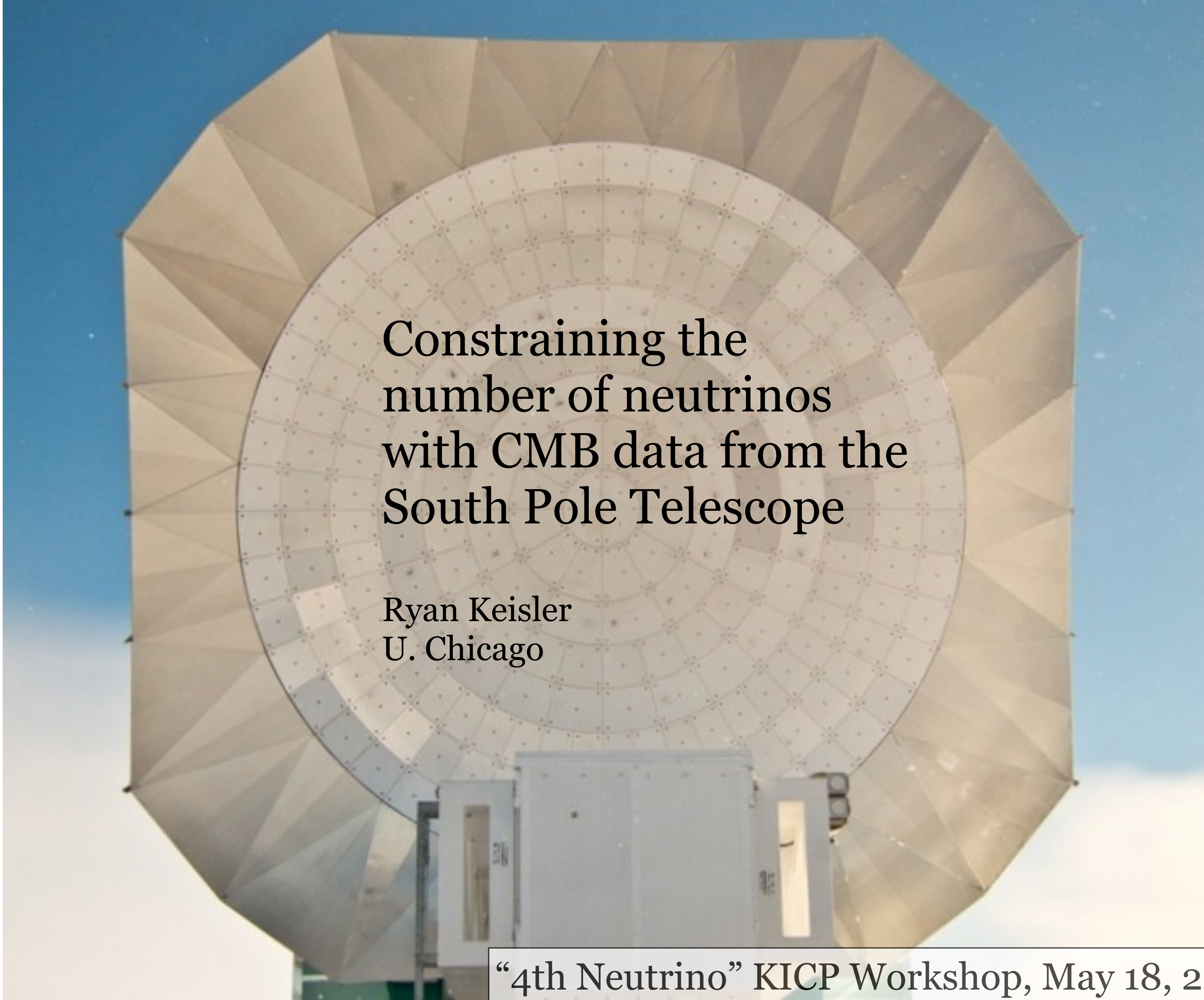

Constraining the number of neutrinos with CMB data from the South Pole Telescope

Ryan Keisler
U. Chicago

“4th Neutrino” KICP Workshop, May 18, 2012

Overview

The effective number of neutrinos, N_{eff}, can be constrained by cosmological data, particularly observations of the cosmic microwave background (CMB).

SPT + WMAP,

N_{eff} = X +/- 0.62

SPT+WMAP+(Hubble Constant+BAO),

N_{eff} = Y +/- 0.42

Overview

The effective number of neutrinos, N_{eff}, can be constrained by cosmological data, particularly observations of the cosmic microwave background (CMB).

SPT + WMAP,

$N_{eff} = 3.85 +/- 0.62$

SPT+WMAP+(Hubble Constant+BAO),

$N_{eff} = 3.86 +/- 0.42$ (~2σ preference for Neff>3)

Outline

1. What is the CMB, and how does an extra neutrino affect it?

2. Constraints from SPT+WMAP

3. What's next?

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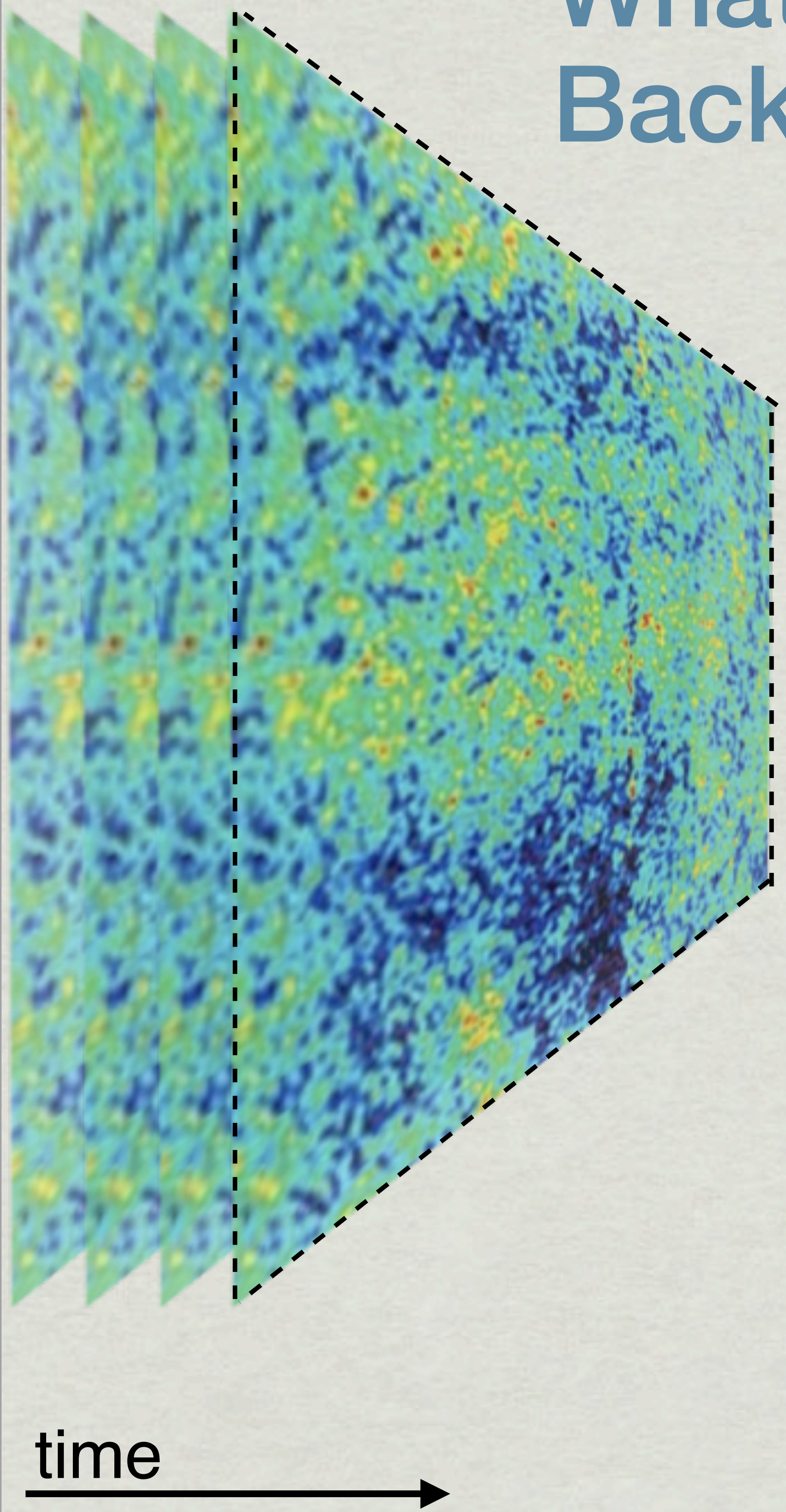
What is the Cosmic Microwave Background?

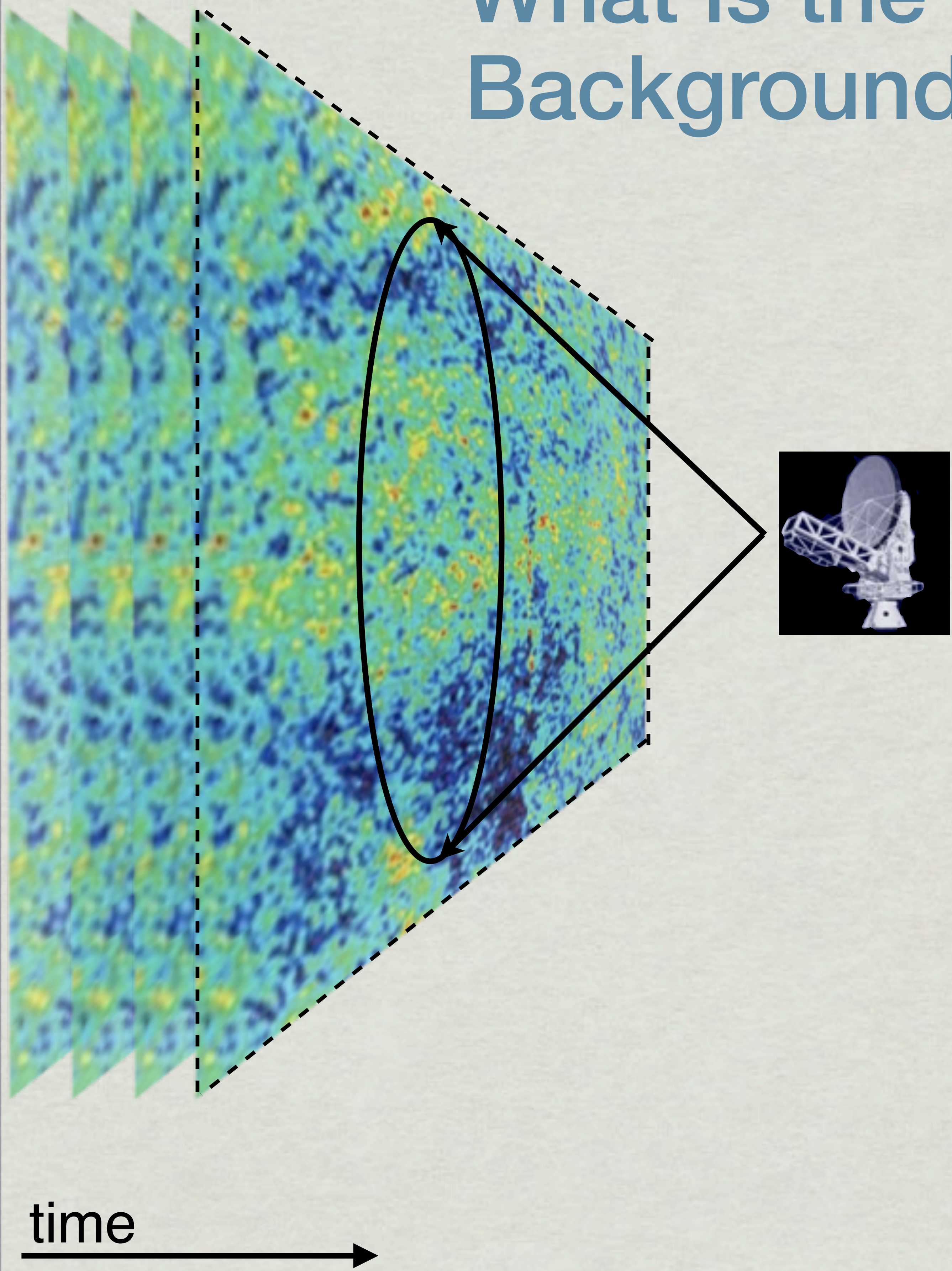


The constituents of the early universe (photons, electrons, protons, dark matter, neutrinos, ...) were coupled.

- gravity pulls,
- radiation pressure pushes (on some of them)

=> **oscillations**

What is the Cosmic Microwave Background?



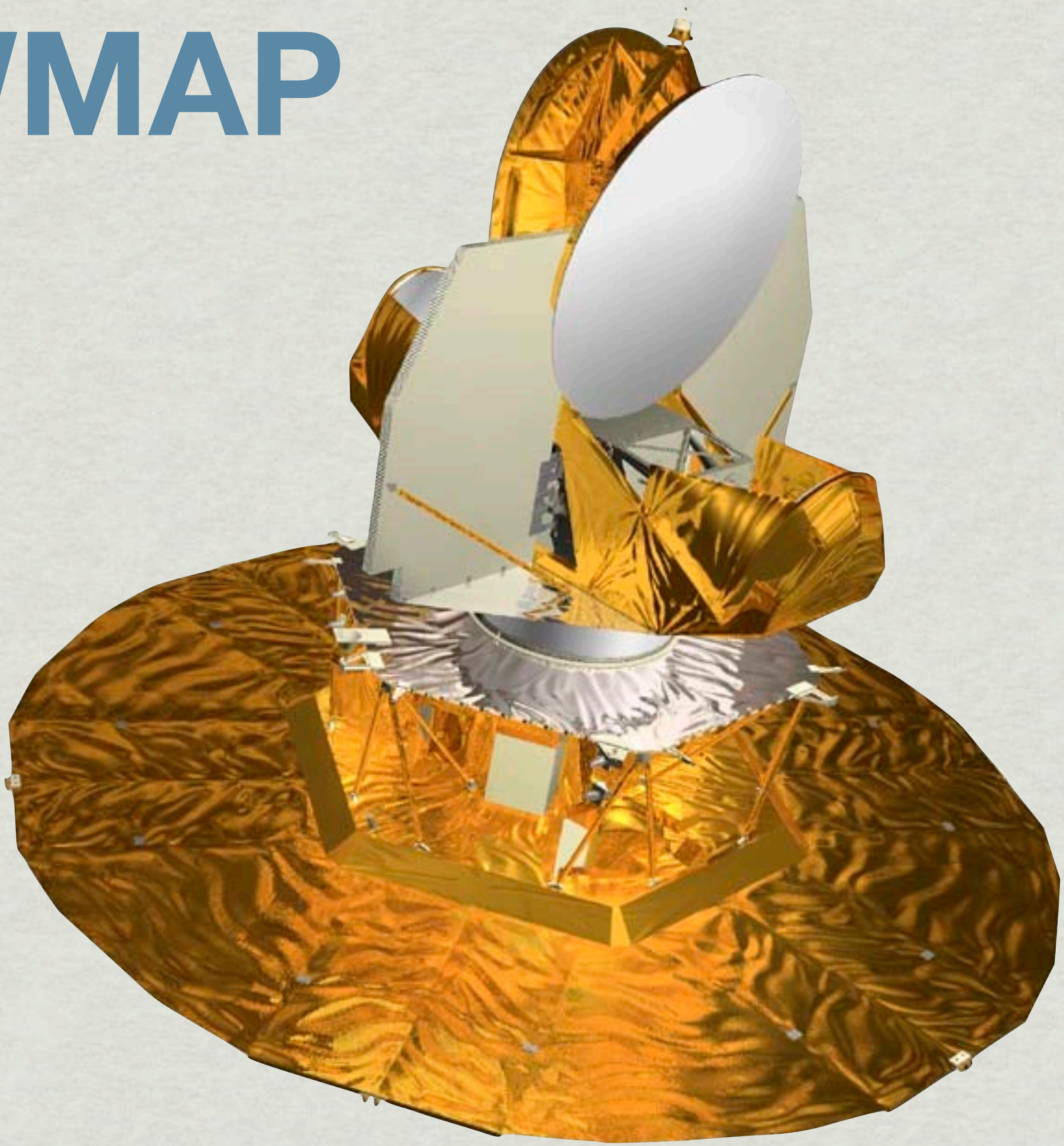
Eventually the universe expands and cools such that **neutral hydrogen can form**. "Recombination"

No more free electrons, no more Thomson scattering between photons and electrons.

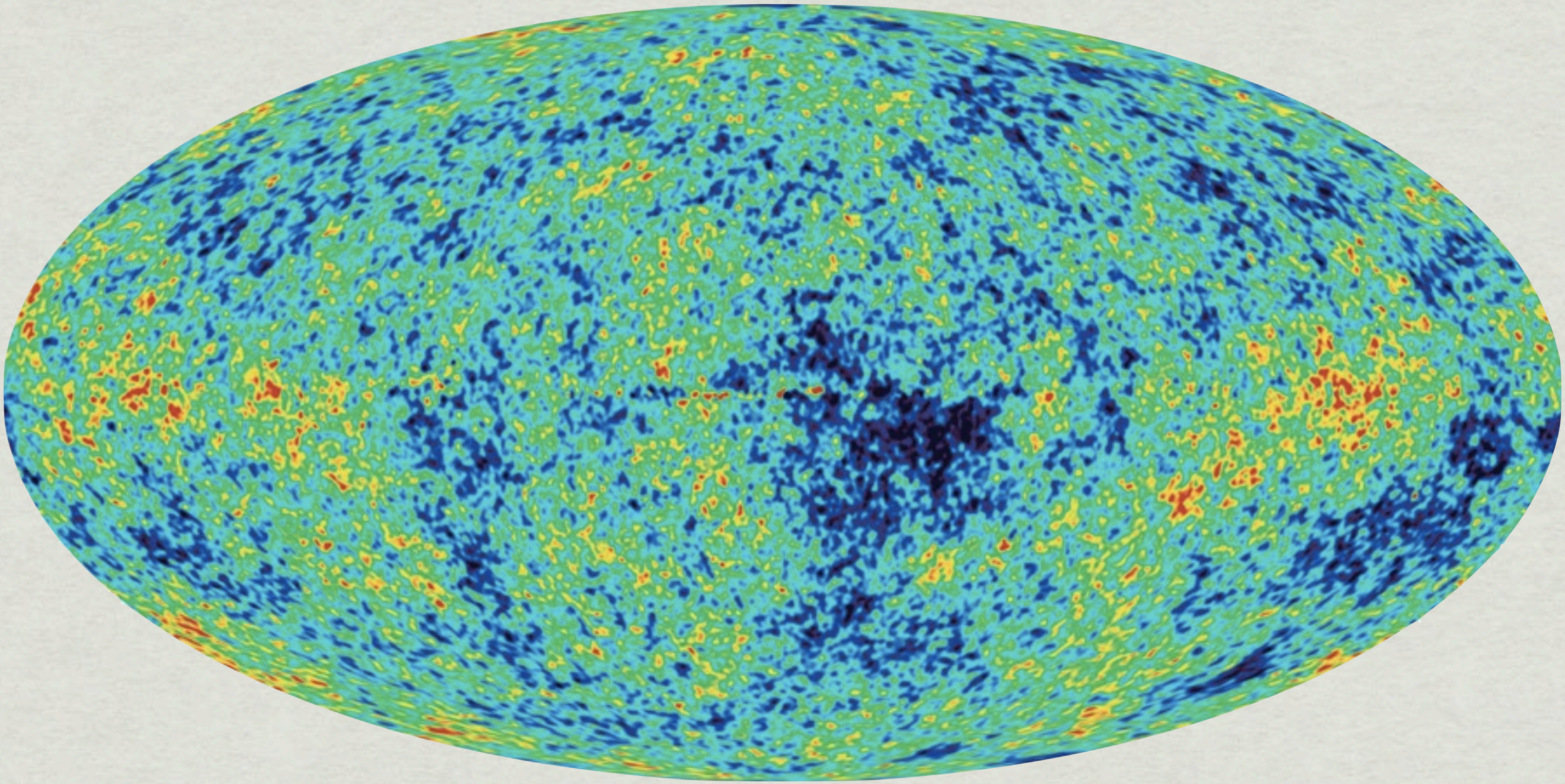
=> Photons can travel freely, and we see them today as a blackbody with T=2.73K.

The small anisotropies we see in the CMB are due to oscillations in early plasma.

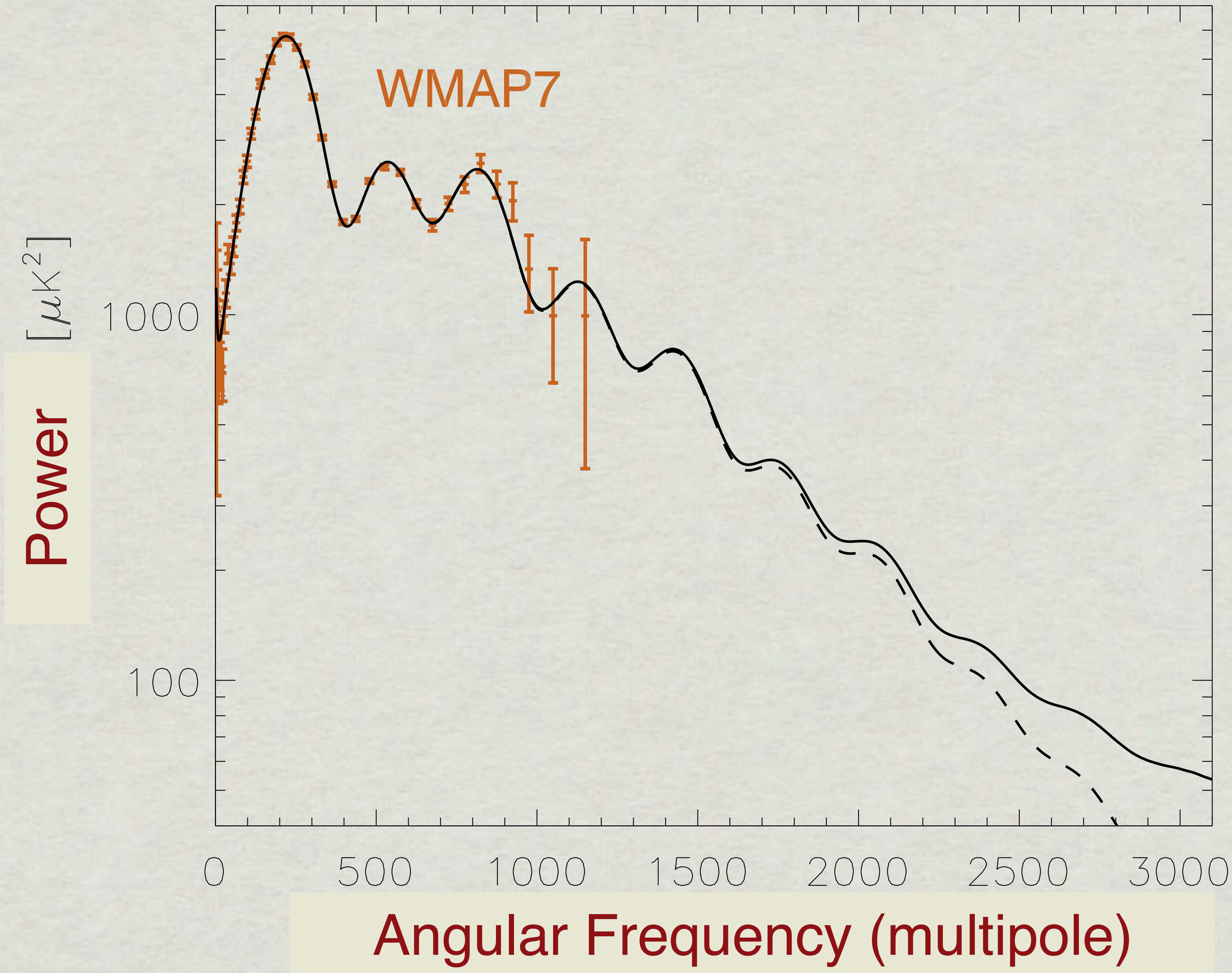
WMAP



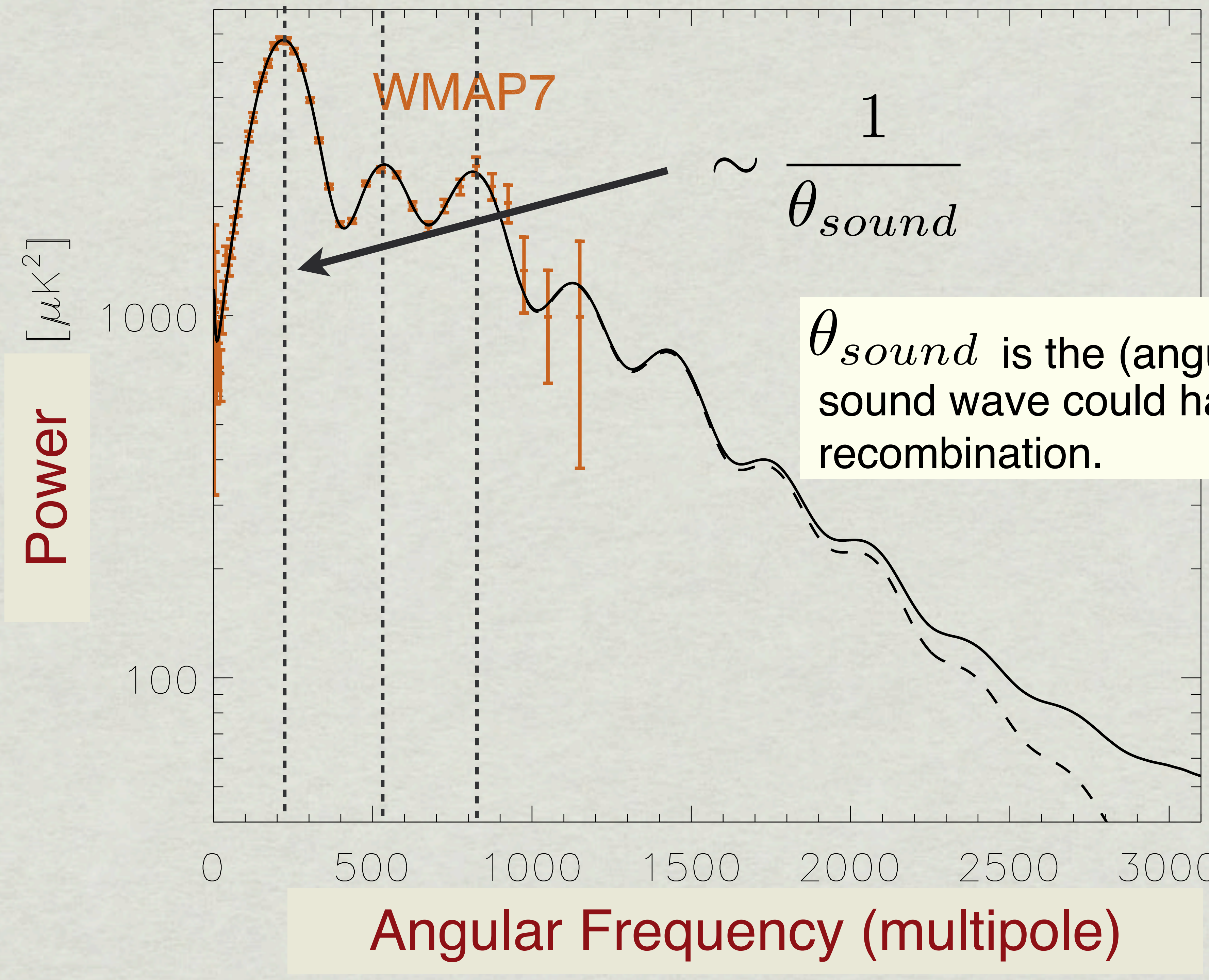
WMAP



Angular Power Spectrum



The *Sound* Scale

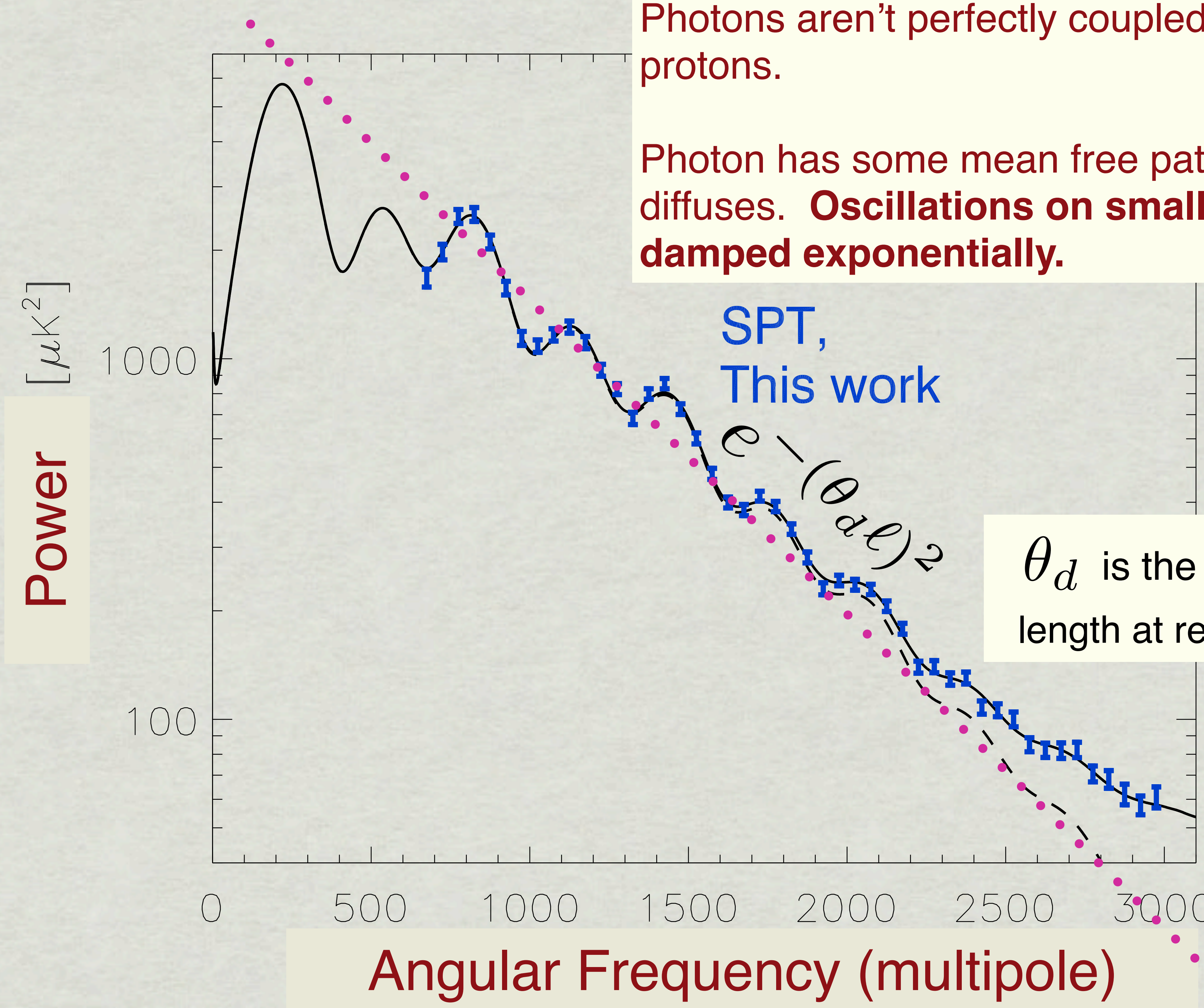


θ_{sound} is the (angular) distance a sound wave could have traveled by recombination.

The *Damping* Scale

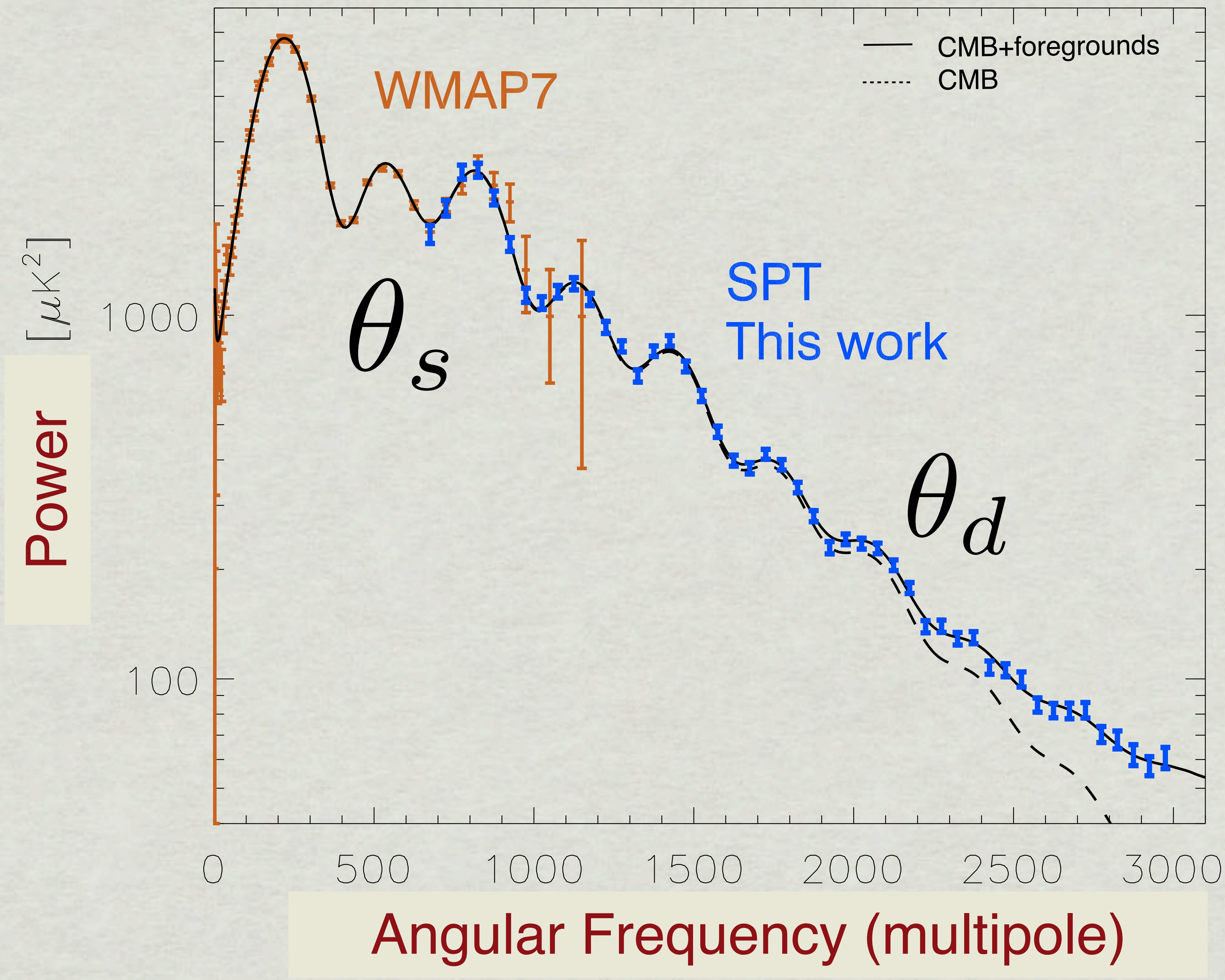
Photons aren't perfectly coupled to electrons/ protons.

Photon has some mean free path and diffuses. **Oscillations on small scales are damped exponentially.**



θ_d is the (angular) diffusion length at recombination.

Angular Power Spectrum



Sensitivity to Neutrinos

How does an extra neutrino affect these CMB observables, θ_s and θ_d ?

An extra neutrino species **increases the expansion rate** during this radiation-dominated era.

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 \propto (\rho_\gamma + \rho_\nu + \rho_{\rm matter} + ...)$$

More neutrinos => higher density => faster expansion

Sensitivity to Neutrinos

Consider how the real space equivalents, **r_s** and **r_d**, depend on the expansion rate, *H:*

Sound Scale

$$r_s \propto \int_0^{a^*} \frac{c_s da}{a^2 H}$$

$$r_s \propto H^{-1}$$

Damping Scale

$$r_d^2 \propto \int_0^{a^*} \frac{da}{a^3 \sigma_{\mathrm{T}} n_e H} \propto \frac{1}{H}$$

$$r_d \propto H^{-0.5}$$

$$\frac{r_d}{r_s} = \frac{\theta_d}{\theta_s} \propto H^{0.5}$$

(see 1104.2333, Z. Hou, RK, L. Knox, C. Reichardt)

Sensitivity to Neutrinos

$$\frac{r_d}{r_s} \propto H^{0.5} \propto (\rho_\gamma + \rho_\nu + \rho_m + ...)^{0.25}$$

$$\frac{\theta_d}{\theta_s} \propto (\rho_\gamma + \rho_\nu + \rho_m + ...)^{0.25}$$

- The ratio $\frac{\theta_d}{\theta_s}$ is measured well using the CMB.

- The photon density ρ_γ is well known from 3K temperature of CMB.

- The ratio $\frac{\rho_m}{\rho_\gamma + \rho_\nu} = 1 + z_{\mathrm{EQ}}$ is also well measured using CMB.

We can solve for the neutrino density ρ_ν .

(see 1104.2333, Z. Hou, RK, L. Knox, C. Reichardt)

in practice...

$$\frac{\theta_d}{\theta_s} \propto (\rho_\gamma + \rho_\nu + \rho_m + \ldots)^{0.22}$$

~0.22, not 0.25, due to two competing effects (a*, the scale factor at recombination, is a function of expansion rate, as is electron density). See 1104.2333, Z. Hou, RK, L. Knox, C. Reichardt, for details.

(see 1104.2333, Z. Hou, RK, L. Knox, C. Reichardt)

defining N_{eff}

N_{eff} is the *effective number of relativistic species.*

$$N_{\rm eff} \equiv \frac{\rho_\nu}{\rho_\gamma}\left(\frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\right)$$

The standard value is **Neff = 3.046.**

This is

3.000 for the 3 neutrino species,
0.046 for energy injected by electron/positron annihilation.

Neff > 3.046 could correspond to a new particle species that is relativistic prior to recombination and has the energy density of one of the standard neutrinos.

Take Away #1

CMB data that measures $\frac{\theta_d}{\theta_s}$ can constrain the number of neutrinos, due to the sensitivity of that ratio to the expansion rate prior to recombination.

Outline

1. What is the CMB, and how does an extra neutrino affect it?

2. Constraints from SPT+WMAP

3. What's next?

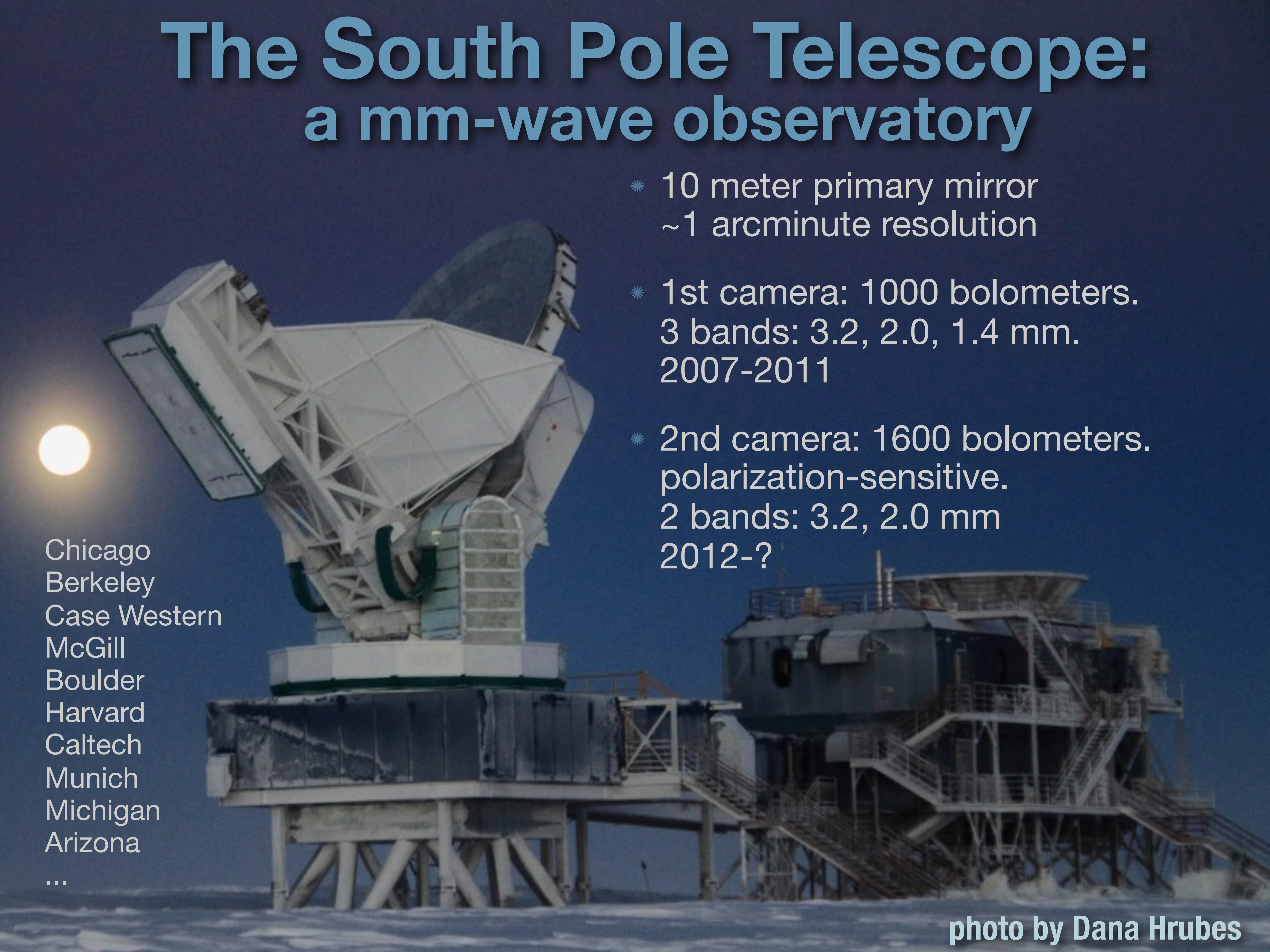
Outline

1. What is the CMB, and how does an extra neutrino affect it?

2. Constraints from SPT+WMAP

   Next talk: ACT+WMAP results from Sudeep Das.

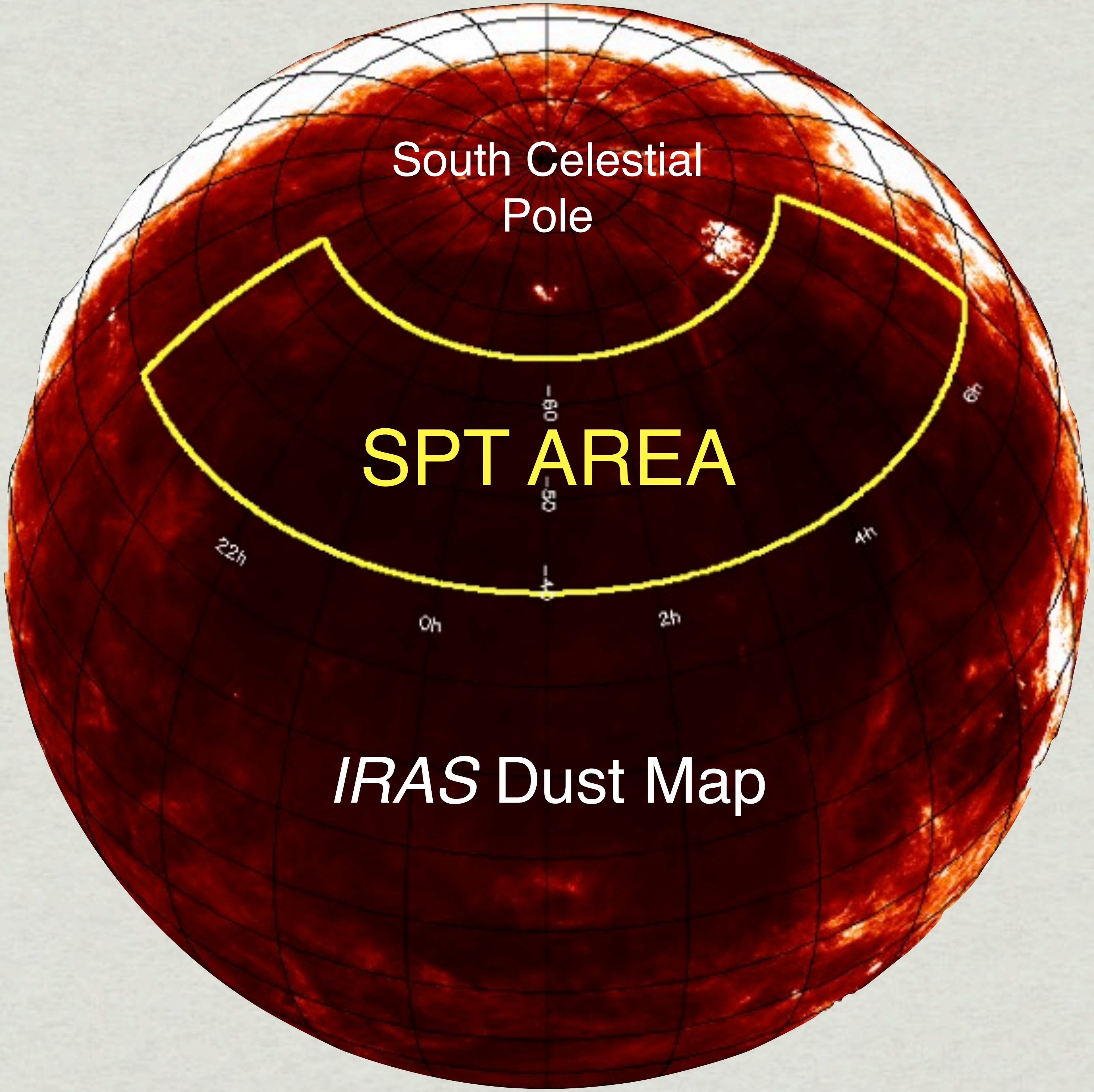
3. What's next?


The South Pole Telescope:
a mm-wave observatory
10 meter primary mirror
~1 arcminute resolution
1st camera: 1000 bolometers.
3 bands: 3.2, 2.0, 1.4 mm.
2007-2011
2nd camera: 1600 bolometers.
polarization-sensitive.
2 bands: 3.2, 2.0 mm
2012-?
Chicago
Berkeley
Case Western
McGill
Boulder
Harvard
Caltech
Munich
Michigan
Arizona
...
photo by Dana Hrubes

Why the South Pole?

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

SPT 2500 deg² "SZ" Survey



- 2500 deg² at high galactic latitude in Southern Sky.

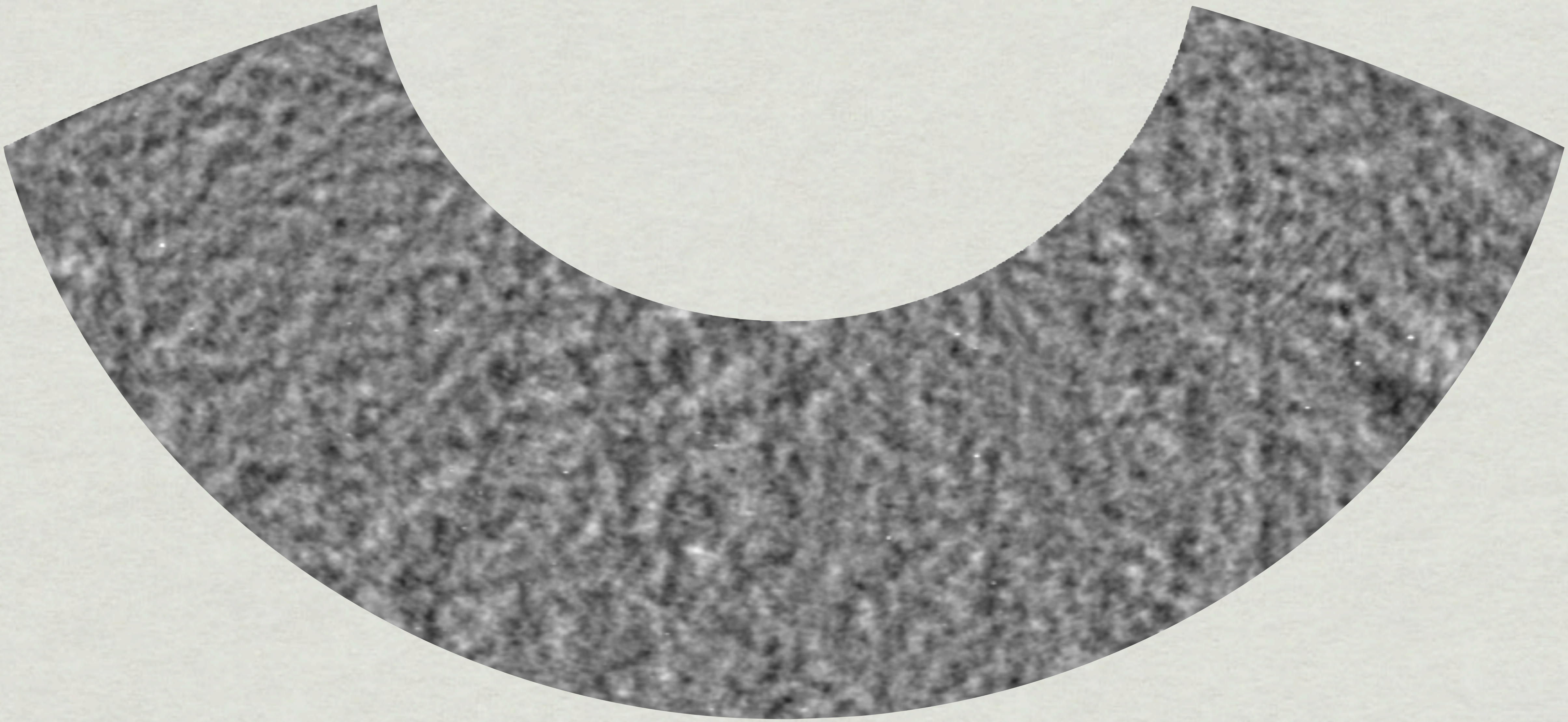
- 6% of the sky.

- RA: 20h to 7h
- Dec: -40 to -65

Final survey depths of:
- 90 GHz: 42 uK_{CMB}-arcmin
- 150 GHz: 18 uK_{CMB}-arcmin
- 220 GHz: 85 uK_{CMB}-arcmin

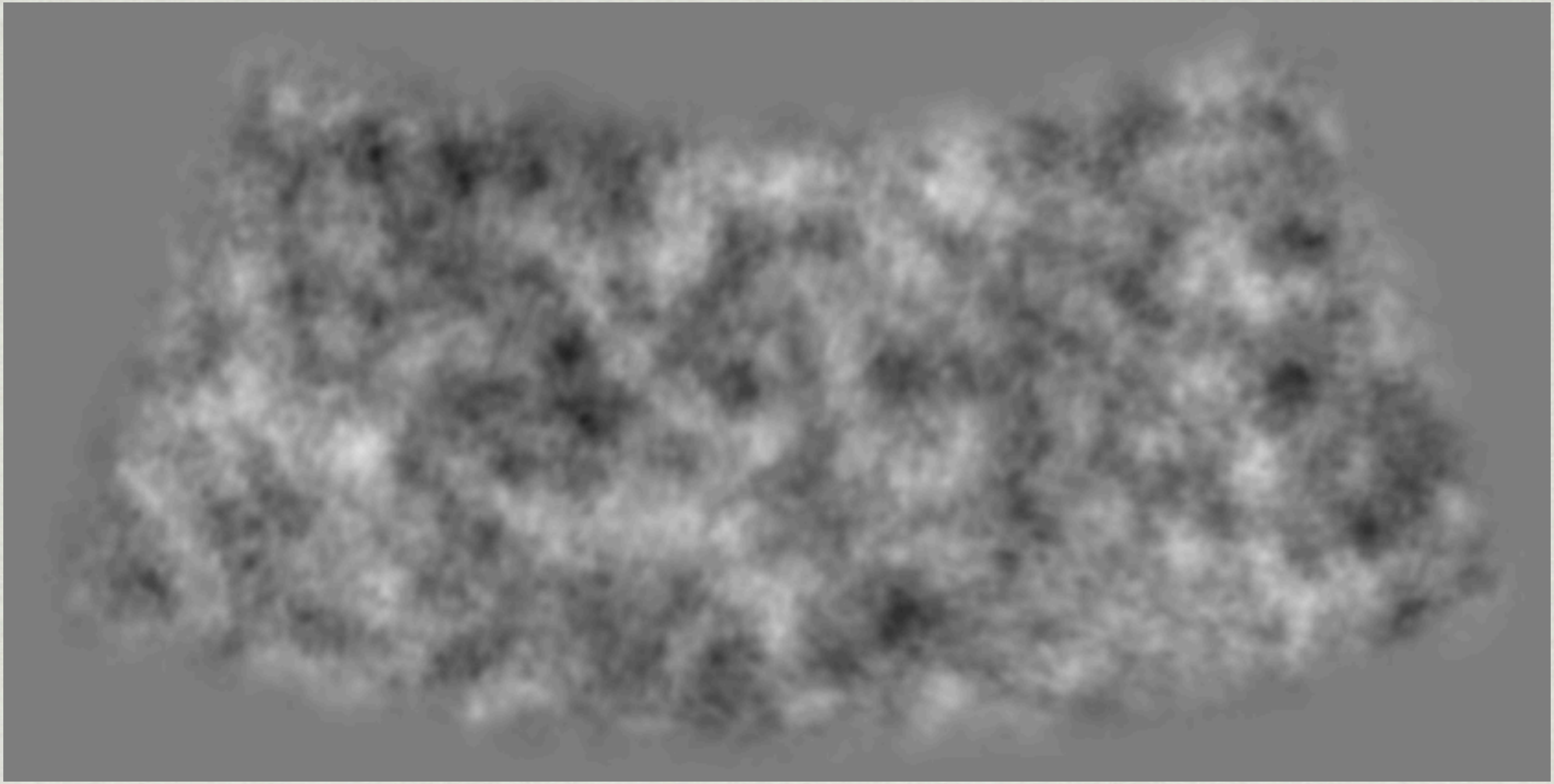
(In these units, tSZ is 1.7 times brighter at 90 GHz than at 150 GHz.)

SPT 2500 deg^2 SZ Survey

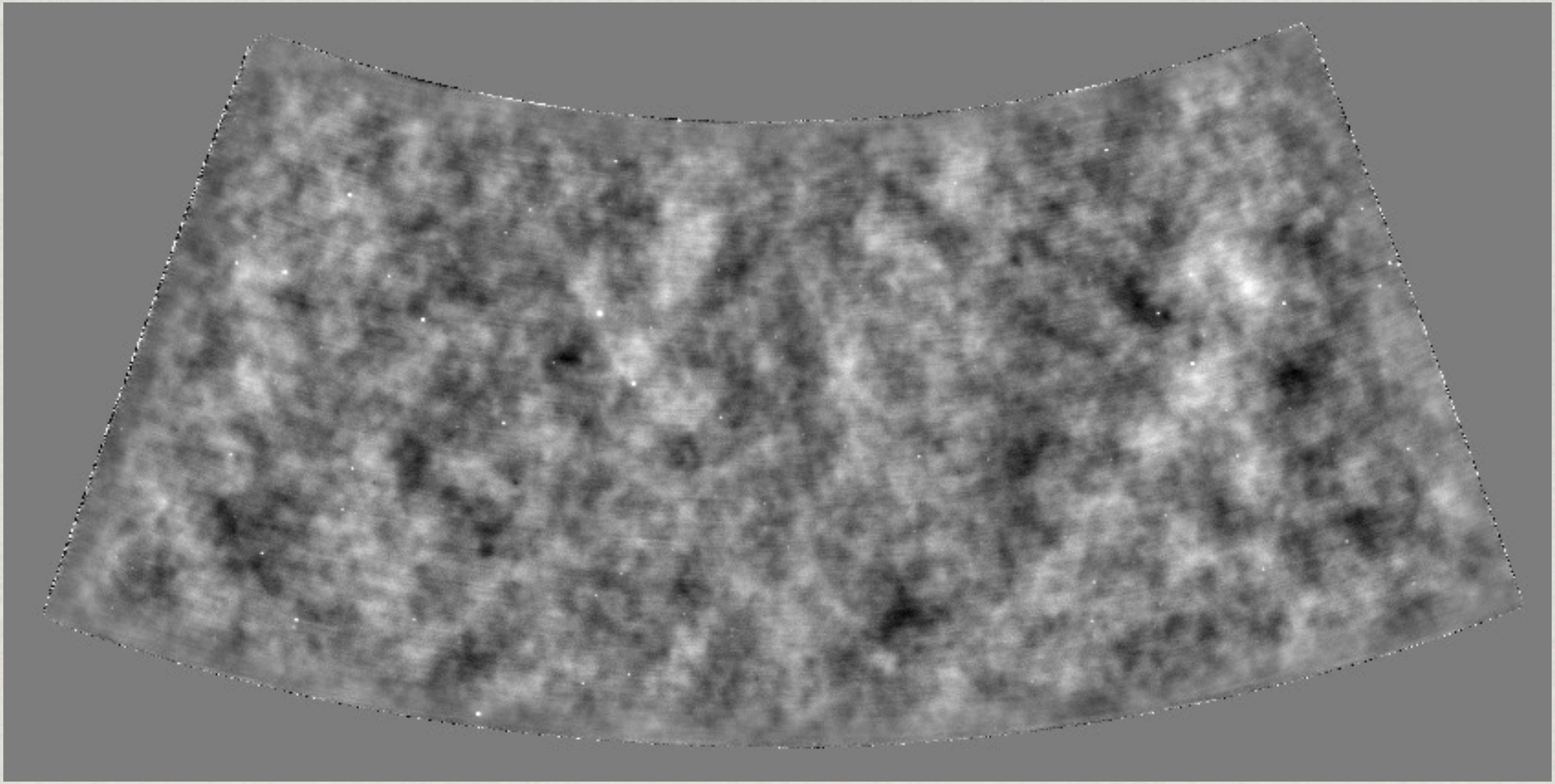


Status: finished in *Nov. 2011*.
All results shown today use **1/3** of this data.

WMAP

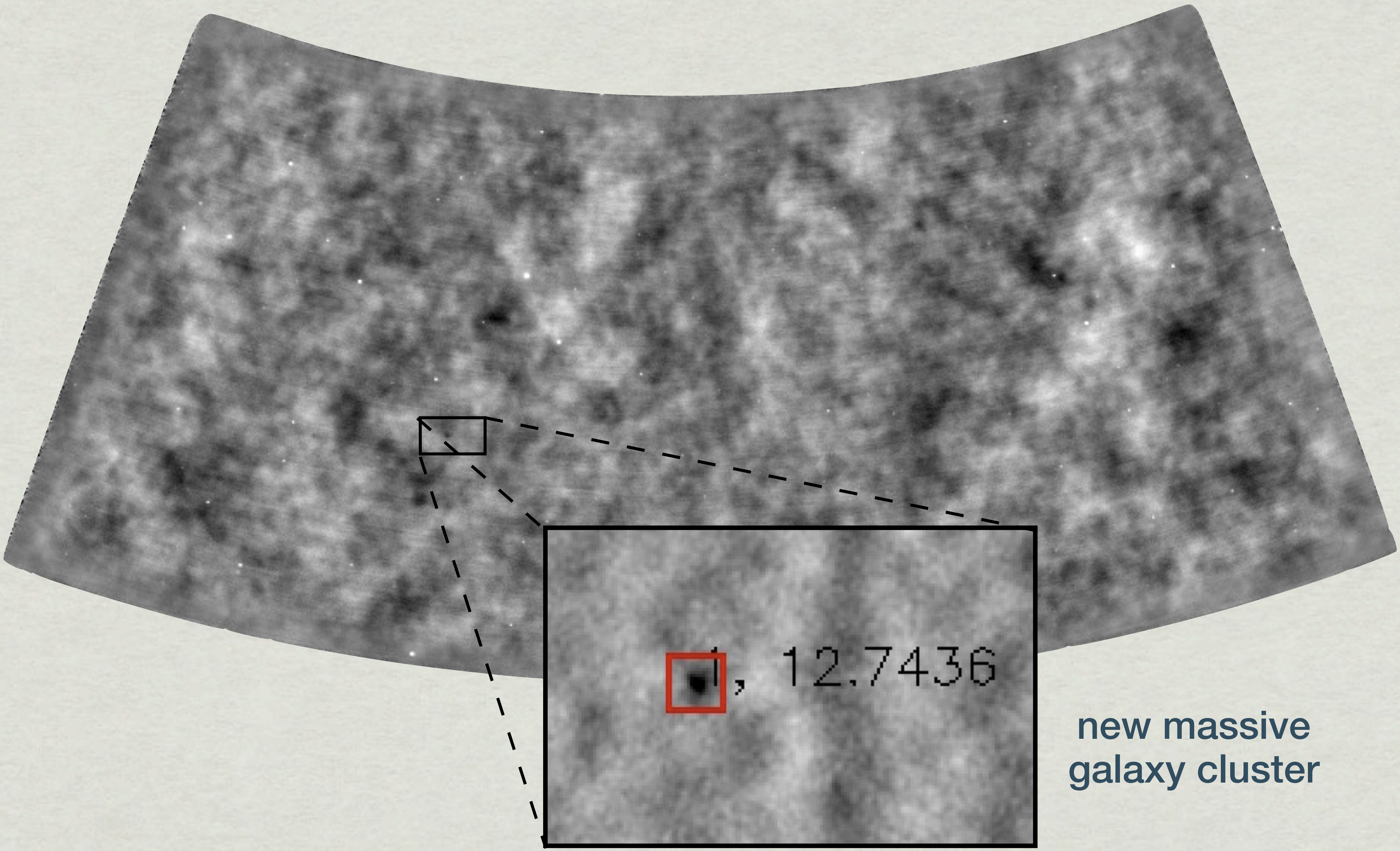


SPT



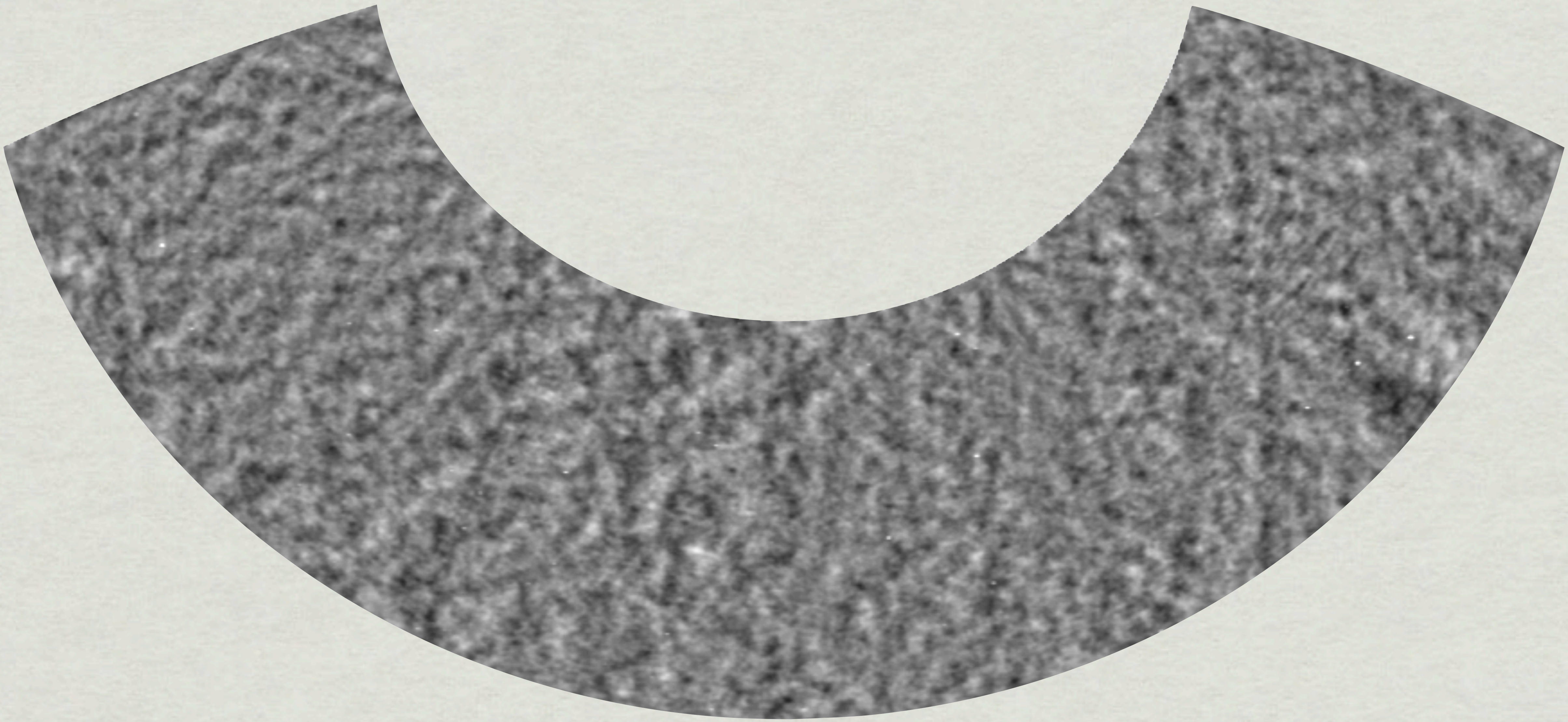
SPT has ~20X better resolution and lower noise, but covers only ~5% of the sky.

SPT map

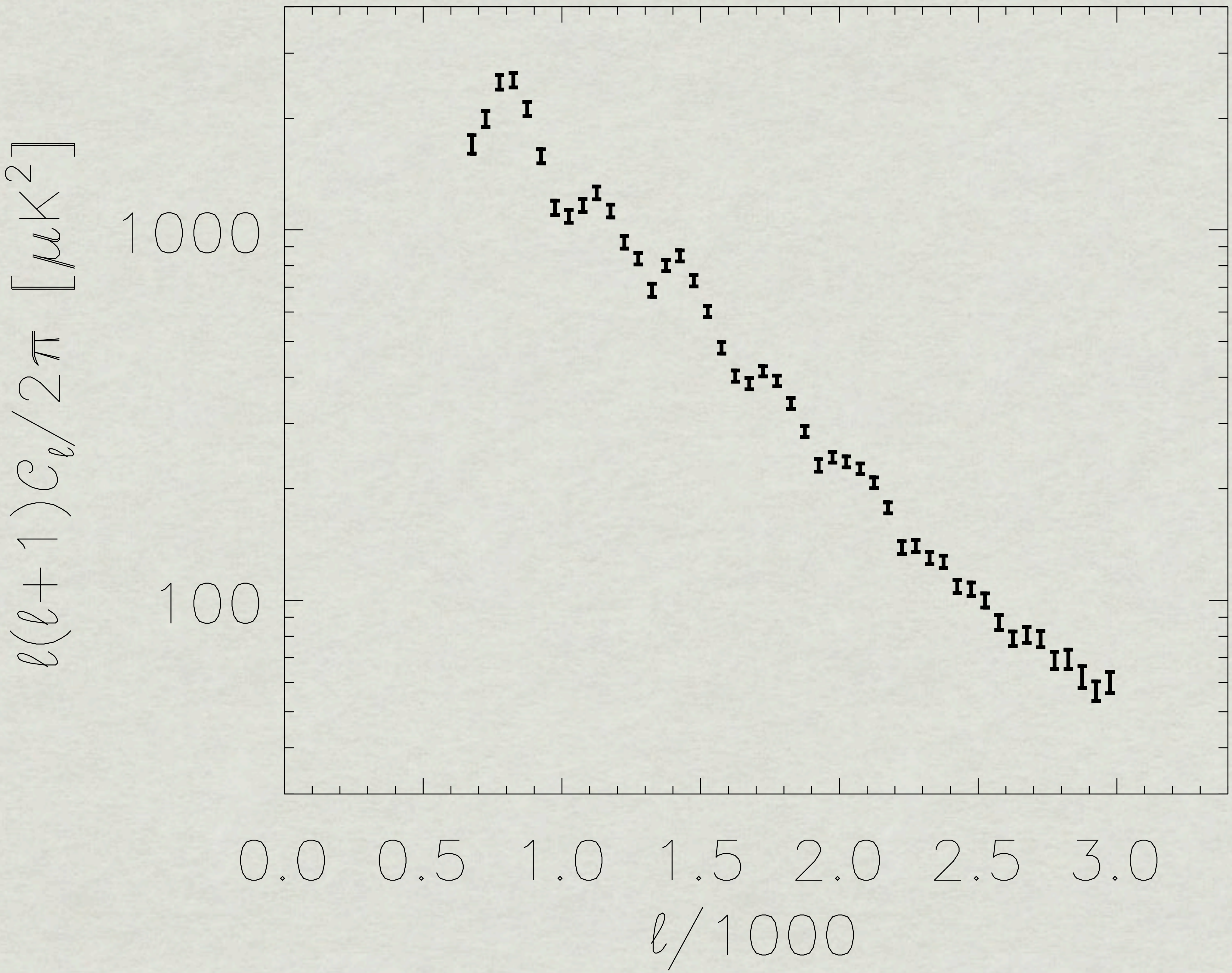


new massive
galaxy cluster

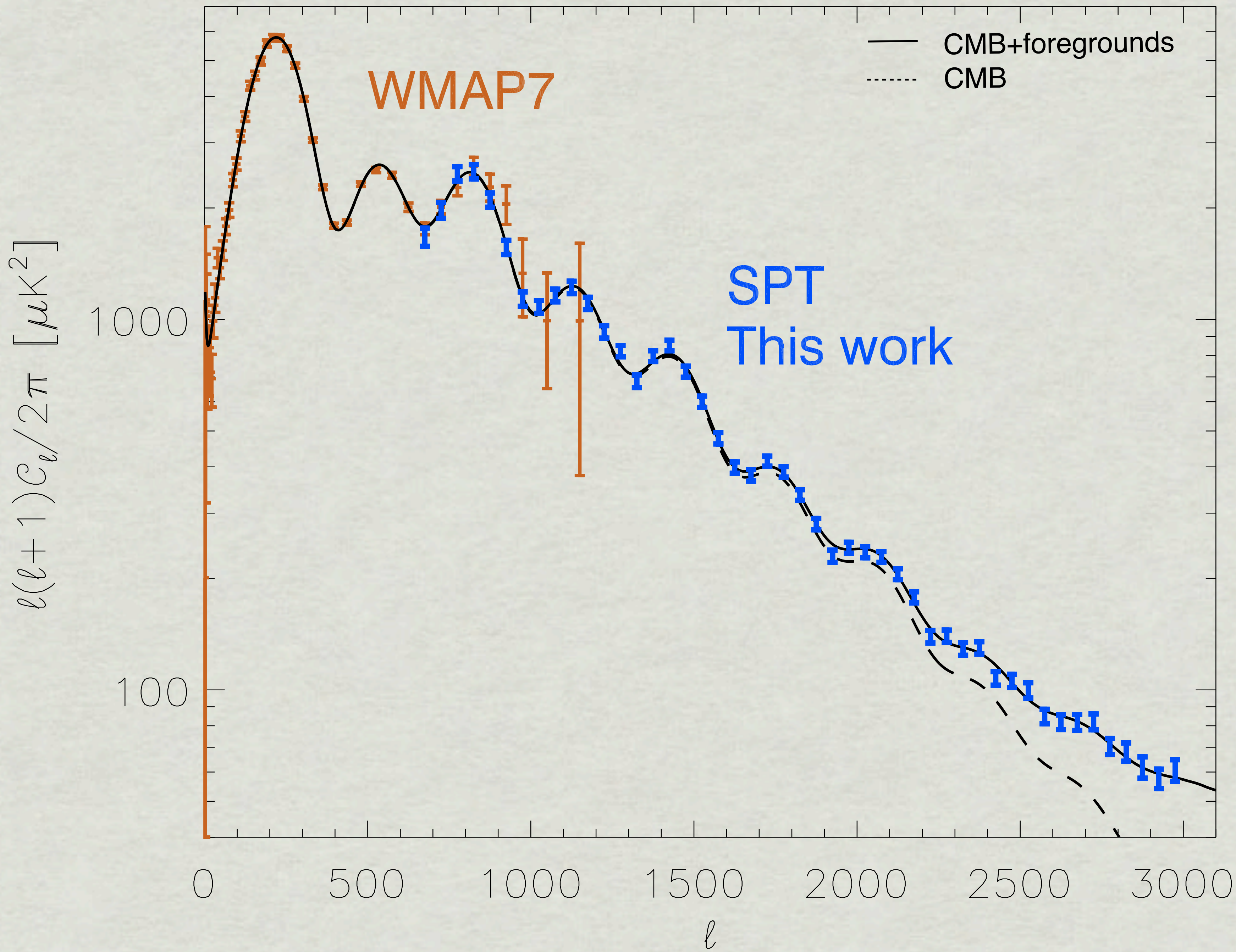
Take the angular power spectrum of 1/3 of this:



...and you get this.



SPT + WMAP



See "A Measurement of the Damping Tail of the Cosmic Microwave Background Power Spectrum with the South Pole Telescope", RK, C. Reichardt *et al.,* ApJ, 2011, arXiv:1105.3182.

Cosmological Analysis

- **MCMC analysis** (cosmoMC/CAMB)
- **Data:**
    - **CMB** from **SPT**
    - **CMB** from **WMAP7**
    - [H0 from HST, Riess et al]
    - [BAO from SDSS, Percival et al]

Two component model:

- **CMB,** lensed primary CMB from flat ΛCDM, seven parameters: $(\Omega_b h^2, \Omega_c h^2, \ell^*, \tau, \Delta_R^2, n_s$, Neff)

- **Foregrounds**,
  - SZ power (1 parameters)
  - emission from galaxies (shot noise & spatially correlated, 2 parameters)

10 parameters (7 cosmo., 3 "nuisance")

No Neutrinos vs Standard Neutrinos?

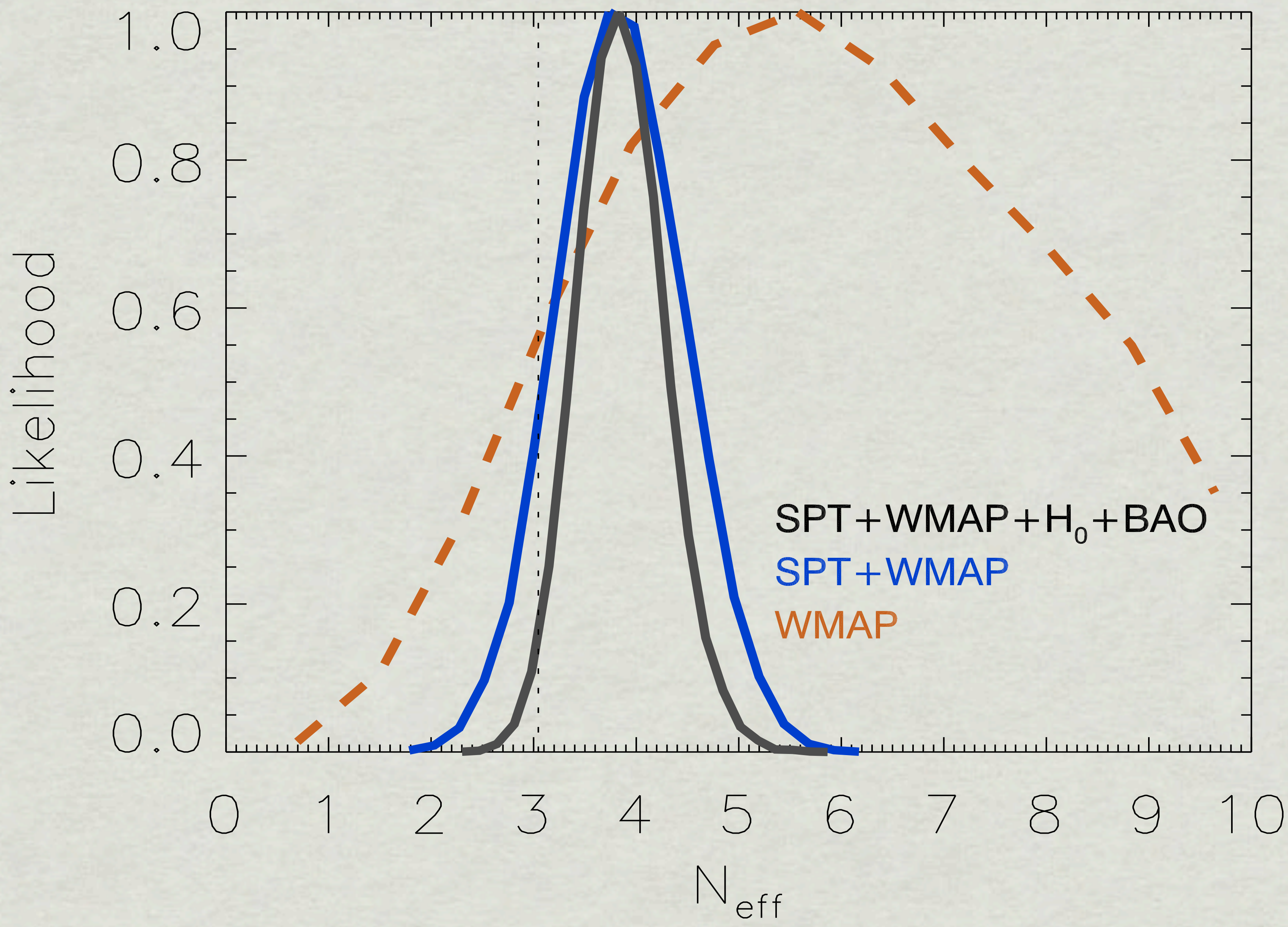
Simple test: compare maximum likelihood in Neff=0 model to that in Neff=3.046 model.

Standard neutrinos are preferred over no neutrinos preferred by $\delta\chi^2 = 56.3$, i.e. 7.5-sigma.

The CMB strongly detects presence of neutrinos in early universe.

See "A Measurement of the Damping Tail of the Cosmic Microwave Background Power Spectrum with the South Pole Telescope", RK, C. Reichardt *et al.,* ApJ, 2011, arXiv:1105.3182.

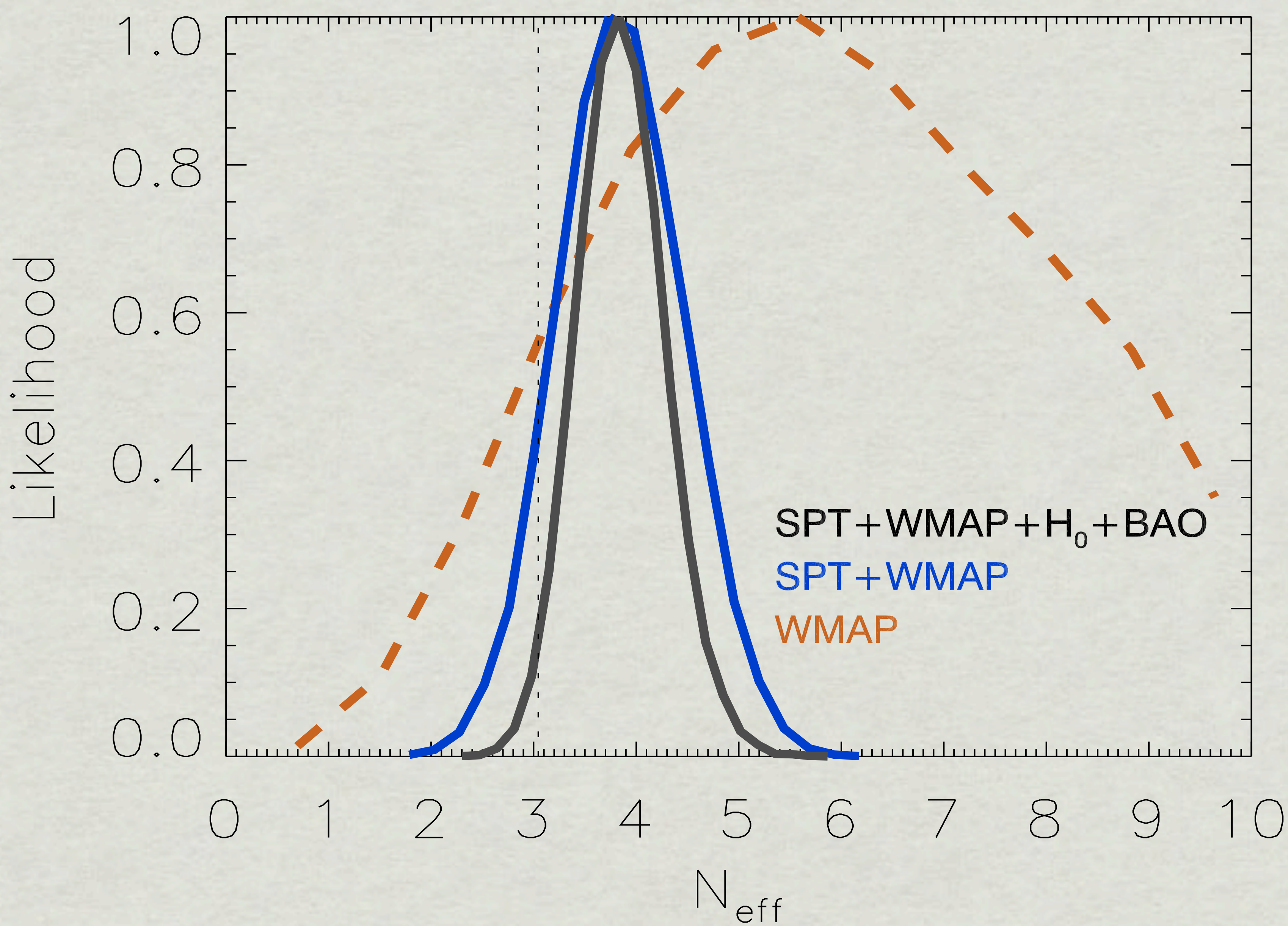
Constraints on Neff



- Neff = 3.85 +/- 0.62 (SPT+WMAP7) (1.3σ higher than 3.046)
- Neff = 3.86 +/- 0.42 (SPT+WMAP7+H0+BAO) (1.9σ higher than 3.046)

see RK, C. Reichardt et al, 1105.3182

Constraints on Neff



The CMB data are consistent with standard Neff. Adding the “low-redshift” data (H0+BAO) then favors Neff>3.046 at ~2σ

(1.3σ higher than 3.046)

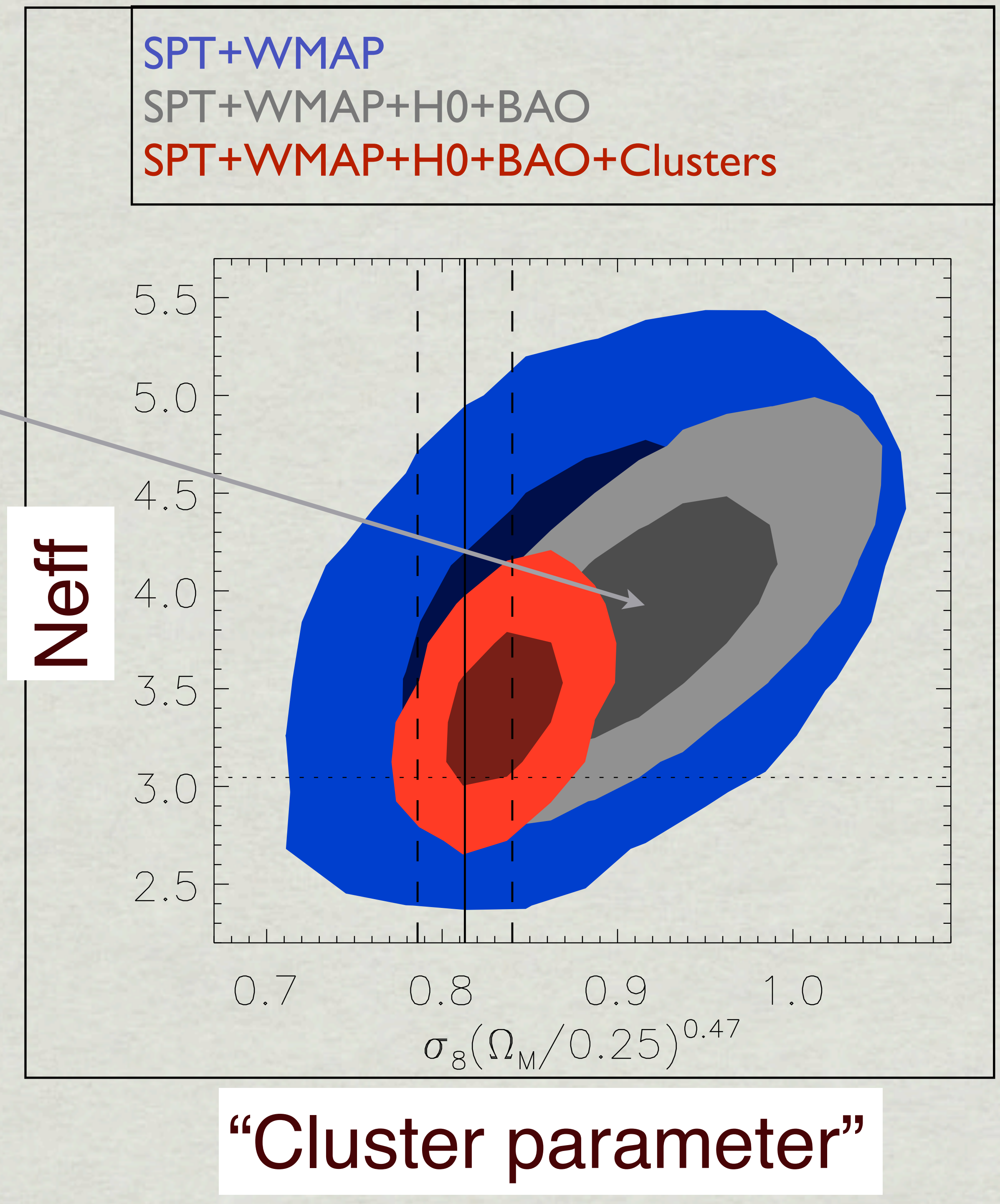
(1.9σ higher than 3.046)

see RK, C. Reichardt et al, 1105.3182

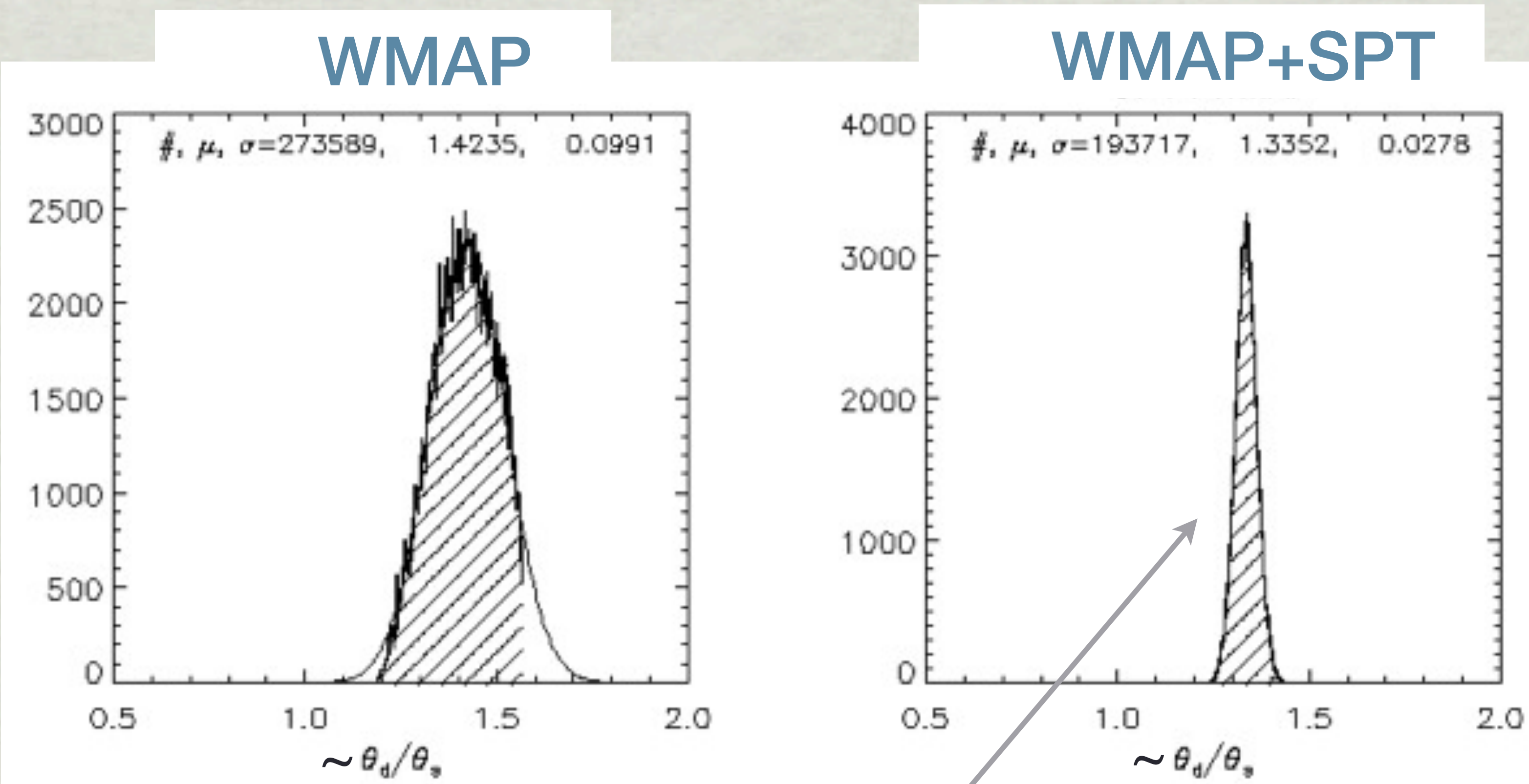
Are high-Neff models consistent with galaxy clusters?

- High-Neff models also have high sigma8's and are disfavored by abundance of low-redshift galaxy clusters (Vikhlinin et al).

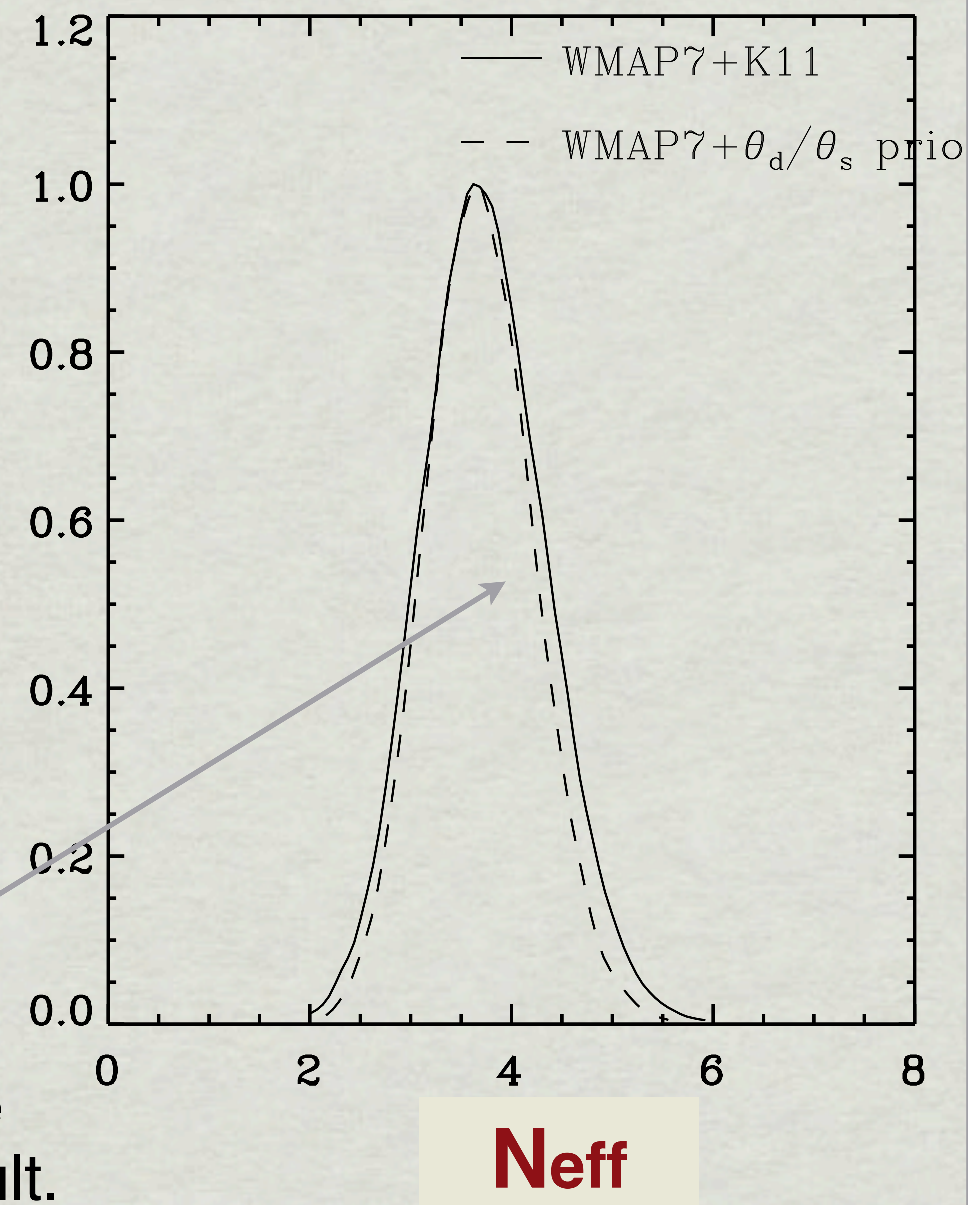
- However, all of this "tension" goes away if neutrinos are allowed to have total mass of ~0.3 eV, since that lowers the CMB prediction for sigma8.



And the improvement on N_{eff} is really due to the improvement on the angle ratio, (theta_d/theta_s).



SPT+WMAP measures the angle ratio, (theta_d / theta_s), much better than WMAP alone.



If you apply a (theta_d/theta_s) prior to the WMAP data, you get the WMAP+SPT result.

(see 1104.2333, Z. Hou, RK, L. Knox, C. Reichardt)

Take Away #2

CMB data strongly detect presence of neutrinos in the early universe and measure Neff to be 1.3σ higher than standard value.

- Neff = 3.85 +/- 0.62

When CMB data are combined with low-redshift data, Neff is measured to be ~2σ higher than standard value.

- Neff = 3.86 +/- 0.42

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Current constraints on Neff:

SPT 800 deg2 (+WMAP7+H0+BAO):
dNeff ~ 0.42

Projections for Neff:

SPT 2500 deg2 (+WMAP7+H0+BAO):
dNeff ~ 0.33

Planck:
dNeff ~ 0.2

CMBpol:
dNeff ~ 0.05 (see Galli et al. 1005.3808)

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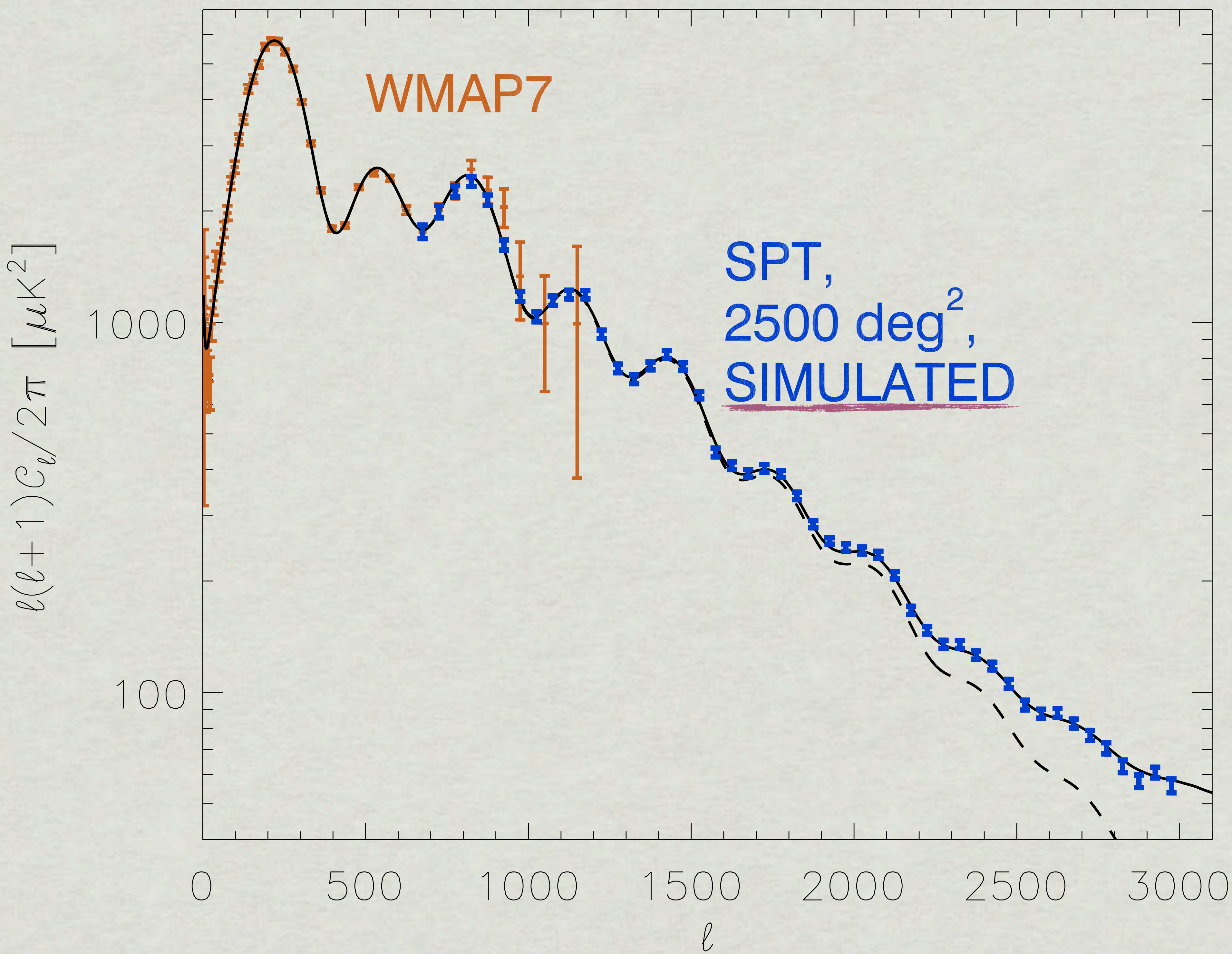
dNeff ~ 0.05 (see Galli et al. 1005.3808)

SPT 2500 sq. deg. Power Spectrum



dNeff ~ 0.33

Work led by **Kyle Story, Zhen Hou**, Christian Reichardt, RK.

Summary

- CMB data can constrain the number of neutrinos due to the neutrinos' effect on the expansion rate.

- Current CMB data detect neutrinos with high significance and are consistent with standard neutrino content. Adding low-redshift data leads to a 2σ preference for high Neff.

- In the next 3 months we should know Neff to 0.33.

In the next 9 months we should know Neff to 0.2.

extra slides

Helium

$$\frac{\theta_d}{\theta_s} \propto \frac{(\rho_\gamma + \rho_\nu + \rho_m + ...)^{0.22}}{\sqrt{1 - Y_p}}$$

This ratio is also a function of the **primordial helium abundance, Yp.** In standard BBN, this is a weak function of Neff.

In our fits to the CMB data, we self-consistently change Yp as a function of the N_{eff} and $\Omega_b h^2$ using a fitting formula from Simha & Steigman 2008). This actually gives us extra sensitivity to N_{eff}.

(see 1104.2333, Z. Hou, RK, L. Knox, C. Reichardt)