Contents

1 Scientific, Technical, and Management Section

1.1 Baselines and Observables

We are proposing to study a probe-scale mission to extract the wealth of cosmological information contained in the spectrum and polarization of the cosmic microwave background (CMB). The starting points for our study of a future probe are two current-decade space missions, EPIC-IM and Super-PIXIE [1, 2]. EPIC-IM was presented to the 2010 decadal panel as a candidate CMB imaging polarization space mission. It was based on a 2 m aperture telescope and 11,094 bolometric transition edge sensors. PIXIE is a proposed Explorer-scale mission focused on a measurement of the spectrum and polarization of the CMB on large angular scales. Super-PIXIE is envisioned to be a scaled up, more capable version of PIXIE. It consists of 4 spectrometers, each operating between 30 and 6015 GHz with 400 15 GHz-wide bands. Improvements in technology by the next decade will enable the design of a mission that is more capable compared to both EPIC-IM and Super-PIXIE. Therefore, all quantitative predictions presented in this proposal for EPIC-IM and Super-PIXIE represent *minimum* capabilities for future similar instruments.

The best measurements of the CMB spectrum – made by COBE/FIRAS approximately 25 years ago – show that the average CMB spectrum is consistent with that of a blackbody to an accuracy of 4 parts in 10^4 [3, 4]. Distortions in this spectrum encode a wealth of new information. The distortion shapes are commonly denoted as μ- and y-types [5, 6]. The μ-distortion arises from energy release in the early Universe and can only be produced in the hot and dense environment present at high redshifts. This makes μ-distortions a novel messenger from a redshift range $z \geq 5 \times 10^4$. The y distortions are caused by energy exchange between CMB photons and free electrons through inverse Compton scattering. These originate at lower redshifts and are sensitive to the evolution of the large scale structure of the Universe.

Thomson scattering at the surface of last scattering is the source of the polarization of the CMB. It is useful to decompose the polarization field to two modes that are independent over the full sky, E and B modes. Together with the pattern of temperature anisotropy T, the CMB thus gives three auto- and three cross-spectra. The *Planck* satellite and larger aperture ground-based instruments measured the T spectrum to cosmic variance limit for $\ell \leq$??. Much information remains encoded in the E and B spectra, whose full exploration has just begun [7, 8**? ?**].

A future CMB Probe-scale mission will address the physics of the big bang and of quantum gravity; it will measure the sum of the neutrino masses, constrain the effective number of light particle species, and the nature of dark matter; it will probe the existence of new forms of matter at the early Universe; it will give new insights on the star-formation history across cosmic times, and it will provide information about the processes that control structure formation. In addressing these questions the Probe firmly fits into NASA's strategic plan as articulated by its Strategic Goal 1 "Expand the frontiers of knowledge", and specifically Objective 1.6 "Discover how the Universe works, [and] explore how it began and evolved".

1.2 Science Objectives

1.2.1 The Primordial Universe and Cosmic Inflation

The observed temperature and E-mode polarization of the CMB require primordial inhomogeneities in the gravitational potential, providing a remarkable observational link to the dynamics of the Universe near the big bang. Inflation, a primordial era of accelerated expansion, provides a compelling dynamical origin for the observed nearly scale-invariant spectrum of the primordial perturbations [9, 10, 11, 12, 13]. 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. These gravitational waves make a distinct B-mode imprint on the polarization of the CMB. Any detection of B-mode polarization, whether generated by the primordial gravitational waves of Inflation [14, 15] or by any other source of early time vector or tensor perturbations, would reveal completely new information about the primordial era. The results would provide significant constraints and consistency checks for current models or could perhaps even overturn them. A detection would have implications for fundamental physics by providing evidence for a new energy scale near the GUT scale. In the context of Inflation, the relationship is particularly clear: the potential energy V of the inflaton is related to the tensor-to-scalar ratio r at the peak of the spectrum by $V^{1/4} = 3.7 \times 10^{16}\, r^{1/4}$ GeV.

Figure 1 shows current data, B-modes from vacuum fluctuations of the metric during an Inflationary era for two values of r, as well as forecasts for the determination of the CMB spectra for EPIC-IM. For testing inflation, the largest scales $\ell \leq 10$ are particularly important because they reveal the presence of B mode correlations on scales that were super-horizon at the time of recombination [16], and because the signal is strongest relative to the B-mode from lensing. A satellite is by far the most suitable platform to making the all sky observations necessary to reach the lowest ℓ's. In its recent report New Worlds New Horizons (NWNH), the decadal survey committee strongly endorsed 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." [17].

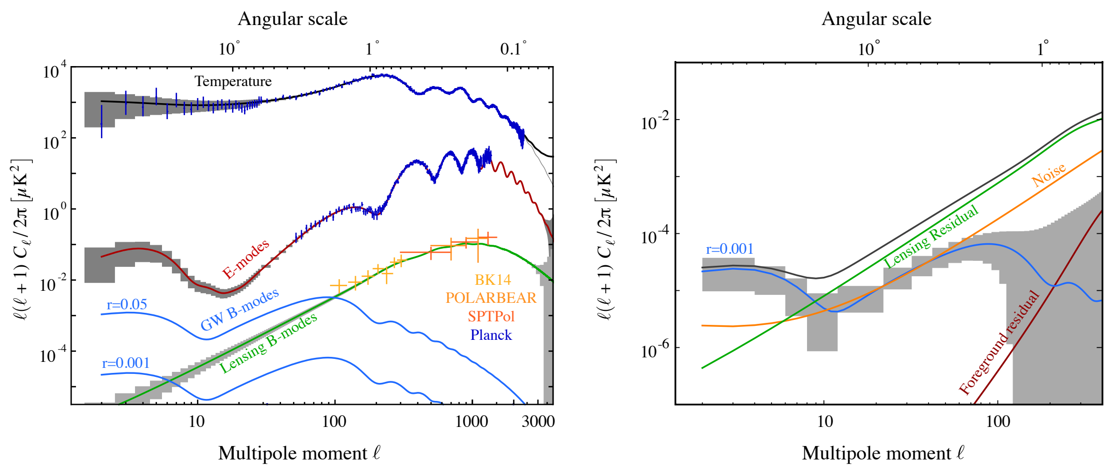

Figure 1: Predicted determination of the CMB power spectra for EPIC-IM (grey boxes) overlaid on theoretical predictions (solid lines) and including Planck measurements of the temperature and E modes (blue) and of several ground-based measurements of the lensing B-modes. The tensor B-mode predictions (blue) are shown for two representative values of the tensor-to-scalar ratio: $r = 0.001$ and $r = 0.05$.

In slow roll Inflation there are just two observationally viable classes of models that naturally explain the measured value of the spectral index n_s. One is the set of potentials $V(\phi) \propto \phi^p$, which contains many of the canonical inflation models. This set 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. The other class of 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 Raphael will update the following to match figures $\sigma(r) \sim 4.8 \times 10^{-4}$ assuming $r = 0.01$ and no foregrounds.

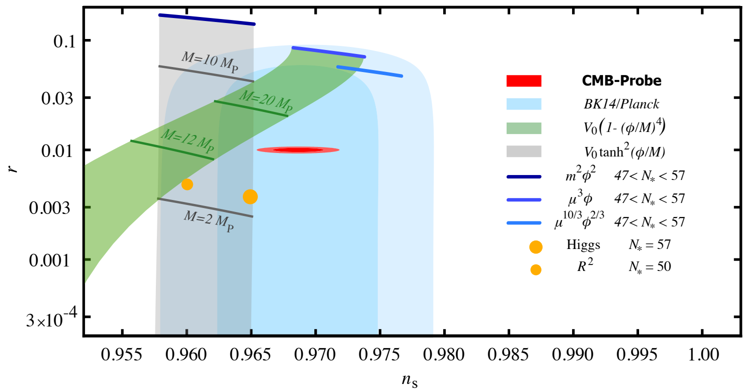

Figure 2: Forecasted constraints in the $n_{\rm s}$–r plane for a fiducial model with $r = 0.01$ for EPIC-IM together with the current measured 1 and 2σ constraints (blue) [18]. Also shown are predictions for the models of the inflaton potential discussed in the text: Chaotic inflation for a range of $N_\star$ values (blue lines); Higgs and R^2 (large and small dots, respectively); quartic hilltop (green band); and a sub-class of α-attractor models [19]

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, any detection with a next generation satellite would be evidence for *large-field* Inflation [20], in which a smooth potential that supports Inflation extends over a distance in field space $\Delta\phi \gtrsim M_p$. Quantum gravity studies of inflation give a generic expectation $\Delta\phi \lesssim M_p$ [21, 22, 23, 24], although there are some mechanisms to realize large-field inflation [25, 26, 27, 28]. A detection of r would therefore provide strong motivation to better understand how large-field inflation can be naturally incorporated into quantum gravity.

All inflation models predict a B-mode spectrum with the shape shown in Figure 1, but inflation need not be correct [29, 30, 31] and does not preclude additional sources of B-mode polarization either during or after inflation. To be confident of the implications of a detection, the shape and Gaussianity of the B-mode spectrum must be characterized. The vast majority of inflation scenarios predict an extremely Gaussian and nearly scale-invariant spectrum for gravitational waves. A target constraint of $\sigma(n_{\rm t}) < 1$ at $r = 0.01$, driven by the information in the reionization bump, would significantly constrain non-vacuum inflationary sources [32, 33] and rule out physics completely inconsistent with inflation.

Deeper mapping of E-mode polarization will also contribute to testing inflationary models. Large scale E-modes will provide new tests of isotropy, a prediction of most models of Inflation; for example, the observations can reject at 99% confidence models in which low multipoles are aligned in the temperature maps [34]. Together with continued improvements at high ℓ from the ground, these modes will also improve constraints on the scalar spectral index and its changes with scale by factors of about two.

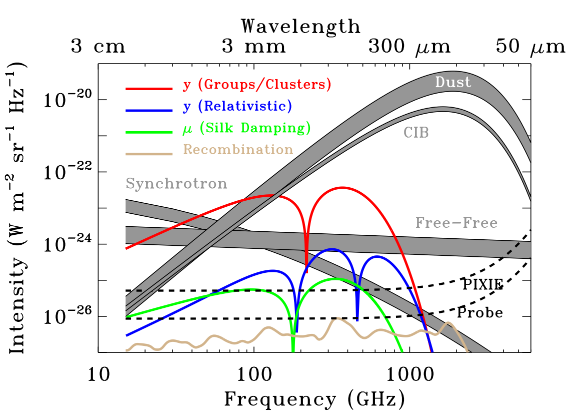

Figure 3: Anticipated y and μ spectral distortions (solid), the signature of resonant recombination lines (solid), and anticipated foreground signal levels relevant for spectral distortion measurements (grey bands). The simplest extension of a proposed Explorer class mission (Probe, dash grey) gives approximately 10 times the Explorer sensitivity (PIXIE). A better optimized Probe may give detections of all anticipated distortions.

Spectral distortion measurements give additional tests of Inflation. The dissipation of small-scale perturbations through Silk-damping leads to μ-distortions [35, 36, 37, 38]. In ΛCDM the

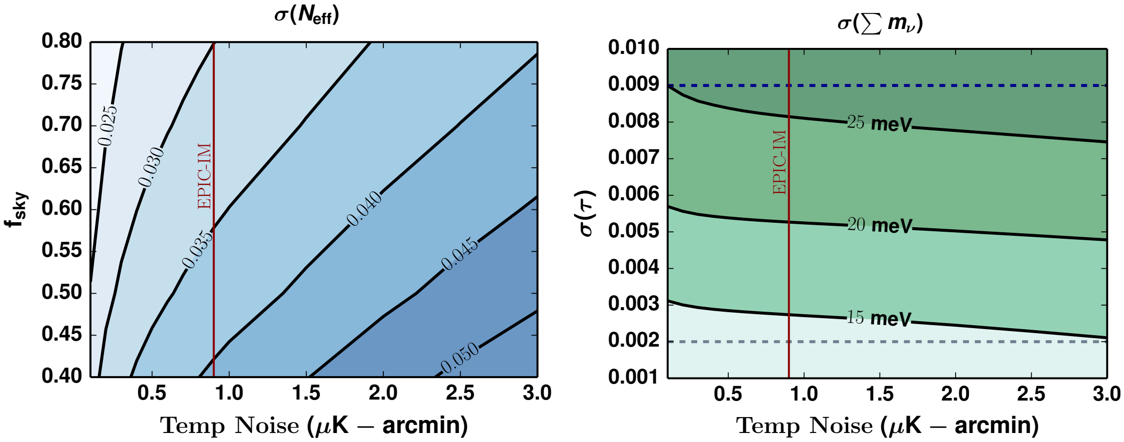

Figure 4: $N_{\rm eff}$ as a function of noise and sky fraction (left) and Neutrino mass constraints as a function of uncertainties in measurement of τ, noise, and sky fraction of $f_{\rm sky} = 0.7$. The resolution assumed is 5'. Vertical lines denote the expected performance of EPIC-IM. The blue dashed line is the current *Planck* limit; the grey dashed line is the limit from cosmic variance measurement of τ. All forecasts assume internal delensing of the T and E-maps [46], including residual non-Gaussian covariances. The $\sum m_\nu$ forecasts includes DESI BAO.

distortions are predicted at a level of $\mu = (2.0 \pm 0.14) \times 10^{-8}$, a level that is readily accessible to a Probe class mission, see Fig. 3 [38, 39].

A better optimized probe may also give the sensitivity to detect the signature of recombination radiation imprinted by cosmological recombination of hydrogen and helium at redshift $z \simeq 10^3 - 10^4$; see Fig. 3 [40, 41]. The detailed physics is sensitive to the values of n_s, which is a direct probe of Inflation.

1.2.2 Light Relics and Dark Matter

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, such as those arising in extensions of the Standard model of particle physics, can be produced in large abundances [42, 43]. As the universe expands and cools, the particles fall out of equilibrium and leave observable signatures in the CMB power spectra. Through these effects the CMB is a sensitive probe of neutrino and of other particles' properties.

One particularly compelling target is the effective number of light relic particle species $N_{\rm eff}$, also called the effective number of neutrinos. The canonical value with three neutrino families is $N_{\rm eff} = 3.046$. Additional light particles contribute a change to $N_{\rm eff}$ of $\Delta N_{\rm eff} \geq 0.027\, g$ where $g \geq 1$ is the number of degrees of freedom of the new particle [44, 45]. This defines a target of $\sigma(N_{\rm eff}) < 0.027$ for future CMB observations. Either a limit or detection of $\Delta N_{\rm eff}$ at this level would provide a powerful insight into the basic constituents of matter.

Forecasts for $N_{\rm eff}$ are shown in Figure 4. The two most important parameters for improving constraints are the fraction of sky observed $f_{\rm sky}$ and the noise. Achieving both larger $f_{\rm sky}$ and lower noise are strengths of the CMB Probe compared to other platforms. Our baseline mission nearly reaches the target constraint with $g = 1$, already exceeding constraints from other astrophysical probes and planned CMB observations. A newly designed mission is likely to reach $\sigma(N_{\rm eff}) < 0.027$ with high signal-to-noise ratio.

Many light relics of the early universe are not stable. They decay, leaving faint evidence of their past existence on other tracers. The relics with sufficiently long lifetime to survive few minutes, past the epoch of light element synthesis, leave a signature on the helium fraction Y_p. If they decay by the time of recombination, their existence through this period is best measured through the ratio of $N_{\rm eff}$ to Y_p. The Probe's cosmic variance limited determination of the E power spectra will improve current limits for these quantities by a factor of five thus eliminating sub-MeV mass thermal relics. Spectrum distortion measurements give additional constraints on the lifetime and abundance of such relics [47, 48, 49, 50]. A future Probe's μ-distortion constraint gives a two orders of magnitude improvement on the abundance and life time of early Universe relics [51, 52] compared to current constraints derived from measurements of light element abundances [53, 54].

Cosmological measurements have already confirmed the existence of one relic that lies beyond the Standard Model: dark matter. For a conventional WIMP candidate, the CMB places very stringent constraints on its properties through the signature of its annihilation on the T and E spectra [55, 56, 57]. Planck currently excludes WIMPs with mass $m_{\rm dm} < 16$ GeV and a future CMB mission could reach $m_{\rm dm} < 45$ GeV for $f_{\rm sky} = 0.8$. The CMB provides the most stringent constraints on the dark matter annihilation cross section for dark matter in this mass range. The CMB is complimentary to direct detection experiments which probe the scattering cross-section of dark matter with Standard model particles.

A particle-independent approach is to constrain dark matter interactions that would affect the evolution of the effective dark matter fluid and its interactions with baryons or photons. The simplest example is to constrain the baryon-dark matter cross section through its effective coupling of the two fluids [58]. These couplings affect the evolution of fluctuations and ultimately the T and E spectra. The current limits of $\sigma \gtrsim 10^{-31} - 10^{-34}\,{\rm cm}^2 \times (m_{\rm dm}/{\rm MeV})$ can be competitive with direct detection for sub-GeV masses. More exotic dark sectors that include long-range forces can produce an even richer phenomenology in the CMB and in the large-scale structure without necessarily producing an associated signature in direct detection experiments or indirect searches (e.g. [59, 60, 61]).

Interactions of dark matter with standard model particles can also be constrained through measurements of spectral distortions [62]. Current constraints from FIRAS are most sensitive to small dark matter mass, $m_{\rm X} \lesssim 0.2\,{\rm MeV}$, but these could be extended to $m_{\rm X} \lesssim 1\,{\rm GeV}$ with a Probe-class mission, testing DM interaction down to cross-sections $\sigma \simeq 10^{-39} - 10^{-35}\,{\rm cm}^2$ [62]. This provides new constraints on the low mass end, $m_{\rm X} \lesssim 10\,{\rm MeV}$ and improve existing limits [63, 64] by up to a factor of $\simeq 50$. Distortion measurements furthermore open a new avenue for testing dark matter-proton interactions [62].

A host of other physical phenomena including the existence and properties of axions, primordial magnetic fields, and superconducting strings, leave signatures on the spectrum of the CMB and can therefore be constrained by the sensitive measurements of a future Probe [e.g., 65, 66, 67, 68, 69].

1.2.3 Neutrino Mass

One of the last unknowns of the Standard model of particle physics is the absolute mass scale of the neutrinos. Cosmology presents a unique opportunity to measure the sum of neutrino masses $\sum m_\nu$ through the suppression of the growth of structures in the Universe on small scales. The sensitivity to $\sum m_\nu$ from suppression of power is 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 *Planck* of $\sigma(\tau) = 0.009$ [] limits $\sigma(\sum m_\nu) \gtrsim 25$ meV. Forcasts for an internal CMB measurement of $\sum m_\nu$ via CMB lensing [70] are shown Figure 4 but the conclusion is the same for any proposed cosmological probe. Therefore, a cosmological detection of the minimum value expected from particle physics $\sum m_\nu = 58$ meV at more than 2σ will require a better measurement of τ. The best constraints on τ come from E-modes with $\ell < 20$ which require measurements over the largest angular scales. To date, the only proven method for such a measurement is from space. The CMB Probe will reach the cosmic variance limit of $\tau \sim 0.002$ and will therefore reach $\sigma(\sum m_\nu) < 15$ meV when combined with DESI's measurements of baryon acoustic oscillations [71]. A detection of $\sum m_\nu$ at this level is not possible with any other existing survey.

1.2.4 Cosmological structure formation

Understanding the evolution of cosmological structures from small density perturbations through the formation of the first stars to present day galaxies and cluster is a key goal of cosmology [72]. Cosmological reionization, the transition of the Universe from dominated by neutral to ionized hydrogen, is a cornerstone of this evolution because it encodes information about the star formation history and the physical processes that formed the galaxies of various luminosities and masses we see today. But when did the epoch of reionization start? How long did it last? Are early galaxies enough to reionize the entire Universe or is another source required?

Measurements of the CMB E mode power spectrum over large angular scales are sensitive to the optical depth to reionization τ, a key parameter for all reionization models that attempt to answer these questions. The *Planck* team reported recently a value of $\tau = 0.055 \pm 0.009$ [**?** **?**]. The level is significantly lower than previous estimates and reduces the tension between CMB-based analyses and constraints from other astrophysical sources. The CMB Probe's cosmic variance limited measurement of E-mode polarization will improve the 1σ error by a factor of 4.5 to reach a cosmic variance limited measurement of τ, thus setting stringent constraints on models of the reionization epoch.

The anisotropy in the cosmic infrared background (CIB) produced by dusty star-forming galaxies in a wide redshift range, are an excellent probe of both the history of star formation and the link between galaxies and dark matter across cosmic time. The *Planck* collaboration derived values of the star formation rate that, at redshifts z~ 3, are three times larger than constraints from number counts measurements ([73, 74, 75]). The new mission probe, By measuring CIB anisotropy with 100 times higher signal-to-noise ratio the CMB Probe will shed light on this intriguing discrepancy. Specifically, it will constrain the star formation rate with one tenth of *Planck*'s uncertainty.

A key parameter in simulations of the angular power spectrum of the CIB is $M_{\rm eff}$, the galaxy hallo mass that is most efficient in producing star formation activity. Comparing measurements of the power spectrum to simulations constrains this parameter, which informs structure formation models. Current models and measurements find $M_{\rm eff} \sim 10^{12}$ solar masses with about 10% uncertainty. The CMB Probe will constrain this parameter at the percent level.

The transition to reionized Universe and the onset of structure formation inject energy into the sea of CMB photons. This injection is detectable through a distinct spectral distortion. This is the largest expected distortion – marked 'y Groups/Clusters' in Figure 3 – and will be clearly detected by the CMB Probe. A detection will give information about the total energy output of the first stars, AGNs, and galaxy clusters, an important parameter in structure formation models.

Group-size clusters that have masses $M \simeq 10^{13}\, M_\odot$ contribute significantly to the signal. With temperature $kT_{\rm e} \simeq 1\,{\rm keV}$ these are sufficiently hot to create a relativistic temperature correction to the large y-distortion. This relativistic correction, denoted 'y relativistic' in Figure 3, will also be detected with high signal-to-noise ratio by the CMB Probe, and will be used to constrain the currently uncertain feedback mechanisms used in hydrodynamical simulations of cosmic structure formation [76].

The CMB spectrum varies spatially across the sky. One source of such anisotropic distortion is due to the spatial distribution clusters of galaxies and has already been measured by Planck [77]. A combination of precise CMB imaging and spectroscopic measurements will allow observing the relativistic temperature correction of individual SZ clusters [78, 79, 80], which will calibrate cluster scaling relations and inform our knowledge of the dynamical state of the cluster atmosphere.

Resonant scattering of the CMB photons during and post last scattering leads to spectral-spatial signals that can be used to constrain the abundance of metals in the dark ages and therefore the make-up of the first, and subsequent generations of stars [81, 82, 83, 84, 85].