Contents

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. A substantial array of measurements, including the cosmic microwave background temperature and E-mode polarization and many surveys of the large scale structure of the universe at later times, have significantly constrained the matter sector of inflation models while confirming the basic structure of the paradigm [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] with an amplitude directly proportional to the Hubble parameter during inflation, and to the potential energy of the matter sector in Planck units. The predicted spectrum peaks near an angular scale of $\ell = 80$, and contains a significant peak at much lower multipoles generated by scattering of CMB photons on the free electrons present at the time of reionization. Figure 1 shows the predicted spectrum and the status of current measurements.

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 suborbital 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 many, many inflationary scenarios have been proposed, 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 $n_{\rm s}(\mathcal{N}) - 1 \propto -\frac{1}{\mathcal{N}}$, 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 observatinoal 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

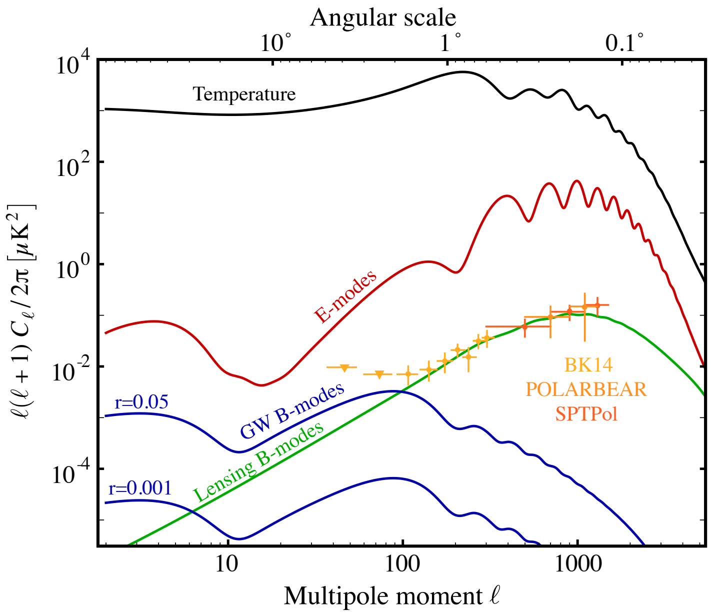

Figure 1: Theoretical predictions for the temperature (black), E-mode (red), and tensor B-mode (blue) power spectra. Primordial B-mode spectra are shown for two representative values of the tensor-to-scalar ratio: $r = 0.001$ and $r = 0.05$. The contribution to tensor B modes from scattering at recombination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

favored inflation model.

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 $n_{\rm t} = -r/8$. While confirming this relation is out of reach, a future mission could perhaps aim for $\sigma(n_{\rm t}) \sim 1$**??** 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 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

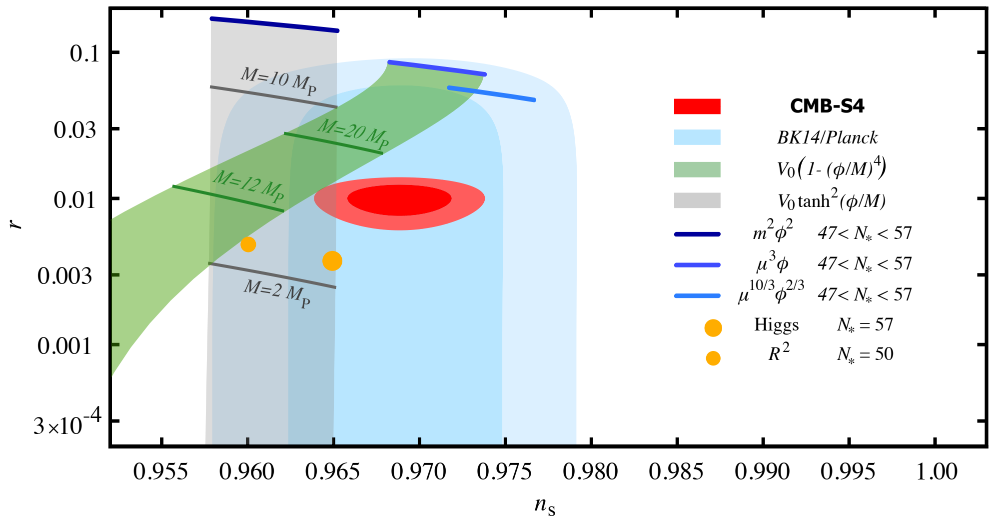

Figure 2: **Perhaps a version of this figure?** Forecast of CMB-S4 constraints in the n_s–r plane for a fiducial model with $r = 0.01$. Constraints on r are derived from the expected CMB-S4 sensitivity to the B-mode power spectrum as described in Section **??**. Constraints on n_s are derived from expected 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 $47 < N_\star < 57$ (with smaller $N_\star$ 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 [**?**].

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

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

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 be 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, $N_{\rm eff}$, 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, $N_{\rm eff} = 3.046$ due to the energy density in the three species of neutrinos. $N_{\rm eff}$ 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 $N_{\rm eff}$ of at least $\Delta N_{\rm eff} \geq g\, 0.027$ where $g \geq 1$ is the number of degrees of freedom of the new particle. This defines a compelling target of $\sigma(N_{\rm eff}) < 0.027$ 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 $\Delta N_{\rm eff}$ 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 $N_{\rm eff}$ a useful proxy for the information available in the high-ℓ power spectra.

Preliminary forecasts for $N_{\rm eff}$ are shown in the right hand panel of Figure 3. A space-based mission reaching an effective temperature noise of 1-2 μK-arcmin over the full sky gives competitive constraining power when compared other proposals. The two most important quantities for improving constraints on $N_{\rm eff}$ and other high-ℓ targets are $f_{\rm sky}$ and the temperature noise. The

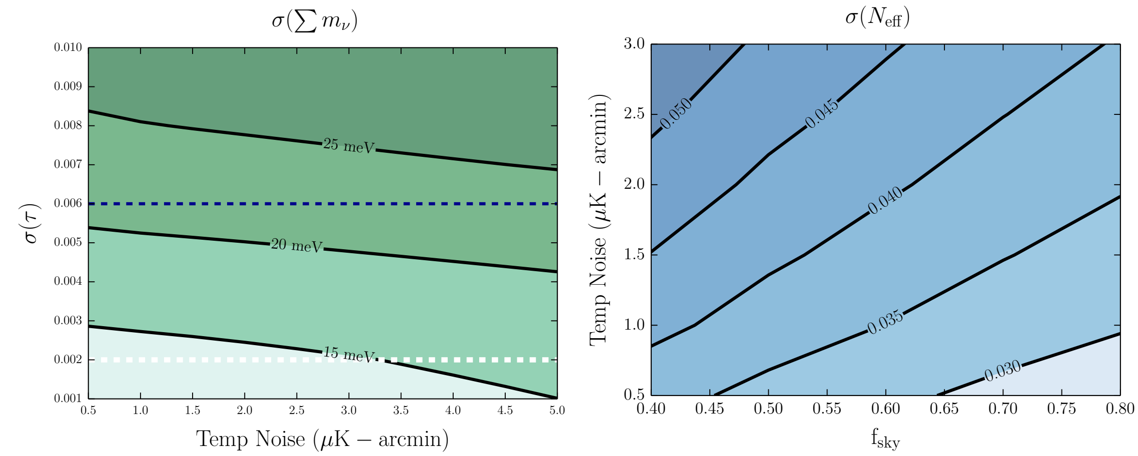

Figure 3: *Left:* Neutrino mass constraints as a function of the prior on τ for a 5' beam and sky fraction of $f_{\rm sky} = 0.7$. The blue dashed line is the Planck blue book expectation and the white dashed line a cosmic variance limit measurement of τ form the CMB. *Right:* $N_{\rm eff}$ Forecasts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

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 then one might naively expected. In particular we can reach $\sigma(N_{\rm eff}) < 0.035$ for temperature noise from 1-2 μK-arcmin and $f_{\rm sky} = 0.6 - 0.8$. 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 $N_{\rm eff}$ which is tantalizingly close to the target of $\sigma(N_{\rm eff}) = 0.027$ 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 $\sum m_\nu = 58$ 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 $\sigma(\sum m_\nu) \gtrsim 25$ 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 $\sum m_\nu = 58$ 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 anisotropies 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 extremely close to that of a blackbody at a temperature $T_0 = (2.726 \pm 0.001)\,\mathrm{K}$ [30, 31]. However, several standard processes 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 are known as Compton-y and chemical potential (μ-type) distortions [35, 36] and are caused by energy exchange of CMB photons with free electrons. A μ-distortion can only be produced in a hot and dense environment present at redshifts $z \gtrsim 5 \times 10^4$, while y-type distortions appear at lower redshifts. This makes μ-distortions a unique messenger from the early Universe.

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 $y \simeq 2 \times 10^{-6}$ [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 seen with next-generation spectrometers, telling us about the total energy output of first stars, AGN and galaxy clusters. In particular, group-size clusters ($M \simeq 10^{13}\,M_\odot$) contribute significantly to the signal. These are still sufficiently hot (temperature $kT_\mathrm{e} \simeq 1\,\mathrm{keV}$) to create a visible relativistic temperature correction to this large y-distortion, which could be used to constrain cluster feedback models [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.

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 $0.1\,\mathrm{kpc} \lesssim \lambda \lesssim 1\,\mathrm{Mpc}$) 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.

Aside from the average CMB distortion signals, the CMB spectrum can also vary across the sky. One source of anisotropic distortions is related to clusters of galaxies and has already been measured [63]. A combination of precise CMB imaging and spectroscopic measurements might allow observing the relativistic temperature correction [64, 65, 66] of individual SZ clusters. This could allow us to calibrate cluster scaling relations and learn about the dynamical state of the cluster atmosphere. Anisotropies in the μ-distortion can be created through ultra-squeezed limit non-Gaussianity [67, 68] and could 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.

In summary, future studies of the CMB spectrum will open a new *unexplored* window to early phases of the Universe ($z > 10^3$), which cannot be probed in any other way. This will not only allow us to test the standard cosmological paradigm (e.g., inflation and reionization) but also opens up a huge discovery space to non-standard physics (e.g., decaying/annihilating particles). This immense potential and complementarity with CMB anisotropy studies makes CMB spectral distortions an important future target and identifying experimental routes towards extracting these tiny signals from the early Universe will be one main objective of the proposed mission study.

1.1.4 The Cosmic Infrared Background

A significant contamination of CMB anisotropy maps is due to the foreground emission from infrared (IR) galaxies, responsible for the Cosmic Infrared background (CIB). The CIB is the second largest extragalactic background after the CMB, with an approximate brightness of 24 nW $\mathrm{m}^{-2}\mathrm{sr}^{-1}$ [76]. Dust enshrouding star-forming galaxies at high redshift is heated by starlight at ultraviolet (UV) and optical wavelengths, and re-radiates at mid-IR to sub-millimetre wavelengths. Thus, the integrated emission from galaxies actively producing stars at the peak of star formation (z $\sim 1 - 3$) reaches us in the far-infrared (FIR) regime, carrying a wealth of information about the the evolution of large-scale structures and the history of star formation. While the CIB is not our only handle on the evolution of the cosmic star formation rate (SFR), it is particularly important because FIR/sub-millimetre surveys are not subjected to some uncertain steps in the conversion from galaxy counts and luminosities to SFRs, affecting, e.g., optical surveys.

The drawback of working with a high density of faint, distant sources in the FIR regime is that individual objects are blended. While both the *Herschel* and *Planck* satellites recently performed ground-breaking measurements of the CIB [77, 78, 79, 80], only a negligible fraction of *Planck* sources have been individually identified, due to its poor angular resolution, while for *Herschel* maps, only 10% of the objects has been resolved into individual galaxies at 857 GHz [81]. However, the anisotropies detected in the unresolved background can be analyzed through statistical tools such as the angular power spectrum [82] and, since they trace the underlying dark matter field, they can be interpreted with phenomenological models linking dark matter halos to IR galaxies, such as the Halo Model [83, 84].

The Planck Collaboration, analyzing CIB anisotropies and their correlation with CMB lensing [79, 85], derived limits on the star formation rate density that, at redshift z > 2, are higher than what found from the analysis of different datasets (see for example [86]). Clearly, more accurate measurements of the CIB clustering at the angular scales probed by *Planck* will be extremely useful to gain more insight on the evolution of the star formation rate at high redshift. 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?*

However, constraining the history of star formation is not the only reason for measuring CIB anisotropies with increased sensitivity from very large to very small scales. Below, we briefly discuss some others.

- The CIB is an important foreground for CMB studies. As shown in [87], a significant contribution to the astrophysical foreground in the 143x217 and 217x217 GHz channels is due to both the clustering and Poisson components of the CIB. 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.

- The CIB, being a tracer of the dark matter field over a broad redshift range, can be cross-correlatated with many other datasets to explore the interplay between CIB galaxies and dark matter. Beyond the cross-correlation with the lensing of the CMB [85, 88], some other 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].

- 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 $\mathrm{N}_{\mathrm{eff}}$ [94].

To summarize, the CIB is a full sky, bright, high redshift extragalactic background that maps star formation at its peak, and carries a tremendous amount of information about the birth and evolution large scale structures in the Universe, and the interplay between light and matter.

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.

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

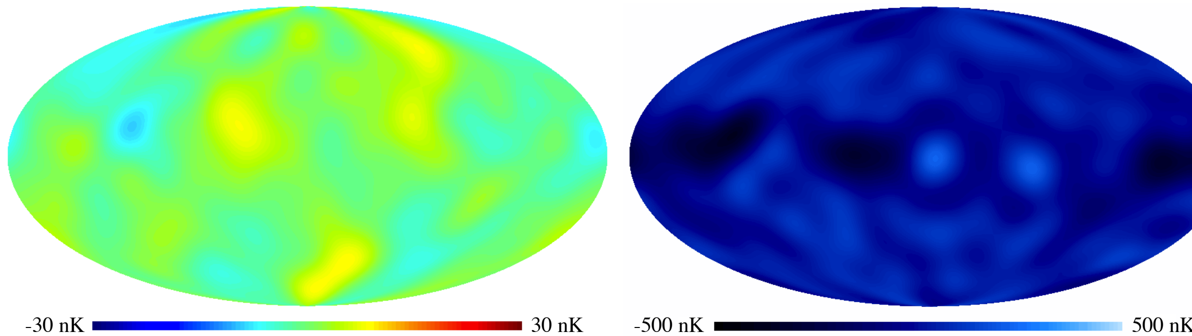

Figure 4: *Left panel:* Contribution to the Stokes Q parameter from inflationary B-modes for $\ell < 12$ for $r = 0.001$. *Right panel:* Noise in the $Planck$ 353 GHz map of the Stokes Q parameter for $\ell < 12$ rescaled to 150 GHz assuming the spectral properties of dust.

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.

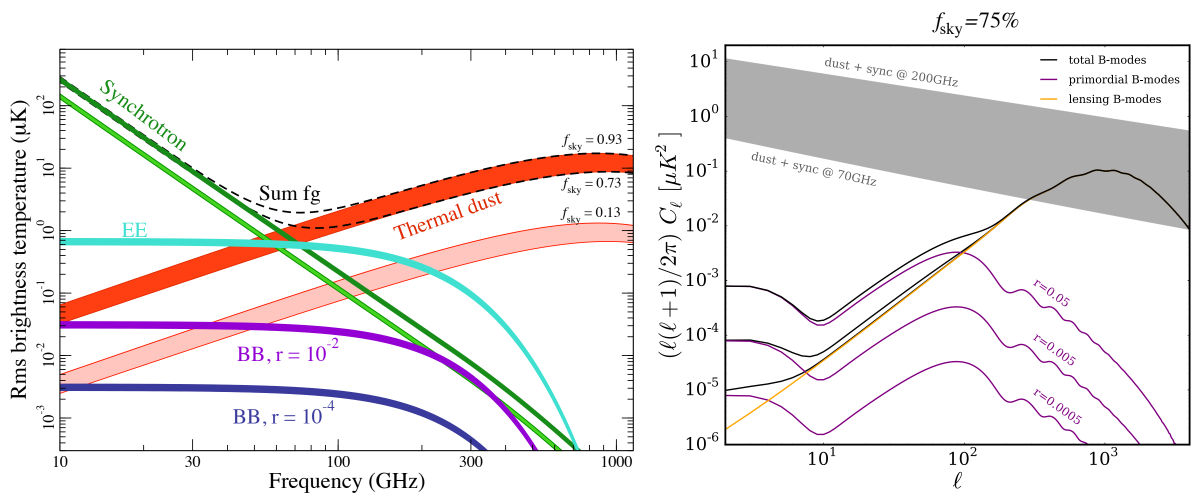

Figure 5: *Left panel:* Brightness temperature as function of frequency for the CMB as well as synchrotron emission (green) and dust emission (red). The darker bands show the brightness temperature for sky fractions between 73% and 93%, the lighter bands show the brightness temperature for the cleanest 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 categrories: 1. Intensity-to-polarization leakage, 2. stability, and 3. straylight. Each of these is considered in light of differential polarimetery; 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 seperated 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

References

[1] A. H. Guth. Inflationary universe: A possible solution to the horizon and flatness problems. *Phys. Rev. D.*, 23:347–356, January 1981.

[2] A. D. Linde. A New Inflationary Universe Scenario: A Possible Solution of the Horizon, Flatness, Homogeneity, Isotropy and Primordial Monopole Problems. *Phys. Lett.*, B108:389–393, 1982.

[3] A. Albrecht and P. J. Steinhardt. Cosmology for grand unified theories with radiatively induced symmetry breaking. *Phys. Rev. Lett.*, 48:1220–1223, 1982.

[4] K. Sato. First-order phase transition of a vacuum and the expansion of the Universe. *MNRAS*, 195:467–479, May 1981.

[5] E. W. Kolb and M. S. Turner. *The Early Universe*. Addison-Wesley, Redwood City, CA, 2nd. edition, 1994.

[6] D. N. Spergel, R. Bean, O. Doré, M. R. Nolta, C. L. Bennett, J. Dunkley, G. Hinshaw, N. Jarosik, E. Komatsu, L. Page, H. V. Peiris, L. Verde, M. Halpern, R. S. Hill, A. Kogut, M. Limon, S. S. Meyer, N. Odegard, G. S. Tucker, J. L. Weiland, E. Wollack, and E. L. Wright. Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Implications for Cosmology, June 2007.

[7] M. Tegmark, D. Eisenstein, M. Strauss, D. Weinberg, M. Blanton, J. Frieman, M. Fukugita, J. Gunn, A. Hamilton, G. Knapp, R. Nichol, J. Ostriker, N. Padmanabhan, W. Percival, D. Schlegel, D. Schneider, R. Scoccimarro, U. Seljak, H. Seo, M. Swanson, A. Szalay, M. Vogeley, J. Yoo, I. Zehavi, K. Abazajian, S. Anderson, J. Annis, N. Bahcall, B. Bassett, A. Berlind, J. Brinkmann, T. Budavari, F. Castander, A. Connolly, I. Csabai, M. Doi, D. Finkbeiner, B. Gillespie, K. Glazebrook, G. Hennessy, D. Hogg, Z. Ivezic, B. Jain, D. Johnston, S. Kent, D. Lamb, B. Lee, H. Lin, J. Loveday, R. Lupton, J. Munn, K. Pan, C. Park, J. Peoples, J. Pier, A. Pope, M. Richmond, C. Rockosi, R. Scranton, R. Sheth, A. Stebbins, C. Stoughton, I. Szapudi, D. Tucker, D. Vanden Berk, B. Yanny, and D. York. Cosmological Constraints from the SDSS Luminous Red Galaxies. *Phys. Rev. D.*, 74:123507, 2006.

[8] Planck Collaboration, P. A. R. Ade, N. Aghanim, M. Arnaud, M. Ashdown, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, J. G. Bartlett, and et al. Planck 2015 results. XIII. Cosmological parameters. *ArXiv e-prints*, February 2015.

[9] Planck Collaboration, P. A. R. Ade, N. Aghanim, M. Arnaud, F. Arroja, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini, A. J. Banday, and et al. Planck 2015. XX. Constraints on inflation. *ArXiv e-prints*, February 2015.

[10] M. Kamionkowski, A. Kosowsky, and A. Stebbins. A Probe of Primordial Gravity Waves and Vorticity. *Phys. Rev. Lett.*, 78:2058–2061, March 1997. astro-ph/9609132.

[11] M. Zaldarriaga and U. Seljak. All-sky analysis of polarization in the microwave background. *Phys. Rev. D.*, 55:1830–1840, 1997.

[12] Committee for a Decadal Survey of Astronomy and Astrophysics. *New Worlds, New Horizons in Astronomy and Astrophysics*. National Academy Press, 2010.

[13] Viatcheslav Mukhanov. Quantum Cosmological Perturbations: Predictions and Observations. *Eur. Phys. J.*, C73:2486, 2013.

[14] Diederik Roest. Universality classes of inflation. *JCAP*, 1401:007, 2014.

[15] Paolo Creminelli, Sergei Dubovsky, Diana Lopez Nacir, Marko Simonovic, Gabriele Trevisan, Giovanni Villadoro, and Matias Zaldarriaga. Implications of the scalar tilt for the tensor-to-scalar ratio. *Phys. Rev.*, D92(12):123528, 2015.

[16] Ryo Namba, Marco Peloso, Maresuke Shiraishi, Lorenzo Sorbo, and Caner Unal. Scale-dependent gravitational waves from a rolling axion. *JCAP*, 1601(01):041, 2016.

[17] Marco Peloso, Lorenzo Sorbo, and Caner Unal. Rolling axions during inflation: perturbativity and signatures. 2016.

[18] Lawrence M. Krauss. Gravitational waves from global phase transitions. *Phys. Lett.*, B284:229–233, 1992.

[19] Katherine Jones-Smith, Lawrence M. Krauss, and Harsh Mathur. A Nearly Scale Invariant Spectrum of Gravitational Radiation from Global Phase Transitions. *Phys. Rev. Lett.*, 100:131302, 2008.

[20] John T. Giblin, Jr., Larry R. Price, Xavier Siemens, and Brian Vlcek. Gravitational Waves from Global Second Order Phase Transitions. *JCAP*, 1211:006, 2012.

[21] Daniel G. Figueroa, Mark Hindmarsh, and Jon Urrestilla. Exact Scale-Invariant Background of Gravitational Waves from Cosmic Defects. *Phys. Rev. Lett.*, 110(10):101302, 2013.

[22] Elisa Fenu, Daniel G. Figueroa, Ruth Durrer, Juan Garcia-Bellido, and Martin Kunz. Cosmic Microwave Background temperature and polarization anisotropies from the large-N limit of global defects. *Phys. Rev.*, D89(8):083512, 2014.

[23] Daniel Baumann and Matias Zaldarriaga. Causality and Primordial Tensor Modes. *JCAP*, 0906:013, 2009.

[24] Hayden Lee, S. C. Su, and Daniel Baumann. The Superhorizon Test of Future B-mode Experiments. *JCAP*, 1502(02):036, 2015.

[25] David H. Lyth. What would we learn by detecting a gravitational wave signal in the cosmic microwave background anisotropy? *Phys.Rev.Lett.*, 78:1861–1863, 1997.

[26] R. A. Sunyaev and Y. B. Zeldovich. The Spectrum of Primordial Radiation, its Distortions and their Significance. *Comments on Astrophysics and Space Physics*, 2:66, March 1970.

[27] C. Burigana. Distortions of the CMB Spectrum by Continuous Heating. In G. L. Chincarini, A. Iovino, T. Maccacaro, & D. Maccagni, editor, *Observational Cosmology*, volume 51 of *Astronomical Society of the Pacific Conference Series*, pages 554–+, January 1993.

[28] W. Hu and J. Silk. Thermalization and spectral distortions of the cosmic background radiation. *Phys. Rev. D.*, 48:485–502, July 1993.

[29] J. Chluba and R. A. Sunyaev. The evolution of CMB spectral distortions in the early Universe. *MNRAS*, 419:1294–1314, January 2012.

[30] J. C. Mather, E. S. Cheng, D. A. Cottingham, R. E. Eplee, Jr., D. J. Fixsen, T. Hewagama, R. B. Isaacman, K. A. Jensen, S. S. Meyer, P. D. Noerdlinger, S. M. Read, and L. P. Rosen. Measurement of the cosmic microwave background spectrum by the COBE FIRAS instrument. *Ap. J.*, 420:439–444, January 1994.

[31] D. J. Fixsen, E. S. Cheng, J. M. Gales, J. C. Mather, R. A. Shafer, and E. L. Wright. The Cosmic Microwave Background Spectrum from the Full COBE FIRAS Data Set. *Ap. J.*, 473:576–+, December 1996.

[32] J. Chluba. Which spectral distortions does ΛCDM actually predict? *MNRAS*, 460:227–239, July 2016.

[33] A. Kogut, D. J. Fixsen, D. T. Chuss, J. Dotson, E. Dwek, M. Halpern, G. F. Hinshaw, S. M. Meyer, S. H. Moseley, M. D. Seiffert, D. N. Spergel, and E. J. Wollack. The Primordial Inflation Explorer (PIXIE): a nulling polarimeter for cosmic microwave background observations. *JCAP*, 7:25–+, July 2011.

[34] P. André, C. Baccigalupi, A. Banday, D. Barbosa, B. Barreiro, J. Bartlett, N. Bartolo, E. Battistelli, R. Battye, G. Bendo, A. Beno#523t, J.-P. Bernard, M. Bersanelli, M. Béthermin, P. Bielewicz, A. Bonaldi, F. Bouchet, F. Boulanger, J. Brand, M. Bucher, C. Burigana, Z.-Y. Cai, P. Camus, F. Casas, V. Casasola, G. Castex, A. Challinor, J. Chluba, G. Chon, S. Colafrancesco, B. Comis, F. Cuttaia, G. D'Alessandro, A. Da Silva, R. Davis, M. de Avillez, P. de Bernardis, M. de Petris, A. de Rosa, G. de Zotti, J. Delabrouille, F.-X. Désert, C. Dickinson, J. M. Diego, J. Dunkley, T. Enßlin, J. Errard, E. Falgarone, P. Ferreira, K. Ferrière, F. Finelli, A. Fletcher, P. Fosalba, G. Fuller, S. Galli, K. Ganga, J. García-Bellido, A. Ghribi, M. Giard, Y. Giraud-Héraud, J. Gonzalez-Nuevo, K. Grainge, A. Gruppuso, A. Hall, J.-C. Hamilton, M. Haverkorn, C. Hernandez-Monteagudo, D. Herranz, M. Jackson, A. Jaffe, R. Khatri, M. Kunz, L. Lamagna, M. Lattanzi, P. Leahy, J. Lesgourgues, M. Liguori, E. Liuzzo, M. Lopez-Caniego, J. Macias-Perez, B. Maffei, D. Maino, A. Mangilli, E. Martinez-Gonzalez, C. Martins, S. Masi, M. Massardi, S. Matarrese, A. Melchiorri, J.-B. Melin, A. Mennella, A. Mignano, M.-A. Miville-Deschênes, A. Monfardini, A. Murphy, P. Naselsky, F. Nati, P. Natoli, M. Negrello, F. Noviello, C. O'Sullivan, F. Paci, L. Pagano, R. Paladino, N. Palanque-Delabrouille, D. Paoletti, H. Peiris, F. Perrotta, F. Piacentini, M. Piat, L. Piccirillo, G. Pisano, G. Polenta, A. Pollo, N. Ponthieu, M. Remazeilles, S. Ricciardi, M. Roman, C. Rosset, J.-A. Rubino-Martin, M. Salatino, A. Schillaci, P. Shellard, J. Silk, A. Starobinsky, R. Stompor, R. Sunyaev, A. Tartari, L. Terenzi, L. Toffolatti, M. Tomasi, N. Trappe, M. Tristram, T. Trombetti, M. Tucci, R. Van de Weijgaert, B. Van Tent, L. Verde, P. Vielva, B. Wandelt, R. Watson, and S. Withington. PRISM (Polarized Radiation Imaging and Spectroscopy Mission): an extended white paper. *JCAP*, 2:6, February 2014.

[35] Y. B. Zeldovich and R. A. Sunyaev. The Interaction of Matter and Radiation in a Hot-Model Universe. *ApSS*, 4:301–316, July 1969.

[36] R. A. Sunyaev and Y. B. Zeldovich. The interaction of matter and radiation in the hot model of the Universe, II. *ApSS*, 7:20–30, April 1970.

[37] R. A. Sunyaev and Y. B. Zeldovich. Formation of Clusters of Galaxies; Protocluster Fragmentation and Intergalactic Gas Heating. *Astron. Astrophys.*, 20:189–+, August 1972.

[38] W. Hu, D. Scott, and J. Silk. Reionization and cosmic microwave background distortions: A complete treatment of second-order Compton scattering. *Phys. Rev. D.*, 49:648–670, January 1994.

[39] S. P. Oh, A. Cooray, and M. Kamionkowski. Sunyaev-Zeldovich fluctuations from the first stars? *MNRAS*, 342:L20–L24, June 2003.

[40] R. Cen and J. P. Ostriker. Where Are the Baryons? *Ap. J.*, 514:1–6, March 1999.

[41] A. Refregier, E. Komatsu, D. N. Spergel, and U.-L. Pen. Power spectrum of the Sunyaev-Zel'dovich effect. *Phys. Rev. D.*, 61(12):123001, June 2000.

[42] J. C. Hill, N. Battaglia, J. Chluba, S. Ferraro, E. Schaan, and D. N. Spergel. Taking the Universe's Temperature with Spectral Distortions of the Cosmic Microwave Background. *Physical Review Letters*, 115(26):261301, December 2015.

[43] W. Hu and J. Silk. Thermalization constraints and spectral distortions for massive unstable relic particles. *Physical Review Letters*, 70:2661–2664, May 1993.

[44] J. Chluba. Distinguishing different scenarios of early energy release with spectral distortions of the cosmic microwave background. *MNRAS*, 436:2232–2243, December 2013.

[45] J. Chluba and D. Jeong. Teasing bits of information out of the CMB energy spectrum. *MNRAS*, 438:2065–2082, March 2014.

[46] E. Dimastrogiovanni, L. M. Krauss, and J. Chluba. Constraints on gravitino decay and the scale of inflation using CMB spectral distortions. *Phys. Rev. D.*, 94(2):023518, July 2016.

[47] K. Jedamzik, V. Katalinić, and A. V. Olinto. Limit on Primordial Small-Scale Magnetic Fields from Cosmic Microwave Background Distortions. *PRL*, 85:700–703, July 2000.

[48] H. Tashiro, E. Sabancilar, and T. Vachaspati. CMB distortions from superconducting cosmic strings. *Phys. Rev. D.*, 85(10):103522, May 2012.

[49] A. D. Dolgov and D. Ejlli. Resonant high energy graviton to photon conversion at the post-recombination epoch. *Phys. Rev. D.*, 87(10):104007, May 2013.

[50] H. Tashiro, J. Silk, and D. J. E. Marsh. Constraints on primordial magnetic fields from CMB distortions in the axiverse. *Phys. Rev. D.*, 88(12):125024, December 2013.

[51] R. R. Caldwell and N. A. Maksimova. Spectral distortion in a radially inhomogeneous cosmology. *Phys. Rev. D.*, 88(10):103502, November 2013.

[52] Y. Ali-Haïmoud, J. Chluba, and M. Kamionkowski. Constraints on Dark Matter Interactions with Standard Model Particles from Cosmic Microwave Background Spectral Distortions. *Physical Review Letters*, 115(7):071304, August 2015.

[53] R. A. Sunyaev and Y. B. Zeldovich. Small scale entropy and adiabatic density perturbations - Antimatter in the Universe. *ApSS*, 9:368–382, December 1970.

[54] R. A. Daly. Spectral distortions of the microwave background radiation resulting from the damping of pressure waves. *Ap. J.*, 371:14–28, April 1991.

[55] W. Hu, D. Scott, and J. Silk. Power spectrum constraints from spectral distortions in the cosmic microwave background. *Ap. J. Lett.*, 430:L5–L8, July 1994.

[56] J. Chluba, R. Khatri, and R. A. Sunyaev. CMB at 2 x 2 order: the dissipation of primordial acoustic waves and the observable part of the associated energy release. *MNRAS*, 425:1129–1169, September 2012.

[57] J. Chluba, A. L. Erickcek, and I. Ben-Dayan. Probing the Inflaton: Small-scale Power Spectrum Constraints from Measurements of the Cosmic Microwave Background Energy Spectrum. *Ap. J.*, 758:76, October 2012.

[58] J. B. Dent, D. A. Easson, and H. Tashiro. Cosmological constraints from CMB distortion. *Phys. Rev. D.*, 86(2):023514, July 2012.

[59] S. Clesse, B. Garbrecht, and Y. Zhu. Testing inflation and curvaton scenarios with CMB distortions. *JCAP*, 10:046, October 2014.

[60] G. Cabass, A. Melchiorri, and E. Pajer. μ distortions or running: A guaranteed discovery from CMB spectrometry. *Phys. Rev. D.*, 93(8):083515, April 2016.

[61] R. A. Sunyaev and J. Chluba. Signals from the epoch of cosmological recombination (Karl Schwarzschild Award Lecture 2008). *Astronomische Nachrichten*, 330:657–+, 2009.

[62] J. Chluba and Y. Ali-Haïmoud. COSMOSPEC: fast and detailed computation of the cosmological recombination radiation from hydrogen and helium. *MNRAS*, 456:3494–3508, March 2016.

[63] Planck Collaboration, P. A. R. Ade, N. Aghanim, C. Armitage-Caplan, M. Arnaud, M. Ashdown, F. Atrio-Barandela, J. Aumont, C. Baccigalupi, A. J. Banday, and et al. Planck 2013 results. XX. Cosmology from Sunyaev-Zeldovich cluster counts. *Astron. Astrophys.*, 571:A20, November 2014.

[64] S. Y. Sazonov and R. A. Sunyaev. Cosmic Microwave Background Radiation in the Direction of a Moving Cluster of Galaxies with Hot Gas: Relativistic Corrections. *Ap. J.*, 508:1–5, November 1998.

[65] N. Itoh, Y. Kohyama, and S. Nozawa. Relativistic corrections to the sunyaev-zeldovich effect for clusters of galaxies. *Ap. J.*, 502:7, July 1998.

[66] A. Challinor and A. Lasenby. Relativistic corrections to the sunyaev-zeldovich effect. *Ap. J.*, 499:1, May 1998.

[67] E. Pajer and M. Zaldarriaga. New Window on Primordial Non-Gaussianity. *Physical Review Letters*, 109(2):021302, July 2012.

[68] J. Ganc and E. Komatsu. Scale-dependent bias of galaxies and μ-type distortion of the cosmic microwave background spectrum from single-field inflation with a modified initial state. *Phys. Rev. D.*, 86(2):023518, July 2012.

[69] M. Biagetti, H. Perrier, A. Riotto, and V. Desjacques. Testing the running of non-Gaussianity through the CMB μ-distortion and the halo bias. *Phys. Rev. D.*, 87(6):063521, March 2013.

[70] R. Emami, E. Dimastrogiovanni, J. Chluba, and M. Kamionkowski. Probing the scale dependence of non-Gaussianity with spectral distortions of the cosmic microwave background. *Phys. Rev. D.*, 91(12):123531, June 2015.

[71] J. A. Rubiño-Martín, C. Hernández-Monteagudo, and R. A. Sunyaev. The imprint of cosmological hydrogen recombination lines on the power spectrum of the CMB. *Astron. Astrophys.*, 438:461–473, August 2005.

[72] C. Hernández-Monteagudo, J. A. Rubiño-Martín, and R. A. Sunyaev. On the influence of resonant scattering on cosmic microwave background polarization anisotropies. *MNRAS*, 380:1656–1668, October 2007.

[73] A. Lewis. Rayleigh scattering: blue sky thinking for future CMB observations. *JCAP*, 8:053, August 2013.

[74] K. Basu, C. Hernández-Monteagudo, and R. A. Sunyaev. CMB observations and the production of chemical elements at the end of the dark ages. *Astron. Astrophys.*, 416:447–466, March 2004.

[75] D. R. G. Schleicher, D. Galli, F. Palla, M. Camenzind, R. S. Klessen, M. Bartelmann, and S. C. O. Glover. Effects of primordial chemistry on the cosmic microwave background. *Astron. Astrophys.*, 490:521–535, November 2008.

[76] H. Dole, G. Lagache, J.-L. Puget, K. I. Caputi, N. Fernández-Conde, E. Le Floc'h, C. Papovich, P. G. Pérez-González, G. H. Rieke, and M. Blaylock. The cosmic infrared background resolved by Spitzer. Contributions of mid-infrared galaxies to the far-infrared background. *Astron. Astrophys.*, 451:417–429, May 2006.

[77] A. Amblard, A. Cooray, P. Serra, B. Altieri, V. Arumugam, H. Aussel, A. Blain, J. Bock, A. Boselli, V. Buat, N. Castro-Rodríguez, A. Cava, P. Chanial, E. Chapin, D. L. Clements, A. Conley, L. Conversi, C. D. Dowell, E. Dwek, S. Eales, D. Elbaz, D. Farrah, A. Franceschini, W. Gear, J. Glenn, M. Griffin, M. Halpern, E. Hatziminaoglou, E. Ibar, K. Isaak, R. J. Ivison, A. A. Khostovan, G. Lagache, L. Levenson, N. Lu, S. Madden, B. Maffei, G. Mainetti, L. Marchetti, G. Marsden, K. Mitchell-Wynne, H. T. Nguyen, B. O'Halloran, S. J. Oliver, A. Omont, M. J. Page, P. Panuzzo, A. Papageorgiou, C. P. Pearson, I. Pérez-Fournon, M. Pohlen, N. Rangwala, I. G. Roseboom, M. Rowan-Robinson, M. S. Portal, B. Schulz, D. Scott, N. Seymour, D. L. Shupe, A. J. Smith, J. A. Stevens, M. Symeonidis, M. Trichas, K. Tugwell, M. Vaccari, E. Valiante, I. Valtchanov, J. D. Vieira, L. Vigroux, L. Wang, R. Ward, G. Wright, C. K. Xu, and M. Zemcov. Submillimetre galaxies reside in dark matter haloes with masses greater than 3×10^{11} solar masses. , 470:510–512, February 2011.

[78] M. P. Viero, L. Wang, M. Zemcov, G. Addison, A. Amblard, V. Arumugam, H. Aussel, M. Béthermin, J. Bock, A. Boselli, V. Buat, D. Burgarella, C. M. Casey, D. L. Clements, A. Conley, L. Conversi, A. Cooray, G. De Zotti, C. D. Dowell, D. Farrah, A. Franceschini, J. Glenn, M. Griffin, E. Hatziminaoglou, S. Heinis, E. Ibar, R. J. Ivison, G. Lagache, L. Levenson, L. Marchetti, G. Marsden, H. T. Nguyen, B. O'Halloran, S. J. Oliver, A. Omont, M. J. Page, A. Papageorgiou, C. P. Pearson, I. Pérez-Fournon, M. Pohlen, D. Rigopoulou, I. G. Roseboom, M. Rowan-Robinson, B. Schulz, D. Scott, N. Seymour, D. L. Shupe, A. J. Smith, M. Symeonidis, M. Vaccari, I. Valtchanov, J. D. Vieira, J. Wardlow, and C. K. Xu. HerMES: Cosmic Infrared Background Anisotropies and the Clustering of Dusty Star-forming Galaxies. *Ap. J.*, 772:77, July 2013.

[79] Planck Collaboration, R. Adam, P. A. R. Ade, N. Aghanim, M. Arnaud, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, J. G. Bartlett, and et al. Planck intermediate results. XXX. The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes. *ArXiv e-prints*, September 2014.

[80] D. S. Y. Mak, A. Challinor, G. Efstathiou, and G. Lagache. Measurement of CIB power spectra over large sky areas from Planck HFI maps. *ArXiv e-prints*, September 2016.

[81] M. Béthermin, H. Dole, M. Cousin, and N. Bavouzet. Submillimeter number counts at 250 μm, 350 μm and 500 μm in BLAST data. *Astron. Astrophys.*, 516:A43, June 2010.

[82] L. Knox, A. Cooray, D. Eisenstein, and Z. Haiman. Probing Early Structure Formation with Far-Infrared Background Correlations. *Ap. J.*, 550:7–20, March 2001.

[83] A. Cooray and R. Sheth. Halo models of large scale structure. , 372:1–129, December 2002.

[84] C. Shang, Z. Haiman, L. Knox, and S. P. Oh. Improved models for cosmic infrared background anisotropies: new constraints on the infrared galaxy population. *MNRAS*, 421:2832–2845, April 2012.

[85] Planck Collaboration, P. A. R. Ade, N. Aghanim, C. Armitage-Caplan, M. Arnaud, M. Ashdown, F. Atrio-Barandela, J. Aumont, C. Baccigalupi, A. J. Banday, and et al. Planck 2013 results. XVIII. The gravitational lensing-infrared background correlation. *Astron. Astrophys.*, 571:A18, November 2014.

[86] P. Madau and M. Dickinson. Cosmic Star-Formation History. , 52:415–486, August 2014.

[87] Planck Collaboration, N. Aghanim, M. Arnaud, M. Ashdown, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, J. G. Bartlett, N. Bartolo, and et al. Planck 2015 results. XI. CMB power spectra, likelihoods, and robustness of parameters. *Astron. Astrophys.*, 594:A11, September 2016.

[88] G. P. Holder, M. P. Viero, O. Zahn, K. A. Aird, B. A. Benson, S. Bhattacharya, L. E. Bleem, J. Bock, M. Brodwin, J. E. Carlstrom, C. L. Chang, H.-M. Cho, A. Conley, T. M. Crawford, A. T. Crites, T. de Haan, M. A. Dobbs, J. Dudley, E. M. George, N. W. Halverson, W. L. Holzapfel, S. Hoover, Z. Hou, J. D. Hrubes, R. Keisler, L. Knox, A. T. Lee, E. M. Leitch, M. Lueker, D. Luong-Van, G. Marsden, D. P. Marrone, J. J. McMahon, J. Mehl, S. S. Meyer, M. Millea, J. J. Mohr, T. E. Montroy, S. Padin, T. Plagge, C. Pryke, C. L. Reichardt, J. E. Ruhl,

J. T. Sayre, K. K. Schaffer, B. Schulz, L. Shaw, E. Shirokoff, H. G. Spieler, Z. Staniszewski, A. A. Stark, K. T. Story, A. van Engelen, K. Vanderlinde, and Vieira.

[89] L. Wang, M. Viero, N. P. Ross, V. Asboth, M. Béthermin, J. Bock, D. Clements, A. Conley, A. Cooray, D. Farrah, A. Hajian, J. Han, G. Lagache, G. Marsden, A. Myers, P. Norberg, S. Oliver, M. Page, M. Symeonidis, B. Schulz, W. Wang, and M. Zemcov. Co-evolution of black hole growth and star formation from a cross-correlation analysis between quasars and the cosmic infrared background. *MNRAS*, 449:4476–4493, June 2015.

[90] P. Serra, G. Lagache, O. Doré, A. Pullen, and M. White. Cross-correlation of cosmic far-infrared background anisotropies with large scale structures. *Astron. Astrophys.*, 570:A98, October 2014.

[91] M. Fornasa, A. Cuoco, J. Zavala, J. M. Gaskins, M. A. Sanchez-Conde, G. Gomez-Vargas, E. Komatsu, T. Linden, F. Prada, F. Zandanel, and A. Morselli. The angular power spectrum of the diffuse gamma-ray emission as measured by the Fermi Large Area Telescope and constraints on its Dark Matter interpretation. *ArXiv e-prints*, August 2016.

[92] C. Feng, A. Cooray, and B. Keating. Planck Lensing and Cosmic Infrared Background Cross-Correlation with Fermi-LAT: Tracing Dark Matter Signals in the γ-ray Background. *ArXiv e-prints*, August 2016.

[93] B. D. Sherwin and M. Schmittfull. Delensing the CMB with the cosmic infrared background. *Phys. Rev. D.*, 92(4):043005, August 2015.

[94] P. Larsen, A. Challinor, B. D. Sherwin, and D. Mak. Demonstration of cosmic microwave background delensing using the cosmic infrared background. *ArXiv e-prints*, July 2016.

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