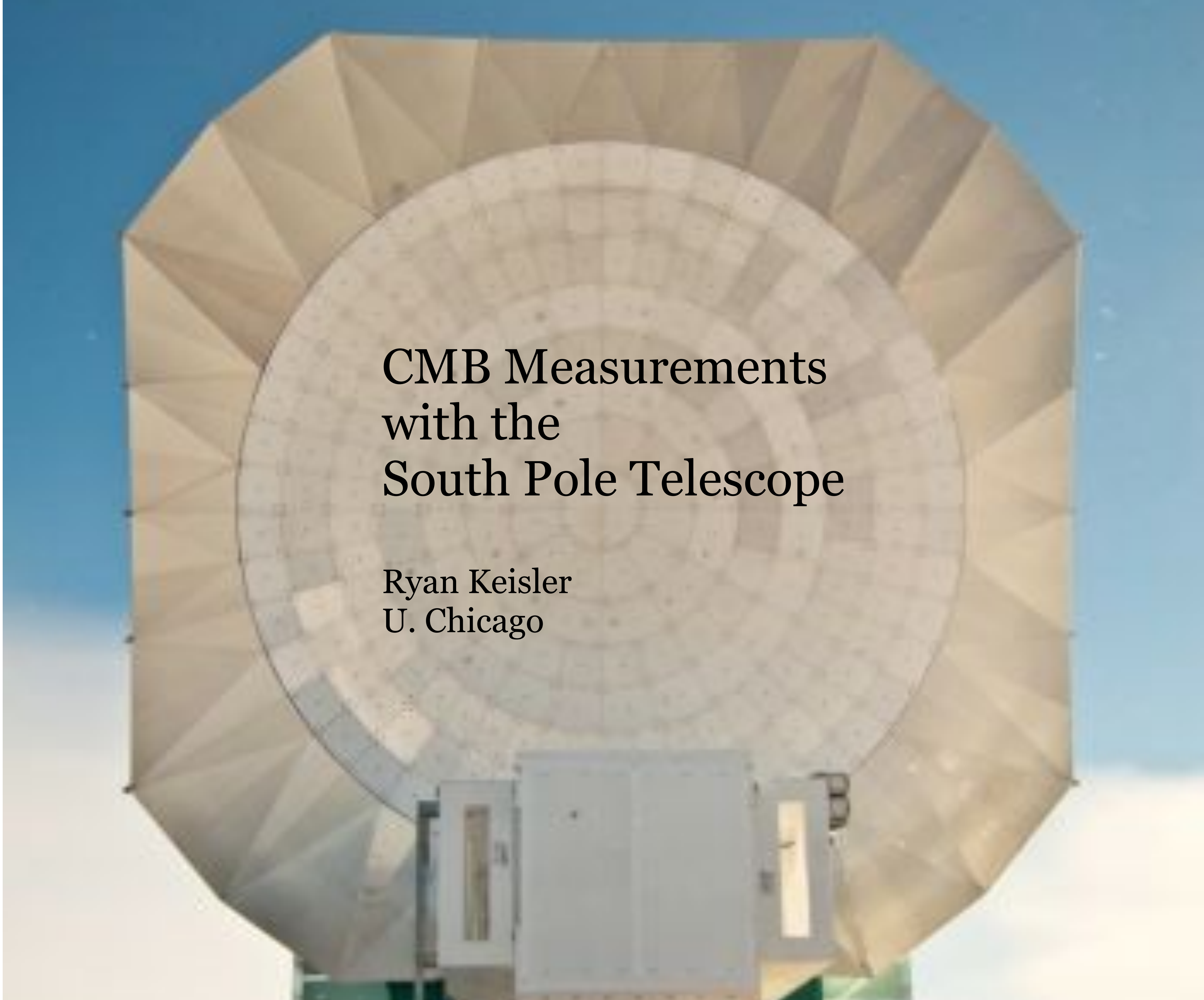
CMB Measurements with the South Pole Telescope

Ryan Keisler
U. Chicago



Outline

1. very brief 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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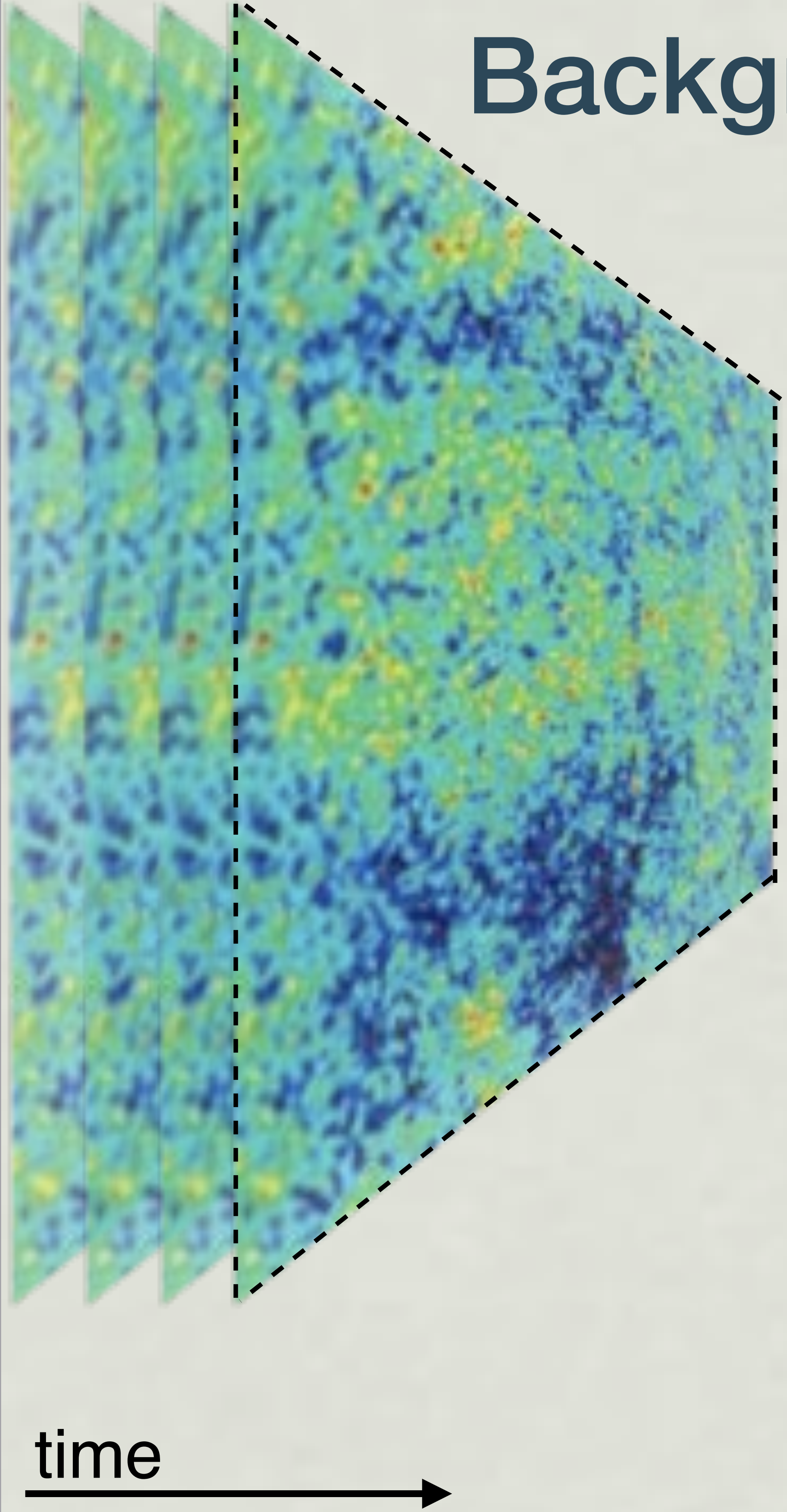
What is the Cosmic Microwave Background?

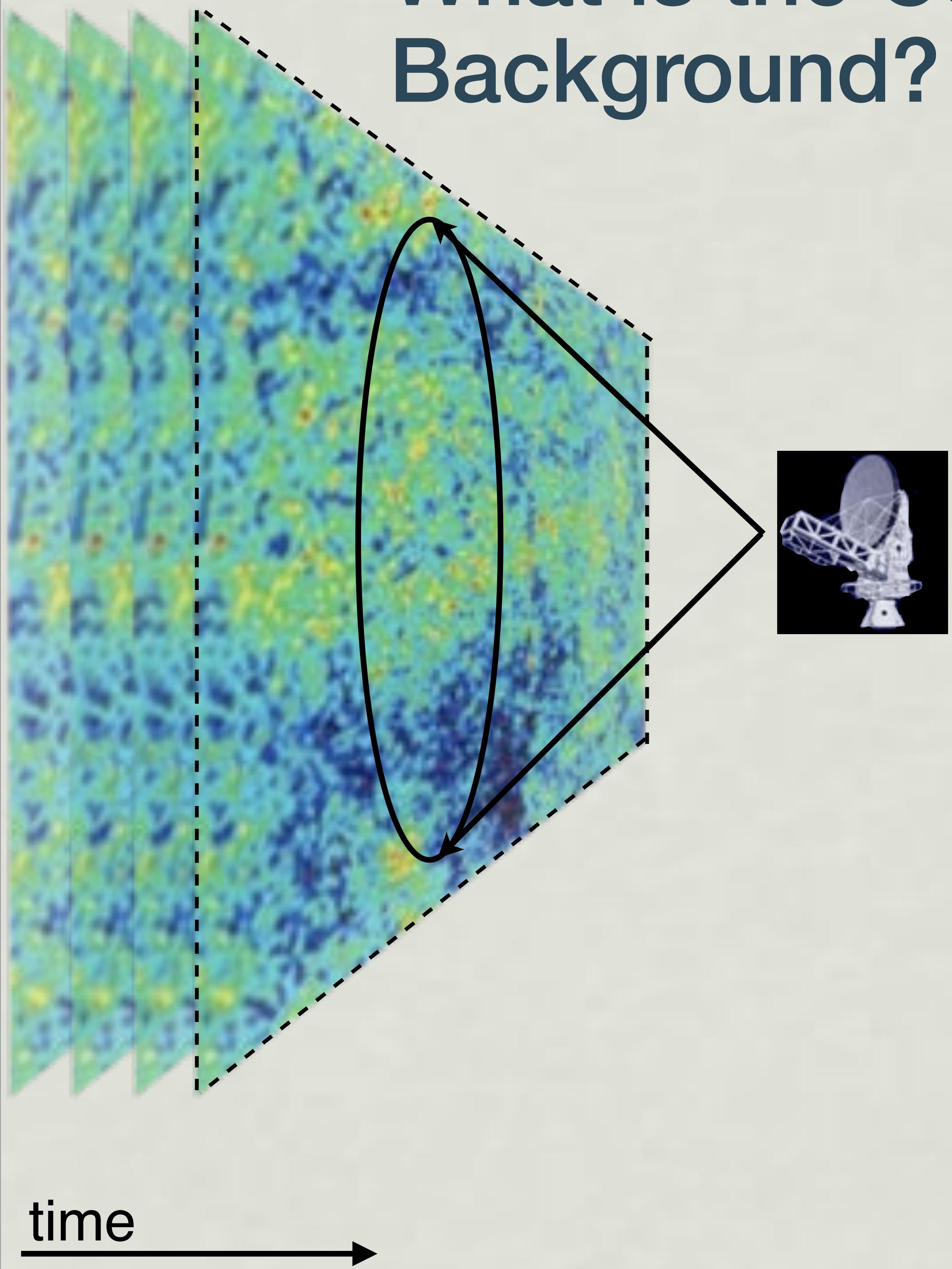


The constituents of the early universe (photons, electrons, protons, dark matter, neutrinos, ...) were coupled.

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

=> **oscillations**

What is the Cosmic Microwave Background?



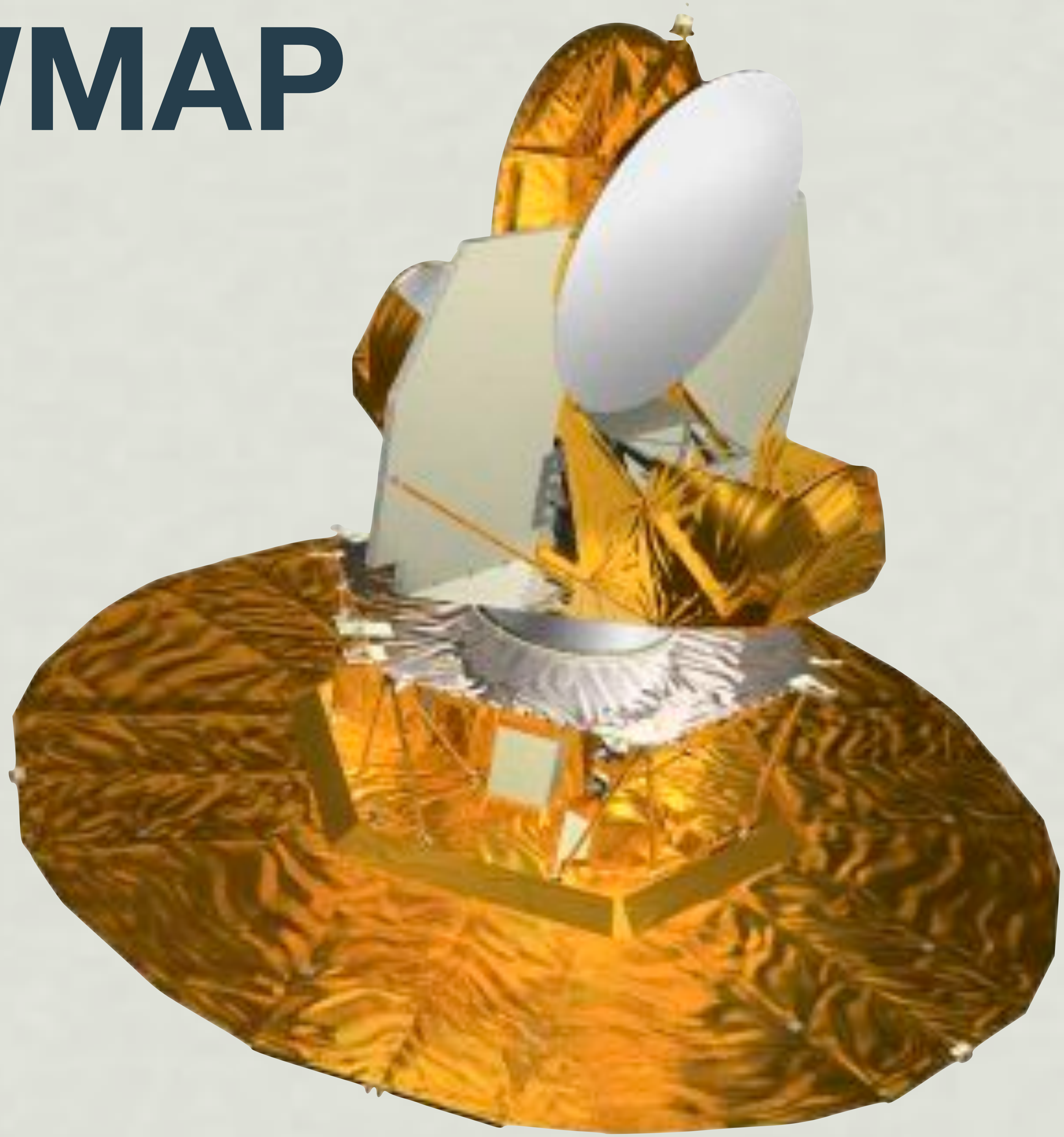
Eventually the universe expands and cools such that **neutral hydrogen can form**. "Recombination"

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

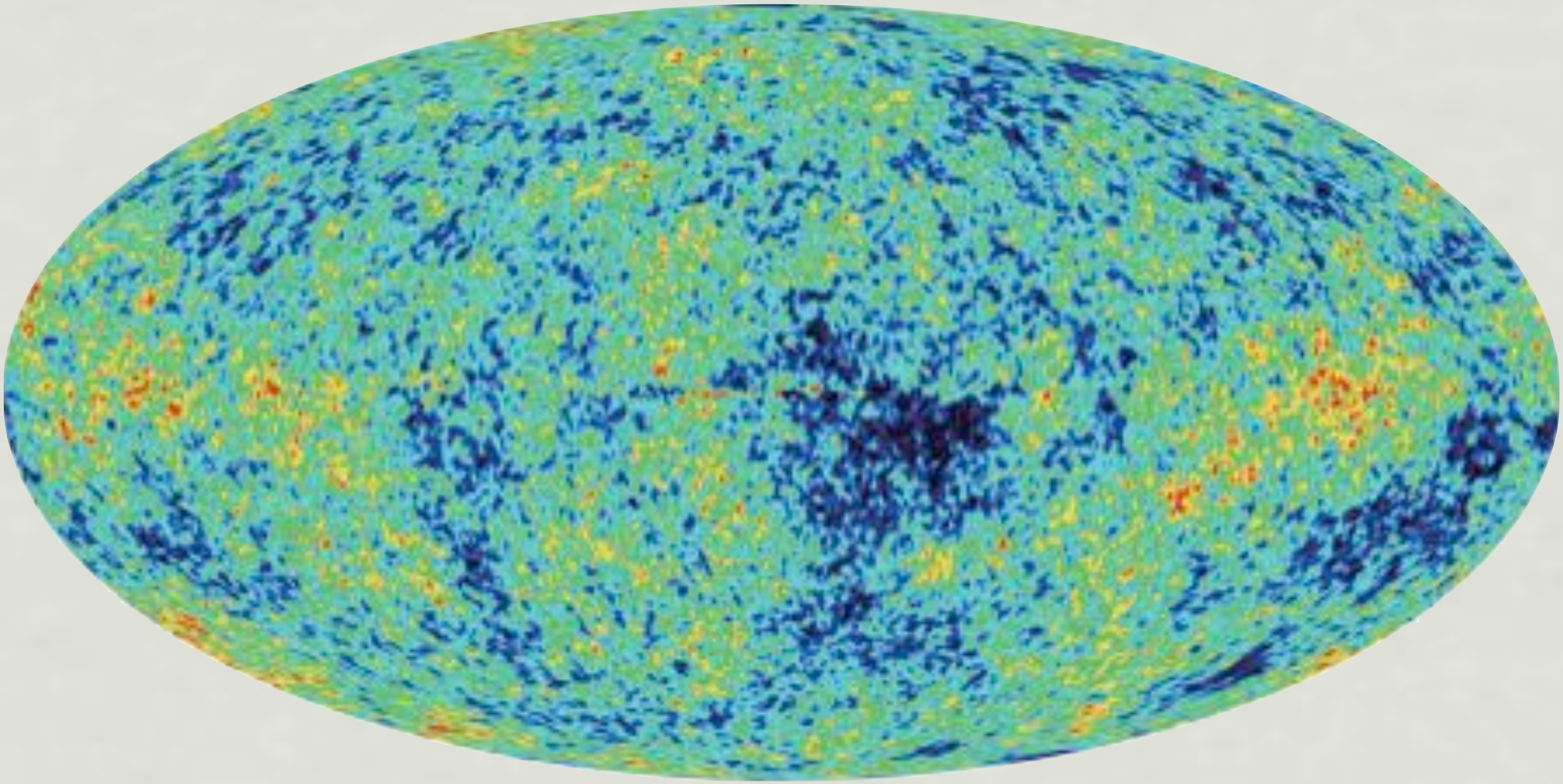
=> **Photons can travel freely**, and we see them today as a blackbody with T=2.73K.

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

WMAP



WMAP



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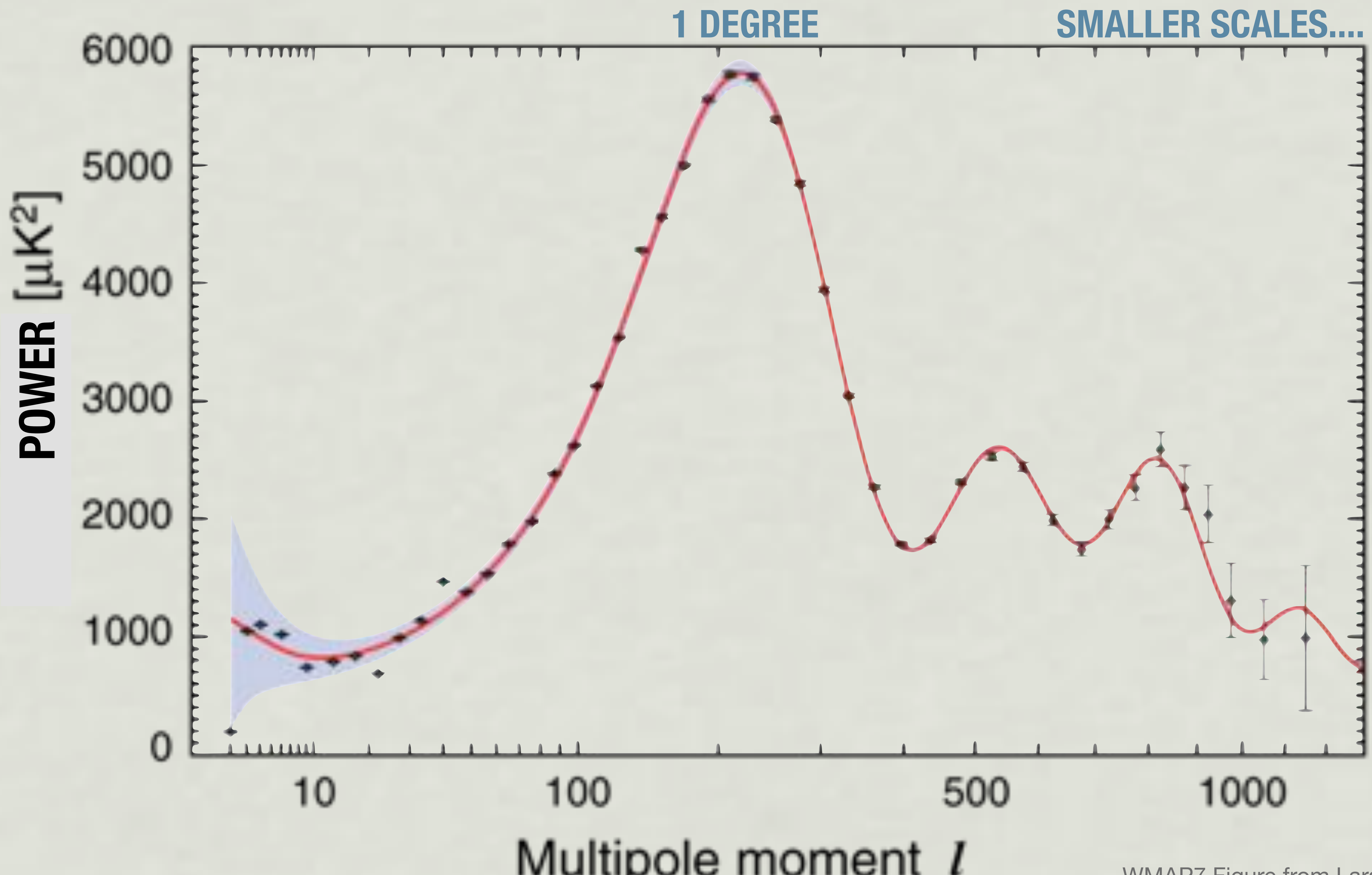
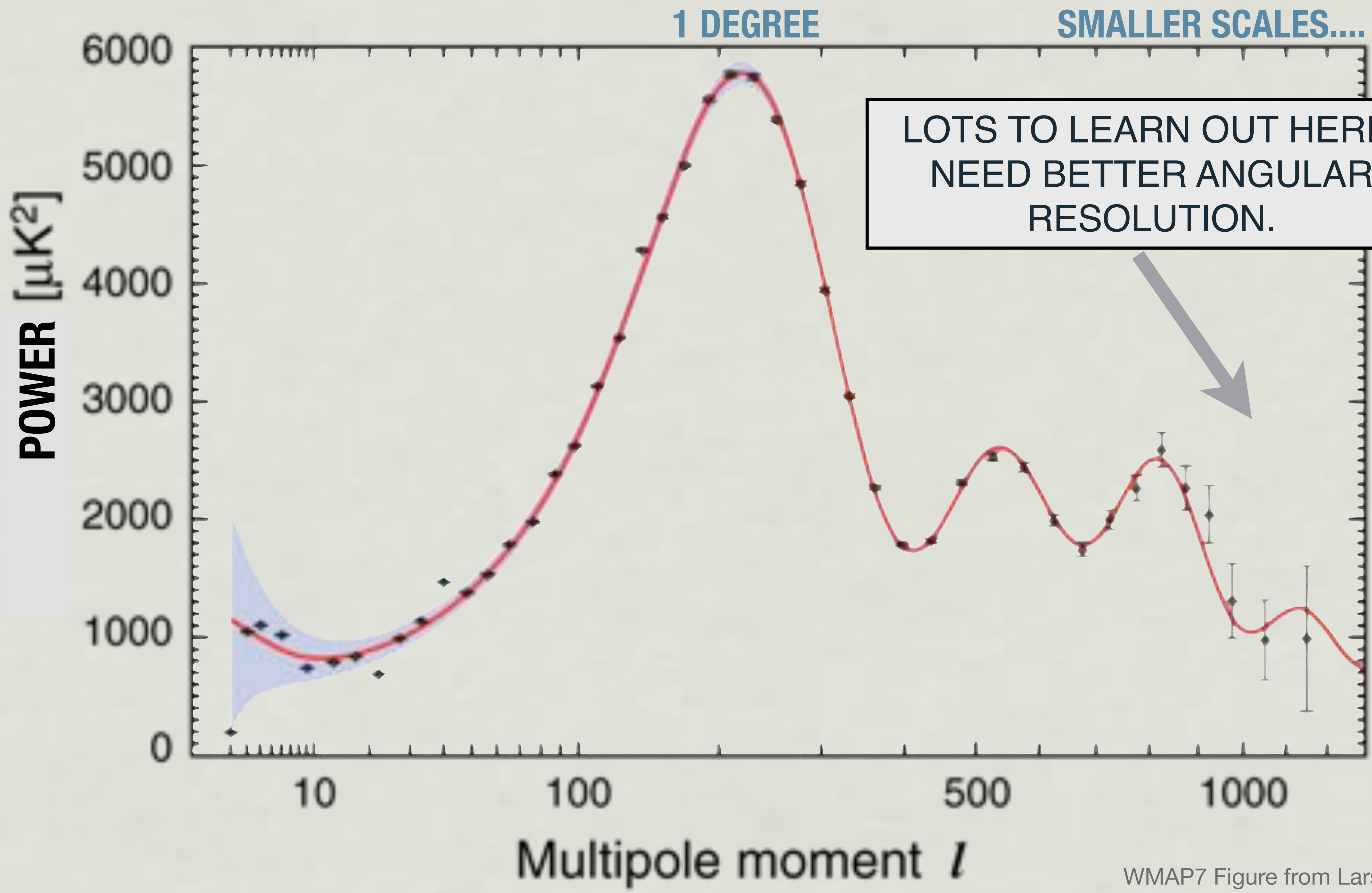


WMAP7 Figure from Larson et al.

WMAP



WMAP7 Figure from Larson et al.

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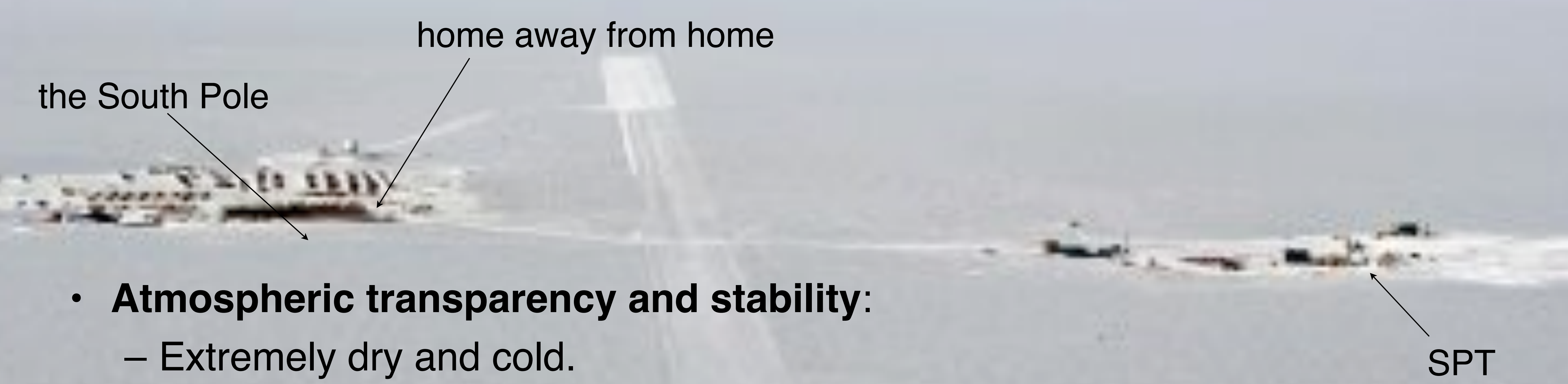
The South Pole Telescope:
a mm-wave observatory

- 10 meter primary mirror
  ~1 arcminute resolution
- 1st camera: 1000 bolometers.
  3 bands: 3.2, 2.0, 1.4 mm.
  2007-2011. “SPT-SZ”
- 2nd camera: 1600 bolometers.
  polarization-sensitive.
  2 bands: 3.2, 2.0 mm
  2012-?. “SPT-POL".

Chicago
Berkeley
Case Western
McGill
Boulder
Harvard
Caltech
Munich
Michigan
Arizona
...

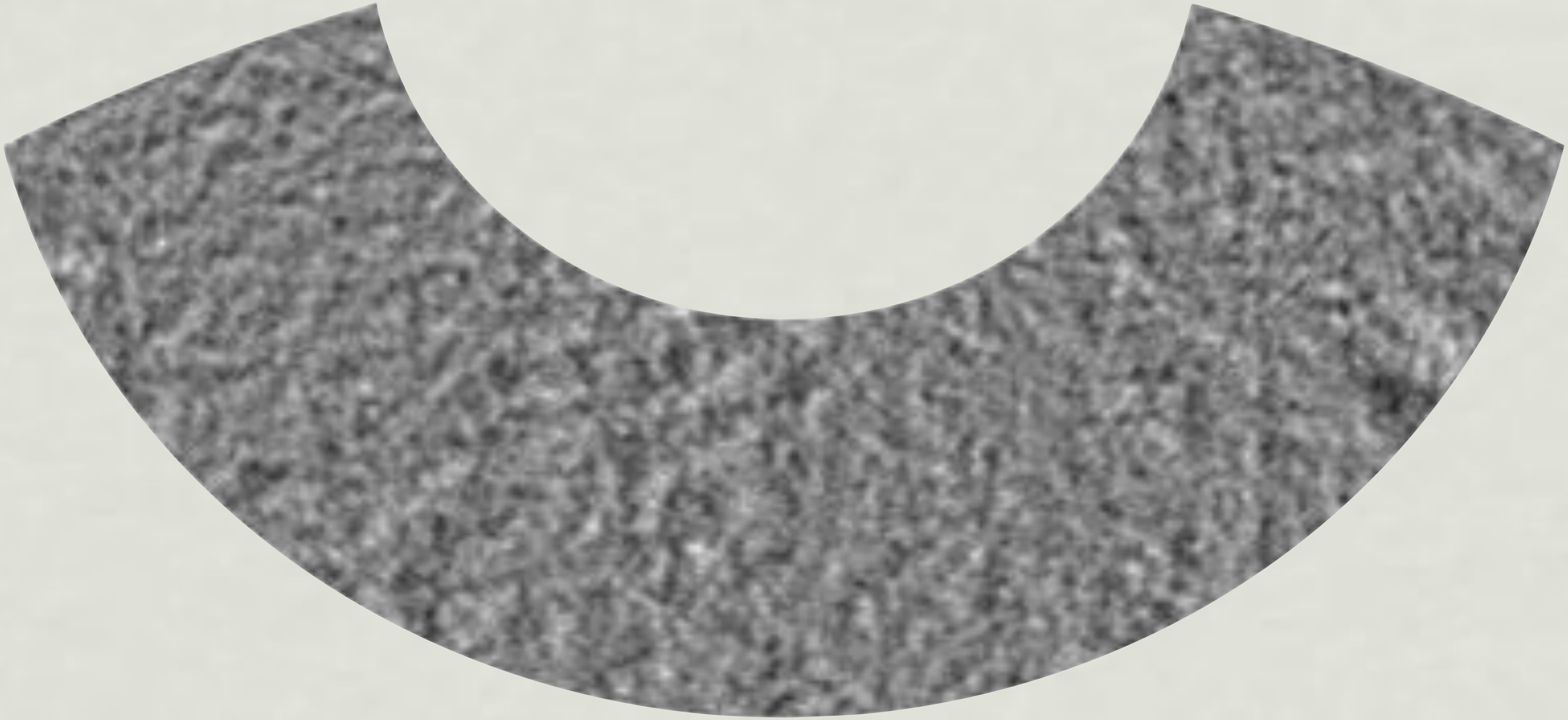
photo by Dana Hrubes

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-SZ 2500 deg^2 Survey
(*6% of sky*)



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

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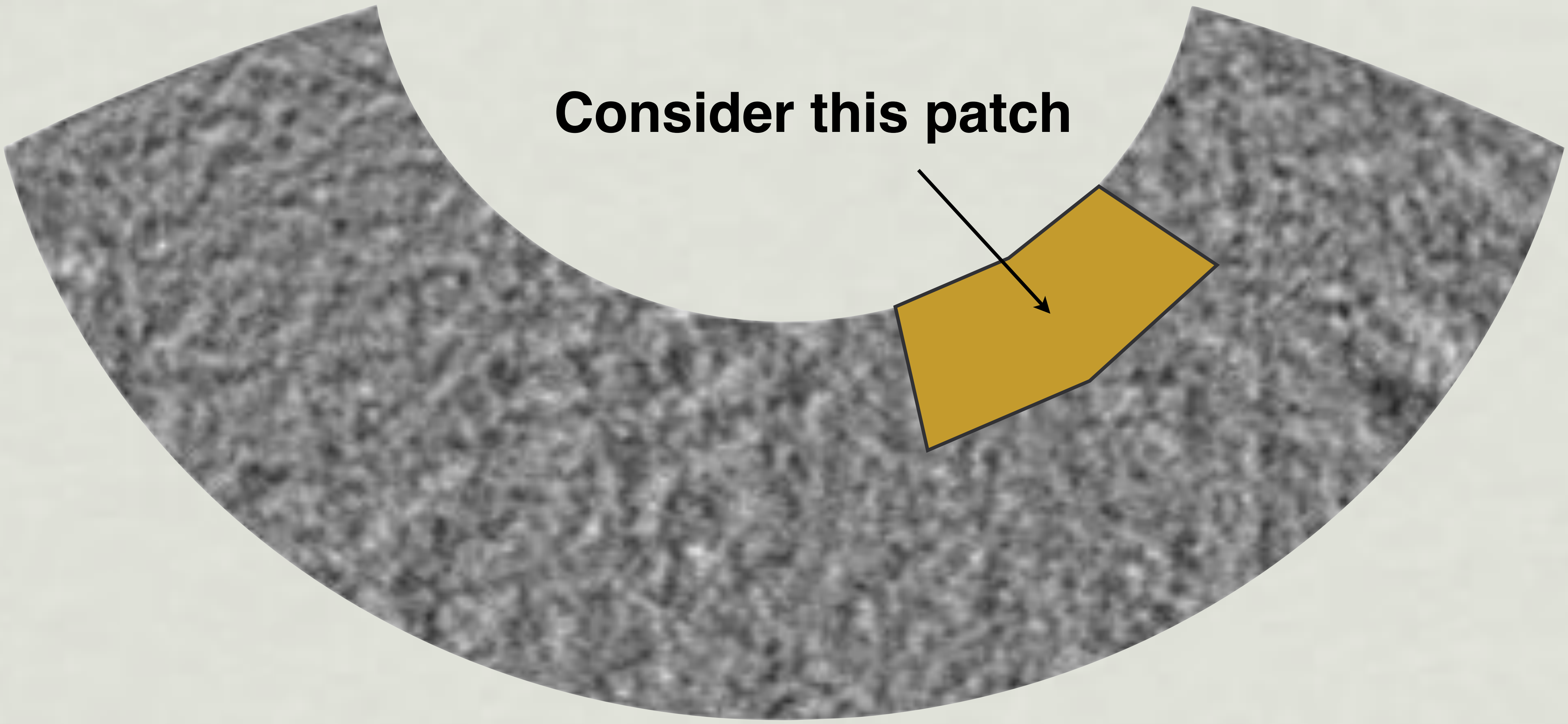

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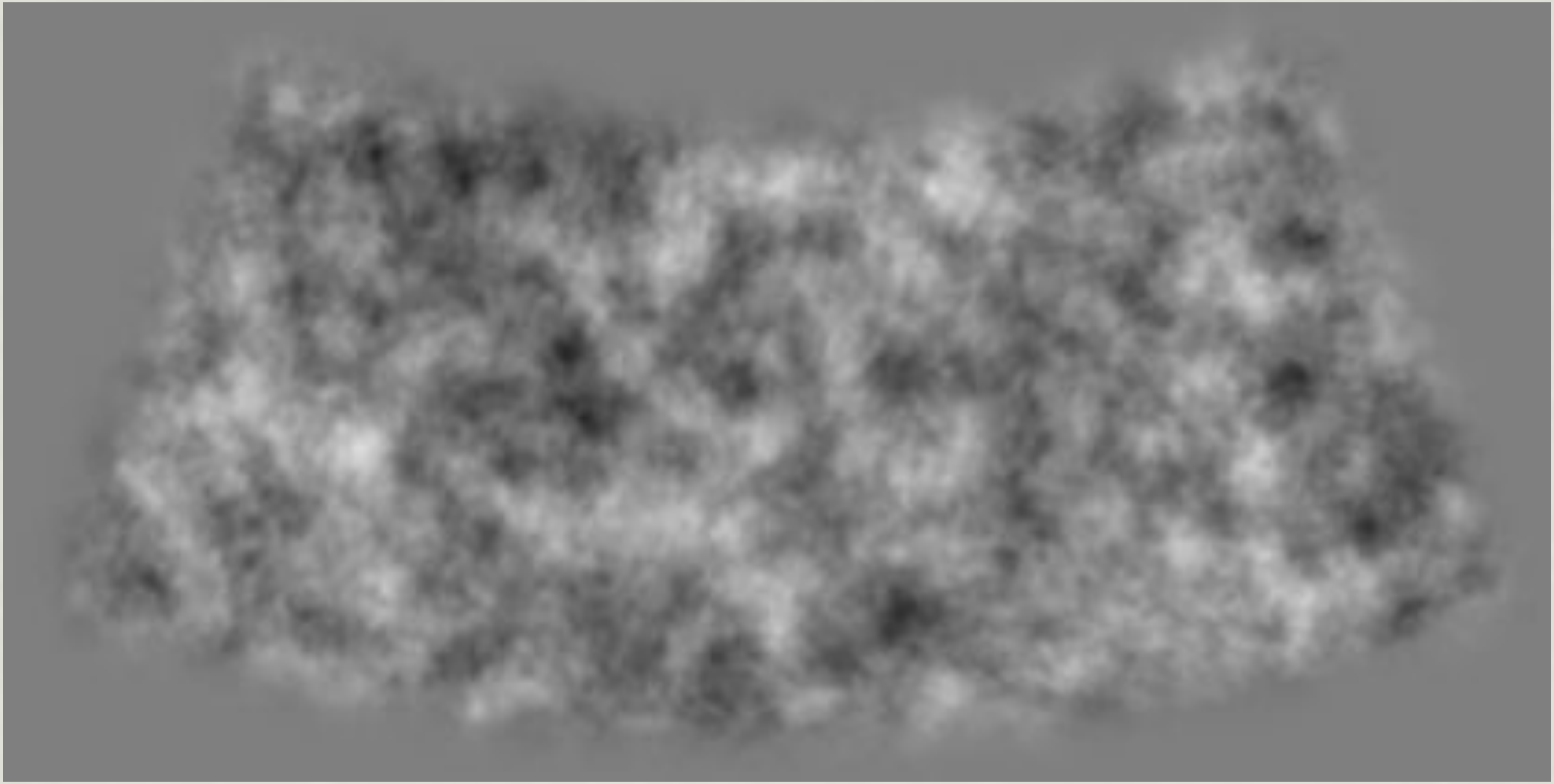
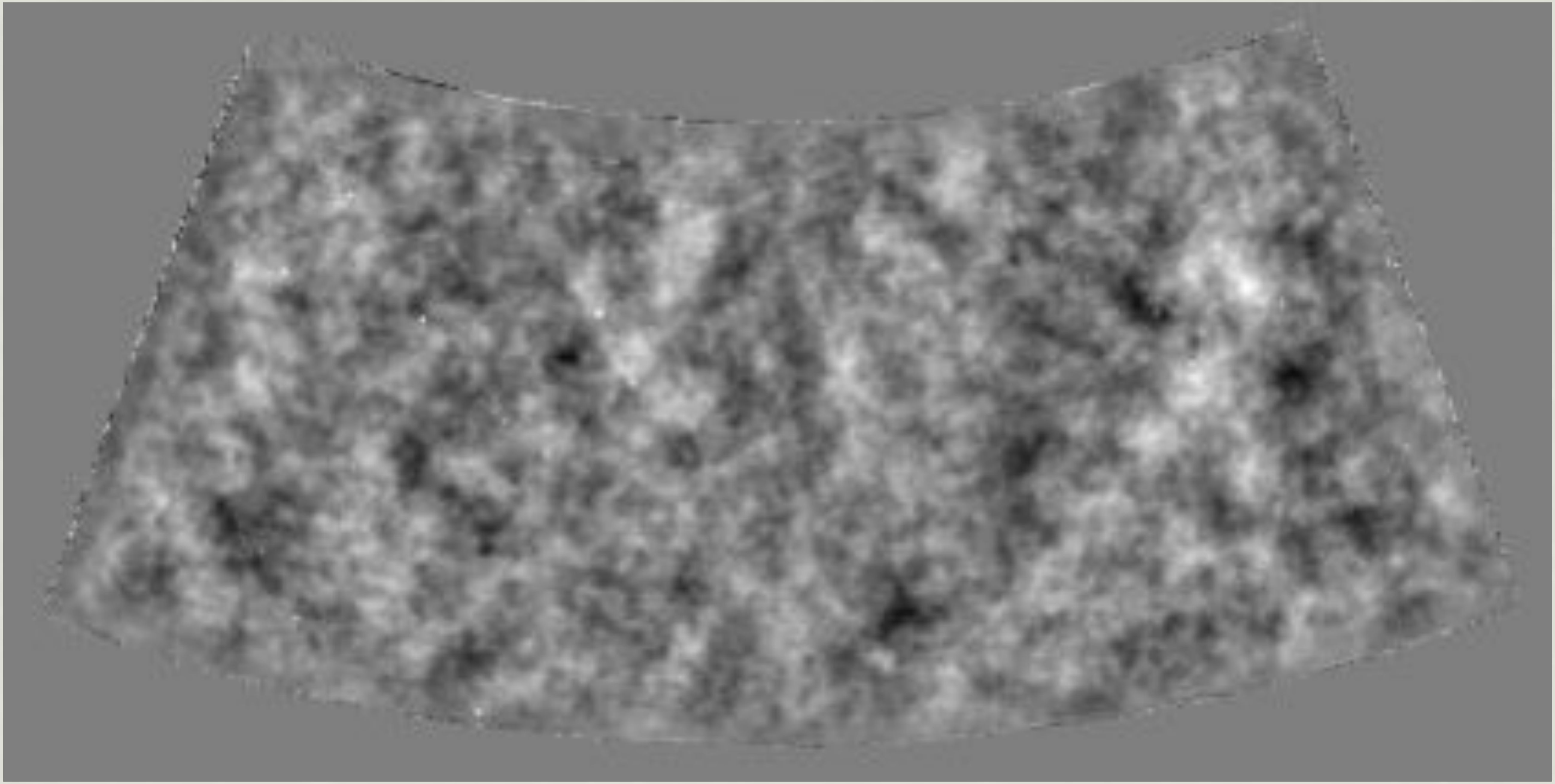
WMAP'S VIEW

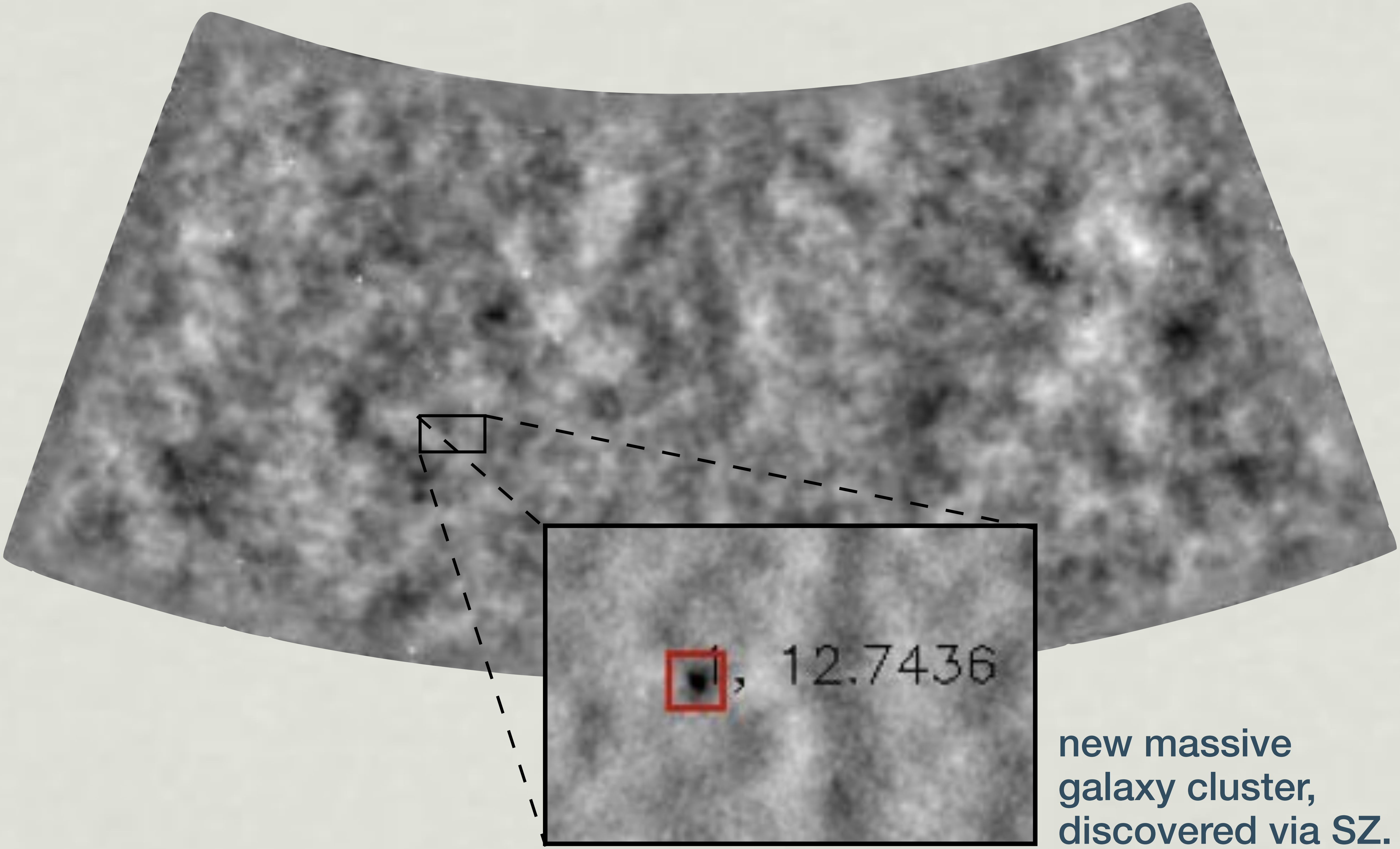


SPT'S VIEW



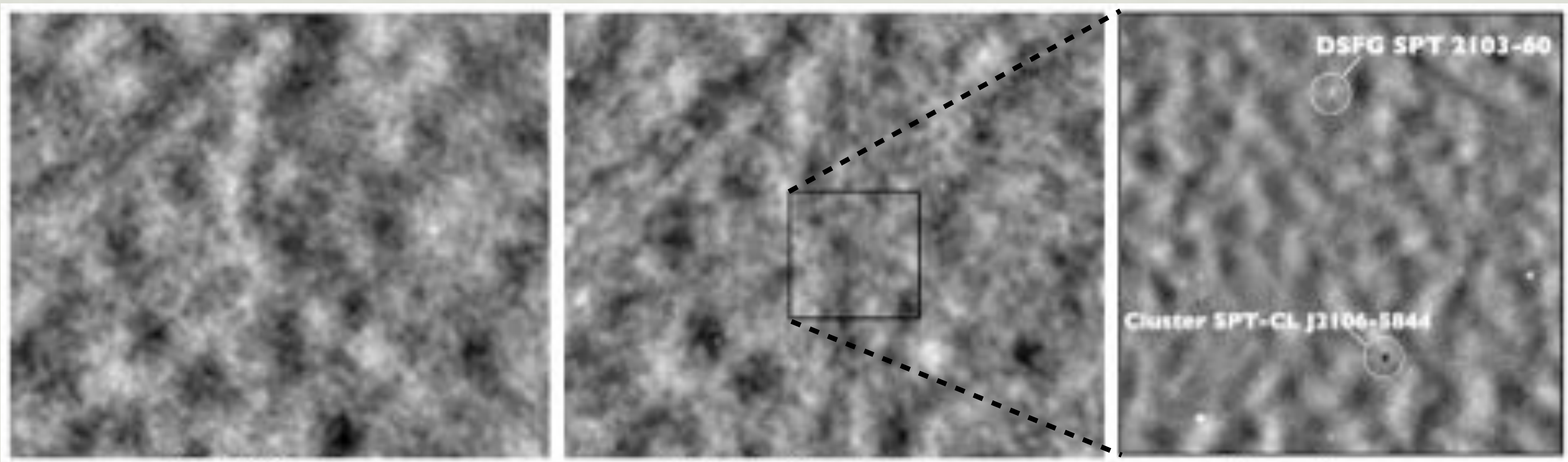
SPT has ~20X better resolution and lower noise than WMAP, but covers only ~6% of the sky. Complementary probes of CMB.

SPT map



new massive
galaxy cluster,
discovered via SZ.

WMAP SPT SPT ZOOM



WMAP W-band map Minimally filtered SPT-SZ map Cutout of SPT-SZ map

BRIEF DETOUR:There's a lot of other SPT science going on. Some examples:

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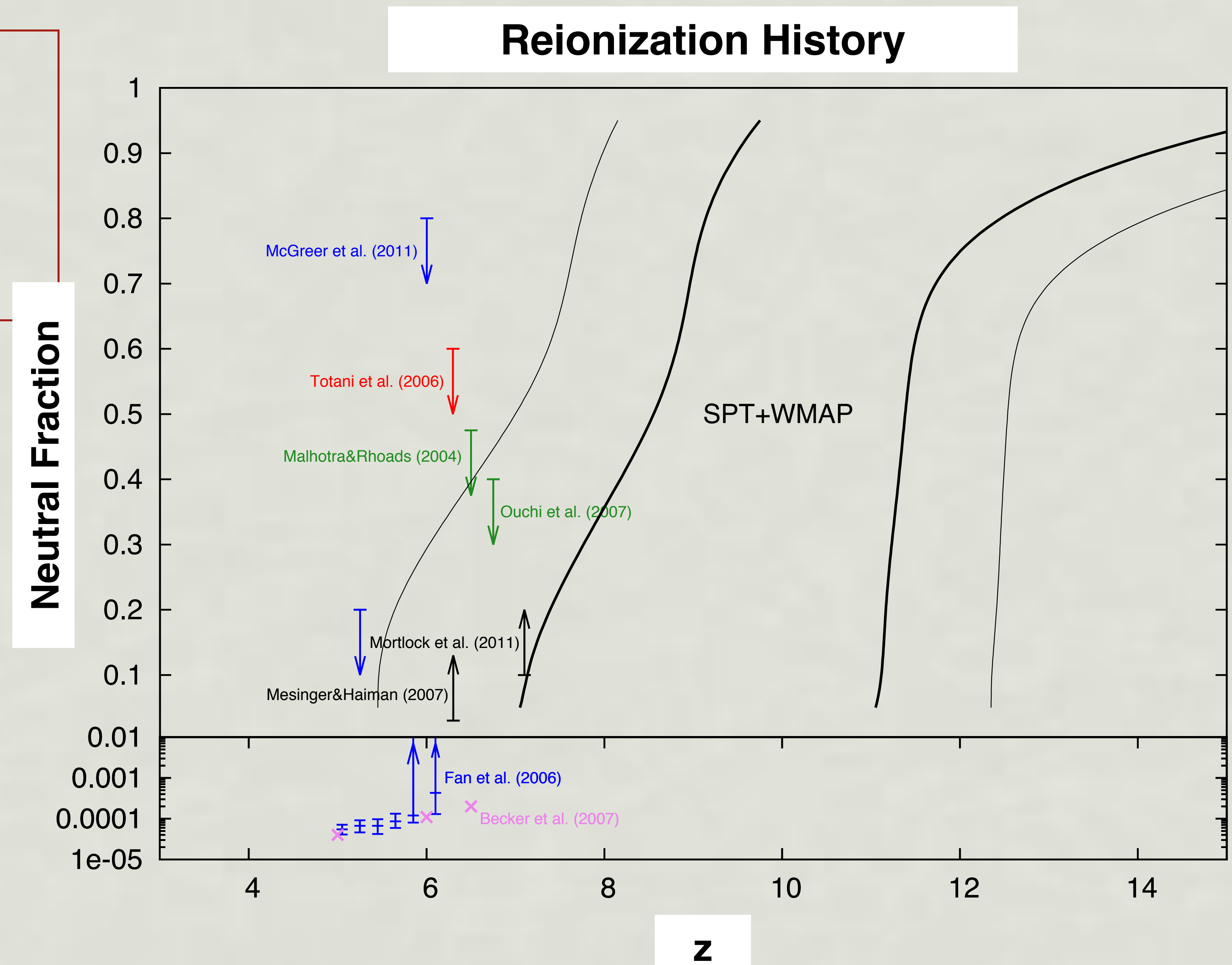
- Tight upper limits on diffuse **kinetic SZ**, and resulting constraints on **duration of reionization.**

- Discovery of 100s of new massive **galaxy clusters** via thermal Sunyaev-Zel’dovich (SZ) Effect.

- Emission from **high-z, dusty, star-forming galaxies** (individual & aggregate).

...



See Reichardt et al. (1111.0932) and Zahn et al (1111.6386)

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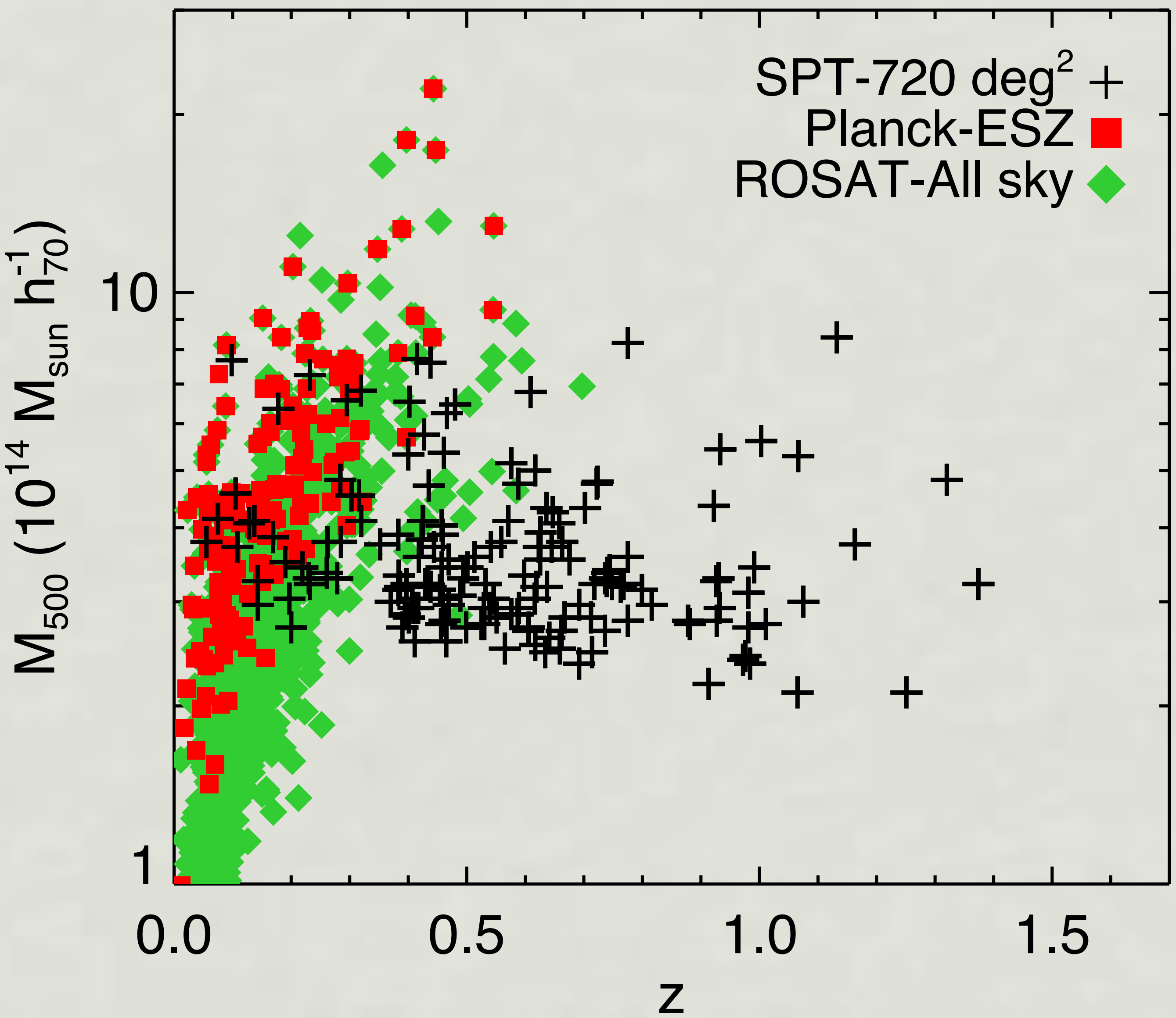

See Benson et al. (1112.5435) and Reichardt et al (1203.5775)

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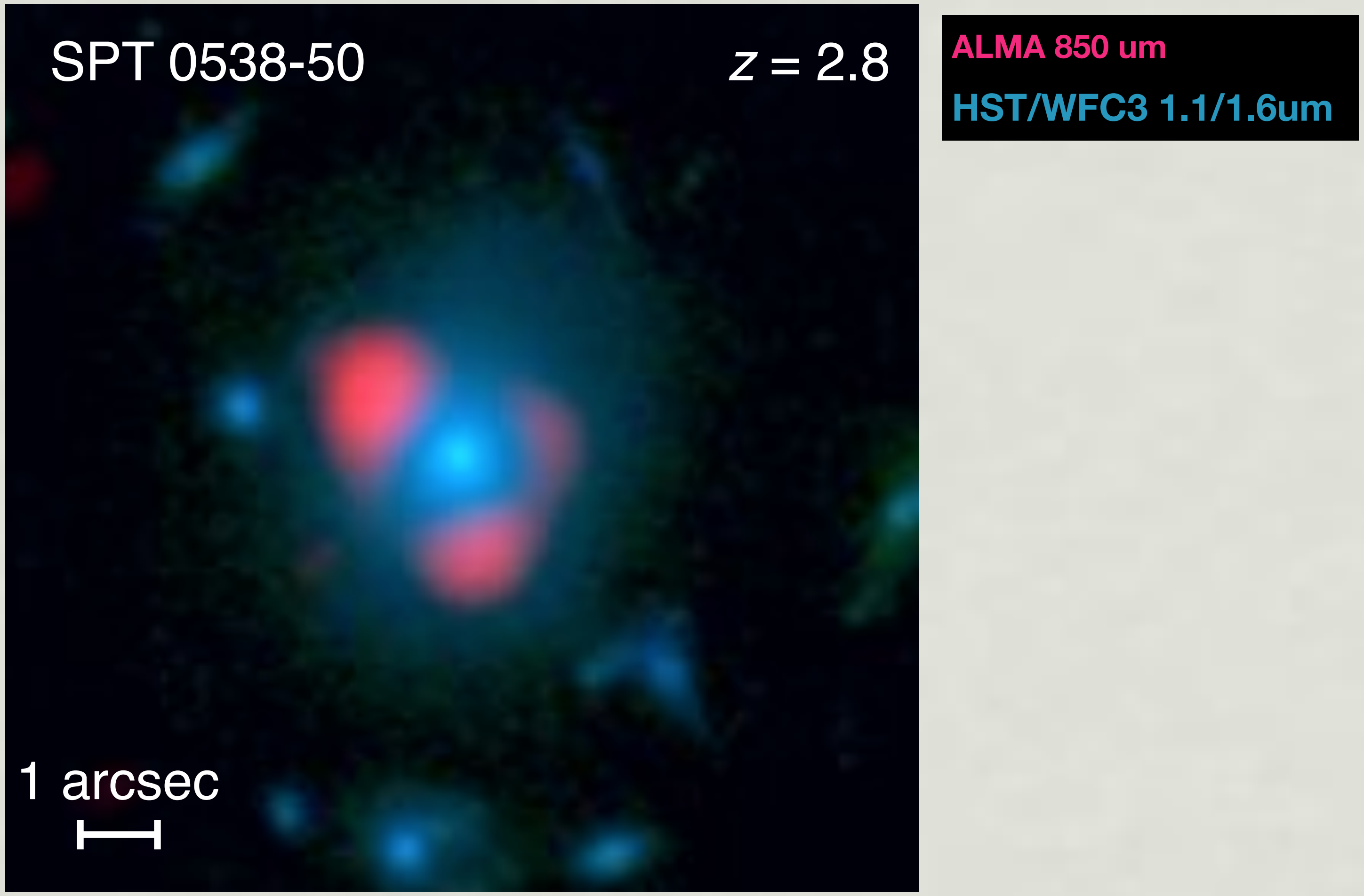
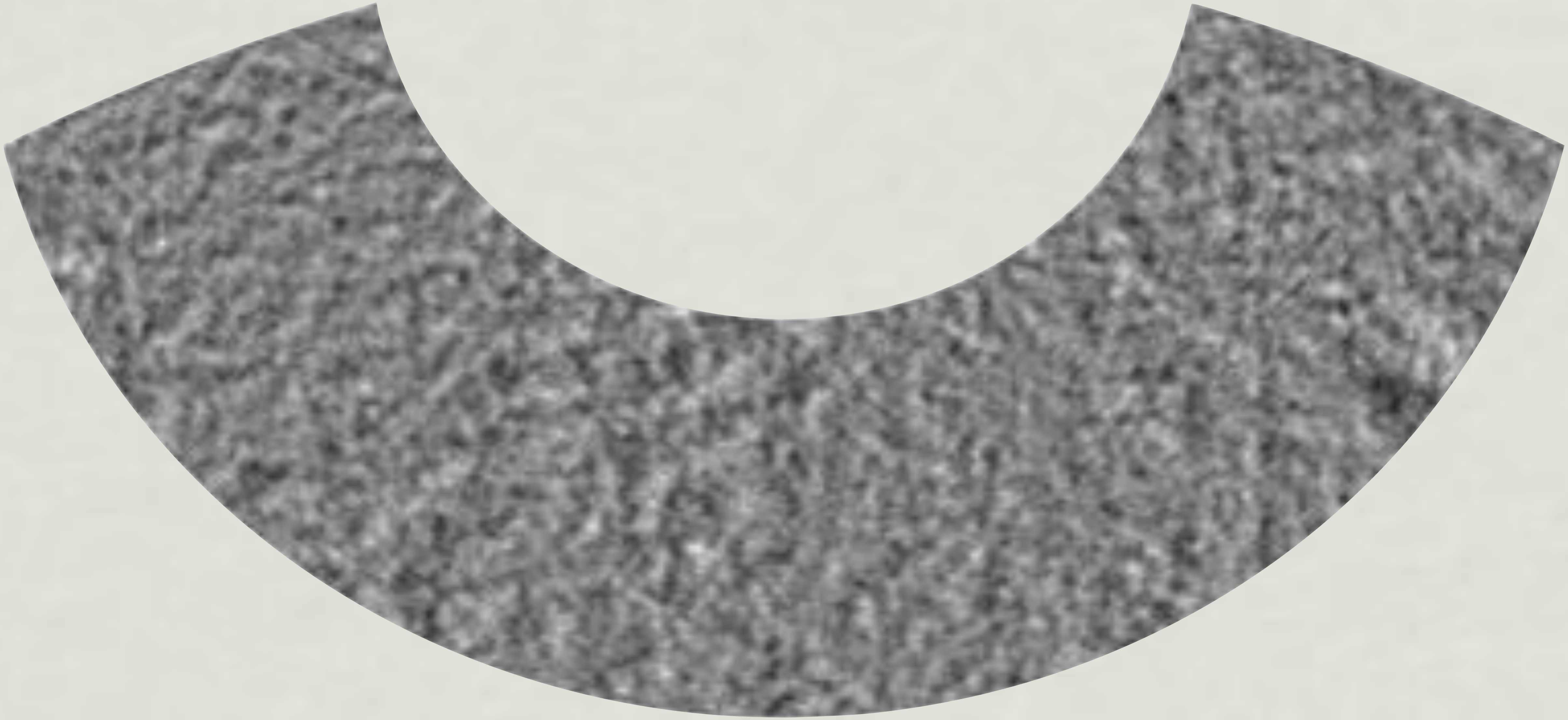


z=2.8 star-forming galaxy discovered by SPT.

Galaxy image is lensed by z=0.443 foreground galaxy, as shown clearly by ALMA and HST/WFC3.

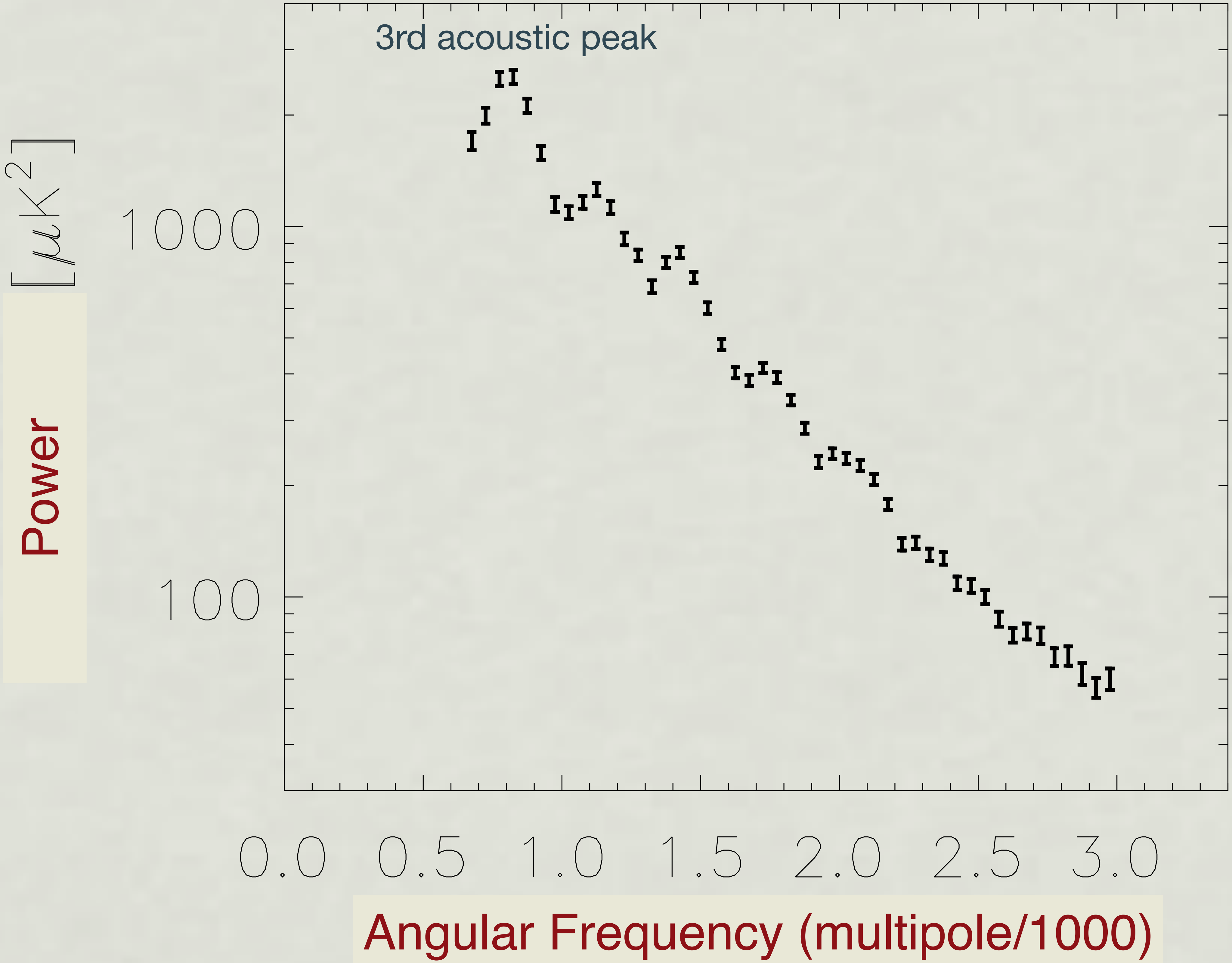
See Vieira et al. (0912.2338).

DETOUR OVER.
Take the angular power spectrum of 1/3 of this:

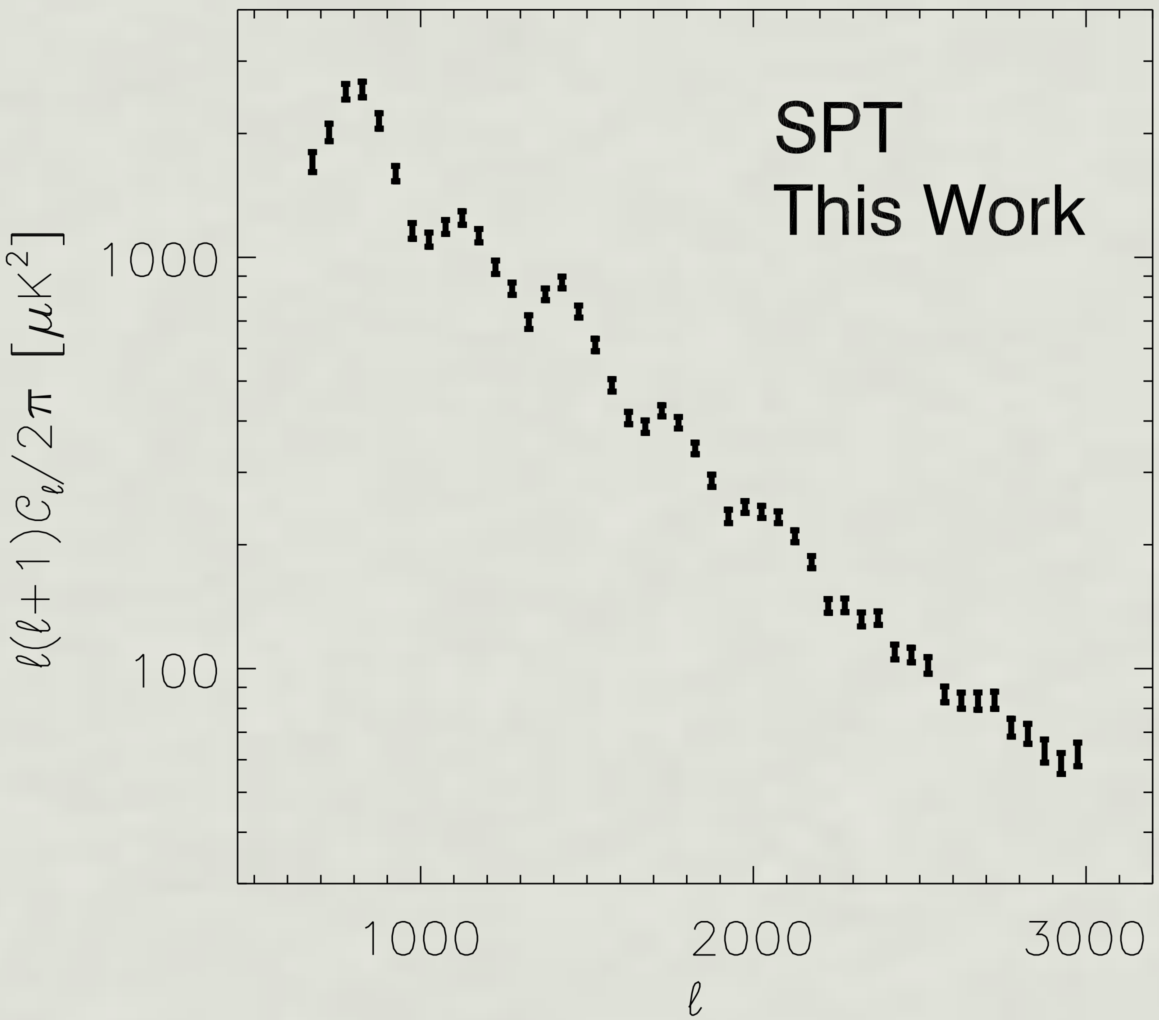


See , arXiv:1105.3182 (RK, C. Reichardt *et al.,* ApJ, 2011).

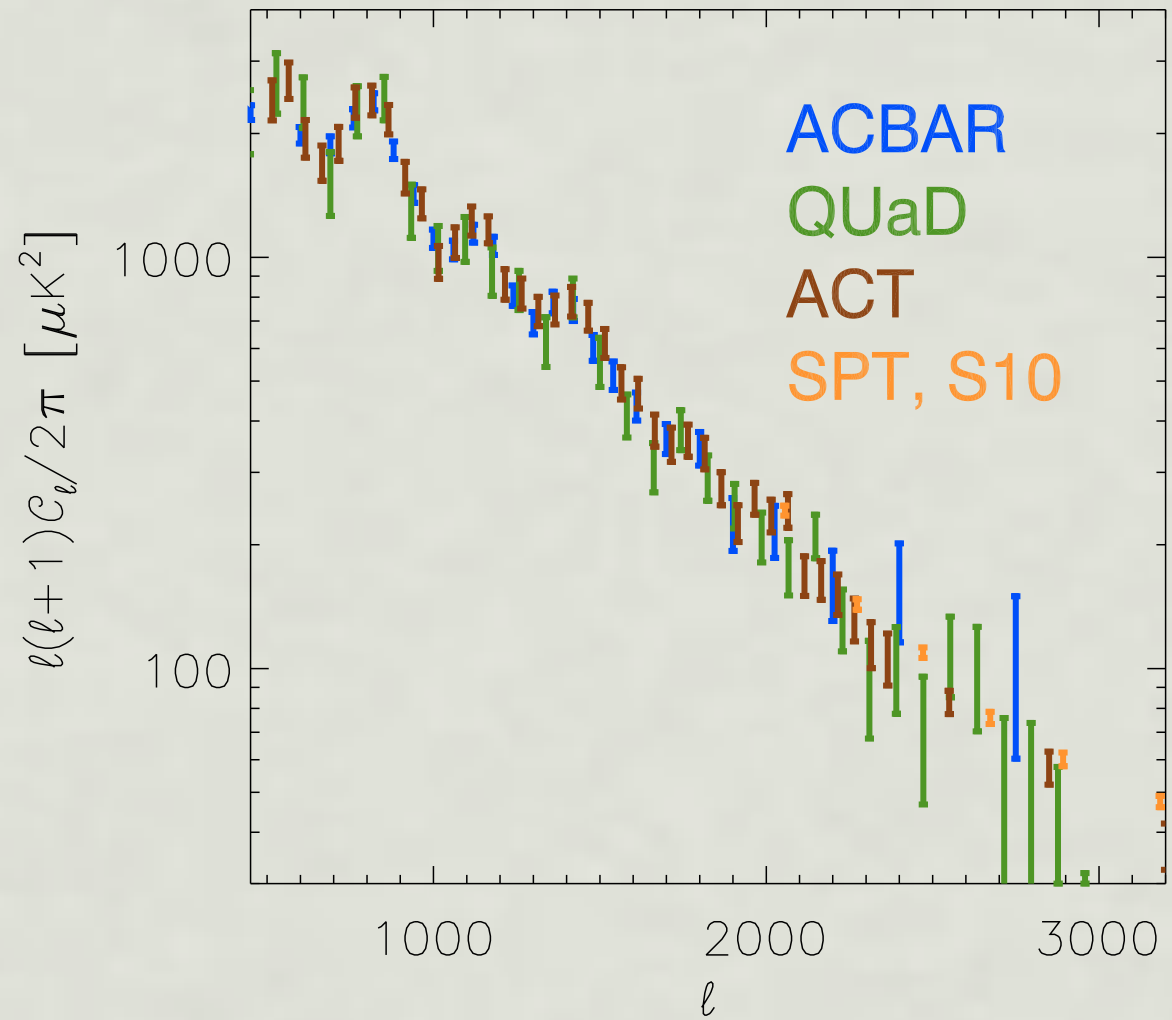
...and you get this.



This work



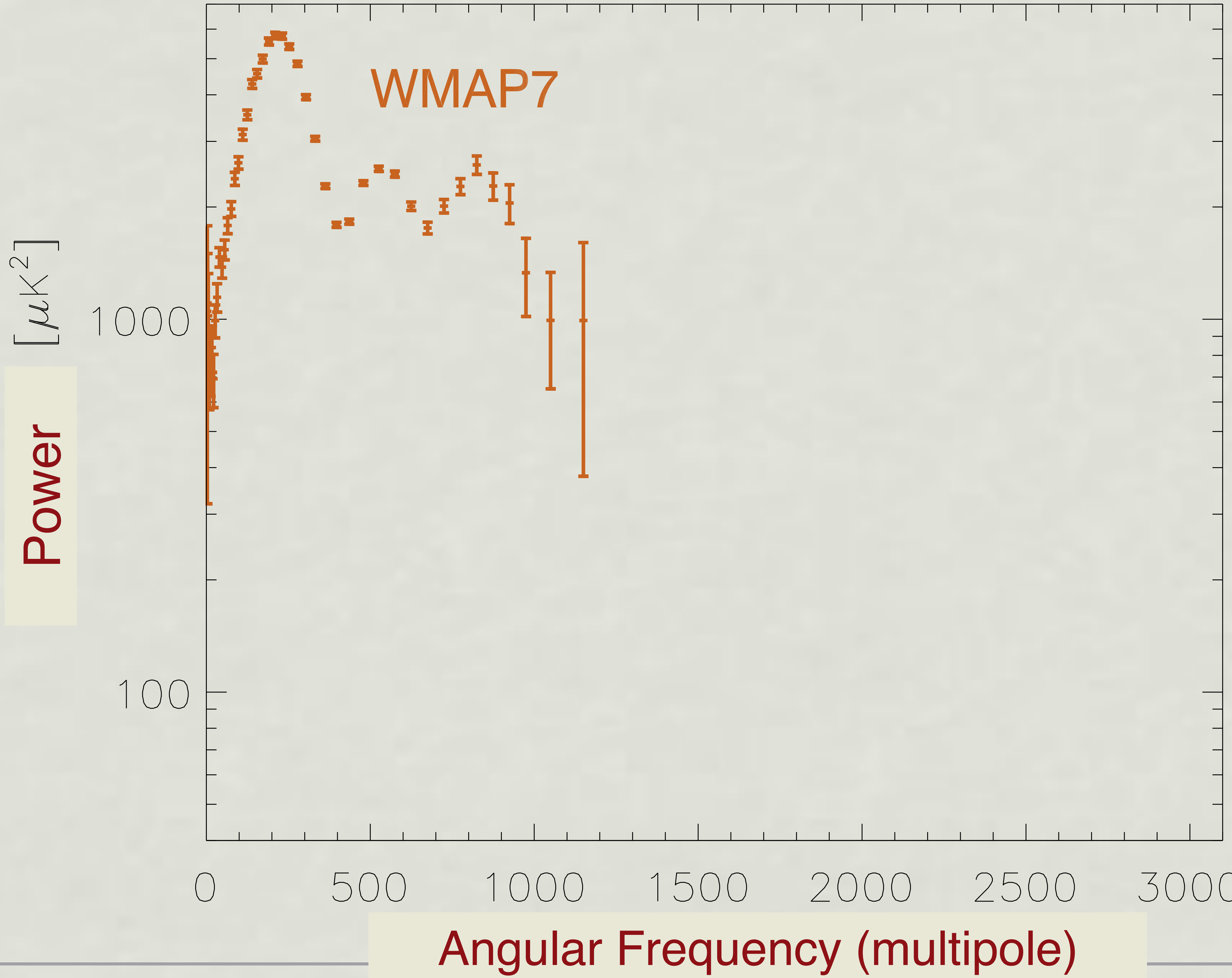
Previous works



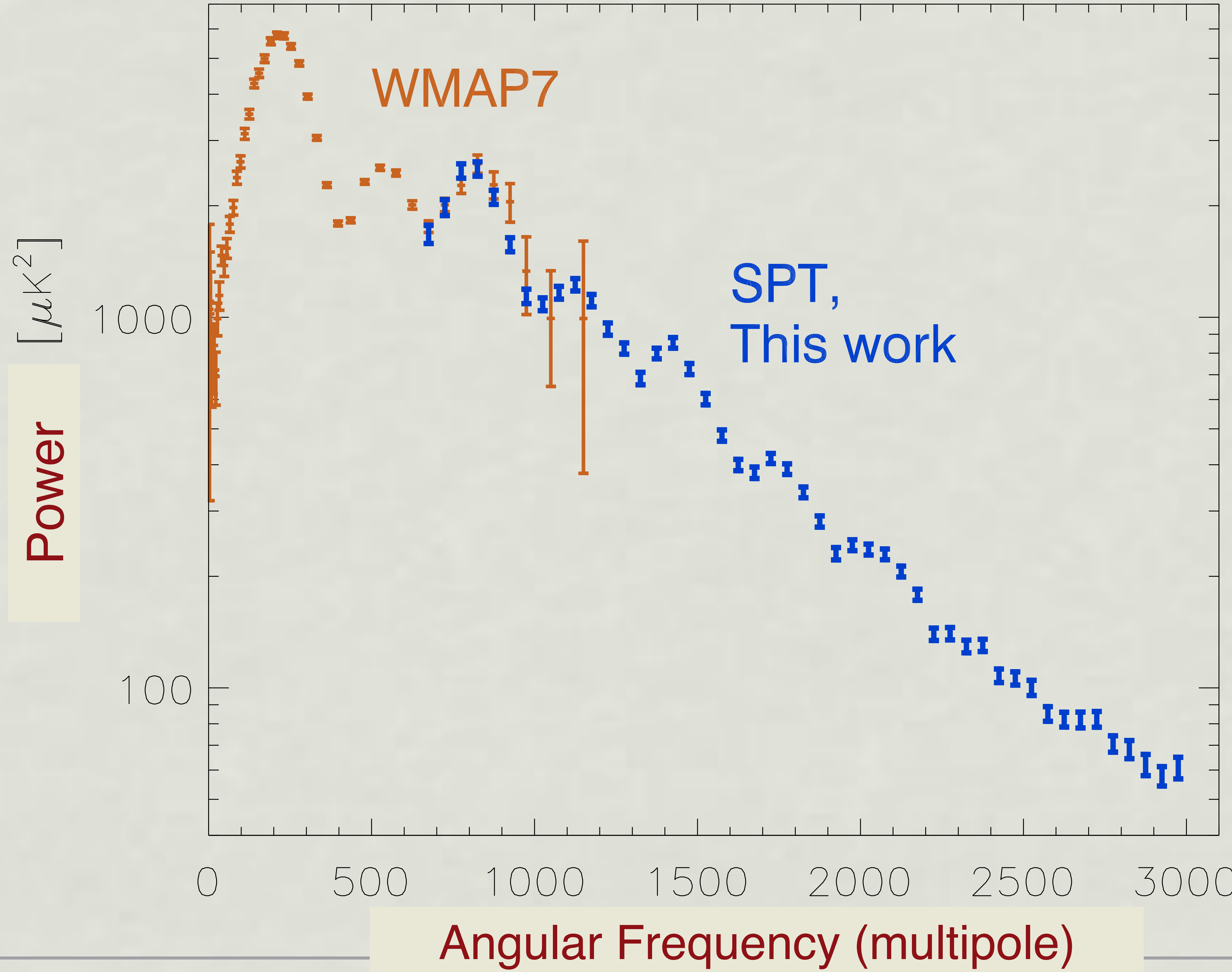
SPT provides ~2X improvement over previous works.

See , arXiv:1105.3182 (RK, C. Reichardt *et al.,* ApJ, 2011).

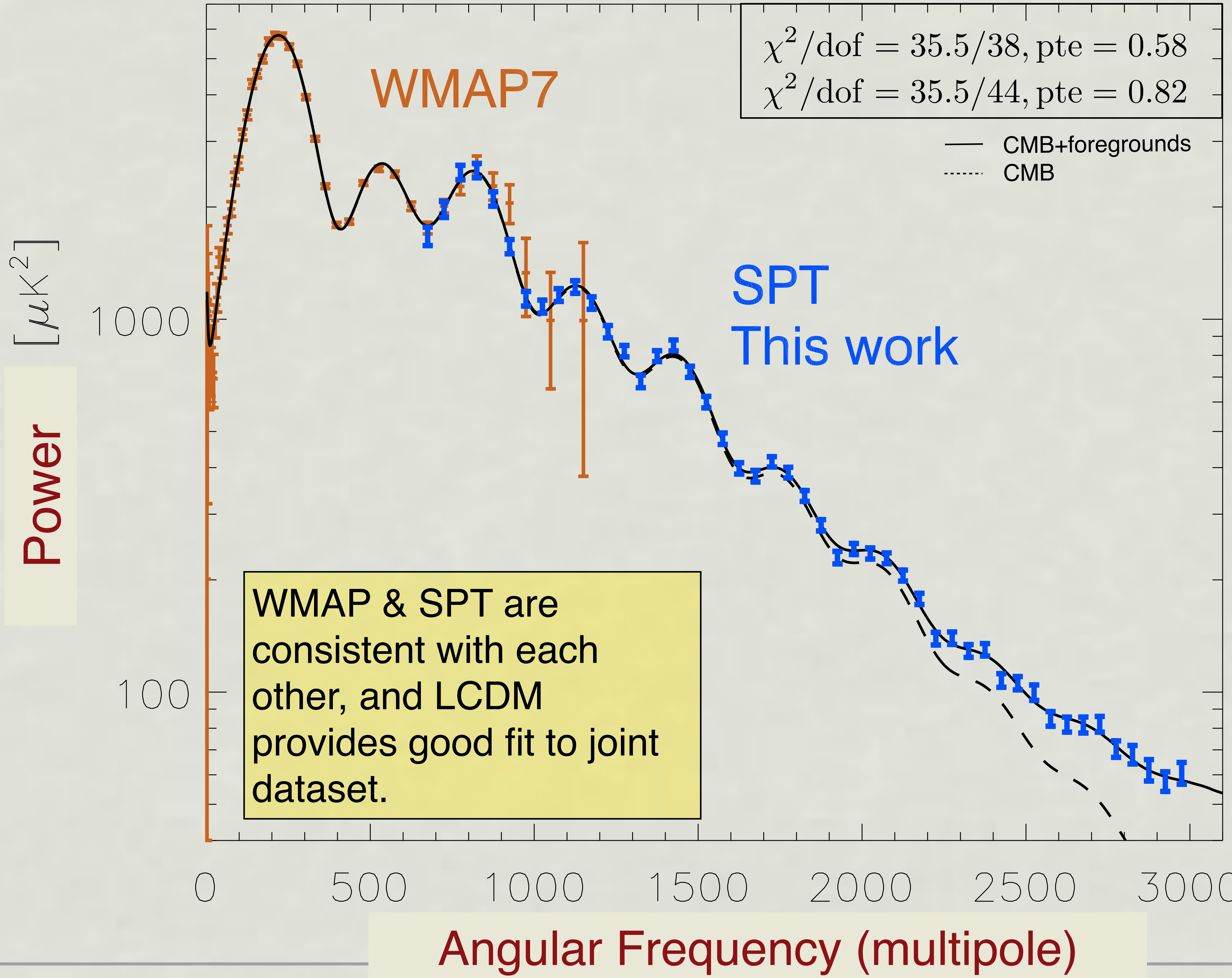
Angular Power Spectrum



Angular Power Spectrum

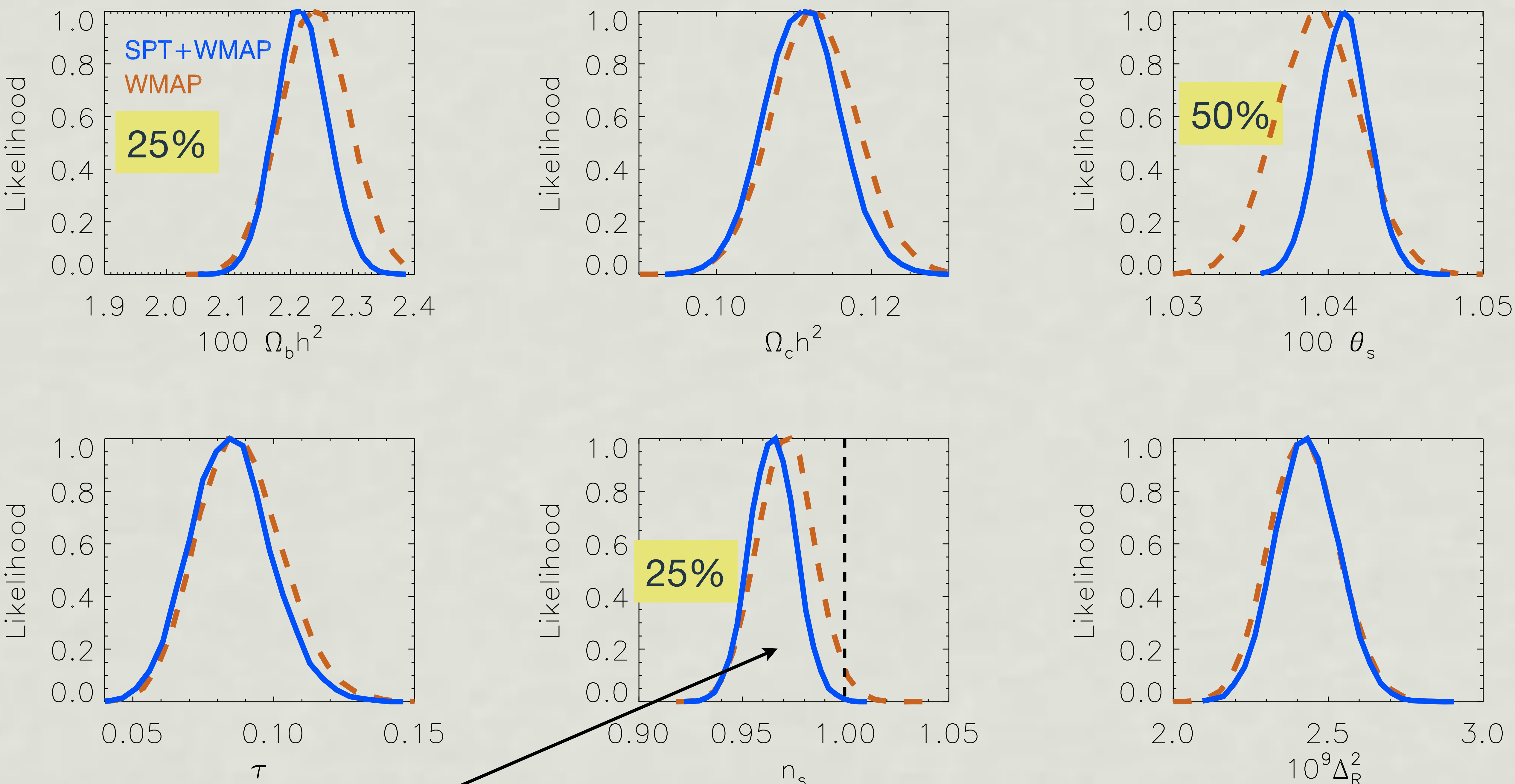


Best-fit Model



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

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)

See , arXiv:1105.3182 (RK, C. Reichardt *et al.,* ApJ, 2011).

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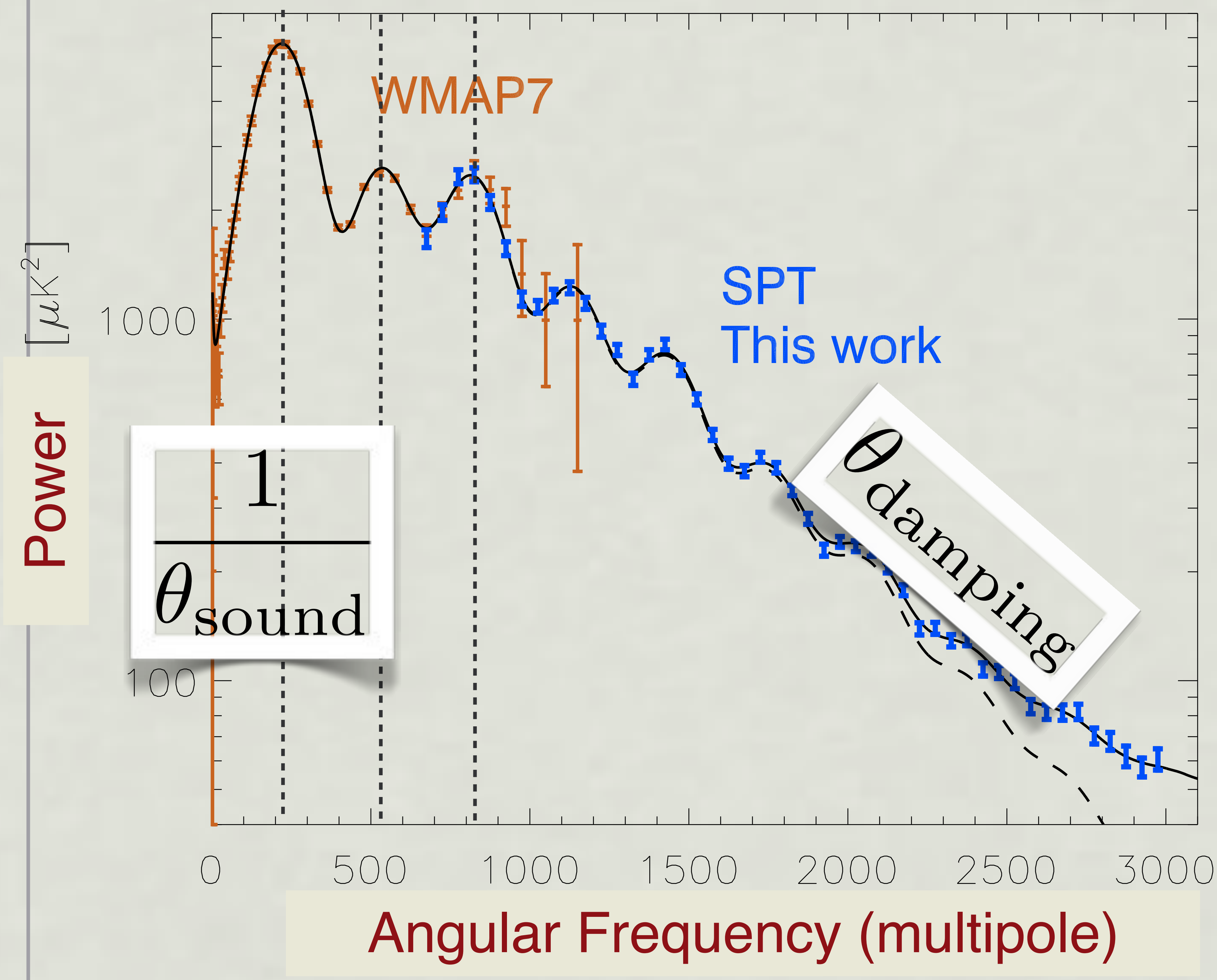
Beyond LCDM: number of neutrinos

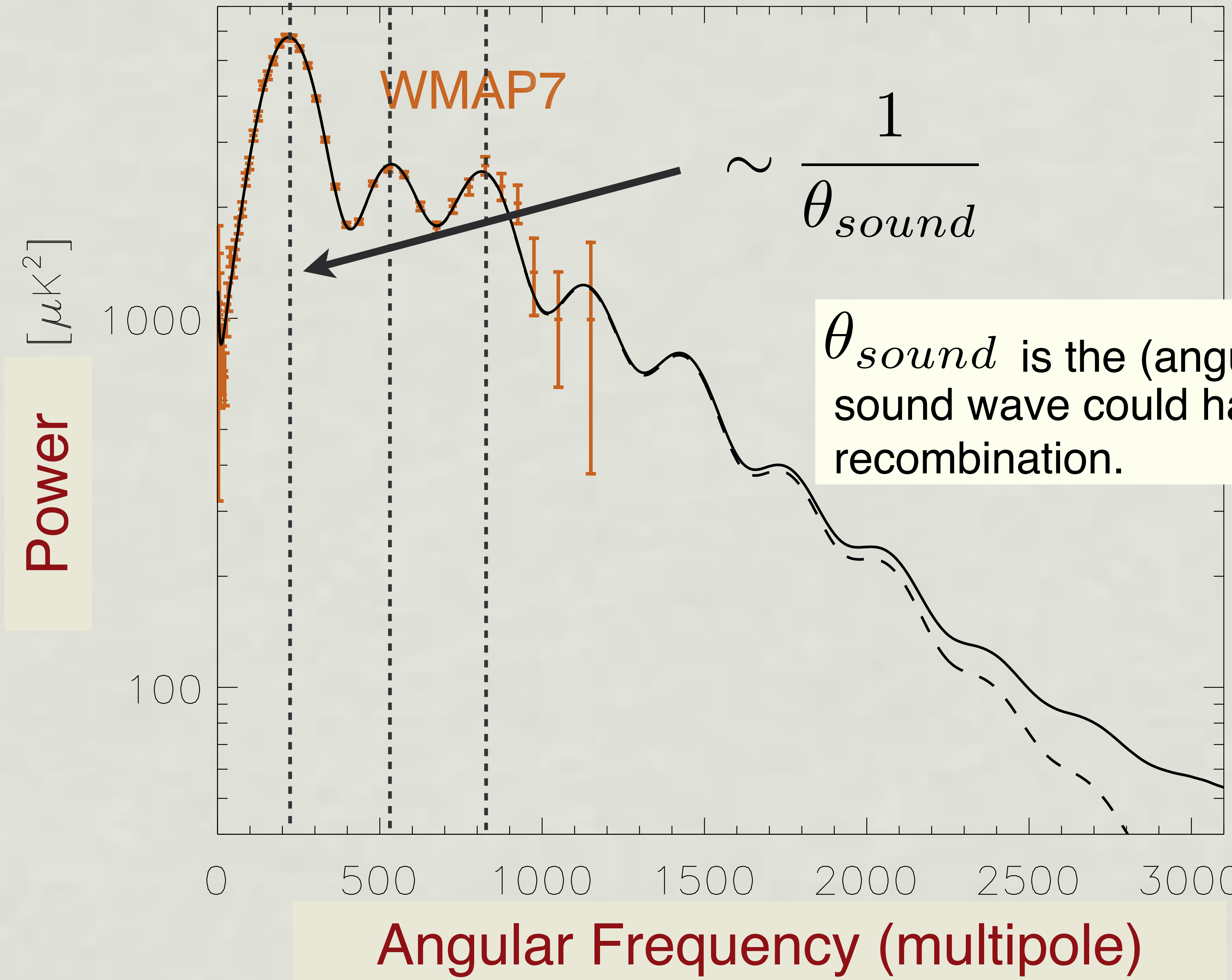


- The **number of relativistic species (think neutrinos)** present in the early universe affects the **expansion rate** during that time.

- 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 + ?)

The *Sound* Scale

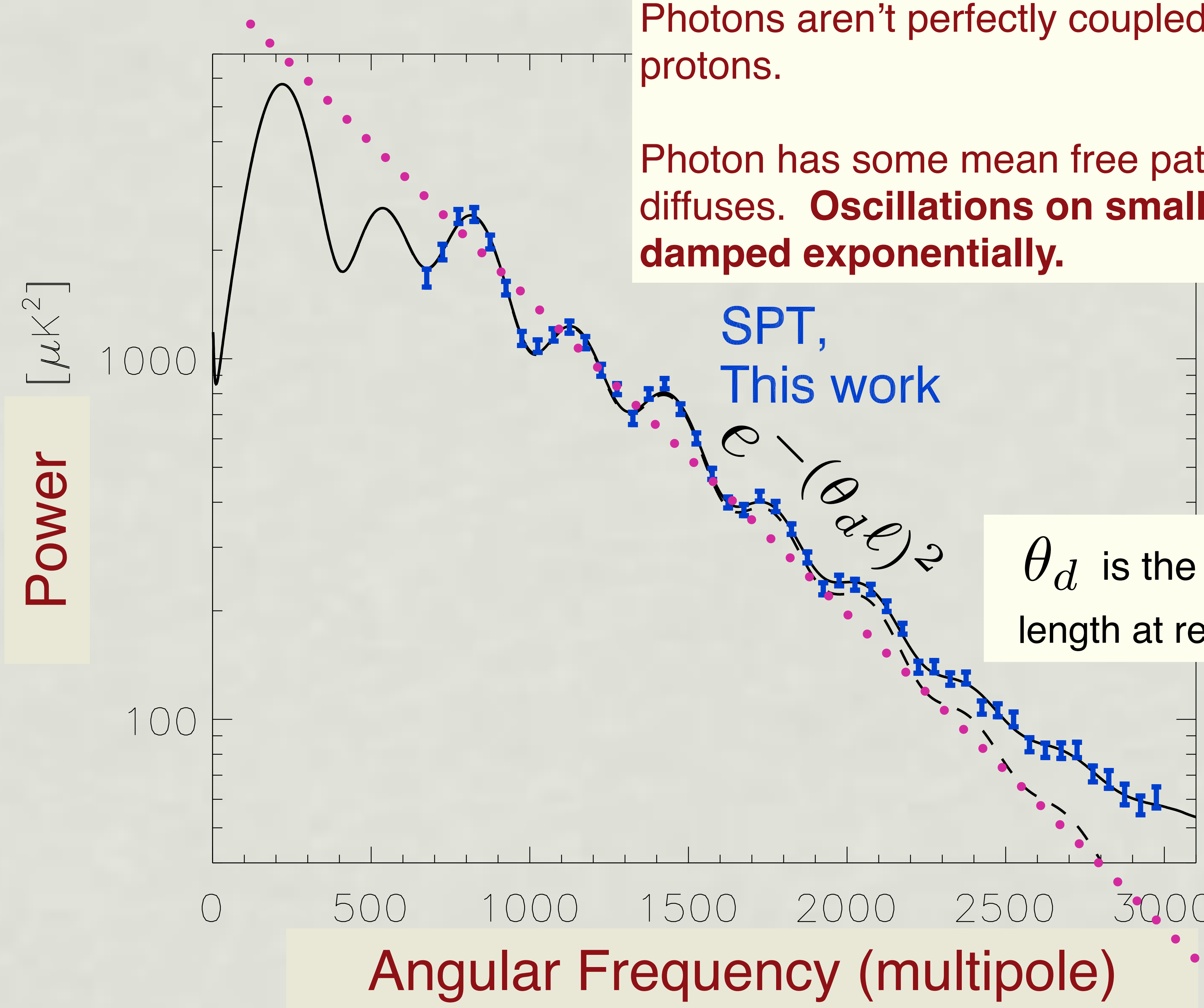


θ_{sound} is the (angular) distance a sound wave could have traveled by recombination.

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.

Sensitivity to Neutrinos

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

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

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

More neutrinos => higher density => faster expansion

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

Sensitivity to Neutrinos

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

Sound Scale

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

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

Damping Scale

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

$$r_d \propto H^{-0.5} \propto \sqrt{\text{time}}$$

(diffusion process. random walk.)

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

(see e.g. 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 e.g. 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 an energy density comparable to the standard neutrinos.

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

Beyond LCDM: No Neutrinos vs Standard Neutrinos?

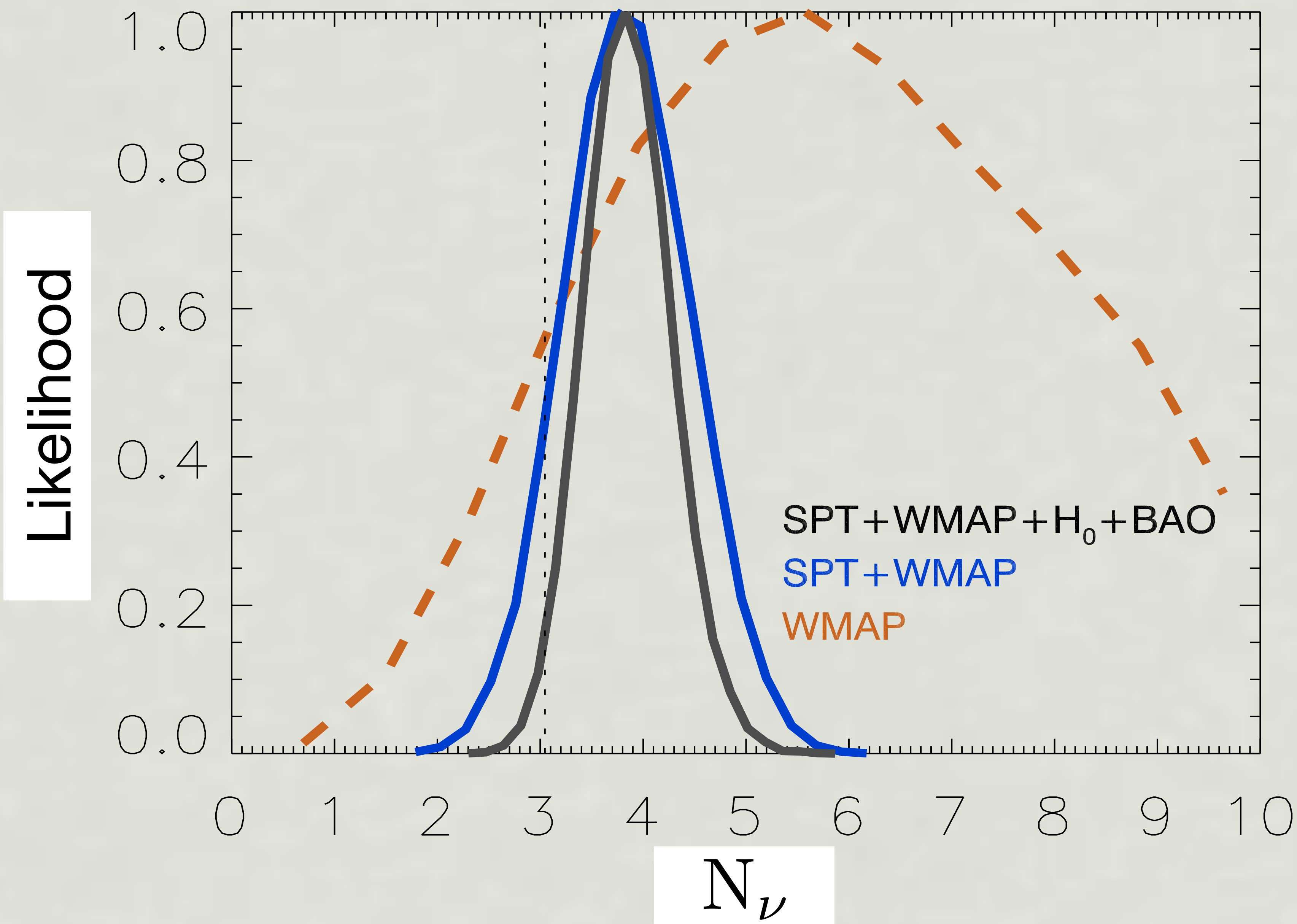
Simple test: compare maximum likelihood in N_nu=0 model to that in N_nu=3.046 model.

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).

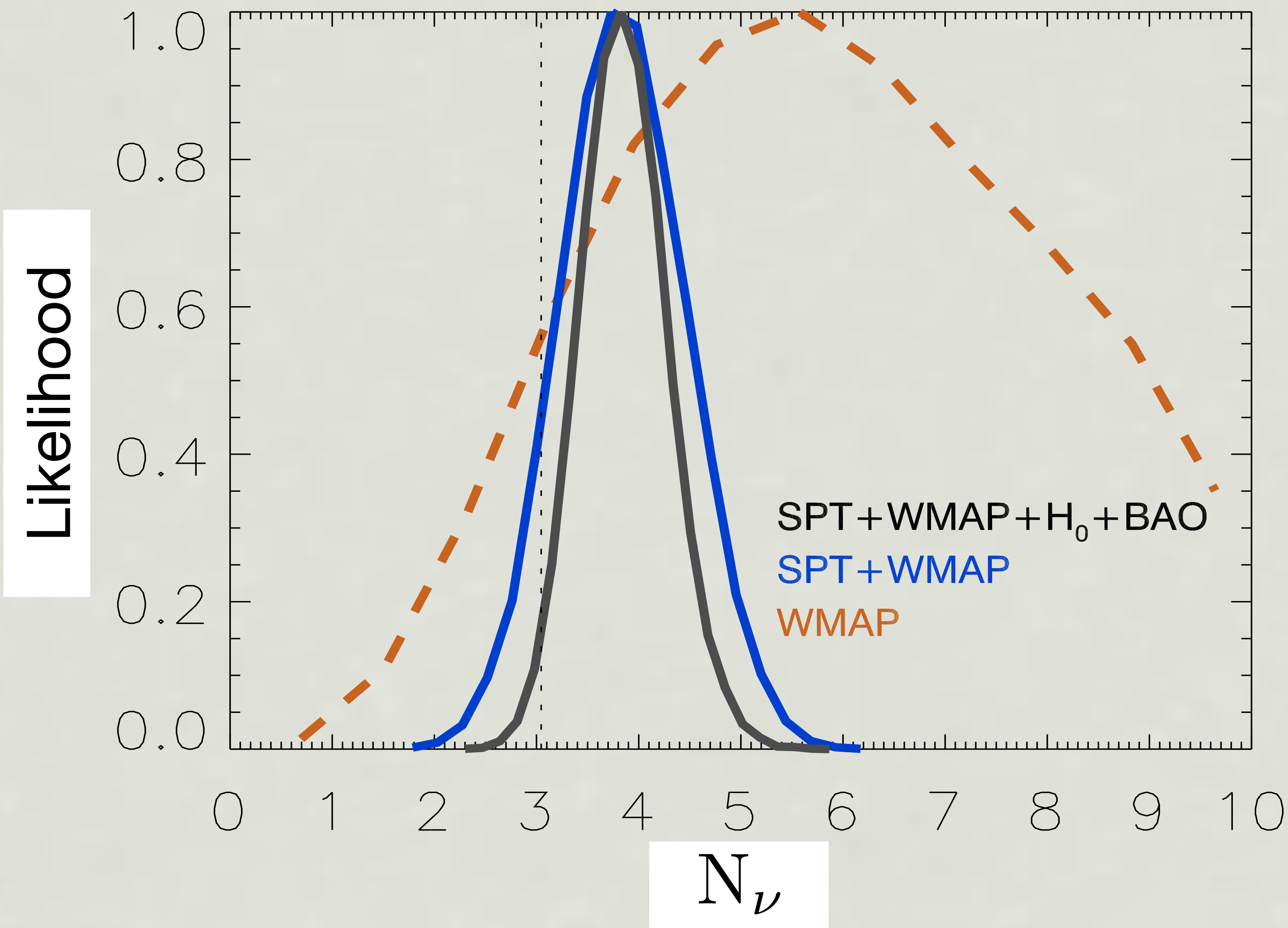
Constraints on N_ν



- $N_\nu = 3.85 \pm 0.62$, (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

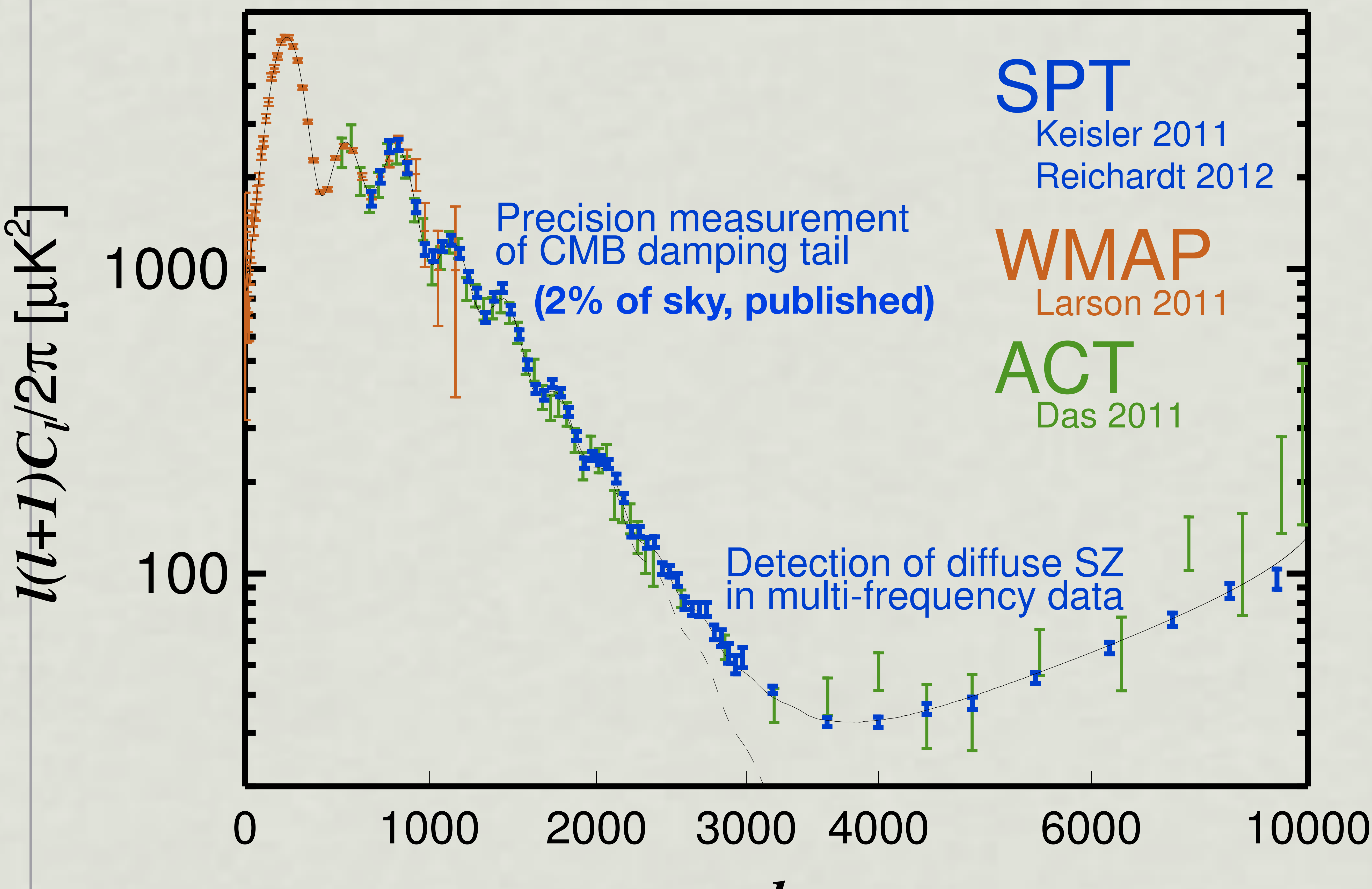


The CMB data are consistent with standard N_nu. Adding the "low-redshift" data (H0+BAO) then favors N_nu>3 at ~2σ

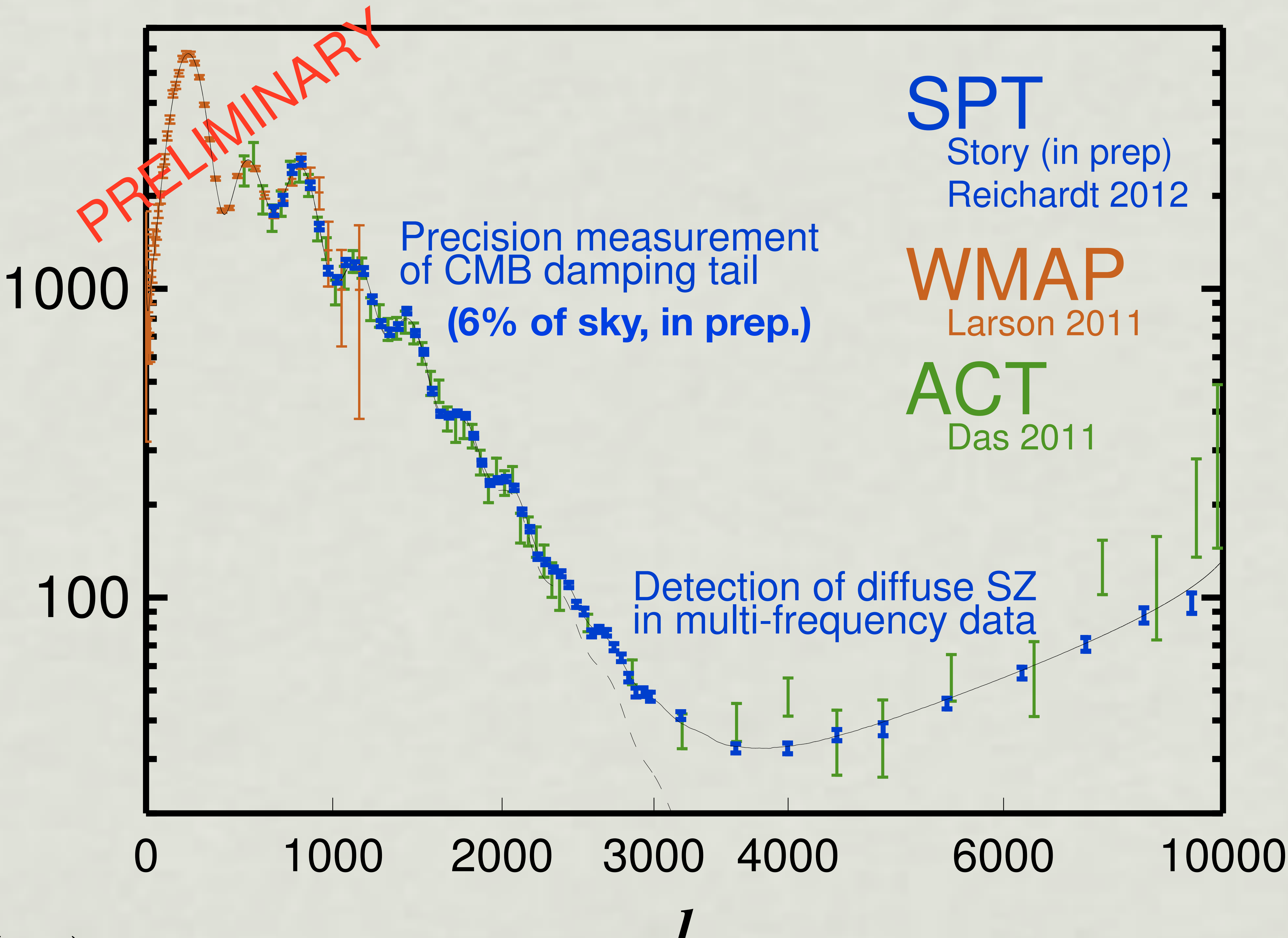
(1.3σ higher than 3.046)

(1.9σ higher than 3.046)

see RK, C. Reichardt et al, 1105.3182

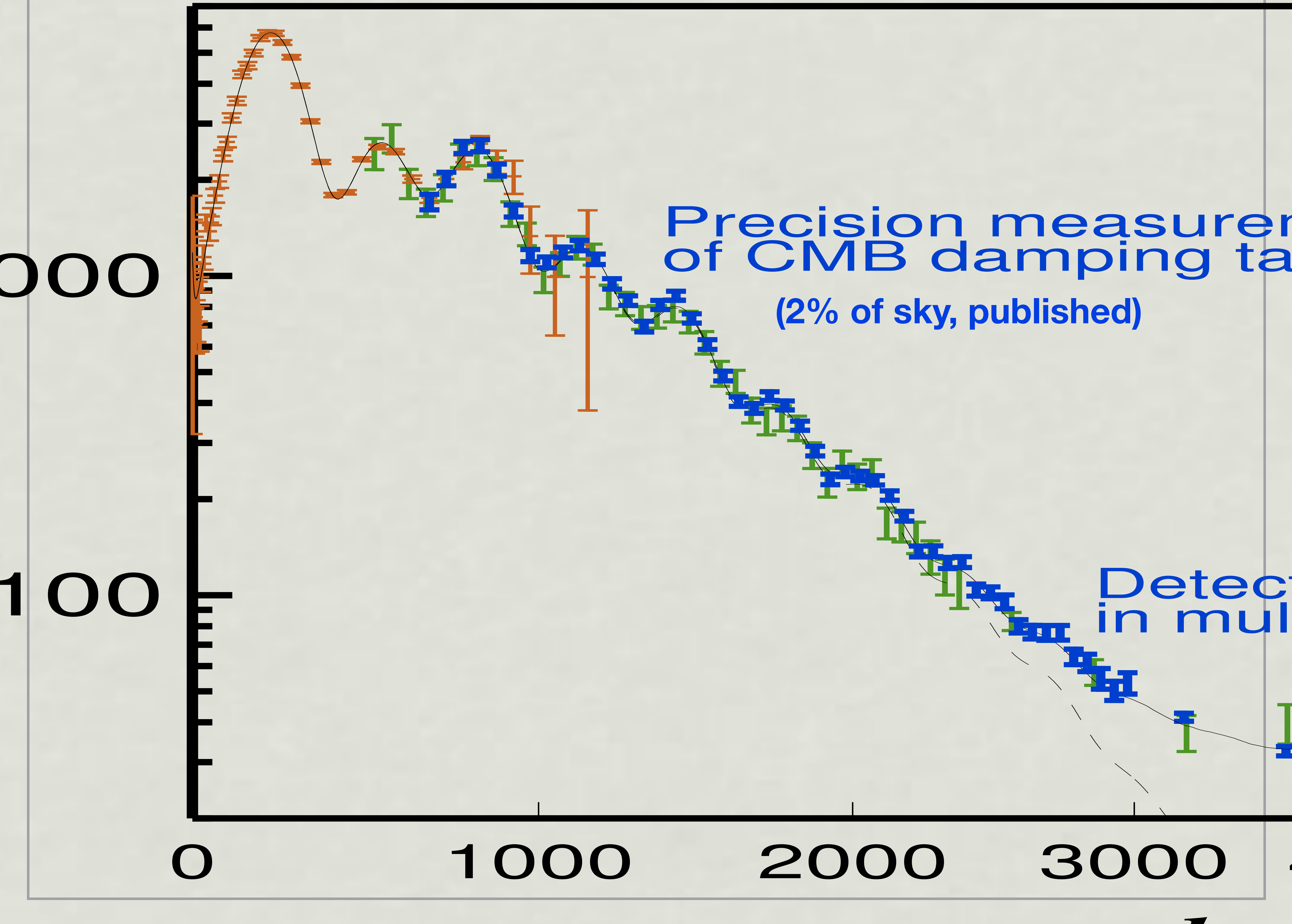


$\sigma(N_\nu) \simeq 0.4$

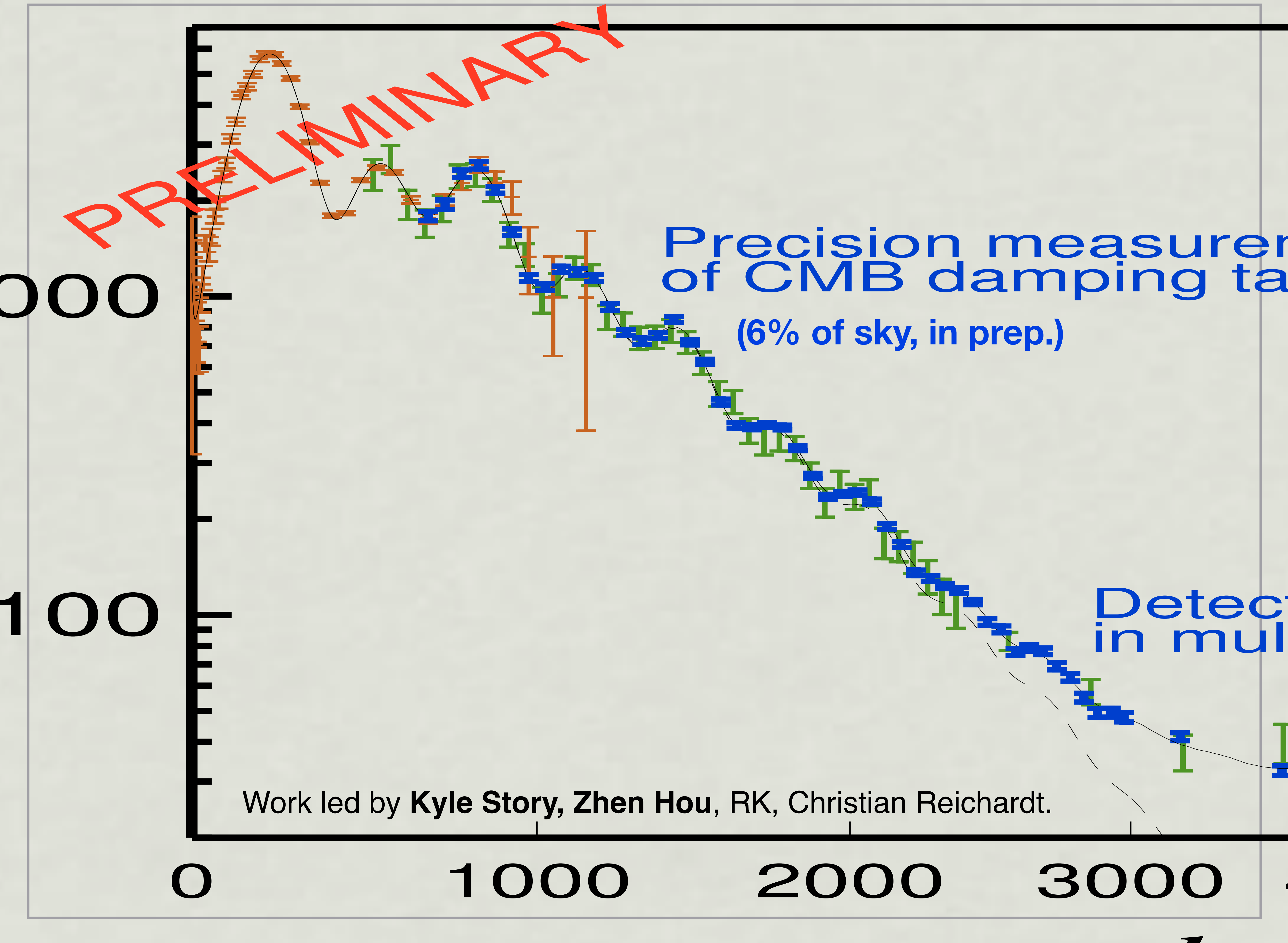


$\sigma(N_\nu) \simeq 0.33$

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



000
100
0
1000
2000
3000
Precision measurem
of CMB damping ta
(2% of sky, published)
Detect
in mul



PRELIMINARY
Precision measurer
of CMB damping ta
(6% of sky, in prep.)
Detect
in mul
Work led by **Kyle Story, Zhen Hou**, RK, Christian Reichardt.
000
100
0
1000
2000
3000

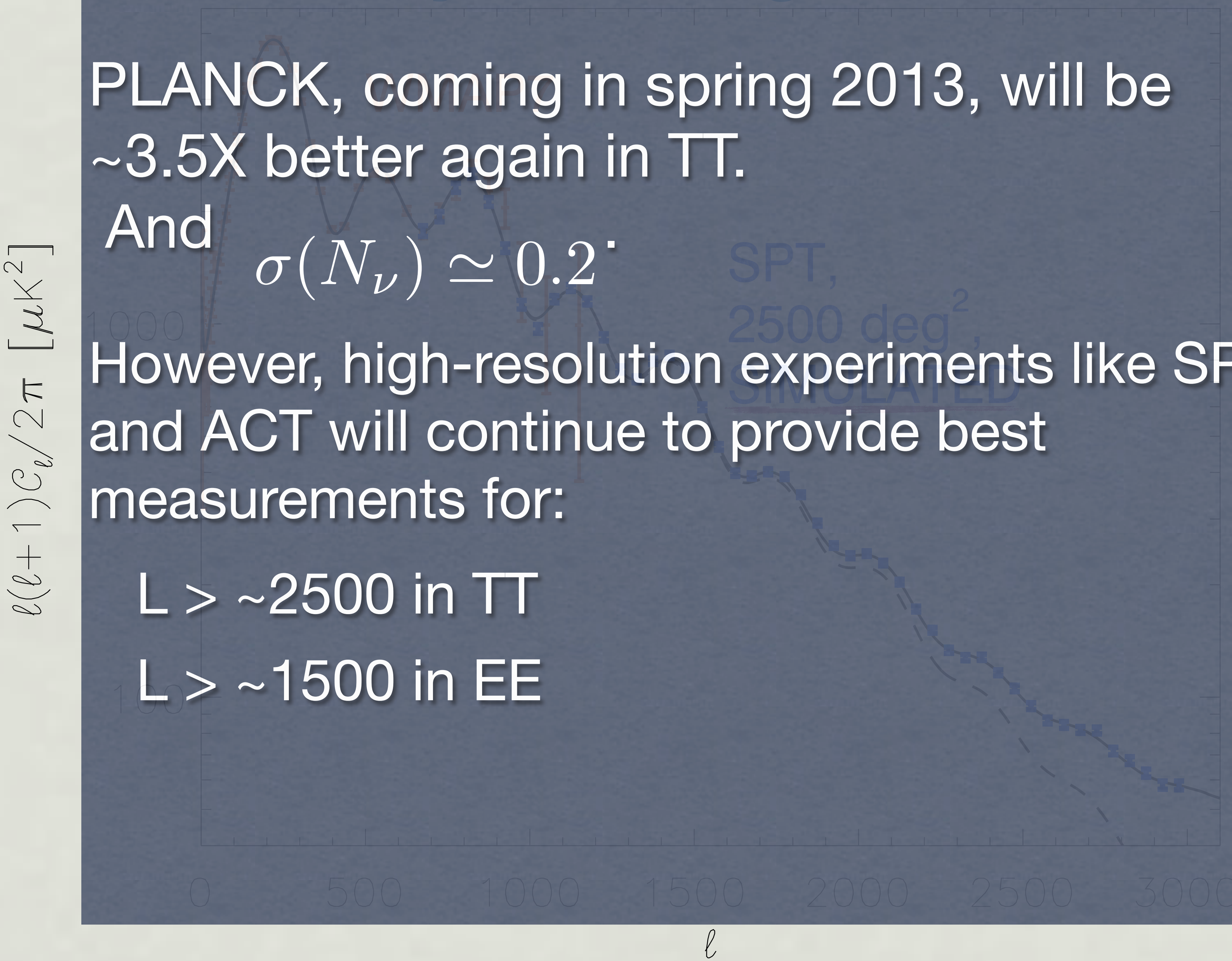
SPT Power Spectrum, 6% of sky, *coming this summer*

PLANCK, coming in spring 2013, will be ~3.5X better again in TT.

And $\sigma(N_\nu) \simeq 0.2$.

However, high-resolution experiments like SPT and ACT will continue to 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.

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.

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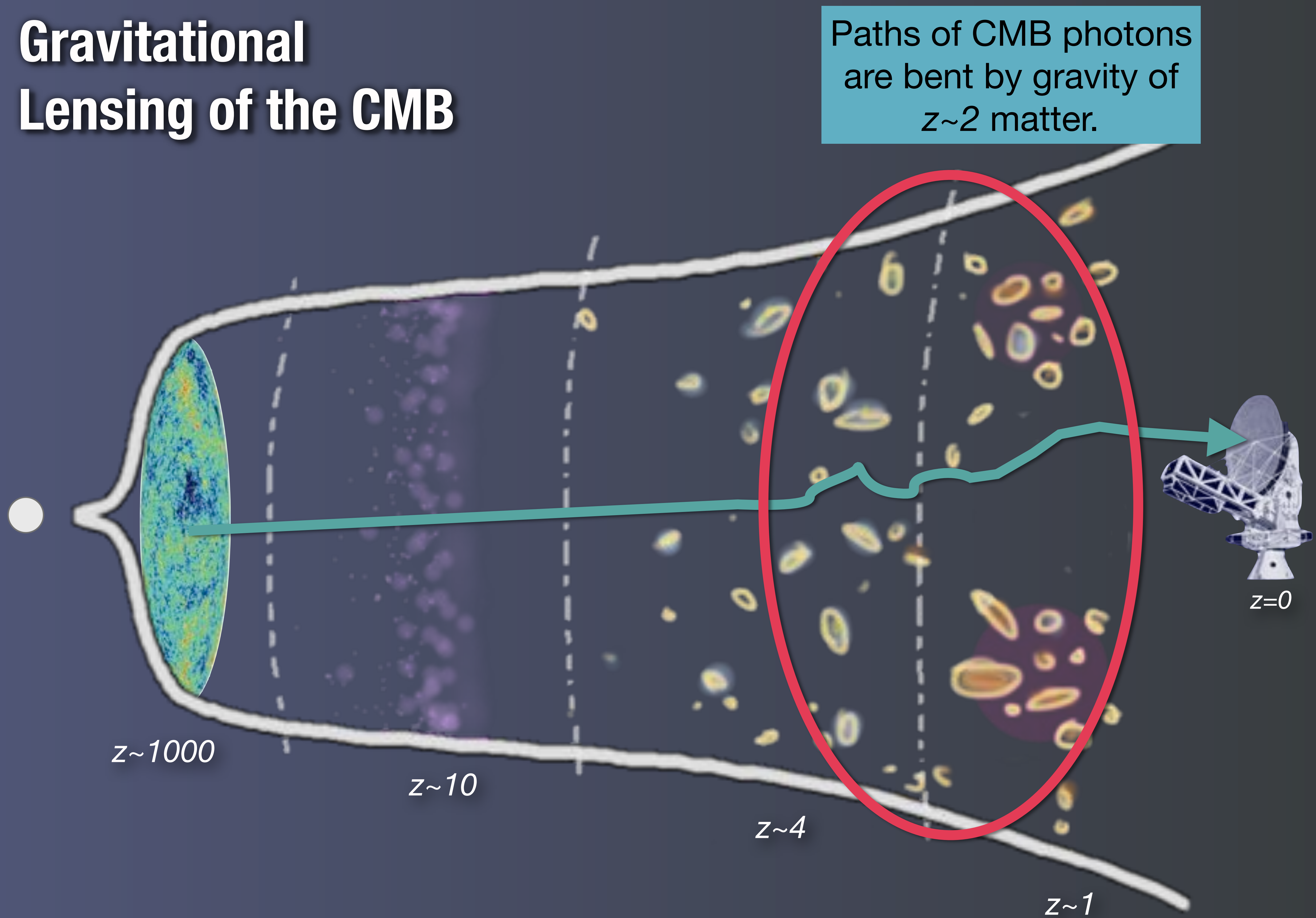
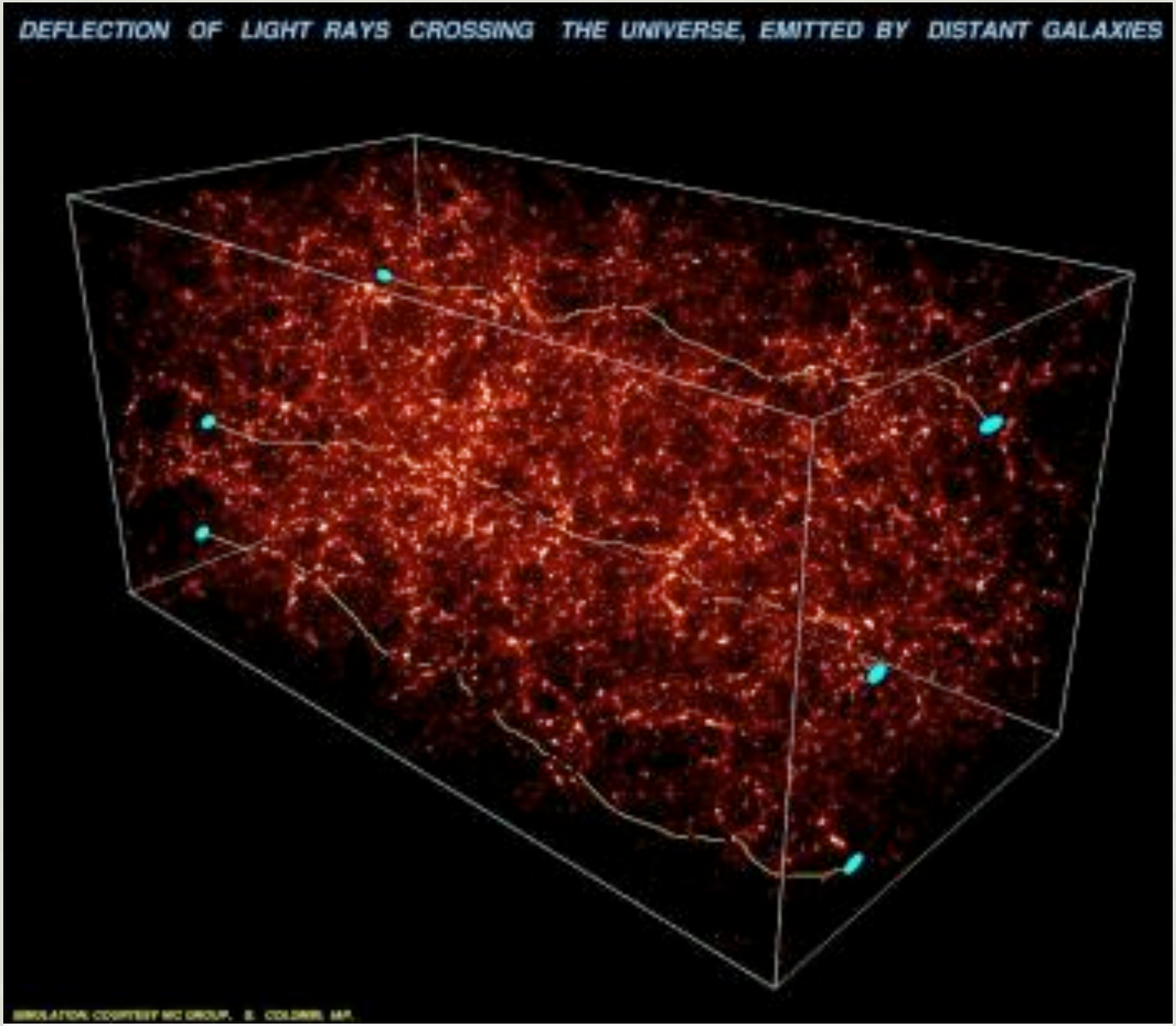
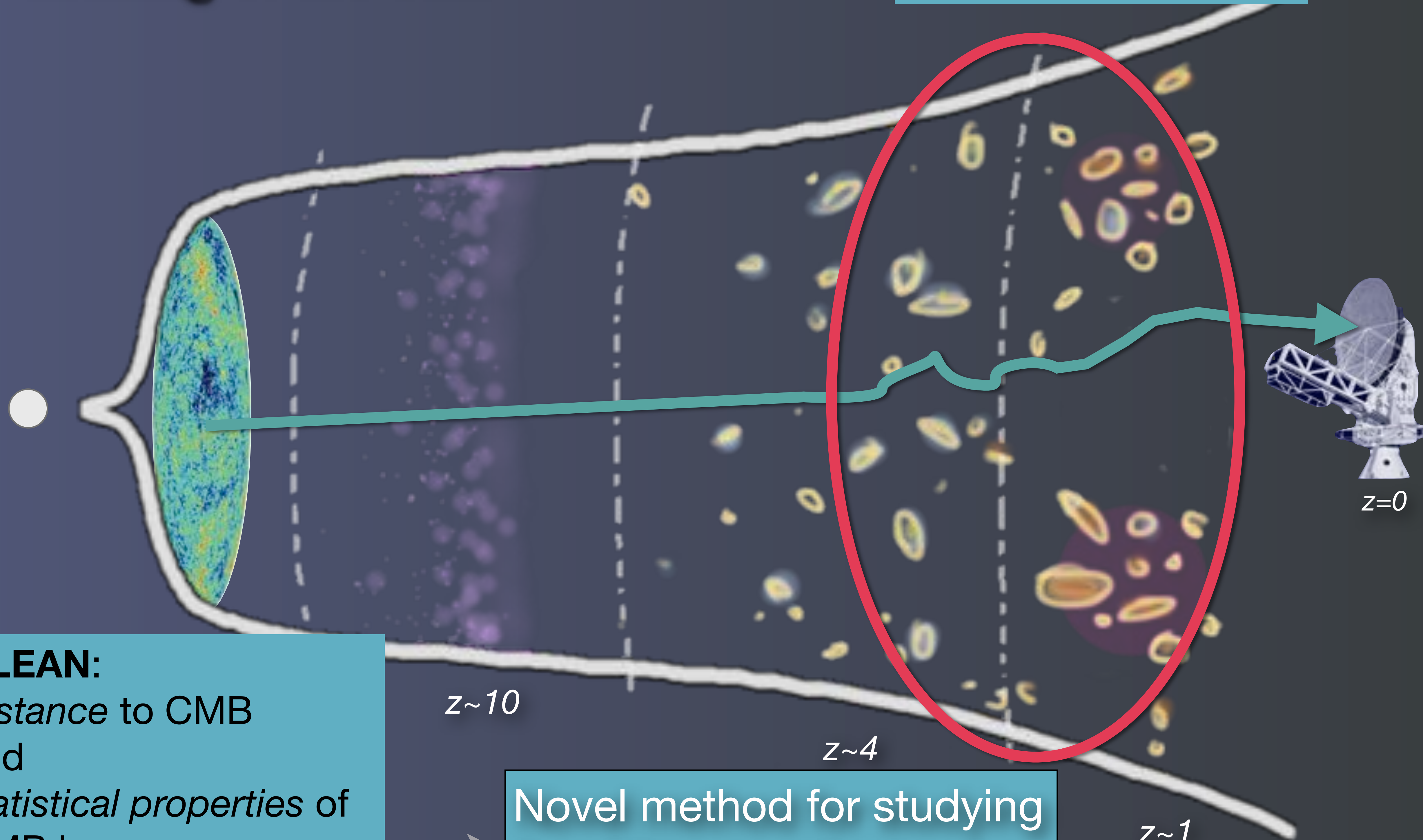
Gravitational Lensing of the CMB




DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERSE, EMITTED BY DISTANT GALAXIES

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~[0.5, 4]*.

Gravitational Lensing of the CMB

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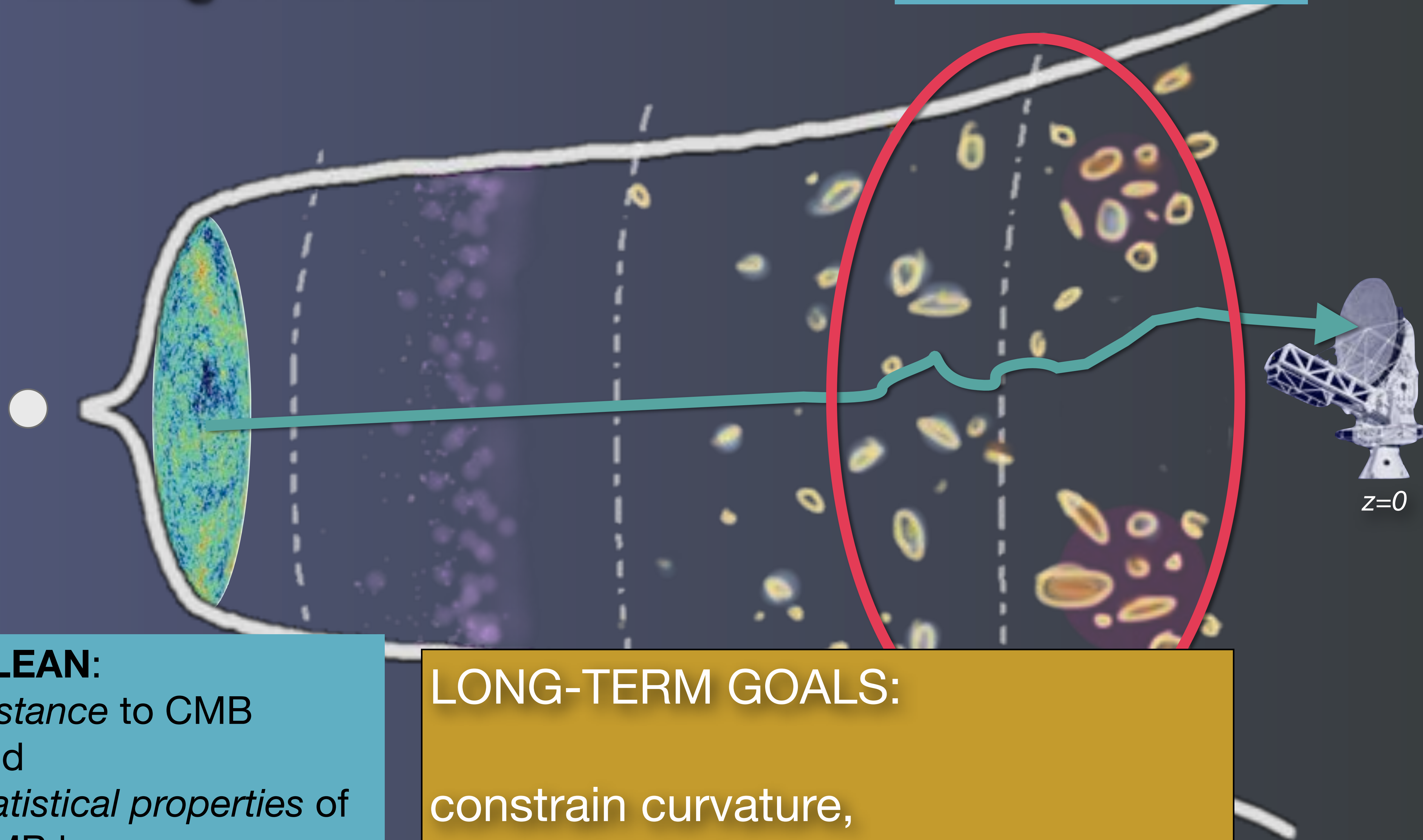

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Distance to CMB
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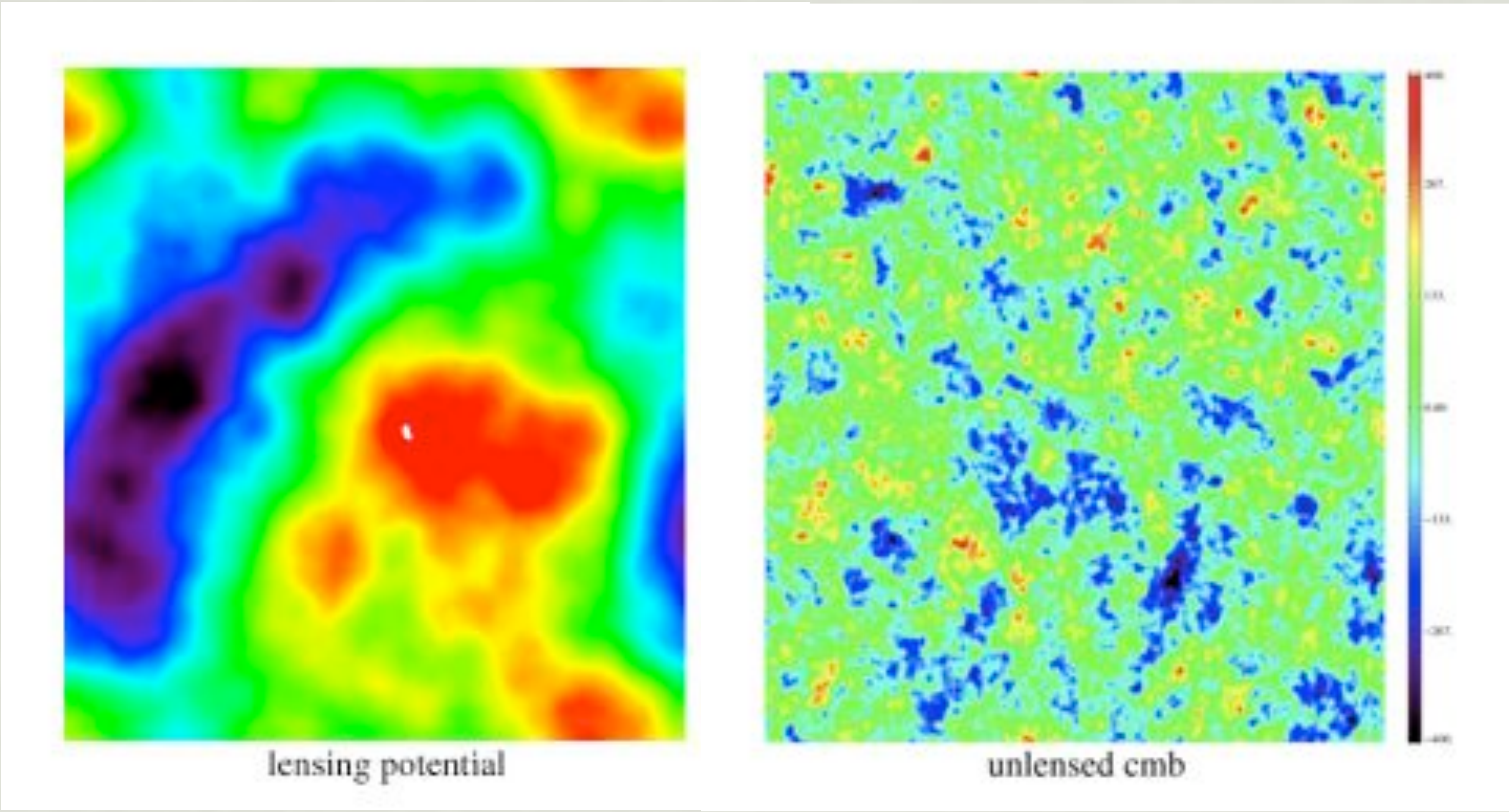
statistical properties of CMB known very accurately, so effects of lensing can be isolated.

LONG-TERM GOALS:

constrain curvature,
constrain dark energy,
measure neutrino mass

Lensing of the CMB

17°x17°



from Alex van Engelen

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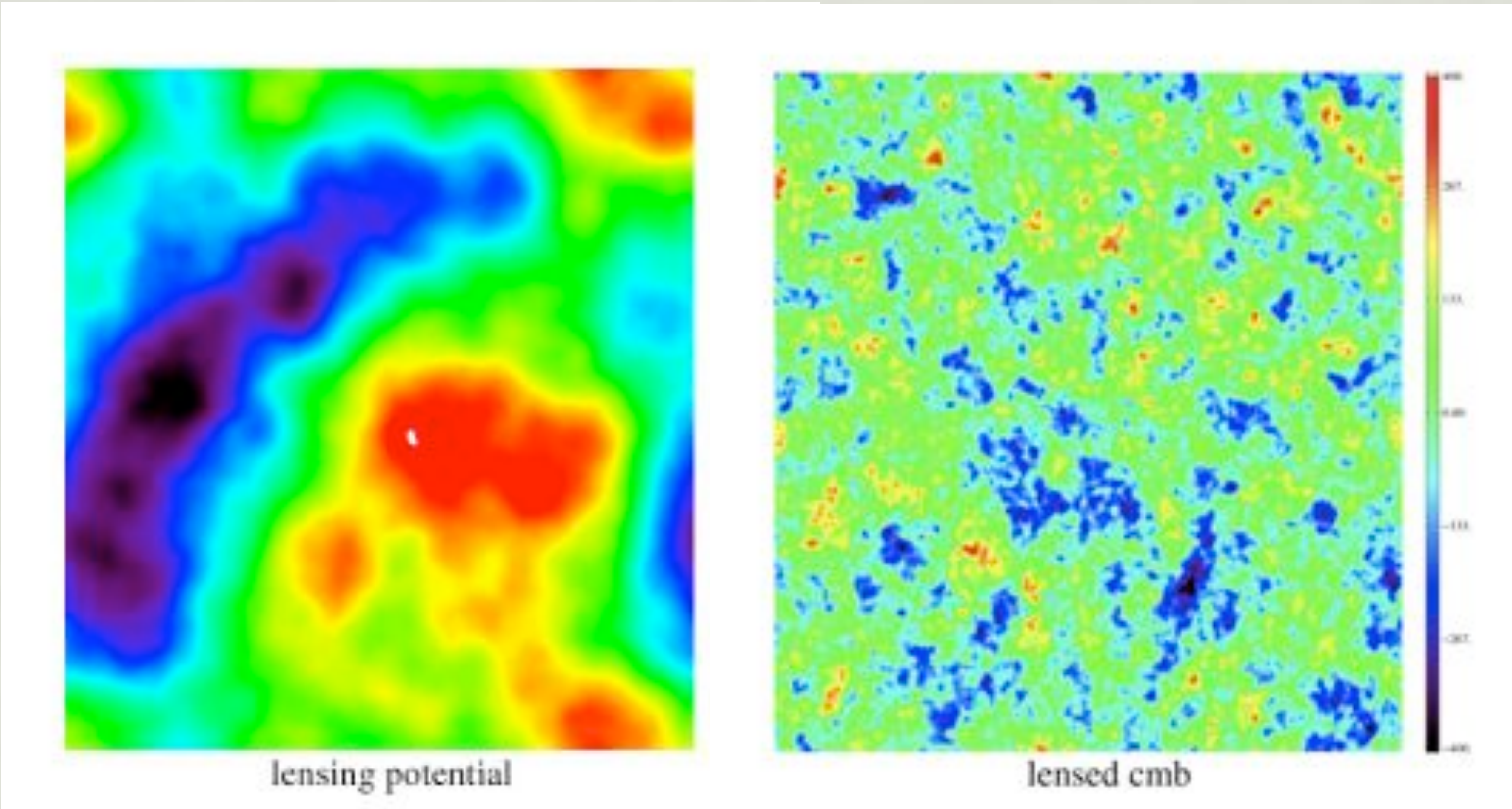

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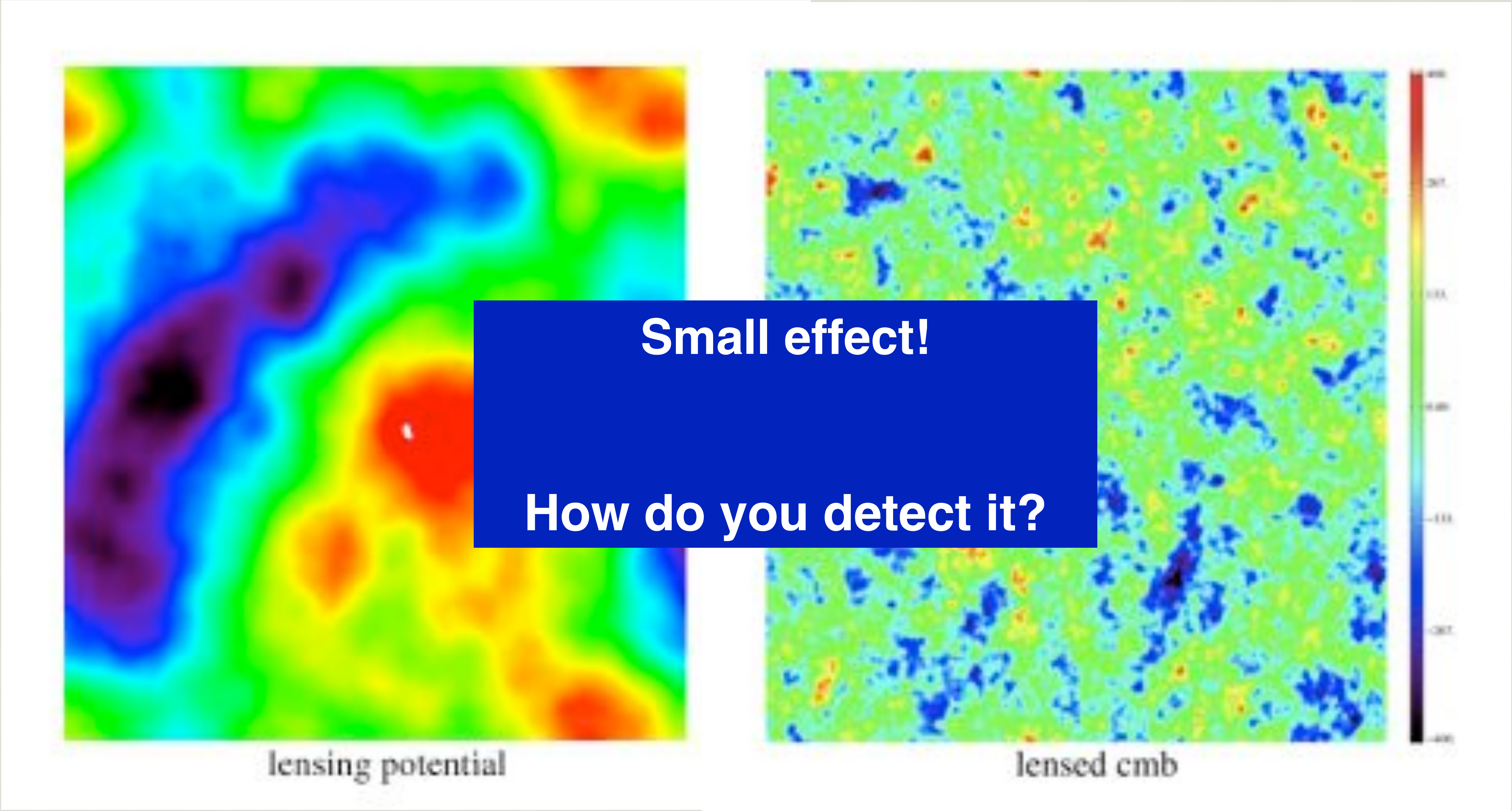
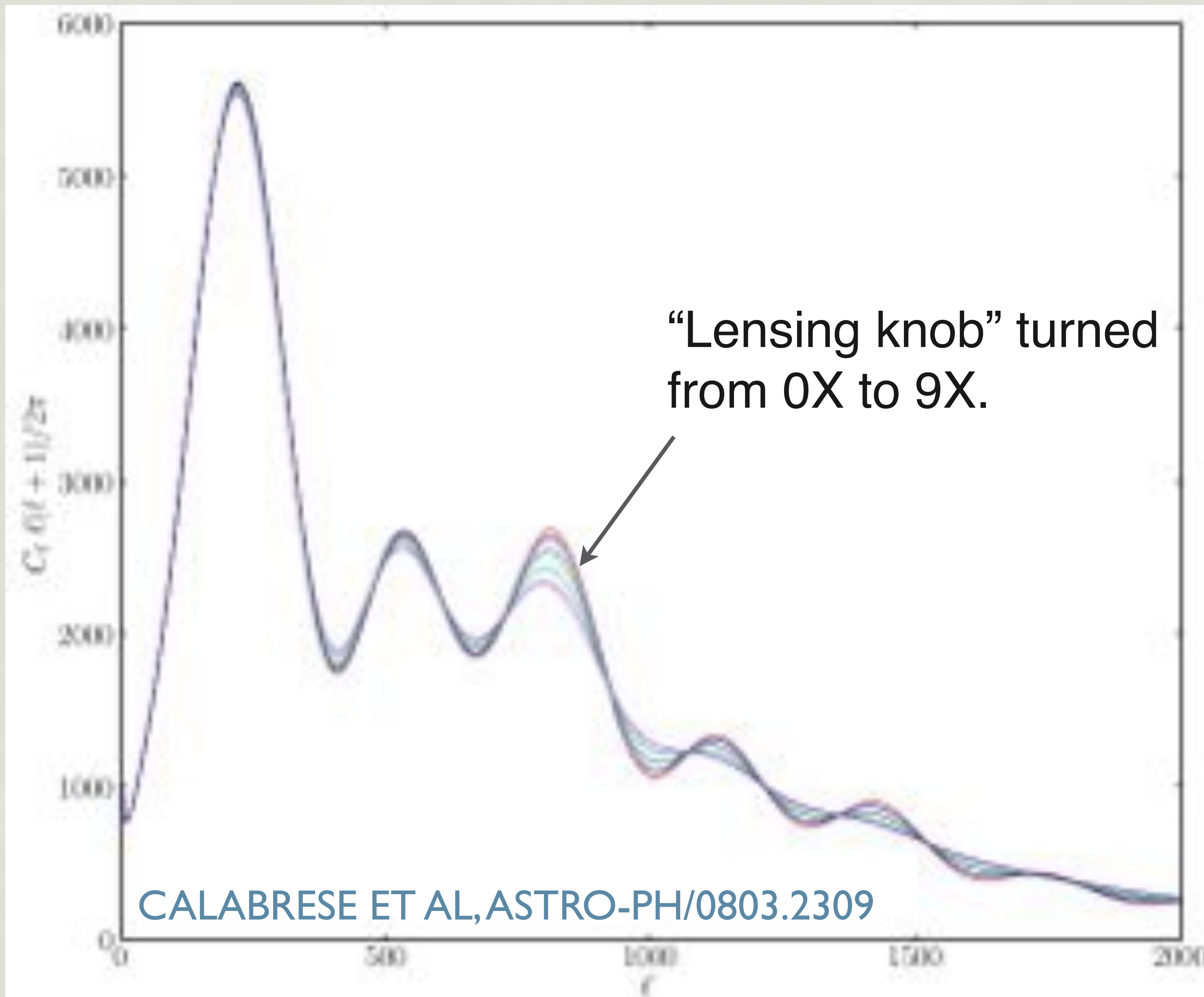


Small effect!

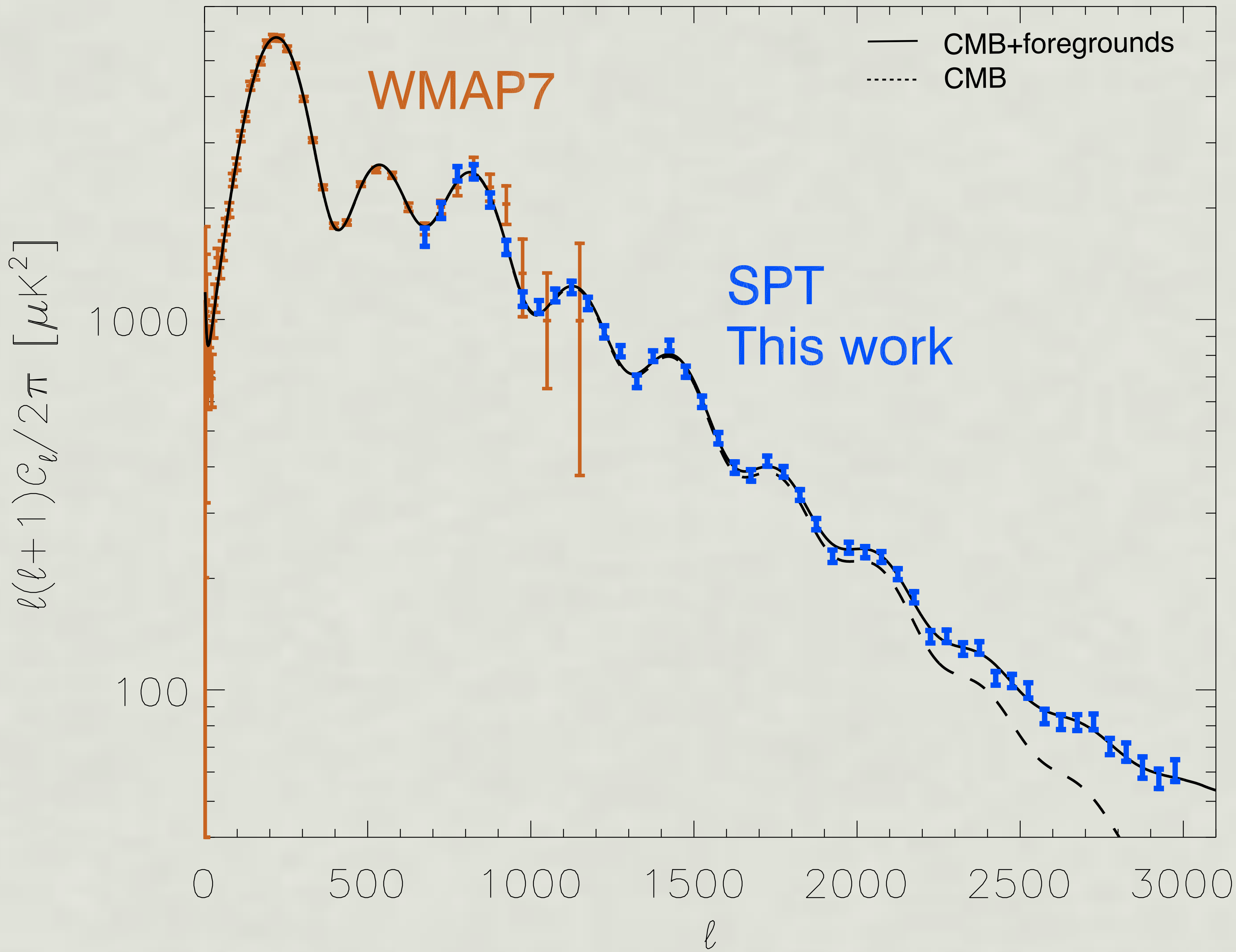
How do you detect it?

from Alex van Engelen

I. Lensing Smooths the "Acoustic Peaks"

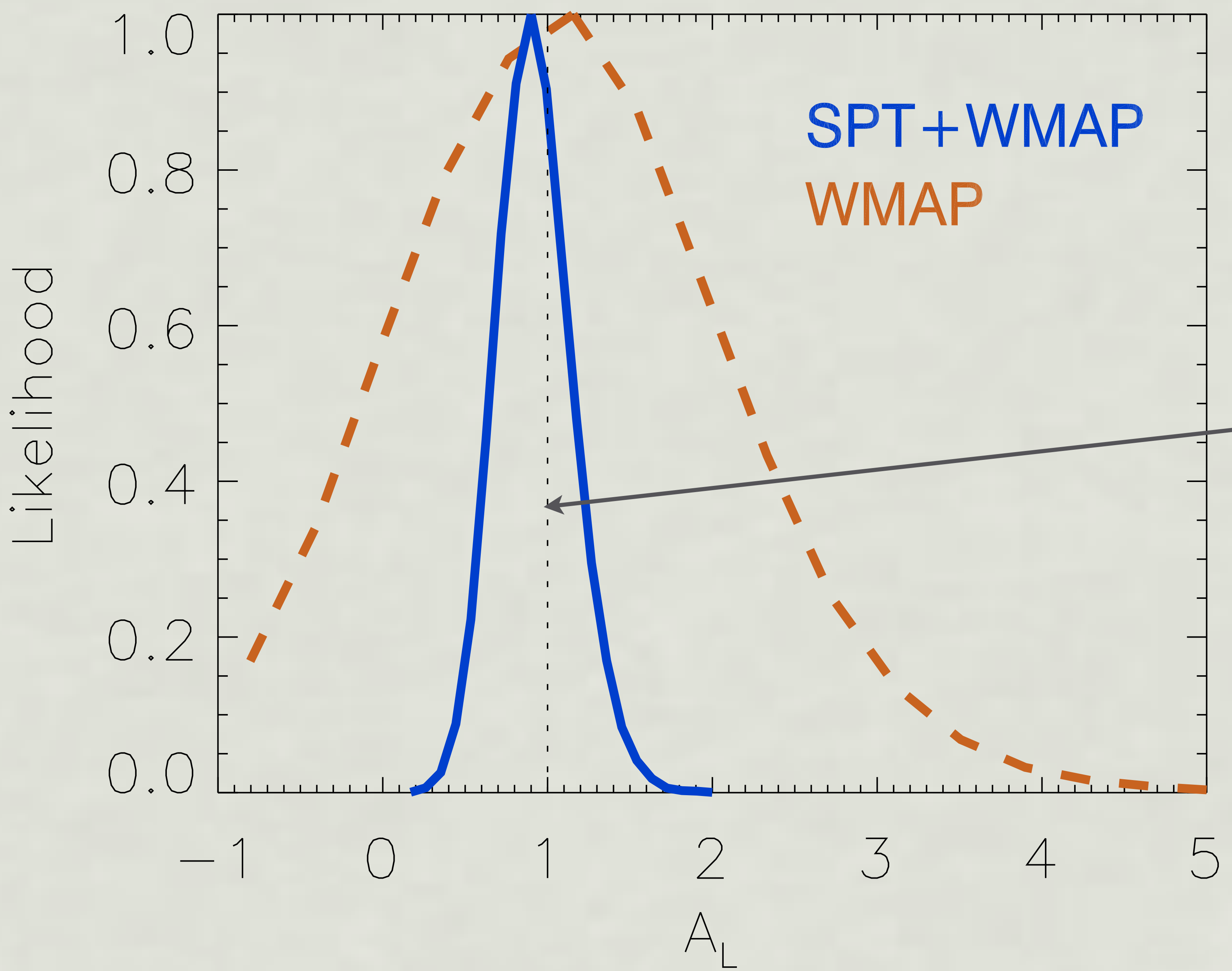


I. Lensing Smooths the "Acoustic Peaks"



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

I. Lensing Smooths the "Acoustic Peaks"



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

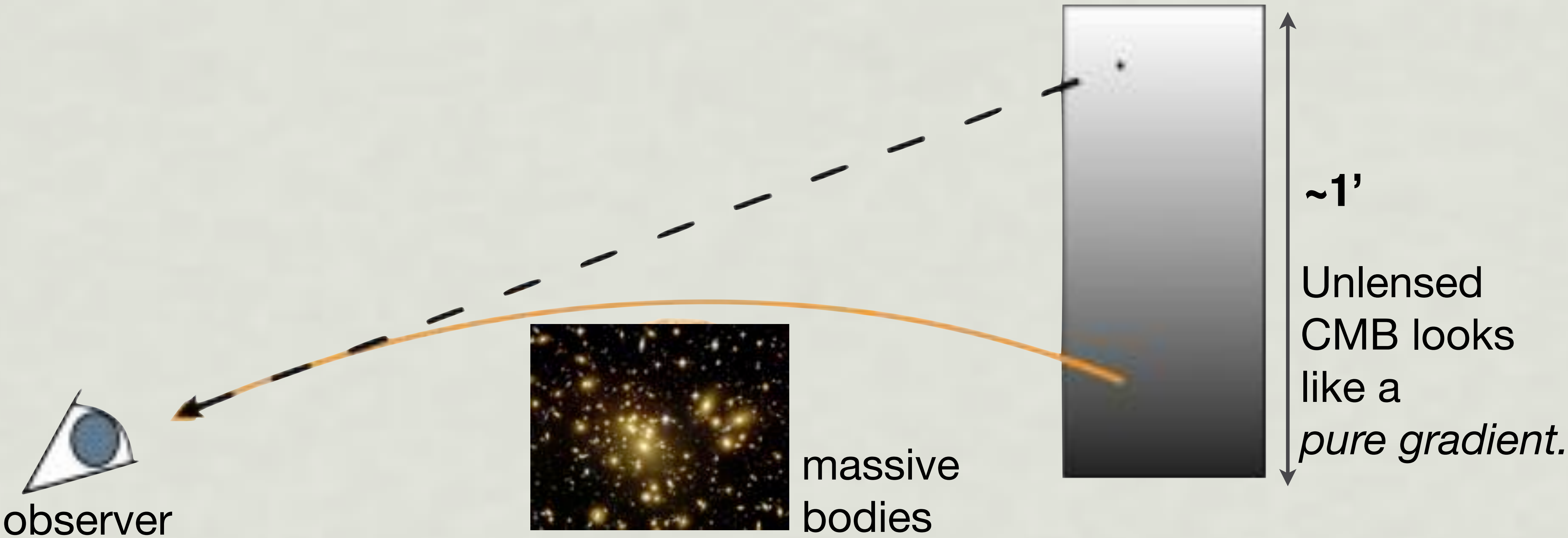
$$(\mathrm{A_{lens}})^{0.65} = 0.94 \pm 0.15$$

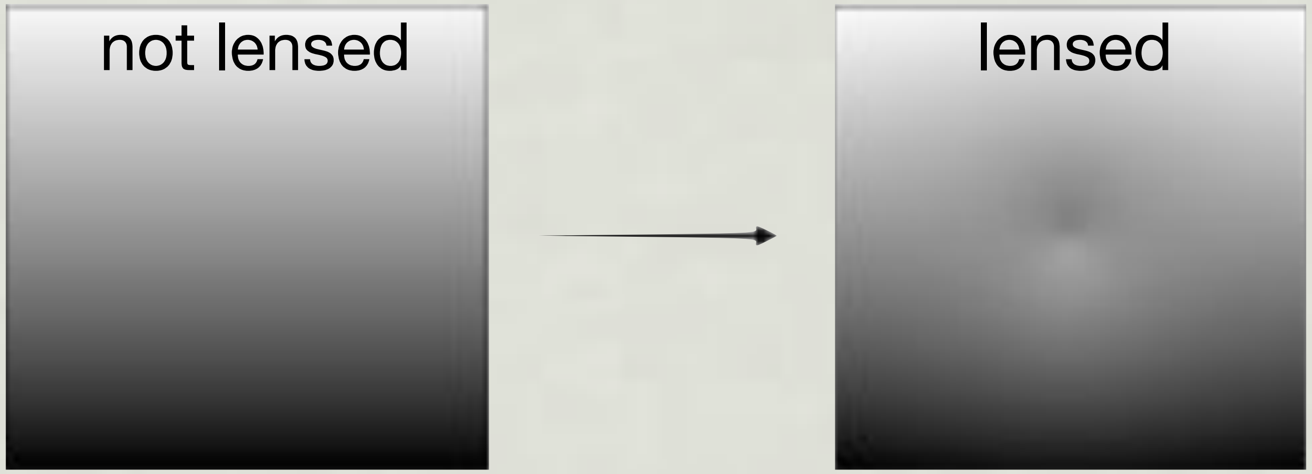
Consistent with expected level of lensing (1.0).

SPT+WMAP give first 5σ detection of CMB lensing.

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

II. Mass Reconstruction
(more powerful, more complicated)





Small-scale wiggles are correlated with large-scale gradient.

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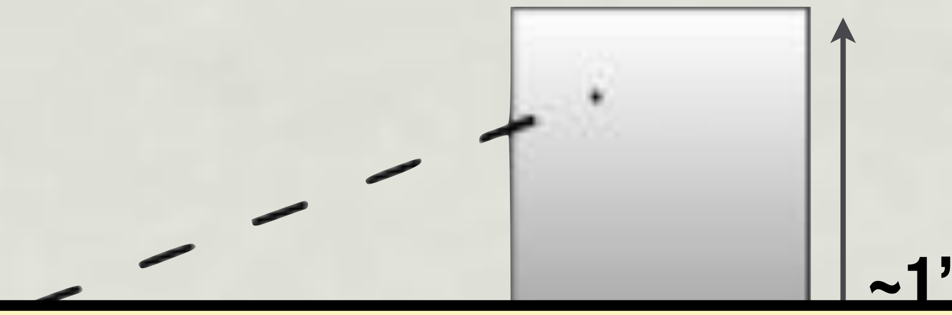
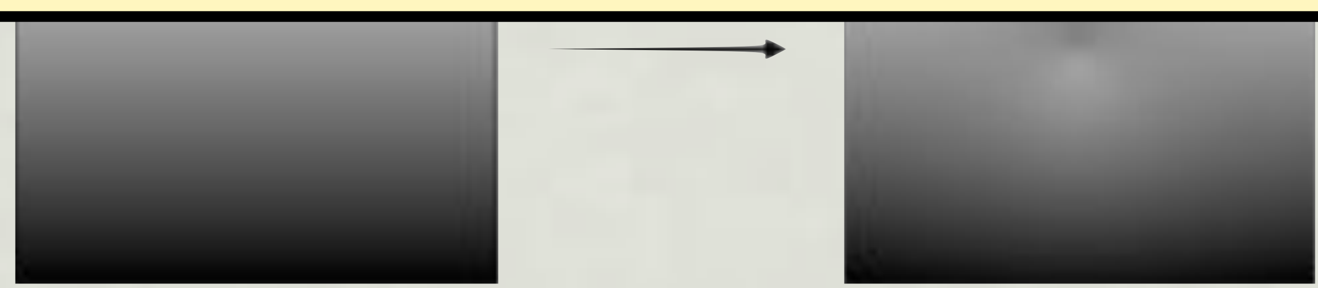
(more powerful, more complicated)



We can use this signature to
image the mass along the LOS to the CMB.

One method (optimal, unbiased):
the “Quadratic Estimator”
(see, e.g. W. Hu 2001; Hu & Okamoto 2002; Okamoto & Hu 2003)



Small-scale wiggles are correlated with large-scale gradient.

Unpacking the *Quadratic Estimator*

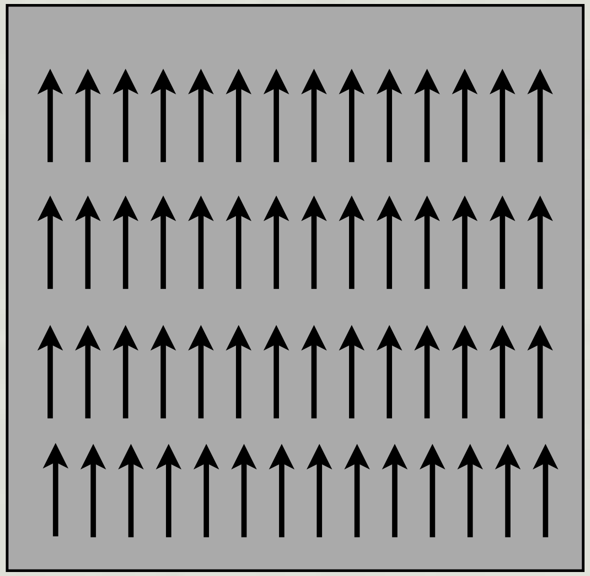
1.

Start with **two** copies of your CMB temperature image.

2.

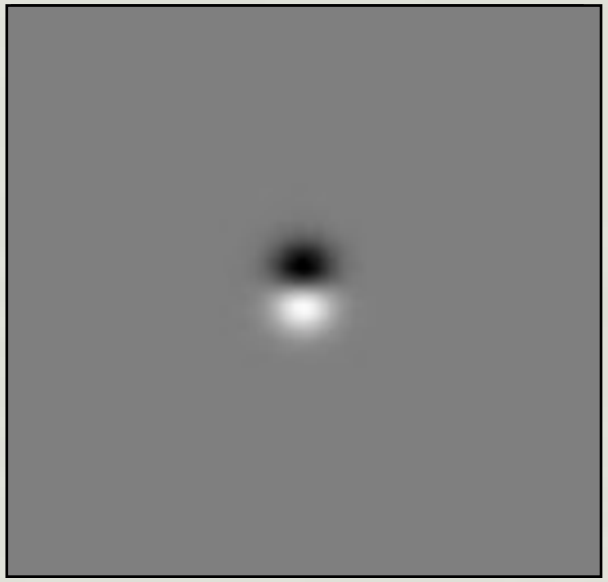
Unpacking the *Quadratic Estimator*

1.



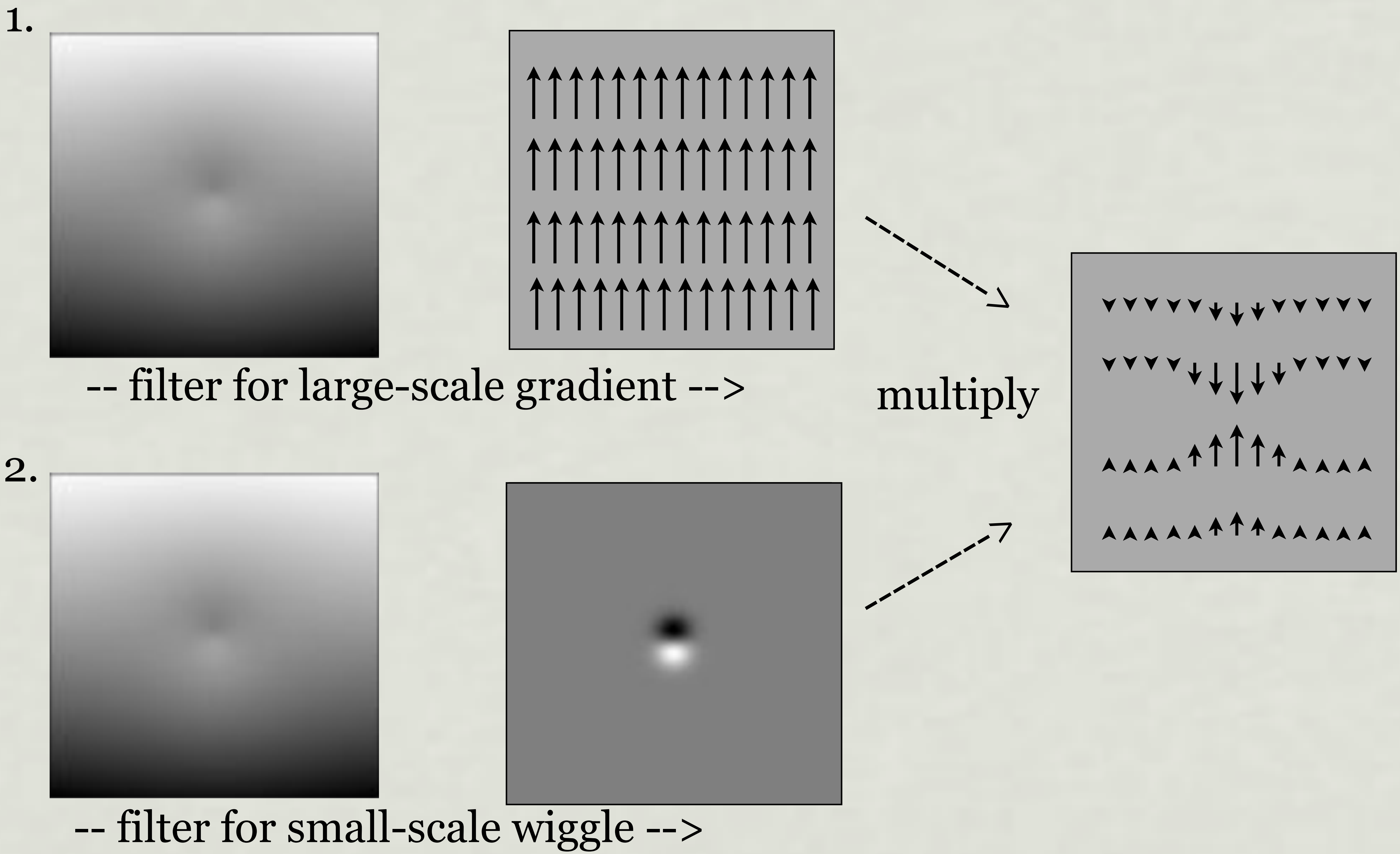
-- filter for large-scale gradient -->

2.

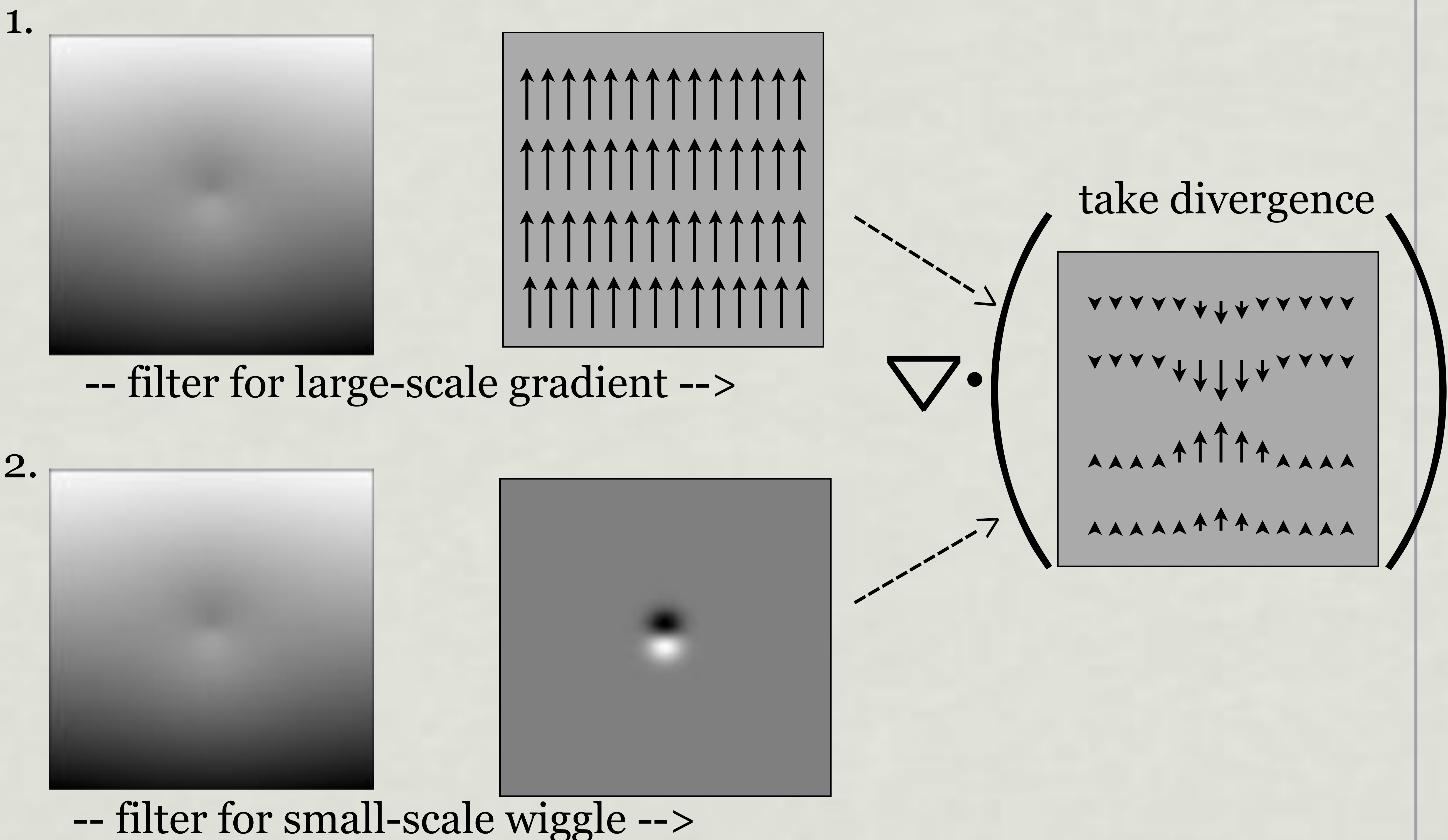


-- filter for small-scale wiggle -->

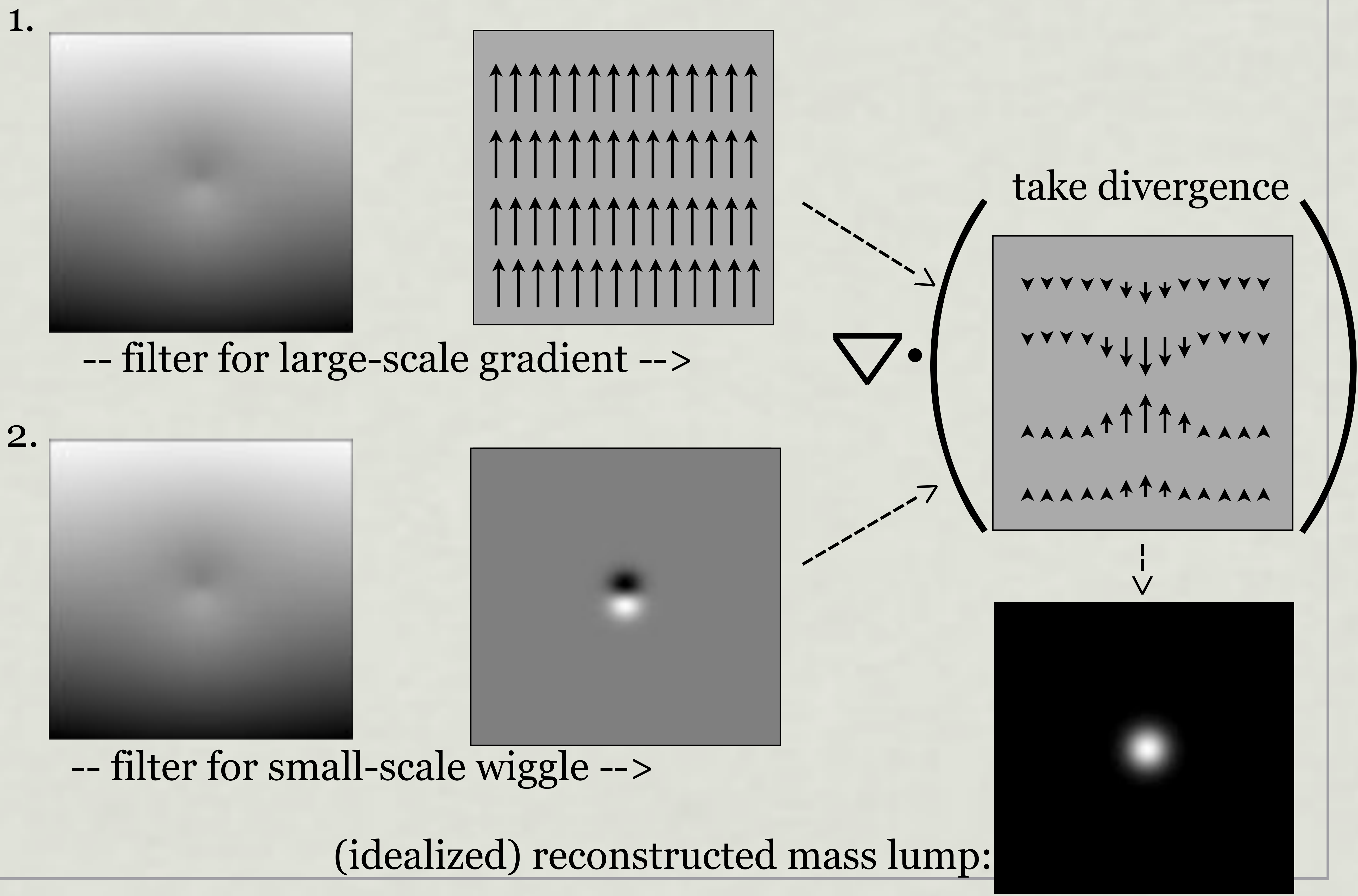
Unpacking the *Quadratic Estimator*



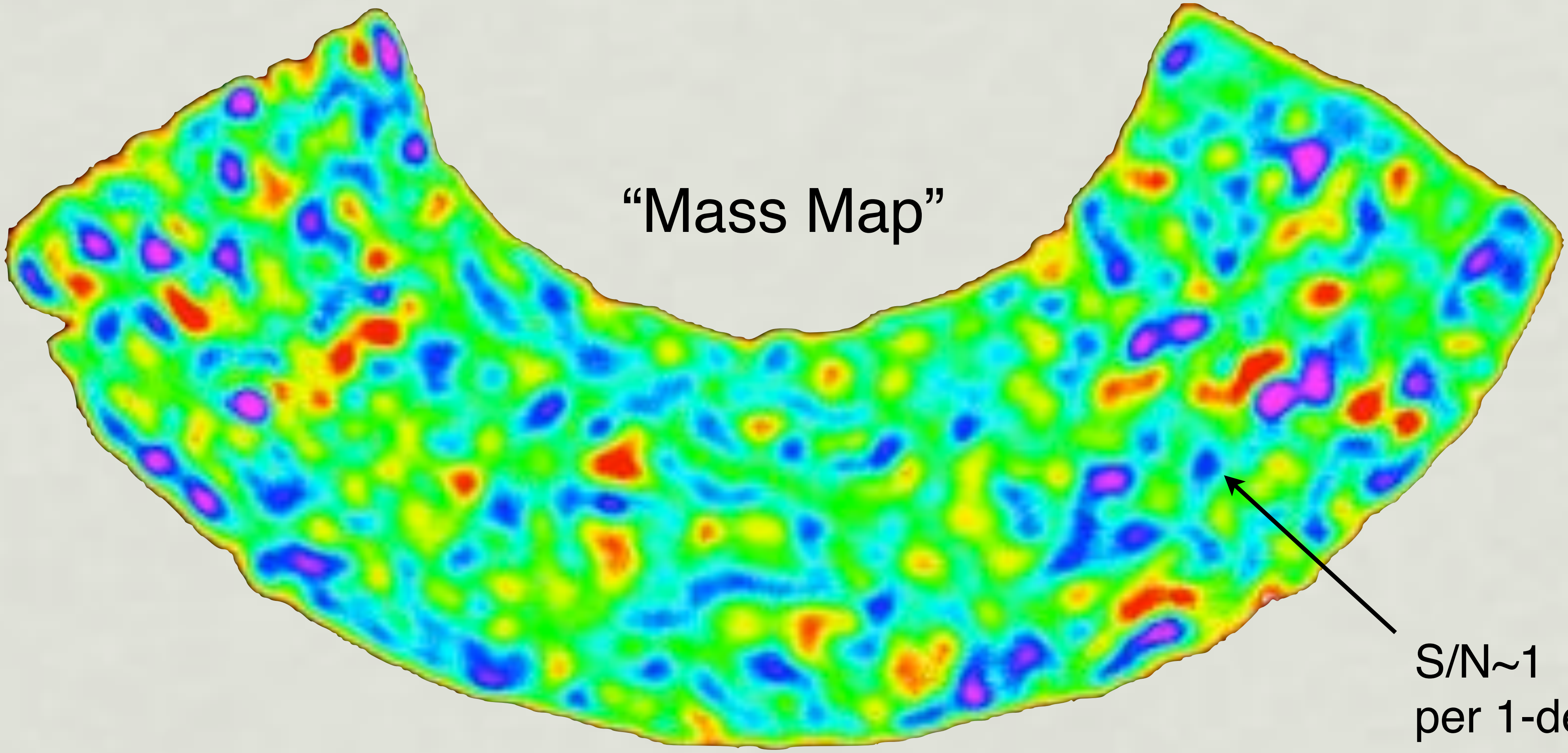
Unpacking the *Quadratic Estimator*



Unpacking the *Quadratic Estimator*



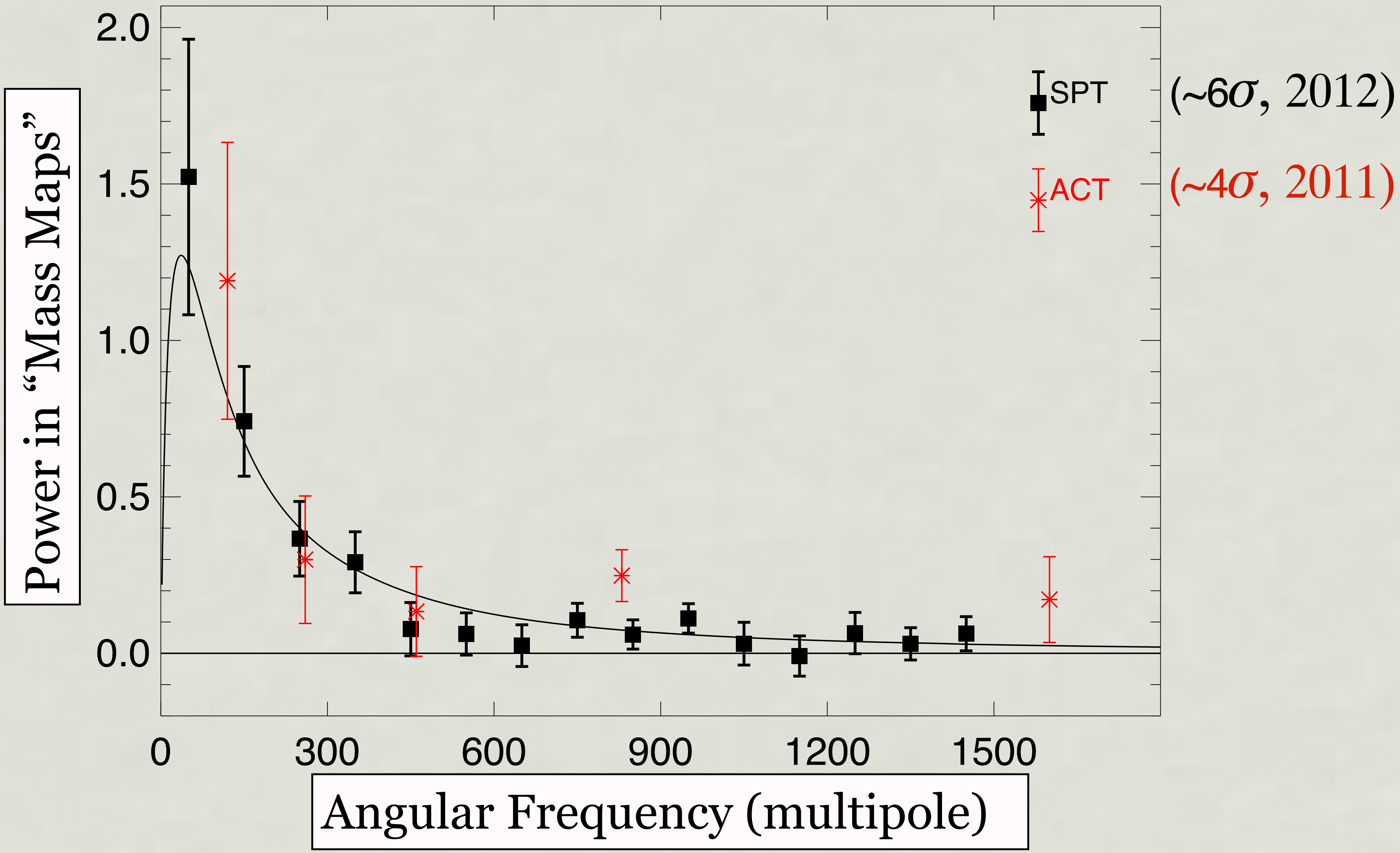
Mass reconstruction: QE in action



S/N~1
per 1-degree-sized
feature.

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

And it works.

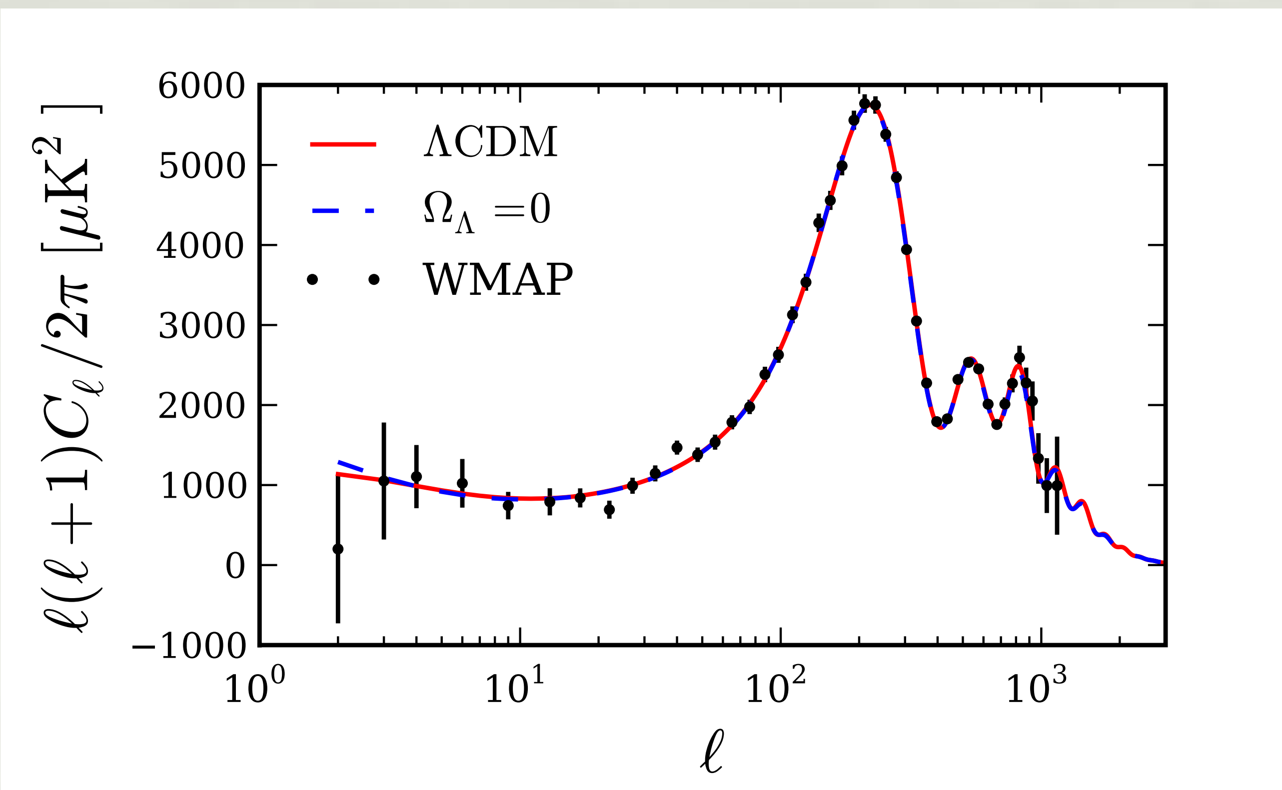


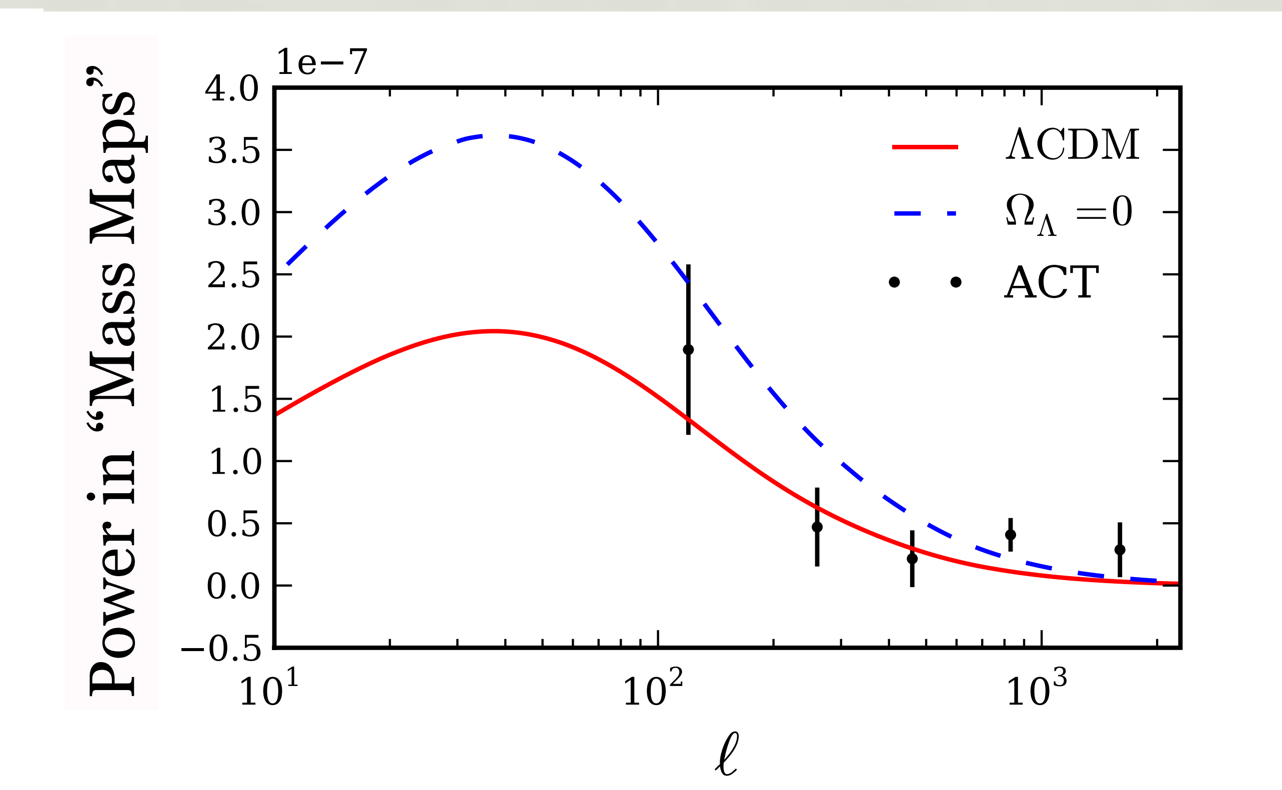
See "**A measurement of gravitational lensing of the microwave background using South Pole Telescope data**", A. Van Engelen, R. Keisler, O. Zahn, *et al.*, arXiv:1202.0546.

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

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

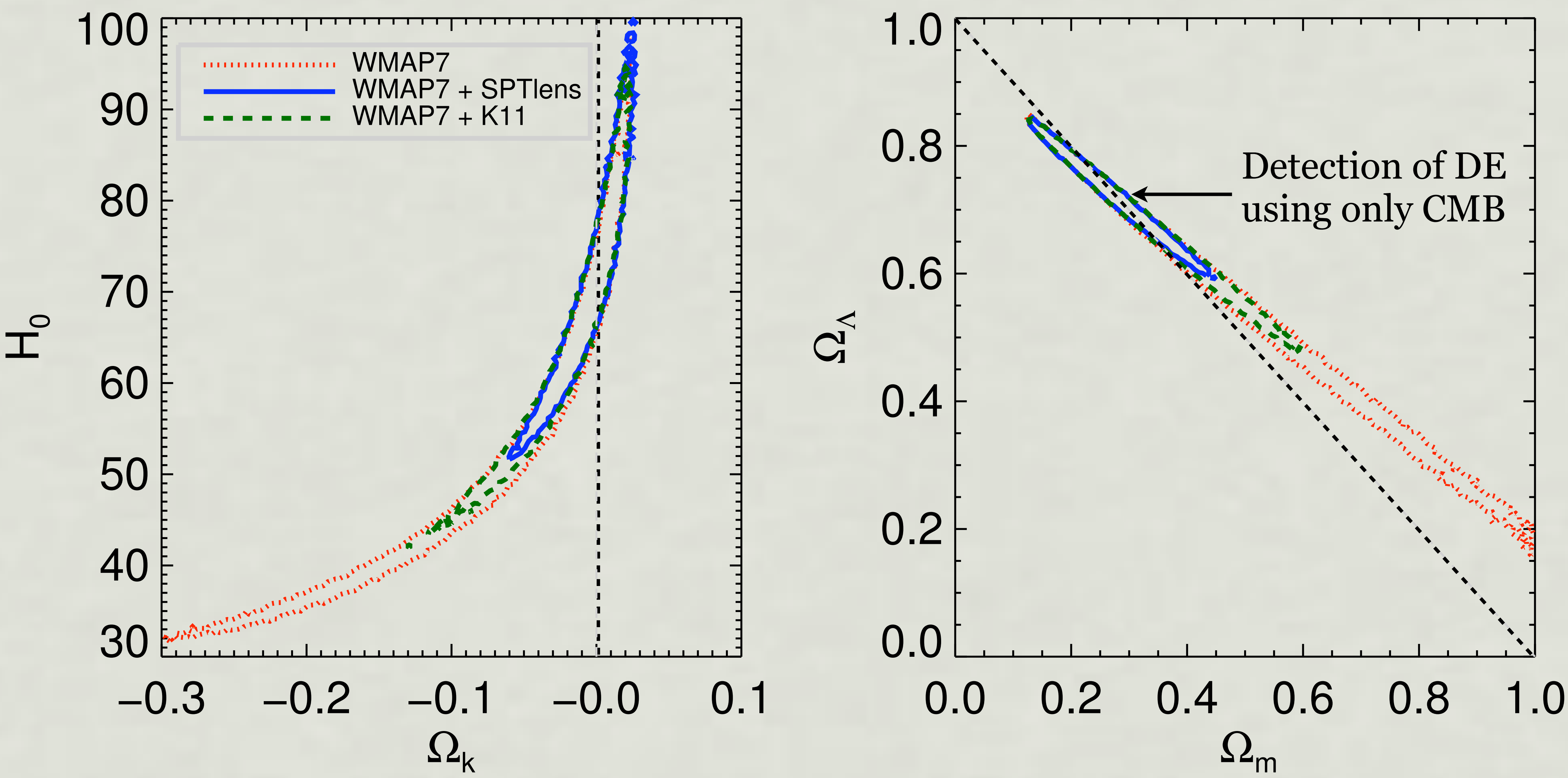
but very different low-redshift behavior: *CMB lensing data* breaks degeneracy and demands DE.





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

Same story, but with SPT data:

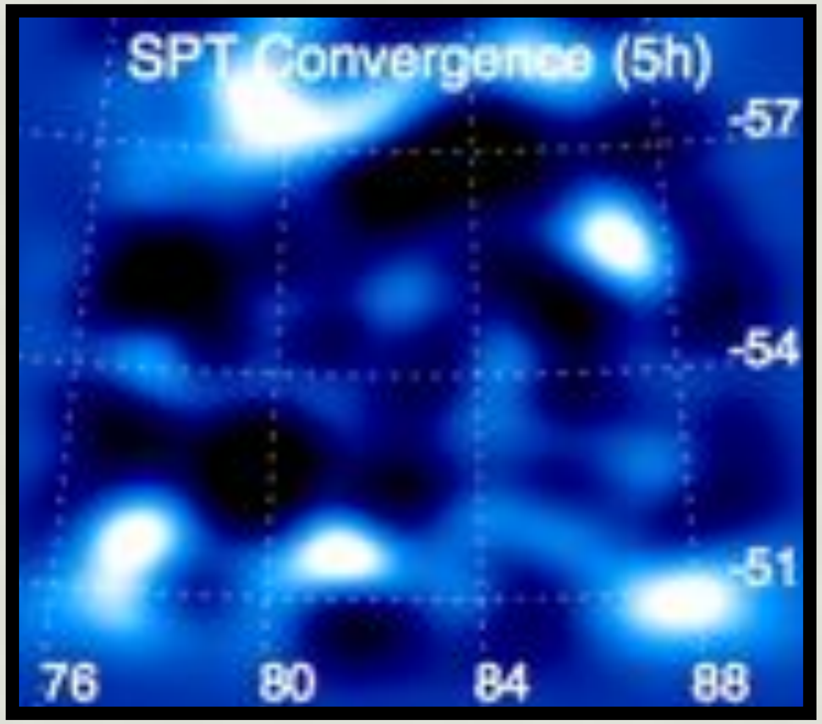


See "**A measurement of gravitational lensing of the microwave background using South Pole Telescope data**", A. Van Engelen, R. Keisler, O. Zahn, *et al.*, arXiv:1202.0546.

And it works, part 2

These CMB-lensing "mass maps" correlate well with other tracers of LSS, like galaxies.

"mass map"



X

 # density of galaxies

Optically-selected galaxies (BCS)

or

IR-selected galaxies (Spitzer, WISE)

=> 5σ detections. Allows one to measure bias of a given population with a well-calibrated mass map.

See "**A measurement of the correlation of galaxy surveys with CMB lensing convergence maps from the South Pole Telescope**", L. Bleem, A. Van Engelen, G. Holder *et al.*, arXiv:1203.4808.

Timeline of CMB Lensing Measurements

- 2007: 3σ (WMAP+) *Smith et al* *(TT) x (LSS)*
- 2008: 3σ (ACBAR+WMAP) *Reichardt et al* *(TT)*
- 2011: 2σ (WMAP) *Smidt et al* *(TTTT)*
- 2011: 4σ (ACT+WMAP) *Das et al* *(TTTT)*
- 2011: 5σ (SPT+WMAP) *Keisler et al* *(TT)*
- 2012: 6σ (SPT) *van Engelen et al* *(TTTT)*
- 2012: >5σ (SPT+) *Bleem et al* *(TT) x (LSS)*

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

(rapidly evolving field: **20-30**σ detections in the next year)

Take Away #2

CMB lensing provides a novel way to measure matter fluctuations at z~[0.5, 4].

Long-term goal is to measure e.g. neutrino masses.

The CMB data is finally good enough for this, and is rapidly getting better.

Outline

1. very brief CMB overview

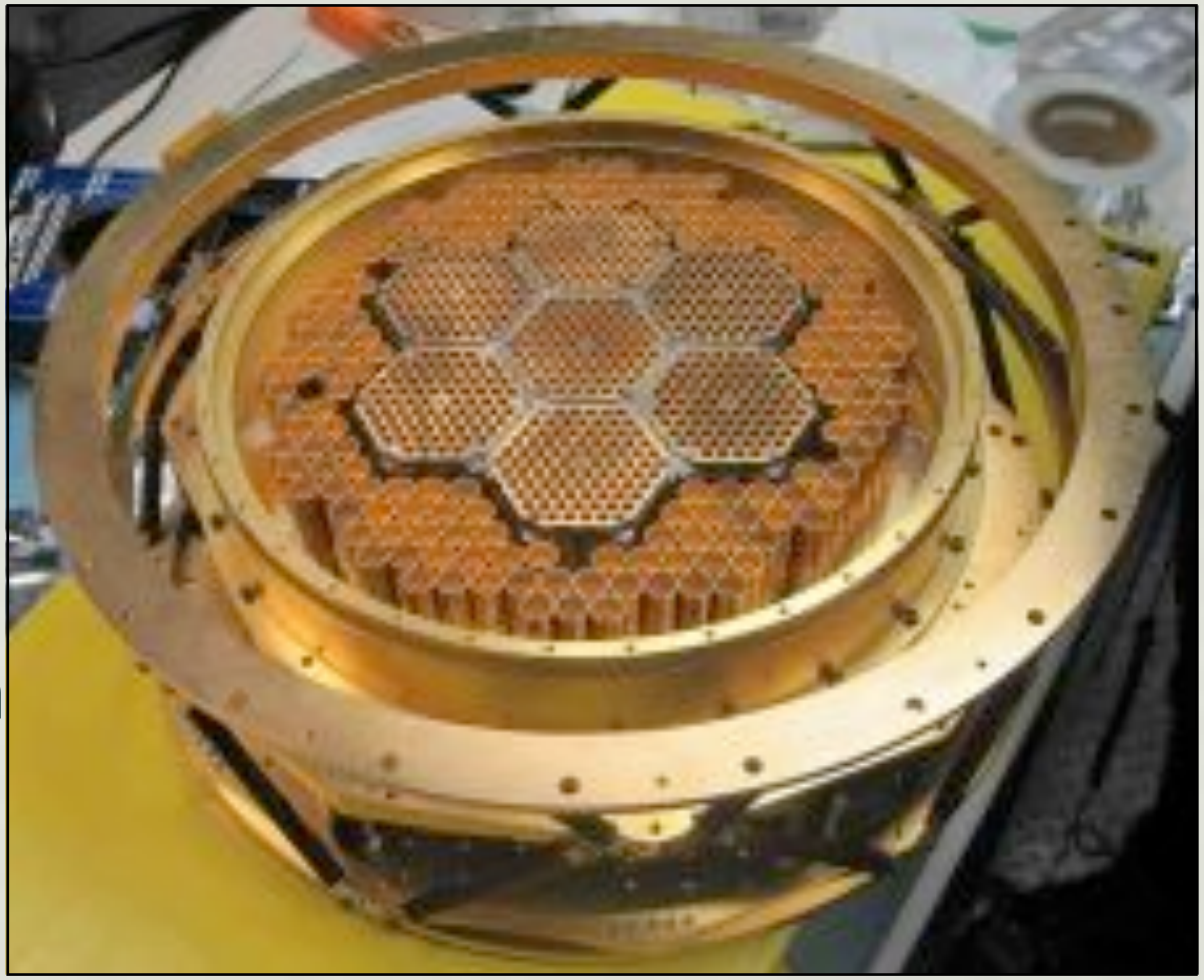
2. New results from SPT:

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

3. New camera: SPT-pol.

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.

thanks

extra slides

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 e.g. 1104.2333, Z. Hou, RK, L. Knox, C. Reichardt)

Helium

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

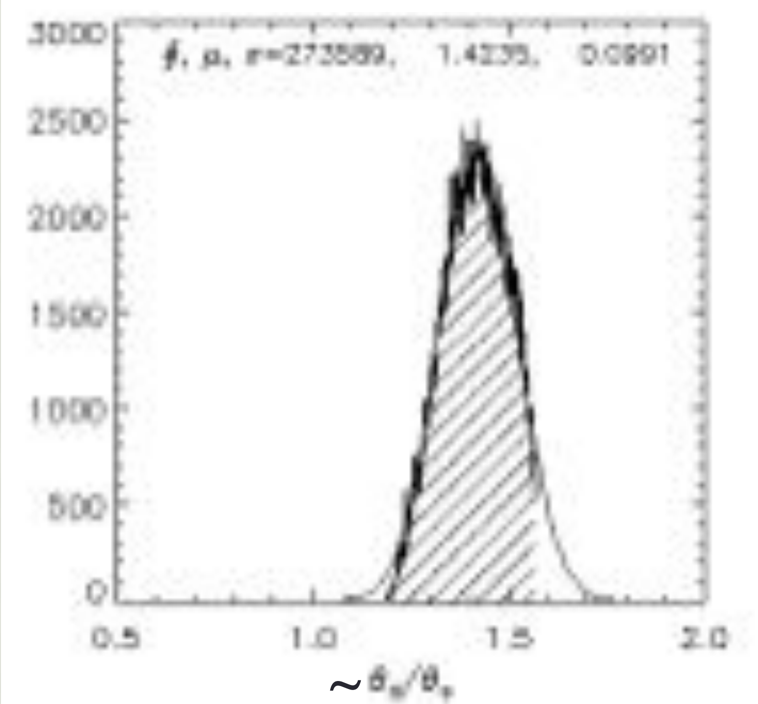
This ratio is also a function of the **primordial helium abundance, Yp.** In standard BBN, this is a weak function of Neff.

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 ~30% extra sensitivity to N_{eff}.

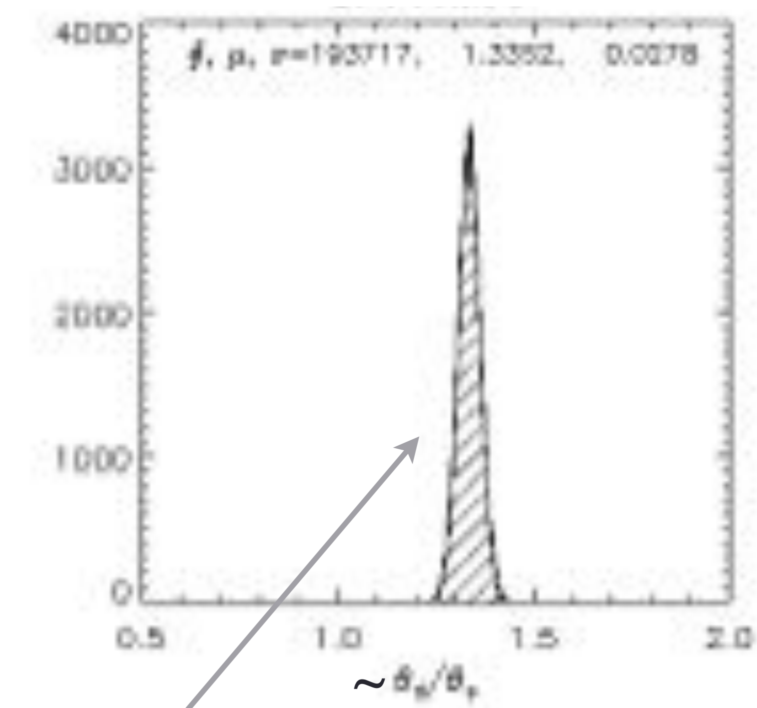
(see 1104.2333, Z. Hou, RK, L. Knox, C. Reichardt)

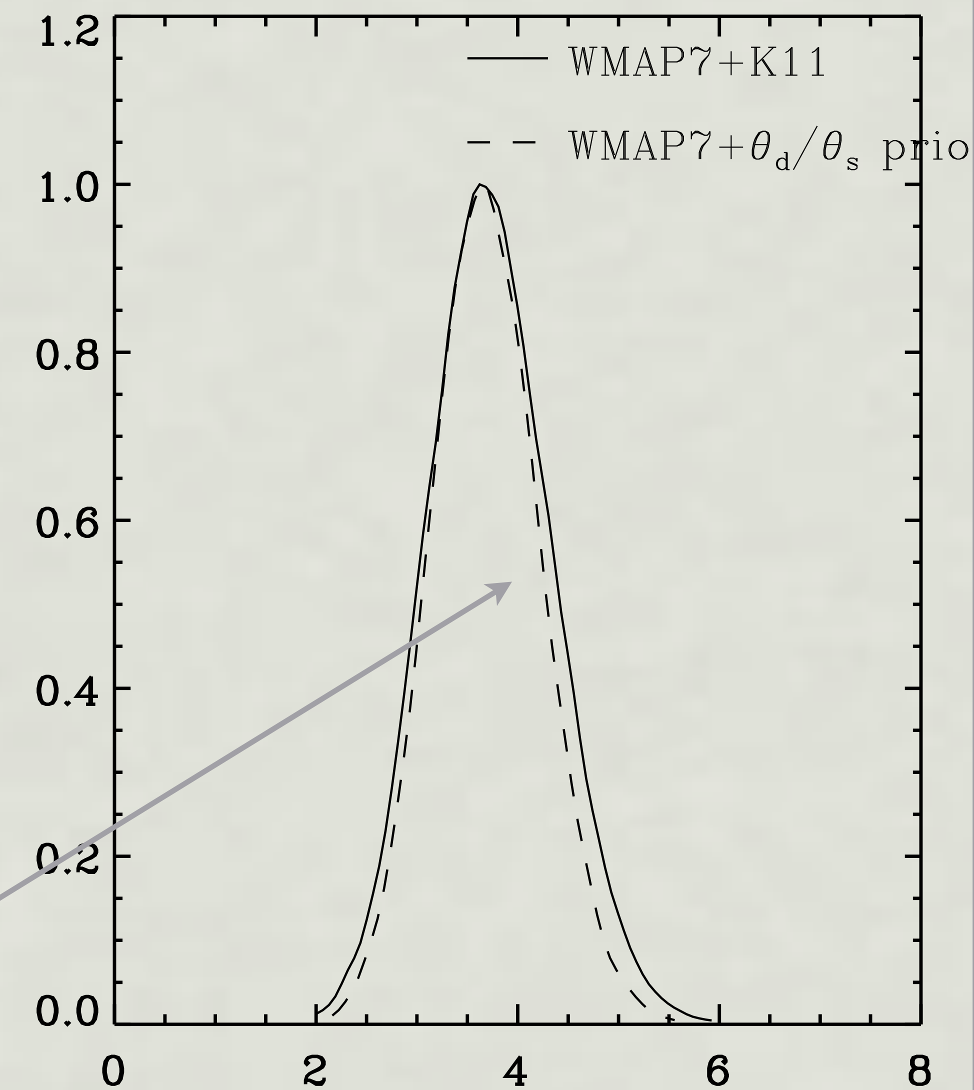
And the improvement on Neff is really due to the improvement on the angle ratio, (theta_d/theta_s).

WMAP



WMAP+SPT





Neff

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 e.g 1104.2333, Z. Hou, RK, L. Knox, C. Reichardt)