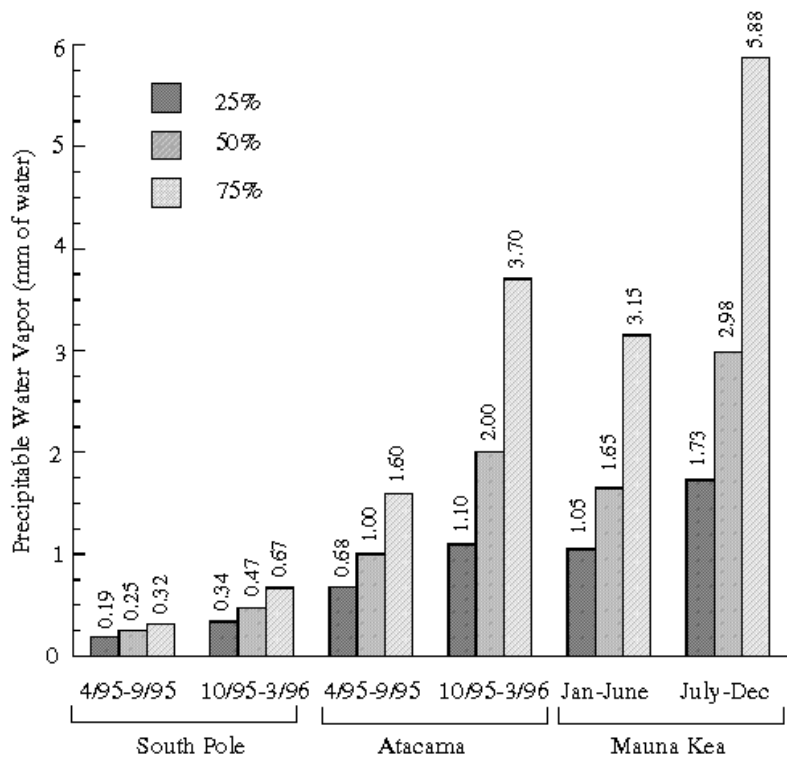
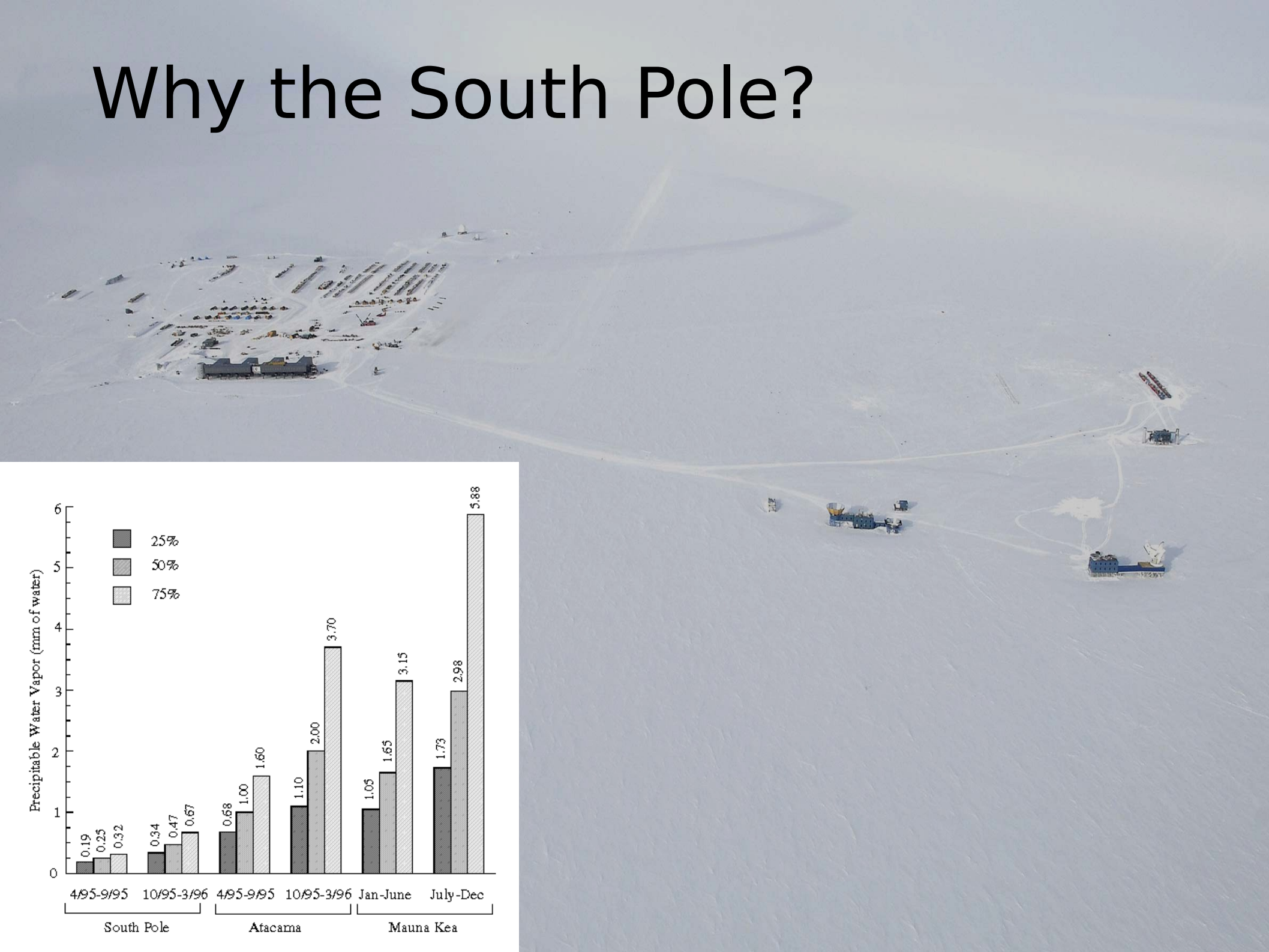


South Pole Telescope: E-Mode, B-Mode, and Gravitational Lensing Spectra



Jason Gallicchio
University of Chicago

Why the South Pole?



South Pole CMB experiments

SPT (2007-2011)

SPTpol (2012-2015)

SPT3G (2016-?)

ACBAR (2001-2005)

DASI (1999-2003)

QUAD (2004-2007)

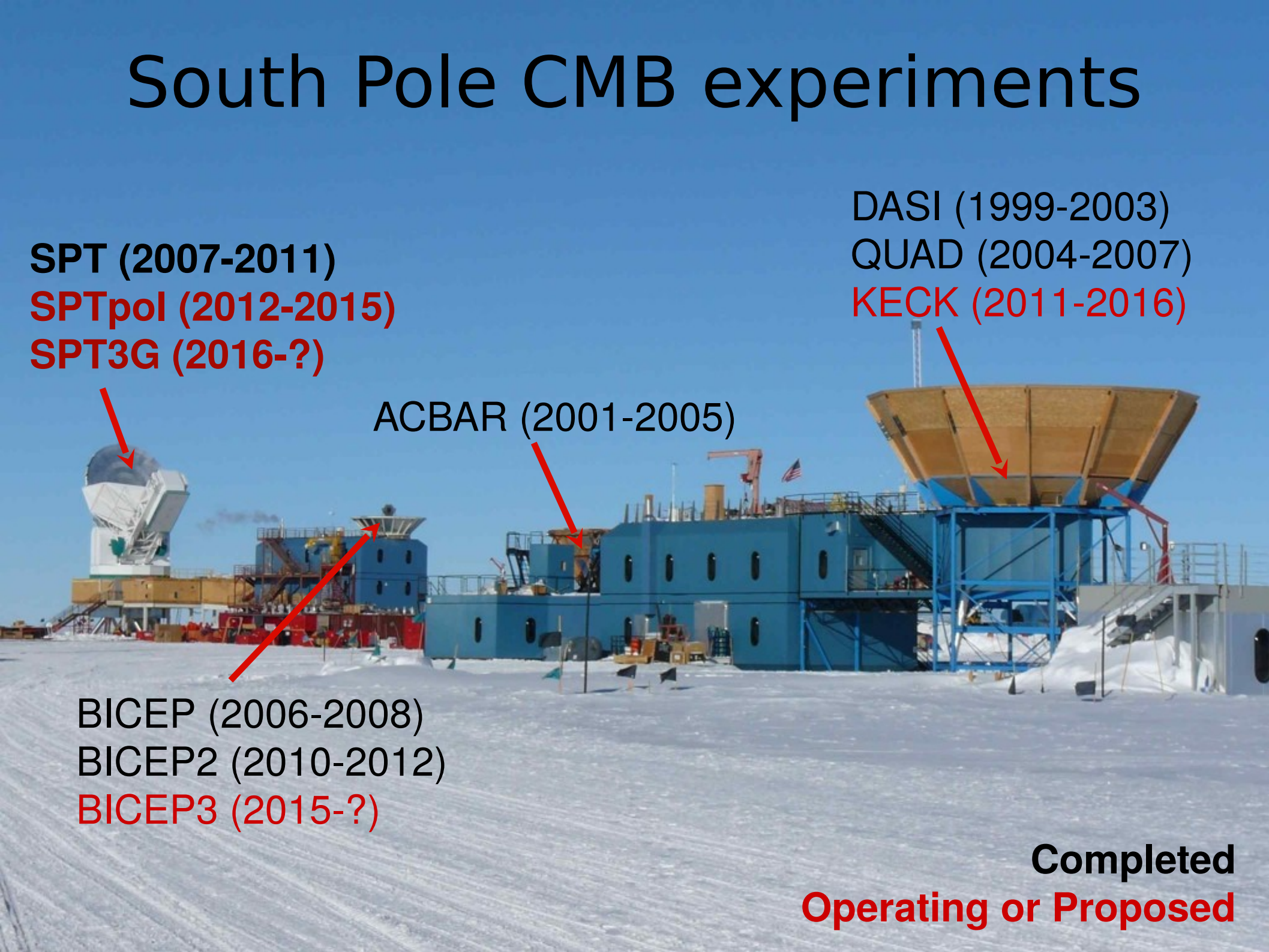
KECK (2011-2016)

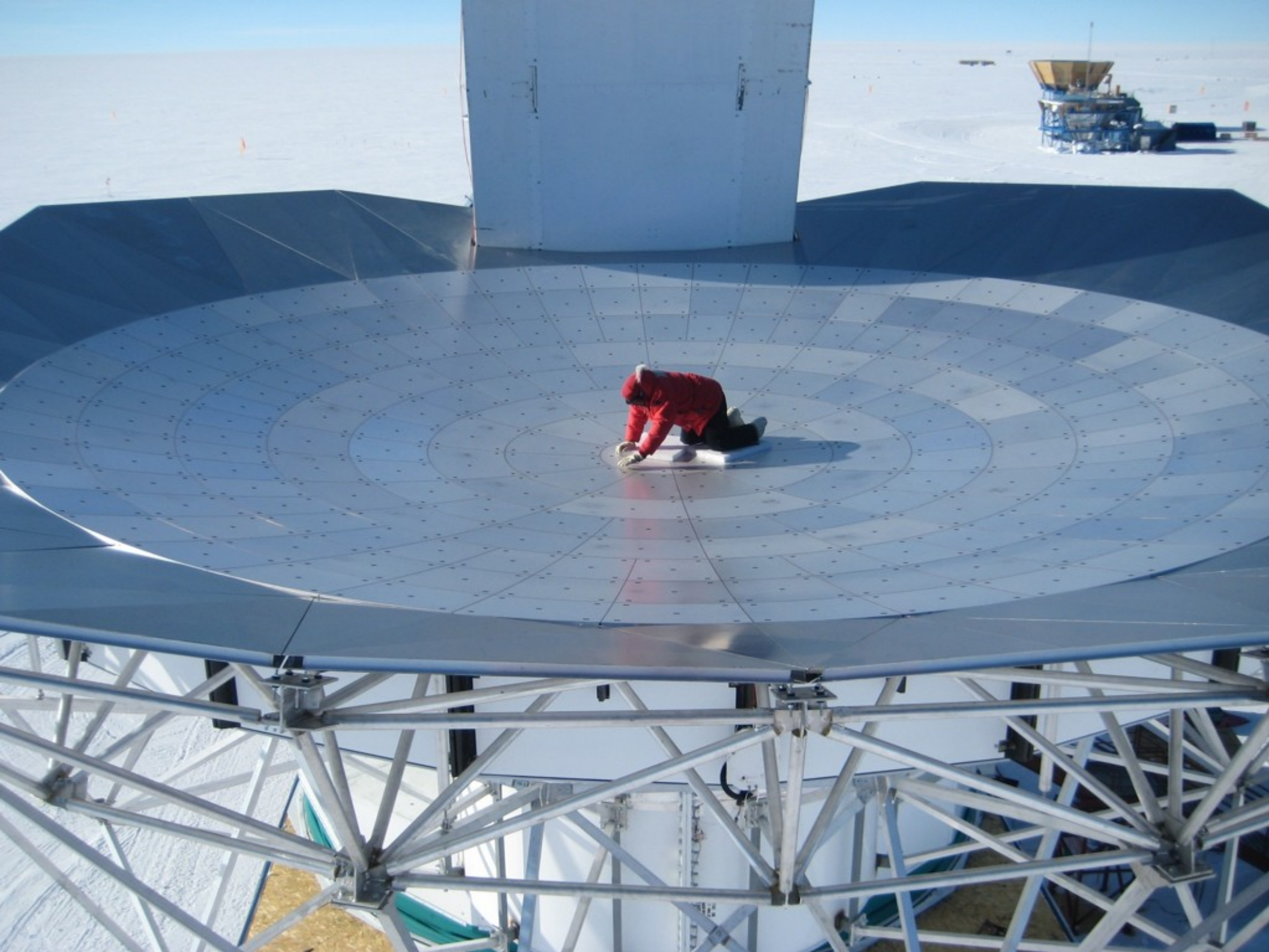
BICEP (2006-2008)

BICEP2 (2010-2012)

BICEP3 (2015-?)

Completed
Operating or Proposed

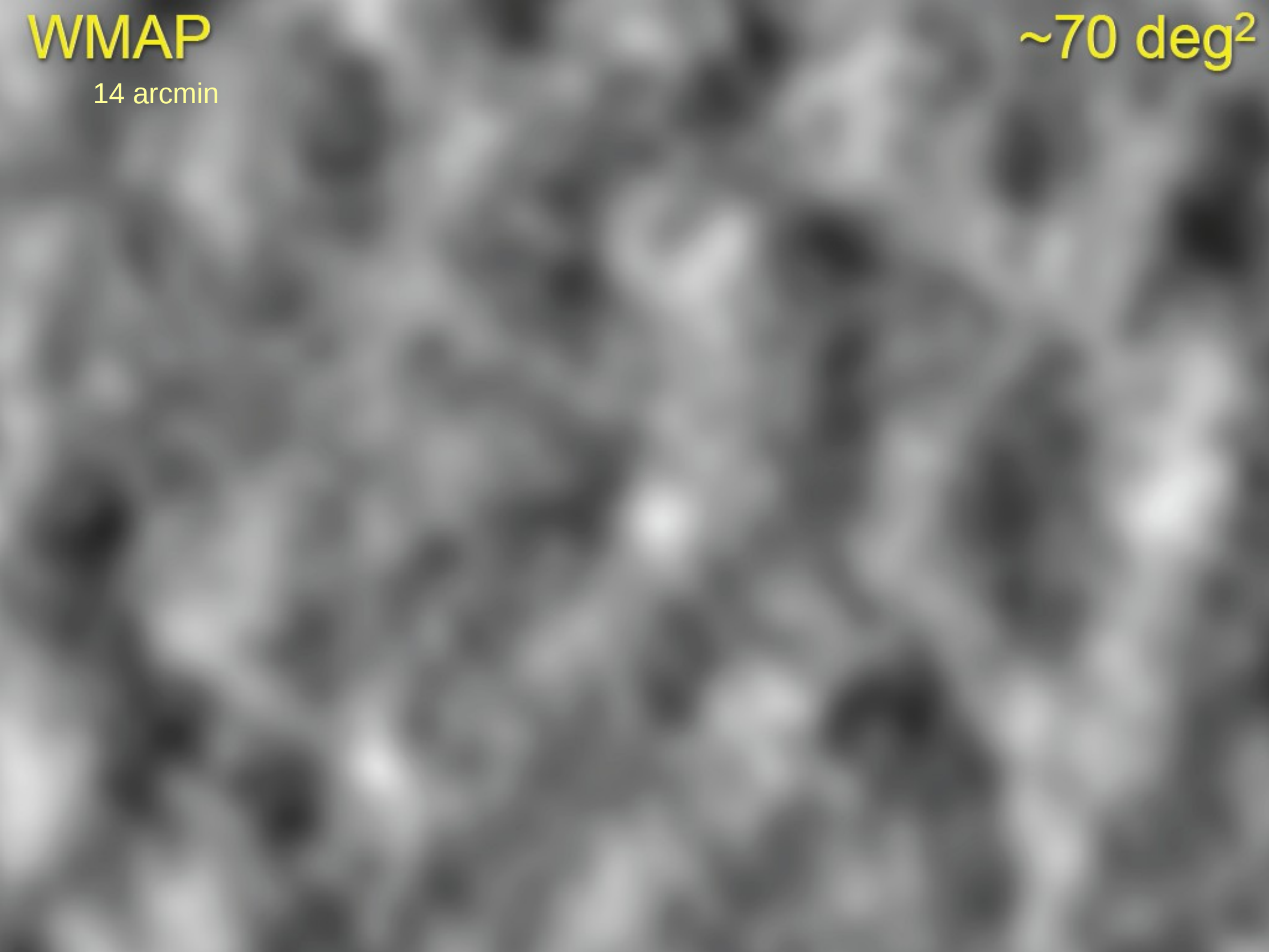




WMAP

14 arcmin

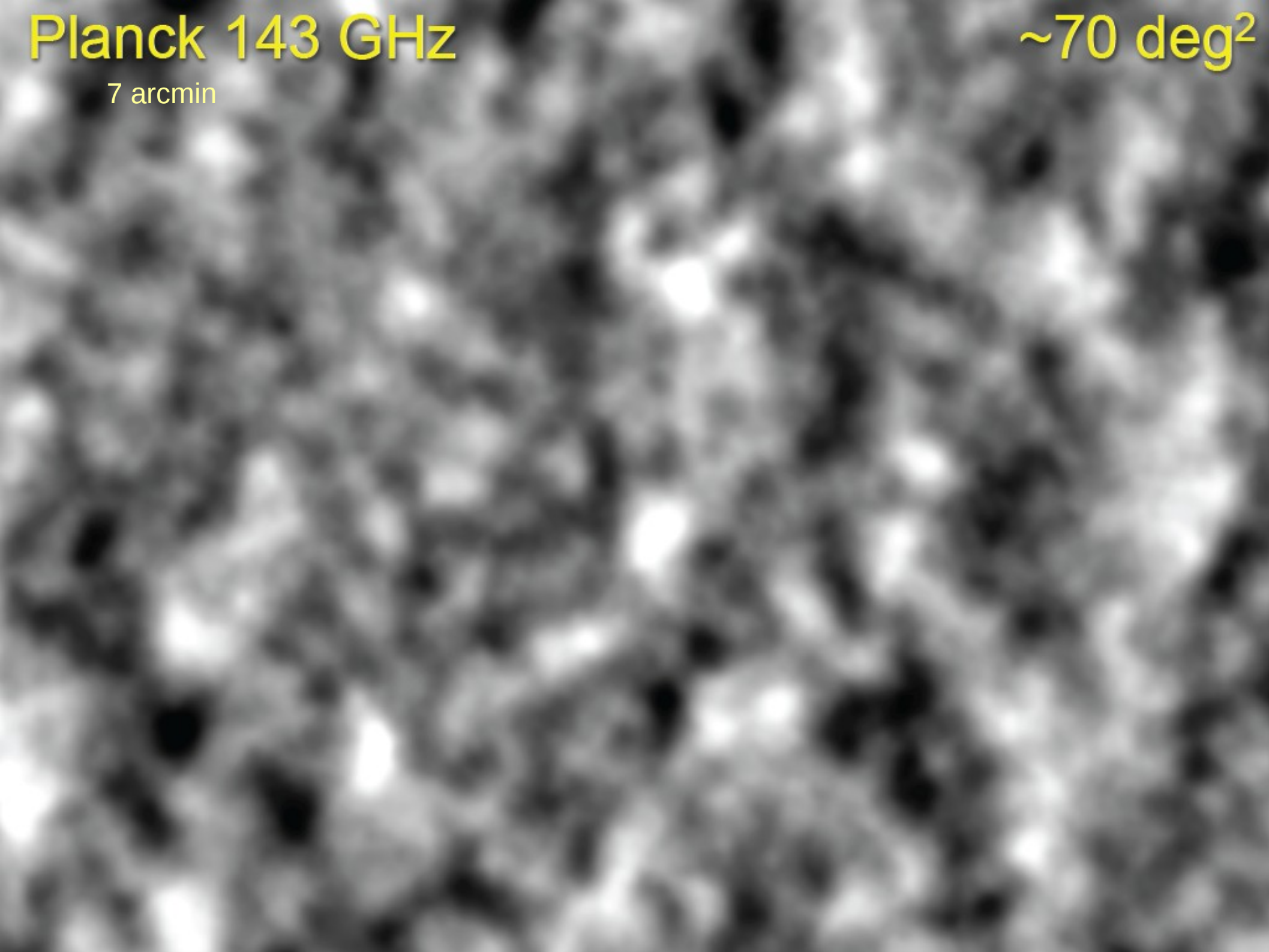
~70 deg²



Planck 143 GHz

~70 deg²

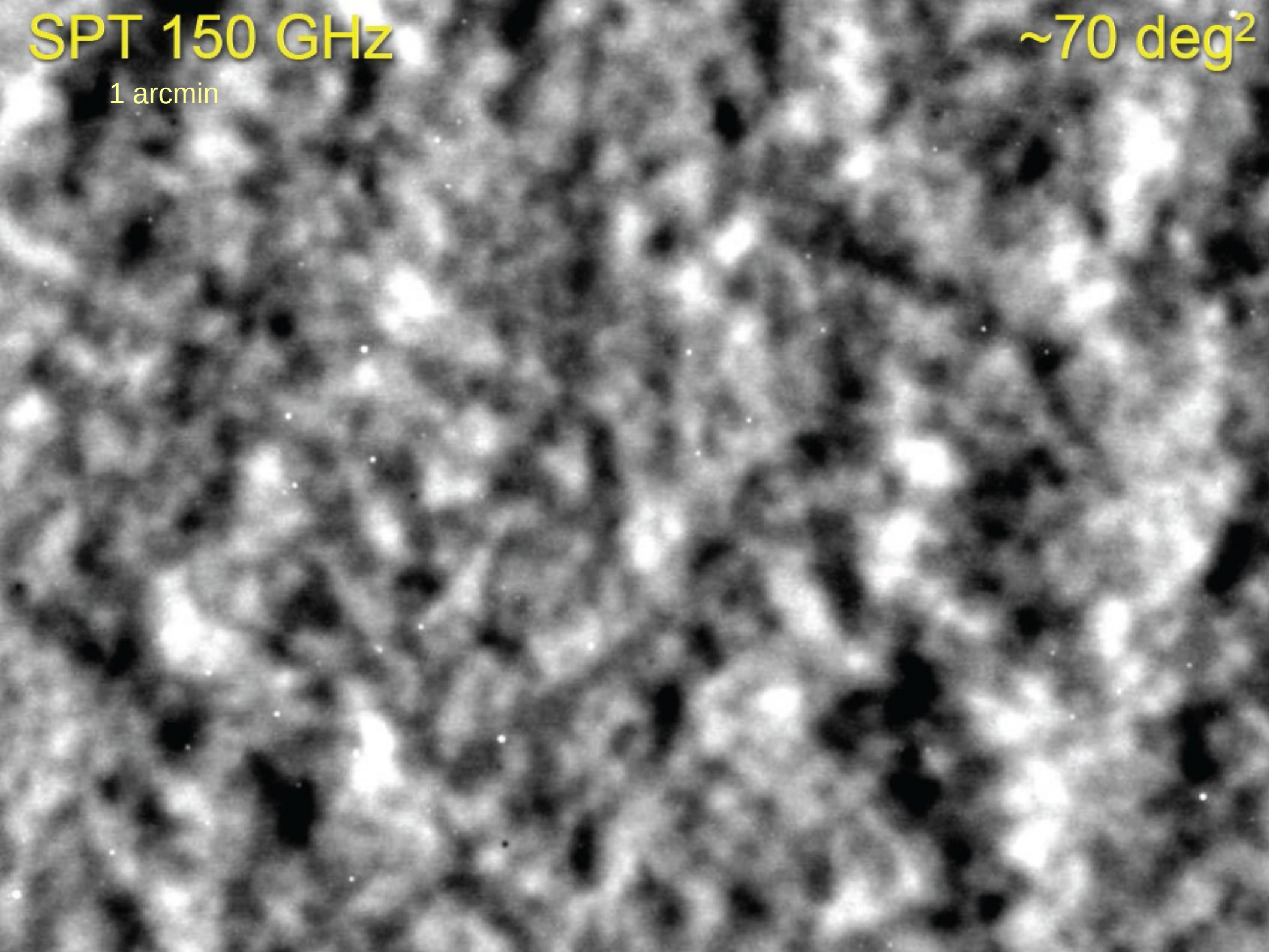
7 arcmin



SPT 150 GHz

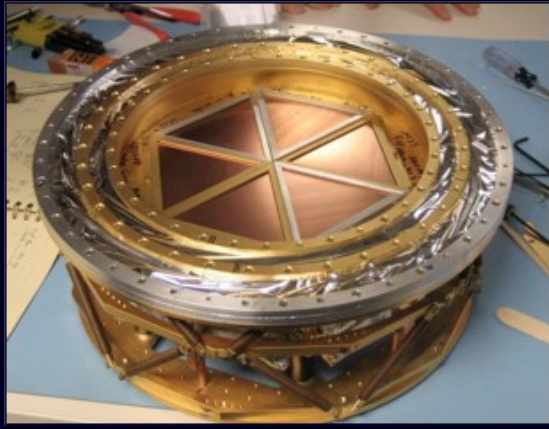
~70 deg²

1 arcmin



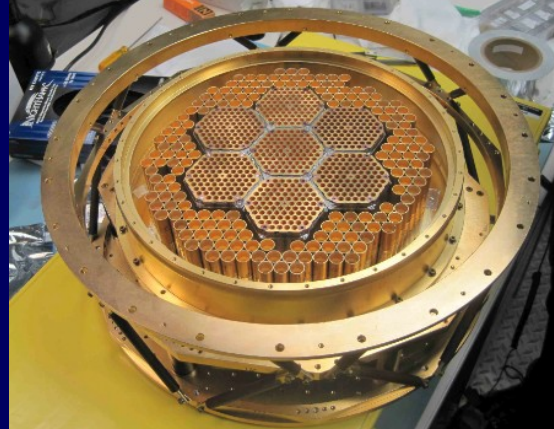
SPT-SZ

0.9k detectors
2007-2011



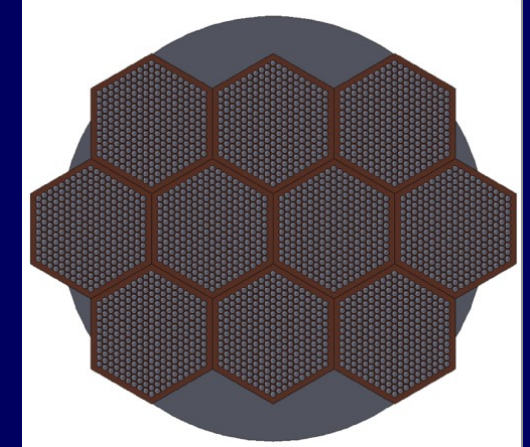
SPTpol

1.6k detectors, pol
2012-2015



SPT-3G

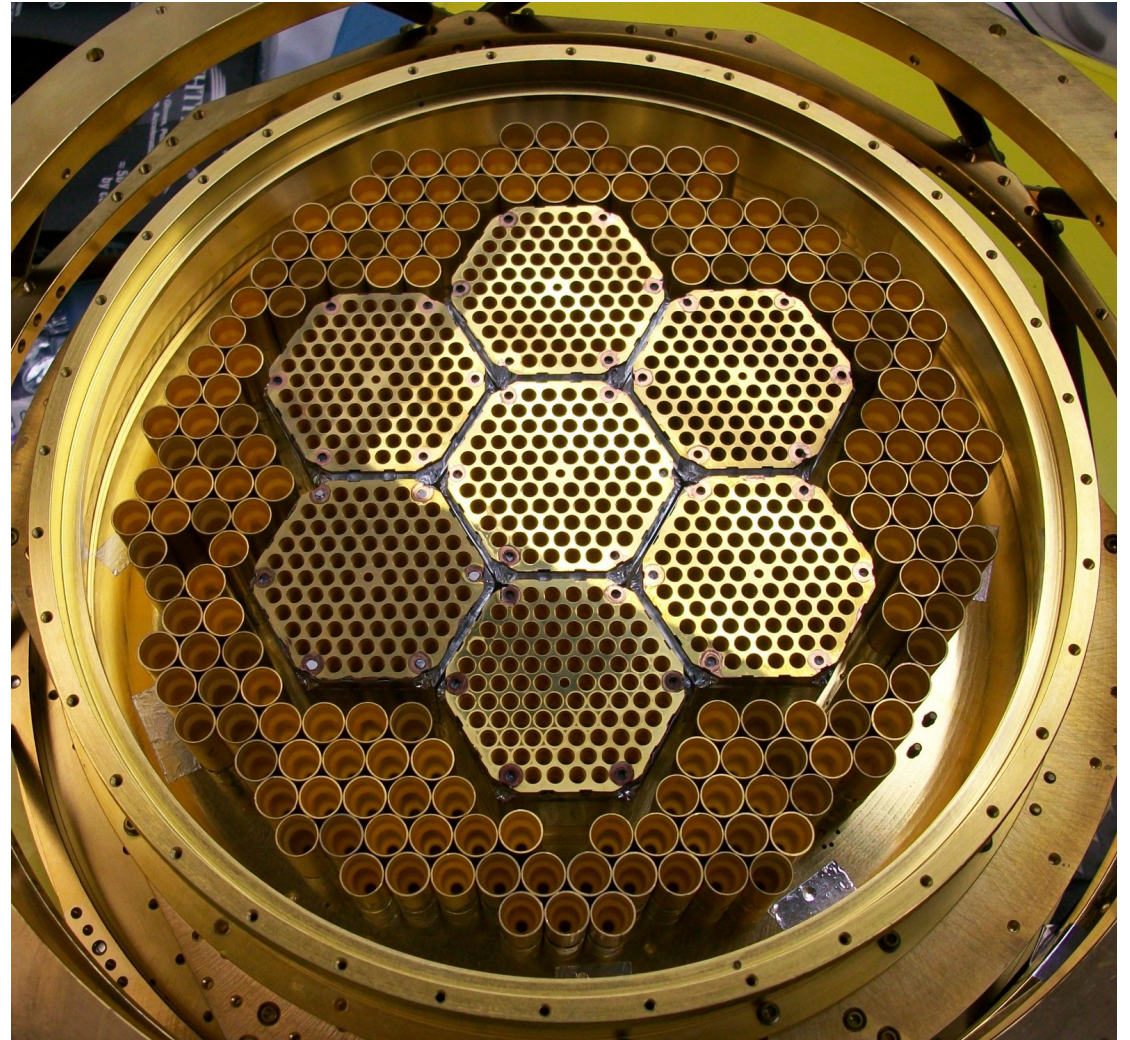
15k detectors, pol
2016-?



~1 arcminute
resolution at
95, 150, 220 GHz

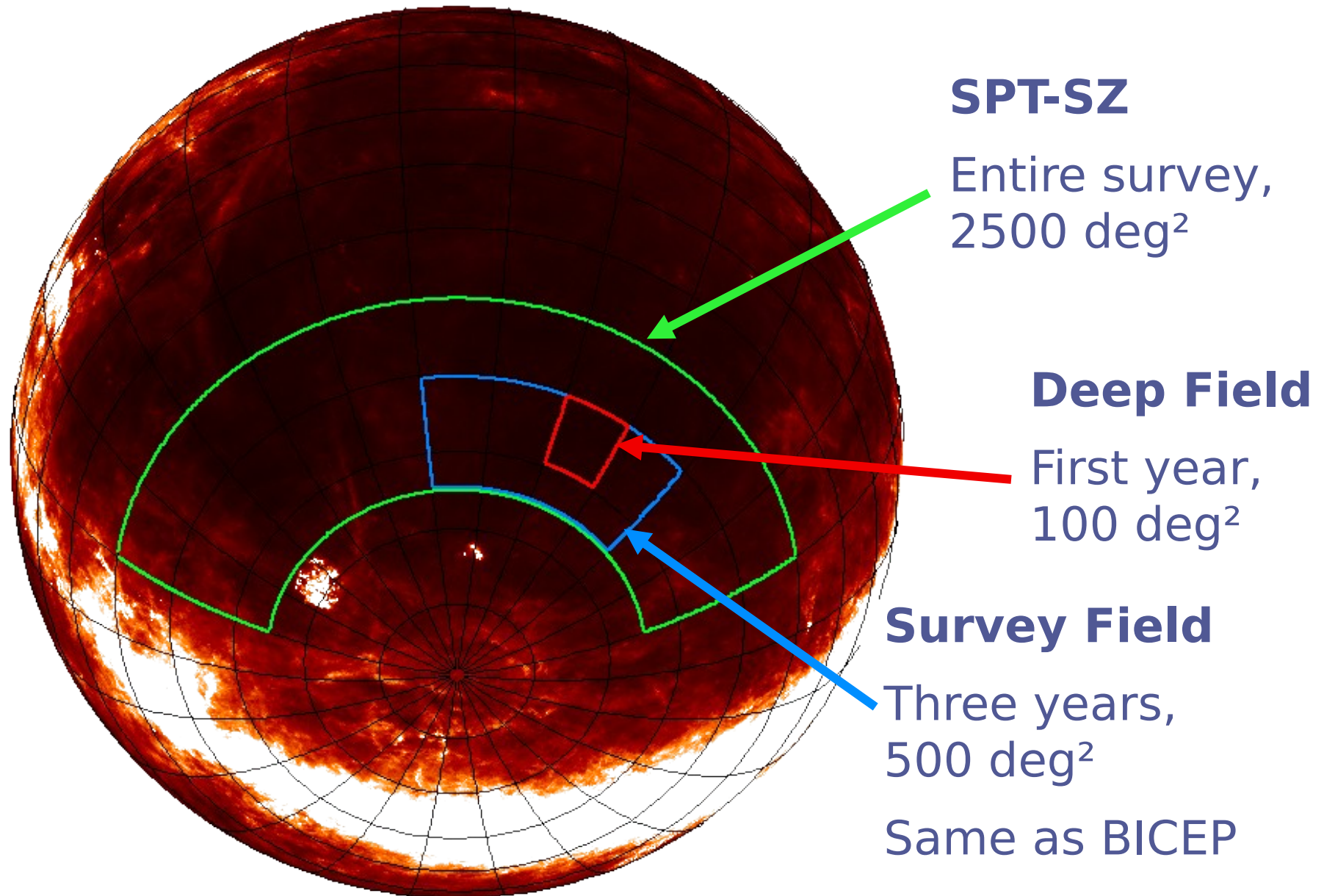
SPTpol is the current camera

- Total of 1536 detectors (TES bolometers).
- 588 pix @ 150 GHz.
- 180 @ 95 GHz.



~22 cm

SPTpol fields: Deep & Survey

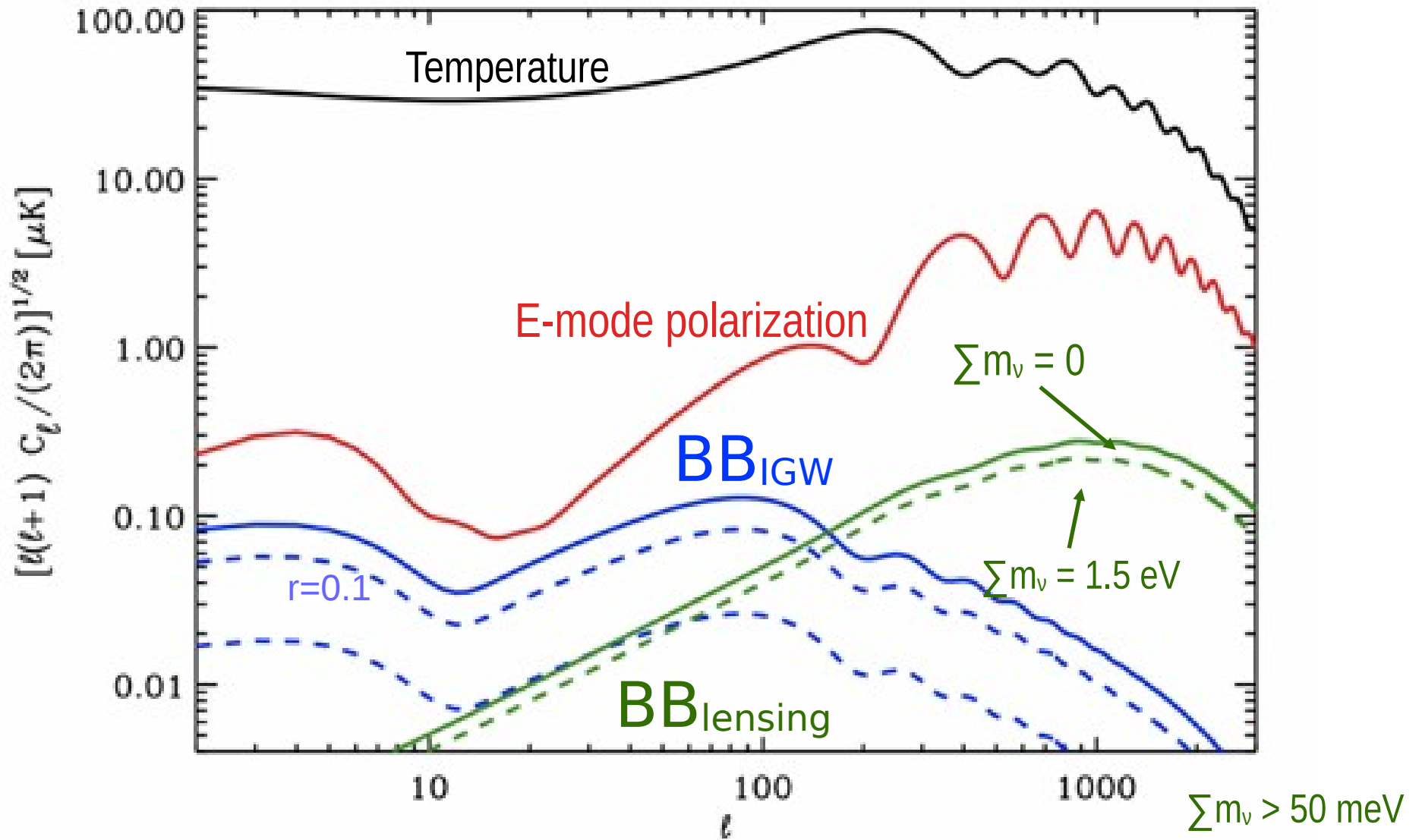


IRAS from Schlegel et al. 1998

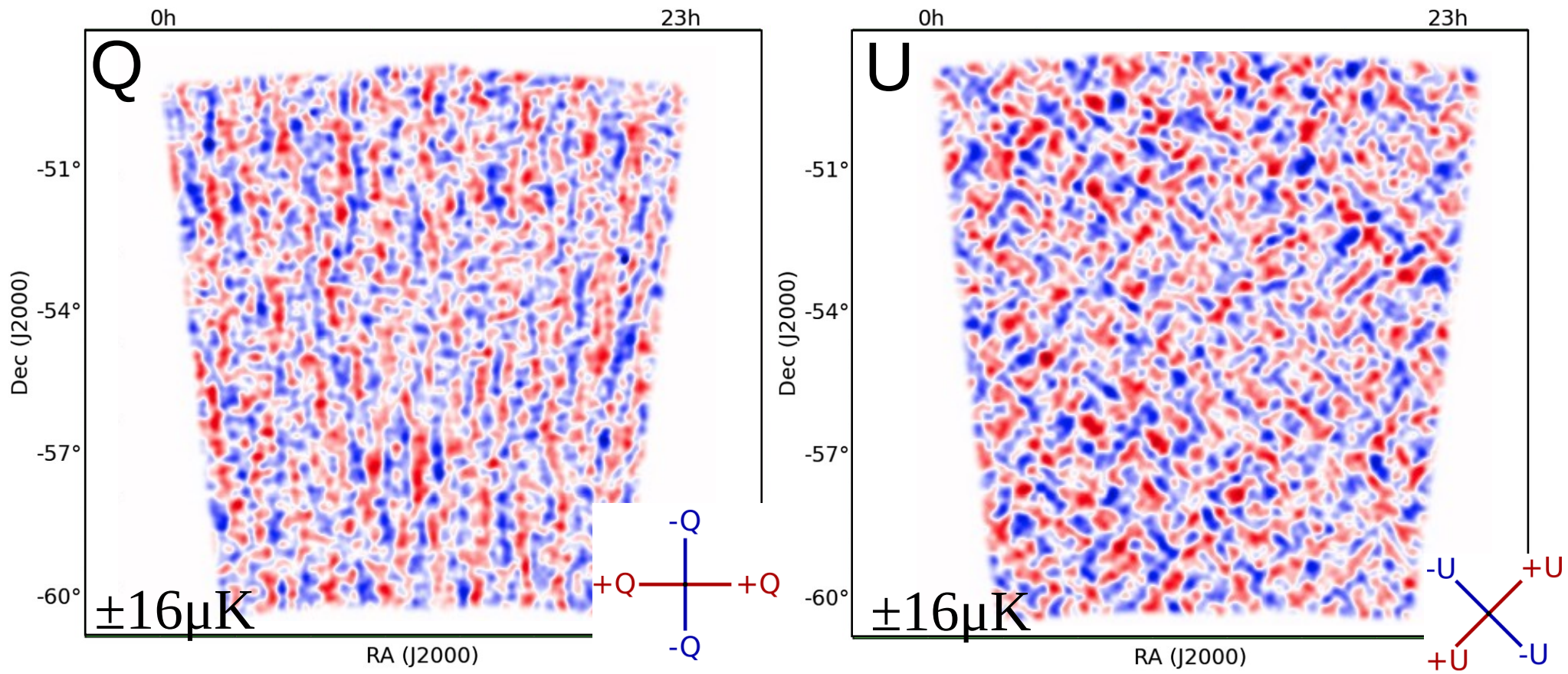
Outline

- South Pole Telescope, SPTpol
- 100 deg²
 - EE ([arXiv:1411.1042](#))
 - BB ([arXiv:1503.02315](#))
 - Lensing Cross ([arXiv:1412.4760](#))
 - Lensing Power Spectrum ([arXiv:1412.4760](#))
- 500 deg² Plans

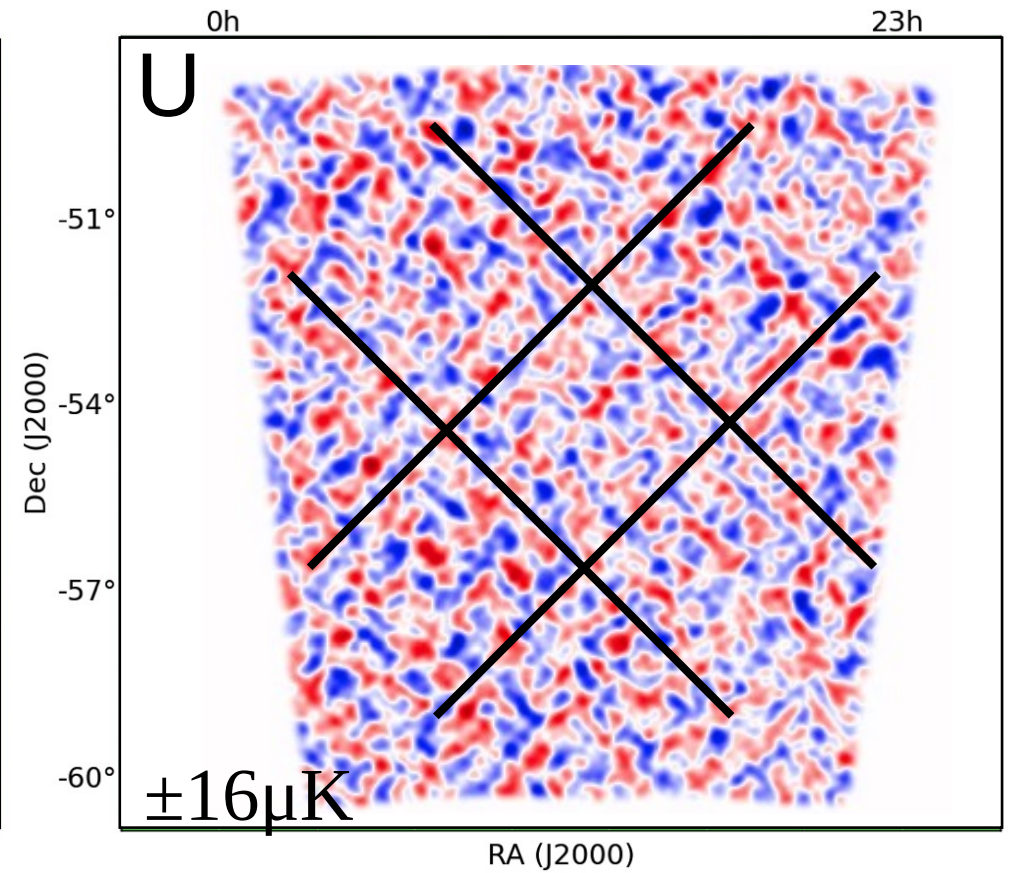
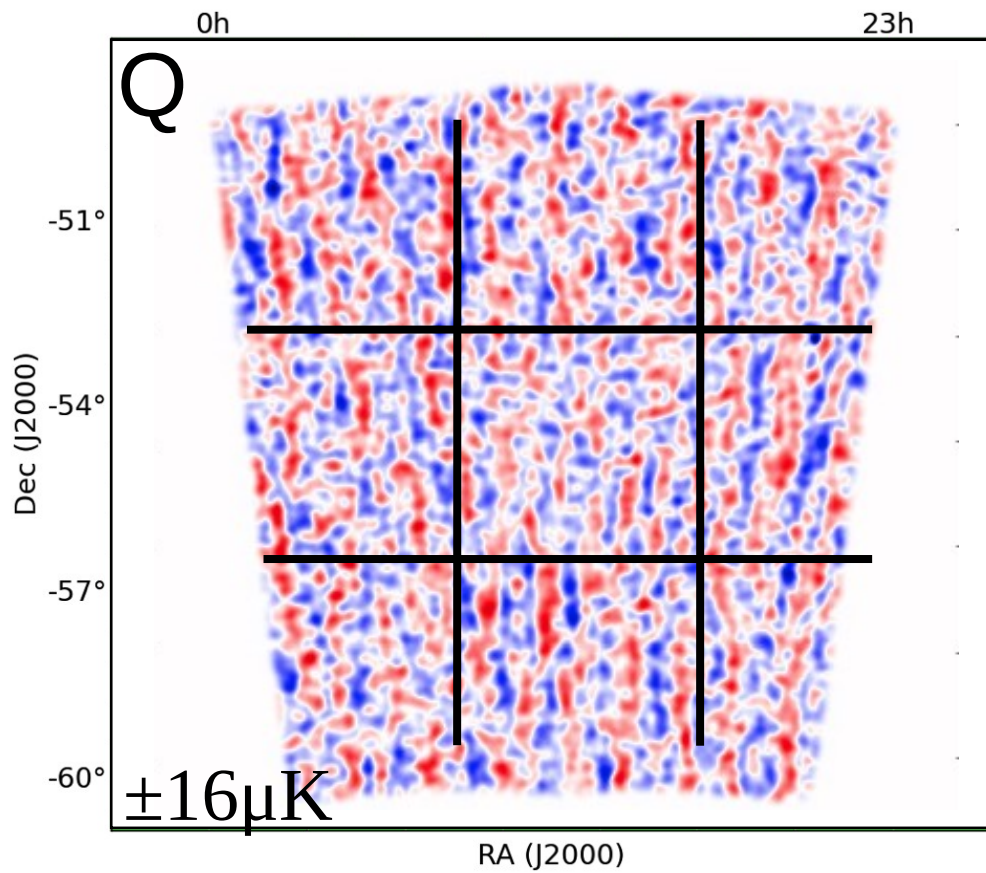
CMB Polarization



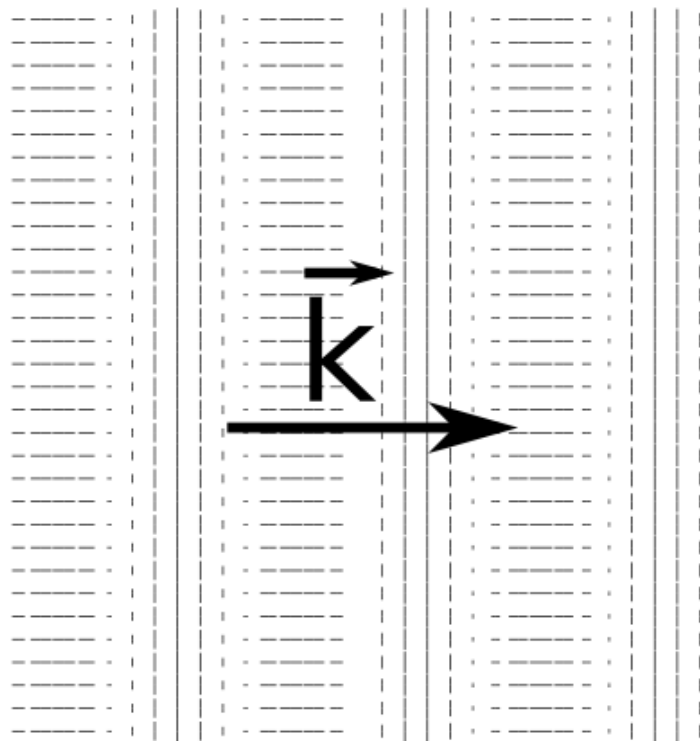
100 Deg² Deep Field (2012,13)



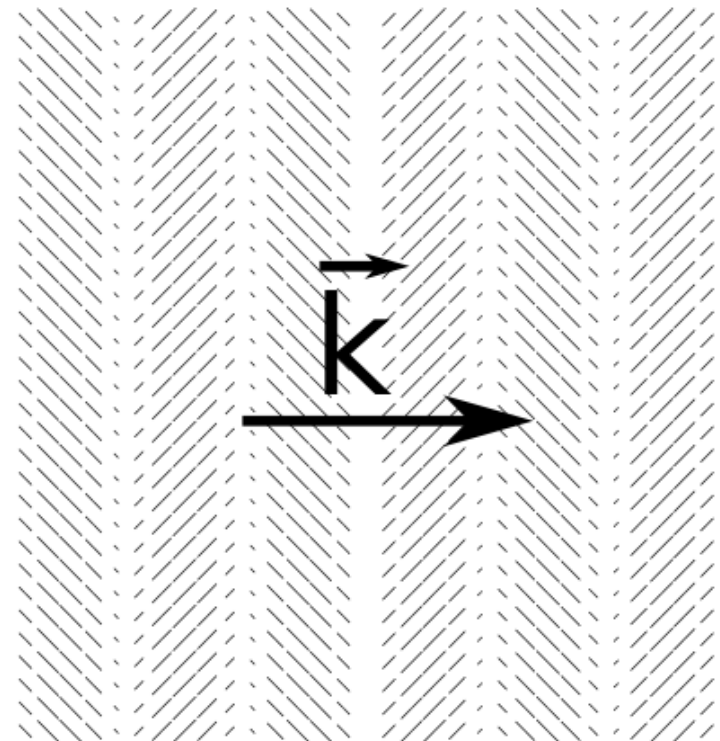
100 Deg² Deep Field (2012,13)



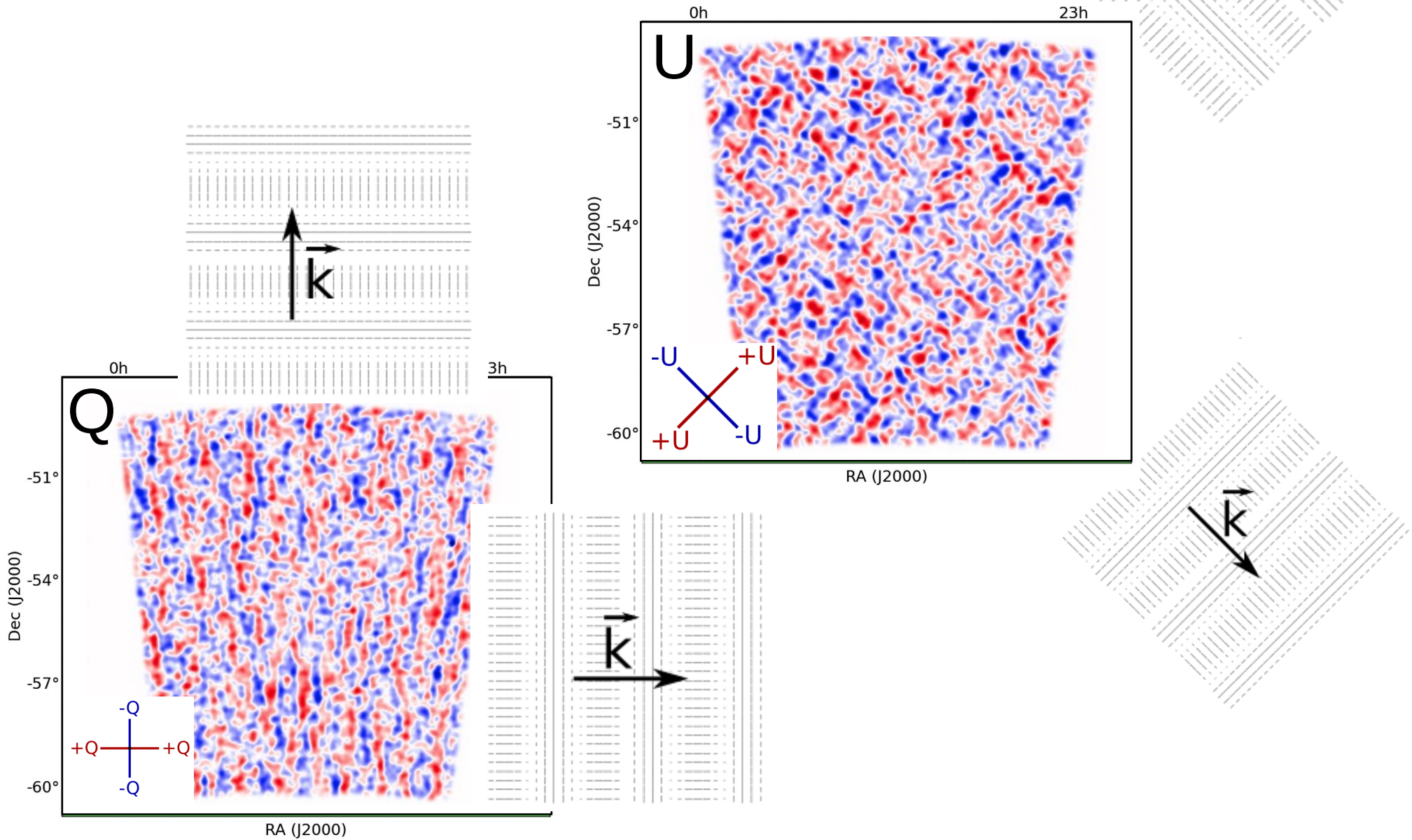
E Modes



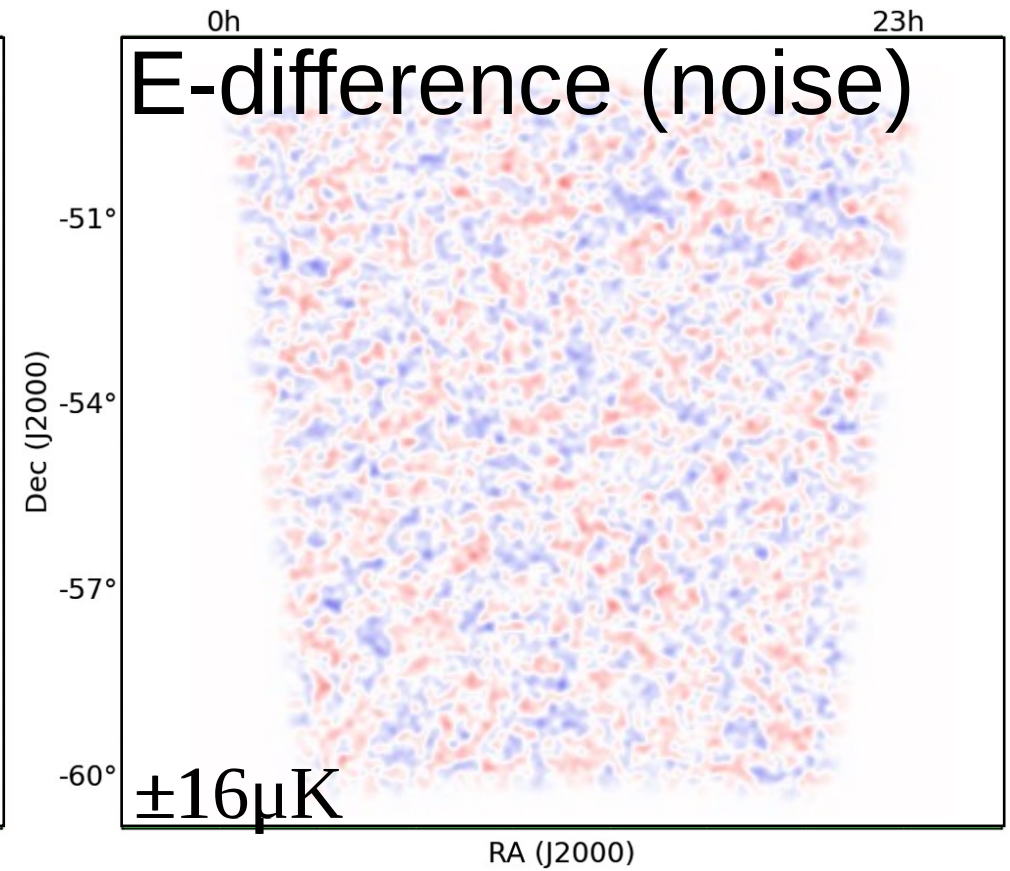
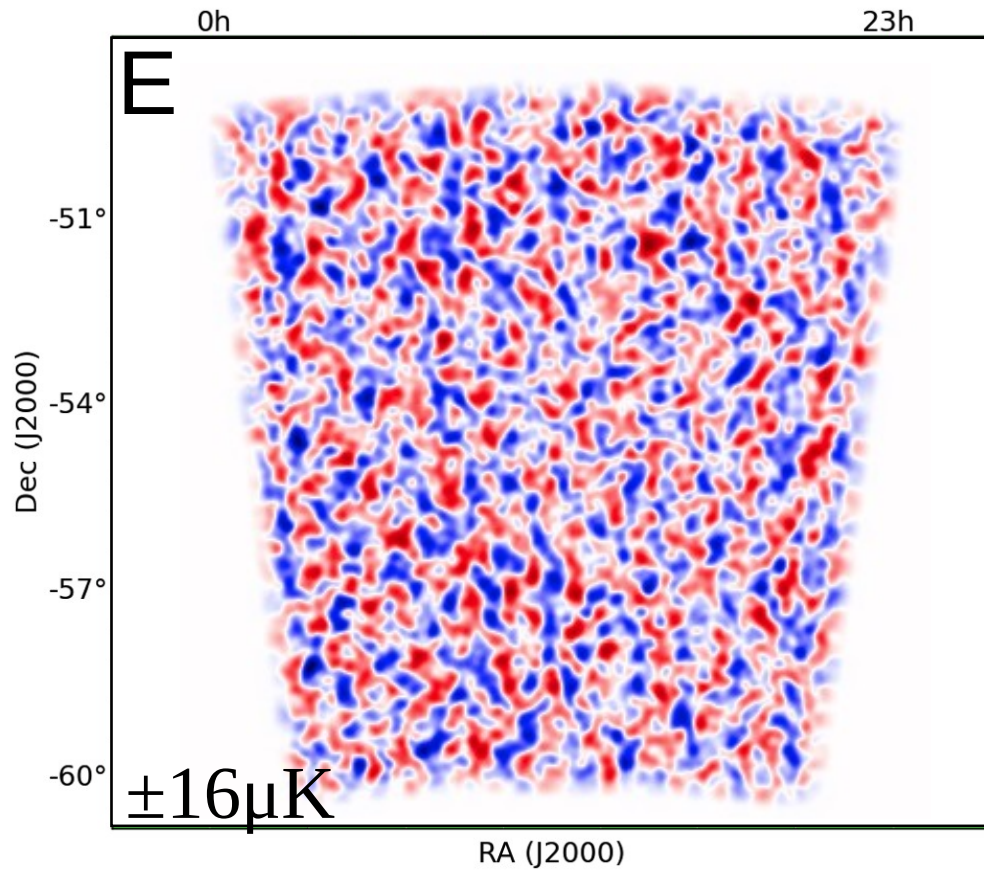
B Modes



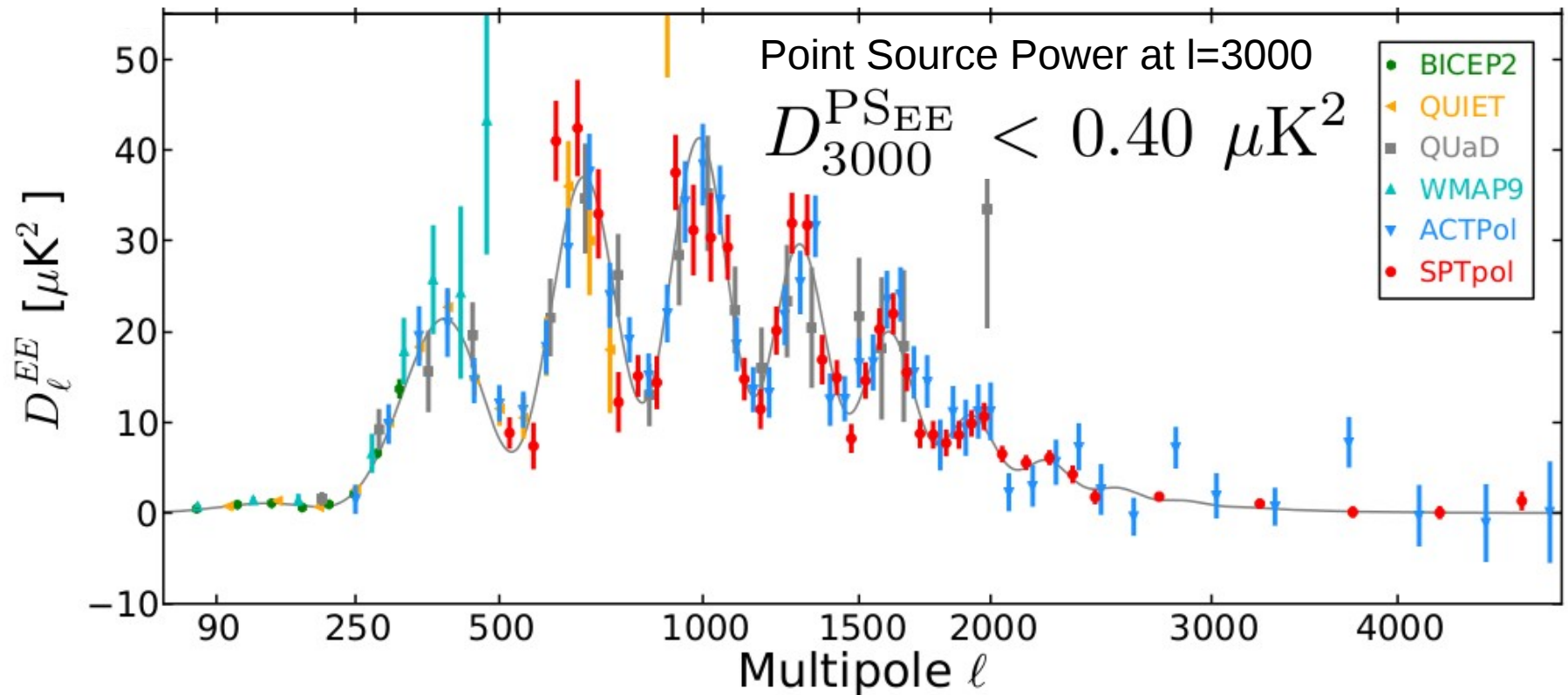
Mostly E Modes



100 Deg² Deep Field (2012,13)



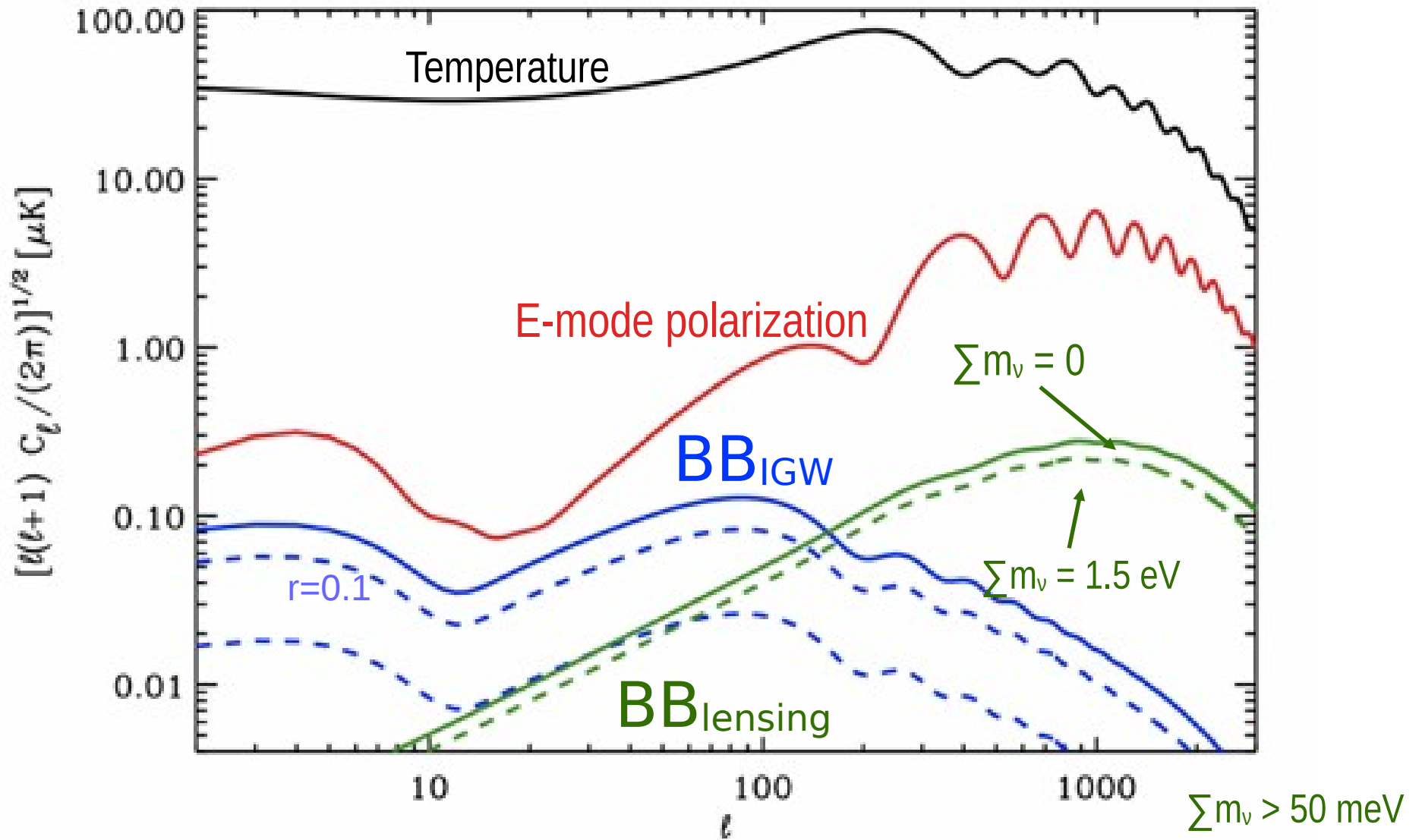
E-Mode Spectrum



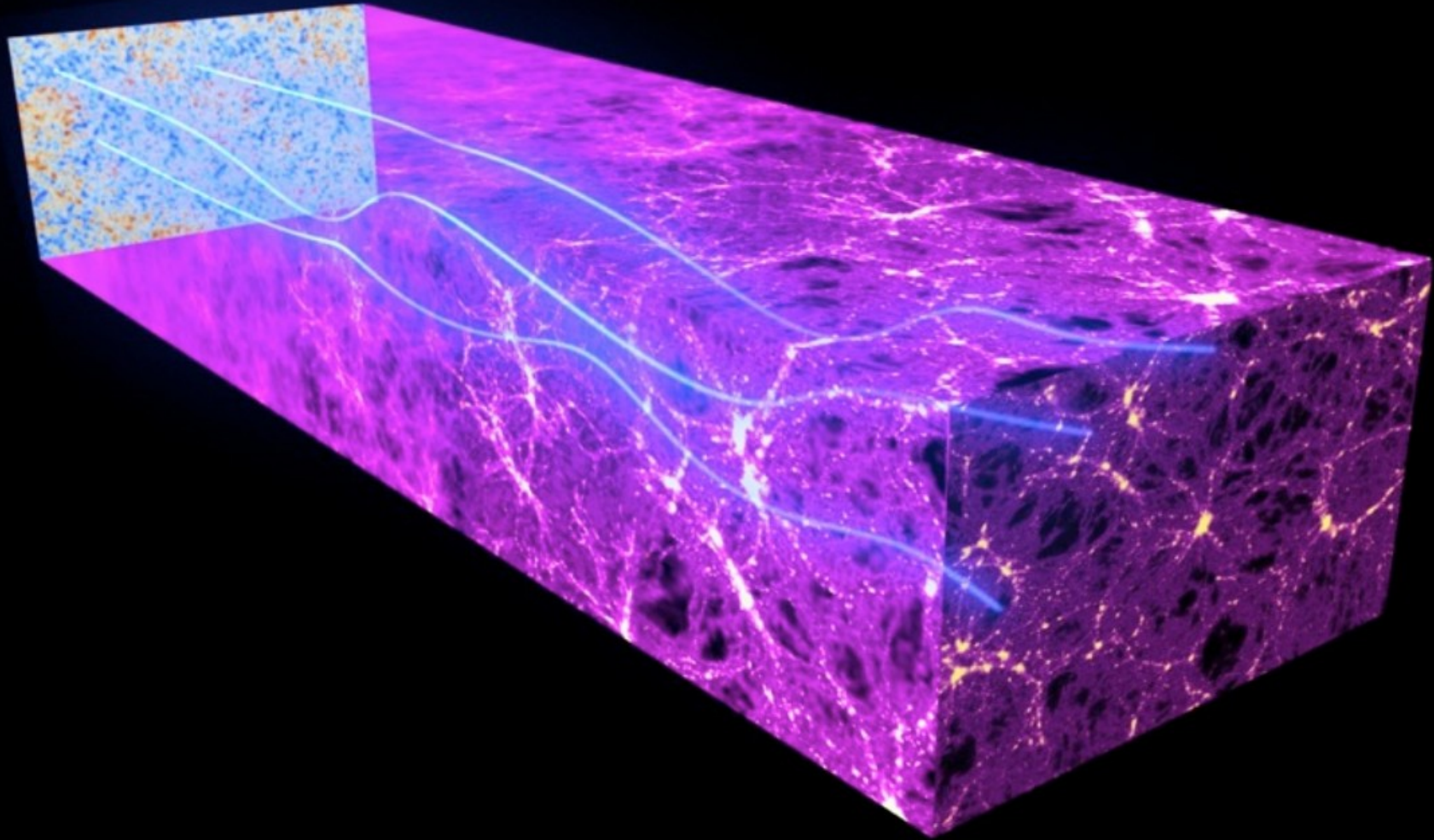
Outline

- South Pole Telescope, SPTpol
- 100 deg²
 - EE (arXiv:1411.1042)
 - **BB (arXiv:1503.02315)**
 - Lensing Cross (arXiv:1412.4760)
 - Lensing Power Spectrum (arXiv:1412.4760)
- 500 deg² Plans

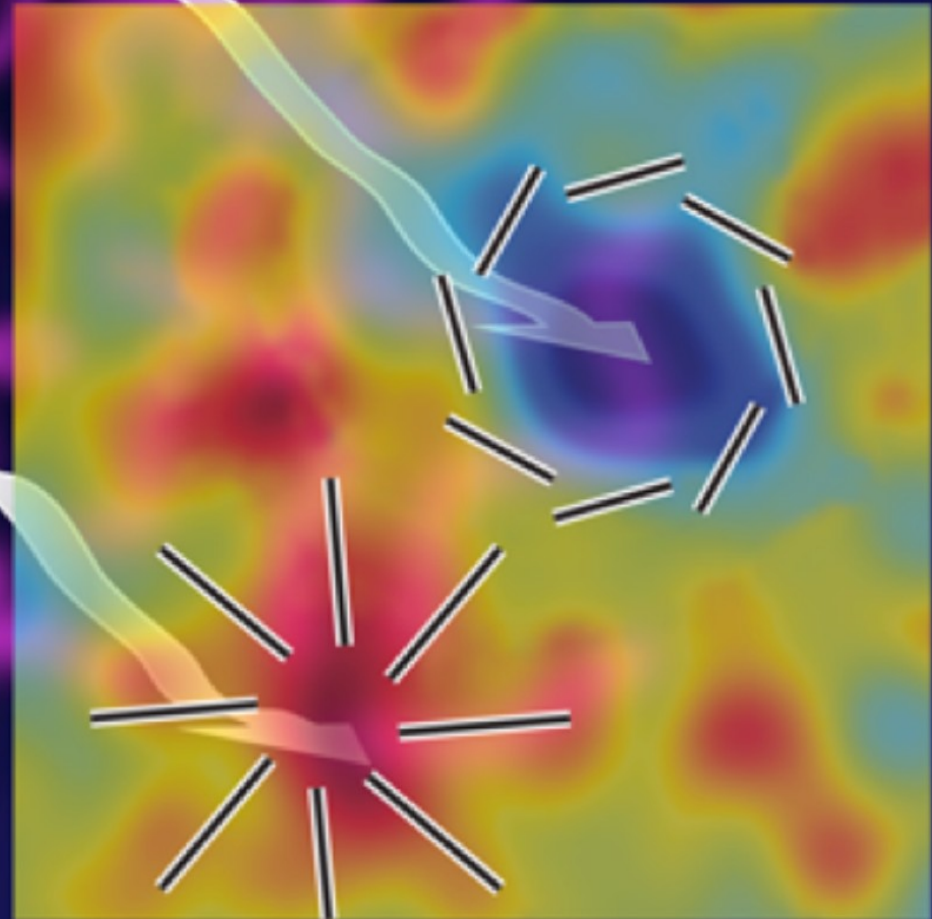
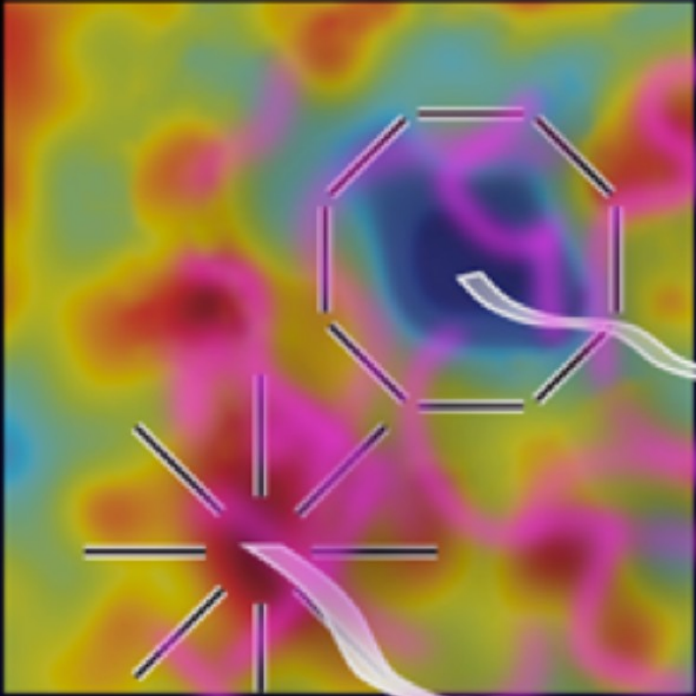
CMB Polarization



Gravitational Lensing of the CMB

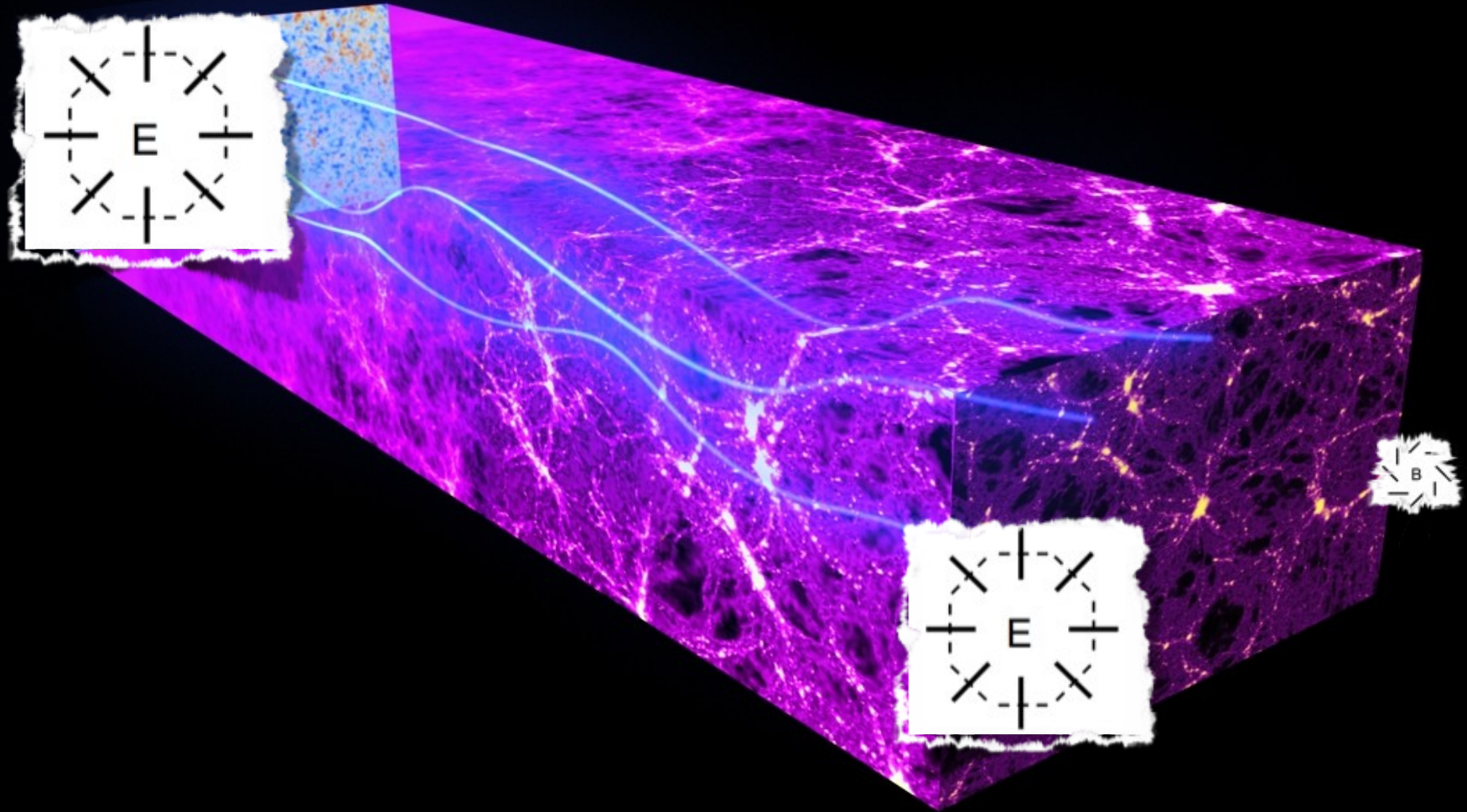


**lensing distorts E-mode
to B-mode polarization**



**Large-Scale
Structure
Lenses the CMB**

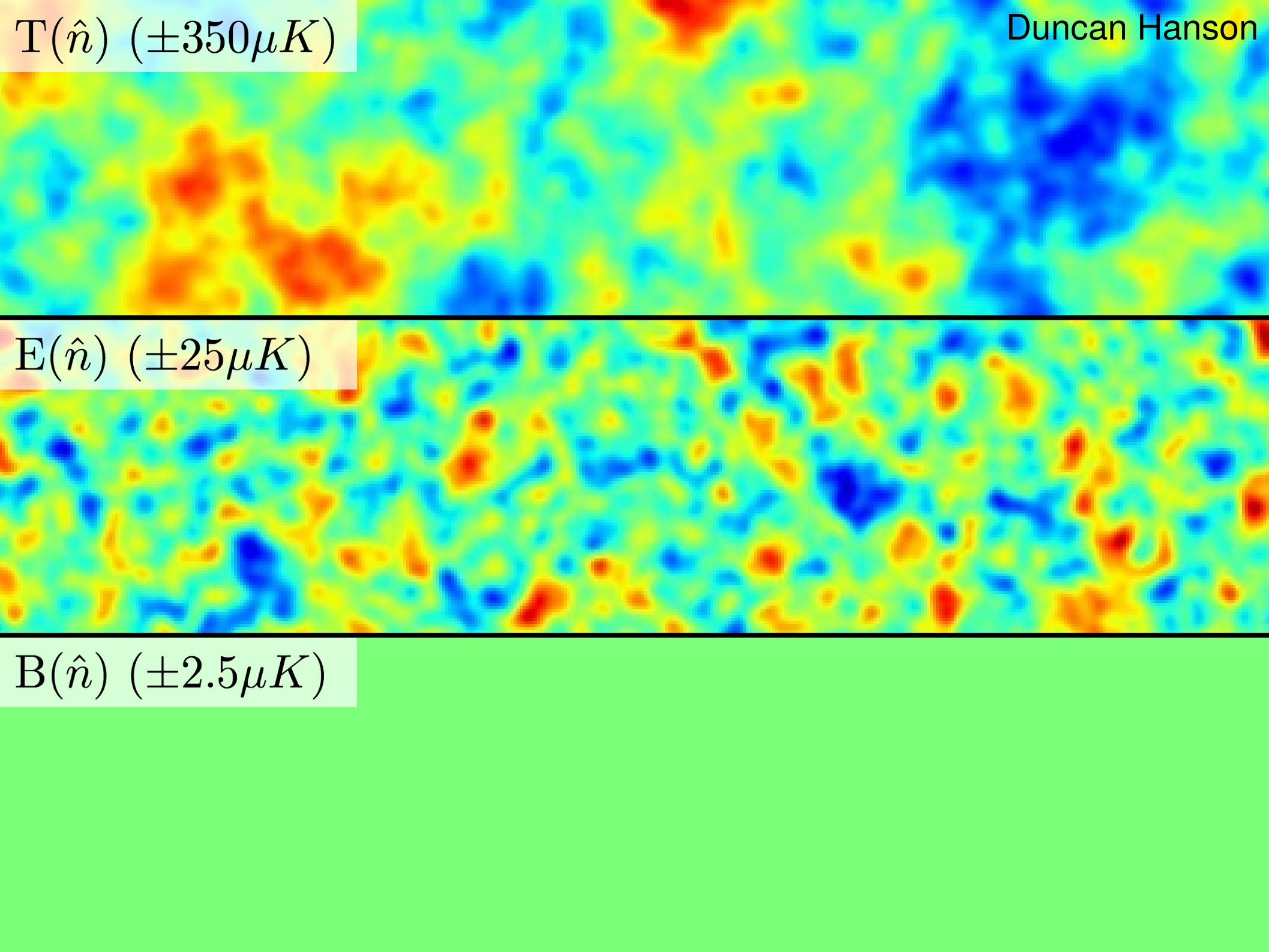
Lensing the *Polarization* of the CMB

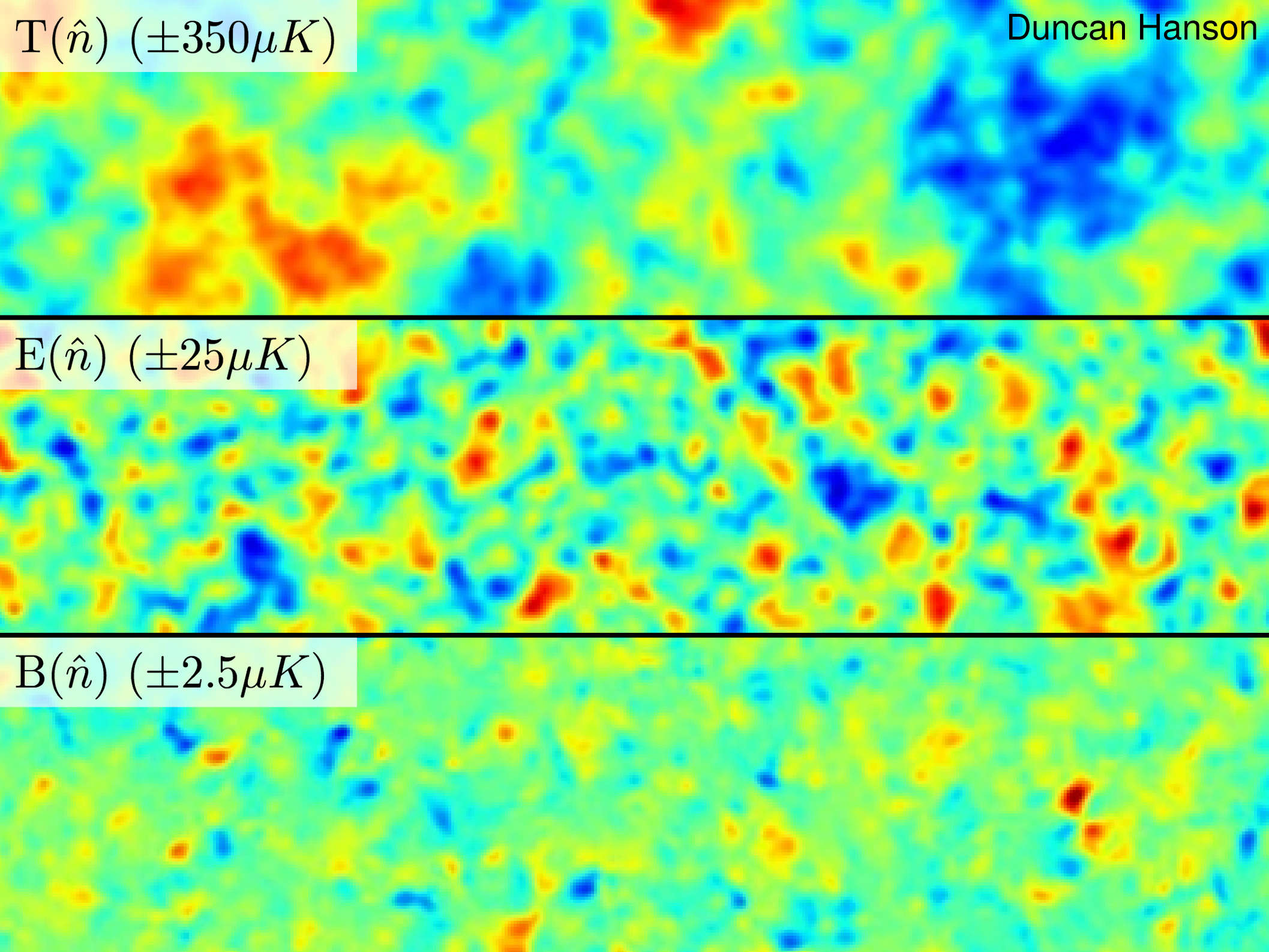


$T(\hat{n}) (\pm 350 \mu K)$

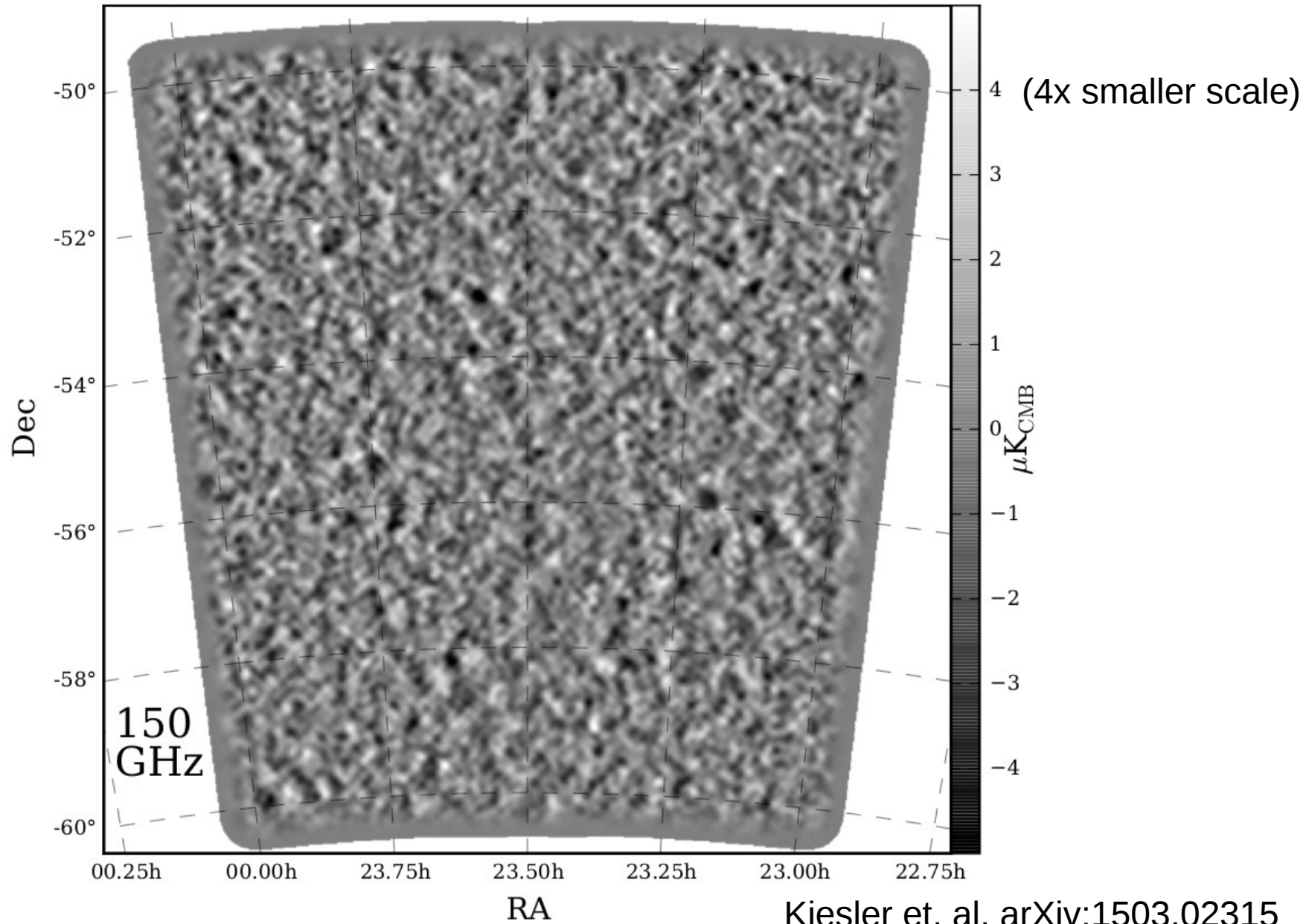
$E(\hat{n}) (\pm 25 \mu K)$

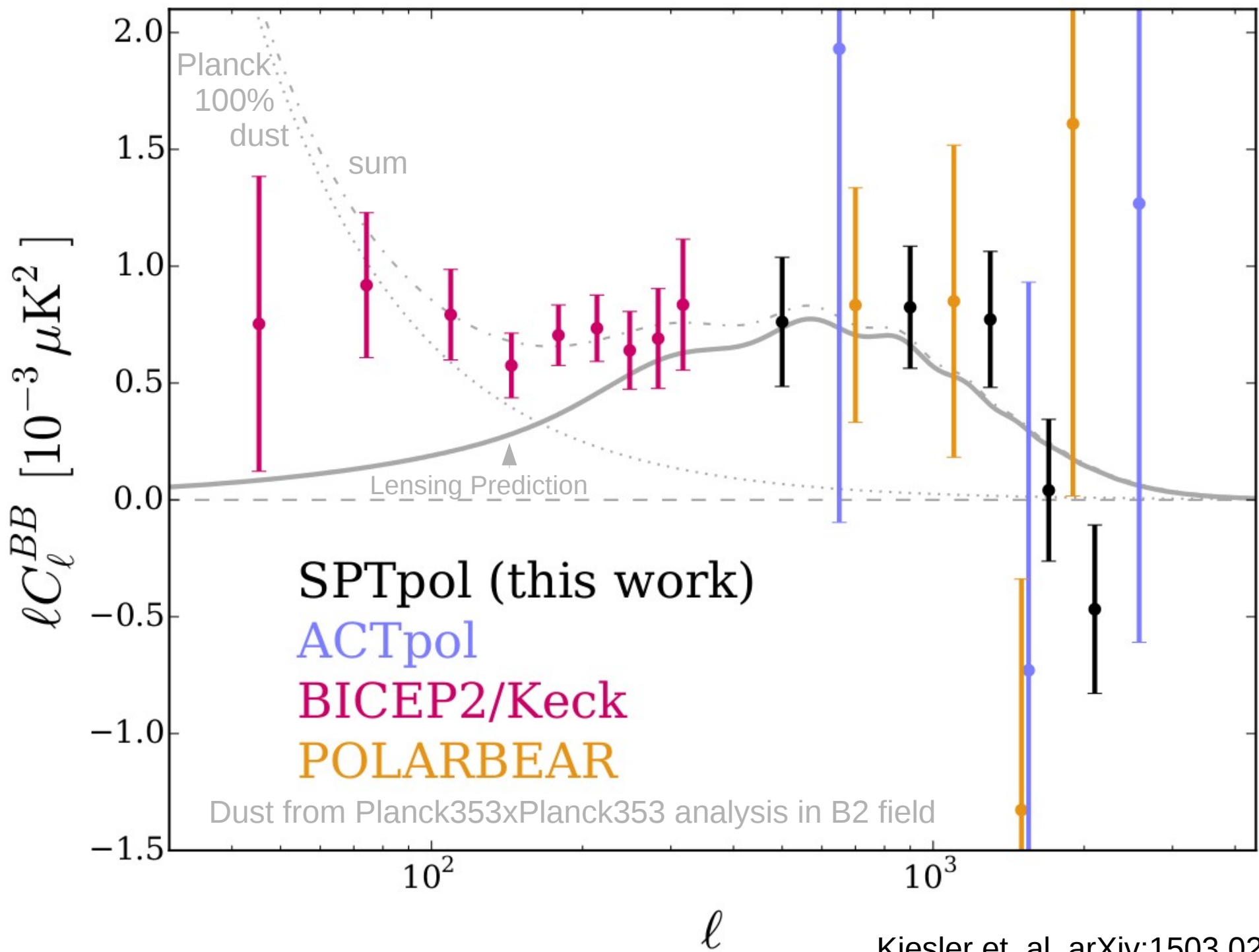
$B(\hat{n}) (\pm 2.5 \mu K)$



$T(\hat{n}) (\pm 350 \mu K)$ $E(\hat{n}) (\pm 25 \mu K)$ $B(\hat{n}) (\pm 2.5 \mu K)$ 

SPTpol 100 deg² B Modes

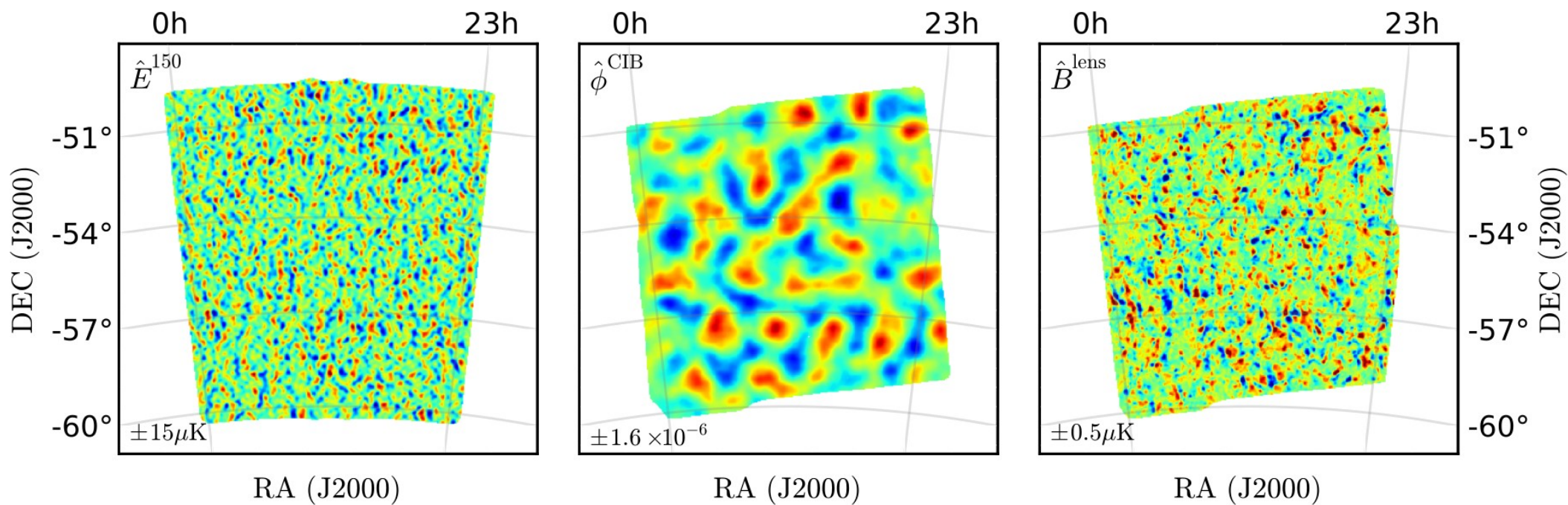




Outline

- South Pole Telescope, SPTpol
- 100 deg²
 - EE (arXiv:1411.1042)
 - BB (arXiv:1503.02315)
 - **Lensing Cross (arXiv:1412.4760)**
 - Lensing Power Spectrum (arXiv:1412.4760)
- 500 deg² Plans

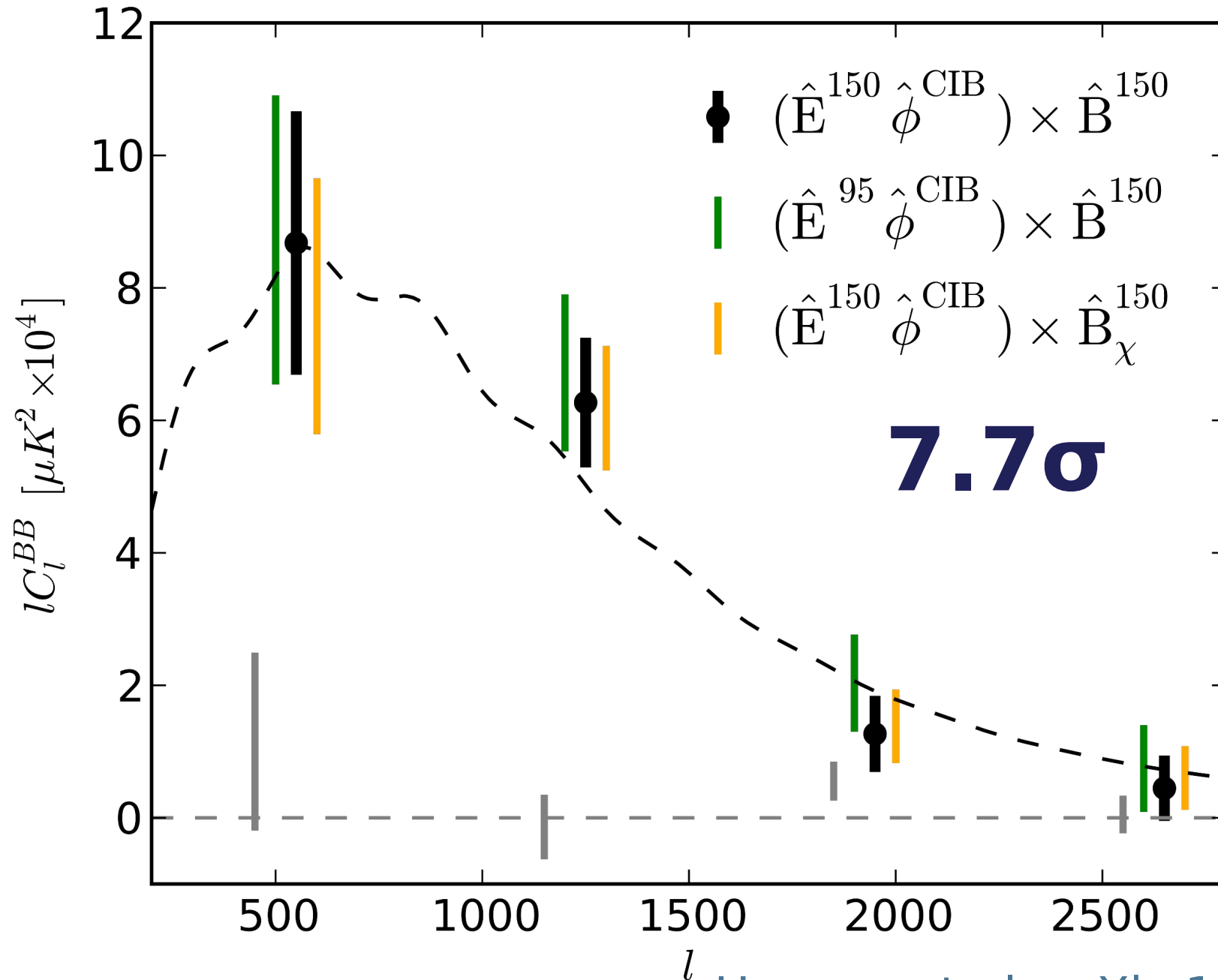
Detection of B -mode Polarization in the Cosmic Microwave Background with Data from the South Pole Telescope



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

Hanson, et al., 2013
arXiv: 1307.5830

First Lensed B-mode detection



Outline

- South Pole Telescope, SPTpol
- 100 deg²
 - EE (arXiv:1411.1042)
 - BB (arXiv:1503.02315)
 - Lensing Cross (arXiv:1412.4760)
 - **Lensing Power Spectrum (arXiv:1412.4760)**
- 500 deg² Plans

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

The diagram illustrates the equation for gravitational lensing of CMB. The equation is $X(\hat{\mathbf{n}}) = \tilde{X}(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}}))$. Three arrows point from labels to terms in the equation: one from 'Observed T, Q, or U' to $X(\hat{\mathbf{n}})$, one from 'Unobservable “true” T, Q, or U' to \tilde{X} , and one from 'Projected Lensing Potential' to $\nabla\phi(\hat{\mathbf{n}})$.

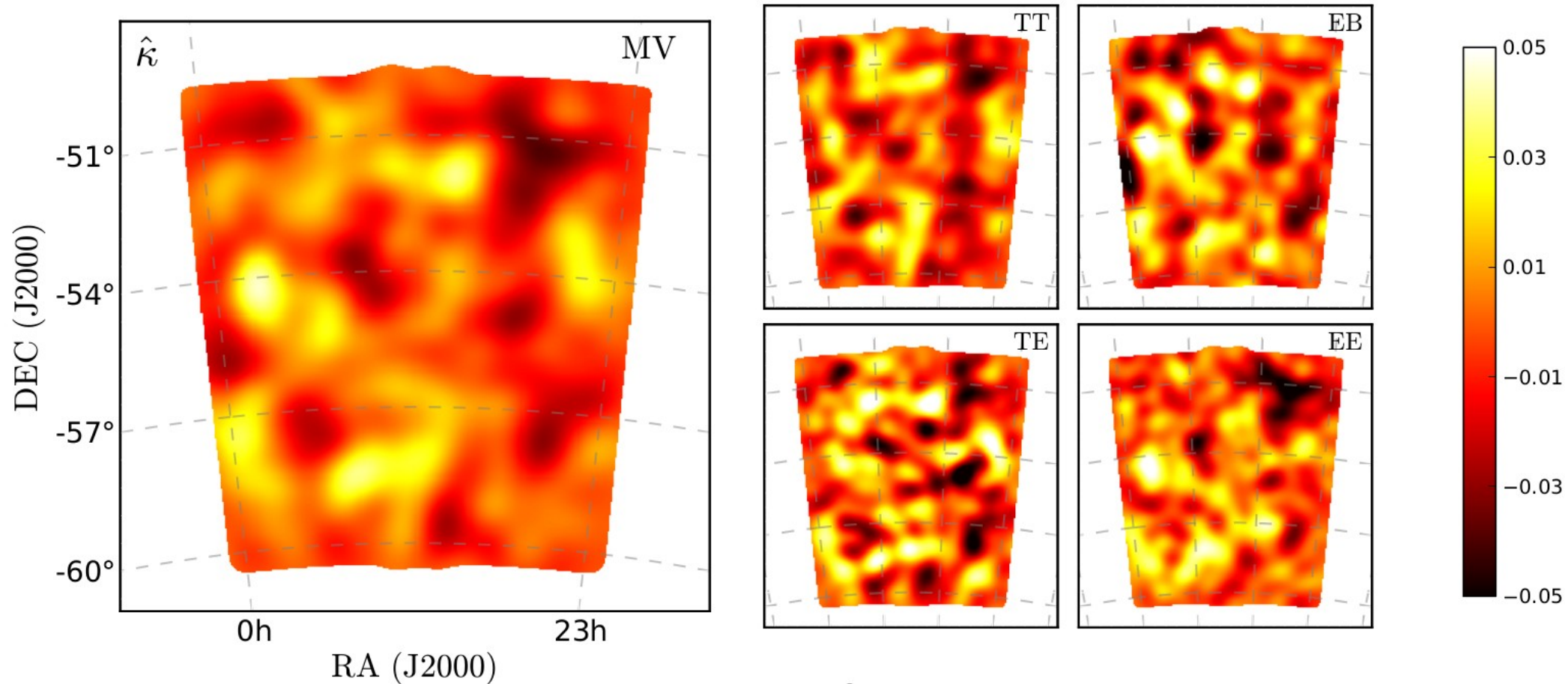
Estimate of Lensing Potential

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

↑ ↑
T, E, or B

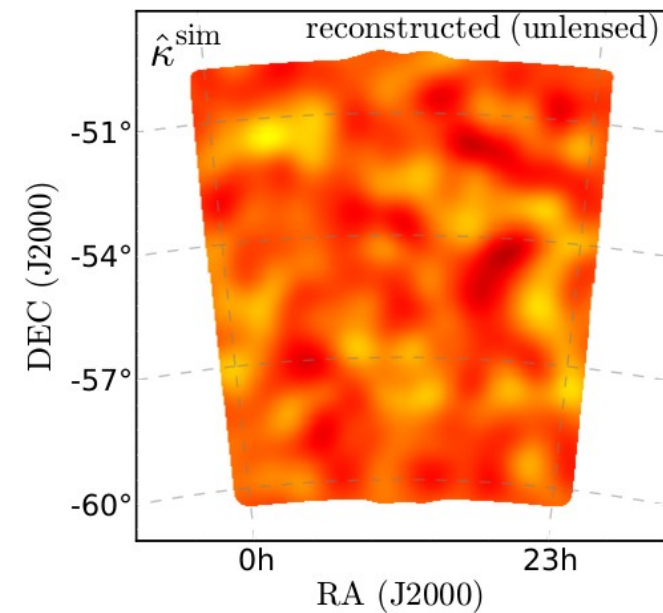
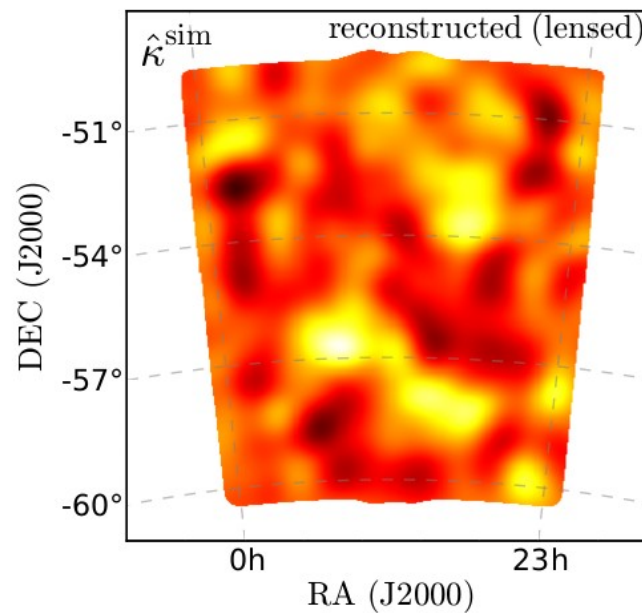
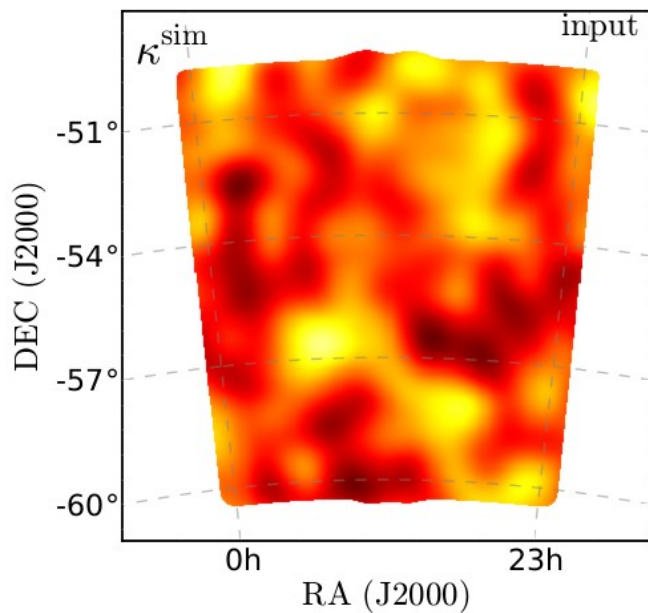
The estimated lensing potential is a weighted average of a product of T, E, or B modes

Combining Multiple Estimates



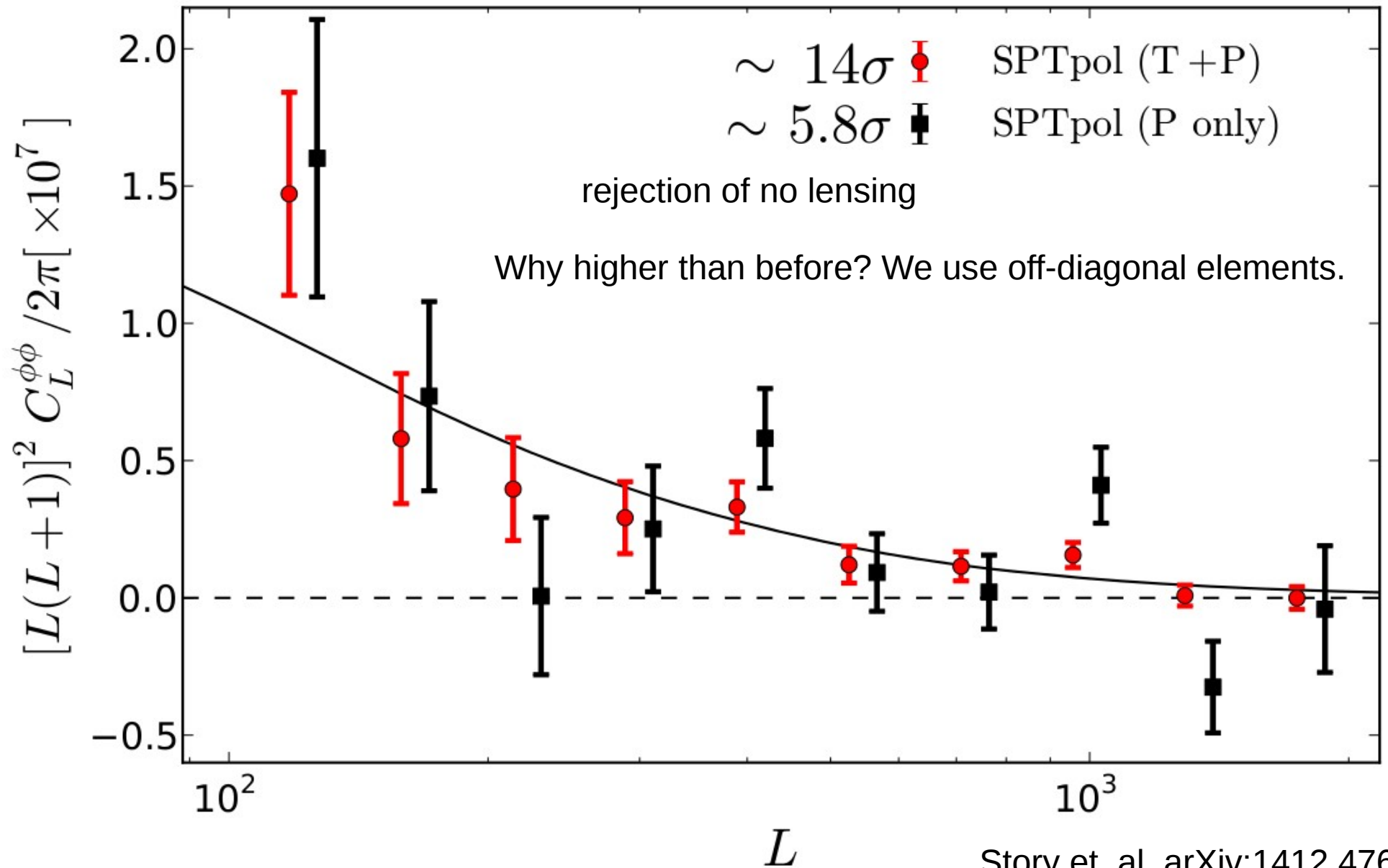
All smoothed with ~ 1 deg Gaussian to show only $S/N > 1$ modes

Unlensed and Reconstructed



Reconstruction with no Input
(Noise/Error estimate)

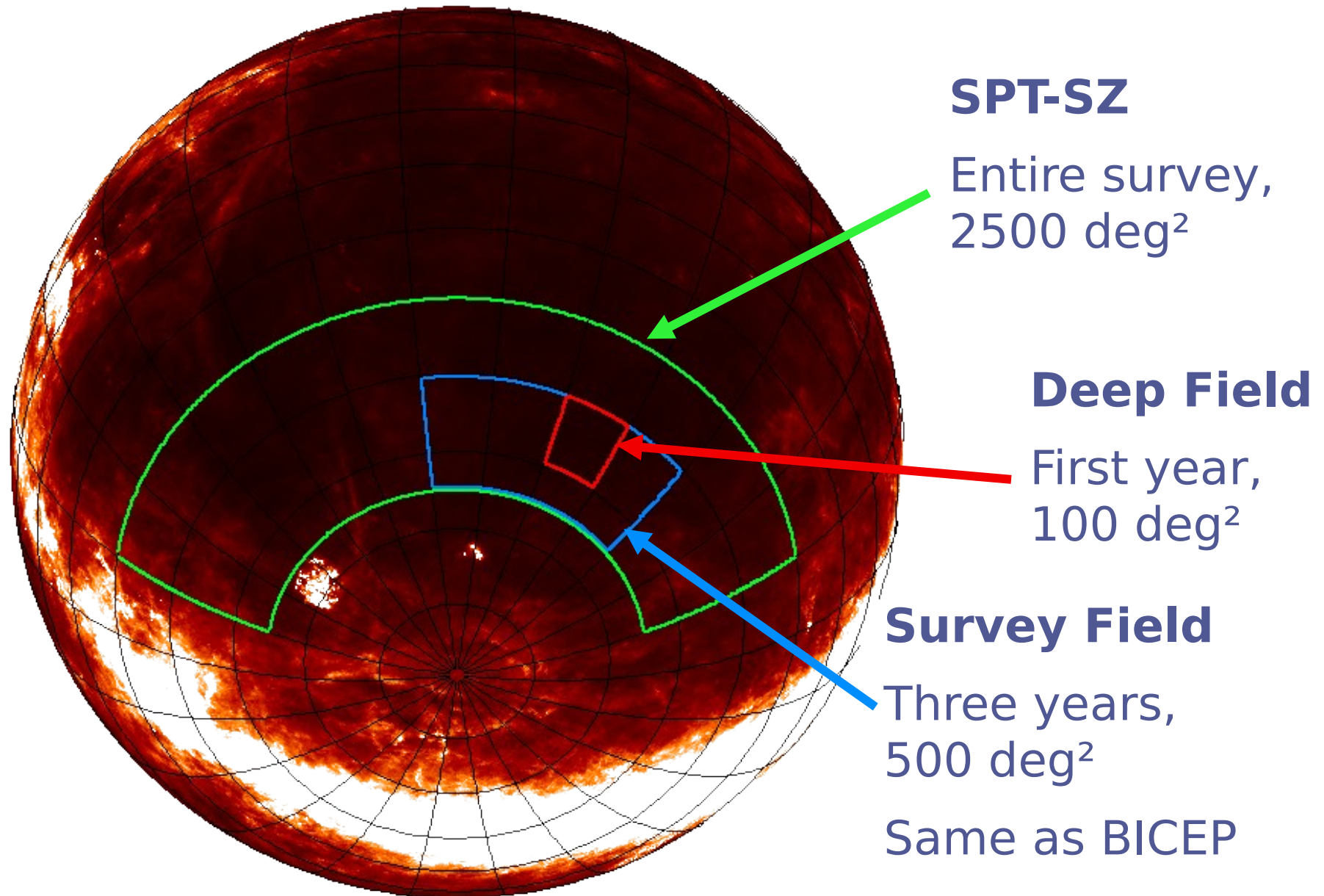
SPTpol Lensing Power Spectrum



Outline

- South Pole Telescope, SPTpol
- 100 deg²
 - EE (arXiv:1411.1042)
 - BB (arXiv:1503.02315)
 - Lensing Cross (arXiv:1412.4760)
 - Lensing Power Spectrum (arXiv:1412.4760)
- 500 deg² Plans

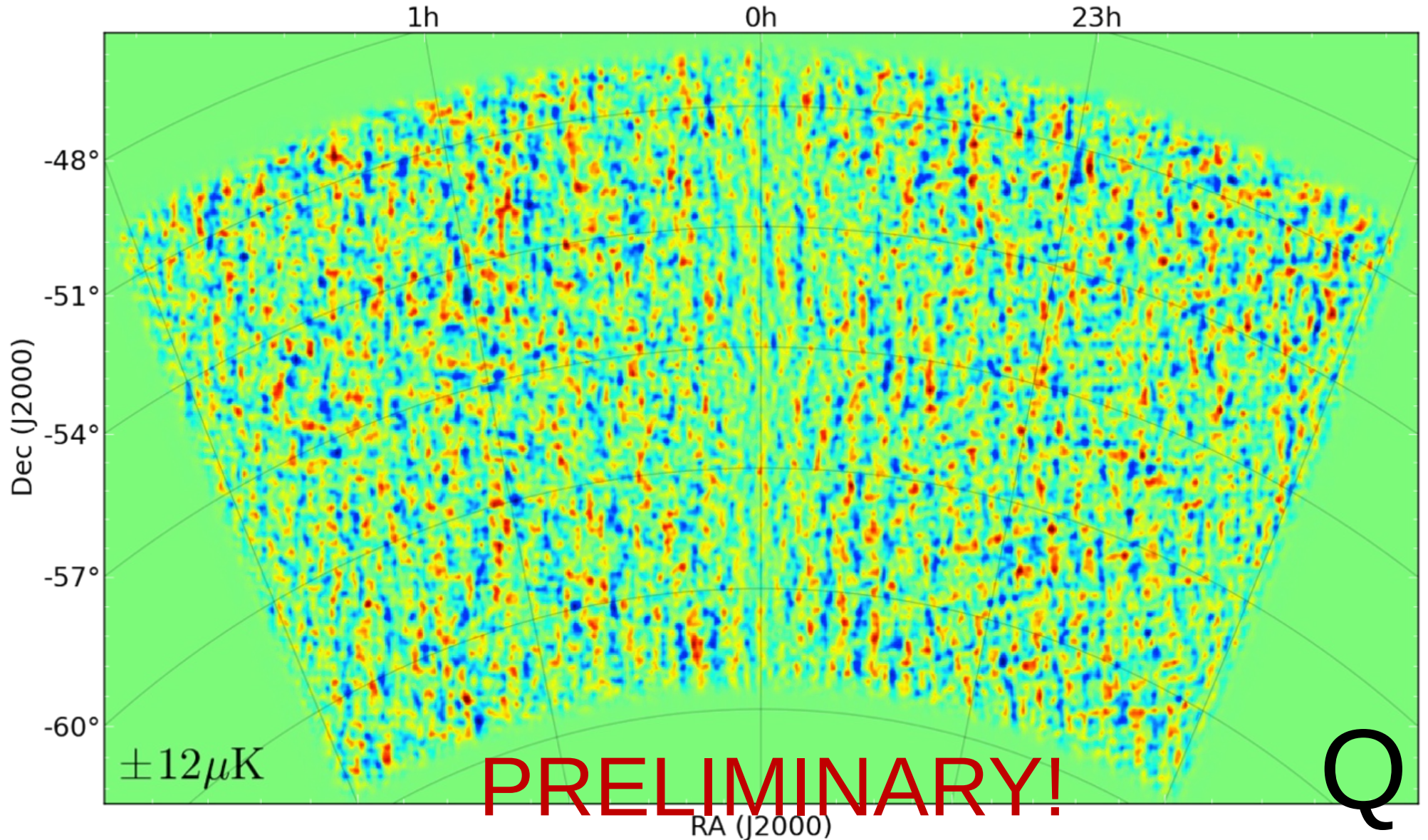
SPTpol fields: Deep & Survey



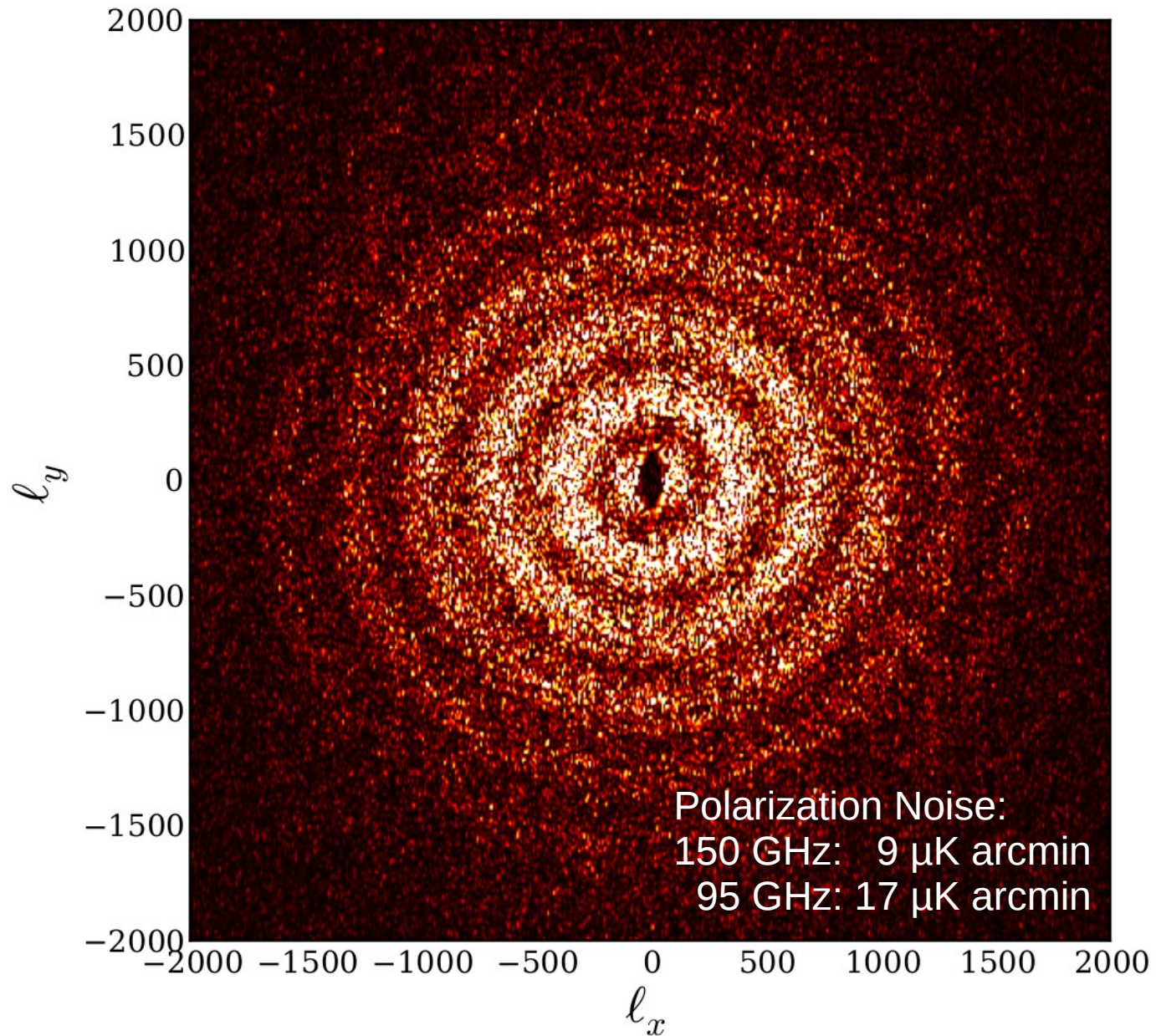
IRAS from Schlegel et al. 1998

500 Deg² Survey Field (2013)

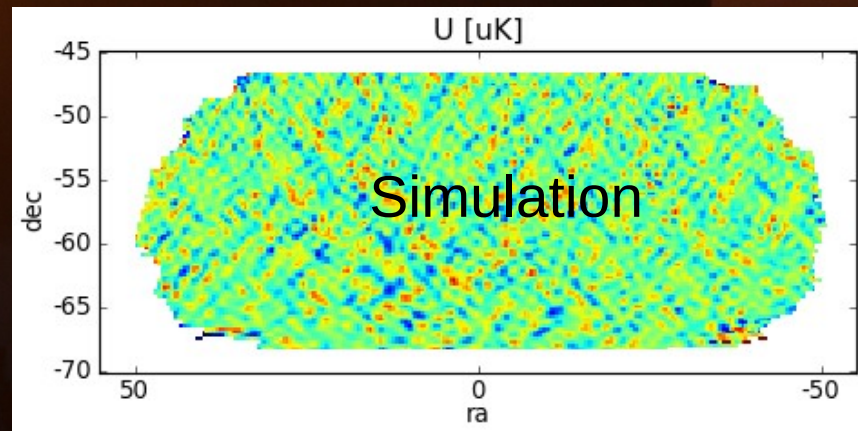
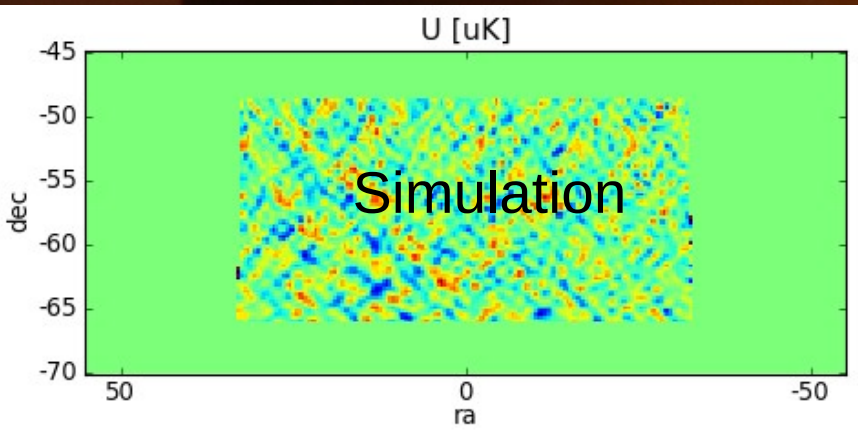
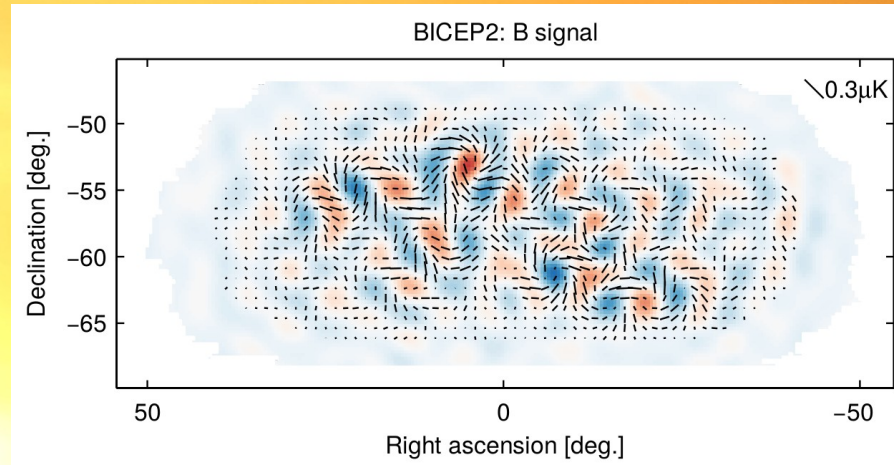
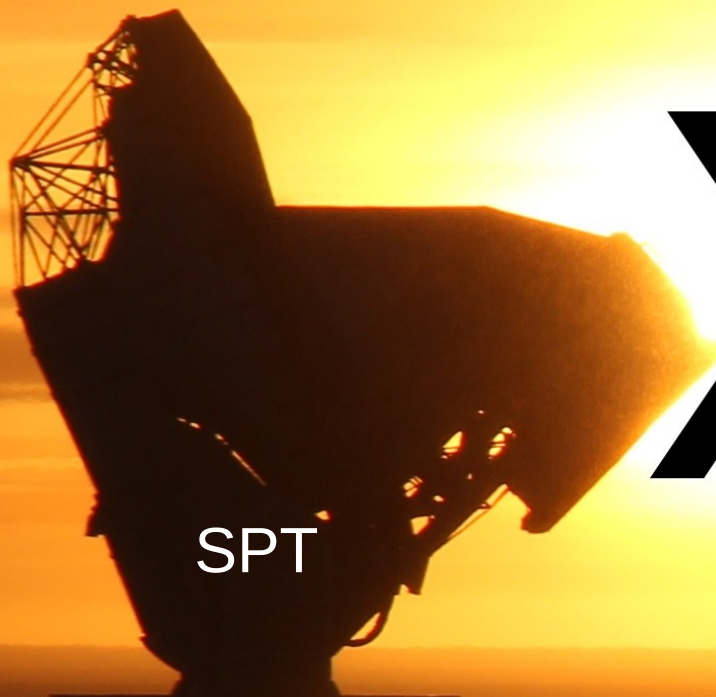
- 150 GHz Stokes Q Map, smoothed by 8 arcmin FWHM Gaussian.
- First year data: 2 years remaining.



500 deg² E-Mode 2D Spectrum

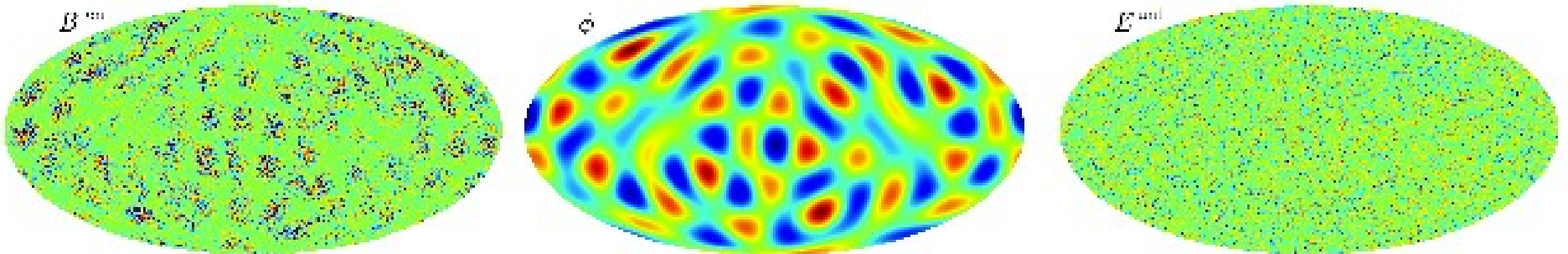


SPT/BICEP Cross Correlation



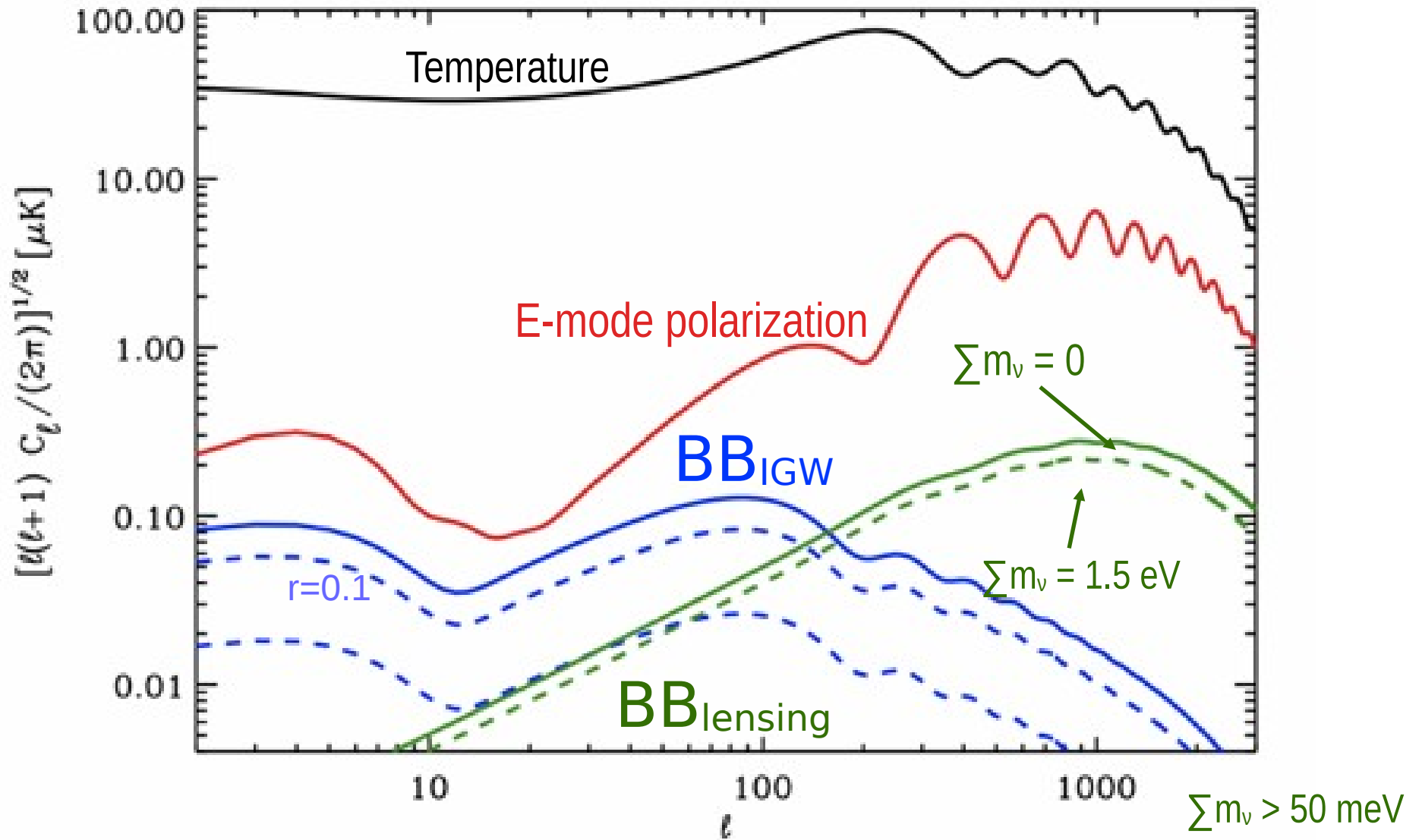
Eventual Delensing

$$B^{\text{lens}}(\vec{l}_B) \approx \int d^2 l_E \int d^2 l_\phi W^\phi(\vec{l}_E, \vec{l}_B, \vec{l}_\phi) E(\vec{l}_E) \phi(\vec{l}_\phi)$$



- Given E and ϕ , can estimate B^{lens}

CMB Polarization



The SPT Collaboration



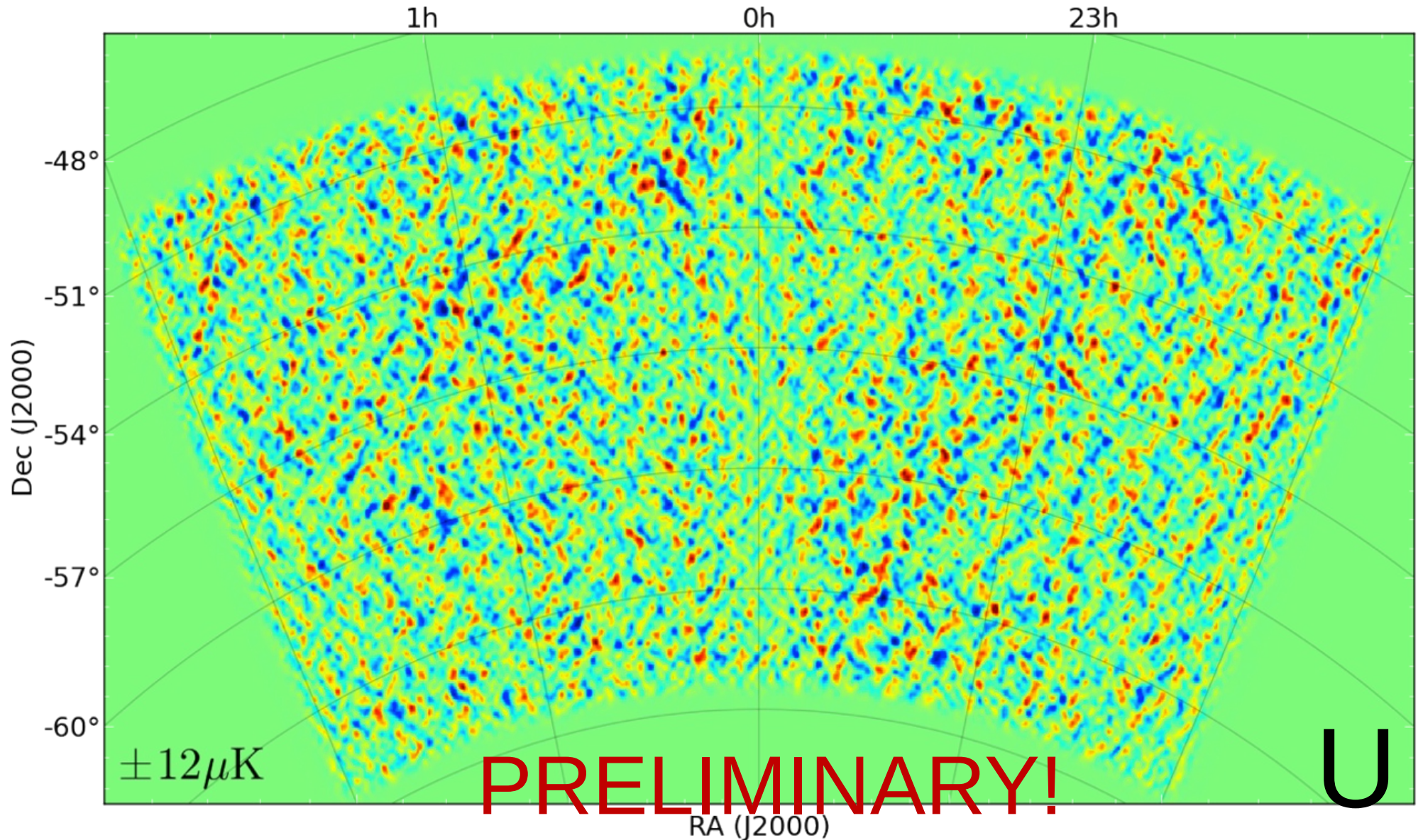




Thank You

500 Deg² Survey Field (2013)

- 150 GHz Stokes Q Map, smoothed by 8 arcmin FWHM Gaussian.
- First year data: 2 years remaining.



Old SPT Noise Numbers

	Focal Plane NET ($\mu\text{K s}^{0.5}$)			
Freq(GHz)	95	150	220	Total
SPT-SZ	60	24.2	115	22.0
SPTpol	30	14.7	---	13.2
SPT-3G	7.2	4.5	7.5	3.4

BICEP2 was 17 $\mu\text{K rtsec}$ in temp

Main Fields	Summer	Sources	Aux
<p>Deep Field</p> <p>ra23h30dec-55 143.8 days</p> <p>150 GHz 7.7T 8.7Q 9.0U uK*arcmin 90 GHz 14.0T 17.9Q 19.6U uK*arcmin</p> <p>2012-Feb to 2012-Nov 2013-Mar to 2013-Apr</p>	<p>ra5h30dec-55 31.4 days</p> <p>2012-Mar 2013-Mar</p>	<p>rcw38 50.1 days</p>	<p>calsource 43.1 days</p>
	<p>ra23hdec-35 16.6 days 29.8, 60.6</p> <p>2014-Jan</p>		
<p>Survey Field</p> <p>ra0hdec-57.5 229.4 days</p> <p>150 GHz T: 9T 12Q 13U uK*arcmin 90 GHz T: 19T 27Q 29U uK*arcmin</p> <p>2013-May to 2013-Nov 2014-Mar to today</p>	<p>ra1hdec-35 10.8 days 26.9, 55.5</p>	<p>mat5a 28.2 days</p>	<p>elnod 12.1 days</p>
	<p>ra3hdec-35 6.9 days 28.9, 54.9</p>		<p>noise 11.5 days</p>
	<p>ra5hdec-35 9.8 days 29.8, 54.9</p>	<p>cena 17.8 days</p>	<p>polcal 10.3 days</p>
	<p>ra3hdec-25 11.1 days 29.7, 47.8</p>		
	<p>venus moon mars</p>		
373.2	86.6	100.7	77.1

Total: 637.6 days out of 998.7 deployed. (63.8% used)