The Cosmic Microwave Background as a Probe of the Early Universe and Novel Physics

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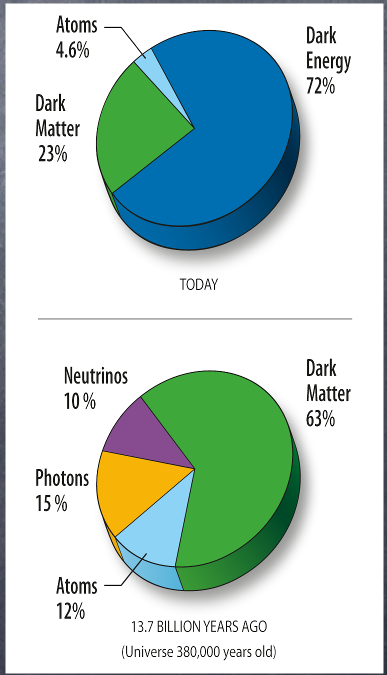
Rutgers
March 5, 2013

Today's Cosmological Model

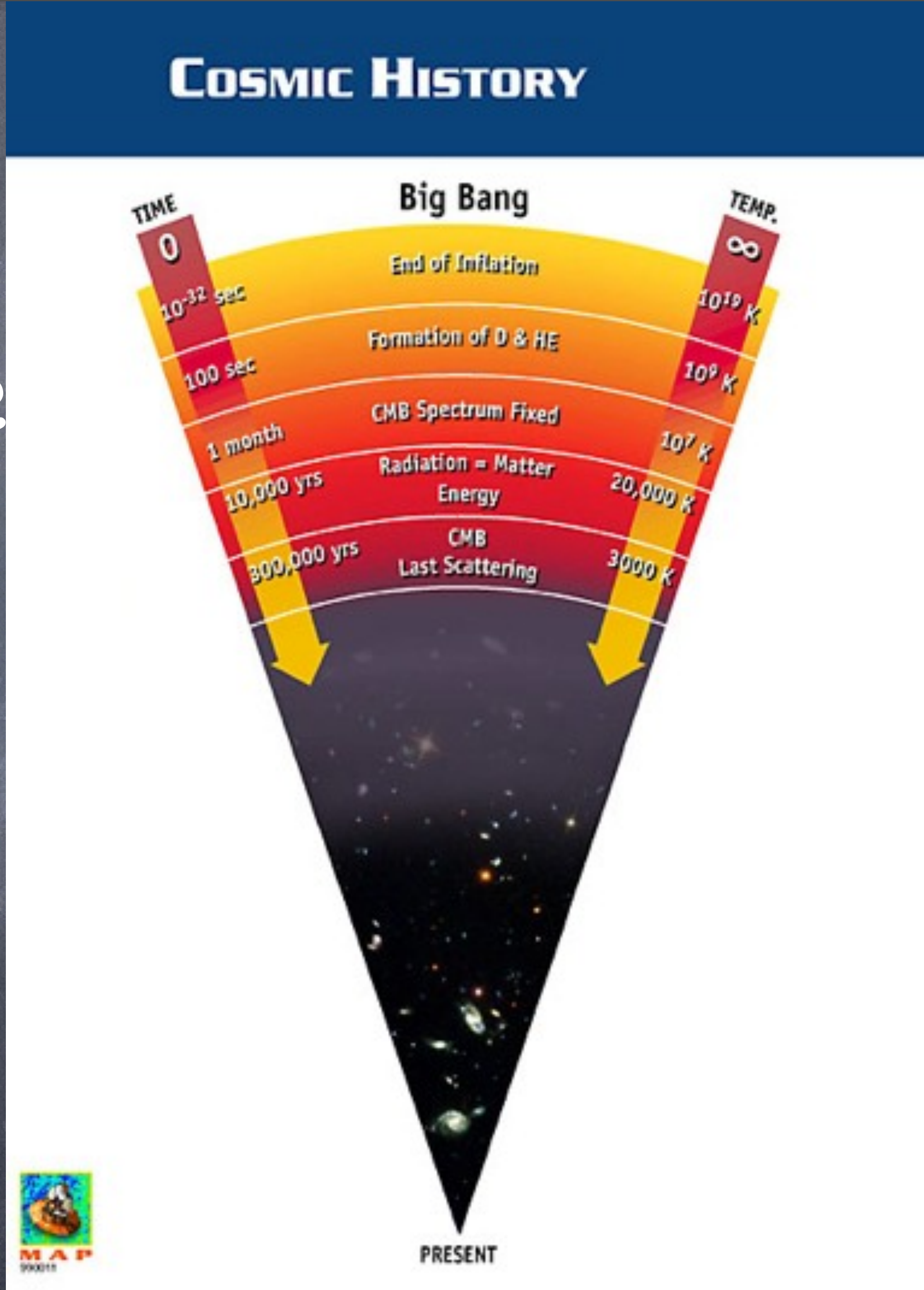
- The universe is simple. We can fit all of our observations of the universe with five numbers:
  - density of atoms
  - age of the universe
  - density of matter
  - amplitude of fluctuations
  - scale dependence of fluctuations



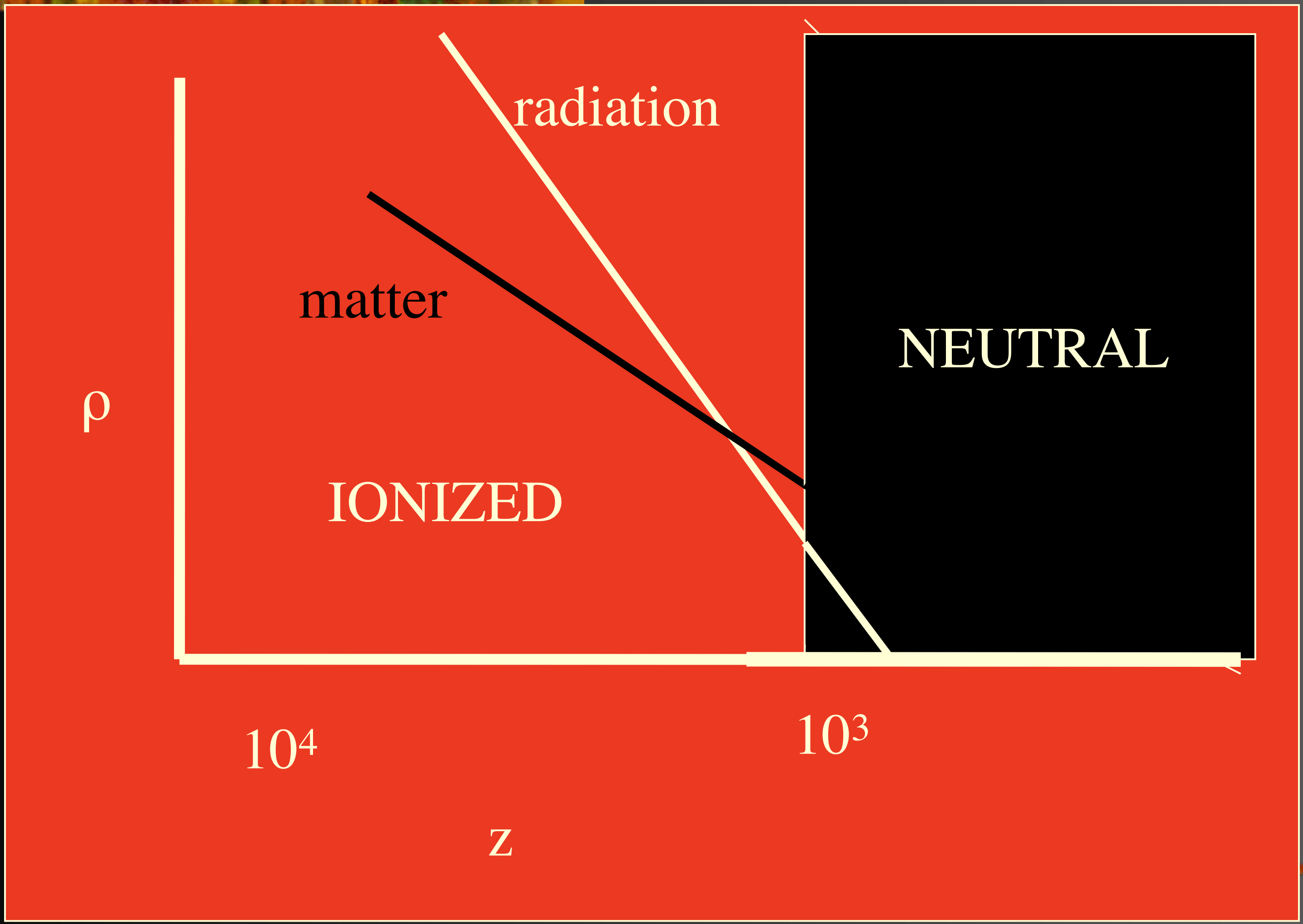
- The universe is strange

Quick History of the Universe

- Universe starts out hot, dense and filled with radiation
- As the universe expands, it cools.
  - During the first minutes, light elements form
  - After 300,000 years, atoms form
  - After 100,000,000 years, stars start to form
  - After 1 Billion years, galaxies and quasars



Thermal History of Universe



Thin Surface of Last Scatter

Because recombination happens fast, the surface of last scatter is thin

$$\tau(z) \doteq 0.37\left(\frac{z}{1000}\right)^{14.25}$$

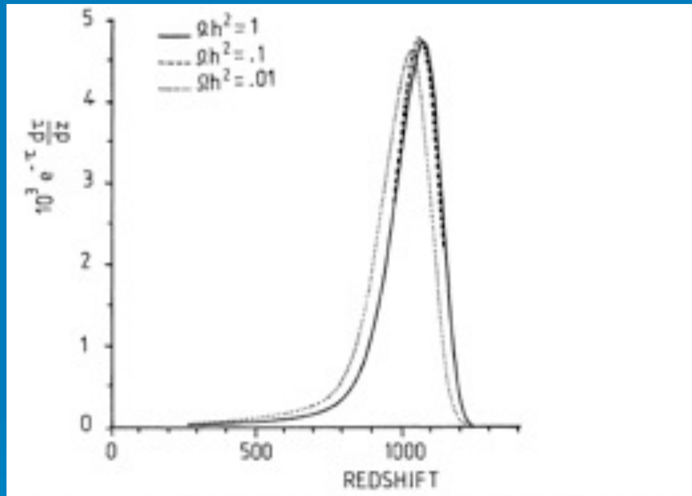
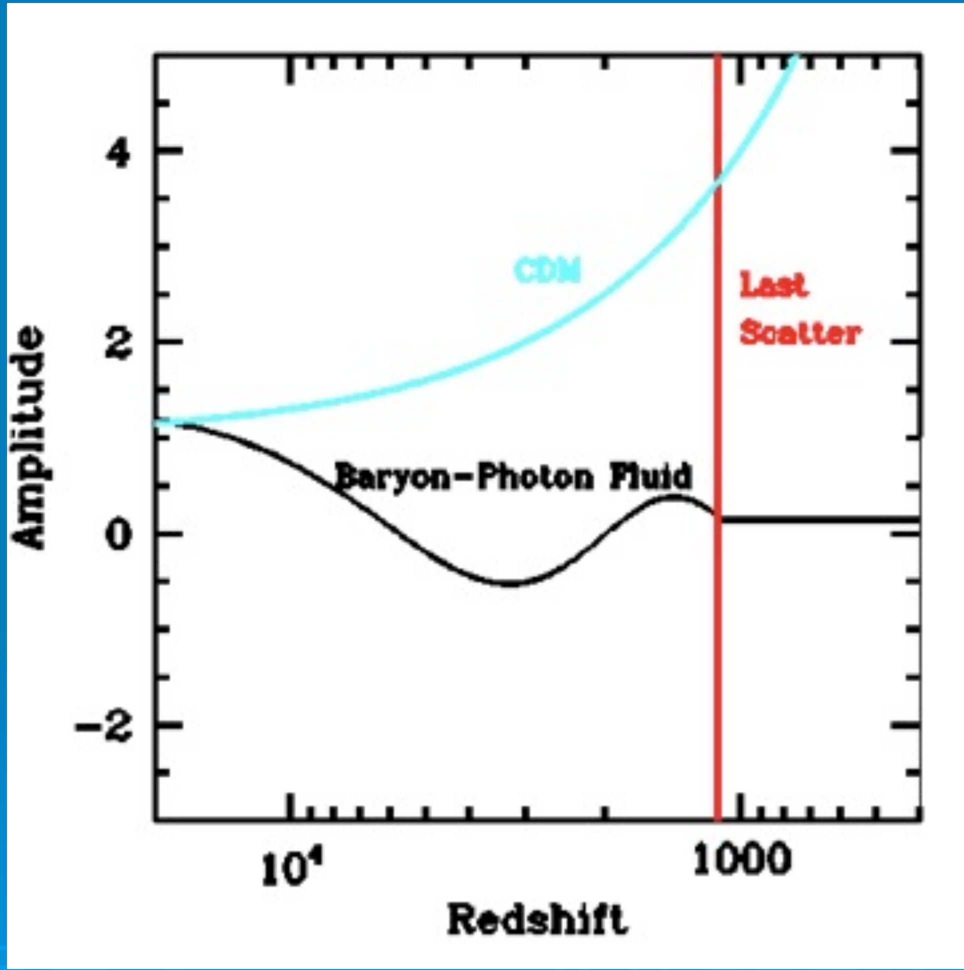


Fig. 4. The "visibility function" in three cosmological models. This function is the probability that a photon observed now was last scattered at redshift z

Growth of Fluctuations

- Linear theory
- Basic elements have been understood for 30 years (Peebles, Sunyaev & Zeldovich)
- Numerical codes agree at better than 0.1% (Seljak et al. 2003)



SMALL-SCALE FLUCTUATIONS OF RELIC RADIATION*

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(Received 11 September, 1969)

Abstract. Perturbations of the matter density in a homogeneous and isotropic cosmological model which leads to the formation of galaxies should, at later stages of evolution, cause spatial fluctuations of relic radiation. Silk assumed that an adiabatic connection existed between the density perturbations at the moment of recombination of the initial plasma and fluctuations of the observed temperature of radiation $\delta T/T = \delta\varrho_m/3\varrho_m$. It is shown in this article that such a simple connection is not applicable due to:

(1) The long time of recombination;

(2) The fact that when regions with $M < 10^{15} M_\odot$ become transparent for radiation, the optical depth to the observer is still large due to Thompson scattering;

(3) The spasmodic increase of $\delta\varrho_m/\varrho_m$ in recombination.

As a result the expected temperature fluctuations of relic radiation should be smaller than adiabatic fluctuations. In this article the value of $\delta T/T$ arising from scattering of radiation on moving electrons is calculated; the velocity field is generated by adiabatic or entropy density perturbations. Fluctuations of the relic radiation due to secondary heating of the intergalactic gas are also estimated. A detailed investigation of the spectrum of fluctuations may, in principle, lead to an understanding of the nature of initial density perturbations since a distinct periodic dependence of the spectral density of perturbations on wavelength (mass) is peculiar to adiabatic perturbations. Practical observations are quite difficult due to the smallness of the effects and the presence of fluctuations connected with discrete sources of radio emission.

Sunyaev & Zeldovich

THE ASTROPHYSICAL JOURNAL, 162:815–836, December 1970

PRIMEVAL ADIABATIC PERTURBATION IN AN EXPANDING UNIVERSE*

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Goddard Institute for Space Studies, NASA, New York
Received 1970 January 5; revised 1970 April 1

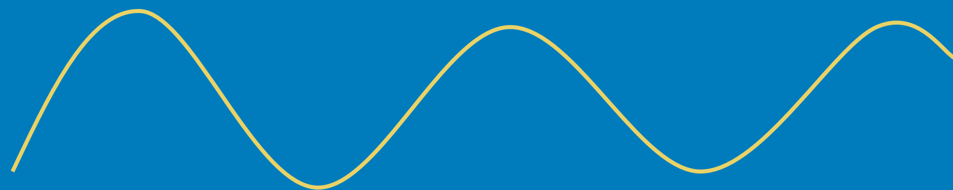
ABSTRACT

The general qualitative behavior of linear, first-order density perturbations in a Friedmann-Lemaître cosmological model with radiation and matter has been known for some time in the various limiting situations. An exact quantitative calculation which traces the entire history of the density fluctuations is lacking because the usual approximations of a very short photon mean free path before plasma recombination, and a very long mean free path after, are inadequate. We present here results of the direct integration of the collision equation of the photon distribution function, which enable us to treat in detail the complicated regime of plasma recombination. Starting from an assumed initial power spectrum well before recombination, we obtain a final spectrum of density perturbations after recombination. The calculations are carried out for several general-relativity models and one scalar-tensor model. One can identify two characteristic masses in the final power spectrum: one is the mass within the Hubble radius ct at recombination, and the other results from the linear dissipation of the perturbations prior to recombination. Conceivably the first of these numbers is associated with the great rich clusters of galaxies, the second with the large galaxies. We compute also the expected residual irregularity in the radiation from the primeval fireball. If we assume that (1) the rich clusters formed from an initially adiabatic perturbation and (2) the fireball radiation has not been seriously perturbed after the epoch of recombination of the primeval plasma, then with an angular resolution of 1 minute of arc the rms fluctuation in antenna temperature should be at least $\delta T/T = 0.00015$.

I. INTRODUCTION

Evolution of CMB Fluctuations

- Linear Regime
- Boltzmann equation
- Numerical Codes available on the web
  - www.cmbfast.org



$$\Theta(\vec{x},t) = \sum_{\vec{k}} \underbrace{A(\vec{k},0)}_{\text{Initial Conditions}} \underbrace{\Theta(k,t)}_{\text{Dynamics}} \exp(i\vec{k}\cdot\vec{x})$$

Initial Conditions

Dynamics

Inflation: Gaussian Random Field

$$< A(\vec{k})A^*(\vec{k}') >= P(k)\delta^{(3)}(\vec{k}-\vec{k}')$$

Evolution of Fluctuations: Tight Coupling

$$\ddot{\Theta}_0 + \frac{\dot{a}}{a}\frac{R}{1+R}\dot{\Theta}_0 + k^2 c_s^2 \Theta_0 = F(\eta)$$

Hubble expansion

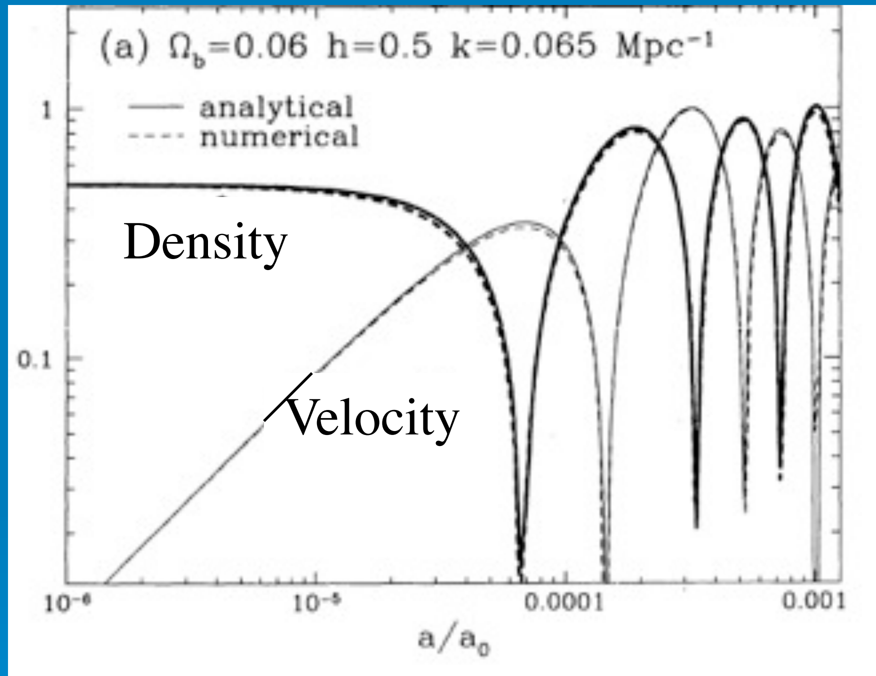
pressure

gravity

$$F(\eta) = -\ddot{\Phi} - \frac{\dot{a}}{a}\frac{R}{1+R}\dot{\Phi} - \frac{k^2}{3}\Psi$$

$$c_s^2 = \frac{1}{3}\frac{1}{1+R}$$

$$R = 3\rho_b/4\rho_\gamma$$

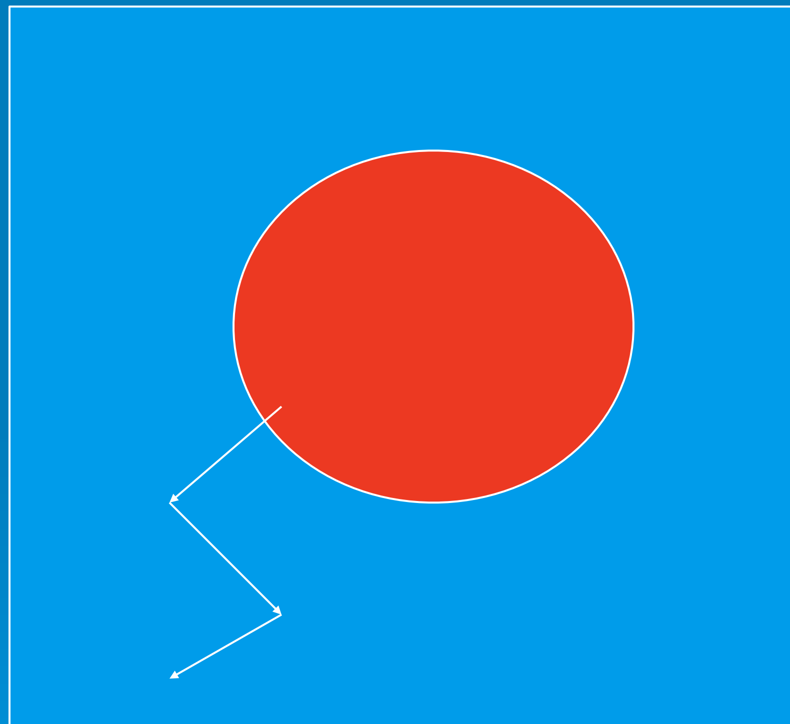


Hu and Sugiyama ApJ 444, 489 (1995)

Silk Damping

$$\Theta(\eta) = \Theta(\eta_1)\exp(-k^2/k_D^2(\eta))$$

$$k_D^{-2}(\eta) = \frac{1}{6}\int_0^{\eta} d\eta \, \frac{1}{\dot{\tau}} \frac{R^2 + 4(1+R)/5}{(1+R)^2}$$



Photon-electron fluid is not a “perfect” fluid

Photons diffuse out of hot spots and erase fluctuations on small scale

CMB Overview

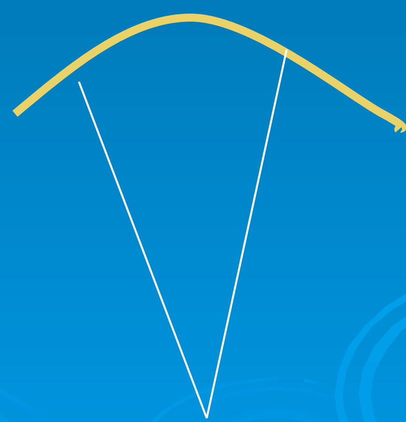
$$T(\hat{n}) = \sum_{lm} a_{lm} Y_{lm}(\hat{n})$$

$$c_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

$$T_l = \frac{l(l+1)c_l}{2\pi}$$

- We can detect both CMB temperature and polarization fluctuations

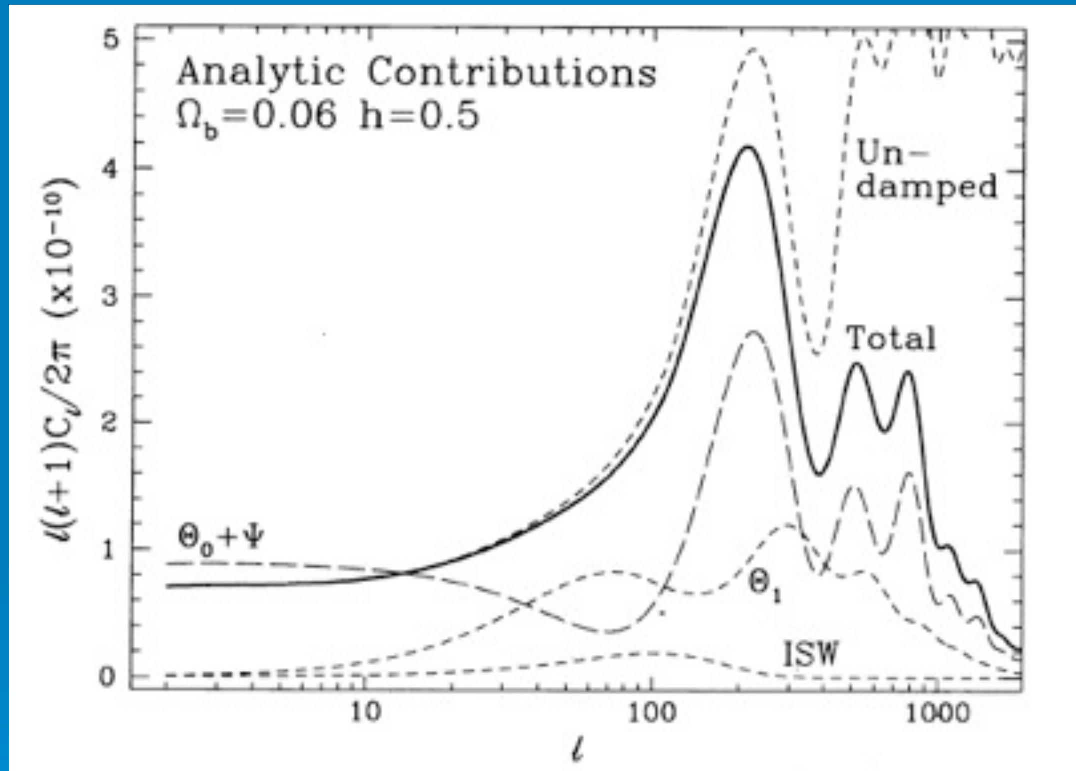
$\theta \sim 180/l$



CMB Spectrum

Density $\Theta_0+\Psi$

Velocity Θ_1



ISW Effect: Photons climbing out of decaying potentials gain energy

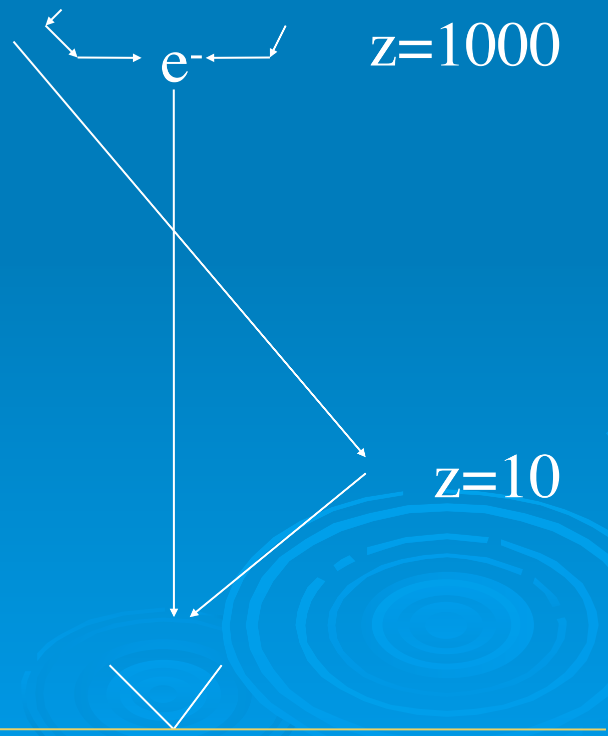
-early ISW (due to universe not being fully matter dominated)

-late ISW (due to vacuum energy)

Polarized Fluctuations

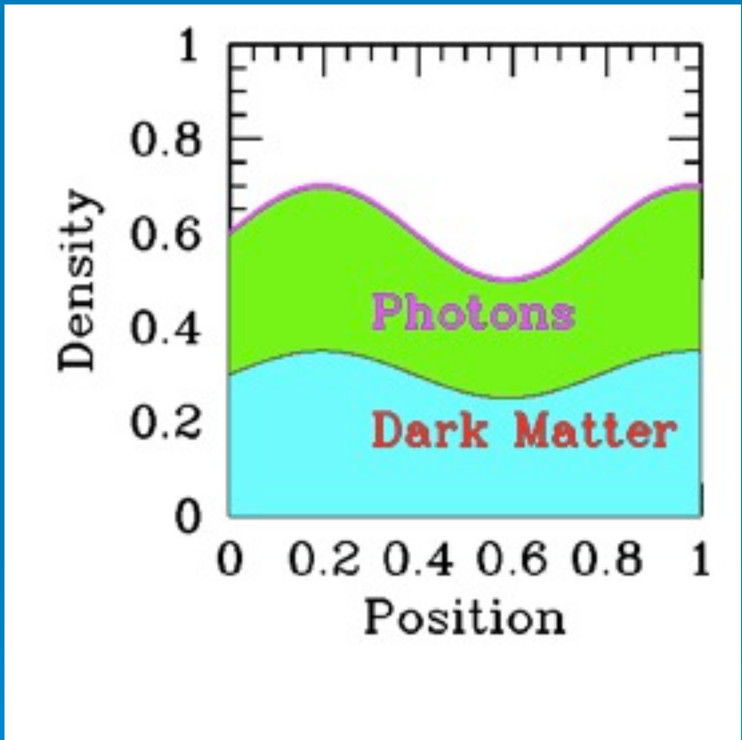
- Small angular scales: polarization signal scales as gradient in the velocity field
- Large angular scales: reionization signal is proportional to optical depth

$$\frac{d\sigma}{d\Omega} = \frac{3\sigma_T}{8\pi} |\hat{\varepsilon}' \cdot \hat{\varepsilon}|^2$$

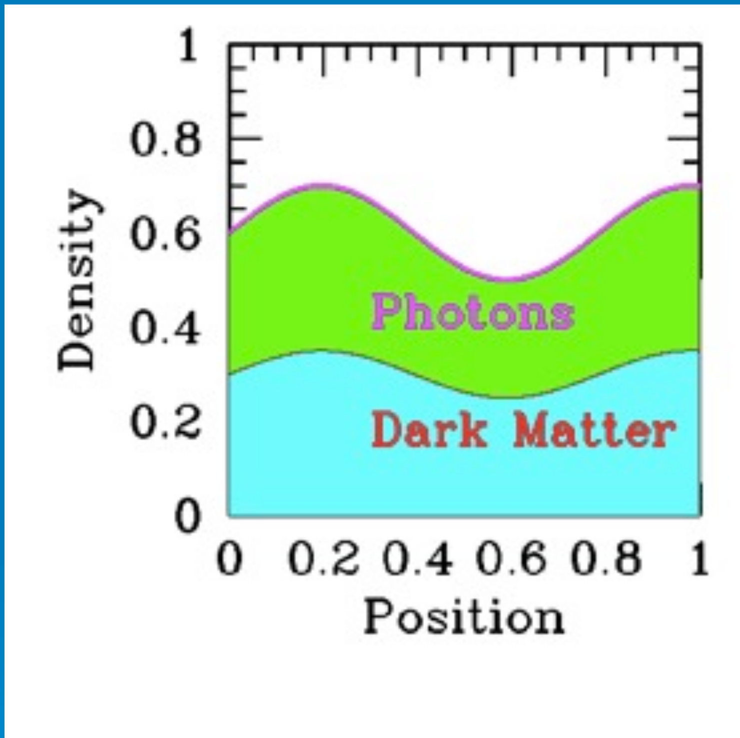


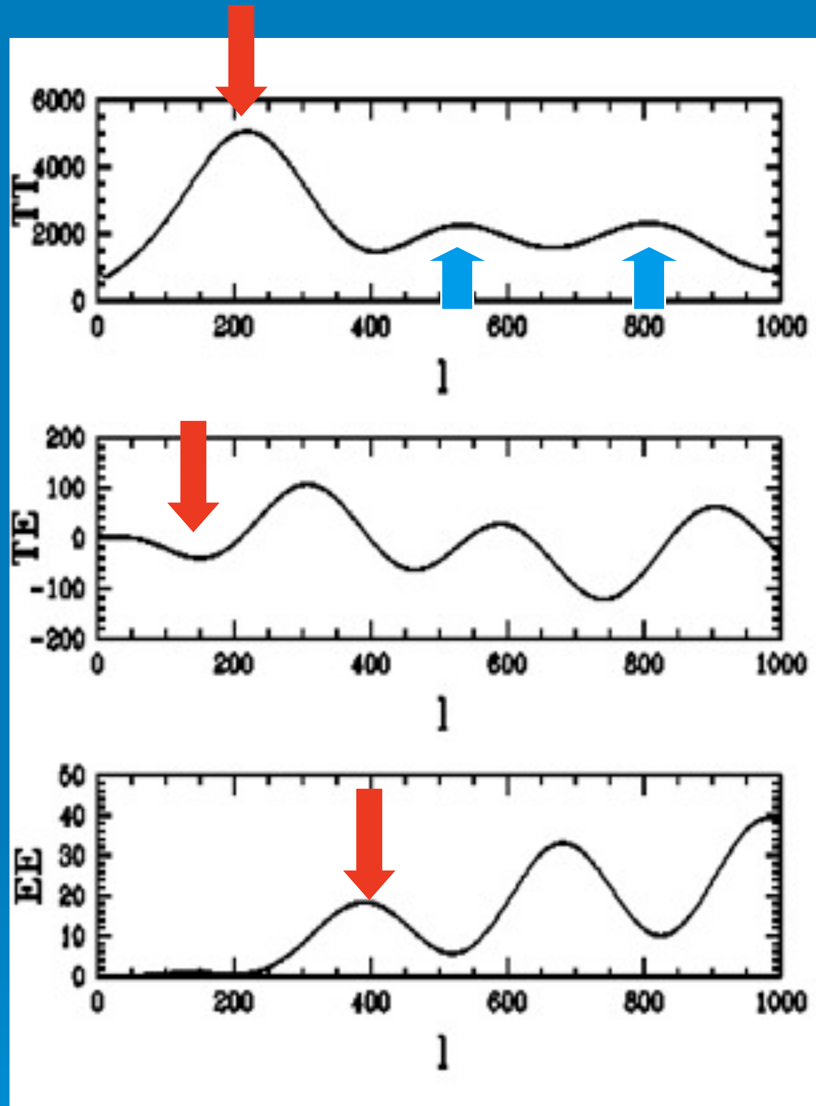
Arthur Kosowsky

New Astron.Rev. 43 (1999) 157



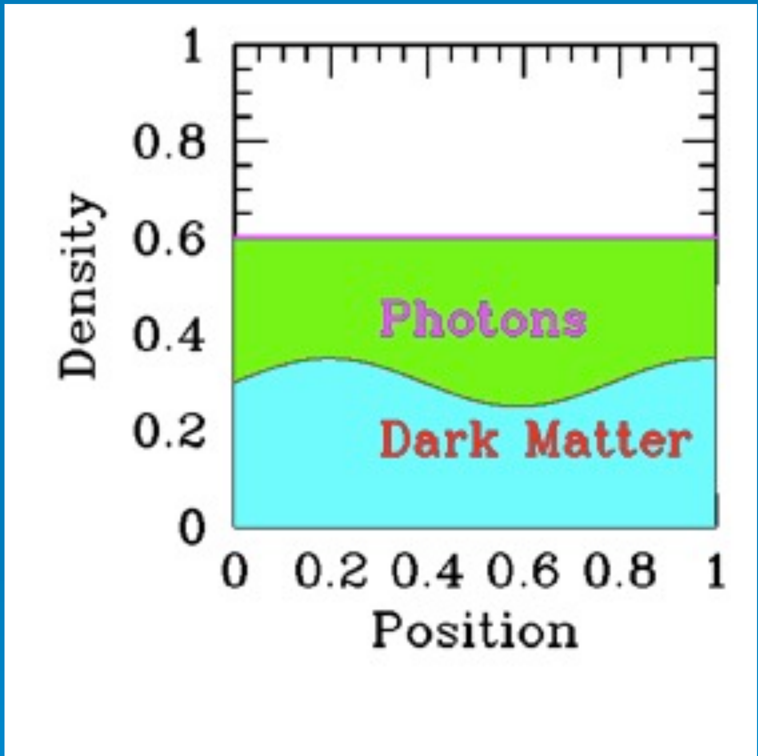
ADIABATIC DENSITY FLUCTUATIONS

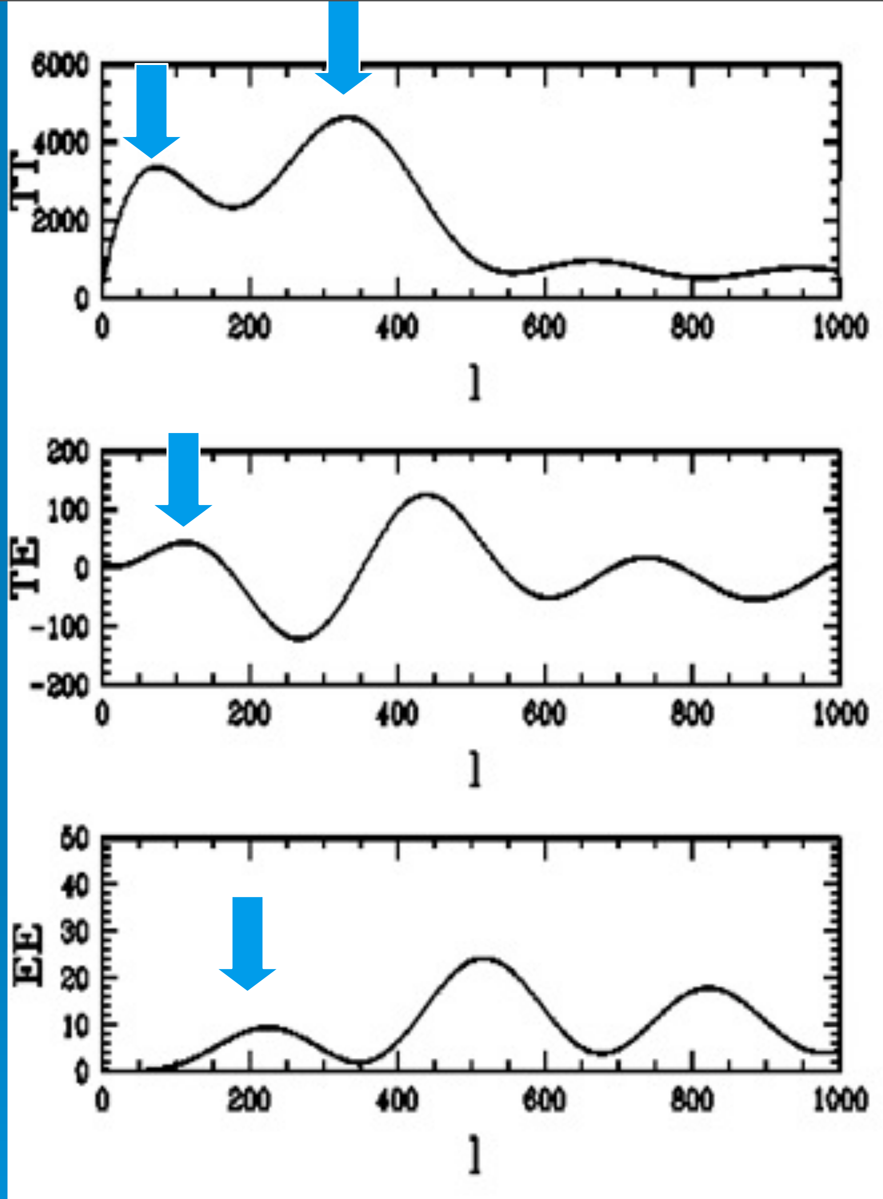




ADIABATIC DENSITY FLUCTUATIONS

ISOCURVATURE ENTROPY FLUCTUATIONS





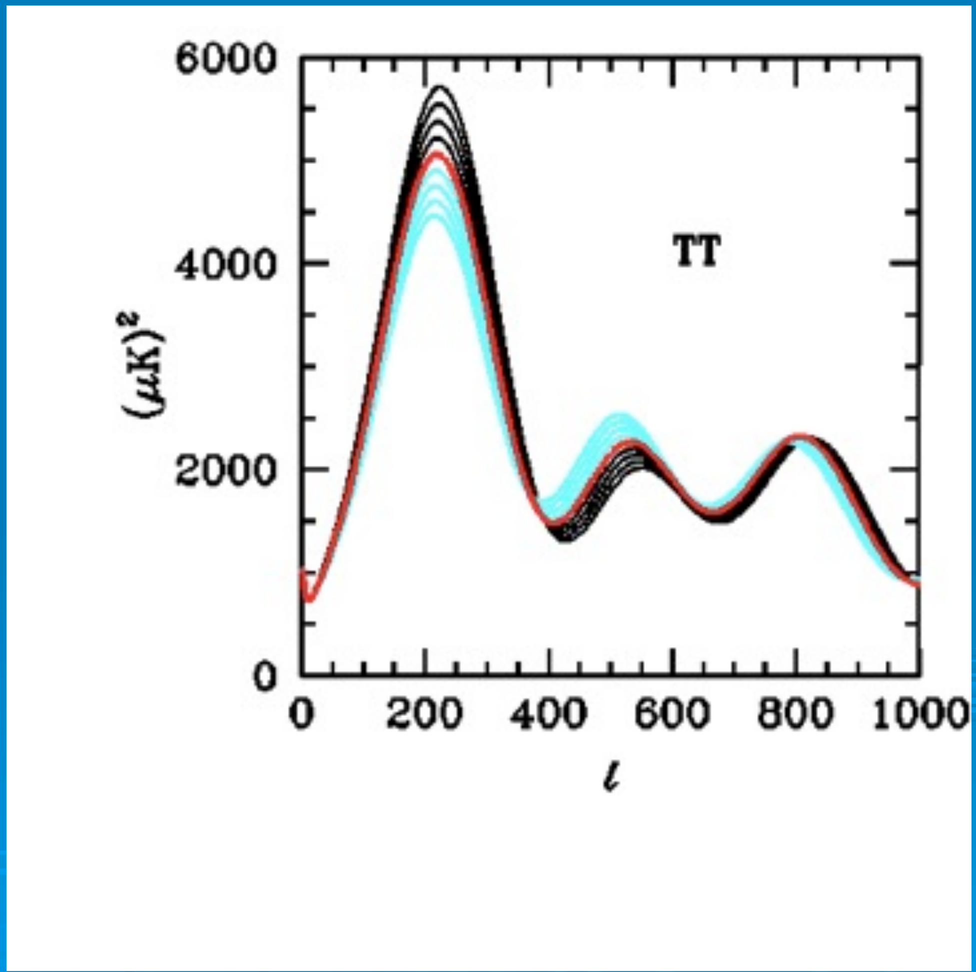
ISOCURVATURE ENTROPY FLUCTUATIONS

Determining Basic Parameters

Baryon Density

$\Omega_b h^2 = 0.015, 0.017..0.031$

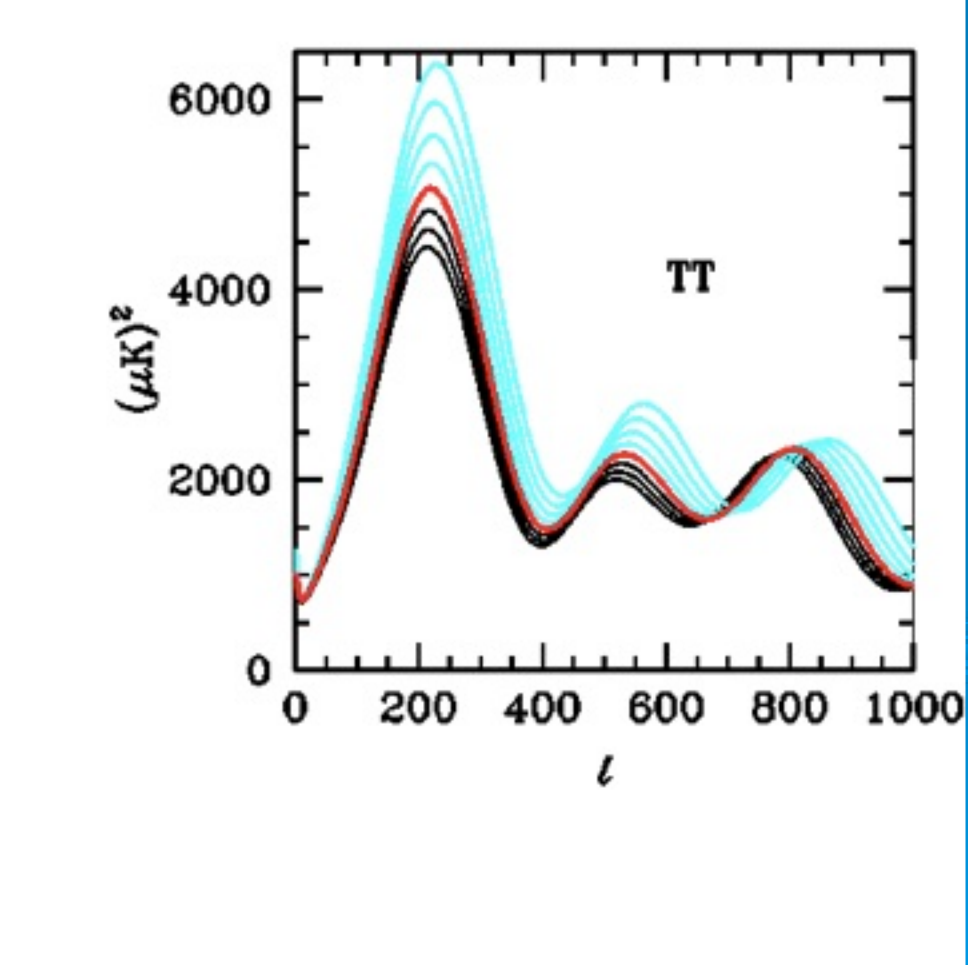
also measured through D/H



Determining Basic Parameters

Matter Density

$\Omega_m h^2 = 0.16,..,0.33$

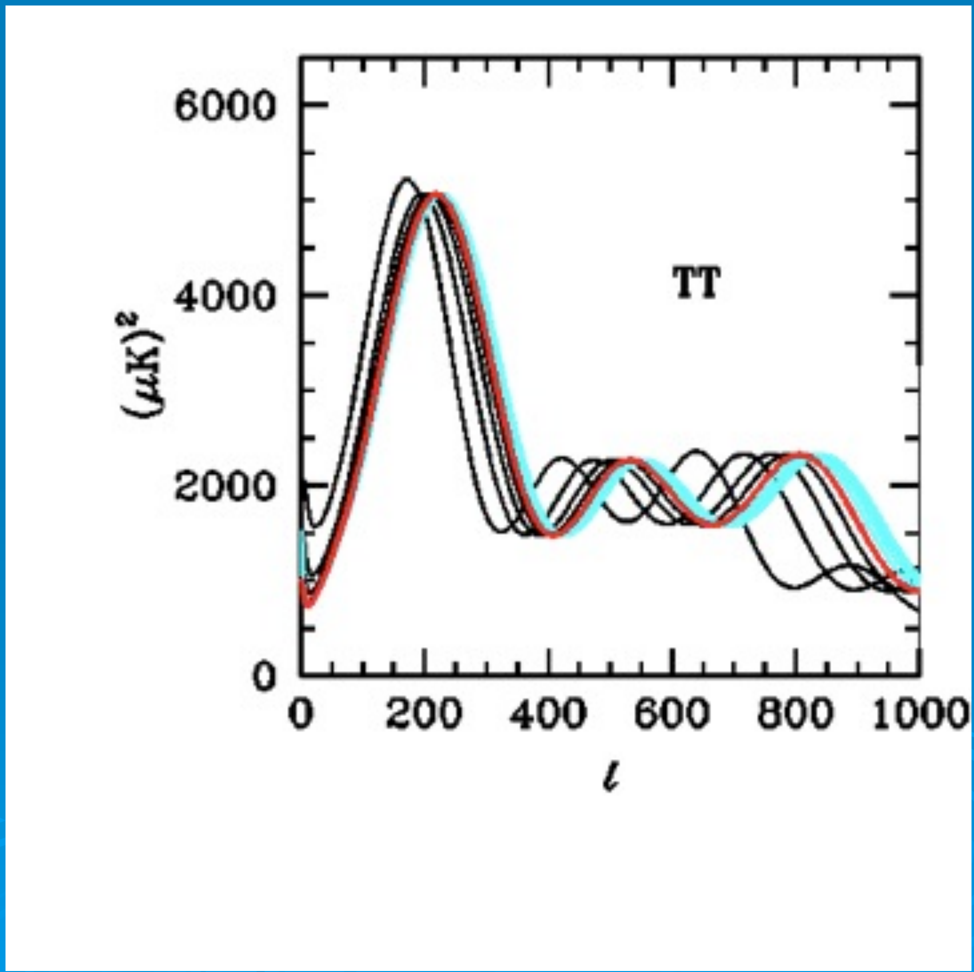


Determining Basic Parameters

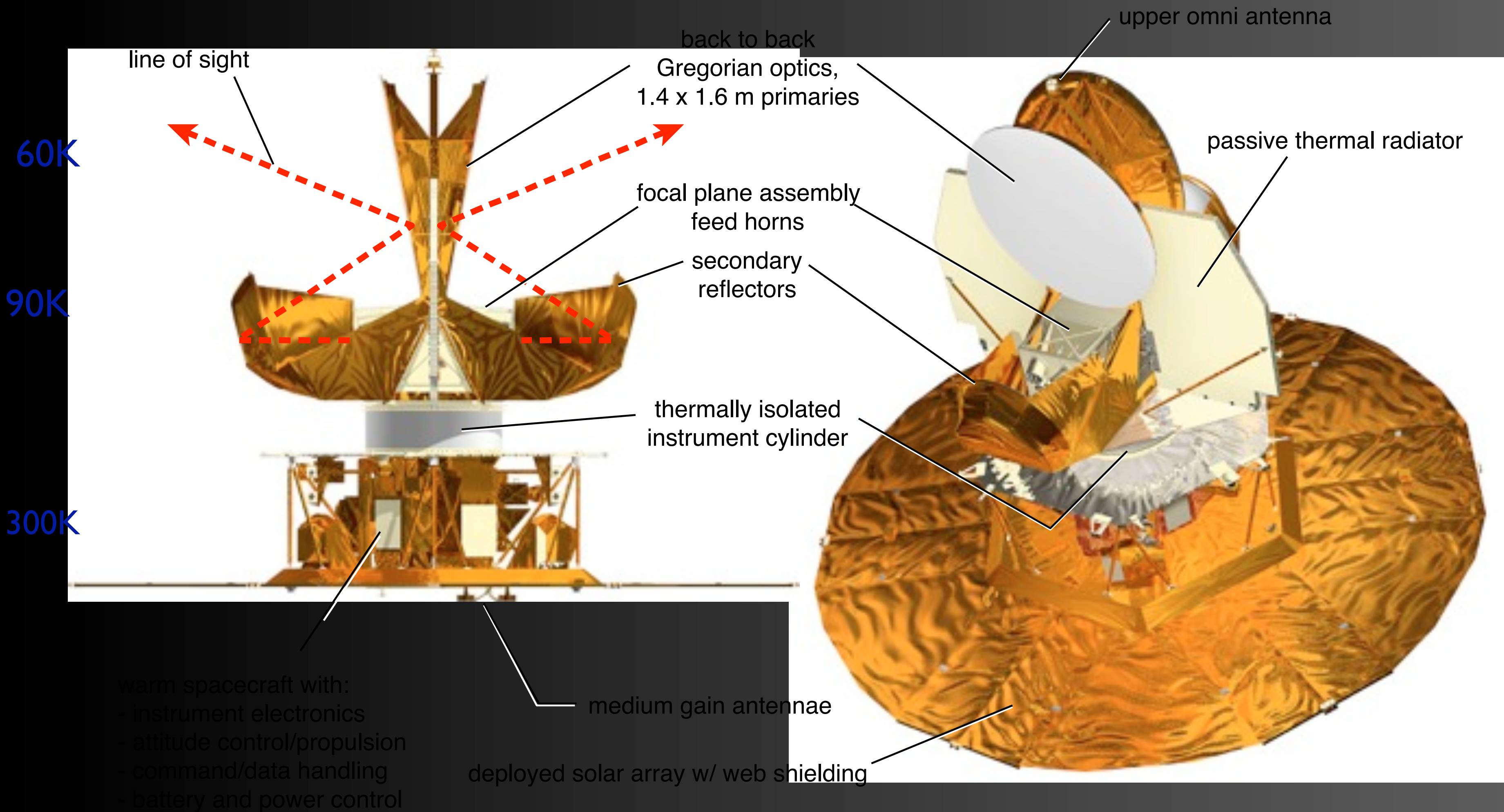
Angular Diameter Distance

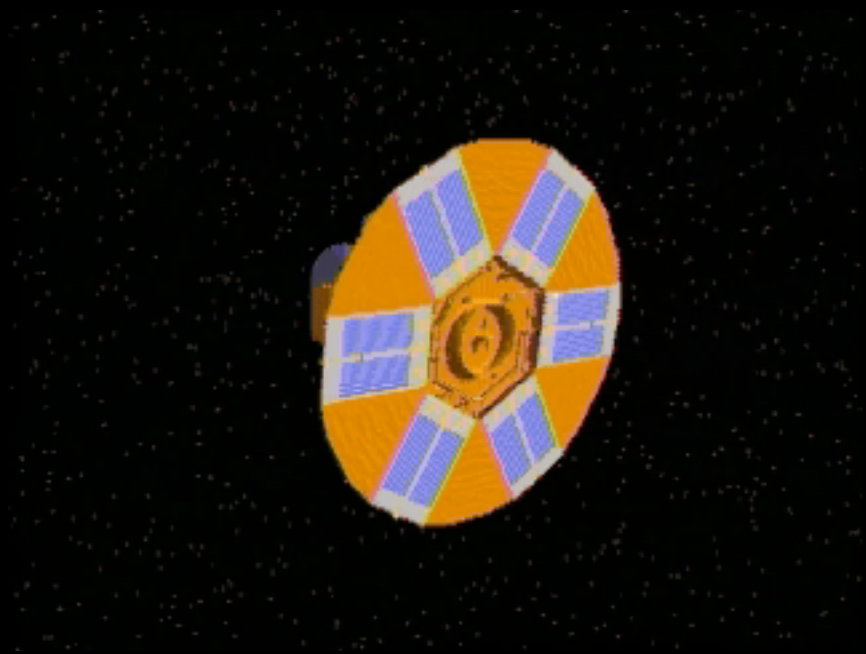
w = -1.8,..,-0.2

When combined with measurement of matter density constrains data to a line in Ω_m-w space

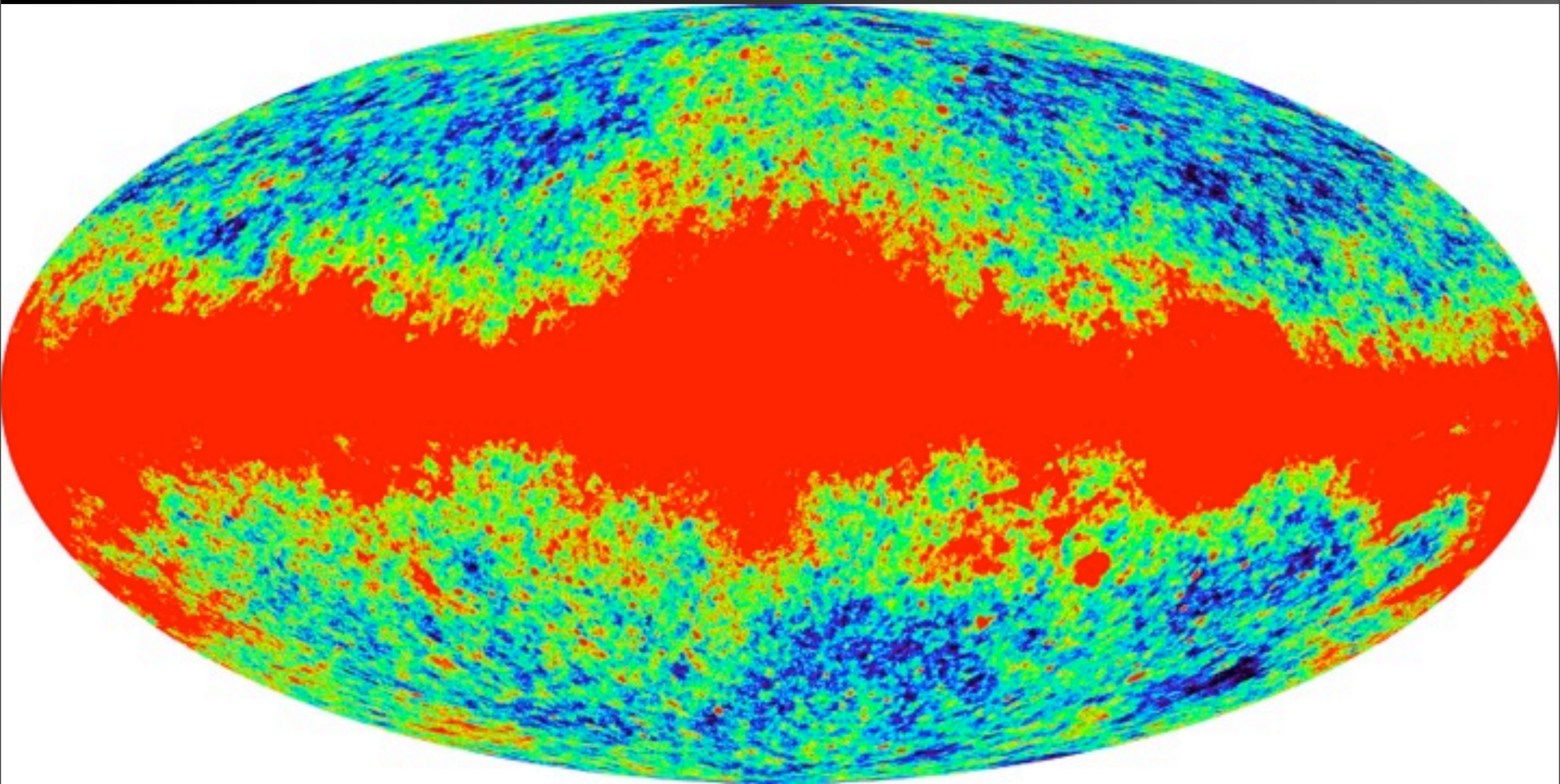


WMAP Spacecraft

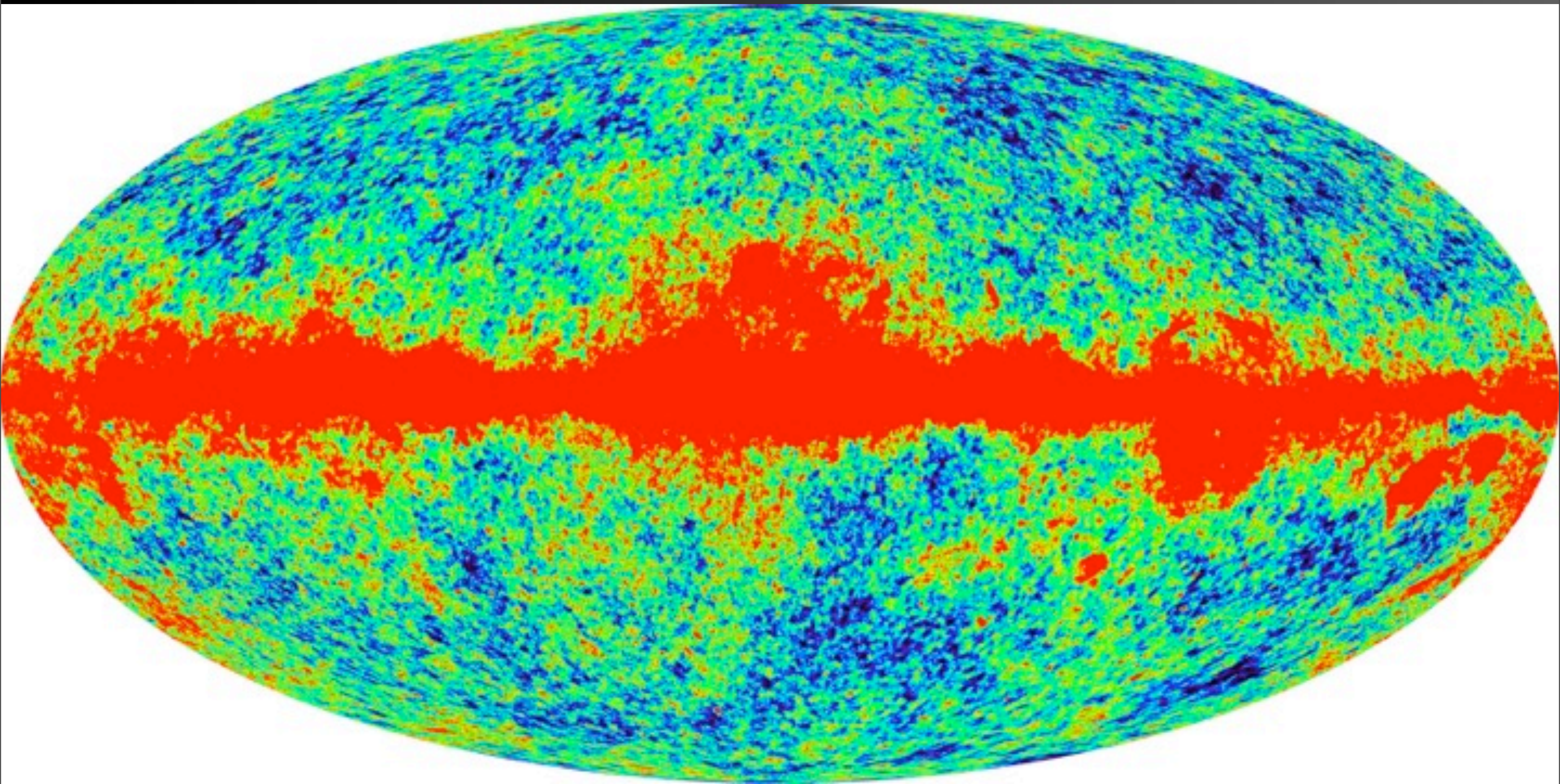




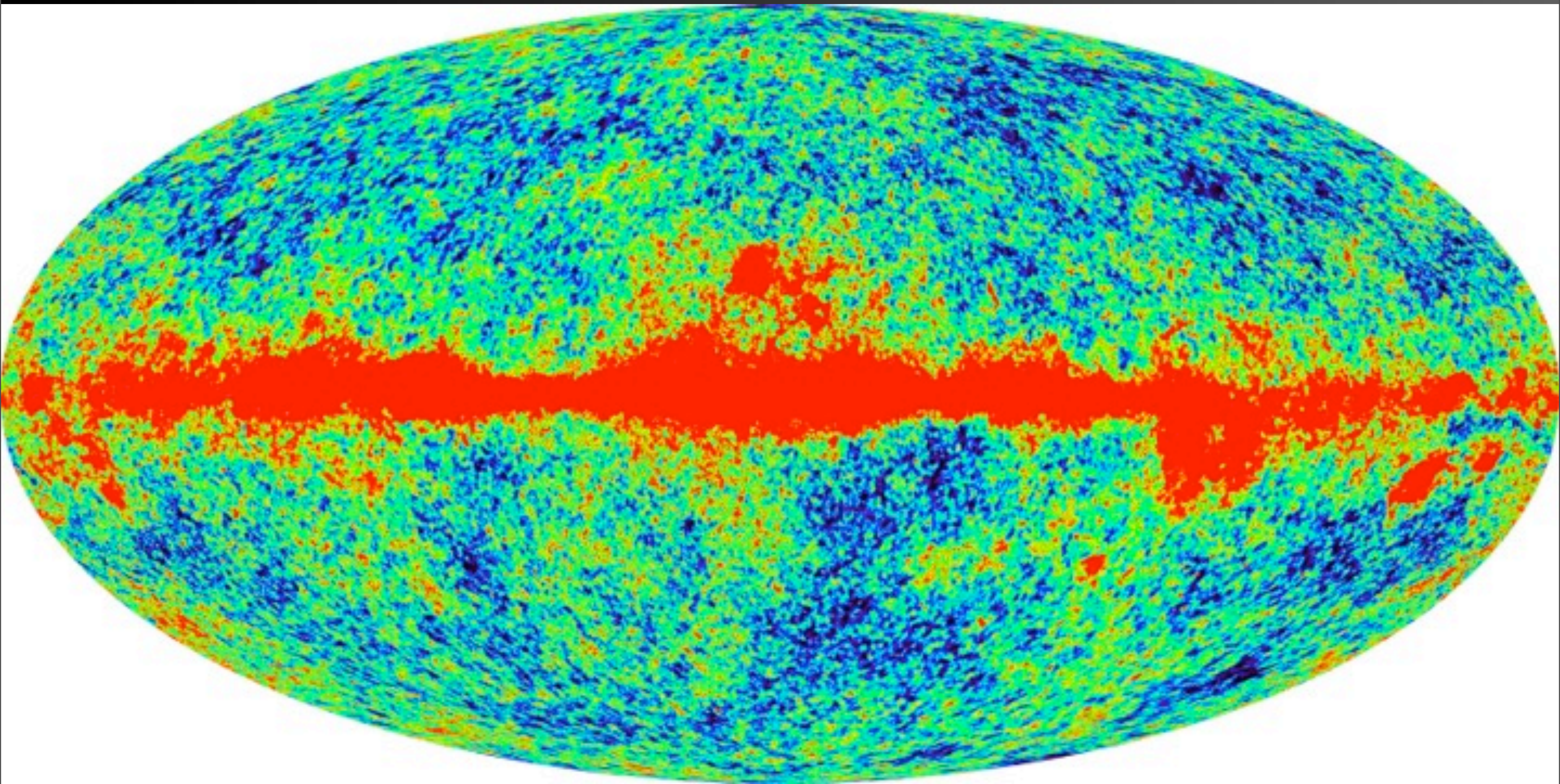
K - 22GHz



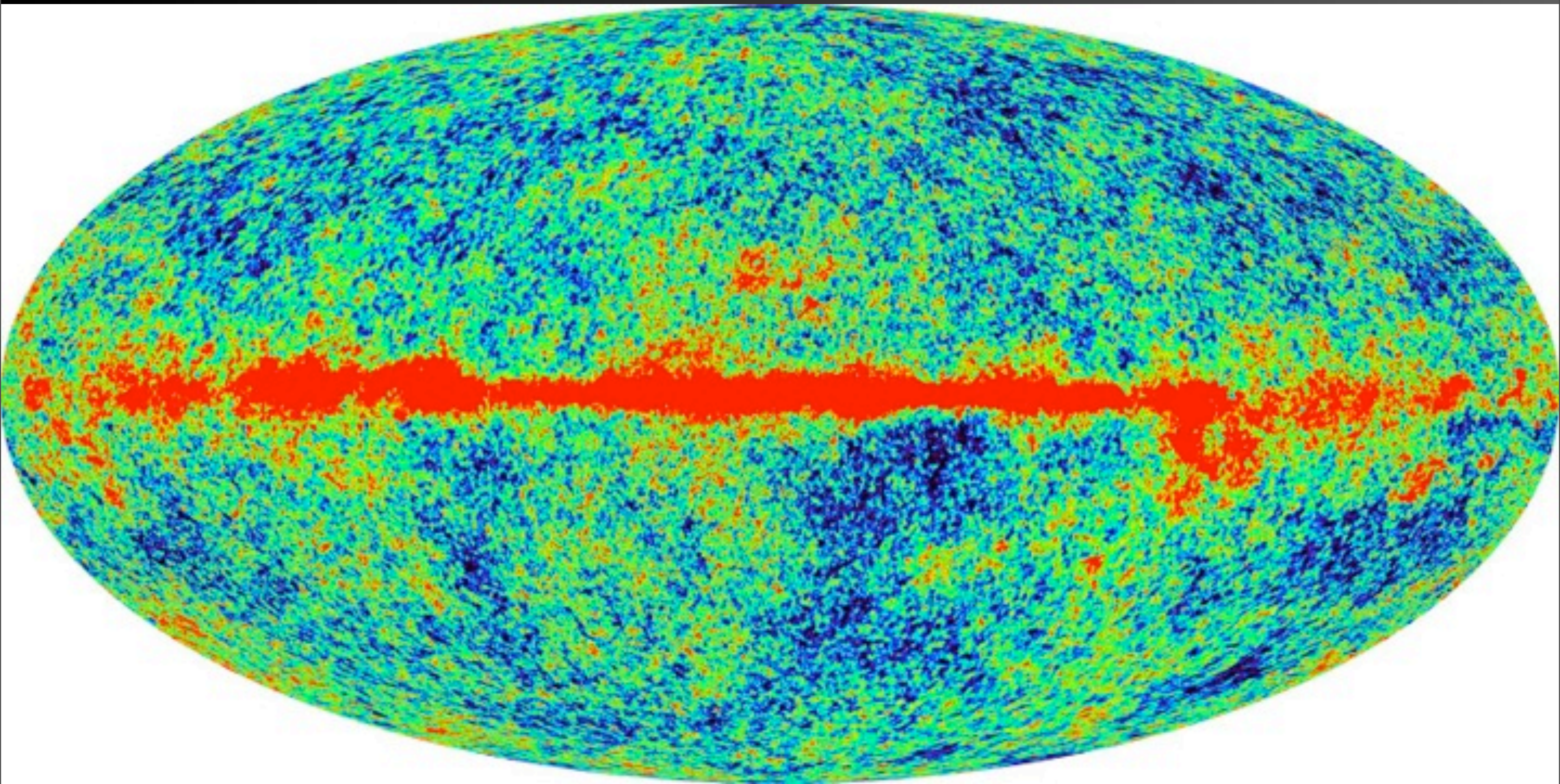
Ka - 33GHz



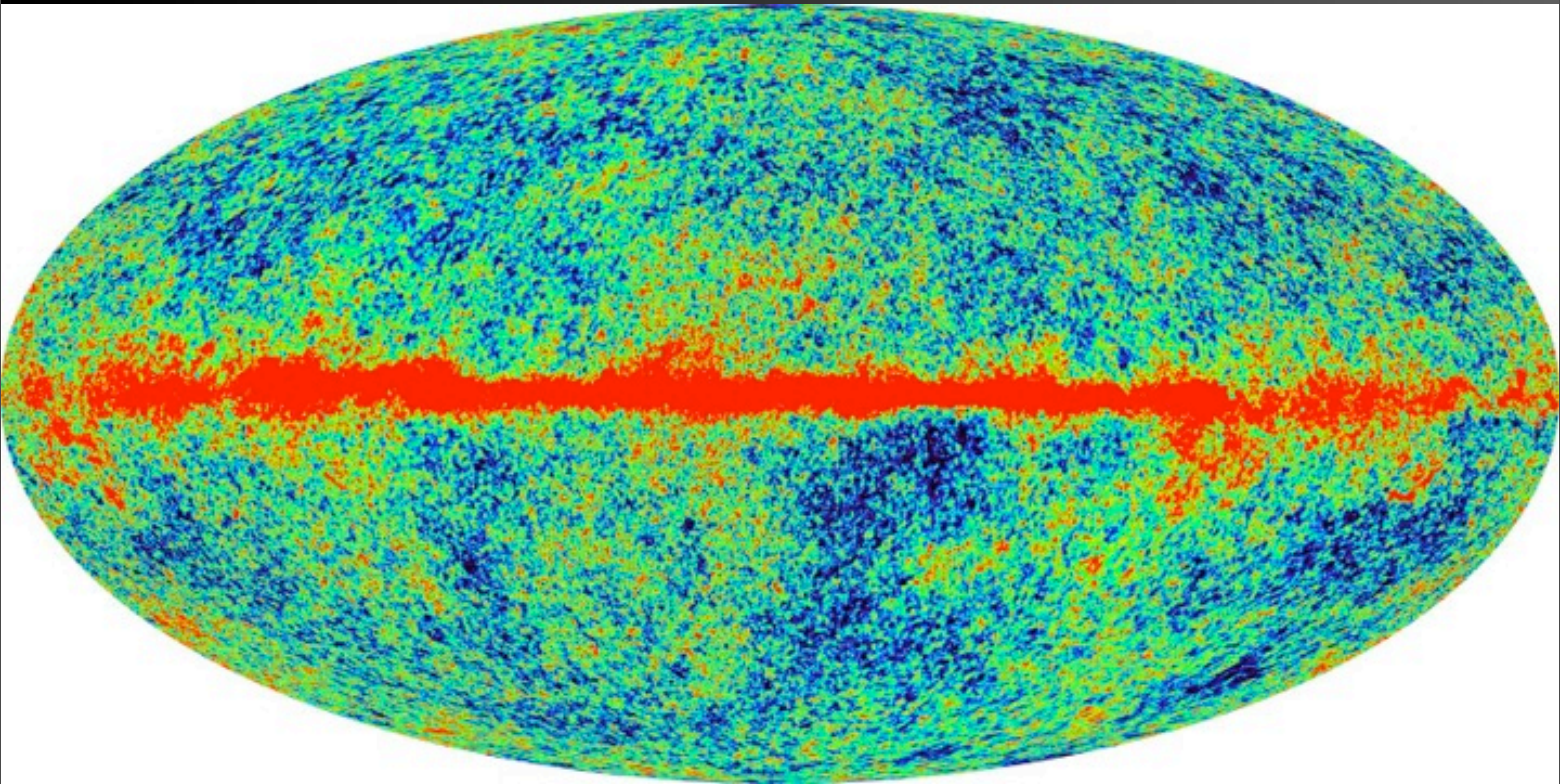
Q - 41GHz



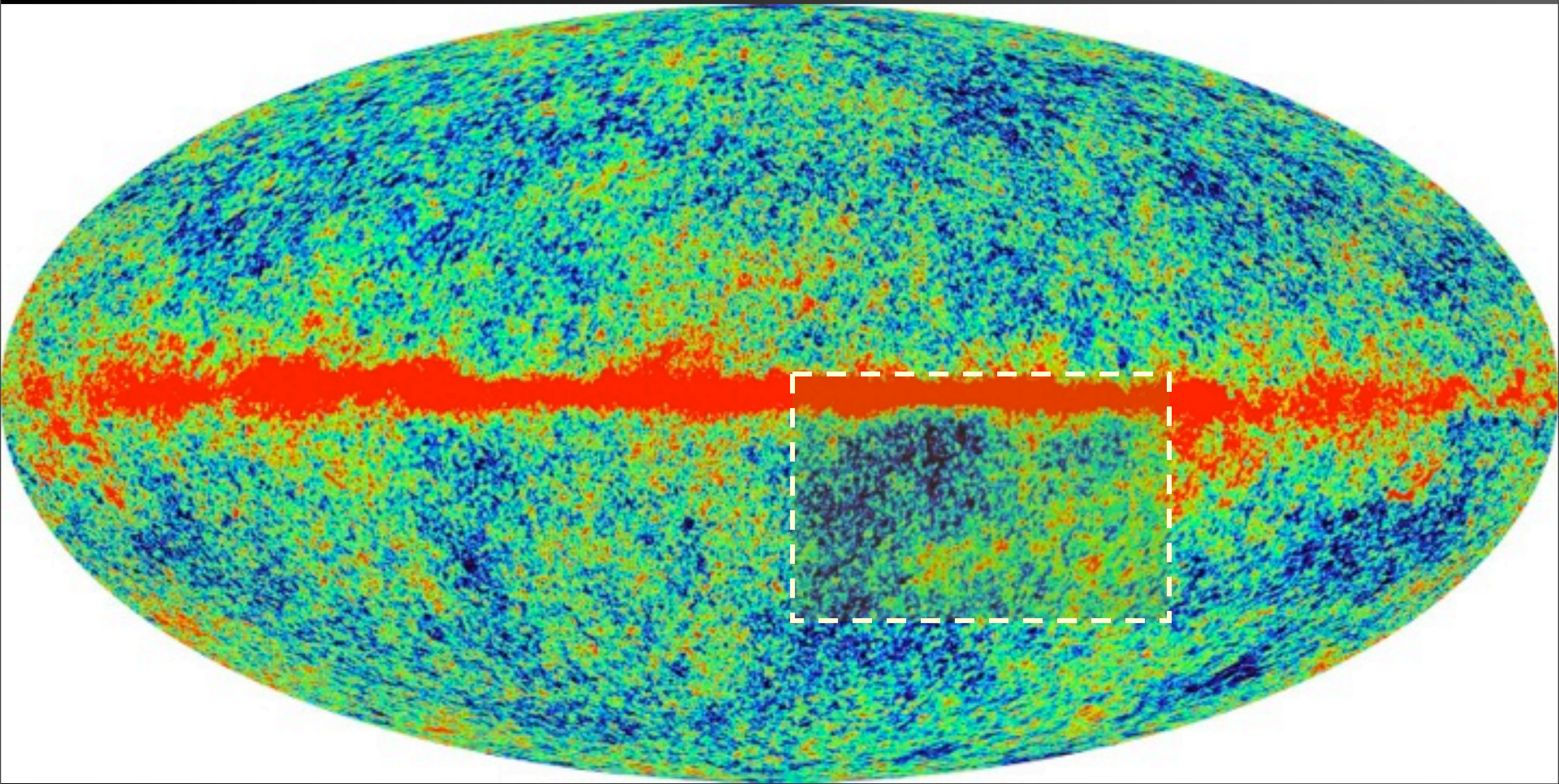
V - 61GHz

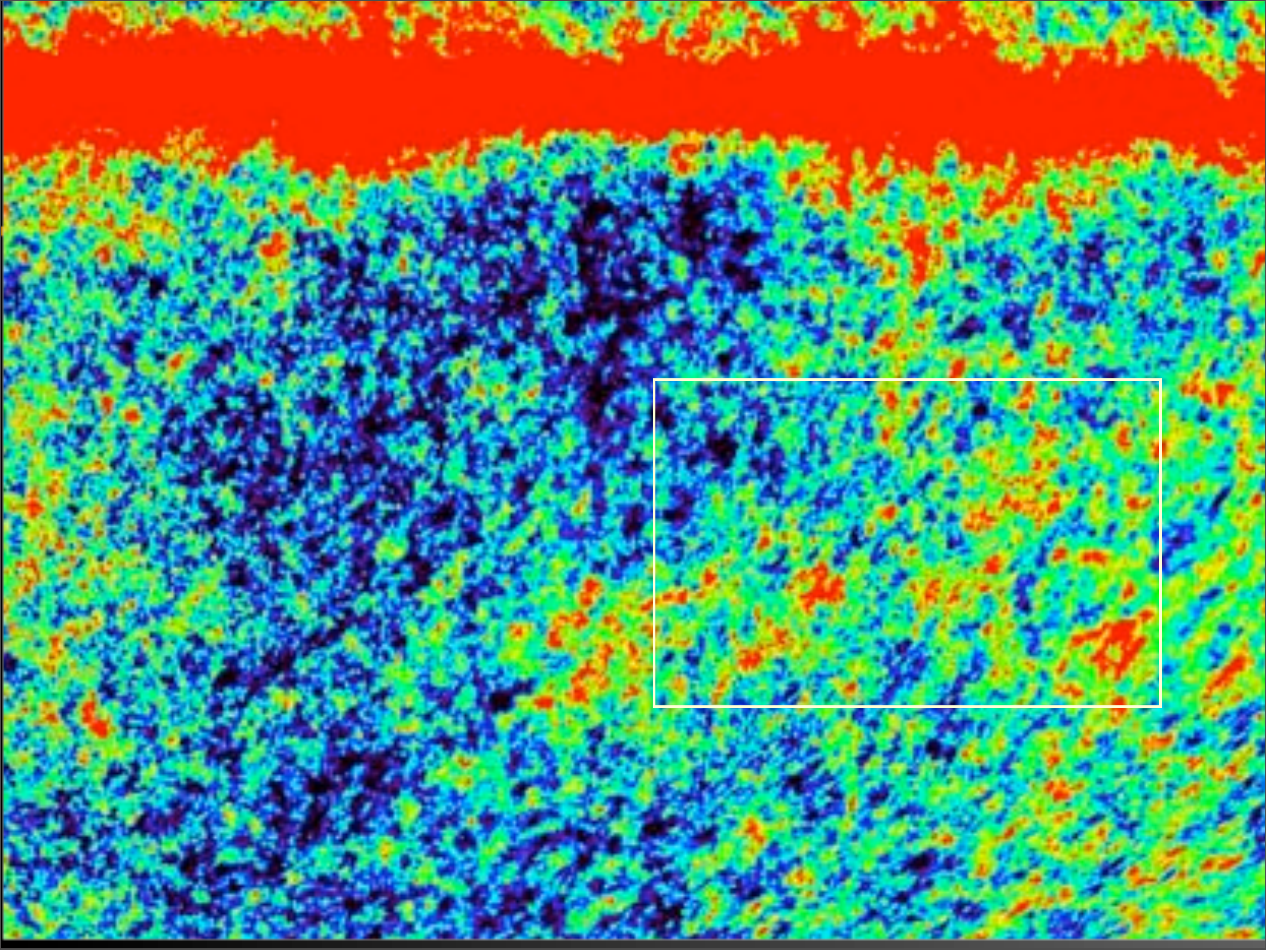


W - 94GHz



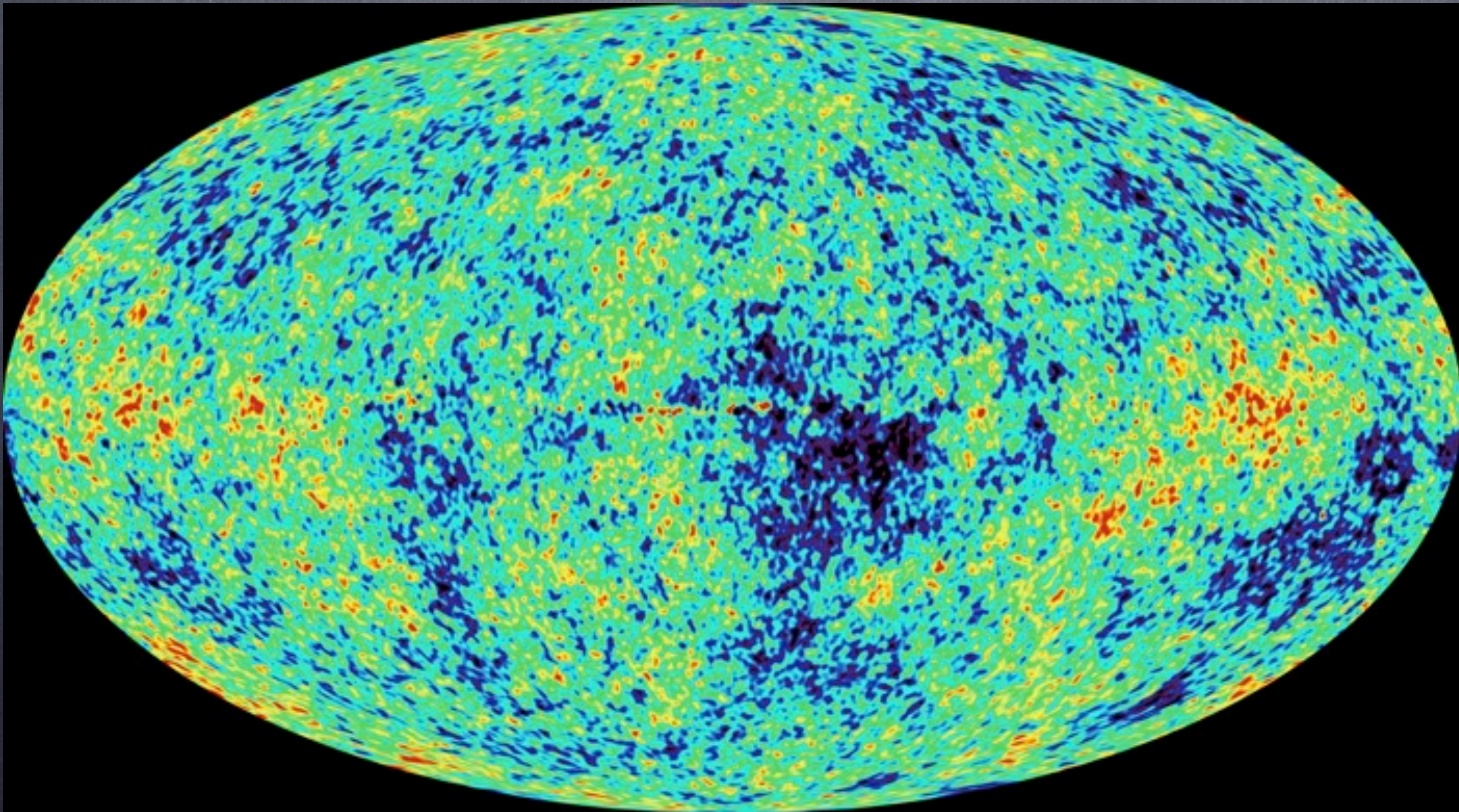
W - 94GHz



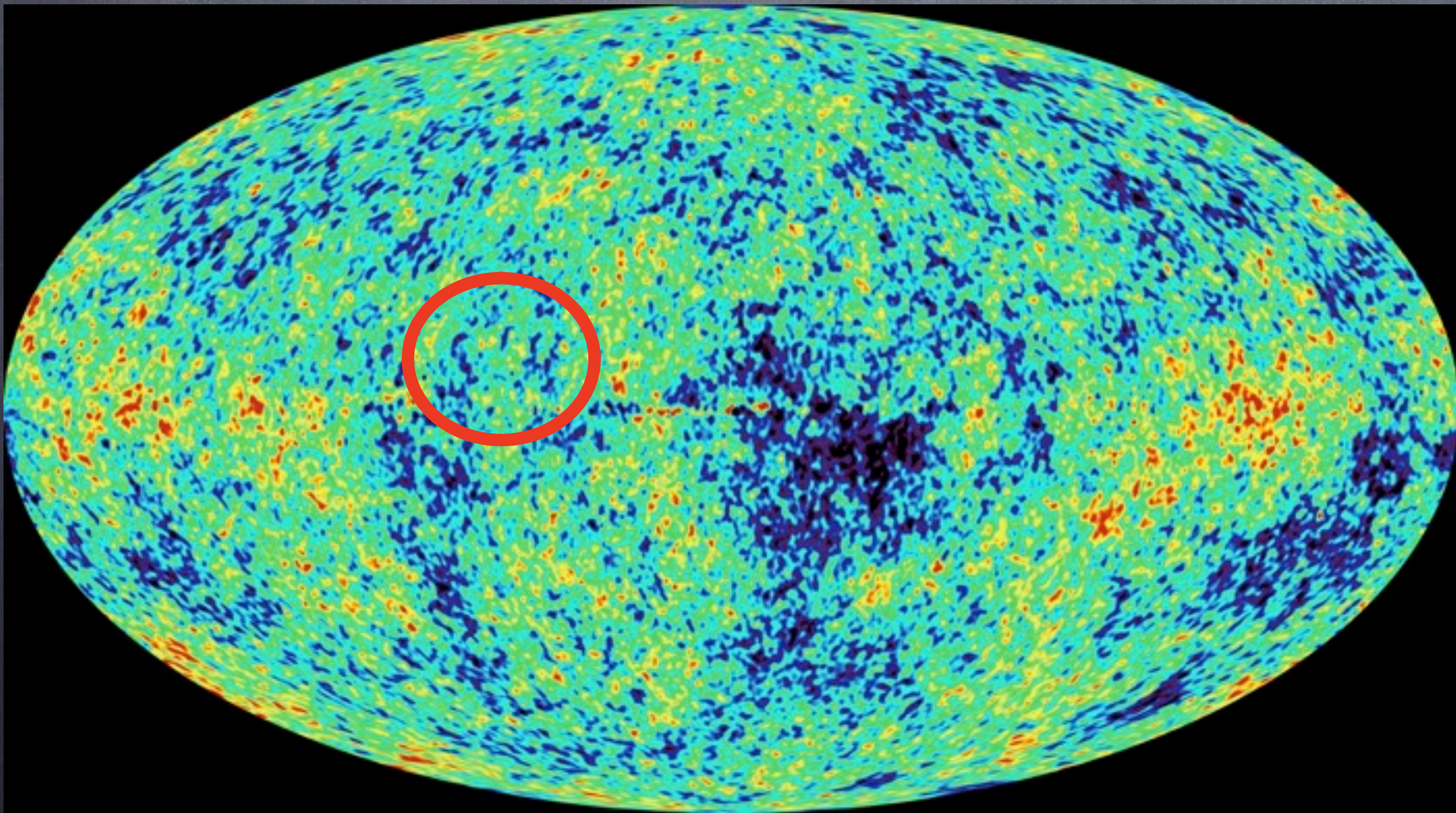


FOREGROUND CORRECTED MAP

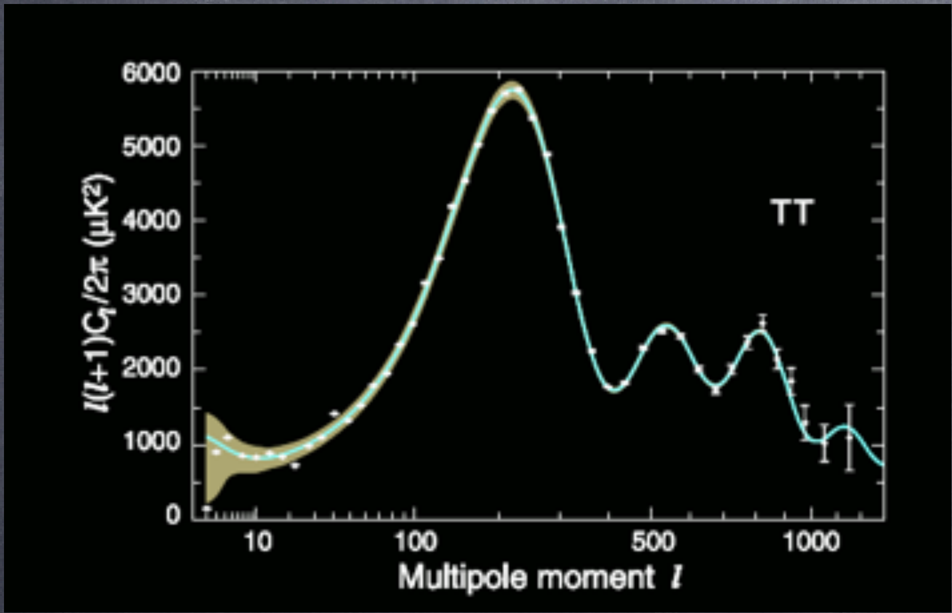
FOREGROUND CORRECTED MAP



FOREGROUND CORRECTED MAP



What Have We Learned?



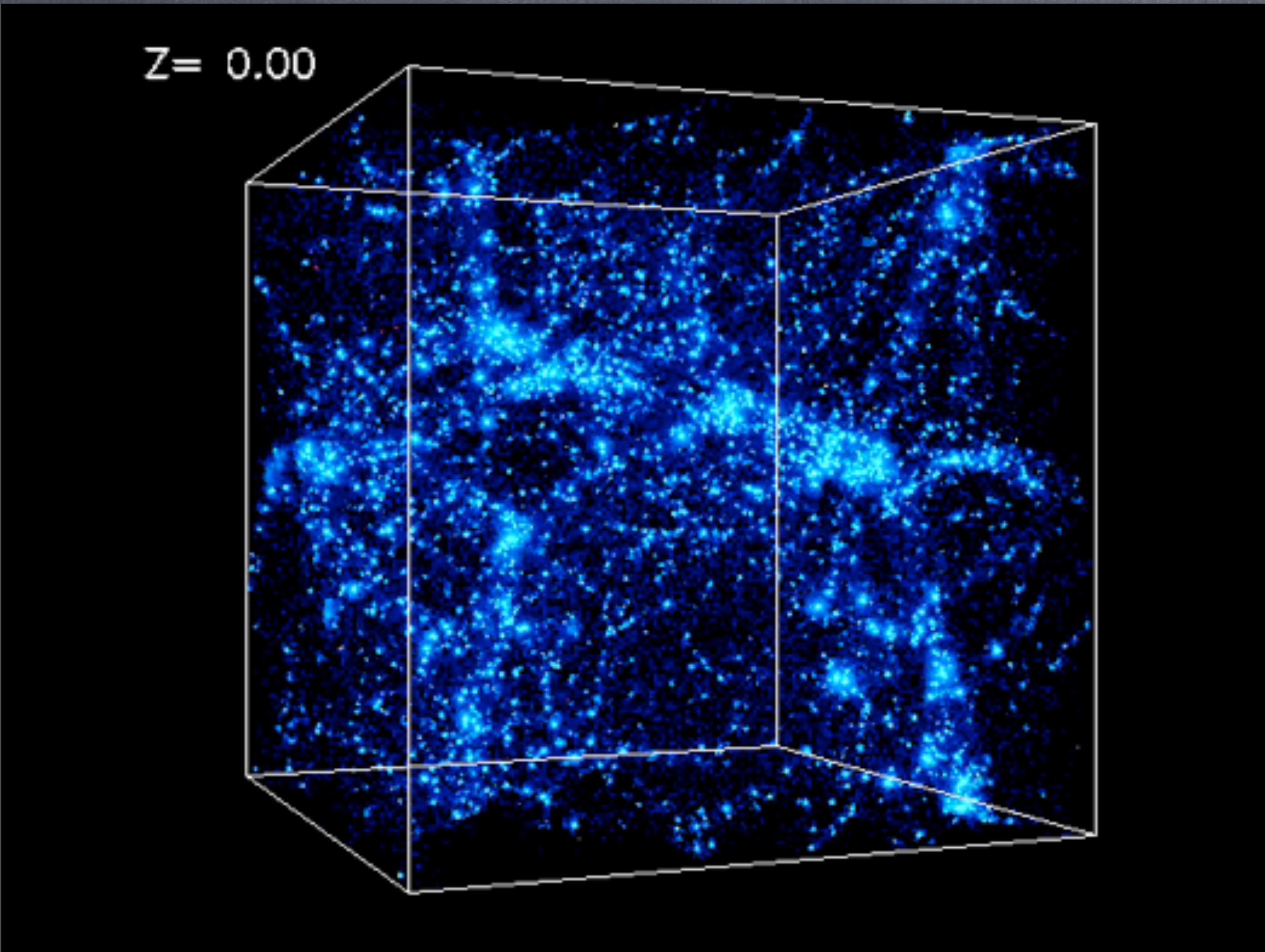
- Simple model fits a wide range of data (only 5 numbers)
- Age of universe:13.7 Gyr
- Composition:
  - Atoms: 4%
  - Matter: 23%
  - Dark Energy: 73%
- Scale Invariant Fluctuations seed growth of galaxies
- First Stars formed ~200 Myr after the big bang

With WMAP9, we have narrowed the constraints on the six-dimensional parameter space by 40,000 from pre-WMAP CMB

Growth of Structure

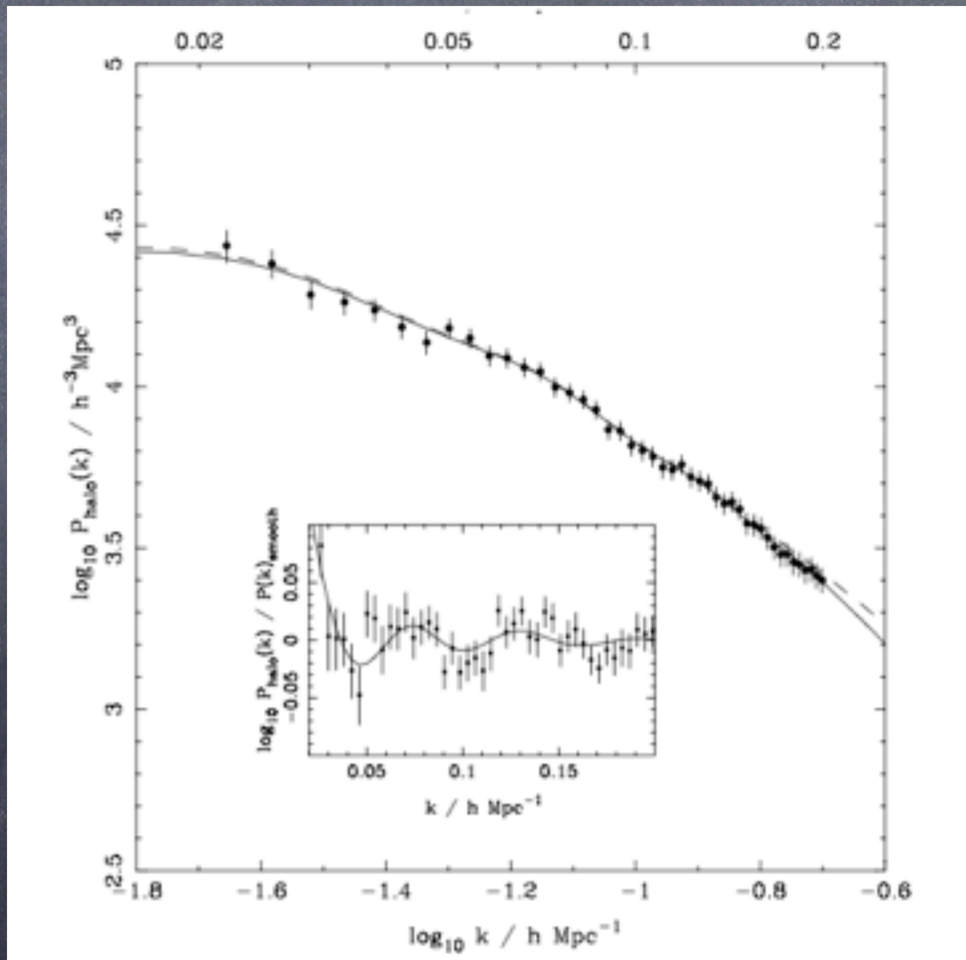
National Center for Supercomputer Applications by Andrey Kravtsov

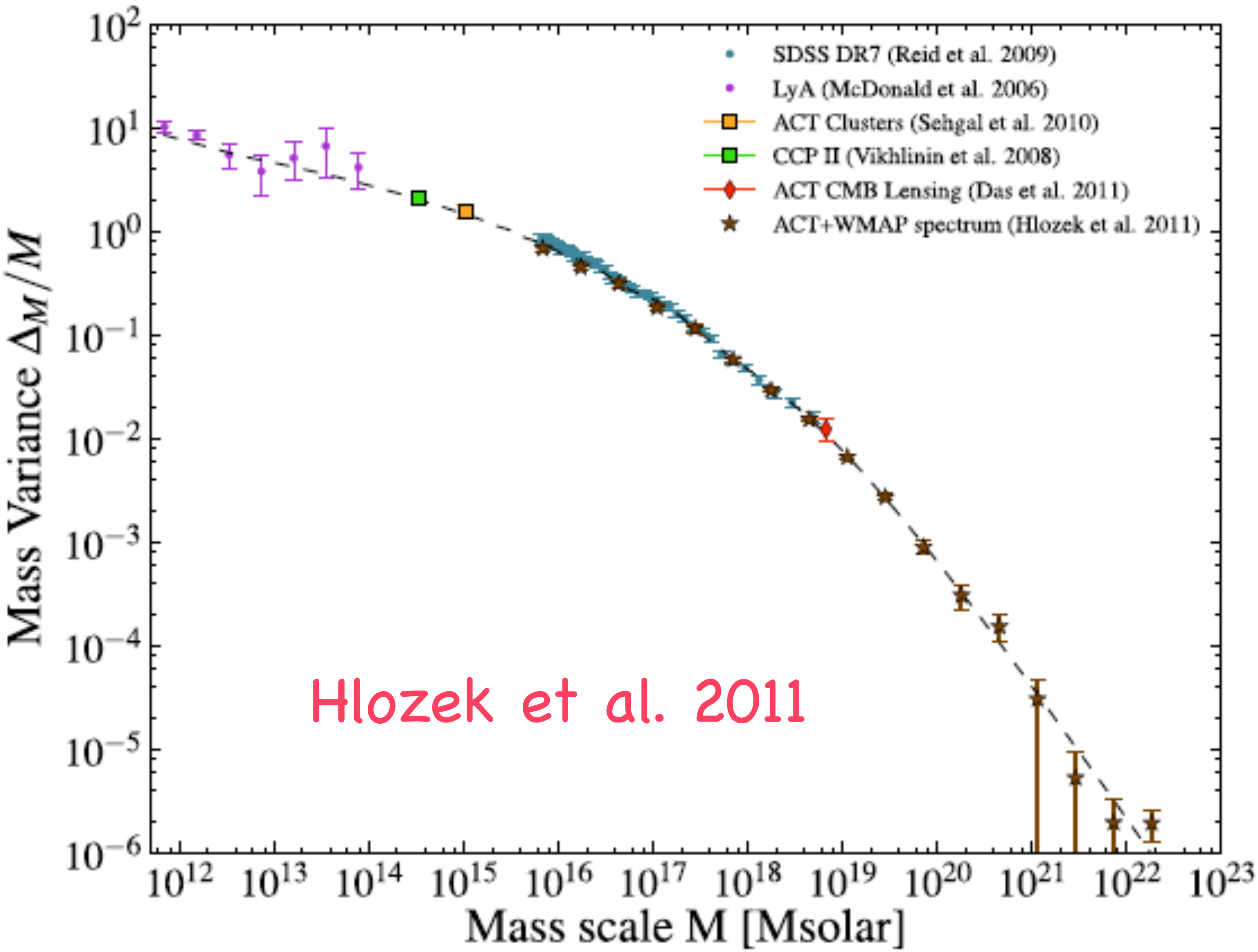
Growth of Structure



National Center for Supercomputer Applications by Andrey Kravtsov

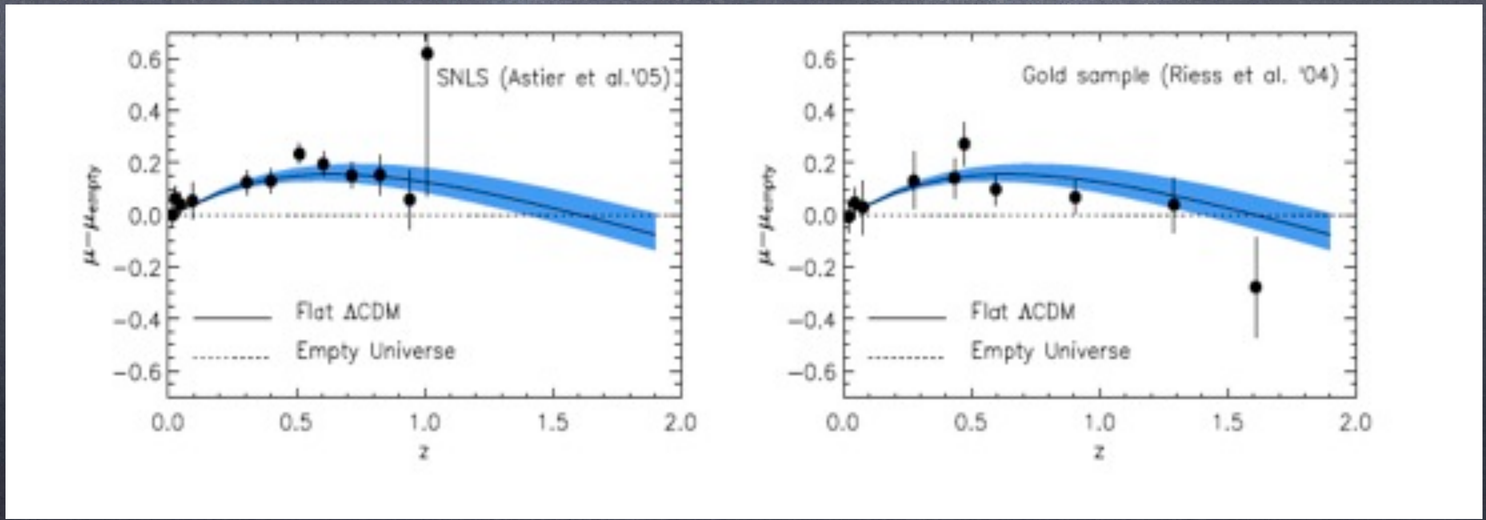
Today's Universe (Sloan Digital Sky Survey)




SDSS DR7 (Reid et al. 2009)
LyA (McDonald et al. 2006)
ACT Clusters (Sehgal et al. 2010)
CCP II (Vikhlinin et al. 2008)
ACT CMB Lensing (Das et al. 2011)
ACT+WMAP spectrum (Hlozek et al. 2011)
Mass Variance Δ_M/M
Mass scale M [Msolar]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21} 10^{22} 10^{23}
Hlozek et al. 2011

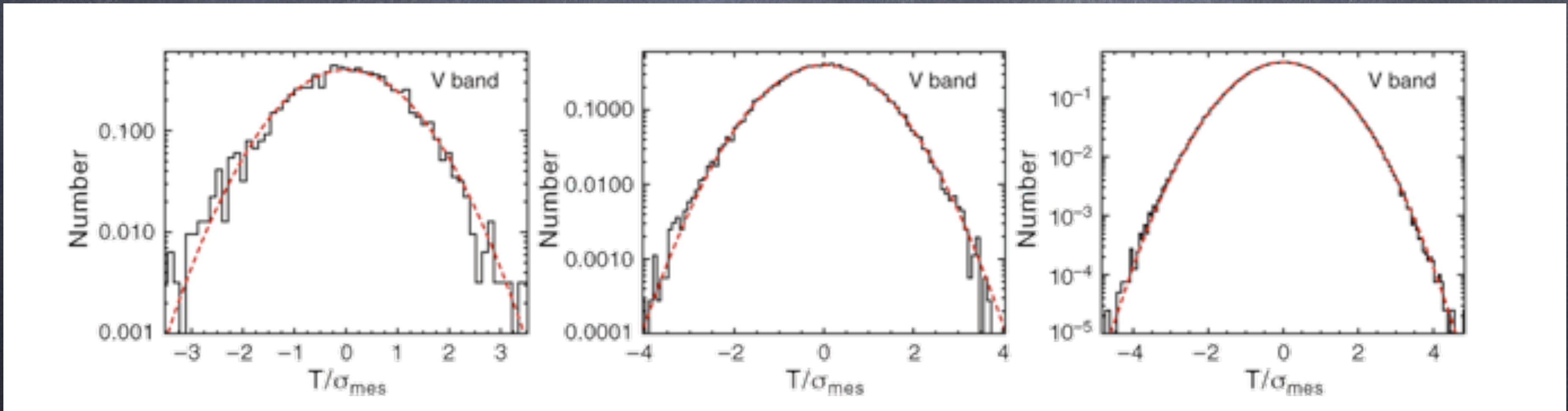
All of the pieces seem to fit....

- Supernova distances
- Hubble Constant
- Age of Universe
- Cluster Properties
- Gravitational Lenses
- Nuclear Abundances
- Lyman alpha forest
- Galaxy Velocities

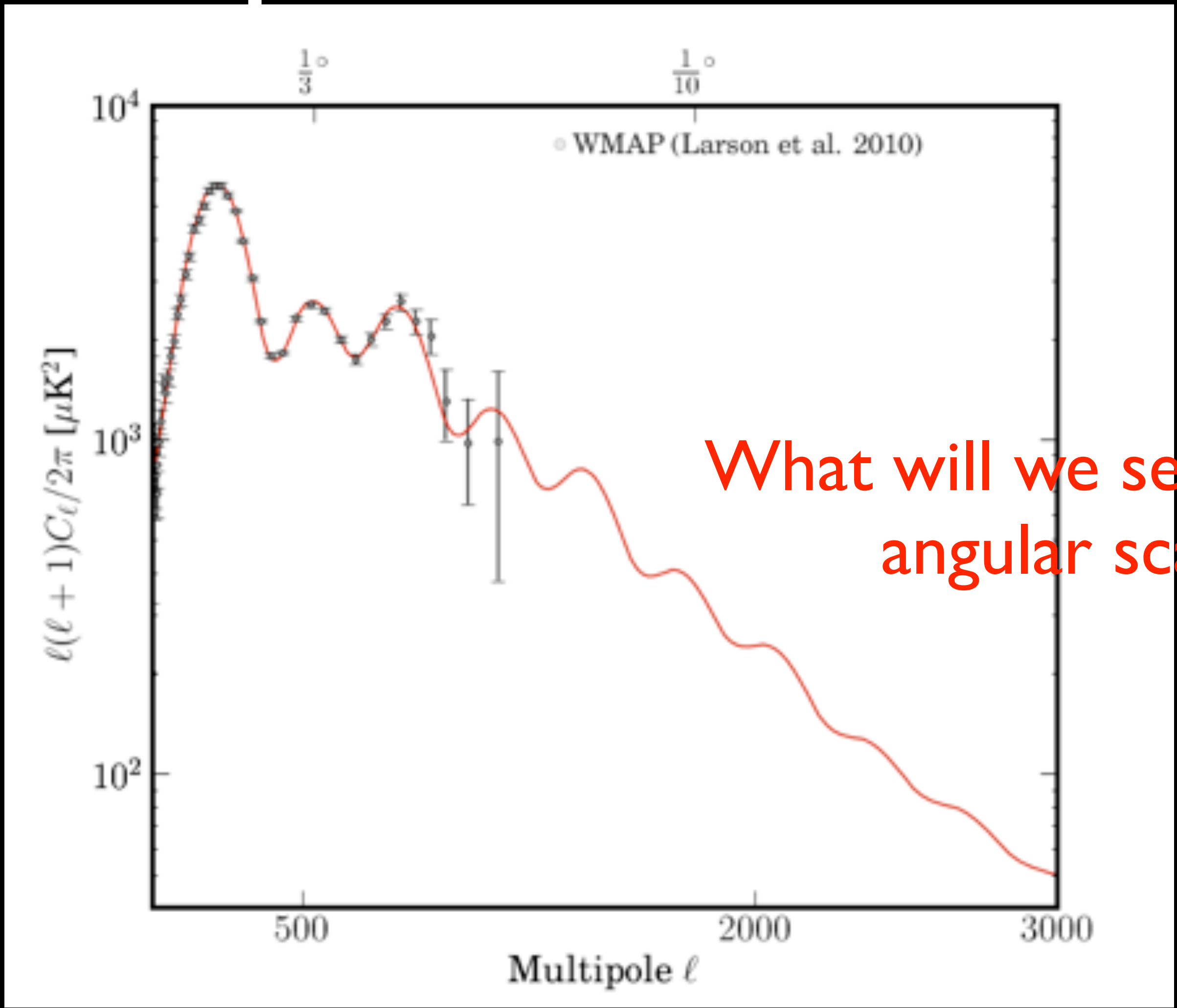


The Universe is Simple?

- Fluctuations are accurately as Gaussian, Random Phase
- No evidence for spatial variations in fluctuation properties
- No evidence for interaction terms
- No sign of global topology



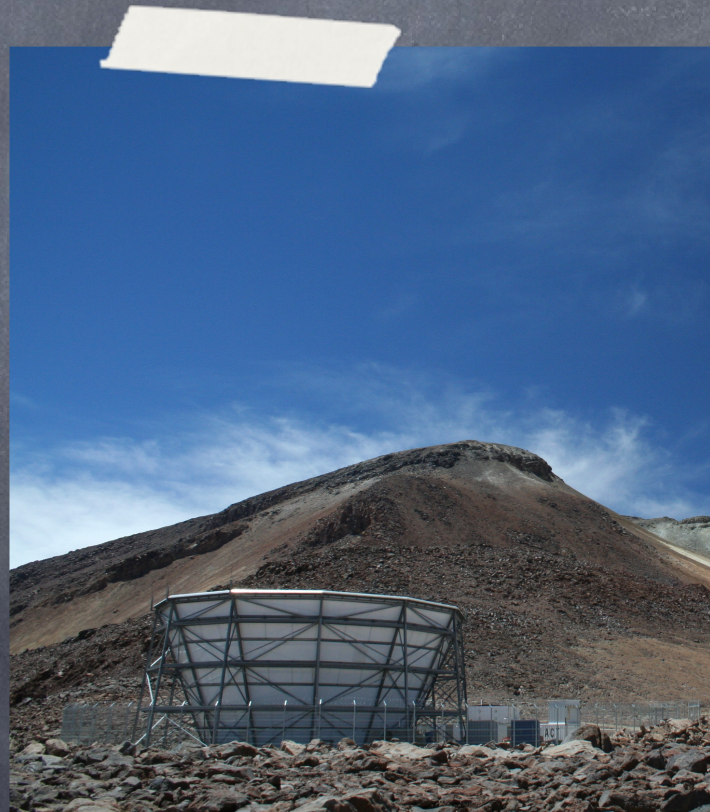
Models make predictions....



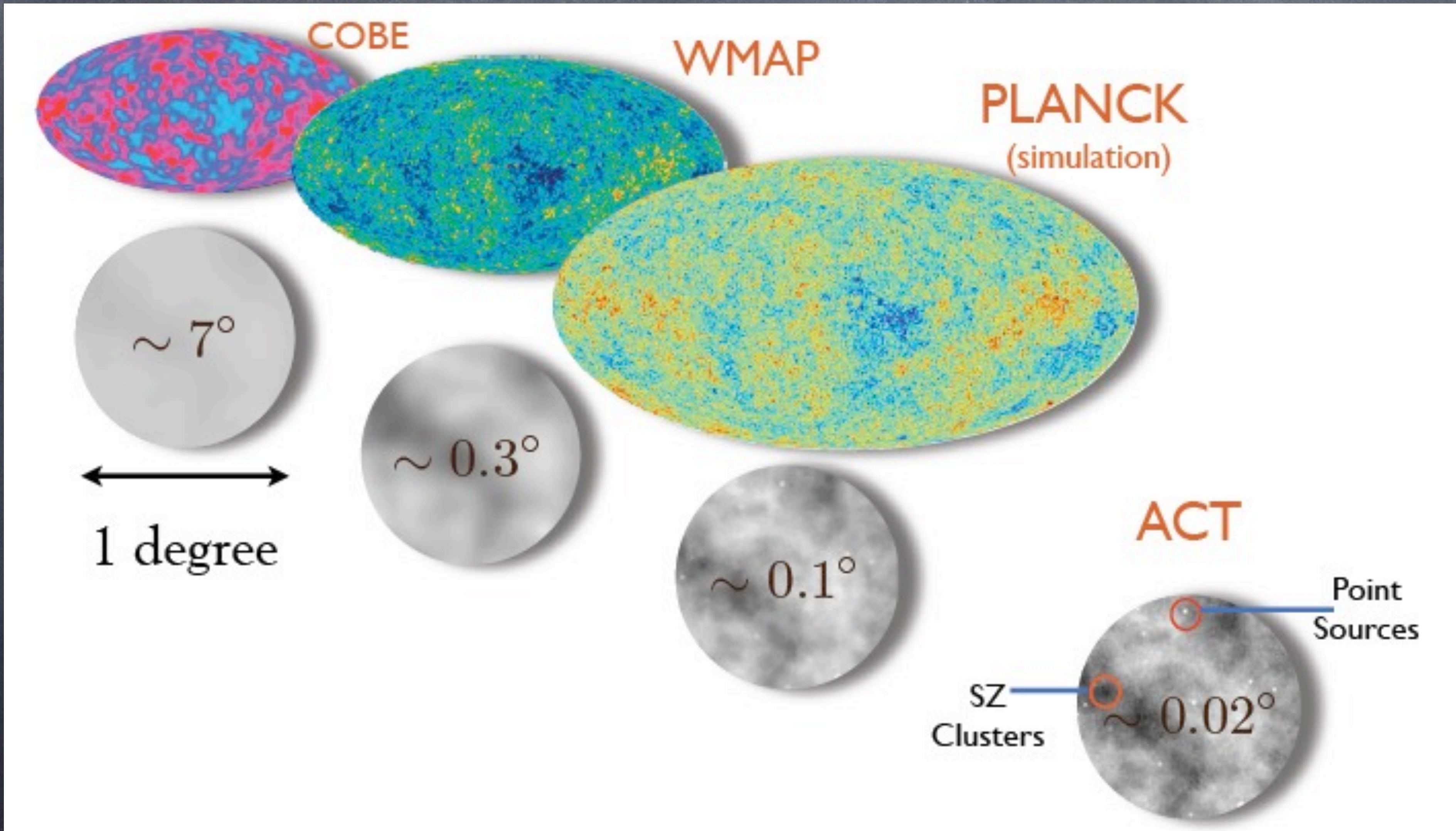
What will we see on small angular scales?

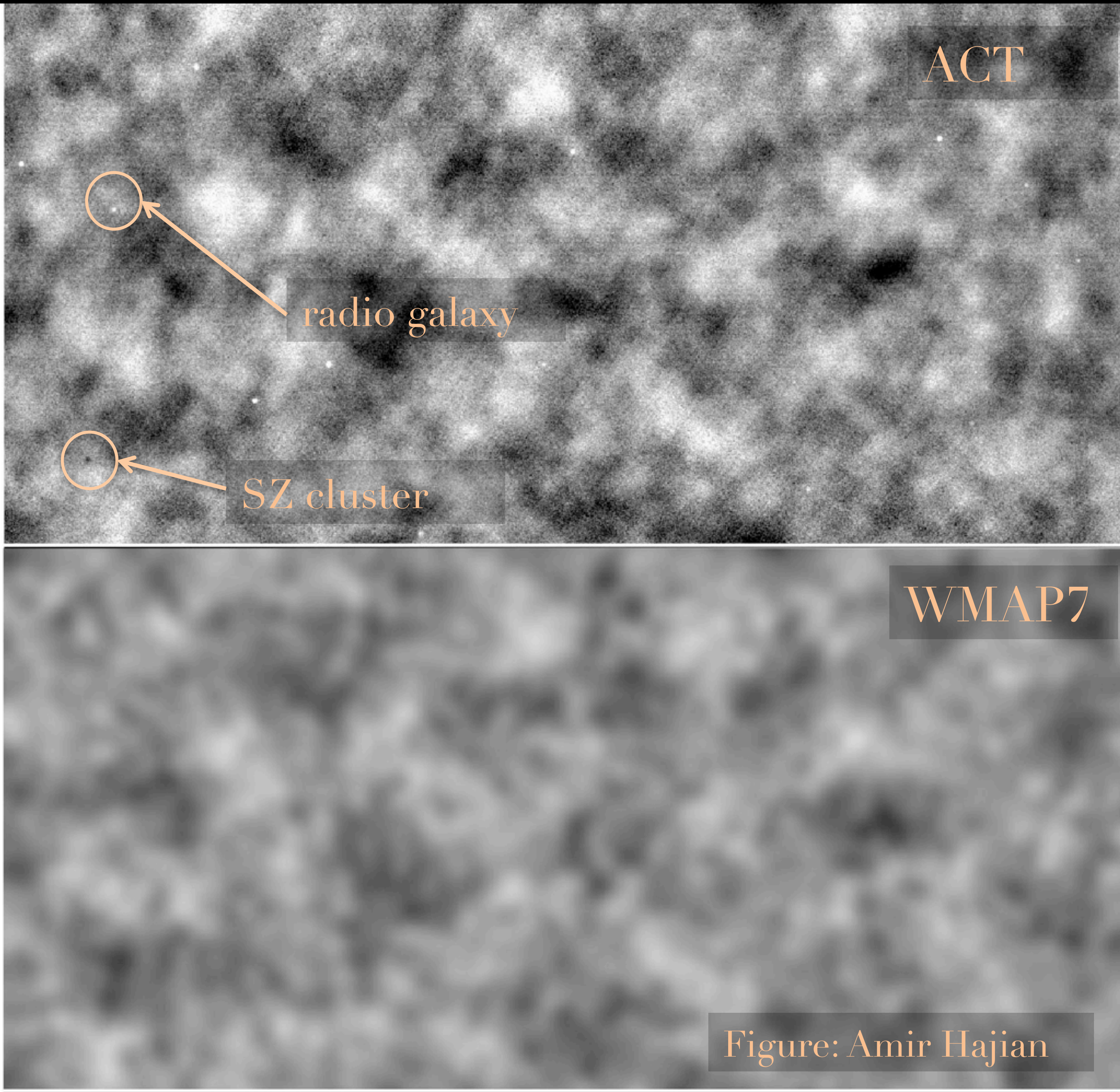
ACT

- Led by Lyman Page
- 80 scientists on 5 continents
- 6-meter telescope on Cerro Tocco (5190 m) in the Atacama Desert. Observing the sky at 148, 218 and 277 Ghz

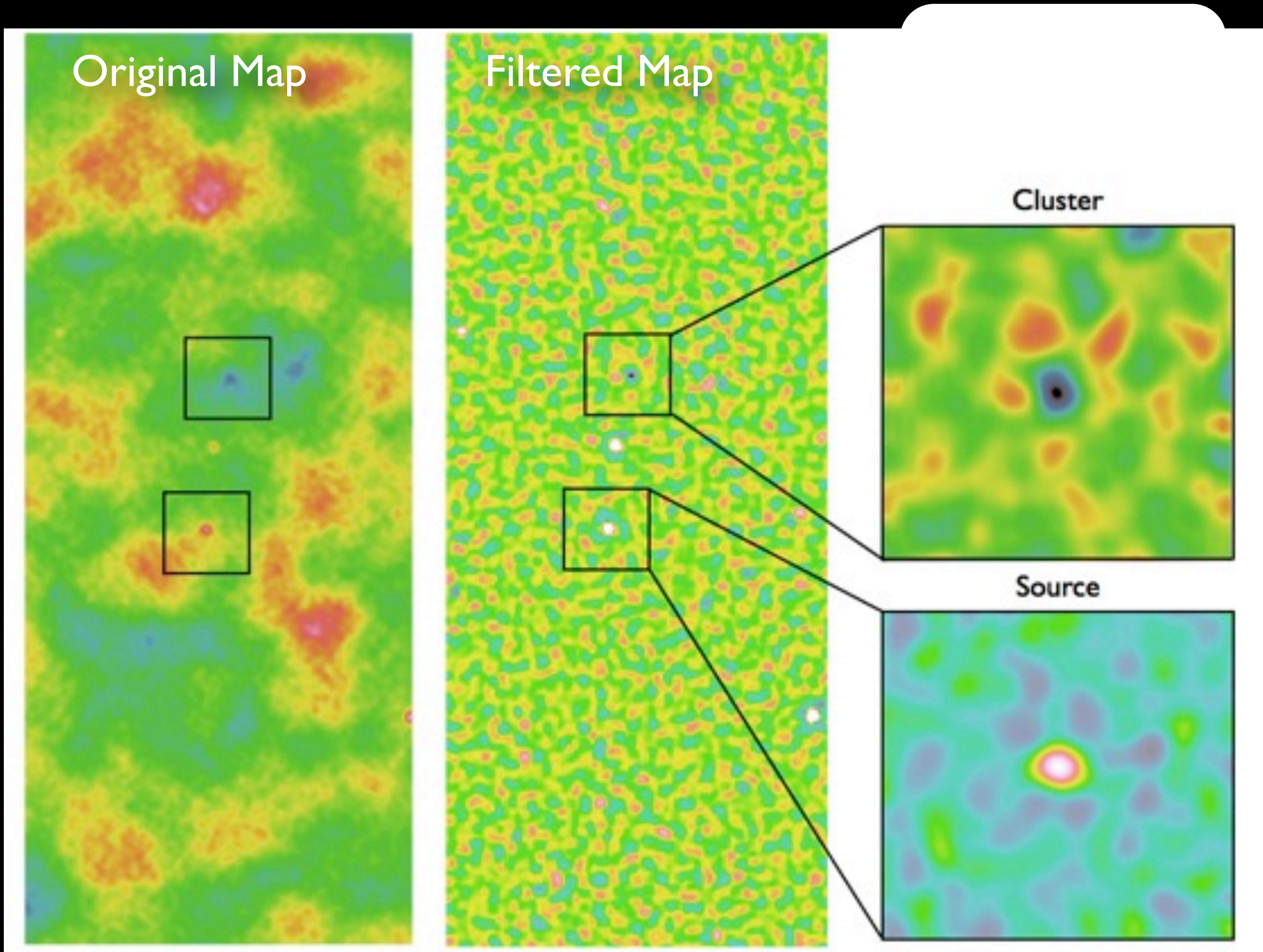


ACT and SPT probe smaller scales

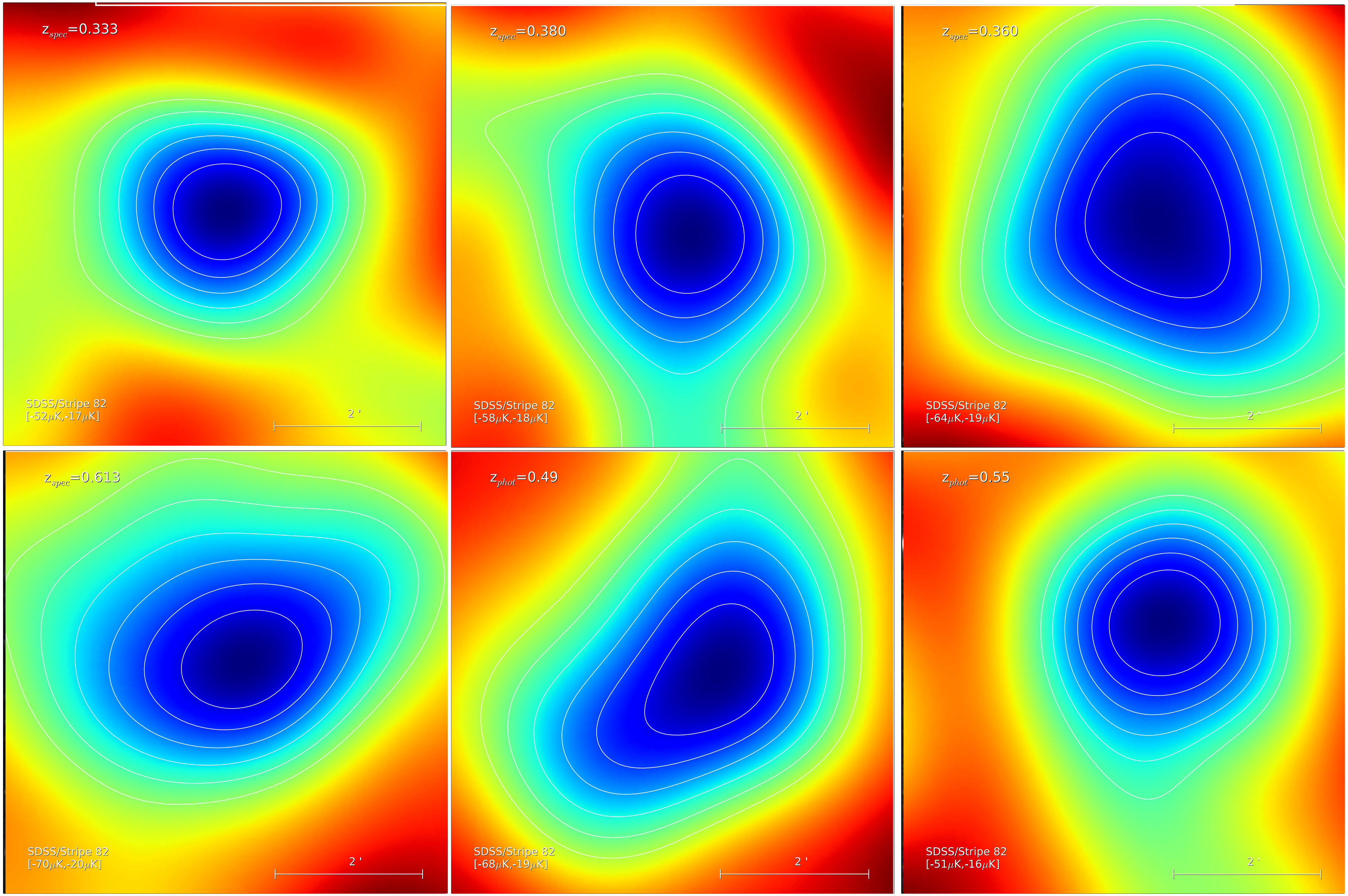



ACT
radio galaxy
SZ cluster
WMAP7
Figure: Amir Hajian

Detecting Clusters and Sources

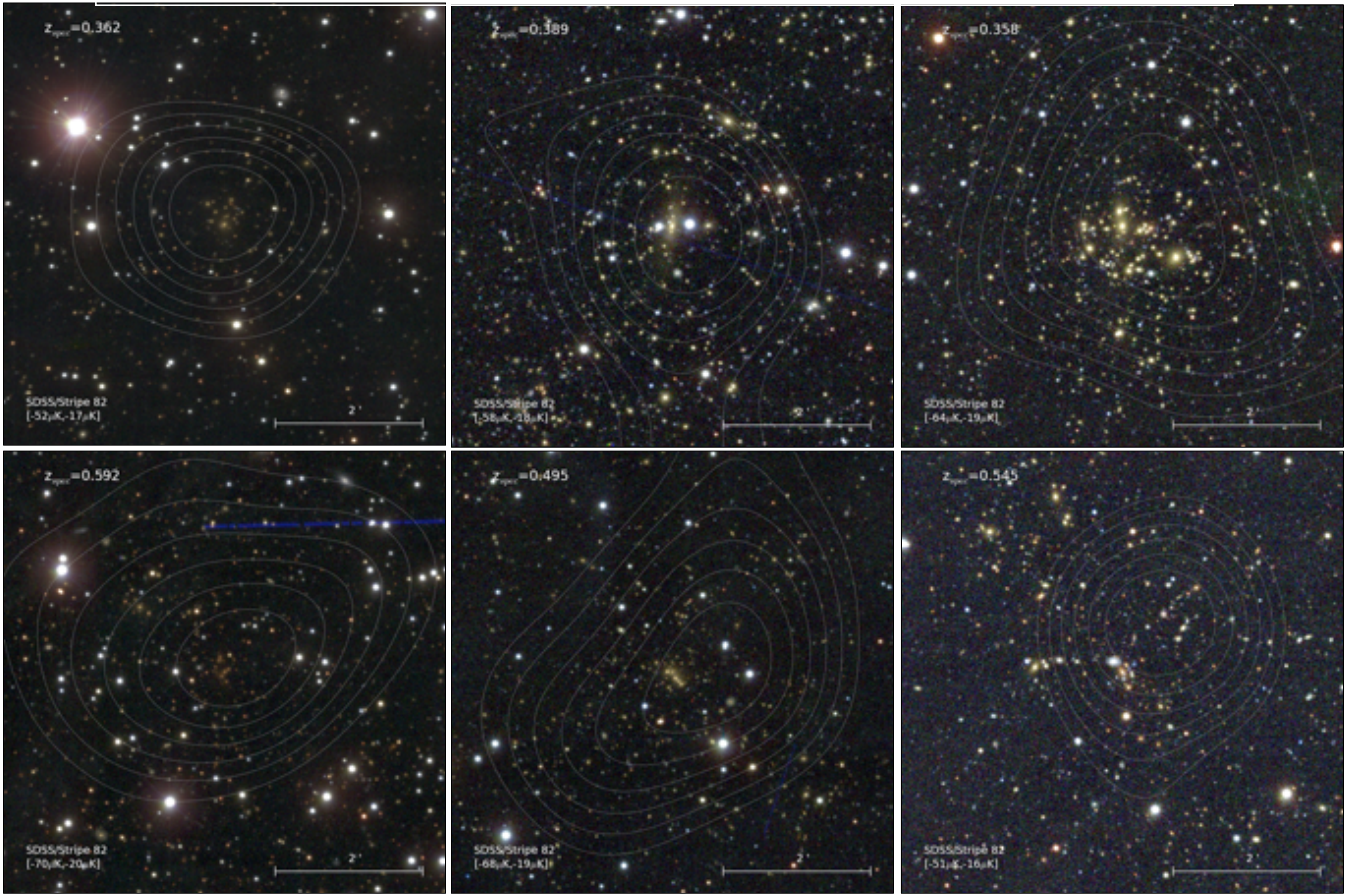


Some New Clusters on SDSS/Stripe 82



Menanteau et al. (in prep)

Some New Clusters on SDSS/Stripe 82



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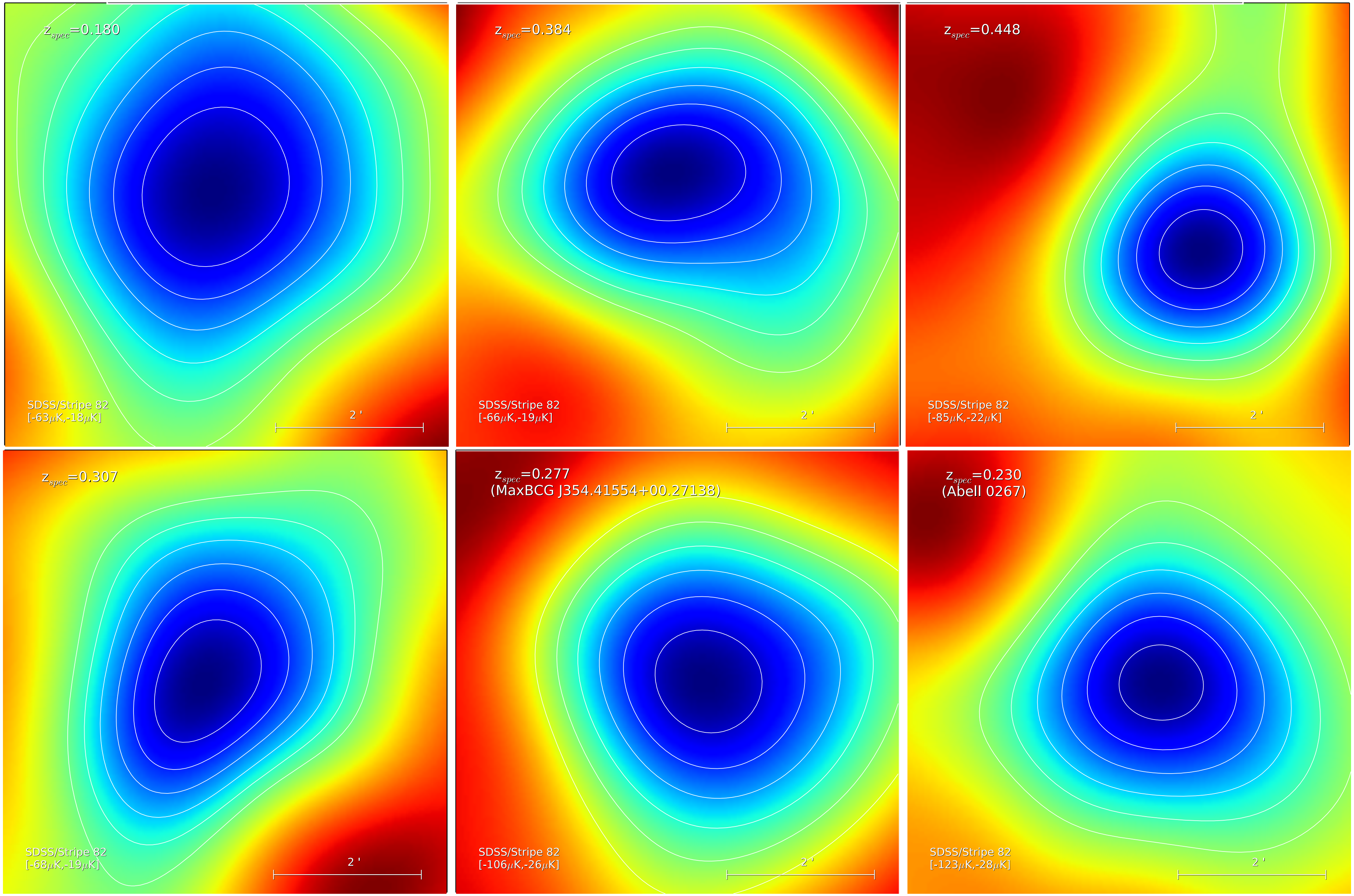

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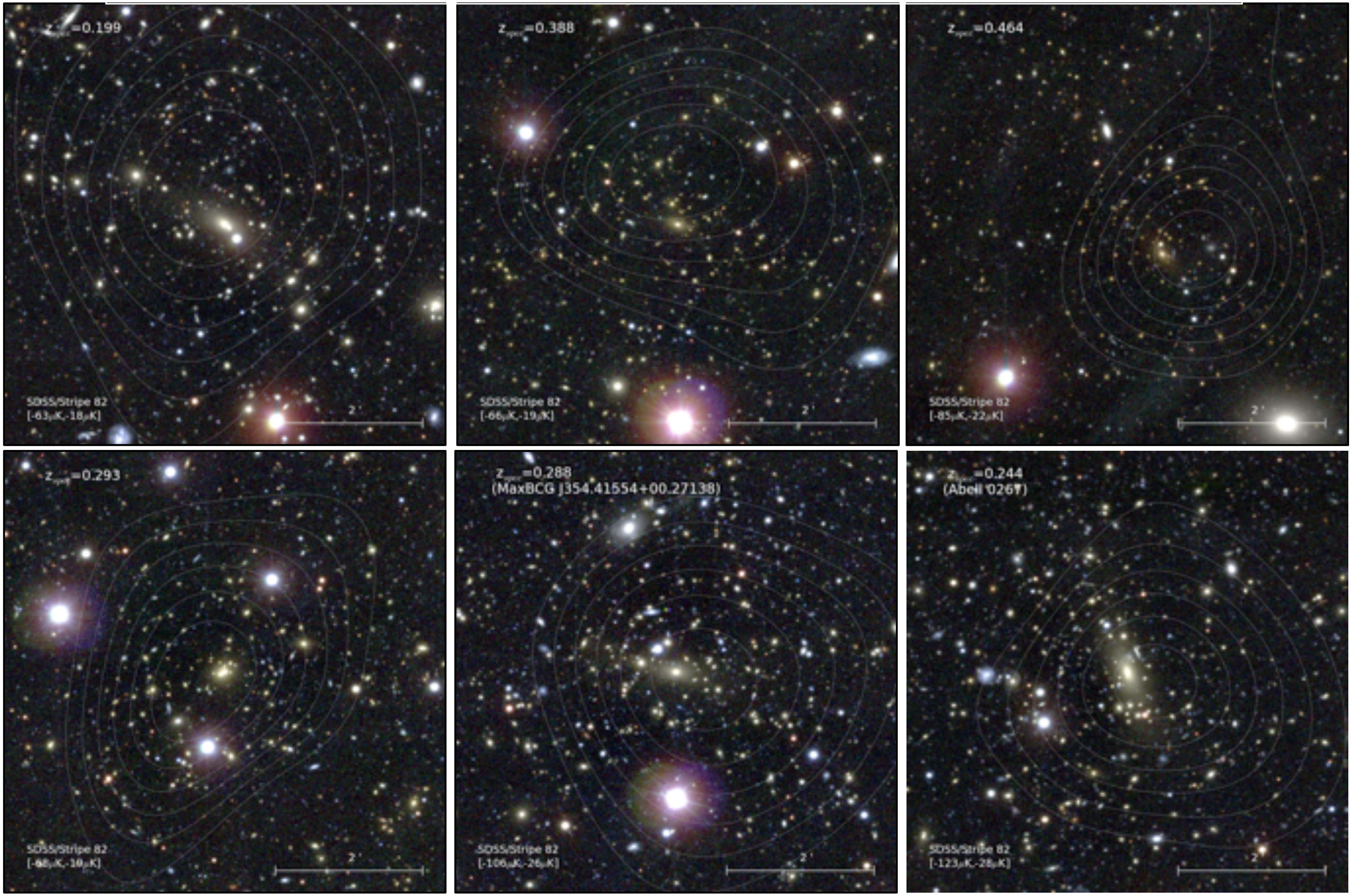


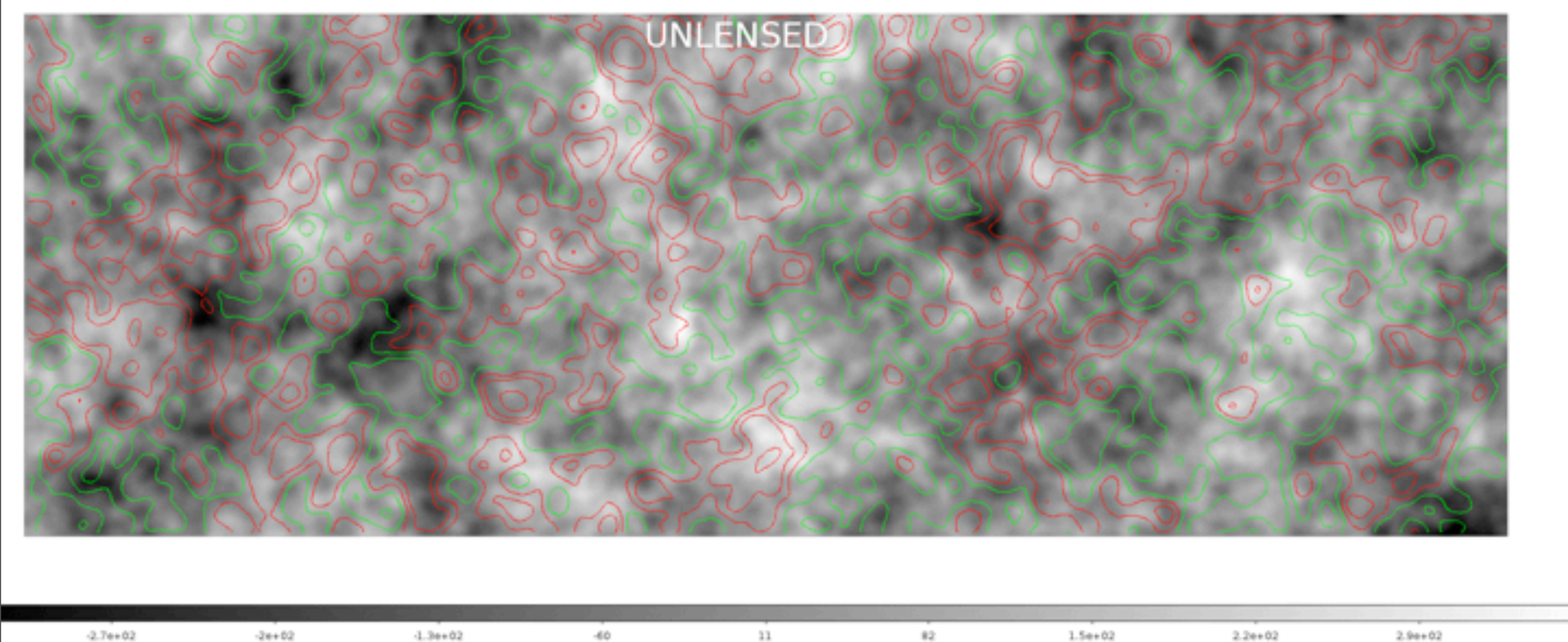
Menanteau et al. (in prep)

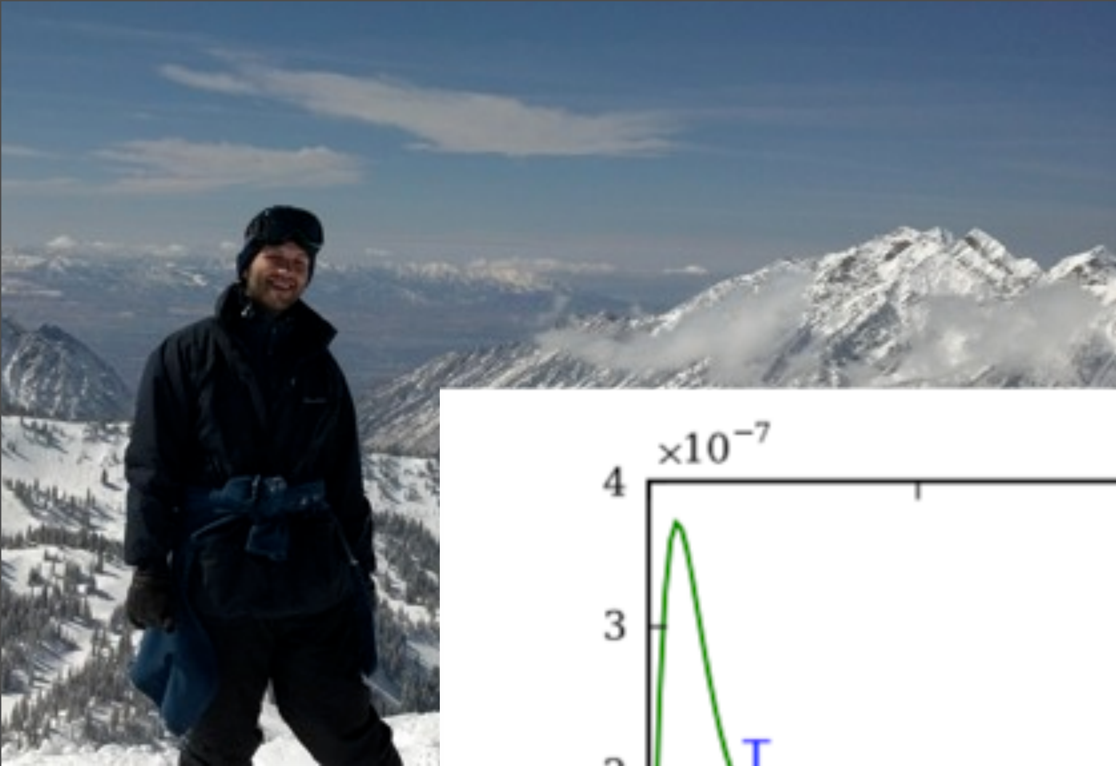
Wednesday, March 6, 13

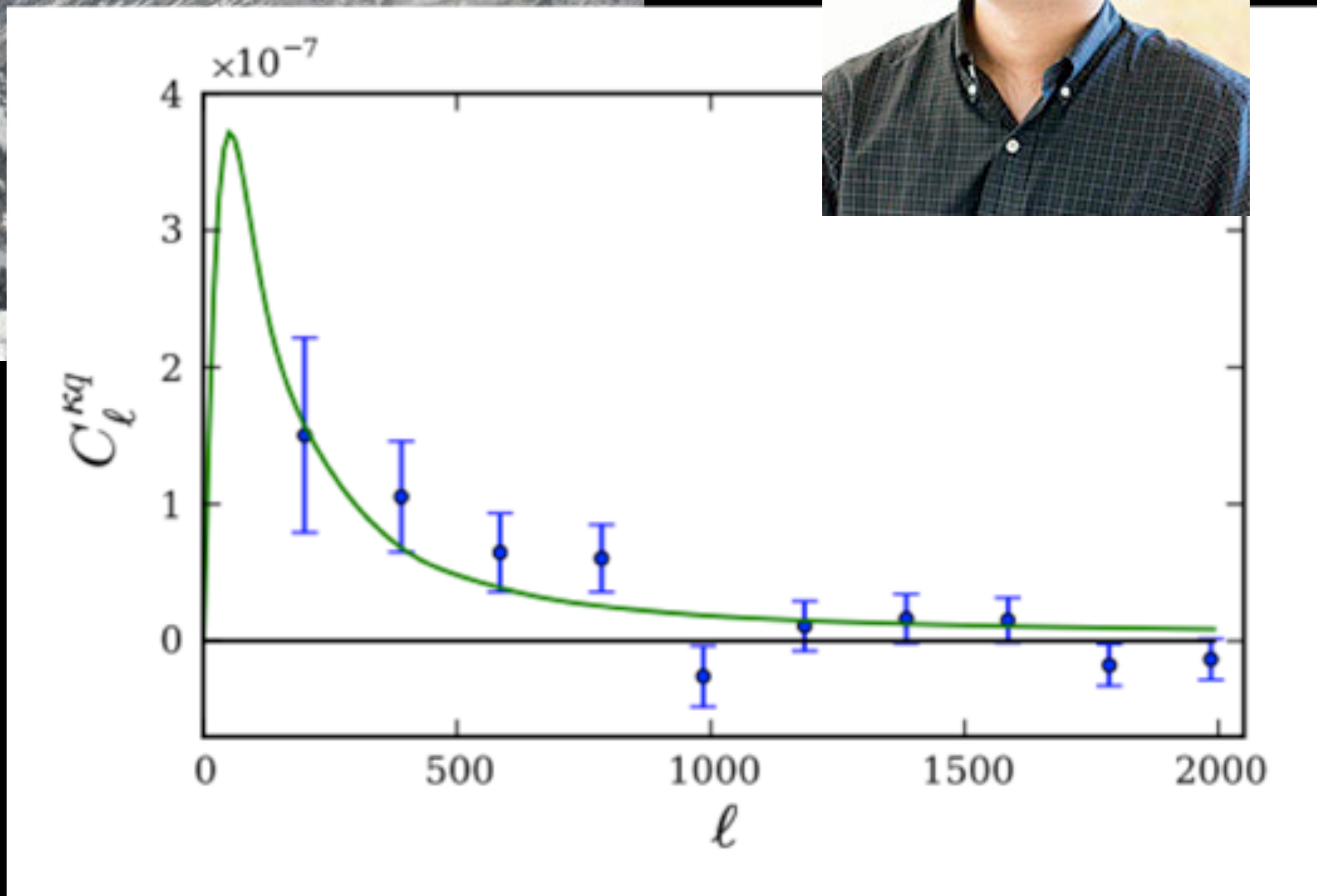
Gravitational Lensing of the CMB

Intervening large-scale potentials deflect CMB photons and distorts the CMB.

The rms deflection is about 2.7 arcmins, but the deflections are coherent on degree scales.

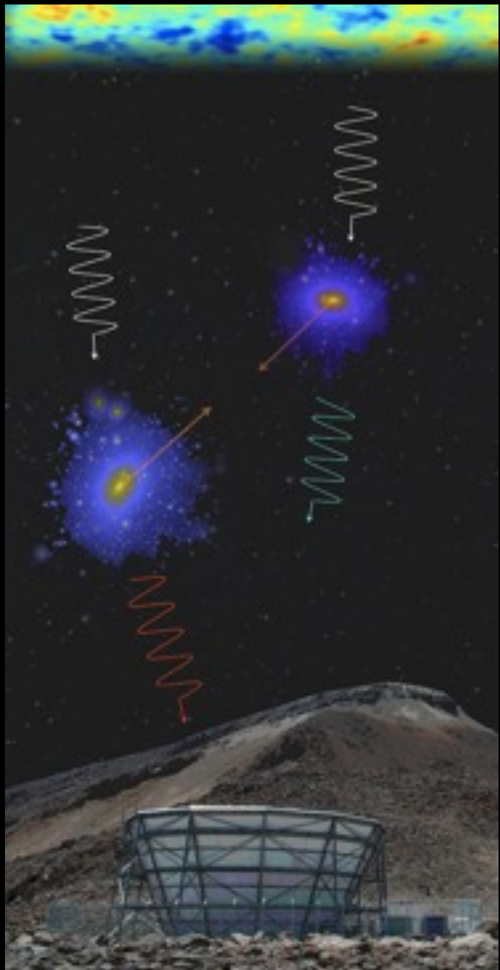

UNLENSED
-2.7e+02
-2e+02
-1.3e+02
-60
11
82
1.5e+02
2.2e+02
2.9e+02

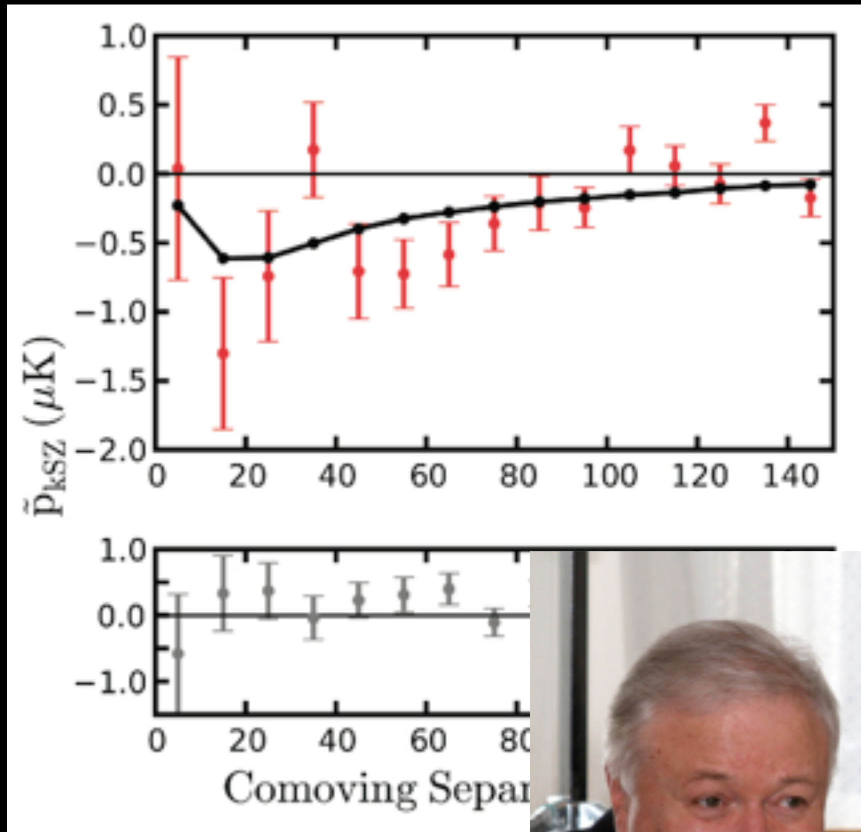




×10^−7
4
3
2
1
0
$C_\ell^{\kappa q}$
0
500
1000
1500
2000
ℓ

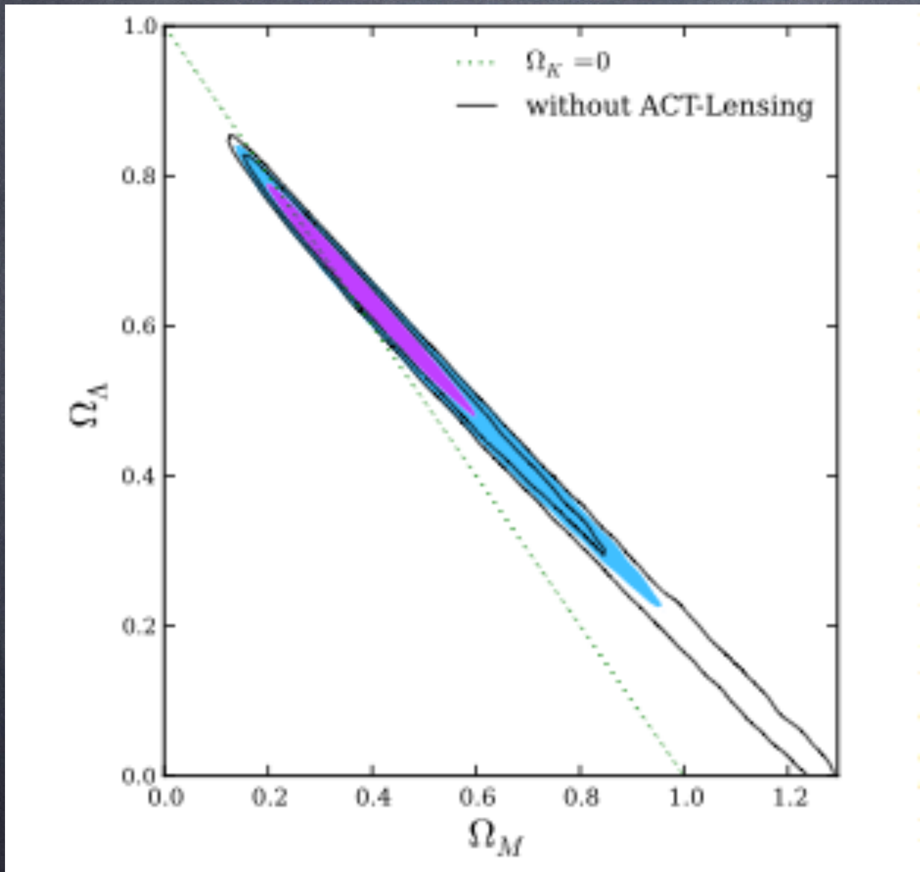
Kinematic SZ Effect

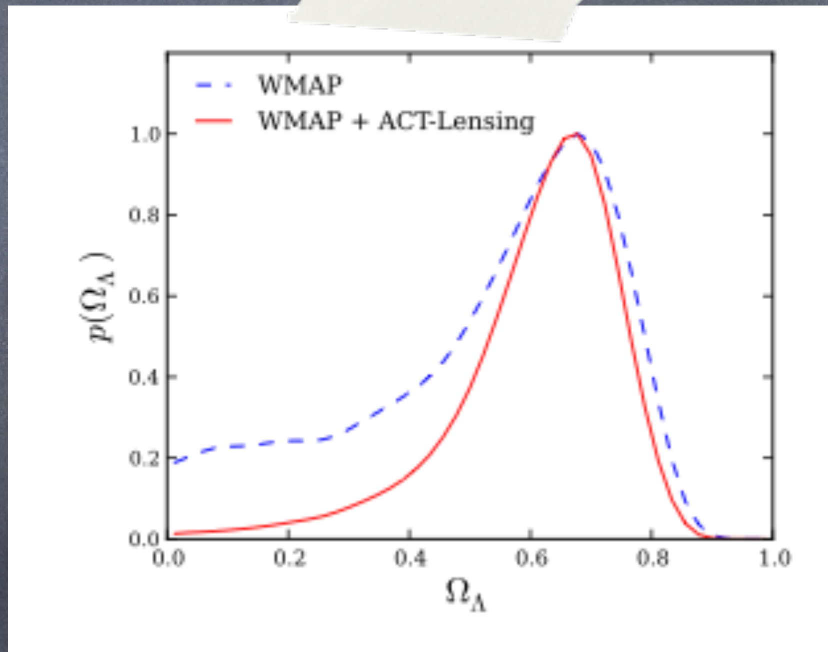




Hand et al. 1203.4219

Direct Detection of Dark Energy from the CMB



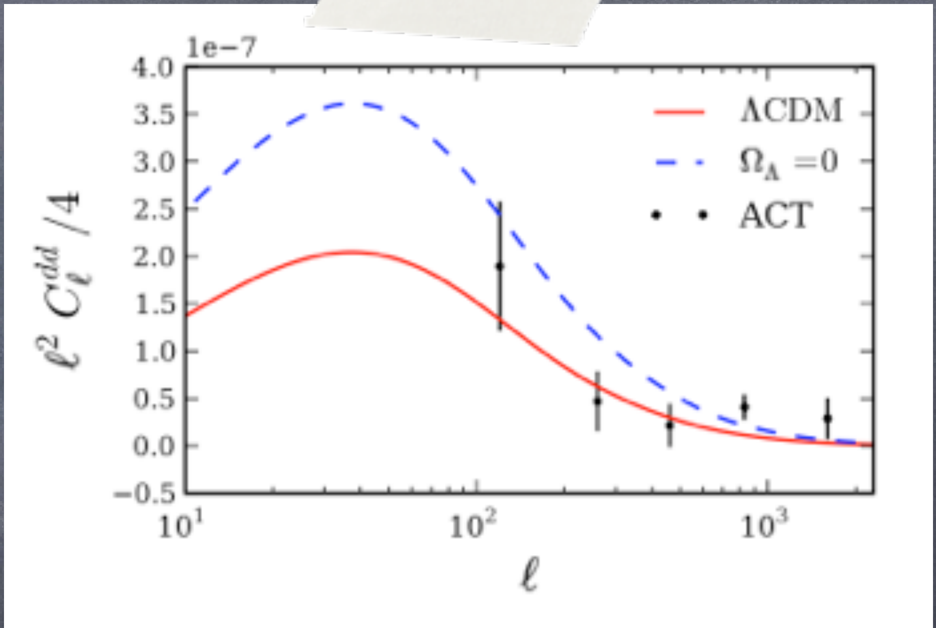


ACT Lensing Detection

- Lensing deflects photons and produce non-Gaussian signal:

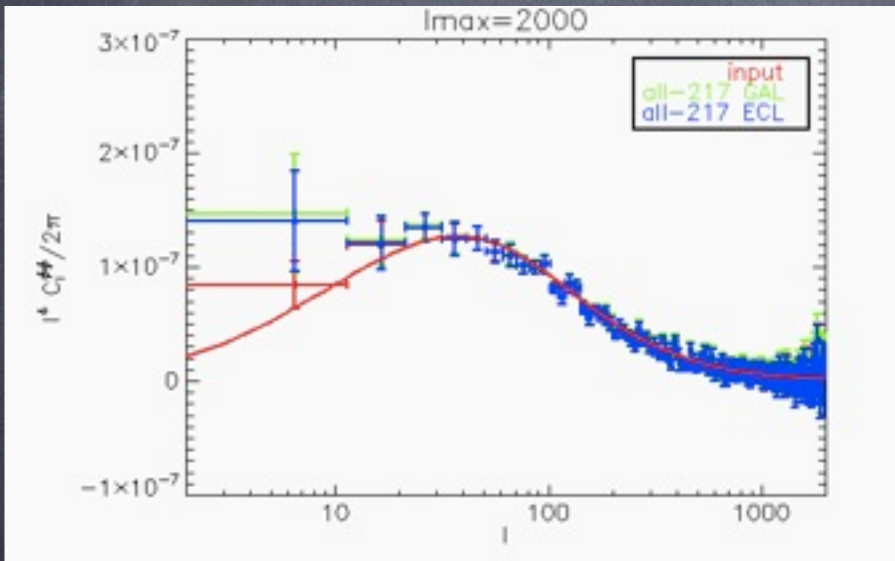
$$T_{obs}(\hat{n}) = T(\hat{n} + \nabla\phi) \simeq T(\hat{n}) + \nabla\phi \cdot \nabla T$$

- Non-trivial 4-pt function
- Lensing power spectrum is a meausure of the amplitude of fluctuations along the line of sign

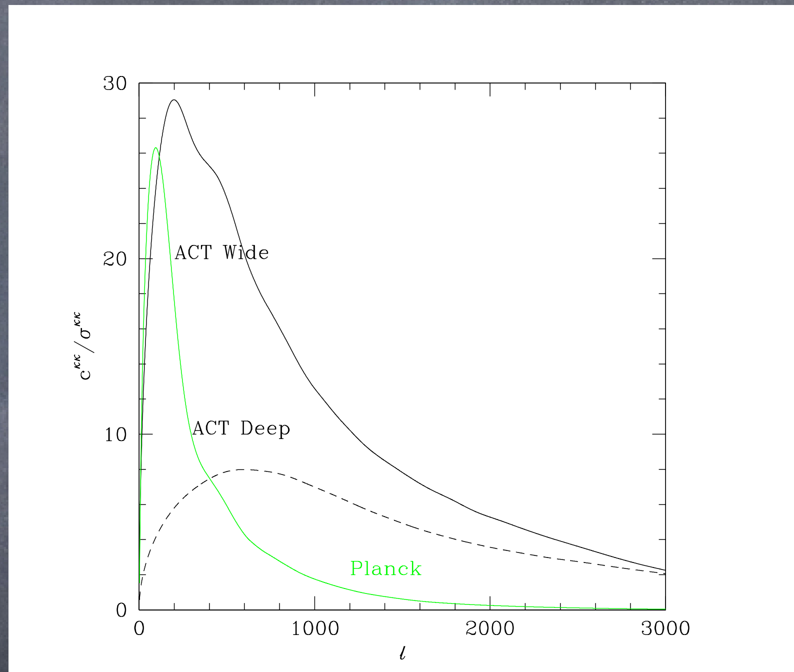


Das et al. arXiv 1103.0419

This is just the beginning of CMB Lensing Studies



Planck

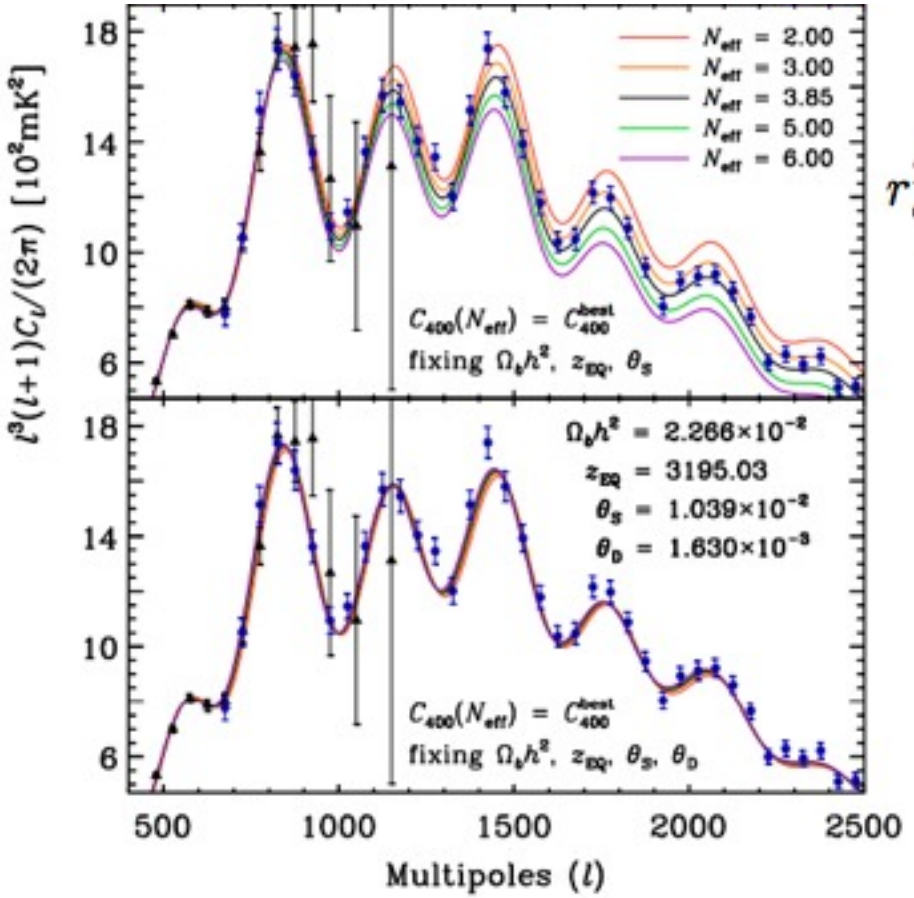


ACTPOL

CMB Lensing Studies: New Tool for DE Studies

- Sensitive to early dark energy (Verde & Spergel 2002)
- Probes growth rate of structure from z = 1000
- Cross-correlation with large-scale structure:
  - Planck/BOSS S/N > 20
  - ACTPOL/PFS S/N > 100

Effective relativistic species



$$r_d^2 = \pi^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H} \left[\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)} \right]$$

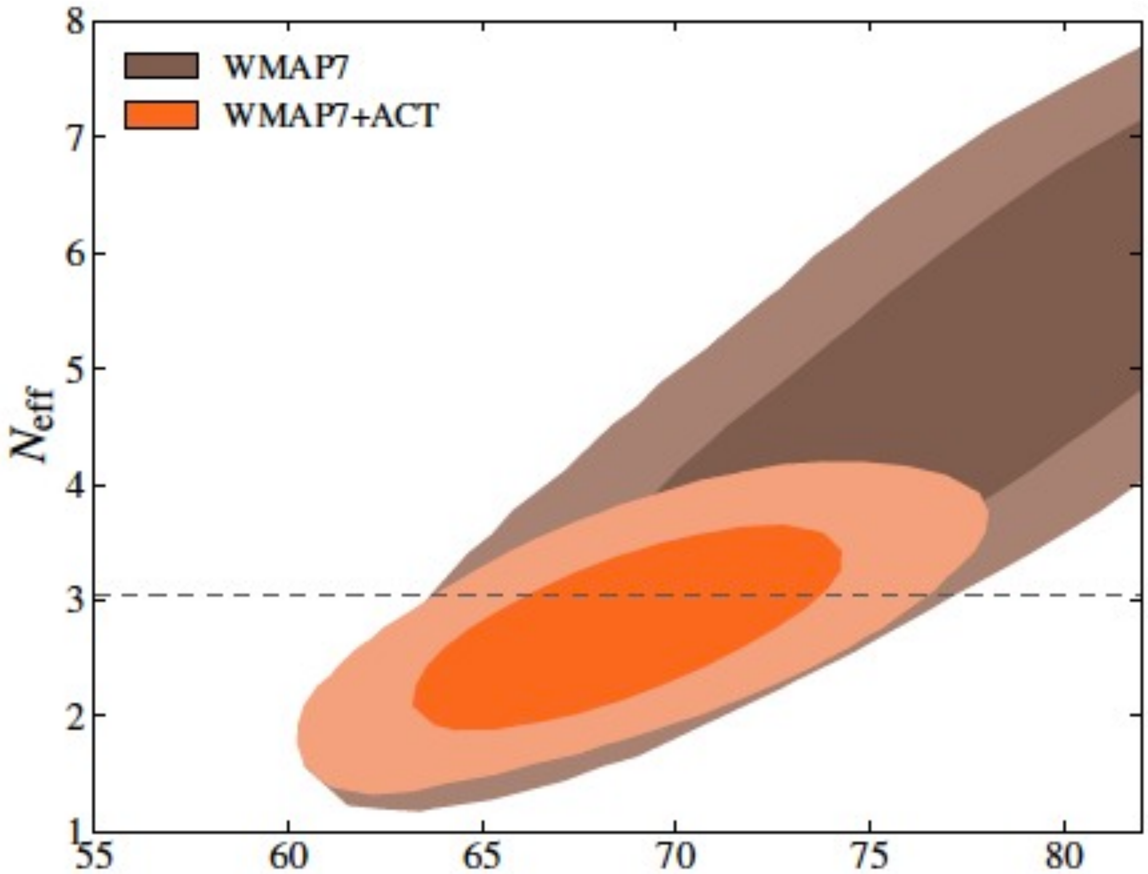
$$r_s = \int_0^{t_*} c_s\, dt/a = \int_0^{a_*} \frac{c_s\, da}{a^2 H}$$

$$R = 3\rho_b/(4\rho_\gamma)$$

Hou, Keisler, Knox et al. 2011

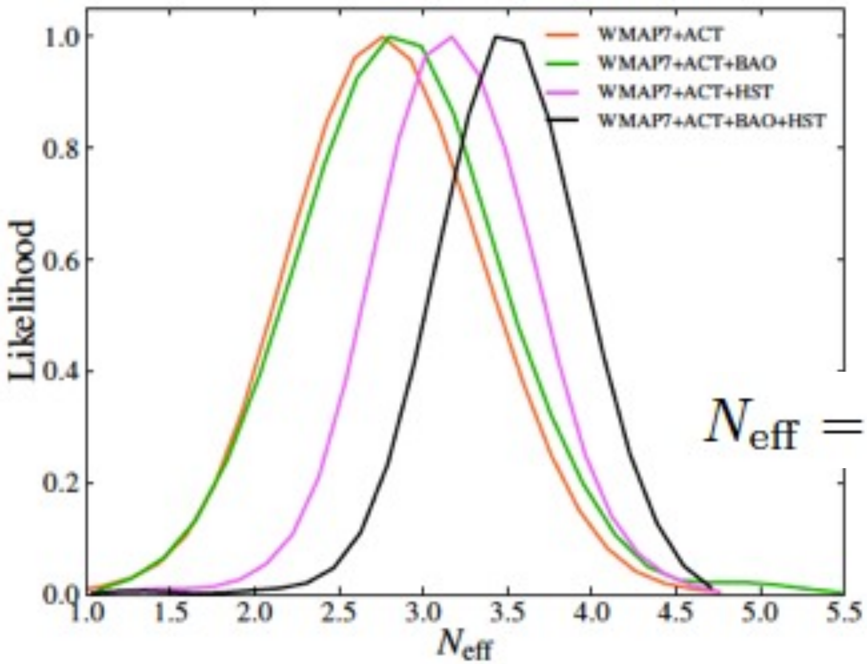
Effective relativistic species

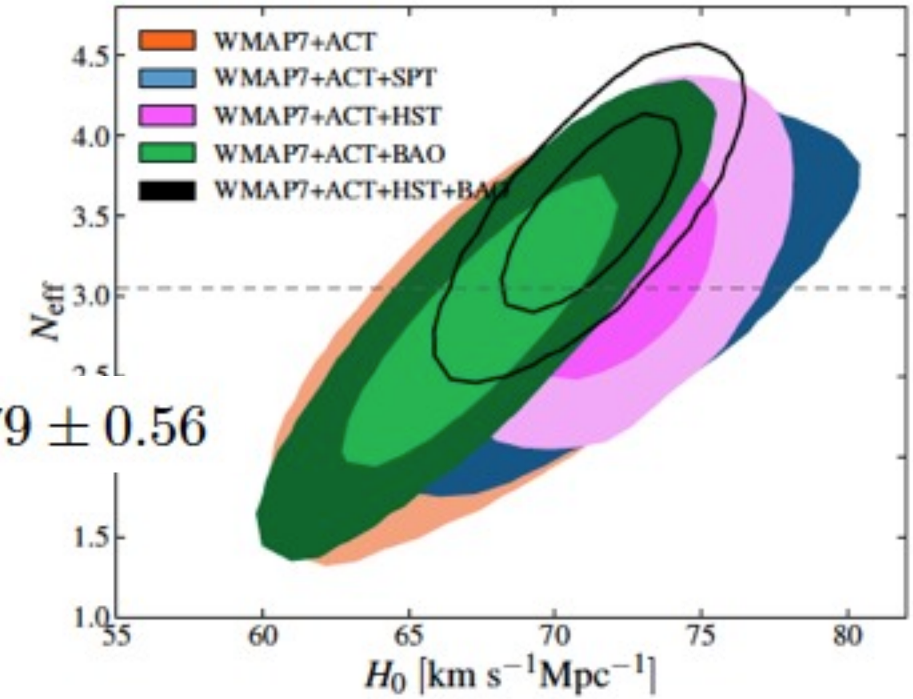
Consistent with 3 neutrino model.



Sievers, Hlozek, Nolta et al. 2013

Effective relativistic species

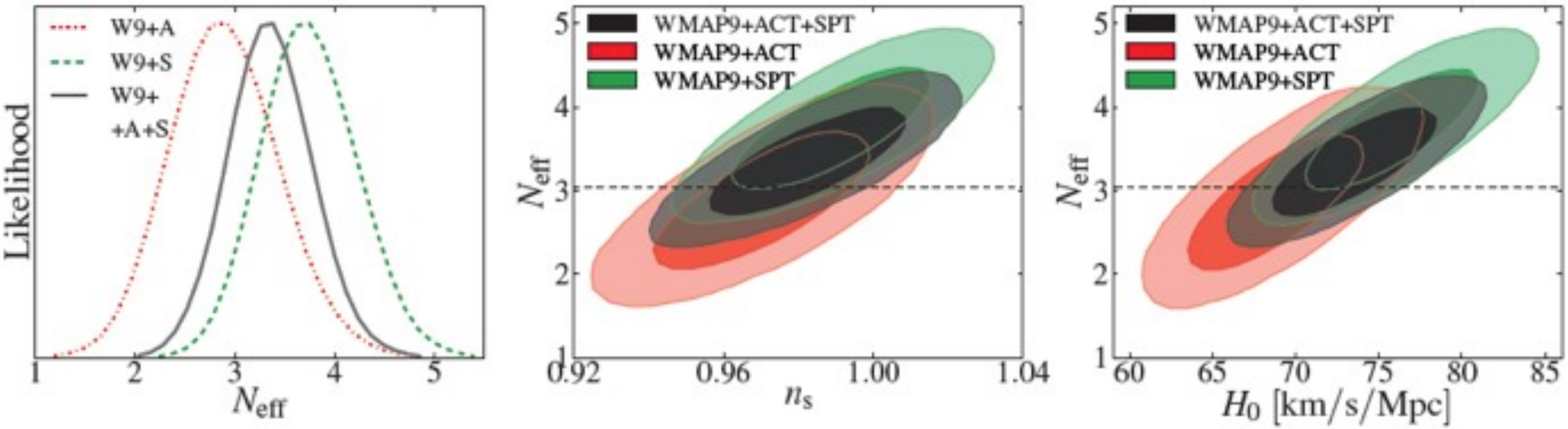




$$N_{\rm eff} = 2.79 \pm 0.56$$

Sievers, Hlozek, Nolta et al. 2013

ACT-SPT Consistency

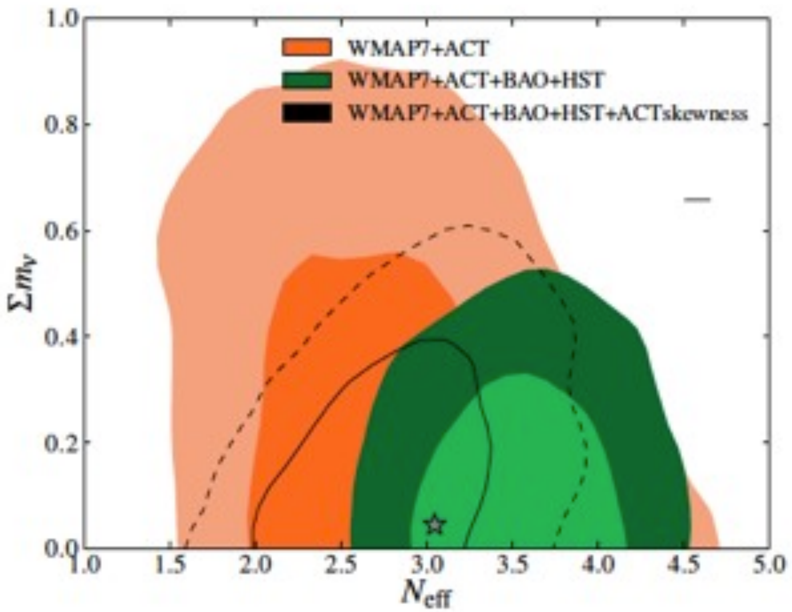


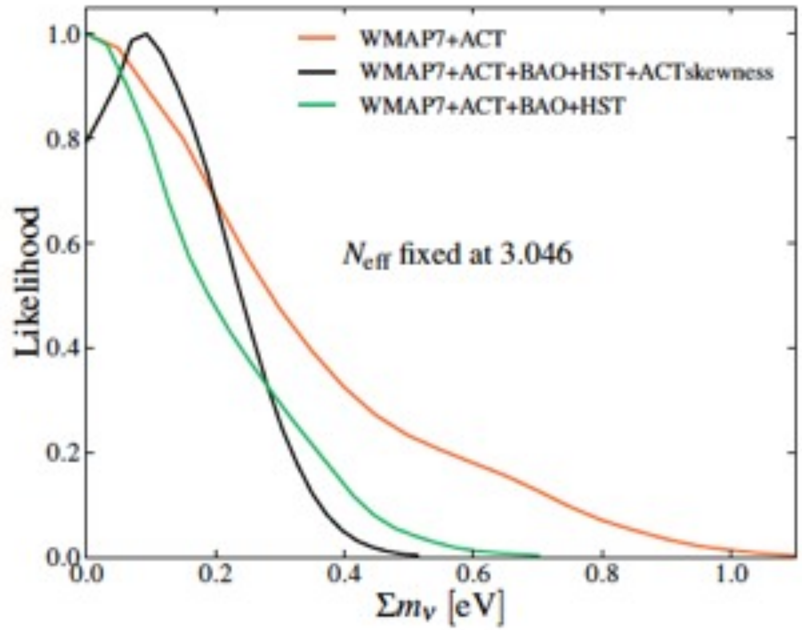
$$N_{\rm eff} = 2.90 \pm 0.53 \quad \text{(WMAP9 + ACT)}$$
$$N_{\rm eff} = 3.75 \pm 0.47 \quad \text{(WMAP9 + SPT)}$$
$$N_{\rm eff} = 3.34 \pm 0.40 \quad \text{(WMAP9 + ACT + SPT)}.$$

Calabrese, Hlozek, et al. 2013

Relativistic species and neutrinos

$$\Sigma m_\nu < 0.3\ (\mathrm{WMAP7 + ACT + ACTSkewness + BAO} + H_0)$$





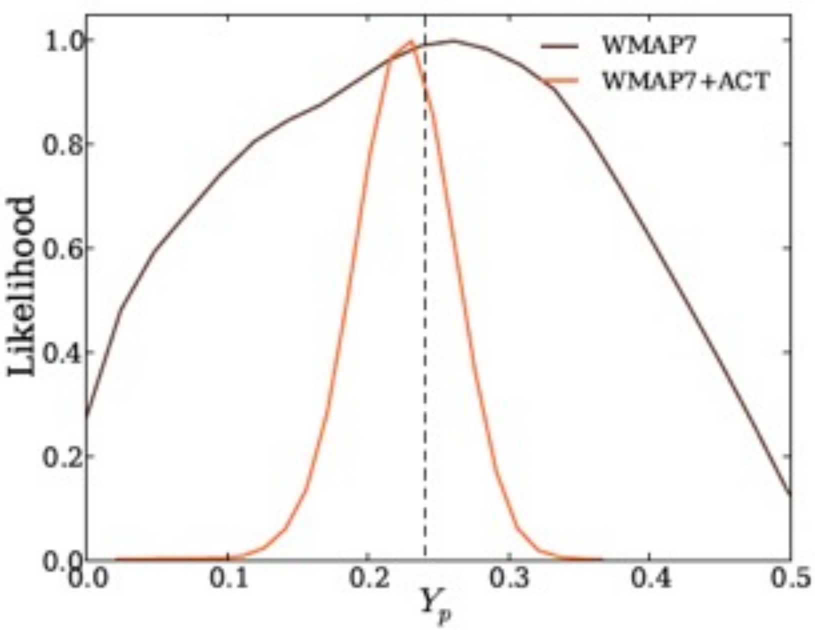
Sievers, Hlozek, Nolta et al. 2013

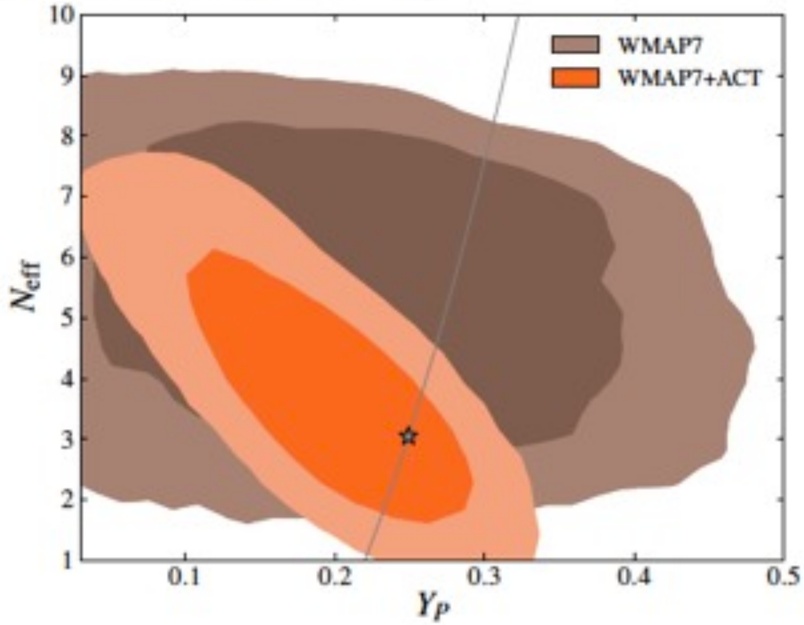
Effective relativistic degrees of freedom not strongly correlated with neutrino mass.

Primordial Helium

Sievers, Hlozek, Nolta et al. 2013

$$Y_p = 0.225 \pm 0.034 \text{ (WMAP7 + ACT)}$$





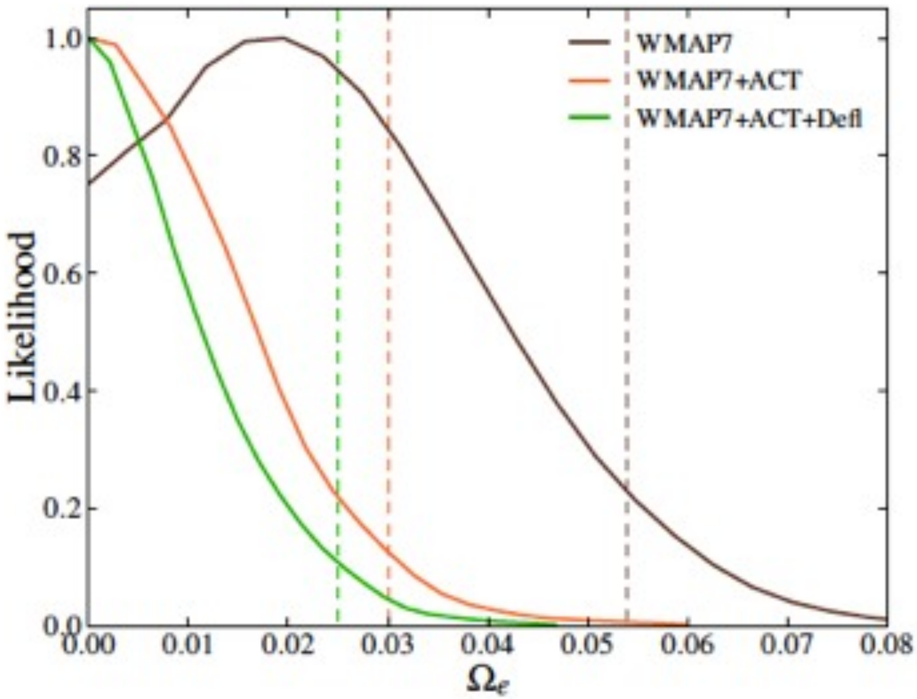
More Y_P decreases electrons available for recombination, leading to suppression of power

Consistency relation is tested, rather than applied.

$$Y_P = 0.2485 + 0.0016[(273.9\Omega_b h^2 - 6) + 100(S-1)];$$
$$S = \sqrt{1 + (7/43)(N_{\rm eff} - 3)}$$

Non-standard physics

Dark energy also acting like a 'relativistic species' at early times.



Sievers Hlozek, Nolta et al. 2013

$$\Omega_{\rm de}(a) = \frac{\Omega_{\rm de}(0) - \Omega_{\rm e}(1 - a^{-3w_0})}{\Omega_{\rm de}(0) + \Omega_m(0)a^{3w_0}} + \Omega_{\rm e}(1 - a^{-3w_0})$$

$$w(a) = -\frac{1}{3(1 - \Omega_{\rm de}(a))}\frac{d\ln\Omega_{\rm de}(a)}{d\ln a} + \frac{a_{\rm eq}}{3(a + a_{\rm eq})}$$

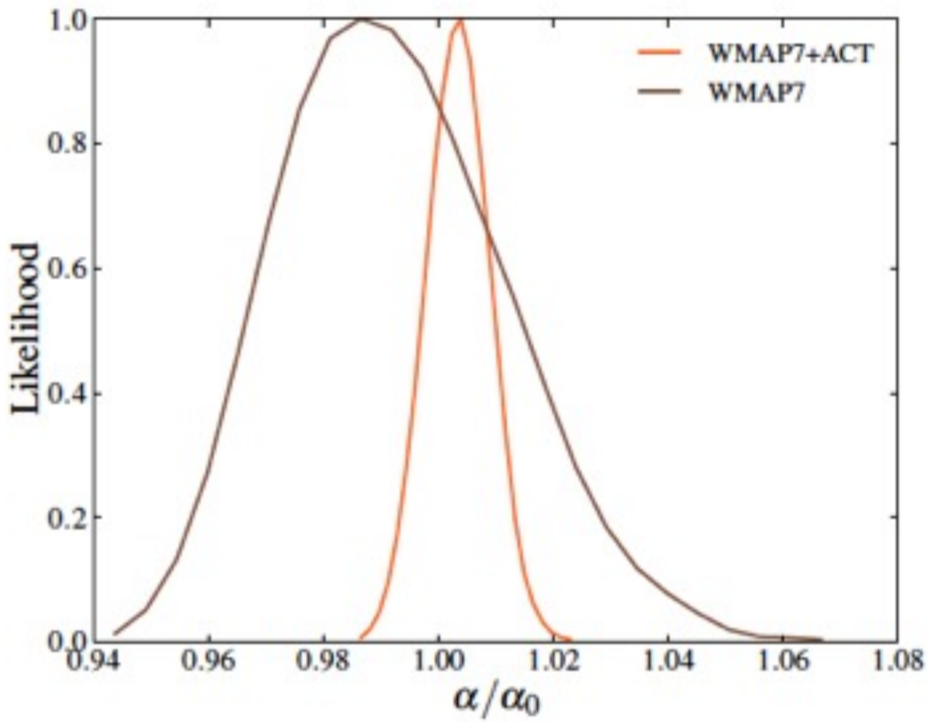
$$\Omega_e < 0.025 \ (95\% \ \text{C.L., WMAP7 + ACT + ACTDefl})$$

Fine structure constant

$$\alpha = e^2/\hbar c$$

Claims of deviation from unity at low redshifts z~2 using quasar absorption spectra (Webb et al.)

$$\sigma_T = \frac{1}{6\pi}\frac{e^4}{m_e^2}$$



Sievers Hlozek, Nolta et al. 2013

α changes the physics of recombination

$$\frac{dx_e}{d\tau} = aC_r\left[\beta(T_b)(1-x_e) - n_H\alpha^{(2)}(T_b)x_e^2\right]$$

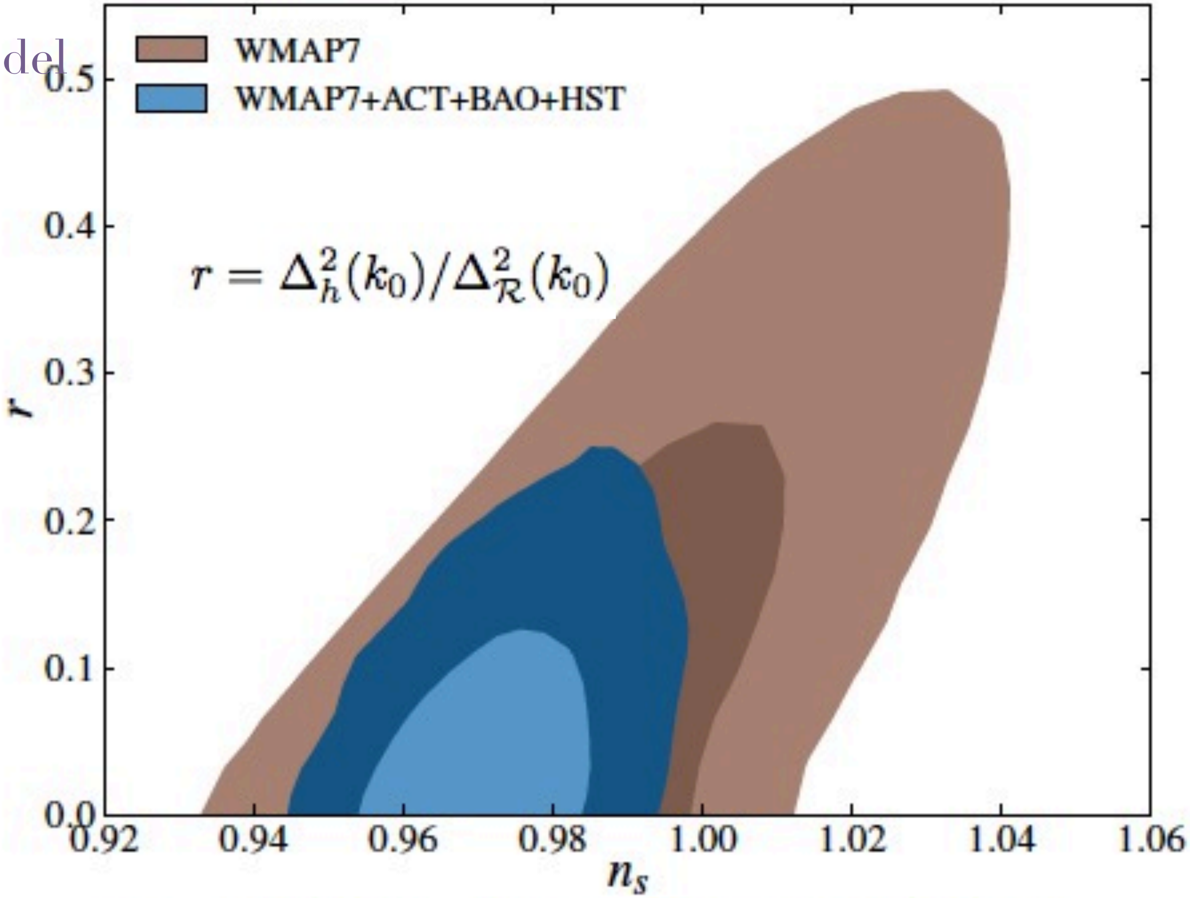
WMAP7+ACT – consistent with no

$$\alpha/\alpha_0 = 1.004 \pm 0.008$$

Inflationary parameters

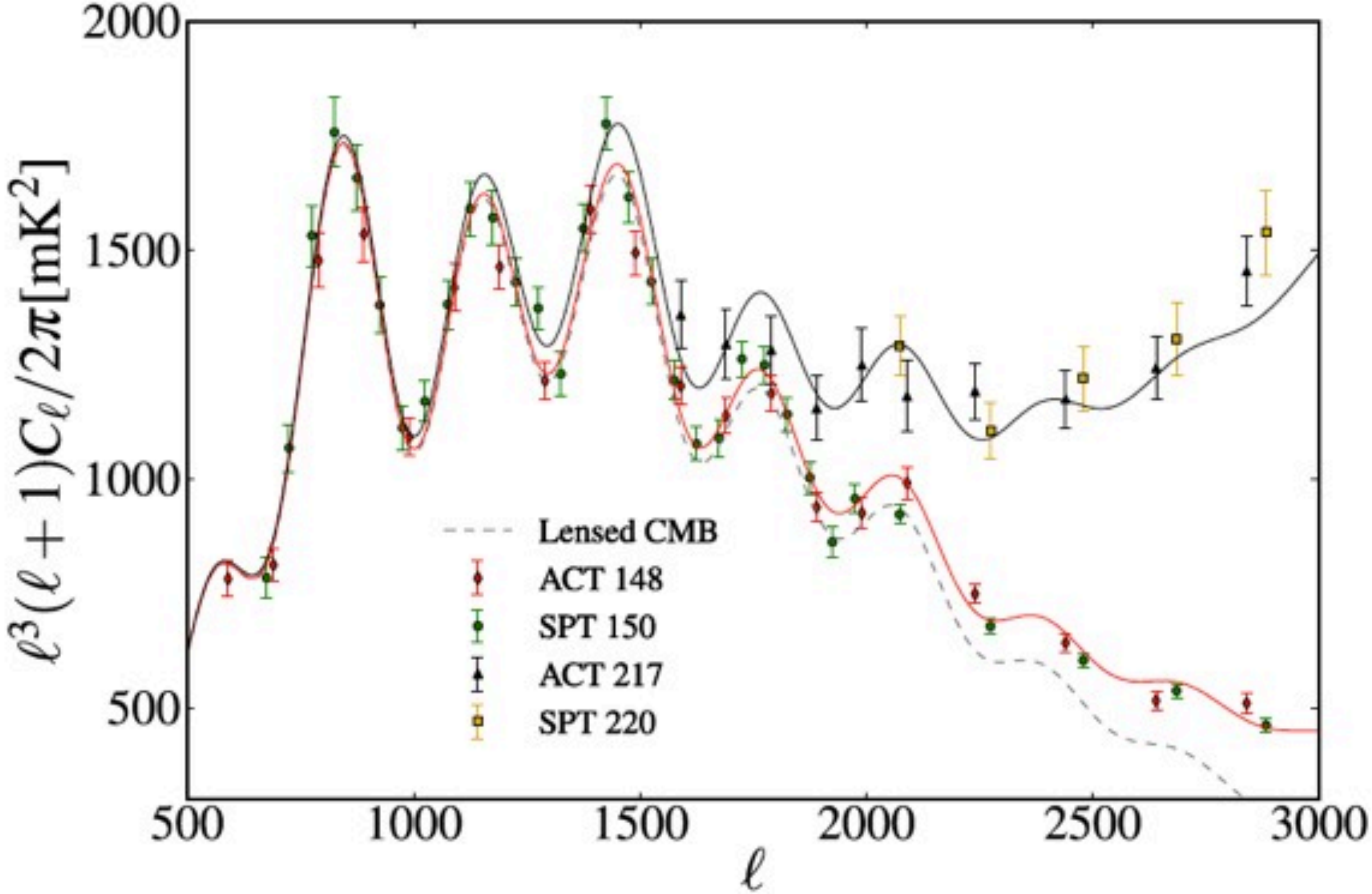
Sievers, Hlozek, Nolta et al. 2013

Changes in model for
Recfast v1.5
compared to
Recfast 1.4.2



$r < 0.19$ (WMAP7 + ACT + BAO+H_0, 95% CL)

Damping

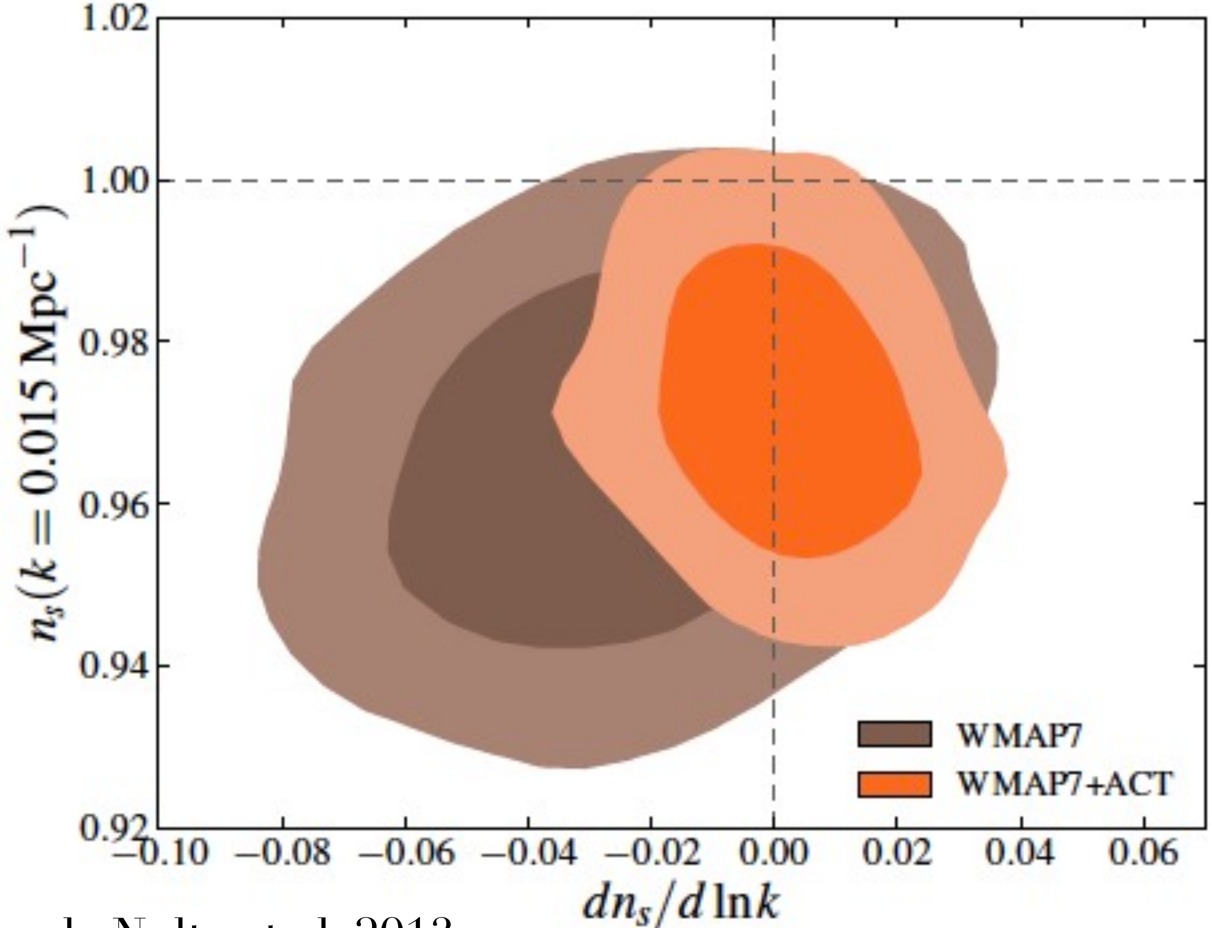


Dunkley, Calabrese, Sievers, et al. 2013

Inflationary parameters

$$\Delta^2_{\mathcal{R}}(k) = \Delta^2_{\mathcal{R}}(k_0)\left(\frac{k}{k_0}\right)^{n_s(k_0)-1+\frac{1}{2}\ln(k/k_0)dn_s/d\ln k}$$

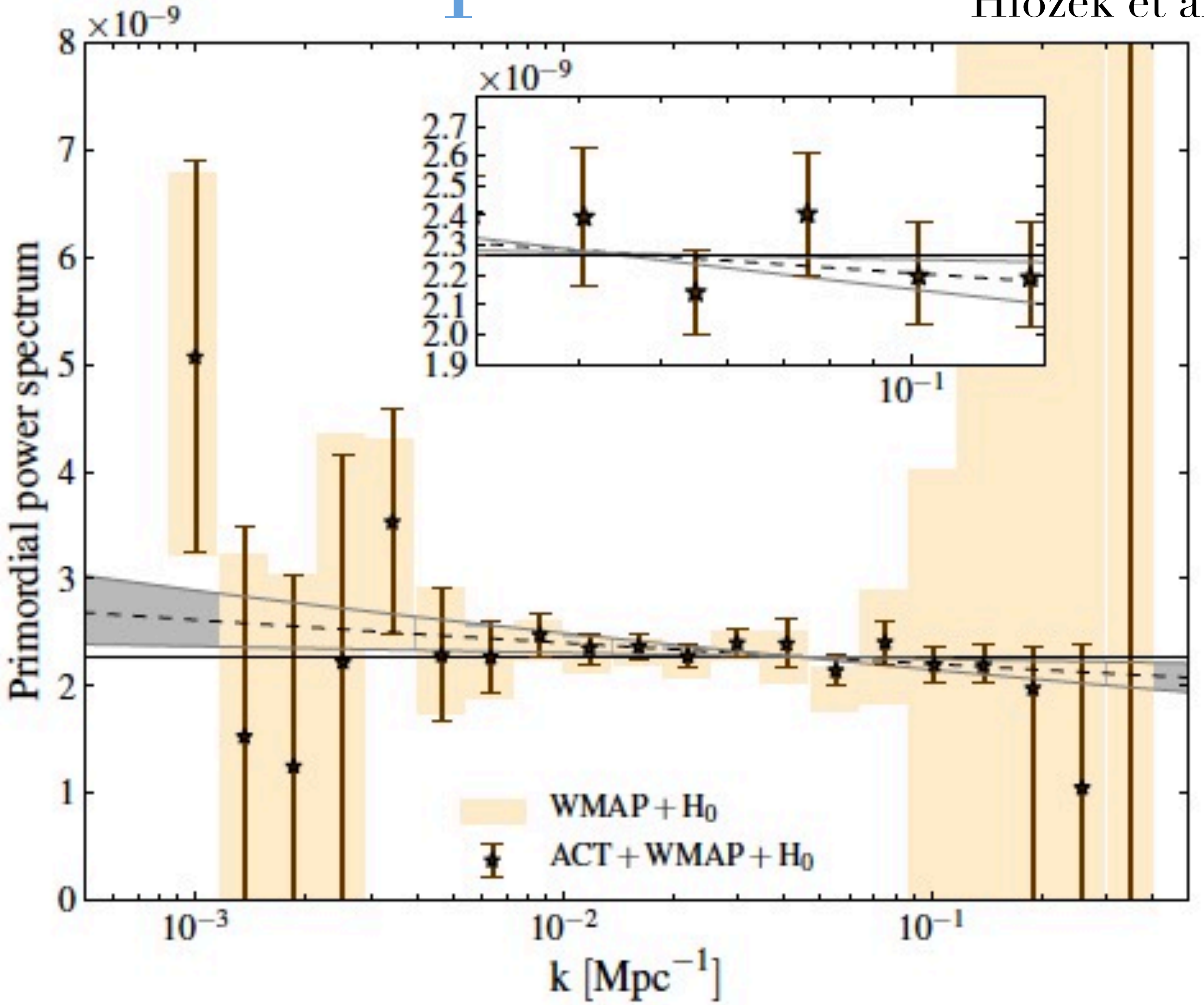
$$\frac{dn_s}{d\ln k} = -16\epsilon\eta + 24\epsilon^2 + 2\xi_i^2$$



Sievers, Hlozek, Nolta et al. 2013

Constraints on the primordial power

Hlozek et al. 2011



Renée Hlozek – Caltech Tea Talk

Next Step: ACTPOL

- Funded by NSF for 2011-2016
- Camera now under construction... 25 times faster survey speed and polarization sensitivity
- First light in 2012
- Wide survey (~4000 sq. degrees)
- Deep survey (5 x 25 sq degree fields)

E + B modes

- Scalar fluctuations generate E-modes. They produce TT, TE and EE correlations
- Tensor fluctuations generate equal amounts of E and B modes. They produce TT, EE and BB correlations
- Gravitational lensing rotate polarization and converts E modes into B modes.

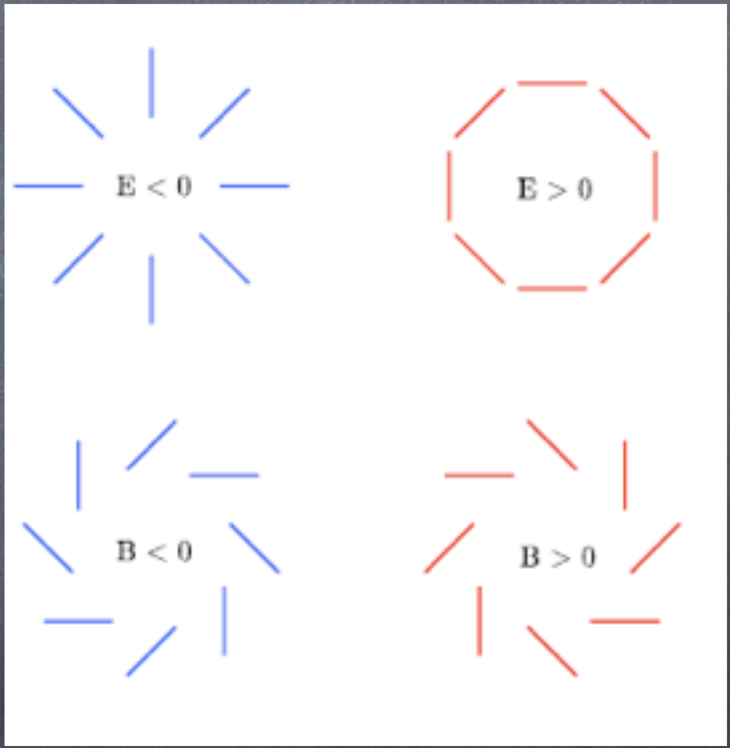
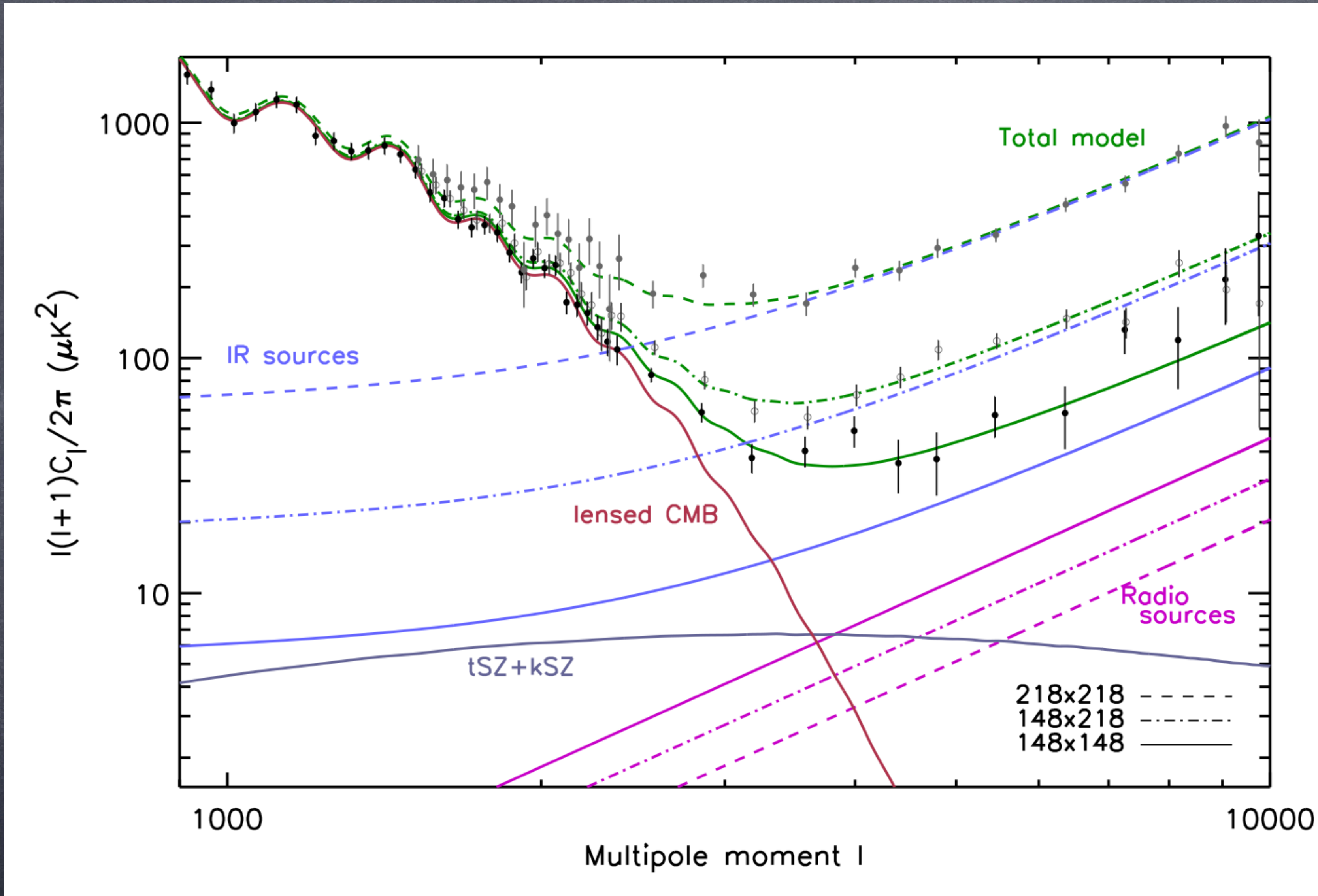


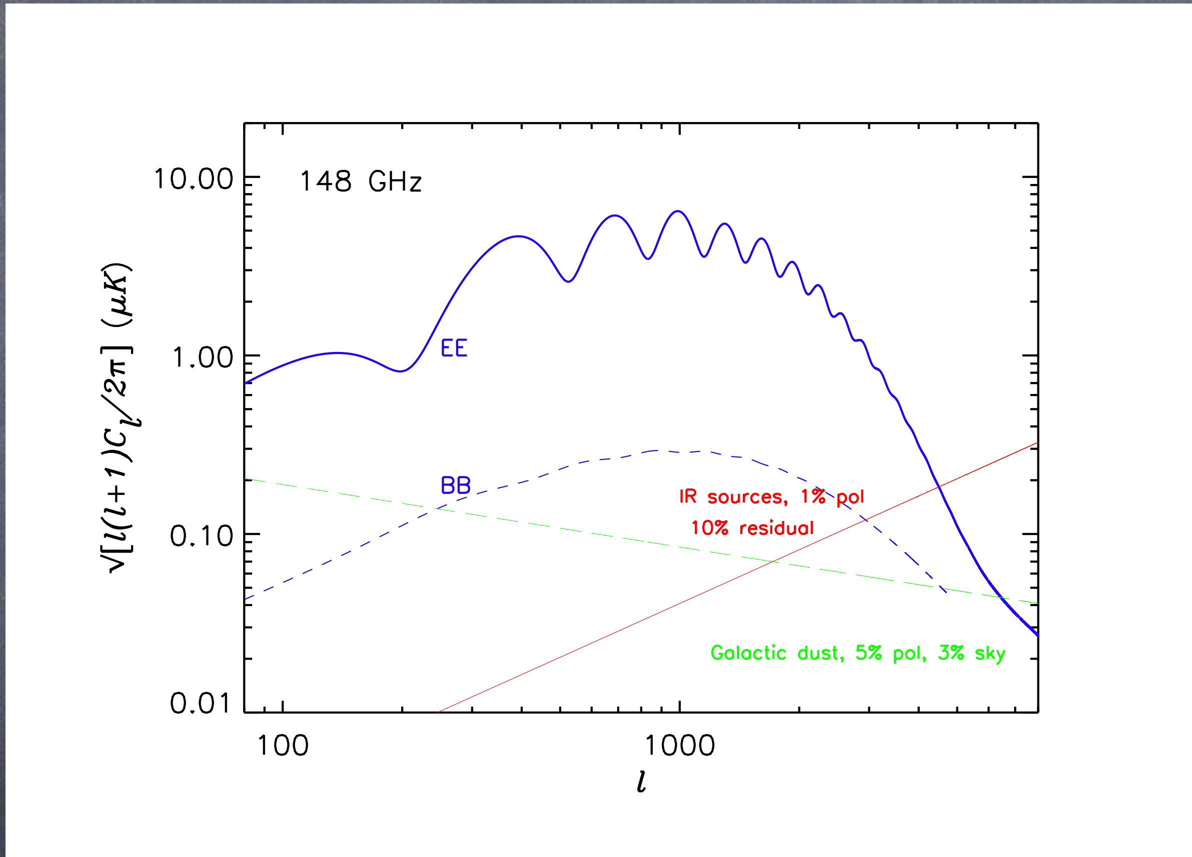
Figure from Dodelson et al. NAS White Paper astro-ph/0902.3796

Why Measure High l Polarization?

- More modes/more sky coverage leads to more accurate parameters.
- New discovery space (another e-fold of inflation)
- Sensitive to ionization history
- New Lens sheet: BB power spectrum (directly related to the convergence power spectrum) has a signal/noise of 3000 in an all-sky 0.1 uK^2

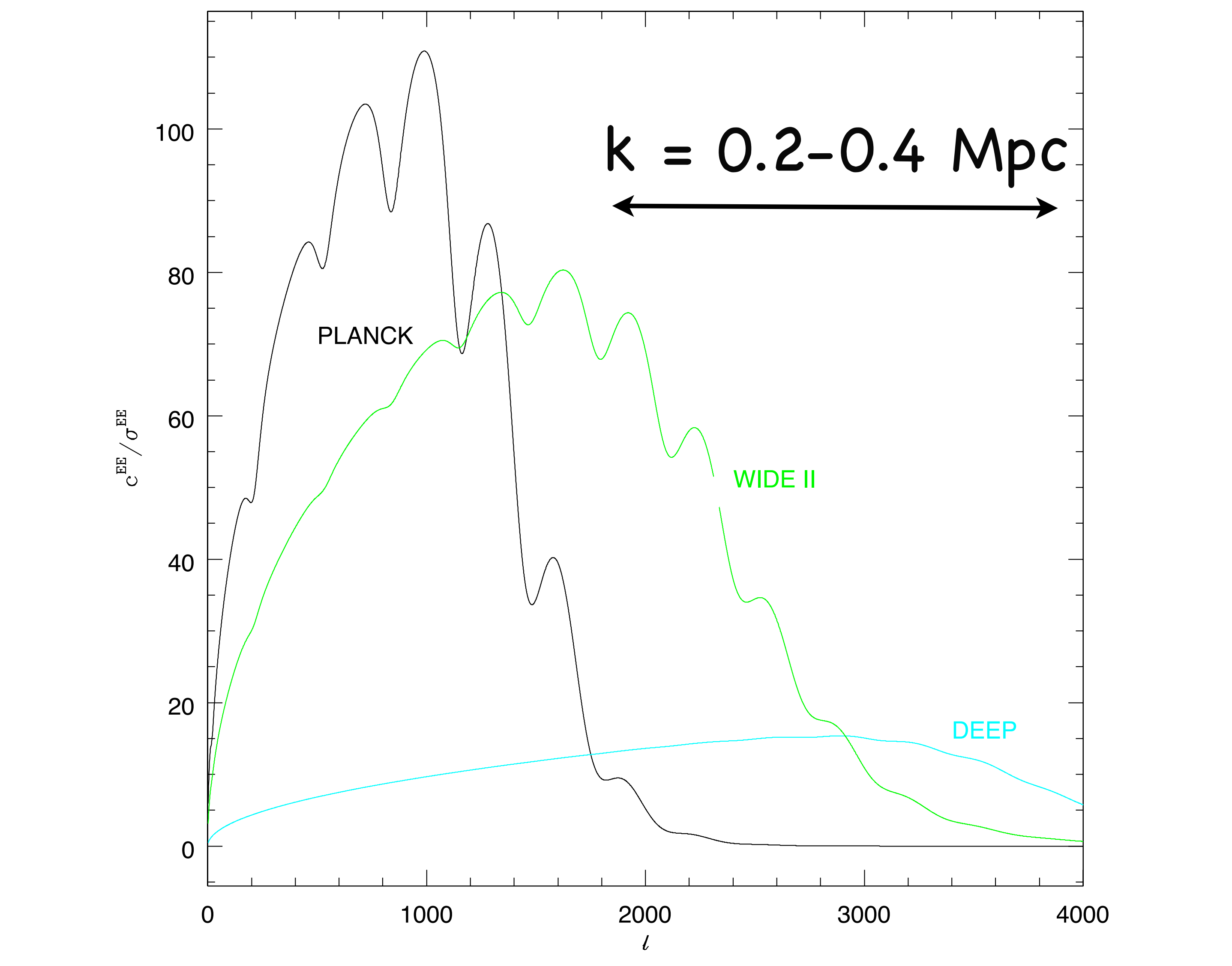

1000
100
10
$l(l+1)C_l/2\pi$ (μK^2)
Total model
IR sources
lensed CMB
Radio sources
tSZ+kSZ
218x218
148x218
148x148
1000
10000
Multipole moment l

The New Frontier



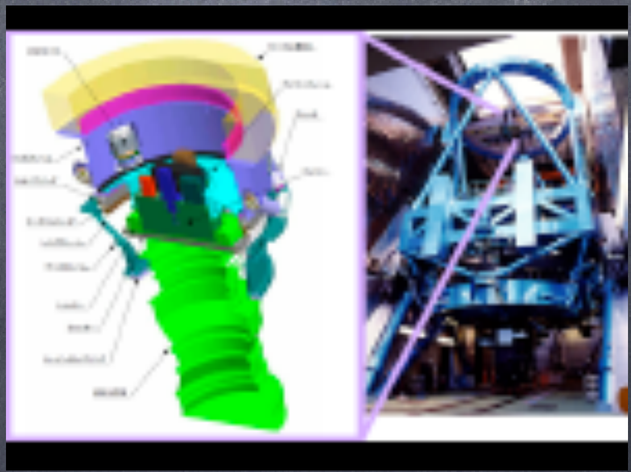
Full sky polarization survey
to l = 5000 would have 6 times the
number of modes as Planck

ACTPol's Discovery Space



ACTPOL Wide

- Survey 4000 sq degrees with sensitivity of 28 microK/arcmin (polarization) and 20 microK/arcmin (temperature)
- Overlap SDSS III spectroscopy and imaging (600,000 LRGs, 80,000 quasar spectra)
- SUMIRE program: HSC imaging (under construction) + PFS (under review)
- Science goals:
  - EE power spectrum out to l ~2000
  - CMB lensing (and cross-correlations with low z surveys)
  - Clusters
  - Missing Baryons
  - Dark energy (calibrate BAOs; measure power spectrum at z ~ 1-2)



ACTPOL Deep

- Deep observing program:
  - 5 2x15 degree regions. Plan to target regions with extensive deep data
  - 4 uK/arcmin in polarization
- Science goals:
  - high l EE tail
  - stacking of astronomical objects
  - characterization of foregrounds
  - delensing gravity wave B-mode (see Smith et al. astro-ph0811.3916)

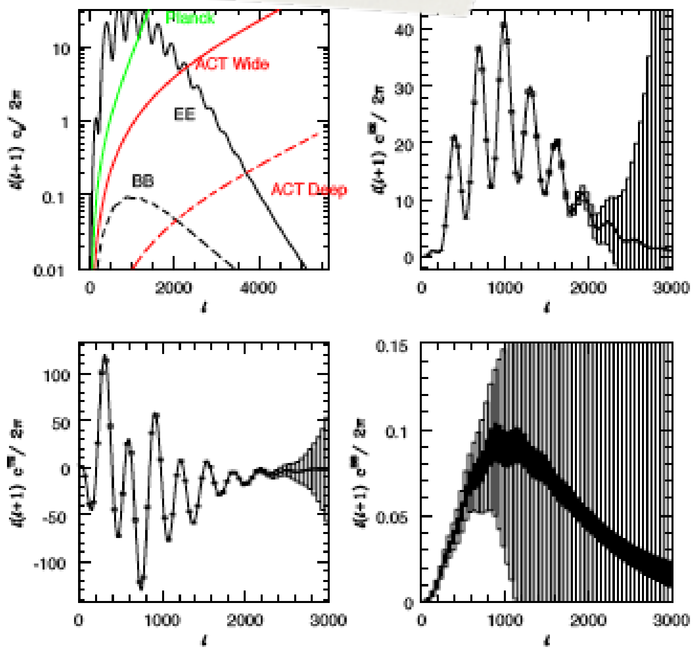
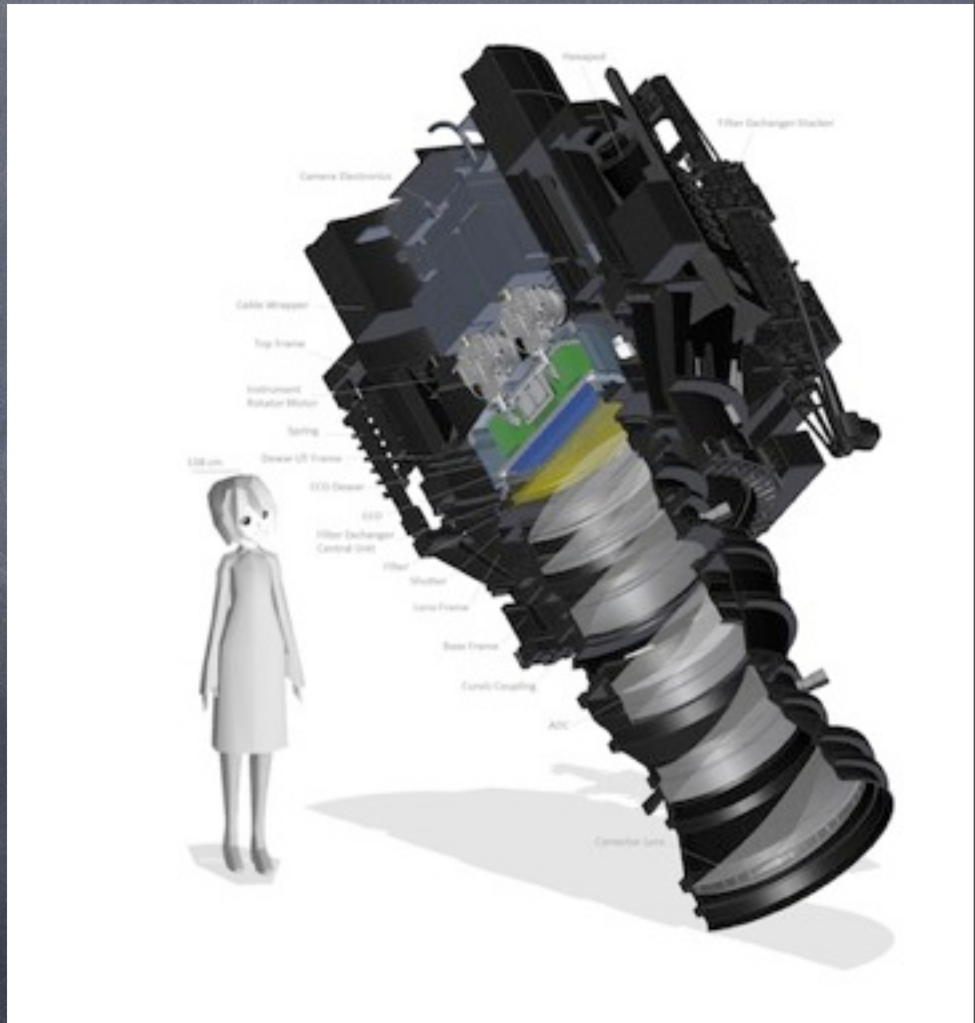


Figure 5. The upper left panel shows the noise per multipole for Planck, ACT Wide and ACT Deep and the predicted EE and BB power spectrum. The other three panels show the EE, BB and TE spectrum with anticipated ACT (filled boxes, at places small on a linear scale, see Figure 2) and Planck errors (open boxes). When the Planck errors are smaller, only they (open boxes) are shown. The deep field errors are shown by the grey boxes and are only shown when they are smaller than the wide field errors. The other three panels shows the expected signal/noise for the EE, TE and BB angular power spectra binned with $\Delta l = 50$.

HyperSuprime Camera

- 1.5 x 1.5 degree camera on Subaru (8.3 meter telescope)
- First light in early 2012
- Survey begins in 2013 (~200-300 nights) grizY
  - Wide survey
    - 1500 sq deg i~25.8
  - Deep survey
    - 30 sq deg i ~27.2 (+Narrow Bands)
  - Ultradeep survey
    - 3 sq deg i~28 (+NB)



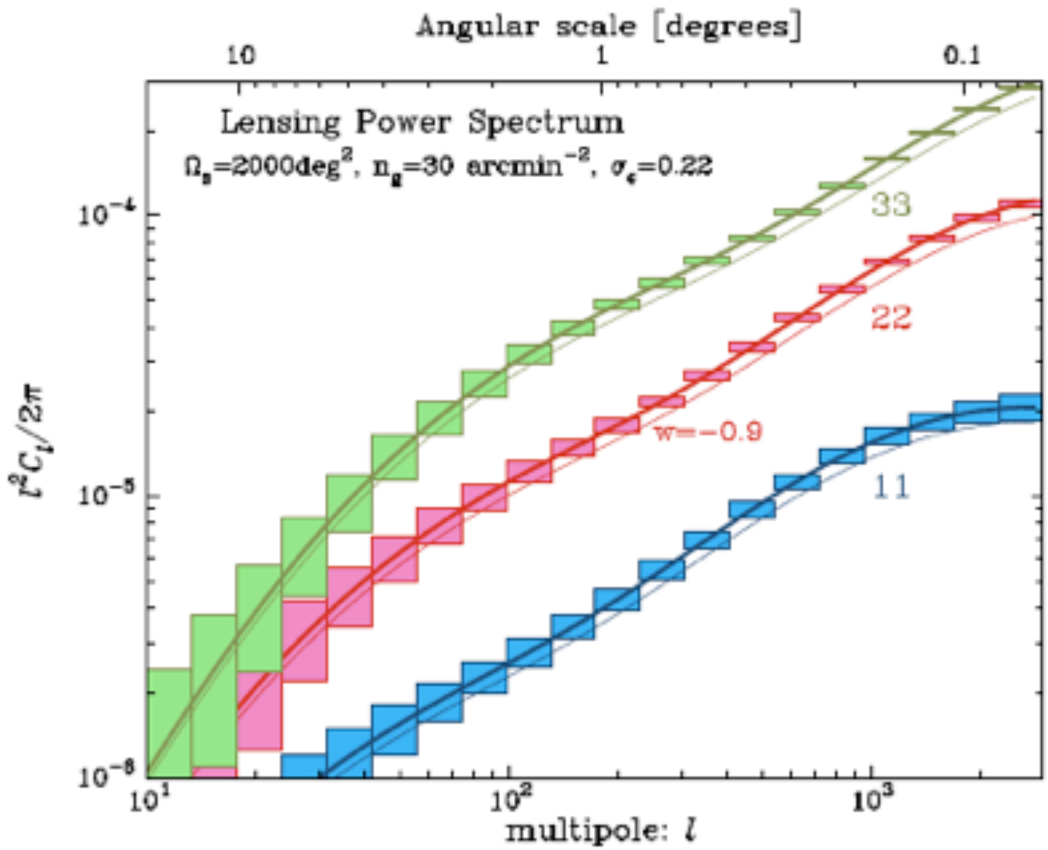
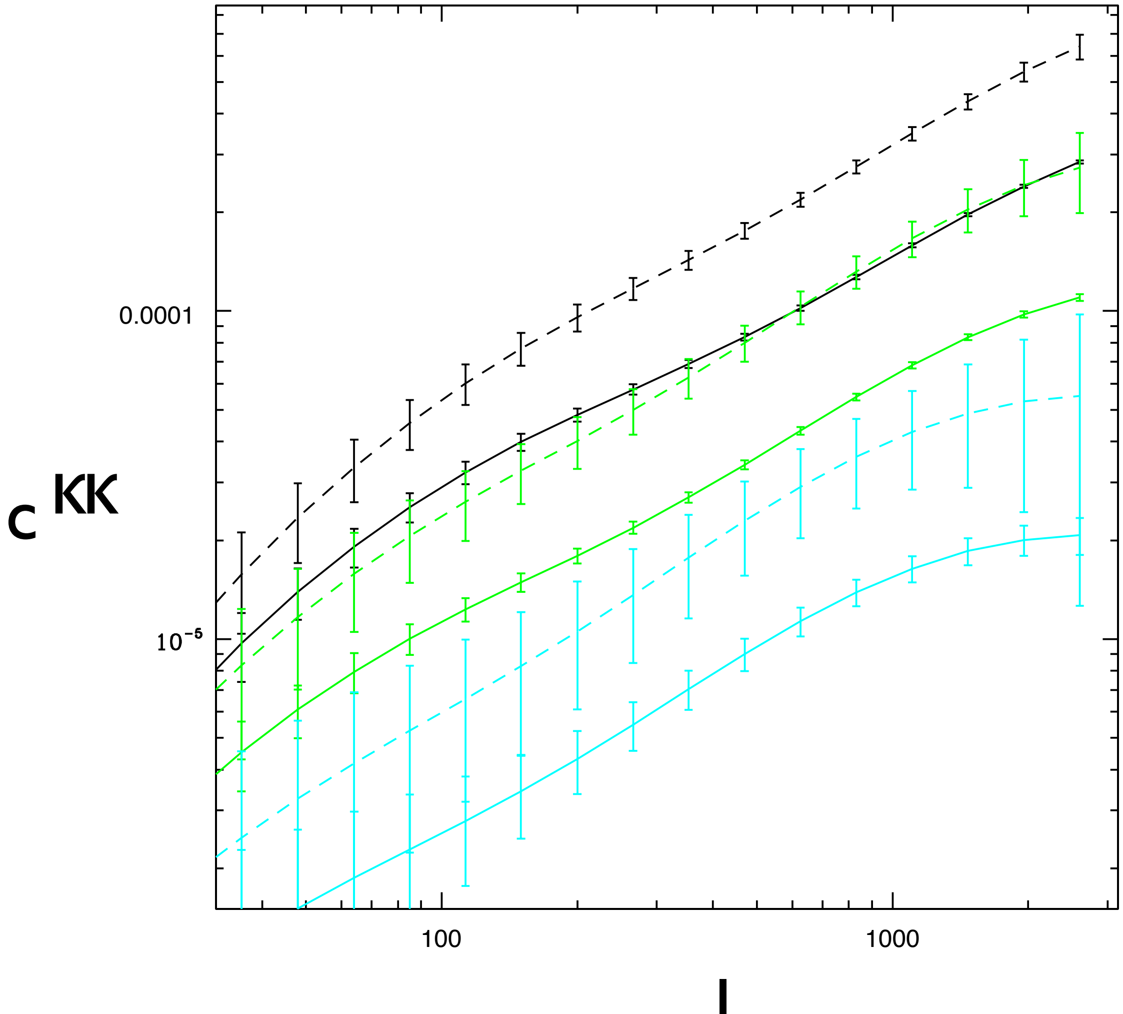


Figure 5.3: The cosmic shear power spectra for galaxy distribution divided in three redshift slices, $0 \le z_1 \le 0.6$, $0.6 \le z_2 \le 1$, and $z_3 \ge 1$. The bold solid curves show the auto-spectra of 3 redshift bins for a ΛCDM model, while the thin curves are the results for a model with the dark energy equation of state $w = -0.9$. The boxes around the bold curves show the expected measurement error due to the sample variance and the intrinsic galaxy shapes for the HSC-wide survey.

HSC-HSC: Solid
HSC-ACTPOL: Dashed



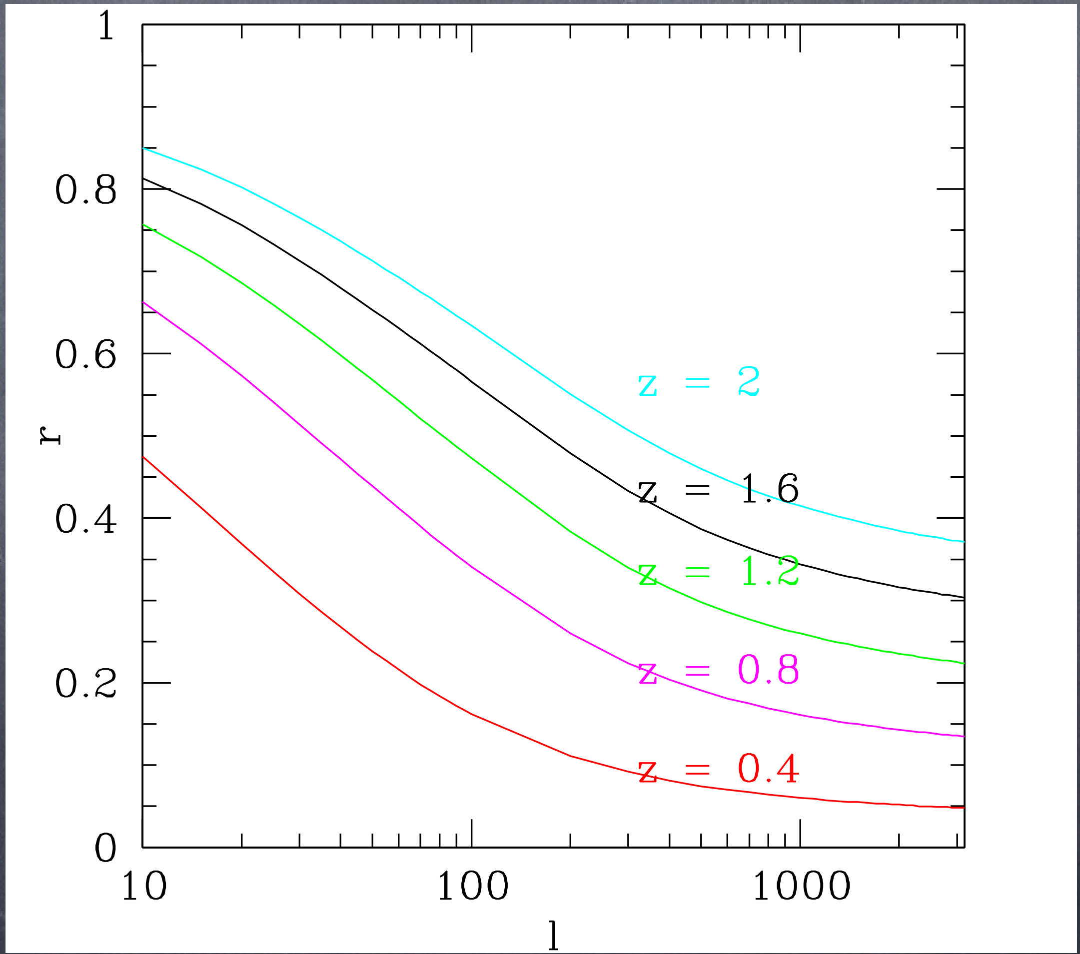
z ~1.5 (black)
z~0.8 (green)
z~0.4 (cyan)

ACT + HSC + XMM Deep

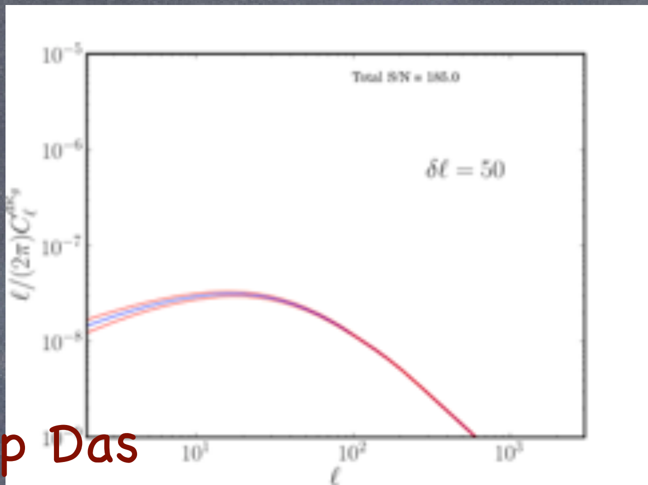
- ACTPOL should get first light in late spring 2012 and being surveying in fall 2012.
- XMM is already taking its XMM-XXL data
- HSC will get first light in early spring 2012
- The first target field is XMM-LSS field
  - Herschel: 17 sq. deg
  - XMM: 25 sq. deg
  - UKIRT: J+K
  - SWIRE
  - VIPERS
  - 2 uK-arcmin sensitivity

CMB Lensing-Optical Lensing Cross-correlation

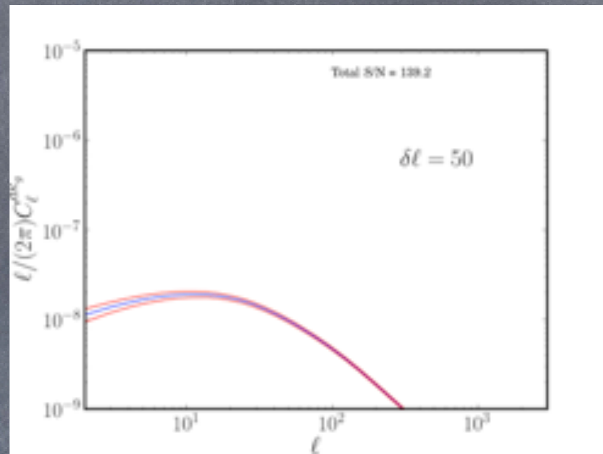
Correlation Coeff

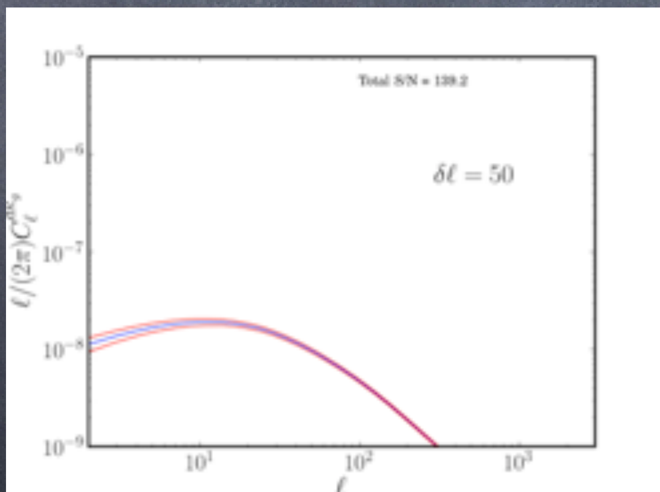


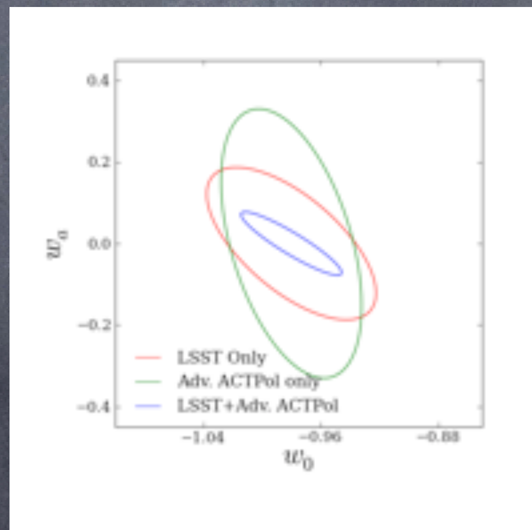
LSST + Advanced ACTPOL



From Sudeep Das

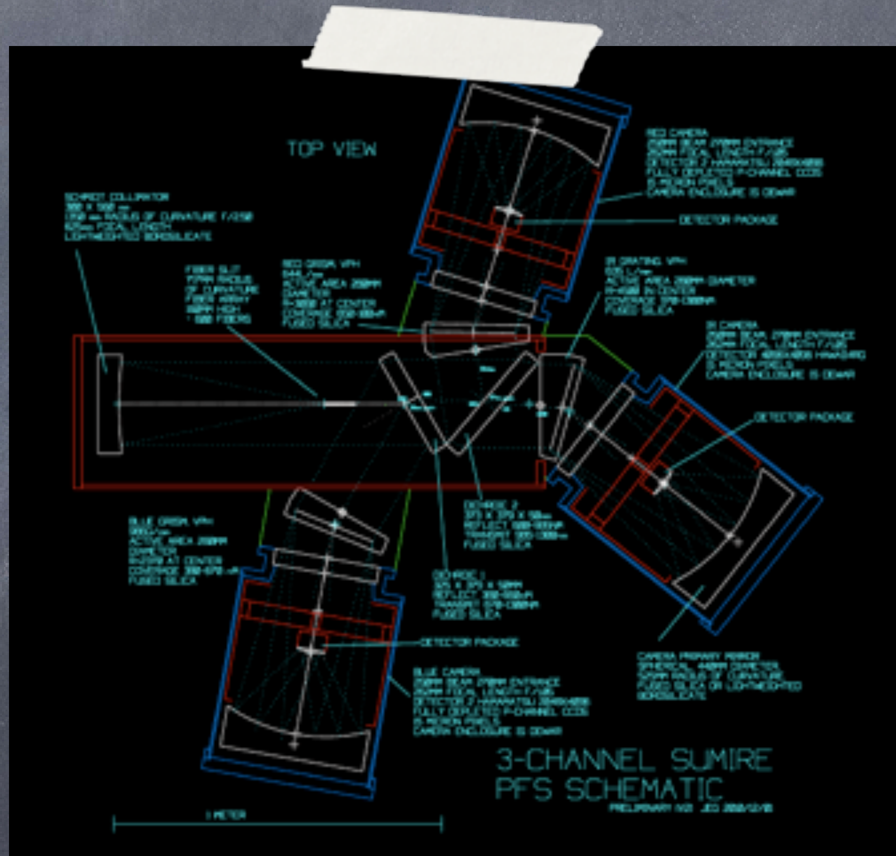






Prime Focus Spectrograph

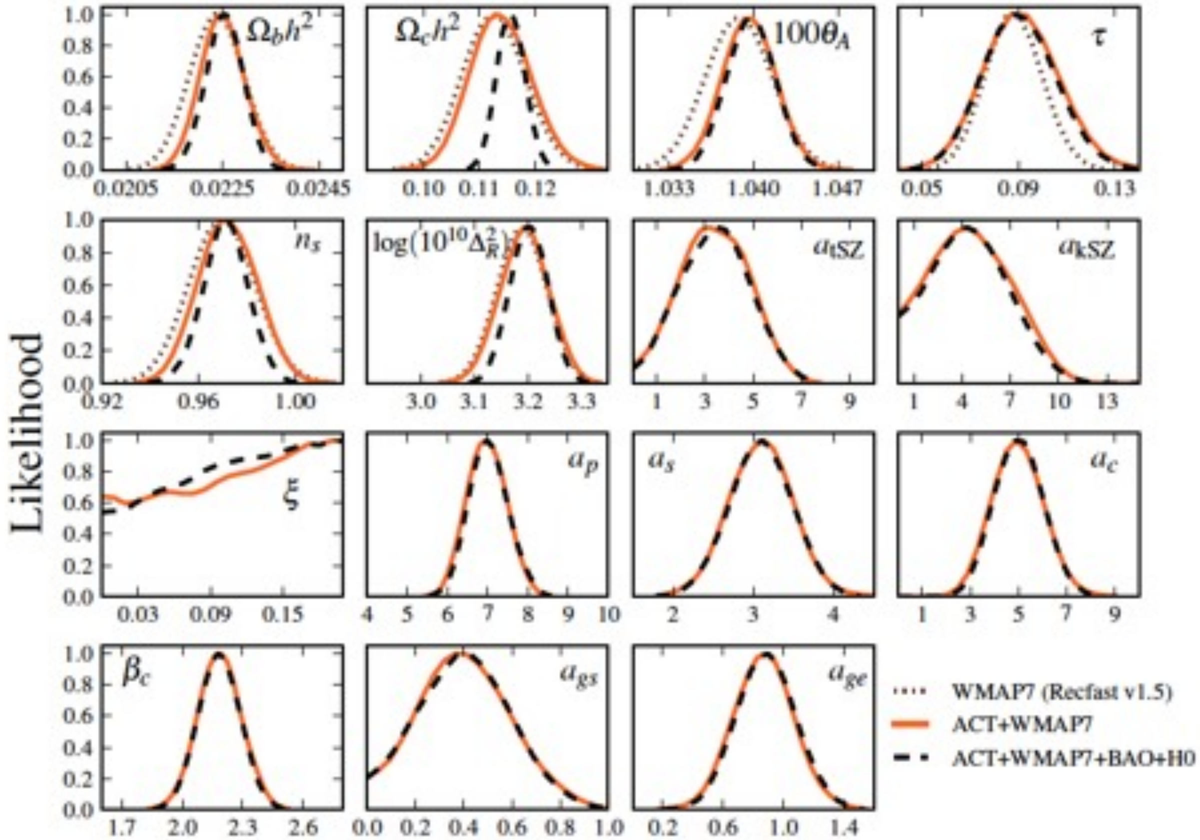
- Lots of imaging surveys (DES, HSC, LSST)....need spectroscopy
- 2400 fibers feeding three spectrographs covering 3800 - 13000 with 3 Angstrom res.
- IPMU/NAOJ/Princeton/Caltech/Sao Paolo/Marseilles/Edinburgh



Conclusions

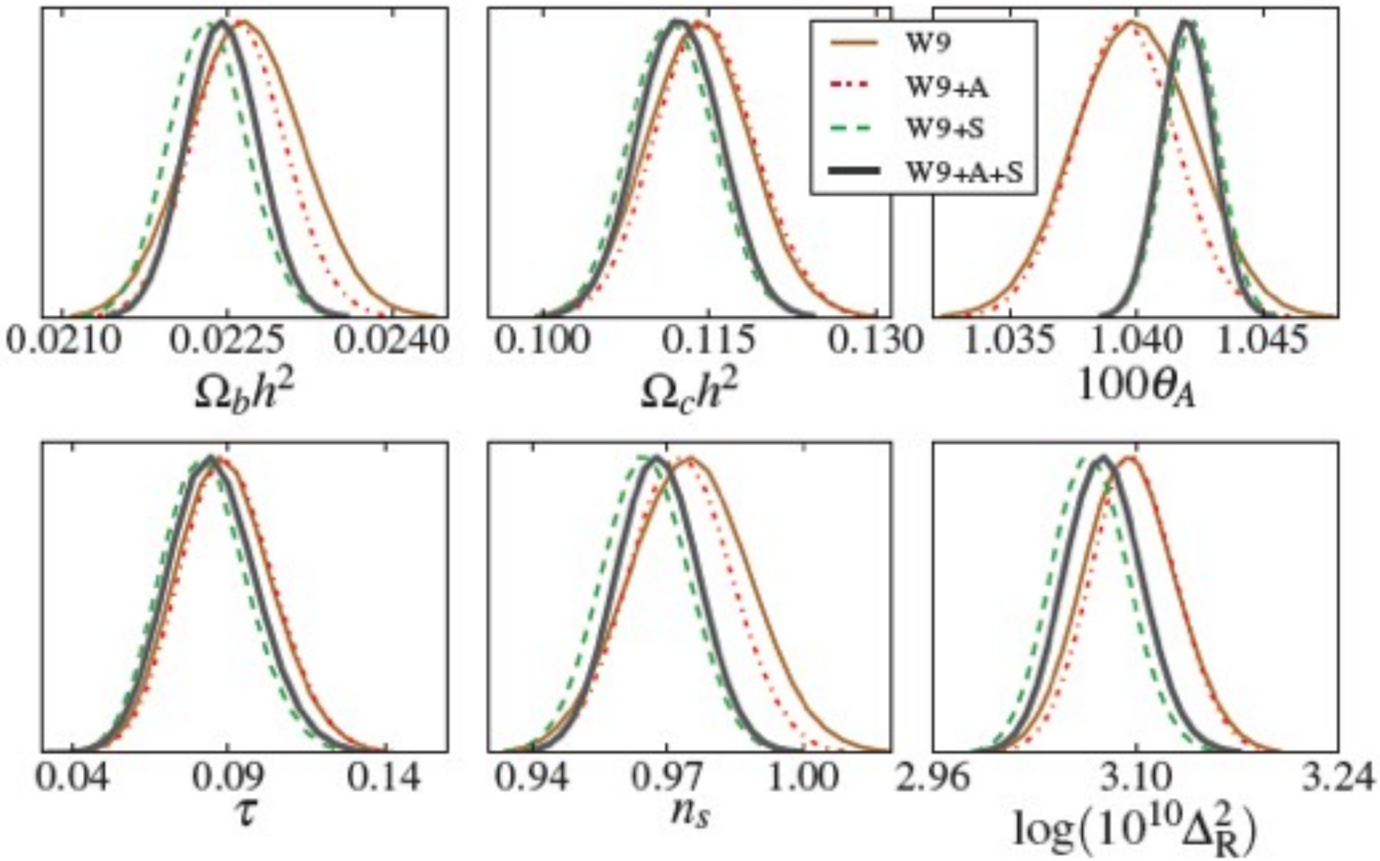
- The Universe is strange, but simple
- CMB Lensing: The fun is only just starting! Data is about to rapidly improve:
  - Planck, ACTPOL, SPTPOL
- Polarization measurements enable precision lensing measurements for high z source plane
- Cross-correlations with Optical Lensing: New Approach to reduce Systematics

ACT consistency



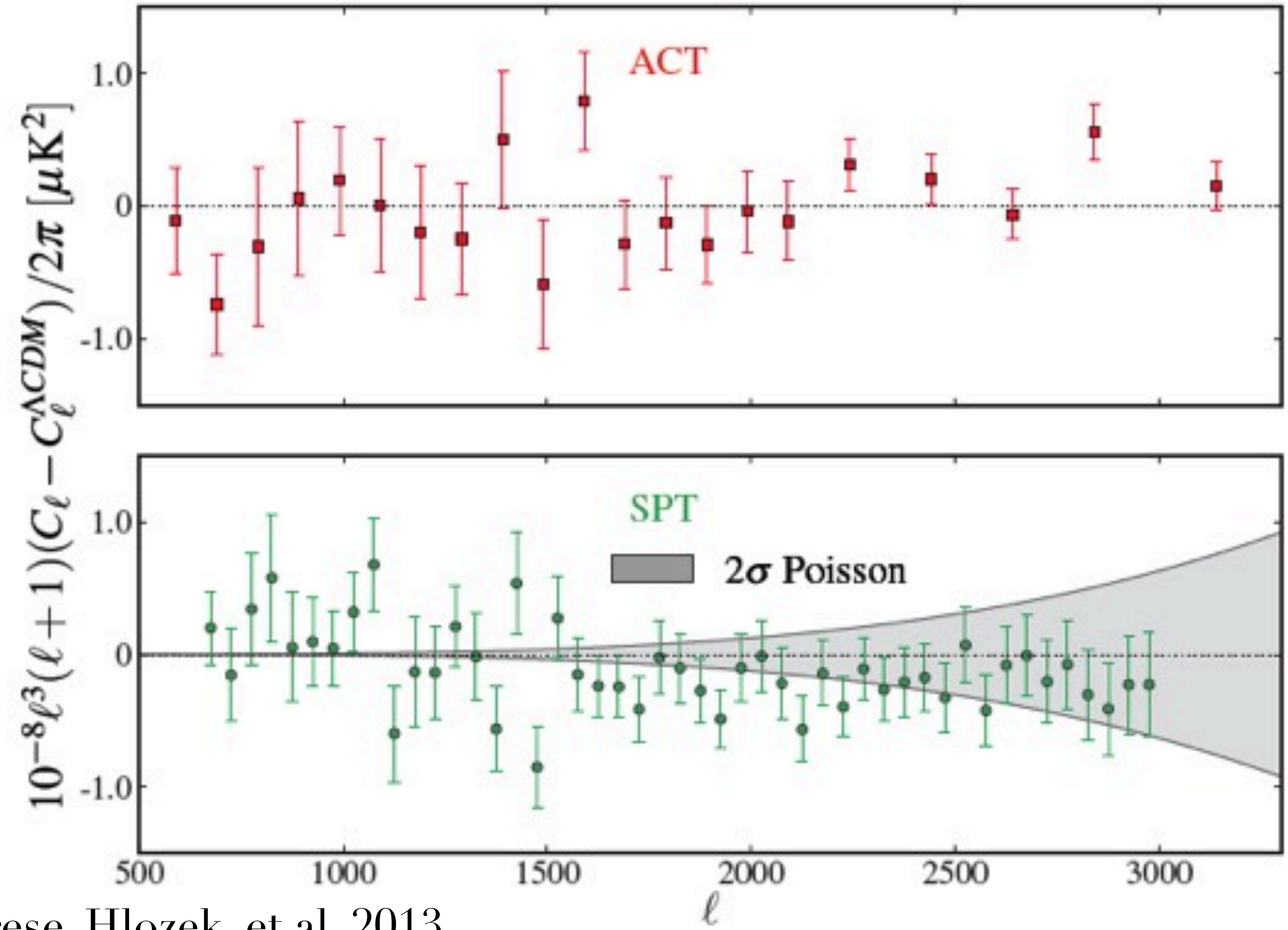
Sievers, Hlozek, Nolta et al. 2013

Consistency between experiments



Calabrese, Hlozek, et al. 2013

ACT consistency



Calabrese, Hlozek, et al. 2013