The CMB Power Spectrum

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

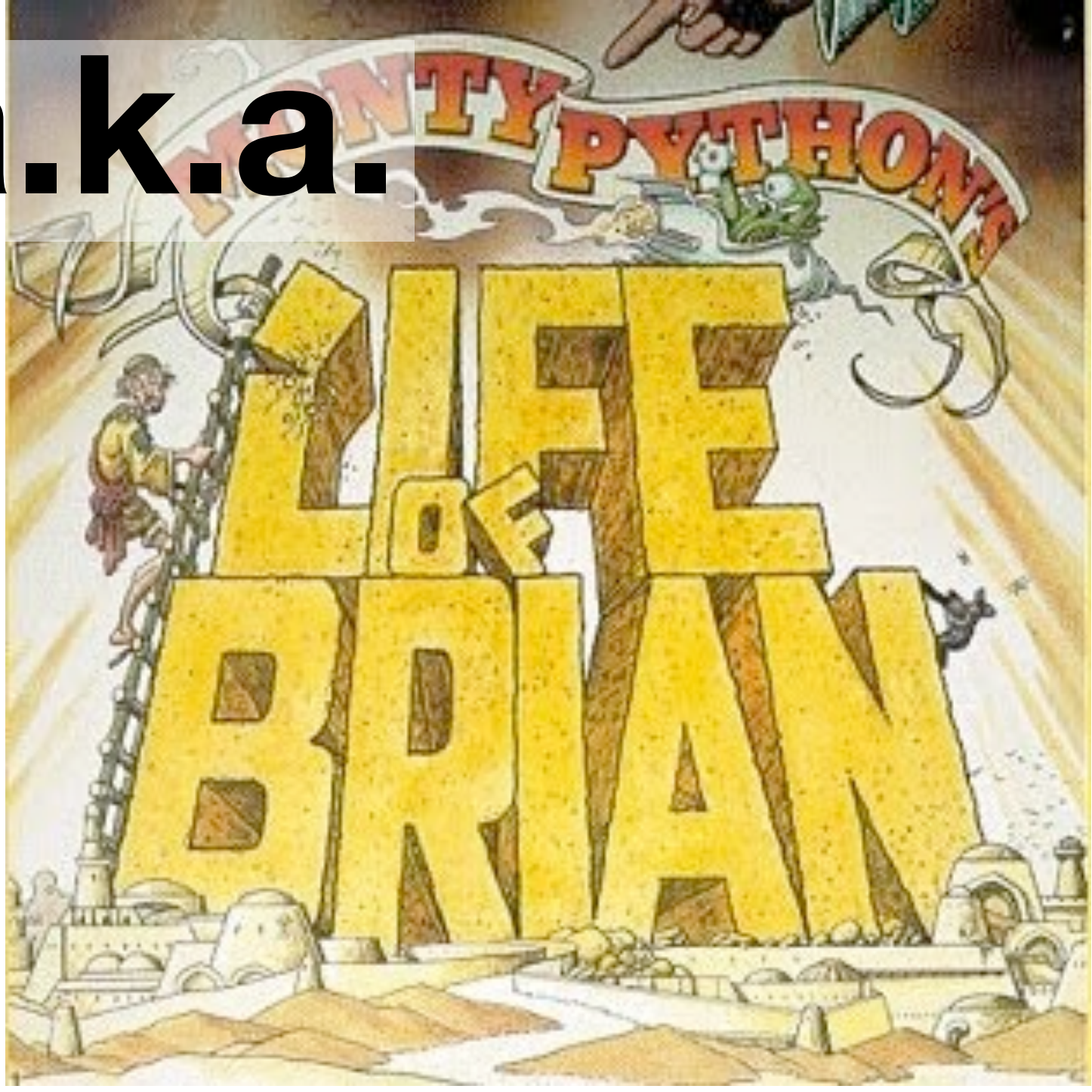
Kyle Story

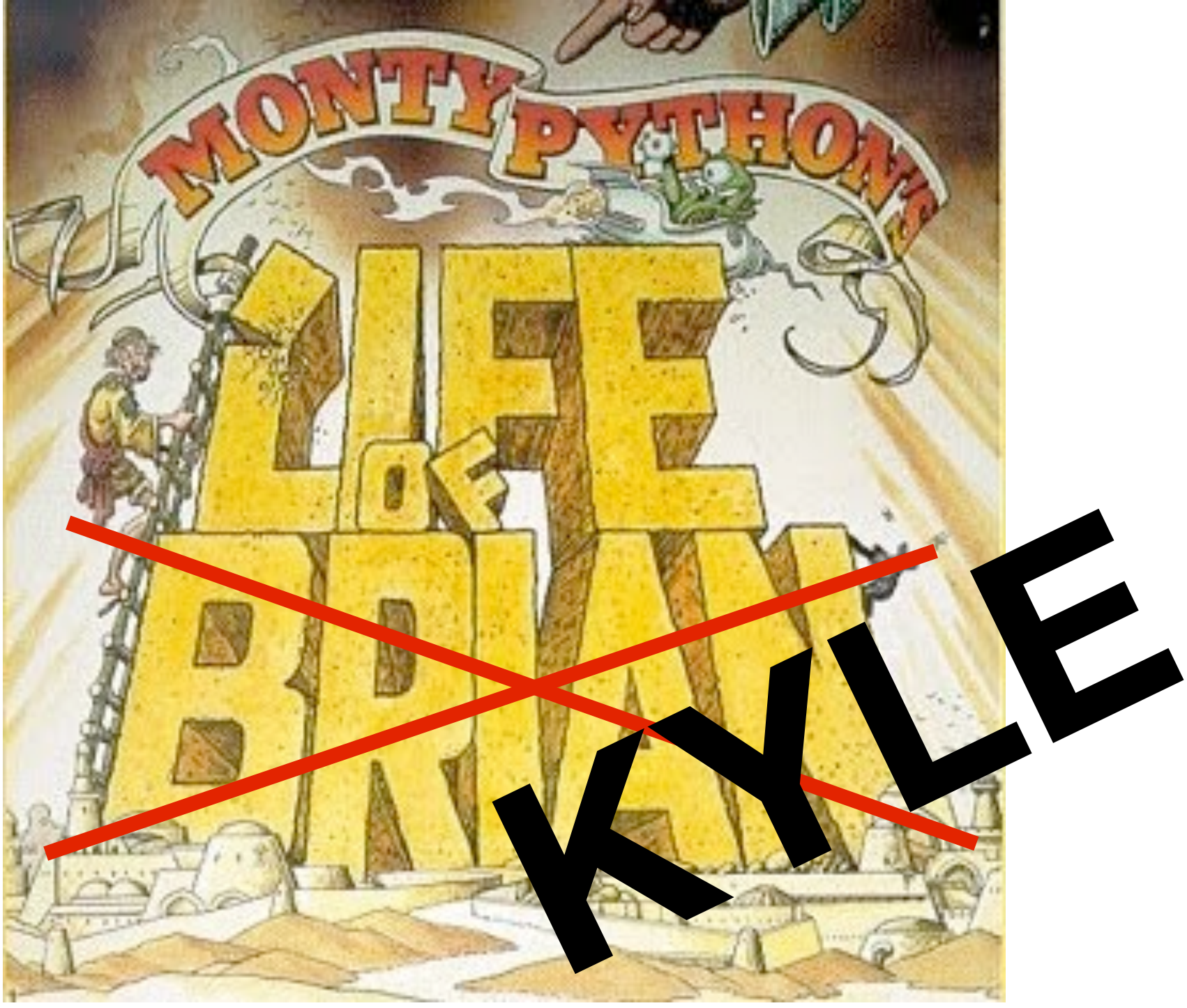
astro-ph: 1210.7231

November 5, 2012

Photo Credit: Daniel and Dana; Sunset 2011

a.k.a.

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Submitted to ApJ
Preprint typeset using LaTeX style emulateapj v. 08/22/09

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

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Submitted to ApJ

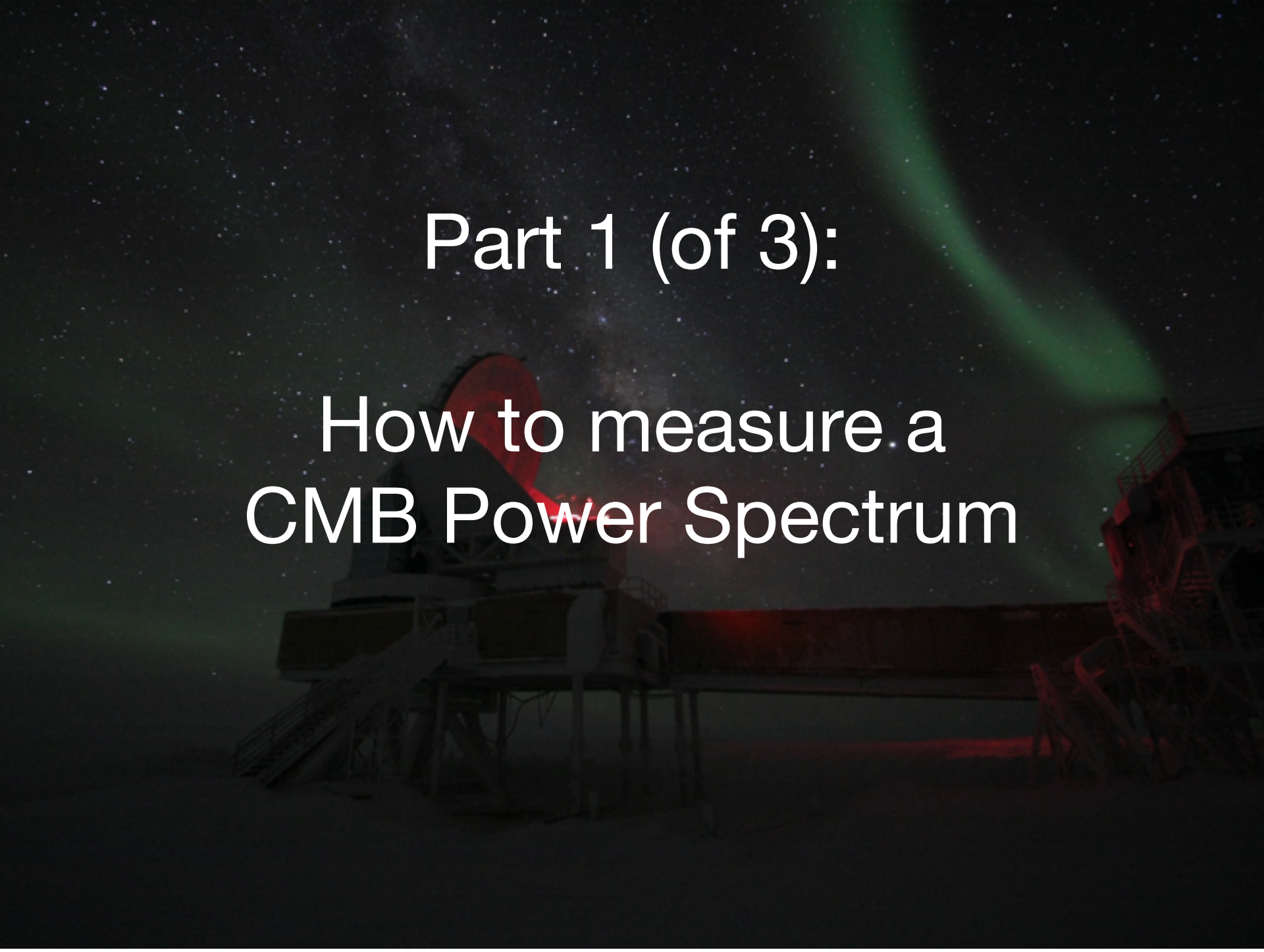
ABSTRACT

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

What I hope to answer:

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?

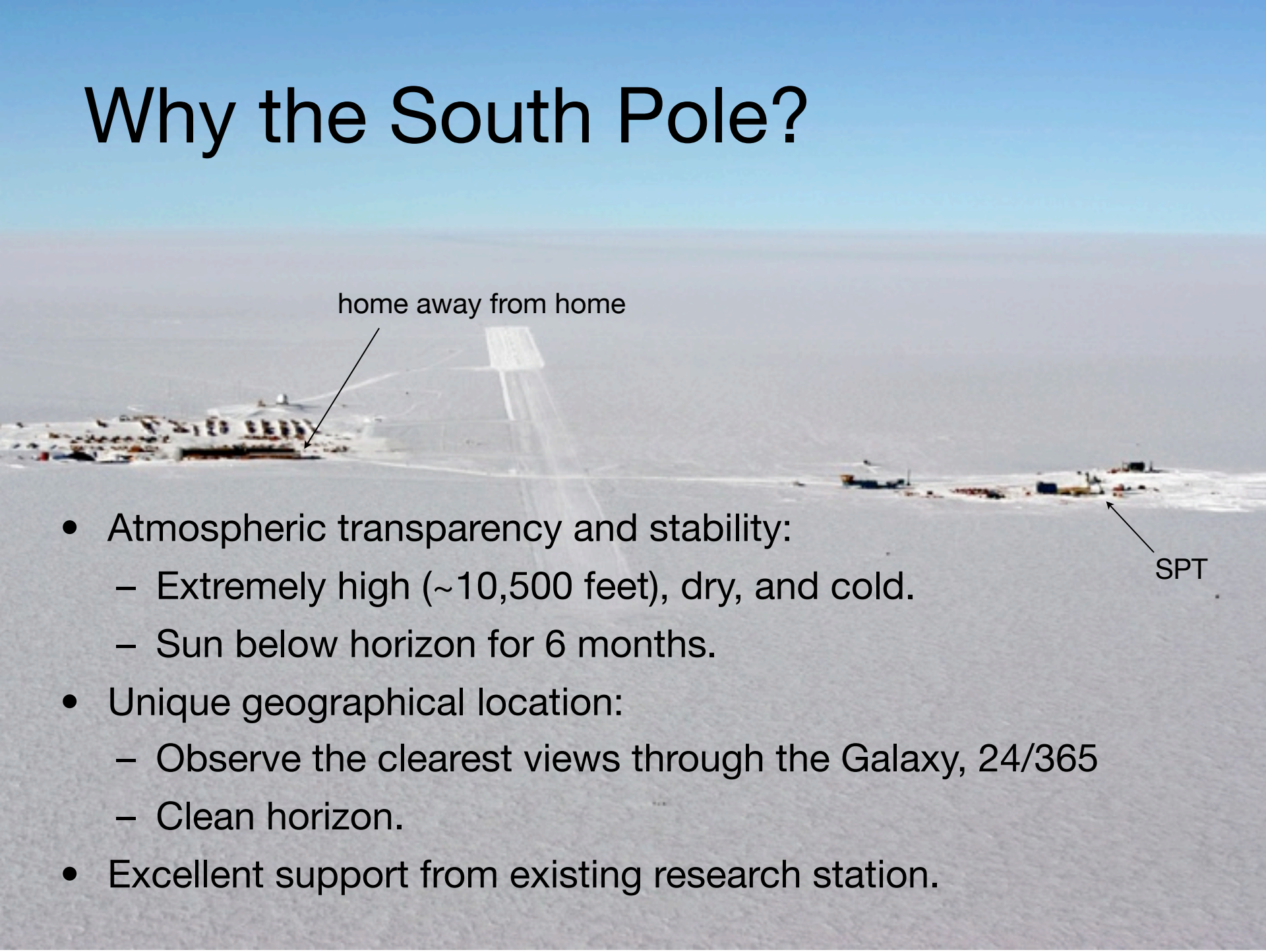


Part 1 (of 3):

How to measure a CMB Power Spectrum

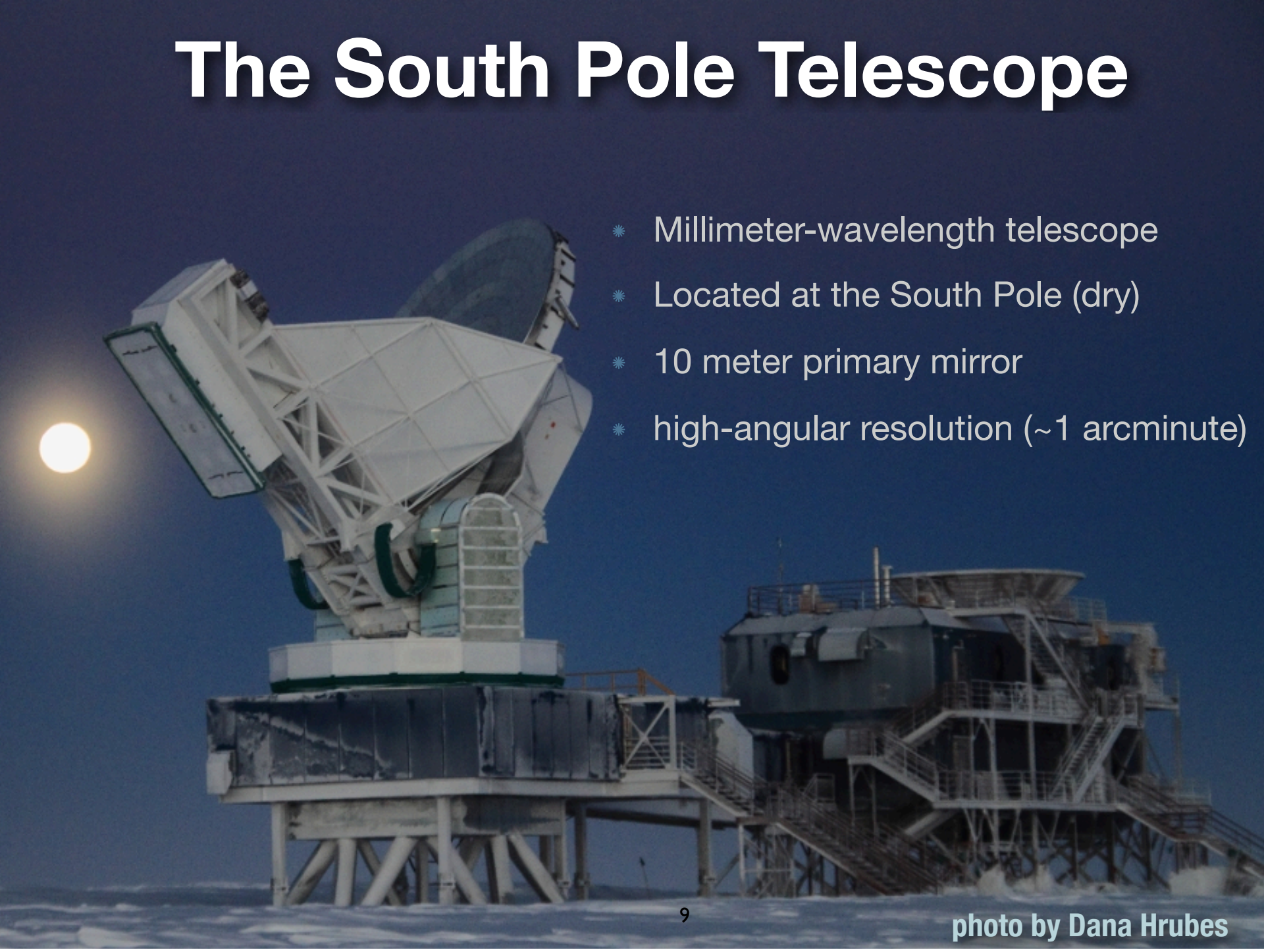
<u>Step 1:</u>
Build a 10-meter telescope at the South Pole

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



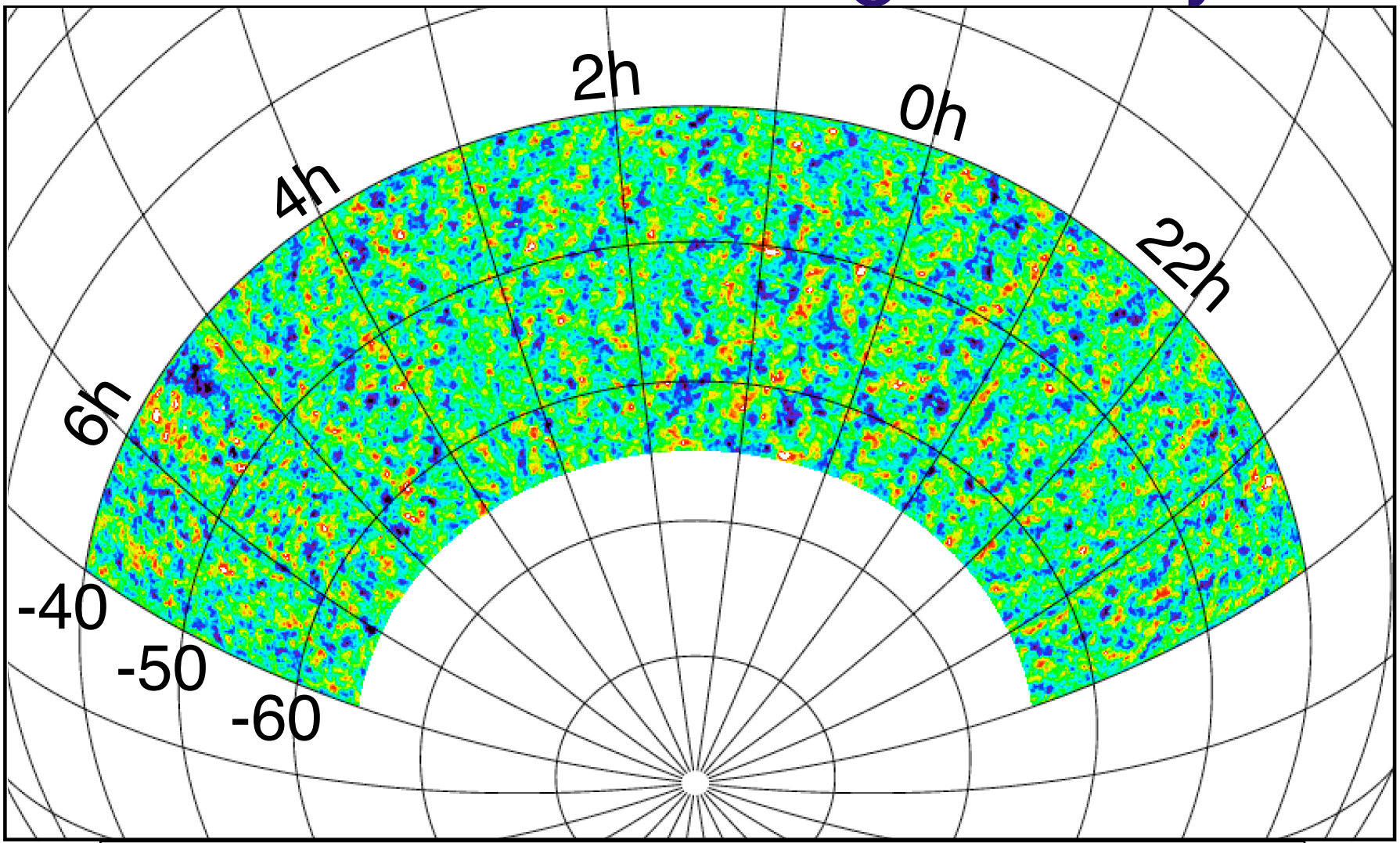
- Millimeter-wavelength telescope
- Located at the South Pole (dry)
- 10 meter primary mirror
- high-angular resolution (~1 arcminute)

photo by Dana Hrubes

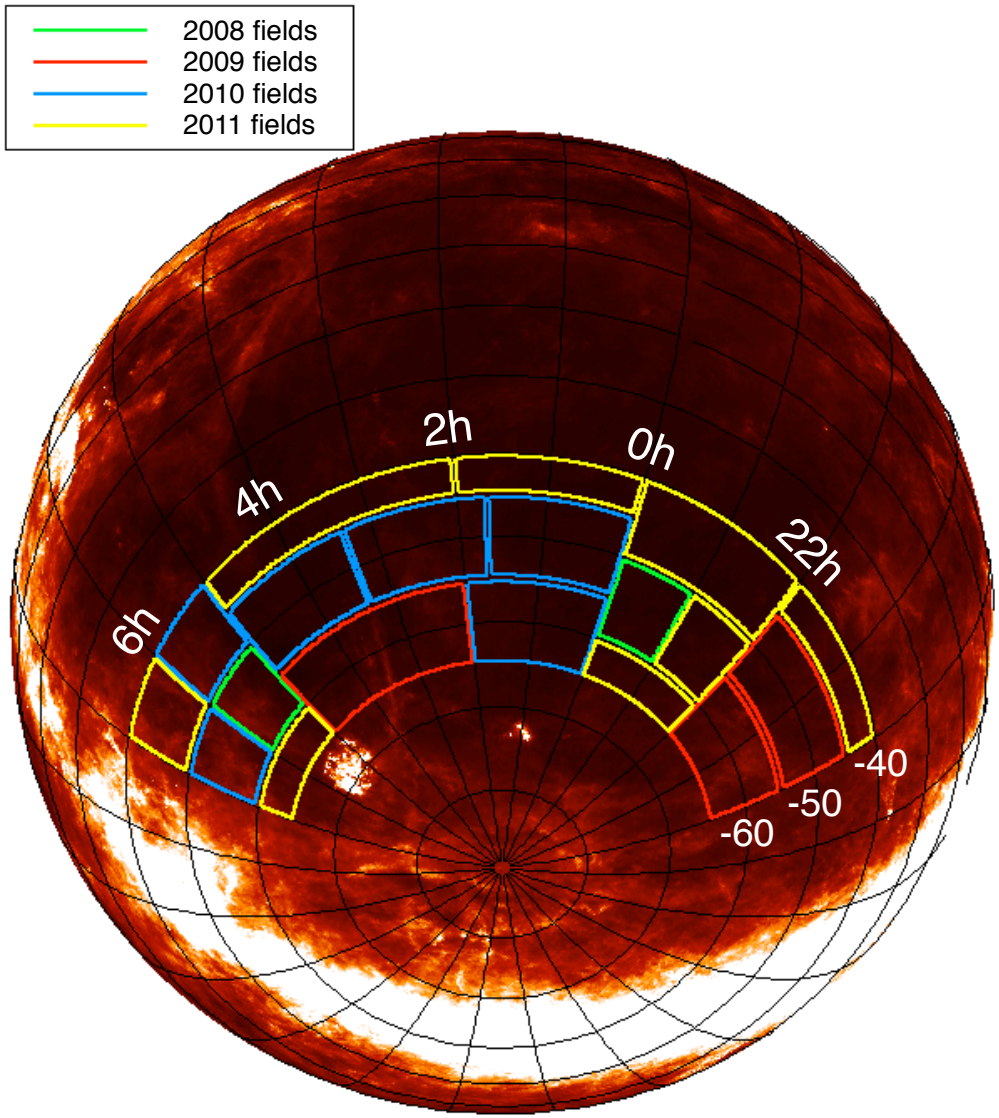
<u>Step 2:</u>

Observe 2500 deg^2 of sky

SPT-SZ 2500 deg^2 survey

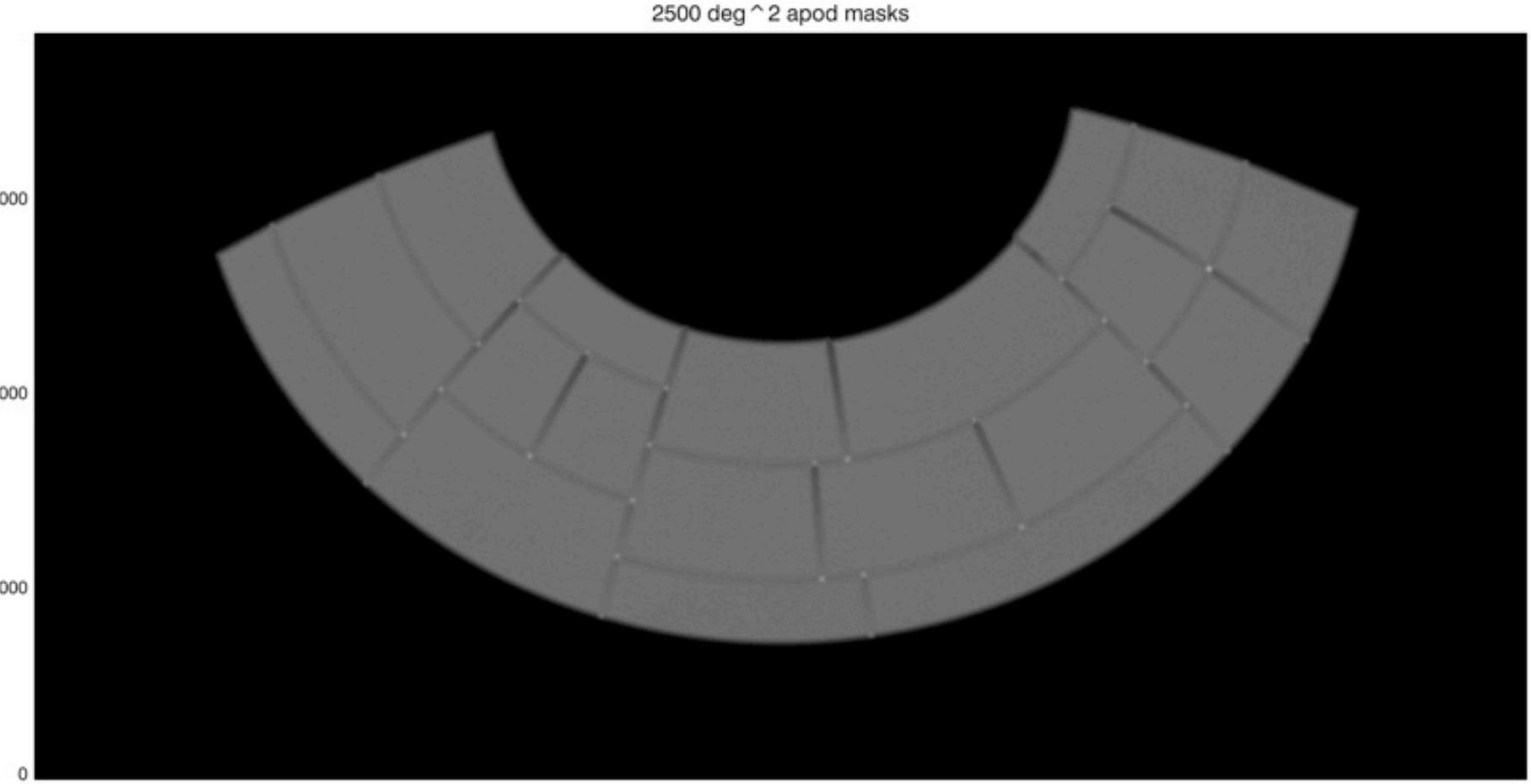


Status: finished in *Nov. 2011*.



Observation Strategy:

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

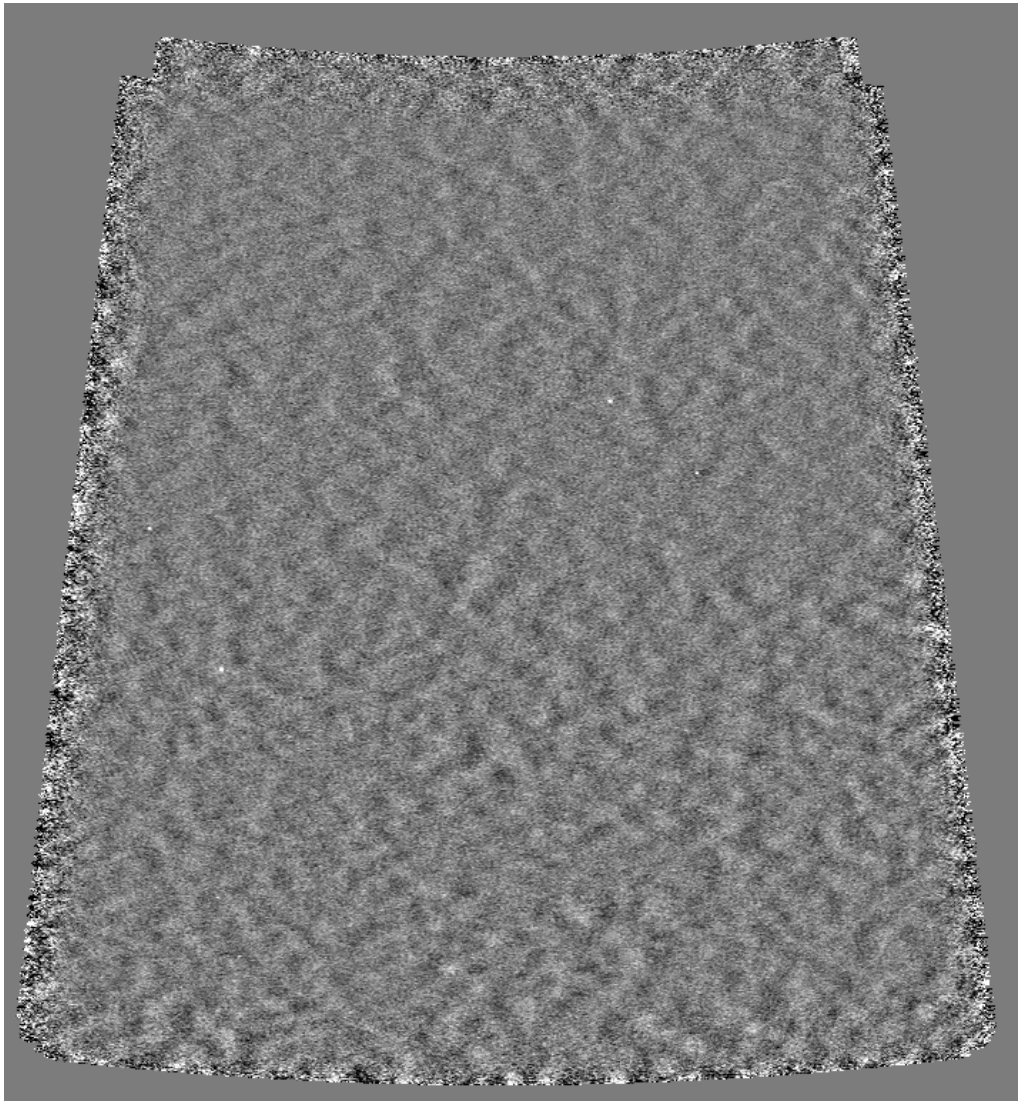


Observation Strategy:

Sweep in azimuth, then step in elevation

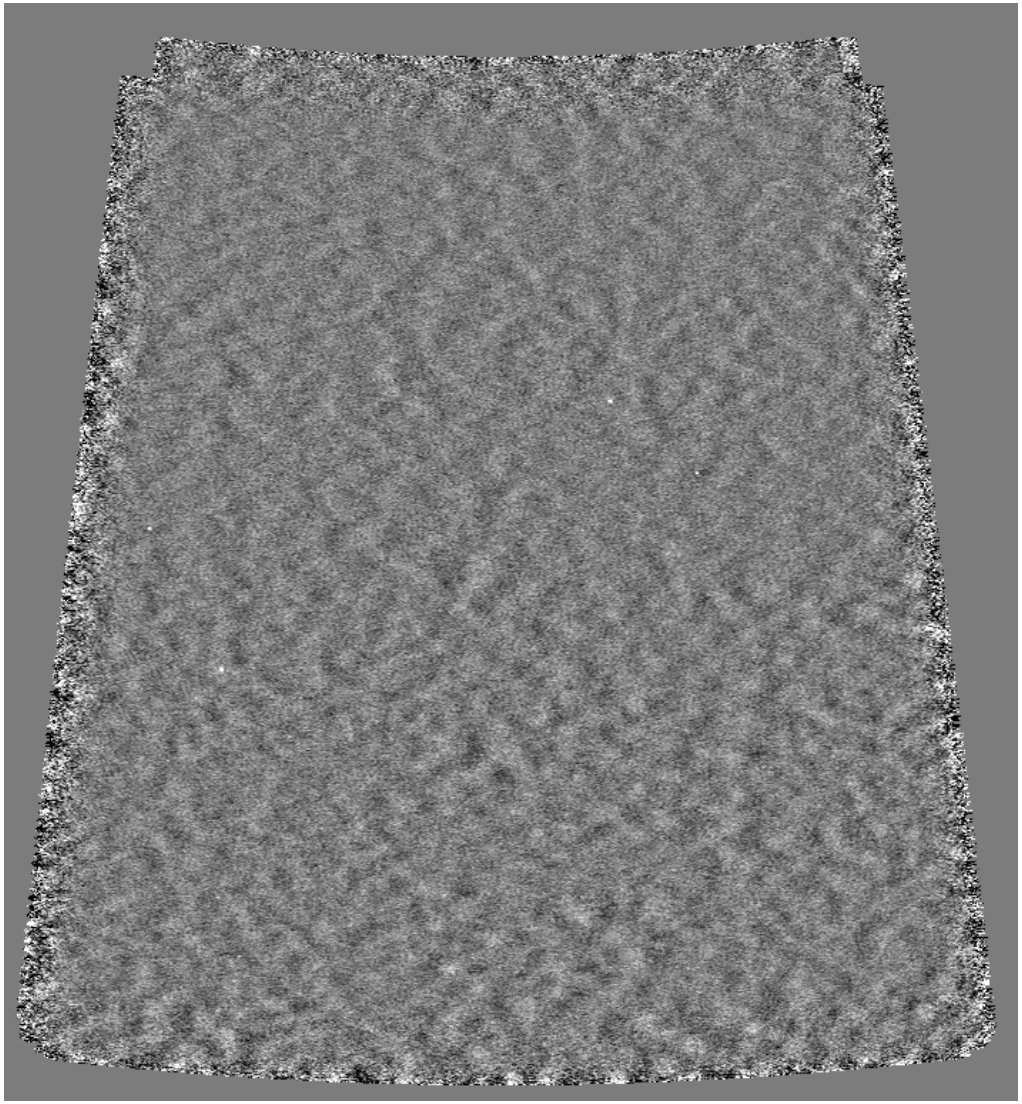
Observe 1 field to desired noise level, then move to next field

The result is maps of 19 fields,



ra22h30dec-55
Single Observation

The result is maps of 19 fields,

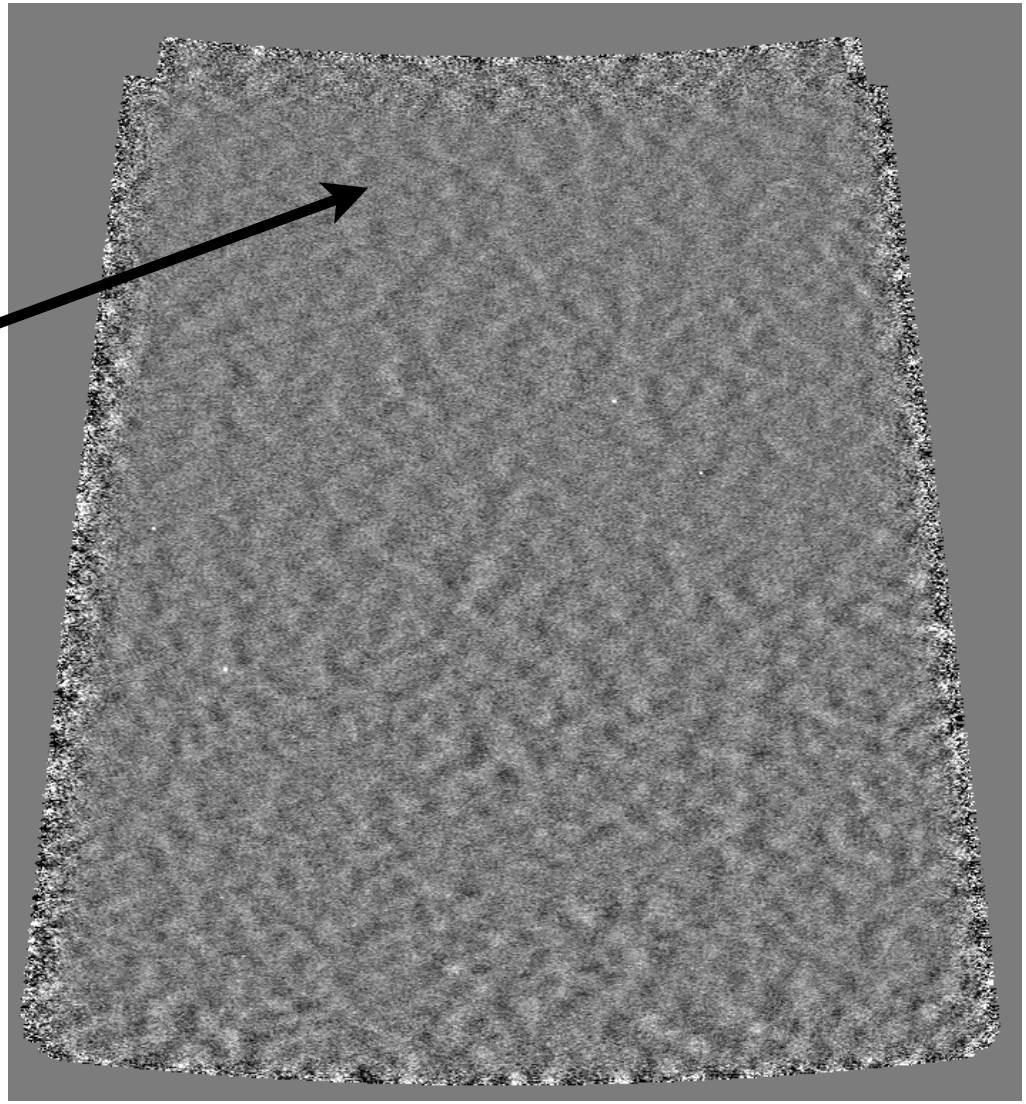


X ~200
per field

ra22h30dec-55
Single Observation

The result is maps of 19 fields,

mostly noise
(atmosphere)

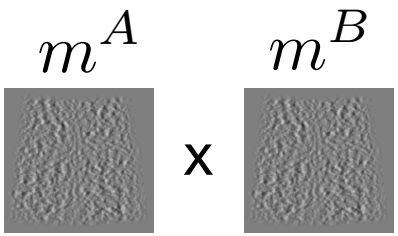


X ~200
per field

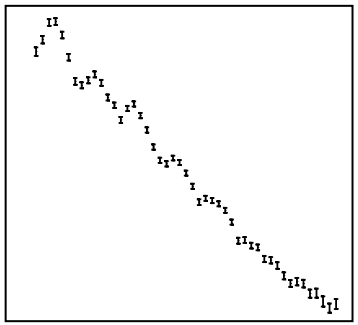
ra22h30dec-55
Single Observation

How do we calculate a power spectrum from the maps?

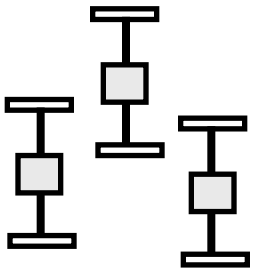
- **Cross-correlate** and average all pairs of observations (noise doesn't correlate)



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



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



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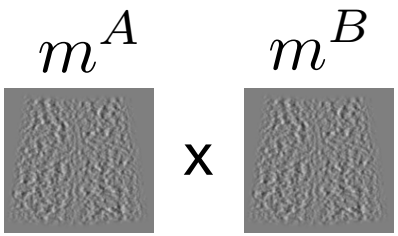

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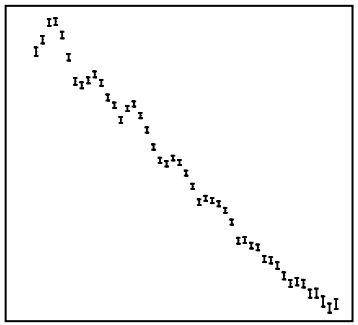

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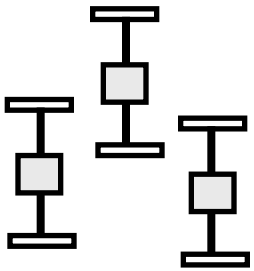
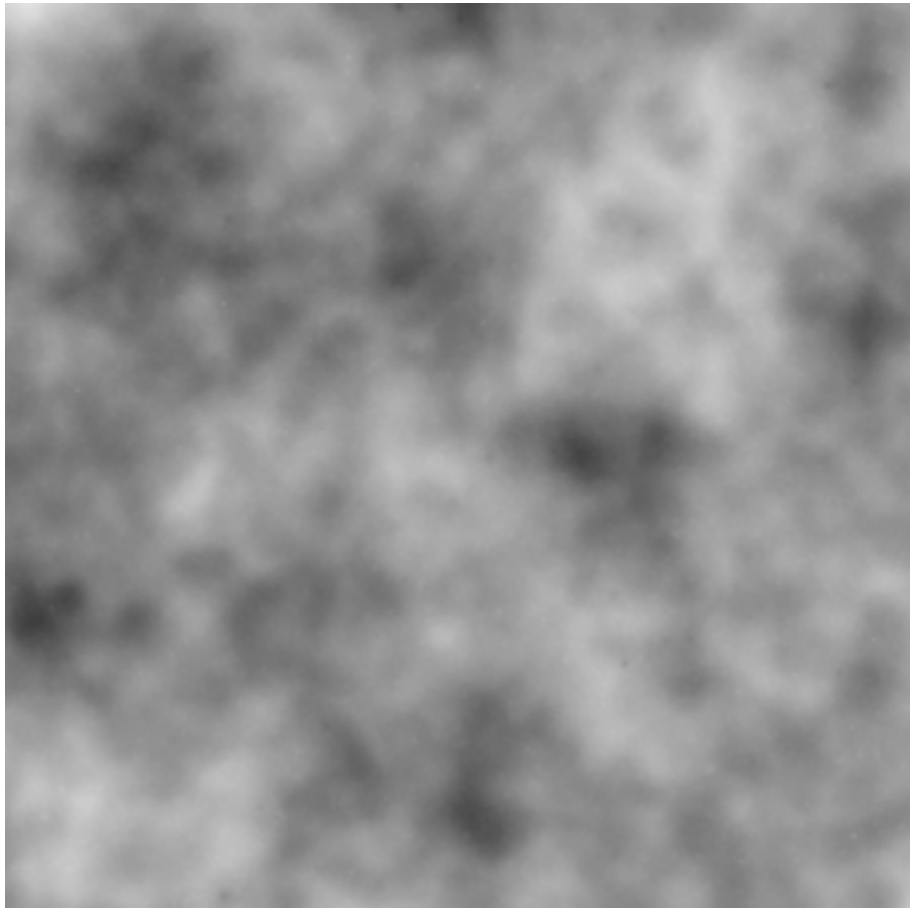


SPT “Pseudo-Cl” Analysis

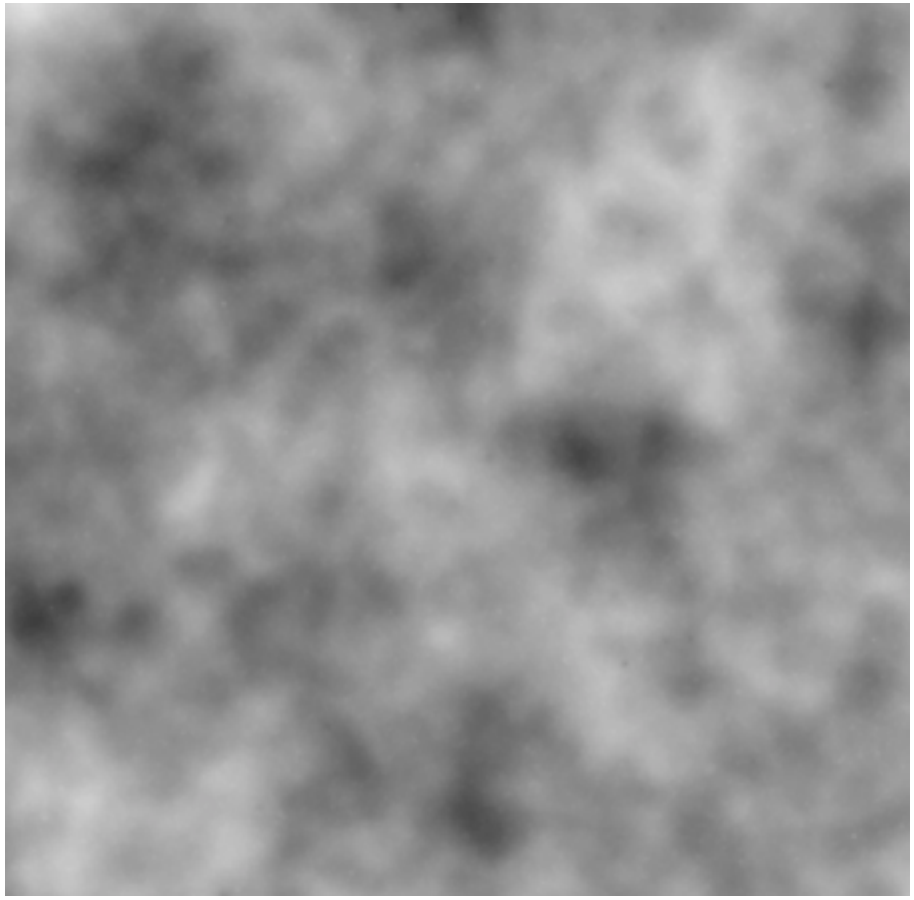


Key concept:

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

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

Fourier Transform



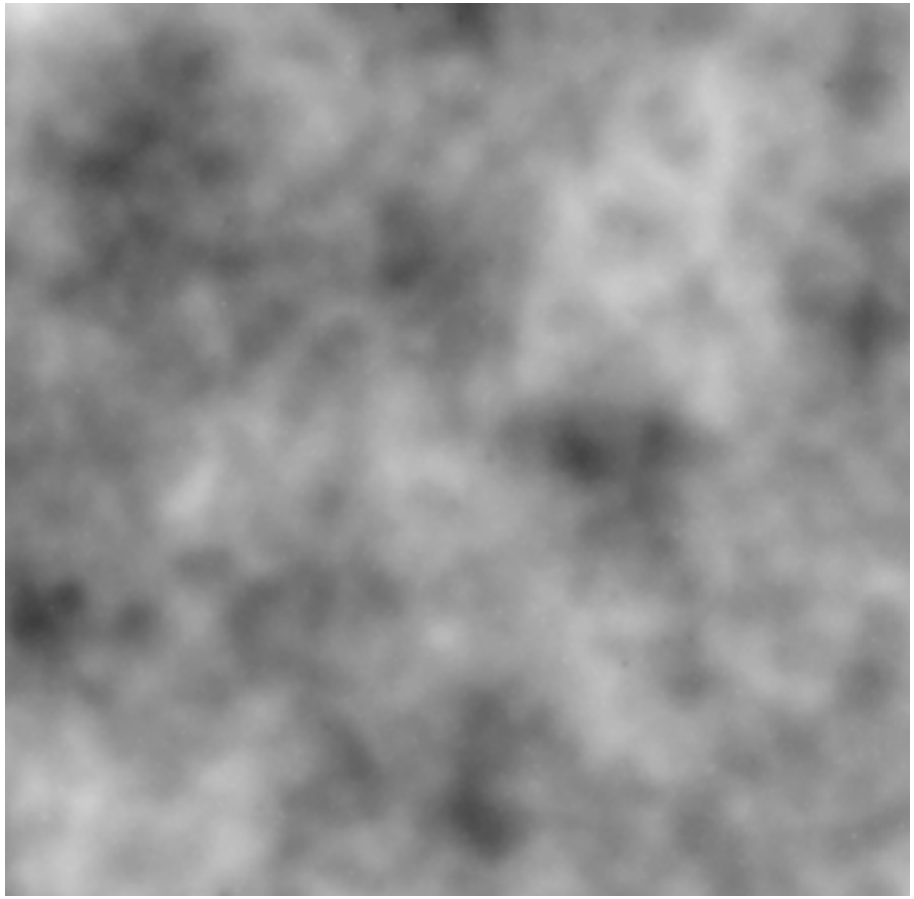
Basic Idea:

1) 2D Fourier Transform* each map

$$\widehat{D}_b^{AB} \equiv \left\langle \frac{\ell(\ell+1)}{2\pi} H_\ell Re[\tilde{m}_\ell^A \tilde{m}_\ell^{B*}] \right\rangle_{\ell \in b}$$

*Flat Sky approximation

Cross-correlate



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Basic Idea:

1) 2D Fourier Transform each map

2) Cross-correlate all pairs of maps

Noise weight

Basic Idea:

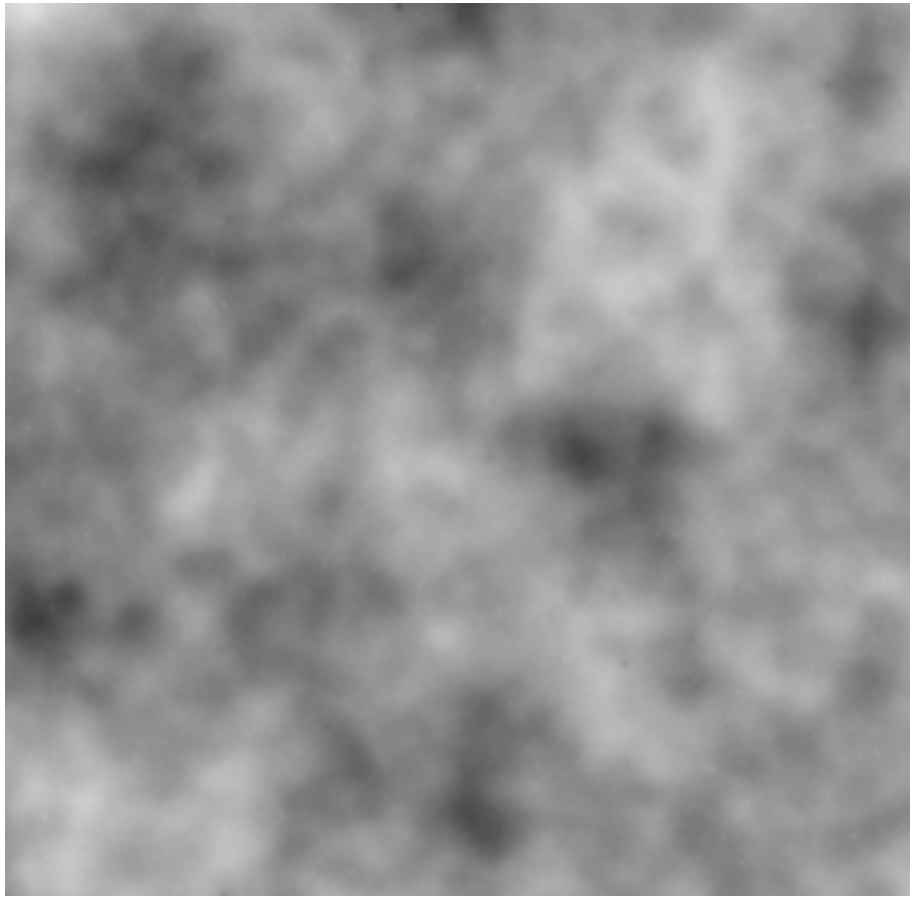
1) 2D Fourier Transform each map

2) Cross-correlate all pairs of maps

Account for anisotropic noise

$$\widehat{D}_b^{AB} \equiv \left\langle \frac{\ell(\ell+1)}{2\pi} H_\ell \mathrm{Re}[\tilde{m}_\ell^A \tilde{m}_\ell^{B*}] \right\rangle_{\ell \in b}$$

Average over ell



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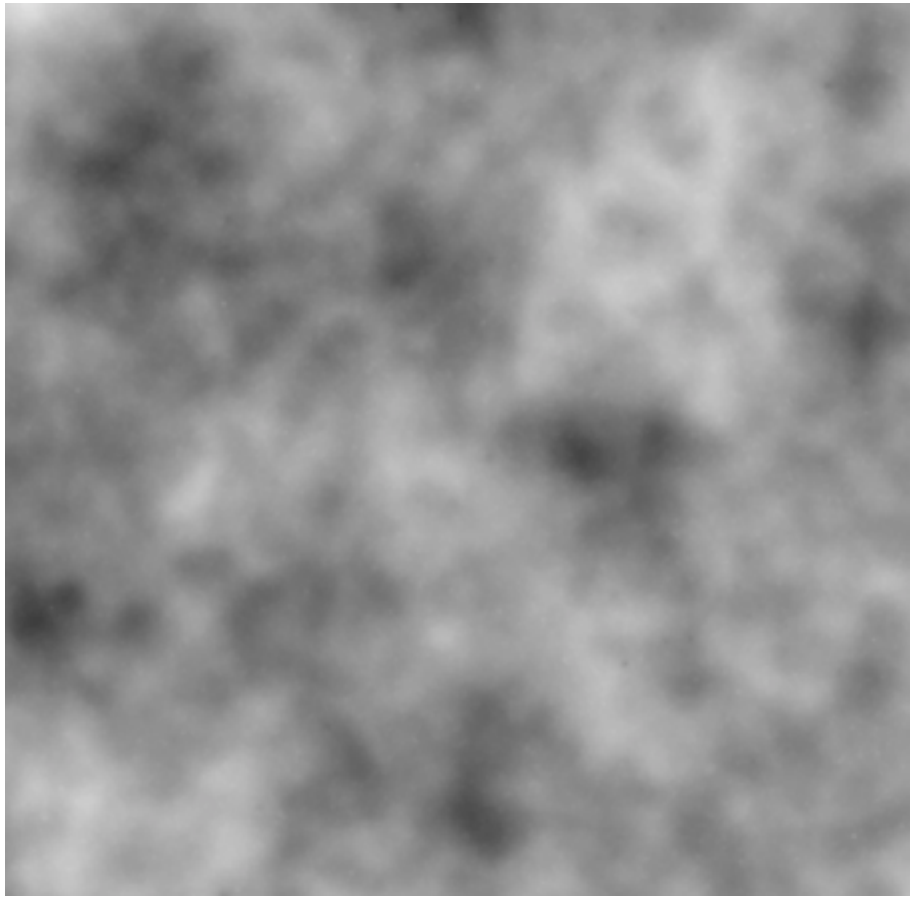
Basic Idea:

1) 2D Fourier Transform each map

2) Cross-correlate all pairs of maps

3) Average over ell (assume isotropy)

Average over Maps



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Basic Idea:

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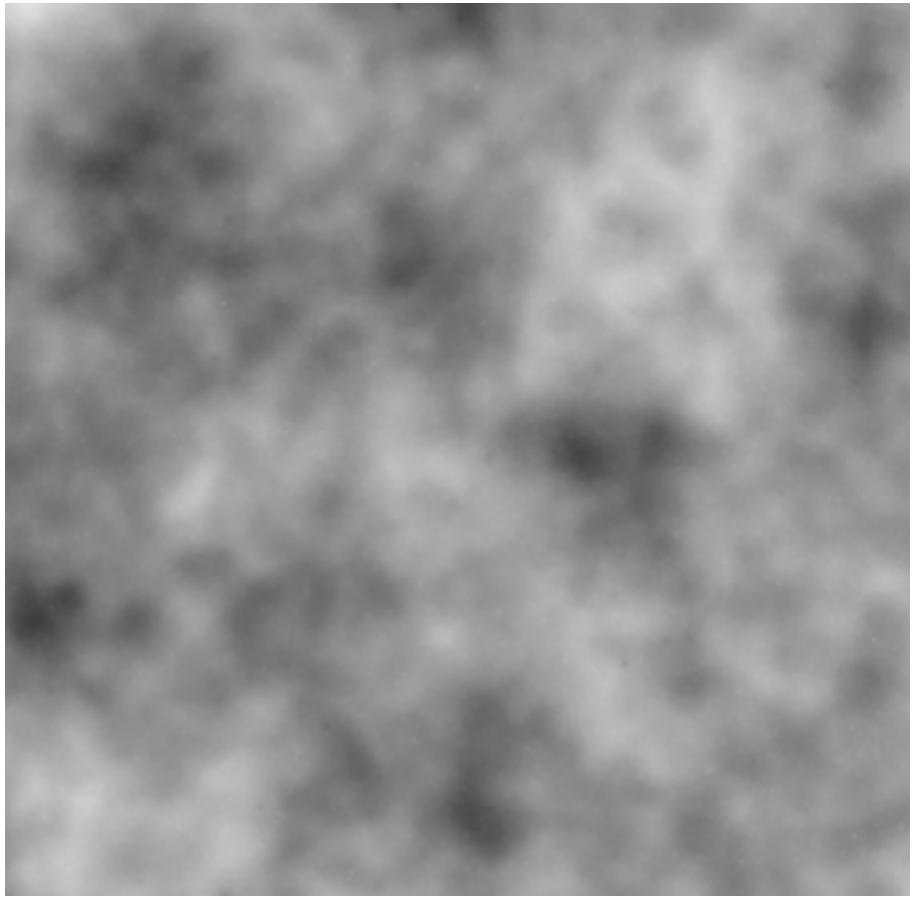
2) Cross-correlate all pairs of maps

3) Average over ell (assume isotropy)

4) Average over pairs A&B

Average over Fields



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Basic Idea:

1) 2D Fourier Transform each map

2) Cross-correlate all pairs of maps

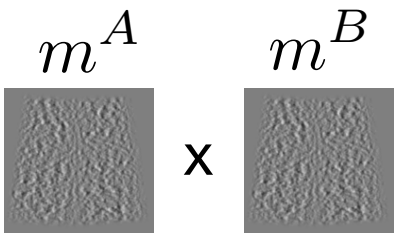
3) Average over ell (assume isotropy)

4) Average over pairs A&B

5) Average over the 19 fields

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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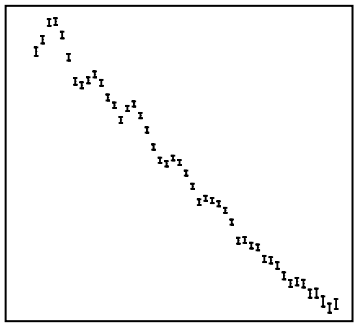

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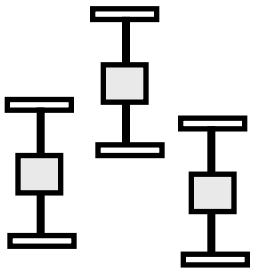

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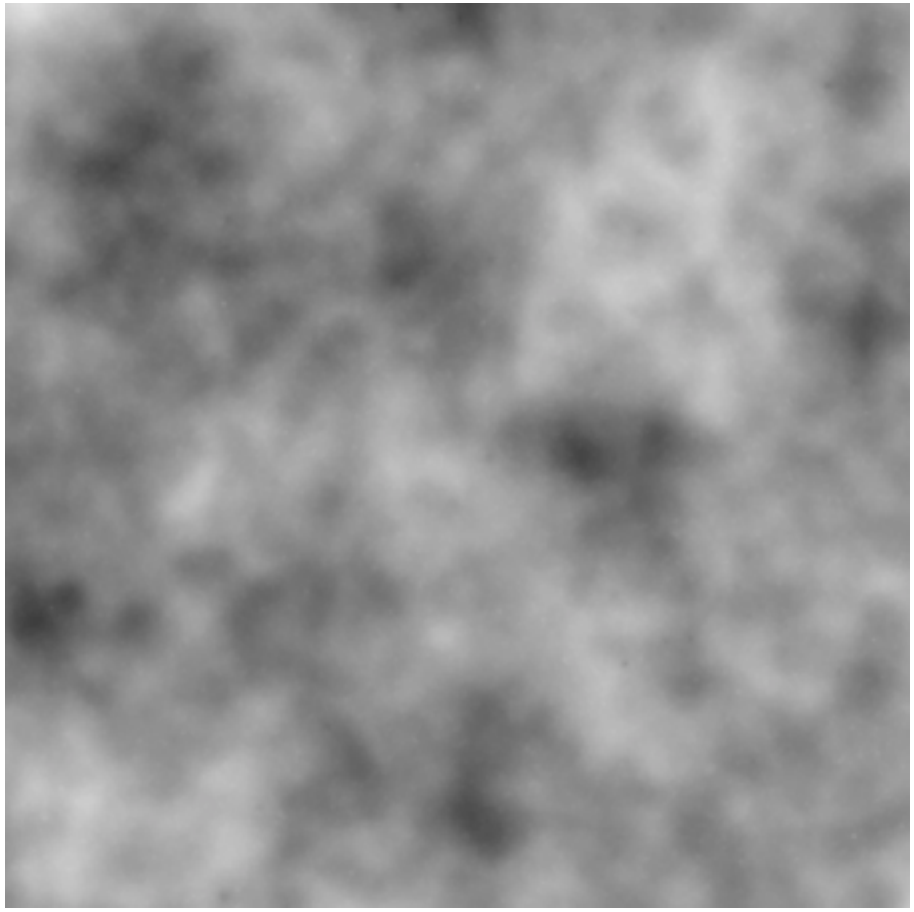


$$< \tilde{C}_\ell^{ii} >= B_\ell^2 < C_{\ell'} >$$

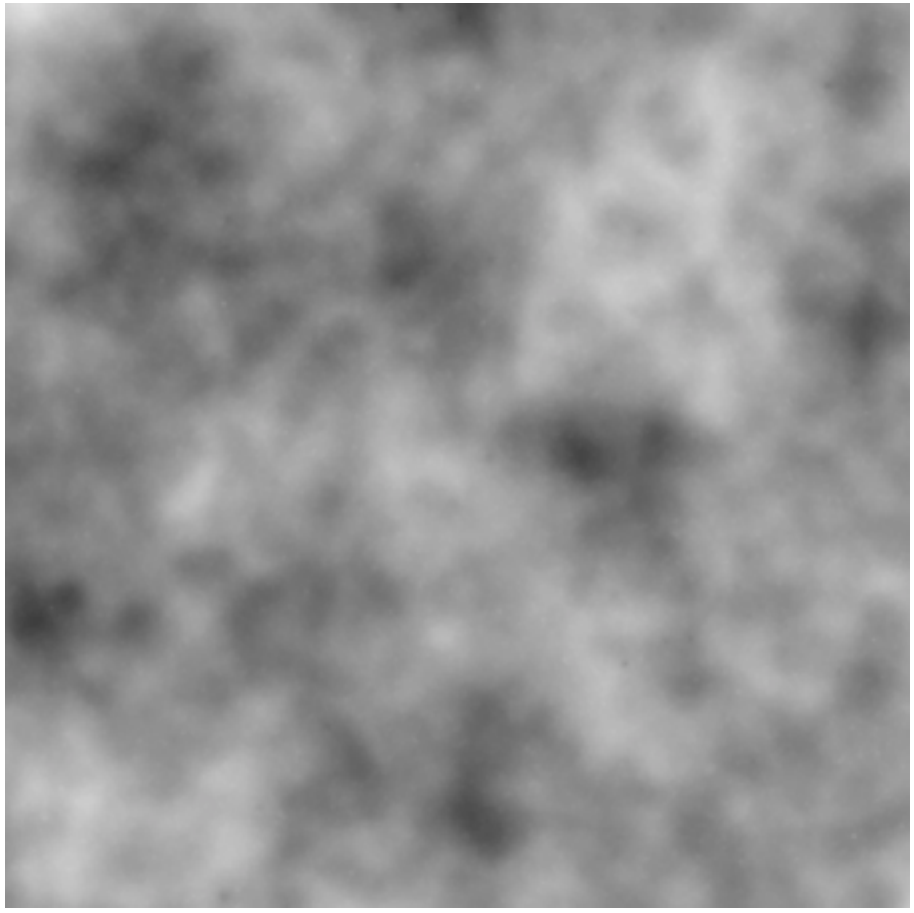
In Equations:

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

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

Need to explicitly account for:

Beam



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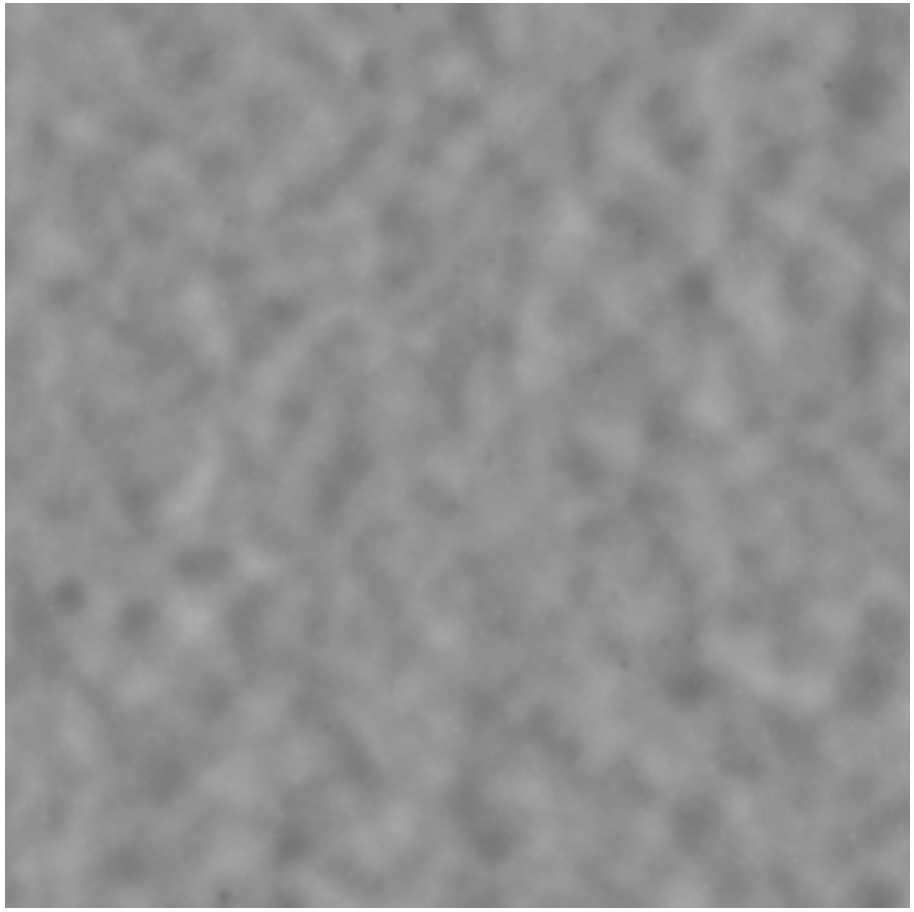
Need to explicitly account for:

•Experimental beam shape

Filtering



$$< \tilde{C}_\ell^{ii} >= F_\ell B_\ell^2 < C_{\ell'} >$$

In Equations:

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

Need to explicitly account for:

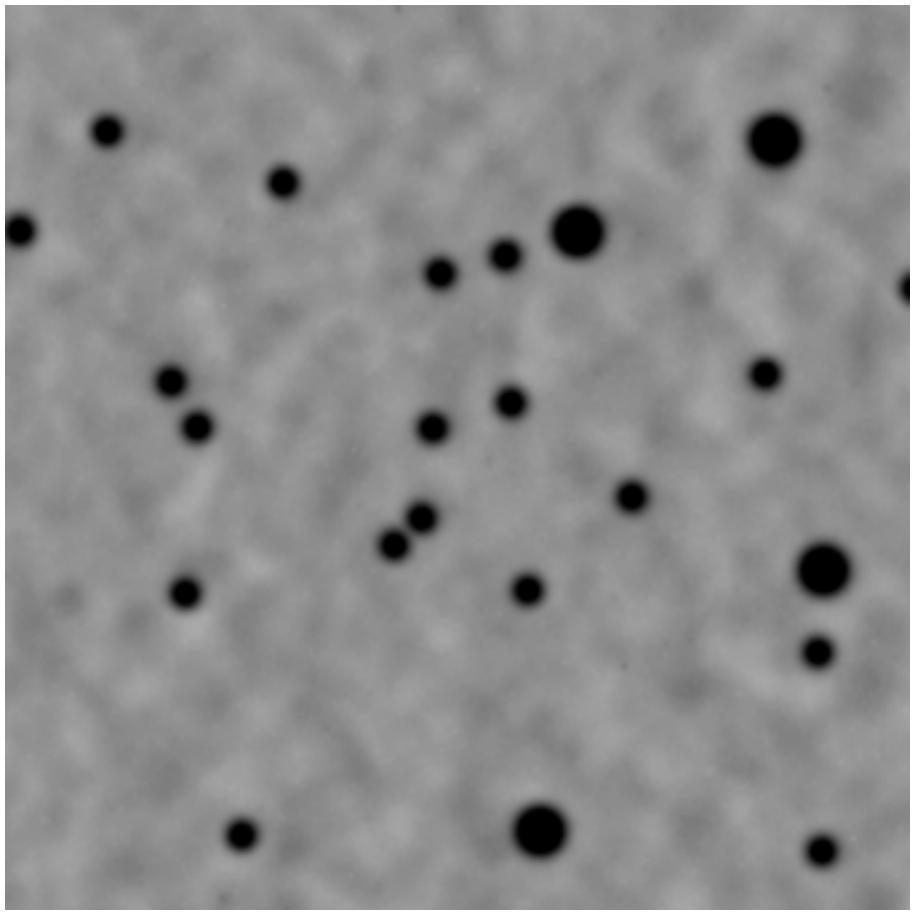
- Experimental beam shape
- Filtering of timestream data

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:

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

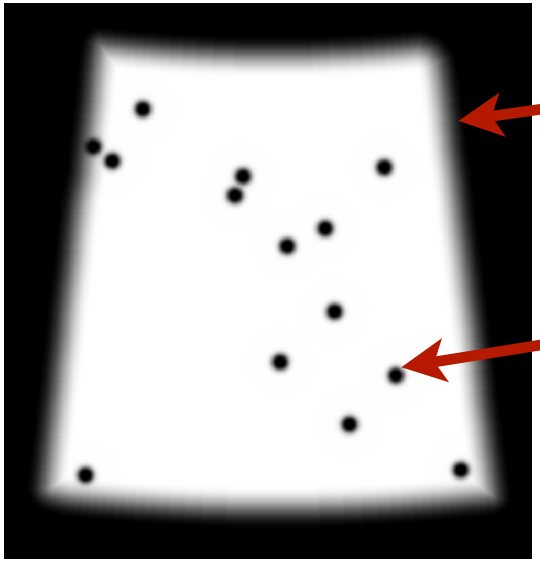
$$\tilde{C}^{ii}_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |\tilde{a}^i_{\ell m}|^2$$

Need to explicitly account for:

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

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

Account for masking: “Mode coupling”



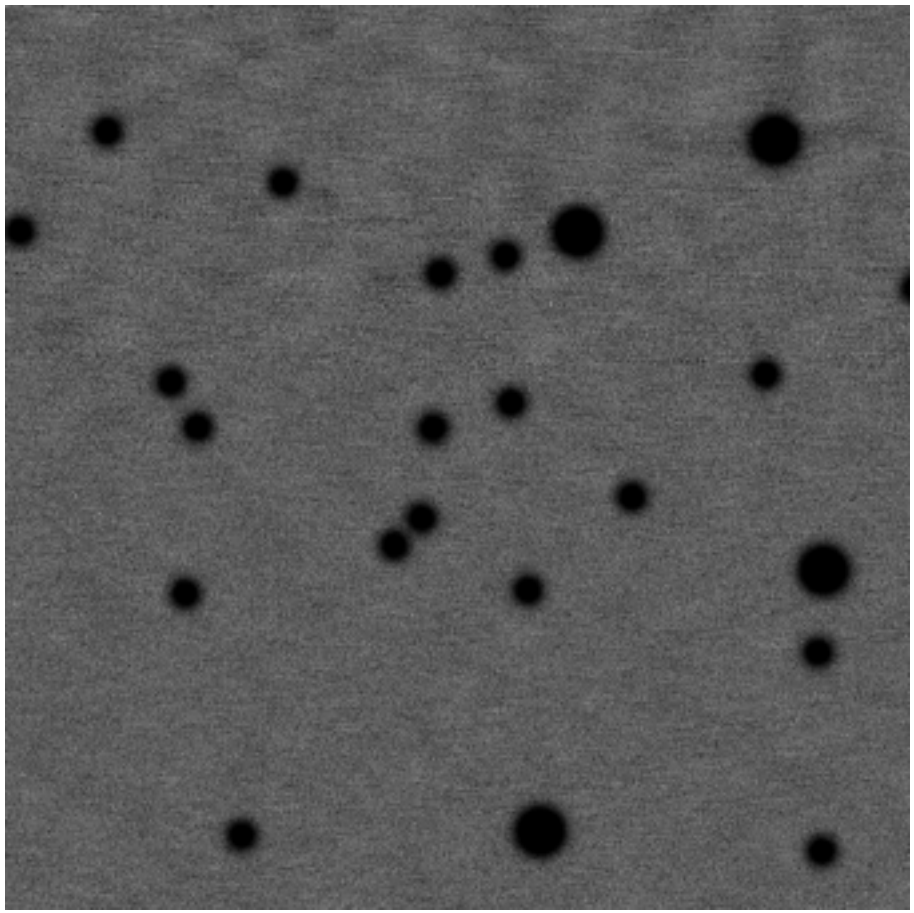
Apodize edges of each field

Mask point-sources

(Unmasked point-sources are accounted for in the cosmological fits)

Analytically calculate the mode coupling:
Hivon et al. 2002, ApJ, 567, 2

Noise bias



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

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)

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

How do we calculate a power spectrum from the maps?

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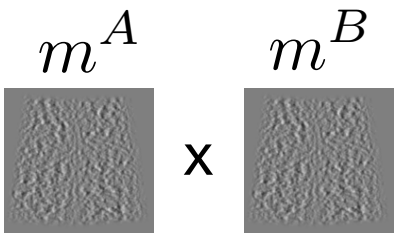

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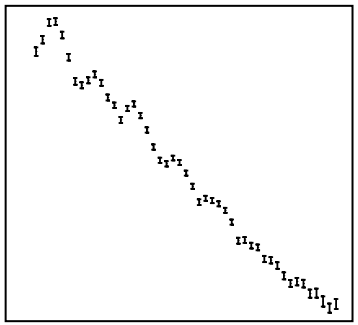
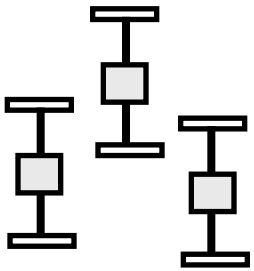


- Estimate **errors** from simulations and data.



Bandpower uncertainties contain contributions from: **noise**, **sample variance**, and **other uncertainties**

Cov = Cov_noise + Cov_sv + other uncertainties

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$$\boxed{\text{Cov} = \text{Cov\_noise} + \text{Cov\_sv} + \text{other uncertainties}}$$

1) Cov_noise is the variance between the cross-spectra:

$$\boxed{\text{cov\_ij} = \langle (\text{dl\_i} - \mu) * (\text{dl\_j} - \mu) \rangle}$$

Where $\mu = \langle \text{dl} \rangle$

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Where $\mu = \langle dl \rangle$

2) Cov_sv is calculated directly from the 100 independent (2500 deg^2) simulated spectra.

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$$\boxed{\text{cov\_ij} = \langle (\text{dl\_i} - \mu) * (\text{dl\_j} - \mu) \rangle}$$

Where $\mu = \langle \text{dl} \rangle$

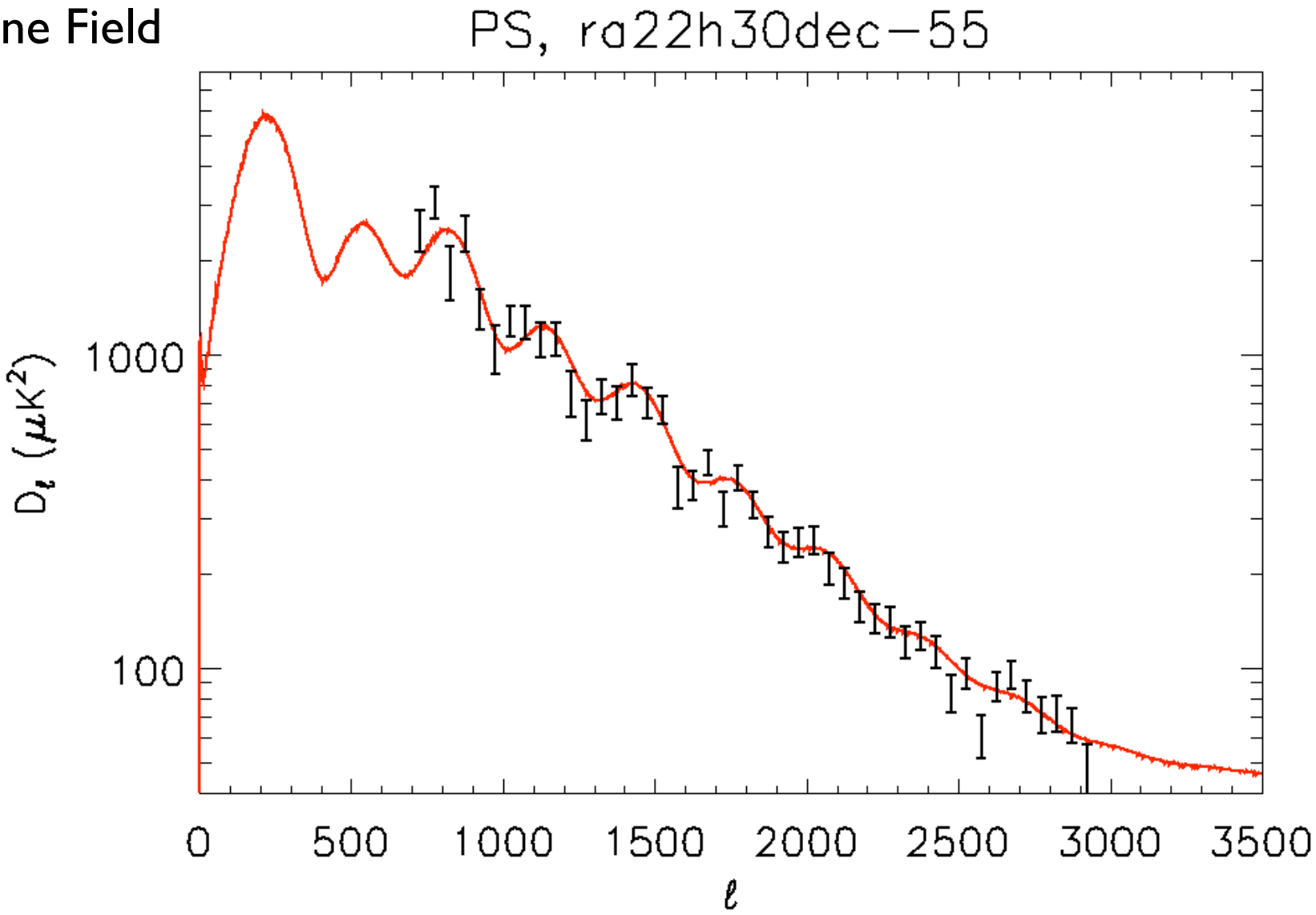
2) Cov_sv is calculated directly from the 100 independent (2500 deg^2) simulated spectra.

3) Other uncertainties:

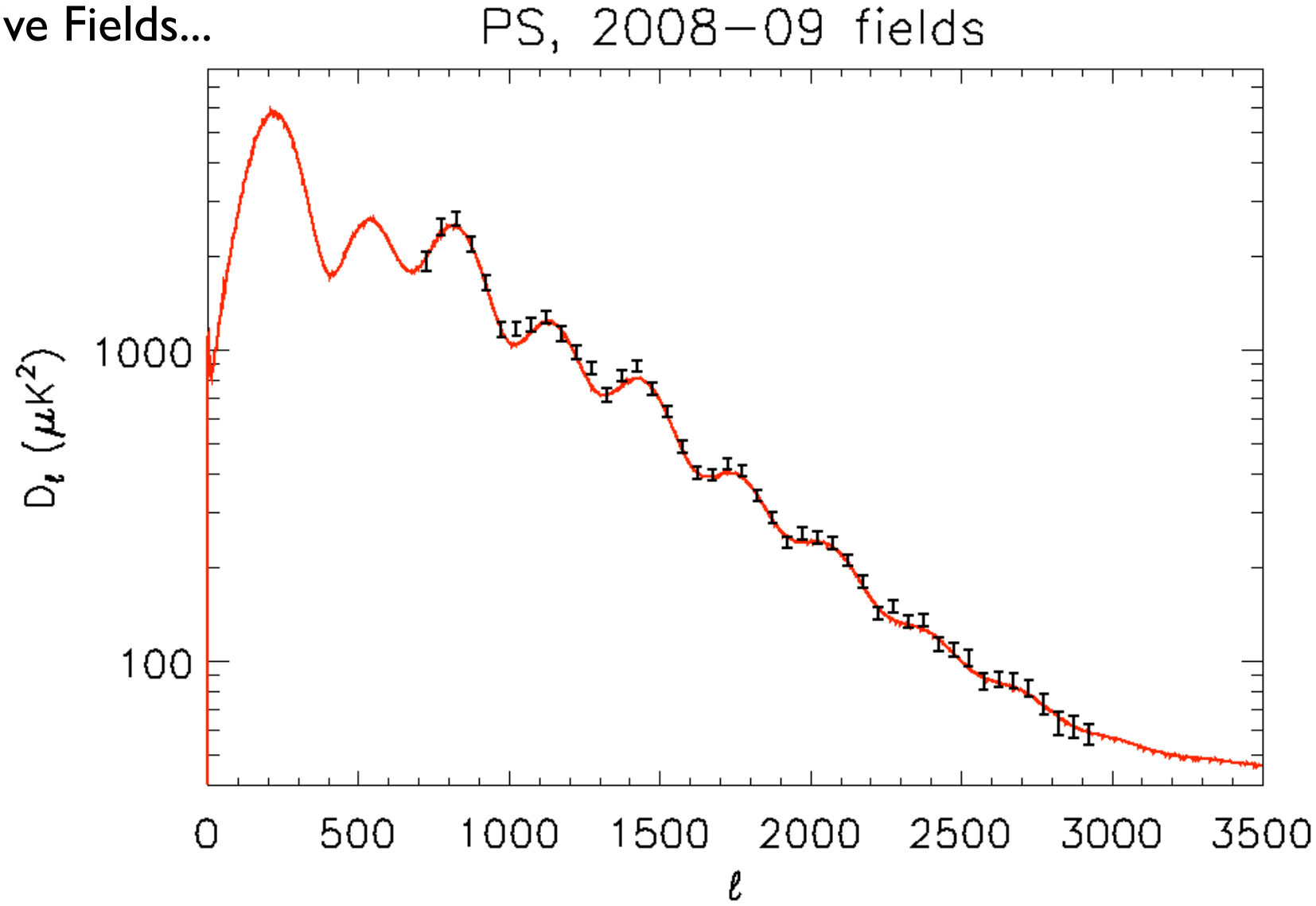
Beam uncertainties: ell-dependent, up to 10% of error bars.
Calibration uncertainties: 2.6% in power

Put this all together and you get ...

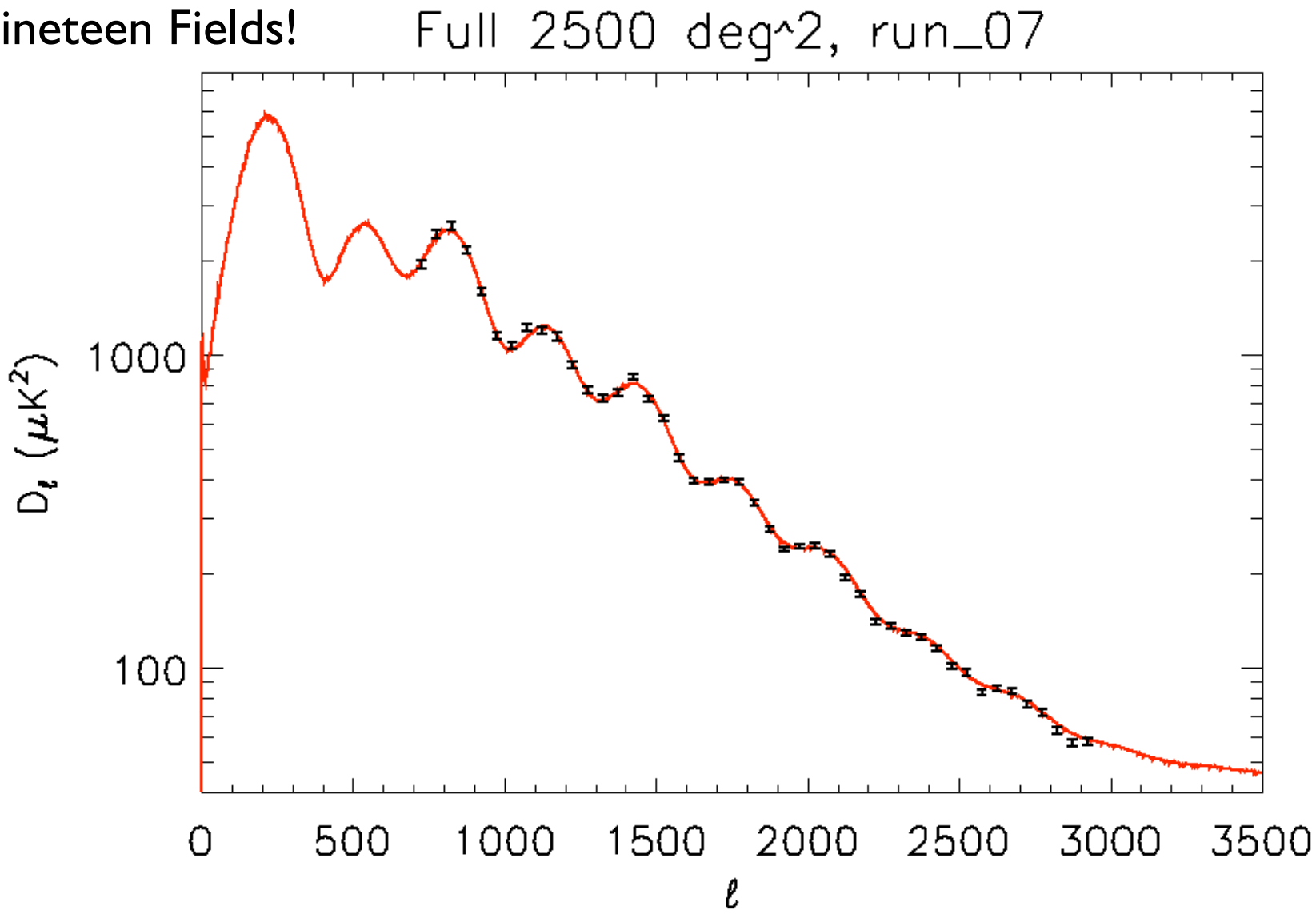
One Field


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

Five Fields...

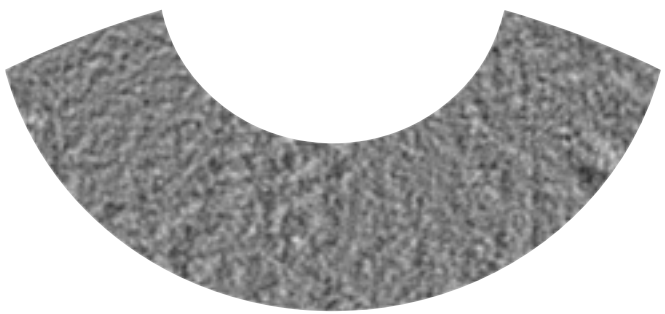

PS, 2008−09 fields
D_ℓ (μK^2)
1000
100
0
500
1000
1500
2000
2500
3000
3500
ℓ

Nineteen Fields!

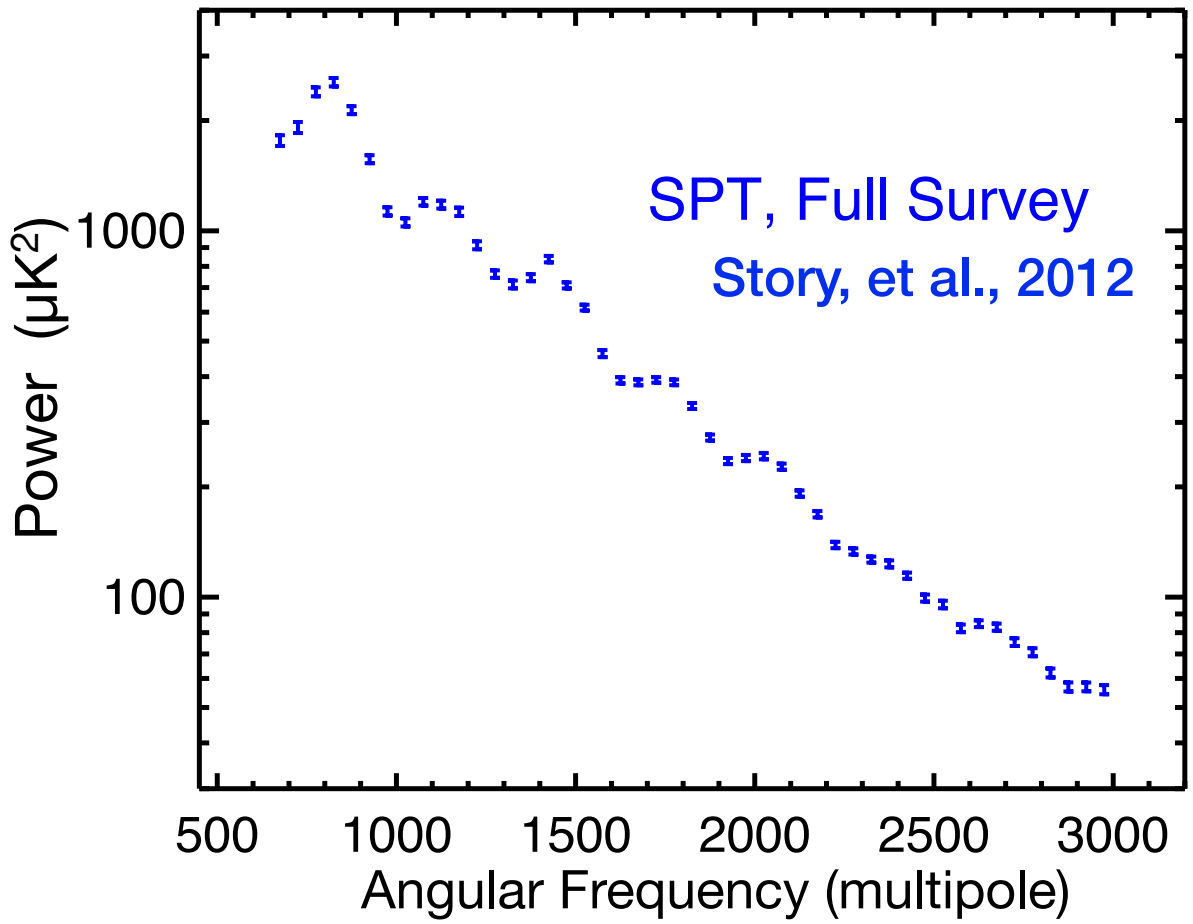


CMB Power Spectrum

Fourier transform this



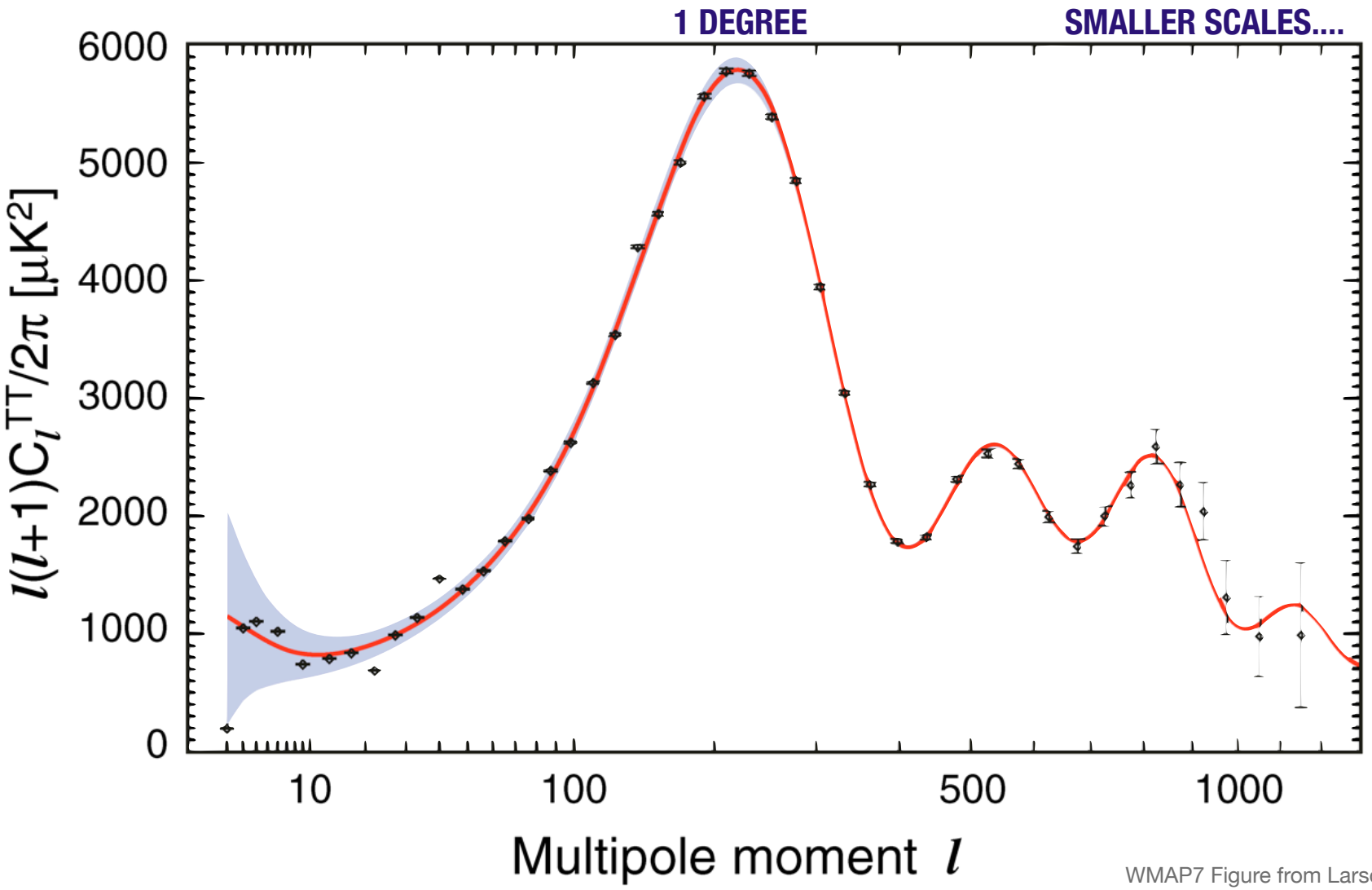
and you get....



Part 2 (of 3):

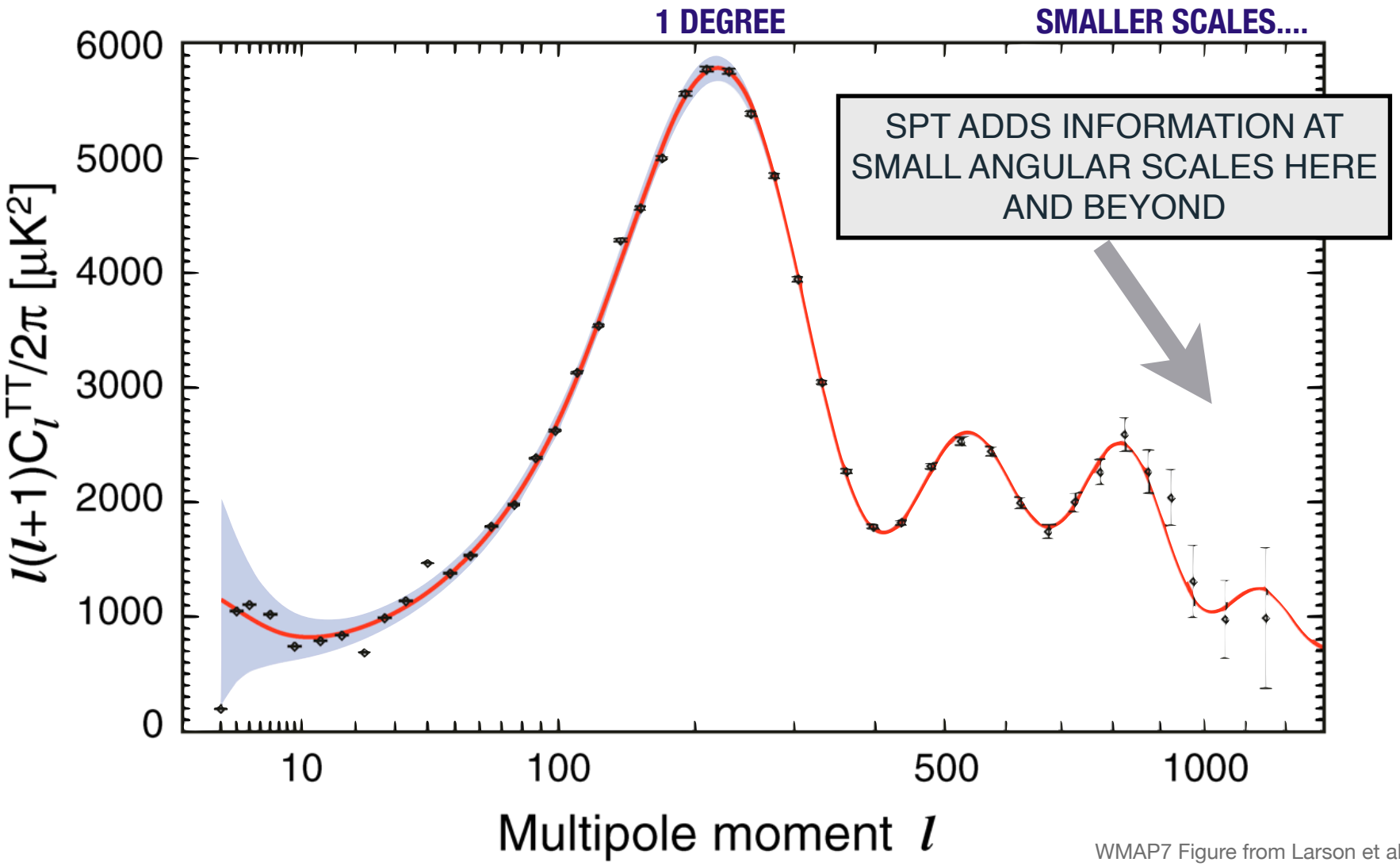
Context for the SPT power spectrum

WMAP



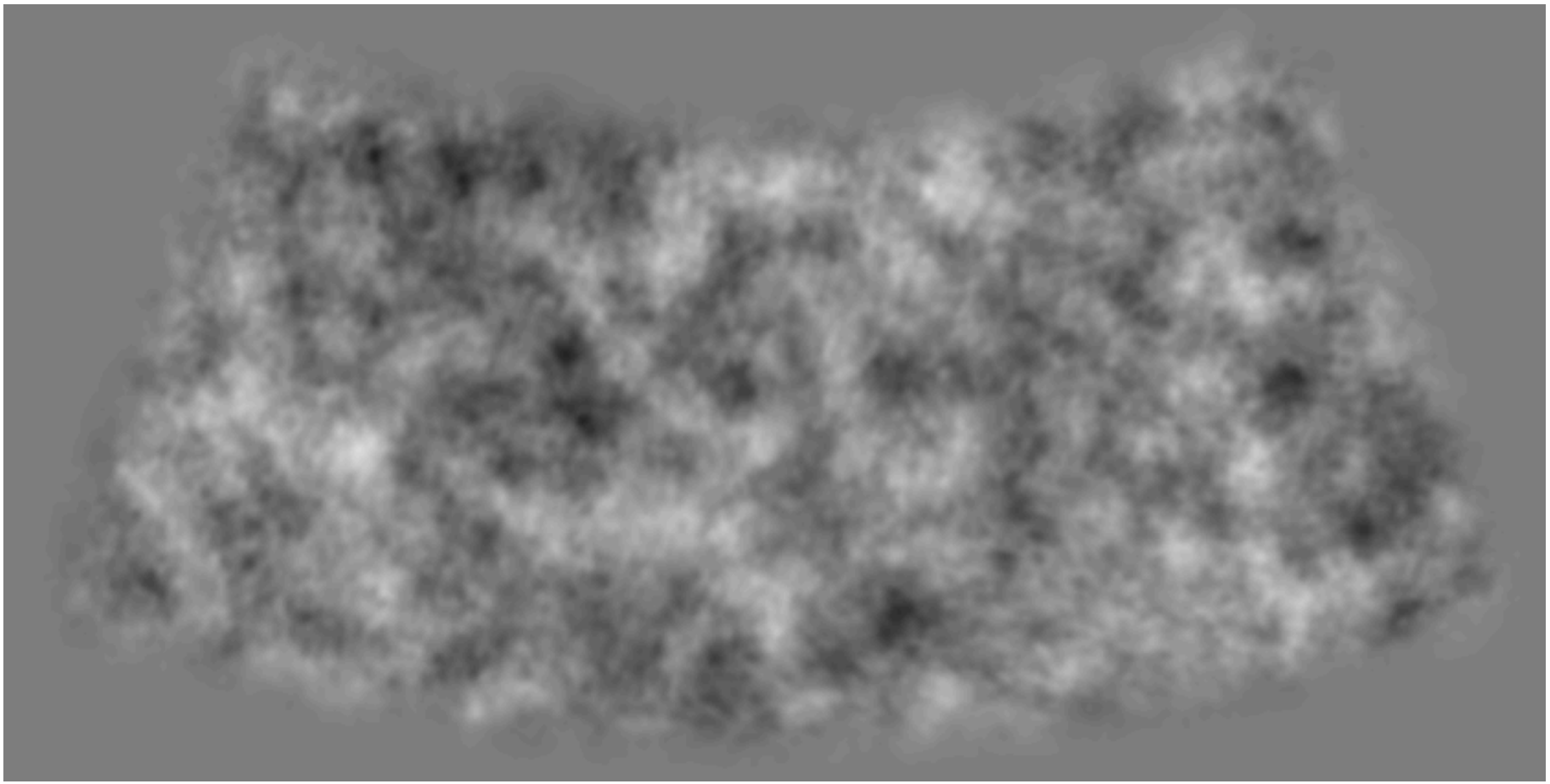
WMAP7 Figure from Larson et al.

WMAP

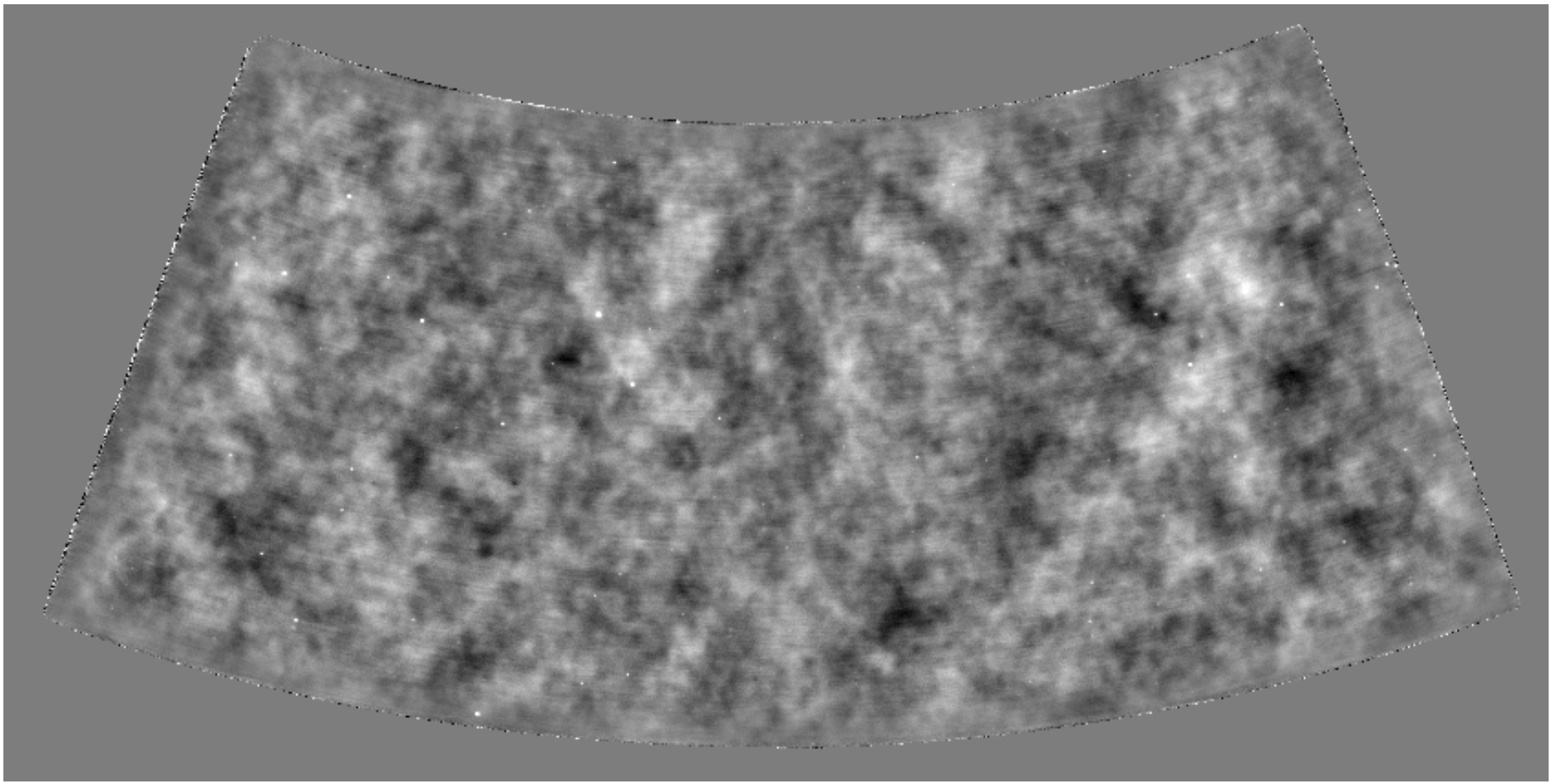


WMAP7 Figure from Larson et al.

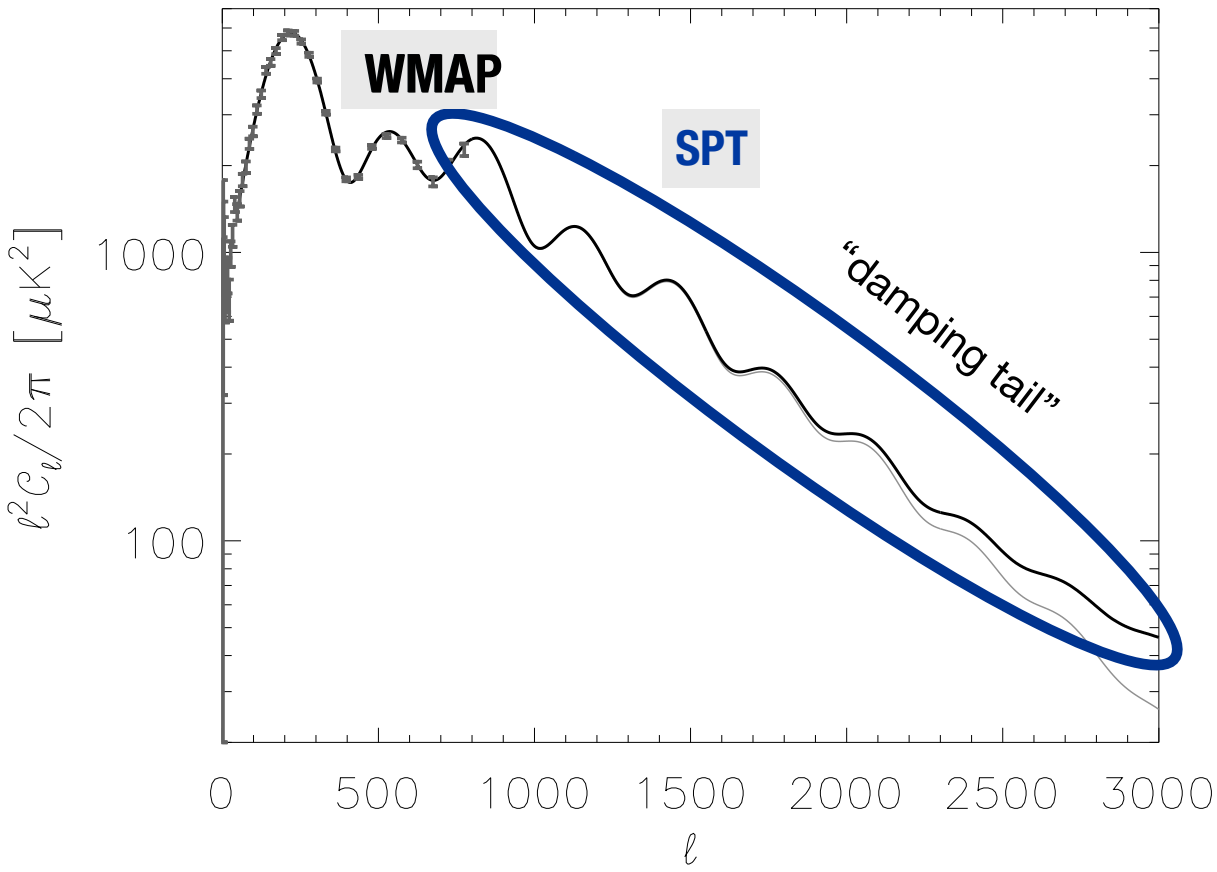
WMAP'S VIEW



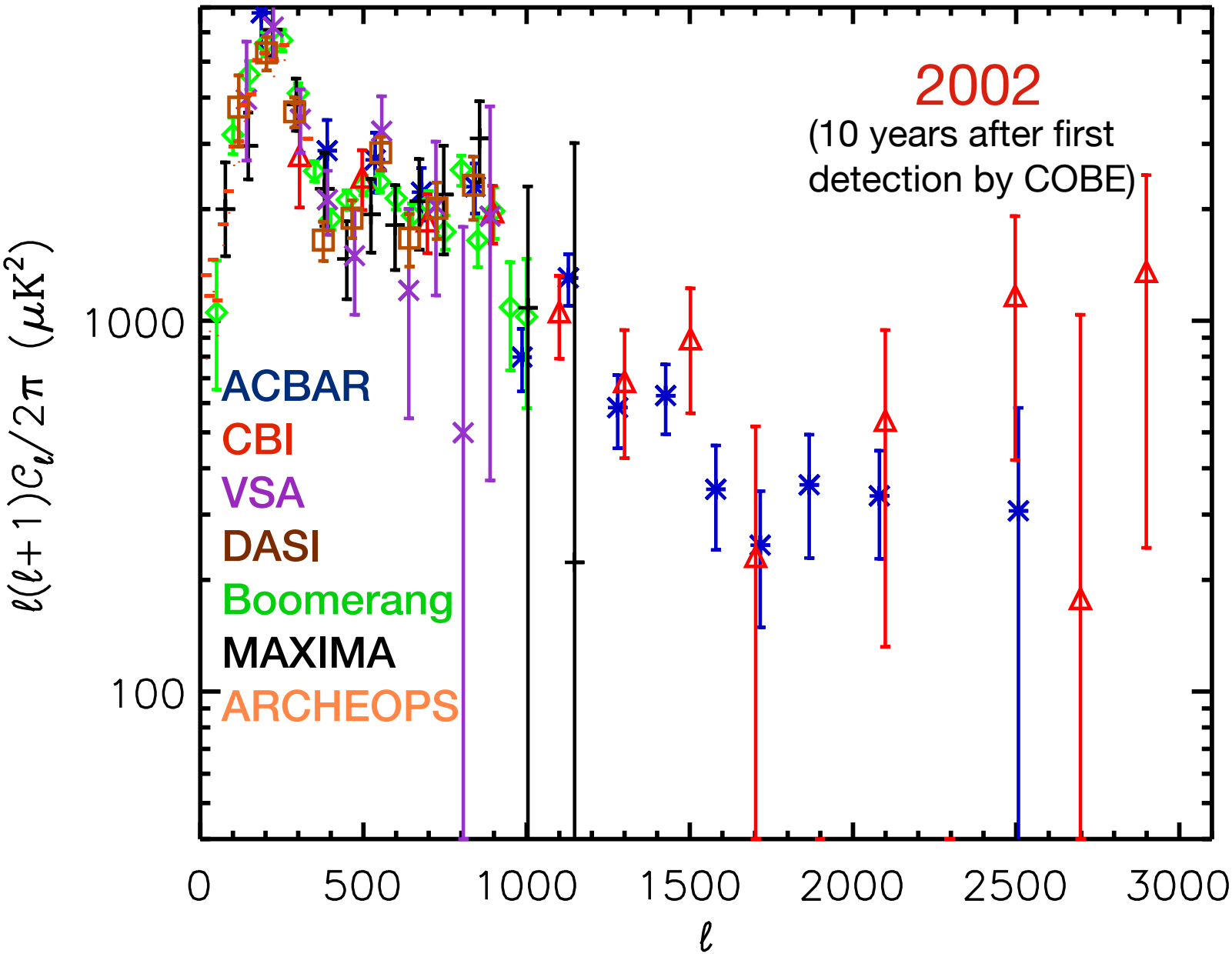
SPT'S VIEW



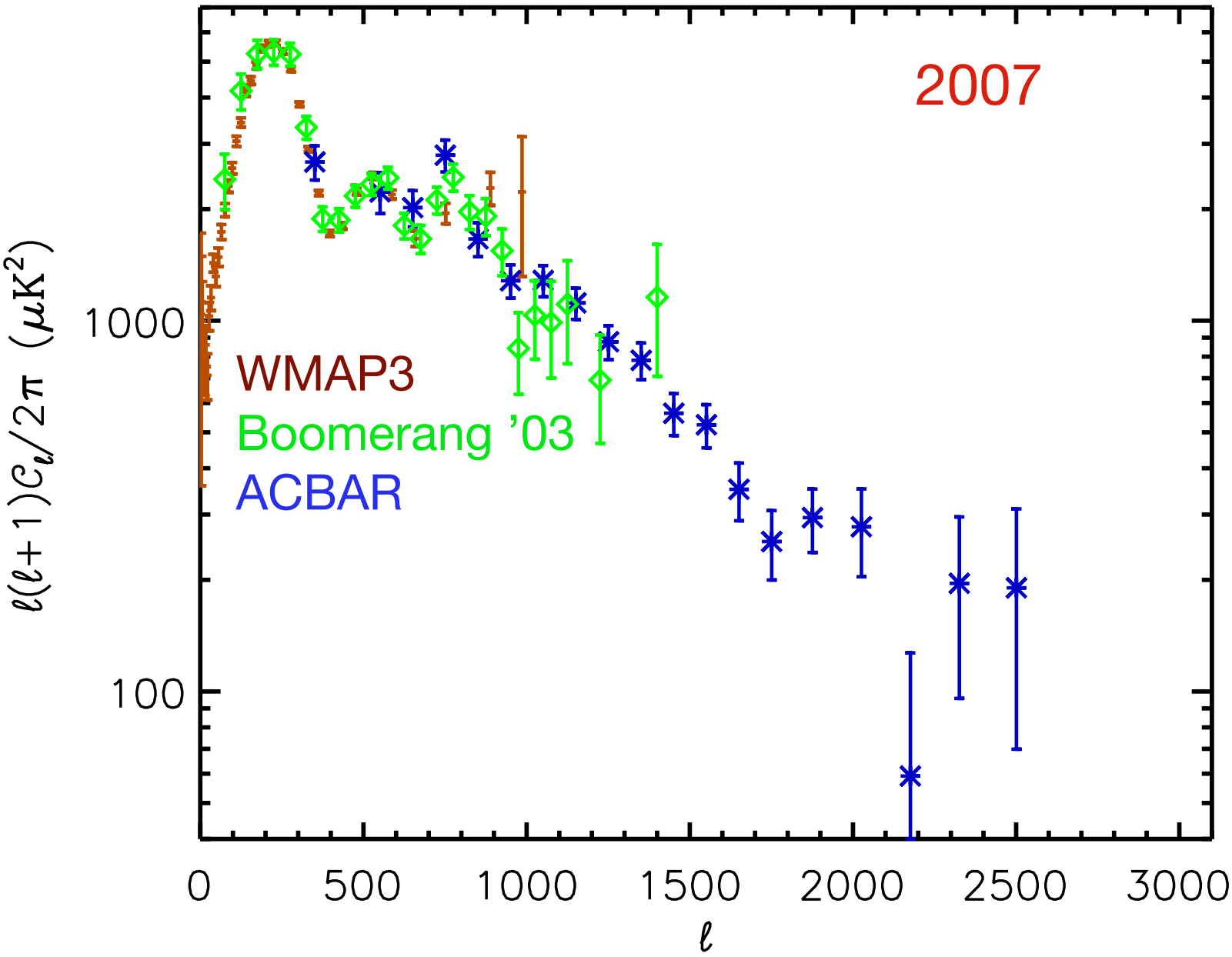
Recent measurement from SPT



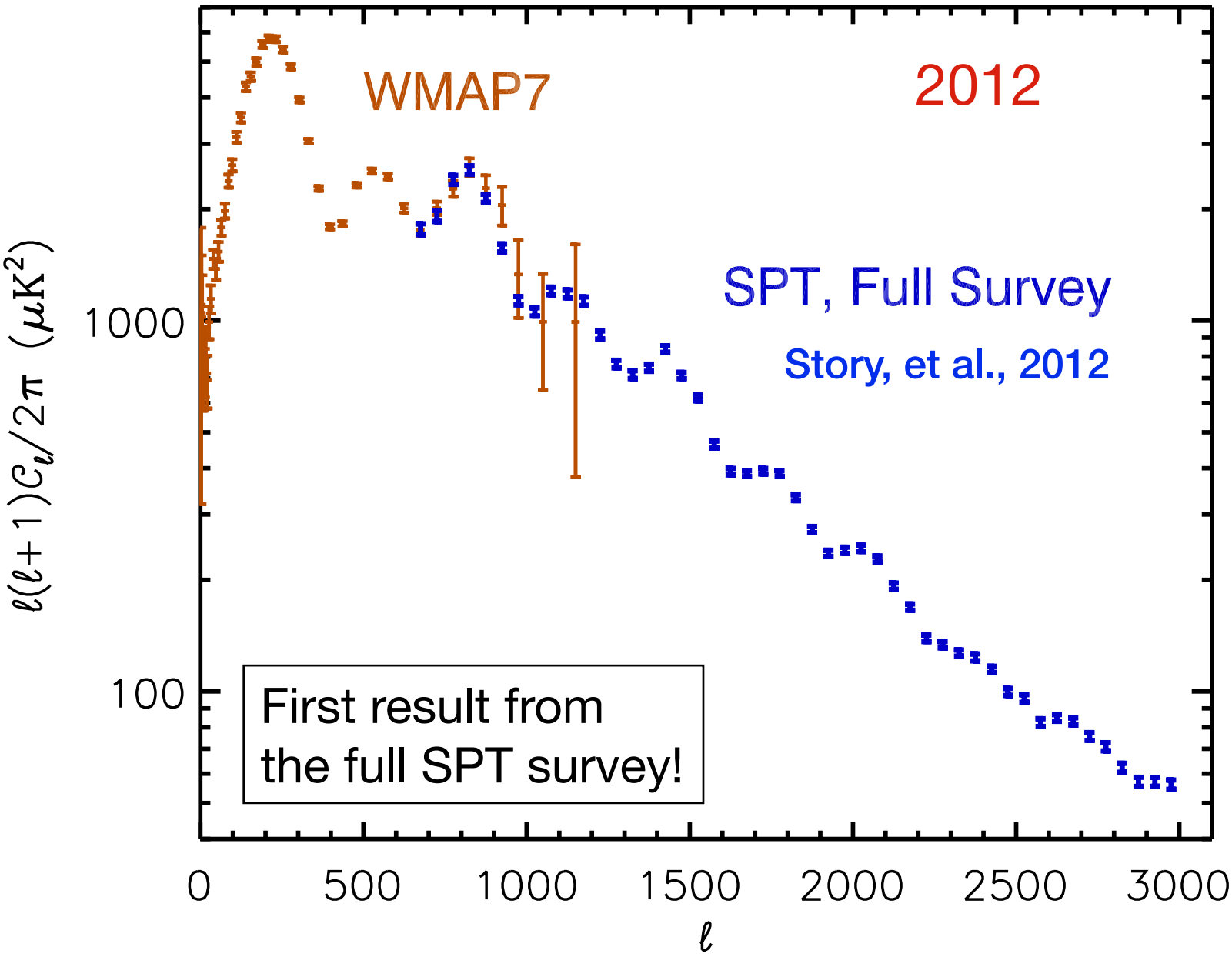
Strong experimental progress



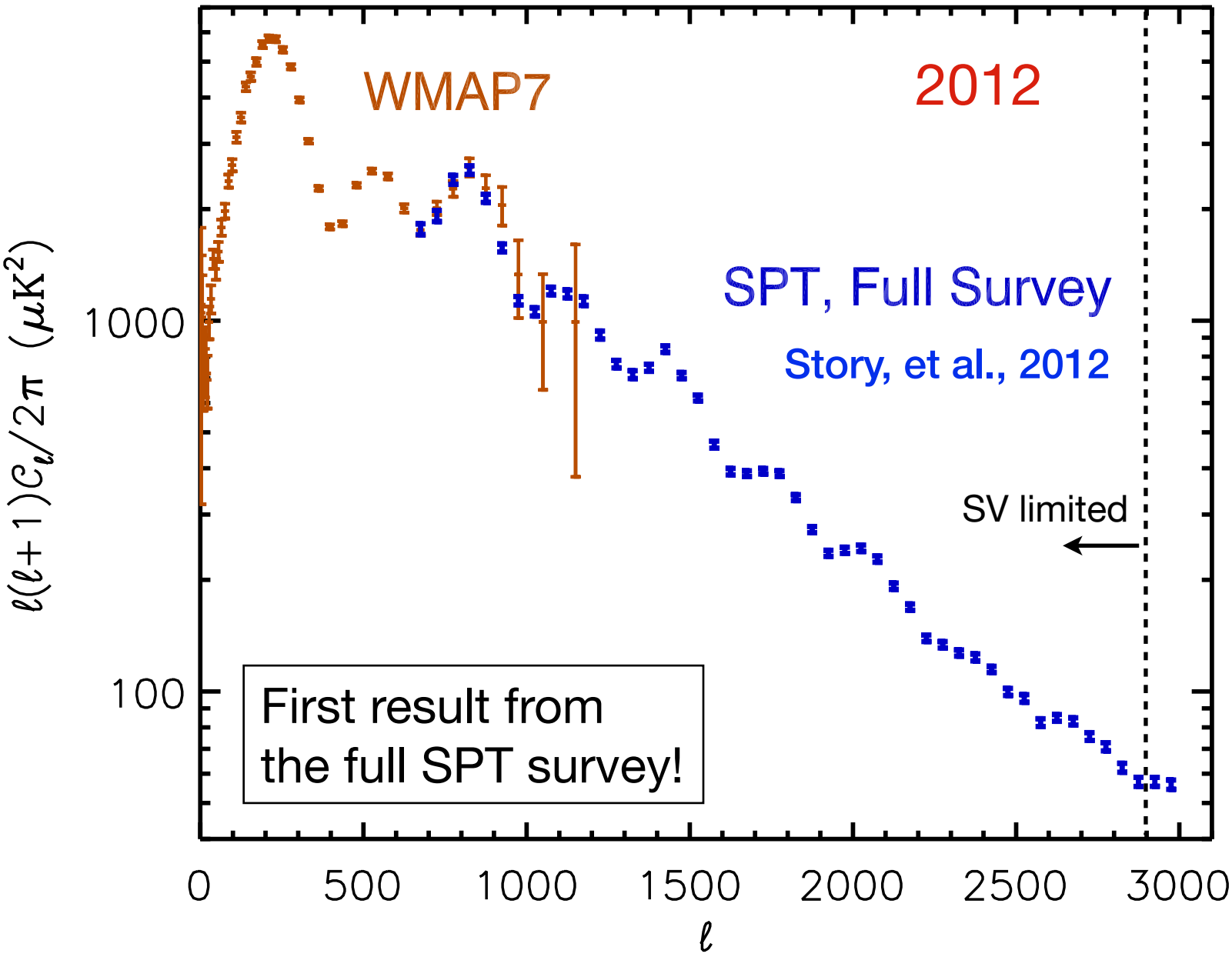
Strong experimental progress



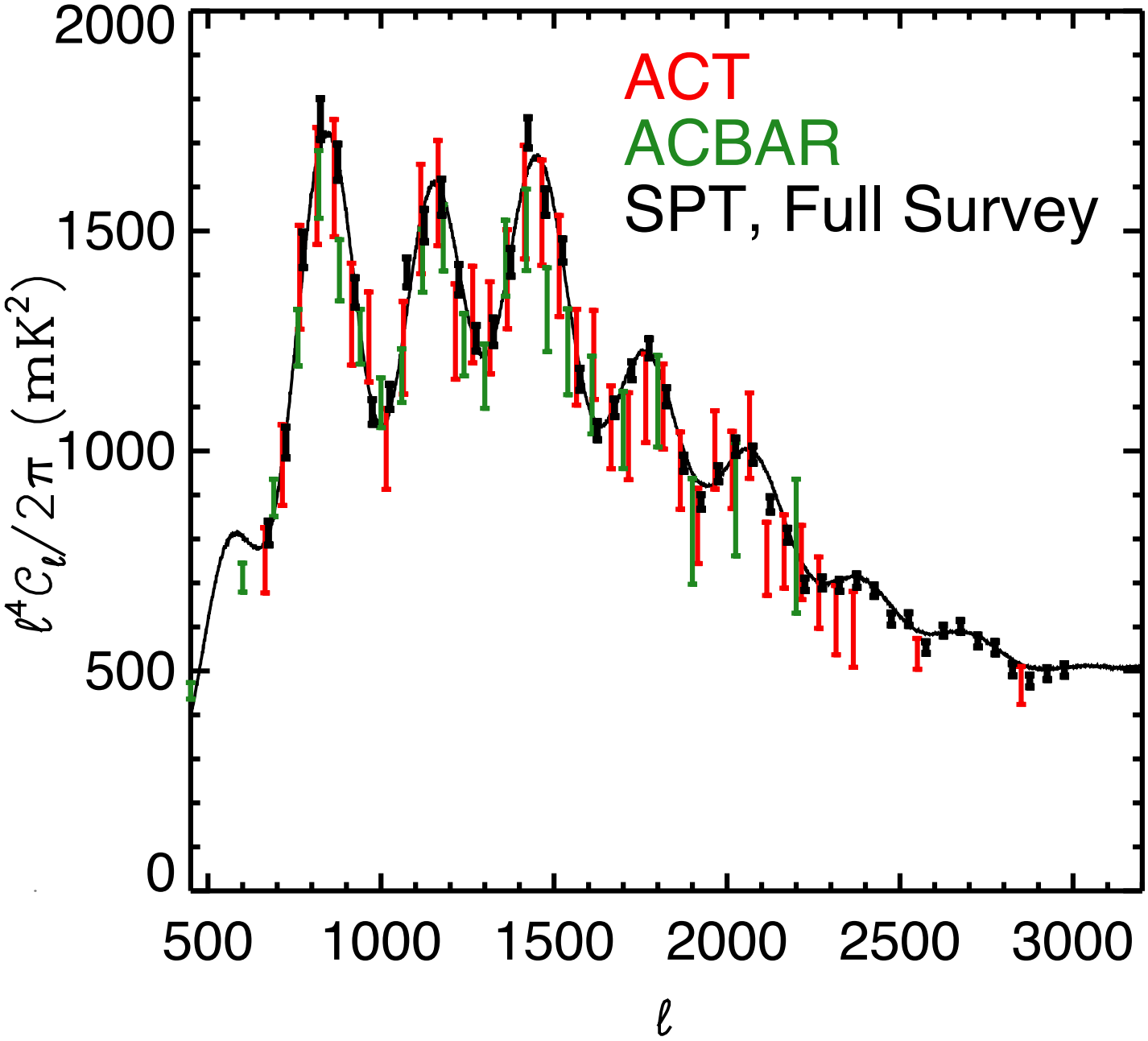
Strong experimental progress



Strong experimental progress



Vs. other small-scale experiments

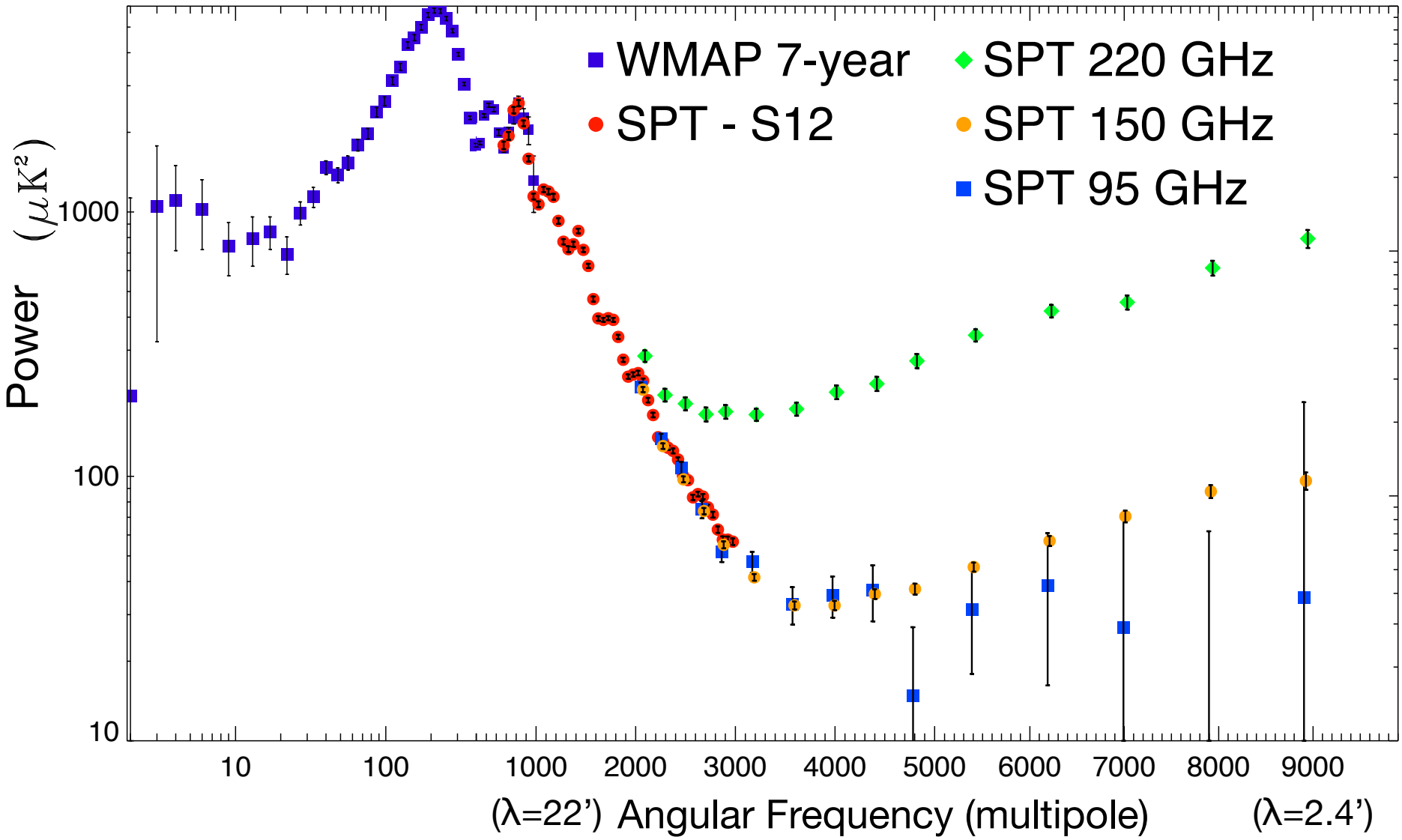


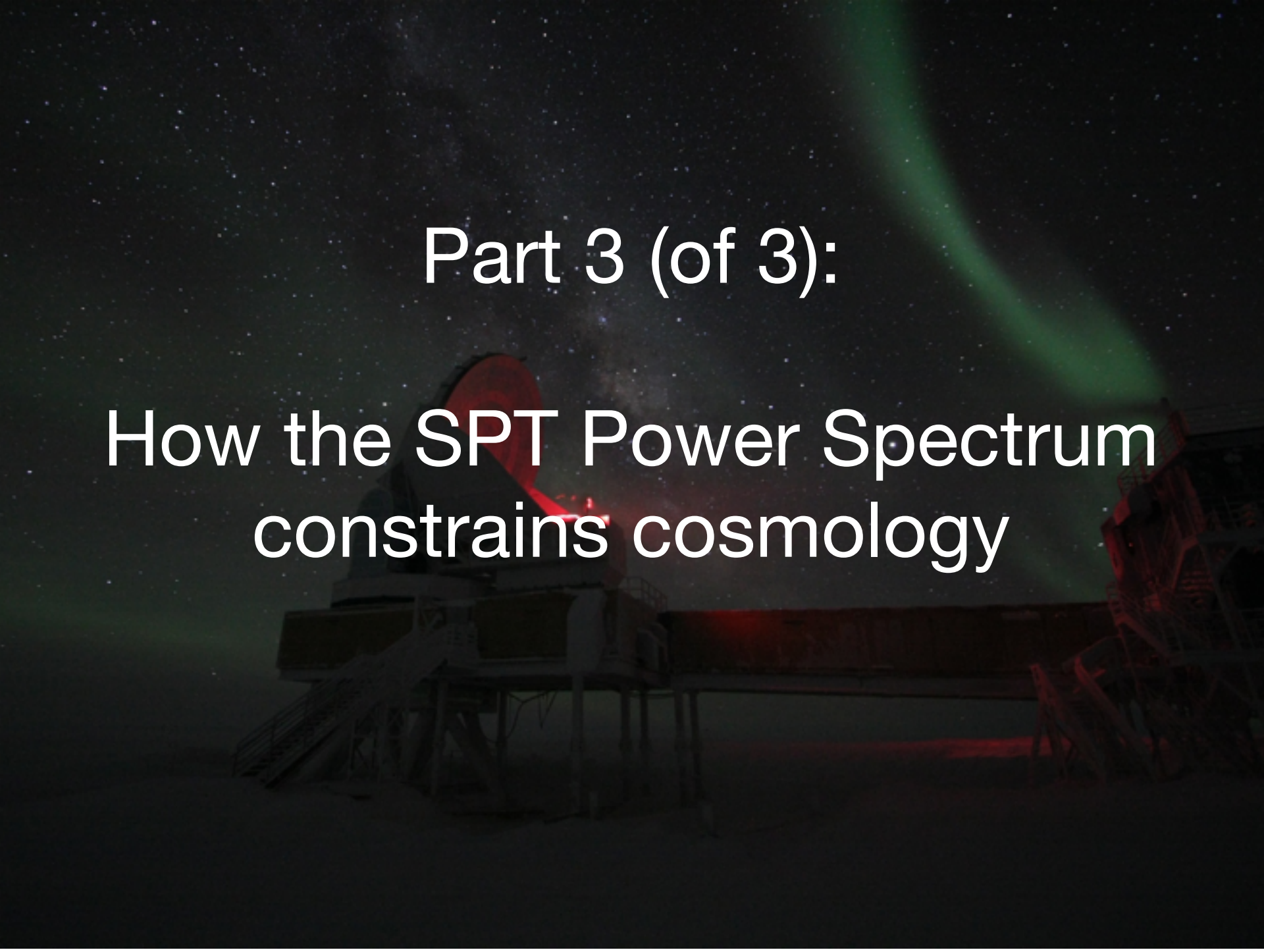
P

Story, *et al.*, 2012 arXiv:1210.7231

State of the art

Reichardt *et al.* 2012 arXiv:1111:0932





Part 3 (of 3):

How the SPT Power Spectrum constrains cosmology

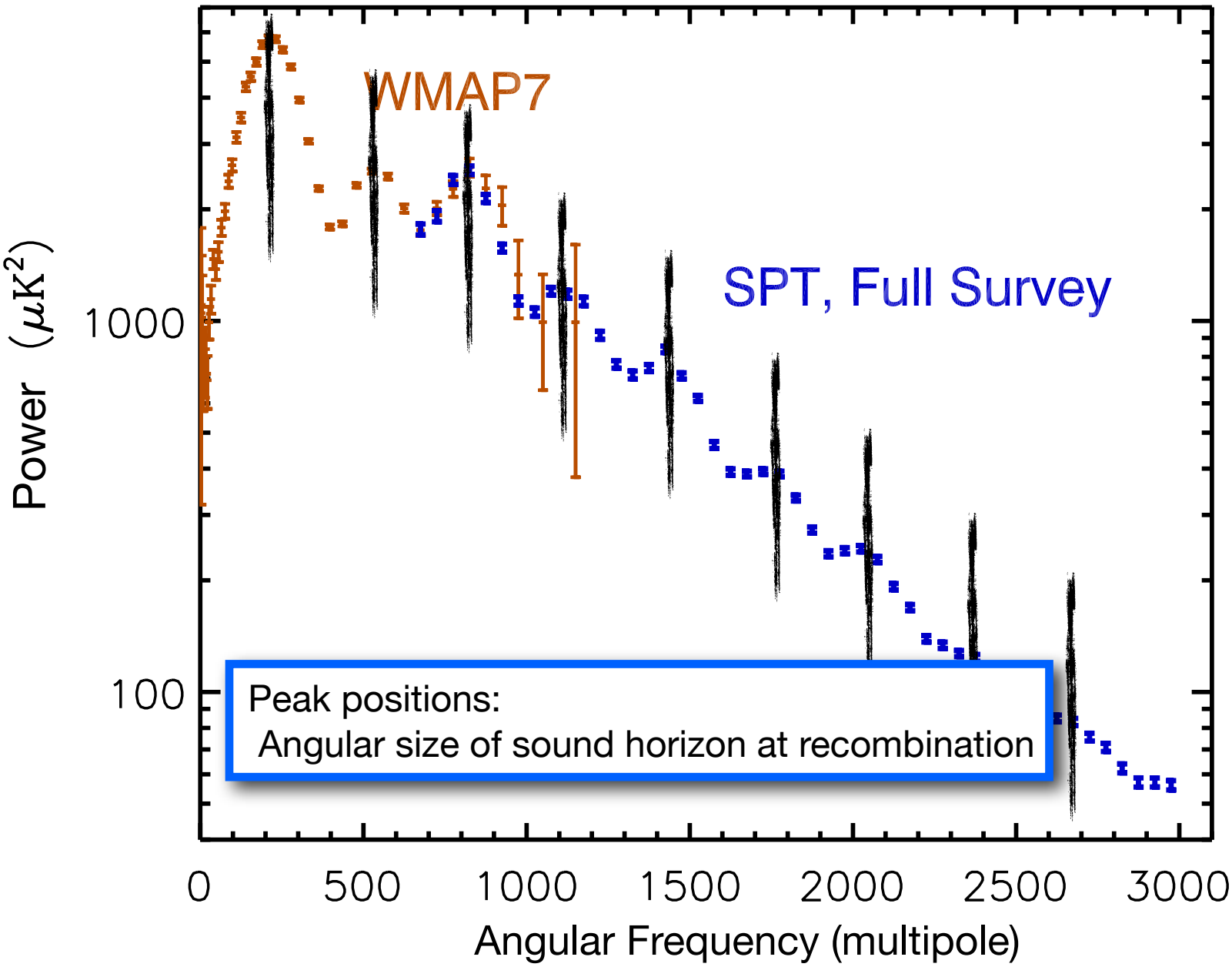
The SPT spectrum adds 3 important pieces:

(1) Peak position (angular scale) and size

(2) Damping scale (slope of damping tail)

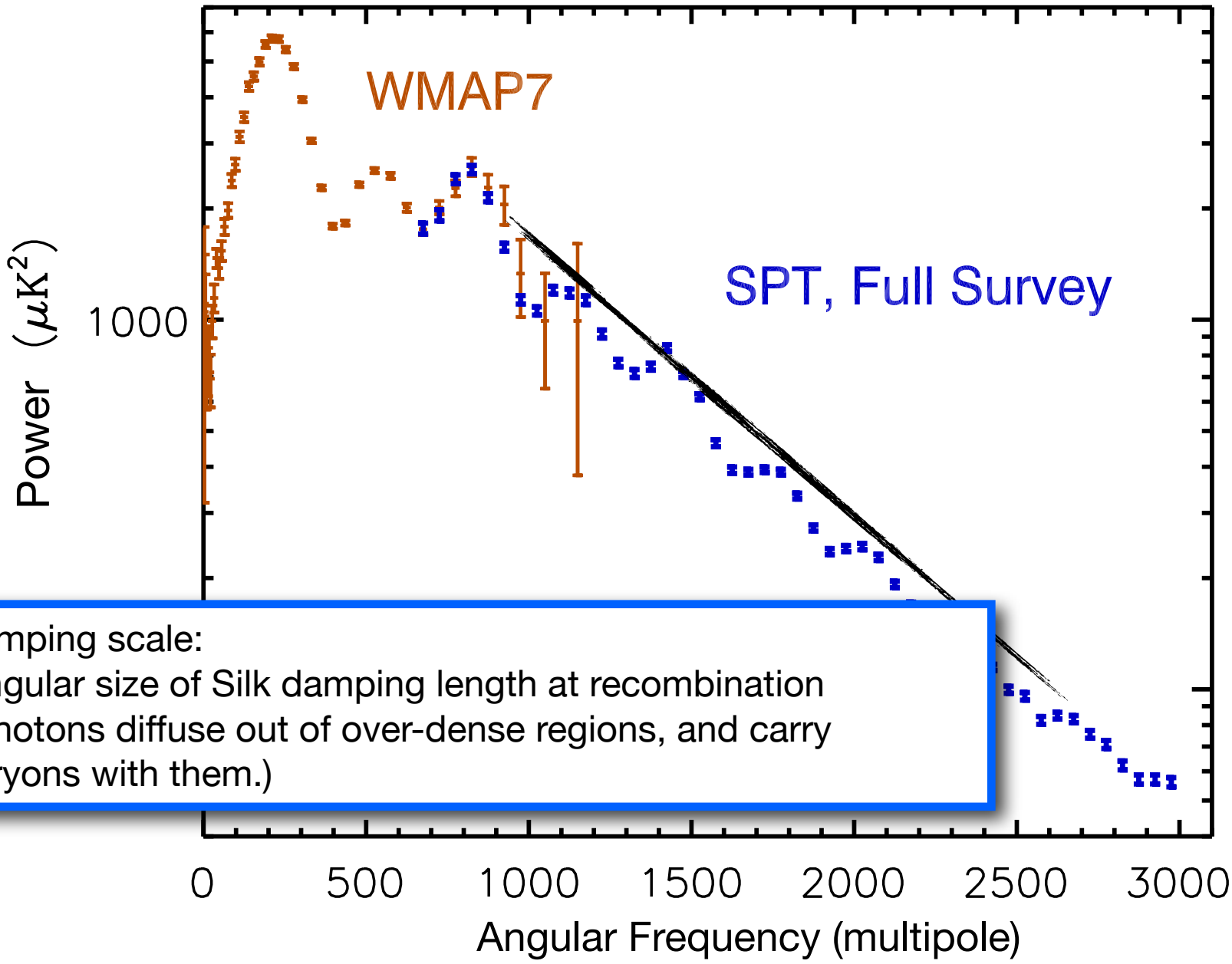
(3) Height of 3rd peak

What's in a power spectrum?



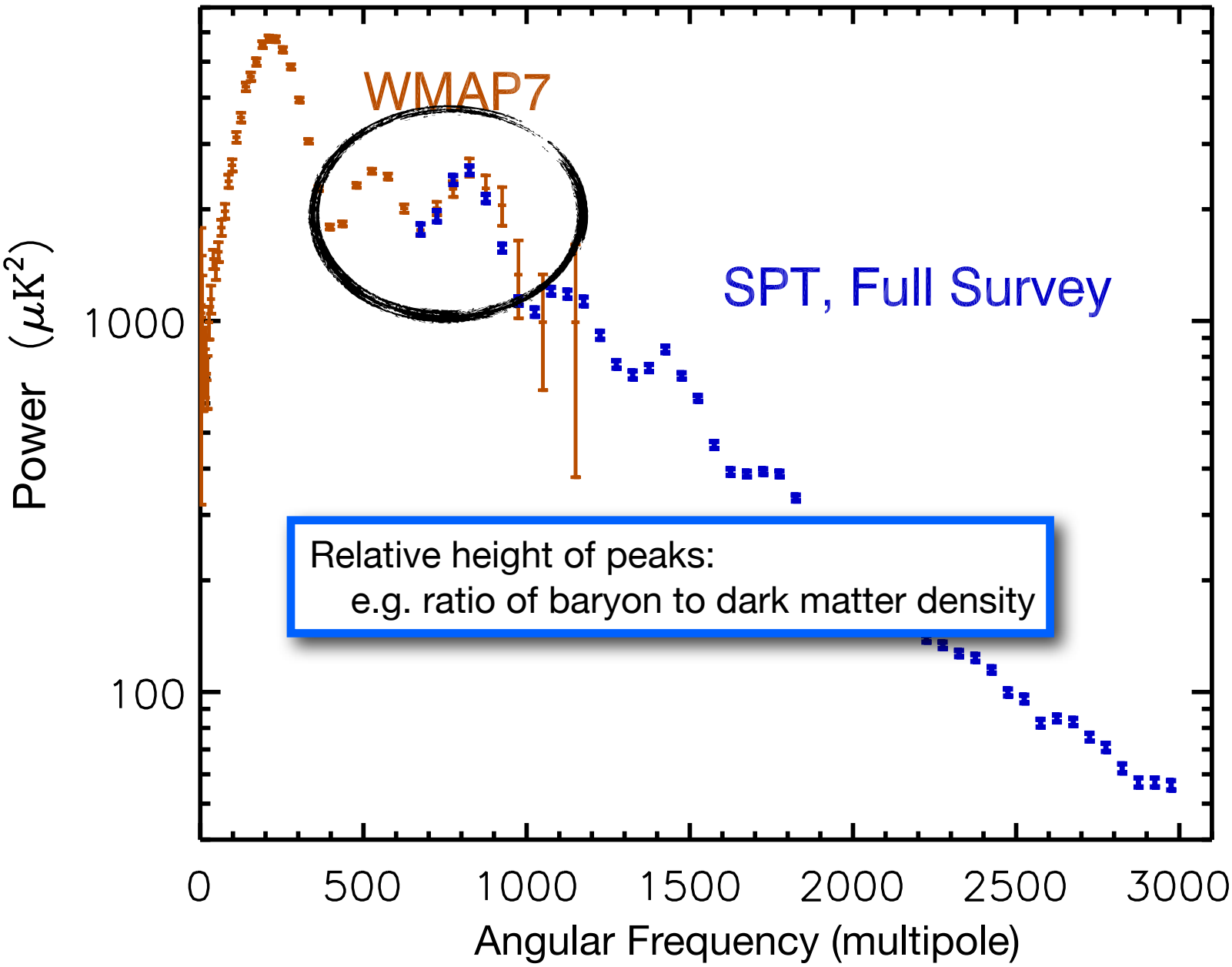
Peak positions:
Angular size of sound horizon at recombination

What's in a power spectrum?



Damping scale:
Angular size of Silk damping length at recombination
(Photons diffuse out of over-dense regions, and carry baryons with them.)

What's in a power spectrum?



Relative height of peaks:
e.g. ratio of baryon to dark matter density

Fitting a model

Markov Chain Monte Carlo (MCMC)

- **CosmoMC** (Lewis & Bridle 2002)
- **CAMB** (Lewis et al. 2000)
- **PICO** (Fendt & Wandelt 2007)

The baseline model: ΛCDM

Cosmological Parameters

- **CMB** for a flat ΛCDM model with six parameters: $\{\Omega_b h^2, \Omega_c h^2, \theta_s, \tau, n_s, \Delta_R^2\}$

The baseline model: ΛCDM

Cosmological Parameters

- **CMB** for a flat ΛCDM model with six parameters: $\{\Omega_b h^2, \Omega_c h^2, \theta_s, \tau, n_s, \Delta_R^2\}$

Foreground/Nuisance Parameters

- **Sunyaev-Zel'dovich effect** [Thomson/Compton scattering off electrons in large-scale structure]
- **Poisson** [random point sources (galaxies)]
- **Clustered** point sources.

9 parameters (6 cosmo., 3 "nuisance")

Fitting a model

Models

- Baseline: LCDM
- Extensions: LCDM+Alens
- LCDM+Ω_K
- LCDM+r

Neff, $\sum m_\nu$, ω, $dn_s/d\ln k$, etc - > H12

Fitting a model

Datasets

- **Baryon Acoustic Oscillations (BAO)**

- WiggleZ survey (Blake et al. 2011)

- SDSS-II (DR7) (Padmanabhan et al. 2012)

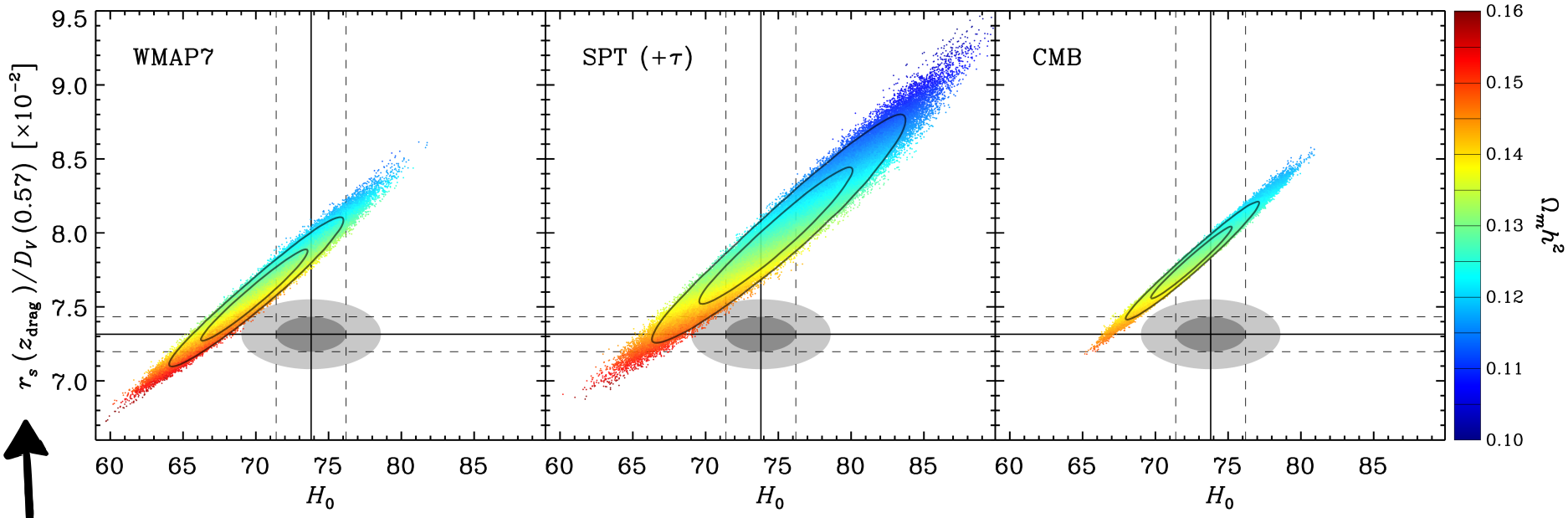
- BOSS (Anderson et al. 2012)

- **Local Expansion Rate (H_0)**

- Riess et al. 2012

Consistency between datasets

LCDM, 3 different datasets

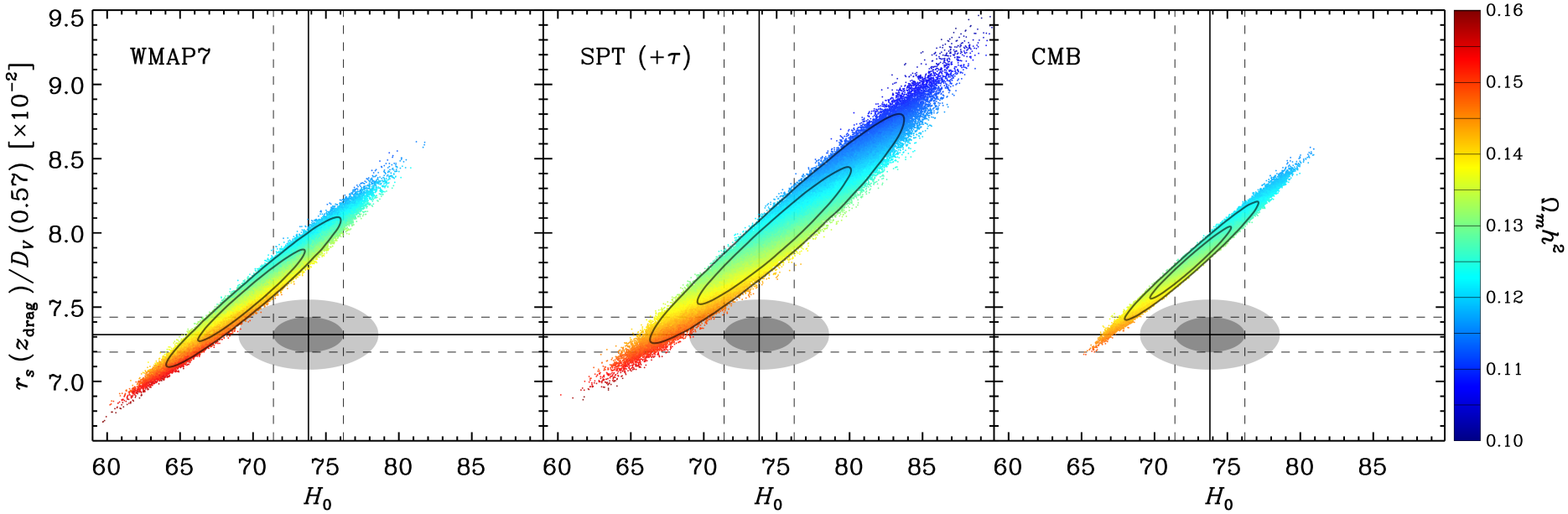


BAO observable rs/Dv

H_0 observable

Consistency between datasets

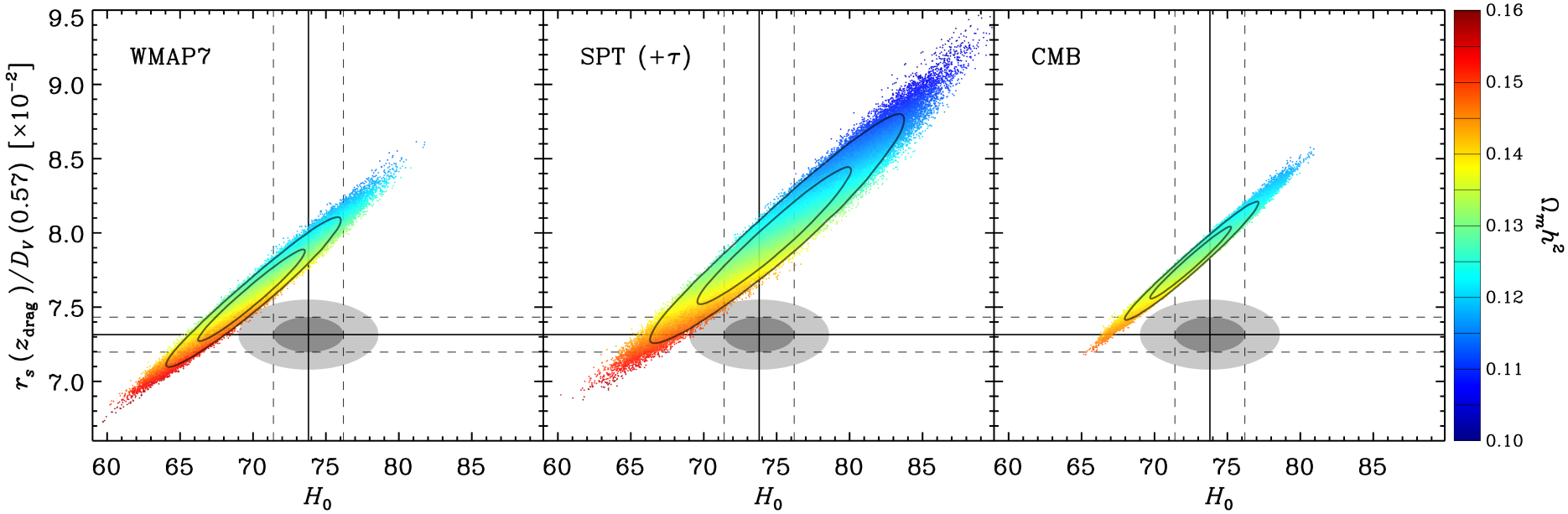
LCDM, 3 different datasets



- CMB and H_0 differ by $0.3\,\sigma$.
- CMB and BAO differ by $1.5\,\sigma$.
- (CMB+BAO) and H_0 differ by $1.8\,\sigma$.
- (CMB+H_0) and BAO differ by $2.1\,\sigma$.

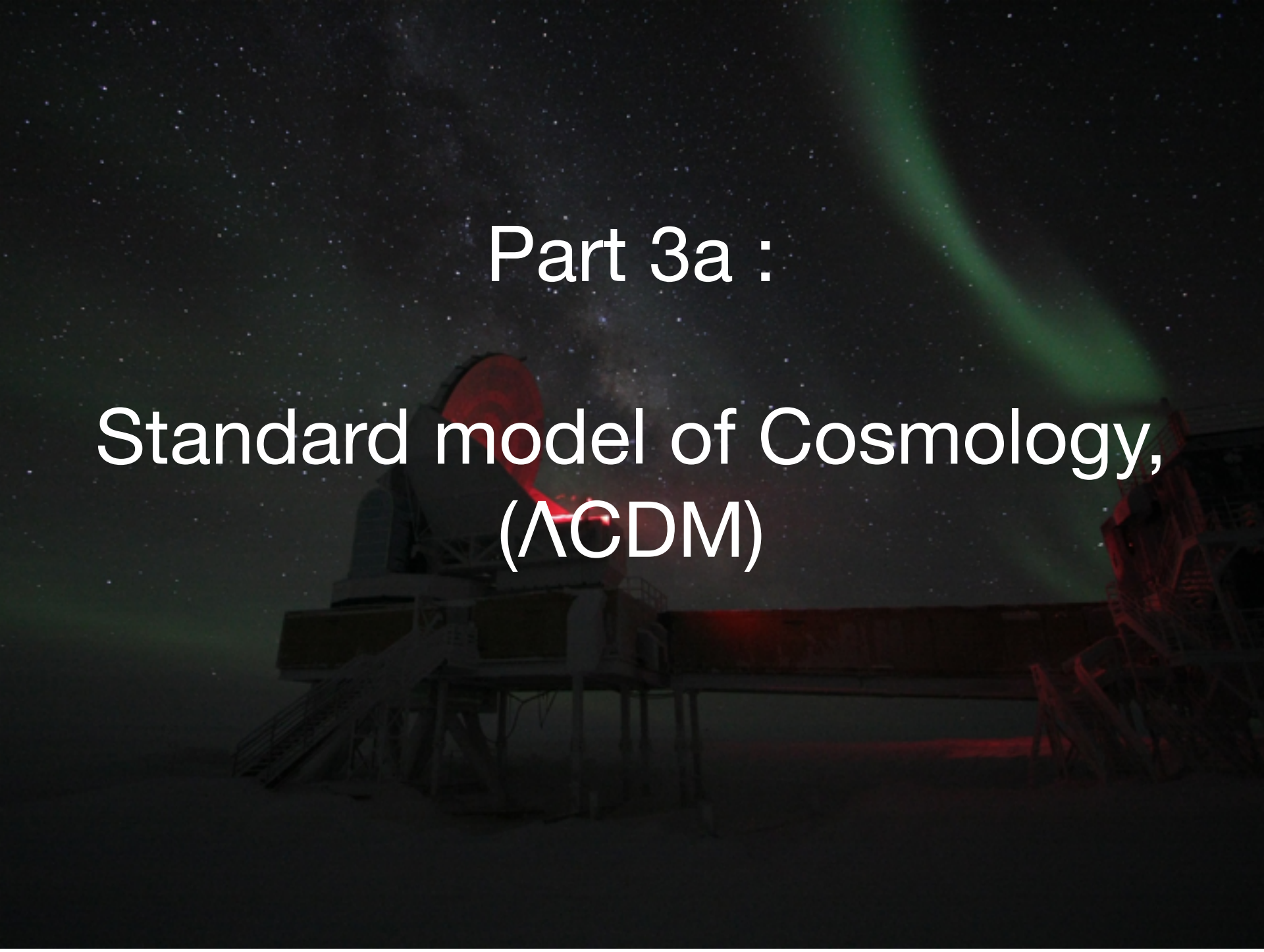
Consistency between datasets

LCDM, 3 different datasets



Possible Explanations:

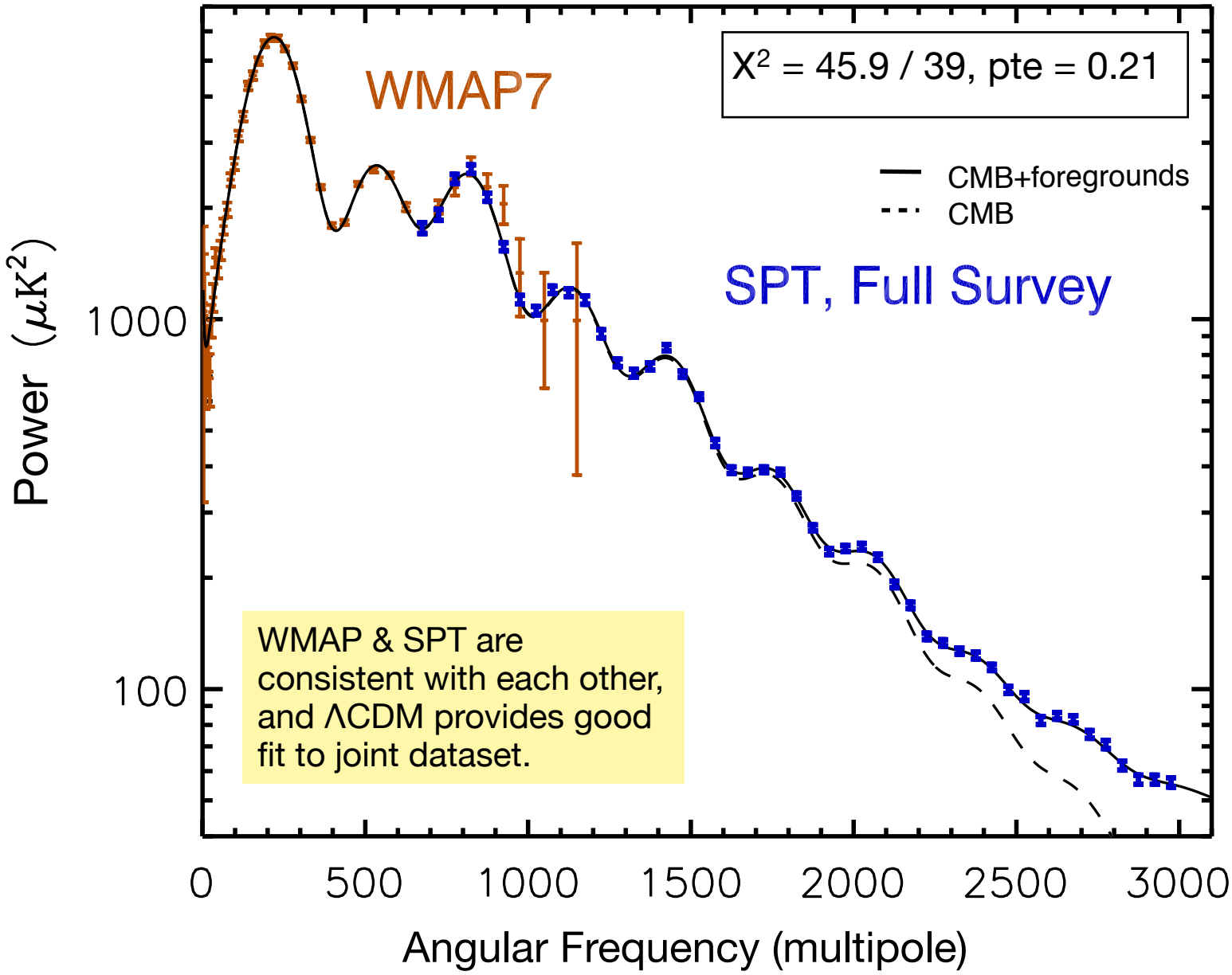
- statistical fluctuations
- systematic errors / bias
- evidence for a departure from ΛCDM



Part 3a :

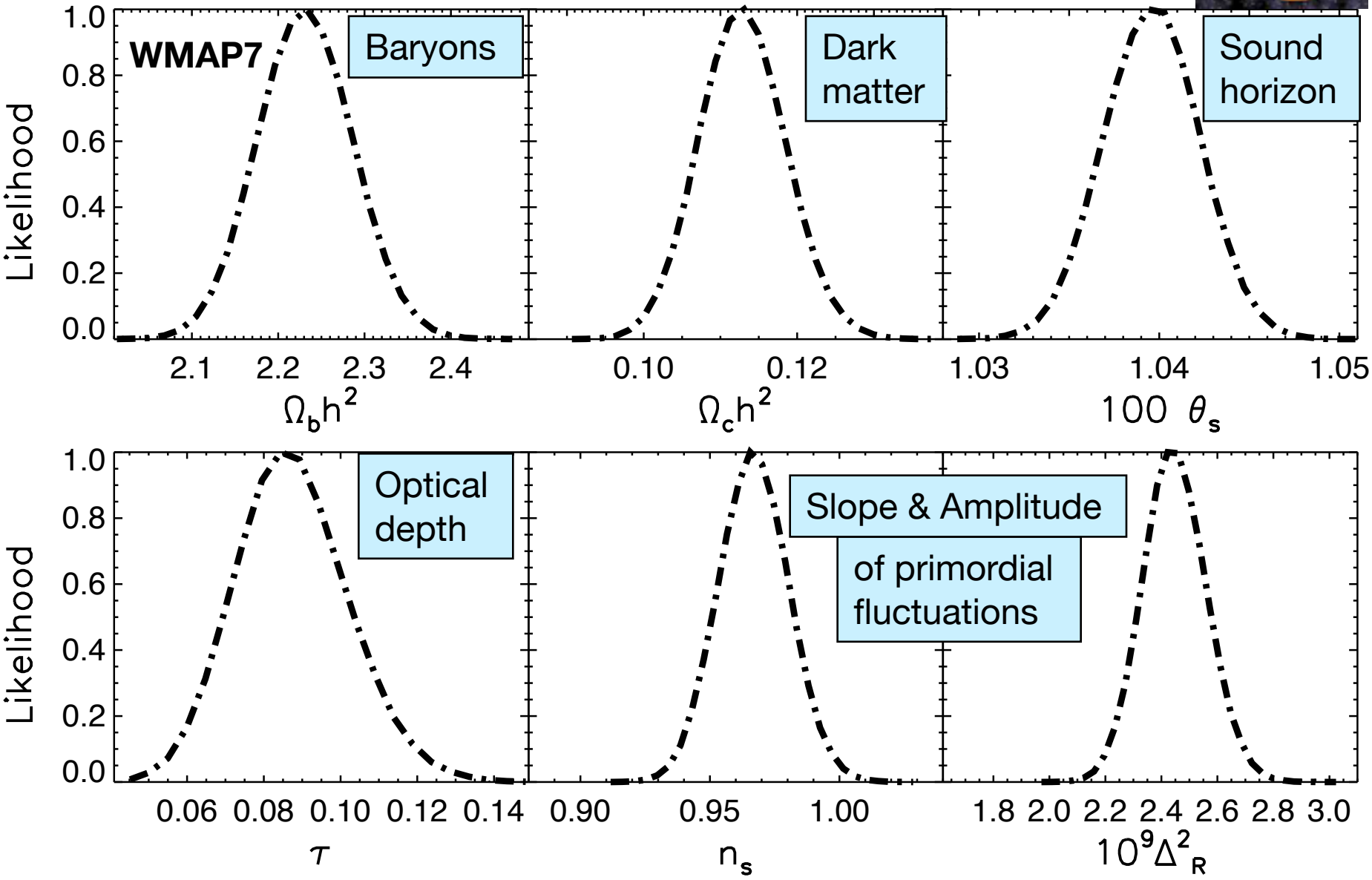
Standard model of Cosmology, (ΛCDM)

Quality of fit

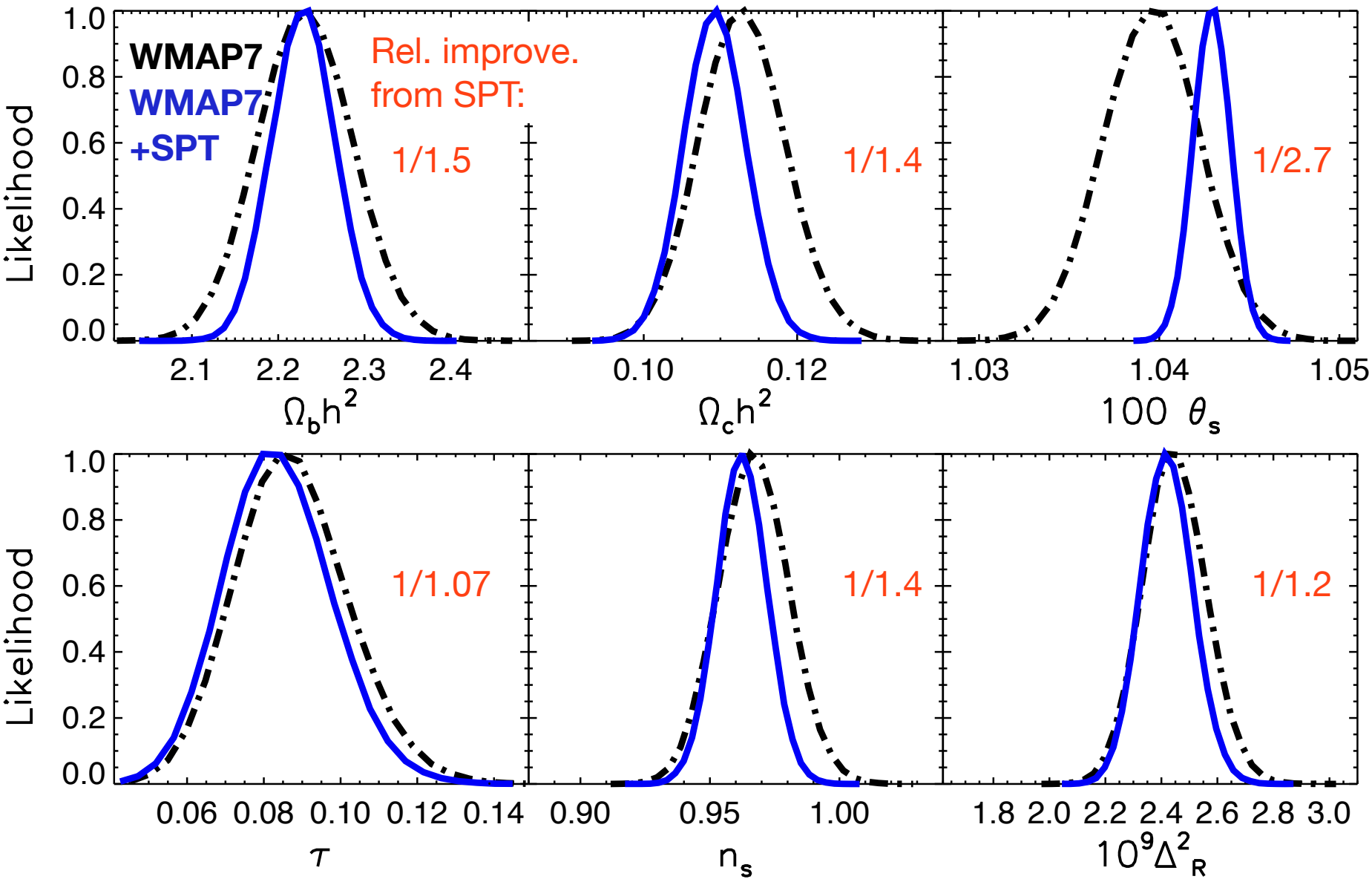


WMAP & SPT are consistent with each other, and ΛCDM provides good fit to joint dataset.

Basic ΛCDM results: WMAP7



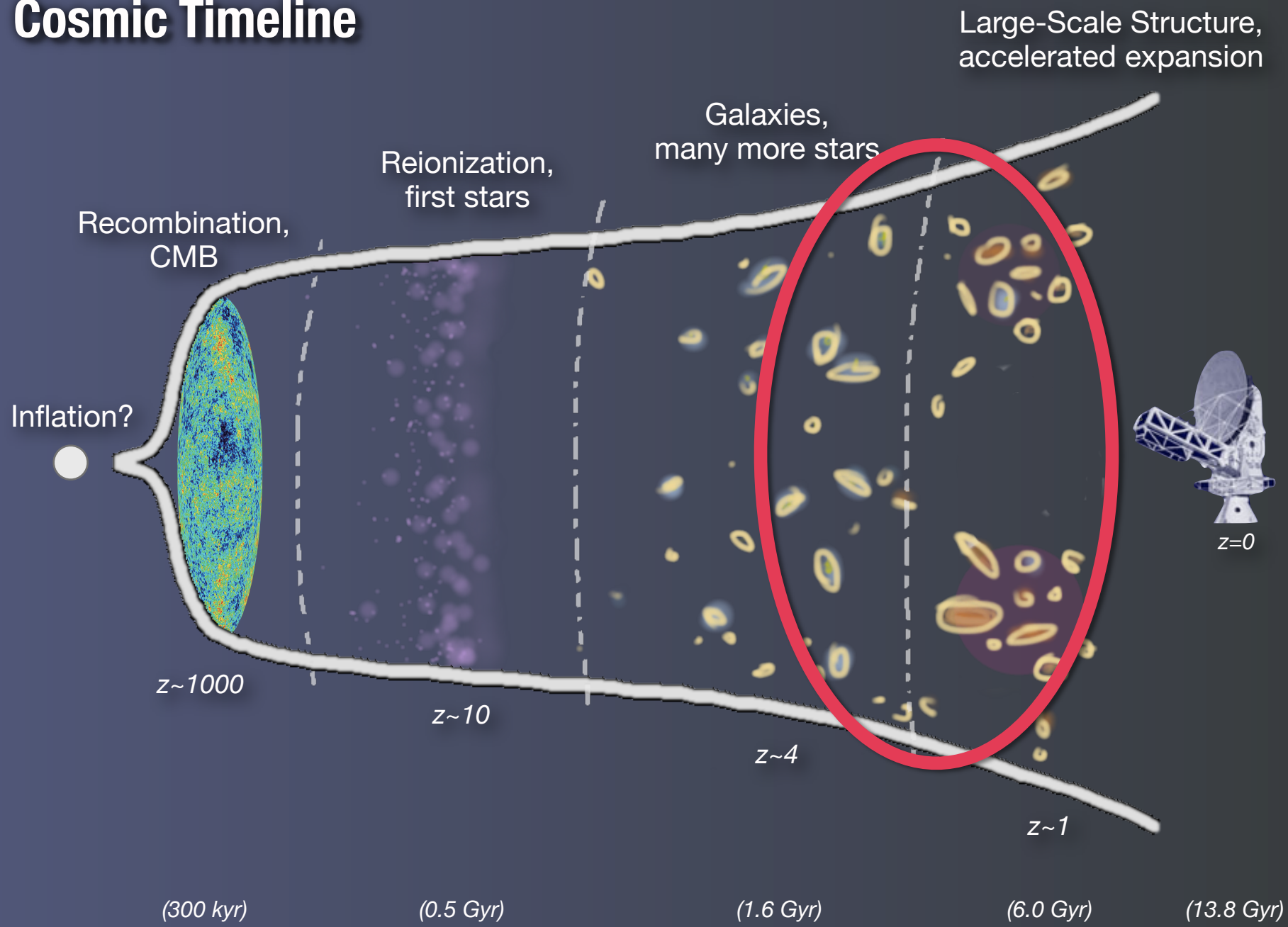
Basic ΛCDM results: WMAP7+SPT



Part 3b :

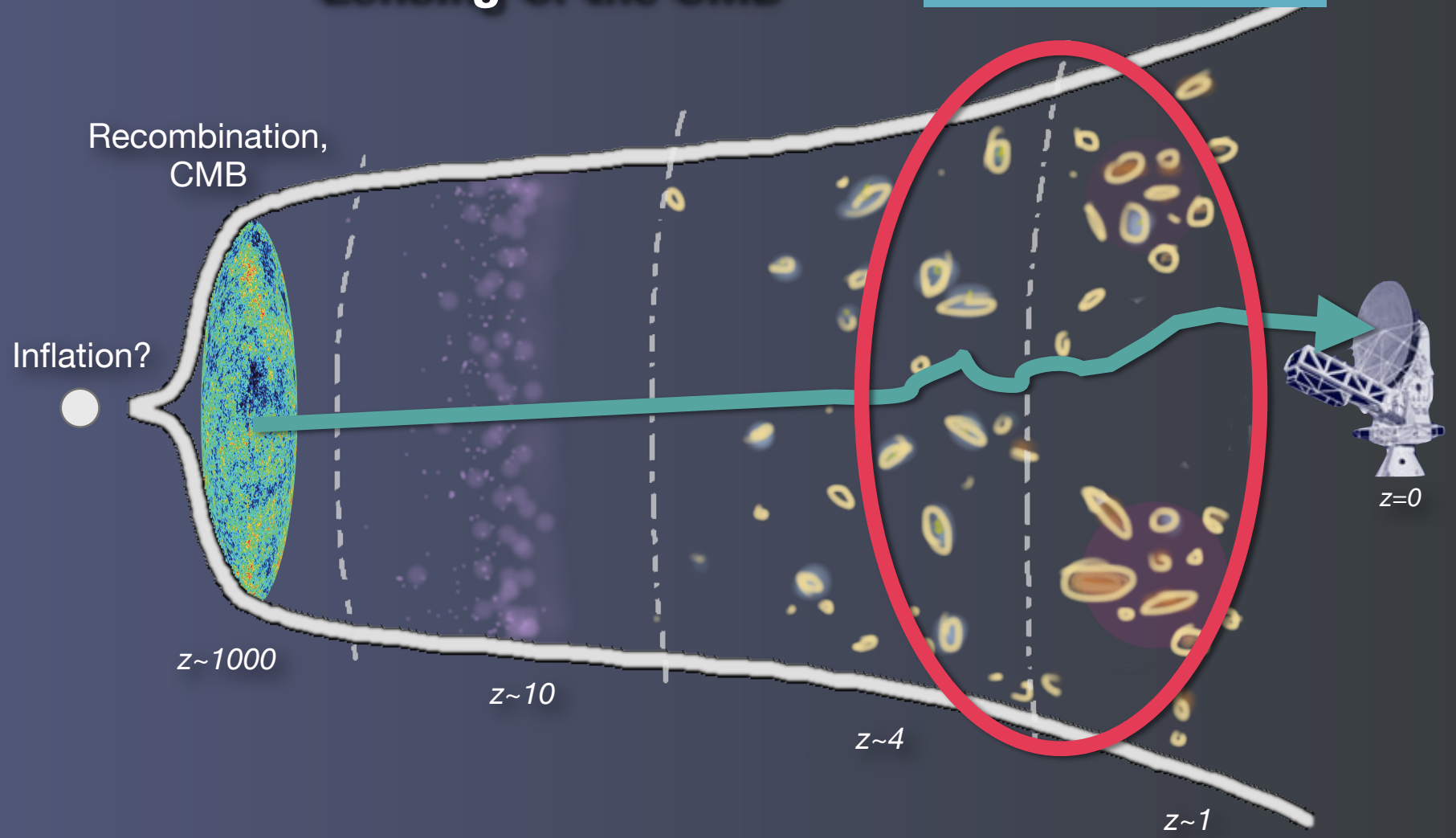
Gravitational Lensing (ΛCDM+A_{lens})

Cosmic Timeline



Gravitational Lensing of the CMB

Paths of CMB photons are bent by gravity of *z*~2 matter.



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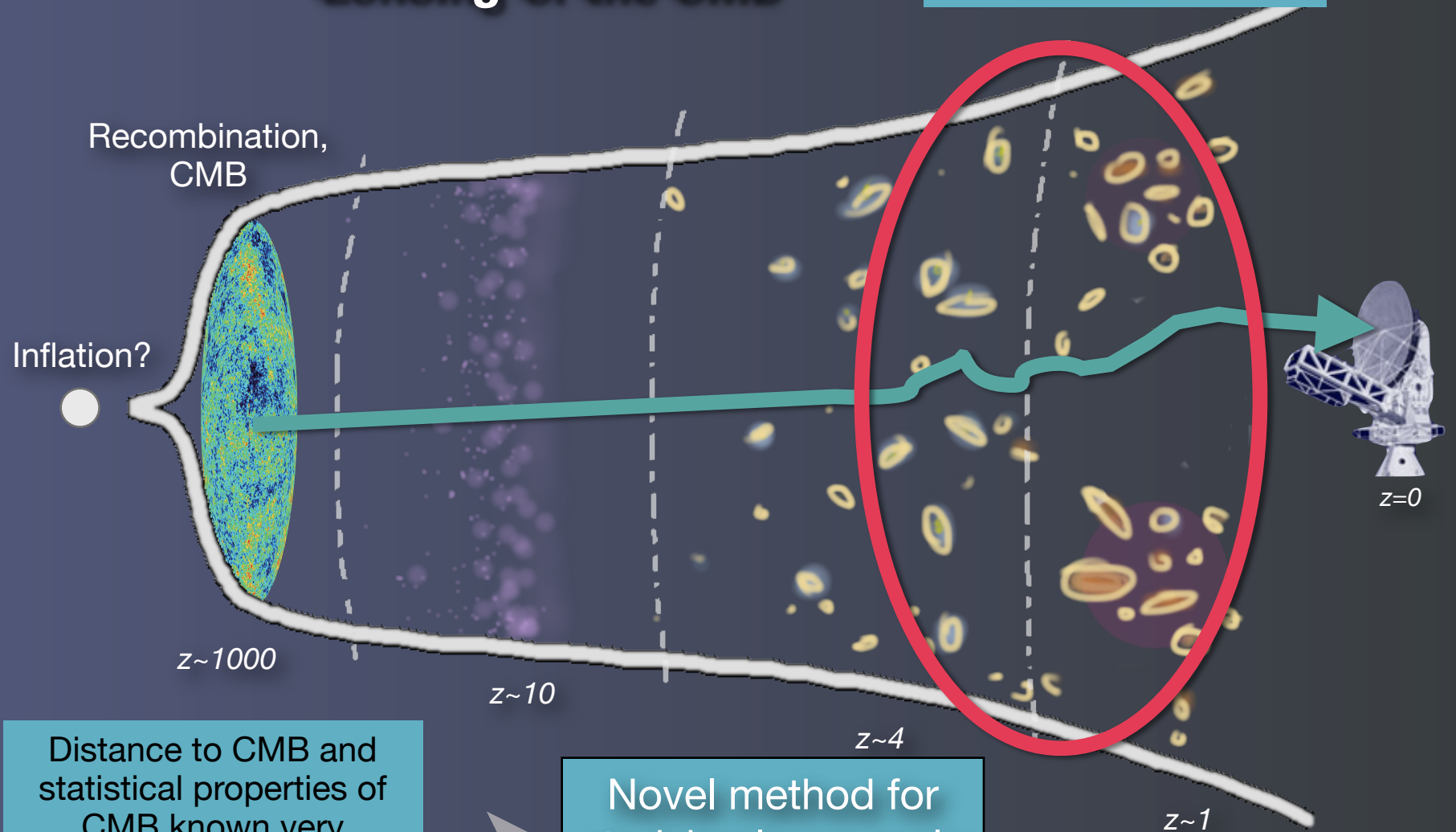
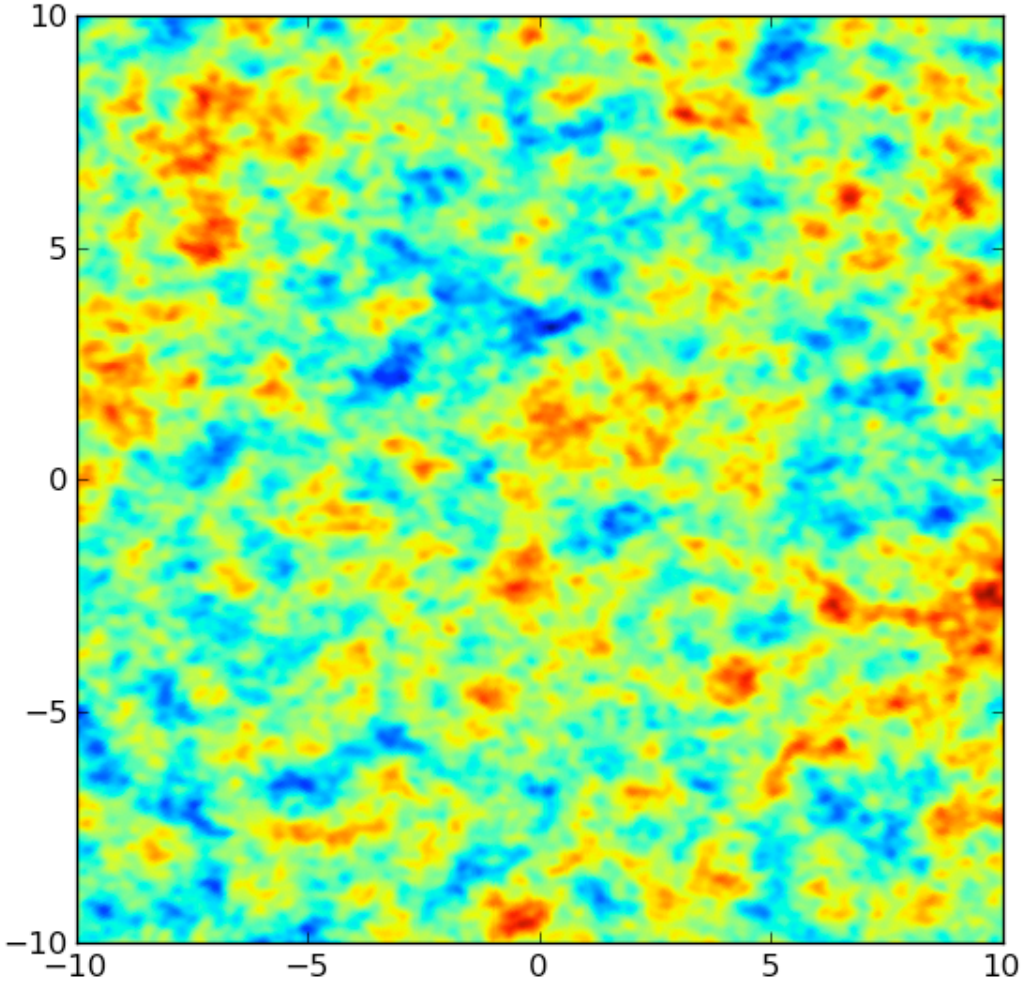


Distance to CMB and statistical properties of CMB known very accurately, so effects of lensing can be isolated.

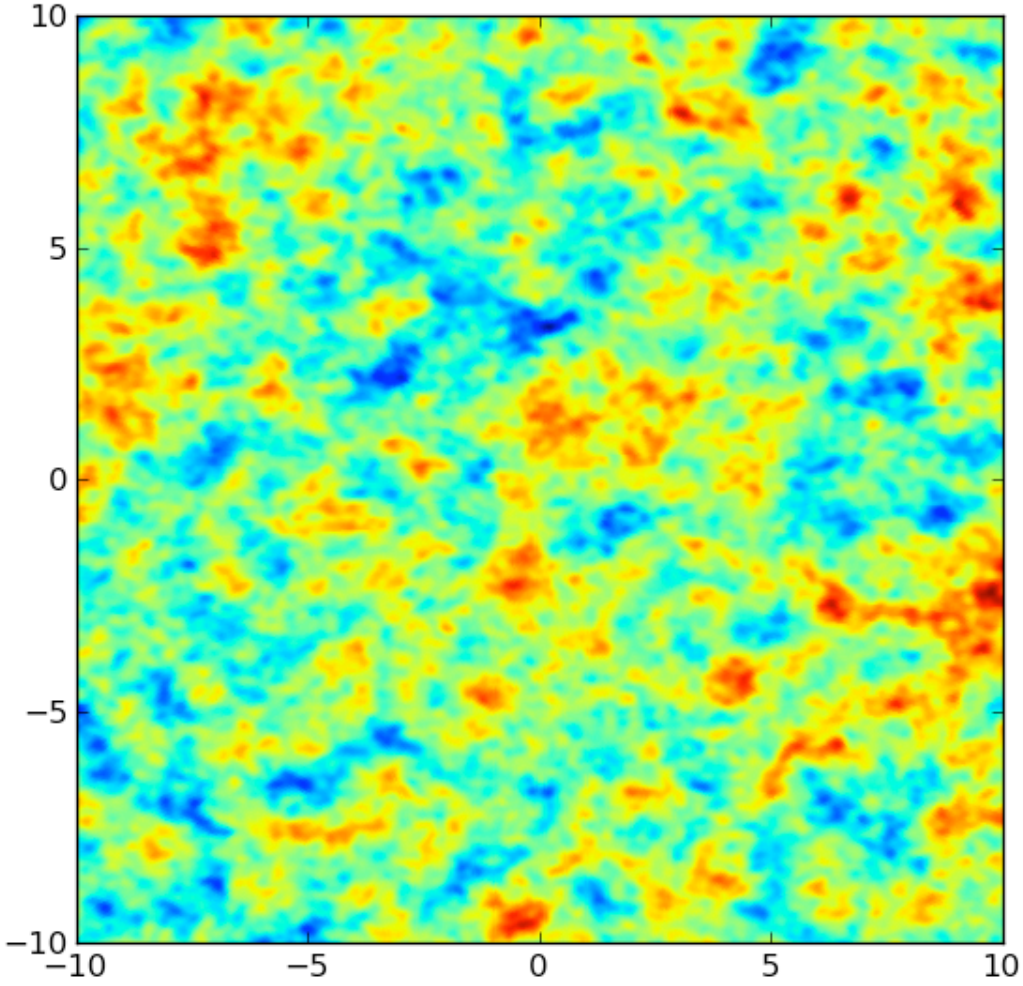
Novel method for studying large-scale structure at *z*~2.

Unlensed vs lensed CMB



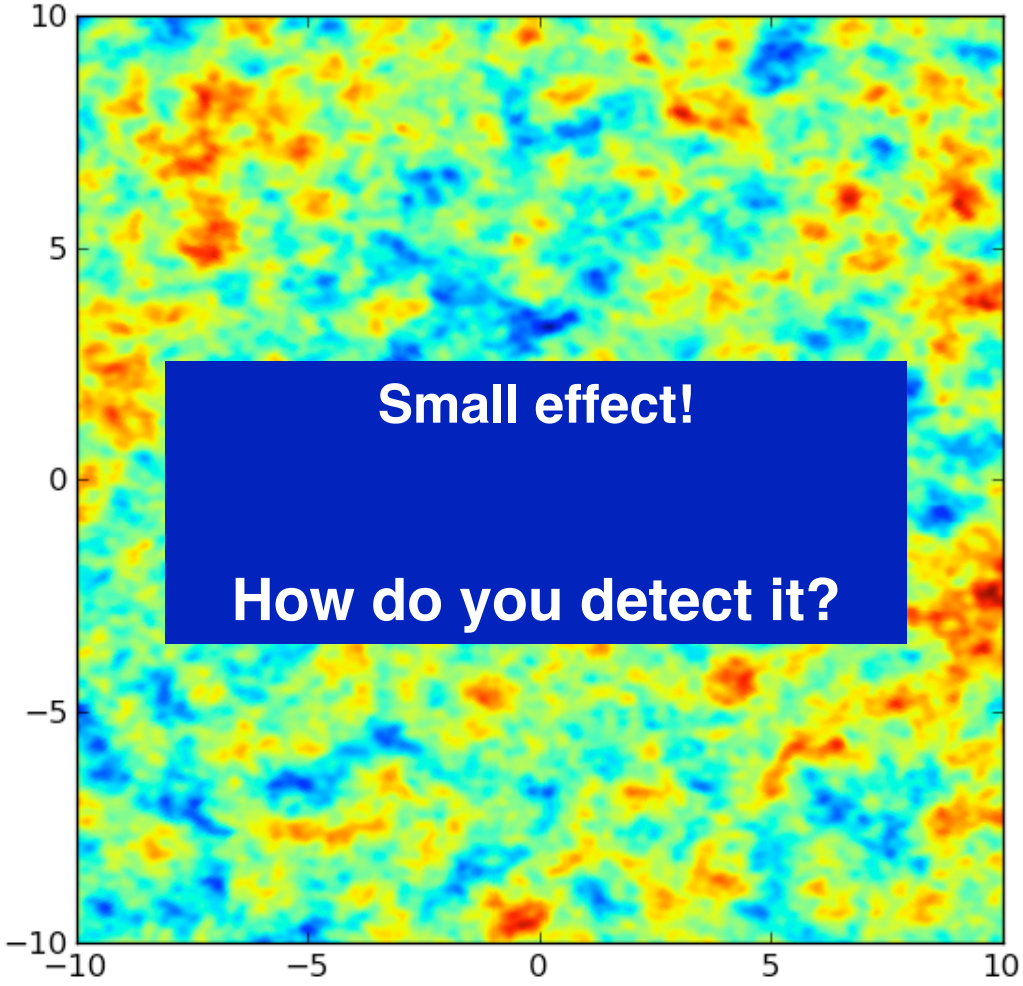
Duncan Hanson
via Kendrick Smith

Unlensed vs lensed CMB



Duncan Hanson
via Kendrick Smith

Unlensed vs lensed CMB

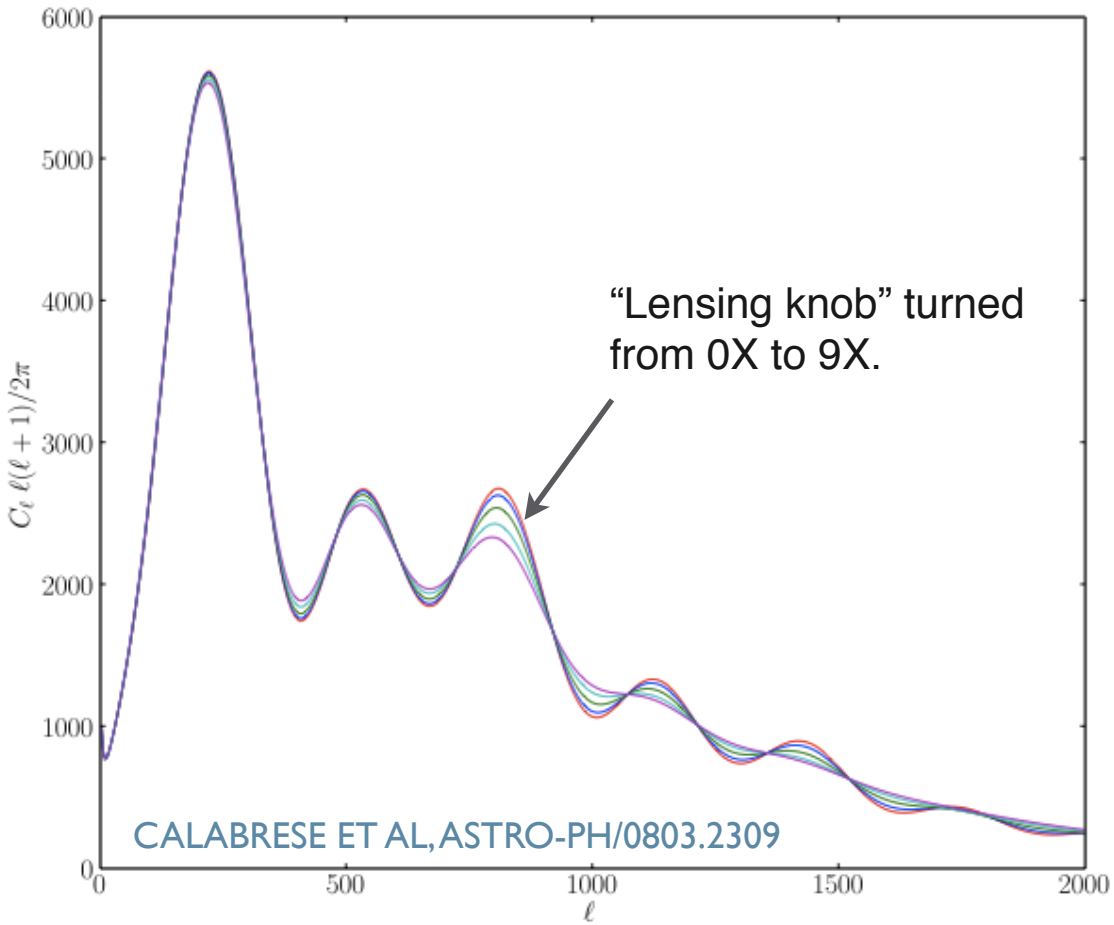


Small effect!

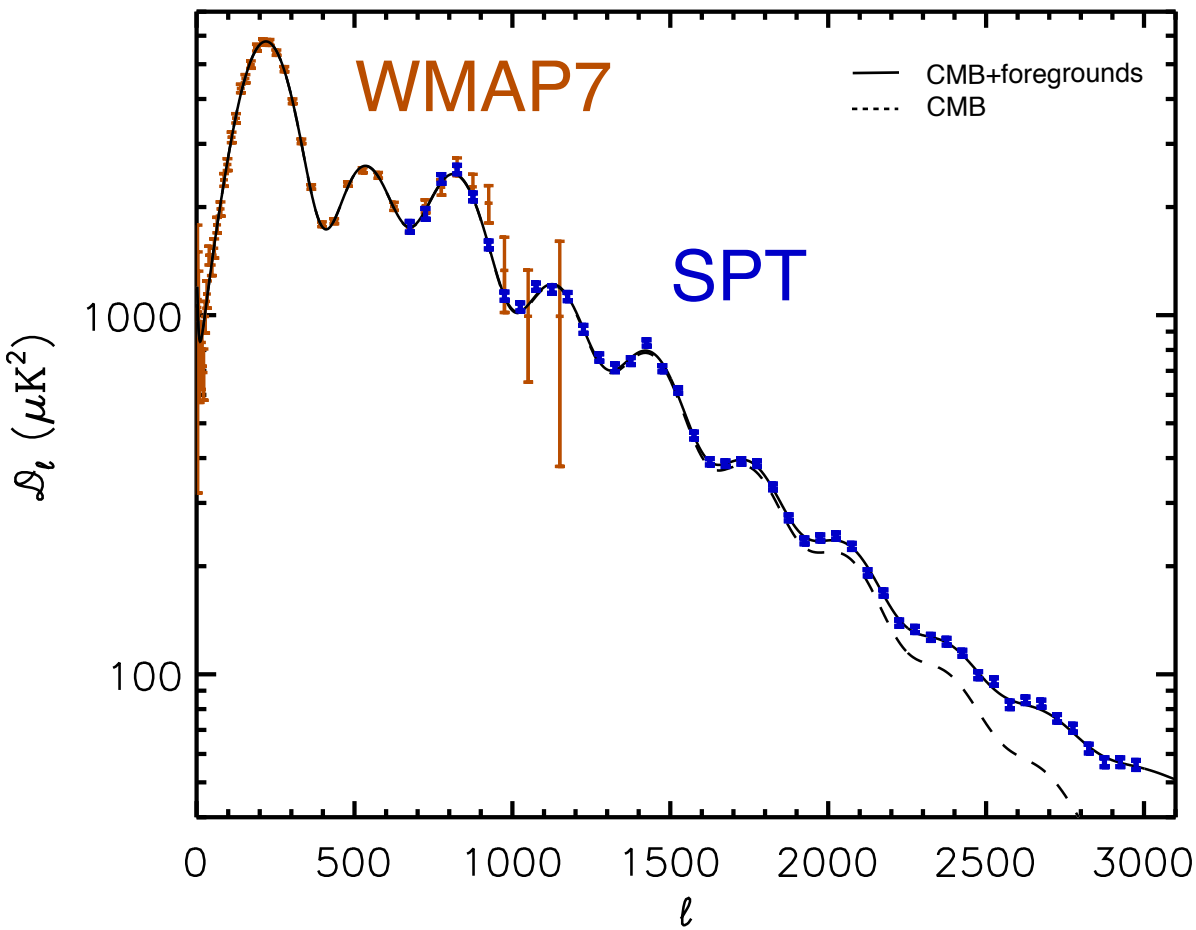
How do you detect it?

Duncan Hanson
via Kendrick Smith

Lensing Smooths the Acoustic Peaks



Lensing Smooths the Acoustic Peaks

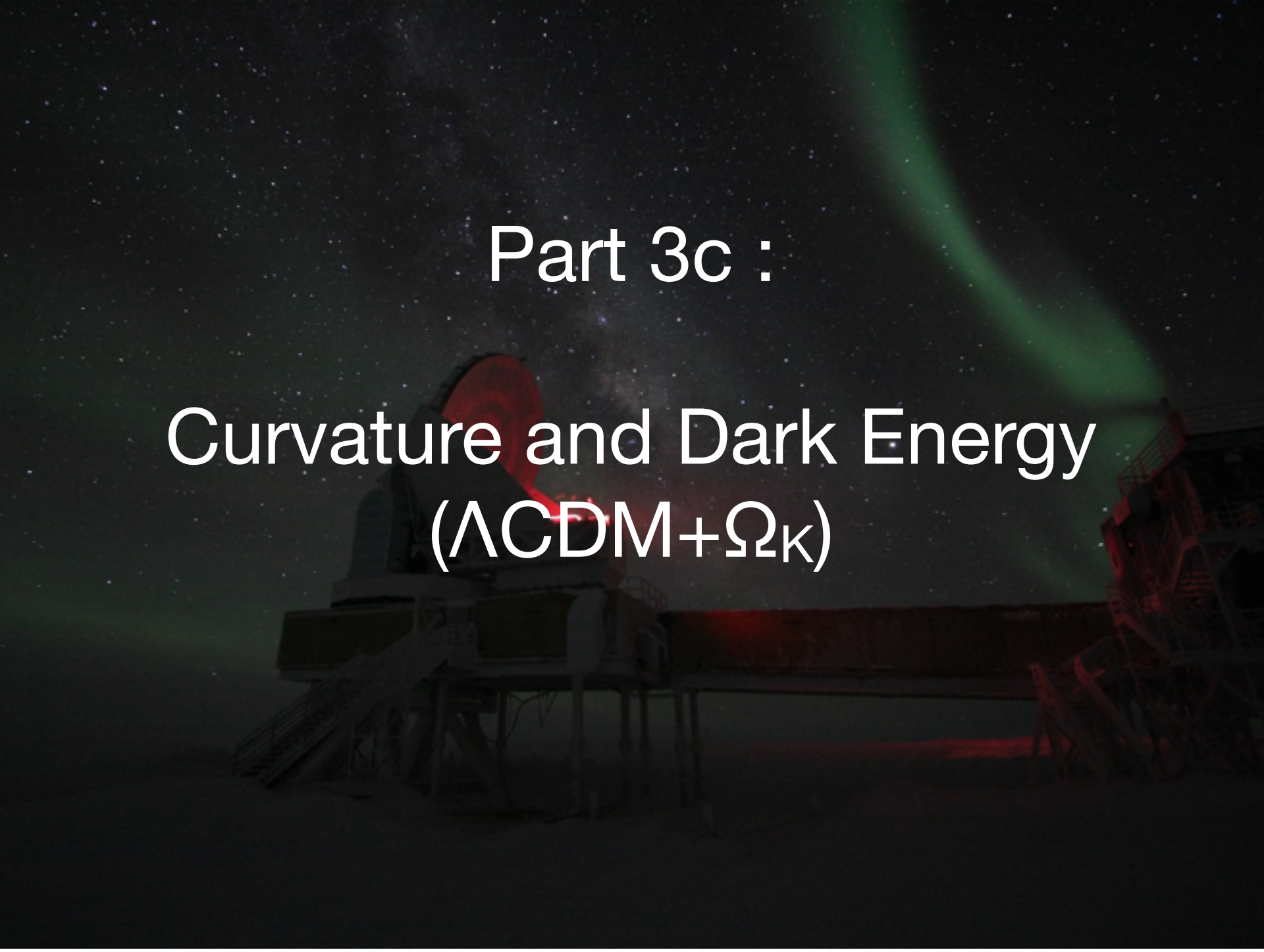


$$C_\ell^\psi \rightarrow A_{\rm lens} C_\ell^\psi$$

$A_{\rm lens} = 0.86^{+0.15}_{-0.13}$

Consistent with expected level ($A_{\rm lens}$=1.0)

SPT+WMAP give **8.1σ** detection of CMB lensing.



Part 3c :

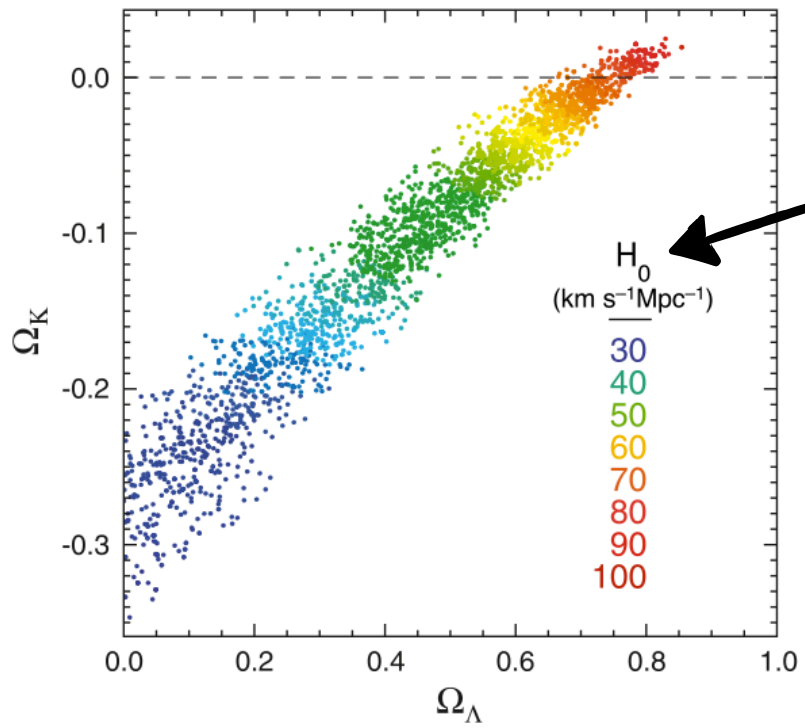
Curvature and Dark Energy (ΛCDM+Ω_K)

Curvature and Dark Energy:

Ω_K - Ω_Λ degeneracy in large-scale data

Hubble Constant

Curvature

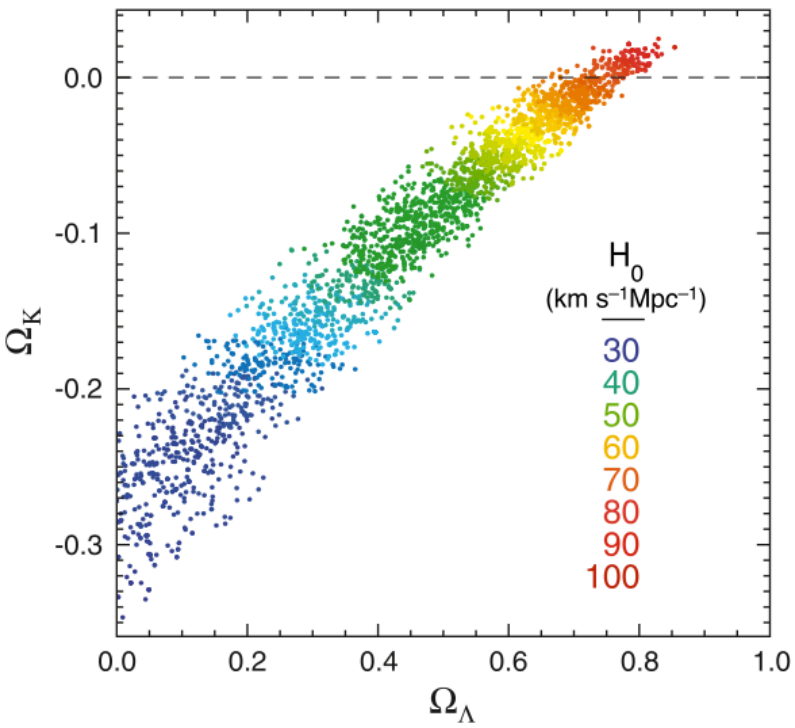


Dark Energy

Source: WMAP5: arXiv 0803.0586

Curvature and Dark Energy:

Ω_K - Ω_Λ degeneracy in large-scale data



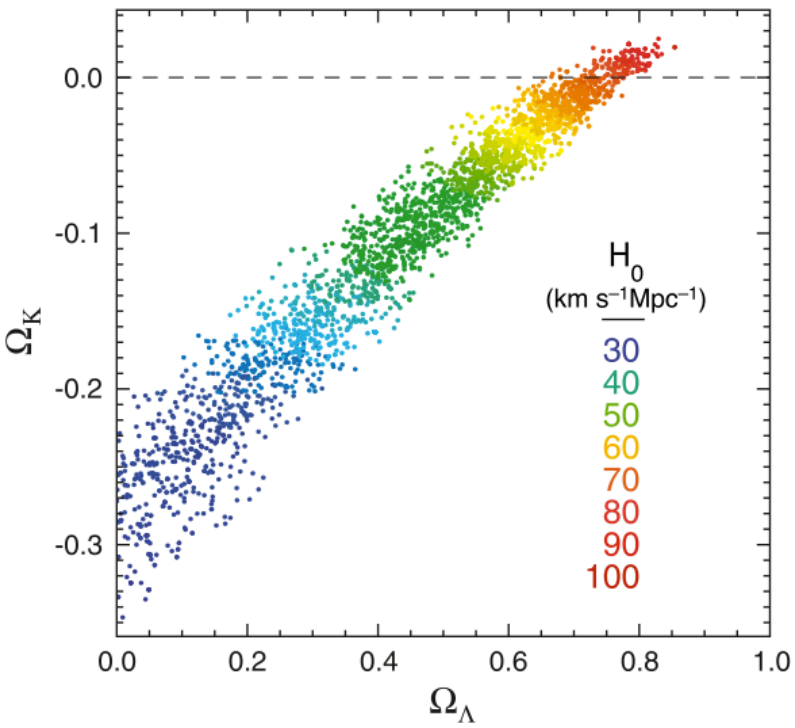
The data is consistent with:

- Young Universe
  - (big Ω_Λ, Ω_K>0, large H_0)
- Old Universe
  - (Ω_Λ =0, Ω_K<0, small H_0)
- Flat Universe

Source: WMAP5: arXiv 0803.0586

Curvature and Dark Energy:

Ω_K - Ω_Λ degeneracy in large-scale data



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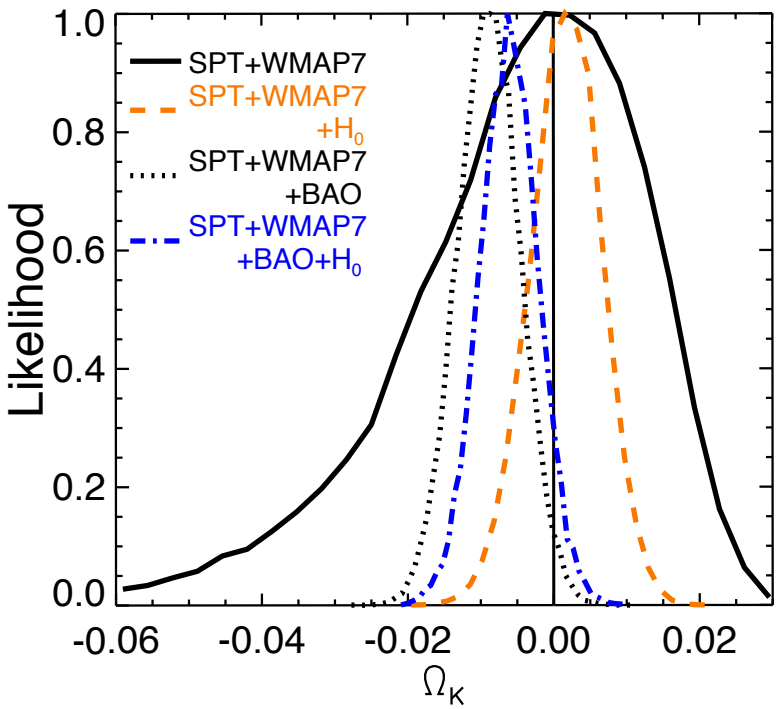
- Young Universe
  - (big Ω_Λ, Ω_K>0, large H_0)
- Old Universe
  - (Ω_Λ =0, Ω_K<0, small H_0)
- Flat Universe

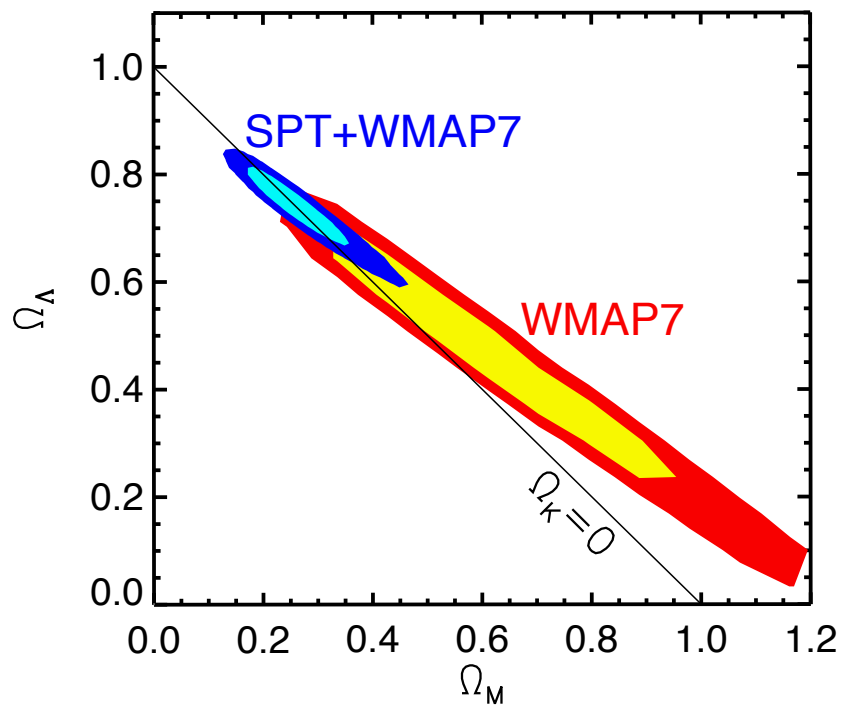
Break the degeneracy:

- low-redshift distance measures (BAO, H_0)
- Gravitational lensing of the CMB

Curvature and Dark Energy:

Ω_K - Ω_Λ degeneracy in large-scale data



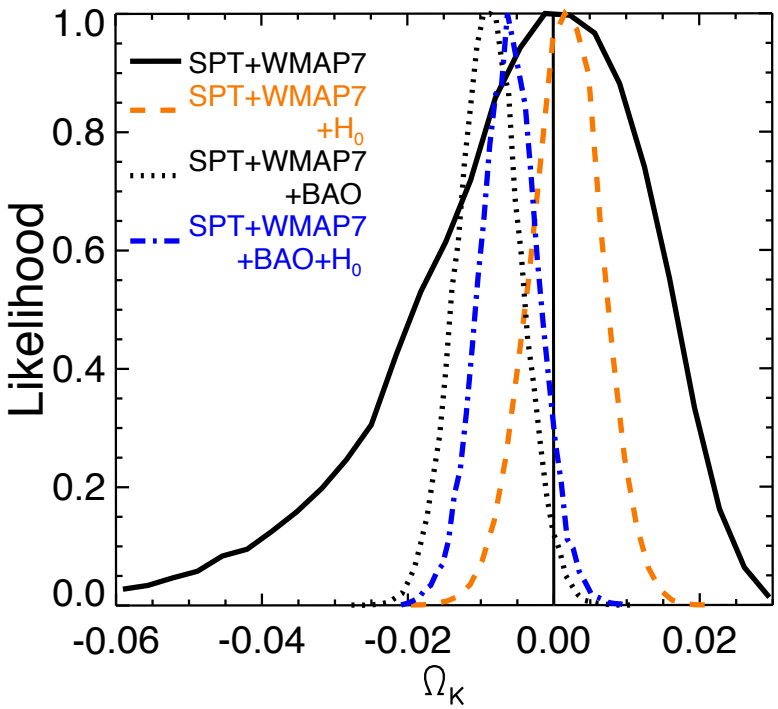


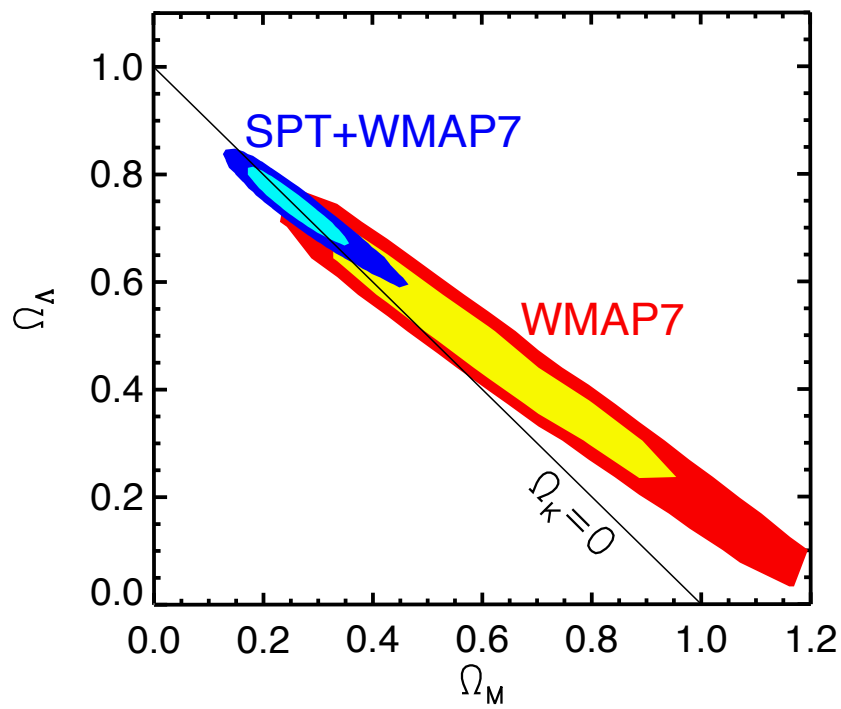
SPT+WMAP7: $\Omega_K = -0.003 \; +0.014 - 0.018$

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

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: $\Omega_K = -0.0059 +/- 0.0040$

Part 3d :

Inflation
(ΛCDM+r)

Initial perturbations

Scalar perturbations (already included)

- Perturbations in the energy density.
- The *only* perturbations which form structure due to gravitational instability (therefore only ones required in a minimal model)

$$\Delta_R^2(k) = \Delta_R^2(k_0)\left(\frac{k}{k_0}\right)^{n_s-1}$$

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Vector perturbations

- "Eddies" in matter with $\nabla \times \mathbf{v} \neq 0$ and $\nabla \cdot \mathbf{v} = 0$
- Exponentially damped by expansion of Universe (negligible with inflation, but can be significant for defect/string models)

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Vector perturbations

Tensor perturbations

- Gravity waves - transverse-traceless metric perturbations
- Generally predicted by inflation models; amplitude related to energy scale at which inflation occurs.
- Convention: amplitude parameter is **r**, the ratio of tensor to scalar power.

$$\Delta_h^2(k) = \Delta_h^2(k_0)\left(\frac{k}{k_0}\right)^{n_t}$$

SPT Power Spectrum has 2 experimental handles:

$$\Delta_R^2(k) = \Delta_R^2(k_0)\left(\frac{k}{k_0}\right)^{n_s-1}$$

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$$r = \left.\frac{\Delta_h^2(k)}{\Delta_R^2(k)}\right|_{k=0.002\,\mathrm{Mpc}^{-1}}$$

2 Parameters: n_s, and r

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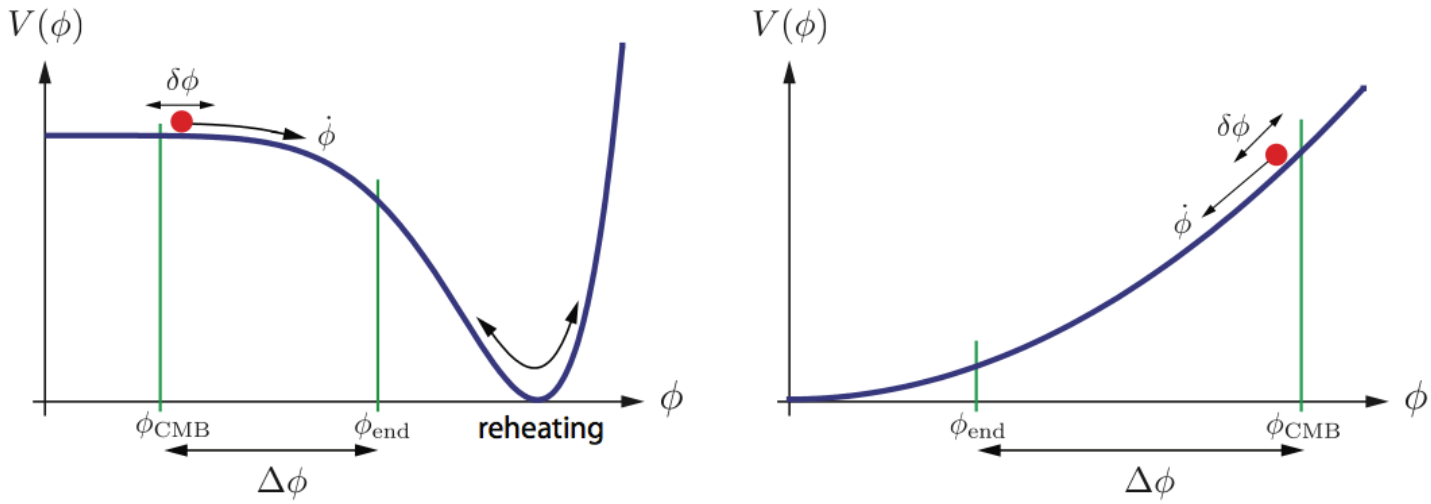
2 Parameters: n_s, and r

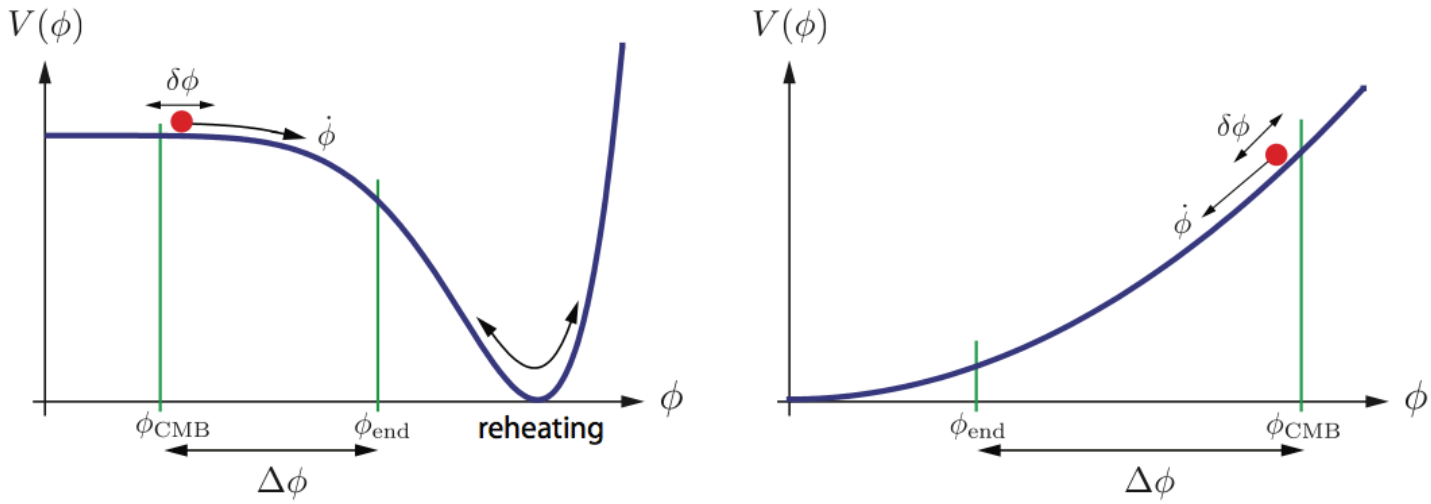
Inflation makes predictions for n_s and r



1) The potential describes the model

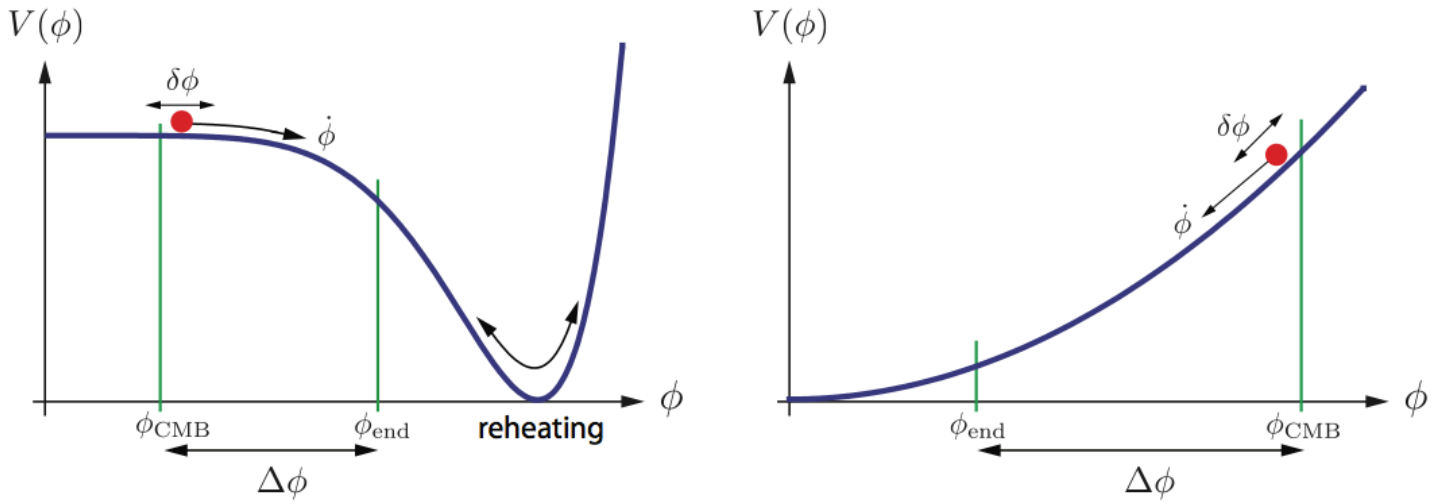
*Figure from Baumann et al. 2009 (arXiv:0811.3919v2)

Inflation makes predictions for n_s and r



1) The potential describes the model
2) $\Delta\phi$ separates "large-field" and "small-field" models.
   The dividing line is (r = 0.01)

Inflation makes predictions for n_s and r



"Slow-roll" parameters:

$$\epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{M_{\rm pl}^2}{2}\frac{\dot{\phi}^2}{H^2} \approx \frac{M_{\rm pl}^2}{2}\left(\frac{V'}{V}\right)^2$$

$$|\eta| \approx M_{\rm pl}^2 \left|\frac{V''}{V}\right| .$$

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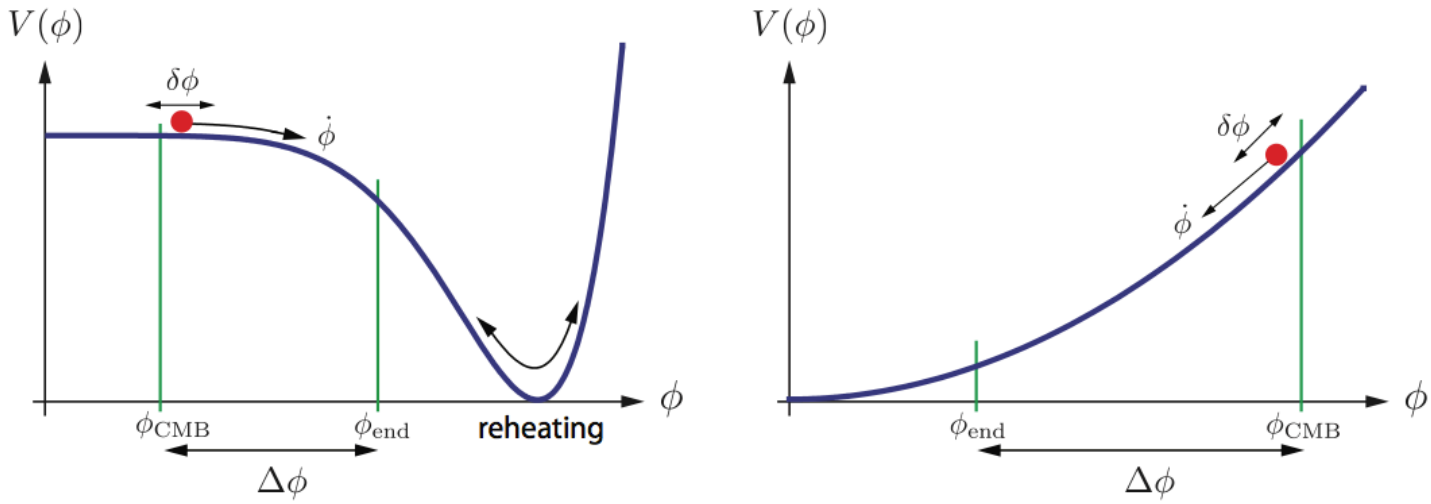

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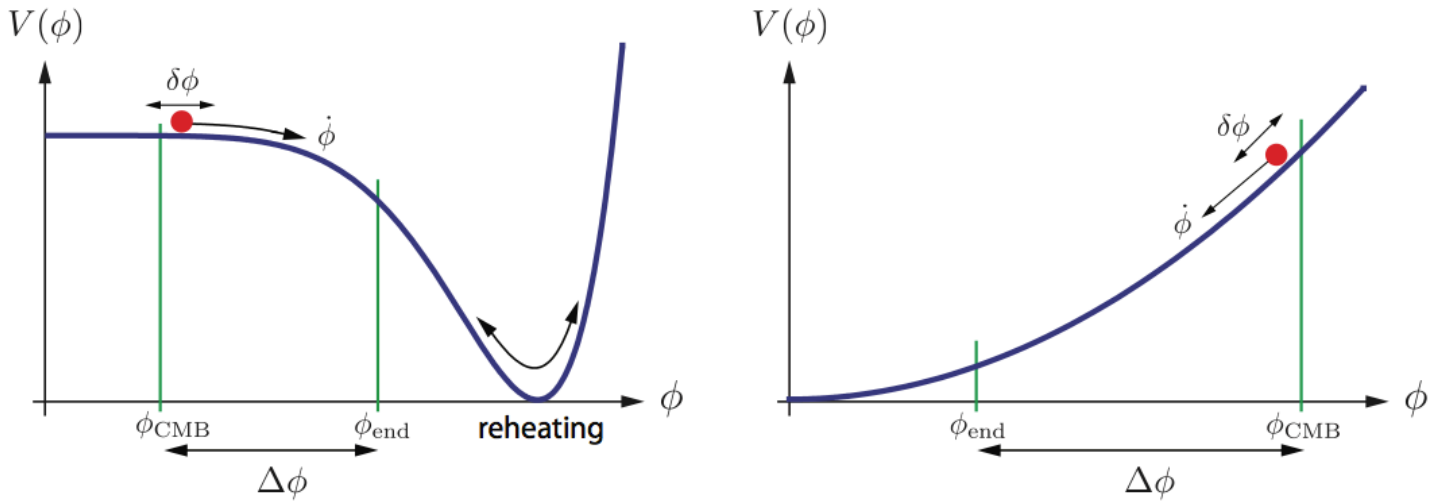
$$n_s = 1 - 4\epsilon_{\rm CMB} + 2\eta_{\rm CMB}$$

$$r = 13.7\epsilon_{CMB}.$$

Inflation makes predictions for n_s and r



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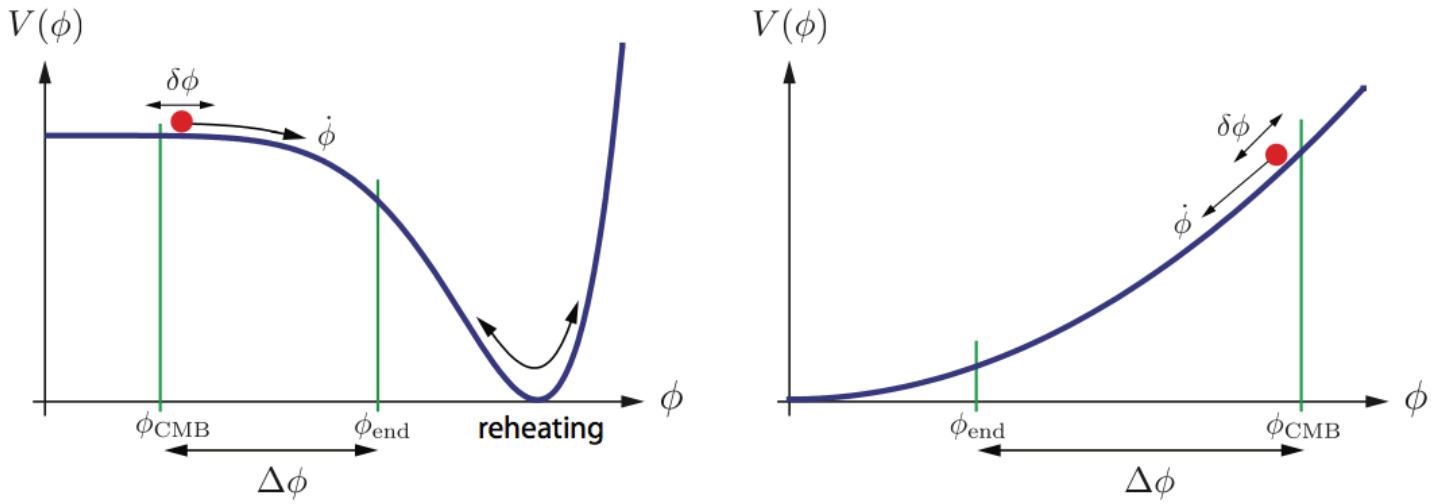
Inflation must end: ns ≠ 1

Inflation makes predictions for n_s and r



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$$r = 13.7\epsilon_{CMB}.$$

$$V^{1/4} = 1.06 \times 10^{16}\,{\rm GeV}\left(\frac{r_\star}{0.01}\right)^{1/4}$$

"Energy Scale of Inflaiton"

In Summary:

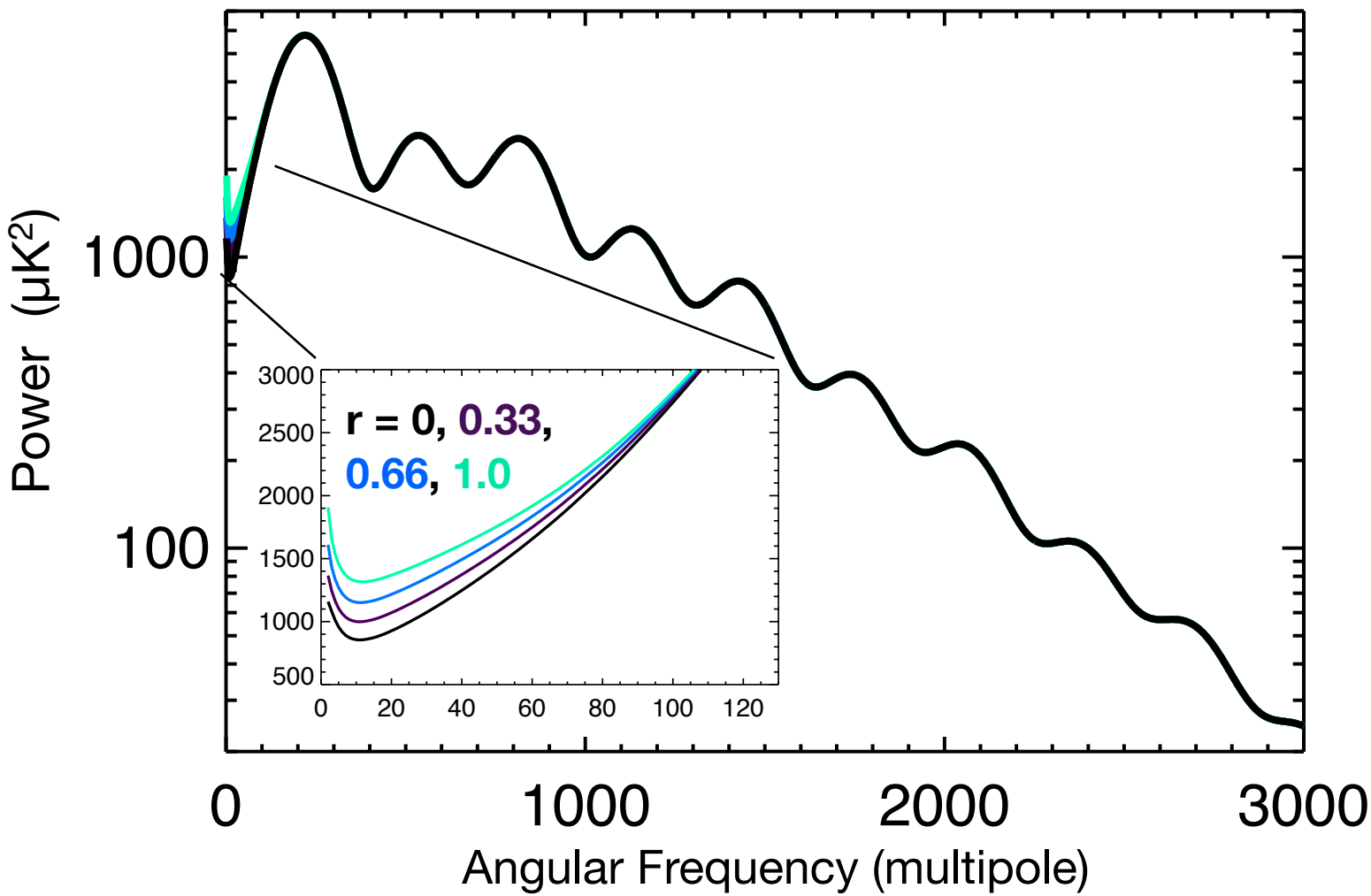
Measure ns, r ⇒constrain inflation

$$n_s = 1 - 4\epsilon_{\rm CMB} + 2\eta_{\rm CMB}$$

$$r = 13.7\epsilon_{CMB}.$$

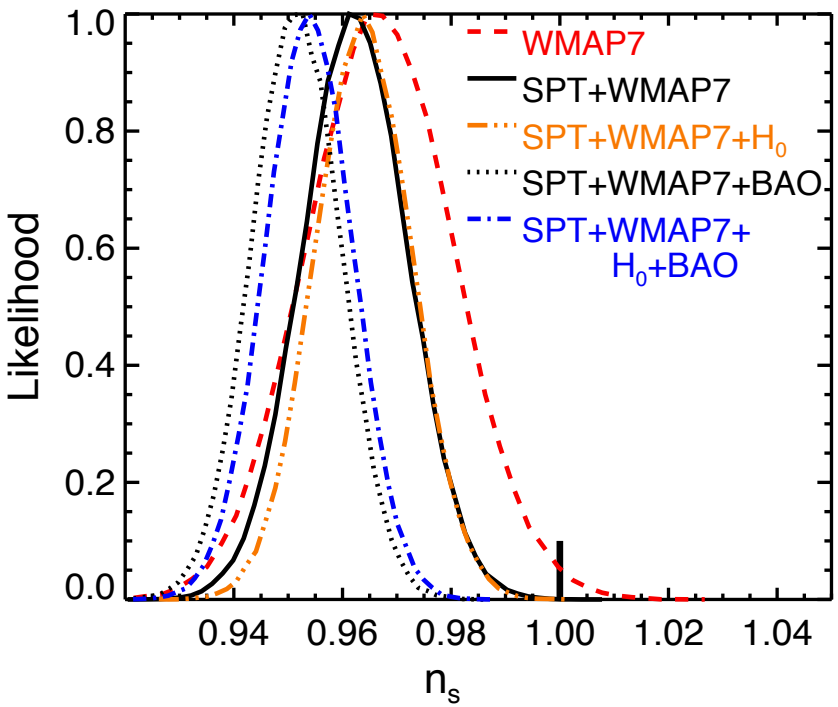
Tensor perturbations:

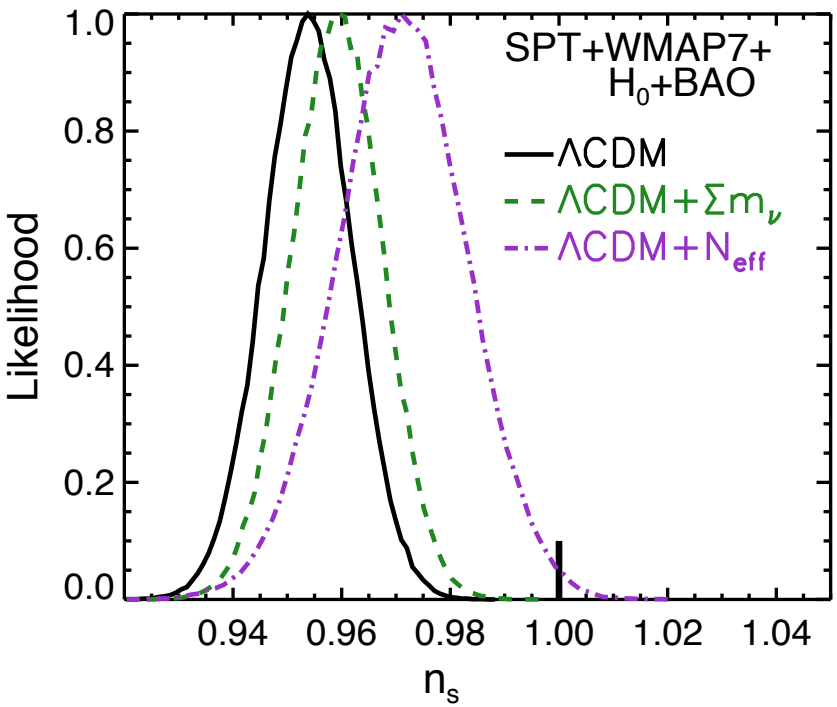
Damping tail measurements break the n_s - r degeneracy



SPT constraints

ΛCDM Results



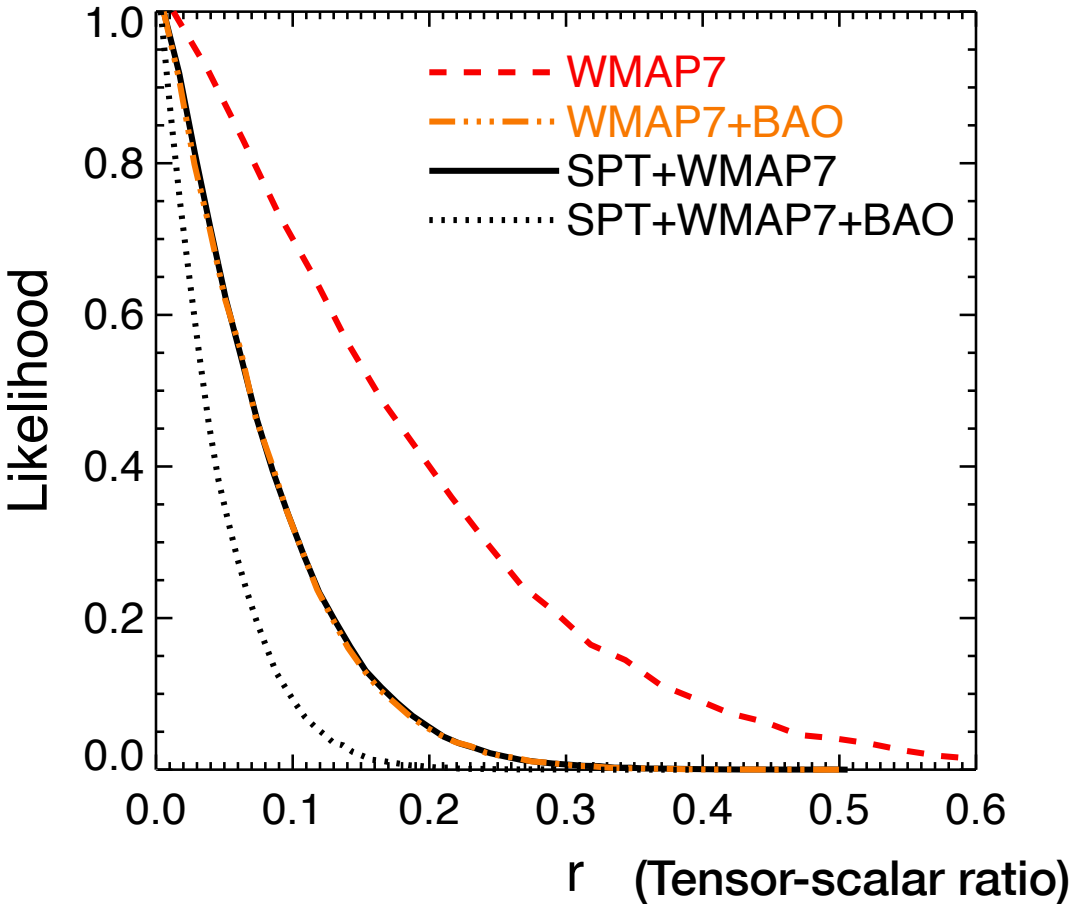


Most significant detection of a departure from scale-invariance!

n_s: WMAP7 = 0.969 ± 0.014
WMAP7+SPT (CMB) = 0.962 ± 0.010
CMB+BAO+H_0 = 0.954 ± 0.008

$P(n_s > 1)$: WMAP7 = 1.4e-2 (2.2 σ)
+SPT = 3.9e-4 (3.9 σ)
+BAO+H_0=1.4e-9 (5.9 σ)

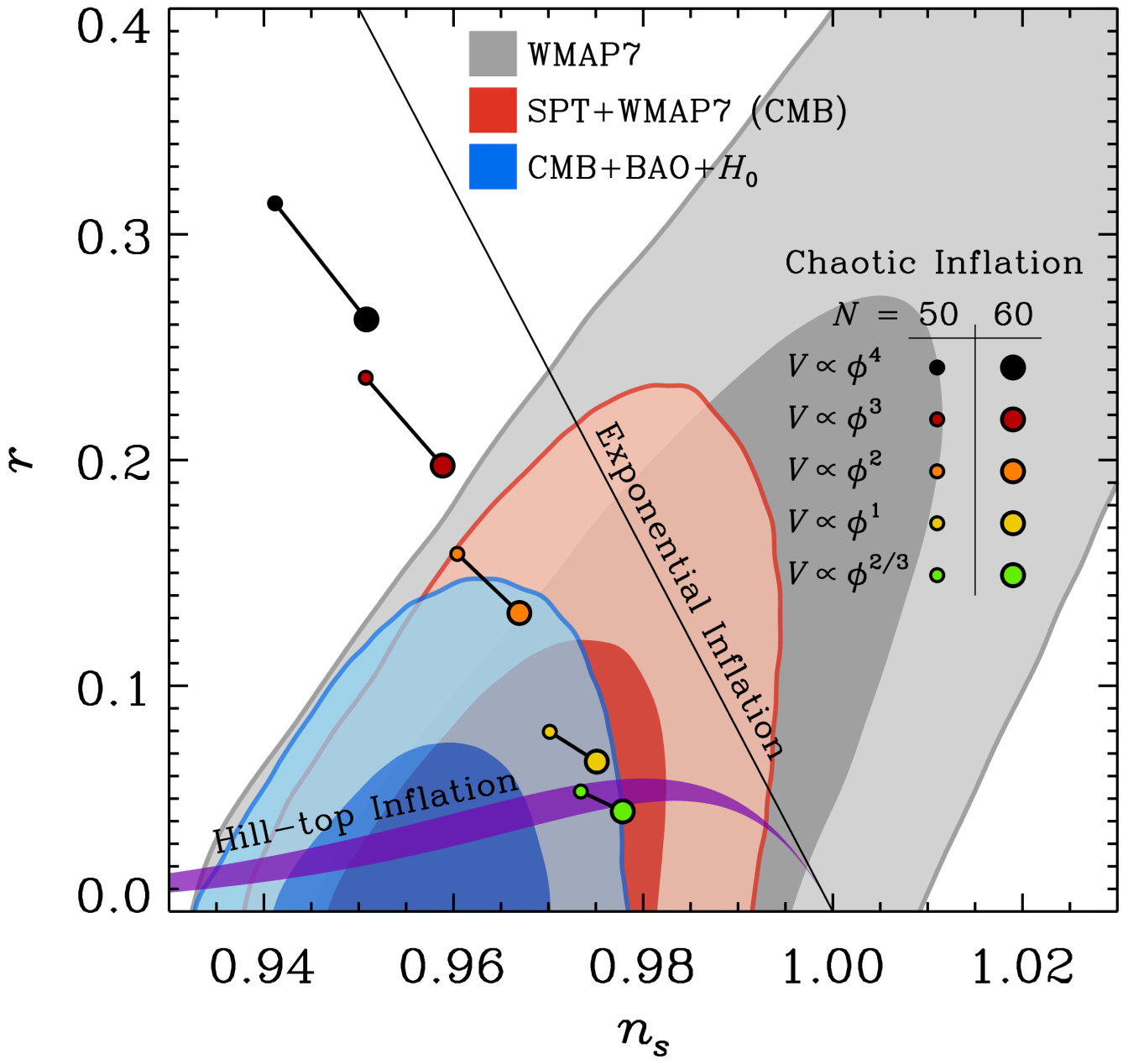
Best limits on tensors!



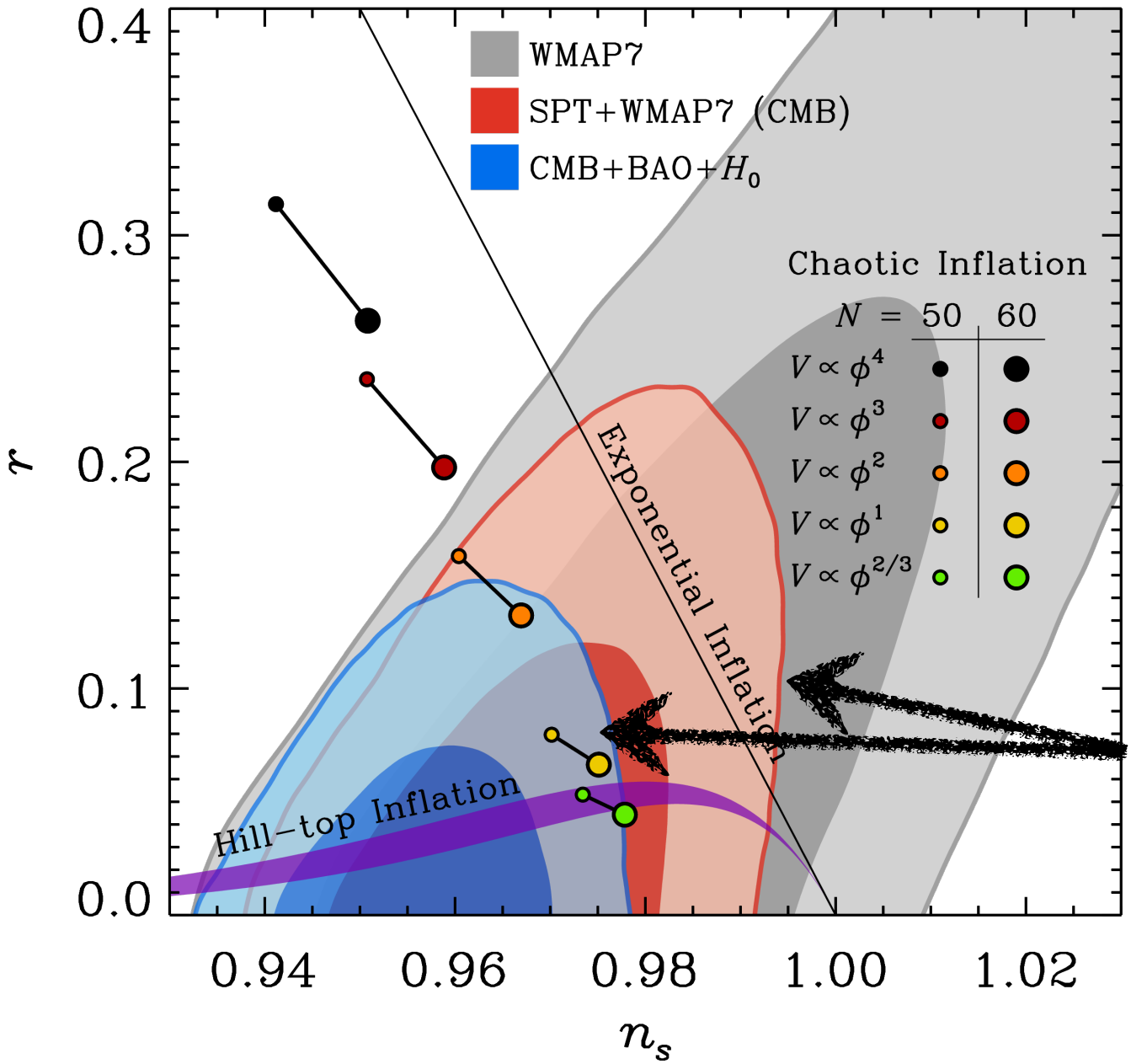
No evidence for tensors yet; 95% upper limits are:

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

Implications

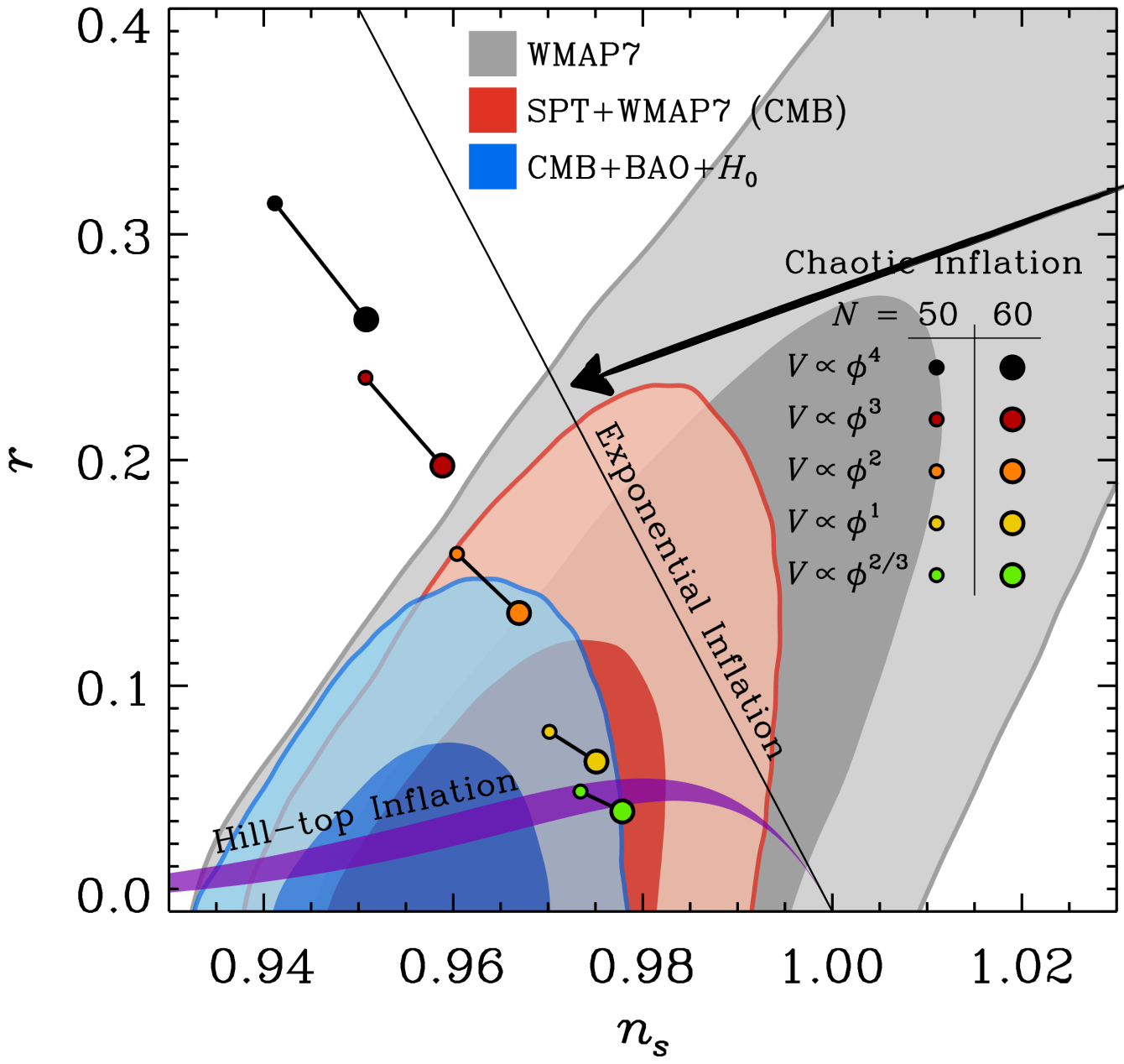


Data Constraints



Weakened degeneracy between n_s and r

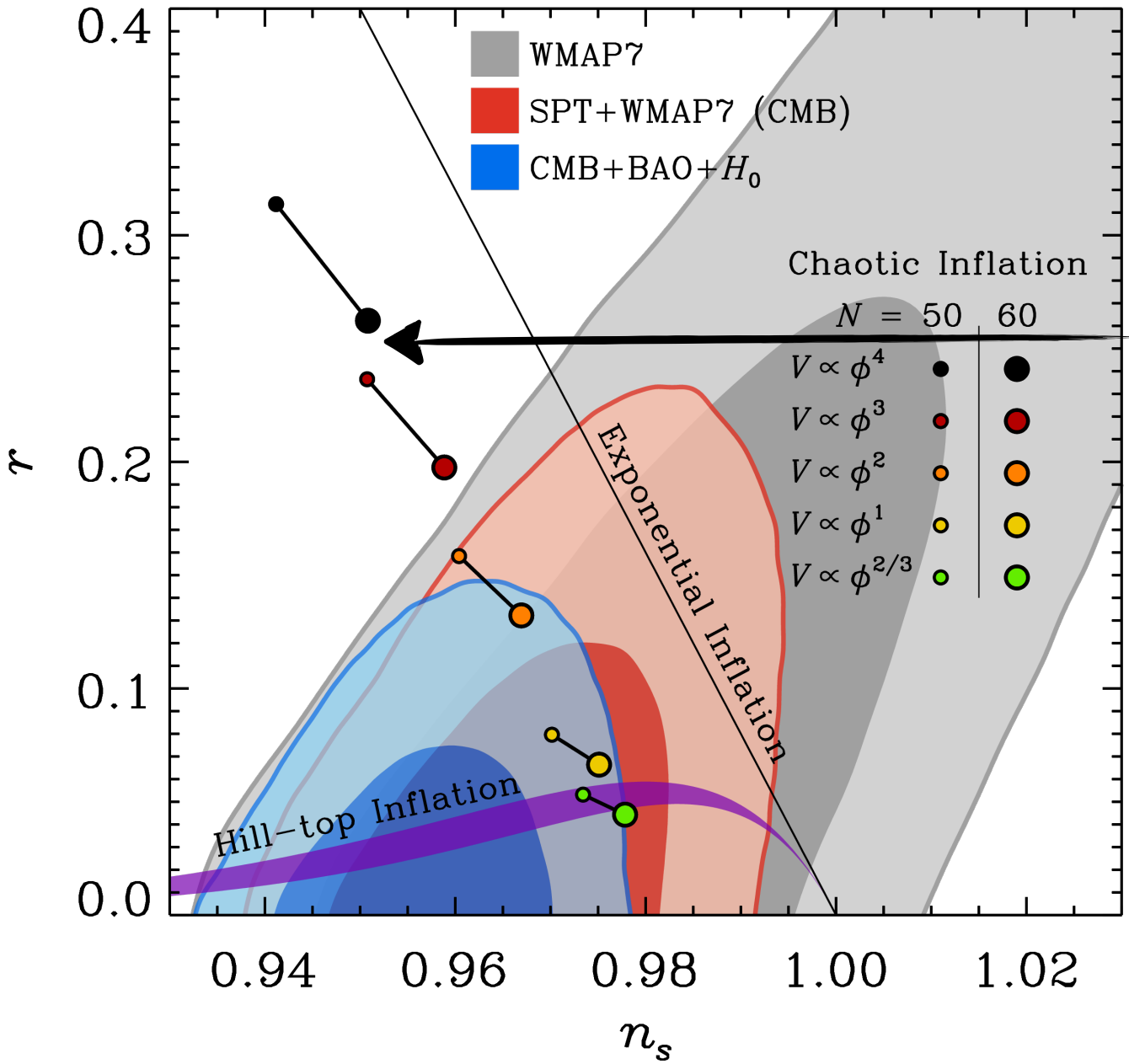
Inflation Models



Models of Inflation

Exponential:
$V(\Phi) \sim \exp(\sqrt{(\Phi^2/p)})$

Inflation Models



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Chaotic:
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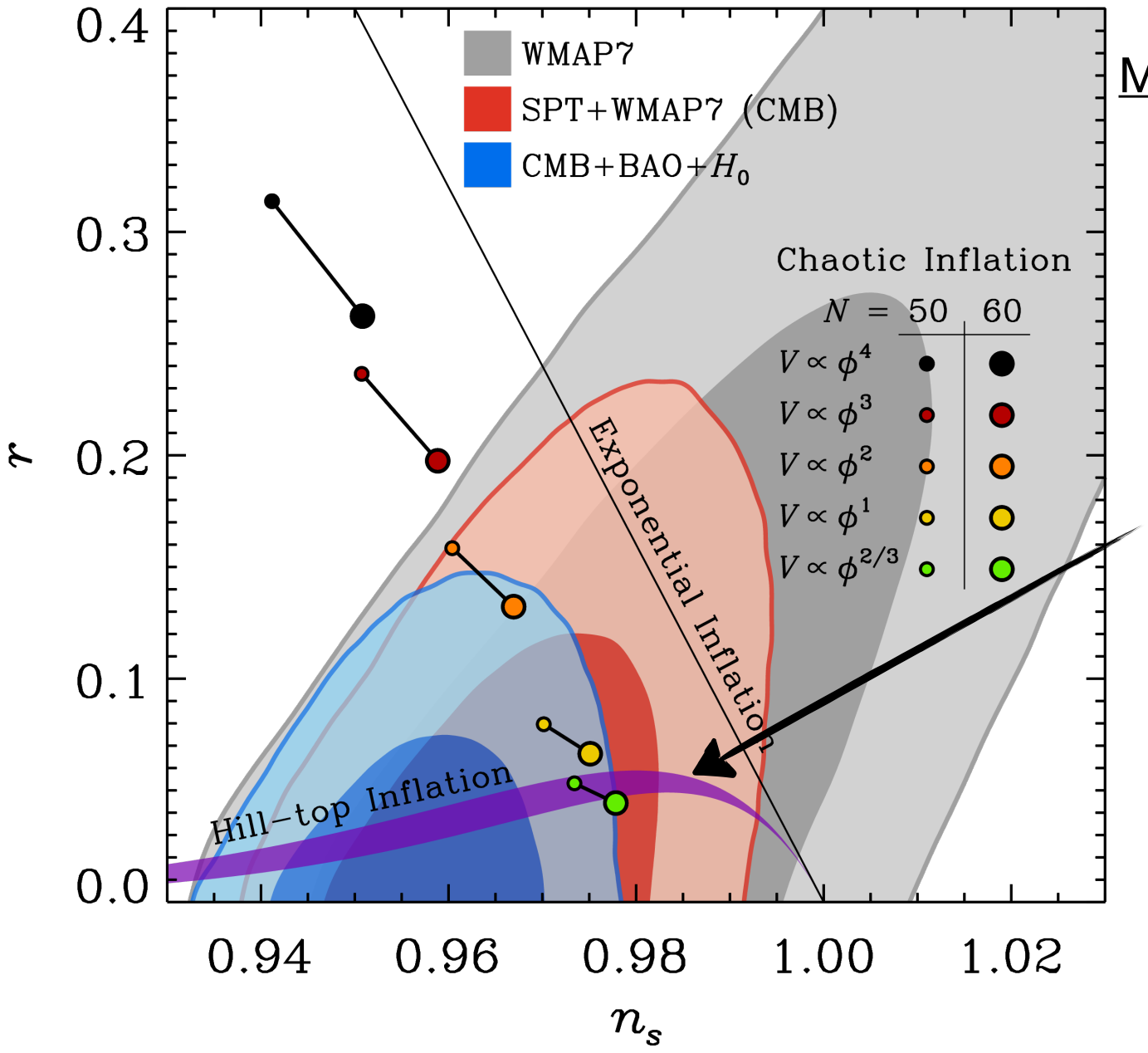
Inflation Models



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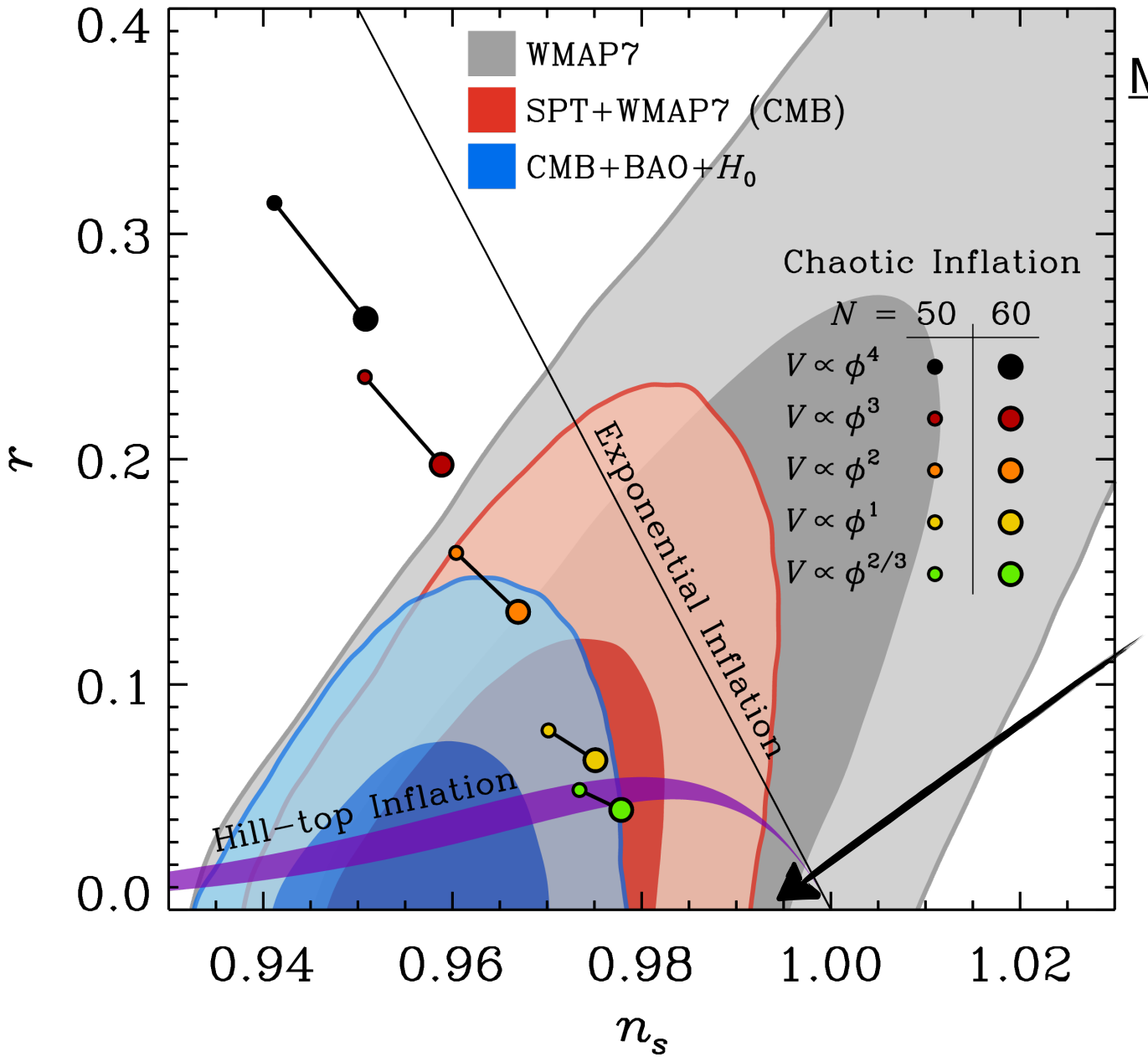
Inflation Models



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Small-field:
$r < 0.01$

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

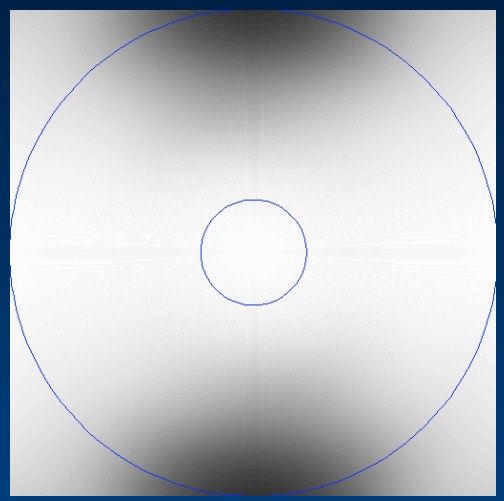
Thanks!

2D Kweights: We apply a weight-mask to each map in fourier-space to down-weight noisy regions.

The 2d kweight is defined as:

$$\text{weight\_2d} = \frac{1}{(\text{GS}\{\text{cl\_th}\} + \text{GS}\{\text{noise/TF}\})^2}$$

In Pictures, the 2d kweight looks like:



$$= \frac{1}{\left(GS\{\ \ \}+GS\{\ \ \}\right)^2}$$

Uncertainty in Inflation predictions