Alessandro Manzotti
Lagrange fellow
Institute D'Astrophysique de Paris

CMB Lensing with the South Pole Telescope

COSMOS Ferrara

SPT: A LOW NOISE, HIGH RESOLUTION, CMB POLARIZATION EXPERIMENTS AT THE POLE

High-resolution of 1 arcmin

Large and small scale 50<ell<8000

Polarization detector with great systematic controls (90-150 -220 Ghz)

Low/stable atmospheric noise and great depth

Strategy: dig down! small-ish area very low noise

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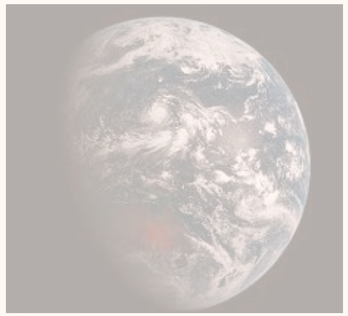

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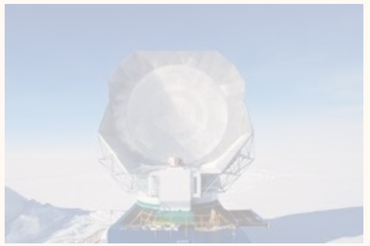


Strategy: dig down! small-ish area very low noise

SPT-POL: OPENED A NEW CMB POLARIZATION WINDOW, MATCHED AND IMPROVED PREVIOUS RESULTS.

Polarization contains more information than temperature.
It is affected by different systematics and foreground. It is very clean at small scales.

High resolutions allow seeing astrophysical objects: clusters, GRBs etc.

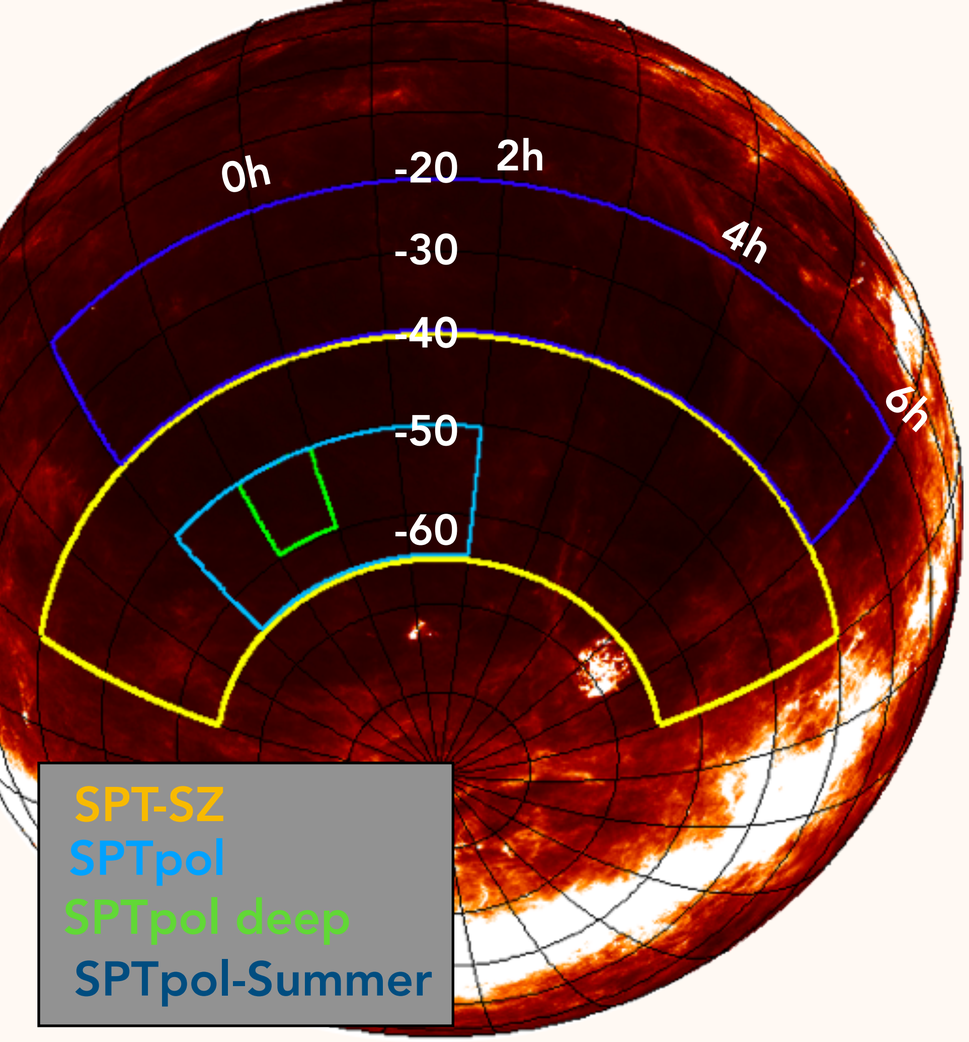
↓

Measuring very high S/N of gravitational lensing, also from CMB polarization maps.

Measure CMB E-modes B-modes both at large and small scales and improve constraints on inflation and early universe physics.

Find more clusters, reducing mass detection threshold (higher-z).
With less contamination (Polarization)

THE SPT SPECS YOU NEED TO KNOW



5000 deg^2 surveyed in total by SPT-SZ and SPTpol
150 GHz depths between
4-30 uK-arcmin
(from ~Planck depth, to ~7 times deeper)

Noise in temperature

ultra deep

Freq (GHz)	SPT-SZ	SPTpol deep	SPTpol	SPTpol Summer	SPT 3G
95	40	10	12,5	50	2.8
150	17	5/3.5	5,3	30	2.6
220	80	40	40/80	-	6.6
Area (deg^2)	2500	100	500	2500	1500
Status	*Complete*	*Complete*	*Complete*	*Complete*	*Ongoing*

2 HIGHLIGHTS FROM PAST:

CMB LENSING FROM SPT-SZ AND POL

DELENSING AND CLUSTER LENSING

FUTURE:

SPT-3G LENSING

ASK FOR MORE !

CMB Lensing with SPT-SZ and SPT-Pol

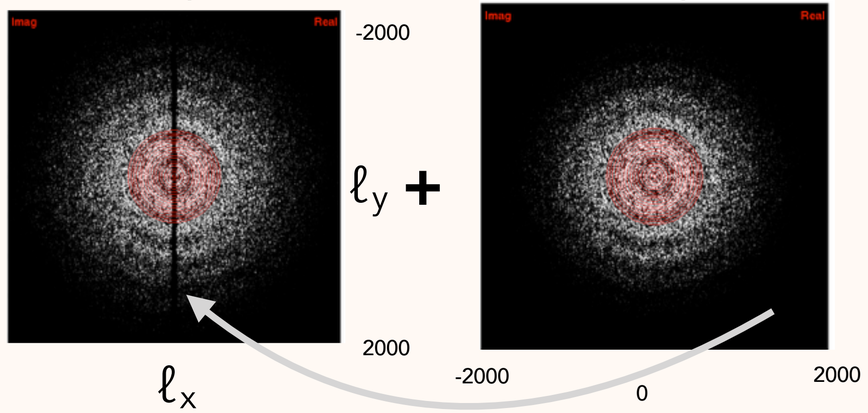
THE FINAL SPT-SZ (2500 DEG²), LENSING RESULTS

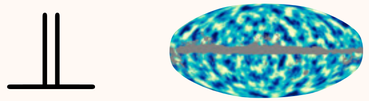
We fill the missing filtered modes with Planck maps.

Inverse variance weighted.

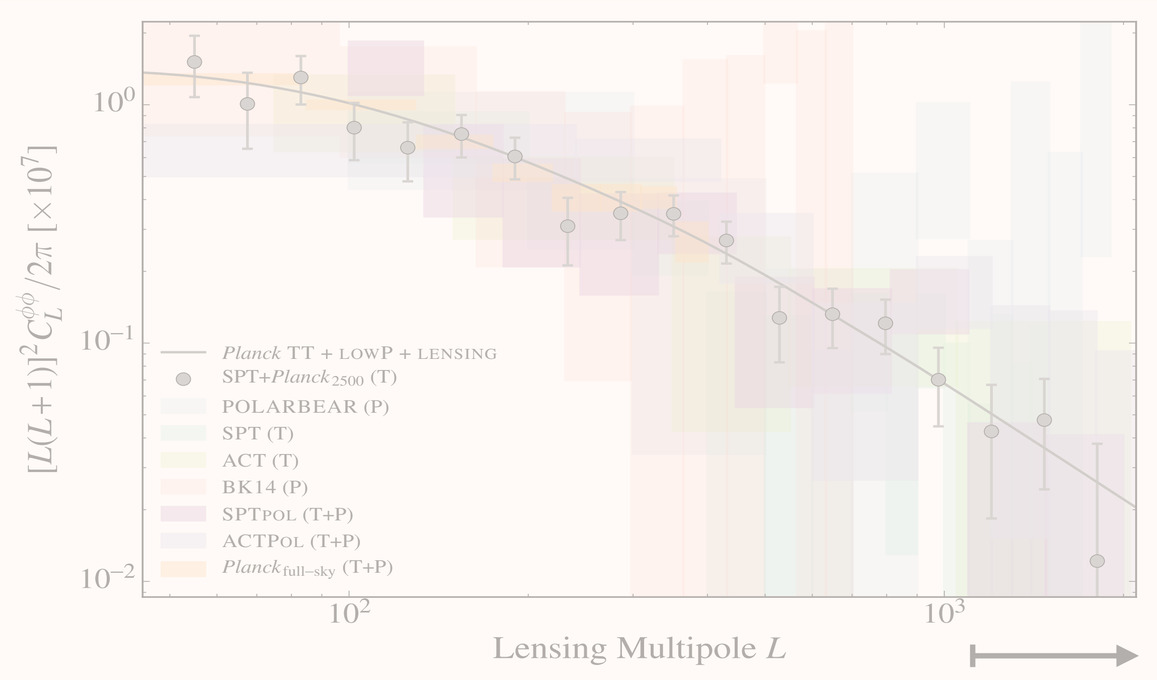
SPT SZ temperature Fourier space

Planck (on SPT-SZ Patch) Fourier space





<u>independent</u> from Planck full sky



Biggest CMB lensing maps from ground.

7% constraint on the amplitude.

Planck has little effect, but it improves small scale lensing: important for cross correlation

Maps (both of temperature and lensing) available!

gets better Planck full sky

Simard, Omori et al.

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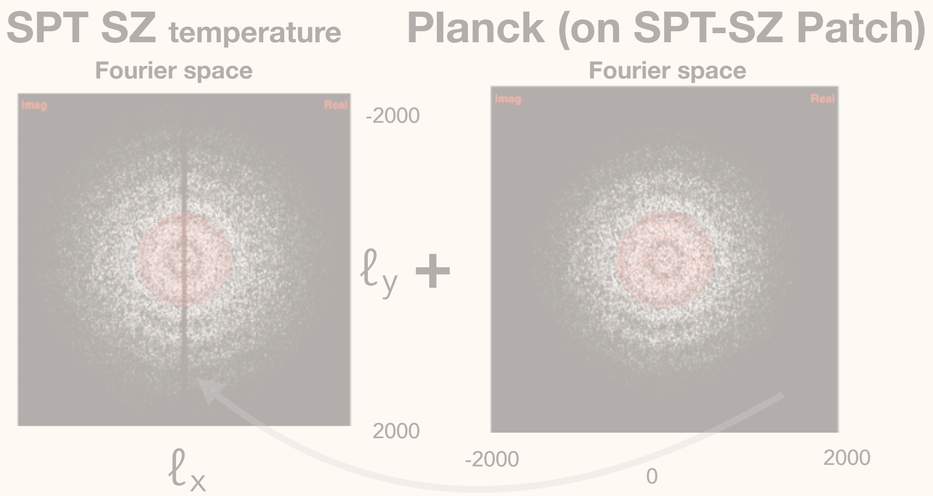

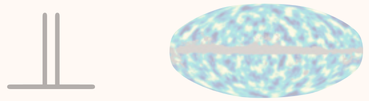

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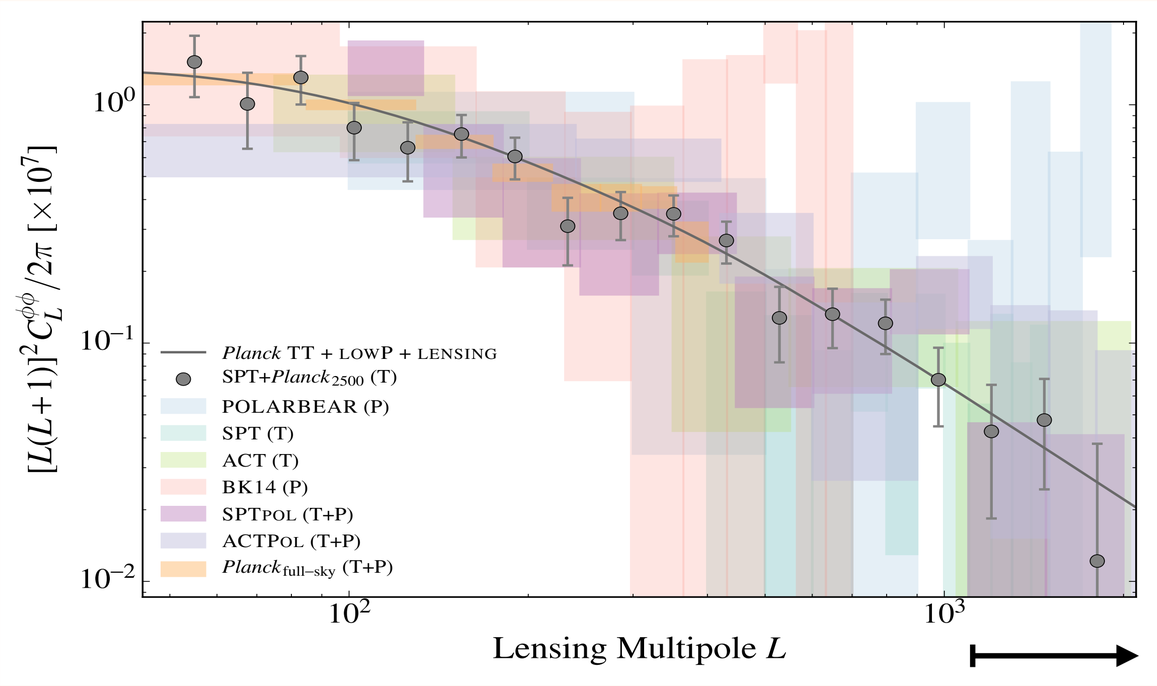

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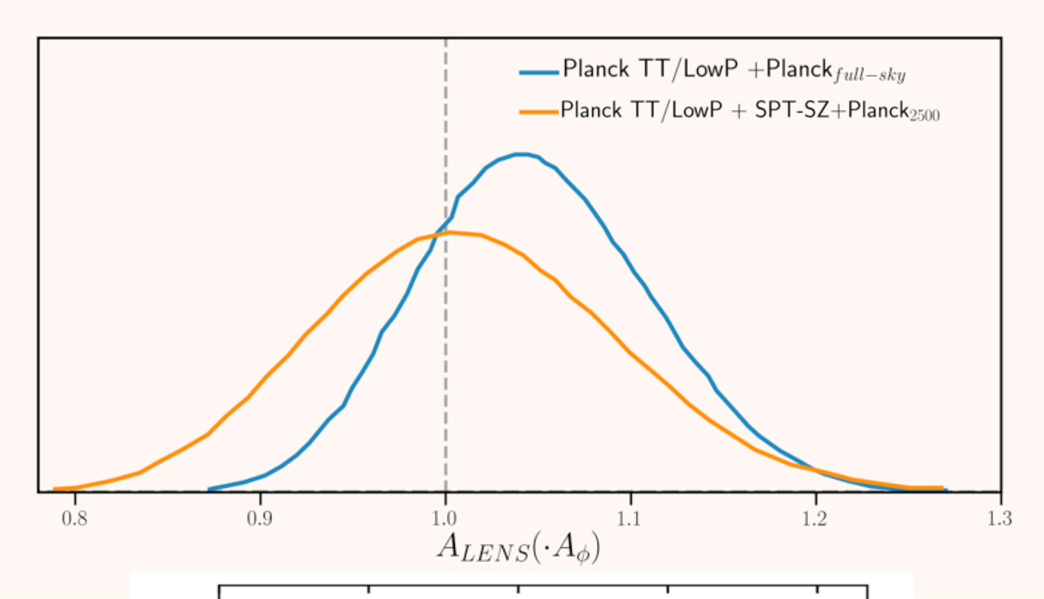
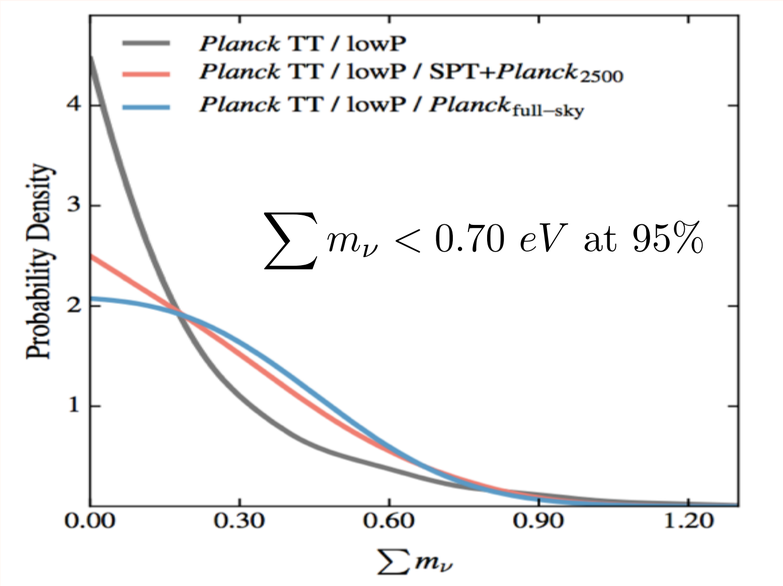
Simard, Omori et al.

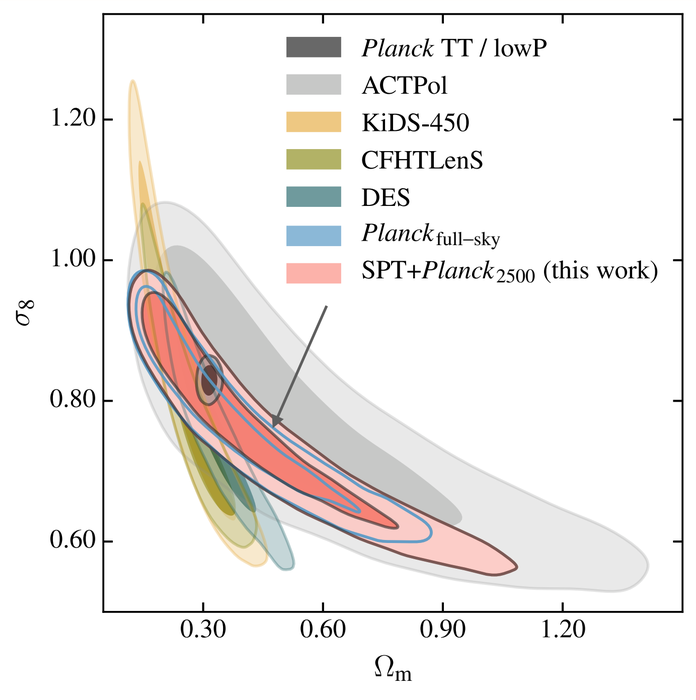
7% AMPLITUDE CONSTRAINT. CONSISTENT WITH OTHER PROBES.

LCDM





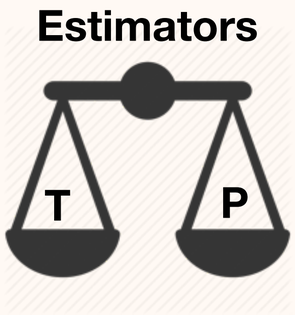
Bandpowers ,likelihood and maps available on LAMBDA!

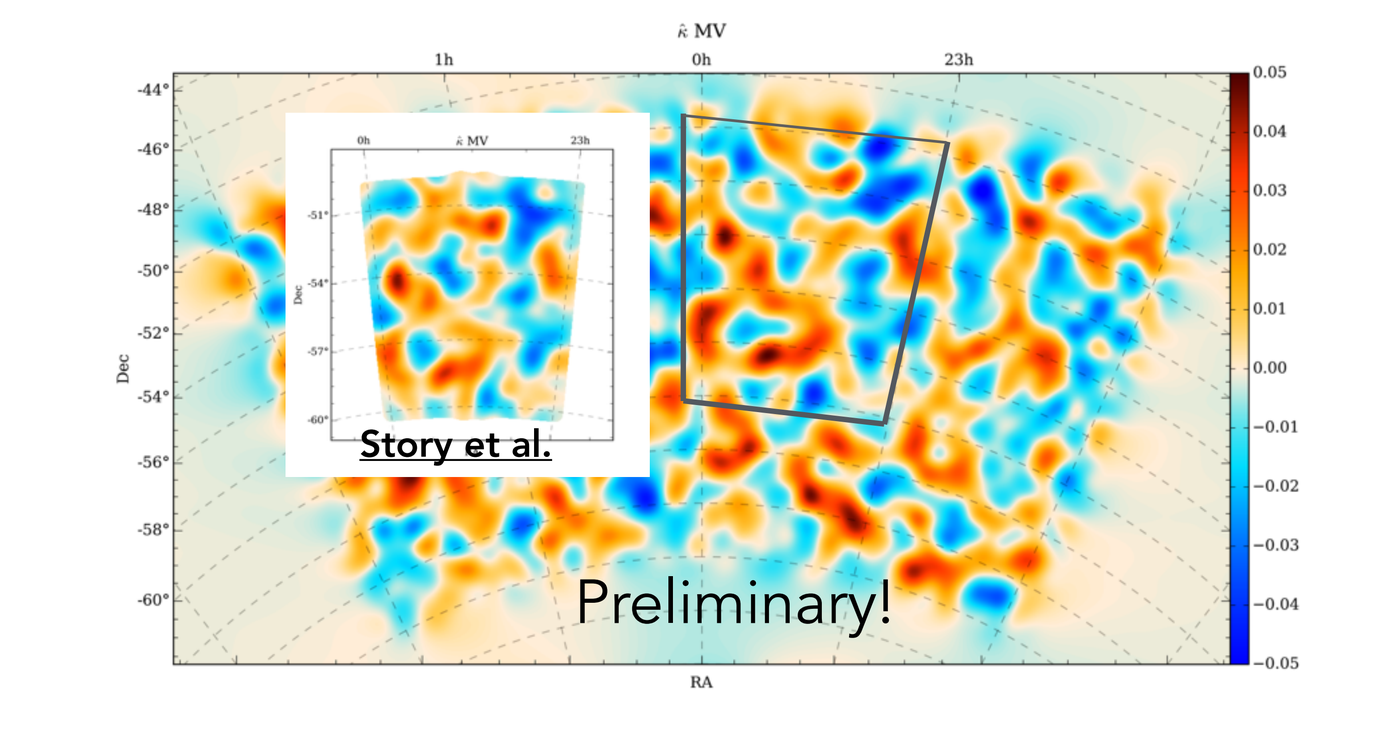


CIB bias already a limit for cross-correlation, polarisation?

Simard, Omori et al.

SPT POL 500^2 LENSING: ~7% A_{LENS}
POLARIZATION ALMOST AS GOOD AS TEMPERATURE!



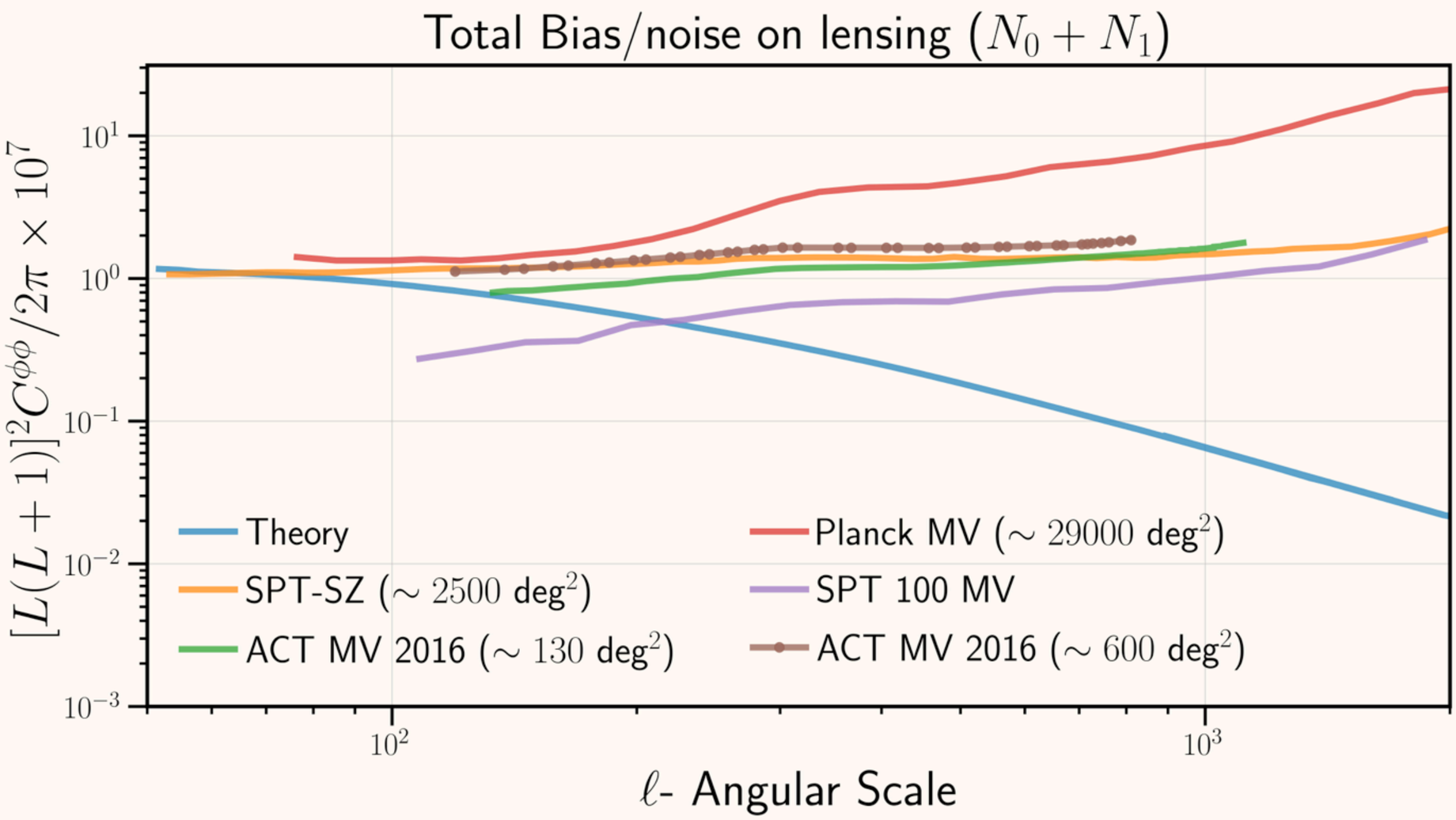


Constraints ~ SPT-SZ+Planck, even on 1/5 area.

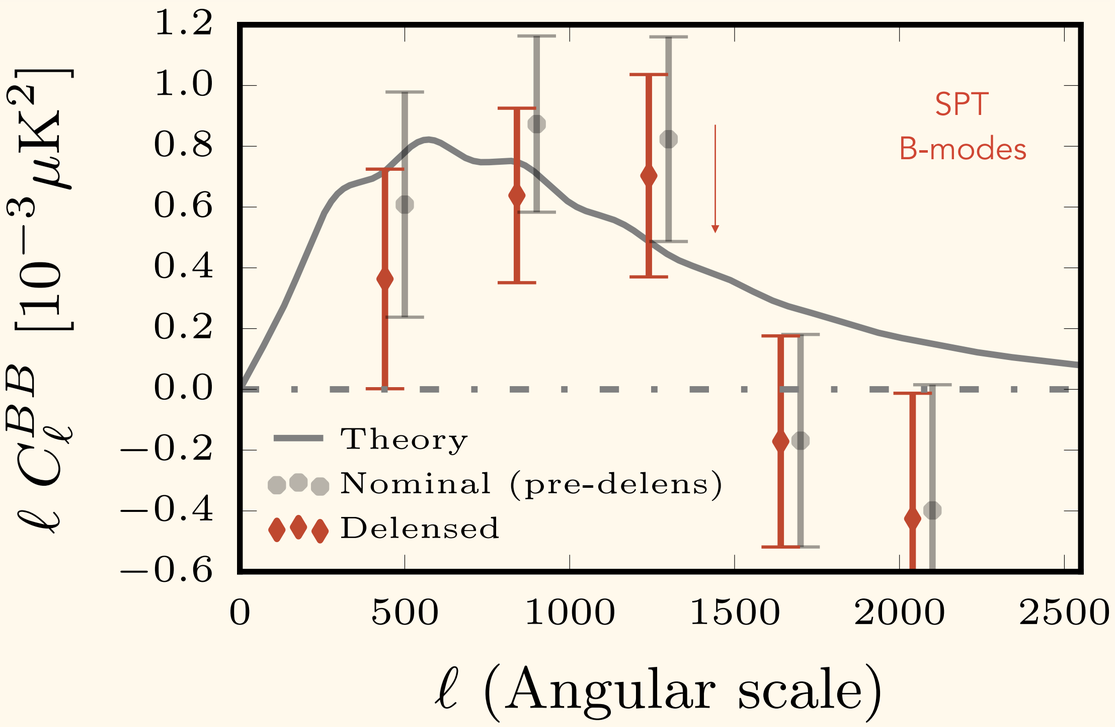
Polarization-only competitive with Planck polarization-only!

Spectra constraints not everything: these maps have L ~< 250 modes imaged with S/N > 1. Cross correlation with DES, Delensing, cluster lensing etc..

AMAZING SIGNAL TO NOISE MAPS



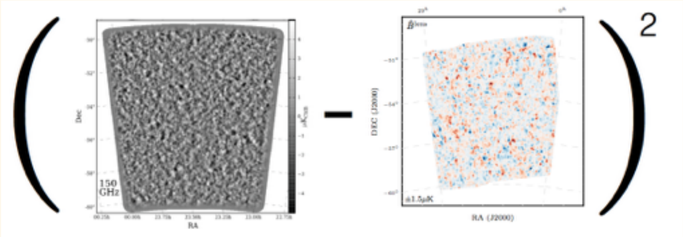
DELENSING: A NEEDED STEP TO INFLATIONARY B-MODES



Delensing
Removed power and variance. Improve inflationary constraints

Manzotti et al. 2017

With CIB as tracer.
Adding CMB lensing right now



Delensing of the CMB B-mode power spectrum using data from **SPTpol and Herschel CIB** as a tracer of the lensing potential.

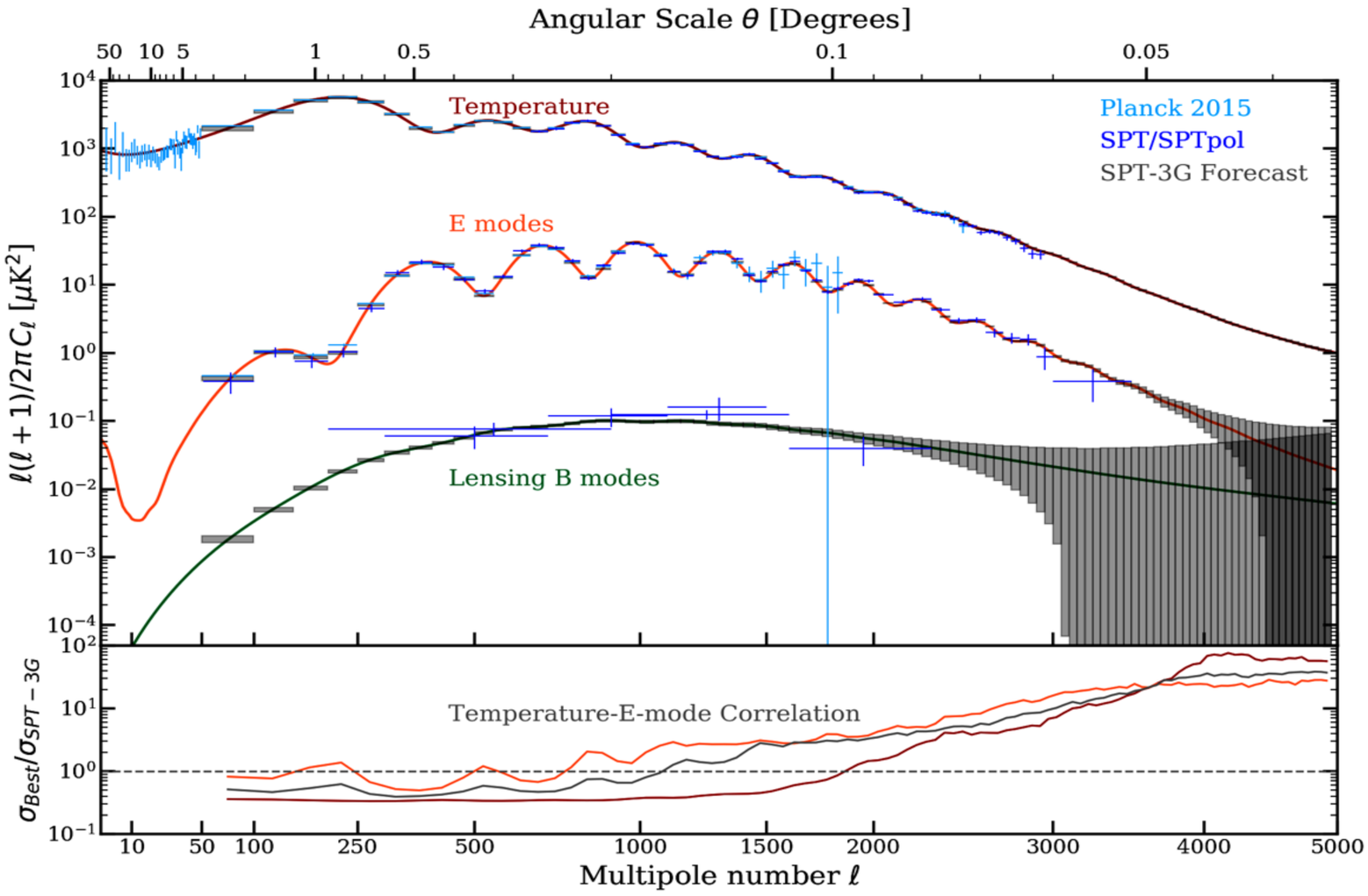
- Lensing **B-mode power** spectrum reduced by **28%** on sub-degree scales
- 6.9 sigmas, the **highest delensing efficiency so far**.
- **Work** is **ongoing** to **delens Bicep-keck data** with SPT-Pol maps.

SPT 3G

THE FUTURE (ALREADY PRESENT) SPT 3G

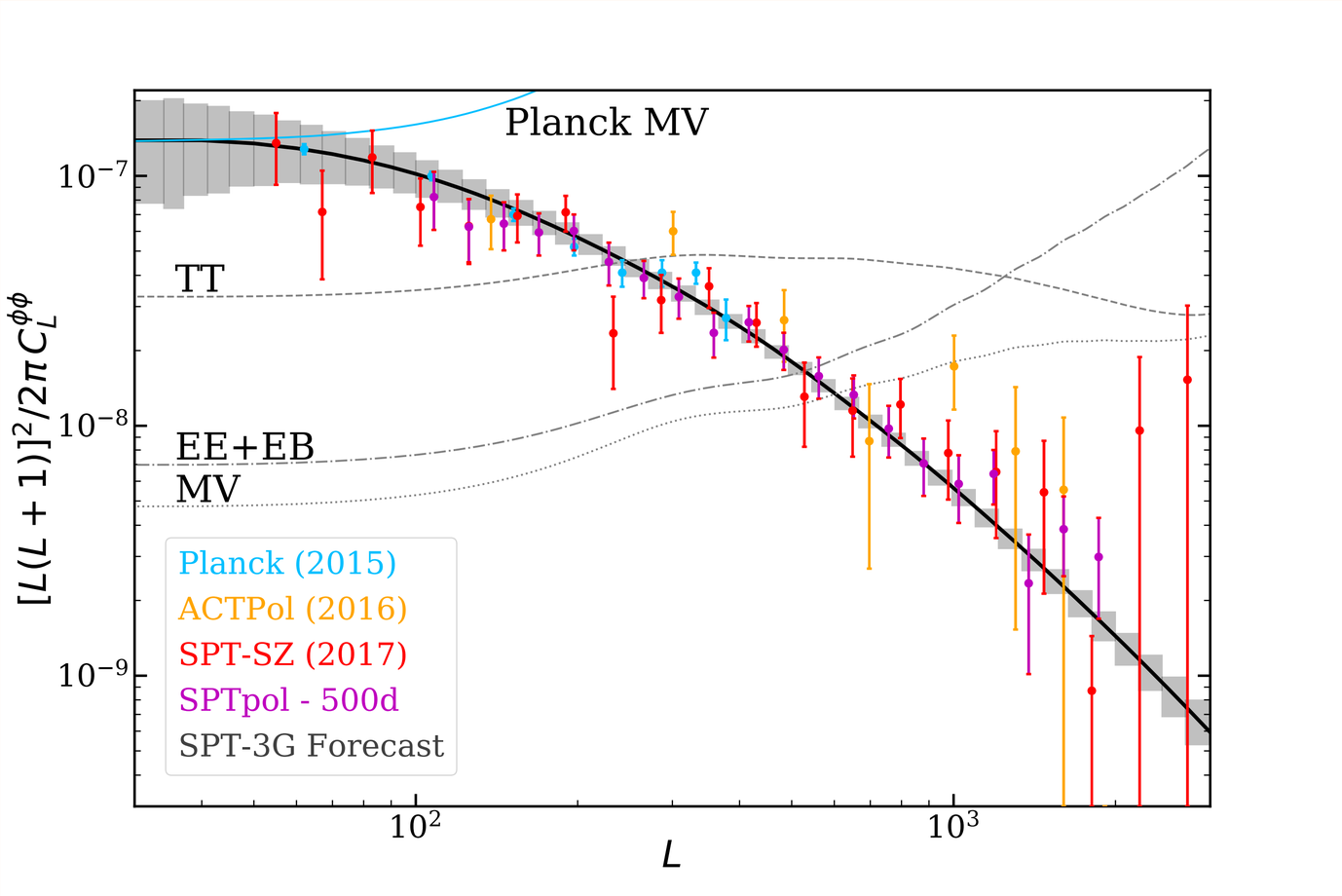
One more frequency than Pol (220

Ghz), already taking science data



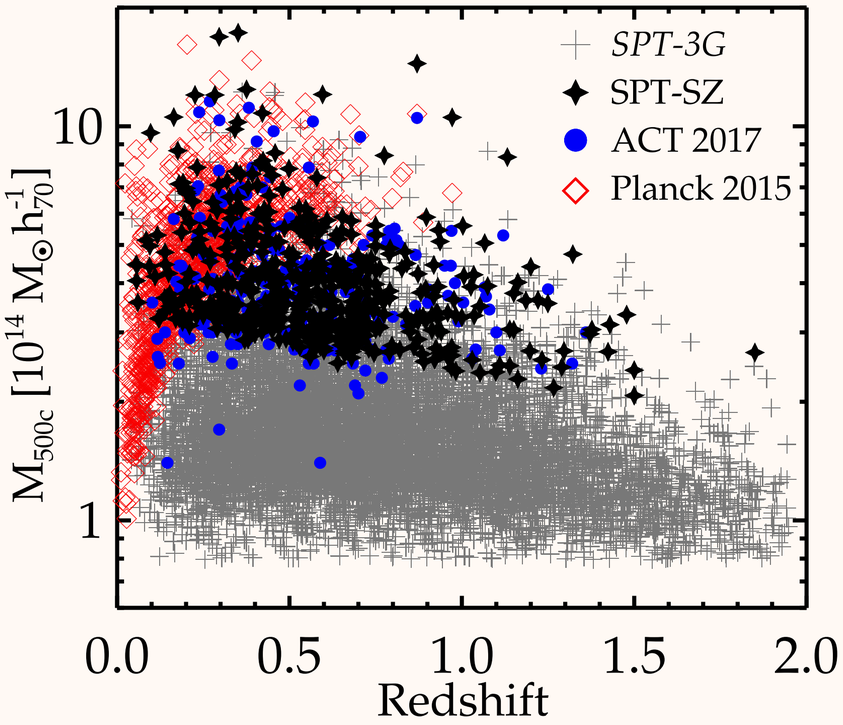
SPT 3G CMB LENSING IMPROVING PLANCK WITH GREAT S/N MAPS

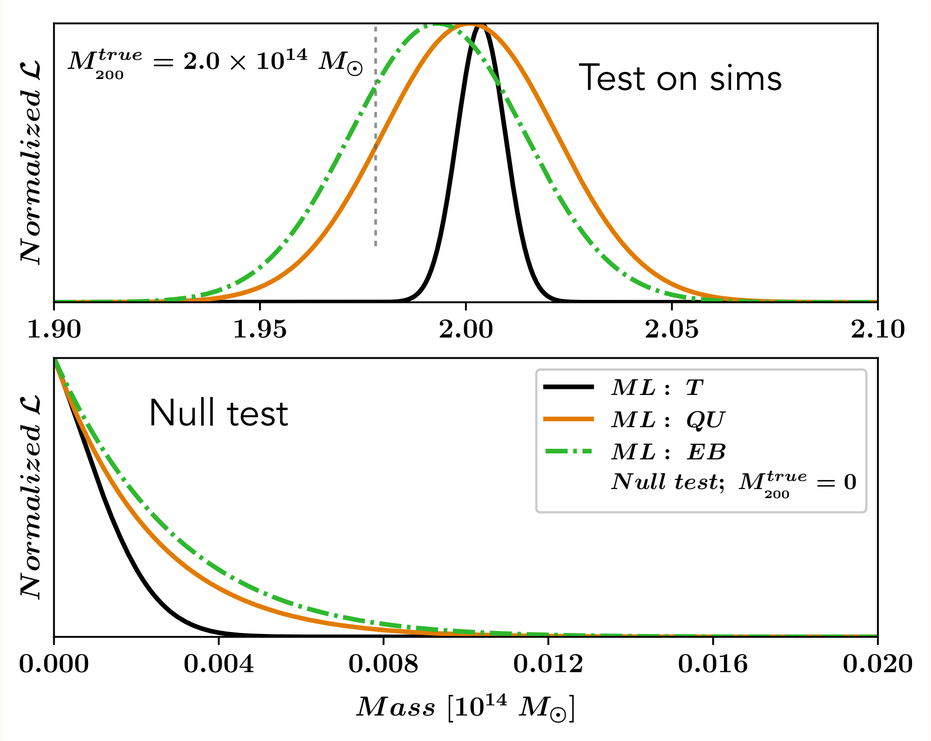
An LSST noise level lensing screen at z =1100!
We will improve on Planck spectrum
Again a very different approach: very accurate map on a small area



$$\sigma(\sum m_\nu) \simeq 0.06eV$$
external τ

CLUSTER LENSING WITH SET 3G: ALTERNATIVE NEUTRINO CONSTRAINT





$$\sigma(\sum m_\nu) \simeq 0.06eV$$

We predict the cluster mass uncertainties will be 3 - 6% for SPT-3G.

Another exciting way to constrain neutrino properties !! Similar constraints of CMB lensing expected

A LOT OF SPT SCIENCE I HAVE NOT TALKED ABOUT

Baryons: KSZ with DES cross-correlation

Detailed systematics tests against Planck: polarisation, lensing

A lot of cluster physics.

Ultra Deep 100: amazing 5 muK in pol at 1 arc min resolution.

We have 1 summer observation of the KIDS field.

Clusters (for example lensing polarization, you will hear from us soon)

Transients searches. GRB afterglows.

DES cross-correlations (again:you will hear from us soon).

Stay - tuned
Thanks!!

Alessandro Manzotti

Lagrange fellow
Institute D'Astrophysique de Paris
for the SPT collaboration

Available spectra/likelihood

lambda.gsfc.nasa.gov/product/spt/:

SPT Pol EE,TE: goo.gl/Tp8VMT

SPT SZ -Planck lensing like: goo.gl/KXtH6D

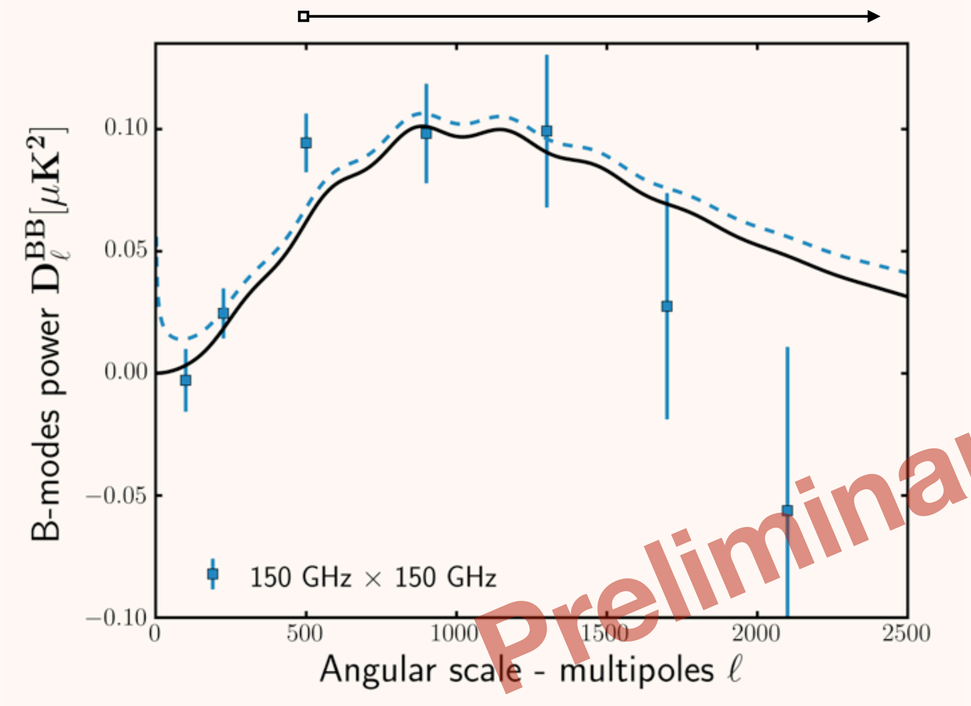
SPT SZ -Planck T, lensing Maps: goo.gl/LEVT6k

SPT BB-modes: BP and like by the end of summer

100 deg^2 available

AND WE WILL DELENS OUR OWN 500D DATA TOO

The most sensitive spectra at ℓ >300

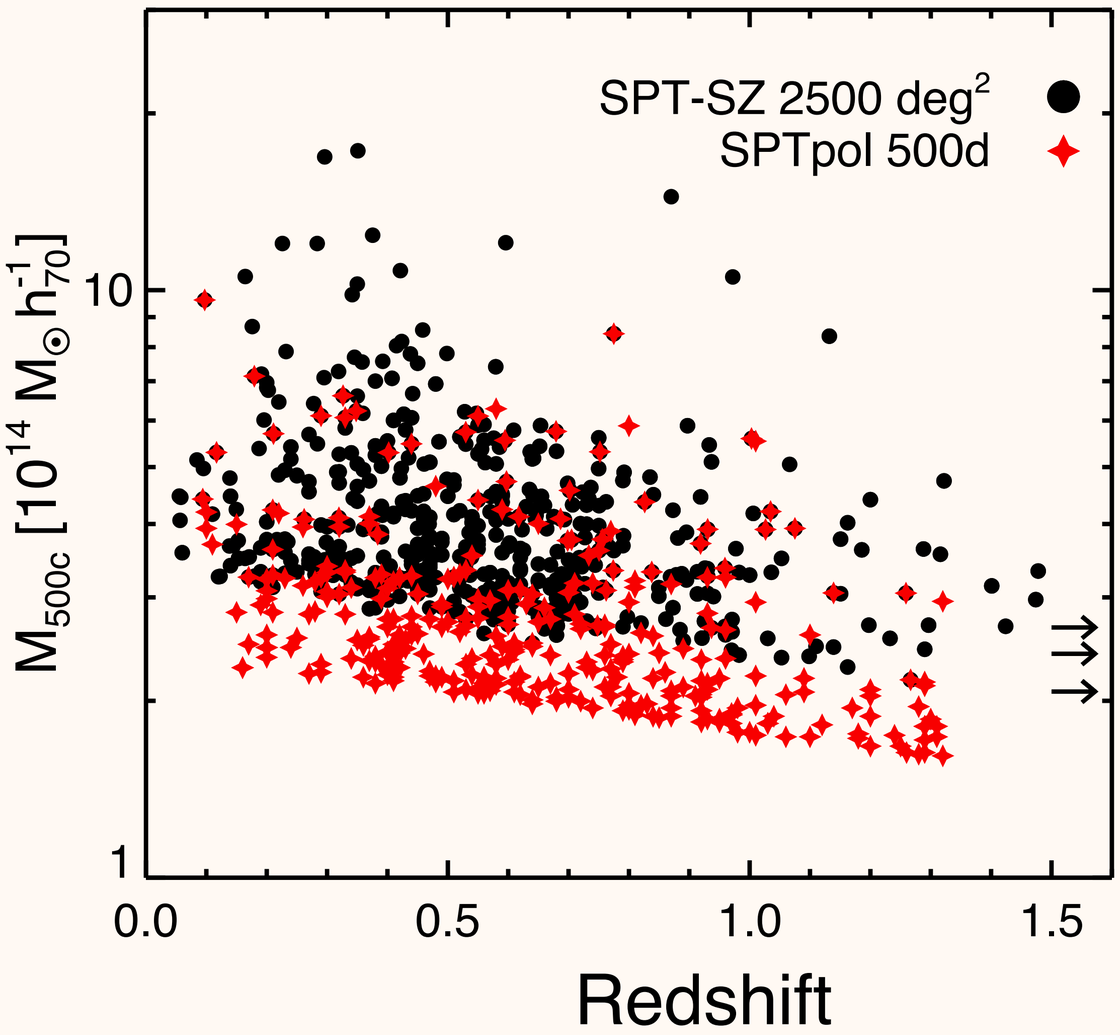


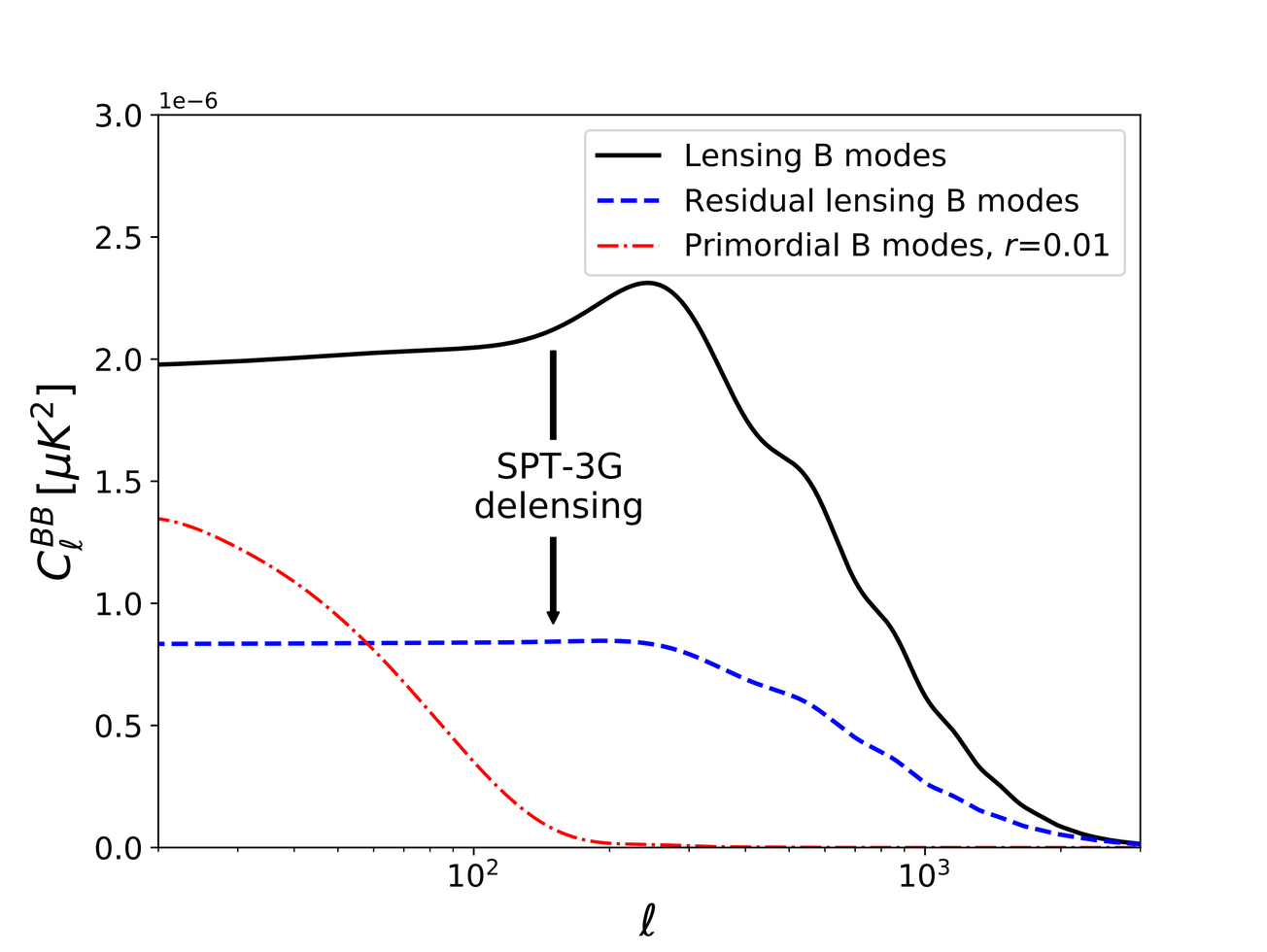
r < ~0.3-0.4 at 95% from SPTPol B-modes alone.

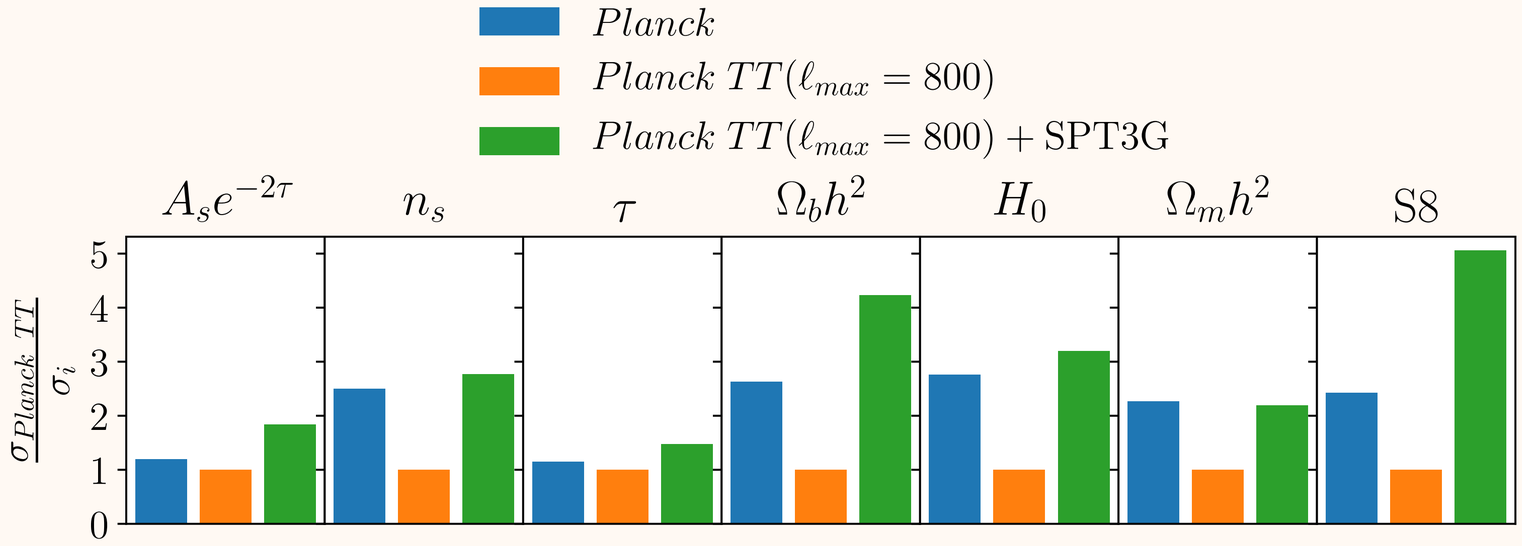
First step towards inflationary constraints. We will helens with CIB+ internal CMB lensing

10-15% constrain on the amplitude (A_{lens}), 7.5 sigma.

Backup Slides


SPT-SZ 2500 deg^2
SPTpol 500d
M_{500c} [10^{14} $M_\odot$ h_{70}^{-1}]
10
1
0.0
0.5
1.0
1.5
Redshift


1e−6
3.0
2.5
2.0
1.5
1.0
0.5
0.0
C_ℓ^{BB} [μK^2]
10^2
10^3
ℓ
Lensing B modes
Residual lensing B modes
Primordial B modes, r=0.01
SPT-3G
delensing


Planck
Planck TT(ℓmax = 800)
Planck TT(ℓmax = 800) + SPT3G
Ase−2τ
ns
τ
Ωbh2
H0
Ωmh2
S8
σPlanck TT / σi
0
1
2
3
4
5

SPT 3G

ONE MORE FREQUENCY

UP AND RUNNING

DELENSING AND CLUSTER LENSING

CLUSTER PHYSICS

FINAL NOISE (PESSIMISTIC)

we will be the first to test new techniques

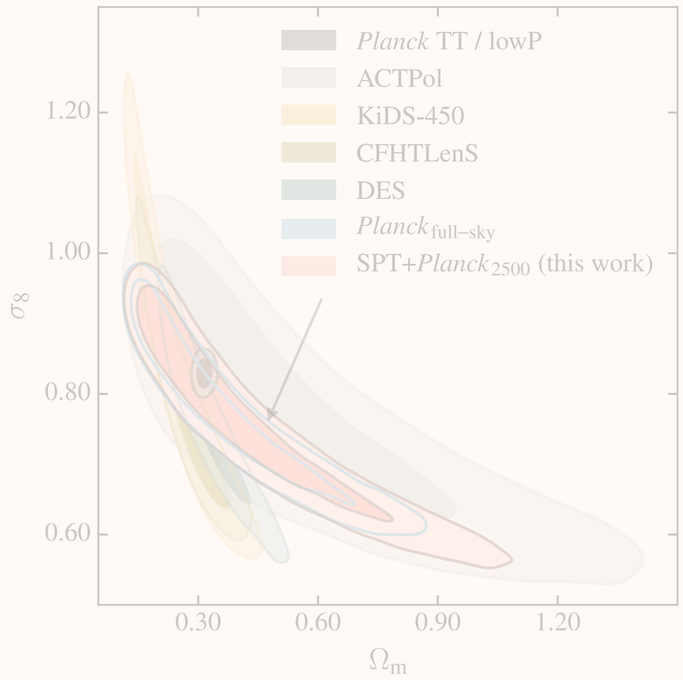
THE SPT COLLABORATION (~EARLY 2016)
~70 SCIENTISTS (~HALF POSTDOCS AND STUDENTS)
ACROSS ~20+ INSTITUTIONS

SPT-POL: AN AMAZING HIGH RESOLUTION POLARIZATION CMB EXPERIMENT .

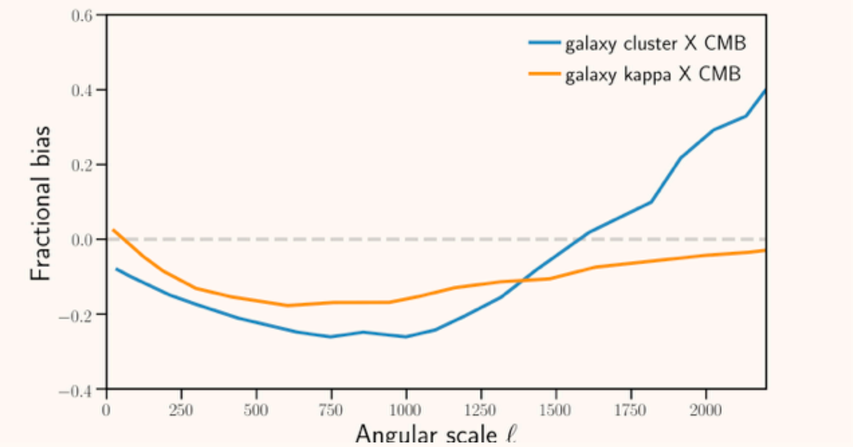
7% AMPLITUDE CONSTRAINT. CONSISTENT WITH OTHER DATA.

LCDM

Simard, Omori et al.



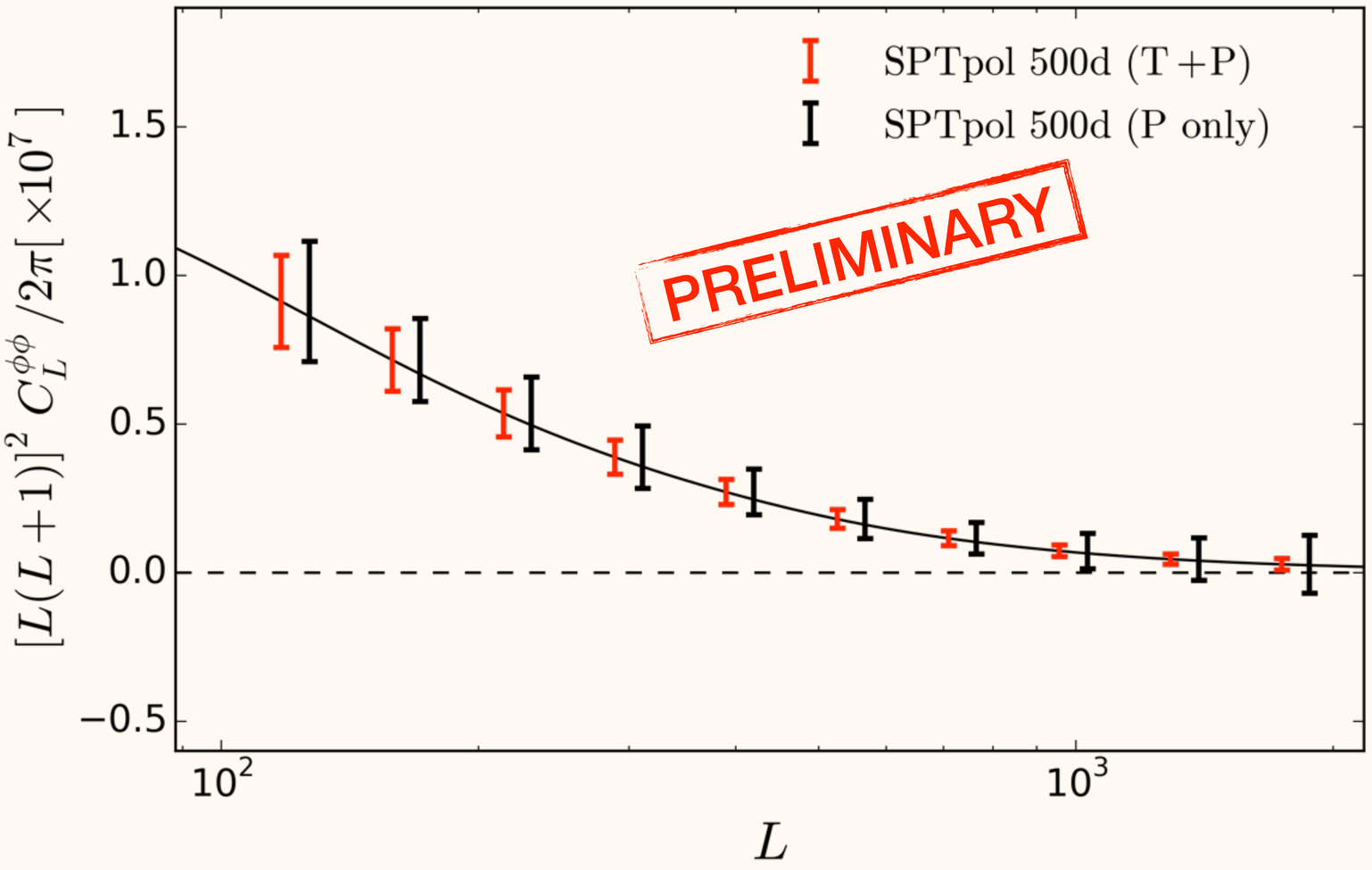
DES correlations show SZ bias at ~20%
Correct with sims / use polarization?



Bandpowers ,likelihood and maps available on LAMBDA!

Baxter, Omori et al.

Power Spectrum uncertainty



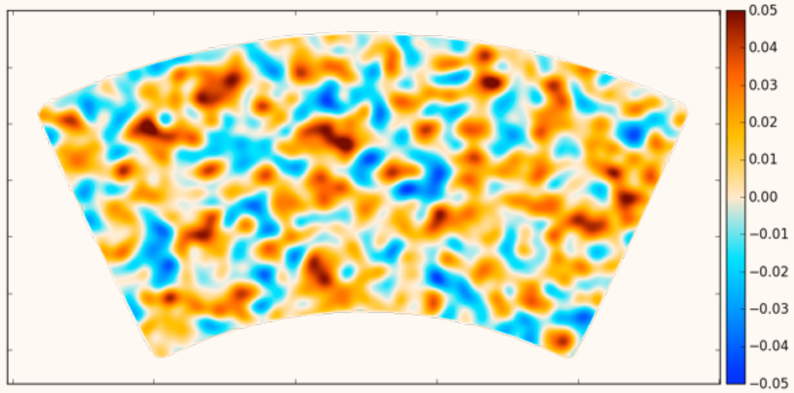
We measure the lensing potential power spectrum. We expect a statistical uncertainty on the amplitude of ~5-6%.

Work lead by Monica Mocanu

SPTpol survey field analysis

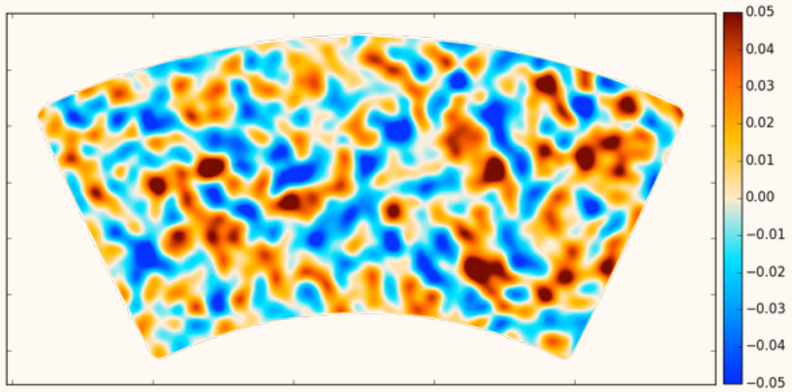
$$\bar{\phi}^{XY}_{\mathbf{L}} = \frac{1}{\mathcal{R}^{XY}_{\mathbf{L}}} \int d^2\boldsymbol{\ell} W^{XY}_{\boldsymbol{\ell},\boldsymbol{\ell}-\mathbf{L}} \bar{X}_{\boldsymbol{\ell}} \bar{Y}^*_{\boldsymbol{\ell}-\mathbf{L}}$$

SPTpol TT



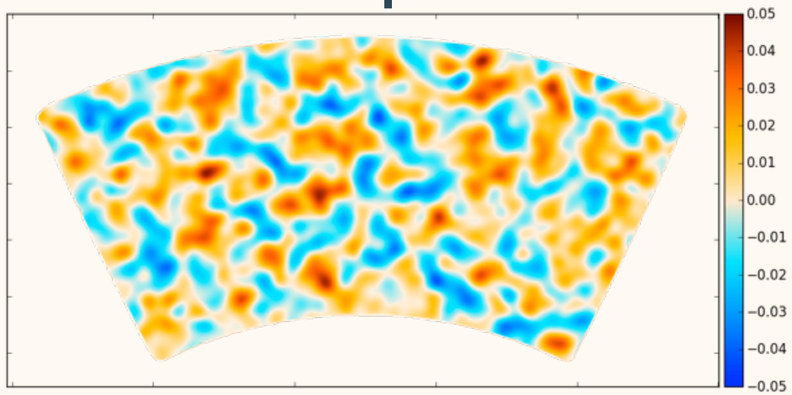
σ A_{Lens} = +- 0.08

SPTpol EB



σ A_{Lens} = +- 0.13

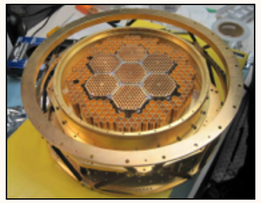
SPTpol MV



σ A_{Lens} = +- 0.06 (Stat)

Work lead by Monica Mocanu

SPT SZ AND POL IN BRIEF



- 768 pixels with two transition-edge sensor (TES) bolometers, orthogonal polarizations, and a total of 1536 bolometers.

2013 SPTpol camera installed and survey begins

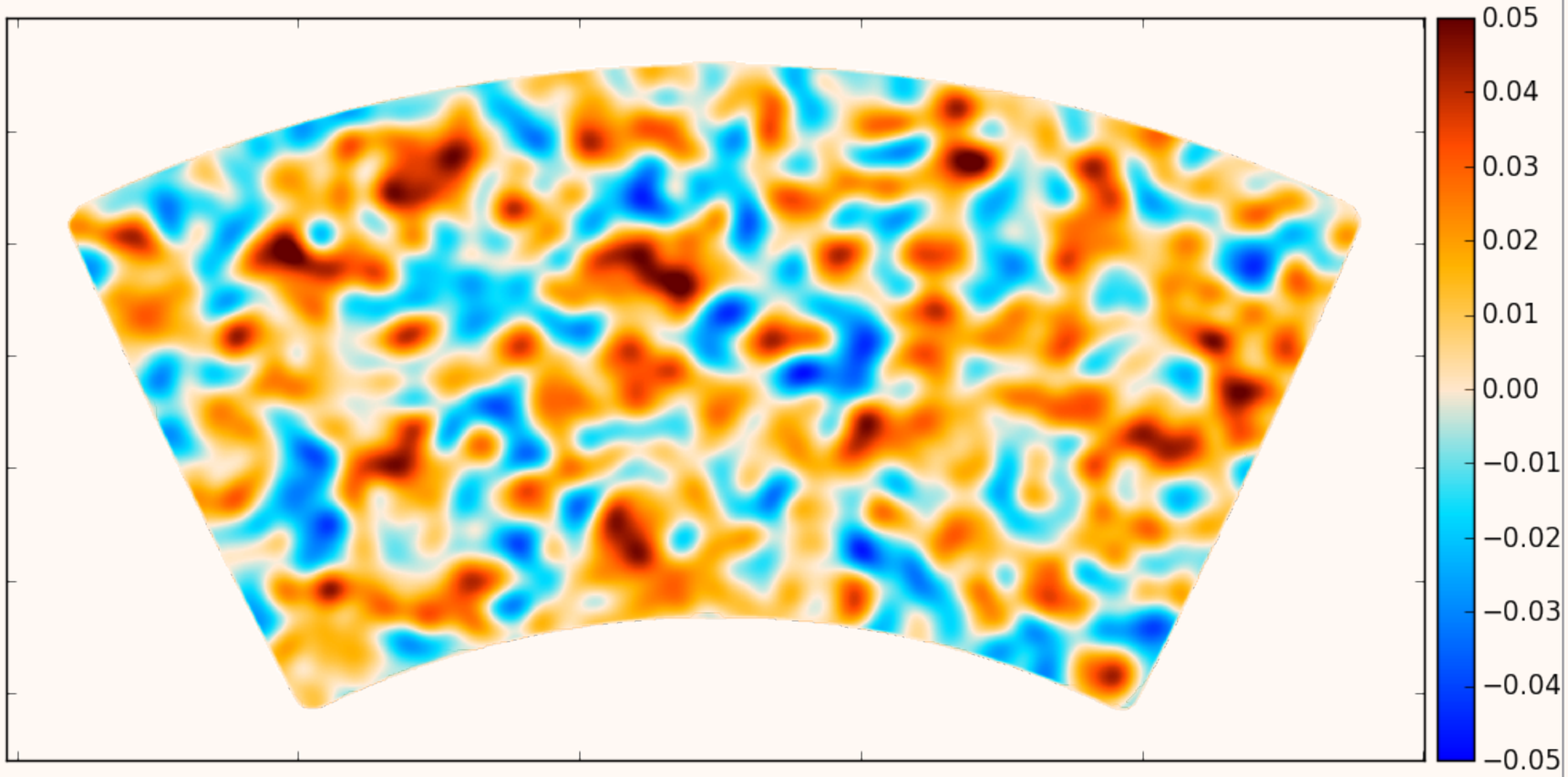
First Detection of CMB B-mode Polarization (Hanson et al.)

2014 Most sensitive measurement of gravitational lensing of CMB yet made (Story et al.)

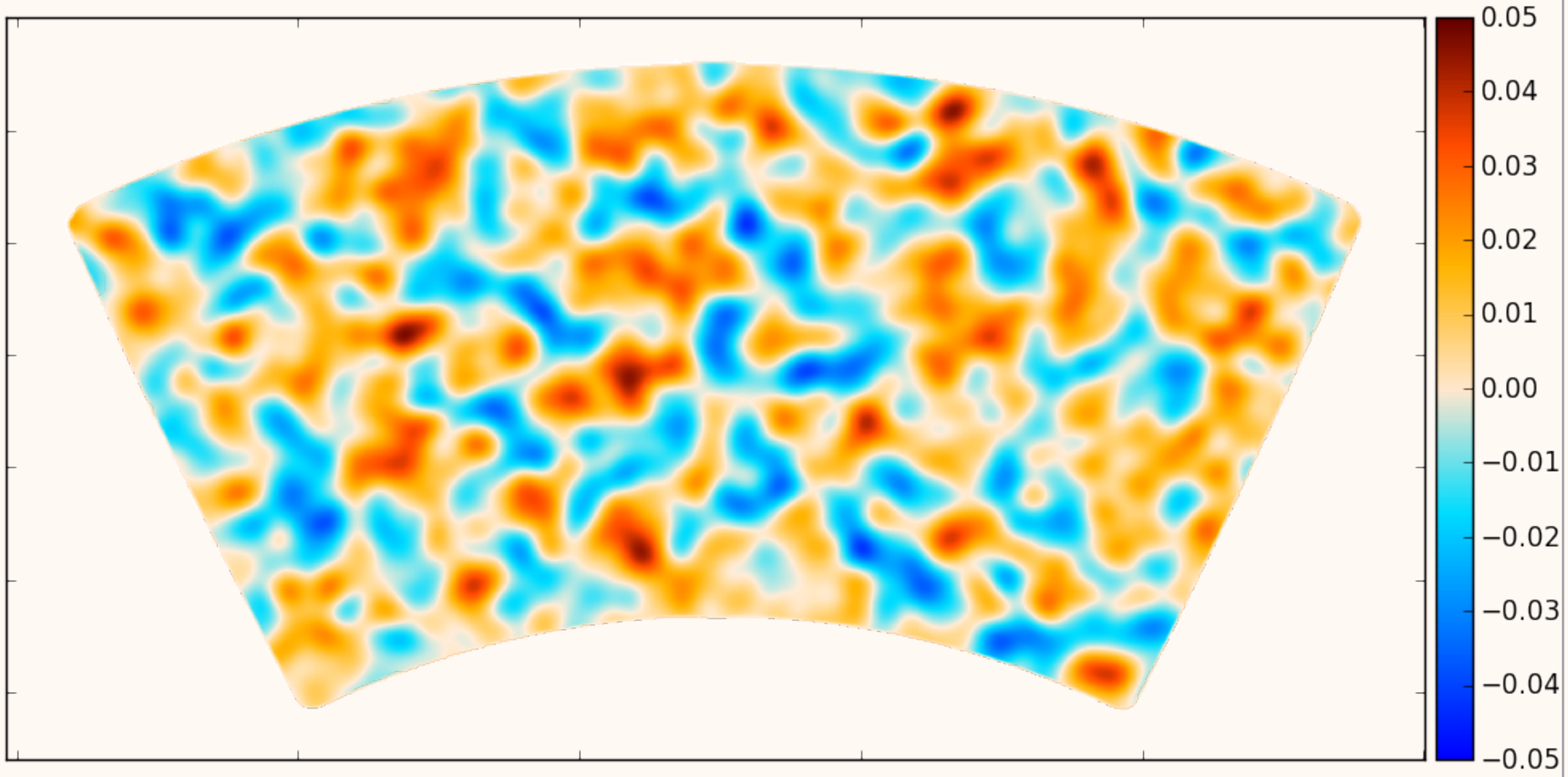
2016 First astronomical constraints on mm-wavelength transients (Whitehorn et al.)

2016-17 Installation of the SPT-3G camera

SPTpol TT



SPTpol MV



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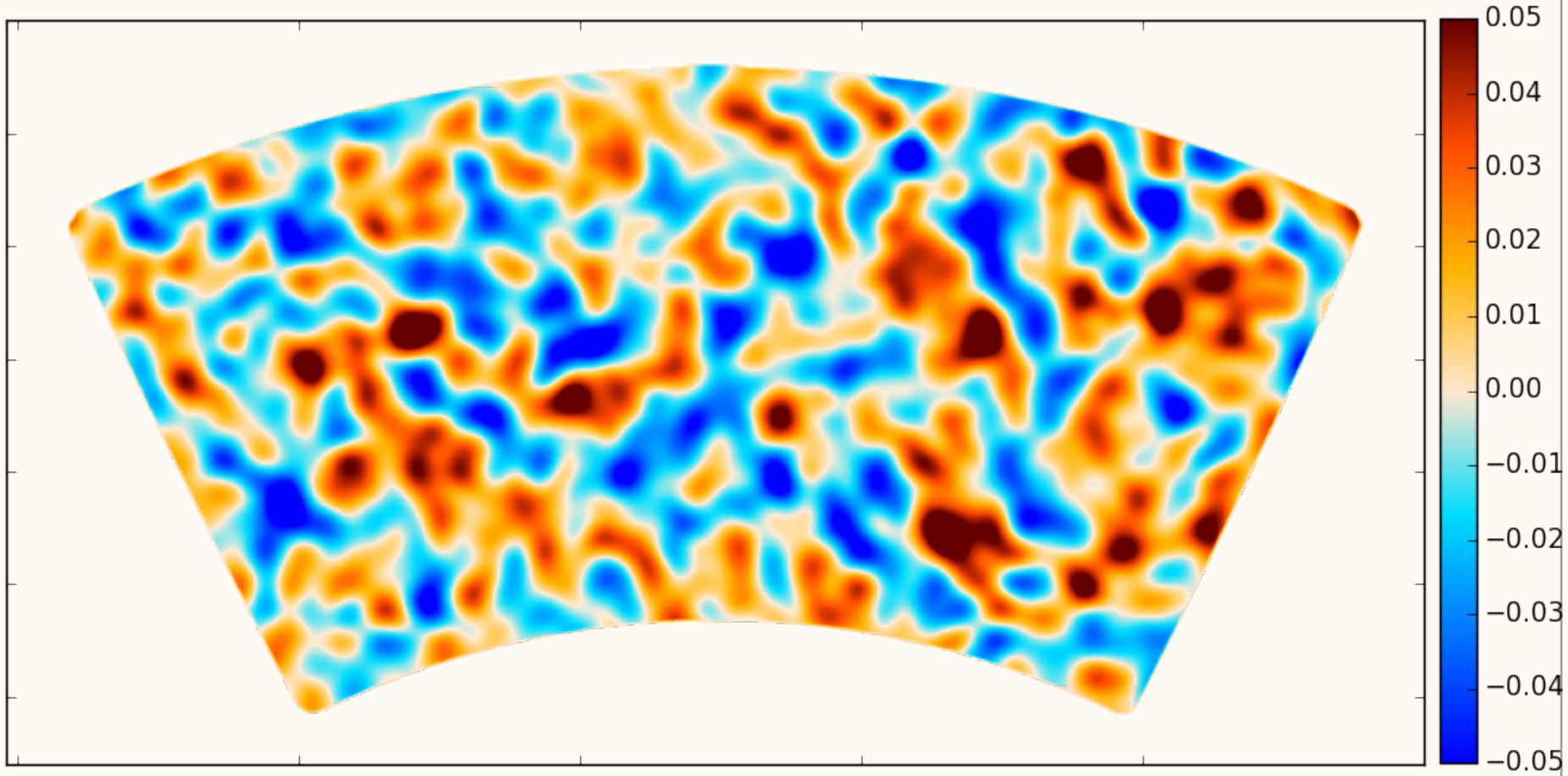
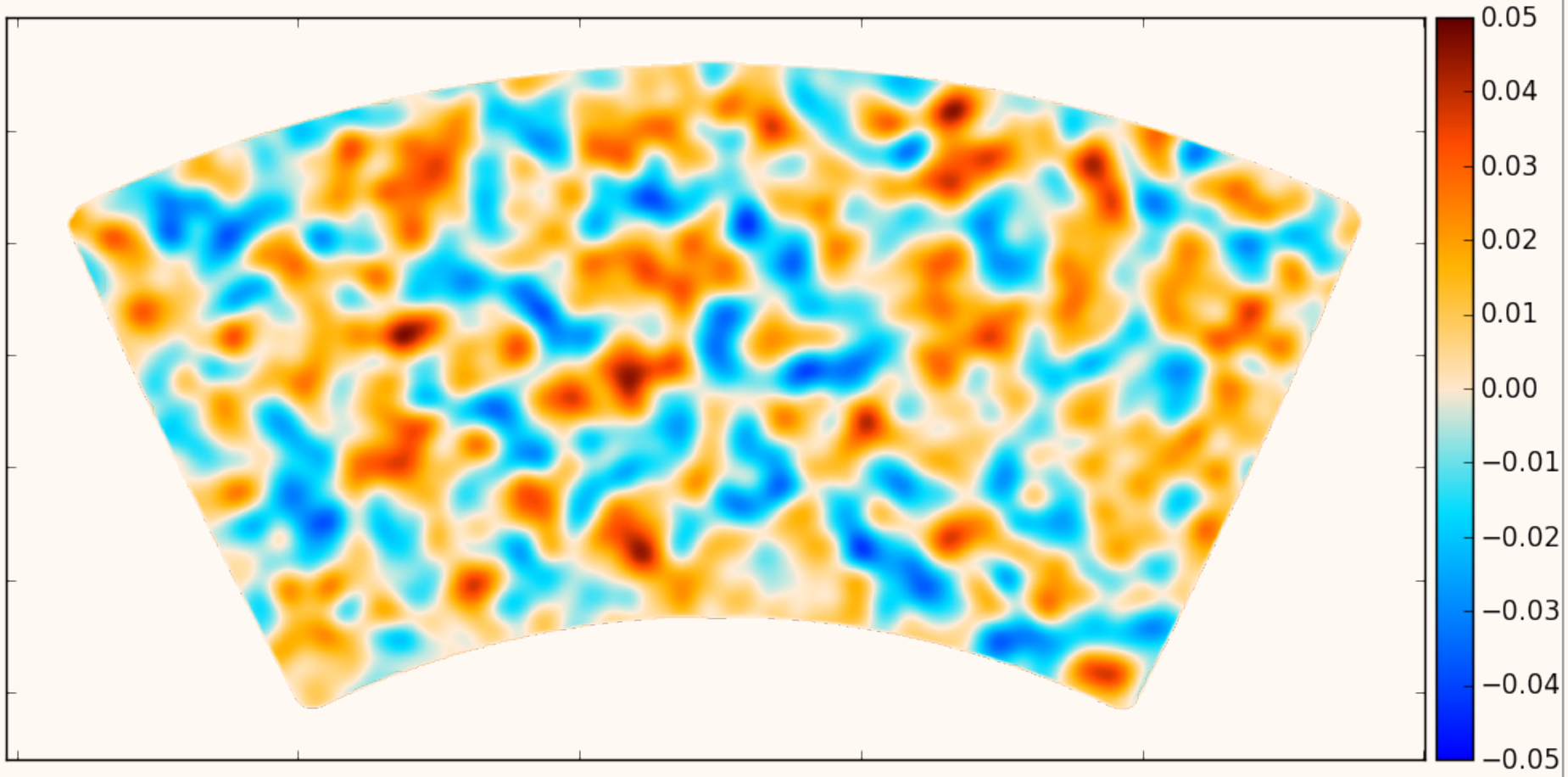
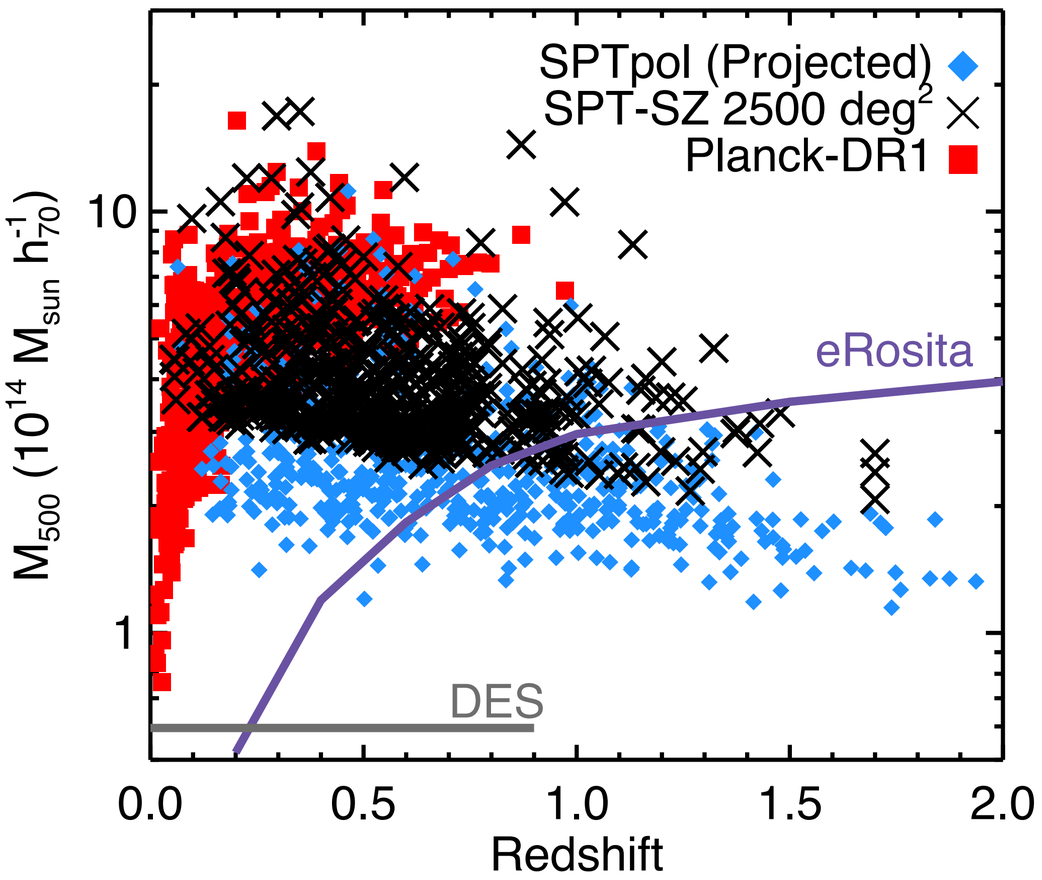


SPTpol MV



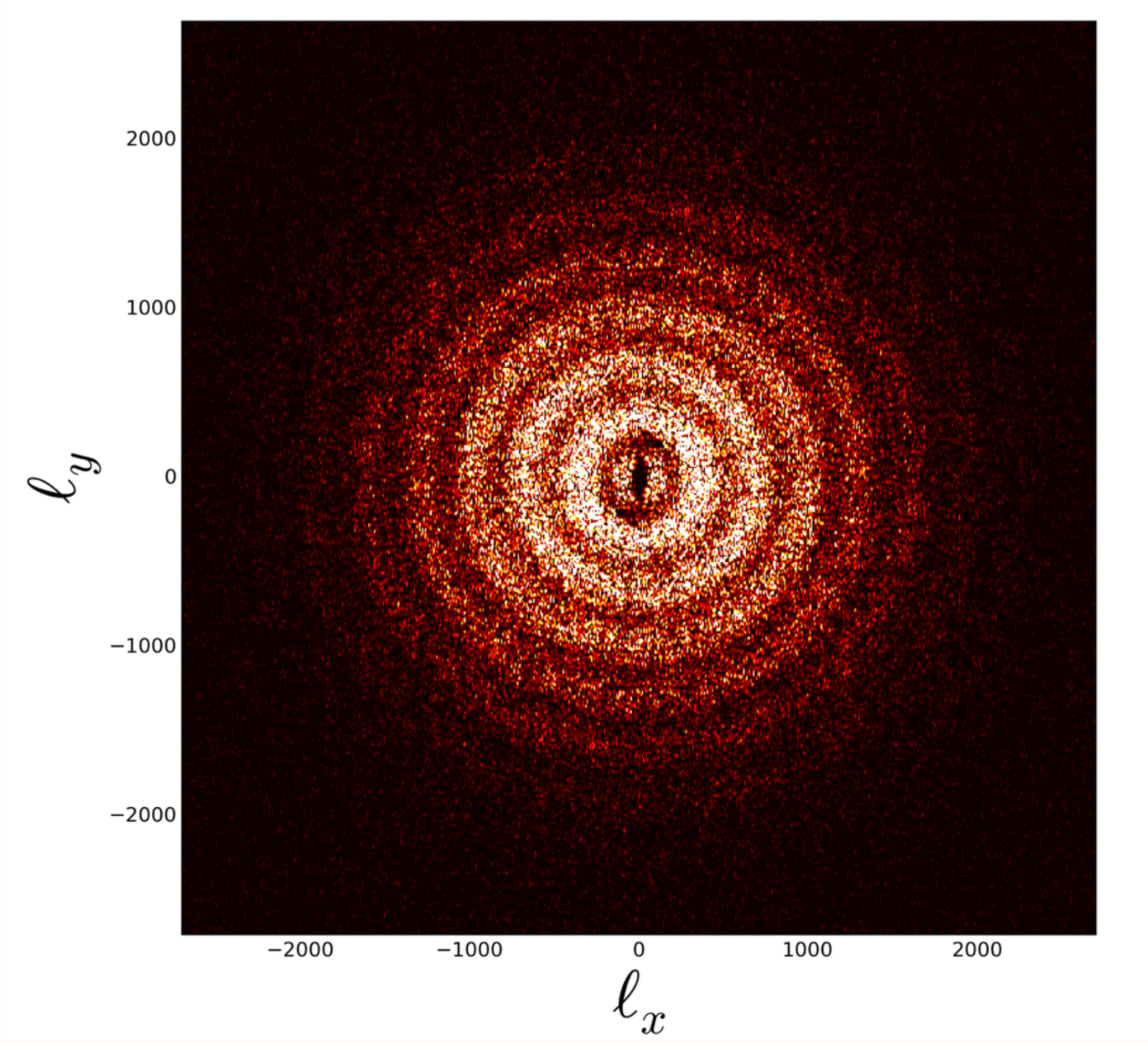
500d Catalog Construction well underway!

- Incorporating all SPTpol 500d data; Final 150 GHz map depth ~5 uK-arcmin
- Ongoing DES-SPT projection for cluster confirmation
- 2 Spitzer programs complete
- NIR imaging on Magellan/ FOURSTAR obtained Oct 17



CMB POLARIZATION E-MODE MEASUREMENT

First 7 acoustic peaks visible BEFORE azimuthal averaging!!



Cosmological Constraints

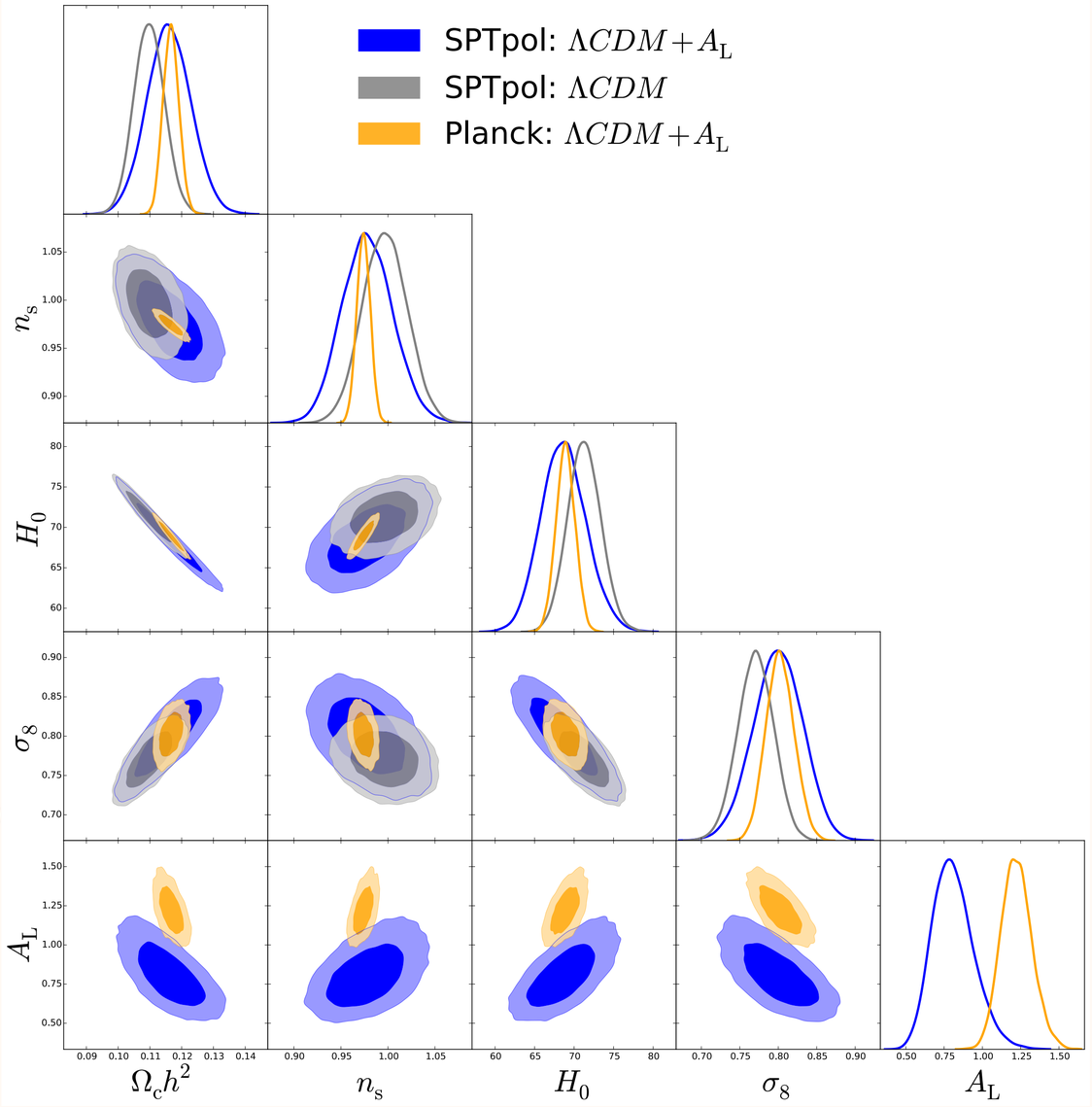
JWH, Sayre, Reichardt, et al., 2017

- Marginalizing over A_L brings SPTpol and *Planck* constraints into agreement.

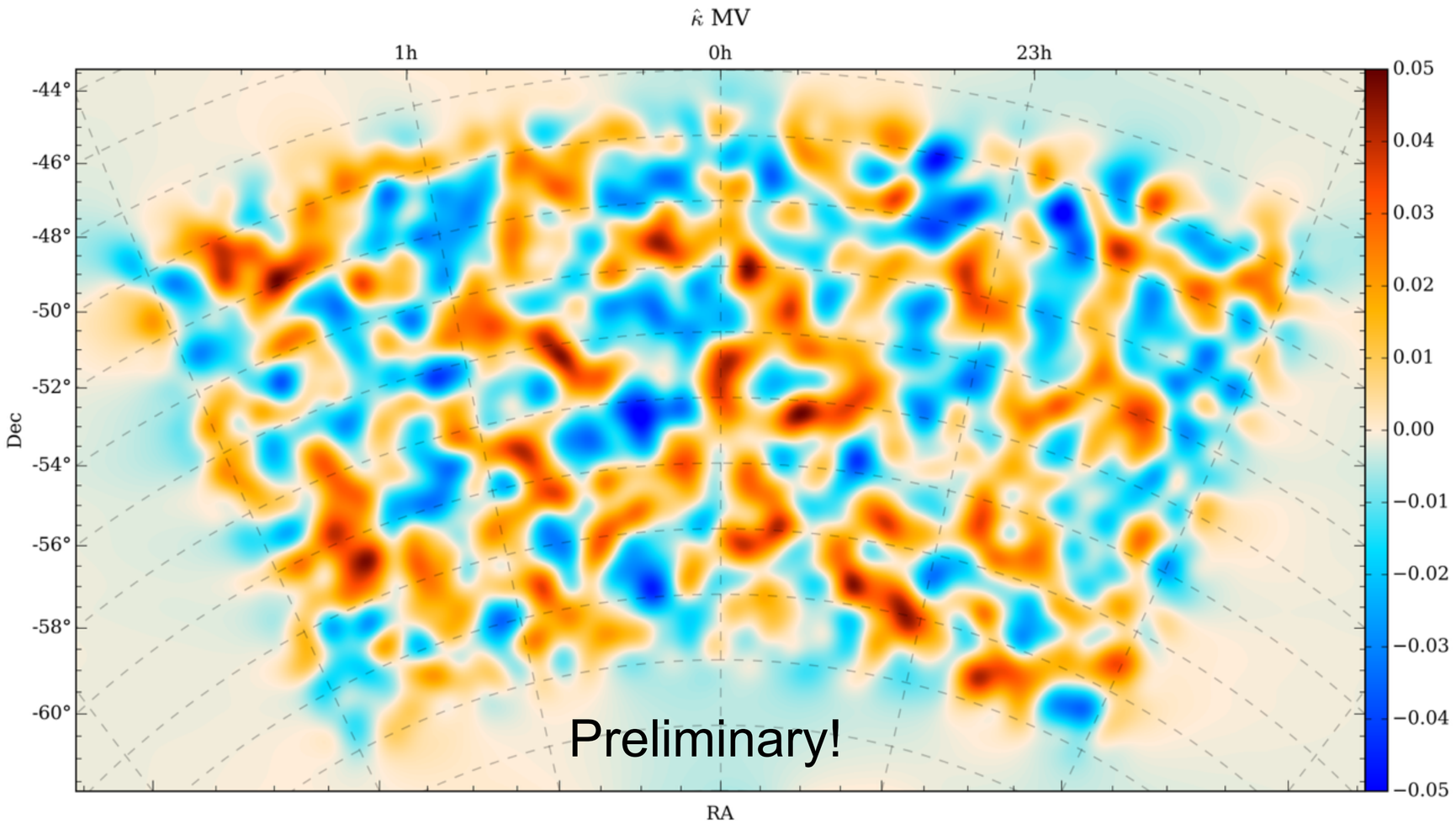
- SPTpol finds A_L 2.9 σ lower than value preferred by *Planck*TT:

$$A_L = 0.81 \pm 0.14$$ (SPTpol)

$$A_L = 1.22 \pm 0.10$$ (*Planck*TT)



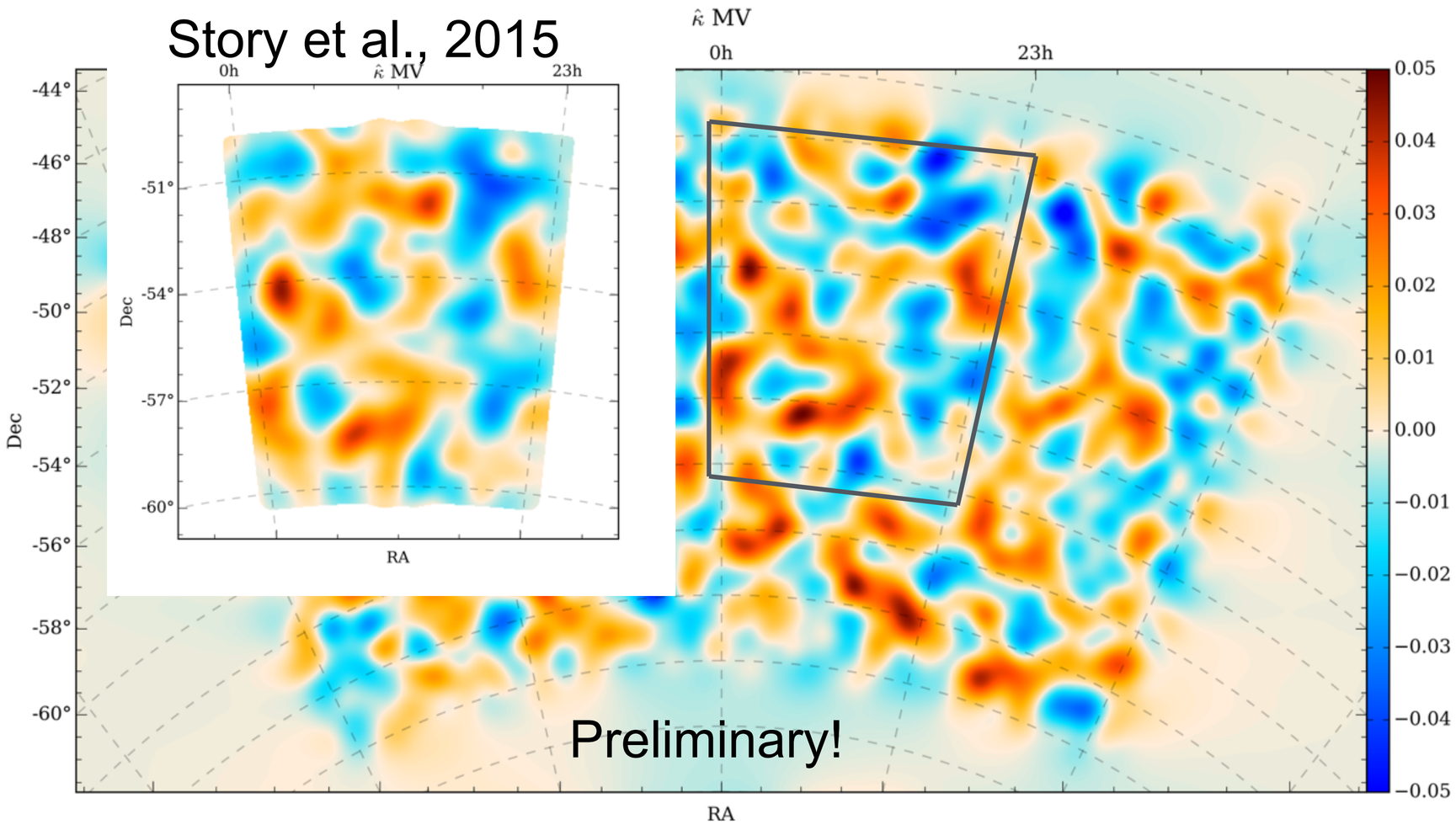
CMB Lensing Potential



- Lensing convergence map with L ~< 250 modes imaged with S/N > 1.

- **Monica Mocanu (U. Chicago)**

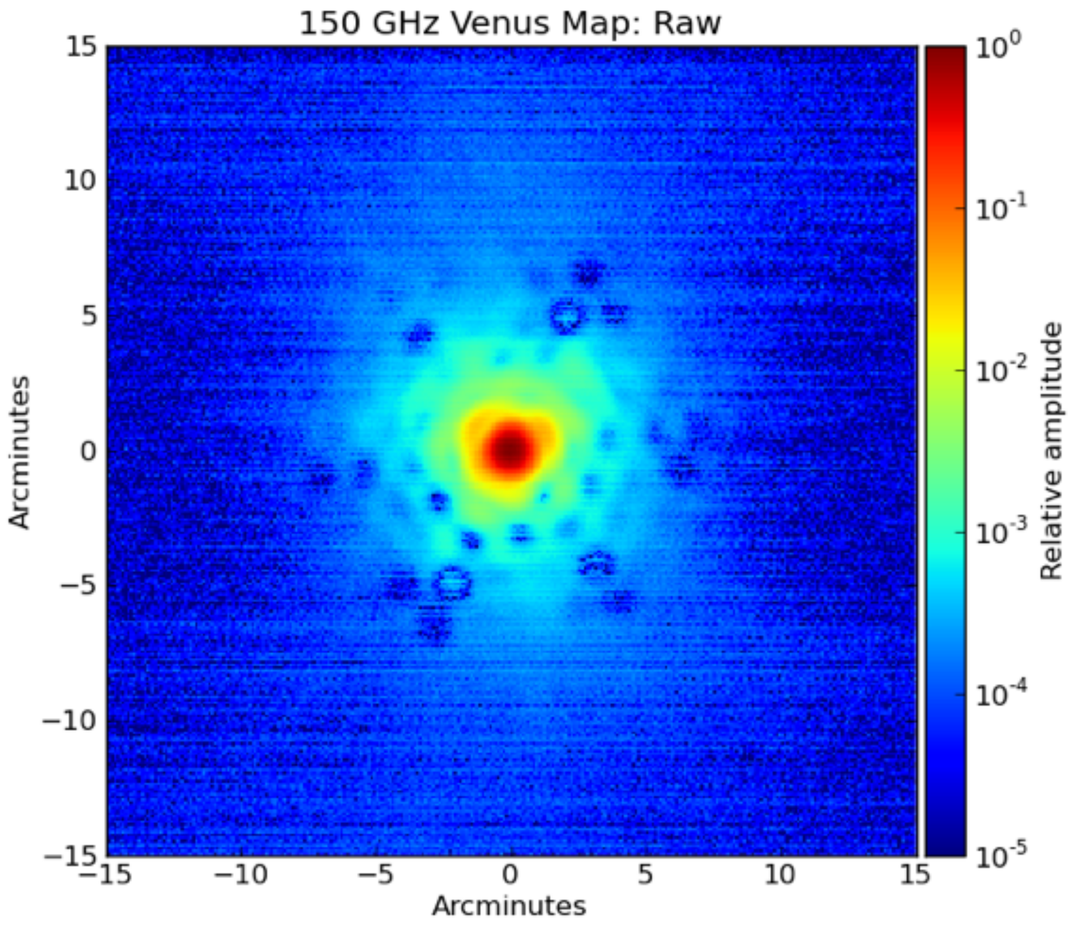
CMB Lensing Potential



- Lensing convergence map with L ~< 250 modes imaged with S/N > 1.

- **Monica Mocanu (U. Chicago)**

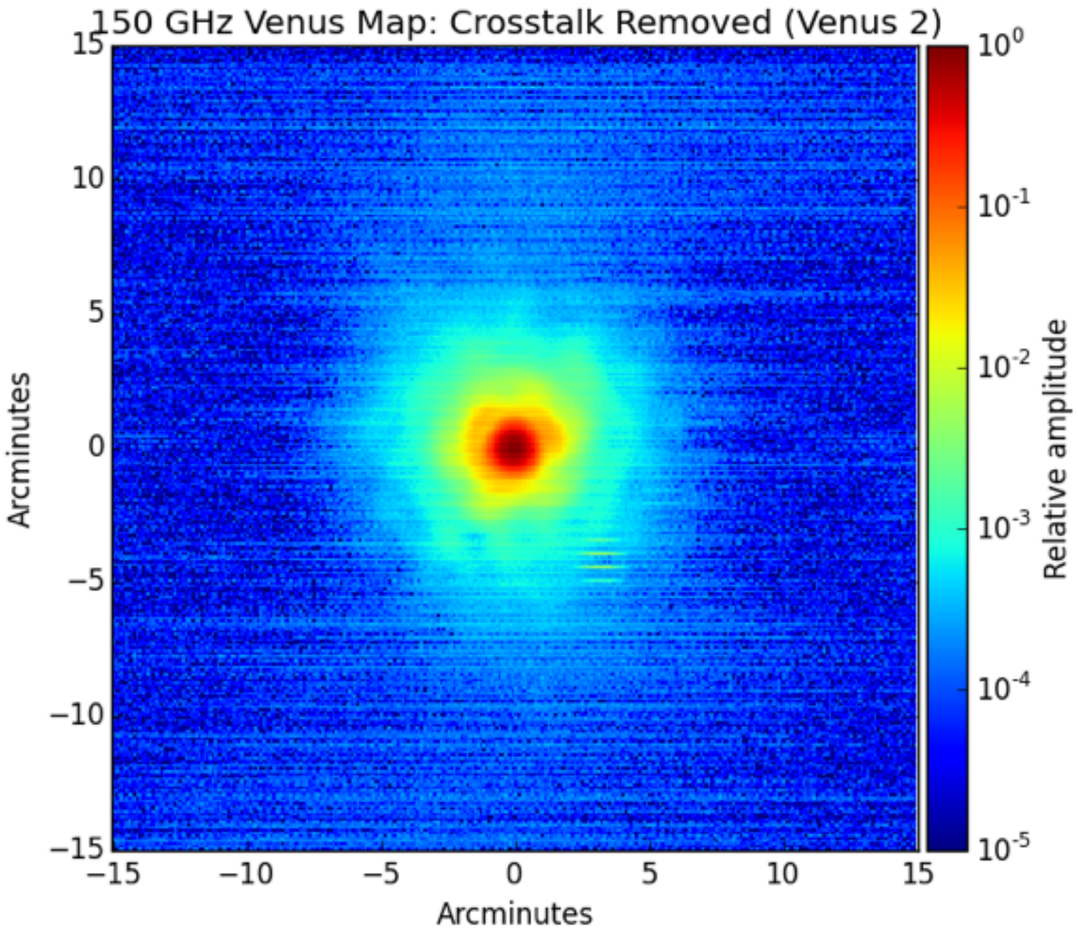
Corrections for Bias: Crosstalk



Detectors exhibit negative crosstalk.

~ Few percent multiplicative bias in the power spectrum (Crites, et al., 2015).

Corrections for Bias: Crosstalk

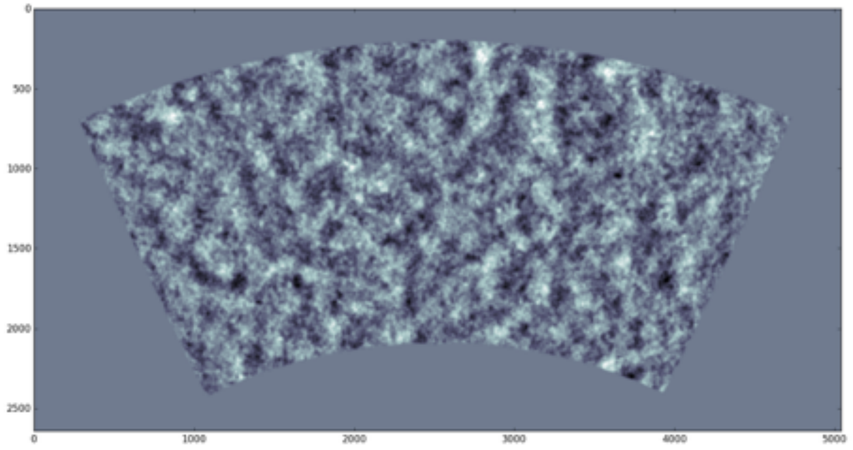


- Now corrected at timestream-level before binning into maps.

- Measure correlations **X** between detector timestreams, d.

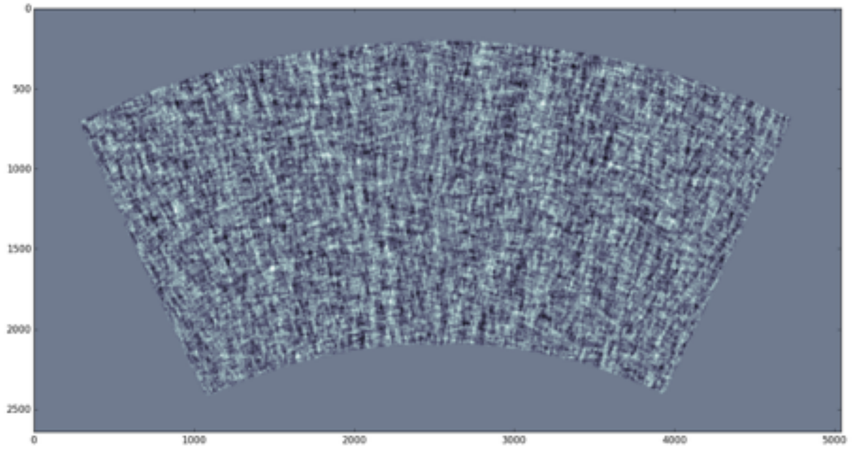
$$\hat{\vec{d}} = \mathbf{X}^{-1}\vec{d}$$

Corrections for Bias: T-> P Leakage

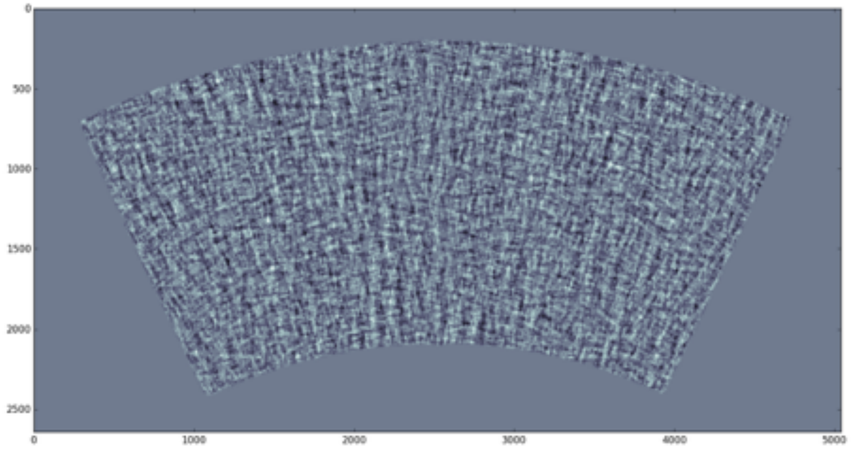


$$\epsilon^P = \frac{\sum w_\ell \frac{C_\ell^{TP}}{C_\ell^{TT}}}{\sum w_\ell}$$

$$\hat{P} = P - \epsilon^P T$$

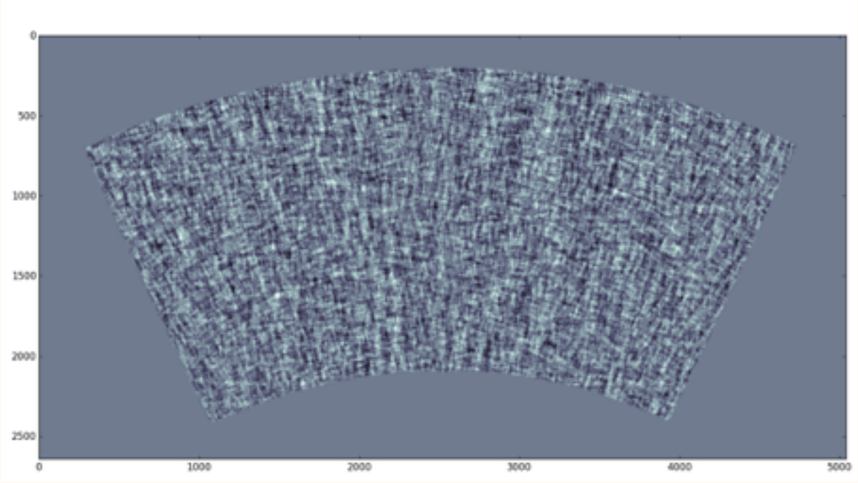


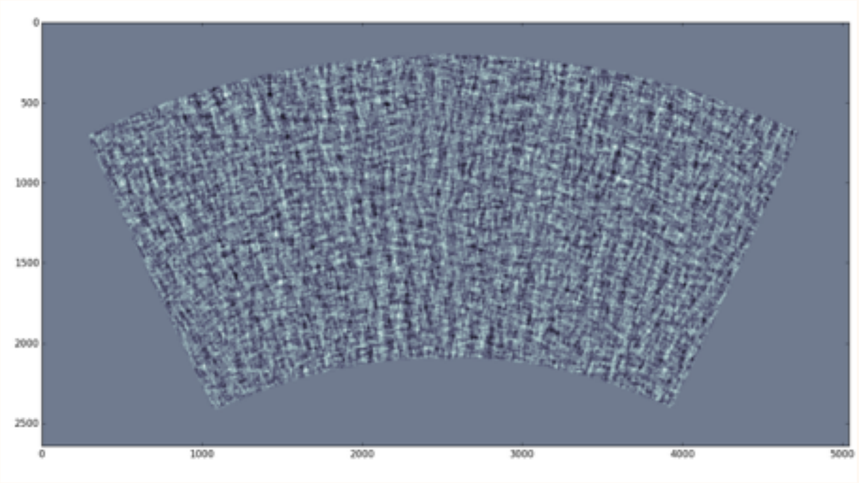
Contaminated Q Map



Cleaned Q Map

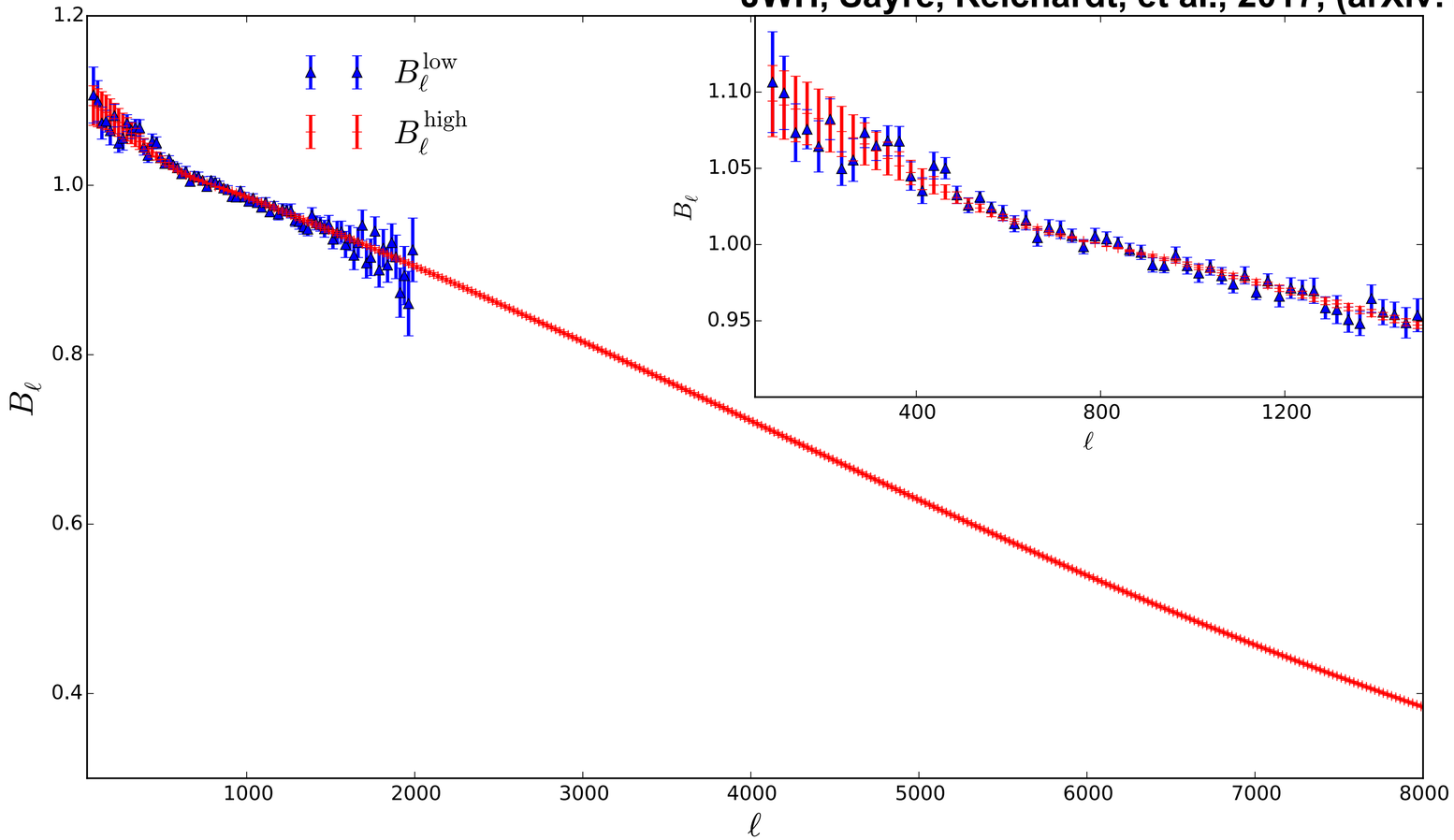
- “Monopole” leakage - constant fraction of T map in Q and U.


0
500
1000
1500
2000
2500
0
1000
2000
3000
4000
5000


0
500
1000
1500
2000
2500
0
1000
2000
3000
4000
5000

Corrections for Bias: Beam

JWH, Sayre, Reichardt, et al., 2017, (arXiv:1707.09353)



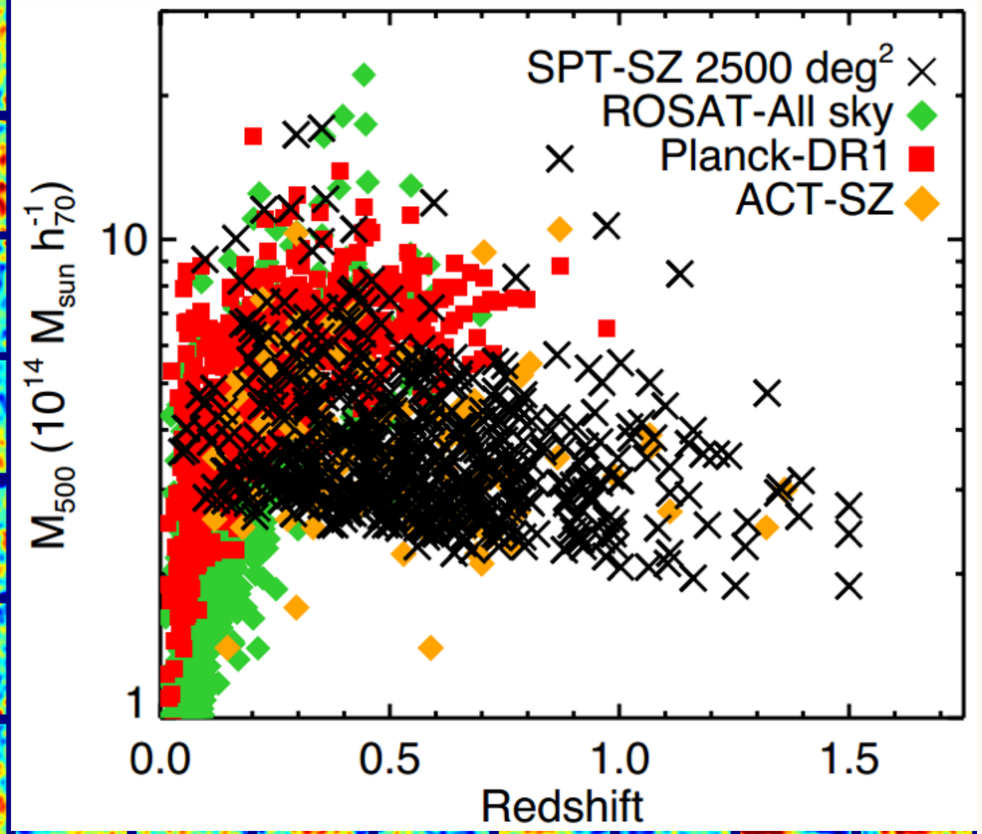
- Excellent agreement between “large-scale” beam from Planck X SPTpol and “small-scale” beam from Venus measurements.

- Beam from Venus and field point sources also in agreement.

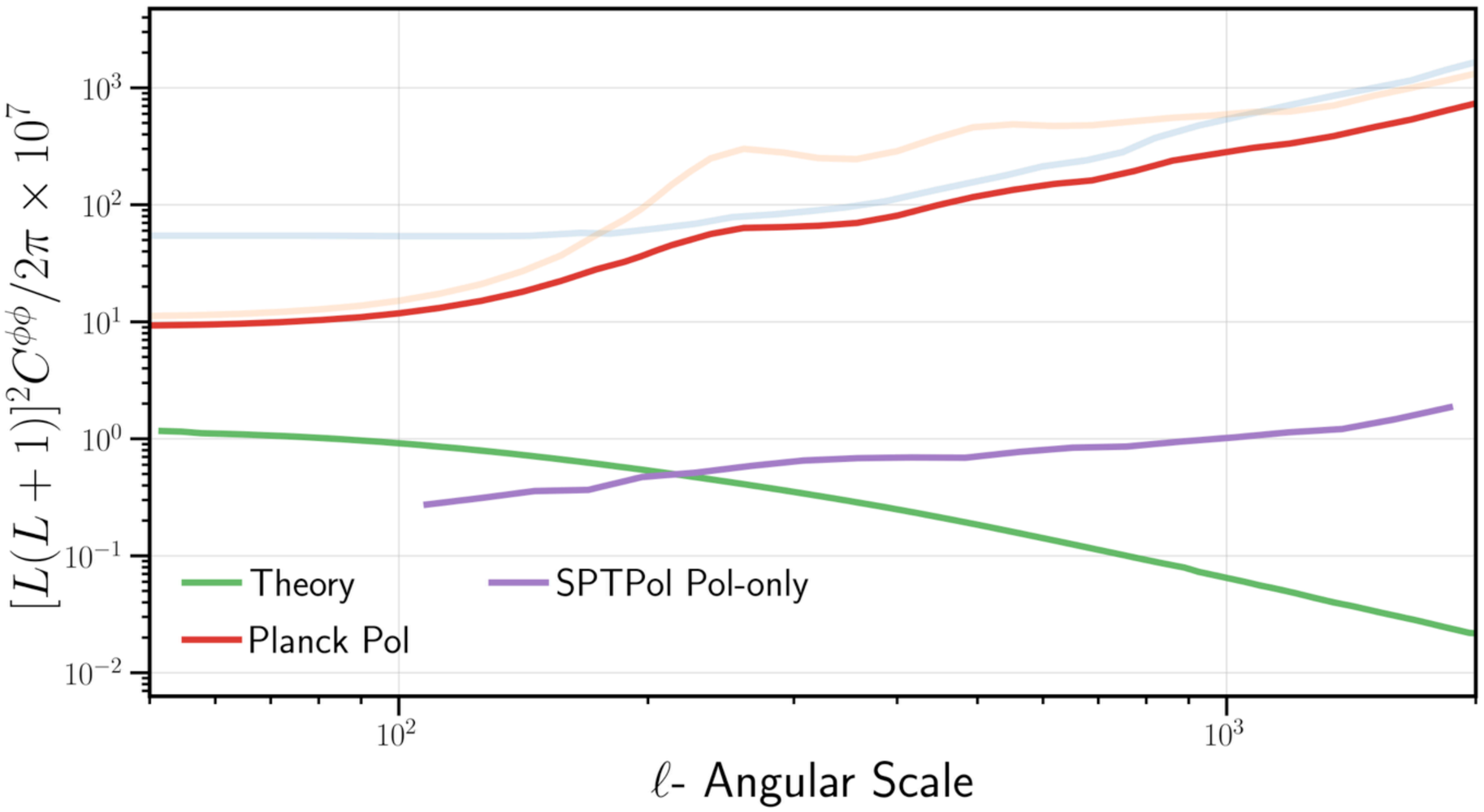
- We use Venus beam for all scales.

Cluster Catalog

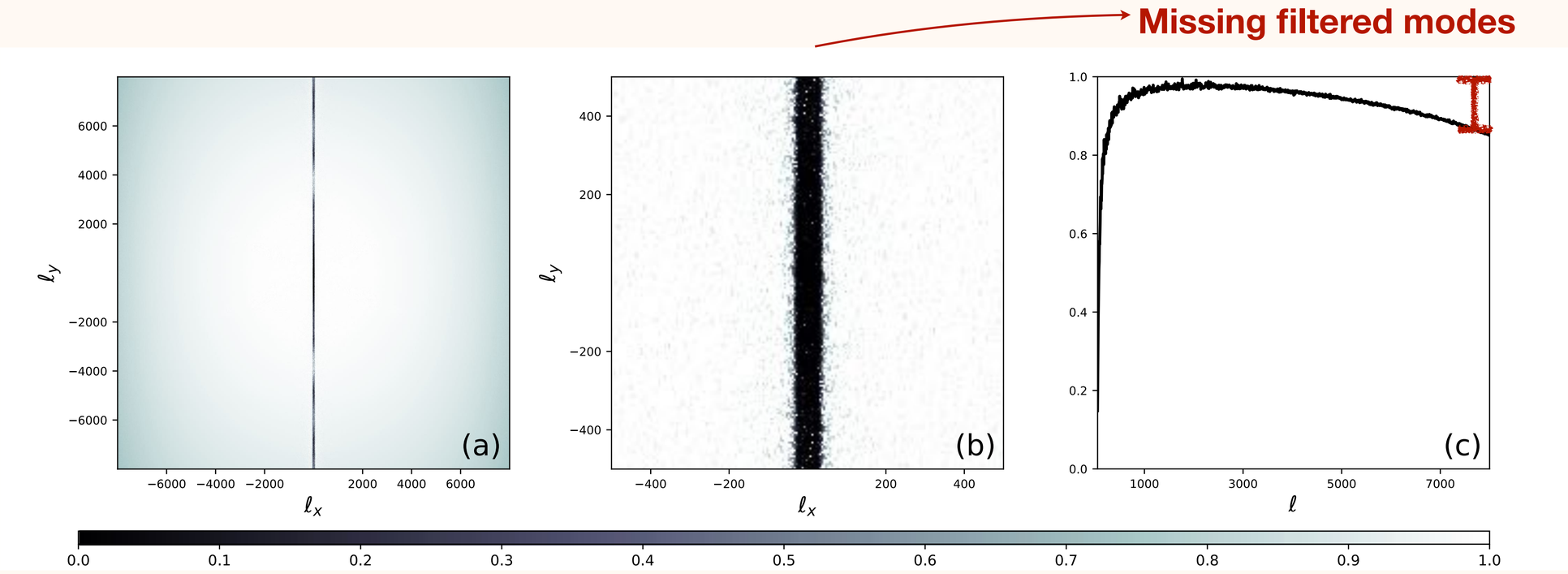
~400 clusters in cosmology sample (detected at >5σ)



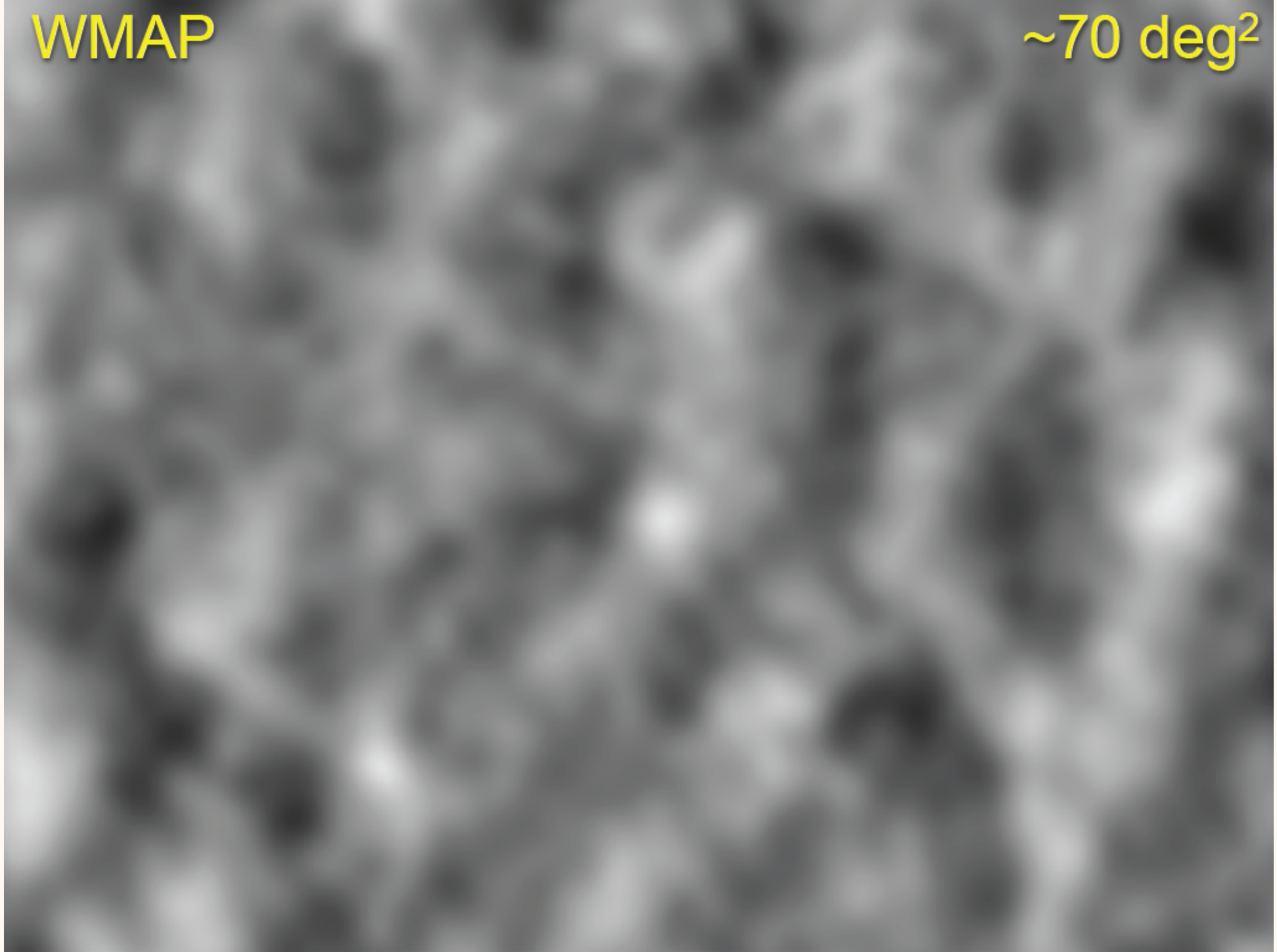
TOTAL NOISE IN POLARIZATION CMB LENSING MAPS

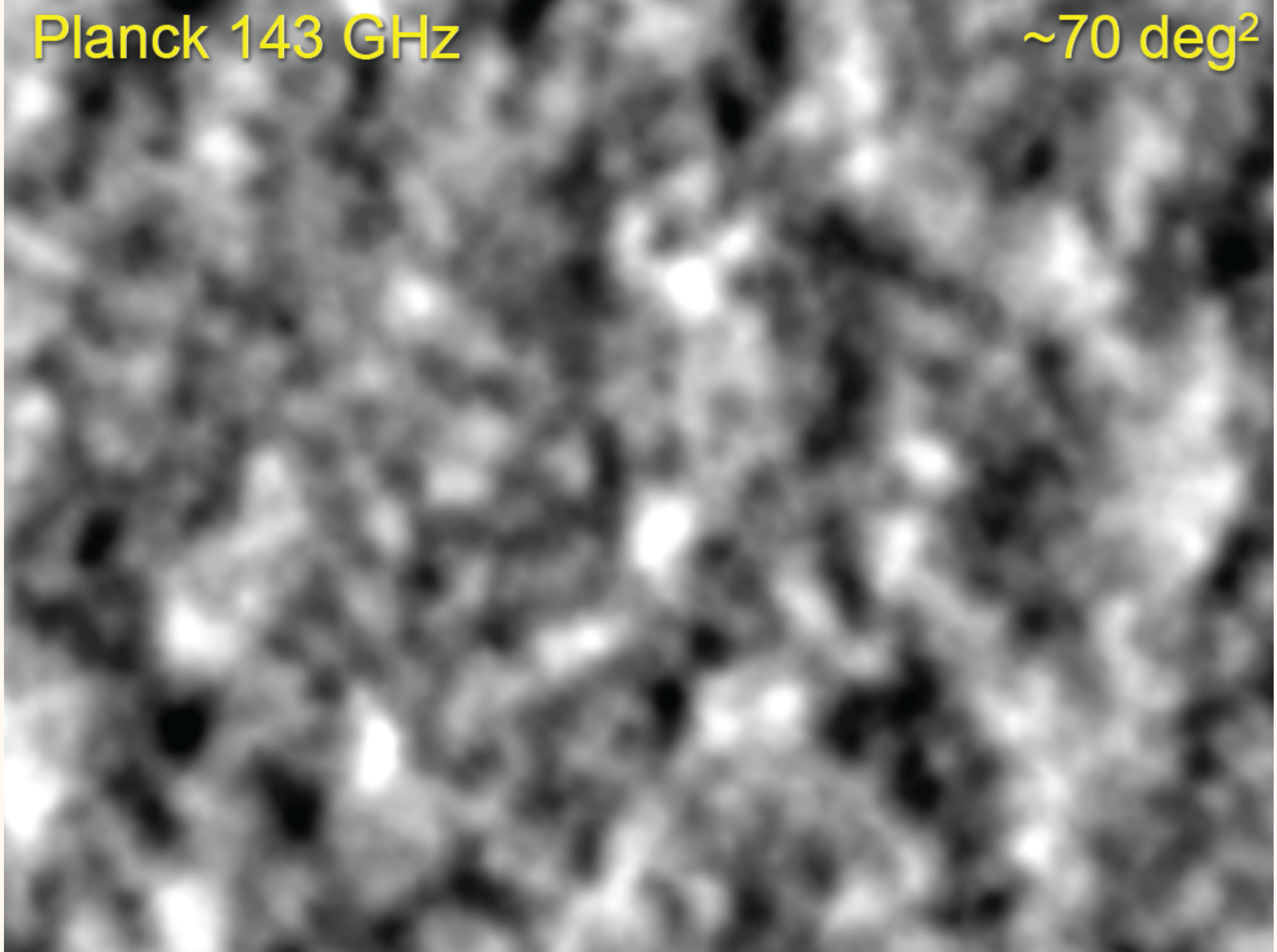


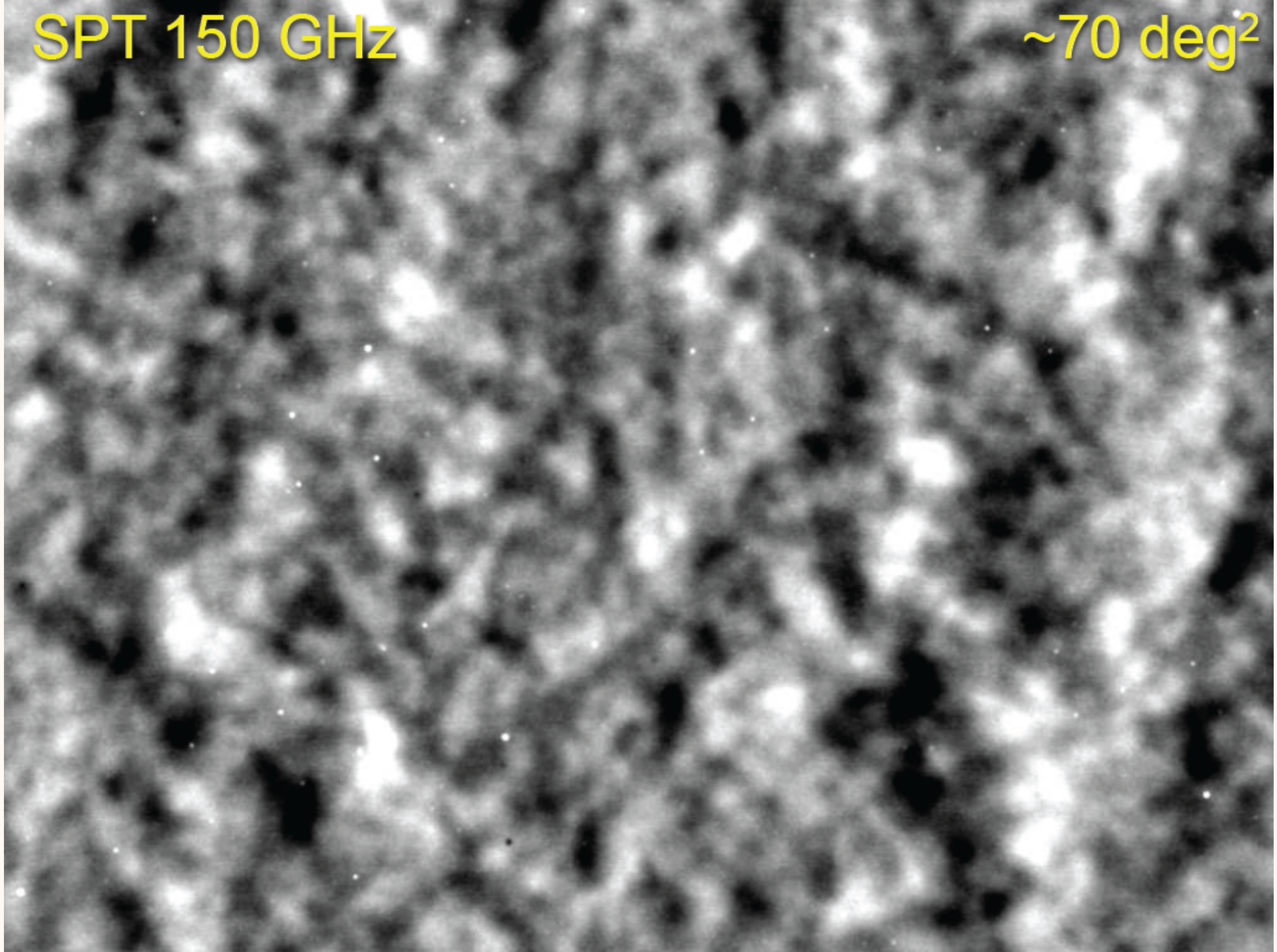
SPT POL 500D FILTERING AND TRANSFER FUNCTIONS

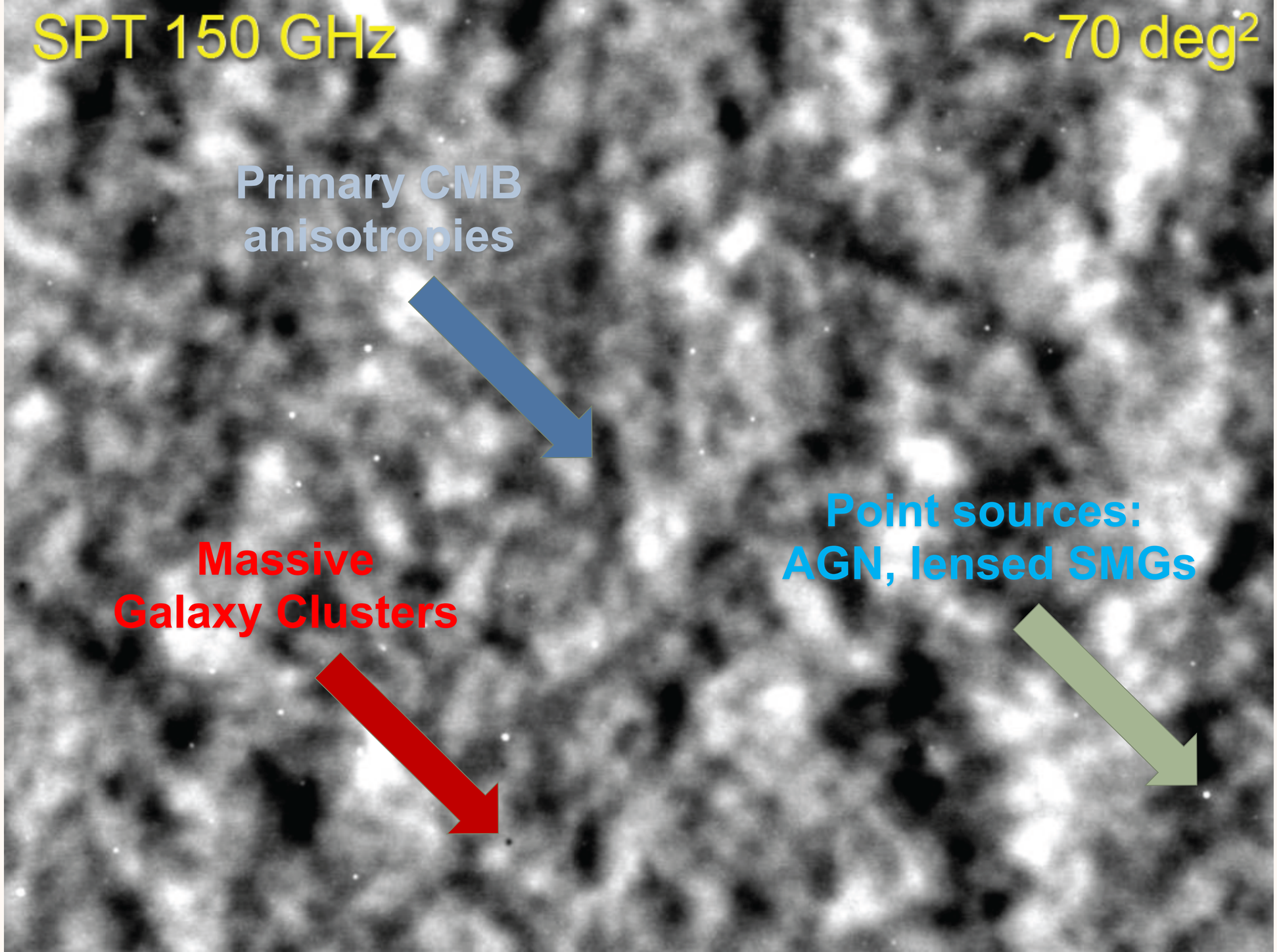


(A=1 at 2.5 nG): 0.76 —> 0.36 (+SPT Pol 100 + BK)—> (0.18-0.25) (+SPTPol 500)


WMAP
~70 deg^2


Planck 143 GHz
~70 deg^2


SPT 150 GHz
~70 deg^2


SPT 150 GHz
~70 deg^2
Primary CMB anisotropies
Point sources: AGN, lensed SMGs
Massive Galaxy Clusters

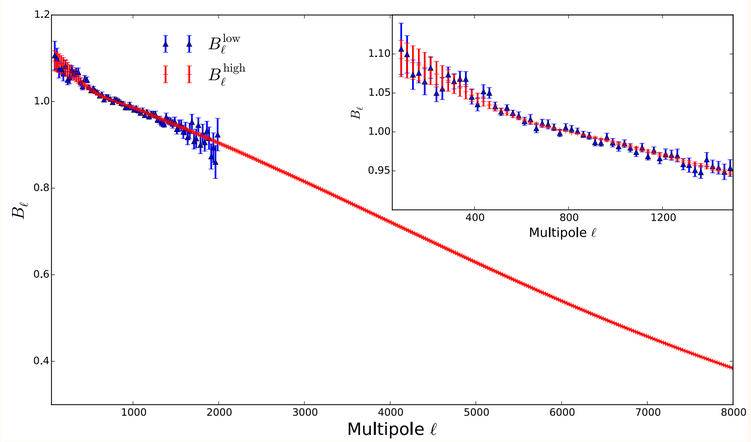
Polarizations results

ALSO CHALLENGES: SMALL SIGNAL NEEDS EXCELLENT CONTROL OF SYSTEMATICS

The SPTpol control polarization systematics:

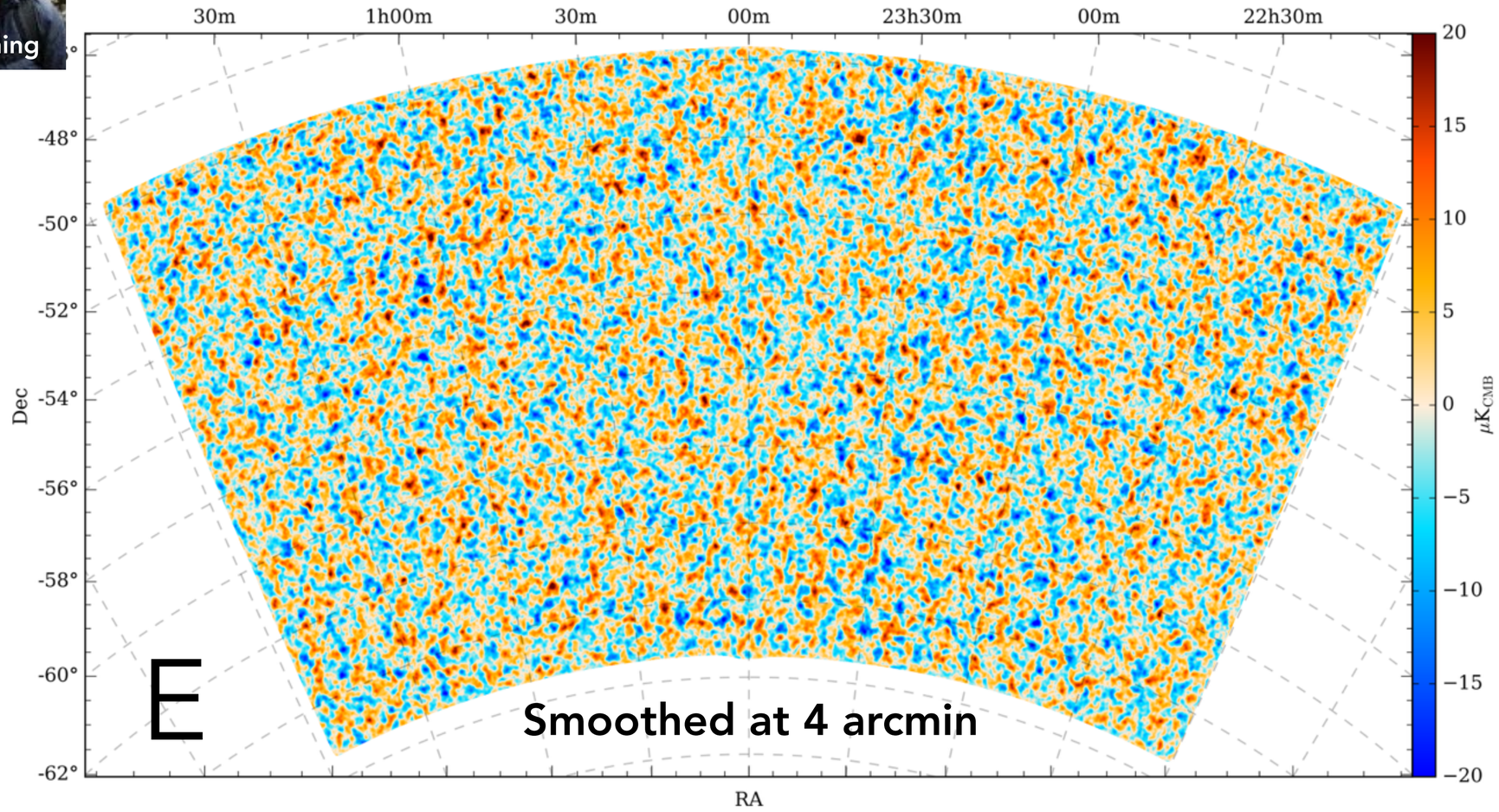
single-moded feedhorns with low cross-polarization
bolometer pairs well-matched to difference atmospheric signals,
improved ground shield design
small beam to reduce temperature to polarization leakage

Accurate beam, polarization efficiency,
polarization angle calibration.



Can we do large scales ell<200 with large telescopes from the ground?

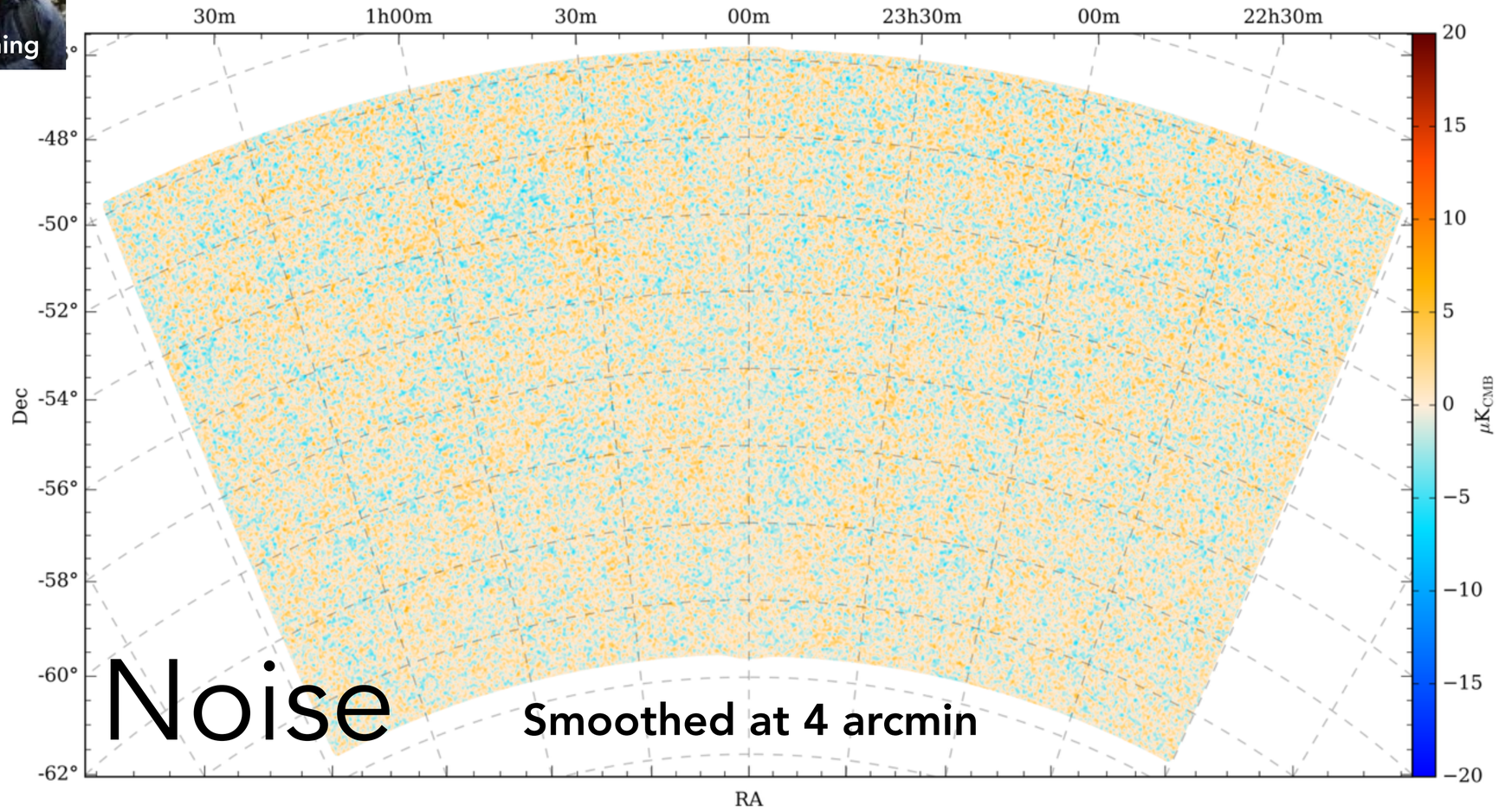
SPT POLARIZATION E-MODE. SMALL AND LARGE (ELL>50) FROM THE GROUND



SPTpol 150 GHz

9.4 μK-arcmin between 2000 < ℓ < 4000.

SPT POLARIZATION E-MODE. VERY HIGH SIGNAL TO NOISE ON 500 DEG^2

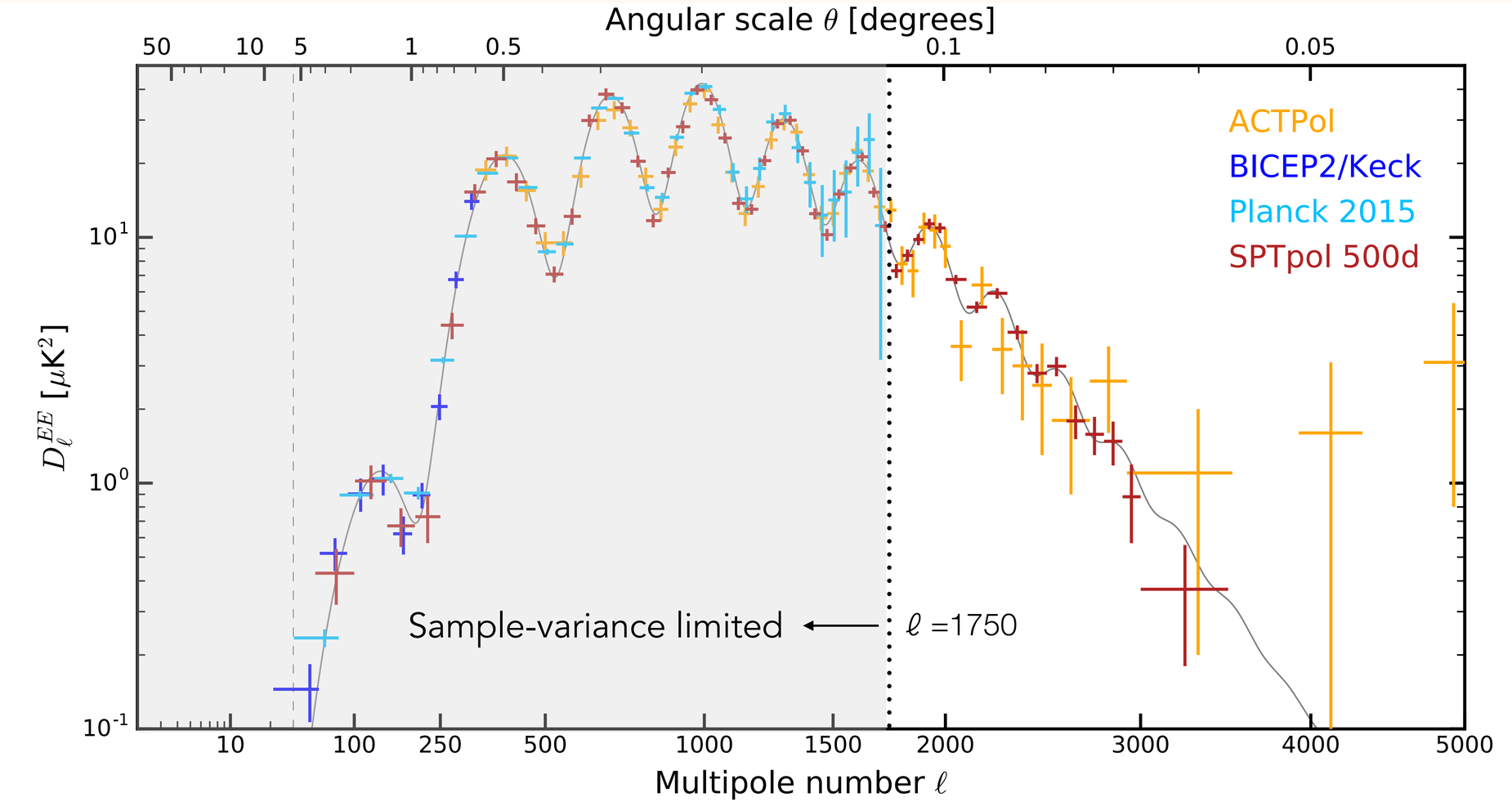


SPTpol 150 GHz

Noise: First-half map minus second-half map.

SPT POL FROM LARGE TO SMALL SCALES!

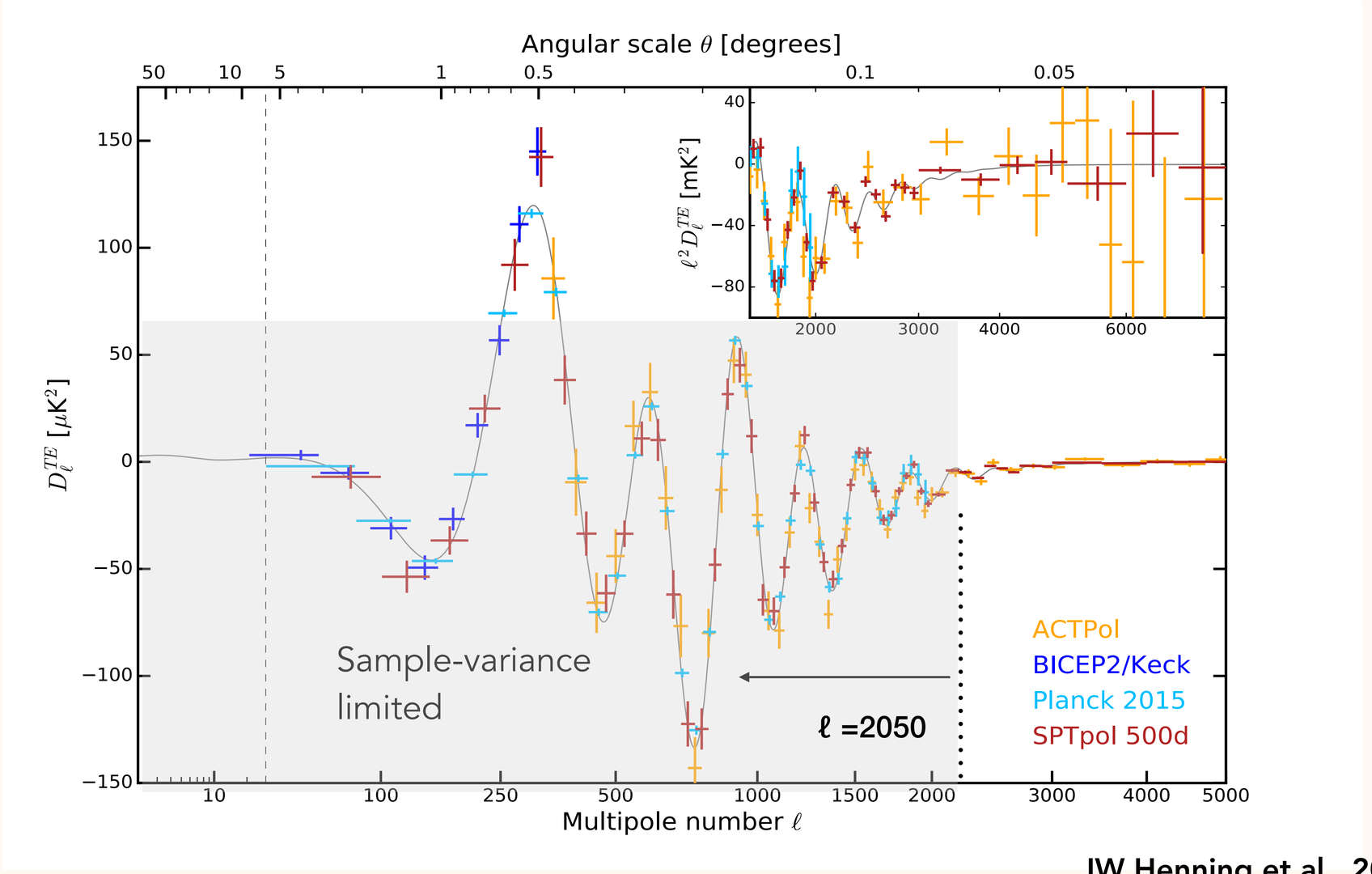
The most sensitive spectra at ℓ >1050



JW Henning et al., 2017

THE MOST SENSITIVE SPECTRA ON SMALL SCALES

The most sensitive spectra at ℓ >1475



JW Henning et al., 2017

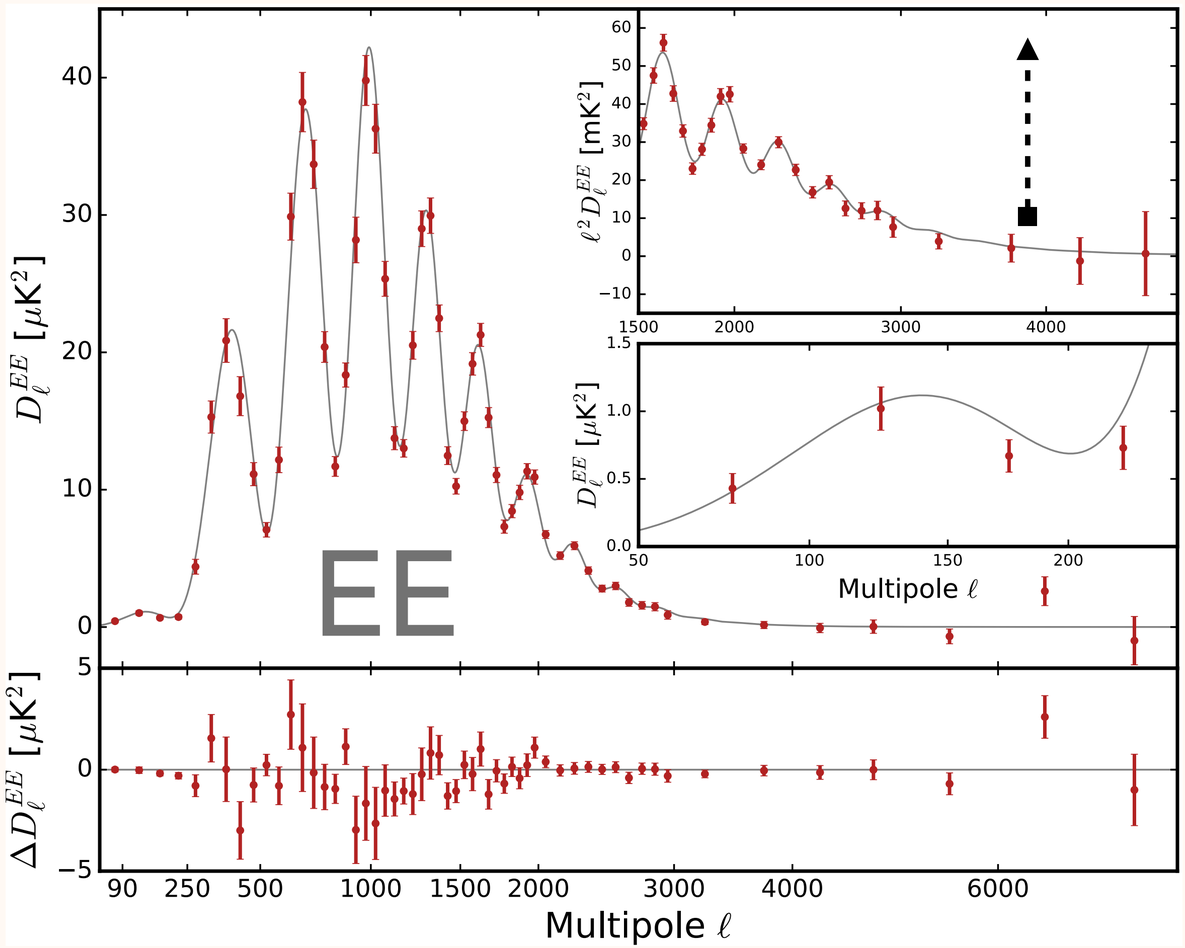
9 PEAKS (50 < ℓ < 3000) AND 4 TIMES TIGHTER UPPER LIMITS ON FOREGROUNDS

Poisson power crosses EE at ℓ ~ 3800.

- D_ℓ^{PS} < 0.1 μK^2 at 95% confidence

  (Contributes < 1 μK-arcmin to rms map noise).

  Source cut at > 50 mJy in T.

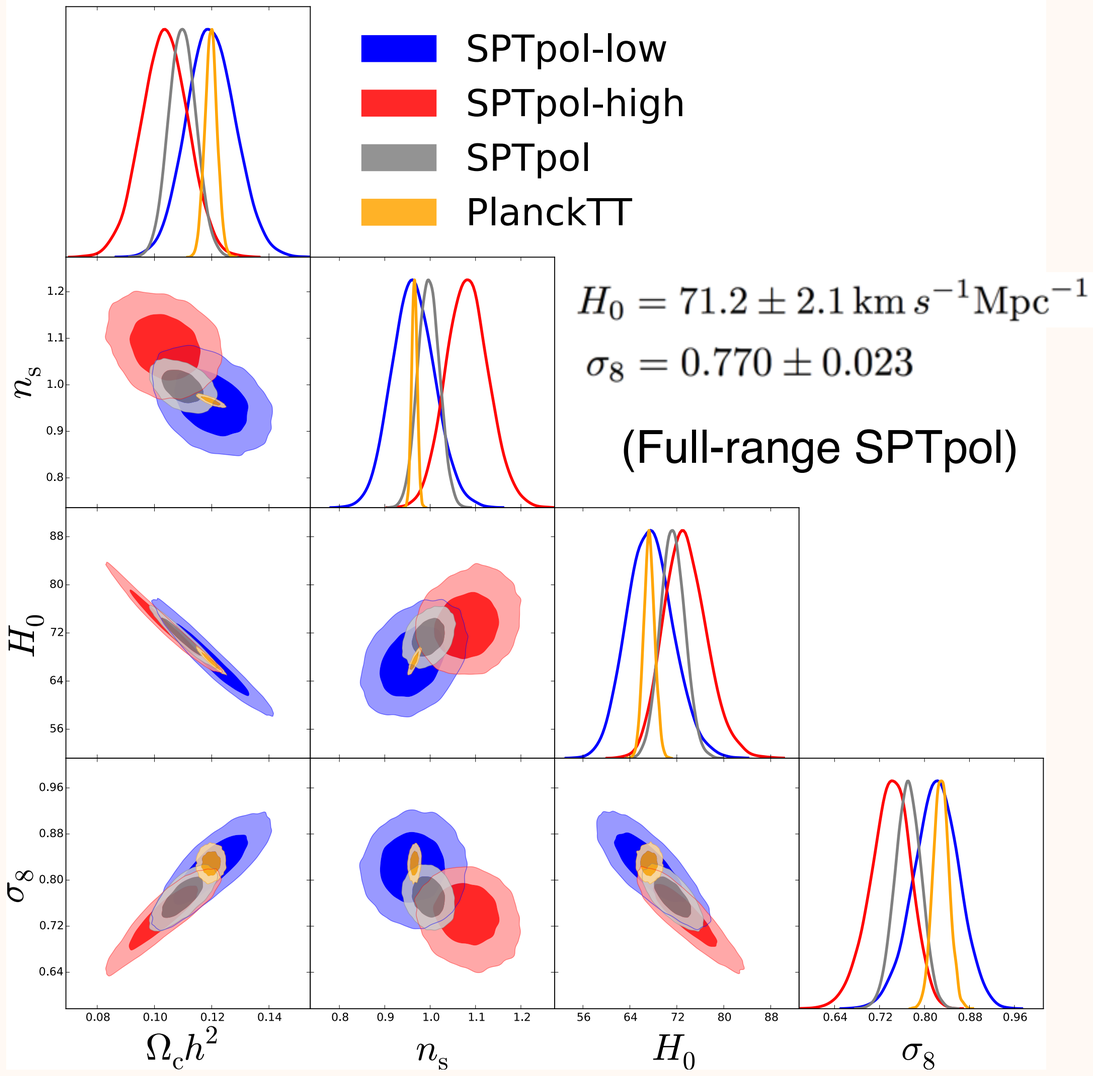


JW Henning et al., 2017

Bandpowers and likelihood available on LAMBDA!

2.7-3.0 REDUCTION OF PARAMETER SPACE VOLUME (COMPARED TO PLANCK). ALL CONSISTENT SO FAR

- "Low-ℓ" SPTpol data (ℓ < 1000) in good agreement with *Planck*TT results.
- Adding "high-ℓ" data (ℓ > 1000) pushes H_0 higher σ_8 lower compared to *Planck*TT:
- Similar to trends seen in SPT-SZ TT data (Aylor et al., 2017, arXiv:1706.10286)
  - Consistent with Planck when matching modes.



J.W. Henning, Sayre, Reichardt, et al., 2017

B-MODES, NOW ON 500 DEG^2 AND IMPROVES ANALYSIS

Improved from the100d: better detector reading cross-talk cleaning and monopole T—>P leakage removal.

Also: we demonstrate we can go to larger scale from the ground (ℓ_{min}=50)!!

5 times the area, $\sqrt{5}$ noise improvement.