Cosmic Microwave Background

High Energy Physics via CMB temperature and polarization measurements with the South Pole Telescope.

Argonne CMB Detector Development Collaboration between High Energy Physics, the Material Science Division, and the Center for Nanoscale Materials.

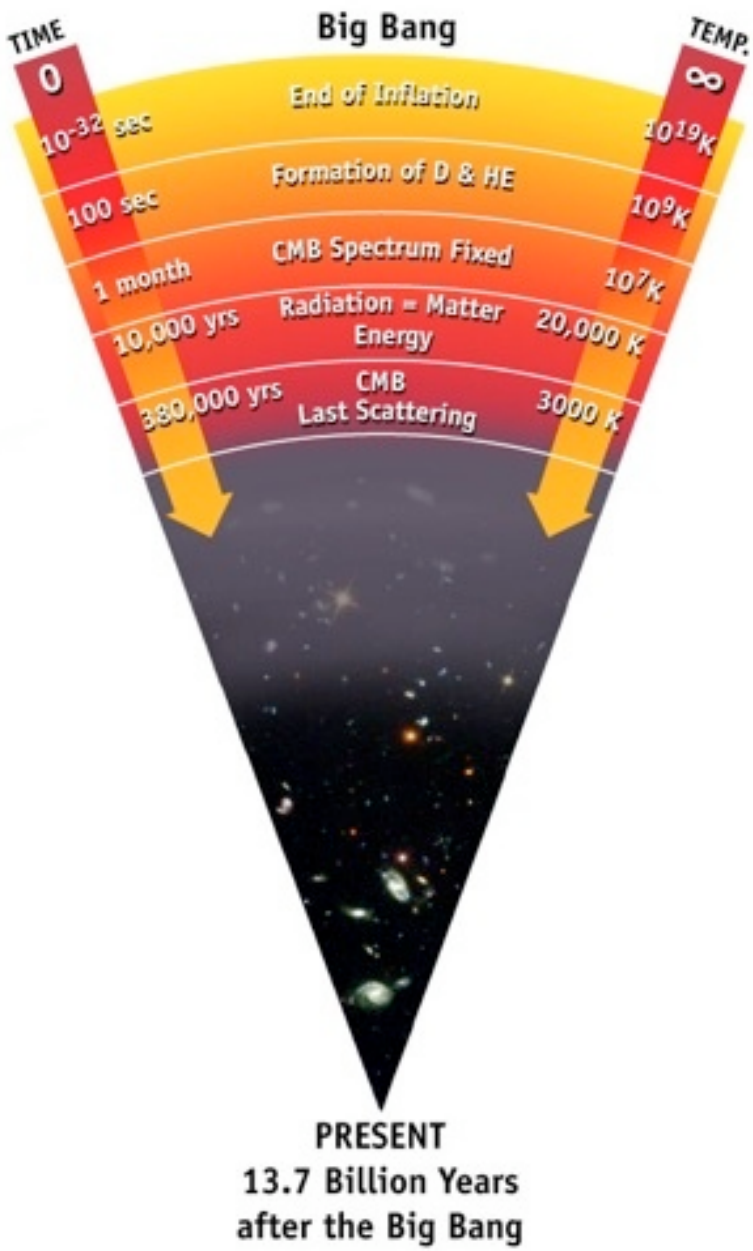
And with strong University Partners:
University of Chicago/KICP,
U.C.Berkeley & LBL,
U.Colorado at Boulder & NIST,
Case Western,
U. Michigan, and
McGill University.

Probing the Cosmic Frontier

We now have a model that describes the evolution of our Universe from a hot and dense state and allows precision tests.

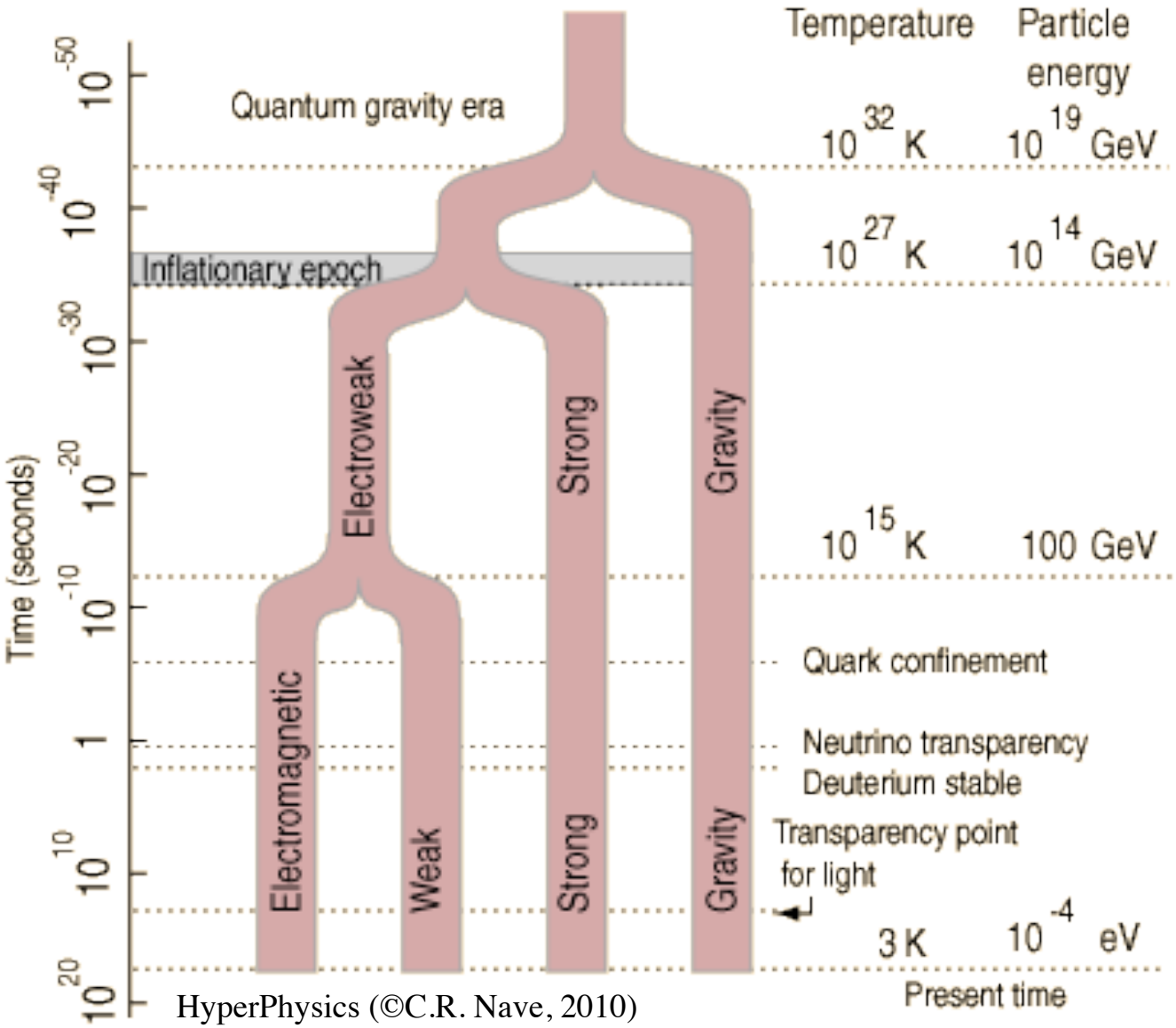
The model has some unusual features - *new physics* - <u>Dark Matter</u>, <u>Dark Energy</u>, and starts with a period of <u>Inflation</u>.

Much of the model has been learned from measurements of the cosmic microwave background (CMB).



from NASA/WMAP Team

Early universe as an HEP lab



HyperPhysics (©C.R. Nave, 2010)

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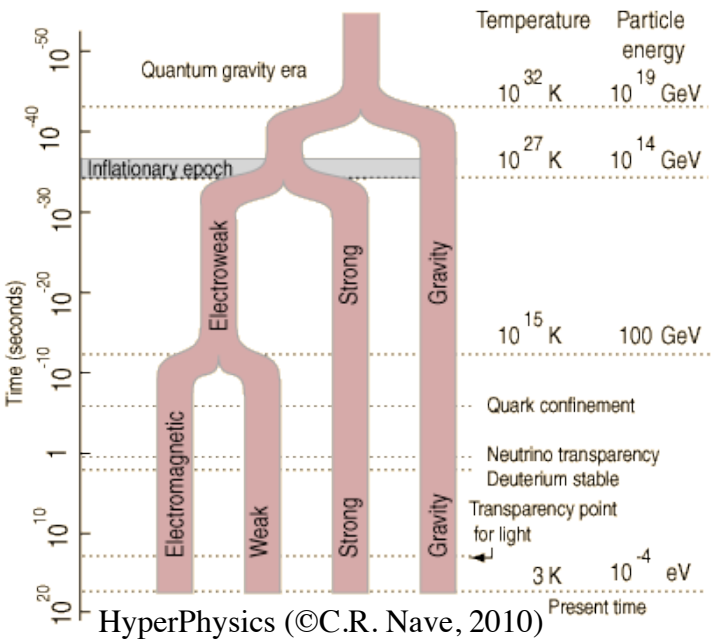

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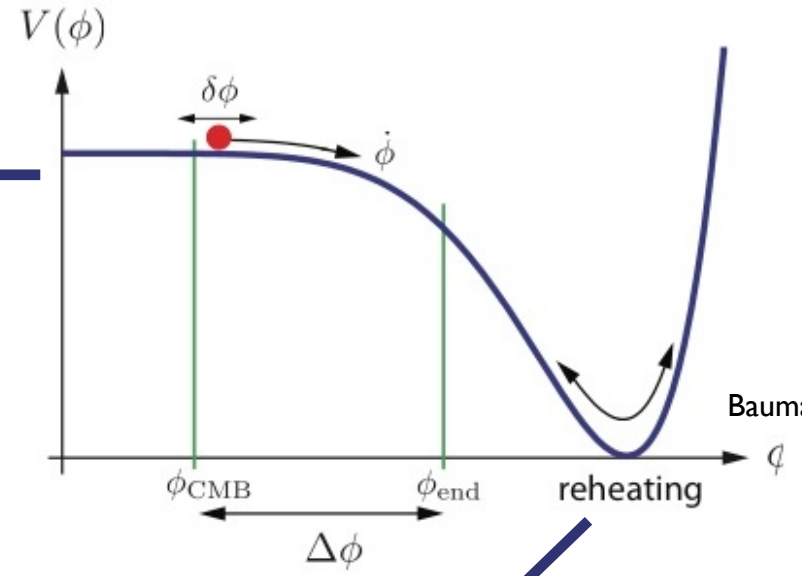


Baumann et al. 2008

Inflation generates

- Density (scalar) fluctuations:

$$P_s(k) = \mathbf{A_s} k^{(\mathbf{n_s} - 1 + \frac{1}{2}\alpha_{\mathbf{s}} \ln k)}$$

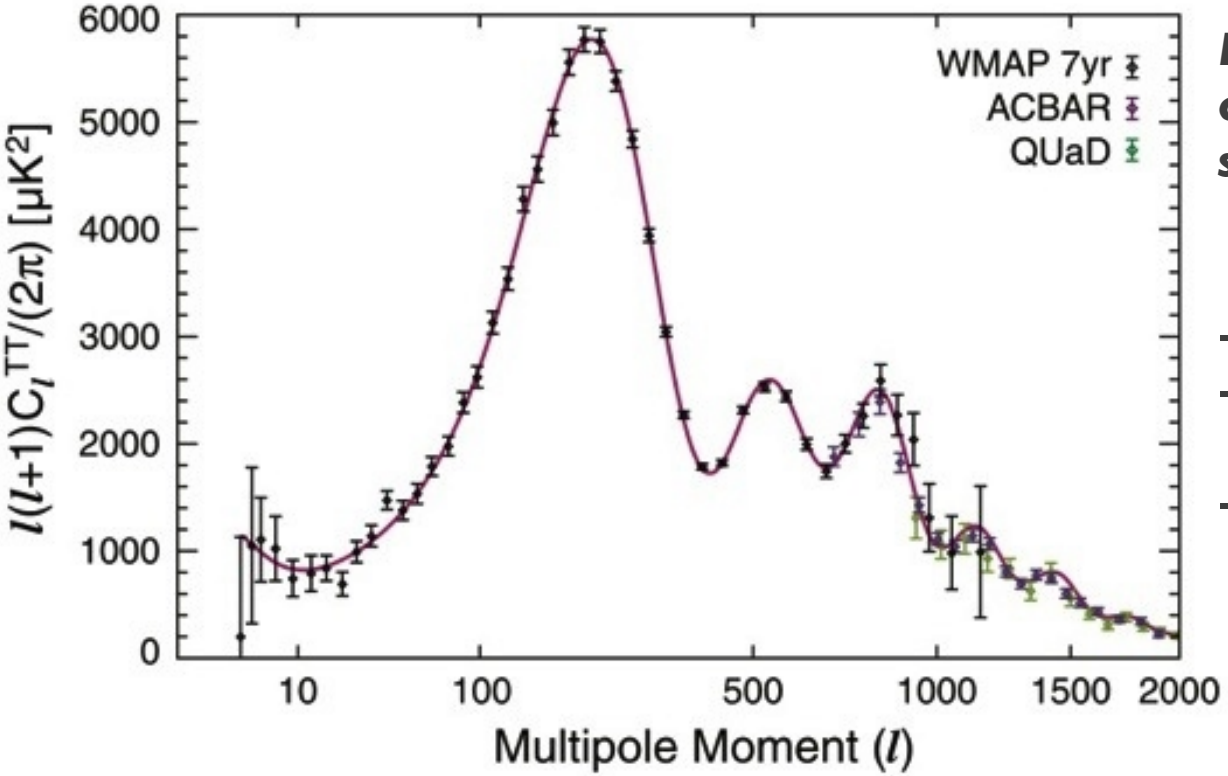
- Gravitational wave (tensor) fluctuations:

$$P_t(k) = \mathbf{A_t} k^{\mathbf{n_t}}$$

A_s, n_s, α_s, A_t, n_t are measurable and related to the shape of the inflaton potential

$r \equiv A_t/A_s$ determines the energy scale

Incredible progress with CMB



Line is fit to a flat ΛCDM cosmology model with just six parameters:

$\Omega_b h^2$, $\Omega_m h^2$, A_s, τ, n_s, Ω_Λ

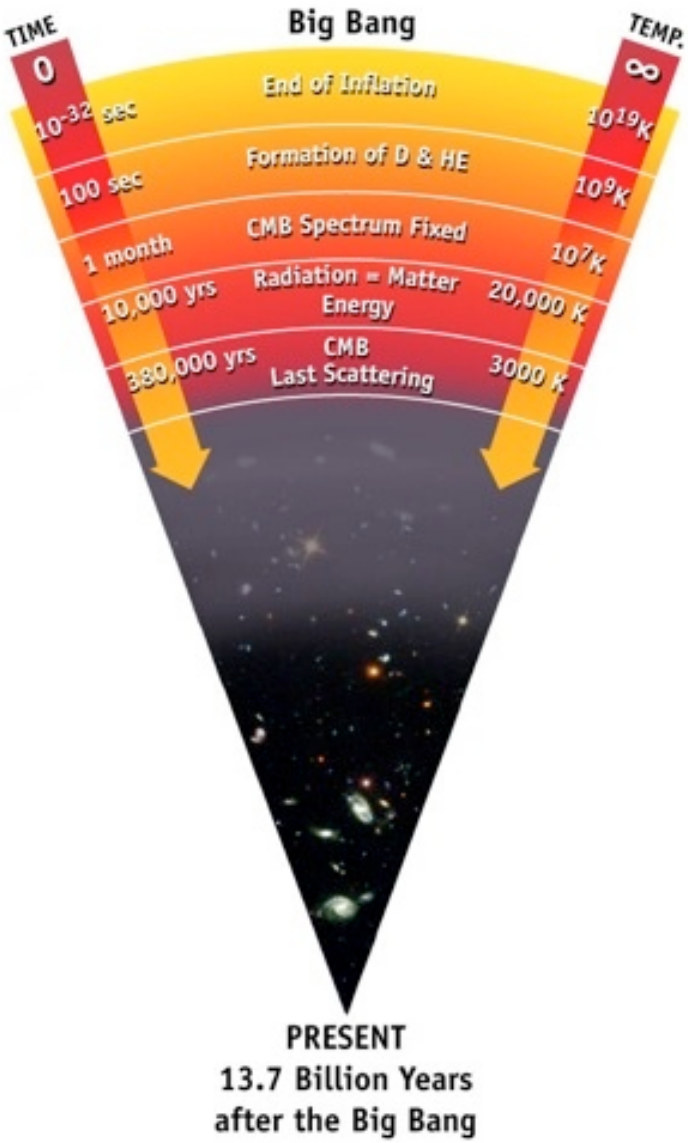
- ***Inflation (flat, n_s)***
- ***Non-baryonic dark matter (3rd peak)***
- ***Dark Energy***

Komatsu et al., arXiv:1001:4538; Larson et al., arXiv:1001.4635

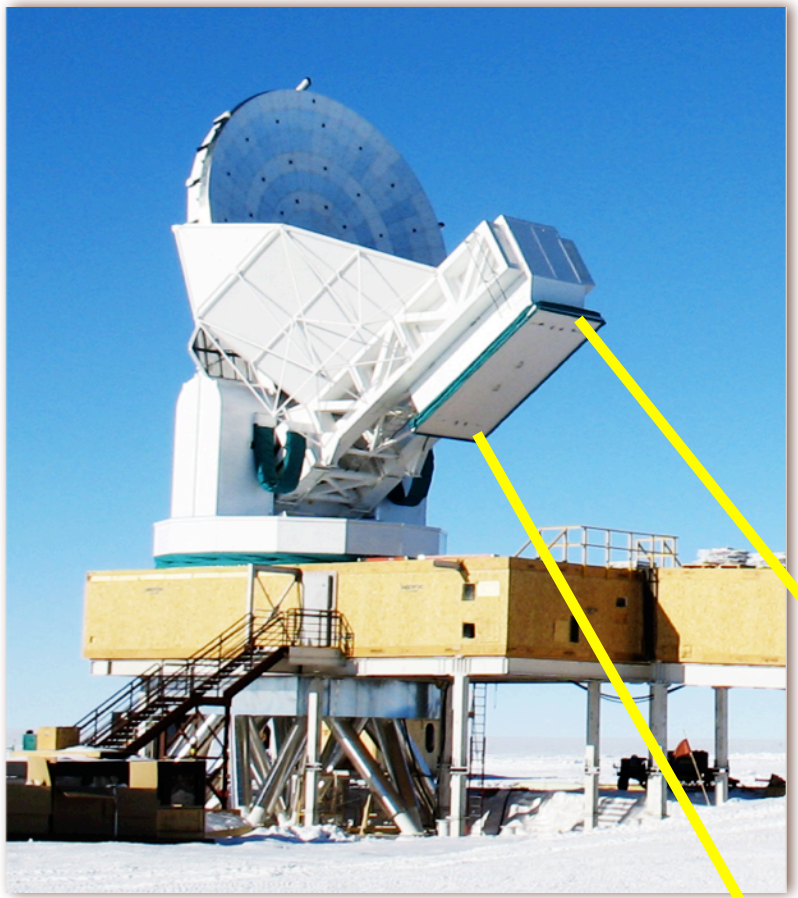
What's next?

Much more fundamental physics remains to be extracted from the CMB

- From intrinsic CMB temperature variations on the sky, especially on small angular scales.
- From small scale distortions to the CMB as it passes through the universe. Evolution of the universe. *Dark Energy*
- From polarization patterns imprinted by gravitational waves generated in the first instants of the universe. *Inflation*

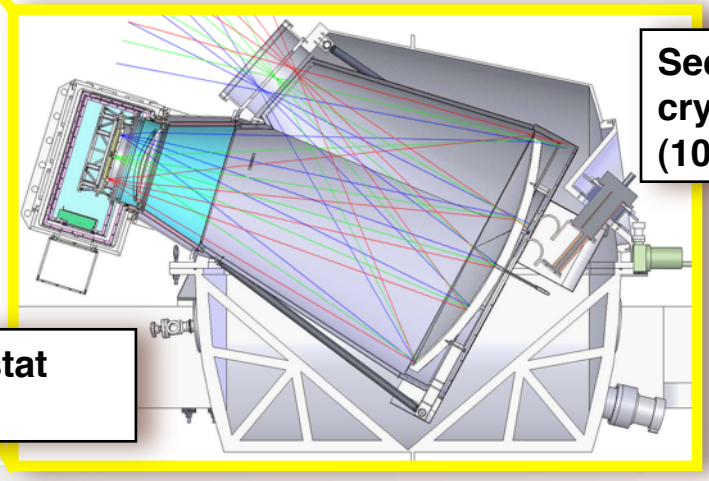


The 10 meter South Pole Telescope

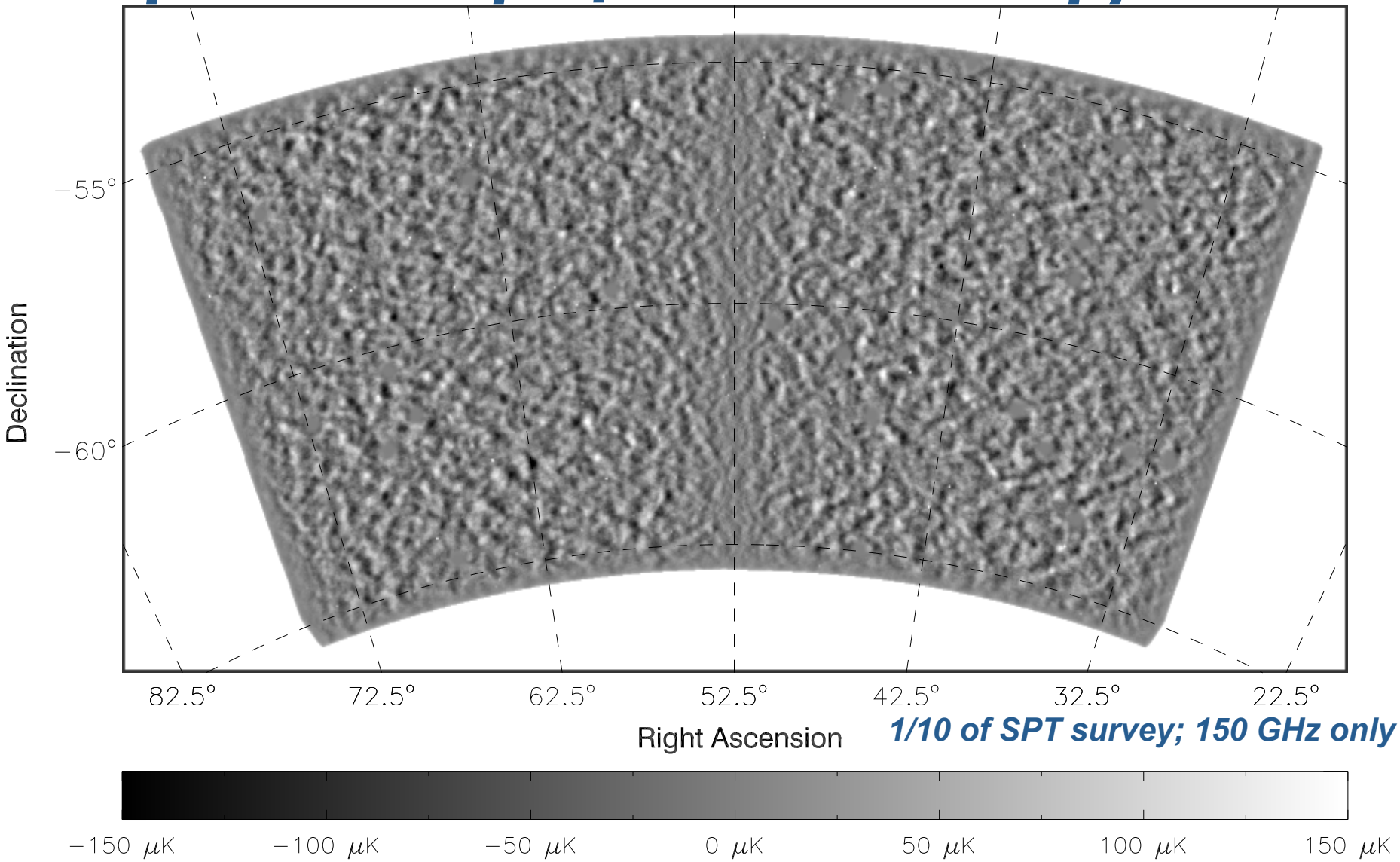


Some Key Features:

- 1 arcmin resolution at 150 GHz
- 1 deg FOV, unblocked optics
- 960 feedhorn coupled detectors
- Observe in 3+ bands 90, 150 & 220 GHz simultaneously with a modular focal plane
- Site: fantastic atmospheric transparency and stability, 24/7/52 observing

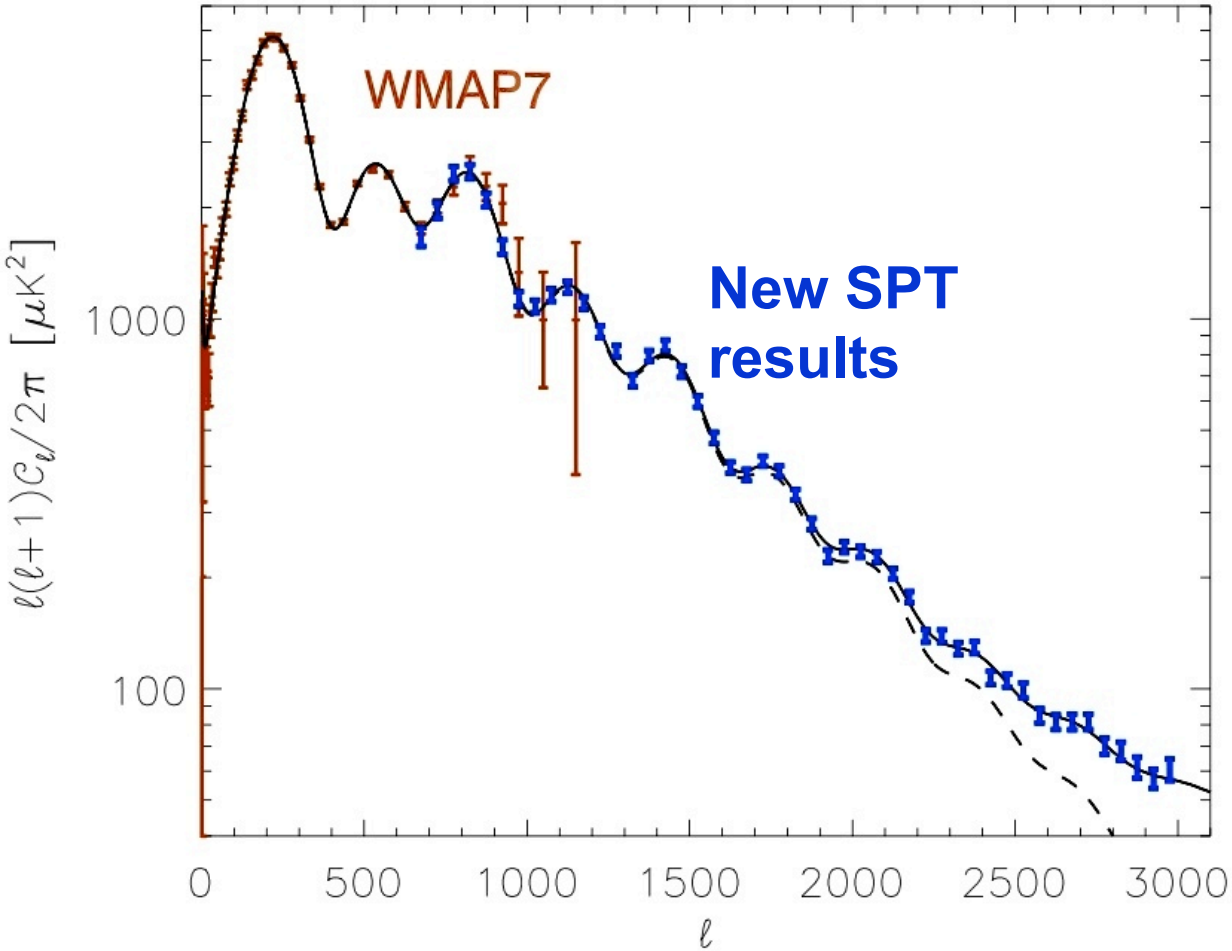


Sample SPT map of CMB anisotropy



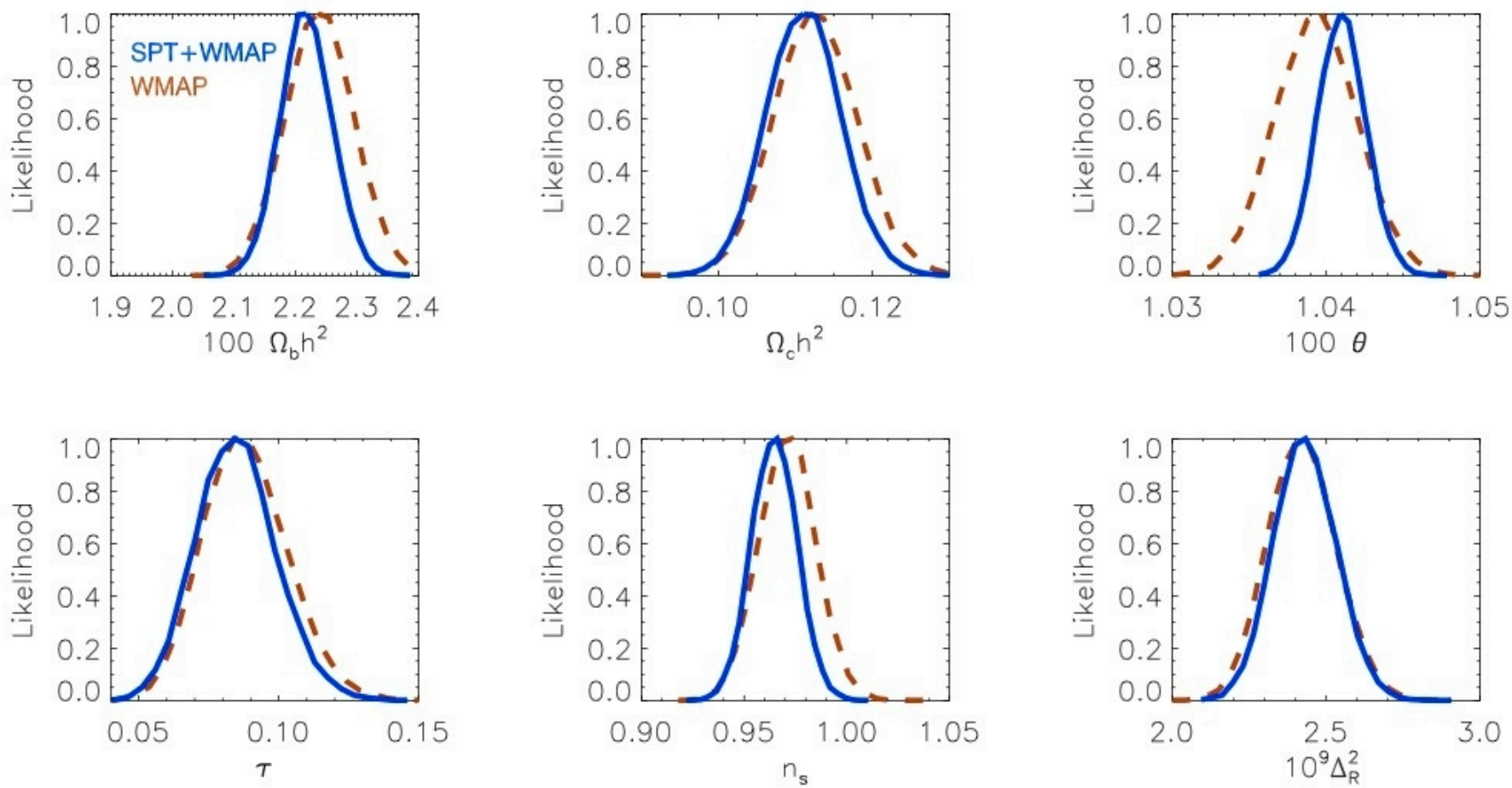
1/10 of SPT survey; 150 GHz only

Recent SPT results



Keisler et al., arXiv:1105.3182

SPT and WMAP give consistent values for standard ΛCDM 6-parameters, so we fit jointly.



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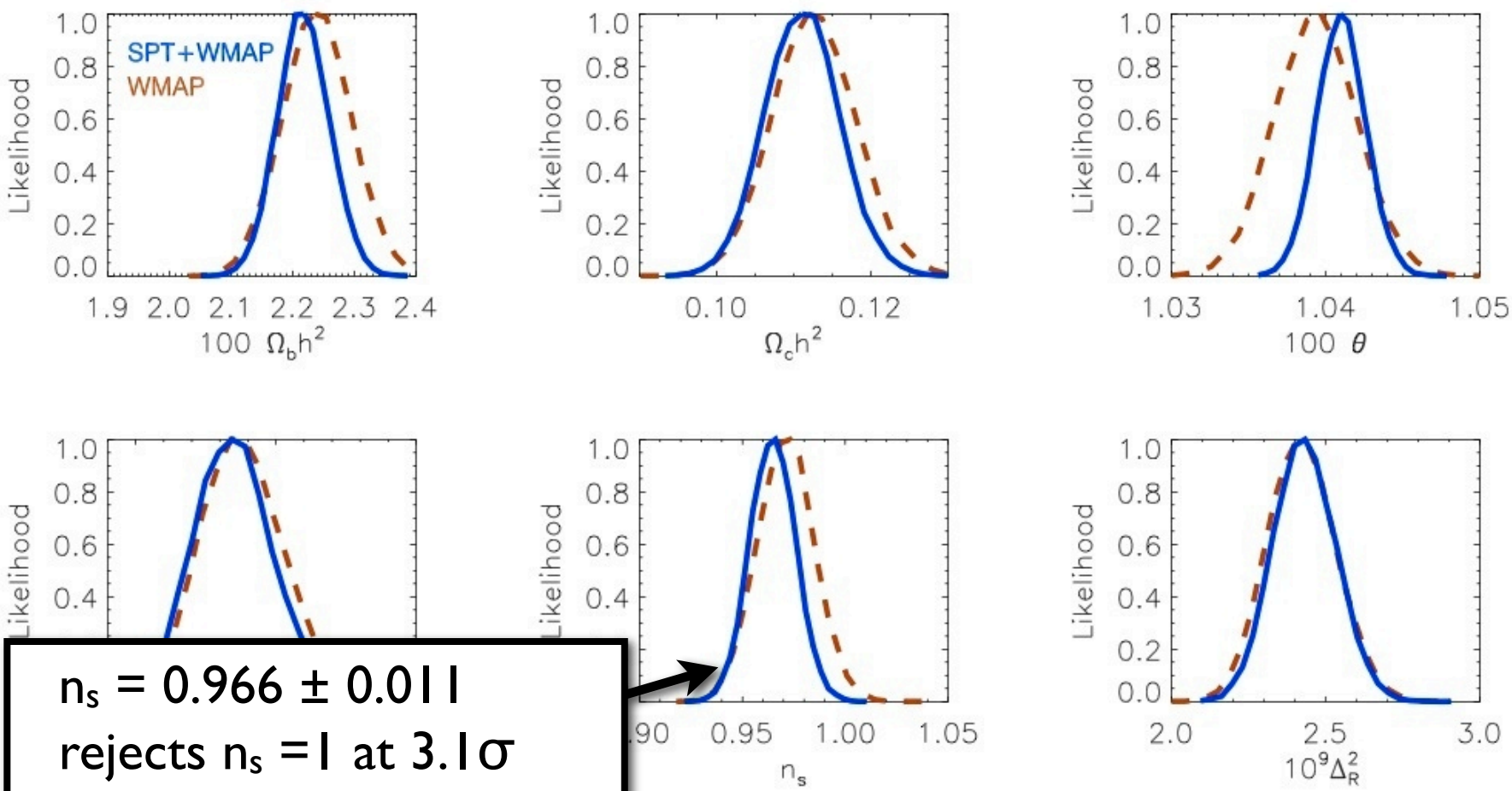


$n_s = 0.966 \pm 0.011$

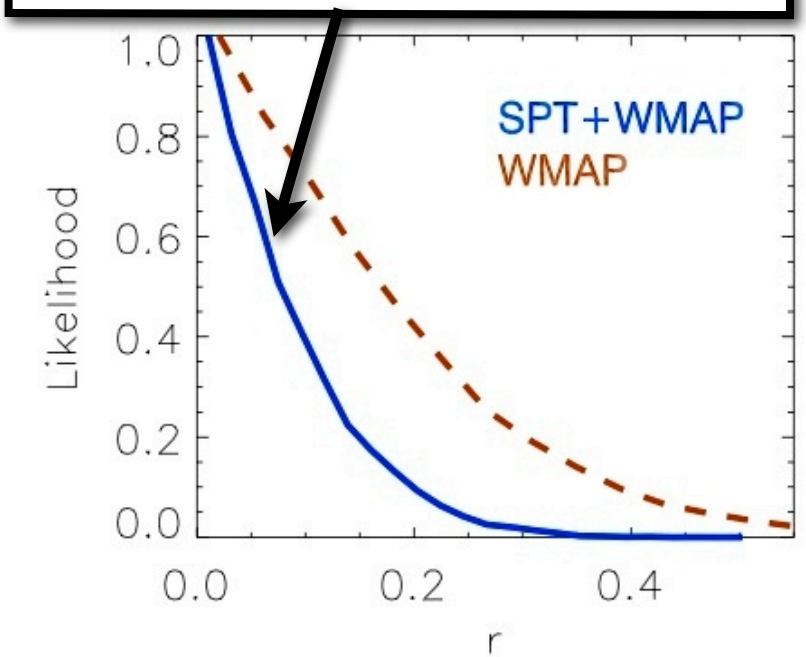
rejects $n_s = 1$ at 3.1σ

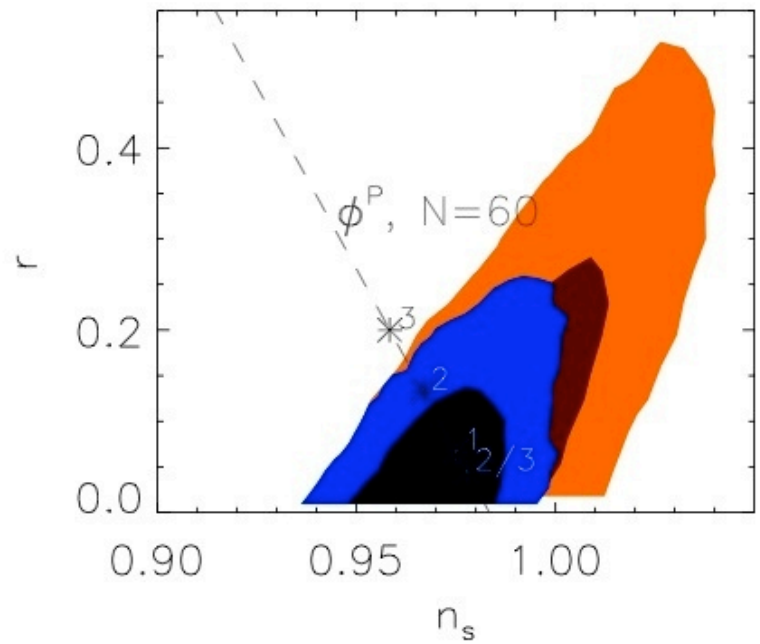
(at 3.6 σ with Ho and BAO included)

Going beyond the 6 ΛCDM parameters: fitting an additional parameter

Improved limit to tensor perturbations

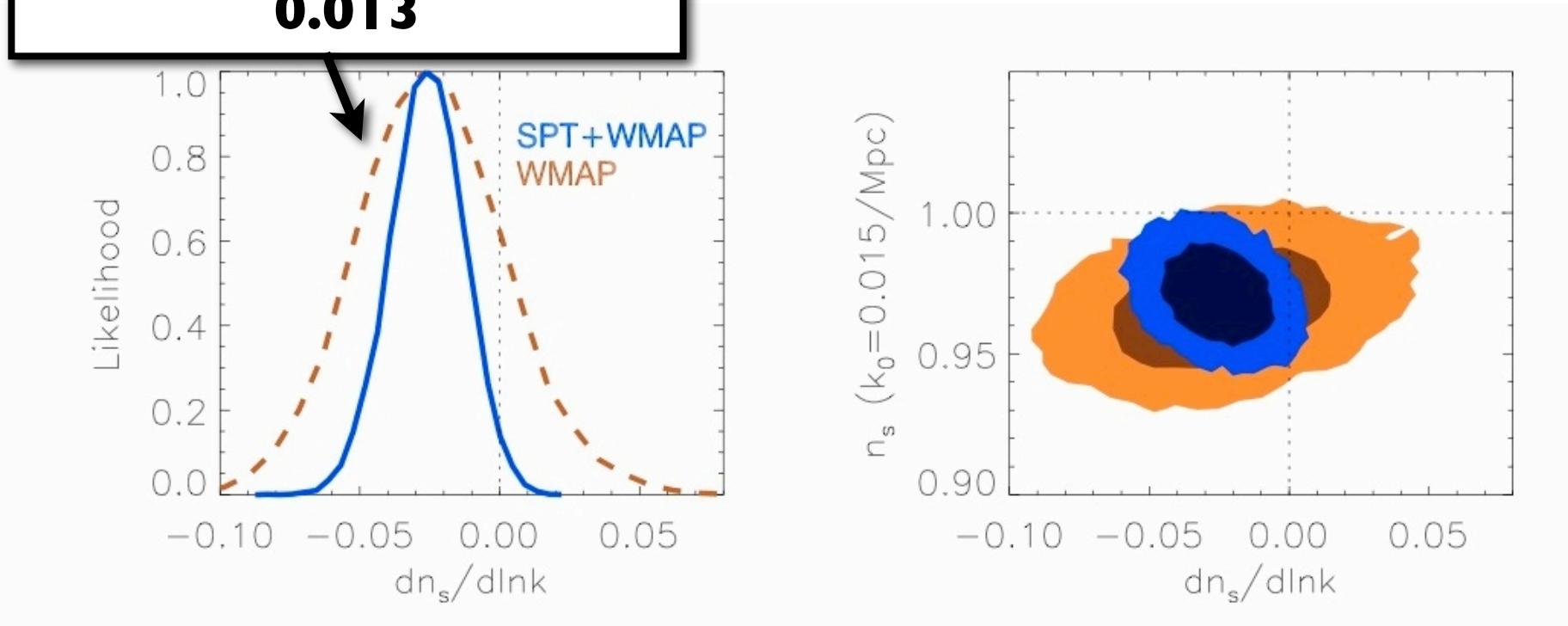
r < 0.21 at 95% CL
(r < 0.17 with Ho and BAO included)



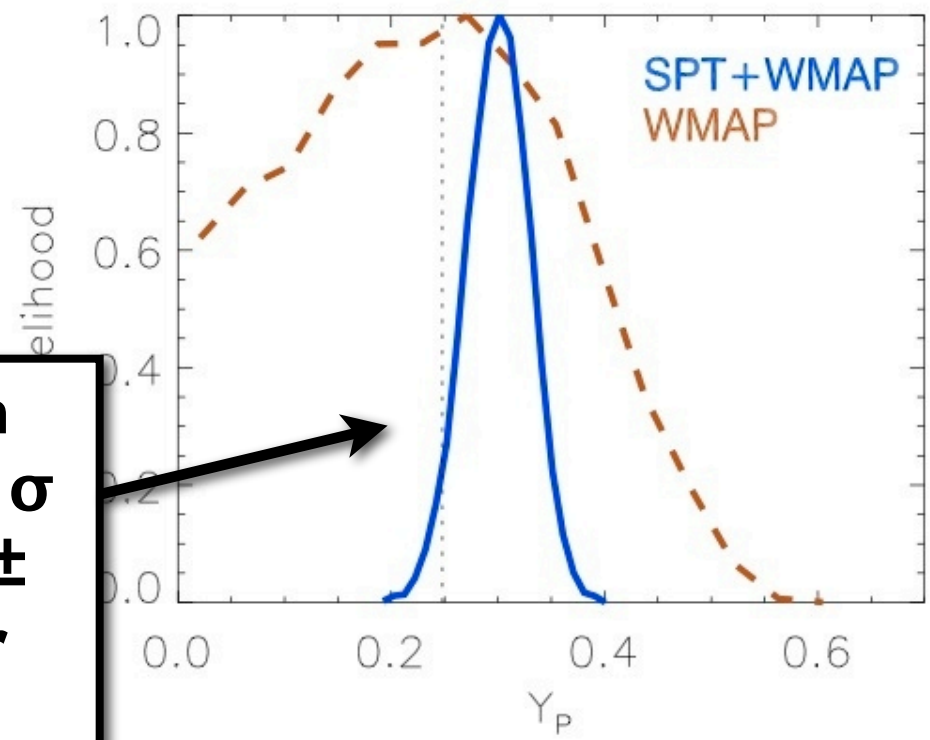


Running of the spectral index?

$dn_s/d\ln k = -0.024 \pm 0.013$

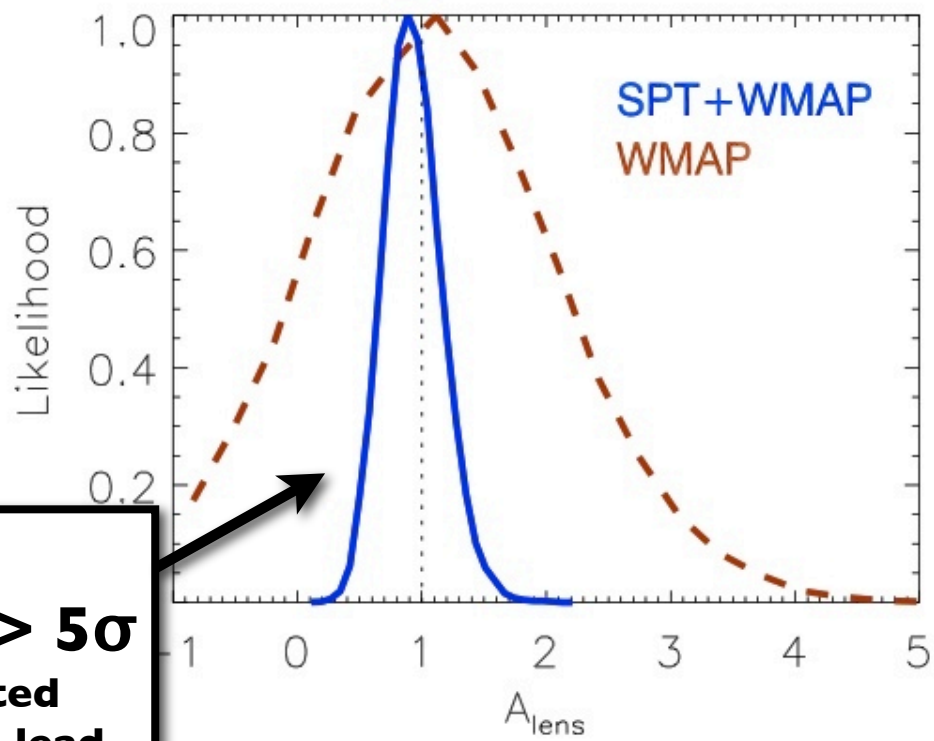


Primordial Helium abundance



Primordial Helium $Y_P = 0$ rejected at 8 σ prefers $Y_P = 0.300 \pm 0.030$ (1.6σ higher than BBN)

Strong detection of gravitational lensing



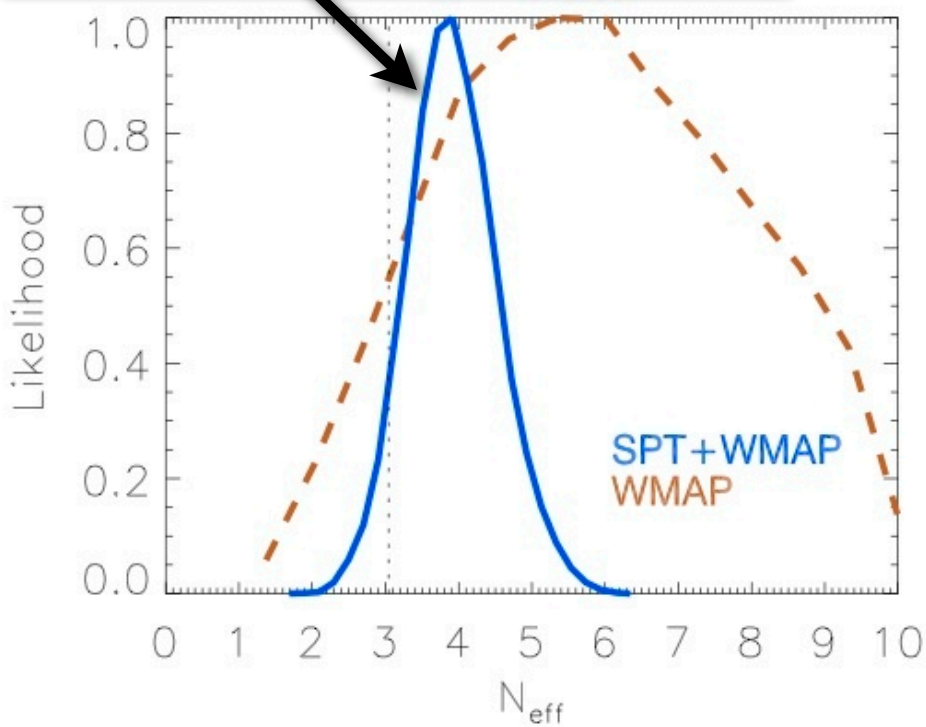
A_{lens} = 0.94 ± 0.15

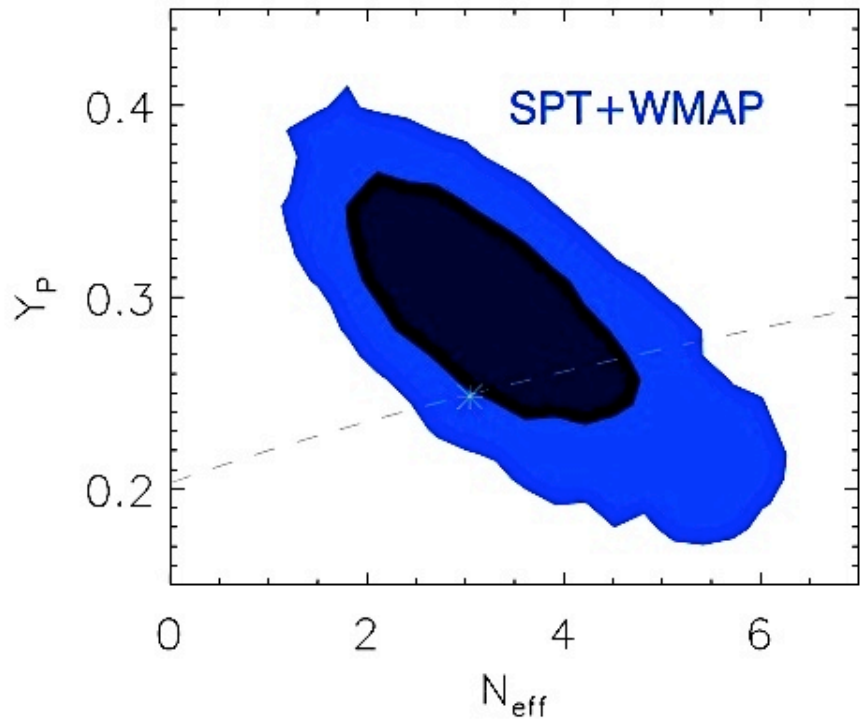
rejects no lensing at > 5σ

(Much higher s/n in reconstructed potential power spectrum. Will lead to Σm_ν. VanEngelen in prep.)

Number of relativistic species, N_{eff}

N_{eff} = 3.87 ± 0.61
rejects N_{eff} = 0 at 7.5σ
(N_{eff} = 3.85 ± 0.44 with H_o and BAO)





To understand CMB sensitivity to N_{eff}, see Hou et al., arXiv: 1104.2333

Additional neutrinos?

Adding cluster abundance constraint on σ_8 pushes N_{eff} closer to 3

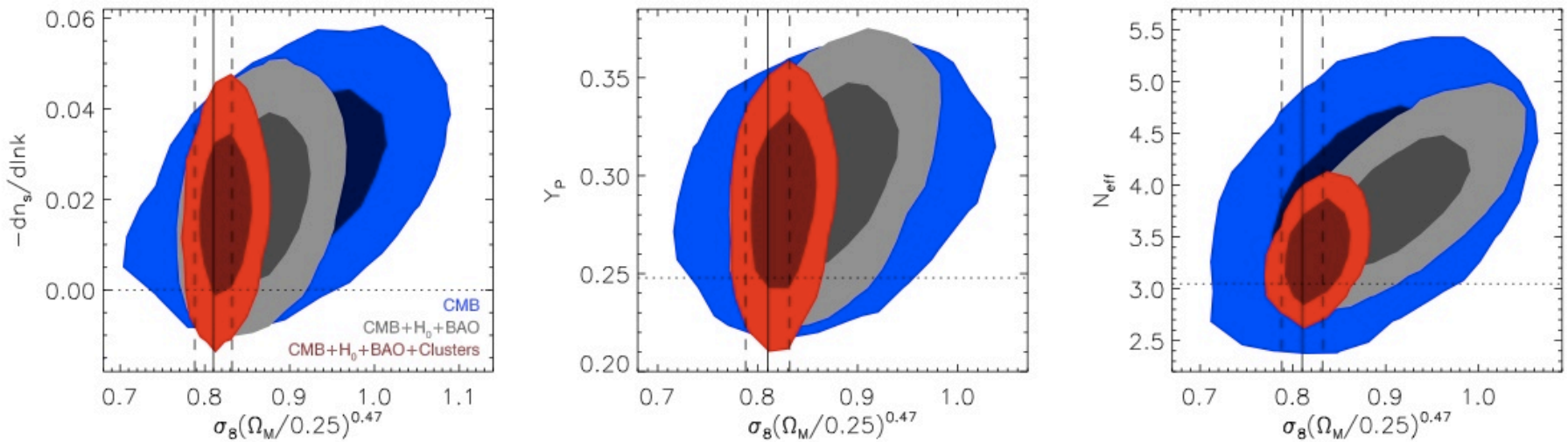
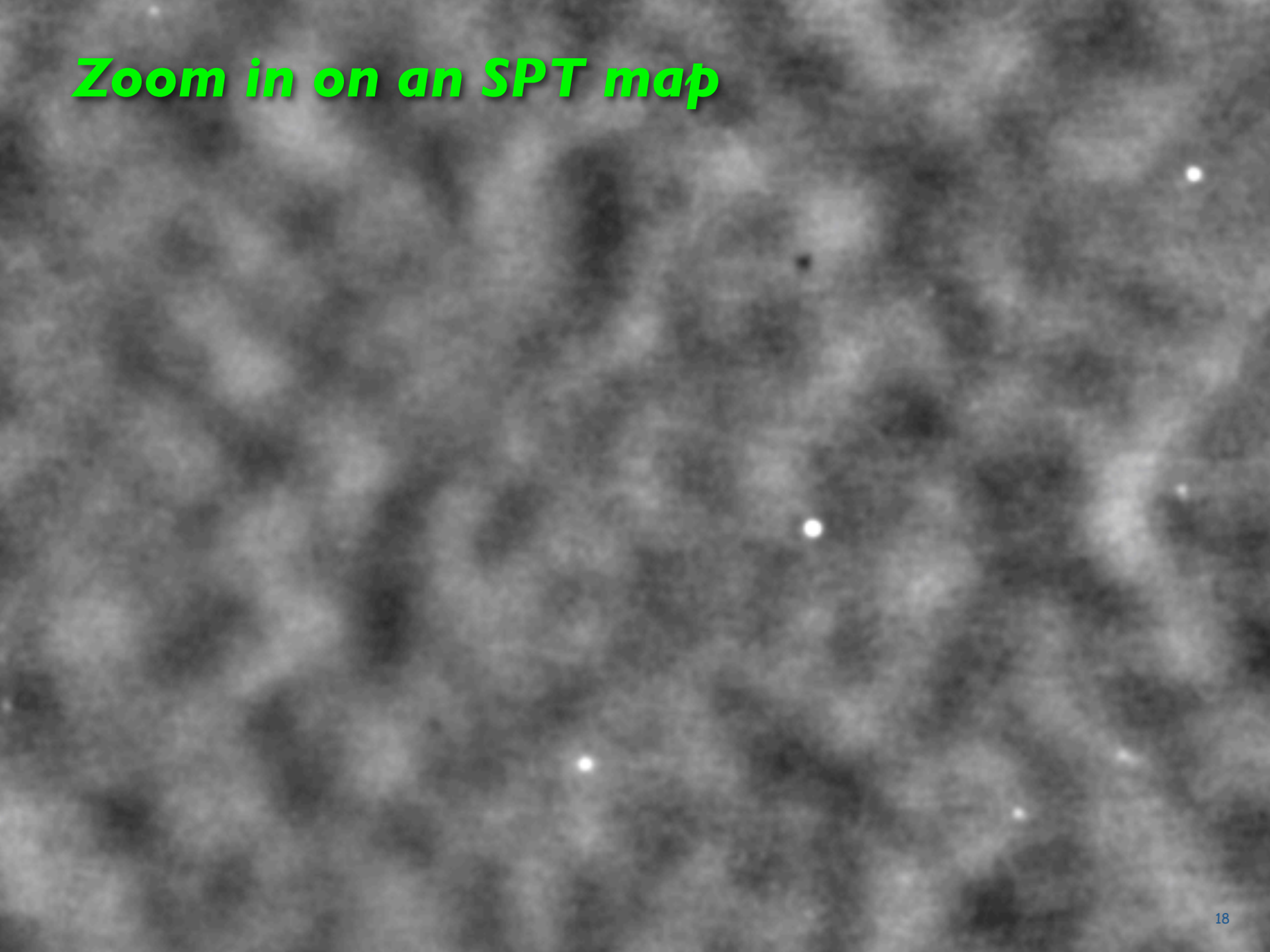


FIG. 14.— The two-dimensional marginalized constraint on spectral running, primordial helium, or the effective number of relativistic species versus the combination $\sigma_8(\Omega_M/0.25)^{0.47}$, which is well constrained by the cluster abundance measurement of Vikhlinin et al. (2009). "CMB" corresponds to SPT+WMAP7. The constraint on $\sigma_8(\Omega_M/0.25)^{0.47}$ from the clusters and the corresponding 1σ uncertainties are shown by the vertical lines. The standard values of the spectral running, primordial helium, and the effective number of relativistic species are shown by the dotted horizontal lines. Adding the cluster abundance information moves the constraints on these parameters closer to their standard values.

Zoom in on an SPT map



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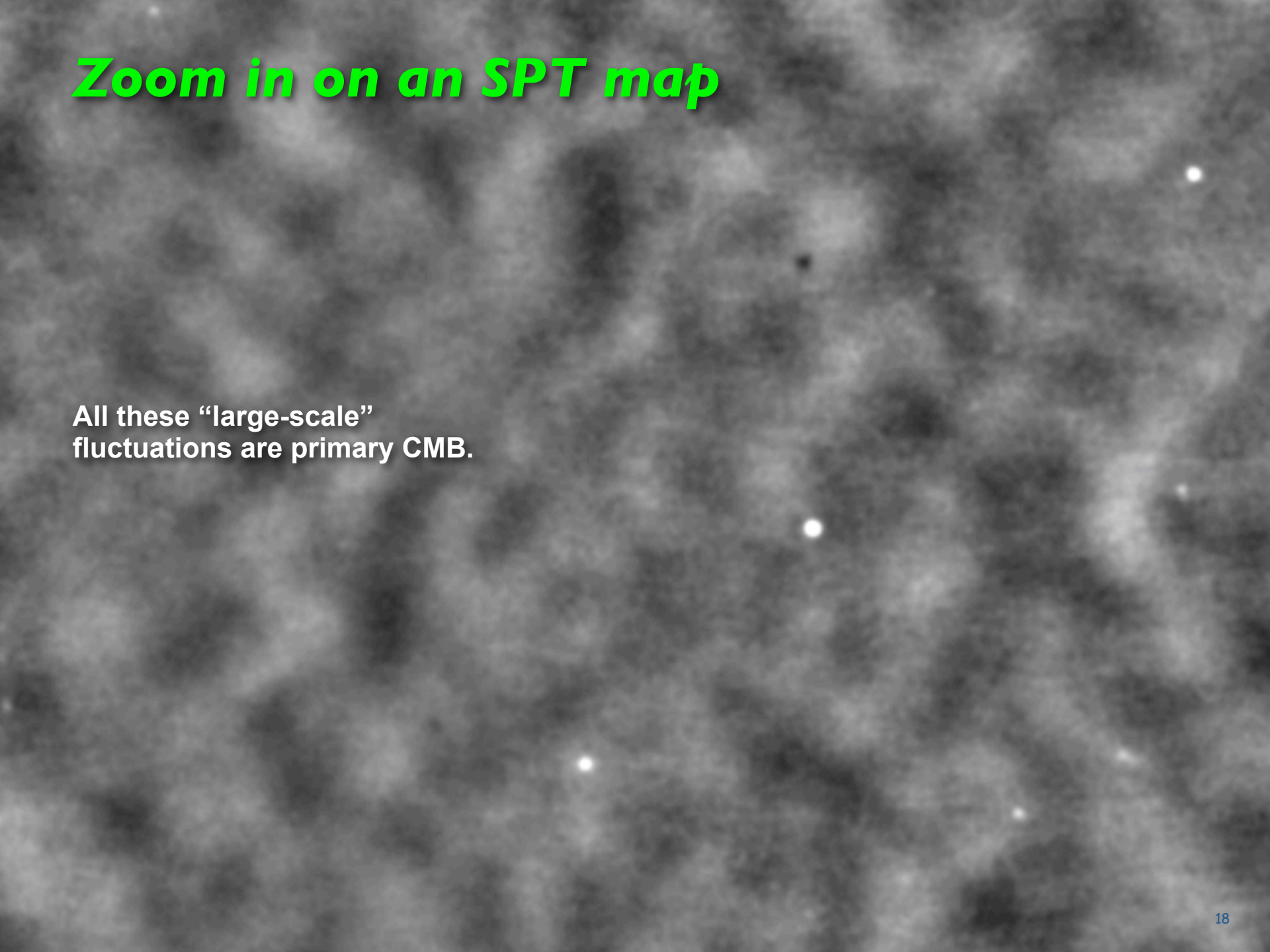
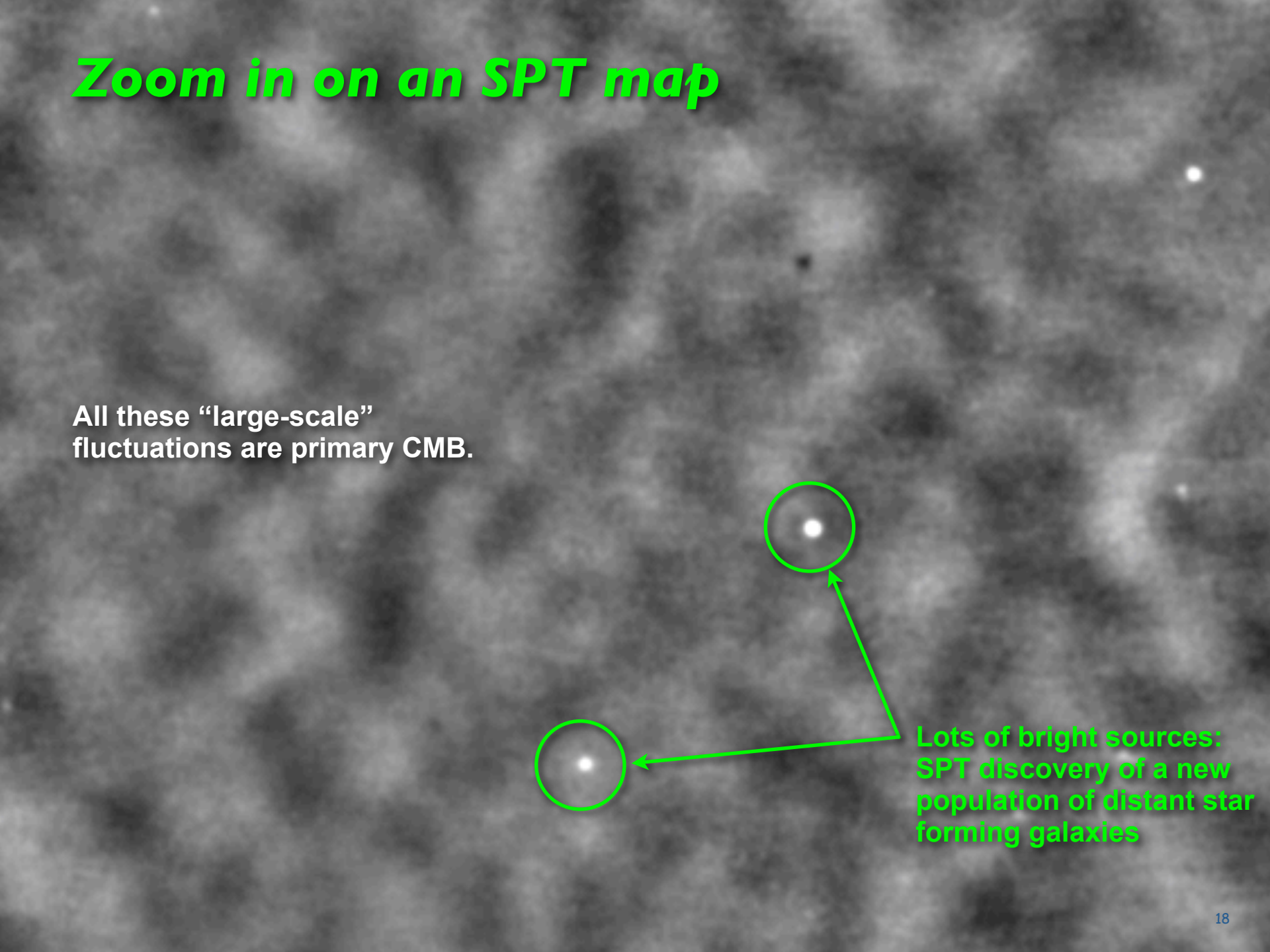
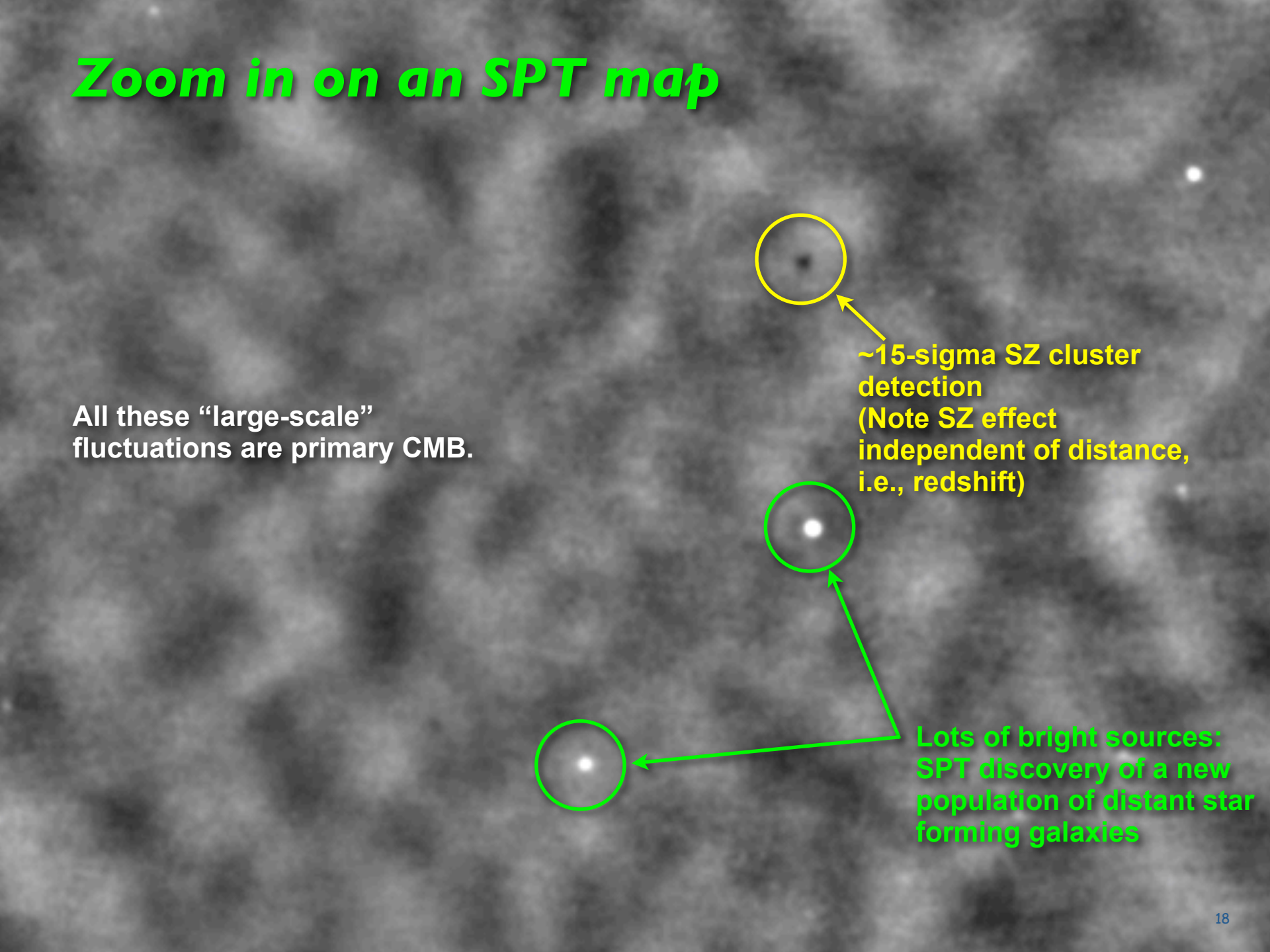


All these “large-scale” fluctuations are primary CMB.

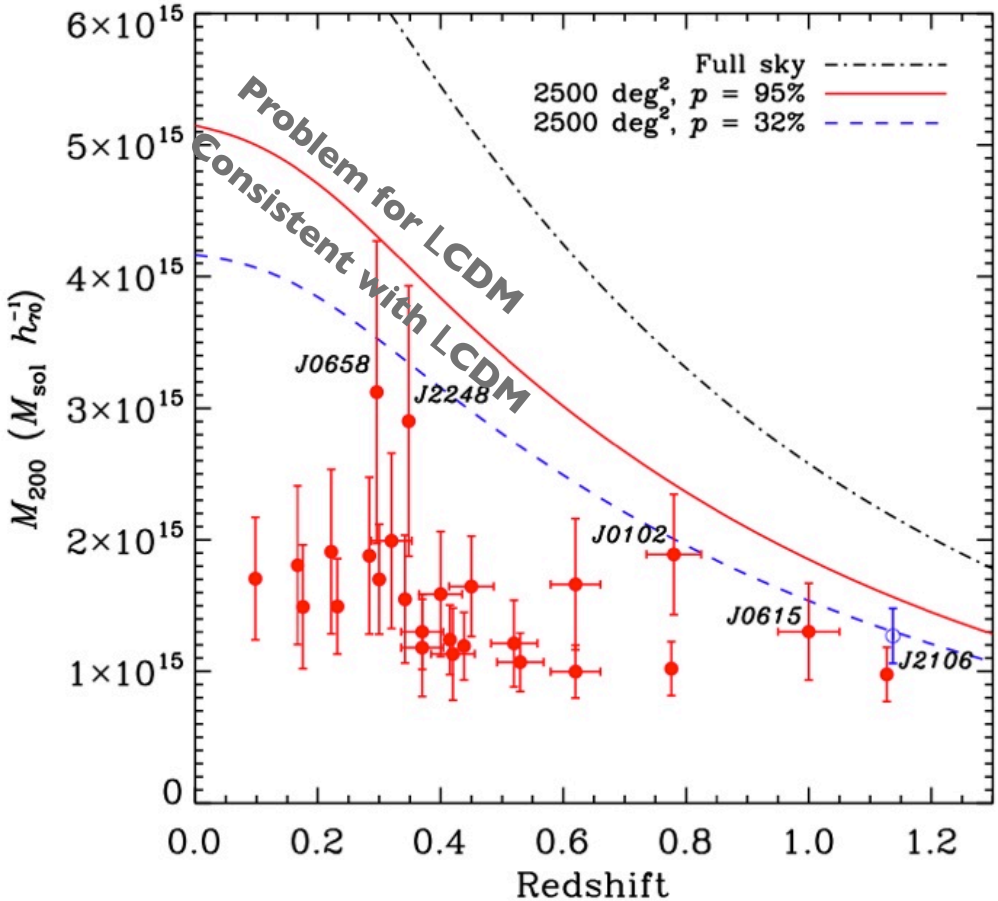
Zoom in on an SPT map



Zoom in on an SPT map



Tests of ΛCDM and Non-Gaussianity



Most massive clusters over the full 2500 deg^2 SPT survey.

(from all redshifts)

- **Probes the extreme tail of the matter power spectrum.**
- **Even a single massive cluster could indicate tension with ΛCDM (Mortonson, Hu, Huterer 2010).**

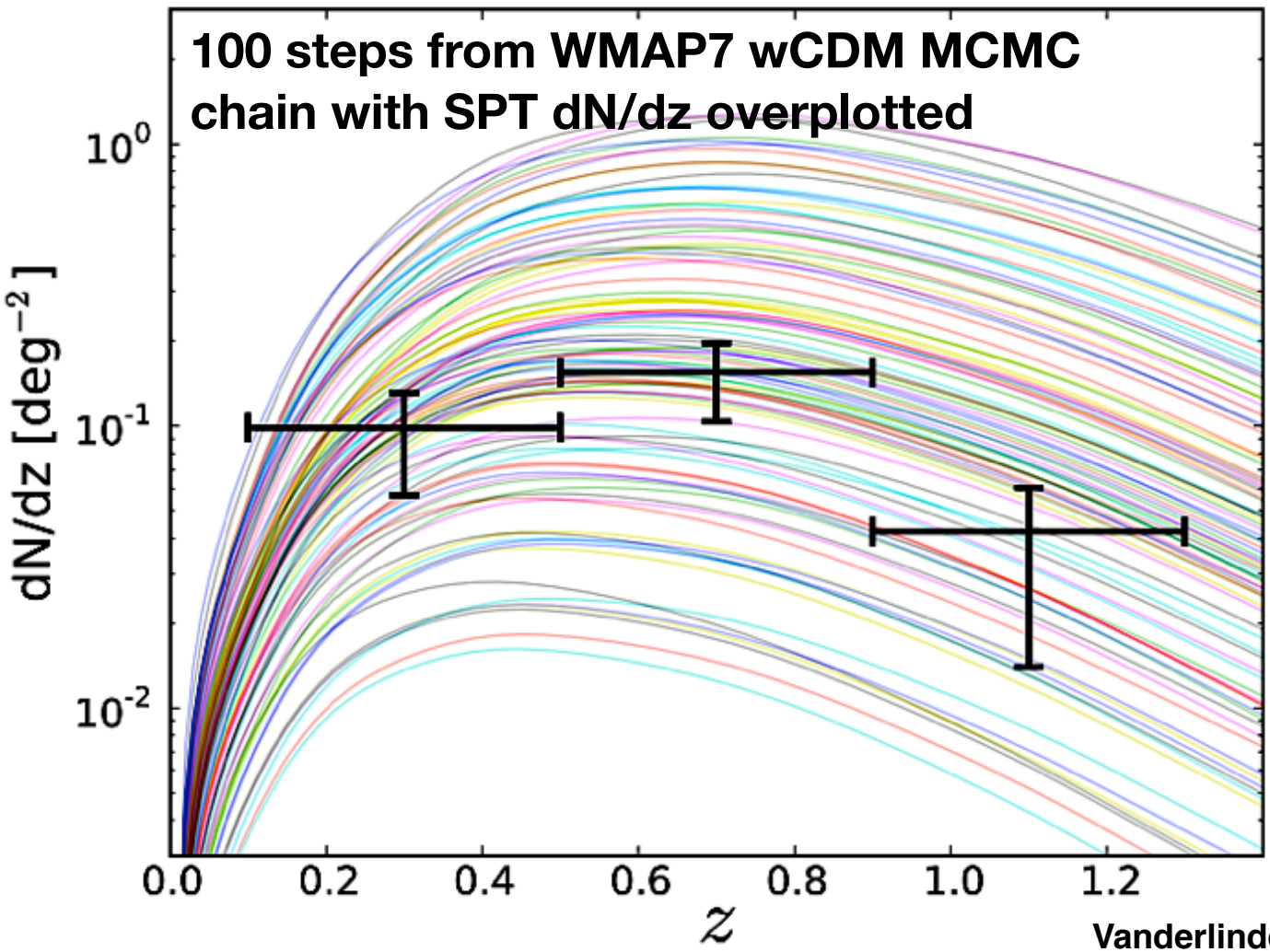
We find:

- **7% chance of finding J2106**
- **consistent with ΛCDM and Gaussian initial density fluctuations**

Williamson et al 2011, arXiv:1101.1290

First step to Dark Energy

Using <u>only first 8%</u> of survey to constrain cosmology.



Vanderlinde et al 2010

First step to Dark Energy

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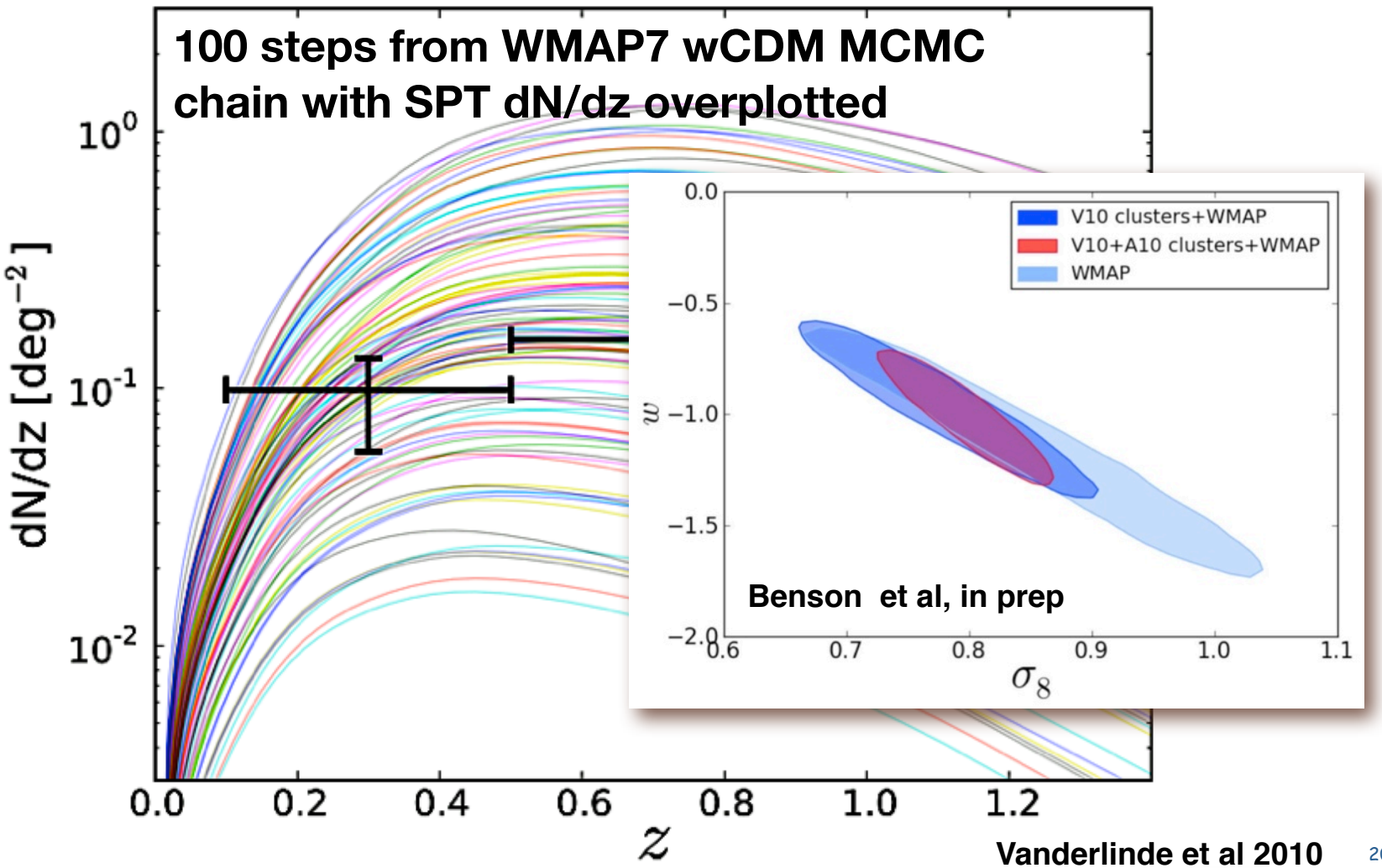

Vanderlinde et al 2010

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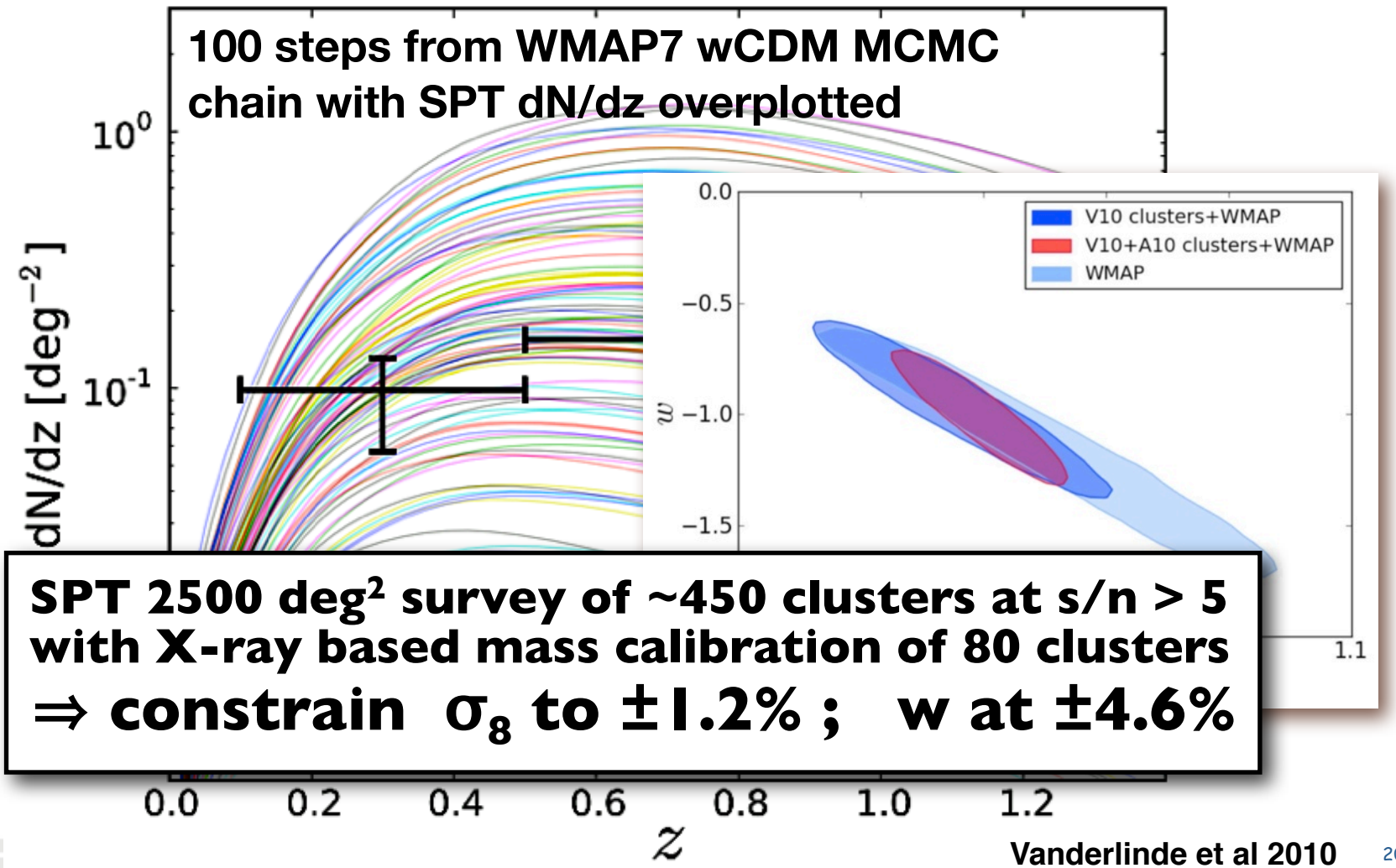


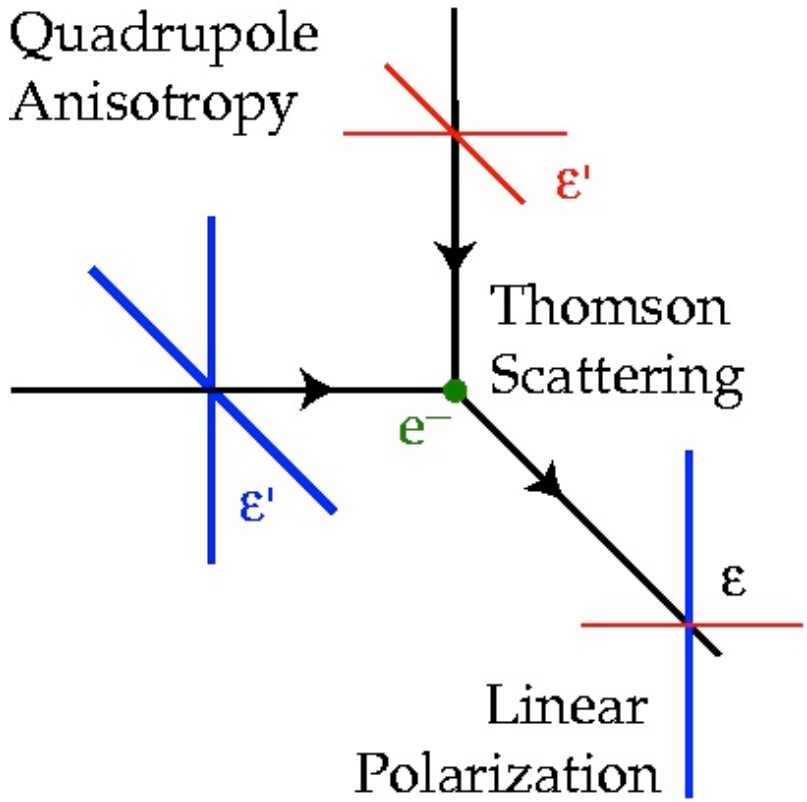
SPT 2500 deg^2 survey of ~450 clusters at s/n > 5 with X-ray based mass calibration of 80 clusters

⇒ constrain σ_8 to ±1.2% ; w at ±4.6%

Vanderlinde et al 2010

Polarization of the CMB

The *CMB must be polarized* due to Thomson scattering



from W. Hu's web page

Polarization of the CMB

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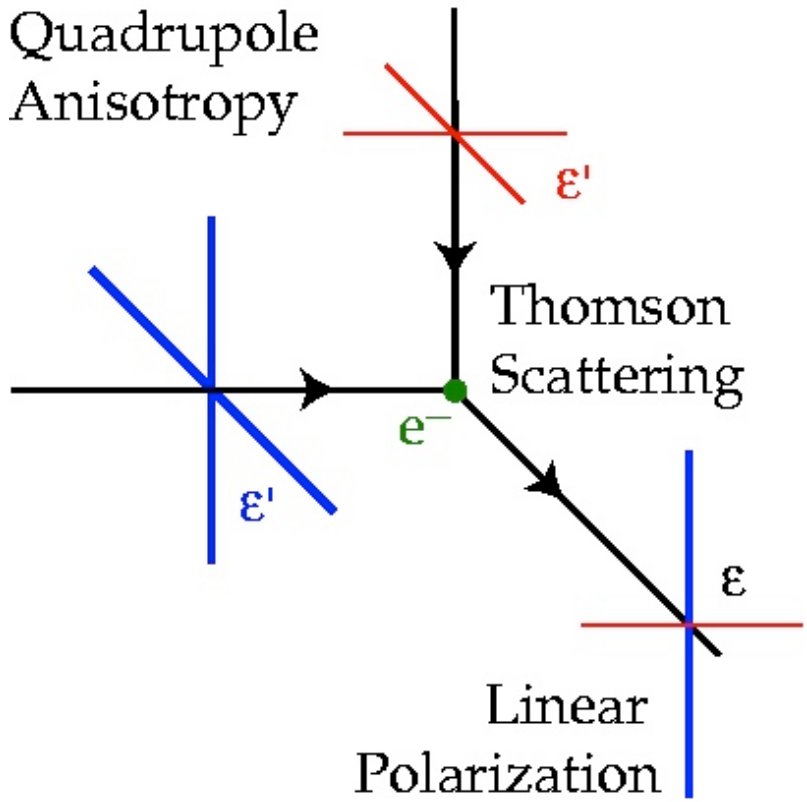

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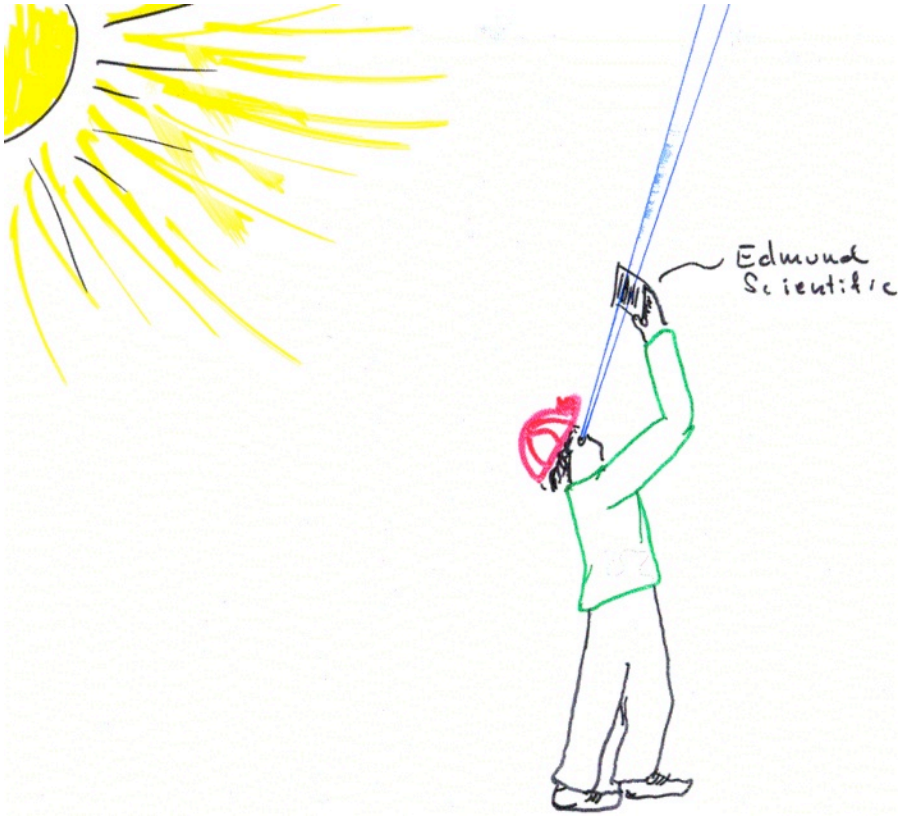
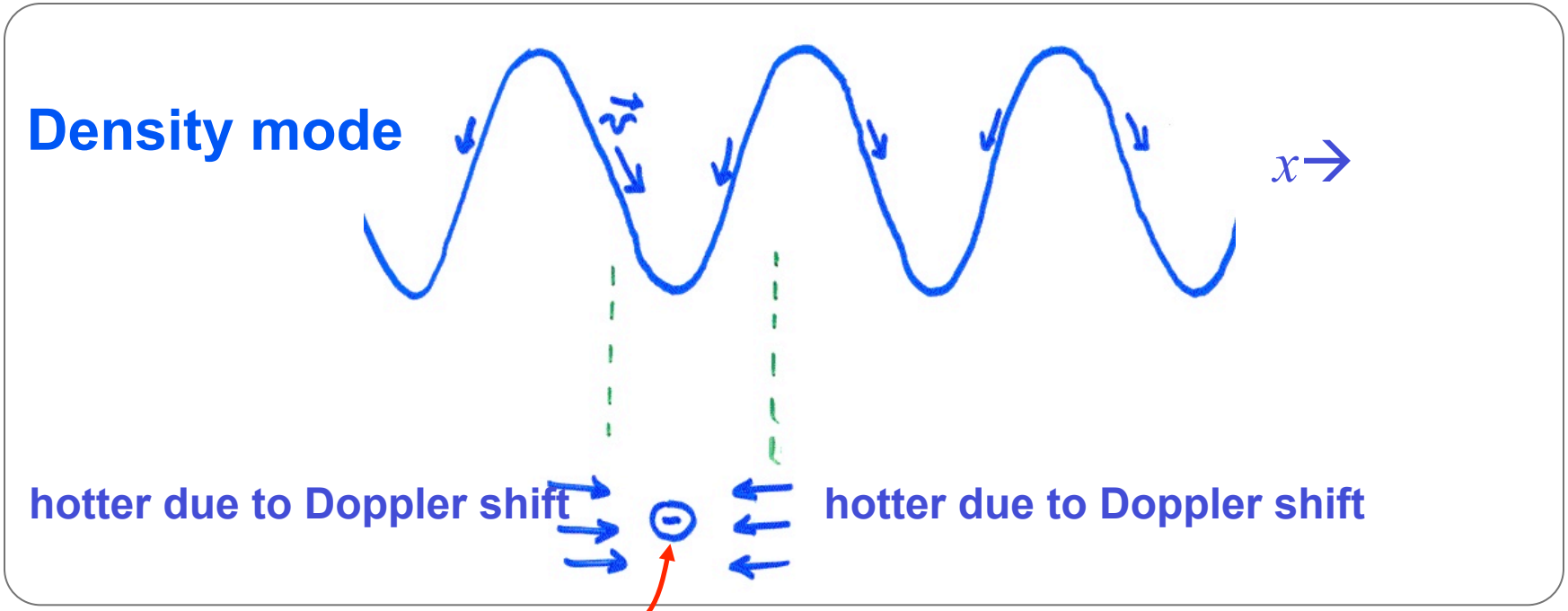


Generating CMB polarization



Before decoupling:

- electron 'sees' only a local monopole

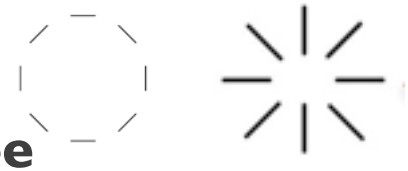
During decoupling:

- mean free path increases and electron 'sees' quadrupole
- scattered light is polarized

E-mode from density modes (scalar fluctuations)

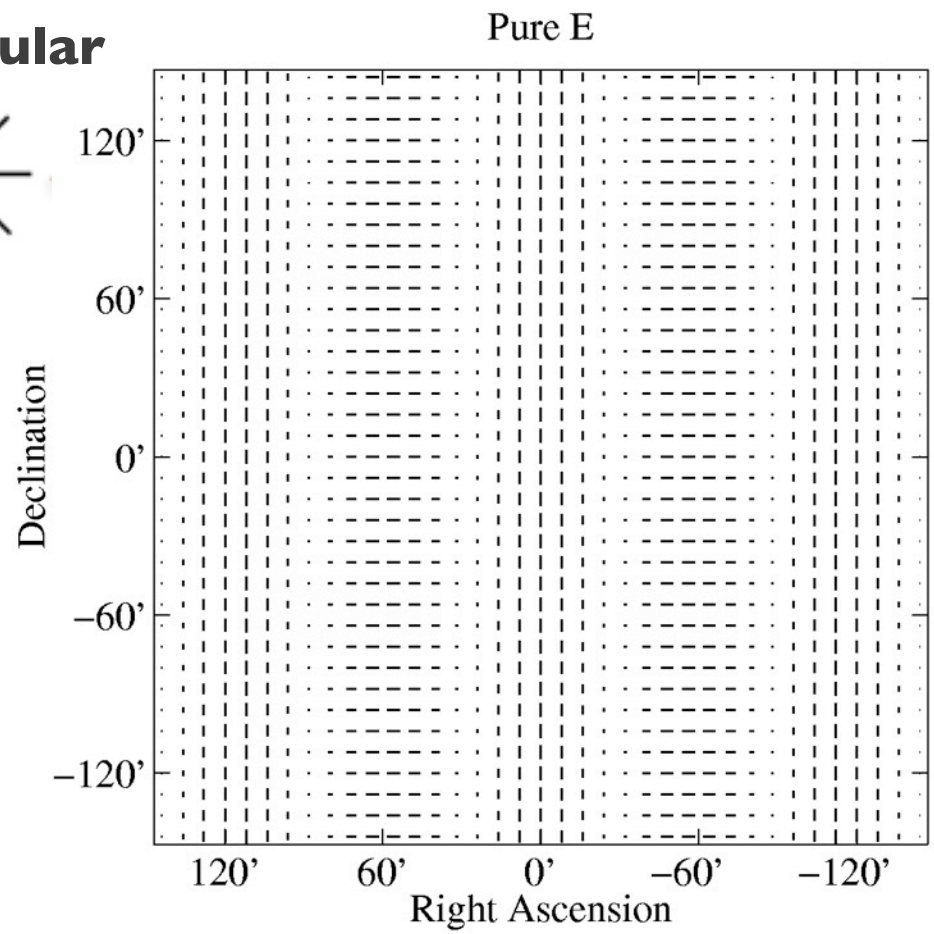
E-mode Polarization (even parity)

Polarization parallel & perpendicular to wave vector

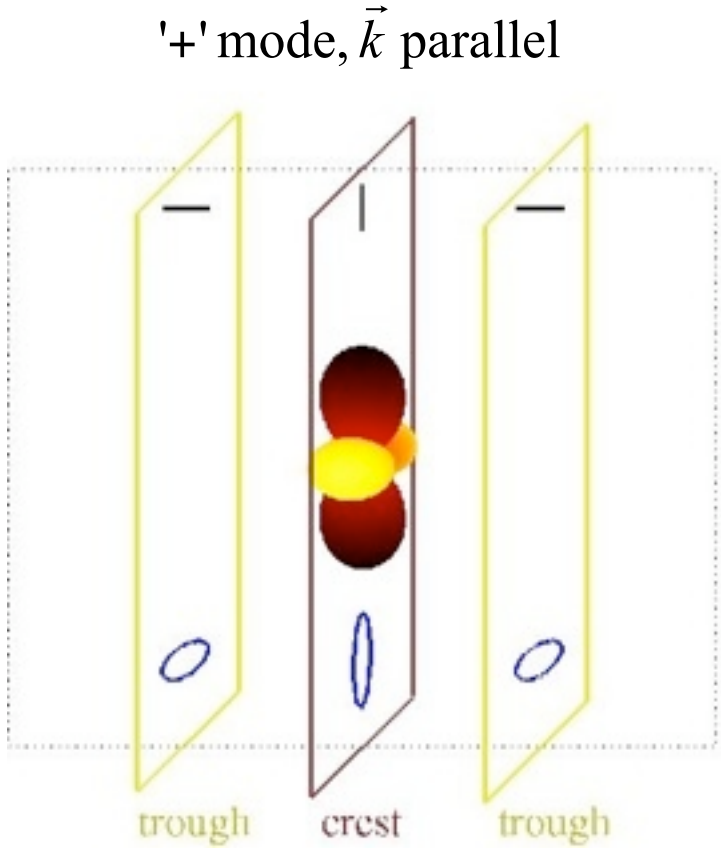


Even parity, curl-free

Density (scalar) fluctuations generate only E-Polarization



Gravitational wave induced CMB polarization

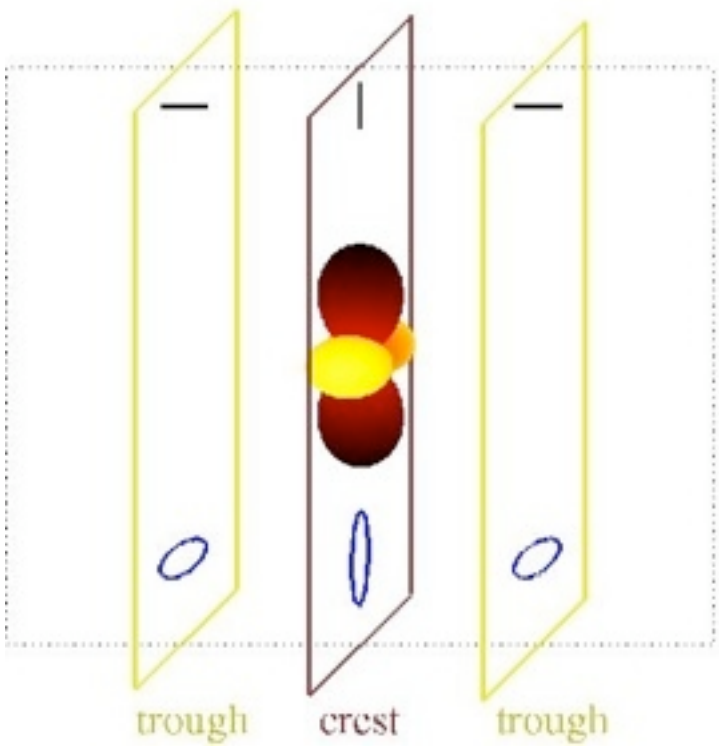


E-mode

Figure from John Kovac's thesis

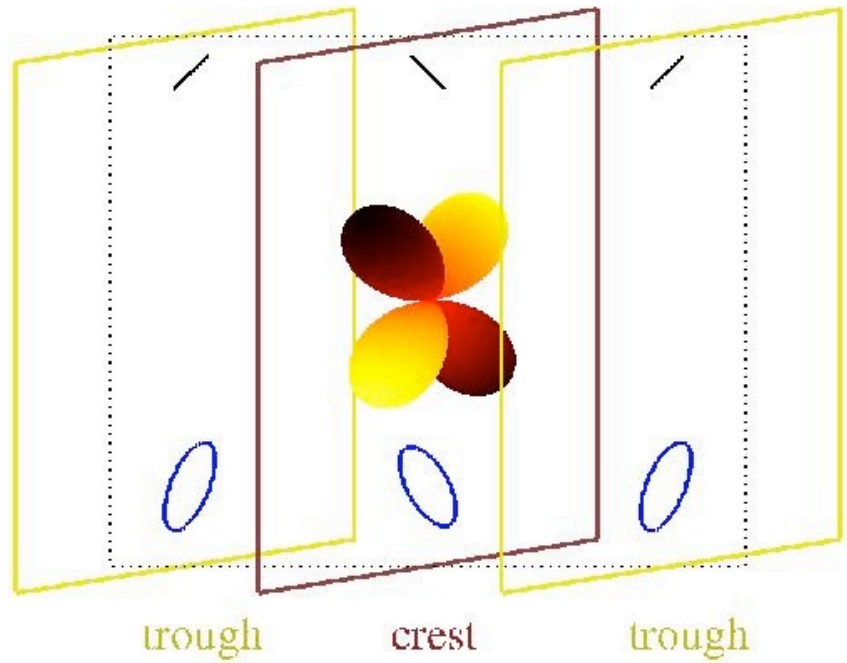
Gravitational wave induced CMB polarization

'+' mode, $\vec{k}$ parallel



E-mode

'×' mode, $\vec{k}$ not parallel



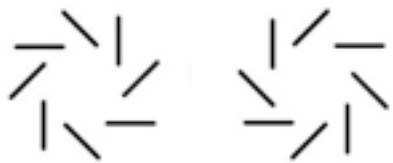
B-mode

(Inflationary GW B-modes)

Figure from John Kovac's thesis

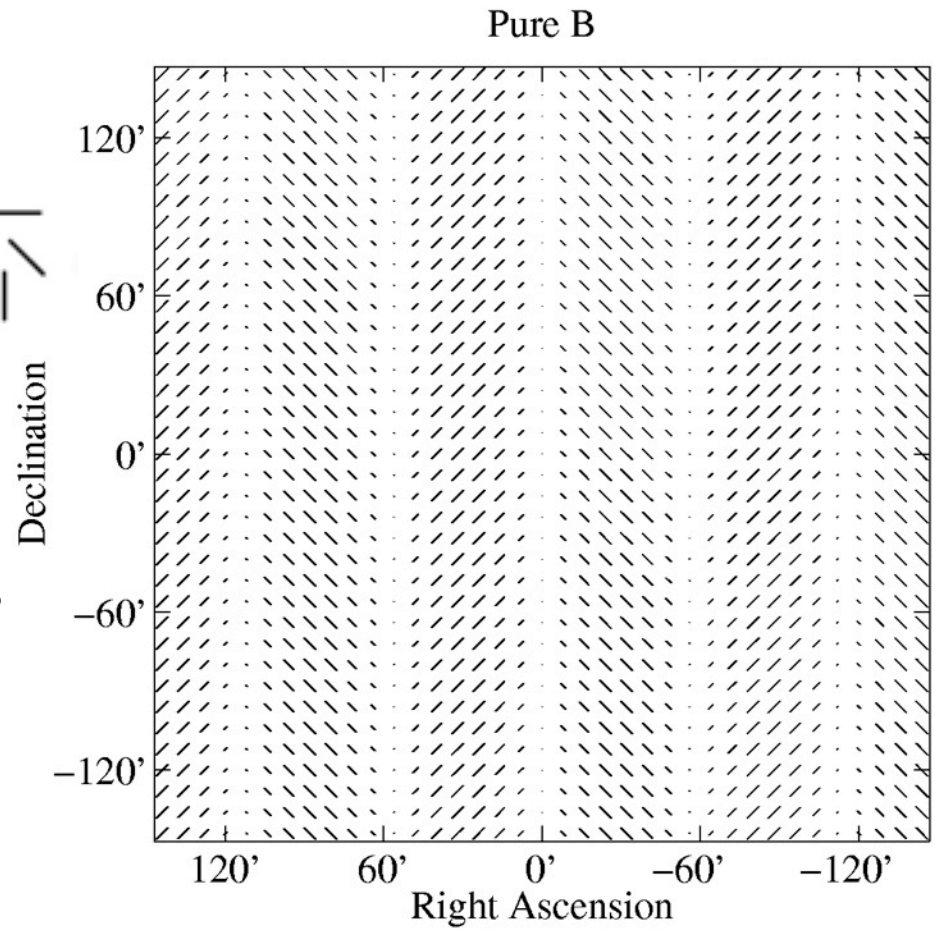
B-mode Polarization (odd parity)

Polarization oriented ±45 degrees to wave vector



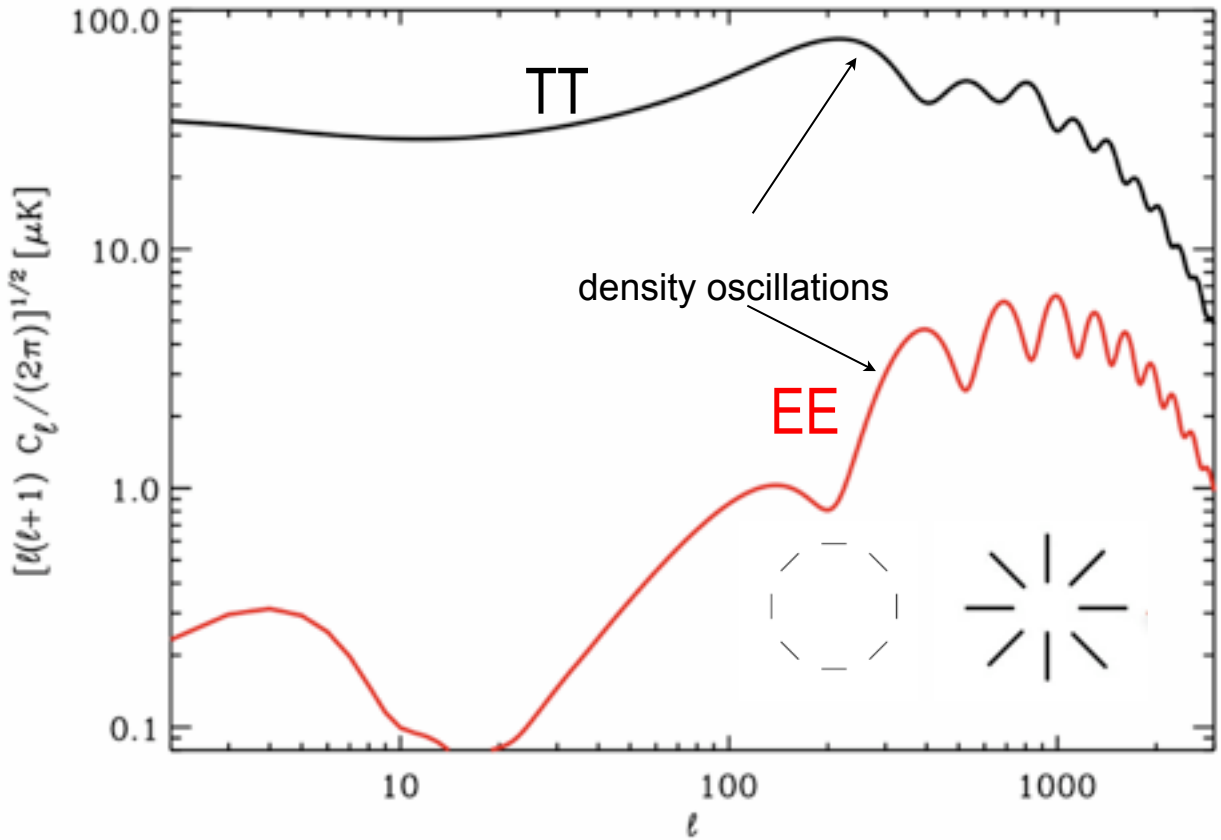
Odd parity, div free

Can NOT be generated by the density fluctuations, but can be generated by gravitational waves sourced by Inflation in the first instants of the universe, 10^{-35} seconds, at GUT energies.



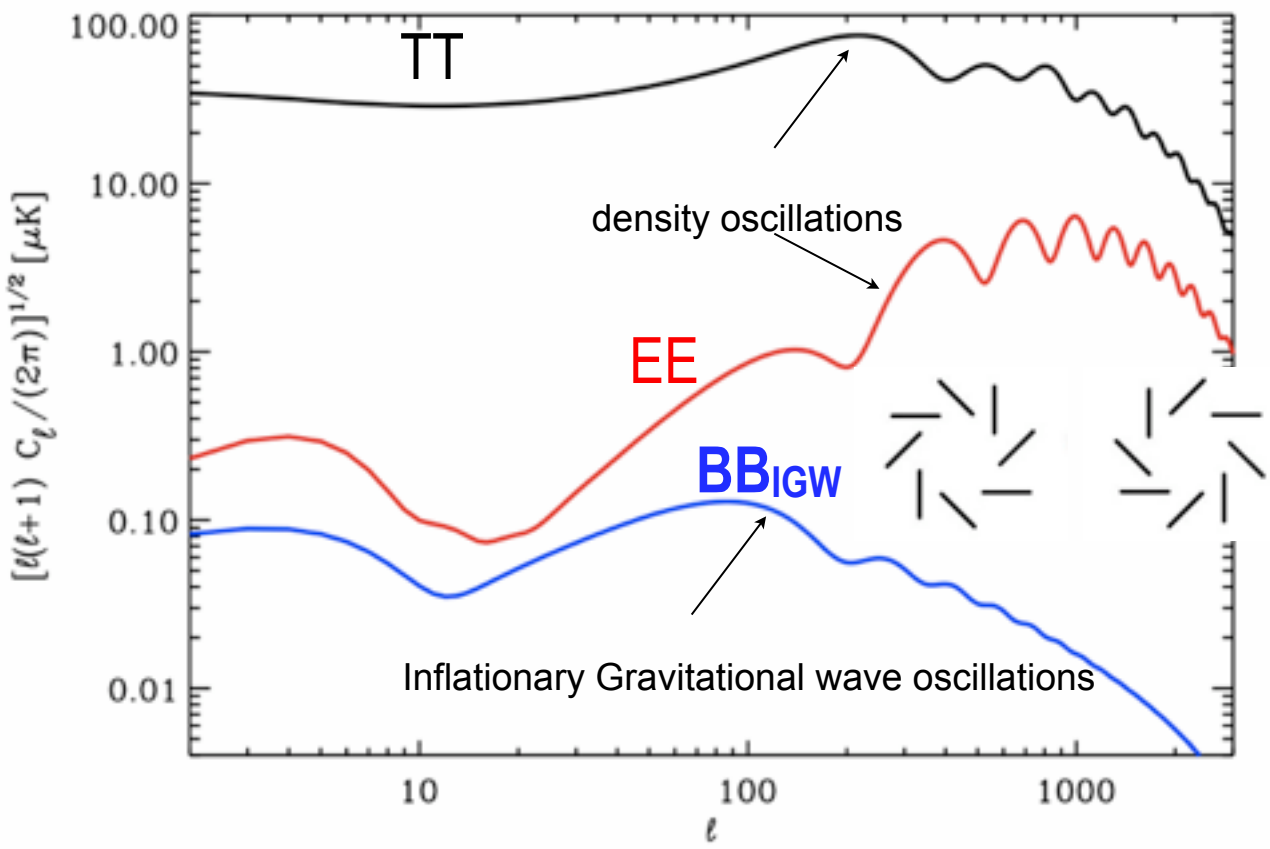
"Smoking gun" test of Inflation and direct measure of its energy scale

CMB polarization

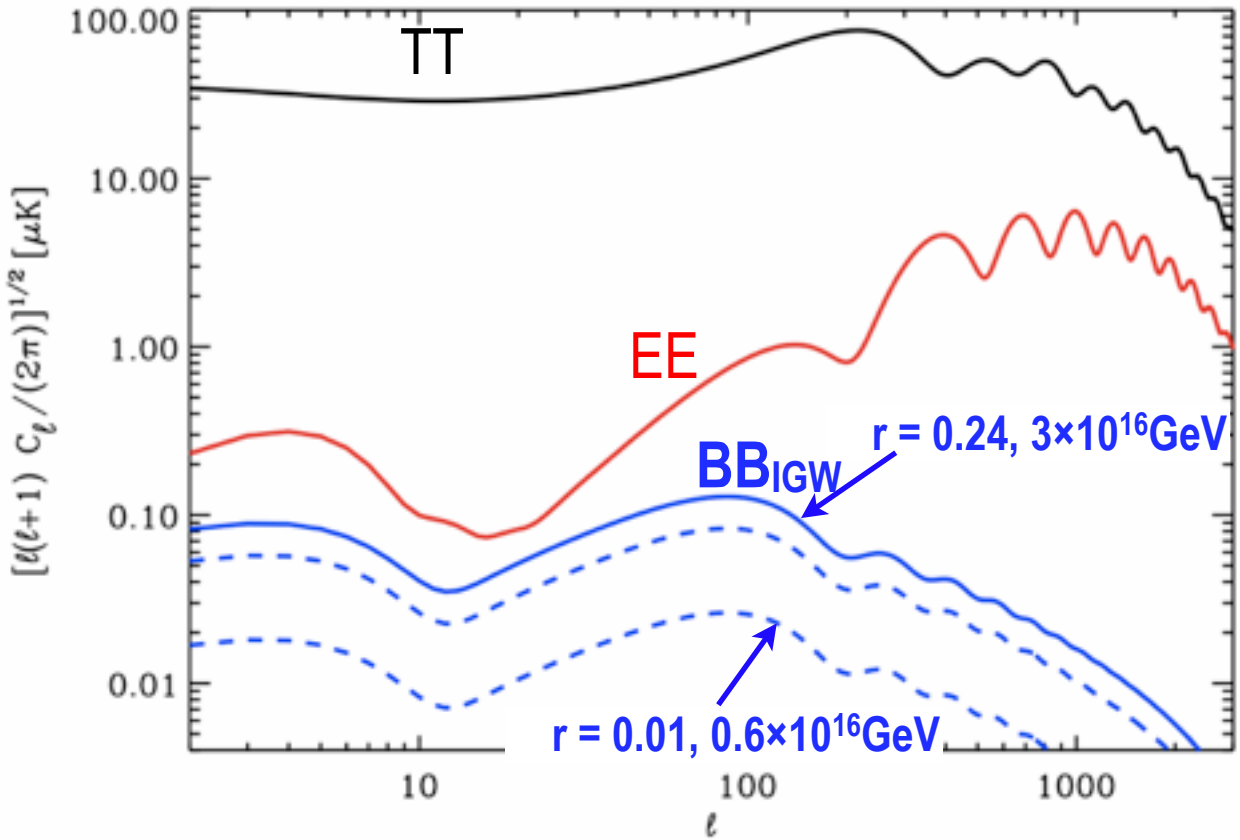


Spectra generated with WMAP7 parameters using CAMB, Lewis and Challinor

CMB polarization

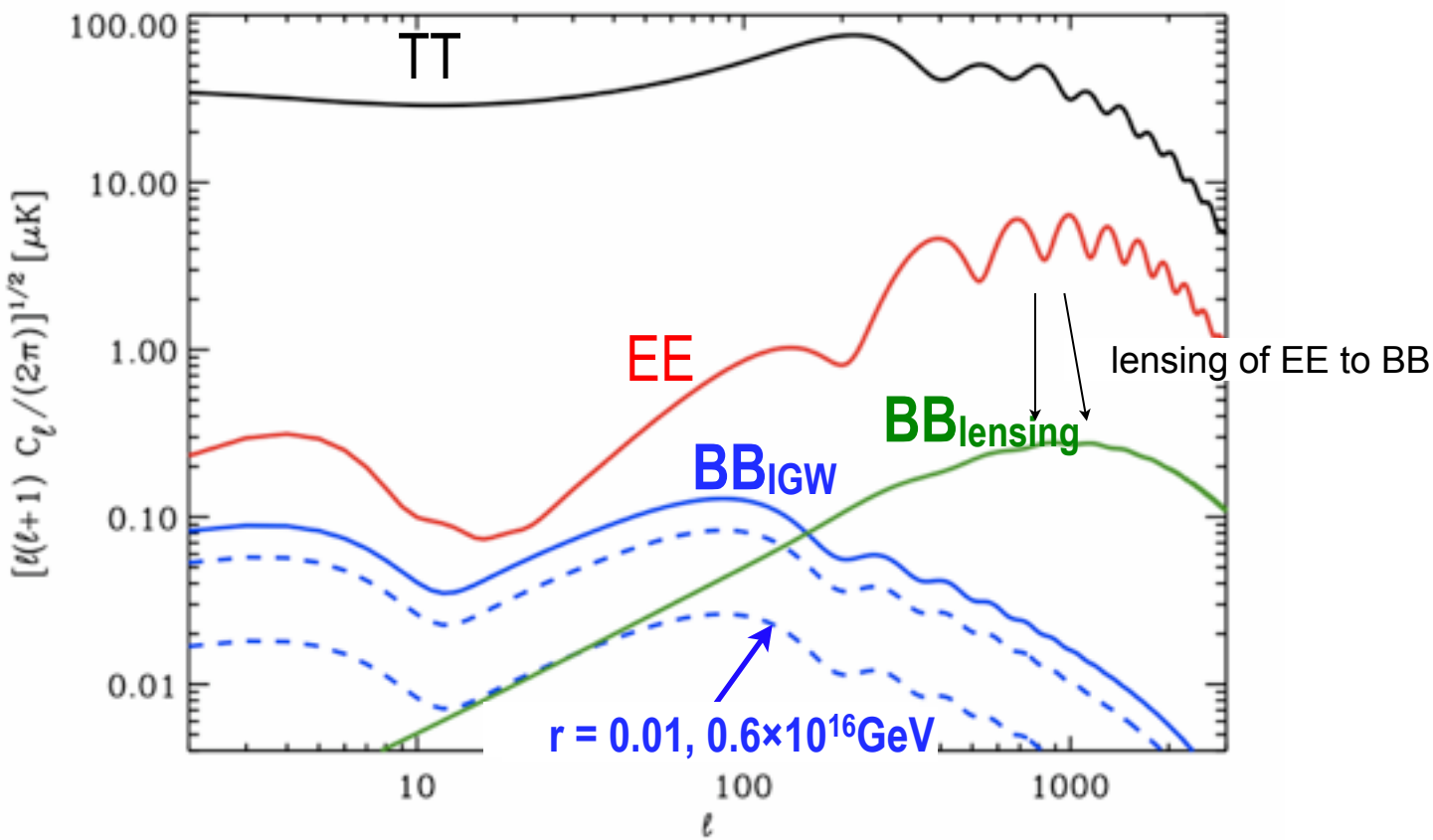


CMB polarization

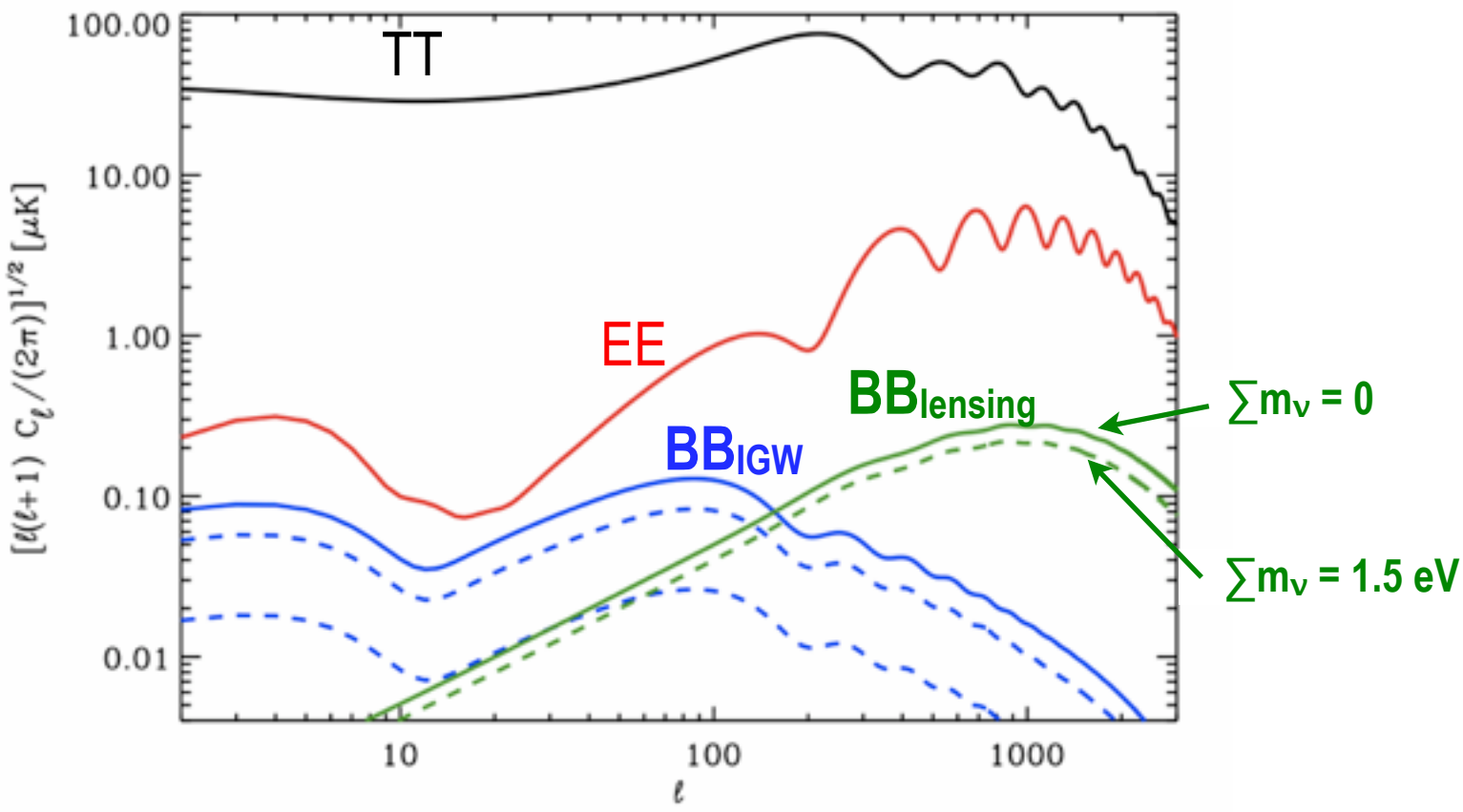


r is the tensor to scalar ratio of the primordial fluctuations

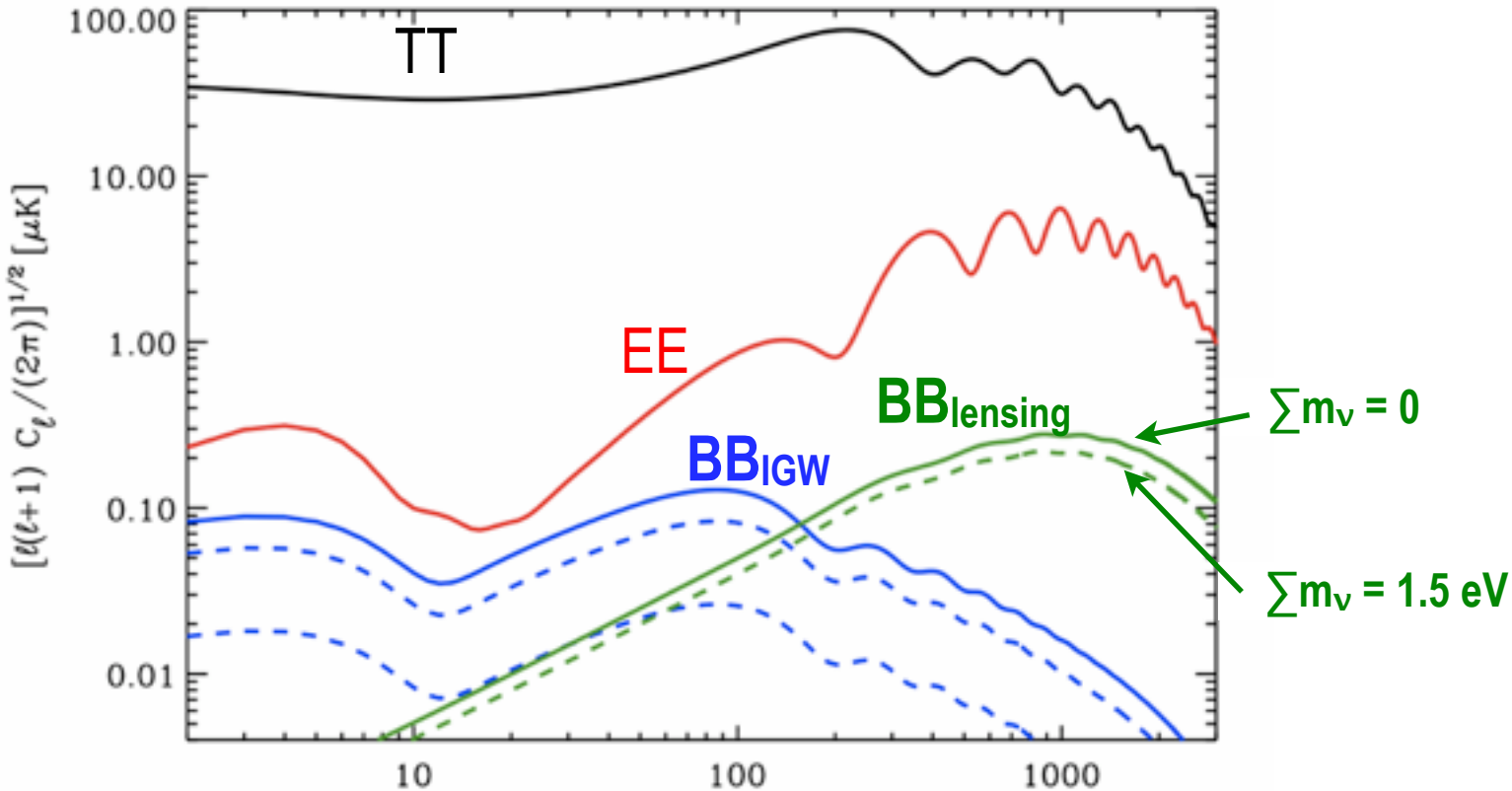
CMB polarization



CMB polarization

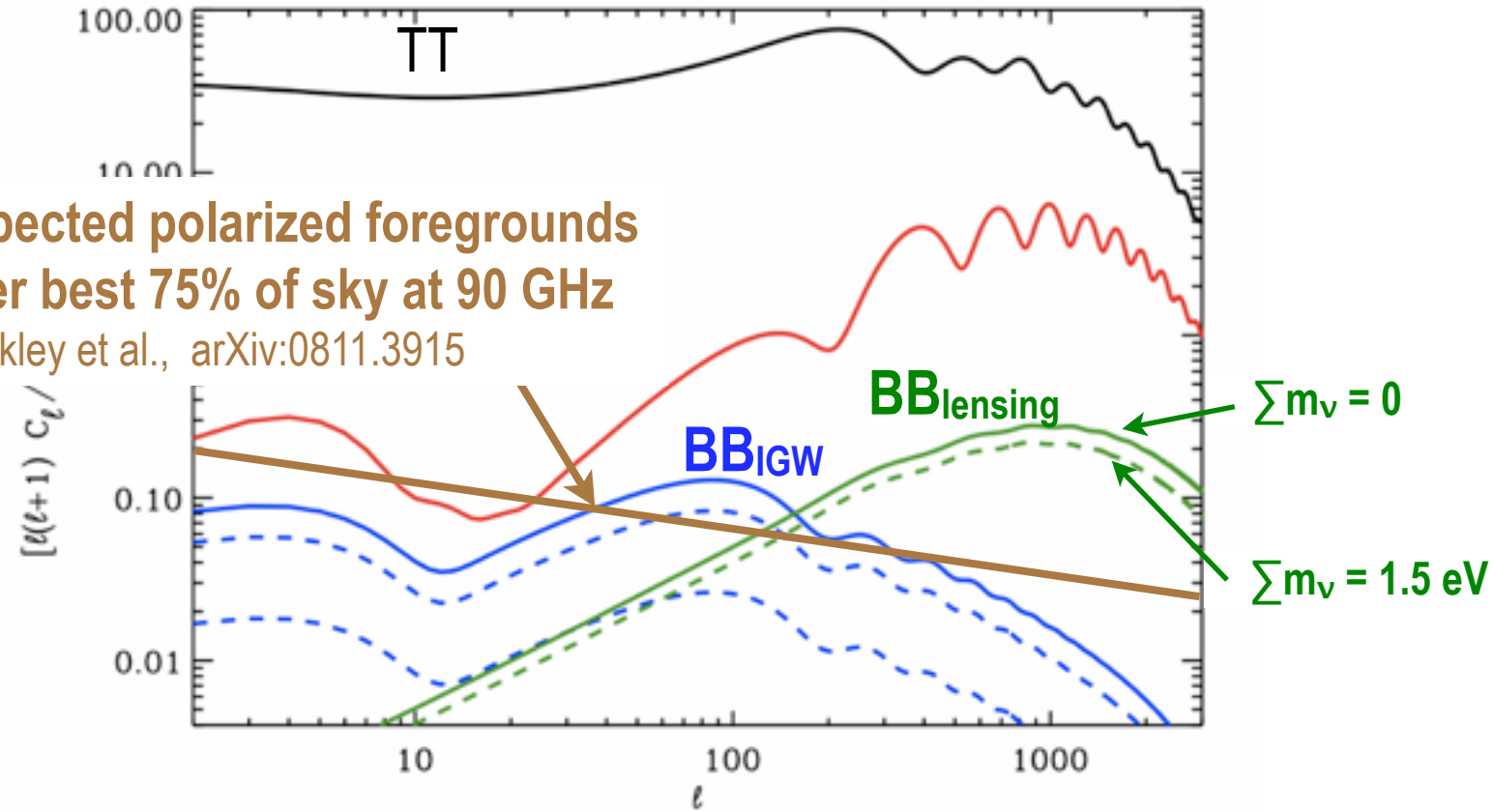


CMB polarization

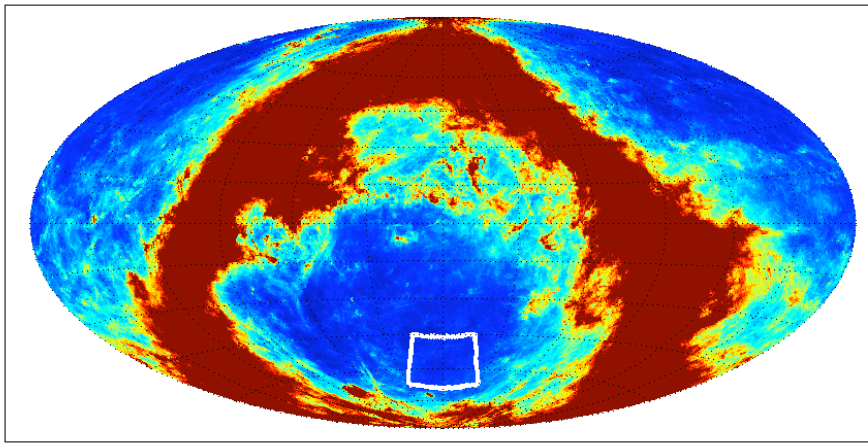


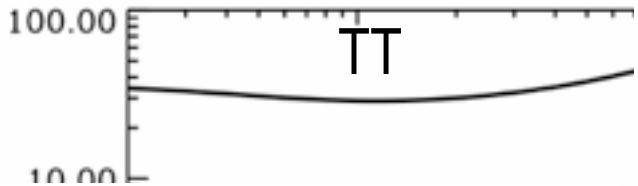
CMB measurements should be able to achieve σ(∑mν) = 0.05eV, comparable to Δm measured by neutrino oscillations.

CMB polarization

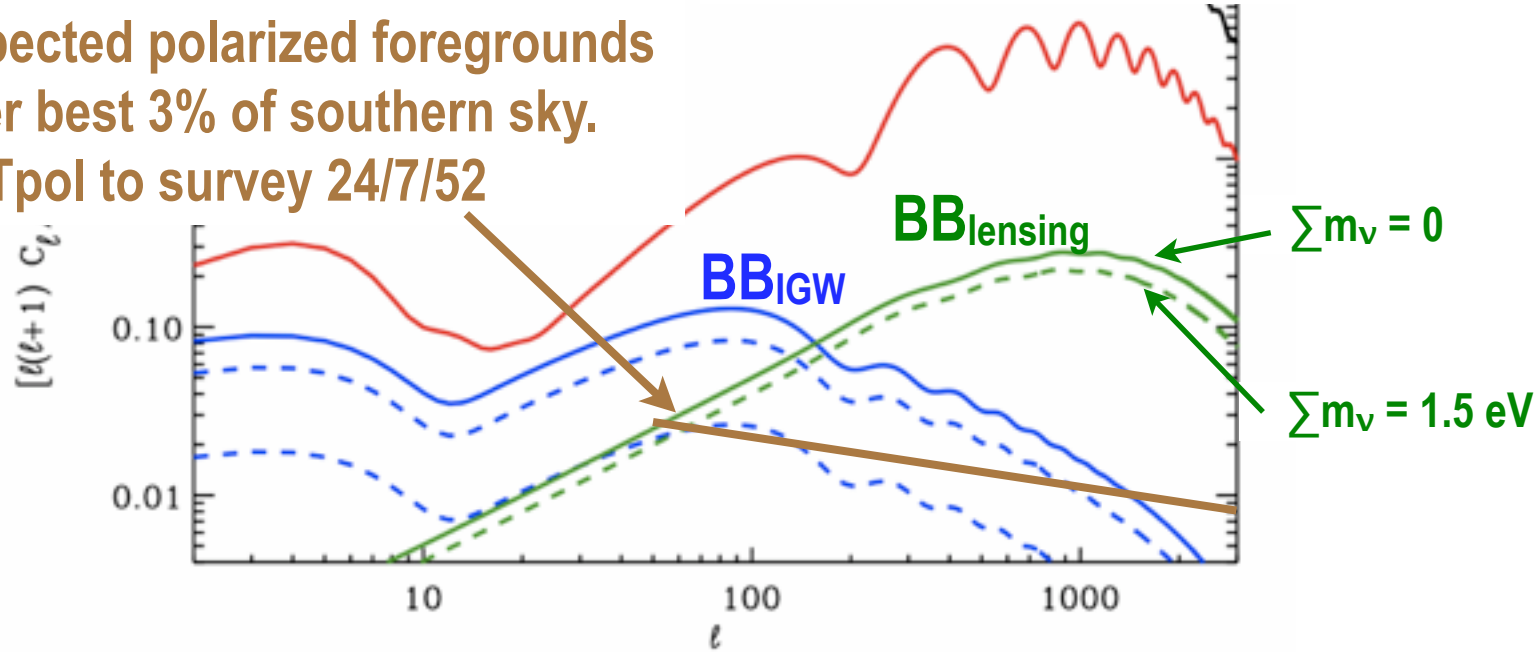


CMB polarization

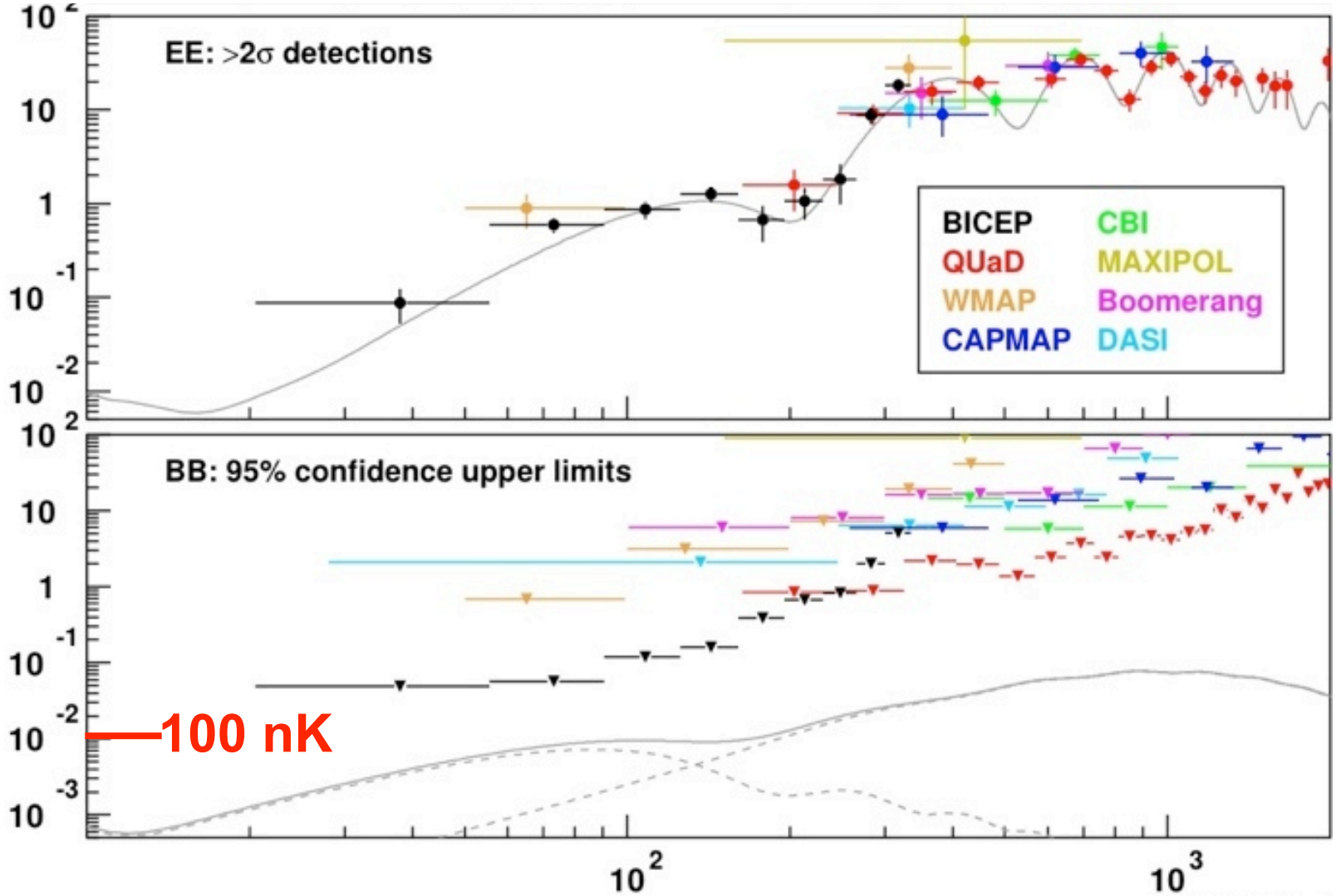




Expected polarized foregrounds over best 3% of southern sky. SPTpol to survey 24/7/52

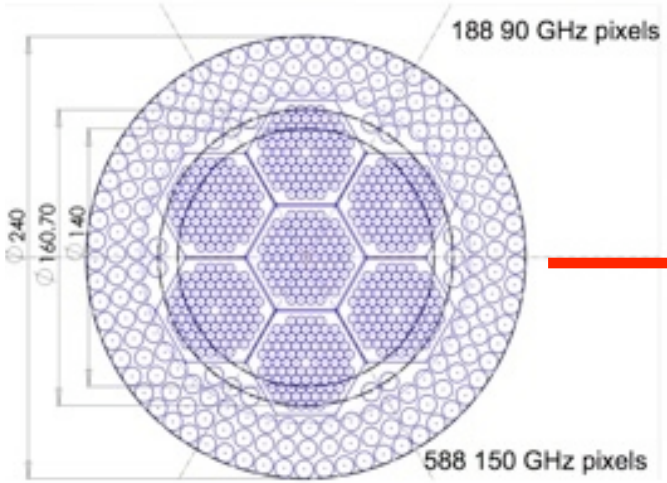


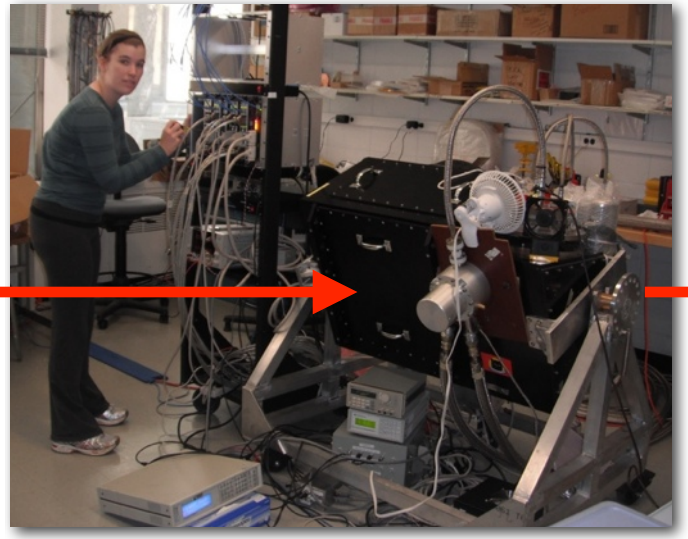
Closing in on inflation

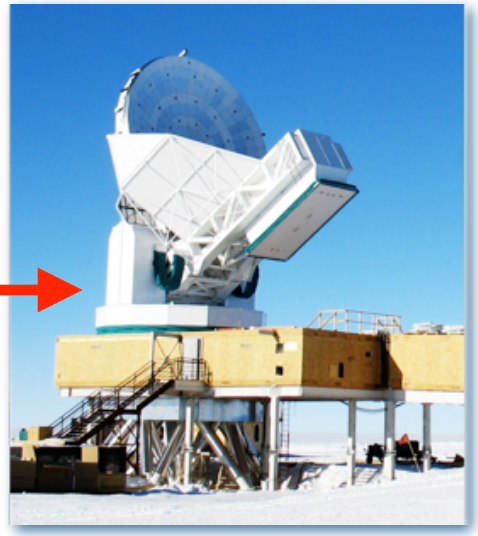


see Brown et al., arXiv:0906.1003 & Chiang et al., arXiv:0906.1181

SPTpol deployment plan



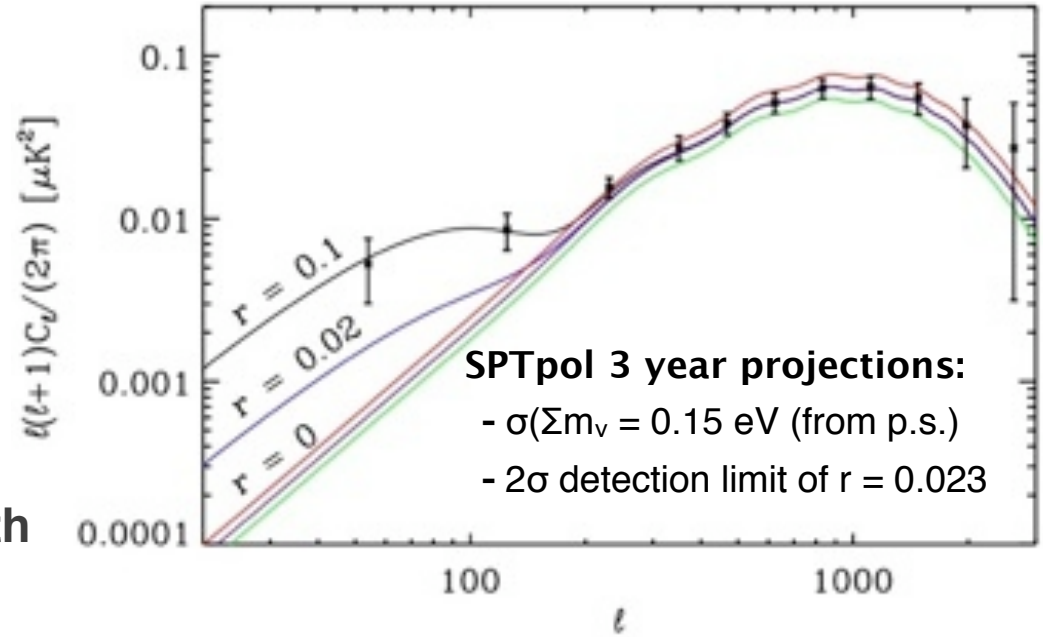




Deploy SPTpol (11/2011)

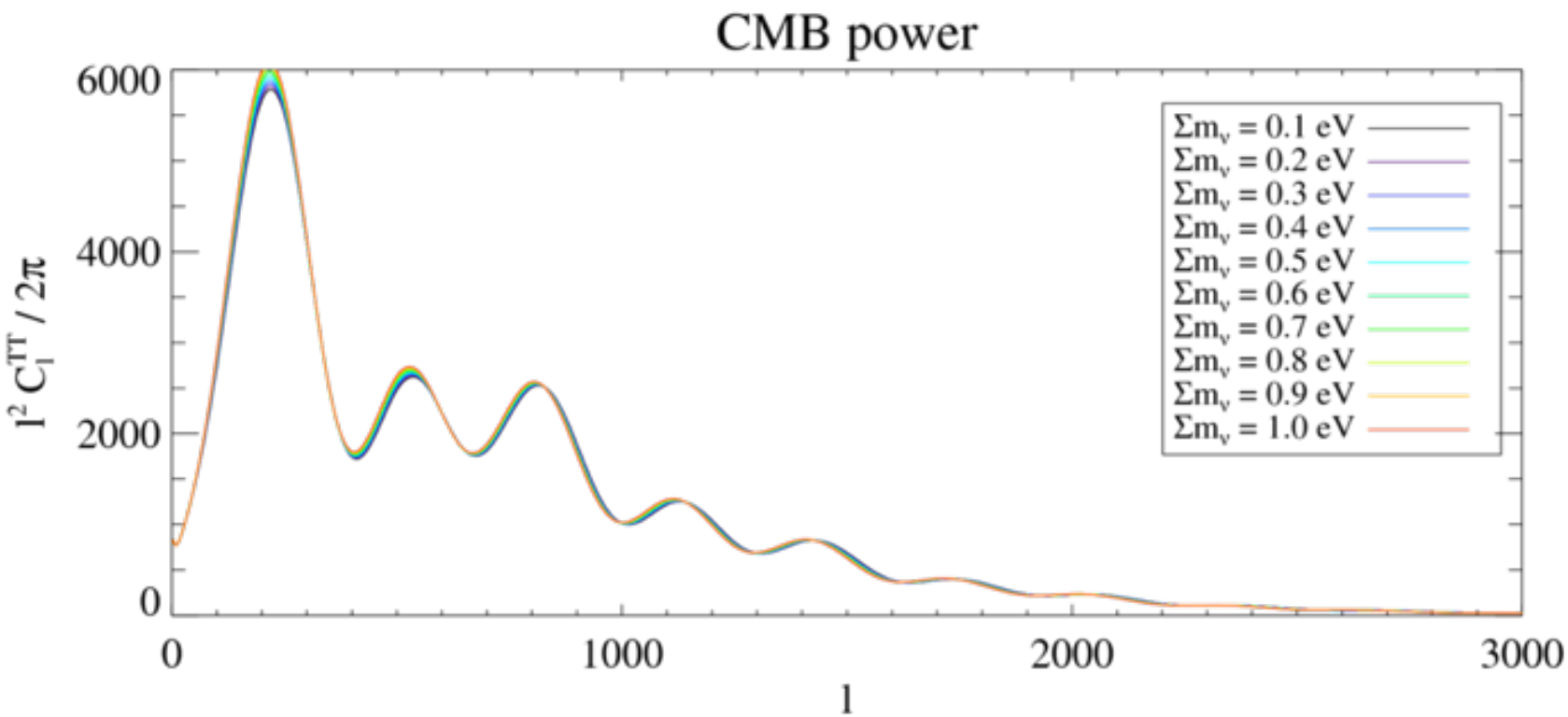
ANL providing 90 GHz channel and participating in SPTpol & ongoing dark energy data analysis

Near term future plan is to significantly improve sensitivity with new ANL detector development

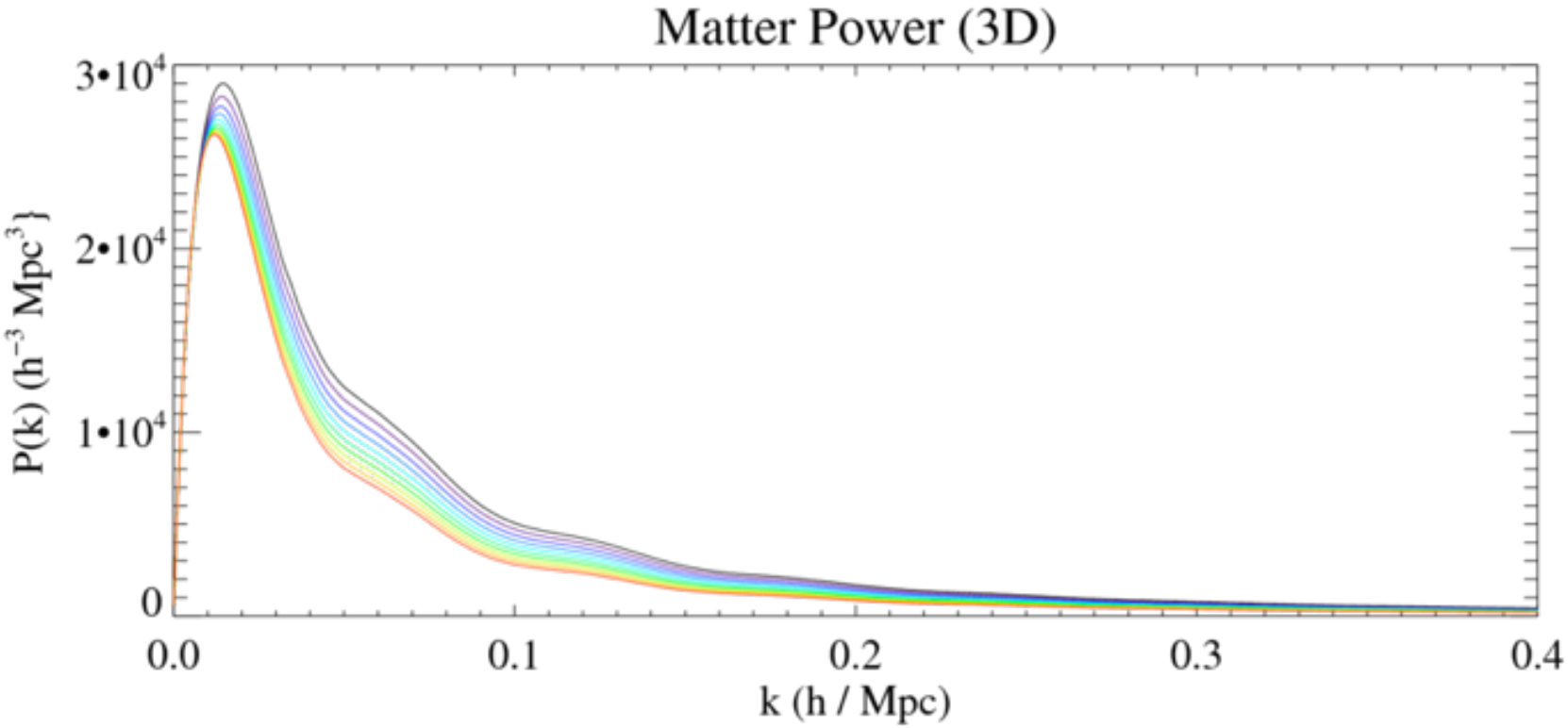


Back up slides

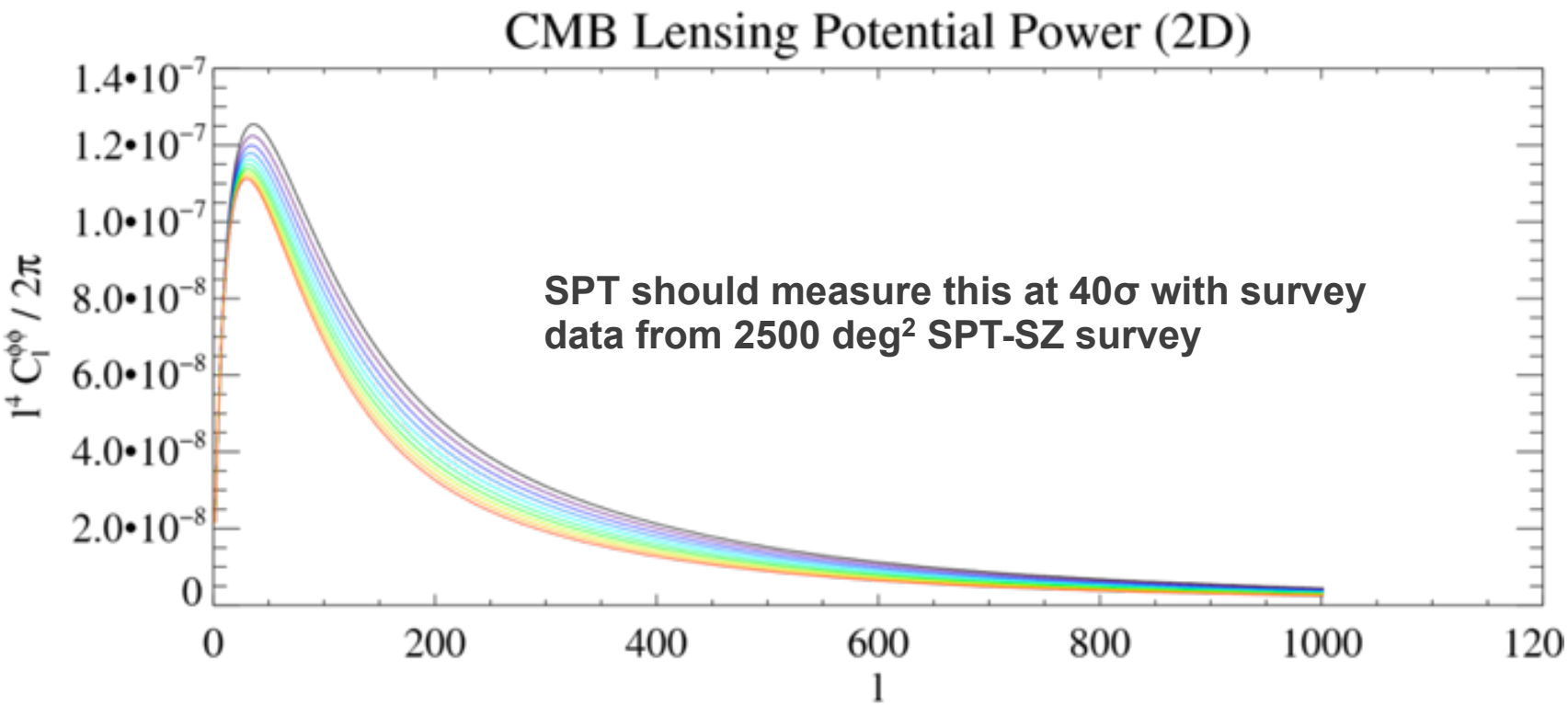
CMB Lensing constraints on Σm_ν



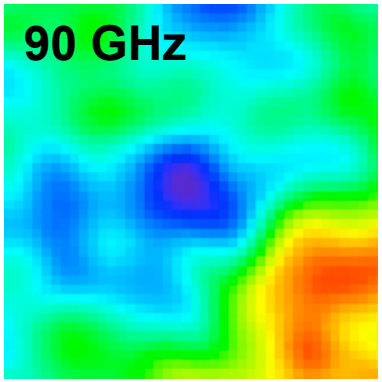
CMB Lensing constraints on Σm_ν

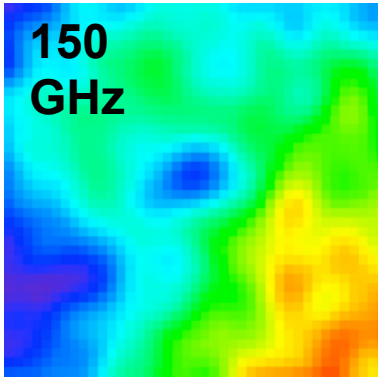


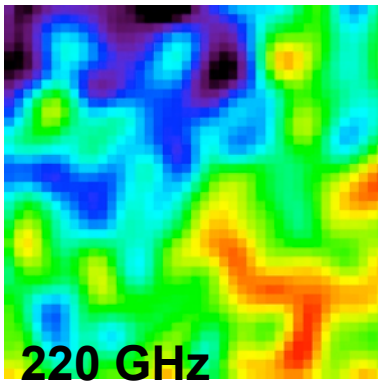
CMB Lensing constraints on Σm_ν



Finding Clusters in a SZ Survey

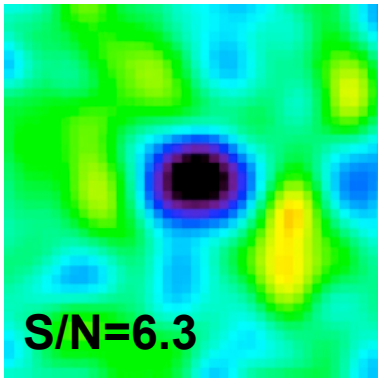


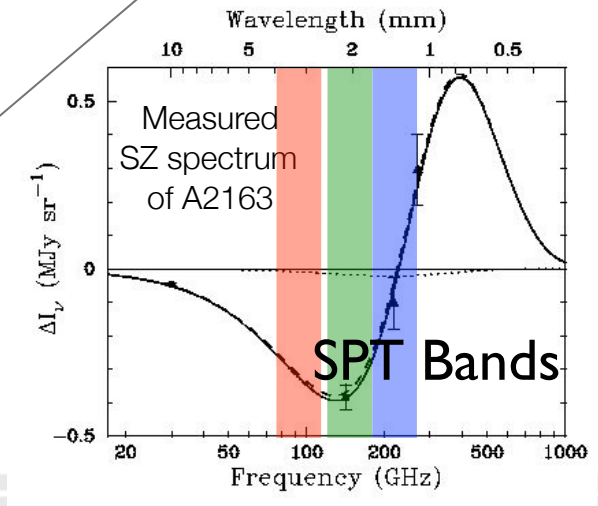




- Combine maps at different frequencies into a synthesized thermal SZ map, and find significant objects in that map
- [OR: these steps can be combined into a single spatial-spectral filter (e.g. ,Tegmark 2000, Herranz et al. 2002, Melin et al. 2006).]

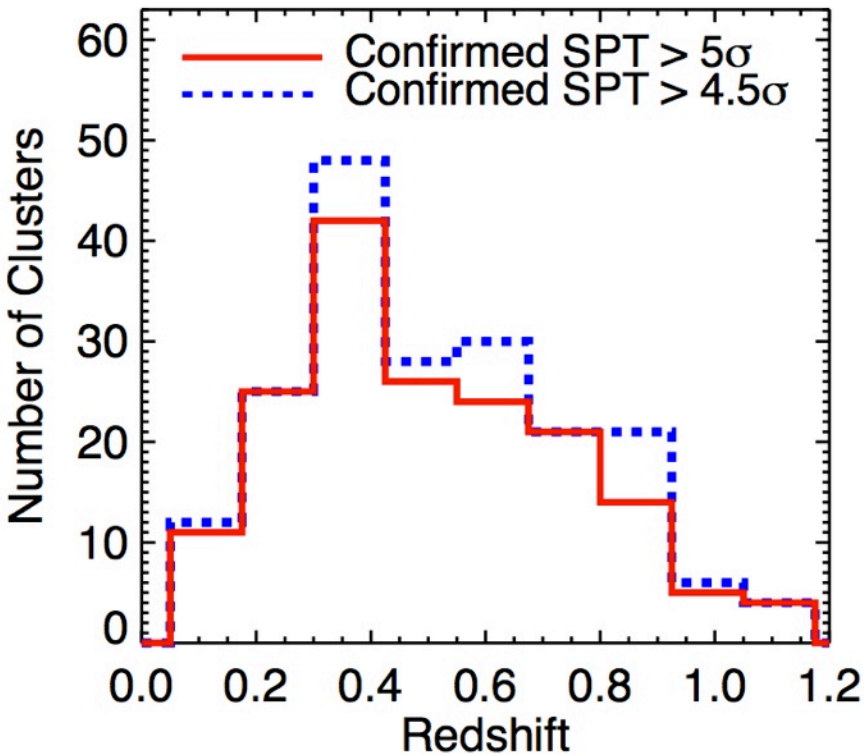
Matched Filter



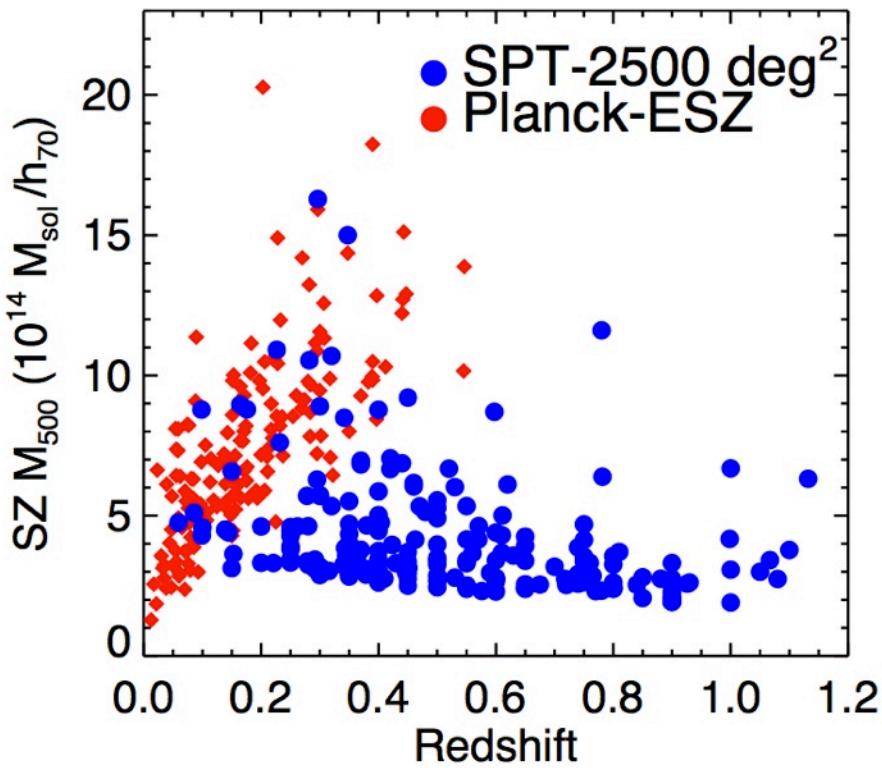


SPT Cluster Sample Update

Redshift Histogram



SZ Mass vs Redshift



Over 300 clusters optically confirmed, ~80% new discoveries

(already more new massive high z clusters than previously known)

ANL HEP provides enabling technology for frontier research - excellent synergy.

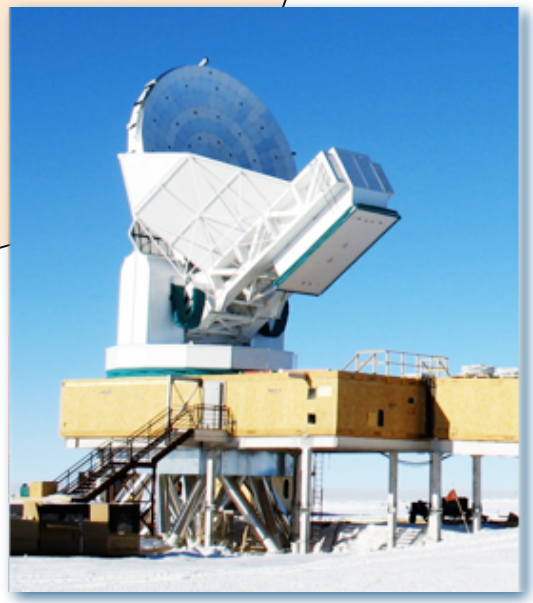
TECHNOLOGY

- Superconducting Transition-Edge Sensor (TES) Detectors
- Argonne TES Development Project

PLATFORM

- South Pole Telescope. Cutting edge instrument & strong collaboration
- PI: John Carlstrom

SPTpol

COSMIC FRONTIER

- Inflation
- Neutrino masses
- Dark Energy