CMB Measurements with the South Pole Telescope

Ryan Keisler
Univ. of Chicago

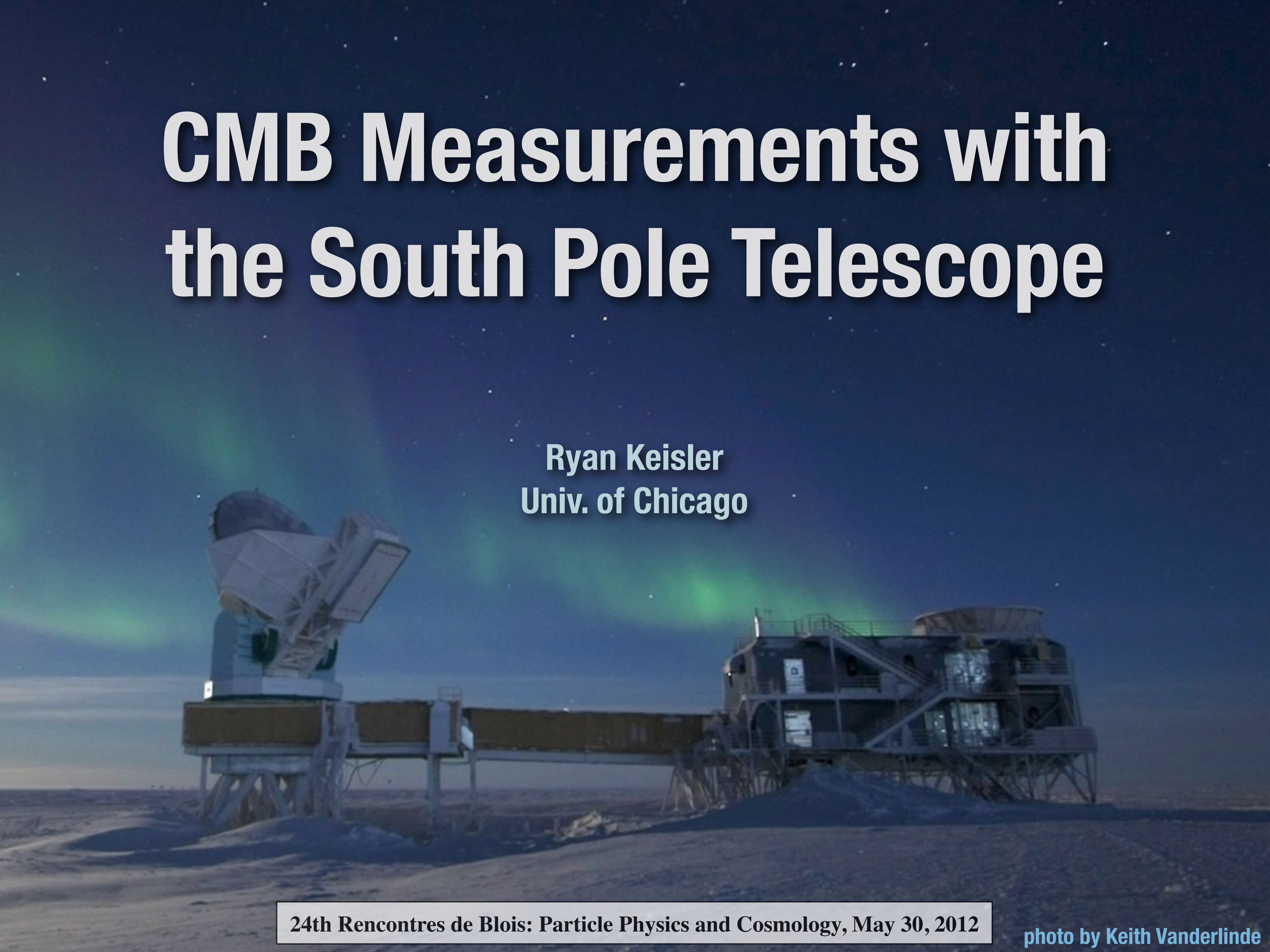

photo by Keith Vanderlinde

24th Rencontres de Blois: Particle Physics and Cosmology, May 30, 2012

Outline

1. CMB overview

2. New results from SPT:

- Number of $\nu -$ like particle species, N_ν
- Gravitational Lensing of the CMB

3. New camera: SPT-pol.

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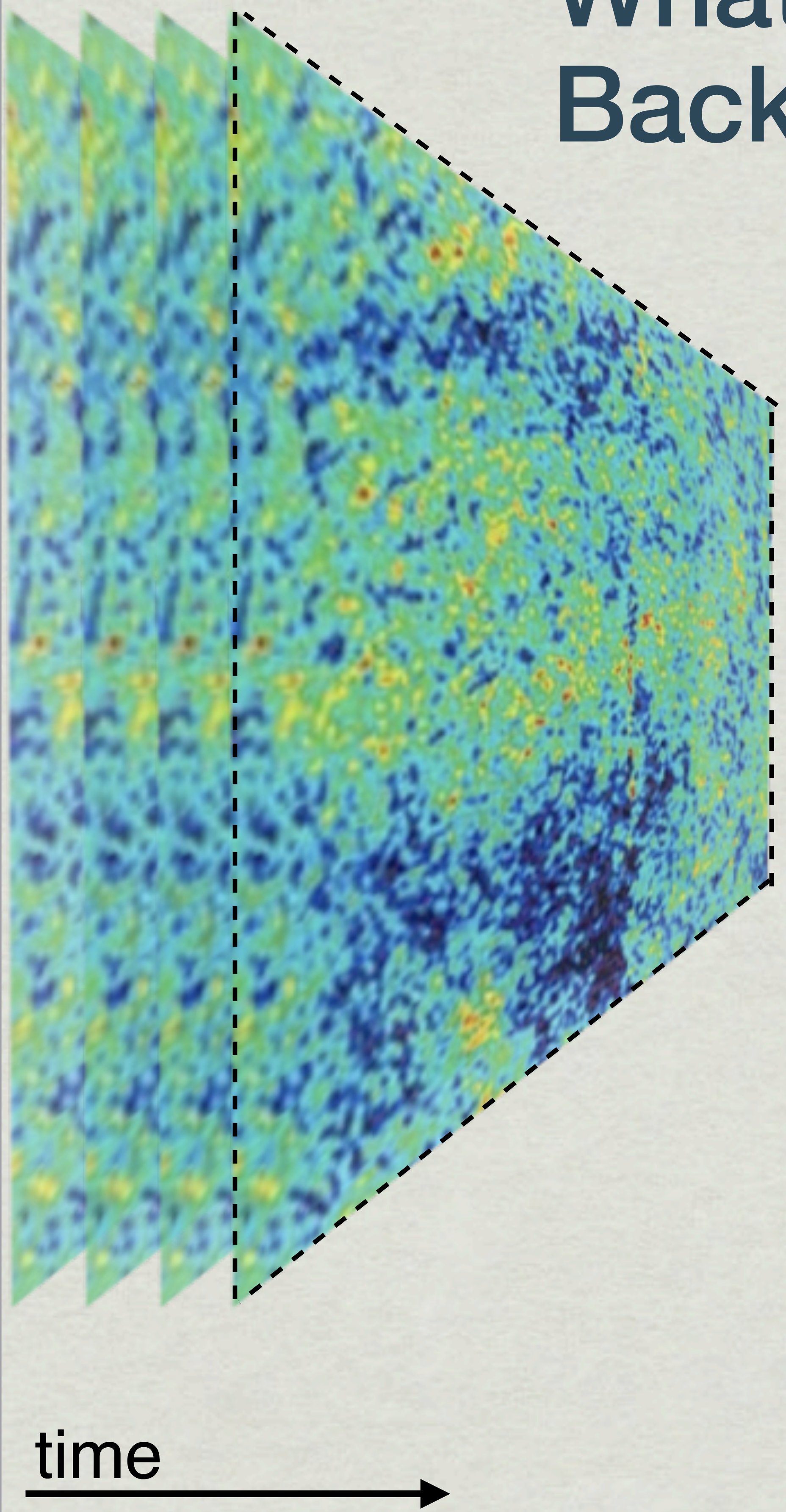
What is the Cosmic Microwave Background?

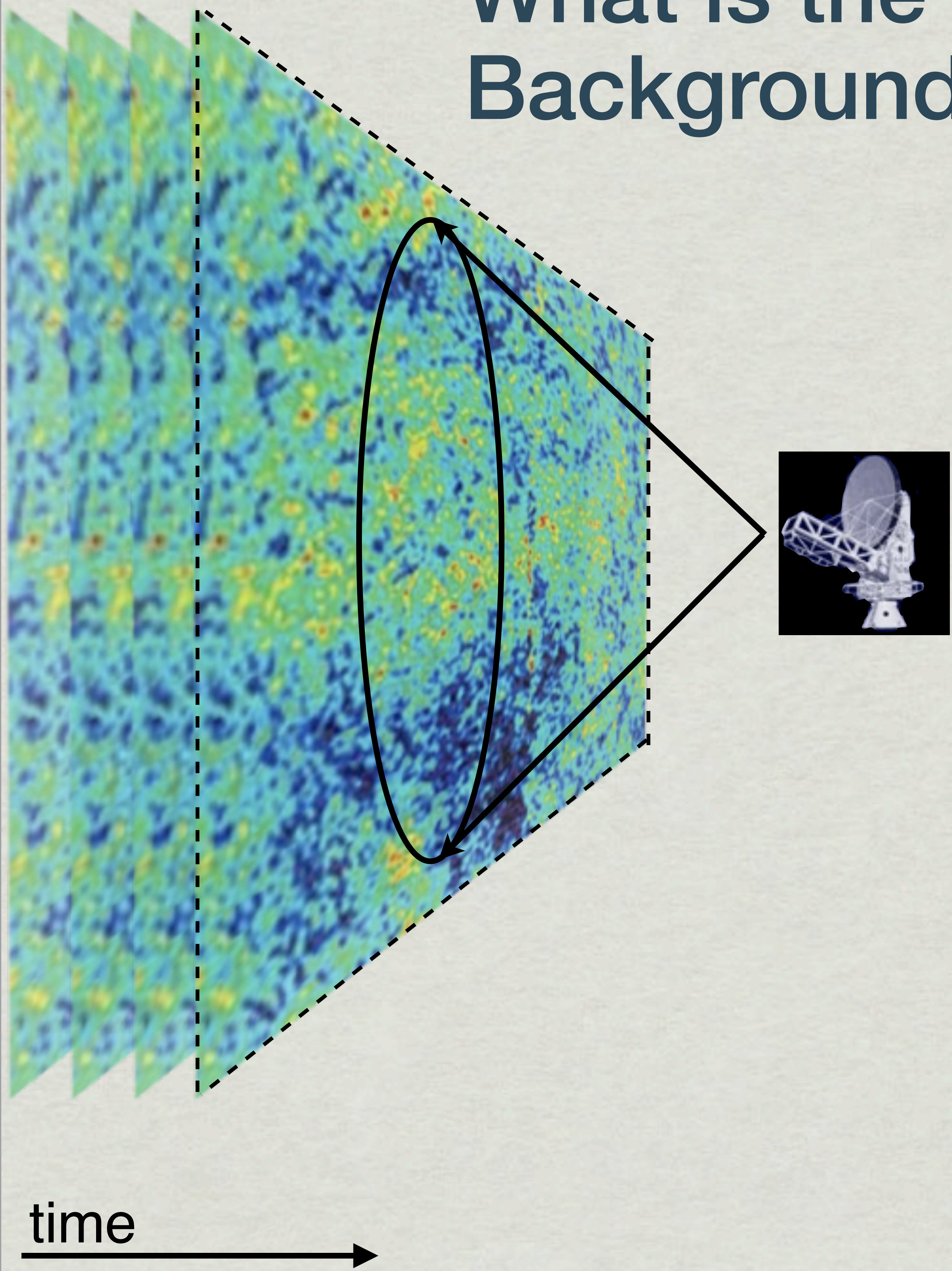


The constituents of the early universe (photons, electrons, protons, dark matter, neutrinos, ...) were coupled.

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

=> **oscillations**

What is the Cosmic Microwave Background?



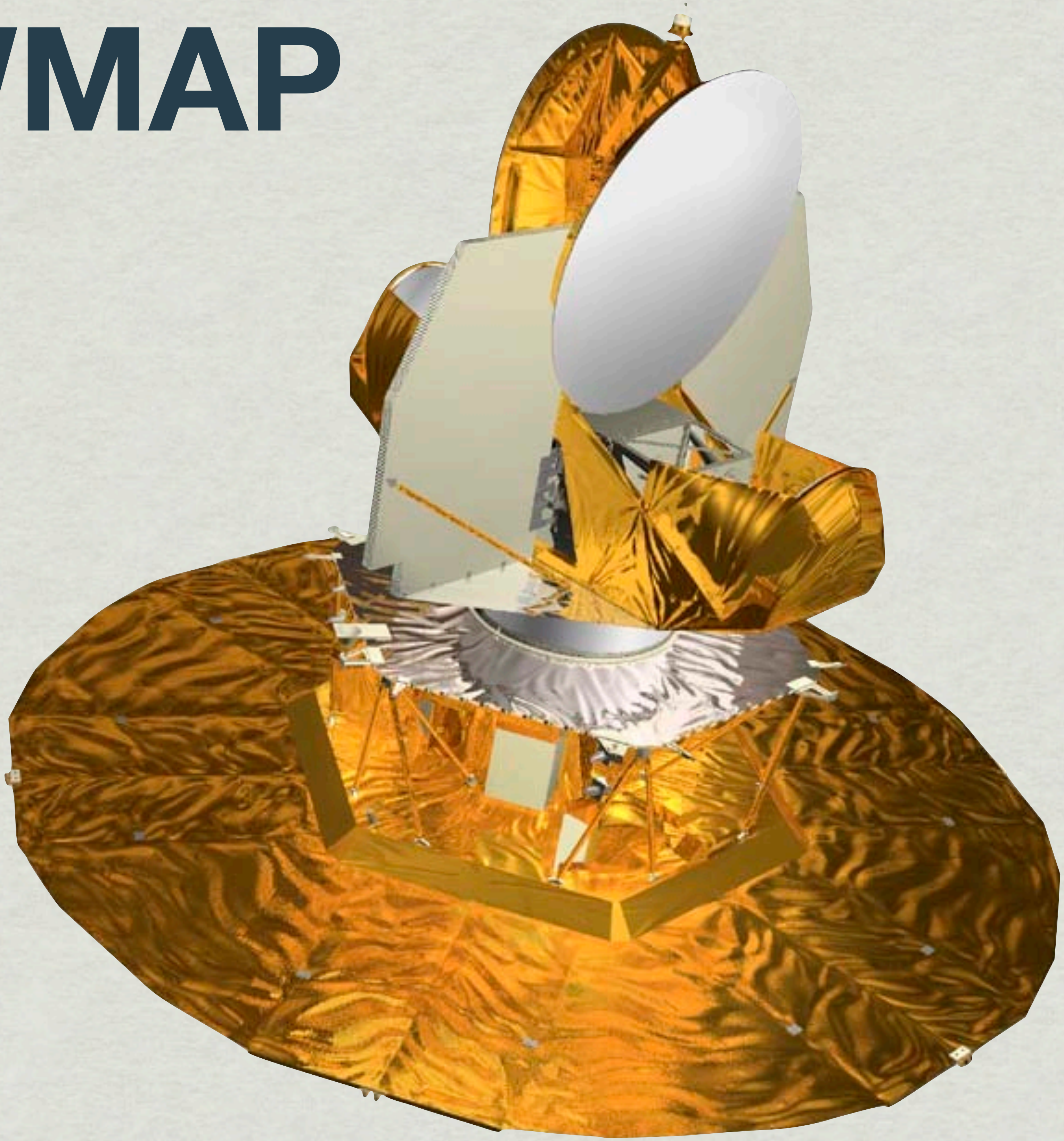
Eventually the universe expands and cools such that **neutral hydrogen can form**. "Recombination"

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

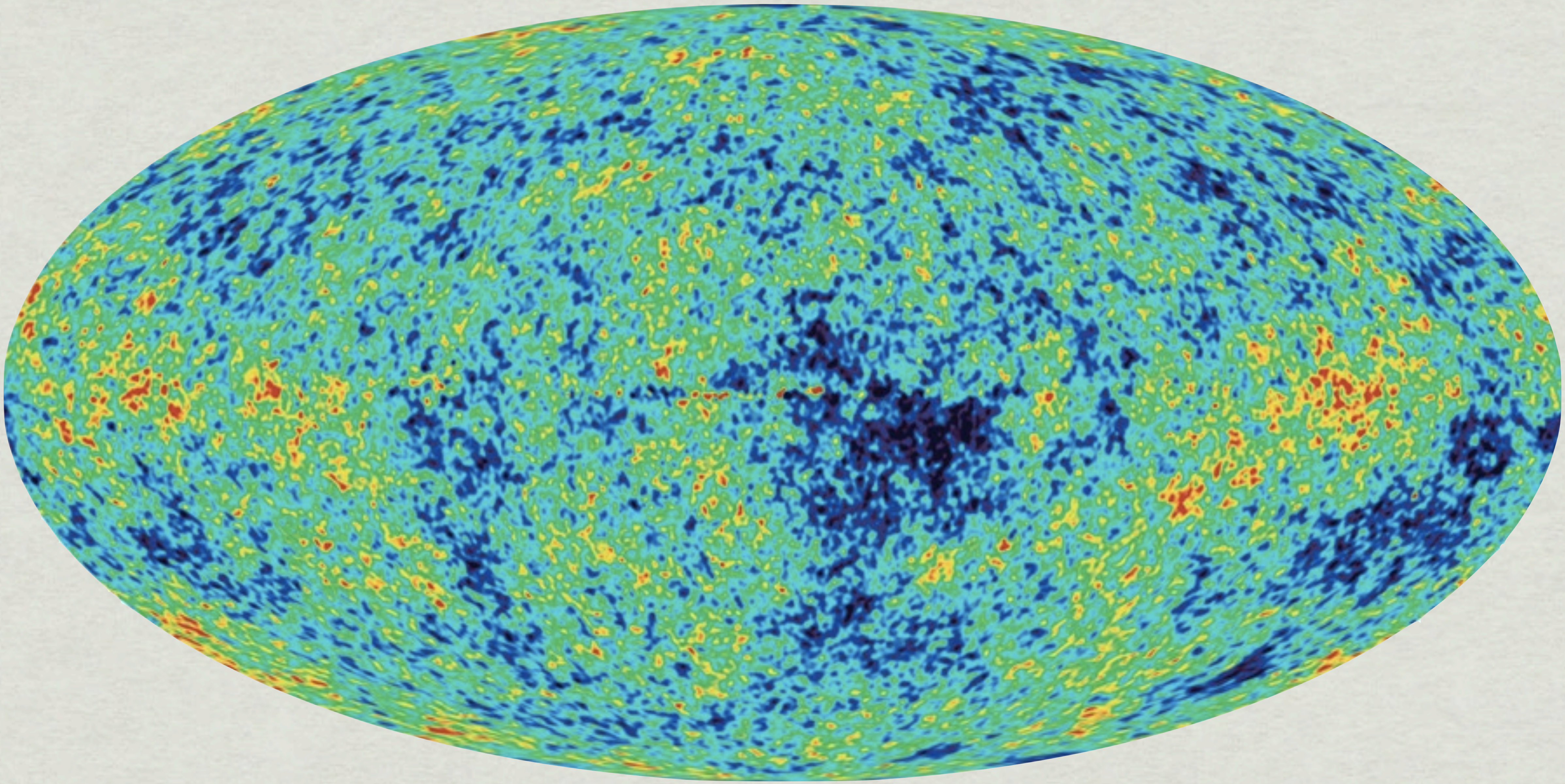
=> **Photons can travel freely**, and we see them today as a blackbody with T=2.73K.

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

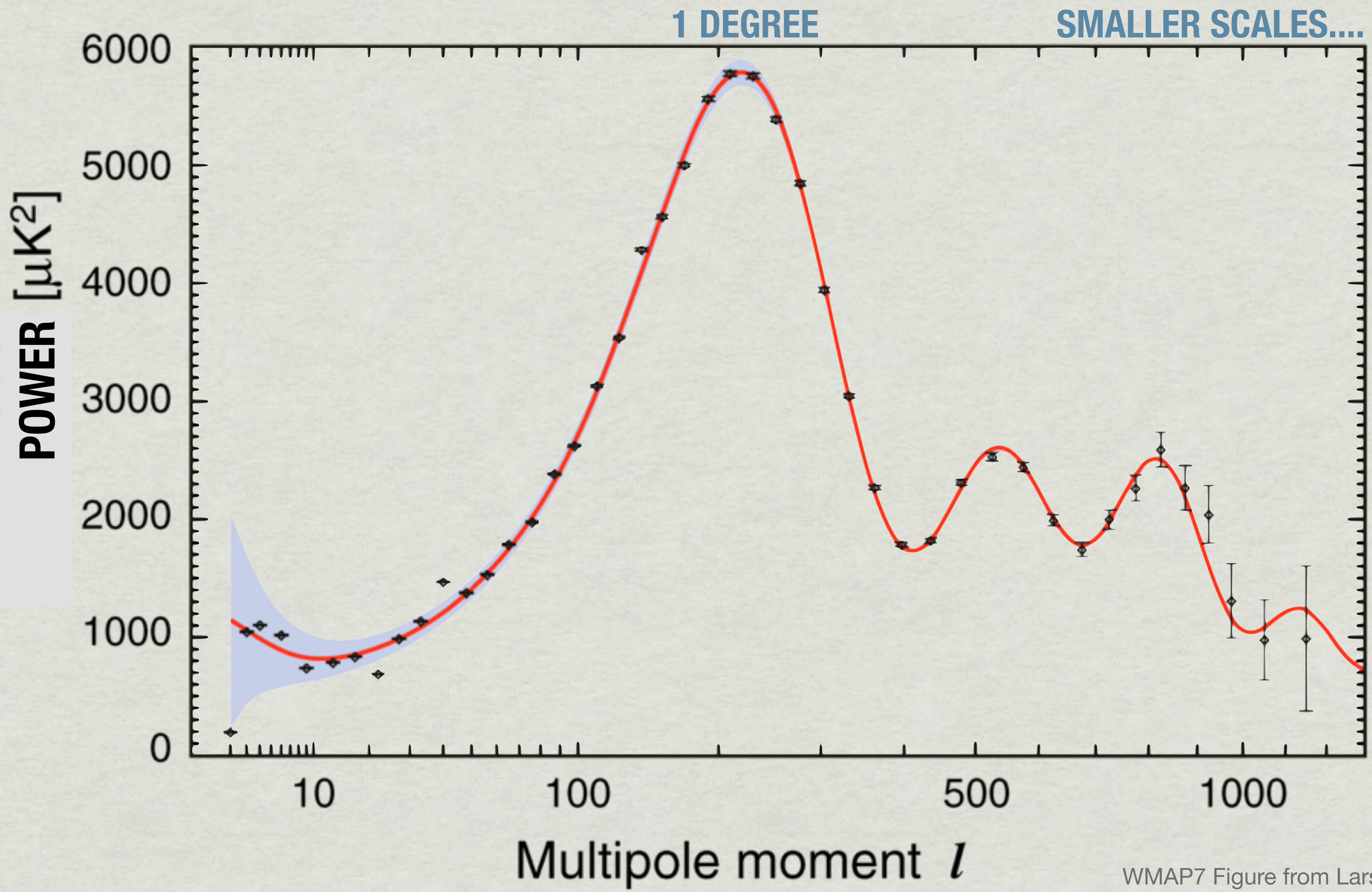
WMAP



WMAP

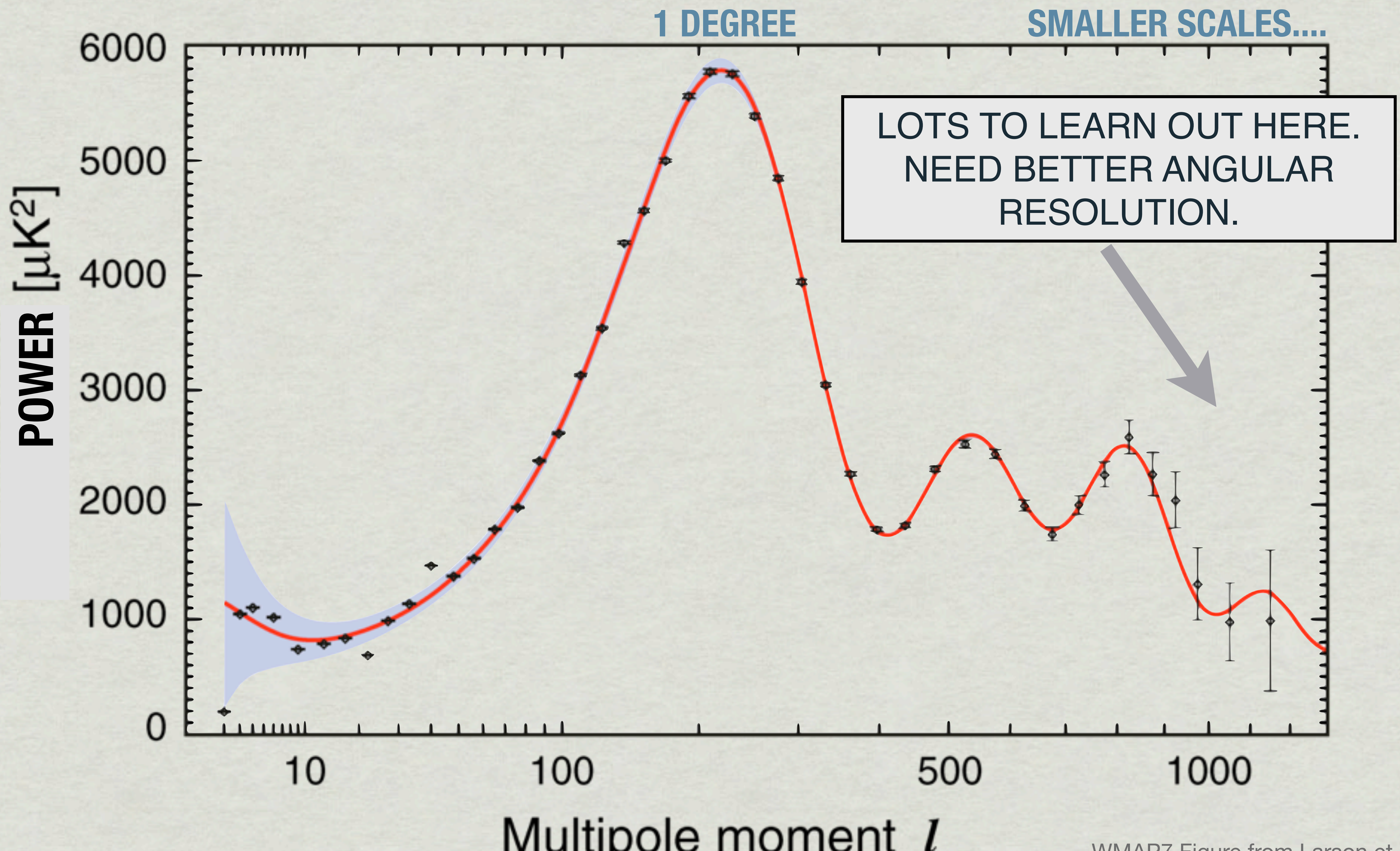


WMAP



WMAP7 Figure from Larson et al.

WMAP



WMAP7 Figure from Larson et al.

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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
...

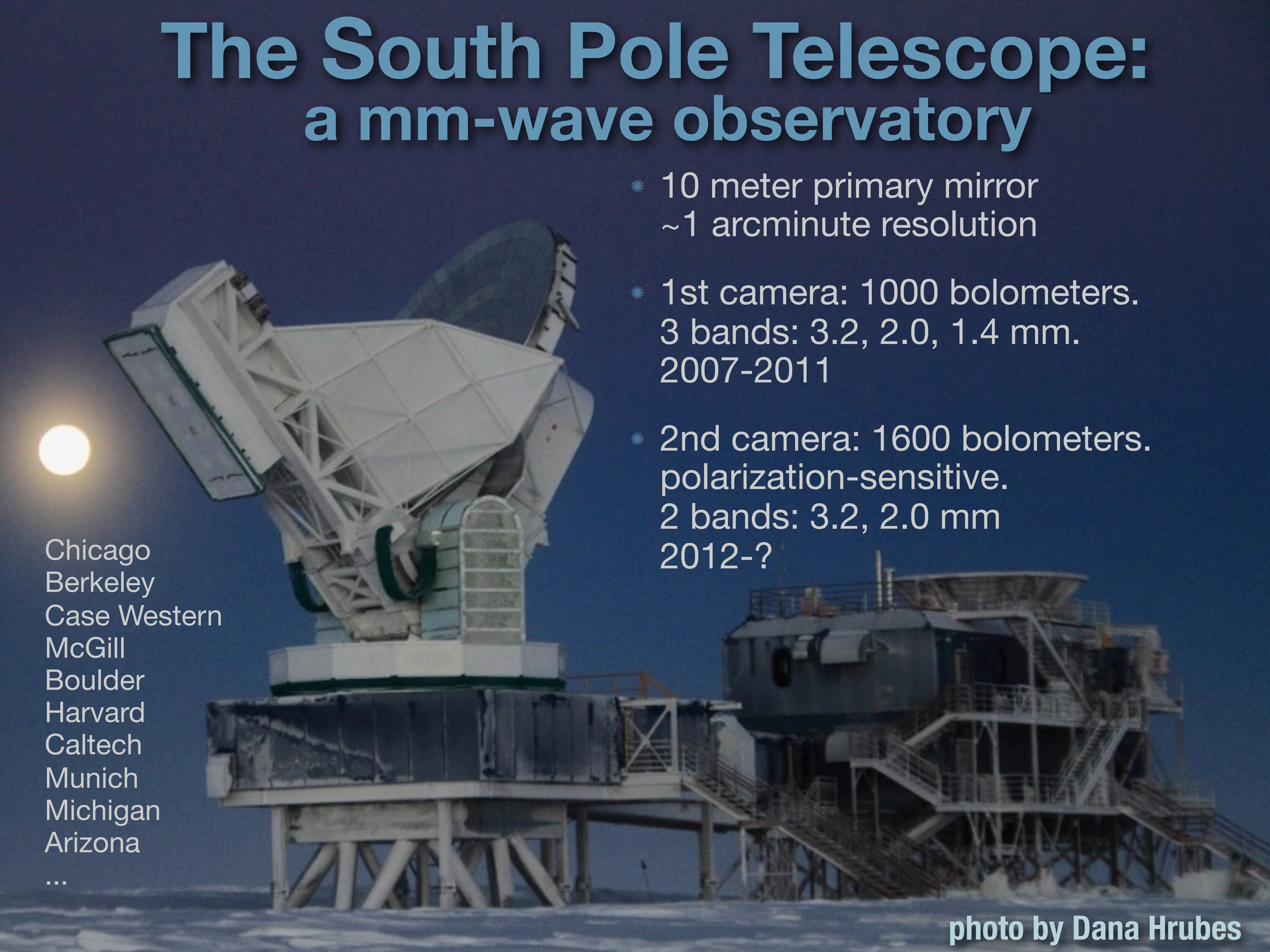
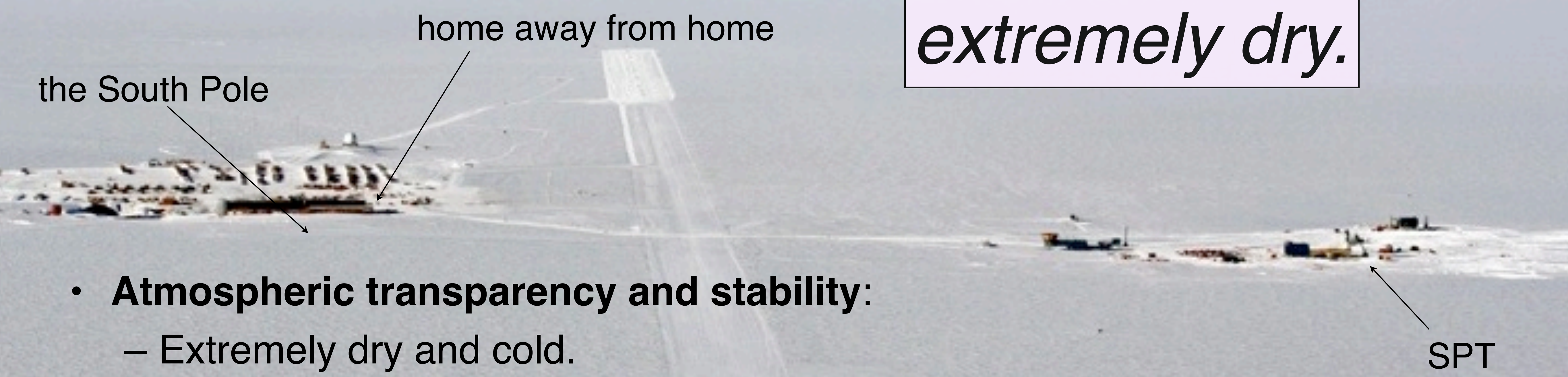


photo by Dana Hrubes

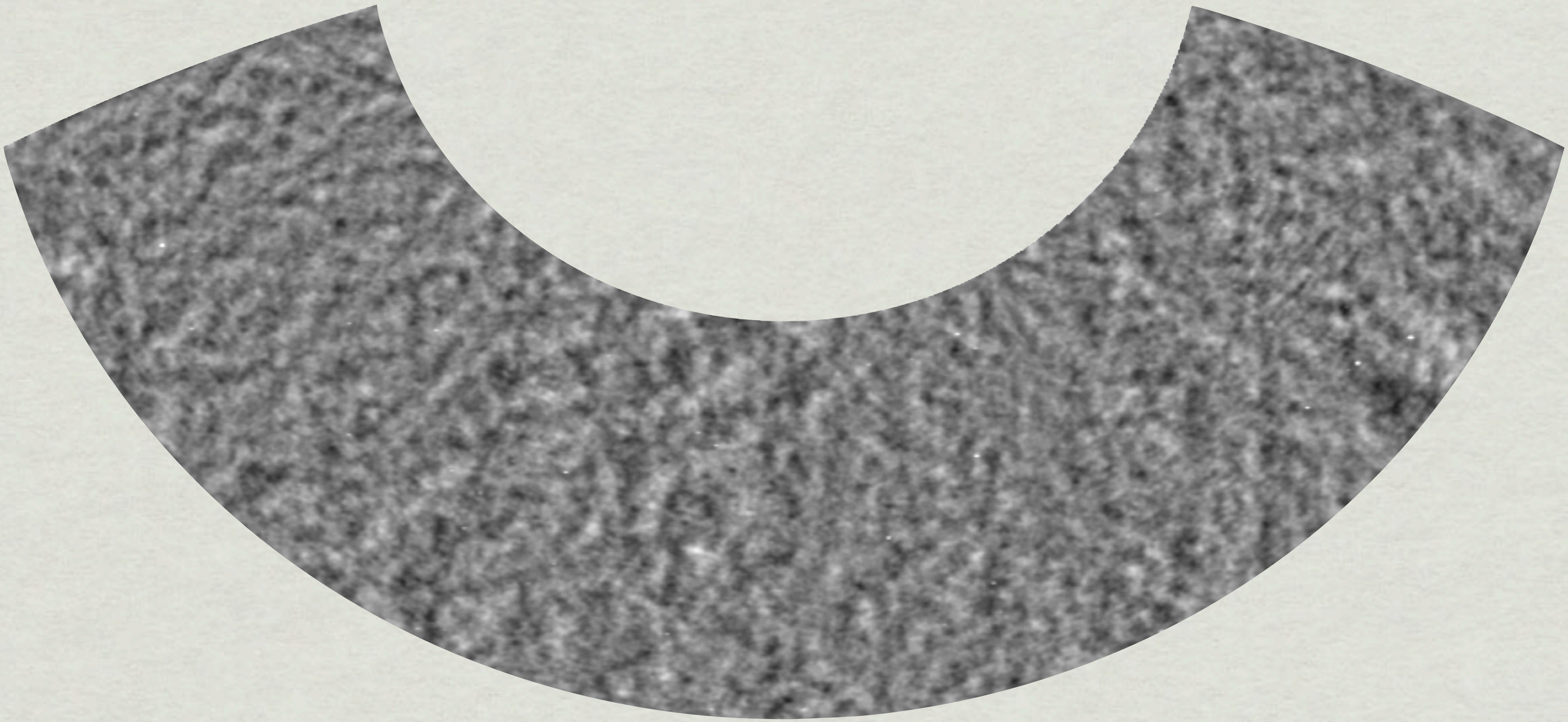
Why the South Pole?

Because it's *extremely dry.*



- **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 deg^2 SZ Survey
(*6% of sky*)



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

SPT 2500 deg^2 SZ Survey
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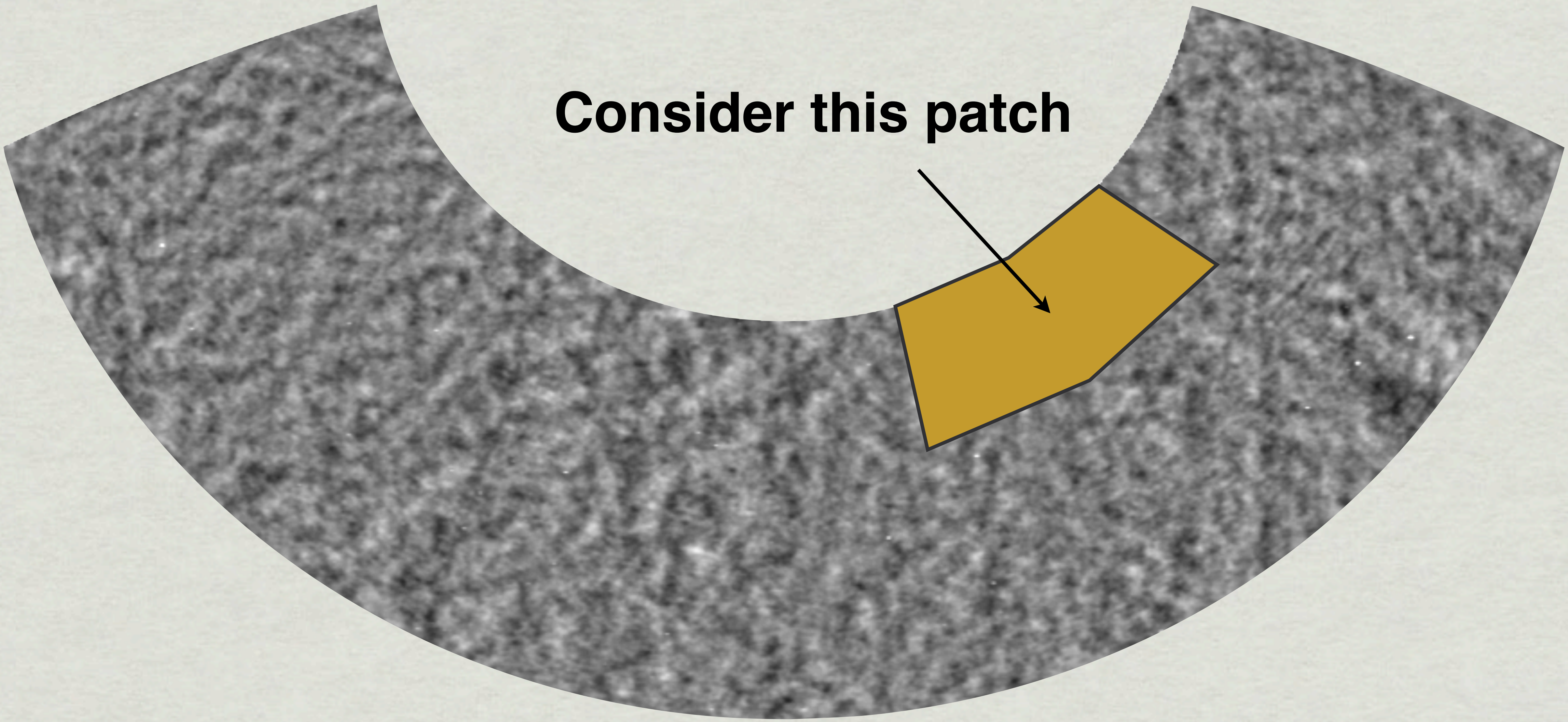

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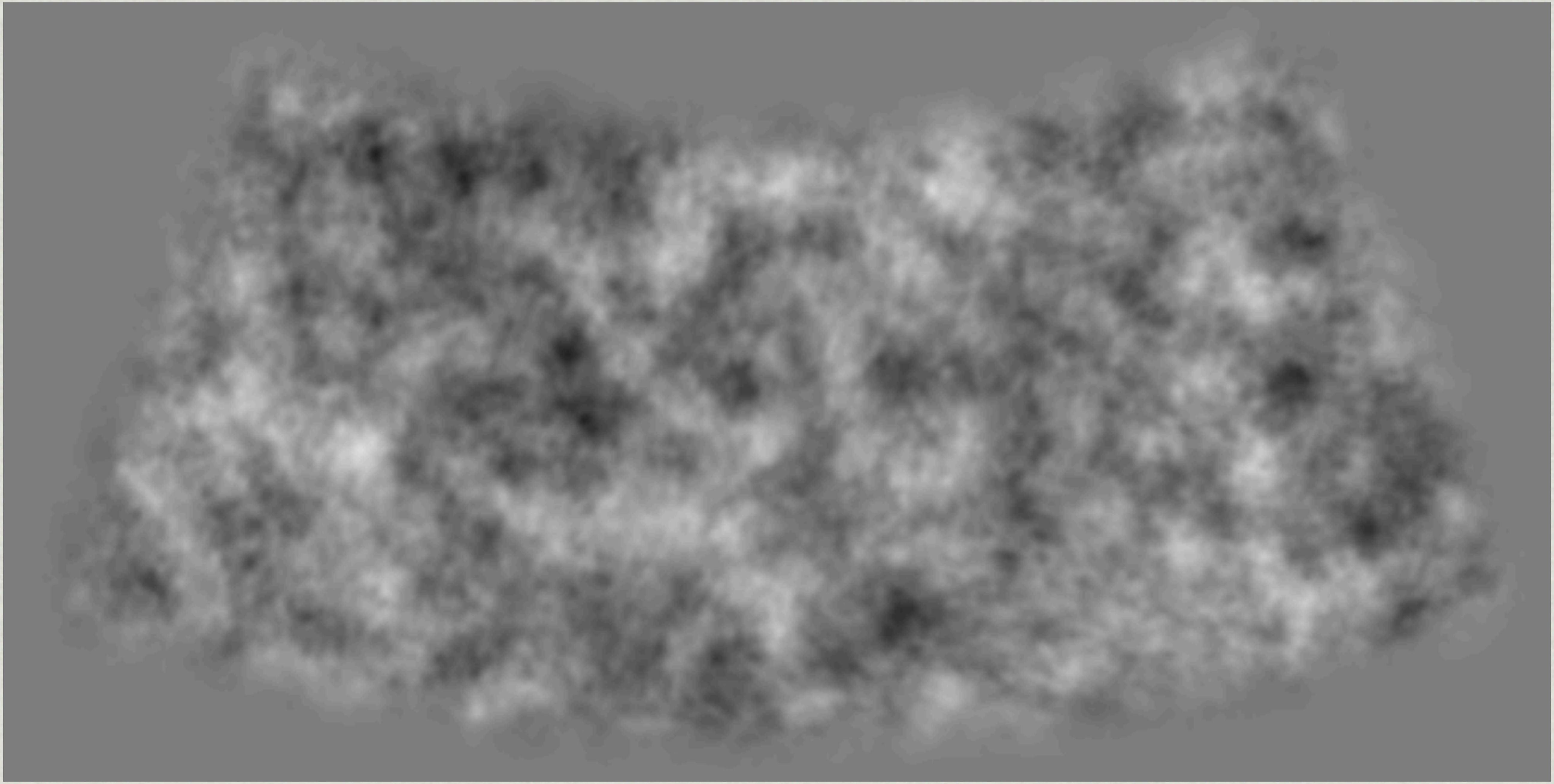
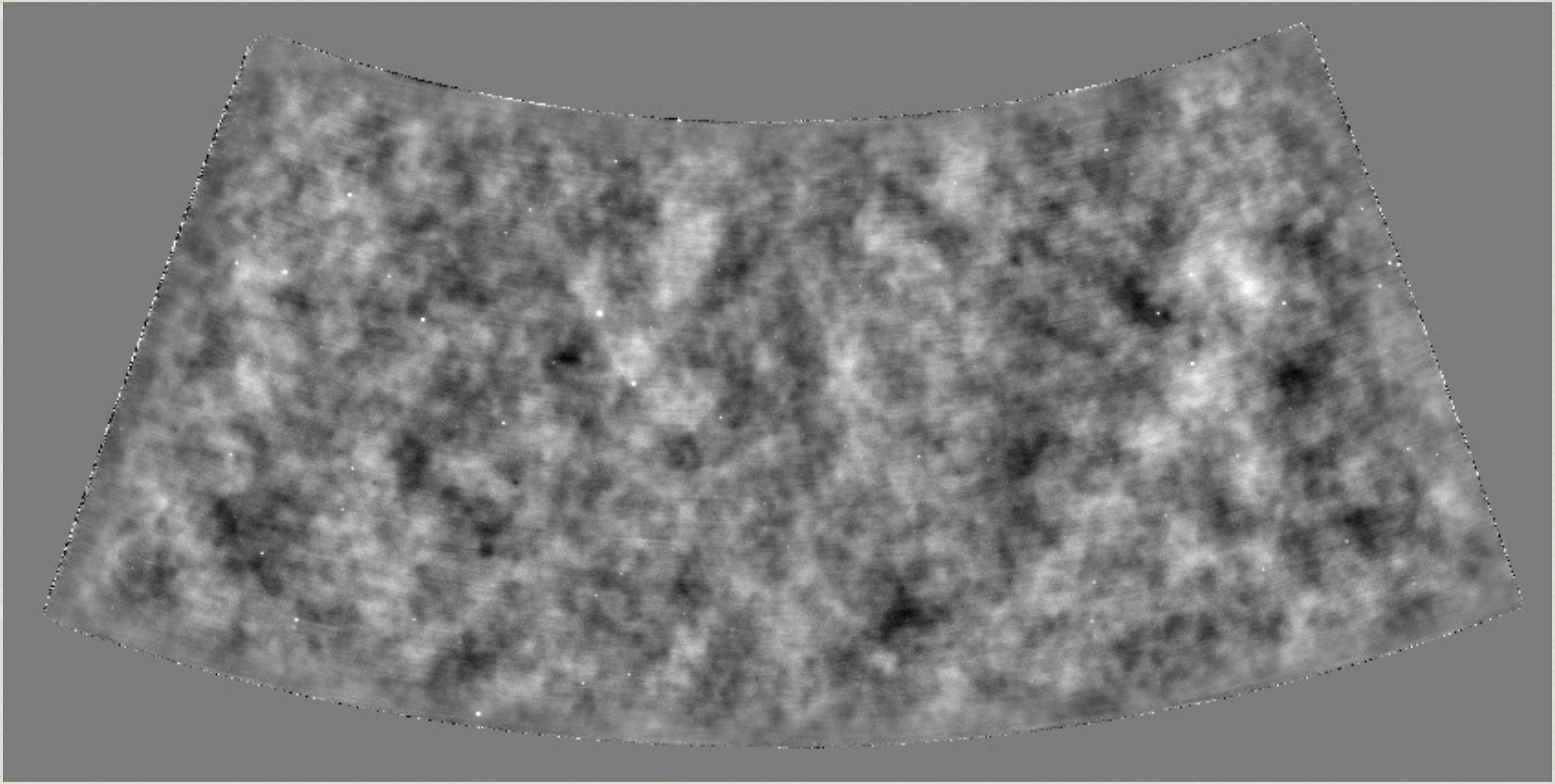
WMAP'S VIEW

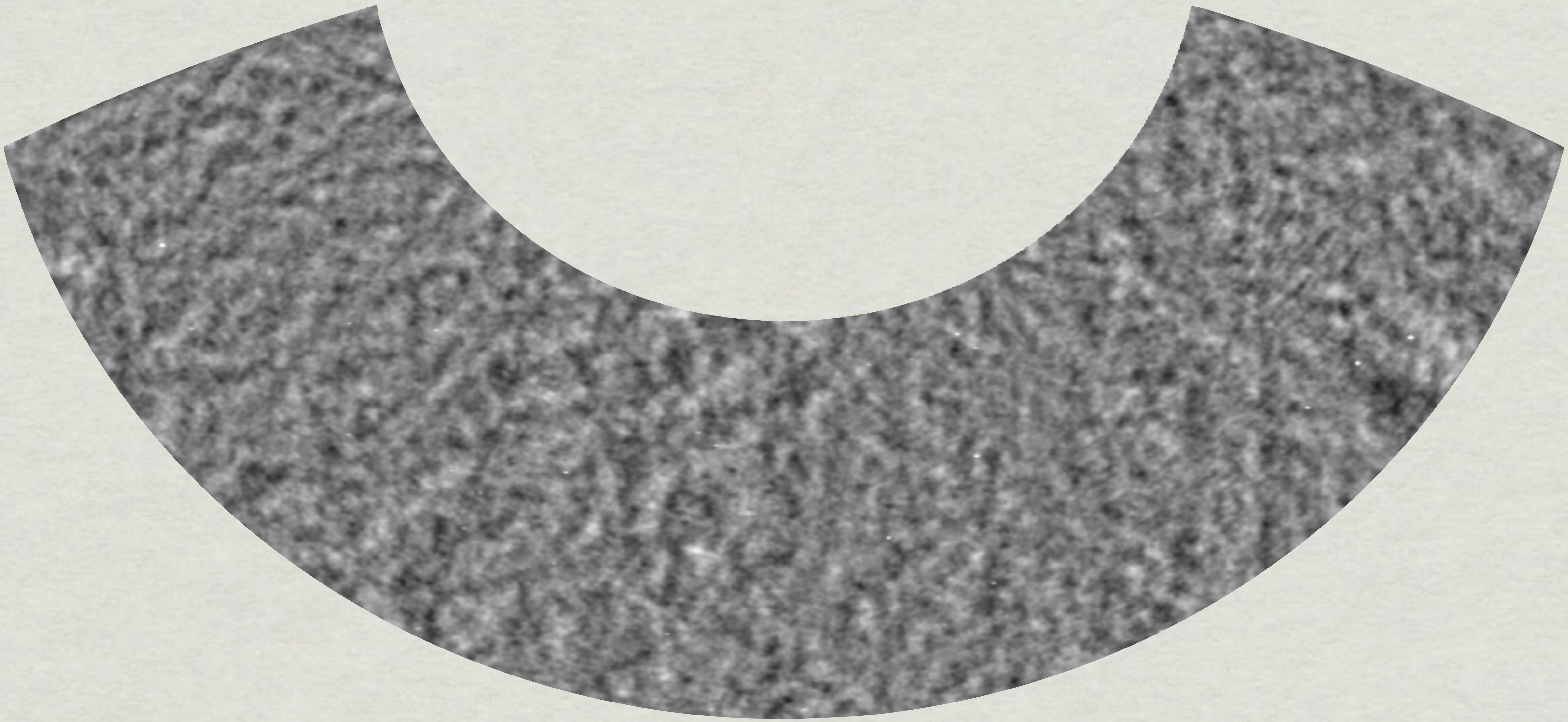


SPT'S VIEW

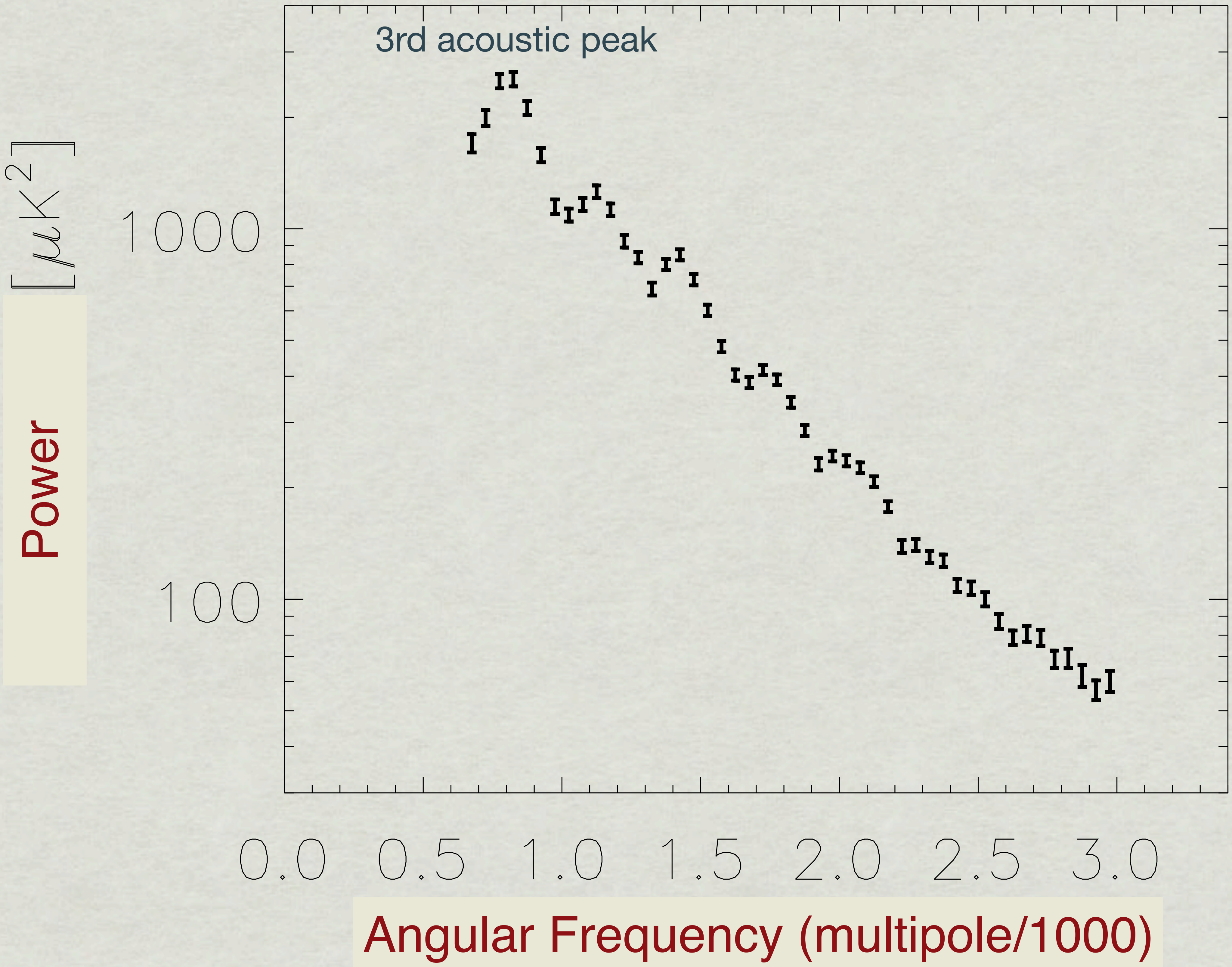


SPT has ~20X better resolution and lower noise than WMAP, but covers only ~6% of the sky. Complementary probes of CMB.

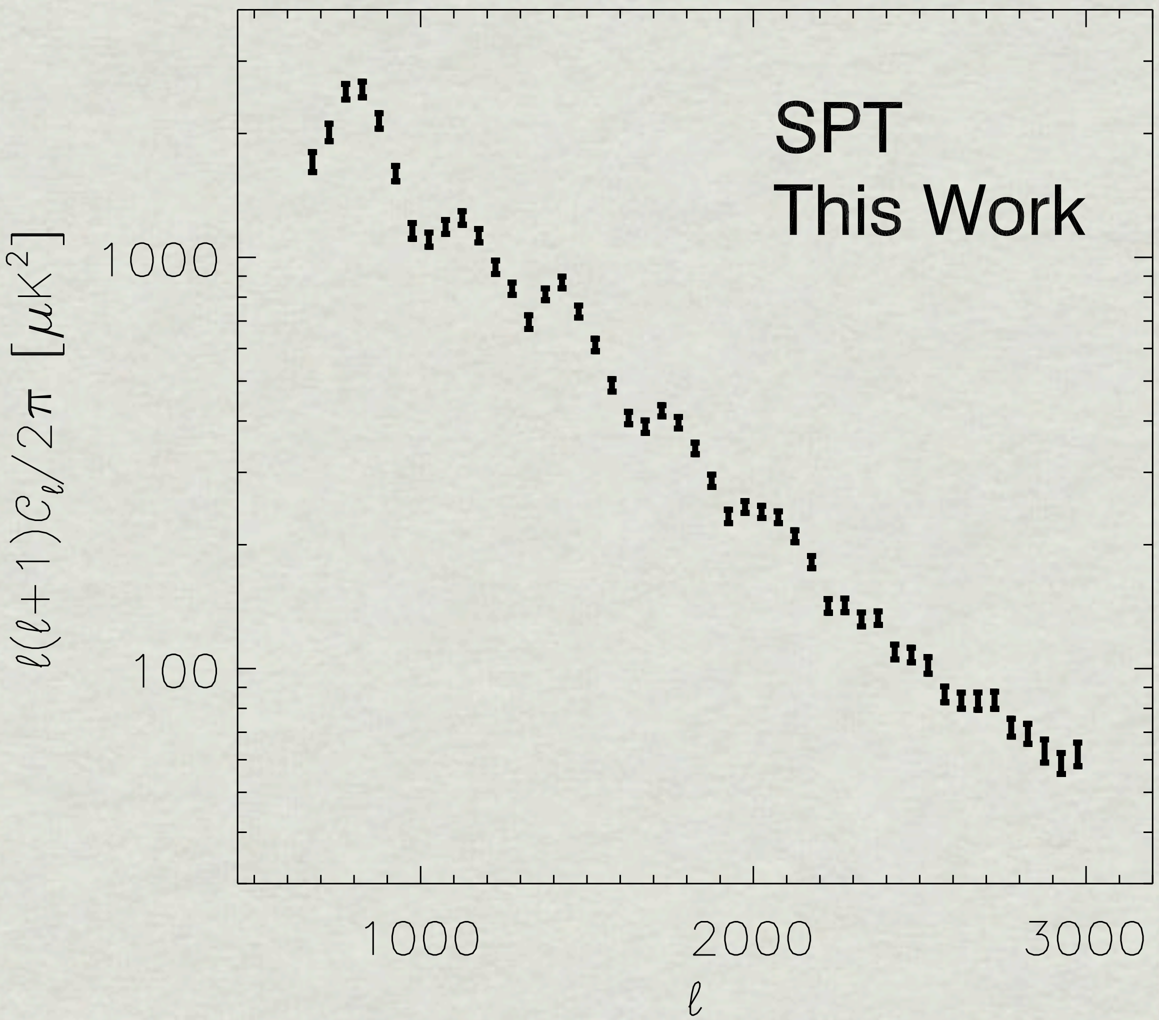
Take the angular power spectrum of 1/3 of this:



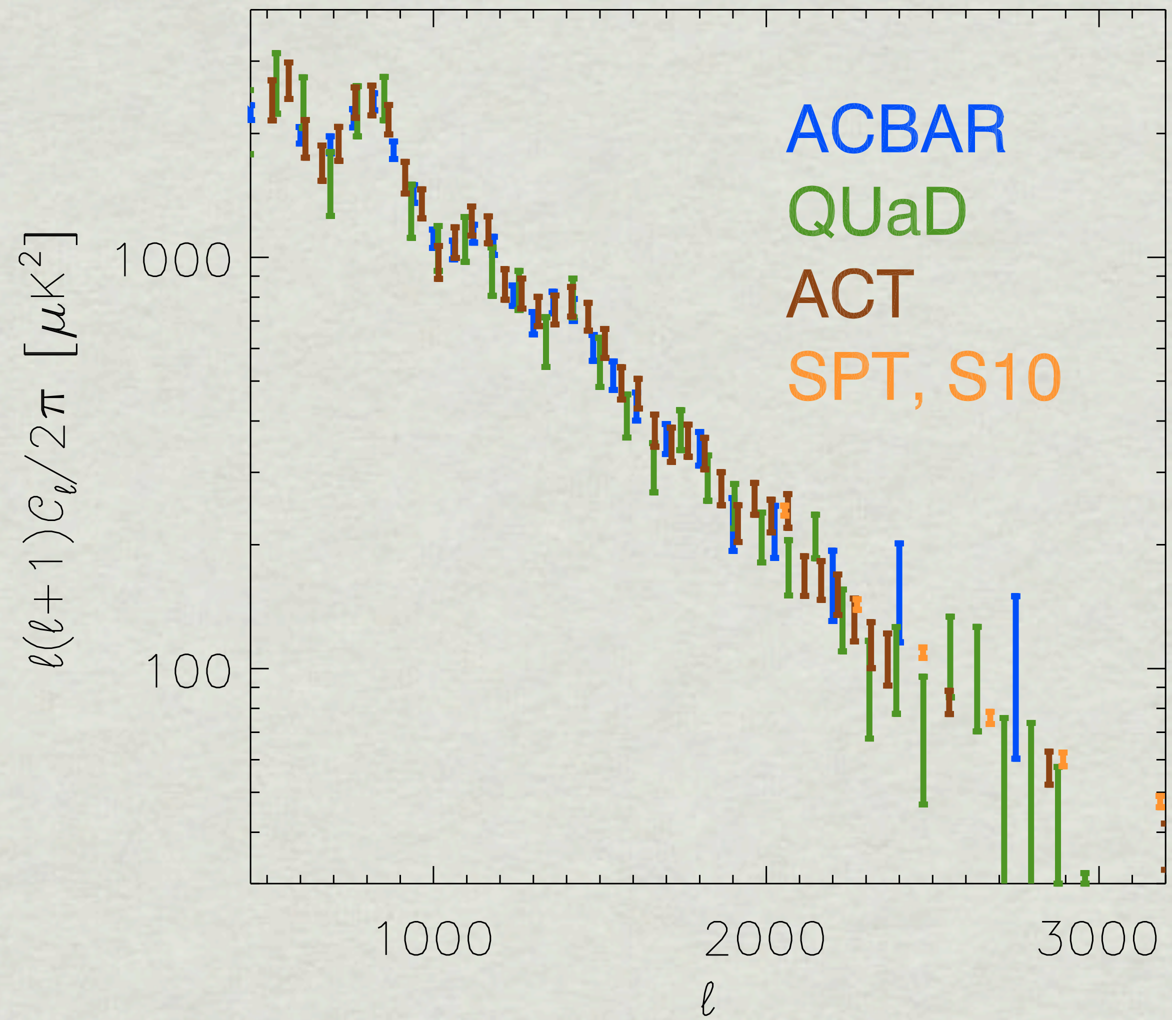
...and you get this.



This work

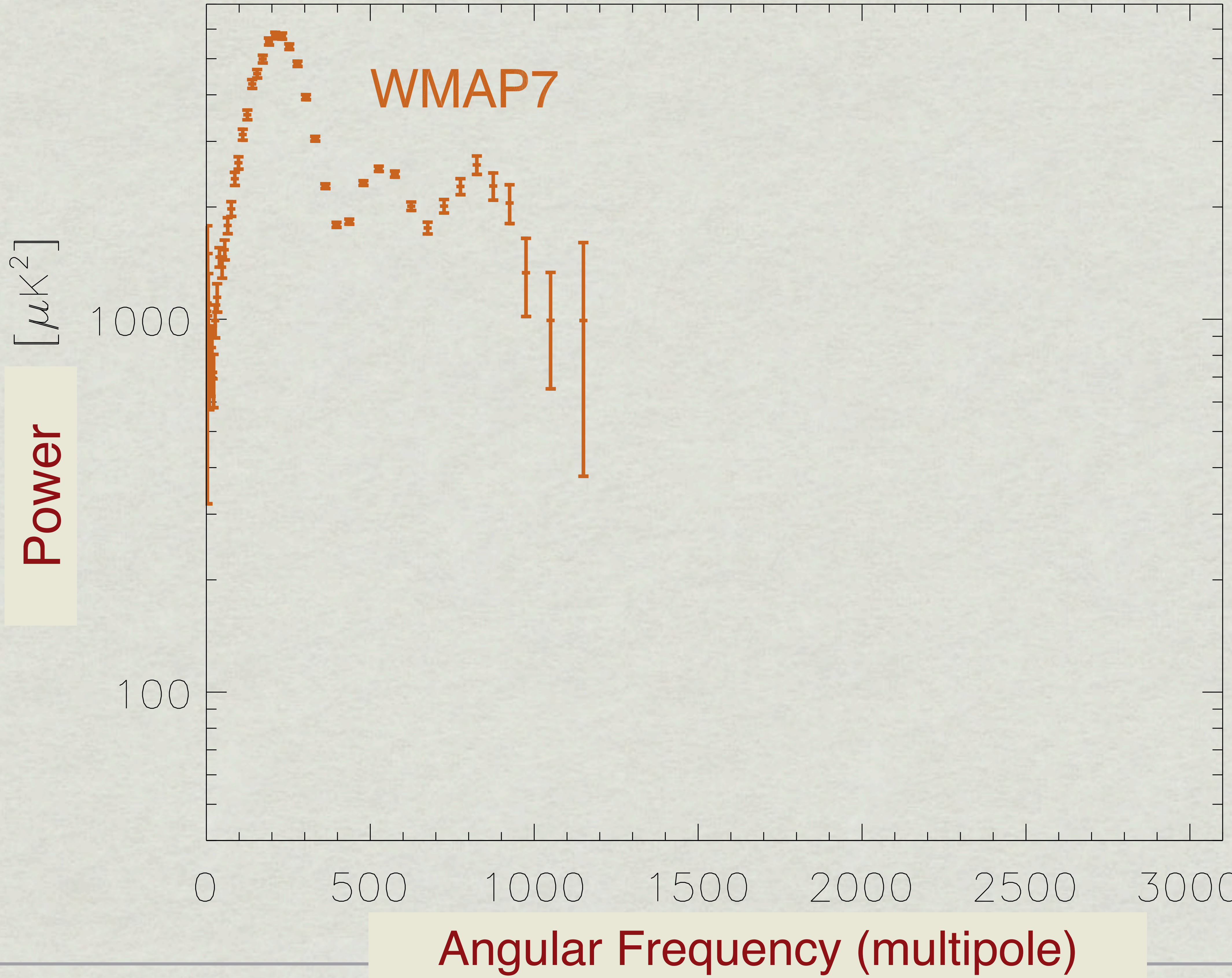


Previous works

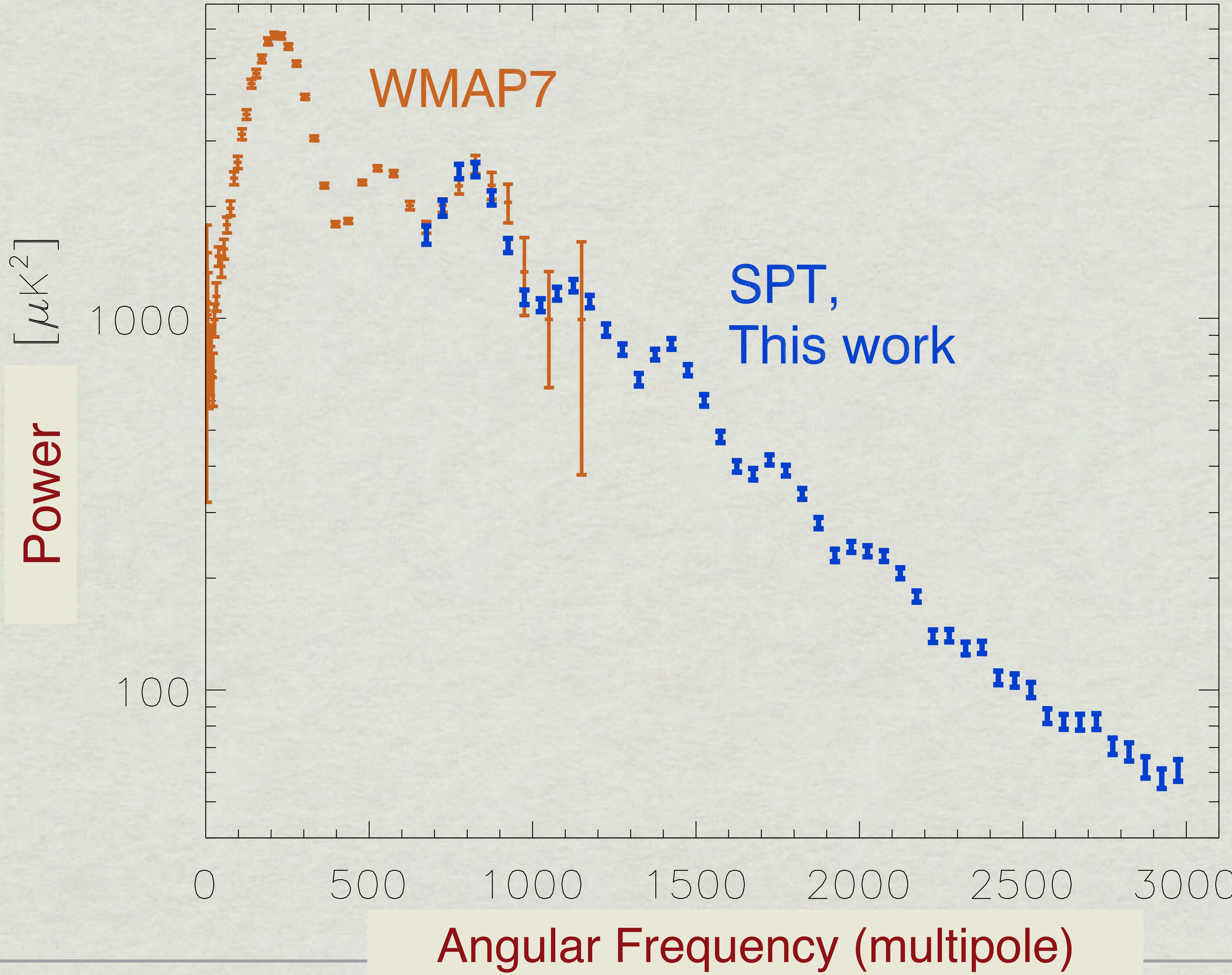


SPT provides 2X improvement over previous works.

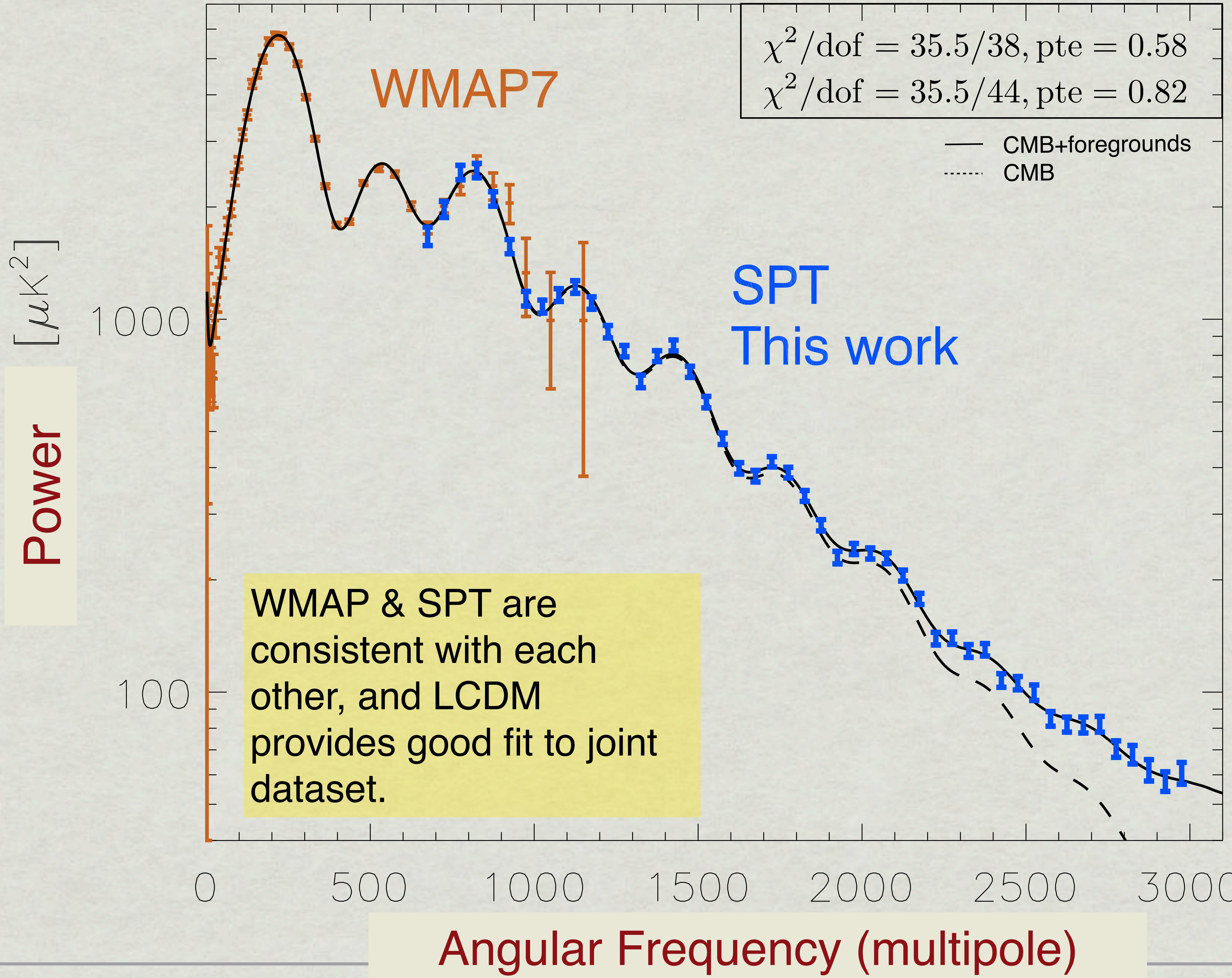
Angular Power Spectrum



Angular Power Spectrum



Best-fit Model



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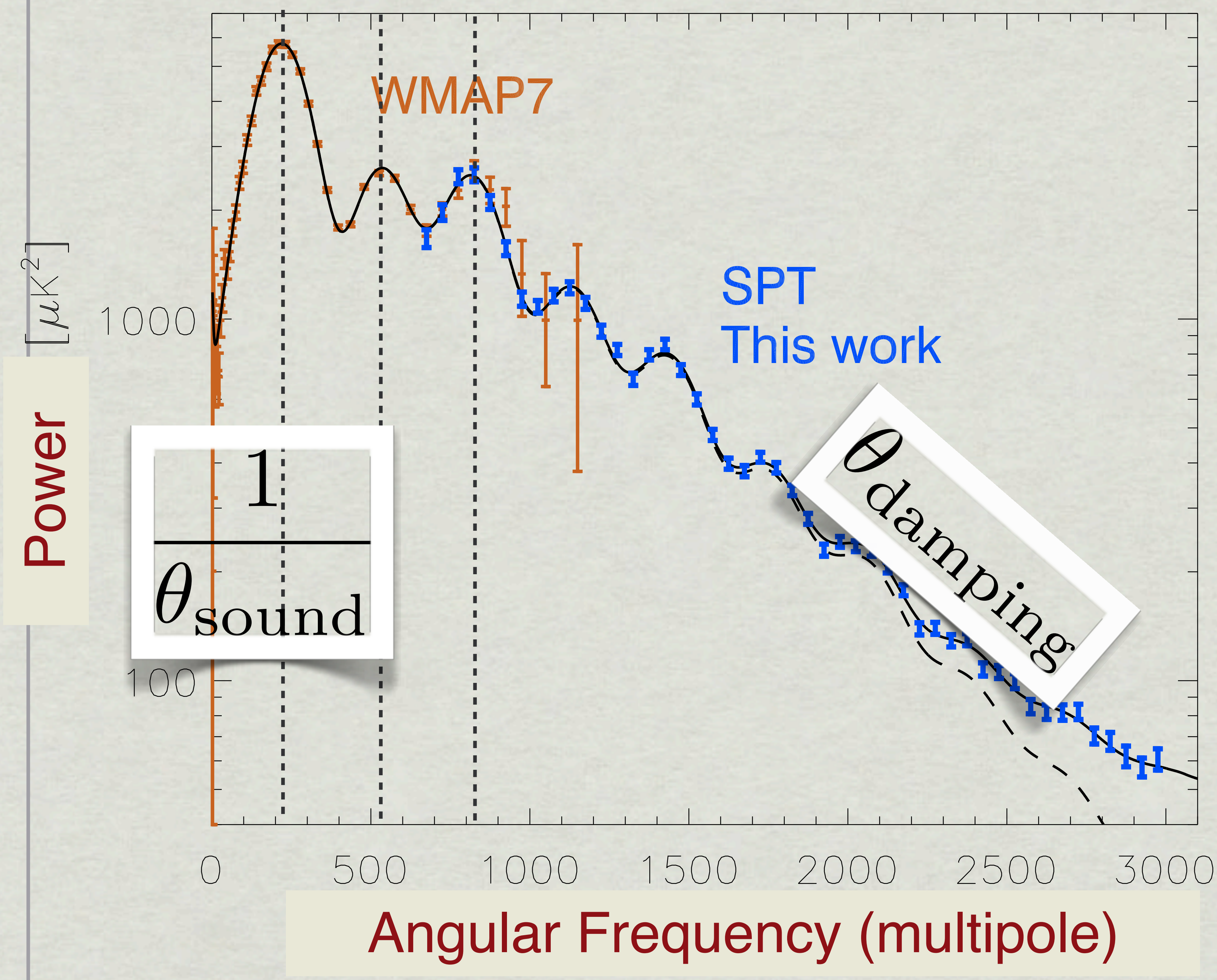
Beyond LCDM: number of neutrinos



- The **number of relativistic species (think neutrinos)** present in the early universe affects the **expansion rate** during that time.

- The ratio $\frac{\theta_{\text{damping}}}{\theta_{\text{sound}}}$ is sensitive to the expansion rate.

- **SPT+WMAP can measure the number of relativistic species.** (3 neutrinos + ?)

Beyond LCDM: No Neutrinos vs Standard Neutrinos?

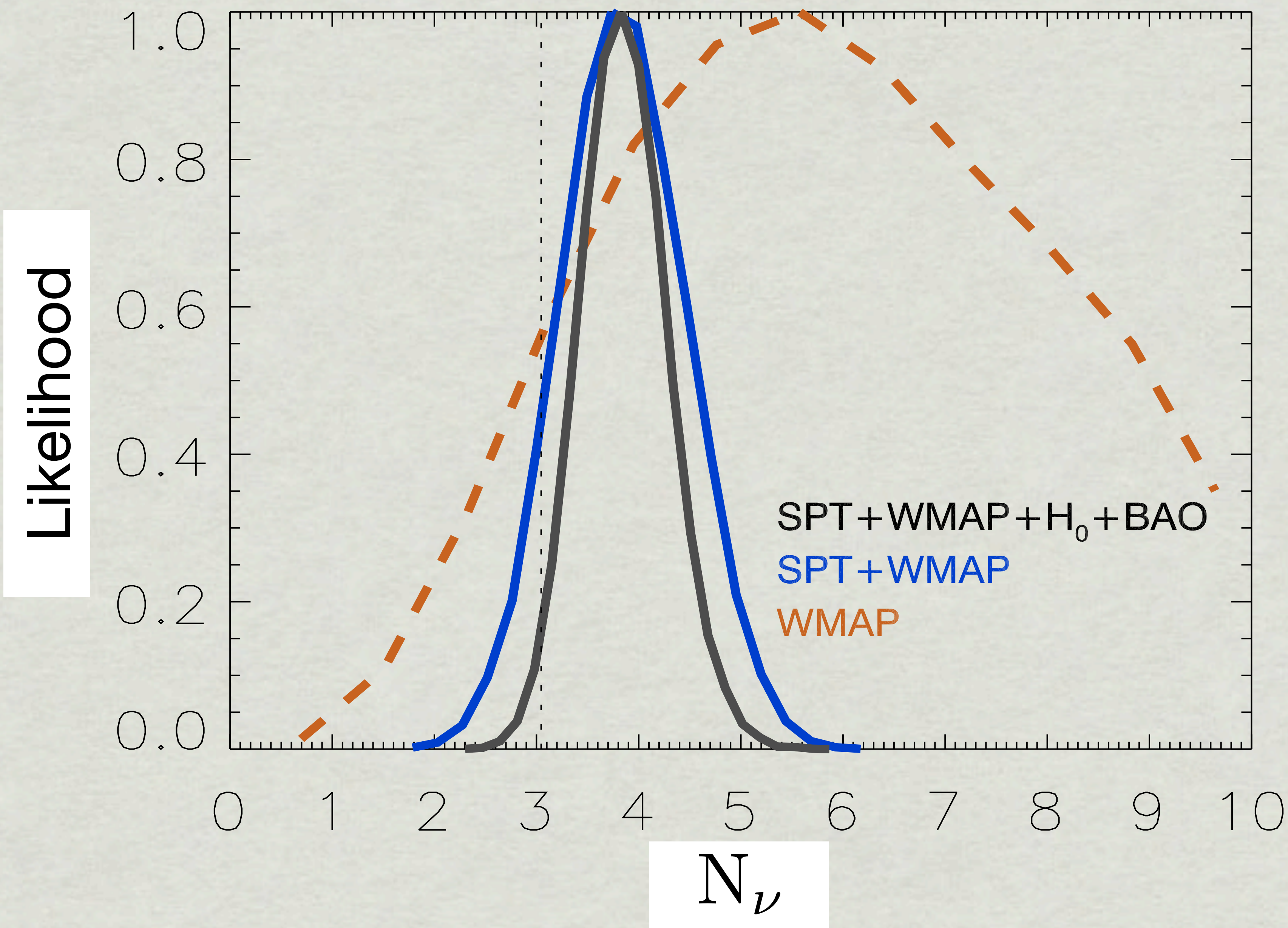
Simple test: compare maximum likelihood in N_nu=0 model to that in N_nu=3.046 model.

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 , arXiv:1105.3182 (RK, C. Reichardt *et al.,* ApJ, 2011). Data publicly available.

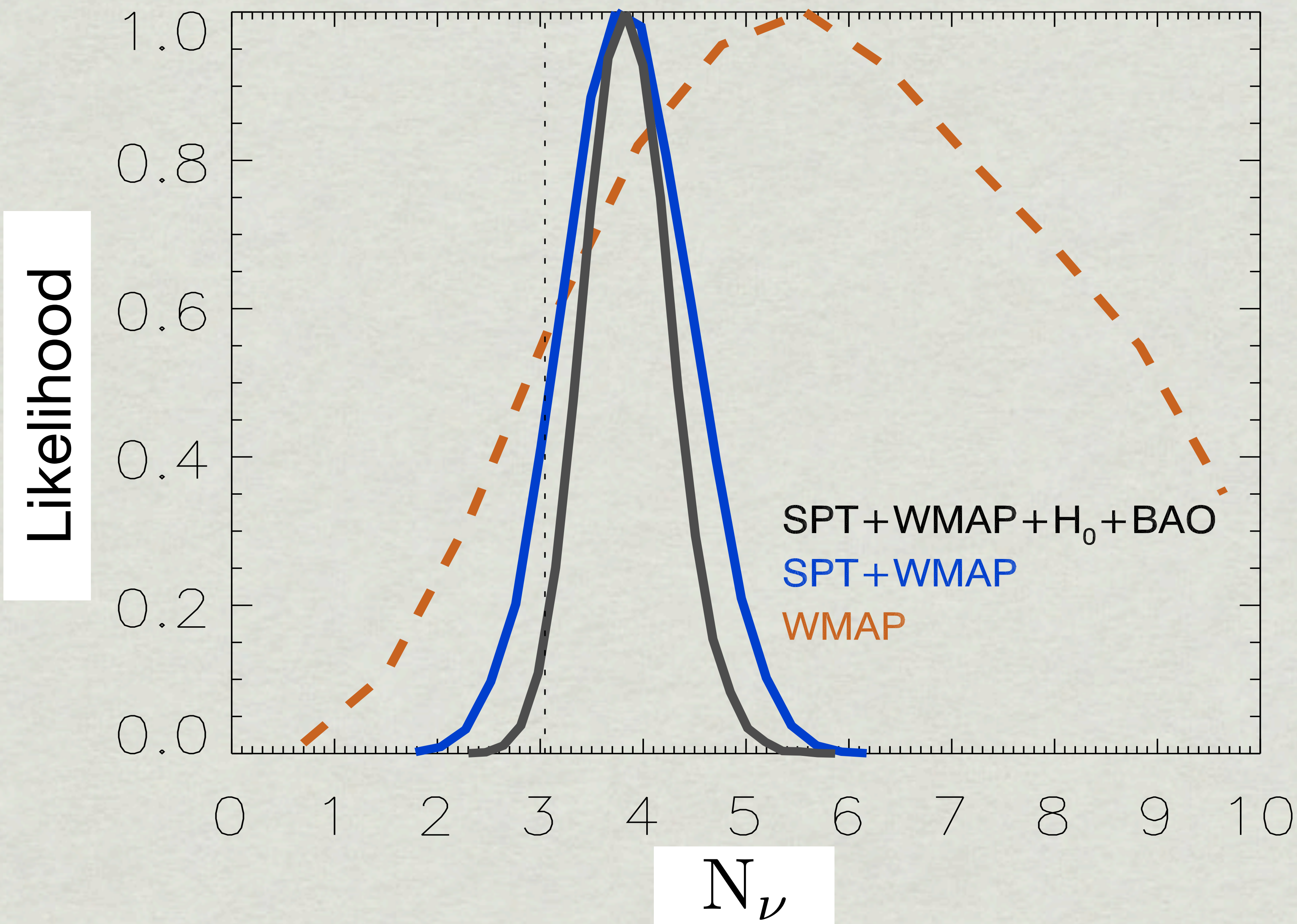
Constraints on N_ν



- $N_\nu = 3.85 \pm 0.62$, (SPT + WMAP) (1.3σ higher than 3.046)
- $N_\nu = 3.86 \pm 0.42$, (SPT + WMAP + H_0 + BAO) (1.9σ higher than 3.046)

see RK, C. Reichardt et al, 1105.3182

Constraints on N_ν



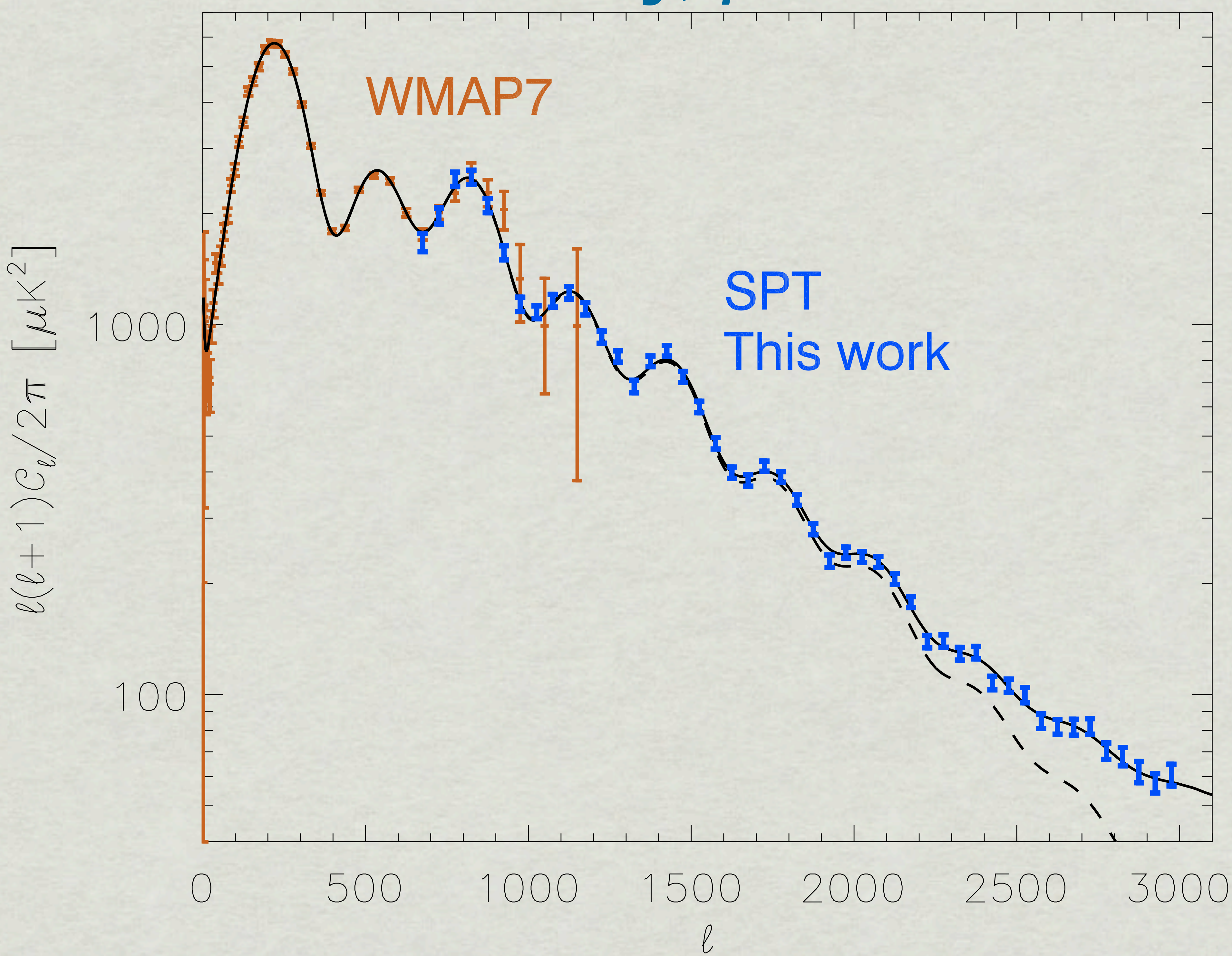
The CMB data are consistent with standard N_nu. Adding the "low-redshift" data (H0+BAO) then favors N_nu>3 at ~2σ

(1.3σ higher than 3.046)

(1.9σ higher than 3.046)

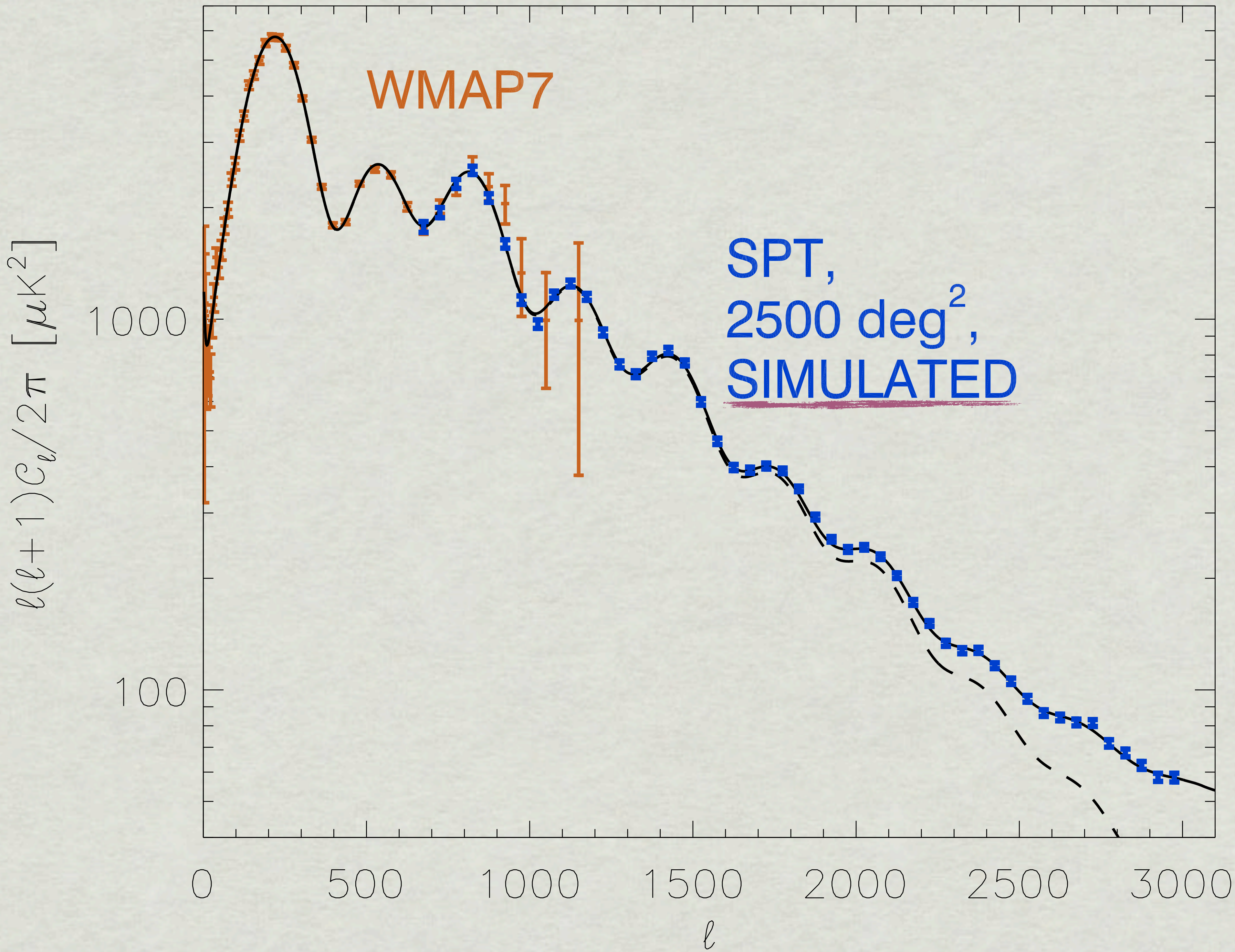
see RK, C. Reichardt et al, 1105.3182

SPT Power Spectrum,
2% of sky, *published*



$\sigma(N_\nu) \simeq 0.4$

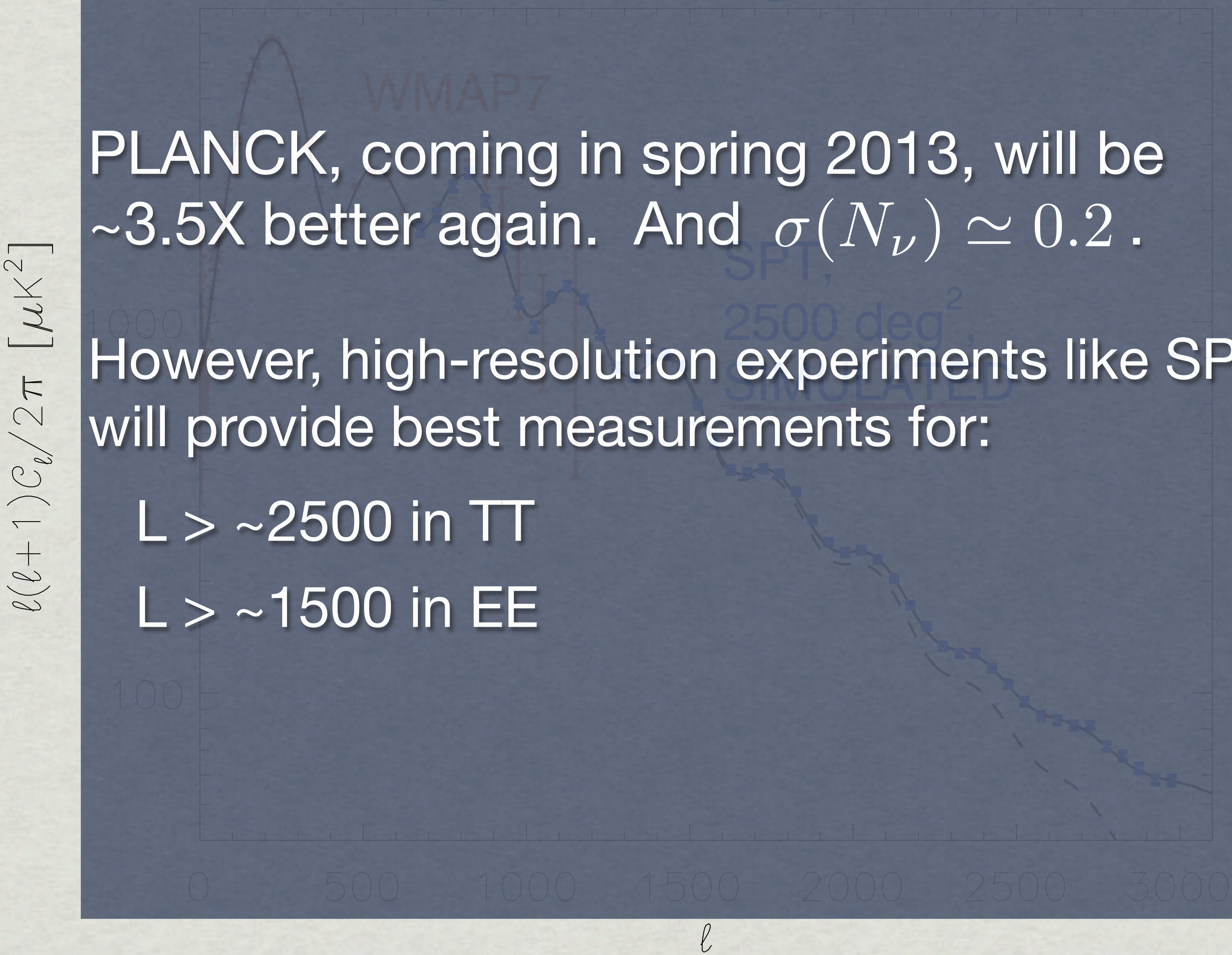
SPT Power Spectrum,
6% of sky, *coming this summer*



$\sigma(N_\nu) \simeq 0.33$

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

SPT Power Spectrum, 6% of sky, *coming this summer*



PLANCK, coming in spring 2013, will be ~3.5X better again. And $\sigma(N_\nu) \simeq 0.2$.

However, high-resolution experiments like SPT will provide best measurements for:

L > ~2500 in TT

L > ~1500 in EE

$\sigma(N_\nu) \simeq 0.33$

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

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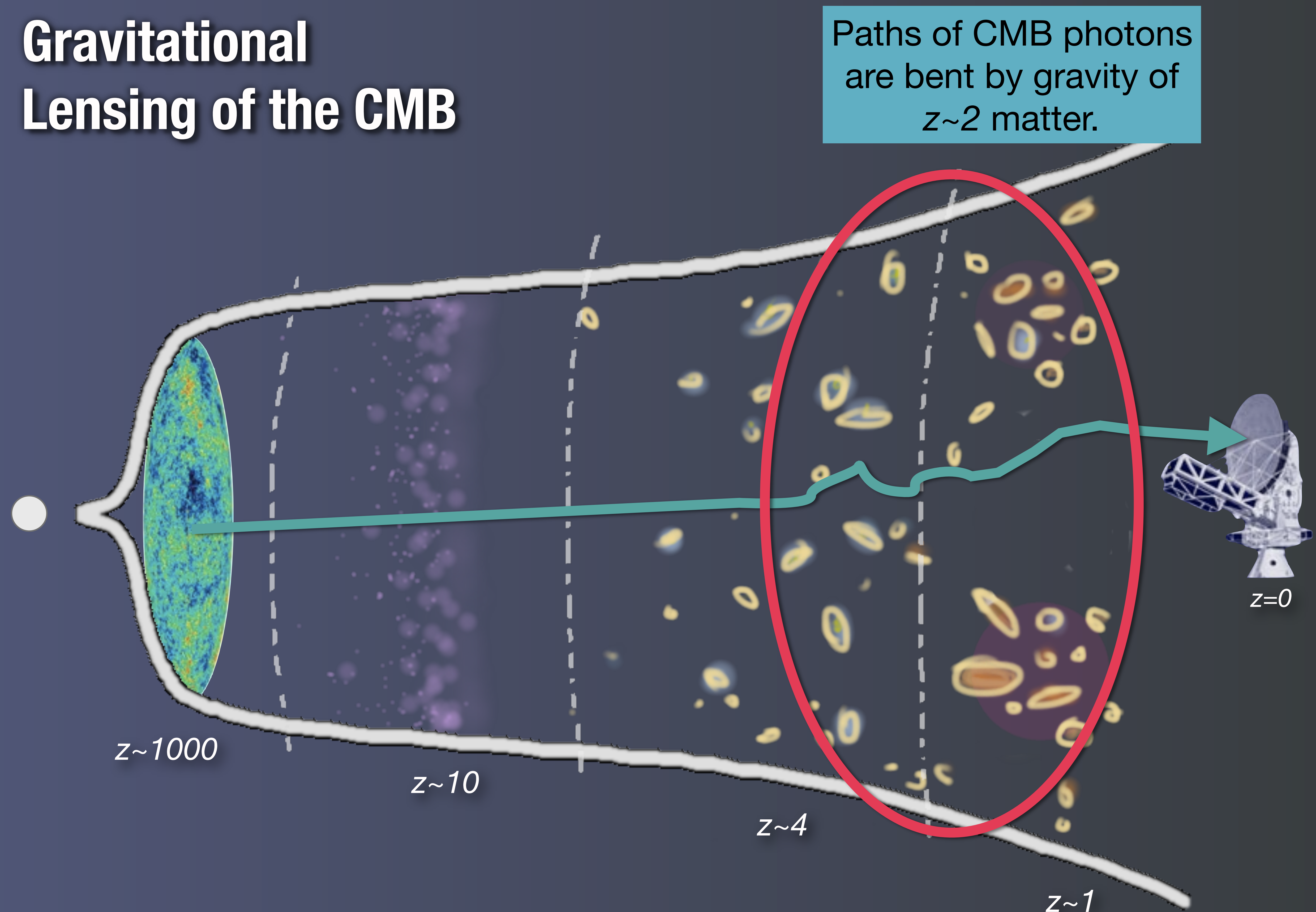
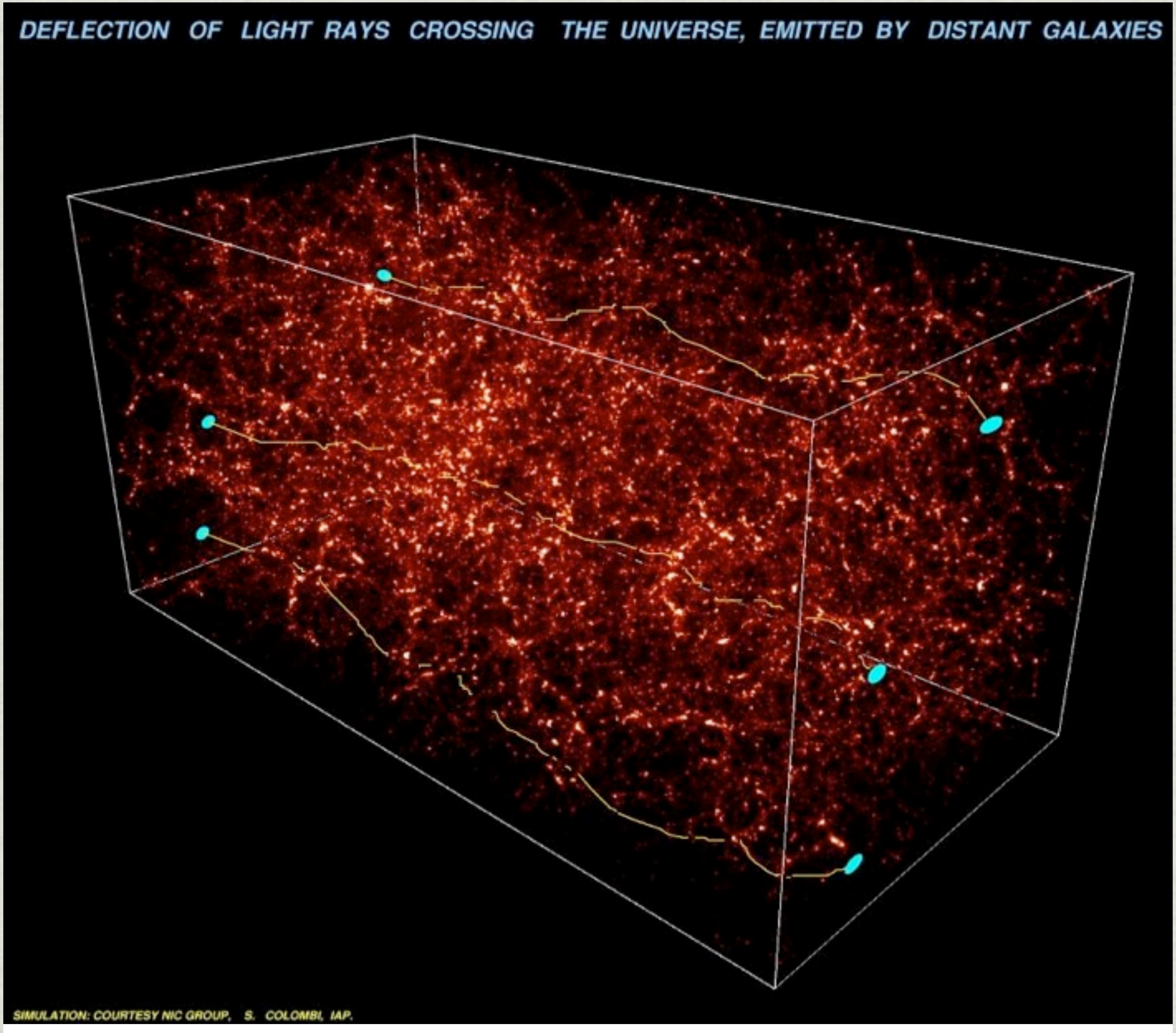
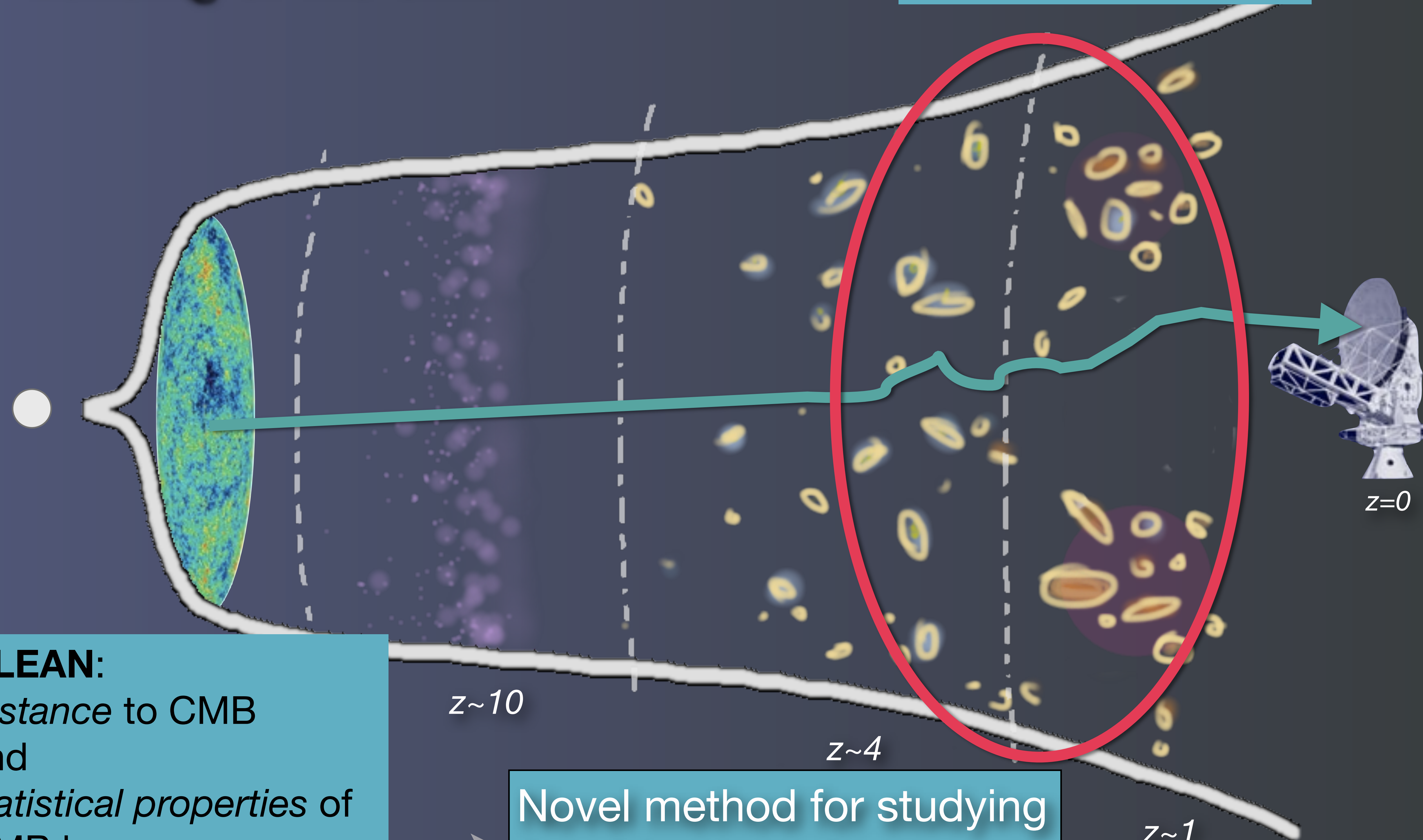
Gravitational Lensing of the CMB




DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERSE, EMITTED BY DISTANT GALAXIES
SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.

Gravitational Lensing of the CMB

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

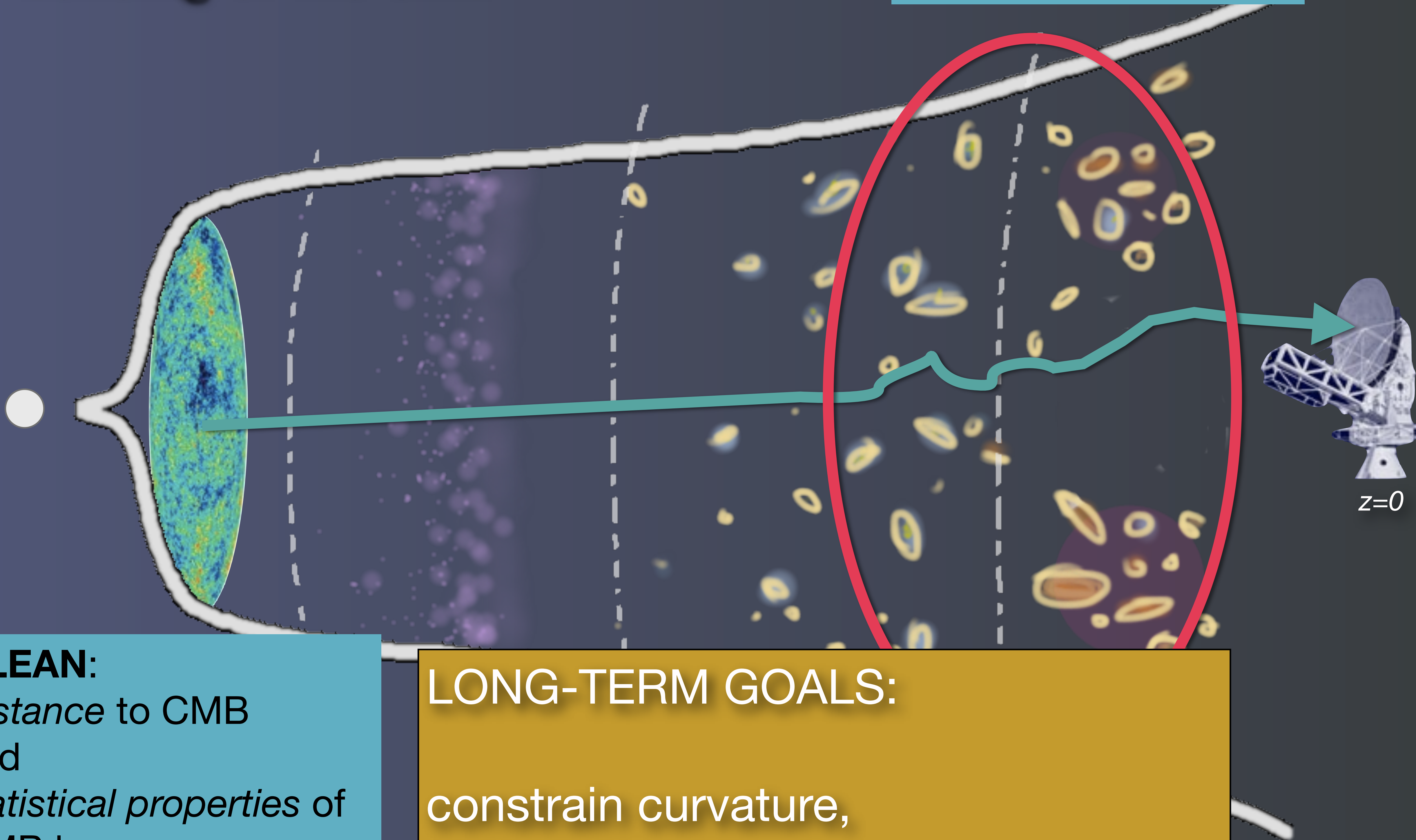


CLEAN:
Distance to CMB
and
statistical properties of CMB known very accurately, so effects of lensing can be isolated.

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

Gravitational Lensing of the CMB

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



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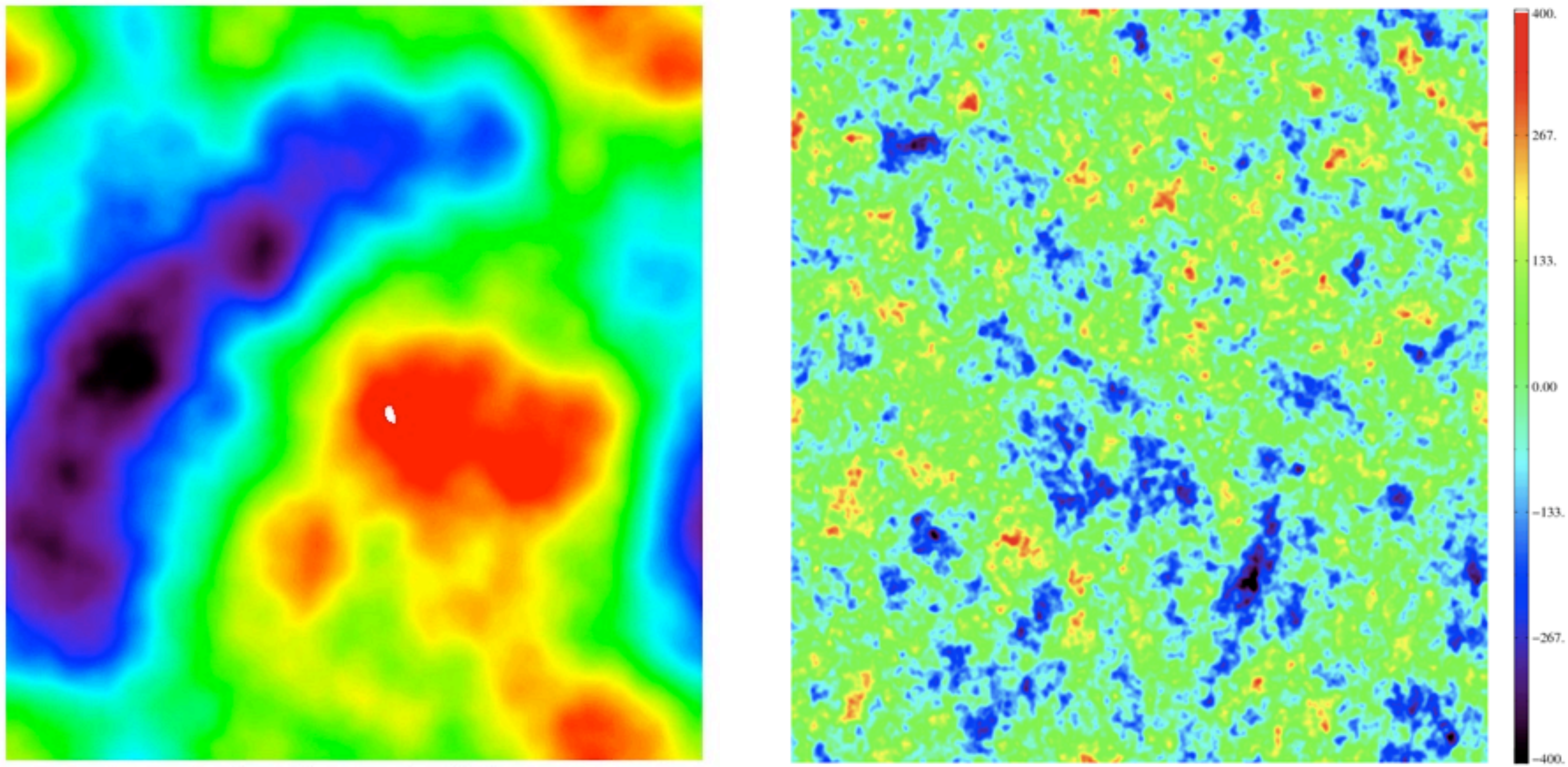
statistical properties of CMB known very accurately, so effects of lensing can be isolated.

LONG-TERM GOALS:

constrain curvature,
constrain dark energy,
measure neutrino mass

Lensing of the CMB

17°x17°



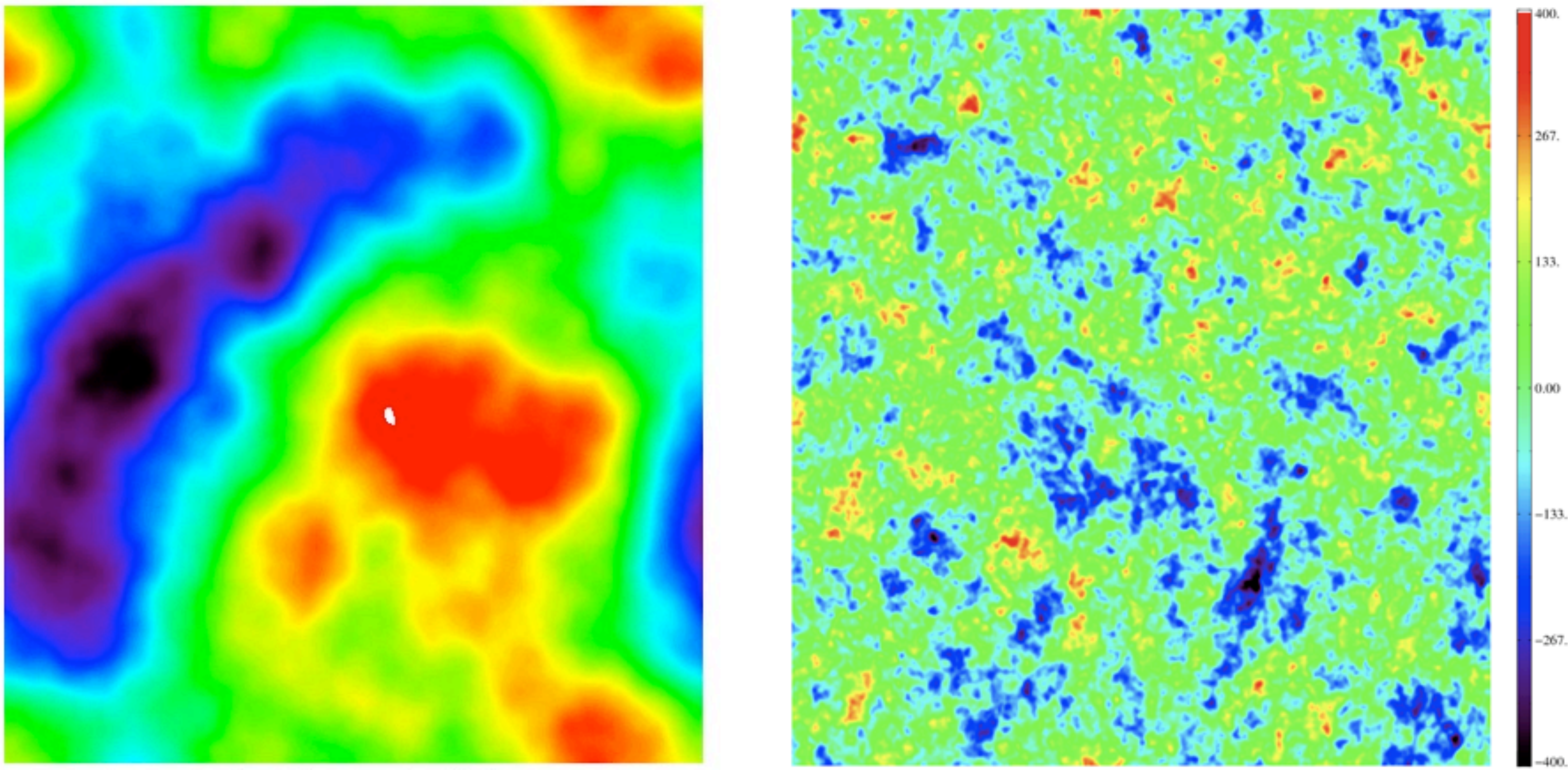
lensing potential

unlensed cmb

from Alex van Engelen

Lensing of the CMB

17°x17°



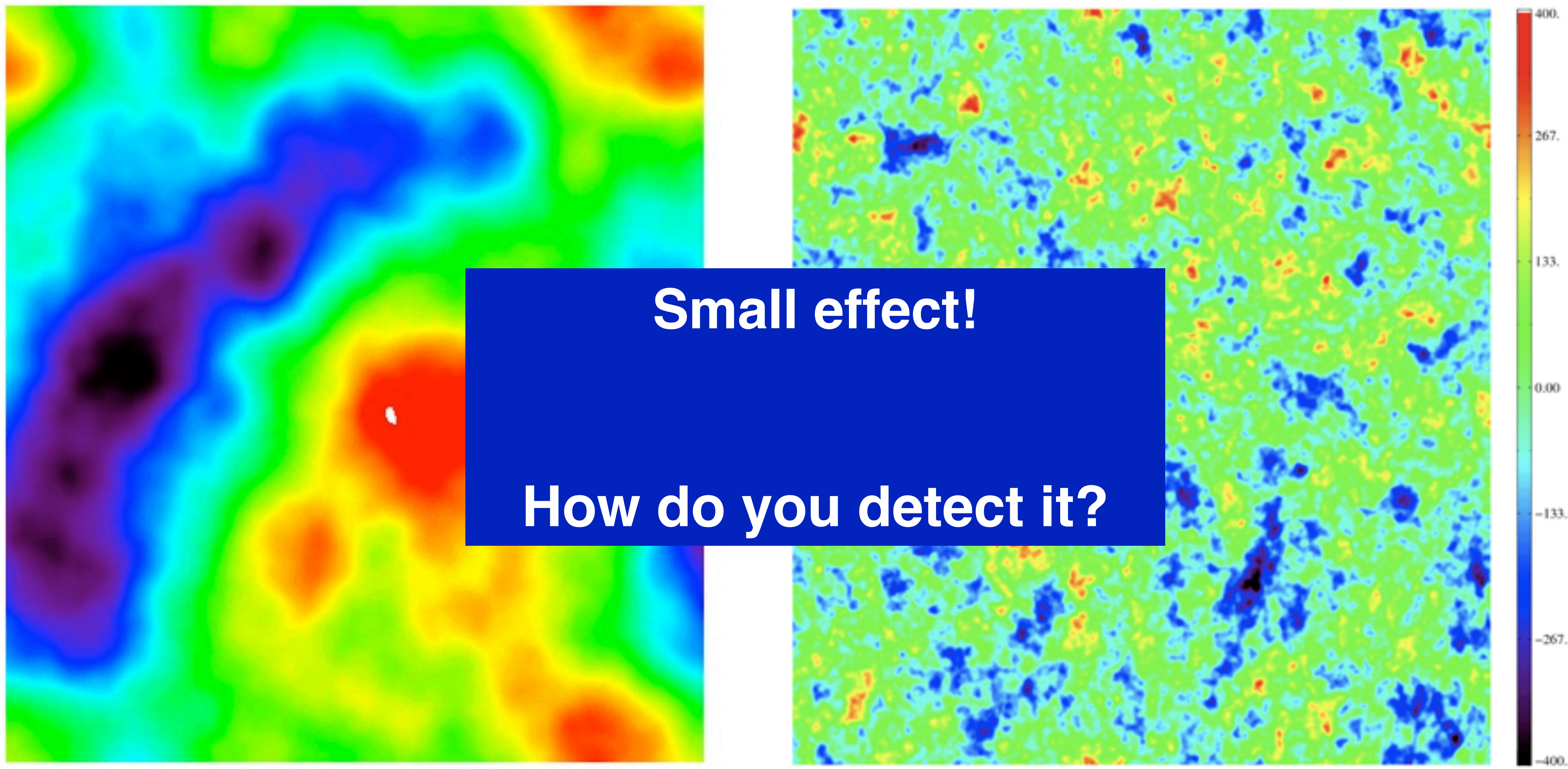
lensing potential

lensed cmb

from Alex van Engelen

Lensing of the CMB

17°x17°



lensing potential

lensed cmb

Small effect!

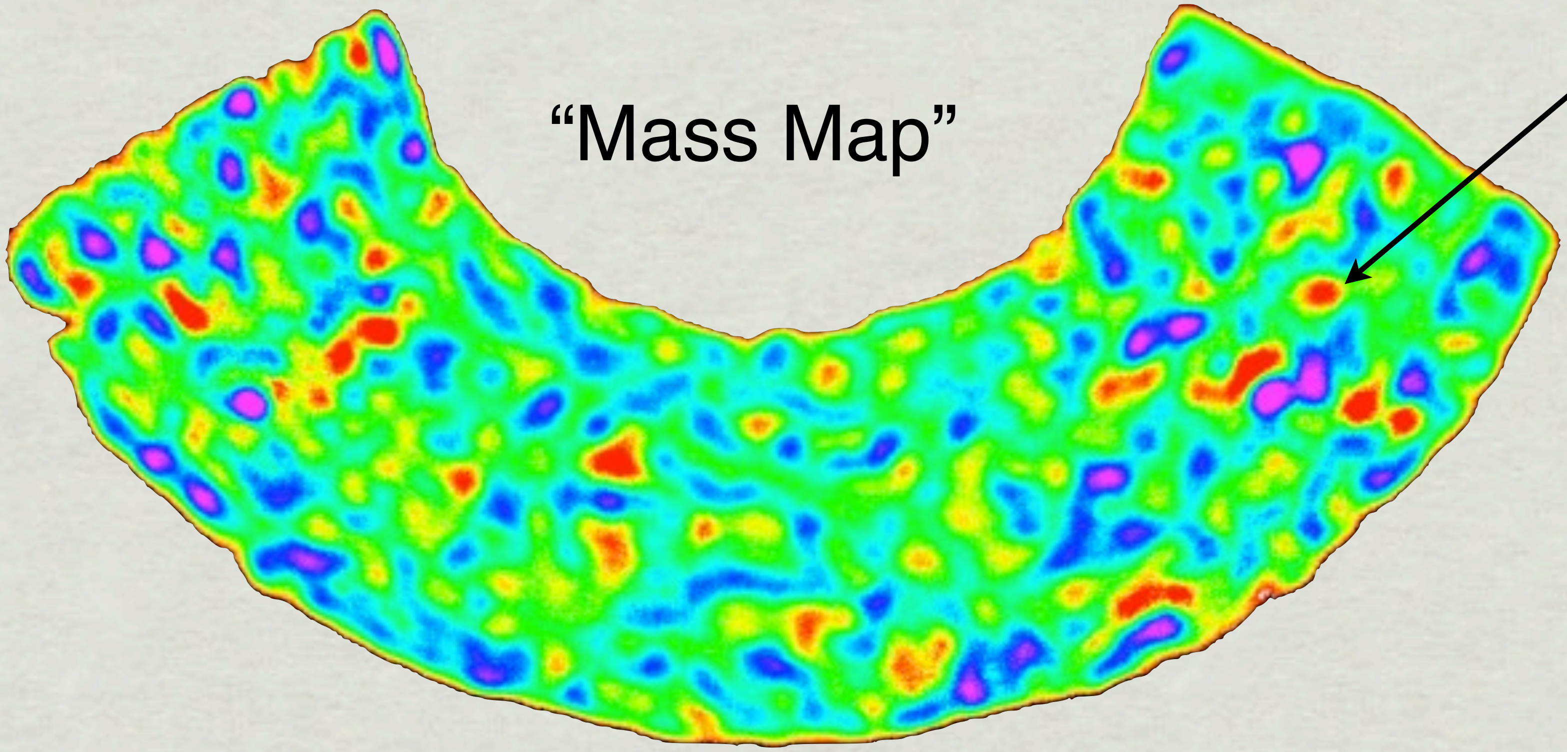
How do you detect it?

from Alex van Engelen

Mass reconstruction

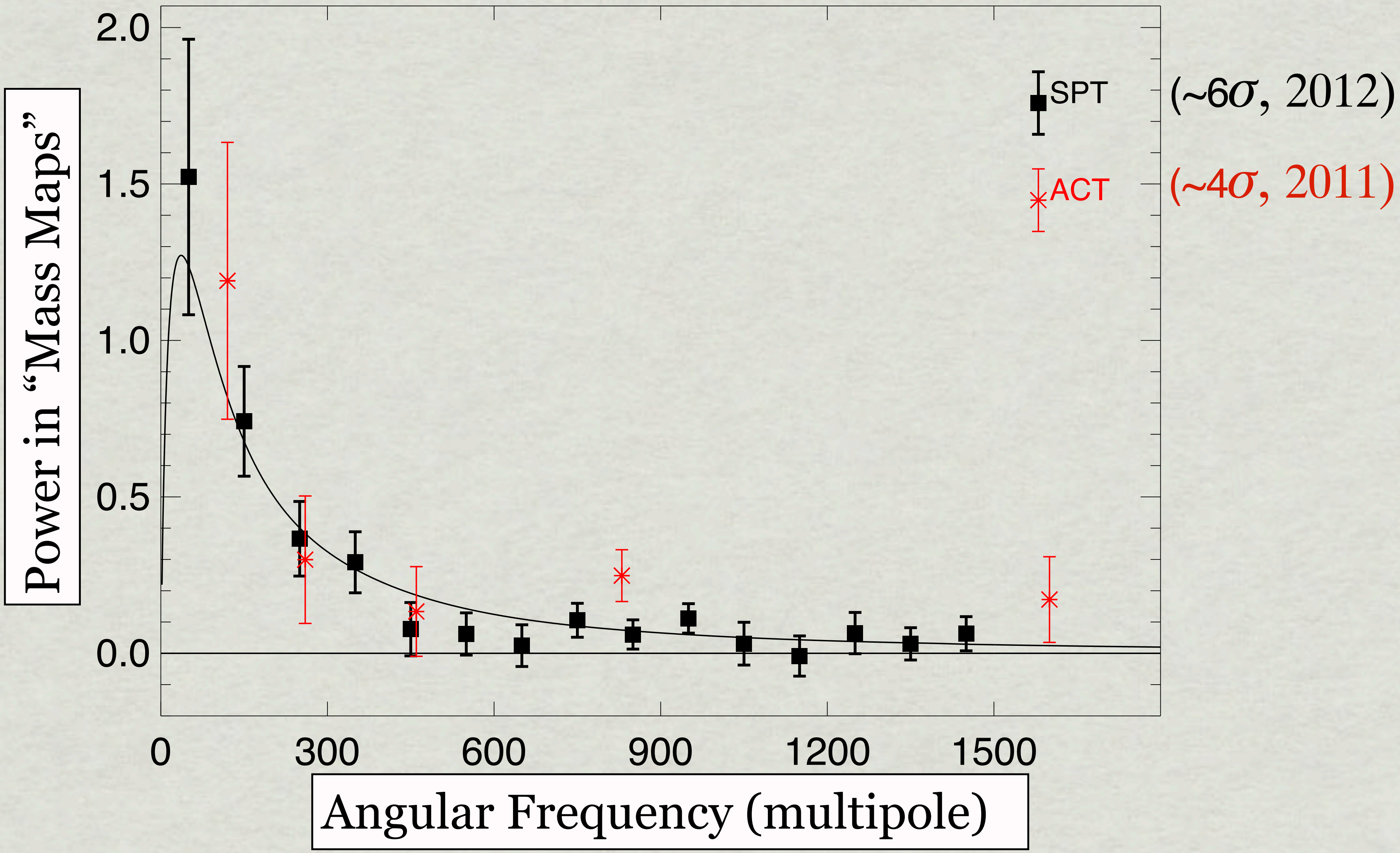
- Lensing imprints “non-gaussian” structure into the CMB.

- Take advantage of this fact to *reconstruct the mass projected along the line of sight to the CMB.*



preliminary SPT 2500 sq. deg. mass map from Gil Holder

And it works.



See "**A measurement of gravitational lensing of the microwave background using South Pole Telescope data**", A. Van Engelen, R. Keisler, O. Zahn, *et al.,* arXiv:1202.0546.

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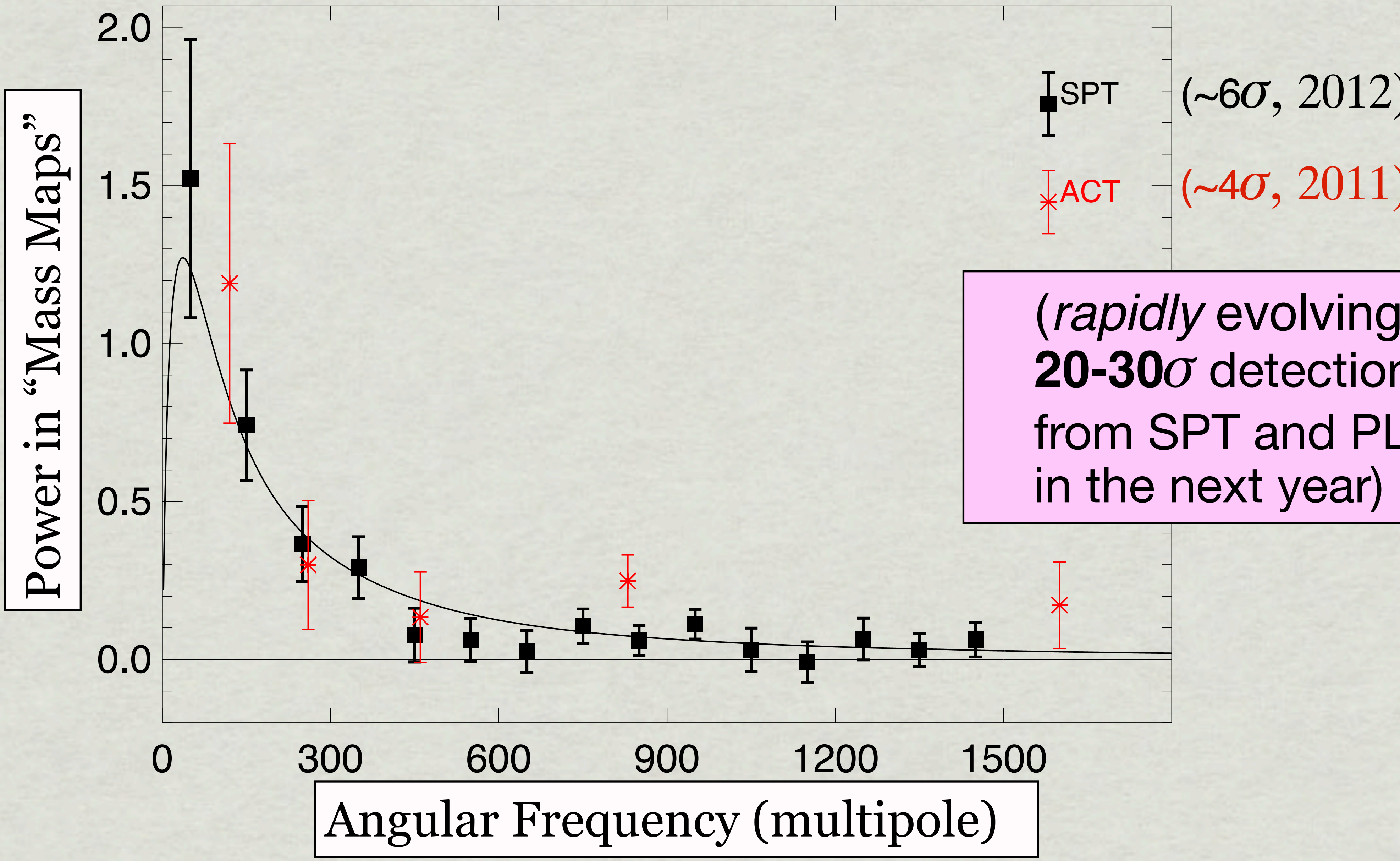
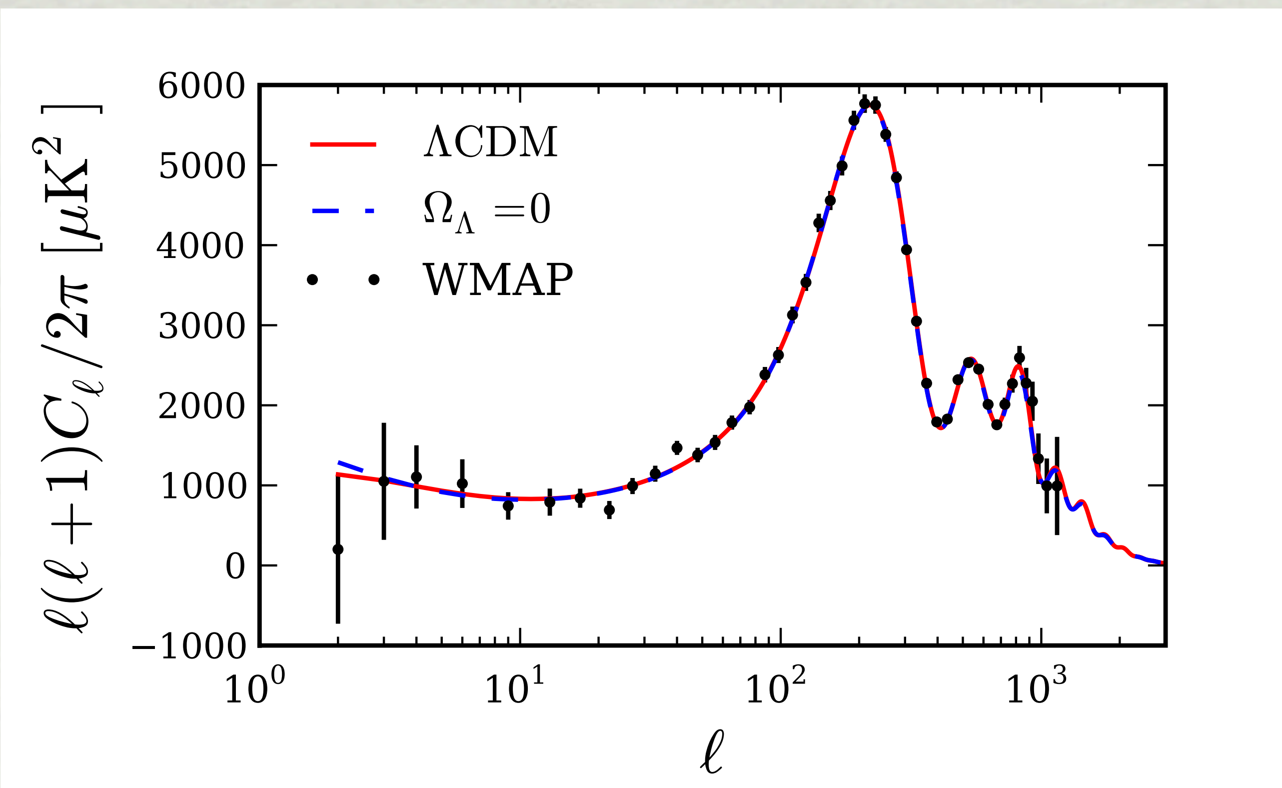


(*rapidly* evolving: **20-30σ** detections from SPT and PLANCK in the next year)

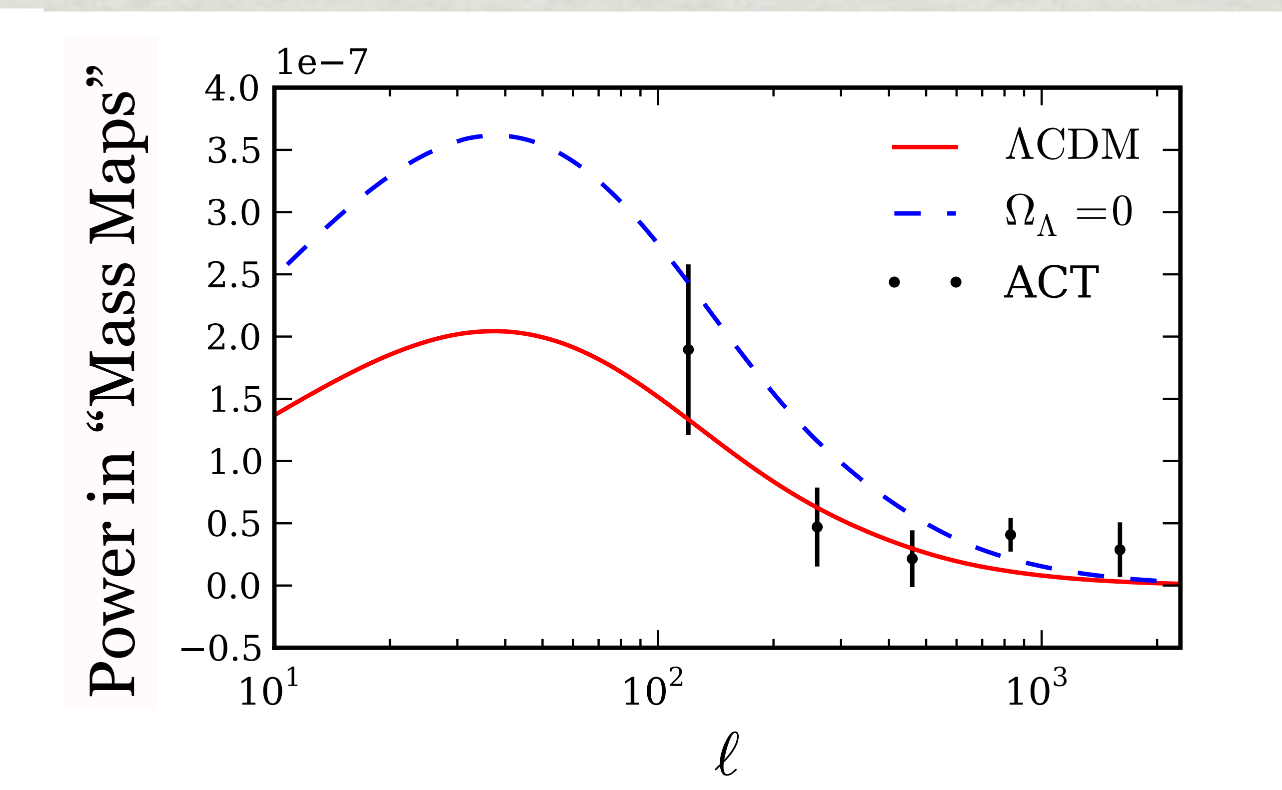
See "**A measurement of gravitational lensing of the microwave background using South Pole Telescope data**", A. Van Engelen, R. Keisler, O. Zahn, *et al.*, arXiv:1202.0546.

As a proof of principle, let's rediscover DE using only the CMB.

Two models with/without DE are identical in CMB *temperature power spectrum*...

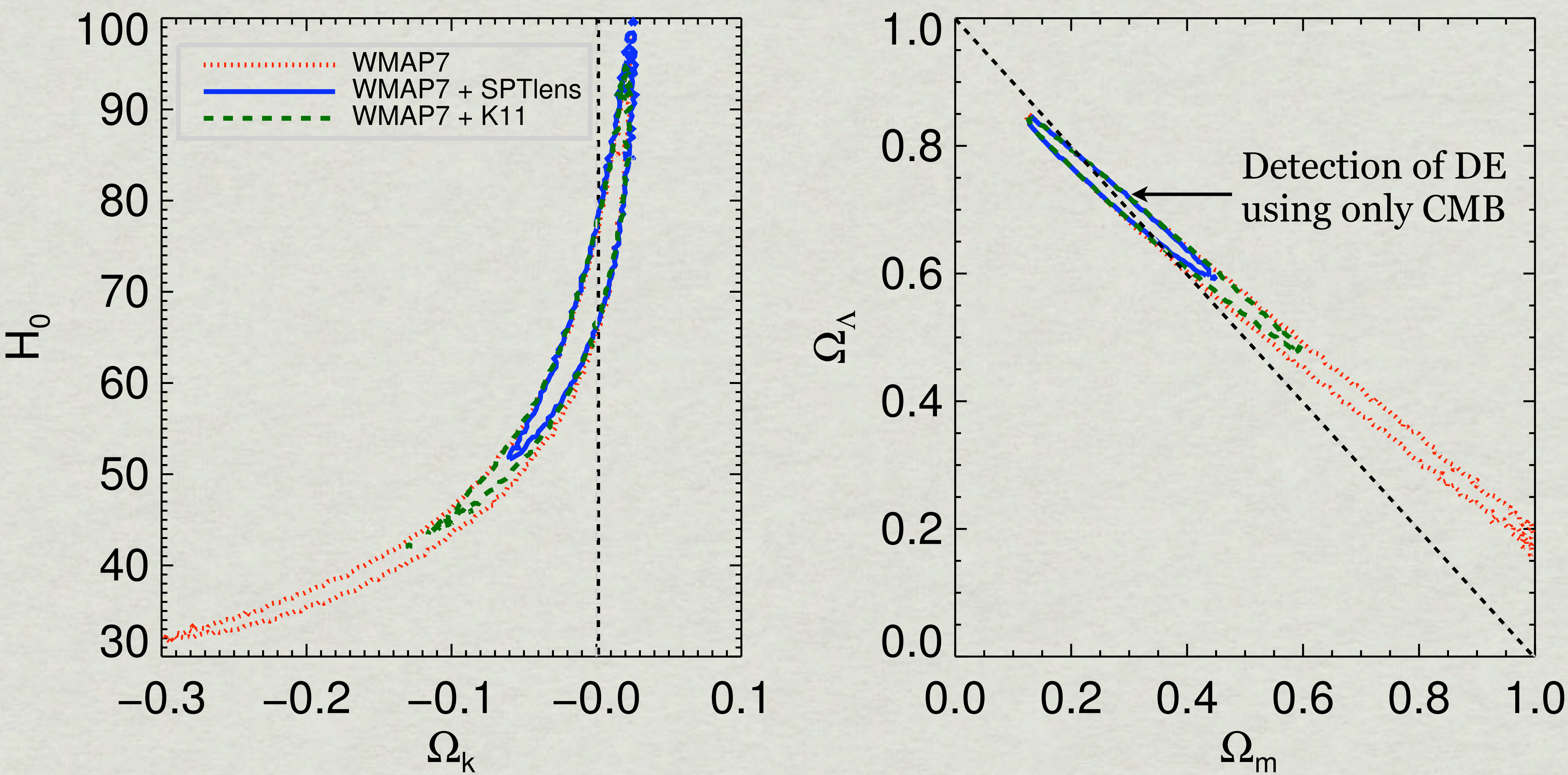


but very different low-redshift behavior: *CMB lensing data* breaks degeneracy and demands DE.



See ACT papers: Das et al. 2011, Sherwin et al. 2011

Same story, but with SPT data:



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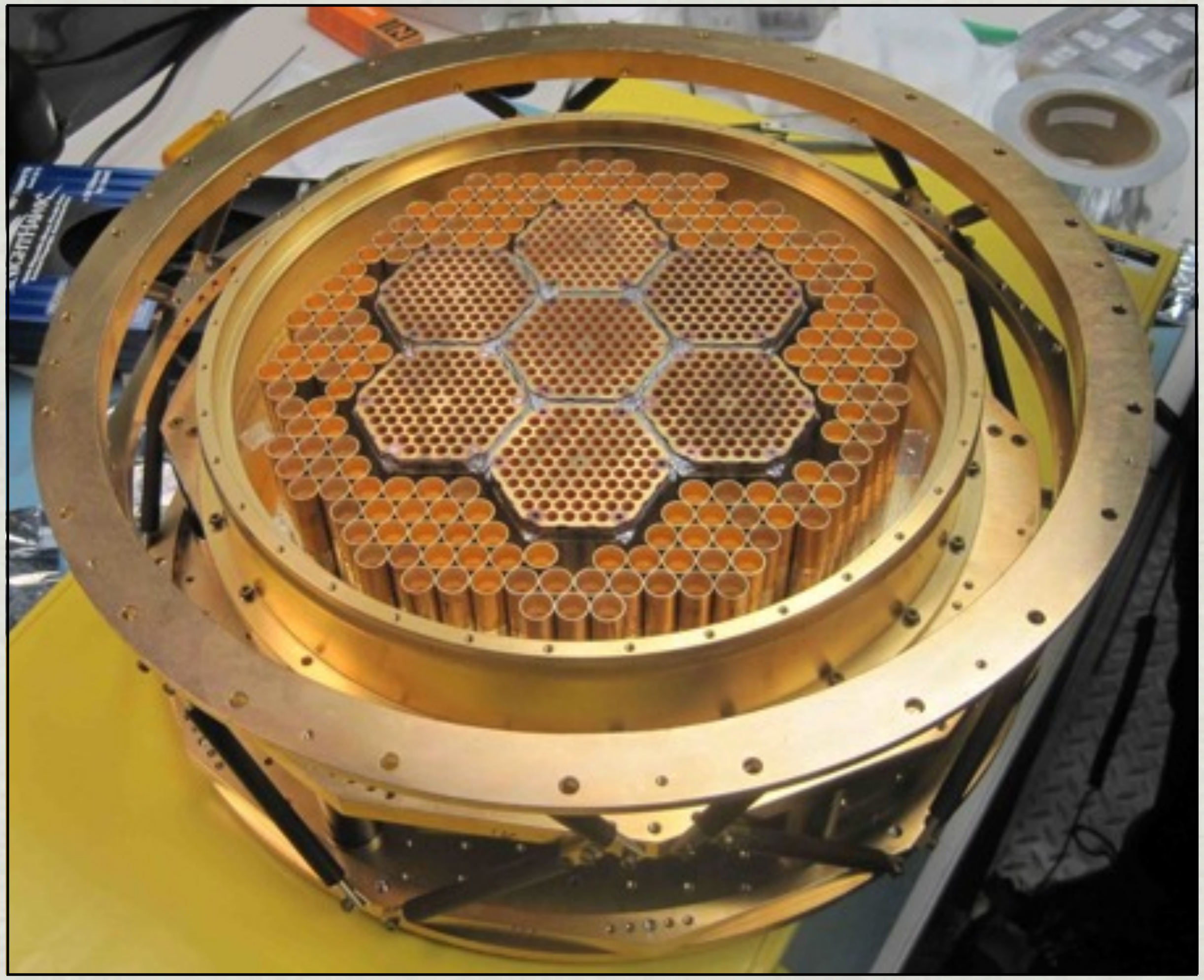
SPTpol

A new *polarization*-sensitive camera for SPT



Science targets:

- first measurement of "B-mode" polarization of CMB
- constrain neutrino mass
- constrain energy scale of inflation

Status:

- First light was seen in Jan. 2012.
- Operating well.
  Potential to detect "lensing B-modes" using 2012 data.

Summary

- CMB data can now constrain the number of relativistic particle species present in the early universe.

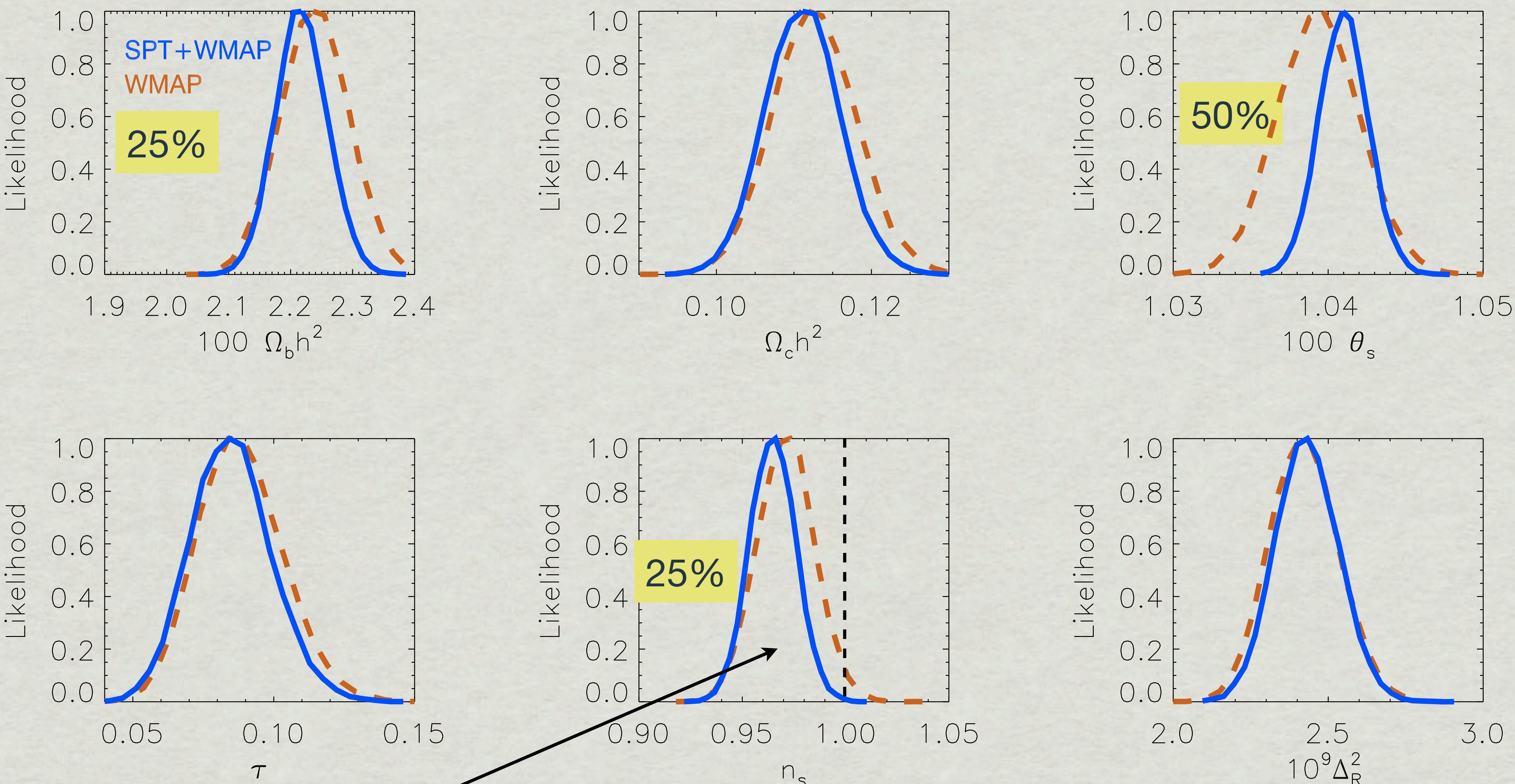
- Gravitational lensing of the CMB has been detected and provides a new cosmological probe.

- New generation of high-resolution, polarization-sensitive cameras like SPT-pol is coming online now.

- Long-term goals:
  measure neutrino mass,
  measure energy scale of inflation

extra slides

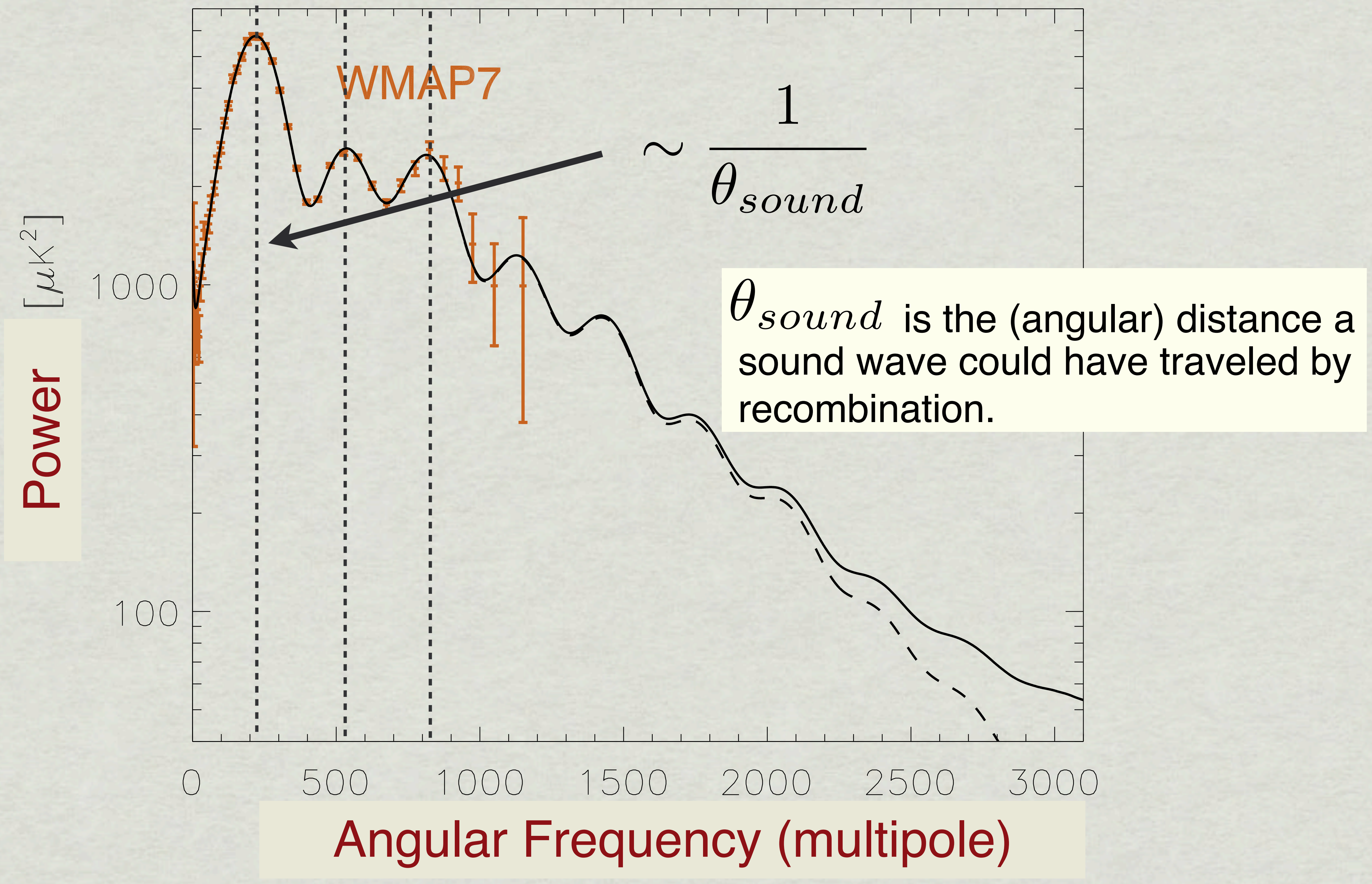
SPT provides modest improvement on 6 “vanilla” cosmo. parameters



$$n_s = 0.965 \pm 0.011$$

(3.2σ preference for n_s<1 inflation-like)

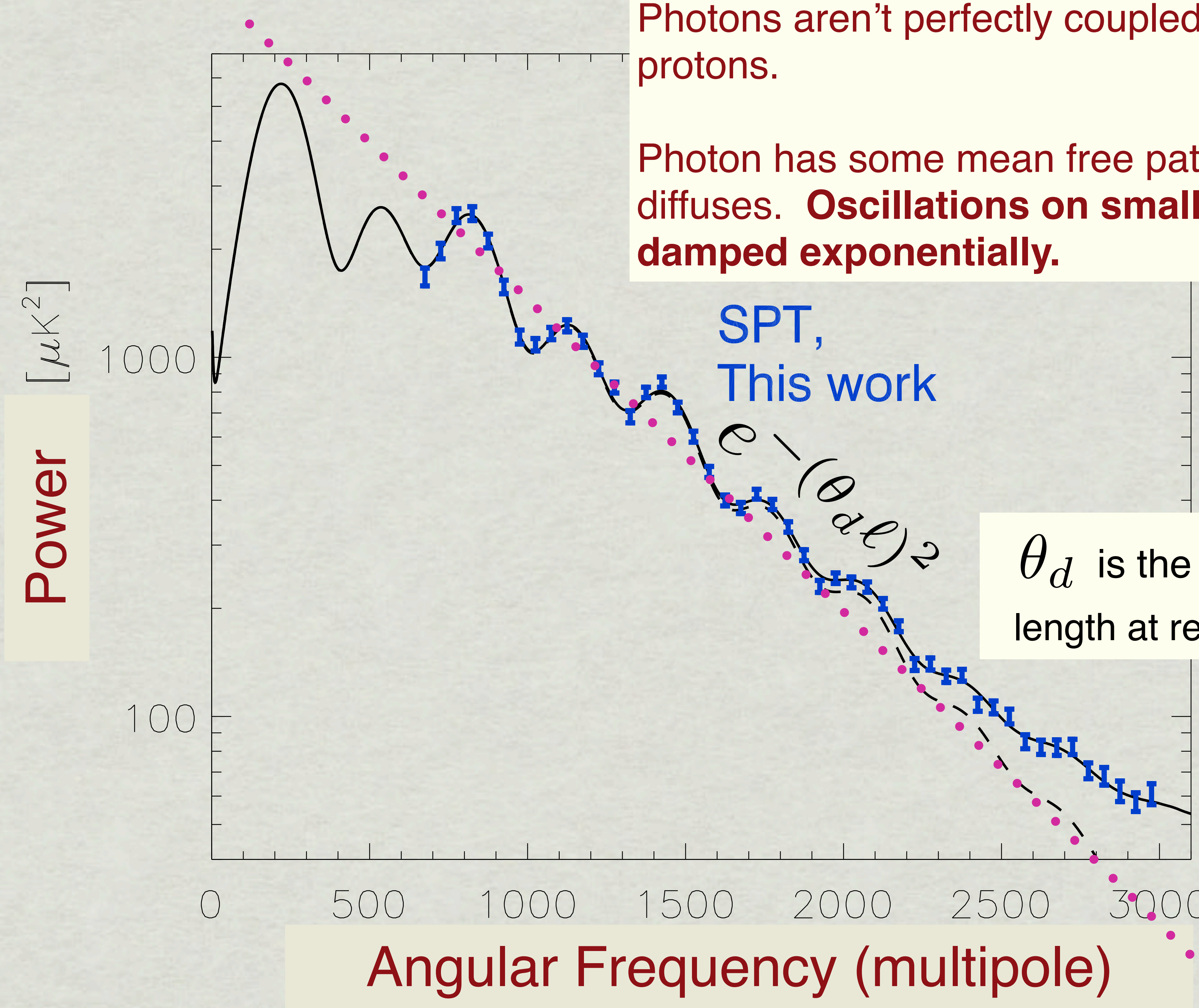
The *Sound* Scale



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.

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.

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

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 $\frac{\rho_m}{\rho_\gamma + \rho_\nu} = 1 + z_{\rm EQ}$ 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...

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

~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.*

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

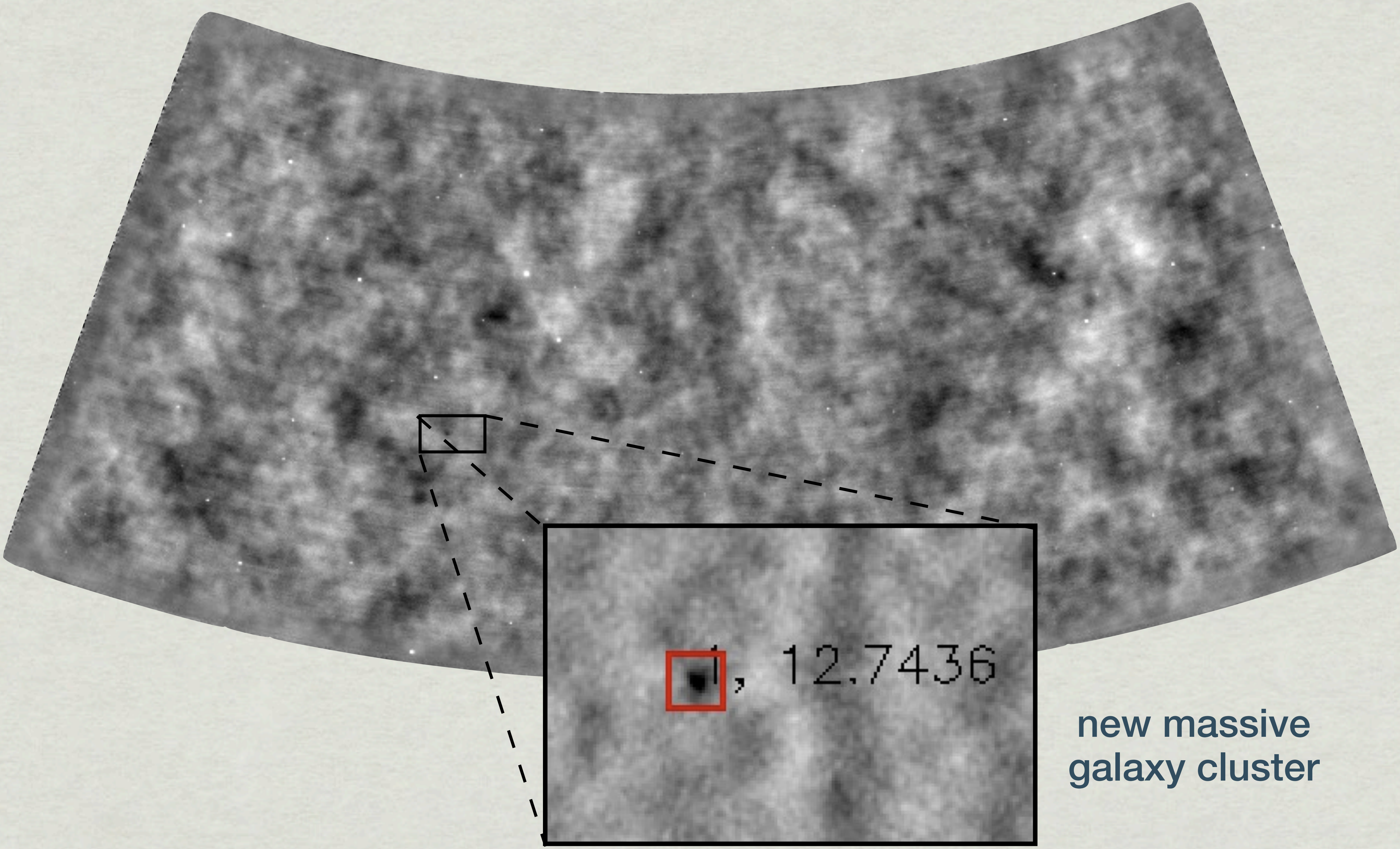
The standard value is **Neff = 3.046.**

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.

SPT map



new massive
galaxy cluster

Timeline of CMB Lensing Measurements

- 2007: 3σ (WMAP+) *Smith et al*
- 2008: 3σ (ACBAR) *Reichardt et al*
- 2011: <2σ (WMAP7) *Smidt et al*
- 2011: 4σ (ACT) *Das et al*
- 2011: 5σ (SPT) *Keisler et al*
- 2012: 6σ (SPT) *van Engelen et al*

- 2012: ~20σ (SPT)
- 2013: ~30σ (PLANCK) [all-sky]
- 2013: >40(?) σ (SPTPol; ACTPol) [500+ sq deg]
  +Polarbear; +Polar