SAT Beam Systematics

Clara Vergès, Kirit Karkare

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Outline

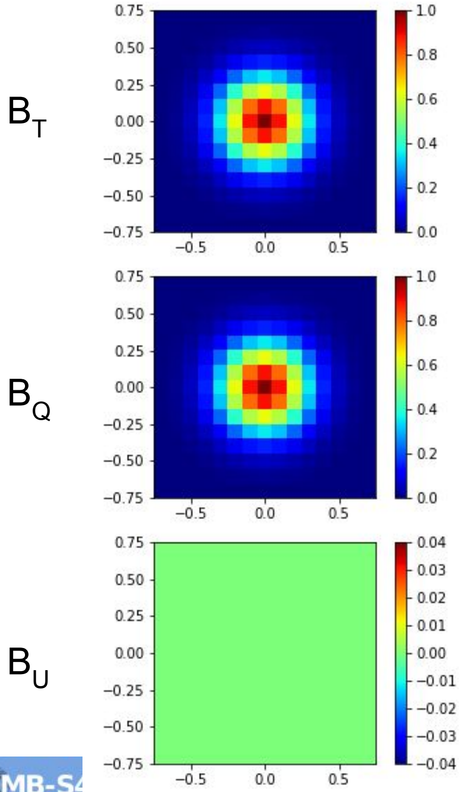
- Brief overview of potential beam systematics and relevant definitions
- Beam requirements update
- Systematics forecasting
  - Preliminary beam map sensitivity results
  - Plans to extend for generic calibration requirements

Beam Systematics

- Departures from ideal, matched beams within a polarized detector pair can cause leakage from T→P or E→B
  - HWP non-idealities can cause similar leakage
- A large part of this leakage (lowest-order modes) can be modeled/marginalized out with deprojection, but we still need to minimize beam mismatch in hardware and quantify the unmodeled residuals.
- We are now working on setting concrete requirements on
  - Beams/optics using language most relevant for SAT systematics
  - Calibration/measurements needed for verification
- Requirements should be general enough for HWP possibility

TQU Beam Definitions

$$\int d\Omega \left[B_T(\mathbf{x})T(\mathbf{x}) + B_Q(\mathbf{x})Q(\mathbf{x}) + B_U(\mathbf{x})U(\mathbf{x})\right]$$



Ideal detector:

- $B_T = B_Q$
- $B_U = 0$

A dedicated beam definitions document will supplement the SAT optics requirements

References: BK-IV 1502.00596
BK-XI 1904.01640

TQU Beam Definitions

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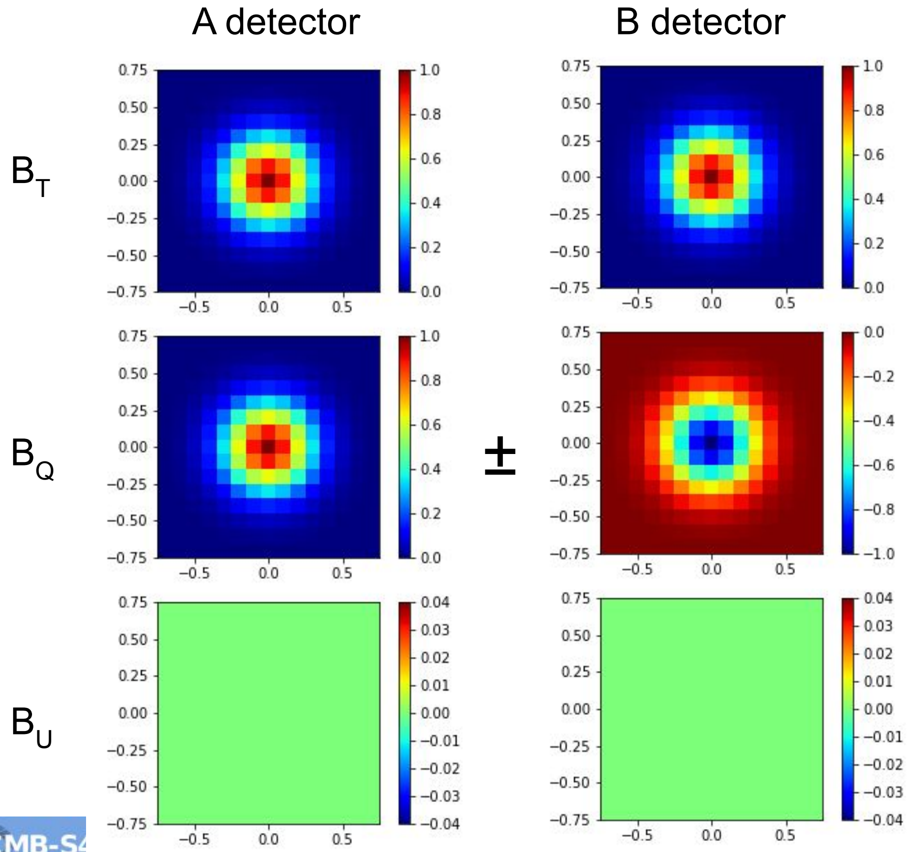
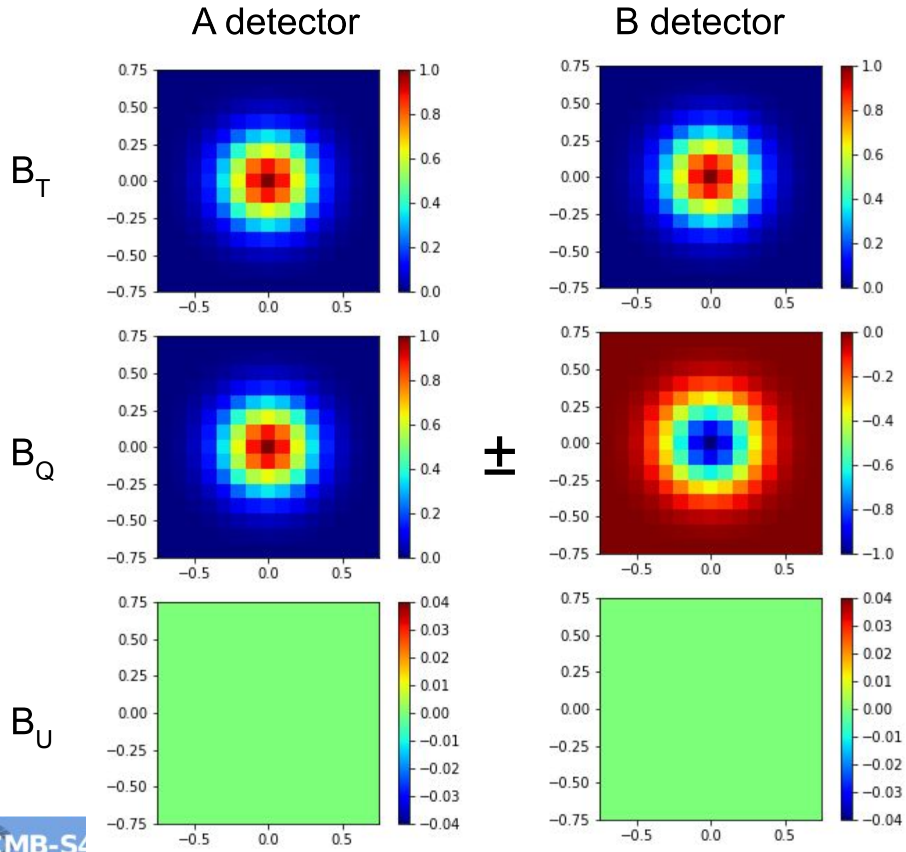


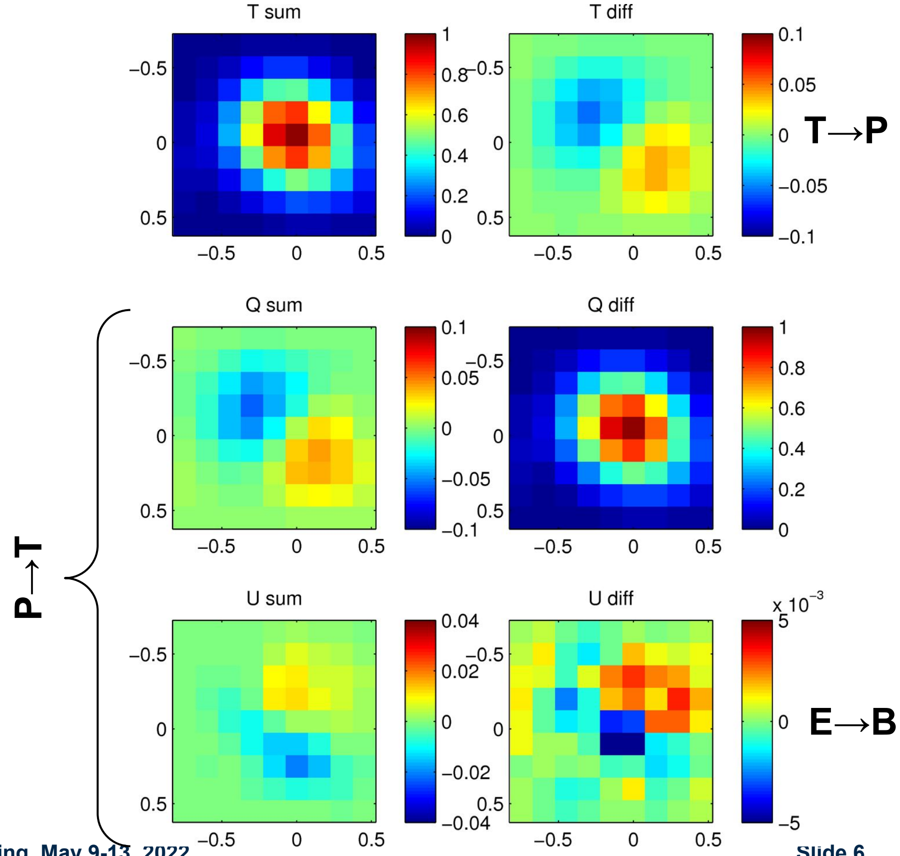
Ideal pair sum: T only
Ideal pair difference: Q only

(B detector is sensitive to -Q)

TQU Beam Definitions

$$\int d\Omega\,[B_T(\mathbf{x})T(\mathbf{x}) + B_Q(\mathbf{x})Q(\mathbf{x}) + B_U(\mathbf{x})U(\mathbf{x})]$$





Beam Regions and Measurements

- **Main beam**:
  - Response out to the first minimum
  - FWHM for each frequency set by L1/L2 requirements
- **Sidelobes**
  - Near/Mid sidelobes are within the FOV of the instrument, set by the forebaffle cutoff (~30 deg)
  - Far sidelobes are outside the FOV
- **Measurements**
  - Near field
    - Hot thermal chopper in the near field (at aperture & forebaffle) for beam power exiting the window
  - Far field (mast on separate building)
    - Thermal chopper for T beams in the FOV
    - Amplified polarized source for QU beams in the FOV
  - Mid field (mast adjacent to mount)
    - Amplified polarized source for far sidelobes

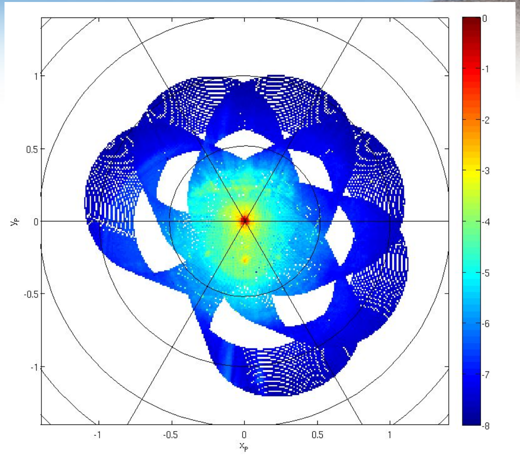
Refining Beam Requirements

L2: Spurious polarized signal power from beams delivered to the detector modules for integrated polarization maps shall not exceed 10% of the final statistical uncertainty on the angular power spectrum at any multipole from 40 to 200.

Break out into specific measurements at L3 level, e.g.

- **In FOV of instrument**: Leakage from T→P and E→B shall be < XXX
  - Verified by convolution of TQU maps with T/E skies
- **Far sidelobe region**: Total response in T and P shall not exceed XXX [power]; Leakage from T→P and E→B leakage shall be < XXX
  - Verified by convolution of sidelobe TQU maps with ground template, galaxy, etc.

How do we set these requirements and design the calibration strategy to verify them?



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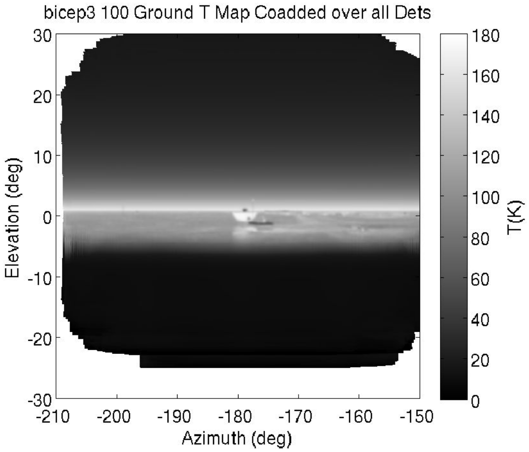


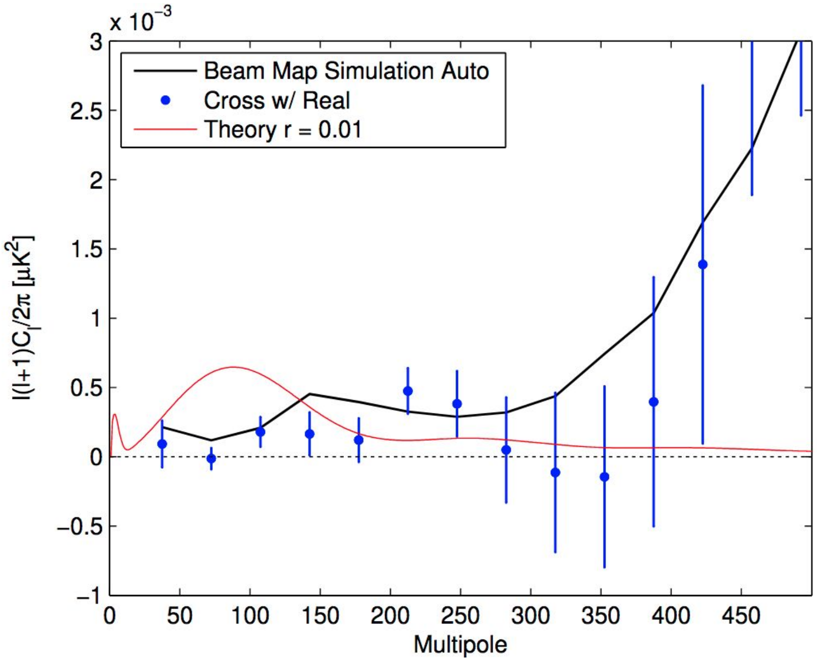
Setting Measurement Requirements

For a systematic of interest…

1. Given an estimate of the systematics form and amplitude, estimate
   a. $\Delta(r)$ = the bias on *r*
   b. $\sigma(\Delta(r))$ = the uncertainty this bias given depth of calibration measurements
2. Set a calibration sensitivity requirement, i.e. target $\sigma(\Delta(r))$
3. Tie this calibration sensitivity requirement to calibrator design and schedule
   → Define hardware to be built
   → Scale from heritage calibration data & refine approach

Worked example in the following slides: T→P leakage

Cross-Spectrum Framework



BB power spectra corresponding to T → P leakage in BICEP3
Figure 24 of BK18 - Appendix F

We have deep beam maps of all detectors contributing to the BK18 CMB maps, which can be used to estimate T->P leakage.

There may be low-level systematics in the beam maps, so we estimate leakage with the cross spectrum:

Estimate of T->P from beam maps, after deprojection X Real BK18 maps

BK18: **Δ(r) = (1.5 ± 1.1) x 10^{-3}**

Compare to σ(r) = 9 x 10^{-3}

Uncertainty currently driven by noise in CMB maps, but this may not be true at CMB-S4 sensitivity.

Tie to measurement requirements

- How does our estimate of the bias on *r* and its precision scale with noise levels in beam maps and CMB maps?
  - For a given CMB map sensitivity, what beam map sensitivity do we need?
  - Informs design of thermal sources and amount of time spent on calibrations
- Using existing calibration data:
  - Quantify typical calibration noise levels and verify scaling with more data
  - Quantify systematics in the measurement and identify where more work is needed to reduce them

Generic systematics forecasting plan

- Extend framework used in the *r* forecasting paper to determine the required precision on systematics estimates/calibration measurements
  - Add ability to use a template of systematic contamination in cross with real maps
  - Add uncertainties on systematics estimate
  - Power spectrum level - meant for quick turnaround
  - By taking foreground separation into account, allows for different calibration requirements at different frequencies
- Variables
  - Frequency-dependent power spectra of systematic contamination
    - Experiments can provide templates for systematics derived from e.g. timestream sims
  - Calibration uncertainties and possibly systematics in the calibration measurement
  - CMB + noise power spectra for various experimental configurations (can feed into AoA)

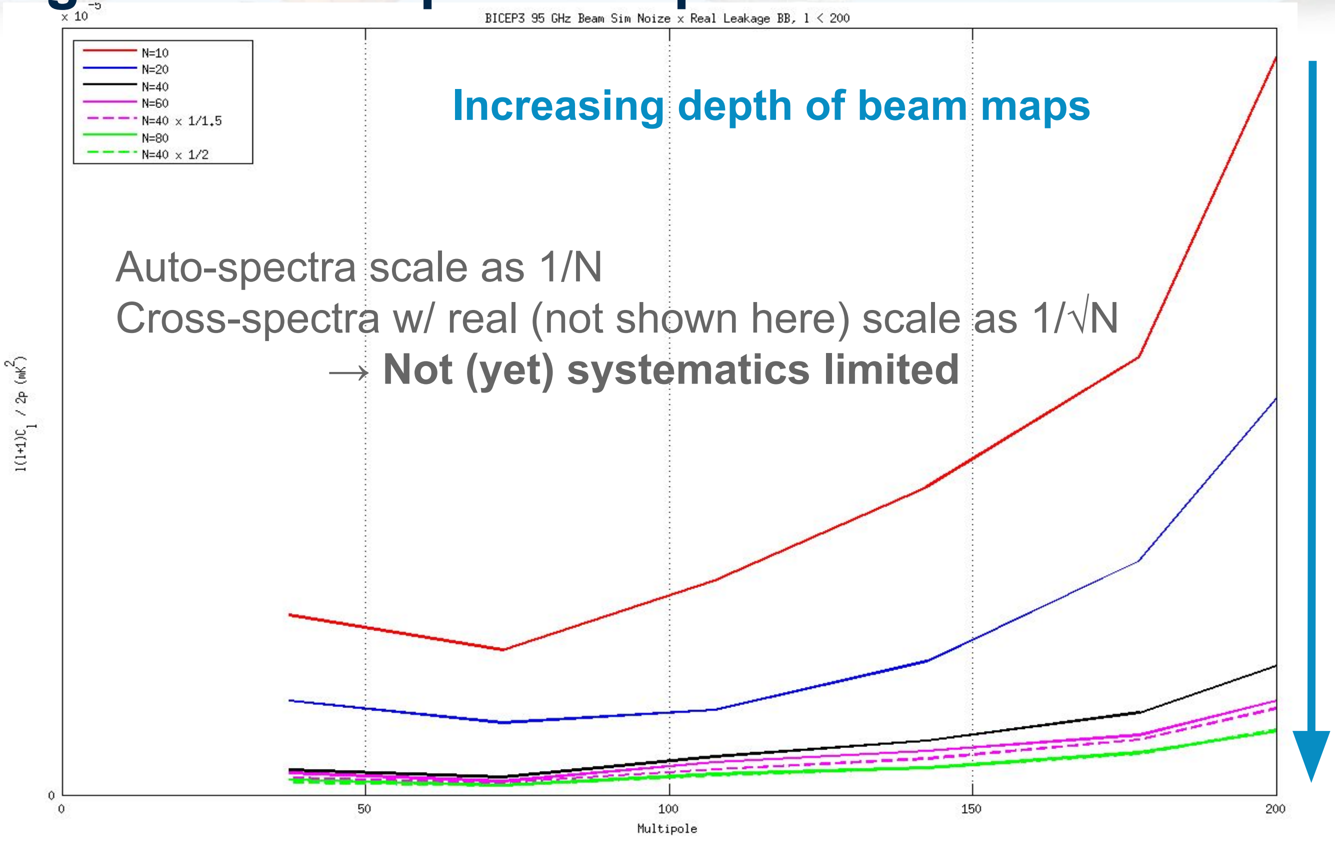
Conclusions

- We are refining SAT Beams/Optics requirements to better reflect how we think about systematics and calibration measurements
  - Beam definitions document to supplement requirements
  - Include HWP possibility for AoA
  - Detailed verification methods (coordinated with requirements on SAT Calibration hardware)
- We are extending the existing systematics framework to quantify calibration requirements
  - Start by scaling current estimates of T→P leakage from published BK data
  - Generic enough to set measurement requirements given approximate templates for various systematics

Backup slides

T→P leakage - beam map noise spectra

CMB noise is FIXED to BK18 level



Increasing depth of beam maps

Auto-spectra scale as 1/N
Cross-spectra w/ real (not shown here) scale as 1/√N
→ **Not (yet) systematics limited**

Beam map noise auto spectra as a function of number of beam maps

Impact on $\sigma(\Delta(r))$ - CMB noise fixed

- Cross-spectra of T→P leakage noise maps with 499 simulations
- Add these T→P leakage beam noise spectra to data and run standard analysis pipeline

NB: no mean bias is added, so $\Delta(r) = 0$

NB2: actual values are not *that* important, the *scaling* is

Number of beam maps	10	20	40	60	80
$\sigma(\Delta(r)) \times 10^{-4}$	5.20	4.03	2.10	2.01	1.94

→

More beam map data = smaller uncertainty on $\Delta(r)$

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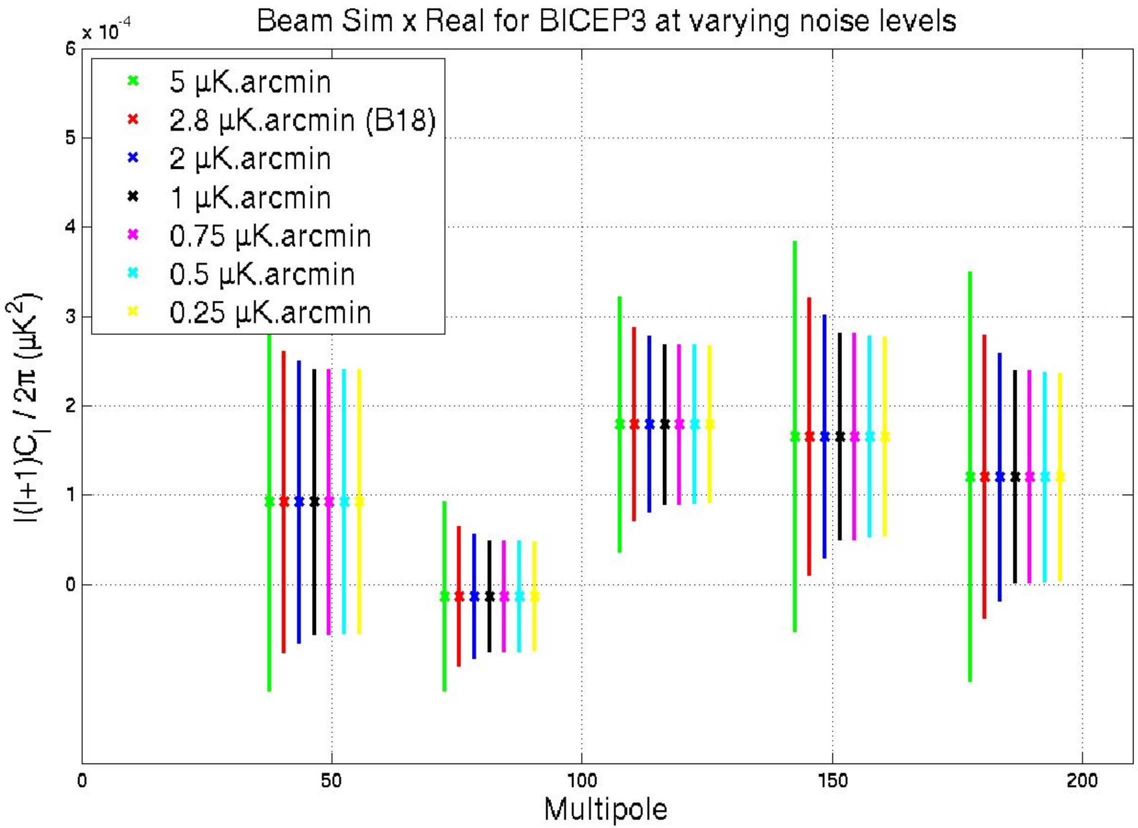
T→P leakage - cross-spectra with CMB maps



Beam map noise is FIXED to BK18 level

Impact on $\sigma(\Delta(r))$ - beam map noise fixed

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