The Universe

as seen by the South Pole Telescope

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University of Chicago

July 8, 2013

Santa Fe Cosmology Workshop, 2013

Outline

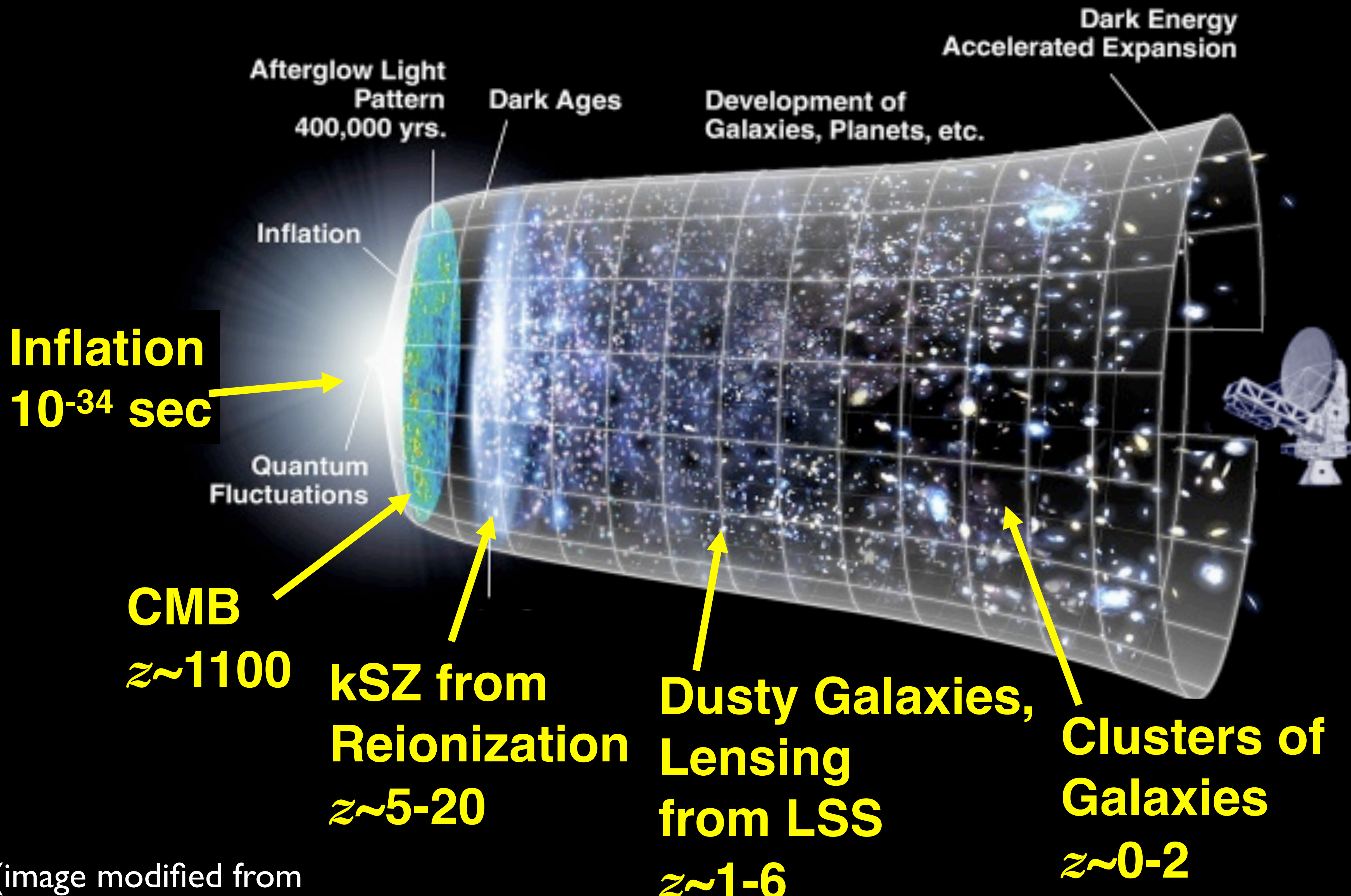
1. Overview of SPT

2. Results from SPT:

- SPT data
- primordial power spectra (inflation)
- massive neutrinos
- gravitational lensing of CMB

3. The Future is Now: SPTpol and SPT-3G

The CMB is a Unique Tool for Cosmology



(image modified from
NASA/WMAP)

Planck

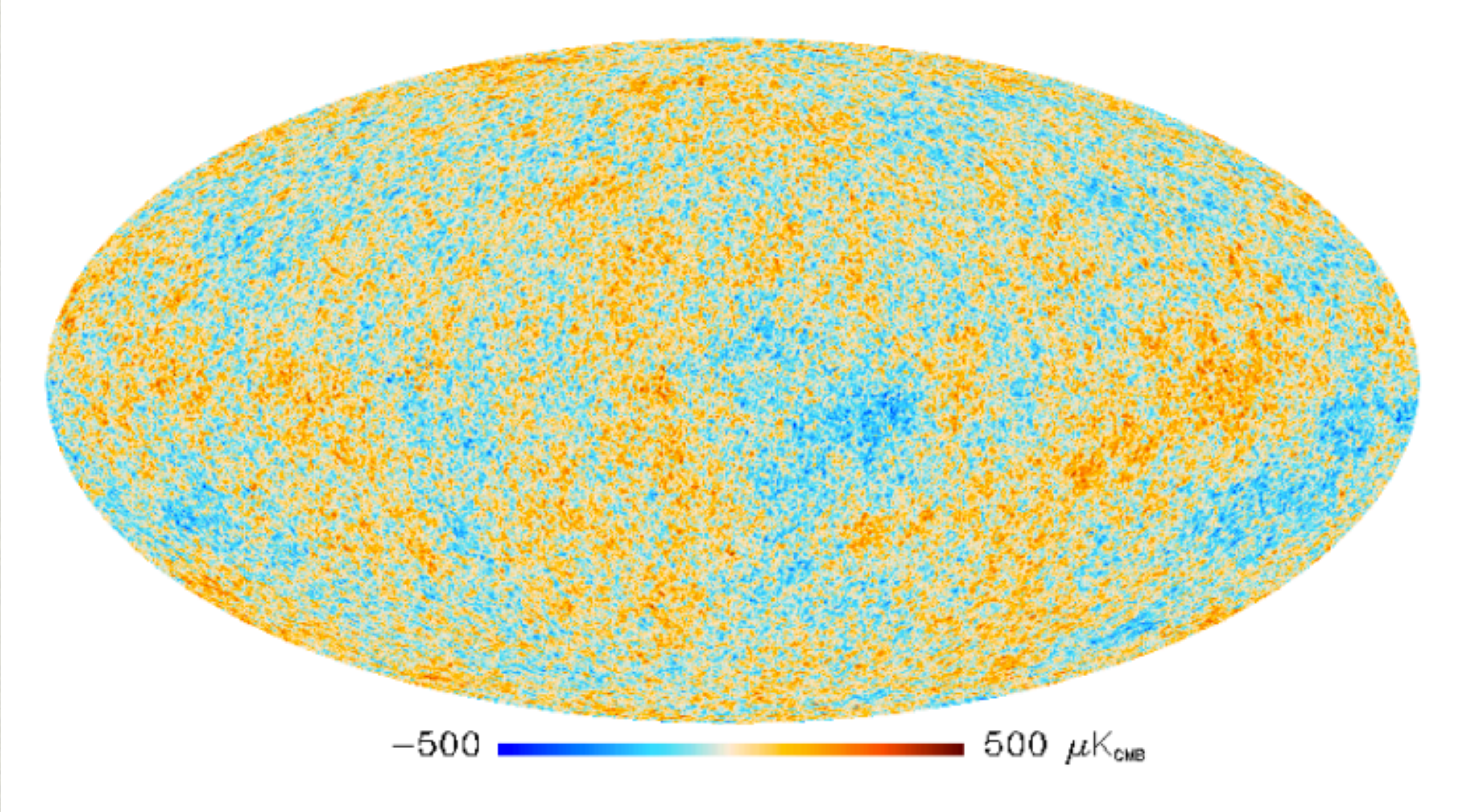
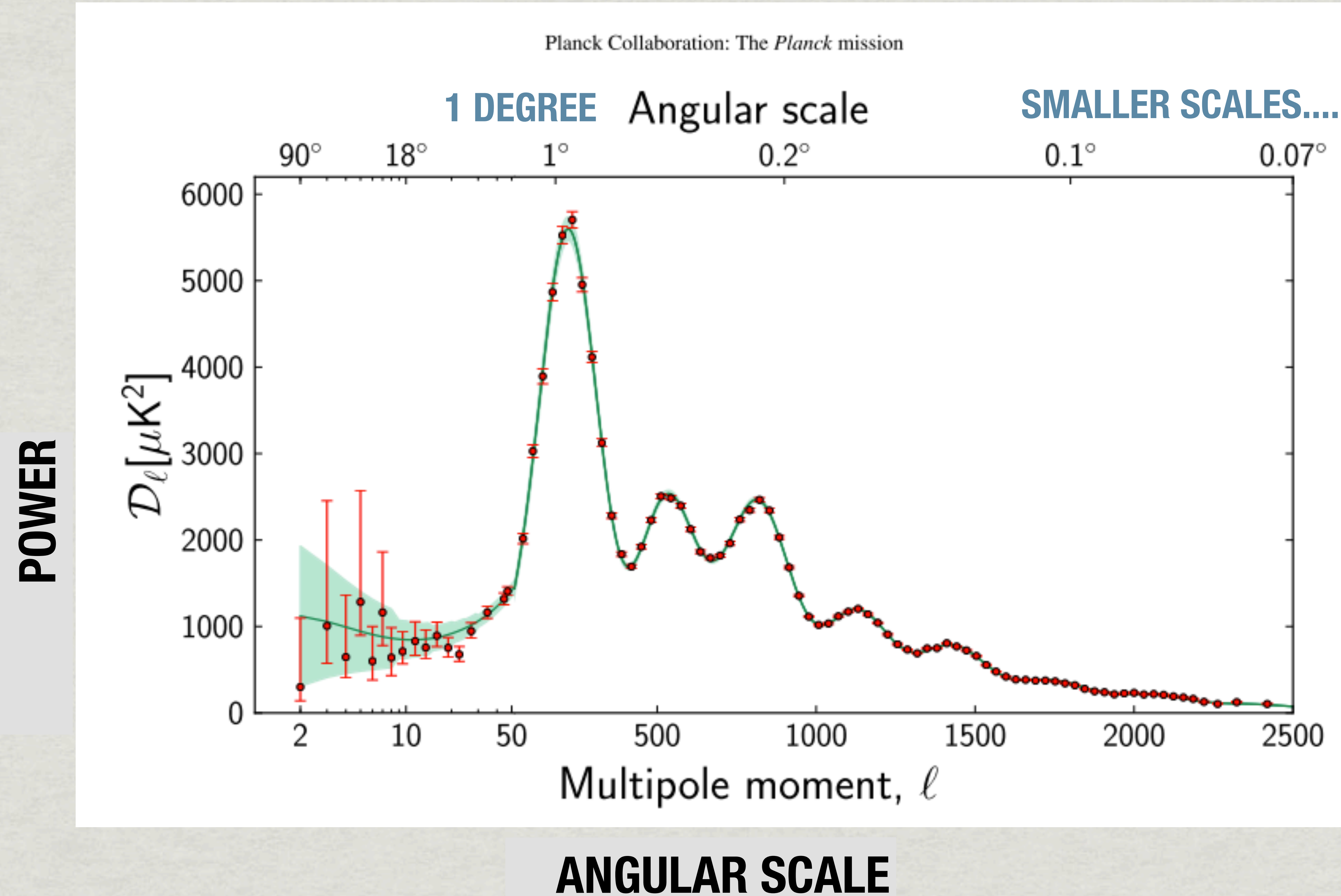


Figure from Planck Paper I : Arxiv 1303.5062

Planck



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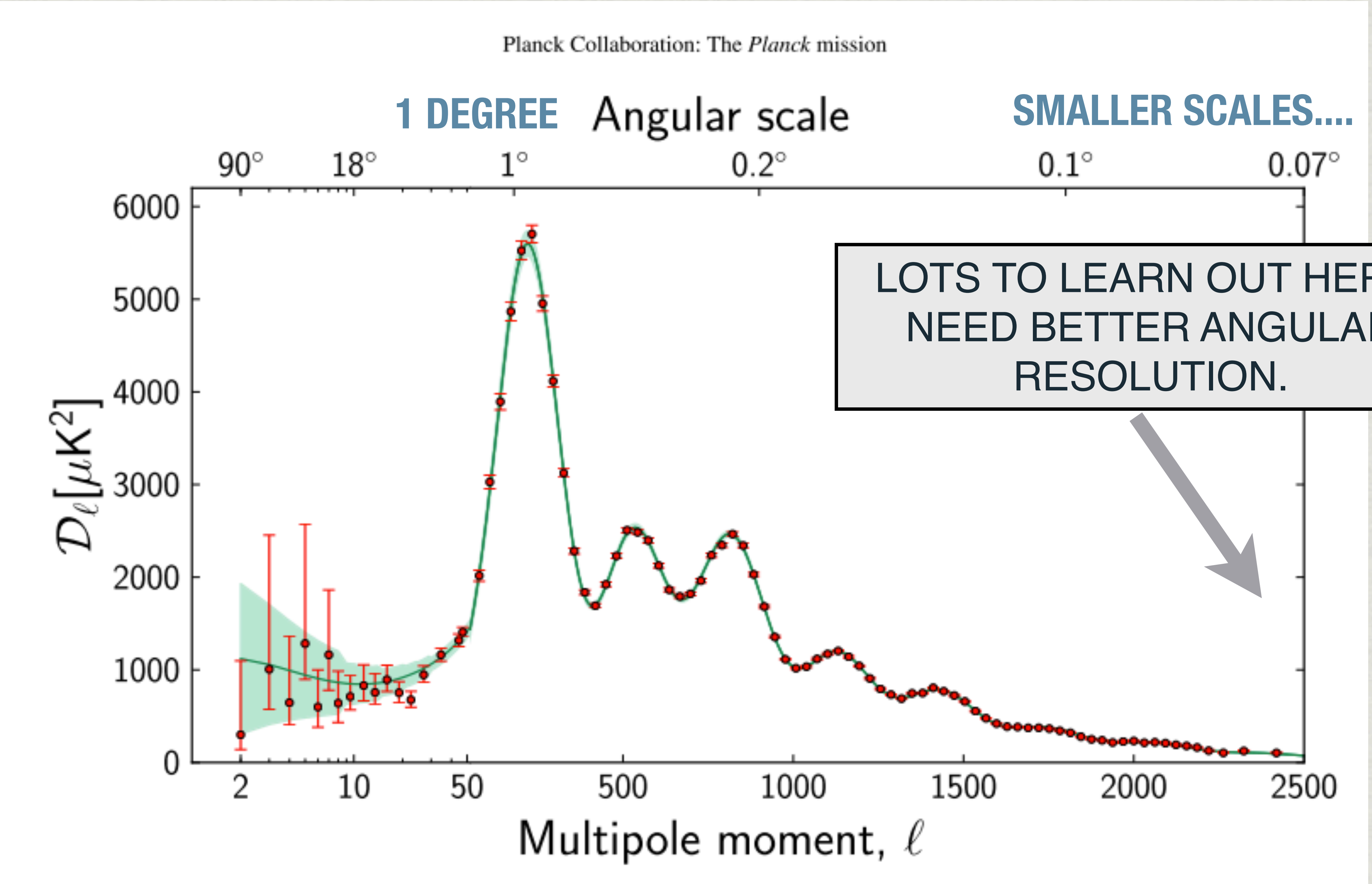


POWER

ANGULAR SCALE

Figure from Planck Paper I : Arxiv 1303.5062

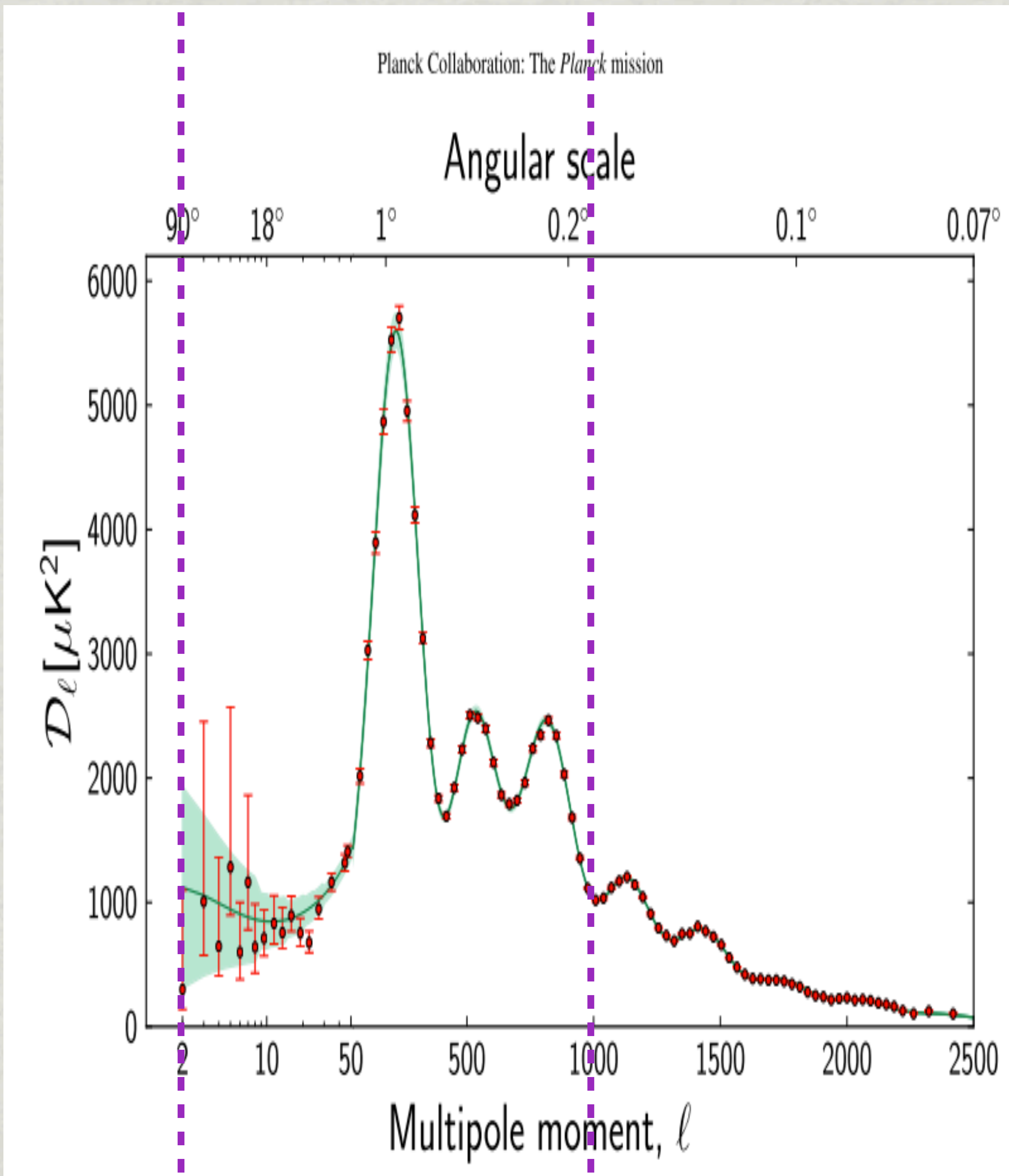
How is SPT relevant?

PRIMARY ANISOTROPIES

DAMPING TAIL

GALAXIES, FOREGROUND EMISSION, TSZ, KSZ

POWER



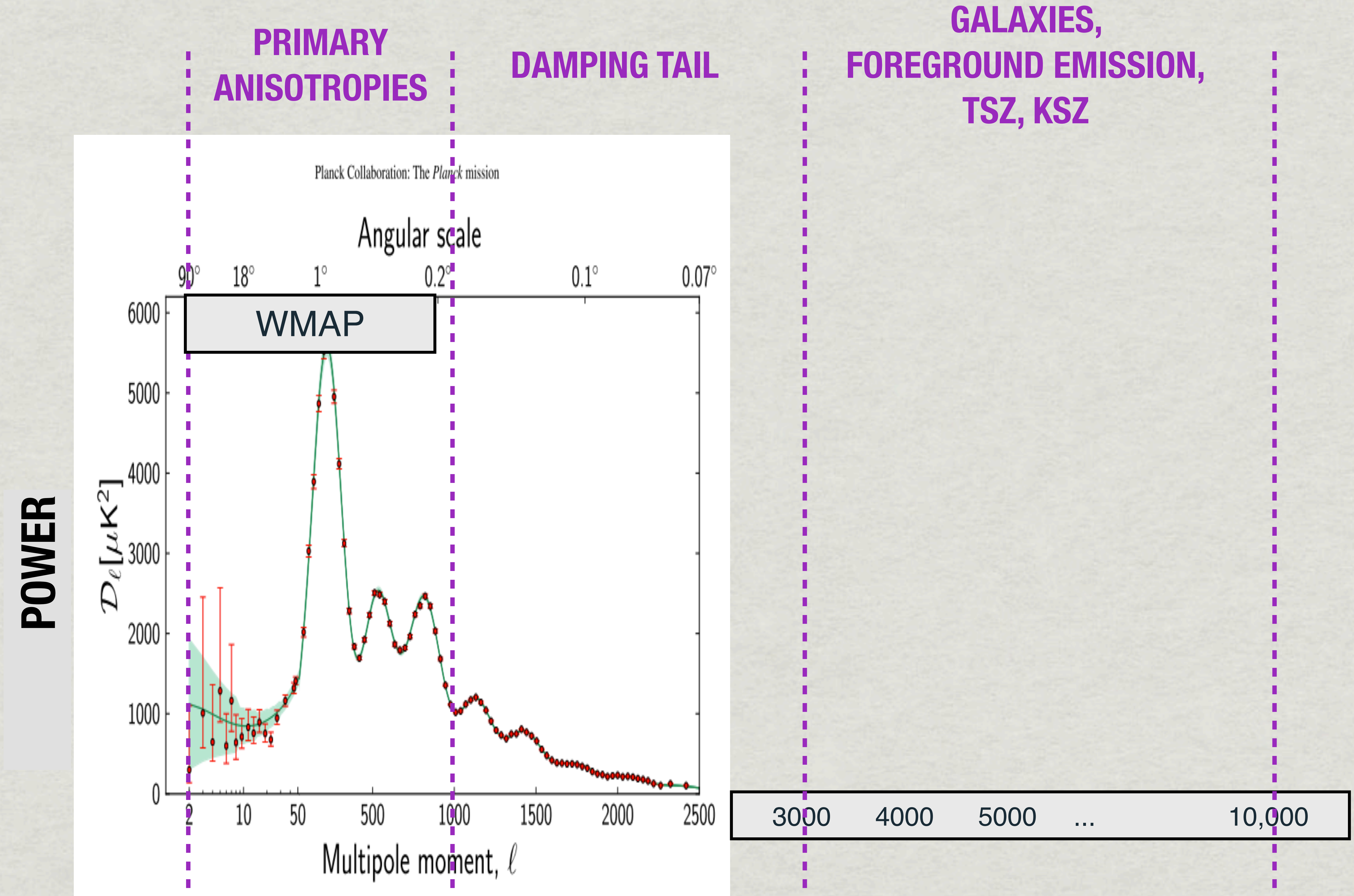
3000 4000 5000 ... 10,000

LOTS TO LEARN OUT HERE. NEED BETTER ANGULAR RESOLUTION.

ELL-RANGES ARE HEURISTIC

Figure from Planck Paper I : Arxiv 1303.5062

How is SPT relevant?



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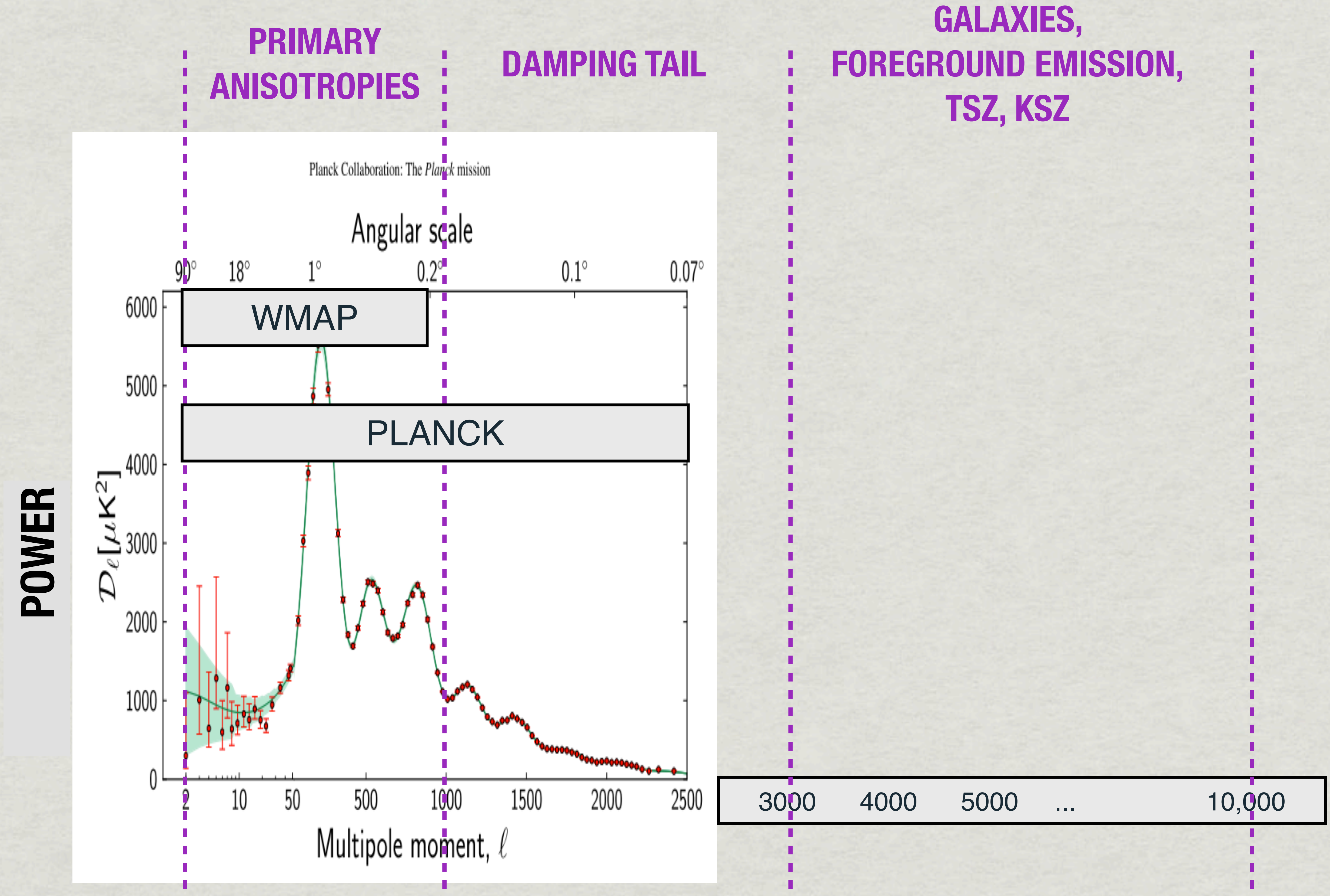

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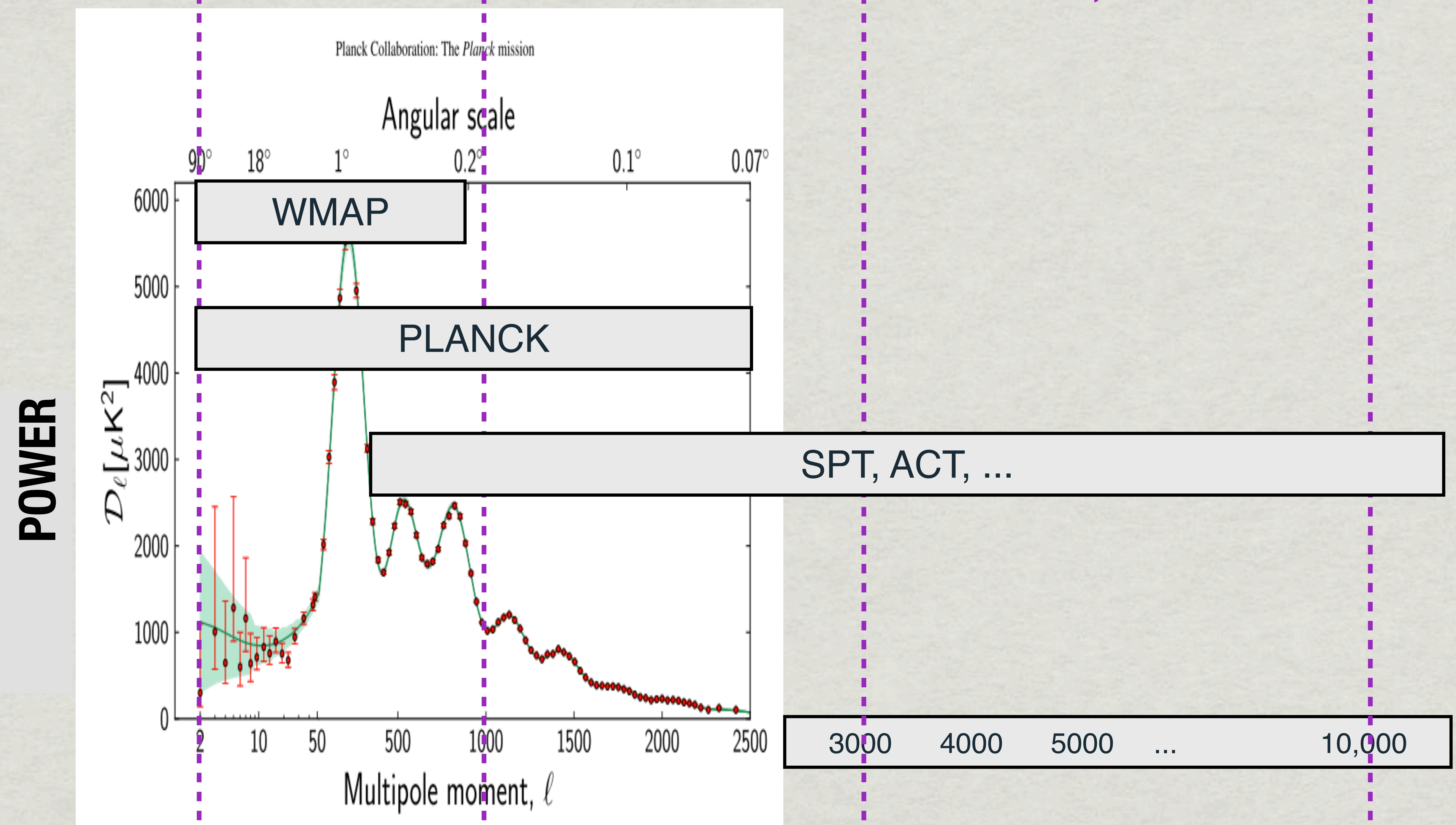

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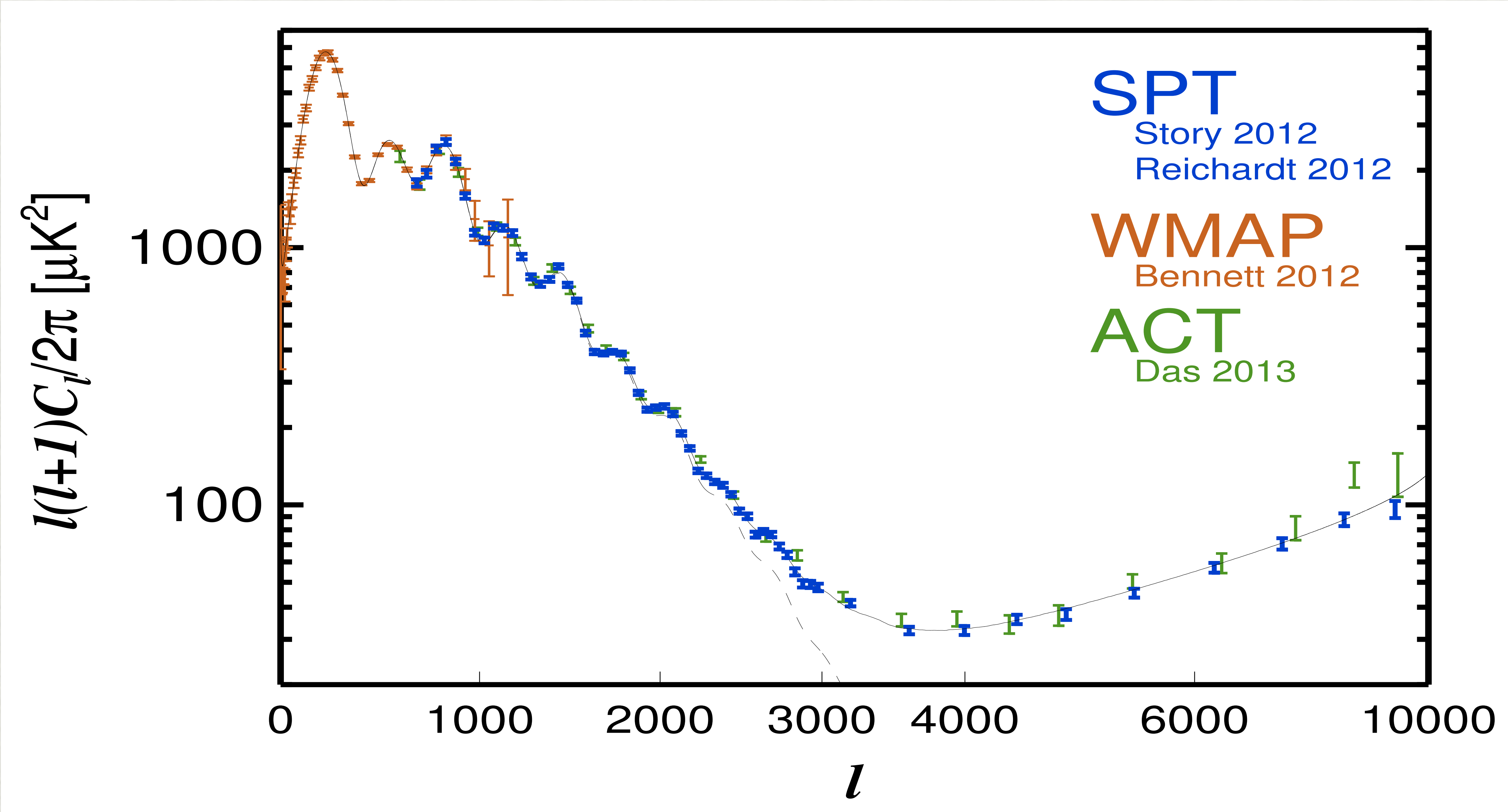


SPT measures CMB power up to l~10,000.

Story et al 2012 (1210.7231),
Reichardt et al. 2012 (1111:0932)

The South Pole Telescope:
a mm-wave observatory

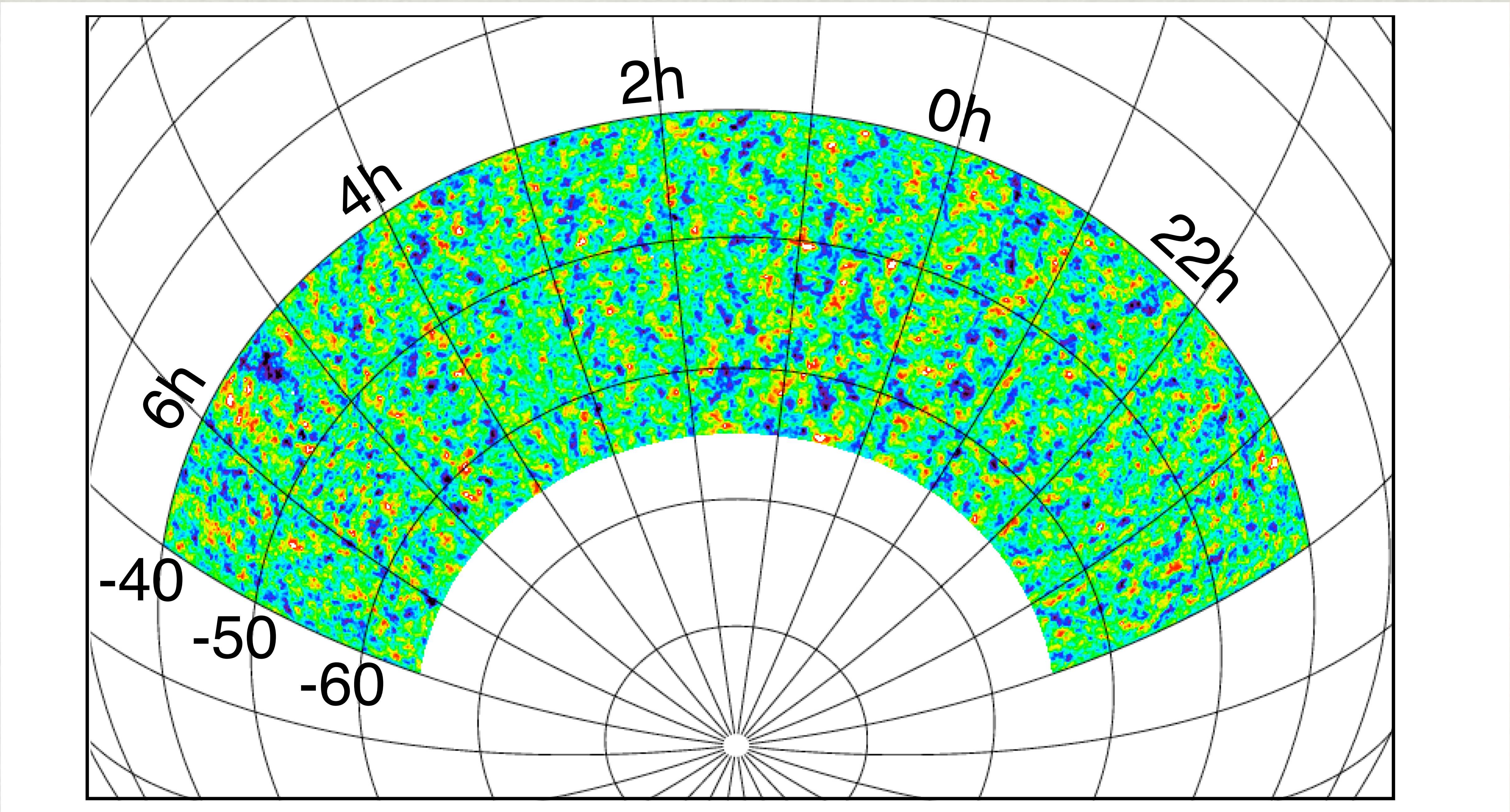
- 10 meter primary mirror
  ~1 arcminute resolution
- 1st camera: 2007-2011. "SPT-SZ"
  1000 bolometers.
  3 bands: 90, 150, 220 GHz.
- 2nd camera: 2012-?. "SPT-POL".
  1600 bolometers. polarization-sensitive.
  2 bands: 90, 150 GHz

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

photo by Dana Hrubes

SPT-SZ 2500 deg² Survey

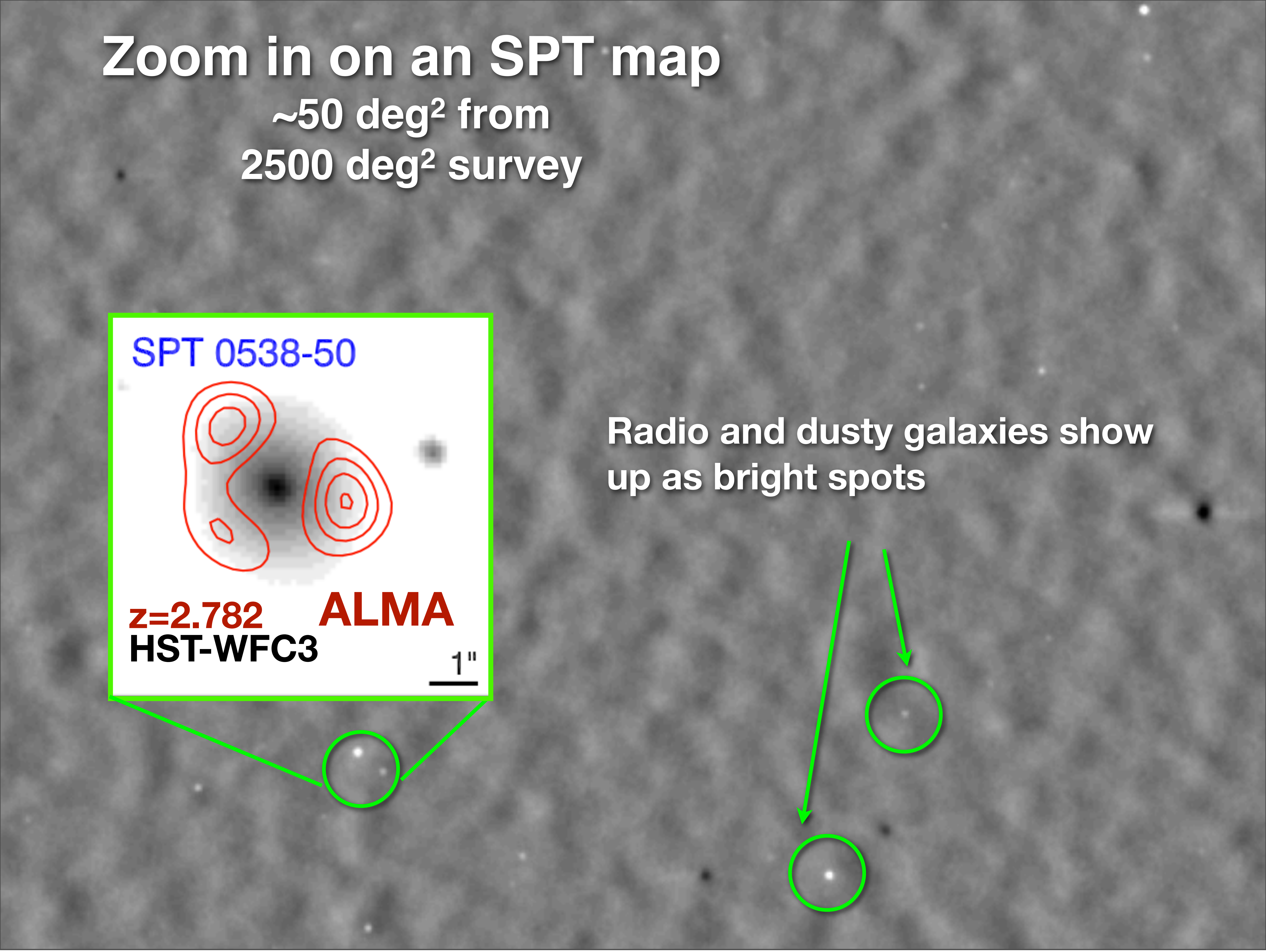
(*6% of sky*)

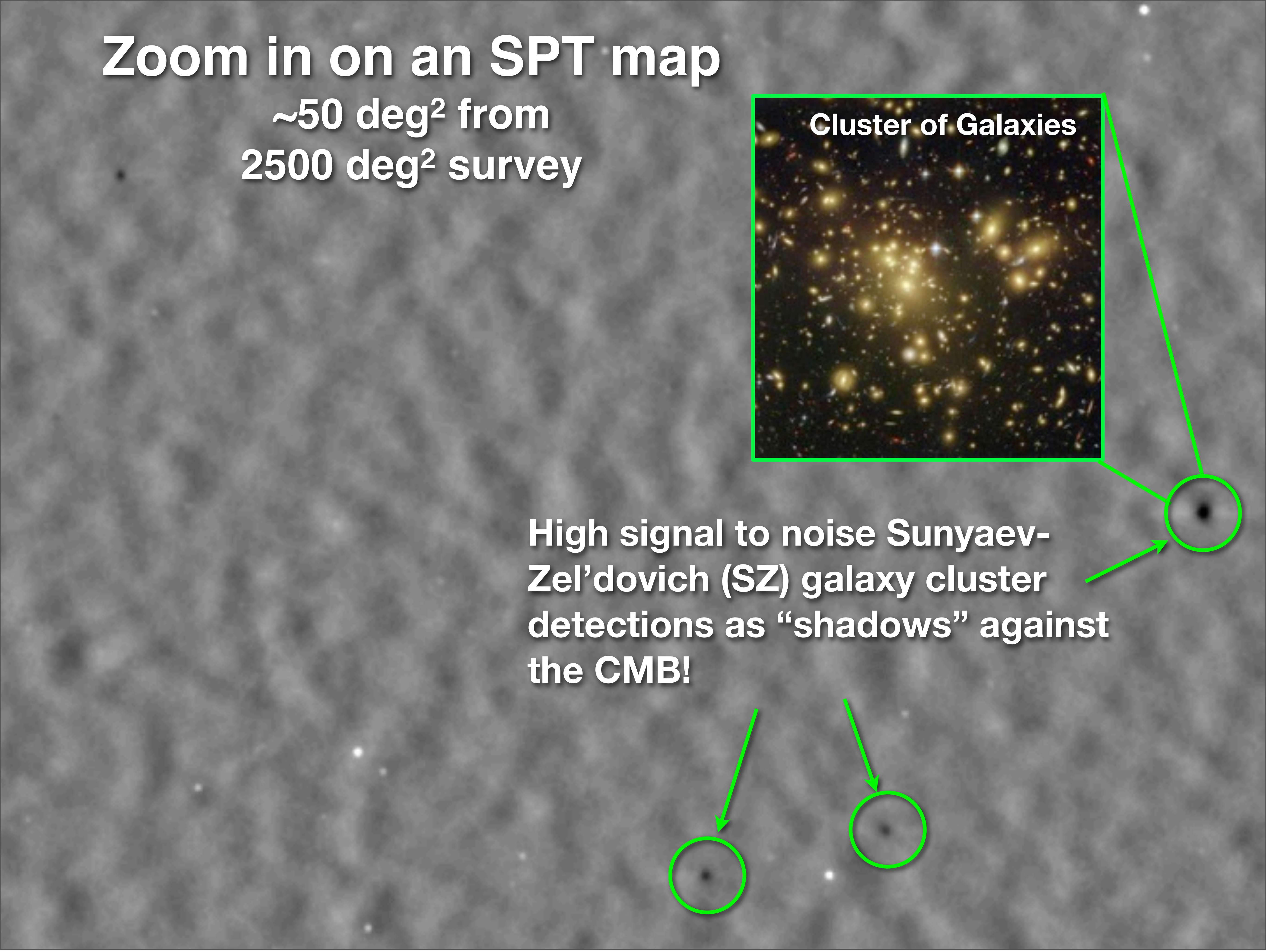


Status: finished in *Nov. 2011*.

Results shown today use all of this data.

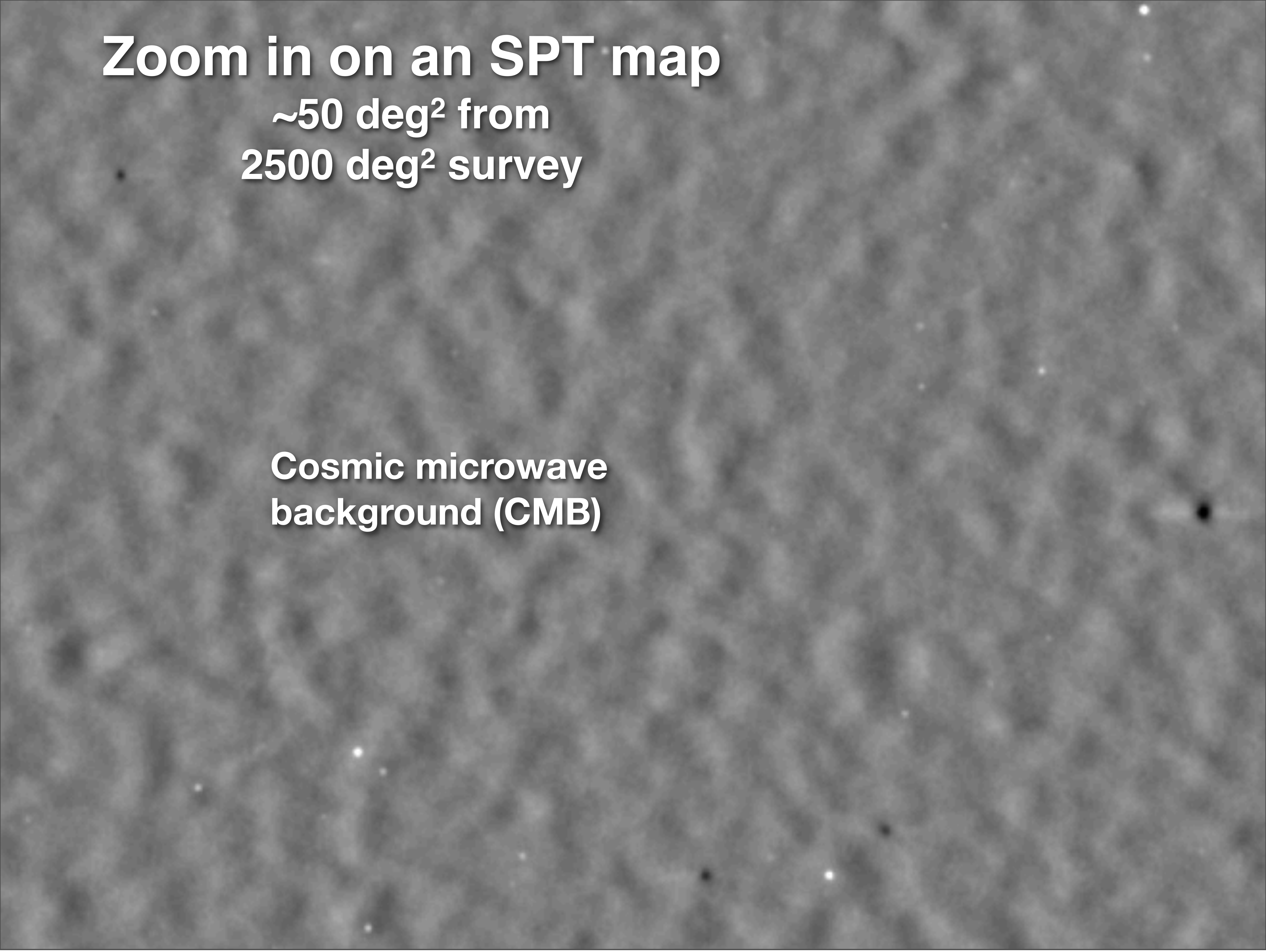
BRIEF DETOUR: What science can you do with this map?


Zoom in on an SPT map
~50 deg² from
2500 deg² survey
SPT 0538-50
z=2.782
ALMA
HST-WFC3
1"
Radio and dusty galaxies show
up as bright spots


Zoom in on an SPT map
~50 deg² from
2500 deg² survey
High signal to noise Sunyaev-Zel’dovich (SZ) galaxy cluster detections as “shadows” against the CMB!
Cluster of Galaxies

Zoom in on an SPT map

~50 deg² from 2500 deg² survey



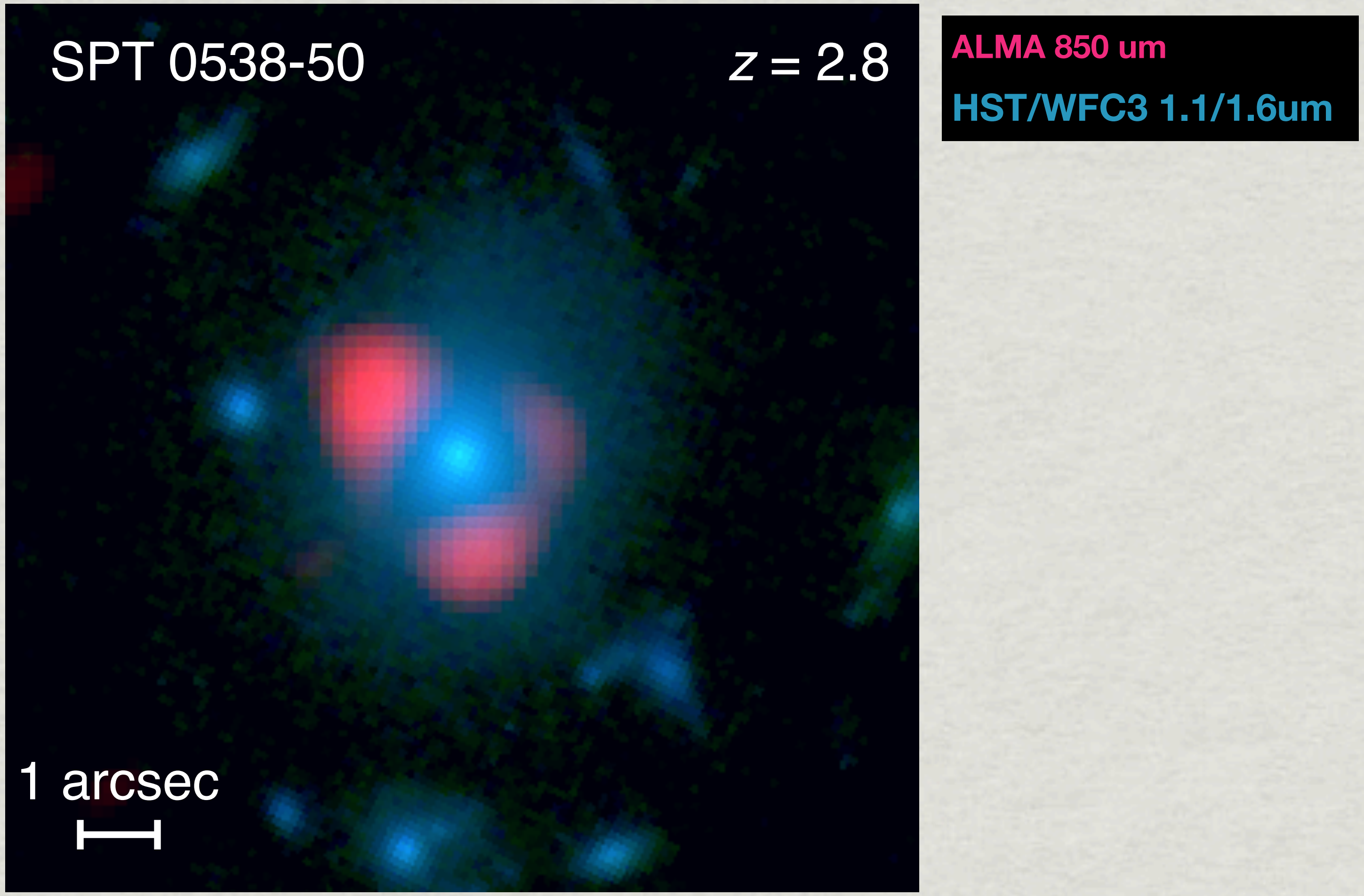
BRIEF DETOUR:There's a lot of other SPT science going on. Some examples:

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

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

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

...



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), Mocanu et al. (1306.3470)

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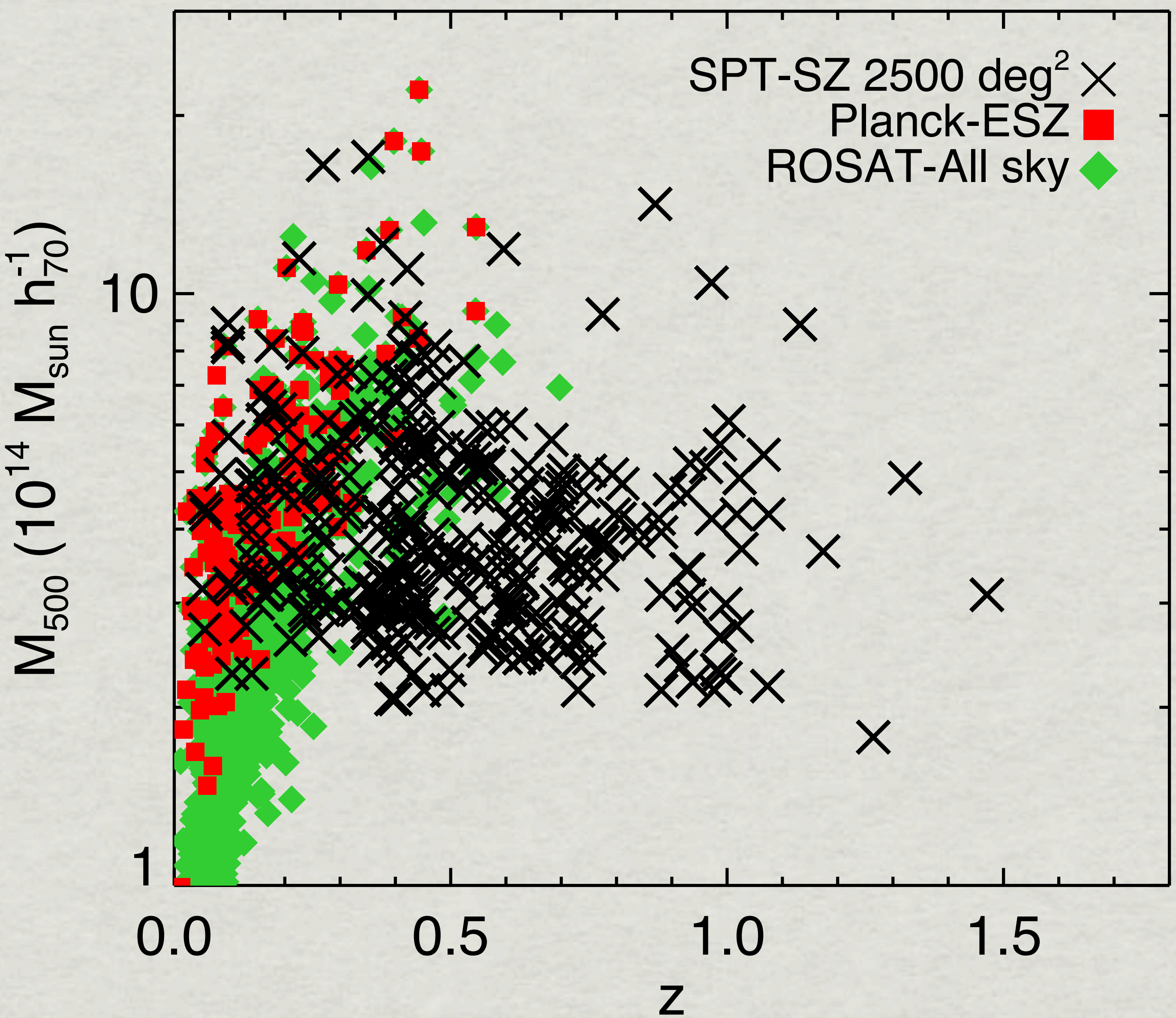

See Benson et al. (1112.5435) and Reichardt et al (1203.5775)

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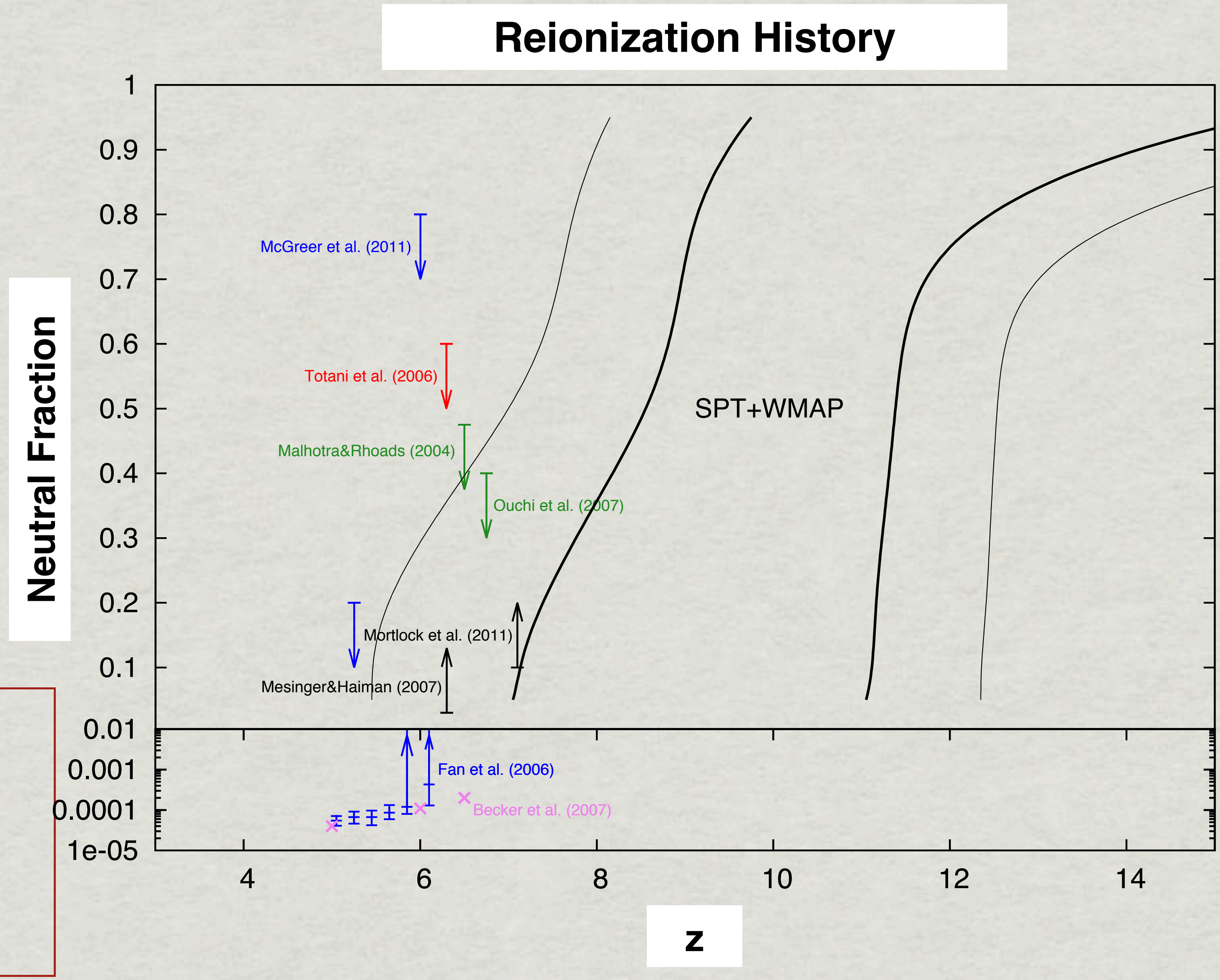

See Reichardt et al. (1111.0932) and Zahn et al (1111.6386)

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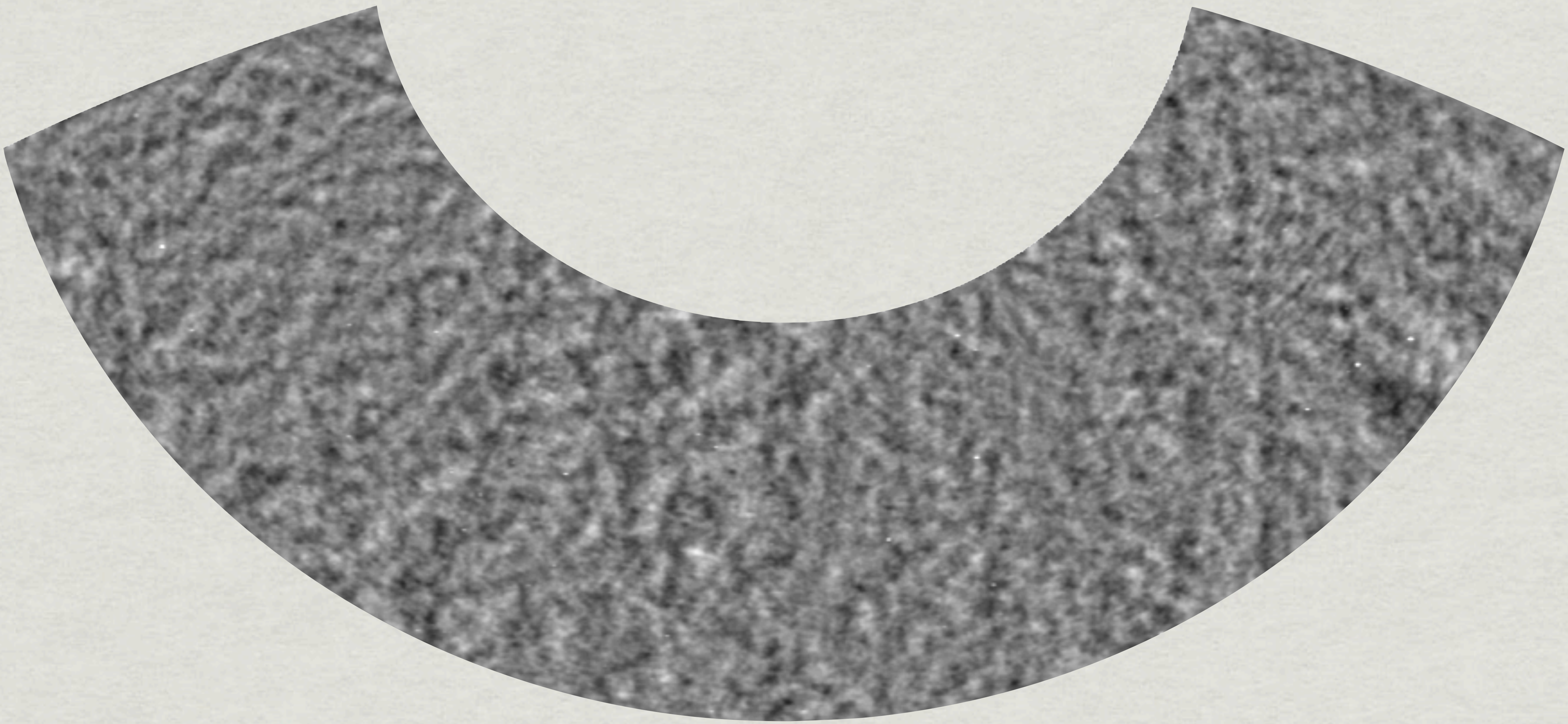
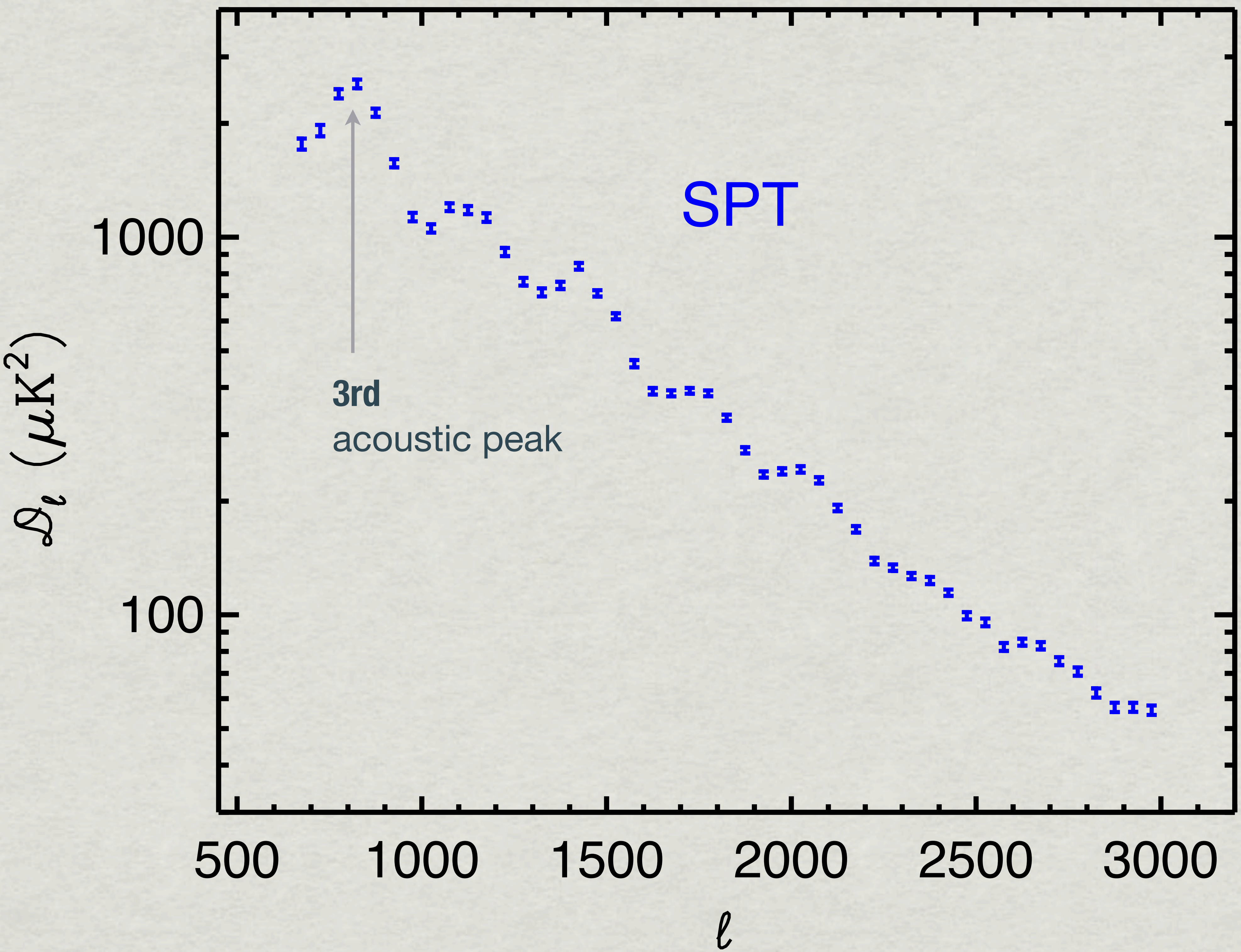
Take the angular power spectrum of the 2500 sq. deg. SPT-SZ survey...

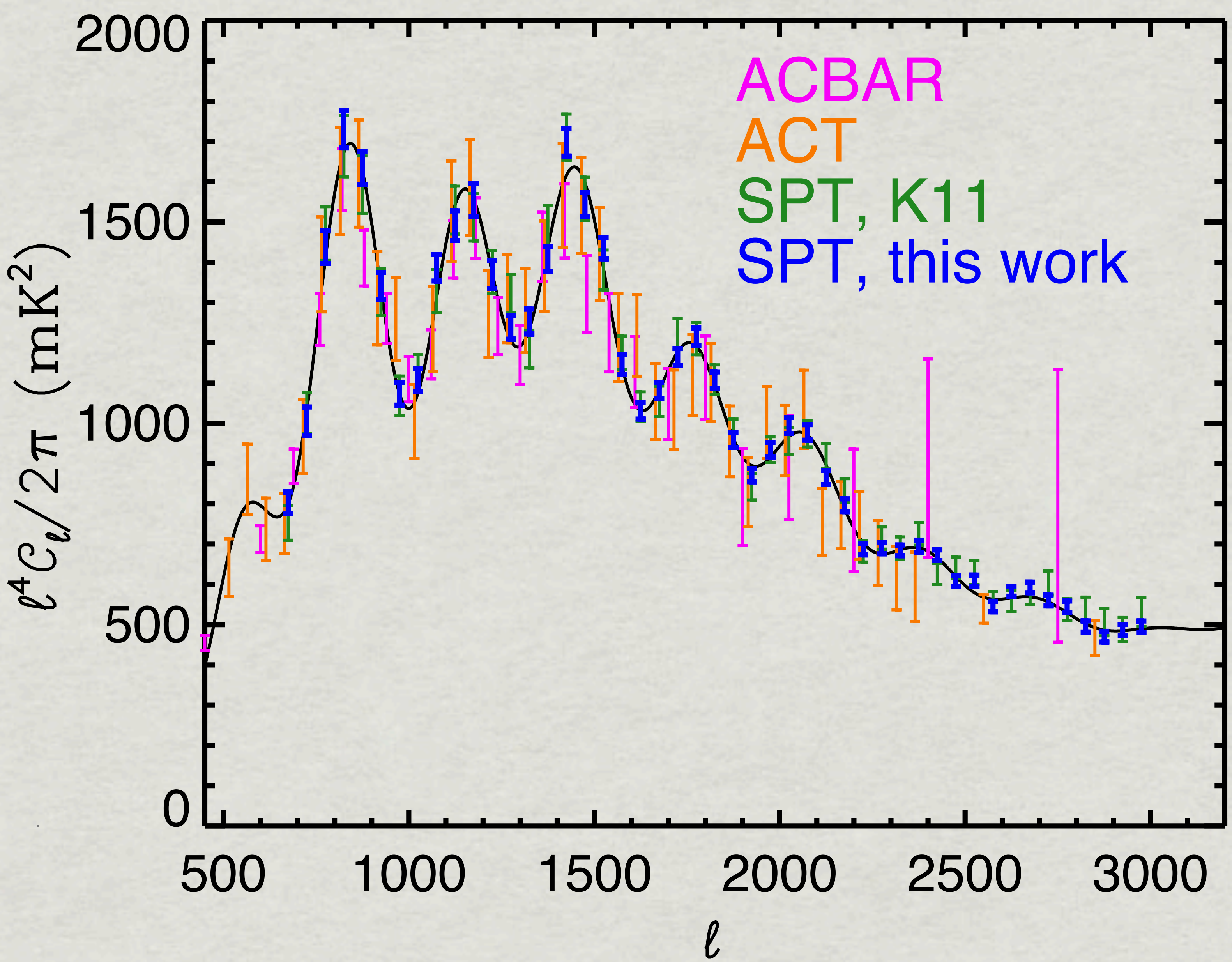


See arXiv:1210.7231 (KTS, Reichardt, Hou, Keisler *et al.)*

...and you get this.



Comparison to previous works



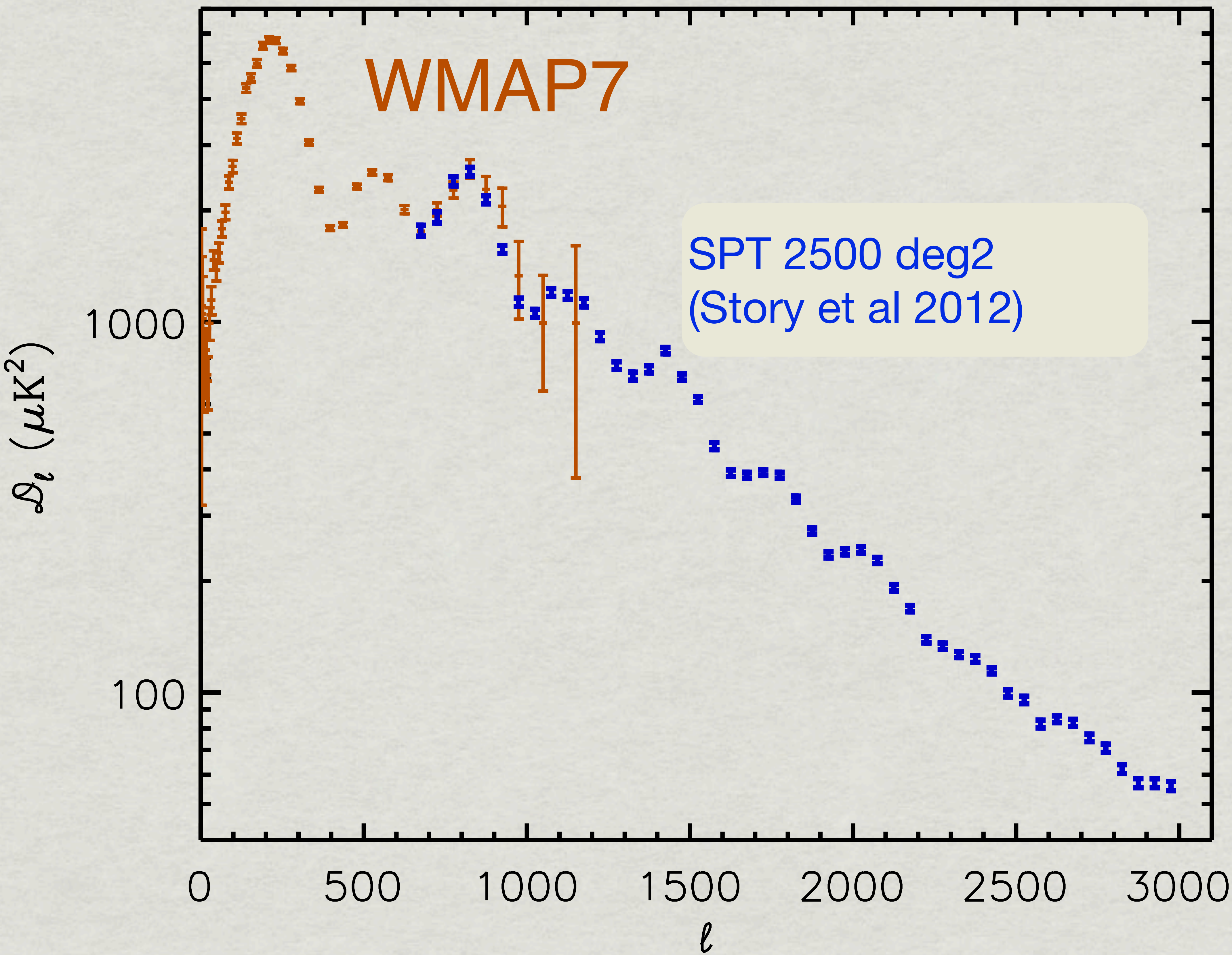
New SPT work provides:

~3X improvement over previous non-SPT works

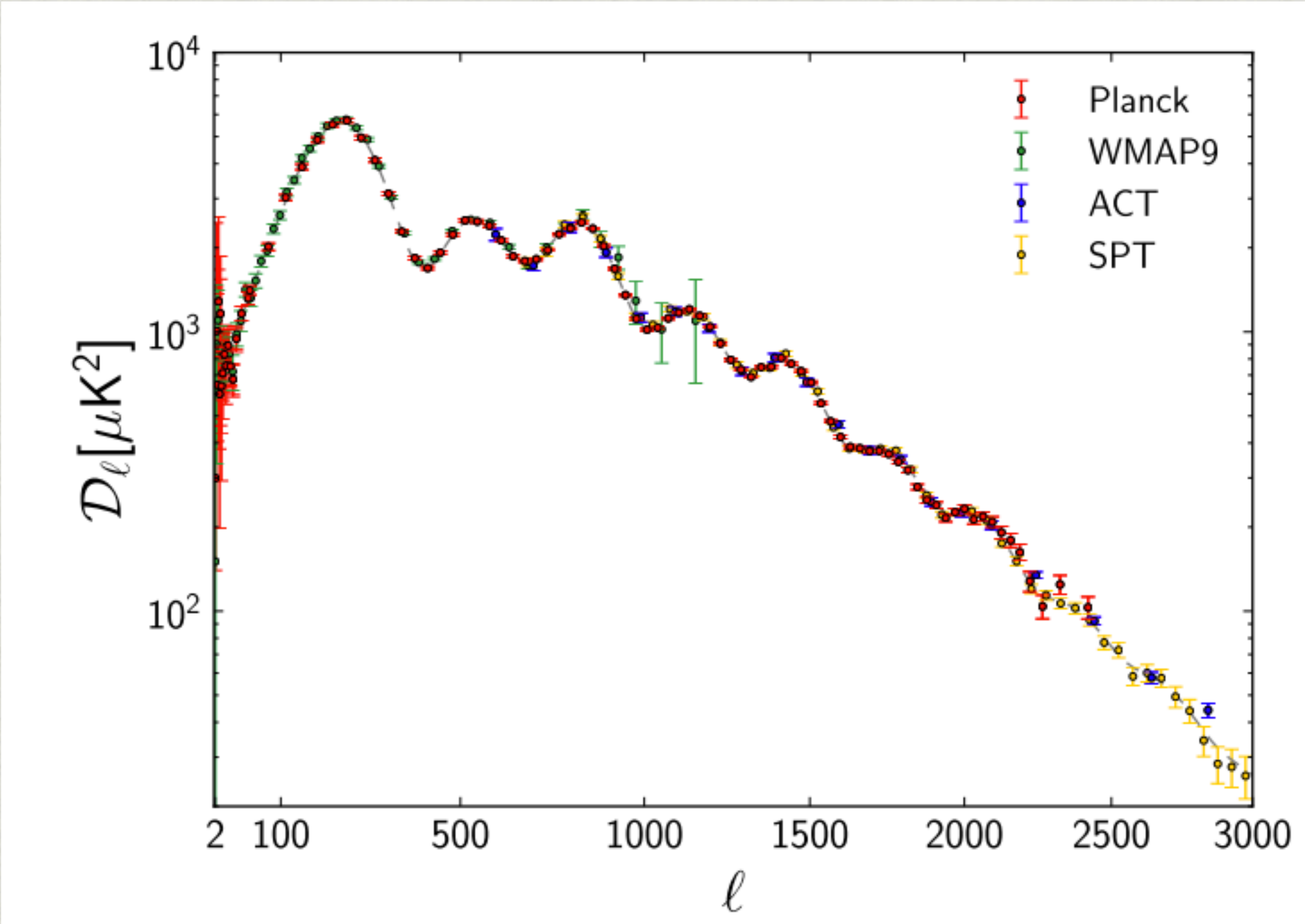
~1.8X improvement over previous SPT work.

See arXiv:1210.7231 (Story, Reichardt, Hou, RK *et al.*)

Angular Power Spectrum



Outstanding agreement between CMB power spectrum measurements



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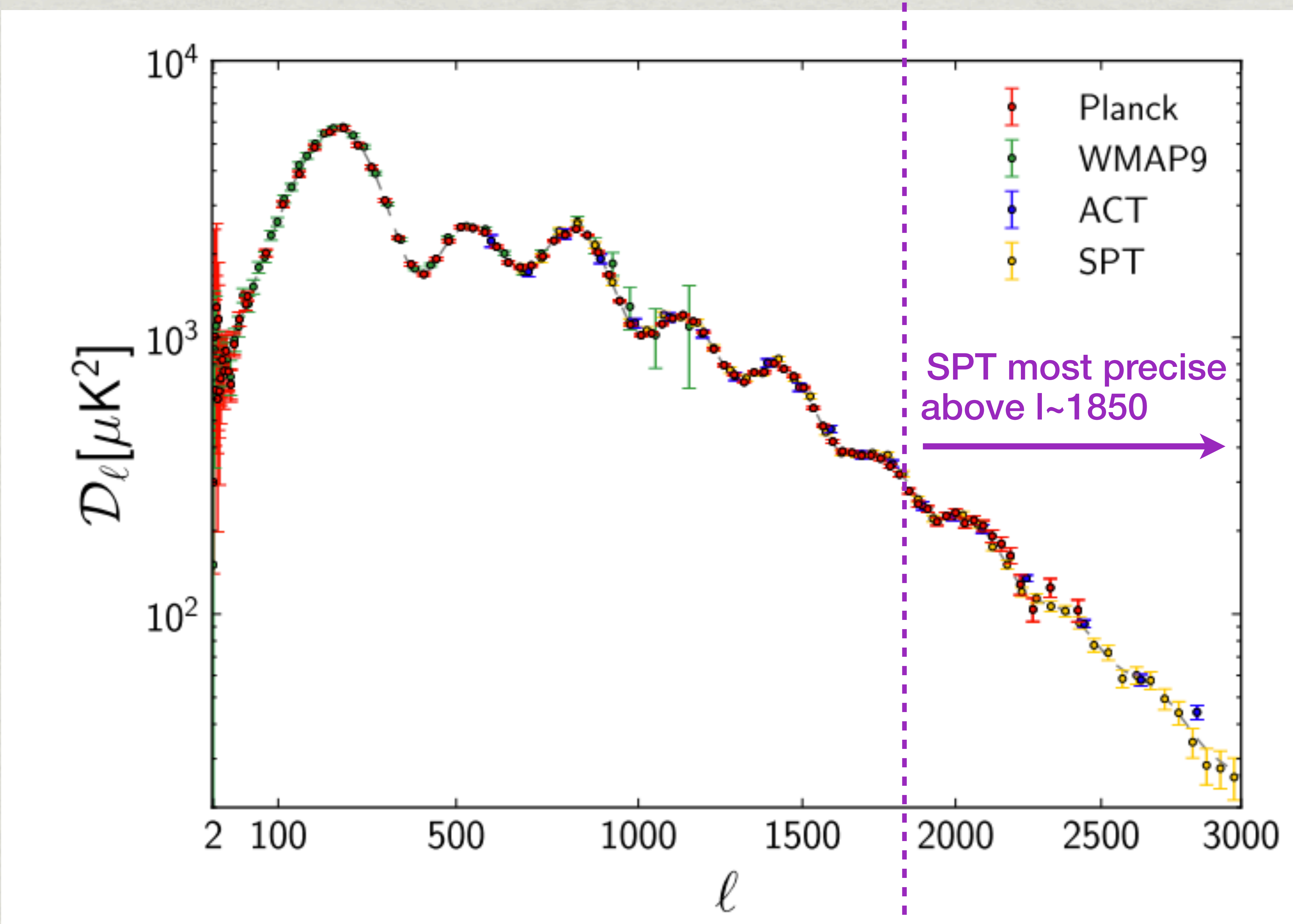
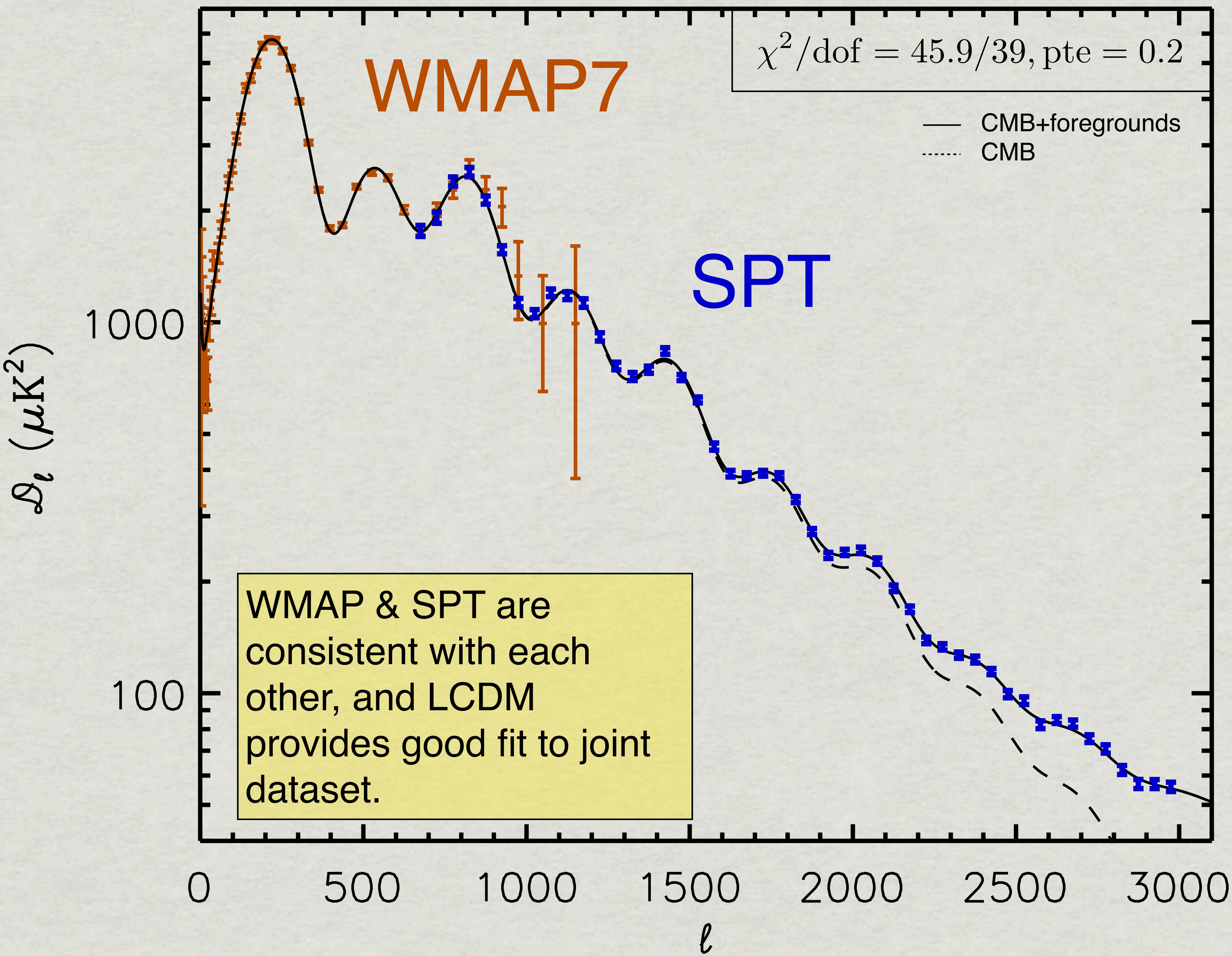


Fitting the data to ΛCDM (and beyond)

work led by Zhen Hou, UC Davis

(see Hou, Reichardt, **KTS**, Follin, Keisler, et al, 1212.7231)

Best-fit ΛCDM



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n_s: spectral tilt

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

n_s generically departs from *n_s*=1 in inflationary models, because of lack of time-invariance of inflation.

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$n_s = 0.9623 \pm 0.0097$ (SPT+WMAP)

3.9σ preference for ns<1

$n_s = 0.9538 \pm 0.0081$ (SPT+WMAP+ H0+BAO)

5.7σ preference for ns<1

(first >5σ preference for ns<1)

quick detour: H0 and BAO data

H0

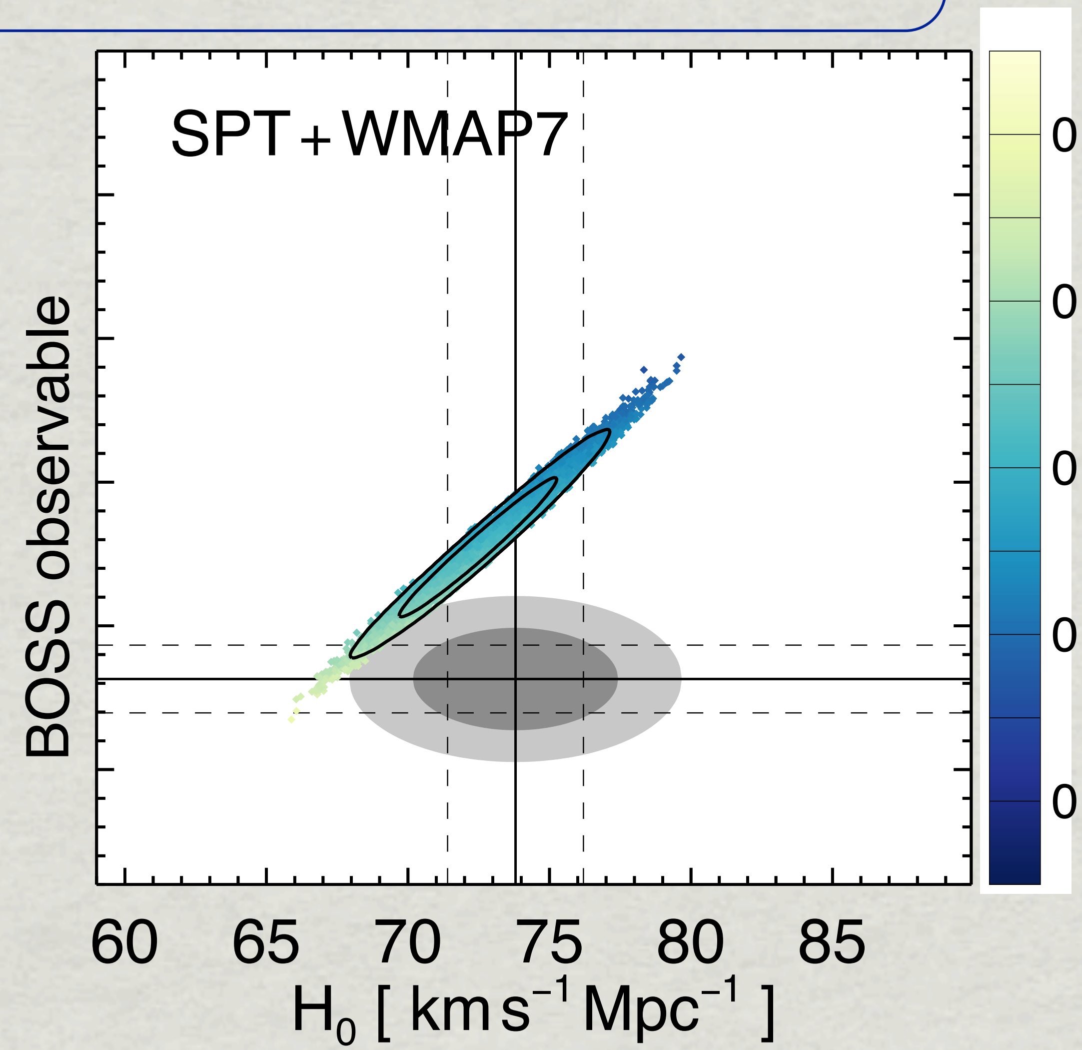
Riess et al 2011

BAO

BOSS (z=0.57), Anderson et al 2012
SDSS (z=0.35), Padmanabhan et al 2012
WiggleZ (z=0.44-0.73), Blake et al 2011

There is some ~2-sigma tension between CMB, H0, and BAO.

This is true in LCDM, and in most other models.



(see Hou, Reichardt, KTS, Follin, Keisler, et al, 1212.7231)

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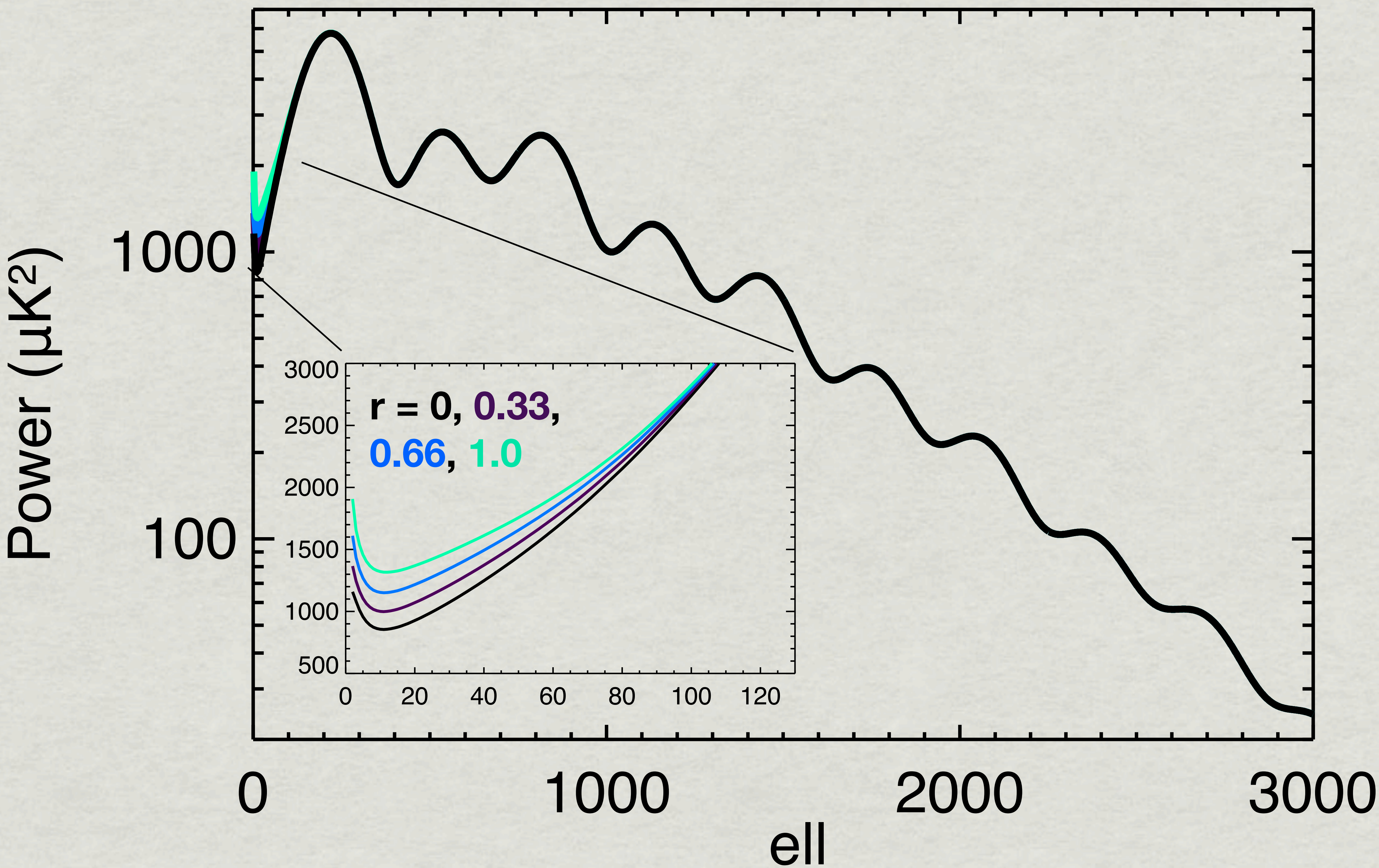
r: tensor power

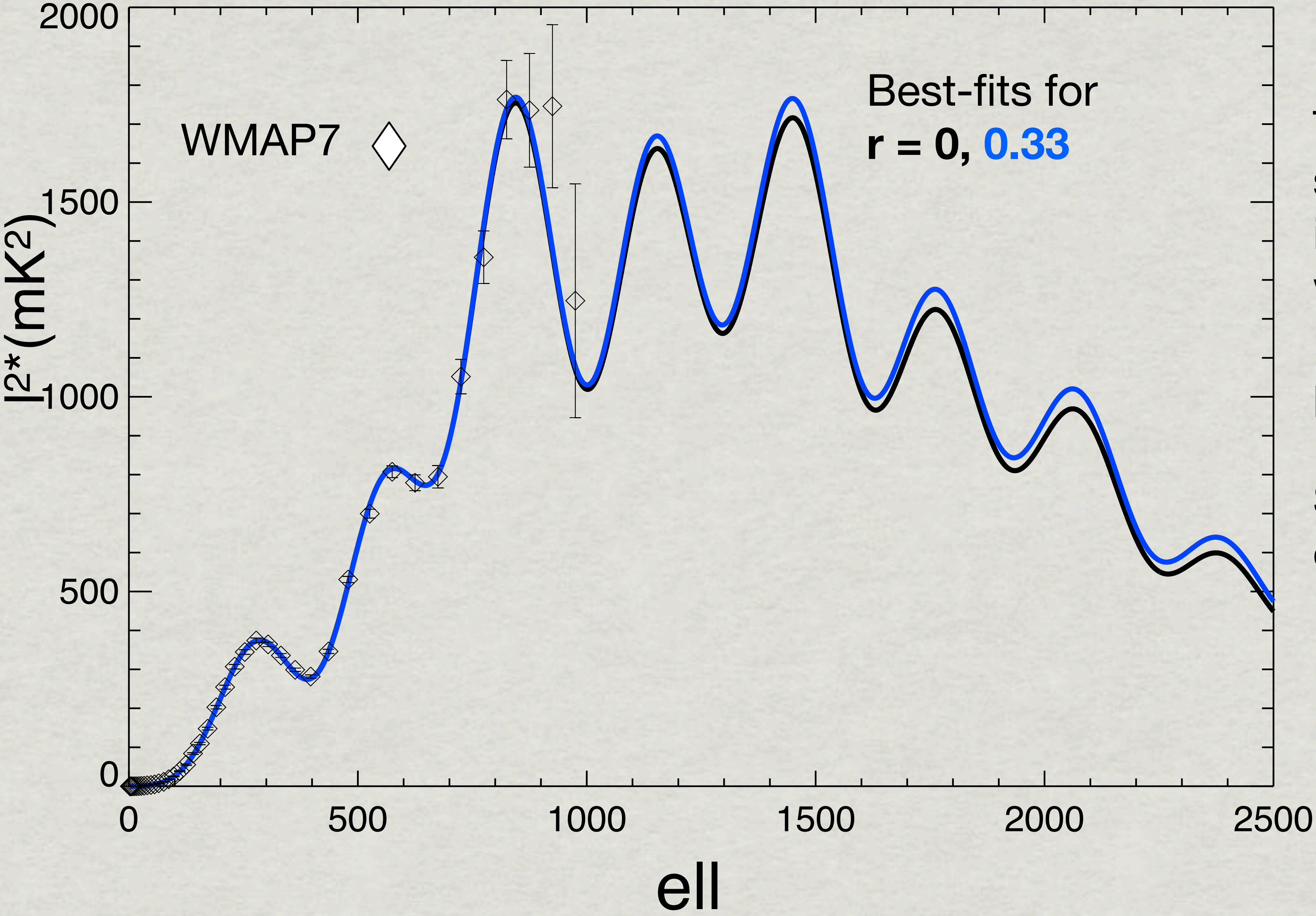
$$\Delta_h^2(k) = \Delta_h^2(k_0)\left(\frac{k}{k_0}\right)^{n_t} \quad , \quad \text{(tensor/scalar) ratio } r \equiv \frac{\Delta_h^2}{\Delta_R^2}$$

Tensor power can be generated from inflationary gravitation waves, and a detection of r>0 could provide a handle on the energy scale of inflation.

Tensor perturbations and temperature anisotropy



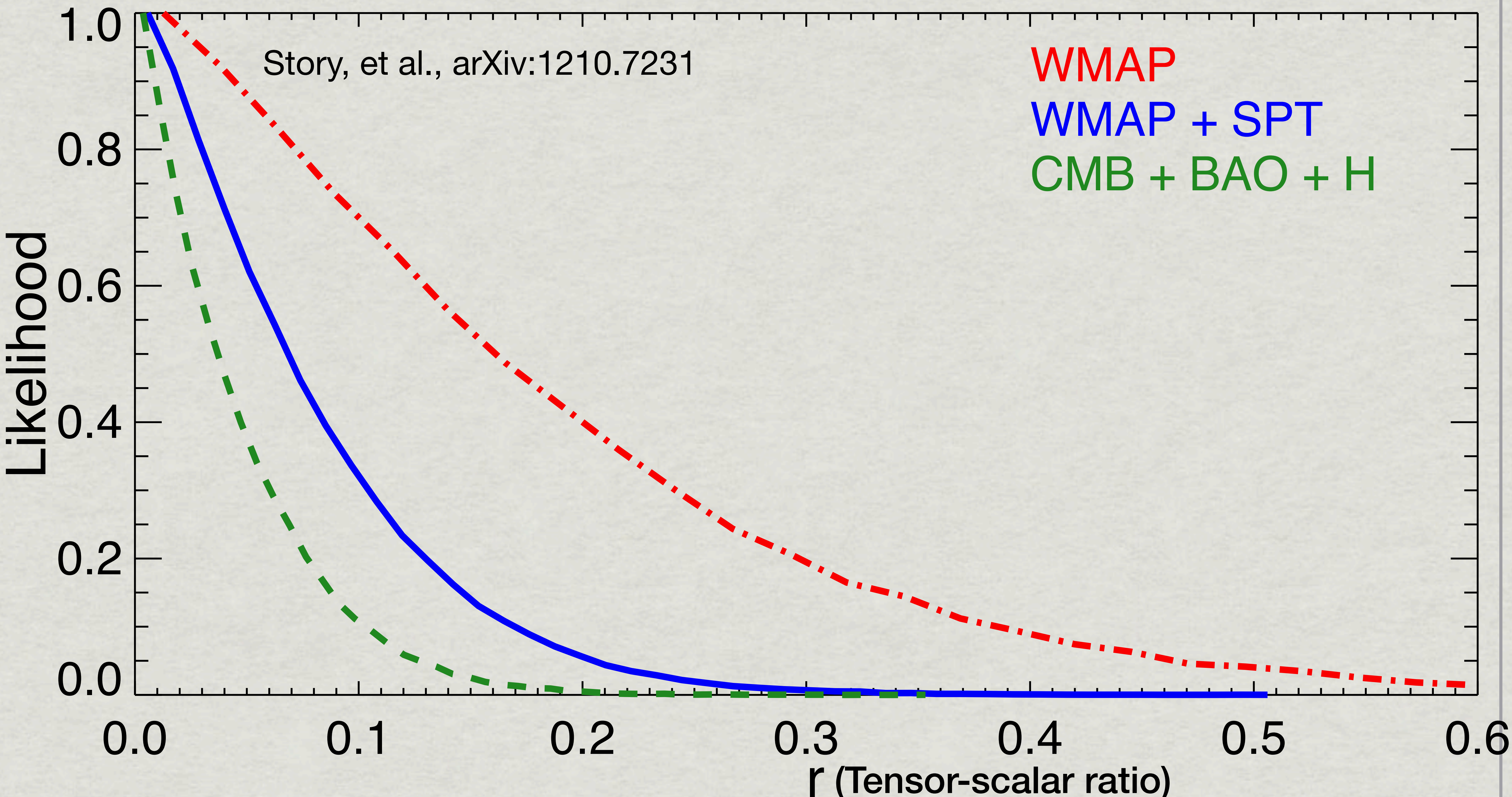
Role of small-scale data



Tensors only affect large scales, but their impact is partially degenerate with the scalar power law slope (n_s) and other parameters.

Small-scale data help disentangle the two.

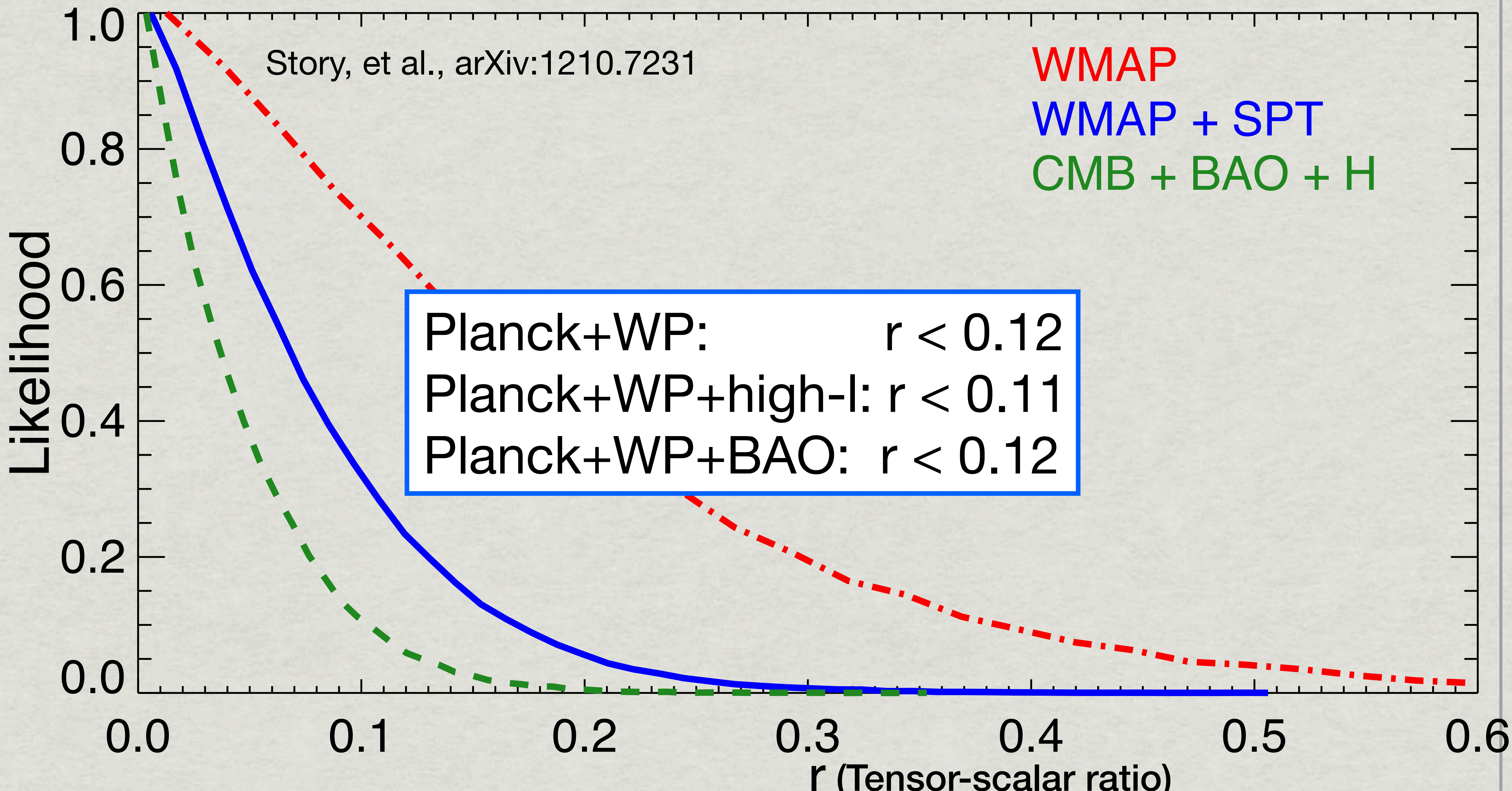
Hitting TT sample variance limit



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

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

Planck - same limits internally



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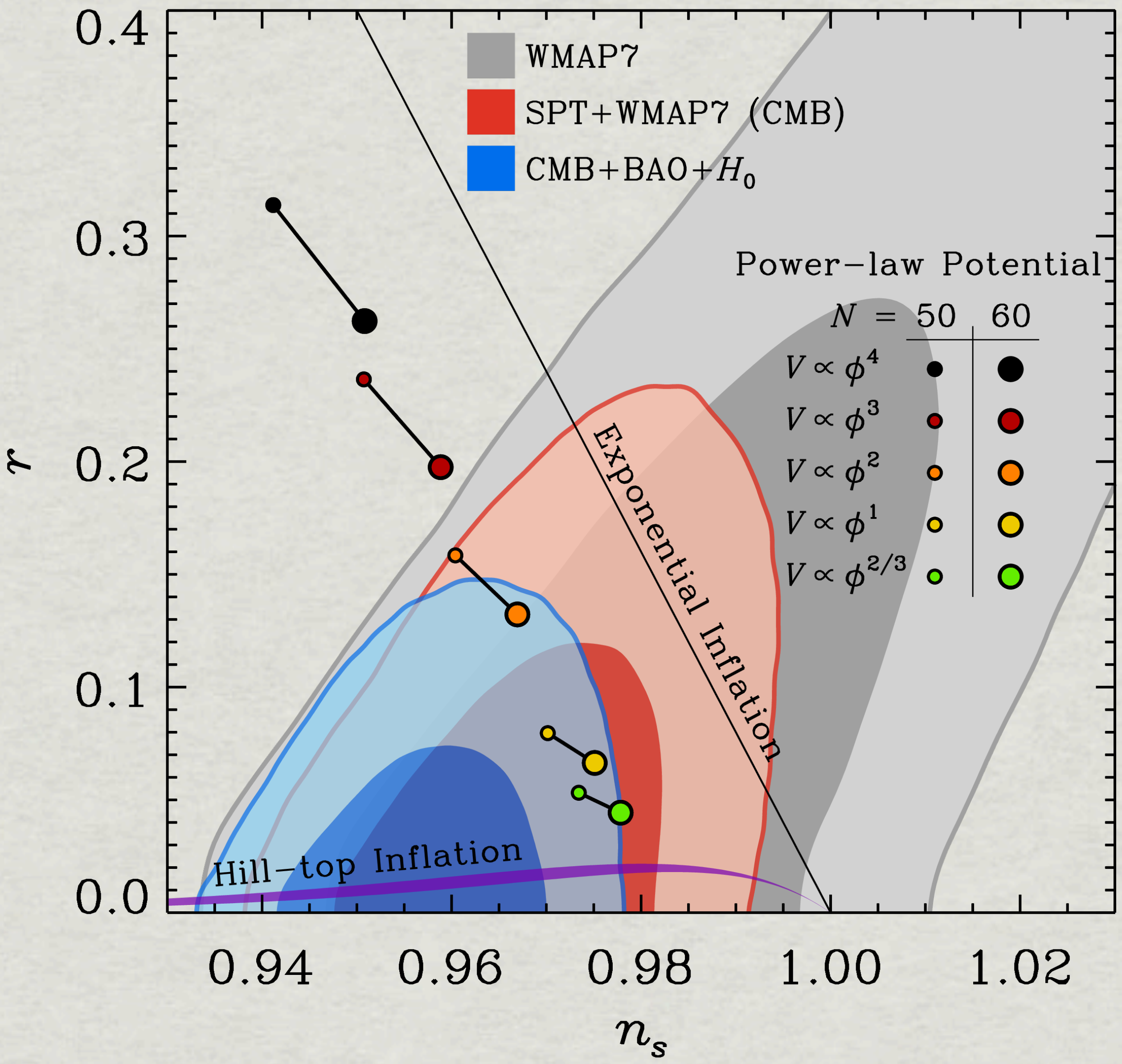
n_s *vs* r

Use data to constrain some simple cases of single-field, slow-roll inflation, based on their predictions for relationship between n_s and r.



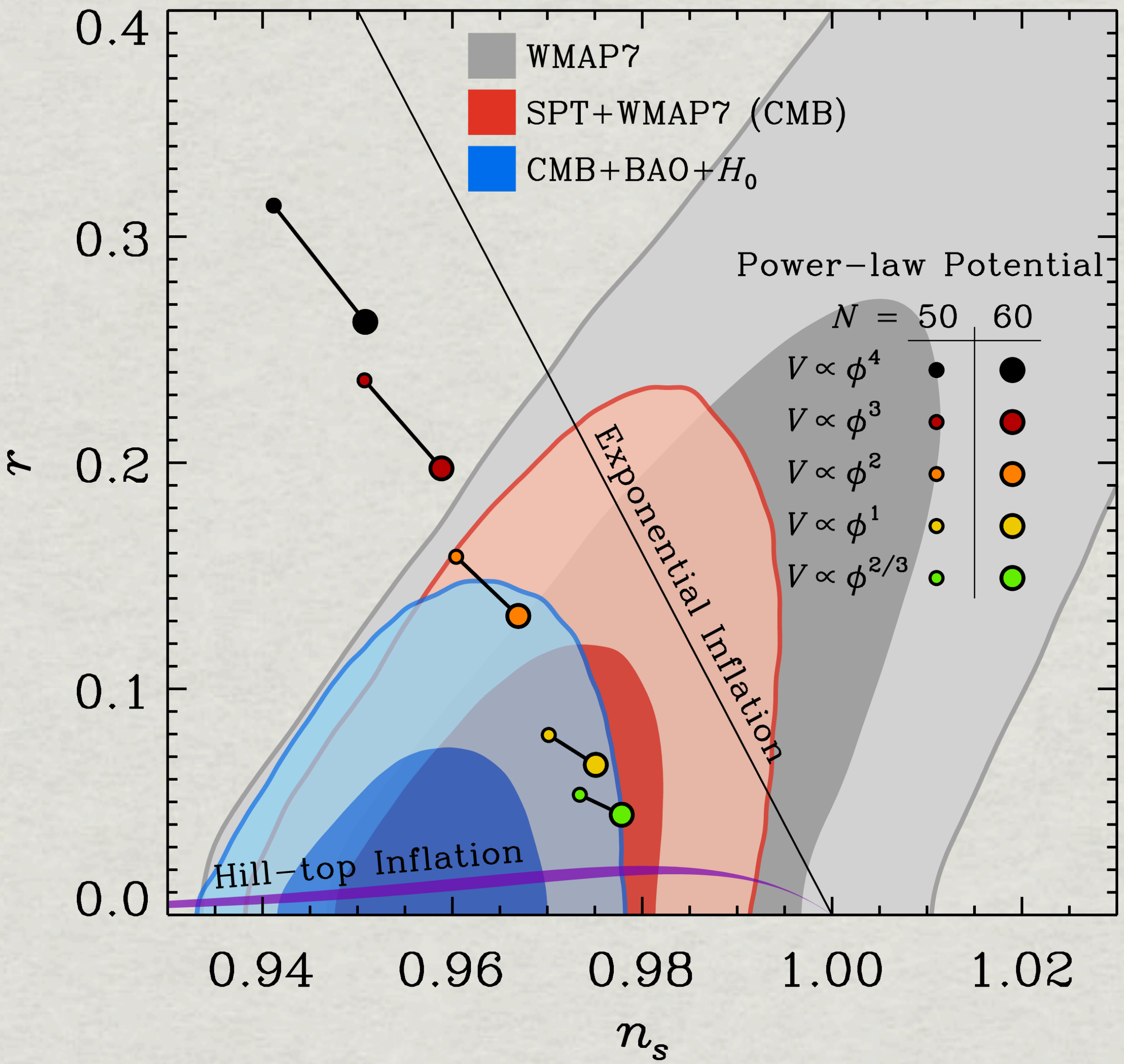
These constraints put pressure on models of inflation.

We are hitting the TT sample variance limit.

Figure by Brent Follin, UC Davis

n_s VS r

Use data to constrain some simple cases of single-field, slow-roll inflation, based on their predictions for relationship between n_s and r.



SPT constraints on inflation are consistent with those from Planck

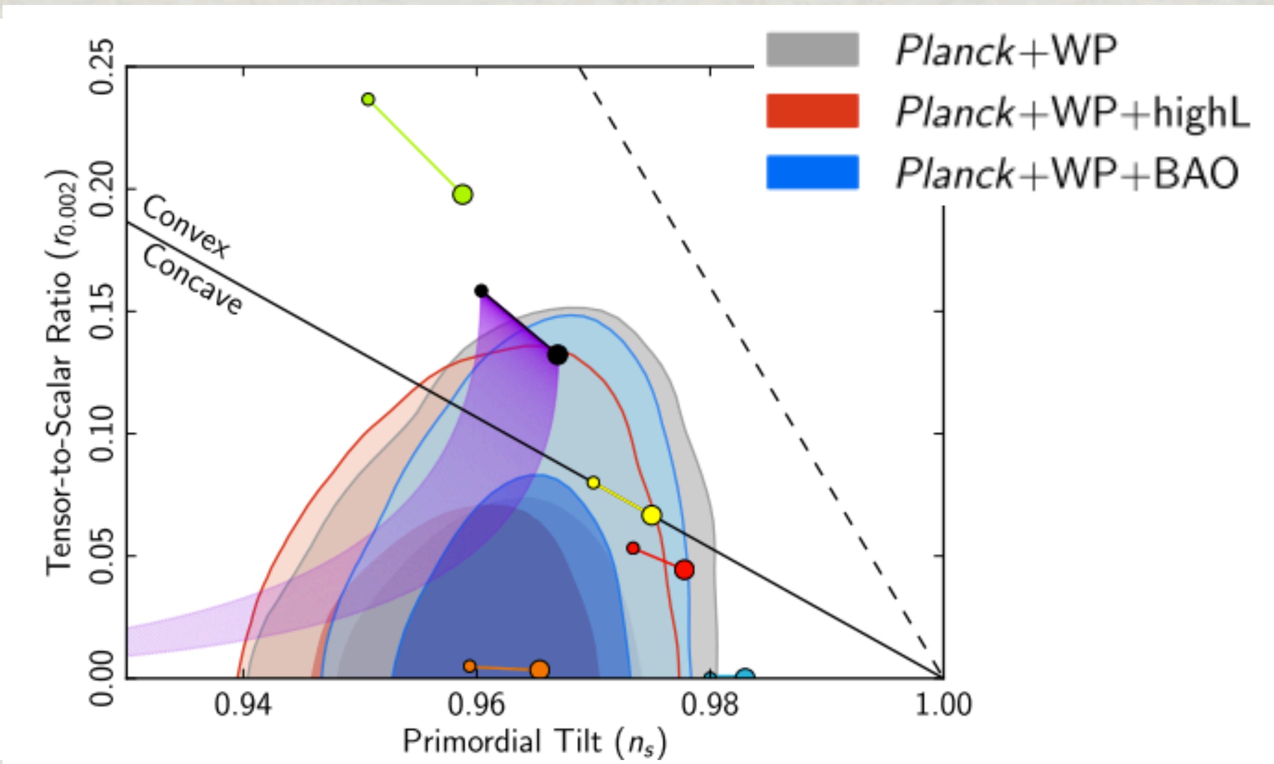


Figure by Brent Follin, UC Davis

Take Away #1

Detected departure from scale invariance ($n_s < 1$) at $> 5\sigma$.

We are hitting the TT sample variance limit on constraints on ***r*** (need CMB Polarization measurements to go further)

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Massive Neutrinos

From neutrino oscillations experiments, we know neutrinos have mass. These experiments measure *mass differences* $(\Delta m)^2$, but what is the *absolute mass*? Related question: what's the *mass hierarchy*?

From oscillation expt's and double-beta decay expt's, we know:

$$0.06 \text{ eV} \leq \Sigma m_\nu \leq 1.8 \text{ eV}$$

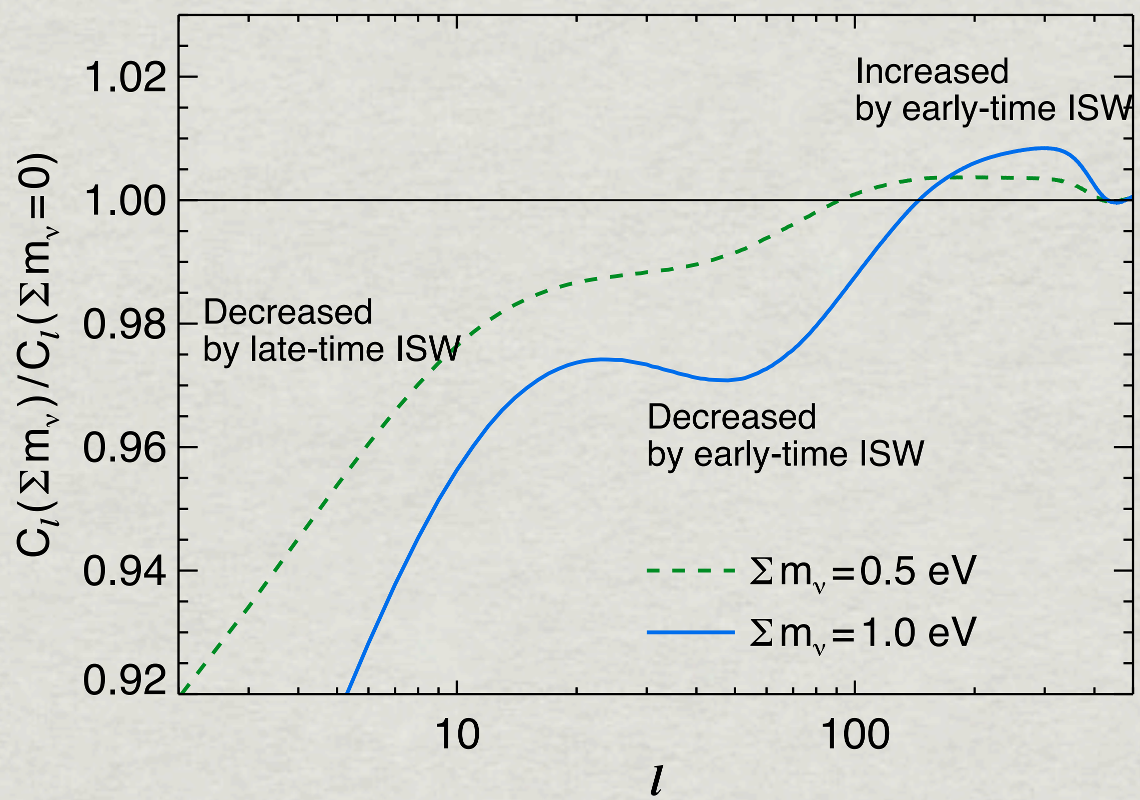
What can we learn from cosmology, which is sensitive primarily to Σm_ν , as opposed to $(\Delta m)^2$?

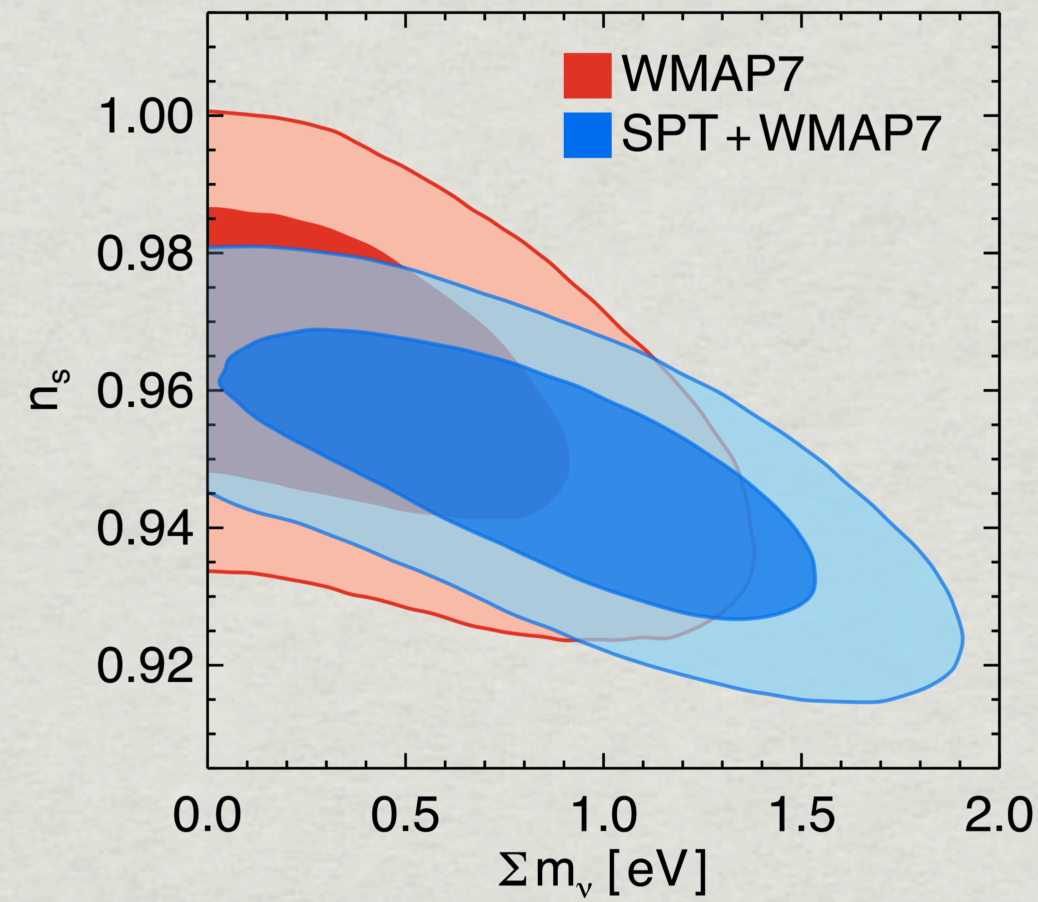
CMB+ constraints on massive nu's

CMB data are sensitive to neutrino mass through the early ISW effect and associated parameters degeneracies.

BAO/H0 are sensitive to the late-time expansion rate, which depends on the neutrino contribution to the energy density.

Measures of low-redshift growth (CMB lensing, Clusters, LRGs) are sensitive to neutrino mass through its effect on the matter power spectrum.





(see Hou, Reichardt, KTS, Follin, Keisler, et al, 1212.7231)

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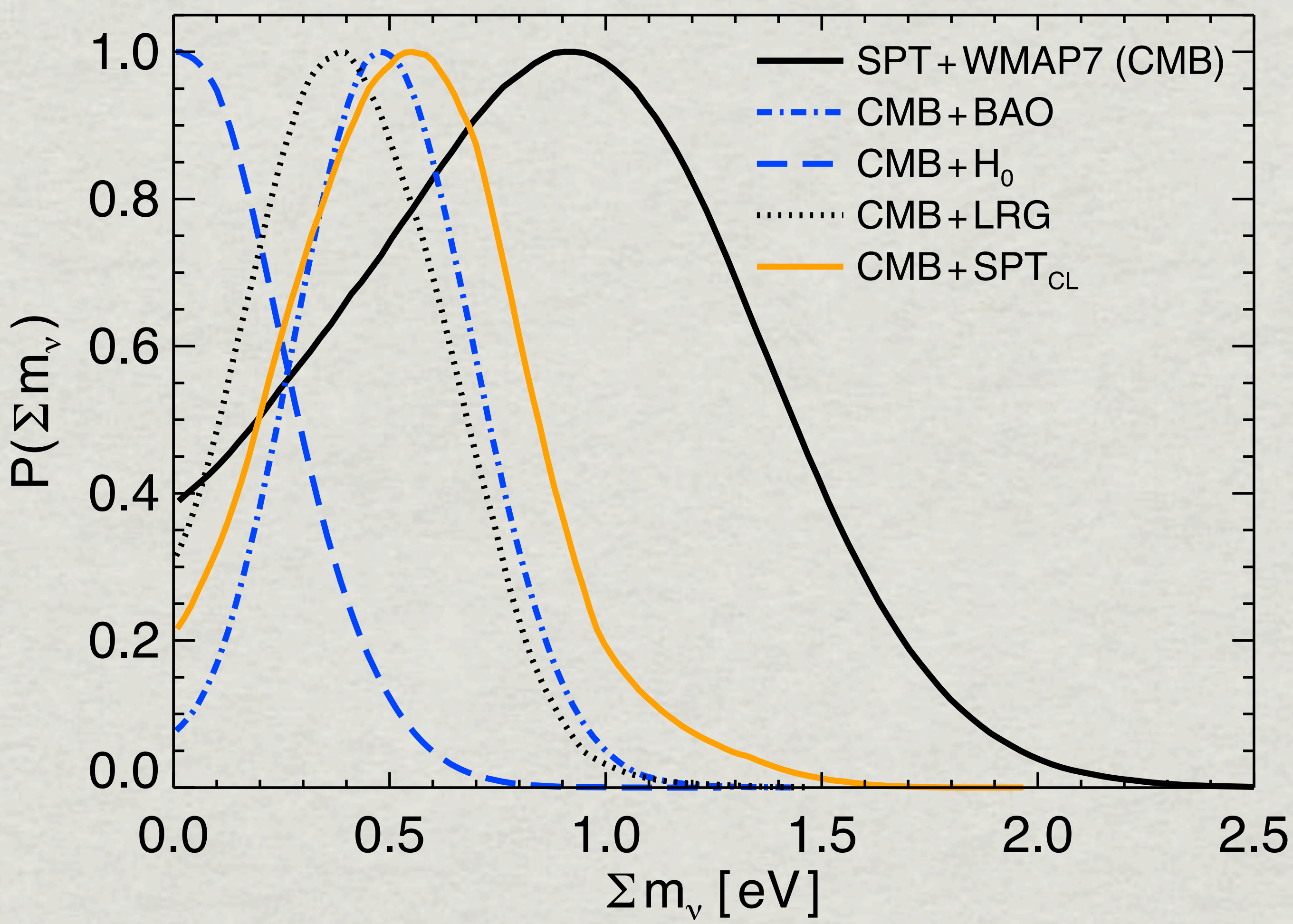
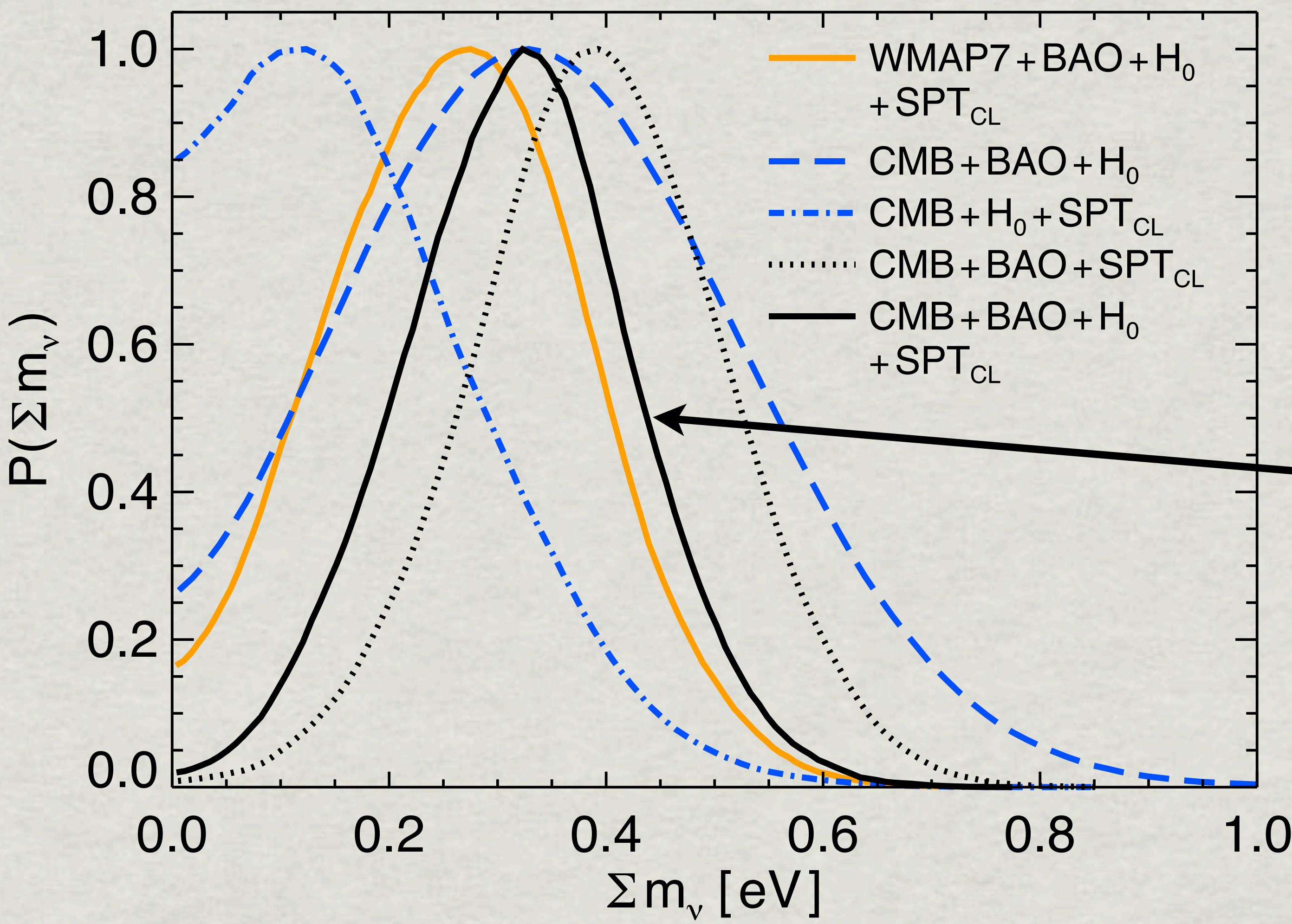


SPT+WMAP (CMB) prefers massive neutrinos at ~1σ.

BAO data add ~1σ.

SPT_clusters add another ~1σ.

CMB++ constraints on massive nu's



CMB+BAO+H0+SPT_CL yields

Σm = (0.32 +/- 0.11) eV

a **3σ** preference for Σm>0.

Remains at >2σ if you drop only clusters.

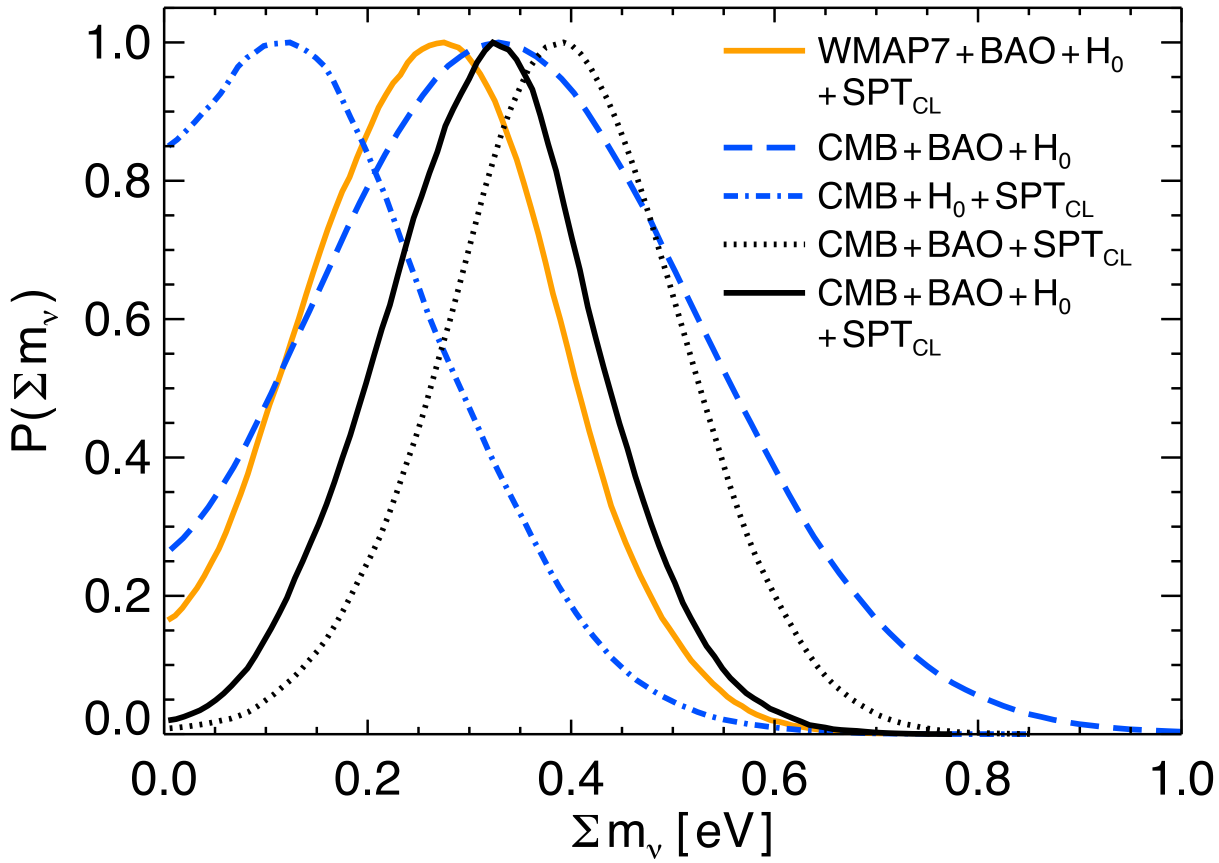
Drops to >1σ if you drop only BAO.

There are data combinations that yield a 3σ "detection" of non-zero neutrino mass, at ~0.3 eV or ~6X the minimum Σm.

Will this hold up with future CMB/BAO/H0/LSS data?

CMB++ constraints on massive nu's

SPT++



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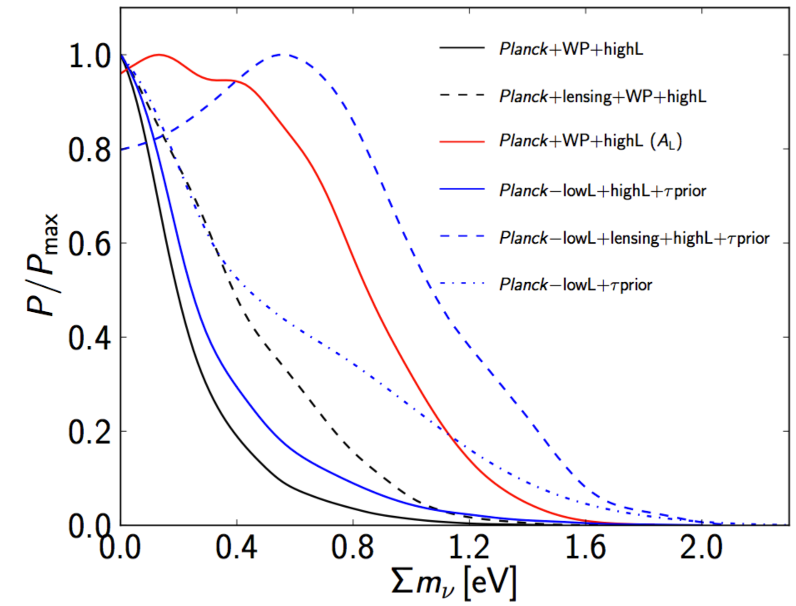
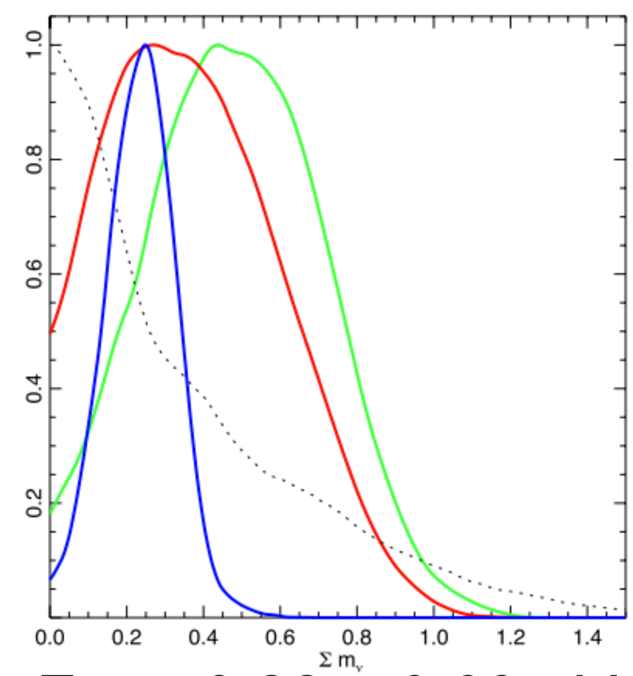
CMB+BAO+H0+SPT_CL

Planck++



Σm < 0.23 eV

Planck+WP+highL+BAO



Σm = 0.22 ± 0.09 eV

Planck+BAO+Clusters

Planck++ data prefer less massive neutrinos:

- combining H0 with BAO prefers massive neutrinos
- Planck observes *stronger* gravitational lensing of the CMB, implying more clustering, and *lower* neutrino mass.
- Planck++ constraints do not include Clusters

Take Away #2

CMB data is sensitive to Σm_ν through the early ISW effect.

CMB++ data from the SPT prefer $\Sigma m_\nu > 0$ at ~3σ.

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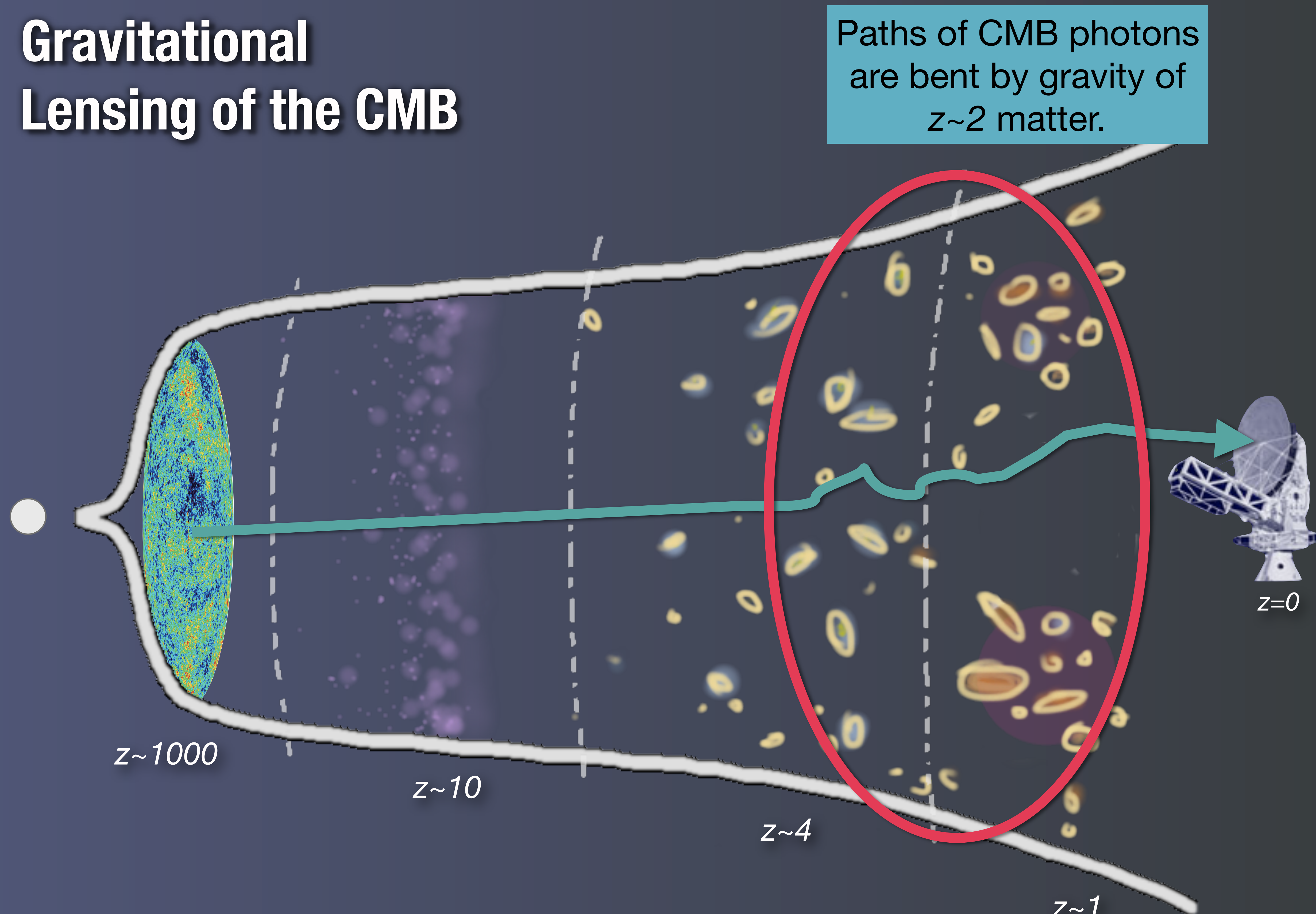
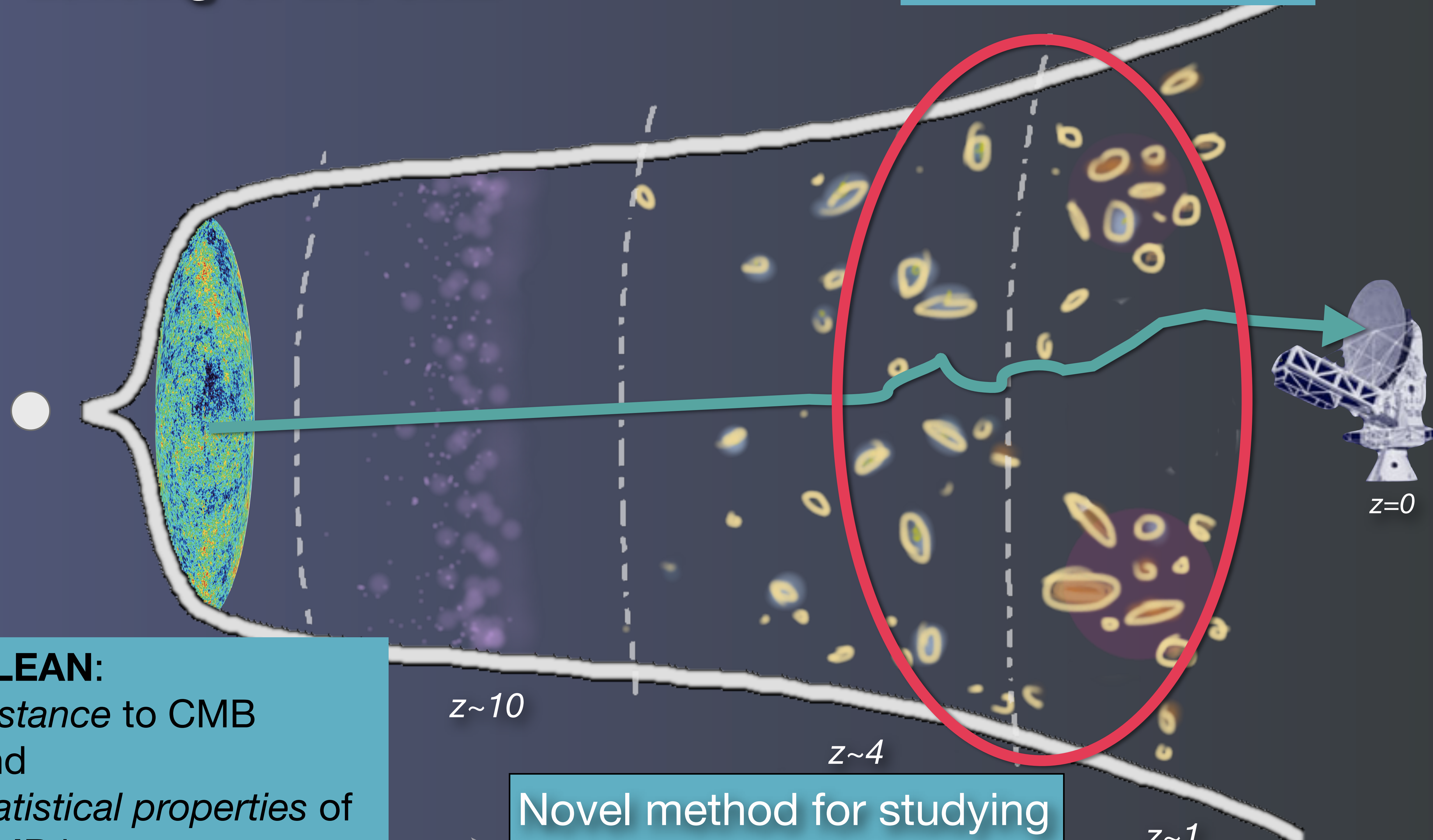
Gravitational Lensing of the CMB



Gravitational Lensing of the CMB

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

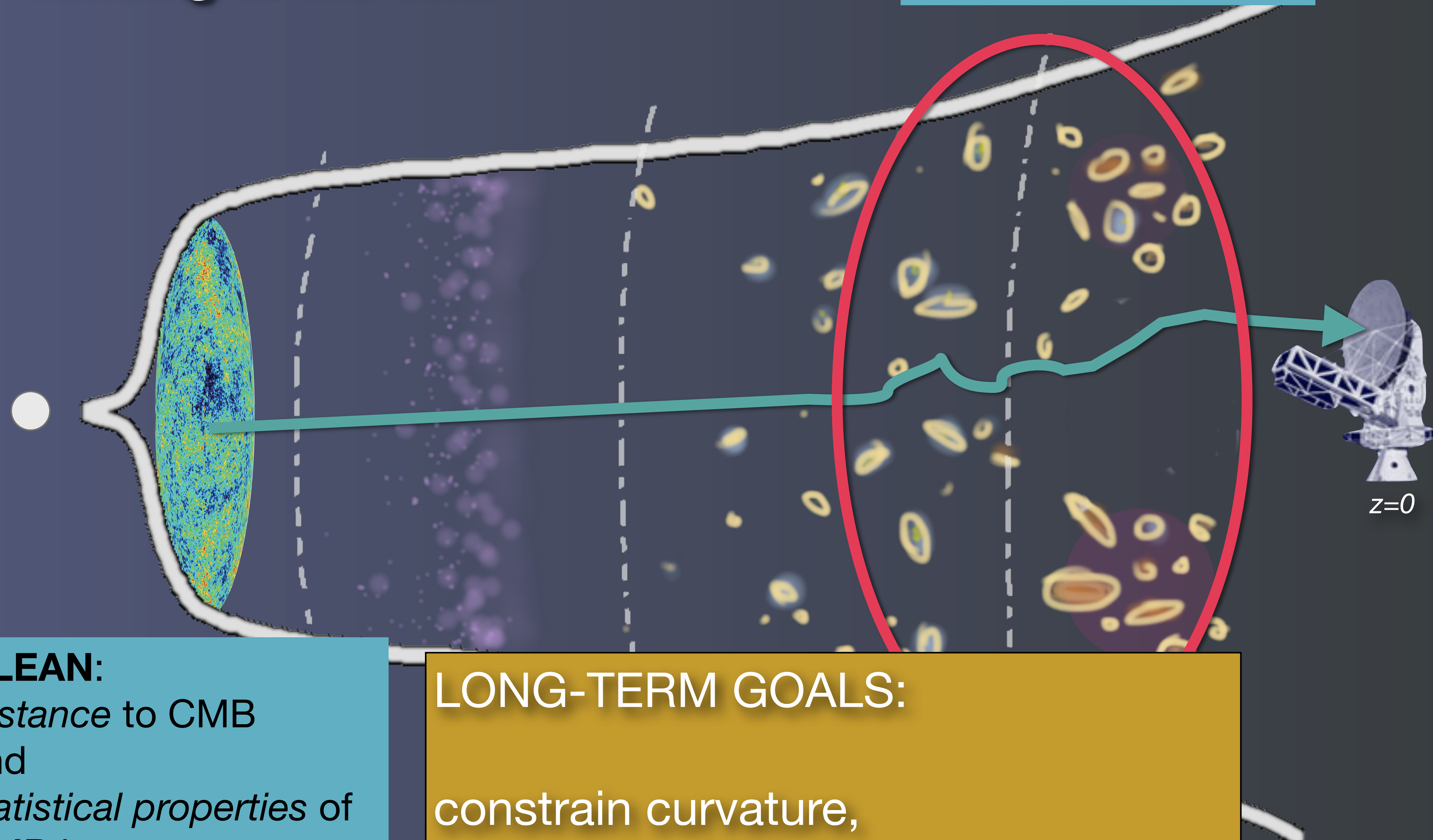


CLEAN:
Distance to CMB
and
statistical properties of CMB known very accurately, so effects of lensing can be isolated.

→ Novel method for studying (very) large-scale structure at *z~[0.5, 4]*.

Gravitational Lensing of the CMB

Paths of CMB photons are bent by gravity of $z\sim2$ matter.



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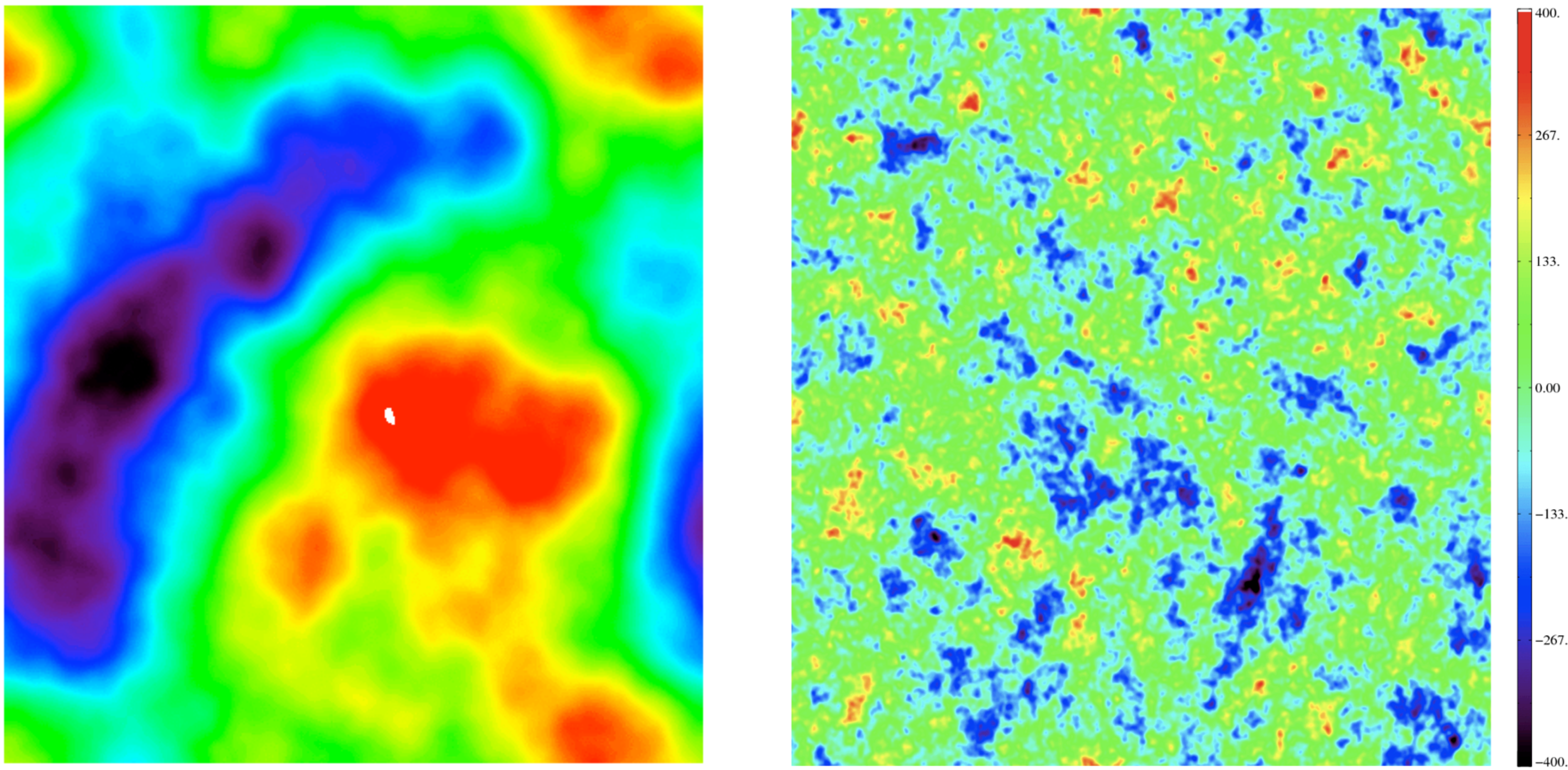
LONG-TERM GOALS:

constrain curvature,
constrain dark energy,
measure neutrino mass

Lensing of the CMB

17°x17°



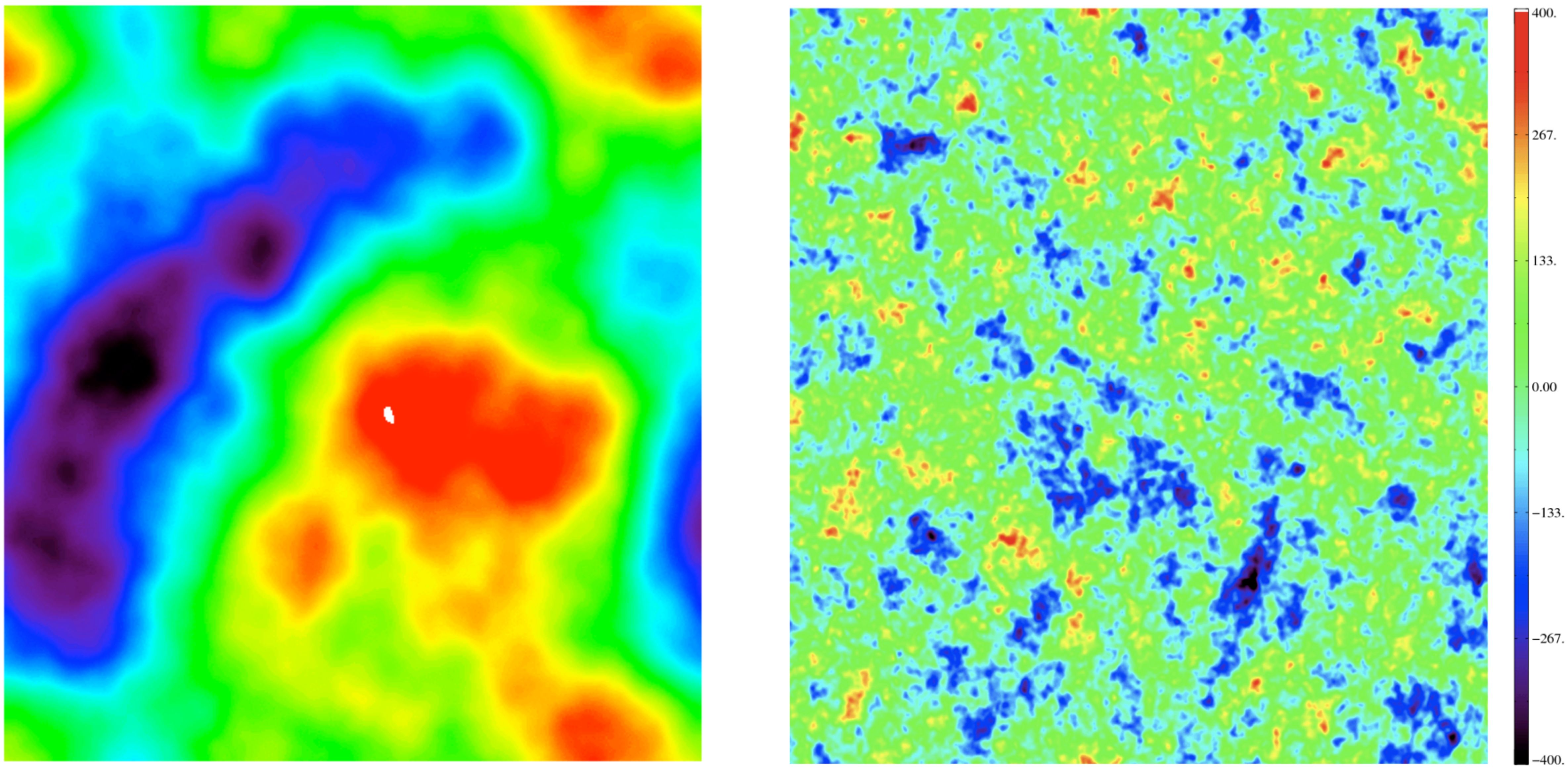
lensing potential

unlensed cmb

from Alex van Engelen

Lensing of the CMB

17°x17°



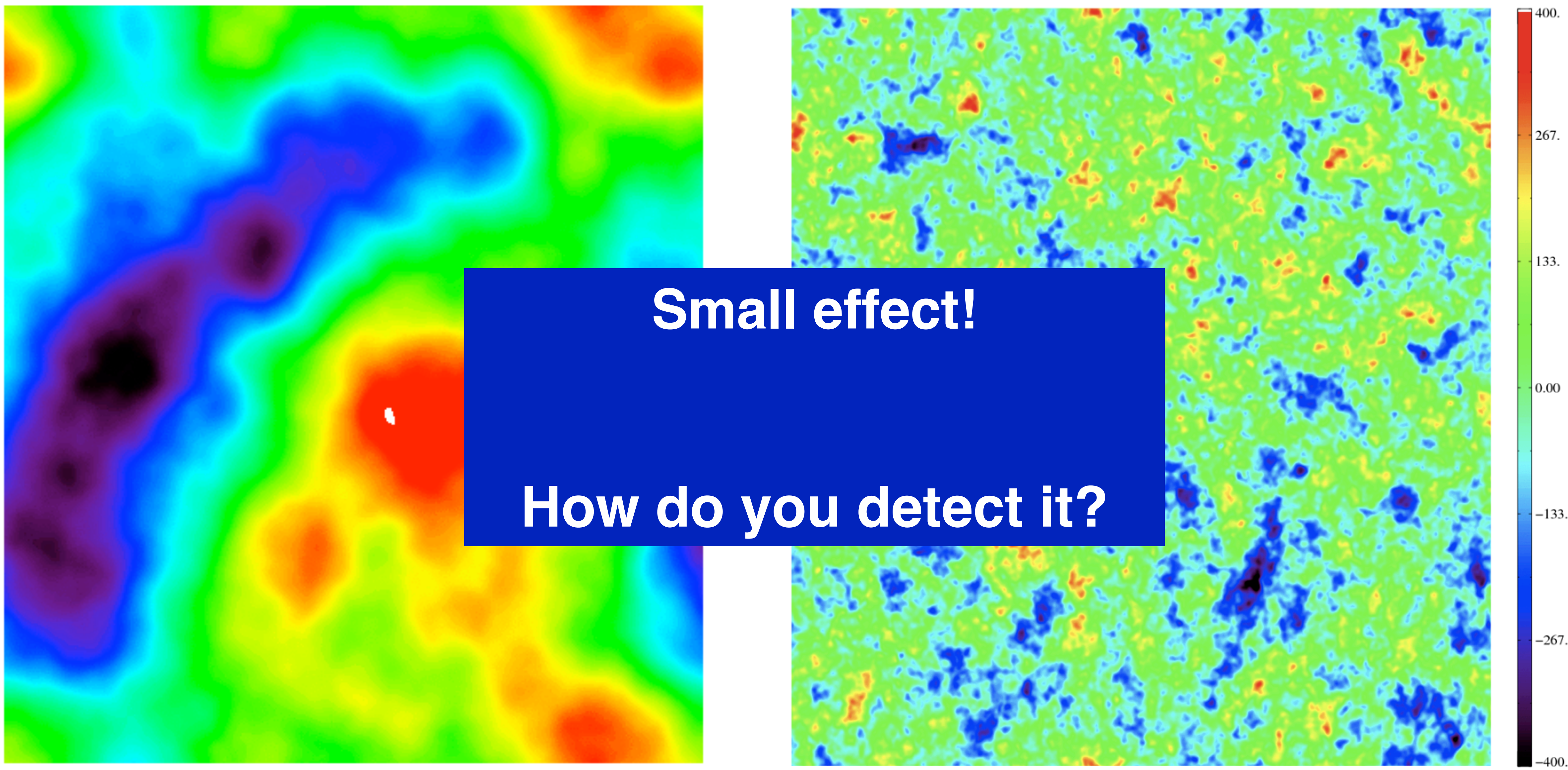
lensing potential

lensed cmb

from Alex van Engelen

Lensing of the CMB

17°x17°



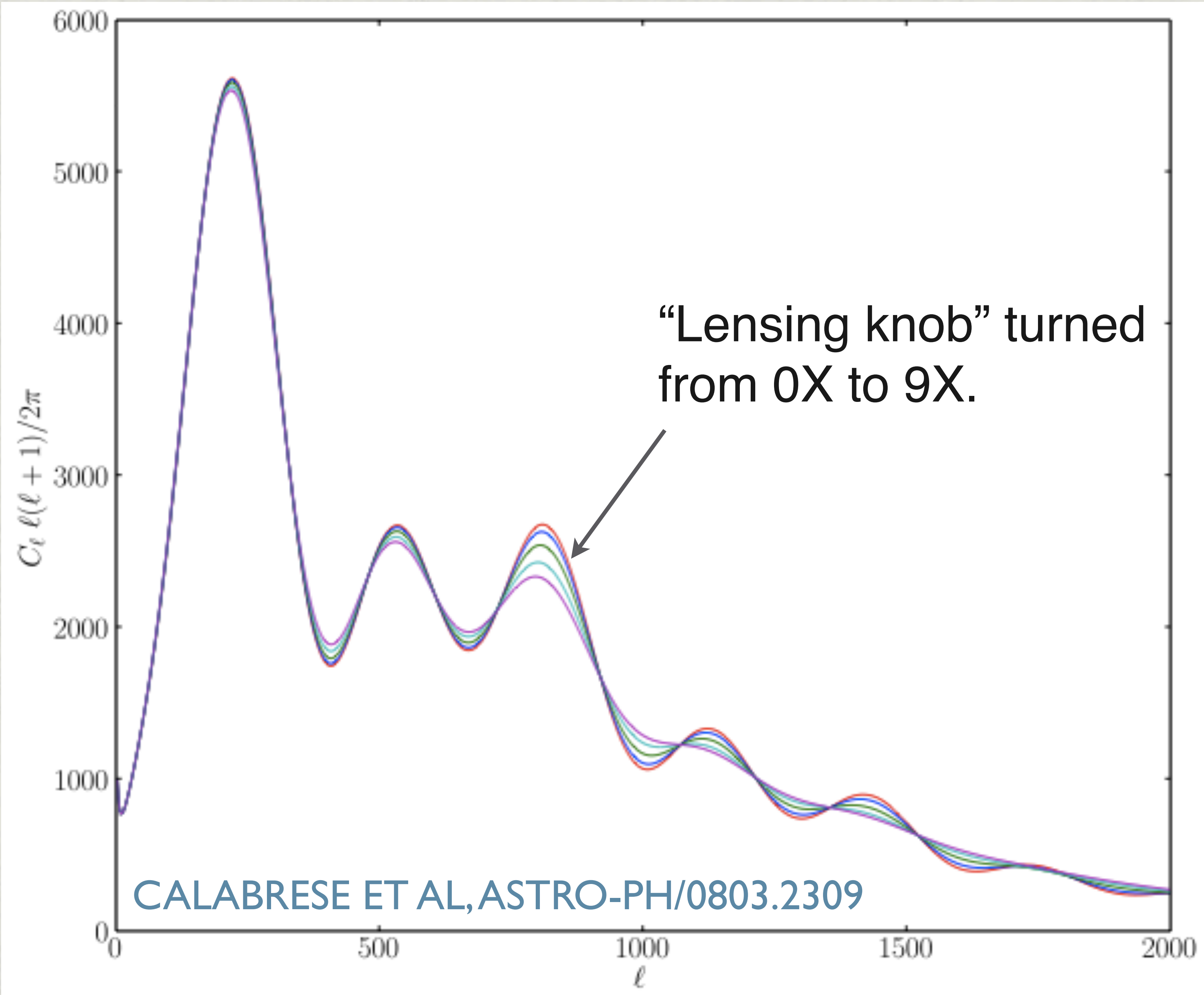
lensing potential   lensed cmb

Small effect!

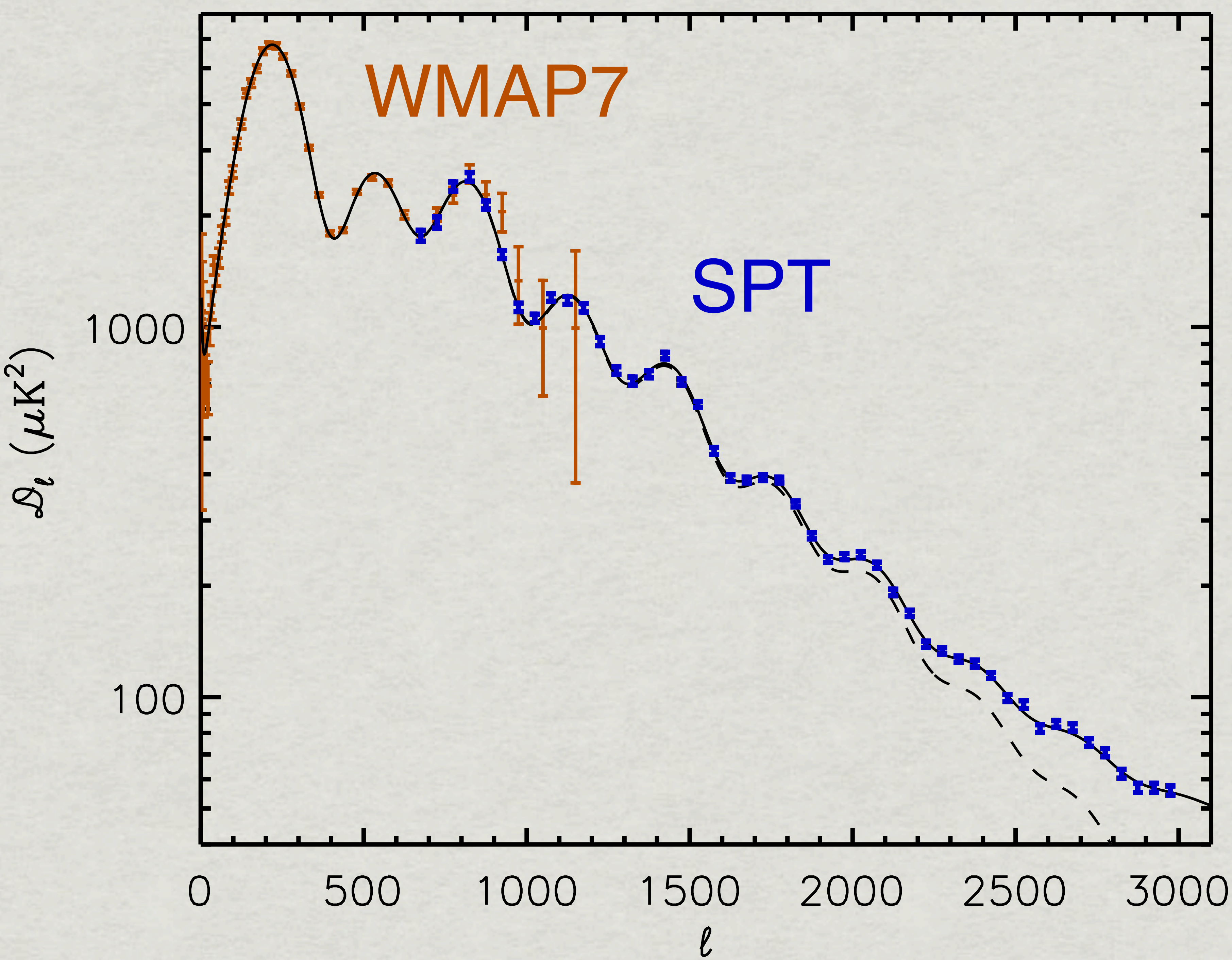
How do you detect it?

from Alex van Engelen

I. Lensing Smooths the "Acoustic Peaks"

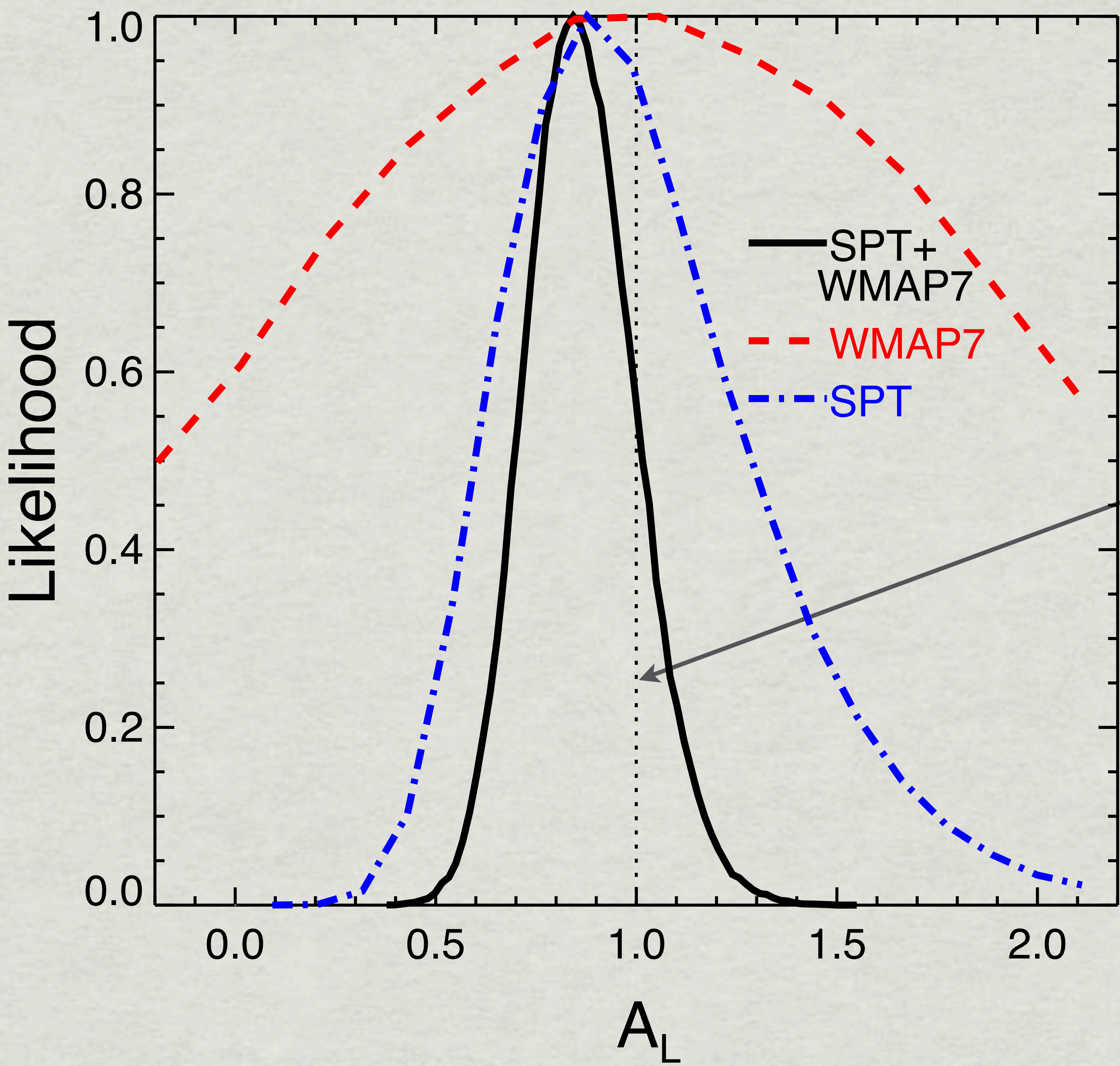


I. Lensing Smooths the "Acoustic Peaks"



See arXiv:1210.7231 (KTS, Reichardt, Hou, Keisler *et al.)*

I. Lensing Smooths the “Acoustic Peaks”



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

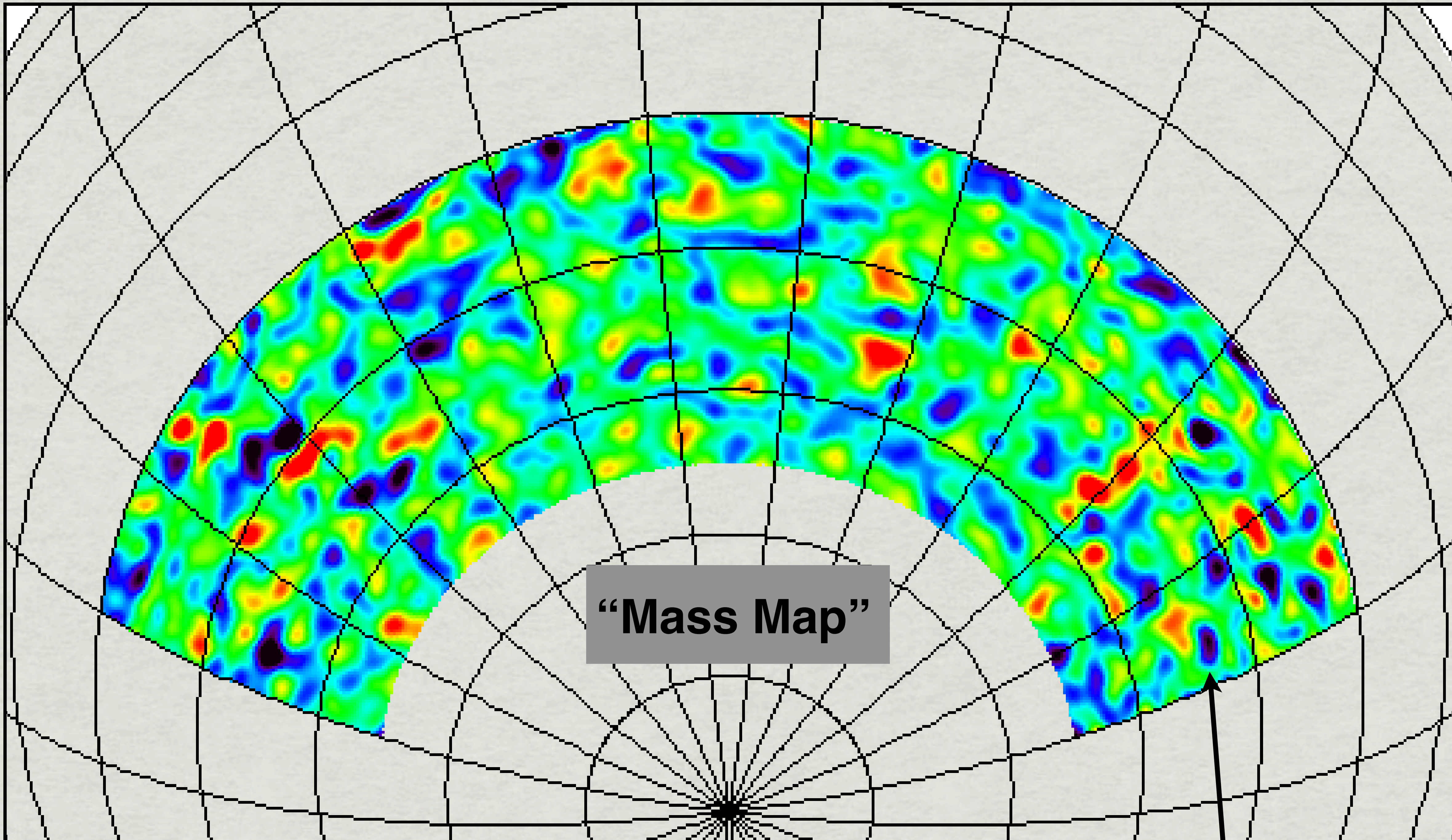
$A_{lens} = 0.86^{+0.15}_{-0.13}$

Consistent with expected level of lensing (1.0).

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

See arXiv:1210.7231 (KTS, Reichardt, Hou, Keisler *et al.)*

2. Mass reconstruction: Quadratic Estimator (TTTT)

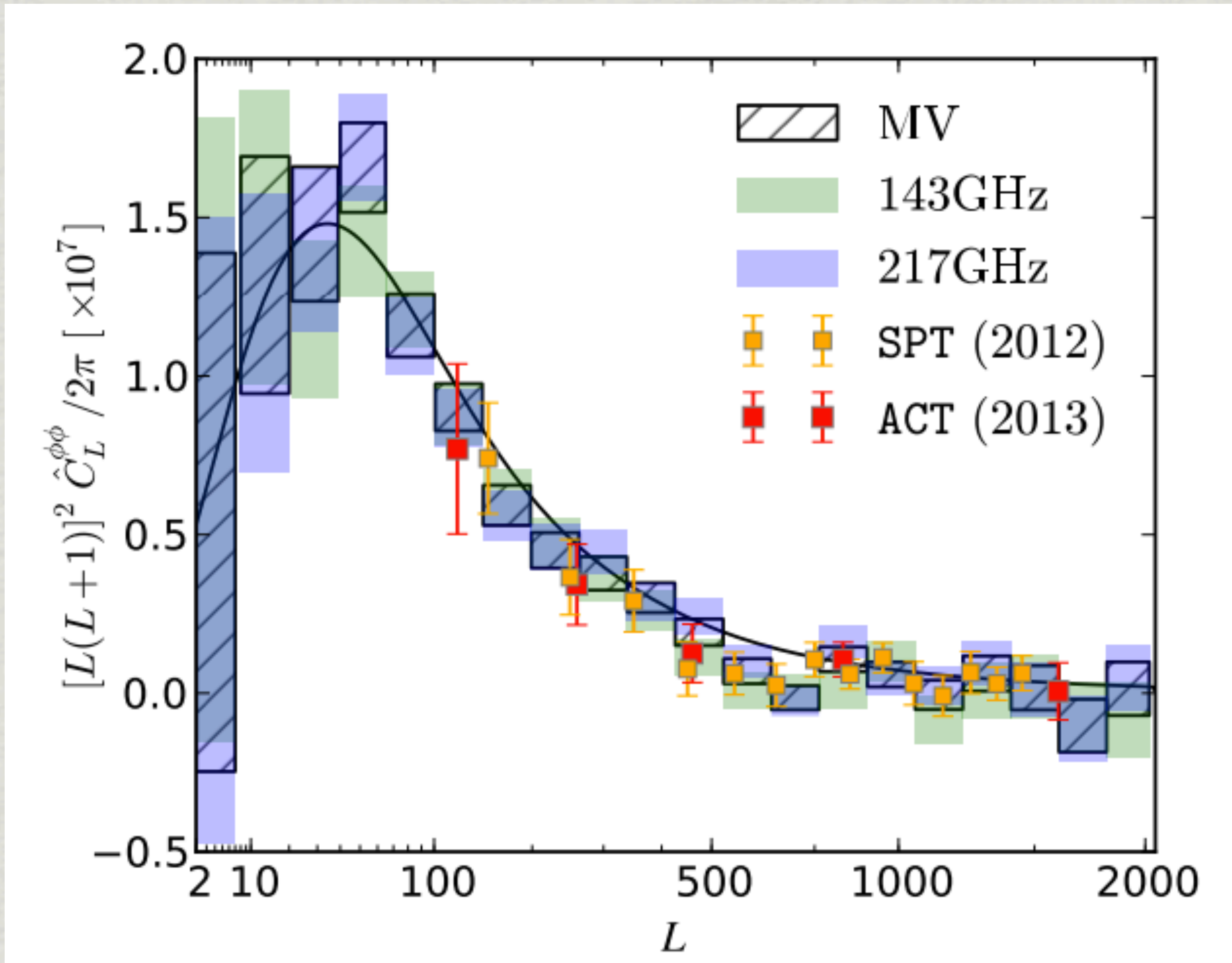


S/N~1
per 1-degree-sized feature.

preliminary SPT 2500 sq. deg. mass map (see Geach et al. (in prep)), full analysis in Zahn et al. (in prep)

Quadratic Estimator works.

Power in “Mass Maps”



(ACT ~4.6σ, 2013)

(SPT ~6σ, 2012)

(Planck >25σ, 2013)

Angular Frequency (multipole)

Figure from Planck Paper XVII : Arxiv 1303.5077

See A. Van Engelen, *et al.*, arXiv:1202.0546.

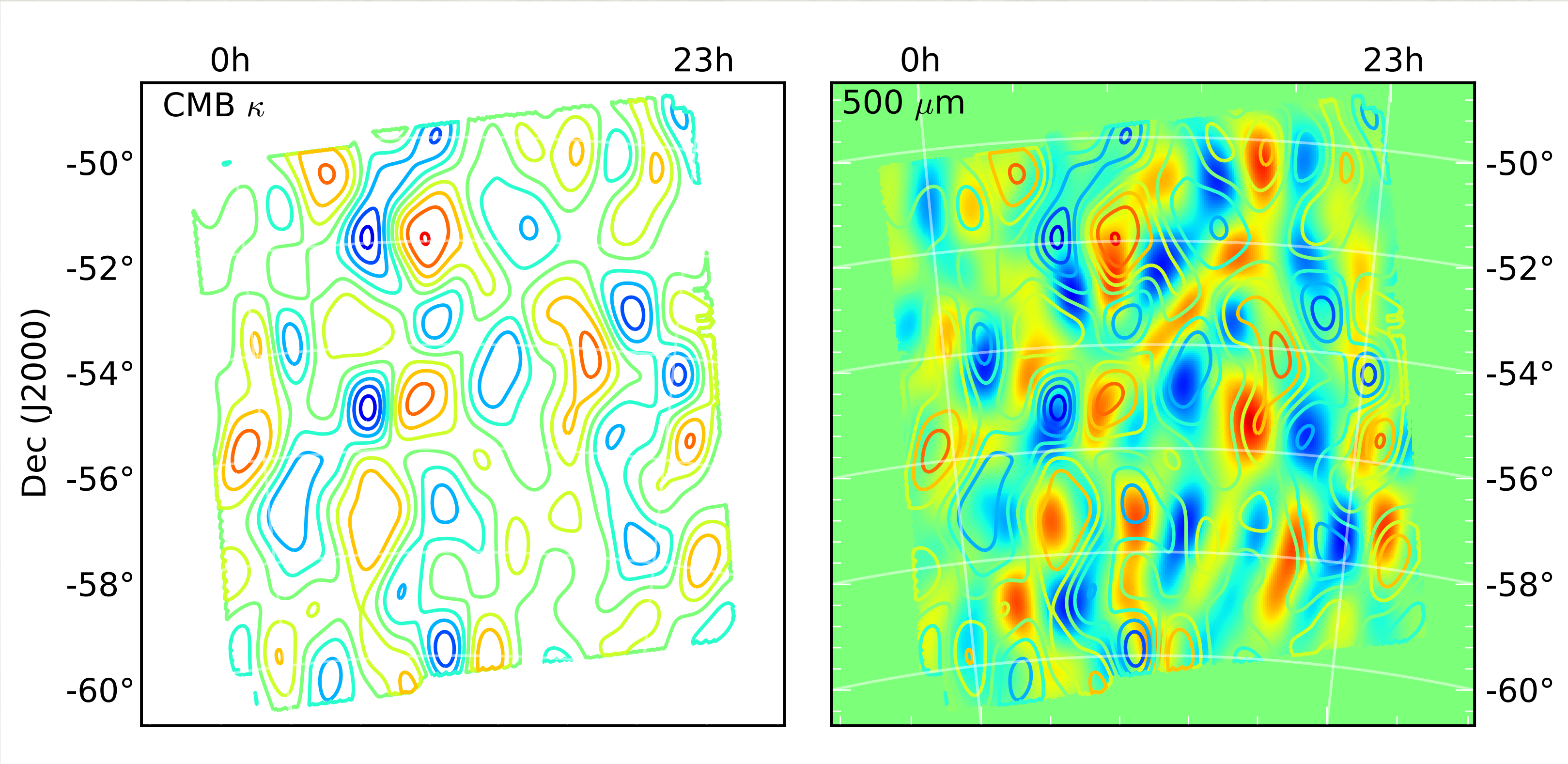
And it works, part 2

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

"mass map"

Infrared emission from Galaxies

CMB mass-map



Herschel/ SPIRE infrared map

=> 6.7-8.8σ detections. Allows one to measure bias of a given population with a well-calibrated mass map.

See G. Holder, *et al.*, arXiv:1303.5048.

Take Away #3

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 doing this now, and is rapidly getting better.

Outline

1. Overview of SPT

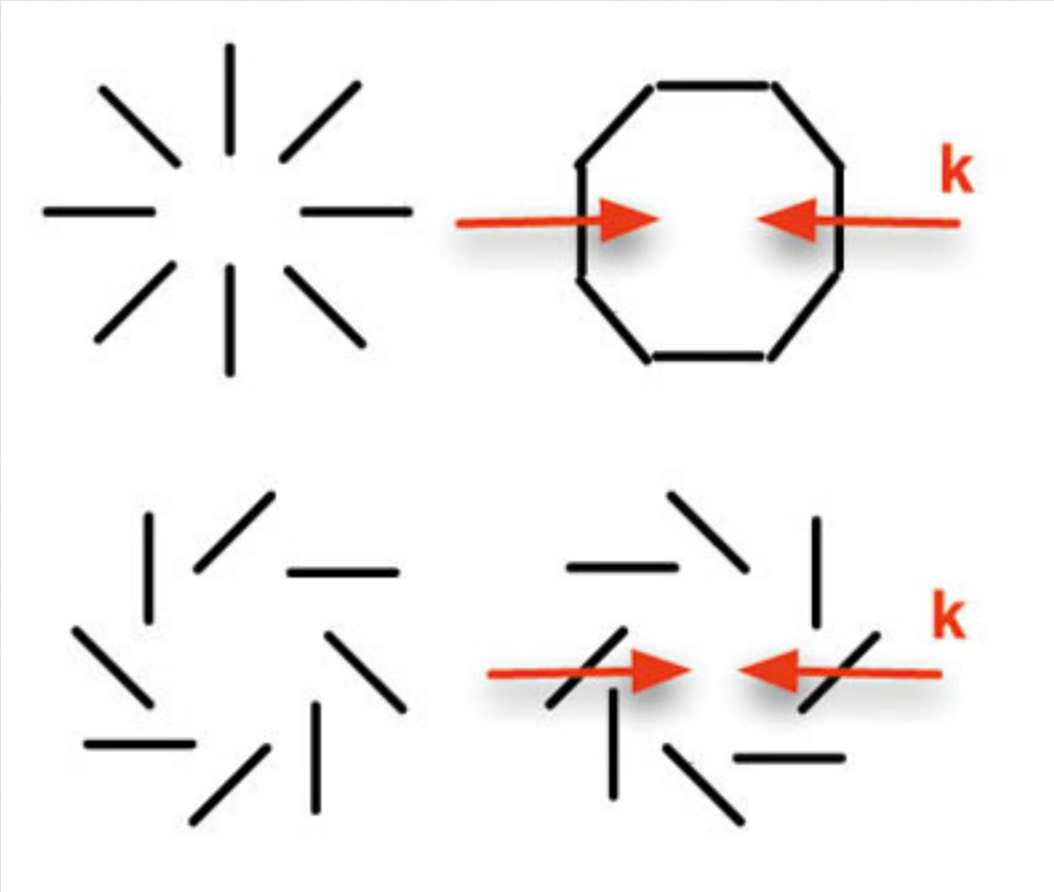
2. Results from SPT:
   - SPT data
   - primordial power spectra (inflation)
   - massive neutrinos
   - gravitational lensing of CMB

3. The Future is Now: SPTpol and SPT-3G

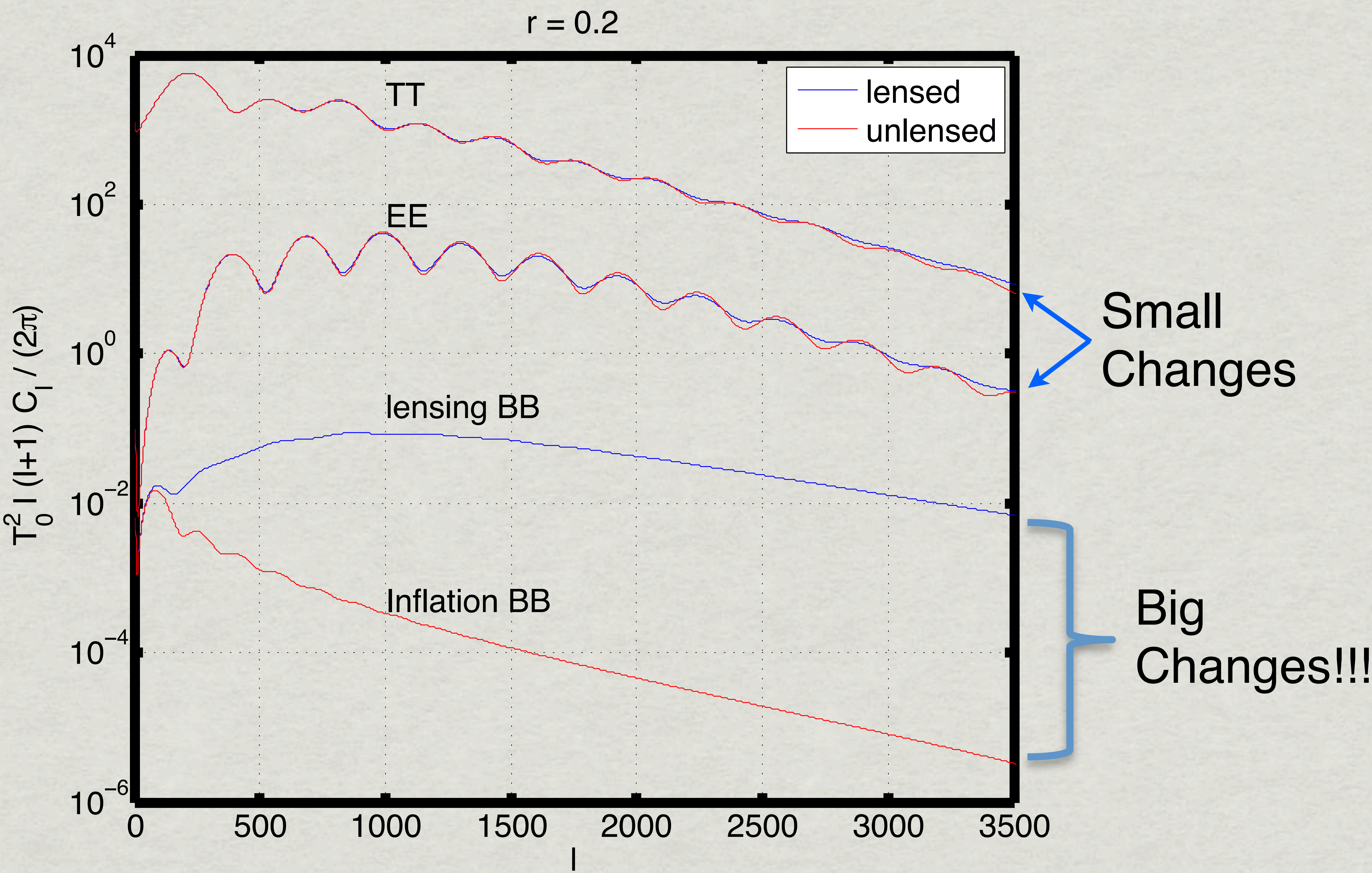
CMB polarization: terminology

E-modes:
even parity

B-modes:
odd parity



CMB lensing Causes "Big Changes" in Polarization Power Spectrum



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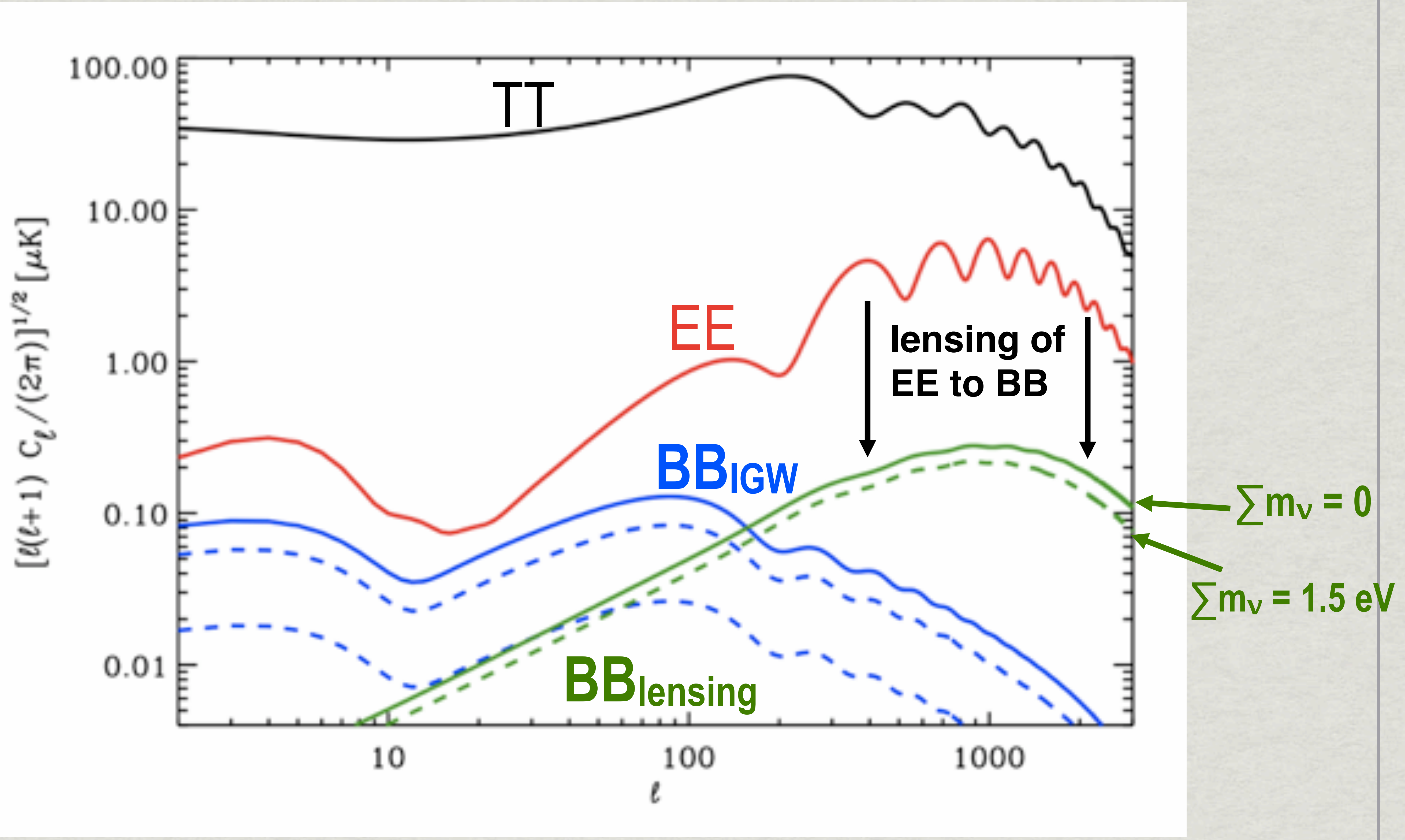
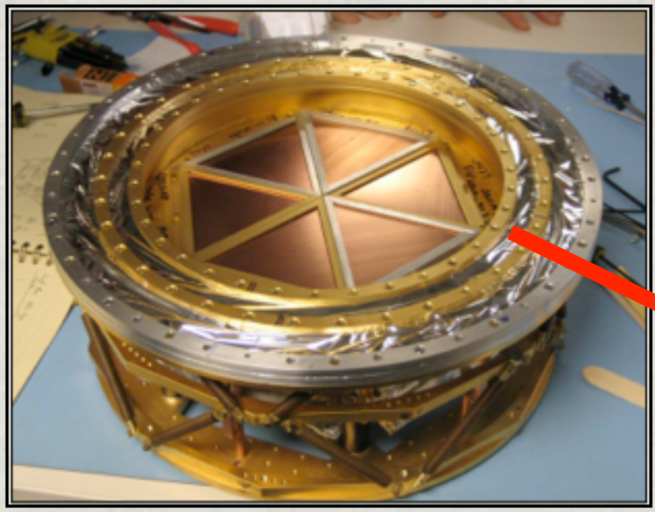
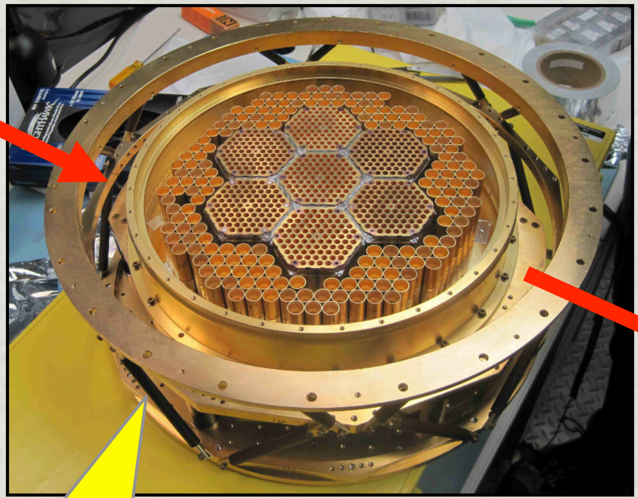


The progression of SPT: moving to CMB polarization

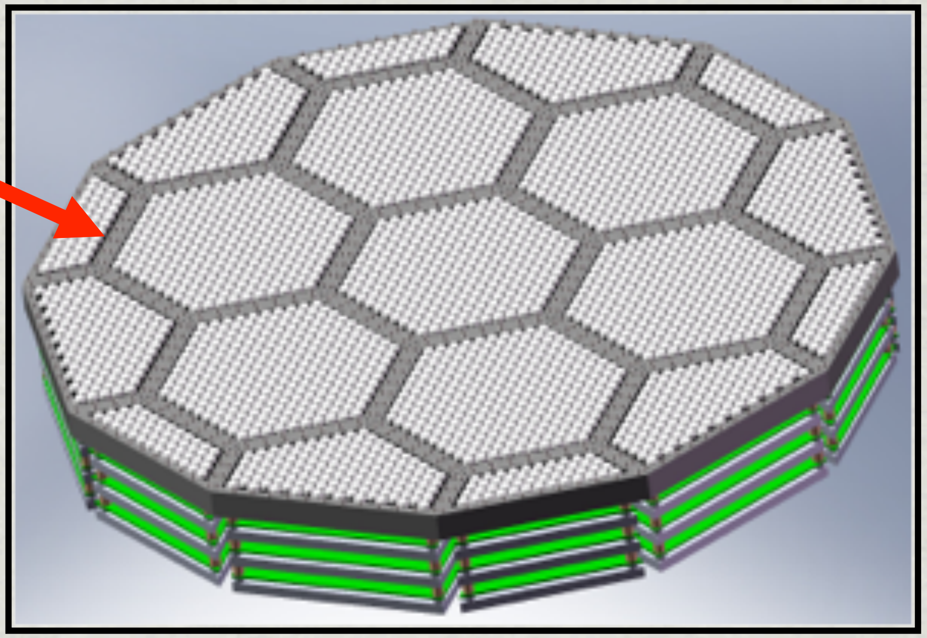
2007-2011: SPT
960 detectors



2012-2015: SPTpol
~1600 detectors



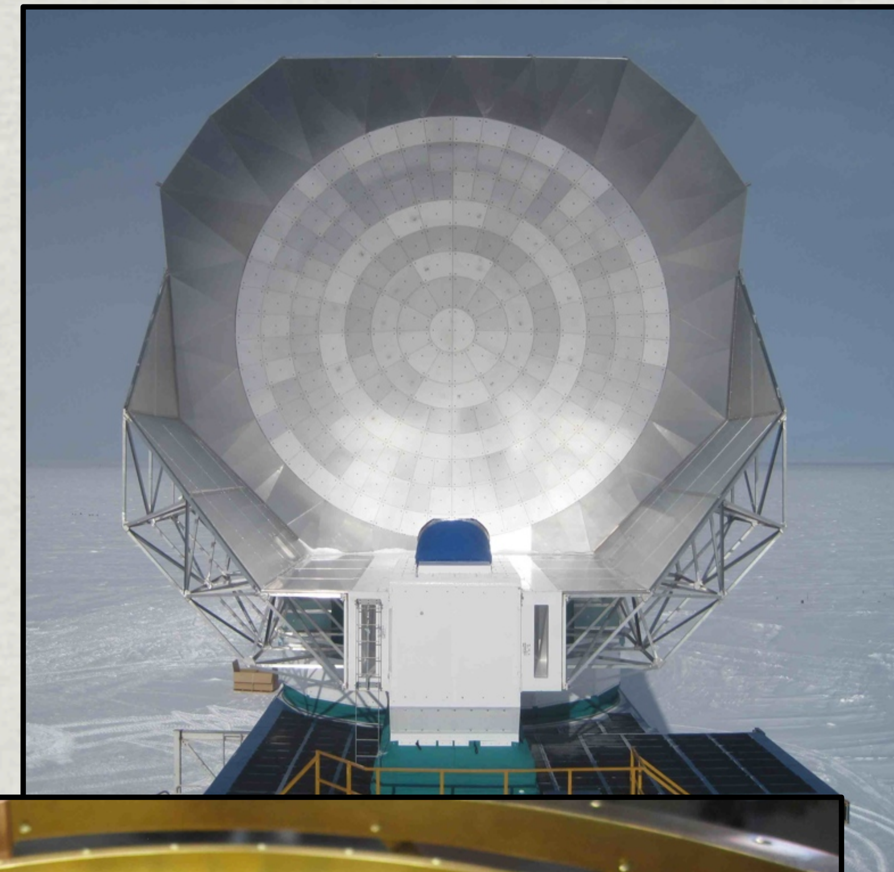
2016: SPT-3G
~15,200 detectors



Now with polarization!

SPTpol:
a new **polarization-** sensitive camera for SPT

First light Jan. 2012



Measure “B-mode” polarization to constrain **neutrino mass** and **energy scale of inflation.**

$\sigma(\sum m_\nu) \sim 0.09$ eV

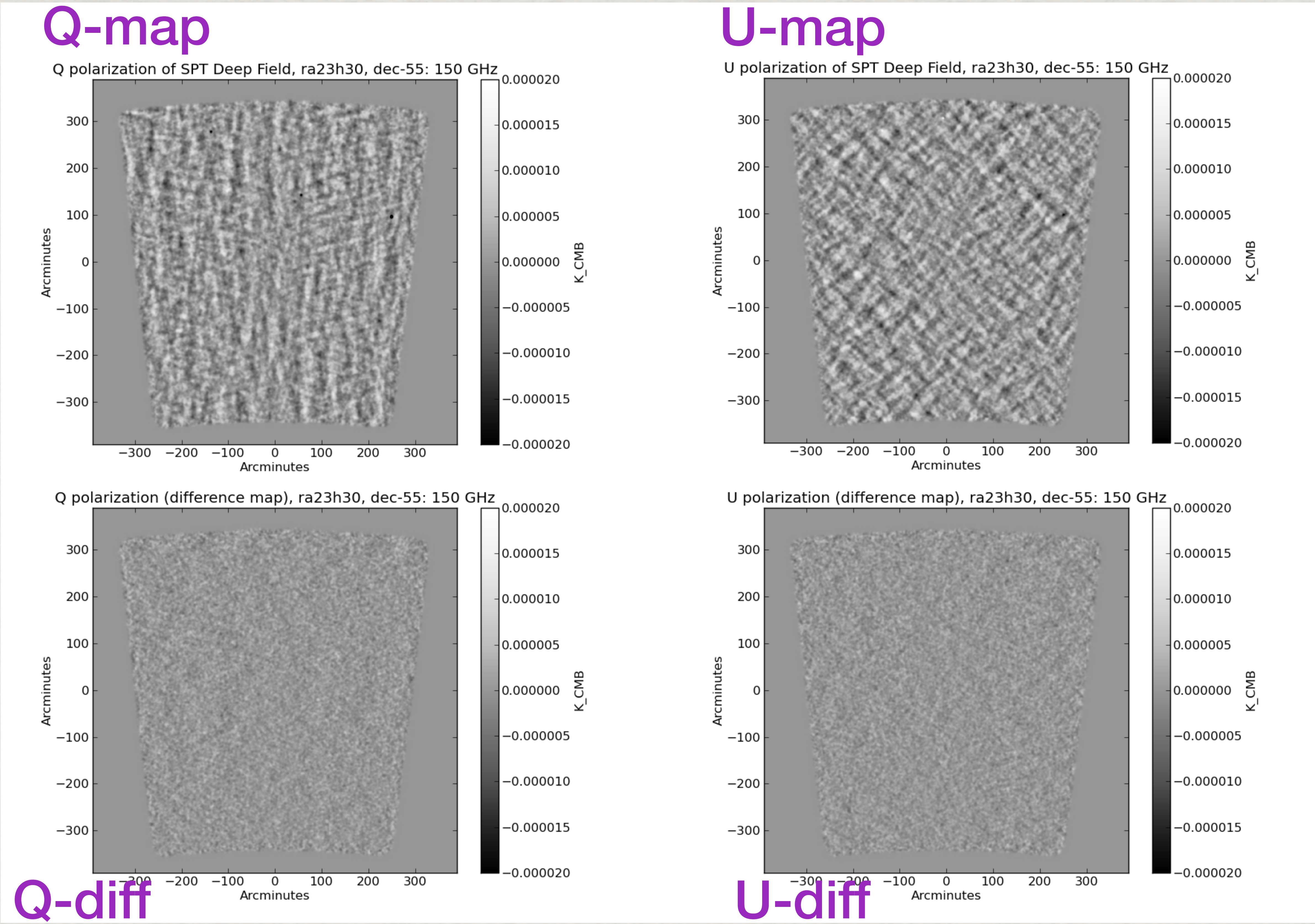
$r \lesssim 0.06$ (95%)

Investigate dark energy using **galaxy cluster abundances** - deeper cluster survey

360 - 100 GHz

1176 - 150 GHz

1st year SPTpol data looks great!



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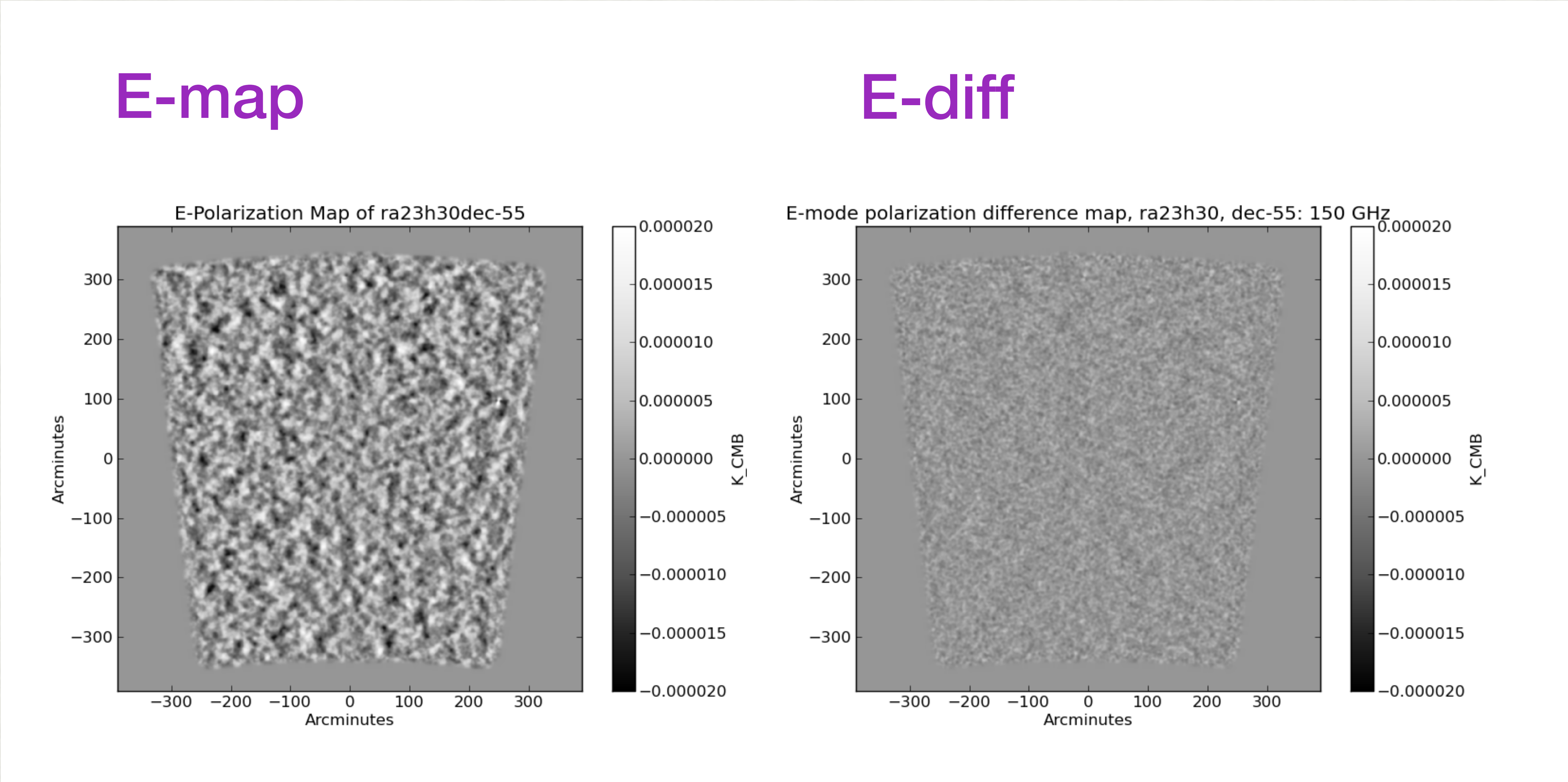
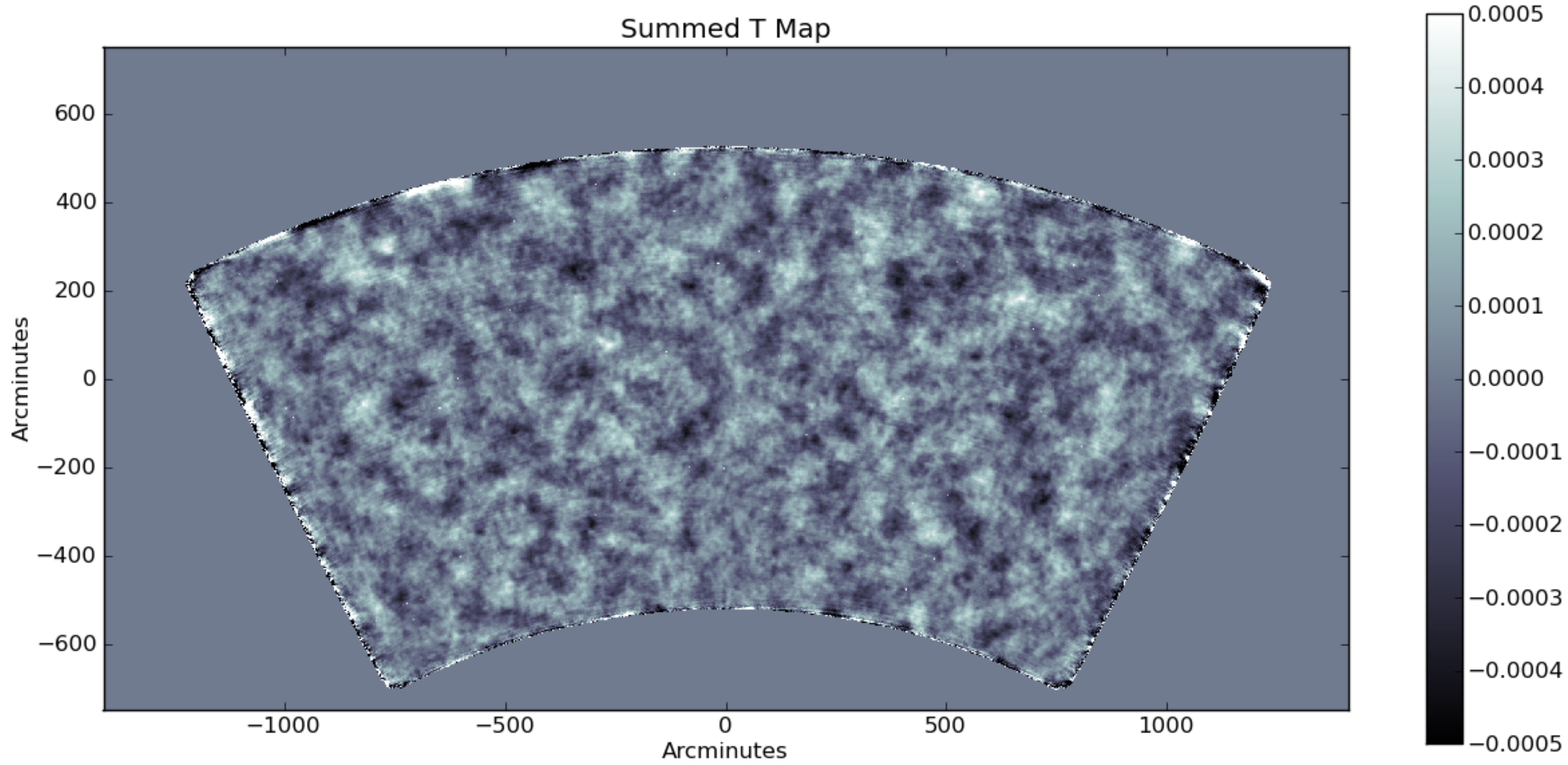


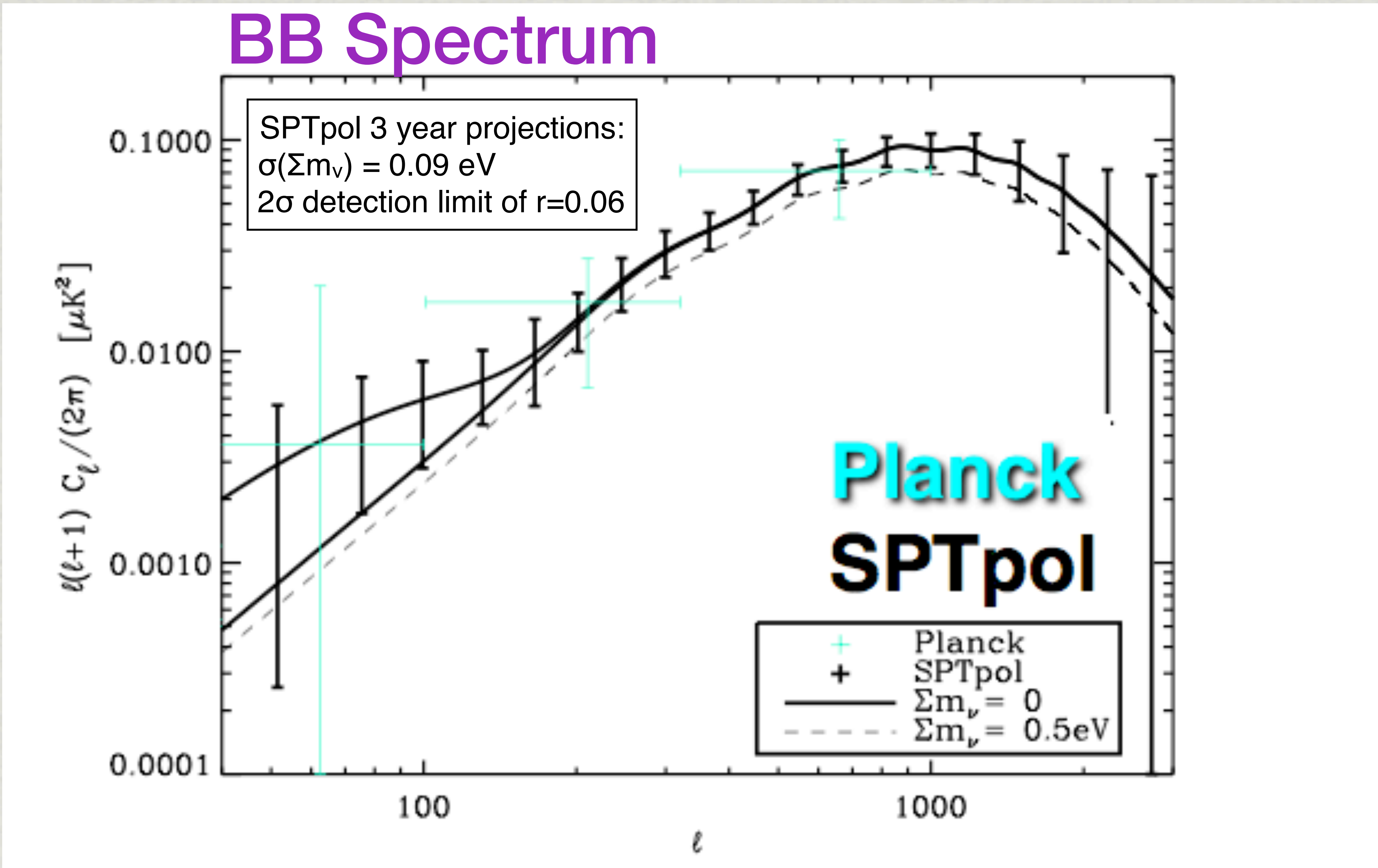
Power Spectra coming soon...

The first month of the full survey field already has a beautiful T map!

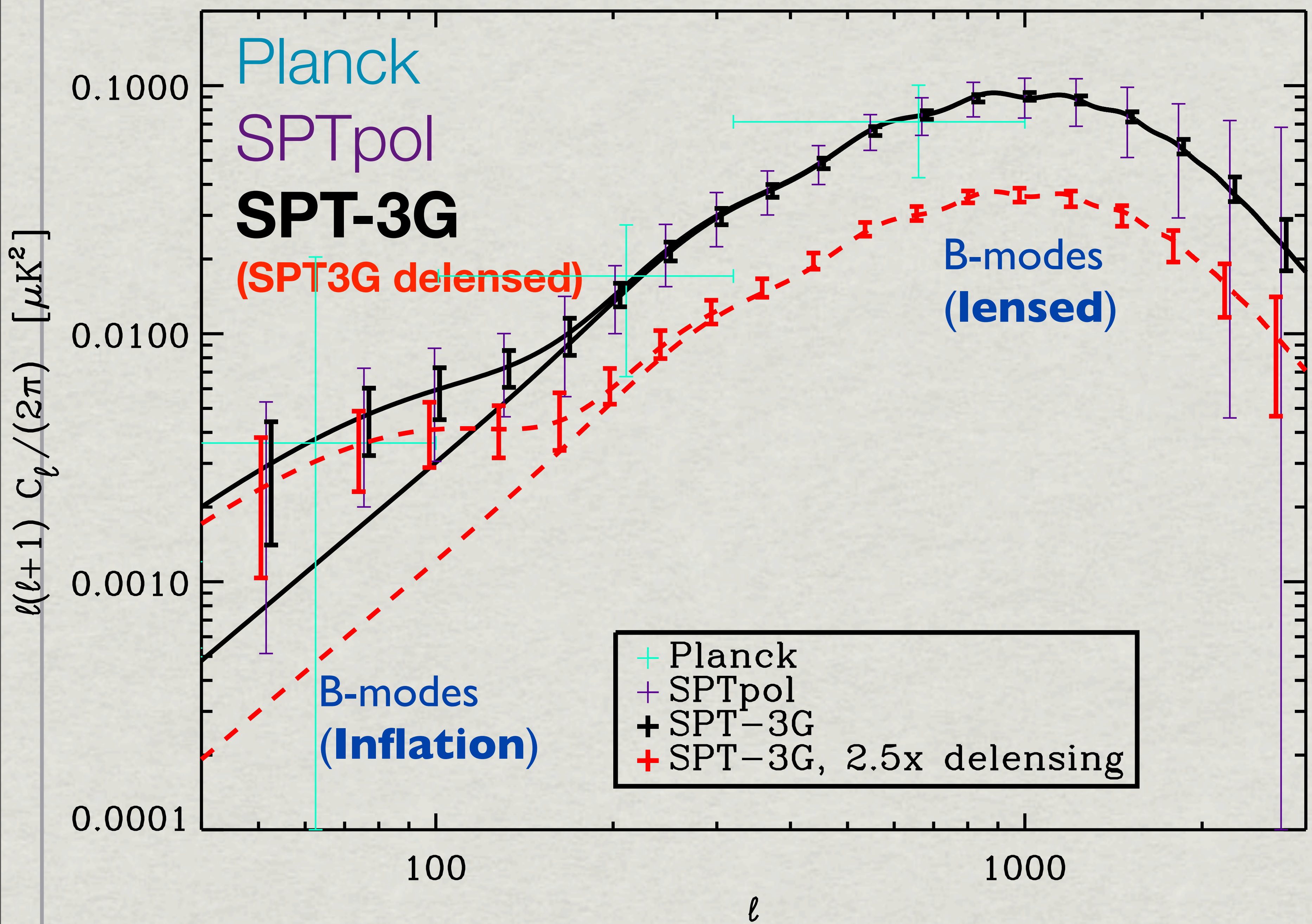
May 2013 data



SPTpol will make a strong detection of B-mode polarization.



SPT-3G:
Projected B-mode Power Spectrum



- Neutrino Constraints:
  - ***$\sigma(\Sigma m_\nu)$ = 0.06 eV***
- "De-lens" the CMB at large-angular scales and improve "r" Inflation constraint
  - ***$\sigma(r)$ = 0.01***

Credit: T. Crawford

Summary

- **SPT-SZ survey complete with broad science impact:**
  - **High-redshift galaxies:** Early star and galaxy formation
  - **Distant, massive clusters:** Dark energy, neutrinos, cluster evolution
  - **Primordial CMB anisotropy:** Inflation, early universe physics
  - **CMB lensing:** “weighing” the universe, neutrinos
- In conjunction with WMAP, SPT data probes a wide range of topics relevant to physics:
  - primordial power spectra & inflation
  - neutrino mass
  - dark energy
- SPTpol: 1.4 years into 4 year survey
  - **Lensing “B”-modes:** Detection imminent, improve neutrino constraints
  - **Inflationary “B”-modes:** Improve constraints on inflation’s energy scale
- SPT-3G: Development underway
  - Observations begin in 2016
  - Inflation, Lensing (neutrino masses), Clusters, kSZ/tSZ

- **Expect first B-mode CMB polarization results this year!**
  - New window into inflation and structure growth at z~2


Thank You!

Backup Slides

How does the CMB constrain Neff?

How many light, ν-like particle species are there?

from the Particle Data Group,
number of light ($m < \frac{m_Z}{2}$) particles that couple to the Z,

$N_\nu = 2.984 \pm 0.0082$ *(LEP)*

A much less accurate, but more generic test can be done by measuring the *expansion rate* of the early, radiation-dominated universe (see *e.g*. Steigman, Schramm, Gunn 1976).

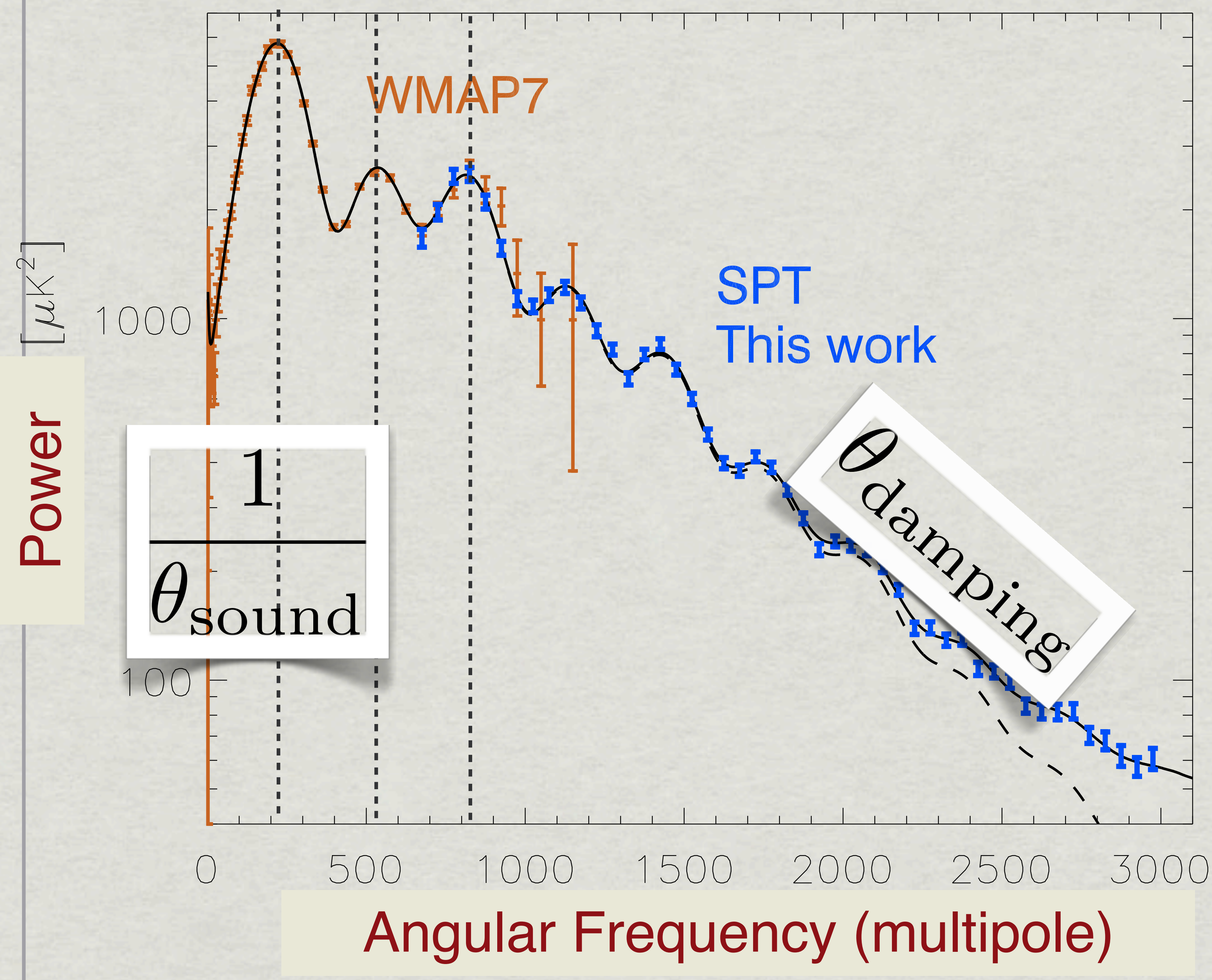
In this way, the abundance of BBN elements can be used to constrain N_ν:

$N_\nu = 3.82 \pm 0.45$ *(Izotov & Thuan)*
$N_\nu = 3.13 \pm 0.21$ *(Peimbert et al)*

from Nollett & Holder 2011

What about the CMB?

CMB sensitivity to Nν

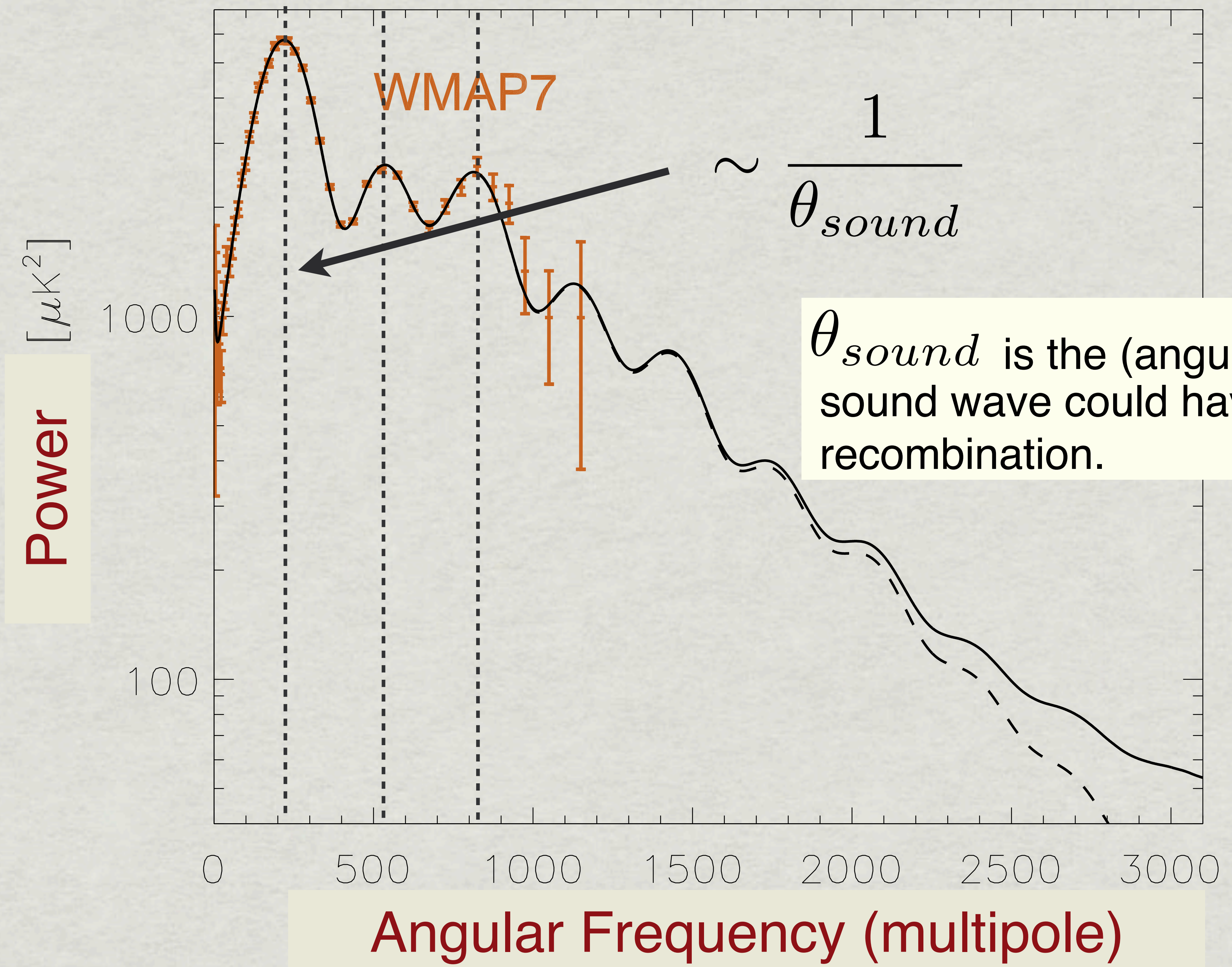


- The **number of relativistic species (think neutrinos)** present in the early universe affects the **expansion rate** during that time.

- 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

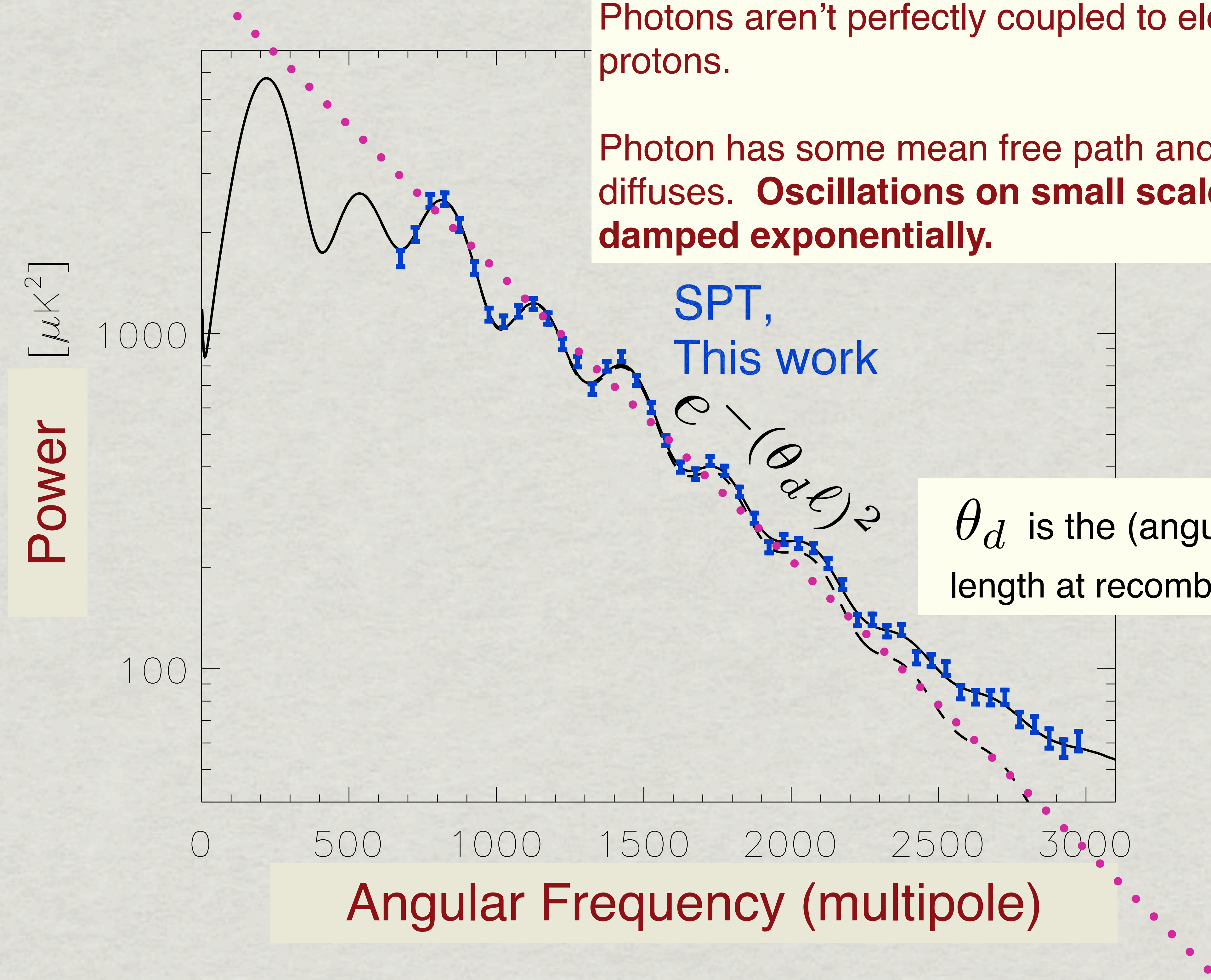


θ_{sound} is the (angular) distance a sound wave could have traveled by recombination.

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.

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

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 of sound scale **r_s** and damping scale **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.**

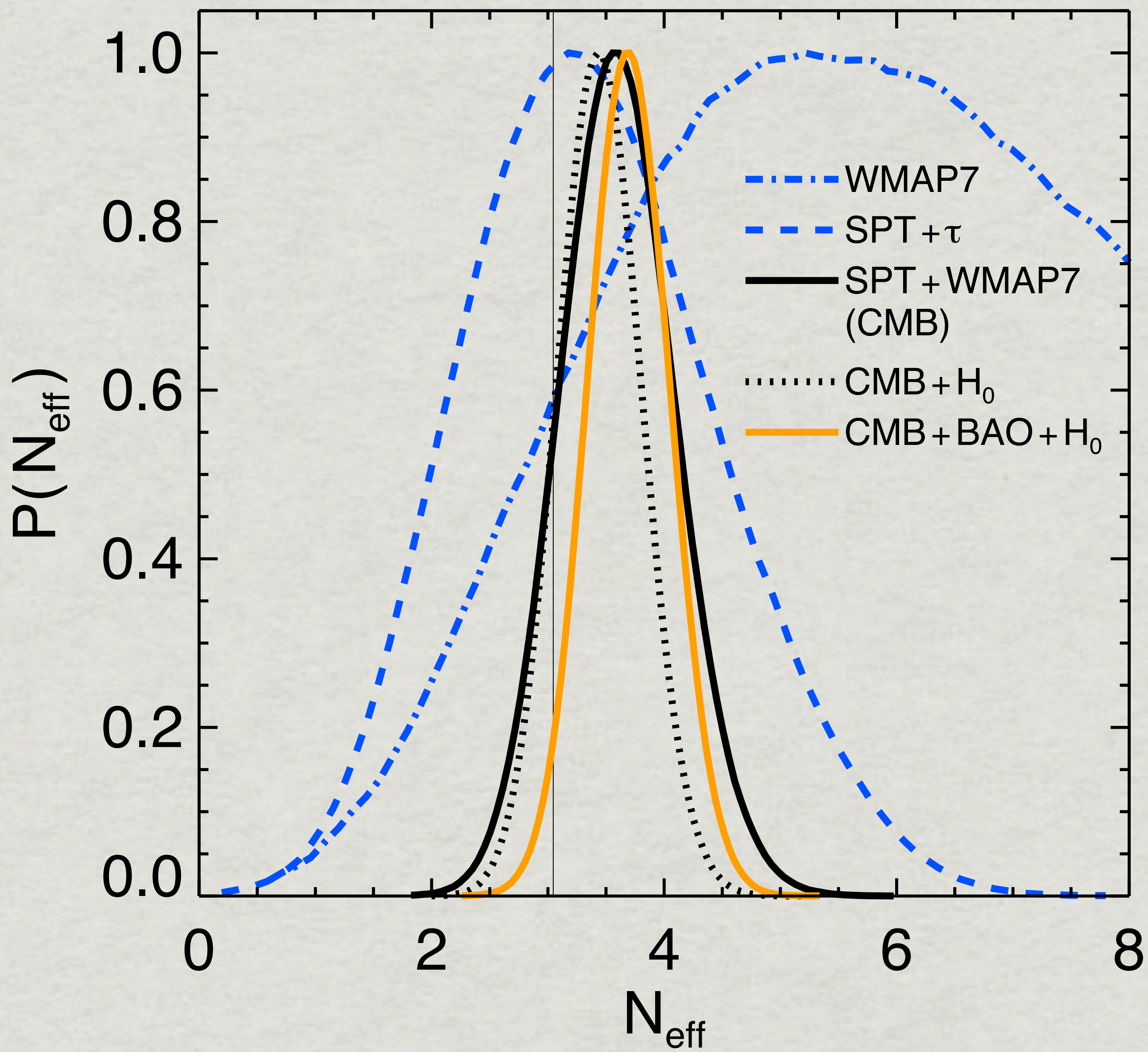
This is

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)

CMB Constraints on N_{eff}



- N_{eff} = 3.62 +/- 0.48 (SPT+WMAP) (1.2σ higher than 3.046)
- N_{eff} = 3.71 +/- 0.35 (SPT+WMAP+H0+BAO) (1.9σ higher than 3.046)

WMAP 9-year

WMAP9 papers and new SPT paper came out within days of each other. CMB-only N_{eff} consistent with new SPT paper:

N_{eff} *= 3.89 +/- 0.67 (**WMAP9** + eCMB)* ← ("eCMB" dominated by old SPT data)

N_{eff} *= 3.62 +/- 0.48 (**WMAP7** + new SPT)*

But differences in N_{eff} when BAO is included?

N_{eff} *= 3.26 +/- 0.35 (**WMAP9** + eCMB +H0+BAO)*

N_{eff} *= 3.71 +/- 0.35 (**WMAP7** + new SPT +H0+BAO)*

Huh?

WMAP 9-year

WMAP9 papers and new SPT paper came out within days of each other. CMB-only Neff consistent with new SPT paper:

*N_{eff} = 3.89 +/- 0.67 (**WMAP9** + eCMB)* ← ("eCMB" dominated by old SPT data)

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But differences in N_{eff} when BAO is included?

*N_{eff} = 3.26 +/- 0.35 (**WMAP9** + eCMB +H0+BAO)*

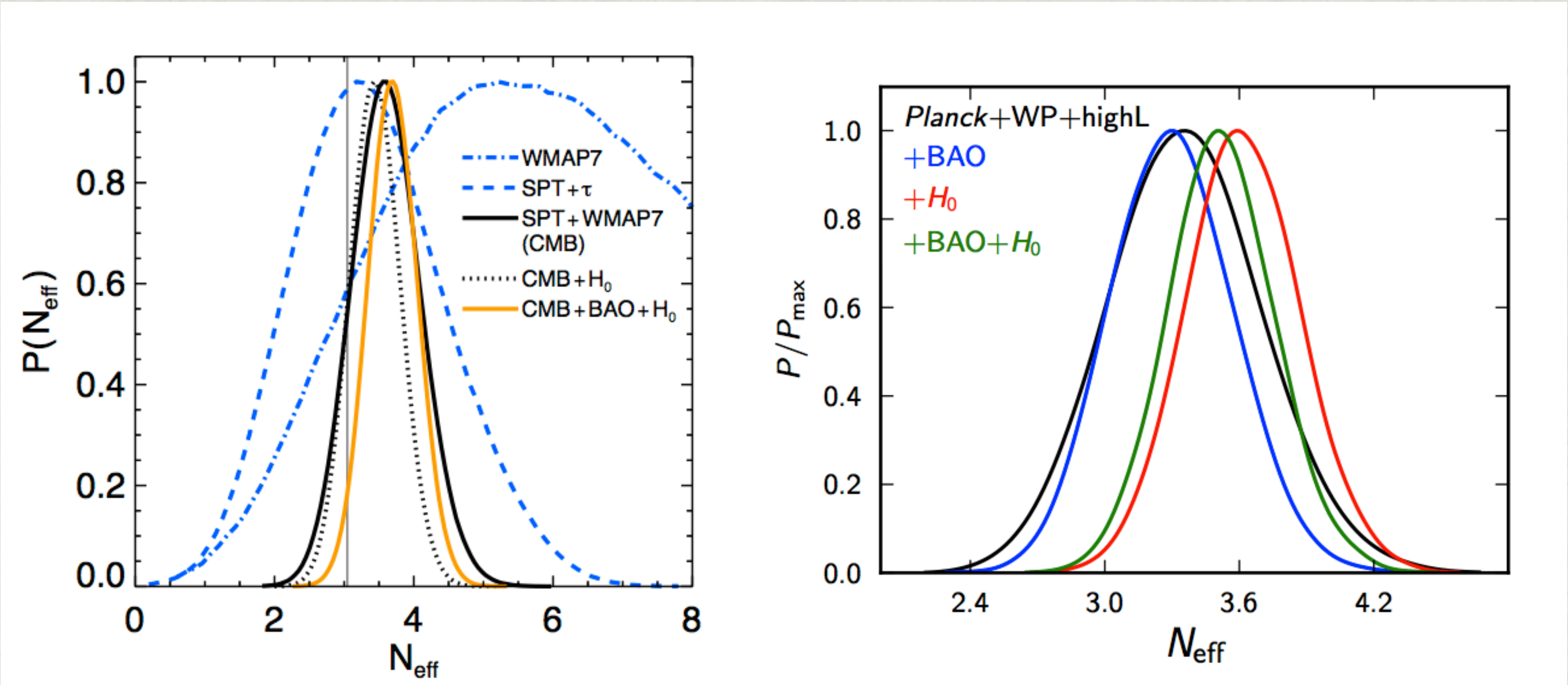
*N_{eff} = 3.71 +/- 0.35 (**WMAP7** + new SPT +H0+BAO)*

Caused by bug in WMAP9 which shifted and artificially tightened constraint on Neff when BAO data was used.

Regardless of bug, the new SPT papers provide the best constraints across the board, because they use the new SPT data, which WMAP9 Hinshaw et al did not.

Furthermore, updating SPT results to include WMAP9 rather than WMAP7 shows no appreciable changes (preliminary).

CMB Constraints on N_{eff}



<u>SPT + WMAP7:</u>

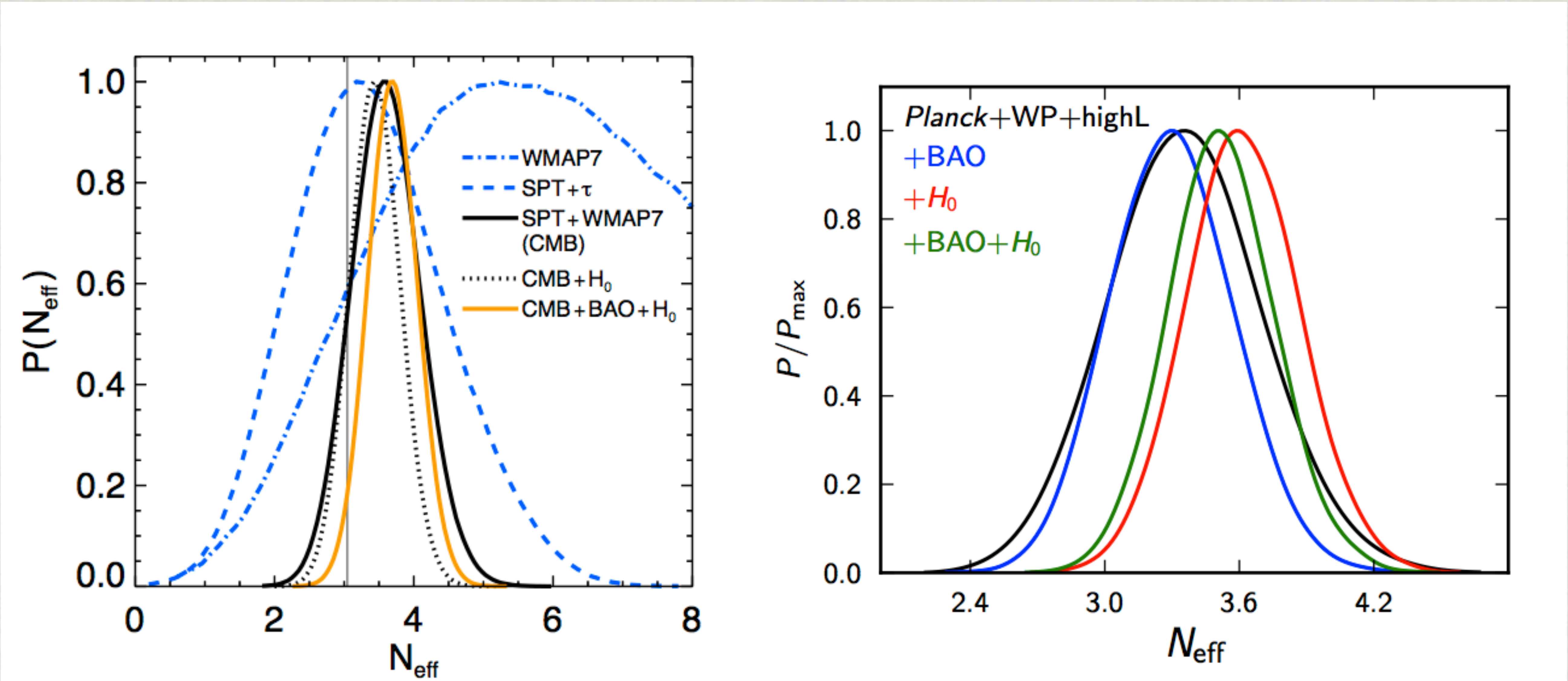
N_{eff} = 3.62 ± 0.48

<u>Planck + WP + highL:</u>

N_{eff} = 3.36 ± 0.34

- Planck and SPT are consistent with each other, and the ΛCDM prediction.

CMB Constraints on N_{eff}



SPT + WMAP7:

N_{eff} = 3.62 ± 0.48

Planck + WP + highL:

N_{eff} = 3.36 ± 0.34

N_{eff} = 3.71 ± 0.35

Add BAO+H_0

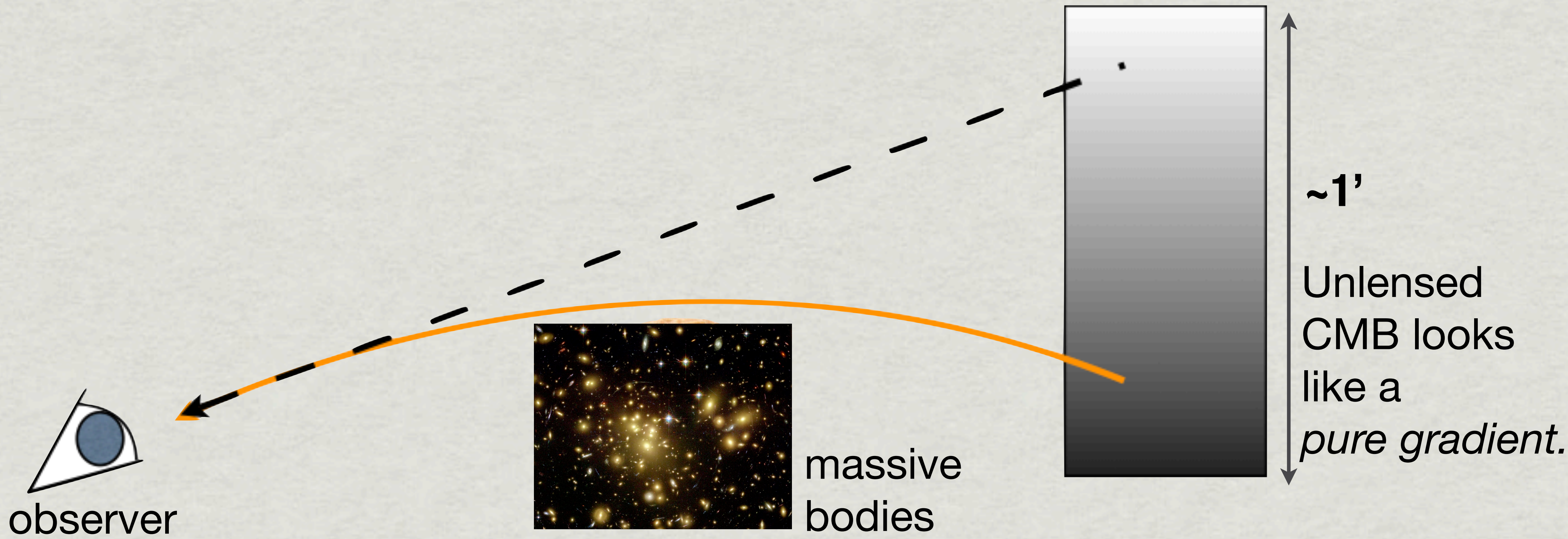
N_{eff} = 3.52 ± 0.24

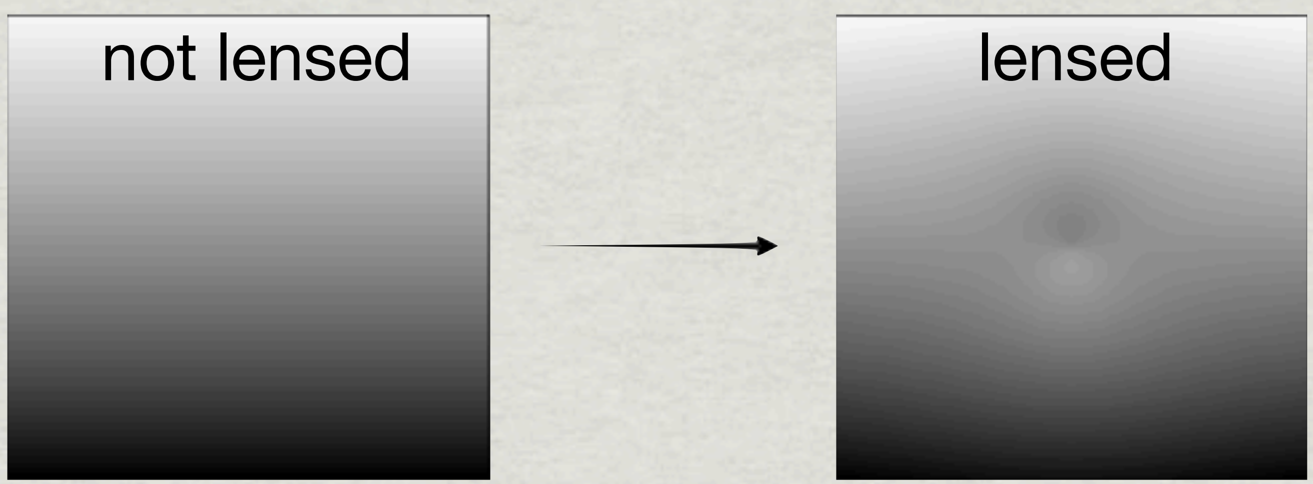
Take Away #ν

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.

Understanding the Quadratic Estimator

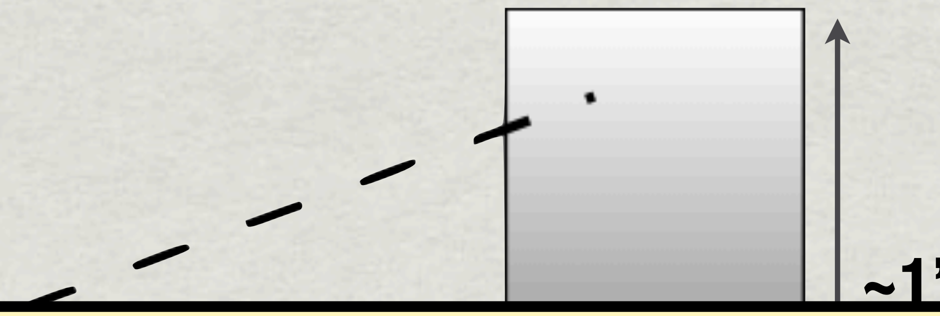
II. Mass Reconstruction
(more powerful, more complicated)





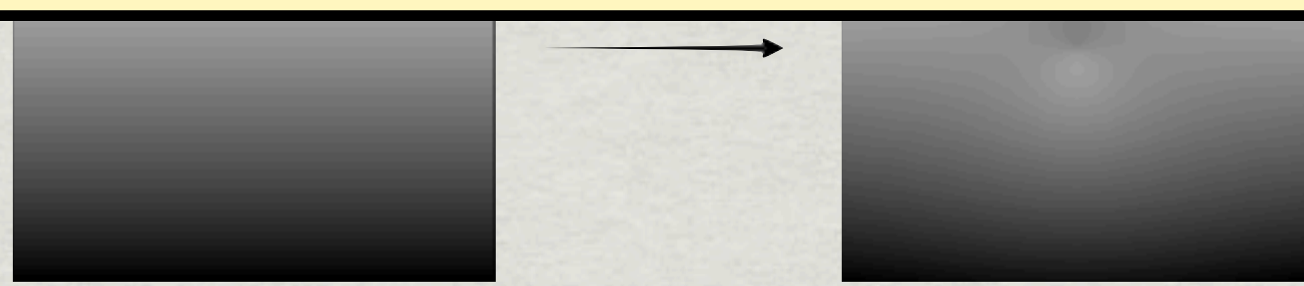
Small-scale wiggles are correlated with large-scale gradient.

II. Mass Reconstruction
(more powerful, more complicated)



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

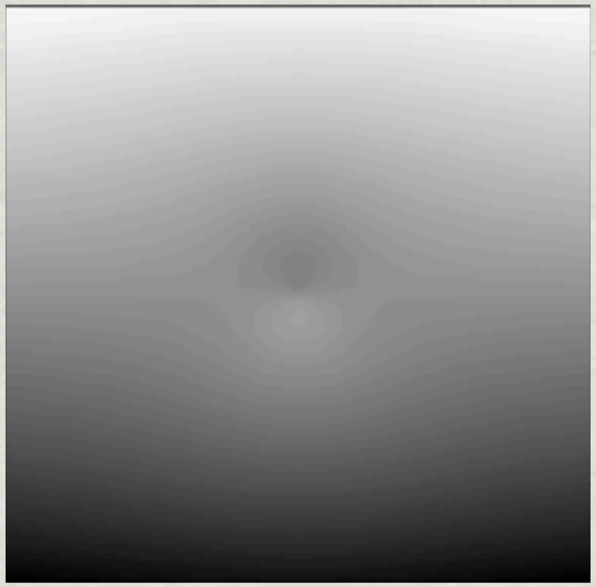
One method (optimal, unbiased):
the “Quadratic Estimator”
(see, e.g. W. Hu 2001; Hu & Okamoto 2002; Okamoto & Hu 2003)



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

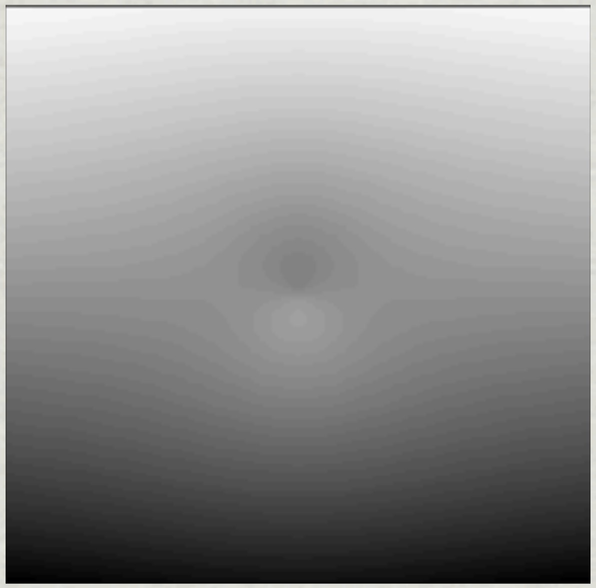
Unpacking the *Quadratic Estimator*

1.



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

2.



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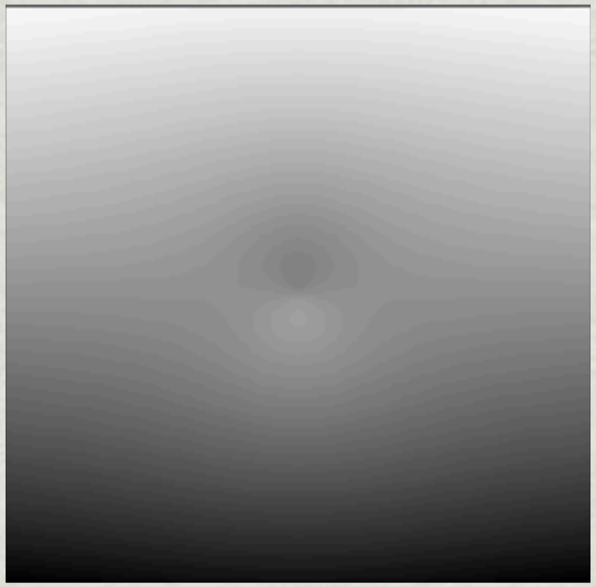
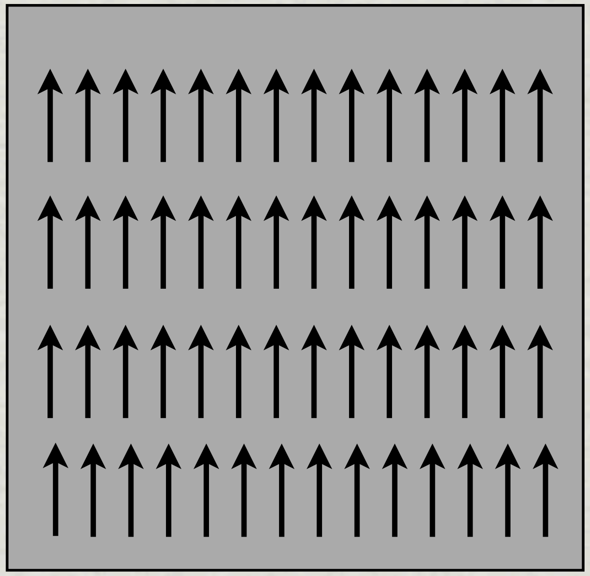
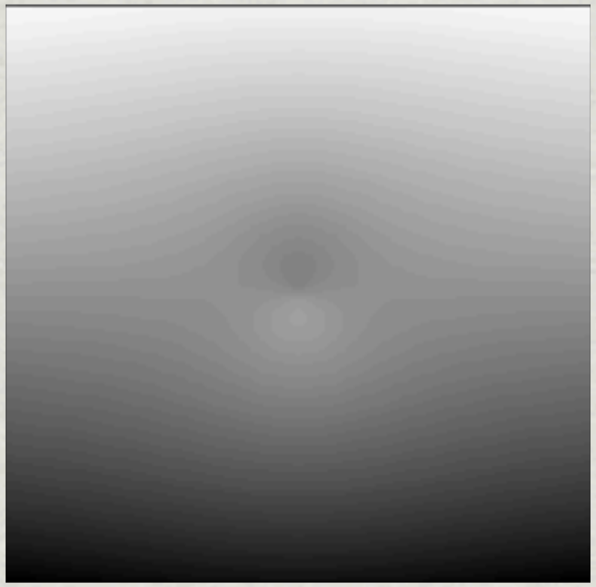
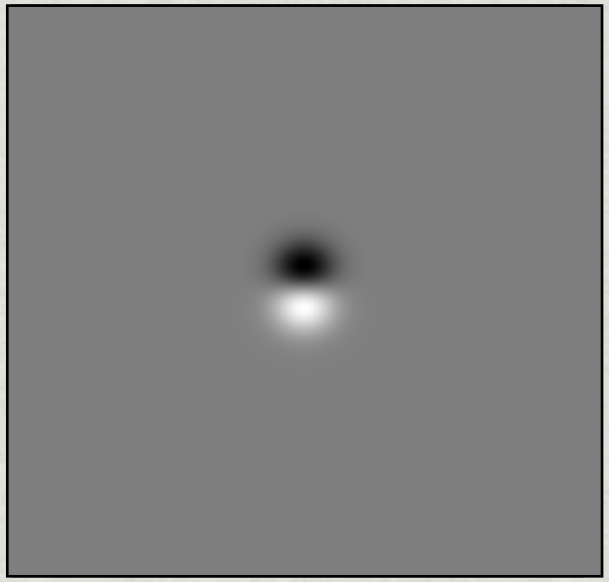




-- filter for large-scale gradient -->

2.

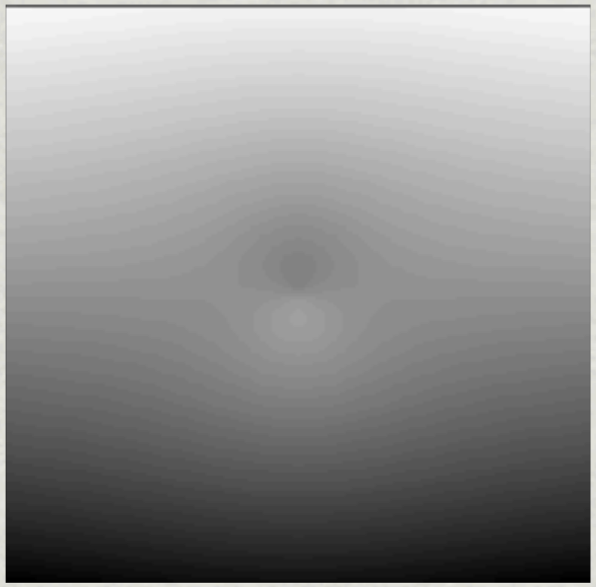


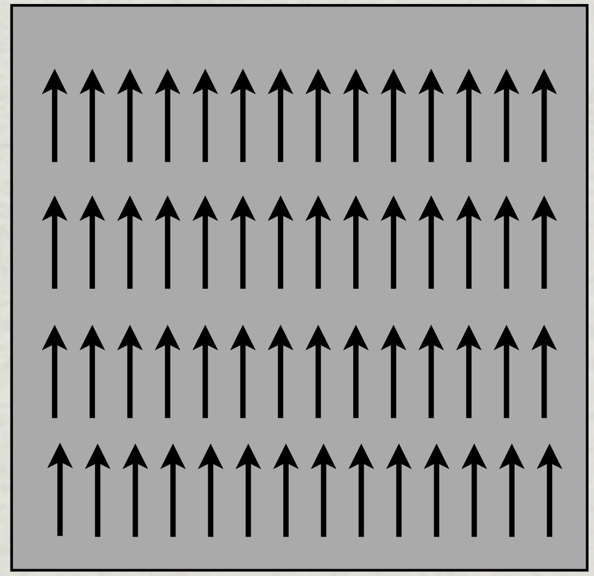


-- filter for small-scale wiggle -->

Unpacking the *Quadratic Estimator*

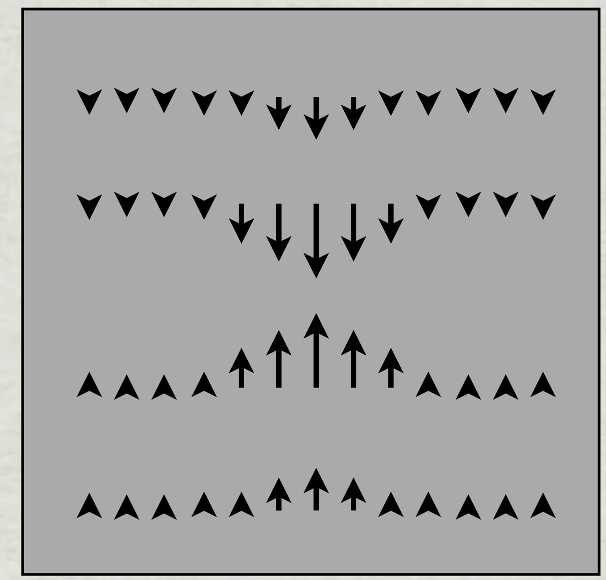
1.



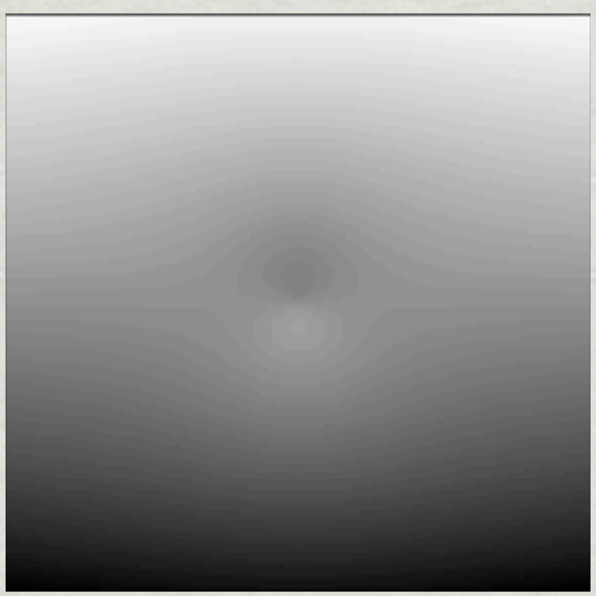


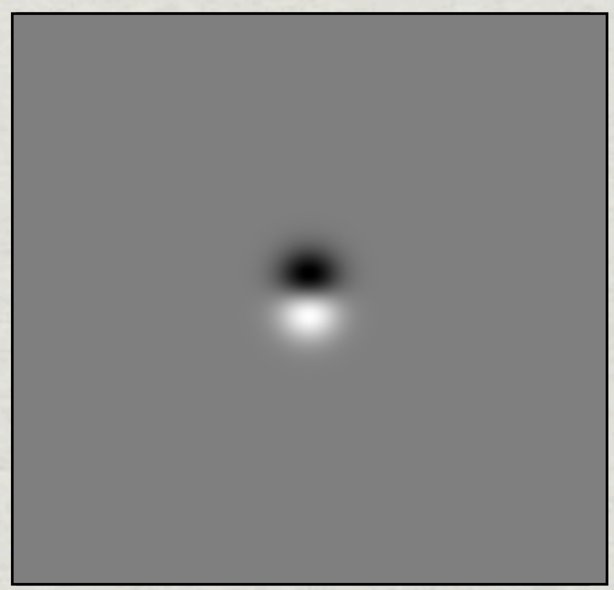
-- filter for large-scale gradient -->

multiply



2.

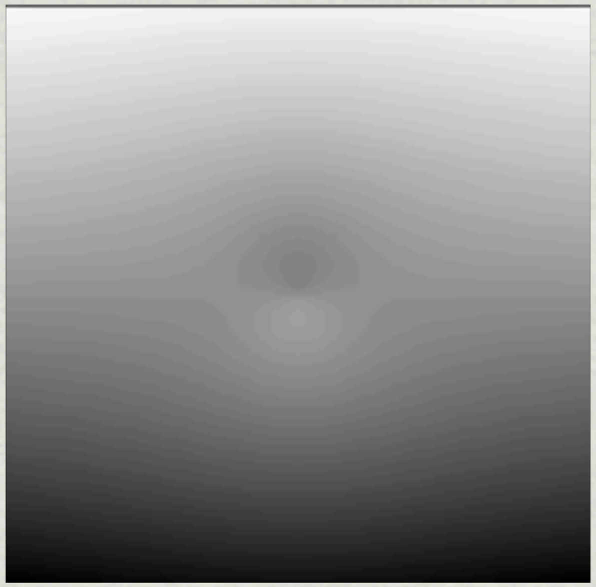


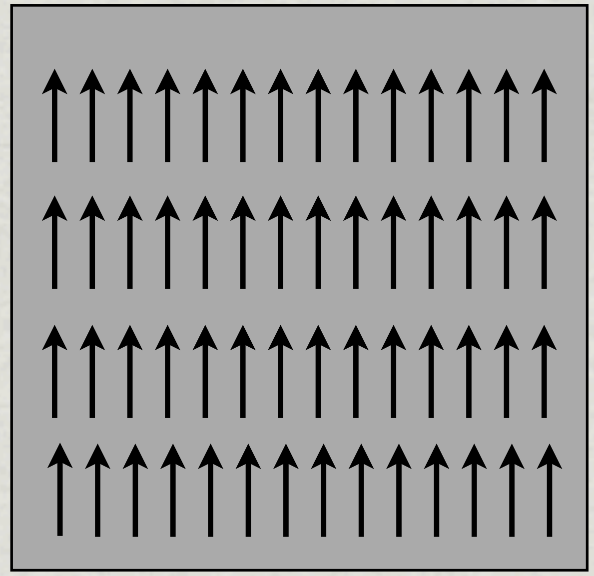


-- filter for small-scale wiggle -->

Unpacking the *Quadratic Estimator*

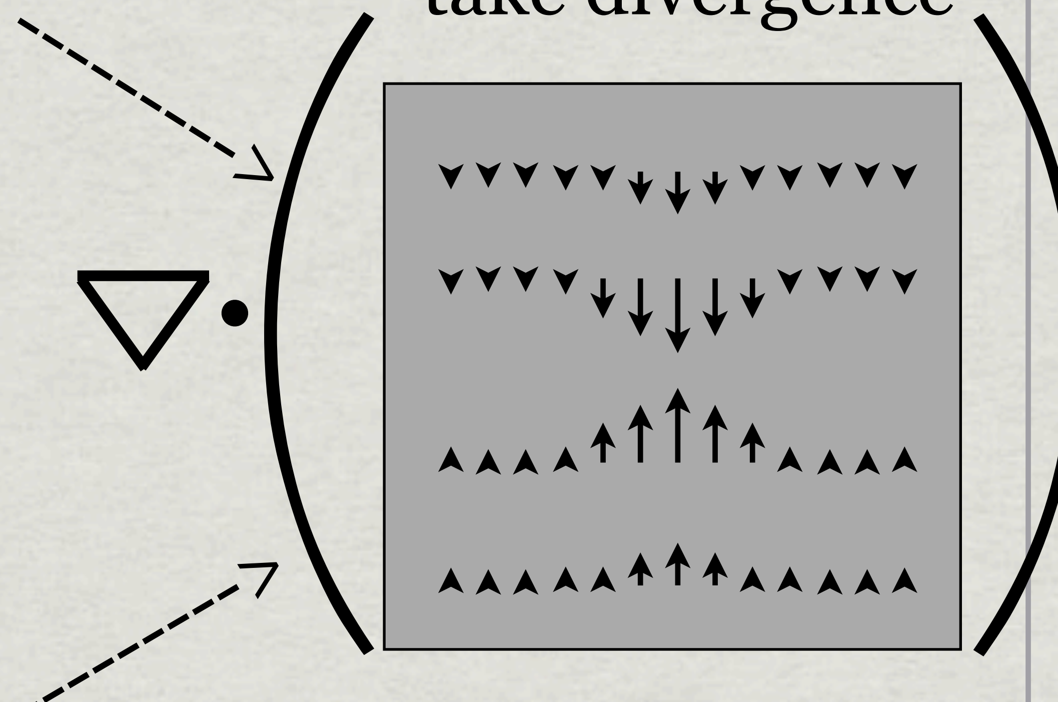
1.



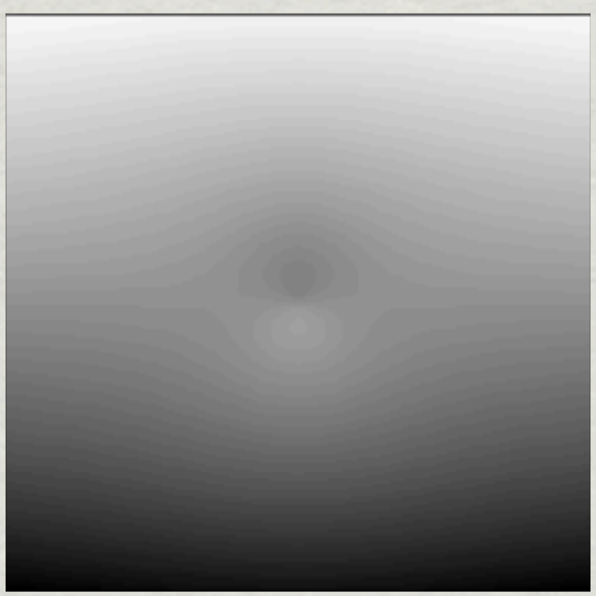


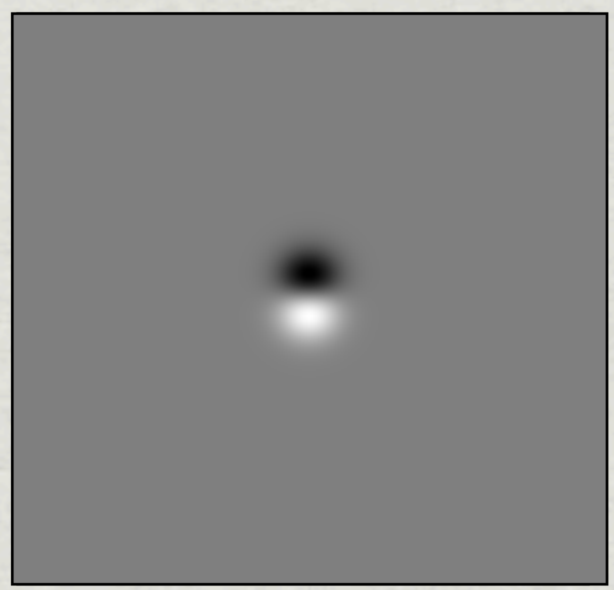
-- filter for large-scale gradient -->

take divergence



2.





-- filter for small-scale wiggle -->

Unpacking the *Quadratic Estimator*