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

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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
960 detectors
95, 150, 220 GHz

2012: SPTpol
1500 detectors
95, 150 GHz
+Polarization

2017: SPT-3G
16,200 detectors
95, 150, 220 GHz
+Polarization
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
SPT 150 GHz Smoothed

RA

349°  352°  355°

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.

Aylor et al., 2017

Planck (in-patch) $\times 143$

SPTxPlanck $\times 150$

SPTxSPT $\times 150$
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>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>PTEs Between Parameters in SPT Sky Patch.</td>
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<tr>
<td>( \ell_{\text{max}} )</td>
</tr>
<tr>
<td>( 150 \times 150 - 150 \times 143 )</td>
</tr>
<tr>
<td>( 150 \times 150 - 143 \times 143 )</td>
</tr>
<tr>
<td>( 150 \times 143 - 143 \times 143 )</td>
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</table>

Aylor et al., 2017
SPT-SZ Cosmological Constraints

- Lower triangle: Posterior parameter distributions for 150x150, 150x143 (both $\ell_{\text{max}}=2000$), and *Planck* FS (all with *Planck* FS best-fit subtracted).

- Upper triangle: Posterior distributions from sim realizations of 150x150 - 150x143 bandpowers ($\ell_{\text{max}}=2000$).

- Black stars are parameter differences in the data.

- Differences reduce parameter space volume by 300! -> strong test of instrumental systematics.
Conclusions from Aylor et al. 2017:

1) Cosmology is consistent between SPT-SZ and *Planck* when restricted to measuring identical modes (650 ≤ ℓ ≤ 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 (~ 2 σ) when *both* are relaxed.

3) Including high-ell SPT-SZ data (2000 ≤ ℓ ≤ 3000) drives density parameters away from *Planck* FS results, pushing H₀ higher.
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SPTpol 500 Deg² Field Power Spectra

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

JWH, Sayre, Reichardt, et al., 2018
- Sample-variance limited at $\ell < 1750$
- 9 acoustic peaks between $50 < \ell < 3000$
- $D_{\ell}^{PS} < 0.1 \mu K^2$ at 95% confidence
  - (Contributes $< 1 \mu K$-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)!

SPTpol 500 Deg$^2$ Field Power Spectra

JWH, Sayre, Reichardt, et al., 2018

$D_{\ell}^{EE}$
SPTpol Cosmological Constraints

- “Low-ℓ” SPTpol data (ℓ < 1000) in good agreement with PlanckTT results.
  \[ H_0 = 67.5 \pm 4.0 \text{ km s}^{-1} \text{Mpc}^{-1} \] ("Low-ℓ” SPTpol range)

- Adding “high-ℓ” data (ℓ > 1000) pushes \( H_0 \) higher compared to PlanckTT:
  \[ H_0 = 73.5 \pm 3.7 \text{ km s}^{-1} \text{Mpc}^{-1} \] ("High-ℓ” SPTpol range)
  \[ H_0 = 71.3 \pm 2.1 \text{ km s}^{-1} \text{Mpc}^{-1} \] (Full SPTpol range)

- Similar to trends seen in Aylor et al. 2017 (but now in polarization, and 1/5 the area).
- Marginalizing over $A_L$ brings (full-range) SPTpol and Planck constraints into agreement.

- SPTpol finds $A_L$ 2.9 $\sigma$ lower than value preferred by Planck:

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

$$A_L = 1.22 \pm 0.10 \text{ (Planck)}$$
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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- 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).
- Is sample variance self-consistent with input cosmology in sims?
  - Bandpower $\chi^2$ 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.
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 $\sigma=1$.
- Repeat 100,000 times by drawing from SPTpol covariance (black).
- No evidence SPTpol data residuals are statistically inconsistent with covariance.

<table>
<thead>
<tr>
<th>Fraction of Sims Outside Data Residual Bounds</th>
<th>Lower</th>
<th>Higher</th>
<th>Lower+Higher</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE+EE</td>
<td>0.182</td>
<td>0.170</td>
<td>0.030</td>
</tr>
<tr>
<td>TE</td>
<td>0.176</td>
<td>0.866</td>
<td>0.152</td>
</tr>
<tr>
<td>EE</td>
<td>0.491</td>
<td>0.520</td>
<td>0.253</td>
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- 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-Dℓ 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.
- 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?
- 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.
Summary

- SPT data show a trend towards higher $H_0$ as $\ell_{\text{max}}$ 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 $\sim 2\sigma$.
  - 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).