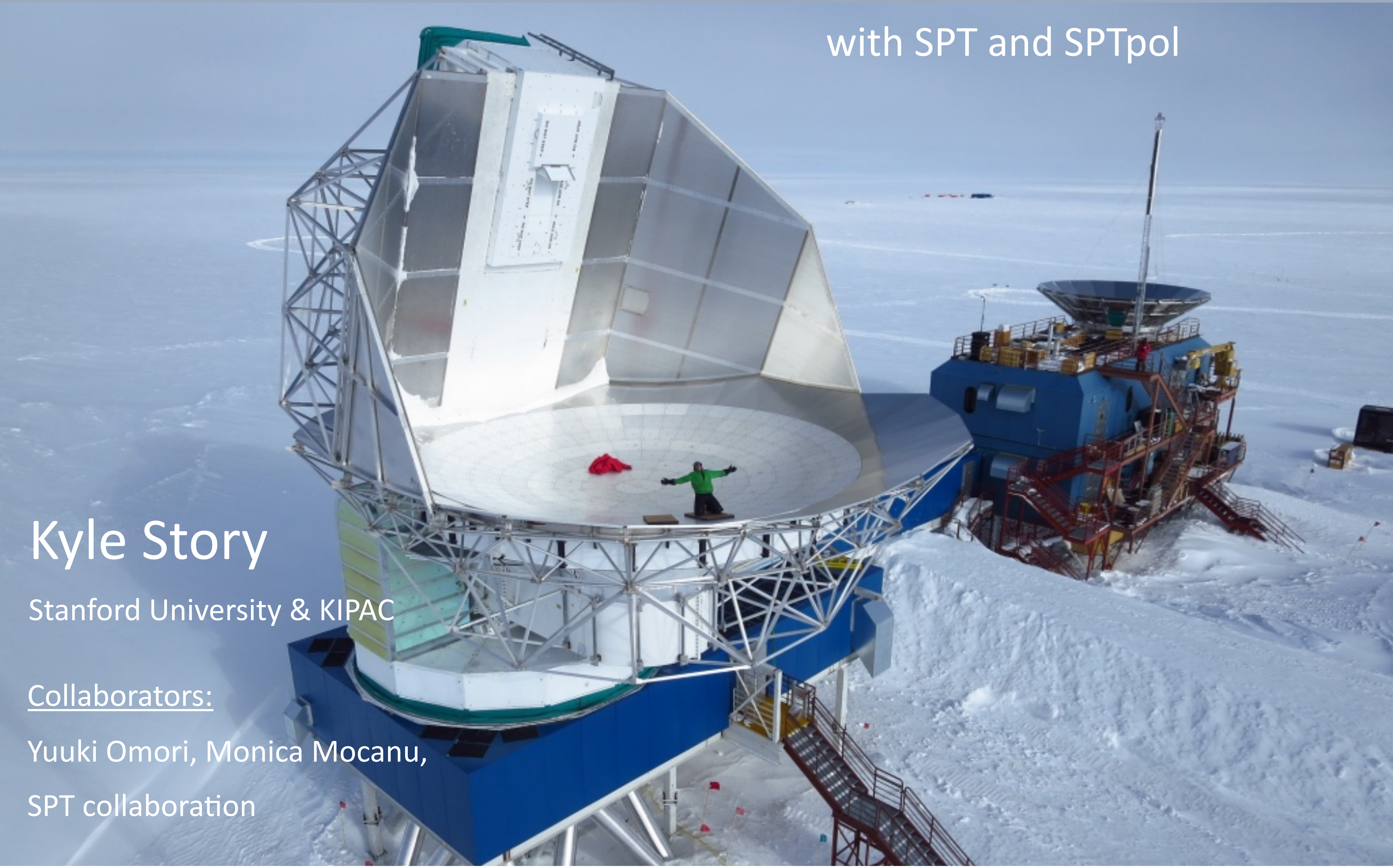
CMB Lensing Reconstruction

with SPT and SPTpol



Kyle Story

Stanford University & KIPAC

Collaborators:

Yuuki Omori, Monica Mocanu,

SPT collaboration

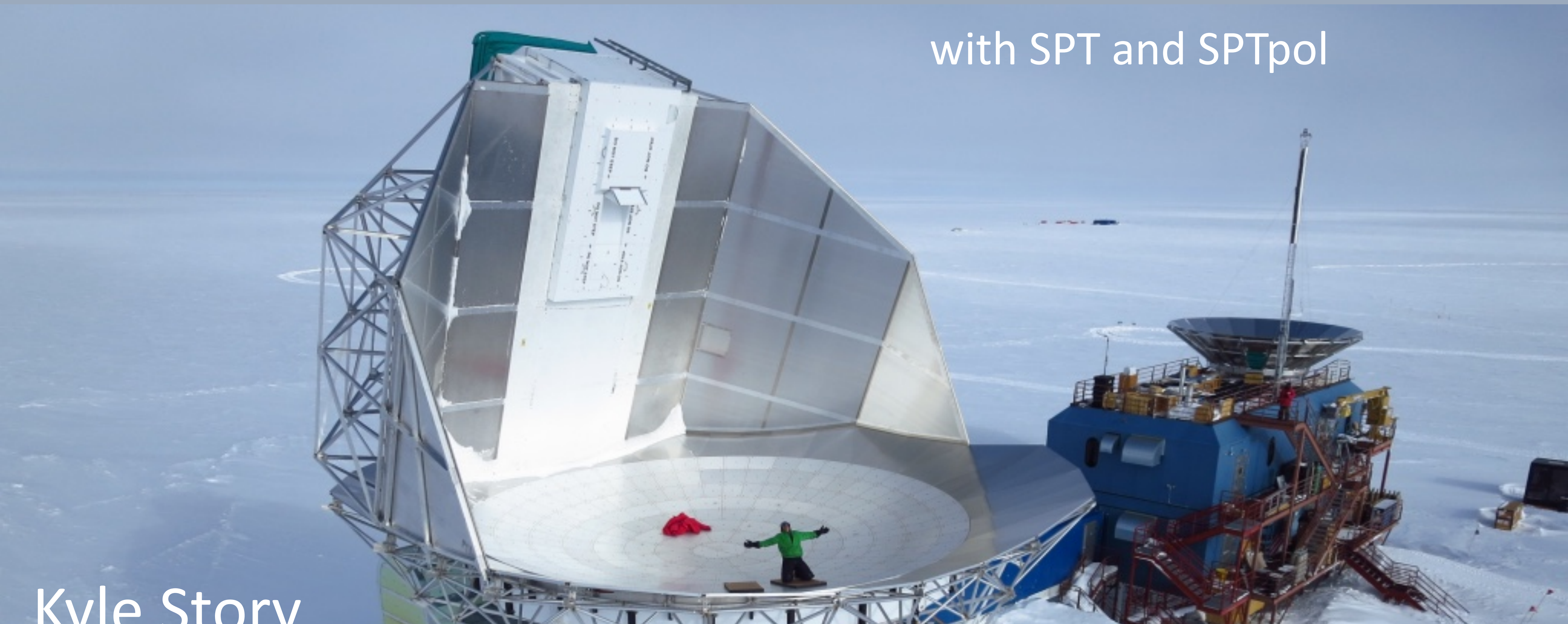
Nordita Cosmology Conference

July 21, 2017

STANFORD UNIVERSITY

CMB Lensing Reconstruction

with SPT and SPTpol



Kyle Story

Stanford University & KIPAC

Collaborators:

Yuuki Omori, Monica Mocanu,

SPT collaboration

KIPAC

Nordita Cosmology Conference

July 21, 2017

STANFORD UNIVERSITY

The SPT Collaboration (Feb. 2016)

~70 scientists (~half postdocs and students)

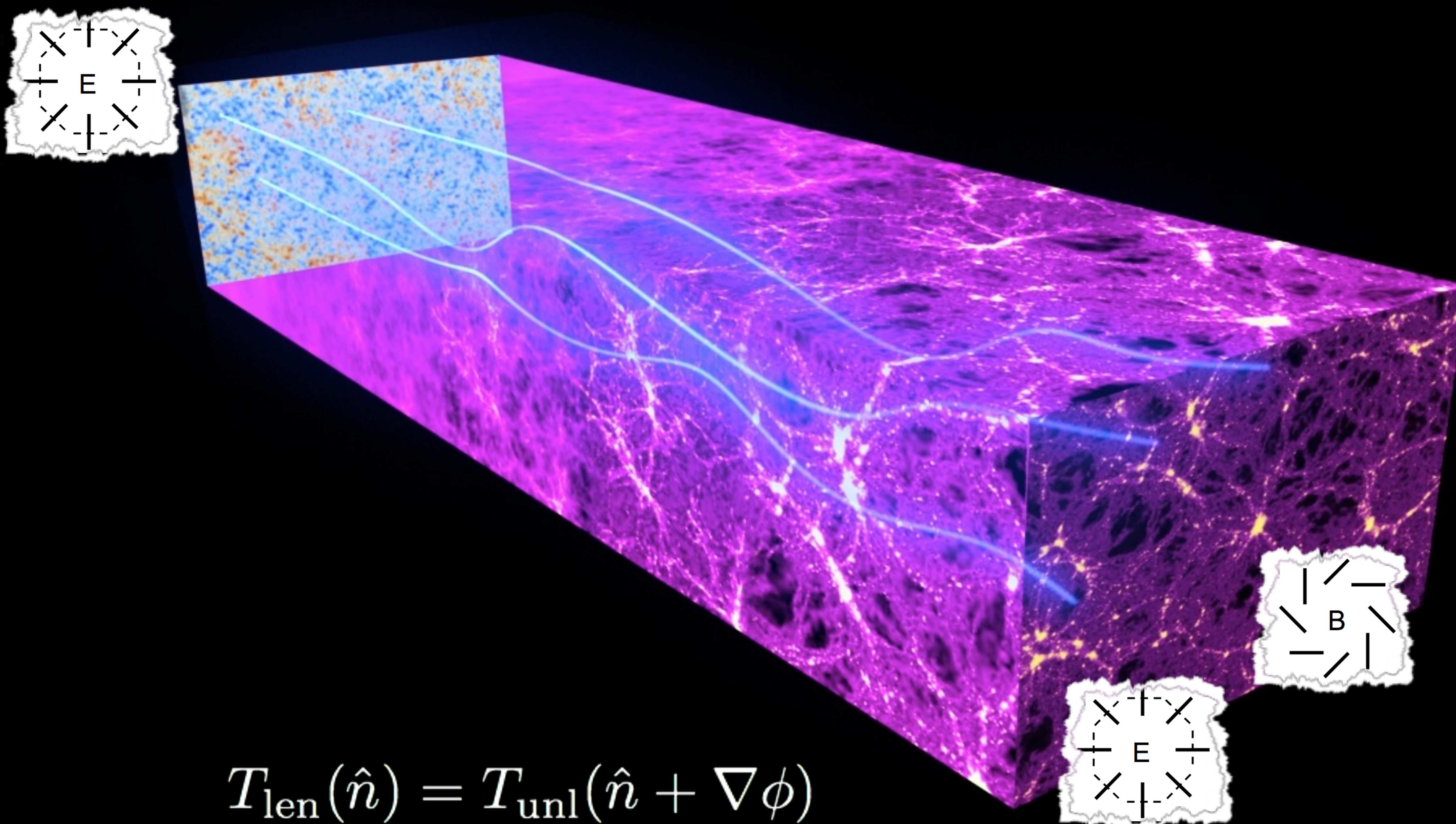
across ~20+ institutions

Argonne National Laboratory
Berkeley Lab
NIST
Fermilab
KICP Kavli Institute for Cosmological Physics at the University of Chicago
Berkeley University of California
Case Western Reserve University
McGill
Colorado University of Colorado at Boulder
Cardiff University Prifysgol Caerdydd
UC Davis University of California
The University of Chicago
LMU Ludwig-Maximilians-Universität München
Harvard-Smithsonian Center for Astrophysics
M
University of Illinois
SLAC National Accelerator Laboratory

Funded By:

U.S. Department of Energy

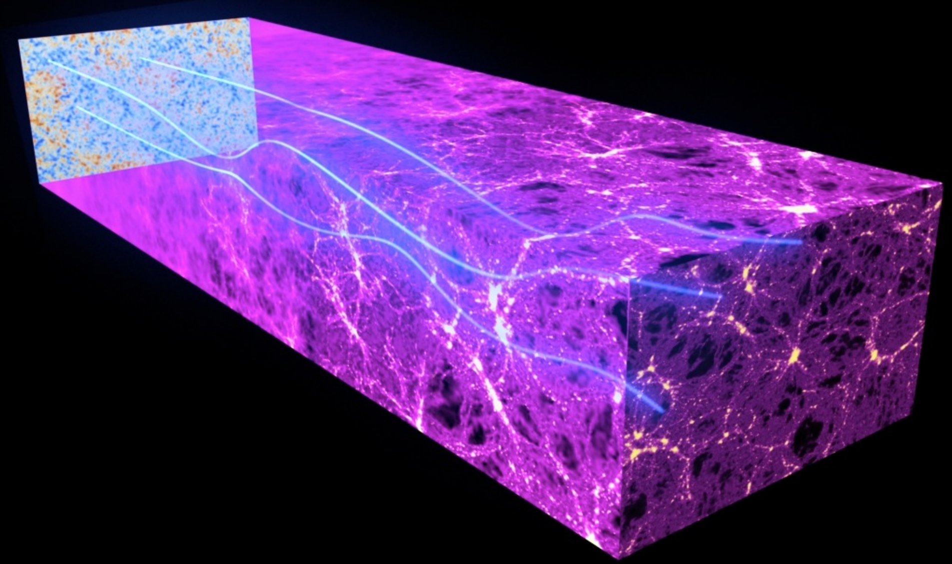
Gravitational Lensing: As CMB photons travel from the last-scattering surface, their paths are bent by intervening matter structure.

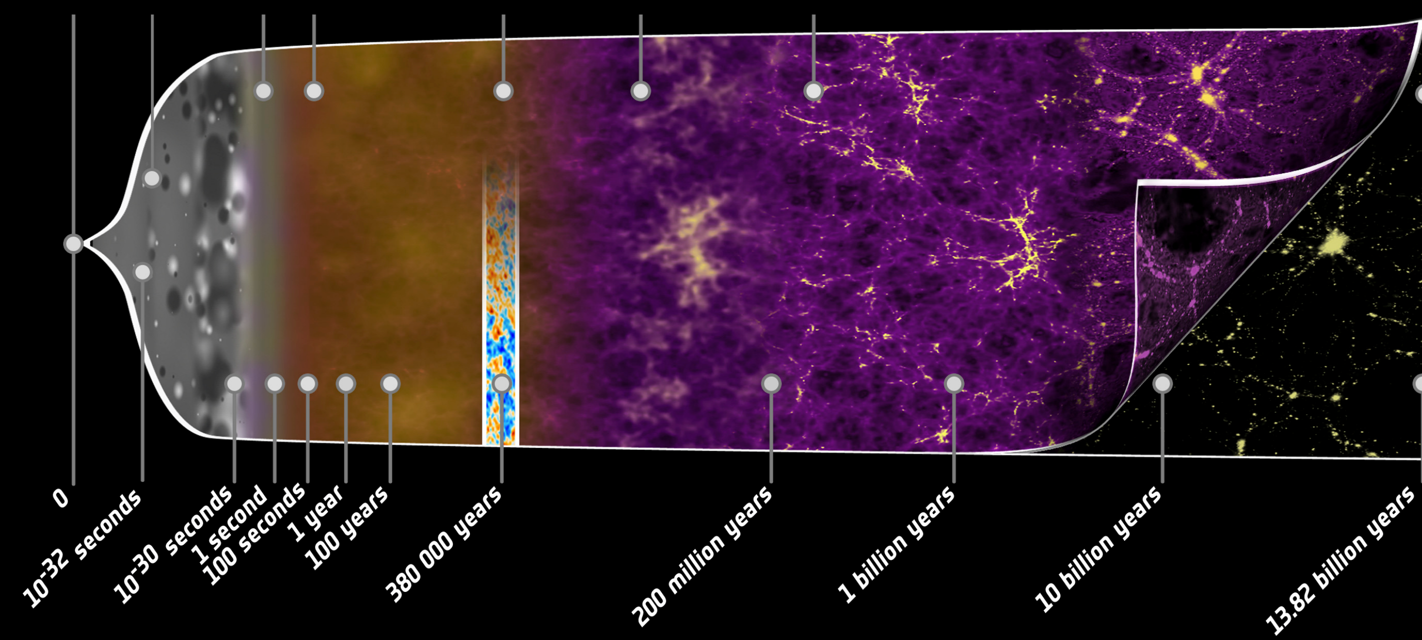


$$T_{\mathrm{len}}(\hat{n}) = T_{\mathrm{unl}}(\hat{n} + \nabla\phi)$$
$$(Q \pm iU)_{\mathrm{len}}(\hat{n}) = (Q \pm iU)_{\mathrm{unl}}(\hat{n} + \nabla\phi)$$

(images modified from ESA/Planck)

CMB lensing will be a primary source of information in current and future experiments:





- Probe distribution of matter over a broad range of redshifts (approximately $0.5 < z < 2$).
- Map the mass in the universe.
- Sensitive to both the geometry and growth of structure in the universe.
- Characterize and remove lensing B modes to improve search for Inflation.

(images modified from ESA/Planck)

Lensing Reconstruction
estimators of Φ(L)

In equations, Φ(L) can be estimated as follows:

$$\bar{\phi}^{XY}_{\mathbf{L}} = \frac{1}{\mathcal{R}^{XY}_{\mathbf{L}}} \int d^2\boldsymbol{\ell} W^{XY}_{\boldsymbol{\ell},\boldsymbol{\ell}-\mathbf{L}} \bar{X}_{\boldsymbol{\ell}} \bar{Y}^{*}_{\boldsymbol{\ell}-\mathbf{L}}$$

Lensing Potential

Normalization

Optimally-chosen weight function

Filtered maps (data),

X, Y in [T, E, B]

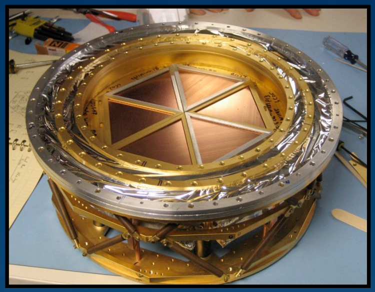
This estimator calculates a weighted sum of off-diagonal elements in the correlations of X and Y.

Note: ℓ is the angular scale of CMB fluctuations,
L is the angular scale of the gravitational lenses

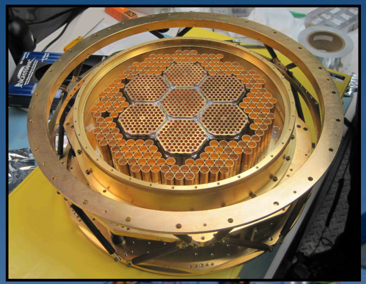
The South Pole Telescope (SPT)

10-meter primary dish, observe the CMB with arcminute resolution

SPT-SZ (2007)
960 detectors
95,150,220 GHz

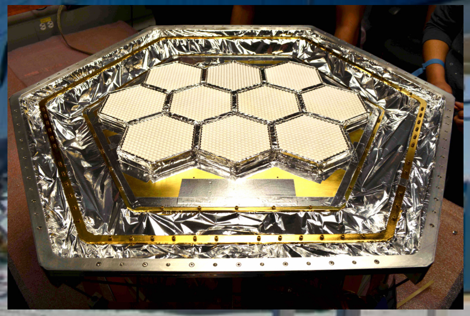


SPTpol (2012)
1600 detectors
95,150 GHz
+Polarization



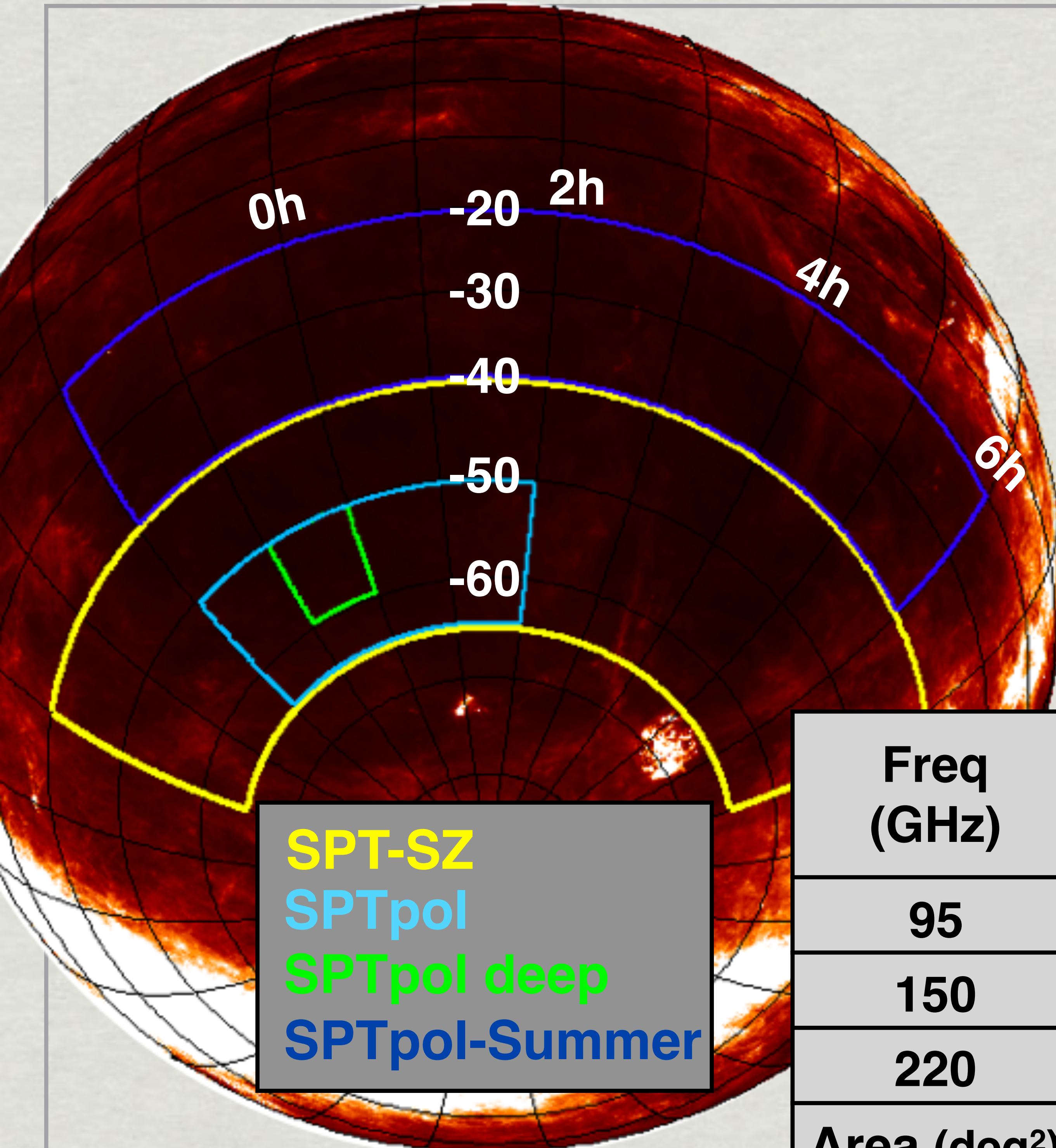
(see talk by Alessandro Manzotti)

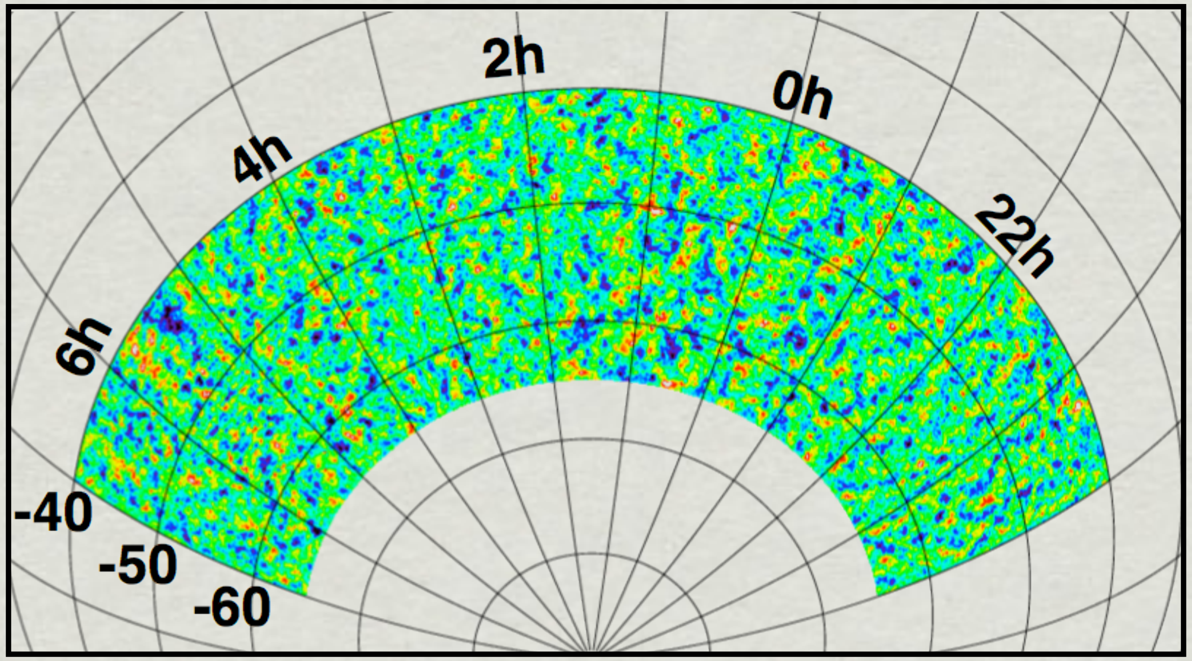
SPT-3G (2017)
~16,000 detectors
95,150,220 GHz
+Polarization



(see talk by Sasha Rahlin)

The SPT Surveys



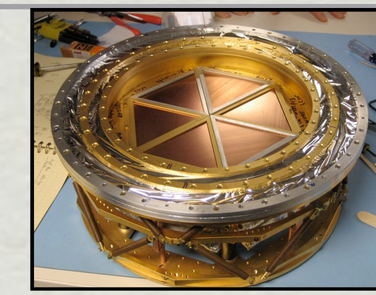


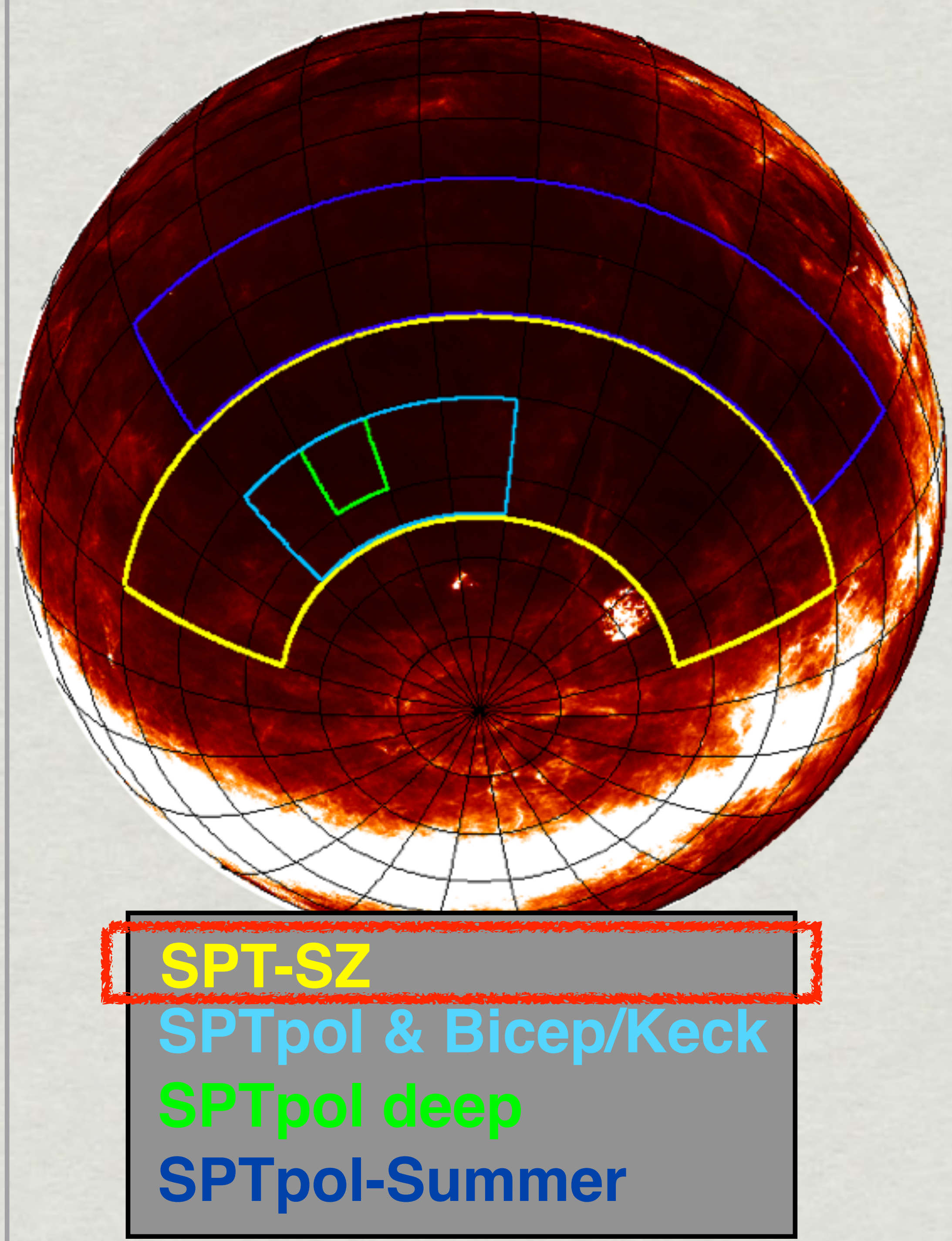
Freq (GHz)	SPT-SZ	SPTpol deep	SPTpol	SPTpol Summer
95	40	10	13	50
150	17	5/3.5	5	30
220	80	40	40/80	-
Area (deg²)	2500	100	500	2500
Status	*Complete*	*Complete*	*Complete*	*Complete*

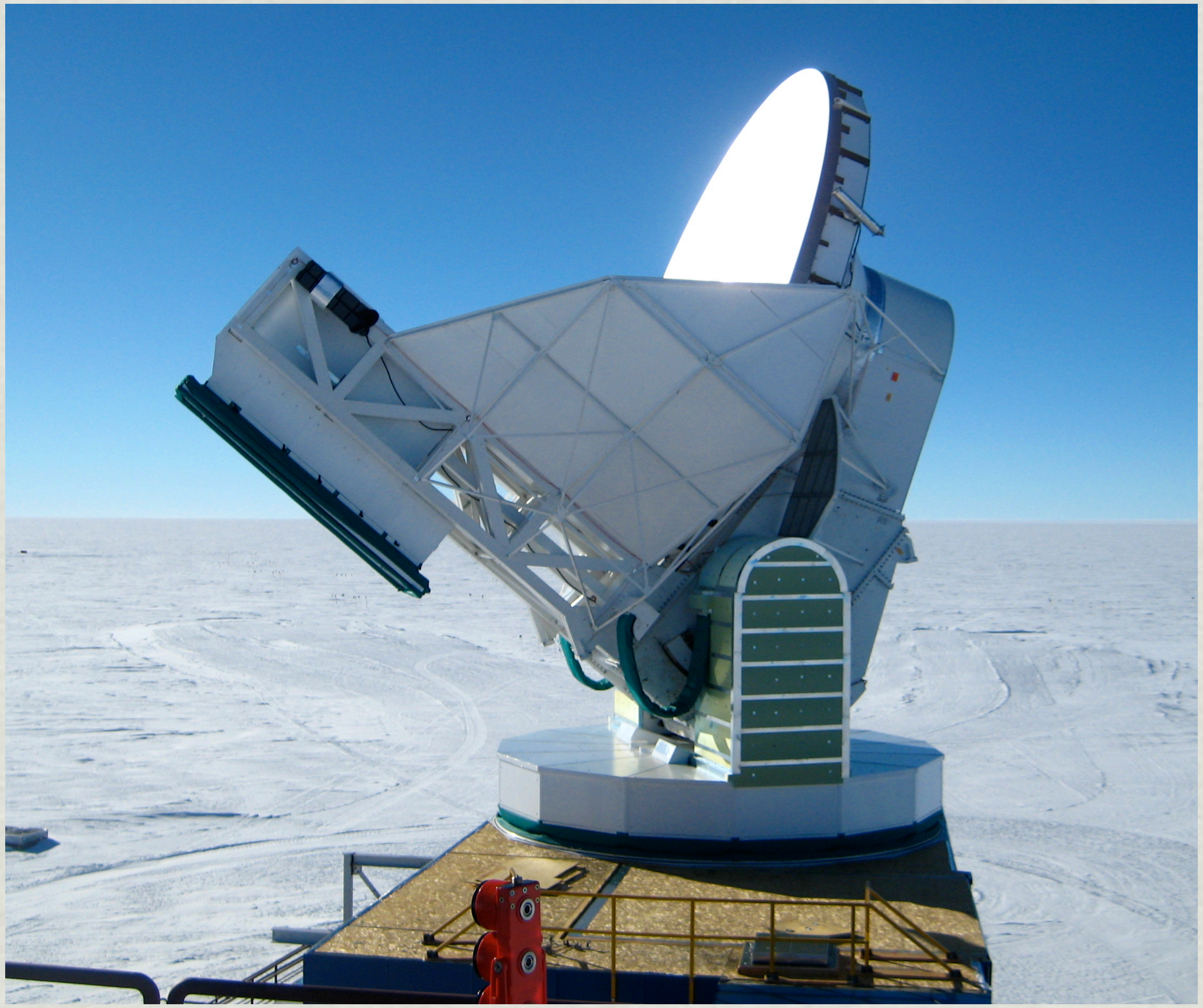
5000 deg² surveyed in total by SPT-SZ and SPTpol

- 150 GHz depths between 4-30 uK-arcmin (from ~Planck depth, to ~7 times deeper)

SPT-SZ survey field analysis





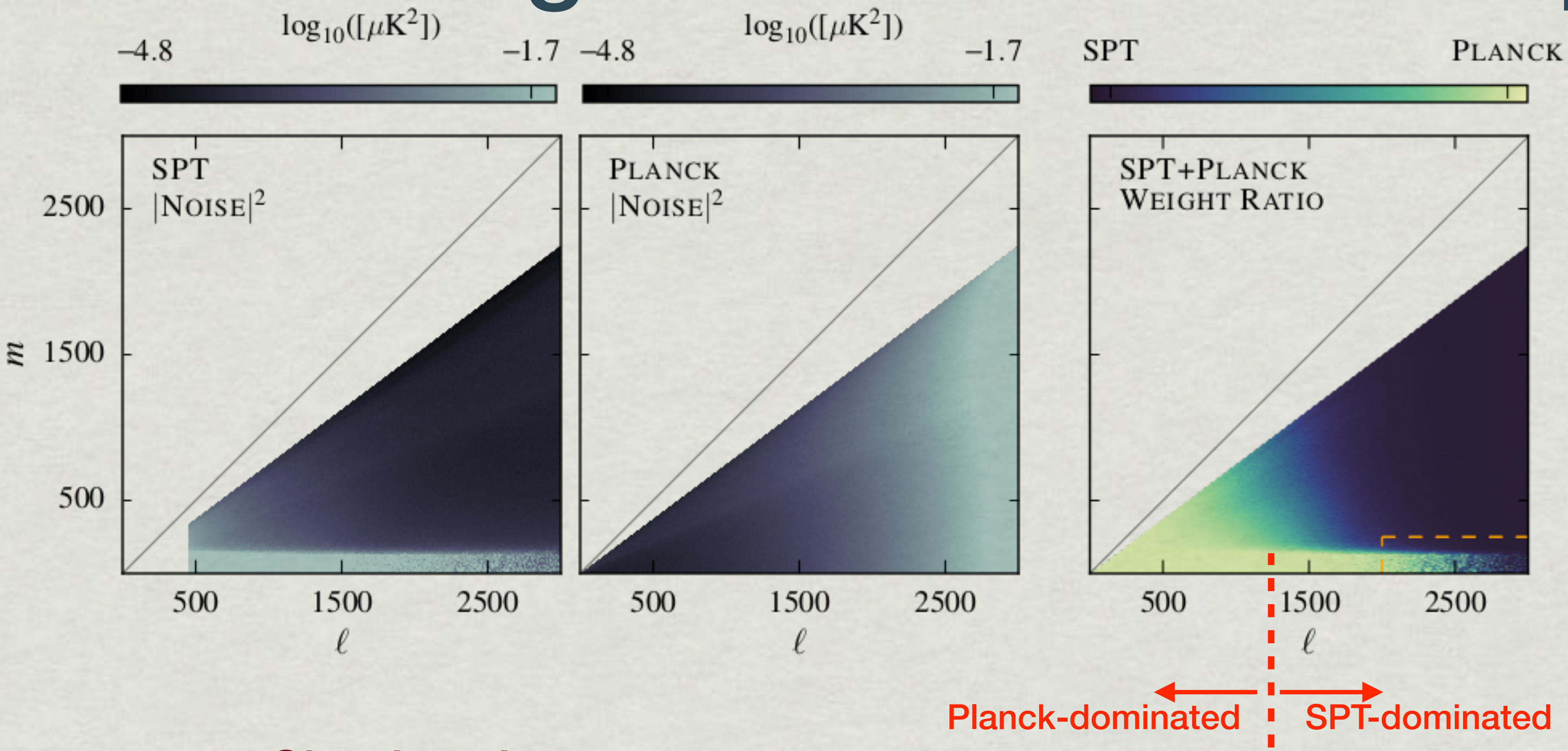


SPT in early 2012

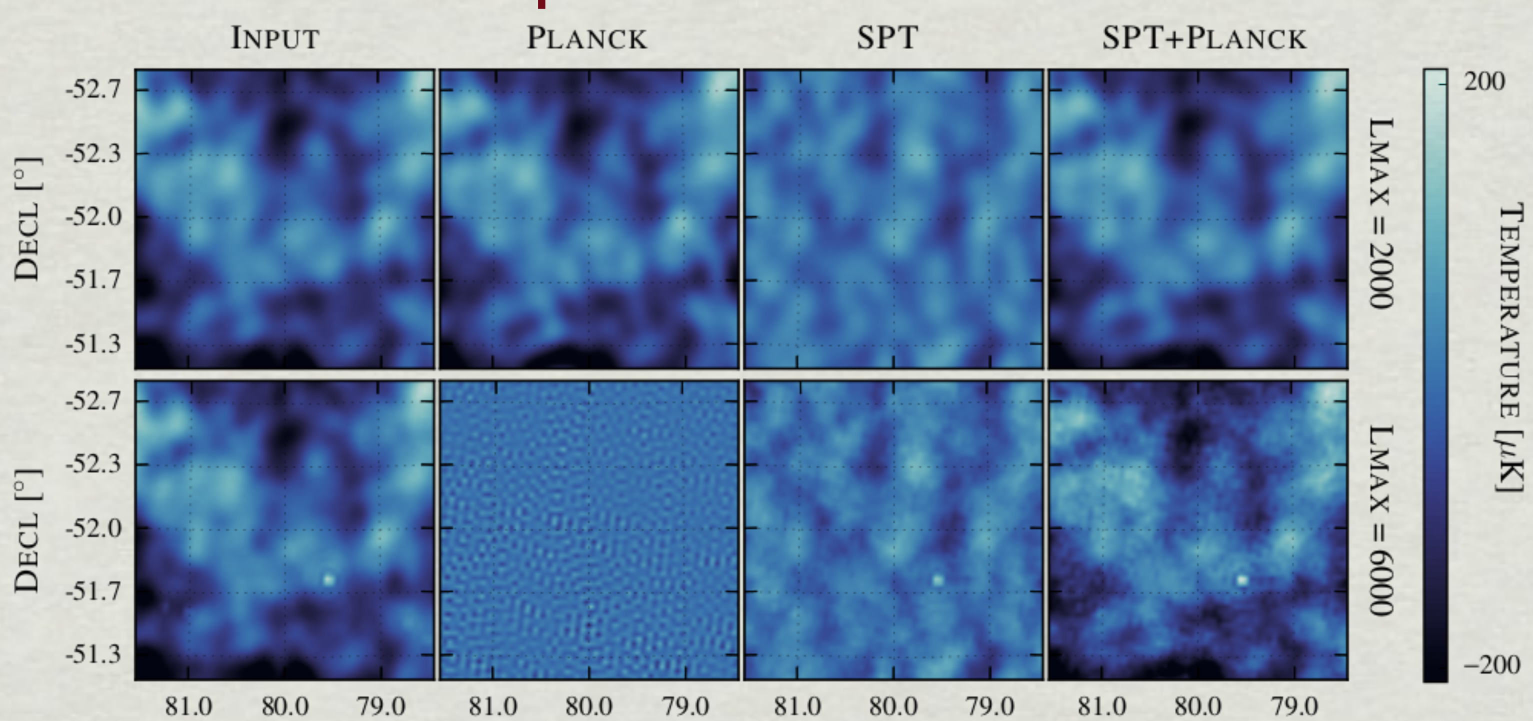
Data: 2500 deg^2, temperature, noise ~ 18 uK-arcmin (@150 GHz)

Work lead by Yuuki Omori

Combining SPT and Planck maps

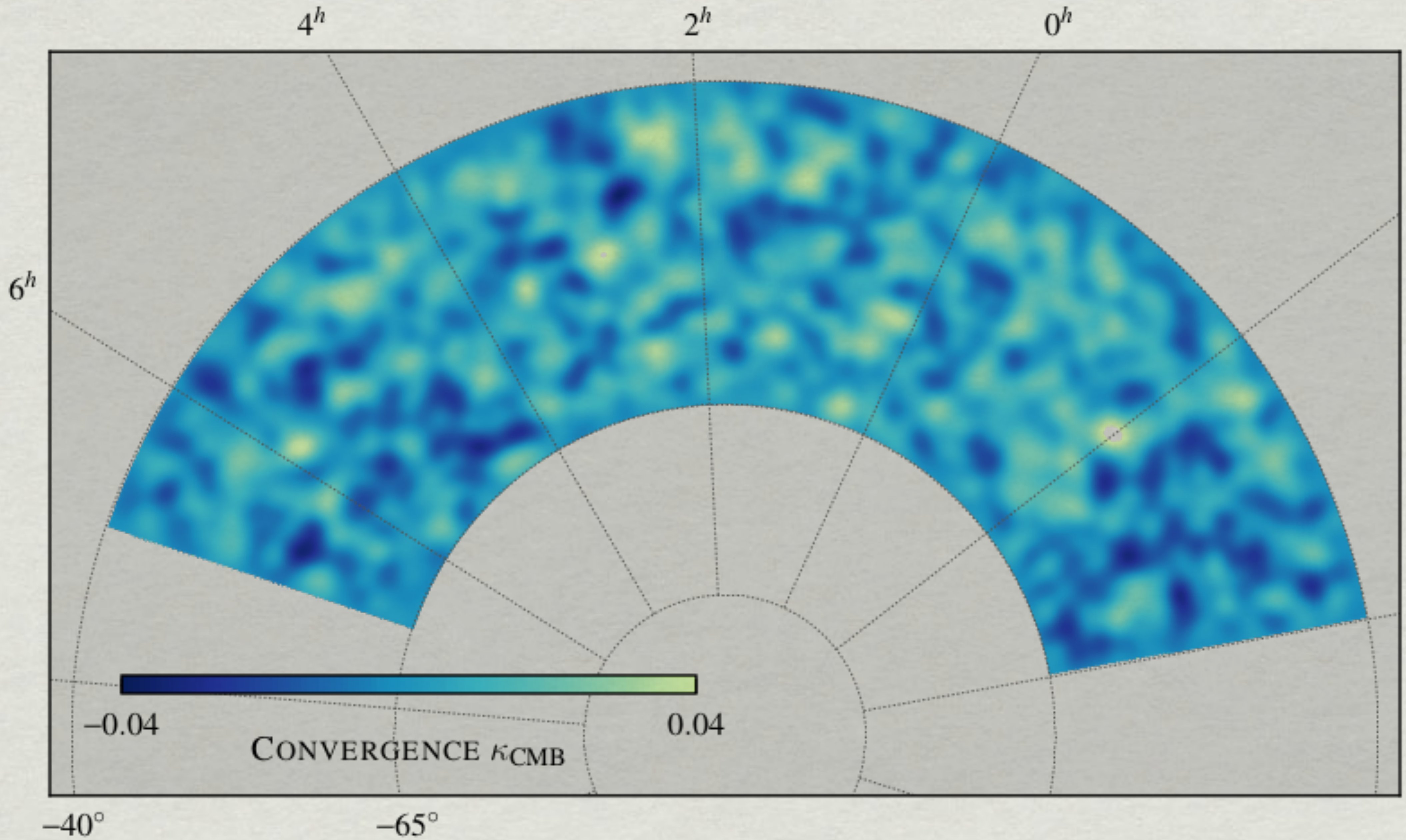


Simulated maps



Omori, Chown, Simard, KTS, et. al (arXv:1705.00743)

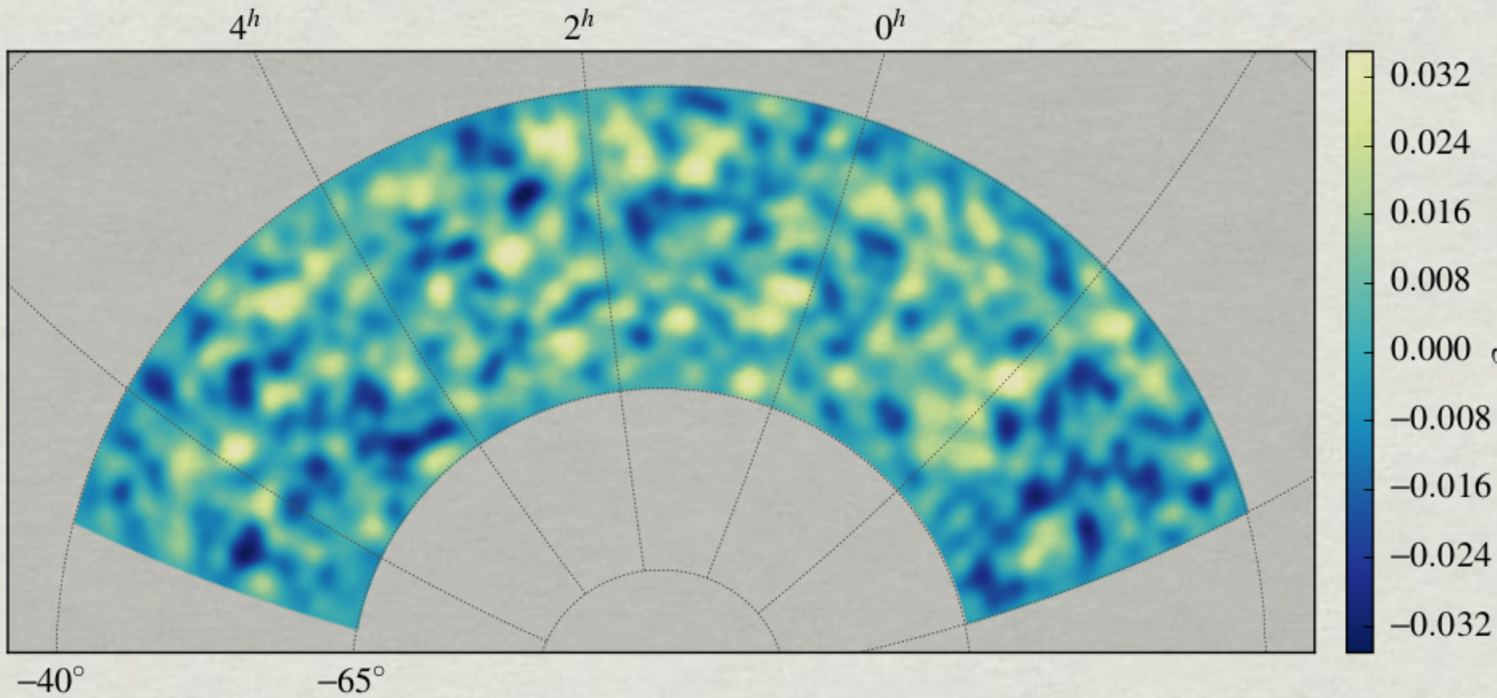
Lensing Reconstruction

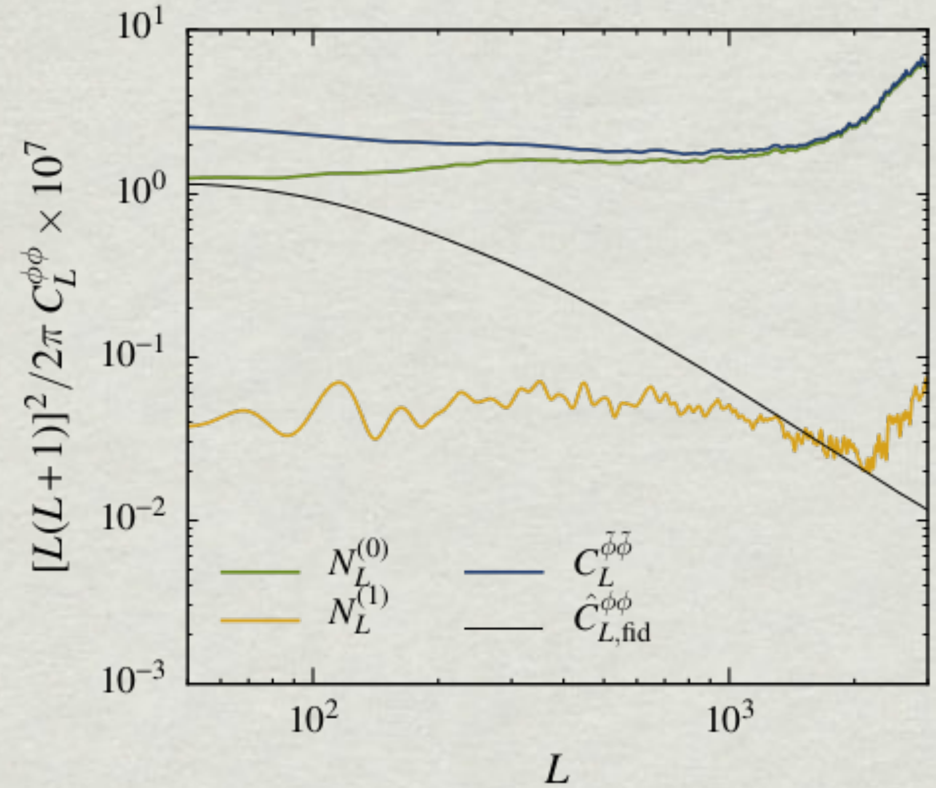


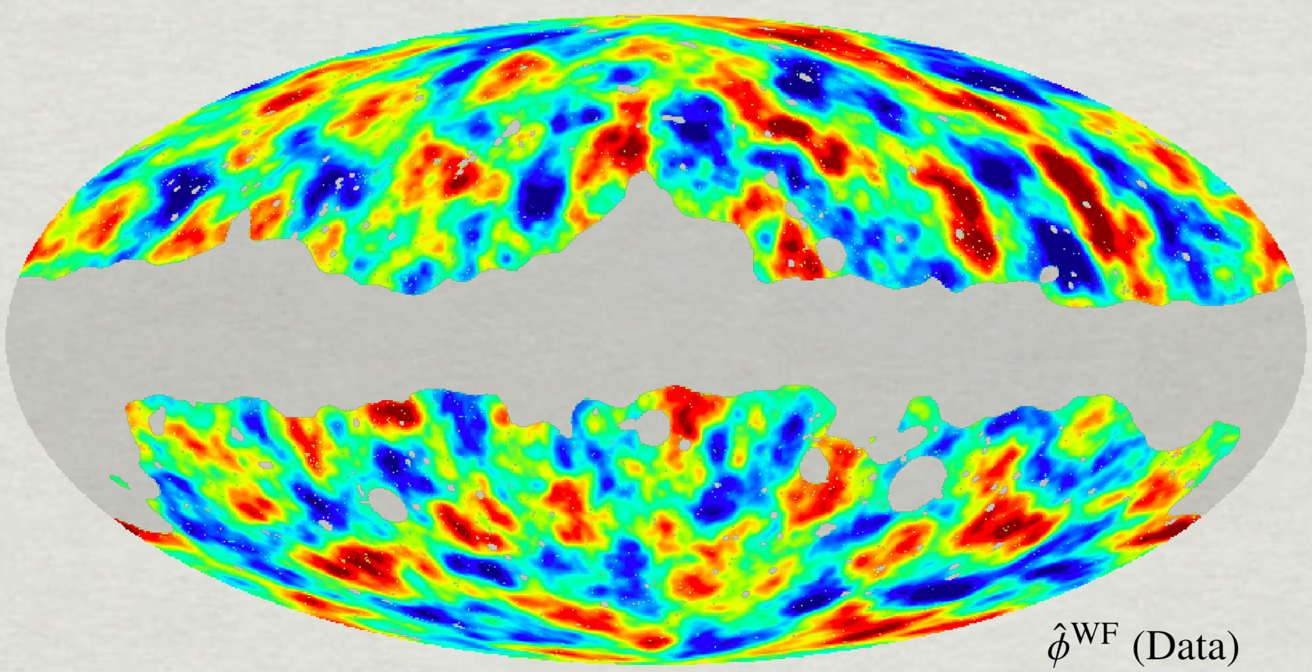
We have produced a CMB lensing map over the SPT-SZ survey with S/N~1for a significant number of modes.

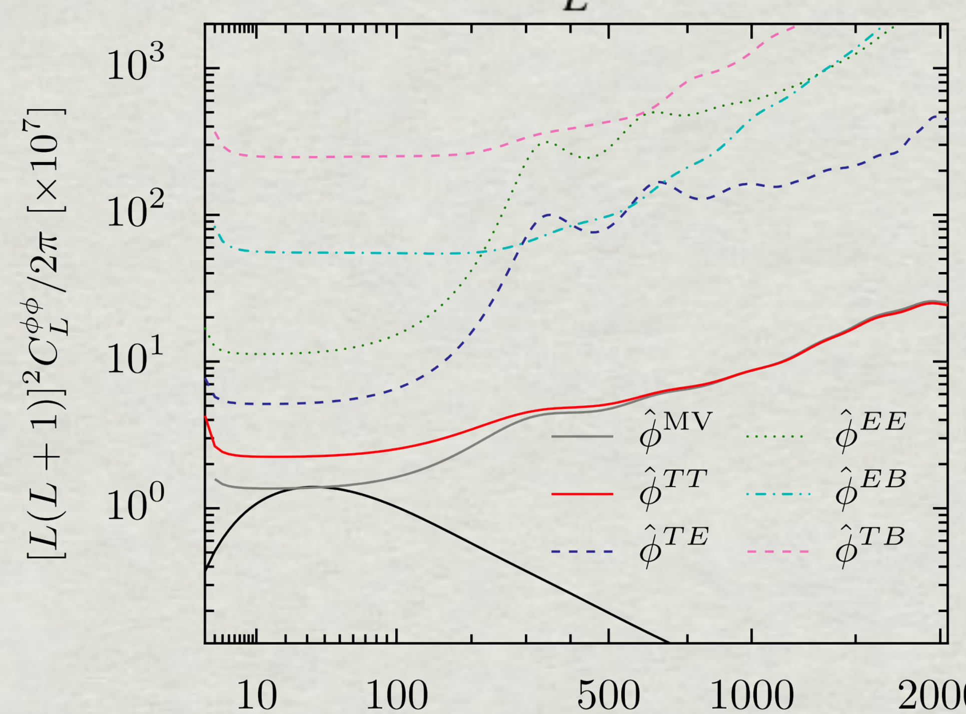
Omori, Chown, Simard, KTS, et. al (arXv:1705.00743)

Lensing Map noise levels





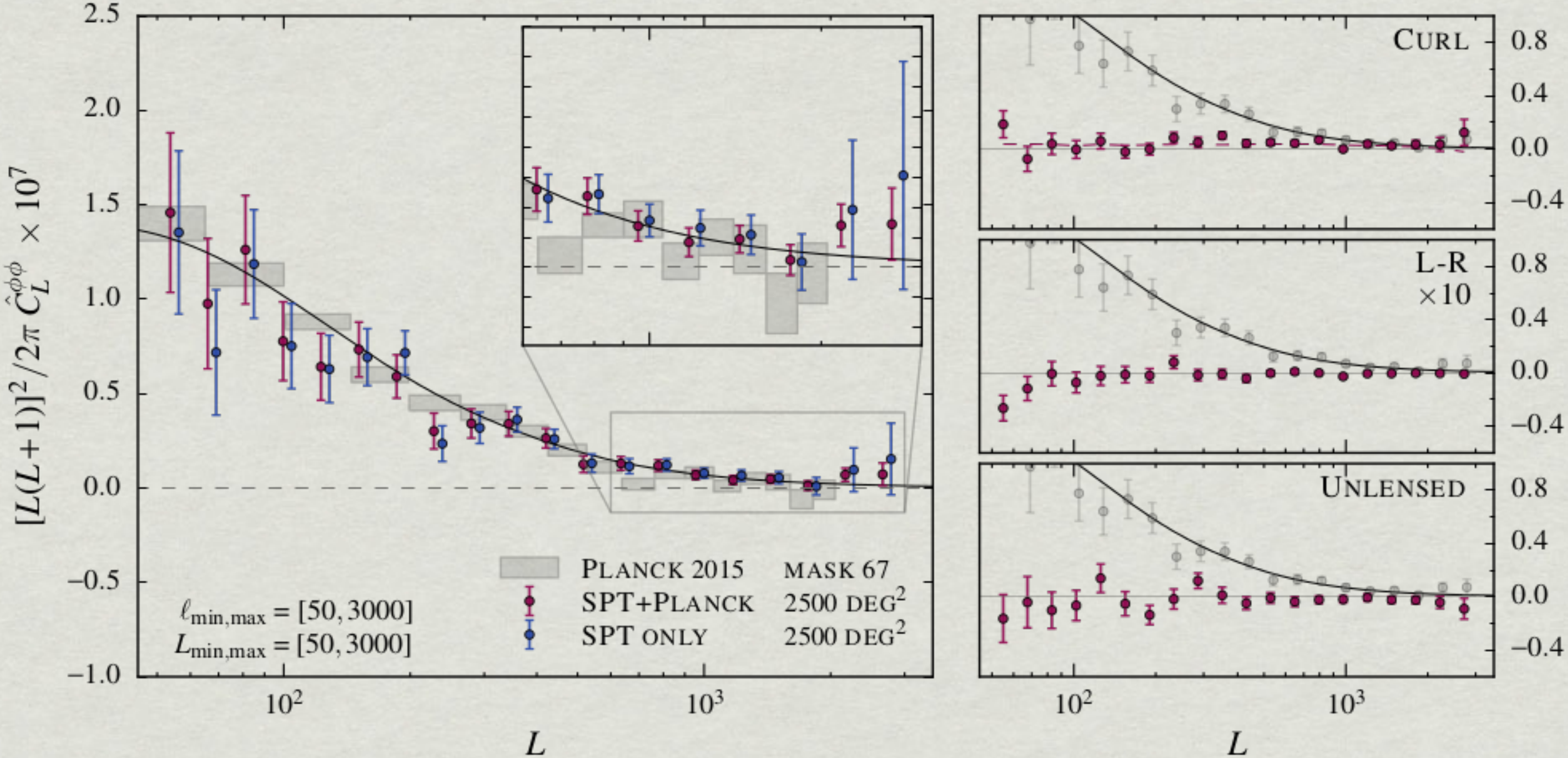




While Planck measures the power spectrum exquisitely (s~2%), the SPT maps are significantly lower noise, especially at small scales.

Omori, Chown, Simard, KTS, et. al (arXv:1705.00743)

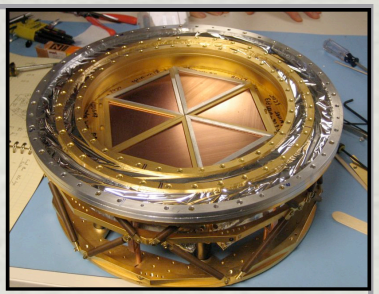
Lensing Power Spectrum

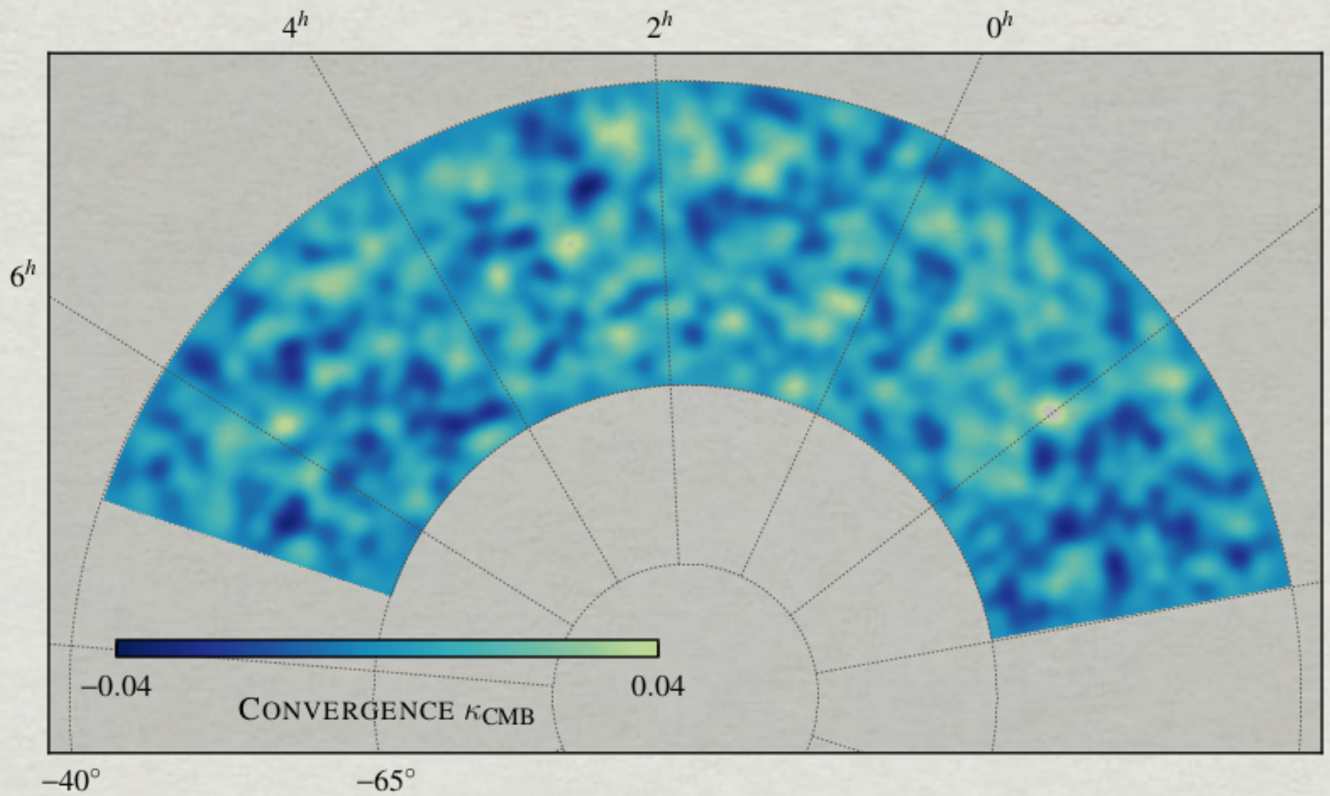


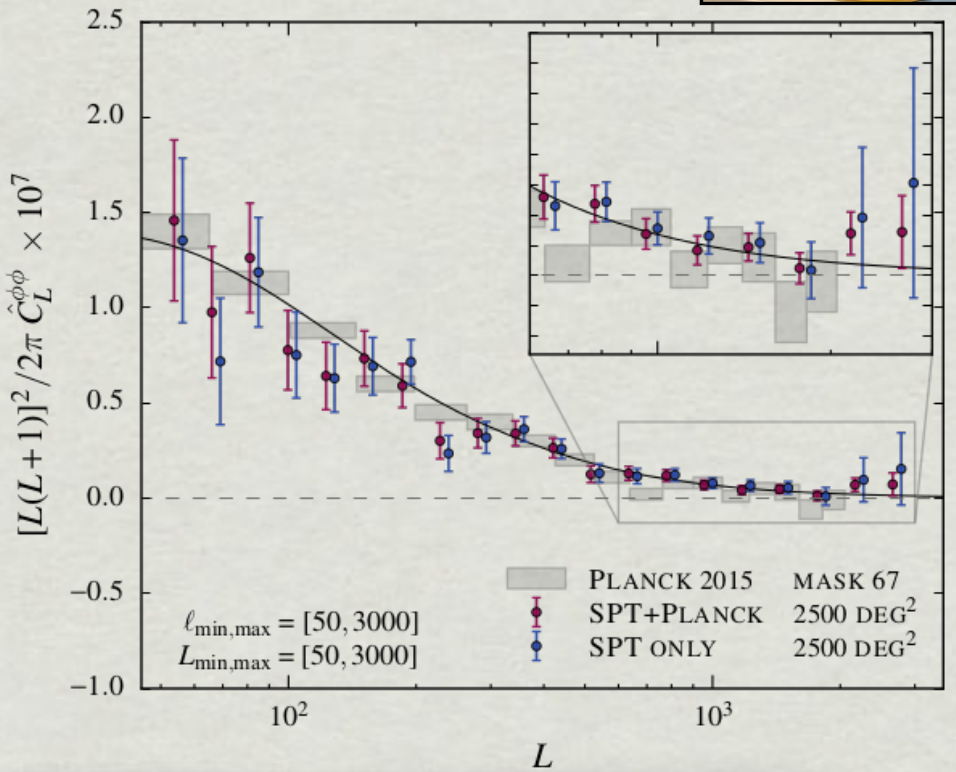
We measure the lensing power spectrum and find an amplitude of:
A_lens = 0.95 +-0.06 (Stat.) +- 0.01 (Sys.)
relative to the Planck 2015 best-fit cosmology.

This rejects no lensing at 24 σ.

Key Take-away points:





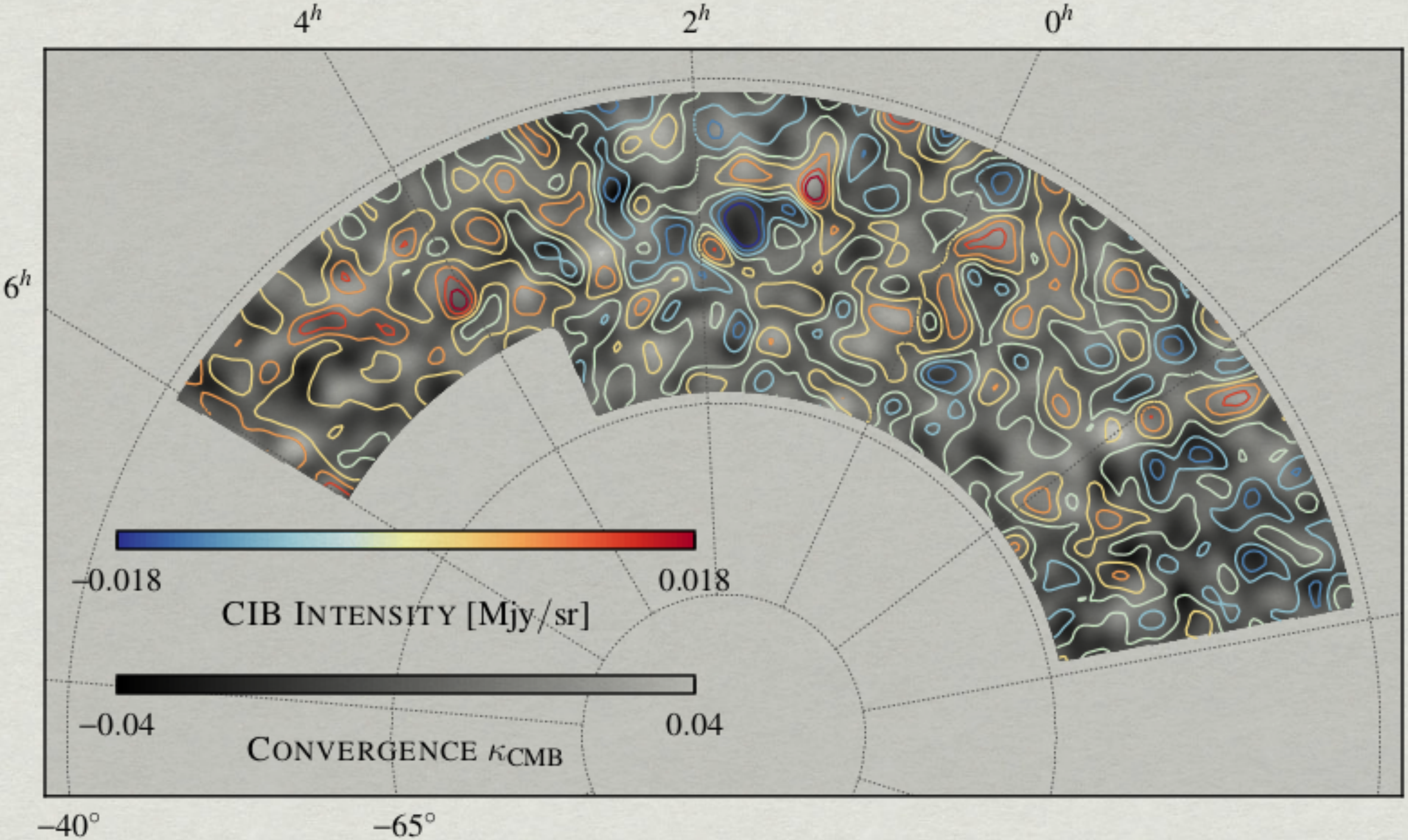


Key Take-away points:

- **SPT information dominates at small scales, Planck at large scales**
- **Lensing power spectrum measurement is dominated by SPT information at ~few-arcmin scales.**
- **Adding Planck data has almost no improvement on measuring the lensing power spectrum, but…**
- **Large-scale information from Planck improves small-scale lensing information that is important for cross-correlations.**

Omori, Chown, Simard, KTS, et. al (arXv:1705.00743)

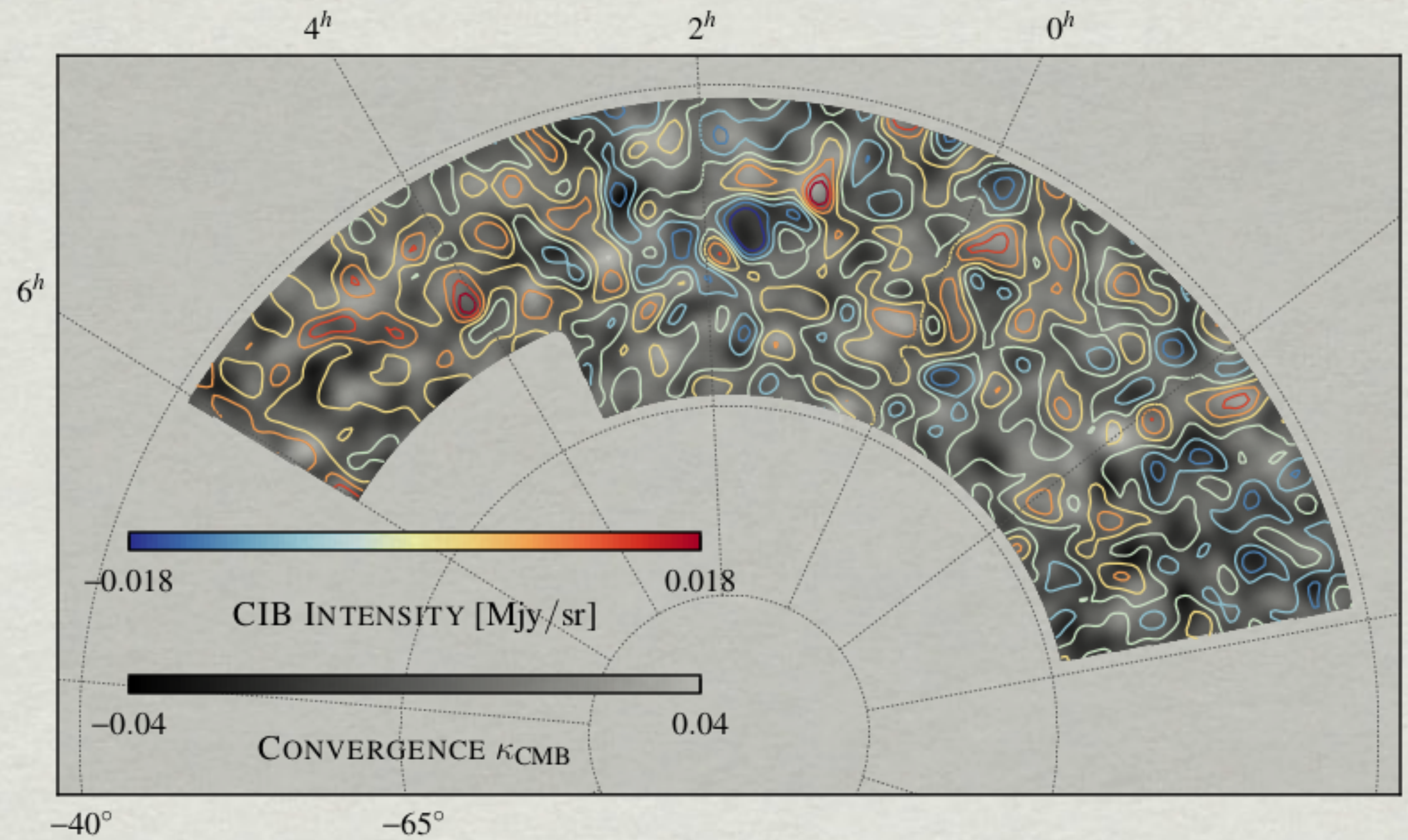
CMB-LSS cross-correlation: CIB

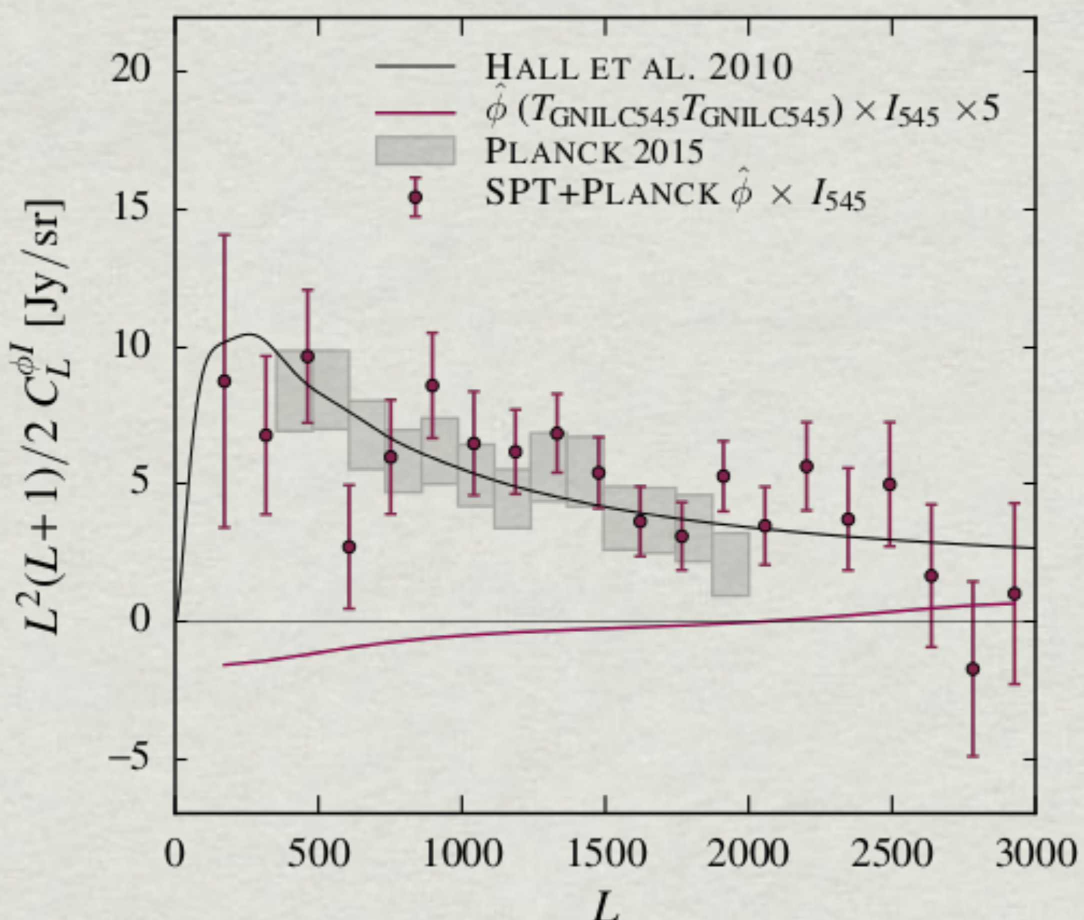


CIB map from Planck GNLIC 545 GHz

Omori, Chown, Simard, KTS, et. al (arXv:1705.00743)

CMB-LSS cross-correlation: CIB





CIB map from Planck GNILC 545 GHz

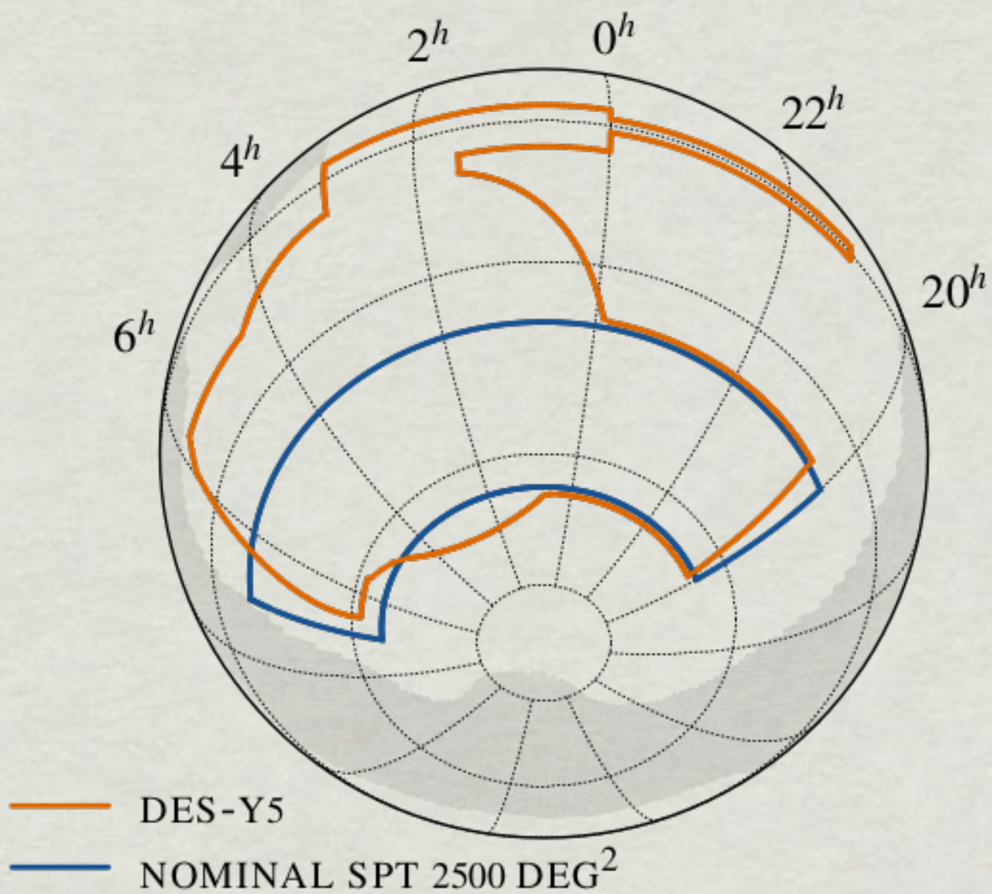
K x CIB correlation

We measure the lensing - CIB cross-correlation spectrum. This measurement is consistent with the correlation measured by Planck.

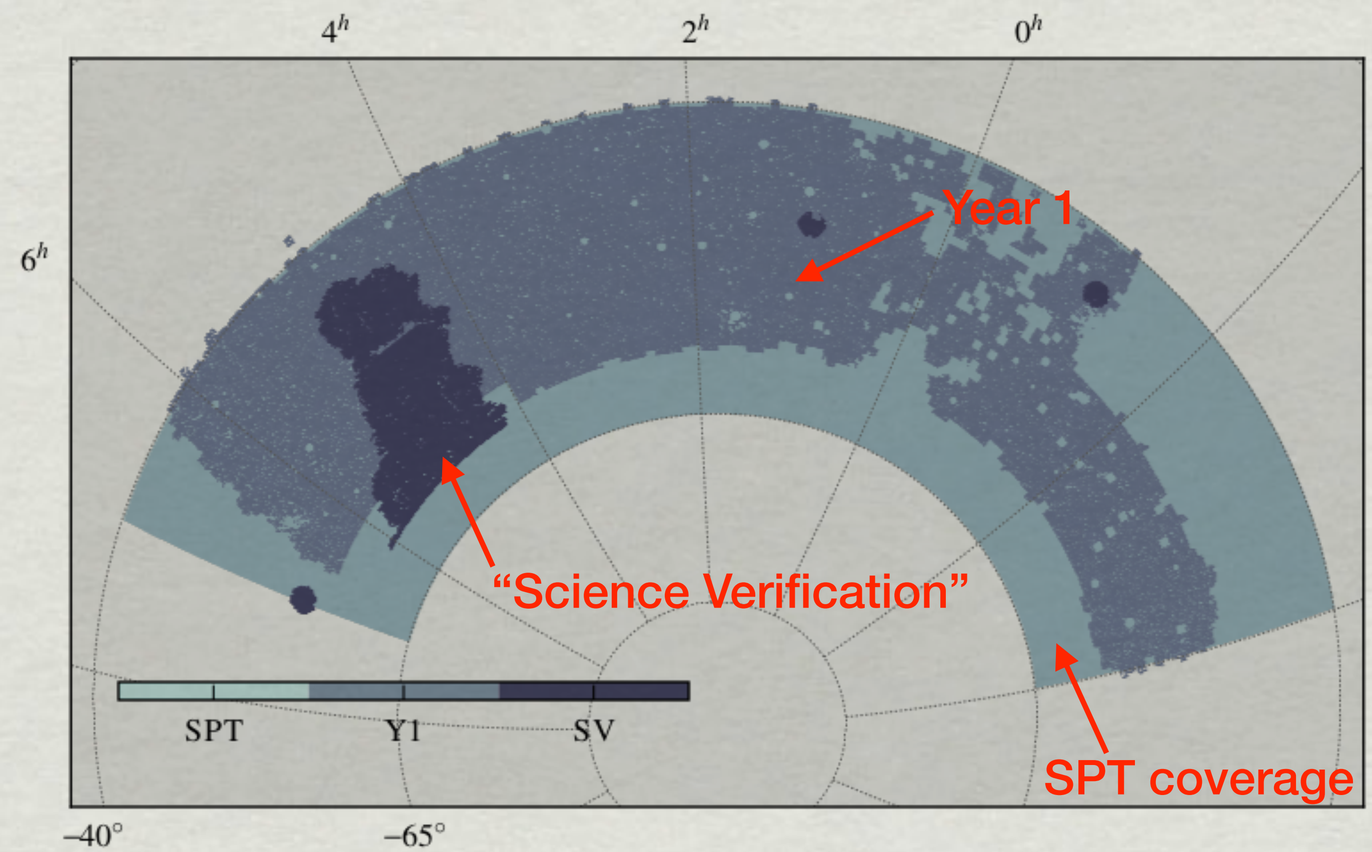
Omori, Chown, Simard, KTS, et. al (arXv:1705.00743)

These mass maps are the being used in joint analyses with DES.

DES and SPT survey regions



Detailed view of survey overlap

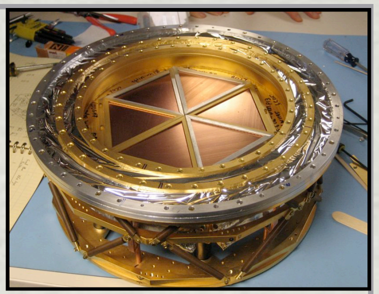


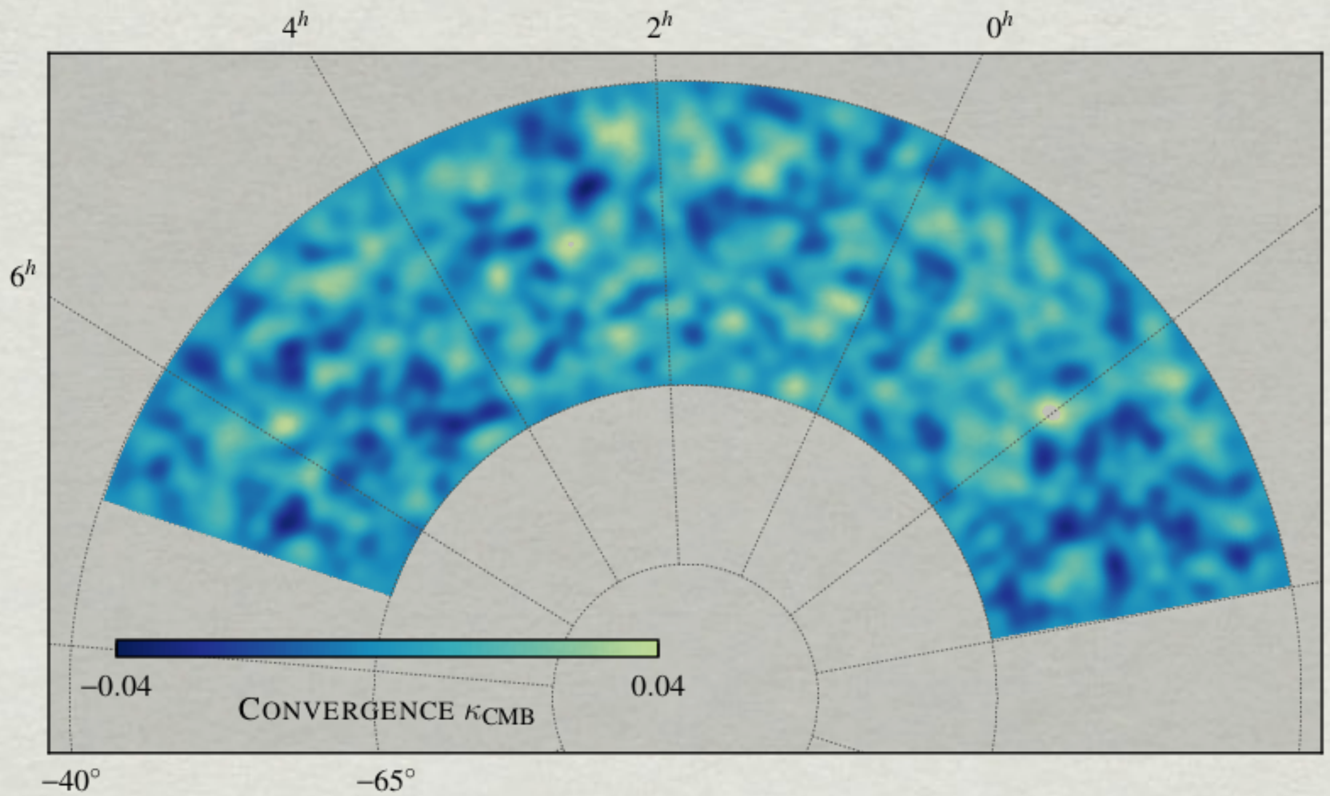
These mass maps have ~1300 deg^2 of overlap with DES Y1.

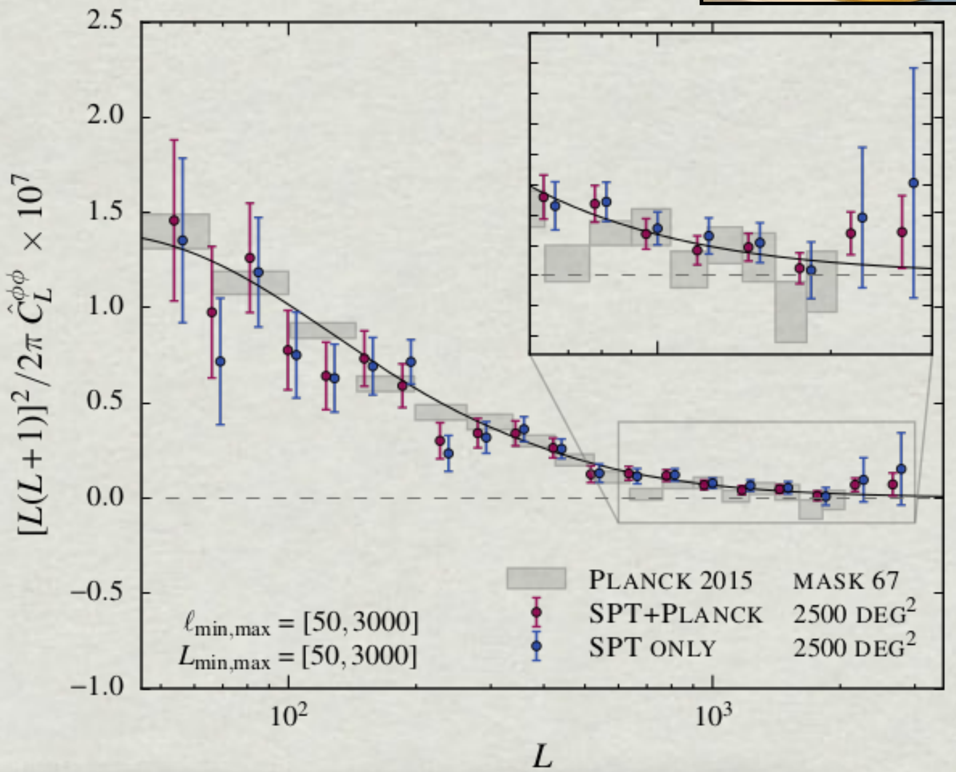
- Lensing x gal density
- Lensing x shear
- CMB cluster lensing for measuring cluster masses

Omori, Chown, Simard, KTS, et. al (arXv:1705.00743)

Key Take-away points:





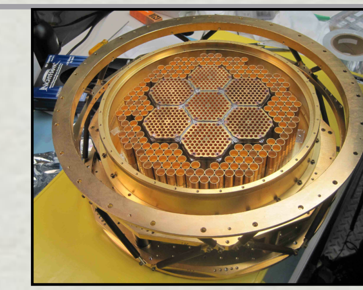


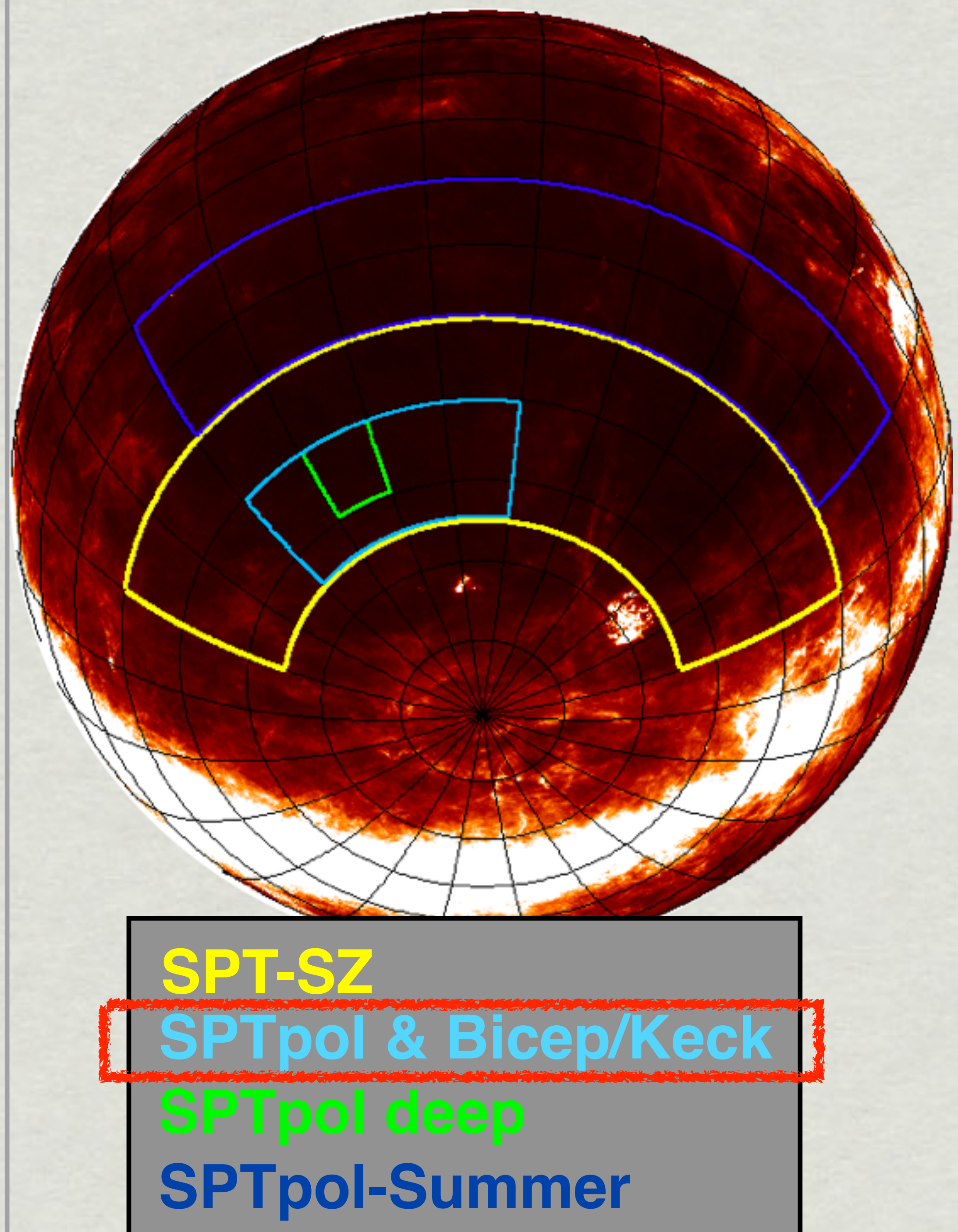
This measurement is important because:

- **Precise measurement of the lensing power spectrum**
- **Signal-dominated map for cross-correlations**
- **Excellent coverage of DES observations. This will be the primary lensing map for cross-correlations with DES.**

Omori, Chown, Simard, KTS, et. al (arXv:1705.00743)

SPTpol survey field analysis





SPTpol receiver installation, late 2011

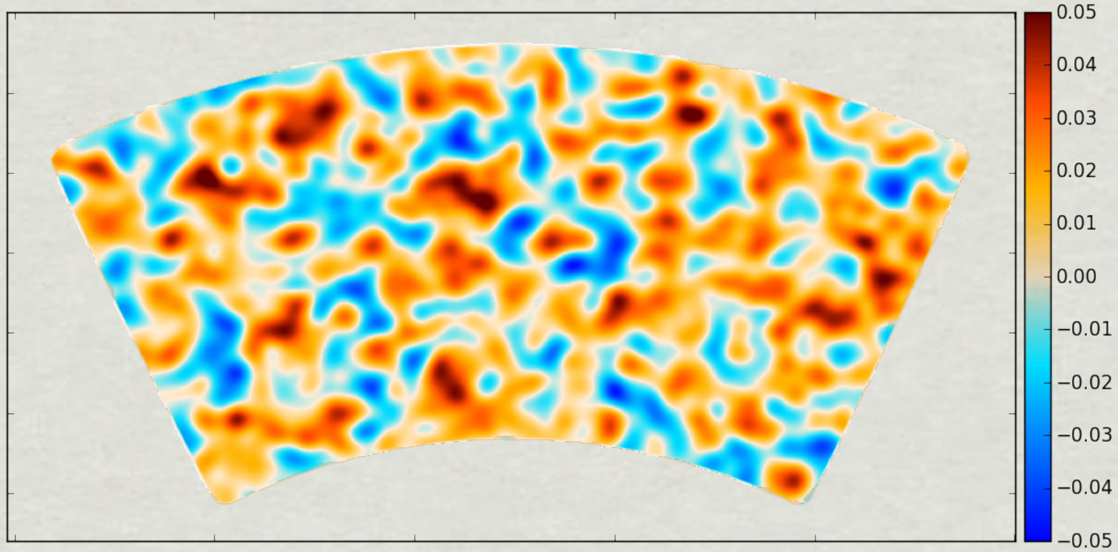
Data: 500 deg^2, T + pol, noise ~ 9.4 uK-arcmin (@150 GHz, pol)

Work lead by Monica Mocanu

SPTpol survey field analysis

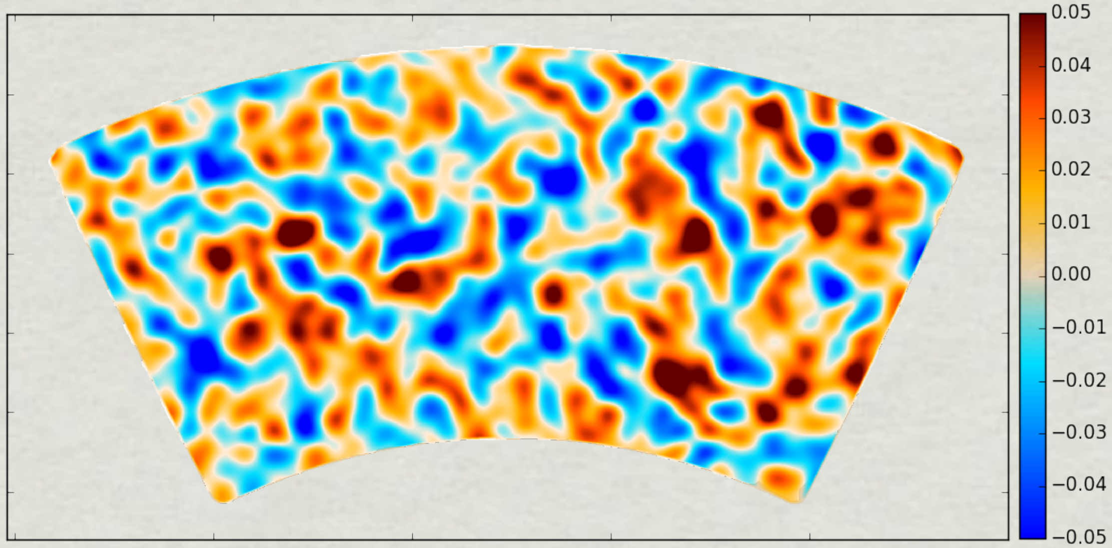
$$\bar{\phi}^{XY}_{\mathbf{L}} = \frac{1}{\mathcal{R}^{XY}_{\mathbf{L}}} \int d^2\boldsymbol{\ell}\, W^{XY}_{\boldsymbol{\ell},\boldsymbol{\ell}-\mathbf{L}} \bar{X}_{\boldsymbol{\ell}} \bar{Y}^{*}_{\boldsymbol{\ell}-\mathbf{L}}$$

SPTpol TT



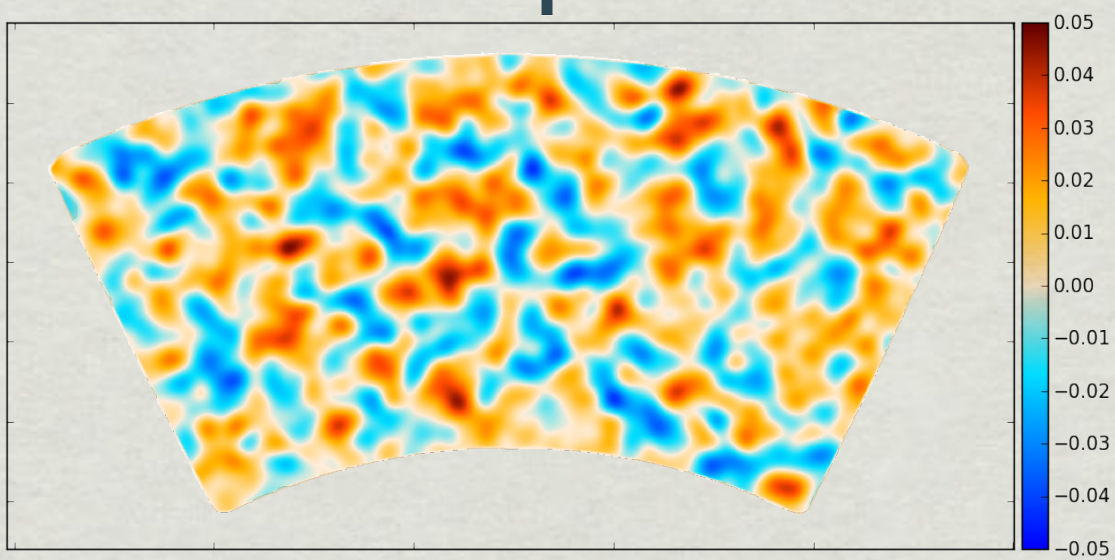
σ A_{Lens} = +- 0.08

SPTpol EB



σ A_{Lens} = +- 0.13

SPTpol MV



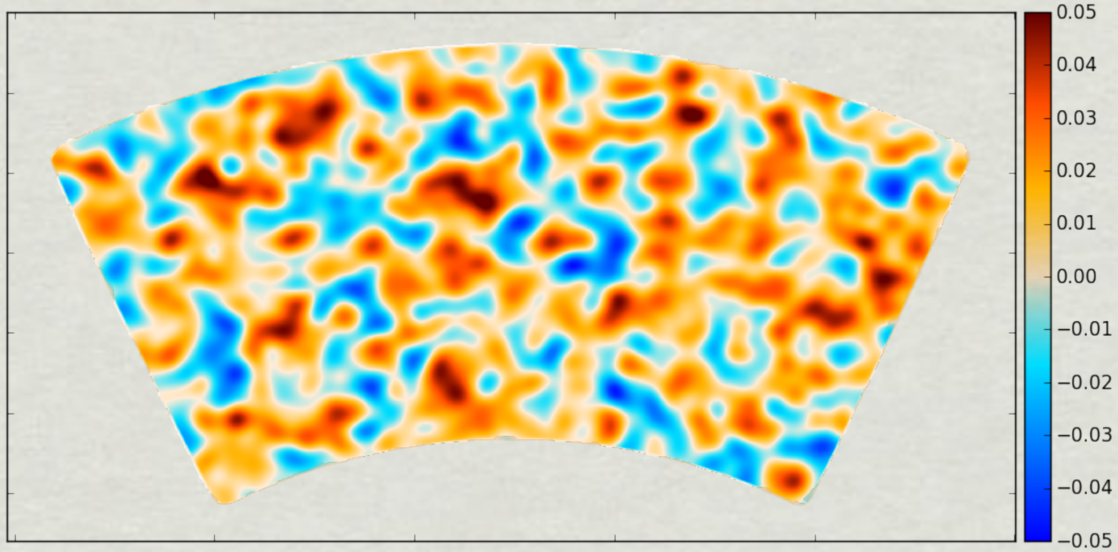
σ A_{Lens} = +- 0.06 (Stat)

Work lead by Monica Mocanu

SPTpol survey field analysis

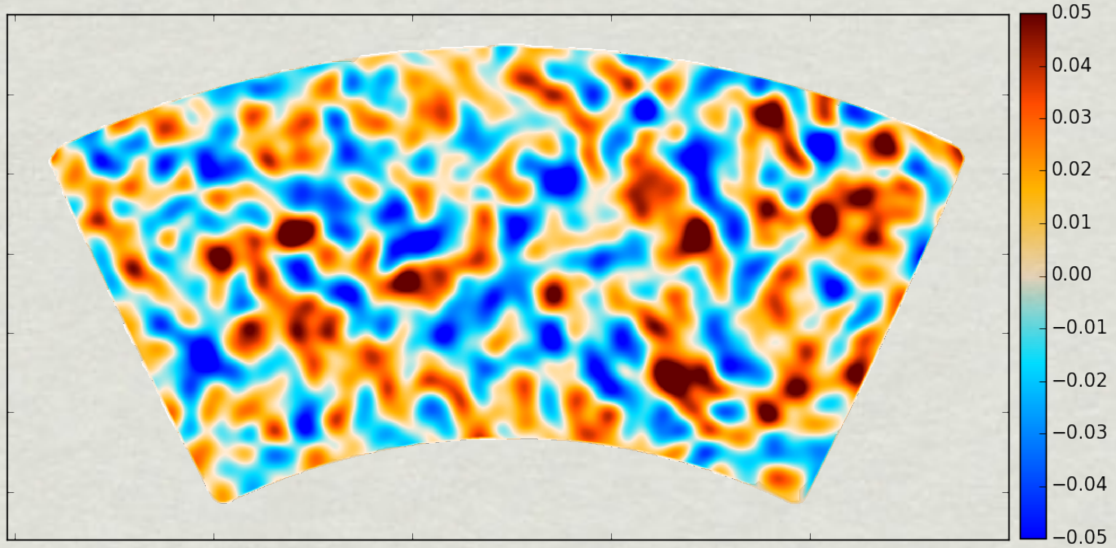
$$\bar{\phi}^{XY}_{\mathbf{L}} = \frac{1}{\mathcal{R}^{XY}_{\mathbf{L}}} \int d^2\boldsymbol{\ell}\, W^{XY}_{\boldsymbol{\ell},\boldsymbol{\ell}-\mathbf{L}} \bar{X}_{\boldsymbol{\ell}} \bar{Y}^{*}_{\boldsymbol{\ell}-\mathbf{L}}$$

SPTpol TT



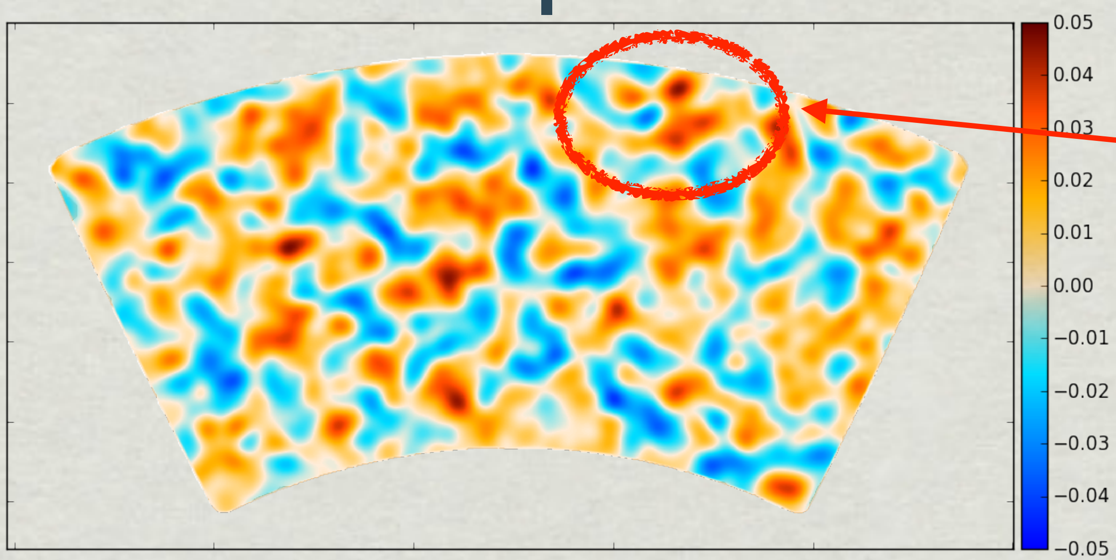
σ A_{Lens} = +- 0.08

SPTpol EB



σ A_{Lens} = +- 0.13

SPTpol MV

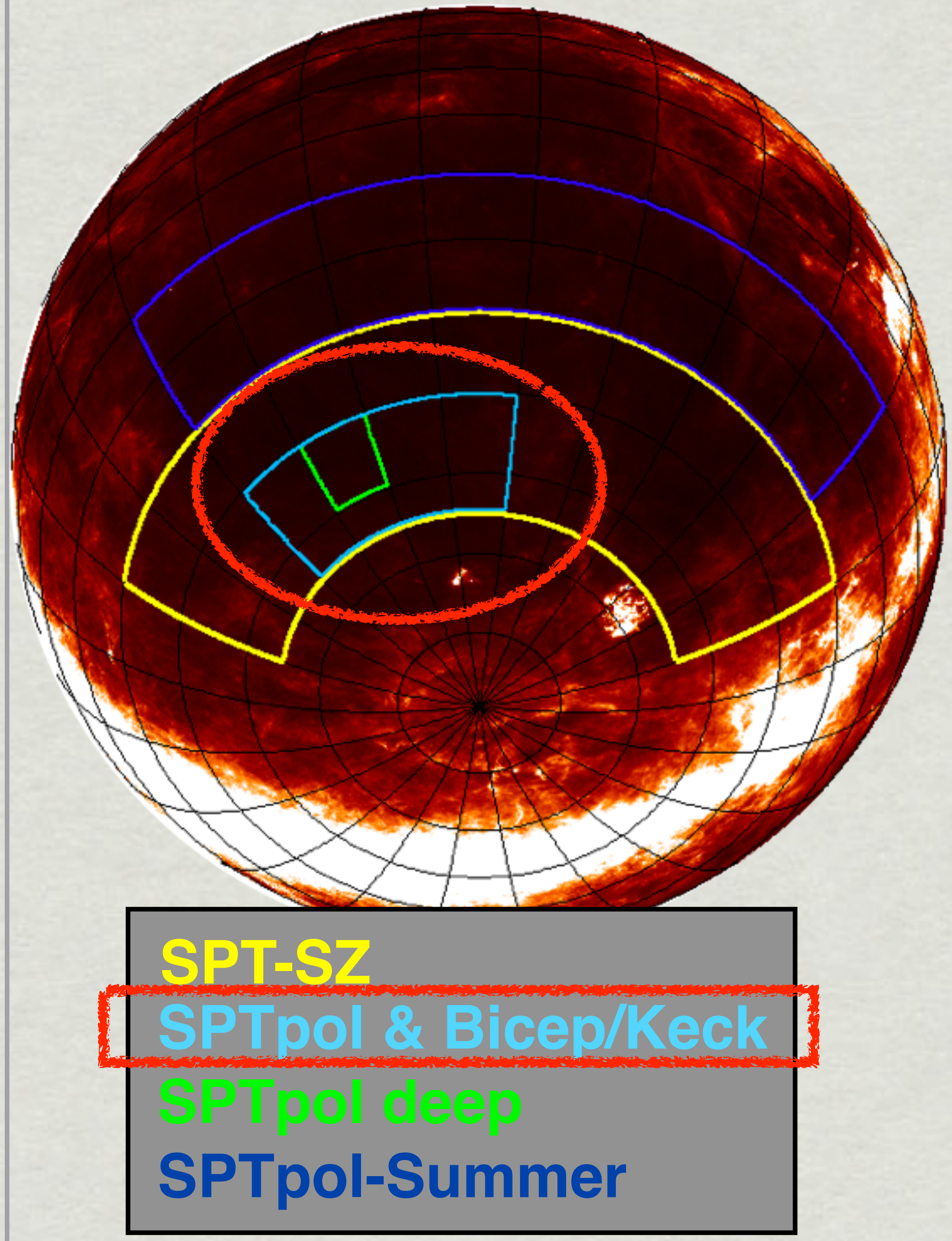


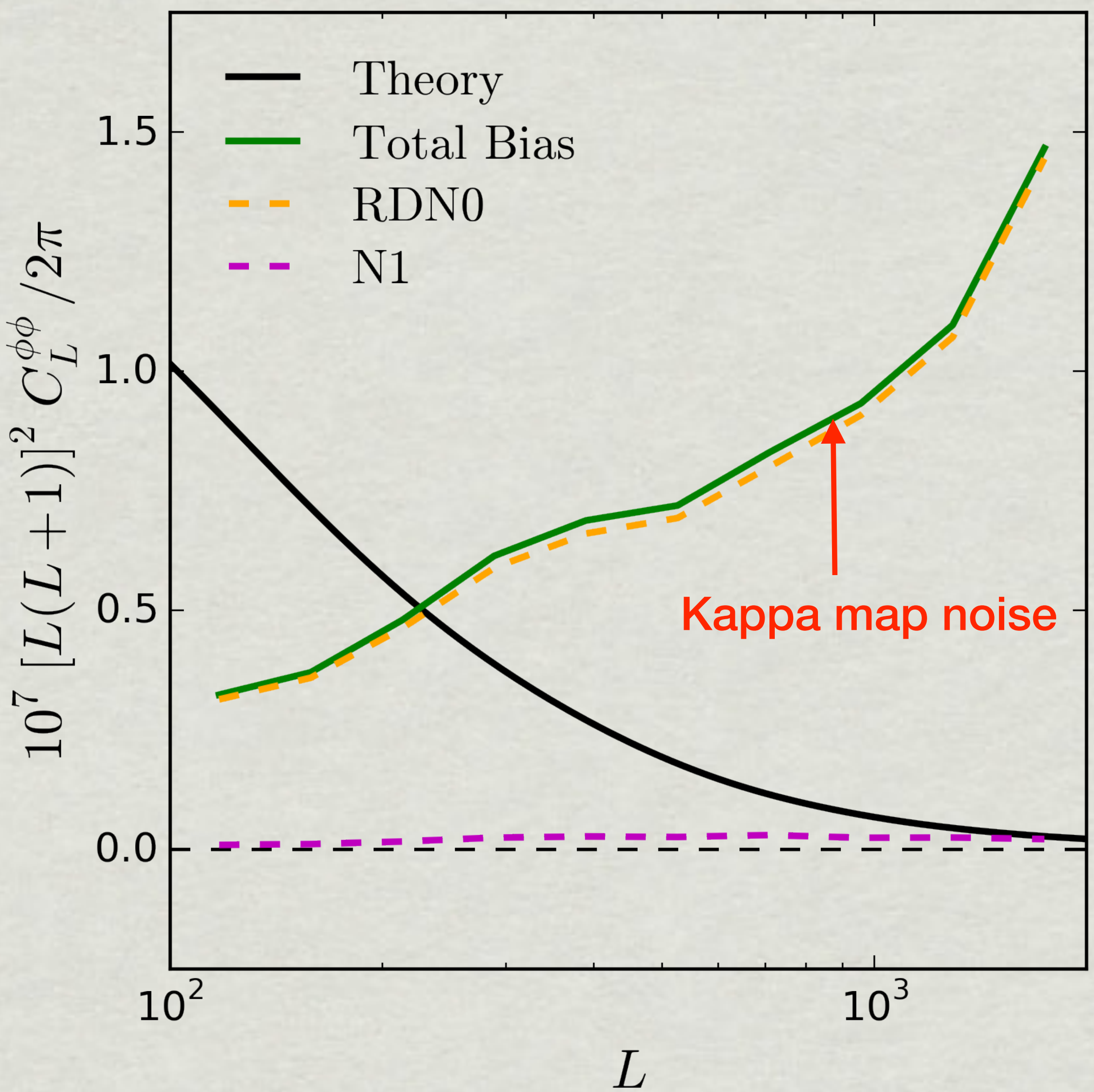
Cosmic Duck!

σ A_{Lens} = +- 0.06 (Stat)

Work lead by Monica Mocanu

Lensing map noise

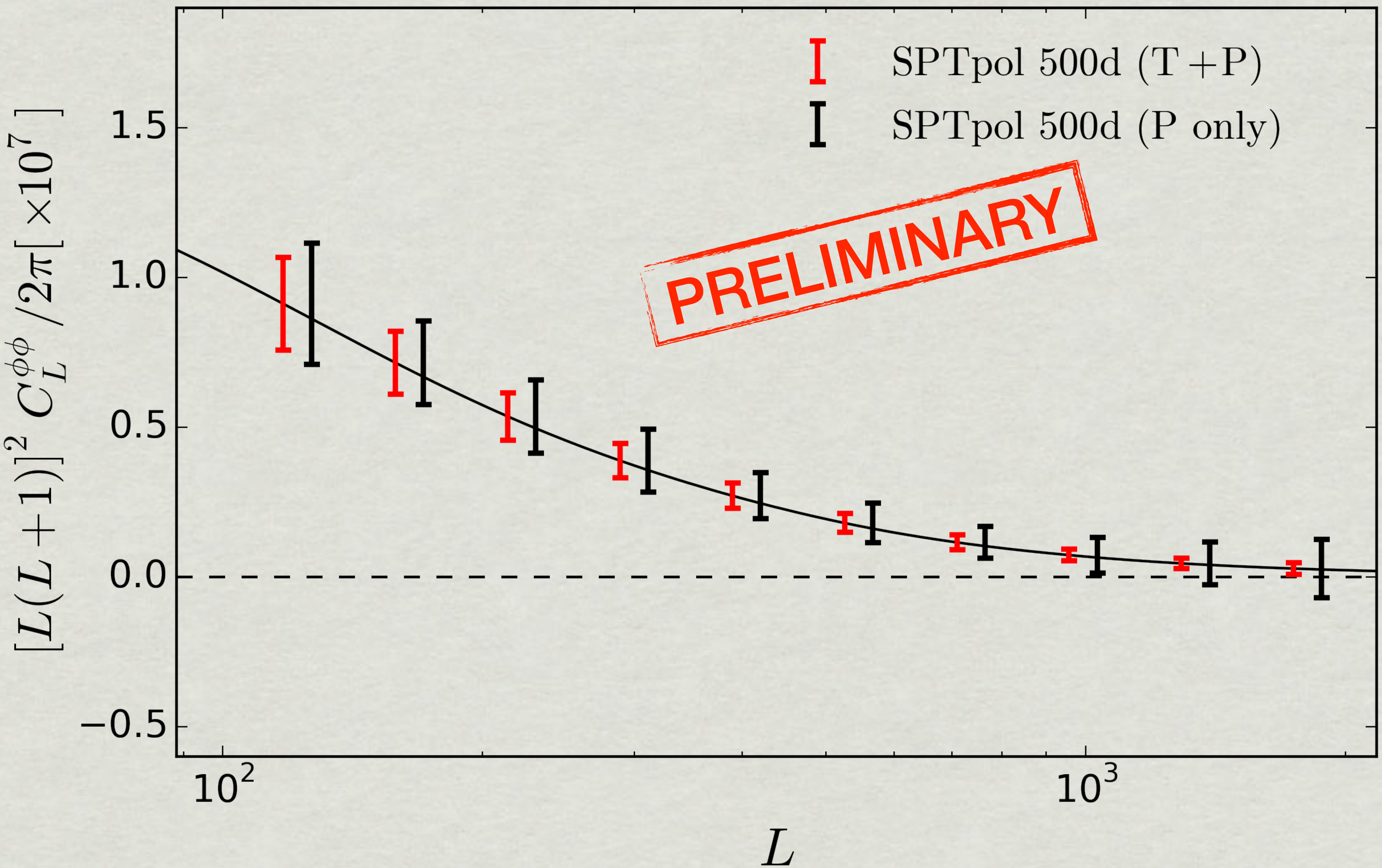




These maps have S/N >1 up to L~250.
The sky patch overlaps with Bicep/Keck -> will use for delensing B modes.

Work lead by Monica Mocanu

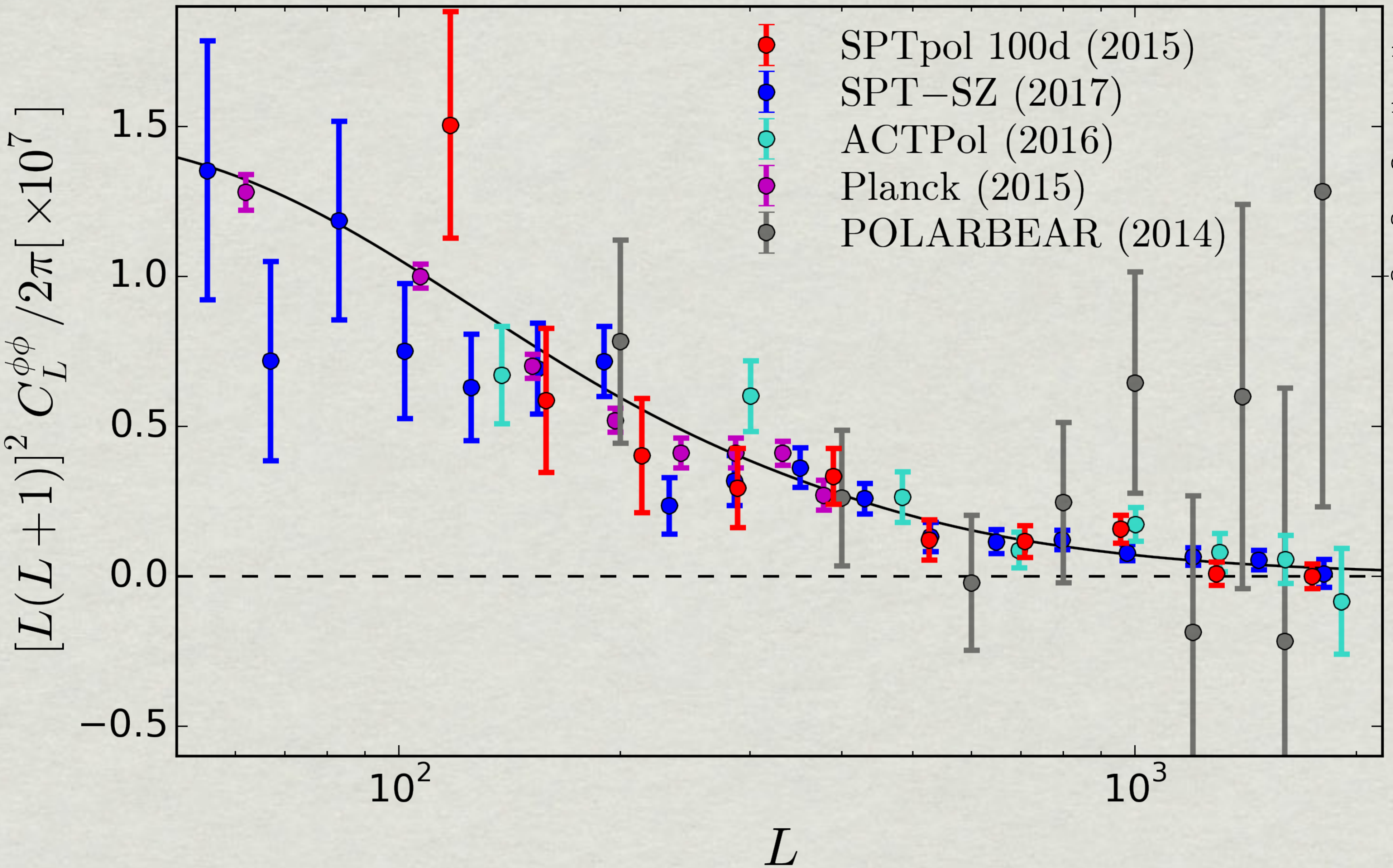
Power Spectrum uncertainty

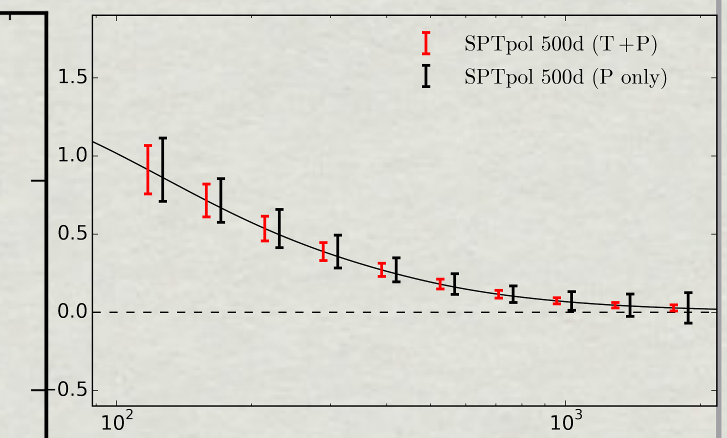


We measure the lensing potential power spectrum. We expect a statistical uncertainty on the amplitude of ~5-6%.

Work lead by Monica Mocanu

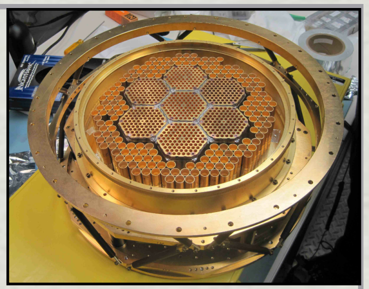
Lensing potential power spectrum





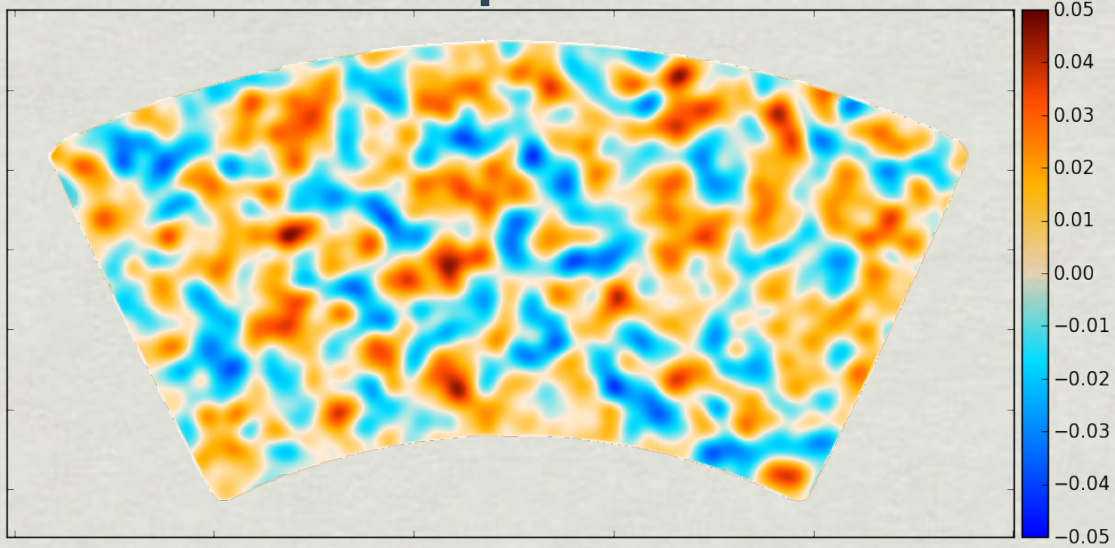
From this 500 deg^2 map, we measures the lensing power spectrum with similar precision to the 2500 deg^2 SPT-SZ spectrum.

Work lead by Monica Mocanu

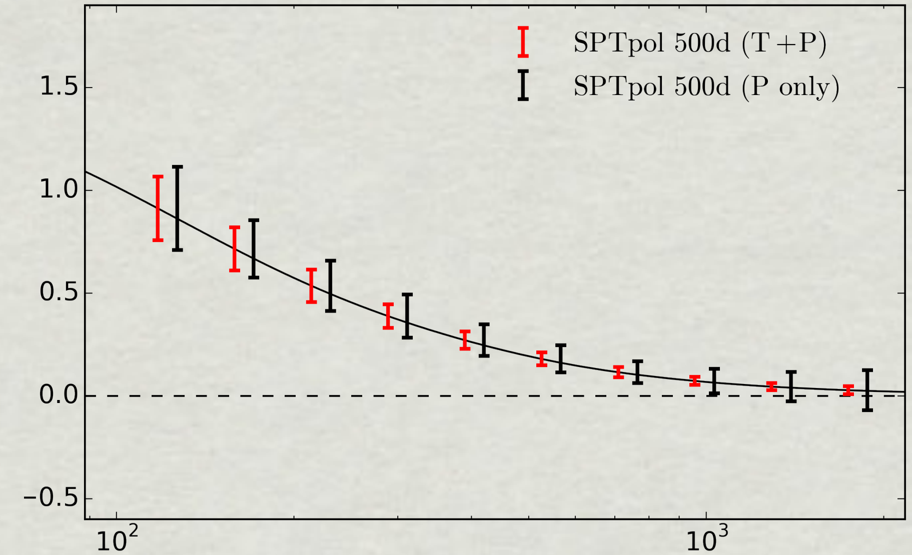


Key Take-away points:

SPTpol MV

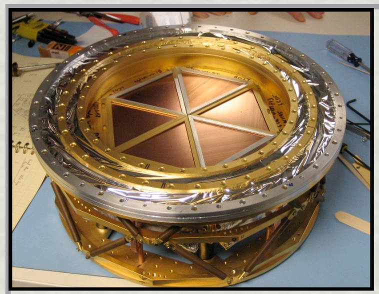


Clkk uncertainty

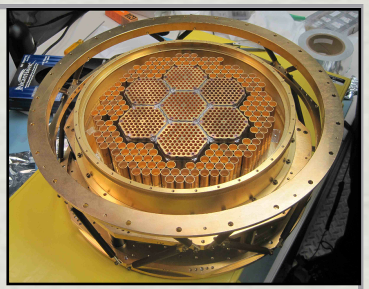


<u>This measurement is important because:</u>

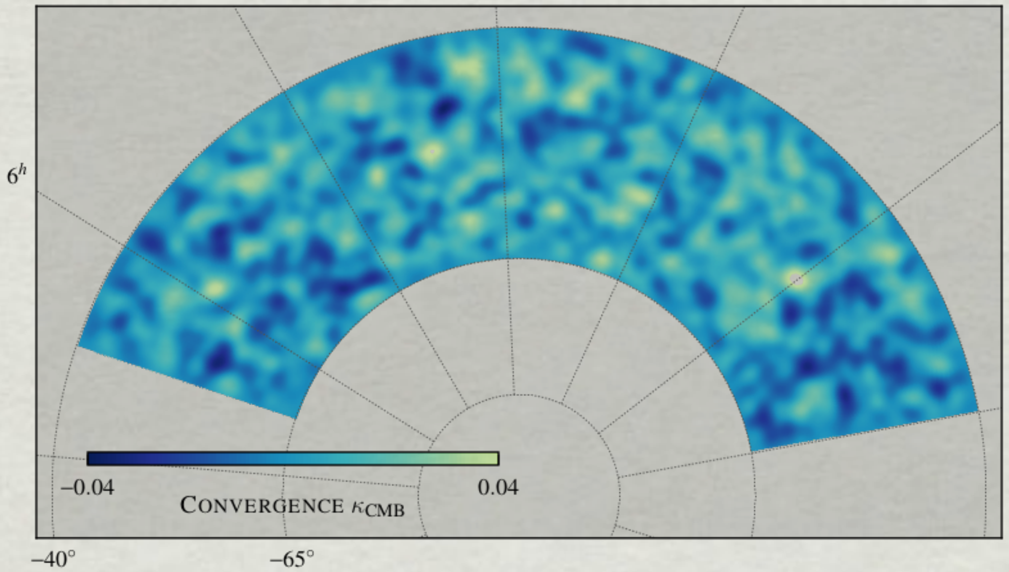
- **Precise measurement of the lensing power spectrum on 500 deg^2.**
- **Significant measurement in polarization, EB**
- **Will provide interesting cosmological constraints.**
- **B-mode Delensing: exact overlap with Bicep/KECK**



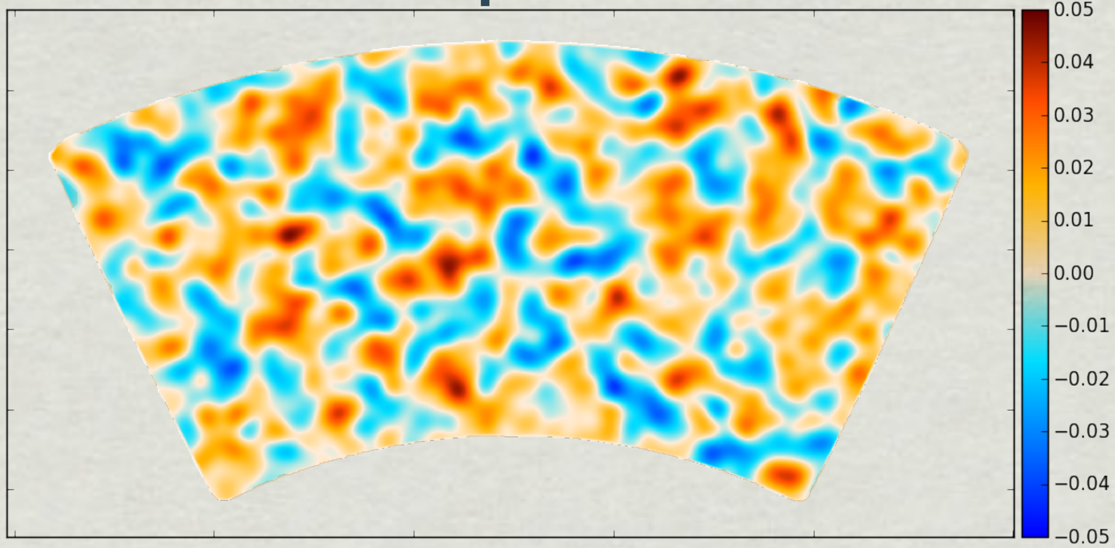
Conclusion:



SPT-SZ TT



SPTpol MV

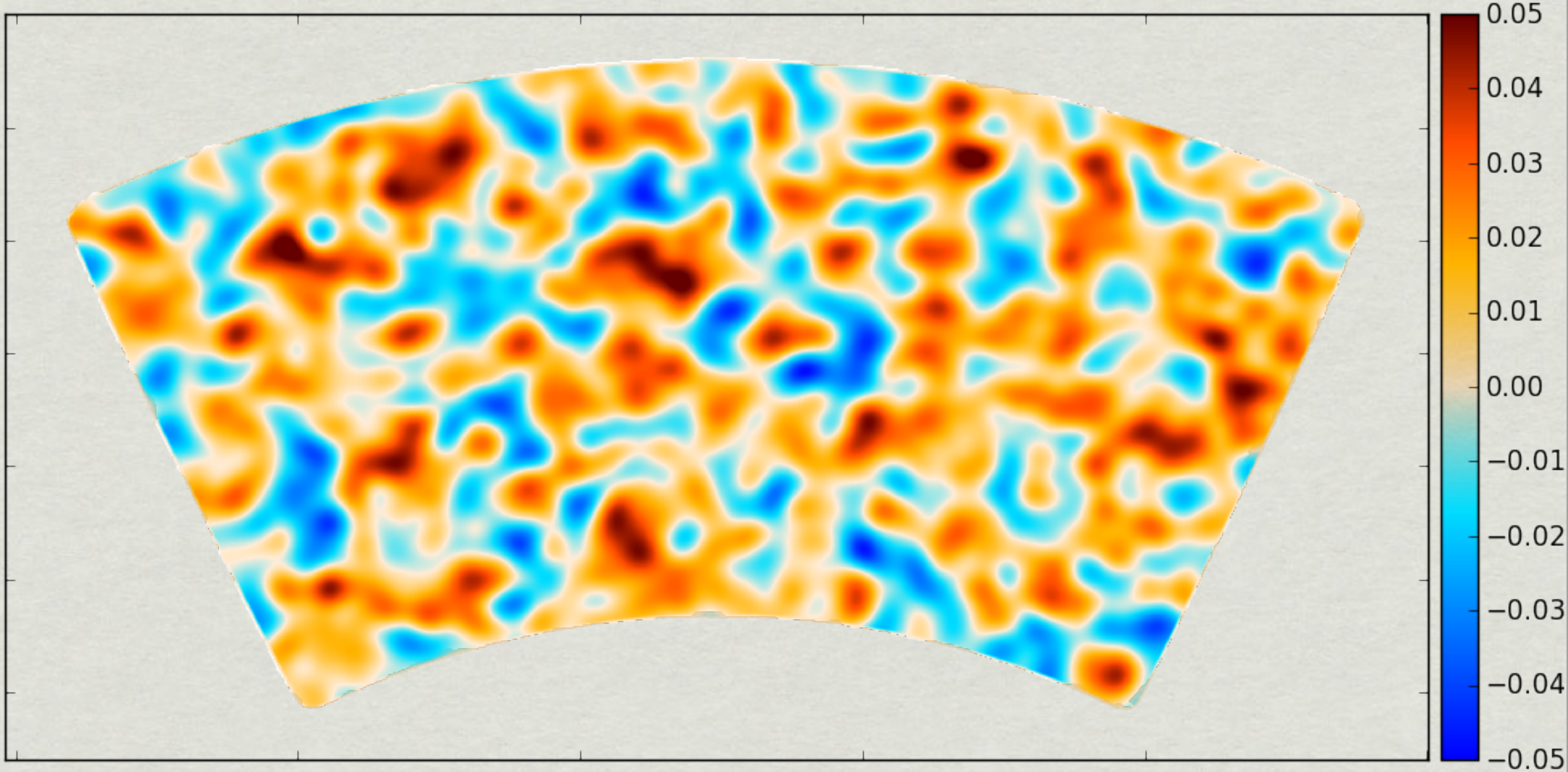


- **We have published a lensing map from the 2500 deg2 SPT-SZ survey from the combination of SPT and Planck temperature maps.**
- **We measure the lensing potential power spectrum with 6% precision.**
- **This map is being used for cross-correlations, particularly with DES.**
- **We are far along in measuring the lensing potential from the 500 deg^2 SPTpol survey field.**
- **This will provide high significance measurements from polarization, and will be useful for delensing B-modes in conjunction with BICEP/Keck.**

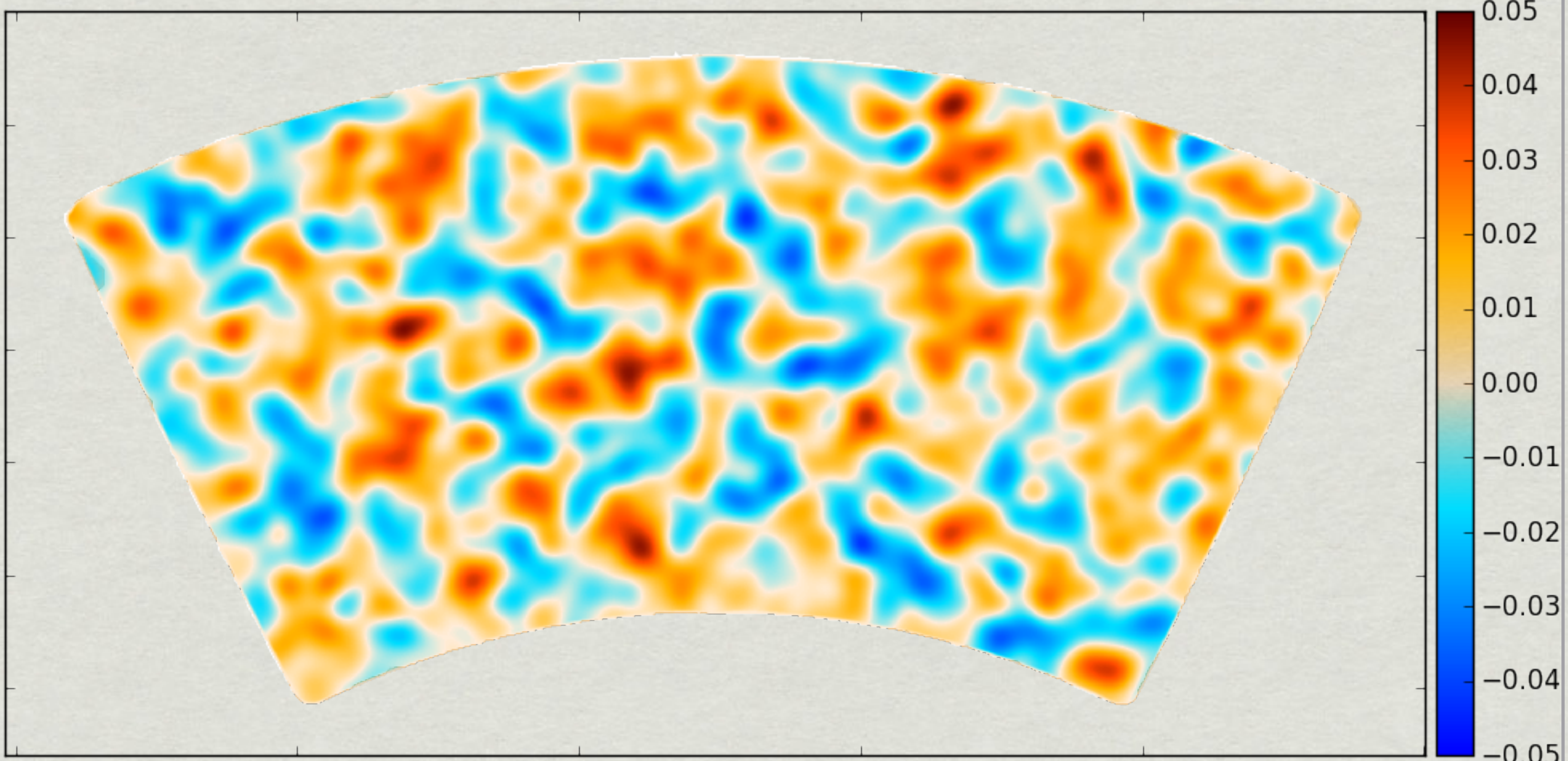
Thanks for listening!

Backup Slides

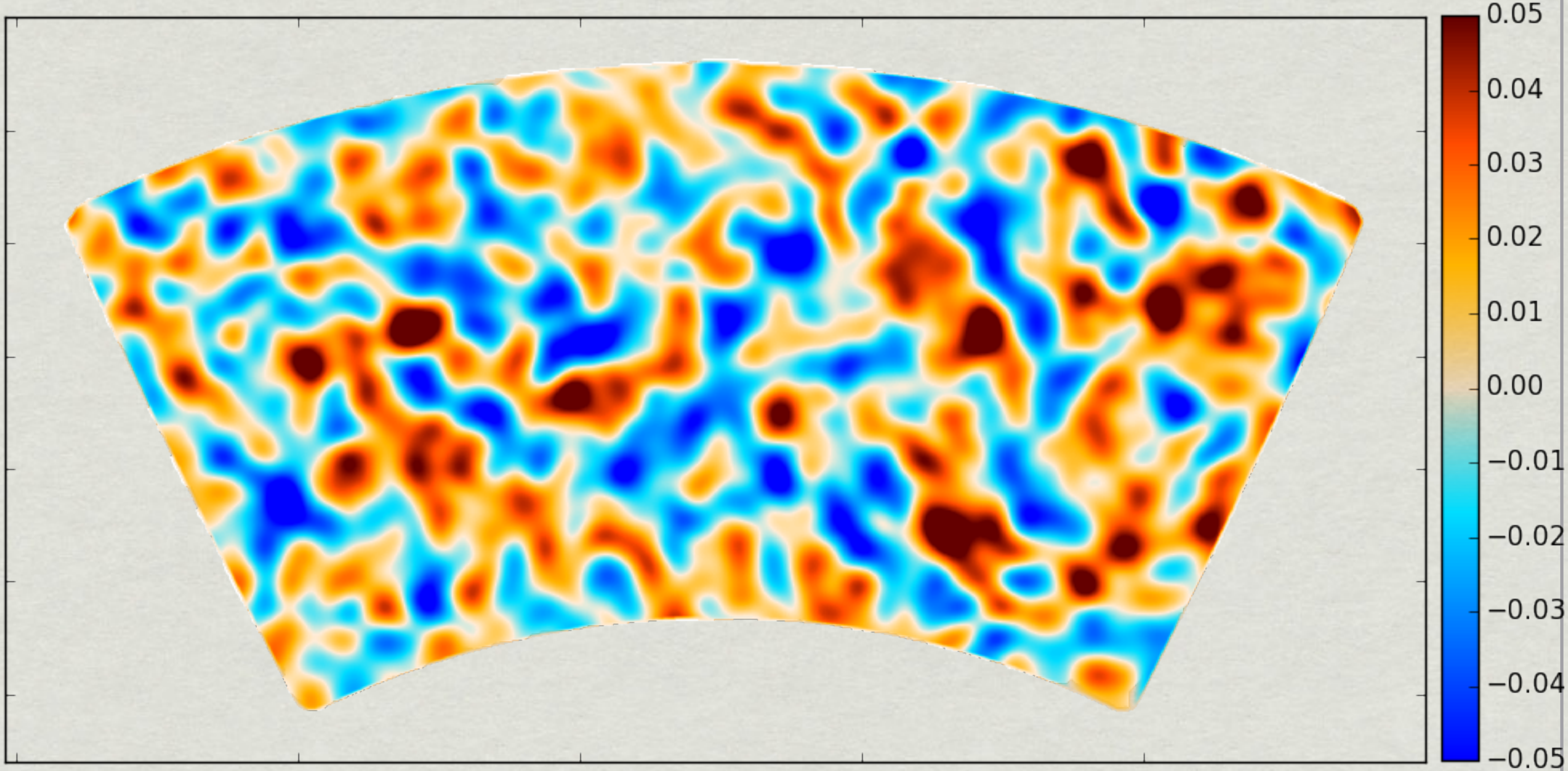
SPTpol TT



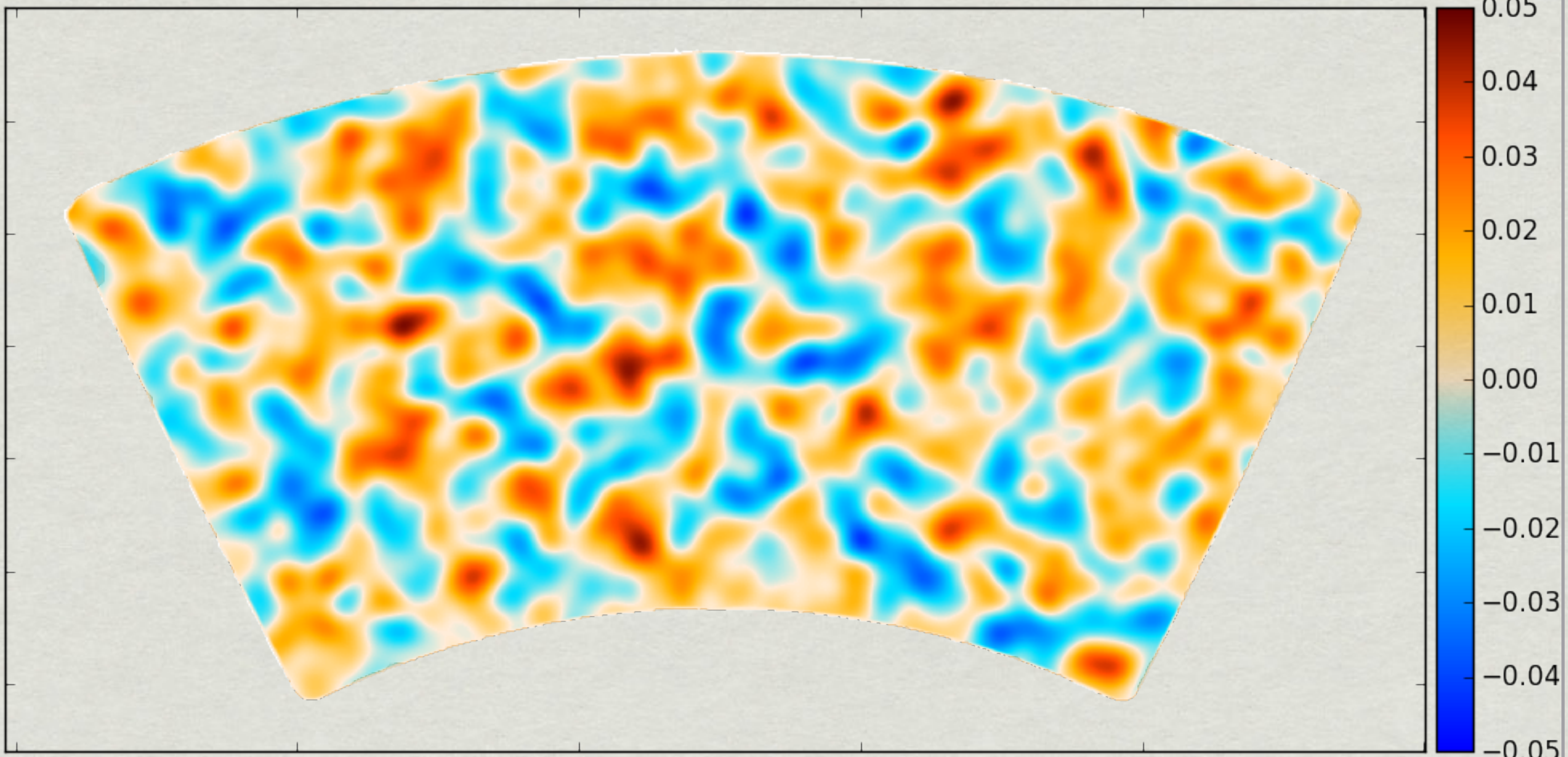
SPTpol MV



SPTpol EB



SPTpol MV



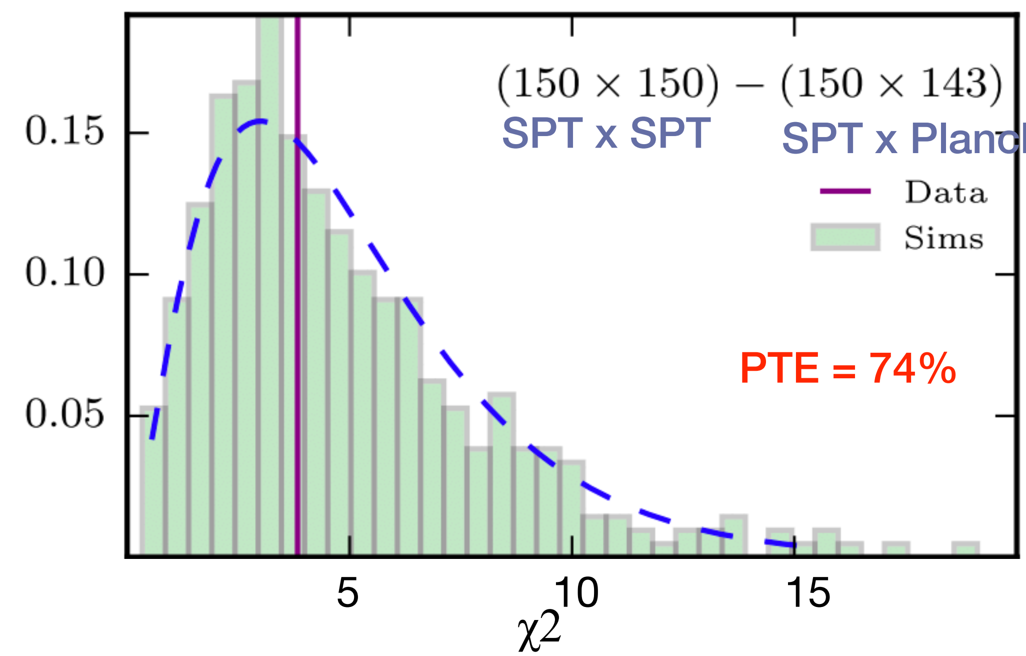
SPT - Planck TT power spectrum comparison

1) When Planck and SPT are restricted to measure the same modes on the sky (SPT-SZ patch between 650 < ell < 2000), the resulting cosmological parameters are fully consistent.

2) The observed tension between Planck on the full sky and SPT arise from both sky area and from the data above ell>2000 measured by SPT.

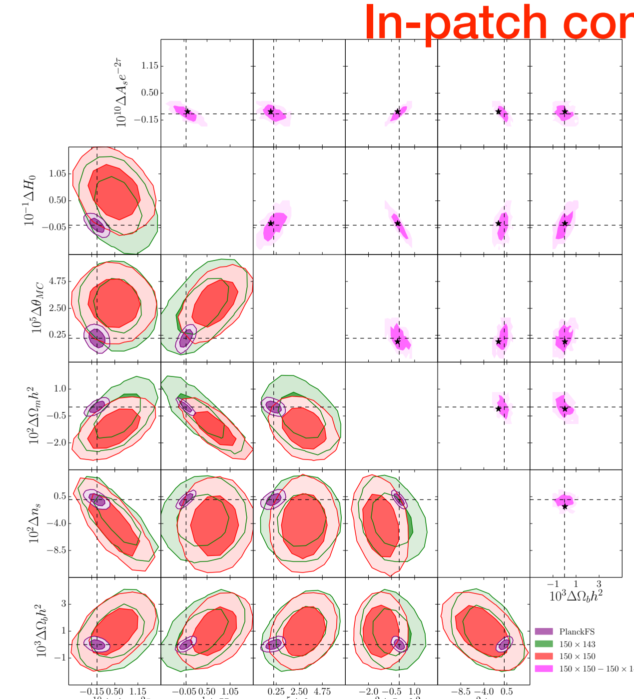
3) The high-ell SPT data (between 2000 < ell < 3000) drive shifts away from Planck full sky in the two density parameters $\Omega_m h^2$ and $\Omega_b h^2$ - and therefore H_0.

$\chi 2$ for differences in ΛCDM parameters



Parameter Differences:

In-patch comparison

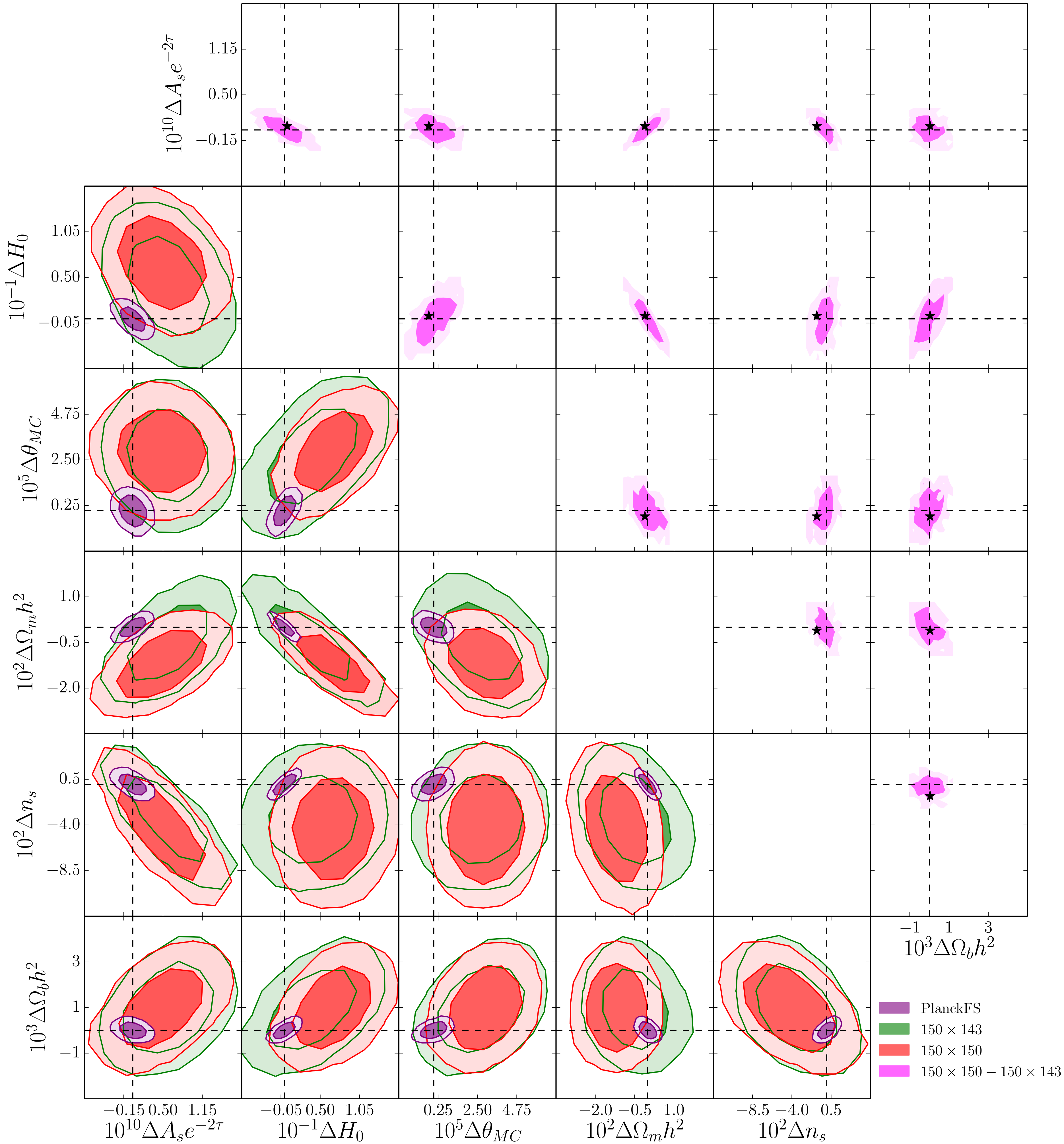


Planck FS v.s. SPT

This test is 300 times more precise than comparing to full-sky.

Aylor, Hou, Knox, KTS, et. al (arXv:1706.10286)

Hou, Aylor, et. al (arXv:1704.00884)



$10^{10}\Delta A_s e^{-2\tau}$
$10^{-1}\Delta H_0$
$10^5\Delta\theta_{MC}$
$10^2\Delta\Omega_m h^2$
$10^2\Delta n_s$
$10^3\Delta\Omega_b h^2$
PlanckFS
150×143
150×150
$150\times150-150\times143$