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1 Scientific, Technical, and Management Section

0.5 pg. executive summary goes here: the sky is sunny

1.1 Science Objectives

5 pages for all science goals including the (temporary) two sections below.

1.1.1 The Inflationary Gravitational Wave Background

Some text recycled from placeholder/old proposal text that was here. Some text below recycled from CMB-S4 science book. Figures currently from CMB-S4.

Inflation [1, 2, 3, 4, 5], a primordial era of accelerated expansion, provides a compelling dynamical origin for the observed statistical homogeneity of our universe on even the largest scales. Inflation dramatically smoothes away classical inhomogeneities, leaving the inevitable quantum fluctuations of the matter fields and the space-time metric during inflation as the source of structure today. The predictions of inflation are consistent with an impressive array of observations, including the cosmic microwave background temperature and E-mode polarization and many surveys of the large scale structure of the universe at later times [6, 7, 8, 9]. But, inflation also predicts a spectrum of primordial gravitational waves sourced directly by quantum fluctuations of the tensor component of the metric. The gravitational waves in turn source B-mode polarization in the CMB fluctuations [10, 11]. The predicted spectrum has peaks near an angular scale of $\ell = 80$, and another at very low ℓ from the epoch of reionization. Figure 1 shows the predicted spectrum, current upper limits and measured B -modes from lensing, as well as a range of forecasts for future satellite missions. **Is this a figure we want?**

Measurements of the CMB temperature fluctuations can be used to relate the inflationary potential energy V to r , the ratio of the temperature quadrupoles produced by gravitational waves to those from density perturbations, at the peak of the spectrum by $V^{1/4} = 3.7 \times 10^{16} r^{1/4}$ GeV. The observation of an all-sky, statistically homogeneous gravitational wave background would generate a revolution in our understanding the origin of our universe and the nature of particle physics, including gravity, at and above the Grand Unification scale of 10^{16} GeV. In its recent report New Worlds New Horizons (NWNH), the decadal survey committee strongly endorsed sub-orbital searches for the B-mode signal from inflation saying that “The convincing detection of B-mode polarization in the CMB produced in the epoch of reionization would represent a watershed discovery.” [12].

The predicted amplitude of the B -mode signal depends on the nature of the scalar sector driving inflation. Although there are many proposed inflationary scenarios, when the slow-roll expansion is valid ($\epsilon \equiv -\dot{H}/H^2 \ll 1$) there are just two observationally viable classes of models that naturally explain the value of the spectral index n_s (by requiring $n_s(\mathcal{N}) - 1 \propto -\frac{1}{\mathcal{N}}$, where \mathcal{N} is the number of e-folds between the scale n_s where is observed and end of inflation) [13, 14, 15]. One class is the set of monomial potentials, which contains many of the canonical inflation models (eg, a quadratic potential) and is already under significant observational pressure. If the error bars on the spectral index tighten by a factor of about 2, and the 95% C.L. upper limit on r is pushed down to about 0.01, all such models would be ruled out (see Figure 2.). The remaining class of natural models includes Starobinsky and Higgs inflation (which have $r \sim 0.003$). A future mission capable of reaching $\sigma_r \sim \mathcal{O}(10^{-4})$ would provide significant constraints on nearly every currently favored inflation model.

Forecasts for the capability of a variety of configurations for a future satellite mission (including

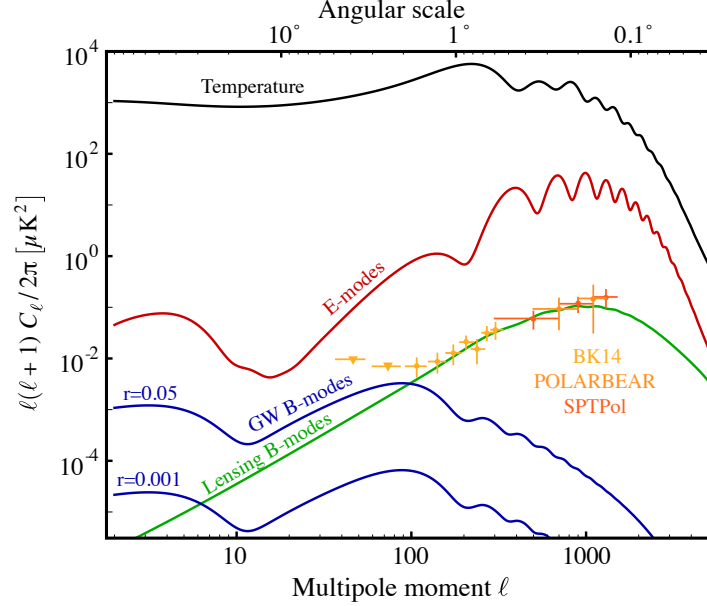


Figure 1: Theoretical predictions for the temperature (black), E-mode (red), and tensor B-mode (blue) power spectra. Primordial B-mode spectra are shown for two representative values of the tensor-to-scalar ratio: $r = 0.001$ and $r = 0.05$. The contribution to tensor B modes from scattering at recombination peaks at $\ell \sim 80$ and from reionization at $\ell < 10$. Also shown are expected values for the contribution to B modes from gravitationally lensed E modes (green). Current measurements of the B-mode spectrum are shown for BICEP2/Keck Array (light orange), POLARBEAR (orange), and SPTPol (dark orange). The lensing contribution to the B-mode spectrum can be partially removed by measuring the E and exploiting the non-Gaussian statistics of the lensing.

PIXIE, LiteBird, CORE+, EPIC-2m) are reported to find $\sigma(r) \sim 4 \times 10^{-4}$ assuming $r = 0.01$, and $\sigma(r) \sim 2 \times 10^{-4}$ for $r = 0$. **Do we want a figure of $\sigma(r)$ versus something? A figure/table with some example specs and $\sigma(r)$?**

Inflation generically predicts primordial gravitational waves just from the vacuum fluctuations of the metric during inflation, but of course does not preclude additional sources of B -mode polarization either during or after inflation. If B -modes are detected, it would be important to characterize the signal to rule out the possibility of a non-inflationary source. The vast majority of inflation scenarios predict a red spectrum for gravitational waves, and in the simplest cases the canonical single-field consistency relation fixes $n_t = -r/8$. While confirming this relation is out of reach, a future mission could perhaps aim for $\sigma(n_t) \sim 1??$ to at least rule out non-vacuum inflationary sources [16, 17]. Post-inflationary phase transitions have been proposed as a non-inflationary source of nearly scale-invariant gravitational waves [18, 19, 20, 21, 22], but can be distinguished by the absence of super-horizon correlations at the time of recombination. A framework to extract specifically this part of the signal was proposed in Ref. [23] and could be applied to robustly extract the component of any signal that must come from physics outside of the hot big bang paradigm. Existing forecasts in the literature [24] indicate that a ground-based survey alone will not be able to detect super-horizon correlations at high significance if r is much below 0.1; a satellite will be required.

A detection of B -modes consistent with a primordial spectrum of vacuum fluctuations would be

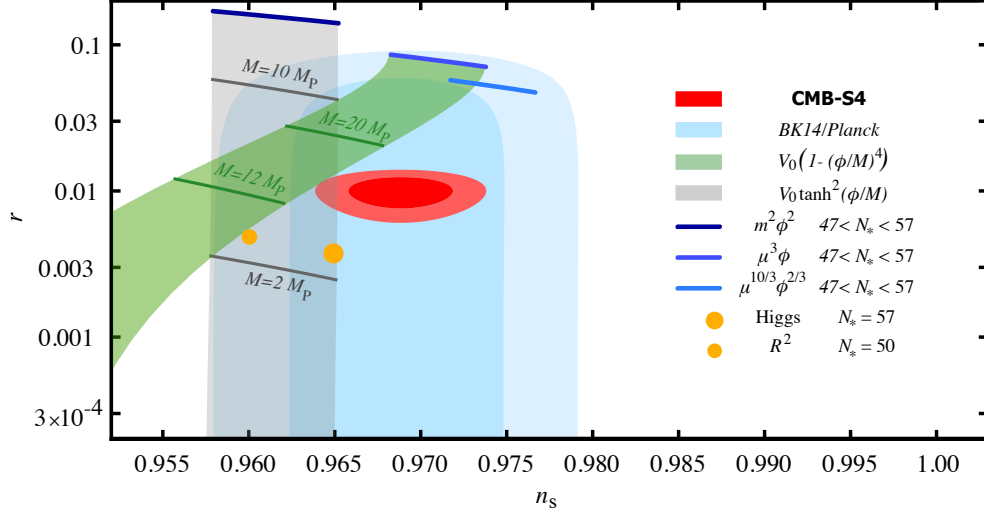


Figure 2: **Perhaps a version of this figure?** Forecast of CMB-S4 constraints in the n_s – r plane for a fiducial model with $r = 0.01$. Constraints on r are derived from the expected CMB-S4 sensitivity to the B-mode power spectrum as described in Section ?? . Constraints on n_s are derived from expected CMB-S4 sensitivity to temperature and E-mode power spectra as described in Section ?? . Also shown are the current best constraints from a combination of the BICEP2/Keck Array experiments and Planck [?]. Chaotic inflation with $V(\phi) = \mu^{4-p}\phi^p$ for $p = 2/3, 1, 2$ are shown as blue lines for $47 < N_* < 57$ (with smaller N_* predicting lower values of n_s). The Starobinsky model and Higgs inflation are shown as small and large filled orange circles, respectively. The lines show the classes of models discussed in Section ?? . The green band shows the predictions for quartic hilltop models, and the gray band shows the prediction of a sub-class of α -attractor models [?].

the first observation of a phenomena directly related to quantum gravity. In addition, evidence for “large field” inflation would provide strong evidence that the complete theory of quantum gravity must accommodate a Planckian field range for the inflaton. The spectrum of tensor fluctuations depends only on the Hubble parameter H during inflation, while the scalar power depends on both H and the evolution of the homogeneous field sourcing inflation. As a consequence, the tensor-to-scalar ratio r determines the inflaton field range in Planck units (called the “Lyth bound” [25]) In many common inflationary models r is a monotonic function of \mathcal{N} so that the tensor-to-scalar ratio at the CMB pivot point k_* is related to the distance the inflaton moves ($\delta\phi$) in Planck units by

$$\frac{\Delta\phi}{M_{\text{P}}} \gtrsim \left(\frac{r_*}{8}\right)^{1/2} \mathcal{N}_* \gtrsim \left(\frac{r}{0.01}\right)^{1/2}. \quad (1)$$

The value of \mathcal{N}_* is not well constrained and depends on unknown details of reheating, but $\mathcal{N}_* \gtrsim 30$ provides a conservative lower limit, justifying the second inequality in Eq. (1). Thus, a tensor-to-scalar ratio $r > 10^{-2}$ typically corresponds to a trans-Planckian excursion in field space between the end of inflation and the epoch when the modes we observe in the CMB exit the horizon. The relationship in Eq. (1) is significant because it relates the observed amplitude of linearized metric fluctuations to a property of the full quantum field theory for gravity coupled to the inflaton. The action describing inflation, like the action for any other particle physics phenomena, in general will include terms that encode the effects from degrees of freedom that couple to the inflaton, but are too energetic to be probed directly by physics near the inflationary scale. The field range is

a measure of the distance in field space over which the corrections from the unknown physics do not significantly affect the low energy dynamics, since otherwise slow-roll inflation would not persist. In theories of quantum gravity we expect degrees of freedom to enter at the Planck scale or below. A field range exceeding the Planck scale would imply that quantum gravity contributions do not have a significant effect over the naively expected scale. A detection of r would therefore provide very strong motivation to better understand how “large-field inflation” can be naturally incorporated in quantum gravity.

Although the B -mode polarization is the richest source of new information, deeper mapping of E -mode polarization will also contribute to testing inflationary models. On the largest scales (accessible only from space), E -modes will provide new tests of isotropy, while on sufficiently small scales they will allow tighter constraints on the shape of the scalar power spectrum, the amplitude of scalar non-Gaussianities, and isocurvature modes.

In summary, a detection of primordial gravitational waves consistent with the standard inflationary prediction would reveal the presence of a new fundamental energy scale for particle physics and would have far reaching implications for quantum gravity. Detecting correlations on the largest scales would confirm a primordial origin. Any departure from a nearly scale-invariant, nearly Gaussian spectrum would reveal new physics beyond the simplest inflationary model. In the absence of a detection, an improvement by a factor of xxx in the upper limit would qualitatively change how we think about the inflationary paradigm.

1.1.2 Neutrinos and Light Relics

Much of the information about our thermal history and the particle content of the universe is encoded in the T and E power spectra. A high-precision measurement of these spectra over the full sky is expected to significantly improve our understanding of the post-inflationary universe. This is particularly true in E -mode polarization where, to date, far fewer modes have been measured at the level of cosmic variance than in temperature.

The spectra at high- ℓ contain important information about the components of the thermal plasma and their interactions around the time of recombination. One particular compelling target is the effective number of neutrino species, N_{eff} , which parameterizes the total amount of energy density in radiation at the time of recombination. It is defined such that in the Standard model of particle physics with normal thermal evolution, $N_{\text{eff}} = 3.046$ due to the energy density in the three species of neutrinos. N_{eff} is also sensitive to any additional light relic particles as their gravitational influence is identical to the neutrinos. In fact, if there was an additional light particle in thermal equilibrium with the Standard model particles at any point in our history, it will contribute a change to N_{eff} of at least $\Delta N_{\text{eff}} \geq g 0.027$ where $g \geq 1$ is the number of degrees of freedom of the new particle. This defines a compelling target of $\sigma(N_{\text{eff}}) < 0.027$ for future CMB observations. New light particles are a common feature of many approaches to beyond the Standard model physics and can be directly tied to some of the most significant problems in the Standard model. Either a limit or detection of ΔN_{eff} at this level would provide a powerful insight into the laws of nature and our thermal history.

The presence of free-streaming radiation changes the detailed features of the TT , TE and EE spectra at all ℓ . In particular, it changes the locations of the acoustic peaks and alters the damping tail at high- ℓ . Similar changes to the spectra arise from many other compelling targets including the helium fraction Y_p and more general dark sector physics. For this reason, constraints on N_{eff} a useful proxy for the information available in the high- ℓ power spectra.

Preliminary forecasts for N_{eff} are shown in the right hand panel of Figure 3. A space-based

mission reaching an effective temperature noise of 1-2 $\mu\text{K-arcmin}$ over the full sky gives competitive constraining power when compared other proposals. The two most important quantities for improving constraints on N_{eff} and other high- ℓ targets are f_{sky} and the temperature noise. The full-sky nature of the proposed mission would allow for cosmic variance limited E -modes over most of the sky and a large range of ℓ .

The main downside of a space-based mission is that we cannot reach the resolutions available from the ground. However, we see that at 5' resolution and 1 $\mu\text{K-arcminute}$ noise the forecasts are less sensitive to the resolution than one might naively expected. In particular we can reach $\sigma(N_{\text{eff}}) < 0.035$ for temperature noise from 1-2 $\mu\text{K-arcmin}$ and $f_{\text{sky}} = 0.6 - 0.8$. These forecasts are competitive with CMB Stage IV. Specifically, the larger sky fraction and sensitivity available from space appears to compensate for the reduced resolution. In fact, the full sky measurement would provide complimentary information that could be combined with ground based surveys to further improve over the limits available from either experiment. This is particularly important for N_{eff} which is tantalizingly close to the target of $\sigma(N_{\text{eff}}) = 0.027$ and therefore even an apparently modest improvement could have a major scientific impact.

The sum of neutrino masses, $\sum m_\nu$, is another theoretically compelling target that is accessible from Cosmology. The most distinctive feature of $\sum m_\nu$ is that it suppresses the growth of structure on small scales. This suppressed can be measure in the CMB through amplitude of the lensing power spectra compared to the primary CMB. In principle, this relative difference can yield a measurement of the minimum value of $\sum m_\nu = 58 \text{ meV}$ at 4-5 σ for a number of future cosmological surveys. However, sensitivity to $\sum m_\nu$ is ultimately limited by our knowledge of the primordial amplitude of fluctuations A_s which is strongly degenerate with the optical depth τ .

The current limit on τ from the Planck satellite of $\tau = 0.055 \pm 0.009$ ultimately limits $\sigma(\sum m_\nu) \gtrsim 25 \text{ meV}$, as shown in the panel of Figure 3. While the figure shows the sensitivity of a space-based CMB mission to $\sum m_\nu$, this lower limit is common to any measurement that depends on the relative suppression. Therefore, a cosmological detection of $\sum m_\nu = 58 \text{ meV}$ at 3-5 σ depends crucially on an improvement measurement of τ . To date, the only proven method for such a measurement is from a space-based CMB observations. The best constraints on τ come from E -modes with $\ell < 20$ which requires control over the largest angular scales.

1.1.3 CMB spectral distortion science

In addition to the CMB temperature and polarization anisotropy targeted by CMB imagers, *unique* new information about early-universe physics can be gained by studying the energy spectrum of the CMB [26, 27, 28, 29]. The measurements of COBE/FIRAS have shown that the average CMB spectrum is consistent with that of a blackbody to an accuracy of 4 parts in 10^4 : $T_0 = (2.726 \pm 0.001) \text{ K}$ [30, 31]. These are the best measurements of the average spectrum to date. However, several standard processes that encode unique information about the Universe are expected to *distort* the CMB spectrum [e.g., 32] at a level that is within reach of present-day technology [33, 34]. The classical distortion shapes arise from inverse Compton scattering and chemical potential changes [35, 36], commonly denoted as y - and μ -type distortions, respectively, and are caused by energy exchange of CMB photons with free electrons. A μ -distortion can only be produced in the hot and dense environment present at redshifts $z \gtrsim 5 \times 10^4$, while y -type distortions are caused at lower redshifts. This makes μ -distortions a unique messenger from the early Universe.

y Distortion: The largest guaranteed distortion is caused by the late-time energy release of forming structures and from reionization [37, 38, 39, 40, 41], imprinting a y -type distortion with

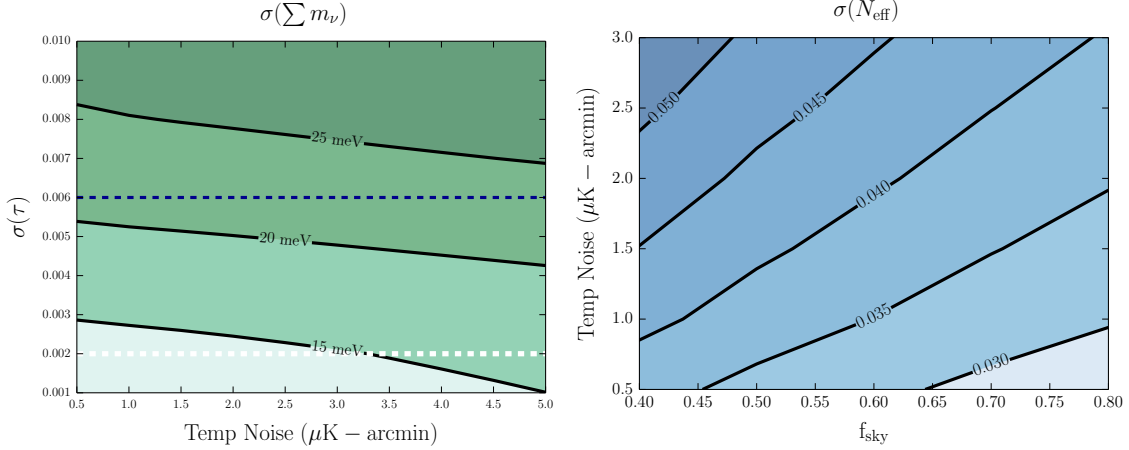


Figure 3: *Left:* Neutrino mass constraints as a function of the prior on τ for a 5' beam and sky fraction of $f_{\text{sky}} = 0.7$. The blue dashed line is the Planck blue book expectation and the white dashed line a cosmic variance limit measurement of τ from the CMB. *Right:* N_{eff} Forecasts as a function temperature noise and sky fraction assuming 5' resolution.

$y \simeq 2 \times 10^{-6}$ [e.g., 41, 42]. This distortion is only one order of magnitude below the current limit from COBE/FIRAS and, even with most pessimistic assumptions about foregrounds, should be clearly detected with the next-generation spectrometers we propose to study. A detection will give information about the total energy output of first stars, AGN and galaxy clusters. In particular, group-size clusters that have masses $M \simeq 10^{13} M_\odot$ contribute significantly to the signal. With temperature $kT_e \simeq 1 \text{ keV}$ these are still sufficiently hot to create a detectable relativistic temperature correction to the large y -distortion, which will be used to constrain the currently uncertain feedback mechanisms used in hydrodynamical simulations of cosmic structure formation [42]. These two inevitable signals probe the low-redshift Universe and provide clear targets for future spectral distortions measurements and their requirements in the presence of foregrounds.

μ Distortion: Next generation CMB spectrometers are also expected to greatly improve the μ -distortion limits of COBE/FIRAS [33]. This will allow us to place stringent bounds on the presence of long-lived decaying particles [43, 44, 45, 46] and other new physics [e.g., 47, 48, 49, 50, 51, 52], but a clear target is predicted by the dissipation of small-scale perturbation through Silk-damping [53, 54, 55, 56]. This process allows us to place stringent constraints on the amplitude of the small-scale curvature power spectrum, present at scales (wavelength $0.1 \text{ kpc} \lesssim \lambda \lesssim 1 \text{ Mpc}$) and epochs ($10^4 \lesssim z \lesssim 10^6$) inaccessible through any other observation. This delivers a complementary test for the inflation paradigm [45, 57, 58, 59, 60], with $\mu = (2.0 \pm 0.14) \times 10^{-8}$ expected in ΛCDM [32]. Precise measurements of signals at this level will be extremely challenging and requires unprecedented control of systematics and modeling of foregrounds. It would also bring us to the sensitivity level required to detect the cosmological recombination radiation [61, 62] imprinted by the recombination of hydrogen and helium at redshift $z \simeq 10^3 - 10^4$. Optimizing next-generation CMB spectrometers for these purposes requires extensive studies. **how about a plot showing required sensitivity and lines showing the reach of a \$250M and \$700M missions?**

The CMB spectrum also varies spatially across the sky. One source of such anisotropic distortion is related to clusters of galaxies and has already been measured by Planck [63]. A combination of precise CMB imaging and spectroscopic measurements will allow observing the relativistic

temperature correction of individual SZ clusters [64, 65, 66], which will calibrate cluster scaling relations and inform our knowledge of the dynamical state of the cluster atmosphere. Anisotropy in the μ -distortion can be created through ‘ultra-squeezed limit’ non-Gaussianity [67, 68] and will be used to probe scale-dependent non-Gaussianity [69, 70]. Finally, resonant scattering signals in the recombination [71, 72, 73] and post-recombination eras [74, 75] can lead to spectral-spatial CMB signals that can be used to constrain the presence of metals in the dark ages and the physics of recombination. For all these applications, instrumental synergies between CMB imaging and spectroscopy need to be studied in detail.

Future space-borne studies of the CMB spectrum open a new window to early phases of the Universe ($z > 10^3$), which cannot be probed in any other way. This yet unexplored tool for testing the standard cosmological paradigm including inflation and reionization, as well as a host of non-standard physical mechanisms, such as decaying and annihilating particles, can *only* be exploited with a satellite mission.

1.1.4 The Cosmic Infrared Background

Dust enshrouded star-forming galaxies at redshift $z \sim 1 - 3$ is heated by starlight at ultraviolet (UV) and optical wavelengths, and re-radiates at mid-IR to sub-millimetre wavelengths. This emission, from galaxies actively producing stars at their peak of star formation, reaches us in the far-infrared (FIR) regime as the cosmic infrared background (CIB). The CIB carries a wealth of information about the history of star formation and dark matter in the Universe, and will be used to constrain foreground levels and to remove the effects of lensing from the CMB polarization signals.

Star Formation History: The Planck Collaboration, analyzing CIB anisotropy and its correlation with CMB lensing [79, 85], derived limits on the star formation rate that at redshift $z > 2$ are higher than with other datasets (see for example [86]) **by how much higher?** With **100?** times the Planck sensitivity at **?? GHz**, **the constraints on the star formation rate will improve by ??** The new mission probe will measure CIB anisotropies with only one tenth of *Planck*’s instrumental noise at the critical scales where the clustering of galaxies in the same dark matter halo (the 1-halo term) has the same amplitude as the clustering due to galaxies in separated halos (the 2-halo term). Assuming a precise knowledge of the Poisson level of CIB galaxies, we will be able to firmly constrain our models of CIB clustering, and thus address three of the seven key questions identified in the Astro2010 report “New Worlds, New Horizons in Astronomy and Astrophysics” (NAS Decadal Survey, p. 47): *What is the fossil record of galaxy assembly from the first stars to present? What are the connections between dark and luminous matter? How do cosmic structures form and evolve?* **deliverables from previous paragraph not clear**

Dark Matter: The CIB, being a tracer of the dark matter field over a broad redshift range, can be cross-correlated with many other datasets to explore the interplay between CIB galaxies and dark matter. examples include the cross-correlations with catalogs of quasars [89] and galaxies [90] to constrain the interplay between SFR and halo mass, and the cross-correlation with the Cosmic γ -ray background from *Fermi*-LAT [91] to constrain the dark matter annihilation cross-section [92]. **what are the quantitative outcomes of these cross-correlations**

CMB Delensing: Since they are both tracers of the underlying mass distribution over a broad range of redshifts, the CIB and CMB lensing are highly correlated [85]. In particular, the CIB can be used as an ideal proxy for the CMB lensing field in delensing studies, aiming at reducing the confusion due to B-modes from lensing in the search of the signal from primordial gravitational waves. Recently [93, 94] showed that co-adding *Planck* CIB maps greatly improves the delensing

performance. Upcoming CMB surveys will heavily rely on delensing methods for constraining the inflationary B-mode polarization signal, and CIB delensing of temperature and E-mode polarization might also help improving constraints on other parameters such as the effective number of neutrino species N_{eff} [94]. **can we be quantitative**

CMB Foregrounds: The Planck collaboration found that the CIB is a significant contributor to foregrounds in the 143x217 and 217x217 GHz band correlations [87]. Both the clustering and Poisson components of the CIB were found to be important. The cross-correlation between IR galaxies and the thermal Sunyaev-Zeldovich (tSZ) effect provides an additional contamination. Thus, an accurate determination of both CIB and CIB-tSZ power spectra will be extremely useful when accounting for these foregrounds in the CMB parameter estimation. **make quantitative?**

1.2 The Challenges: Foregrounds, systematics

3 pages. Discuss the challenge of Foregrounds and Systematics.

A satellite mission provides the best both the inflationary B-mode polarization that originates from the epoch of recombination and peaks around $\ell = 80$ and the contribution from reionization that peaks on significantly larger scales at $\ell \lesssim 12$. The contribution from reionization to the Stokes Q -parameter for a tensor-to-scalar ratio $r = 0.001$ in the left panel of Figure 4. The amplitude of the signal is approximately 10 nK so that both residual foregrounds and systematics must be controlled at an unprecedented level of a few nK.

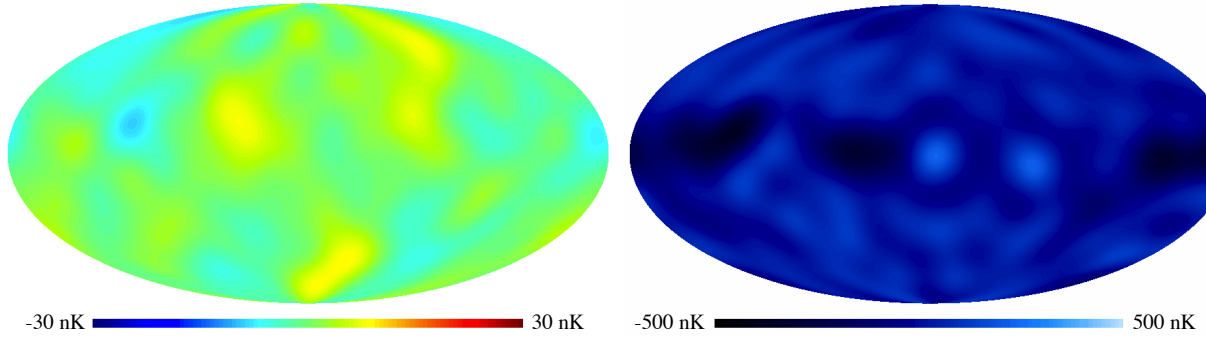


Figure 4: *Left panel:* Contribution to the Stokes Q parameter from inflationary B-modes for $\ell < 12$ for $r = 0.001$. *Right panel:* Noise in the *Planck* 353 GHz map of the Stokes Q parameter for $\ell < 12$ rescaled to 150 GHz assuming the spectral properties of dust.

Data from the *Planck* satellite has recently led to a significant improvement in our understanding of foregrounds in both intensity and polarization. In intensity, *Planck*, for example, showed the unexpected relevance of Carbon-Monoxide lines at moderate latitudes as well as the existence of an anomalous emission from dust at low frequencies. In polarization, the sky appears to be dominated by the expected polarized foregrounds, synchrotron and dust. Our knowledge is limited, of course, by the sensitivity of *Planck*, and this does not mean that additional components, especially anomalous dust, could not have a certain degree of polarization.

Planck has also provided us with much improved measurements of the amplitude and spectral dependence of synchrotron emission and dust. The spectral dependence of both foregrounds and signal is summarized in the left panel of Figure 5 for different sky fractions. The power spectrum of foregrounds over 75% of the sky for frequencies between 70 and 200 GHz is shown in the right

panel, together with the inflationary contribution for different values of the tensor-to-scalar ratio.

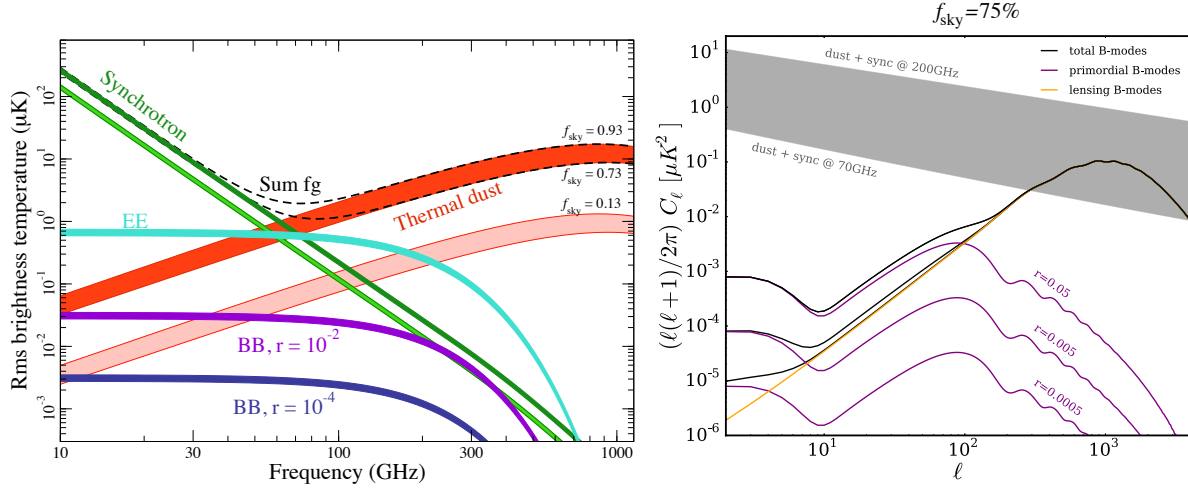


Figure 5: *Left panel:* Brightness temperature as function of frequency for the CMB as well as synchrotron emission (green) and dust emission (red). The darker bands show the brightness temperature for sky fractions between 73% and 93%, the lighter bands show the brightness temperature for the cleanest 13% with the width indicating the uncertainty. *Right panel:* Angular power spectrum for B-mode polarization of the CMB for $r = 0.0005$, $r = 0.005$, and $r = 0.05$ as well as for foreground emission between 70 and 200 GHz.

Perfect knowledge of the foreground components would allow to remove them, but the sensitivity of *Planck* sets limits. The right panel in Figure 4 shows the noise in the *Planck* map of the Stokes Q -parameter at 353 GHz rescaled to 150 GHz assuming the same spectral dependence as for dust and on the angular scales relevant for the measurement of the inflationary B -modes on large angular scales. The noise is more than an order of magnitude larger than the inflationary contribution for $r = 0.001$, clearly indicating the necessity to measure foregrounds with a potential future space mission.

One of the key ingredients in the design of a CMB experiment is the frequency coverage required to achieve the science goals. Consequently, optimizing frequency coverage in light of the new information from *Planck* and its limitations will be one of key task of the study proposed here.

1.2.1 Systematic Errors

Advances in detector technology since the formulation of *Planck* and *WMAP* will enable huge gains in raw sensitivity for a CMB probe. To fully take advantage of this sensitivity, systematic errors must be controlled to detect polarization signals at nano-Kelvin levels. The proposed study will invest heavily in designing an instrument, test plan, and observation strategy to address systematic errors, gathering decades of experience of ground-, balloon-, and space-based CMB polarimetry. The latest analyses of *Planck* HFI and LFI data in particular show the effects likely to be important to a future space mission (<https://arxiv.org/abs/1605.02985>). These systematic errors can be considered in three broad categories: 1. Intensity-to-polarization leakage, 2. stability, and 3. straylight. Each of these is considered in light of differential polarimetry; the instantaneous signals measured by polarization-sensitive detectors at different times and orientations are combined

to recover the maximum likelihood polarization signal from each point on the sky.

Leakage. The CMB temperature signal is many orders of magnitude larger than the polarization B-mode signal (see, e.g. Fig. 1). Therefore, instrumental mismatch effects that can leak even a very small fraction of an intensity fluctuation into a spurious polarization signal must be addressed. The main effects are relative gain and bandpass calibration, differential pointing error, and differential beam shapes.

Relative calibration requirements are likely to exceed those of Planck, whose High Frequency Instrument achieved of order 0.01% (cite <https://arxiv.org/abs/1605.02985>). Bandpass mismatch between polarized detectors gives an error in relative calibration when the SED of the sky signal differs from that of the calibrator. This gives a spatial dependence to the leakage, potentially complicating the component separation.

These systematics are likely to drive the instrumental requirements on the optical system as well as the uniformity of the bandpass of each polarimeter. Calibration requirements will also be set by limiting these systematics: particularly on the knowledge of the polarization parameters (such as cross-polar leakage and the angle of polarization sensitivity), as well as measurement of the beam shape (in general a function of the SED of the observed source). These systematic effects can potentially be mitigated by modulation of the sky signal in such a way that allows complete reconstruction of the polarized sky signal using each photometer, for example, using a half-wave plate.

Stability. Given the need to avoid light from the Sun, Earth, and Moon, the full reconstruction of the polarized sky will necessarily involve combination of measurements made at times separated by months, requiring stability of the response of the instrument on corresponding time scales. This systematic error puts requirements on control of thermal drifts of spacecraft temperatures, to mitigate thermal emissivity changes and thermoelastic deformation of telescope structures. The cryogenic operating temperatures of detectors or reference calibration loads must be controlled adequately as well. Careful design of the scan strategy can shorten the time scales needed for stringent stability, for example Planck's scan strategy traced out great circles which overlapped on 1 minute timescales, giving a shorter effective time scale for stability requirements.

Additionally, the space radiation environment is modulated by the solar activity and can introduce drifts in the cryogenic thermal environment as well as introducing correlated transients in detectors and readout electronics. The design of the instrument must account this environment, which following Planck is much better understood.

Straylight. The brightest cm-wave and mm-wave sources in the sky (such as the Sun, Moon, planets, and Galactic center) passing into the far sidelobes of the telescope (defined as the response of a detector from a source more than a few degrees from the optical axis) in a sky-synchronous way can create a spurious polarization signal. The far sidelobes can be reduced by optical design and baffling, but diffraction ensures that this off-axis response will always be present at some level. Measurement on the ground can allow for some correction, and design of the scan strategy can modulate the sidelobe pickup in a different way from the true on-axis polarization signal, allowing its removal.

1.3 Current and Forthcoming Efforts and the CMB Probe

2.5 pages. S3 experiments, forthcoming S4, Baselines CMB Probe options and their complementarity with S4.

1.4 State of Technologies

2 pages. Discuss the technologies, their TRL, and what will be studied

1.5 Mission Study, and Management Plan

1.5 pages; Describe what we want to do, who is doing what, what we are funding

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2 Curriculum Vitae

3 Summary of Work Effort

4 Current and Pending Support

5 Letters of Support

6 Budget Details - Narrative

6.1 Team, and Work Effort

6.1.1 Funded Team Members

6.1.2 Non-Funded Team Members

6.2 Costing Principles

- **Summer Salaries:**
 - **Workshop:**

6.3 University of Minnesota Budget

6.3.1 Direct Labor

6.3.2 Supplies

6.3.3 Travel

6.3.4 Other Direct Costs

Publications and Teleconferencing

Other Subcontracts

6.3.5 Facilities and Administrative Costs

7 Budget Sheets