SPT Data Analysis

ENABLING A MEASUREMENT OF THE COSMIC MICROWAVE BACKGROUND DAMPING TAIL FROM THE 2500-SQUARE-DEGREE SPT-SZ SURVEY

Ken Aird

March 12, 2013 Photo Credit: Daniel and Dana; Sunset 2011 Slides by Kyle Story

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A MEASUREMENT OF THE COSMIC MICROWAVE BACKGROUND DAMPING TAIL FROM THE 2500-SQUARE-DEGREE SPT-SZ SURVEY

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Submitted to ApJ

ABSTRACT

We present a measurement of the cosmic microwave background (CMB) temperature power spectrum using data from the recently completed South Pole Telescope Sunyaev-Zel'dovich (SPT-SZ) survey. This measurement is made from observations of 2540 $\deg^2$ of sky with arcminute resolution at 150 GHz, and improves upon previous measurements using the SPT by tripling the sky area. We report CMB temperature anisotropy power over the multipole range $650 < \ell < 3000$. We fit the SPT bandpowers, combined with the results from the seven-year Wilkinson Microwave Anisotropy Probe (*WMAP*7) data release, with a six-parameter ΛCDM cosmological model and find that the two datasets are consistent and well fit by the model. Adding SPT measurements significantly improves ΛCDM parameter constraints, and in particular tightens the constraint on the angular sound horizon θ_s by a factor of 2.7. The impact of gravitational lensing on the CMB power spectrum is detected with $8.1\,\sigma$, the most significant detection to date. The inferred amplitude of the lensing spectrum is consistent with the ΛCDM prediction. This sensitivity of the SPT+*WMAP*7 data to lensing by large-scale structure at low redshifts allows us to constrain the mean curvature of the observable universe with CMB data alone to be $\Omega_k = -0.003^{+0.014}_{-0.018}$. Using the SPT+*WMAP*7 data, we measure the spectral index of scalar fluctuations to be $n_s = 0.9623 \pm 0.0097$ in the ΛCDM model, a $3.9\,\sigma$ preference for a scale-dependent spectrum with $n_s < 1$. The SPT measurement of the CMB damping tail helps break the degeneracy that exists between the tensor-to-scalar ratio r and n_s in large-scale CMB measurements, leading to an upper limit of $r < 0.18$ (95% C.L.) in the ΛCDM+r model. Adding low-redshift measurements of the Hubble constant (H_0) and the baryon acoustic oscillation (BAO) feature to the SPT+*WMAP*7 data leads to further improvements. The combination of SPT+*WMAP*7+H_0+BAO constrains $n_s = 0.9538 \pm 0.0081$ in the ΛCDM model, a $5.7\,\sigma$ detection of $n_s < 1$, and places an upper limit of $r < 0.11$ (95% C.L.) in the ΛCDM+r model. These new constraints on n_s and r have significant implications for our understanding of inflation, which we discuss in the context of selected single-field inflation models.

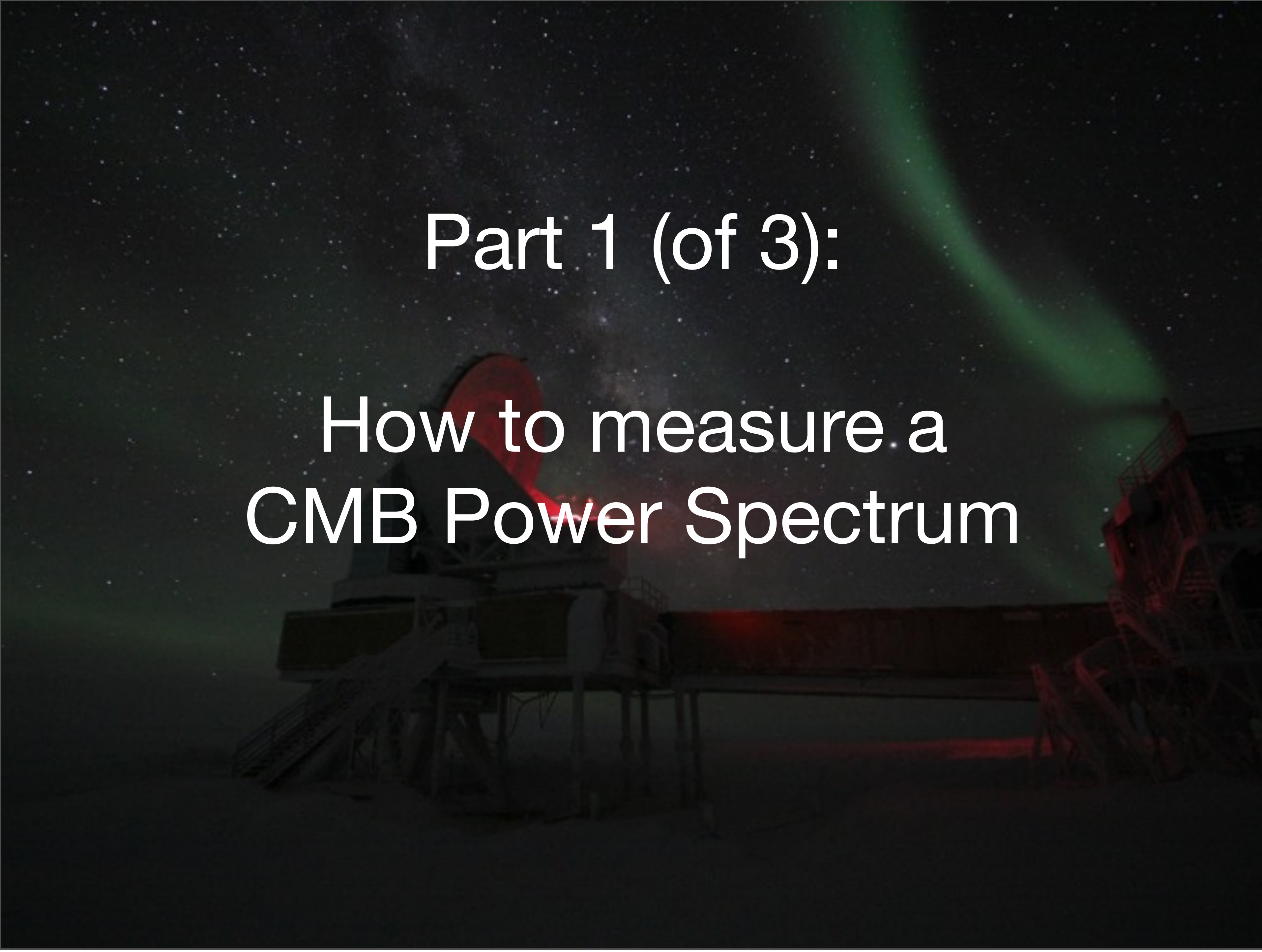
Subject headings: cosmology – cosmology:cosmic microwave background – cosmology: observations – large-scale structure of universe

Outline

1) How does one actually measure the CMB power spectrum?

2) How does the SPT measurement fit into the rest of the field?

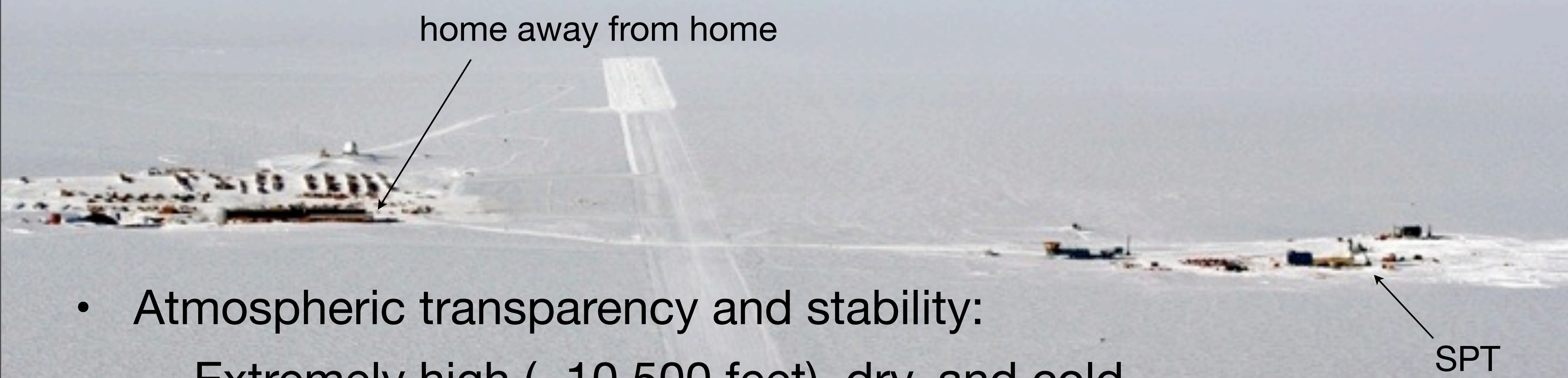
3) How does one constrain cosmology with the CMB power spectrum?


Part 1 (of 3):
How to measure a
CMB Power Spectrum

Step 1:

Build a 10-meter telescope at the South Pole

Why the South Pole?



- Atmospheric transparency and stability:
  - Extremely high (~10,500 feet), dry, and cold.
  - Sun below horizon for 6 months.
- Unique geographical location:
  - Observe the clearest views through the Galaxy, 24/365
  - Clean horizon.
- Excellent support from existing research station.

The South Pole Telescope

- Millimeter-wavelength telescope
- Located at the South Pole (dry)
- 10 meter primary mirror
- high-angular resolution (~1 arcminute)

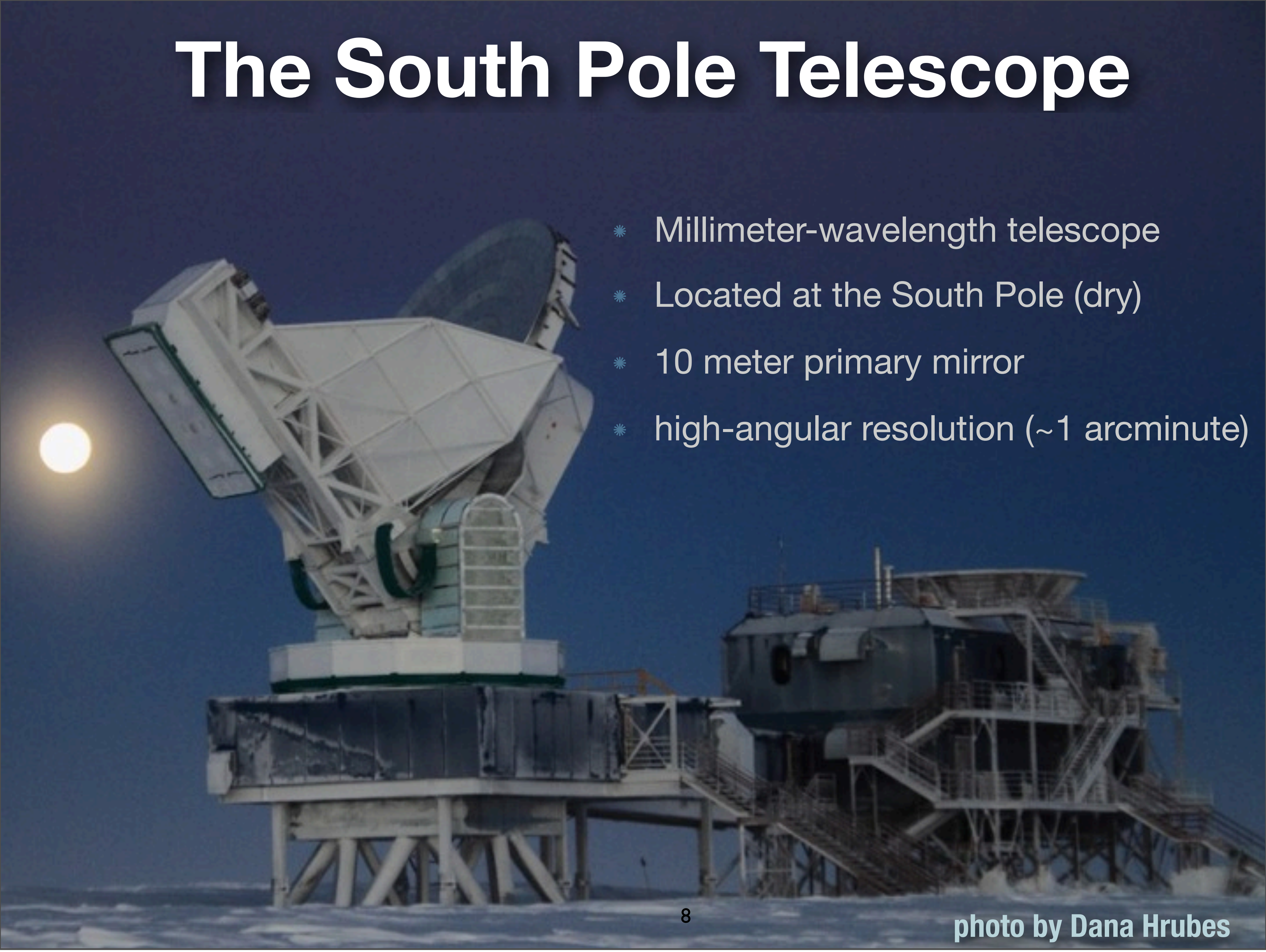
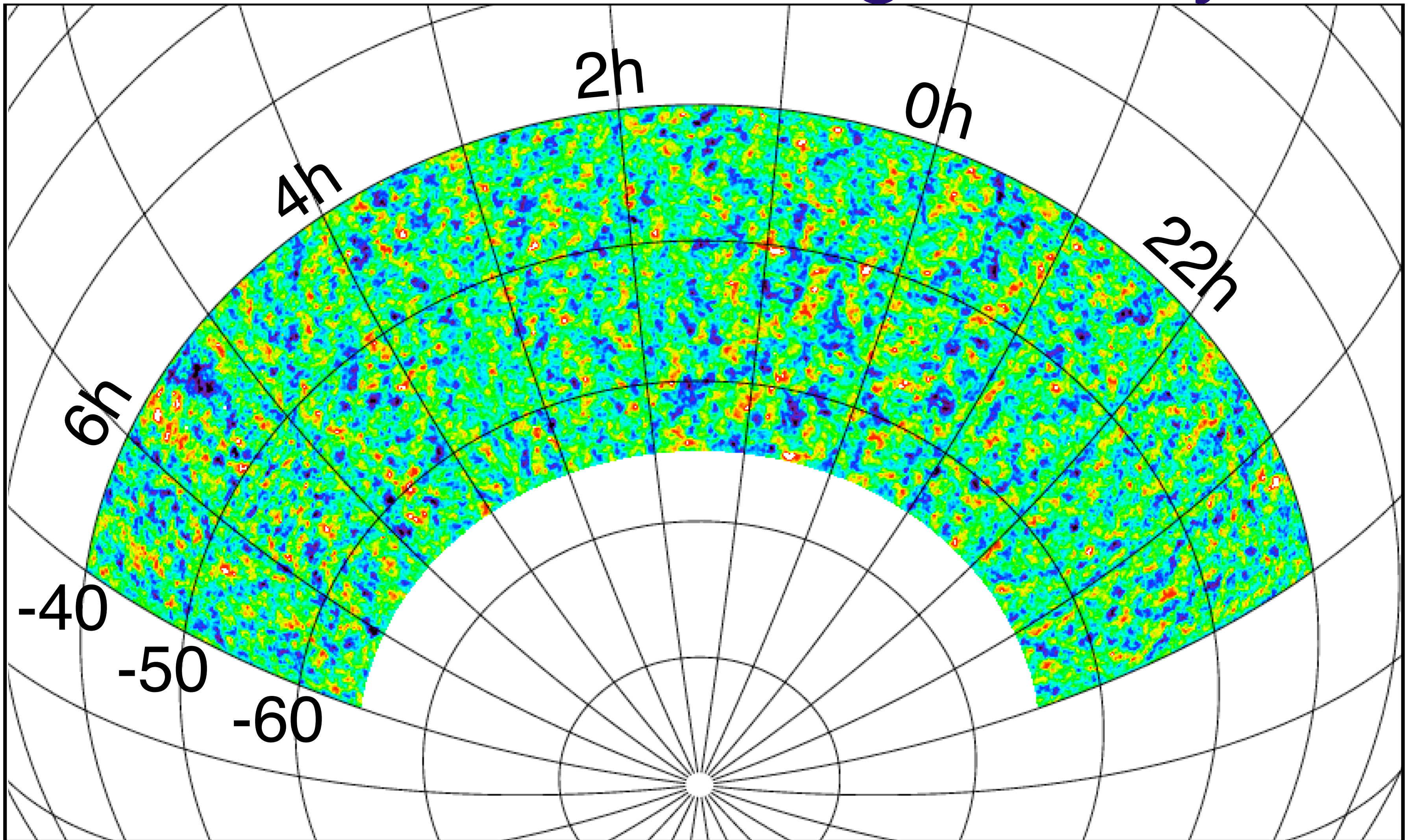


photo by Dana Hrubes

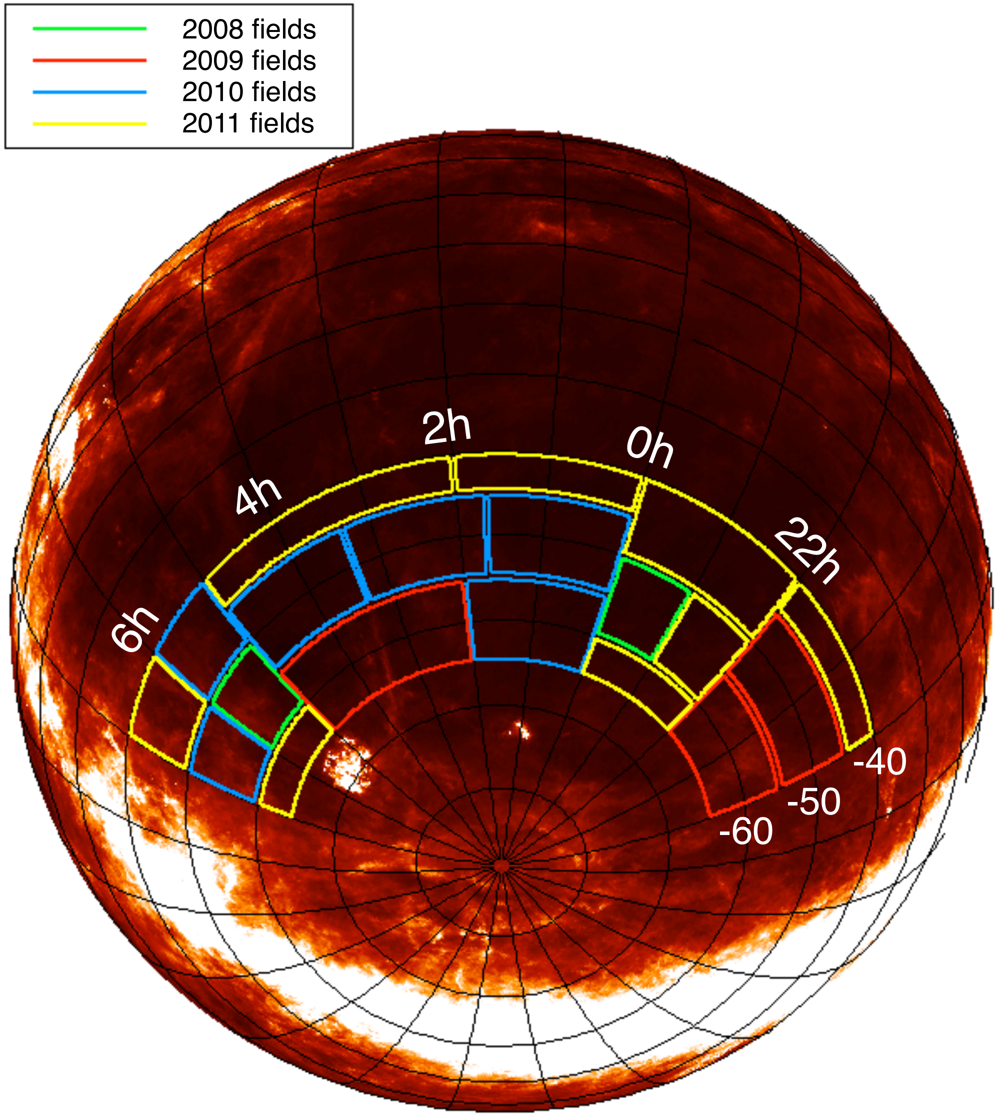
Step 2:

Observe 2500 deg^2 of sky

SPT-SZ 2500 deg^2 survey



Status: finished in *Nov. 2011*.

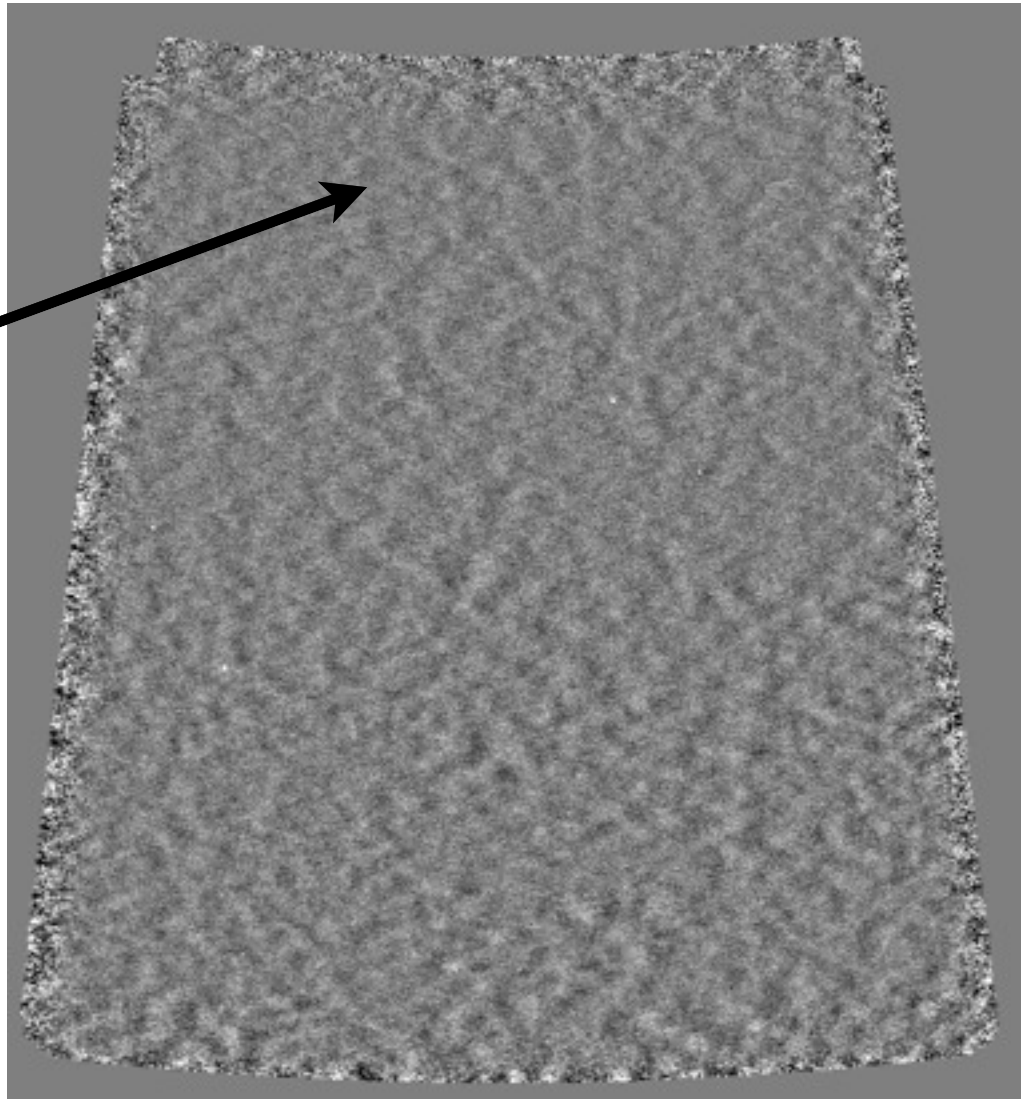


Observation Strategy:

- 19 observation fields
- 3 frequencies (90, 150, and 220 GHz)
- Avoid the Galaxy

The result is maps of 19 fields,

mostly noise
(atmosphere)

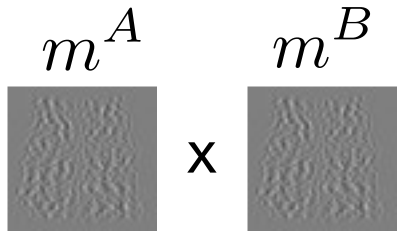


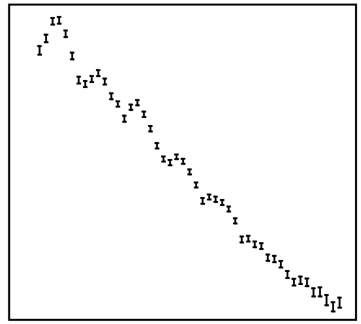
X ~200
per field

ra22h30dec-55
Single Observation

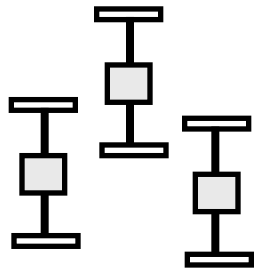
How do we calculate a power spectrum from the maps?

- **Cross-correlate** and average all pairs of observations (noise doesn't correlate)





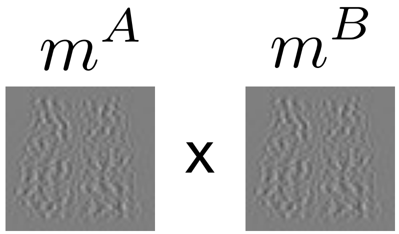
- Correct for **filtering of time-ordered data**, **PSF**, **mode-coupling** from finite sky.



- Estimate **errors** from simulations and data.

How do we calculate a power spectrum from the maps?

- **Cross-correlate** and average all pairs of observations (noise doesn't correlate)



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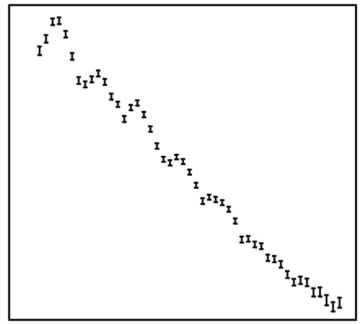
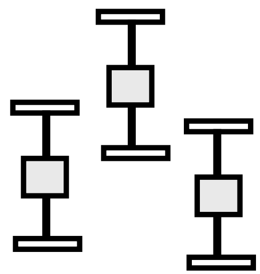
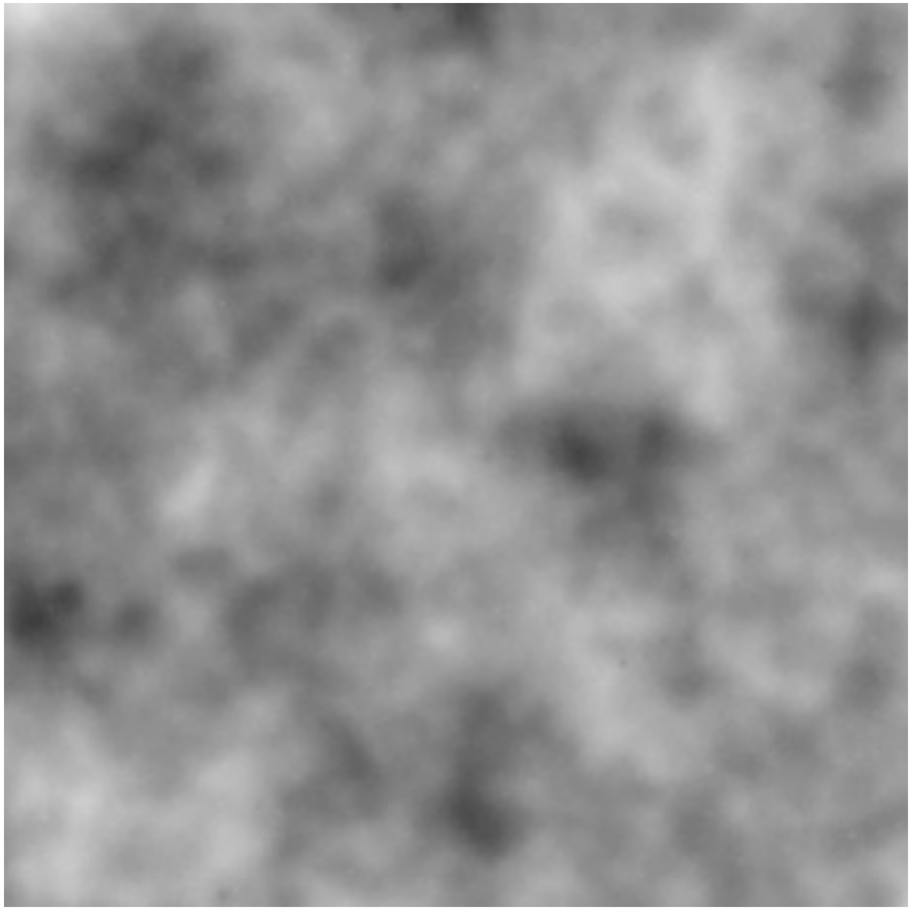


- Estimate **errors** from simulations and data.



SPT “Pseudo-Cl” Analysis

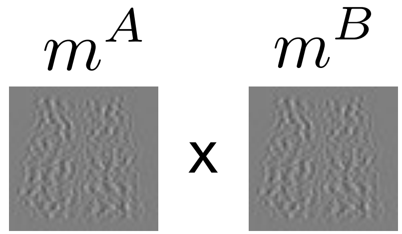


Key concept:

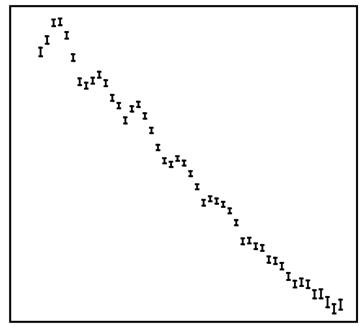
The CMB signal is spatially correlated, while the noise is *uncorrelated*.

By cross-correlating observations, the CMB signal can be recovered.

How do we calculate a power spectrum from the maps?



- **Cross-correlate** and average all pairs of observations (noise doesn't correlate)



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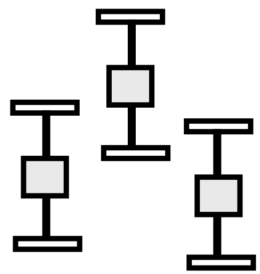


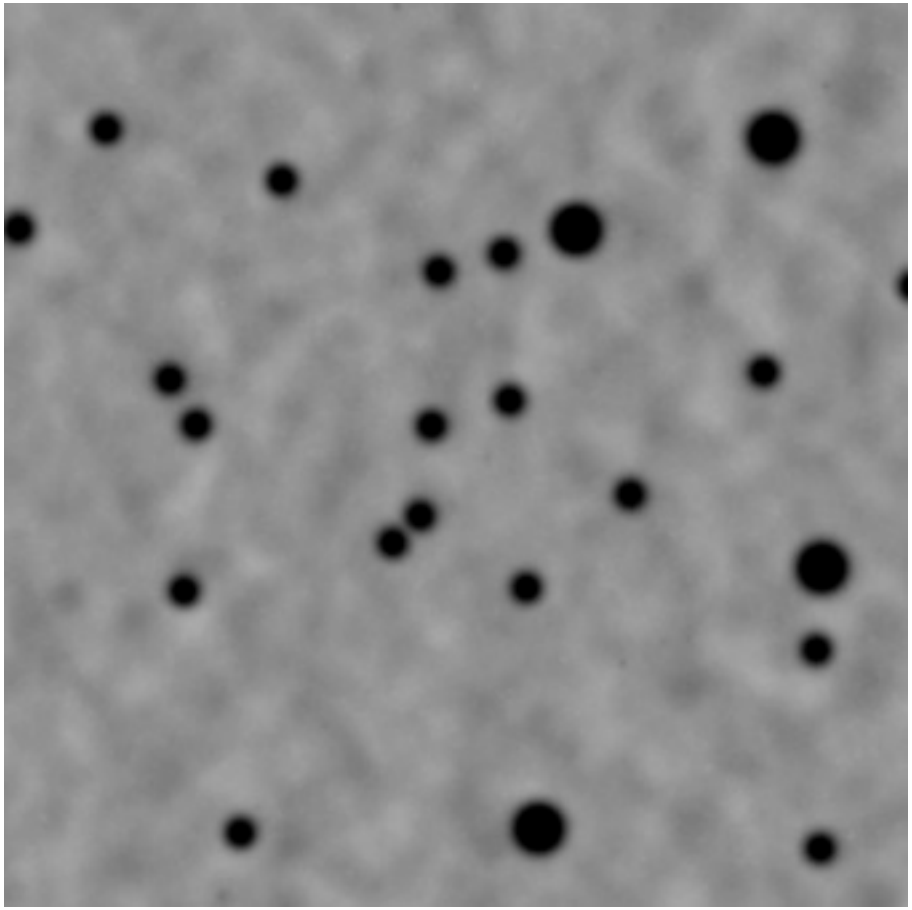
- Estimate **errors** from simulations and data.

Account for timestream filtering: "Transfer Function"

- Simulate 100 CMB skies (healpix)
- Project onto flat-sky maps for 19 fields
- Calculate the power spectrum from simulated maps
- Transfer Function

$$F_l = C_l^{(input)} / C_l^{(measured)}$$

Masking



In Equations:

$$\tilde{a}^i_{\ell m} = \int d\hat{n} \left[\Delta T^i(\hat{n}) W(\hat{n})\right] Y_{\ell m}(\hat{n})$$

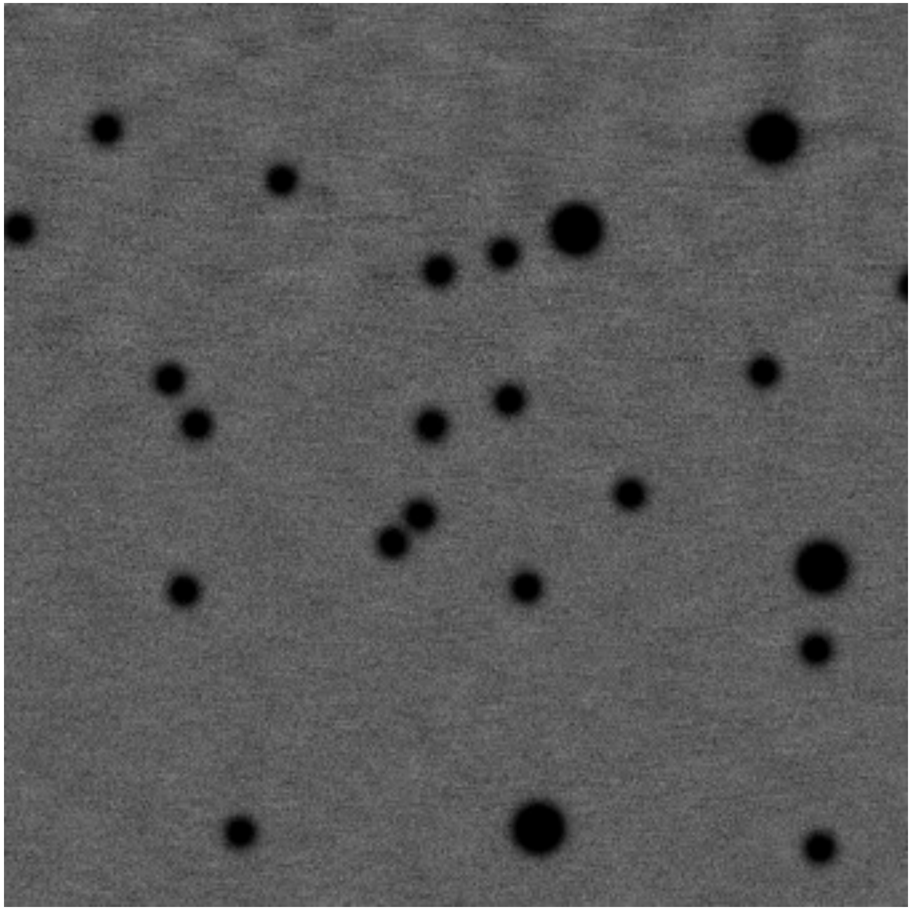
$$\tilde{C}^{ii}_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |\tilde{a}^i_{\ell m}|^2$$

Need to explicitly account for:

- Experimental beam shape
- Filtering of timestream data
- Masking for unwanted sources

$$< \tilde{C}^{ii}_\ell >= \sum_{\ell'} M_{\ell\ell'}[W] F_{\ell'} B^2_{\ell'} < C_{\ell'} >$$

Noise bias



In Equations:

$$\tilde{a}^i_{\ell m} = \int d\hat{n} \left[\Delta T^i(\hat{n}) W(\hat{n})\right] Y_{\ell m}(\hat{n})$$

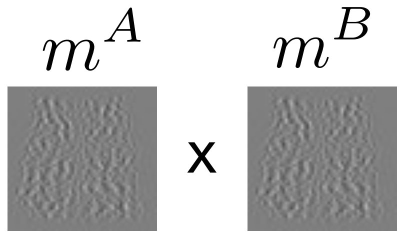
$$\tilde{C}^{ii}_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |\tilde{a}^i_{\ell m}|^2$$

Need to explicitly account for:
- Experimental beam shape
- Filtering of timestream data
- Masking for unwanted sources
- Avoid noise bias with cross-spectra (no noise model required)

$$< \tilde{C}^{ii}_\ell > = \sum_{\ell'} M_{\ell\ell'}[W] F_{\ell'} B^2_{\ell'} < C_{\ell'} > + < N_\ell >$$

How do we calculate a power spectrum from the maps?

- **Cross-correlate** and average all pairs of observations (noise doesn't correlate)



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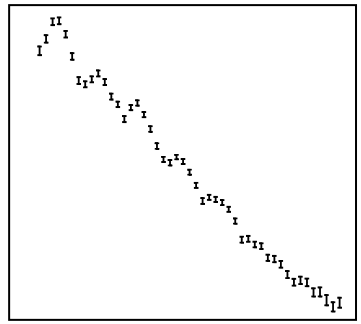

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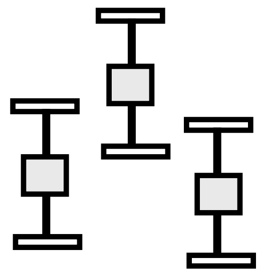
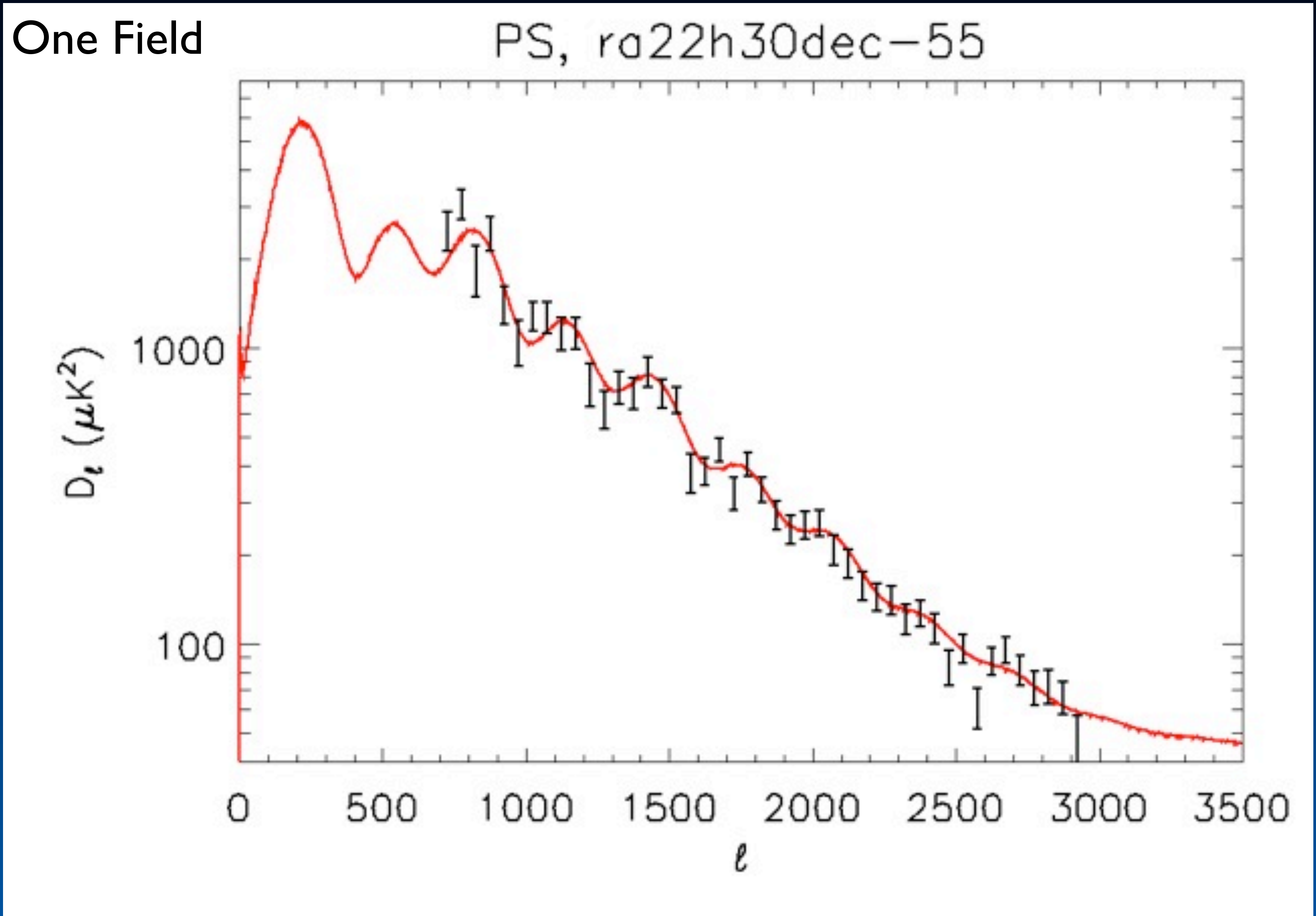
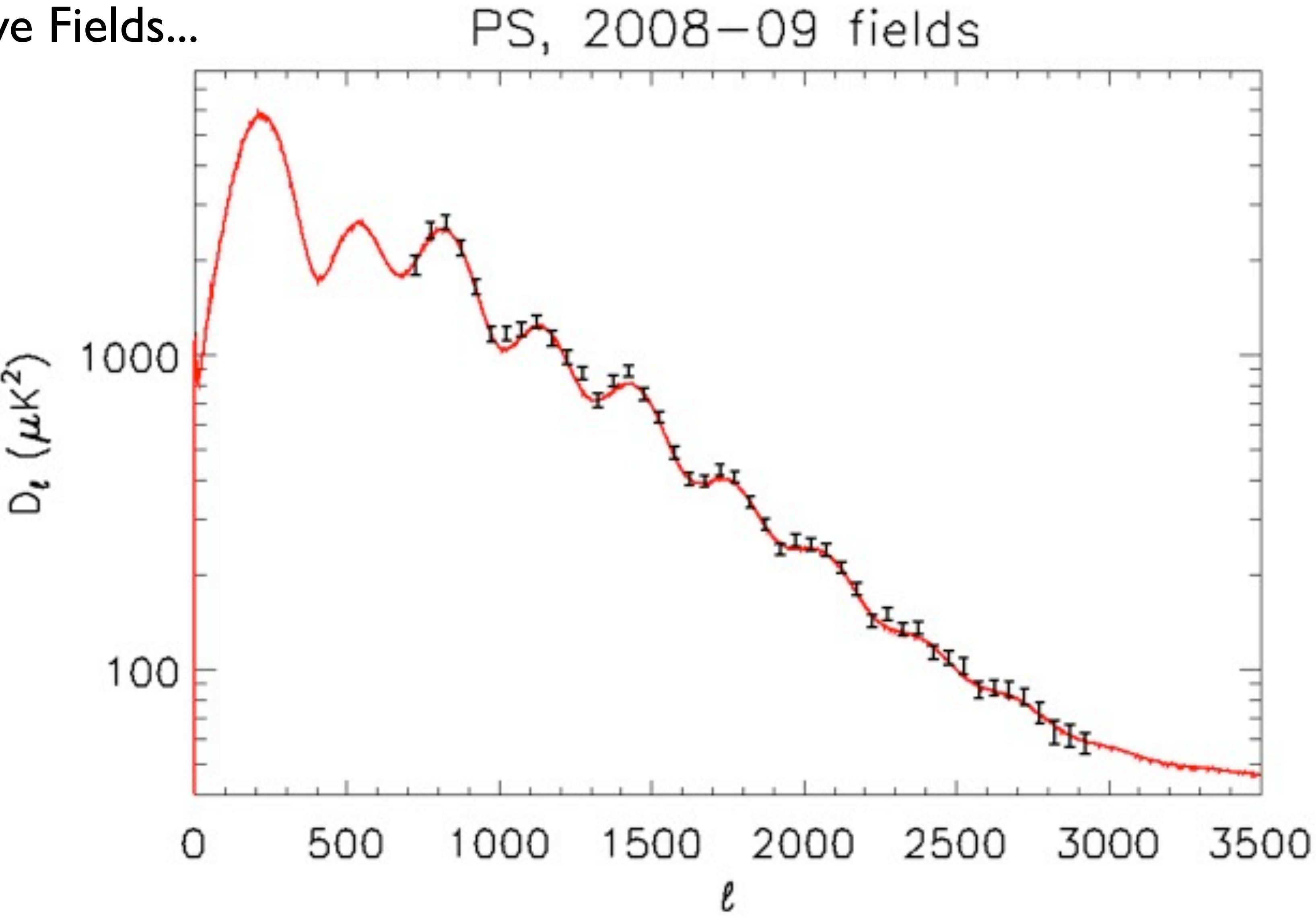


Put this all together and you get ...

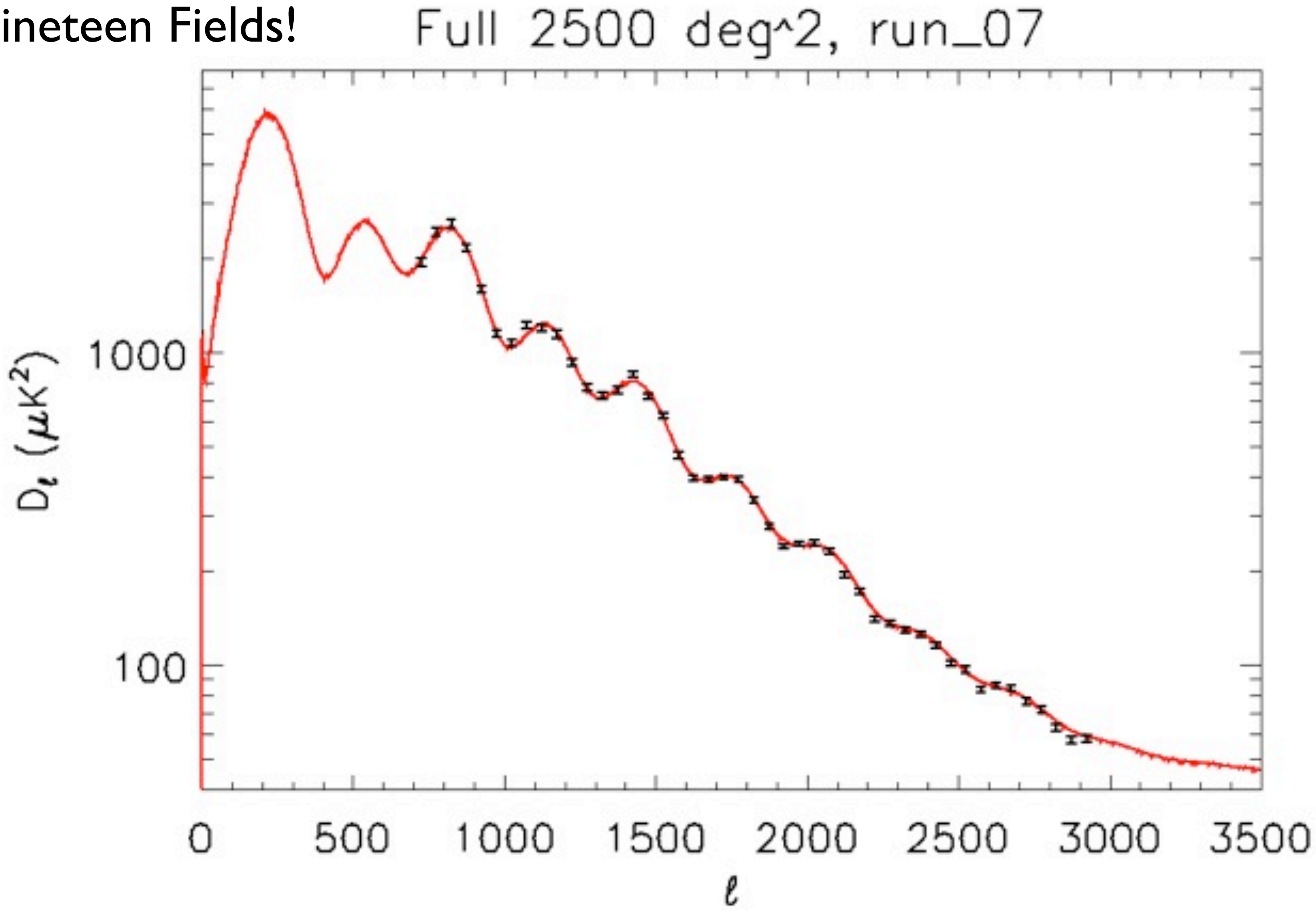

One Field
PS, ra22h30dec-55
1000
100
D_ℓ (μK^2)
0
500
1000
1500
2000
2500
3000
3500
ℓ

Five Fields...



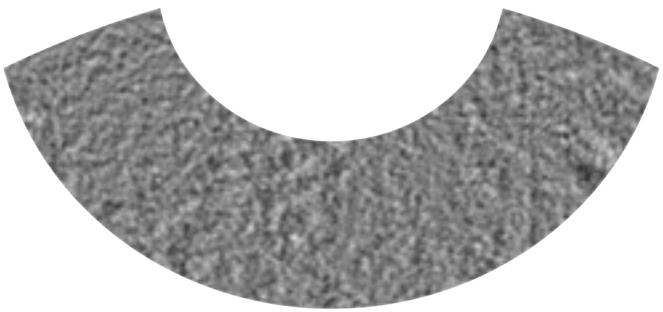
PS, 2008−09 fields
1000
100
D_ℓ (μK^2)
0
500
1000
1500
2000
2500
3000
3500
ℓ

Nineteen Fields!

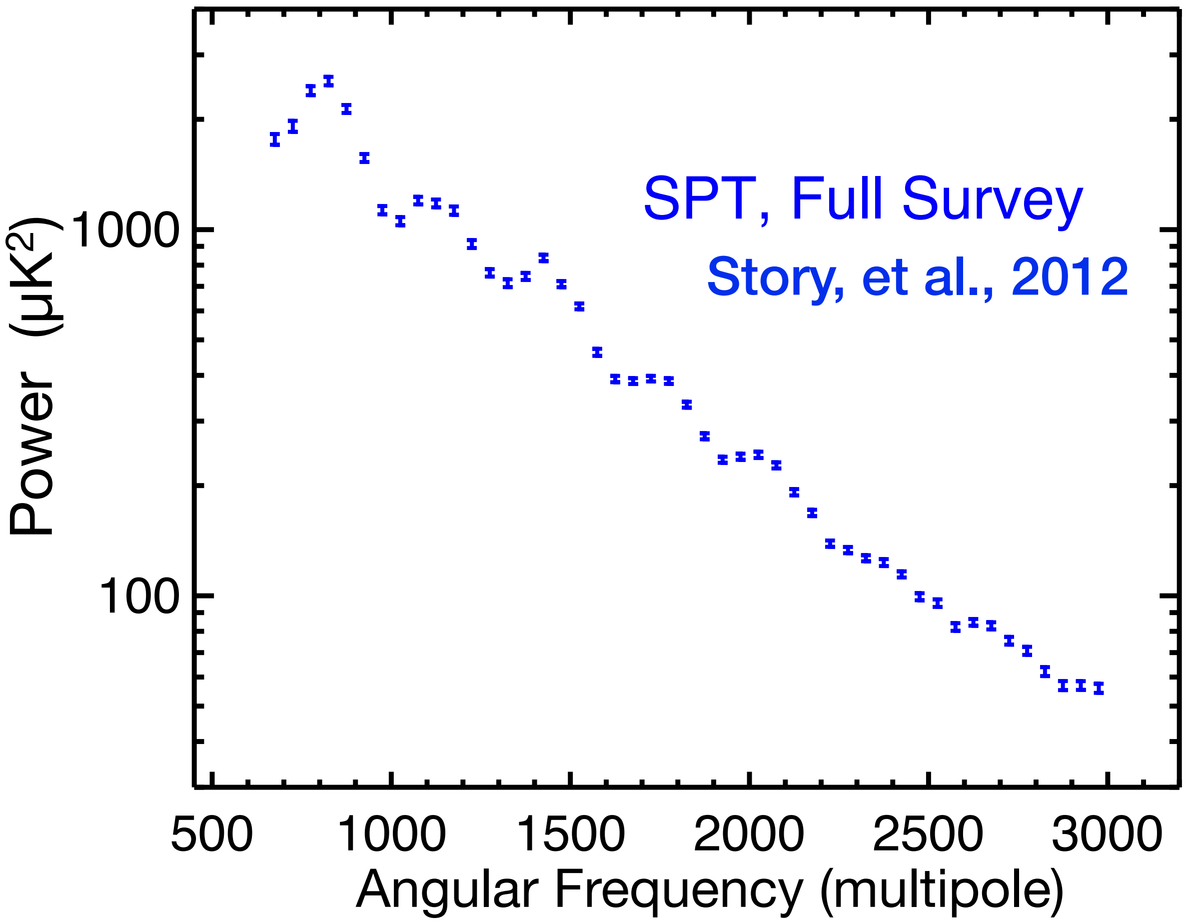


CMB Power Spectrum

Fourier transform this



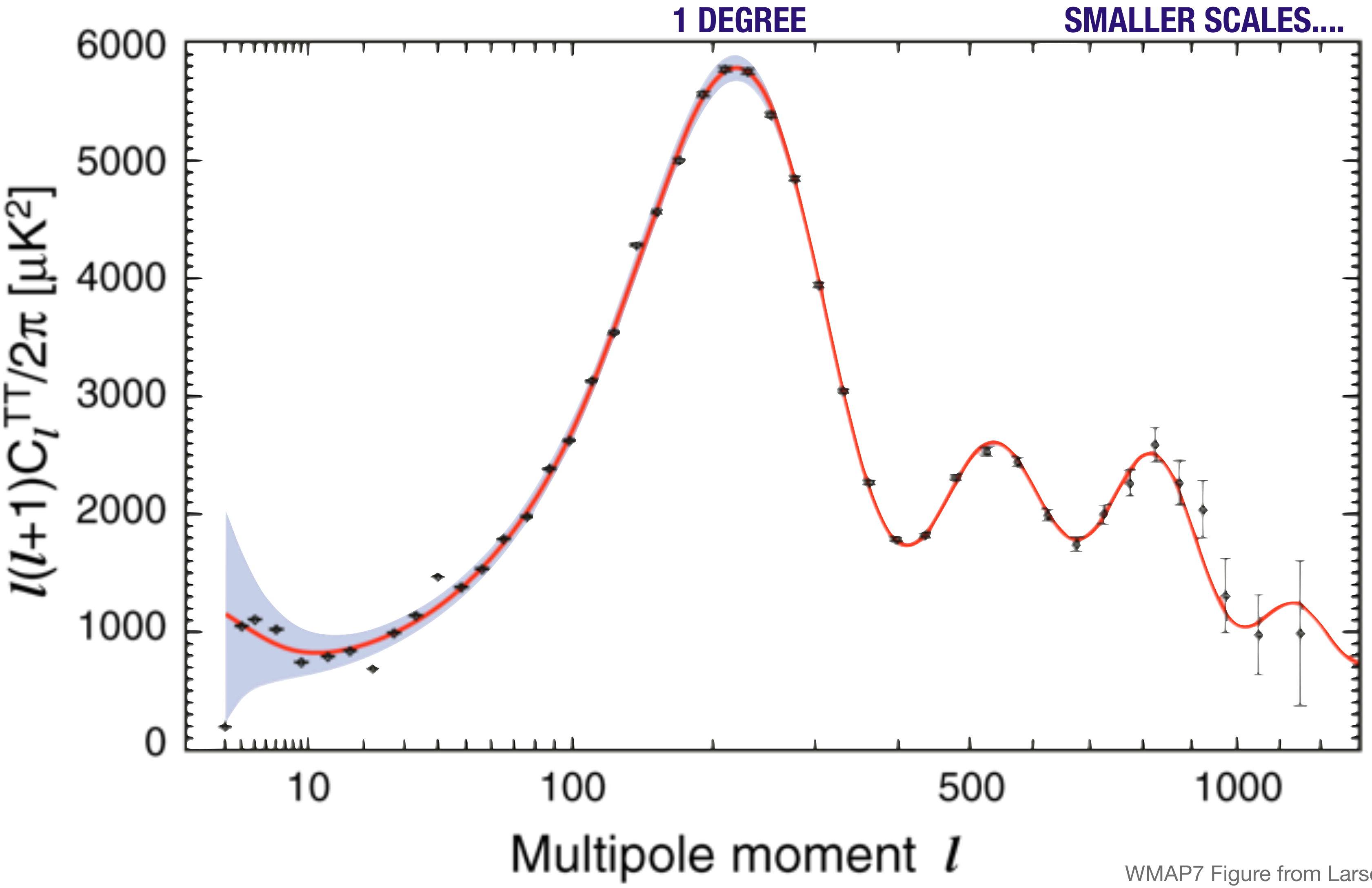
and you get....



Part 2 (of 3):

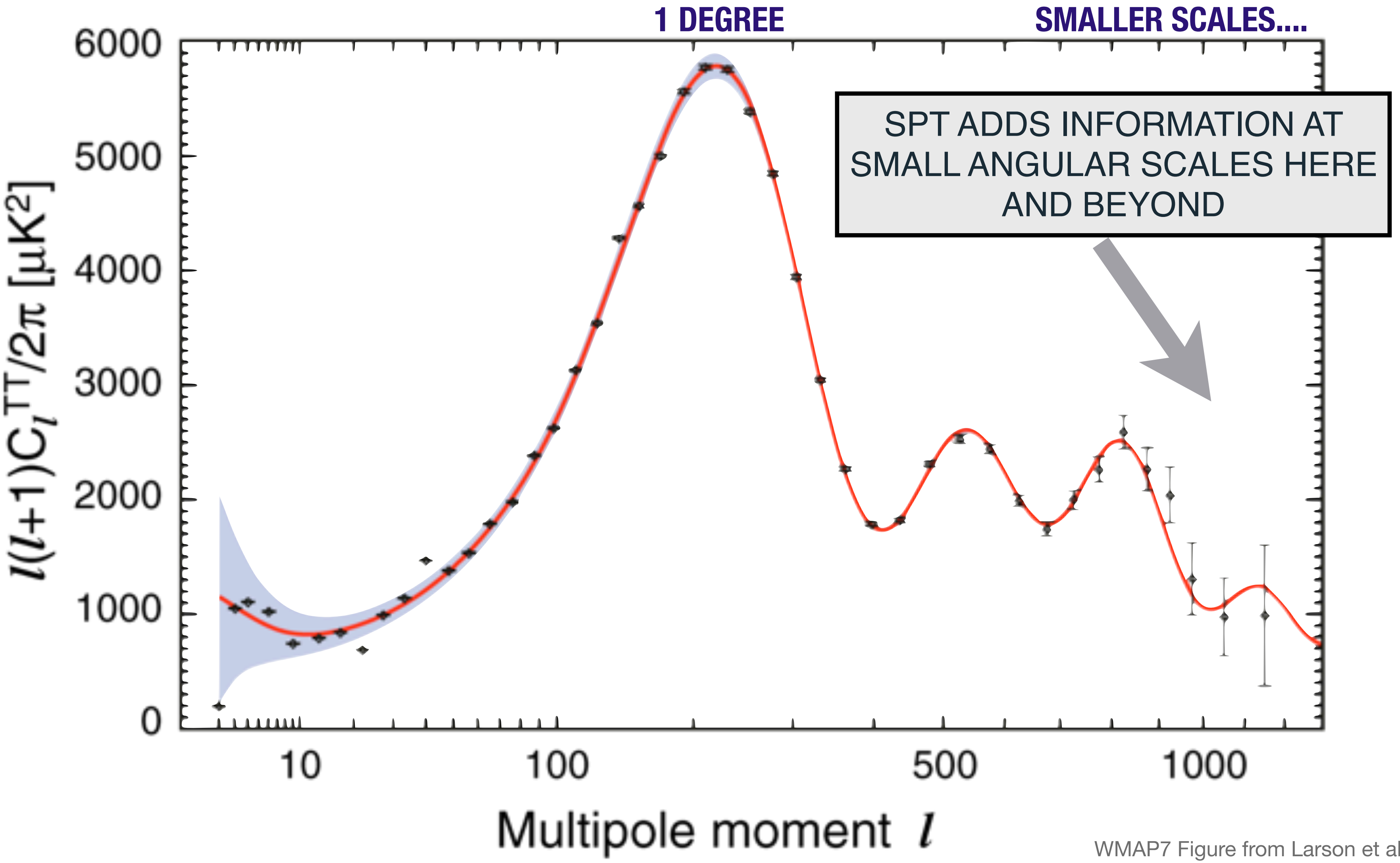
Context for the SPT power spectrum

WMAP



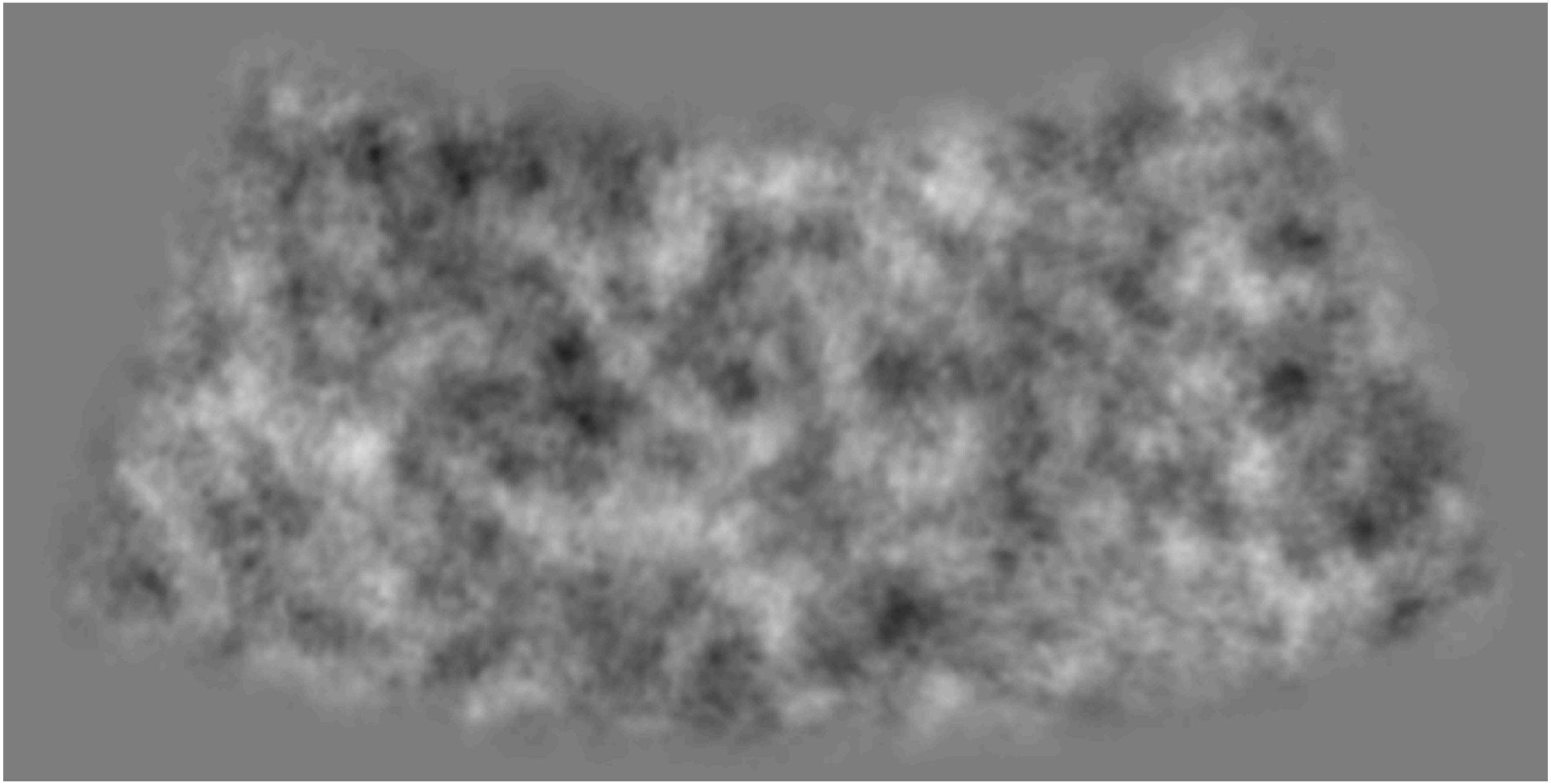
WMAP7 Figure from Larson et al.

WMAP

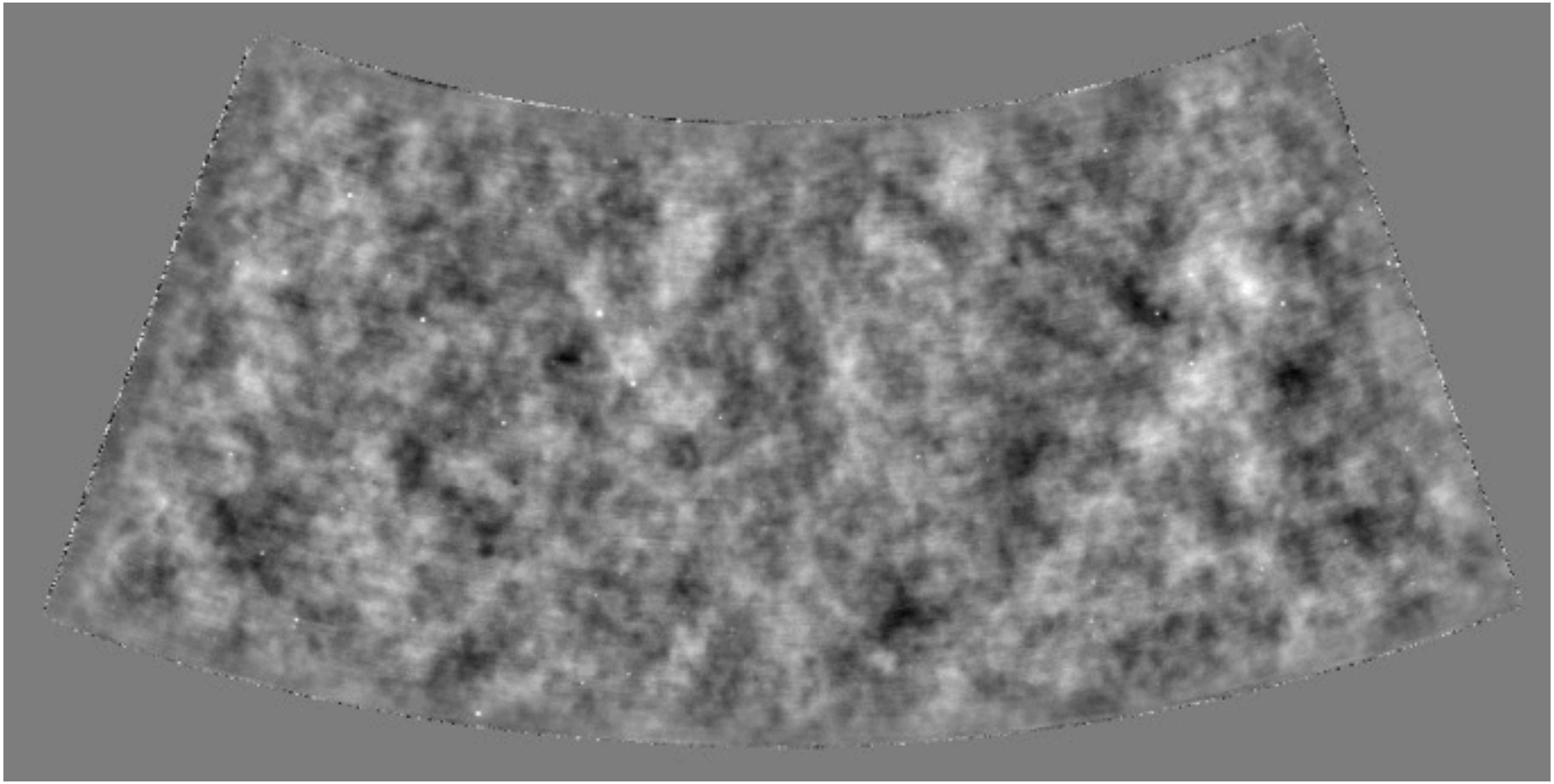


WMAP7 Figure from Larson et al.

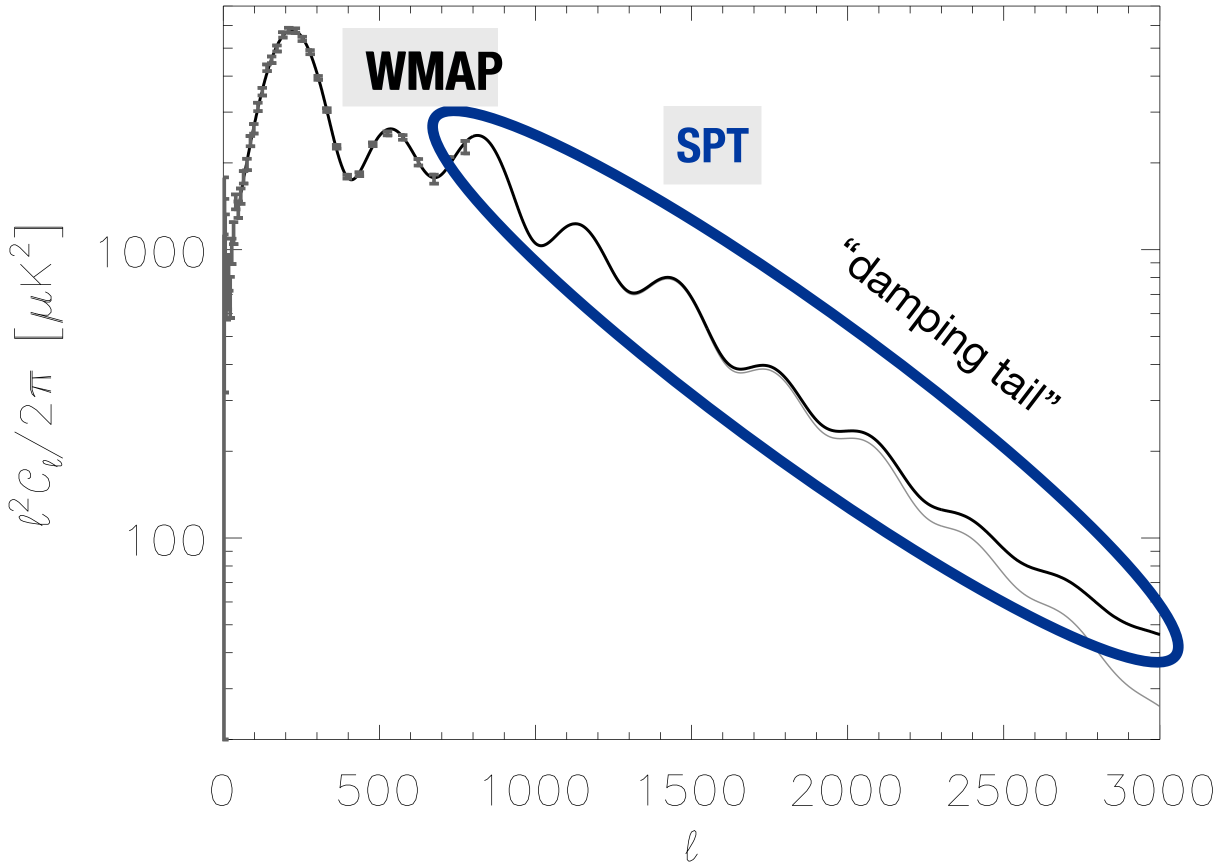
WMAP'S VIEW



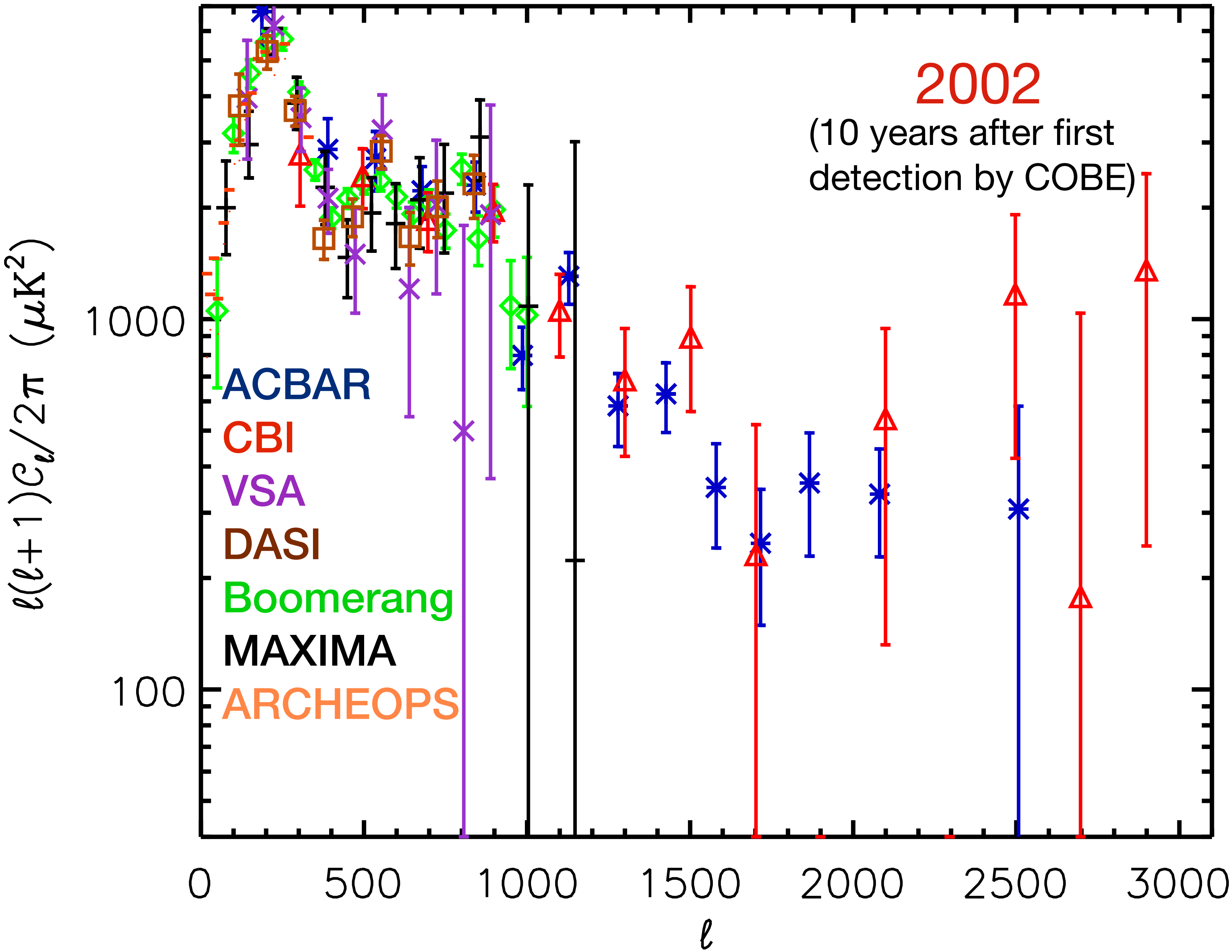
SPT'S VIEW



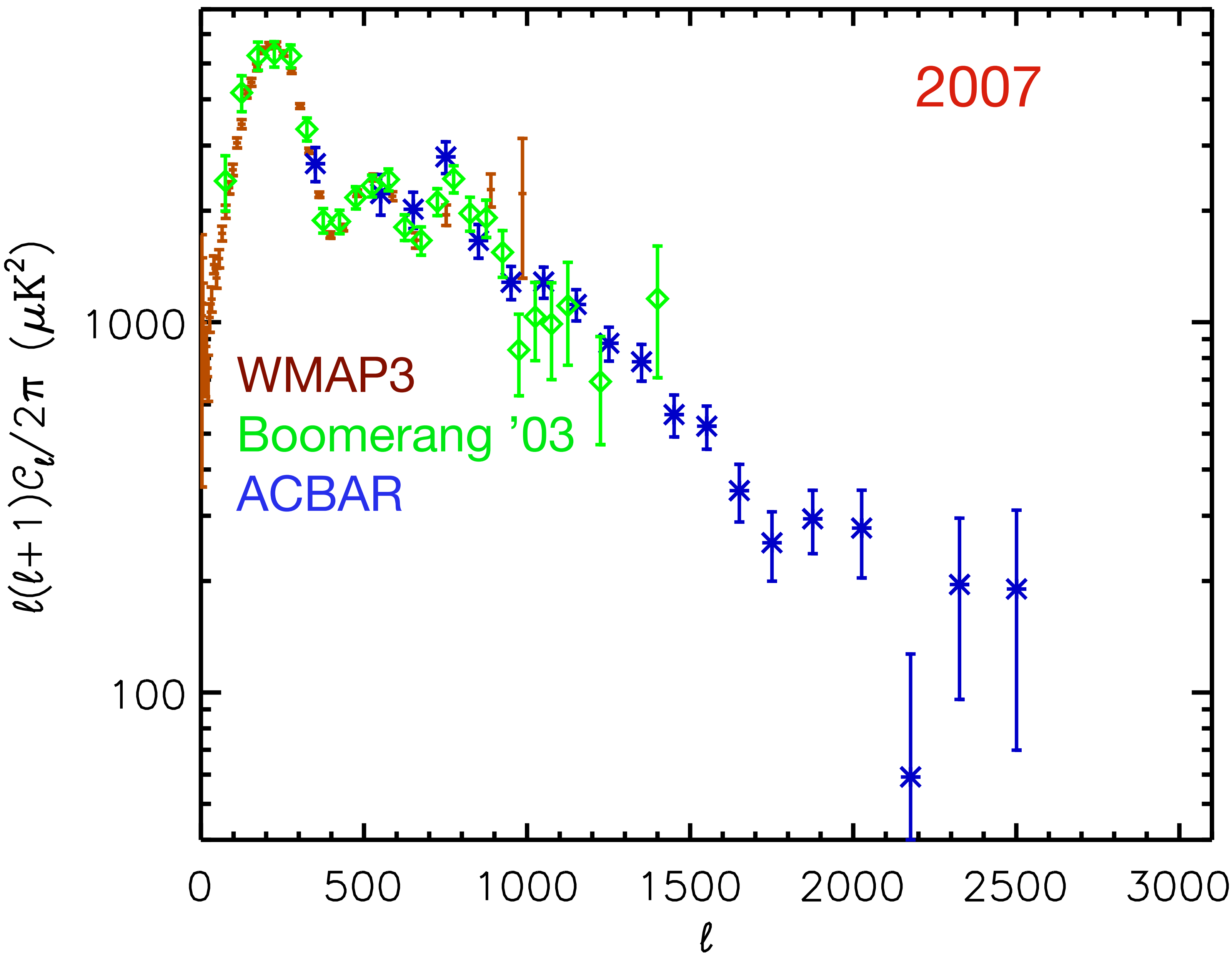
Recent measurement from SPT



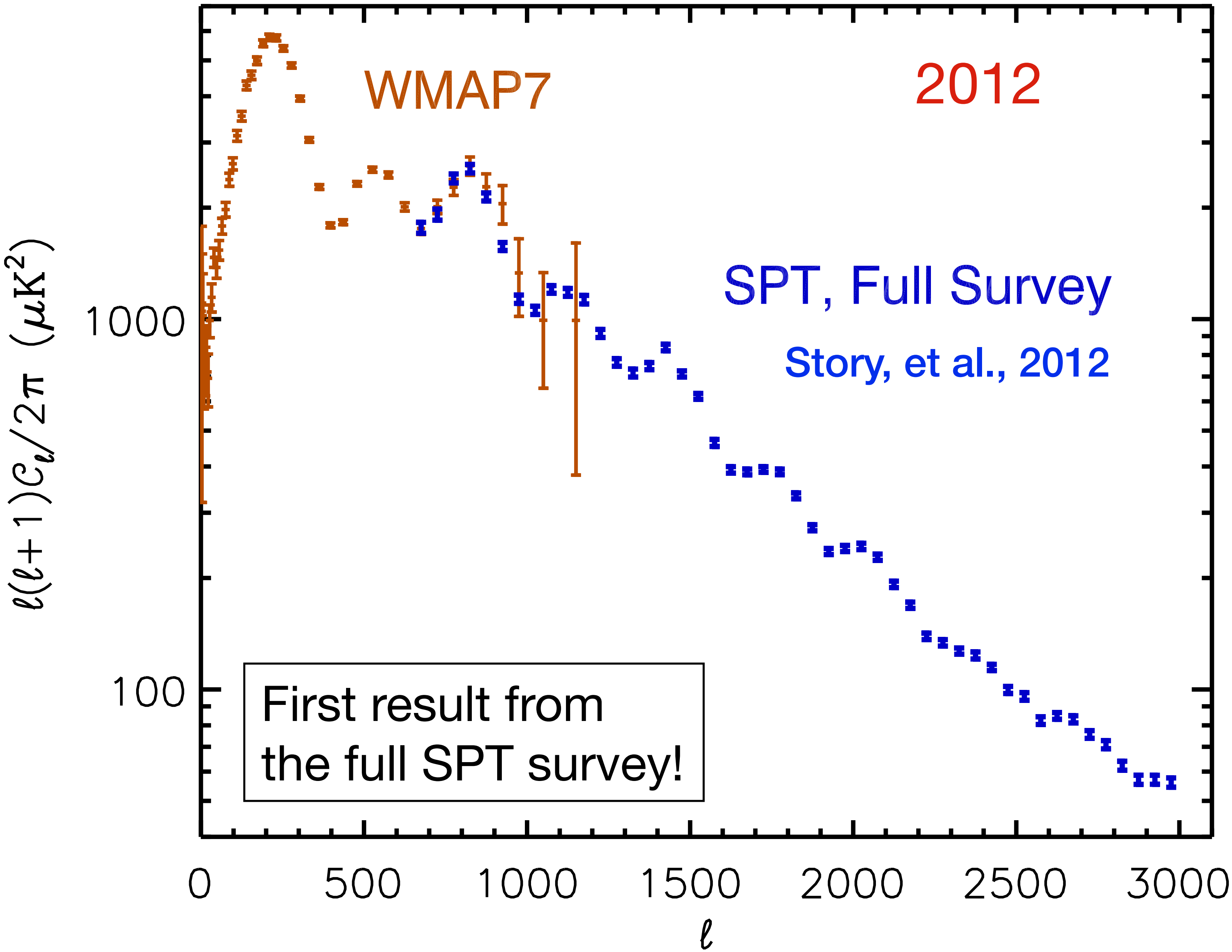
Strong experimental progress

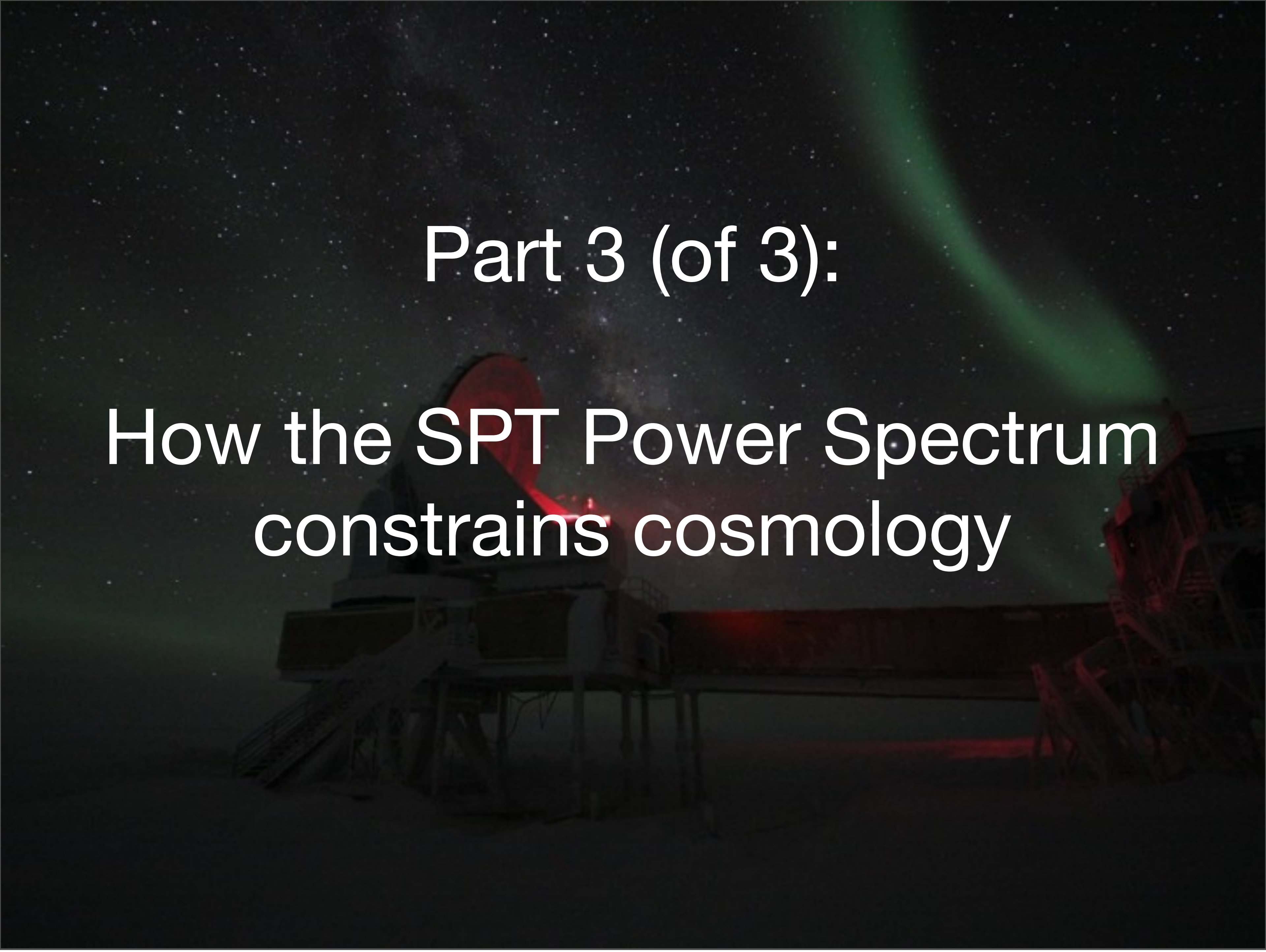


Strong experimental progress



Strong experimental progress

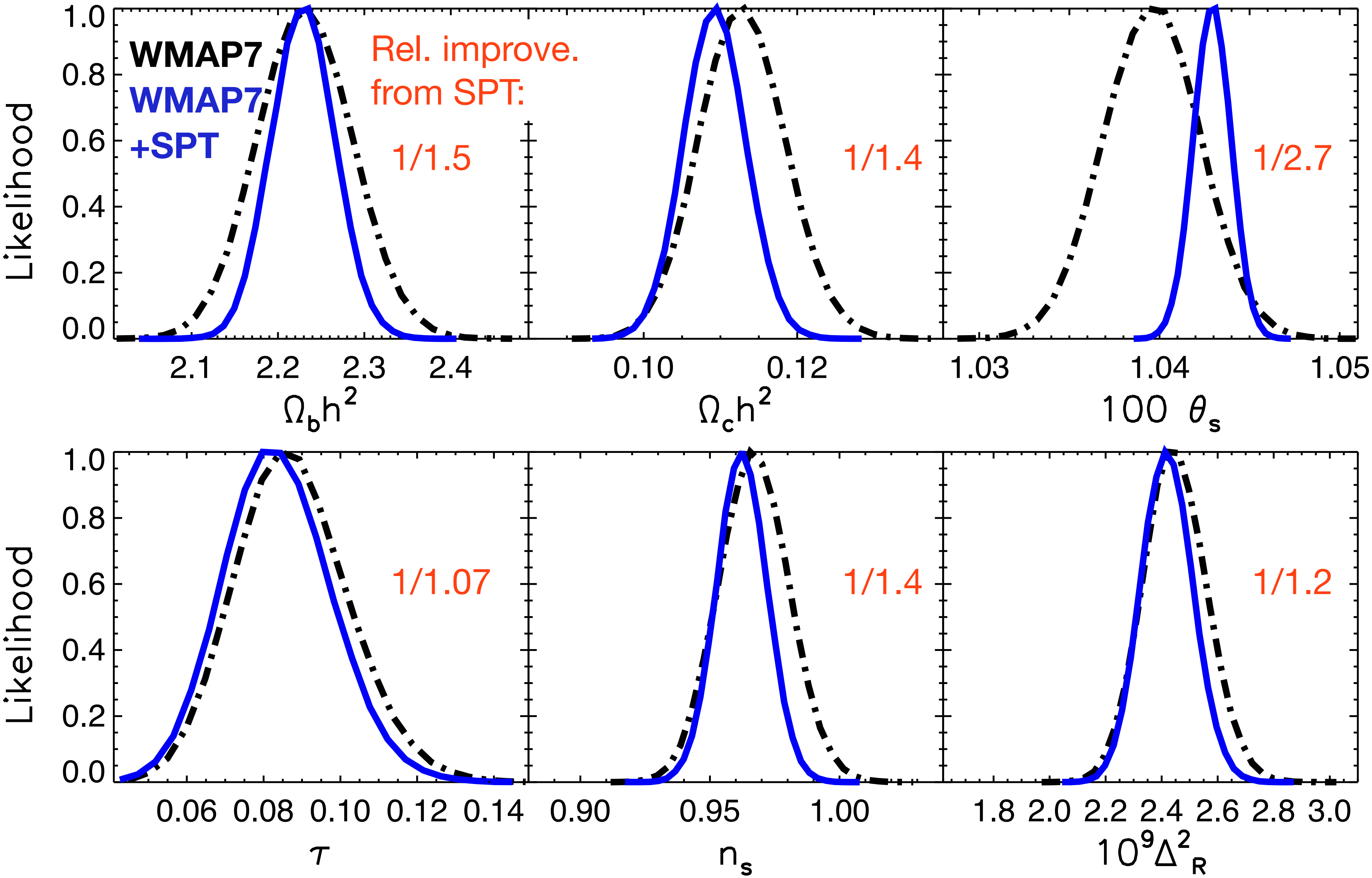




Part 3 (of 3):

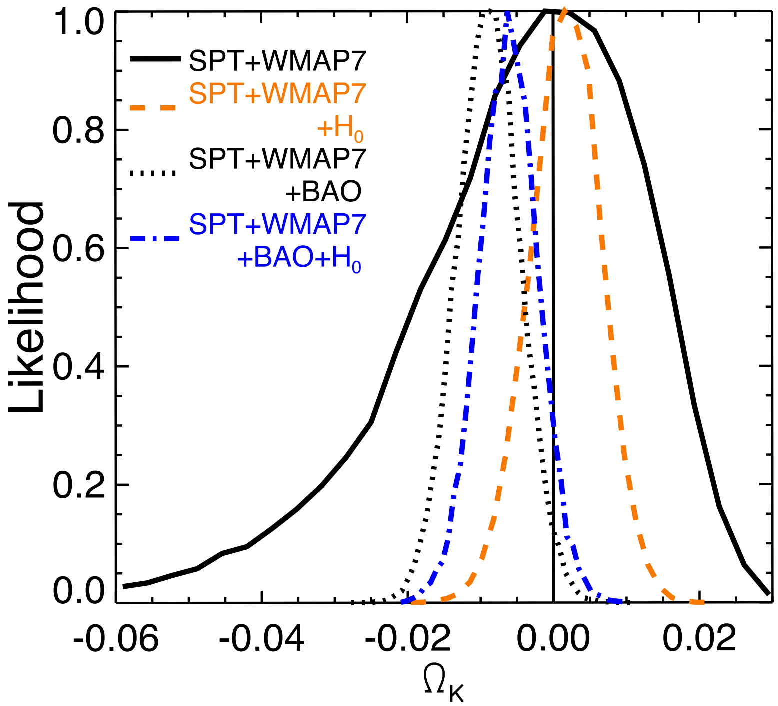
How the SPT Power Spectrum constrains cosmology

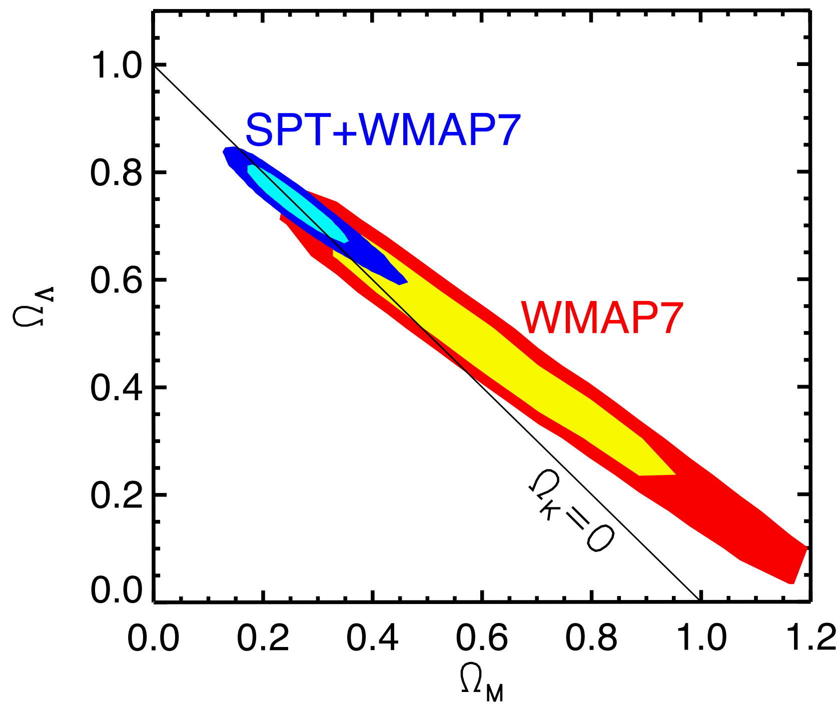
Basic ΛCDM results: WMAP7+SPT



Curvature and Dark Energy:

Ω_K - Ω_Λ degeneracy in large-scale data

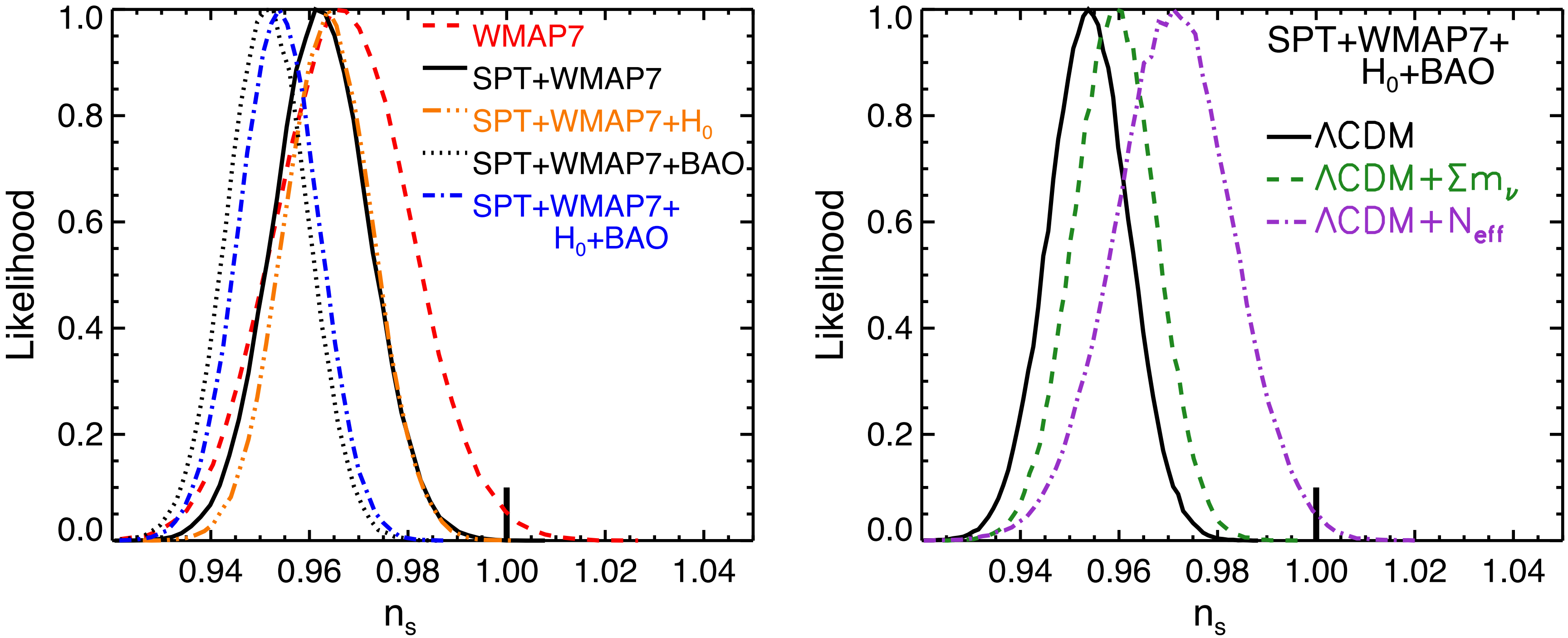




SPT+WMAP7: $\Omega_K = -0.003\ +0.014\ -0.018$ → $\Omega_\Lambda > 0$ at 5.4 σ

CMB+BAO+H0: $\Omega_K = -0.0059 +/- 0.0040$

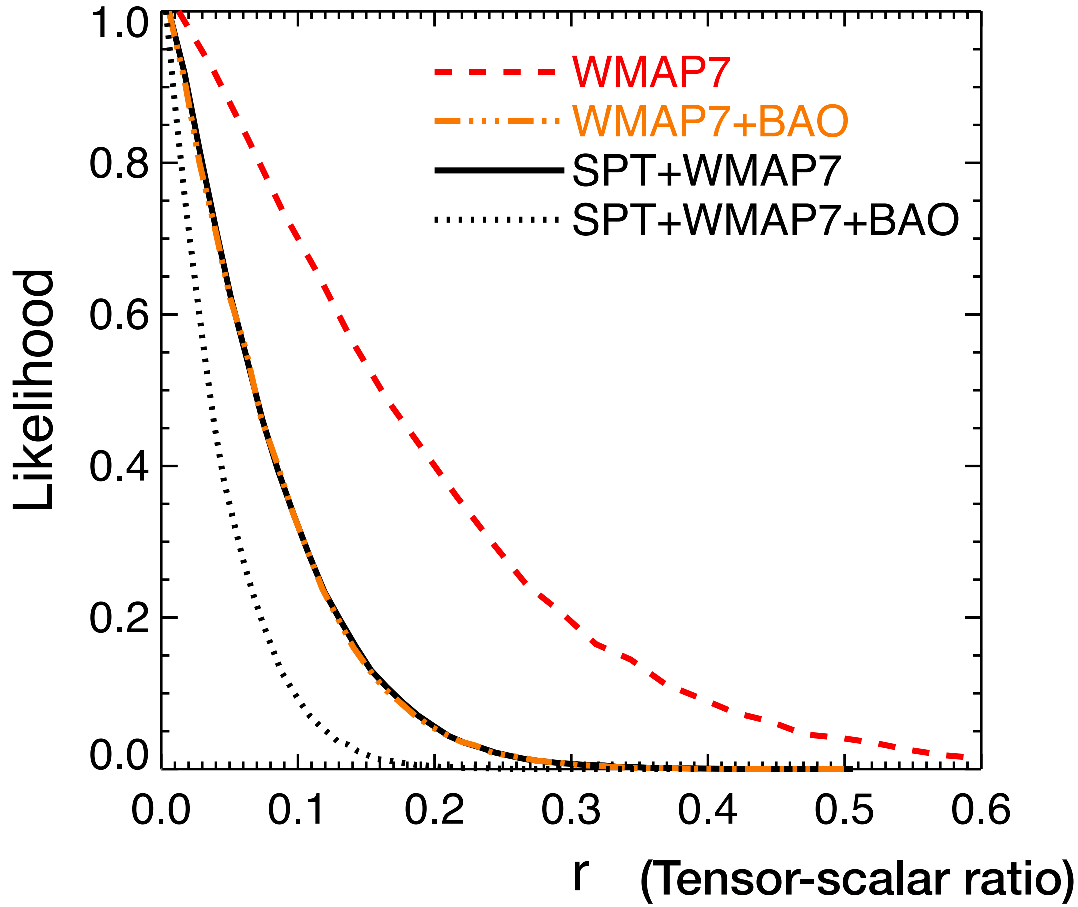
ΛCDM Results



Most significant detection of a departure from scale-invariance!

n_s: WMAP7 = 0.969 ± 0.014	$P(n_s > 1)$: WMAP7	= 1.4e-2 (2.2 σ)
WMAP7+SPT (CMB) = 0.962 ± 0.010	+SPT	= 3.9e-4 (3.9 σ)
CMB+BAO+H_0 = 0.954 ± 0.008	+BAO+H_0	=1.4e-9 (5.9 σ)

Best limits on tensors!



No evidence for tensors yet; 95% upper limits are:

WMAP: $r < 0.36$ **WMAP+SPT: $r < 0.18$** **CMB+BAO+H0: $r < 0.11$**

Summary of results from Story et al. 2012:

- Most precise measurement of the CMB damping tail from 650 < ell < 3000
- Detect gravitational lensing at 8.1 σ, consistent with ΛCDM (highest significance to date from CMB alone)
- Measure curvature to 1.5% accuracy with CMB alone
- Measure $n_s < 1$ at 5.9 σ (1st >5σ detection
- Constrain r < 0.11 (CMB+BAO+H_0)
- Place constraints on simple models of inflation

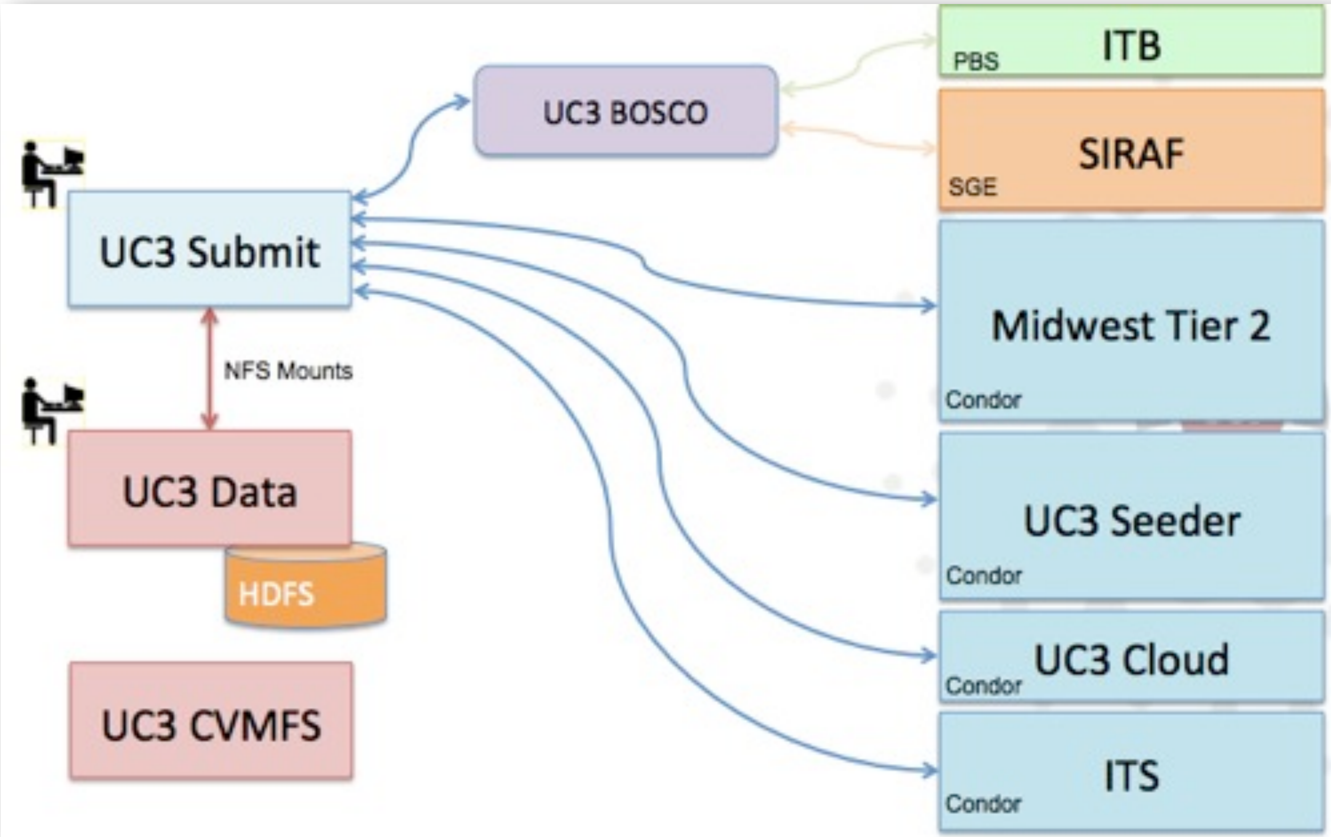
*Further extensions explored in H12

Constrains on Cosmology (H12)

- Neutrino Mass
- Effective Number of Neutrino Species
- Primordial Helium
- Running of the Spectral Index

- http://arxiv.org/pdf/1212.6267v1

Computing on UC3



Thanks!