The BICEP/Keck CMB Polarization Approach: Measuring Degree Scales with Small Apertures

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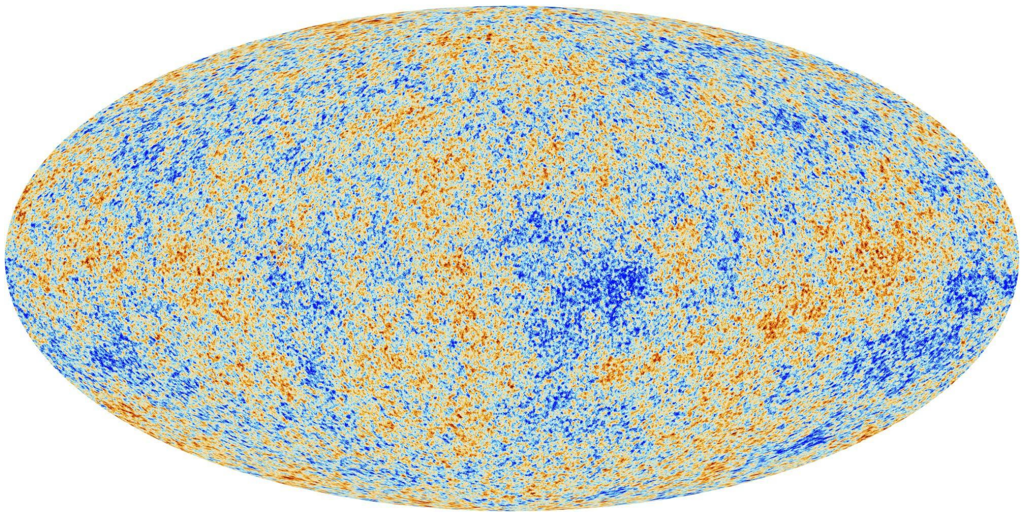
1891

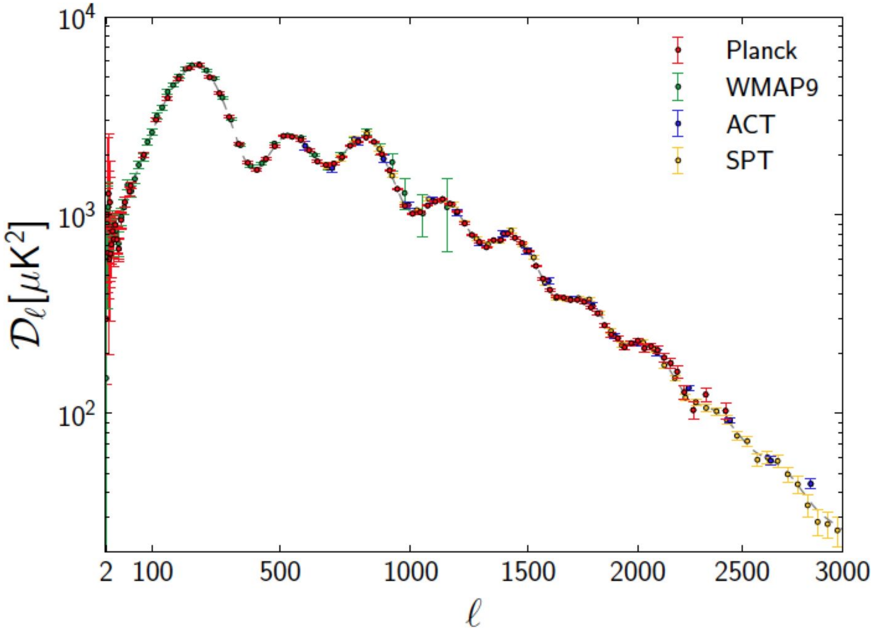
Why Inflation?

CMB Temperature shows…

- Nearly uniform 3 K background with 1/10^5 anisotropies
- Highly adiabatic, Gaussian fluctuations
- Nearly scale-invariant spectrum
- Well-fit by a flat LCDM model

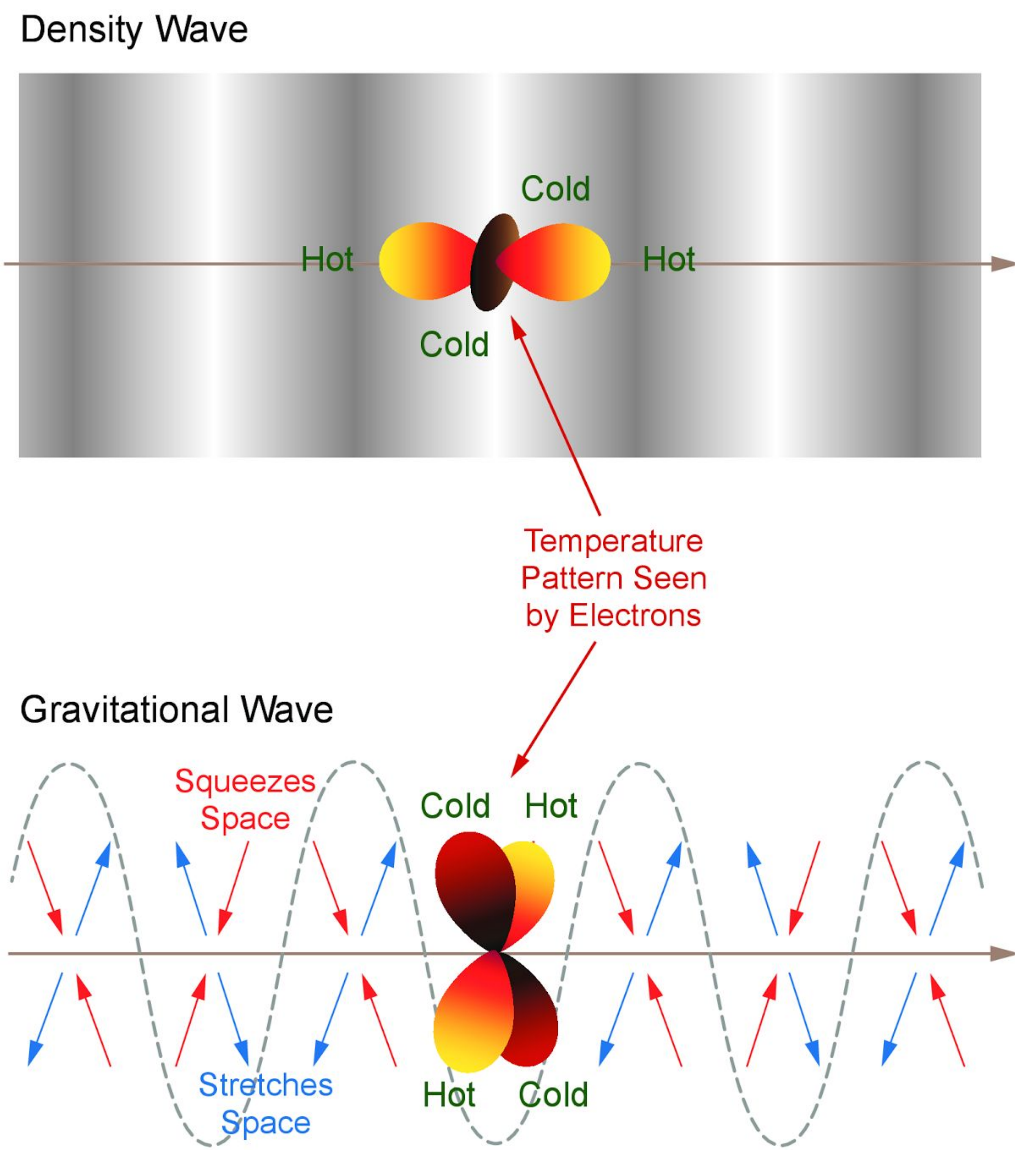
An inflationary expansion naturally produces these features and is consistent with all observations.



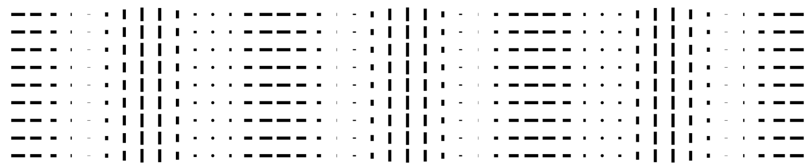


Planck Collaboration & ESA

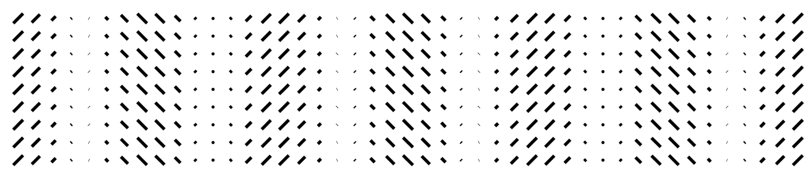
CMB Polarization



E-Mode Polarization Pattern

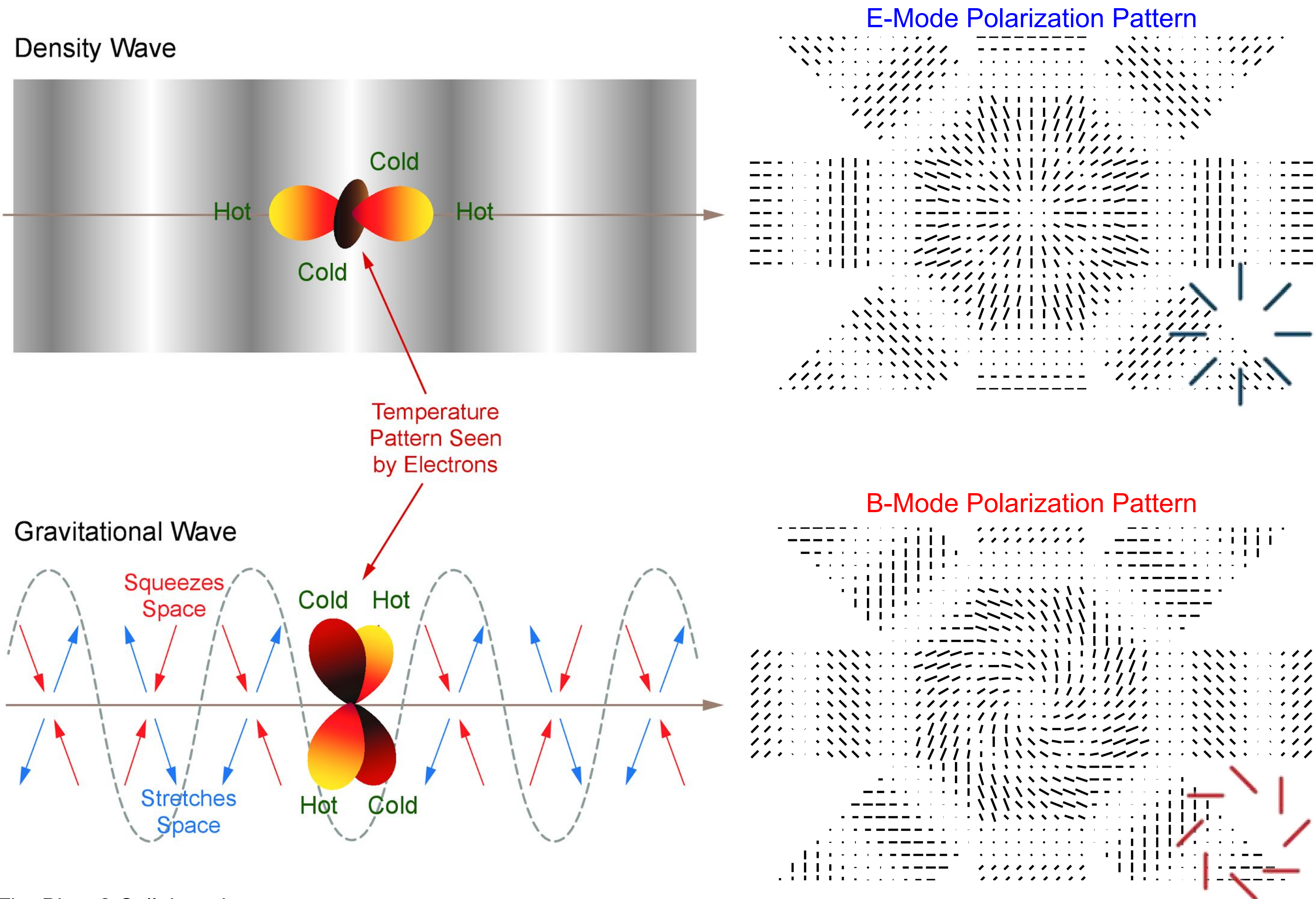


B-Mode Polarization Pattern

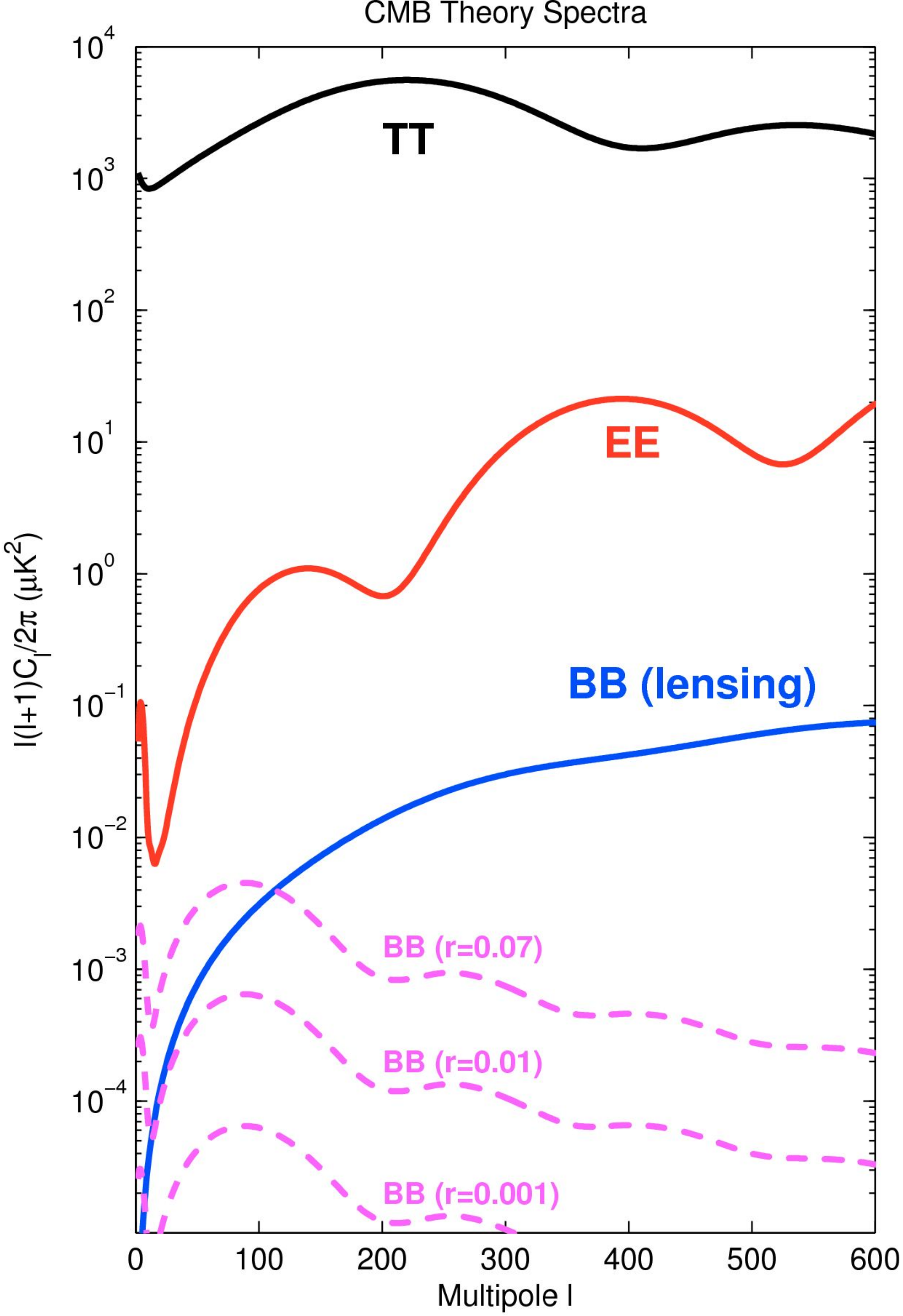


The Bicep2 Collaboration

CMB Polarization



The Bicep2 Collaboration



CMB Theory Spectra
TT
EE
BB (lensing)
BB (r=0.07)
BB (r=0.01)
BB (r=0.001)
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
100
200
300
400
500
600
Multipole l
$l(l+1)C_l/2\pi$ (μK^2)

Maximizing Degree-Scale Sensitivity

On-axis compact cold optics, minimizing instrumental polarization and loading

Suppressing far sidelobe pickup with comoving forebaffles

Pair differencing for common-mode noise rejection

Systematics checks and suppression:

- Boresight rotation
- Filtering known classes of T -> Pol leakage
- Far field beam measurements

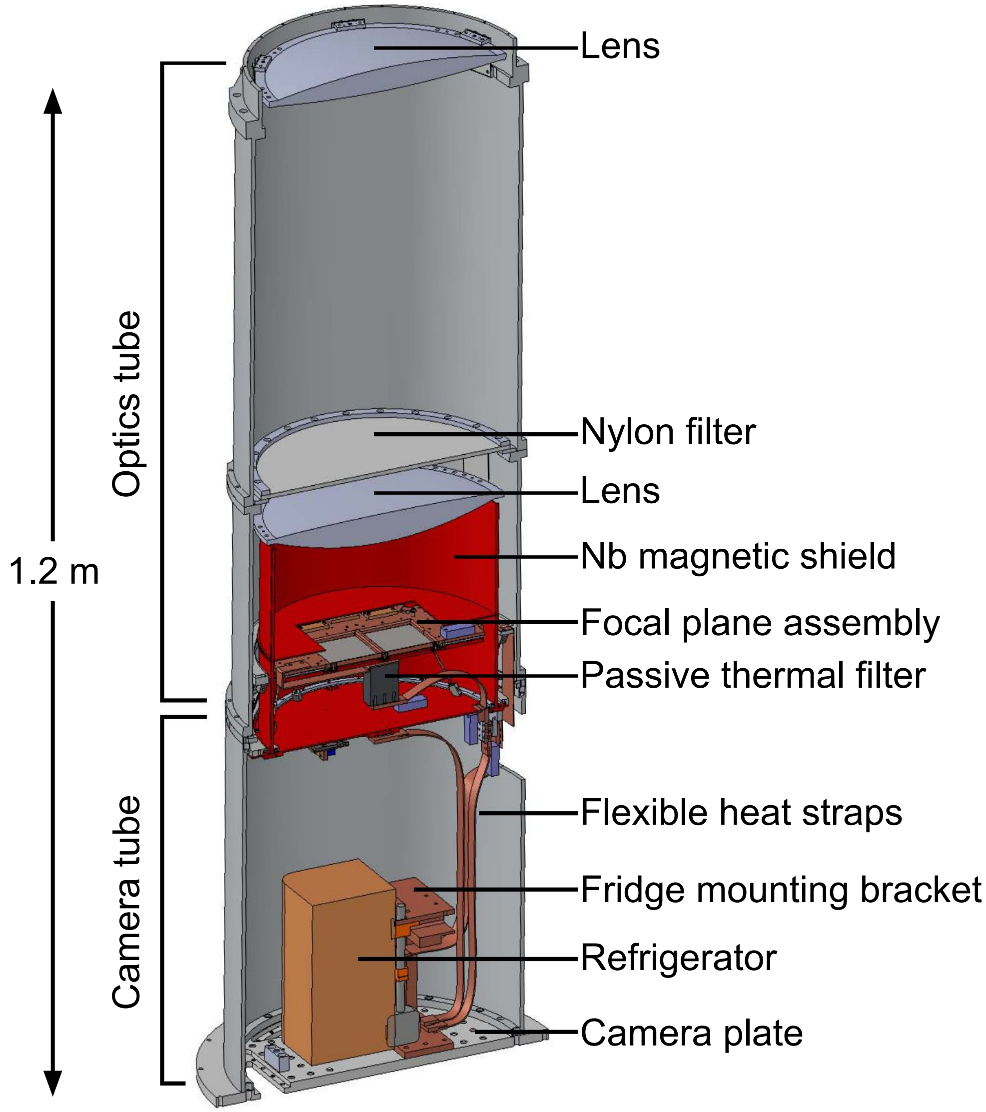
The BICEP2/Keck Telescopes

Telescope as compact as possible while still having the angular resolution to observe degree-scale features

On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation

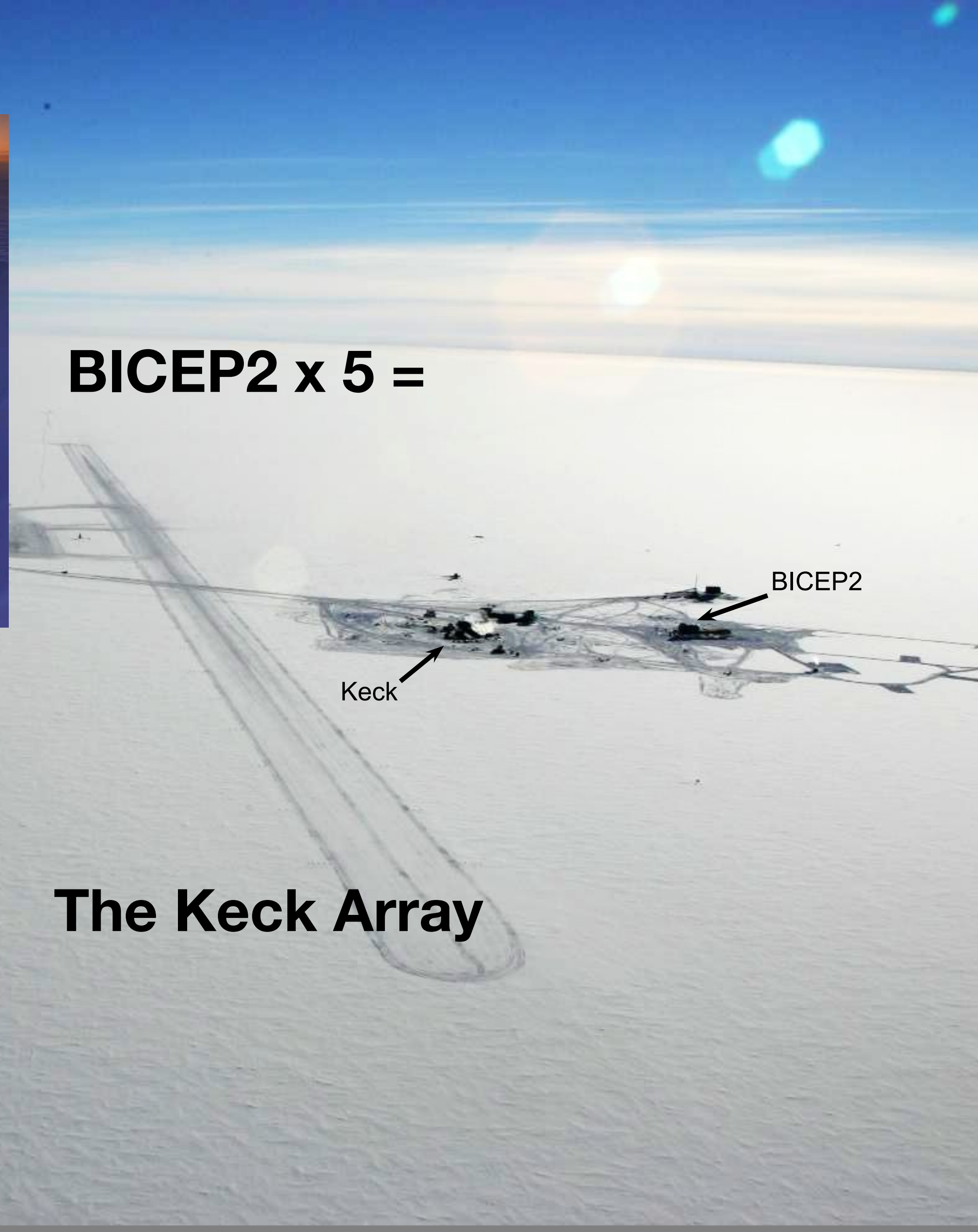
Liquid helium/pulse tube cools the optical elements to 4 K

3-stage helium sorption refrigerator further cools the detectors to 0.27 K



The BICEP/Keck Collaboration


BICEP2 2010-2012

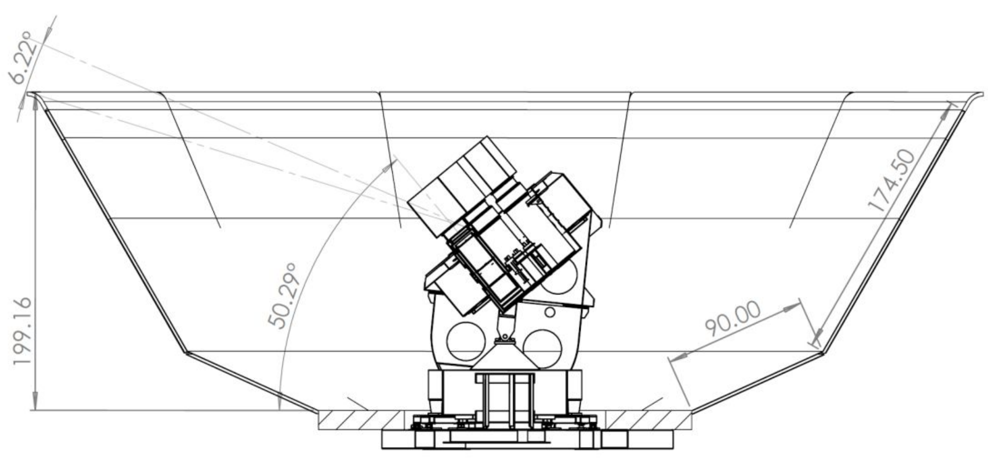

Keck Array 2011-present
BICEP2 x 5 =
BICEP2
Keck
The Keck Array

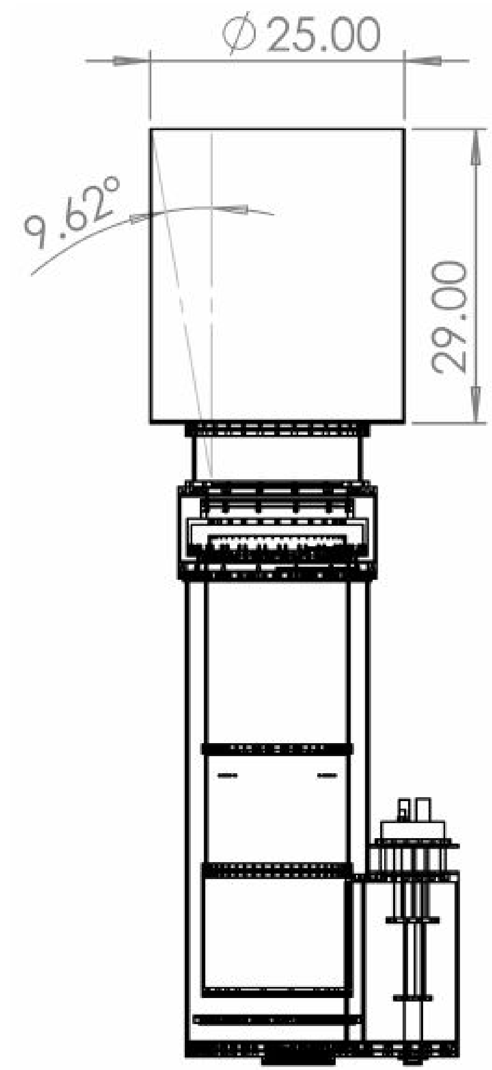
Co-Moving Absorptive Forebaffles

“Far sidelobe” = part of beam pattern which could potentially pick up Galaxy or ground, >15 deg from beam center

Forebaffle absorbs beam outside 10 deg

Reflective ground screen requires 2 diffractions to hit ground





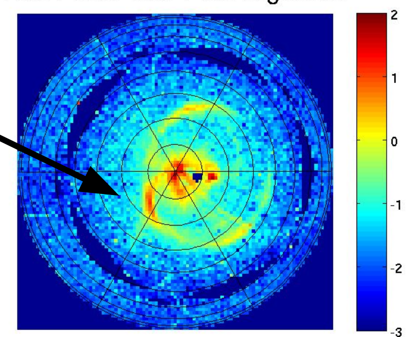
Far Sidelobe Measurement

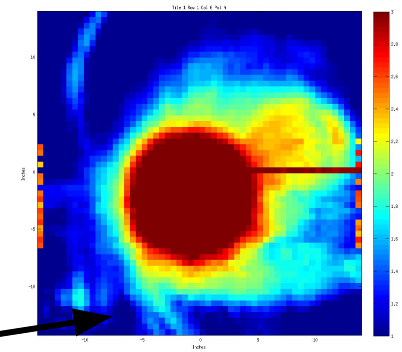
Keck 2013 no-forebaffle wide-angle maps with amplified source found “ring sidelobes” at ~20 degrees from main beam

Qualitatively present in mid-field beam maps

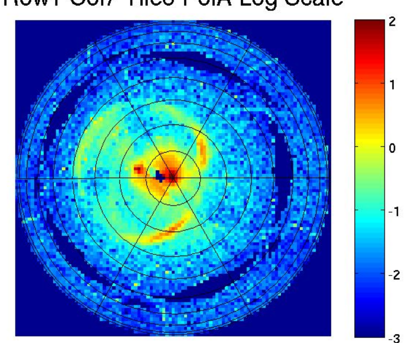
Suspected specular reflection in telescope tube

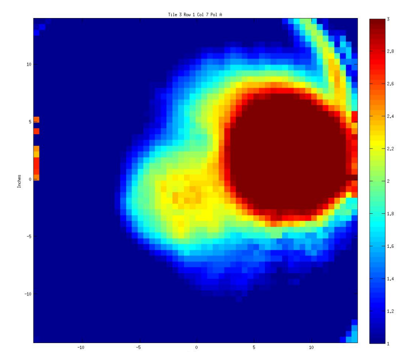
Row1 Col6 Tile1 PolA Log Scale





Row1 Col7 Tile3 PolA Log Scale





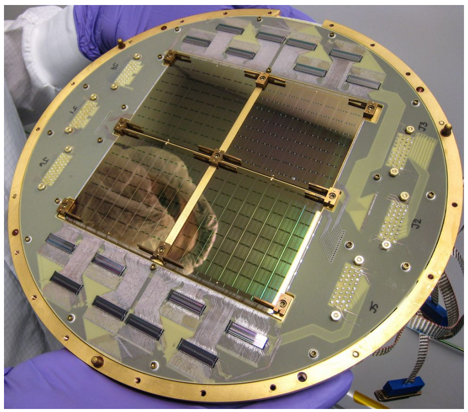
...and suppression

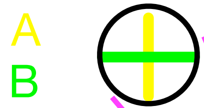
Adding baffling to telescope tube eliminates rings

...and we gain 5-10% in NET

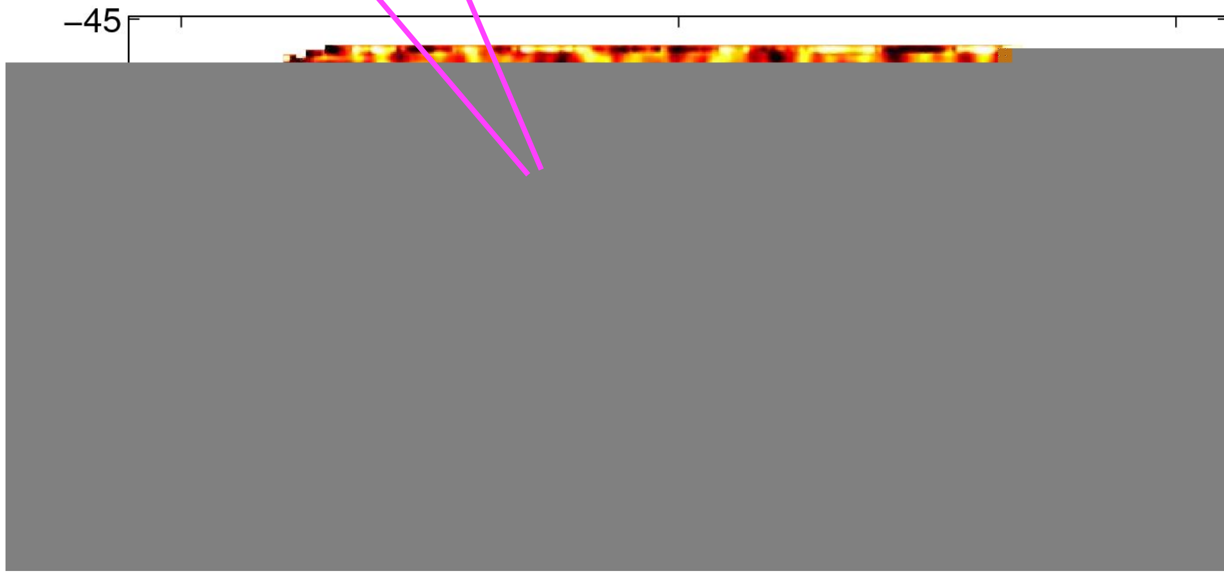
Moral: comoving forebaffle helped us avoid a potentially significant far sidelobe systematic in early seasons, and we eventually removed it altogether

Measuring Polarization with Pair Differencing





Each focal plane pixel is really *two* detectors — a horizontally polarized one and a vertically polarized one

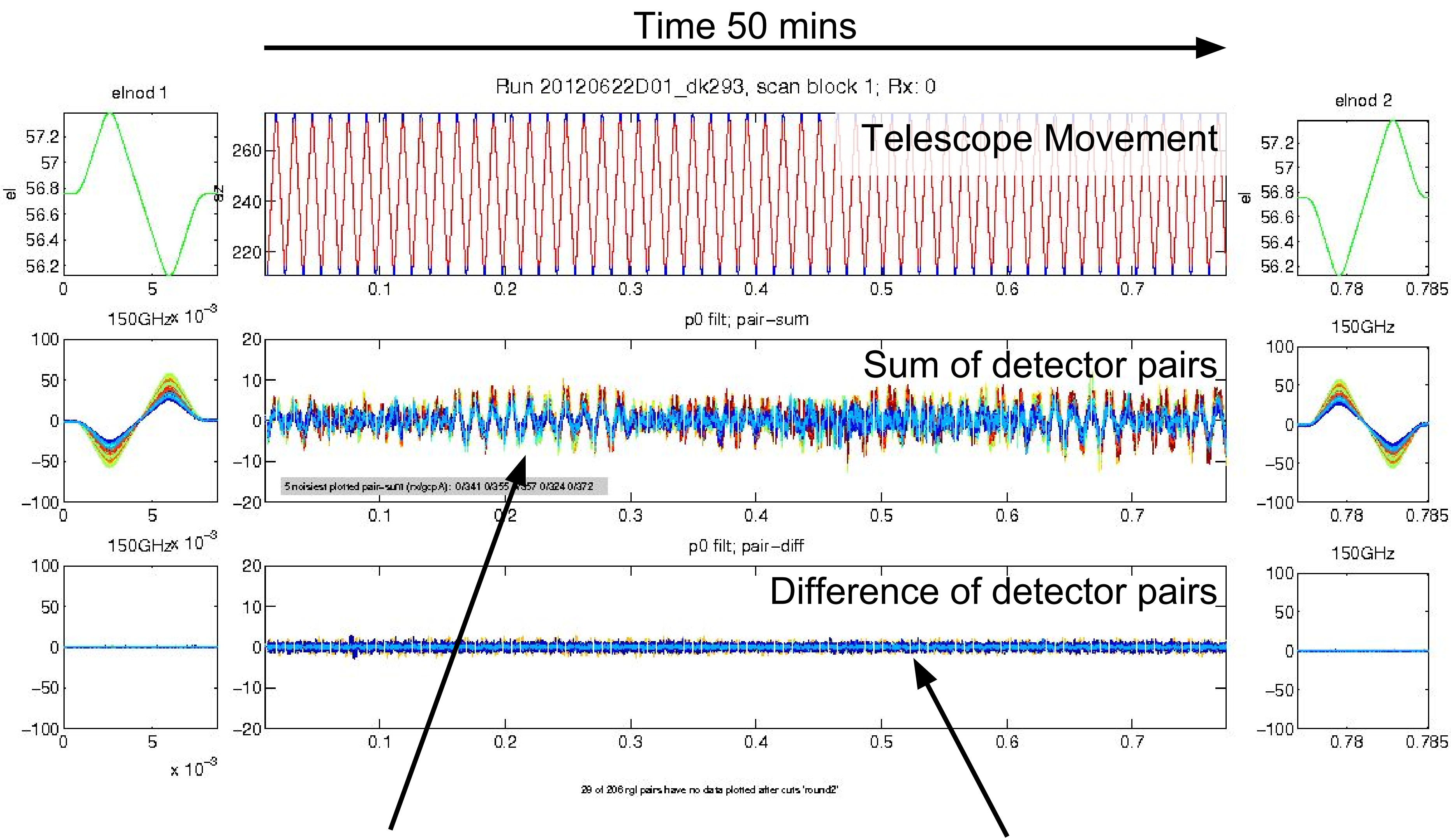


$$A = T + Q\cos 2\psi + U\sin 2\psi$$
$$B = T + Q\cos 2(\psi + \pi/2) + U\sin 2(\psi + \pi/2)$$

$$\frac{A + B}{2} = T$$

$$\frac{A - B}{2} = Q\cos 2\psi + U\sin 2\psi$$

Raw Data

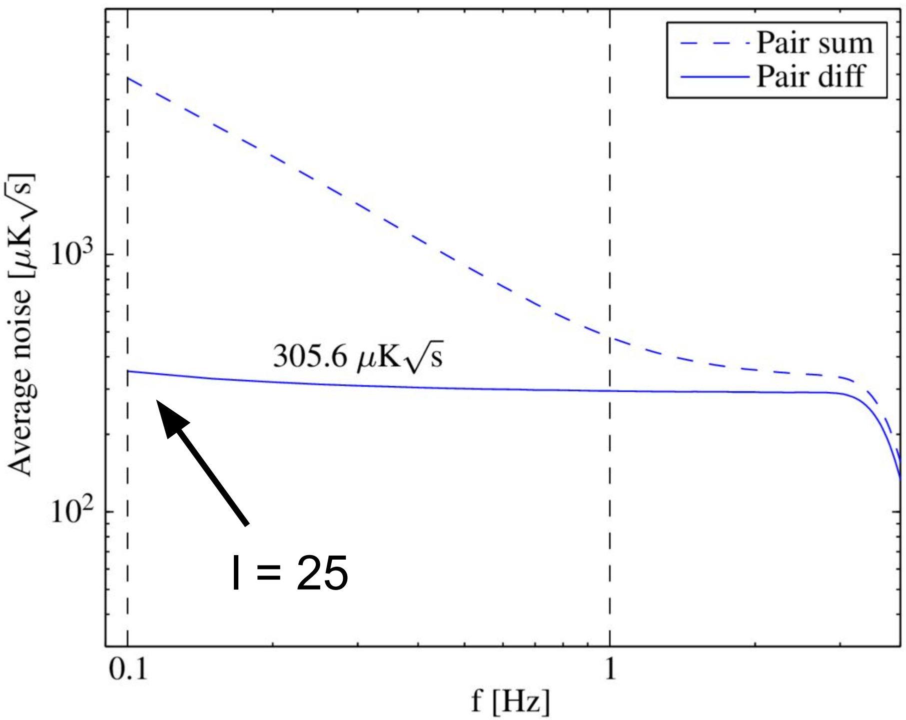


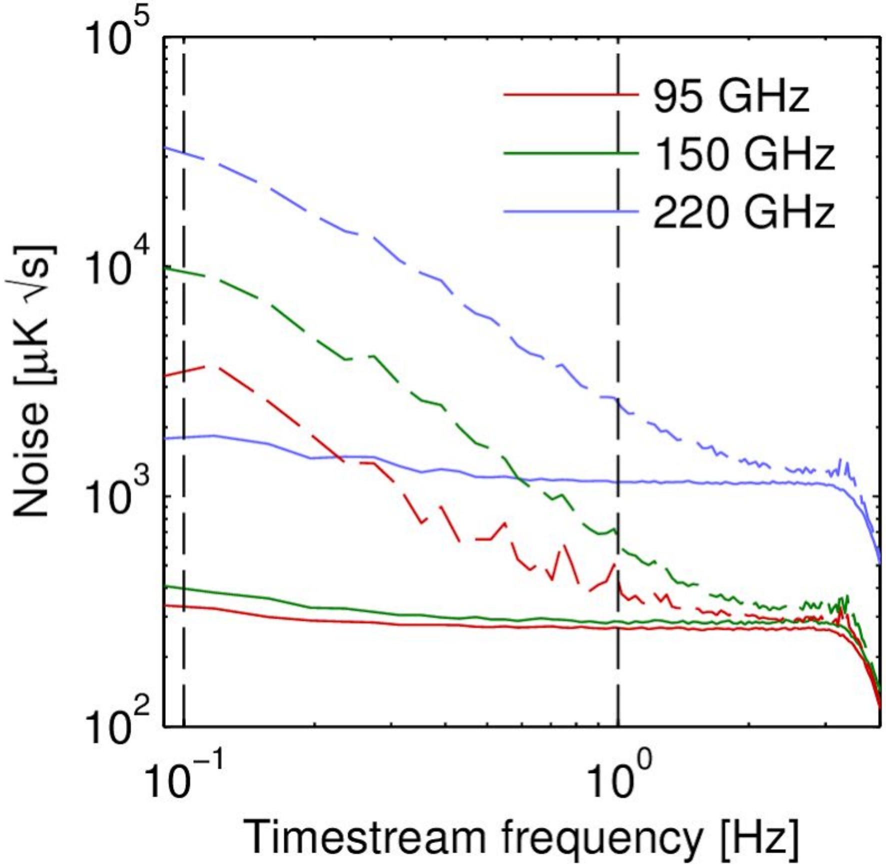
Scanning over lumpy atmosphere
→ "clouds"

Pair difference still clean
→ atmosphere is unpolarized

The BICEP/Keck Collaboration

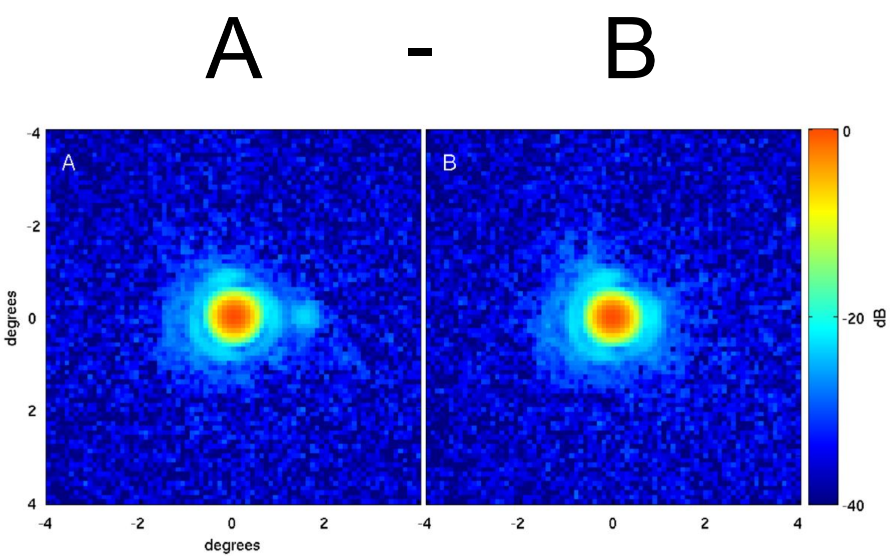
BICEP2/Keck PSDs





Pair differencing is extremely effective at rejecting common-mode noise even at low frequencies

Temperature to Polarization Leakage



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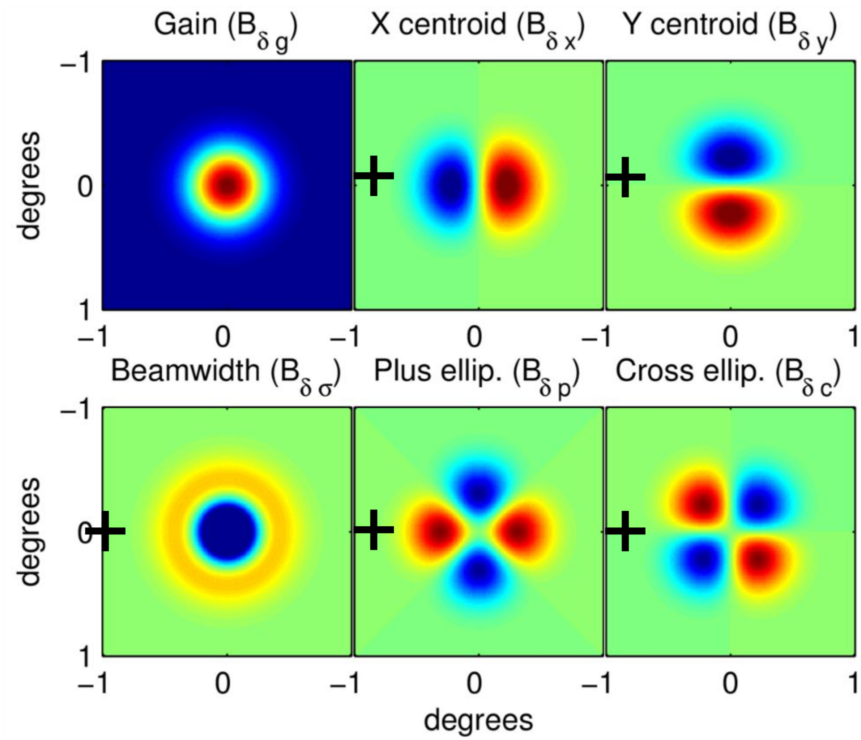
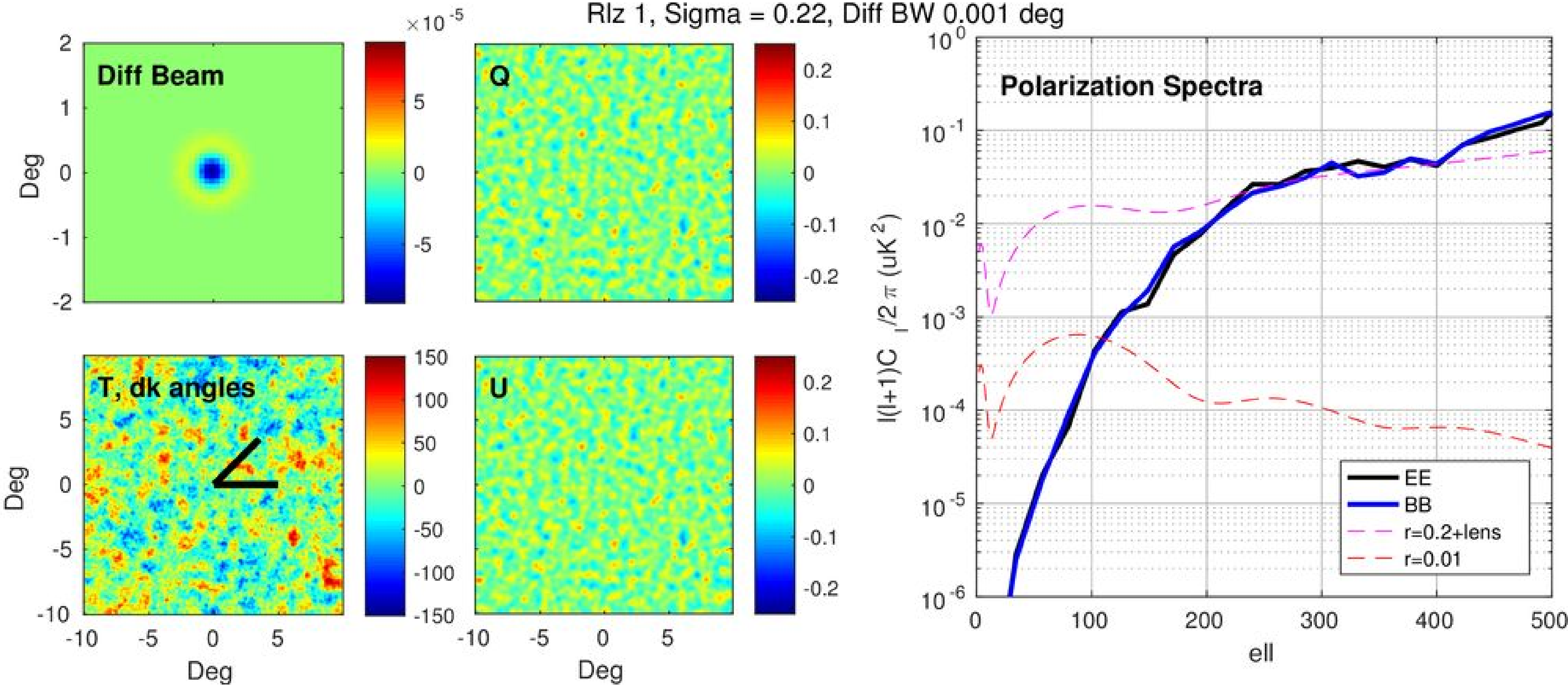


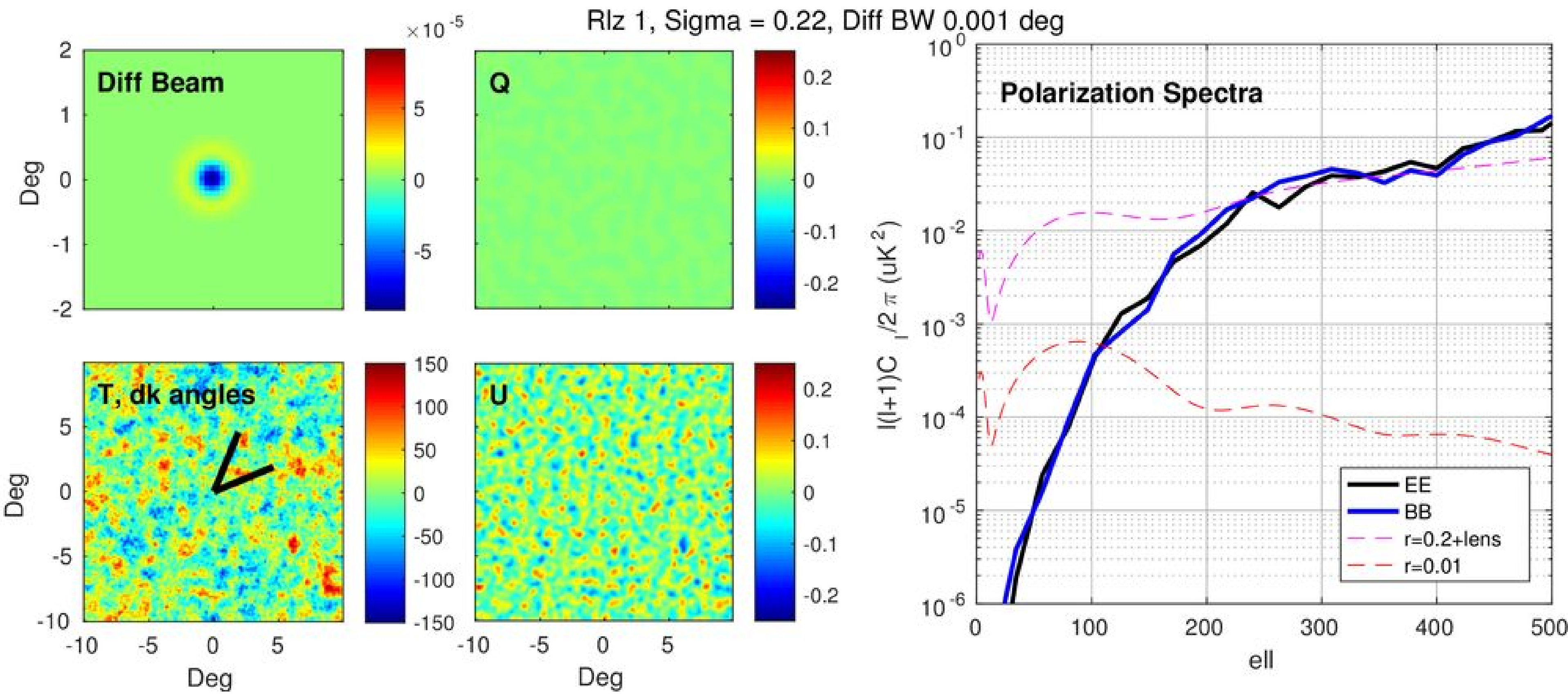
1. Natural cancellation via boresight rotation
2. Filtering (i.e. deprojection)
3. Check with explicit beam measurement

\+ Higher order residuals

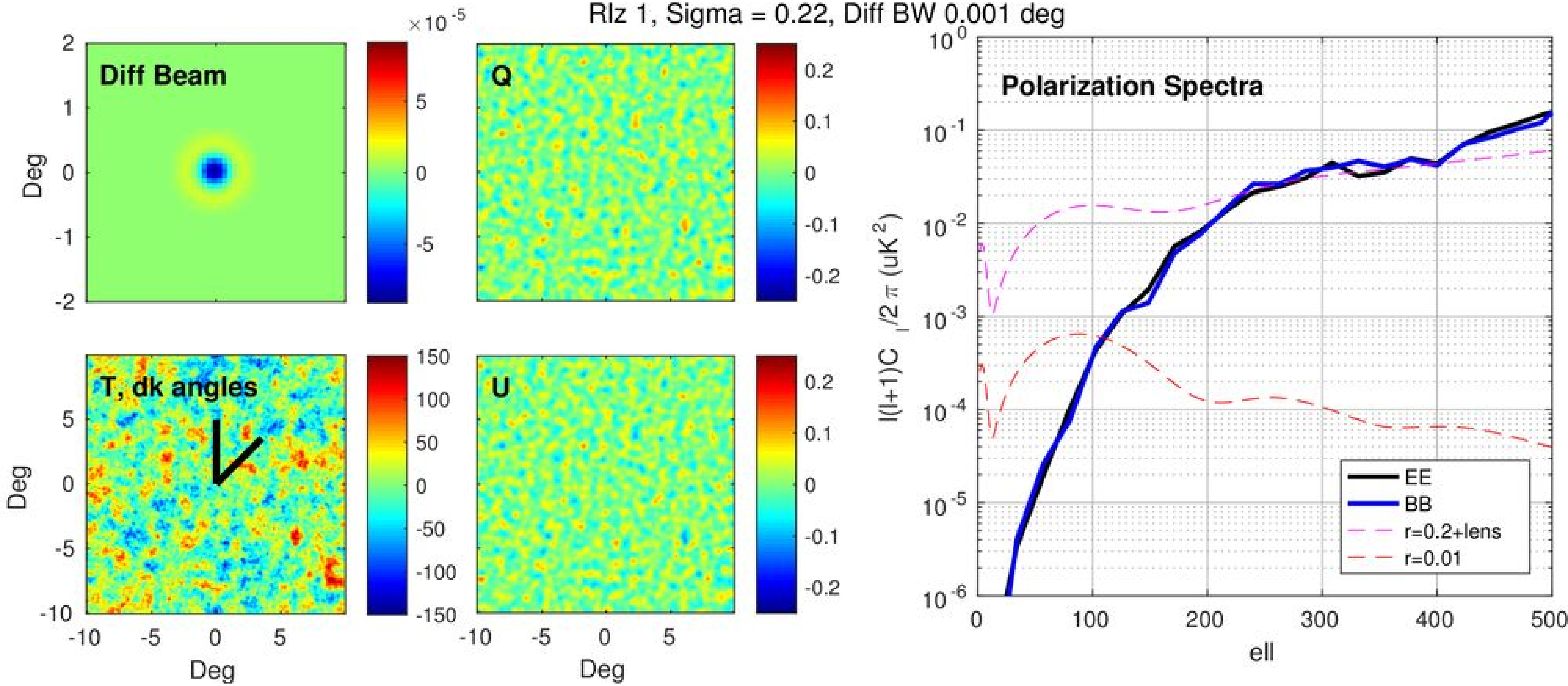
Single pair monopole leakage



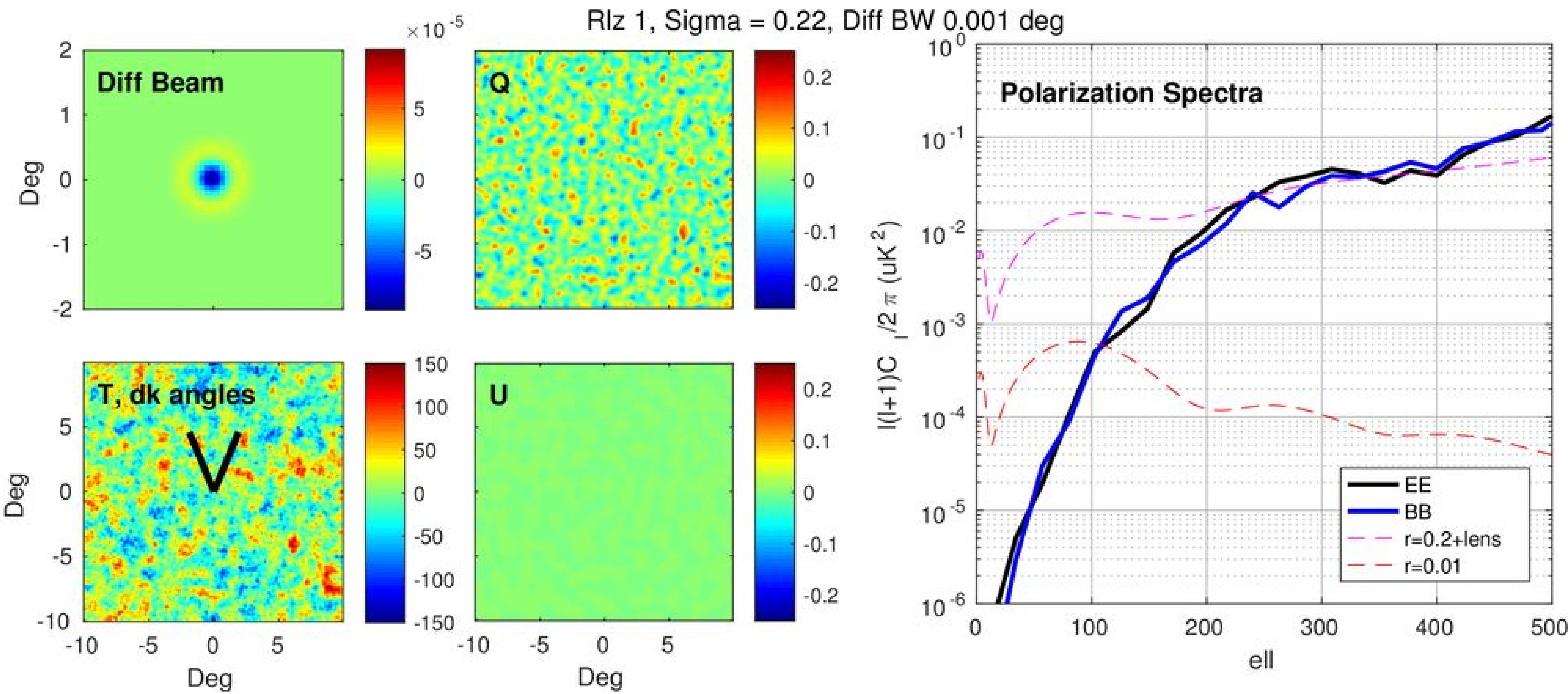
Single pair monopole leakage



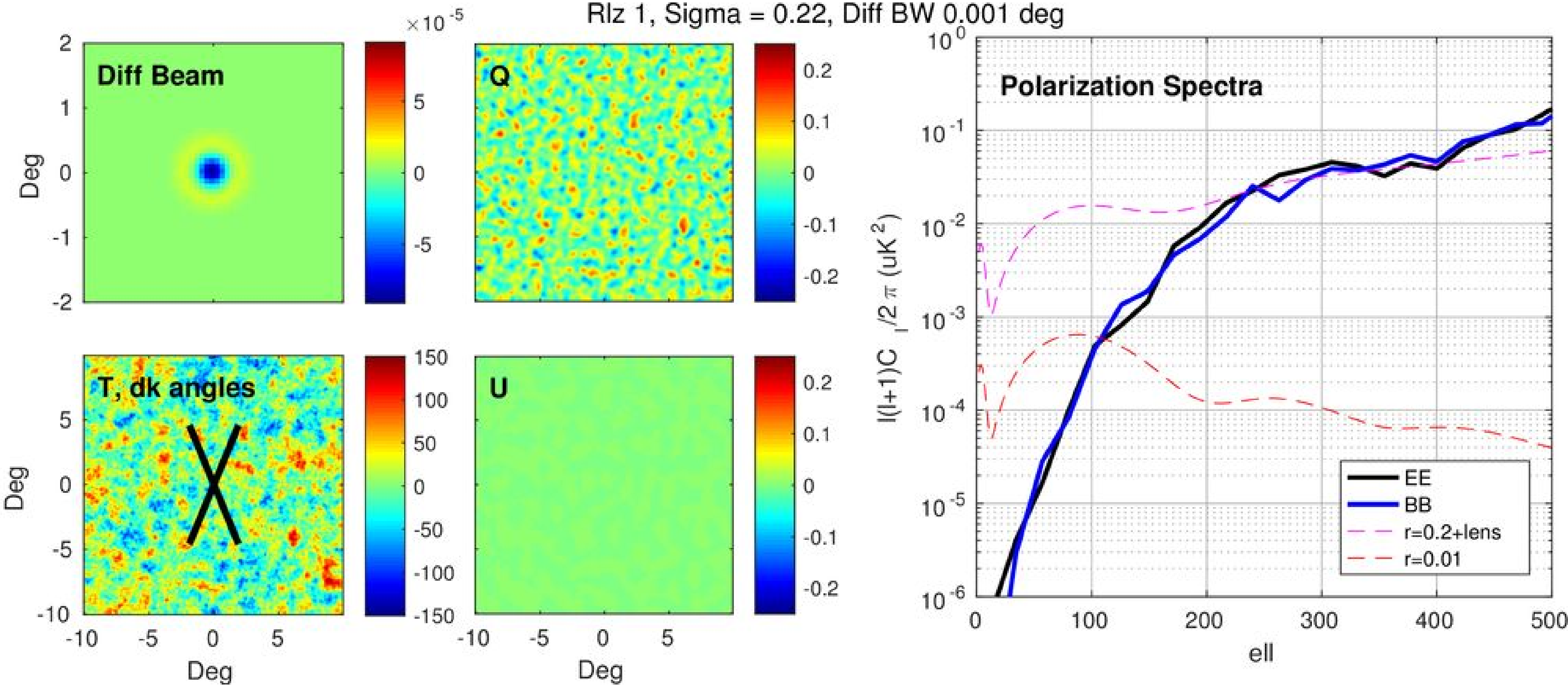
Single pair monopole leakage



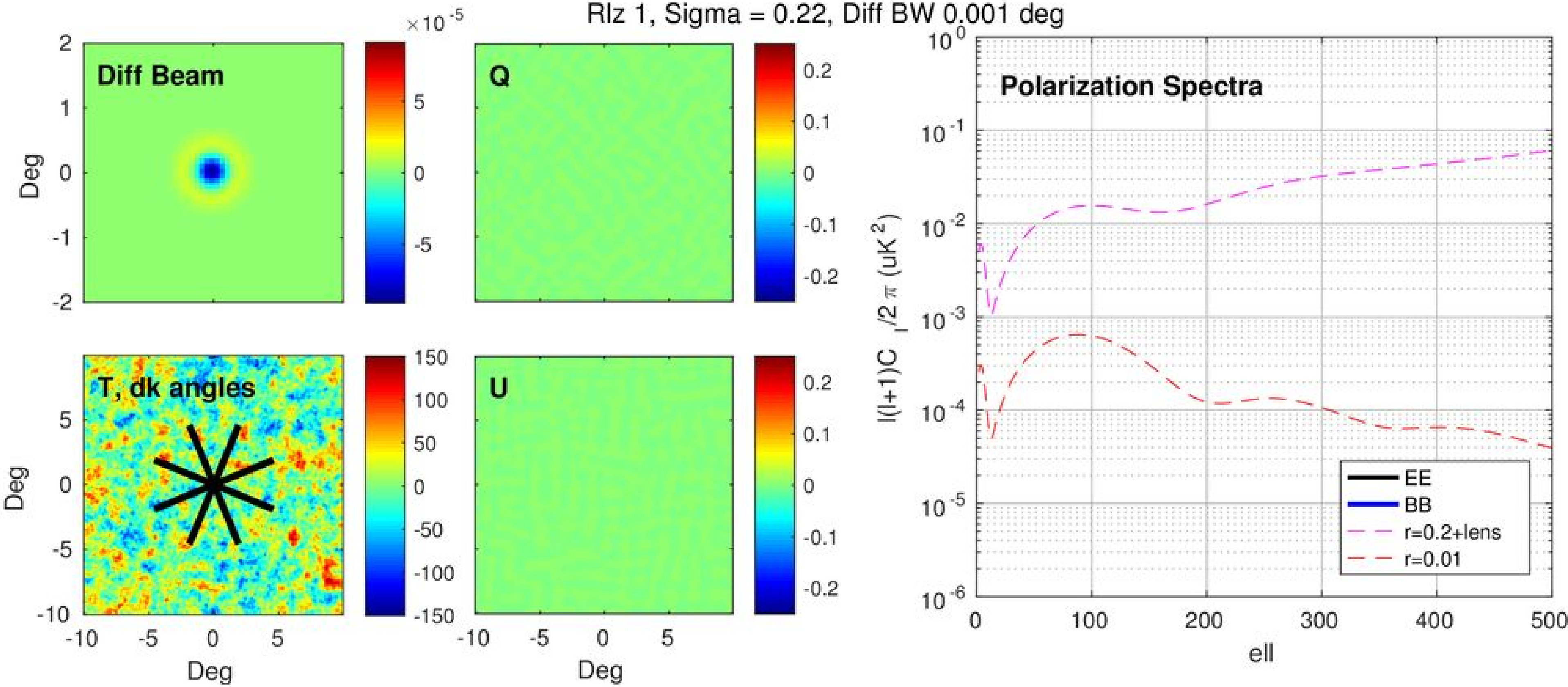
Single pair monopole leakage



Single pair monopole leakage



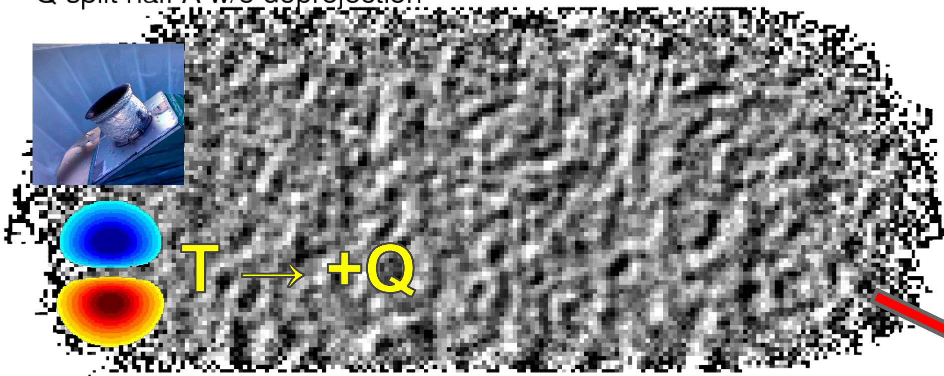
Single pair monopole leakage



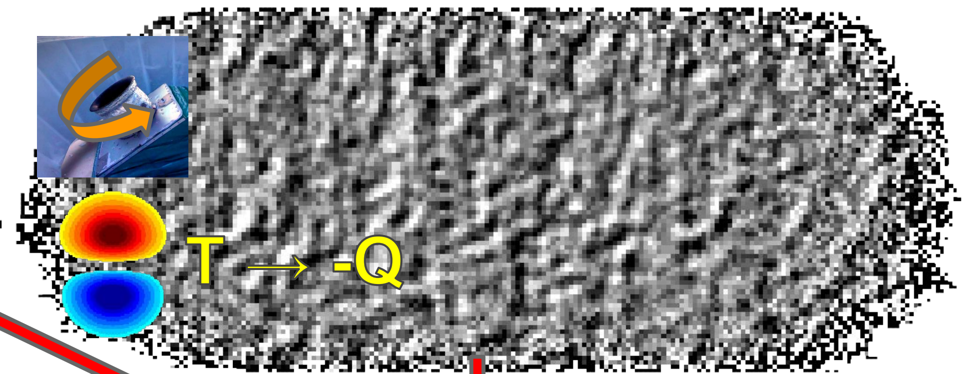
Cancellation of Systematics: Real Maps

Maps using just half the boresight rotation angles:

Q split half A w/o deprojection

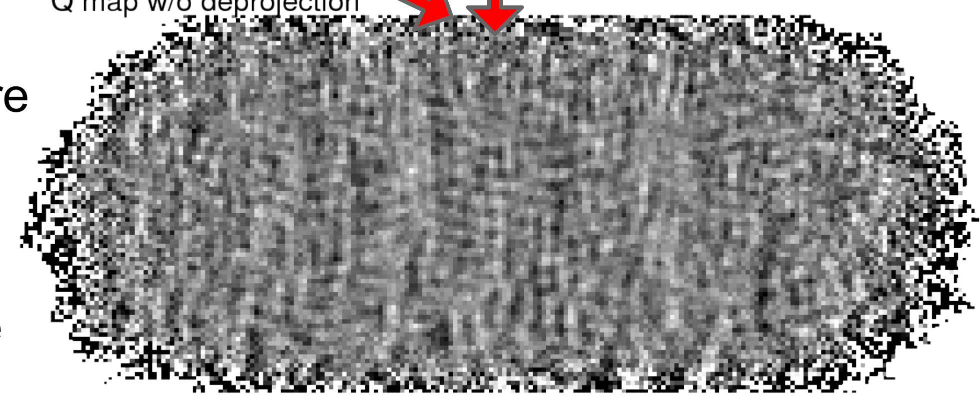


Q split half B w/o deprojection



add

Q map w/o deprojection

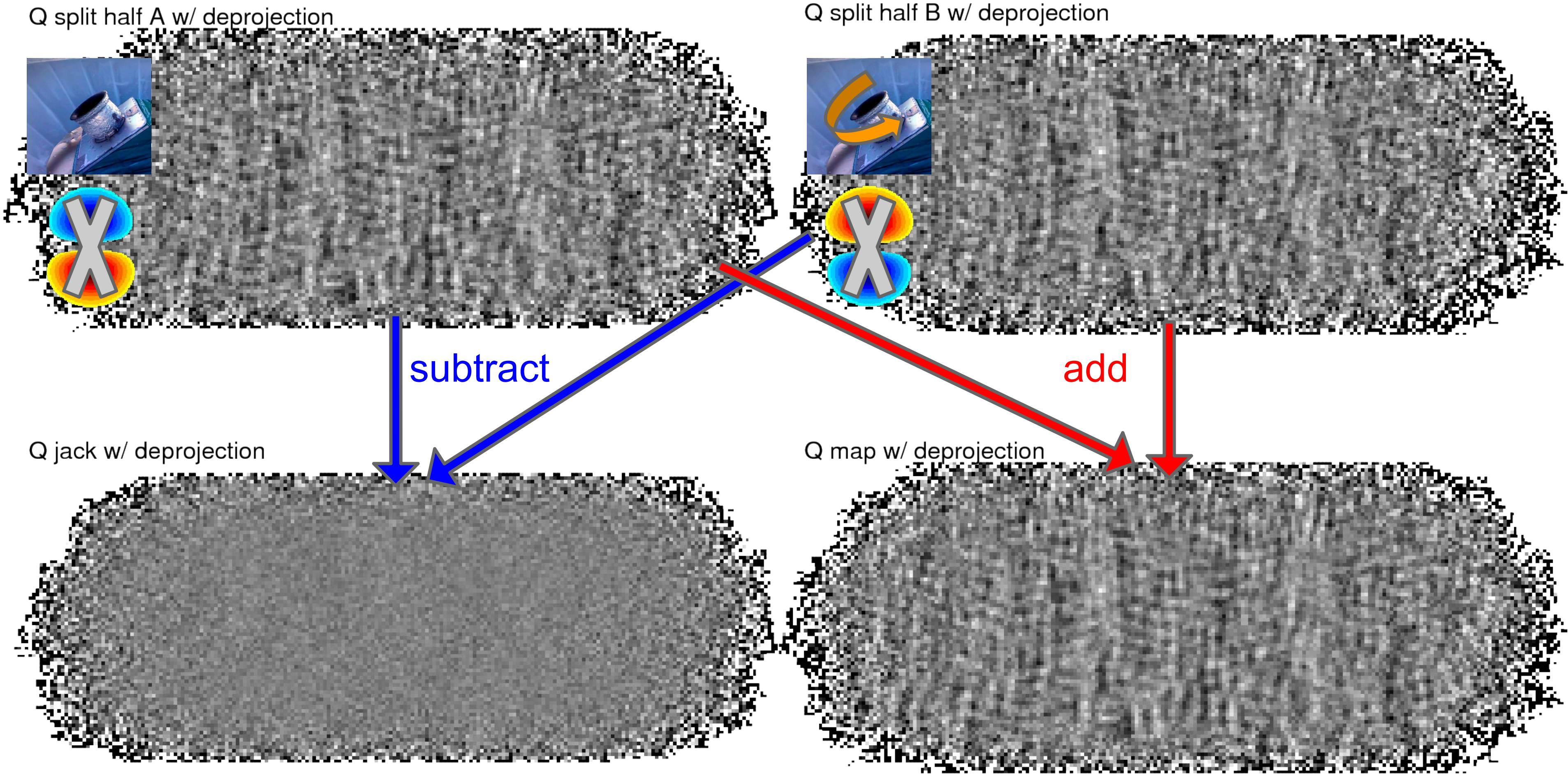


w/o boresight rotation
- ➢ Differential pointing leaks temperature sky into polarization maps

with boresight rotation
- ➢ systematic heavily suppressed in the full map (real signal remains)

Systematics Removal: Deprojection

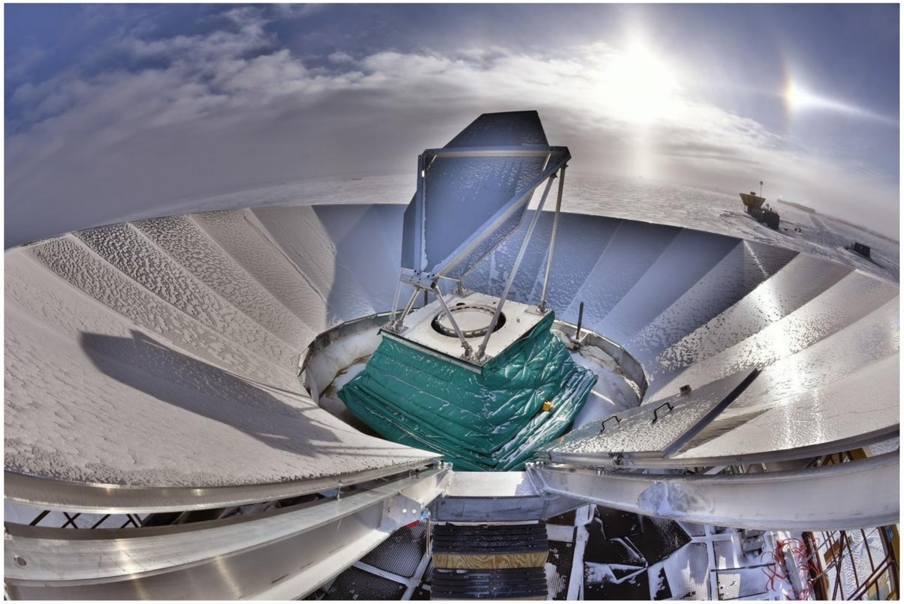
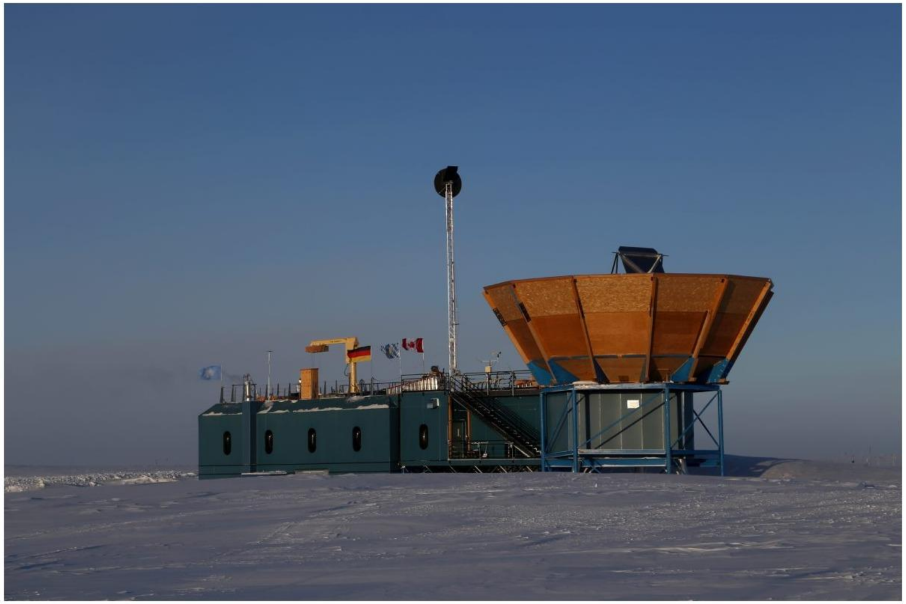
Maps using just half the boresight rotation angles:

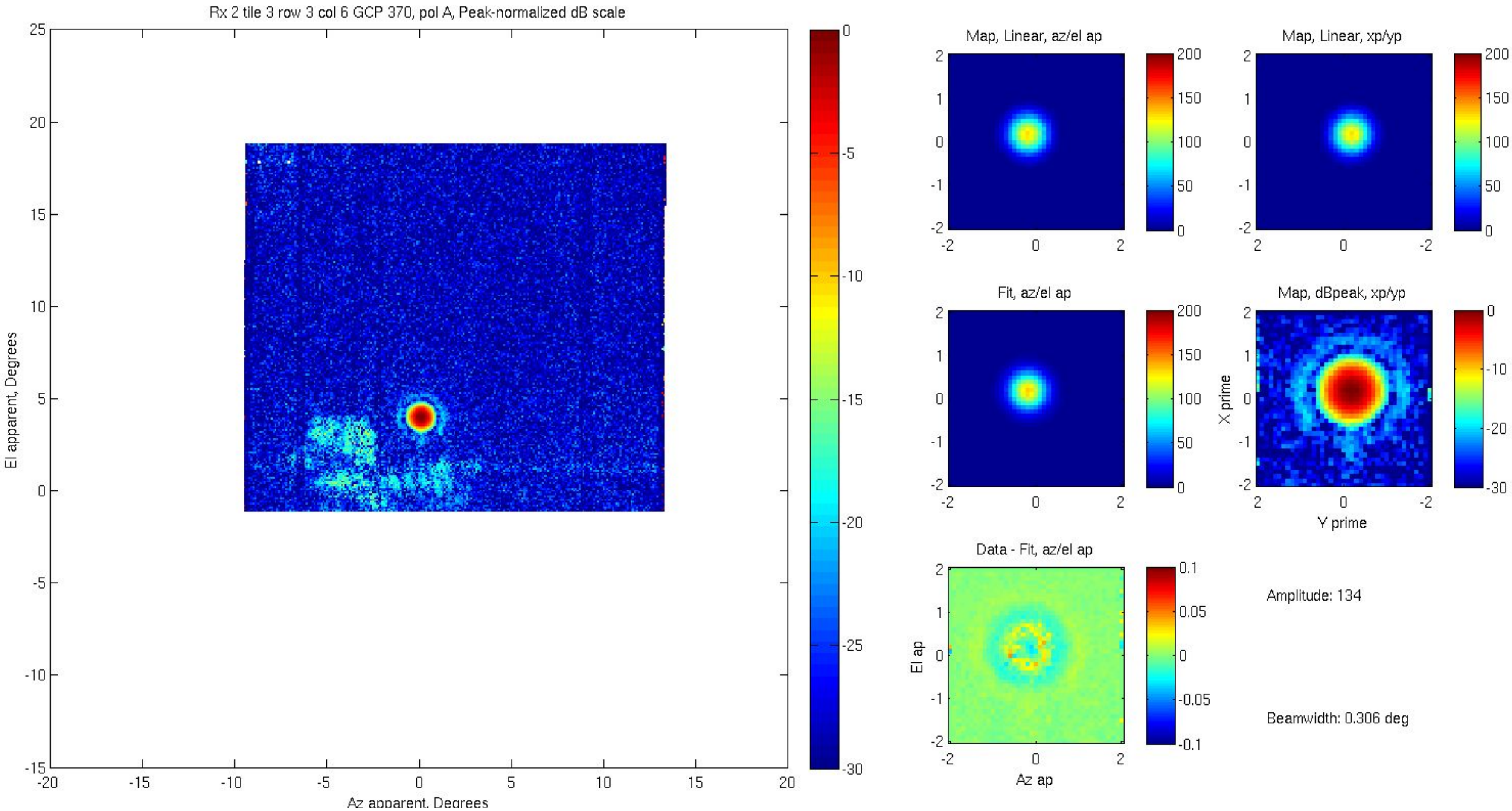


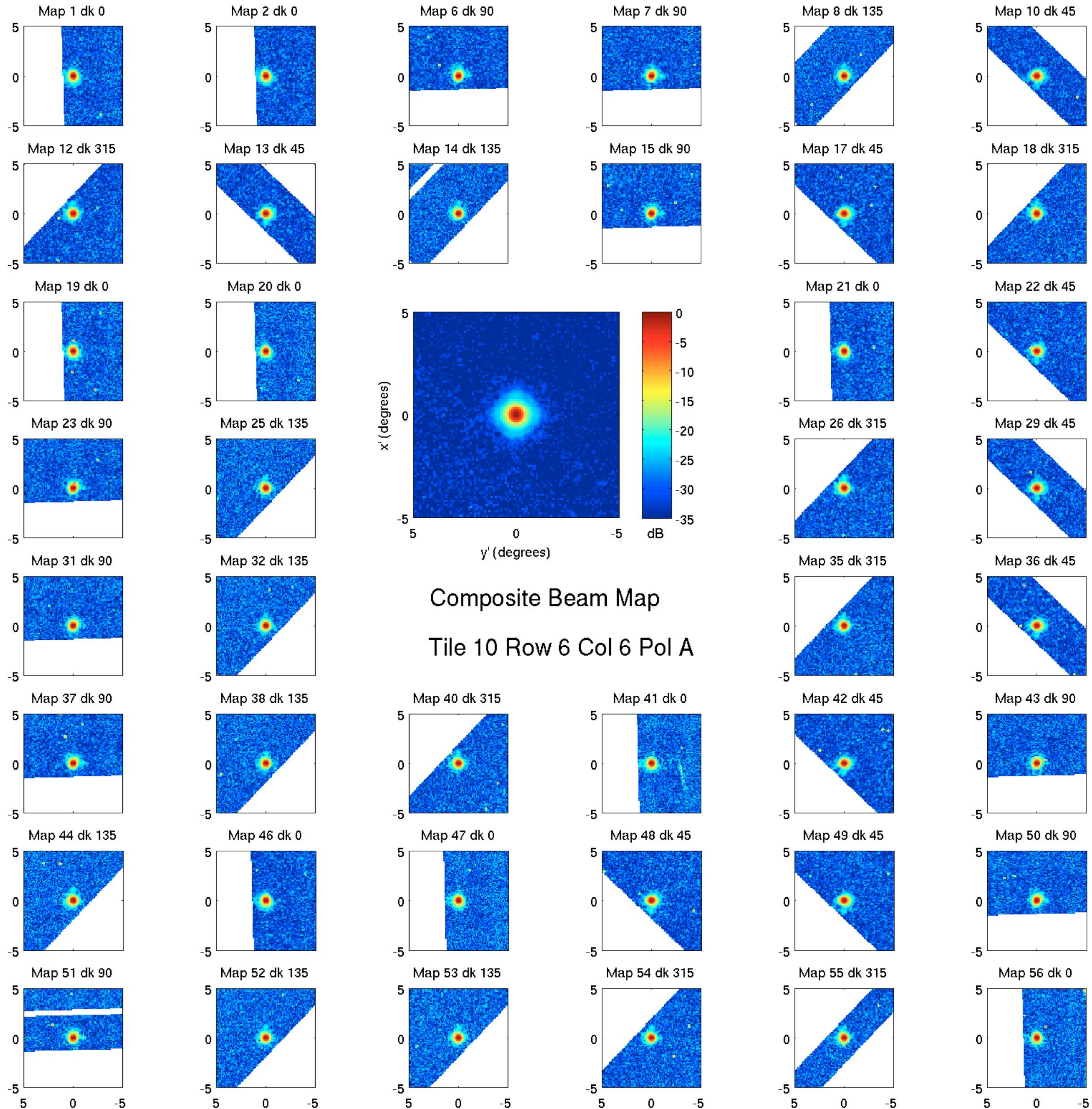
"Deprojection":

- ➢ From well-known temperature sky form a prediction of the leakage and remove it
- ➢ Cleans up maps even without cancellation from boresight rotation

Far Field Beam Measurements

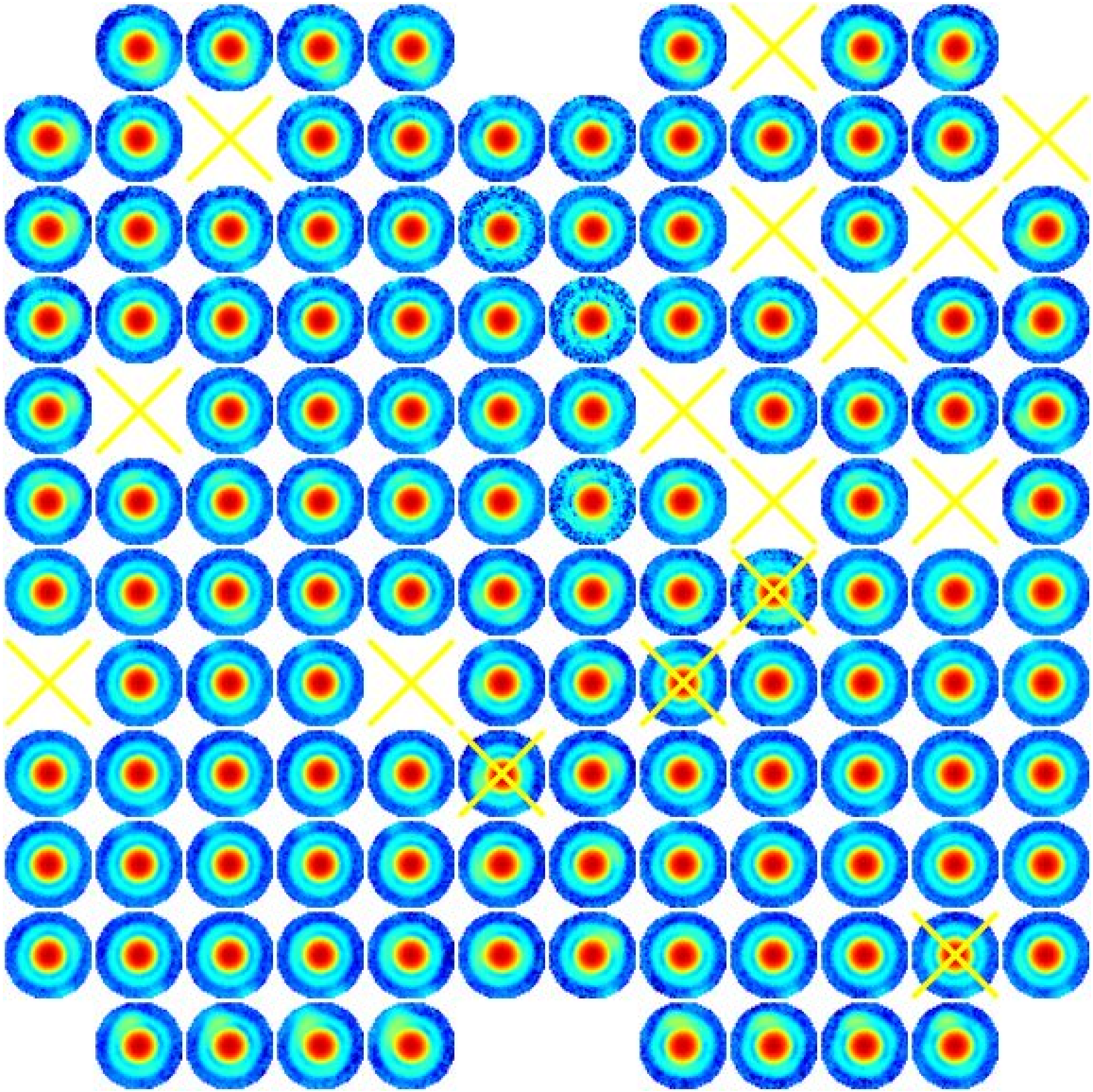





Rx 2 tile 3 row 3 col 6 GCP 370, pol A, Peak-normalized dB scale
El apparent, Degrees
Az apparent, Degrees
Map, Linear, az/el ap
Map, Linear, xp/yp
Fit, az/el ap
Map, dBpeak, xp/yp
X prime
Y prime
Data - Fit, az/el ap
El ap
Az ap
Amplitude: 134
Beamwidth: 0.306 deg

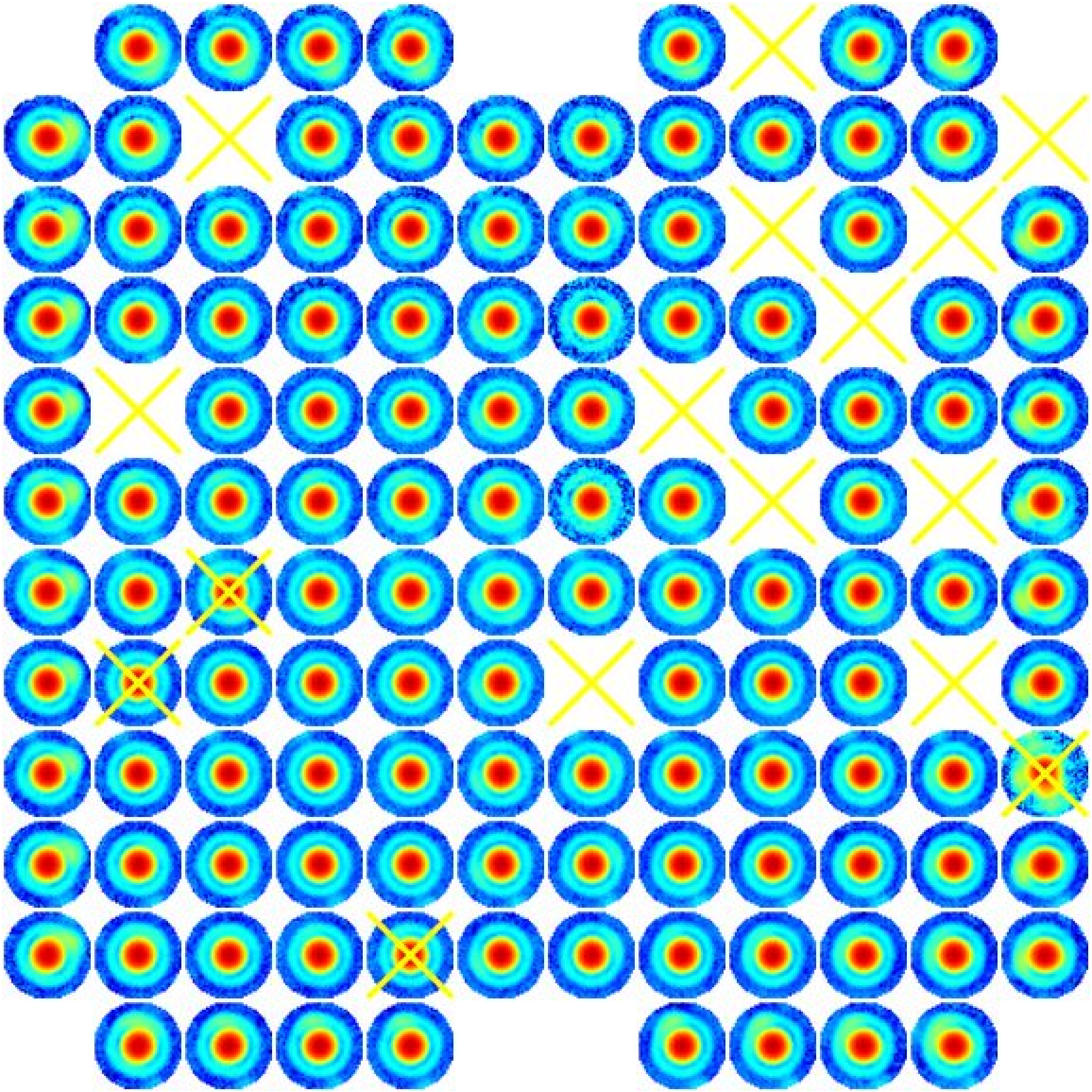


Map 1 dk 0
Map 2 dk 0
Map 6 dk 90
Map 7 dk 90
Map 8 dk 135
Map 10 dk 45
Map 12 dk 315
Map 13 dk 45
Map 14 dk 135
Map 15 dk 90
Map 17 dk 45
Map 18 dk 315
Map 19 dk 0
Map 20 dk 0
Map 21 dk 0
Map 22 dk 45
Map 23 dk 90
Map 25 dk 135
Map 26 dk 315
Map 29 dk 45
Map 31 dk 90
Map 32 dk 135
Map 35 dk 315
Map 36 dk 45
Map 37 dk 90
Map 38 dk 135
Map 40 dk 315
Map 41 dk 0
Map 42 dk 45
Map 43 dk 90
Map 44 dk 135
Map 46 dk 0
Map 47 dk 0
Map 48 dk 45
Map 49 dk 45
Map 50 dk 90
Map 51 dk 90
Map 52 dk 135
Map 53 dk 135
Map 54 dk 315
Map 55 dk 315
Map 56 dk 0
x' (degrees)
y' (degrees)
dB
0
-5
-10
-15
-20
-25
-30
-35
Composite Beam Map
Tile 10 Row 6 Col 6 Pol A

A beam

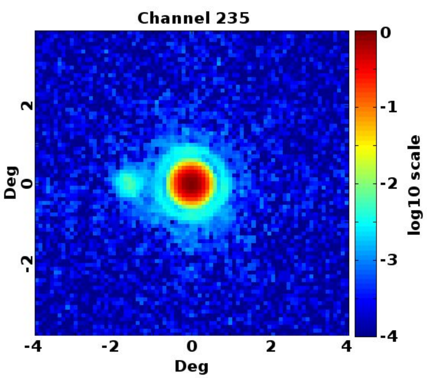


B beam



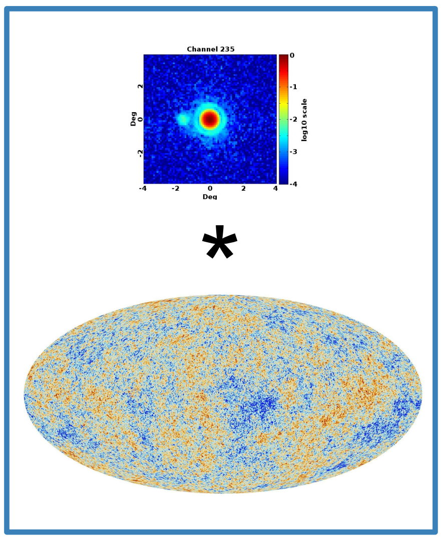
Predicting T->Pol Leakage

Per-Channel Beam Maps

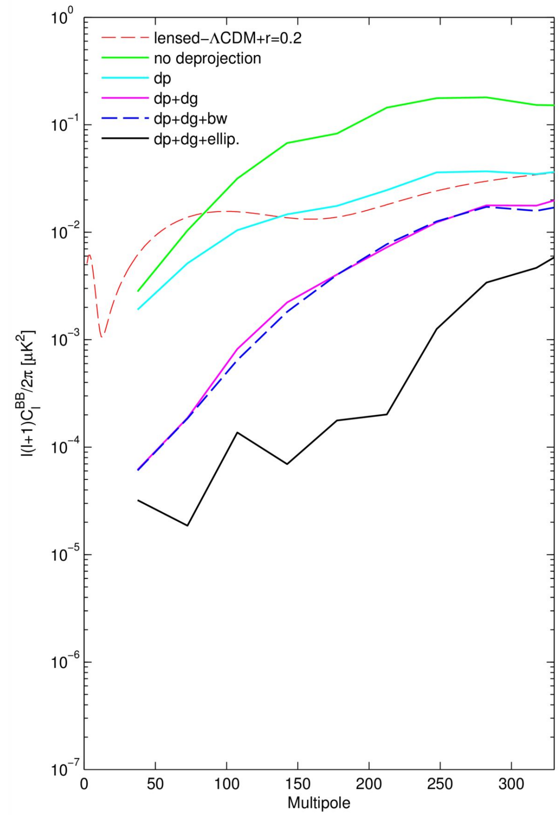


Simulation

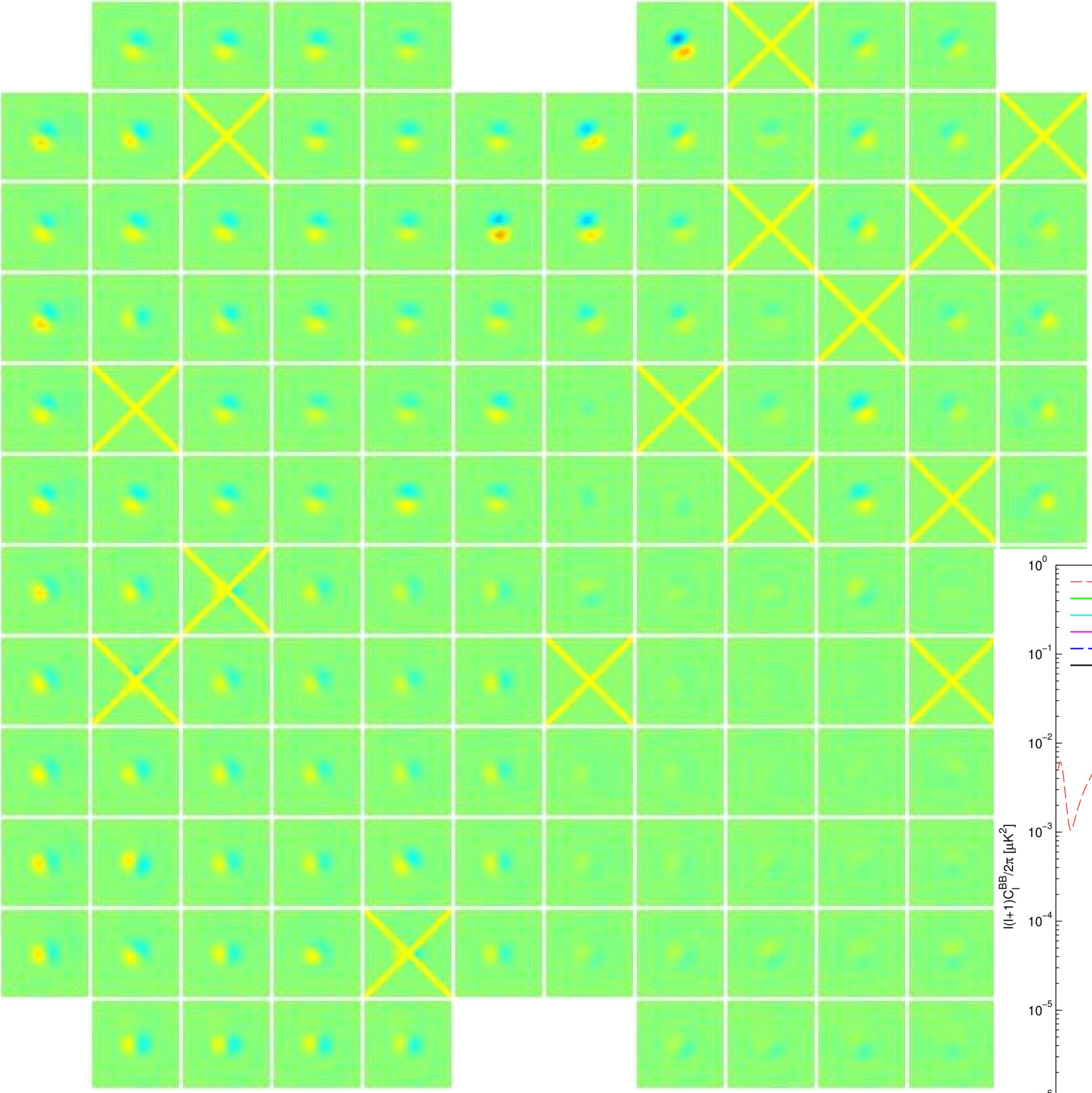
(explicit convolution with Planck T map)

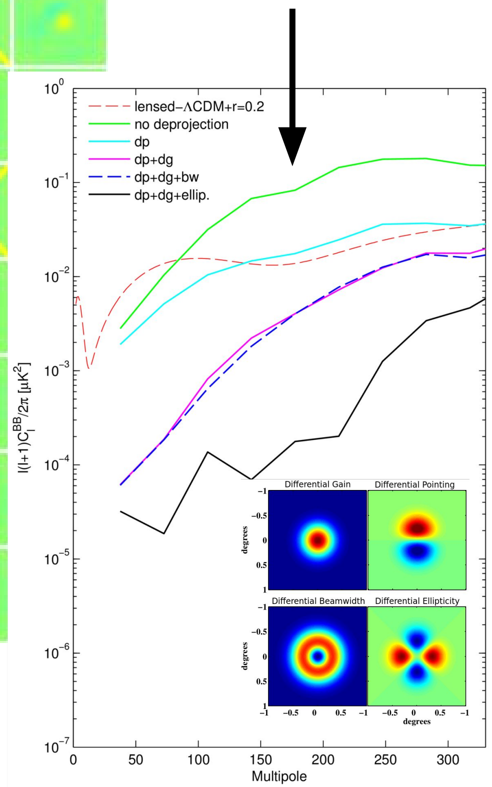


Predictions of contamination

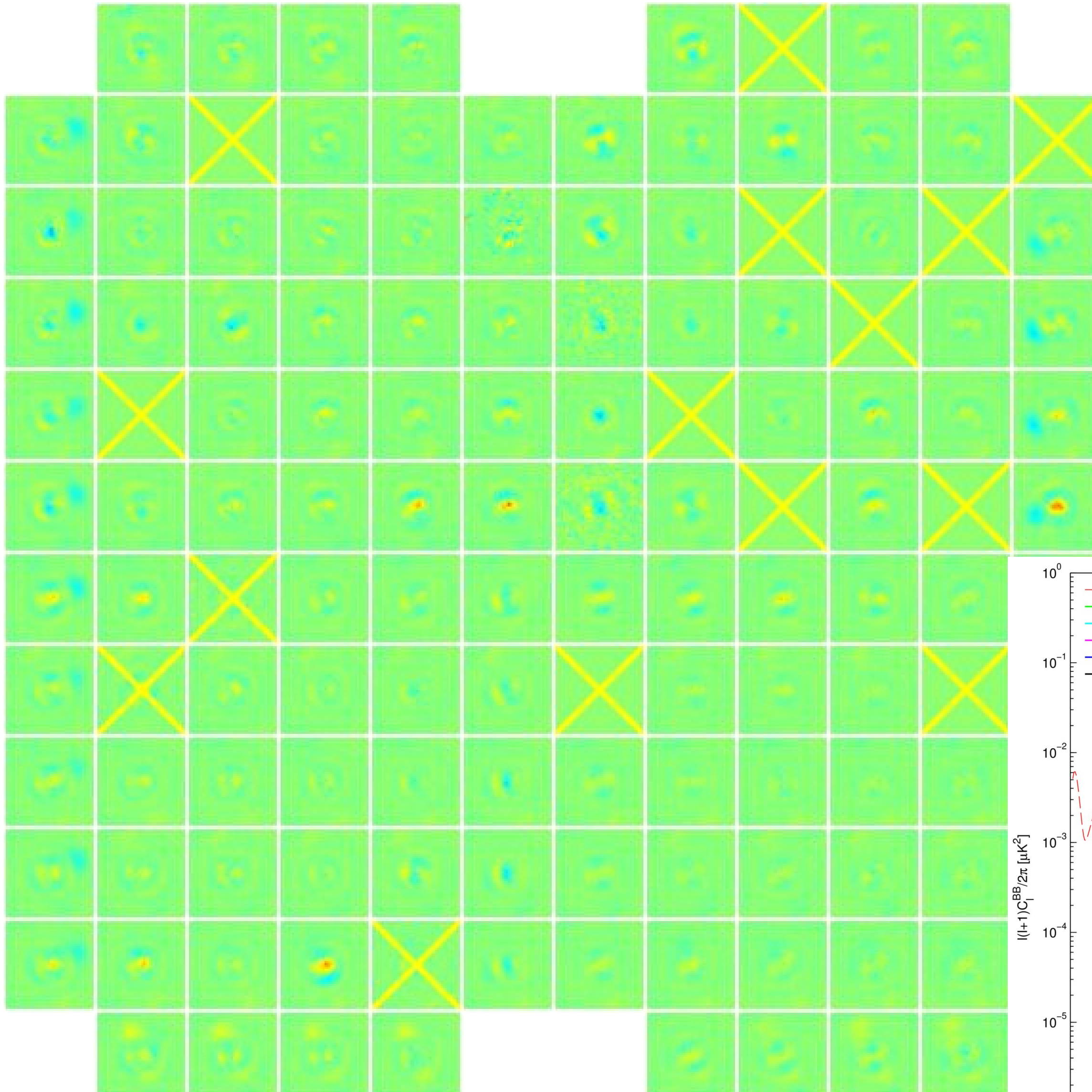


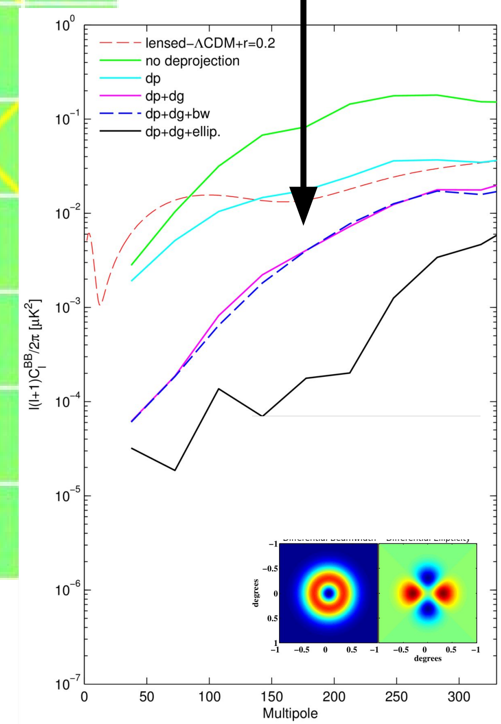
diff beam



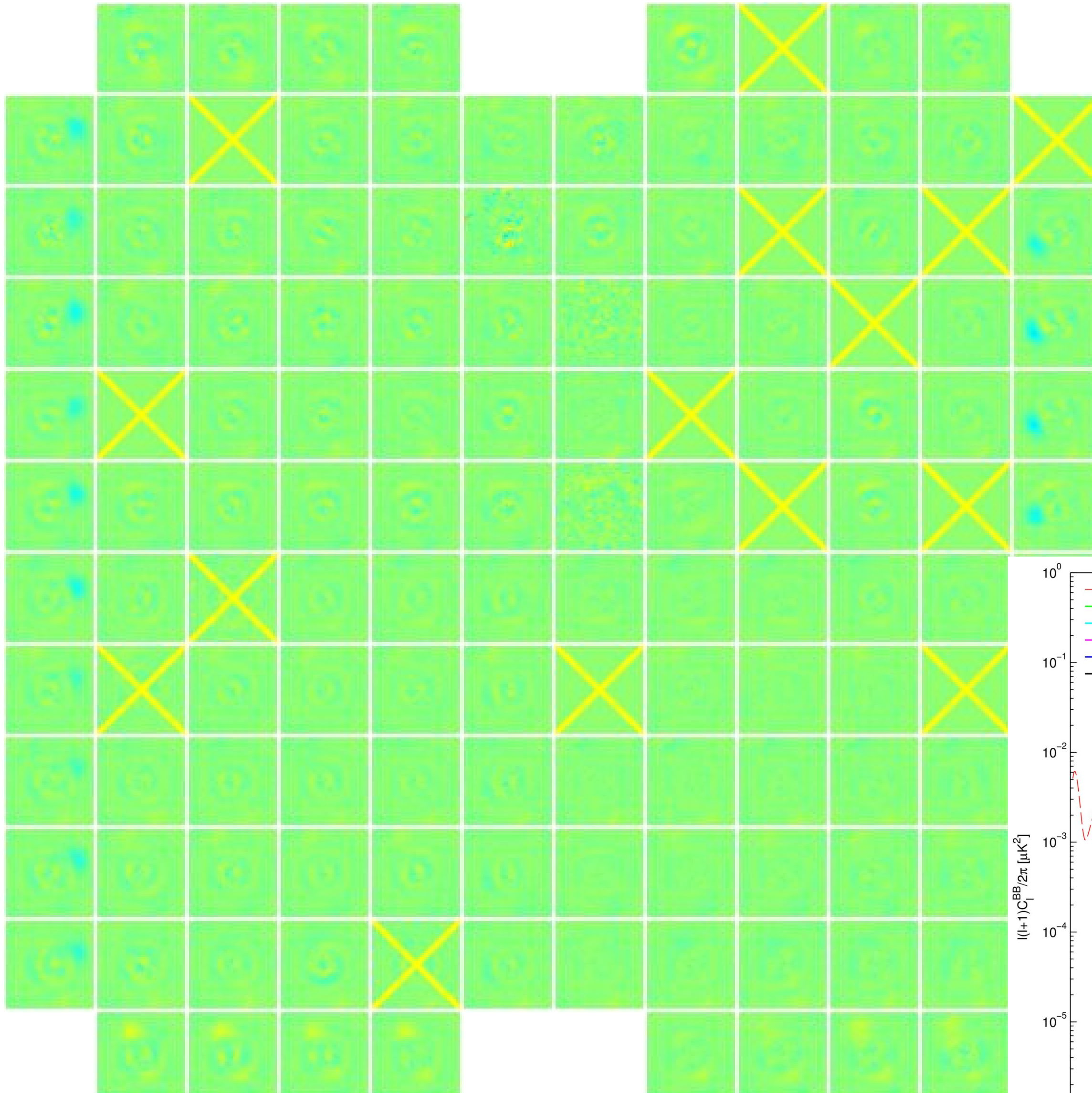

lensed−ΛCDM+r=0.2
no deprojection
dp
dp+dg
dp+dg+bw
dp+dg+ellip.
$l(l+1)C_l^{BB}/2\pi\ [\mu K^2]$
Multipole
Differential Gain
Differential Pointing
Differential Beamwidth
Differential Ellipticity
degrees

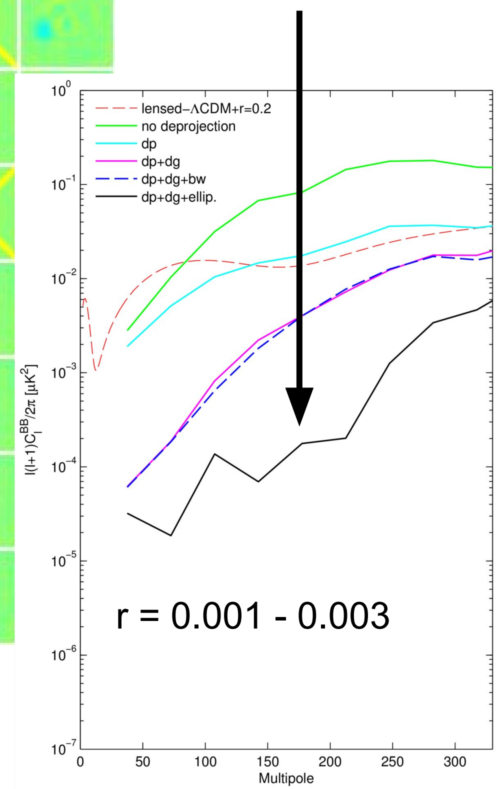
Filter:
relgain
diff pointing

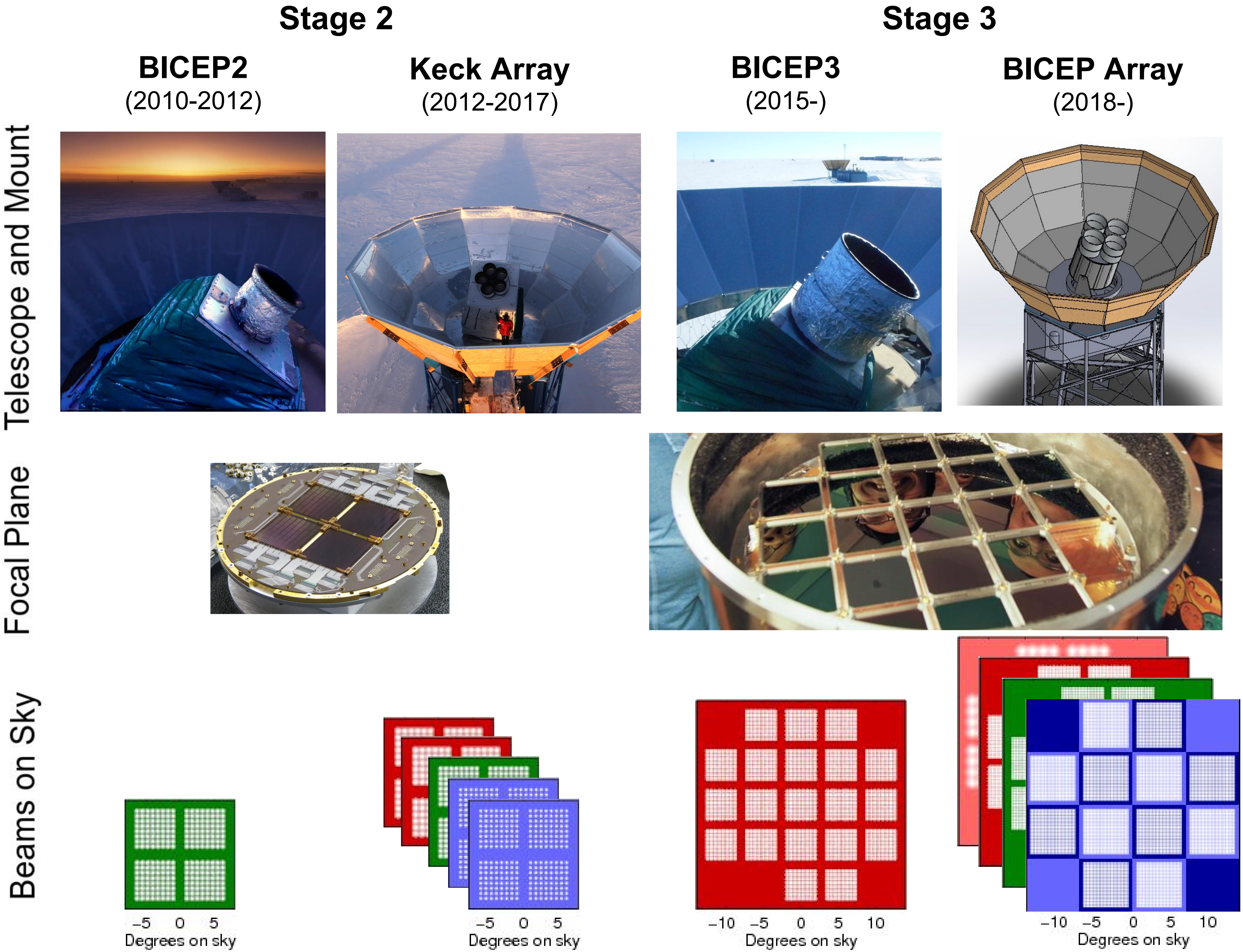


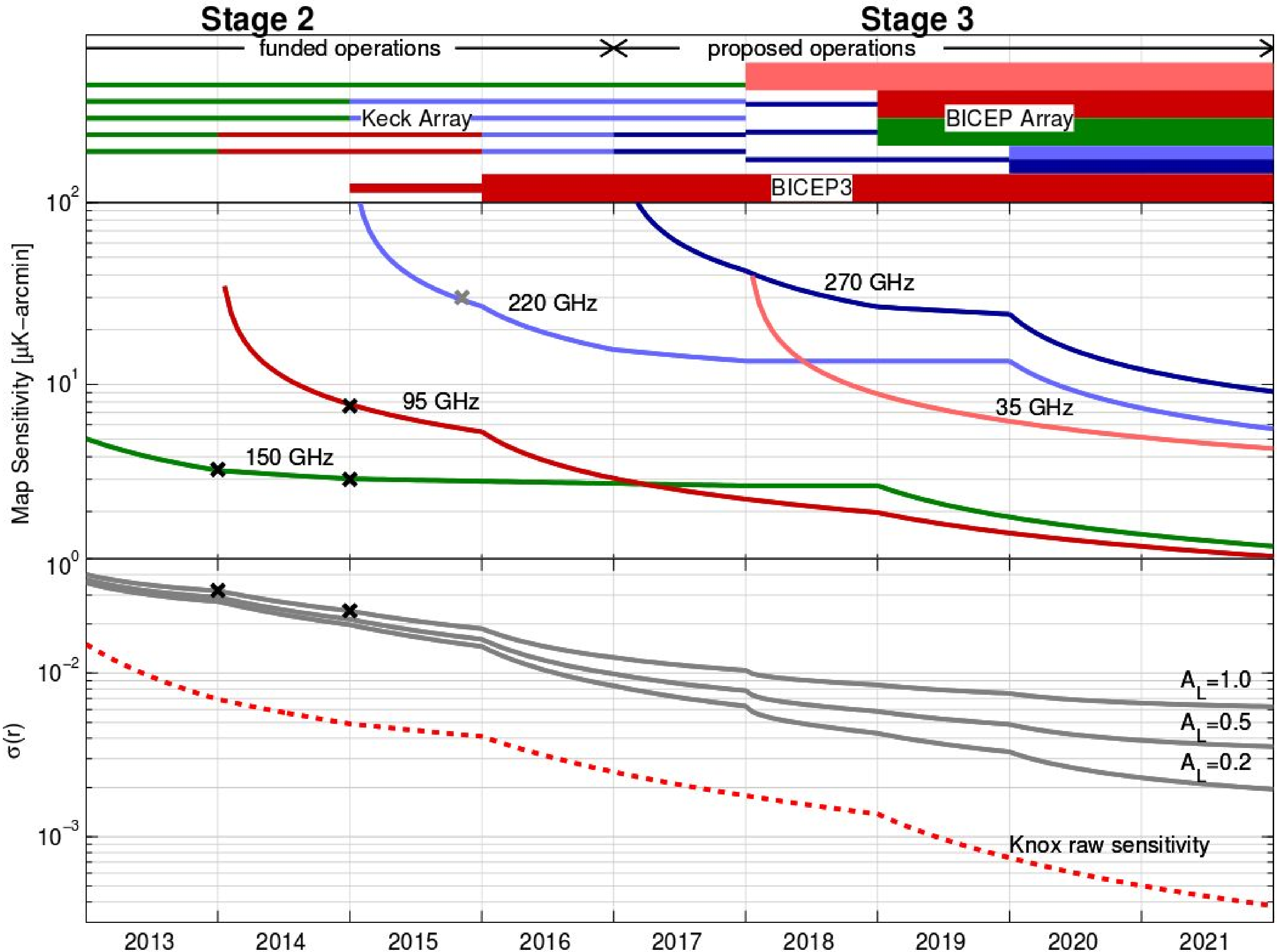


Filter:
relgain
diff pointing
diff bw
diff ellip

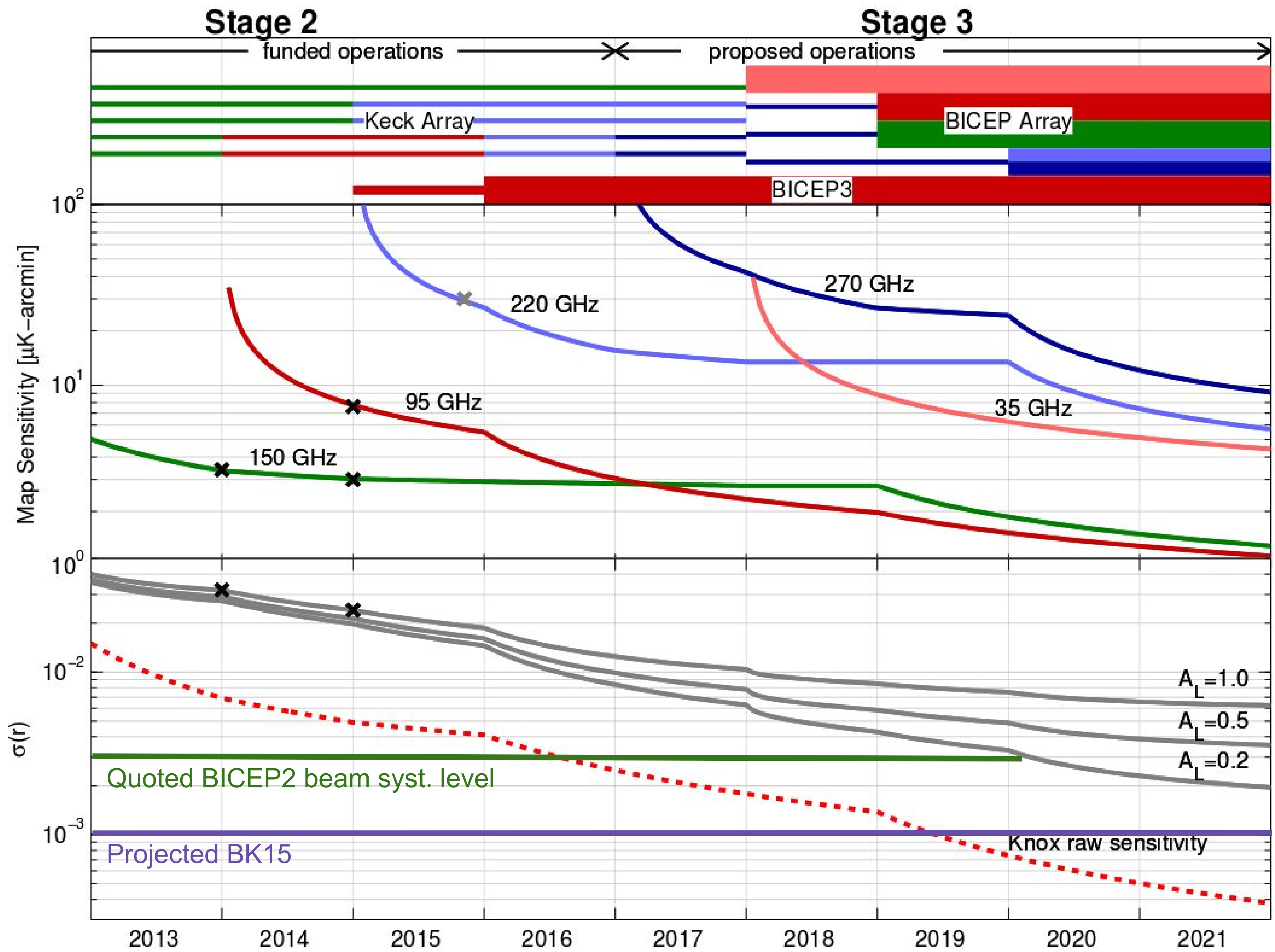





Stage 2
Stage 3
BICEP2
(2010-2012)
Keck Array
(2012-2017)
BICEP3
(2015-)
BICEP Array
(2018-)
Telescope and Mount
Focal Plane
Beams on Sky
−5 0 5
Degrees on sky
−5 0 5
Degrees on sky
−10 −5 0 5 10
Degrees on sky
−10 −5 0 5 10
Degrees on sky



Stage 2
Stage 3
funded operations
proposed operations
Keck Array
BICEP Array
BICEP3
270 GHz
220 GHz
95 GHz
150 GHz
35 GHz
Map Sensitivity [μK−arcmin]
σ(r)
A_L=1.0
A_L=0.5
A_L=0.2
Knox raw sensitivity
2013
2014
2015
2016
2017
2018
2019
2020
2021



Stage 2
Stage 3
funded operations
proposed operations
Keck Array
BICEP Array
BICEP3
Map Sensitivity [μK−arcmin]
270 GHz
220 GHz
95 GHz
35 GHz
150 GHz
σ(r)
A_L=1.0
A_L=0.5
A_L=0.2
Quoted BICEP2 beam syst. level
Knox raw sensitivity
Projected BK15
2013
2014
2015
2016
2017
2018
2019
2020
2021

Conclusions

Small apertures have the best proven performance at degree angular scales: sigma(r) = 0.024 for BK14

Pair differencing is simple with good noise performance

Boresight pol modulation + deprojection work extremely well to remove systematics...

But explicit beam measurement is key!

We can expect beam systematics levels of r < 0.001 with current generation, and lower in the next few years


Stay tuned!