Some BICEP/Keck perspective on systematics

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Actual systematics issues have been very hard to predict

- Hu, Hedman, Zaldarriaga considered systematics for B-mode experiments way back in 2002. Includes many effects that we still worry about, but BICEP/Keck has had success without following their prescribed solutions.

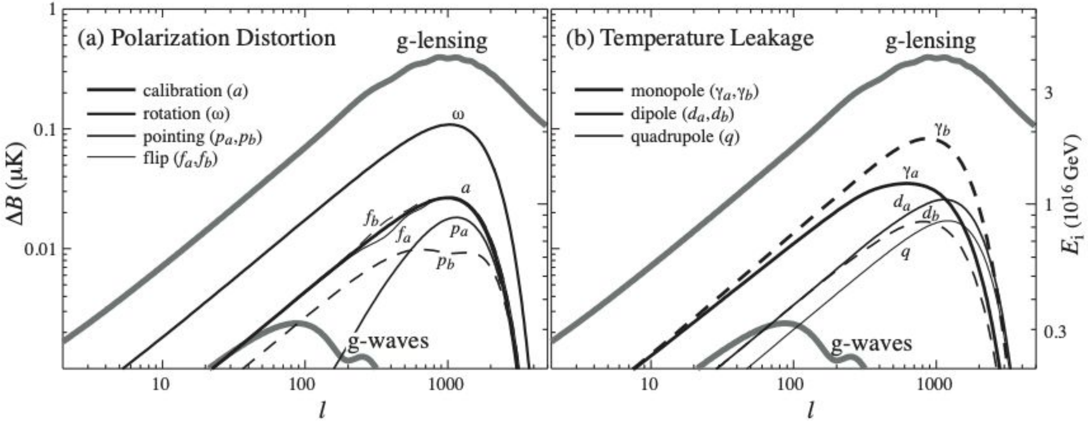

FIG. 5: All effects for a beam and coherence of FWHM $= (8 \ln 2)^{1/2}\sigma = 10'$. (a) Polarization distortion for an rms of $A = 10^{-2}$ from calibration a, rotation ω (0.6° rms), pointing (p_a,p_b) (2.5″ rms) , and spin flip (f_a,f_b). (b) Temperature leakage for an rms of $A = 10^{-3}$ from monopole (γ_a,γ_b), dipole (d_a,d_b) and quadrupole (q) terms. The "b" component of each effect is shown with dashed lines.

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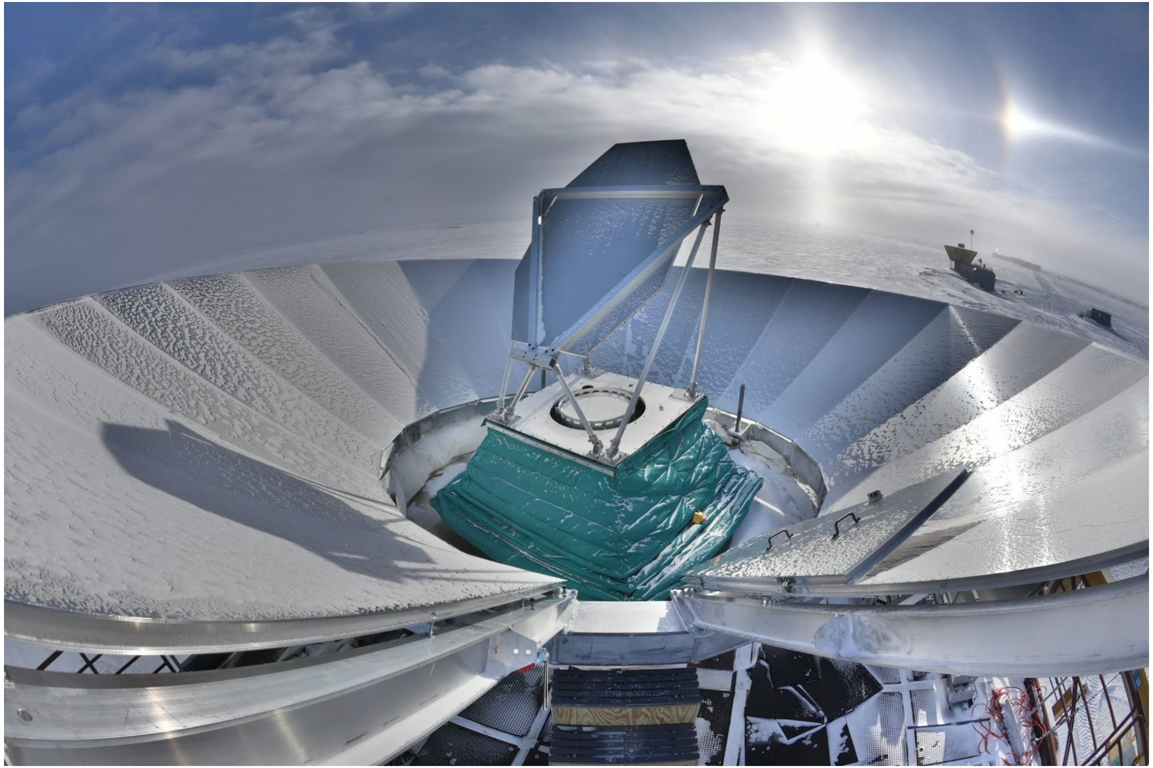
> Many of these problems are greatly reduced by having an instrumental beam that resolves the primary anisotropies (FWHM $\ll 10'$). To reach the ultimate goal of an inflationary energy scale of 3×10^{15} GeV, polarization distortion fluctuations must be controlled at the $10^{-2} - 10^{-3}$ level and temperature leakage to the $10^{-4} - 10^{-3}$ level depending on effect. For example pointing errors must be controlled to $1.5''$ rms for arcminute scale beams or a percent of the Gaussian beam width for larger beams; low spatial frequency differential gain fluctuations or line cross-coupling must be eliminated at the level of 10^{-4} rms.

- BICEP beam is much larger than 10 arcmin, differential gain (for T→P leakage) is few percent, etc. Achieved systematics control through a combination of instrument design, calibration, and analysis mitigation.

Intensive calibration enables analysis mitigation

- Far field beam maps with unpolarized source
- Far field beam maps with rotating polarized source
- Near field beam maps
- Far sidelobe maps (~2π sr)
- Measure optical coupling to absorptive forebaffles



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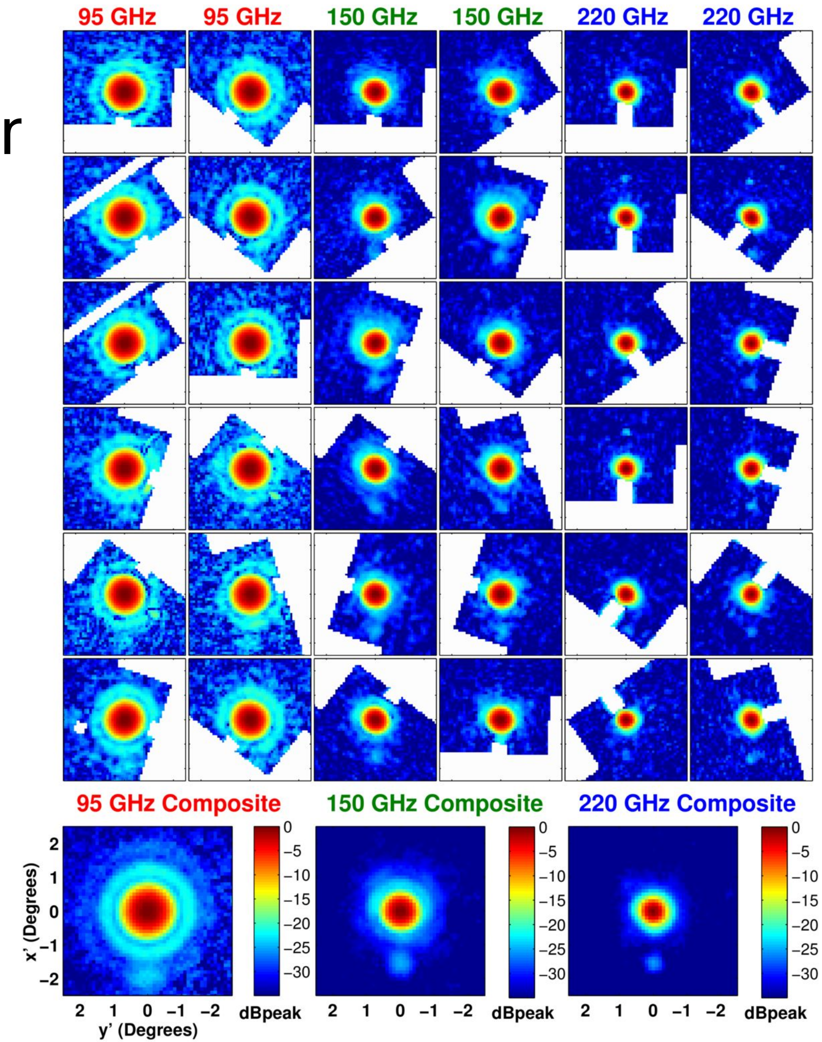
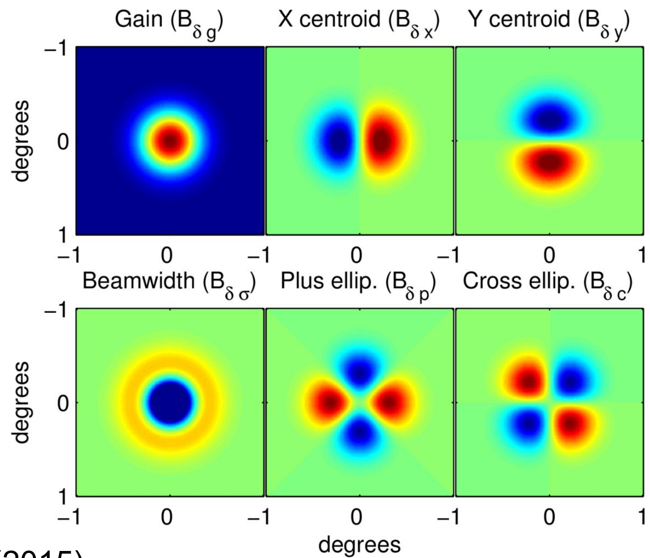


Figure 4 from BK-XI (2019)

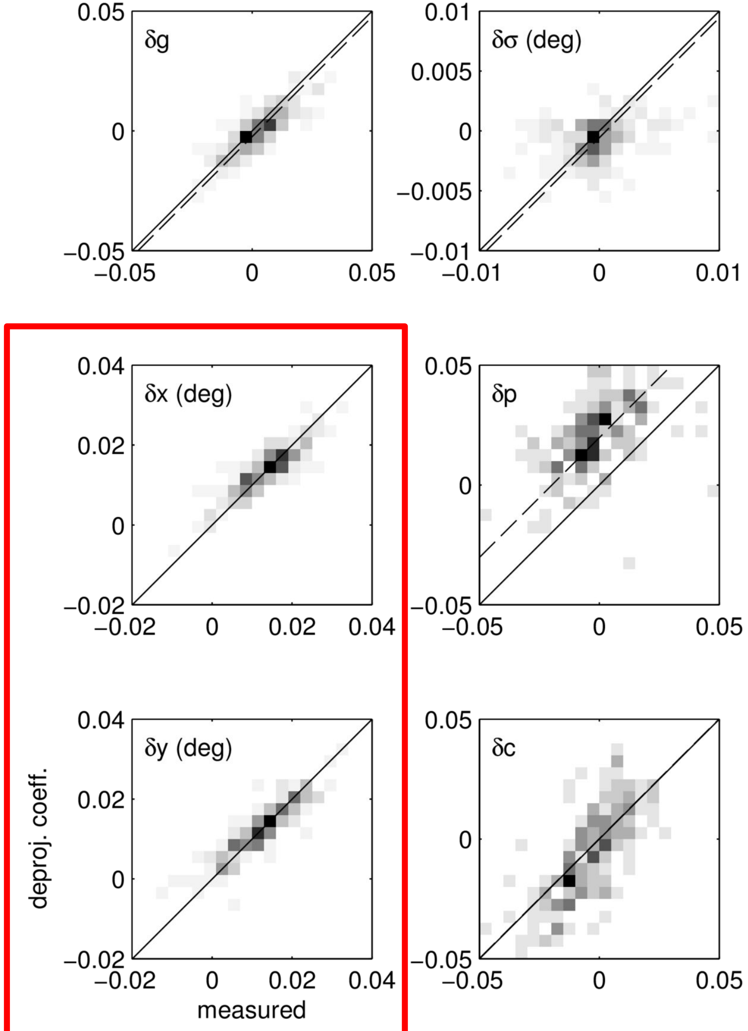
Systematics deprojection

Project modes out of polarization maps that correspond to five difference beam modes.

Deprojection coefficients from CMB maps match expectation from beam calibration.



(Differential beamwidth not deprojected because it isn't present for our detectors/optics)



Figures from BK-III (2015)

Jackknives

Jackknife tests can be targeted for sensitivity to particular systematics.

In this case (BICEP2 example), a jackknife between detectors at the center vs edge of the focal plane shows more sensitivity to differential ellipticity (center-right panel) than the signal spectrum (left and top-right panels).

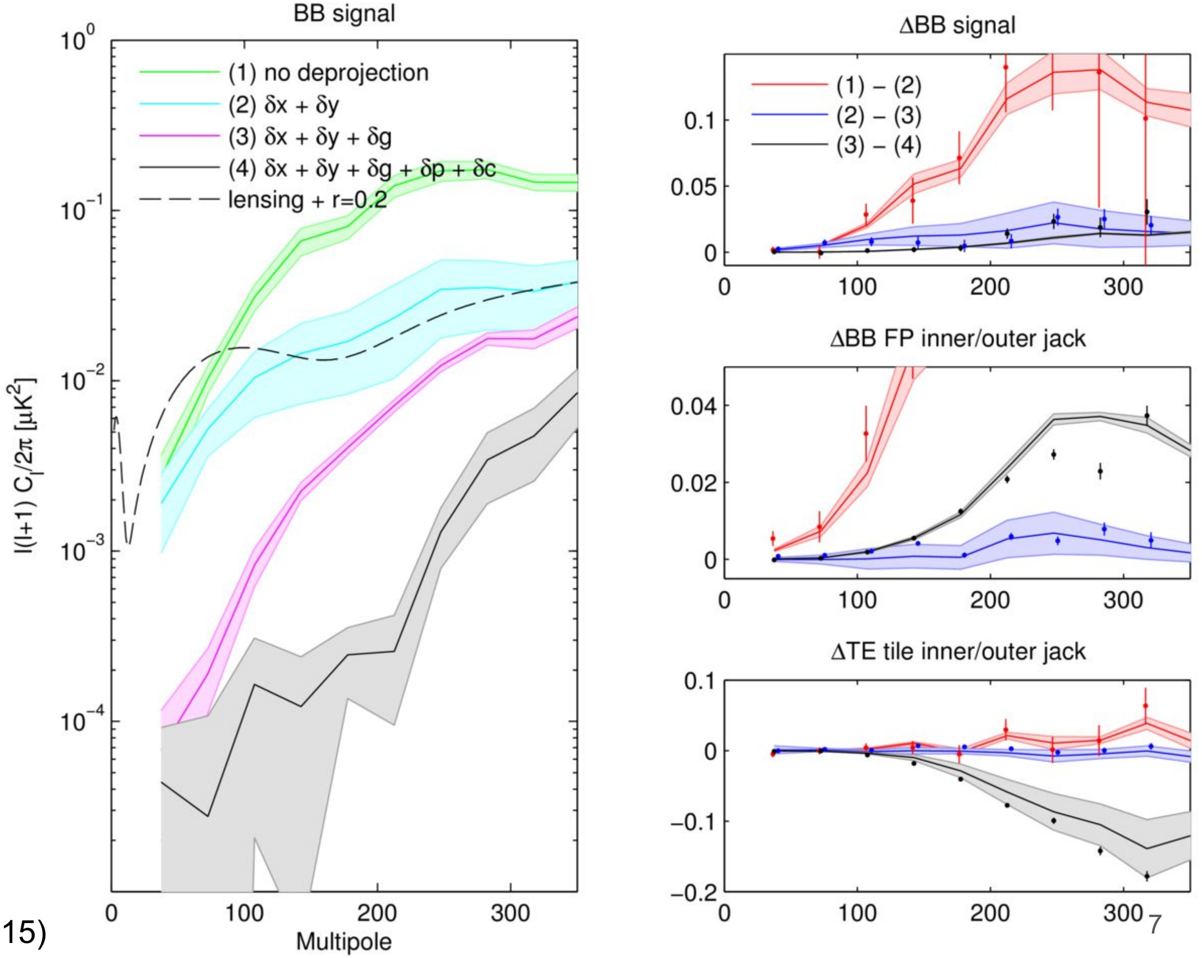
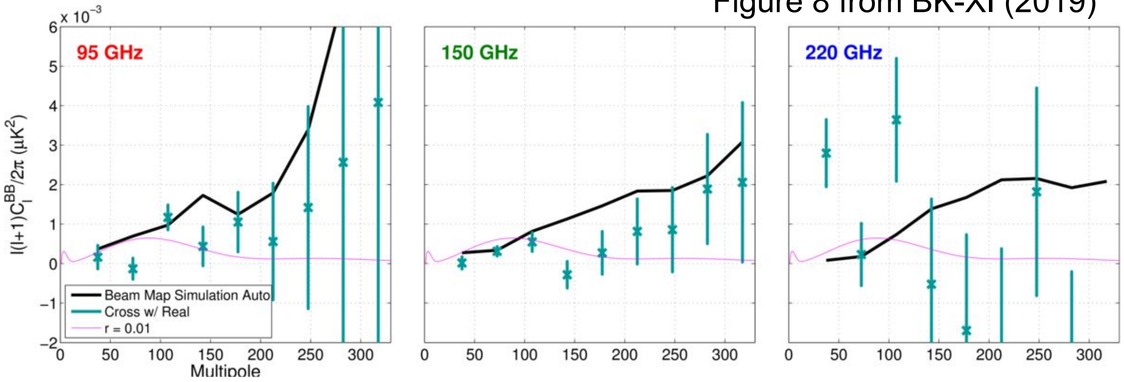


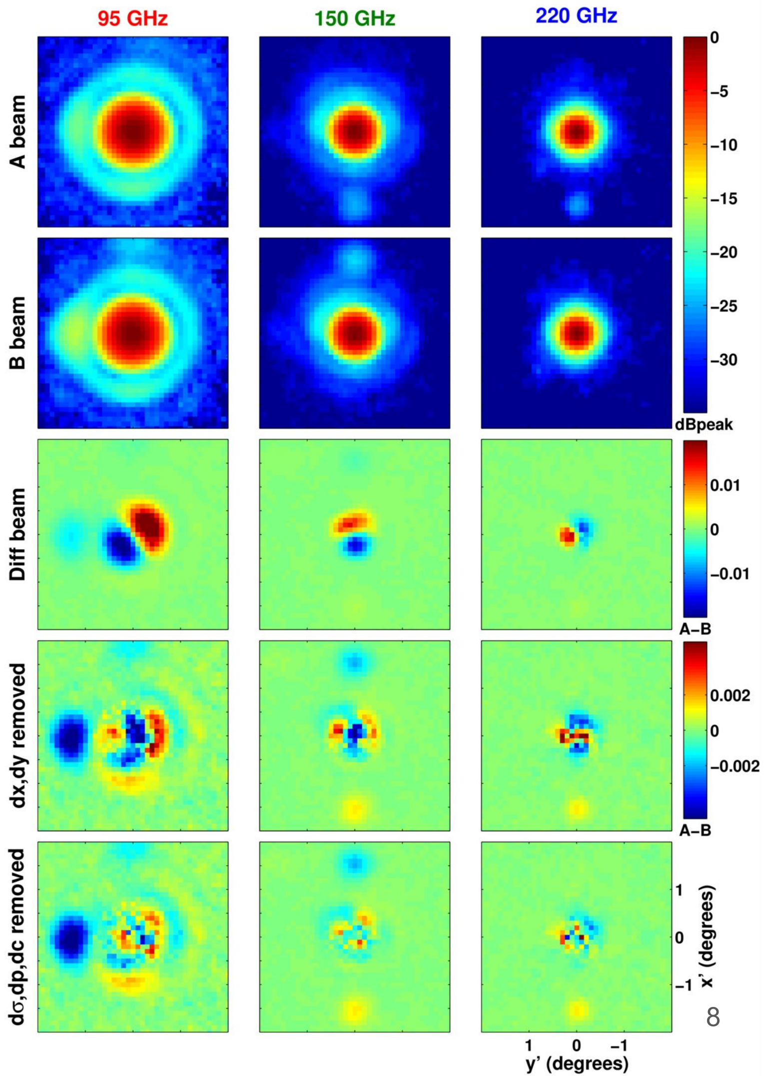
Figure 11 from BK-III (2015)

Undeprojected residuals

T→P leakage from sub-percent differential beam residuals (after deprojection) is measured through simulations

Figure 8 from BK-XI (2019)





- Solid lines = auto-spectrum of simulated leakage
- Points with error bars = cross-spectrum between simulated leakage and real CMB polarization maps

Advantage of deep, narrow maps

Jackknives are the final defense against unanticipated systematics. At fixed effort, the error bar on a jackknife bandpower scales as $N_\ell/f_{\rm sky}^{1/2} \sim f_{\rm sky}^{1/2}$, so an additive systematic at a specific amplitude will be detected more readily in a deep, narrow map.

Higher signal-to-noise detections of a systematic allows us to identify it, remove it with filters, and design targeted jackknives to assess whether the filtering is adequate.

- We can deproject differential gain, pointing, and ellipticity and compare results to beam map calibration.
- Undeprojected residuals represent the terms that are poorly measured. Attempts to debias in the likelihood are comparatively crude.

Similarly, the repetitive BICEP/Keck scan strategy allows us to concentrate our sensitivity to systematics. The high symmetry of this scan strategy helps reject some systematics and allows for construction of jackknives targeting them.

Summary / recommendations

- Use experience of Stage 2 and 3 experiments on instrumental systematics, calibration, and analysis mitigation.
- Ground CMB-S4 systematics simulations in actual data from existing experiments. This means more analysis of current data in many cases!
- Before adding a systematic to the simulations, need to consider how this will be addressed through calibration and analysis mitigation. It is easy to corrupt the maps with systematics, hard to restore them to science quality. This is an argument against including systematics in “mainline” data challenges / in favor of including them in focused studies.