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ISOCURVATURE FORECASTS FOR PLANCK, CMB S4, AND PIXIE, AND MAYBE CONSTRAINTS FOR ACTPOL

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ABSTRACT

We provide forecasts of cold dark matter isocurvature (CDI) constraints for combinations of Planck, CMB S4, and PIXIE. Using MCMC methods on fiducial power spectra, we find substantial improvements in the measurement of the large scale isocurvature power.

1. INTRODUCTION

The primordial cosmological perturbations are primarily adiabatic fluctuations, which come from a spatially uniform equation of state and initial velocity field and lock together the density perturbations of the different components (Planck Collaboration et al. 2014). Several scenarios allow for spatially varying equations of state or initial velocity fields, producing isocurvature perturbations.

Motivations. Inflation with a single scalar field and slow-roll initial conditions excites only adiabatic perturbations. However, multiple field inflation can produce an isocurvature spectrum as well as an adiabatic spectrum, with possible correlations between the two (Langlois 1999). Commonly studied isocurvature perturbations arise from variations between photon density, cold dark matter (CDM) density, neutrino density (NID), and neutrino velocity (NIV). CDM isocurvature is much more physically well-motivated, as there are few scenarios which can generate neutrino isocurvature. Quantum fluctuations can lead to the curvaton scenario, which generates CDM isocurvature perturbations correlated with the adiabatic modes (Baumann et al. 2009). Some string theory axions can also carry isocurvature fluctuations from quantum fluctuations, with an axion decay to dark matter leading to uncorrelated adiabatic and CDM isocurvature perturbations.

In this paper we forecast constraints on CDM isocurvature using MCMC on fiducial power spectra and simulations of future CMB experiments. The CDM isocurvature contribution to TT, TE, and EE power spectra is out of phase with the adiabatic perturbations in C_l, so improvements in CMB polarization measurements can considerably improve upon current constraints (see Section X.X). CMB-S4, a next-generation ground-based CMB experiment planned for observations in 2021, will involve $\tilde{5}00{,}000$ detectors and provide polarization noise levels with almost a factor of 100 improvement over Planck over $30 \leq l \leq 3000$. PIXIE, a full-sky space telescope proposed for 20XX, will offer similar levels of improvement in polarization but for large scales $2 \leq l < 150$.

Current Constraints. Current measurements of isocurvature are consistent with fully adiabatic primordial density fluctuations. Previous constraints on isocurvature constraints have come from precision measurements of the CMB power spectrum, with WMAP (Moodley et al. 2004) and Planck (Planck Collaboration et al. 2014).

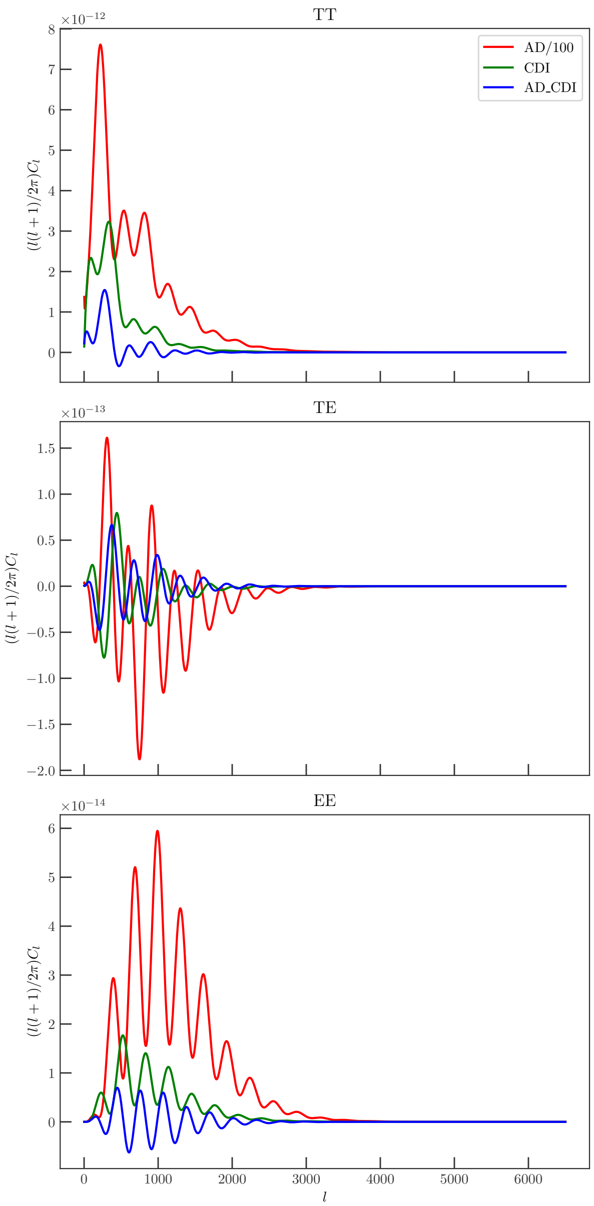

Fig. 1.— Scaled adiabatic and isocurvature contributions to $\mathcal{D}_l$ for a model with nonzero isocurvature consistent with the Planck measurements. overplot ACTPol error bars, plot adiabatic normally and scale isocurvature contributions by 100

Joint WMAP and BAO constraints on fully uncorrelated and anticorrelated modes put upper bounds on the isocurvature at less than a percent (Hinshaw et al. 2013). Should I include actual numbers? The tightest constraints on isocurvature using both Planck temperature and polarization (Planck Collaboration et al. 2016a) currently limit the amplitude of CDM isocurvature fluctuations to 2% at large scales ($k = 0.002$ Mpc^{-1}), and 51.8% at small scales ($k = 0.1$ Mpc^{-1}). These use polarization measurements over the Planck range of $l = 2 - 2508$ for TT and $2 - 1996$ for TE and EE.

Recent Forecasting Papers. Simulated forecasts for only CMB-S4 (Abazajian et al. 2016) predict increases in sensitivity by a factor of 3-6 over Planck for only the curvaton scenario. Smith & Grin (2016) make forecasts using an MCMC analysis for a cosmic-variance limited experiment also for the curvaton scenario. We improve upon these results by including an atmospheric model calibrated for the Atacama desert for CMB-S4, and choose a more general isocurvature model. Muya Kasanda & Moodley (2014) make isocurvature forecasts for the PRISM experiment and investigate the effects of the CMB lensing potential in-depth. While we do not involve PRISM, we do explore combinations of Planck, S4, and PIXIE. should the PRISM citation be included?

What's in each section. In Section 2, we describe the effect of isocurvature on power spectra, and our parametrization of it when sampling. We also discuss how our forecasts are implemented with respect to instrument properties and the resulting noise model. In Section 3, we present our forecasted isocurvature constraints and discuss how different combinations of experiments lead to different sensitivities, and briefly discuss the impact of introducing the ACTPol Season 2 polarization data. In Section ?? we provide some conclusions about the science yield from each experiment and the whether future measurements will be able to differentiate between models for the origin of the primordial density fluctuations.

2. METHODS

2.1. *Perturbations and Power Spectra*

todo: heuristic description of isocurvature effects on CMB power spectra. maybe I include something like the dD_l/dP^j_{II} plots.

Gaussian fluctuations for a general cosmological perturbation are described by a matrix of power spectra, referring to correlations and amplitudes. In this paper, we only consider primordial CDM isocurvature, so the matrix is 2×2 where $\mathcal{P}_{\mathcal{II}}(k)$ is the power spectrum of $\delta\rho_{CDM}/\rho_{CDM}$, with $\rho_{CDM} = n_c/n_\gamma$, the ratio of primordial CDM to photon number densities.

$$\boldsymbol{\mathcal{P}}(k) = \begin{pmatrix} \mathcal{P}_{\mathcal{RR}}(k) & \mathcal{P}_{\mathcal{RI}}(k) \\ \mathcal{P}_{\mathcal{RI}}(k) & \mathcal{P}_{\mathcal{II}}(k) \end{pmatrix} \tag{1}$$

Following Planck Collaboration et al. (2016a), we parametrize $\mathcal{P}_{\mathcal{RR}}$, $\mathcal{P}_{\mathcal{RI}}$, and $\mathcal{P}_{\mathcal{II}}$ by choosing the power at two scales, $k_1 = 0.002$ Mpc^{-1} and $k_2 = 0.100$ Mpc^{-1} and interpolating geometrically,

$$\mathcal{P}_{ab}(k) = \exp\left[\left(\frac{\ln(k) - \ln(k_2)}{\ln(k_1) - \ln(k_2)} \right) \ln\left(\mathcal{P}^1_{ab}\right) + \left(\frac{\ln(k) - \ln(k_1)}{\ln(k_2) - \ln(k_1)} \right) \ln\left(\mathcal{P}^2_{ab}\right) \right].$$

Thus one can recover the tilt by computing the log-log slope,

$$n_{\rm ab} = \frac{\log(\mathcal{P}^2_{\rm ab}/\mathcal{P}^1_{\rm ab})}{\log(k_2/k_1)}. \tag{2}$$

For a set of the standard cosmological parameters with the additional isocurvature parameters, we compute a theoretical power spectrum with CLASS, a fast Boltzmann code written in C (citation). The adiabatic and isocurvature are contained in three functions, $\mathcal{P}_{\mathcal{RR}}(k)$, $\mathcal{P}_{\mathcal{II}}(k)$, and $\mathcal{P}_{\mathcal{RI}}(k)$, the curvature, isocurvature, and cross-correlation power spectra, respectively (cite Planck 2015 XX). We use the same uniform priors as Planck,

$$\mathcal{P}^{(1)}_{\mathcal{RR}}, \mathcal{P}^{(2)}_{\mathcal{RR}} \in (10^{-9}, 10^{-8}), \tag{3}$$

$$\mathcal{P}^{(1)}_{\mathcal{II}}, \mathcal{P}^{(2)}_{\mathcal{II}} \in (0, 10^{-8}), \tag{4}$$

$$\mathcal{P}^{(1)}_{\mathcal{RI}} \in (-10^{-8}, 10^{-8}). \tag{5}$$

We follow Planck 2015 XX's convention of only sampling over $\mathcal{P}^1_{\mathcal{RI}}$ and fixing $\mathcal{P}^{(2)}_{\mathcal{RI}}$ by restricting the correlation fraction to be scale-independent,

$$\cos\Delta_{\rm ab} = \frac{\mathcal{P}_{\rm ab}}{(\mathcal{P}_{\rm aa}\mathcal{P}_{\rm bb})^{1/2}} \in (-1, 1), \tag{6}$$

so that

$$\mathcal{P}^{(2)}_{\rm ab} = \mathcal{P}^{(1)}_{\rm ab} \frac{\left(\mathcal{P}^{(2)}_{\rm aa}\mathcal{P}^{(2)}_{\rm bb}\right)^{1/2}}{\left(\mathcal{P}^{(1)}_{\rm aa}\mathcal{P}^{(1)}_{\rm bb}\right)^{1/2}}. \tag{7}$$

We also present the results in terms of derived parameters following Planck Collaboration et al. (2016a), defining the primordial isocurvature fraction as

$$\beta_{\rm iso}(k) = \frac{\mathcal{P}_{\mathcal{II}}(k)}{\mathcal{P}_{\mathcal{RR}}(k) + \mathcal{P}_{\mathcal{II}}(k)}. \tag{8}$$

Then we sample over the ΛCDM scenario, but replace A_s and n_s with $\mathcal{P}^{(1)}_{\mathcal{RR}}$, $\mathcal{P}^{(2)}_{\mathcal{RR}}$ and add the three isocurvature parameters $\mathcal{P}^{(1)}_{\mathcal{II}}$, $\mathcal{P}^{(2)}_{\mathcal{II}}$, $\mathcal{P}^{(1)}_{\mathcal{RI}}$.

$$\{\Omega_b h^2, \Omega_c h^2, \theta_A, \tau_{reio}, \mathcal{P}^{(1)}_{\mathcal{RR}}, \mathcal{P}^{(2)}_{\mathcal{RR}} \tag{9}$$

$$\mathcal{P}^{(1)}_{\mathcal{II}}, \mathcal{P}^{(2)}_{\mathcal{II}}, \mathcal{P}^{(1)}_{\mathcal{RI}}\} \tag{10}$$

2.2. *Forecasting*

We create mock likelihoods following Perotto et al. (2006), in which for each experiment we are using in our forecasts, we estimate an l-range, $f_{\rm sky}$, beam width $\theta_{\rm fwhm}$, temperature noise σ_T, and polarization noise σ_P. Then we have, for $X, Y \in \{T, E, B\}$ (Perotto et al. 2006),

$$\mathbf{N}^{XY}_l = \delta_{XY}\theta^2_{\rm fwhm}\sigma^2_X \exp\left[l(l+1)\frac{\theta_{\rm fwhm}}{8\ln 2} \right] \tag{11}$$

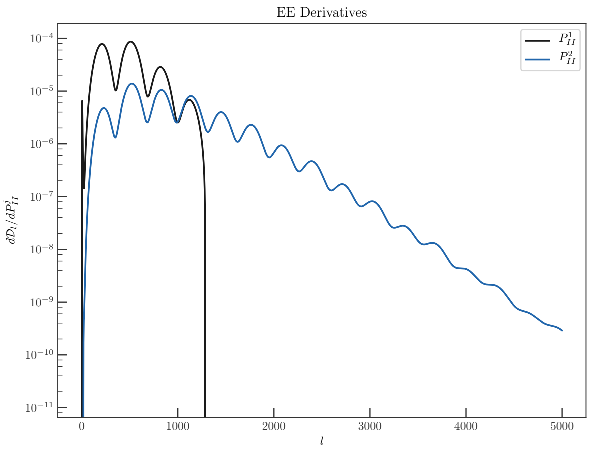

FIG. 2.— A measurement of the impact of the two isocurvature powers $\mathcal{P}^1_{\mathcal{II}}$ and $\mathcal{P}^2_{\mathcal{II}}$, by taking the derivative of $\mathcal{D}_l$ with respect to $\mathcal{P}^i_{\mathcal{II}}$, for a model with nonzero isocurvature consistent with the Planck measurements.

The parameters we use for each experiment are in Table 1.

For CMB-S4, we also include a multiplicative factor for atmospheric noise, in the form of a fitting function with $l_{\rm knee} = 330$, $\alpha = -3.8$,

$$N_l = N_0 \left(1 + \left(\frac{l}{l_{\rm knee}}\right)^{\alpha}\right) \tag{12}$$

We then use this N_l with a fiducial power spectrum generated in CLASS with the Planck 2015 cosmological parameters (Planck Collaboration et al. 2016b). We investigate both a fiducial spectrum with zero isocurvature, and one a relatively extreme model which is still consistent with the Planck constraints.

We find constraints for the isocurvature parameters using these likelihood parameters and Markov Chain Monte Carlo (MCMC) sampling. We use Monte Python, a Python-based implementation of Metropolis-Hastings and interface for cosmological likelihoods. We use six different combinations of experiments.

1. Planck TT ($2 \leq l \leq 2500$), Planck TEB ($2 \leq l \leq 30$).
2. Planck TEB ($2 \leq l \leq 2500$).
3. Planck TEB ($2 \leq l \leq 30$,) CMB-S4 ($30 < l \leq 3000$).
4. PIXIE over ($2 \leq l \leq 150$), Planck TEB ($150 < l \leq 2500$).
5. PIXIE over ($2 \leq l \leq 150$), CMB-S4 ($150 < l \leq 2500$).

3. RESULTS

The bestfit values are $\mathcal{P}^1_{\mathcal{II}} = \textit{something}$, $\mathcal{P}^2_{\mathcal{II}} = \textit{something}$.

- How much does S4 improve the constraint? Numbers!
- What's the effect of low l and high l on these constraints? Refer to figure 1.
- Provide a table with upper bounds on the derived parameters.
- PIXIE's improvement on $\mathcal{P}_{\mathcal{RR}}$ and τ.
- Answer the question "Should I build this experiment to measure isocurvature better?"
- Need good polarization, emphasize
- l ranges that matter

- Write about triangle plot
- Write about derived parameters
- Make a table summarizing various parameters with errors

3.1. *ACTPol Likelihood*

We also calculated the isocurvature constraints provided by the ACTPol Season 2 polarization data. We use the same methods as in Louis et al. 2016 for the ACT likelihood, marginalizing the ACTPol spectrum from $350 < l < 4000$ to construct a Gaussian likelihood function with an overall calibration parameter. We produce our parameter constraints by summing this with the Planck 2015 likelihood. We use the public CMB-marginalized 'plik-lite' Planck 2015 likelihood which uses TT for $30 \leq l \leq 2508$, a likelihood generated from CMB lensing, and a joint TT, EE, BB, and TE likelihood for the range $2 \leq l < 30$. Introducing ACTPol provided a minor improvement of roughly 10% in constraining both $\mathcal{P}^1_{\mathcal{II}}$ and $\mathcal{P}^2_{\mathcal{II}}$.

4. DISCUSSION

- can we constrain or rule out theoretical models?
- CMB-S4 – are there models we can elminate or fit?
- fraction of cosmic variance limit?
- reiterate that isocurvature is a unique probe of the primordial fluctuations

APPENDIX

comparing the fiducial power spectrum Planck parameter estimates with real Planck

REFERENCES

TABLE 1
FORECASTING PARAMETERS

Experiment	l_{min} - l_{max}	$f_{\rm sky}$	$\theta_{\rm FWHM}$	σ_T (μK arcmin)	σ_P (μK arcmin)
CMB-S4	30-3000	0.40	3.0	1.0	1.4
PIXIE	2 - 150	0.8	120	2.9	4.0
Planck 2015 high_l + pol	2 - 2500	0.65	10,7.1,5.0	65.0, 43.0, 66.0	103.0, 81.0, 134.0

NOTE. — Noise parameters for CMB-S4 (Abazajian et al. 2016), PIXIE (FIND CITATION), and Planck + Planck Polarization (Planck Collaboration et al. 2016a). The three Planck noise levels come from three channels at 70, 100 and 143 GHz respectively.

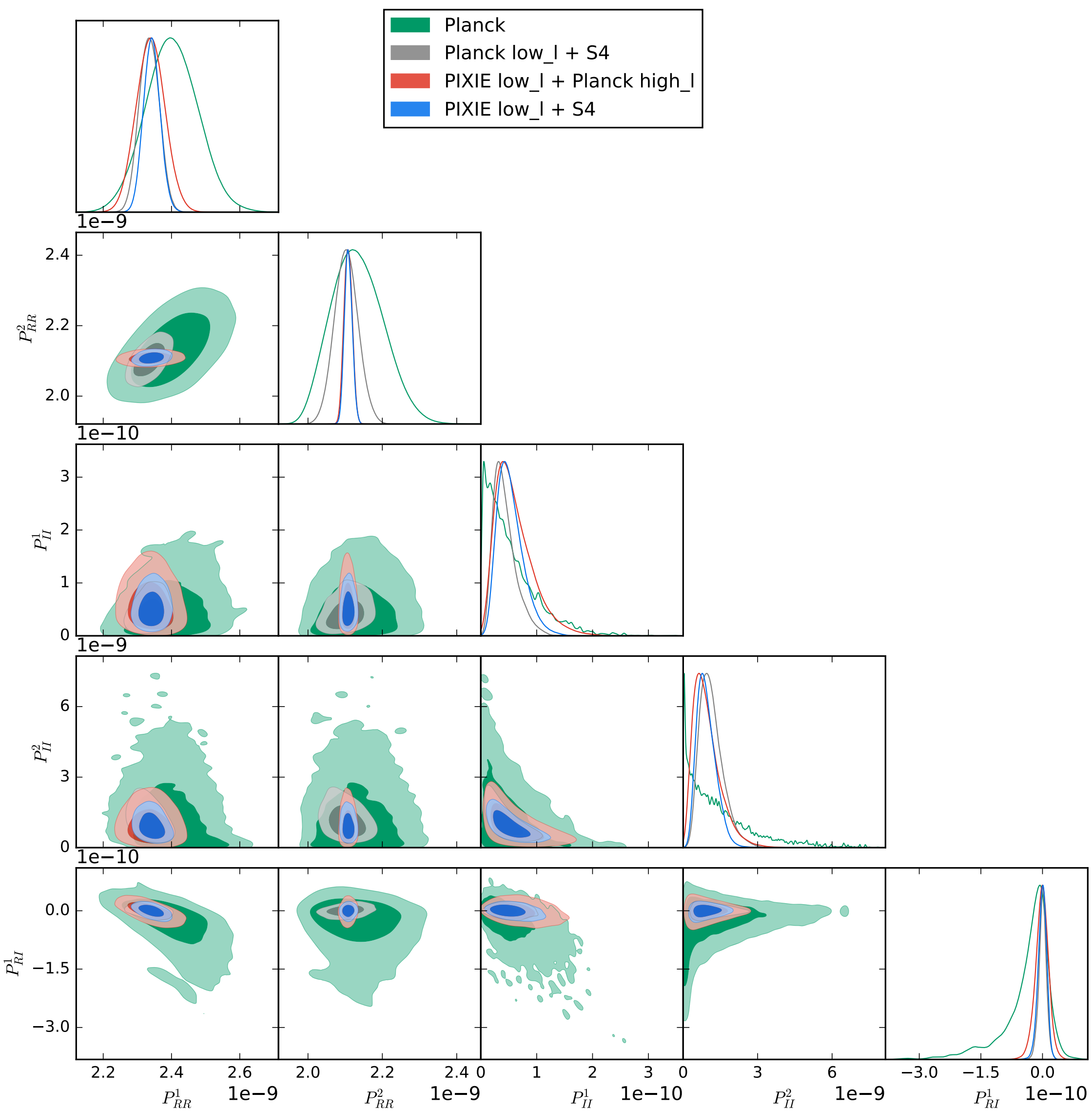

FIG. 3.— Isocurvature constraints for future CMB experiments.

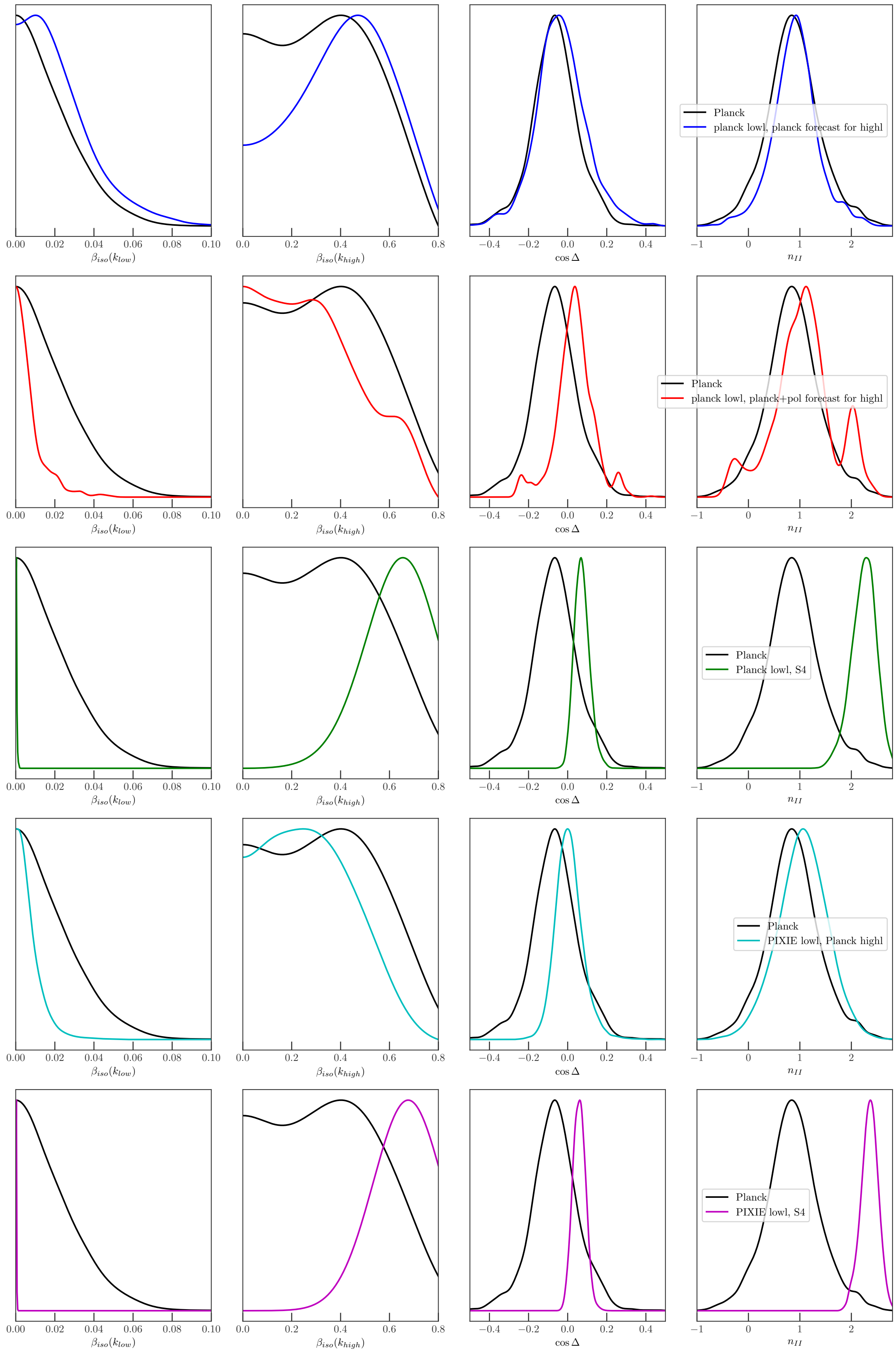

FIG. 4.— Derived parameter estimates for future CMB experiments.

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