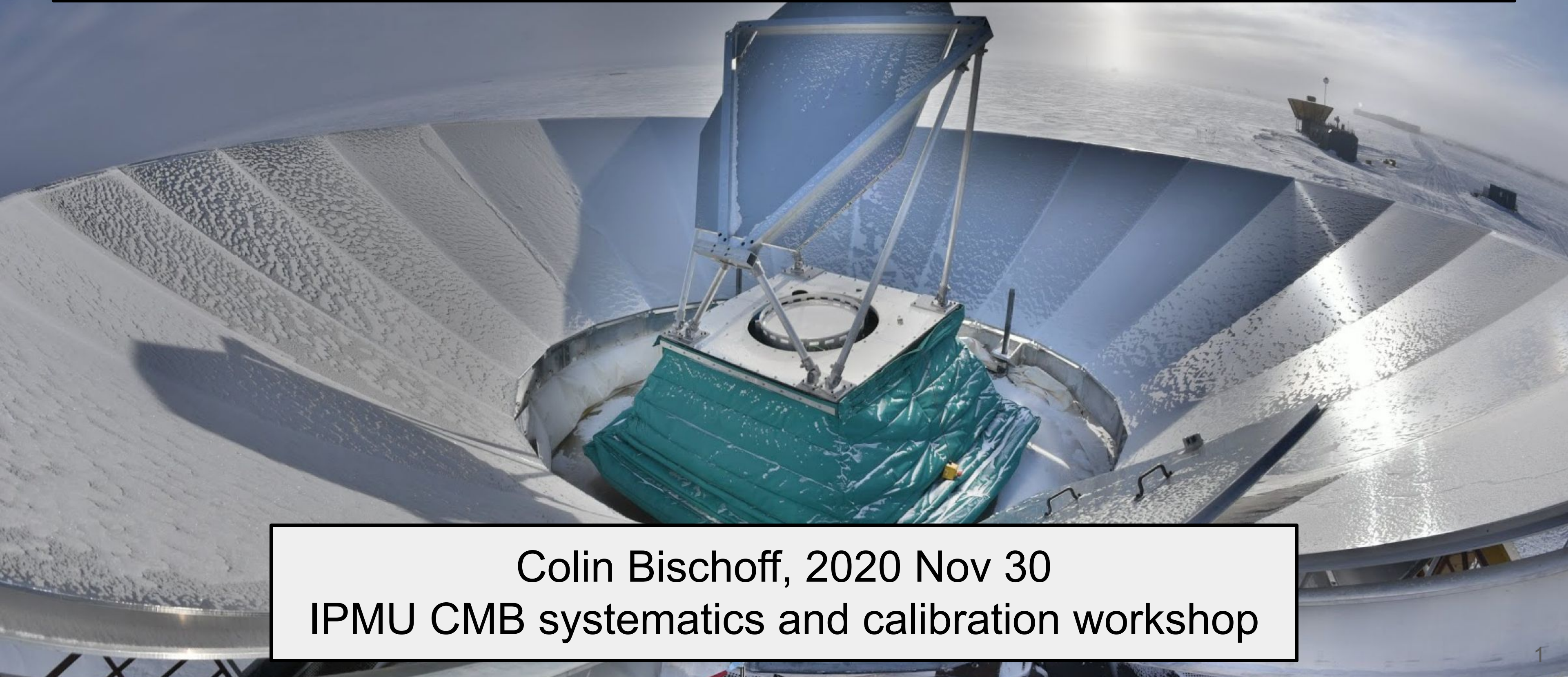
Systematics control and mitigation for BICEP/Keck deep polarization maps



Colin Bischoff, 2020 Nov 30

IPMU CMB systematics and calibration workshop

Lessons learned from BICEP/Keck

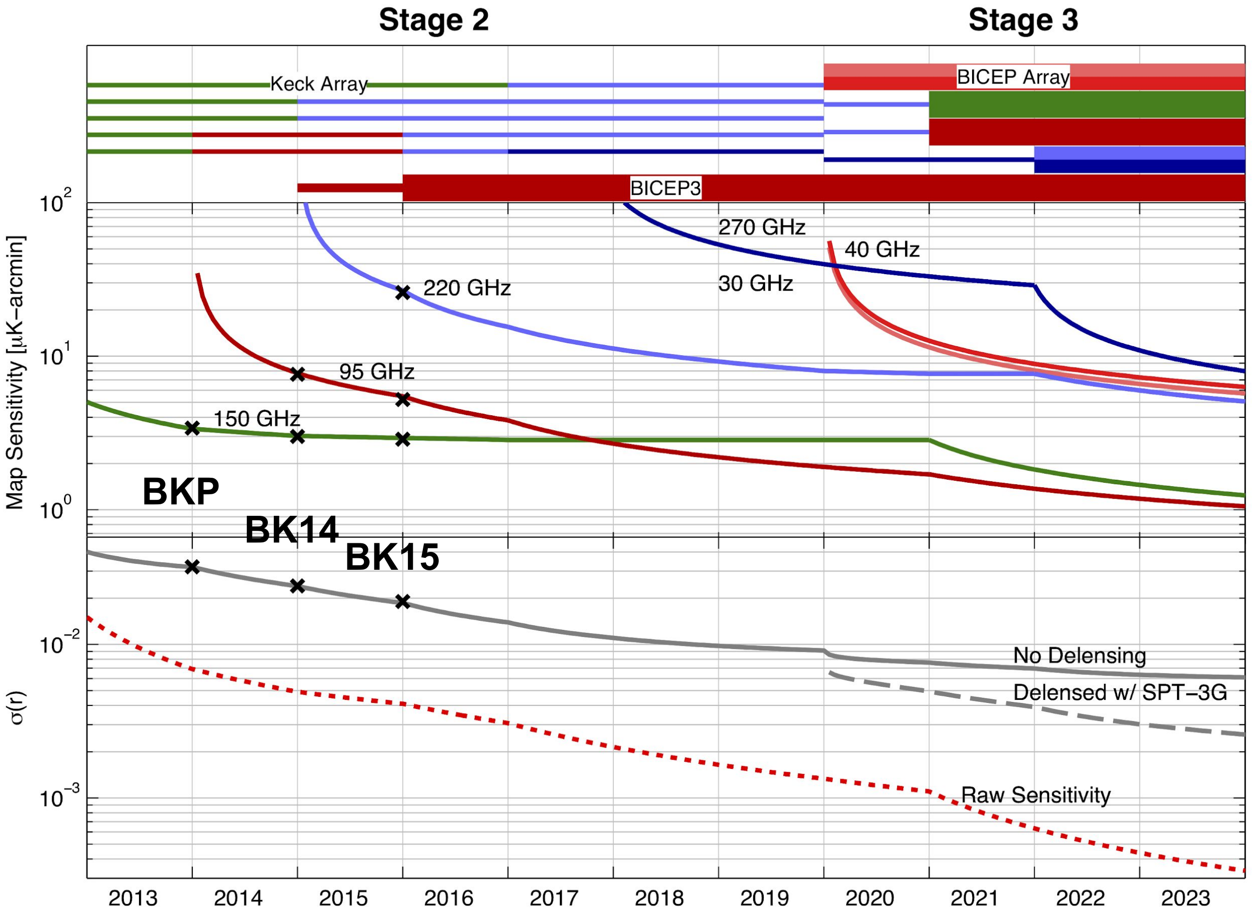
- Simple telescope design with many choices made to minimize systematics. The BICEP telescope design has been proven over a decade+ of observing and several generations of instruments. Similar cryogenic refractors are planned for BICEP Array, Simons Observatory, and CMB-S4.
- Telescope and detector performance is verified with extensive calibration campaigns.
- Temperature-to-polarization leakage from beam mismatch of paired detectors is an important additive systematic for the BB spectrum. Leading-order modes can be filtered out using high signal-to-noise Planck T maps. This filter is independent of, but in agreement with, beam map calibrations.
- Making deep maps of a small region of sky and using a repetitive scan strategy with high degree of symmetry helps us to identify and remove systematic contamination.

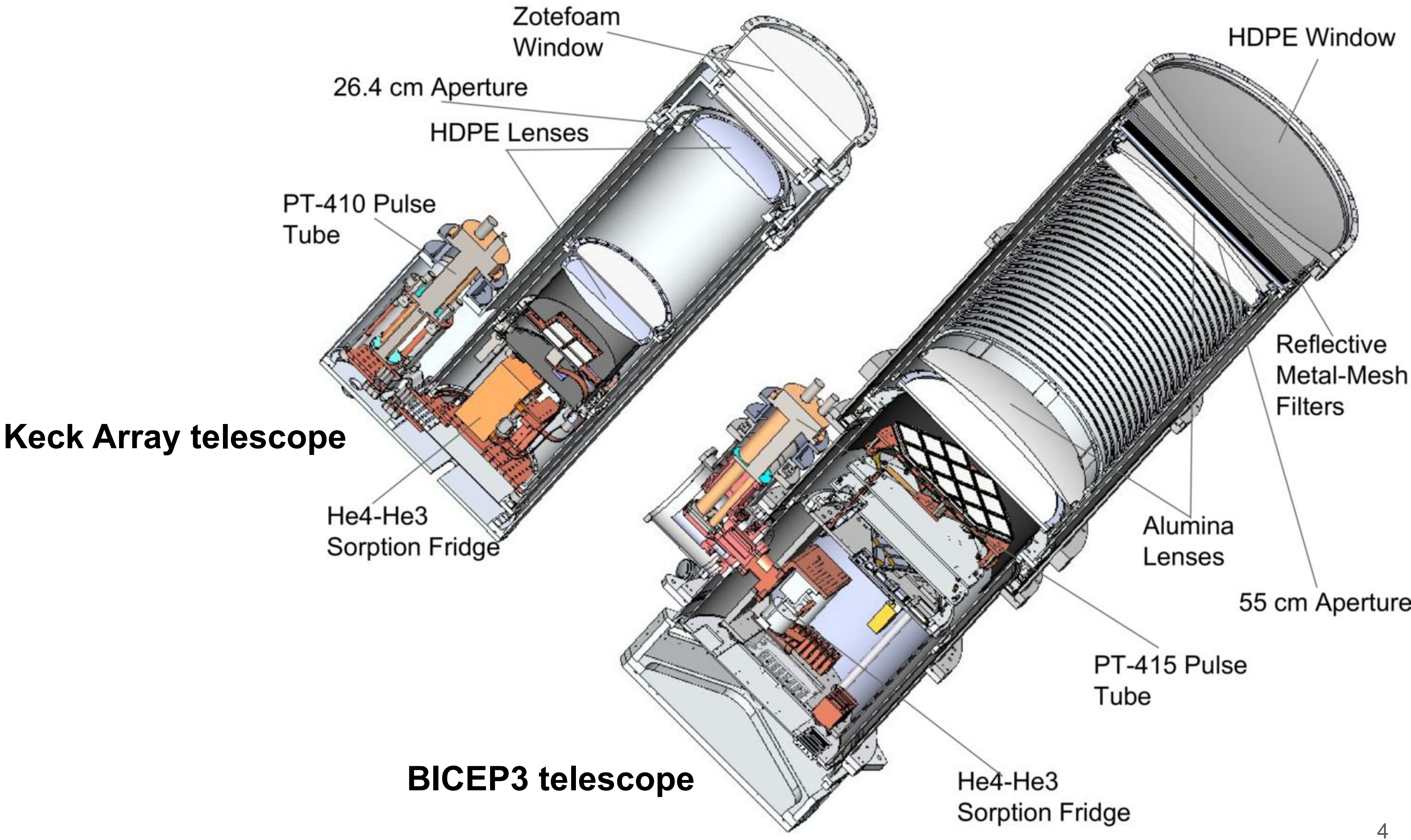
BICEP/Keck experimental program

Single-minded effort to achieve the best sensitivity to r using B-mode polarization at degree angular scales and multiple frequencies.

Published r constraints have been limited by raw noise levels and foreground separation, not systematics…

...but this obscures a huge effort on calibration and systematics mitigation!




Zotefoam
Window
26.4 cm Aperture
HDPE Lenses
PT-410 Pulse
Tube
Keck Array telescope
He4-He3
Sorption Fridge
HDPE Window
Reflective
Metal-Mesh
Filters
Alumina
Lenses
55 cm Aperture
PT-415 Pulse
Tube
BICEP3 telescope
He4-He3
Sorption Fridge

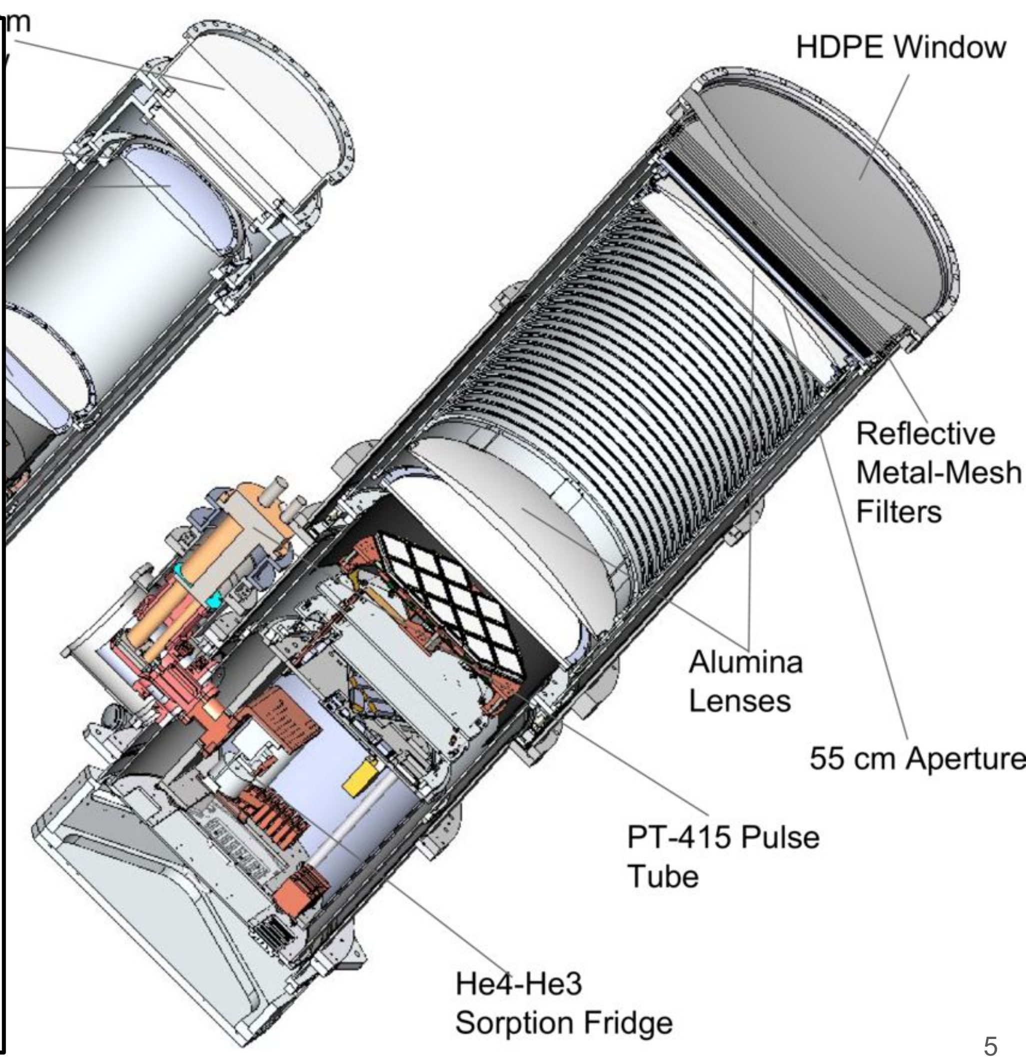
Simple on-axis cryogenic refractor with high throughput for sensitivity

Multi-color sensitivity achieved with an array of monochromatic telescopes:

- Avoids complexity and performance issues of broadband AR coatings, broadband optical couplings, and multichroic detectors
- BICEP Array does feature a 30/40 GHz receiver and (eventually) a 220/270 GHz receiver

Optical design avoids sources of diffraction and reflection

- Under-illuminate cold aperture stop (-10 dB) to minimize diffraction
- Absorptive baffling in telescope tube to prevent reflection at glancing incidence



Comoving absorptive forebaffle intercepts rays outside the field of view

Fixed reflective groundshield redirects diffracted rays to the sky

Double-diffraction criteria:

- No direct line from window to fixed groundshield (must diffract around edge of forebaffle)
- No direct line from edge of forebaffle to horizon (must diffract over the top of groundshield)

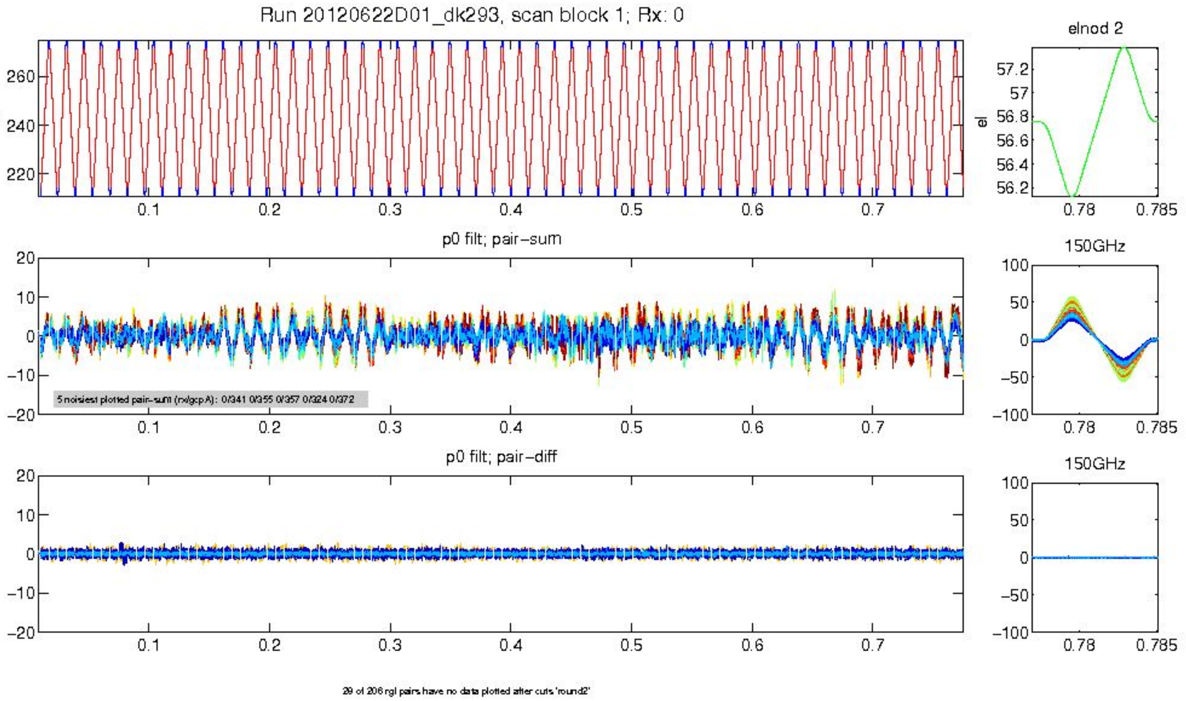
Atmosphere noise removed by pair differencing

Fast azimuth scanning for signal modulation. Boresight rotation for Q/U coverage.

Detector pair sums are sensitive to total intensity and show lumpy atmospheric structure

Detector pair differences reject unpolarized atmosphere and remain clean even in marginal weather (i.e., these data)

Avoids need for a fast spinning half-wave plate, which introduces its own systematic issues



Intensive calibration campaigns

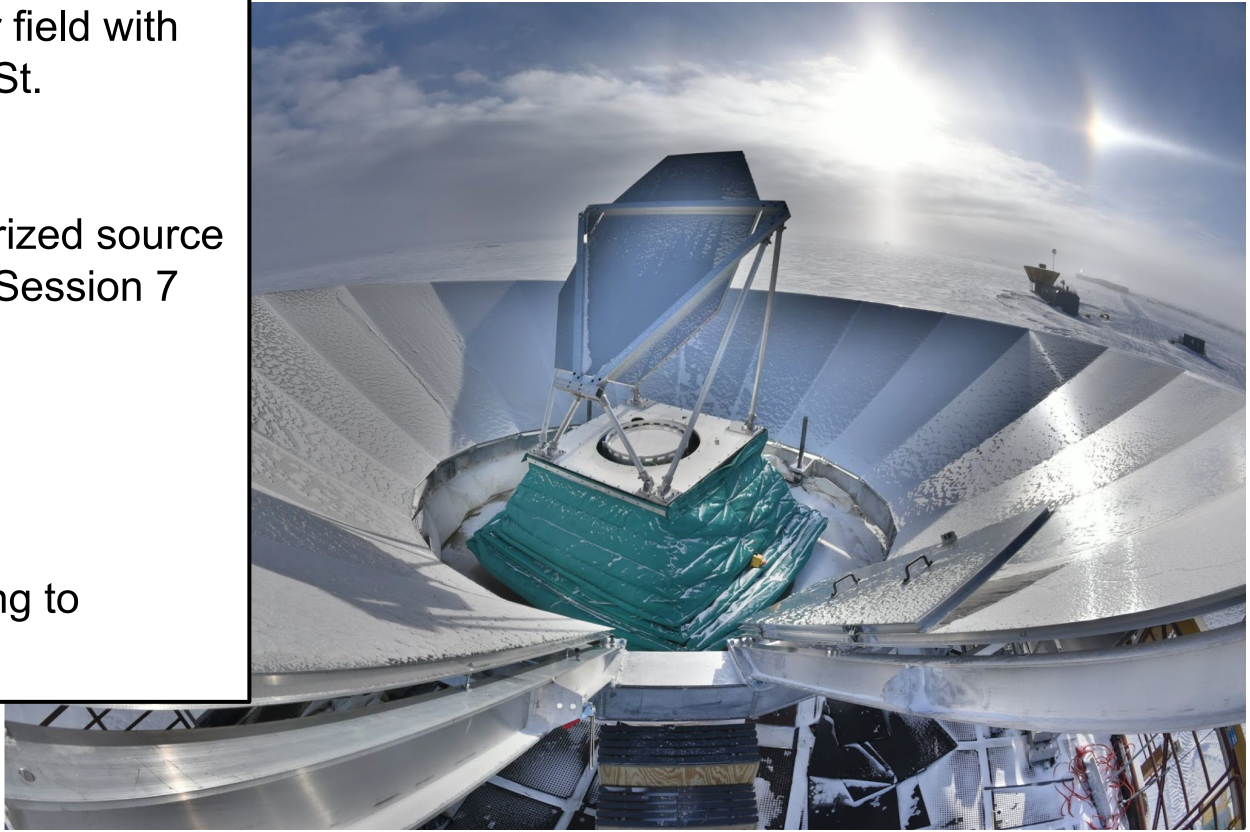
Beam maps measured in the far field with unpolarized source -- see Tyler St. Germaine talk in Session 11

Beam maps with a rotating polarized source -- see James Cornelison talk in Session 7

Near field beam maps

Far sidelobe maps (~2π sr)

Measure detector optical coupling to absorptive forebaffles



Intensive calibration camp

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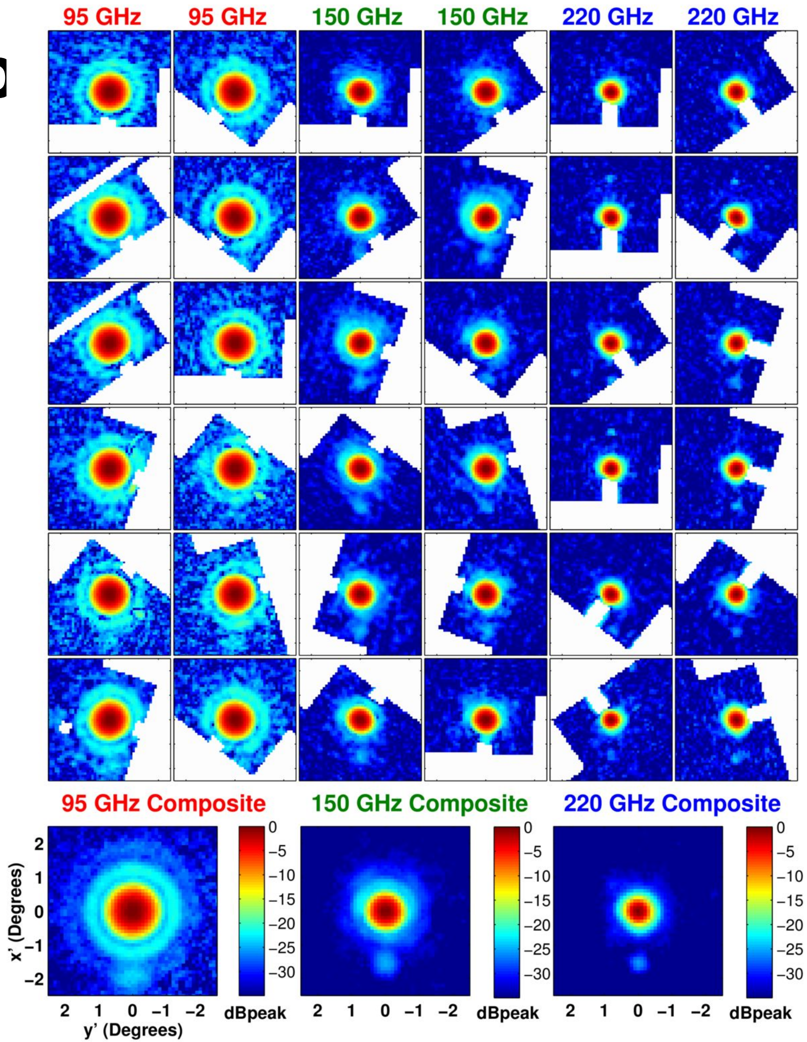
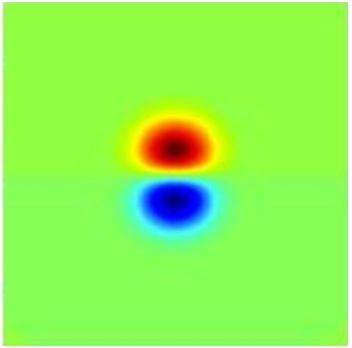


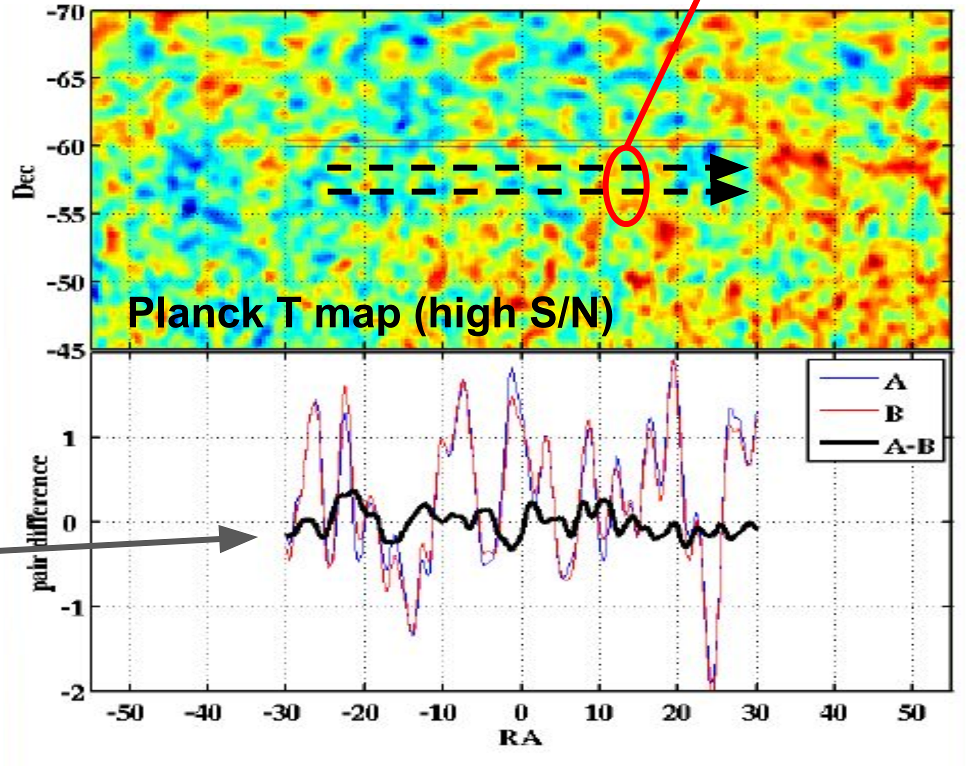
Figure 4 from BK-XI (2019)

Measured beams predict T→P leakage

A-B difference beam



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

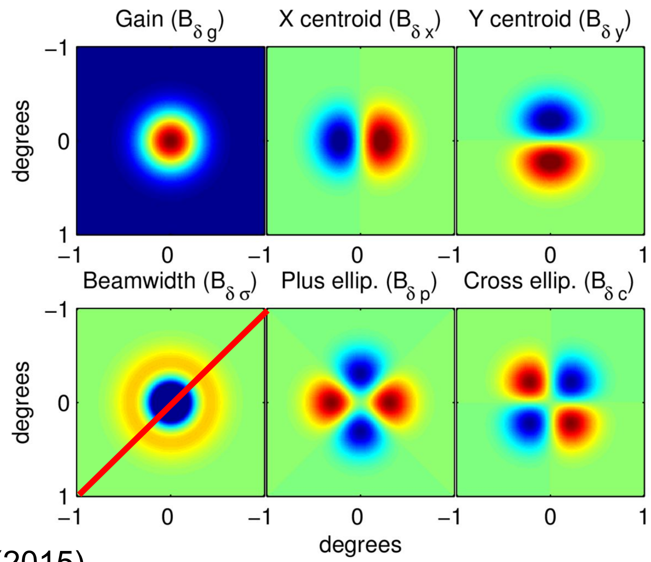


Predicted T→P leakage

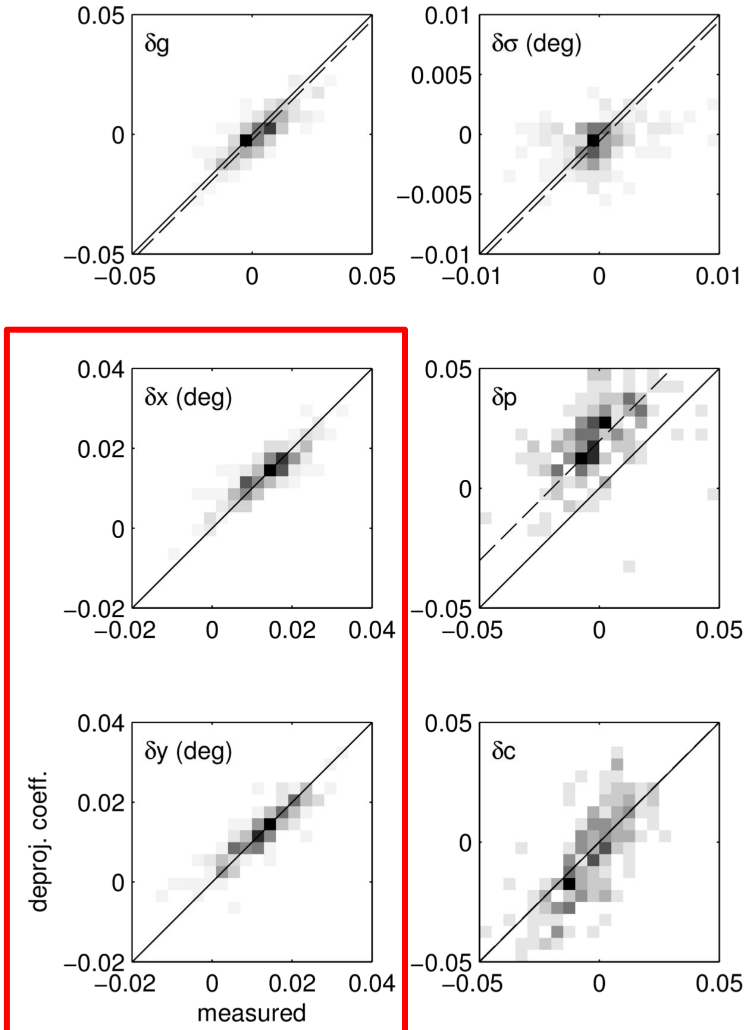
Deprojection filter

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

Deprojection coefficients from CMB maps match expectation from beam map calibration



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



Figures from BK-III (2015)

Deprojection filter

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).

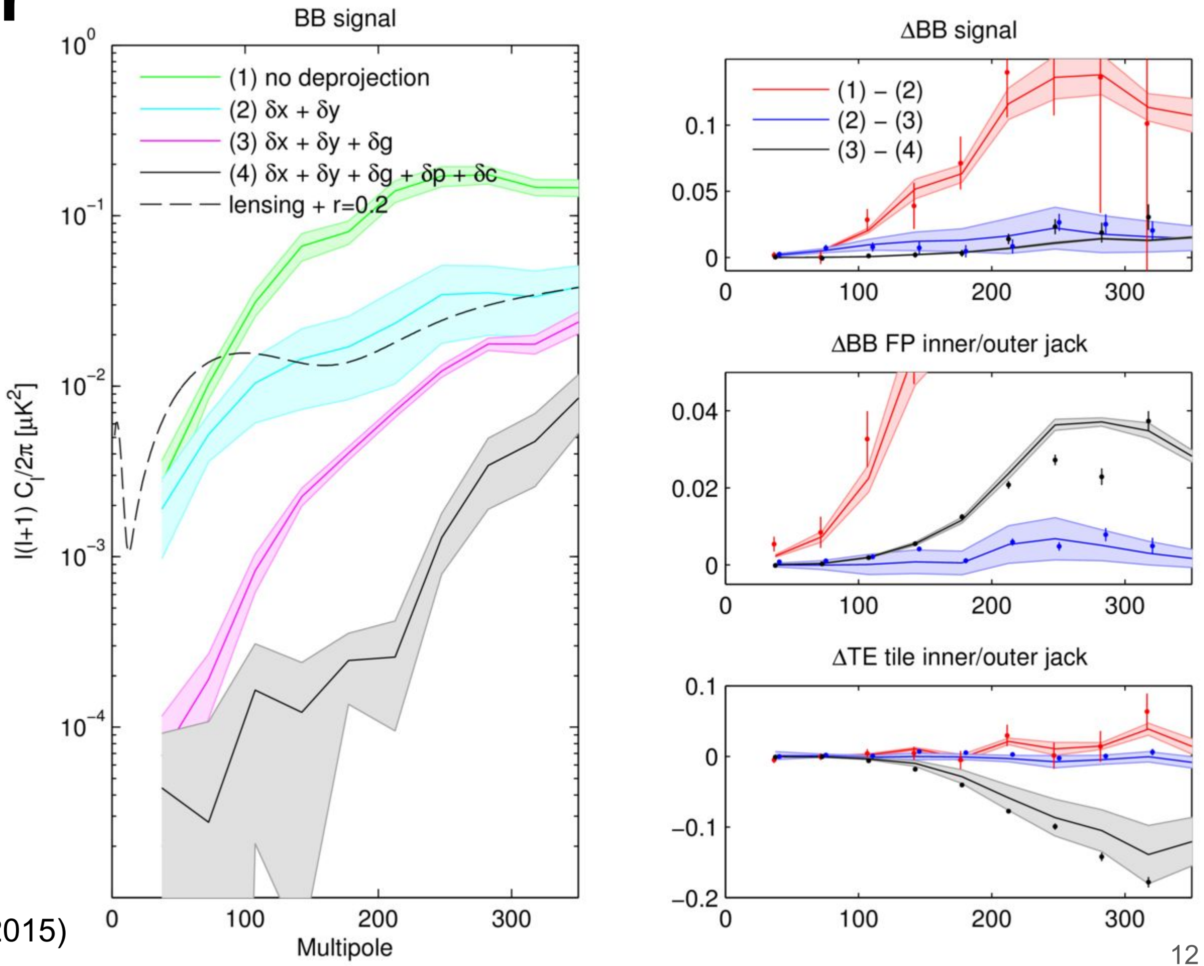
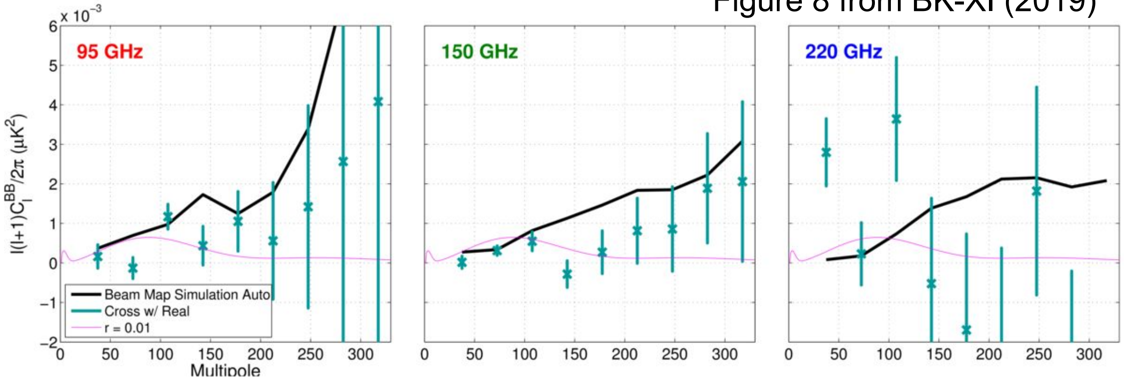


Figure 11 from BK-III (2015)

Undeprojected residuals

Temperature to polarization leakage from sub-percent difference 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

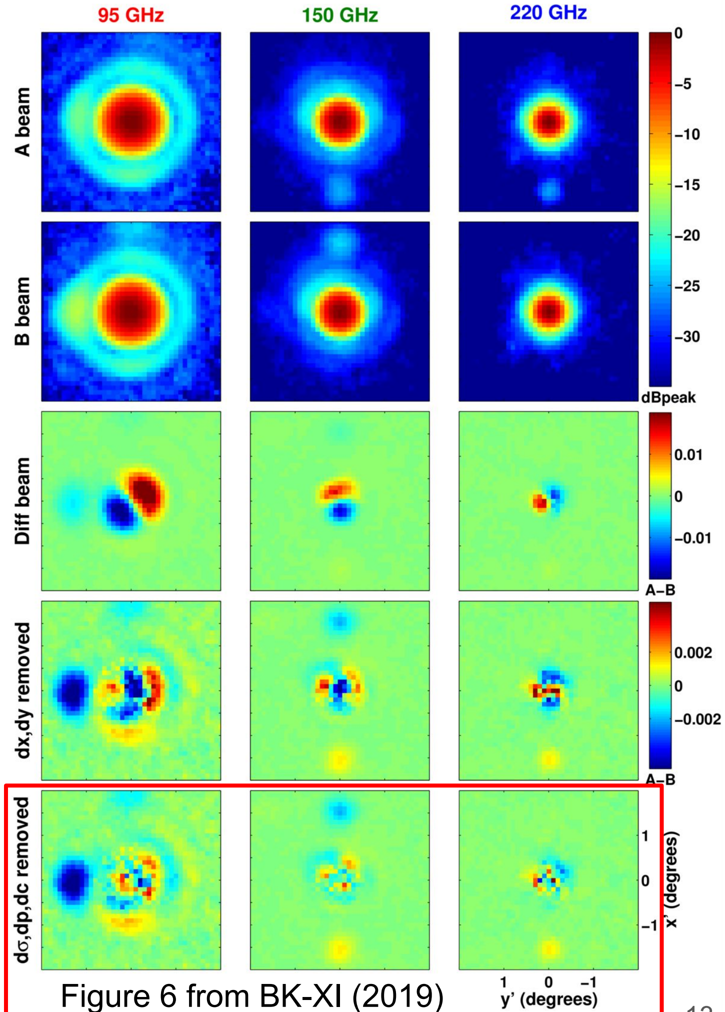


Figure 6 from BK-XI (2019)

Undeprojected residuals

A BB additive systematic can be propagated through multi-component likelihood analysis to estimate bias on r

We can also attempt to remove this bias by adding a nuisance parameter to the likelihood model (green and red points). In this case, the nuisance parameter is a scale factor multiplying the systematic templates derived from simulations.

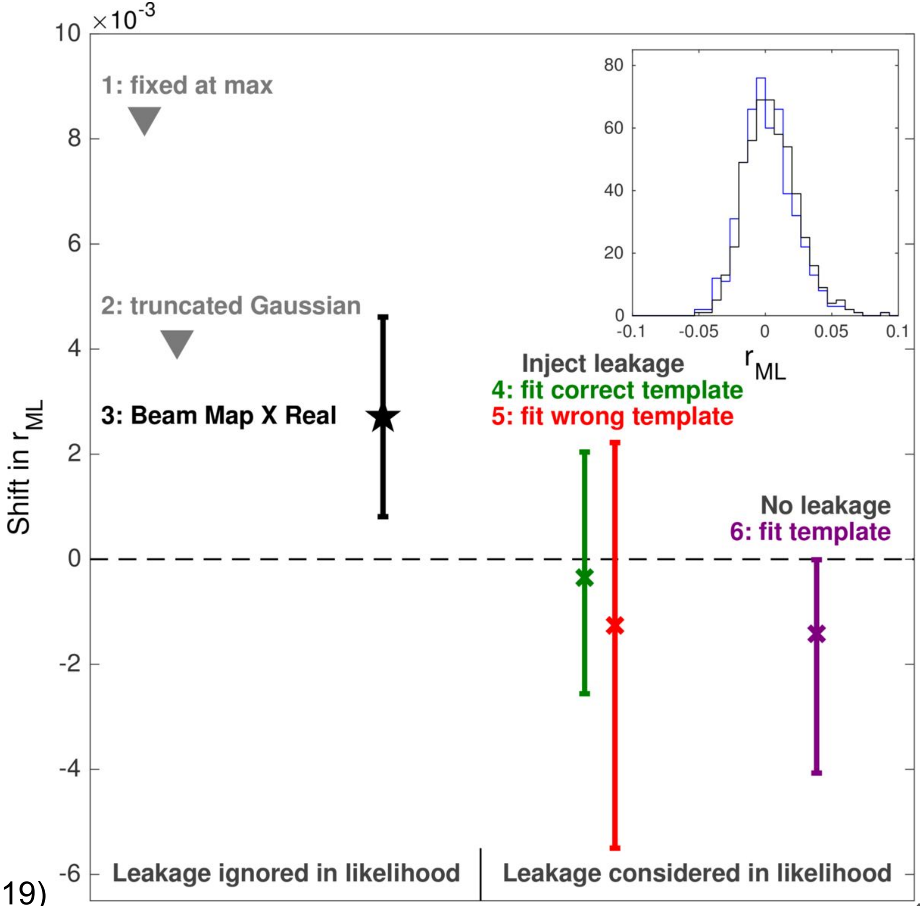


Figure 9 from BK-XI (2019)

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 $N_\ell / f_{\mathrm{sky}}^{1/2} \sim f_{\mathrm{sky}}^{1/2}$, 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.

For more details

- http://www.bicepkeck.org
- BK-III: Instrumental Systematics; arXiv:1502.00608
- BK-XI: Beam Characterization and Temperature-to-Polarization Leakage in the BK15 Dataset; arXiv:1904.01640
- Tyler St. Germaine talk in Session 11, “Analysis of Temperature-to-Polarization Leakage in BICEP3 and Keck Array CMB Data from 2016 to 2018”
- James Cornelison talk in Session 7, “Broad Spectrum Noise Sources for Calibration of the BICEP/Keck CMB polarimeters”
- Eric Yang talk in Session 12, “Systematics diagnostics and self-calibration of CMB B-mode measurements with distortion fields for BICEP/Keck and LiteBIRD”
- Kimmy Wu talk in Session 11, “Systematics in Delensing”