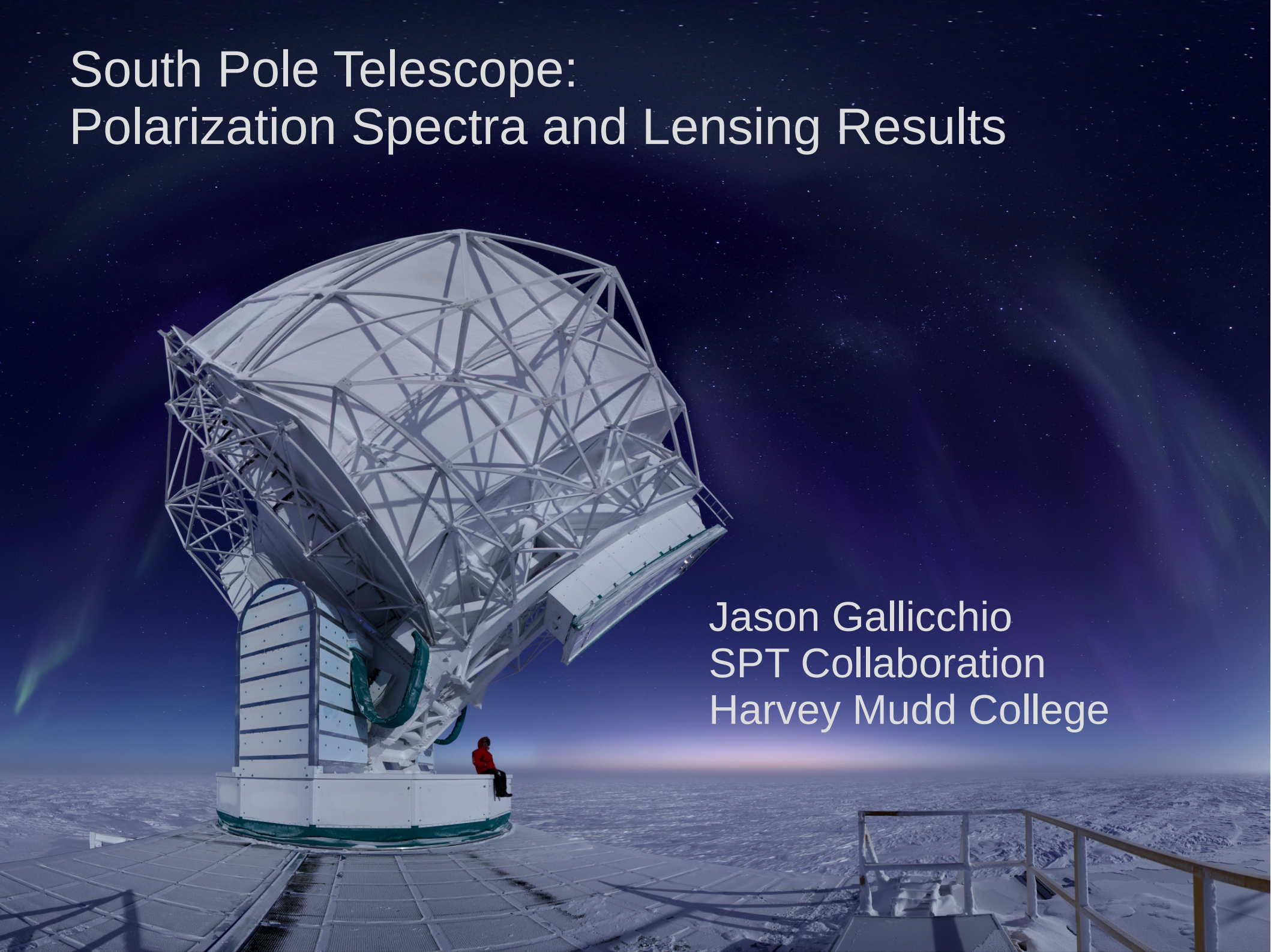
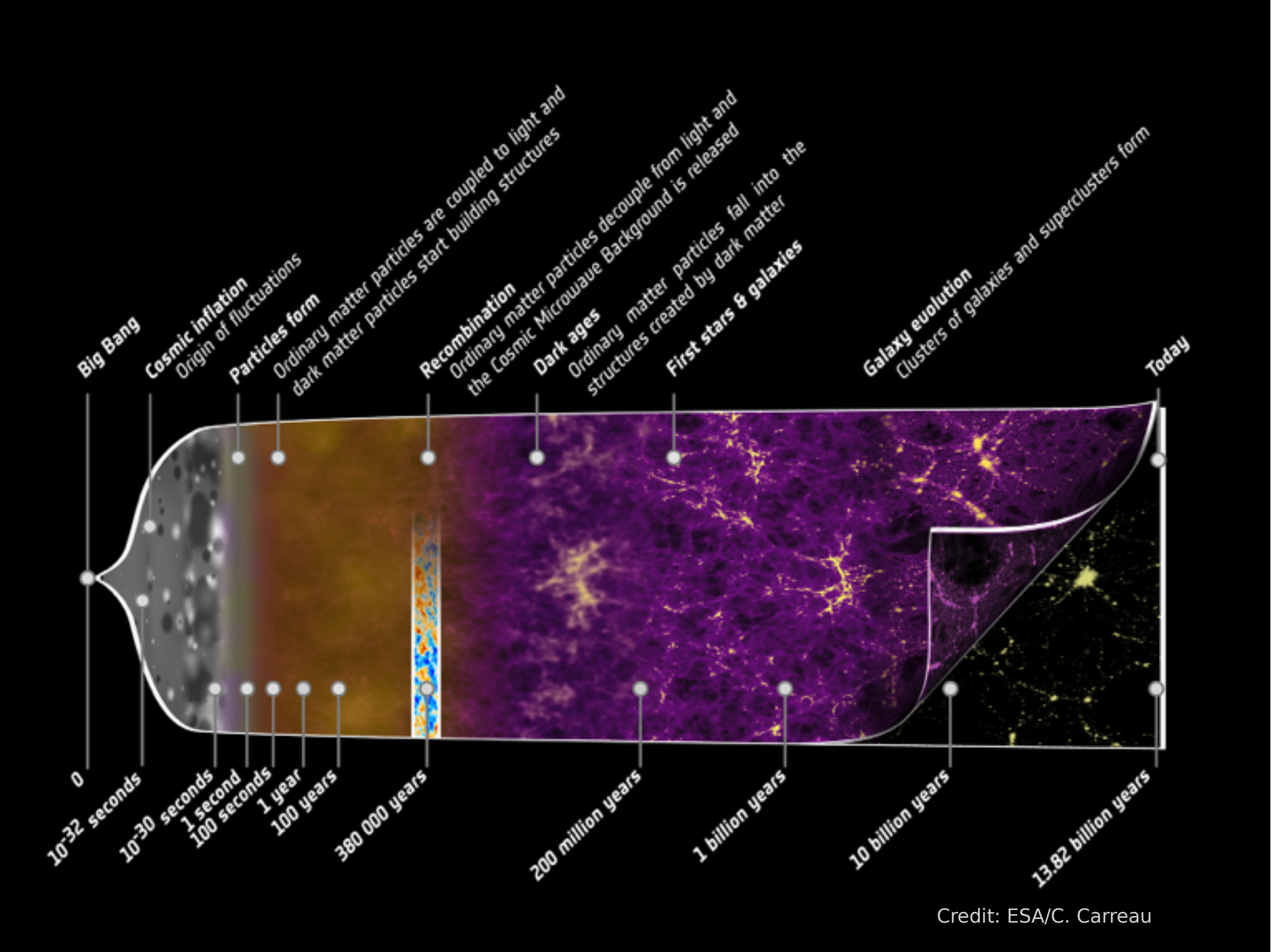
South Pole Telescope: Polarization Spectra and Lensing Results

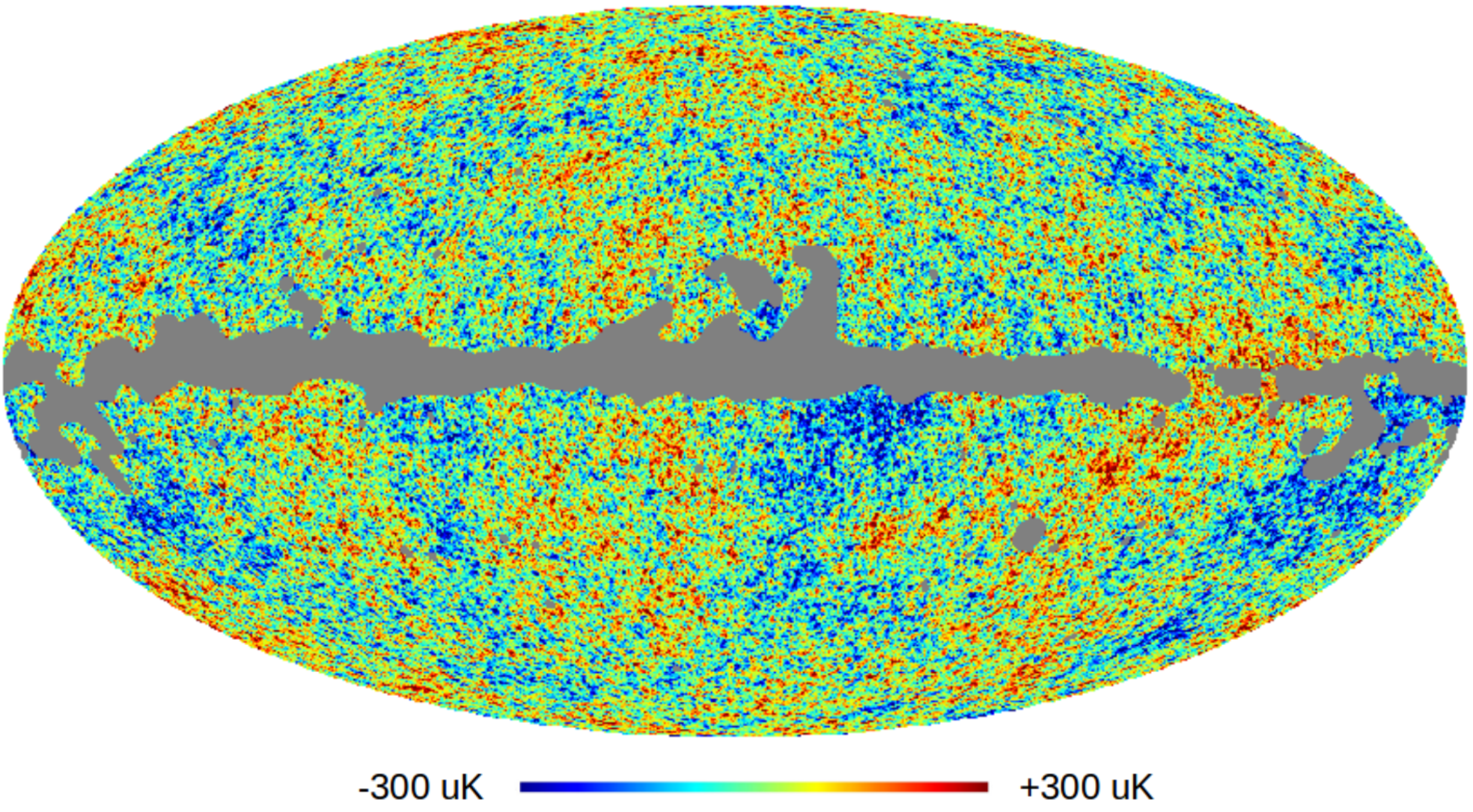


Jason Gallicchio
SPT Collaboration
Harvey Mudd College

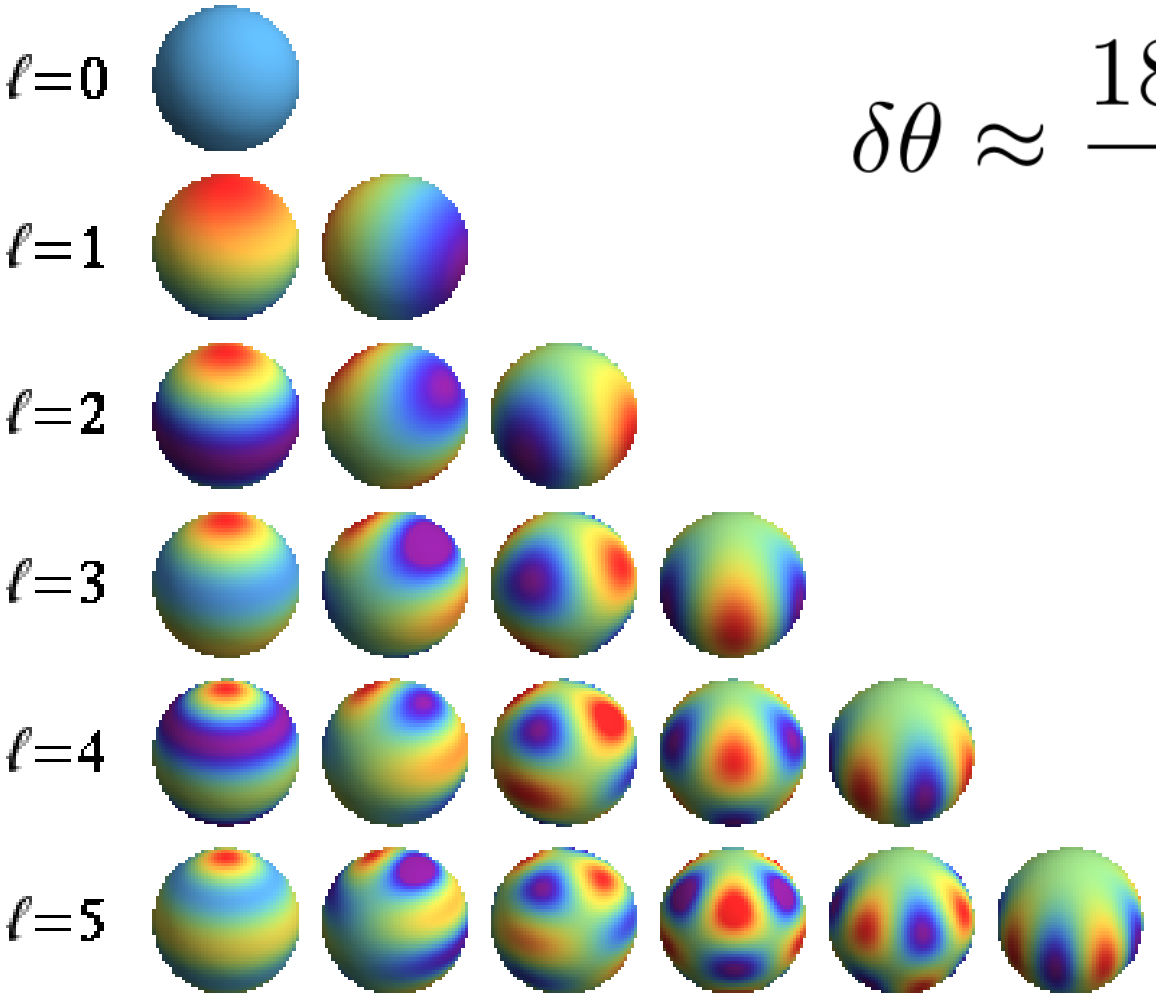


Credit: ESA/C. Carreau

Planck CMB Map

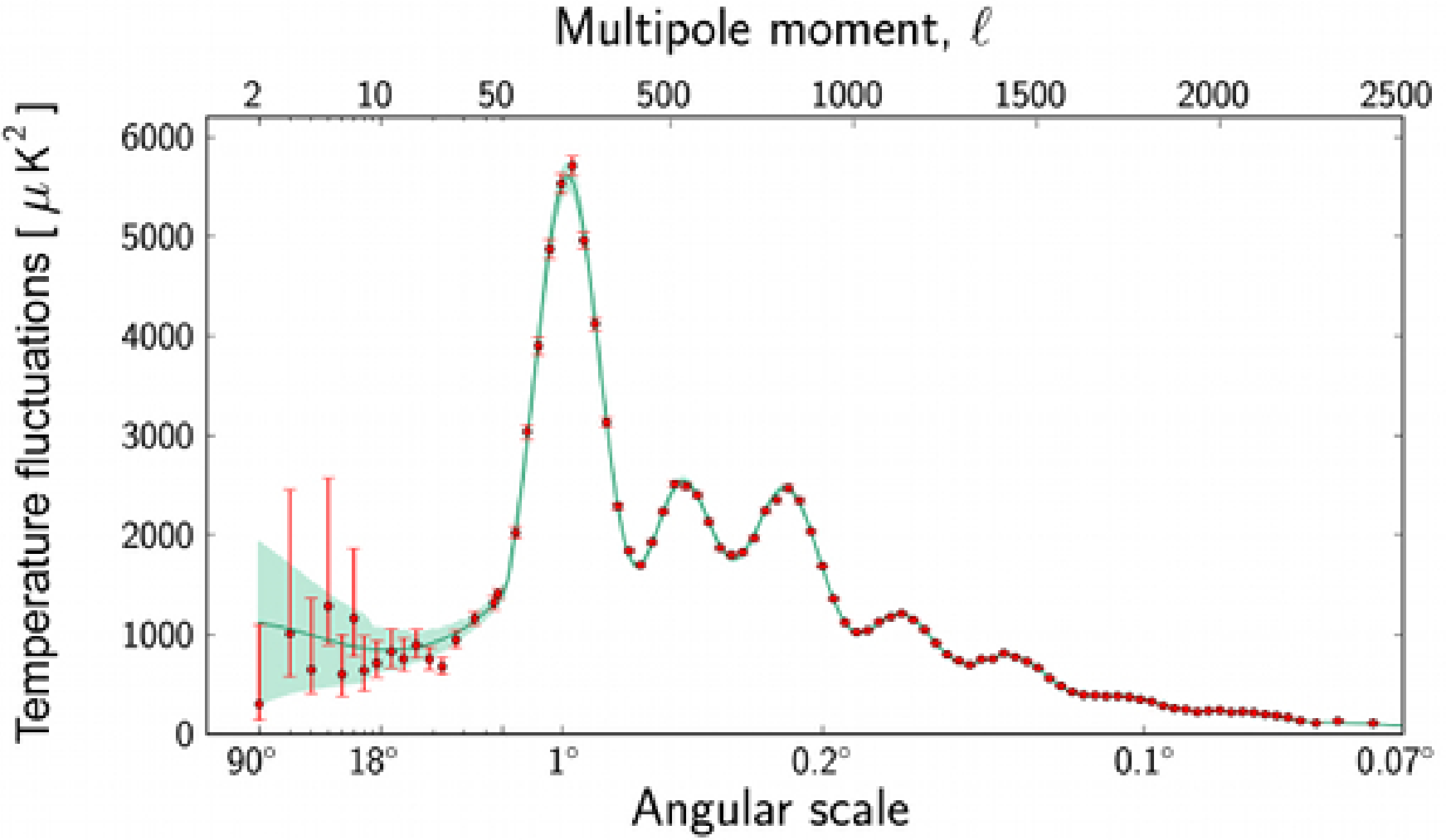


Spherical Harmonic Multipoles



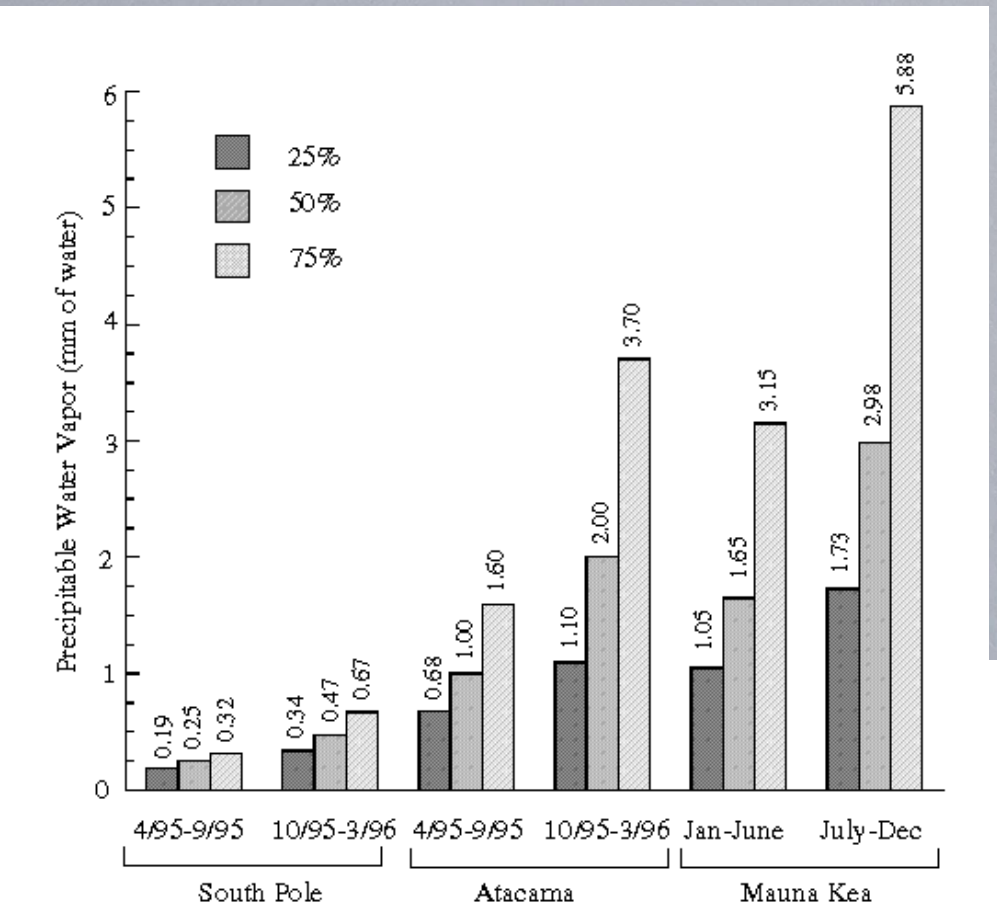
$$\delta\theta \approx \frac{180^\circ}{\ell}$$

Planck Temperature Spectrum



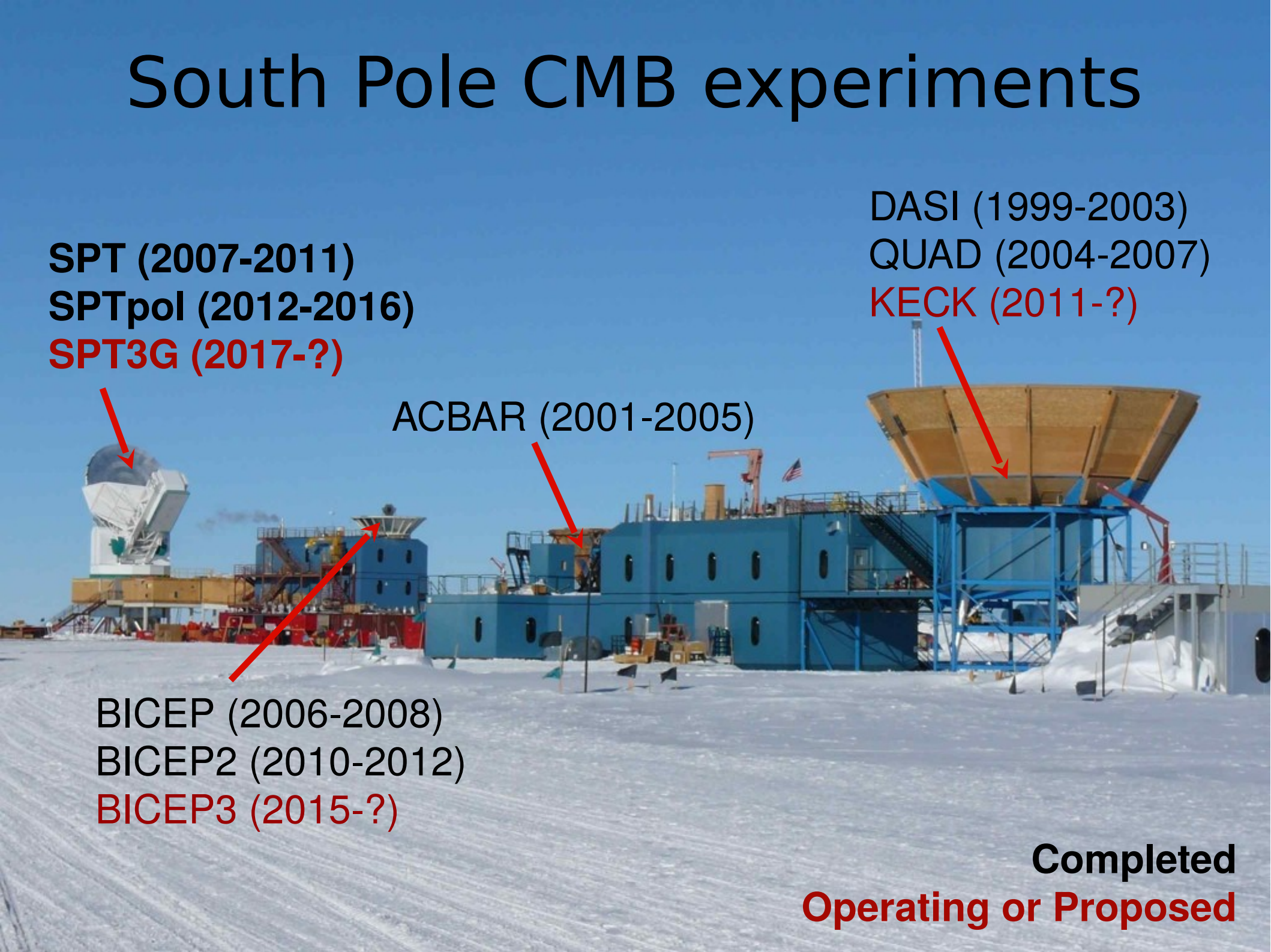
Why the South Pole?

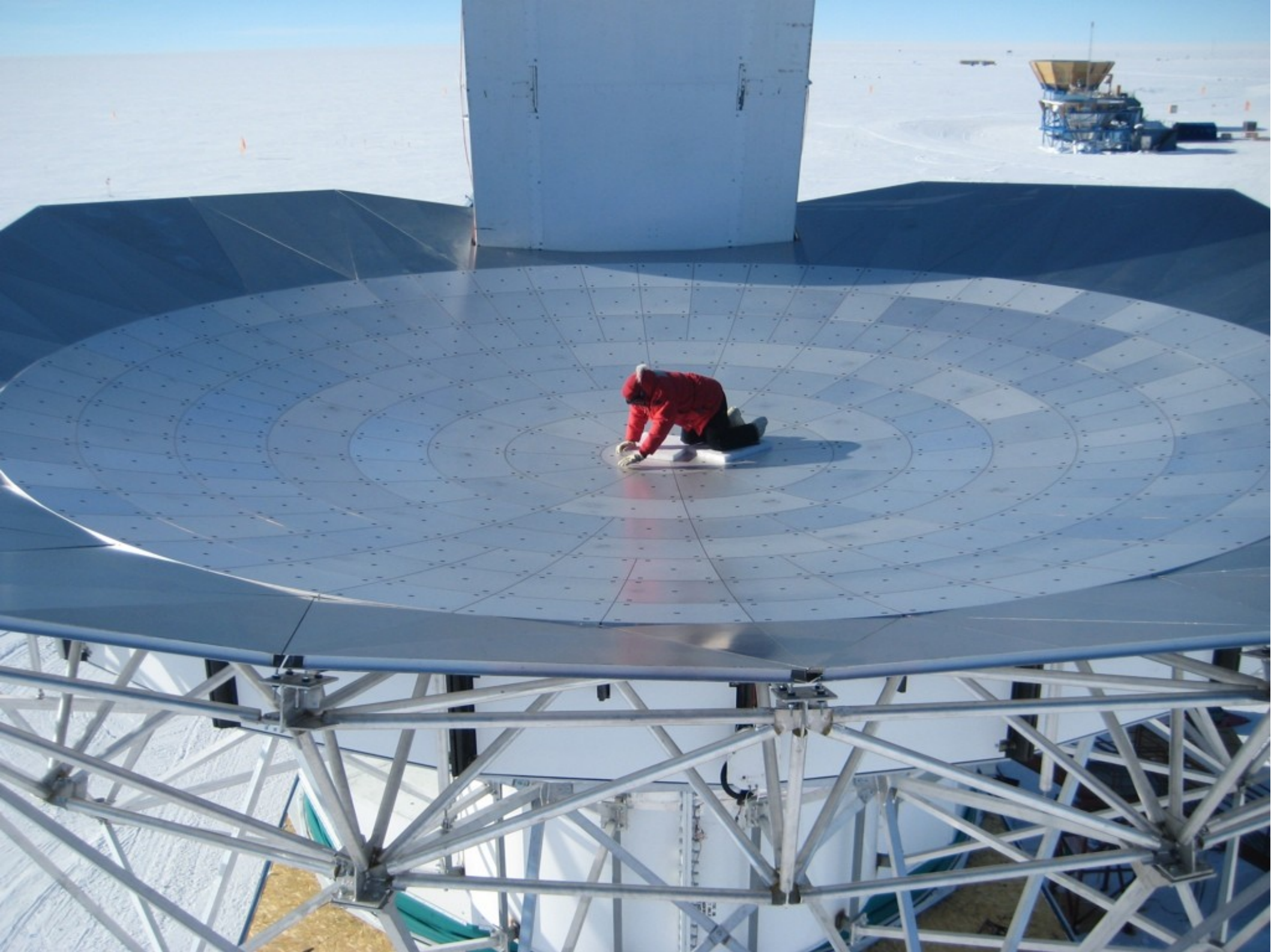
Why the South Pole?

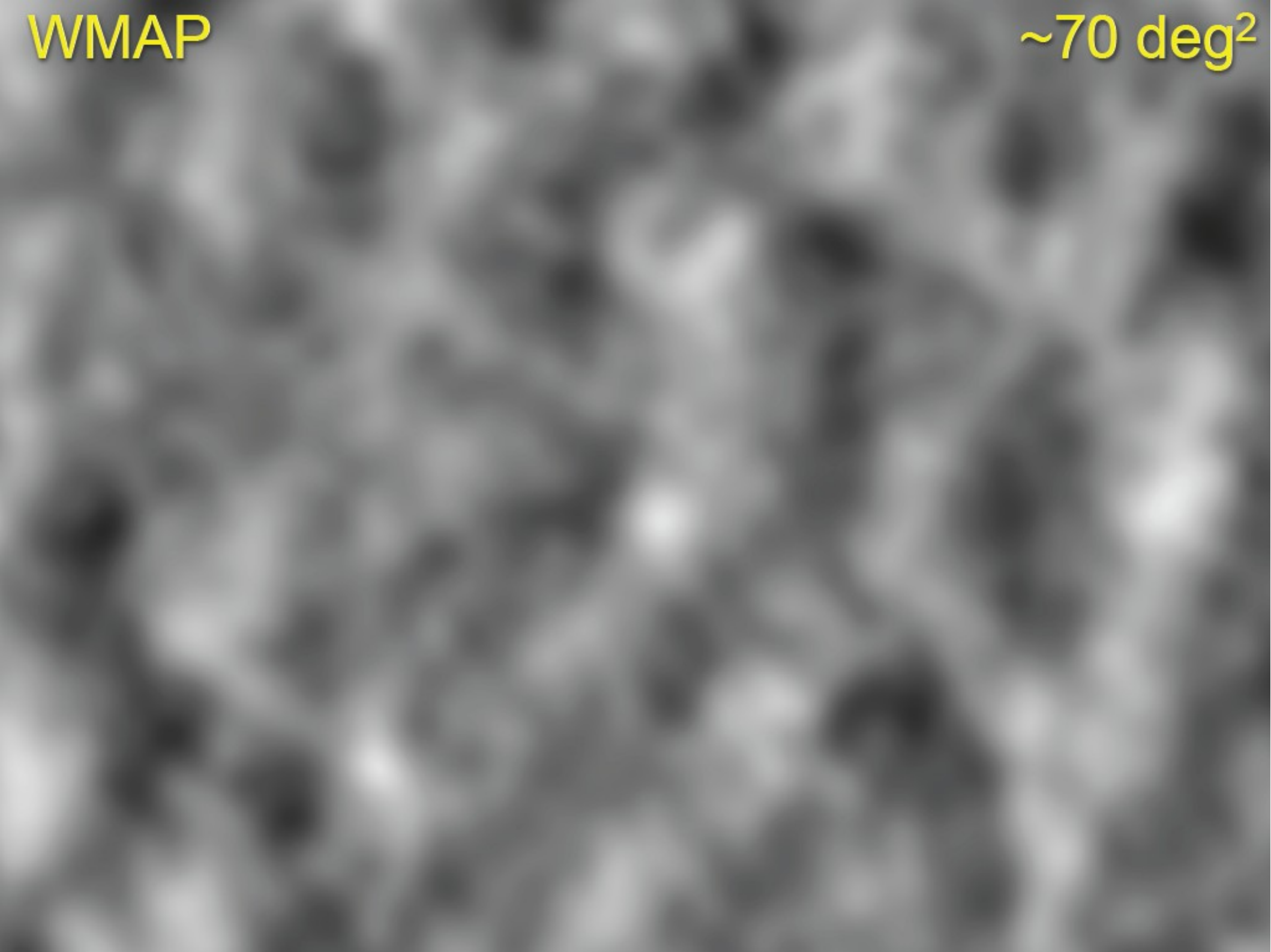


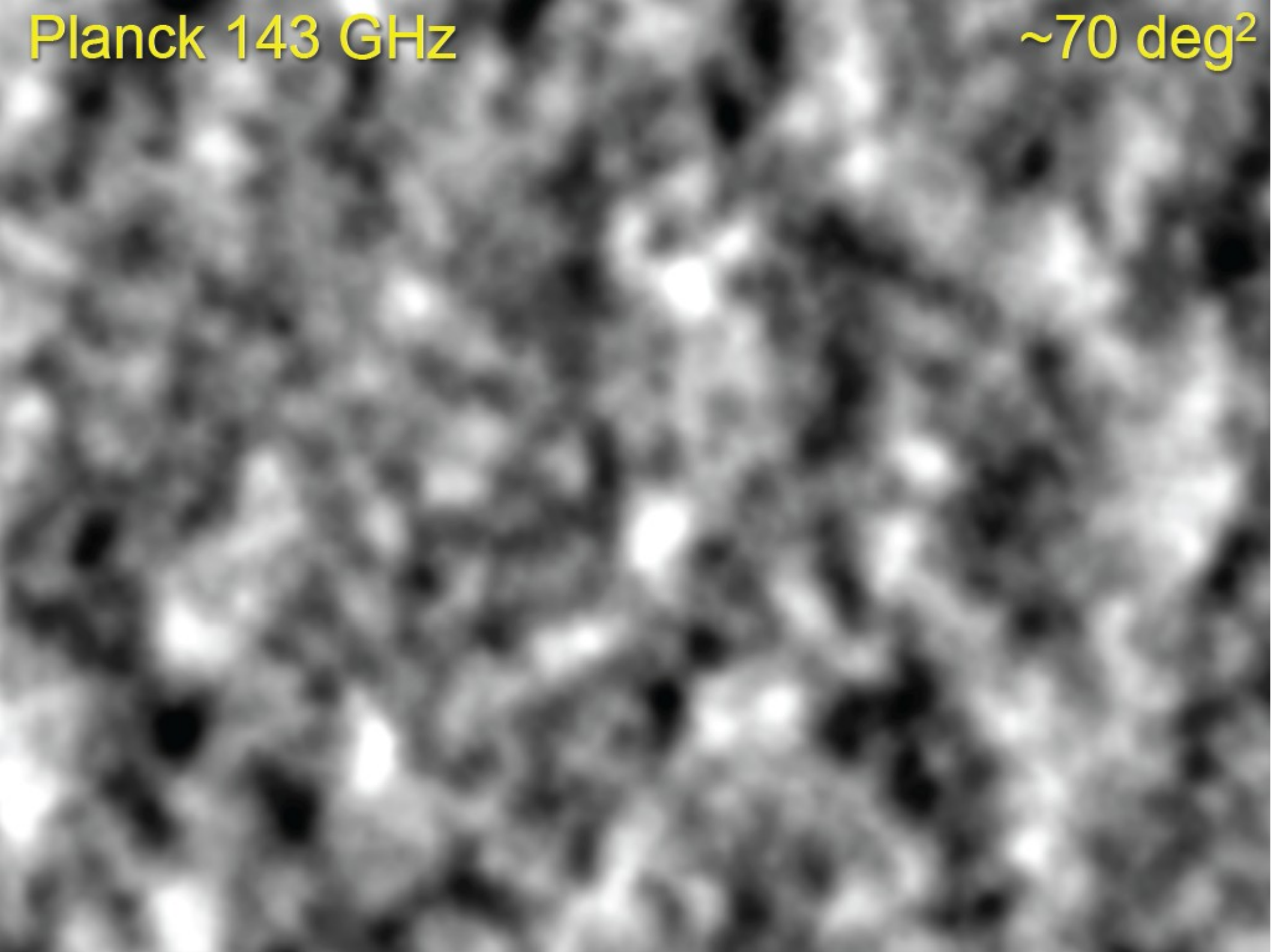
- Precipitable water vapor (PWV) is the bane of ground-based mm-wave experiments

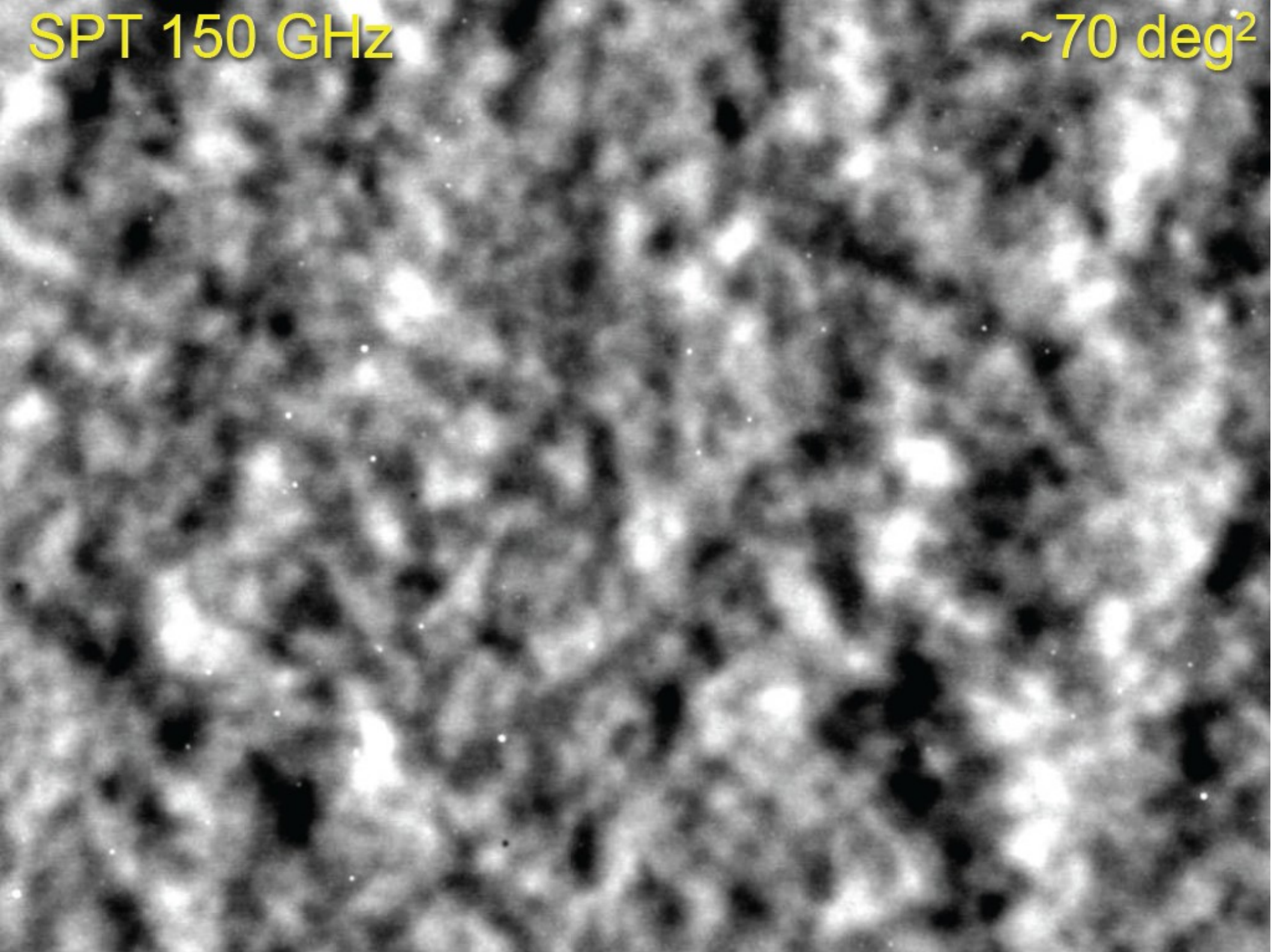
South Pole CMB experiments

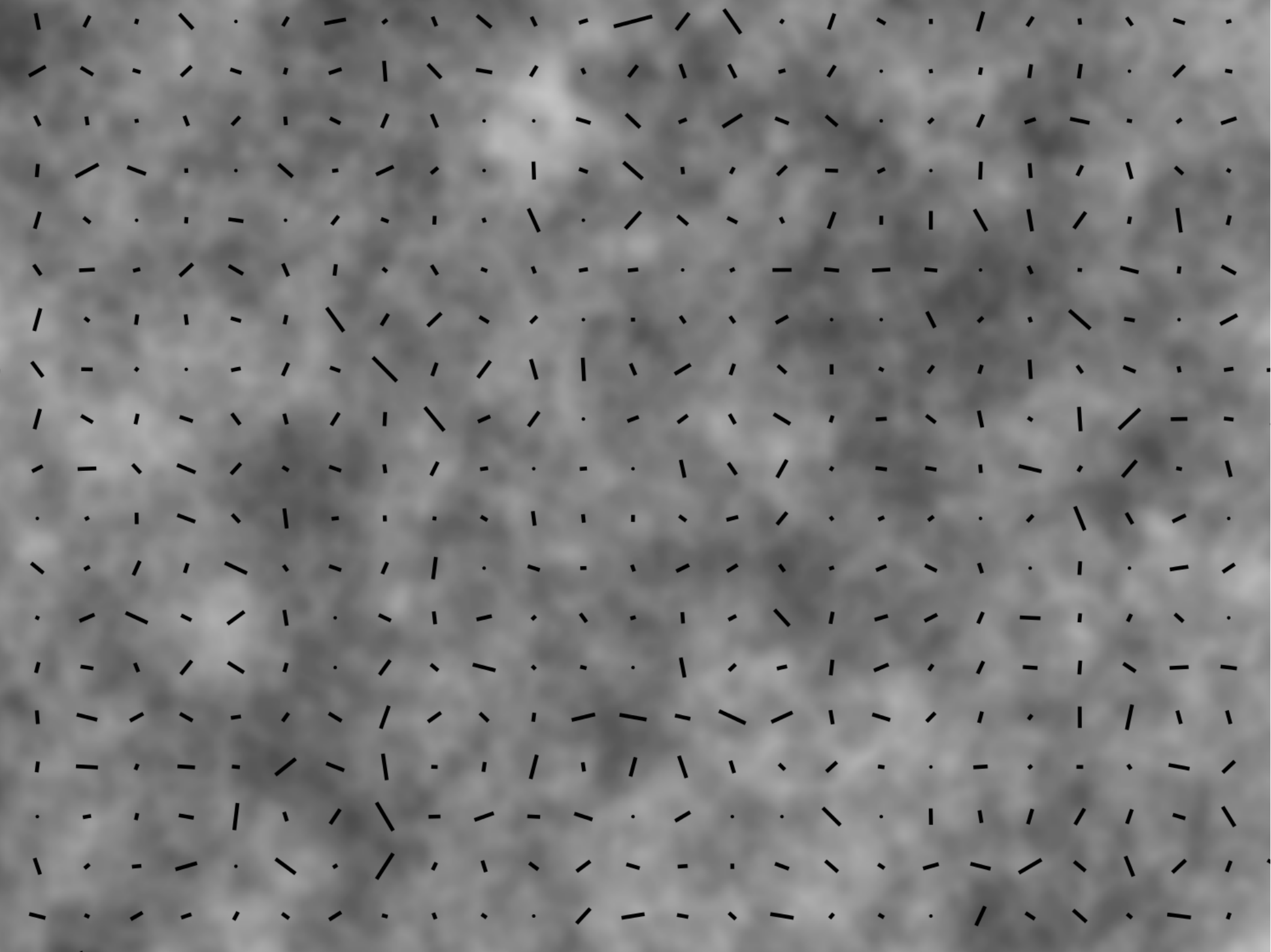




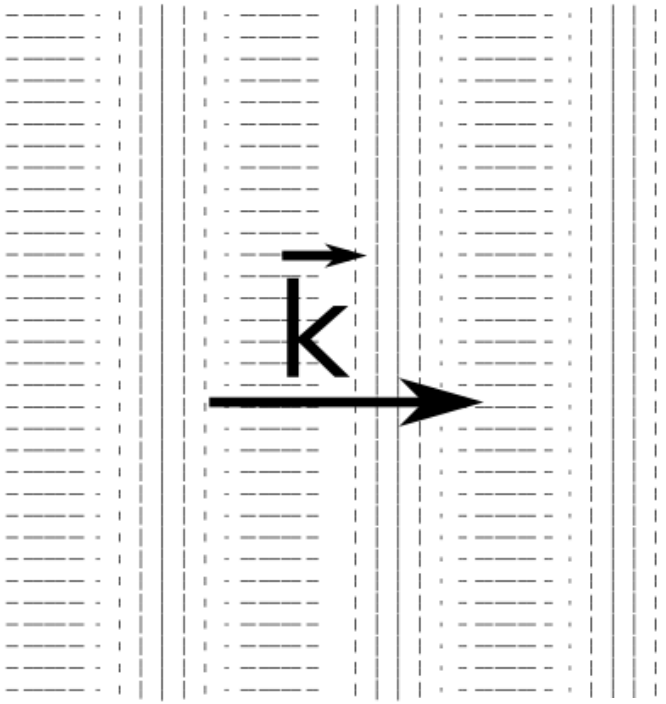

WMAP
~70 deg²


Planck 143 GHz
~70 deg²

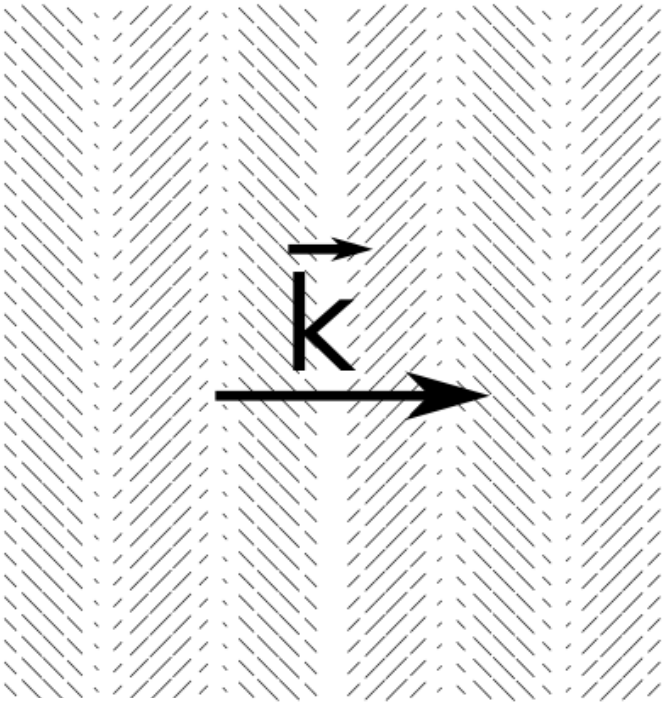

SPT 150 GHz
~70 deg²

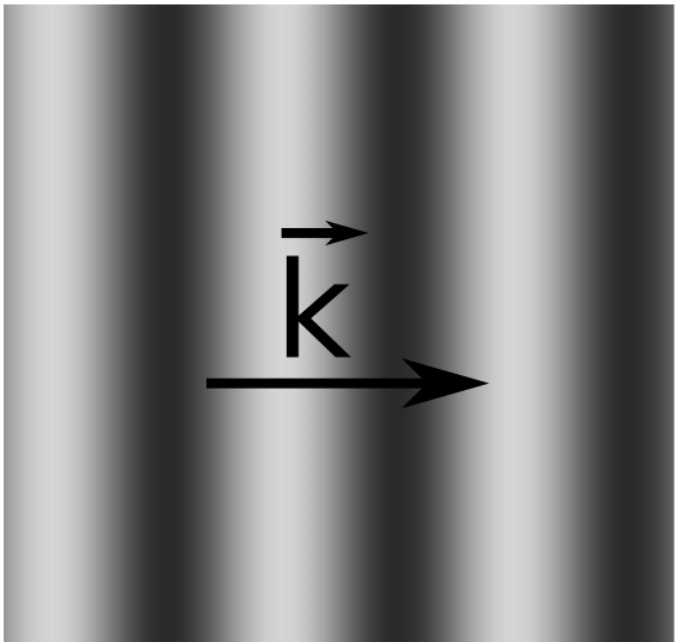


E Modes

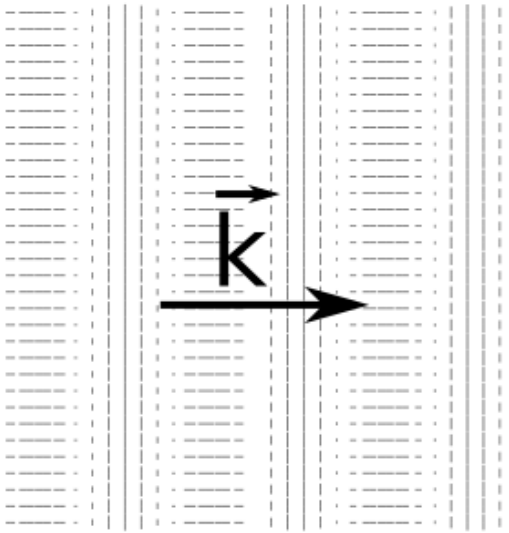


B Modes

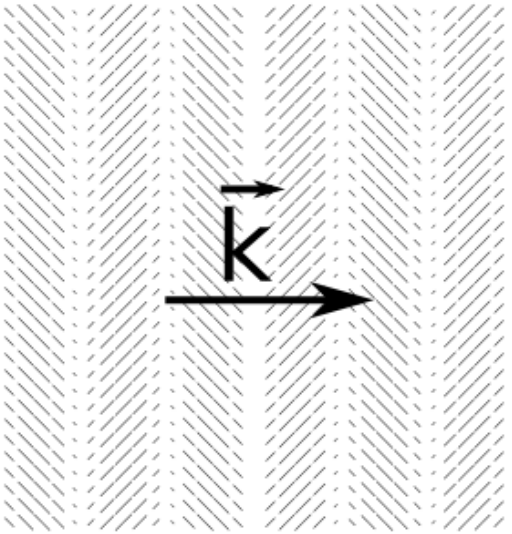




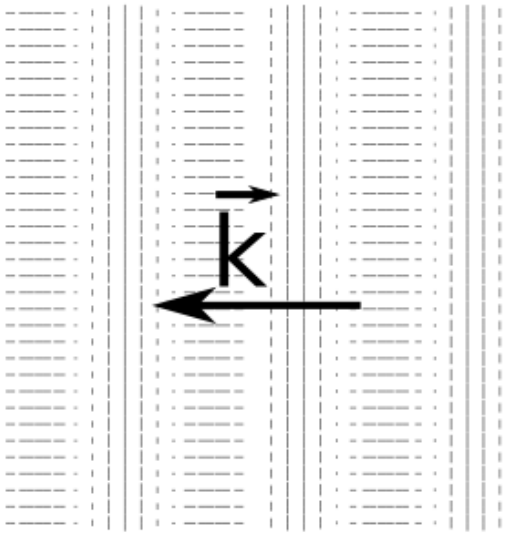
E Modes

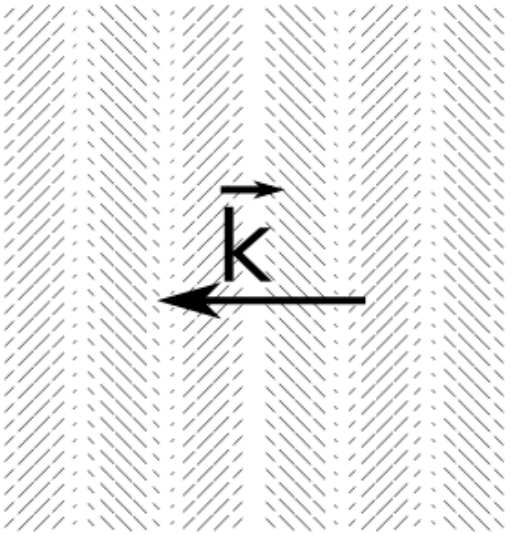


B Modes



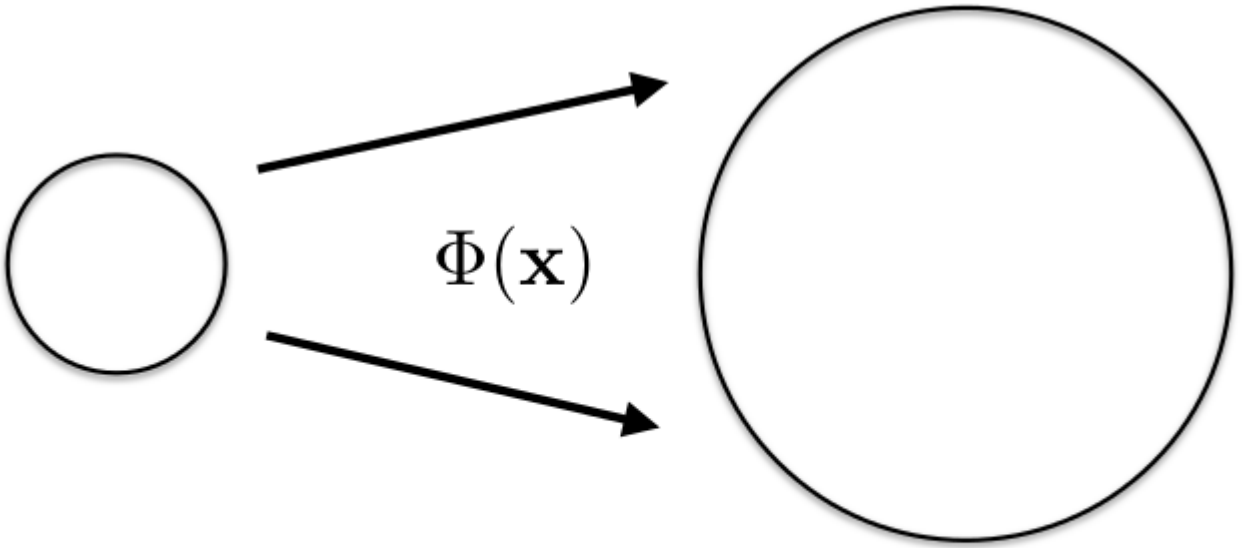
Parity Flip:





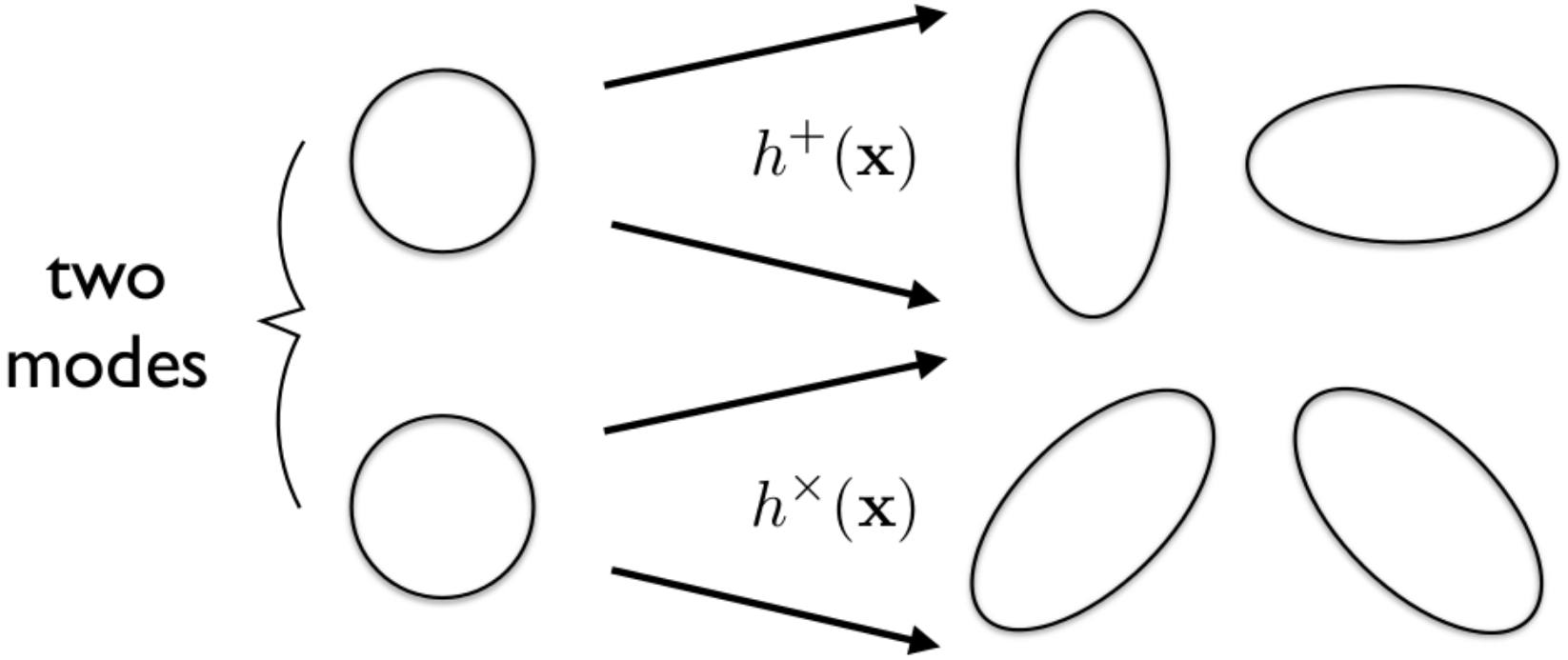
(send $\vec{k}$ to $-\vec{k}$ and reflect the polarization at each point)

Scalar Fluctuations

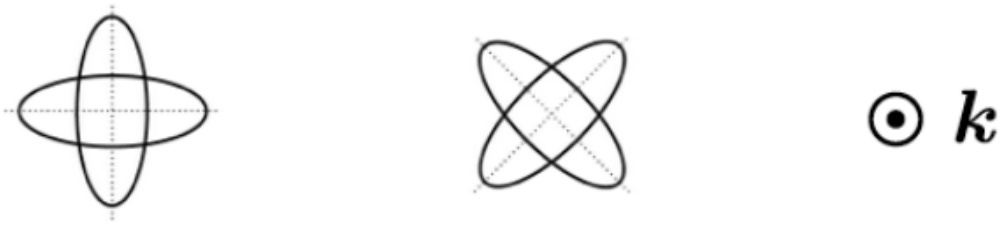


"Stretching that preserves shape"

Gravity (Tensor) Fluctuations

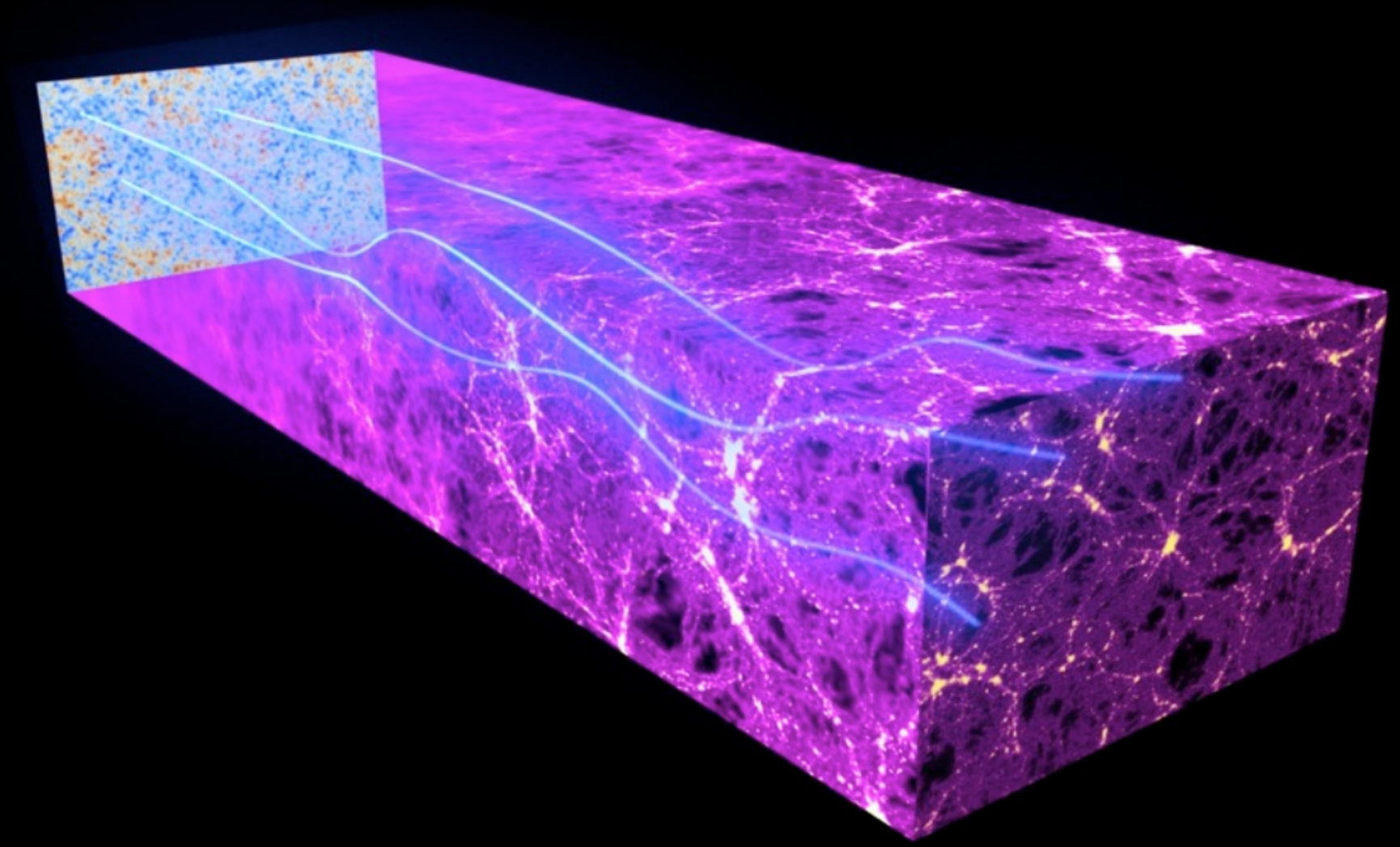


"Stretching that preserves volume"



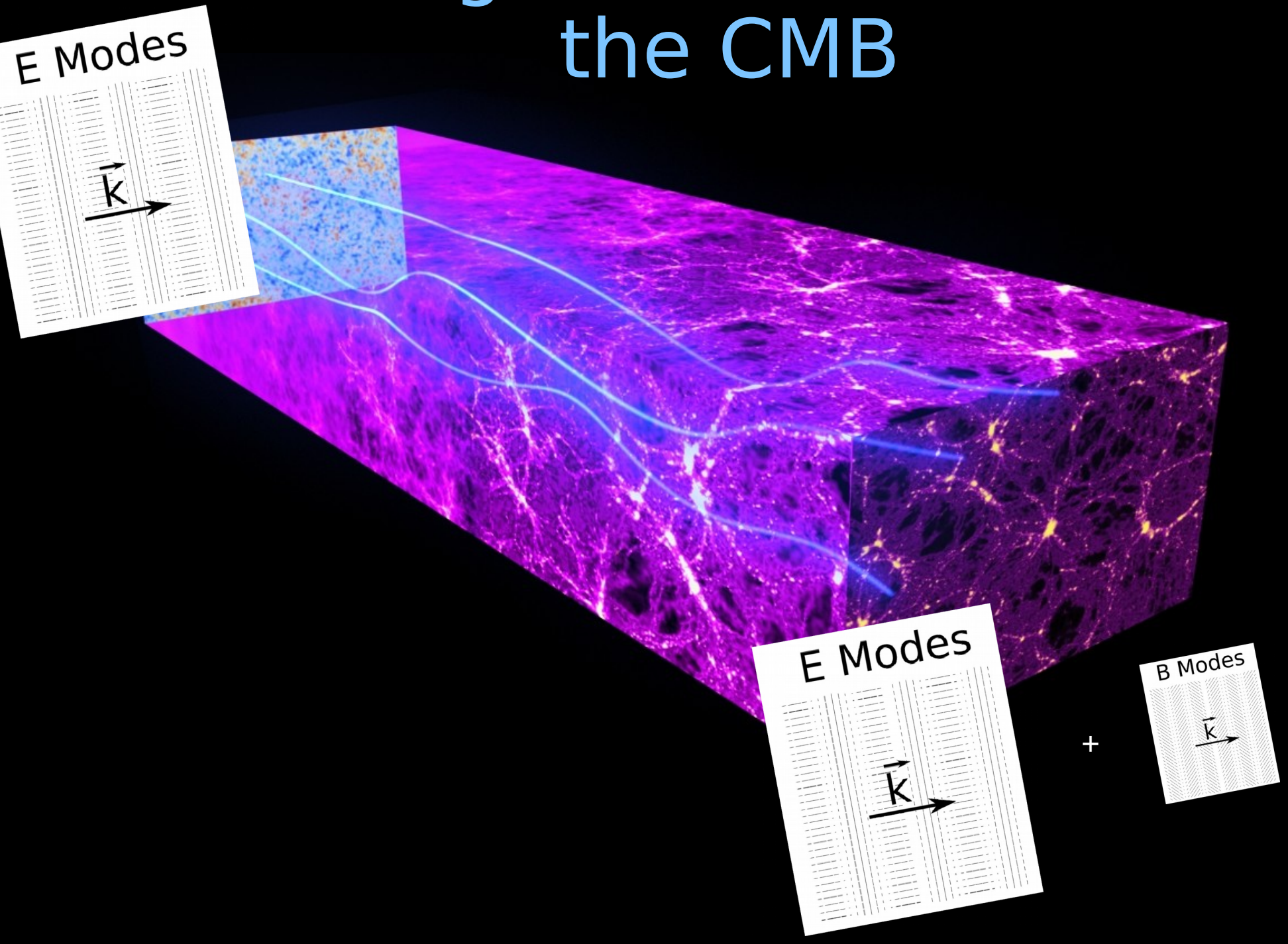
These are gravitational waves!

Gravitational Lensing of the CMB



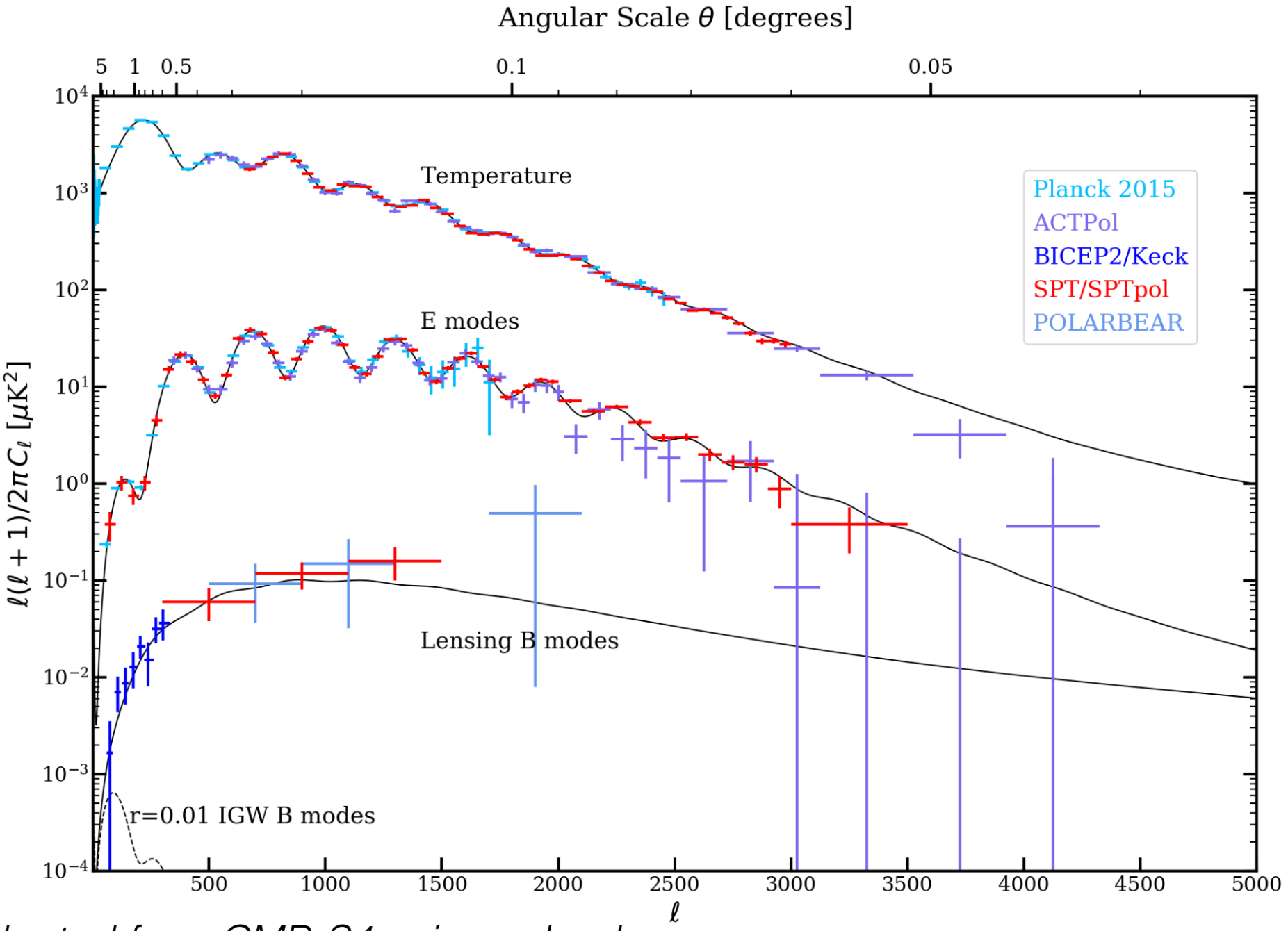
ESA

Lensing the *Polarization* of the CMB



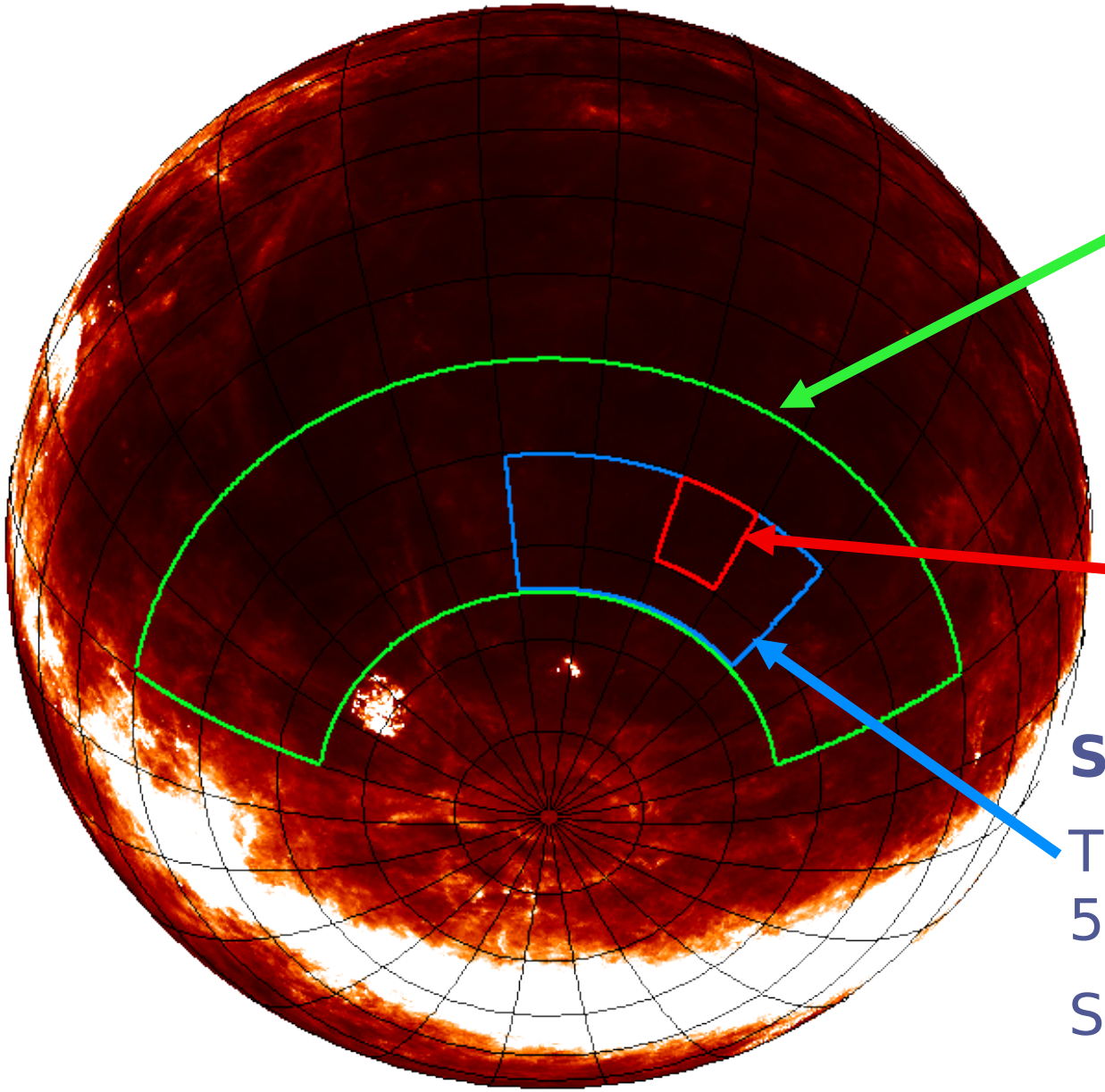
ESA

CMB Power Spectra



Adapted from CMB-S4 science book

SPTpol fields: Deep & Survey



SPT-SZ

2500 deg²

Deep Field

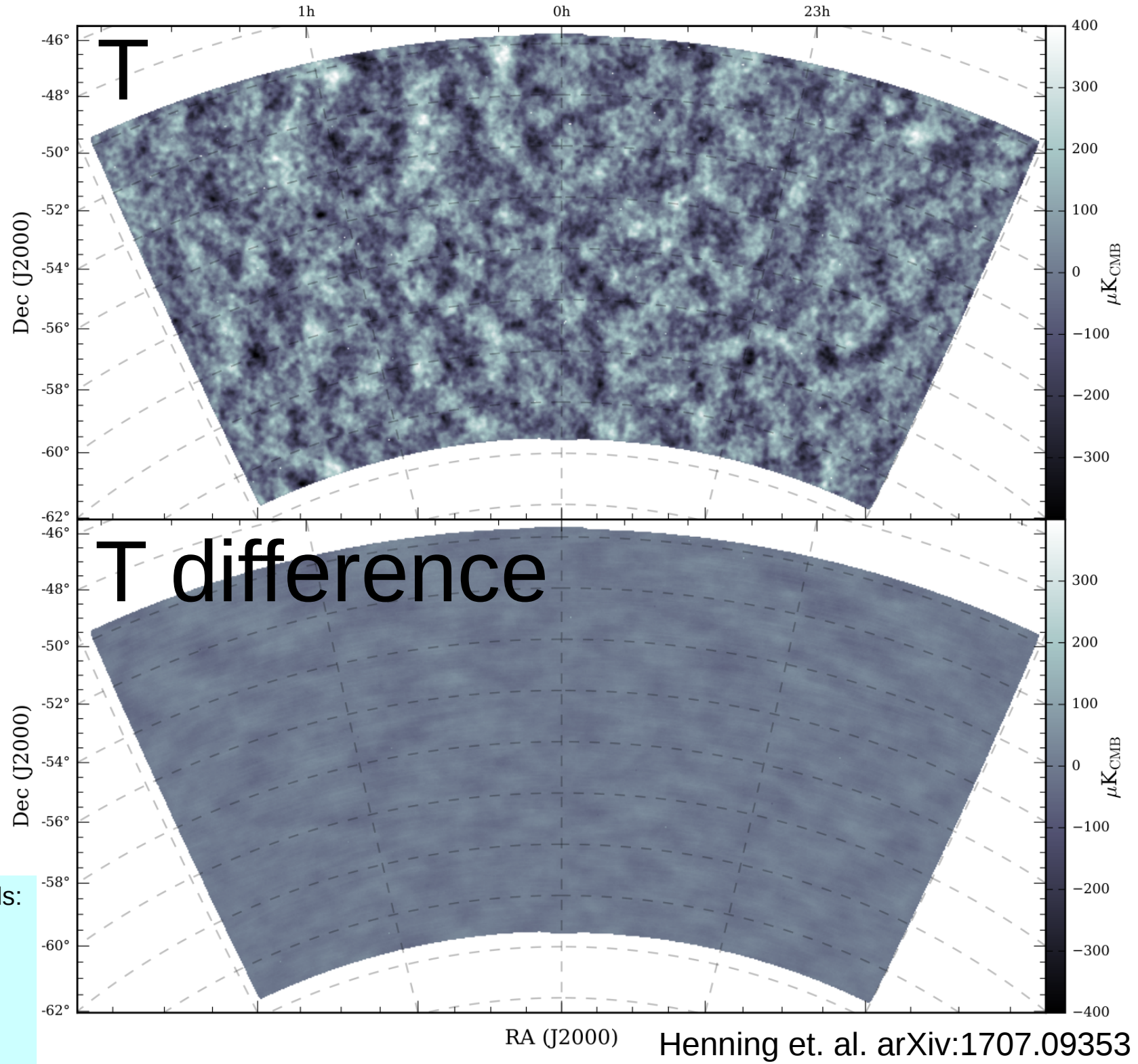
First year,
100 deg²

Survey Field

Three years,
500 deg²

Same as BICEP

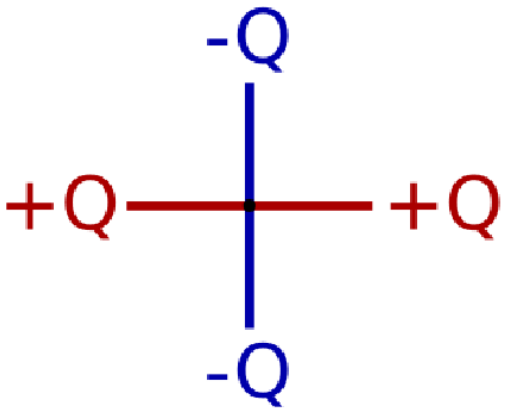
IRAS from Schlegel et al. 1998

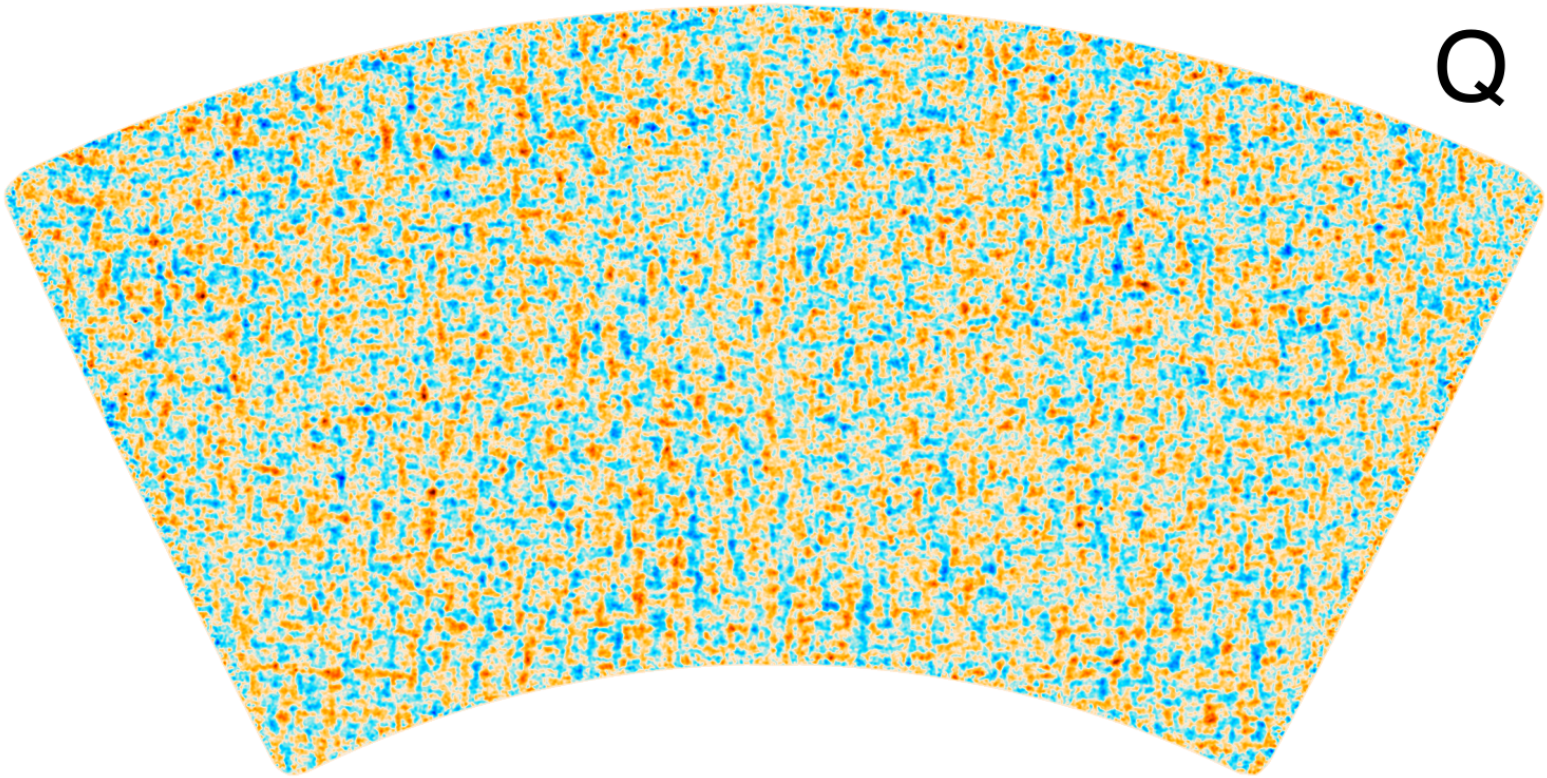


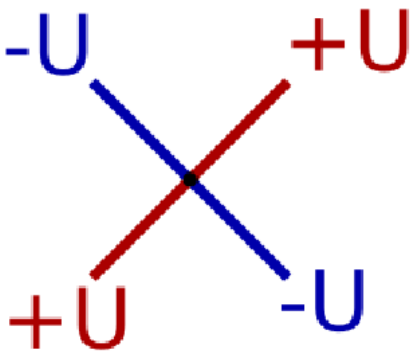
SPTpol Temp noise levels:
150 GHz: 5 uK-arcmin
90 GHz: 10 uK-arcmin

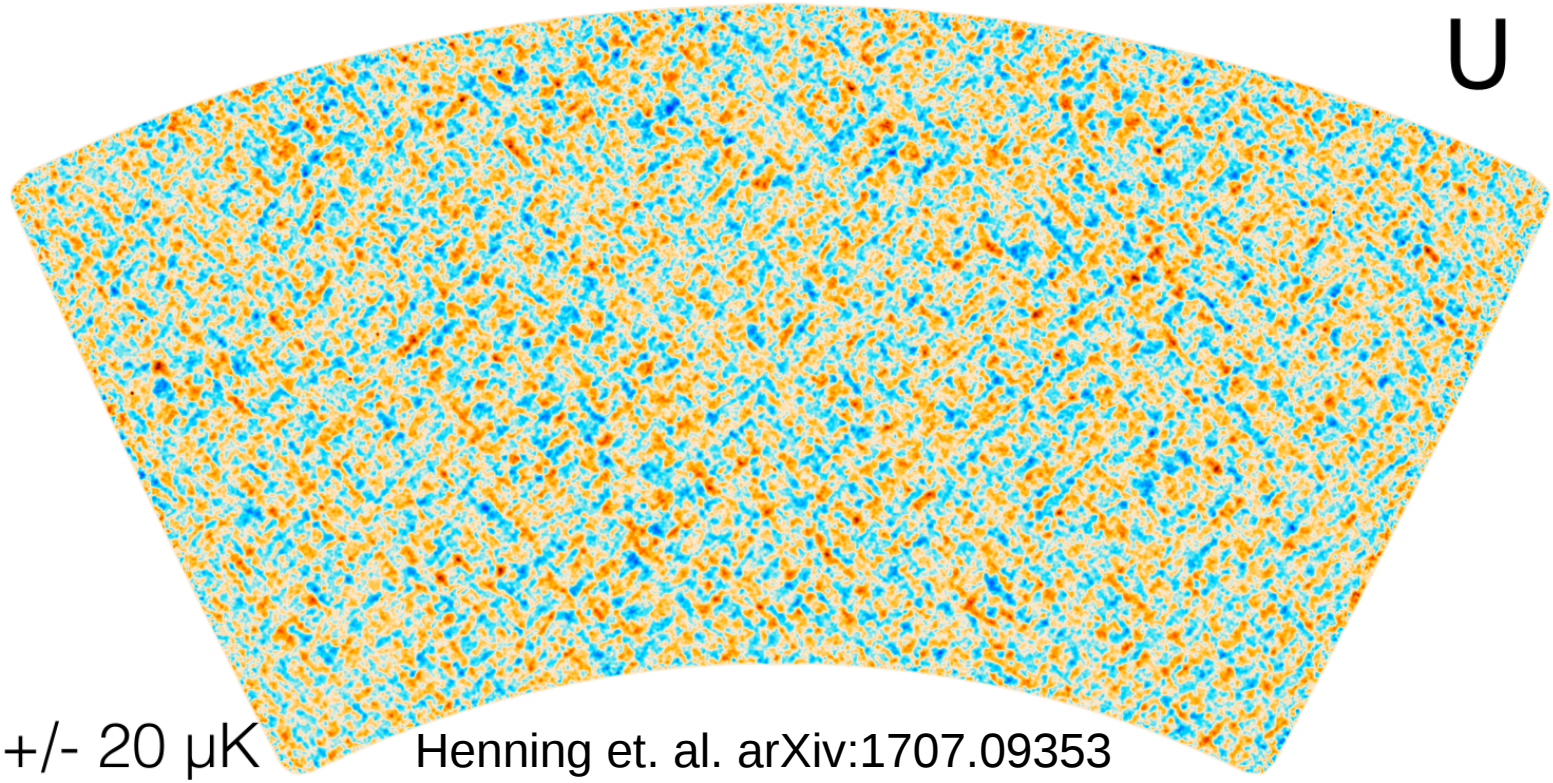
√2 less within the
100 deg^2 sub field.

Henning et. al. arXiv:1707.09353



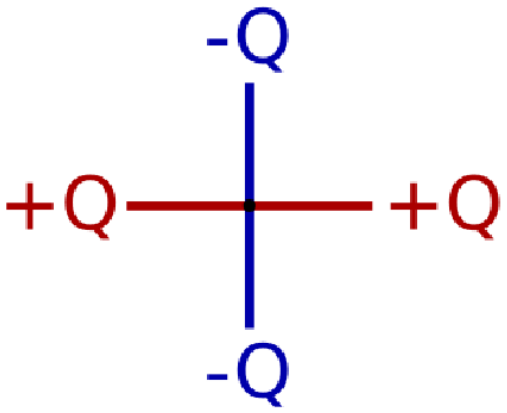


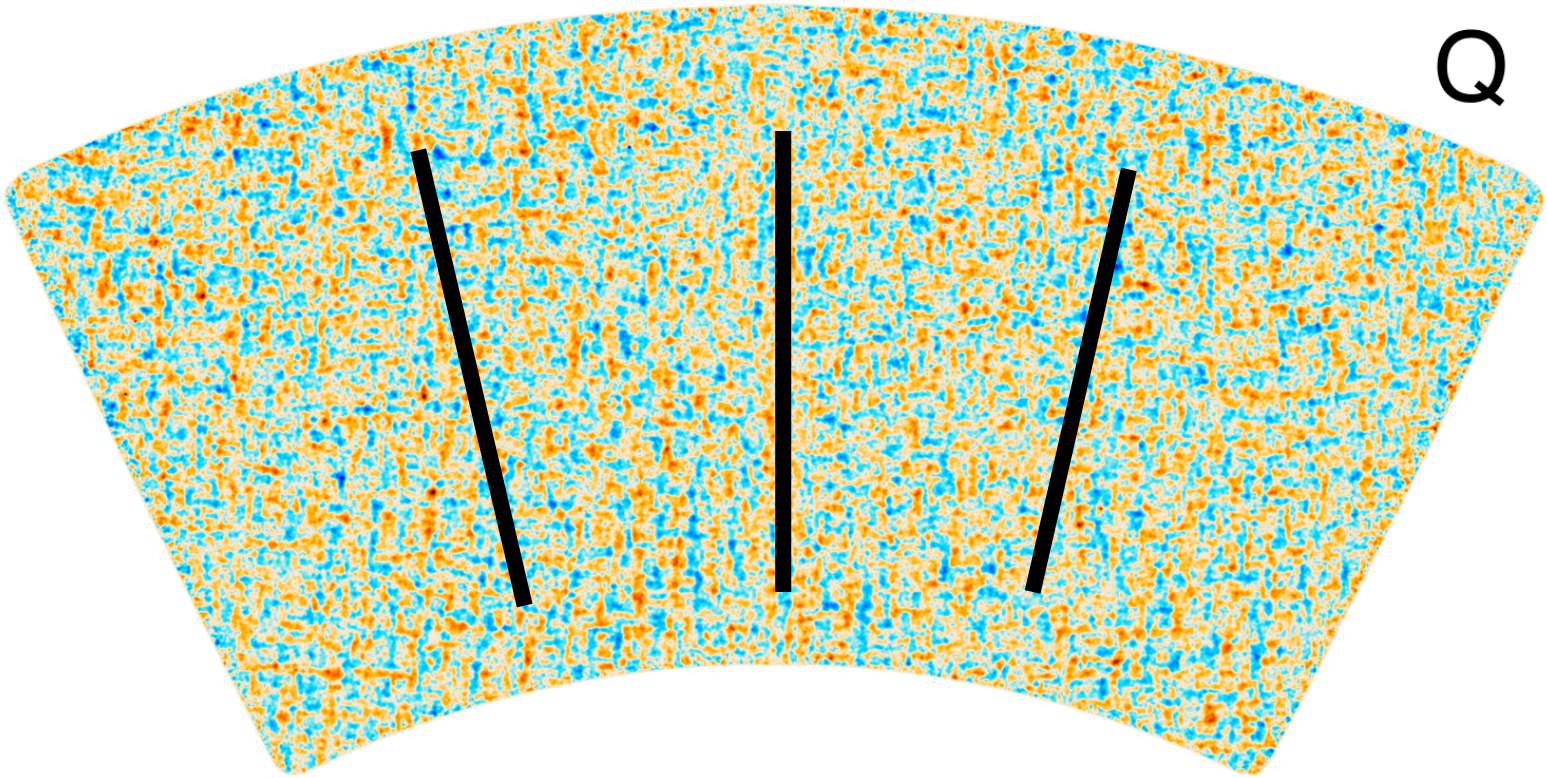


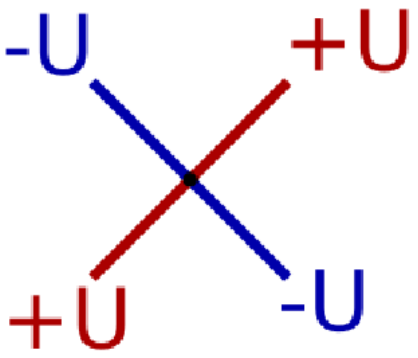


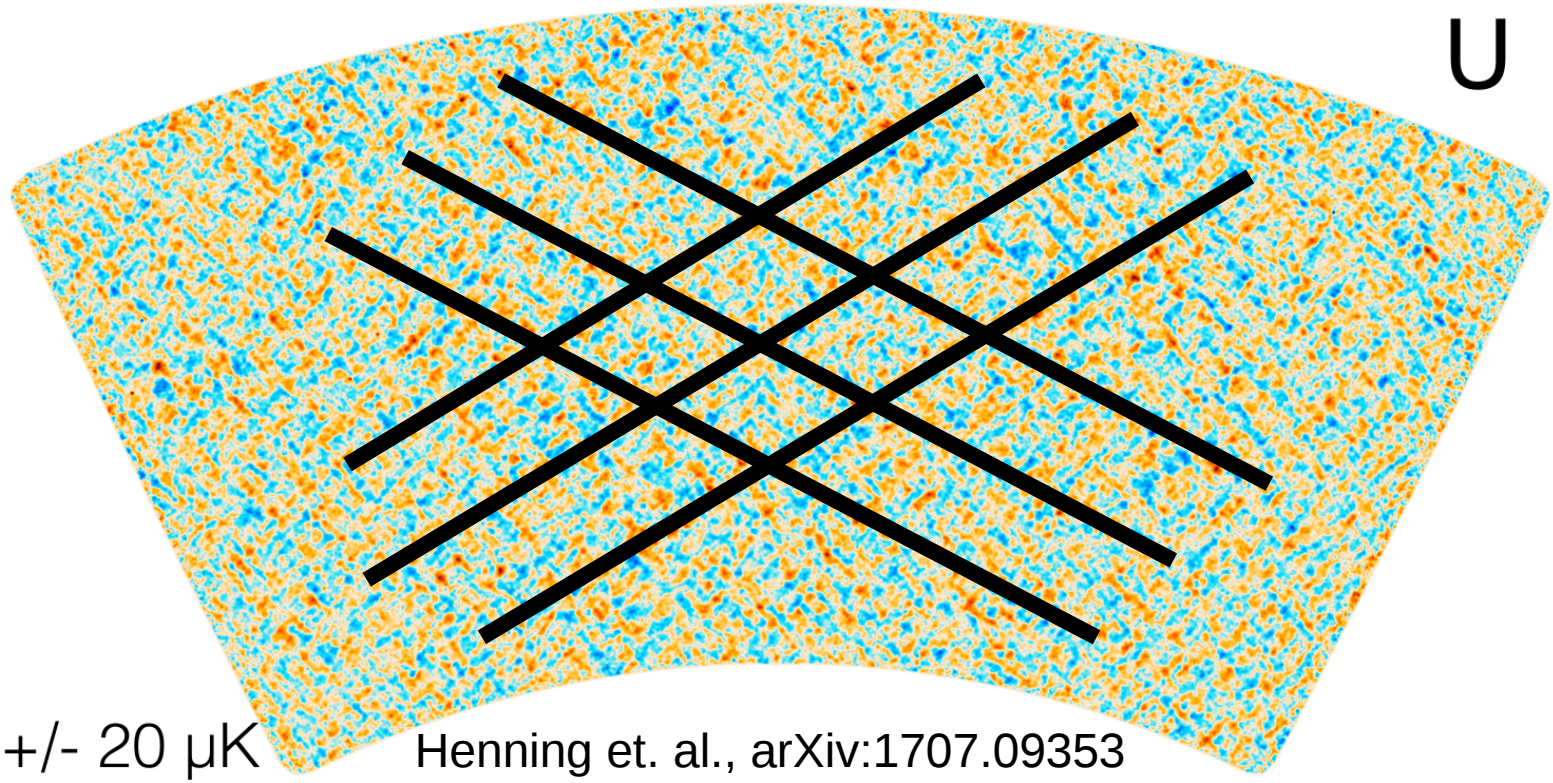
+/- 20 μK

Henning et. al. arXiv:1707.09353



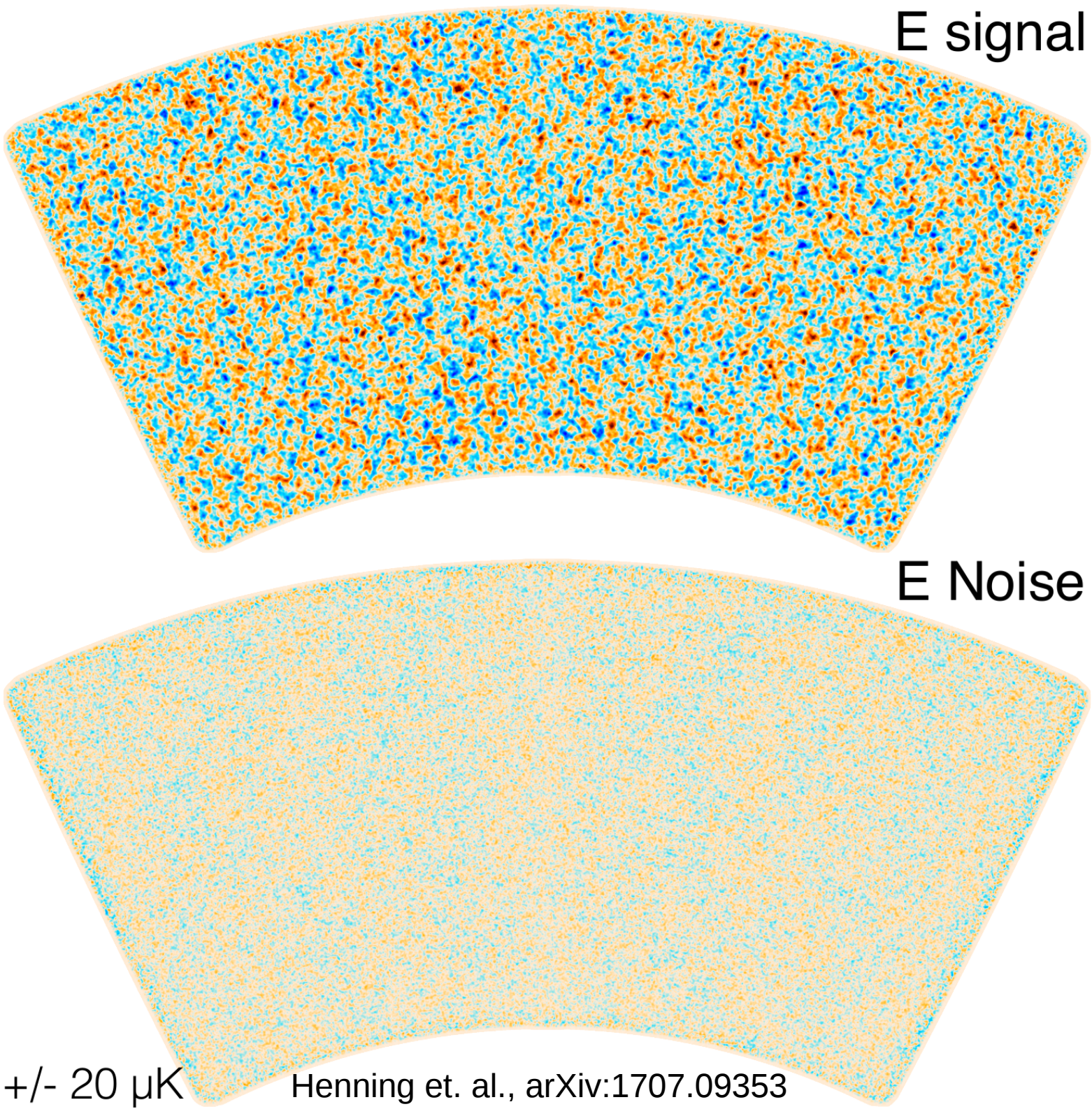




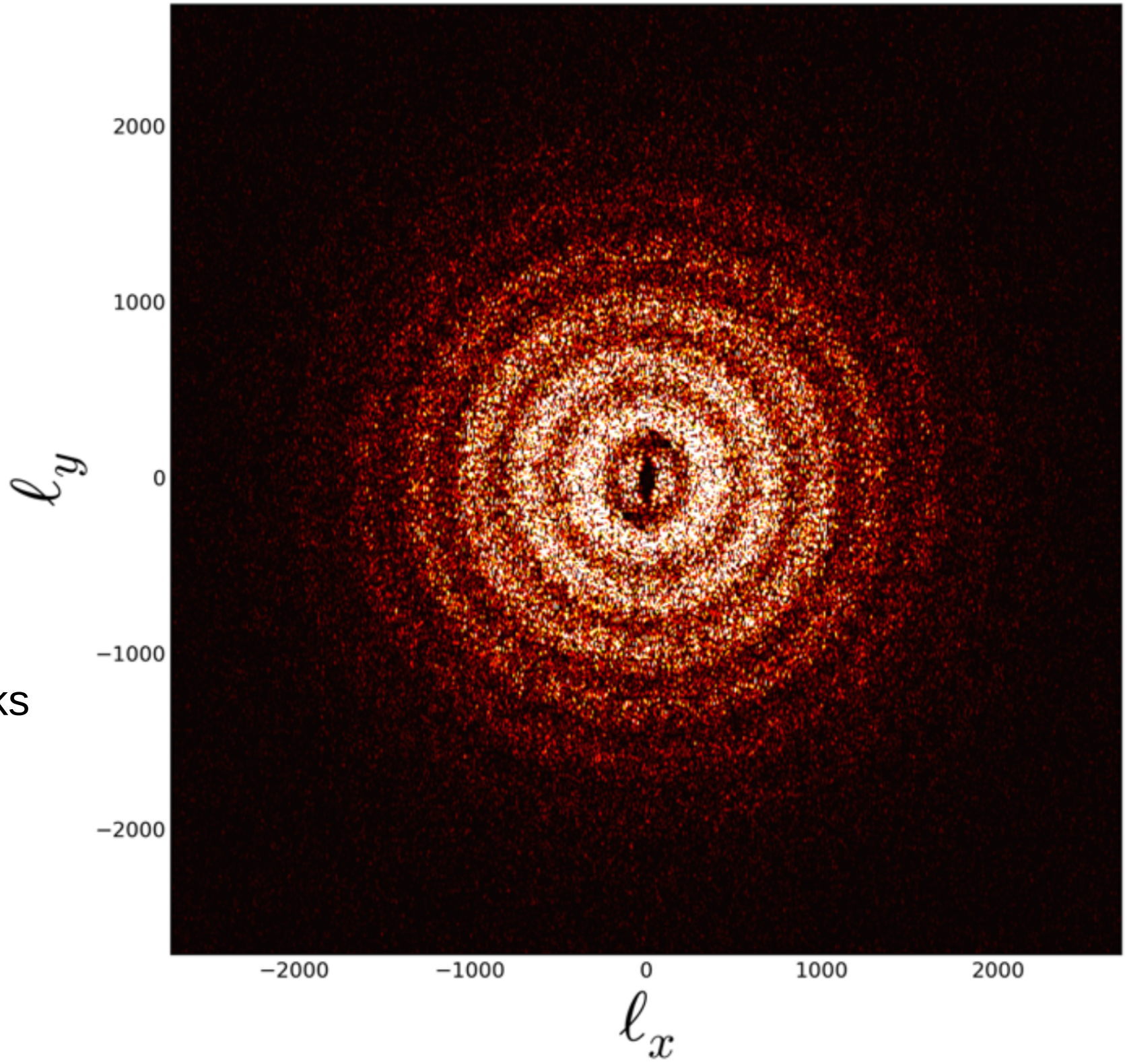


+/- 20 μK

Henning et. al., arXiv:1707.09353

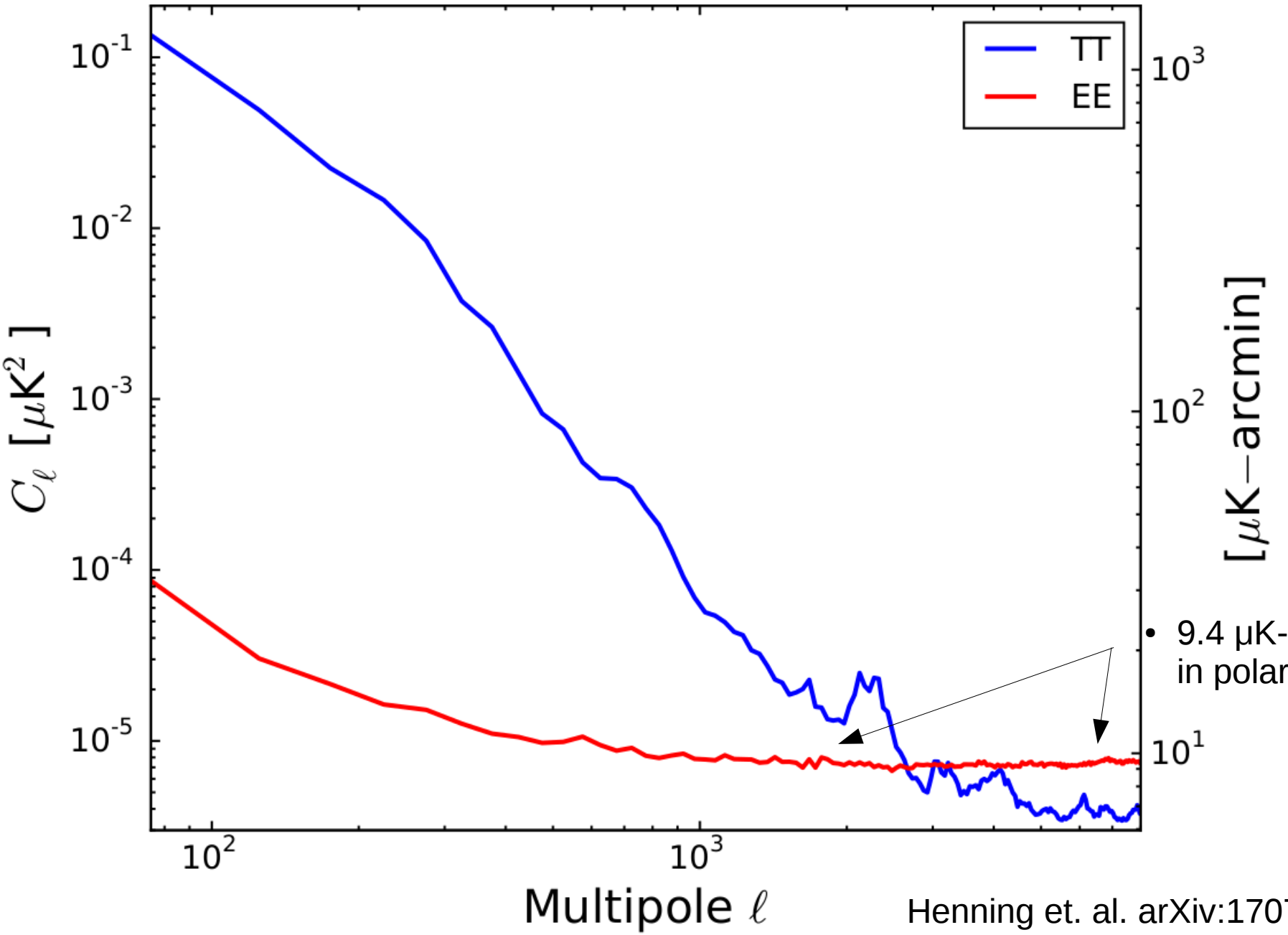

E signal
E Noise
+/- 20 μK
Henning et. al., arXiv:1707.09353

E-map 2D Fourier Transform



First seven acoustic peaks visible *before* azimuthal averaging

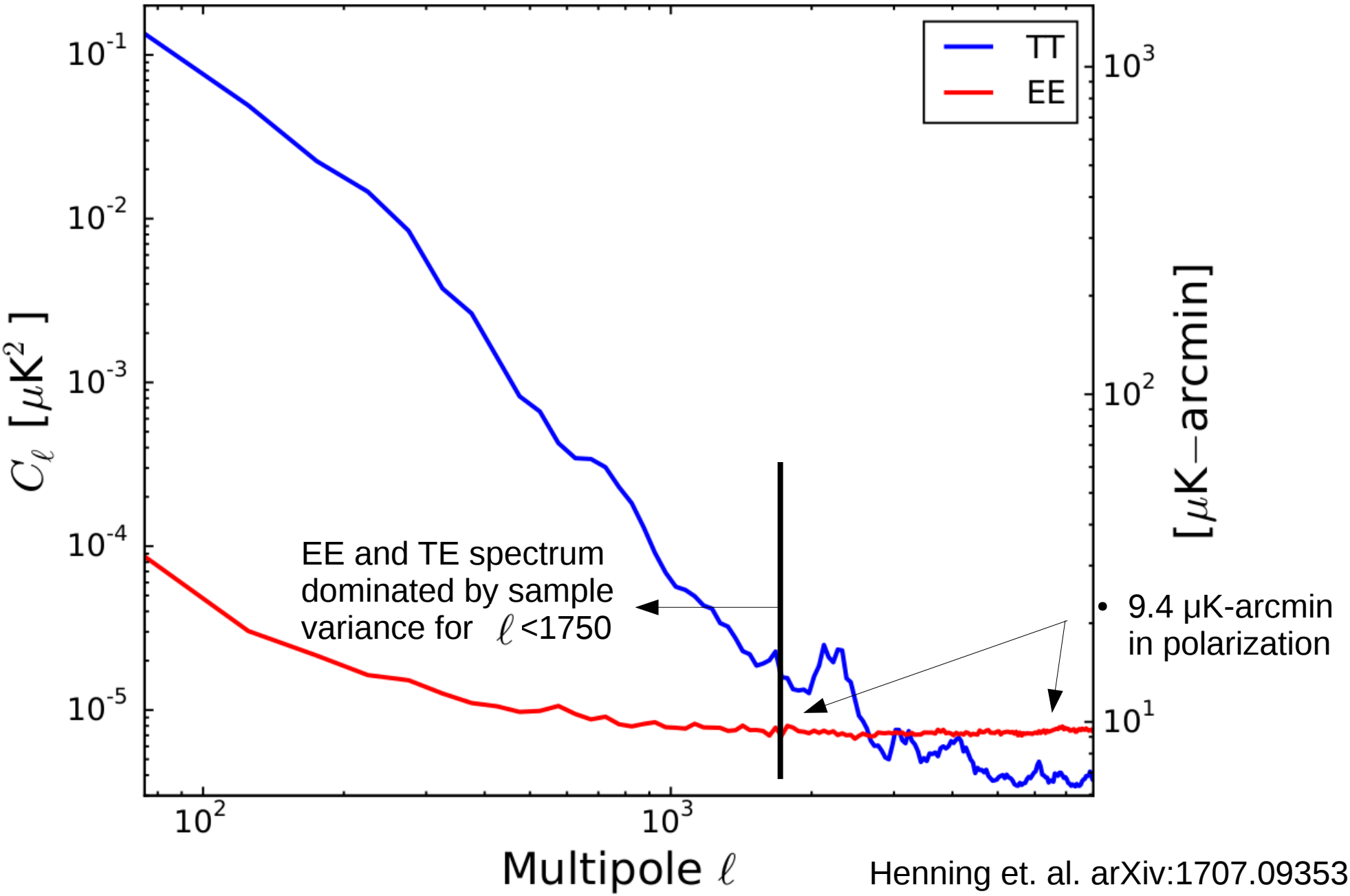
SPTpol 500 deg^2 Noise Spectra



- 9.4 μK-arcmin in polarization

Henning et. al. arXiv:1707.09353

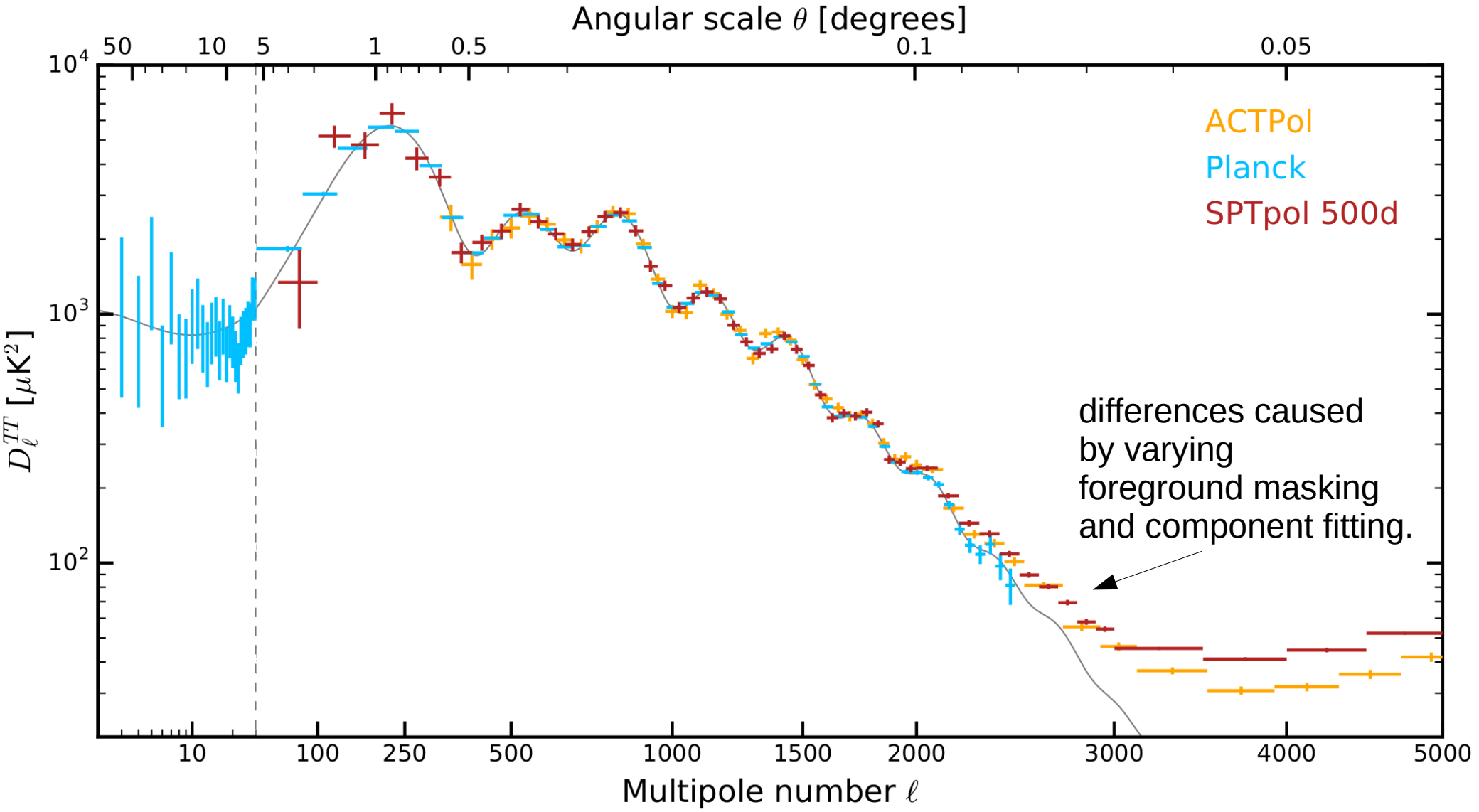
SPTpol 500 deg^2 Noise Spectra



- 9.4 μK-arcmin in polarization

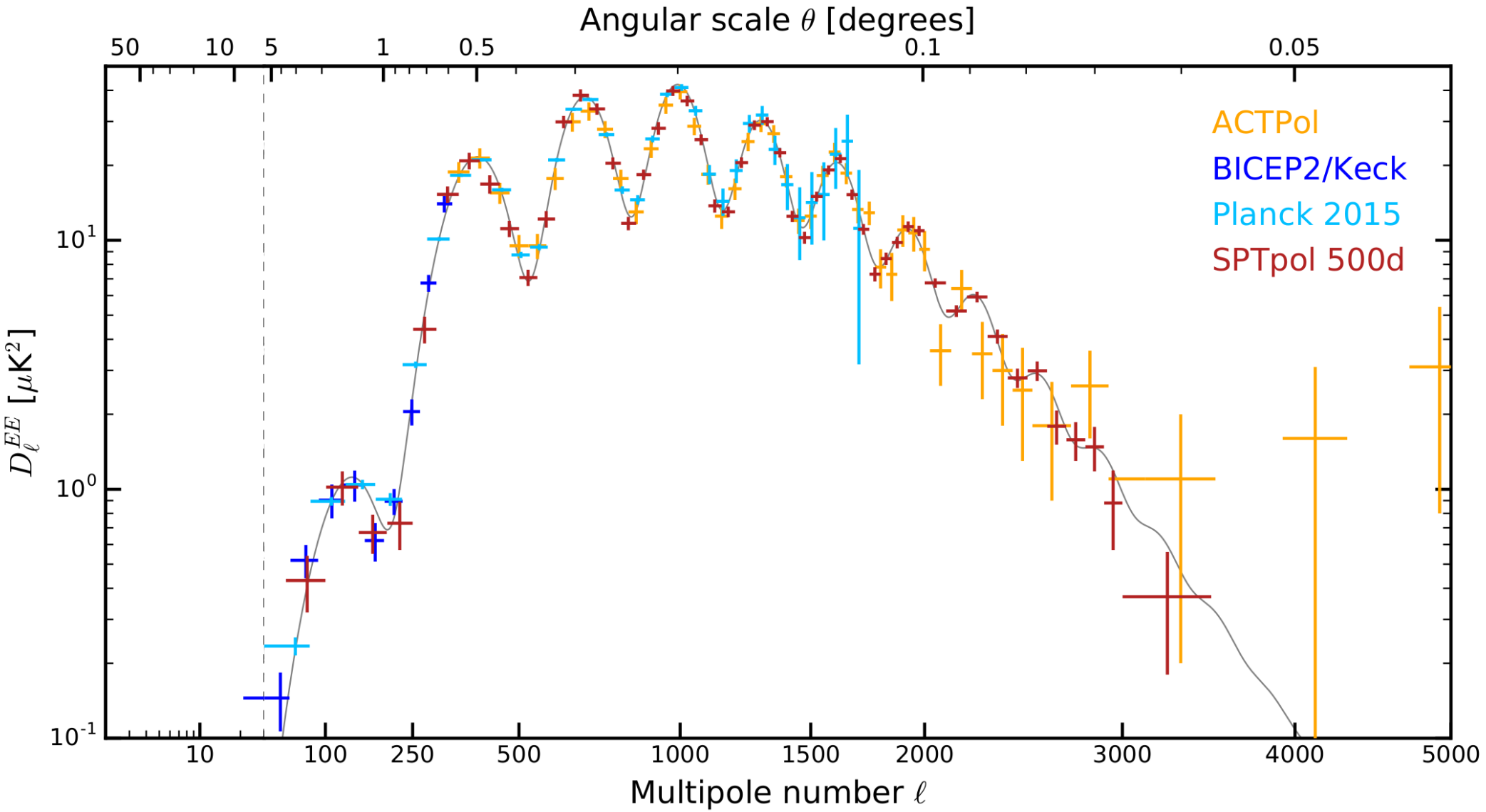
Henning et. al. arXiv:1707.09353

Temperature Spectrum



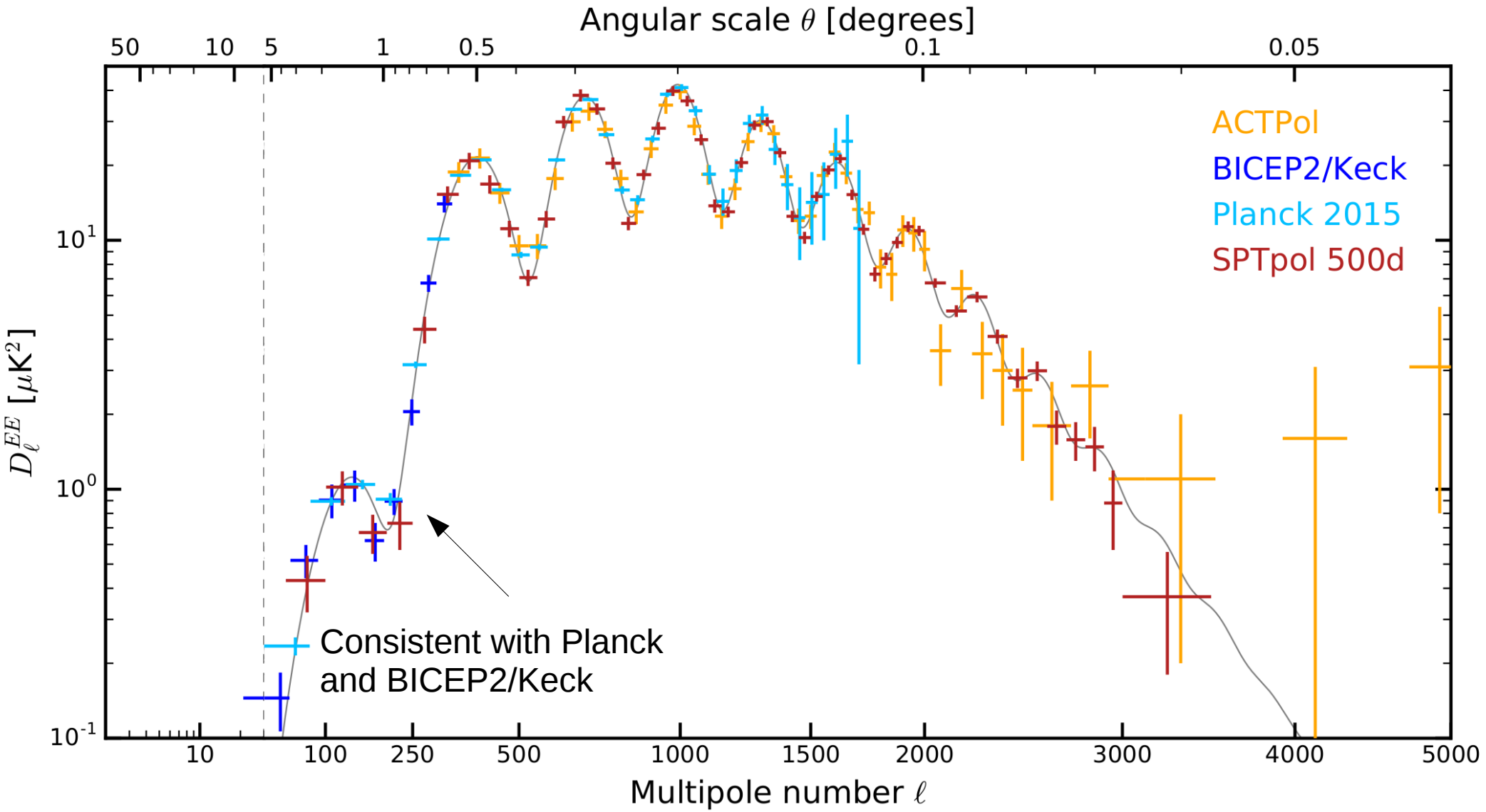
Henning et. al., 2018, Planck 2016; Louis et al. 2017

E-Mode Spectrum
(9 acoustic peaks visible)



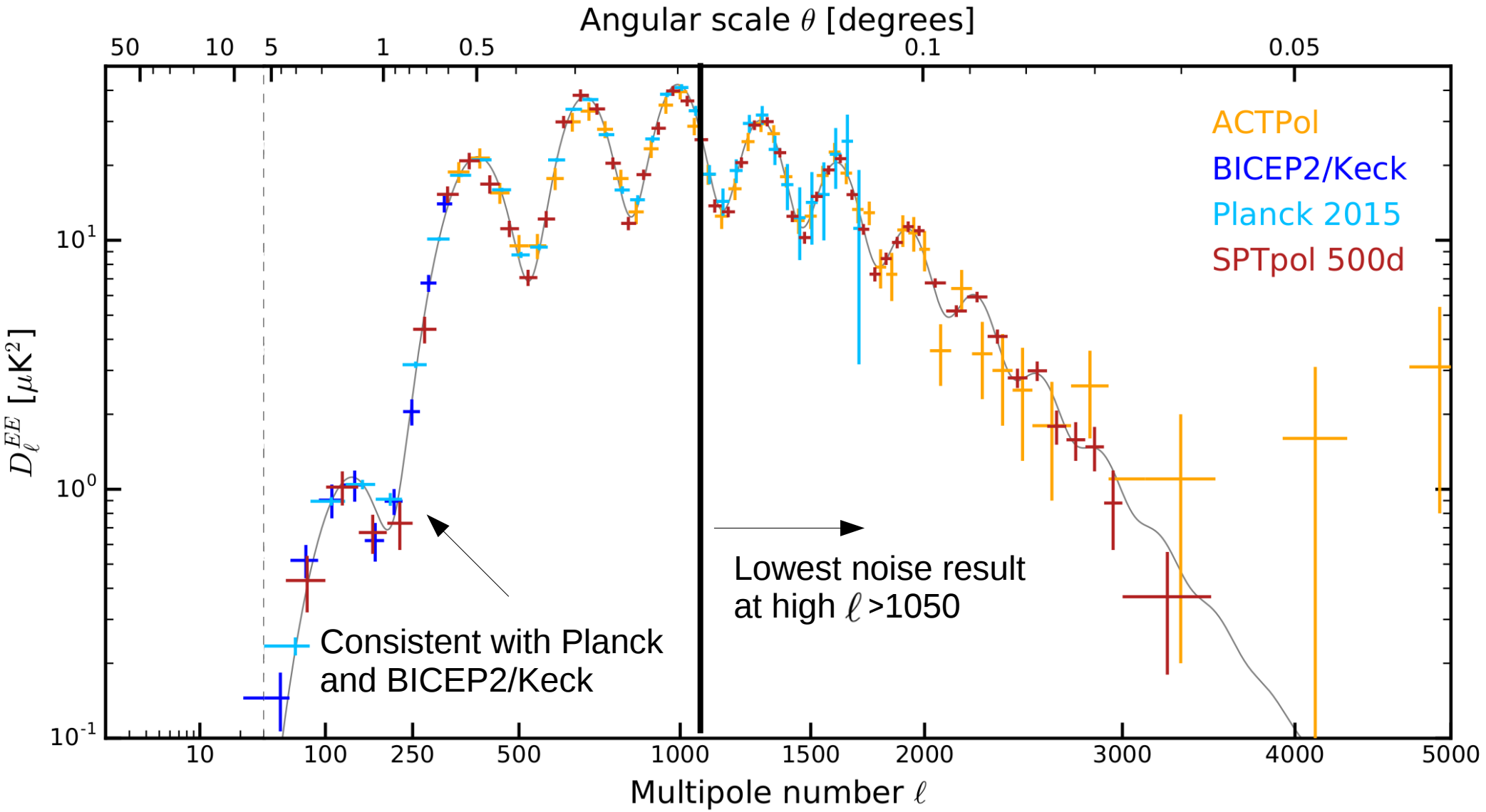
Henning et. al., 2018, Planck 2016; BICEP/Keck 2015, Louis et al. 2017

E-Mode Spectrum (9 acoustic peaks visible)



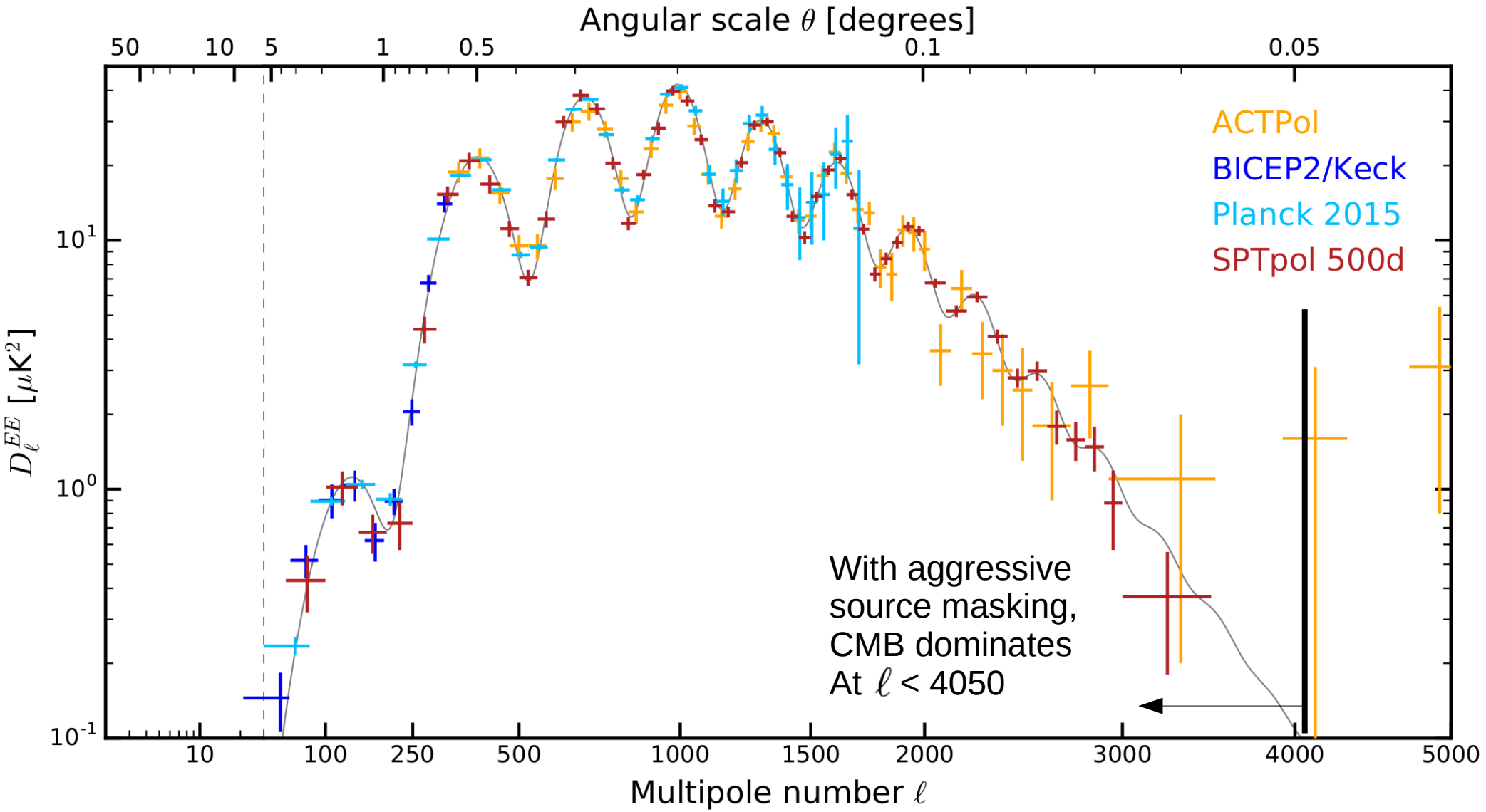
Henning et. al., 2018, Planck 2016; BICEP/Keck 2015, Louis et al. 2017

E-Mode Spectrum
(9 acoustic peaks visible)



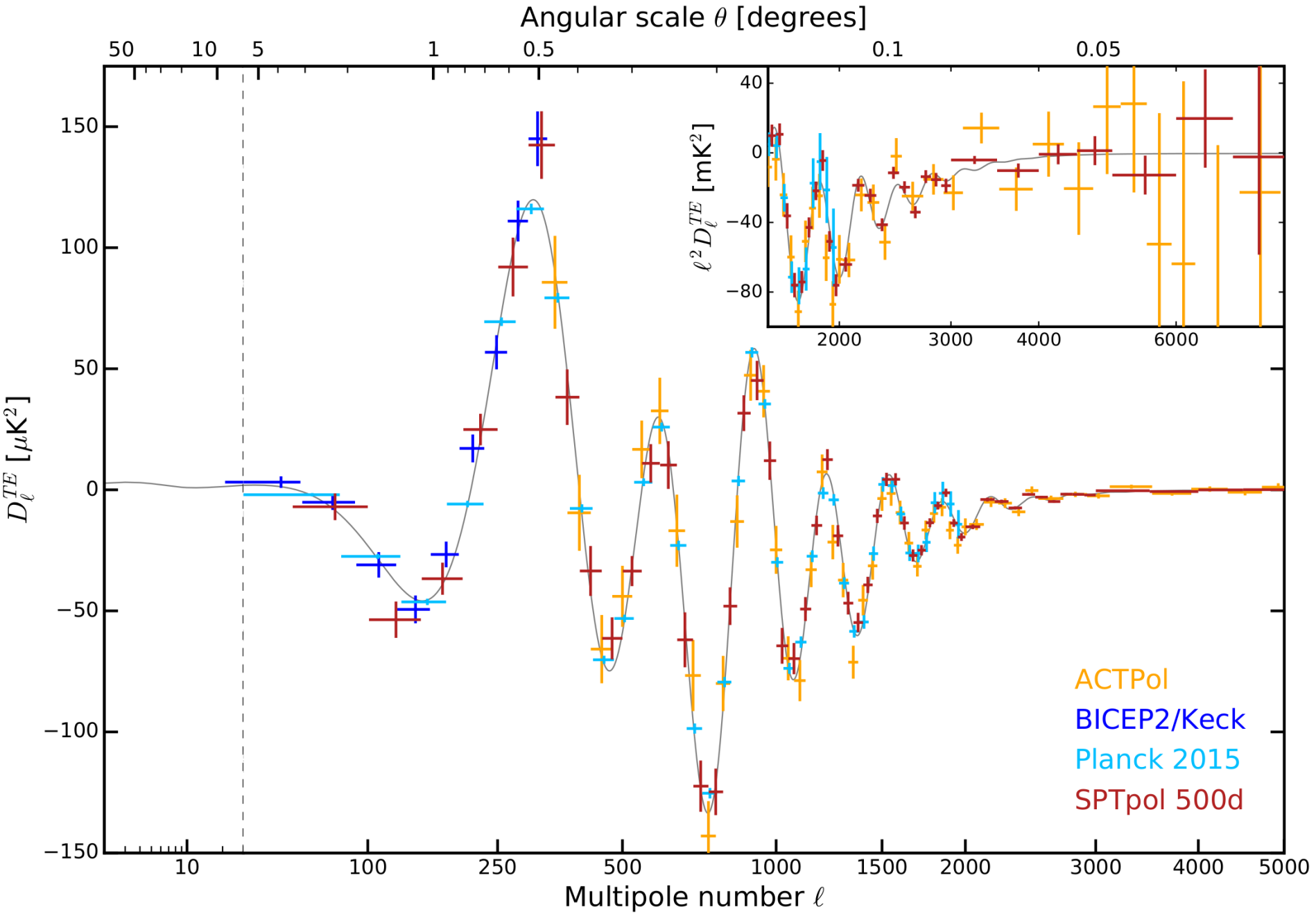
Henning et. al., 2018, Planck 2016; BICEP/Keck 2015, Louis et al. 2017

Polarized Point Source Power in E-Mode Spectrum



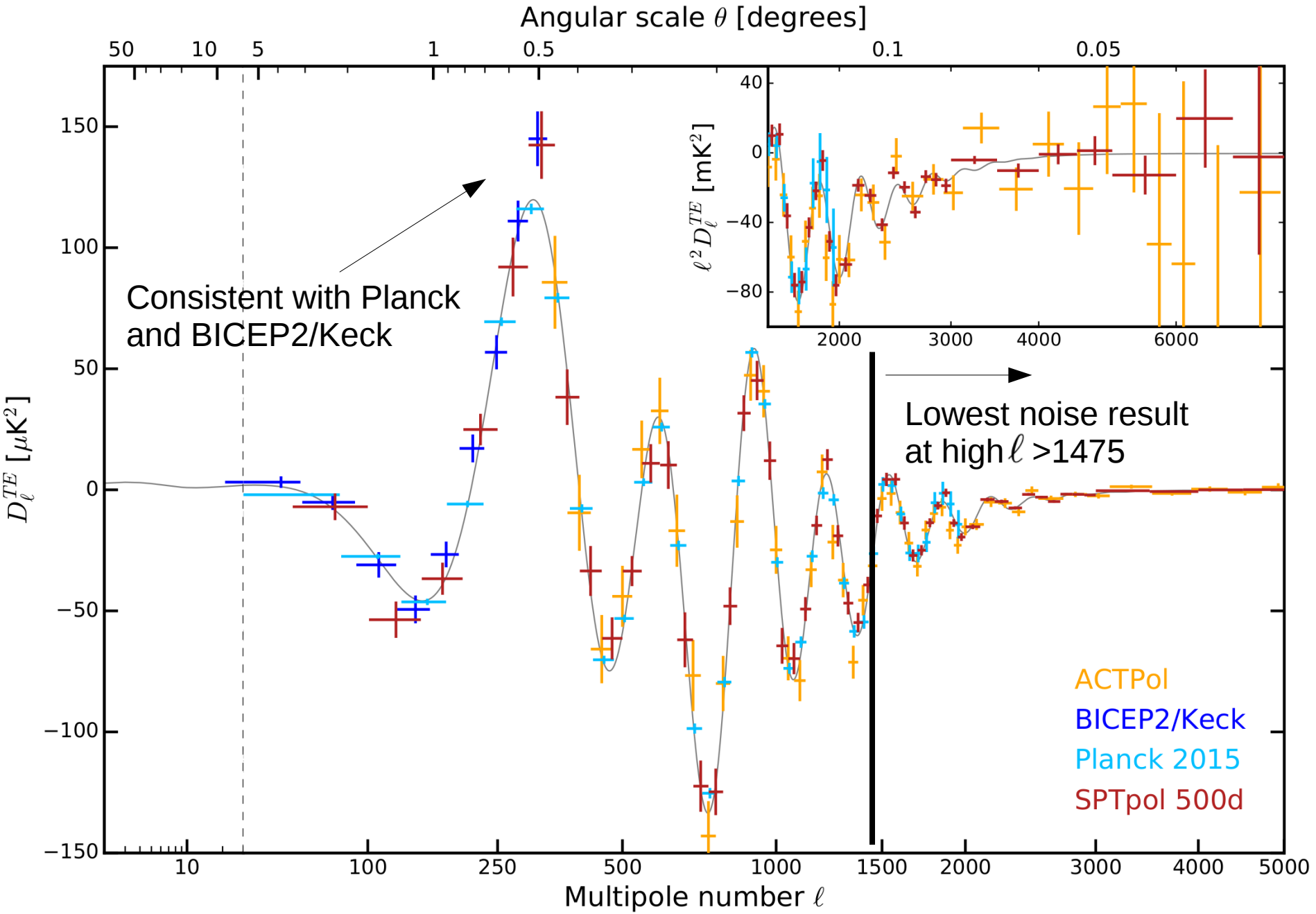
Henning et. al., 2018, Planck 2016; BICEP/Keck 2015, Louis et al. 2017

TE Cross Spectrum



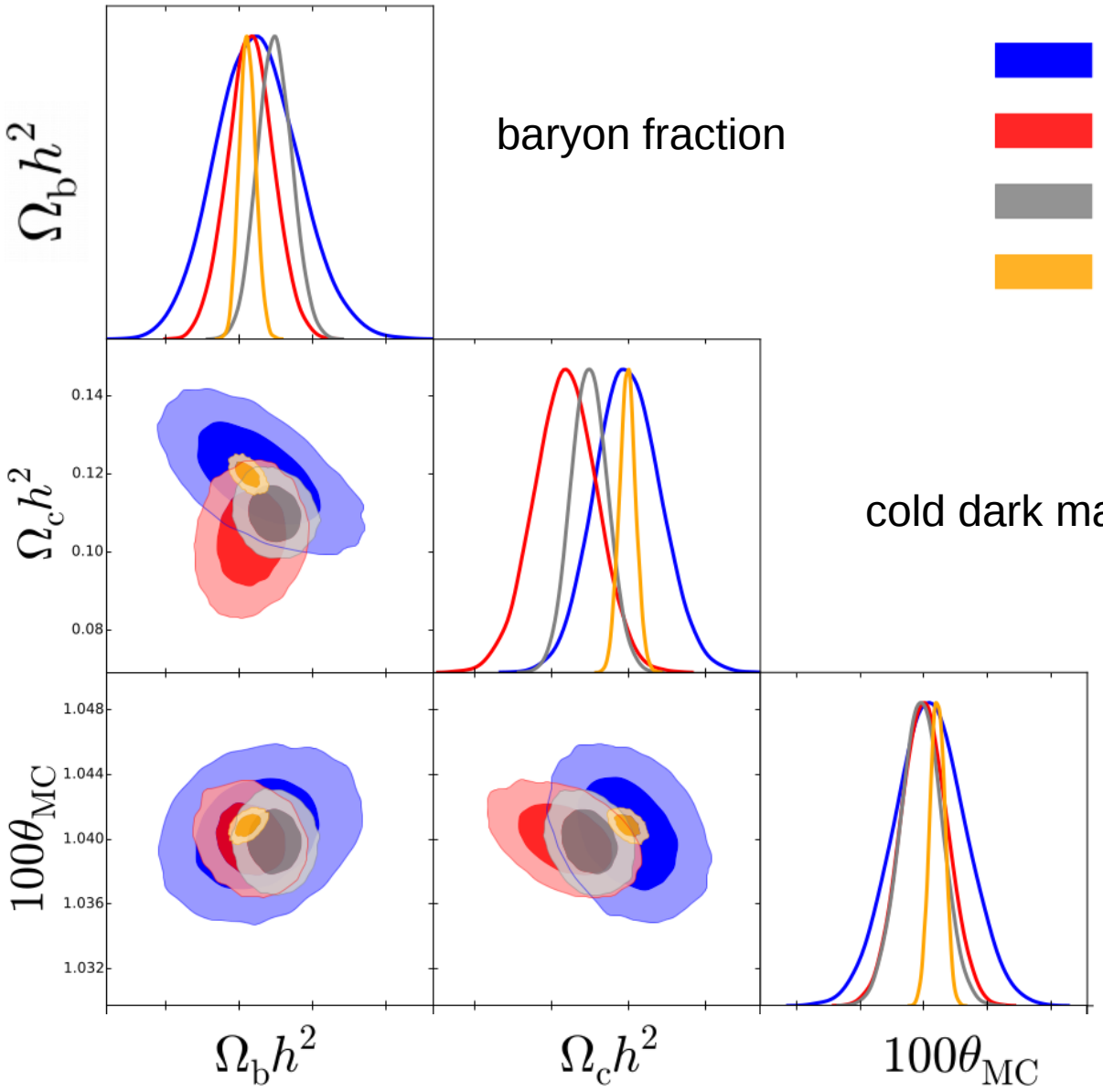
Henning et. al., 2018, Planck 2016; BICEP/Keck 2015, Louis et al. 2017

TE Cross Spectrum



Henning et. al., 2018, Planck 2016; BICEP/Keck 2015, Louis et al. 2017

Fitting Cosmological Parameters



baryon fraction

SPTpol-low $50 < \ell \leq 1000$

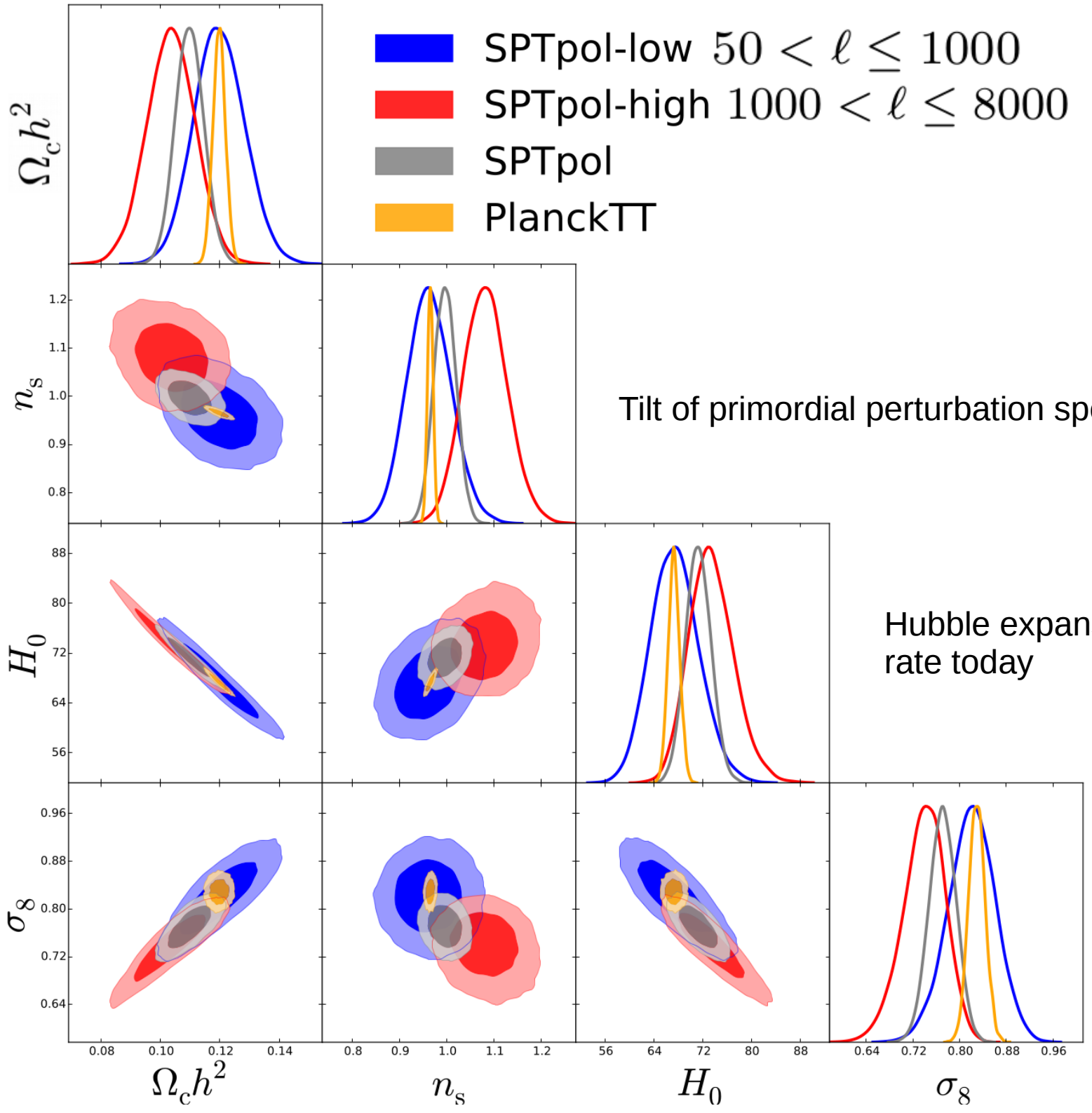
SPTpol-high $1000 < \ell \leq 8000$

SPTpol

PlanckTT

cold dark matter energy-density fraction

angular scale of the sound horizon

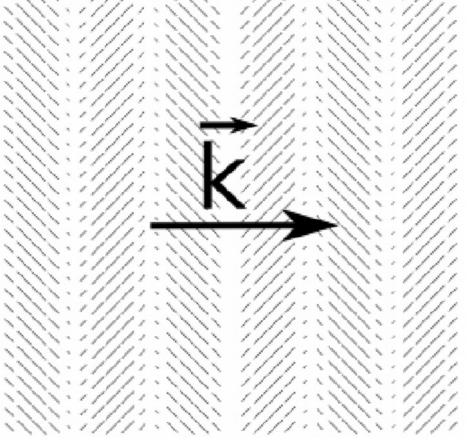


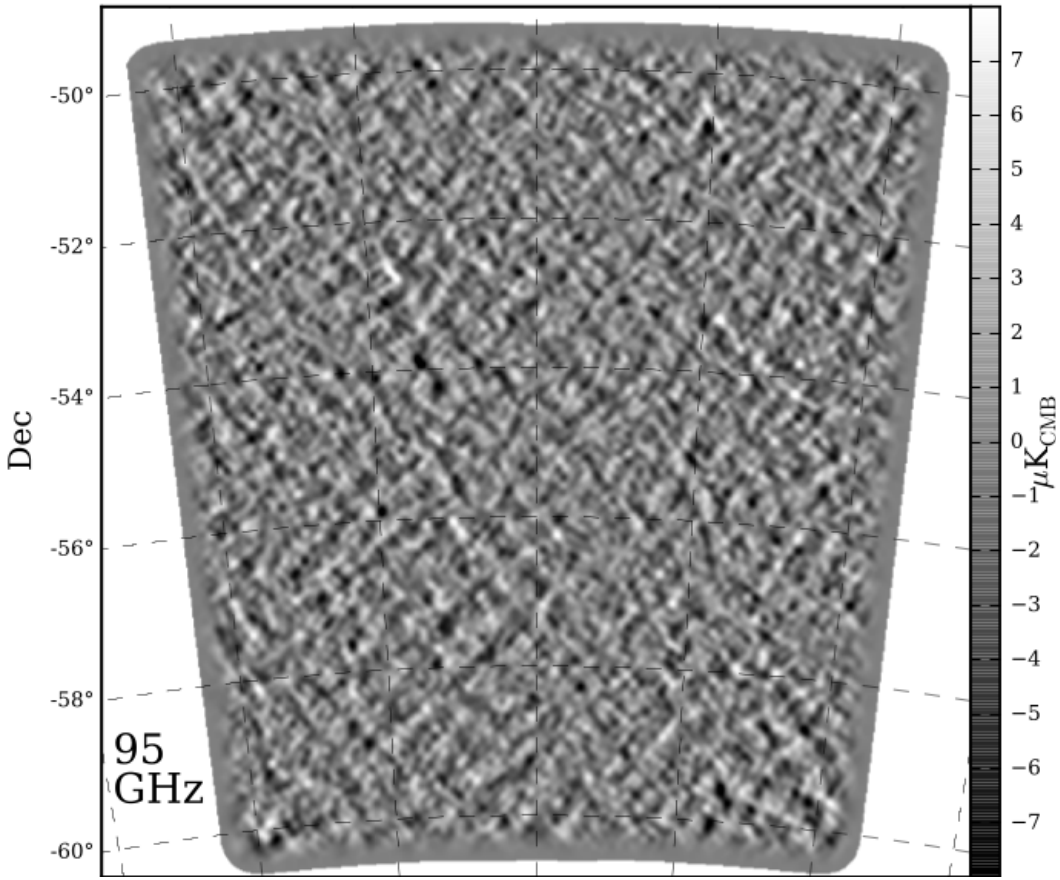
Tilt of primordial perturbation spectrum

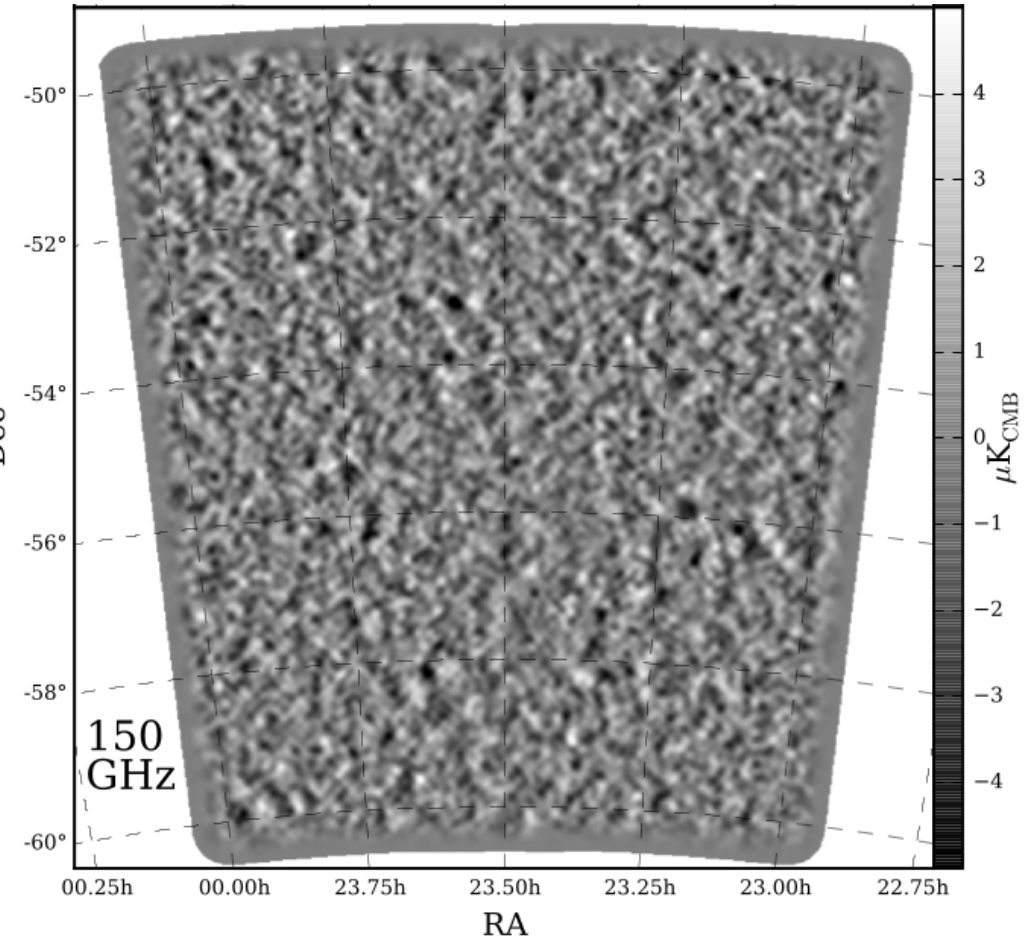
Hubble expansion rate today

amplitude of matter fluctuations at 8 Mpc scales

B-Modes from 100 deg^2

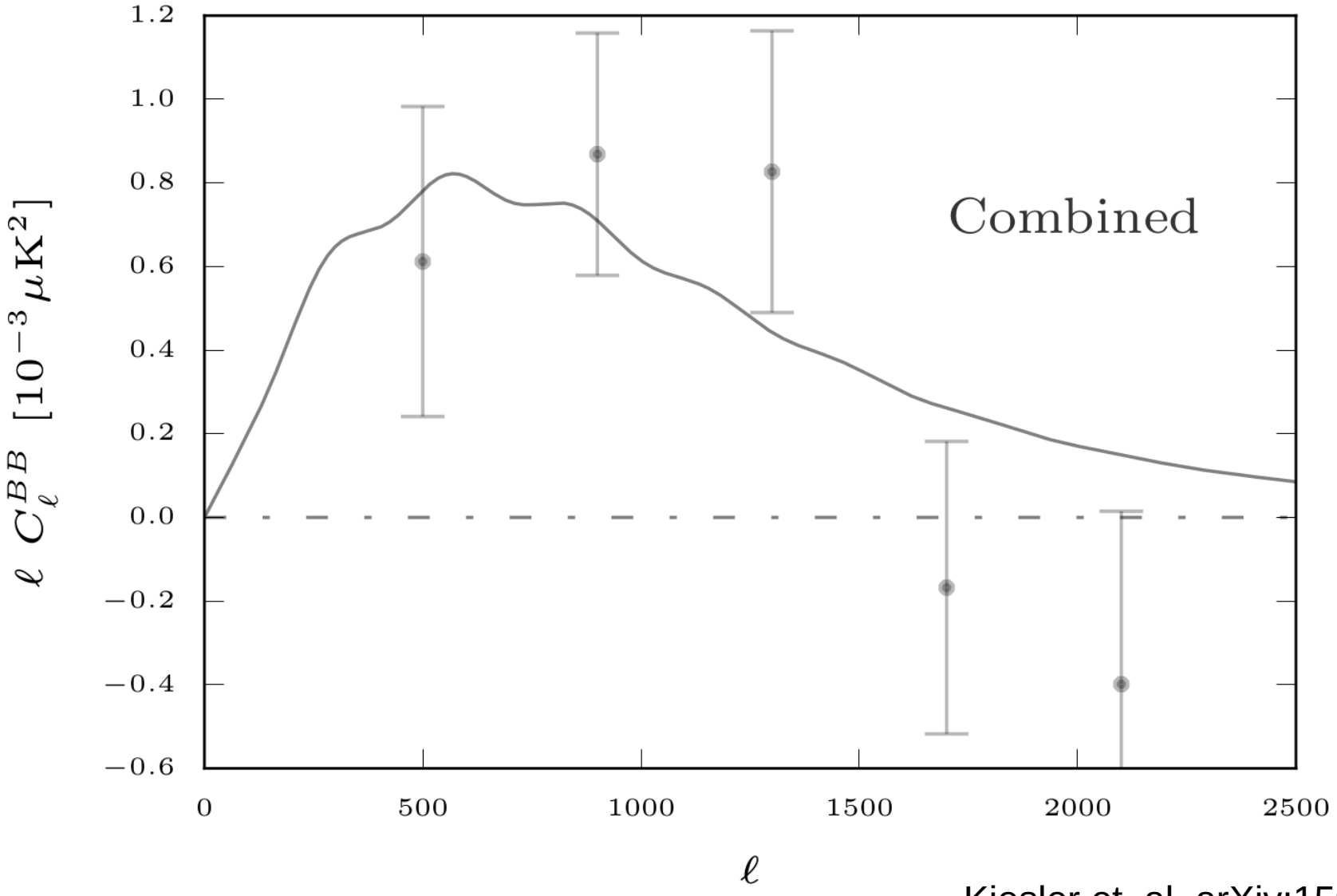






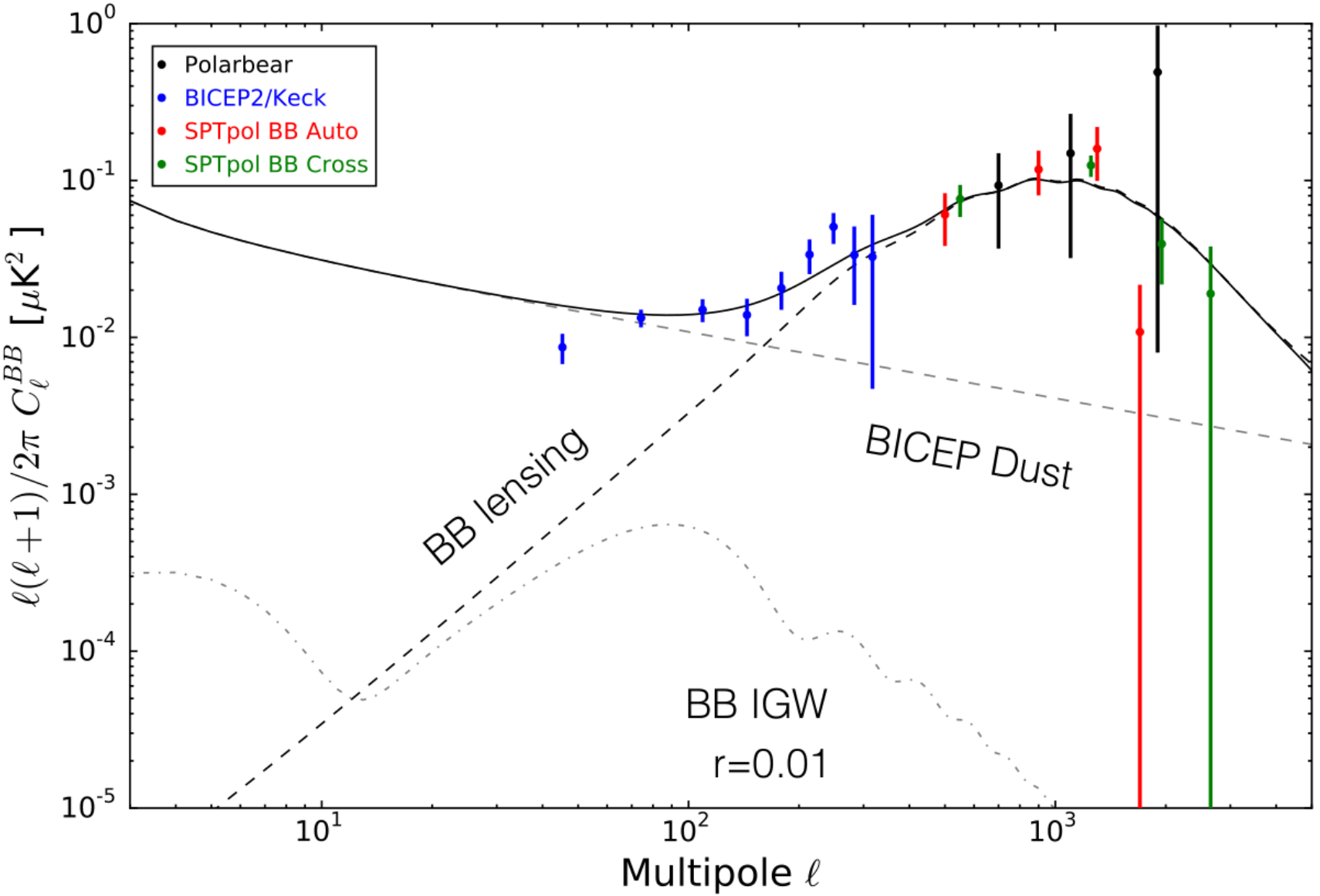
Kiesler et. al. arXiv:1503.02315

SPT B-Mode Spectrum

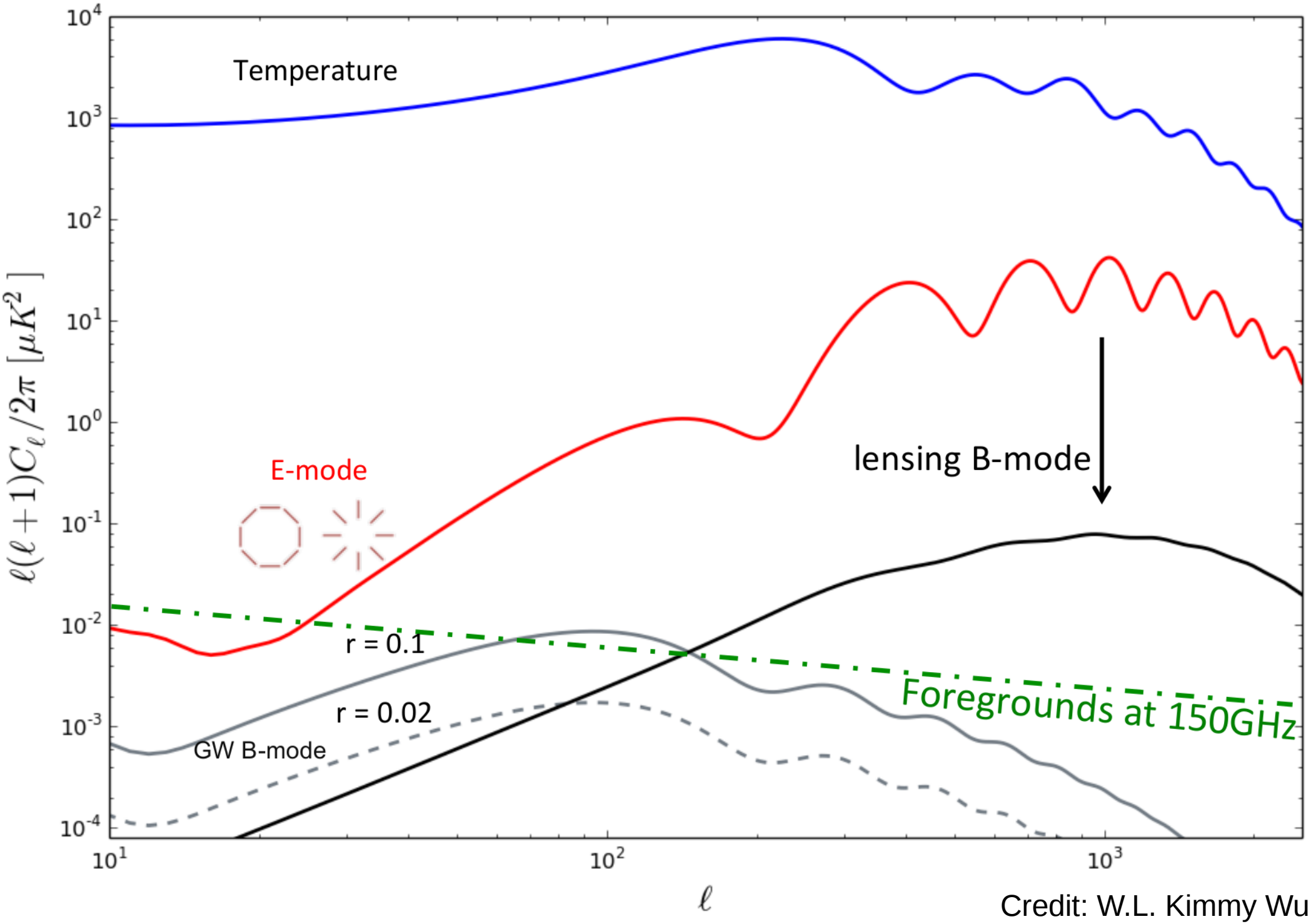


Kiesler et. al. arXiv:1503.02315

B-Mode Spectrum (Log Scale)

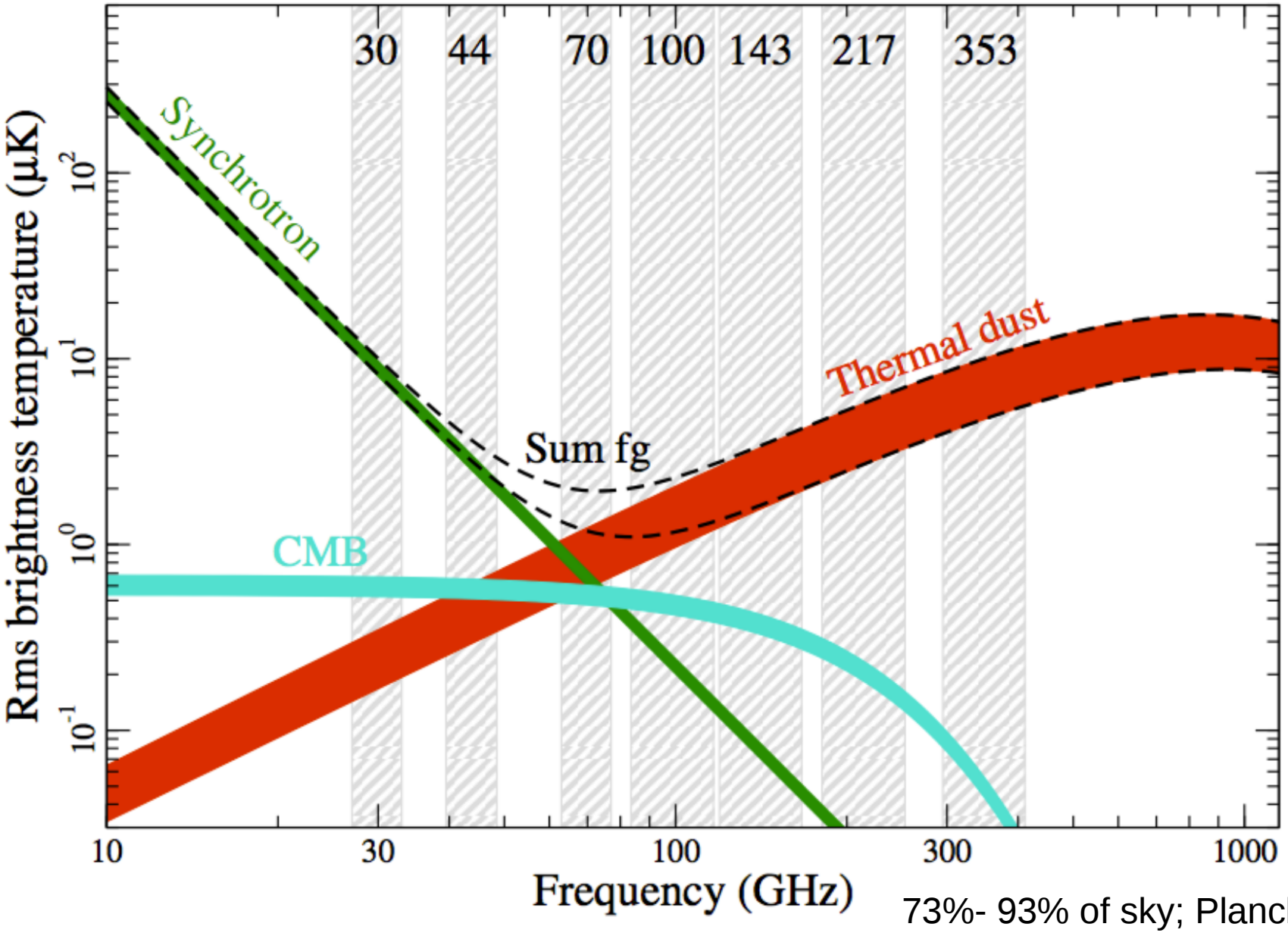


Kiesler et. al. arXiv:1503.02315

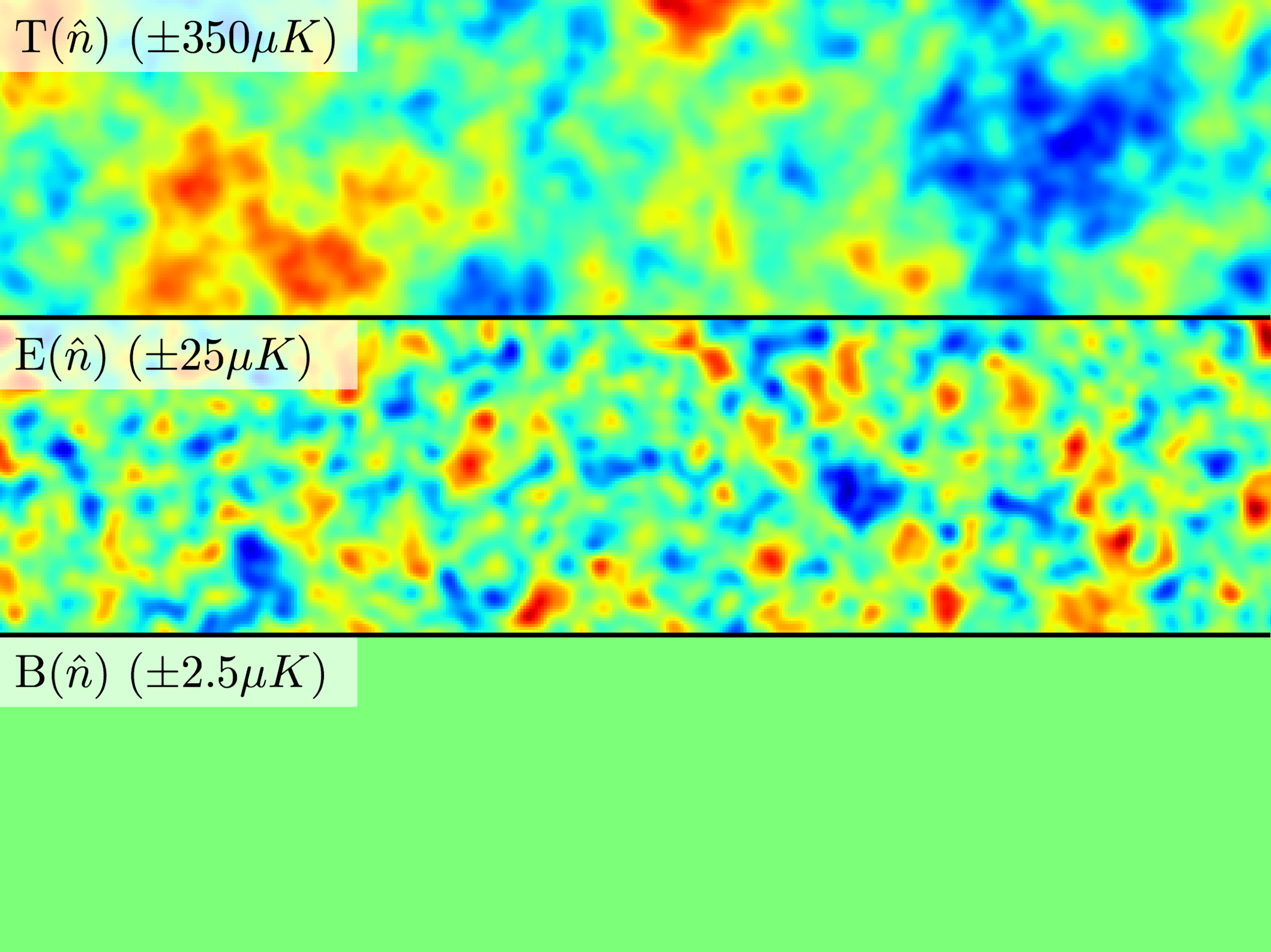


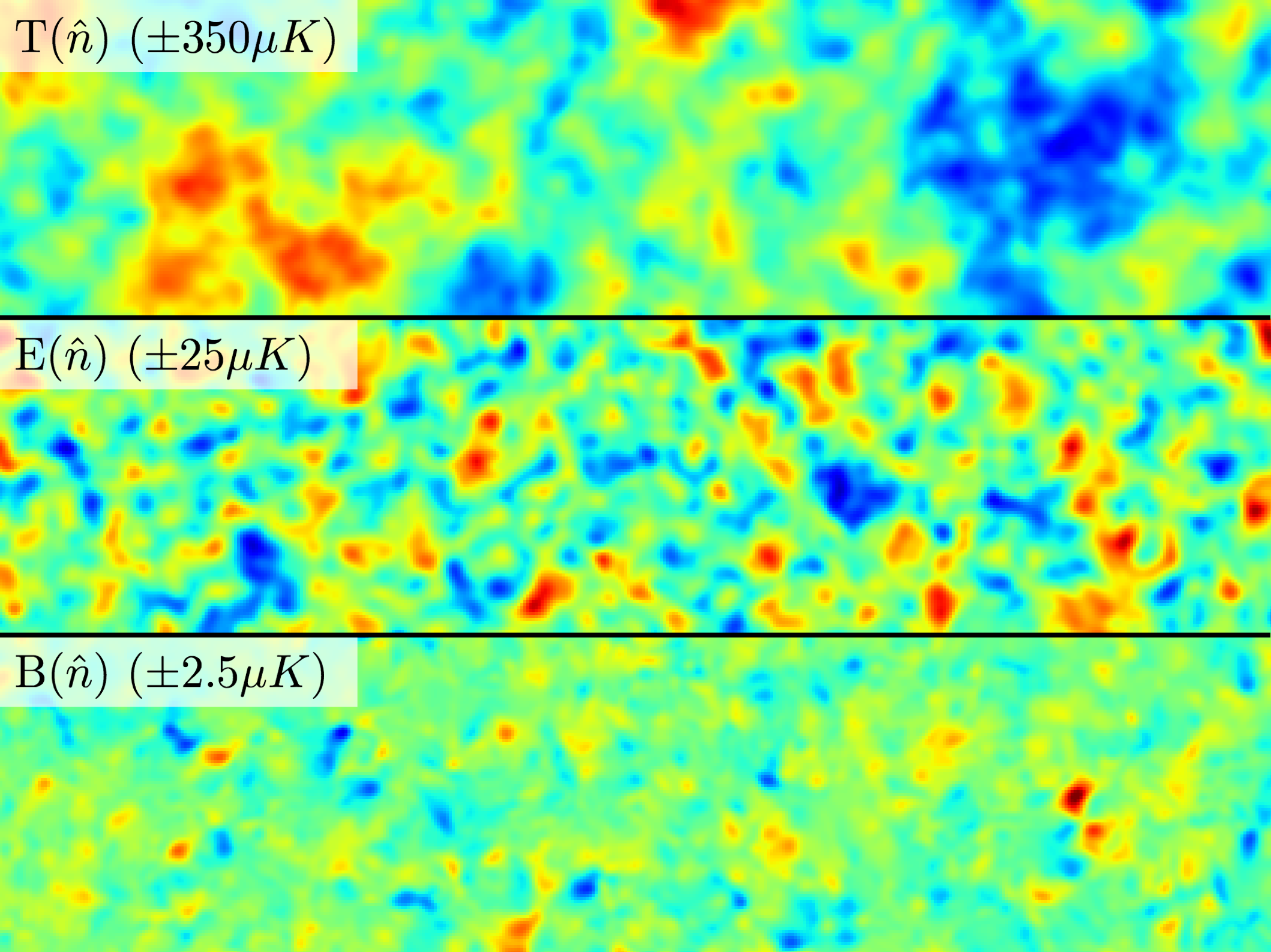
Credit: W.L. Kimmy Wu

B-Mode Polarized Foregrounds



73%- 93% of sky; Planck 2015 X

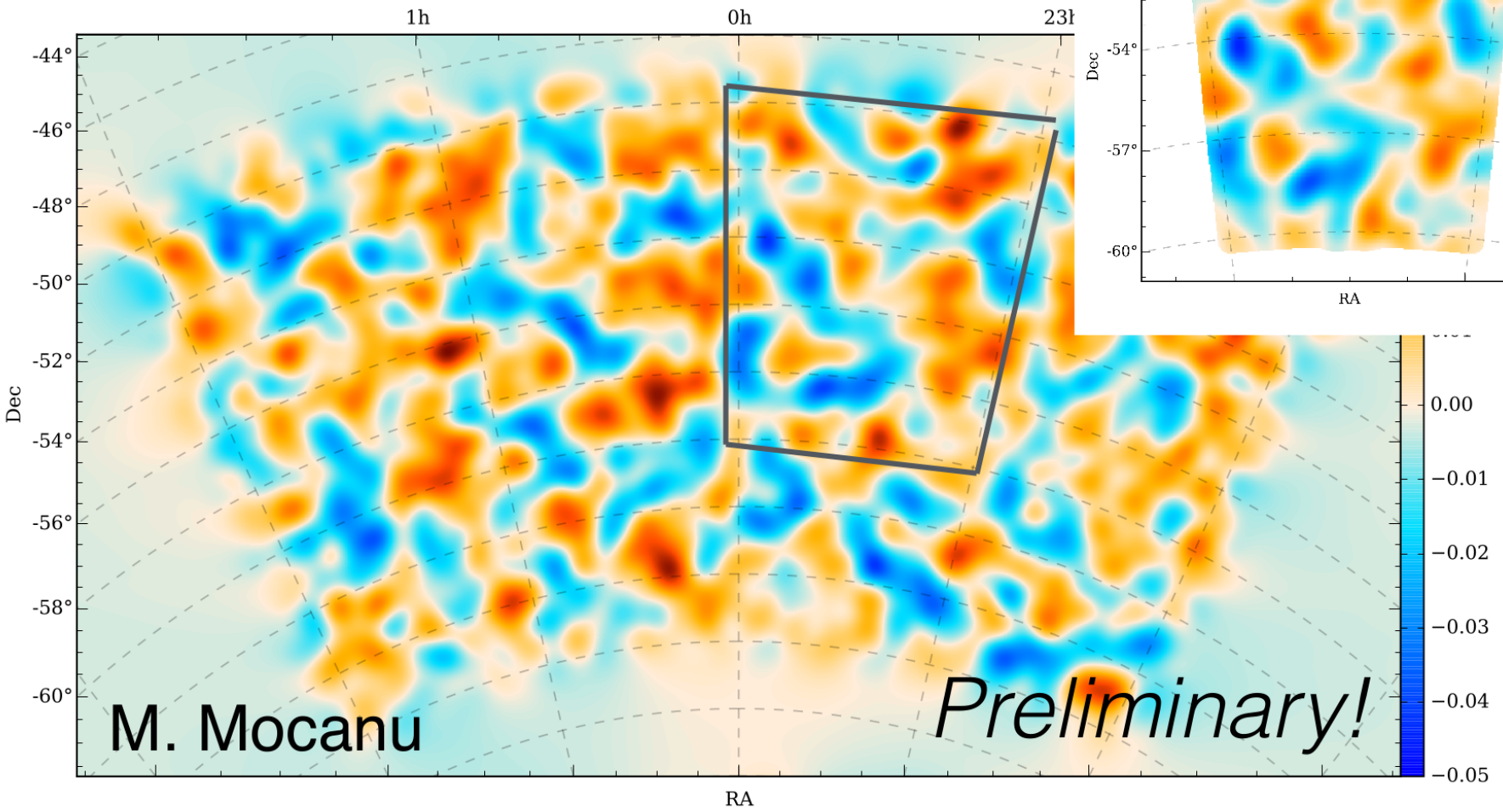

$\mathrm{T}(\hat{n})\ (\pm 350\mu K)$
$\mathrm{E}(\hat{n})\ (\pm 25\mu K)$
$\mathrm{B}(\hat{n})\ (\pm 2.5\mu K)$


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

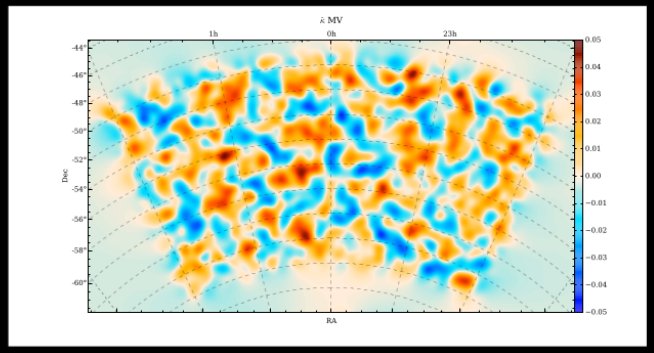
CMB Lensing

Story 2015

CMB Deflection Map (dark matter distribution) $\hat{\kappa}$ MV

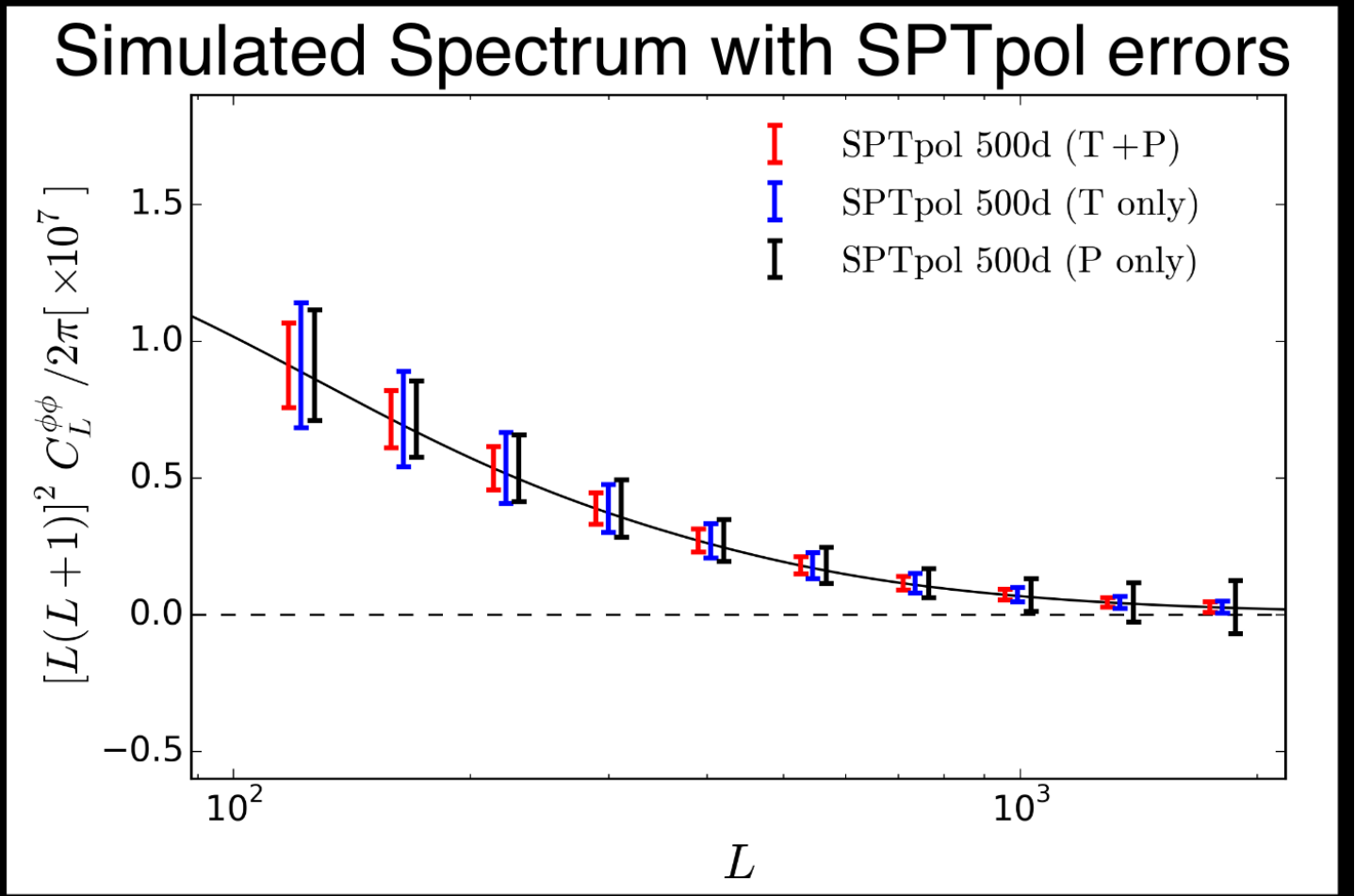


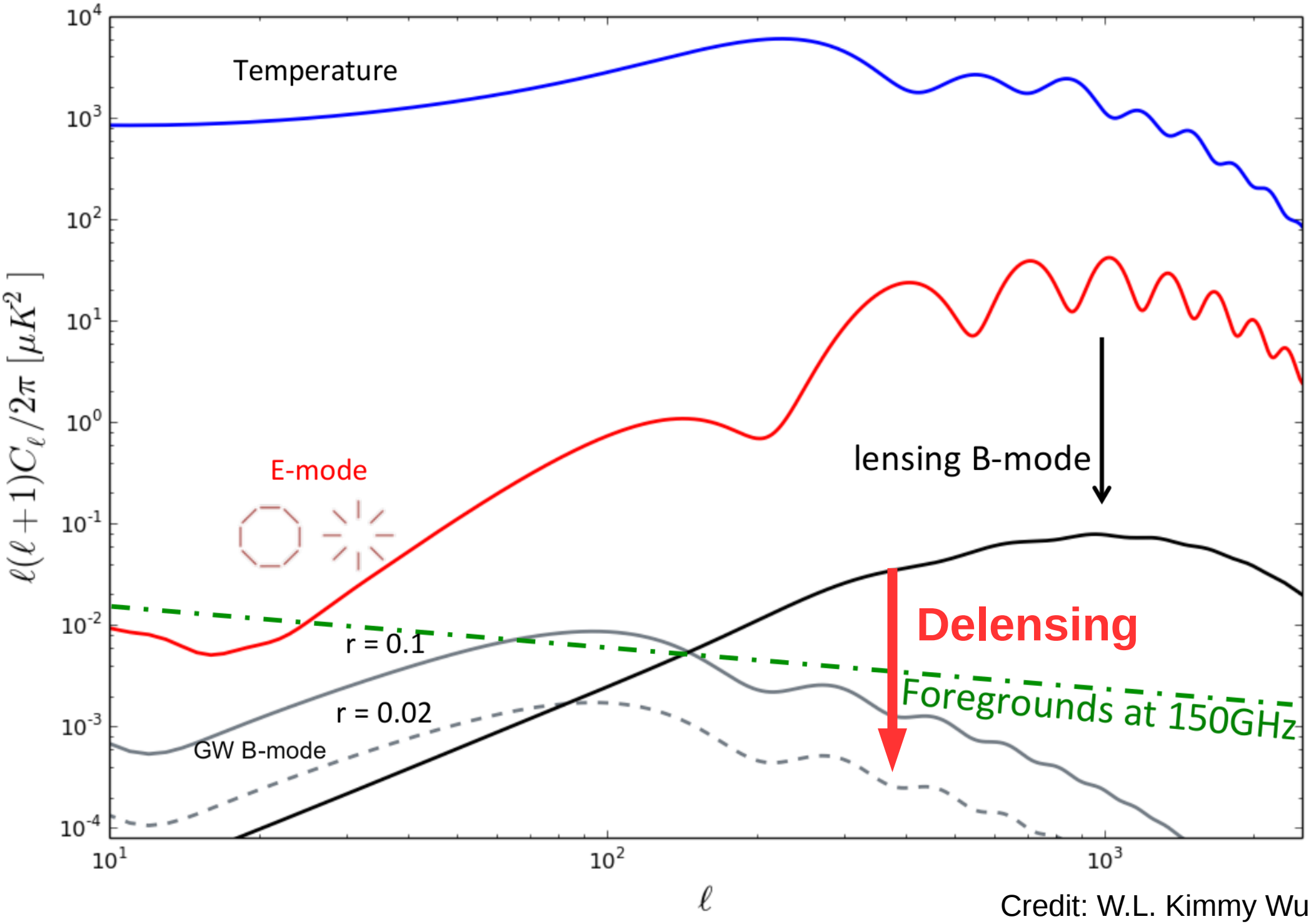
CMB Lensing Spectrum

FFT ()→

M. Mocanu

Preliminary!





Credit: W.L. Kimmy Wu

Delensing B Modes

VOLUME 89, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JULY 2002

Limit on the Detectability of the Energy Scale of Inflation

Lloyd Knox and Yong-Seon Song

Department of Physics, One Shields Avenue, University of California, Davis, California 95616

(Received 18 February 2002; published 18 June 2002)

We show that the polarization of the cosmic microwave background can be used to detect gravity waves from inflation if the energy scale of inflation is above 2×10^{15} GeV. These gravity waves generate polarization patterns with a curl, whereas (to first order in perturbation theory) density perturbations do not. The limiting "noise" arises from the second-order generation of curl from density perturbations, or rather residuals from its subtraction. We calculate optimal sky coverage and detectability limits as a function of detector sensitivity and observing

DOI: 10.1103/PhysRevLett.89.011303

PHYSICAL REVIEW D **69**, 043005 (2004)

Gravitational lensing as a contaminant of the gravity wave signal in the CMB

Uroš Seljak* and Christopher M. Hirata†

Department of Physics, Jadwin Hall, Princeton University, Princeton, New Jersey 08544, USA

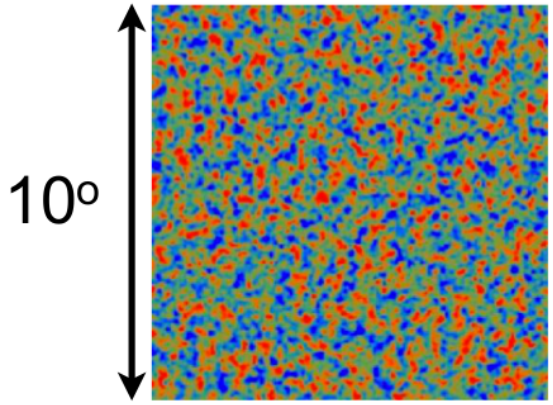
(Received 7 October 2003; published 27 February 2004)

Gravity waves (GWs) in the early Universe generate *B*-type polarization in the cosmic microwave background (CMB), which can be used as a direct way to measure the energy scale of inflation. Gravitational lensing contaminates the GW signal by converting the dominant *E* polarization into *B* polarization. By reconstructing the lensing potential from the CMB itself one can decontaminate the *B* mode induced by lensing. We present results of numerical simulations of *B* mode delensing using quadratic and iterative maximum-likelihood lensing reconstruction methods as a function of detector noise and beam. In our simulations we find that the quadratic method can reduce the lensing *B* noise power by up to a factor of 7, close to the no noise limit. In contrast, the iterative method shows significant improvements even at the lowest noise levels we tested. We demonstrate explicitly that with this method at least a factor of 40 noise power reduction in lensing induced *B* power is possible, suggesting that $r = P_h / P_R \sim 10^{-6}$ may be achievable in the absence of sky cuts, foregrounds, and instrumental systematics. While we do not find any fundamental lower limit due to lensing, we find that for high-sensitivity detectors residual lensing noise dominates over the detector noise.

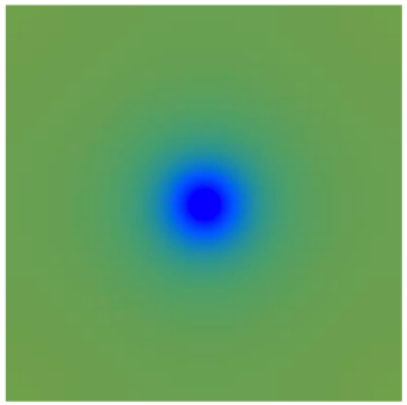
DOI: 10.1103/PhysRevD.69.043005 PACS number(s): 98.70.Vc

Manzotti, Story, Wu, et al (arXiv:1701.04396)

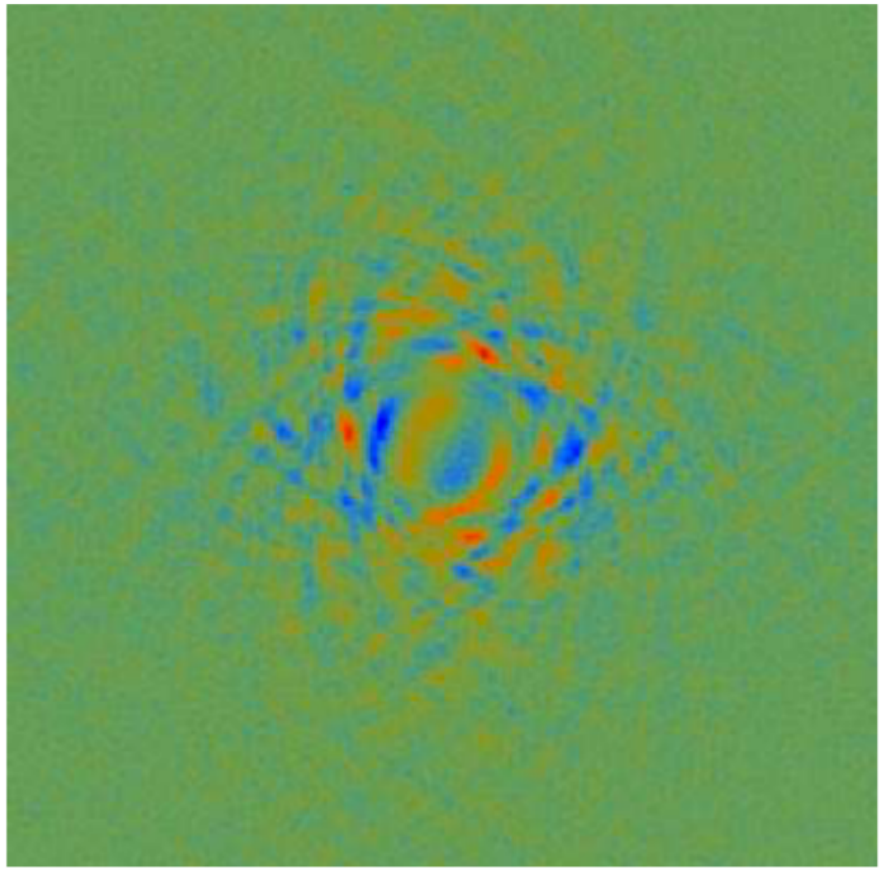
Effect of Lensing



Unlensed E-mode map



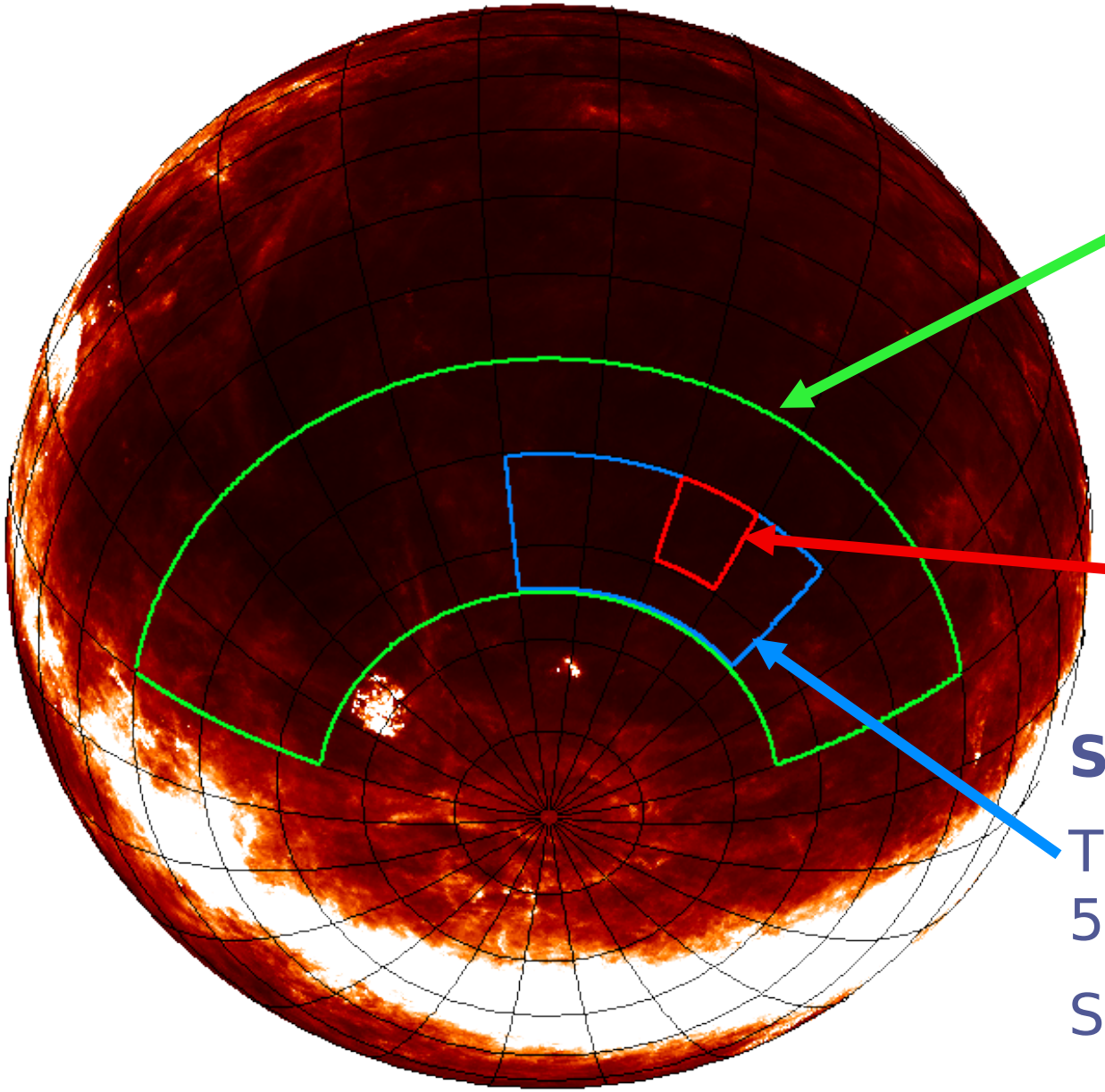
Lensing deflection field



Lensed B-mode map

Figure Credit: Hu & Okamoto (2002)

SPTpol fields: Deep & Survey



SPT-SZ

2500 deg²

Deep Field

First year,
100 deg²

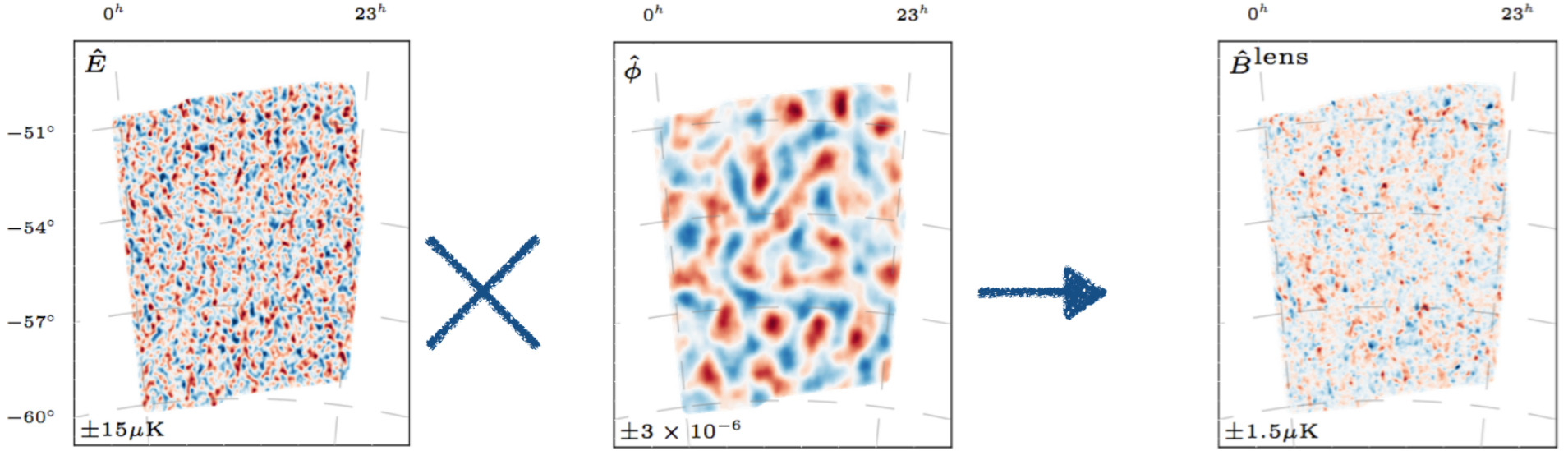
Survey Field

Three years,
500 deg²

Same as BICEP

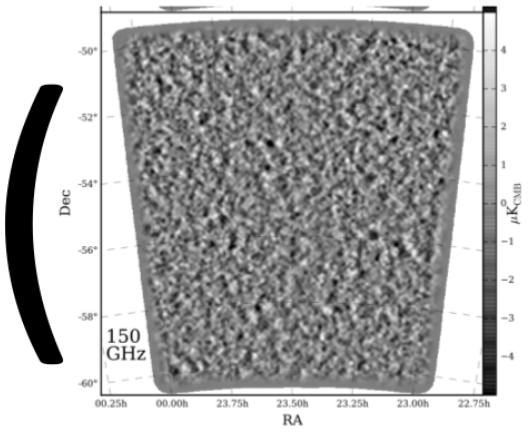
IRAS from Schlegel et al. 1998

Delensing: Create a template of lensed B modes from maps of E and Φ, then remove this template from measured B-mode maps.

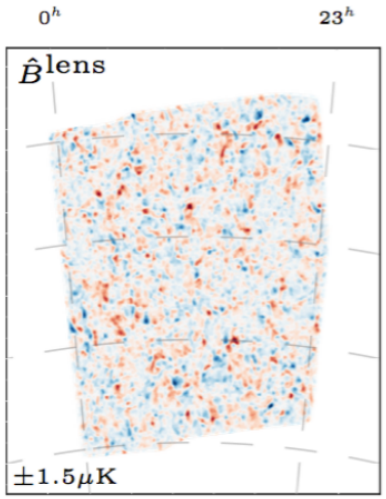


E-mode | Lensing | B-mode lensing template

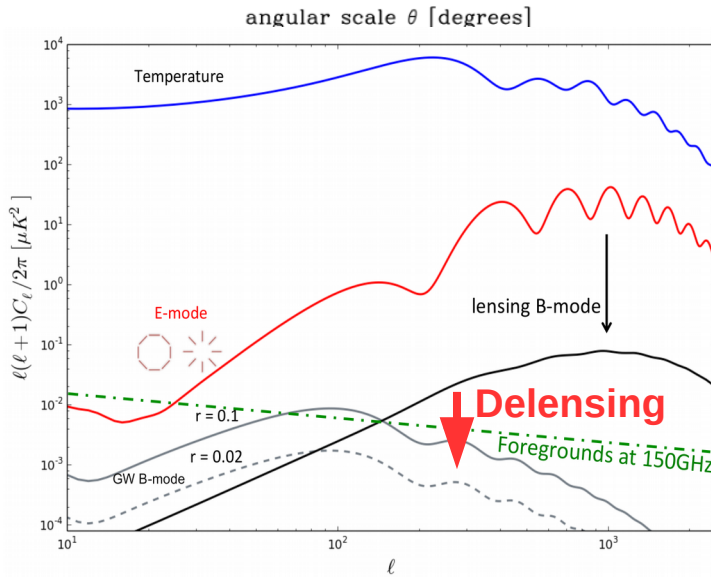
B-mode data



B-mode lensing template



Delensed spectra

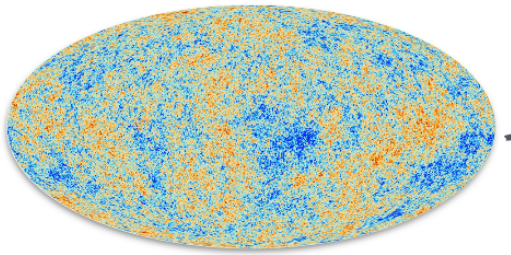


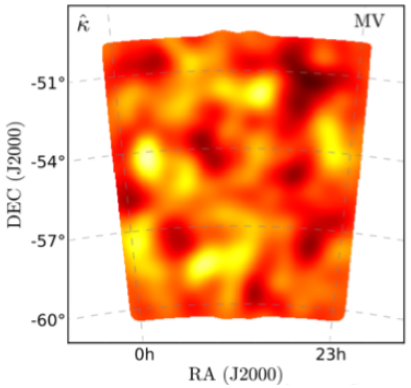
Manzotti, Story, Wu, et al (arXiv:1701.04396)

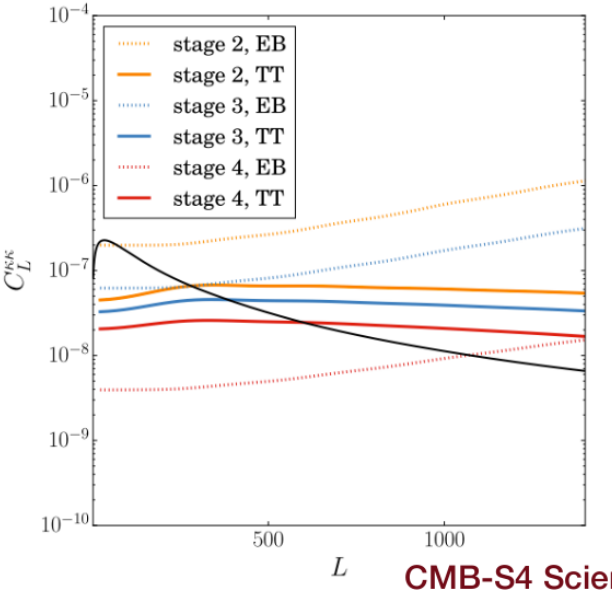
Where to get the lensing potential?

Source | **Map of ϕ** | **Noise**

Option 1: internal reconstruction from the CMB

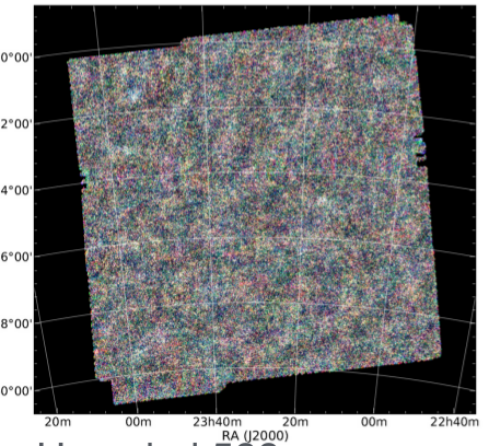




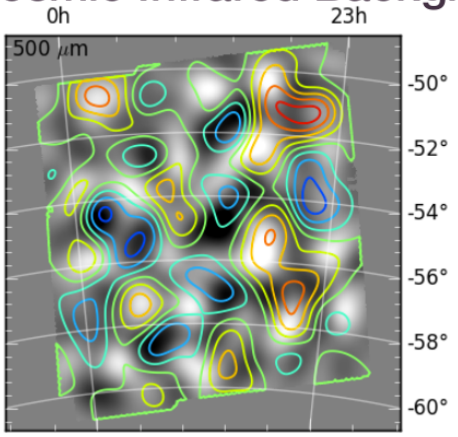


CMB-S4 Science Book

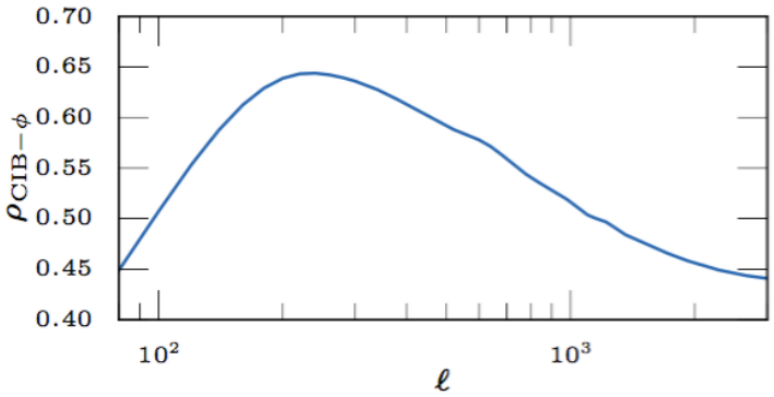
Option 2: intensity map of the Cosmic Infrared Background



Herschel 500 μm map



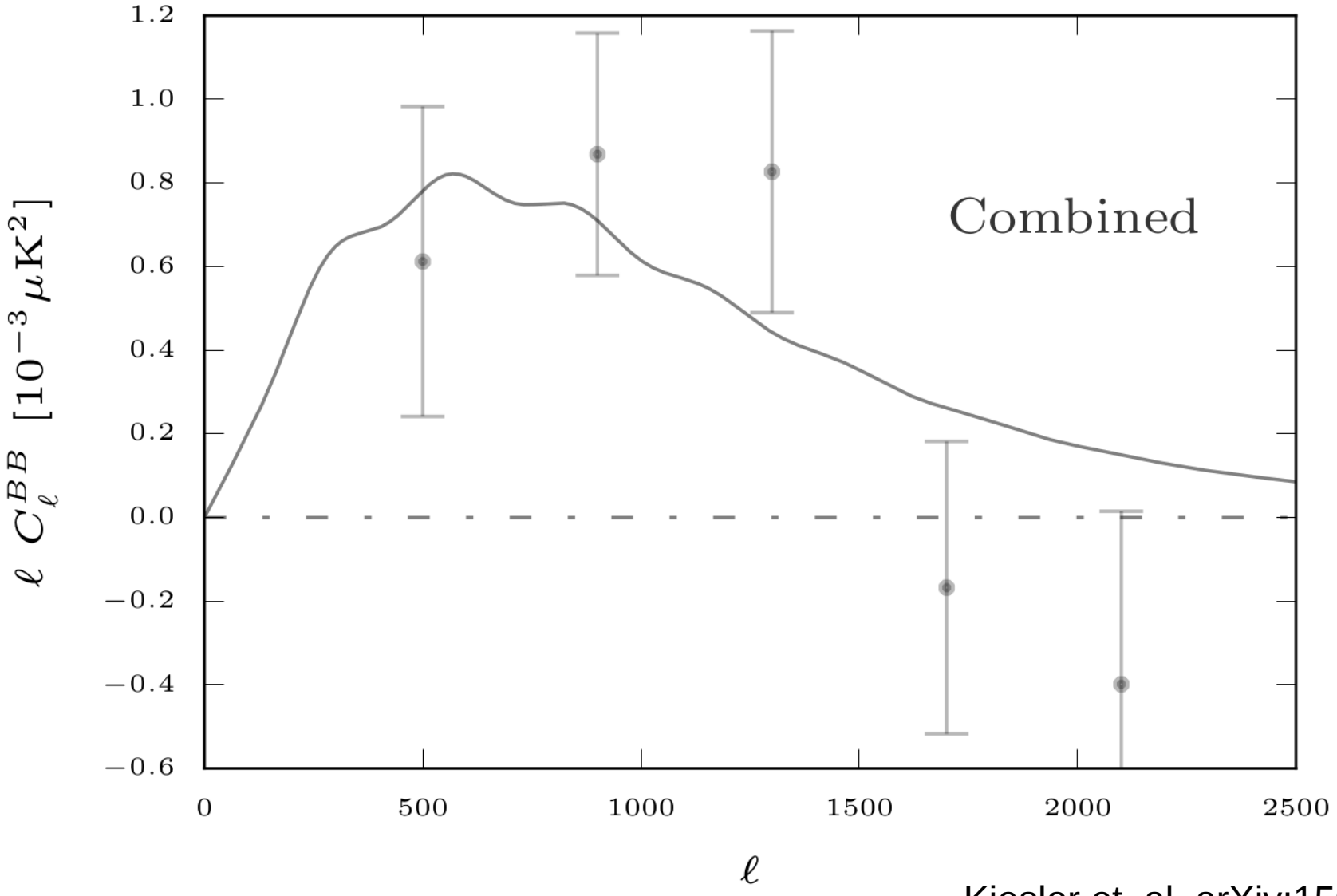
Grey: Herschel 500 μm map
Color: CMB lensing (Story et al 2015)



CIB-ϕ correlation model

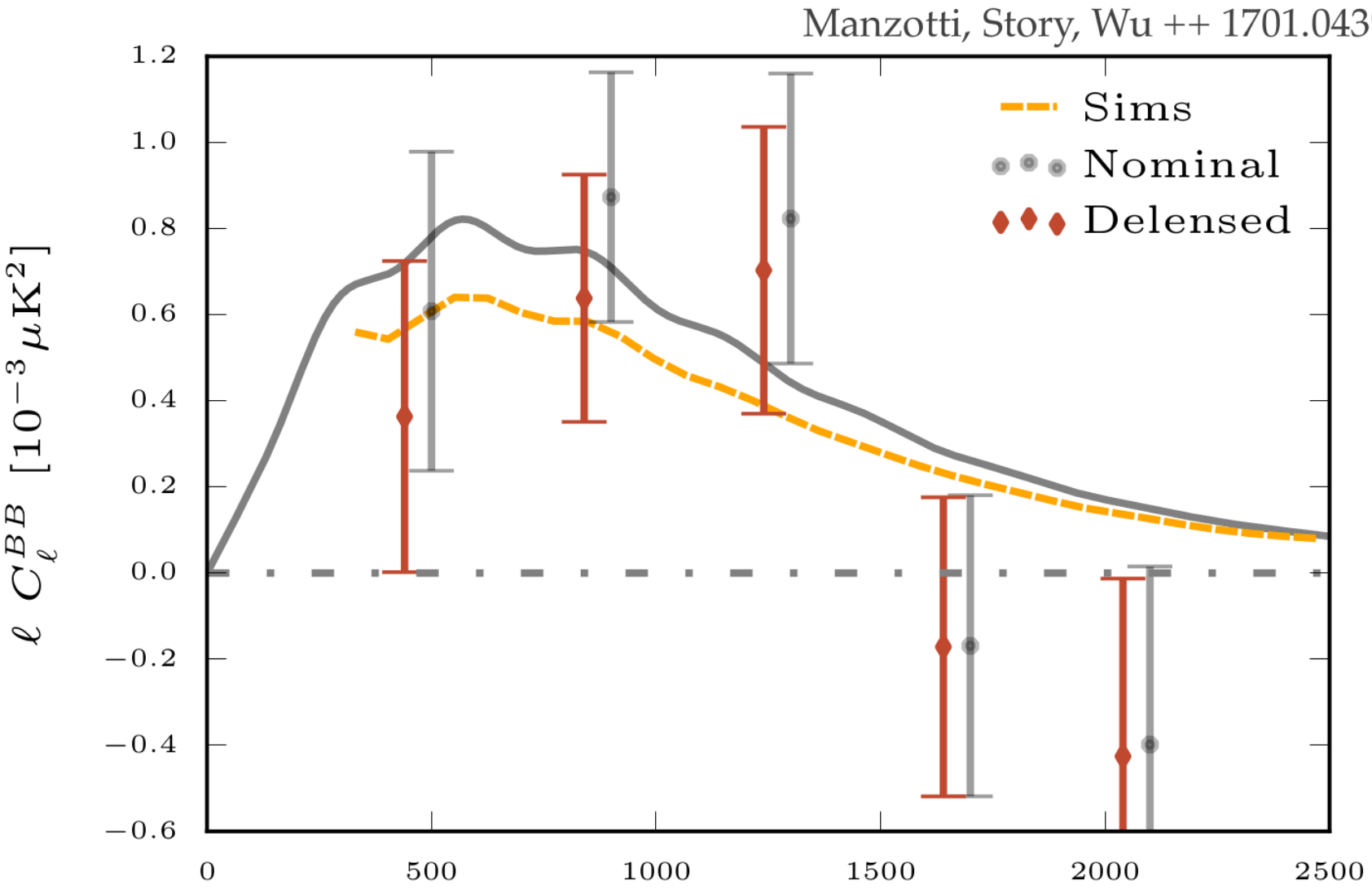
Manzotti, Story, Wu, et al (arXiv:1701.04396)

SPT B-Mode Spectrum



Kiesler et. al. arXiv:1503.02315

SPT Delensed B-Mode Spectrum

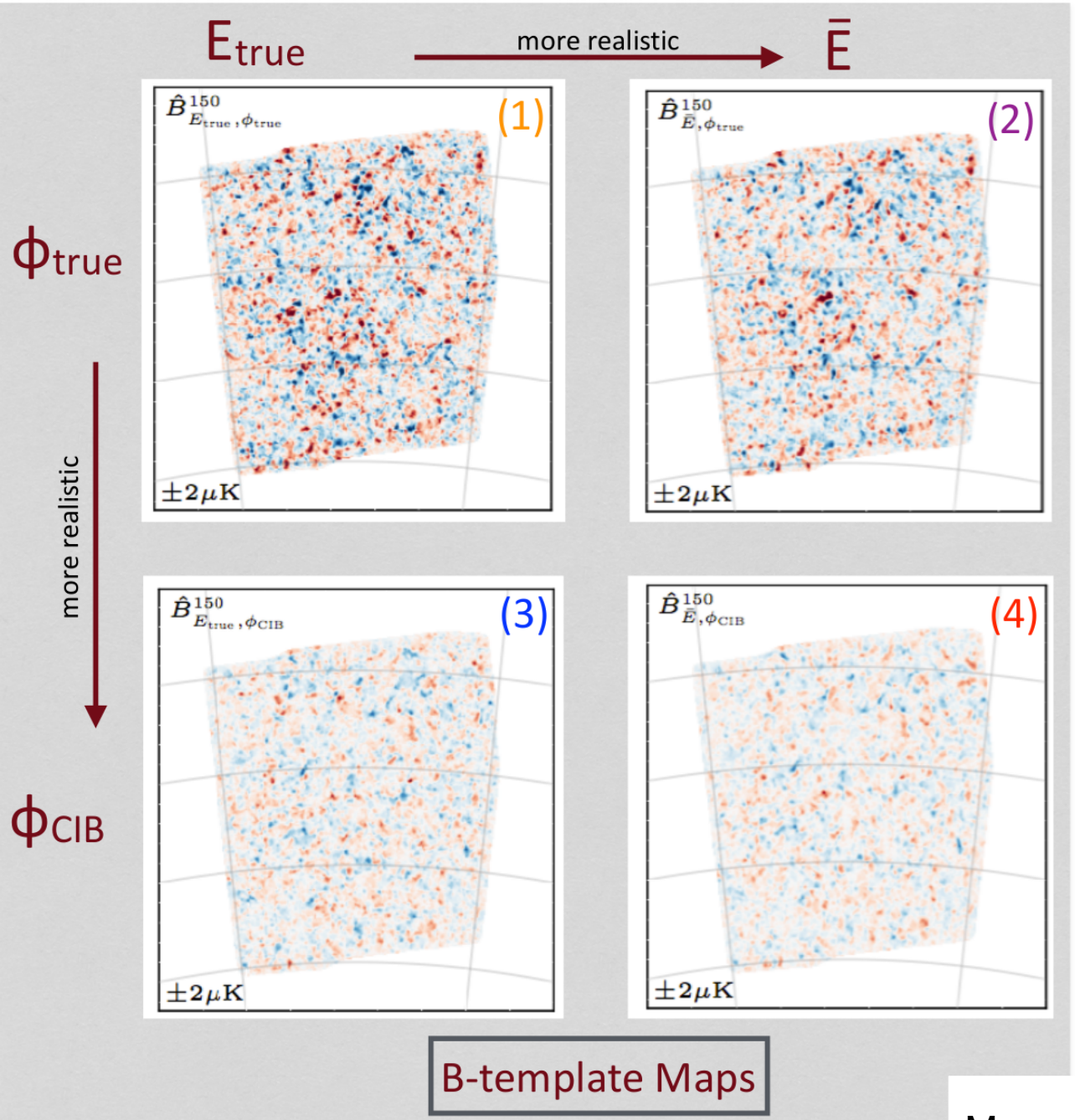


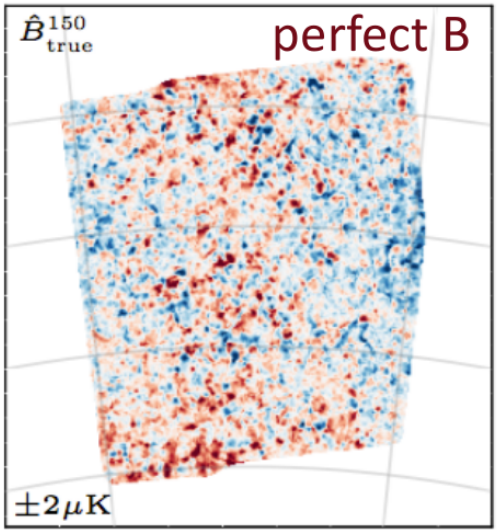
28% reduction in best-fit A_L
Reject no delensing at 6.9 sigma

Manzotti, Story, Wu, et al (arXiv:1701.04396)

Understanding Delensing efficiency (sims)

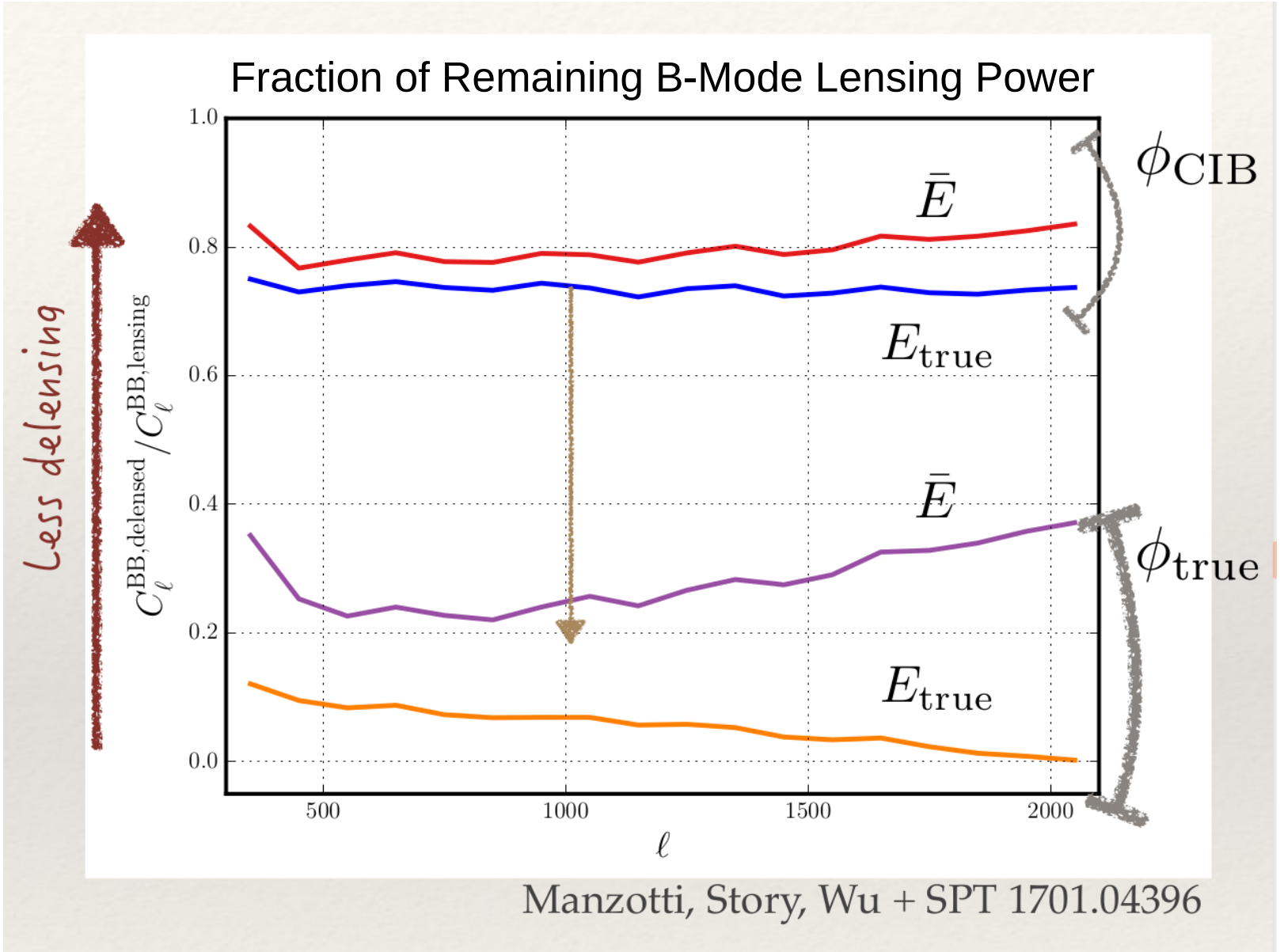
Filtering the btemplate: noisier templates have less total power.





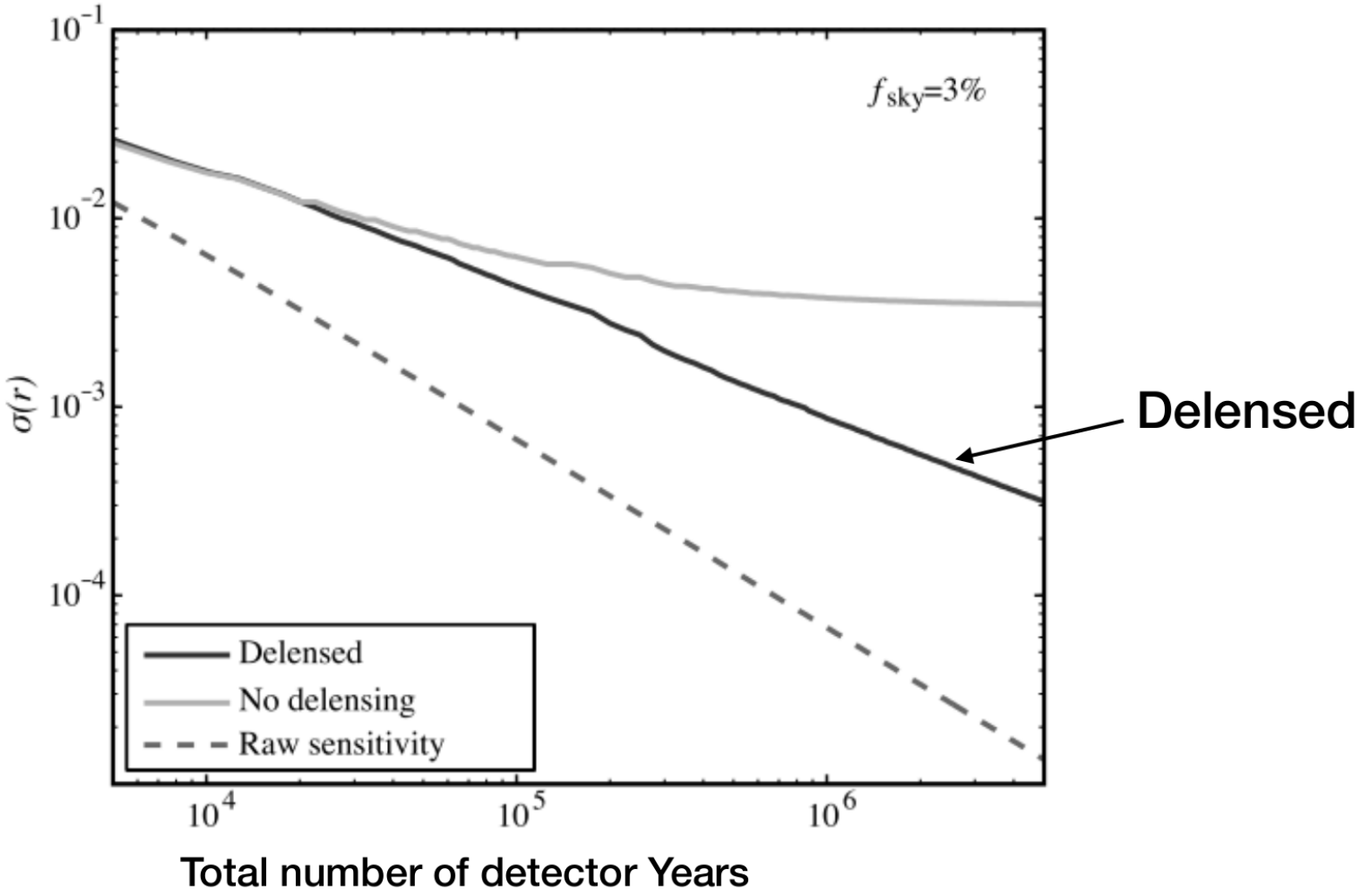
Manzotti, Story, Wu, et al (arXiv:1701.04396)

What Limits Delensing?



Manzotti, Story, Wu + SPT 1701.04396

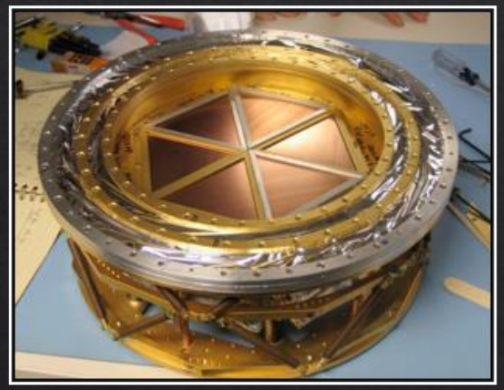
The Future of r involves Delensing



CMB-S4 Science Book

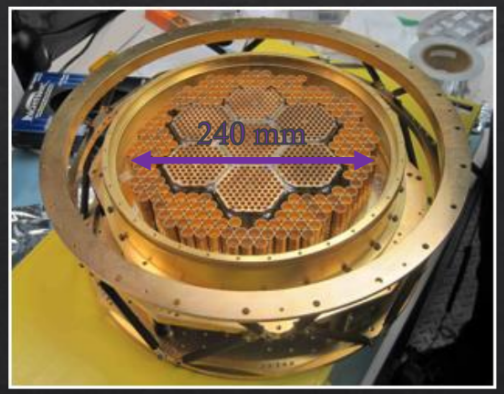
SPT-3G

2007: SPT-SZ
960 Detectors



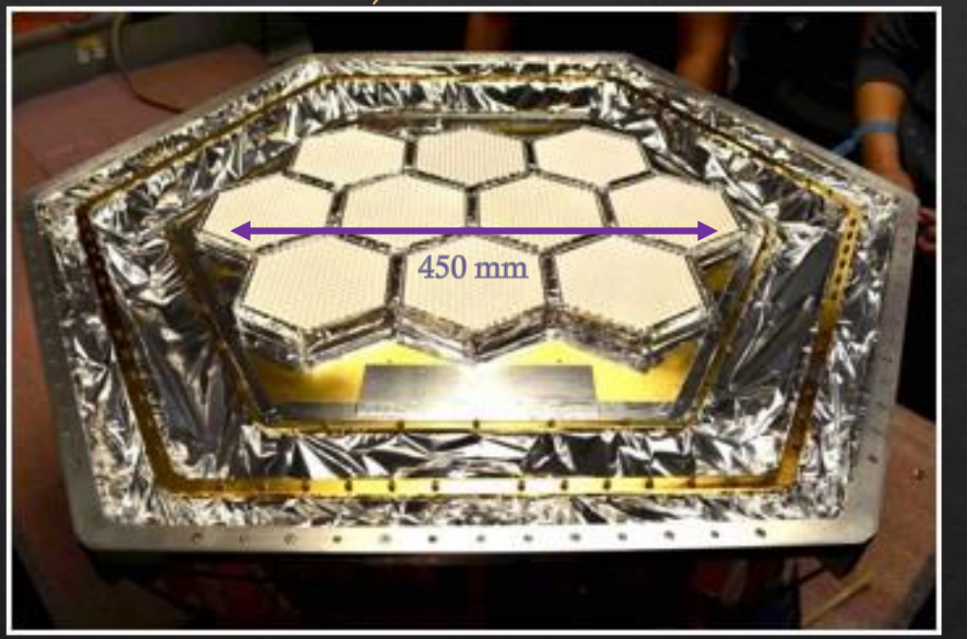
90, 150, 220 GHz

2012: SPTpol
1,500 Detectors



90, 150 GHz + Polarization

2017: SPT-3G
16,000 Detectors



90, 150, 220 GHz + Polarization
(but in every pixel…)

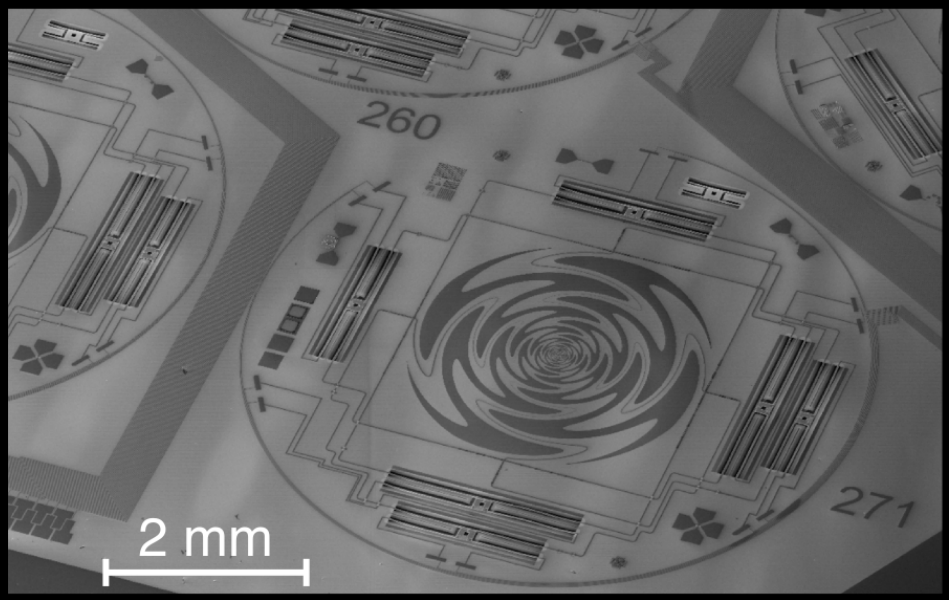
Shot Noise → More Detectors

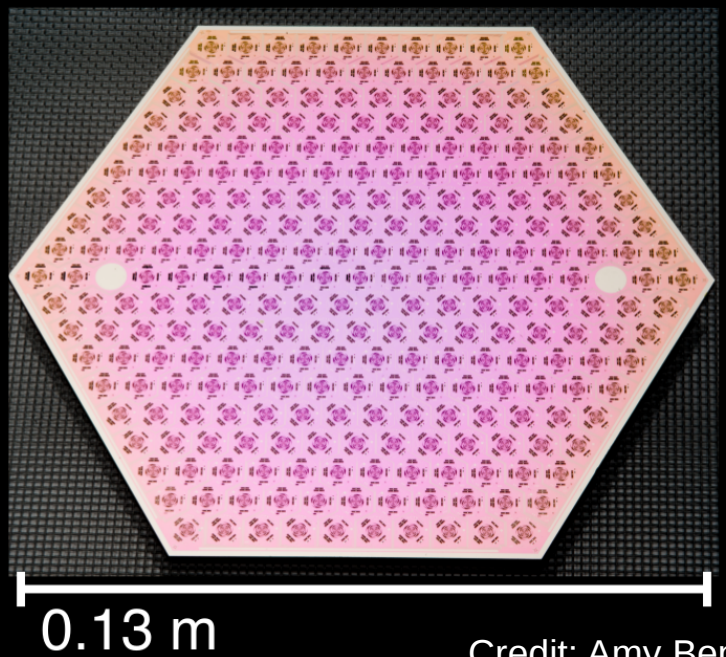
Foregrounds → More Frequency Coverage

Credit: Joshua Sobrin

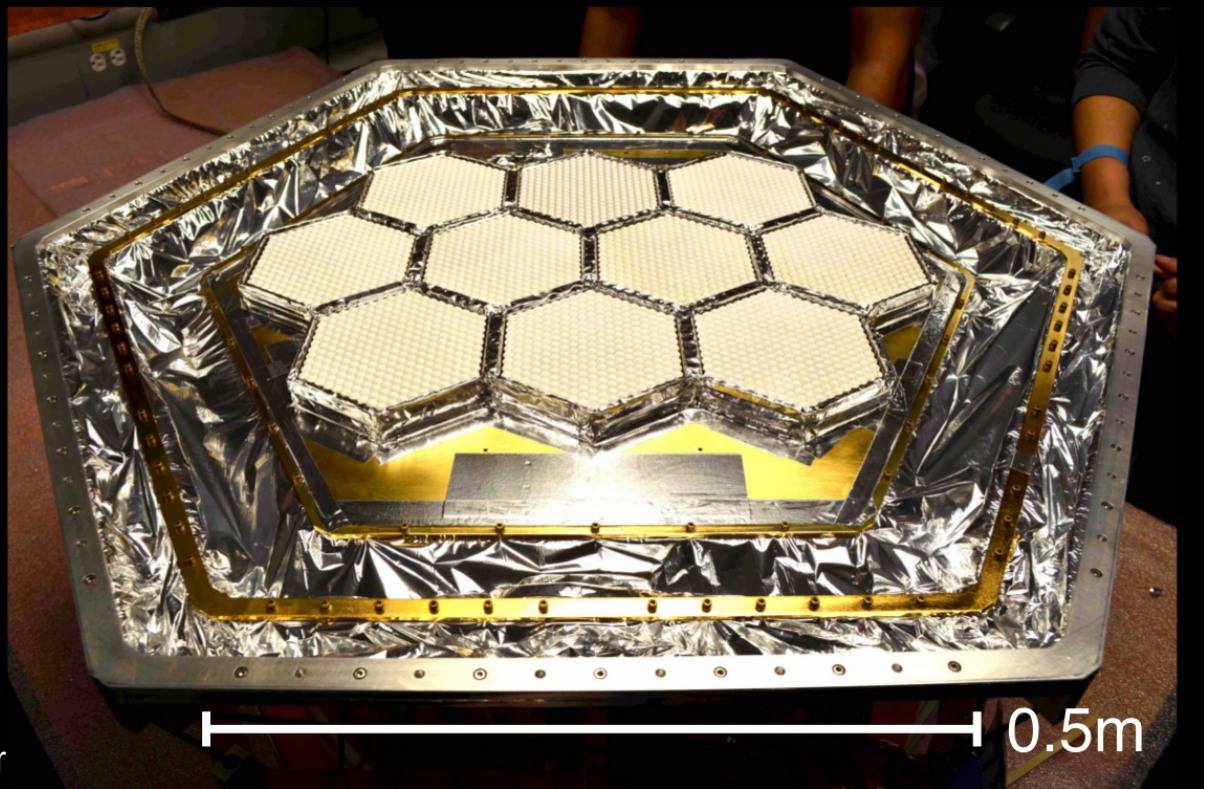
SPT-3G Focal Plane

- TES bolometers
  - Design by UC Berkeley
  - Fabricated at Argonne
- 6 TES coupled to each sinuous antenna
  - sensitive to 2 orthogonal polarizations & 3 bands (95/150/220 GHz)
- 16,140 TES in the SPT-3G focal plane
- Frequency domain multiplexing to bias and read out the bolometers

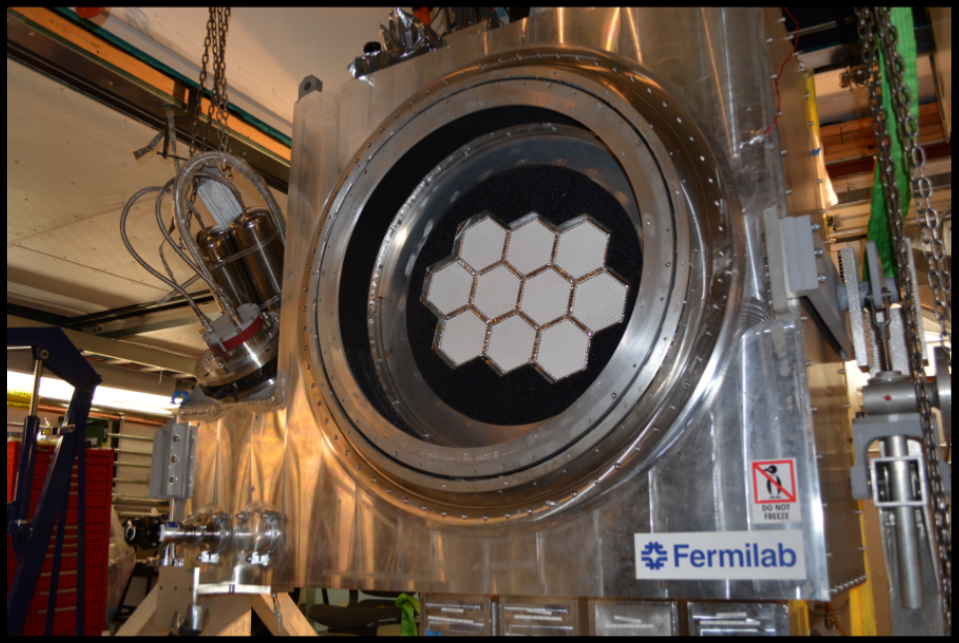


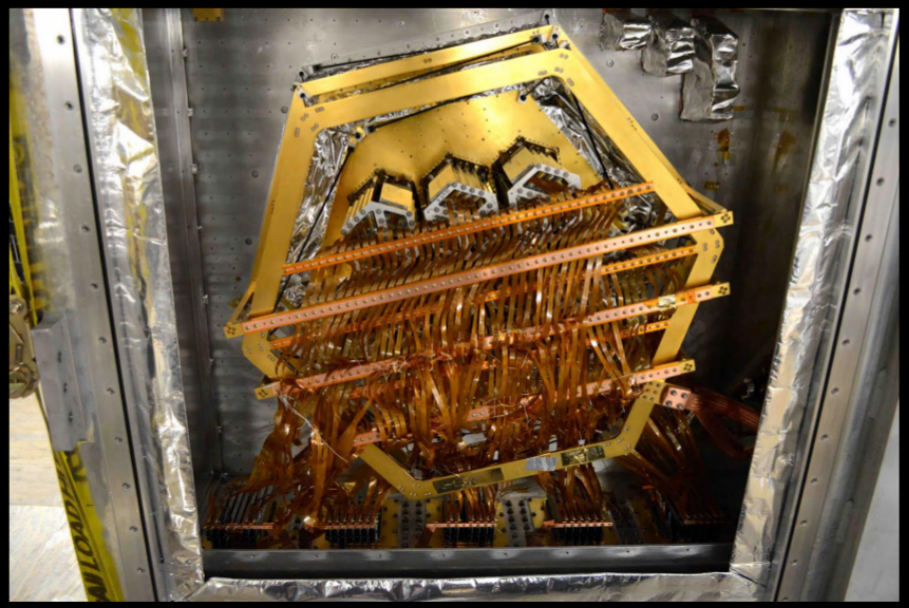


Credit: Amy Bender



SPT-3G Receiver



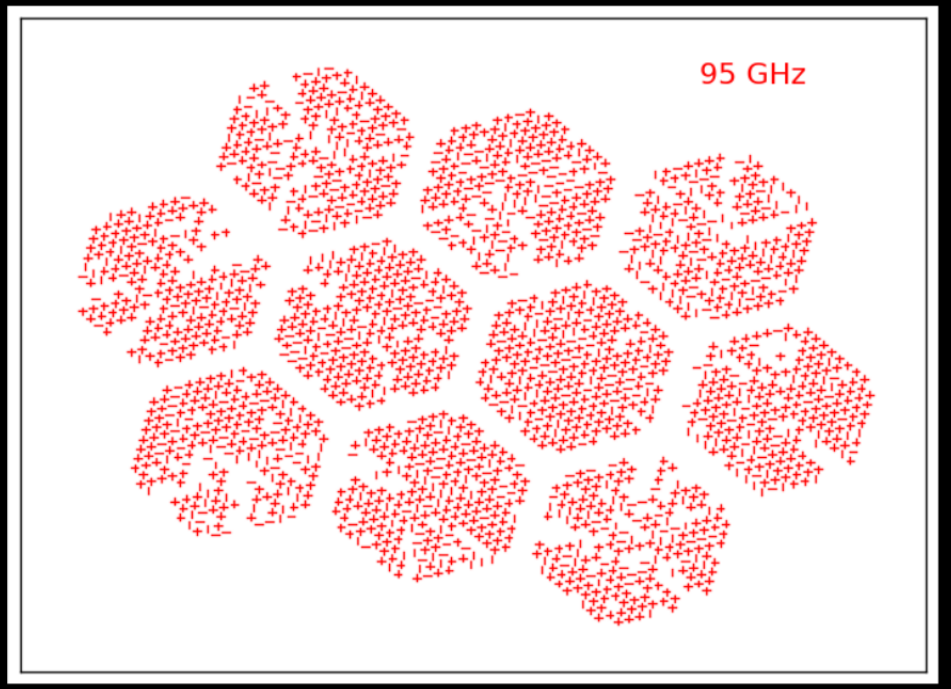


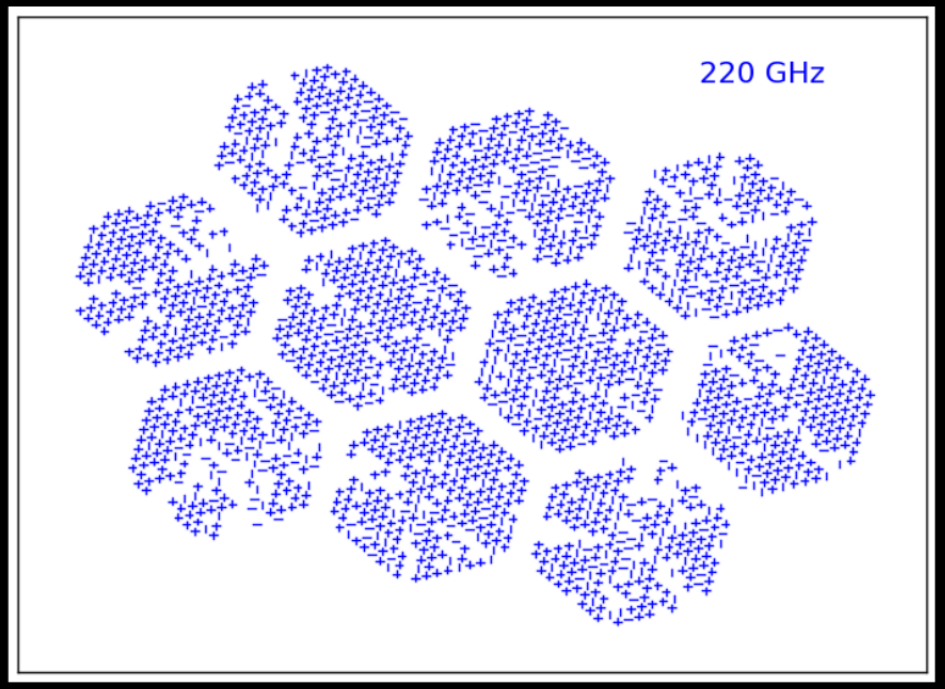
Credit: Amy Bender

Array Yield

Instrumental Sensitivity ~ $N_{detectors}$

~11,000 on-sky detectors



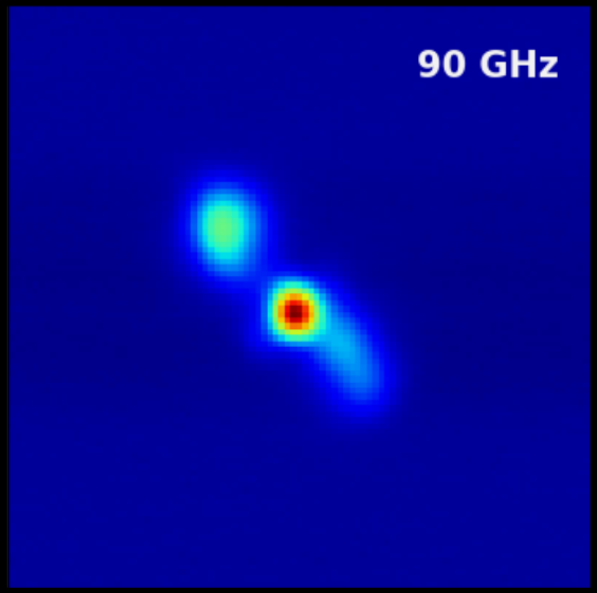


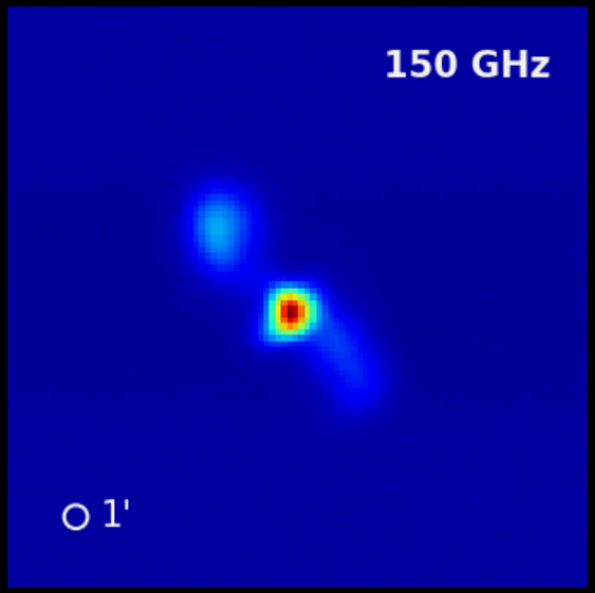
Credit: Amy Bender

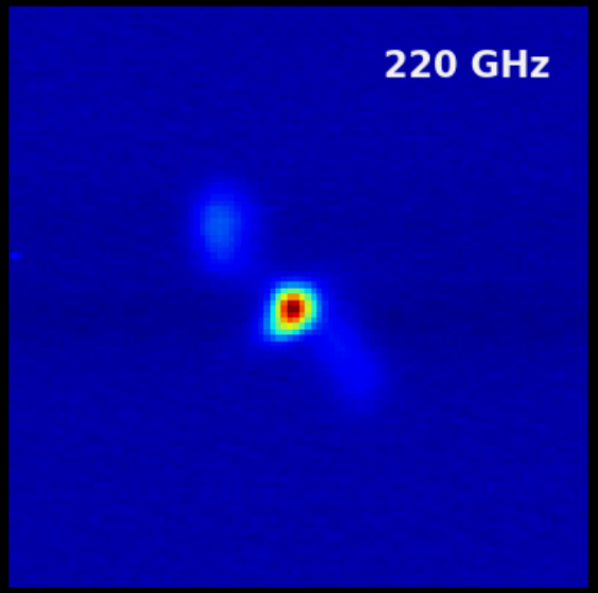
Each mark indicates an optically sensitive detector.

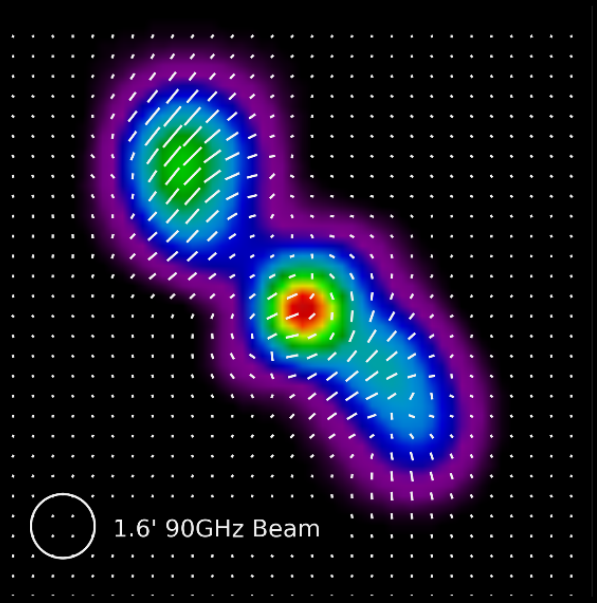
Polarized Source Maps

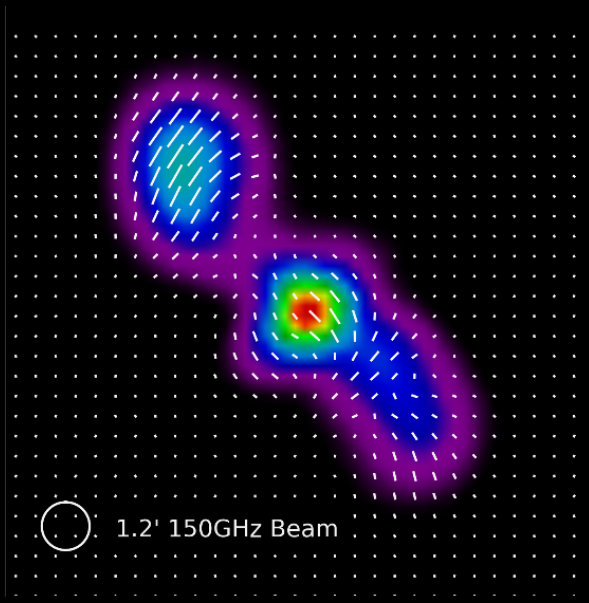
Centaurus A

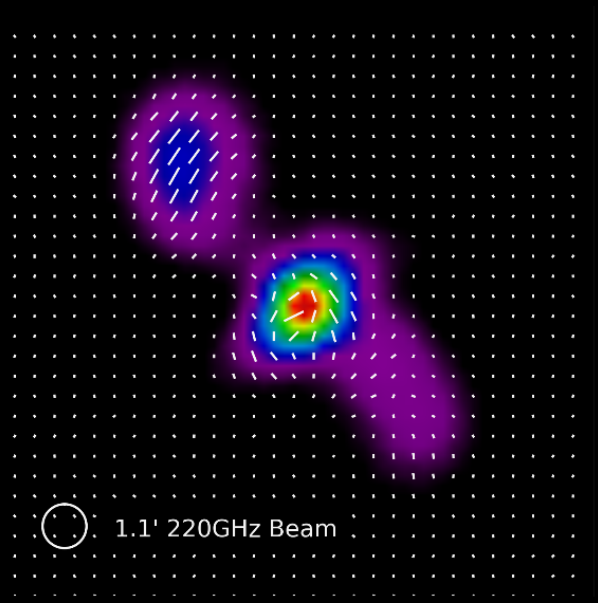






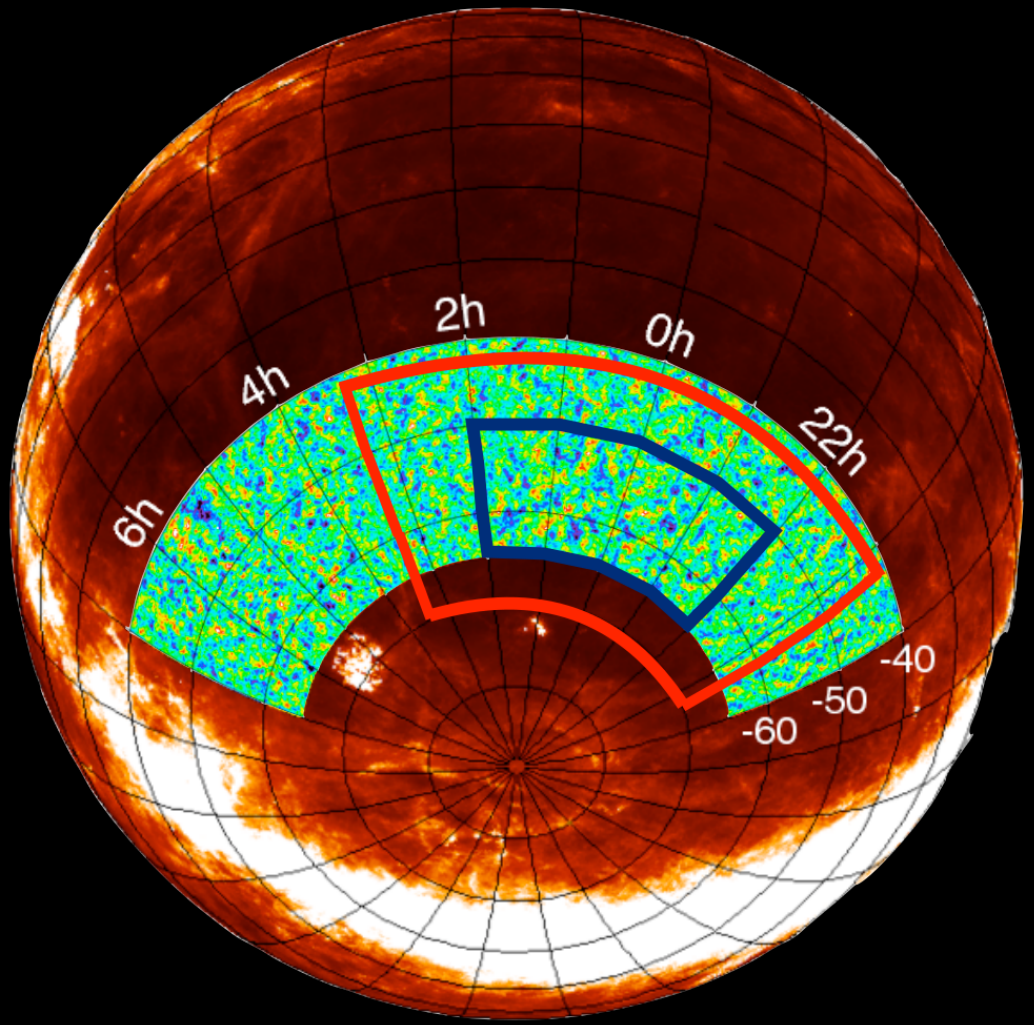






Credit: Amy Bender

Survey Strategy



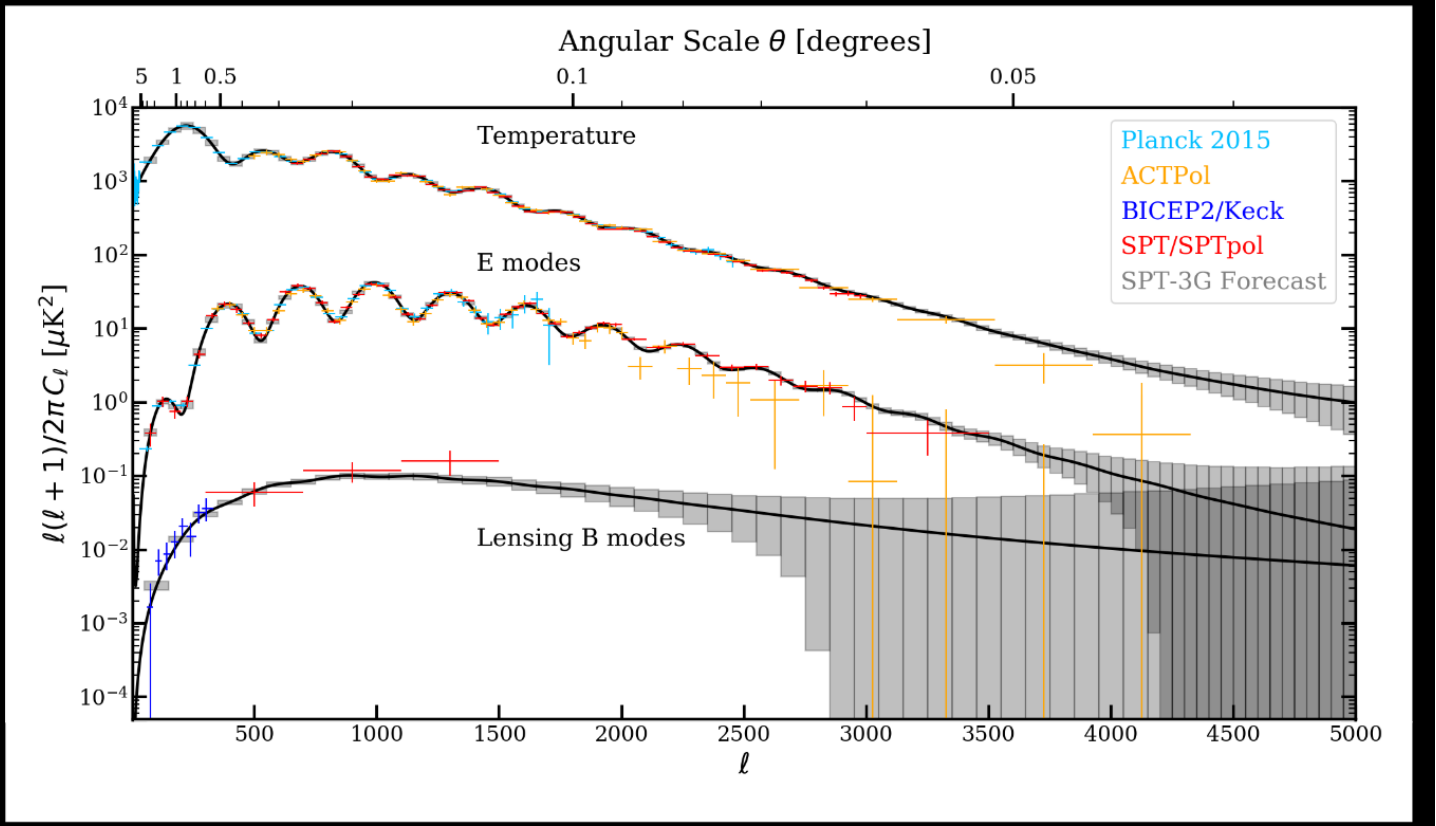
IRAS dust-map
Schlegel et al 1998

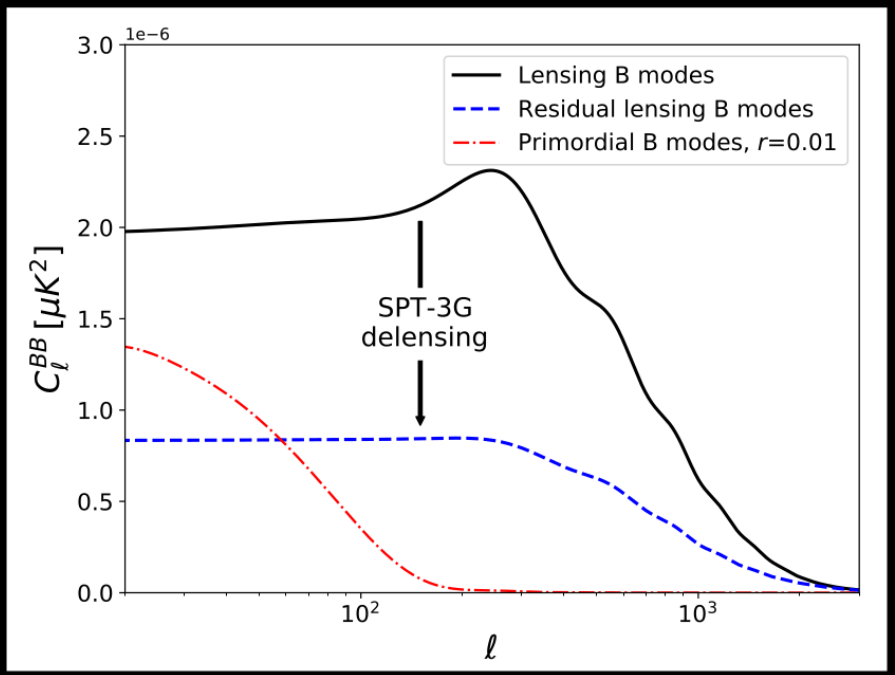
4 year survey
1500 sq degree

	95 GHz	150 GHz	220 GHz
T (μK-arcmin)	3.3	2.5	9.8
P (μK-arcmin)	4.7	3.5	13.9

Credit: Amy Bender

Forecasts





- High S/N measurement on the small scale (lensing) B-modes
  - Ability to ‘delens’ and clean B-mode maps!
  - 100% overlap with BICEP/Keck field
- Test ΛCDM
- Thousands of new galaxy clusters

Credit: Amy Bender

SPT Collaboration

Funded By:

Argonne NATIONAL LABORATORY
Berkeley Lab
NIST
Fermilab
ILLINOIS
University of Illinois at Urbana-Champaign
KICP
Kavli Institute for Cosmological Physics at the University of Chicago
Berkeley University of California
Case
Case Western Reserve University
McGill
Colorado
University of Colorado at Boulder
The University of Chicago
LMU
Ludwig-Maximilians-Universität München
Harvard-Smithsonian Center for Astrophysics
UC Davis
University of California
Cardiff University
Prifysgol Caerdydd
National Science Foundation
U.S. Department of Energy

Backup Slides

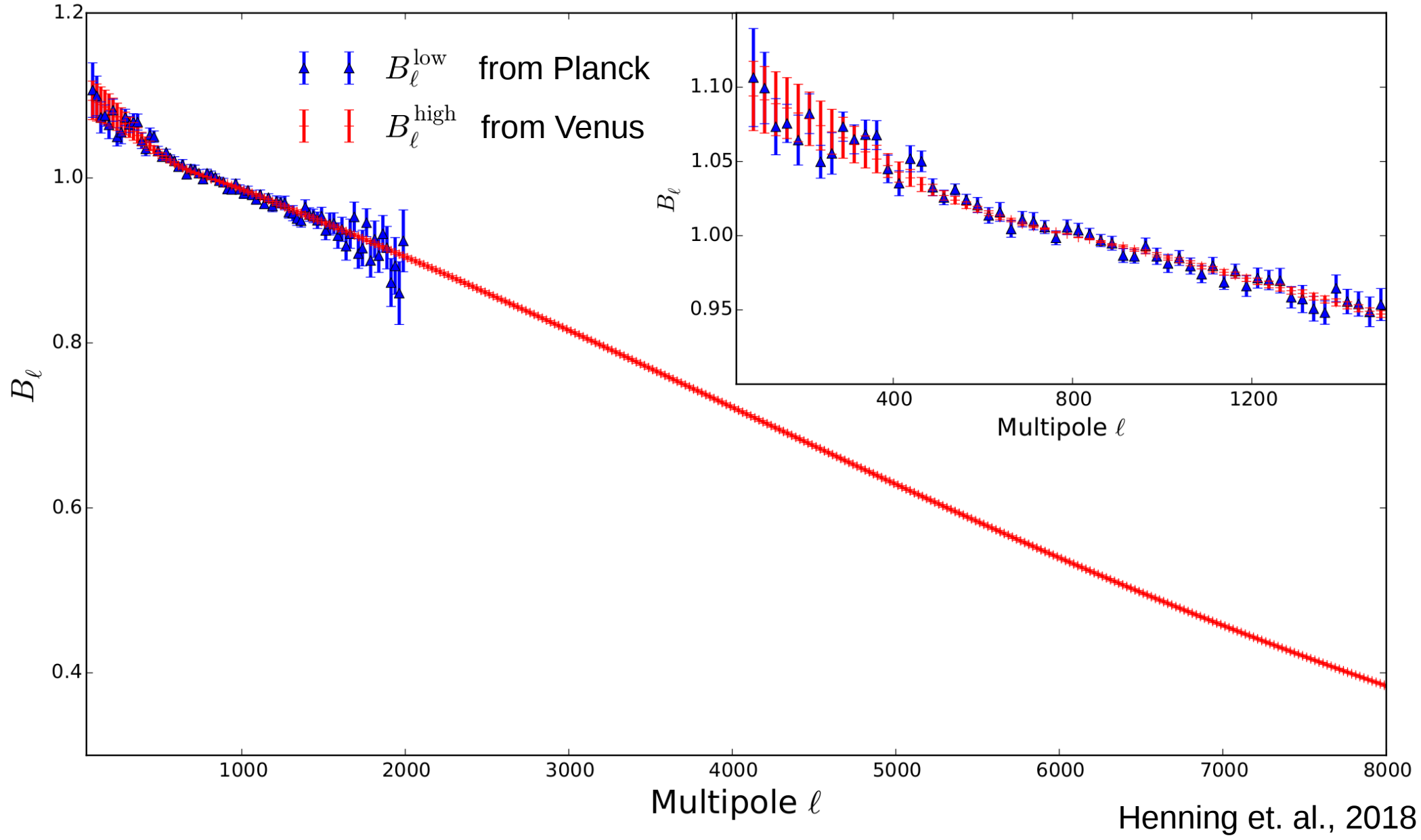
500 $\deg^2$ Spectra

- 125 “bundles” of maps with uniform coverage
- Cross spectra of all bundle pairs: avoids noise bias
- MASTER formalism (Hivon et al. 2002)
  - with 300 simulated skies
  - each mock observed the same 3491 times

Null Tests (Jackknife Splits)

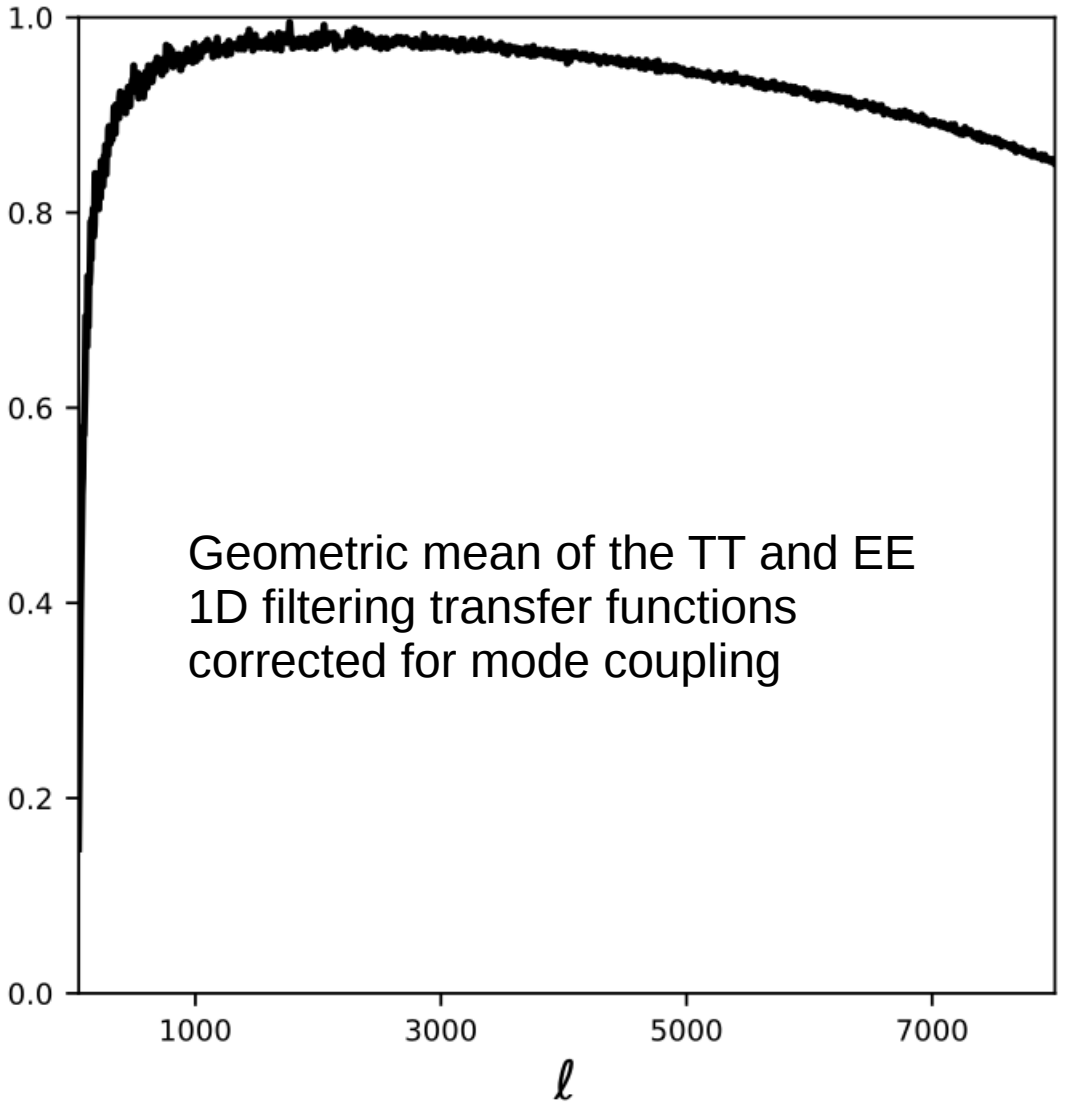
1) **Left-Right:** left-going or right-going telescope scans.
2) **1st Half-2nd Half:** time-dependent errors
3) **Sun:** beam sidelobe pickup sun above or below the horizon.
4) **Moon:** We test for additional beam sidelobe pickup from the Moon
5) **Azimuth:** contamination from stationary objects or ground. Compare “noisiest az” to “quietest az”

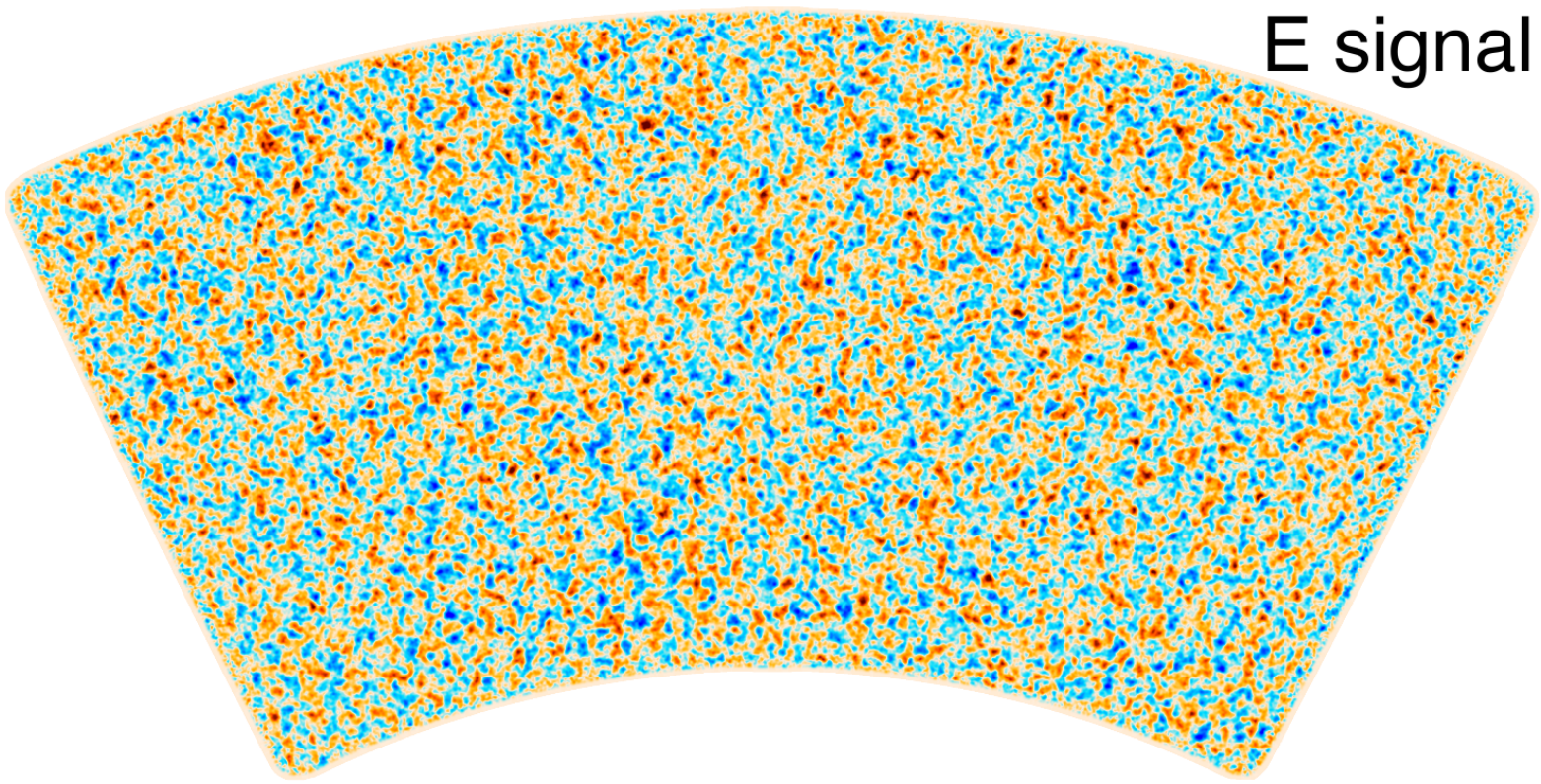
SPTpol Beam

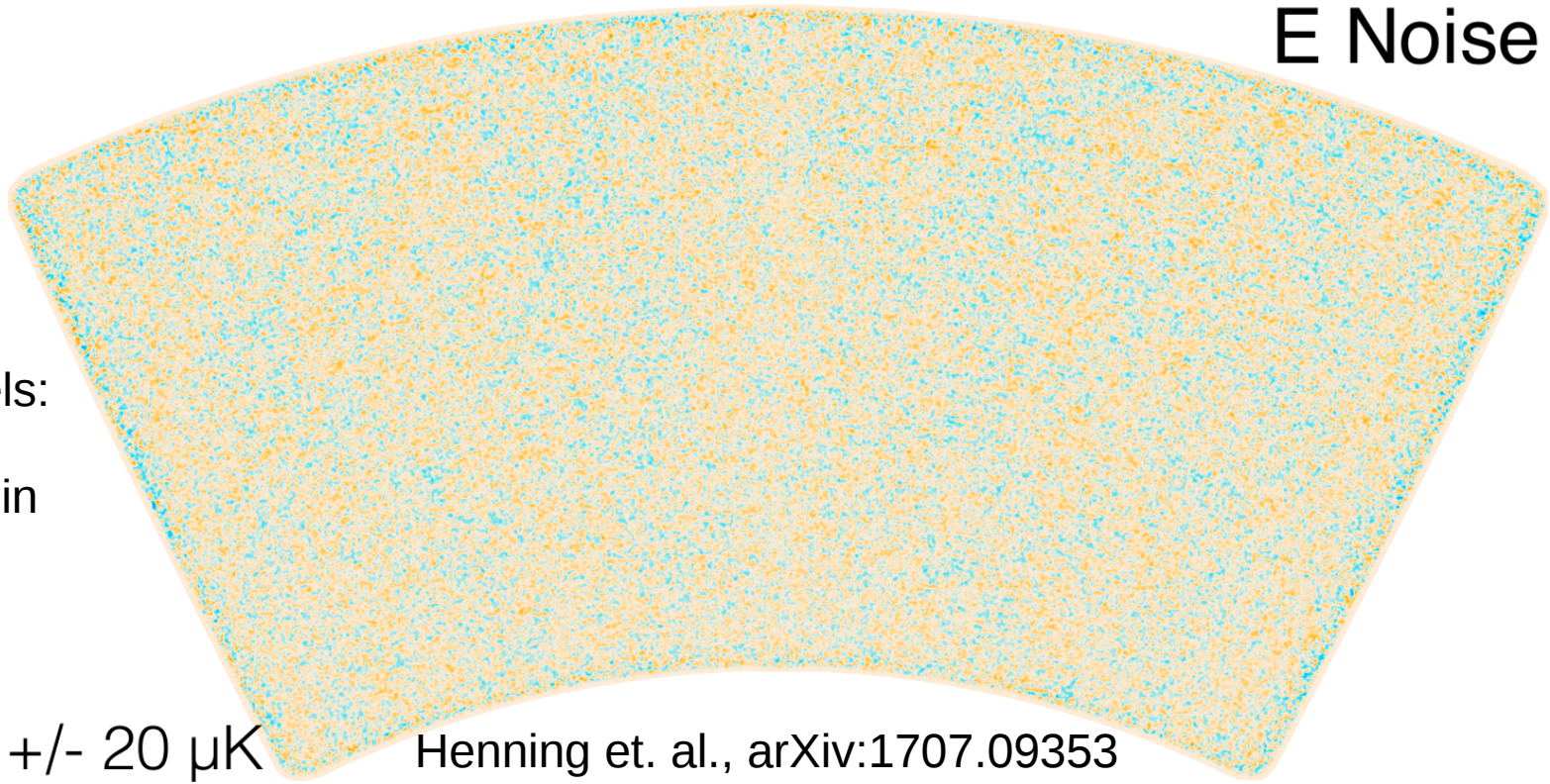


Henning et. al., 2018

Transfer Function





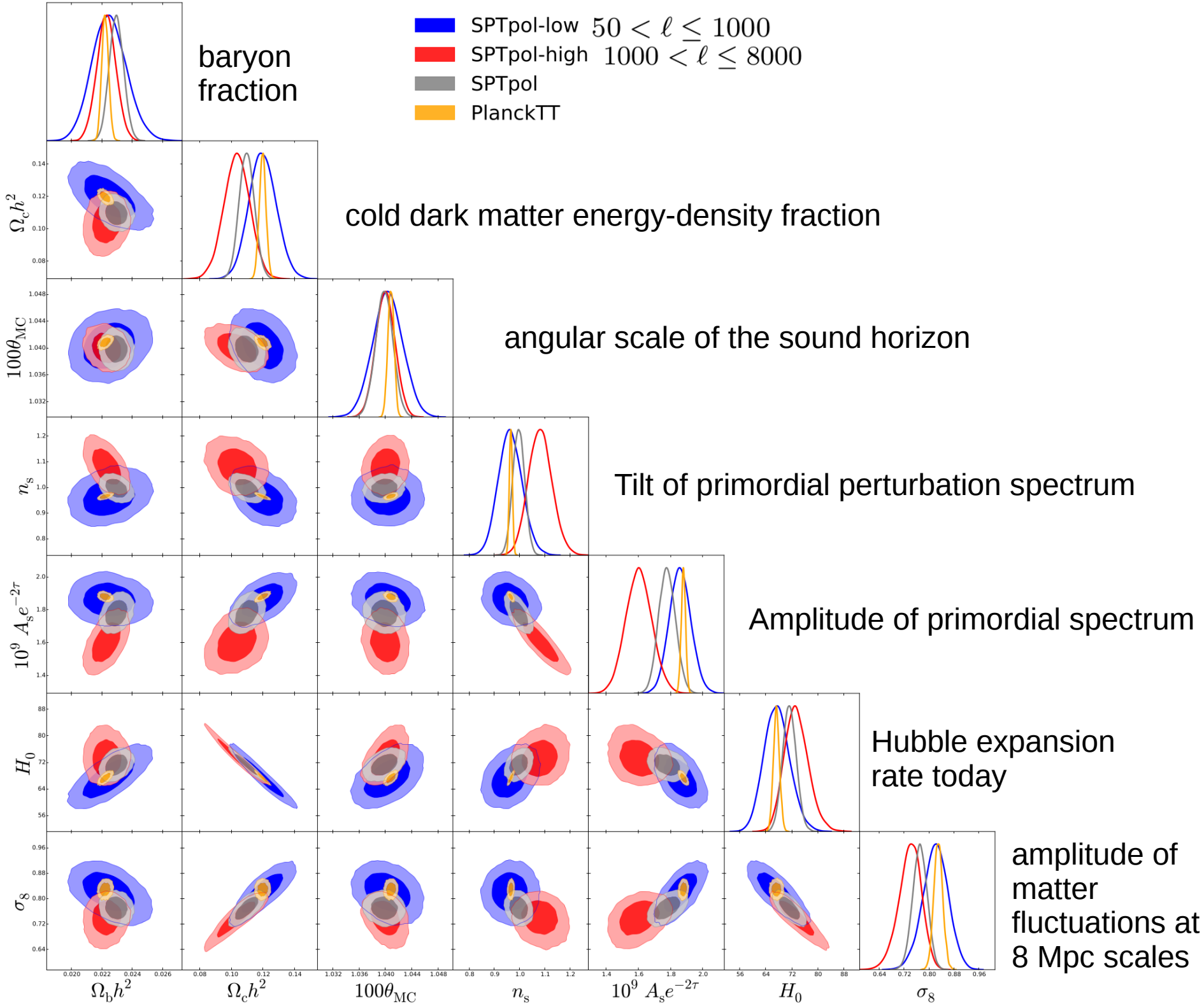


SPTpol Temp noise levels:
150 GHz: 5 uK-arcmin
 90 GHz: 10 uK-arcmin in

√2 less in the
100 deg^2 sub field.

+/- 20 μK

Henning et. al., arXiv:1707.09353


SPTpol-low $50 < \ell \leq 1000$
SPTpol-high $1000 < \ell \leq 8000$
SPTpol
PlanckTT
baryon fraction
cold dark matter energy-density fraction
angular scale of the sound horizon
Tilt of primordial perturbation spectrum
Amplitude of primordial spectrum
Hubble expansion rate today
amplitude of matter fluctuations at 8 Mpc scales
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_{MC}$
n_s
$10^9\ A_s e^{-2\tau}$
H_0
σ_8

ΛCDM Constraints

Parameter	Data Set		
	SPTpol-$\ell < 1000$	SPTpol-$\ell > 1000$	SPTpol
Free			
$100\Omega_{\rm b}h^2$	2.250 ± 0.114	2.230 ± 0.063	2.296 ± 0.048
$\Omega_{\rm c}h^2$	0.1198 ± 0.0087	0.1036 ± 0.0083	0.1098 ± 0.0048
$100\theta_{\rm MC}$	1.0404 ± 0.0023	1.0400 ± 0.0015	1.0398 ± 0.0013
$n_{\rm s}$	0.9635 ± 0.0478	1.0827 ± 0.0472	0.9967 ± 0.0238
$10^9 A_{\rm s}e^{-2\tau}$	1.8604 ± 0.0675	1.6035 ± 0.0818	1.7791 ± 0.0528
Derived			
Ω_Λ	0.681 ± 0.055	0.762 ± 0.039	0.736 ± 0.025
σ_8	0.820 ± 0.041	0.738 ± 0.037	0.771 ± 0.024
H_0	67.49 ± 3.99	73.49 ± 3.73	71.29 ± 2.12

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H_0	67.49 ± 3.99	73.49 ± 3.73	71.29 ± 2.12

2σ tension with Planck
0.8102 ± 0.0060

ΛCDM Constraints

Parameter	Data Set		
	SPTpol-$\ell < 1000$	SPTpol-$\ell > 1000$	SPTpol
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$100\Omega_{\rm b}h^2$	2.250 ± 0.114	2.230 ± 0.063	2.296 ± 0.048
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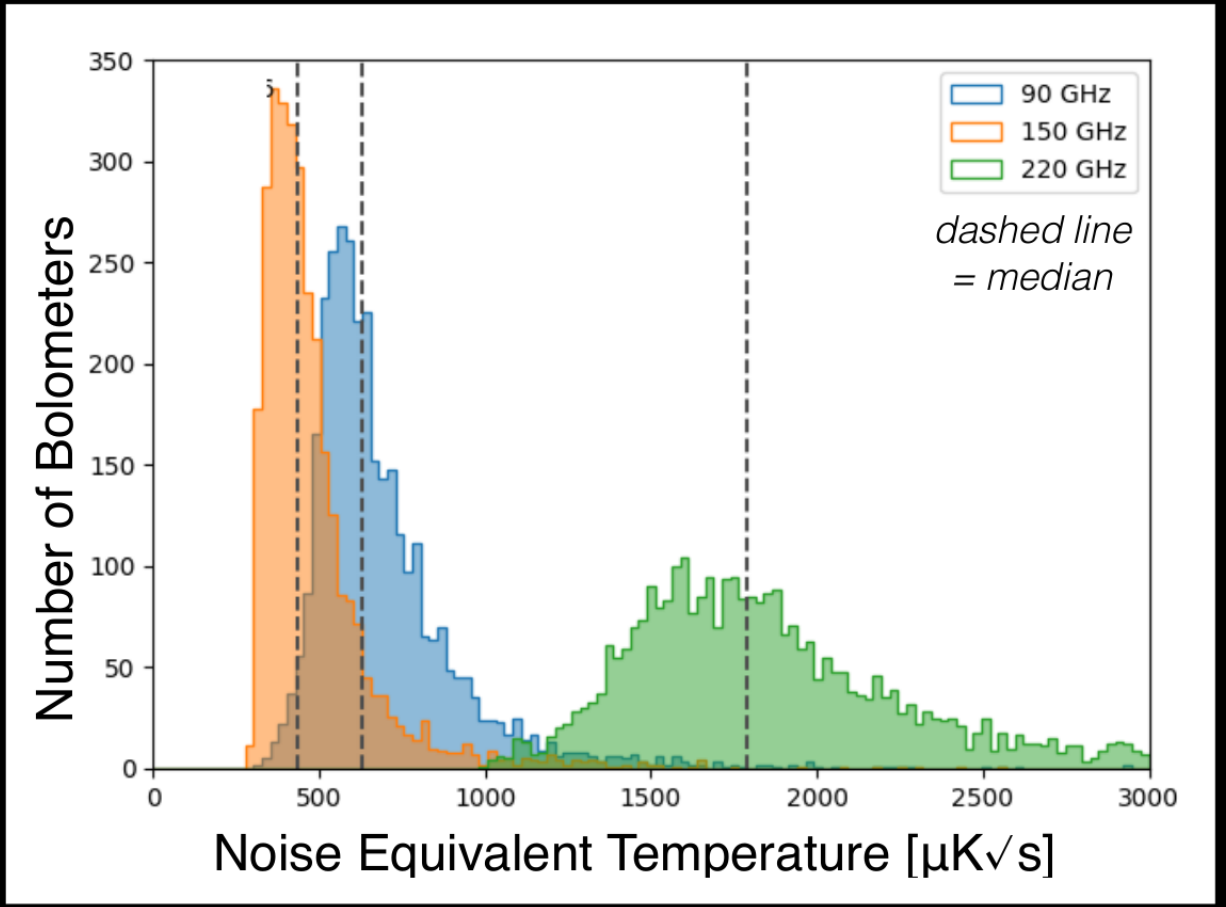
H_0	67.49 ± 3.99	73.49 ± 3.73	71.29 ± 2.12

1.5σ tension with Planck
67.66 ± 0.42

Year 2 Sensitivity

- Photon noise dominated performance at 95/150/220 GHz, consistent with expectations
- 220 GHz NET is 1.5x expected, believed due to poor transmission in AR coatings of alumina surfaces



	95 GHz	150 GHz	220 GHz
NET Array (μK√s)	10	8	30
Mapping speed relative to SPTpol	9x	4x	∞x

Credit: Amy Bender