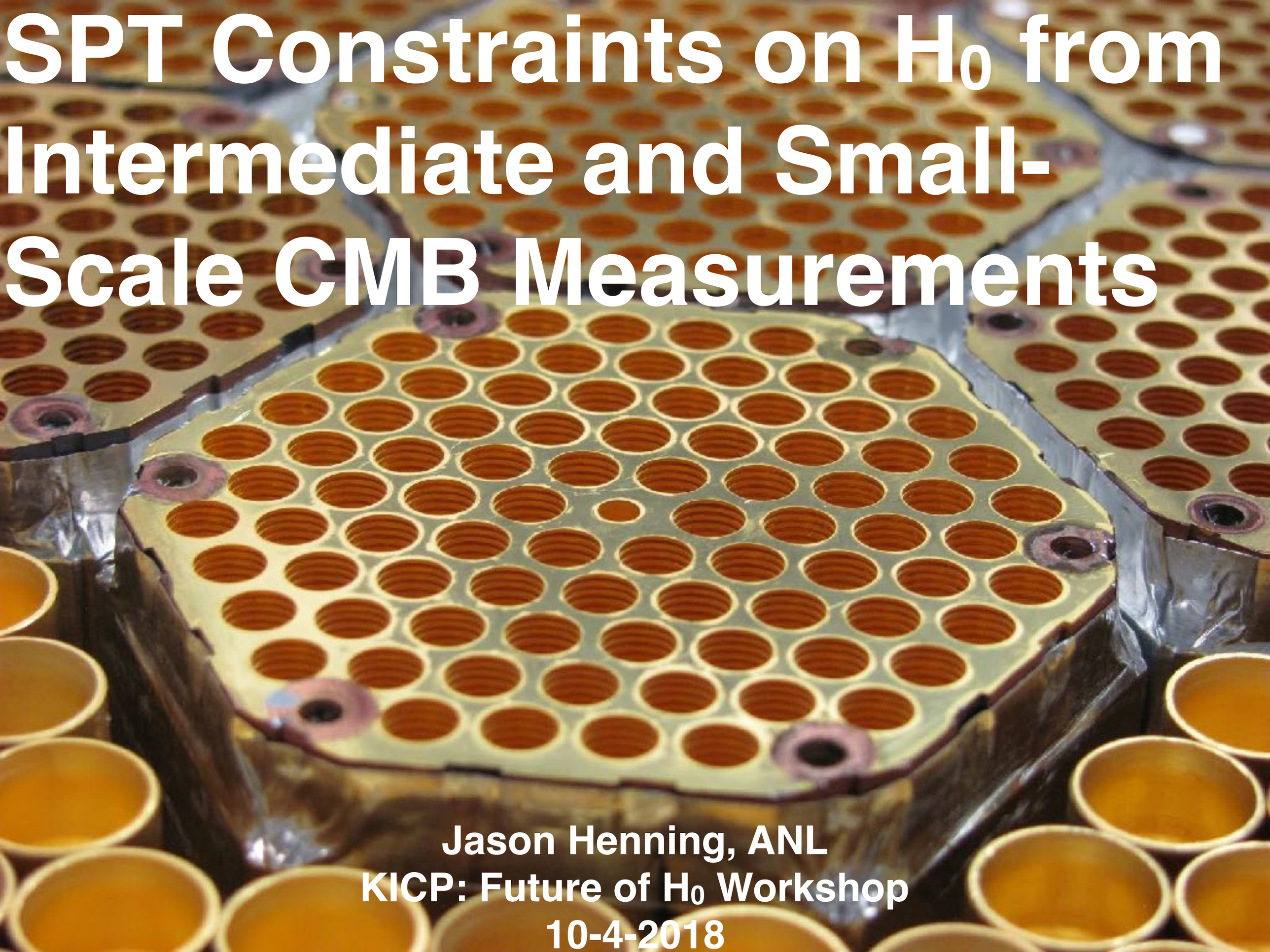
SPT Constraints on H_0 from Intermediate and Small-Scale CMB Measurements



Jason Henning, ANL

KICP: Future of H_0 Workshop

10-4-2018

Outline

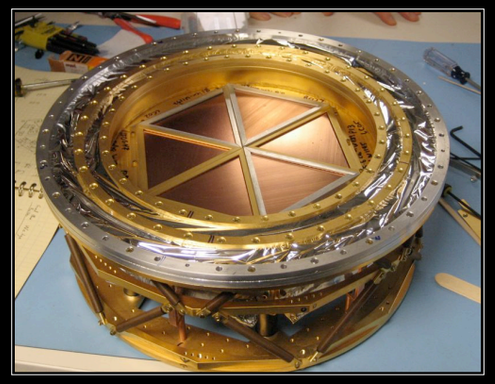
- Overview of SPT Surveys
- SPT-SZ H_0 Constraints (Hou/Aylor et al.)
- SPTpol H_0 Constraints (JWH et al.)
- Covariance Tests: SPTpol
- Additional studies and future work

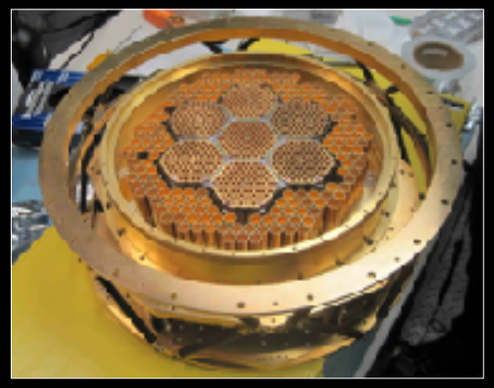
The South Pole Telescope (SPT)

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:

SPT Surveys

SPTpol Survey - 500 deg^2

~ 7 μK-arcmin map depth (T)

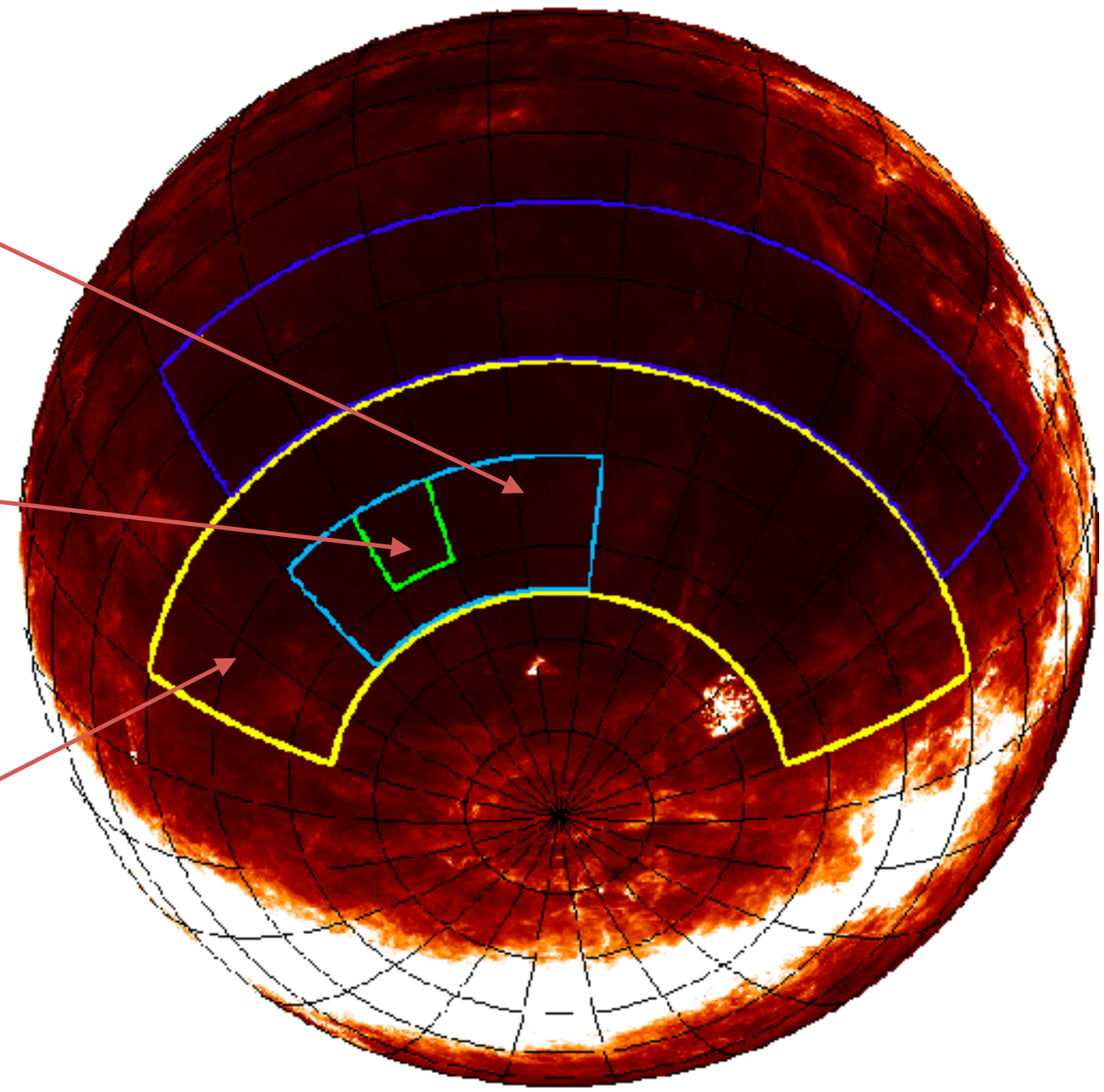
SPTpol Deep - 100 deg^2

~ 7 μK-arcmin map depth (T)

(from 2012 + early 2013 only)

SPT-SZ - 2500 deg^2

~ 18 μK-arcmin map depth (T)



IRAS dust-map

Schlegel et al., 1998

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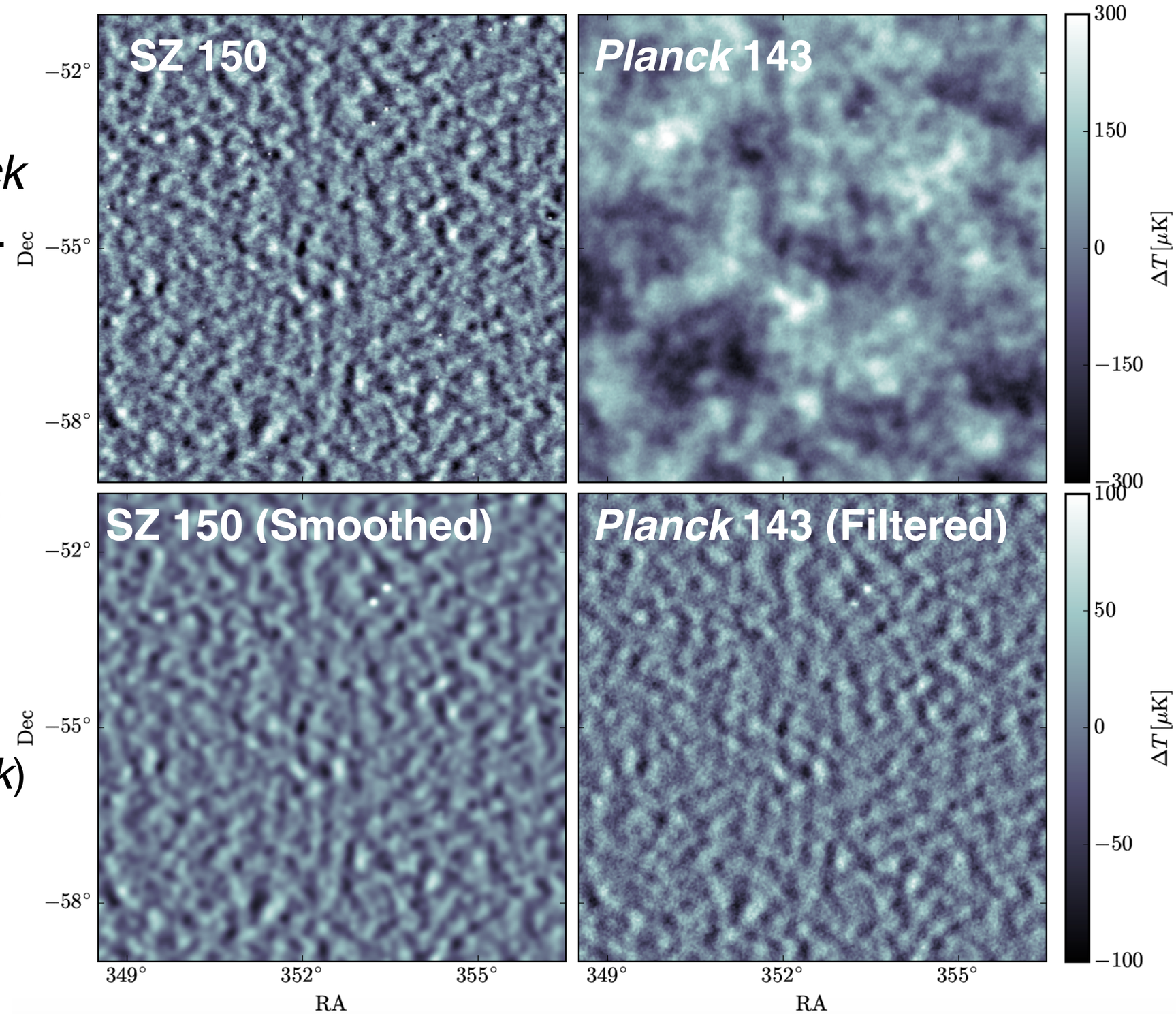
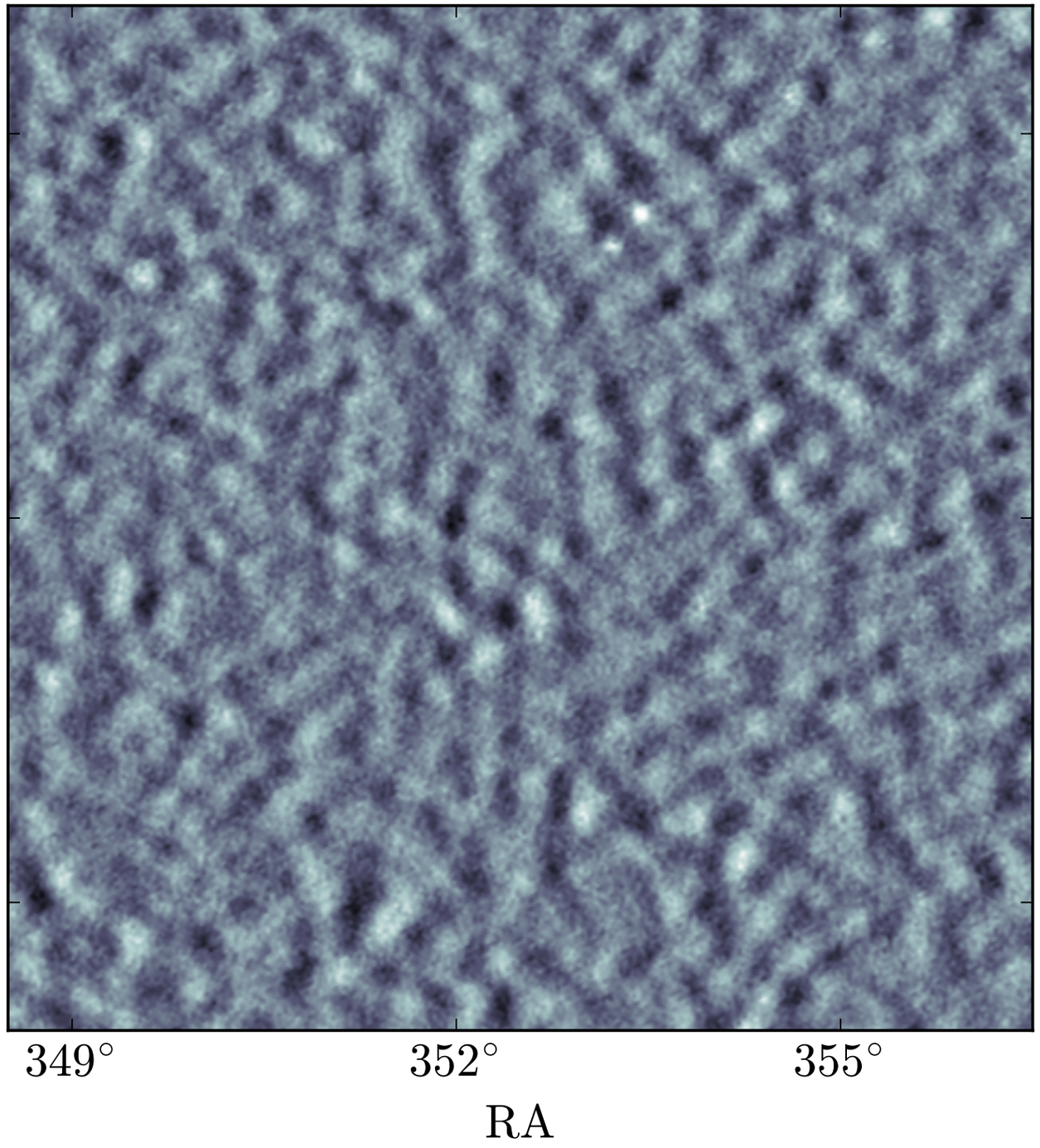
SPT-SZ Cosmological Constraints

- In-patch comparison of SPT-SZ (150) and *Planck* (143) temperature maps.
- Filter *Planck* maps to match modes in SZ.
- Study bandpowers and cosmologies for data set cross-spectra:
  - 150 x 150 (SPT x SPT)
  - 150 x 143 (SPT x *Planck*)
  - 143 x 143 (*Planck* x *Planck* in the SZ patch)

Hou et al., 2017

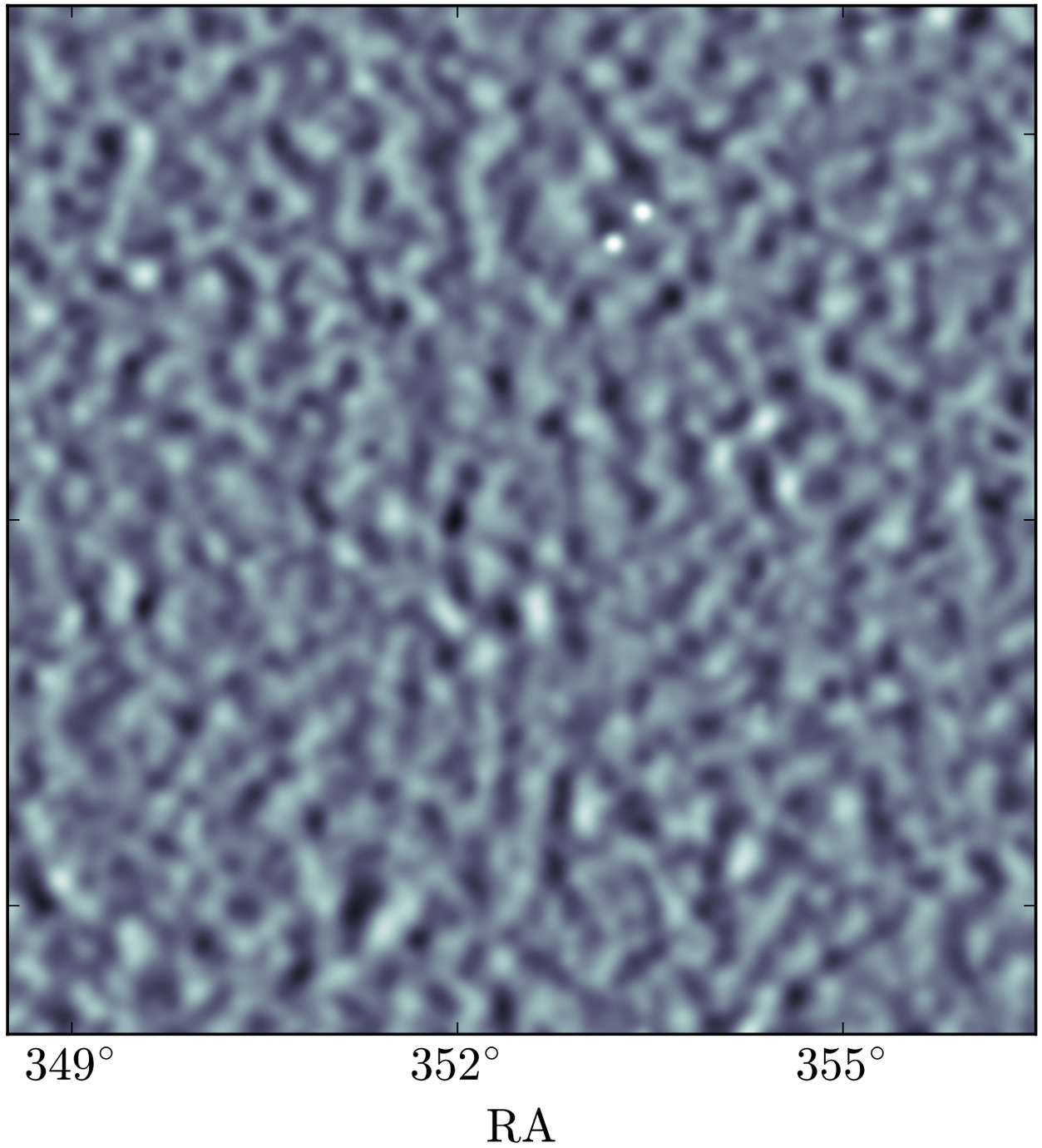


Planck 143 GHz Filtered



Courtesy L. Knox

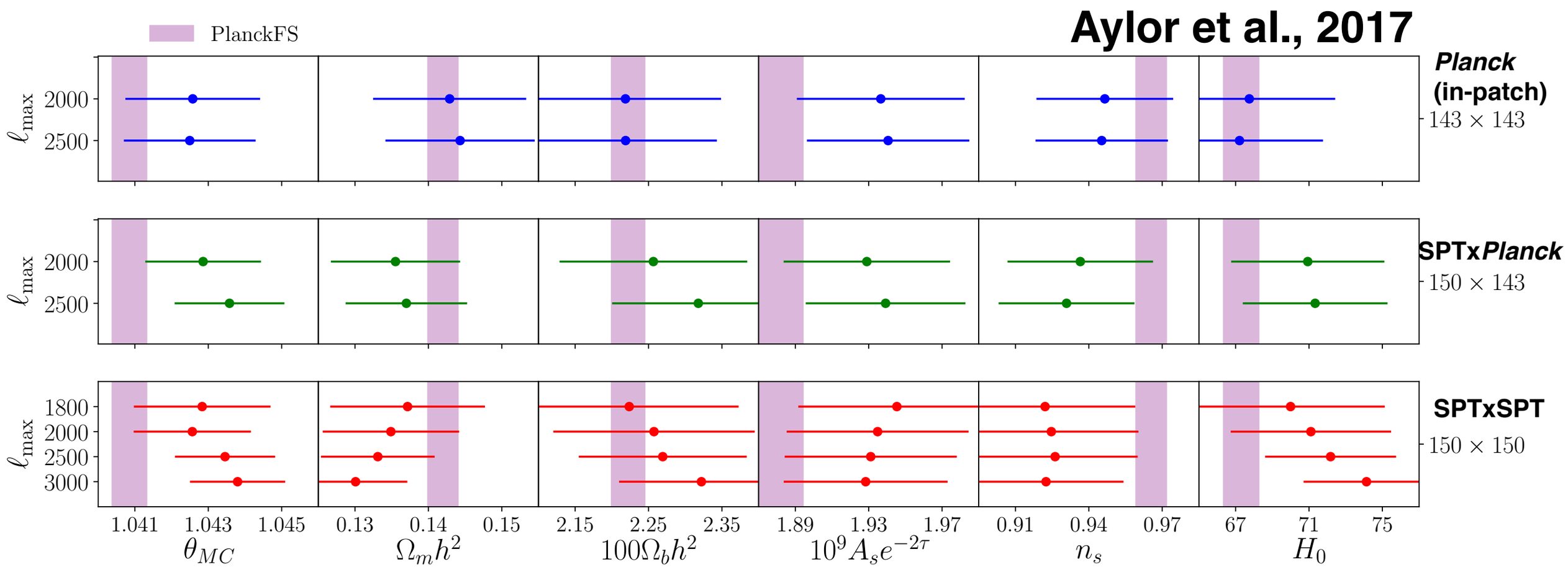
SPT 150 GHz Smoothed



Courtesy L. Knox

SPT-SZ Cosmological Constraints

- Comparison of cosmologies from SPT-SZ (150) and *Planck* (143) temperature spectra.
- Density parameters (and H_0) shift away from *Planck* full-sky (FS) in SPTxSPT when higher multipole information added.
- Consistent with *Planck* FS, but constraints are weak since sample variance included and shared between data sets.



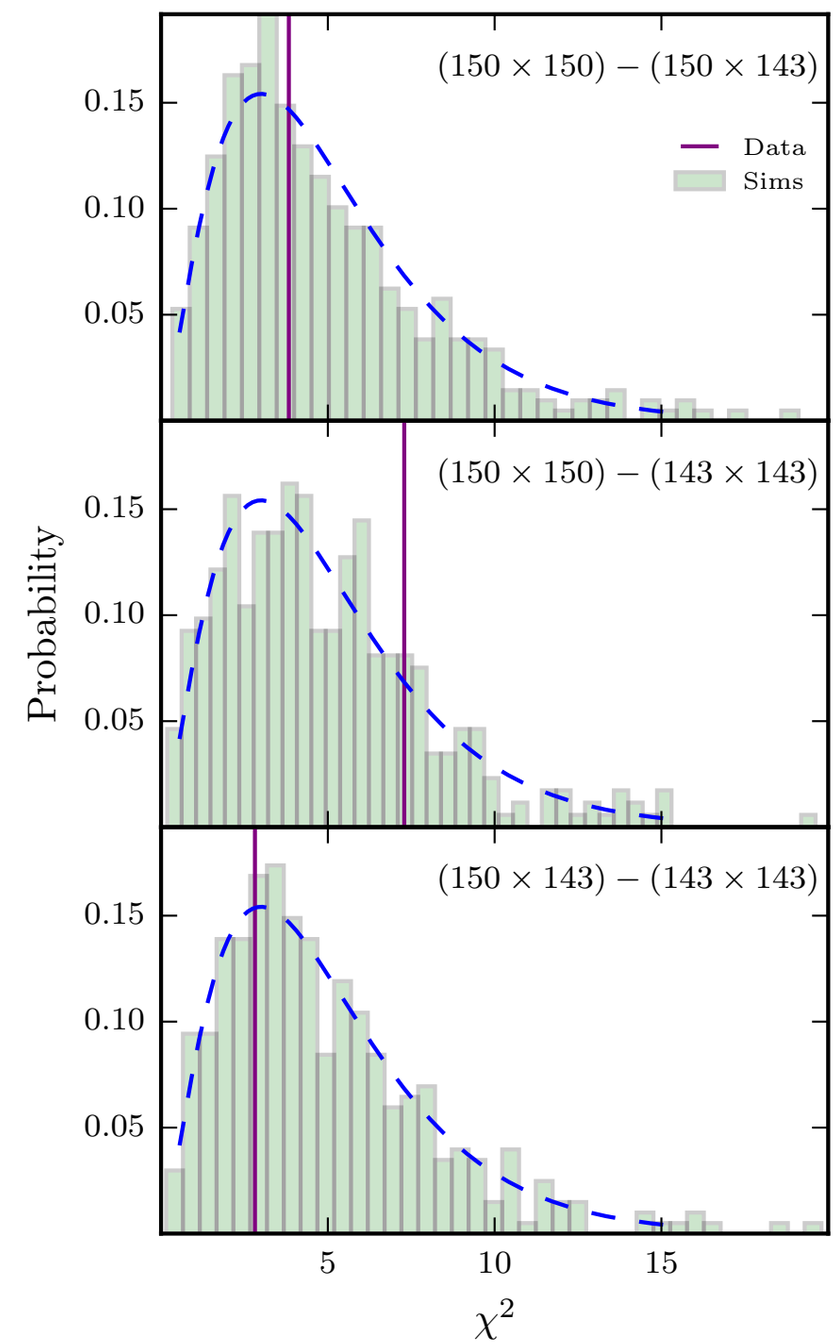
SPT-SZ Cosmological Constraints

- Considering differenced spectra removes sample variance.
- Comparing simulated realizations of differenced spectra to data yields reasonable PTEs at several maximum multipole cuts.
  - Parameter constraints from all 3 cross-spectra consistent with null hypothesis (ΛCDM, and statistical models of data sets are accurate).

TABLE 1
PTEs Between Parameters in SPT Sky Patch.

	$\ell_{\max}$		
	2000	2500	3000
$150 \times 150 - 150 \times 143$	0.74	0.66	0.57
$150 \times 150 - 143 \times 143$	0.32	0.38	0.20
$150 \times 143 - 143 \times 143$	0.62	0.73	

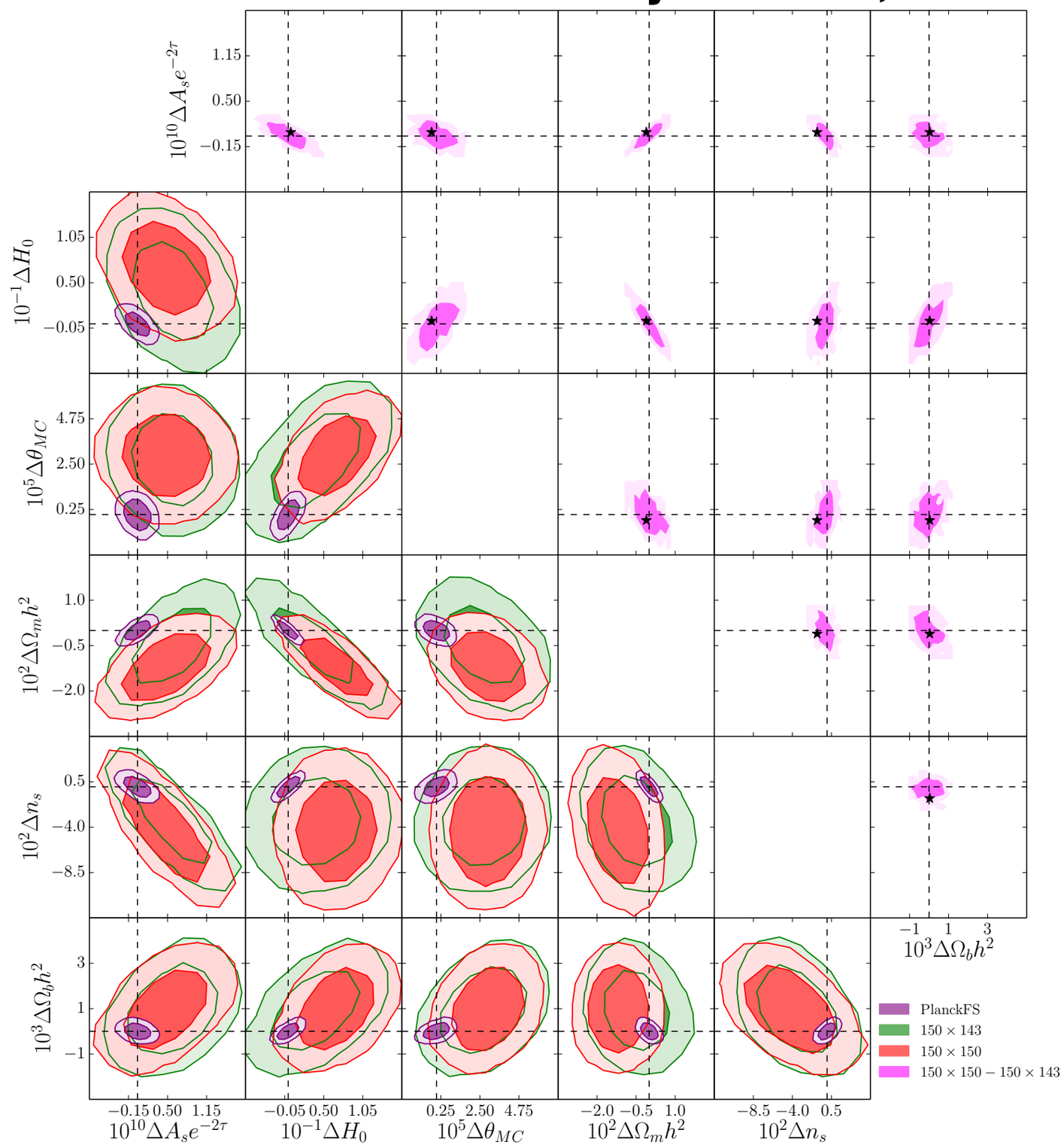
Aylor et al., 2017



SPT-SZ Cosmological Constraints

Aylor et al., 2017

- Lower triangle: Posterior parameter distributions for 150x150, 150x143 (both ℓ_{max}=2000), and *Planck* FS (all with *Planck* FS best-fit subtracted).
- Upper triangle: Posterior distributions from sim realizations of 150x150 - 150x143 bandpowers (ℓ_{max}=2000).
  - Black stars are parameter differences in the data.
  - Differences reduce parameter space volume by 300! -> strong test of instrumental systematics.



SPT-SZ Cosmological Constraints

Conclusions from Aylor et al. 2017:

1) Cosmology is consistent between SPT-SZ and *Planck* when restricted to measuring identical modes ($650 \leq \ell \leq 2000$ in SPT-SZ patch).

2) No tension between data sets when restriction on **either** sky coverage **or** multipole range is relaxed. Only in tension ($\sim 2\ \sigma$) when **both** are relaxed.

3) Including high-ell SPT-SZ data ($2000 \leq \ell \leq 3000$) drives density parameters away from *Planck* FS results, pushing H_0 higher.

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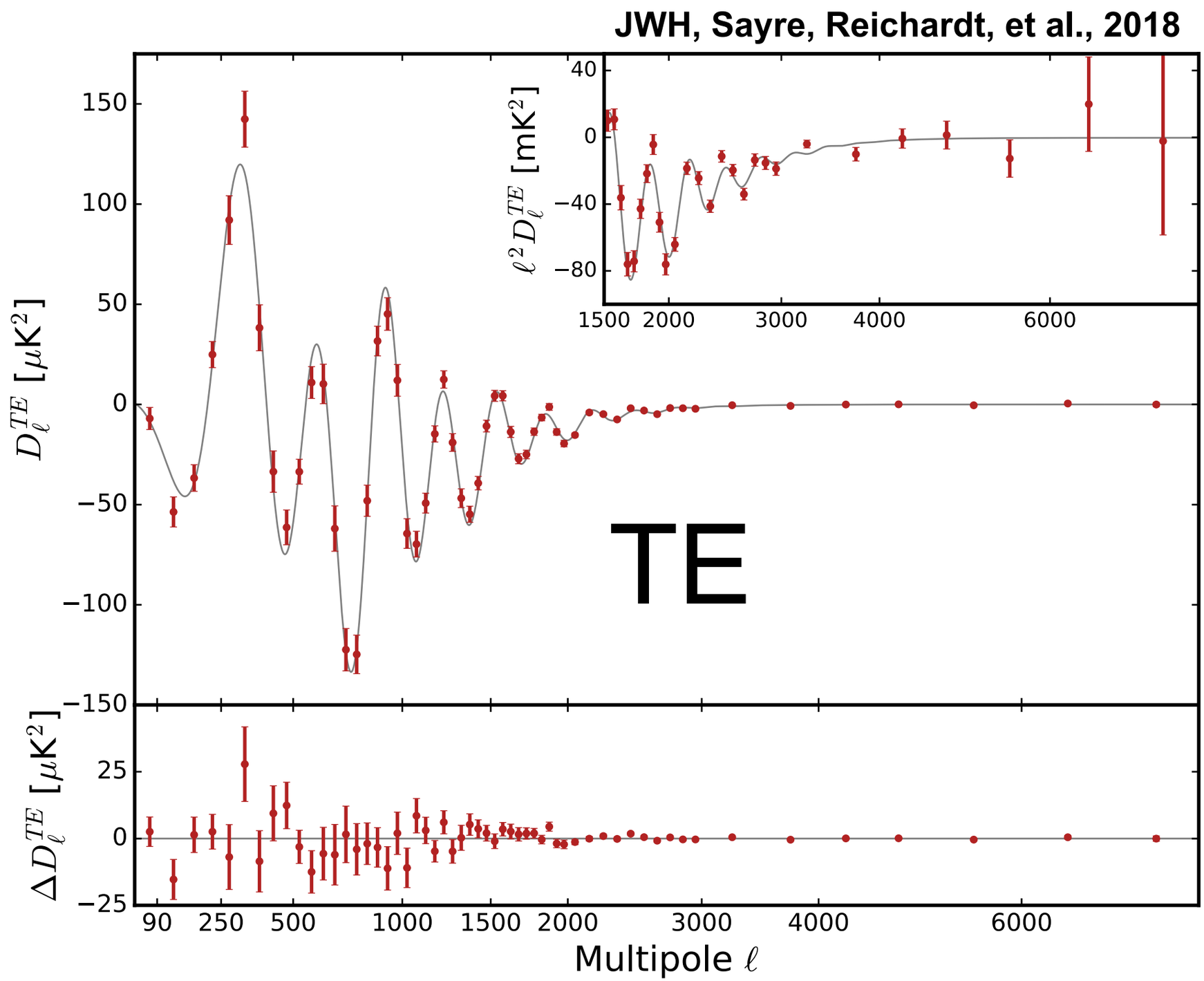
SPTpol 500 Deg² Field Power Spectra

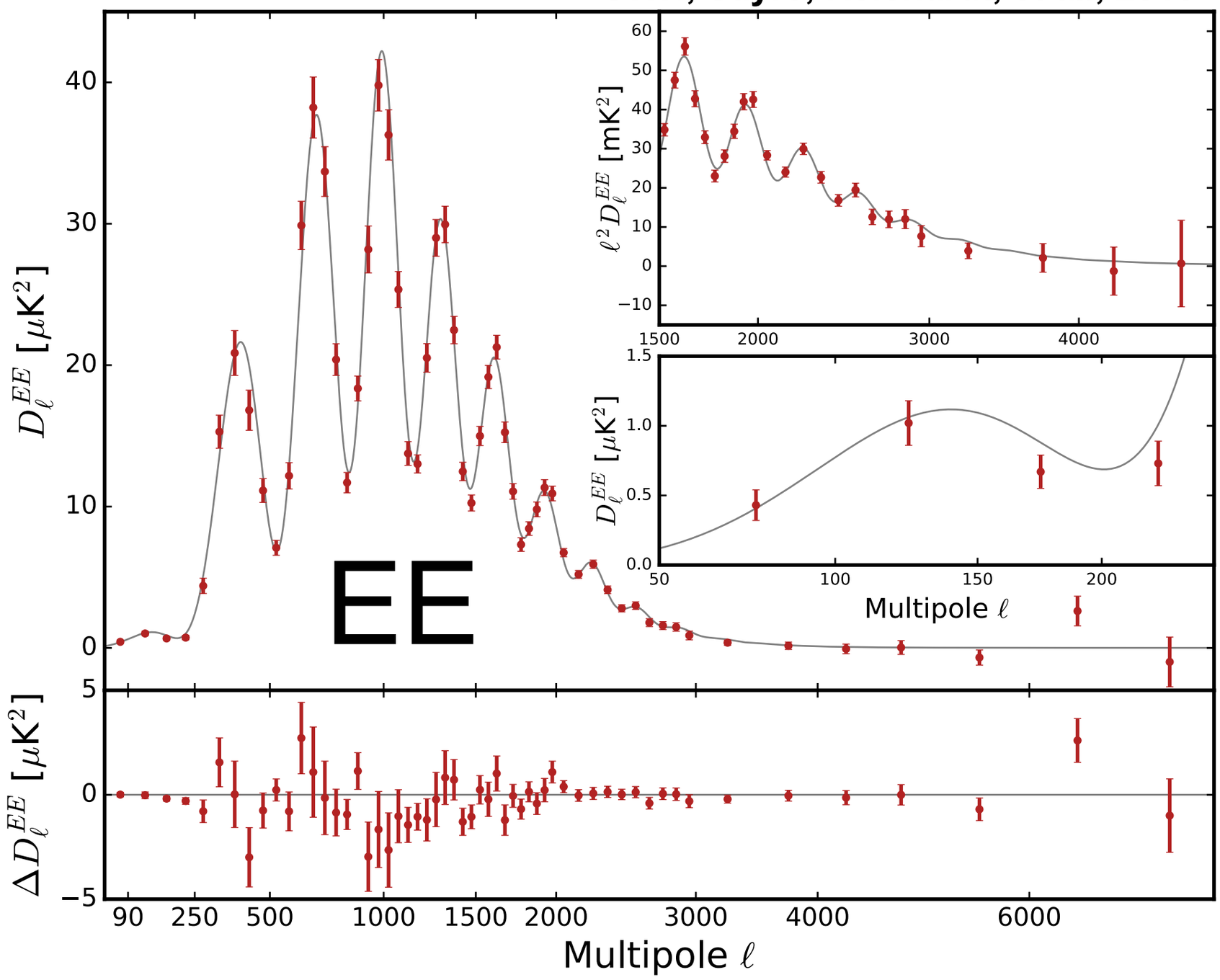
- Theory curve is *Planck* 2015 plikHM_TT_lowTEB (*Planck*TT)
- Residuals calculated against this theory
- Only sample and noise variance
- Sample-variance limited at $\ell < 2050$



SPTpol 500 Deg² Field Power Spectra

- Sample-variance limited at $\ell < 1750$
- 9 acoustic peaks between $50 < \ell < 3000$
- **$D_\ell^{PS} < 0.1$ μK² 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 (upper limits on power)!

JWH, Sayre, Reichardt, et al., 2018



SPTpol Cosmological Constraints

- "Low-ℓ" SPTpol data ($\ell < 1000$) in good agreement with *Planck*TT results.

$$H_0 = 67.5 \pm 4.0\,\mathrm{km\ s^{-1}Mpc^{-1}}$$

("Low-ℓ" SPTpol range)

- Adding "high-ℓ" data ($\ell > 1000$) pushes H_0 higher compared to *Planck*TT:

$$H_0 = 73.5 \pm 3.7\,\mathrm{km\ s^{-1}Mpc^{-1}}$$

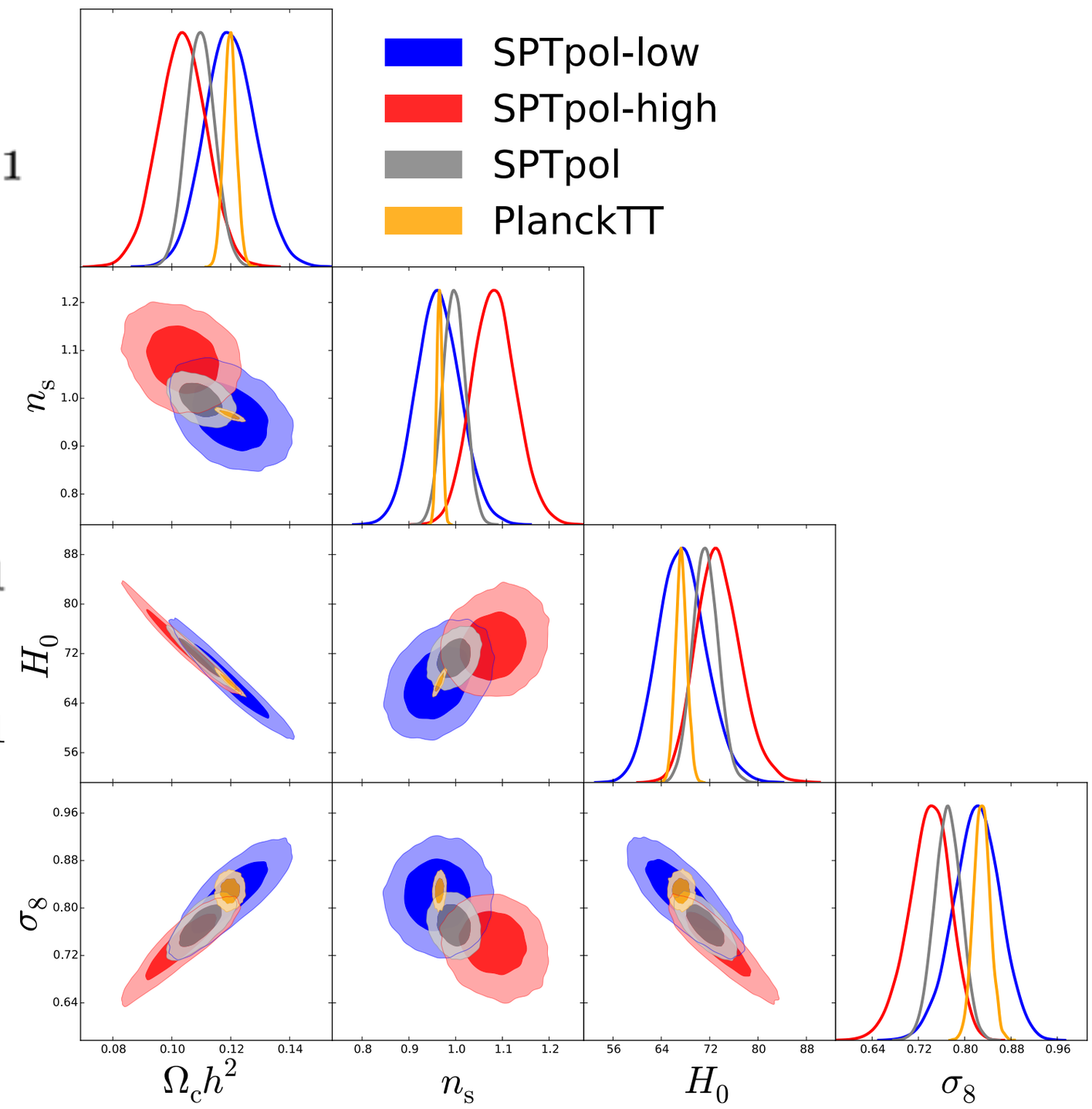
("High-ℓ" SPTpol range)

$$H_0 = 71.3 \pm 2.1\,\mathrm{km\ s^{-1}Mpc^{-1}}$$

(Full SPTpol range)

- Similar to trends seen in Aylor et al. 2017 (but now in polarization, and 1/5 the area).

JWH, Sayre, Reichardt, et al., 2018



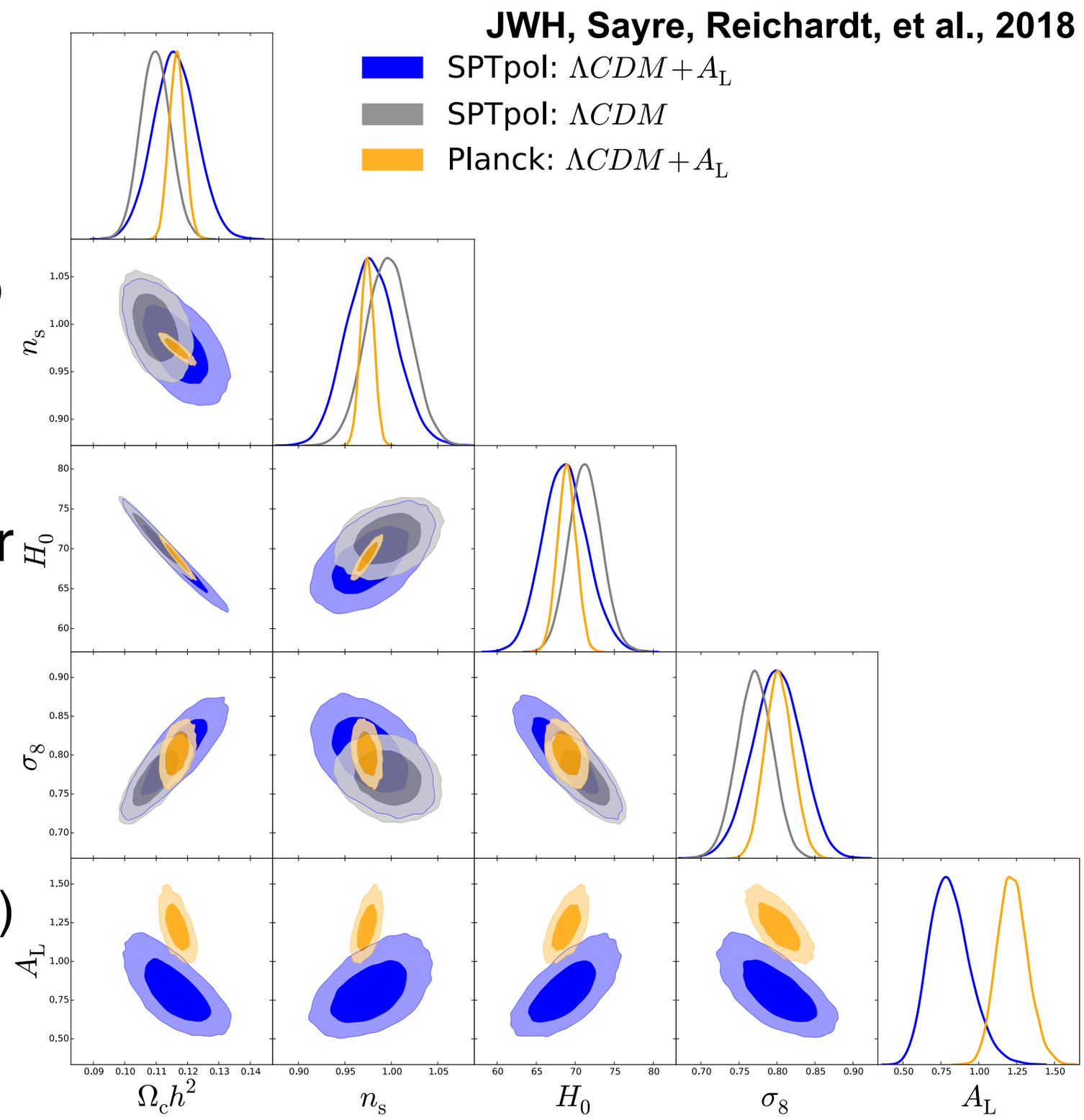
SPTpol Cosmological Constraints

- Marginalizing over A_L brings (full-range) SPTpol and *Planck* constraints into agreement.

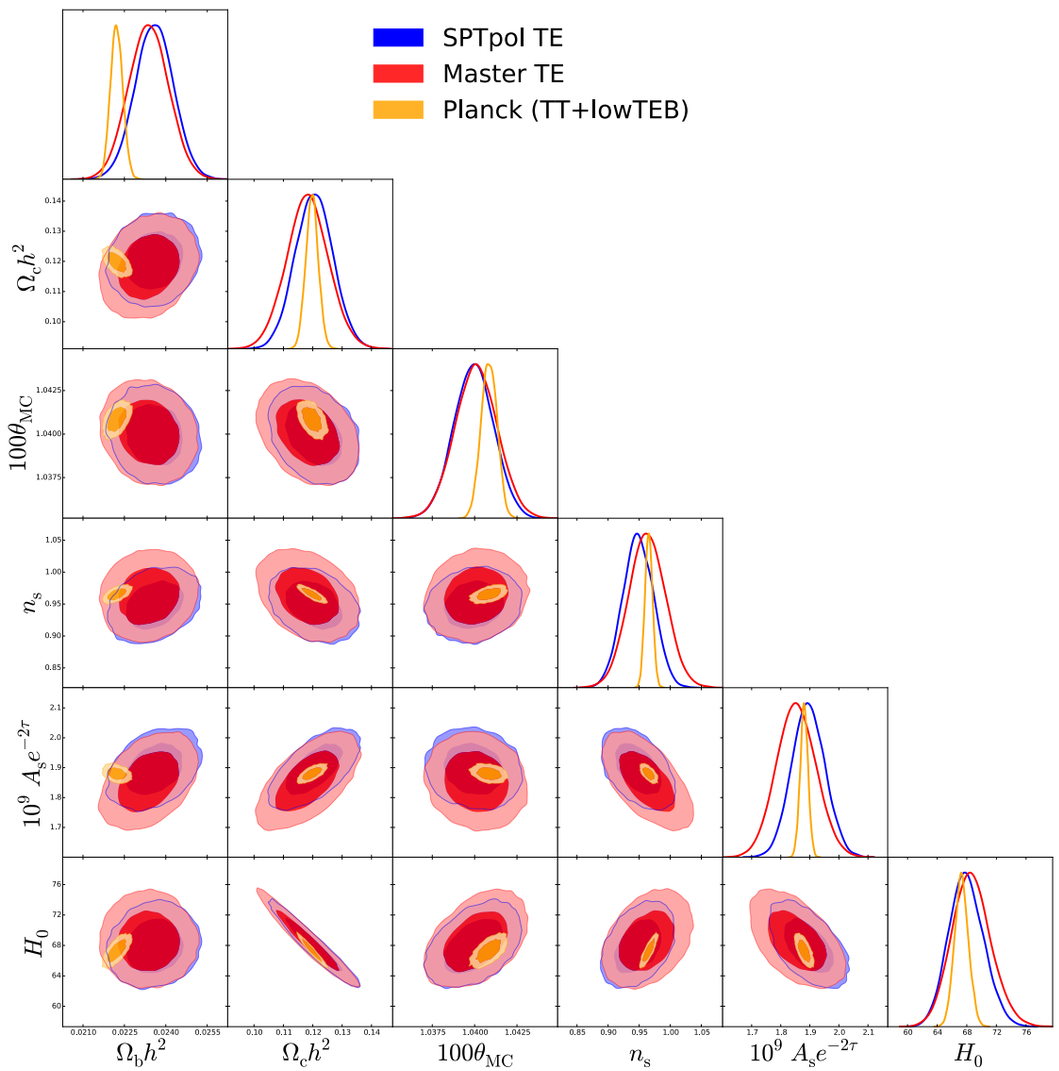
- SPTpol finds A_L 2.9 σ lower than value preferred by *Planck*TT:

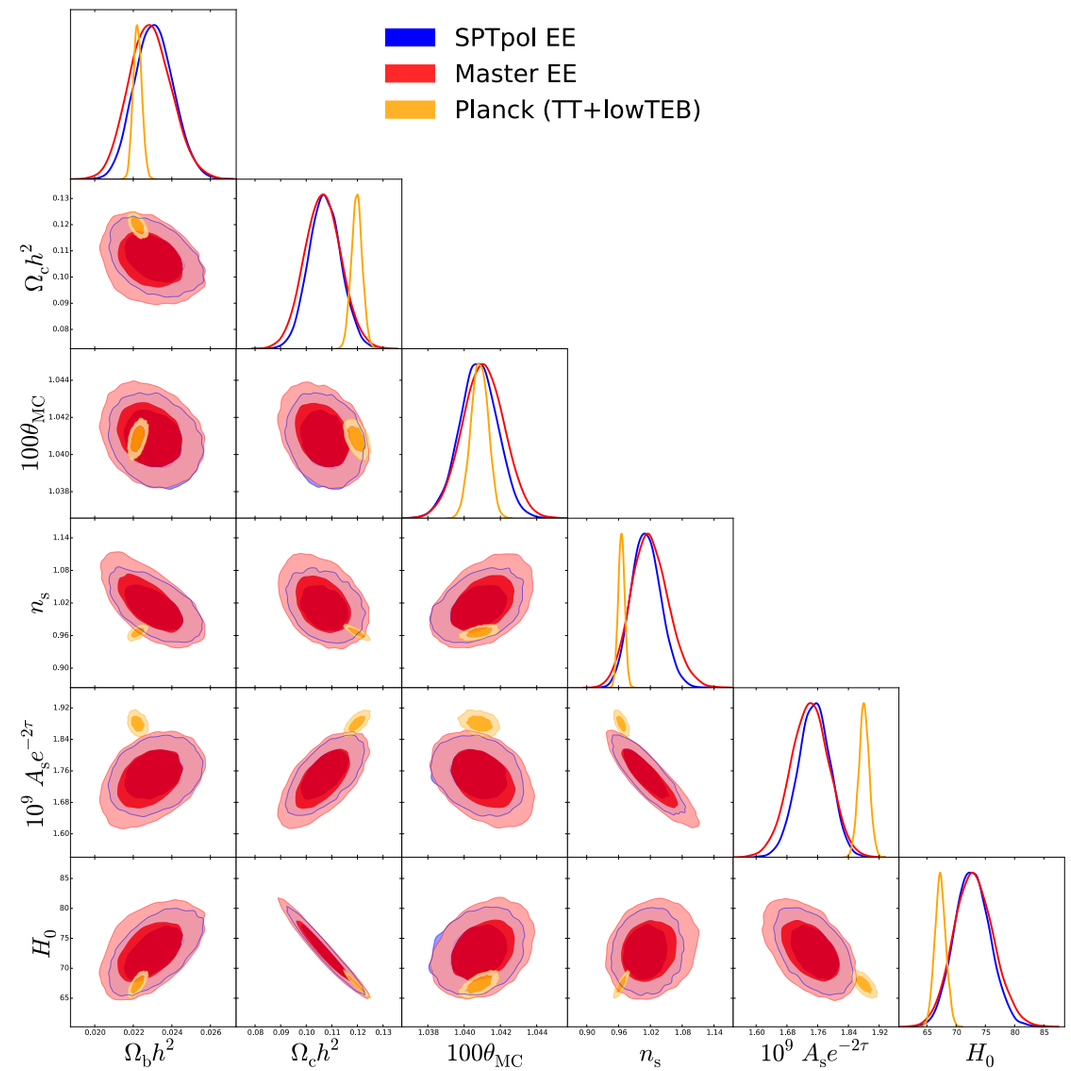
$$A_L = 0.81 \pm 0.14 \text{ (SPTpol)}$$

$$A_L = 1.22 \pm 0.10 \text{ (}Planck\text{TT)}$$



Improved TE/EE PTEs





- Bug in likelihood caused small shifts in TE-only and EE-only parameter constraints (blue -> red).
- Does not affect TE+EE constraints.
- New generalized SPT likelihood corrects problem (and public SPTpol likelihood is patched).
- Calculating PTEs for SPTpol bandpowers compared to best-fit SPTpol ΛCDM model:
  - TE: PTE = 0.007 (blue=old value), PTE = 0.042 (red=new value)
  - EE: PTE = 0.022 (blue=old value), PTE = 0.113 (red=new value)

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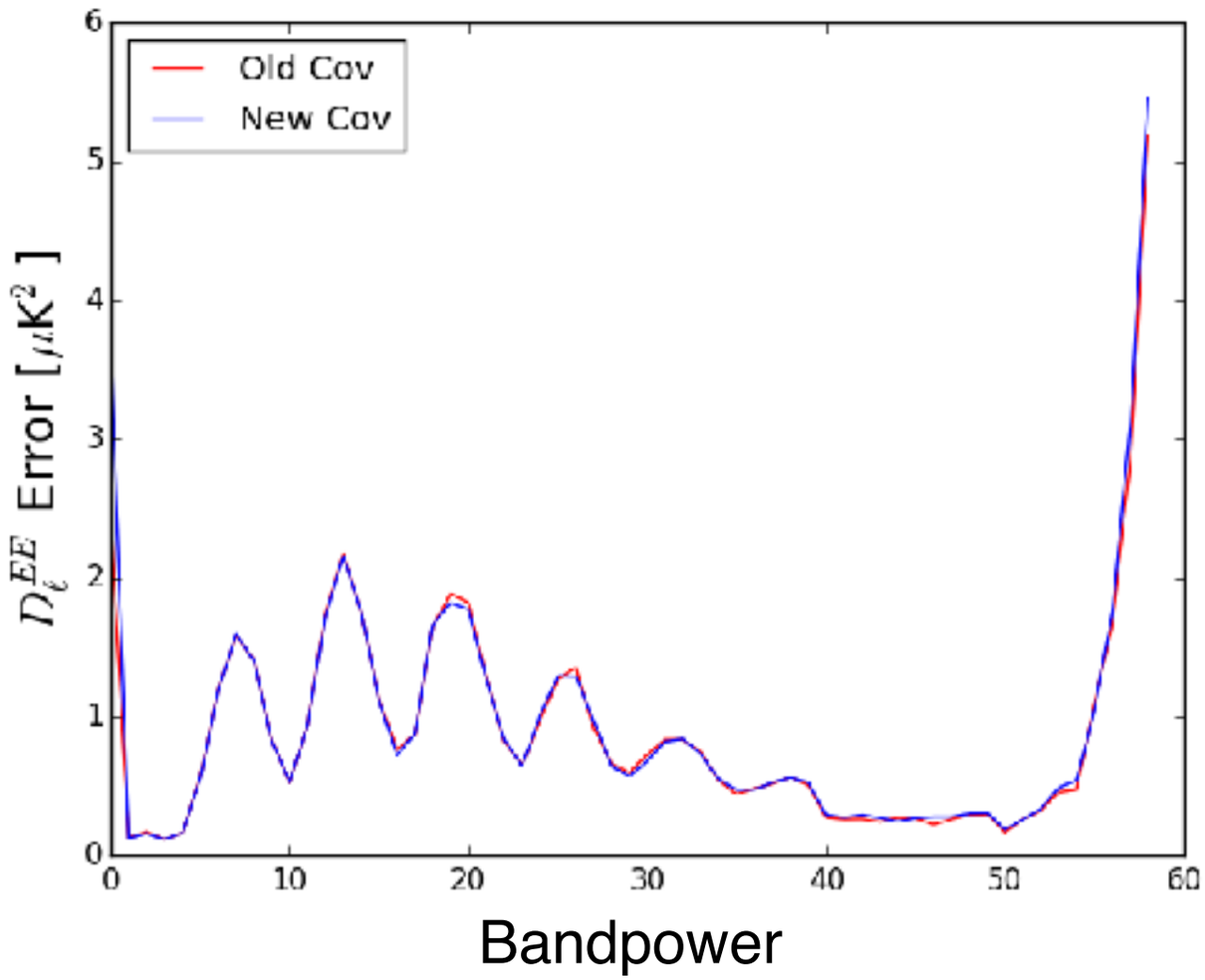
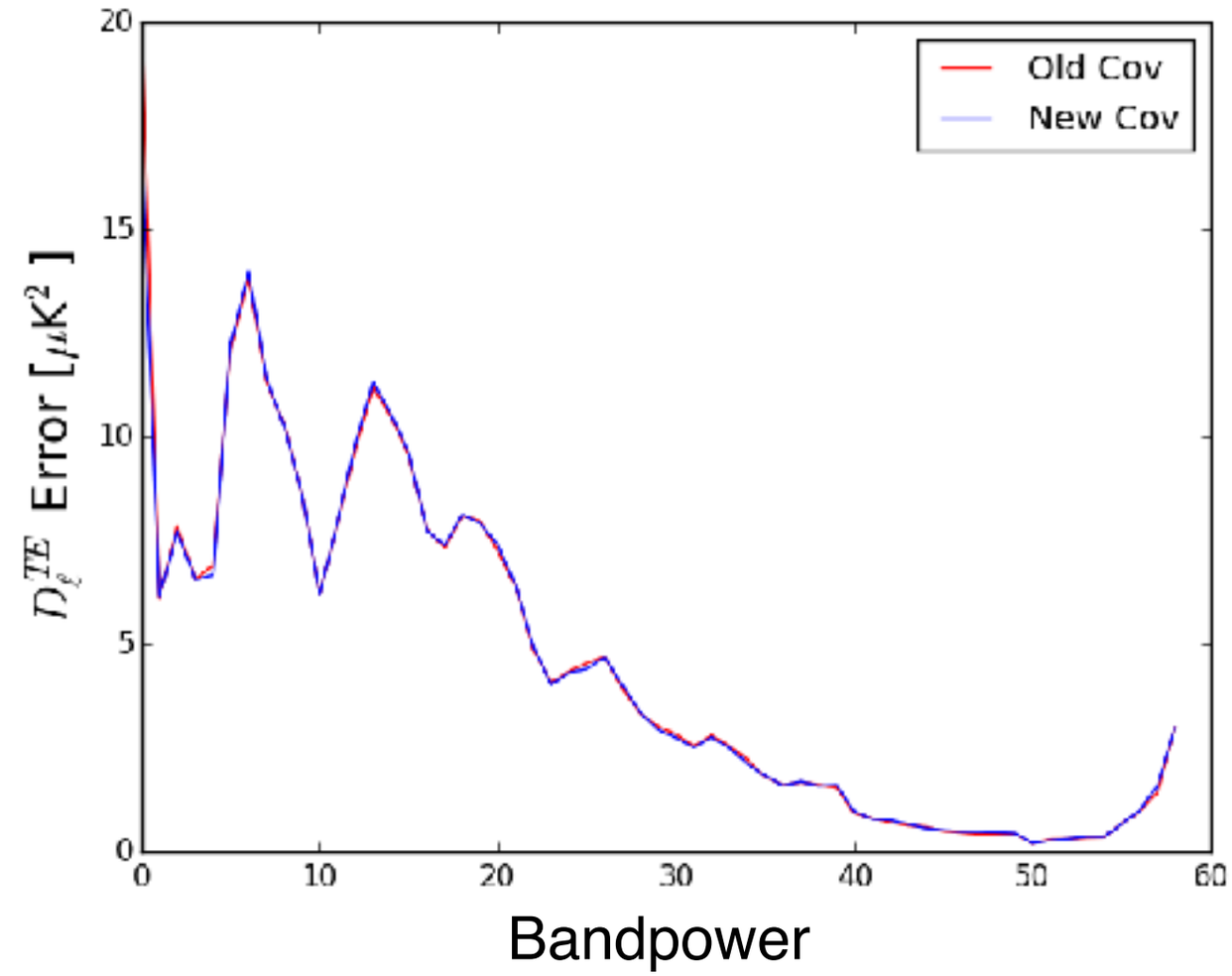
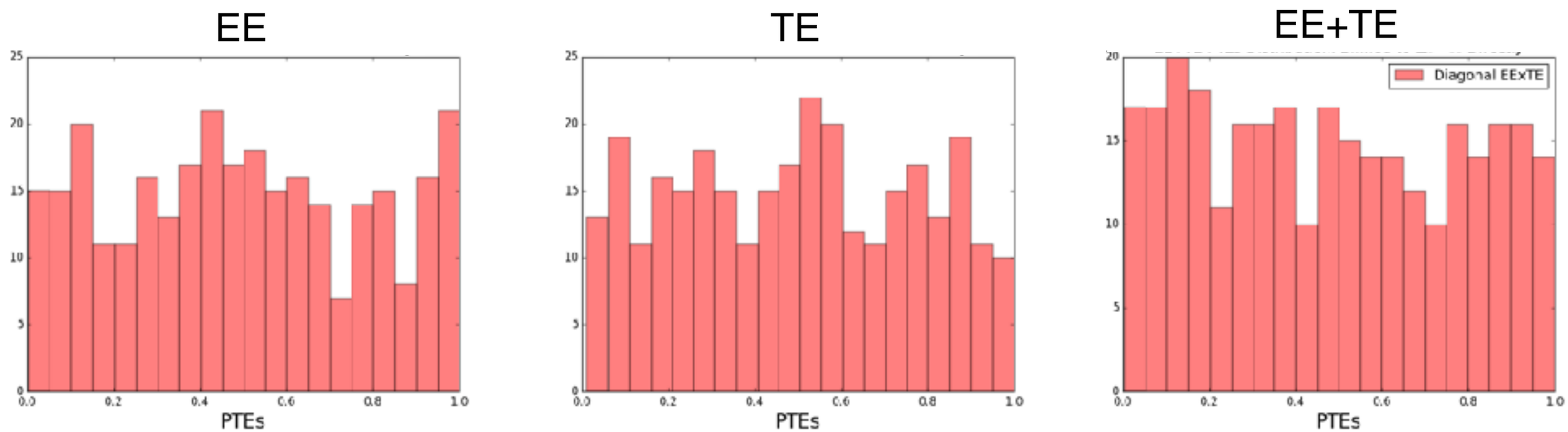
SPTpol Covariance Tests





- Two methods of covariance construction yield consistent bandpower errors.
  - 1) Signal-only sims for sample variance, noise variance + S*N terms from SPTpol data. (Old).
  - 2) Construct full covariance from signal+noise sim realizations.
    - (Noise constructed from SPTpol data jackknives). (New).

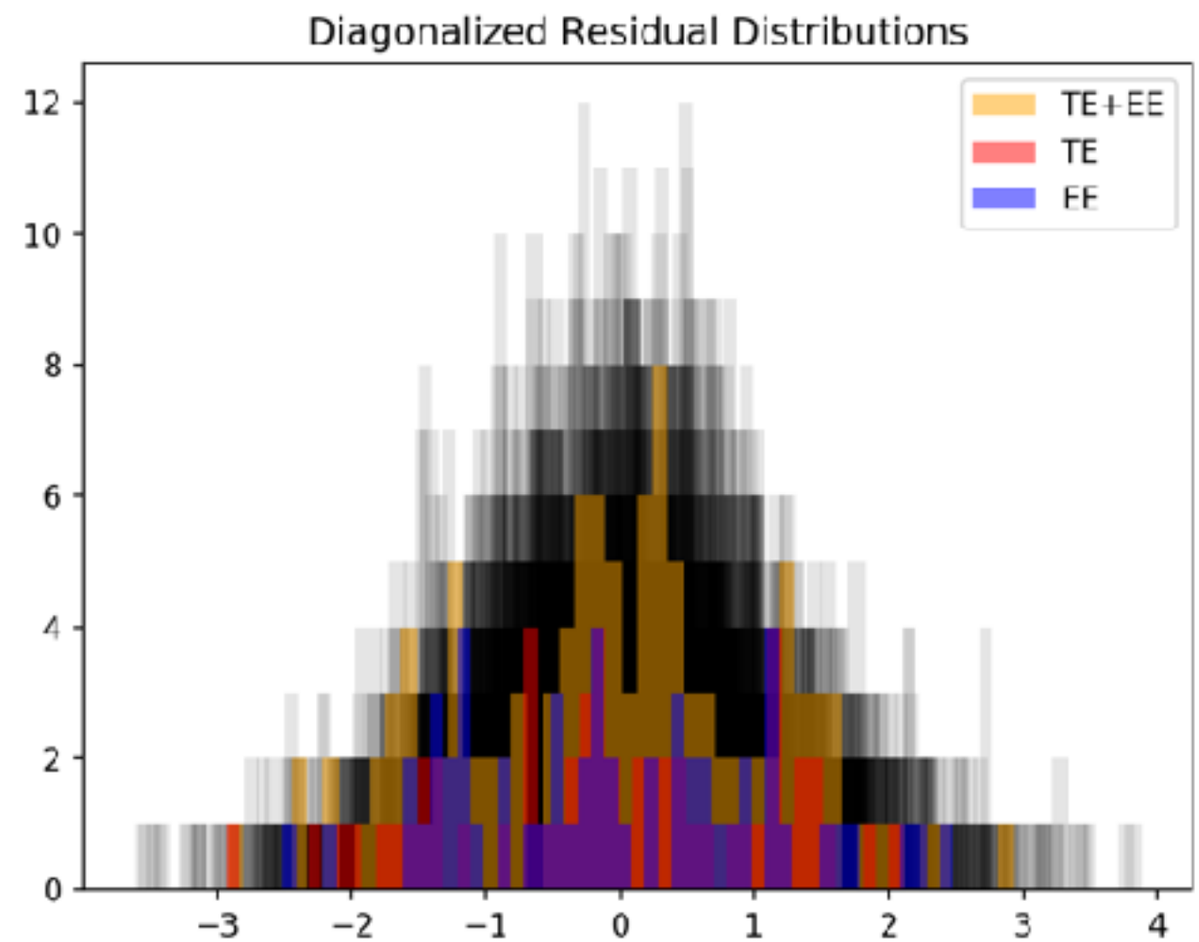
SPTpol Covariance Tests



- Is sample variance self-consistent with input cosmology in sims?
  - Bandpower χ^2 test comparing 300 realizations of bandpowers to binned input theory yields PTE distributions consistent with being uniform.
  - Covariance matrix is self-consistent with sim realizations.

SPTpol Covariance Tests

- Are SPTpol residuals to *Planck* too large compared to SPTpol covariance?
  - Diagonalize covariance, and divide transformed residual bandpowers by errors (eigenvalues of new covariance).
  - Distribution of normalized residuals should be Gaussian with σ=1.
  - Repeat 100,000 times by drawing from SPTpol covariance (black).
  - No evidence SPTpol data residuals are statistically inconsistent with covariance.



Fraction of Sims Outside Data Residual Bounds

	Lower	Higher	Lower+Higher
TE+EE	0.182	0.170	0.030
TE	0.176	0.866	0.152
EE	0.491	0.520	0.253

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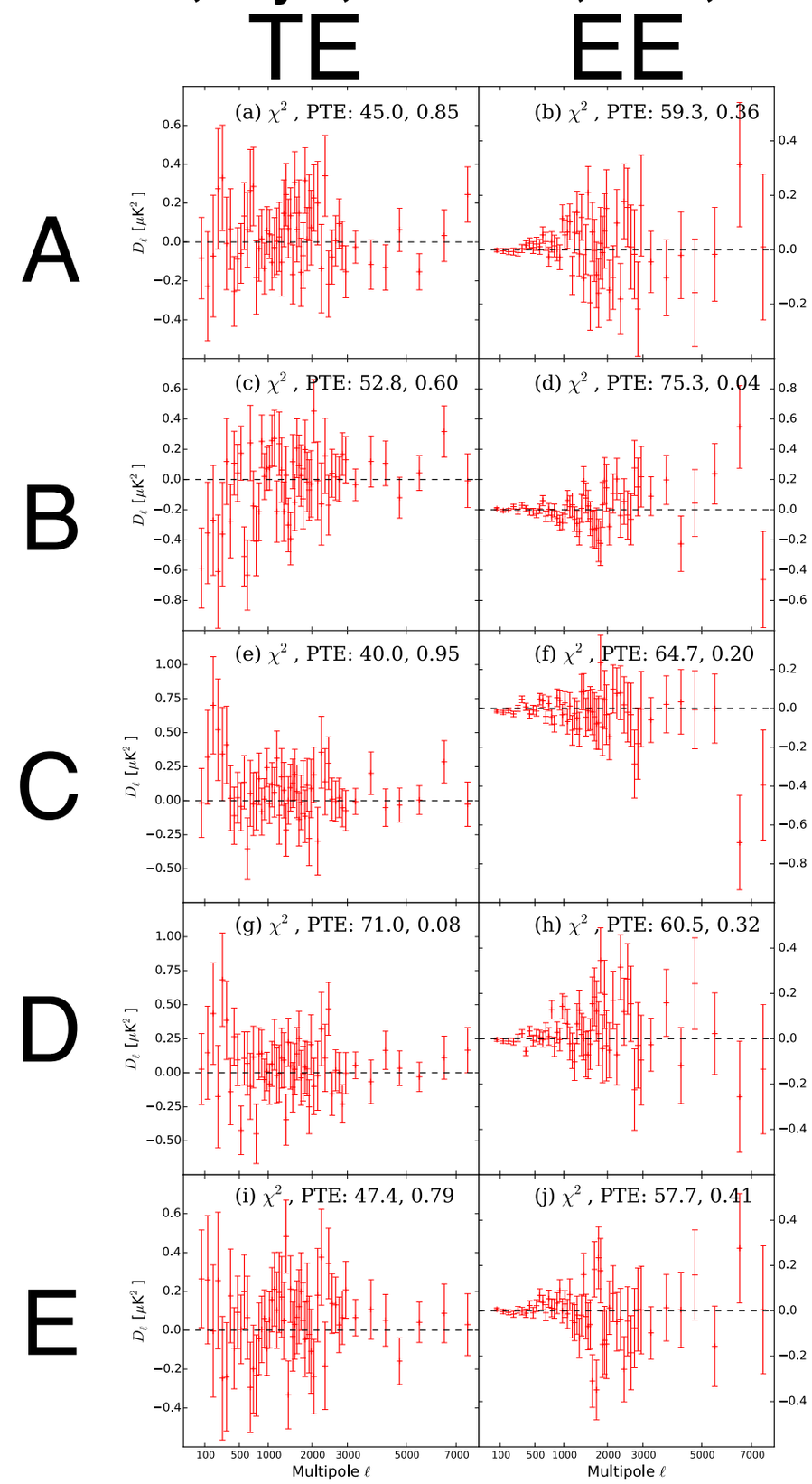
Statistics or Systematics?

- TE and EE data pass jackknife tests.
  - A. Left-going - Right-going
  - B. First-half - Second-Half
  - C. Sun up/down
  - D. Moon up/down
  - E. Azimuth
- Null spectra plotted in pseudo-D_ℓ space, so mode-coupling and other correlations still present.
- Null spectra amplitude several times smaller than TE and EE residuals to *PlanckTT* cosmology.
- Additional tests:
  - T->P monopole leakage robust to changes in multipole. Errors in leakage correction negligible for TE/EE spectra.
  - Detector responsivity does not change appreciably with elevation.

Null Test PTEs

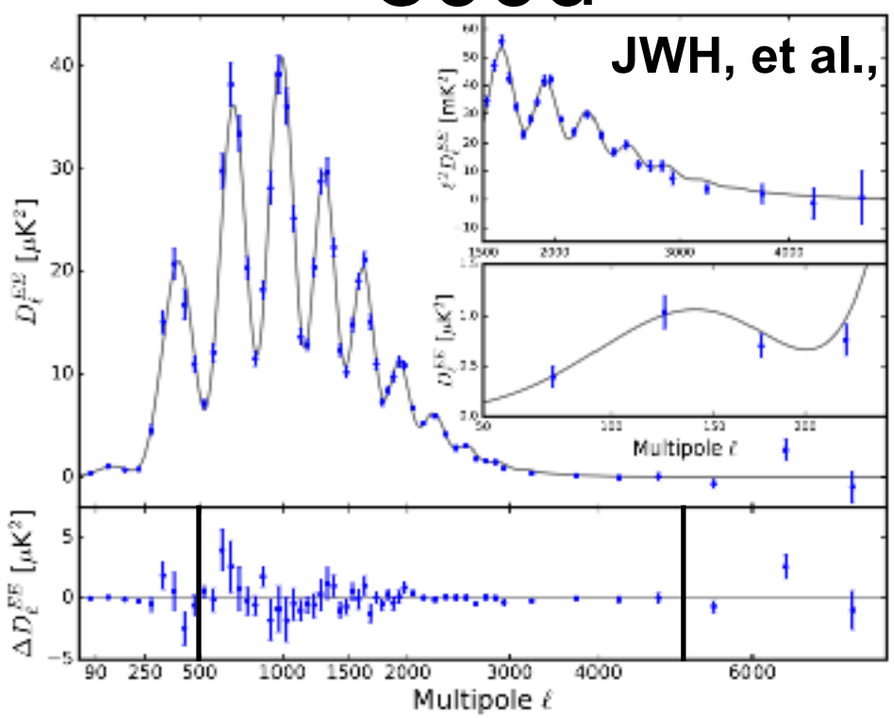
	TE	EE
A	0.85	0.36
B	0.60	0.04
C	0.95	0.20
D	0.08	0.32
E	0.79	0.41

JWH, Sayre, Reichardt, et al., 2018

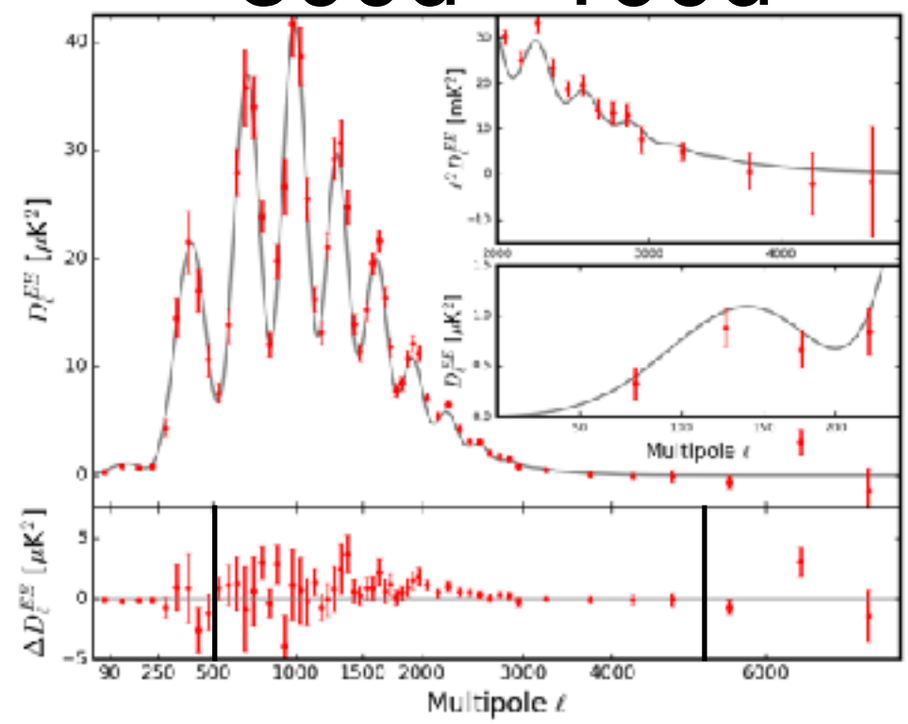


Statistics or Systematics?

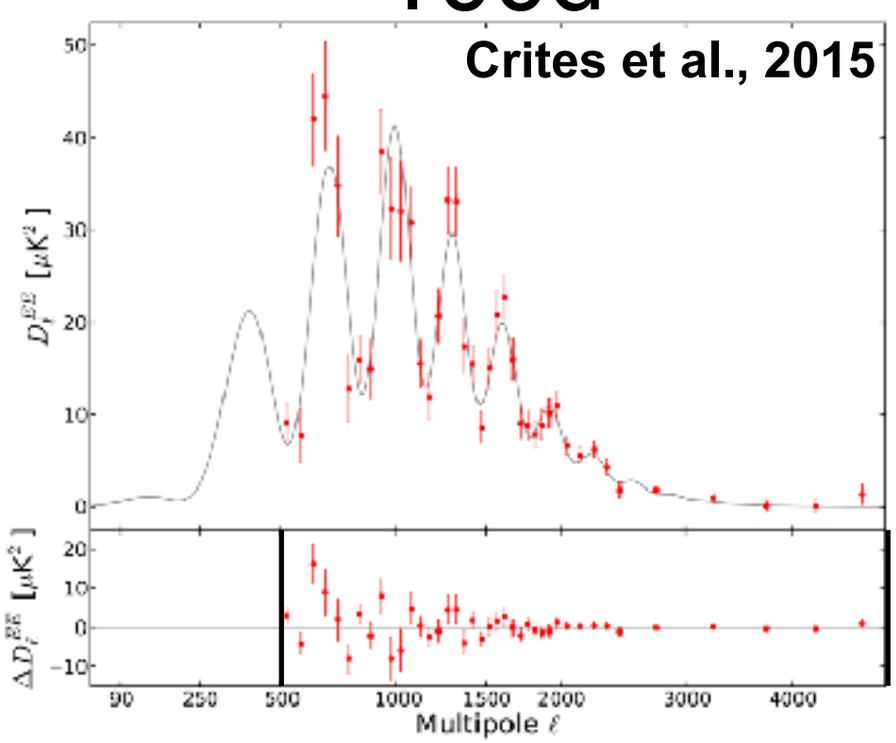
500d



500d - 100d

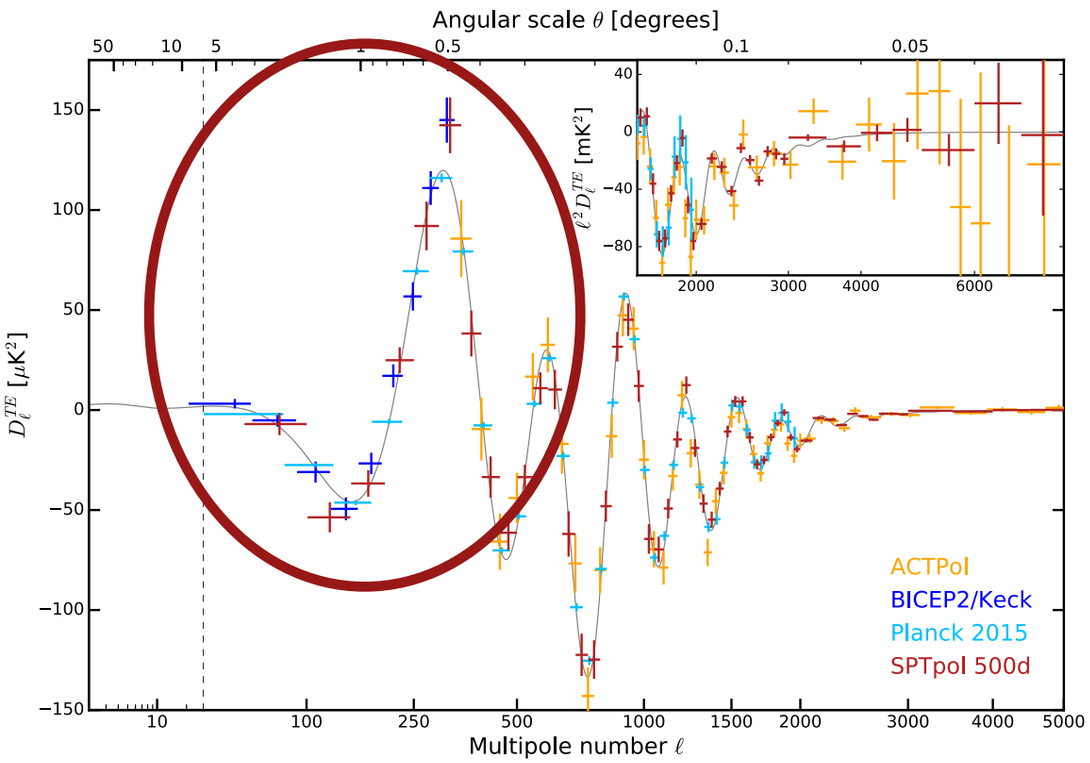


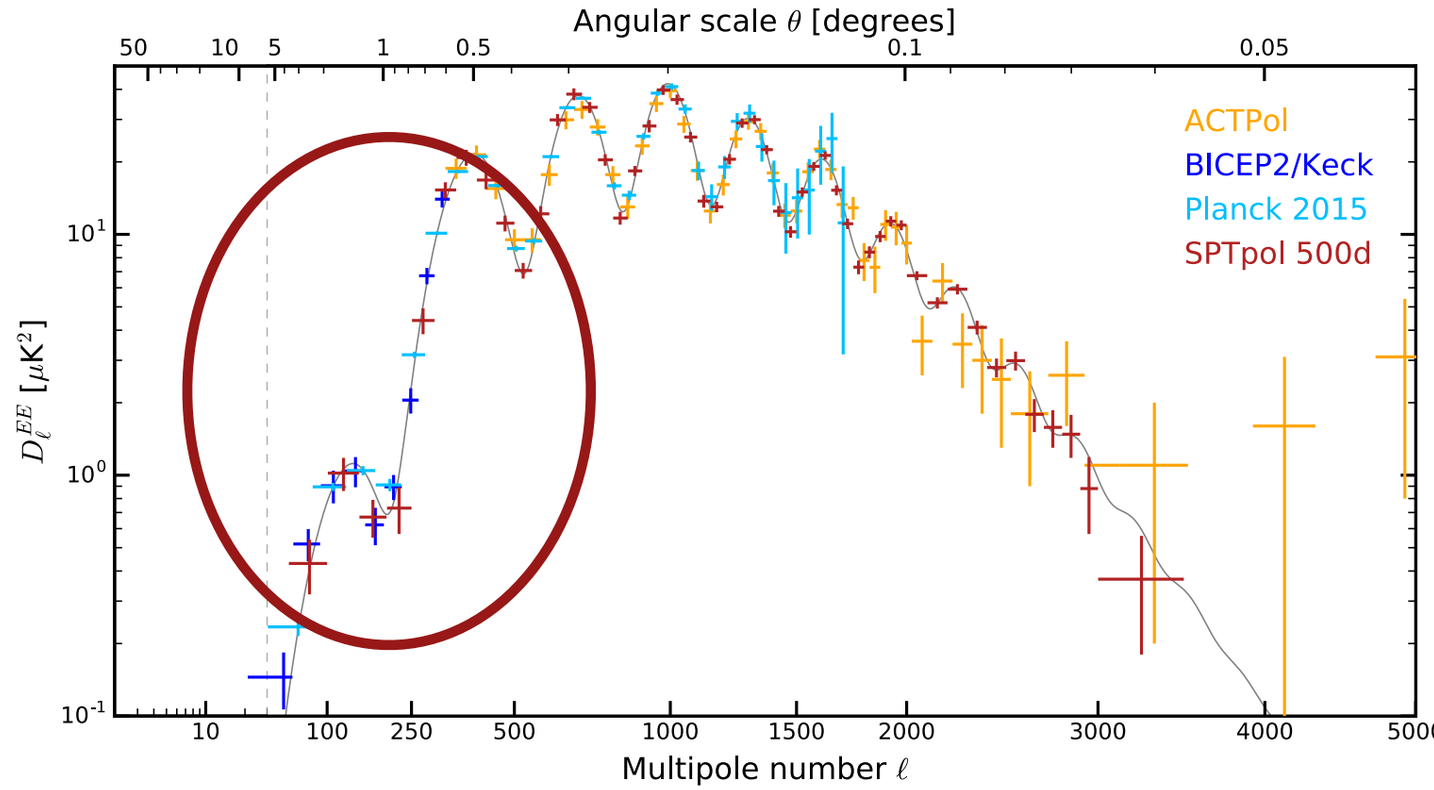
100d



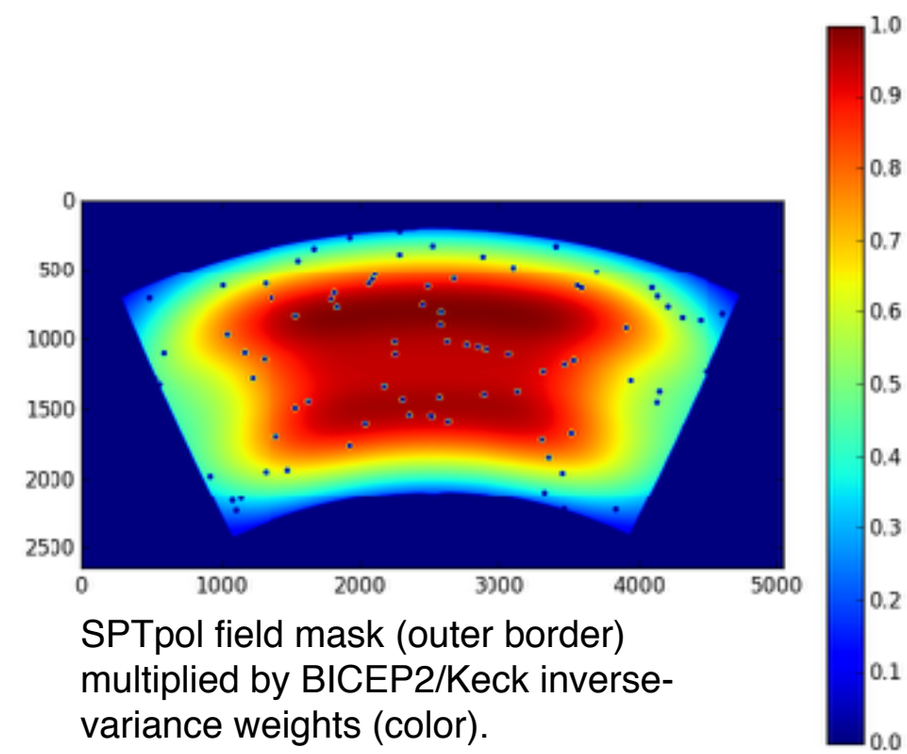
- Residuals between 500d and 100d results have similar structure in overlapping multipole range, but scaled by difference in area.
- No shared data between 500d and 100d residual plots!
  - Also used different scan strategies and filtering.
- Masking 100d field from 500d survey area qualitatively changes residuals structure. Hinting at statistical fluctuations in 100d sub-patch?

Statistics or Systematics?





- Different binning, but hints at similar features between SPTpol and BICEP2/Keck on the same patch of sky.
- Careful cross-spectrum analyses (with both BICEP2/Keck and *Planck*) with proper mode-matching a la Hou/Aylor et al. 2017 is worth pursuing.



SPTpol field mask (outer border) multiplied by BICEP2/Keck inverse-variance weights (color).

Summary

- SPT data show a trend towards higher H_0 as ℓ_{max} increases in both SPT-SZ temperature (Aylor et al. 2017) and SPTpol polarization (JWH, et al. 2018) results.
  - Mode-matching with *Planck* yields cosmological constraints consistent between data sets.
  - Must relax restrictions on both multipole range and area to increase tension with *Planck* FS to ~ 2 σ.
  - Marginalizing SPTpol constraints over A_L brings *Planck* and SPTpol into agreement.
- SPTpol residuals to *Planck* cosmology consistent with variance allowed by SPTpol covariance.
- Careful mode-matching analyses with BICEP2/Keck and *Planck* on SPTpol patch could help resolve remaining questions about presence of lingering systematics or simply statistical fluctuations in the SPTpol survey field.
- Internal SPT-SZ/SPTpol temperature/polarization consistency is addressed in ongoing generalized likelihood analysis (see Kimmy Wu's talk).