Research Summary

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I. IMPACTS OF PRIMORDIAL MAGNETIC FIELD ON CMB ANISOTROPIES

One of the primary goals of the next generation CMB experiments is to detect the primordial B-mode signal from the tensor perturbations generated by inflation. A detection of such signal will be a solid evidence of inflation and work as a "smoking gun" for various inflationary models. The current best constraint on the tensor-to-scalar ratio is $r < 0.056$ at 95% C.L. through a combined analysis of Planck and BICEP2 [?], and this bound is expected to be lowered to $r \sim 10^{-3}$ by the upcoming CMB experiments such as Simons Observertory [?] and CMB-S4 [?]. However, the tensor perturbation from inflation is not the only source of B-mode polarizations in CMB. Effects such as topological defects [?], cosmic birefringence [?], and primordial magnetic field [?] may also contribute to the B-mode polarizations in CMB and can be mistaken as an inflationary tensor signal if not accounted for properly.

In particular, magnetic fields with strengths of a few μG coherent across galactic and cluster scales are ubiquitous in the universe. There are evidences that they also exist in the inter-cluster-space coherent on the Mpc scale [?]. On the other hand, the physical origin of the cosmic magnetic field is still poorly understood. One proposed mechanism is that cosmic magnetic fields are produced in the very early universe such as during inflation [?] or in phase transitions [?] and act as the initial seeds to the observed magnetic fields in galaxies and galaxy clusters. If existed, primordial magnetic fields (PMF) would impact both cosmology and particle physics leaving imprints on different observables such as the CMB anisotropies and the matter power spectrum. On the other hand, PMF is poorly constrained by the existing observations. The 2015 Planck bound on the scale invariant PMF is $B_{1\mathrm{Mpc}} < 2\mathrm{nG}$ [?]. However, it has been suggested that a field of $B \sim 1\mathrm{nG}$ can generate detectable patterns in CMB anisotropies [?]. Therefore, it's important to evaluate the impacts of PMF on the science goals of the upcoming CMB experiments. In particular, how the B-mode measurements will be affected by the PMF.

PMF affects CMB power spectra primarily through metric perturbation sourced by its stress-energy tensor and through the Lorentz force felt by the baryons in the plasma [?]. Prior to the neutrino decoupling, the universe is dominated by a tightly coupled radiative fluid that hinders the development of any significant anisotropic stress. Therefore, the total anisotropic stress is dominated by that from the PMF. This leads to the so called "passive" mode of PMF. After the neutrino decoupling, the anisotropic stress from the neutrinos will compensate that of the PMF, and this leads to the "compensated" mode of PMF [?].

PMF sources all modes of metric perturbation: scalar, vector and tensor mode. In particular, the passive tensor mode contributes significantly to the B-mode polarization for low-ℓ similar to what one would expect from an inflationary B-mode signal. It has been shown that the tensor mode signal from a 1.08 nG PMF looks identical to an $r = 0.0042$ inflationary B-mode signal [?] in CMB B-mode power spectrum. On the other hand, PMF also generates a vector mode that causes dominant B-mode polarization anisotropies that survives well below the Silk scale. Knowing the extent of which the PMF signal can confuse us as an inflationary signal without having its other imprints such as the vector mode signal being detected is very important for the upcoming CMB experiments, but the answer is unclear.

In this study, we simulate the observed CMB angular power spectra for different sets of hypothetical experimental settings with varying noise levels. The simulated power spectra are based on a fiducial model with the best-fit cosmology from the latest Planck result [?] adding in a non-zero tensor-to-scalar ratio r. We fit the simulated observations to two different cosmological models: one with a non-zero r but zero PMF (termed ΛCDM+r hereafter), and one with a non-zero PMF but with $r = 0$ (termed ΛCDM+PMF hereafter). We find the best-fit cosmology using an MCMC-based maximum likehood approach with the likelihood calculated using the exact likelihood method following Ref. [?]. We calculate the maximum likelihood value that corresponds to the best-fit cosmology for both ΛCDM+r model and ΛCDM+PMF model. A significantly lower likelihood for the ΛCDM+PMF model indicates a good distinguishability between the two cosmological models, but a close match is the sign of a potential confusion between the two cosmological models. We repeat this comparison for $r = 0.01$, $r = 0.004$, $r = 0.003$, and $r = 0.001$ to understand the extent of the confusion for different science targets.

Preliminary results show that the degeneracy between the ΛCDM+r model and the

ΛCDM+PMF model is broken in the noiseless limit, but for a SO-like noise level ($\sim 4\mu$K arcmin) the two models are highly degenerate in the power spectra. Therefore, to be convinced of a detection of the primordial B-mode signals, SO will need to perform additional checks beyond the power spectra level such as the non-gaussianity check [?] and the Faraday's rotation check [?] to rule out the possibility of seeing the PMF instead.

II. INVOLVEMENTS IN THE COLLABORATION

As a member of both the Atacama Cosmology Telescope (ACT) and the Simons Observatory (SO), I am actively involved in the research and analysis projects in the collaborations. A short summary of each of my involvements is listed below.

- **Constraining Cosmic Birefringence with ACT Data:** Cosmic birefringence refers an effect where the propagation of different polarization states is different. This leads to a rotation of CMB polarization from E-modes to B-modes. It can be caused by a parity-violating physics in the early universe such as a coupling between photons and an axion-like pseudoscalar field via the Chern-Simons interaction term [? ?]. It can also be caused by primordial magnetic fields via Faraday rotation [?]. The inhomogeneities in the pseudoscalar fields or the PMF produce anisotropies in the rotation angle that can be reconstructed from the CMB trispectrum similar to weak lensing [?]. Using the ACT data from s14 to s16, we perform a full-sky reconstruction of the rotational field with quadratic estimators to constrain the cosmic birefringence. Preliminary study shows that we expect to improve the current best constraint by an order of magnitude.

- **Search for Fast Radio Bursts in ACT Data:** Fast radio bursts (FRB) are the mysterious bursts in radio emission that last for only a few milliseconds [?]. They have been observed in various radio telescopes [?], but their physical origin remains a mystery. Preliminary estimates show that we may potentially observe them in the ACT telescope as a short glitch that affects no more than two adjacent feedforns, and they are expected to occur on the order of a few times each month. We perform a matched-filter search for potential FRB signals in ACT data collected in 2016. Success or failure to find such signals in microwave band will be equally important in helping us constrain the underlying models of FRBs.

- **Automate Data Cuts with Machine Learning:** In order to obtain high quality CMB maps, an expert knowledge based data cuts pipeline is implemented in ACT that selects good chunks of data and reliable list of detectors for mapping [**?**]. However, it requires too much human intervention due to the large number of parameters that one needs to tune for each array and each season. This makes it difficult to scale to the newer seasons of ACT and the upcoming SO. We explore the use of machine learning methods to automate the data cuts process. We train our models using the existing data cuts that are generated by expert knoweldge. Preliminary results show that one can achieve $> 90\%$ accuracy with machine learning without any human intervention.

My other responsibilities in the collaborations involve generating data cuts and atmosphere calibrations for ACT and developing a similar pipeline for SO.