Improved CMB Polarization Measurements from SPTpol

Jason Henning, KICP, ANL

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The South Pole Telescope Collaboration

Outline

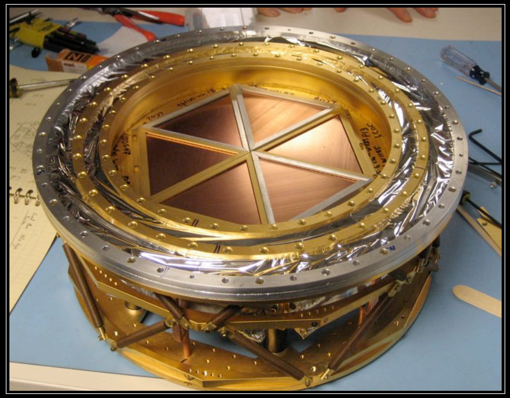
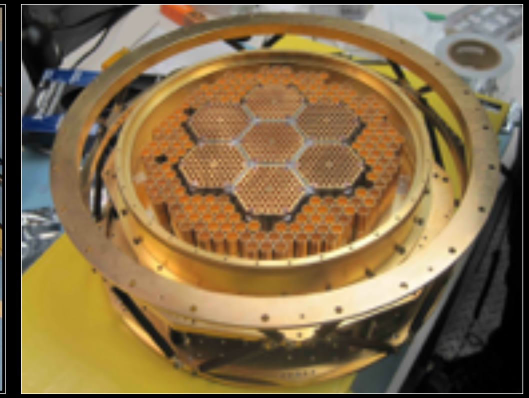
- SPTpol instrument and data
- Unbiasing techniques
- EE/TE results from 500 deg^2

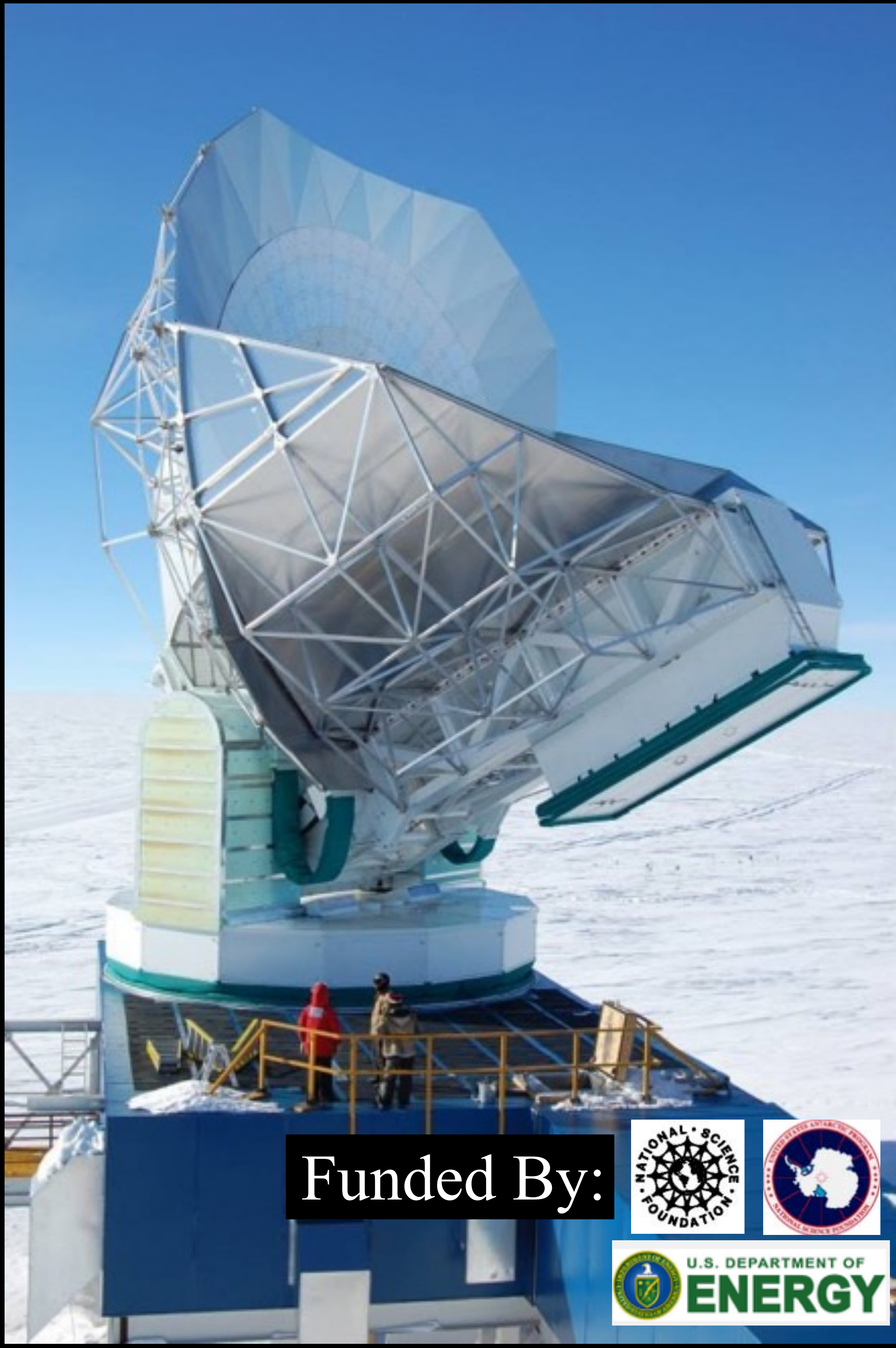
The South Pole Telescope (SPT)

10-meter sub-mm quality wavelength telescope

95, **150**, **220** GHz and
1.6, **1.2**, **1.0** arcmin resolution

2007: SPT-SZ	2012: SPTpol	2017: SPT-3G
960 detectors	1500 detectors	16,200 detectors
95,150,220 GHz	95,150 GHz	95,150,220 GHz
	+Polarization	*+Polarization*



Funded By:

U.S. DEPARTMENT OF ENERGY

SPT(pol) Surveys

SPTpol Summer - 2000 deg^2

~ 30 μK-arcmin map depth (T)

SPTpol Survey - 500 deg^2

~ 7 μK-arcmin map depth (T)

- Henning, 2017 (EE, TE)

SPTpol Deep - 100 deg^2

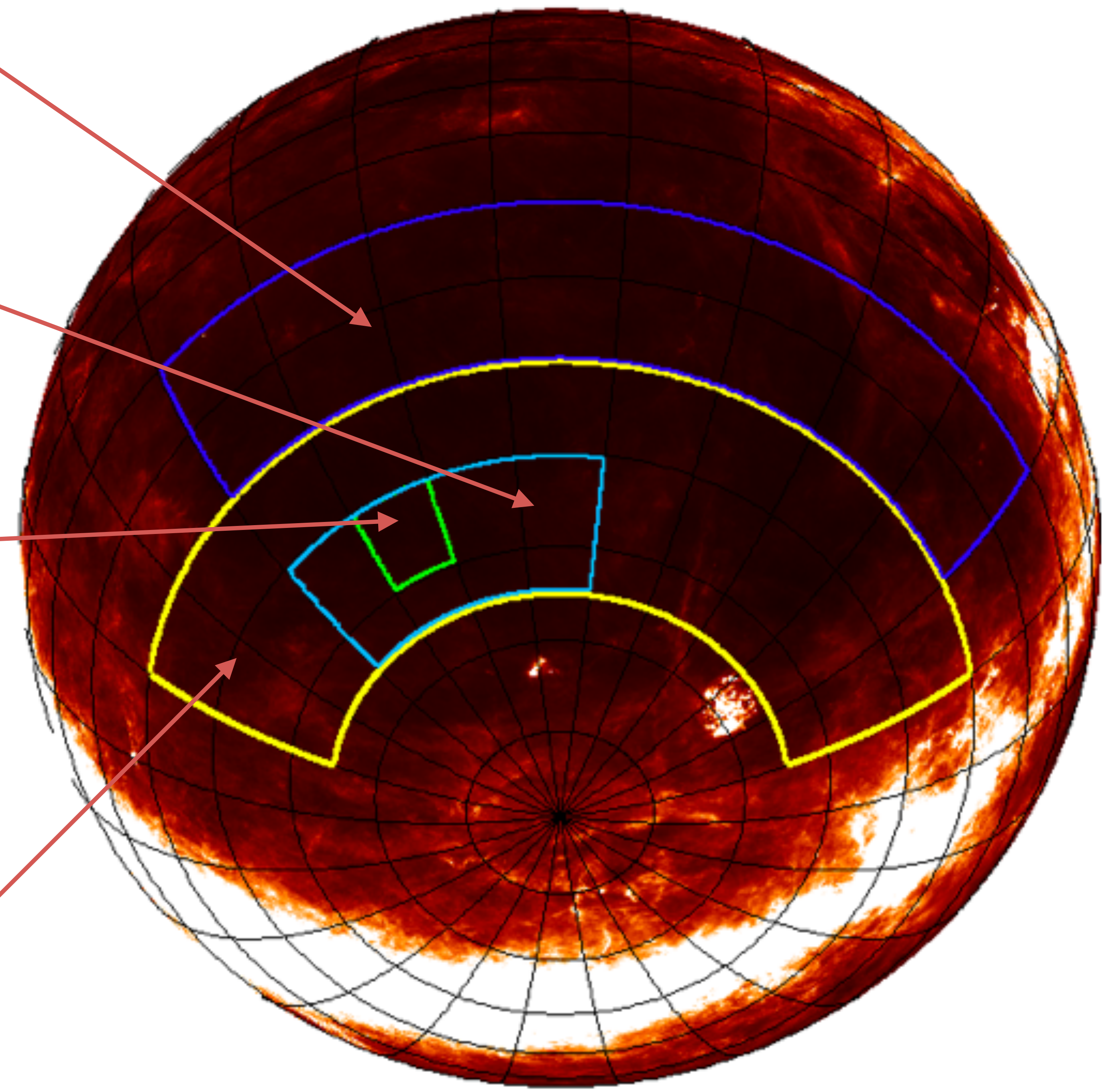
~ 7 μK-arcmin map depth (T)

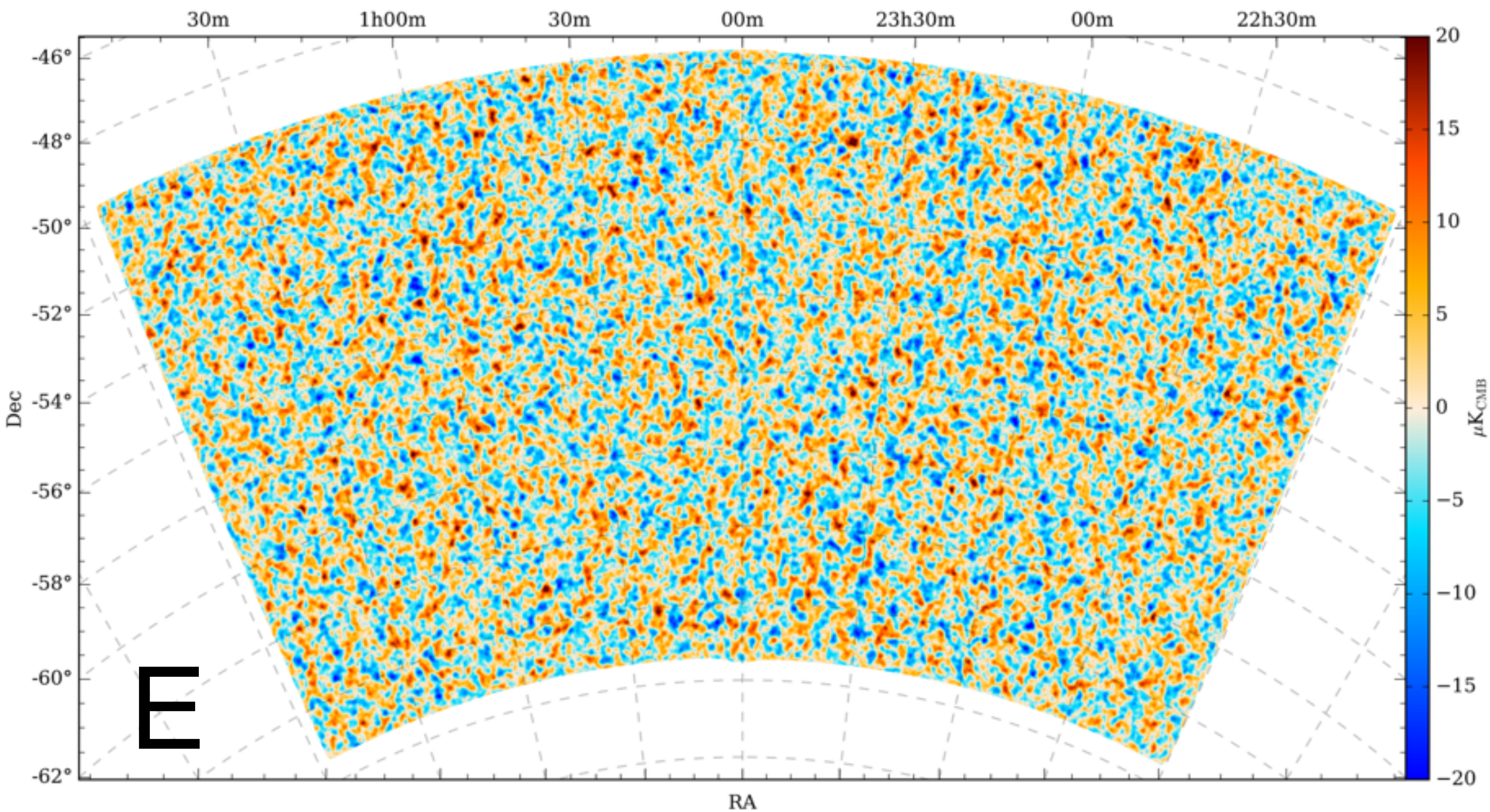
(from 2012 + early 2013 only)

- Hanson, 2013 (BB Cross)
- Crites, 2015 (EE, TE)
- Keisler, 2015 (BB Auto)
- Story, 2015 (ϕϕ)
- Whitehorn, 2016 (Transients)
- Manzotti, 2017 (BB Delensing)

SPTsz - 2500 deg^2

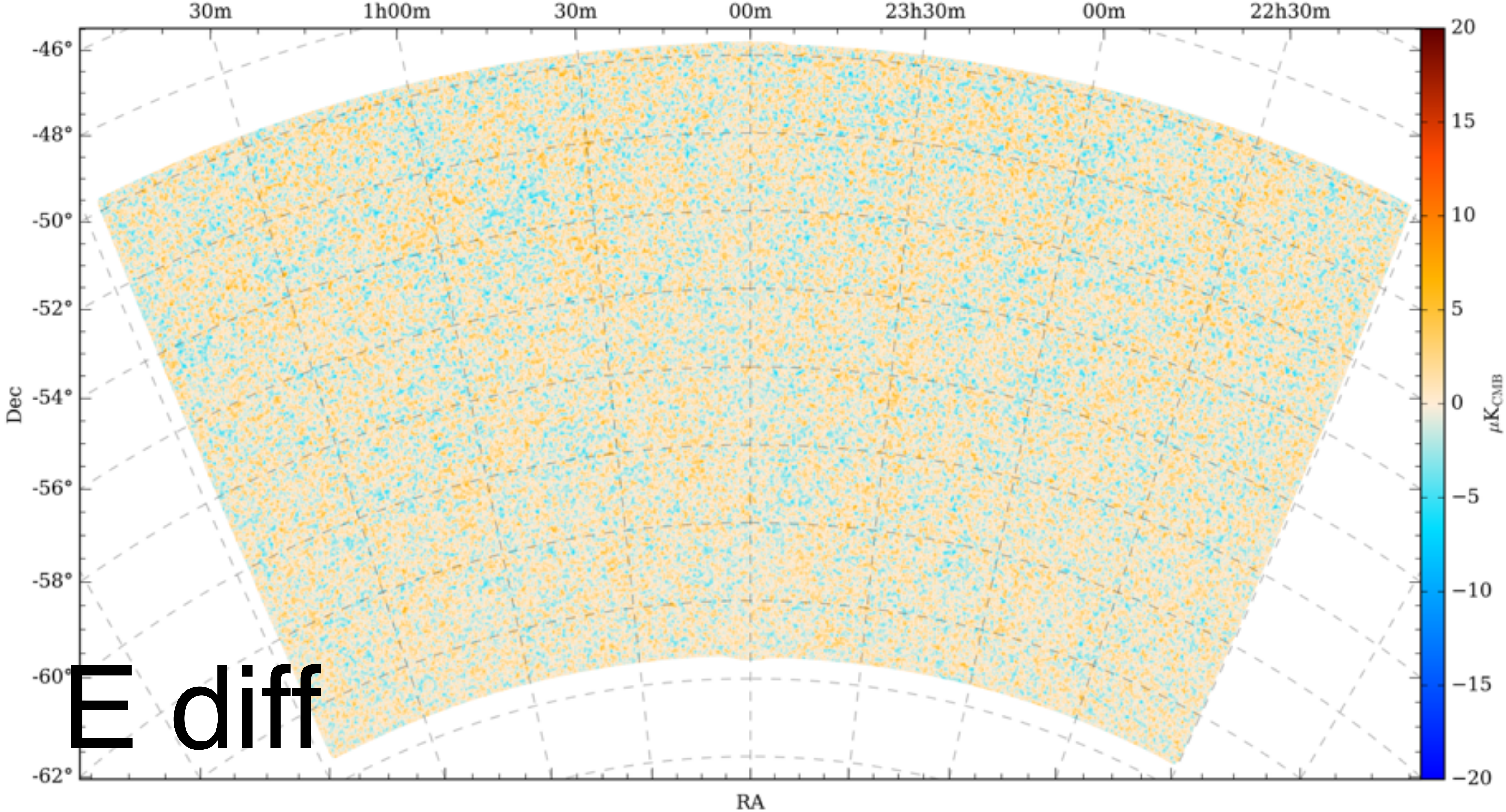
~ 18 μK-arcmin map depth (T)





SPTpol 150 GHz

- 9.4 μK-arcmin between $2000 < \ell < 4000$.
- Smoothed by 4 arcmin FWHM Gaussian.

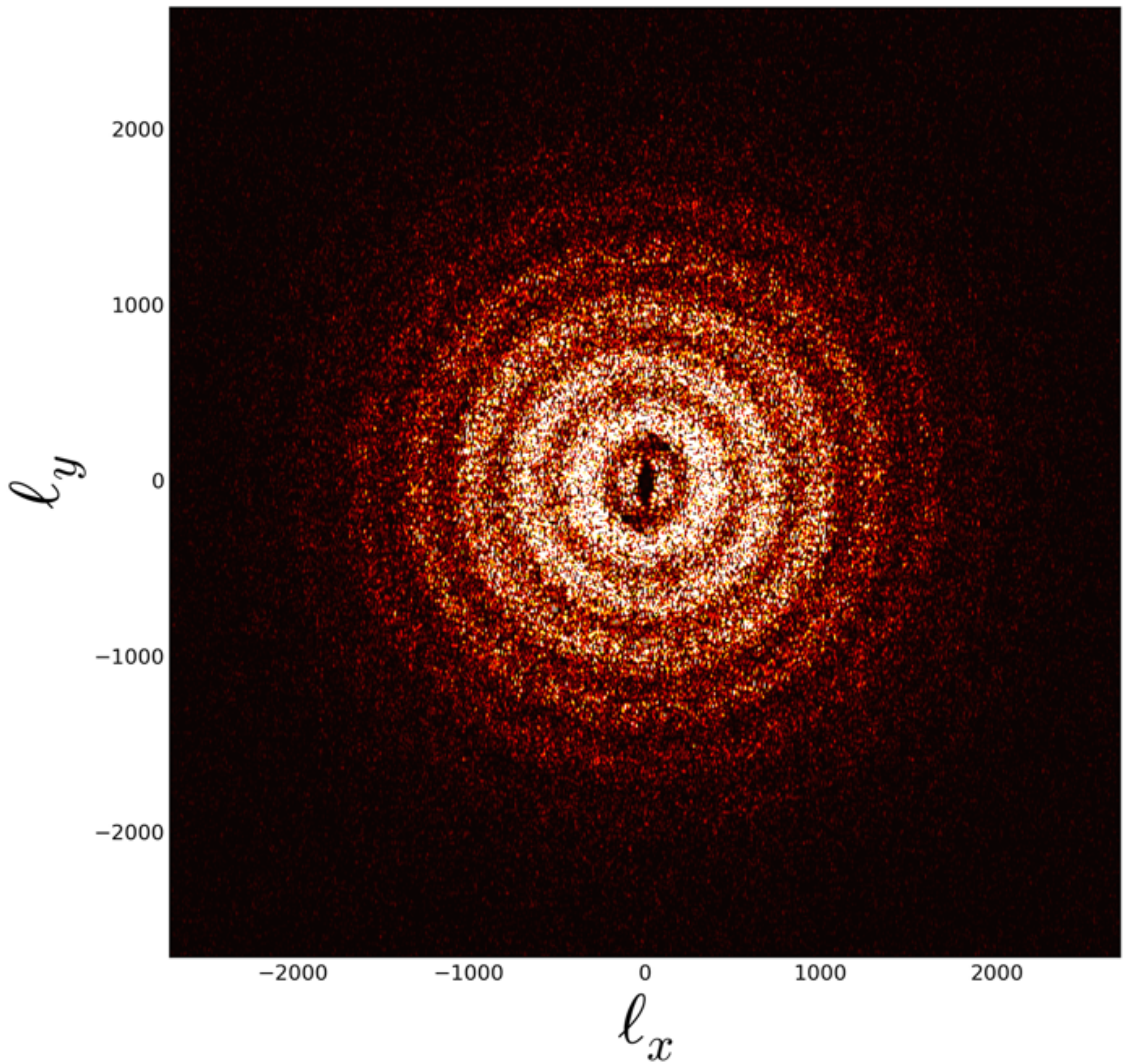


SPTpol 150 GHz

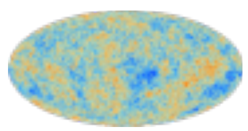
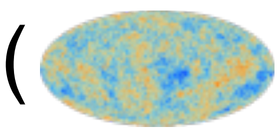
- First-half map minus second-half map.

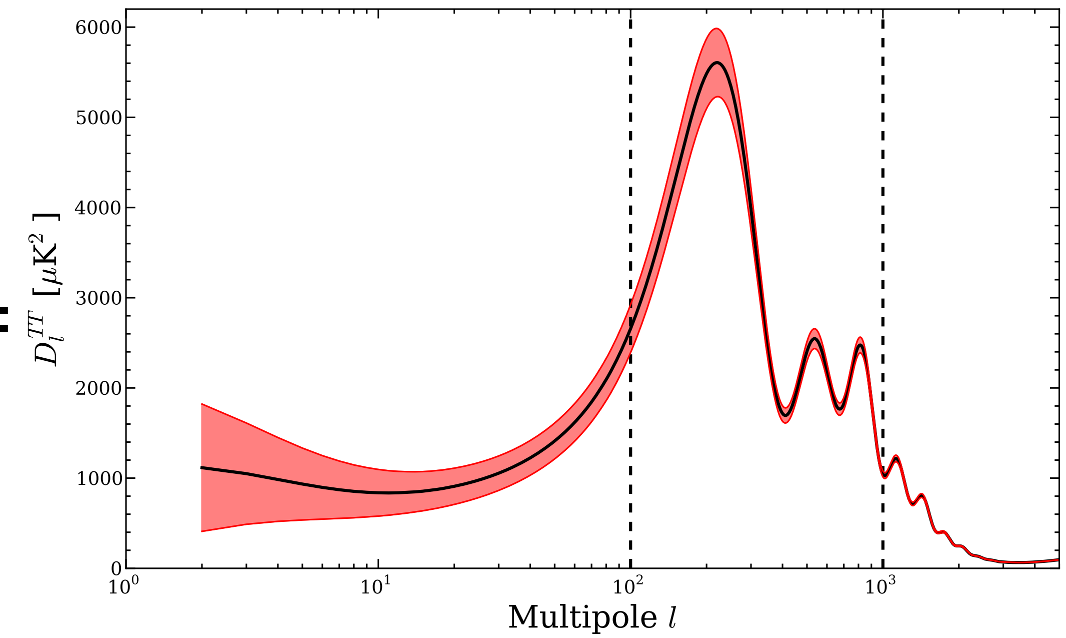
Hit E Map with Cosmologist's Hammer

First 7 acoustic peaks visible BEFORE azimuthal averaging



Pseudo-Power Spectrum

2DFFT () X Conj(2DFFT()) =



- Raw data have biases.
- Naive power spectrum biased by observing, and map/instrument processing.
- Must account for biasing effects, use pseudo-C_ℓ MASTER method of Hivon, et al. 2002.

$$K_{bb'} = P_{bl}\left(M_{\ell\ell'}[\mathrm{W}]F_{\ell'}B^2_{\ell'}\right)Q_{\ell' b'}$$

Mode-Coupling

Transfer Function

Beam Function

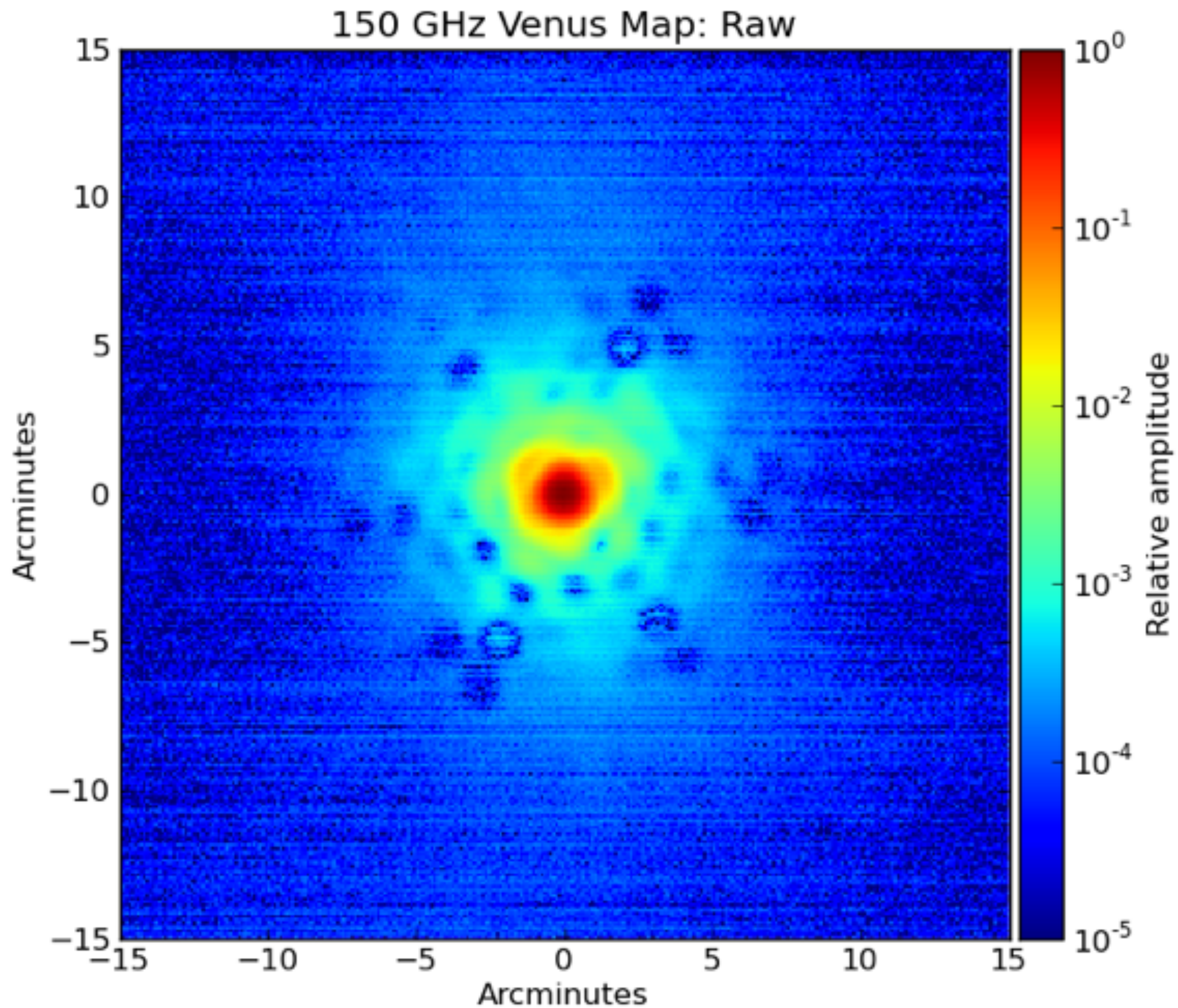
Binning Operators

$$D_b^{XY} = K^{-1}_{bb'}\hat{D}^{XY}_{b'}$$

Unbiased

Biased

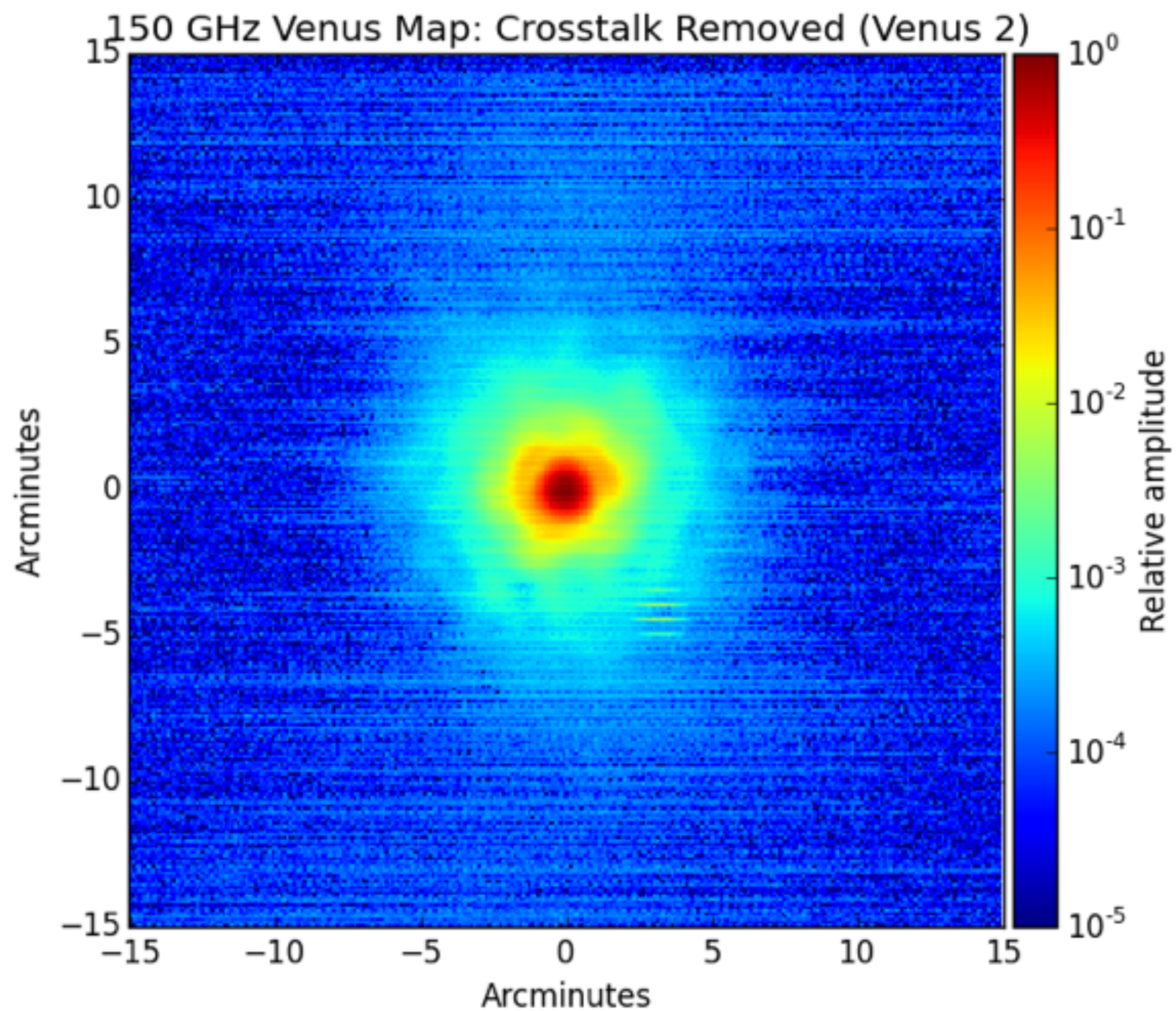
Corrections for Bias: Crosstalk



Detectors exhibit negative crosstalk.

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

Corrections for Bias: Crosstalk

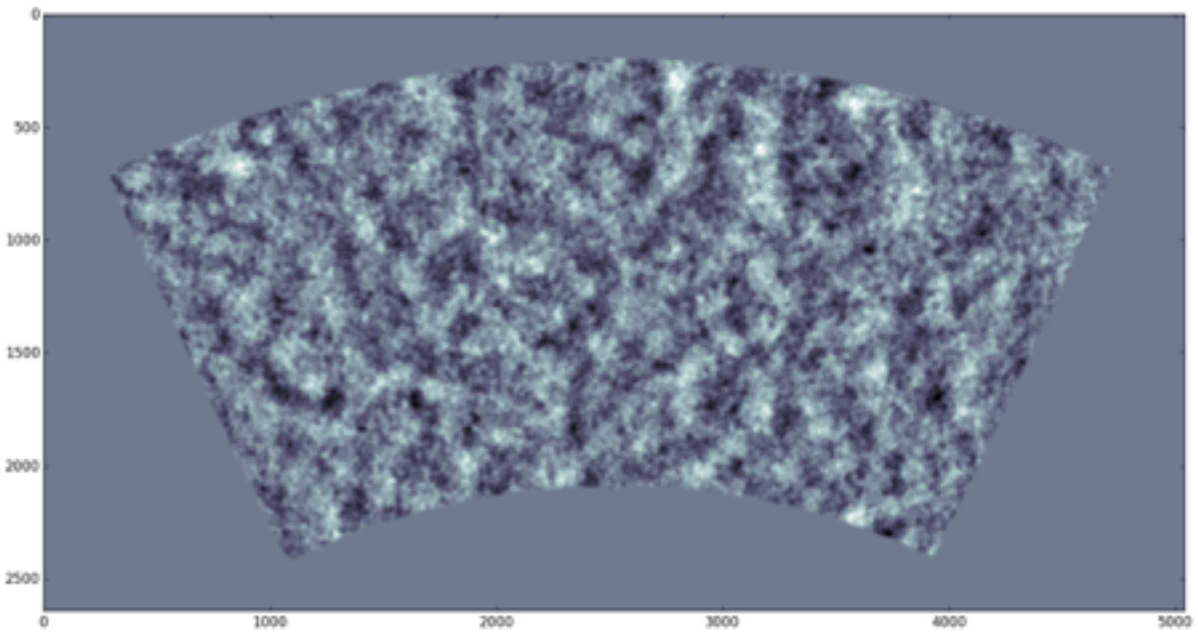


- Now corrected at timestream-level before binning into maps.

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

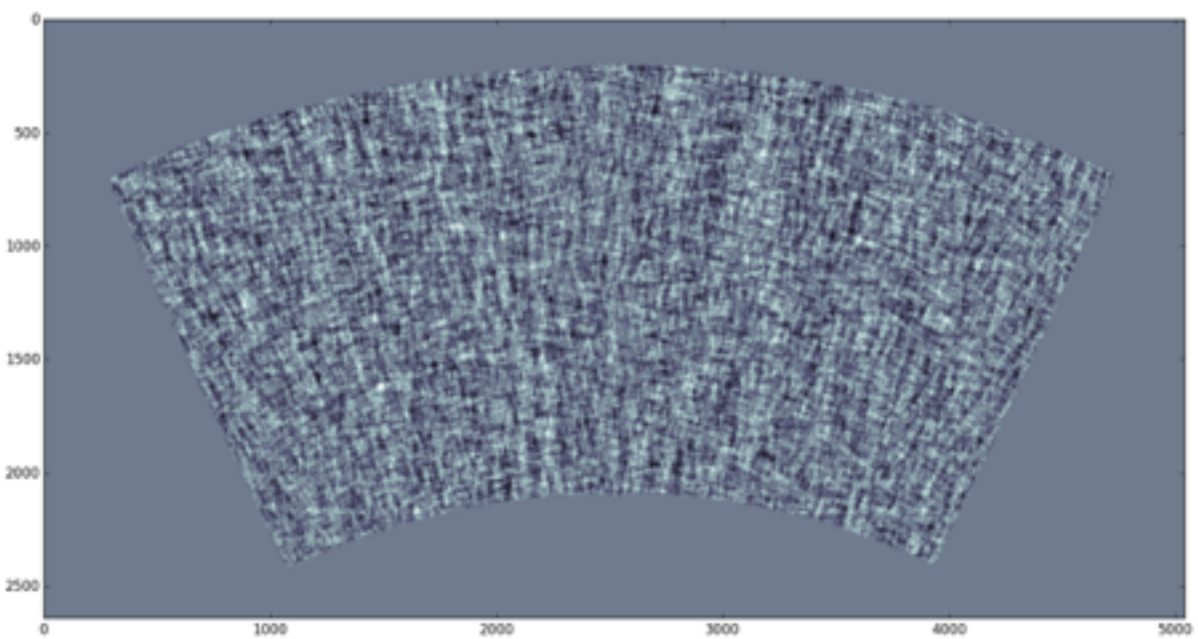
$$\hat{\vec{d}} = \mathbf{X}^{-1}\vec{d}$$

Corrections for Bias: T-> P Leakage

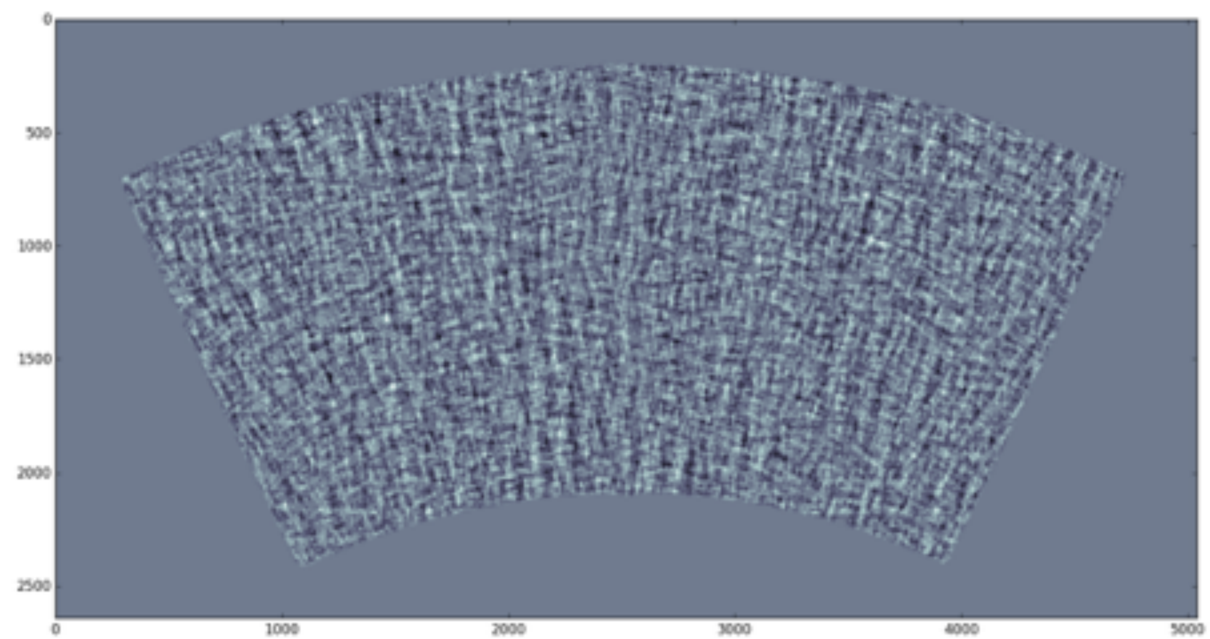


$$\epsilon^P = \frac{\sum w_\ell \frac{C_\ell^{TP}}{C_\ell^{TT}}}{\sum w_\ell}$$

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



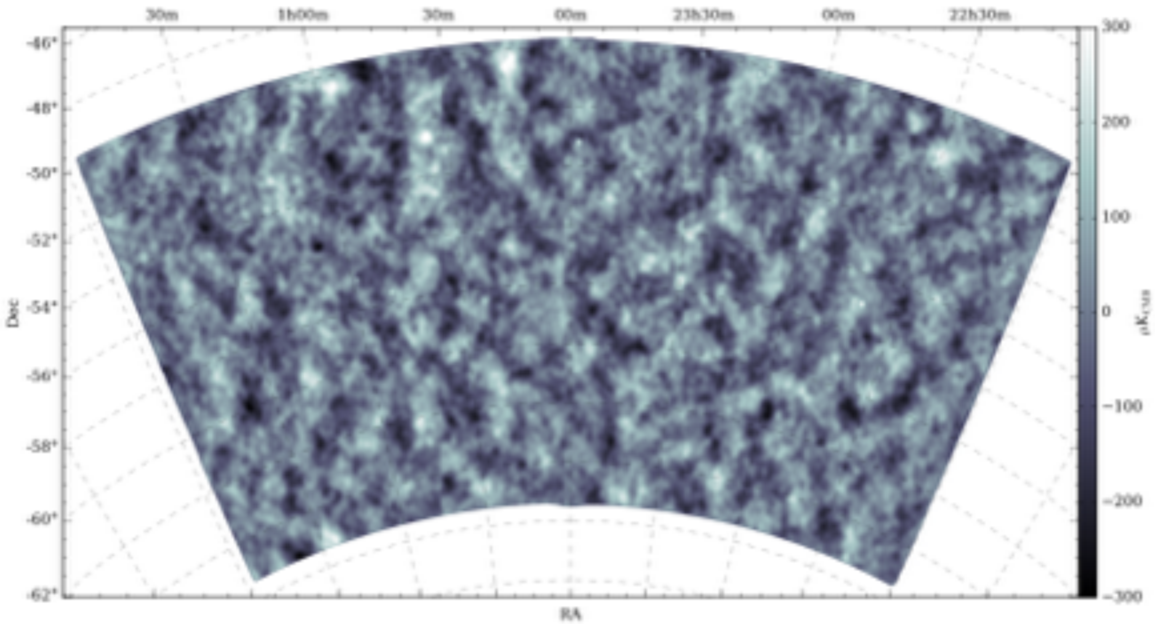
Contaminated Q Map



Cleaned Q Map

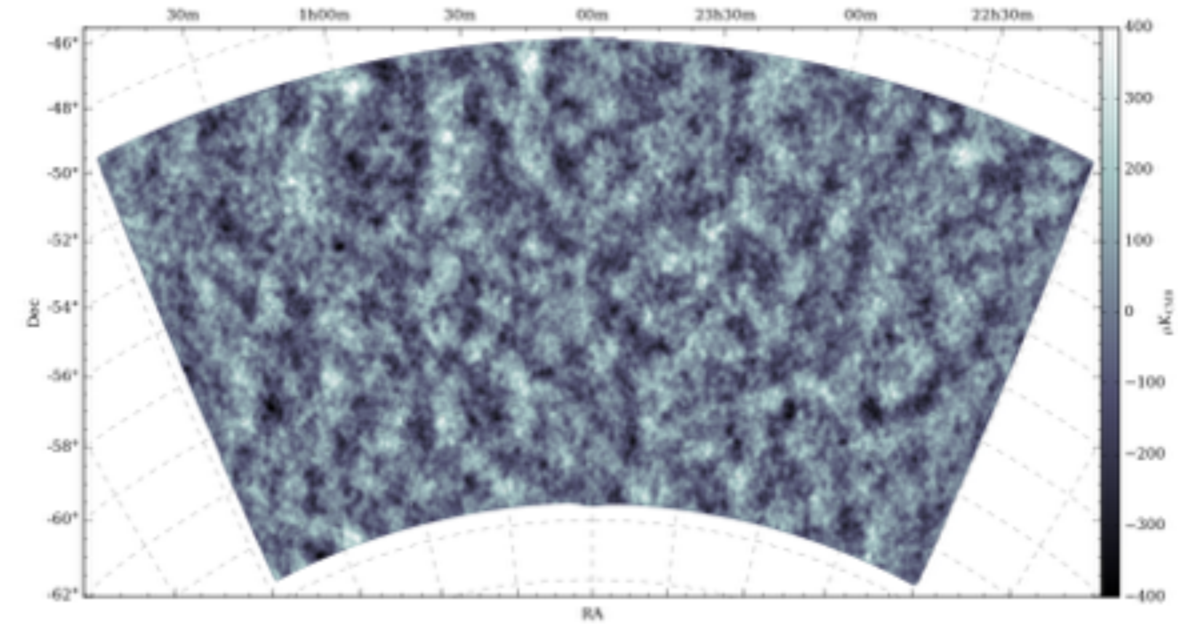
- "Monopole" leakage - constant fraction of T map in Q and U.

Corrections for Bias: Beam



Planck

x



SPTpol

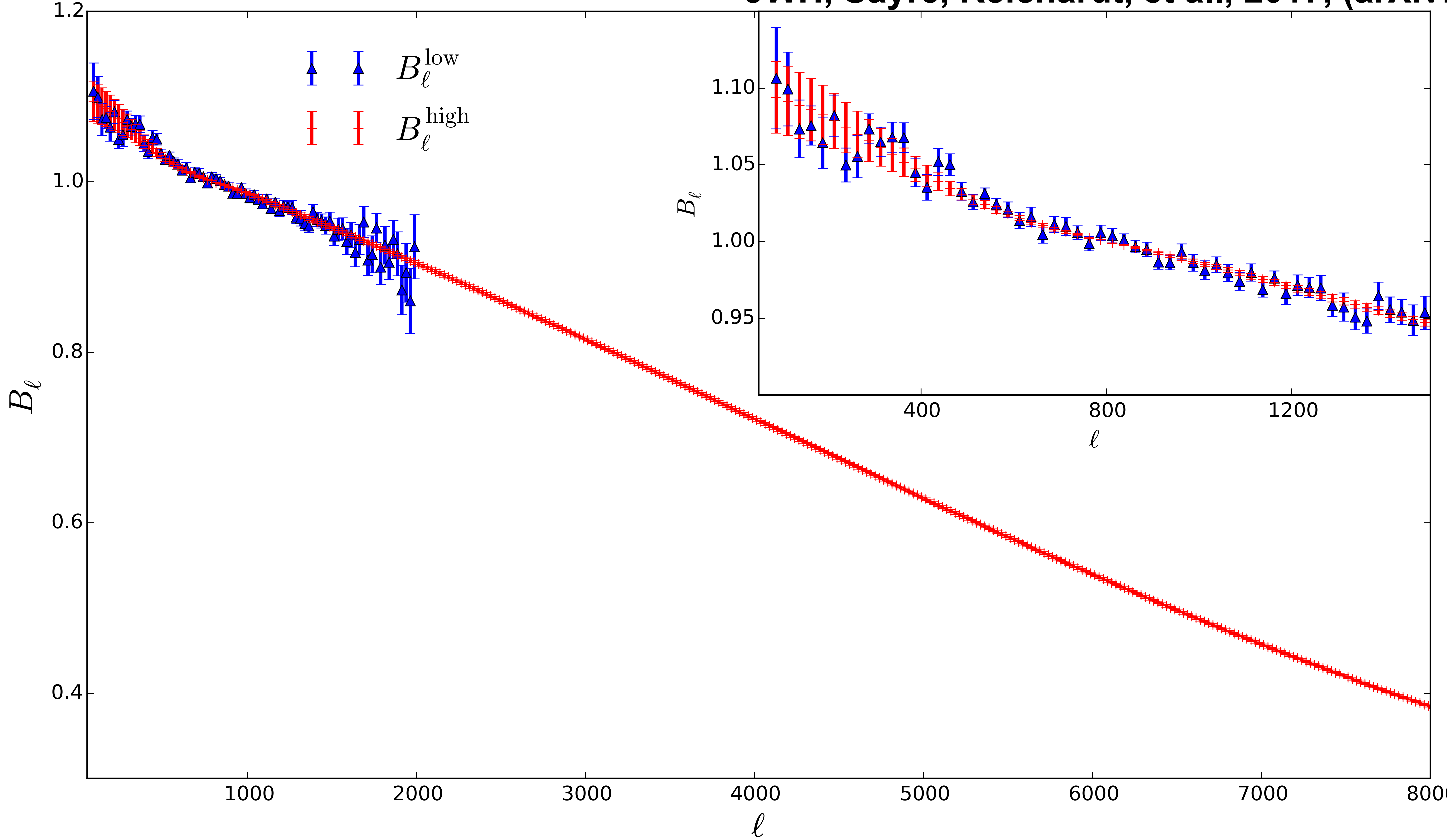
$$\frac{\left\langle \tilde{m}_T^S \tilde{m}_T^{S*} \right\rangle}{\left\langle \tilde{m}_T^P \tilde{m}_T^{S*} \right\rangle} = \frac{\epsilon_T B_\ell^S}{B_\ell^P}$$

- Get beam on large scales by cross-correlating filtered Planck and SPTpol maps.

- Beam on small scales from planets (Venus).

Corrections for Bias: Beam

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

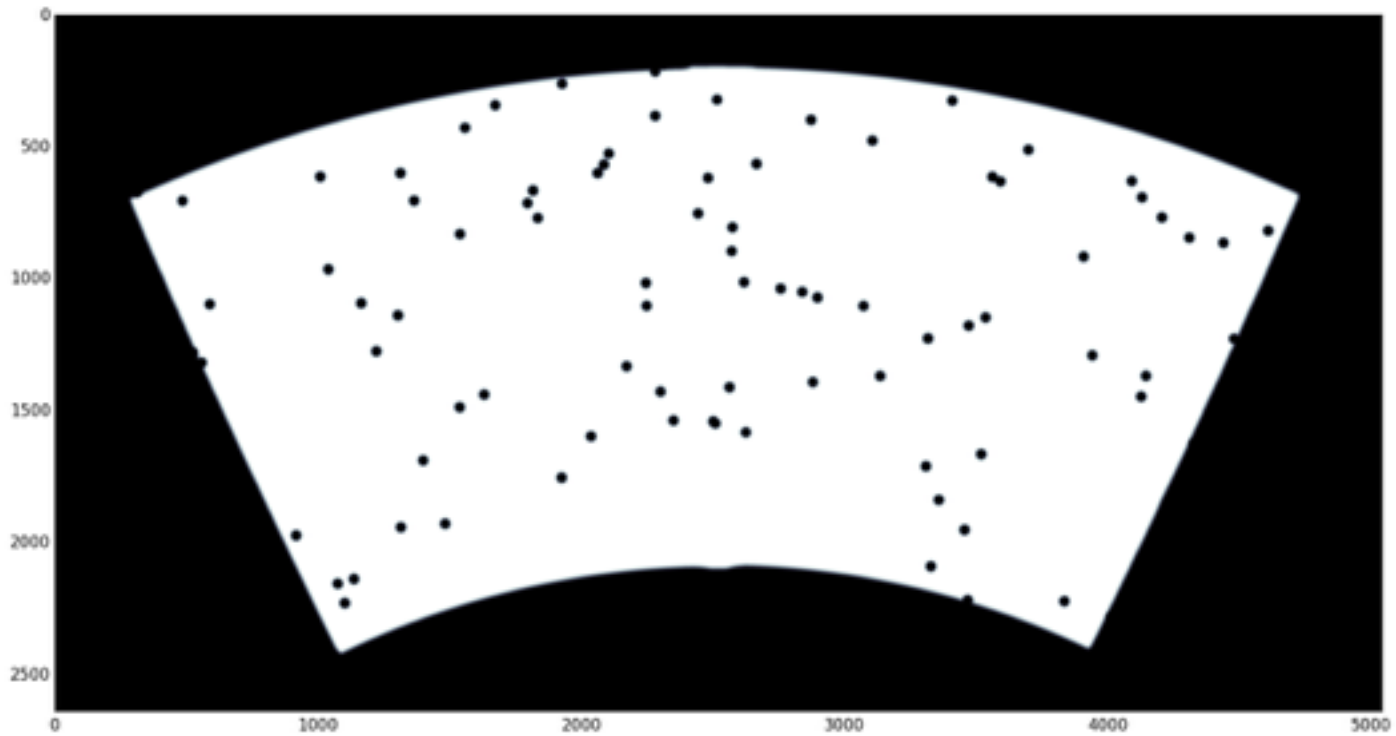


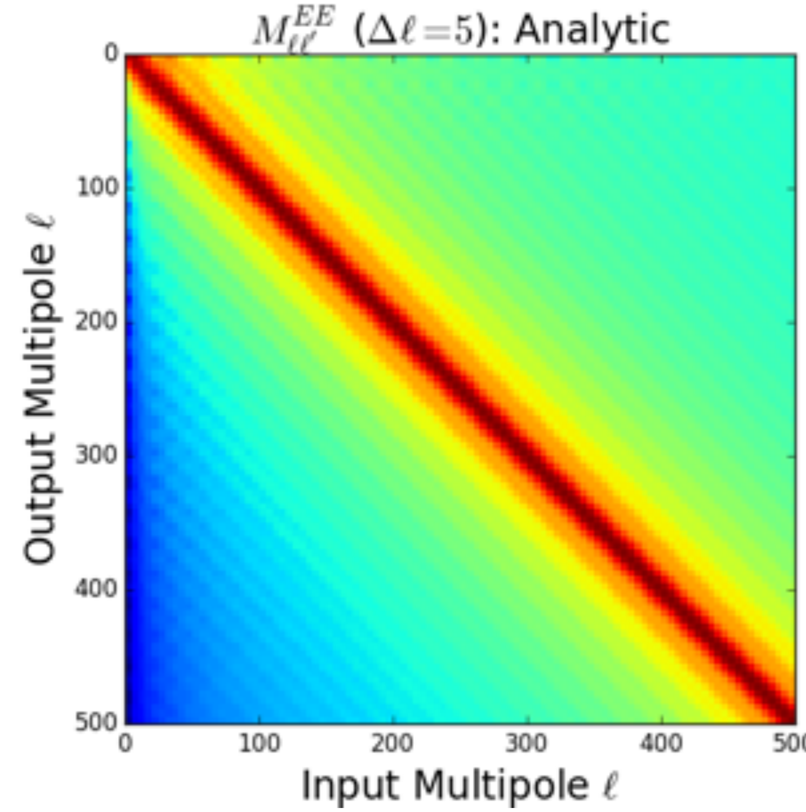
- Excellent agreement between “large-scale” beam from Planck X SPTpol and “small-scale” beam from Venus measurements.

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

- We use Venus beam for all scales.

Corrections for Bias: Mode-Coupling

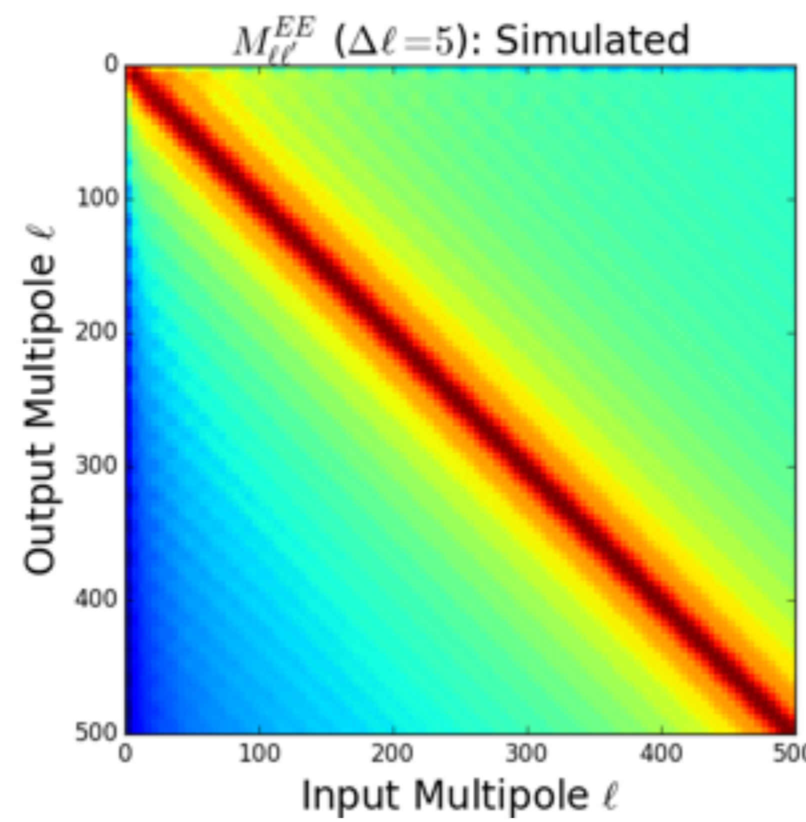




- Masking the sky couples otherwise independent Fourier modes (non-diagonal).

- Can calculate this effect analytically for a given mask using flat-sky approximation.

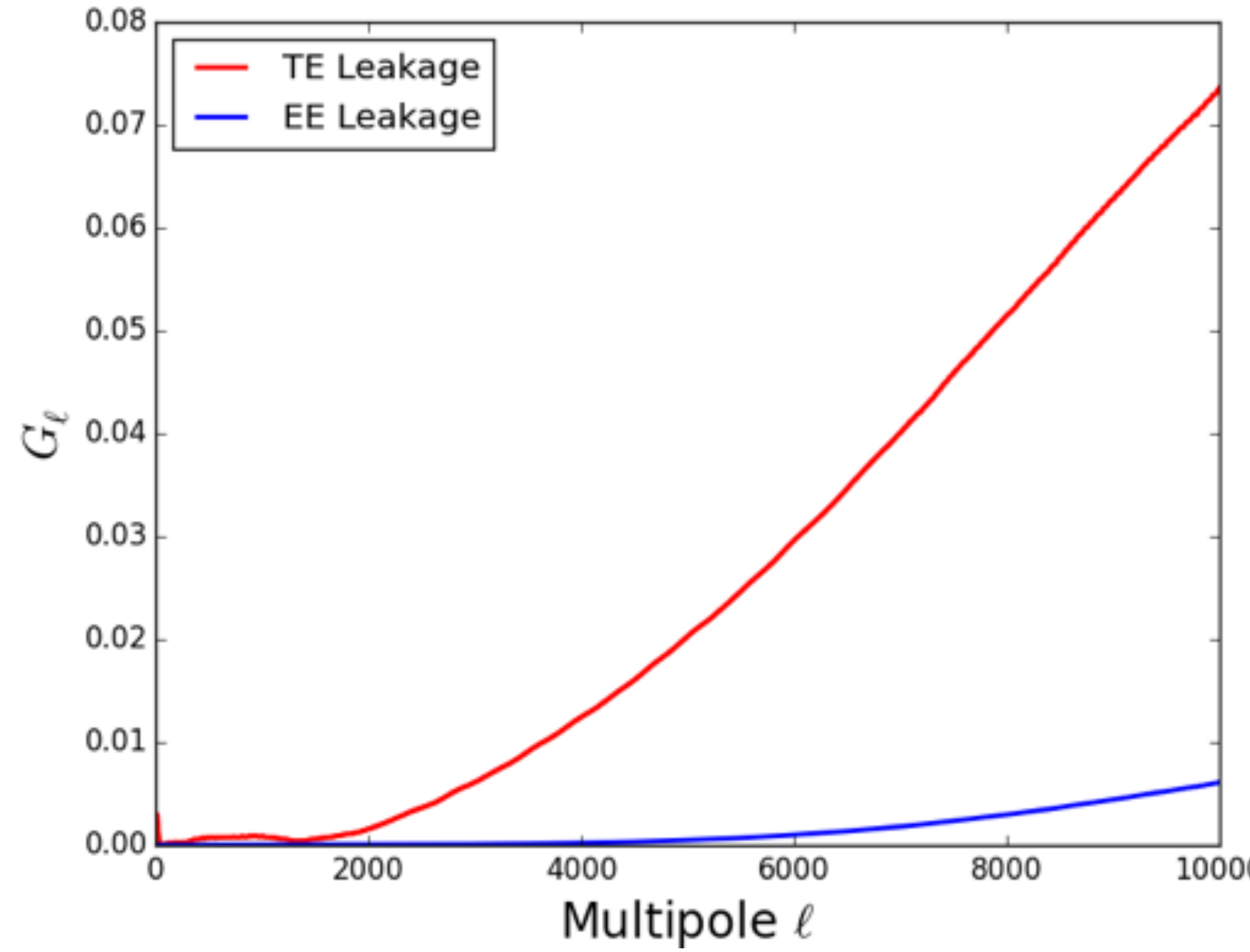
- Also simulated coupling at large scales using HEALPix maps (curved-sky). Solutions consistent.



Corrections for Bias: T-> P Leakage (Revisited)

$$G_\ell^{XY} = \frac{\sum_{\phi_\ell}\left(C_{\ell,\phi_\ell}^{XY}\right)_{\mathrm{Venus}}}{\sum_{\phi_\ell}\left(C_{\ell,\phi_\ell}^{TT}\right)_{\mathrm{Venus}}}$$

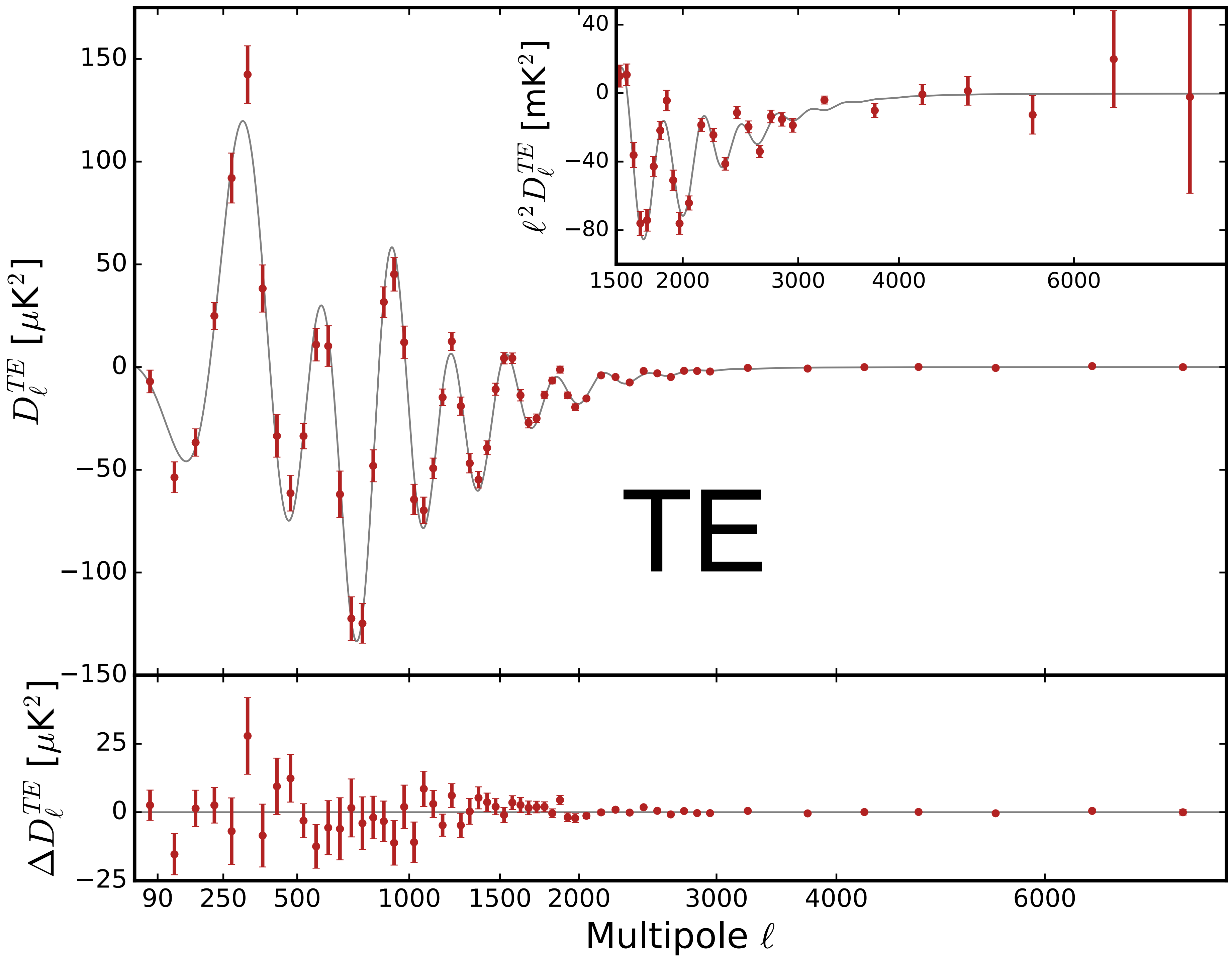
$$C_{\ell,\mathrm{corrected}}^{XY} = C_{\ell,\mathrm{uncorrected}}^{XY} - G_\ell^{XY} C_\ell^{TT}$$



- T leaks into P at higher multipoles (differential pointing, beam ellipticity, etc.)
- Leakage consistent with 1% differential beam ellipticity.

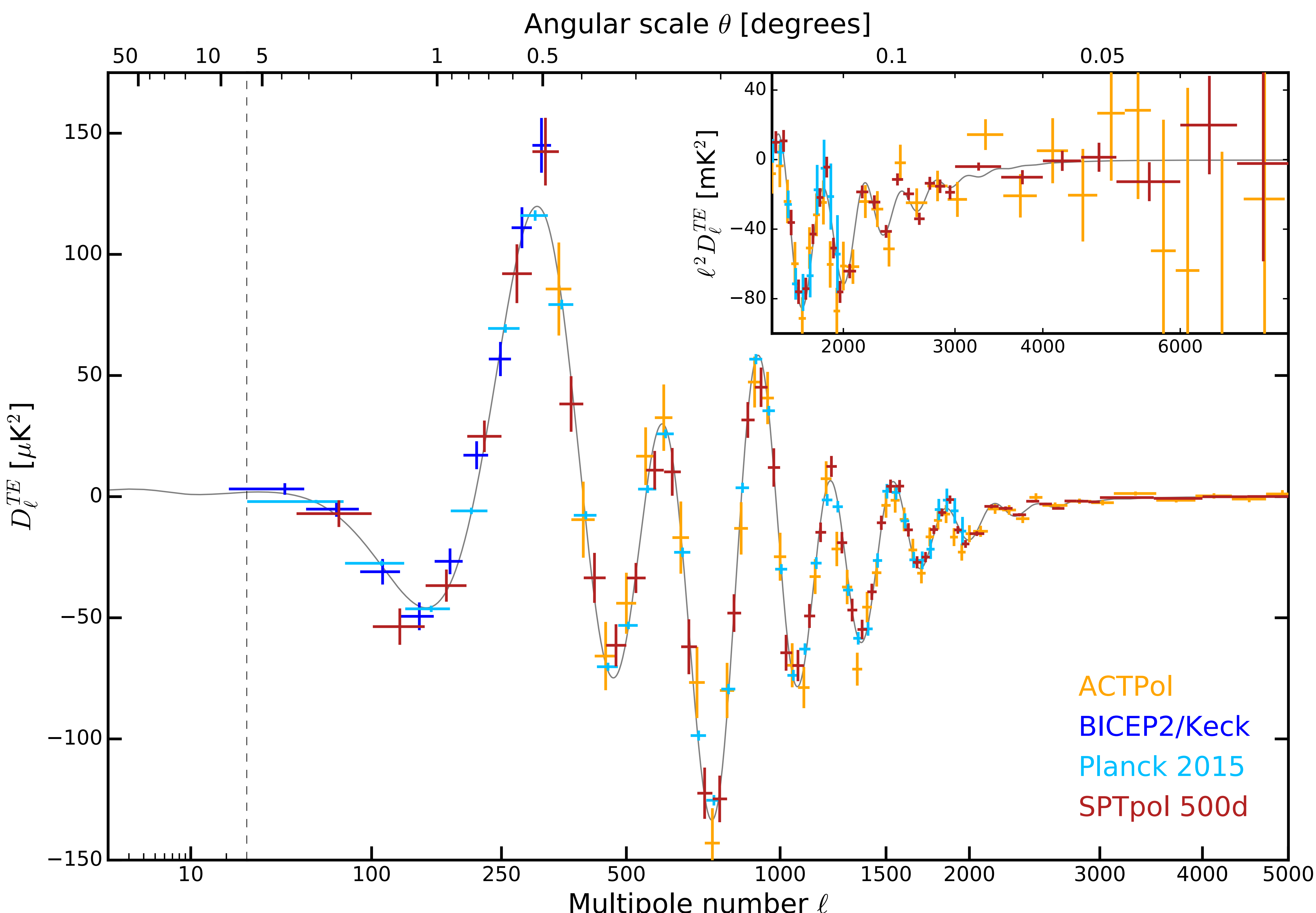
500 Deg² Field Power Spectra

- Theory curve is *Planck* 2015 plikHM_TT_lowTEB (*Planck*TT)
- Residuals calculated against this theory
- Only sample and noise variance
- Sample-variance limited at $\ell < 2050$



JWH, Sayre, Reichardt, et al., 2017

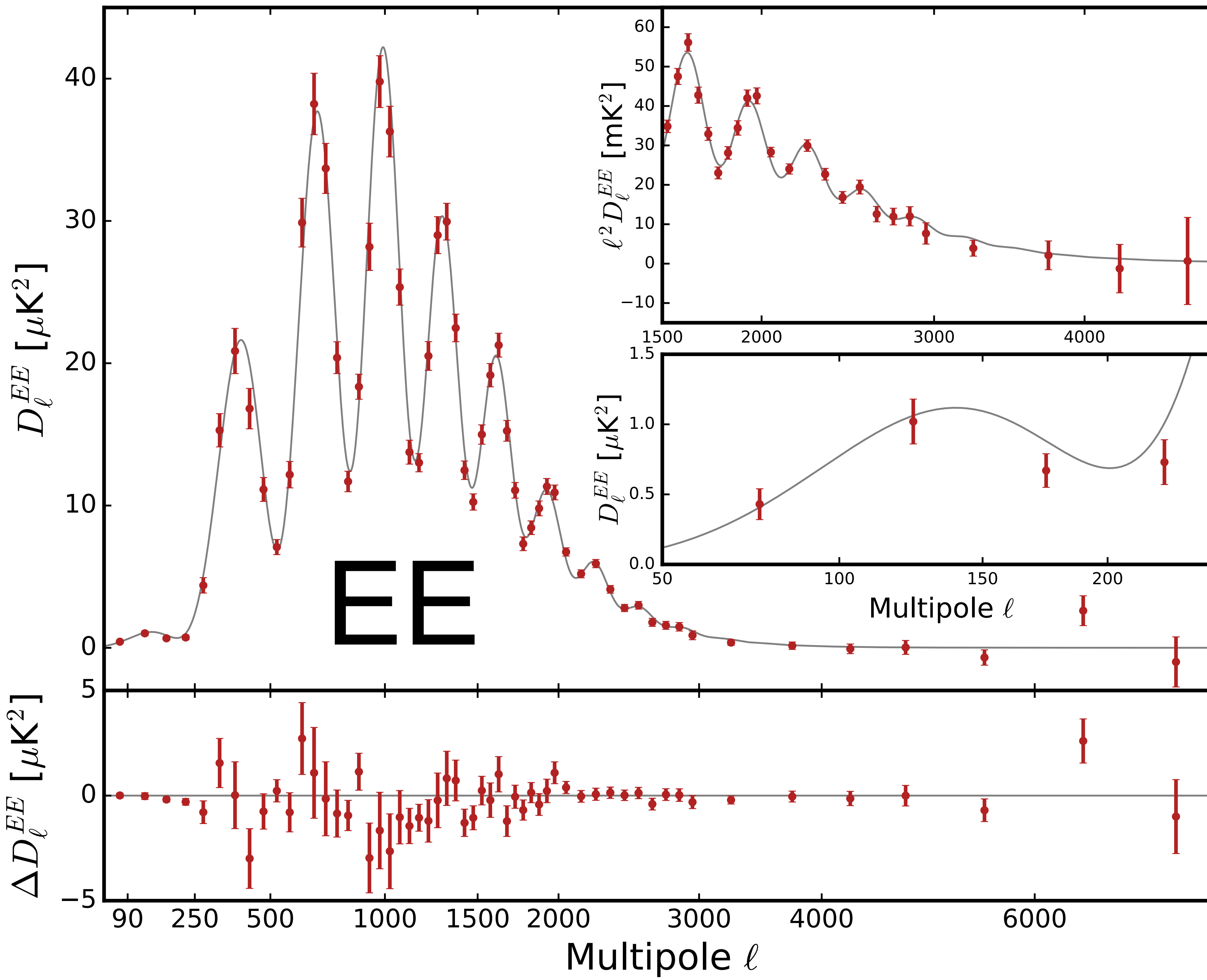
Compilation of TE Measurements



JWH, Sayre, Reichardt, et al., 2017

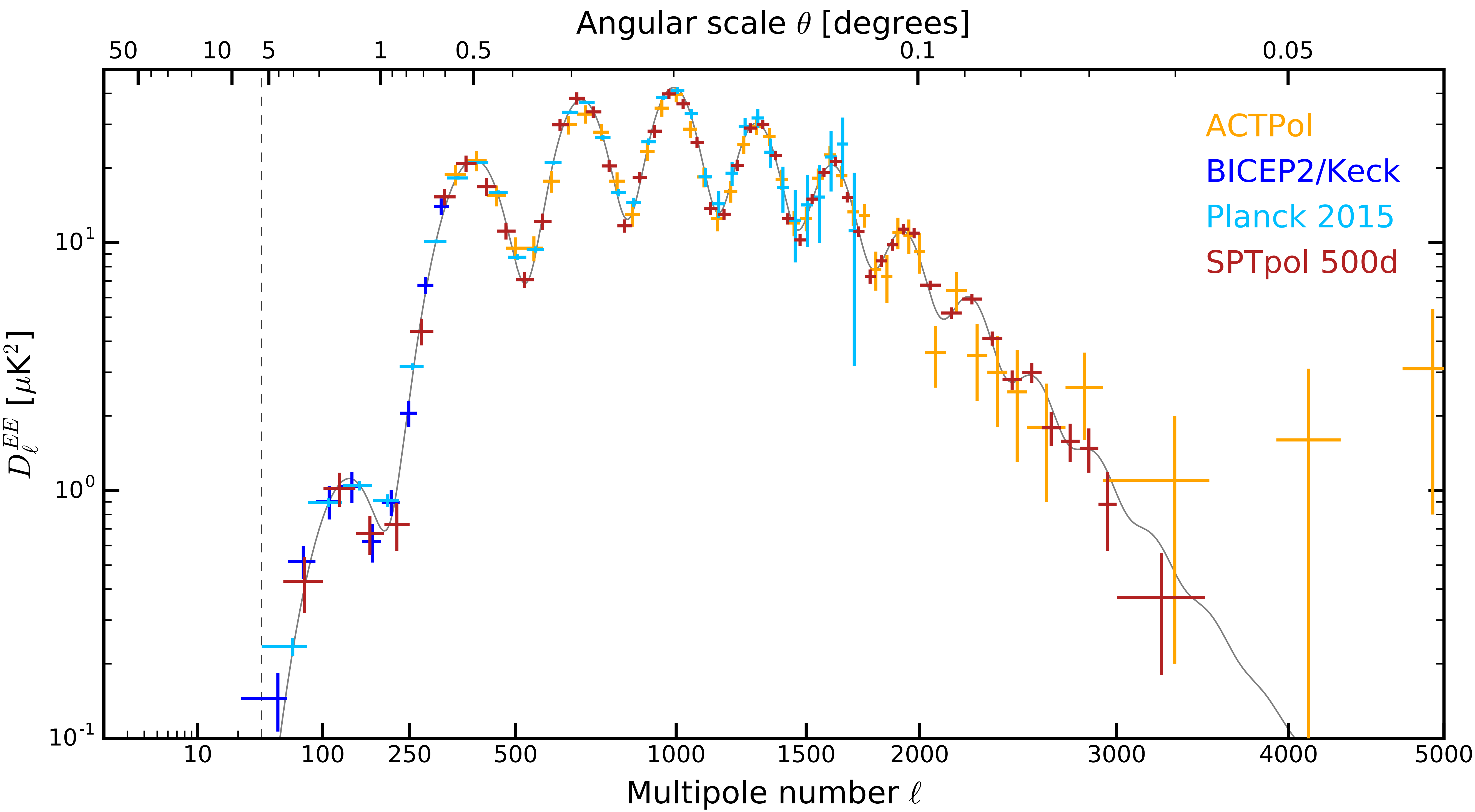
500 Deg^2 Field Power Spectra

- Sample-variance limited at $\ell < 1750$
- 9 acoustic peaks between $50 < \ell < 3000$
- **$D_\ell^{PS} < 0.1$ μK^2 at 95% confidence**
    - **(Contributes < 1 μK-arcmin to rms map noise).**
    - Weak source cut at > 50 mJy in T.
    - Poisson power crosses EE at $\ell \sim$ 3800.
    - Minimal foregrounds!



JWH, Sayre, Reichardt, et al., 2017

Compilation of EE



JWH, Sayre, Reichardt, et al., 2017

Cosmological Constraints

- "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:

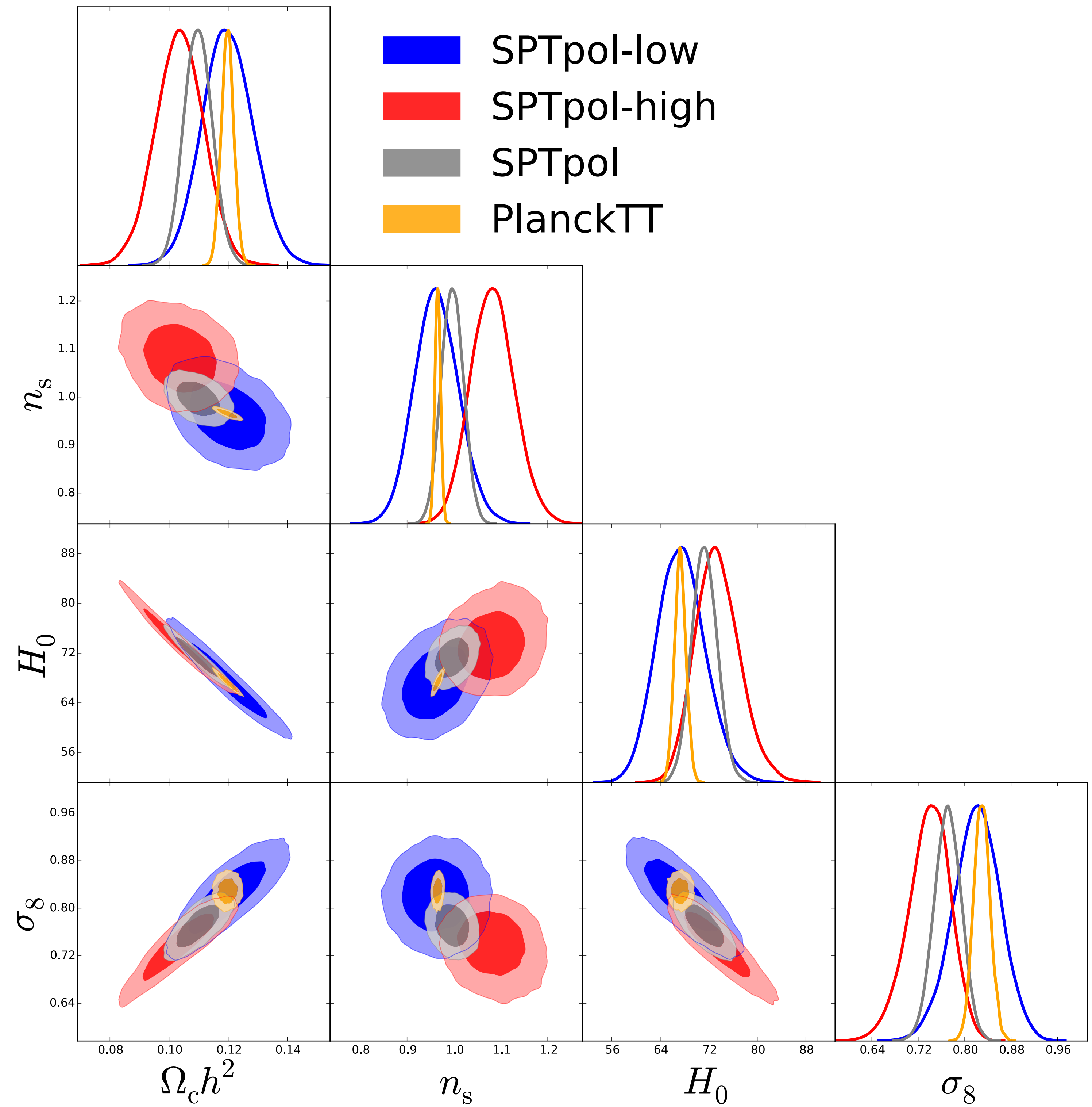
$$H_0 = 71.2 \pm 2.1\,\mathrm{km\,s^{-1}Mpc^{-1}}$$

$$\sigma_8 = 0.770 \pm 0.023$$

(Full-range SPTpol)

- Similar to trends seen in SPT-SZ TT data (Aylor et al., 2017, arXiv:1706.10286)
  - Consistent with Planck when matching modes.

JWH, Sayre, Reichardt, et al., 2017



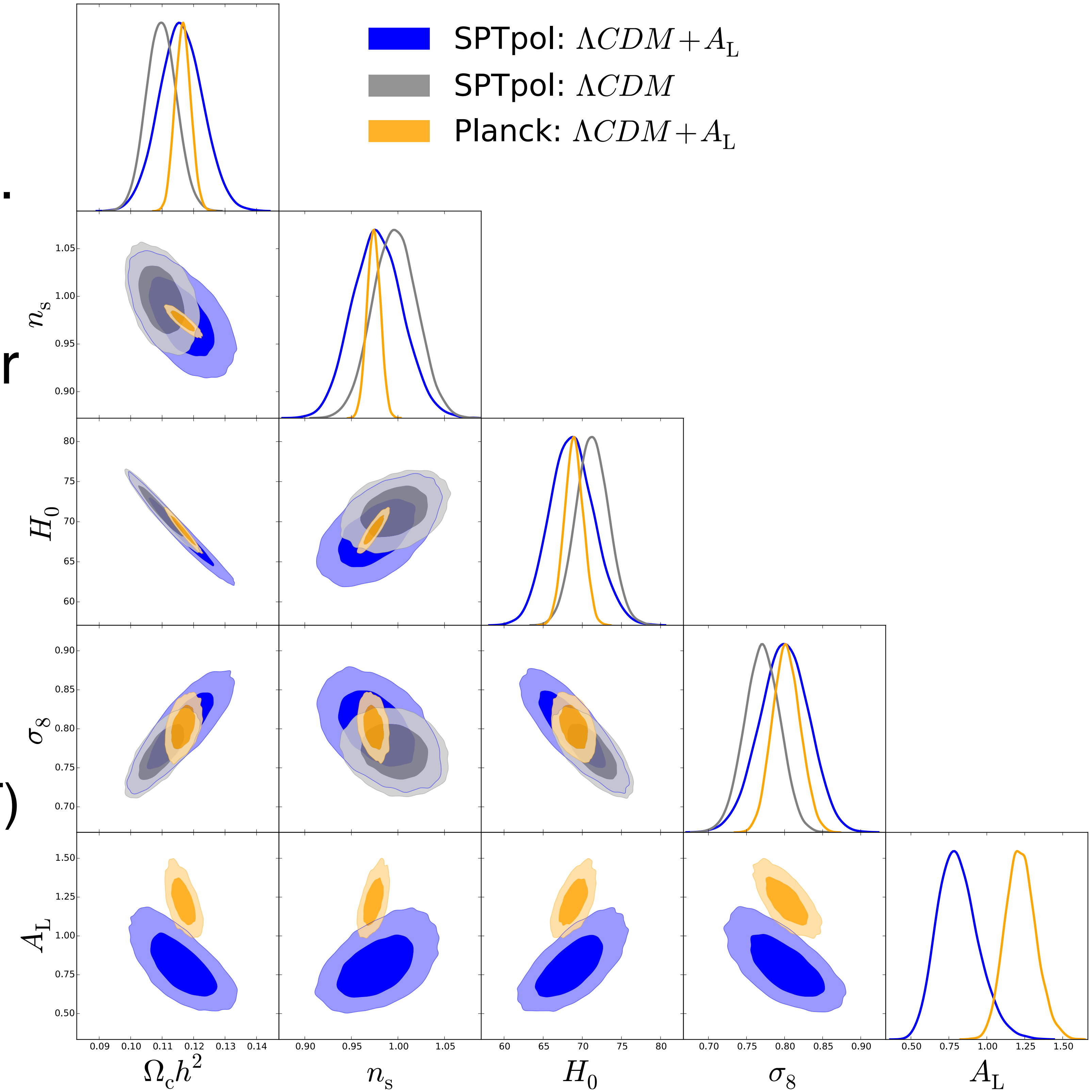
Cosmological Constraints

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:

$$A_L = 0.81 \pm 0.14 \text{ (SPTpol)}$$
$$A_L = 1.22 \pm 0.10 \text{ (\textit{Planck}TT)}$$

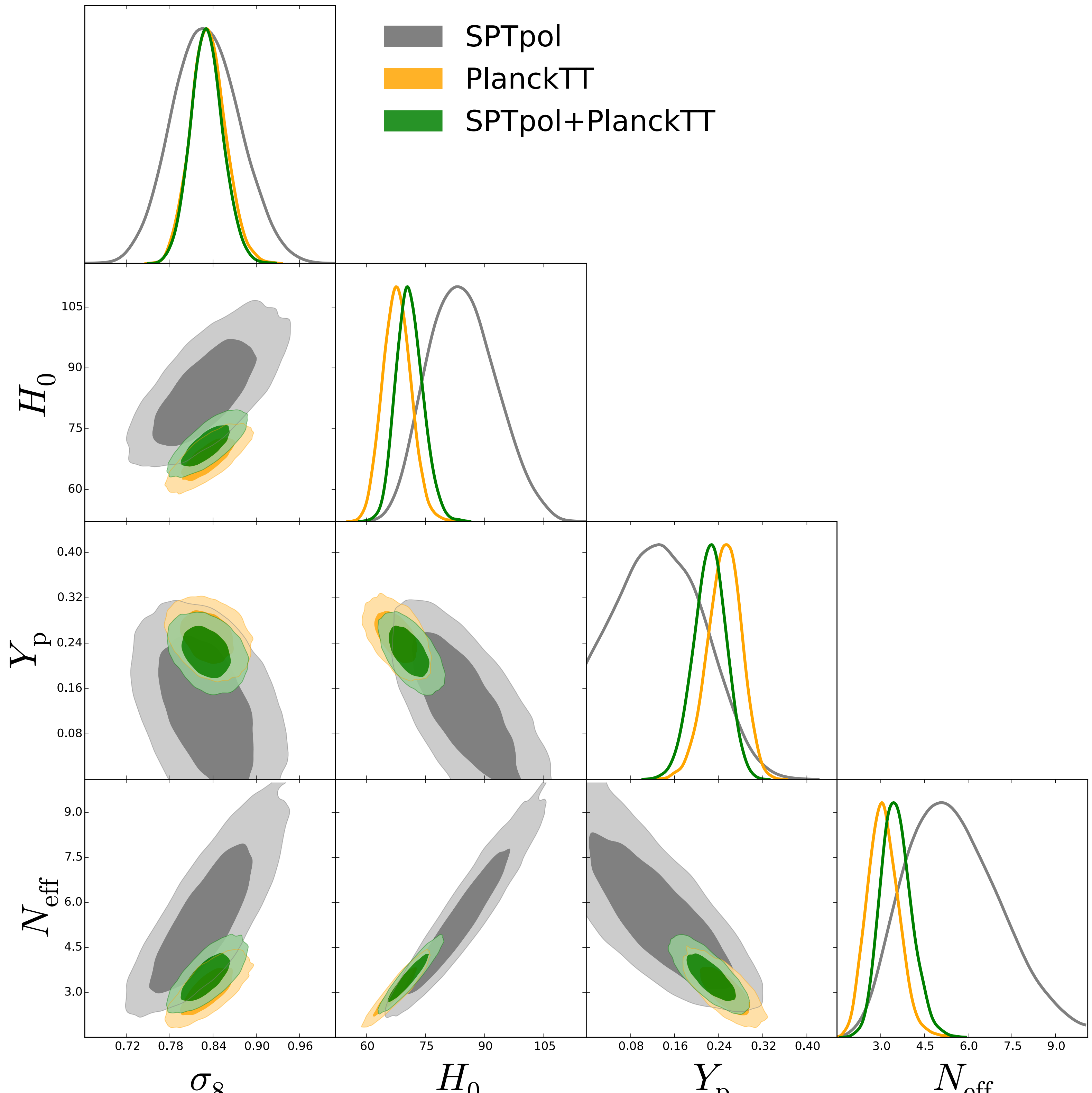


Extensions to ΛCDM

JWH, Sayre, Reichardt, et al., 2017

- Damping tail measurement reduces volume of parameter space for one- and two-parameter extensions (Y_p, N_eff).

- ΛCDM+Y_p: 2.7x (7-D)
- ΛCDM+N_eff: 3.2x (7-D)
- ΛCDM+Y_p + N_eff: 2.7x (8-D)



Summary

- Maps and power spectra from ~ 3 seasons of observing 500 deg^2 with SPTpol. Another year in hand.
- Detect 9 acoustic peaks in EE between $50 < \ell < 3000$.
    - Probing deep into polarization damping tail for first time.
    - Larger scales too (with a large-aperture telescope)!
- Sample variance limited at $\ell < 1750$ (2050) in EE (TE).
- $D_\ell^{PS} < 0.1\ \mu K^2$ at 95% confidence with weak source cut.
- Tensions between SPTpol and Planck emerge when including ℓ>1000 SPTpol data. A careful cross-spectrum analysis is merited.

$$H_0 = 71.2 \pm 2.1\,\mathrm{km}\,s^{-1}\mathrm{Mpc}^{-1} \quad \sigma_8 = 0.770 \pm 0.023$$ (Full-range SPTpol)

    - Tension in ΛCDM parameters removed when marginalizing over A_L, but A_L itself 2.9 sigma discrepant between experiments.
- Sensitivity to polarized damping tail starting to exhibit constraining power in extension models.