Beam calibration campaign requirements to control temperature-to-polarisation leakage for CMB-Stage 4

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From Planck to the future of the CMB - Ferrara - May 23th, 2022

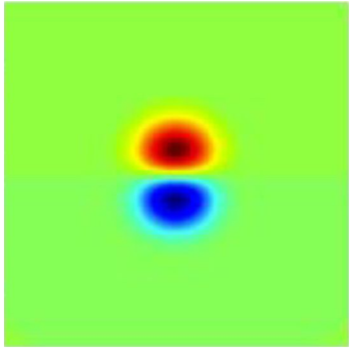
Context

- CMB-Stage 4 Small Aperture Telescopes (SATs)
  - 18 SATs to be deployed at the geographic South Pole (baseline)
  - Specifically targeting low-ℓ B-modes with $\sigma(r) = 5 \times 10^{-4}$
  - On going effort to model SATs systematics and deriving calibration requirements (→ see also Kirit Karkare's talk tomorrow!)
- Heritage design from the BICEP/*Keck* telescopes
  - Compact, on-axis, refractive optics
  - Polarisation reconstruction achieved by pair difference
- Temperature-to-polarisation leakage arising from mismatched beams
  - Deprojection/subtraction of common, low order modes
    → what about **undeprojected beam residuals?**
    → we can estimate their impact on *r* using high fidelity beam maps

How well do we need to characterise S4 beams to meet σ(r) requirement?

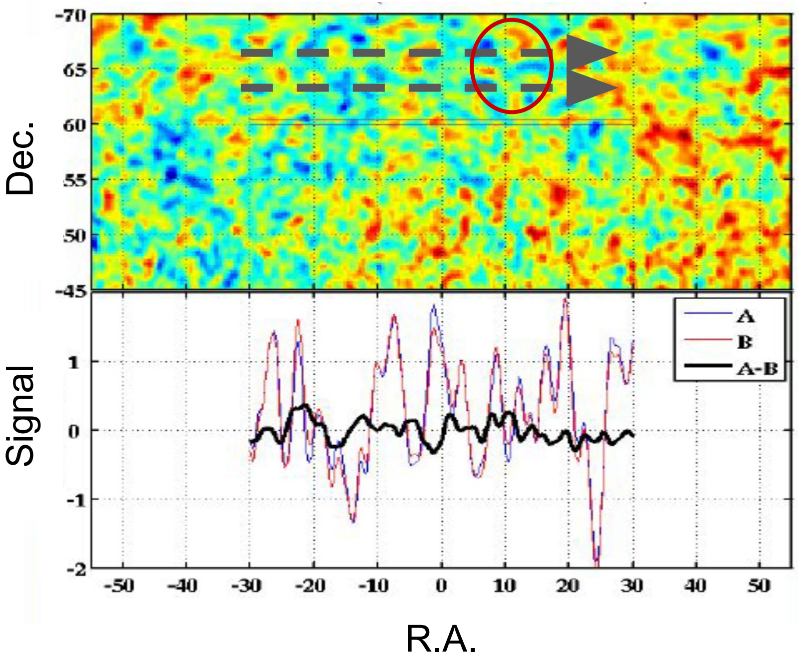
T→P leakage mechanism

Polarised signal = (A-B)/2
→ If the A beam does not match the B beam, temperature does *not* cancel, leading to
temperature-to-polarization leakage



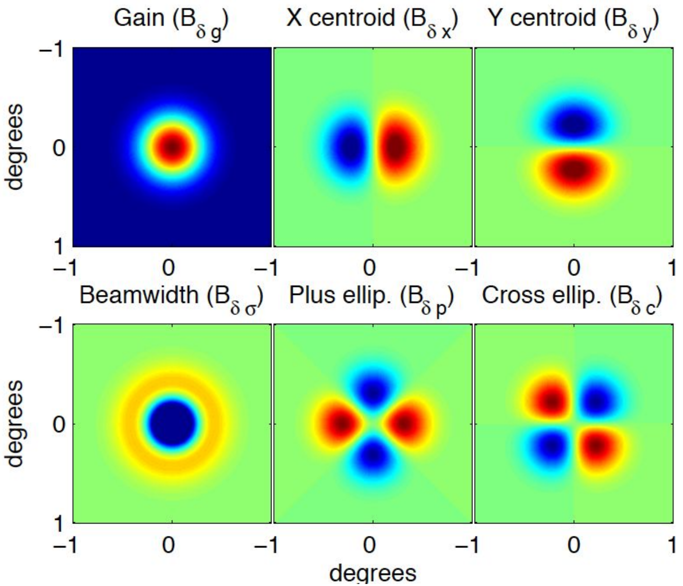
Differential pointing in the y direction, measured in beam map space

Pointing of A and B is **slightly offset** as they scan across the sky

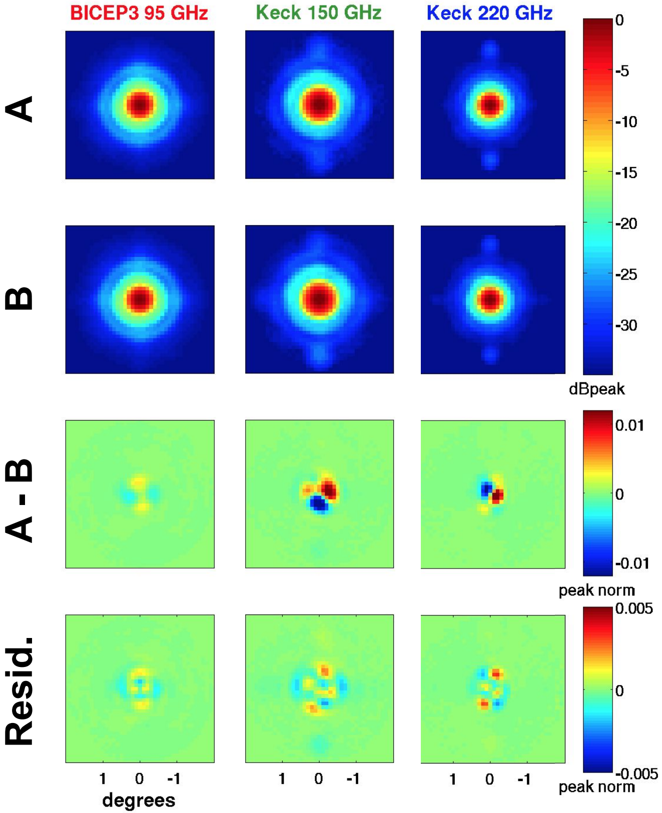


T→P leakage from differential pointing in timestream space

T→P leakage mitigation



We **deproject the 6 lowest orders** of an expansion of our measured beam profile, by regressing against the Planck T sky and its derivatives



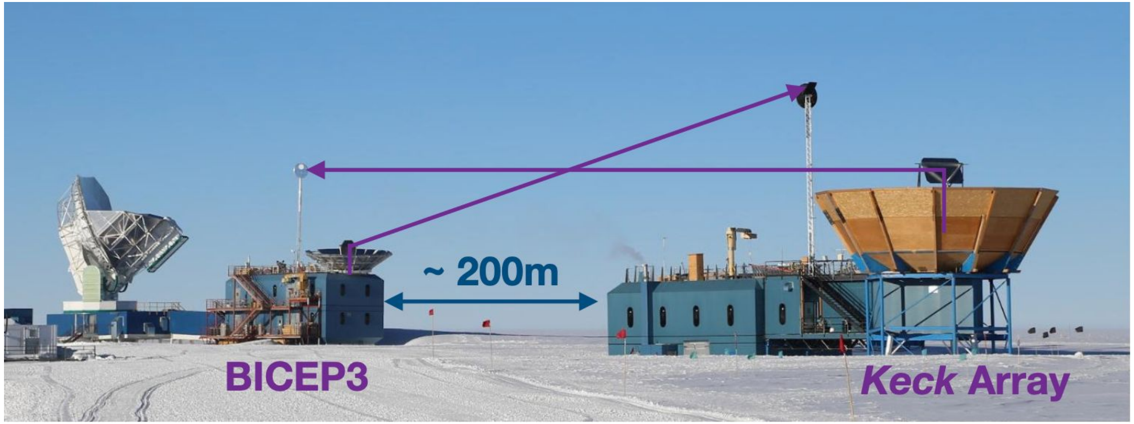
After each mode is deprojected out, what remains are the **undeprojected beam residuals**

These cause unmitigated T→P leakage!

Far Field Beam Mapping at the South Pole

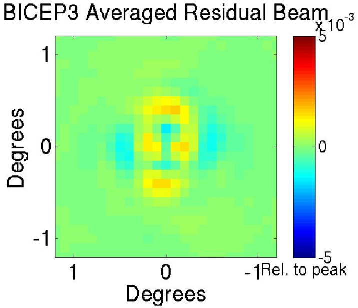
- We take high fidelity, deep beam maps by observing a 24 inches* chopped thermal source in the far field of the telescope

  * that's 61 cm if you don't speak imperial units;)
- Measuring every beam on the focal plane (FOV ~28°) with 0.1° resolution takes 11 hours
- We typically spend several weeks repeating measurements at different boresight angles for systematics checks



T→P leakage analysis framework

Goal: estimate T→P leakage bias on *r* from undeprojected main beam residuals



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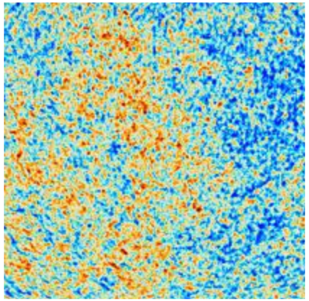
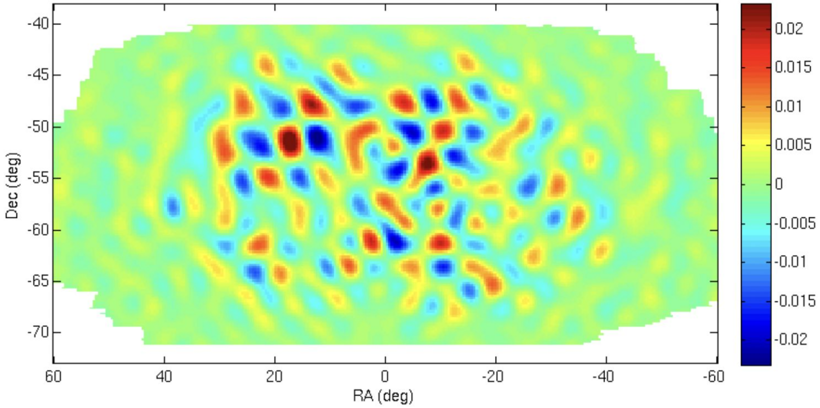


1. Construct **T→P leakage map template** by convolving measured differential beams with T only CMB map, following actual scanning strategy



So-called "beam sim" representing expected T→P leakage in the BICEP field from undeprojected main beam residuals (purified B map shown here)

T→P leakage analysis framework

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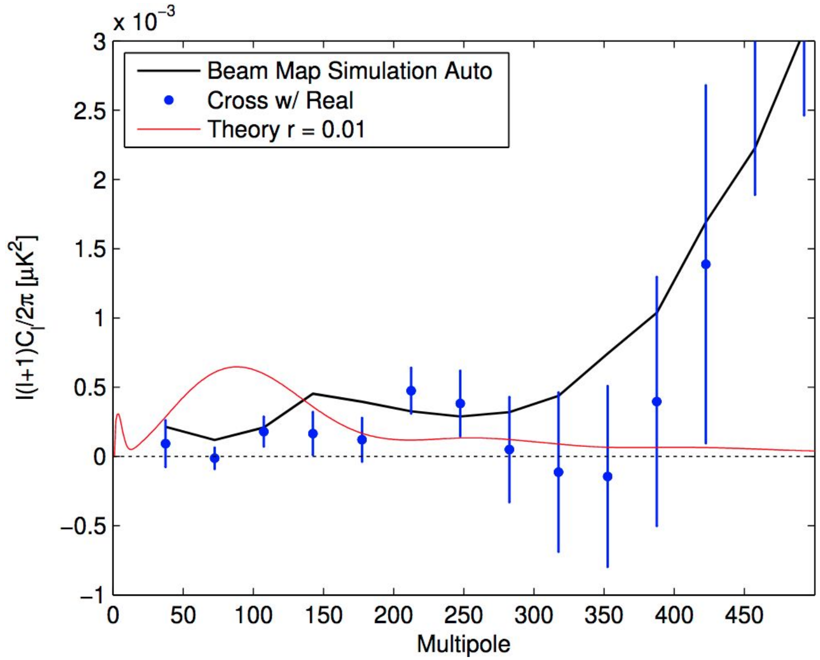


BB T → P leakage in BICEP3
BK18 - Appendix F

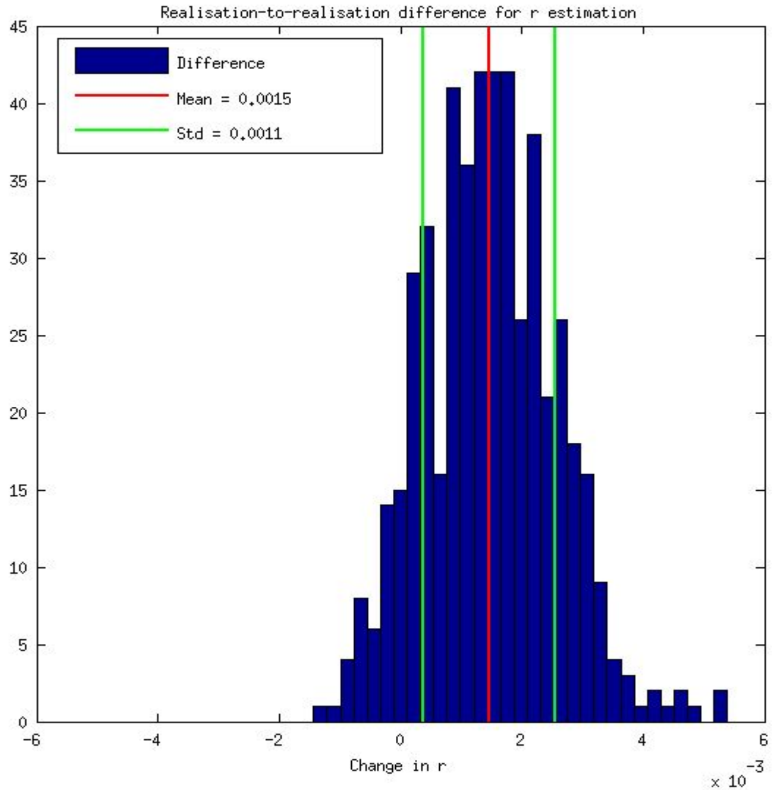
1. Construct T→P leakage map template by convolving measured differential beams with T only CMB map, following actual scanning strategy
2. Take **auto and cross-spectrum of this map template** with BK maps/sims

TP leakage map template x BK CMB maps

The cross-spectrum with real data is ~half the amplitude of the auto spectra, with somewhat large error bars when crossing with 499 sims

T→P leakage analysis framework

Goal: estimate T→P leakage bias on *r* from undeprojected main beam residuals



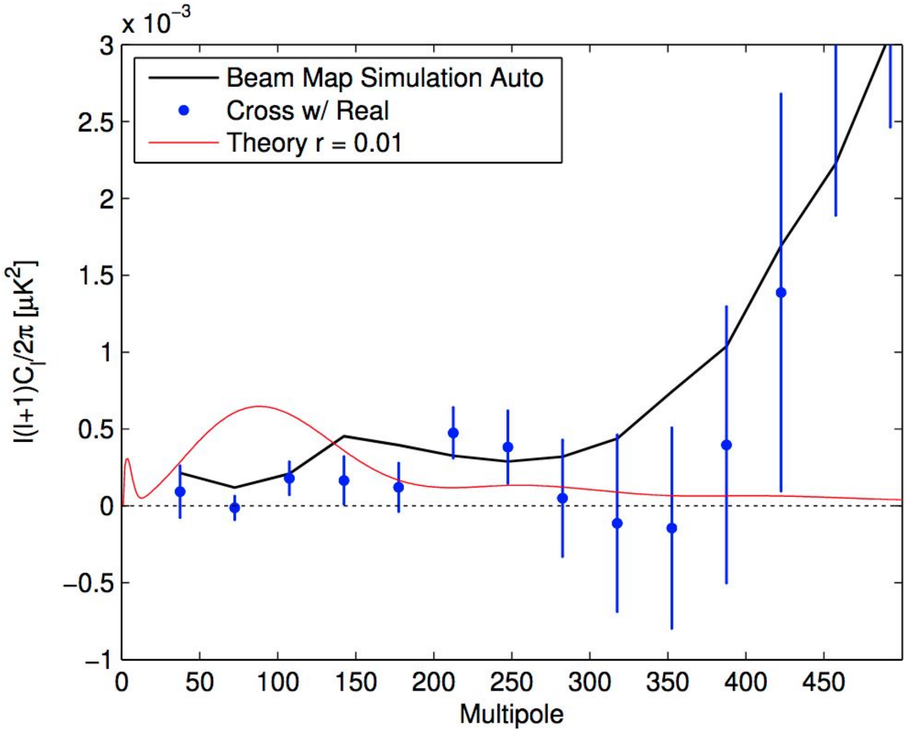
1. Construct T→P leakage map template by convolving measured differential beams with T only CMB map, following actual scanning strategy
2. Take cross-spectrum of this map template with BK maps/sims
3. Add cross-spectrum to sims for likelihood search, and **compute shift in *r* best fit**

BK18: **$\Delta(r) = (1.5 \pm 1.1) \times 10^{-3}$**

$\sigma(r) = 9 \times 10^{-3}$

That's not good enough for S4 sensitivity, even if we had better matched beams

What limits the uncertainty σ(Δ(r))?



TP leakage map template x CMB maps

Noise in the CMB maps

- Directly tied to instrument achieved sensitivity
- Currently driving factor on the final uncertainty

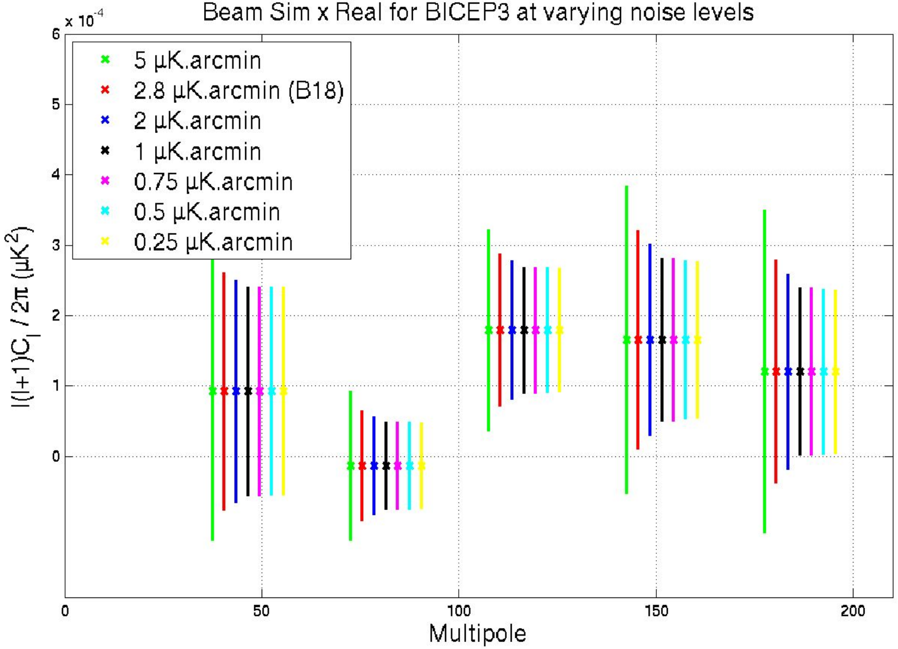
Calibration noise in the beam maps

- Statistical noise & how it scales with number of beam maps/detector
- Systematic noise & contamination

Noise in the CMB maps

- Beam map data is fixed and identical to BK18
- Cross-spectrum between TP leakage map template with sims with scaled CMB noise

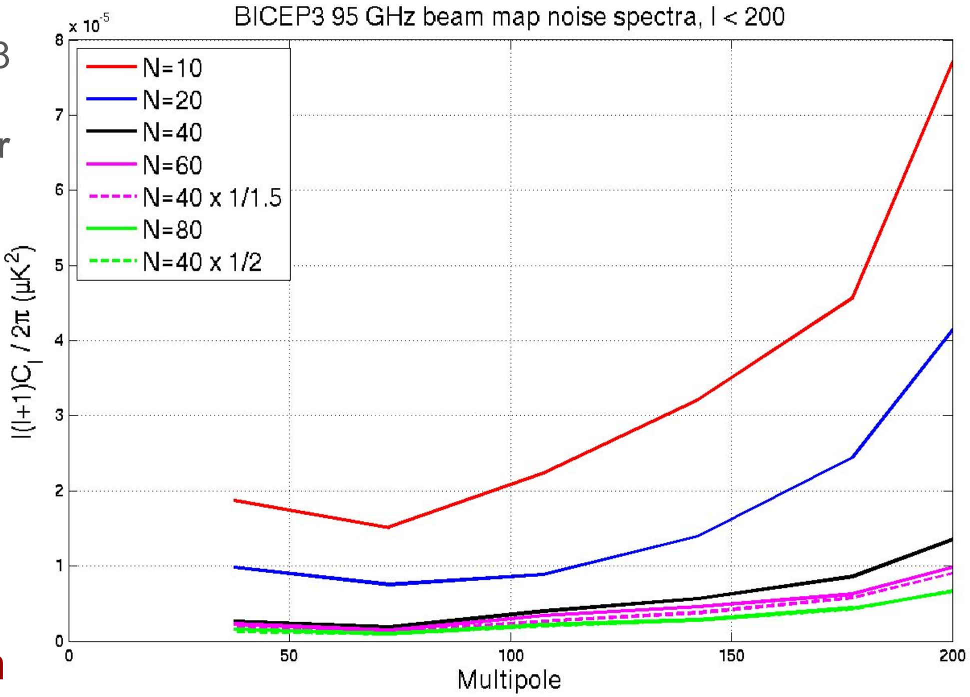
At S4 level of CMB sensitivity, our current beam mapping strategy does not yield sufficient beam map sensitivity



Noise in CMB map [μK.arcmin]	5	2.8 (BK18)	2	1	0.25
$\sigma(\Delta(r)) \times 10^{-4}$	13	10	8.6	8.7	8.4

Noise in the beam maps

- Statistical noise
  - CMB data is fixed and identical to BK18
  - **Uncertainty on cross spectra and σ (Δ(r)) scales as 1/√N with the number of beam map N used to produce the TP leakage map template**
- Systematic contamination
  - Demodulation systematics
  - Other factors?



The scaling of σ(Δ(r)) with statistical noise in the beam maps is relatively well understood, but we need to investigate systematic contamination better because it's the dominant noise source

Investigating noise in the beam maps

- Different scanning strategy to construct more reliable noise estimates
  - Current way of estimating noise in individual beam maps suffers from coverage issues for a given detector
  - We'd like a straightforward correspondence
    number of beam maps → statistical noise in a combined beam map
- Different chopper rate for a given instrument and chopper size
  - Amplitude-dependent noise from demodulation, maybe linked to chopper rate?
  - Test demodulation routines
  - Chopping slower would ease constraints on large hardware required for future experiments

We took data to investigate this in Nov 2021 with BICEP3 - analysis on-going!

Conclusion - Toward a beam calibration plan for the SATs

✅ **Demonstrated approach**

- End-to-end framework going from beam map data to bias on *r*
- Preliminary results & fairly good understanding of limitations

👉 **Next steps!**

- within this framework…
  - better understanding of beam map noise
  - multi-frequency configuration
- .. and other avenues to explore!
  - refine deprojection framework to lower Δ(r)
  - include the T→P leakage information in the *r* pipeline analysis
  - explore regions of the beam further away from the main beam