The Probe of Inflation and Cosmic Origins

A Space Mission Study Report
December, 2018

Principal Investigator:
Steering Committee:
Executive Committee:
Contributors:
Endorsers:

1 Executive Summary (2 pg, Hanany)

2 Science (31 pages)

48 pages are currently distributed as 29/19: 29 pages for science (including foregrounds and systematics), 19 for instrument, technology, mission, management and cost.

2.1 Introduction (1.5 pgs, Hanany + (?))

NASA suggested table of contents says Science Intro or Landscape section should include:

- State of the Art in the Field
- Compelling Outstanding Questions
- Needed Capabilities for Progress

2.2 Science Objectives (17.5 pgs)

The PICO Science Traceability Matrix (2pg, Hanany&Trangsrud) will be inserted around here. It is an 11x17 foldout, so it counts as 2 pages, which leaves 15.5 to all the rest in 2.2. Currently allocating 15 pages.

FOR EACH OF THE BELOW SUBSECTIONS:

- Introduce and elaborate on the applicable PICO “Science Objectives” from the STM table (what do they mean and why are they important)
- Observations/Measurements that enable PICO to accomplish each Science Objective (tell the data analysis story that connects the Observations column of the STM to the Science Objective column)
- Contextualize relative to sub-orbital and other space missions. *Emphasize where capabilities are unique to space.*
- Science yield estimate (be quantitative. how well will PICO do at Baseline/Required performance? at Current Best Estimate performance?)
- Include a summary plot or table which demonstrates PICO’s performance against the Science Objective as written (e.g. how it discriminates between different theories)
- Perceived science impact. (The impact isn’t reducing sigma on a parameter. It is about what we will learn about nature.)

2.2.1 Fundamental Physics (6 pgs, Flauger, Green)

Gravitational waves and inflation

Measurements of the CMB together with Einstein's theory of general relativity imply that the observed density perturbations must have been created long before the CMB was released, and rather remarkably even before the universe became filled with a hot and dense plasma of fundamental particles. What generated these perturbations is one of the biggest questions in cosmology.
While the dynamics of the plasma produces some amount of gravitational waves, the amplitude is too small to be detected in existing or planned CMB experiments. So any imprint of gravitational waves on the cosmic microwave background detected by PICO would constitute evidence for gravitational waves from the same primordial period that created the density perturbations. Because the dynamics of gravitational waves is essentially unaffected by the plasma physics, they would be a pristine relic left over from the earliest moments of our universe, and their properties would shed light on the mechanism that created the primordial perturbations that grew into the anisotropies of the CMB and the stars and galaxies around us. Knowledge of the strength of the signal and their statistical properties would transform our understanding of many areas of fundamental physics.
Inflation, a period of nearly exponential expansion of the early universe, is the leading paradigm explaining the origin of the primordial density perturbations. It predicts a nearly scale invariant spectrum of primordial gravitational waves originating from quantum fluctuations. Thus, a detection of these gravitational waves would be the first detection of phenomenon associated with quantum gravity. Because the spectrum is scale-invariant, one may hope to detect primordial gravitational waves over a wide range of frequencies including, for example, at LIGO or LISA frequencies. However, as a consequence of the expansion of the universe, the energy density in the gravitational waves rapidly dilutes with increasing frequency, and observations of the CMB provide the easiest, and for the foreseeable future only way to detect these gravitational waves.

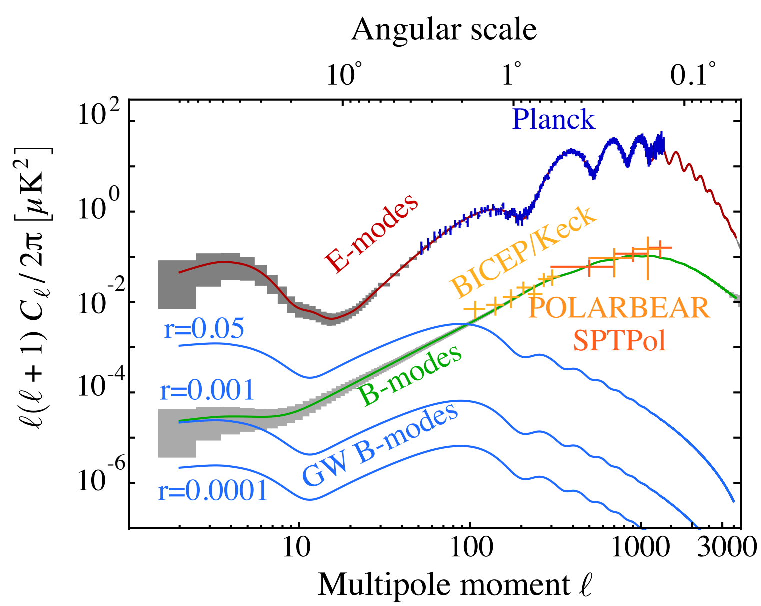

Figure 1: power spectrum place holder

The strength of the signal, often quantified by the tensor-to-scalar ratio r, is a direct measure of the expansion rate of the universe during inflation. Together with the Friedmann equation, this reveals one of the most important characteristics of inflation, its energy scale. PICO will be able to detect primordial gravitational waves if inflation occurred at an energy scale of at least 4×10^{15} GeV. A detection would have profound implications for fundamental physics because it would provide evidence for a new energy scale, and would allow us to probe physics at energies far beyond the reach of terrestrial colliders.

The signal would have two contributions, one on degree angular scales or multipoles of $\ell \sim 80$, typically referred to as the recombination peak, and another contribution for multipoles of $\ell \lesssim 20$ from reionization. The contribution from reionization is expected to be strongest relative to the contribution from weak lensing and instrumental noise. No sub-orbital experiment has meaningfully measured modes at $\ell < 40$ and a satellite like PICO is the most suitable approach to reach the lowest multipoles.

There are two classes of slow-roll inflation that naturally explain the observed value of the spectral index of primordial fluctuations, n_s. The first class is characterized by potentials of the form $V(\phi) \propto \phi^p$. This class includes many of of the simplest models of inflation, some of which have already been strongly disfavored by existing observations. If the constraints on the spectral index tighten by about a factor 2 with the central value unchanged, and the upper limits on r improve by an order of magnitude, this class would be ruled out.

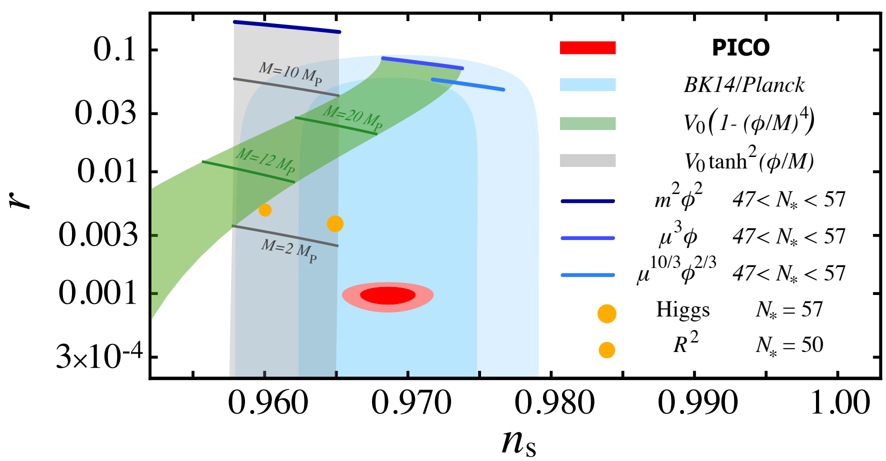

Figure 2: nsr placeholder

The second class is characterized by potentials that exponentially approach a plateau and include R^2 inflation. This model predicts a tensor-to-scalar ratio of $r \sim 0.003$. All models in this class with a characteristic scale in the potential that is larger than the Planck scale predict a tensor-to-scalar ratio of $r \gtrsim 0.001$, and an experiment like CMB-S4 could exclude these scenarios. However, there are models such as the Goncharov-Linde model with a somewhat smaller characteristic scale that predict a tensor-to-scalar ratio of $r \sim 4 \times 10^{-4}$.

In the absence of a detection, PICO would limit the amount of gravitational waves to $r < 10^{-4}$ at 95% CL. This is stronger than current upper limits by three orders of magnitude, and stronger than those expected for the ground-based experiment CMB-S4 by an order of magnitude.

Models of inflation, or the early universe more generally, differ in their predictions for the scalar spectral index n_s and its scale dependence, often referred to as the running of the spectral index

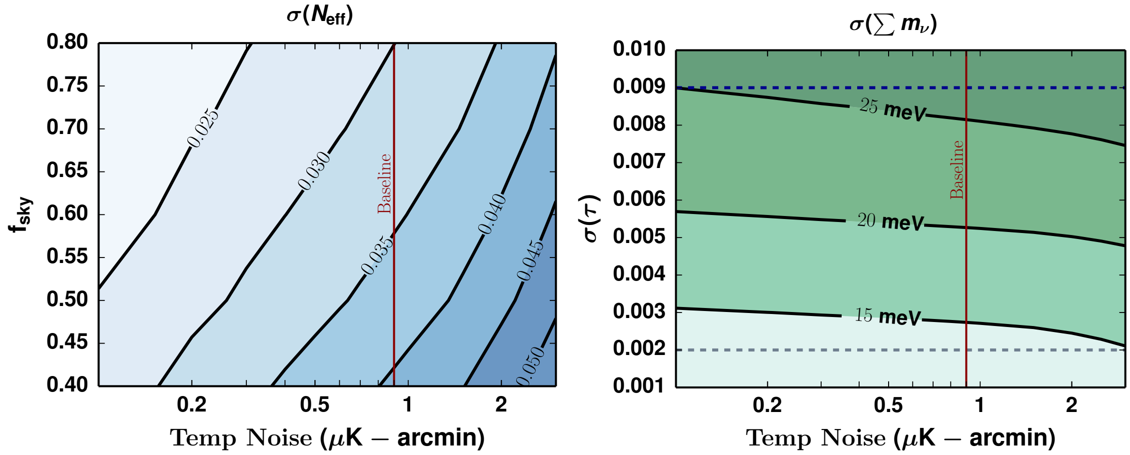

Figure 3: $N_{\rm eff}$ uncertainty as a function of noise and sky fraction (left) and sum of neutrino masses uncertainty as a function of noise and the uncertainty in the measurement of τ, for 0.7 sky fraction (right). The resolution assumed is 5'. Vertical lines denote the expected performance of the 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 [**?**], including residual non-Gaussian covariances. The $\sum m_\nu$ forecasts include DESI BAO.

$n_{\rm run}$. With its high resolution and low noise levels, PICO will improve the constraints on $n_{\rm s}$ and $n_{\rm run}$ by a factor of about two. In addition, PICO will probe the statistical properties of the primordial fluctuations over a wide range of scales with exquisite precision and improve constraints on departures from Gaussianity by a factor $2-3$.

Light relics

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 [**? ?**]. 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 [**? ?**]. 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 3. 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 [**? ? ? ?**].

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 [**? ? ?**]. *Planck* currently excludes WIMPs with mass $m_{\rm dm} < 16$ GeV and a future CMB mission could reach $m_{\rm dm} < 45$ GeV for $f_{\rm sky} = 0.8$. The CMB provides the most stringent constraints on the dark matter annihilation cross section for dark matter in this mass range.

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 [**?**]. 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. [**? ? ?**]).

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 $\sigma \simeq 10^{-39} - 10^{-35}\,{\rm cm}^2$ [**?**]. Spectral distortion measurements also open a new avenue for testing dark matter-proton interactions [**?**].

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., **? ? ? ? ?**].

Neutrino mass

One of the last unknowns of the Standard model of particle physics is the absolute mass scale of the neutrinos. While measurements of neutrino oscillations demonstrate the neutrinos have mass, directly measuring the scale of the masses is challenging experimentally. Current measurement of $N_{\rm eff}$ confirm the existence of a cosmological abundance of neutrinos whose gravitational influence is detectable in the CMB and in large scale structure. 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* [3]. Forecasts for a CMB measurement of $\sum m_\nu$ using the lensing B mode [**?**] are shown in Figure 3. 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 cosmic microwave background (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 [**?**]. 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.
To include: Cosmic Inflation, Particle Physics (Neutrinos and Light Relics), primordial EM fields
Should address these Science Objectives from the STM:

- "Probe the physics of the big bang by detecting the energy scale at which inflation occurred if it is above 4×10^{15} GeV, or place an upper limit if it is below" [r]
- "Probe the physics of the big bang by excluding classes of potentials as the driving force of inflation" [n_s, n_{run}]
- "Determine the sum of neutrino masses, and distinguish between inverted and normal neutrino mass hierarchies" [Σm_ν]
- "Detect departures from or tightly constrain the thermal history of the universe" [N_{eff}]
- Origin of magnetic fields and cosmic birefringence

2.2.2 Cosmic Structure Formation and Evolution (4 pgs. Hill, Battaglia (& Alvarez))

Should address these Science Objectives from the STM that relate to reionization + ??

2.2.3 Galactic Structure and Star Formation (3 pgs, Chuss & Fissel)

Should address these Science Objectives from the STM:

- "Determine whether the interstellar medium of our galaxy is unique by comparing the ratio of energy in magnetic field to turbulence to that in nearby galaxies."
- "Determine if magnetic fields are the dominant cause of low star formation efficiency in our Galaxy."
- "Determine whether radiative torque is responsible for the alignment of dust grains with magnetic fields"
- "Determine the influence of the magnetic field on Galactic dynamics within the Milky Way."

2.3 Measurement Requirements (2 pgs, Hanany & Trangsrud)

Some requirements derive from the science (e.g. τ = full sky, r = depth, lensing = resolution) Some requirements derive from foregrounds (e.g. frequency breadth) and some from systematics (e.g. particular scan pattern)

2.4 Additional Science (2 pgs, de Zotti)

Describe science that we get for free.

2.5 Complementarity with other Measurements and Surveys (1 pg, Lawrence? Schmidt?)

Should describe complementarity with sub-orbital CMB measurements and with other surveys, both in space and on the ground. This is summary text (more detail in subsections about specific objectives)

2.6 Foregrounds (4 pgs, Jacques and Clem)

The state of knowledge and known challenges; how does PICO address the challenges; forecast of performance.

2.7 Systematic Errors (3 pgs, Crill)

In developing the theoretical framework for measuring the faint CMB polarization signal, the CMB community has long recognized the impacts of systematic errors due to instrumentation, observation strategies, and data analysis. A rich literature investigates the types of systematic errors that confound the polarization measurement [1]. Ground-based and suborbital experiments have found themselves to be limited by systematic errors rather than random noise, and have advanced many sophisticated techniques to mitigate systematics, finding both new technological solutions and new analysis techniques. An example in progress made within a single ground-based program can be seen by comparing BICEP's systematics limits at r=0.1[**?**] to those of BICEP2 at r=6×10^{-3}[**?**]). On-orbit systematic errors, especially those related to stability, are likely to be at a lower level as compared to the ground, and in fact all prior on-orbit measurements of CMB polarization were limited by systematic errors until an in-depth study of the systematics was performed and the post-processing data analysis suppressed them[2, 3]. Additionally, recently proposed CMB missions, such as LiteBird and *CORE*, have placed systematic error mitigation at the forefront of the case for their mission[4, 5, 6]. The ground based and suborbital CMB community will continue to develop new techniques in handling systematics.

Note: Calculate a defensible level of acceptable systematics. For example, integrate r 10^{-3} and 10^{-4} power from ell 2-10, 10-50,(do a signal to noise calculation), then state what map rms that corresponds to.

A CMB mission aiming for the unprescedented sensitivity of PICO must control systematic errors to avoid bias or an increased variance of the science measurement. Systematics must be controlled or corrected to a level that enables the PICO science goals (better than 1 nanoKelvin (**Note: make sure this is a correct statement - also be careful about reducing a complicated concept such as systematic errors to a single map rms number, could also quote this as a δr error**) in the map). Mitigation of systematic errors is the most important reason (along with the availability of broad wavelength coverage) to perform a measurement of the CMB polarization from a space telescope; Compared with a ground-based, sub-orbital, or even a space mission in low-Earth orbit, the L2 environment offers excellent stability as well as the ability to observe large fractions of the sky on many time scales without interference from the Sun, Earth, or Moon. This redundancy of observations allows the checking of consisitency of results and an improved ability to correct systematic errors in post-processing analysis.

During the course of the PICO Study, a systematics working group examined systematic errors affecting PICO, Most systematic errors can be mitigated by careful design and engineering of the spacecraft and instrument, and the use of present-day state-of-the-art technology and data analysis tools. However, some systematic errors may limit the precision of the B-mode measurement and the group studied these in further detail. The work was based on the experience of the group's involvement with past missions, in particular Planck, and in recent detailed studies of the *CORE* and LiteBird concepts.

End-to-end simulation of the experiment is an essential tool, including realistic instabilities and non-idealities of the spacecraft, telescope, instrument and folding in data post-processing techniques used to mitigate the effects. Systematics are coupled with the spacecraft scan strategy, and the details of the data analysis pipeline. During the study, the PICO team used simulation and analysis tools developed for the Planck mission[7] and the *CORE* mission concept, adapting them for PICO. These tools allowed a deeper examination of several key systematic errors.

2.7.1 List of Systematics

The systematic errors face by PICO can be categorized into three broad categories 1) Intensity-to-polarization leakage, 2) stability, and 3) straylight. These were prioritized for further study based on the team's assessment of how well these systematics are understood by the community, whether mitigation techniques exist - either in instrument design or in data analysis.

In many cases the systematics are completely mitigated through the use of a polarization modulator such as a half-wave plate or a variable phase delay modulator. For the purposes of the cost constraints of PICO, in each case we investigated mitigation techniques that do not require a modulator.

2.7.2 Absolute polarization angle calibration

The rotation of the CMB polarization can have different causes, including 1. a birefringent primordial Universe, or a Faraday rotation due a primordial magnetic field [11], 2. birefringent foregrounds, or interaction with the Galactic magnetic field, 3. systematic effects in the instrument, and in particular an error on the actual direction of polarization measured by each detector. While the first two sources create a rotation that may depend on scale, position and/or frequency, the latter is expected to mostly depend on the detector considered.

A rotation α of the direction of polarization mixes the Q and U Stokes parameters via $Q \pm iU \longrightarrow e^{\mp i2\alpha}(Q \pm iU)$ and affects the power spectra via (assuming the rotation to be independent on scale and location)

$$\begin{aligned}
C_\ell^{TT} &\longrightarrow & C_\ell^{TT} &= & C_\ell^{TT} \quad &(1a)\\
C_\ell^{TE} &\longrightarrow & \cos 2\alpha\, C_\ell^{TE} &\sim & \left(1-2\alpha^2\right)\, C_\ell^{TE} \quad &(1b)\\
C_\ell^{EE} &\longrightarrow & \cos^2 2\alpha\, C_\ell^{EE} + \sin^2 2\alpha\, C_\ell^{BB} &\sim & C_\ell^{EE} - 4\alpha^2\, \left(C_\ell^{EE} - C_\ell^{BB}\right) \quad &(1c)\\
C_\ell^{BB} &\longrightarrow & \sin^2 2\alpha\, C_\ell^{EE} + \cos^2 2\alpha\, C_\ell^{BB} &\sim & C_\ell^{BB} + 4\alpha^2\, \left(C_\ell^{EE} - C_\ell^{BB}\right) \quad &(1d)\\
C_\ell^{TB} &\longrightarrow & \sin 2\alpha\, C_\ell^{TE} &\sim & 2\alpha\, C_\ell^{TE} \quad &(1e)\\
C_\ell^{EB} &\longrightarrow & \sin 2\alpha \cos 2\alpha \left(C_\ell^{EE} - C_\ell^{BB}\right) &\sim & 2\alpha\, \left(C_\ell^{EE} - C_\ell^{BB}\right) \quad &(1f)
\end{aligned}$$

as illustrated in Fig. 4.

In Planck, the ground measurements of the detectors orientation had an error of $\pm 0.9^o$ (rel.) $\pm 0.3^o$ (abs.) [13].

Name	Description	State-of-the-art	Additional Possible Mitigation
Leakage			
Bandpass Mismatch	Edges and shapes of the the spectral filters vary from detector to detector. leaks T $\rightarrow$ P, P $\rightarrow$ P if the source's bandpass differs from calibrator's bandpass[**?**]	Precise bandpass measurement[**?**]; SRoll algorithm[**?**]; filtering technique[**?**];	polarization modulation; full I/Q/U maps for individual detectors mitigates; additional component solution (see Banerji& Delabrouille (in prep).Current techniques meet requirements.
Beam mismatch	Beam shapes differ between detectors that are combined to reconstruct polarization; leaks T $\rightarrow$ P, P $\rightarrow$ P	See Sect. 2.7.2	Current techniques meet requirements.
Gain mismatch	Relative gain between detectors that are combined to reconstruct polarization; error leaks T$\rightarrow$P	mission-average relative calibration demonstrated to 10^{-4} to 10^{-5} level [**?**]	Sect. 2.7.3 describes effects of stability in time in relative gains.
Time Response Accuracy and Stability	Uncertainty of detector in time constants (measurement errors, time variability) biases polarization angle, pointing and beam size. In a constant spin-rate mission (PICO) is degenerate with the beam shape. leaks T$\rightarrow$P, P$\rightarrow$P	On-orbit reconstruction of time response to 0.1% across a wide signal band[8], residuals corrected as part of beam and map-making algorithm[**?**].	Treatment of residual time response as part of the beam meets requirements.
Readout Cross-talk	Power in one detector leaks into other detectors	*Planck*'s high-impedence bolometers with crosstalk measured at the level of 10^{-3} did not impact CMB polarization science[**?**]. Cross-talk low-impedence bolometers measured at XXX.	State-of-the-art (reconstruction and correction at map-making level) meets requirements.
Polarization Angle	Uncertainty in polarization calibration leaks E$\rightarrow$B.	Knowledge of astrophysical calibrators to 0.3°**(author?)** [9]; ground measurement to 0.9° reconstruction to 0.2° using TB and EB demonstrated by *Planck***?**]	Polarization modulation; See Sect. 2.7.2 for discussion; Must mitigate through developing further analysis techniques.
Cross-polarization	Q$\rightarrow$U rotation by the optical elements of the instrument.	Degenerate with polarization gain calibration.	State-of-the-art polarization gain calibration meets requirement at .
Chromatic beam shape	Beam shape is a function of source SED: measured using a planet, used to build a window function to correct CMB power spectrum.	*Planck* simulations and parameterization as part of the likelihood.	Should be further investigated in Phase A of a mission using physical optics simulations.
Stability			
Pointing jitter	Random pointing error mixes T, E and B at small angular scale	Pointing reconstruction in *Planck* to	
Gain Stability	Time-variation of detector gain due to time variability of bath temperature variations, optical power.	Reconstruction of time variability of gain to 0.2% in *Planck*[**?**].	See Sect. 2.7.3; Gain fluctuations in PICO on the level of XXX% on time scales of YYY can be corrected in post-processing.
Straylight			
Far Sidelobes	Pickup of Galactic signals at large angles from the main beam axis; Spillover can be highly polarized.	*Planck* validated straylight model in anechoic chamber to -80 dBi[10].	Design of optical system and baffling, informed by telescope straylight simulations. See Sect. 2.7.4 for a study of beams calculated with a physical optics code for the PICO telescope and simulated Galactic pickup during the reference mission.
Other			
Residual correlated cosmic ray hits	detectors experience correlated cosmic ray hits below detection threshold resulting in misestimated noise covariance.	*Planck*/HFI found the 5% percent noise correlation due to this effect did not impact results[**?**].	Detector design to reduce cosmic ray cross-section; Current analysis techniques (accounting for correlated noise) meet the needs.

Table 1: Systematic errors expected in PICO's measurement of CMB polarization, with assessment of currently known mitigation techniques. Those systematic errors found to be most likely to impact PICO are described further in the text.

The most recent constraints on cosmological birefringence (or systematic rotation) was set in **(author?)** [14], looking for residual signal in TB and EB spectra, but are dominated by the uncertainties on the detector orientations.

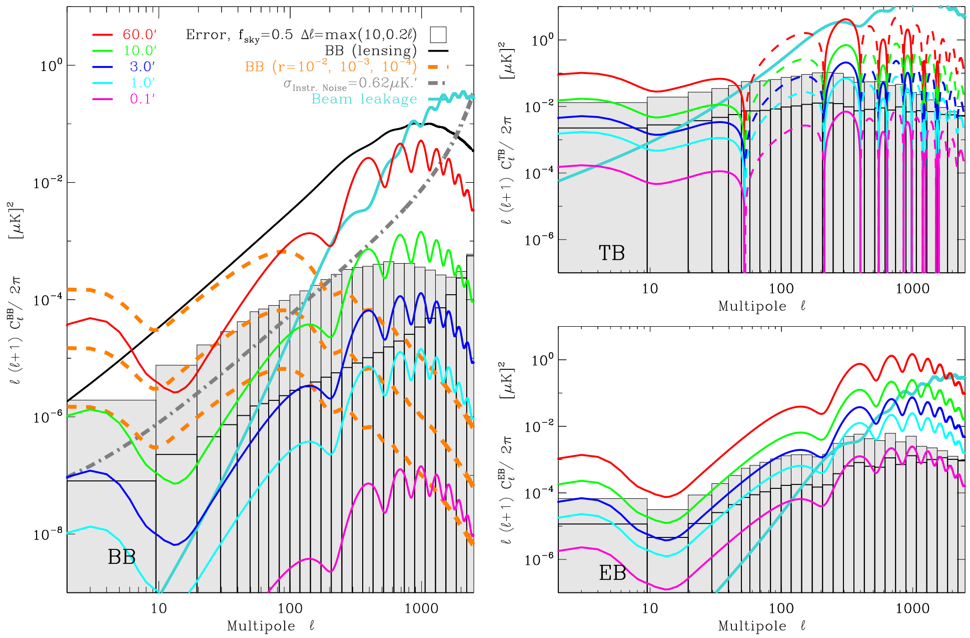

Figure 4: Effect of a rotation of the angle of polarization, assuming the Planck 2018 Λ-CDM best fit model [12] and expected PICOperformances, with a perfect delensing †[(the beam related systematics effects are still arbitrary; to be improved or removed)]†.

In PICO, the relative rotation of the detectors, could be measured with a good accuracy (a few $0.1'$?, †[refs?]†) on the CMB, but the overall rotation is difficult to determine. Known polarized sources, such as the Crab Nebula, could be used to do that but **(author?)** [9] show that the current uncertainty of $0.33^o = 20'$ on the Crab polarization orientation, obtained when combining all the available measurements, would not the measurement of tensorial B modes below $r \sim 0.01$ (assuming everything else to be nominal), far from PICO's target.

Figures 5 and 6 show how the measurement of r by PICO is degraded because of an overall rotation of polarization, and how TB and EB can be used to monitor precisely this rotation, assuming that the only source of polarization rotation is instrumental. These results are obtained assuming the spectra to have a Gaussian likelihood, with a variance $\propto 1/f_{\text{sky}}$, and ignoring the foreground contributions.

TB and EB spectra can detect and measure a global polarisation rotation at levels ($0.1'$) well below those affecting r measurements in BB ($> 1'$). However, in doing such studies, one can not ignore other important aspects of the measurements of CMB polarization: For instance, one has to consider how the delensing will affect the B maps and their final noise levels. At large scales, the interaction with foregrounds makes masking necessary, which creates some extra E to B leakage, and complicates the estimation of B modes and of their likelihood. It also necessitates a proper component separation technique, especially in presence of finite and probably mismatched spectral bandwith of the detectors. The time correlation of the noise (with a $1/f$ spectral shape), will also complicate the analysis. At intermediate and small scales, many other systematics, like those related to beams, will also have to be modeled.

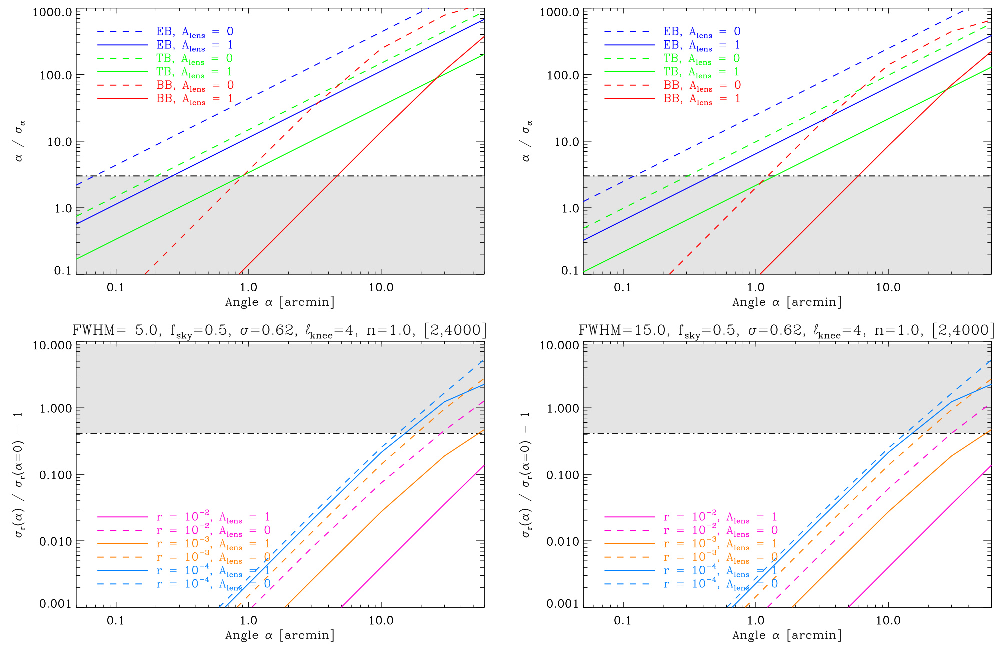

Figure 5: Upper panels: signal to noise ratio of the polarization angle α measurement by EB (blue lines), TB (green lines) and BB (red lines), assuming either no delensing (solid lines) or perfect delensing (dashes); the shaded area is $|\alpha|/\sigma_\alpha < 3$. Lower panels: degradation on measurement of r, for $r = 10^{-2},\ 10^{-3},\ 10^{-4}$ (magenta, orange and cyan lines, respectively), either with no delensing (solid lines) or perfect delensing (dashes). The underlying cosmology is Planck 2018 Λ-CDM model (with $\tau = 0.054$), and assuming a polarized noise of rms = $0.62\mu K.'$ and power spectrum $(1 + (\ell_{\rm knee}/\ell)^n)$ with $\ell_{\rm knee} = 4$ and $n = 1$, with the analysis done on the multipole range $[2, 4000]$ over a sky fraction $f_{\rm sky} = 0.5$. The beam FWHM= $5'$ on the *lhs* and $15'$ on the *rhs* panels.

2.7.3 Gain Stability

Photometric calibration is the process of converting the raw output of the receivers into a physically-meaningful quantity, such as thermodynamic temperature or brightness. As CMB receivers are usually linear, this process reduces to the characterization of the *gain factor* G:

$$y(t) = G(t) \times T\big(\vec{x}(t)\big) + n(t), \tag{2}$$

where $y(t)$ is the timestream of raw samples produced by the detector, $G(t)$ is the gain factor (which we allow to vary with time), T is the sky temperature observed along direction $\vec{x}(t)$ (which varies with time as the spacecraft spins), and $n(t)$ is a noise term that includes both uncorrelated and correlated noise. It is assumed that the timescale of variation in G ($G/\dot{G}$) is much longer than the typical timescale of variations in T: in the case of Planck, this was of the order of several days. In the case of space CMB experiments, the characterization of $G(t)$ is commonly done using the signal caused by the motion of the spacecraft with respect to the rest frame of the CMB itself. This signal is commonly called the *dipole*, as its most significant contribute is at multipole $\ell = 1$. For the PICO concept study, we evaluated the impact of noise in the estimation of $G(t)$ using the tools developed for the Planck/LFI instrument and the CORE mission proposal. The quality of the estimate depends on the noise level of the receiverse, but also on the details of the scanning strategy. The Planck/LFI experiment, because of a poor choice of the scanning strategy parameters

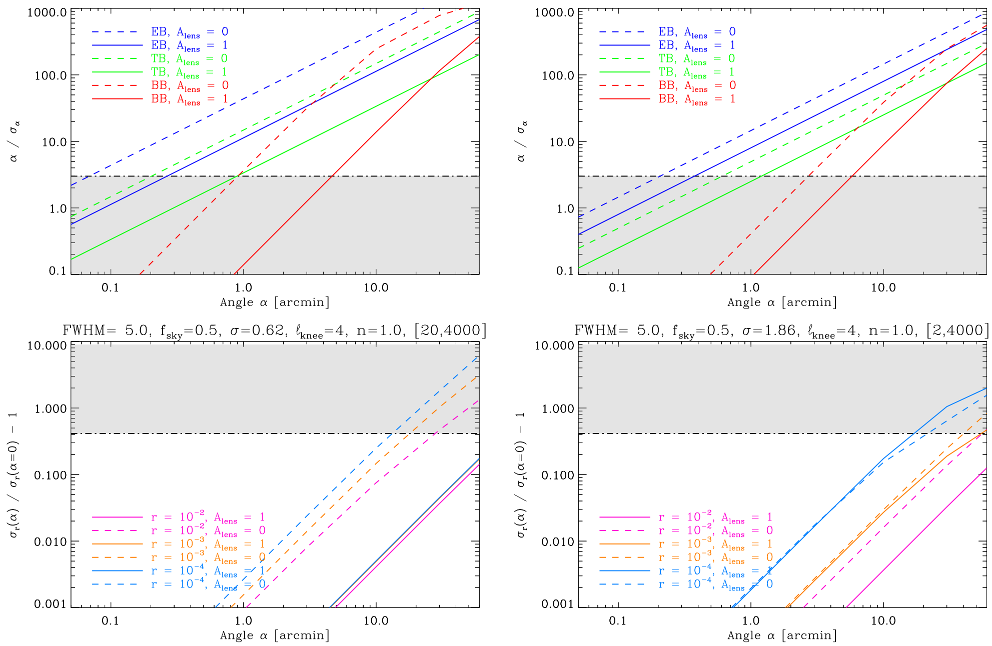

Figure 6: Same as Fig. 5, left panels, reducing the multipole range $[20, 4000]$ (*lhs*) or with a noise rms multiplied by 3 (*rhs*).

(namely, a too slow precession motion), was forced to avoid using one year out of four in the 2015 data release [REF]. We can anticipate that this problem is not expected in PICO, thanks to the significantly faster precession envisaged.
In order to test the impact of calibration uncertainties, we have run the following analysis:

1. We simulated the observation of the sky, assuming four receivers and the nominal scanning strategy. We included both white noise and $1/f$ noise. The sky only contained CMB anisotropies, plus the CMB dipole.

2. We ran the calibration code to fit the dipole against the raw data simulated during step 1.

3. We simulated again the observation of the sky, but this time we used the values of G computed during step 2, which contain errors due to the presence of $n(t)$ and the CMB signal in Eq. (2). The noise in the output map is therefore the sum of the noise in the error on G and the term n.

The presence of foregrounds in the sky signal would cause a bias in the estimation of the calibration constants, due to the presence of large scale features in the Milky Way at microwave frequencies. A full data analysis pipeline for PICO should pair the calibration step with the component separation step, following a schema similar to what has been done by the Planck/LFI team for the 2018 data release [CITATION]: the application of the calibration code should be followed by a component separation analysis, and these two steps should be iterated until the result converge to a solution. In this analysis we assume to study the calibration at the last iteration, when the components have already been properly separated.
Results of the simulation are shown in Figures XXX and YYY. The scanning strategy employed by PICO allows for a much better calibration than in the case of Planck's, thanks to the much faster precession.

2.7.4 Far Sidelobe Pickup

The main beam (within a few degrees of the axis of beam response) in a CMB mission can be measured to high precision using the planets as compact sources. Measurement of each detector's response to signals more than a few degrees off axis, which tends to be at a very low level (more than –80dB less than the peak response) but spread over a very large solid angle, is difficult to do pre-launch, and may not be done accurately after launch. Nonetheless, this far sidelobe can couple bright Galactic signal from many tens of degrees off-axis and confuse it with polarized signal from the CMB off the Galactic plane.

To evaluate this systematic error, GRASP software[1] was used to compute the PICO telescope's pickup over the full sky. This full-sky beam was convolved with a polarized Galactic signal and a full PICO mission scan using the simulation pipeline. The far sidelibe pickup was estimated to contribute less than XXX to the B-mode angular power spectrum and thus an error in r of YYY.

In a real mission due to the difficulties of measuring this beam, physical optics simulation capabilities must be maintained and validated as well as possible with on-orbit data.

2.7.5 Key Findings

Understanding and controlling the effects of systematic errors in a next-generation CMB probe is critical.

The raw sensitivity of the instrument should include enough margin that data subsets can independently achieve the science goals. This allows testing of the results in the data analysis and additional data cuts, if needed.

NASA's support of ground-based and suborbital CMB missions will mitigate risk to a future space mission as PICO by continuing to develop analysis techniques and technology for mitigation of systematic errors.

In a PICO mission's phase A, a complete end-to-end system-level simulation software facility would be developed to assist the team in setting requirements and conducting trades between subsystem requirements while realistically accounting for post-processing mitigation. Any future CMB mission is likely to have similar orbit and scan characteristics to those of PICO, thus there is an opportunity for NASA and the CMB community to invest in further development of this capability now.

3 Instrument (6 pgs, Hanany & Trangsrud)

Telescope (Hanany / Young), focal plane (Hanany / Young), cooling (Trangsrud), readout (O'Brient)
Review: Bock, Hubmayr, Suzuki,

4 Mission (5 pgs, Trangsrud)

To be included: mission architecture, spacecraft and subsystems, orbit, attitude control and determination (Trangsrud)

[1] https://www.ticra.com

5 Technology Maturation (4 pgs, O'Brient & Trangsrud)

Requirements, planned activities, schedules and milestones, estimated cost (O'Brient?)
For each technology include:

- Requirements
- Planned activities
- Schedule and Milestones
- Estimated Cost

6 Management, Risk, Heritage, and Cost (4 pgs, Trangsrud)

cost, risk, heritage (Trangsrud)

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