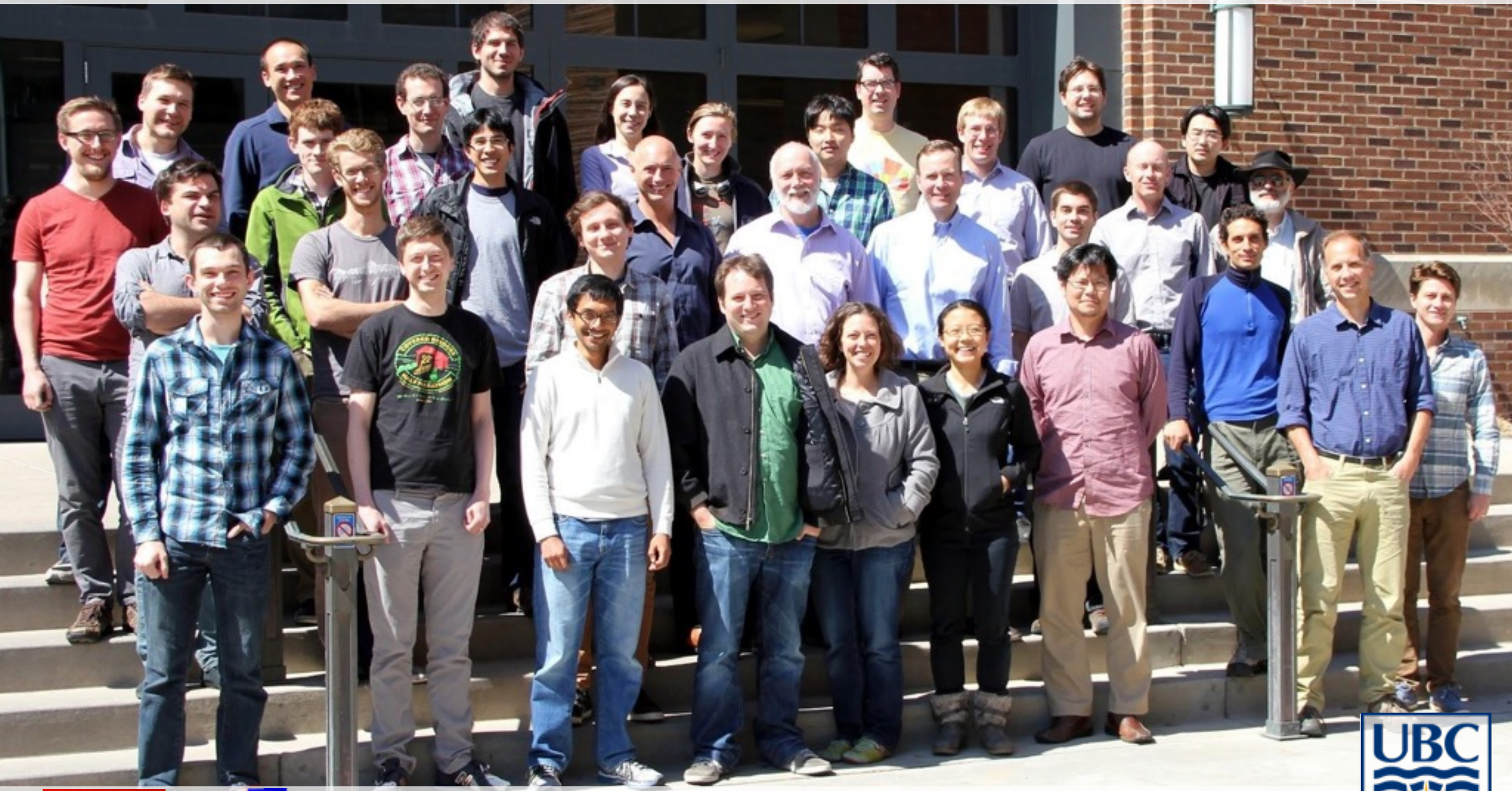
CMB Polarization at 90°S

Zeeshan Ahmed
KIPAC, Stanford/SLAC

(BK slides from ZA, BK collaboration)
SPT slides from Jason Gallicchio, SPT collaboration)

August 8, 2015
3rd SCAR AAA workshop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HARVARD
CALIFORNIA INSTITUTE OF TECHNOLOGY
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UCSD
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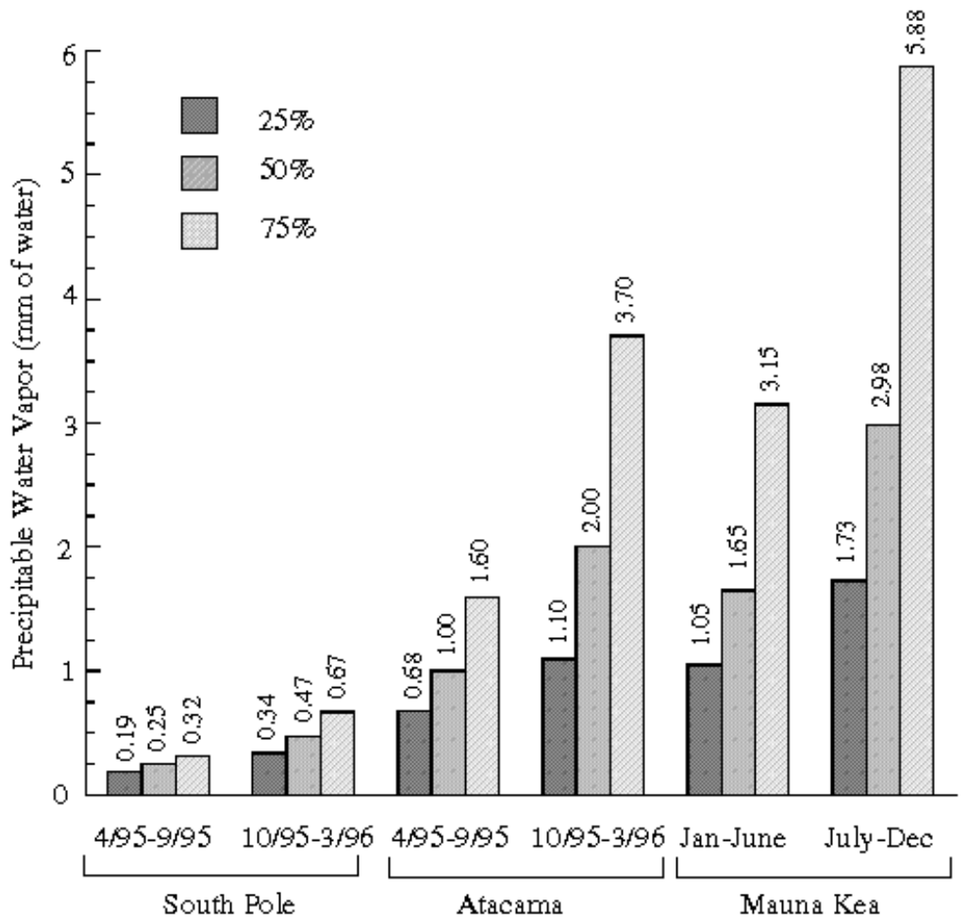
NIST
CARDIFF UNIVERSITY
UNIVERSITY OF TORONTO
UBC

The SPT Collaboration

Why the South Pole?



South Pole Research Station, Antarctica

~10,000ft, ~0.25mm PWV

6 months of cold, stable sky with uninterrupted integration

South Pole CMB experiments

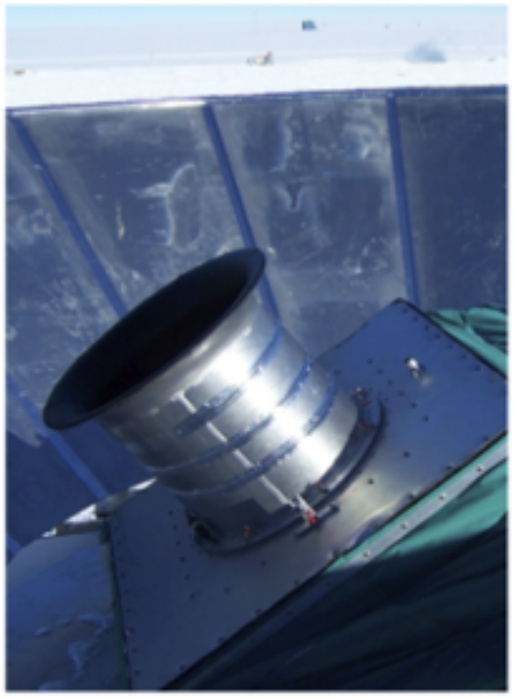
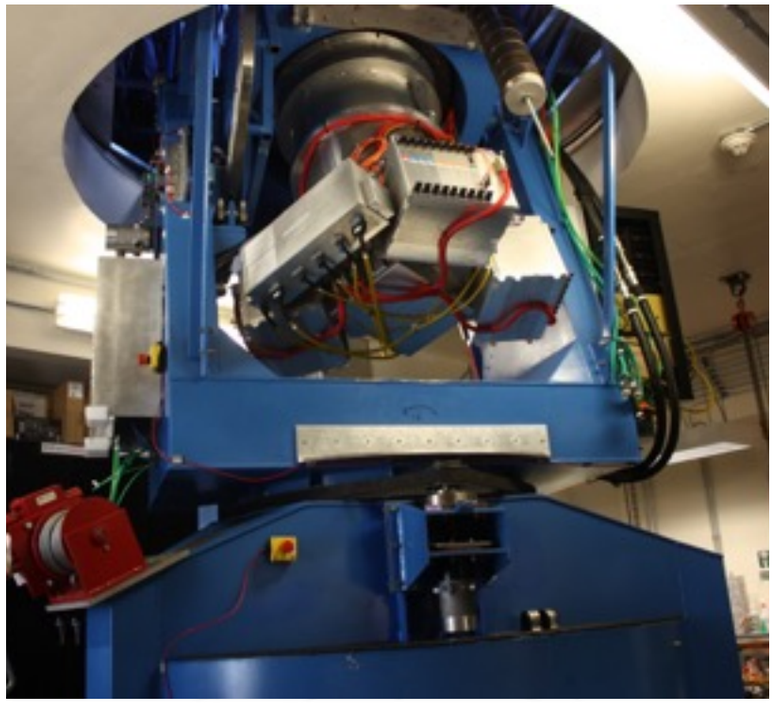
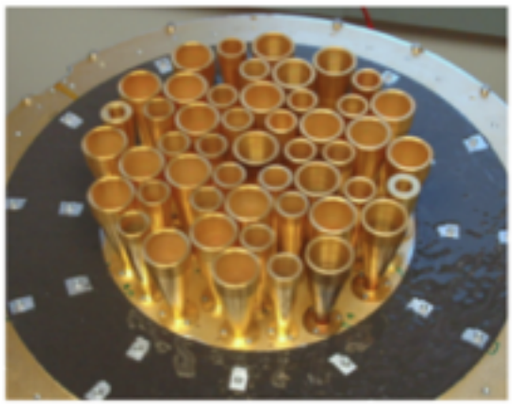
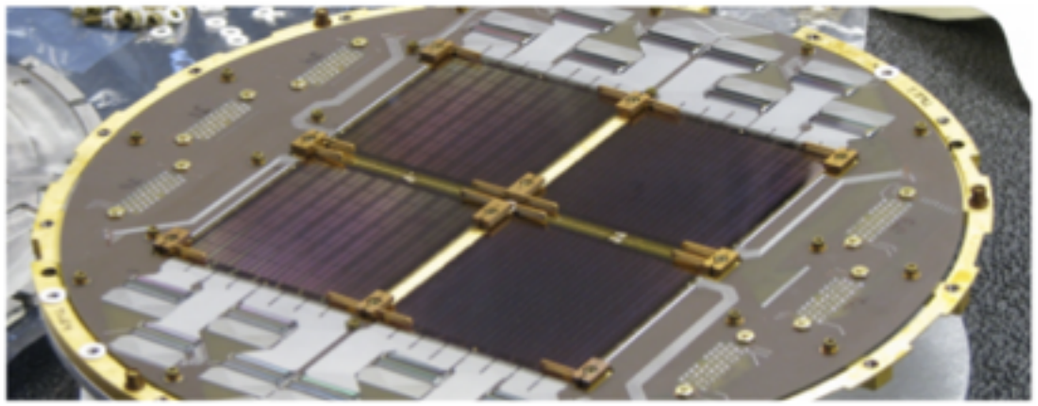
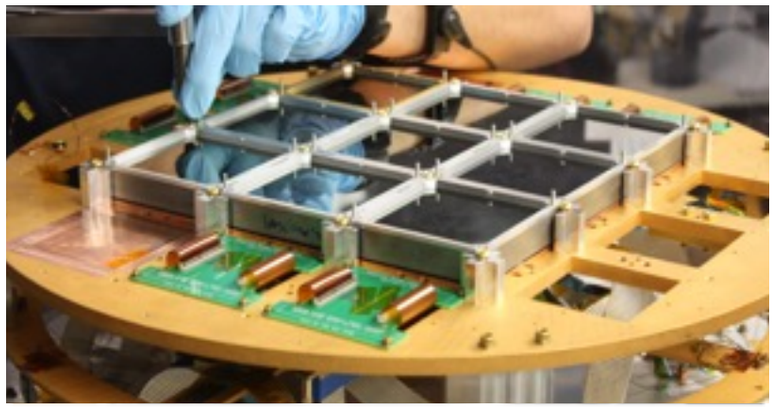
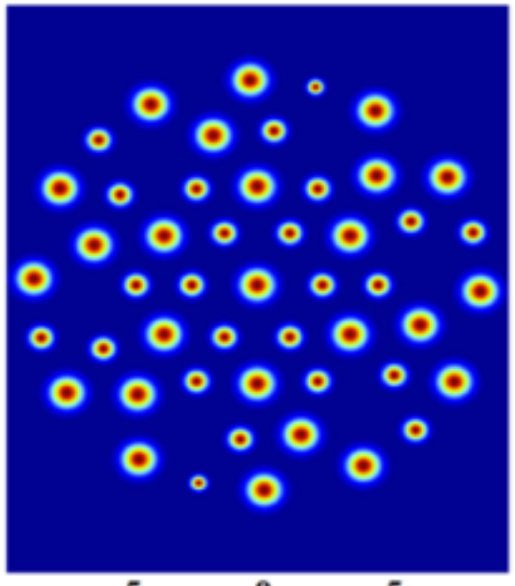
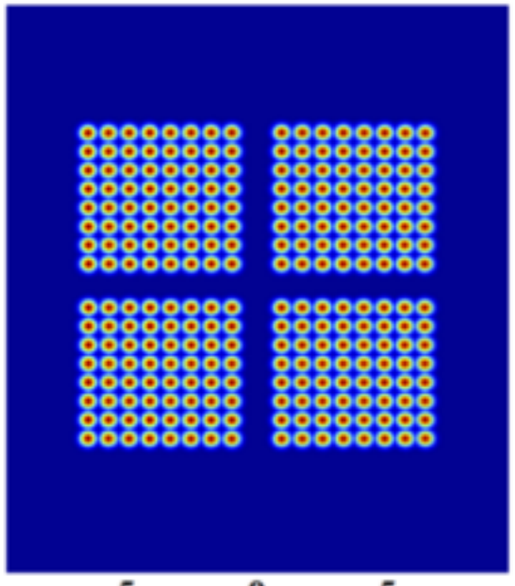
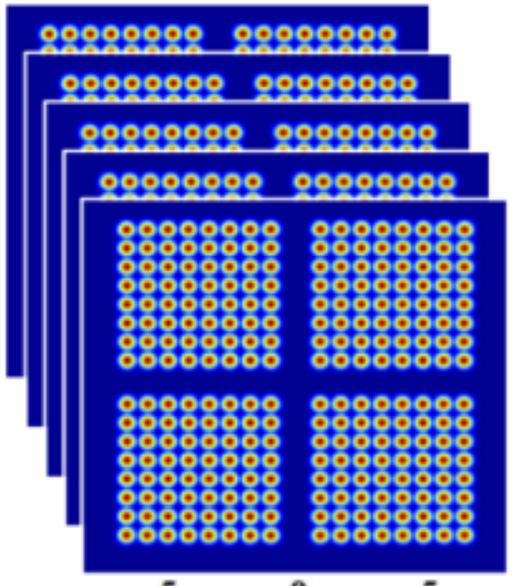
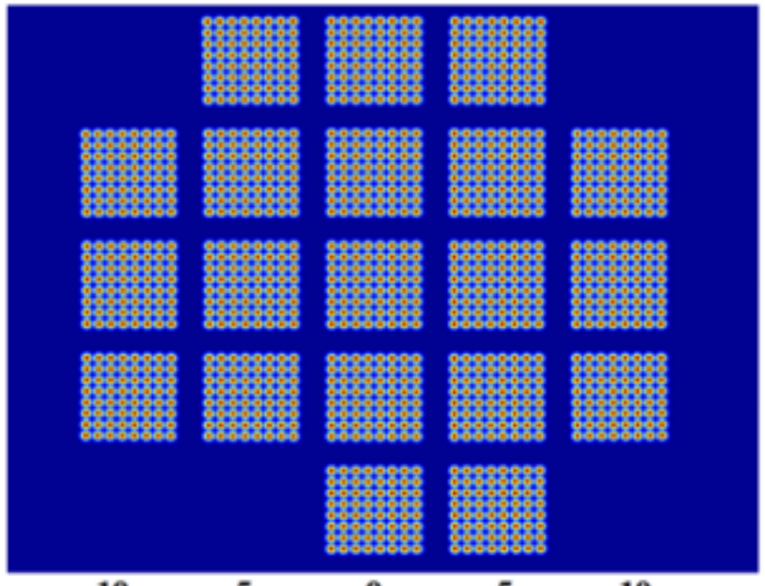
SPT (2007-2011)
SPTpol (2012-2015)
SPT3G (2016-?)

ACBAR (2001-2005)

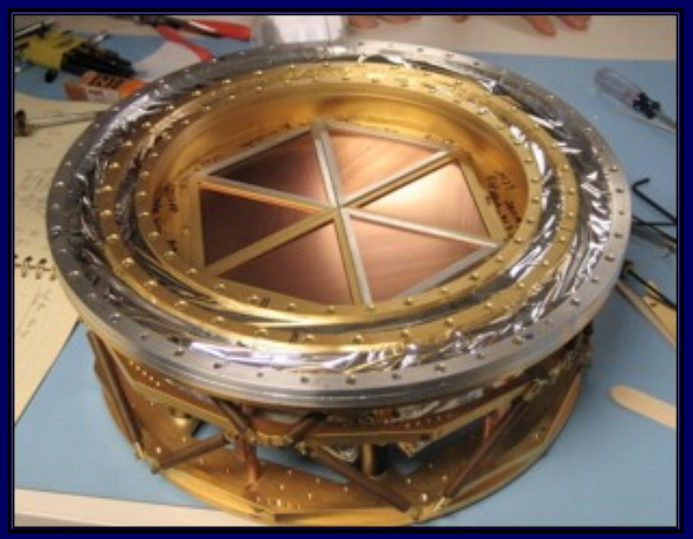
DASI (1999-2003)
QUAD (2004-2007)
KECK (2011-2016)

BICEP (2006-2008)
BICEP2 (2010-2012)
BICEP3 (2015-?)

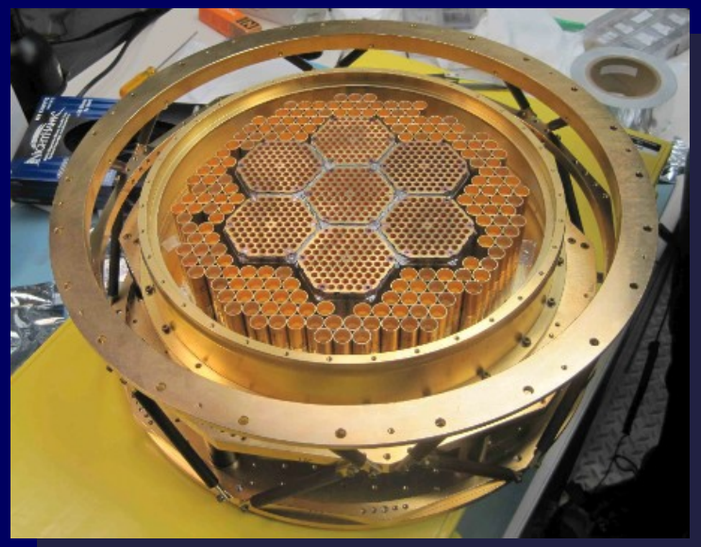
Completed
Operating or Proposed

	BICEP1 (2006 - 8)	BICEP2 (2010 - 12)	Keck Array (2011 -)	BICEP3 (2015-)
Telescope and Mount				
Focal Plane				
Beams on Sky				

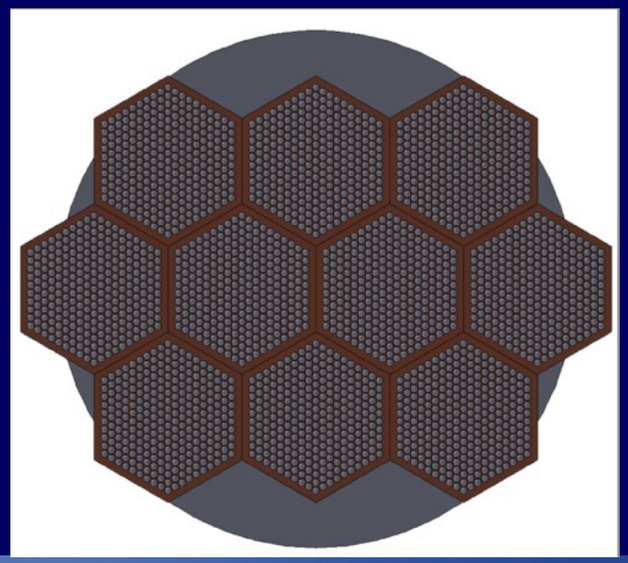
SPT-SZ
0.9k detectors
2007-2011



SPTpol
1.6k detectors, pol
2012-2015

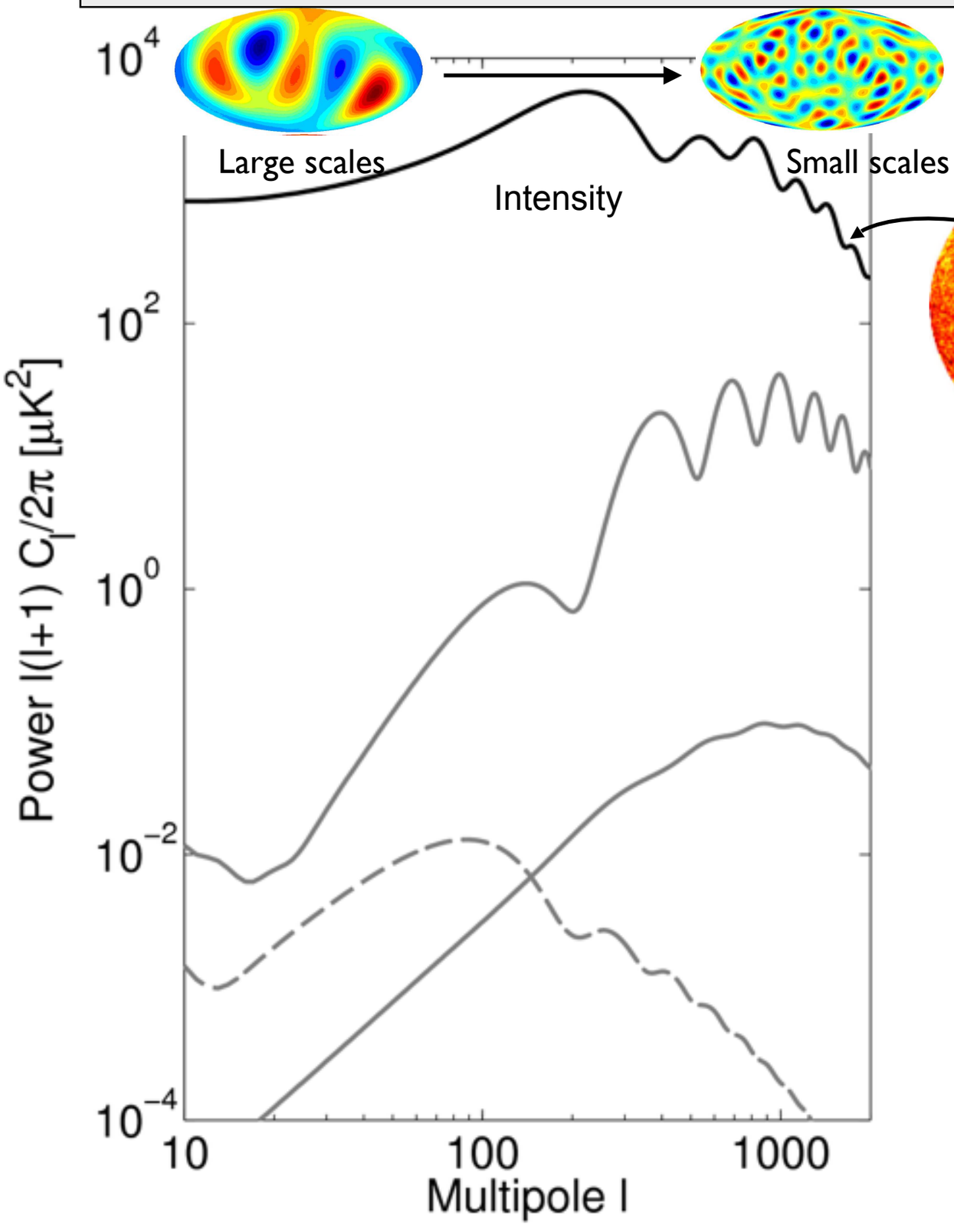


SPT-3G
15k detectors, pol
2016-?

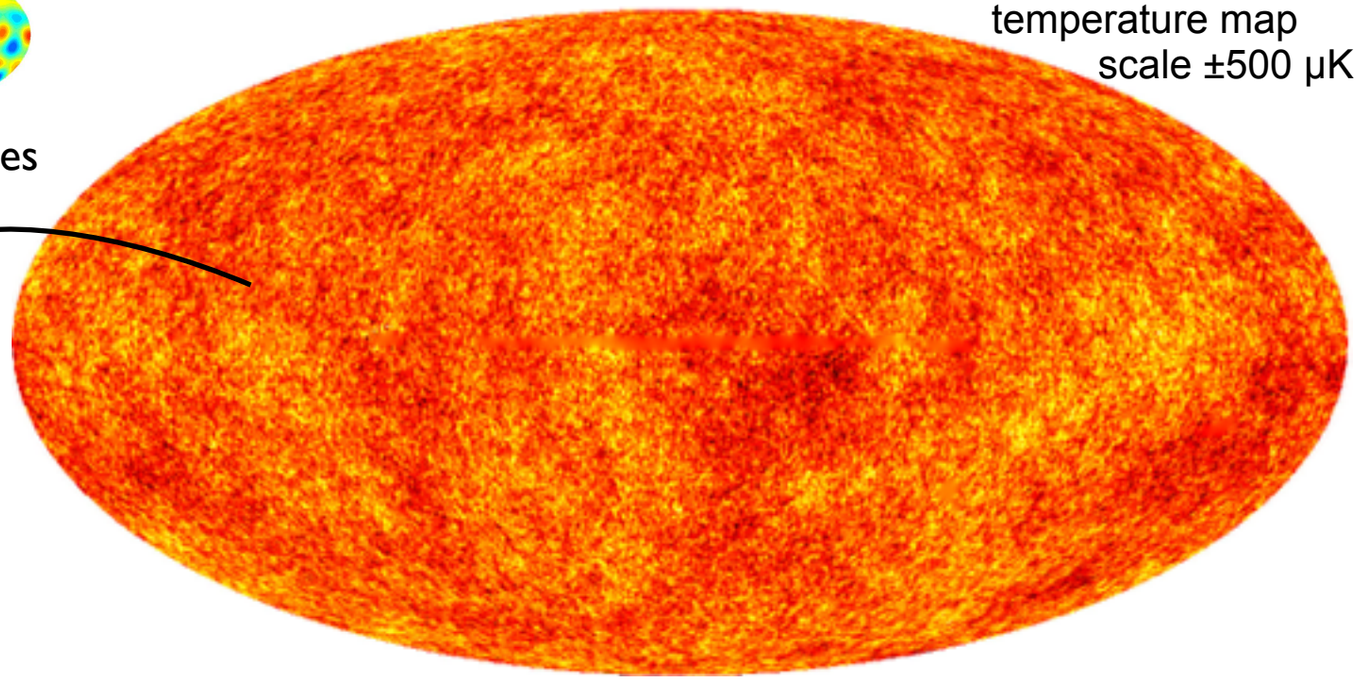


~1 arcminute
resolution at
95, 150, 220 GHz

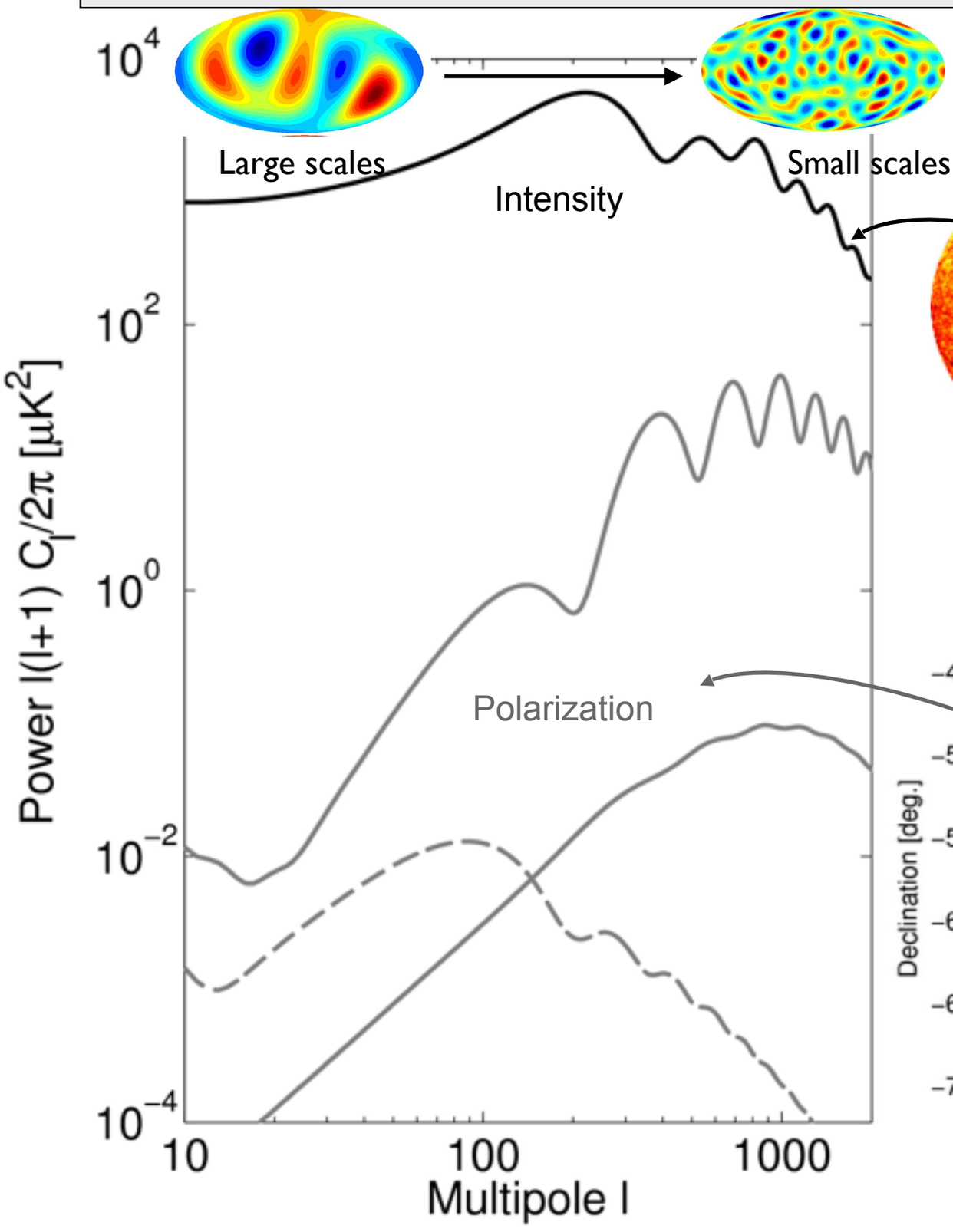
Understanding CMB Polarization angular power

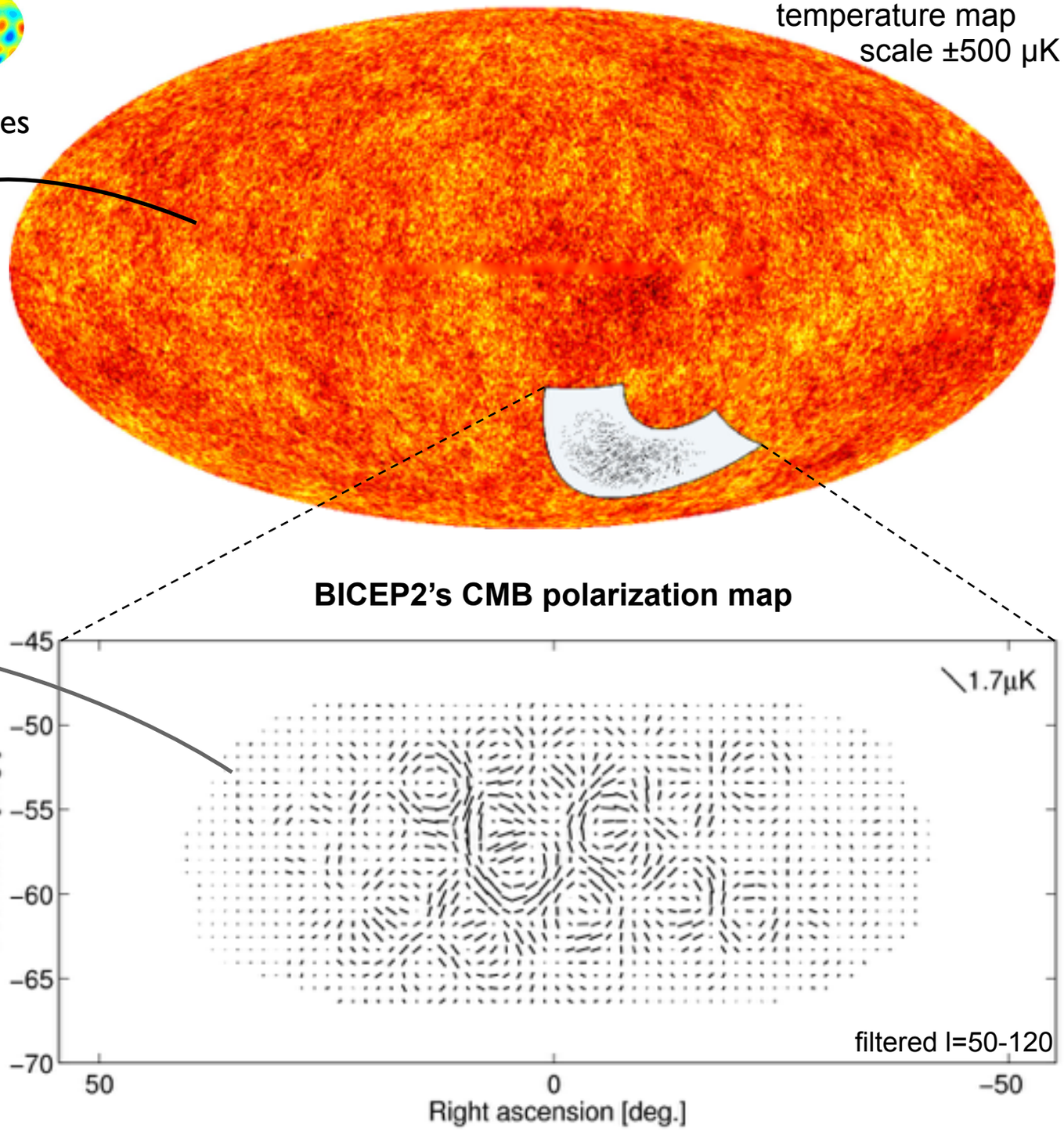


Planck's all sky CMB temperature map scale ±500 μK

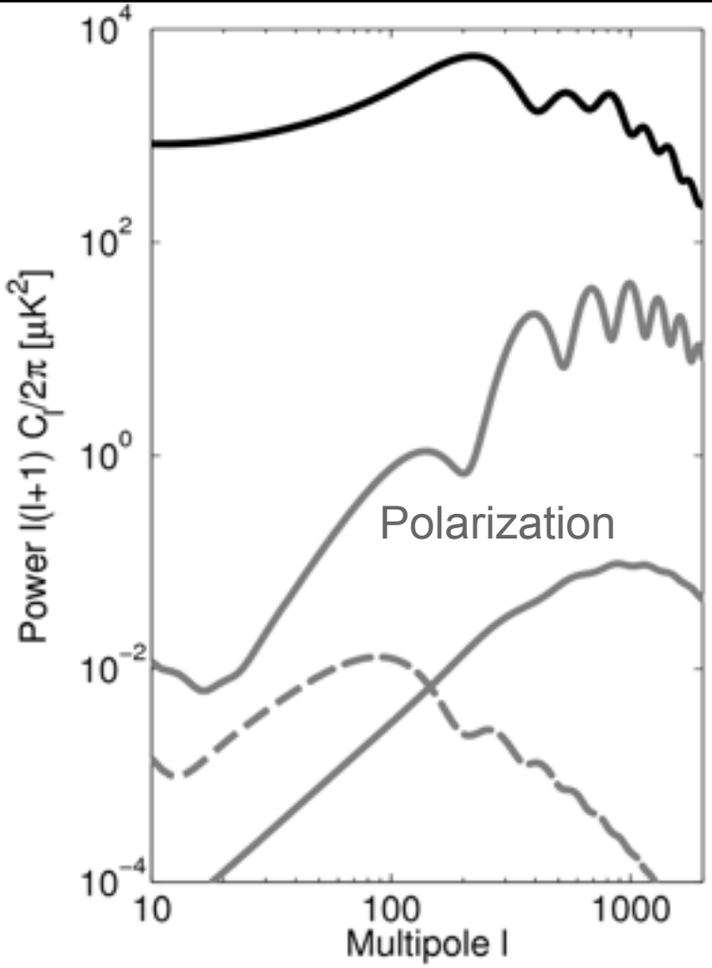


Understanding CMB Polarization angular power

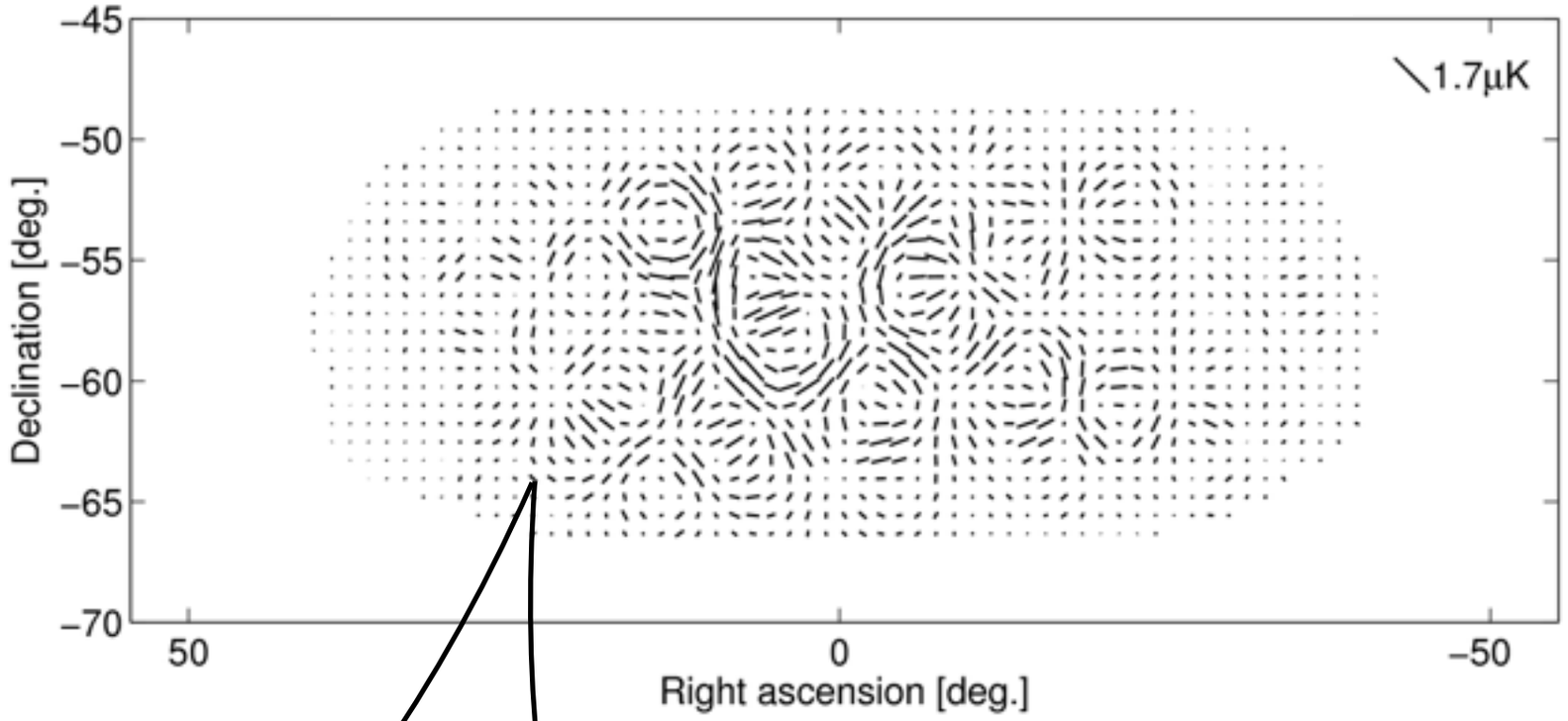


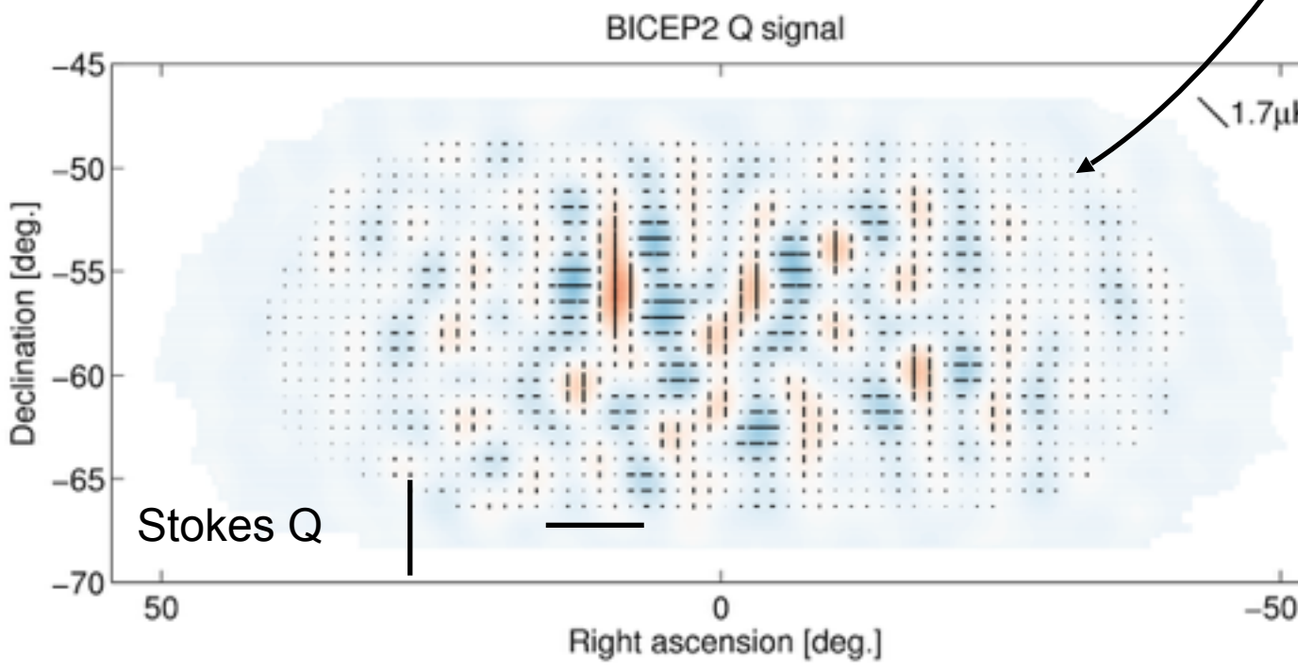


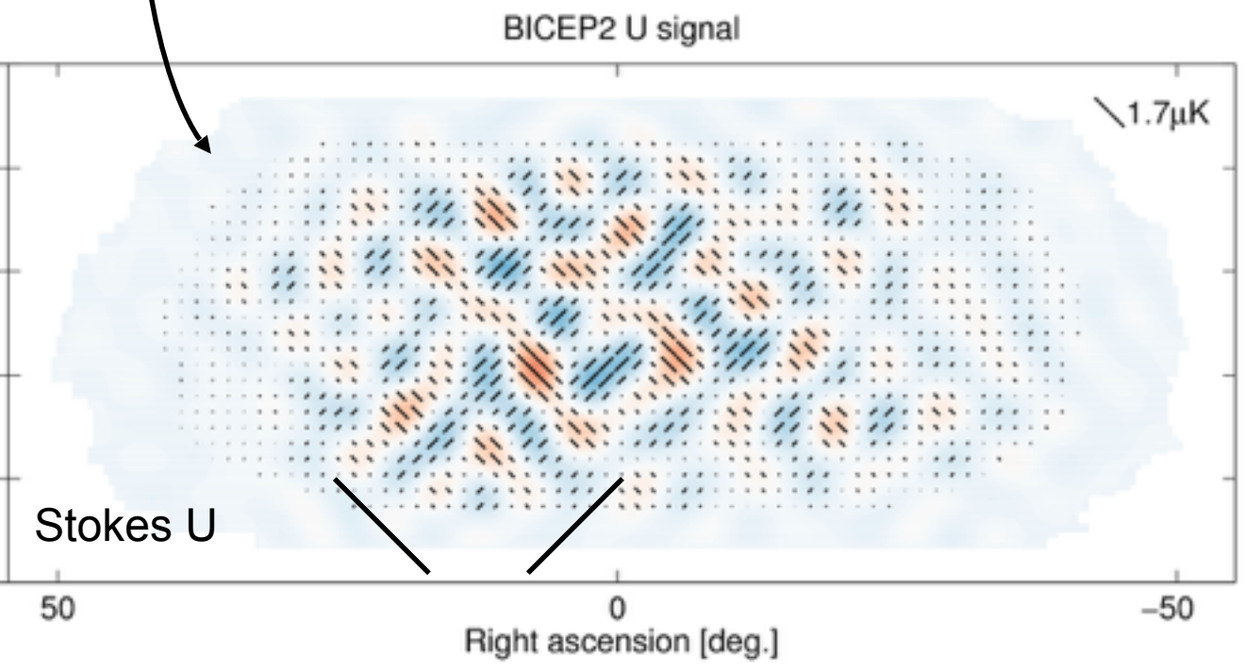
Understanding CMB Polarization angular power



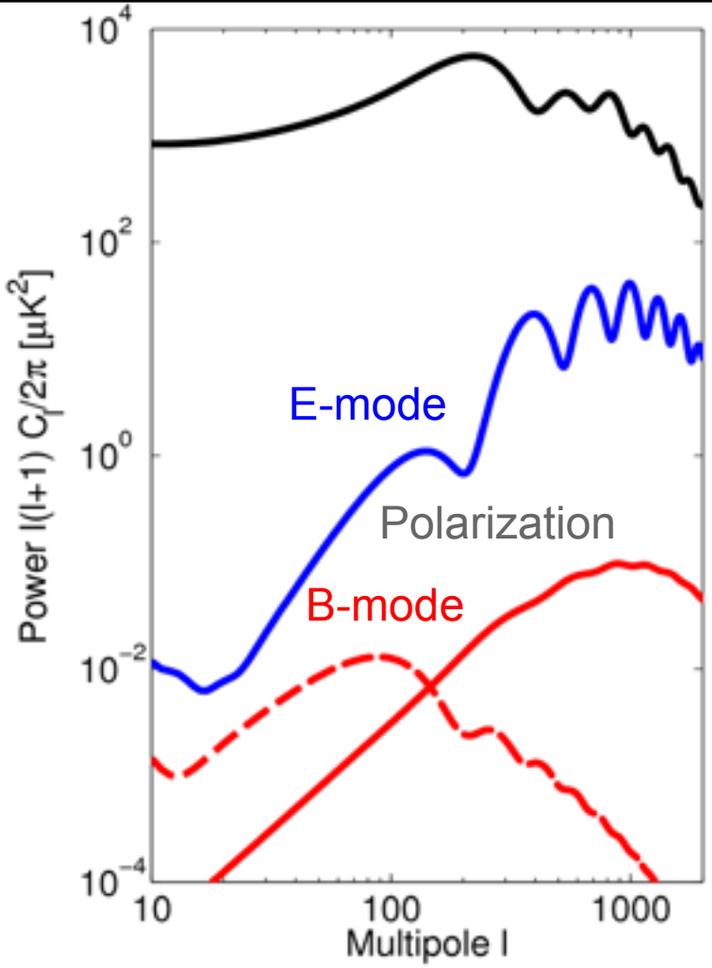
BICEP2's CMB polarization map

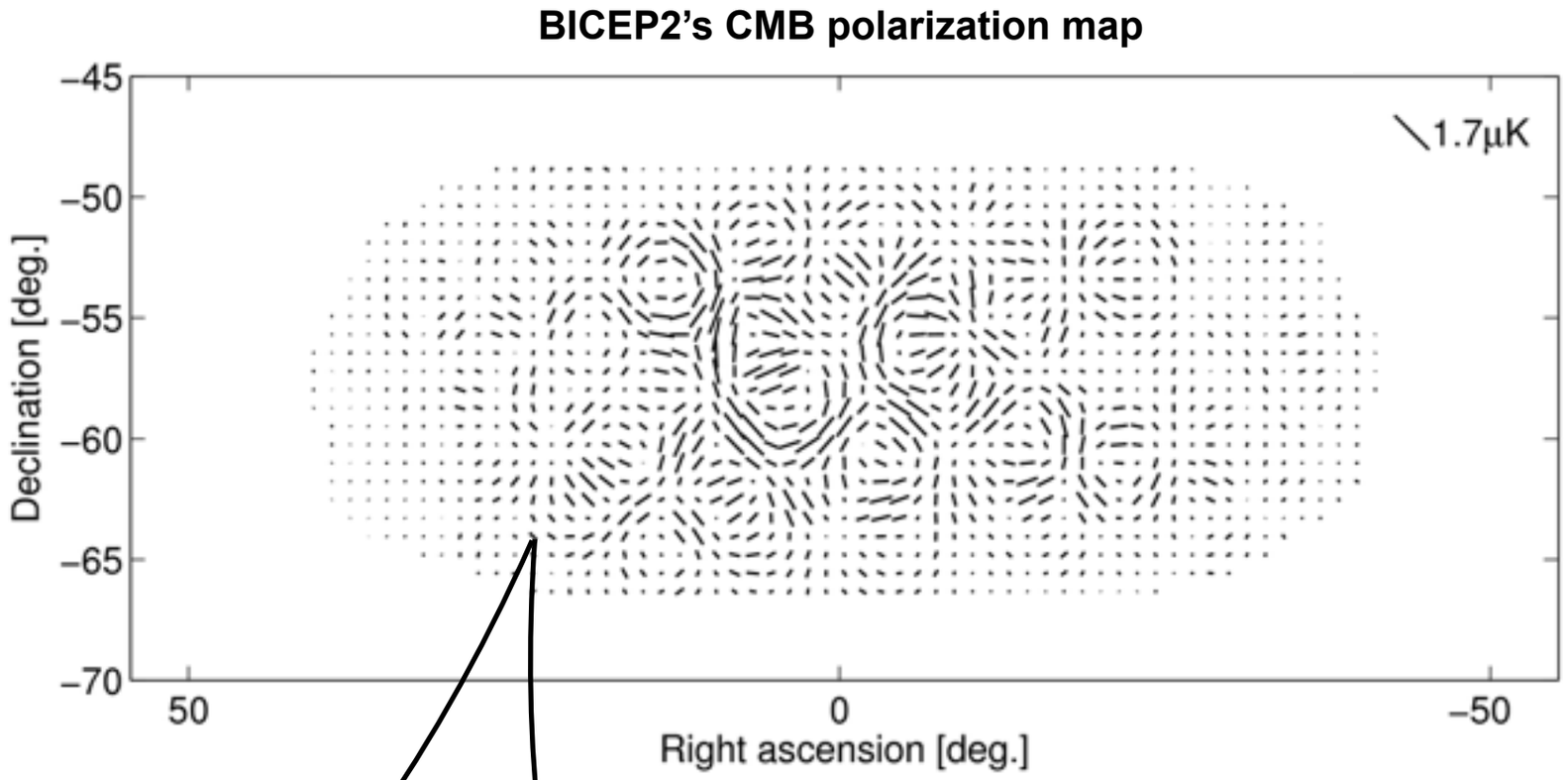




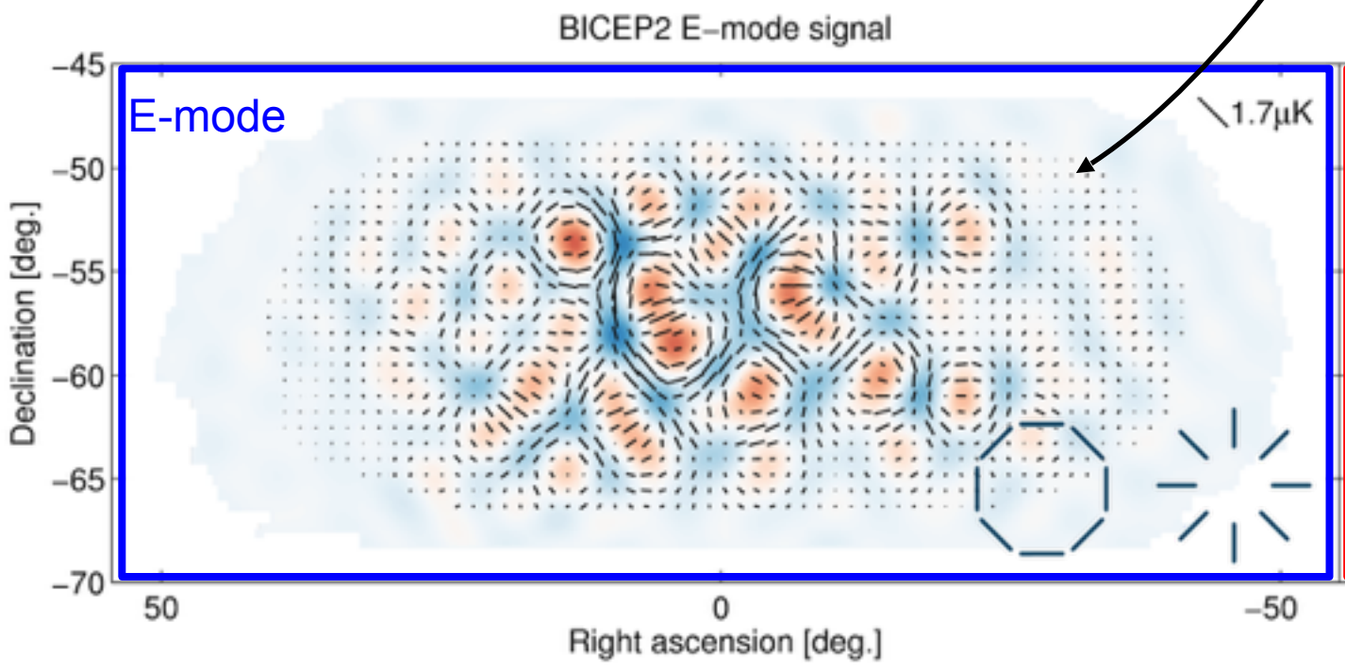


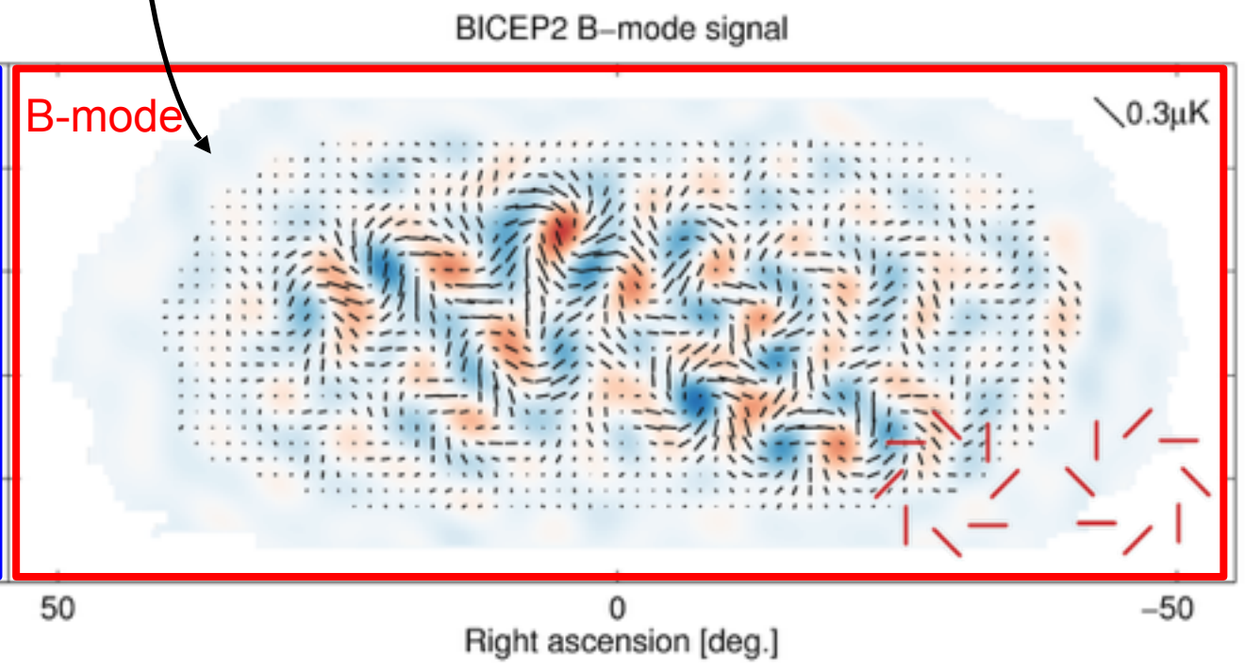
Understanding CMB Polarization angular power



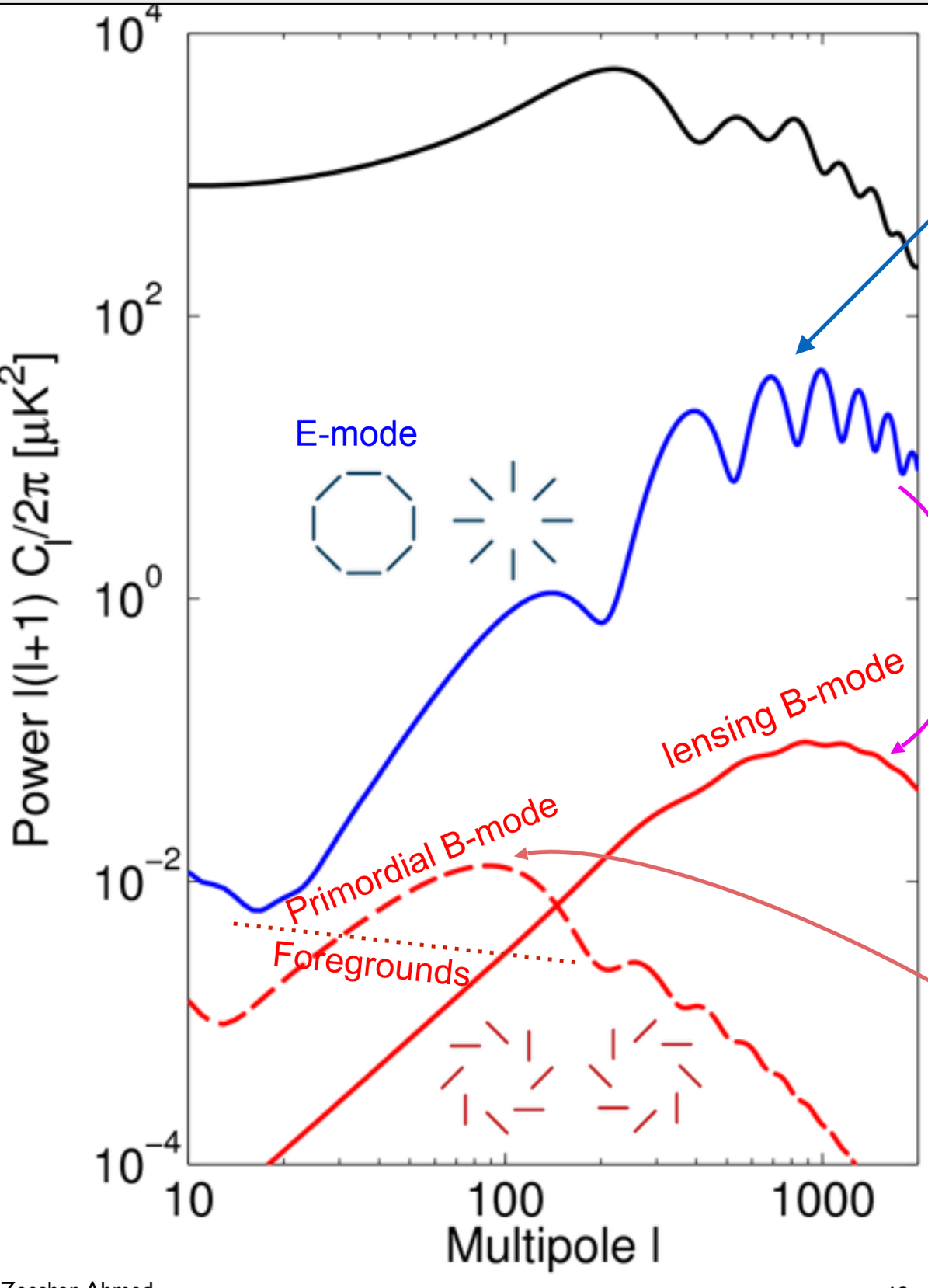


...clever choice for cosmology: E&B-modes

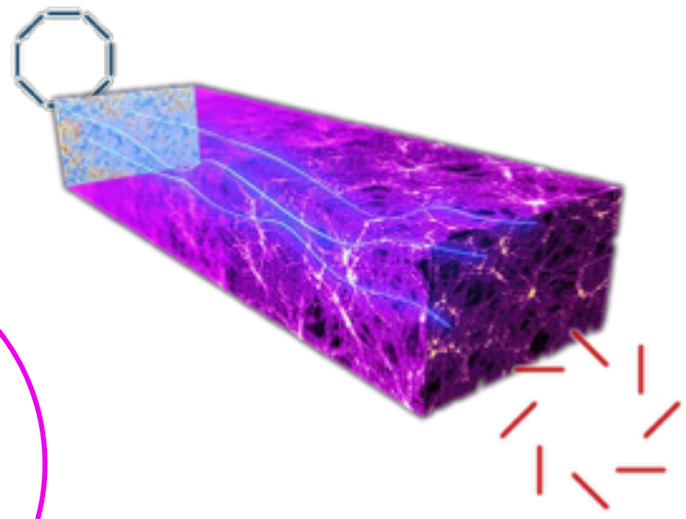




Understanding CMB Polarization angular power



In standard ΛCDM only E-modes are present at last scattering



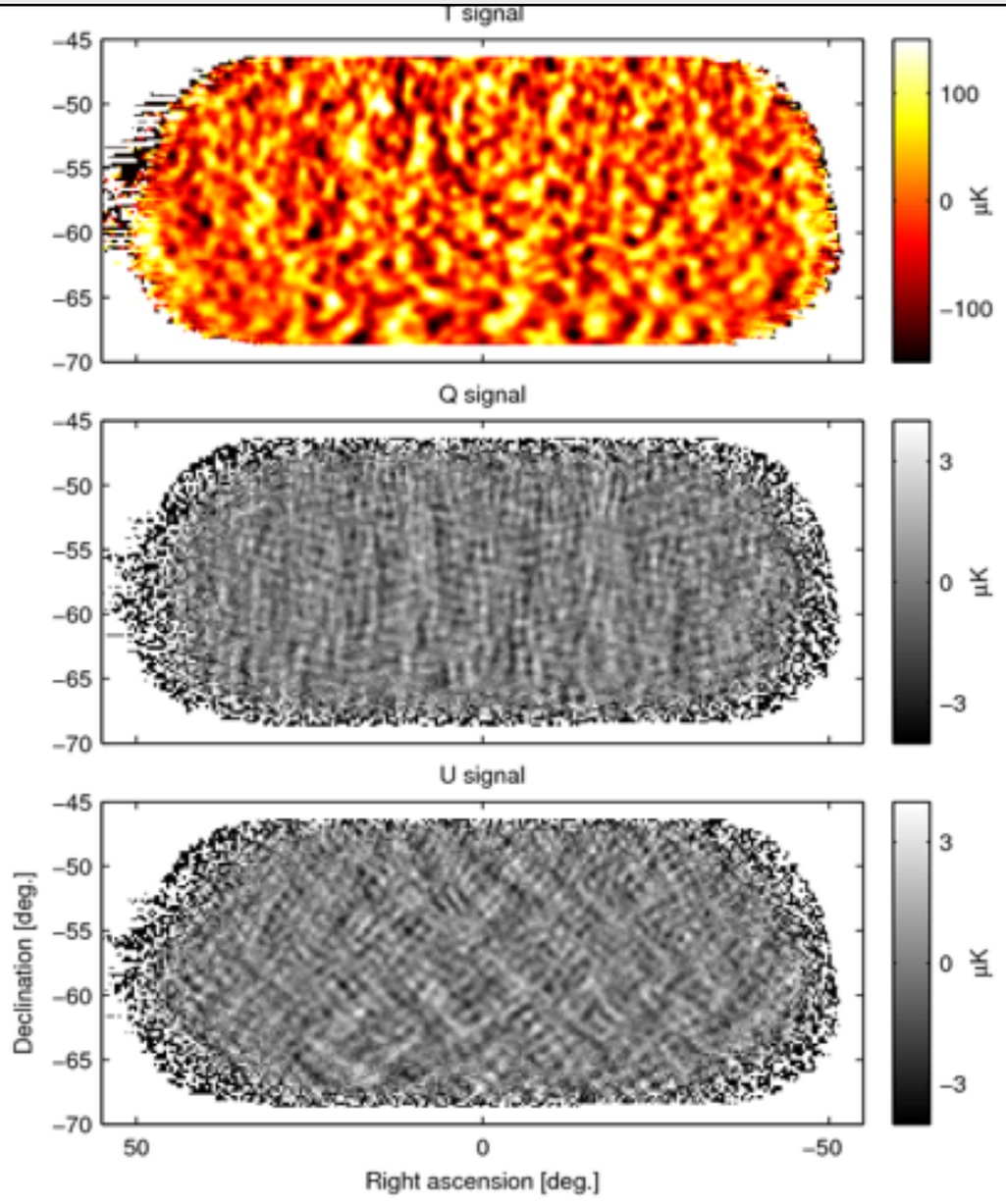
Lensing by intervening structure converts some to B-modes

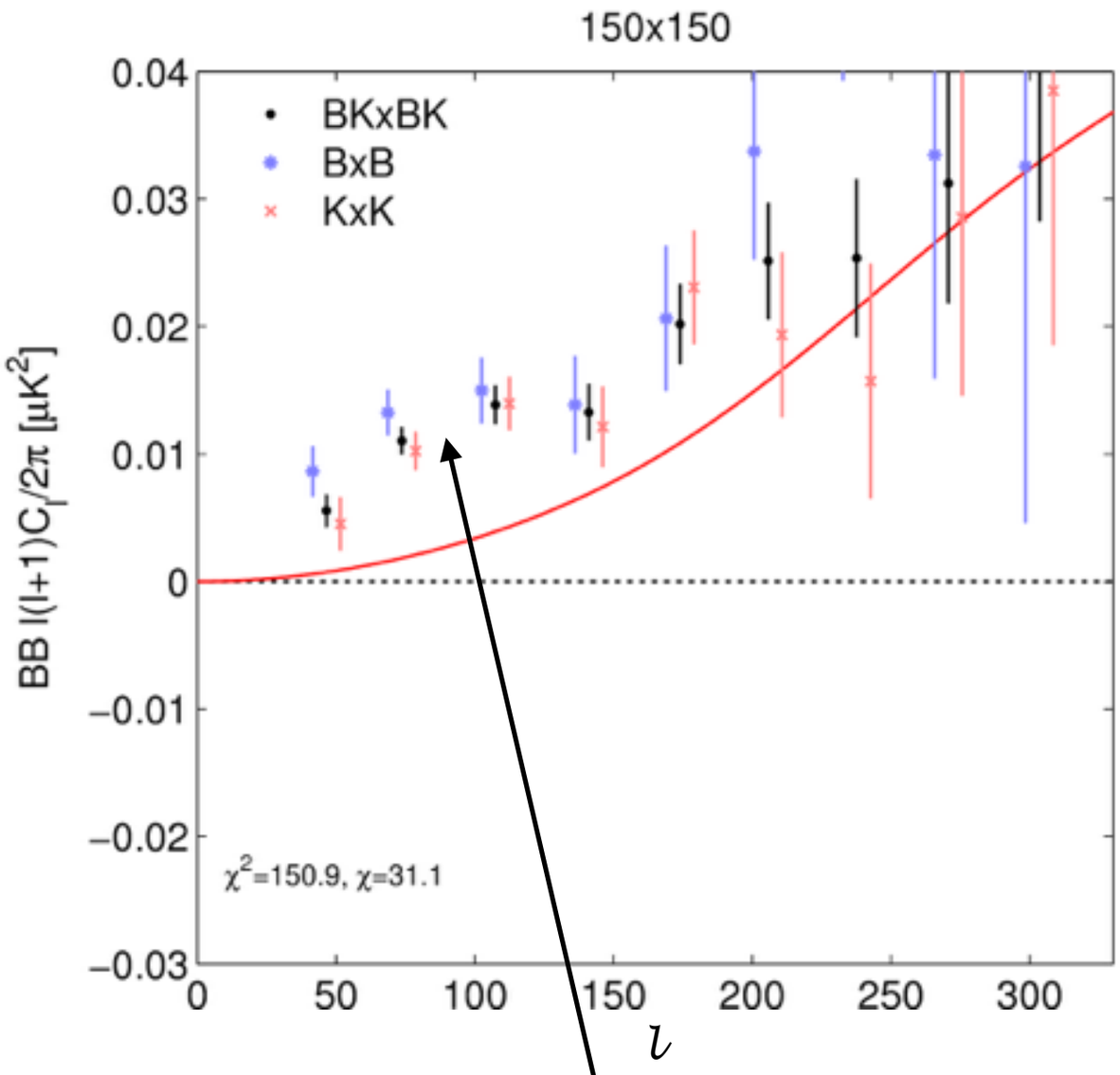
Enables reconstruction of a map of all matter between us and recombination. Measures neutrino properties!

Inflationary gravity waves produce B-modes peaking at l≈100 : degree scales. Measure tensor-to-scalar ratio, *r*

Foregrounds also generate polarized emission. Can be teased apart from different spectral dependence cf CMB

BICEP2+Keck through 2013 (150 GHz)





Observation at 150 GHz focused on ~**400 deg^2** patch = 1% of the sky

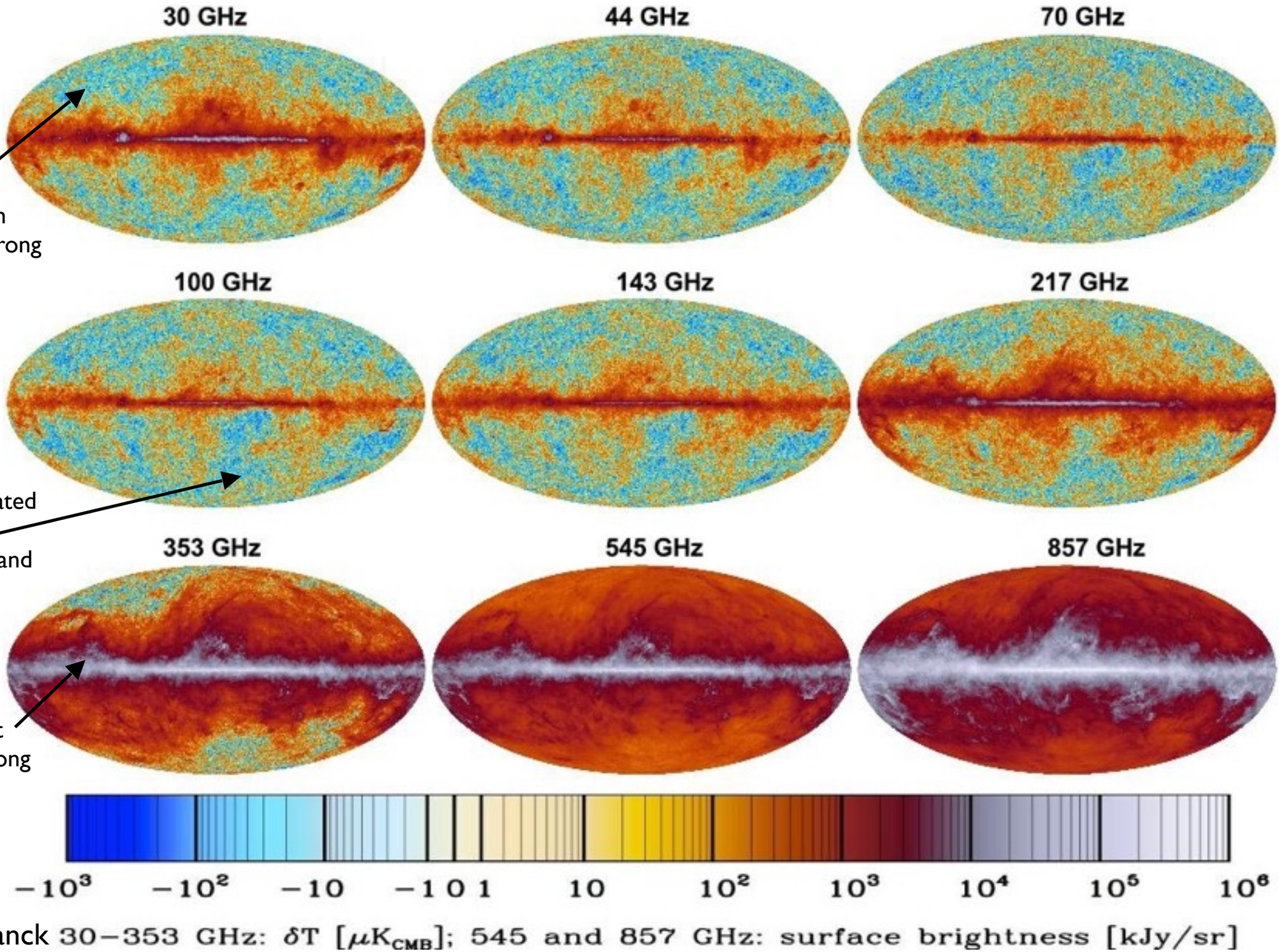
BICEP2 + Keck thru 2013 → Final map depth: 3.4 μK arcmin / 57 nK deg

(RMS noise in sq-deg pixels)

BB power spectrum shows excess over lensed ΛCDM at degree scales.

To investigate this, we do a joint analysis w/ Planck, which has frequency bands w/ sensitivity to dust

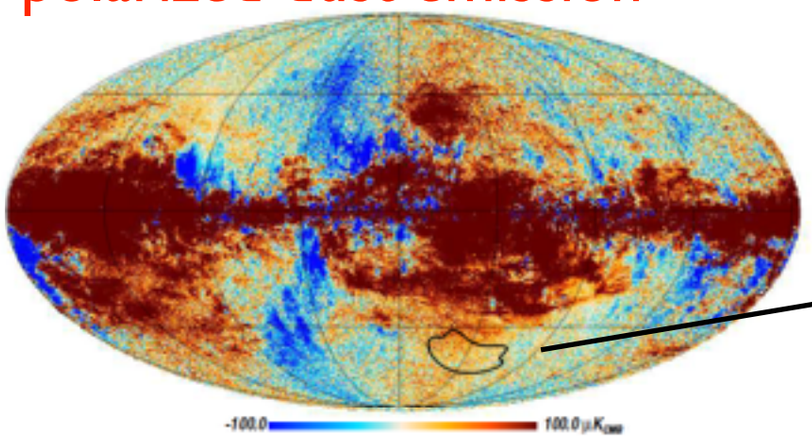
Spectral dependence of CMB & contaminants



Planck 353 GHz

- Planck is the third generation space mission to observe the CMB: observes the full sky in multiple frequency bands.
- Full sky measurement, but in any given sky patch much less deep than BICEP2+Keck
- 353 GHz band is very sensitive to polarized dust emission

Q



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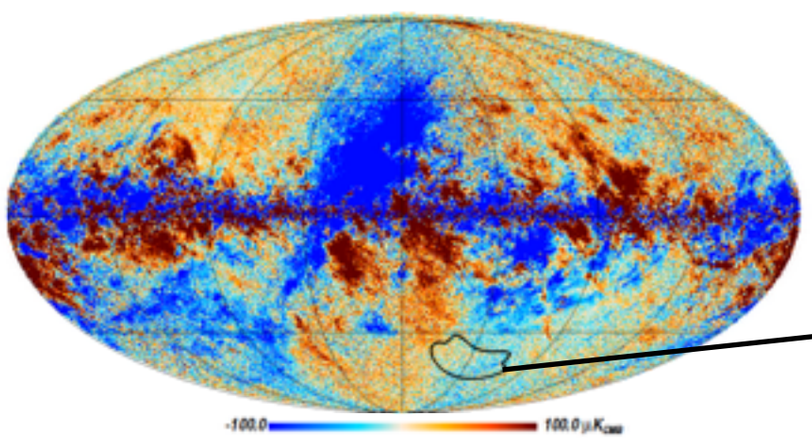
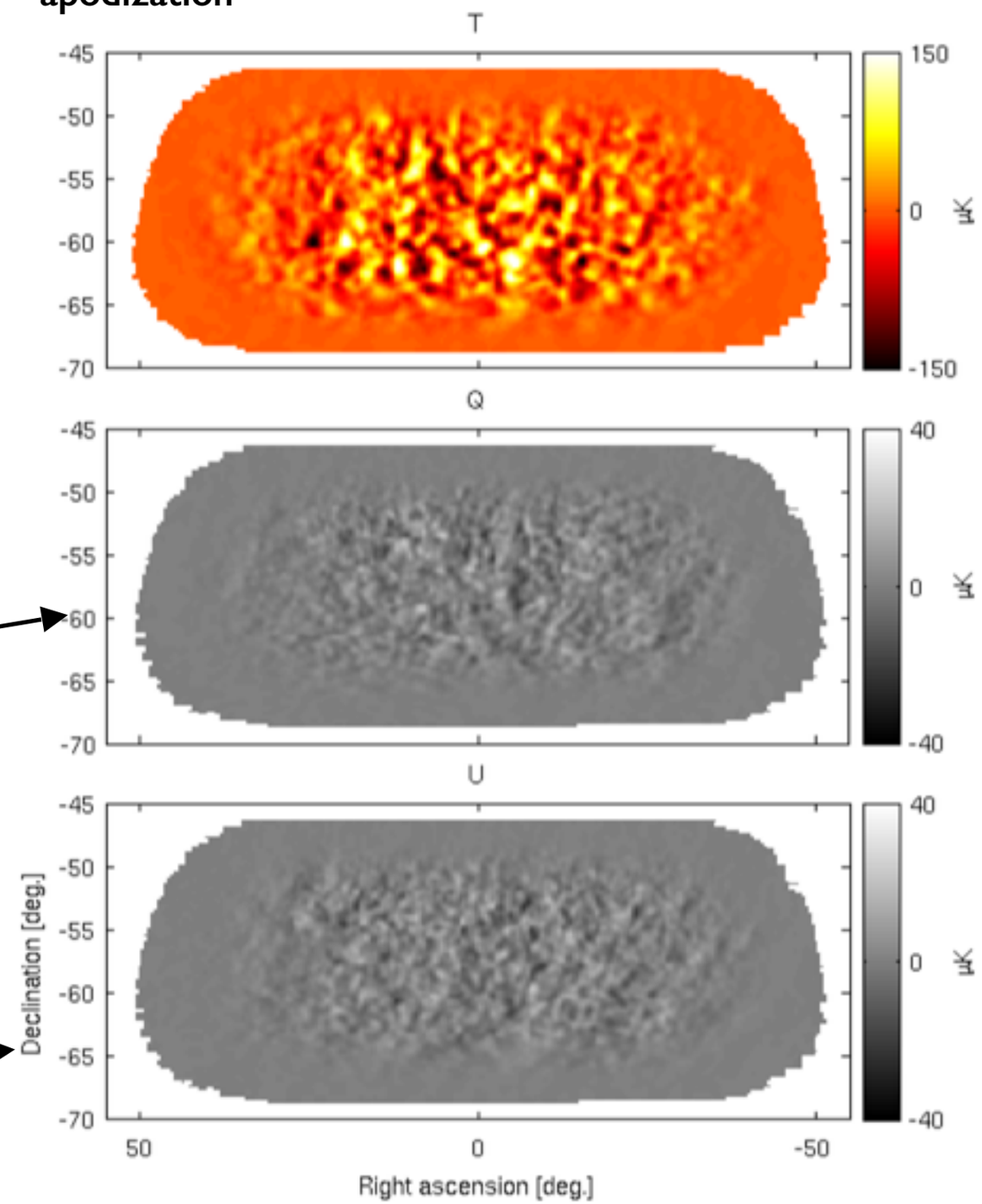
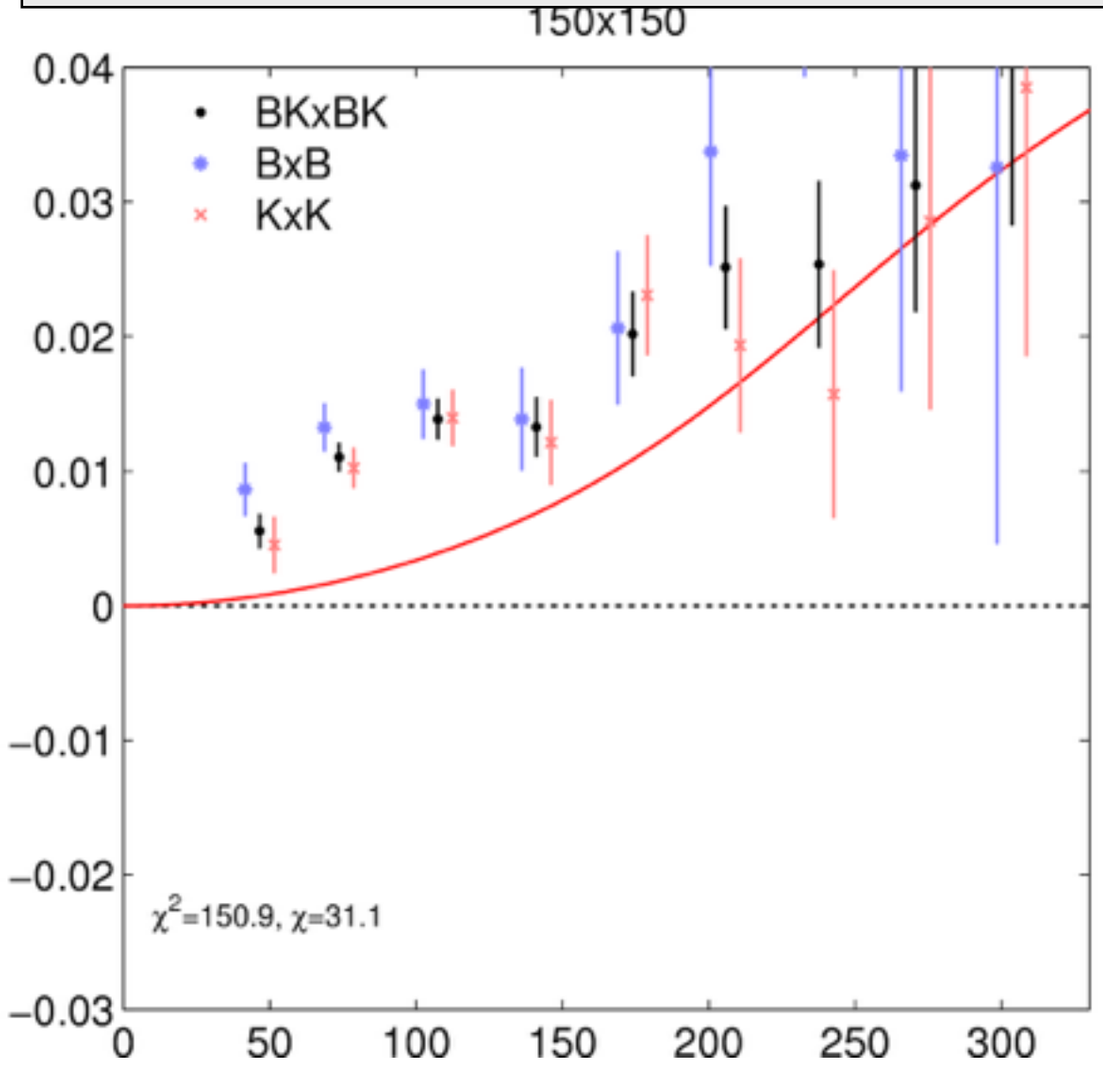
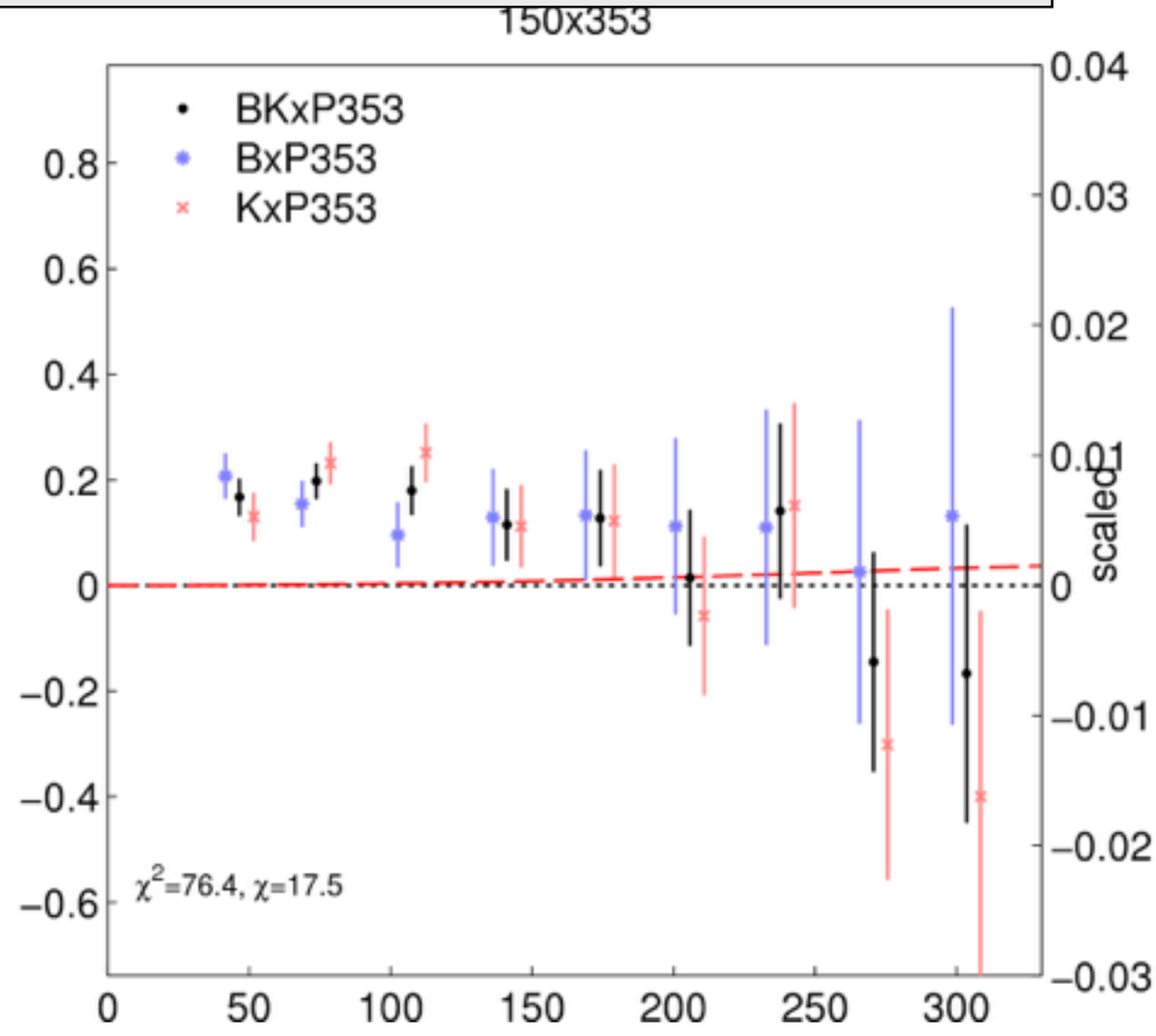


Planck 353GHz maps in BICEP2+Keck sky region with full simulation of observation and filtering applied plus apodization



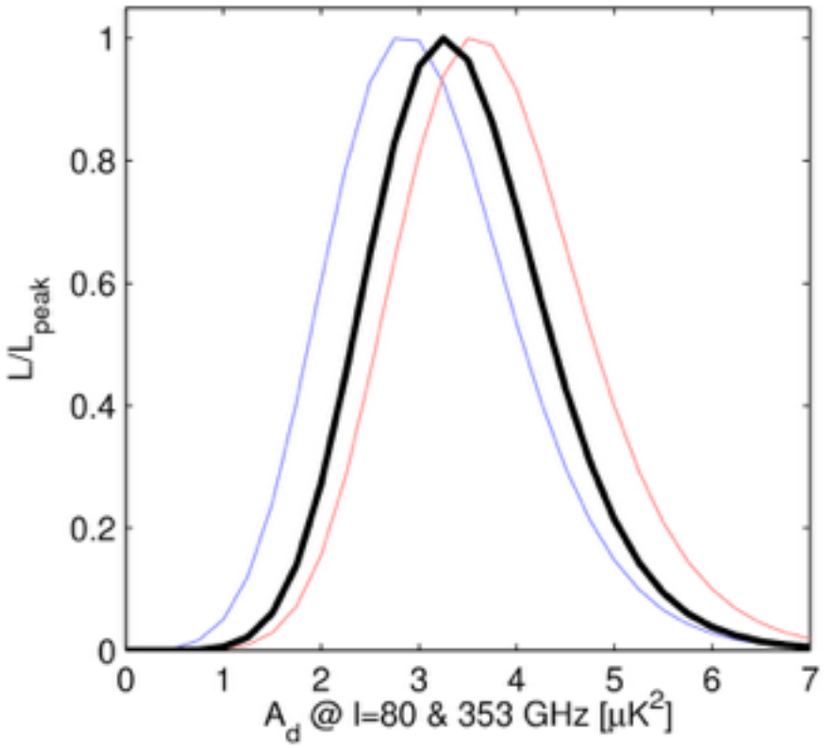
BB Spectra

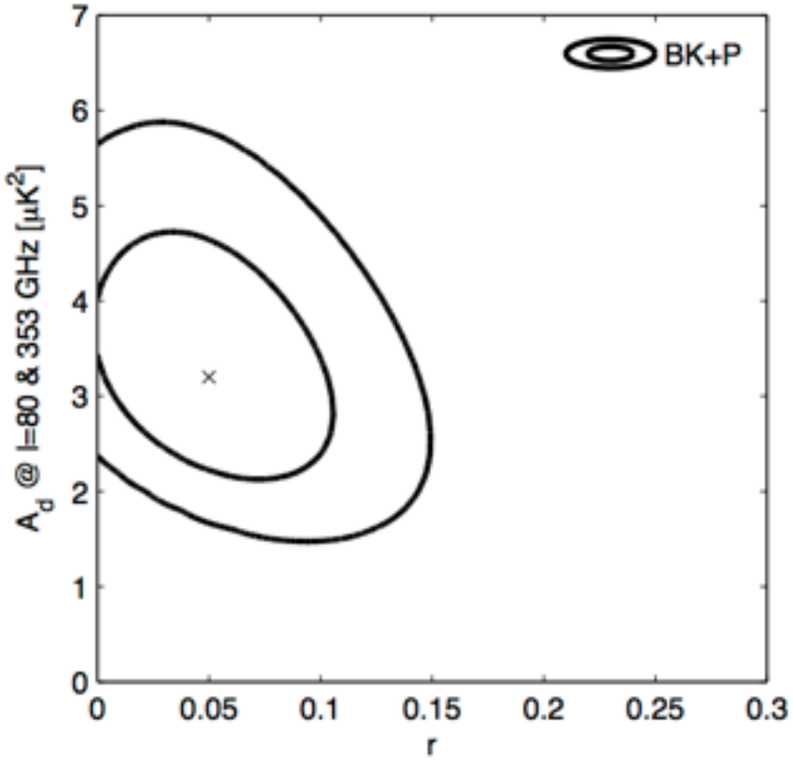


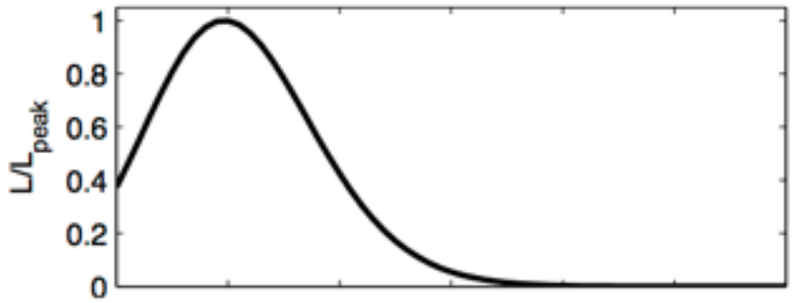


- Correlation of 150 GHz and 353 GHz B-modes is detected with high signal-to-noise.
- Scaling the cross-frequency spectrum by the expected brightness ratio (x25) of dust (right y-axis) indicates that dust contribution is comparable in magnitude to BICEP2+Keck excess over ΛCDM.

Multi-component multi-spectral likelihood analysis

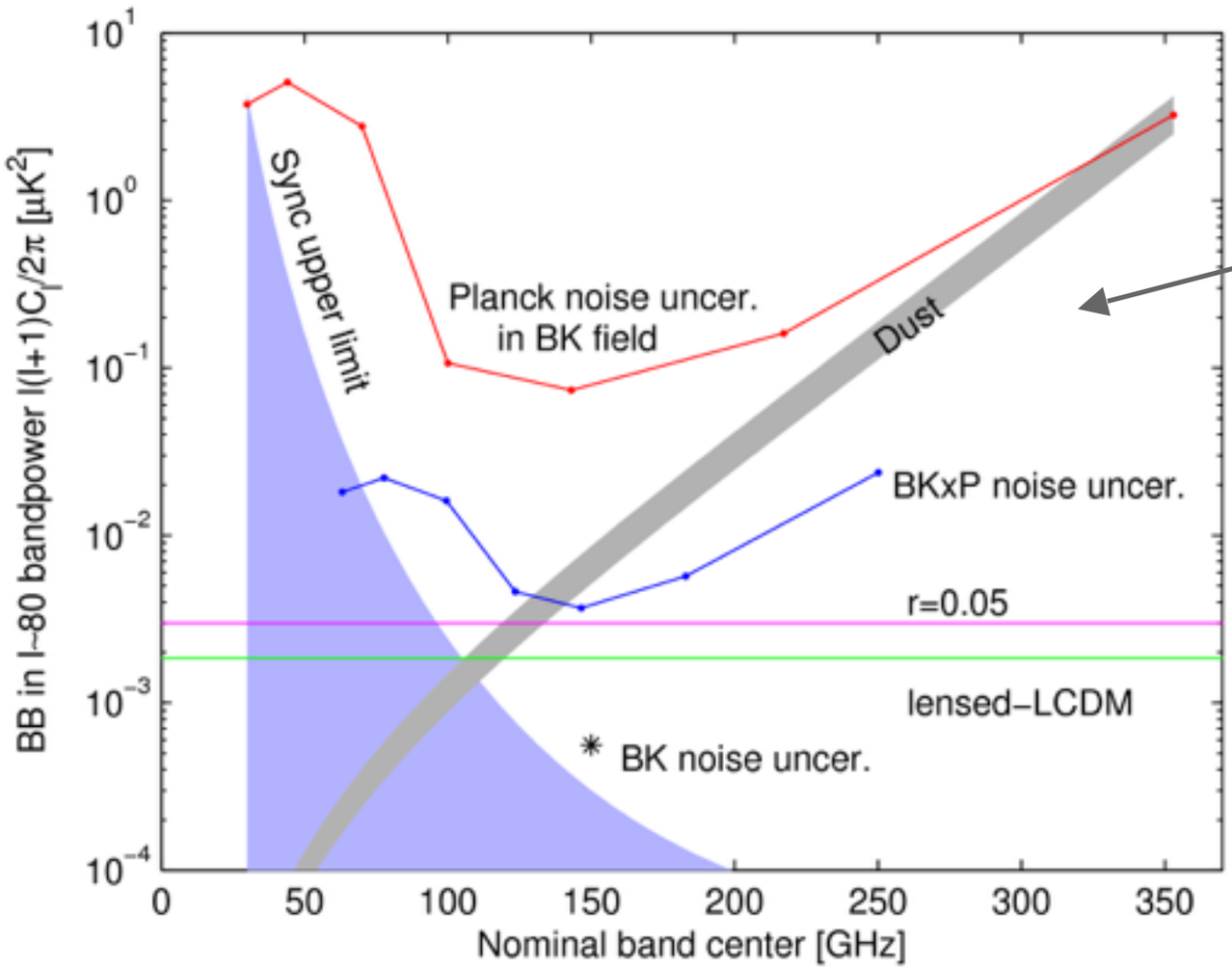






- Use single- and cross-frequency spectra between BK 150 GHz and Planck 217 & 353 GHz channels.
- Vary *r* and amplitude of dust, A_d
- Dust is detected with 5.1 σ significance
- *r* likelihood peaks at 0.05 but constraint consistent with zero; r < 0.12 (95% CL)

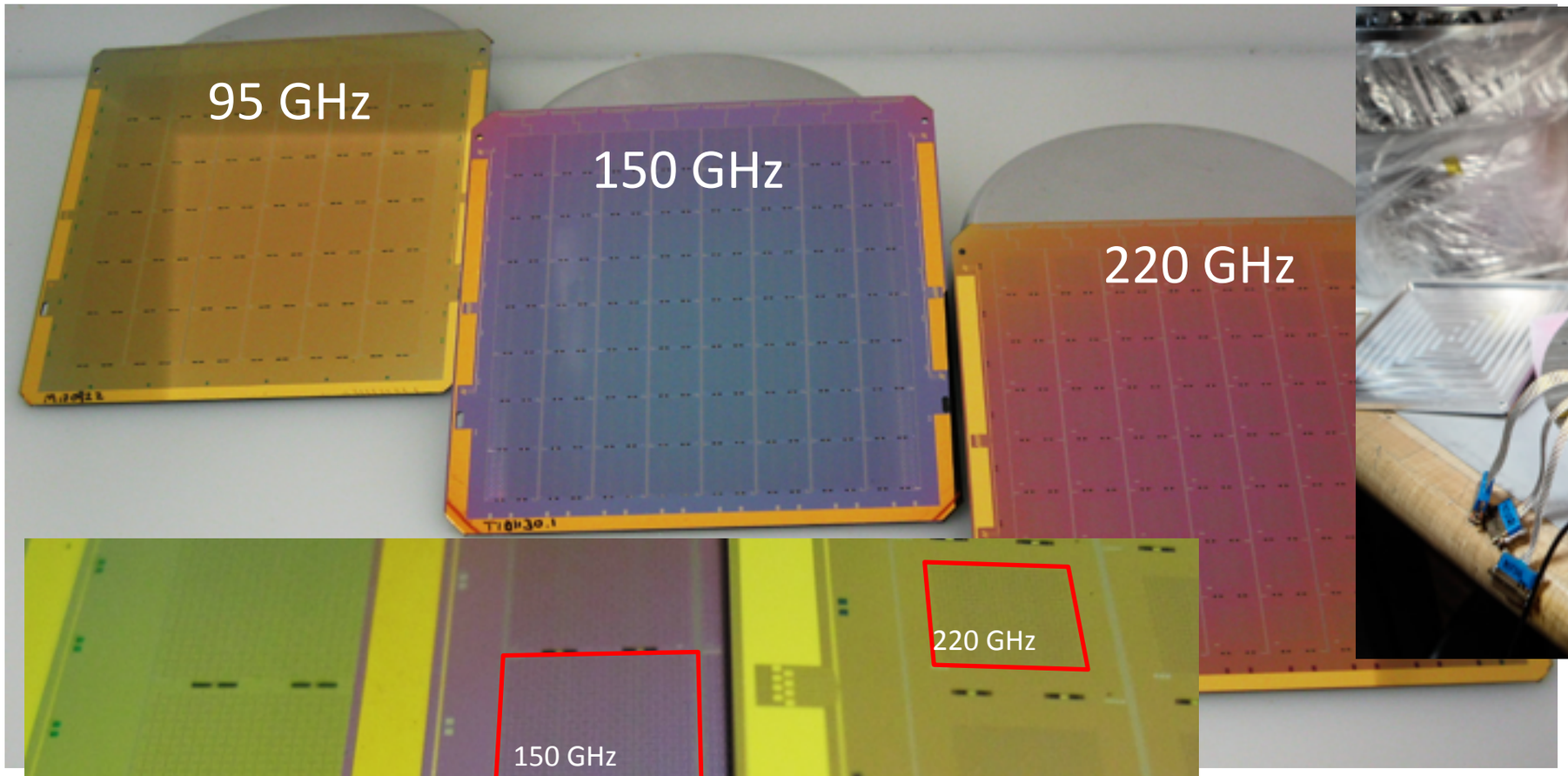
Comparison of signal levels and noise uncertainties

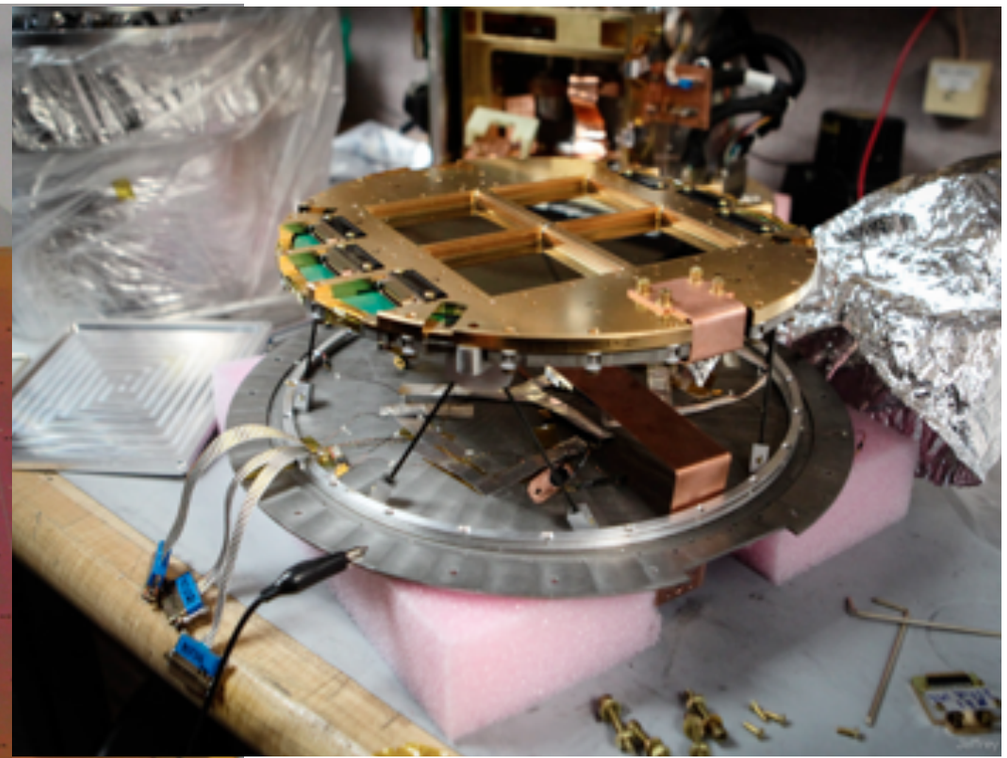


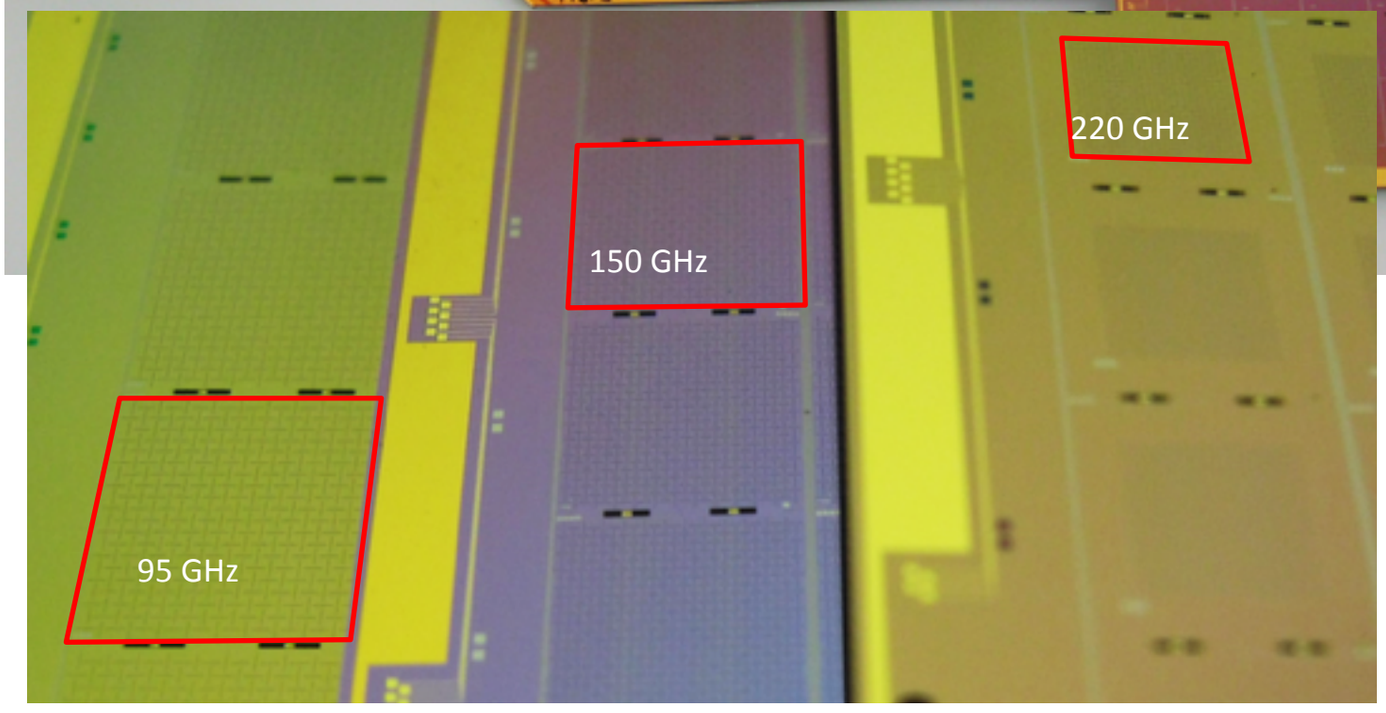
Noise uncertainty and signal levels in single ell=80 bandpower

- The BICEP2+Keck noise is lower than the Planck noise in observed patch
- The noise in the cross spectra is the geometric mean providing high sensitivity to dust for 150x353. Thus a tight constraint can be set on dust amplitude.
- **Noise in P353 is the limiting factor and to make further progress; better data at frequencies other than 150 GHz is required**

Keck 2014, 2015 multi-frequency upgrades



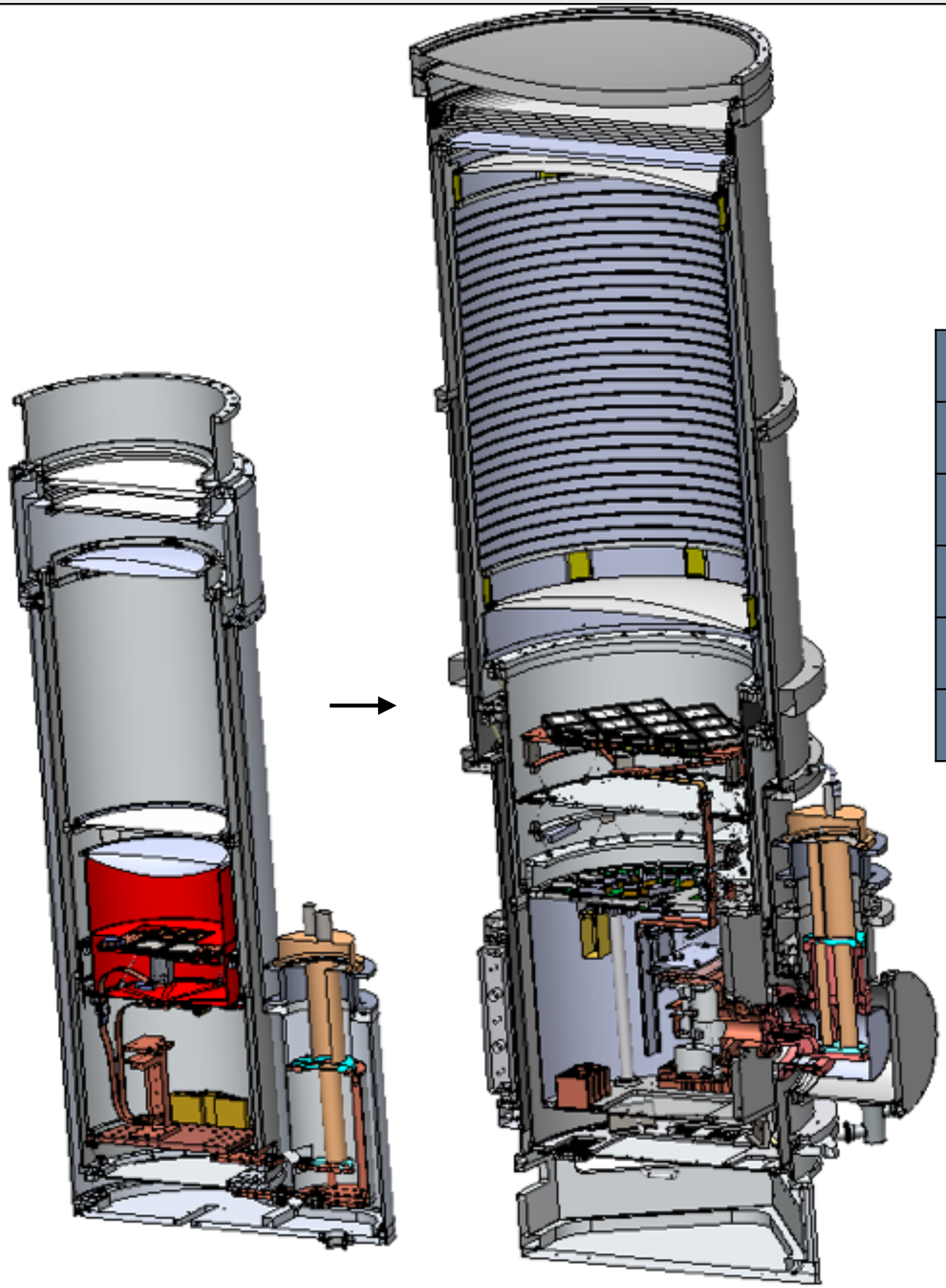




Keck now observing at multiple frequencies

- Changed 2 focal planes to 95 GHz in 2014
- Changed 2 focal planes to 220 GHz in 2015

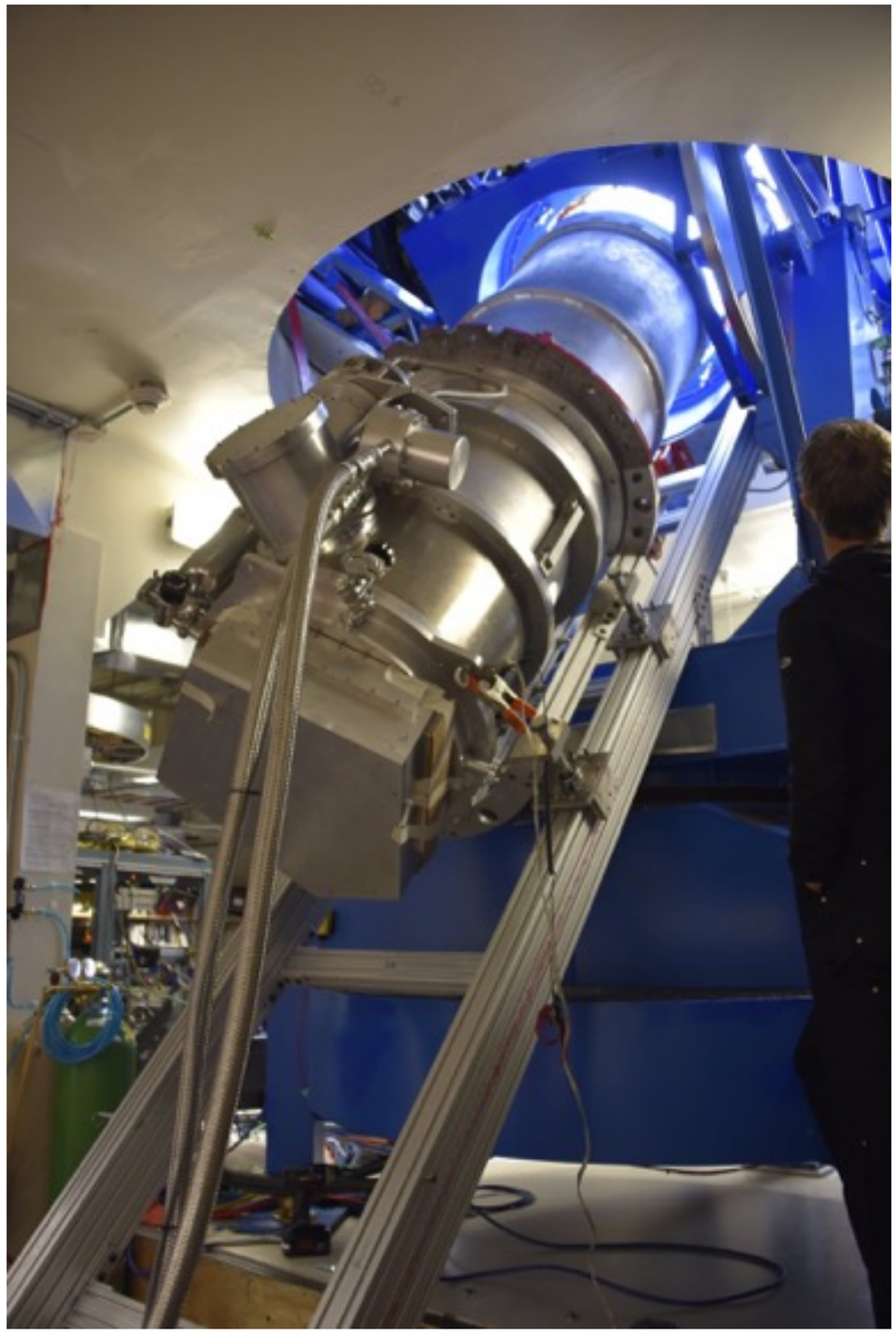
BICEP3 has 10x throughput of BICEP2/Keck

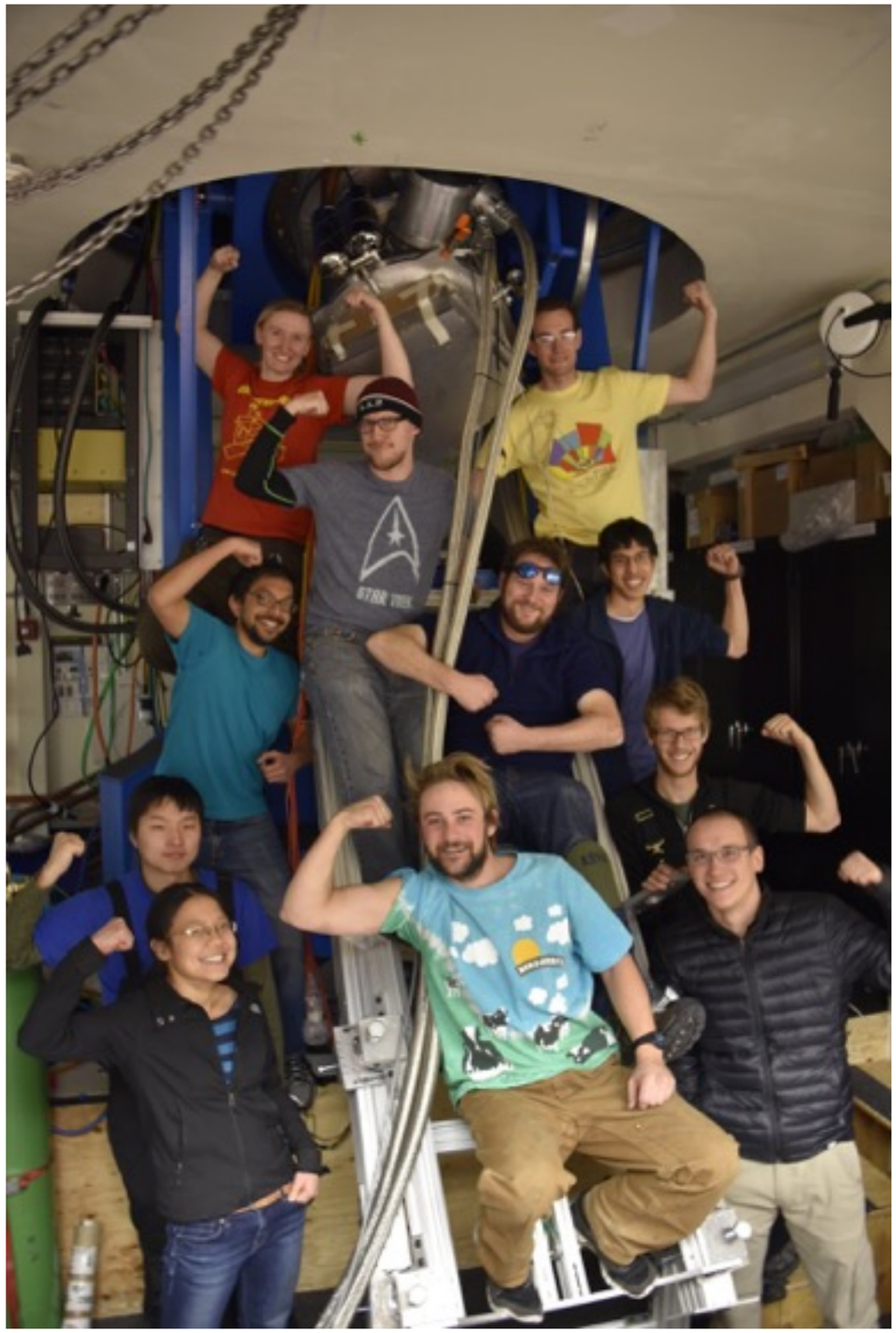


	B2/Keck	BICEP3
Aperture	260mm	680mm
Optics	f/2.4	f/1.6
FOV	18 deg	28 deg
Beams	0.7 deg	0.35 deg
Dets	288	2560

*comparisons at 95 GHz

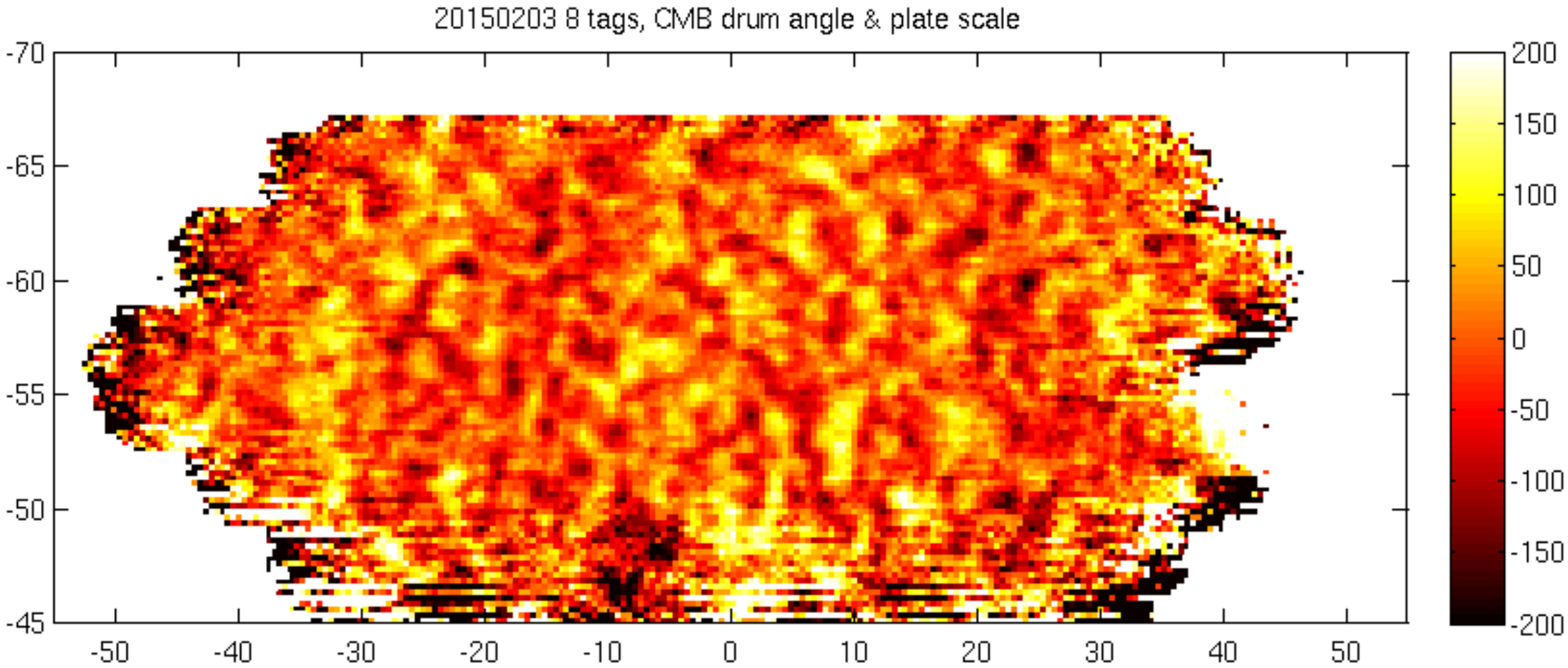
January 2015: Installed in BICEP mount





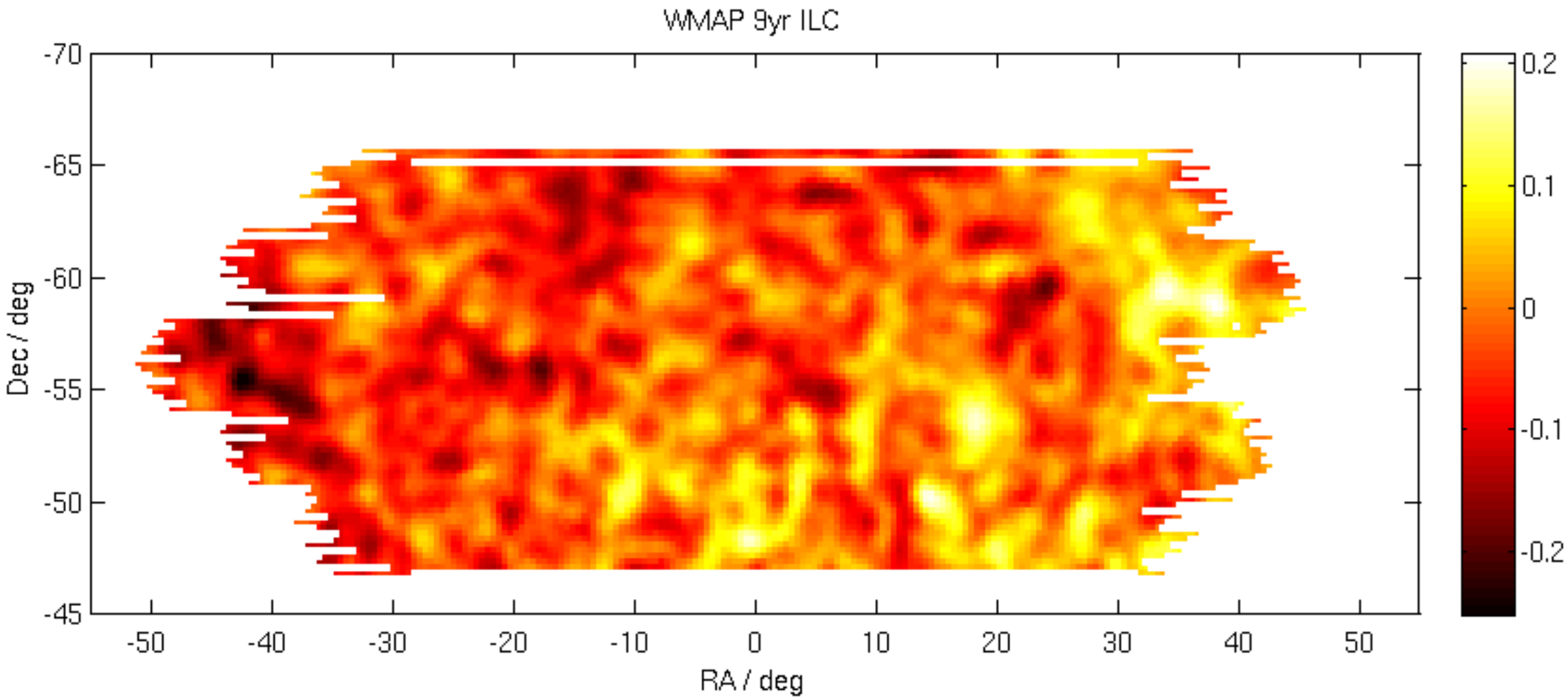
Replaces BICEP2 in Dark Sector Lab at South Pole

First light: See CMB T anisotropies in 6 hours!



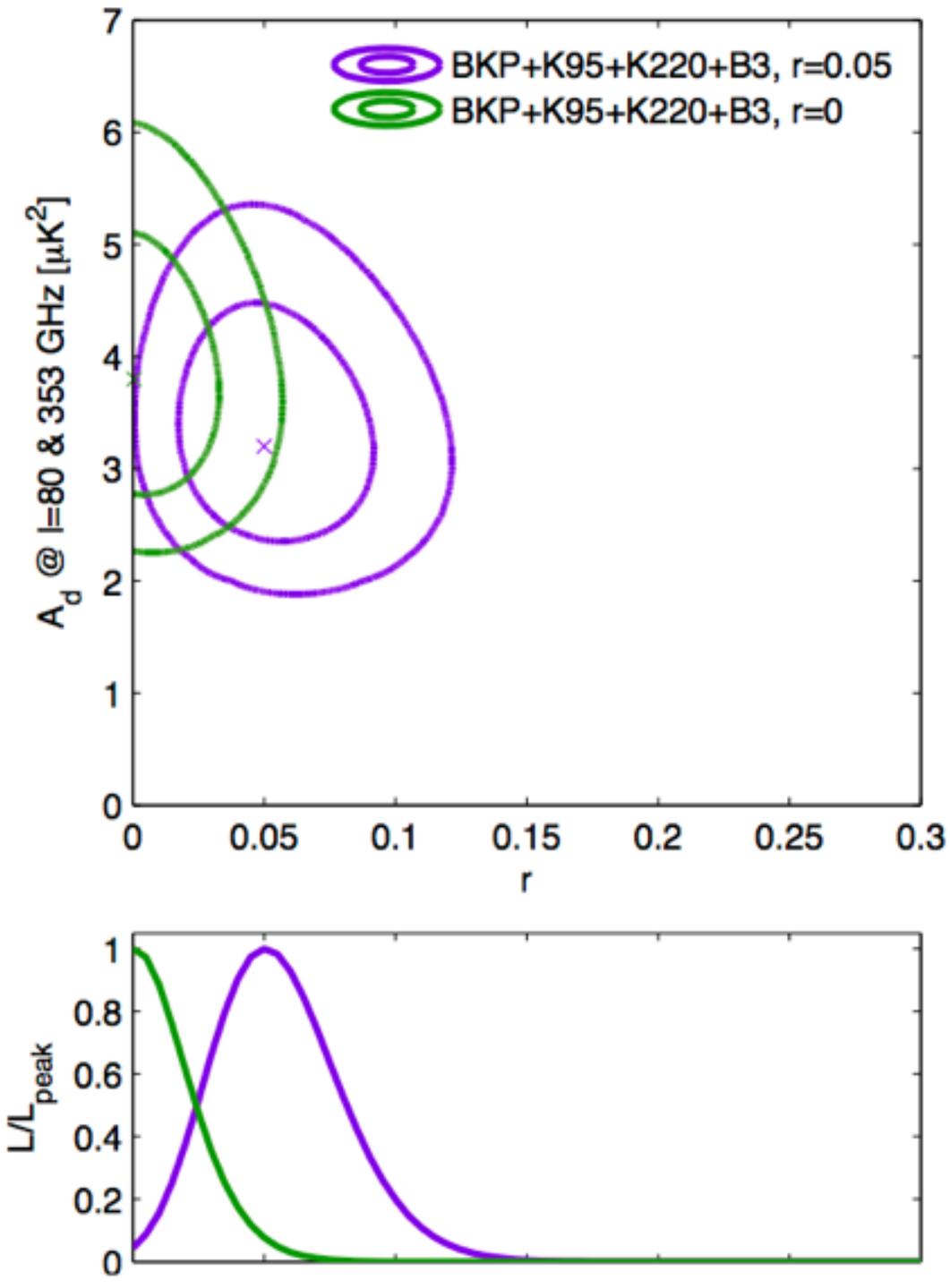
BICEP3 first six hours of test CMB scans,
no filtering, approximate noise weighting and calibration

First light: Compare with WMAP 9 yr



WMAP 9yr T anisotropies as seen in BICEP field

Likelihood forecast for BKP through 2015



Data Included:

- BK150 GHz (through 2013)
- Planck 30 - 353 GHz
- BK 95 GHz, 220 GHz (through 2015)

Contours are projected likelihood contours centered on different expectation values:

$r = 0.05, A_d = 3.3\ \mu K^2_{CMB}$ (BKP ML point)

$r = 0, \quad A_d = 3.8\ \mu K^2_{CMB}$

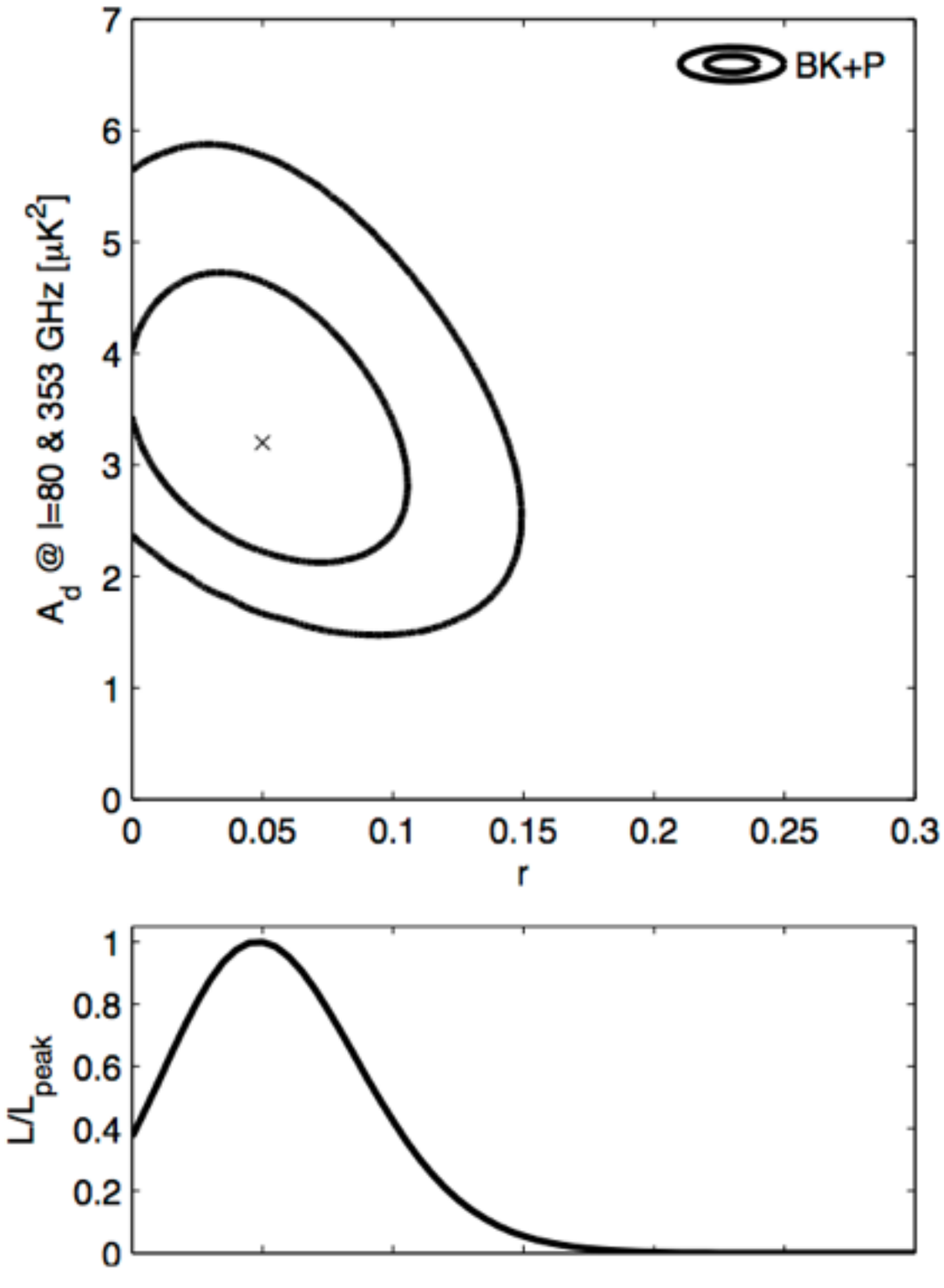
Both cases here assume synchrotron contribution, β_s=-3.3 and A_{sync} = 3e-4 μK^2_{CMB} (current BKP 95% upper limit).

Foregrounds only PTE = 0.6%

— or —

r < 0.041 (95%)

BKP through 2013



Data Included:

- BK150 GHz (through 2013)
- Planck 217 and 353 GHz

Likelihood results from a basic lensed-ΛCDM+r +dust model, fitting the 5 lowest bandpowers of the BB auto- and cross-spectra taken between maps at the above frequencies.

The Maximum likelihood on the grid has:

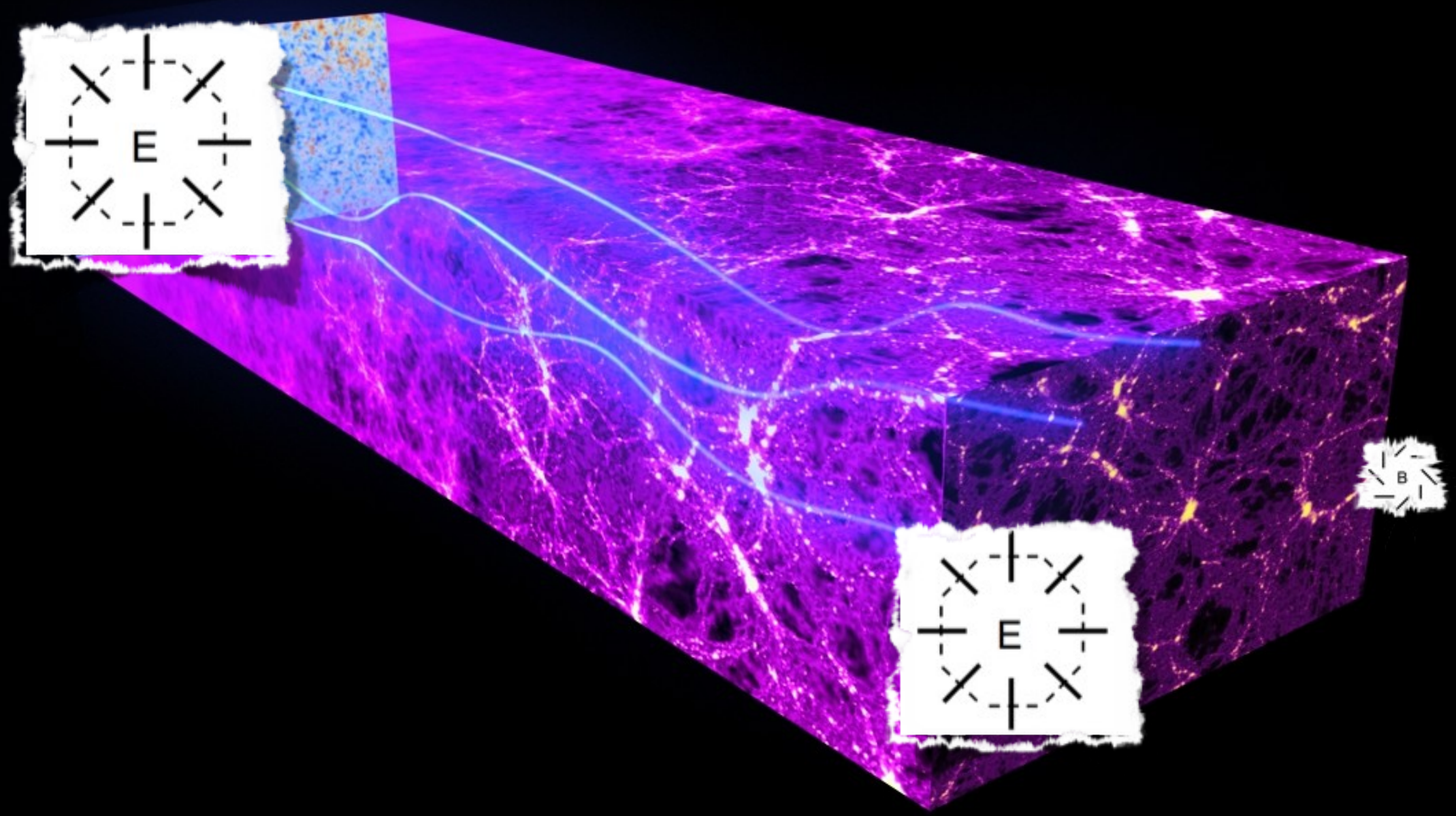
$r = 0.05, A_d = 3.3\ \mu K^2_{CMB}$ (BKP ML point)

For dust SED use modified blackbody model and marginalize over range $\beta_d = 1.59 \pm 0.11$

We assume no synchrotron contribution here.

Foregrounds only PTE = 8.0%

Lensing the *Polarization* of the CMB



ESA

Gravitational Lensing of CMB

$$X(\hat{\mathbf{n}}) = \tilde{X}(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}}))$$

Observed T, Q, or U

Unobservable “true” T, Q, or U

Projected Lensing Potential

Hu & Okamoto 2002

$\mathrm{T}(\hat{n})\ (\pm 350\mu K)$

Duncan Hanson

$\mathrm{E}(\hat{n})\ (\pm 25\mu K)$

$\mathrm{B}(\hat{n})\ (\pm 2.5\mu K)$

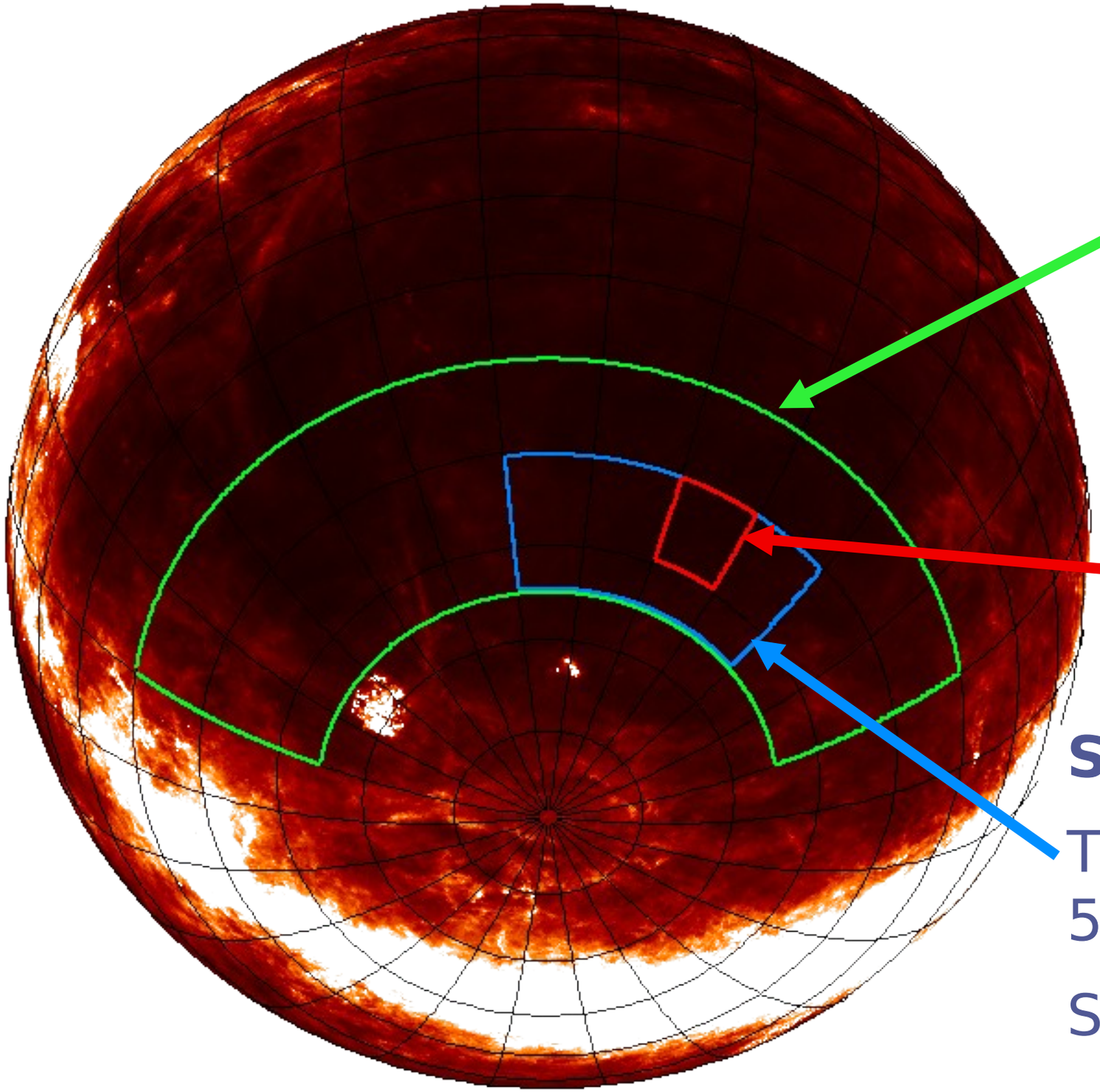
$\mathrm{T}(\hat{n})\ (\pm 350\mu K)$

Duncan Hanson

$\mathrm{E}(\hat{n})\ (\pm 25\mu K)$

$\mathrm{B}(\hat{n})\ (\pm 2.5\mu K)$

SPTpol fields: Deep & Survey



SPT-SZ

Entire survey,
2500 deg²

Deep Field

First year,
100 deg²

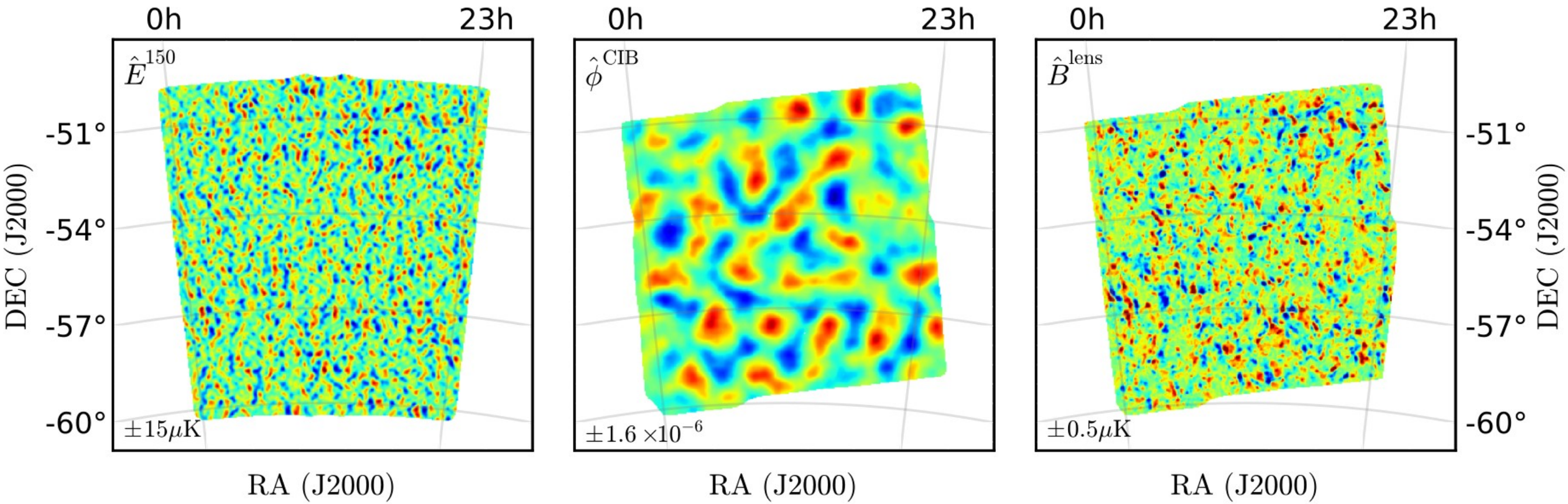
Survey Field

Three years,
500 deg²

Same as BICEP

IRAS from Schlegel et al. 1998

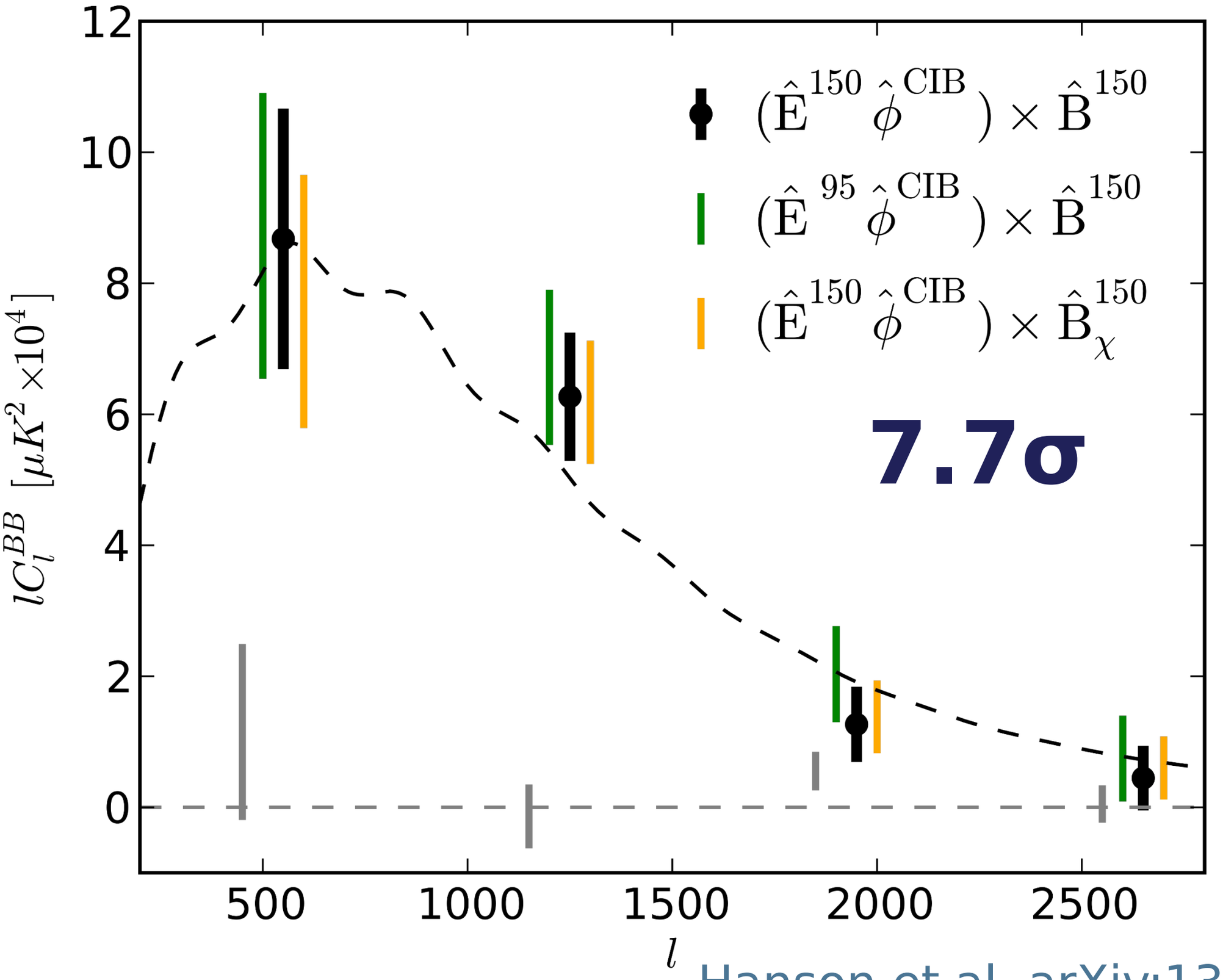
Detection of B-mode Polarization in the Cosmic Microwave Background with Data from the South Pole Telescope



E-modes from SPTpol + Φ-modes from Herschel/SPIRE → Synthesized lensing B-mode template.

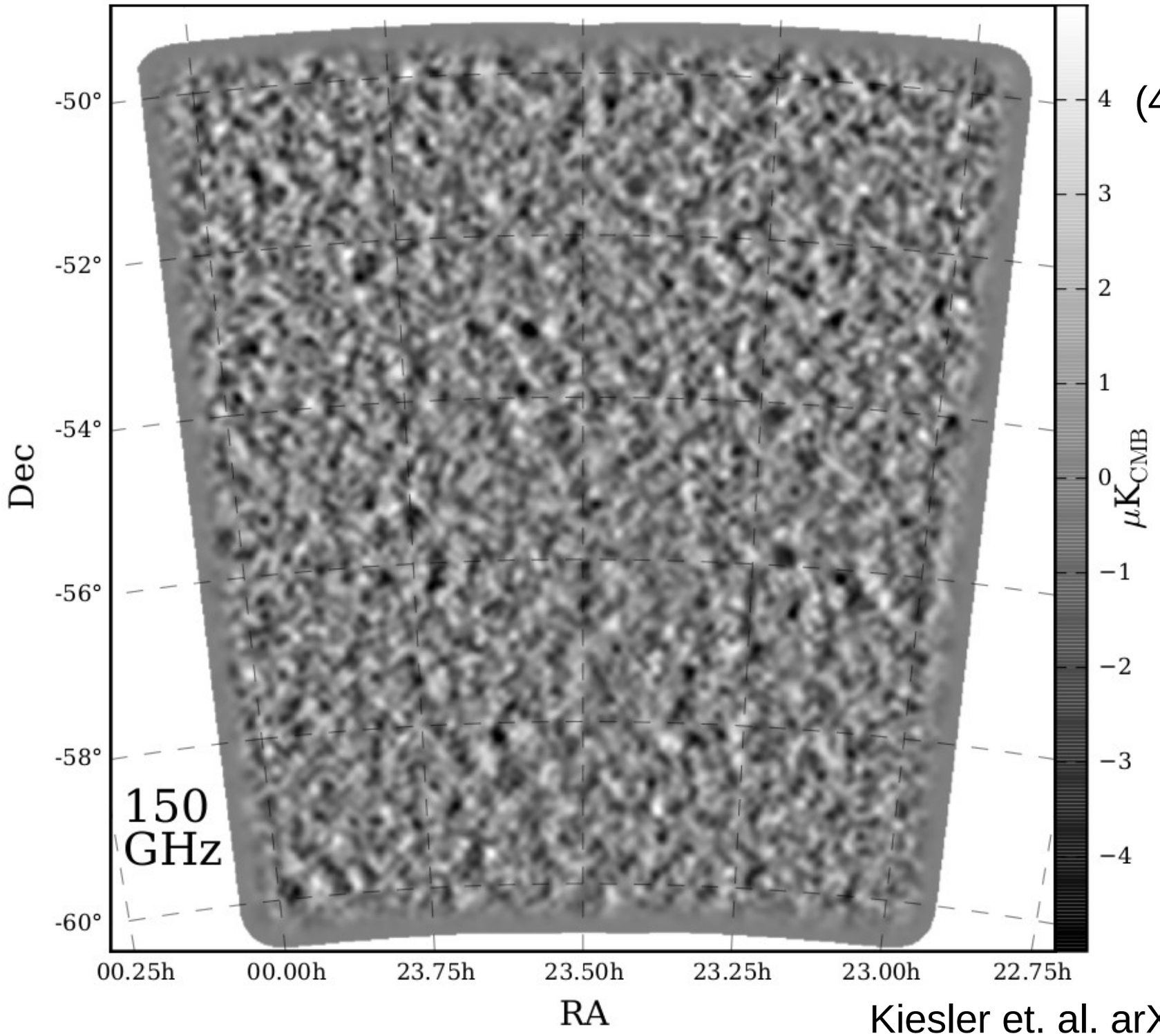
Hanson, et al., 2013
arXiv: 1307.5830

First Lensed B-mode detection



Hanson et al. arXiv:1307.5830

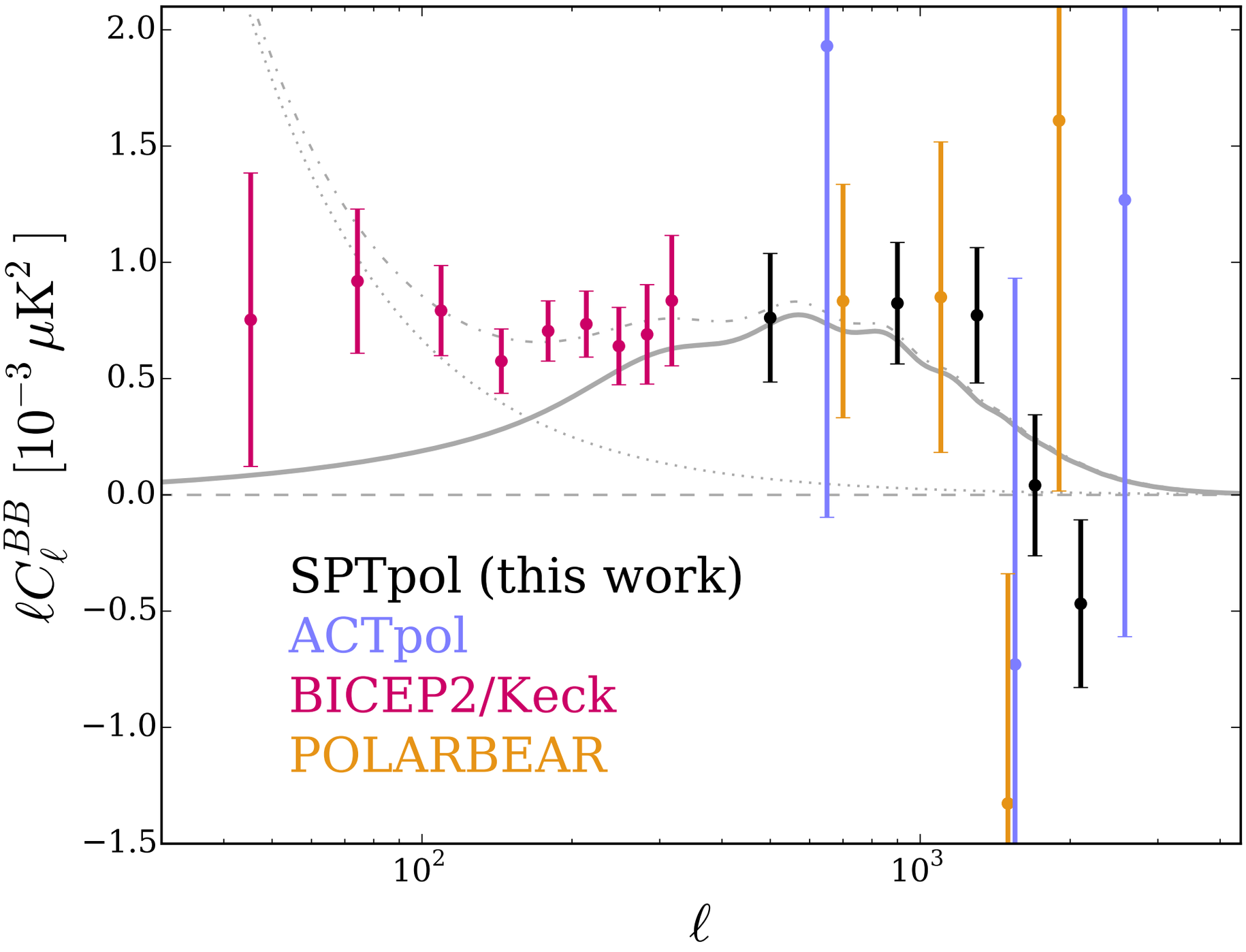
SPTpol 100 deg² B Modes



(4x smaller scale)

Kiesler et. al. arXiv:1503.02315

SPTPol BB Power spectrum



Keisler et al (2015)

Lensing Potential Reconstruction

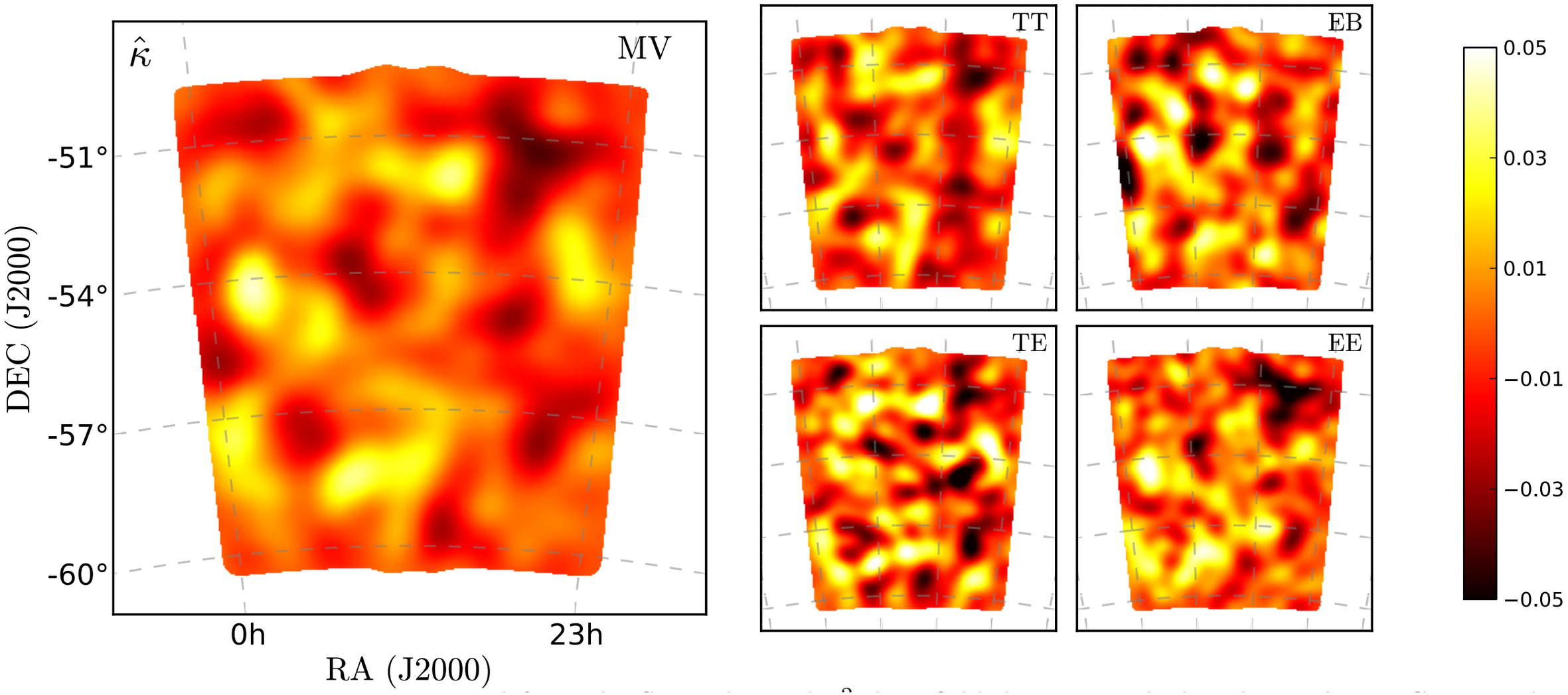
$$\bar{\phi}^{XY}_{\mathbf{L}} = \int d^2\boldsymbol{\ell}' W^{XY}_{\boldsymbol{\ell}',\boldsymbol{\ell}'-\mathbf{L}} \bar{X}_{\boldsymbol{\ell}'} \bar{Y}^{*}_{\boldsymbol{\ell}'-\mathbf{L}}$$

T, E, or B

The estimated lensing potential is a weighted average of a product of T, E, or B modes

Hu & Okamoto 2002

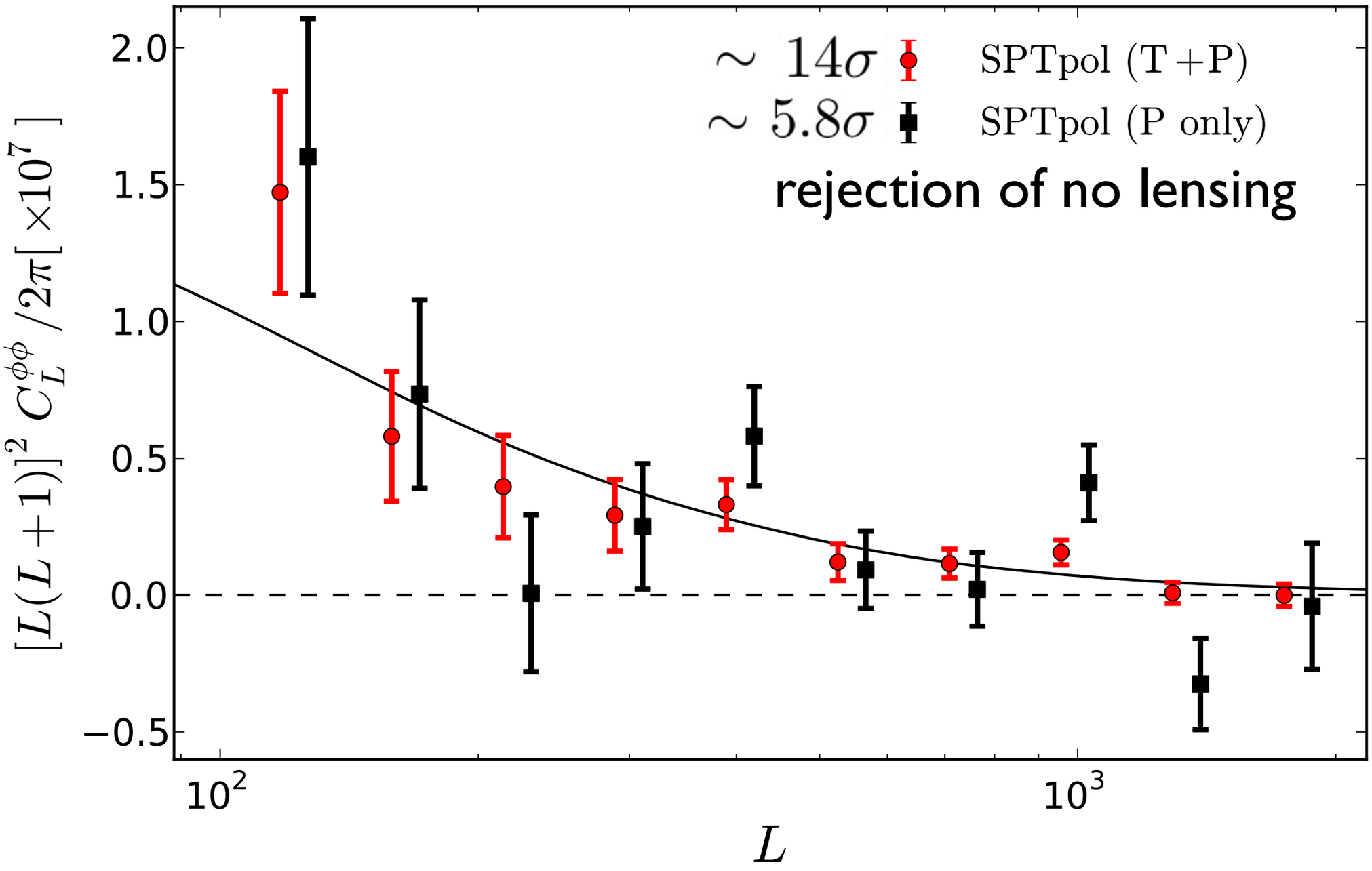
Lensing Convergence Map Reconstruction



All smoothed with ~1deg Gaussian to show only S/N>1 modes

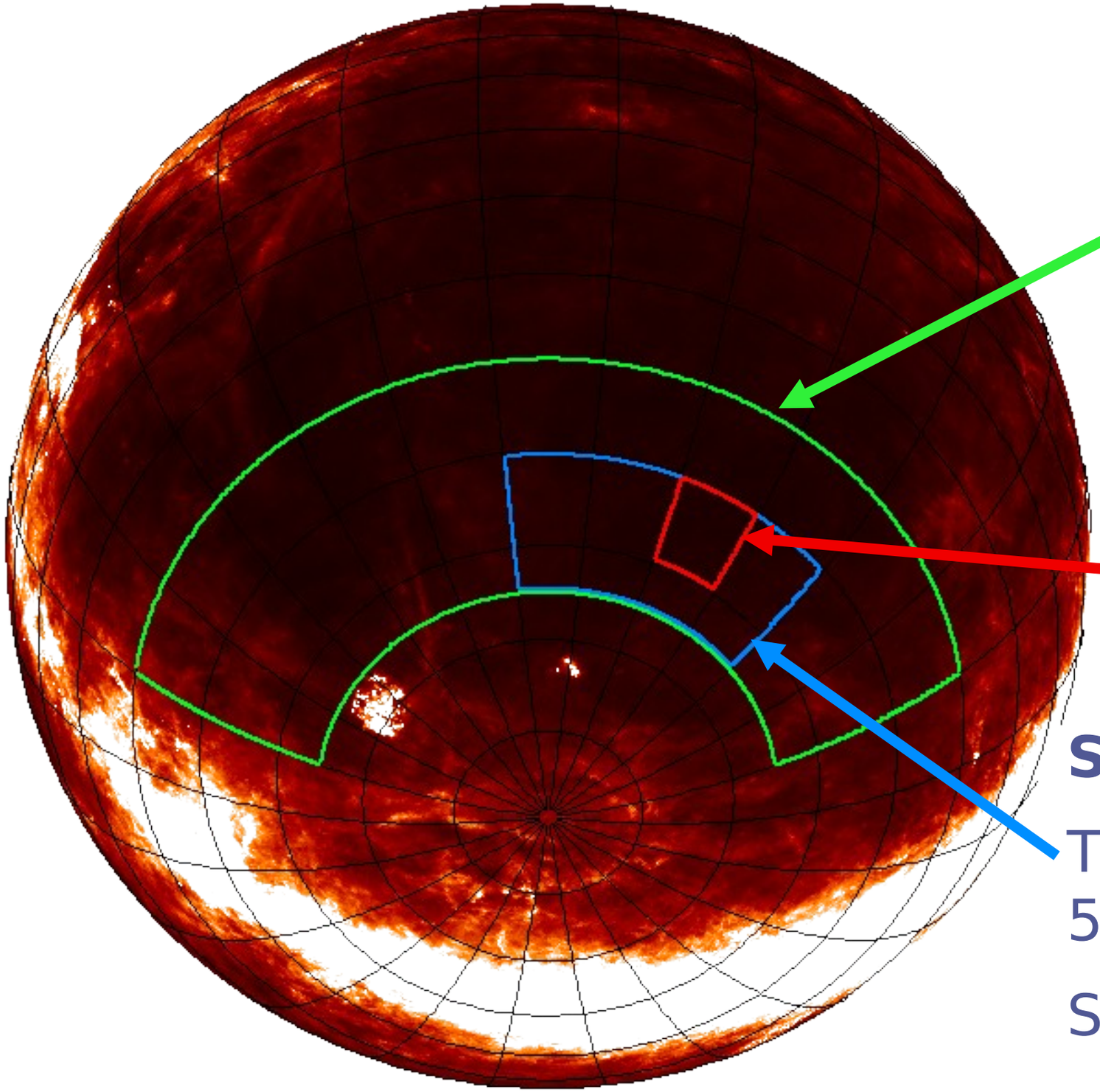
Story et al

SPTpol Lensing Power Spectrum



Story et al (2014)

SPTpol fields: Deep & Survey



SPT-SZ

Entire survey,
2500 deg²

Deep Field

First year,
100 deg²

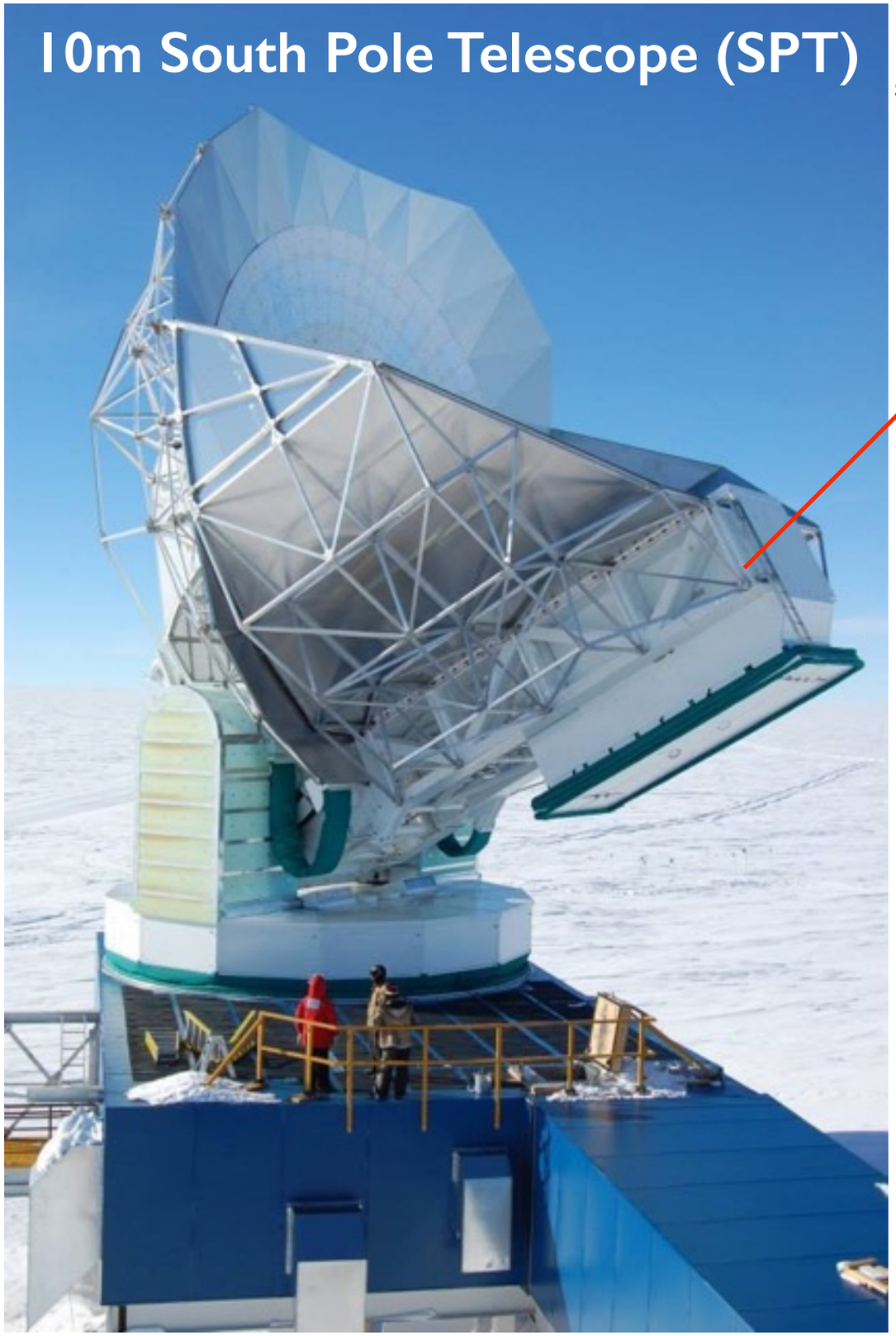
Survey Field

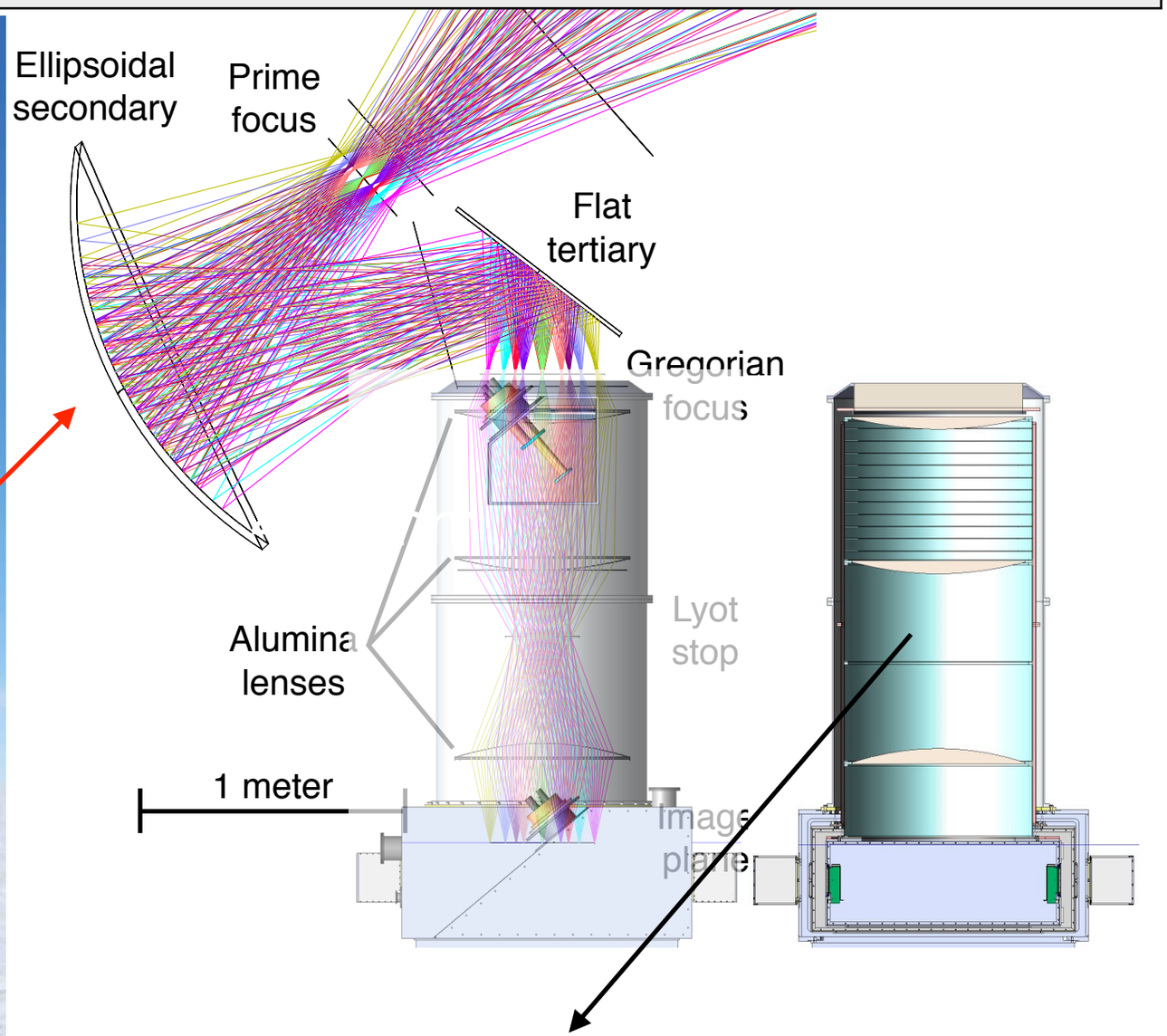
Three years,
500 deg²

Same as BICEP

IRAS from Schlegel et al. 1998

SPT-3G

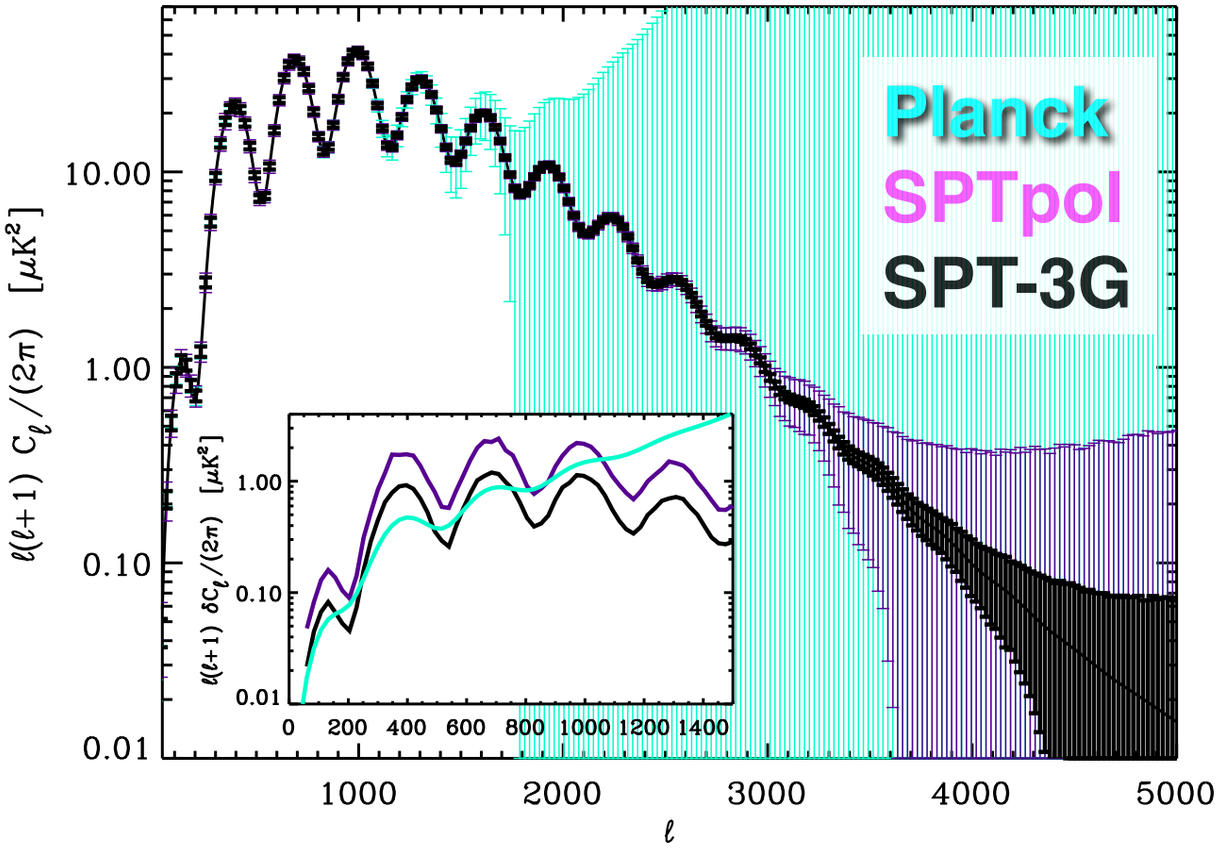




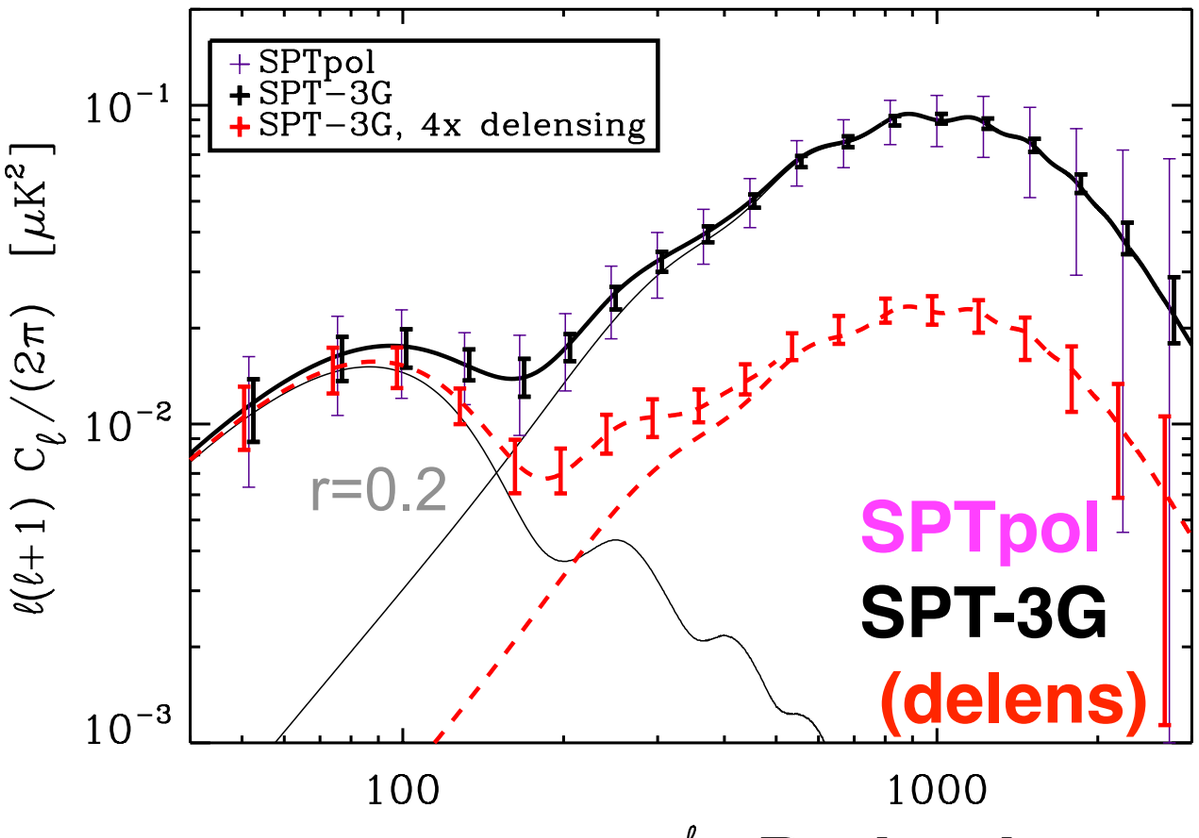
- Next gen upgrade, SPT-3G (2017)
- New secondary mirror and receiver
- 2700 multi-color camera pixels

SPT-3G projections

EE-Spectrum



BB-Spectrum



- Expected ~150-σ detection of CMB Lensing
- 20 meV neutrino mass -> 1% shift in lensing spectrum

Projections

(w/ Planck priors)

	SPT-3G (2019)
$\sigma(N_{eff})$	**0.058**
$\sigma(\Sigma m_\nu)$	**0.061 eV***

* Includes BOSS prior

Conclusions

- South Pole one of best site for CMB polarimetry from ground
- Joint analysis of BICEP/Keck+Planck data finds dust at high significance; limit on tensor-to-scalar ratio
- Progress requires multi-frequency observation. Implemented in Keck Array and BICEP3
- SPTpol detects gravitational lensing of CMB — BB power, also demonstrated reconstruction of lensing potential with high S/N
- SPTpol 500 sq. deg survey has 3 years of data in pipeline.
- SPT-3G will tighten neutrino parameter space, and will help delens inflationary searches

Thanks for your attention!