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1 Scientific, Technical, and Management Section

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Shaul is writing this. Due by Nov. 4.

[ADDED THIS STATEMENT SINCE IT IS OUT OF PLACE IN ANY OF THE SCIENCE OBJECTIVES SECTIONS] 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 Observables

[JUST A PLACEHOLDER; COPIED ALL DISTORTION INTRO HERE. SHAUL IS WRITING THIS.] 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 [1, 2, 3, 4]. 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 at a temperature $T_0 = (2.726 \pm 0.001)$ K [5, 6]. These are the best measurements of the average spectrum to date, but next generation CMB spectrometers are expected to greatly improve the μ -distortion limits of COBE/FIRAS [7]. Several standard processes that encode unique information about the Universe are expected to *distort* the CMB spectrum [e.g., 8] at a level that is within reach of present-day technology [7, 9]. The classical distortion shapes, commonly denoted as y - and μ -type distortions, arise from early energy release and subsequent energy exchange of CMB photons with free electrons through inverse Compton scattering [10, 11]. 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.

1.2 Science Objectives

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

1.2.1 Cosmic inflation

Inflation [12, 13, 14, 15, 16], 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 [17, 18, 19, 20]. But, inflation also predicts an as yet unobserved 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 [21, 22].

Figure 1 shows the predicted spectrum, current upper limits and measured B -modes from lensing, as well as forecasts for the EPIC-IM satellite. **should we put Planck E-modes on here?** The large-scale information provided by a satellite mission is complementary to the smaller scales accessible from the ground. For testing inflation, the largest scales are particularly important: only a satellite can demonstrate the presence of B-mode correlations on scales that were super-horizon at the time of recombination [23]. In addition, new tests of isotropy on the largest scales can only

come from the reionization bump in the E-mode polarization [] and may contain information about the beginning of inflation. 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.” [24].

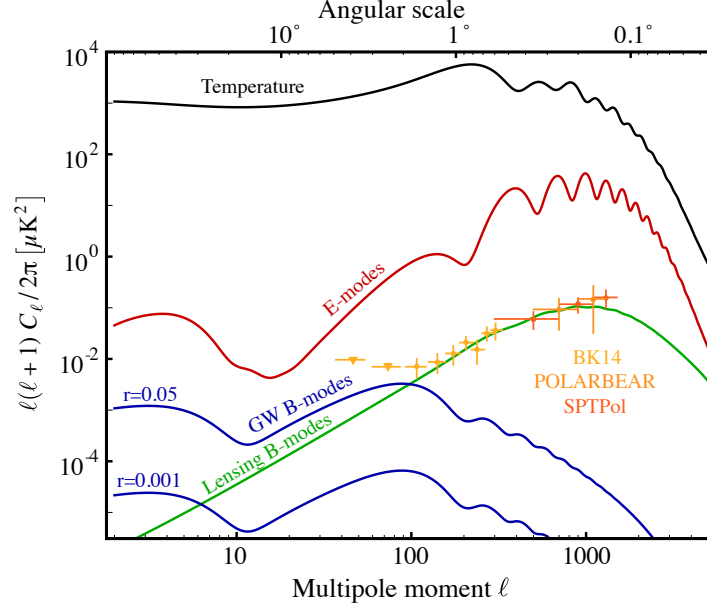


Figure 1: Theoretical predictions for the temperature (black), E-mode (red), and tensor B-mode (blue) power spectra. Primordial B-mode spectra are shown for two representative values of the tensor-to-scalar ratio: $r = 0.001$ and $r = 0.05$. The contribution to tensor B modes from scattering at recombination 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.

The predicted amplitude of the B -mode signal depends on the nature of the scalar sector driving inflation. 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 a primordial 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.

Although there are many proposed inflationary scenarios, when the slow-roll criteria is met ($\epsilon \equiv -\dot{H}/H^2 \ll 1$) 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) [25, 26, 27]. 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 to even

~ 0.01 , all such models would be ruled out (see Figure 2.). The remaining class of natural models includes Starobinsky and Higgs inflation (which both 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. The EPIC-IM configuration is forecasted to achieve $\sigma(r) \sim 4.8 \times 10^{-4}$ assuming $r = 0.01$ and no foregrounds. **This number is for "EPIC-2m" from CMBPol paper. Couldn't find the comparable number in the EPIC-IM report.**

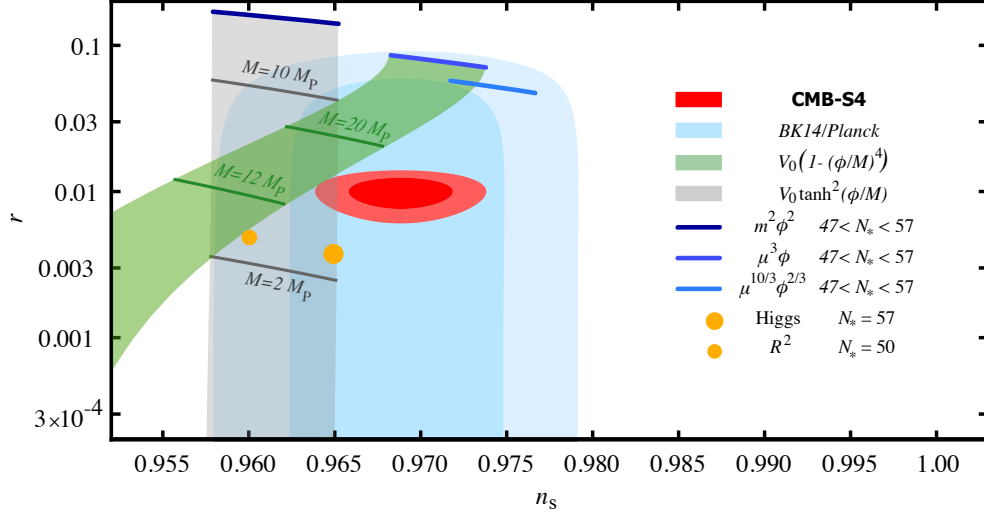


Figure 2: **Perhaps a version of this figure?** Forecast of CMB-S4 constraints in the n_s - r plane for a fiducial model with $r = 0.01$. Constraints on r are derived from the expected CMB-S4 sensitivity to the B-mode power spectrum as described in Section ???. Constraints on n_s are derived from expected 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 [?].

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. To be confident of the implications of a detection, the B-mode spectrum must be characterized. 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 satellite mission, combined with stage 3 ground based observations, could perhaps aim for $\sigma(n_t) \lesssim 1$ to at least rule out non-vacuum inflationary sources [28, 29]. Post-inflationary phase transitions have been proposed as a non-inflationary source of nearly scale-invariant gravitational waves [30, 31, 32, 33, 34], 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. [35] 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 [23] 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 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” [36]) 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 about two orders of magnitude on the current upper limit would qualitatively change how we think about the inflationary paradigm.

[DISTORTION PART DOES NOT LINK TO WHAT IS WRITTEN BEFORE YET. THE TEXT BEFORE HAS TO BE WORKED OVER SIGNIFICANTLY TO MAKE THAT MATCH.] Another clear target is predicted by the dissipation of small-scale perturbation through Silk-damping [37, 38, 39, 40]. 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. It delivers a complementary test for the inflation paradigm [41, 42, 43, 44, 45], with $\mu = (2.0 \pm 0.14) \times 10^{-8}$ expected in ΛCDM [8]. 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 [46, 47] imprinted by the recombination of hydrogen and helium at redshift $z \simeq 10^3 - 10^4$, which can be used to probe the physics of recombination. Anisotropy in the μ -distortion can furthermore be created through ‘ultra-squeezed limit’ non-Gaussianity [48, 49] and can be used to probe scale-dependent non-Gaussianity [50, 51]. Optimizing next-generation CMB spectrometers for these purposes requires extensive studies.

1.2.2 Neutrinos and Light Relics

After inflation, the universe was reheated to temperatures of at least 10 MeV and perhaps as high as 10^{10} GeV. At these high temperatures, even very weakly interacting or very massive particles can be produced in large abundances including those that would arise in extensions of the Standard model of particles physics. As the universe expands and cools, these particles will fall out of equilibrium and can leave observable signatures in, for example, the primary CMB and/or through gravitational lensing. Through these effects, the CMB is a very sensitive probe of neutrinos and their mass and many hypothetical light particles.

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

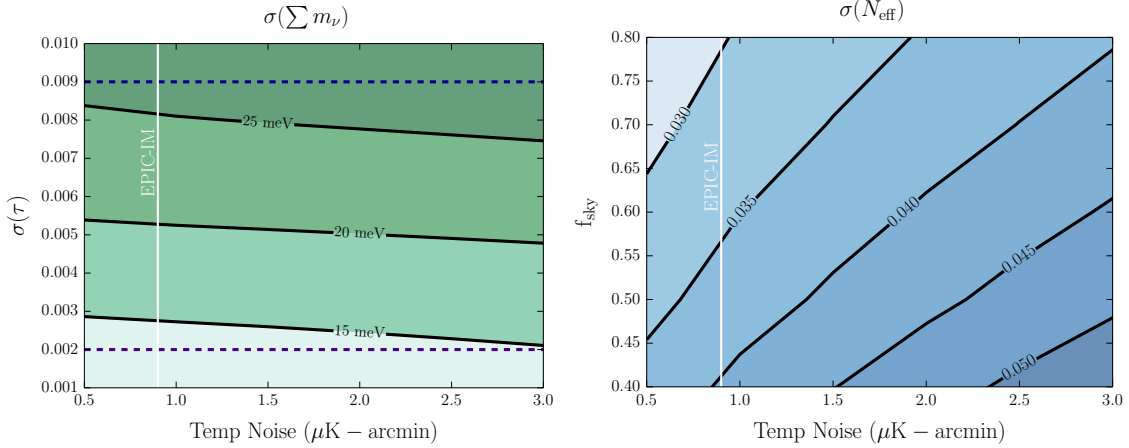


Figure 3: *Left:* Neutrino mass constraints as a function of the prior on τ for a 5' beam and sky fraction of $f_{\text{sky}} = 0.7$. The blue dashed line is current Planck limit and the white dashed line a cosmic variance limit measurement of τ from the CMB. *Right:* N_{eff} Forecasts as a function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

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 μK -arcminute noise the forecasts are less sensitive to the resolution than one might naively expect. In particular we can reach $\sigma(N_{\text{eff}}) < 0.035$ for temperature noise from 1-2 μK -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.

Measurements of the primary CMB and CMB lensing are very sensitive to particles with long-lifetimes that service until the era of recombination. Furthermore, the primary CMB is indirectly sensitive to BBN through the helium fraction, Y_p , that can be detect energy injections at those times. However, many relics of the early universe are not cosmologically stable but can survive beyond the time of BBN. Energy injection between the two eras is not directly captured by the CMB anisotropies but can be tested by BBN consistency of Y_p with the measured value of N_{eff} .

Additional, far more sensitive measurements of this intermediate era are possible through the *distortions* of the CMB black-body spectrum. This will allow us to place stringent bounds on the presence of long-lived decaying particles [43, 52, 53, 54] and other non-standard physics, such as axions, primordial magnetic fields and superconducting strings [e.g., 55, 56, 57, 58, 59].

1.2.3 Cosmological structure formation

Understanding the evolution of cosmological structures from the formation of the first stars to the present time is a key goal of cosmology **add Dunlop, Science**. However, current measurements of the star formation rate density (SFRD) from number counts are quite uncertain at high redshifts (~ 3), where multiple assumptions about conversion factors and dust attenuation are at play. The Cosmic Infrared Background (CIB), produced by dusty star-forming galaxies (DSFGs), is a robust tracer of the history of star formation, and an ideal probe of the link between galaxies and dark matter across cosmic time. The Planck Collaboration [60, 61], derived limits on the star formation rate density that, at high redshifts ($z \sim 3$) are about three times higher than what found by other probes (see for example [62]). The new mission probe, by measuring CIB anisotropies with 100 times more sensitivity than *Planck*, will be able to constrain the SFRD at high redshifts with, at least **more here ******. Moreover, because DSFGs trace the underlying dark matter field in a broad redshift range, the CIB will correlate with multiple dark matters tracers such as galaxy catalogs, quasars, diffuse maps from the γ -ray and the X-ray background. These cross-correlations will not only provide an additional probe of the global star formation history, but they will shed light on the interaction between light and matter in a large wavelength range. As an example, it will be possible to constrain the dark matter halo mass which is most efficient at hosting star formation **add here**.

Large-scale structure can also be probed using CMB spectral distortions measurements. In fact, the largest guaranteed distortion is caused by the associated late-time energy release of forming structures and from reionization [63, 64, 65, 66, 67], imprinting a y -type distortion with $y \simeq 2 \times 10^{-6}$ [e.g., 67, 68]. 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 can be used to constrain the currently uncertain feedback mechanisms used in hydrodynamical simulations of cosmic structure formation [68]. 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.

The CMB spectrum varies spatially across the sky. One source of such anisotropic distortion is related to clusters of galaxies and has already been measured by Planck [69]. A combination of precise CMB imaging and spectroscopic measurements will allow observing the relativistic

temperature correction of individual SZ clusters [70, 71, 72], which will calibrate cluster scaling relations and inform our knowledge of the dynamical state of the cluster atmosphere. Finally, resonant scattering signals in the recombination [73, 74, 75] and post-recombination eras [76, 77] 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.

These studies will be key to 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?*

1.2.4 Dark Matter

Characterizing the nature of dark matter is one of the most basic problems in cosmology and astroparticle physics. For a conventional WIMP candidate, the CMB places very stringent constraints on dark matter through possible energy injection at the time of recombination. A thermal relic will necessarily annihilate into Standard model particles which distorts the Thomson visibility function and ultimately the shape of the primary T and E spectra [78, 79, 80]. In principle, a dark matter candidate can also have a slow decay to dark matter particles which is similarly constrained by the CMB. **add citations**

A somewhat more model-independent approach is to constraint dark matter interactions that would effect the evolution of the effective dark matter fluid and its interactions with baryons or photons. The simplest example is to constraint the baryon-dark matter cross section through its effective coupling of the two fluids. These couplings effect the evolution of fluctuations and ultimately the T and E spectra. More exotic dark sectors can produce a rich phenomenology in the CMB and in the large-scale structure without necessarily producing an associated signature in direct detection experiments or indirect searches. **add citations**

Interactions of DM with standard model particles can also be constrained through CMB spectral distortions [81]. As the Universe expands, the matter cools. Compton interactions with electrons keep the normal matter at the CMB temperature until well after recombination. This leads to a small distortion of the CMB with a negative chemical potential [4]. In a similar manner, interactions of DM with electron, protons or directly with CMB photons can lead to a distortion. These constraints could be strongly improved with future CMB spectroscopy [81].

1.3 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.

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

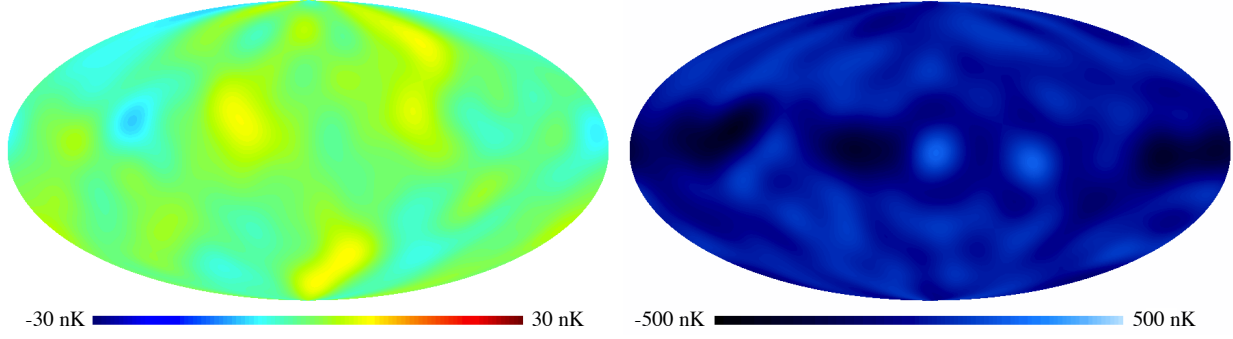


Figure 4: *Left panel:* Contribution to the Stokes Q parameter from inflationary B-modes for $\ell < 12$ for $r = 0.001$. *Right panel:* Noise in the *Planck* 353 GHz map of the Stokes Q parameter for $\ell < 12$ rescaled to 150 GHz assuming the spectral properties of dust.

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.

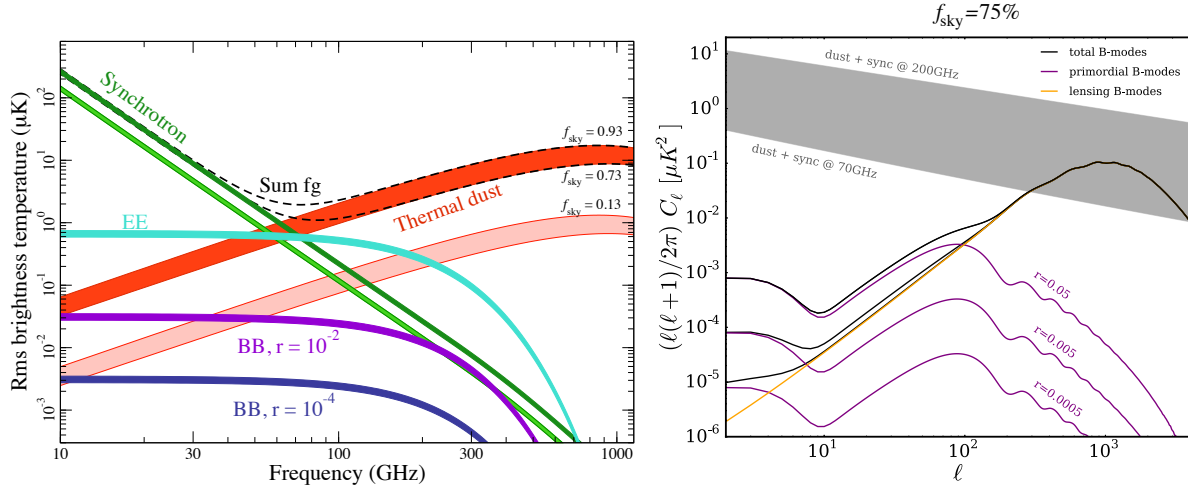


Figure 5: *Left panel:* Brightness temperature as function of frequency for the CMB as well as synchrotron emission (green) and dust emission (red). The darker bands show the brightness temperature for sky fractions between 73% and 93%, the lighter bands show the brightness temperature for the cleanest 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 sensi-

tivity 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.

1.3.1 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 is the imperfect matching of the frequency dependant gain of the two detectors or acquisition channels used to estimate the polarized signal. Any asymmetry turns into a spurious polarization signal when viewing sources with SED different from the calibrator. For CMB-probe, this includes every foreground contaminant on the sky. The effect can be minimized by matching the bandpasses, and residual mismatch can be estimated by measuring the bandpasses on the ground, however, for both instruments of Planck the ground based measurements of the bandpasses were found to be insufficient to determine the impact on the polarized maps. In both cases estimates of the bandpass mismatch needed to be determined as part of the mapmaking pipeline, and bandpass mismatch remains one of the most problematic systematics in the pipelines. CMB-probe will need a more robust program to mitigate this problem on ground, simulate the impact, and to deal with it in the flight data.

A second order complication of unmatched bandpasses is unmatched far sidelobe contamination, leading to a spurious polarized component from bright unpolarized signals far from the main lobe.

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 sidelobe response can be reduced by the optical design and baffling, but will always be present at a non-trivial level. The Planck experience is instructive here as well. The detailed GRASP model of the telescope, convolved with the sky model, predicted sidelobe contamination at a visible (10’s of microK) level in the 30 GHz maps, which was observed in difference maps. As a result the LFI maps have had an estimate of the sidelobe contamination removed from the timelines as part of the mapmaking process. The more stringent requirements for CMB-probe will necessitate at least this level of mitigation. A major limitation to the analysis of far sidelobe contamination in the Planck data has been the lack of bright enough on-orbit sources to validate the GRASP simulation as adjusted by optical and bandpass parameters estimated on-orbit. Finding a way to better validate the FSL model on-orbit for CMB-probe may be critical to successfully removing FSL contamination.

1.4 Current and Forthcoming Efforts and the CMB Probe

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

Bill Jones is writing this. Due by Oct. 28

1.5 State of Technologies

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

A fourth generation CMB satellite targeting a map sensitivity of $\sim 1\mu\text{K} - \text{arcmin}$ will require, extremely sensitive detector arrays, tight control over systematics, and ability to reject polarized foregrounds as is described in Section 1.2. Given the frequency dependence of synchrotron and dust foregrounds, this last requirement translates into the need for a large number of spectral bands covering the approximate frequency range from $\sim 30\text{ GHz}$ to $\sim 800\text{ GHz}$. Development of the

CMB technologies needed to meet these requirements is actively being pursued by many groups who are also demonstrating these technologies on ground, balloon, and satellite platforms. We describe the status and needs in the areas of telescopes, optics, detector coupling, detectors, and readout.

Telescopes: Carbon Fiber Reinforced Polymer (CFRP) mirrors are at TRL 9 as they have flown on the Planck satellite. Their 1.9x1.5 m mirror weighted only 28 lbs and met all surface quality requirements. However, small deformations in the mirror caused by its structural supports had a measurable impact to the beam far-sidelobes that was not captured by preflight measurements or the corresponding beam modeling. Future CMB satellites will require improved pre-flight characterization of *polarized beam* at operating temperature augmented by improved simulation tools to meet even more systematics requirements. Current ground and balloon born optical designs achieve large field of views (FOVs) with reflective and refractive designs; related designs and their implementation should be studied in the context of a satellite mission as the sensitivity requirements lead to the need to maximize the size of the FOV while fitting within the tight mass and size constraints imposed by a space mission. Given the heritage of past satellite missions it will be possible to develop a telescope design that meets the requirements for a future mission and uses high TRL components.

Optical Coupling: The need for sensitivity drives the push for high efficiency optics; wide bandwidth to compliment multichroic detector ; infrared filters to maximize cryogenic performance; and polarization modulators to suppress $1/f$ noise and mitigate instrument systematics. The CMB field has made tremendous progress recently by drawing on advances in materials, processing techniques, and developments in electrical engineering including meta-material research. Single crystals such as silicon and sapphire are attractive since they offer extremely low dielectric losses and high indices of refraction to better manipulate light. New coating techniques have been developed for silicon and sapphire that span 2:1 bandwidth (TRL 5+ for silicon) and can realize up to 5:1 bandwidth. EBEX deployed broadband cryogenic polarization modulator with a superconducting bearing that covered 150 GHz band to 410 GHz band raising the modulators to TRL 5+ for space. Meta-material metal-mesh optical filters were deployed with the Planck satellite and they are extensively used by ground based and balloon experiments making these TRL6 optical elements. It is necessary to develop a plan for a satellite mission that will cover ~ 30 GHz to ~ 800 GHz. Two configurations could be considered: multiple optical paths with $< 3 : 1$ bandwidth and a potentially simpler design with only two optical paths with $\sim 5 : 1$ bandwidth. These studies include evaluating the design tradeoffs inherent to these approaches, developing the new coatings needed, and evaluating the promise of hybrid approaches where filters and lenses are implemented in the same optical elements. In addition, the cryogenic rotation mechanism should be demonstrated at the robustness (eg lifetime) needed for for a satellite mission.

Detector Coupling: The focal-plane feed determines the shape and polarization properties of the pixel beams and therefore plays a strong role in controlling systematic errors. The feed design also can determine the total bandwidth and number of photometric bands of each pixel which is important for the efficient use of a telescope's focal plane area. CMB experiments developed broadband multi-chroic *detector* to increase optical throughput of a focal plane. Broadband feed captures signal over wide frequency range. Then on-chip superconducting filter partitions signal into multiple

frequency bands prior to detection. Broadband detectors were realized with spline profiled horn and lenslet coupled antenna. Broadband horn detector deployed a pixel that covers 2.3:1 bandwidth with on going development for extending bandwidth to 6:1. Broadband lenslet coupled antenna will deploy 3:1 bandwidth detector this year. Lenslet coupled antenna demonstrated 5:1 bandwidth in laboratory. RF-techniques to partition broadband signals into multiple band are mature. For a future CMB polarization satellite mission, broadband feed should be demonstrated at high frequency where alignment and line width for micro-fabrication becomes challenging. Detectors for CMB satellite mission were hand picked one by one for optimal performance. Next generation of detector array will be fabricated on a silicon wafer. Micro-fabrication process should demonstrate high yield and uniformity across a wafer that can meet tight requirement of satellite mission. Also detector test need to be able to characterize detector beyond the level of systematic required by next generation CMB satellite experiment.

The Planck HFI deployed Neutron Transmutation Doped Germanium high-resistance bolometer at 100 milli-Kelvin to achieve photon noise limited detector performance. A Transition Edge Sensor (TES) bolometer uses a steep transition of superconducting metal to improve linearity of the detector. TES bolometers have been deployed on 100 milli-Kelvin and 250 milli-Kelvin platform. TES bolometers have been deployed across ground based and balloon CMB experiments spanning 40 GHz-410 GHz with detectors achieving NEPs of $20\text{-}50\text{ aW}/\sqrt{\text{Hz}}$, nearly background limited at CMB frequencies. TES bolometers deployed at low optical frequencies ($\sim 40\text{ GHz}$) and balloon-borne payloads should realized even lower NEPs of $\sim 10\text{ aW}/\sqrt{\text{Hz}}$. Emerging detector technology for CMB experiment is kinetic-inductance detector (KIDs). The KIDs detector detects signal as change in kinetic inductance. KIDs detectors can be frequency multiplexed easily to $\sim 1,000$ detectors. Recently, on-sky demonstration at 150 GHz and 230 GHz was done with lumped element KID detector. Noise performance of KID detector at low frequency channels ($< 40\text{ GHz}$) need some improvement to be photon-noise limited. Currently there is no CMB polarization power spectrum data produced with KID detector. Coupling between RF (100 GHz) signal to micro-wave KID (MKID) detector is in a development stage. Planck detectors experienced unexpectedly high rate of cosmic ray events. Data was successfully cleaned with analysis technique. Study of impact of cosmic rays on a detector is crucial for next CMB satellite mission.

Multiplexed readout is being used by CMB experiments to readout thousands of TES bolometers, and readout multiplexing is built into KID detector architecture. Voltage bias and low impedance of a TES bolometer facilitates multiplexing readout by Superconducting Quantum Interference Device (SQUID). Time domain multiplexing uses a SQUID at milli-Kelvin as a switch to rapidly cycle through bolometers. Highest achieved multiplexing factor is 64 channels. Frequency domain multiplexing uses superconducting resonators to assign bolometers to different frequency channels. Highest achieved multiplexing factor is 68 channels. New readout scheme, such as microwave SQUID readout, is emerging to increase multiplexing factor for TES bolometer. MKID detector architecture has multiple resonators coming off from a transmission line. A resonator is both a detector and multiplexer. MKID demonstrated multiplexing factor that exceeds 1,000 channels. For next generation satellite experiment that will readout over thousands detectors require high multiplexing factor. Multiplexing factor is directly related to readout complexity and power consumption. Also the Planck mission experienced ADC non-linearity, thus extensive characterization of end to end readout architecture should be performed pre-flight.

A future CMB satellite mission offers exciting opportunity for millimeter wave polarization science. Experience from Planck mission will be studied to learn lessons for the future mission. Development for CMB instrumentation is an active field with many institutions developing new

technologies for ground based, balloon, and proposed satellite missions. For a satellite instrumentation, there is a difficult trade off between desire to have high performance instrument and desire to keep cost manageable. Many developments that is going on for ground based and balloon experiment have similar goal as satellite mission that collaborative development across all platform will be beneficial.

1.6 Mission Study, and Management Plan

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

Shaul is writing this. Due by Tuesday Nov. 1

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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