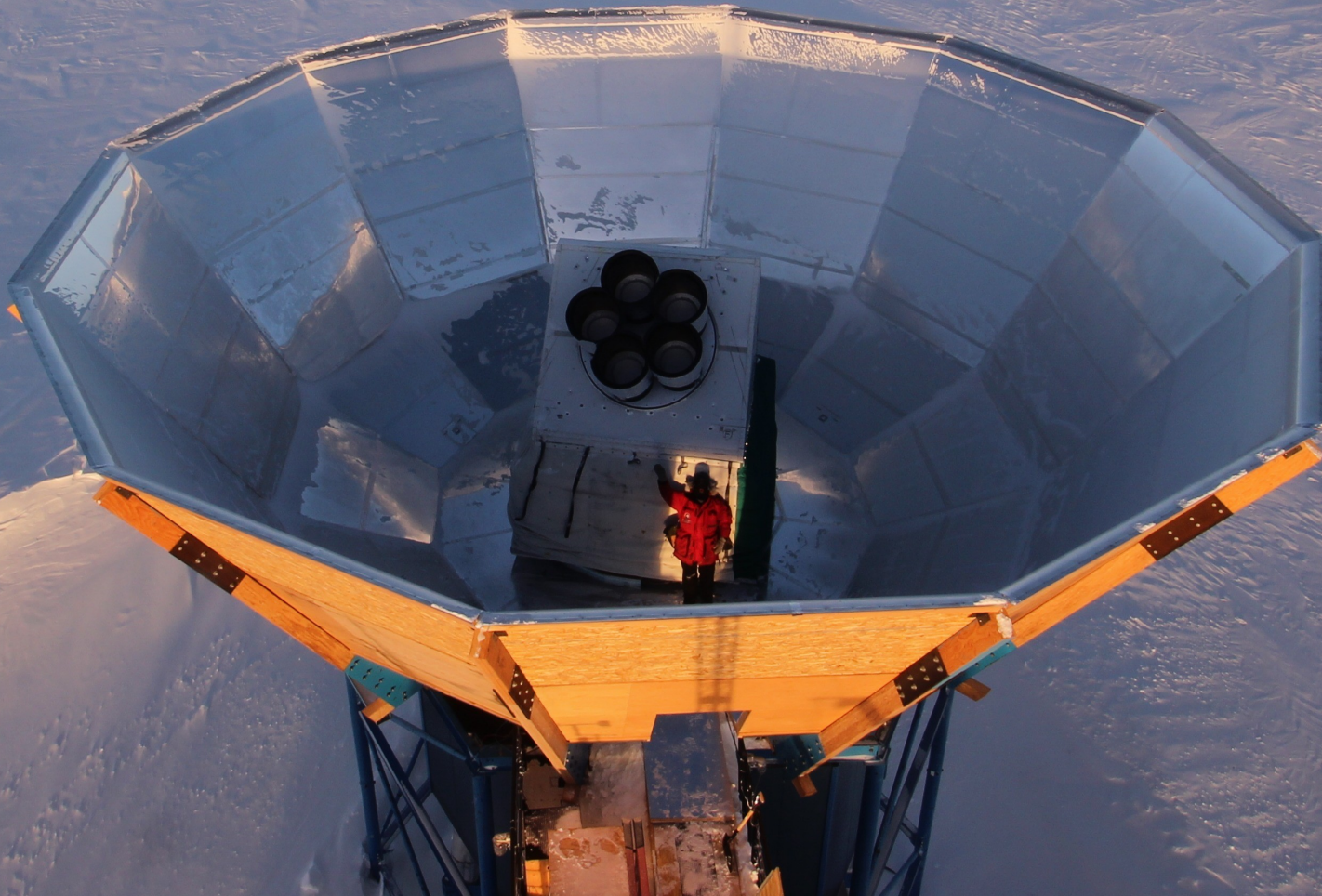# CMB polarimetry at the South Pole with BICEP2/Keck Array

## Grant Teply
Windows on the Universe

BICEP2/Keck Array collaboration

Cosmology according to the CMB

- The cosmic microwave background (CMB) traces the conditions of the universe during recombination.

- The measured fluctuations of the CMB are consistent with the ΛCDM model, a universe composed primarily of dark energy and dark matter.

- Cosmic inflation attempts to make the initial conditions of the model seem more natural.
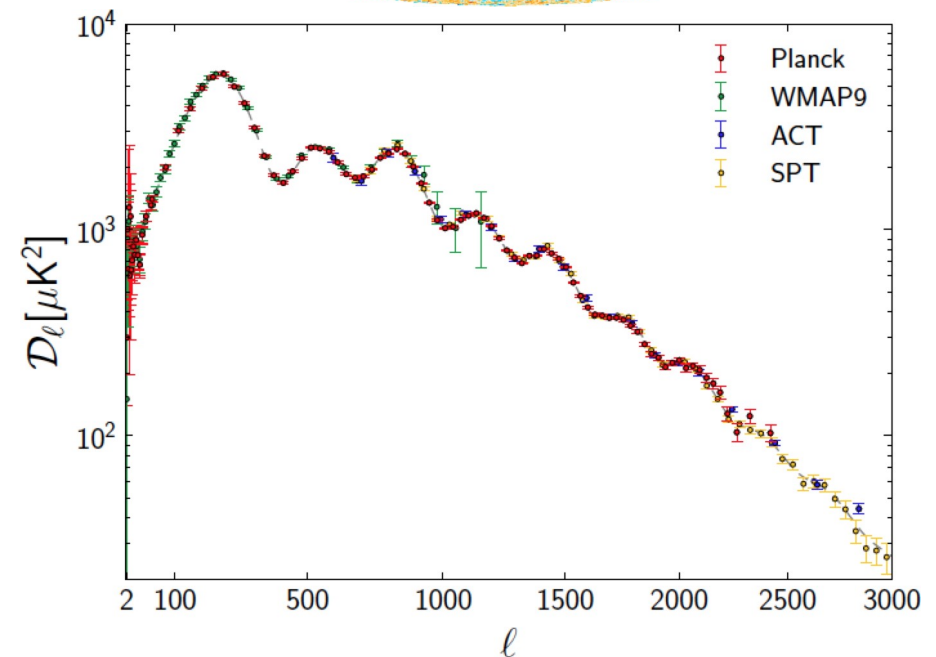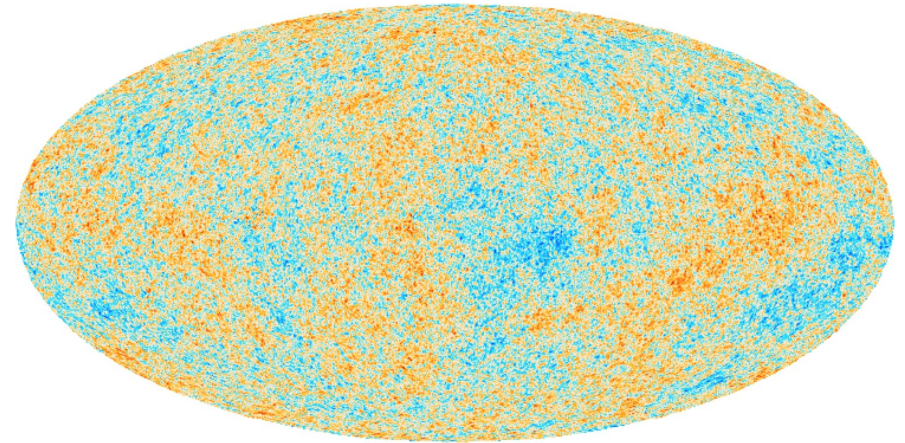
Planck 2013 results. I. Overview of products and results

Cosmic inflation

- Period of rapid expansion of the primordial universe

- Predicts adiabatic, nearly scale-invariant fluctuations, consistent with observations

- Predicts a cosmic gravitational-wave background (CGB) related to the energy scale of inflation

- What causes inflation? Did inflation occur at the GUT scale?
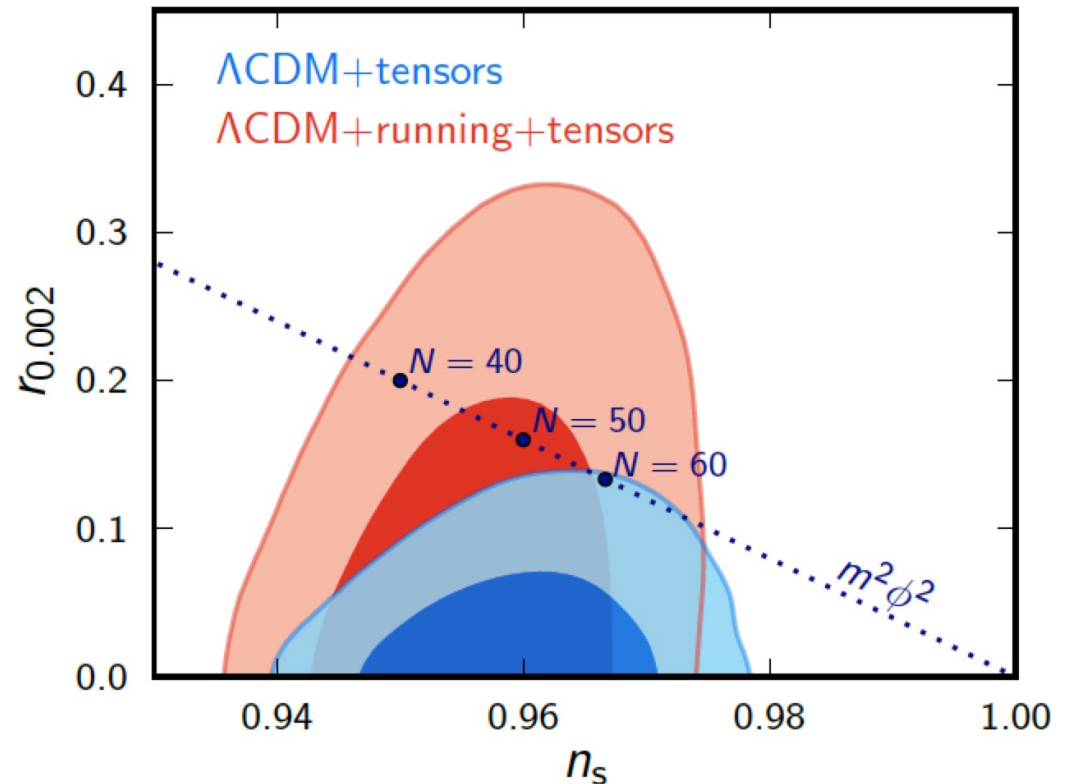
Planck 2013 results. XVI. Cosmological parameters

Tensor-to-scalar ratio $r < 0.12$ (95% CL) for a single-parameter extension to ΛCDM

CMB polarization

- Around the epoch of recombination, photons undergo Thomson scattering.

- Local anisotropies in the plasma generate a net, linear polarization.

- The CMB photons observed today are those from the surface of last scattering.
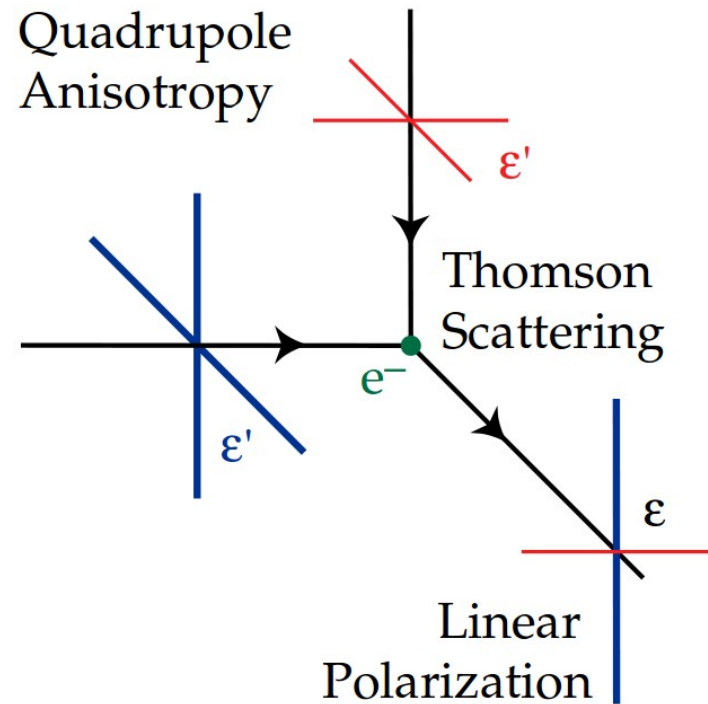
Hu & White – A CMB Polarization Primer

Read more at arXiv:astro-ph/9706147

CMB polarization

- Analogous to the fundamental theorem of vector calculus, the polarization map is a sum of even-parity "E-mode" and odd-parity "B-mode" patterns.

- In linear perturbation theory, scalar fluctuations can only source E-modes.

- Tensor fluctuations (CGB) can source both E-modes and B-modes.

E-modes

B-modes
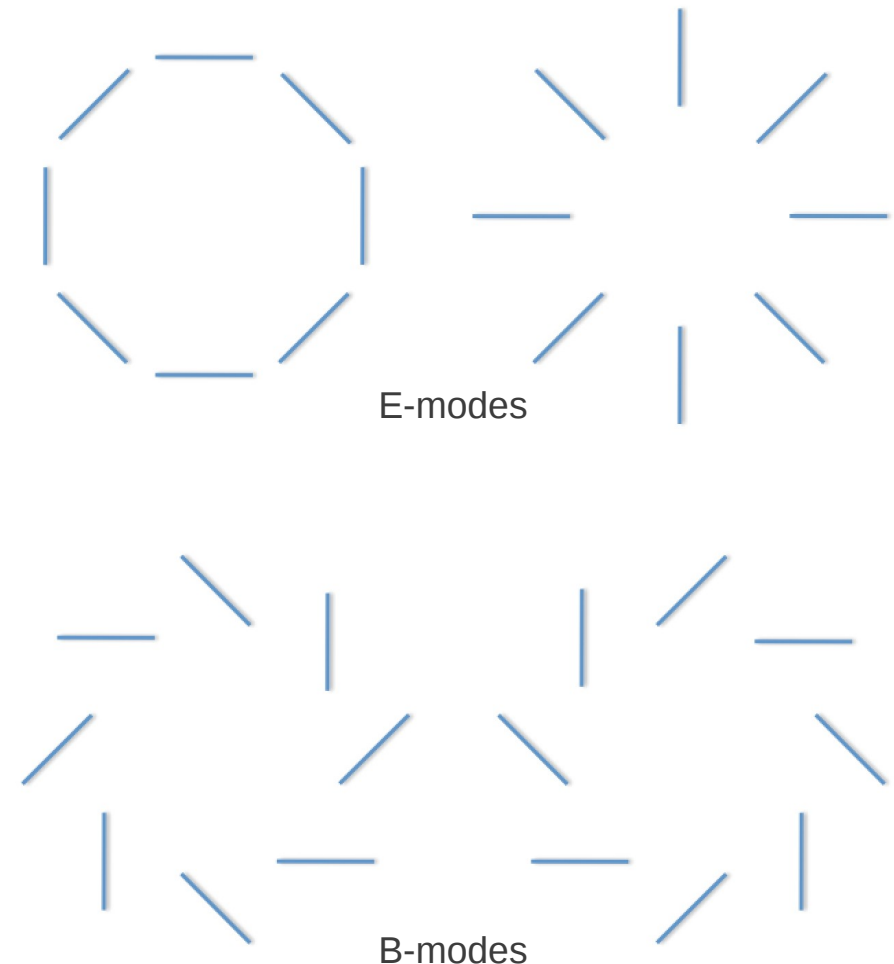
CMB polarization

- Stacking CMB maps at local maxima and minima in temperature reveals the correlation with E-mode polarization, as predicted.

- Images shown are from real BICEP2 data.
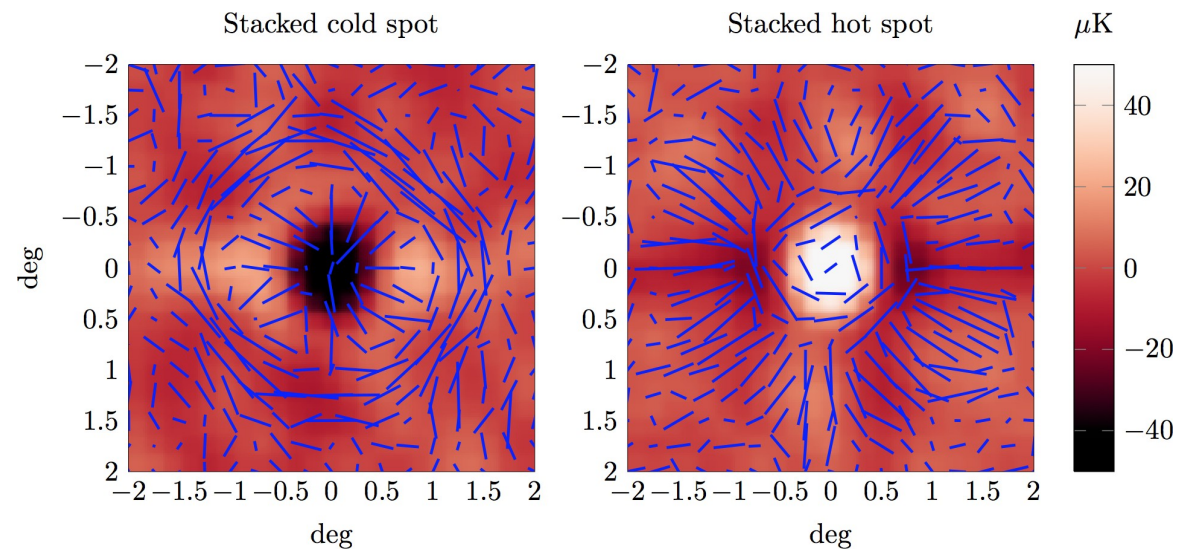

R. Aikin – 2013 PhD thesis

CMB polarization

- Experiments have confirmed the E-mode signal at all angular scales, consistent with ΛCDM.

- Peak B-mode power from the CGB is expected to appear on large angular scales.

- Gravitational lensing distorts E-modes into B-modes on small angular scales.

- Measurements of TB and EB correlations also probe possible cosmic birefringence.
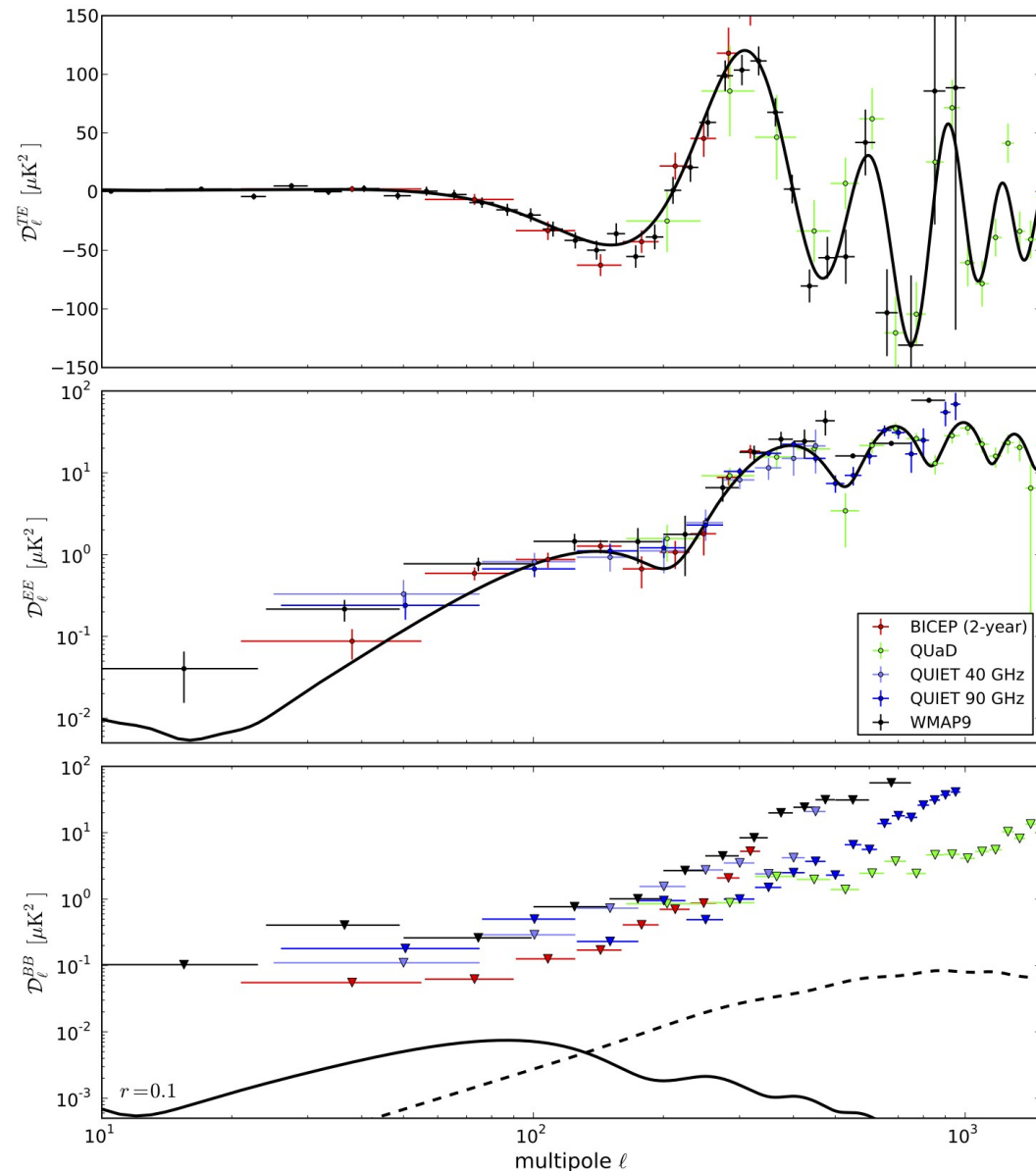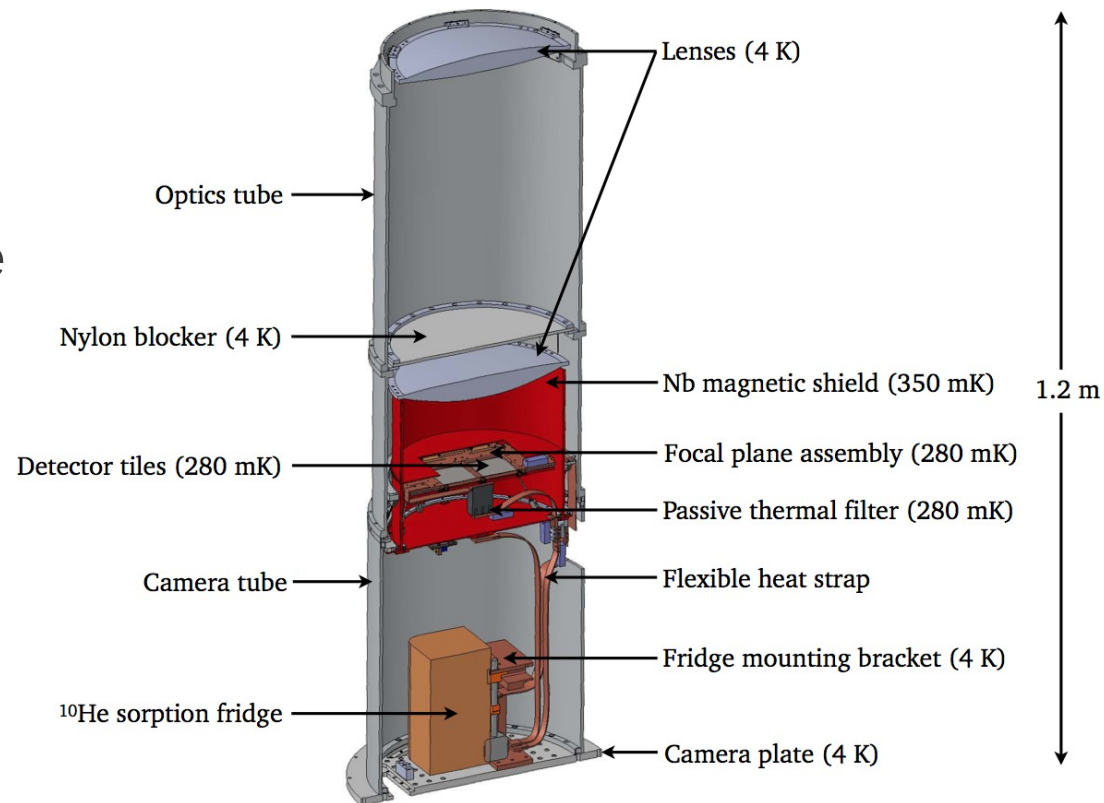
BICEP2/Keck Array strategy

- Polarized foregrounds include galactic synchrotron and dust.

- Target an exceptionally clean field.

- Tune to 150 GHz, near the peak of the 2.7 K blackbody spectrum, where CMB signal should dominate over foregrounds.

- Residual foreground components are estimated to appear as false signal at a level around $r = 0.03$.
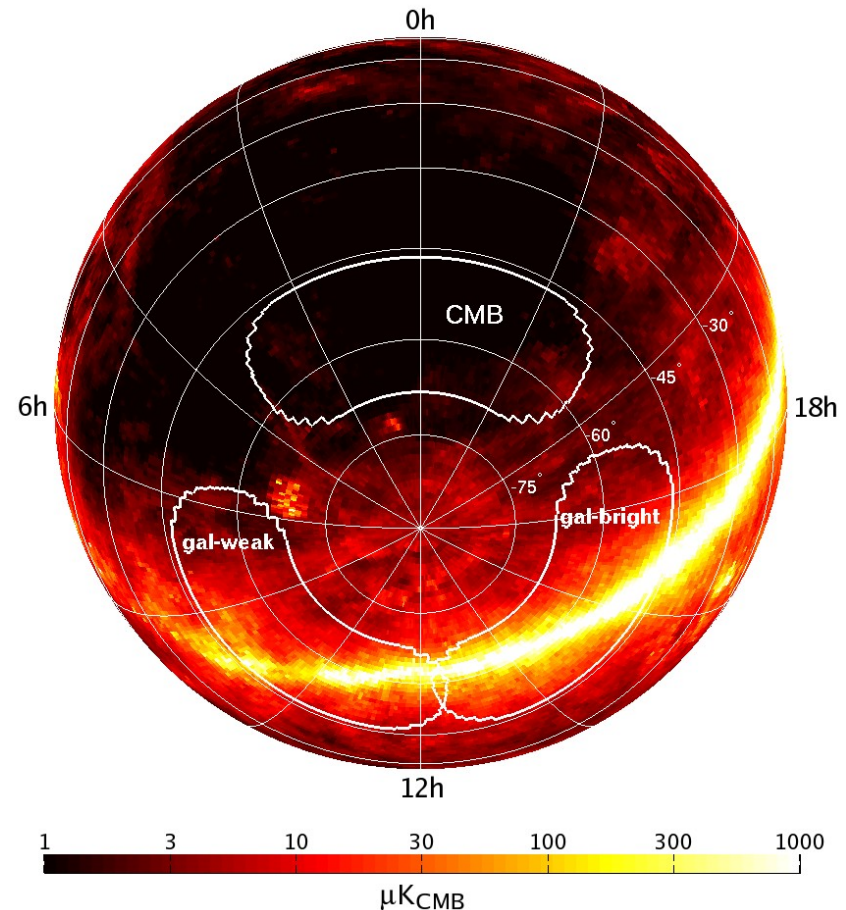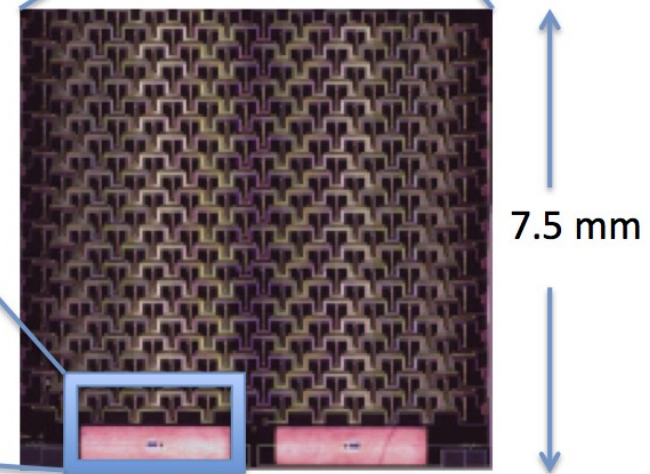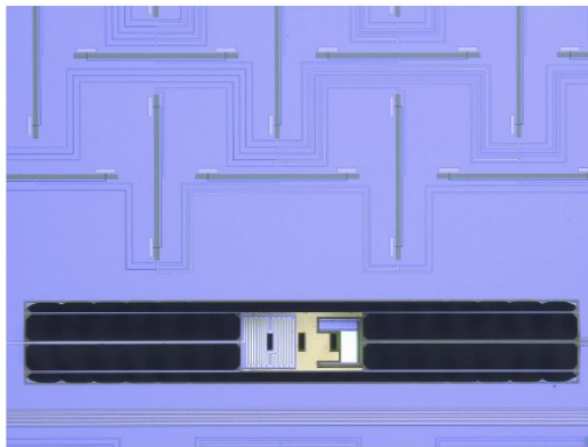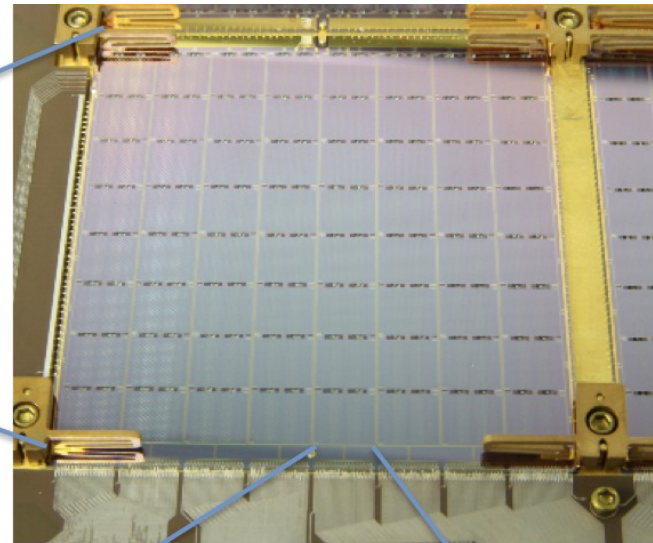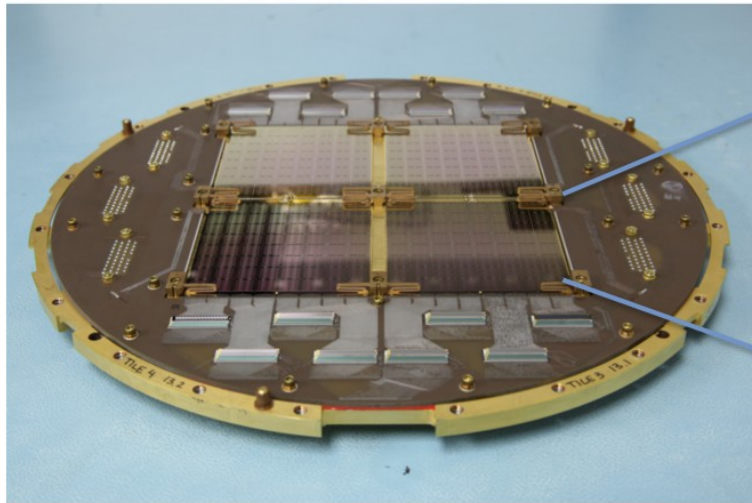

Chiang et al. – arXiv:0906.1181

BICEP2/Keck Array instrument

- Refractive, telecentric optics treat all polarization states equally.

- Relatively coarse resolution of ~32' is still sufficient to resolve the primordial B-mode peak.

- The entire telescope rotates around boresight to measure both Stokes Q and U.

- BICEP2 was held at cryogenic temperatures with liquid helium.

- Keck Array uses less expensive pulse tube refrigerators.

Lenses (4 K)

Optics tube

Nylon blocker (4 K)

Nb magnetic shield (350 mK)

1.2 m

Detector tiles (280 mK)

Focal plane assembly (280 mK)

Passive thermal filter (280 mK)

Camera tube

Flexible heat strap

Fridge mounting bracket (4 K)

^{10}He sorption fridge

Camera plate (4 K)

BICEP2/Keck Array detectors

7.5 mm

BICEP2/Keck Array detectors

- Radiation focuses onto a phased array of slot antennas.

- Power is deposited onto a transition edge sensor (TES) for each polarization.

- Signals are read using time-domain multiplexed SQUIDs.

- Keck Array instantaneous sensitivity is 9.5 µK√s.
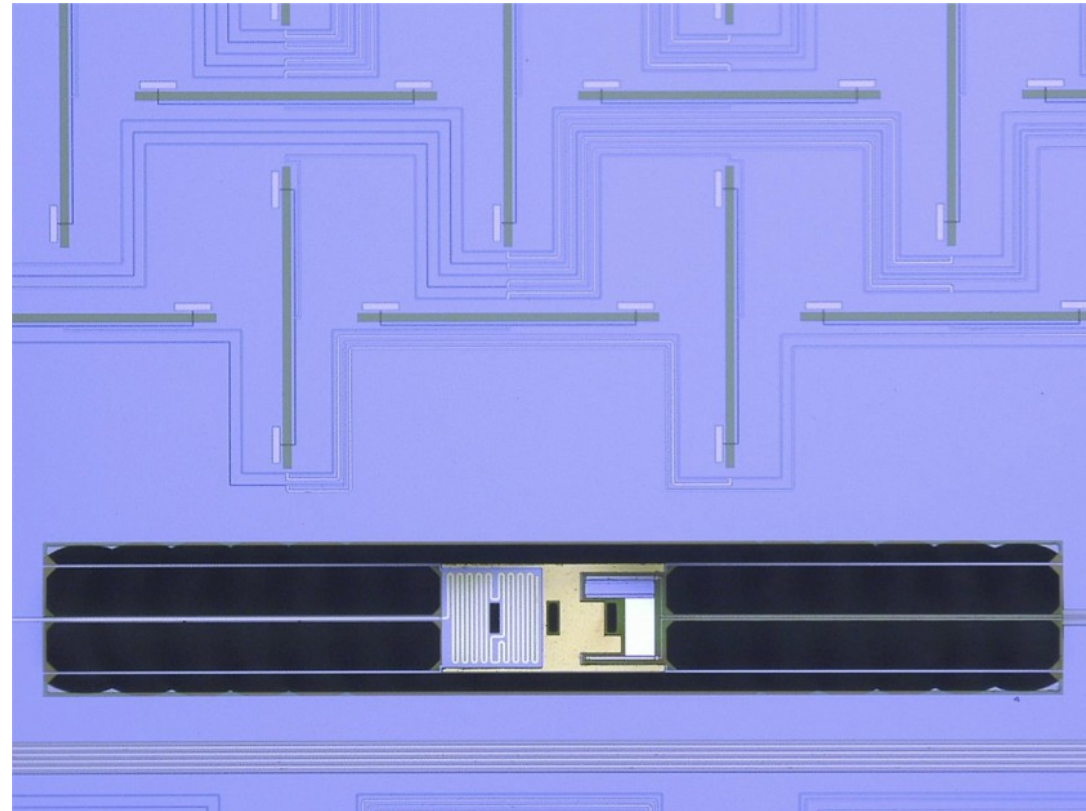
BICEP2/Keck Array calibration

- Detector point spread functions are mapped using a calibration source on a mast 200 m away.

- Relative detector gain is measured by regressing against the atmosphere.

- The absolute polarization angle and efficiency are measured with a rotating, polarized source or tilted dielectric sheet.

- Spectral response is measured using a Martin-Puplett interferometer.
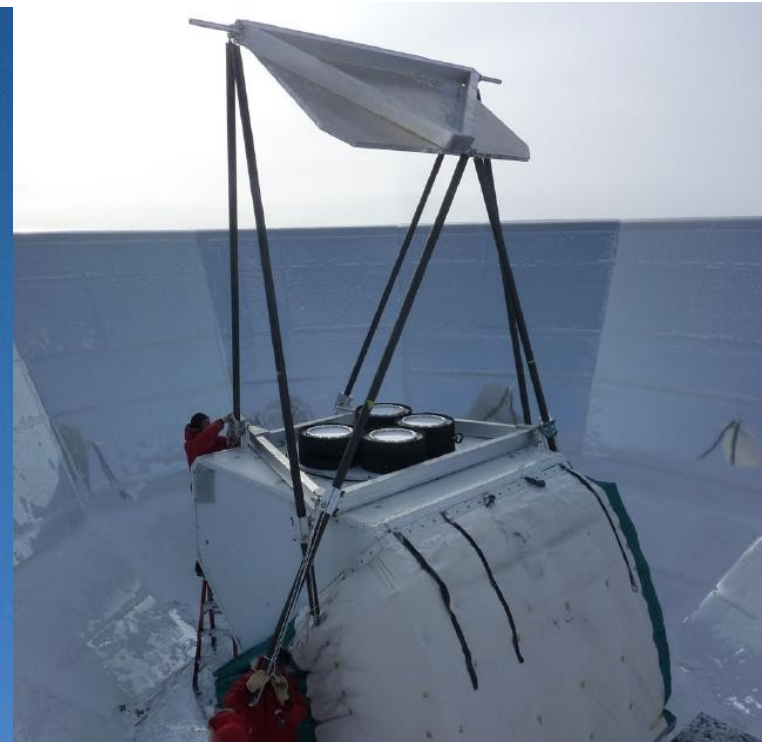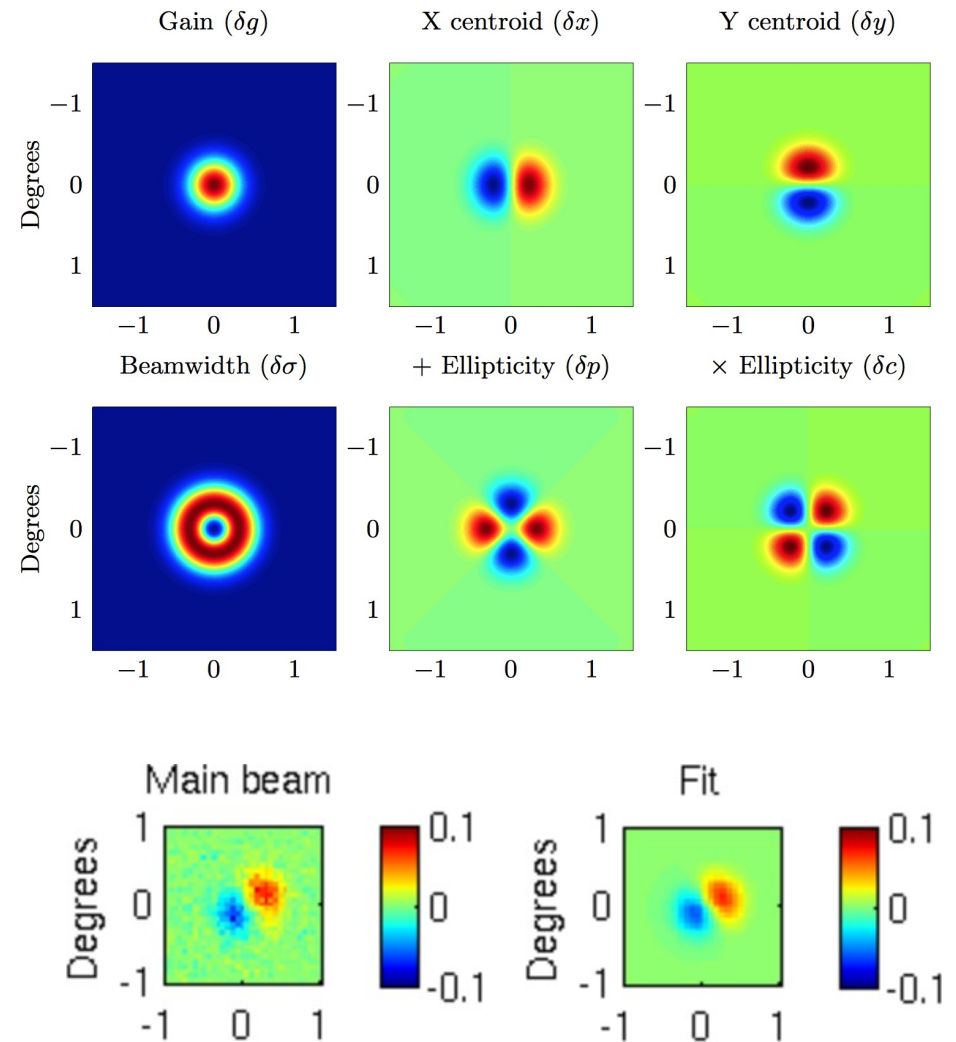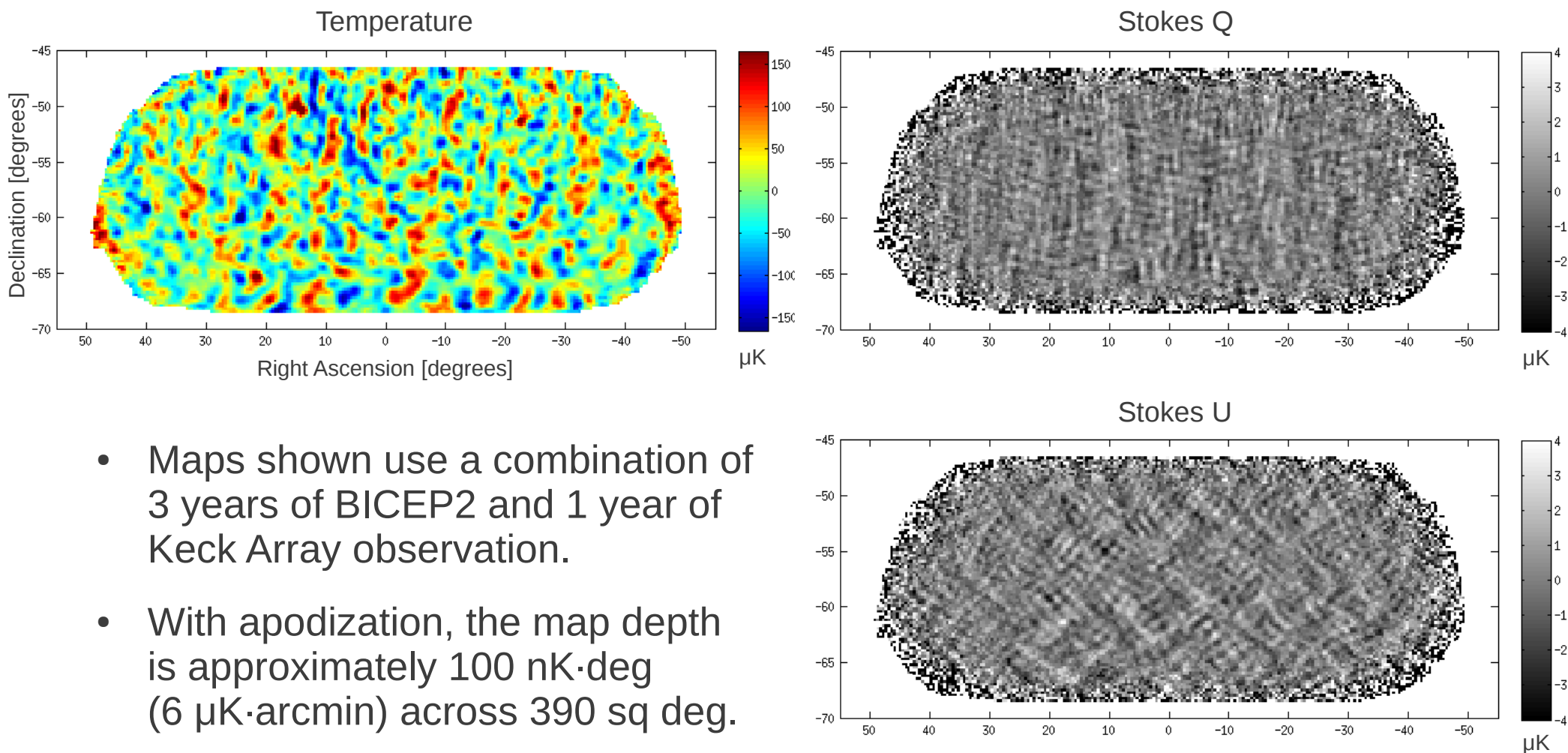
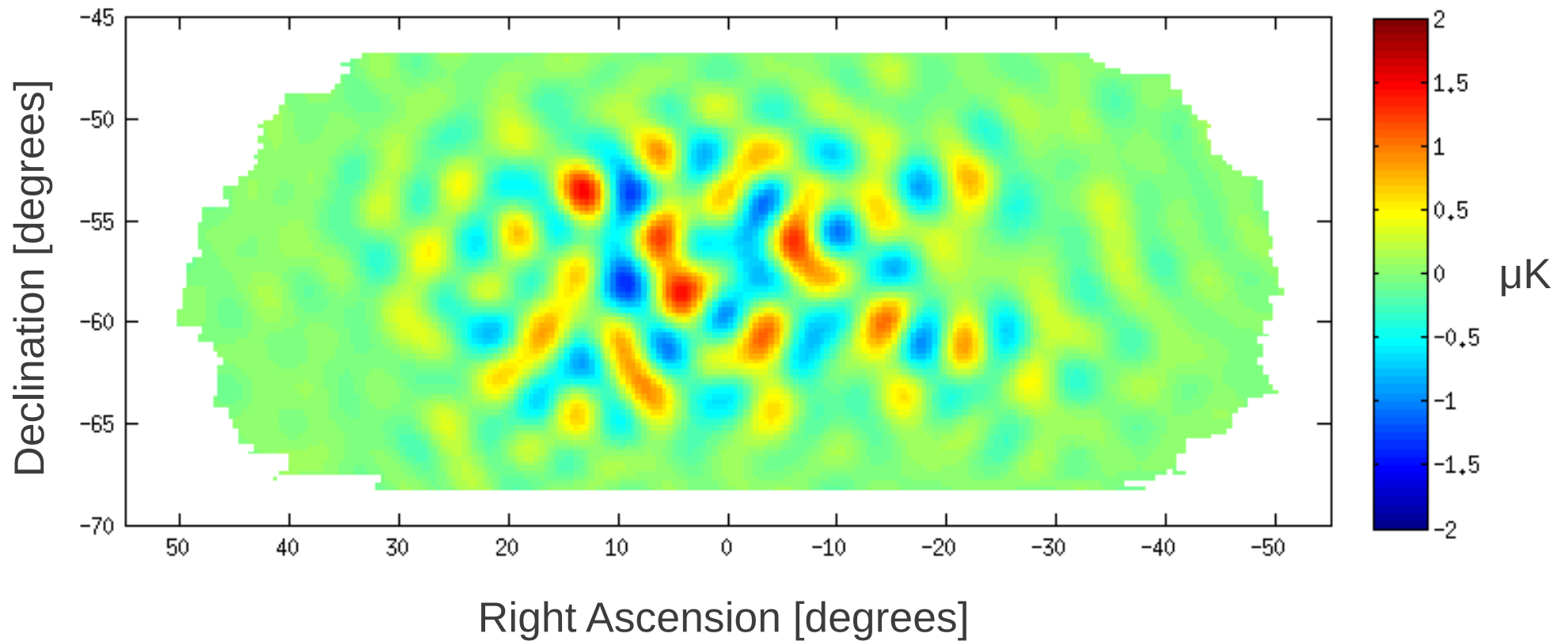# BICEP2/Keck Array calibration
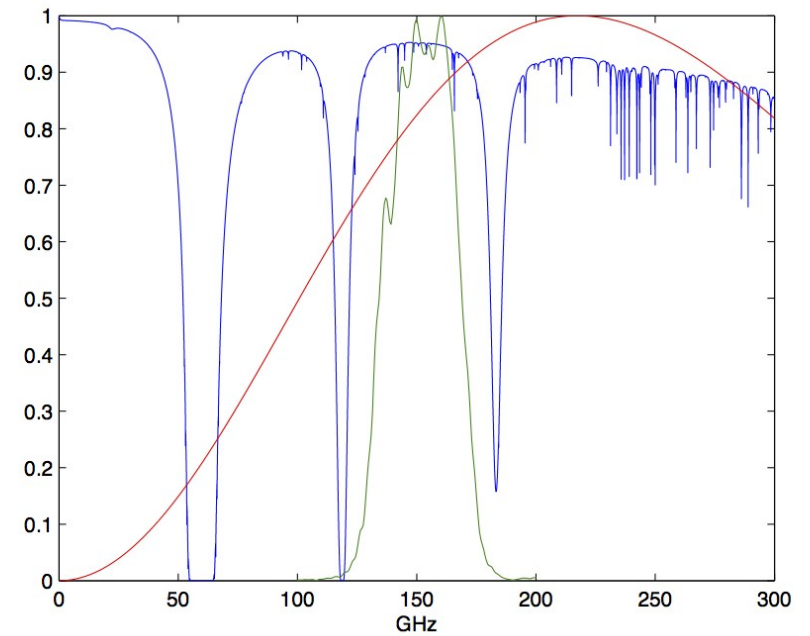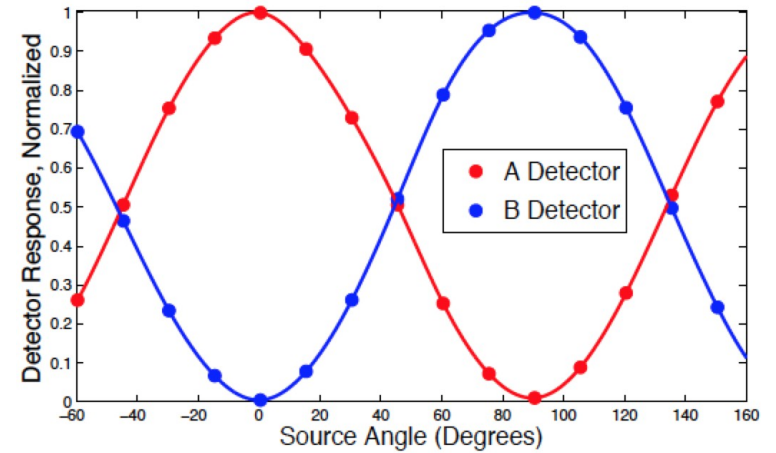
BICEP2/Keck Array systematics

- The most important systematics to control are those that could leak temperature into polarization.

- Significant differential pointing has been observed.

- A new, advanced analysis method removes differential pointing by constructing a template of the CMB temperature and derivatives, then subtracts the projection of the templates on the raw data.
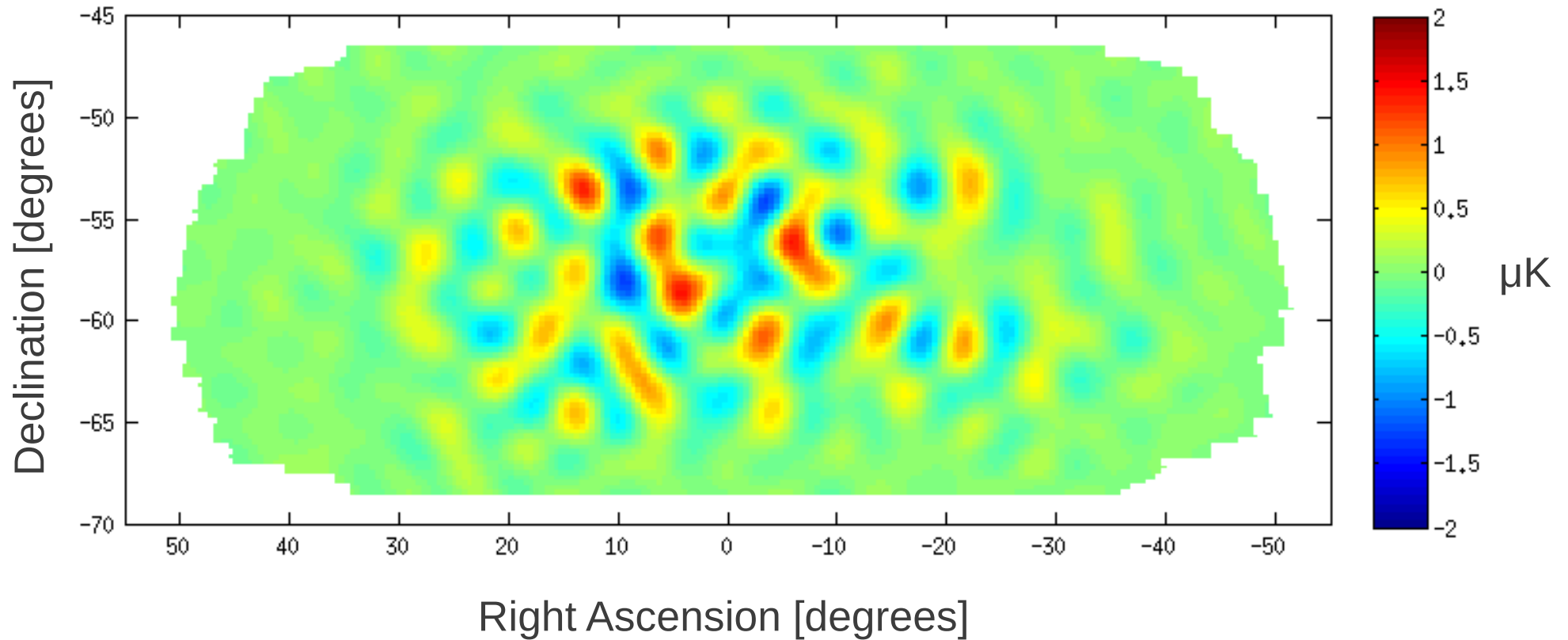
- New detectors have reduced differential pointing.

BICEP2/Keck Array preliminary data

Temperature

Stokes Q

Stokes U

- Maps shown use a combination of 3 years of BICEP2 and 1 year of Keck Array observation.

- With apodization, the map depth is approximately 100 nK·deg (6 µK·arcmin) across 390 sq deg.

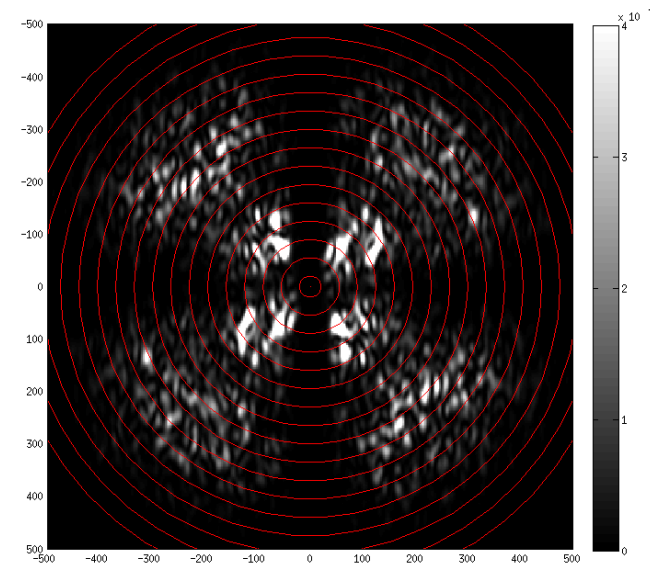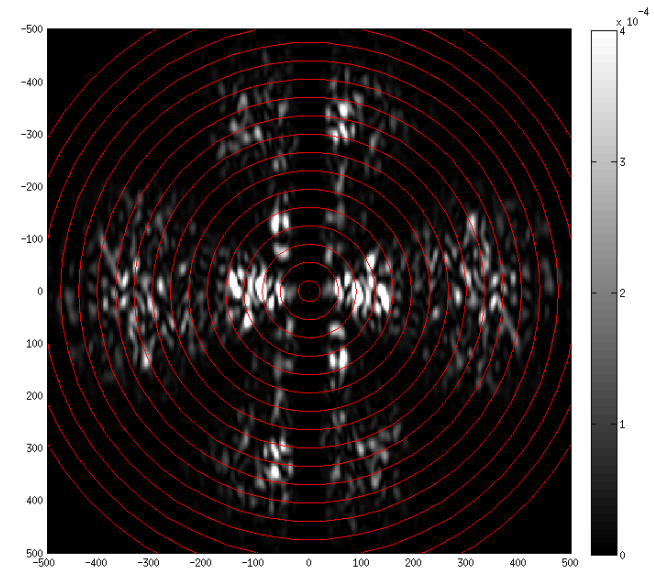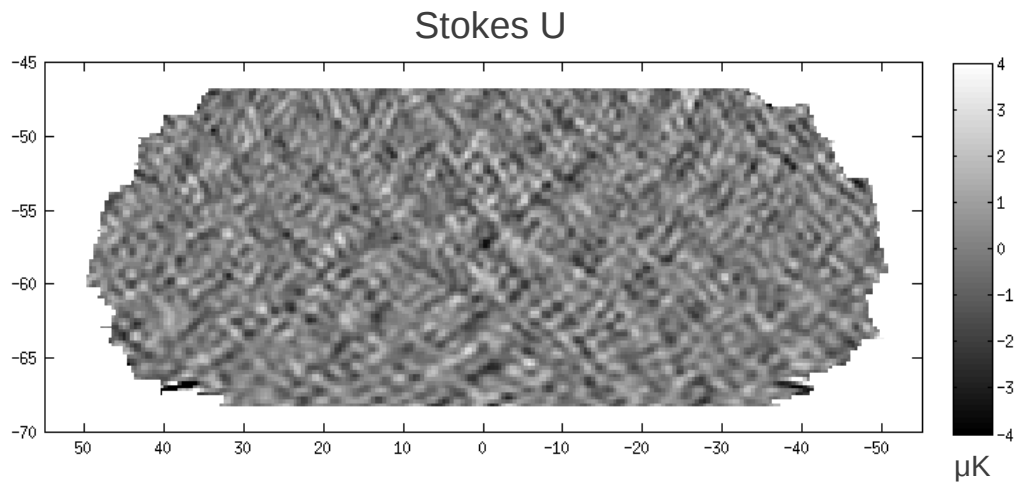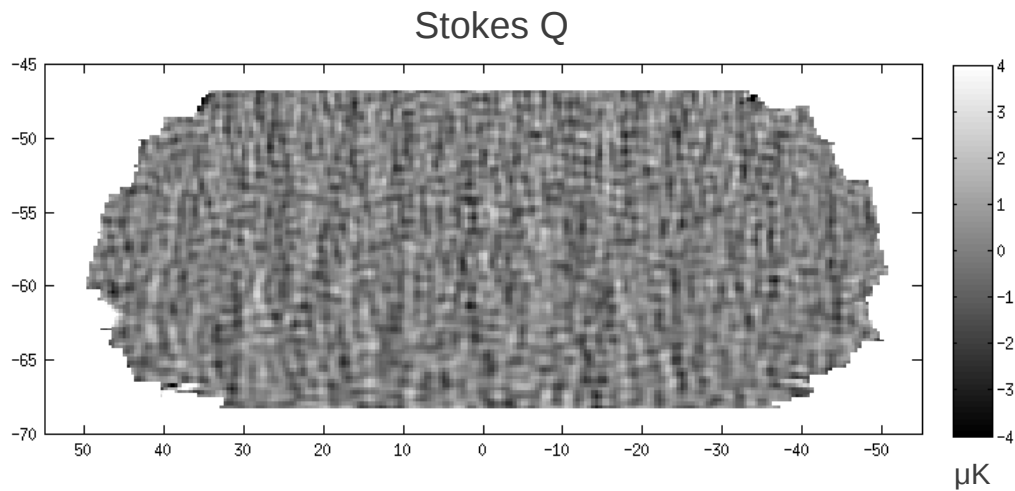# BICEP2 real E-modes

Keck Array real E-modes

Future directions and conclusion

- Keck Array has the ability to switch its 150 GHz detectors to new ones at 100 and 220 GHz for further systematics control.

- Forthcoming experiments Spider and BICEP3 will use similar technology on new platforms.
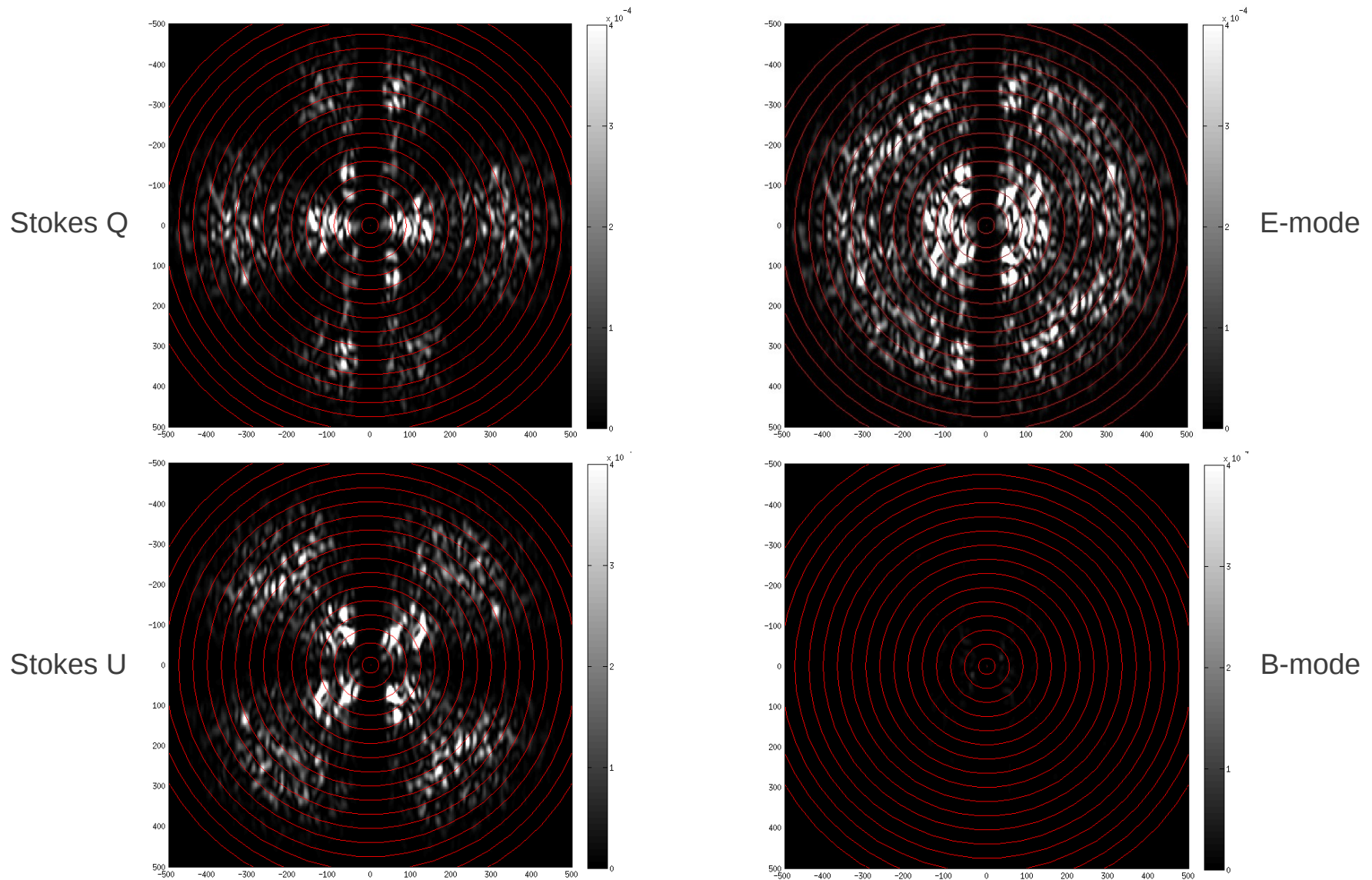
- **Stay tuned! BICEP2 final results coming soon!**
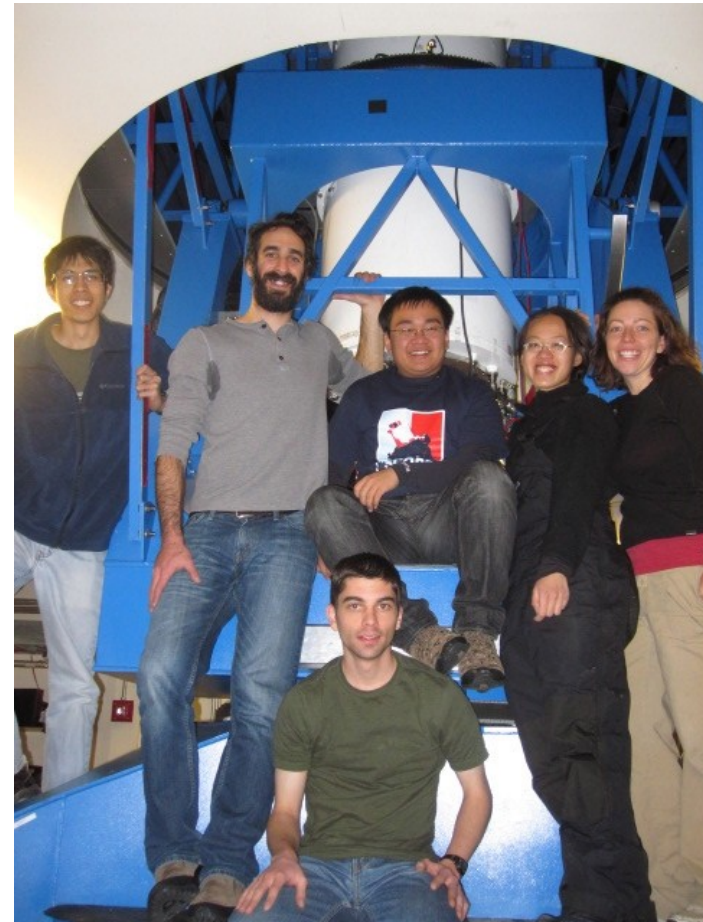
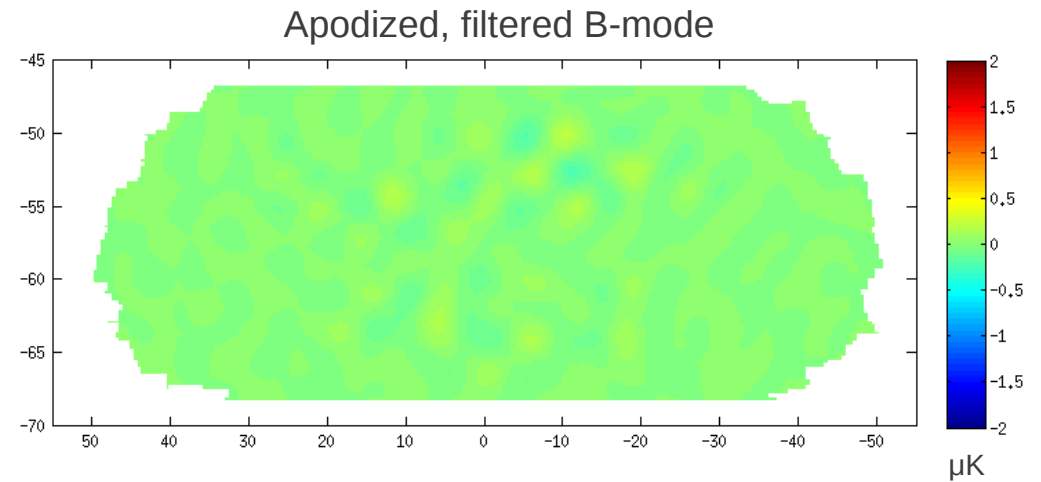# Backup slides
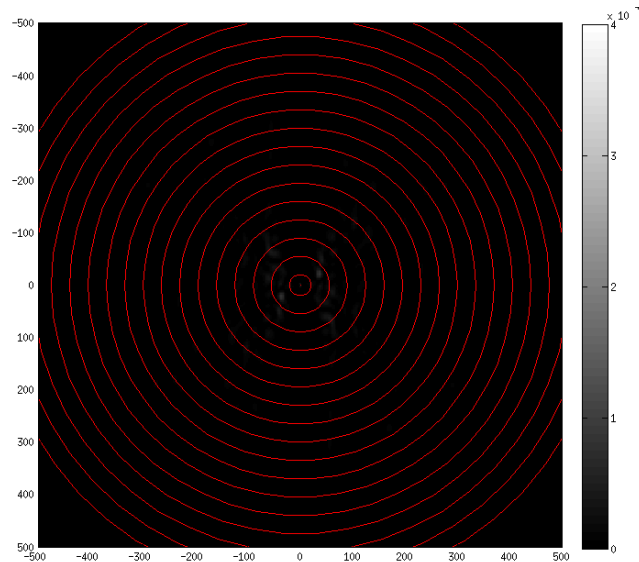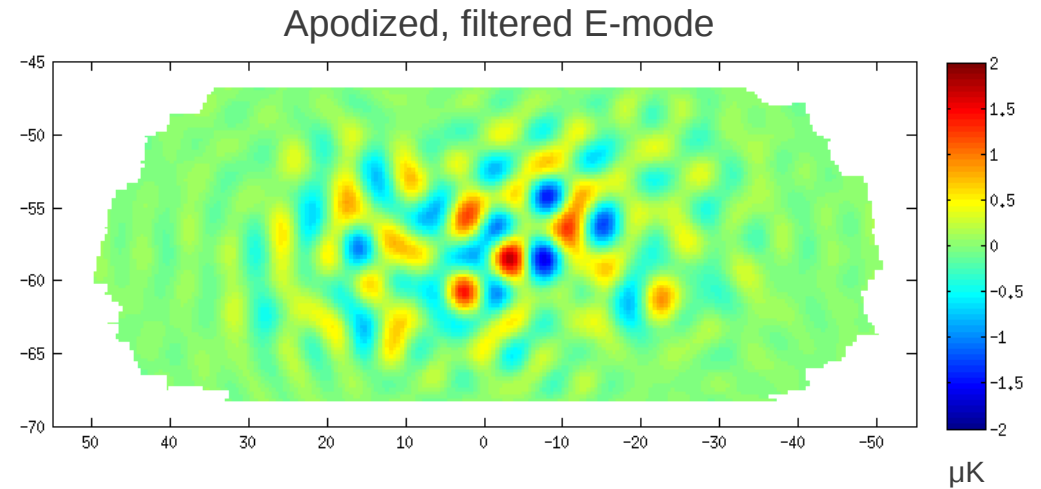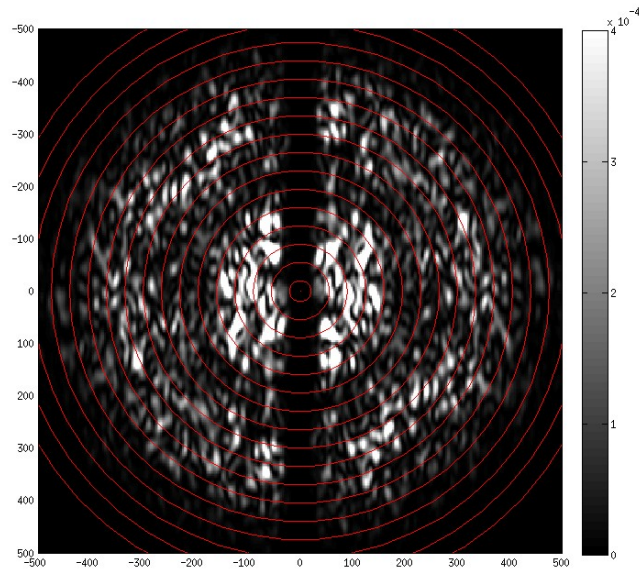
Sim. - Unlensed ΛCDM with *r* = 0.1

Stokes Q

Stokes U

Effective multipole

Sim. - Unlensed ΛCDM with *r* = 0.1

Stokes Q

E-mode

Stokes U

B-mode

Sim. - Unlensed ΛCDM with *r* = 0.1

Apodized, filtered E-mode

Apodized, filtered B-mode

Sim. - Unlensed ΛCDM with *r* = 0.1

Apodized, filtered E-mode

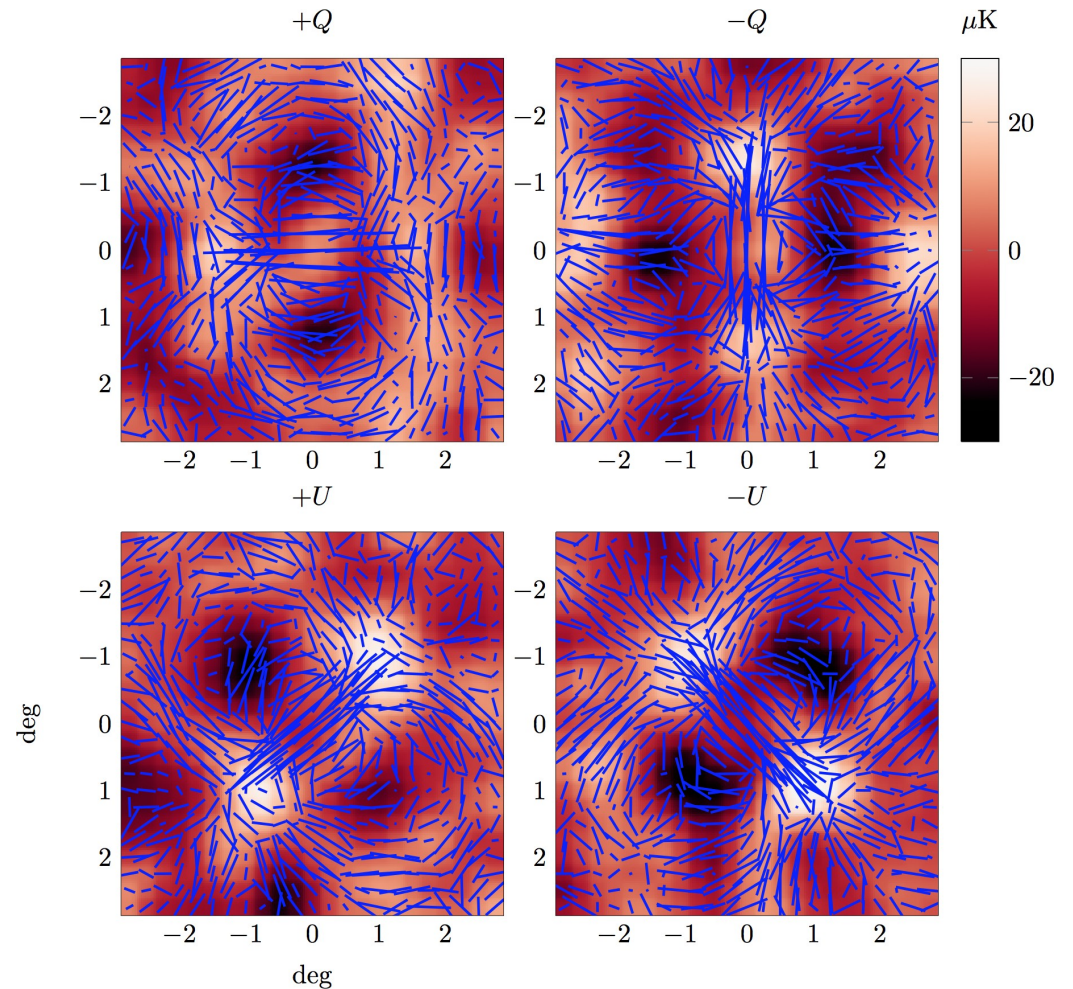Apodized, filtered B-mode
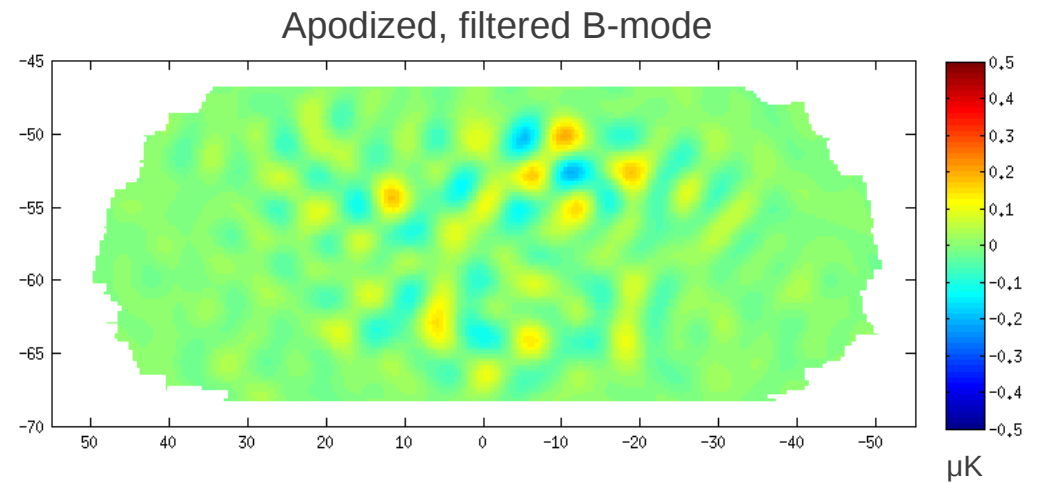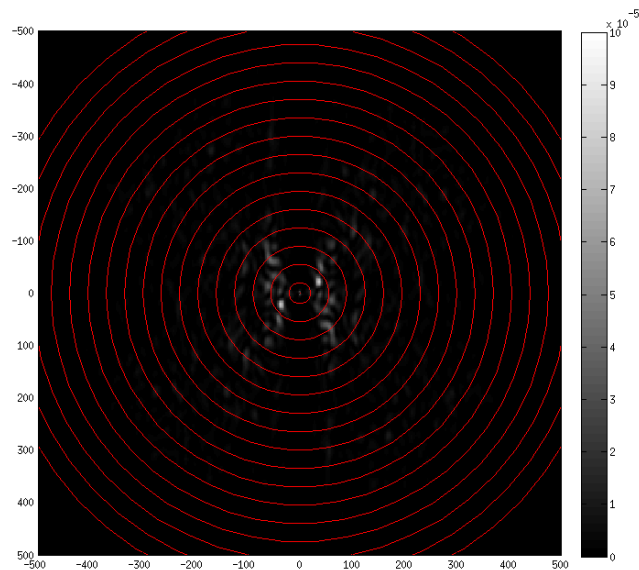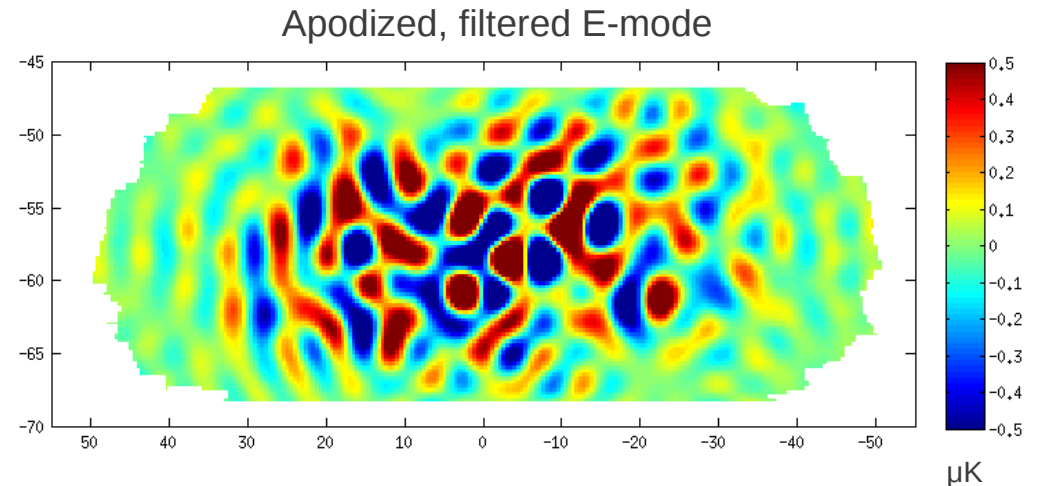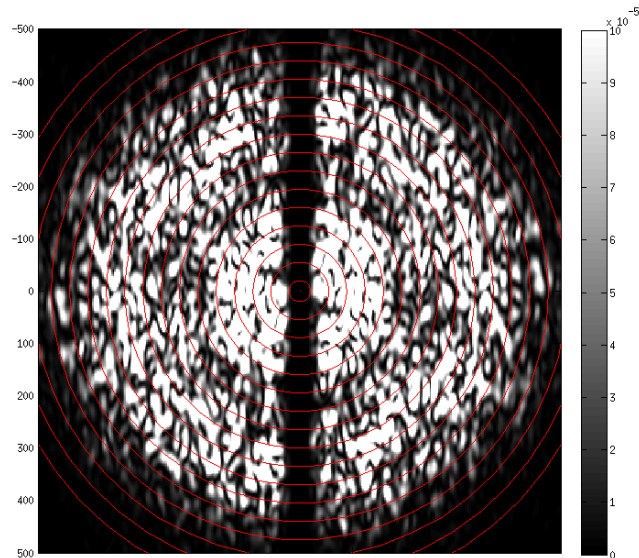
CMB polarization

- Stacking CMB maps at local maxima and minima in Stokes Q/U reveals the local quadrupole anisotropy.

- Images shown are from real BICEP2 data.

R. Aikin – 2013 PhD thesis