Design Validation: Measurement to Science - Light Relics
Systematic studies: beam effects

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Maps to Power Spectra Working Group
  + useful conversations with R. B. Partridge

building on past efforts by Calabrese, van Engelen Green, Meyers 5/2017 +Green, Crawford, Hasselfield, van Engelen 8/2017

CMB-S4 Spring Collaboration Meeting - March 11th, 2021
You shouldn’t beam at the history of this topic …

**Boomerang and the second acoustic peak** …

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**Telescope pointing jitter and change in effective beam by 2’!**

P. de Bernardis *et al.* Nature 404, 955–959 (2000), presentation slides from P. de Bernardis
Beams and neutrino science

- B(eam)asics
  \[ T_{\text{obs}}(\hat{n}) = \int d\hat{n}' B(\hat{n}, \hat{n}') T(\hat{n}') + \text{noise} \]

- Mean beam (e.g. DSR S4 forecast)

- Standard model

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**Figure 75.** Impact of changes to the noise level, beam size, and sky fraction on forecasted 1σ constraints on \( N_{\text{eff}} \) with \( Y_p \) fixed by BBN consistency. Changes to \( f_{\text{sky}} \) are taken here at fixed map depth. The forecasts shown in this figure have less detailed modeling of atmospheric effects and foreground cleaning than those shown elsewhere. The results should therefore be taken as a guide to how various experimental design choices impact the constraining power for light relics, but the specific values of the constraints should be taken to be accurate only at the level of about 10%.

\[ \theta_{\text{FWHM}} \text{ from arXiv:1907.04473} \]

\[ N_{\text{eff}} = 3.045 \] — fraction from decoupling details, e.g. 1606.06986
**ACT/SPT-3G beams**

- Roughly a Central Gaussian with $\sim 1/\theta^3$ sidelobe

*Dutcher et al. 2021 (2018 data)*


- Beam error driven by residual atmospheric noise in planetary flux, fitting noise, CMB fluctuations, + others…

- FWHM of $\sim 1.0'$ at 150 Ghz (~target for S4-LATS), $\sim 1\%$ uncertainty

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**Fig. 2** — Window functions for the mean instantaneous beam of each array and band in each season. The window functions used for interpretation of the survey maps are slightly modified to account for residual pointing variance in the observations contributing to each map. The window function errors shown in the bottom panel are strongly correlated between multipoles.
Beam uncertainty as a nuisance parameter

- Beam parameters can be treated as other parameters for Fisher forecasting purposes.

\[
C_\ell^\text{map} = C_\ell^\text{theory} B_\ell^2 + N_\ell \rightarrow \hat{C}_\ell^\text{theory} = \left\{ 1 - \frac{2\delta B_\ell}{B_\ell} \right\} C_\ell^\text{theory}
\]

- Beam expanded in terms of eigen-modes of beam covariance:

\[
\delta B_\ell = \sum_i a_i f^i_\ell \quad \quad \Sigma_{\ell\ell'} \equiv \langle \delta B_\ell \delta B_{\ell'} \rangle
\]

- Fisher analysis with beam uncertainty folded in —

\[
\bar{\theta} = \{ \Omega_c h^2, \Omega_b h^2, A_s, n_s, N_\nu, \tau, H_0 \} \rightarrow \{ \Omega_c h^2, \Omega_b h^2, A_s, n_s, N_\nu, \tau, H_0, [a_1, \ldots, a_n] \}
\]

\[
\tilde{F}_{\alpha\beta} = F_{\alpha\beta} + \frac{\delta_{\alpha\beta}}{\sigma_{i=\alpha}^2}
\]

Forecasts done with modified Fisher module from DRAFT tool, S. Raghunathan

https://github.com/sriniraghunathan/cmbs4_fisher_forecasting

- Explore SPT/ACTPol type beams, with better uncertainties
Seasonal/detector/field driven beam variations

Beam data products from https://lambda.gsfc.nasa.gov/product/act/actpol_prod_table.cfm

ACT — 2008-2018 data, 2020 papers
Ongoing efforts have noticeably different eigenmodes:
(3G vs. ACTPol)

Preliminary beams provided for analysis by SPT-3G collaboration

Eigenmode Plot by N. G-Wald, F. Cyr-Racine
Seasonal/detector/field driven beam variations- effect on $N_{\text{eff}}$

Normalization chosen so that $\{\sigma_i = 1\} \forall i \rightarrow$ reproduces fiducial experimental error.
Hypothetical S4 with 3G/ACTPol-`like' beams

plots here by D.G. and F. C-R.
**Spectra of point-source beam calibrators**


- Beams used are from point sources (AGN, synchrotron), signal of interest is thermal
- Diffraction freq. dep. variation in beams: $\theta_{\text{FWHM}} \propto 1/\nu$
Impact of non-thermal point-source beam calibrators: 
*Preliminary results*

\[
\nu_0 = 145 \text{ GHz}, \Delta \nu = 36 \text{ GHz}, \theta_{\text{FWHM,true}} = 1.4' 
\]

*Next step - fold into cosmological parameter sensitivity forecasting*
Take-aways and next steps…

✴ Moderate (factor of 3-10) improvement in beam calibration needed to meet hot relic science goals

✴ More realistic follow-up: Use DRAFT tool to run full sky cut, secondary, point source, parameter forecasts, “observe” with different beams used sampling from existing eigenmodes with varying prior

✴ Explore additional effects - Non-thermal source calibration, Jitter-convolved beams, temperature-polarization leakage
Other science targets (inflation, primordial power spectrum)

1.2 Primordial gravitational waves and inflation

Figure 8. Forecast of CMB-S4 constraints in the $n_s$–$r$ plane for a fiducial model with $r = 0$. Also shown are the current best constraints from a combination of the BICEP2/Keck Array experiments and Planck [5]. The Starobinsky model and Higgs inflation are shown as small and large orange filled circles. The lines show the classes of model that naturally explain the observed value of $n_s$. The corresponding potentials all either polynomially or exponentially approach a plateau. The scale in field space over which the potential approaches the plateau is referred to as the "characteristic scale" (see Ref. [3] for more details). We show different values, $M = M_P/2$, $M = M_P$, $M = 2M_P$, and $M = 5M_P$. Longer dashes correspond to larger values of the scale $M$. The Planck scale plays an important role because the gravitational scale and the characteristic scale share a common origin. The number of e-folds $N^{\ast}$ chosen for the figure corresponds to nearly instantaneous reheating, which leads to the smallest values for $r$ for a given model. Other reheating scenarios predict larger values of $r$ and are easier to detect or exclude.

Fig. 7, and the entire class of models is shown in Fig. 8. The second class consists of models in which the potential $V(a)$ approaches a plateau, either polynomially or exponentially. The potential for models in this class has a characteristic scale over which the potential varies [3]. The sensitivity of CMB-S4 is chosen to exclude all models in this class with a characteristic scale that exceeds the Planck scale. The Planck scale constitutes an important threshold because the scale of gravitational interactions and the characteristic scale may share a common origin and be linked to each other, such as in the Starobinsky model [7], in Higgs inflation [8], or more general models involving non-minimally coupled scalar fields. As a consequence, even in the absence of a detection CMB-S4 would significantly advance our understanding of inflation, and would dramatically affect how we think about the theory. The classes of model that naturally predict the observed value of $n_s$, together with current constraints and constraints expected for CMB-S4, are shown in Fig. 8.

1.2.2 Primordial density perturbations

CMB-S4 can also seek to characterize the primordial Universe by searching for well-motivated signatures in the scalar fluctuations, in the primordial power spectrum, and non-Gaussianities.

More generally …

plots here by D.G. and F. C-R.

arXiv:1907.04473
SPT-3G beam calibration

- Roughly a Central Gaussian with $\sim 1/\theta^3$ sidelobe
- Beams calibrated using brightest QSOs in the 1500 deg$^2$ field and five dedicated Mars observations (2018), convolved with pointing jitter. Dutcher et al. 2021, arxiv: 2101.01684, applying stitching technique of Schaffer et al. 2011, Story et al. 2013, Crites et al. 2015

- Beam error driven by residual atmospheric noise in planetary flux, fitting noise, CMB fluctuations, + others…
- FWHM of 1.0’ at 90 Ghz, 1.4’ at 150 Ghz, 1.2’ at 220 GhZ (~target for S4-LATS), 1.5% uncertainty

* Dutcher et al. 2021 (2019 data)
Mean beams but not beam errors included in DSR forecasts, even though beam covariance enters any real-life data analysis (e.g. SPT-3G 2020, ACTPol 2020)
SPT-3G beam calibration

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Dutcher et al. 2021 (2019 data)
ACTPol beam calibration

- Roughly a Central Gaussian with ~ $1/\theta^3$ sidelobe
- Observations of Uranus, Saturn
- FWHM of 1.4' at 140 Ghz (~target for S4-LATS)

Fig. 1.— The average 98 GHz (cyan) and 150 GHz (black) beam profiles in “gain above isotropic” ($4\pi/\Omega_B$). The forward gains are 74.5 and 78.4 dBi respectively. The two dashed curves on the bottom show the scattering beam due to the surface roughness. For reference, the blue dash-dot line, offset for clarity, shows the slope of a $1/\theta^3$ profile. Negative values due to noise fluctuations are not plotted.
Past collaboration work

Calabrese, van Engelen Green, Meyers 5/2017

\[ B_\ell = e^{\ell(\ell+1)\sigma^2} \left\{ b_1 + b_2 (\ell/3000) + b_3 (\ell/3000)^2 \right\} \]

Point-source secondaries

\[ D_{\ell}^{TT,ps} \approx 6 \left( \frac{\ell}{3000} \right)^2 (\mu K)^2 \]
\[ D_{\ell}^{EE,ps} \approx 3 \times 10^{-3} \times D_{\ell}^{TT,ps} \]

Atmospheric noise

\[ N_{\ell}^{TT} \rightarrow N_{\ell}^{TT} \left[ 1 + \left( \frac{l}{3400} \right)^{-4.7} \right] \]
\[ N_{\ell}^{EE} \rightarrow N_{\ell}^{EE} \left[ 1 + \left( \frac{l}{340} \right)^{-4.7} \right] \]

Green, Crawford, Hasselfield van Engelen 8/2017

using ACT 2013 eigenmodes