polarization into B-mode polarization, producing a lensing B-mode signal that dominates at small angular scales and acts as a contaminating "noise floor" that must be removed (via delensing) to isolate the much fainter primordial B-mode signal from inflationary gravitational waves at large angular scales.[27]

SECTION 4: CMB MODELLING AND ANALYSIS

For the analysis portion of this work, we employ the Jupyter notebook series from the CMB Analysis Summer School, developed by Jeff McMahon and Renee Hlozek (with contributions from Sigurd Naess on mapmaking techniques) for the 2016 workshop held at the University of Michigan.[28] These notebooks provide a pipeline for CMB data analysis, beginning with an introduction to Fast Fourier Transforms and the simulation of CMB temperature and polarization maps from theoretical angular power spectra, proceeding through map-level analysis techniques including power spectrum estimation, transfer function calibration, and noise characterization, and culminating in the analysis of real Atacama Cosmology Telescope (ACT) data and cosmological parameter estimation via Markov Chain Monte Carlo methods.

Section 1: Simulating the CMB: From Power Spectrum to Map

The starting point of any CMB analysis is the theoretical angular power spectrum, which describes the statistical distribution of temperature fluctuations as a function of angular scale. Using the Code for

[26] "E and B Mode Power Spectra for a Tensor-to-Scalar Ratio Saturating Current Bounds," figure, ResearchGate, accessed 2026, https://www.researchgate.net/figure/E-and-B-mode-power-spectra-for-a-tensor-to-scalar-ratio-saturating-current-bounds-r_fig3_23420670.
[27] Matias Zaldarriaga and Uroš Seljak, "Gravitational Lensing Effect on Cosmic Microwave Background Polarization," Physical Review D 58, no. 2 (1998): 023003, https://doi.org/10.1103/PhysRevD.58.023003.
[28] Jeffrey McMahon, CMB Analysis Summer School, GitHub repository, 2017, https://github.com/jeffmcm1977/CMBAnalysis_SummerSchool.

Anisotropies in the Microwave Background (CAMB), we generate the theoretical TT power spectrum shown in Figure 6, which displays the characteristic acoustic peaks: the first peak near $\ell \approx 200$ corresponding to the fundamental sound horizon at recombination, with subsequent peaks at higher multipoles reflecting the oscillatory dynamics of the photon-baryon fluid before recombination.

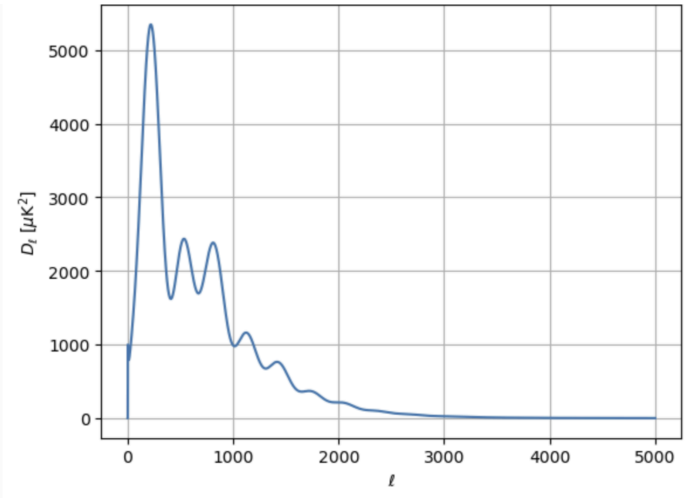


Figure 6: Theoretical CMb temperature (TT) angular power spectrum

From this power spectrum, we simulate a CMB temperature map by treating the sky as a Gaussian random field. The procedure involves generating a 2D power spectrum by rotating the 1D spectrum about the polar axis, creating a Gaussian random map with unit variance, multiplying the two in Fourier space, and applying an inverse Fourier transform to recover a real-space map. The resulting simulated CMB map, shown in Figure 7, reproduces the statistical properties of the observed CMB sky. This simulation confirms that the power spectrum serves as a key prediction of standard inflationary models.

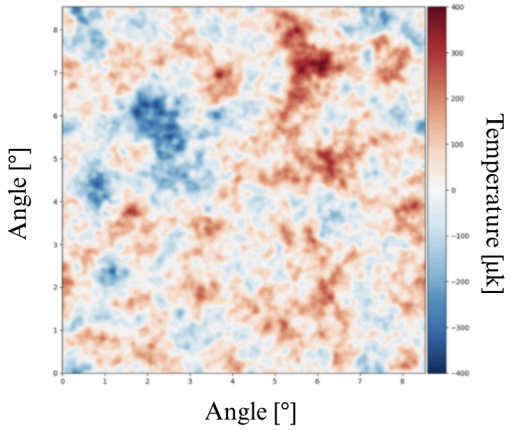


Figure 7: Simulated CMB map

Section 2: Noise and Foregrounds

A real CMB observation is not a clean signal; it is the sum of the cosmological signal, astrophysical foregrounds, and instrument noise. Understanding each of these contaminants is essential, because any attempt to extract cosmological parameters from the power spectrum requires separating the underlying signal from these components.

Instrument noise itself has multiple components: white noise, which is frequency-independent and arises from detector thermal fluctuations; atmospheric noise, which is correlated along scan directions and is particularly problematic for ground-based telescopes; and 1/f noise, a low-frequency noise component that introduces large-scale correlations. To explore how each of these affects the observed map, we systematically vary the noise parameters while holding all others constant.

Figures 8 through 10 show the effect of varying atmospheric noise levels from 5 down to 0.05. At the highest level (Figure 8, atmospheric noise = 5), the map is almost entirely dominated by large-scale red and blue fluctuations with sharp, saturated boundaries, completely obscuring any underlying CMB signal. Reducing the atmospheric noise to 0.5 (Figure 9) allows faint CMB features to emerge, though significant large-scale contamination remains. At the lowest level of 0.05 (Figure 10), the atmospheric contribution becomes negligible, and the map approaches the appearance of the clean signal map.

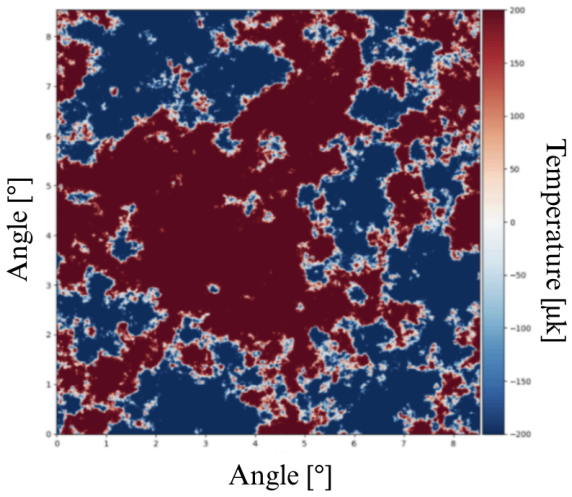


Figure 8: Instrument noise maps at varying atmospheric levels (Atmospheric noise = 5)

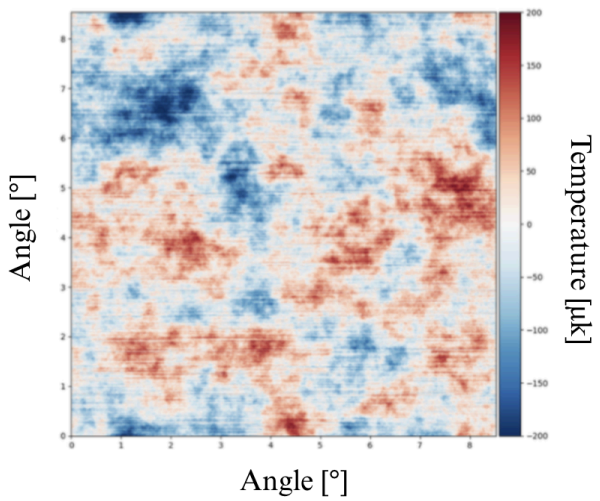


Figure 9: Instrument noise maps at varying atmospheric levels (Atmospheric noise = 0.5)

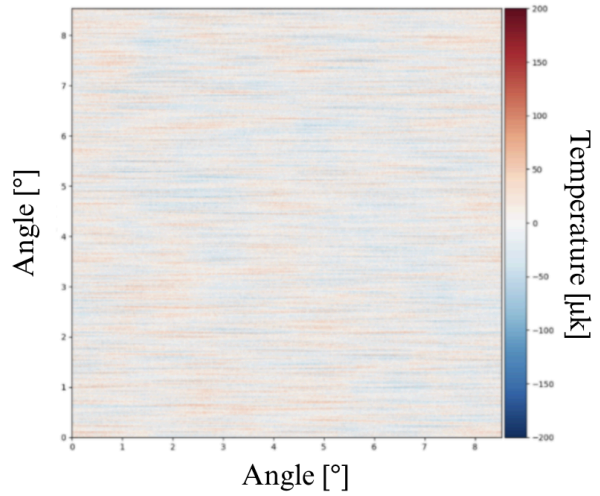


Figure 10: Instrument noise maps at varying atmospheric levels (Atmospheric noise = 0.05)

A parallel exploration of white noise is shown in Figures 11 and 12. At a white noise level of 5 (Figure 11), the noise is modest relative to the CMB signal amplitude, and the map retains recognizable large-scale structure. However, at a white noise level of 100 (Figure 12), the detector noise overwhelms the CMB anisotropies at all angular scales, demonstrating why achieving low noise levels is one of the important aspects of modern CMB experiments such as CMB-S4 and the Simons Observatory.

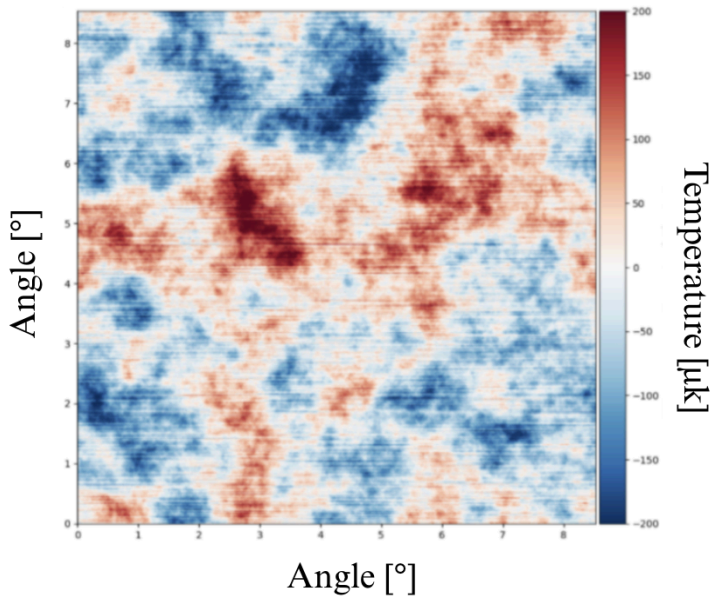


Figure 11: Varying white noise (White noise level = 5)

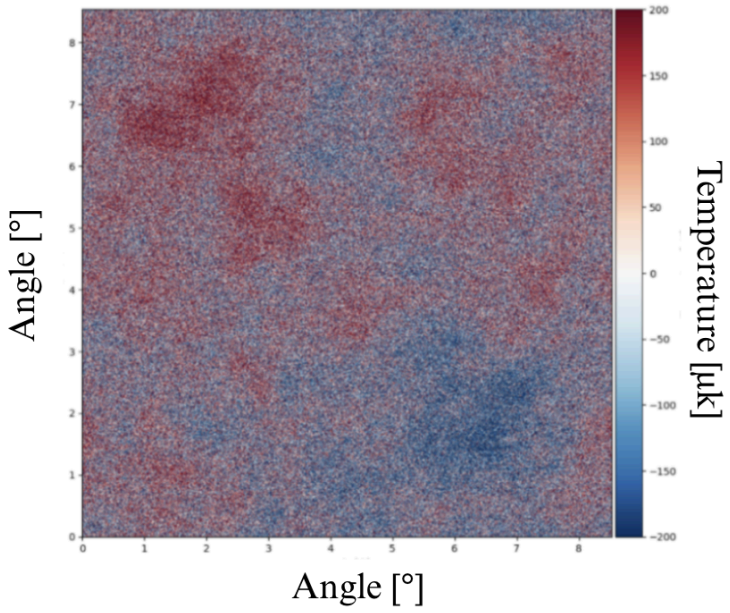


Figure 12: Varying white noise (White noise level = 100)

Section 3: Filtering and Signal Recovery

Given that any real observation contains noise, the next step is to apply filtering techniques that suppress noise while preserving the cosmological signal. The notebooks implement this through an Nmask filter, which masks the brightest point sources in the map and applies a Fourier-space filter to suppress noise-dominated modes.

Figures 13 and 14 illustrate the effect of increasing the Nmask parameter. With Nmask = 4 (Figure 13), only the brightest sources are masked, and the map retains much of its noisiness. With Nmask = 20 (Figure 14), the filtering is more aggressive, so the map becomes significantly smoother, with noise suppressed, but some small-scale CMB features were also attenuated. This illustrates a fundamental trade-off in CMB analysis: more aggressive filtering reduces noise contamination but also removes real signal at small angular scales, limiting the range of multipoles over which the power spectrum can be reliably estimated. Thus, effective analysis requires balancing noise suppression against signal loss.

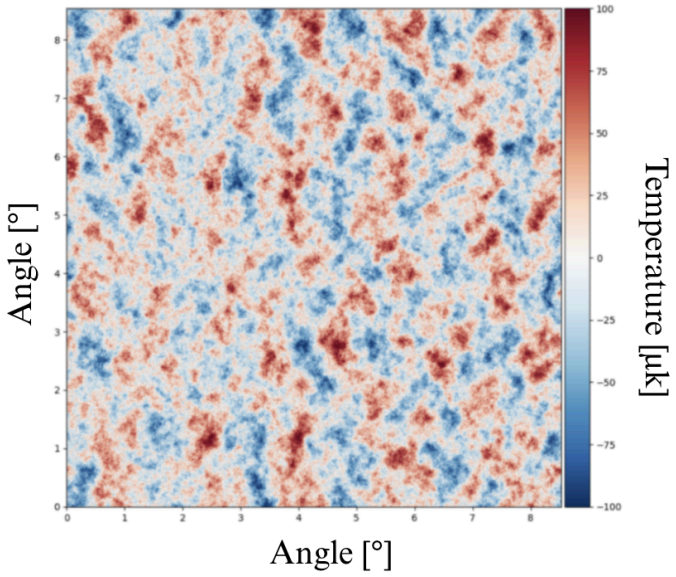


Figure 13: Nmask filtering sequence (Nmask = 4)

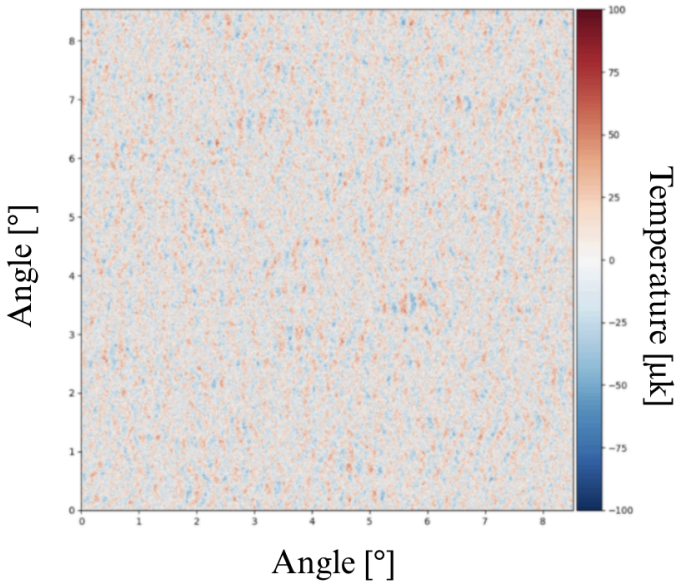


Figure 14: Nmask filtering sequence (Nmask = 20)

After filtering, we estimate the angular power spectrum from the processed map by taking the 2D Fast Fourier Transform, computing the absolute value squared in Fourier space, and averaging the signal in annular bins of wavenumber, which are then converted to multipole bins using the flat-sky approximation. Figure 15 compares this recovered spectrum against the theoretical input spectrum. The acoustic peaks are clearly recovered at low to intermediate multipoles, but at higher multipoles the recovered spectrum flattens into a noise plateau, diverging from the theoretical curve. This divergence marks the angular scale at which instrument noise overwhelms the CMB signal, demonstrating a boundary that determines the maximum usability for estimation.

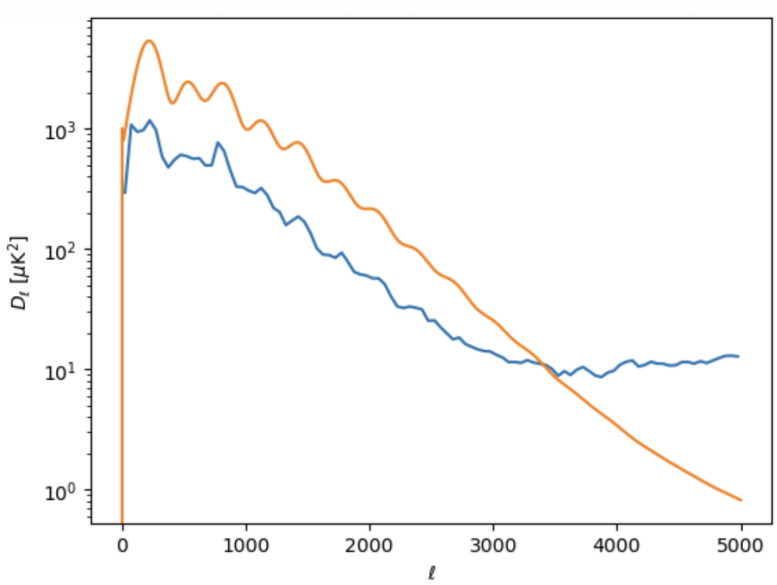


Figure 15: Recovered angular power spectrum (blue curve) derived via 2D Fast Fourier Transform map binning compared against the input theoretical spectrum (orange curve). The recovered spectrum accurately traces primary acoustic peaks before diverging into a flat noise-dominated plateau at high multipoles.

To quantify the uncertainty on the recovered spectrum, error bars are computed by generating multiple signal-plus-noise simulations, computing the power spectrum from each, and taking the root-mean-square deviation across the ensemble. Figure 16 shows the binned spectrum estimate with 1σ error bars overlaid on the theoretical prediction. The error bars are narrow at low ℓ, where the signal is strong and the number of modes per bin is large, and widen at high ℓ as noise dominates. This figure demonstrates that the pipeline produces a statistically meaningful estimate of the power spectrum; the theoretical curve falls within the error envelope across the multipole range where the signal is detectable. Together, these results confirm that the pipeline accurately recovers the underlying theoretical spectrum within its detectable signal regime.

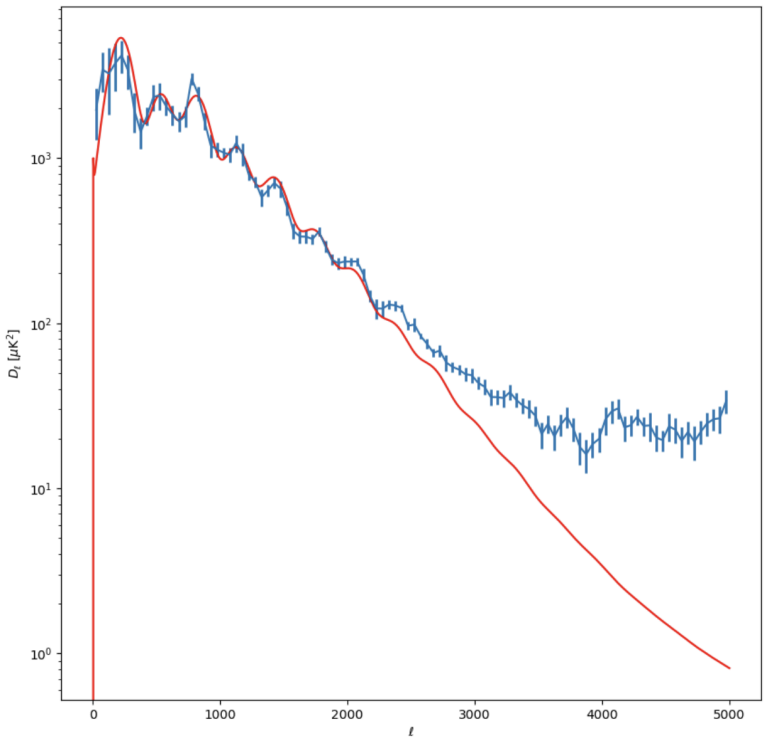


Figure 16: Spectrum Estimate with Error Bars

Section 4: Polarization Power Spectrum

The polarization power spectra provide the most direct connection to inflation. Thomson scattering at recombination and reionization linearly polarizes the CMB, producing two distinct patterns: E-modes (curl-free, gradient-type) and B-modes (curl-type). E-mode polarization arises naturally from density perturbations and has been well measured. B-mode polarization, however, can only be generated by tensor perturbations—primordial gravitational waves—at large angular scales or by gravitational lensing of E-modes into B-modes at small angular scales.

Figure 17 shows the four power spectra: TT (Temperature - Temperature), EE (E-mode - E-mode), BB (B-mode - B-mode), and TE (Temperature - E-mode). The TT spectrum (red) displays the familiar acoustic peaks. The EE spectrum (green) shows peak structure offset from TT, reflecting the different phase evolution of polarization compared to temperature. The TE spectrum (yellow) oscillates around zero, as it is a cross-correlation between temperature and E-mode polarization, with sign changes reflecting the phase relationship between the two fields. The BB spectrum (blue) is the faintest of the four, lying several orders of magnitude below TT, showing why detecting B-modes is so challenging

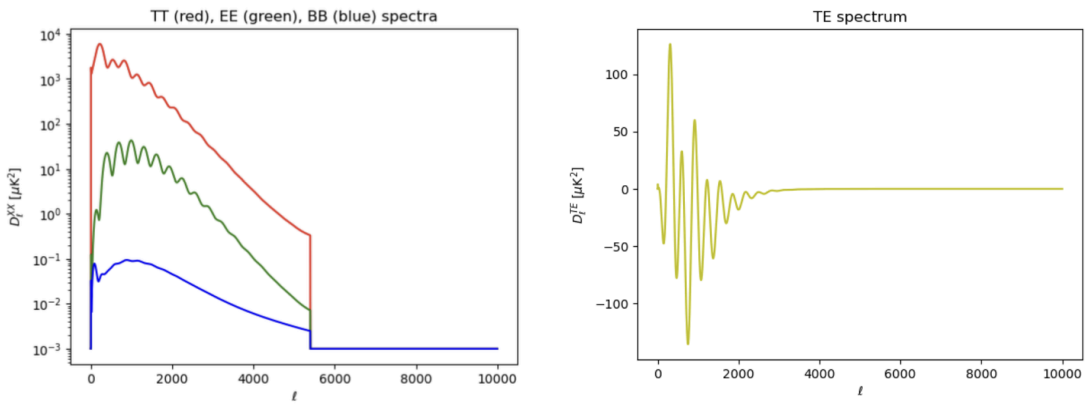


Figure 17: Primary CMB power spectra: TT (red, temperature), EE (green, E-mode polarization), BB (blue, B-mode polarization), and TE (yellow panel, cross-correlation). EE peaks are phase-shifted relative to TT, while BB power lies several orders of magnitude lower, showing the small-scale lensing signature and large-scale primordial tensor contribution.

However, gravitational lensing of the CMB converts E-mode polarization into B-mode polarization, producing a lensing B-mode signal that dominates at small angular scales and acts as a contaminating noise floor that must be removed (via delensing) to isolate the much fainter primordial B-mode signal from inflationary gravitational waves at large angular scales, as mentioned earlier in this paper. This is one of the central challenges in contemporary CMB cosmology: the lensing signal is itself scientifically valuable for constraining structure formation, but it constitutes the primary obstacle to detecting the primordial gravitational wave signature that would confirm inflation.

Finally, Figure 18 shows a simulated polarization field map with a beam size of fwhm = 30 arcminutes. The map displays the polarization amplitude as a temperature field, where the fluctuations represent the E-mode polarization pattern across the sky. The beam size determines the angular resolution of the observation: a smaller beam resolves finer-scale structure, which is critical for measuring the high ℓ acoustic peaks in EE and for distinguishing lensing B-modes from primordial B-modes. The choice of beam size is therefore a key instrumental parameter that directly affects the sensitivity of an experiment to the inflationary signal.

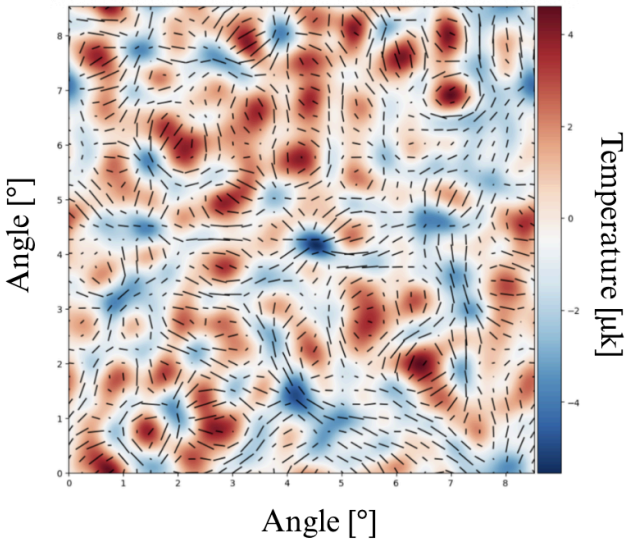


Figure 18: Polarization field maps with vector overlays (fwhm = 30)

CONCLUSION

This paper has examined the role of the CMB in separating circumstantial support for cosmic inflation from definitive proof. The temperature power spectrum, with its acoustic peak structure, confirms key predictions of inflation by verifying spatial flatness, constraining dark matter densities, and supporting a nearly scale-invariant spectrum of primordial perturbations. Polarization analysis offers a more direct probe: while E-modes corroborate the standard cosmological model, the detection of primordial B-modes at large angular scales would constitute definitive evidence of inflationary gravitational waves. Our computational analysis using the CMB Analysis Summer School pipeline demonstrated the practical challenges of extracting these signals, including noise contamination, the filtering trade-off between noise suppression and signal preservation, and the lensing B-mode floor that obscures the primordial signal. While current observations are consistent with inflationary predictions, the definitive detection of primordial B-modes remains the outstanding goal of next-generation experiments such as CMB-S4.