Contents

1 Scientific, Technical, and Management Section

1.1 Executive Summary

We are proposing to study a probe-scale mission to extract the wealth of physical, cosmological, and astrophysical information contained in the spectrum and polarization of the cosmic microwave background (CMB). The CMB Probe will search for the signature of primordial gravitational waves from the big bang and thus probe quantum gravity. It will constrain the effective number of light particle species, with precision only available to CMB measurements. With its full sky coverage, it will measure the sum of the neutrino masses, doubling the significance of a 2σ detection reachable by experiments that measure only smaller portions of the sky. It will probe the nature of dark matter and the existence of new forms of matter in 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 on all scales, from clusters of galaxies to the collapse of a protostellar core. With high sensitivity, access to the entire sky, broad frequency coverage, and exquisite control of systematic effects the Probe is best poised to realize the fidelity of measurements necessary to extract these science goals.

The last US CMB community's consensus assessment of the case for and design of a space mission took place 8 years ago. Since then theoretical considerations, available data from *Planck* and sub-orbital measurements, technology advances, and plans for new sub-orbital experiments have changed the landscape considerably. We propose to provide the 2020 decadal panel with a fresh expert assessment.

The scope of science we envision for the Probe is achievable within the approximate technical envelope of our 2010 baseline mission, which was near \$900M. This scope of science is also targeted by a recently submitted proposal for a European-based mission that has similar cost. Both of these missions have broader science reach than a more focused Japanese-led mission, which is near the \$400M limit. We thus assess that the CMB mission is in the Probe cost window.

The mission study is led by Steering and Executive Committees made up of scientists who built COBE, WMAP, *Planck*, and the leading sub-orbital experiments in the world; by scientists who processed, analyzed, and simulated data from these experiments; and who interpreted the results and put them in a physics and cosmology context. It is open to all member of the CMB community, and will represent hundreds of person years of accumulated knowledge, expertise, and experience.

1.2 Observables and Baselines

It is useful to decompose the polarization field of the CMB 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 $\ell \leq 1500$. Much information remains encoded in the E and B spectra, whose full exploration has just begun [1, 2, 3, 4, 5]. The B mode has two contributions: a primordial component at a level that is theoretically characterized using r, and a 'lensing' component that is due to gravitational lensing of E modes by the large scale structure of the universe; See Figure 1. The current upper limit on r is $r < 0.07\,(95\%)$ [6].

The best measurement of the CMB spectrum – made by COBE/FIRAS approximately 25 years ago – shows that the average CMB spectrum is consistent with that of a blackbody to an accuracy of 5 parts in 10^5 [7, 8]. Distortions in this spectrum encode a wealth of new information. The distortion shapes are commonly denoted as μ- and y-types [9, 10]. 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 $z \geq 5 \times 10^4$. The y distortions are caused by energy exchange between

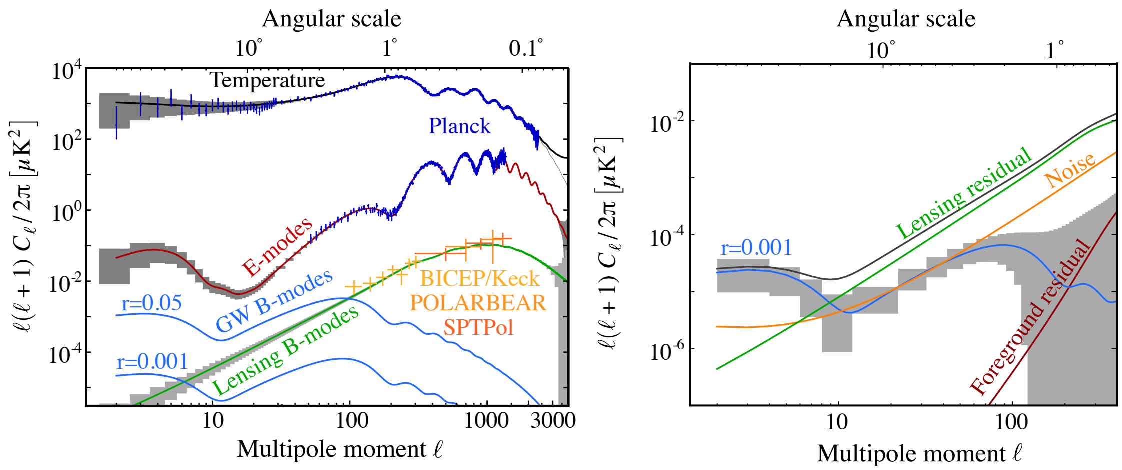

Figure 1: Predicted determination of the CMB power spectra for EPIC-IM (grey boxes) after foreground removal for $r = 0$ (left) and after foreground removal and delensing for $r = 0.001$ (right) overlaid on theoretical predictions (solid lines) and including *Planck* measurements of the temperature and E modes (dark blue) and of several ground-based measurements of the lensing B modes. The primordial B mode predictions (blue) are shown for two values of r.

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.

Quantitative performance assessments in this proposal are based on two current-decade mission designs, EPIC-IM and Super-PIXIE [11, 12]. EPIC-IM was presented to the 2010 decadal panel as a candidate CMB imaging polarization mission. It was based on a 1.4 m effective 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 version consisting of 4 spectrometers, each operating between 30 and 6000 GHz with 400 $\sim$15 GHz-wide bands. The two designs are our starting point for consideration of a future Probe; they are generically referred to as 'baselines'. We will show that the Probe will require higher sensitivity than the baseline; the requirement will be determined during the study. Improvements in technology by the next decade will enable the design of a mission that is much more capable compared to the baselines.

1.3 Science Objectives

The broad array of fundamental questions the CMB Probe will address, as describe in this section, firmly fit 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".

1.3.1 The Primordial Universe and Cosmic Inflation

The simplest models of inflation, a primordial era of accelerated expansion, predict an as yet unobserved primordial gravitational waves with a nearly scale-invariant spectrum, sourced by quantum fluctuations of the tensor component of the metric. These gravitational waves leave a distinct B-mode imprint on the polarization of the CMB. Any detection of primordial B-mode polarization, whether generated by the gravitational waves of inflation [13, 14] or any other source of vector or tensor perturbations, such as primordial magnetic fields [15, 16, 17, 18] and cosmic strings [19, 20, 21, 22] would reveal completely new information about the early universe. The results would either provide additional confirmation for current models or could overturn them. A detection would also have implications for fundamental physics by providing evidence for a new energy scale near the GUT scale, probing physics well beyond that reachable with terrestrial colliders.

To test inflation, the largest scales $\ell \leq 10$ are particularly important because they may reveal the presence of B-mode correlations on scales that were super-horizon at the time of recombination [23], and because on large scales the signal is strongest relative to the lensing B mode and instrumental noise; see Figure 1. No sub-orbital platform has yet produced measurements of B modes at $\ell < 40$, and a satellite is by far the most suitable platform for the all-sky observations necessary to reach the lowest modes, $\ell < 20$.

In slow-roll inflation there are two classes of models that naturally explain the measured value of the spectral index of primordial fluctuations $n_{\rm s}$. 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; see Figure 2.

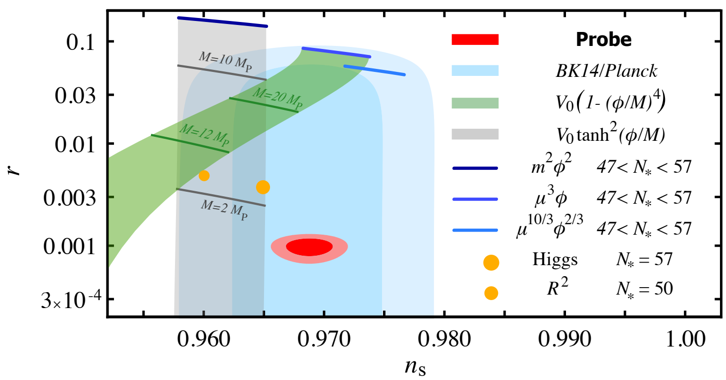

Figure 2: Current 1 and 2σ limits on r and $n_{\rm s}$ (blue) [6] and forecasted constraints for a fiducial model with $r = 0.001$ for the baseline probe. Also shown are predictions for the models of the inflaton potential discussed in the text.

Another class of models includes R^2 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 virtually all models that naturally explain $n_{\rm s}$. The baseline probe would achieve $\sigma(r) \sim 1.3 \times 10^{-4}$ assuming $r = 0.001$. (This prediction includes subtraction of a Galactic dust foreground model with two component power law emissivities, synchrotron emission with a single power law, that all power laws are spatially uniform, and self delensing.)

A detection of B modes consistent with a primordial spectrum of vacuum fluctuations would be the first observation of a phenomenon directly related to quantum gravity. In addition, a Probe mission would allow a high significance detection of any model of large-field inflation. A detection of r would therefore provide motivation to better understand how large-field inflation can be naturally incorporated into quantum gravity [24, 25, 26, 27, 28, 29, 30, 31].

Inflation predicts a B-mode spectrum with the shape shown in Figure 1, but there may be 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 a Gaussian and nearly scale-invariant spectrum for gravitational waves. A target constraint of $\sigma(n_{\rm t}) < 1$ at $r = 0.01$, easily achievable with a Probe mission, would significantly constrain non-vacuum inflationary sources [32, 33].

Deeper mapping of large scale E modes will provide new tests of isotropy, a prediction of most models of inflation; for example, observations with a CMB Probe could reject at 99% confidence models designed to explain the alignment of low multipoles in the temperature maps [34]. Cosmic variance limited measurement of these modes will also improve constraints on n_s, its changes with scale, and on primordial non-Gaussianity by factors of about two.

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 distortions are predicted at a level of $\mu = (2.0 \pm 0.14) \times 10^{-8}$, a level that is readily accessible

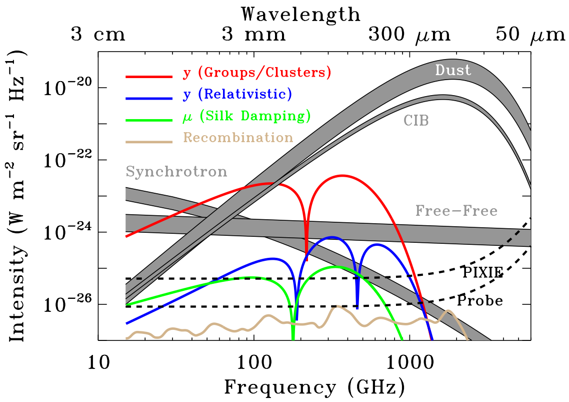

Figure 3: Anticipated y and μ spectral distortions (solid), the signature of resonant recombination lines (solid), and anticipated foreground signal levels relevant for spectral distortion measurements (grey bands). The simplest baseline spectrometer (Probe, dash) gives approximately 10 times the Explorer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

to a Probe class mission, see Figure 3 [38, 39]. A Probe may also give the sensitivity to detect the signature of recombination radiation imprinted by recombination of hydrogen and helium at redshift $z \simeq 10^3 - 10^4$; see Figure 3 [40, 41]. The detailed physics is sensitive to the values of $n_{\rm s}$, which is a direct probe of inflation.

1.3.2 Light Relics and Dark Matter

In the inflationary paradigm, the universe was reheated to temperatures of at least 10 MeV and perhaps as high as 10^{12} 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, leaving 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 powerful insights 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 $g = 1$. A newly designed mission with only 10 times higher sensitivity will reach $\sigma(N_{\rm eff}) < 0.025$. A high precision measurement of the CMB in temperature and polarization is the only proven approach to reach this important threshold.

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-mode power spectra will improve current limits for these quantities by a factor of five thus eliminating sub-MeV mass thermal relics. The Probe's μ-distortion measurement gives a two orders of magnitude improvement on the abundance and lifetime of early universe relics compared to current constraints derived from measurements of light element abundances [47, 48, 49, 50].

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 [51, 52, 53]. *Planck* currently excludes WIMPs with mass $m_{\rm dm} < 16$ GeV and a future

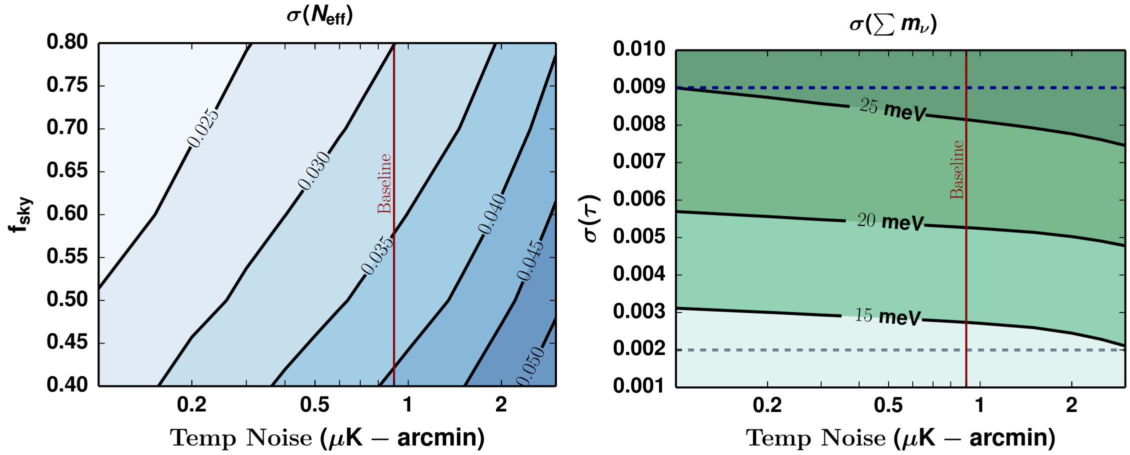

Figure 4: $N_{\rm eff}$ uncertainty as a function of noise and sky fraction (left) and sum of neutrino masses uncertainty as a function of noise and the uncertainty in the measurement of τ, for 0.7 sky fraction (right). The resolution assumed is 5'. Vertical lines denote the expected performance of the baseline mission. The upper blue dashed line is the current *Planck* limit; the lower grey dashed line is the limit from cosmic variance limited 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 include DESI BAO.

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.

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 [54]. These couplings affect the evolution of fluctuations and ultimately the T and E spectra. The current limits of $\sigma \lesssim 10^{-31} - 10^{-34}\,{\rm cm}^2 \times (m_{\rm dm}/{\rm MeV})$ 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. [55, 56, 57]).

Current constraints from FIRAS's spectrum measurement 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, thus testing DM interaction down to cross-sections $\sigma \simeq 10^{-39} - 10^{-35}\,{\rm cm}^2$ [58]. Spectral distortion measurements also open a new avenue for testing dark matter-proton interactions [58].

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., 59, 60, 61, 62, 63].

1.3.3 Neutrino Mass

Cosmology is uniquely capable of measuring the sum of neutrino masses, $\sum m_\nu$, through the suppression of the growth of structures in the universe on small scales. However, all cosmological measurements of $\sum m_\nu$ are fundamentally limited by our uncertainty in τ due to the strong degeneracy between the optical depth to reionization τ and the amplitude of the primordial perturbation power spectrum A_s. Although many surveys hope to detect $\sum m_\nu$, any 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 current limit of $\sigma(\tau) = 0.009$ is from *Planck* [64]. Forecasts for a CMB measurement of $\sum m_\nu$ using lensing B modes [65] are shown in Figure 4. With the current uncertainty in τ one is limited to $\sigma(\sum m_\nu) \gtrsim 25$ meV; no other survey or cosmological probe would improve this constraint. But 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 [66]. Robustly detecting neutrino mass at $> 3\sigma$ in any cosmological setting is only possible with an improved measurement of τ like the one achievable with the CMB Probe.

1.3.4 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 clusters is a key goal of cosmology. An open frontier in this quest is to discover the details of reionization – the transition of the universe from dominated by neutral to ionized hydrogen – and to establish a connection between the history of reionization and our knowledge of galaxy evolution. When did the epoch of reionization start? How long did it last? Are early galaxies enough to reionize the entire universe or is another population 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. The *Planck* team reported recently a value of $\tau = 0.055 \pm 0.009$ [64, 67]. The level is lower than previous estimates and reduces the tension between CMB-based analyses and constraints from other astrophysical sources [68]. The CMB Probe's measurement of E-mode polarization will improve $\sigma(\tau)$ by a factor of 4.5, reaching the cosmic variance limit and setting stringent constraints on models of the reionization epoch.

The anisotropy of the cosmic infrared background (CIB), produced by dusty star-forming galaxies in a wide redshift range, is 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 up to redshifts z~ 4 [69, 70, 71]). By measuring CIB anisotropy with $\simeq 100$ times higher signal-to-noise ratio at multiple frequencies, the CMB Probe will constrain the star formation rate with one tenth of *Planck*'s uncertainty. Similar improvement will be achieved in constraining $M_{\rm eff}$, the galaxy halo mass that is most efficient in producing star formation activity.

Reionization of the 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 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 Probe. It will be used to constrain the currently uncertain feedback mechanisms used in hydrodynamical simulations of cosmic structure formation [72].

The CMB spectrum varies spatially across the sky. One source of such anisotropic distortion is due to the spatial distribution of clusters and has already been measured by *Planck* [73]. A combination of precise CMB imaging and spectroscopic measurements will allow observing the relativistic temperature correction of individual SZ clusters [74, 75, 76], 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 [77, 78, 79, 80, 81].

1.3.5 Galactic Magnetic Fields and The Star Formation Process

Magnetohydrodynamic turbulence is a key regulator of the star-formation process. It acts over a range of spatial scales extending from the the largest eddies in the diffuse interstellar medium down to the scales of protostellar cores, envelopes, disks, outflows, and jets. Despite extensive work on observing density, velocity, and magnetic field structure, key questions remain open. For example, we don't yet know the characteristic magnetic field strength in molecular clouds, nor do we know the scales and mechanisms for dissipation of magnetized turbulence. Recent years have witnessed the development of sophisticated high-resolution 3-d simulations of magnetized turbulence, allowing us to constrain both the field structure and the associated grain alignment parameters via statistical comparisons between observed and simulated submillimeter-wave polarization maps. Our proposed probe-scale mission will provide tens of millions of independent magnetic field measurements, covering the missing spatial scales not recoverable via interferometric polarimetry with the Atacama Large Millimeter-Submillimeter Array, and thereby characterizing definitively the magnetic links between protostellar structures and the Galactic ISM.

1.4 The Challenges: Foregrounds and Systematics

The search for primordial B modes poses the most stringent requirements on foreground removal and control of systematic effects. A tentative target for the CMB Probe is to constrain the tensor-to-scalar ratio with an uncertainty that is a factor of 50-100 smaller than the current upper limit $r < 0.07\,(95\%)$, that is, to reach $\sigma(r) \lesssim 0.0005$ limited by foreground uncertainties. Foregrounds already dominate the signal. The large reduction in the size of the final error will require exquisite measurements and modeling of their properties.

To ascertain that the uncertainty on the measurement is dominated by statistics, or foreground uncertainties, rather than systematic errors, the contribution due to instrumental systematic effects should be $\sigma(r) \lesssim 0.0001$. To achieve these unprecedented levels the mission design, execution, and data analysis will be driven by control of systematic uncertainties.

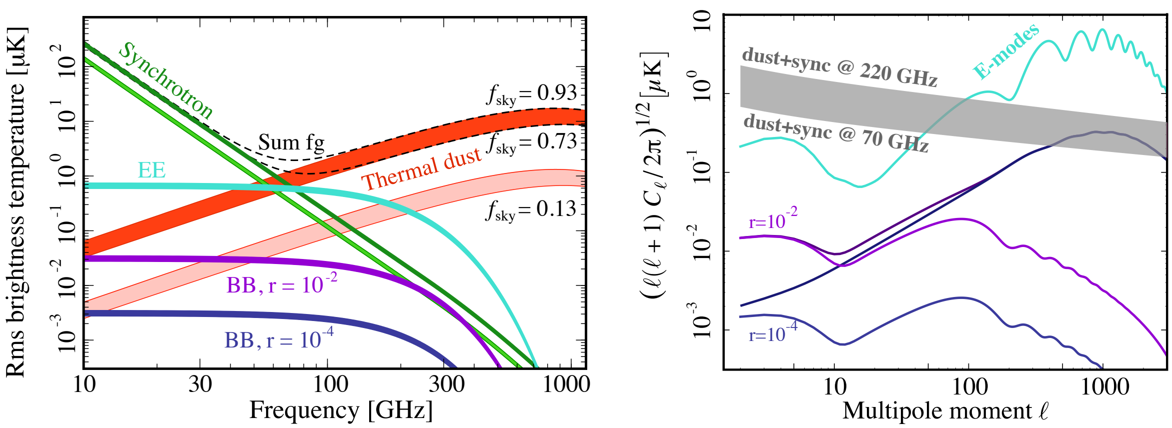

Figure 5: *Left:* Brightness temperature as function of frequency for the polarized CMB (cyan, purple, blue) and Galactic foreground signals: dust (red) and synchrotron (green). The darker bands correspond to sky fractions between 73% and 93%; the lighter bands to the cleanest 13%, with the width indicating the uncertainty. *Right:* Angular power spectra for inflationary, and for the sum of inflationary and lensing B modes for two values of r; for E-mode polarization; and for foreground emission between 70 and 220 GHz.

1.4.1 Foregrounds

Whereas the CMB temperature anisotropy signal dominates Galactic sources of emission over much of the sky, this is not the case for polarization. Figure 5 compares the expected RMS brightness temperature of polarized emission from Galactic sources to E and B modes as a function of

frequency and gives the expected signal levels as a function of angular scale ℓ.
The conclusions are that:

- over the largest angular scales (lowest ℓs), which are crucial for a range of science goals and where inflationary B modes would be largest relative to those from lensing and instrument noise, foreground sources will need to be measured and subtracted to a level better than 1 part in 10 for E and in 100 for B;
- foregrounds dominate the inflationary B-mode signal on *all* angular scales by an order of magnitude or more.

Known signals can be accounted for and removed even if their amplitude is large. But the best measurements to date, from *Planck*, have uncertainties that fall far short of the goals envisioned for the Probe. This is visually demonstrated by Figure 6, which compares the level of B modes at low ℓ for $r = 0.001$ to the *Planck* 353 GHz noise, extrapolated to 150 GHz, a frequency band in which the inflationary signal is among the strongest.

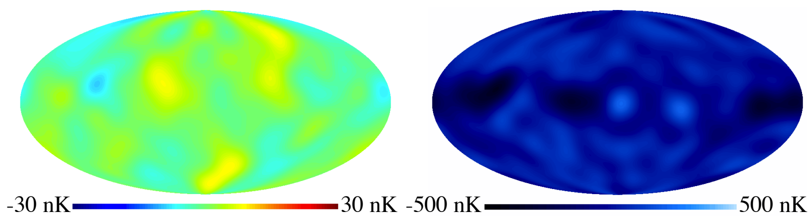

Figure 6: *Left:* Stokes Q for inflationary B modes for $\ell < 12$ and $r = 0.001$. *Right:* Noise in the $Planck$ 353 GHz map of Stokes Q for $\ell < 12$ extrapolated to 150 GHz assuming the (sky average) spectral properties of dust. Note the color scales.

Removal of foregrounds based on multi-frequency data relies on extrapolations between frequencies based on an assumed spectral dependence. At the current level of precision a power law dependence for synchrotron radiation and a spatially uniform modified black body spectrum for dust emission give a reasonable fit to the data. But the complex composition of Galactic dust – for example, the grains' size distribution, the different materials, and different radiative envirnoments – suggests that this simple phenomenological description would no longer be valid at higher precision levels. One expects departures from a modified black body spectrum, and the emission properties are expected to vary spatially. The details of foreground emission, at every point on the sky, must ultimately be measured with the Probe itself. The challenge is to design the frequency coverage to do so optimally.

For $r < 0.01$ the inflationary signal is at or below the lensing B mode; see Figure 1. Using high resolution polarization measurements, it is possible to reconstruct the lensing field and 'delens' and thus remove the effect of lensing. But for low r values significant delensing is required, and it is an open question at which point foregrounds will become the limiting factor.

Good control of foregrounds is also necessary for the other science objectives. Detailed information about the reionization history, available by a cosmic variance limited measurement of the E power spectrum, is buried below the foregrounds at $\ell < 10$. And recovering the spectral distortions signals will require proper accounting of emission by dust grains, synchrotron emission from electrons spiraling in the Galactic magnetic field, Coulomb scattering of charged particles ('free-free', see Figure 3), as well as anomalous microwave and CO emission.

1.4.2 Systematic Errors

The latest experience with *Planck* points to the following systematic error categories likely to be important for the CMB Probe, or for that matter, for any instrument striving to map the polarization over large portions of the sky to the levels targeted by the Probe [64]: 1) Intensity-to-polarization leakage, 2) stability, and 3) straylight. Each of these is considered below in light of polarimetry measurements through differencing the signals of two detectors that are sensitive to orthogonal polarization states. Currently, the most sensitive sub-orbital experiments have shown control of systematics at a level of $r \lesssim 0.006$ ($r \lesssim 0.001$ with a polarization modulator on the main beam pattern) on small (1%) sky fractions [82, 83].

Leakage The CMB temperature anisotropy signal is a factor of 1000 larger than the strongest possible inflationary B modes. Therefore instrumental effects that leak even a small fraction of an intensity fluctuation into spurious polarization must be understood and controlled. The main effects are differences between gains of detectors, their frequency bandpass mismatch, their differential pointing on the sky, and their differential antenna patterns. These differential effects need to be controlled, through instrument design, characterization, and data analysis to levels that are another factor of 10-100 more stringent.

Leakage-related effects will drive requirements on the optical system, the uniformity of the bandpass of each polarimeter, calibration requirements on the level of cross-polar leakage and its angle, and measurements of the the beam shape as a function of source spectrum. 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 The reconstruction of deep, full sky polarization maps involves a combination of measurements made at times separated by months, requiring stability of the response of the instrument on corresponding time scales. Random deviations from stability are a source of noise; systematic deviations are a source of systematic error. These types of systematic errors require 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.

The spacecraft's ambient radiation environment is modulated by the solar activity and can introduce temperature drifts in the cryogenic stages, leading to correlated transients in detectors and readout electronics. For example, cosmic ray energy deposition in the Planck/HFI focal plane was a source of correlated noise between detectors and created a factor $\sim$5 additional noise at ℓ=2 [64]. The design of the instrument must account for these effects.

Straylight When the brightest sources in the sky – the Sun, Moon, planets, and Galaxy – are passing through the far sidelobes of the telescope they create a spurious polarization signal. If they are passing in repeated, scan synchronous pattern, the spurious signal becomes a source of systematic error. This far sidelobe response can be reduced through careful optical design and baffling, but will always be present at a non-trivial level. Detailed modeling of the *Planck* telescope, convolved with sky sources, gave a predicted sidelobe contamination at a detectable level of tens of micro-Kelvin in the 30 GHz maps. This contamination has been observed in *Planck* difference maps. As a result an estimate of the sidelobe contamination was removed from some of the *Planck* time ordered data as part of the mapmaking process. The more stringent requirements for the Probe will necessitate a much stronger level of mitigation.

1.5 The CMB Probe in Context

1.5.1 Current and Forthcoming Sub-Orbital Efforts

The remarkable scientific yield has motivated significant agency investments in current and future sub-orbital experiments. These experiments are designed to exploit the comparative advantages of the sub-orbital platforms, while providing the design heritage and experience necessary to maximize the probability of success of an orbital mission.

For the ground-based efforts, these include combinations of *i)* provision for large apertures and therefore high angular resolution, *ii)* flexibility to rapidly deploy new technologies, and *iii)* allowance for detector formats that are relatively unconstrained by mass and power limitations. To date, these efforts have demonstrated low noise measurements of small and intermediate angular scale E and B polarization structures over less than 2% fractional areas of the sky.

Balloon-borne missions *i)* extend the frequency reach of the ground based telescopes, *ii)* enable high fidelity measurements on larger angular scales than can be probed from the ground, and *iii)* grant access to an environment with similar requirements and constraints as in orbit, providing heritage for future space missions as well as experience in dealing with the analysis of data that are representative of a space mission. In this way, the sub-orbital programs are important in their own right and are critical preparation for a space mission.

The 2010 Decadal Panel strongly recommended supporting sub-orbital efforts in preparation for a possible space mission that would make a definitive and high quality measurement of primordial gravitational waves. As a result, the US has clear leadership in the field, both in terms of ground- and balloon-based experiments and results.

This leadership will continue into the foreseeable future. In aggregate, funded, now-being-built 'Stage 3' CMB experiments will deploy approximately 100,000 detectors on various sub-orbital experiments within the next 3-5 years. Ground-based experiments plan to extend measurements from few percent of the sky to few tens, although in a limited frequency range between 30 and 300 GHz. Balloon-borne payloads operating at even higher frequencies strive to cover even larger fractions.

1.5.2 Proposed Efforts: LiteBIRD, CORE, and CMB-S4

Japan, in collaboration with NASA, is now considering whether to proceed with LiteBIRD, a space mission designed to search for primordial B modes. The US Team has submitted its Phase A report to NASA; Phase A in Japan will conclude in about a year. LiteBIRD is a smaller, more focused mission compared to CMB Probe. It is an imager based on a 0.4 m aperture telescope. Its reach in ℓ space is 2.5-4 times less compared to the 1-1.5 m aperture we are considering for Probe making the science at ℓ's above a few hundred in E and B modes unreachable. It has no spectroscopic capabilities and thus not sensitive to the spectral distortion science goals.

A collaboration of scientists in Europe has just recently proposed CORE to ESA as part of the M5 round of space mission proposals. The team includes a number of US collaborators; the PI of this proposal is a member of CORE's Executive Board. CORE is a CMB polarization imager that is based on a 1.2 m aperture telescope and thus intended to reach 3 times the resolution of LiteBIRD. It will have a resolution of 5-10 arcmin in the 100-200 GHz bands. CORE targets similar breadth of science as the CMB Probe. Selection of missions for Phase A studies is expected in June 2017, and end of Phase A in summer 2019.

The US CMB community has proposed, and the Particle Physics Project Prioritization Panel (P5) has recommended to the DOE, the establishment of a 4th generation CMB experiment called CMB-S4. This is an ambitious program to field approximately 5 times the number of detectors fielded by Stage 3 experiments. If and when funded, CMB-S4 will enable unprecedented sensitivity at frequency bands accessible from the ground, and with telescopes that enable high resolution.

1.5.3 Why Study a CMB Probe?

Learning from the successes of COBE/FIRAS, COBE/DMR, WMAP, and *Planck*, a CMB Probe is the single most suitable vehicle to deliver complete sky coverage, comprehensive frequency coverage, and exquisite control of systematic effects. No sub-orbital experiment has yet produced any polarization results on more than 2% of the sky, let alone on scales requiring $> 70\%$, which are crucial for achieving some of the science goals described in Section 1.3. The broad frequency coverage of the space mission is best suited to mitigate the foregrounds expected on a broad range of angular scales. The mission will provide a single self-consistent and self-calibrated data set;

and it will provide legacy maps at many frequency bands that will become the basis for hundreds of new papers.

If the inflationary signal is detected by sub-orbital experiments any time soon, a space mission to characterize the signal in full detail is equally compelling. The existence of ambitious sub-orbital programs is a complementary strength. How to make the best use of this complementarity is an explicit goal of our study; see Section 1.7.

1.5.4 Does the CMB Probe Fit Within the Cost Window?

The total cost estimate for the EPIC-IM mission, as generated by JPL's Team X, was $920M in 2009 [11]. The mission had a 1.4 m effective entrance aperture, a telescope that was maintained at 4 K, and focal plane with 11,094 TES detectors operating at 0.1 K. The CORE mission, that has just been proposed to ESA, has an aperture of 1.2 m, a telescope cooled to 40 K or less, and a focal plane with few thousand bolometric detectors operating at 0.1 K. It was estimated by the proposing team to have a total cost of $\sim$$750M, which includes an ESA contribution of $610M and the rest is from member countries. LiteBIRD has a 0.4 m aperture telescope feeding one of two focal planes. The telescope is cooled to 4 K and has a continuously rotating polarization modulator. The second focal plane is coupled to the sky without reflectors; it has a second continuously rotating polarization modulator. Both focal planes are cooled to 0.1 K and contain few thousand detectors. LiteBIRD is estimated to be within JAXA's $300M class and the US contribution is $65M.

The science goals we are envisioning for the CMB Probe, the effective aperture size, between 1 and 1.5 m, and the telescope and focal plane temperatures are most akin to EPIC-IM and CORE. While the relation between these parameters and total cost will be analyzed during this study, these past exercises suggest that a polarization imager fits within the $400M - $1000M class.

PIXIE, which consists of a single spectrometer, is being proposed as an Explorer class mission. Super-PIXIE, consisting of four spectrometers, but sharing the same spacecraft should fit within the Probe cost bracket. Whether a scientifically compelling mission that has a combined imager/spectrometer instruments can be constructed within the Probe cost cap is one of the questions we will address during the study.

1.5.5 This Study in the Context of Previous Mission Studies

The US CMB community's most recent view of the anticipated science reach and the path to implementation of a possible future US space mission were summarized in an unpublished report to the 2010 decadal panel. That report drew upon the EPIC-IM mission design, which is nearly 10 years old. The landscape has since changed. Theoretical advances in physics and astrophysics give updated science goals, and therefore new targets for the fidelity of measurements of E and B modes. Existing and forthcoming data, from new astrophysical surveys and particle physics experiments, present opportunities for new synergies and complementarities. A slew of sub-orbital experiments together with the *Planck* mission have transformed our view of the mm-wave polarized sky, highlighting the requirement on thorough understanding of the foregrounds. Advances in detector technologies, multiplexed readouts, and optical components now enable a significantly more capable mission than the one envisioned ten years ago. And the community has vastly more experience with designs of polarimeters and the control of their systematic uncertainties. A new study based on this accumulated information and experience is timely.

The US LiteBIRD team has proposed participation in LiteBIRD and recently submitted its Phase A report. The proposal and report were conducted by a subset of the community for the purpose of supporting a mission design that matches JAXA's plans and its cost caps.

Work on our proposal, and the subsequent mission study, represent a collaborative effort by all interested members of the CMB community, including US members of the LiteBIRD team. We have also reached out to our international partners and invited them to participate. The final report will present a consensus view of the US CMB community. This would be the proper input for the deliberations of the next US decadal panel.

1.6 State of Technologies

The imager version of the probe consists of the following main technical elements: a telescope with an effective aperture size of $\lesssim 1.5$ m, a focal plane consisting of thousands of detectors, coolers that provide a focal plane temperature between 0.1 and 0.3 K, and a multiplexed readout system with which a handful of wires are used to readout hundreds or thousands of detectors. Additional elements could include filters and potentially lenses and polarization modulators. The spectrometer version is also a cryogenic mission, and has two main elements: a spectrometer, and the cold load that provides its absolute calibration. Both versions have the standard complement of spacecraft bus features to provide pointing control and sensing, telemetry, and power.

Planck, which was the last CMB imaging cryogenic mission, had 65 polarization sensitive detectors. The most significant advances since *Planck* have been in developing detector and readout technologies, and optical components. The baseline imager, enjoying technologies of a decade ago, had $\sim$30 times the sensitivity of *Planck*. As the paragraphs below describe, a mission with today's technologies would already be more powerful than the baseline mission. The CMB Probe promises to be orders of magnitude more sensitive than *Planck*.

Arrays of Detectors Most modern sub-orbital experiments use TES bolometers, with thousands of detectors with TRL≥ 5. HEMT amplifiers, which are a competitive technology below 100 GHz, also have high TRL. The bolometric arrays have been successfully implemented with a variety of optical coupling schemes such as horns, contacting lenslets, and antenna arrays. Some instruments have deployed newer technology with arrays of 'muti-chroic pixels'. With this technology several frequency bands are detected through the same focal plane pixel. As of now, arrays with up to 3 bands and 6 detectors per pixel are being used. A new detector technology using kinetic inductance inductors (KIDs) is emerging, which may have benefits in simplicity of fabrication and scalability to arrays with hundreds of thousands of elements.

Readout Two families of readout technologies are in use: frequency- and time-domain multiplexing, FDM, and TDM, respectively. Both offer 64 channels per readout module and have mature TRLs having been flown on balloon payloads. Increasing the multiplexing factor, a goal in both approaches, decreases the heat load due to wiring on the focal plane. The microwave FDM is an emerging technology which promises to incorporate $\gtrsim 500$ channels of TES detectors or KIDs per multiplexed module. It is attractive because there is no dissipation at the coldest stage, but there is increased dissipation at ~ 4 K and further development is required to reduce the ambient temperature power consumption. Currently the ambient temperature power consumption of TDM systems is $\times 2 - 3$ lower, but development is necessary to reduce the higher power consumption at the coldest stage.

Polarization Modulators and Other Optical Components A polarization modulator presents an attractive means to reject a host of systematic uncertainties. Some sub-orbital experiments have used modulators and experience with their operation, efficacy, and the systematic errors they present, is growing. For use with the Probe, the modulators will need to have high polarization efficiency over a broad bandwidth. A fractional bandwidth of $\sim$100% has been demonstrated. Optical systems that incorporate refractive elements can realize higher throughput than reflectors alone; the use of refractors – or a modulator – requires broad-band anti-reflection coatings. Groups have developed specialized sprays and techniques to fabricate sub-wavelength structures. Most of these technologies have TRL$\geq$5.

Spectrometer The polarizing Fourier transform spectrometer builds on the COBE/FIRAS mission using mature technology with TRL $\geq$6. The baseline spectrometer we have assumed here is comprised of a number of individual spectrometers, each with its own absolute reference calibrator, Multi-moded optics, concentrators, detectors, and calibrators have been demonstrated. The detector readout is copied from the that used for the Hitomi mission. But the Probe version may combine multiple spectrometer beams within a single telescope. How to achieve that will be part of this study.

Cryogenics For providing an operating temperature of 0.1 K: an open cycle dilution refrigerator, a European technology, was flown on *Planck*. A closed cycle version is under development (also in Europe) and has TRL 3-4. A Goddard continuous adiabatic demagnetization refrigerator (ADR) will soon be flown on a balloon payload. The Hitomi spacecraft operated a staged version of such an ADR. For higher operating temperatures, refrigerator technologies are standard, but suitability for the mission thermal loads will be assessed during the study.

1.7 Mission Study and Management Plan

1.7.1 Study Plan

The mission study is open to the entire CMB community and includes more than 75 scientists. To gain maximum benefit from *Planck*, LiteBIRD, and CORE we invited international members to participate. The work is organized into Working Groups (WG); see Figure 7. Working groups are led by members of the study's Executive Committee, as listed in the Figure. Although Figure 7 suggests distinct boundaries between the WGs we expect and encourage significant overlap and feedback. It is not practical to enumerate all the interdependencies.

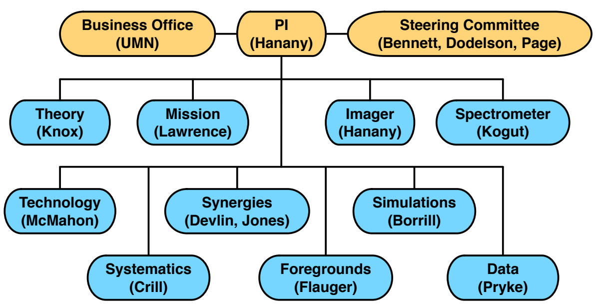

Figure 7: Management structure of the CMB Probe. A steering committee advises the PI. The study is led by the PI through an Executive Committee. Each member of the committee is in charge of a specific Working Group (blue boxes). Significant overlap and feedback is expected between the working groups. Participation in the Working Groups is open to all members of the CMB community.

The study will be carried out through intra- and inter-WG teleconferences; mission design teleconference with JPL engineers; mission design meetings at JPL; and a community workshop.

By the time the CMB probe is likely to fly, significant advances will have been made with sub-orbital efforts. This is true regardless of the state of the proposed CMB-S4 effort, and even more so should funding for S4 become available soon. A central study activity will be to investigate and clarify the complementarity between the space mission and sub-orbital efforts. The workshop is dedicated to discussing this topic. Pertinent topics include: the extent to which the aperture size of the imaging probe relies on delensing capabilities provided by high resolution measurements from the ground; the optimal resolution of a space-based mission from the point of view of providing foreground information to sub-orbital missions; the optimal overlap in ℓ-space; the relation between the design of a spectrometer and forthcoming sub-orbital measurements; and the necessity for a space mission in the era of sub-orbital experiments with 500,000 detectors.

Another central activity that cuts across several of the WGs is the development and use of a 'Mission Performance Simulator'. The mission performance simulator takes as input a particular instrument configuration (e.g number of detectors, frequencies, resolutions), sky observing pattern, models of sky emission (including CMB and foregrounds), and systematic effects. It generates detector timestreams that are used to make maps. The maps are analyzed for their astrophysical content.

We now describe the work of each of the WGs and, where appropriate, lay out responsibilities for elements of the mission performance simulator.

• **Theory (Knox)** This WG will survey, summarize, and prioritize the set of science goals for the Probe. Given input on target frequency bands, assumptions about foregrounds, instrument systematics, and instrument noise levels the group will generate forecasts for the impact of the Probes products and their significance to physics and astrophysics. This group will also investigate which other astrophysical data sets are most suitable for cross-correlation analysis with the Probe's data.

• **Mission and connection with JPL (Lawrence)** The Mission WG is responsible for defining the overall mission architecture including telescope implementation, cooling, telemetry, mass, power, and cost. We are requesting that engineering and costing session be conducted with JPL. Charles Lawrence, Chief Scientist of the Astronomy, Physics, and Space Technology Directorate at JPL, and the *Planck* US PI, will lead this WG.

• **Imager (Hanany) and Spectrometer (Kogut)** The imager and spectrometer WGs will translate the science goals to mission requirements and to nominal designs. The designs will include telescopes of various configurations, focal planes with several candidate detector technologies and readout schemes, optical elements, and cooling strategies. These groups will similarly consider the options for spectrometers. Both groups will interact frequently with JPL the Mission WG. The WG will consider an imager-only design, a spectrometer-only design, and a combined instrument. This group will provide focal plane configurations for the mission performance simulator.

• **Technology (McMahon)** This working group will provide technical input to the team designing the mission and instruments. It will assess the most appropriate technologies given the implementation of the mission and identify technologies that are in need of development. A central topic of assessment will be the technical readiness and possible implementation of a polarization modulator.

• **Space / Sub-Orbital Synergy (Devlin, Jones)** This WG will coordinate the study of complementarity between the Probe and sub-orbital efforts. It will also prepare, organize, and run the community workshop, and will be in charge of summarizing the conclusions.

• **Foregrounds (Flauger)** This WG will construct foregrounds models that encompass all the known and expected emission complexities. The models will be informed by data and physical inputs and will include, for example, spatial variations of the spectral dependence, decorrelation between frequencies, and departures from a simple modified black body law for Galactic dust [84, 85, 86, 87, 88, 89]. The models will be used as part of the Mission Performance Simulator. The WG will also study, develop, test, and recommend methods for component separation including those used with *Planck* [90].

• **Systematics (Crill)** This WG will identify sources of systematic effects, evaluate their approximate magnitude, and will construct the tools to integrate the these systematic effects into the mission performance simulator. Examples include frequency band mismatches, differential gains, and sidelobes. The WG will explore mitigation of systematic errors by design, for example implementing modulation schemes and modulator technologies, and mitigation by analysis techniques.

• **Simulations (Borrill)** This WG will be in charge of building and running the mission performance simulator. It is based on the massively parallel tools built for the Planck Full Focal Plane simulations [91]. The simulations will use the high performance computing resources available to the CMB community at the DOE's National Energy Research Scientific Computing (NERSC) Center at Lawrence Berkeley National Laboratory.

• **Data Analysis and Exploitation (Pryke)** The full sky nature, the broad frequency coverage, and the high sensitivity of the CMB-Probe will generate a legacy data set surpassing that of *Planck*'s. This WG will plan for the extraction of cosmological and astrophysical products from the Probe's data. This includes exploring optimal implementation of component separation techniques, of combining sub-orbital CMB data with the Probe's, and of cross-correlating with data at other wavelengths. The WG will assess whether specific synergies suggest preferring some mission parameter values over others. The group will use outputs of the mission performance simulator.

1.7.2 Mission Study Timeline

The study will be conducted in three broad phases with several months overlap to allow for the non-linear nature of the progression: Mission Definition; Mission Implementation; Report Writeup.

Mission Definition: 3/2017 - 12/2017 The primary output of this period is a set of mission requirements that will feed into the Mission Implementation phase. To achieve a set of mission requirements we will use the mission performance simulator to iterate over various angular resolutions, focal plane configurations, detector noise properties and progressively more complex foreground and systematic effect models. Having extracted astrophysical information from the resulting multifrequency maps we will have determined the necessary e.g. focal plane sensitivity, or the number of frequency bands. The set of these parameters gives the set of mission requirements.

In summer of 2017 we are planning to hold the community workshop. The conclusions from the workshop, regarding the complementarity between the Probe and sub-orbital experiments, will inform the design parameters of the mission.

Mission Implementation: 9/2017 - 6/2018 This is the period during which baseline instrument parameters become a space mission. We will finalize the detector and readout technologies, or identify several acceptable options. We will investigate the impact of target telescope size and temperature on cooling resources and cost. Readout technologies will also have impact on cooling resources – because of the number of wires reaching the focal plane – and on power budget. The preferred scan strategy has consequences on maneuvering the spacecraft and on attitude reconstruction. The large number of detectors will impose constraints on the telemetry. This is the period during which we will have defined a nominal design for the mission and a relevant exploration space around it. These will be the basis for the design session with JPL's Team X, and for the 'report about findings' as prescribed by NASA.

Report Writeup: 3/2018 - 9/2018 Writing the final report.

1.7.3 Study Team

The study consists of more than 75 scientists representing hundreds of person years of experience with CMB theory, data analysis, and measurements on all platforms including satellite missions that have already flown (COBE, WMAP, and *Planck*) and the two proposed (LiteBIRD and CORE). The PI Hanany, who has more than 20 years of CMB ballooning experience, co-led MAXIMA and Archeops, was the PI of MAXIPOL and EBEX, and is a member of CORE's Executive Board, will have ultimate responsibility for the study. He is advised by a Steering Committee – Bennett (Johns Hopkins), Dodelson (Chicago), and Page (Princeton) – and assisted by a business office at the University of Minnesota. An Executive Committee (EC) is in charge of the daily operation of the collaboration. The members of the Steering and Executive Committees led and are leading operating CMB experiments that have produced the most compelling CMB polarization results to date. They include leaders and members of the WMAP, US *Planck*, US LiteBIRD, and US CORE teams; the leader of the PIXIE spectrometer proposal; initiators and implementors of new millimeter-wave technologies; and of recognized experts in data analysis and theory.

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Education

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1992	M.Phil., Physics, Columbia University
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1987	B.Sc. Physics, Tel Aviv University, Israel

Honors and Awards (abridged)

2016	George W. Taylor/CSE Alumni Society Award for Distinguished Teaching, College of Science and Engineering, University of Minnesota
2012	Fellow, American Physics Society
2003 & 2010	‘Best Professor in Physics’, Institute of Technology Student Board, University of Minnesota
2001 – 2003	McKnight-Land Distinguished Professor, University of Minnesota/Twin Cities
2000	Results published by Hanany et al (2000) were cited as “One of the 10 most important breakthroughs in science for the year 2000” by *Science* magazine (*Science*, **290**, 2221)

Membership

American Physical Society (fellow); Division of Astrophysics
American Astronomical Society

Scientific Projects (abridged)

CORE: Lead US Investigator	A proposed European CMB polarization satellite
EPIC-IM: Co-I	A NASA mission concept for a CMB polarization satellite
EBEX: PI	A long duration balloon experiment to measure the CMB polarization
Magnetic Bearing: PI	Development of bearings based on high Tc superconducting materials
MAXIPOL: PI	A North American balloon experiment to measure the CMB polarization
Archeops: Co-I	A European balloon borne CMB temperature and polarization experiment
MAXIMA: Co-I	A North American balloon experiment to measure the CMB

Recent Relevant Invited Talks (partial list)

2016	“The US CMB Balloon Program”, American Physical Society Meeting, Salt Lake City, Utah, April 2016
2015	“The EBEX HWP”, B-mode from Space Workshop, Tokyo, Japan, December 2015
2015	“The US Balloon Program and Lessons for LiteBIRD”, B-mode from Space Workshop, Tokyo, Japan, December 2015

2015 "Potential US Participation in the CoRE+ Space Mission",
CoRE+ Collaboration Meeting, Paris, France, October 2015

2015 "The US Balloon Program",
European CMB Coordination Workshop, Florence, Italy, August 2015

2015 "The Legacy of Planck: CMB Measurements after 2020 ",
International Astronomical Union, Hawaii, August 2015 (declined)

2015 "CMB Measurements with EBEX and Future Space Missions ",
Marcel Grossman Conference 14, Rome, July 2015 (declined)

2014 "The Polarization of the CMB ",
Israeli Physical Society Plenary Session, Beer Sheva, Israel, Decmeber 2014

Relevant Community Service (partial list)

- Committee Member, Balloon Working Group, NASA's Balloon Program Office, 2011 - present
- Editor, Journal of Cosmology and Astro-Particle Physics, 2000 – present
- Co-Organizer, "Cosmology with the CMB and its polarization", January 2015, Minneapolis, MN
- Committee Member, European Space Agency's Planck satellite Mid-Term Review Board, 2011 - 2014
- Lead Coordinator, Inflation Probe Science Interest Group, a subgroup of the Physics of The Cosmos Program Analysis Group, 2011 - present
- Executive Committee Member, Physics of The Cosmos Program Analysis Group for NASA's Astrophysic Subcommittee, 2010 - present
- Member, Astrophysics Subcommittee to NASA's Science Advisory Committee, 2008 - 2012
- Co-Organizer, CMBPol Technology Workshop, Boulder, CO, August 2008
- Chair, Primordial Polarization Program Definition Team, A NASA appointed committee to coordinate activities toward a future CMB polarization satellite, 2007 – 2010

Recent Significant Relevant Publications (underlines denote Hanany group members)

- *'The EBEX Balloon Borne Experiment - Optics, Receiver, and Polarimetry'* The EBEX Collaboration: A. Aboobaker,...F. Aubin,...C. Bao,... S. Hanany,...J. Klein,...K. Raach,...I. Sagiv,... K. Young, K. Zilic, 2016, ApJSupp, in print.
- *'Millimeter-Wave Broadband Anti-Reflection Coatings Using Laser Ablation of Sub-Wavelength Structures'* T. Matsumura, K. Young, Q. Wen, S. Hanany, ... 2016, Applied Optics, Vol. 55, #13, pg. 3502
- *'Maximum Likelihood Foreground Cleaning for Cosmic Microwave Background Polarimeters in the Presence of Systematic Effects'* C. Bao,...B. Gold, S. Hanany,... 2016, ApJ, Vol. 819, pg. 12
- *'CMB Telescopes and Optical Systems'*, S. Hanany, M Niemack, and L. Page; to appear in 'Planets, Stars and Stellar Systems - Volume 1: Telescopes and Instrumentation' . Ian Maclean Ed., Springer 2012.
- *'The performance of the bolometer array and readout system during the 2012/2013 flight of the E and B experiment (EBEX)*, K. Macdermid, ..., ...A. Aboobaker,... S. Hanany, ... J. Klein, ...M. Milligan, ...K. Raach,... I. Sagiv, ... K. Zilic, 2008, Appl. Opt., Vol. 47, Pgs. 103 – 109
- *'MAXIPOL: Cosmic Microwave Background Polarimetry Using a Rotating Half Wave Plate'*, B. R. Johnson, ..., M. E. Abroe, ..., S. Hanany, ..., T. Jones, ..., T. Matsumura, ..., T. Renbarger, ..., 2007, ApJ, Vol. 665, Pg. 42, astro-ph/0611394,
- *'Temperature and polarization angular power spectra of Galactic dust radiation at 353 GHz as measured by Archeops,* N. Ponthieu, ..., S. Hanany, ..., 2005, A&A, Vol. 444, Pg. 327, astro-ph/0501427
- *'Millimeter-Wave Achromatic Half Wave Plate* S. Hanany, J. Hubmayr, B. R. Johnson, T. Matsumura, P. Oxley, M. Thibodeau, Applied Optics, 2005, Vol. 44, Pgs. 4666-4670, physics/0503122
- *'First Detection of Polarization of the Submillimetre Galactic Dust Emission by Archeops'* A. Benoit, ..., S. Hanany, ..., D. P. Marrone, ... 2004, Astronomy and Astrophysics, Vol. 424, Pg. 571, astro-ph/0306222
- *'MAXIMA-1: A Measurement of the Cosmic Microwave Background Anisotropy on Angular Scale of 10 arcminutes to 5 degrees'* S. Hanany, ..., 2000, ApJ, Vol. 545L, pg. 5, astro-ph/0005123

Charles L. Bennett

Professional Preparation:

Massachussets Institute of Technology	Physics	Ph.D. 1978-1984
Univ. of Maryland, *cum laude*, High Honors in Astronomy	Physics	B.S. 1974-1978

Appointments:

2005 - Present	Professor of Physics & Astronomy, Johns Hopkins Univ, Baltimore, MD
1984 - 2005	Senior Scientist for Experimental Cosmology, Infrared Astrophysics Branch Head, Astrophysics Staff Scientist, NASA-GSFC, Greenbelt, MD

Experience and Awards:
Observational/experimental cosmology. CLASS PI. WMAP PI. COBE-DMR Deputy PI. COSPAR Space Science Award Shaw Prize in Astronomy. Gruber Cosmology Prize (once for COBE, once for WMAP). Caterina Tomassoni and Felice Pietro Chisesi Prize. Comstock Prize in Physics. Harvey Prize. Henry Draper Medal. John C. Lindsay Award. NASA Exceptional Scientific Achievement (once for COBE, once for WMAP). NASA Outstanding Leadership Medal for WMAP. National Academy of Sciences. American Academy of Arts and Sciences. Fellow of American Assn for the Advancement of Science. Fellow of the American Physical Society.

Select Publications:

1. Watts, D. J., Larson, D., Marriage, T. A., Abitbol, M. H., Appel, J. W., **Bennett, C. L.**, Chuss, D. T., Eimer, J. R., Essinger-Hileman, T., Miller, N. J., Rostem, K., Wollack, E. J., "Measuring the Largest Angular Scale CMB B-mode Polarization with Galactic Foregrounds on a Cut Sky," ApJ, 814, Issue 2, article id. 103, 2015.
2. Essinger-Hileman, T. et al., "CLASS: The Cosmology Large Angular Scale Surveyor," arXiv:1408.4788, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Volume 9153, 2014.
3. **Bennett, C. L.**; Larson, D.; Weiland, J. L.; Jarosik, N.; Hinshaw, G.; Odegard, N.; Smith, K. M.; Hill, R. S.; Gold, B.; Halpern, M.; Komatsu, E.; Nolta, M. R.; Page, L.; Spergel, D. N.; Wollack, E.; Dunkley, J.; Kogut, A.; Limon, M.; Meyer, S. S.; Tucker, G. S.; Wright, E. L., "Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Final Maps and Results," ApJ Supp, 208, id 20, 2013.
4. **Bennett, C.L.**, Bay, M., Halpern, M., Hinshaw, G., Jackson, C., Jarosik, N., Kogut, A., Limon, M., Meyer, S.S., Page, L., Spergel, D.N., Tucker, G.S., Wilkinson, D.T., Wollack, E., Wright, E.L., "The Microwave Anisotropy Probe (MAP) Mission," ApJ, 583, 1, 2002.
5. **Bennett, C.L.**, Halpern, M., Hinshaw, G., Jarosik, N., Kogut, A., Limon, M., Meyer, S.S., Page, L., Spergel, D.N., Tucker, G.S., Wollack, E., Wright, E.L., Barnes, C., Greason, M.R., Hill, R.S., Komatsu, E., Nolta, M.R., Odegard, N., Peiris, H.V., Verde, L., Weiland, J.L., "First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Preliminary Maps and Basic Results," ApJ Supp, 148, 1, 2003.
6. **Bennett, C.L.**, Hill, R.S., Hinshaw, G., Nolta, M.R., Odegard, N., Page, L., Spergel, D.N., Weiland, J.L., Wright, E.L., Halpern, M., Jarosik, N., Kogut, A., Limon, M., Meyer, S.S., Tucker, G.S., Wollack, E., "First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Foreground Emission," ApJ Supp, 148, 97, 2003.
7. Spergel, D.N., Verde, L., Peiris, V., Komatsu, E., Nolta, M.R., **Bennett, C.L.**, Halpern, M., Hinshaw, G., Jarosik, N., Kogut, A., Limon, M., Meyer, S.S., Page, L., Tucker, G.S., Weiland, J.L., Wollack, E., Wright, E.L., "First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Determination of Cosmological Parameters," ApJ Supp, 148, 175, 2003.

Curriculum Vitae for Julian Borrill

Contact Information

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email: jdborrill@lbl.gov
web: http;//crd.lbl.gov/borrill

Space Sciences Laboratory
University of California at Berkeley
Berkeley, CA 94720

Education

1984: MA in Maths & Political Science, Trinity College Cambridge
1990: MSc in Information Technology, Queen Mary College London
1990: MSc in Astrophysics, Queen Mary College London
1993: DPhil in Theoretical Physics, University of Sussex

Employment

1993 - 95: Postdoctoral Researcher, Theoretical Physics Group, Imperial College London
1995 - 97: Postdoctoral Researcher, Department of Physics & Astronomy, Dartmouth College
1997 - 99: Postdoctoral Researcher, NERSC Center, Berkeley Lab
1999 - 2010: Staff Scientist, Computational Research Division, Berkeley Lab
& Research Physicist, Space Sciences Laboratory, UC Berkeley
2010 - present: Senior Scientist, Computational Research Division, Berkeley Lab
& Senior Research Physicist, Space Sciences Laboratory, UC Berkeley

Awards

Berkeley Lab Outstanding Perfromance Award (2003)
NASA Public Service Award (2010, 2010, 2014)
NASA Group Achievement Award (2011, 2013)
NERSC Achievement Award for High Impact Science (2014)
NASA Exceptional Public Achievement Medal (2016)

Synergistic Activities

Chair, NASA 2006 Mission Operations & Data Analysis Senior Review
Member, NASA 2004 Mission Operations & Data Analysis Senior Review
Member, NASA Science Archive Working Group (2003 - 05)
Member, NASA Universe Working Group (2006 - 07)
Member, NASA Primordial Polarization Program Definition Team (2008 - 10)
Member, NERSC User Group Executive Committee (2008 - 2014)
Invited Participant, DOE ASCR/HEP Requirements Review (2009, 2012, 2015)
Reviewer, NASA AISR Program (2005, 2007)
Reviewer, NASA New Technology Refresh (2007)
Reviewer, DOE/NSF Dark Energy Survey (2007 - 2014)
Reviewer, NSF Laser Interferometer Gravitational Wave Observatory (2009, 2012)
Reviewer, NSF Blue Waters Graduate Student Fellowships (2014)
Reviewer, NSF KICP Site Visit (2014, 2016)
Reviewer, DOE INCITE Program (2014)
Reviewer, DOE NERSC-8 Design Review (2014)

Supervision

Computer systems engineers: R. Baird, C. Cantalupo, A. Collier, R. Keskitalo & T. Kisner
Postdoctoral researchers: J. Errard, S. Ricciardi, F. Stivoli, R. Stompor & R. Sudarsan
Summer Students: G. de Gasperis, L. Griffiths, M. Krumholz & J. Urrestilla

Brendan Crill — CV

Education:

Brown University, Physics, B.Sc. 1995 (magna cum laude; honors)
California Institute of Technology, Physics, Ph.D. 2001

Appointments:

2008 – present	Staff Scientist, Jet Propulsion Laboratory
2007 – 2008	Visiting Professor, Astronomy Department, U Toronto
2004 – 2007	Staff Scientist, Infrared Processing and Analysis Center, Caltech
2002 – 2004	Assistant Professor, Physics, California State University Dominguez HIlls

Awards:

2014 NASA exceptional service medal
2013 JPL Mariner award
2011 JPL Ranger award
2004 NASA Faculty Fellowship
1999 Everhart Lectureship, Caltech
1995 R. Bruce Lindsay Prize, Brown University
1991 National Scholarship, Brown University

Selected Publications:

1. "BICEP2 / Keck Array VI: Improved Constraints on Cosmology and Foregrounds from BICEP2 and Keck Array Cosmic Microwave Background Data with Inclusion of 95 GHz Band", Keck Array and BICEP2 Collaborations: P. A. R. Ade et al., Phys. Rev. Lett. 116, 031302 (2016). (astro-ph/1510.09217)
2. "A Joint Analysis of BICEP2/Keck Array and Planck Data", BICEP2/Keck and Planck Collaborations: P. A. R. Ade plus 250 alphabetical authors, Phys. Rev. Lett. 114, 101301 (2015). (astro-ph/1502.00612)
3. "*Planck* 2015 results: I. Overview of Planck Products and Scientific Results", Planck collaboration, A&Ap accepted (2015). (astro-ph/1502.01582)
4. "*Planck* 2013 results: I. Overview of Planck Products and Scientific Results", Planck collaboration, A&Ap 571, A1 (2014).
5. "BOOMERANG: A Balloon-borne Millimeter-Wave Telescope and Total Power Receiver for Mapping Anisotropy in the Cosmic Microwave Background", Crill, B. P. et al.
6. "MASTER of the Cosmic Microwave Background Anisotropy Power Spectrum: A Fast Method for Statistical Analysis of Large and Complex Cosmic Microwave Background Data Sets," Hivon, E. and Gorski, K. M. and Netterfield, C. B. and Crill, B. P. and Prunet, S. and Hansen, F., ApJ 567, 2 (2002)
7. "A flat Universe from high-resolution maps of the cosmic microwave background radiation," de Bernardis, P. et al. Nature 404, 955 (2000).

Biographical Sketch of Mark J. Devlin
June 2016

Department of Physics and Astronomy	Office: (215) 573-7521
University of Pennsylvania	Lab: (215) 573-7558
Philadelphia, Pennsylvania 19104	Fax: (215) 573-3826
http://www.devlinlab.info	email: devlin@physics.upenn.edu

Research Interests: Experimental Cosmology, Millimeter and Sub-millimeter Instrumentation

Professional Preparation:

1988	B.S.	Physics/Math	University of Wisconsin
1993	M.A.	Physics	University of California at Berkeley
1993	Ph.D.	Physics	University of California at Berkeley

Professional Appointments:

2006-	Reese W. Flower Professor of Astronomy and Astrophysics, University of Pennsylvania
2003-2006	Class of 1965 Term Chair, University of Pennsylvania
2000-2003	Associate Professor, University of Pennsylvania
1996-2000	Assistant Professor, University of Pennsylvania
1995-1996	Research Associate, Princeton University
1994-1995	Postdoctoral Researcher, Princeton University
1993-1994	Postdoctoral Researcher, University of California at Berkeley

Honors and Awards:

2015	University of Pennsylvania School of Arts and Sciences Ira H. Abrams Memorial Award for Distinguished Teaching
2015	University of Wisconsin Physics Department Distinguished Alumni Award
2011	American Physical Society Fellow
2010	University of Pennsylvania School of Arts and Sciences Dean's award for Undergraduate Research Mentoring
2008	Kavli Fellow, NAS
2000	Alfred P. Sloan Fellow
1998-2003	NSF Career Award

Experience:

2016 -	Spokesperson for the Simons Observatory
2005 -	PI of the MUSTANG project (90 GHz camera for the Green Bank Telescope)
2003 -	Co-I of the Atacama Cosmology Telescope (co-Director starting 2014)
2001 -	PI of the Balloon-borne Large Aperture Telescope - BLAST

Scott Dodelson

(a) Professional Preparation

Undergraduate: Columbia College and School of Engineering, Joint BA/BS Applied Physics 1983.
Graduate: Columbia University, Physics, PhD, 1988.
Postdoctoral: Harvard University, 1988–1991.
Postdoctoral: Fermi National Accelerator Laboratory, Theoretical Astrophysics, 1991–1994.

(b) Appointments

2011–present, Scientist III, Fermilab
2004–2011, Scientist II, Fermilab
2006–2008, Acting Director, Fermi Center for Particle Astrophysics
2004–2005, Visiting Professor, Northwestern University
2001–2006, Head, Theoretical Astrophysics Group, Fermilab
1999–2004, Scientist I, Fermilab
1994–1999, Associate Scientist, Fermilab
2004–present, Professor, Part Time, Department of Astronomy and Astrophysics, The University of Chicago
1999–2004, Associate Professor, Part Time, Department of Astronomy and Astrophysics, The University of Chicago

(c) Recent Relevant Publications (from 190 total)

1. A. Kovcs *et al.* [DES Collaboration], "Imprint of DES super-structures on the Cosmic Microwave Background," Submitted to: Mon.Not.Roy.Astron.Soc.

2. E. J. Baxter, R. Keiser, S. Dodelson, *et al.*, "A Measurement of Gravitational Lensing of the Cosmic Microwave Background by Galaxy Clusters Using Data from the South Pole Telescope," Astrophys. J. **806**, no. 2, 247 (2015).

3. J. Zuntz, M. Paterno, E. Jennings, D. Rudd, A. Manzotti, S. Dodelson, S. Bridle, S. Sehrish, and J. Kowalkowski, "CosmoSIS: Modular Cosmological Parameter Estimation ," **Astronomy and Computing** 12, 45 (2015).

(d) Relevant Service and Awards

2016-present: Co-Chair, Science Committee, Dark Energy Survey 2015-present: Chair, DOE Cosmic Visions: Dark Energy 2012-present: Co-convener, Computing and Infrastructure Working Group, LSST Dark Energy Science Collaboration
2011-16: Co-convener, Theory and Combined Probes Working Group, Dark Energy Survey

THESIS ADVISOR FOR:
Graduate: Kim Coble (1999), Ryan Scranton (2002), Eduardo Rozo (2006), Fabian Schmidt (2009), Melanie Simet (2012), Eric Baxter (2014), Youngsoo Park (2015), Alessandro Manzotti (current), Sam Passaglia (current). Total Number of Graduate Students Advised is 9.
Undergraduate: Sara Burtwell (2002), Matt Billmire (2003), Brian Klein (2007), Vikram Upadyay (2014), Nianyi Change (2015-present)

POSTDOCS ADVISED SINCE 2005:
Over my career, I have sponsored more than 35 postdoctoral scholars.

Raphael Flauger

EDUCATION

2009 Ph.D. (Physics) – The University of Texas at Austin.
Thesis Advisor: Steven Weinberg.
2003 M.Sc. (Theoretical Physics) – Imperial College London.
2002 M.A. (Physics) – The University of Texas at Austin.
2000 Vordiplom (Physics) – Universität Würzburg.

EMPLOYMENT

2016– Assistant Professor, University of California, San Diego.
2015–2016 Assistant Professor, The University of Texas at Austin.
2014–2015 Assistant Professor, Carnegie Mellon University.
2011–2014 Member, Institute for Advanced Study, Princeton.
2011–2014 Postdoctoral Fellow, New York University.
2009–2011 Postdoctoral Associate, Yale University.

HONORS AND AWARDS

2016 National Academy of Sciences Kavli Fellow.
2016 Recipient of New Horizons in Physics Prize.
2015– Alfred P. Sloan Foundation Research Fellow.
2014 James Arthur Fellow.
2011-2014 Supported by Raymond and Beverly Sackler Foundation.
2008 Graduate Fellow, Kavli Institute for Theoretical Physics.

SELECTED PUBLICATIONS

1. K. Clough, E. A. Lim, B. S. DiNunno, W. Fischler, R. Flauger and S. Paban.
   "Robustness of Inflation to Inhomogeneous Initial Conditions"
   arXiv:1608.04408 [hep-th]
2. R. Flauger, M. Mirbabayi, L. Senatore and E. Silverstein.
   "Productive Interactions: heavy particles and non-Gaussianity"
   arXiv:1606.00513 [hep-th]
3. D. N. Spergel, R. Flauger and R. Hložek.
   "Planck Data Reconsidered"
   Phys. Rev. D **91**, no. 2, 023518 (2015)
4. R. Flauger, J. C. Hill and D. N. Spergel.
   "Toward an Understanding of Foreground Emission in the BICEP2 Region"
   JCAP **1408**, 039 (2014)
5. R. Flauger, L. McAllister, E. Pajer, A. Westphal and G. Xu.
   "Oscillations in the CMB from Axion Monodromy Inflation"
   JCAP **1006**, 009 (2010)

CURRICULUM VITÆ

Krzysztof Marian Górski

Academic Degrees:	Professor of Physical Sciences		Poland	2003
	Doctor Habilitatus	Physics	Warsaw University	1997
	Ph.D.	Physics	Warsaw University	1987
	M.Sc.	Astronomy	Nicolaus Copernicus University	1980

Employment:

California Institute of Technology Jet Propulsion Laboratory, Pasadena, CA
Senior Research Scientist, January 2003—Present

European Southern Observatory, Garching bei München, Germany
Associate Astronomer, August 1999—December 2002

Teoretisk Astrofysik Center, Kobenhavn, Denmark
Associate Professor, June 1996—August 1999

NASA/Goddard Space Flight Center, Raytheon STX, Greenbelt, MD
Chief Scientist, August 1995—July 1996

NASA/Goddard Space Flight Center, Universities Space Research Association
Senior Research Scientist, February 1993—August 1995

Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto, Japan
Visiting Research Scholar, October 1992—January 1993

Institut d'Astrophysique de Paris, CNRS, Paris, France
Visiting Fellow—Poste Rouge, March 1992—October 1992

University of Chicago, Department of Astronomy and Astrophysics, Chicago, IL
Visiting Scholar, October 1991—February 1992

NASA/Goddard Space Flight Center, Universities Space Research Association
Consultant with the *COBE* Science Team, March 1991—January 1993

Princeton University, Department of Astrophysical Sciences, and
Institute for Advanced Study, School of Natural Science, Princeton, NJ
Visiting Research Fellow, March 1991—October 1991

Los Alamos National Laboratory, Theoretical Astrophysics, Los Alamos, NM
Director's Postdoctoral Fellow, February 1989—April 1991

University of California at Berkeley, Astronomy Department, Berkeley, CA
Postdoctoral Fellow, June 1986—February 1989

Copernicus Astronomical Center, Polish Academy of Sciences, Warsaw, Poland
Research Assistant, 1984—1986, Research Associate, 1986

Awards: 2012 NASA Exceptional Achievement Medal — Planck

Selected Publications:

Planck 2016 intermediate results. XLVI. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth, Planck Collaboration 2016, *A&A*, accepted

Planck 2015 results. I. Overview of products and scientific results, Planck Collaboration 2016, *A&A*, **594**, A1

Planck 2015 results. XVI. Isotropy and statistics of the CMB, Planck Collaboration 2016, *A&A*, **594**, A16

Planck 2013 results. I. Overview of products and scientific results, Planck Collaboration 2014, *A&A*, **571**, A1

Planck 2013 results. XXXI. Consistency of the Planck data, Planck Collaboration 2014, *A&A*, **571**, A31

MASTER of the Cosmic Microwave Background Anisotropy Power Spectrum: A Fast Method for Statistical Analysis of Large and Complex CMB Data Sets, Hivon, E., Górski, K.M., et al., 2002, *ApJ*, **567**, p.2

HEALPix: A Framework for High-Resolution Discretization and Fast Analysis of Data Distributed on the Sphere, Górski, K.M., et al., 2005, *ApJ*, **622**, p.759

Power Spectrum of Primordial Inhomogeneity Determined from the Four-Year COBE DMR Sky Maps
Górski, K.M., et al., 1996, *ApJ*, **464**, p.L11

William C. Jones

Email: wcjones@princeton.edu **Phone:** 609.258.4413

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Department of Physics
Joseph Henry Laboratories
222 Jadwin Hall
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Princeton, New Jersey 08544-0708

Education and Honors

David and Lucile Packard Fellowship	2010
Alfred P. Sloan Research Fellowship	2009
Ph.D., Physics, June 2005	California Institute of Technology
– *Milton and Francis Clauser Doctoral Thesis Prize*	June 2005
– *Kingsley Foundation Fellowship*	July 2000
– *NASA Graduate Student Research Fellowship*	2000 – 2003
B.A., Physics, *magna cum laude*, June 1998	Princeton University
– *Certificate in Applied and Computational Mathematics*	June 1998
– *Allen G. Shenstone Prize for Experimental Physics*	June 1998
– *Sigma Xi*	June 1998
– *National Merit Scholarship*	1994 – 1998

Employment

- Associate Professor of Physics, Princeton University — July 2016 – present
- Assistant Professor of Physics, Princeton University — September 2008 – 2016
- Scientist – *Director's Fellow*, Jet Propulsion Laboratory — August 2006 – August 2008
- Adjunct Assistant Professor of Physics, Harvey Mudd College — July 2006 – January 2007
- Postdoctoral Scholar, Dept. of Physics, Caltech — April 2005 – August 2006
- Resident Associate, Avery House, Caltech — June 2002 – June 2008
- Research Assistant, Caltech — September 1998 – April 2005
- Teaching Assistant, Caltech — January 1999 – June 2000

Primary Research

My research is focused on the measurement of anisotropies in the temperature and polarization of the Cosmic Microwave Background Radiation (CMB), with an emphasis on large scale polarization as an observational probe of models of the early Universe. Our group is currently leading the analysis of the Spider 2015 dataset. Recent advances in mid-latitude scientific ballooning open the door for opportunities in the near-UV and visible wavelengths. My group is presently exploring the cosmological potential of persistent, sub-arcsecond imaging of galaxy clusters and quasars. Together with our collaborators we flew SuperBIT on a test flight in 2016. I am the PI of Spider, the PI of SuperBIT, a *Planck* Scientist and member of the HFI Core Team.

October 27, 2016

LLOYD E. KNOX

PROFESSIONAL PREPARATION

University of Chicago, Ph.D. 1995 (Physics)
University of Virgina, B.S. summa cum laude, 1990 (Physics)

APPOINTMENTS

2006– Professor of Physics, University of California at Davis
2002–2006 Associate Professor of Physics, University of California at Davis
2000–2002 Assistant Professor of Physics, University of California at Davis
1998–2000 Edwin P. Hubble Scientist, U. Chicago
1995–1998 Junior Research Associate, Canadian Institute for Theoretical Astrophysics
1995–1995 Research Associate, U. Chicago

SELECTED PUBLICATIONS

1. B. Follin, L. Knox, M. Millea & Z. Pan,"First Detection of the Acoustic Oscillation Phase Shift Expected from the Cosmic Neutrino Background", *Phys. Rev. Lett.* **115**, 091301 (2015).
2. Planck Collaboration, "Planck 2015 results. XIII. Cosmological parameters", *Astronomy & Astrophysics* **594**, 13 (2016).
3. Hou et al., "Constraints on Cosmology from the Cosmic Microwave Background Power Spectrum of the 2500 deg^2 SPT-SZ Survey", *Astrophys. J.* **782**, 74 (2014).
4. Z. Hou, R. Keisler, L. Knox, M. Millea & C. Reichardt,"How Massless Neutrinos Affect the Cosmic Microwave Background Damping Tail", (2013) Phys. Rev. D **87**, 083008 (2013).
5. M. Millea, O. Doré, J. Dudley, G. Holder, L. Knox, L. Shaw, Y.-S. Song, O. Zahn, "Modeling Extragalactic Foregrounds and Secondaries for Unbiased Estimation of Cosmological Parameters From Primary CMB Anisotropy", *Astrophys. J.* **746**, 4 (2012).
6. L. Knox & Y.S. Song, "Limit on the Detectability of the Energy Scale of Inflation", *Phys Rev. Lett.* **89**, 11303 (2002).
7. Z. Hou, R. Keisler, L. Knox, M. Millea & C. Reichardt,"How Massless Neutrinos Affect the Cosmic Microwave Background Damping Tail", *Phys. Rev. D* **87**, 083008 (2013).
8. A. Albrecht et al., "Report of the Dark Energy Task Force", arXiv:astro-ph/0609591 (2006).

PERFORMANCE ON RELEVANT PRIOR RESEARCH PROJECTS: Lloyd Knox is a fellow of the American Physical Society elected in 2013 with the citation, "For motivating major observations (WMAP and Planck), developing widely-using data analysis tools, providing insightful interpretations of data, and calculating the impact of astrophysical processes on the microwave sky. He currently leads the US Planck team estimating cosmological parameters, and works with the South Pole Telescope team measuring signals he predicted over the past 15 years." He had lead responsibility for the Inflation chapter of the recently completed CMB-S4 Science Book and is currently coordinating the data analysis challenges in support of further development of the S4 concept.

Alan Kogut
NASA Goddard Space Flight Center **Co-Investigator**

Eucation

1989	Ph.D., Physics	University of California at Berkeley
1983	A.B., Physics	Princeton University

Professional History

Dr. Kogut joined NASA Goddard Space Flight Center in 1989 as a member of the Cosmic Background Explorer (COBE) team. Since joining NASA Goddard Space Flight Center he has amassed over 25 years of experience building precision instruments to measure the CMB spectrum, anisotropy, and polarization from ground-based, balloon-borne, and satellite platforms, including COBE-DMR, WMAP, ARCADE, and PIPER. He is Principal Investigator of the ARCADE balloon project to measure the CMB spectrum, the PIPER balloon instrument to measure CMB polarization, and the PIXIE mission concept.

Selected Professional Positions and Experience

1998 -- Present	Astrophysicist, NASA Goddard Space Flight Center
1993 -- 1998	Chief Scientist, Hughes STX
1991 -- 1993	Research Scientist, Universities Space Research Association
1989 -- 1991	Research Associate, National Research Council

Selected Publications

"Foreground Bias From Parametric Models of Far-IR Dust Emission", A. Kogut and D.J. Fixsen, The Astrophysical Journal, 826, 101 (2016)

"Spectral Confusion for Cosmological Surveys of Redshifted CII Emission ", A. Kogut, E. Dwek, and S.H. Moseley, The Astrophysical Journal, 806, 234 (2015)

"Systematic Effects in Polarizing Fourier Transform Spectrometers for Cosmic Microwave Background Observations", P.C. Nagler, D.J. Fixsen, A. Kogut, and G.S. Tucker, The Astrophysical Journal Supplement Series, 221, 21 (2015)

"Polarization Properties of A Multi-Moded Concentrator", A. Kogut, D.J. Fixsen, and Robert S. Hill, Journal of the Optical Society of America A, 32, 1040 (2015)

"Synchrotron Spectral Curvature from 22 MHz to 23 GHz", A. Kogut, The Astrophysical Journal,753, 110 (2012)

"The Primordial Inflation Explorer (PIXIE): A Nulling Polarimeter for Cosmic Microwave Background Observations", 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, Journal of Cosmology and Astrophysics, 7, 025 (2011)

"ARCADE 2 Observations of Galactic Radio Emission", A. Kogut, D. J. Fixsen, S. M. Levin, M. Limon, P. M. Lubin, P. Mirel, M. Seiffert, J. Singal, T. Villela, E. Wollack, and C. A. Wuensche, The Astrophysical Journal, 734, 4 (2011)

"Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Foreground Polarization", A. Kogut, J. Dunkley, C. L. Bennett, O. Dore, B. Gold, M. Halpern, G. Hinshaw, N. Jarosik, E. Komatsu, M. R. Nolta, N. Odegard, L. Page, D. N. Spergel, G. S. Tucker, J. L. Weiland, E. Wollack, and E. L. Wright, The Astrophysical Journal, 665, 355 (2007)

CHARLES R. LAWRENCE

EDUCATION

1983	Ph. D. in Physics, Massachusetts Institute of Technology.
1970	B. S. with Distinction, Honors in Physics, University of Michigan, Ann Arbor.

EMPLOYMENT

2013–	Fellow, JPL
2012–	Senior Research Scientist, JPL
2000–	Principal Scientist, Astrophysics, JPL
1993–2000	Research Scientist, Astrophysics, JPL
1993–1994	Visiting Associate, California Institute of Technology
1991–1993	Senior Research Associate, California Institute of Technology
1986–1991	Senior Research Fellow, California Institute of Technology
1983–1986	Research Fellow, California Institute of Technology
1970–1977	Physics Teacher, Baltimore County Public Schools, MD

PROFESSIONAL ACTIVITIES

2014–	Chief Scientist, Astronomy, Physics, and Space Technology Directorate, JPL
2010–	Co-Chair, Planck Editorial Board
1998–	Deputy Project Scientist for SIRTF/Spitzer
1998–	Survey Scientist for Low Frequency Instrument on Planck; member of Planck Science Team
1997–	Project Scientist, US Planck Project, and PI, US Low Frequency Instrument team

AWARDS

2014	NASA Exceptional Achievement Medal — Planck
2010	NASA Outstanding Leadership Medal — Planck
2004	NASA Outstanding Leadership Medal — Spitzer
1999	NASA Exceptional Achievement Medal — Cryogenic HEMT Optimization Program

SELECTED PUBLICATIONS

Planck intermediate results. XLVI. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth, Planck Collaboration 2016, *A&A*, accepted

Planck 2015 results. I. Overview of products and scientific results, Planck Collaboration 2016, *A&A*, **594**, A1

Planck 2013 results. XXXI. Consistency of the Planck data, Planck Collaboration 2014, *A&A*, **571**, 31

Planck 2013 results. I. Overview of products and scientific results, Planck Collaboration 2014, *A&A*, **571**, 1

Planck early results. II. The thermal performance of Planck, Planck Collaboration 2011, *A&A*, **536**, A2

Planck Pre-Launch Status: Design and Description of the Low Frequency Instrument, M. Bersanelli et al. 2010, *A&A*, **520**, A4

The Infrared Spectrograph on the Spitzer Space Telescope, J. R. Houck et al. 2004, *Ap. J. Suppl.*, **154**, 18

The Spitzer Space Telescope Mission, M. W. Werner et al. 2004, *Ap. J. Suppl.*, **154**, 1

Separation of Foreground Radiation from Cosmic Microwave Background Anisotropy Using Multifrequency Measurements, W. N. Brandt, C. R. Lawrence, A. C. S. Readhead, J. Pakianathan, and T. Fiola 1994, *Ap. J.*, **424**, 1.

Jeffrey J. McMahon

The University of Michigan	Office: (734) 615-2553
450 Church Street	Fax: (734) 936-1817
Ann Arbor, Michigan 48109	email: jeffmcm@umich.edu

Primary Research Interests: Cosmology, CMB Instrumentation, Metamaterial Optical Elements, Millimeter Wave Polarization Sensitive Detectors

Professional Preparation:

2006	Ph.D.	Physics	Princeton University	
1999	B.A.	Physics	U. C. Berkeley	High Honors
1999	B.A.	Applied Math	U. C. Berkeley	High Honors

Professional Appointments:

2015—	Associate Professor, The University of Michigan department of Physics
2009-2015	Assistant Professor, The University of Michigan department of Physics
2006-2009	Enrico Fermi *and* KICP postdoctoral fellow, University of Chicago
1999-2000	Assistant Engineer, C. H.Townes group, Space Sciences Lab, UC Berkeley

Professional Honors:

2006	Enrico Fermi Postdoctoral Fellowship, University of Chicago
2006	KICP Postdoctoral Fellowship, University of Chicago
2001	Joseph Henry Prize, Princeton University

Relevant Expertise: McMahon is an expert in millimeter wave detectors and optical systems. McMahon is lead the development of horn coupled multichroic detectors for measurement of the cosmic microwave background. We successfully deployed the first two multichroic polarimeter arrays on a CMB instrument (ACTPOL). These dicrhoic arrays are sensitive to the 90/150 and 150/230 GHz CMB bands and pave the way for widespread use of this technology. McMahon also led the effort to develop antireflection coated silicon lenses for the ACTPol project including the design and fabrication of the Michigan metamaterial AR coating machine. Using this machine our group produced 3:1 bandwidth metamaterial AR coated lenses which are now fielded on the ACTPol experiment and prototypes at frequencies up to 1 THz. McMahoh has 16 years of experience developing and fielding CMB instruments and in his current rols as the technical chair on the Simons Observatory is at the forefront of CMB technology.

Selected Publications:

1. "Design and Deployment of a Multichroic Polarimeter Array on the Atacama Cosmology Telescope",R. Datta et al, Journal of Low Temperature Physics (2015)
2. "Large-aperture wide-bandwidth anti-reflection-coated silicon lenses for millimeter wavelengths",R. Datta (my student) et al, (Submitted) Applied Optics. 2013
3. "The Atacama Cosmology Telescope: CMB Polarization at $200 < \ell < 9000$",S. Naess et al, Astrophysics Journal (2014)

LYMAN ALEXANDER PAGE JR, November, 2016

Department of Physics, Princeton University
Princeton, New Jersey 08544-0708
Phone: (609) 258-5578, Email: Page@Princeton.edu

Education

Massachusetts Institute of Technology, Cambridge, MA	Ph.D. 1989 (Physics)
Thesis Advisor: Stephan S. Meyer	
Bowdoin College, Brunswick, ME	B.A. 1978 (Physics)

Employment and Research History

James S. McDonnell Distinguished University of Physics at Princeton	July 2015 - Present
Professor of Physics at Princeton	July 1998 - Present
Associate Professor of Physics at Princeton	July 1995 - June 1998
Assistant Professor of Physics at Princeton	July 1991 - June 1995
Instructor of Physics at Princeton	July 1990 - July 1991
Postdoctoral Research Fellow at MIT	October 1989 - July 1990
Graduate Student at MIT	September 1983 - September 1989
Self employed as a painter, rigger, & carpenter	February 1980 - September 1983
Research Technician, Bartol Research Foundation, Newark, DE, McMurdo Antarctica, and South Pole, Antarctica.	September 1978 - January 1980

Page's primary research is on measurements of the cosmic microwave background (CMB) from ground-based, balloon-borne, and satellite platforms with HEMT amplifiers, SIS mixers, and bolometers. Page is one of the original co-investigators on the *WMAP* satellite and the founding director of the ACT project.

Honors and Awards

Gruber Prize	August 2015
APS Fellow	December 2013
Gruber Prize with WMAP team	August 2012
Kavli AAS Lecture	January 2012
Shaw Prize	September 2010
Phi Beta Kappa teaching award and induction	June 2010
Welch Lectures	April 2010
Chandrasekhar Lectures (ICTS)	April 2010
Member of the National Academy of Sciences	2006
Philips Lectureship	2006
Fellow of the American Academy of Arts & Sciences	2004
Marc Aaronson Lectureship & Prize	November 2003
Primakoff Lectureship	March 2003
David and Lucile Packard Fellowship	September 1994
Princeton Engineering Council Teaching Award	May 1994 & 1992
Research Corporation Cottrell Scholar	May 1994
National Science Foundation NYI Award	August 1993
NASA Graduate Student Researchers Program Fellowship	1987-1989

Biographical Sketch — Clem Pryke

Professional Preparation:

University of Leeds (UK), Physics, B.Sc. 1992 (First Class Honours)
University of Leeds (UK), Physics, Ph.D. 1996
University of Chicago, McCormick Postdoctoral Fellow, 1996-9

Appointments:

10/15 – 5/16	Visiting Scholar, Harvard/CfA
7/10 – present	Associate Professor, Physics, U. Minnesota
6/02 – 6/10	Assistant Professor, Astronomy and Astrophysics, U. Chicago
1/01 – 6/02	Senior Research Associate, Astronomy and Astrophysics, U. Chicago
4/99 – 1/01	Research Scientist, Enrico Fermi Institute, U. Chicago

Most Related Recent Publications:

1. "BICEP2 / Keck Array VI: Improved Constraints on Cosmology and Foregrounds from BICEP2 and Keck Array Cosmic Microwave Background Data with Inclusion of 95 GHz Band", Keck Array and BICEP2 Collaborations: P. A. R. Ade plus 59 alphabetical authors, Phys. Rev. Lett. 116, 031302 (2016). (astro-ph/1510.09217)

2. "A Joint Analysis of BICEP2/Keck Array and Planck Data", BICEP2/Keck and Planck Collaborations: P. A. R. Ade plus 250 alphabetical authors, Phys. Rev. Lett. 114, 101301 (2015). (astro-ph/1502.00612)

3. "BICEP2 III: Instrumental Systematics", BICEP2 Collaboration: P. A. R. Ade plus 43 alphabetical authors, ApJ, 814, 110 (2015)

4. "BICEP2 II: Experiment and Three-Year Data Set", BICEP2 Collaboration: P. A. R Ade plus 50 alphabetical authors, ApJ, 792, 62 (2014)

5. "BICEP2 I: Detection Of B-mode Polarization at Degree Angular Scales", BICEP2 Collaboration: P. A. R Ade plus 46 alphabetical authors, Phys. Rev. Lett. 112, 241101 (2014). (astro-ph/1403.3985)

Most Related Experience:

Extensive experience of CMB polarization data analysis. Lead analysis of QUaD experiment data. Lead analysis team of BICEP2/Keck experiments. co-PI on multi NSF grants for these experiments.

Synergistic Activities:

- Organized two major community wide workshops on CMB (Chicago 2009 and Minneapolis 2015).
- Designed new graduate level class on practical data analysis integrating real research data.
- Proposal and paper reviews.
- Outreach activities including major public lectures and TV/radio appearances.

Curriculum Vitae — Graça Rocha

Name: **Graça Maria Moreira de Sousa Teixeira da Rocha.**

Education

1997	PhD in Physics, University of Cambridge, UK.
1992	MSc in Mathematics, QMW, University of London, UK.
1991	Licenciatura in Physics and Applied Mathematics, Astronomy, University of Porto, Portugal.
1987	Licenciatura in Mathematics, branch of Pure Mathematics, University of Porto, Portugal.

Employment

2009 –	Staff Research Scientist at JPL
2011 – 2012	Group Supervisor of the 'Evolution of Galaxies' group at JPL
2006 – 2009	Staff Scientist at IPAC, Caltech
2006 –	Visitor at Caltech, Physics, Math & Astronomy Department, Observational Cosmology group
2001 – 2005	Leverhulme Postdoctoral Fellow at the University of Cambridge, UK
2004 – 2005	Lecturer of a graduate course on 'Theoretical Cosmology' at the University of Cambridge
2005	Postdoctoral Scholar in Physics, Observational Cosmology Group, Caltech
2000 – 2001	Visitor at the University of Oxford
2001 –	Collaborator at CAUP, Portugal, & Academic Visitor at the University of Oxford
1998 – 2001	Postdoctoral Fellow at CAUP, & Invited Lecturer at the University of Porto
1997	Postdoctoral Fellow in the Department of Physics, KSA, USA

Recent Honors and Awards: NASA and JPL Awards

2014 –	NASA Exceptional Achievement Medal for the work on Planck Data Analysis
2011 –	NASA Group Achievement Award: Early Release Compact Source Catalogue Team
2011 –	NASA Group Achievement Award: Planck Data Analysis and Operations Support Team
2011 –	NASA Group Achievement Award: Herschel & Planck Projects Teams
2009 –	NASA Group Achievement Award: BICEP Experiment Team
2009 –	NASA Group Achievement Award: Planck Data Analysis Pipeline Development Team
2009 –	NASA Group Achievement Award: Planck Data Analysis Team
2013 –	JPL Mariner Award - Award for leading a team to calculate cosmological parameters from CMB
2012 –	JPL Mariner Award - Award for essential contributions to the Planck data analysis
2011 –	JPL Team Bonus Award: Planck Effective Beamshape Team
2010 –	Certificate of Recognition for 5 years of service to JPL

Areas of Expertise: My Area of expertise is Cosmology, more specifically constraining models of structure formation and fundamental physics with the study of the Cosmic Microwave Background Radiation, CMB. I am member of the ESA-NASA Planck mission, as Planck Scientist and as member of both the LFI and HFI instruments. I coordinated several Planck working groups: the 'Compact Source Investigation', CSI, collaboration; the 'Power Spectrum and Likelihood' WG at JPL; the 'Fundamental Physics' WG (I am the corresponding author of the resulting Planck Intermediate Paper). I was the spokesperson for Planck team at the Planck plenary session at ESLAB, Nordwijk, Netherlands in April 2013.

Selected Publications

Planck 2015 results. XVI. Cosmological parameters, Planck Collaboration 2016, A&A 594, A13
Planck 2015 results. IX. Diffuse component separation: CMB maps, Planck Collaboration 2016, A&A 594, A9
Planck 2015 results. XI. CMB power spectra, likelihoods, and robustness of parameters, Planck Collaboration 2016, A&A 594, A11
Planck intermediate results. XXIV. Constraints on variations in fundamental constants, Planck Collaboration 2016, A&A 580, A22.
PowellSnakes II: a fast Bayesian approach to discrete object detection in multi-frequency astronomical data sets, Carvalho, P., Rocha, G., Hobson, M. P., Lasenby, A. 2012, MNRAS 427, 1384-1400.
Fast Pixel Space Convolution for Cosmic Microwave Background Surveys with Asymmetric Beams and Complex Scan Strategies: FEBeCoP', Mitra, S.; Rocha, G.; Gorski, K. M.; Huffenberger, K. M.; Eriksen, H. K.; Ashdown, M. A. J.; Lawrence, C. R. 2011, ApJS 193 5M.
Measuring α in the early Universe: cosmic microwave background polarization, re-ionization and the Fisher matrix analysis, Rocha, G.; Trotta, R.; Martins, C. J. A. P.; Melchiorri, A.; Avelino, P. P.; Bean, R.; Viana, P. T. P. 2004, MNRAS 352, 20R.
Constraints on cosmological parameters from recent measurements of cosmic microwave background anisotropy, Hancock, S., Rocha, G., Lasenby, A. N., Gutierrez, C. M. 1998, MNRAS 294, L1-L6.

3 Summary of Work Effort

Personnel	Budgeted Effort per Year	
	Year 1	Year 2
Shaul Hanany, PI	0.08*	0.08*
Charles Bennett, Co-I	0.03	0.02
Julian Borrill, Co-I	0.08	0.04
Brendan Crill, Co-I	0.08	0.04
Mark Devlin, Co-I	0.02	0.01
Scott Dodelson, Co-I	0.02	0.01
Raphael Flauger, Co-I	0.08	0.04
Krzysztof Gorski, Co-I	0.08	0.04
William Jones, Co-I	0.08	0.04
Lloyd Knox, Co-I	0.04* / 0.04	0.04
Al Kogut, Co-I	0.08	0.04
Charles Lawrence, Co-I	0.08	0.04
Jeff McMahon, Co-I	0.08	0.04
Lyman Page, Co-I	0.04	0.02
Clem Pryke, Co-I	0.04	0.02
Graca Rocha, Co-I	0.12	0.06
*Funded by NASA		

Table 1: Personnel, their role, and work effort in fractions of a year on the project. All entries are not funded by NASA unless otherwise indicated.

Current and Pending Support

Investigator: Shaul Hanany

Pending:

Project/Proposal Title: EBEX-IDS: A Balloon-Borne Experiment to Observe and Separate Galactic Dust from Cosmic Inflation Signals (selected but not awarded yet)
P.I: Shaul Hanany
Program Name: NASA APRA, POC: Michael Garcia, Michael.r.garcia@nasa.gov
Period of Performance: 01/01/2017-12/31/2017
Person-Months Per Year Committed to the Project. Acad: 0.00 Sumr: 1.00

Project/Proposal Title: Broad-Band Anti-Reflection Coatings for Millimeter-Wave Astrophysics
P.I. Shaul Hanany
Program Name: NSF ATI
Period of Performance: 07/01/2017-06/30/2020
Person-Months Per Year Committed to the Project. Acad: 0.00 Sumr: 1.00

Current:

Project/Proposal Title: Search for Signals of Inflation with the EBEX Balloon-Borne Instrument
P.I. Shaul Hanany,
Program Name: NASA APRA NNX13AE49G, POC: Kartik Sheth, kartik.sheth@nasa.gov
Period of Performance: 01/11/2013-01/10/2017
Person-Months Per Year Committed to the Project. Acad: 0.00 Sumr: 0.50

5 Budget Justification

5.1 General

The majority of funding is allocated to these categories of expenses: summer salary, primarily for the PI who will coordinate the entire effort; travel of team members to JPL to participate in mission design sessions; the community workshop that will discuss the complementarity between a future space mission and sub-orbital efforts.

5.2 Funded Team Members

The PI Shaul Hanany requests 4 weeks of summer salary in year 1 and 3 weeks in year 2. We are also requesting 2 weeks of summer salary to support Knox, the CoI organizing the theory effort.

Support for an administrative assistant is required due to the demand on regular staff that usually accompanies putting on a workshop. This effort is above their normal departmental duties. The assistant will help organize the workshop and develop a website, process registrations, secure accommodations and make other travel arrangements for workshop attendees, work outside their regular work hours attending the meeting and troubleshooting, and will have to process numerous reimbursements. The assistant will also assist with the community organization tasks during the rest of the year.

5.3 Travel

Travel funds are requested for the PI and four others to go to Pasadena, CA to collaborate with JPLs Advanced Projects Design Team (Team X). There will be 2 trips in each budget period. One longer trip of 3 days/2nights and one shorter one of 2 days/1 night. Both trips are based on airfare of $500, lodging of $150/night, and meals of $64/day with 75% on the first and last day and about $250 for ground transportation and other incidentals. This comes to $11,000 per budget period (5 person-trips at $1,200 + 5 person-trips at $1,000).

Also included, is travel for the PI to the AAS 2018 Conference in Budget Period 2, which per the NRA, is where a presentation of findings will be most likely be made. The cost of this trip is $1,700 and is based on airfare to Washington, DC of $500, $226/night hotel x 3, $69/day for meals using 75% for the first and last day), and then $217 for ground transportation and incidentals.

All travel is based on the published GSA rates at the time of this proposal.

5.4 Workshop

A research collaboration workshop will be held in Budget Period 1, most likely in the summer of 2017. It will be attended by approximately 150 people, both domestic and foreign. The cost of $30,000 is based on partial travel support and local lodging for about 25 attendees at $1,000 per person = $25,000. In addition, there will be venue rental costs and provisions for the meetings; breakfast foods, afternoon snacks and beverages for coffee breaks ($5,000).

5.5 Publications

We are planning to publish the results of our study. Page charges of $1,100 are included in both budget periods. A likely journal is the Astrophysics Journal. Page charges are based on publishing a a 10-page article each year. The current rate is $110 for an electronic submission.

5.6 Communication Costs:

This project will required several weekly telecons. The cost budgeted is based on a monthly cost of about $65 based on experience with other projects.