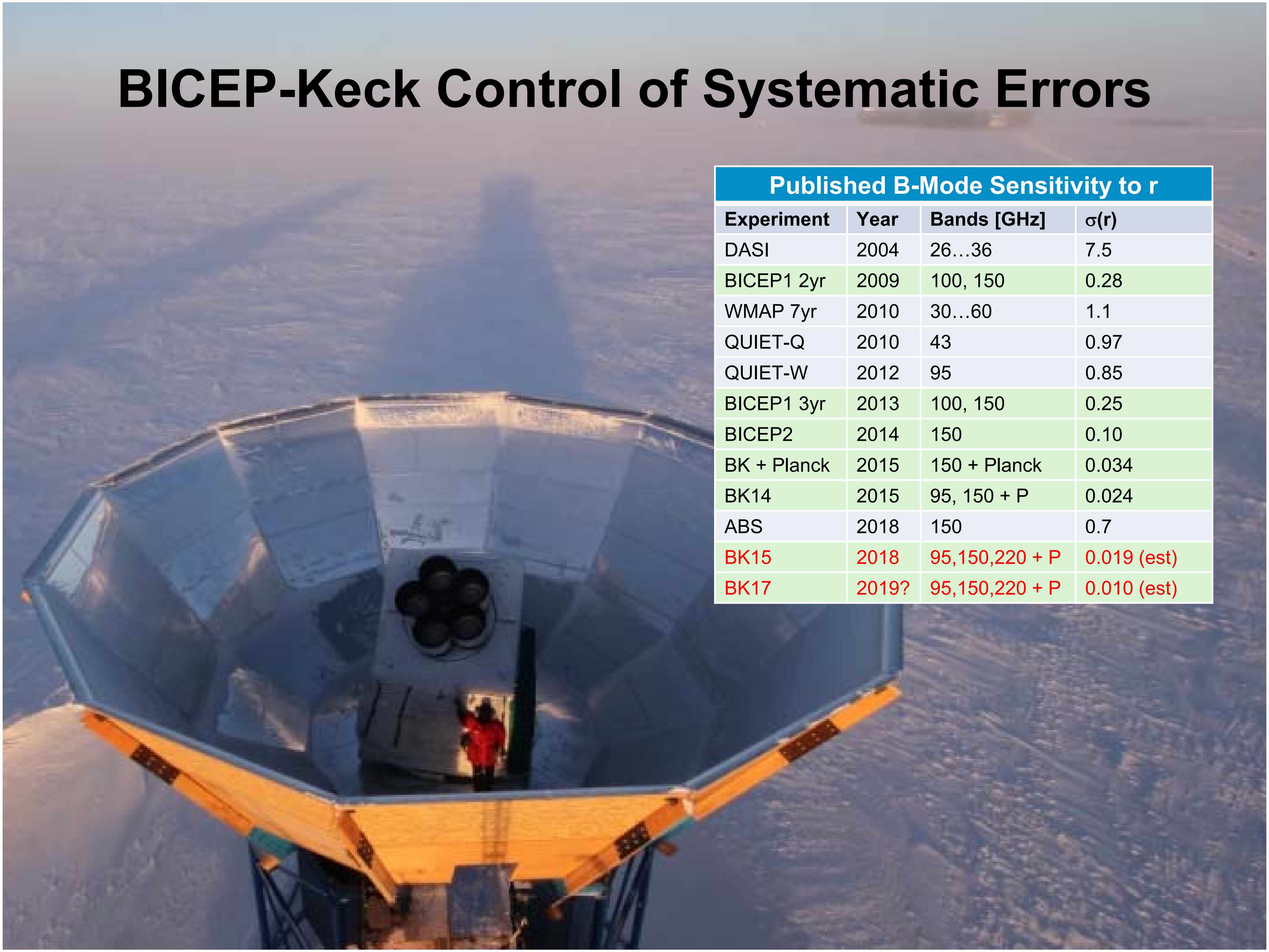
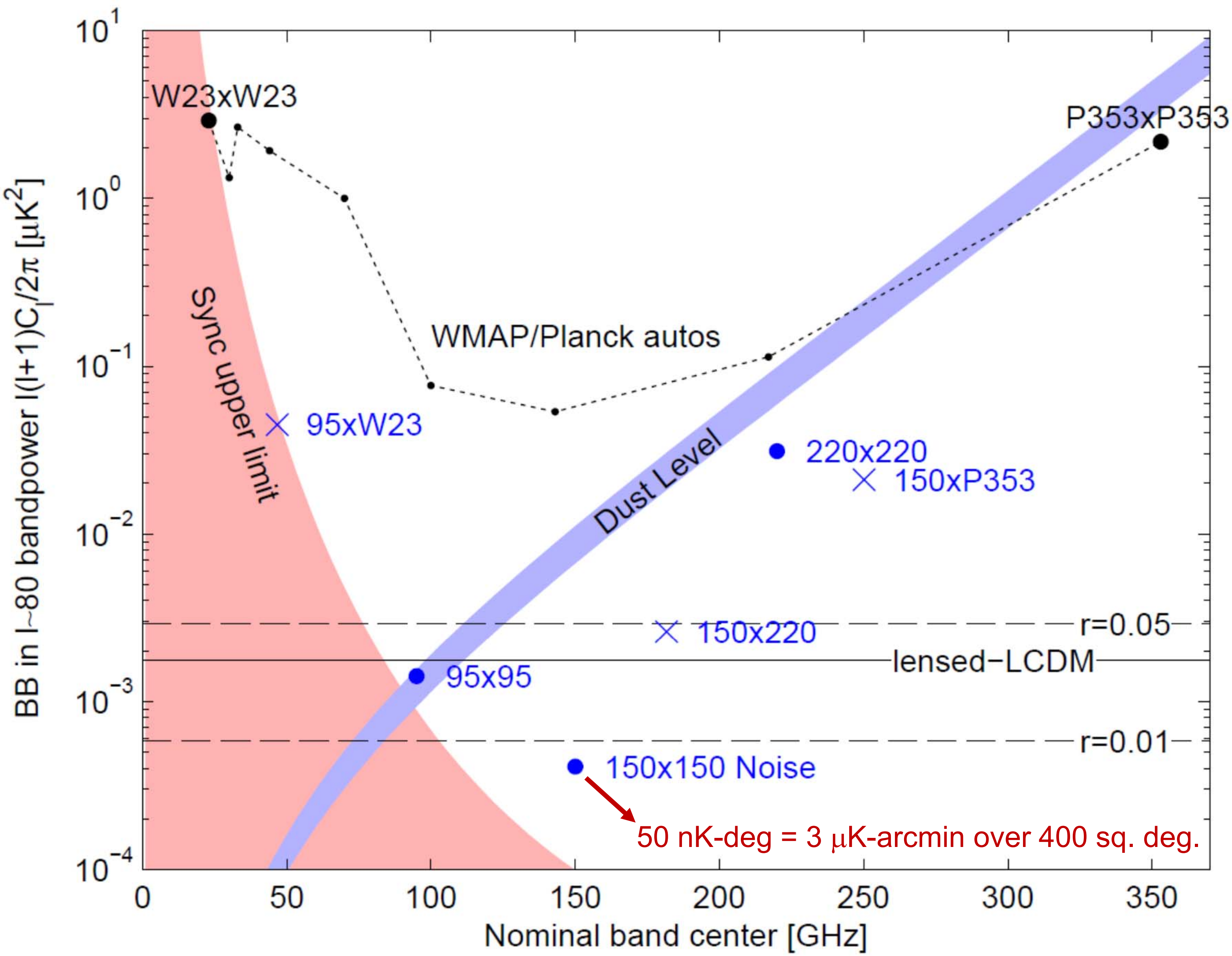
BICEP-Keck Control of Systematic Errors



Published B-Mode Sensitivity to r			
Experiment	**Year**	**Bands [GHz]**	**σ(r)**
DASI	2004	26…36	7.5
BICEP1 2yr	2009	100, 150	0.28
WMAP 7yr	2010	30…60	1.1
QUIET-Q	2010	43	0.97
QUIET-W	2012	95	0.85
BICEP1 3yr	2013	100, 150	0.25
BICEP2	2014	150	0.10
BK + Planck	2015	150 + Planck	0.034
BK14	2015	95, 150 + P	0.024
ABS	2018	150	0.7
BK15	2018	95,150,220 + P	0.019 (est)
BK17	2019?	95,150,220 + P	0.010 (est)

BICEP-Keck Band Sensitivity (at $\ell = 80$)



BK sensitivities through 2015

Experimental Approach

Small aperture telescope
- rotate entire telescope
- control spillover at 4 K primary

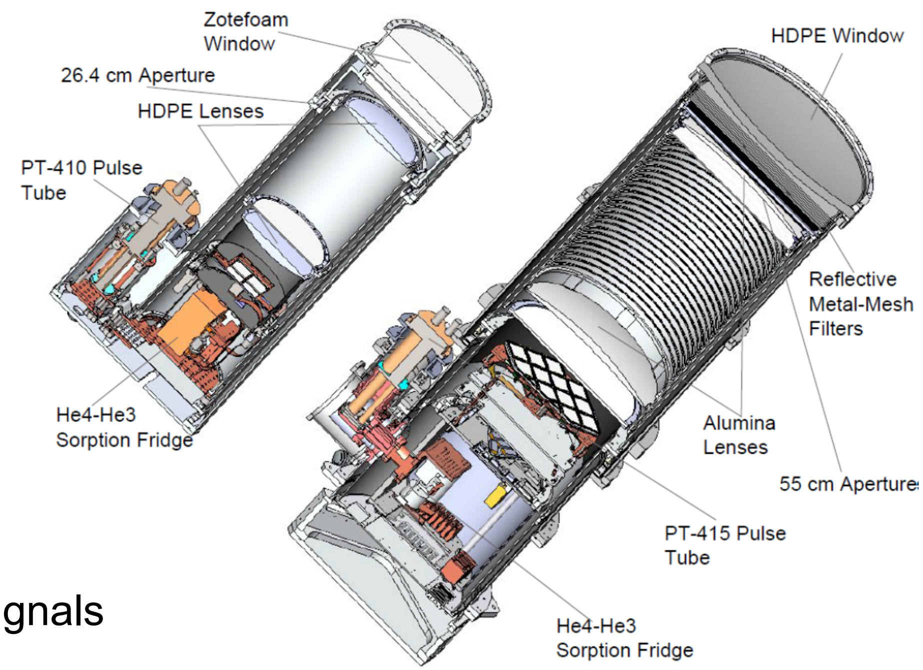
In-situ optical characterization
- dedicated far-field beam mapping campaigns

Planar antennas
- matched properties in polarization

Absorbing + reflecting shields
- controls far sidelobes

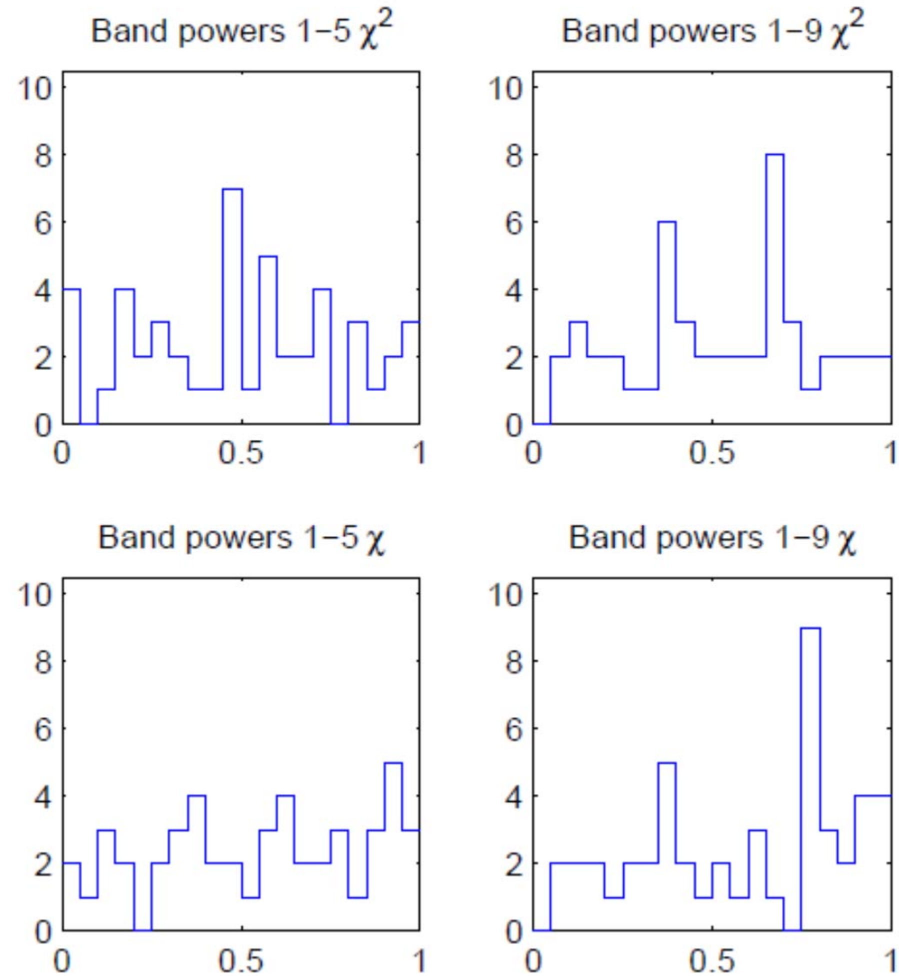
Modulation: pair difference and scan
- detector difference removes common mode signals

Choose simplicity when possible
- monochromatic: avoid the complexities associated with adding dichroic detectors
- No modulator: avoid second-order optical effects



Validating Systematics with Jackknife Tests

- Deck rotation
- Scan direction
- Early/late season
- Year split
- Best/worst tiles
- Phase
- Mux column
- Alt deck rotation #1
- Alt deck rotation #2
- Mux row
- Tile/deck split
- Top vs. bottom pixels
- Inner vs. outer pixels
- Moon up/down
- Best/worst A/B offset

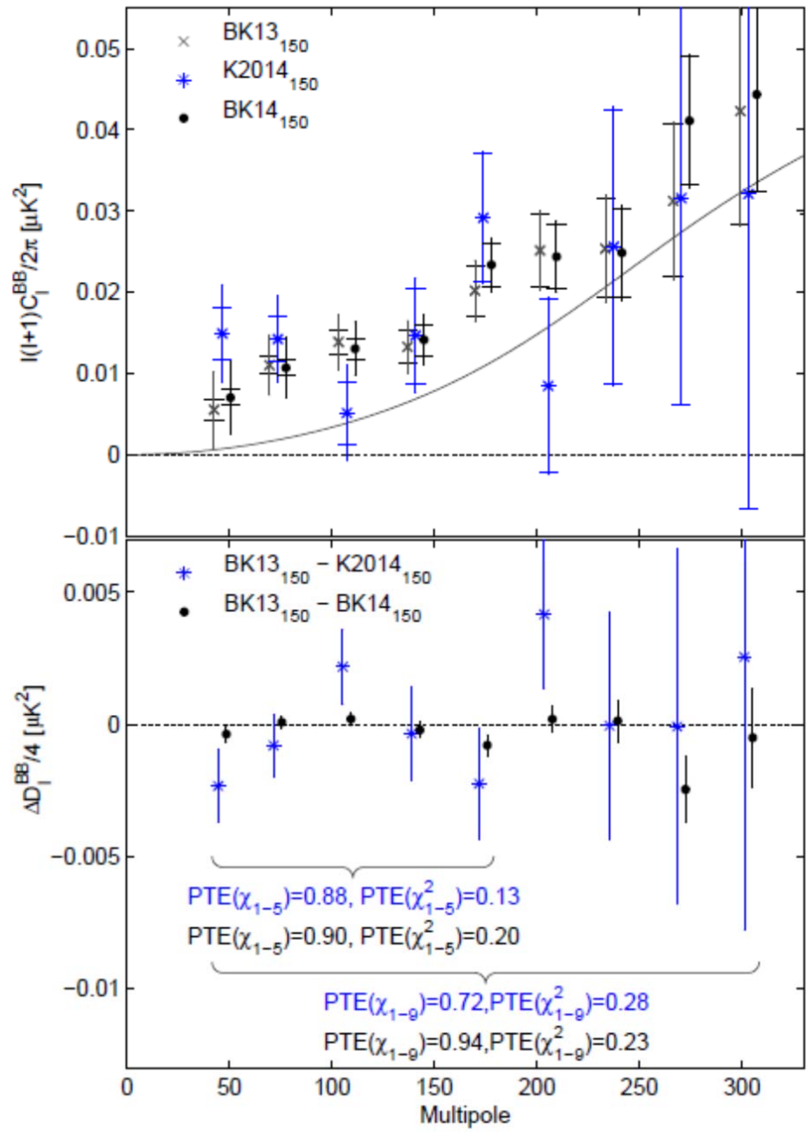


BK13 (1502.00643) test results at 150 GHz

Validating Systematics Across Seasons

Difference spectra made in different years with different receivers and detector for consistency

Use the instrument noise model on simulated difference measurements to account for variation in sky coverage



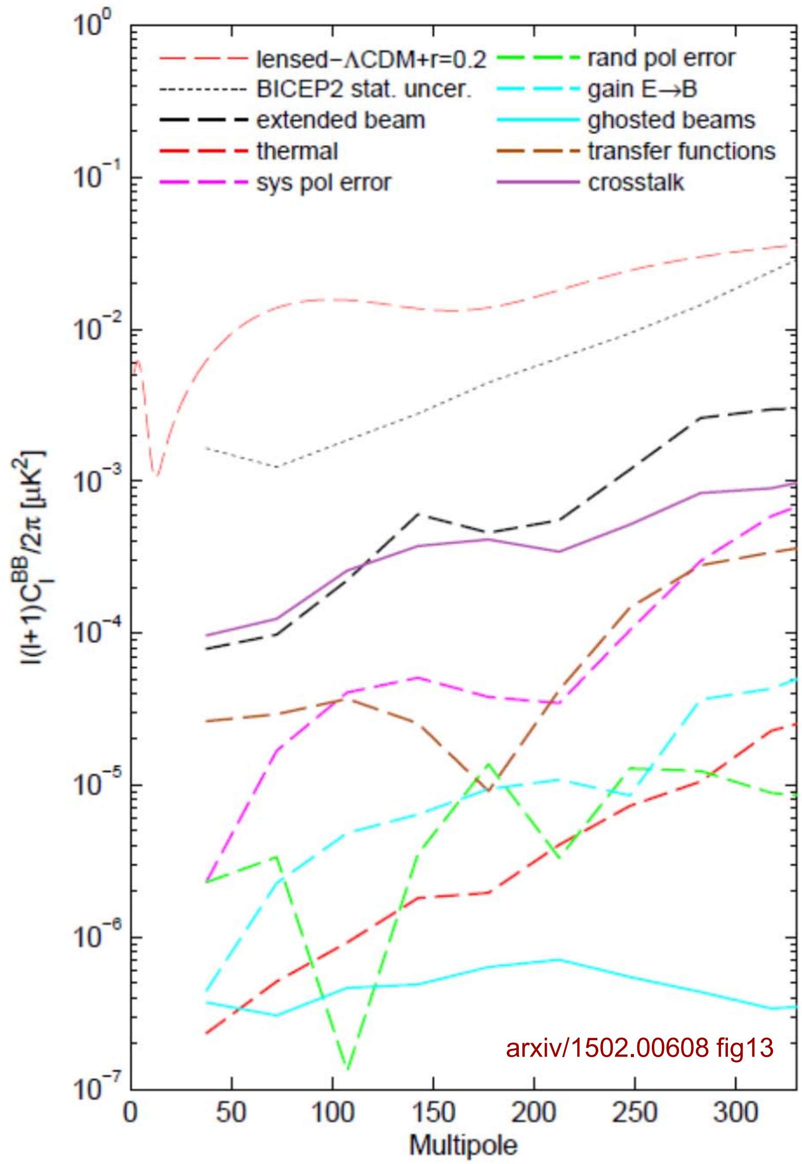
BK14 (1510.09217) tests at 150 GHz

Assessing Systematics from Additional Data

Systematic	Characteristic r
Crosstalk	$\simeq 3.2 \times 10^{-3}$
Beams (including gain mismatch)	$< 3.0 \times 10^{-3}$
EMI	$\lesssim 1.7 \times 10^{-3}$
Cross polar response	$\lesssim 10^{-3}$
Detector transfer functions	$< 5.7 \times 10^{-4}$
Systematic polarization angle error	$< 4.0 \times 10^{-4}$
Gain variation $E \to B$	$< 5.3 \times 10^{-5}$
Random polarization angle error	$\lesssim 5.0 \times 10^{-5}$
Thermal fluctuations	$< 1.2 \times 10^{-5}$
Ghost beams	$\simeq 7.2 \times 10^{-6}$
Scan synchronous contamination	$\lesssim 1 \times 10^{-8}$
Total	$\simeq (3.2-6.5) \times 10^{-3}$

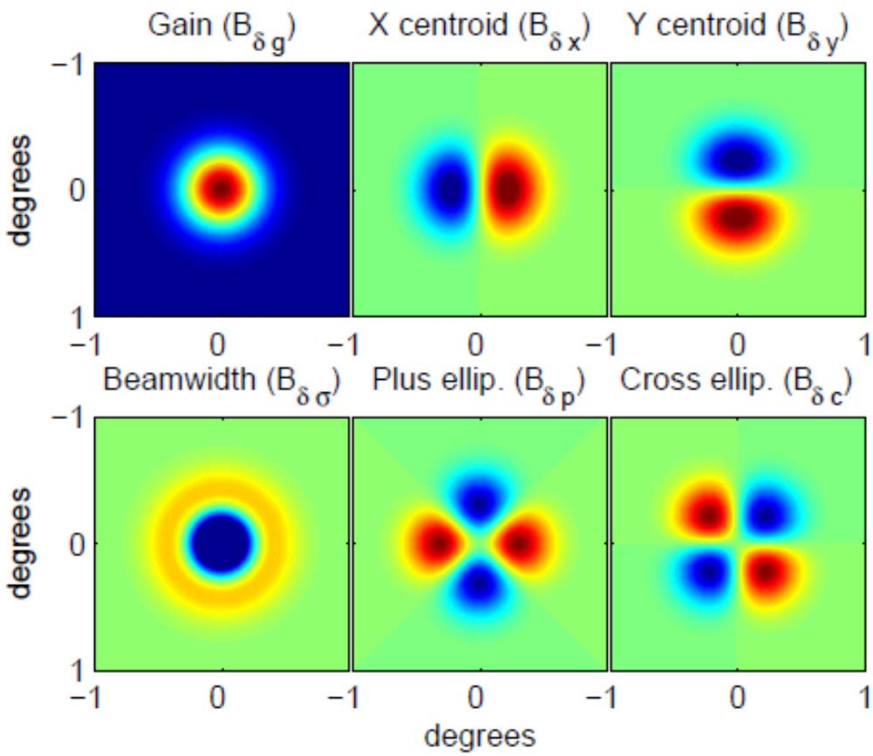
NOTE. — The comparable characteristic r of BICEP2's statistical uncertainty is $r = 3.1 \times 10^{-2}$.

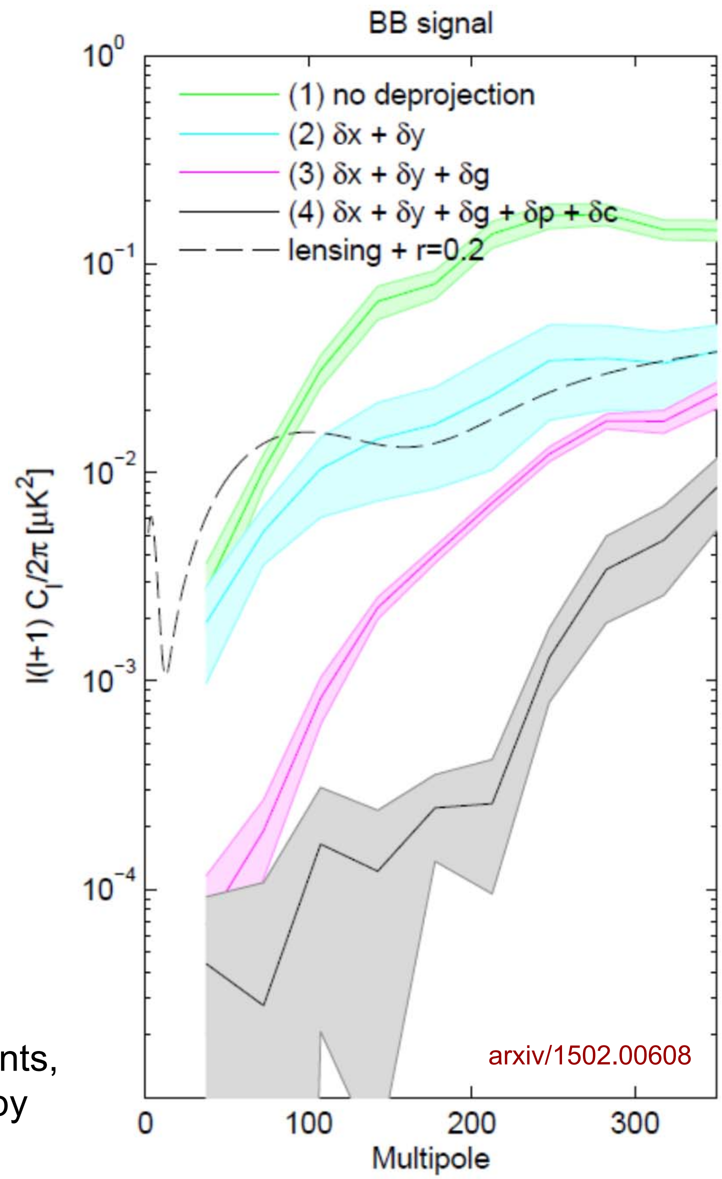
These are assessed by measuring these effects through measurements and modelling their level in CMB data



Things We Worry Less About Now

Main Beam Mismatches





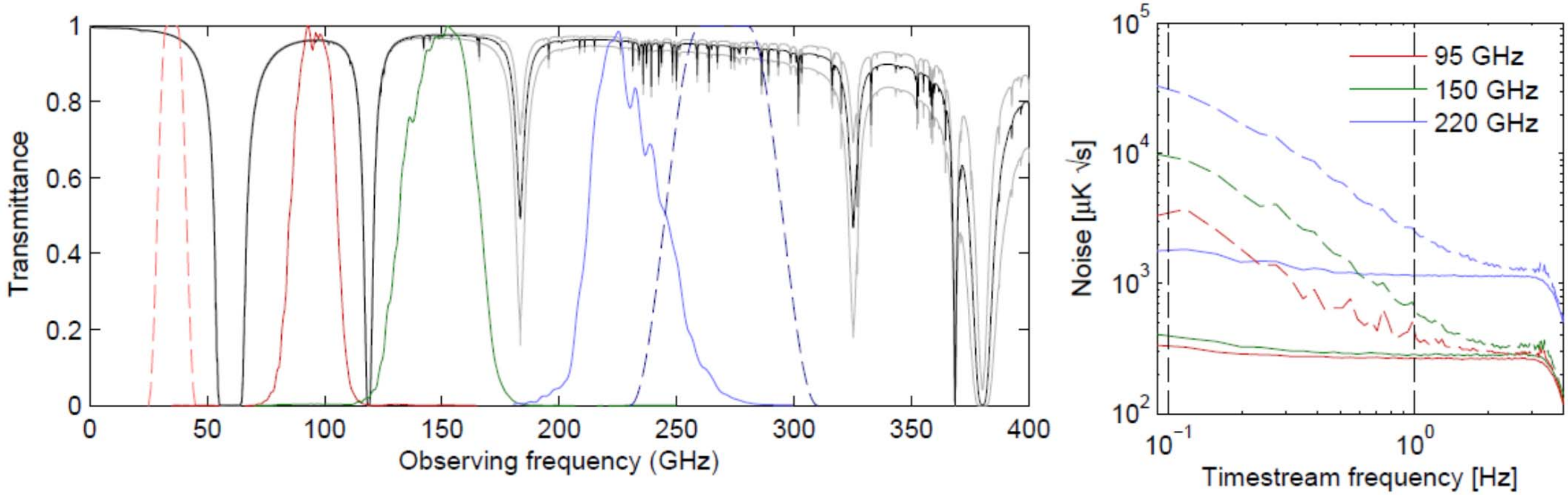
Gain and dipole controlled via deprojection using a template estimation from the Planck CMB temperature map

Effects tested in deck jackknifes, larger in jacks than on sky

Quadrupole and beamwidth removed from beam measurements, but could also be deprojected (slight noise penalty caused by EE sample variance)

Things We Once Worried A Lot About

Sky Noise



Pair-differenced TES bolometers are stable to 0.1 Hz with no additional modulation

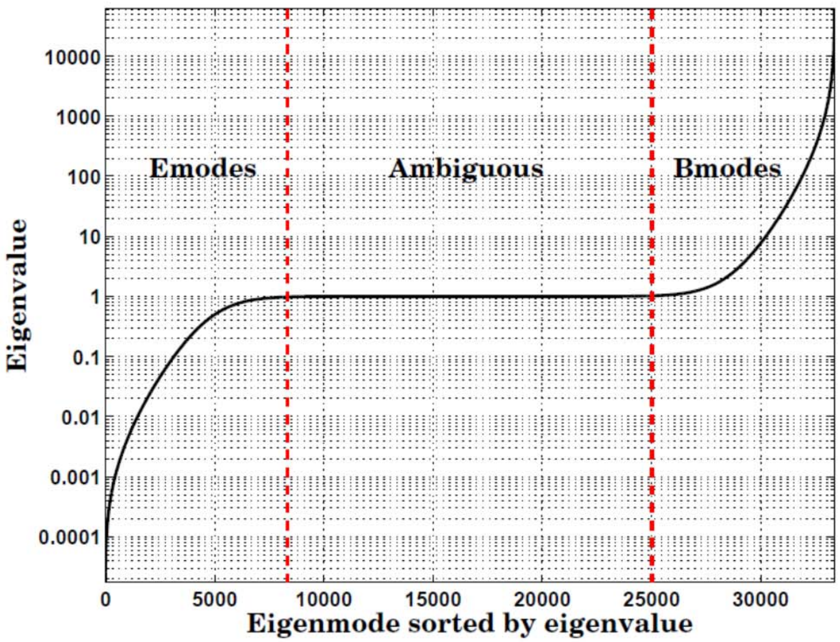
- demonstrated up to 220 GHz, now taking data at 270 GHz
- DC biased, time-domain SQUID readouts

For space we would like stability to 0.01 Hz.

- developing more stable readout circuits seems the best path to me
- not much work has gone into this since it is a space-specific need

Things We Once Worried A Lot About

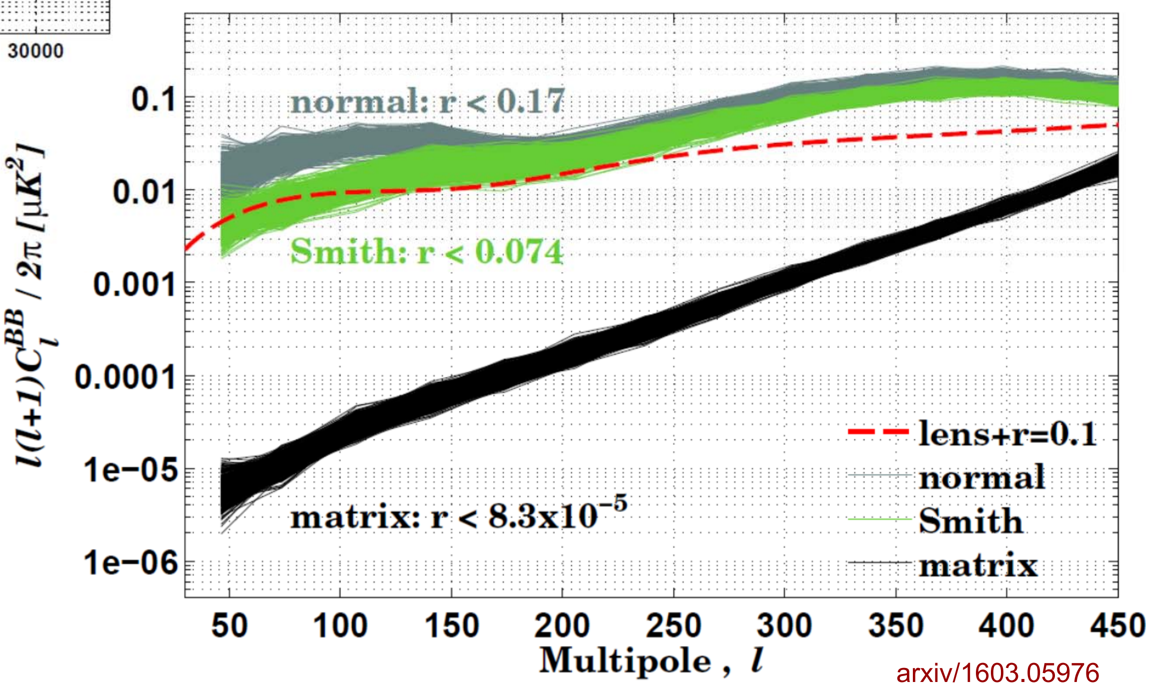
E/B Separation



Cut sky patches convert pure E-modes into false B-modes as well as ambiguous modes

Predicting the average leakage of E-modes into B-modes is not enough due to sample variance

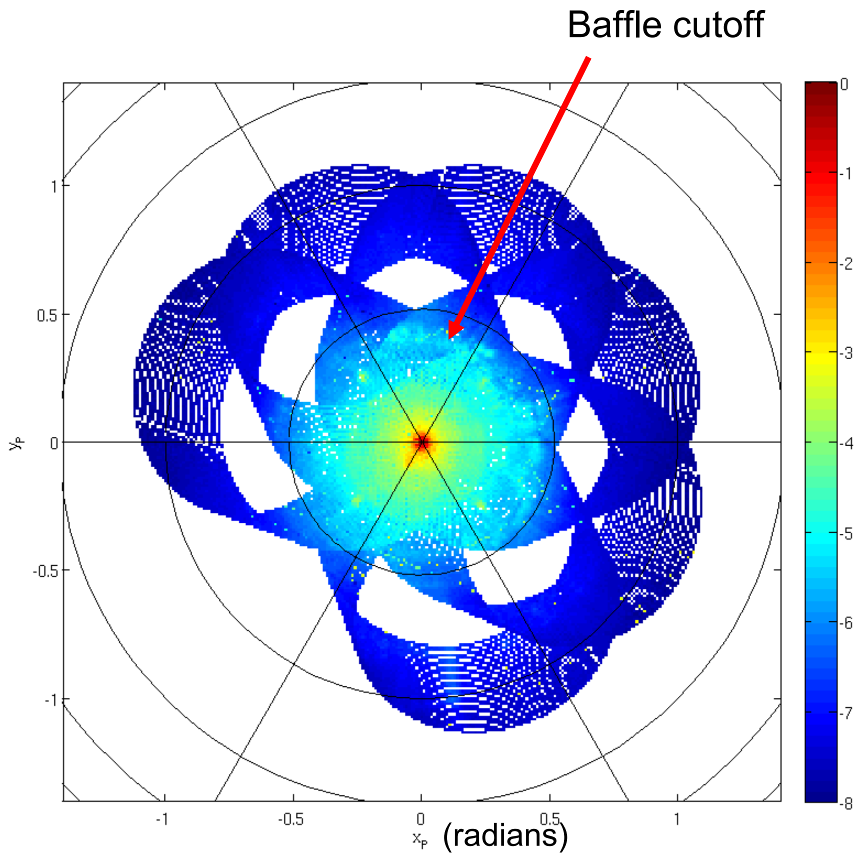
An optimized eigenmode algorithm removes the mixing, and operates in the presence of spatial filtering and map projection



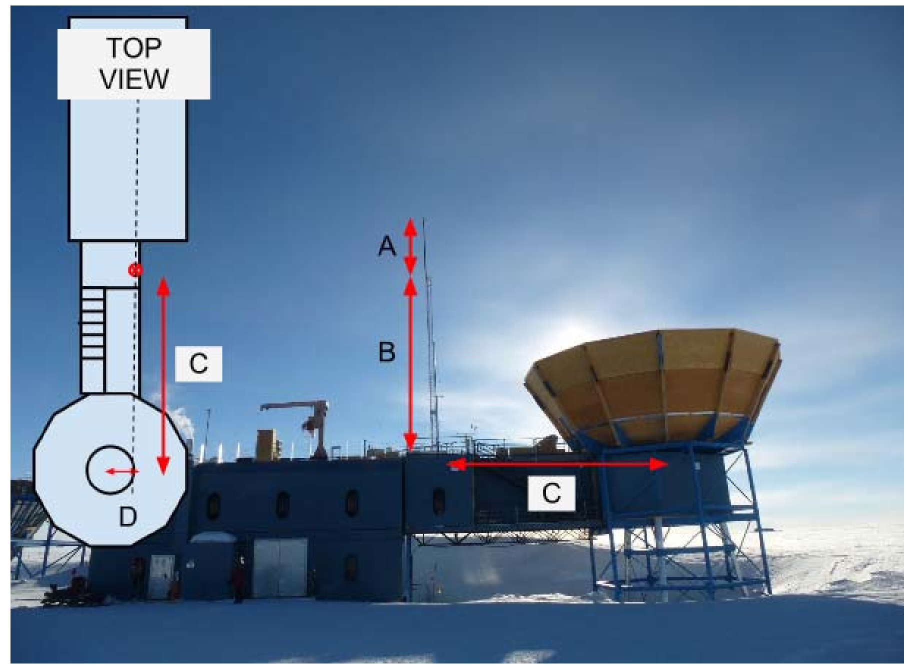
arxiv/1603.05976

Things We Once Worried A Lot About

Far Sidelobes



Polarized far-sidelobe maps

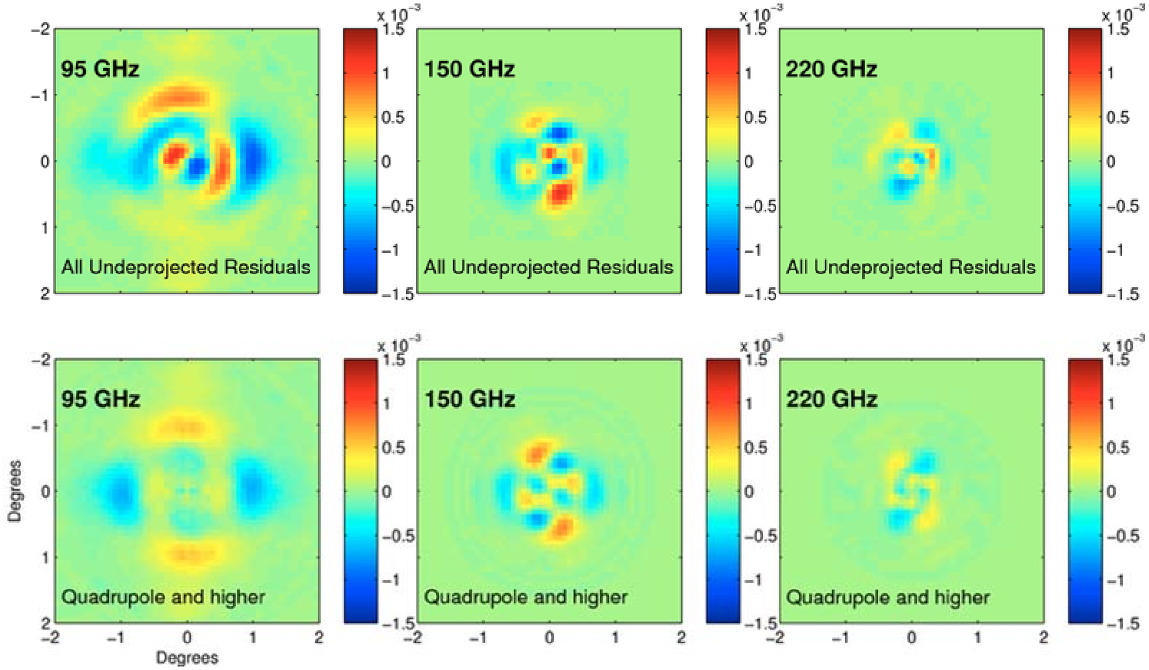


Test setup

Having a small telescope makes direct measurements feasible

Areas We Are Working to Improve

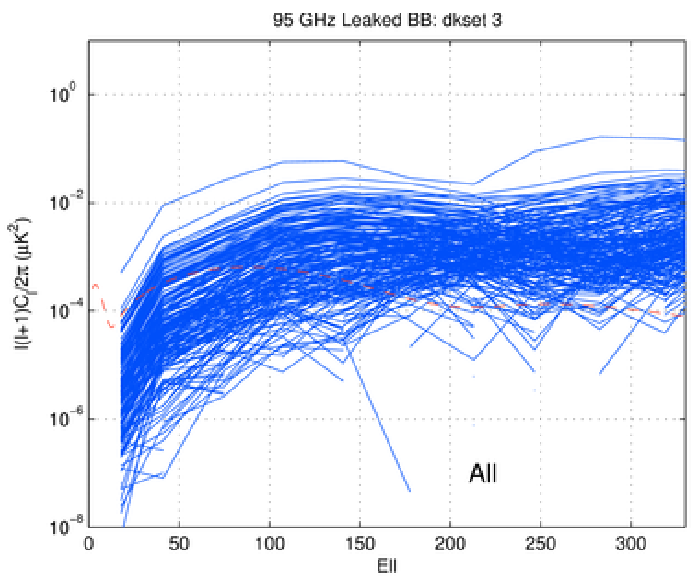
Extended Beams (& Polarization Angle)

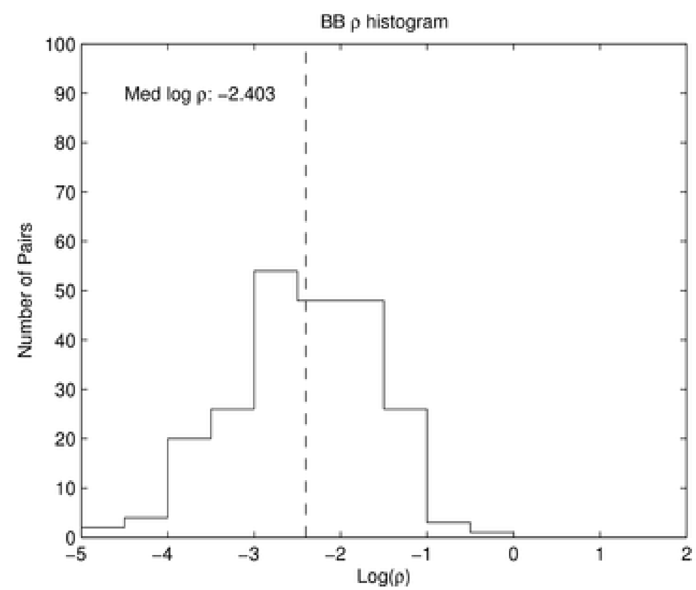


Extended residuals remain after main beam deprojection applied to measured beams.

Generally worse at longer wavelengths. Part of this is caused by interactions with focal plane structure.

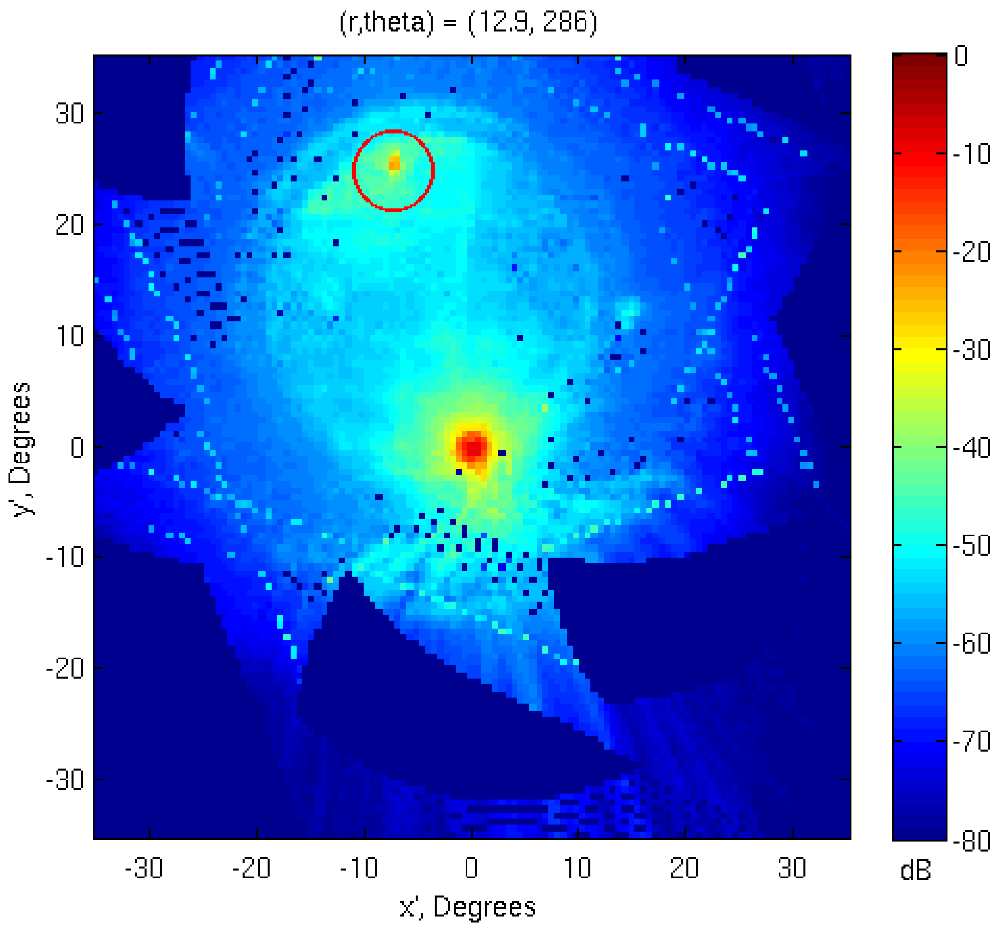
Worst-case effect at 95 GHz without removal is ok at present sensitivity.

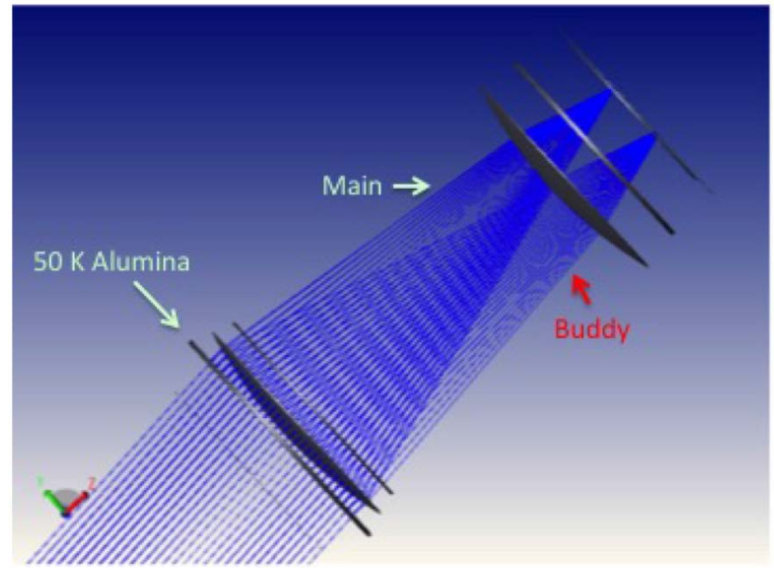


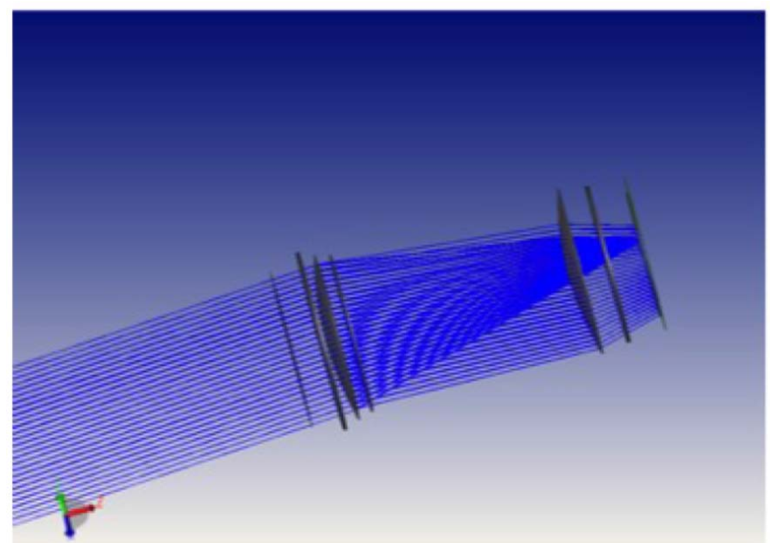


Areas We Are Working to Improve

Extended Beams







Extended beams go out further…

Produces deck-dependent elnods

Working hypothesis is a family of reflections off the optics and focal plane

For the Future: Delensing Systematics