A Program of Technology Development and of Sub-Orbital Observations of the Cosmic Microwave Background Polarization Leading to and Including a Satellite Mission

A Report for the Astro2010 Decadal Committee on Astrophysics

The CMBPol Mission Concept Study Group[1] [2]
The Primordial Polarization Program Definition Team[3]

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Executive Summary

Inflation For the first time, cosmologists are poised to observe a physical process at the energy scale of Grand Unification. Shortly after the Big Bang, the Universe likely experienced a burst of inflation which produced a stochastic background of gravitational waves. The amplitude of this background depends on, and hence probes, the energy scale of inflation. During recombination, the gravitational wave background imprints a distinctive ”curl” pattern in the polarization of the cosmic microwave background (CMB). If inflation occurred at the GUT scale, this pattern would be detectable by CMB experiments we could field in the coming decade, providing a probe of physics unattainable by any other means. A detailed map of CMB polarization would also substantially improve our knowledge of neutrino masses, constrain the dark energy density at high redshift, elucidate the nature of structure formation, provide an excellent probe of reionization, and perhaps yield unanticipated discoveries that could revolutionize our understanding of the Universe.

The Next Decade In the coming decade, CMB polarization experiments will constrain the energy scale of inflation to a degree that was hard to imagine only a few years ago. The *Planck* satellite, which is primarily a temperature anisotropy mission, will launch soon; and a new suite of ground-based and balloon-borne experiments will target CMB polarization with ever increasing sensitivity and immunity to systematic errors. It is possible that these experiments will find evidence for gravitational waves from inflation. But ultimately, the community is convinced that a new space mission will be needed to measure CMB polarization with a reliability that is commensurate with the scientific impact of a gravitational wave detection. Specifically, a CMB polarization satellite would enable: access to the full sky from a single stable platform; observing strategies that can suppress many systematic error sources; access to frequency bands that enhance foreground signal rejection; and higher sensitivity per unit time due to a colder telescope and the lack of atmosphere. A candidate mission that could reach the natural limits imposed by foregrounds is described in this report.

The Plan The CMB community has worked together for the past 2.5 years to assess the current state of the field, and to develop a plan for detecting inflationary gravitational waves. The plan leads to a space mission that would optimally begin in 2015 and cost $800M. It has the following intermediate elements:

- Continue the vigorous program of suborbital experiments
- Support research in theory and data analysis techniques
- Enable the development of needed technology
- Establish a project office to support the development of a new space mission.

The funding required to support the first three items above is $25M/year, comparable to the current level of funding. This amount would: sustain a suborbital program that could lead to the first detection of gravitational waves; continue critical investments in technologies that are central to new experiments; support fundamental research; and enable the development of new foreground and systematic error rejection methods. We also advocate the formation of a project office early in the decade to develop the maturity of the mission concept and to oversee the evolution of technology that is specific to a space mission.

A Introduction

This report is the result of a 2.5-year effort by the entire CMB community. In 2007, the Primordial Polarization Program Definition Team (PPPDT)[4] organized a unified response to NASA’s call for

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[4] This kind of box indicates an active link to on-line reference material.

Astrophysics Strategic Mission Concept Studies. The CMBPol Mission Concept Study team, together with the PPPDT and with broad input from the community, devised the plan we lay out in this document. The plan builds upon the conclusions of the 2005 Task Force on Cosmic Microwave Background Research report (Bock et al., 2006)[5].

The key elements of the community plan are:

Continue the vigorous program of suborbital experiments. Current experiments are on a path towards obtaining strong constraints on inflationary models. They inform models of galactic foreground emission and test the experimental and data analysis techniques, the detector technologies, and the systematic mitigation strategies for a future space mission.

Support research in theory and data analysis techniques. Theoretical advances proceed in lock-step with experimental research in cosmology. As experiments approach the sensitivity to constrain inflation models, it is essential to improve our ability to handle foregrounds and to simulate sources of systematic errors. New experiments are expected to routinely generate many terabytes of data. We must continue to improve our data analysis techniques to keep up with the expected increase in data volume, and develop new numerical and computational methods for these large data sets

Enable the development of needed technology. Spectacular advances in detector and associated technologies now enable experiments with thousands of detectors. As these technologies have grown in complexity and cost, it is clear that a collective method for supporting facilities for technology development is needed.

Establish a project office to support the development of a new space mission. An astrophysically limited CMB B-mode measurement will require a space-based platform. As sub-orbital experiments approach inflation constraining sensitivity, the scientific motivation for such a mission will grow. The planning for a space mission should begin now so that we are in a position to make further advances into understanding inflation.

The CMBPol Mission Concept Study team extended the *EPIC* mission concept work that began four years ago as part of NASA's "beyond Einstein" program (Bock et al., 2008). The new design is summarized in the Space Mission section of this paper (Section E), and more fully in a CMBPol Strategic Mission Concept Study Report that will be completed in late April 2009.

B Science

B.1 Inflation

The leading theoretical paradigm for the initial moments of the Big Bang is *Inflation*, a period of rapid accelerated expansion (Guth, 1981; Linde, 1982; Albrecht and Steinhardt, 1982; Starobinsky, 1980). Inflation sets the initial conditions for conventional Big Bang cosmology by driving the universe towards a homogeneous and spatially flat configuration. At the same time, quantum fluctuations in both matter fields and spacetime produce minute inhomogeneities which grow to form not only the CMB anisotropy, but also galaxies and clusters of galaxies (Mukhanov and Chibisov, 1981; Hawking, 1982; Starobinsky, 1982; Guth and Pi, 1985; Bardeen et al., 1983; Mukhanov, 1985; Starobinsky, 1979). Understanding the physical origin of the inflationary era remains one of the major problems in theoretical physics. Baumann et al. (2008b) have summarized inflation science in a CMBPol white paper.

B.1.a Physics of Inflation

In General Relativity gravity can act as a repulsive force if the universe is dominated by an energy density that varies only slowly with time. Models of inflation exploit this fact to provide early

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[5] This is the link to all bibliographic citations throughout this report.

acceleration of the universe. Phenomenological models often invoke a single scalar field ϕ, the *inflaton* field, as an order parameter to describe the time-evolution of the inflationary potential $V(\phi)$. The term slow-roll inflation then describes the evolution in a flat region of the potential when the kinetic energy of the field is small. Inflation ends when a significant fraction of the inflationary potential energy gets converted into kinetic energy. Subsequently, this energy gets transferred into Standard Model particles during reheating. In addition to this single-field slow-roll paradigm, theorists have proposed a variety of other inflationary mechanisms involving more than one field and/or non-trivial kinetic terms. An important objective for future observations is to distinguish between those distinct possibilities for the physics of inflation.

B.1.b Cosmological Perturbations from Inflation

During inflation, quantum fluctuations were stretched to astronomical sizes. These fluctuations are the source for primordial density perturbations that are the seeds for all structures in the universe. Inflation predicts a nearly *scale-invariant* spectrum of perturbations. Deviation from perfect scale-invariance is an important inflationary observable, which reveals details of the inflationary dynamics, for example, the shape of the potential $V(\phi)$ for slow-roll inflation.

In single-field slow-roll models, the inflaton is very weakly coupled and hence acts like a nearly free field; the fluctuations created are therefore almost precisely *Gaussian*. In addition, for a single fluctuating degree of freedom during inflation, fluctuations in different particle species are correlated and then called *adiabatic*.

The fluctuations in the inflaton field and the resulting CMB temperature fluctuations are categorized as *scalar* fluctuations, due to how they transform. In addition, inflation produces *tensor* perturbations, fluctuations in the spacetime metric, which are gravitational waves. These gravitational waves lead to a unique signature in the CMB polarization. Since polarization is described at every position by an amplitude and an angle of orientation, the polarization field on the sky can be decomposed into two modes, a curl-free E-mode and a divergence-less B-mode. Crucially, *the B-mode pattern cannot be produced by scalar perturbations.* The primordial B-mode signal is proportional to the amplitude of the gravitational waves. It is typically expressed as normalized by the known amplitude of scalar fluctuations $r \equiv P_{\mathrm{t}}/P_{\mathrm{s}}$, where $P_{\mathrm{s}}(k)$ and $P_{\mathrm{t}}(k)$ are the power spectra of scalar and tensor perturbations, respectively. The *tensor-to-scalar ratio* r is a crucial inflationary observable.

Figure 1 shows the E and B mode signals. For the B-mode we show the expected levels for three different values of r. The current upper limit is $r < 0.2$. Observations over the next decade are targeted at setting an upper bound of $r \leq 0.01$.

B.1.c The Scientific Impact of a B-mode Detection

What would the detection of a primordial B-mode signal imply for our understanding of the high-energy mechanism driving the inflationary expansion? A CMBPol Theory Workshop Overview gives a detailed answer (Baumann et al., 2008a). Here we give a brief summary.

1. **Energy scale of inflation**: The tensor-to-scalar ratio r is related directly to the inflationary energy scale, $V^{1/4} = 1.06 \times 10^{16}\,\mathrm{GeV}\left(\frac{r}{0.01}\right)^{1/4}$. A detectably large tensor amplitude, $r \gtrsim 10^{-2}$ say, would therefore convincingly demonstrate that inflation occurred at a tremendously high energy scale, comparable to that of Grand Unified Theories (GUTs). It is difficult to overstate the impact of such a result. To date physicists have only two *indirect* clues about physics at this scale: the apparent unification of gauge couplings, and experimental lower bounds on the proton lifetime.

2. **Super-Planckian field excursion**: The tensor-to-scalar ratio is a measure of the change of inflation field $\Delta\phi \equiv \phi_{\rm cmb} - \phi_{\rm end}$ between the time when CMB fluctuations were created at $\phi_{\rm cmb}$ and the end of inflation at $\phi_{\rm end}$ about 60 *e*-folds of expansion later, giving the limit $\frac{\Delta\phi}{M_{\rm pl}} \gtrsim \left(\frac{r}{0.01}\right)^{1/2}$ (Lyth, 1997). Thus $r \gtrsim 10^{-2}$ implies a field variation that is larger than the Planck mass between $\phi_{\rm cmb}$ and $\phi_{\rm end}$. As explained in detail in the CMBPol Inflation White Paper (Baumann et al., 2008b), measuring $r > 0.01$ would provide definite information about certain properties of the ultraviolet completion of quantum field theory and gravity. An upper limit of $r < 0.01$ would also be very important as it would rule out all large-field models of inflation.
3. **Other models**: Finally, alternatives to inflation, almost universally predict an unobservably low tensor amplitude and would hence be ruled out by a B-mode detection (e.g. Buchbinder et al., 2007; Steinhardt and Turok, 2002; Battefeld and Watson, 2006; Lehners, 2008).

Figure 1 shows the capabilities of a proposed space mission, called *EPIC-IM*, in determining *r*. *EPIC-IM* has the sensitivity to reach levels of $r \simeq 0.001$.

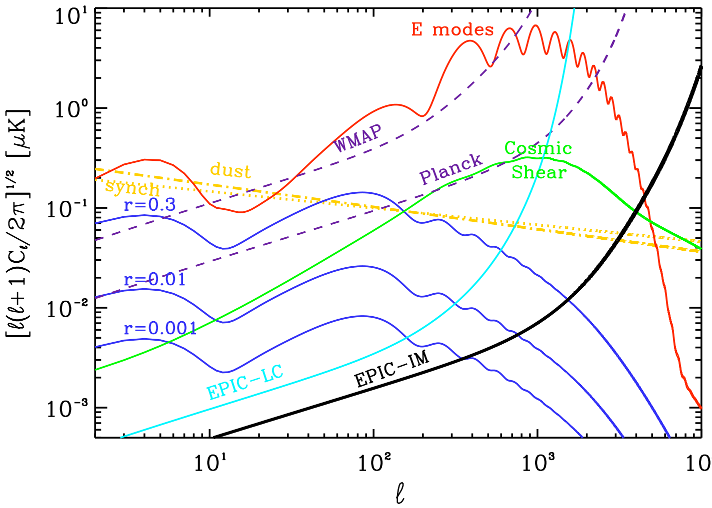

Figure 1: The sensitivity of *EPIC-IM*, *WMAP* and *Planck* to CMB E-mode polarization (red); B-mode polarization from tensor perturbations (blue) for $r = 0.3$, 0.01 and $r = 0.001$; and B-mode polarization produced by lensing of the E-mode polarization (green). The goal for the decade is to reach a level of $r \leq 0.01$ for the entire $2 < \ell < 200$ multipole range *after foreground subtraction*. Expected B-mode foreground power spectra for polarized dust (orange dash-dotted) and synchrotron (orange dotted) at 70 GHz are shown based on best available data for a 65% sky cut. The sensitivity of *EPIC-IM (EPIC-LC)* is for a 4(2)-year mission (see Section E for more details about the missions). *WMAP* assumes an 8-year mission life; *Planck* assumes 1.2 years at goal sensitivity. The sensitivity curves show band-combined sensitivities to C_ℓ in broad $\Delta\ell/\ell = 0.3$ bins in order to compare the full raw statistical power of the three experiments in the same manner.

B.1.d Further Inflationary Observables

The detection of inflationary gravitational waves would be nothing short of revolutionary. Moreover, precision measurements of CMB polarization contain vital *additional* information on the physics of the inflationary era. Here we list some of the main observables that will be extracted from the data:

Deviations from scale-invariance. Any deviation from perfect scale-invariance is a powerful discriminator among inflationary mechanisms. The scale-dependence is often defined by the spectral indices $n_{\rm s}$ and $n_{\rm t}$ with $n_{\rm s} = 1$ and $n_{\rm t} = 0$ corresponding to perfect scale-invariance. The left panel of Figure 2 shows the predictions for the scalar tilt $n_{\rm s}$ for popular inflationary models. The right panel of the figure shows the substantial improvement that *EPIC-IM* will provide in constraining both r and n_s over *WMAP* and *Planck*. *EPIC-IM* should also measure the ‘running’ of n_s - the change of n_s with wavelength - to the cosmic variance limit[6], giving additional constraints on the inflationary parameter space.

Non-Gaussianity. Non-Gaussianity is a measure of interactions of the inflaton. During slow-roll inflation, the inflaton self-interactions are necessarily small and the fluctuations are very nearly Gaussian (Maldacena, 2003). However, in other models, the non-Gaussianity is often large, and contains crucial information about the structure of the inflationary action (Bartolo et al., 2004). Moreover, alternatives to inflation often predict large non-Gaussianity (Lehners and Steinhardt, 2008). The primary signature of non-Gaussian correlations is a non-zero three-point function. Thus, if detected, non-Gaussianity of primordial perturbations would provide a unique avenue for studying the ultra-high-energy physics responsible for inflation or even testing alternative ideas for the dynamics of the early Universe. *EPIC-IM* will extend *Planck’s* constraints on non-Gaussianity by a factor of ~3.

Isocurvature fluctuations. Isocurvature density perturbations are a clean signature of multi-field models of inflation, since single-field inflation produces only adiabatic perturbations. The CMB E-mode polarization gives important constraints on primordial isocurvature fluctuations. *EPIC-IM* will be the first experiment to provide cosmic variance limited E-mode measurements out to $\ell \sim 2500$.

Defects, curvature and anisotropy. In addition to testing the physics during inflation *EPIC-IM* has the potential to provide information on pre- and post-inflationary physics; for example: *i*) defects like cosmic strings produced after inflation create a characteristic B-mode signature; *ii*) a remnant curvature and large-scale anisotropy from pre-inflationary initial conditions leaves signatures in the CMB anisotropy. Relative to *Planck*, *EPIC-IM* will give a factor of ~10 improvement on the constraints on curvature.

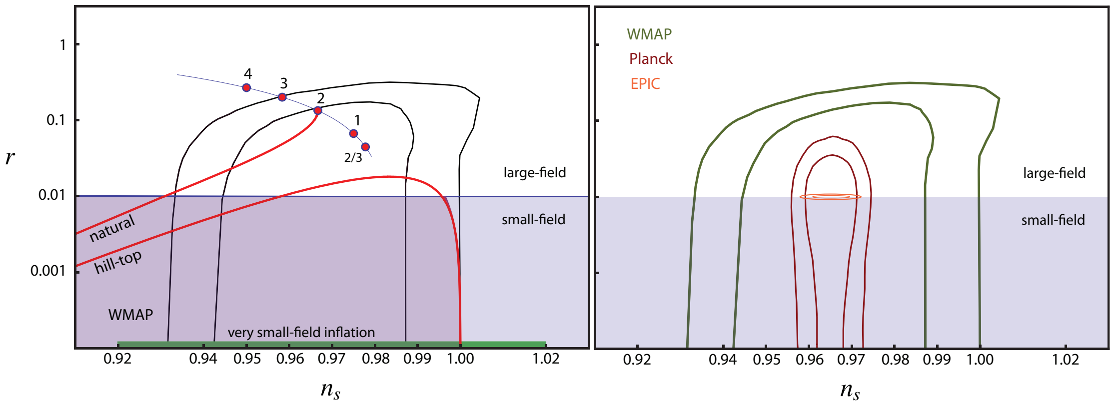

Figure 2: Left Panel: Predictions of single-field slow-roll models in the n_s-r plane. The figure shows the *WMAP* 5-year constraints on n_s and r (68% and 95% confidence levels in black) as well as the predictions of a few representative models of single-field slow-roll inflation: *chaotic inflation* $\lambda_p\,\phi^p$, for general p (thin solid line) and for $p = 4, 3, 2, 1, \frac{2}{3}$(red dots); *natural inflation* and *hill-top inflation* (red solid lines); and *very small-field inflation* (green bar). Right Panel: Same *WMAP* constraints as on the left together with projected 68% and 95% constraints from *Planck* and the proposed *EPIC-IM* space-based mission assuming $r = 0.01$ and $n_s = 0.965$. The *EPIC-IM* prediction *includes errors due to the subtraction of simulated foregrounds.*

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[6] The finite number of ℓ multipoles on our sky gives an irreducible limit to the accuracy at which they can be determined. This is the cosmic variance limit.

B.2 Cosmology from z=1100 to z=0

B.2.a Reionization

CMB photons scatter on electrons in the intergalactic medium, producing a polarization signal related to the depth and ionization history of the universe. Zaldarriaga et al. (2008) summarize the reionization science in a CMBPol white paper. The recent *WMAP* report of a large-angle polarization excess has indicated the possibility of reionization at redshift $z \sim 10$. There is a large uncertainty, however, on both the integrated optical depth as well as the exact reionization history of the Universe. None of the suborbital experiments will improve this result to the limit allowed by foregrounds as observations will be limited to a small area of the sky. *EPIC-IM* is the *only* experiment that will be cosmic-variance limited in its entire measurements of the E-mode spectrum and will therefore extract all of the available information about the reionization process.

B.2.b Cosmic Shear

The CMB signal is distorted by the cumulative effect of gravitational lensing by intervening mass along the line of sight. The effect converts some of the primordial E-mode fluctuations to B-modes with a peak B-mode signal at $\ell = 1000$ (Hu and Okamoto, 2002) (see Figure 1). While cosmic shear polarization has not yet been detected, high sensitivity measurements by upcoming suborbital experiments and by *EPIC-IM* will probe the formation of structure at moderate redshifts, and thus provide new cosmological information on early dark energy density as well as on neutrino masses. For example, *EPIC-IM* will constrain the mass of the neutrino to less than 0.05 eV. This is an interesting level given the atmospheric neutrino oscillation data which suggest a mass squared difference of 2.5×10^{-3} eV^2. A sensitive measurement of cosmic shear can also be used to provide a partial subtraction, allowing a deeper search for inflationary polarization. A CMBPol Theory White Paper on cosmic shear expands on these issues (Smith et al., 2008).

B.3 Galactic Science

Almost all of the information astrophysicists have about Galactic magnetic fields comes from polarimetric observations.

Galactic magnetic fields are strong enough, and sufficiently well coupled to the interstellar gas, to play an important role in the evolution of the interstellar medium (ISM). Most of our information about the large-scale structure and strength of the Galactic fields comes from polarimetric radio observations (synchrotron and Faraday rotation observations) that are sensitive to the ionized component of the ISM. Meanwhile, techniques for probing magnetic fields in the neutral ISM (e.g., Zeeman splitting, polarized extinction and emission from aligned dust grains) generally have been restricted to observations of localized fields on relatively smaller scales. With *ALMA* it will soon be possible to follow the field lines of star forming molecular cloud cores down to still smaller scales, via dust emission polarimetry. For example, it may be possible to trace the fields into magnetized protoplanetary disks.

A space-based CMB polarization experiment like *EPIC-IM* will provide detailed Galaxy-wide maps of polarized dust emission. These maps will reveal the nature of the unexplored links between large-scale Galactic fields and the smaller-scale fields of neutral molecular and atomic clouds. This is timely, because the next decade will also witness (a) an explosion of knowledge concerning the small-scale cloud fields due to *ALMA*, and (b) improved maps of large-scale fields in the ionized component due to ambitious new radio surveys exploiting high-bandwidth technology (e.g., Wolleben et al., 2008). Sensitive ground-based and balloon-borne experiments that also aim to link these small- and large-scale regimes (e.g., Clemens et al., 2007; Marsden et al., 2008) will not approach the sensitivity levels and sky coverage available from space.

Space-based submm polarimetry with angular resolution of order one arcminute, such as provided by *EPIC-IM*'s highest frequencies will provide detailed maps of interior fields, surface fields, and linkages to Galactic fields for hundreds of molecular and neutral atomic clouds. Such maps will probe the role of magnetic fields in the formation of molecular clouds and in the formation of stars, which are hotly debated issues (McKee and Ostriker, 2007). The five arcminute beam of *Planck* for its highest frequency polarimetry band at 353 GHz will provide sufficient spatial resolution only for the closest clouds. Arcminute-scale polarimetry from space will also have a major impact on understanding the relationship between poloidal and toroidal magnetic fields in the center of the Galaxy (Novak et al., 2003; Morris, 2006). This is an important outstanding problem in Galactic astronomy. A CMBPol White Paper on galactic science (Fraisse et al., 2008) expands on what a CMB polarization experiment would contribute to our knowledge of the Galaxy.

C Plan for the Decade

The plan for the decade is to extract all the information in the CMB by measuring: (1) the B-mode CMB polarization signal to $r \leq 0.01$ between $2 < \ell < 200$ after accounting for errors due to the removal of foreground emission, cosmic shear and systematic errors; (2) the B-mode from cosmic-shear to cosmic variance limits up to $\ell \sim 2000$; (3) the E-mode to cosmic variance limit up to $\ell \sim 2500$; (4) the temperature anisotropy signal to cosmic variance limit up to $\ell \sim 3500$.

C.1 Key Issue in Delivering the Science

Suborbital experiments operating in the next 5 years may have the raw sensitivity to measure $r \simeq 0.01$. Because their sensitivity is in the range needed to begin to constrain inflation models, these experiment will inform us about how to overcome key measurement challenges, such as foreground contamination and systematic uncertainties. The measurements will lead to further improvements in suborbital experiments and to an optimized design of a space mission.

Sensitivity Sensitivity is gained mainly by a large instrument throughput which translates to large, high detector-count focal planes. From the ground, detectors are largely at photon noise limits. Additional sensitivity gains come from low emission optics or operation from balloons with a small residual atmosphere, and from space with the possibility of only astrophysical photon noise limits. *WMAP* is expected to ultimately constrain the B-mode signal to the level of $r \simeq 0.1$. *Planck* will improve upon these limits as shown in Figure 1. The *EPIC-IM* mission concept of Section E promises substantial further raw sensitivity gains. As discussed in Section D.2 sensitivity is not enough, however high sensitivity is certainly a necessary ingredient.

Foregrounds Figure 1 shows the *predicted* levels of galactic signals which are based on data from *WMAP*. There remain substantial uncertainties particularly with polarized foregrounds because of *WMAP's* limited sensitivity and frequency coverage. Figure 1 also shows how CMB polarization signal is subdominant to polarized galactic signals and this will be true over much of the sky. Simulations clearly show that the foregrounds can be removed to the needed level if we know how they behave and have a well designed experiment. The right panel for Figure 2 shows the *EPIC-IM* sensitivity to r including the noise due to the removal of simulated foregrounds. The uncertainty in our ability to subtract the foreground will be reduced by what we learn from *Planck* and other experiments currently under development.

Angular Resolution The blue lines on Figure 1 show the characteristic B-mode signal peaking at $\ell = 90$ directly from inflation and at a $\ell = 5$ due to reionization. The shear signal (in green) peaks at $\ell \sim 1000$. Most of the information about Galactic astrophysical sources is accessible at $\ell > 500$, with increasing science return for higher resolution and sensitivity. Measurements of the reionization peak are a challenge for suborbital experiments and are expected to encounter stronger foreground contamination. Ground-based experiments with large apertures are well suited for the range $\ell > 1000$. The *EPIC-IM* line indicates the capability of a 1.4 m space mission.

Control of Systematic Uncertainties The B-mode signal whether it is of cosmological or galactic origin is expected to be at the nano-Kelvin level, 9 orders of magnitude smaller than the uniform glow of the CMB. Although to date CMB experimenters have excelled in providing results free of systematic errors, a new level of characterization and control will be necessary to reach the B-mode signal. These improved capabilities will come from testing techniques employed by the suborbital experiments that are currently being developed and by learning from the experience of the *Planck* satellite.

C.2 Plan

To carry out the goals set out above, we advocate a multi-pronged plan to make progress toward measurements of the polarization at millimeter and sub-millimeter wavelengths that includes:

1. **Continue the vigorous program of suborbital experiments.** Table 1 gives a list of currently ongoing and planned experiments that should begin to deliver valuable information about science, foregrounds, and the state of technology maturity through the first years of the decade. With support similar to current levels (see Section F), the experiments described in Section D.1 and those that are likely to come after them, provide substantial improvements in sensitivity, employ and verify techniques to mitigate systematic uncertainties, bring the technologies necessary for a satellite to TRL-5, and test and challenge foreground reduction techniques. Even after a satellite program has started around mid-decade (see next item) sub-orbital measurements will continue to play a critical role in probing small angular scale features (that may be beyond the resolution of a satellite mission), and in enabling new techniques (e.g. foreground removal and data analysis) and technology.
2. **Support research in theory and data analysis techniques.** CMB science is driven by the interchange between theory and experiment. New science questions, for example the link between inflation and CMB polarization are born by the interplay between measurement and theoretical developments. Full utilization of the large quantities of data that will come from the new generation of experiments requires analysis techniques and data handling facilities.
3. **Enable the development of needed technology.** The technology for CMB anisotropy measurements has become increasingly complex. Individual groups and small suborbital experimental groups can no longer afford to develop the needed techniques nor scale up to the complex focal planes full of detectors that are needed to reach the required sensitivity. As described in Section F.1 development must be carried out with support not tied to an individual experiment.
4. **Establish a project office to support the development of a new space mission.** To ensure that this program has progressed to the point where a satellite mission in mid-decade is possible, a project office should be established. The main goal would be the to foster the continued development of the CMBPol mission concept. In addition the office would track the evolution of technology, particularly that which is specific to a space mission, such as coolers. The project office would also coordinate the community and develop the space mission budgets.

D Where We Are and Where We Need to Be

D.1 Current and Upcoming Experiments

In the first years of the coming decade, an array of experiments will dramatically improve constraints on concordance cosmology through observations of *temperature* anisotropy. Due for launch in early 2009, the *Planck* satellite will carry out an all-sky survey over a broad range of frequencies. *Planck*'s measurements of temperature anisotropy will be cosmic variance limited over an unprecedented range of angular scales and thus dramatically improve inflationary parameter estimation. They will also provide critical information about the spatial distribution of temperature and spectral index of galactic dust and synchrotron radiation. At the same time, ground-based experiments such as the *Atacama Cosmology Telescope* (ACT) and the *South Pole Telescope* (SPT) will measure temperature anisotropy on subsets of the sky at very high angular resolution, exploring secondary anisotropies such as the Sunyaev-Zel'dovich effect with vastly increased accuracy. However, even considering their polarization capabilities, these experiments will shed little light on the key inflationary observable: the amplitude of gravitational waves excited during the inflationary epoch.

Experiments on suborbital (both balloon-borne and ground-based) platforms have historically been very productive in making ground-breaking CMB measurements. They were the first to find the CMB, to give indications of its spectrum, to delineate the acoustic peaks in the power spectrum of the temperature anisotropy (Miller et al., 1999; Hanany et al., 2000; de Bernardis et al., 2000), and were the first to measure CMB polarization (Kovac et al., 2002) Several other experiments have also measured the expected E-mode polarization (Kogut et al., 2003; Readhead et al., 2004; Johnson et al., 2003; Montroy et al., 2006; Bischoff et al., 2008; Pryke et al., 2009). Suborbital experiments may be the first to find a B-mode signal.

Table 1: Future Suborbital CMB Polarization Experiments.

	Technology	FWHM (arcmin)	Frequency (GHz)	Detector Pairs	Modulator
US-led balloon-borne:					
EBEX (Oxley et al., 2004)	TES	8	150/250/410	398/199/141	HWP
Spider (Montroy et al., 2006)	TES	60/40/30	96/145/225	288/512/512	HWP/Scan
PIPER I	TES	21/15	200/270	2560/2560	VPM
PIPER II	TES	14	350/600	2560/2560	VPM
US-led ground-based:					
ABS(Staggs et al., 2008)	TES	30	150	200	HWP
ACTpol(Fowler et al., 2007)	TES	2.2/1.4/1.1	90/145/217	~ 1000	Scan
BICEP 2(Nguyen et al., 2008)	TES	37	150	256	HWP/Scan
Keck Array(Nguyen et al., 2008)	TES	55/37/26	100/150/220	288/512/512	HWP/Scan
MBI(Korotkov et al., 2006)	NTD	60	100	4	Int.
Poincare(Chuss, 2008)	TES	84/30/24	40/90/150	36/300/60	VPM
PolarBeaR(Lee et al., 2008)	TES	7/3.5/2.4	90/150/220	637	HWP
QUIET I(Samtleben, 2008)	MMIC	20/10	44/90	~100/1000	ϕ-switch
SPTpol(Ruhl et al., 2004)	TES	1.5/1.2/1.1	90/150/225	~ 1000	Scan
European-led ground-based:					
BRAIN(Polenta et al., 2007)	TES	60	90/150	256/512	Int.
C_ℓOVER(Piccirillo et al., 2008)	TES	7.5/5.5/5.5	97/150/225	3x96	HWP
QUIJOTE(Rubino-Martin et al., 2008)	HEMT	54-24	10-30	34	HWP

Notes: Abbreviations in the modulator column are for halfwave plates (HWP), pure scanning (Scan), scanning with stepped HWP (HWP/Scan), variable-delay polarization modulators (VPM), waveguide phase switch (ϕ-switch) and interferometers (Int.); experiments with no hardware polarization modulator are indicated by a dash, and will reconstruct polarization via their scan modulation only.

Table 1 lists current and future efforts to search for B-mode polarization. The list illustrates that a variety of technologies and observing strategies are being used. Observations over a wide range of wavelength bands is used to separate galactic from cosmic signals. A range of different angular resolutions, optimized for different, but in many cases overlapping, science goals. The experiments employ a variety of means to detect the polarization. This leads to vastly different implementation of control of systematic errors. This multiplicity of techniques and approaches should be vigorously supported over the next decade because only through experimentation can we learn how to make the measurements more robust and because the different approaches provide a crucial cross-check on the results.

Suborbital experiments are at the cutting edge of developing future technologies. In 2000, arrays of ~20 semiconductor-based bolometers in a focal plane were considered state-of-the-art; now, as described in Table 1, several teams are fielding arrays of ~1000 detectors or more. This advance has been enabled by the introduction of transition edge sensor arrays of bolometers that are easily scalable to large formats using standard fabrication techniques. Another example is in the area of telescope design. The drive toward large focal plane arrays and telescopes with clean polarization performance led to the adoption of on-axis refracting telescopes for CMB measurements and also to the implementation of 'crossed-Dragone' reflecting designs. These developments feed directly into a future space mission. The current design of the *EPIC-IM* satellite mission (see Section E) has more than 11,000 TES detectors and uses a crossed-Dragone telescope design. Suborbital experiments are essential pathfinders for future technologies.

Two additional key capabilities should be highlighted in regard to suborbital measurements over the next decade. First, NASA has recently successfully flown an Ultra Long Duration Balloon payload that carried 1500 lb for 54 days over Antarctica. There are plans to increase this mass limit. The longer flights above much of the atmosphere will provide high signal-to-noise ratio measurements at frequencies above 250 GHz which are not accessible from the ground. Second, ground-based measurements are the only way to conduct CMB polarization measurements at angular resolution less than 5 arcminutes. At these resolutions, the telescope size becomes prohibitive both for balloon and satellite platforms.

D.2 Foregrounds

Polarized emission at microwave frequencies is dominated by two Galactic components, synchrotron radiation and emission by thermal dust. The synchrotron emission dominates at low frequencies and has been well measured on large angular scales by WMAP (Page et al., 2007; Hinshaw et al., 2008). Our knowledge of polarized thermal dust emission is relatively poor, particularly in the low surface brightness regions out of the Galactic plane targeted for CMB observations (Ponthieu et al., 2005; Page et al., 2007; Kogut et al., 2007). Neither of these foregrounds is yet *measured* at the level required such that errors from the subtraction will be negligible compared to a B-mode CMB signal.

With the assumption of a polarized dust fraction of ~1-5%, the polarized foregrounds are expected to be comparable to a primordial polarization signal with tensor-to-scalar ratio $r = 0.01$ at the estimated foreground minimum of ~ 100 GHz *in a small patch (~ 1%) of the sky.* Over 75% of the sky we expect the foreground amplitude to exceed this primordial signal by about a factor of ten at the foreground minimum and on scales of two degrees. On the largest scales the polarized foreground amplitude is expected to exceed the primordial signal by a factor of about 20 (See Figure 1 for estimated level of foregrounds over ~65% of the sky). Thorough understanding of the galactic signals will be paramount.

Establishing how well we can extract the primordial signal, and how this influences mission design, depends on a number of assumptions about the foregrounds, and has been addressed in a number of studies (Amarie et al., 2005; Verde et al., 2006; Bock et al., 2006, 2008). A useful summary is available in the Proceedings of the CMBPol Theory Workshop (Dunkley et al., 2008). Conservative simulations indicate that we can clean Galactic foregrounds from maps of the polarized sky to at least the $5 - 10\%$ level. There is high confidence that with a realistic CMBPol mission design a gravitational wave signal with $r = 0.01$ will be detected at more than 5σ. Moderate confidence realistic estimates indicate detections at more than 10σ (see Figure 2).

The confidence in these projections will vastly improve with data from *Planck* and from suborbital measurements. The abundance of new data will also exercise the multitude of techniques that the community has developed to separate foregrounds from signal, including template cleaning, parametric sampling, and blind component separation. The relative importance of foregrounds requires that strong support be provided to data analysis and foreground identification activities throughout the decade.

D.3 Systematic Control

There are two broad classes of polarization systematics: instrumental polarization, which is the conversion of unpolarized to polarized intensity, and cross-polarization, which is the instrumentally-induced rotation of the incident polarization orientation. Substantial amount of analytic work has gone into understanding systematic errors that are induced by an irregular telescope beam shape. These effects fall under the category of instrumental polarization. O'Dea et al. (2007) and Miller et al. (2008) propagated beam-induced systematics all the way through the analysis and deduced their effect on cosmological parameter estimation. They find that in order to detect a tensor to scalar ratio of $r = 0.01$, beam-induced systematics effects need to be controlled to an unprecedented level of less than 3 nK. This example illustrates that the small amplitude of the Inflationary B-mode signal requires new levels of control and understanding of instrumental systematic effects. There is a bright side: the simulations show that once control of systematics is achieved at the level required for the Inflationary B-mode signal, it is already sufficiently good for all the deliverables from the cosmic shear B-mode measurement, such as neutrino mass, early dark energy density, and the equation of state at $z > 2$.

There are a host of other sources of systematic errors including temperature drifts of optics and detectors, scan synchronous signals from far-sidelobe response to local sources such as the sun, earth, moon and galaxy, $1/f$ noise in the detectors and readouts, calibration errors, and effects introduced by various polarization modulators. The only effective way to understand the effects of these sources on the measurements is through massive simulations, or high fidelity measurements. This is a challenging computational task, compounded in complexity by the large focal plane arrays. For many types of systematic errors *the effect on each detector needs to be calculated separately*. For an experiment with $\sim$1000 detectors such simulations can take weeks at a time. As already advocated earlier, strong support for data analysis and simulations must be maintained throughout the decade.

Ultimately, a satellite platform provides the most stable environment for the measurements. In addition, satellite programs typically have the funding to carry out the ancillary measurements and simulations that are necessary to fully characterize the instrument.

D.4 Technology

Rapid progress in a number of key technologies has considerably augmented the capability of suborbital experiments. Continued progress will further enhance these capabilities and will increase the TRL of a mid-decade space mission. Here we review the technology development which is most important for increasing the power of CMB polarization experiments, particularly in space.

Telescope Optics Several promising solutions have emerged from research into optical designs that are suited for polarization measurements. An example is the 'crossed-Dragone' design in which two mirrors are configured to produce a large, low aberration field of view, and low polarization systematics (Tran et al., 2008). This design is used by *EPIC-IM* to provide a throughput for more than 10,000 detectors in the focal plane. The crossed-Dragone design, as well as other promising designs, will be field tested by suborbital experiments over the next few years. Field tests will be complemented by more research to understand the properties of these designs, as well as to explore new ones. The research for the next decade is detailed in a recent White Paper called 'Optical Elements for a CMBPol Mission' (Tran and Page, 2008).

Coolers There are no cryocooler technology hurdles that will need to be overcome for a space mission. *Planck* will soon fly a cooling chain consisting of passive cooling, a 20 K Hydrogen sorption cooler, a 4 K mechanical cooler, and an open-cycle dilution refrigerator to achieve continuous 100 mK cooling. The system is carefully regulated to achieve the required extreme temperature stability on all stages. The coolers proposed for *EPIC-IM* can be seen as an outgrowth of this successful development. Today's cooler designs have significant margin and can handle the anticipated thermal loads of the *EPIC-IM* design. Johnson (2008) has provided a White Paper on mechanical coolers for a CMB polarization mission. Another CMBPol workshop White Paper of sub-Kelvin coolers is written by Shirron (2008). In these papers the authors give a number of examples of already developed coolers for JWST, *Planck* and SMILES (a Japanese Space Agency mission) that will be adequate for *EPIC-IM.*

Detector Systems Two general types of detection systems are used on CMB experiments: coherent amplifier detector systems and incoherent bolometric systems. WMAP flew coherent detectors (HEMTs). The *Planck* satellite's LFI instrument uses HEMTs, and HFI is bolometric. For future ground-based experiments, both detector types are viable. Table 1 shows that the current generation of sub-orbital experiments largely rely on TES bolometers. The *EPIC-IM* mission, outlined in Section E, is planning to use TES bolometers but may also consider superconducting microresonator bolometers (MKIDS) currently under development.

Ground-based experiments with ~1000 TES detectors are currently in operation. Ground and balloon experiments with ~5000 TES detectors, which will operate in the next 3 years, are in development. While no TES system has yet been demonstrated at the low background, low noise levels needed for space, the existing and planned experiments will test every other aspect of operation needed for an *EPIC-IM* mission. Sensitivity is extrapolated to be limited by CMB and telescope photon noise. Benford (2008) reviews TES detectors and Zmuidzinas (2008) reviews superconducting microresonator development. The development and fabrication of large-scale focal planes essential for both sub-orbital and space missions has grown rapidly. Much of the technology development support shown in Figure 6 is directed at large-scale bolometer array development.

It is expected that a future CMBPol mission will fly bolometric detectors. The biggest challenges facing a coherent system in order to be a viable contender for balloon-borne instruments and a future satellite mission are to demonstrate a) the requisite sensitivity at 90, 150, and 250 GHz and, b) a reduction in power consumption. Progress on (a) has been steady. Arrays of 40 GHz coherent polarimeters have been successfully fielded in the QUIET phase I instrument, and are showing good sensitivities. Arrays of 90 GHz elements are being built for ground based instruments, but none is yet near the target sensitivity. At higher frequencies, the sensitivity is further from what is needed at the moment. A space mission with a 40 GHz band with a premium on focal plane area an amplifier array is not out of the question. A CMBPol White Paper on coherent detectors by Lawrence et al. (2008) reviews the status of these detectors.

Detector Readouts For arrays of a thousand or more bolometer-based detectors, it is necessary to multiplex the signal at the cold stage. The last decade has seen tremendous development in technologies for multiplexed readout of TES arrays. These technologies are now in the field being used for astronomical observations, achieving mapping speeds orders of magnitude faster than previous technologies.

Two complementary multiplexing strategies for TES bolometers are: (1) Time domain multiplexing (Chervenak et al., 1999, 2000; Irwin et al., 2002; Battistelli et al., 2008; Irwin and Halpern, 2008), and (2) Frequency domain multiplexing (Yoon et al., 2001; Lanting et al., 2005; Lanting, 2006; Dobbs et al., 2008; Dobbs and Lee, 2008). In time domain multiplexing, used for example by the Atacama Cosmology Telescope (Kosowsky, 2006), detectors are read out sequentially one at a time. In frequency domain multiplexing, used for example by APEX-SZ (Dobbs et al., 2006), each detector is biased at a unique location in frequency space and read out continuously. Both technologies have been modified for low power operation and will be flown on stratospheric balloon polarimeters (Spider (Crill et al., 2008) and EBEX (Grainger et al., 2008), respectively) in the near future. This will bring the technology to TRL 5. Further development will be required to further reduce power consumption and radiation susceptibility for satellite missions and to increase bandwidth.

A third technology, GHz frequency-division multiplexing with superconducting microresonators can be used with both TES bolometers and microwave kinetic inductance detectors (MKIDs) and is evolving rapidly (Glenn et al., 2008; Mazin et al., 2006). This technology promises focal-plane simplification and scalability to even larger array sizes, but it is at an earlier stage of development relative to the other two technologies.

Other Technology Developments A number of other technological developments are currently taking place. The current status of these technologies for sub-orbital experiments are summarized in white papers written for the CMBPol systematics and technology workshops in the summer of 2008. These technologies include quasi-optical filters, planar transmission line filters, microstrip filters, lens coupled bolometers, planar antenna-coupled bolometers, refractive lenses, antireflection coatings, corrugated platelet feeds, polarization modulators using birefringent crystals, metal mesh, Faraday rotation, photolithographic stripline techniques and reflective polarizers, vacuum windows, ground screens and others. In addition, the ability to model the optics, the scan strategy and the whole experiment has advanced enormously. All these developments are driven and funded largely through the current and future ground-based and balloon-borne experiment support shown in Figure 6, and must be sustained throughout the decade.

D.5 Analysis and Data Handling

The computational cost of analyzing a CMB data set can be quantified by its numbers of observations in the time domain (N_t) and in the pixel (map) domain (N_p). The first is set by the duration of the mission and the numbers and sampling rates of the detectors at each of its observing frequencies, while the second is set by the angular resolution of the detectors and the fractional sky coverage of the mission. Since CMB temperature and especially polarization signals are so faint, their precise measurement requires $10^3 - 10^5$ observations of each point on the sky, so the analysis of a CMB data set is dominated by operations on the N_t time samples. Moreover each sample includes not just CMB signal but also foreground contamination and instrument noise, and these three components are correlated in the multipole-, pixel- and time-domains respectively. Since we have to account precisely for each of these correlations (and indeed the CMB correlations are the fundamental measure of the data we are seeking) the data set has to be treated as a single data object, precluding parallel divide-and-conquer analysis approaches often possible in other data-dominated domains. One consequence of this is that we require massively parallel high performance computing (HPC) resources over which the time-ordered data can be distributed for analysis.

Over the next 15 years we expect the size of CMB time-ordered data to grow by 3 orders of magnitude; coincidentally this exactly matches the projected growth in computing power over the same period assuming a continuation of Moore's Law. Since today's CMB data analyses are already pushing the limits of current HPC systems, this implies that our algorithms and their implementations will have to continue scaling on the leading edge of HPC technology for the next 10 Moore-foldings if we are to be able to support first the design and deployment of these missions and then the scientific exploitation of the data sets they gather.

E The *EPIC-IM* Space Mission Concept [7] [8]

The *EPIC* space mission concept has its beginnings in the Beyond Einstein Program as a candidate Inflation Probe. A mission concept called *EPIC-LC*, a sensitive CMB polarization satellite was the result of that study. The Experimental Probe of Inflationary Cosmology was published by Bock et al. (2008). As part of this study, a new concept, *EPIC-IM* was developed and has substantially enhanced capabilities. The design is summarized in this report and the full report will be available in late April 2009 at `http://cmbpol.uchicago.edu/depot/pdf/epic-im-report.pdf`.

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[7] The work described in this section was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

[8]

Table 2: Scientific Specifications

NASA Objective	Science Objective	Measurement Criteria	Instrumental Requirement
Discover what powered the Big Bang search for gravitational waves from the earliest moments of the Big Bang	Test Inflationary paradigm at GUT energy scales	Measure inflationary B-mode spatial power spectrum for $2 < l < 200$ after foreground removal	All Sky Coverage; 30-300 GHz; Sensitivity $W_p^{-1/2} < 6\,\mu$K-arcmin; Control systematic errors below $r = 0.01$; 1° resolution
Understand how the first stars and galaxies formed	Distinguish models of Reionization history		Parameters above
determine the size, shape, and matter-energy content of the Universe	Extract all cosmological information from E-mode polarization	Measure E-mode power spectrum to cosmic variance	$10'$ resolution
Measure the cosmic evolution of the dark energy, which controls the destiny of the universe	Measure shear signal to determine the neutrino mass below 0.05 eV and early dark energy density at $2 < z < 1100$ to 0.1%	Measure lensing B-mode power spectrum to cosmological limits	$6'$ resolution, $W_p^{-1/2} < 3\,\mu$K-arcmin
Trace the flows of energy and magnetic fields between stars, dust, and gas	Map Galactic magnetic fields	Measure polarization of Galactic dust	500 and 850 GHz bands

E.1 The Case for a Space Mission

A space-borne platform enables an experiment with the following advantages.

All-Sky Coverage While over the decade ground-based experiments can push to a sensitivity of $r \sim 0.01$ in limited regions of sky, the role of a future space mission is to carry out a precise measurement of the inflationary B-mode spatial power spectrum from $\ell = 2$ to $\ell > 1000$. The only credible platform for such an all-sky measurement is from space.

Multi-band Frequency Coverage Subtracting polarized Galactic emission will clearly be necessary to uncover the B-mode spatial power spectrum. At low multipoles, Galactic emission will have to be modeled and subtracted to better than 10 % to reach r = 0.01. At higher multipoles, regions with low Galactic emission are known to exist which require significantly less subtraction to reach this goal. A multi-band frequency approach spanning 30 – 300 GHz is needed to monitor and remove Galactic foregrounds. This subtraction is aided by the fact that the CMB electromagnetic spectrum is known to extremely high precision, and any component which is not CMB can be classified as a contaminant. Coverage of the full range of bands at the required sensitivity is only possible from space.

Sensitivity Achieving the science goal of measuring B-mode polarization to r = 0.01 will require a factor of 10 improvement in sensitivity over the upcoming *Planck* satellite experiment. Only space offers the combination of high instantaneous sensitivity and long integration times needed to reach the required sensitivity over the full sky.

Systematic Error Control Instrumental systematics must be measured and controlled to a new level of precision, particularly those effects that can convert the relatively bright CMB temperature and E-mode polarization signals into B-mode signals. As demonstrated by *COBE* and *WMAP*, a space-borne platform offers quantitatively superior control, stability, and measurement of systematic errors in redundant and uniform observations compared with any sub-orbital platform.

E.2 *EPIC-IM*'s Scientific Capability

The scientific specifications of The *Experimental Probe of Inflationary Cosmology - Intermediate Mission (EPIC-IM)* are summarized in Table 2. In addition to the main science goal of comprehensively measuring inflationary B-mode polarization, *EPIC-IM*'s combination of angular resolution

Table 3: Bands and sensitivity of *EPIC - Intermediate Mission*

Freq GHz	$\theta_{\rm FWHM}$ [arcmin]	$N_{\rm bol}$ [#]	NET/bolo [μK$_{\rm CMB}$]	$w_p^{-1/2}$ [μK-arcmin][a]	$\delta T_{\rm pix}$ [nK][b]
30	28	84	84	14	83
45	19	364	71	5.7	34
70	12	1332	60	2.5	15
100	8.4	2196	54	1.8	10
150	5.6	3048	52	1.4	8
220	3.8	1296	59	2.5	15
340	2.5	744	100	5.6	33
500	1.7	938	-	17(140)[c]	9[c]
850	1.0	1092	-	400(40)[c]	4[c]
Total		11194	0.6	0.9	5.4

Notes: [a] $w_p^{-1/2} = [8\pi \mathrm{NET}^2_{\rm bolo}/(T_{\rm mission} N_{\rm bolo})]^{1/2}$

[b] Sensitivity $\delta T_{\rm CMB}$ in a $2' \times 2'$ pixel (1σ)

[c] Point source sensitivity in μJy (1σ) per beam without confusion; surface brightness in Jy/sr in a $2' \times 2'$ pixel (1σ).

Sensitivity calculated for a 4-year mission, including photon, detector noise and sensitivity margin for focal plane detectors at $2f\lambda$ packing operating at 100 mK.

and sensitivity will constrain at an unprecedented level the scale invariance of the spectral index, cosmological non-gaussianity, isocurvature fluctuations, cosmic defects, and the curvature of the universe (see Section B for more details). *EPIC-IM* will also measure the reionization history parameters of the Universe to cosmic variance limit, will provide a 0.05 eV limit on the mass of neutrino, and will improve constraints on early dark energy by more than a factor of 2 compared to Planck. It will measure the E-mode spatial power spectrum to cosmic variance into the Silk damping tail, completing the measurements of *WMAP* and *Planck*, and extracting all of the cosmological information contained in this signal. *EPIC-IM* includes 2 bands at 500 and 850 GHz (Table 3) to produce high-sensitivity all-sky maps of Galactic polarization with $1'$ resolution, bringing a new capability on the study of Galactic magnetic fields to a wide community of astronomers.

EPIC-IM employs a 1.4 m cooled telescope and more than 11,000 detectors in the focal plane to provide large leaps in polarization sensitivity compared to *WMAP* and the upcoming *Planck* satellite, as shown in Figure 1. Bolometric detector arrays provide both background-limited sensitivity and large formats to achieve the highest possible system sensitivity, and complete band coverage spanning 30 to 850 GHz to allow the best possible characterization and removal of Galactic foregrounds (See Table 3). Based on our best current experimental data, a variety of techniques indicate this band coverage and sensitivity are sufficient to reach the science goal of measuring the full B-mode spatial power spectrum at an amplitude $r = 0.01$ (Tegmark et al., 2003; Eriksen et al., 2006; Dunkley et al., 2008; Betoule et al., 2009; Bock, 2009).

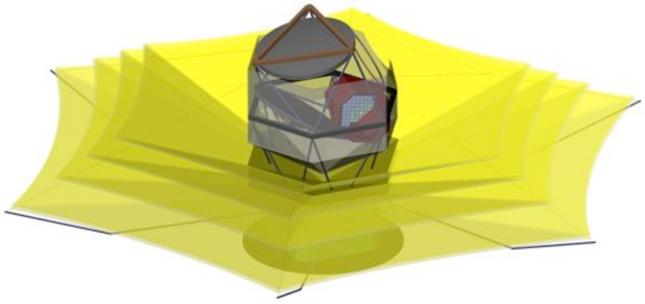

Figure 3: The *EPIC-IM* mission observes the CMB sky with a 1.4 m off-axis telescope and a large focal plane of bolometric detector arrays operating at 100 mK. The telescope is cooled to 4 K, first through 4 fixed V-groove radiators to 25 K, and then by a pulse-tube refrigerator. A deployed 15-m sun shield is used to keep solar radiation from heating the optics. An 18 K radiation shield surrounding the telescope has been removed to show the optics and focal plane.

Table 4: *EPIC-IM* Technical Specifications

Telescope	1.4 m Crossed-Dragone
Focal Plane	TES bolometer or MKID
Cooling System	4-stage passive cooler to 25K Pulse tube cooler to 4K Continuous ADR to 100 mK
Launch Vehicle	Atlas V 401, 4-m fairing
Orbit	Earth-Sun L2 Halo
Mass	
Payload	480 kg (CBE)
Spacecraft, without propellant	920 kg (CBE)
Total with propellent	2295 kg (with 43% contingency)
Power	
Payload	440 W (CBE)
Spacecraft	535 W CBE
Total	1390 W (with 43% contingency)
Science Data Inflow Rate	7.6 Mbps (with 100% contingency)
Lifetime	
Science Requirement	0.5 cruise plus 1 year observations
Spacecraft Resources	4.5 years
Observing Mode(s)	Spin and precess at L2

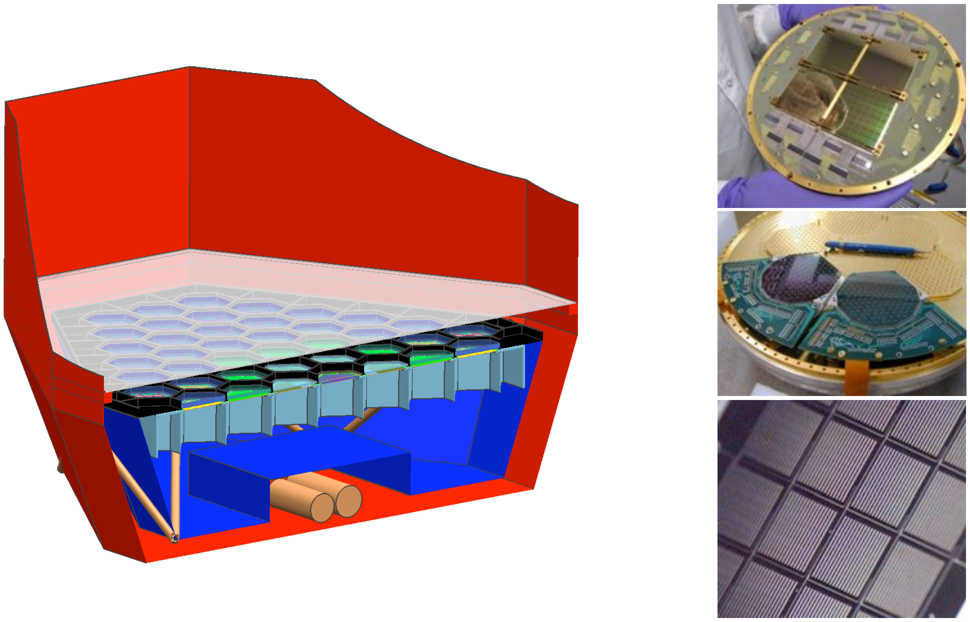

Figure 4: Left: a cross-section of the *EPIC-IM* focal plane, showing detector array tiles operating in multiple bands. The bands are nested with highest frequencies bands at 850 GHz located at the center, and lowest frequency bands at 30 GHz at the extreme edge. The 100 mK detector arrays are surrounded by a 1 K radiation shield with band-defining filters, an intermediate temperature stage provided by the ADR cooler, and an outer 4 K radiation shield. The CMB community is currently developing focal plane arrays suitable for *EPIC-IM*, top to bottom on right: antenna-coupled transition-edge superconducting (TES) bolometer arrays, feed-coupled TES bolometers, and microwave kinetic inductance detectors (MKIDS).

E.3 *EPIC-IM* Design

EPIC-IM, shown in Figure 3 is a scan-imaging polarimeter using direct detectors and drift-scan signal modulation. This approach is widely used in CMB polarization measurements, having been demonstrated on a number of suborbital instruments, and is the same methodology to be used in *Planck*. Available bolometer technology used on *Planck* at 100 mK already approaches the fundamental photon noise from the CMB. To gain further system sensitivity advantage, *EPIC-IM* uses large focal plane bolometer arrays.

EPIC-IM uses an off-axis telescope with a 1.4 m effective aperture. The configuration is known as a compact range antenna or crossed-Dragone, and provides a very large throughput product enabling a large focal plane. It has very small polarization effects (instrument polarization, cross-polarization, differential beam offset, differential ellipticity) over a large 20° × 30° field of view. The telescope realizes extremely low sidelobe response by combining under-illuminated mirrors, a pupil stop, and mm-wave absorbing shields placed at the pupil and surrounding the mirrors. Because the telescope is cooled, these shields introduce negligible photon noise.

A multi-stage system is used to cool the telescope and focal plane. A 4-stage V-groove radiator provides passive cooling to 25 K. A 4-stage deployed sun shield keeps solar radiation from reaching the sensitive instrument. However we note that the deployed sun shield extracts negligible heat from the instrument, due to the low conductivity of the deployed kapton membranes, and that the cooling system can be operated in a test chamber without the sunshade. The instrument is launched at room temperature, and the sun shield is deployed shortly after launch before the cooling process begins in flight. A pulse-tube mechanical cooler, based on *JWST/MIRI* heritage, cools the telescope and focal plane to 4 K. A 2-stage 100 mK cooler, either a continuous ADR (Adiabatic Demagnetization Refrigerator) or closed-cycle dilution refrigerator, cools the focal plane detectors to 100 mK from the 4 K base temperature. *EPIC-IM* is based on a simplified version of the *Planck* cooling chain, which uses a 3-stage V-groove radiator, a mechanical 4 K cooler, and a 100 mK open-cycle dilution refrigerator. The technical specifications of the *EPIC-IM* instrument are summarized in Table 4.

EPIC-IM uses a comprehensive strategy, informed by decades of experience in sub-orbital experiments, *WMAP*, and *Planck*, to mitigate systematic errors; see Table 5. The focal plane uses matched polarization sensitive detectors, the same technique used in *Planck*, to reduce common-mode signals such as unpolarized optical signals and temperature drifts. Differences in polarized beams can produce false polarization signals (Hu and Okamoto, 2002; Shimon et al., 2008). These effects are minimized by optical design and precisely measured in flight on polarized and unpolarized sources. The highly interlaced scan strategy shown in Figure 5 is ideally suited for minimizing many of these effects. It provides highly redundant observations that can be inter-compared daily and are a powerful check on many systematics that vary with time, beam orientation, and detector location. As demonstrated by *WMAP*, the unpolarized dipole signal, modulated by the earth's orbital motion, provides a highly precise source for tracking absolute and channel-to-channel gain. Mirror under-illumination and absorbing baffles are used to reduce far-sidelobe response. The passive thermal design takes maximal advantage of the exquisitely stable thermal environment at L2, demonstrated by *WMAP*. The demanding temperature stability at 100 mK required by *EPIC-IM* will soon be demonstrated by the temperature control system used in *Planck*. Candidate detector array technologies are being fielded in sub-orbital experiments today. They will return results prior to any mission start, and will provide working demonstrations of the focal plane stability, magnetic shielding, and differential passband control needed for space.

E.4 *EPIC-IM* Cost

We carried out a team-x study of several implementations of the *EPIC-IM* mission concept, and derived an estimated cost of \$700M - \$900M [9]. A final report of the mission concept and cost will be posted on in late April and a full description will be made available if the decadal issues an RFI for this mission concept.

Table 5: *EPIC-IM* Systematic Mitigations

Systematic	**Description**	**Effect**	**Mitigation**
Polarized Main Beam Effects			
Beam Mismatches	Differences in polarized beams	$\Delta T, \Delta^2 T \rightarrow B$	Scan Crossings[a]
Cross-Polarization	E, H rotated	$E \rightarrow B$	Measure Beams[b]
Differential Gain	Optical of electrical mismatch	$T \rightarrow B$	Modulated Dipole[a]
Satellite Pointing	Beam centers shifted	ΔT, $E \rightarrow B$	Pointing Specification[a]
Scan Synchronous Signals			
Far Sidelobes	Pickup from sun, earth, galaxy	Scan dependent false polarization signal	Baffling[b]
Thermal Variations	Solar variations		Thermal Design[a]
Magnetic Pickup	Focal Plane susceptibility		Shielding[b]
Thermal Stability			
4K Optics	Varying optical power	Common mode drift	Detector Differencing[a]
100 mK Focal Plane	Induced thermal signal	Common-mode Drift	Temperature Control[a]
Other			
1/f Noise	Detector and readout drift	Degradation at low ℓ	Stabilized readouts[b]
Passband Mismatch	Filter variations	Foregrounds $\rightarrow B$	Measure and remove[b]

[a] Proven in space now or to be demonstrated by *Planck*.

[b] Sub-orbital demonstration planned.

E.5 An Alternate Mission Configuration: *EPIC-LC*

In response to NASA's "Beyond Einstein" call for mission concepts in the beginning of this decade the *EPIC* team has developed a mission configuration called *EPIC-LC* (Bock et al., 2008). *EPIC-LC* has an aperture of 0.3 meter and thus has comparable capabilities to *EPIC-IM* for measuring only the B-mode signal from inflation, see Figure 1. Team-x study of *EPIC-LC* gave a cost estimate of \$660M.

As a result of this study the *EPIC* team has developed the concept of *EPIC-IM*, which is designed for maximum scientific capability, with sufficient angular resolution to return CMB science over a wide range of angular scales, the maximum instrument sensitivity possible, and wide frequency coverage both for deep foreground removal and new Galactic science.

Our scientific knowledge of the amplitude of inflationary polarization, and the full nature of polarized Galactic emission, will significantly improve over the near future as a direct result of the 'Plan for the Decade' that we have been advocating in this document. A detection of inflationary polarization from *Planck* or sub-orbital platforms at an amplitude of $r > 0.01$ may provide the impetus for a smaller mission configuration, perhaps such as *EPIC-LC* or cheaper variants. (Bock et al., 2008)

F Cost and Planning

F.1 Technology and Detector Development

CMB experiments have become more powerful and with faster mapping speeds because of advances in detector and other technologies. Whereas early in the decade experiments used a few hand-built detectors, instruments are now utilizing thousands of detectors with noise-equivalent-power in the low 10^{-17} W/$\sqrt{\text{Hz}}$. In the next decade, arrays of 10,000 polarization sensitive detectors with noise-equivalent-power in the 10^{-18} W/$\sqrt{\text{Hz}}$ range are needed. The model for technology development and detector production of the past is no longer viable. The major advancements that

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[9] The cost estimates were generated as part of a Pre-Phase-A preliminary concept study, are model-based, were prepared without consideration of potential industry participation, and do not constitute an implementation-cost commitment on the part of JPL or Caltech. The accuracy of the cost estimate is commensurate with the level of understanding of the mission concept, typically Pre-Phase A, and should be viewed as indicative rather than predictive. The costing assumes all instrument technologies have advanced to at least TRL = 6 at the start of the mission.

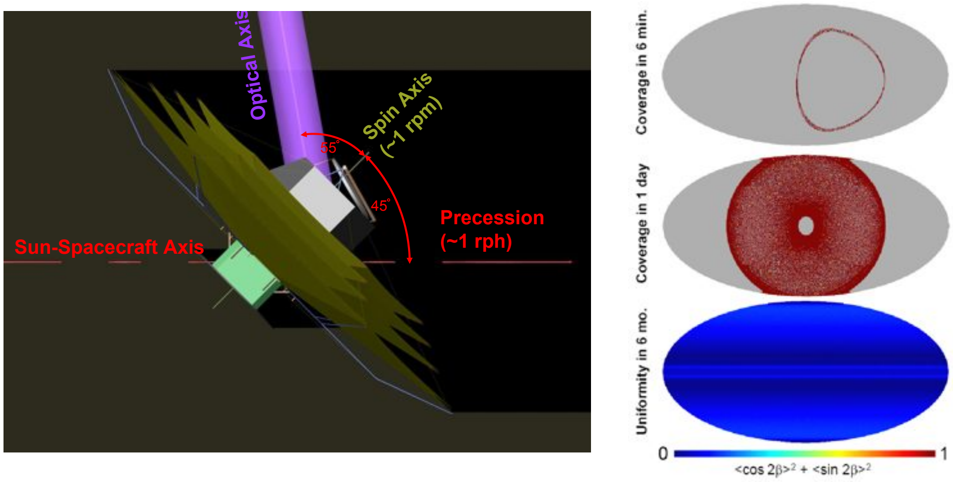


Figure 5: *EPIC-IM* uses an optimized observation strategy at L2 for minimizing instrumental effects. A 3-axis zero-momentum spacecraft spins at 0.5 RPM about the axial direction, rotating the optical beams, which are displaced from the spin axis by 55 degrees, in a circular pattern on the sky (shown in top right figure for a single pixel). The spin axis precesses at 1 RPH, moving the circular pattern on the sky to form an inter-nested scan pattern (middle right figure). Multiple daily highly redundant maps are built up in this way for every detector, ideal for verifying performance for numerous systematic effects. Over the course of 6 months, this pattern is modulated by the orbit to give a full-sky map with nearly perfect uniformity, expressed as the range of angles the instrument observes any patch of sky. This pattern is ideal for polarization, and a significant improvement over the scan patterns developed for *WMAP* and *Planck*. The solar power into the instrument remains unchanged, taking maximal advantage of the incredibly stable thermal environment available at L2.

have driven the field were primarily supported by large satellite projects (e.g. Planck), which generated detector foundries with the capacity to support smaller efforts. Since the Planck development has ended, development has continued in a variety of ways including discretionary funds at major labs (JPL, GSFC, and NIST), small awards from NASA (primarily) and NSF, and some sporadic private support. In the absence of major projects on the horizon, the next decade could begin with no resources allocated to the development of large detector arrays.

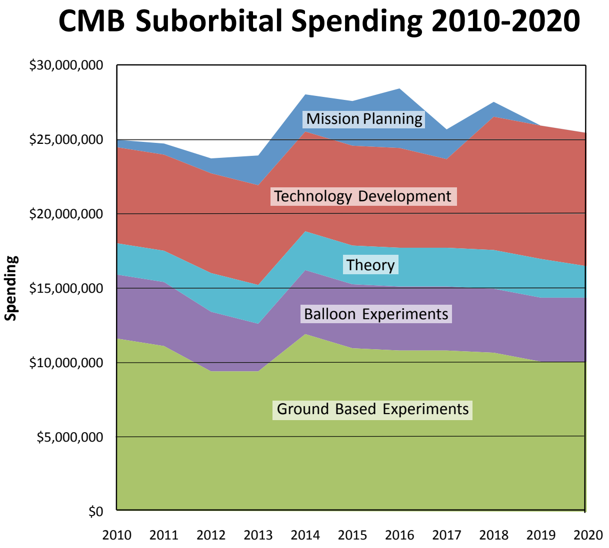
To maintain the capabilities that we have achieved and continue the improvement in sensitivity a significant and sustained investment in technology and detector development and production must be put in place. NASA must be instructed that progress in CMB polarization science requires support even in the absence of an approved mission. We estimate that a total budget of $4M/yr will support the major centers at NASA, NIST and other institutions. The funds will be used for exploration of new technologies while maintaining infrastructure to supply detectors to new and ongoing experimental efforts. In addition, innovative detector technology grants must be increased. These can be funded through NASA and NSF. We advocate at least $1M/year directed to such university-based efforts. A healthy research program in new directions is a crucial component of a plan for progress.

F.2 Suborbital Observations

Ground-based experiments can probe angular scales that are impractical to probe from balloons or from space due to the large (6-10 meter) telescopes that are required. Over the past decade, ground-based observations have been supported well with primary funding coming from NSF. There is also limited funding from NASA and some private foundations. The funding level for all of these efforts has been approximately $10M/year over the last decade. We anticipate that similar levels will be required over the next decade.

The near-space environment and relatively long (10-20 day) observations from balloon flights provide a unique opportunity to approach the detection of primordial B-modes. As with ground-based

Figure 6: Sub-orbital CMB research funding across several broad categories. The plan assumes that space mission spending will begin development in 2017. The mission planning category is a project office which coordinates technology development between experiments and detector development centers. The mission planning expands until the actual start of funding for the mission iteself. The costs for the payload development are not included. We expect that ground-based and suborbital research will continue to yield important results, technology testing, and complementary science throughout the decade.



observations, balloons enable end-to-end testing of state-of-the-art technologies and observing strategies. They also advance the TRL of new technologies and can make observations at frequencies not accessible from the ground. The model of multiple ground and suborbital testing prior to satellite missions has been well proven with *COBE*, *WMAP*, and the upcoming Planck satellites.

Suborbital missions have been underfunded for the last decade. The programs are extremely lean and efficient, but that is generally not enough. The primary strain on the programs has been the need to support detector development and production using funds from the balloon program. Typical awards have been about $700K/year for three years. This is in stark contrast to the 5-7 years it takes to bring a program to fruition and the $1-2M it costs for detectors alone. Some recent extended grants of up to 5 years and modest increases in funding have improved the situation somewhat. Currently about $4M/year is spent for CMB related balloon-borne experiments. We anticipate the need for approximately $5M/year for the next decade assuming there is a separate path for the technology development discussed above.

F.3 Theory and Data Analysis

The rapidly evolving CMB science is backed by a strong theoretical and data analysis community. Theorists and data-analysts must have the resources to explore new areas whether it is the effects of lensing on the CMB or how to model and remove foregrounds from the next generation experiments. To date, funding for these activities has been piecemeal at best. We anticipate a need for approximately $2M/year for theory and analysis over the next decade.

F.4 Satellite Mission Planning

The work described above is geared towards preparing for a space-based CMB polarization mission. The recent BEPAC report highlighted the need for this mission and estimated the cost at near $1B. We advocate a call for proposals in ~2014 with mission funding beginning soon after. As part of this path we advocate a program office be supported by NASA starting in 2010 to guide the planning up to the mid-decade. The office would be funded starting at $500K/yr with increasing levels as the mission call approaches. The project office is part of the item called "Mission Planning" in Figure 6. The program office would coordinate the community, track the technology development that is specific to a satellite project and prepare the space mission budgets.

Link to References

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