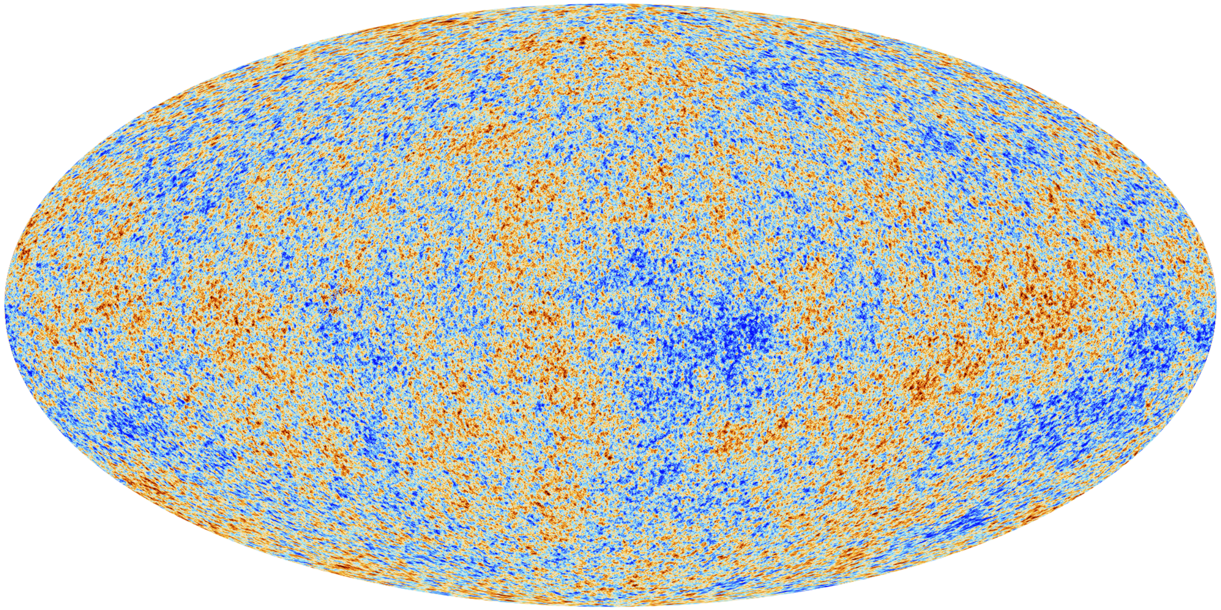
CMB observations



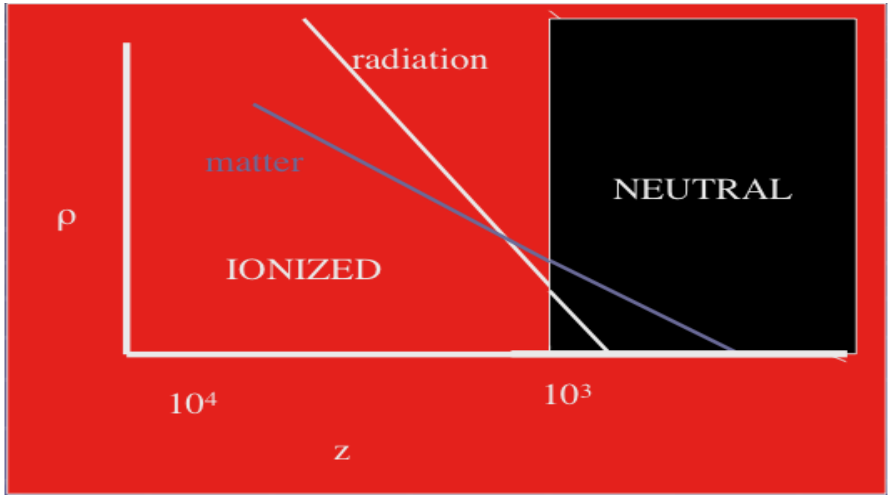
Jo Dunkley

Oxford Astrophysics

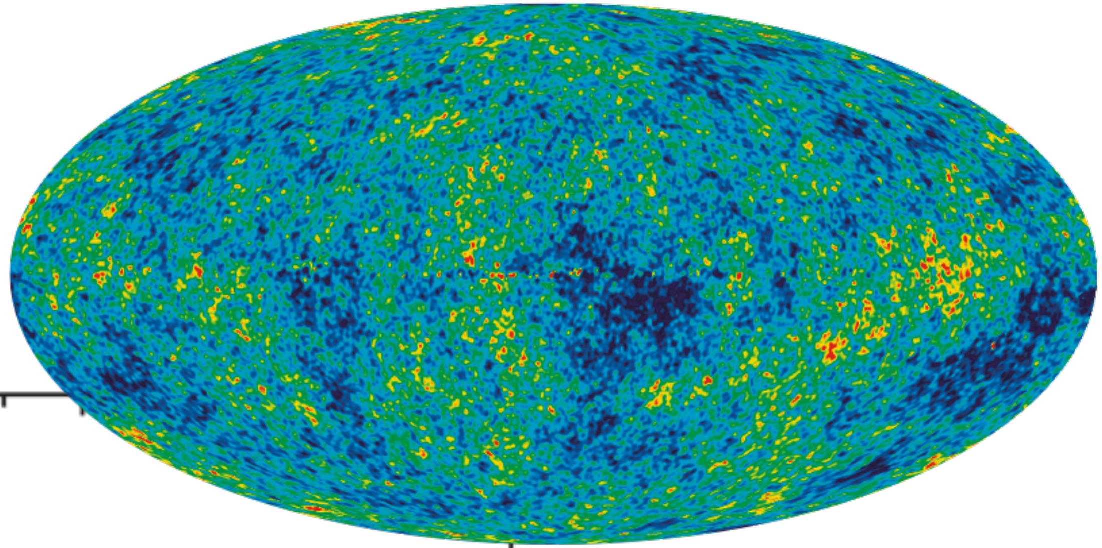
YETI, Jan 8

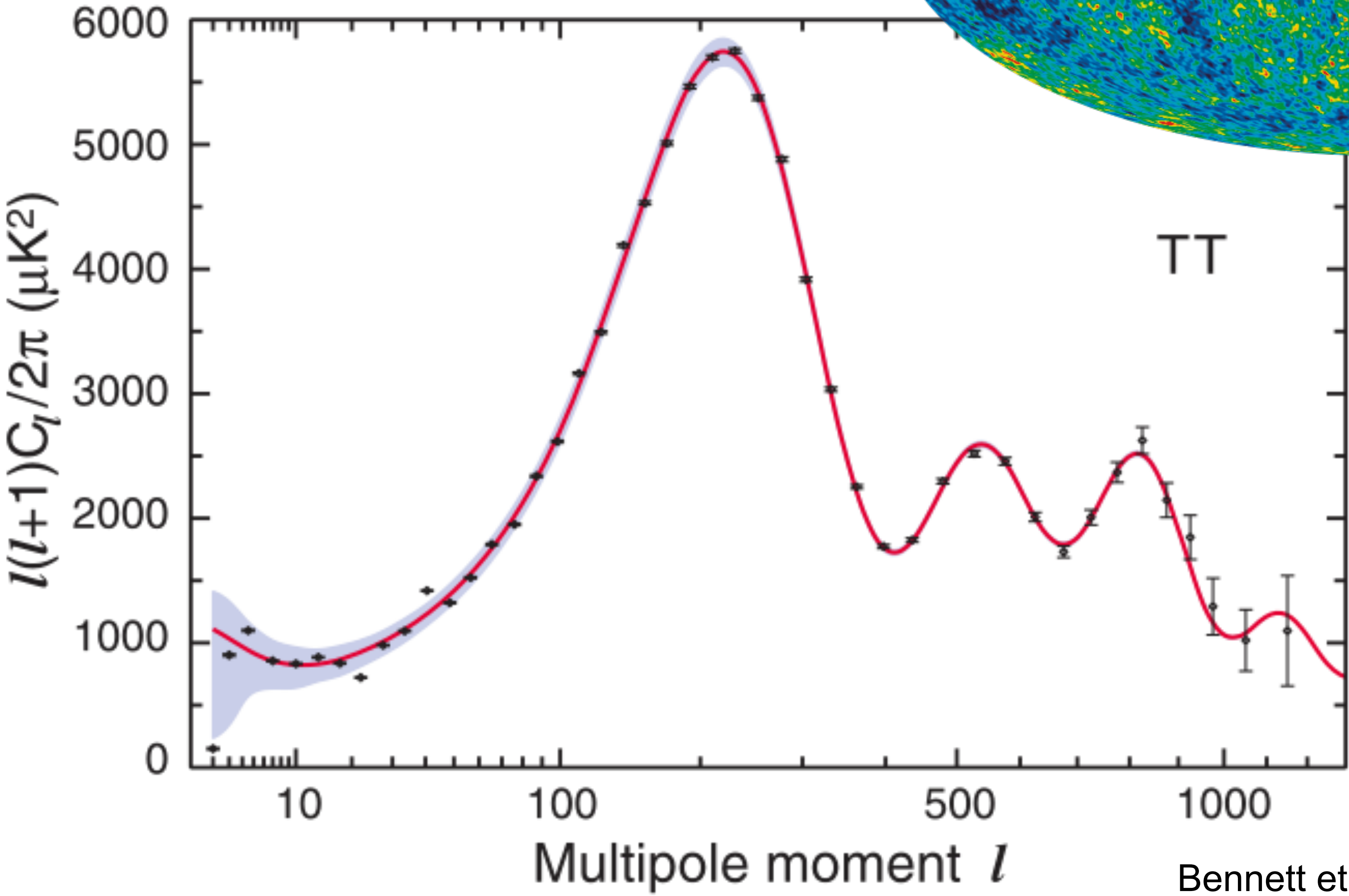
History of early universe

Inflation?	$T \sim 10^{15}$ GeV	$t \sim 10^{-35}$ s
CDM decoupling?	$T \sim 10$ GeV?	$t \sim 10^{-8}$ s
Quark-hadron transition	$T \sim$ GeV	$t \sim 10^{-6}$ s
Neutrino Decoupling	$T \sim 1$MeV	$t \sim 1$s
Big Bang Nucleosynthesis	$T \sim 100$ keV	$t \sim 10$ min
Matter-Radiation Equality	$T \sim 0.8$eV	$t \sim 60000$ yr
Recombination	$T \sim 0.3$eV	$t \sim 380000$ yr



WMAP: 2001-12





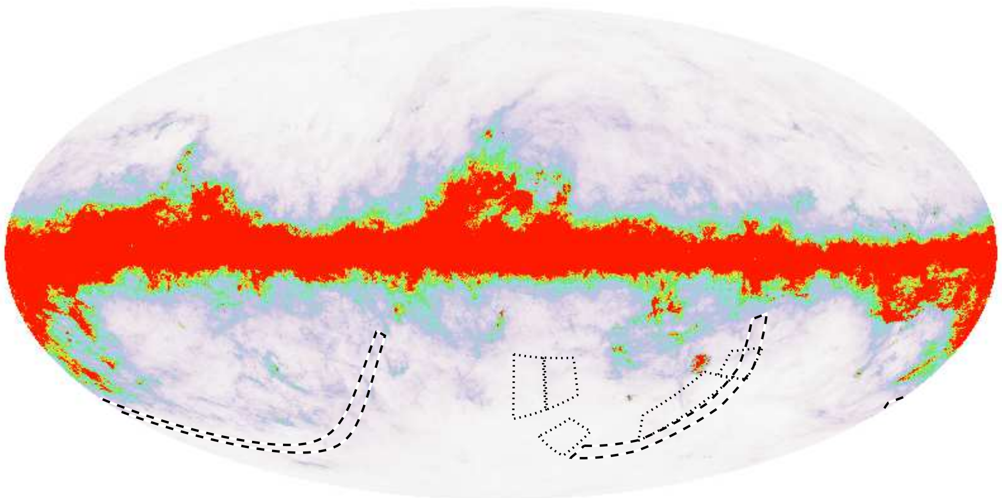
$$T(\hat{n}) = \sum_{lm} a_{lm} Y_{lm}(\hat{n})$$

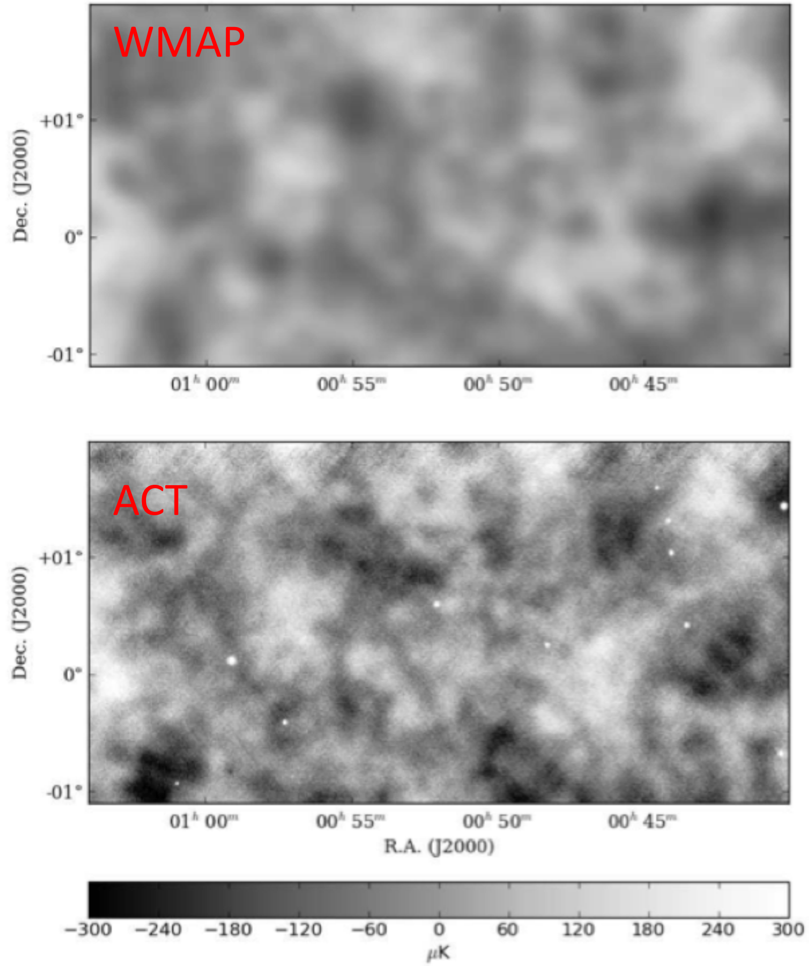
$$c_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

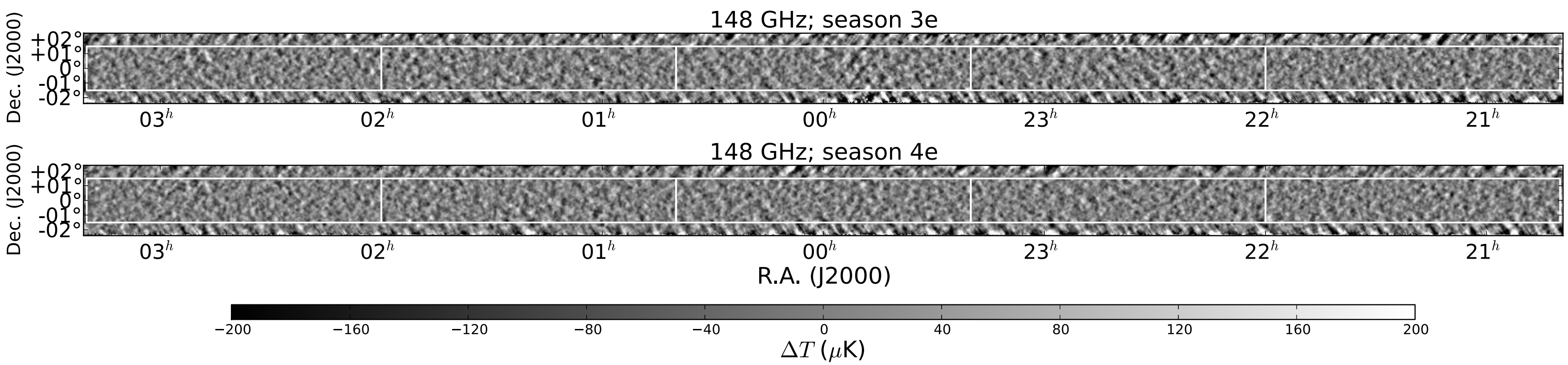
Bennett et al 2012

Established/constrained 6-parameter 'ΛCDM' model

Then came SPT and ACT, 2007-2011

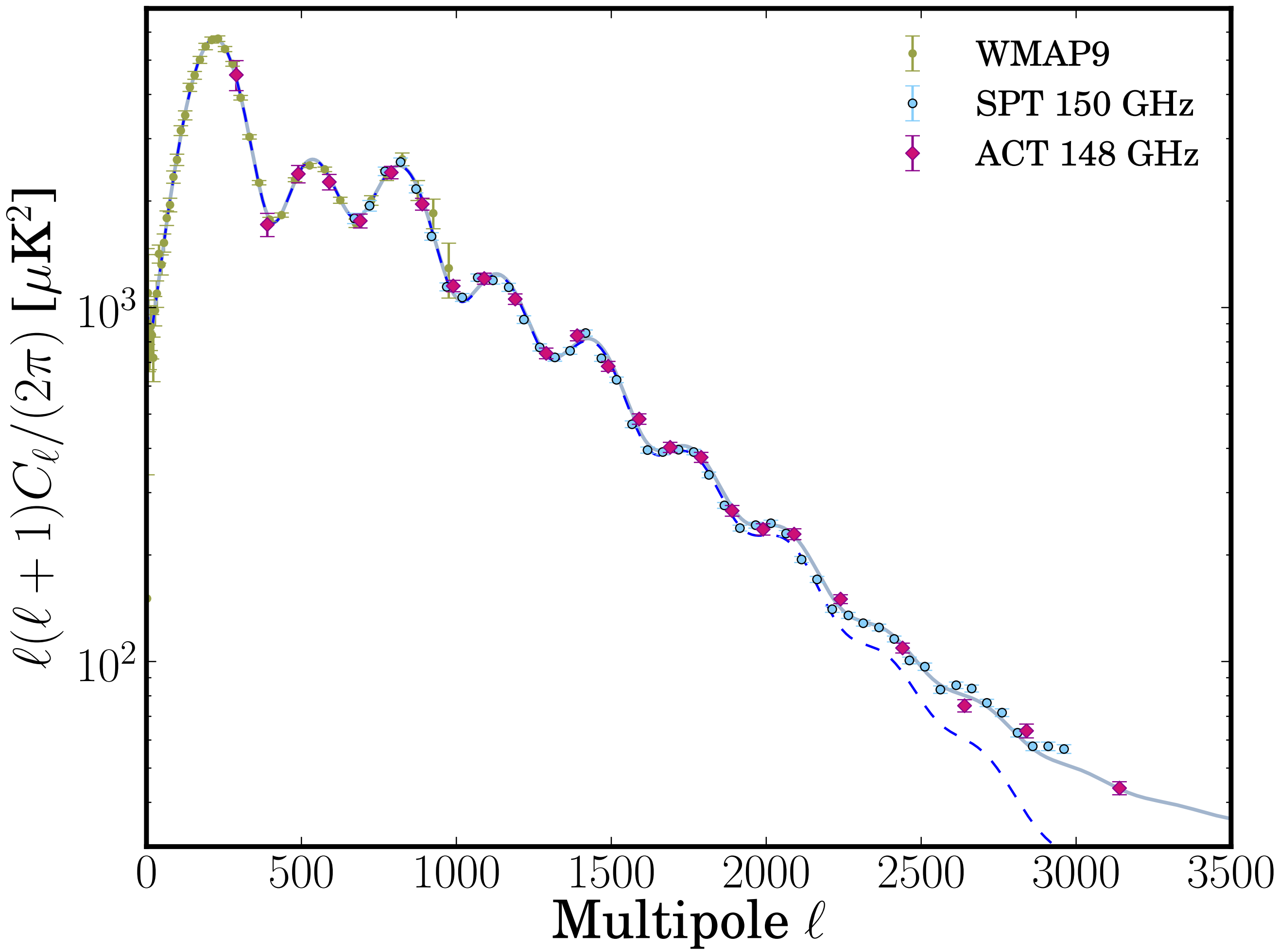






ACT maps, Das et al 2013

Measured to smaller scales by ACT & SPT (2007-11)



Story et al 2012, Das et al 2013

Clearly any deviations from the concordance model would have to be small
Power of these data are to limit extensions to ΛCDM

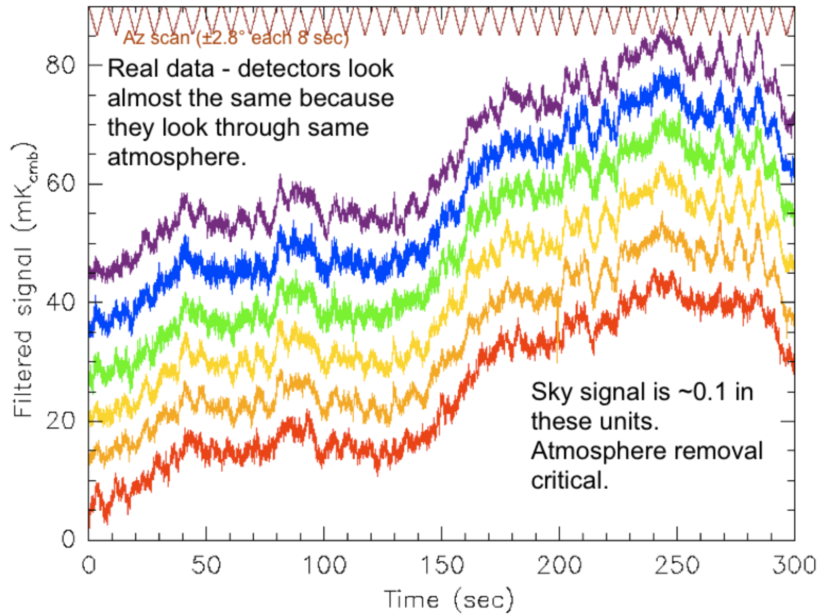
Aside: actually making CMB maps

d = Pm+n, solve

$$P^T N^{-1} P\, m = P^T N^{-1} d$$

d = raw data set (>3TB of data)
m = desired map (200 MB per map)
N = noise covariance between data
P = pointing matrix

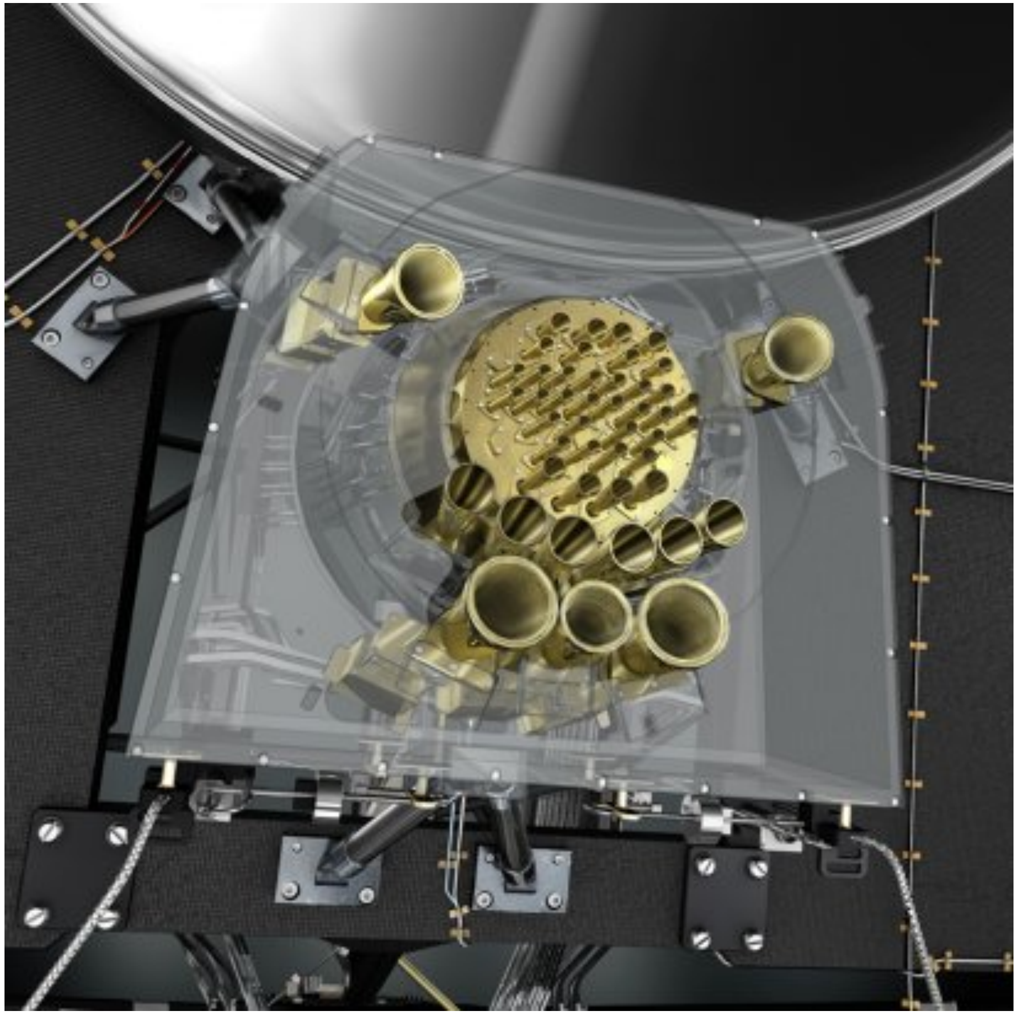
1 season = 100,000 CPU hours on the 22nd fastest supercomputer in the world.



But N is not diagonal.
1. Detectors have non-white noise
2. Any mechanical/electric coupling in camera
3. Atmosphere

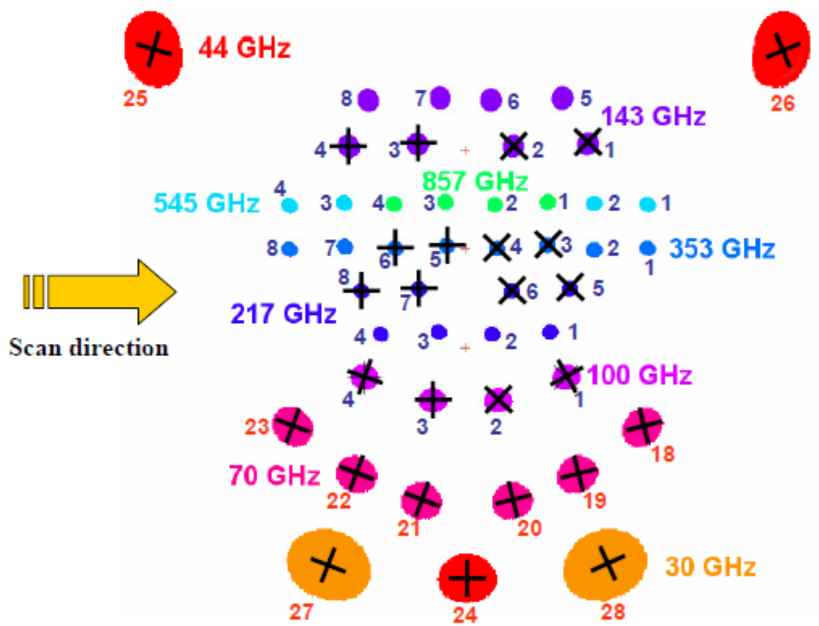
SciNet

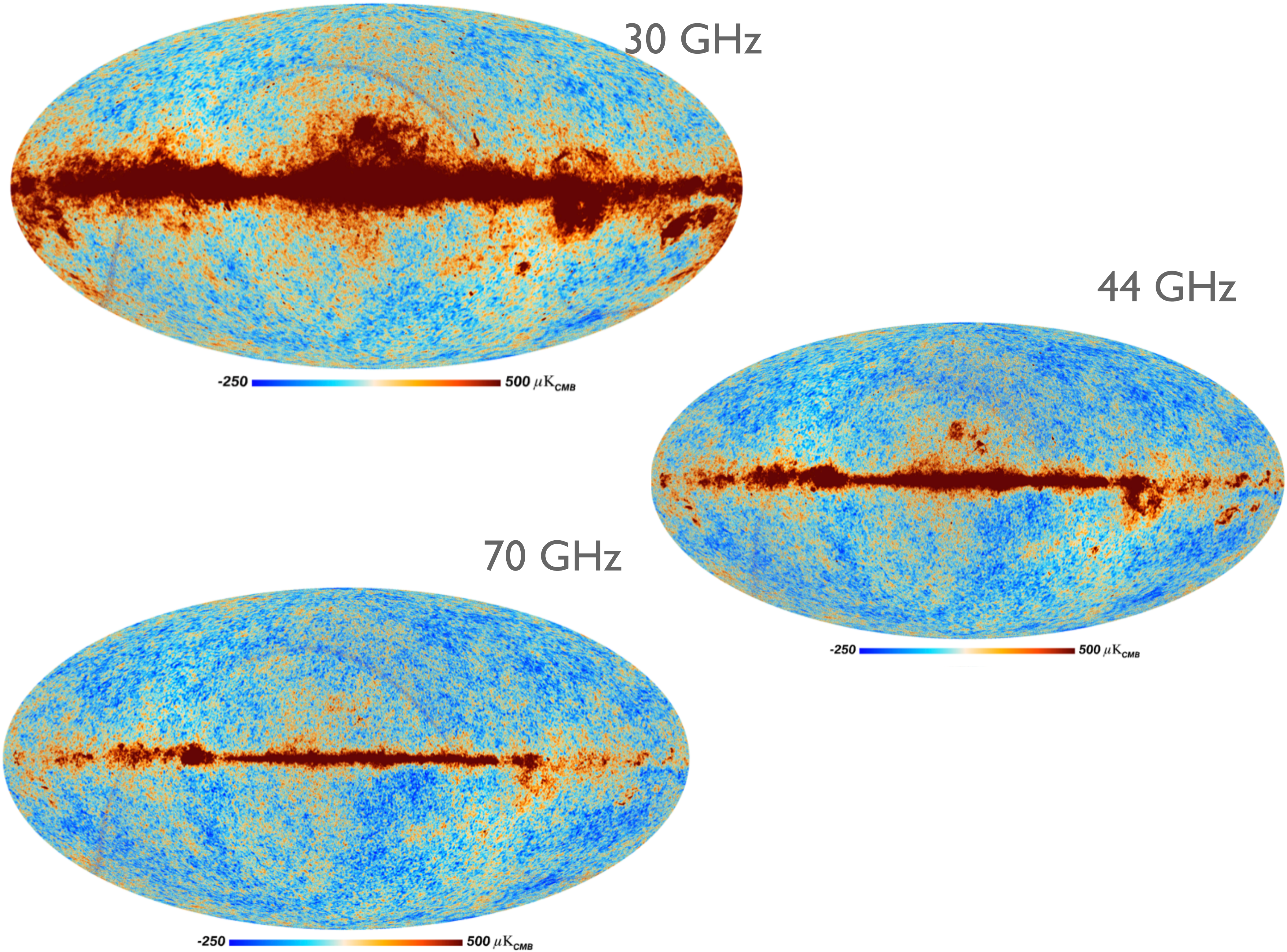
Planck 2009-12/13



Low Frequency Instrument (LFI) – 33-70 GHz
High Frequency Instrument (HFI) – 100-857 GHz.

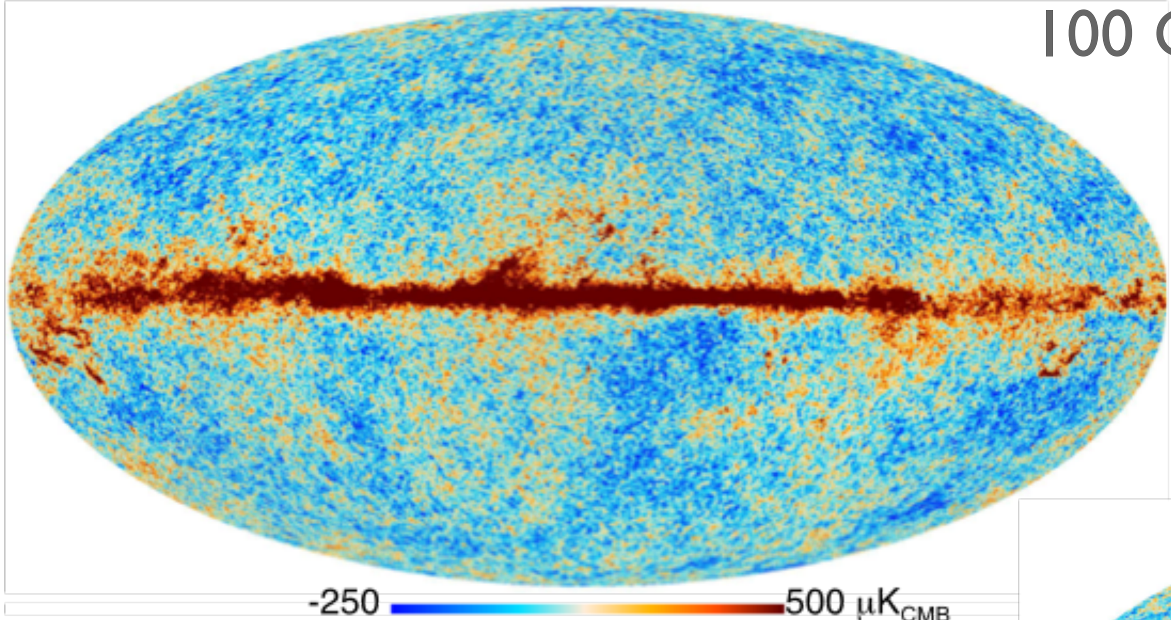
HFI actively cooled to 0.1K so took data until Jan 2012. LFI observed until Oct 2013. Bigger mirror: few arcmin resolution



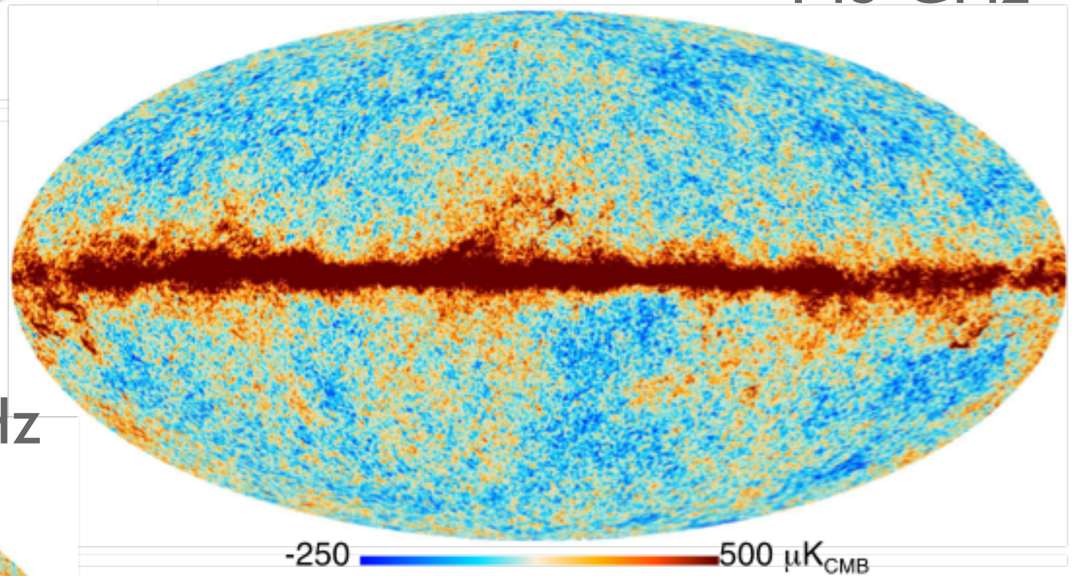


30 GHz
-250
500 μK_{CMB}
44 GHz
-250
500 μK_{CMB}
70 GHz
-250
500 μK_{CMB}

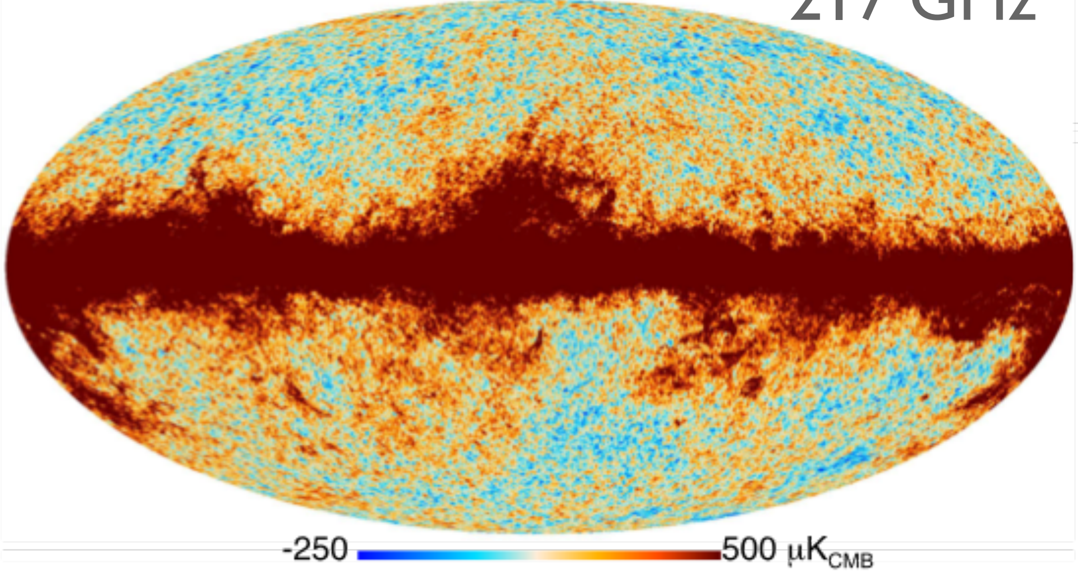
100 GHz



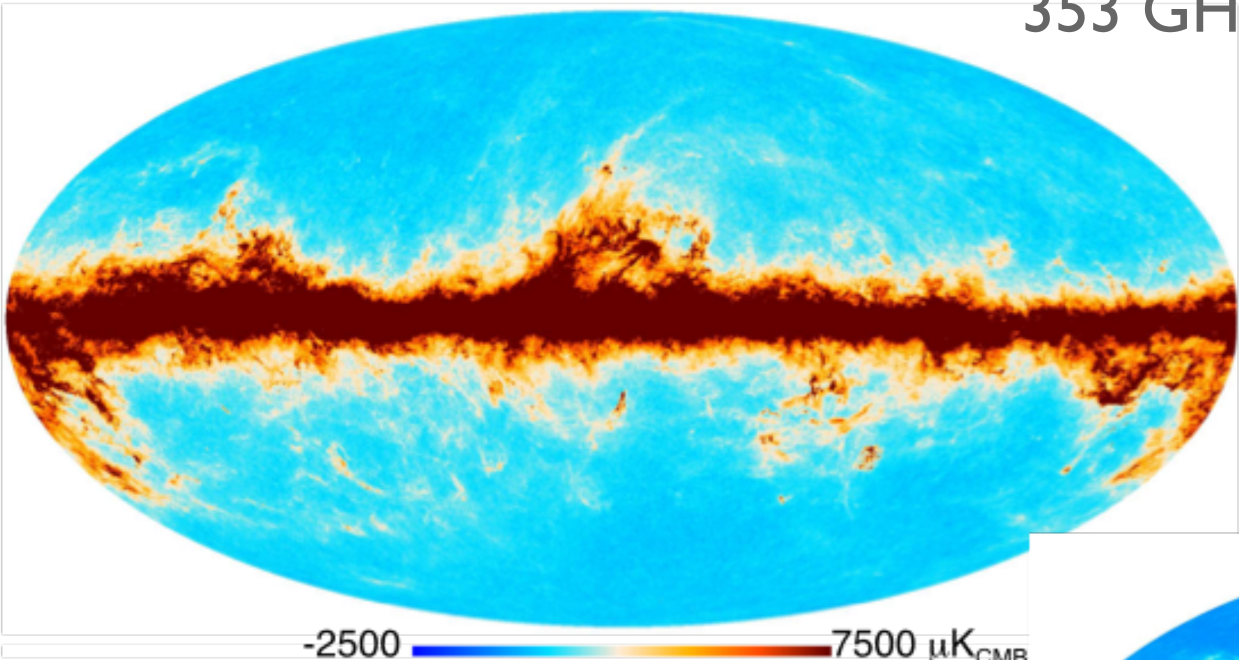
143 GHz



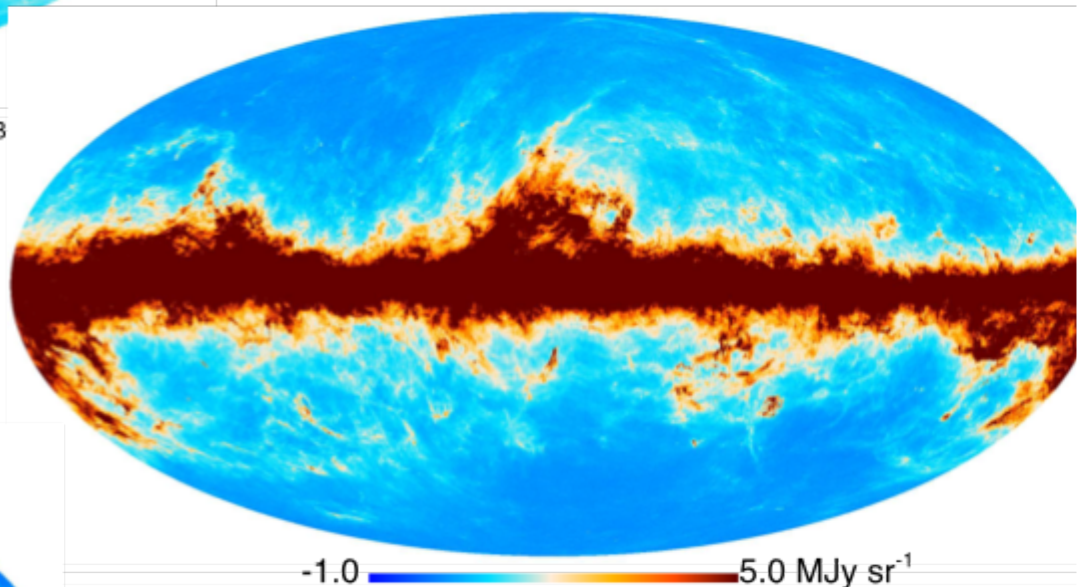
217 GHz



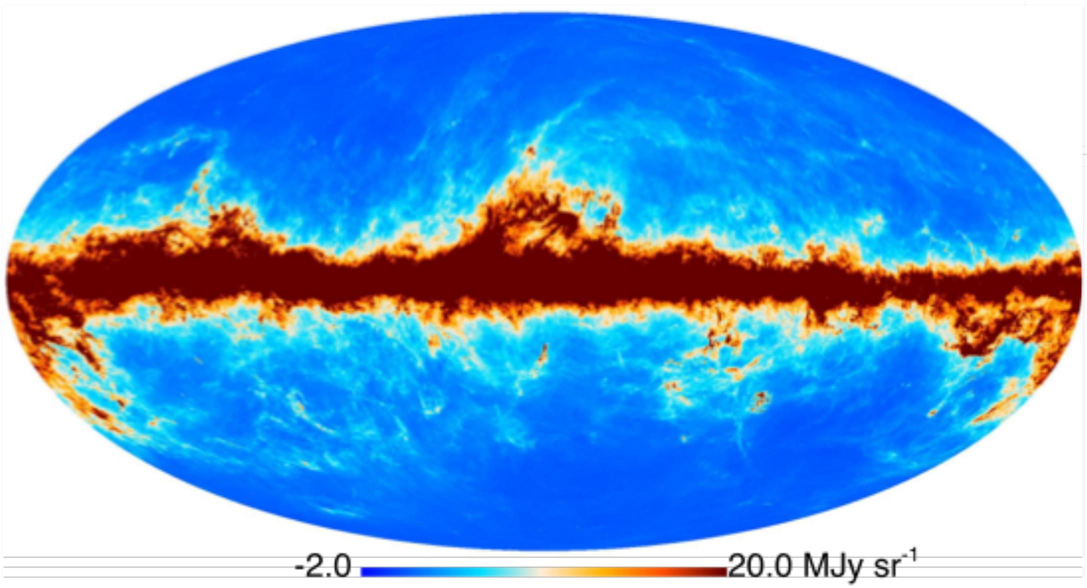
353 GHz

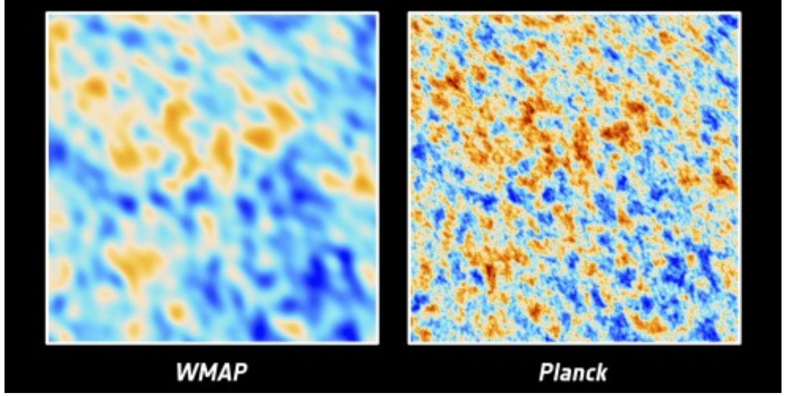


545 GHz

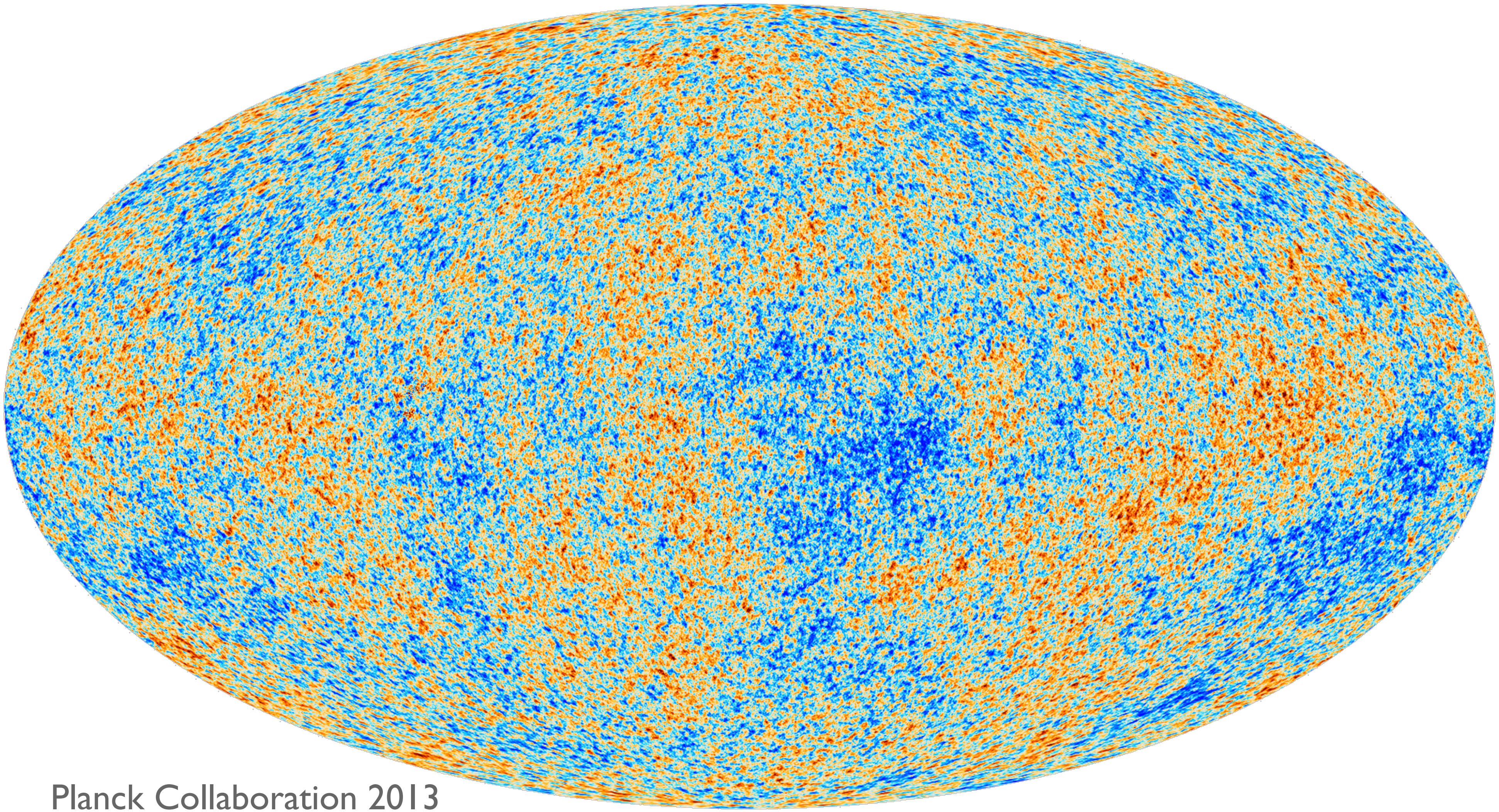


857 GHz



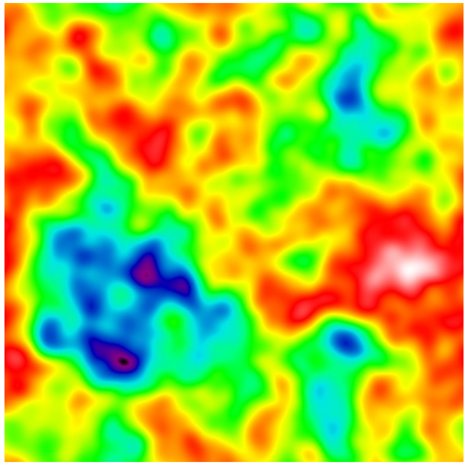


The CMB temperature sky

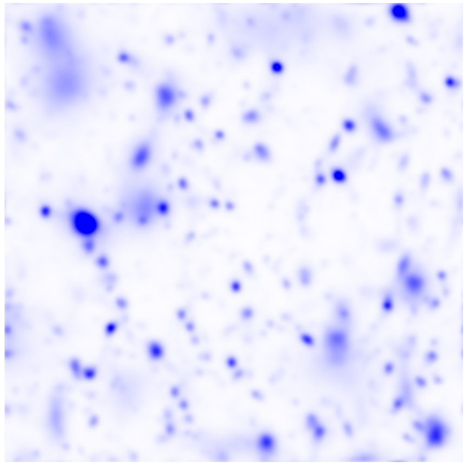


Planck Collaboration 2013

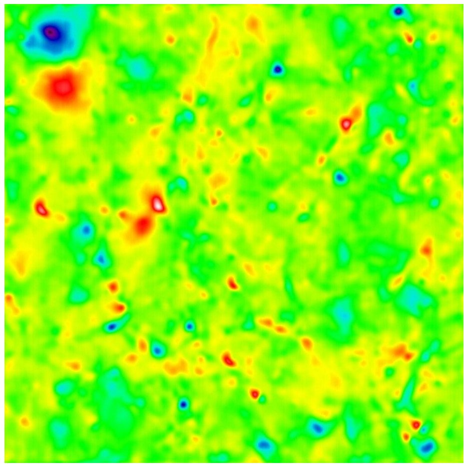
Small-scale components at ~150 GHz



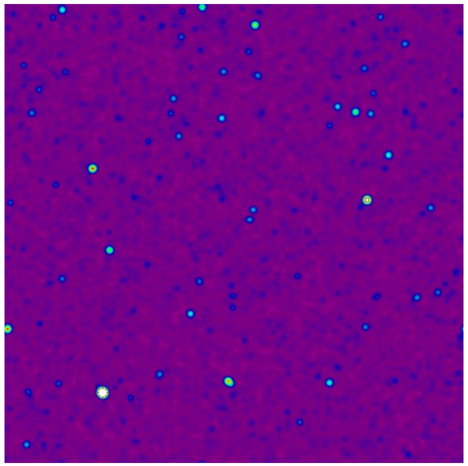
CMB



tSZ

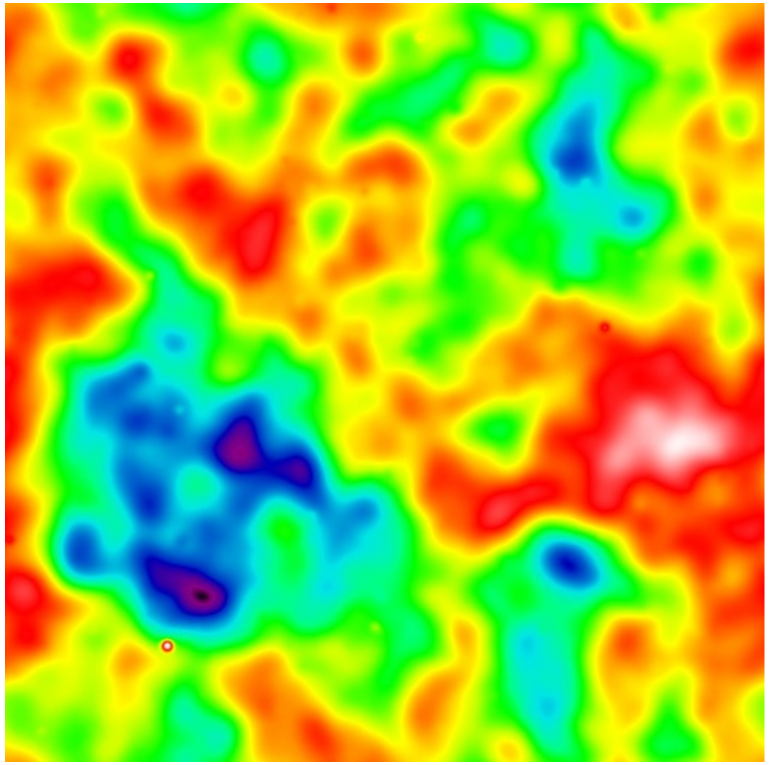


KSZ/OV



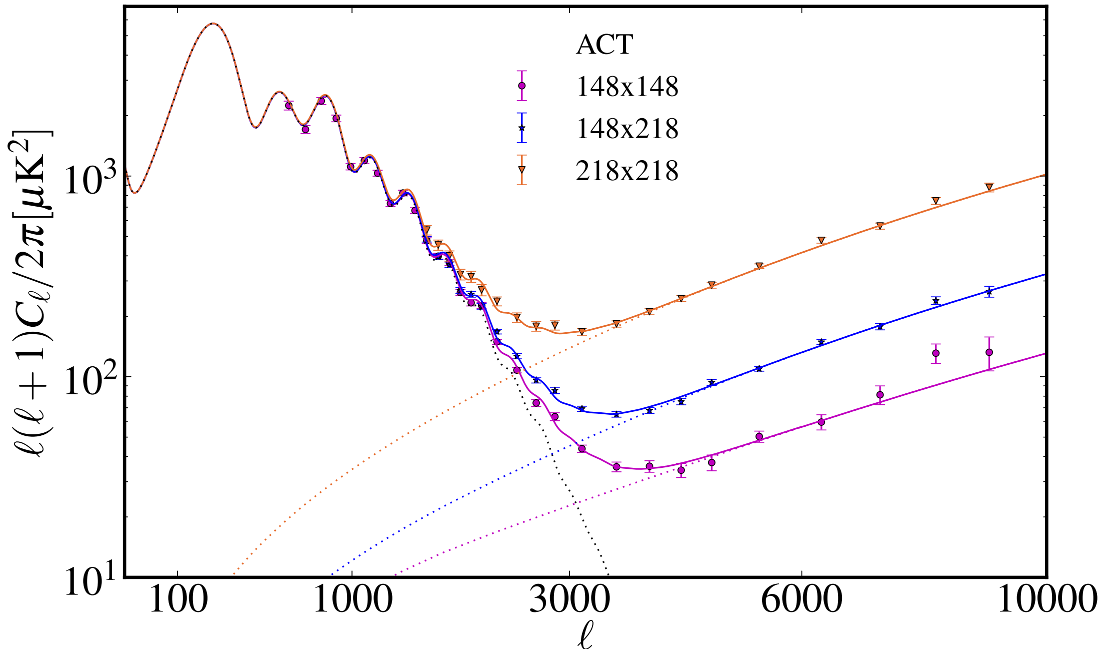
Point Sources

Components Summed



1.4°x 1.4°

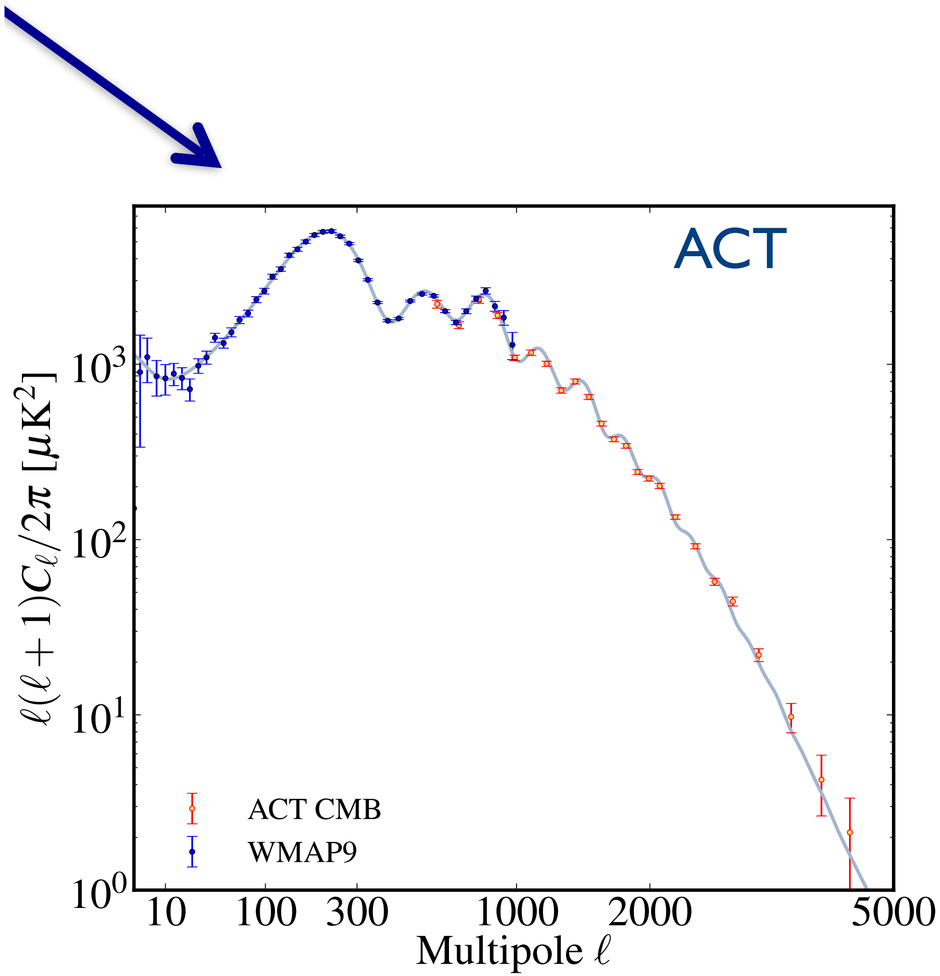
Have to marginalize small-scale foregrounds



Dunkley et al 2013, Sievers et al 2013

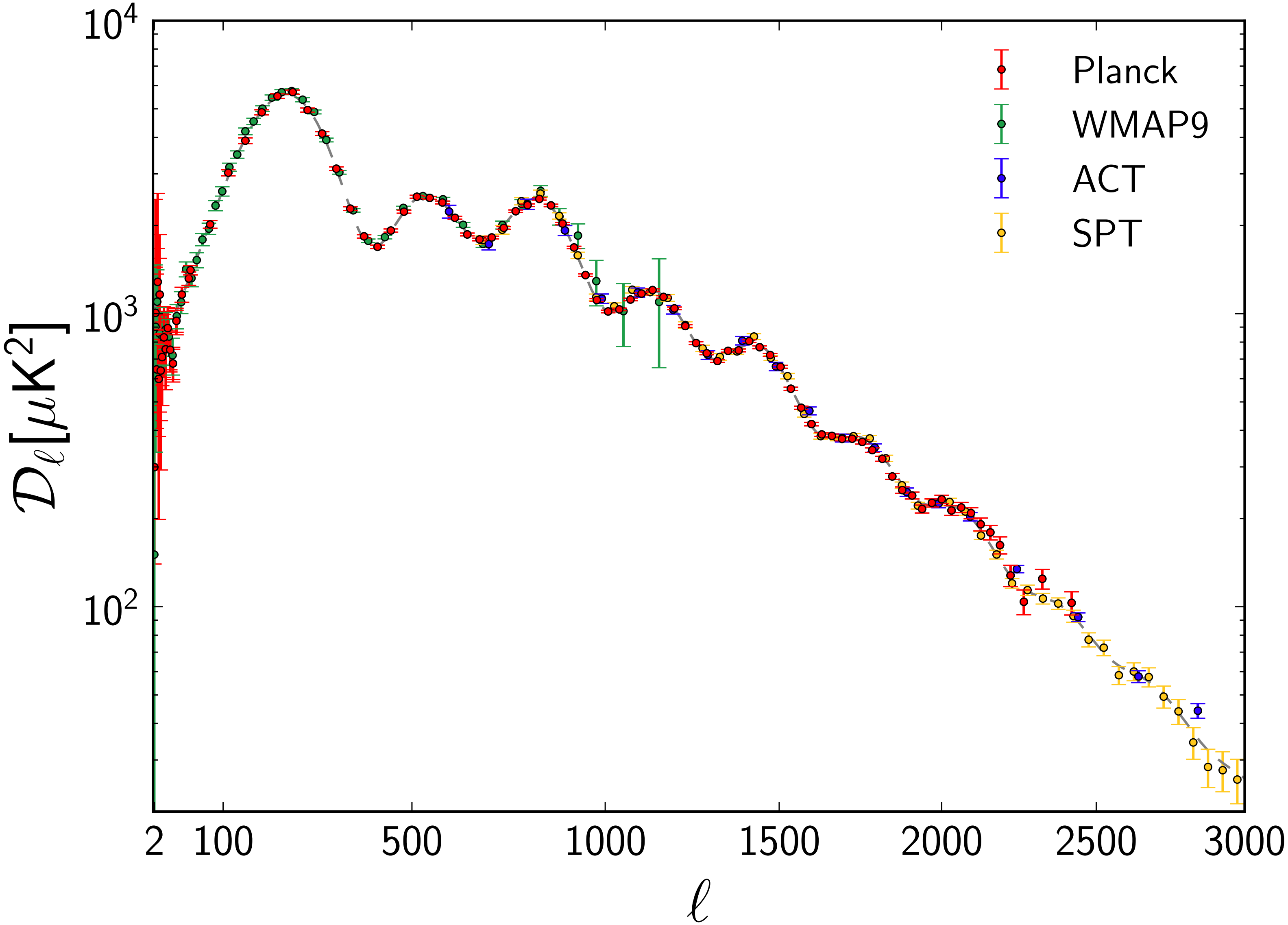
1. Model spectra at multiple frequencies
2. Include point sources, Sunyaev-Zel'dovich effects, Galactic cirrus.
3. Marginalize over non-CMB power using ~10-20 parameters

Used for ACT, SPT and Planck.



Das et al 2013, Dunkley et al 2013

Planck



Strong limits on 6-parameter ΛCDM model
No deviations from ΛCDM seen (some large-scale oddities)

The 6-parameter ΛCDM model

(1) Contents and expansion

Baryon density $\Omega_b h^2$

CDM density $\Omega_c h^2$

Peak position θ ($\sim r_s/D_A$)

(2) Initial fluctuations

Amplitude at k=0.05/Mpc A_s

Spectral index n_s

(3) Impact of reionization

Reionization optical depth τ

(1) Contents and expansion rate

Baryon fraction Ω_b

CDM fraction Ω_c

Cosmol constant fraction $\Omega_\Lambda = 1 - \Omega_b - \Omega_c$

Expansion rate H_0

(2) Late-time size of fluctuations

Amplitude on 8 Mpc/h scales σ_8

(3) Reionization

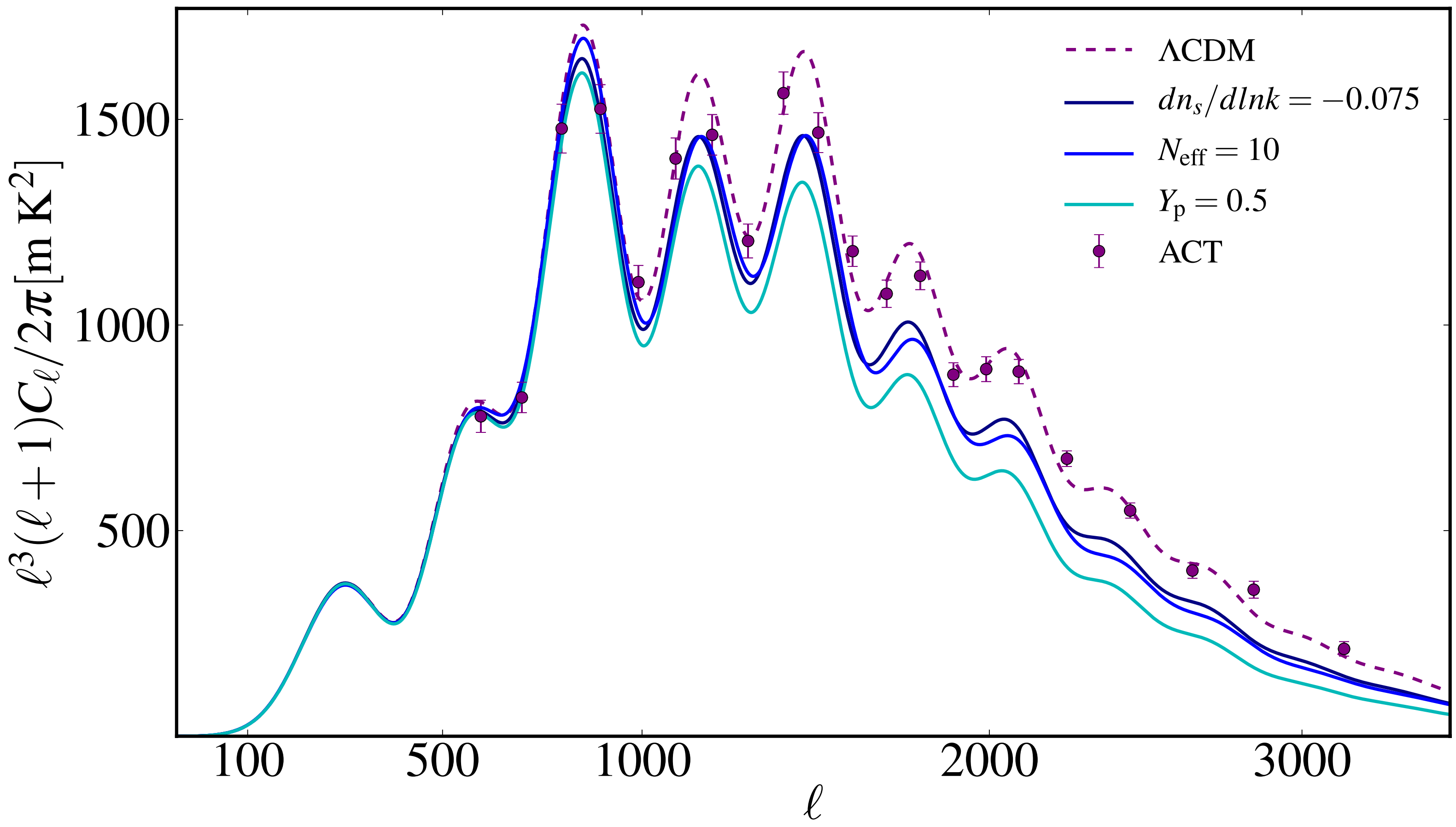
Redshift of reonization z_{re}

Assumptions:

- Geometry/contents: Flat, w=-1, Σm_ν=0.06eV, no warm dark matter, N_{eff}=3.04, Y_P=0.25
- Primordial fluctuations: adiabatic, power-law $P(k) = A(k/k_0)^{n-1}$, no tensors, no cosmic strings
- Smooth, quick reionization of universe

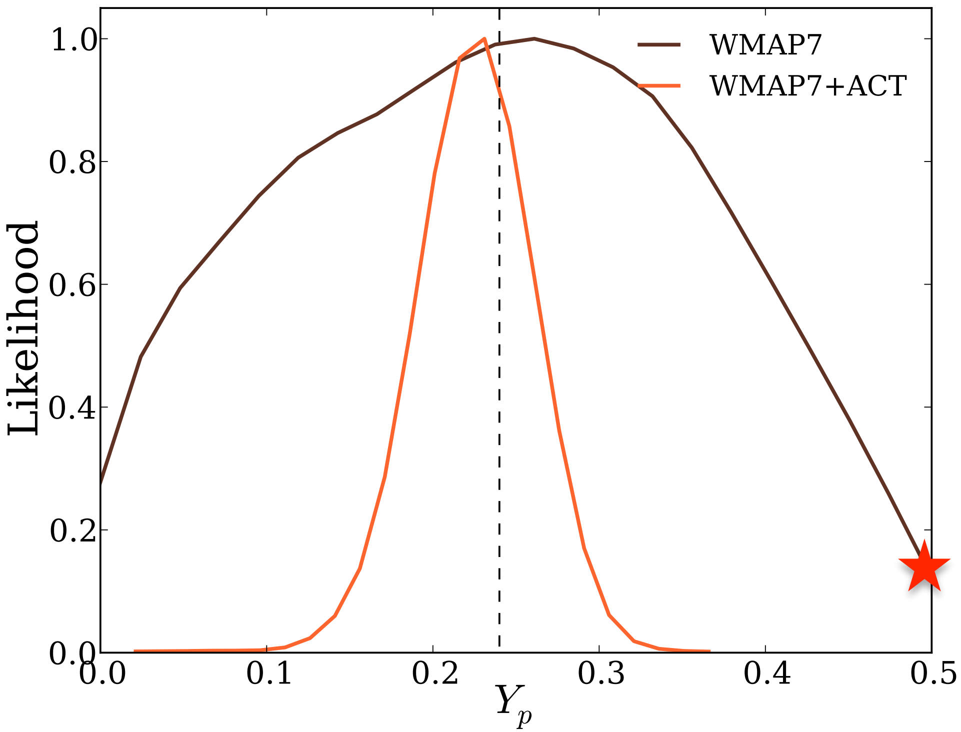
Cosmology from the higher acoustic peaks

1. Measure Silk damping, test recombination *[neutrinos, helium, early dark energy, dark matter annihilation, time-varying constants]*
2. More decades for primordial spectrum *[index and its running]*
3. Probe scales where non-'standard' fluctuations could be seen *[cosmic strings, isocurvature]*

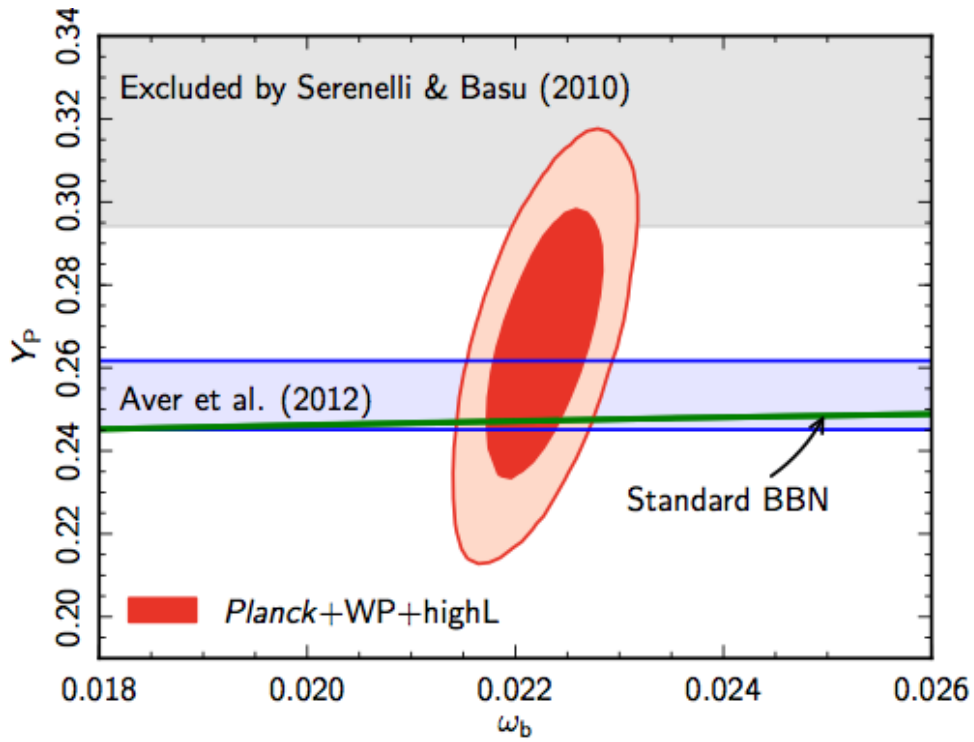


From E. Calabrese, for ACT

(1) Primordial helium



Sievers, Hlozek et al. 2013



Planck collab XVI 2013

Usually assume Y_P predicted by BBN: $Y_P = 0.2485+0.0016[(273.9\Omega_b h^2-6) +100 (S-1)]$

Instead can test BBN: more helium decreases electron density, increasing mean free path and Silk damping: $n_e = n_b(1-Y_P)$

$Y_P = 0.27 \pm 0.02$ (Planck+)

(1) Relativistic species

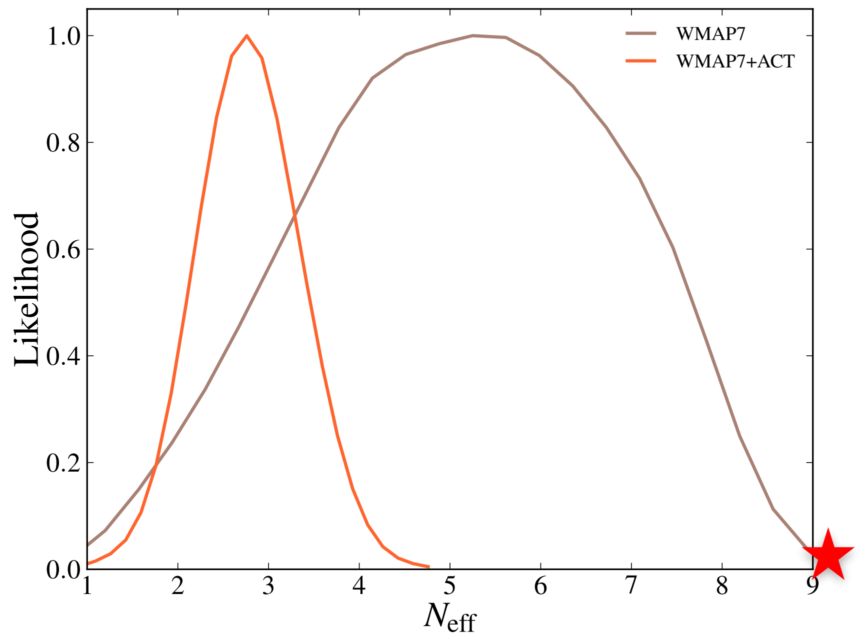
Usually assume 3 neutrino species.

$$\rho_{rel} = \left[\frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{eff} \right] \rho_\gamma$$

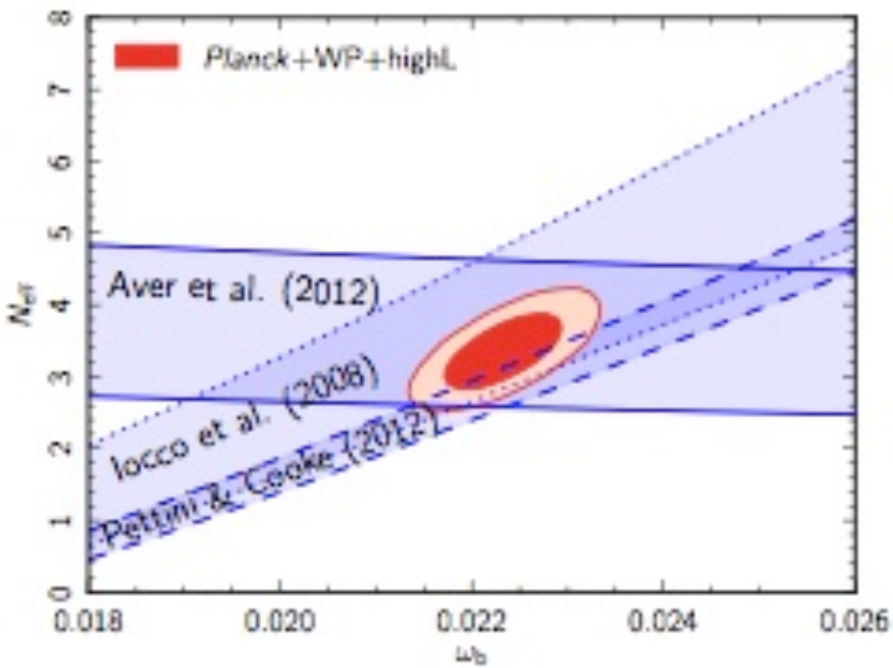
More species: longer radiation domination, suppress early acoustic oscillations, and add phase shift

ACT+SPT+WMAP9: $N_{eff} = 3.4 \pm 0.4$ (Calabrese et al 2013)

Planck+: $N_{eff} = 3.4 \pm 0.3$ (Planck Collab 2013)



ACT: Sievers, Hlozek et al. 2013



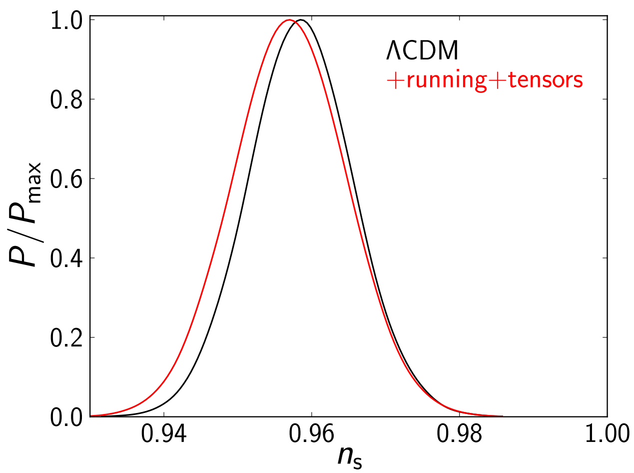
Planck Collab XVI 2013

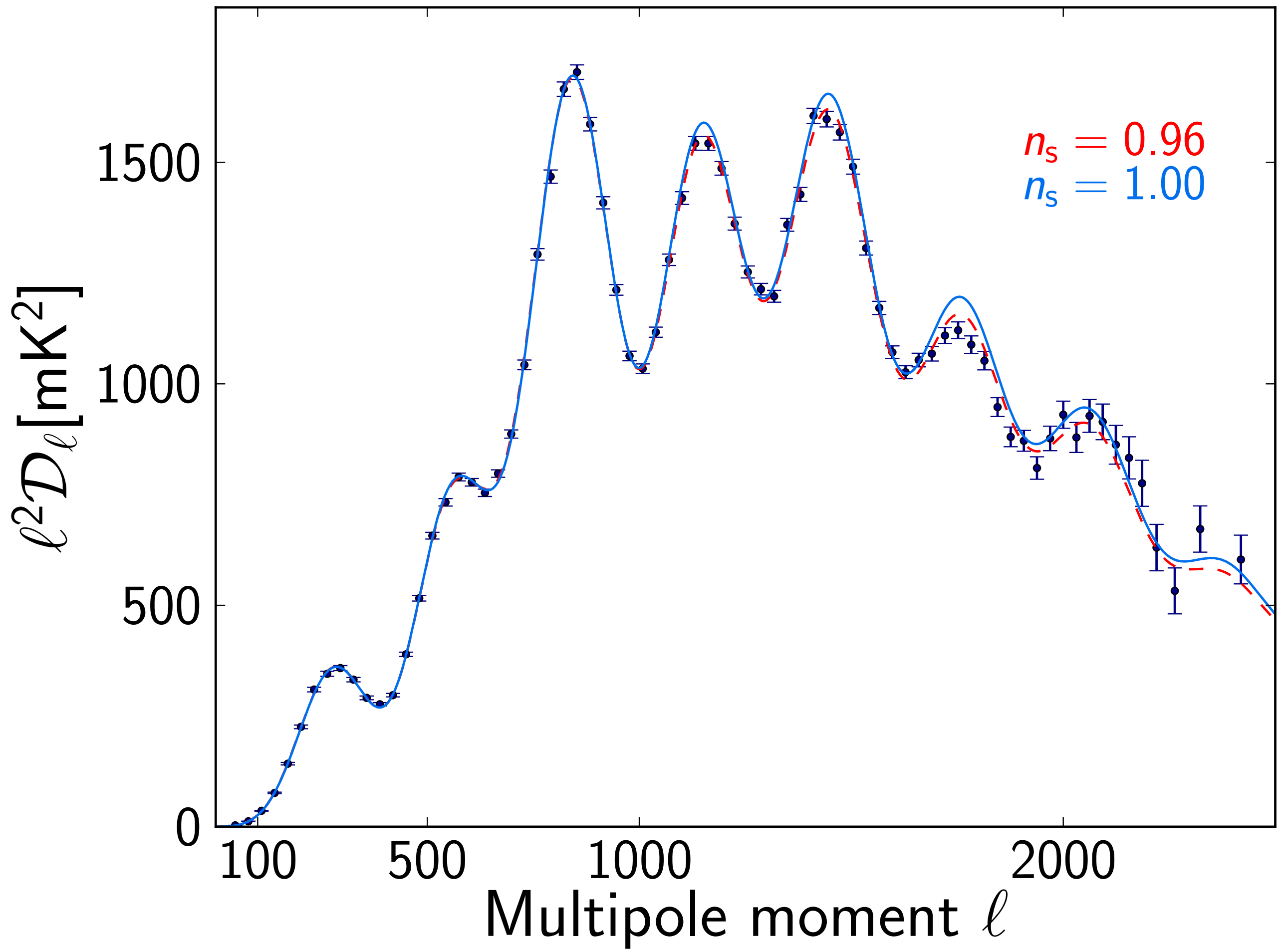
(2) Primordial spectrum: spectral index n<1

Harrison-Zel'dovich generates too much power on small scales

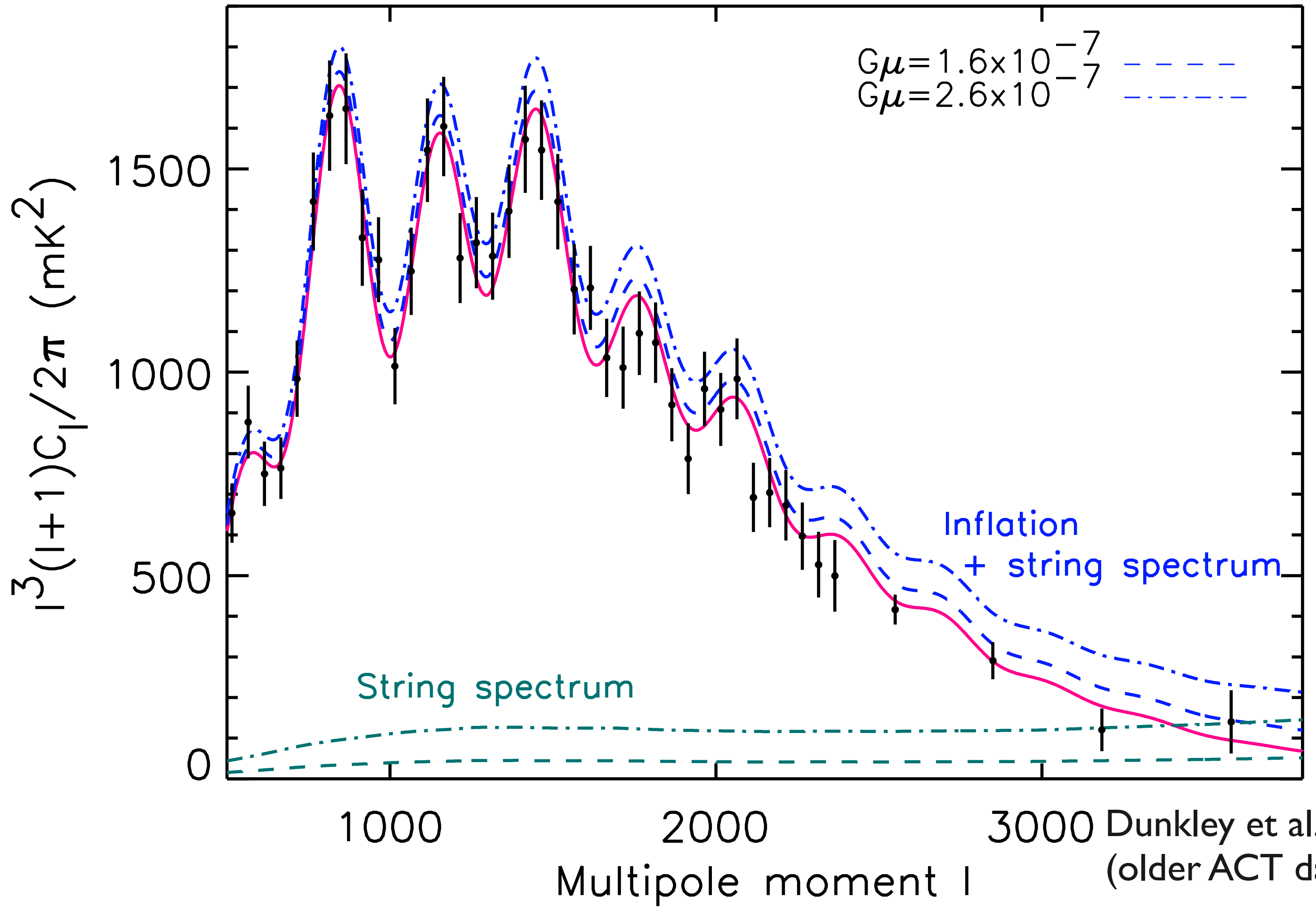
Ruled out at >5σ

$n_s = 0.960 \pm 0.007$





(3) Cosmic strings



Dunkley et al. 2010
(older ACT data)

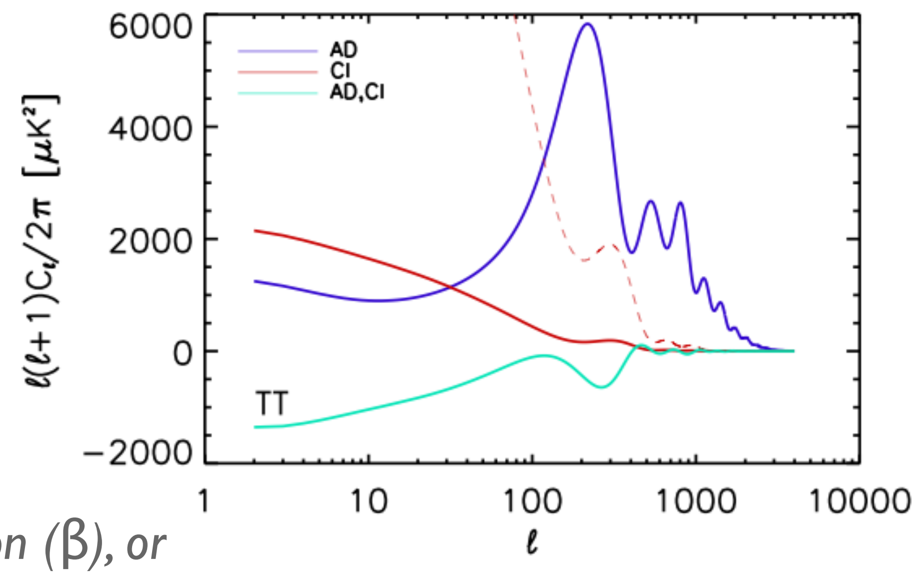
Cosmic strings may be sub-dominant source of anisotropy.

Example: Nambu string sims (Battye & Moss 2010).

$G\mu < 1.1 \times 10^{-7}$ (95%, ACT+WMAP, Sievers et al 2013)

Spectral index less than unity: hybrid inflation disfavored.
Similar limits from Planck.

(3) No evidence for isocurvature

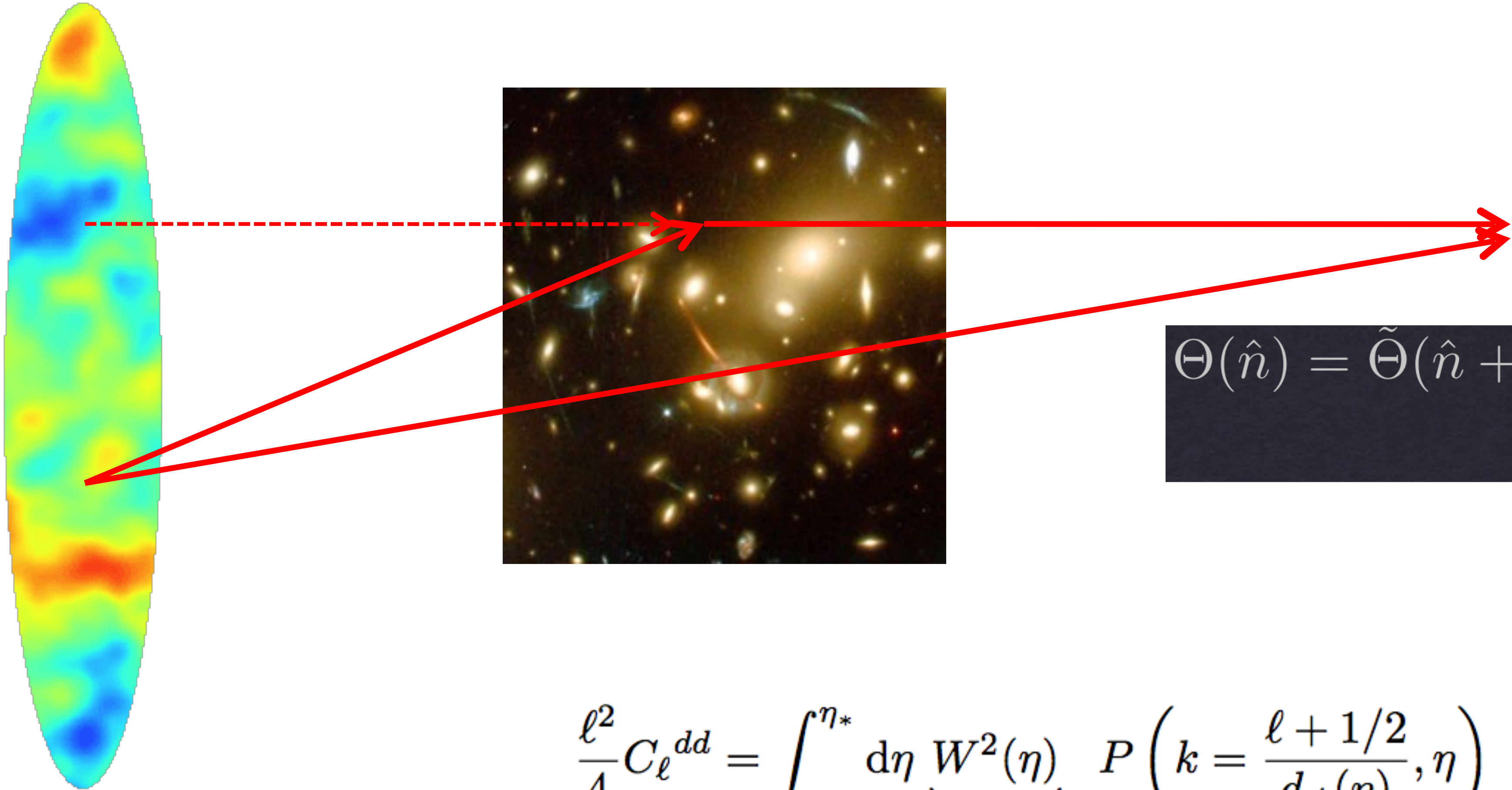


Upper limits on fractional primordial contribution (β), or fractional contribution to CMB power (α):

Model	$\beta_{iso}(k_{low})$	$\beta_{iso}(k_{mid})$	$\beta_{iso}(k_{high})$	$\alpha_{\mathcal{RR}}^{(2,2500)}$	$\alpha_{\mathcal{II}}^{(2,2500)}$	$\alpha_{\mathcal{RI}}^{(2,2500)}$
General model:						
CDM isocurvature	0.075	0.39	0.60	[0.98:1.07]	0.039	[-0.093:0.014]
ND isocurvature	0.27	0.27	0.32	[0.99:1.09]	0.093	[-0.18:0]
NV isocurvature	0.18	0.14	0.17	[0.96:1.05]	0.068	[-0.090:0.026]
Special CDM isocurvature cases:						
Uncorrelated, $n_{\mathcal{II}} = 1$, ("axion")	0.036	0.039	0.040	[0.98:1]	0.016	–
Fully correlated, $n_{\mathcal{II}} = n_{\mathcal{RR}}$, ("curvaton")	0.0025	0.0025	0.0025	[0.97:1]	0.0011	[0:0.028]
Fully anti-correlated, $n_{\mathcal{II}} = n_{\mathcal{RR}}$	0.0087	0.0087	0.0087	[1:1.06]	0.0046	[-0.067:0]

Planck Collab XXII 2013

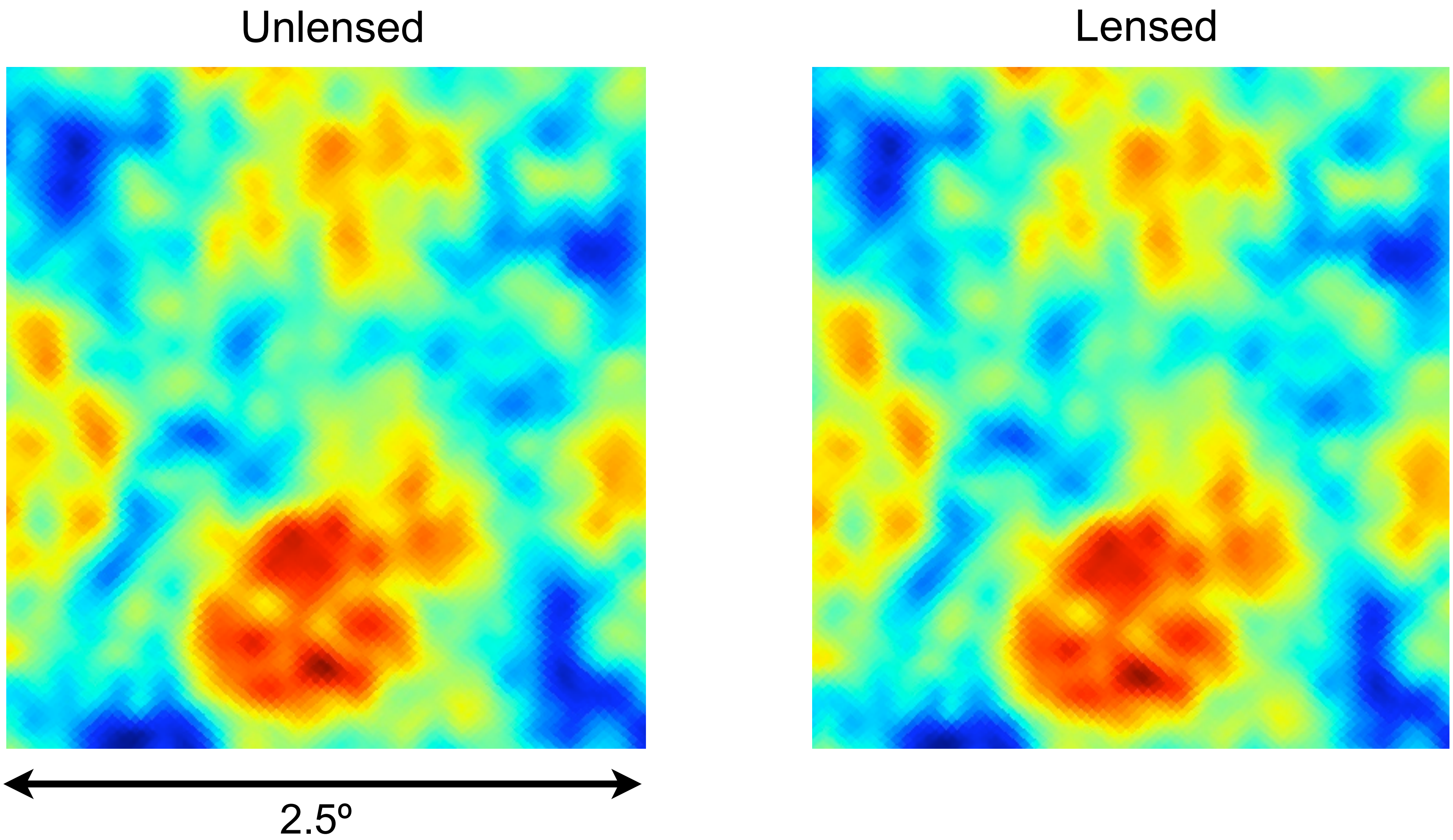
Lensing of the CMB

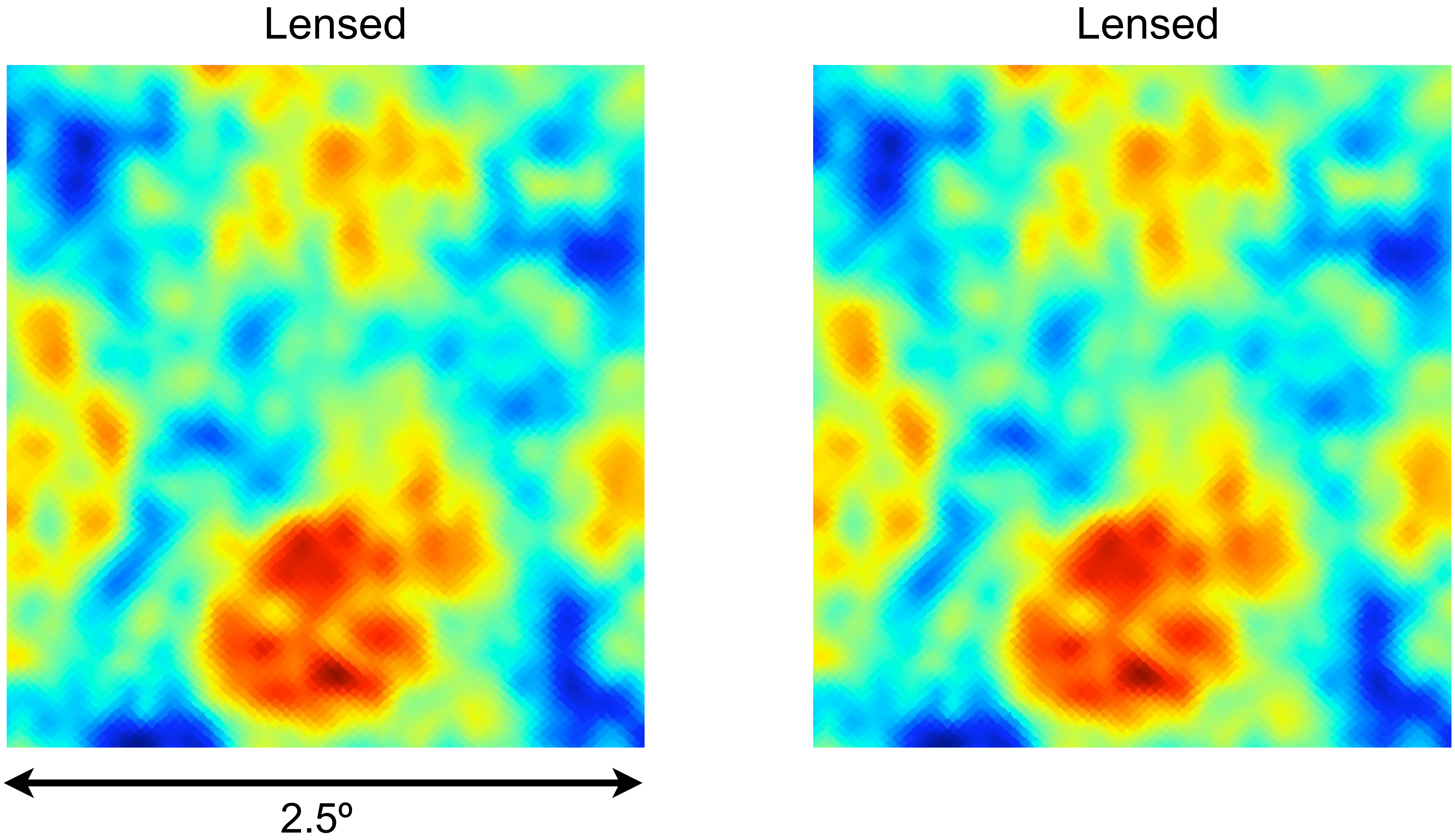


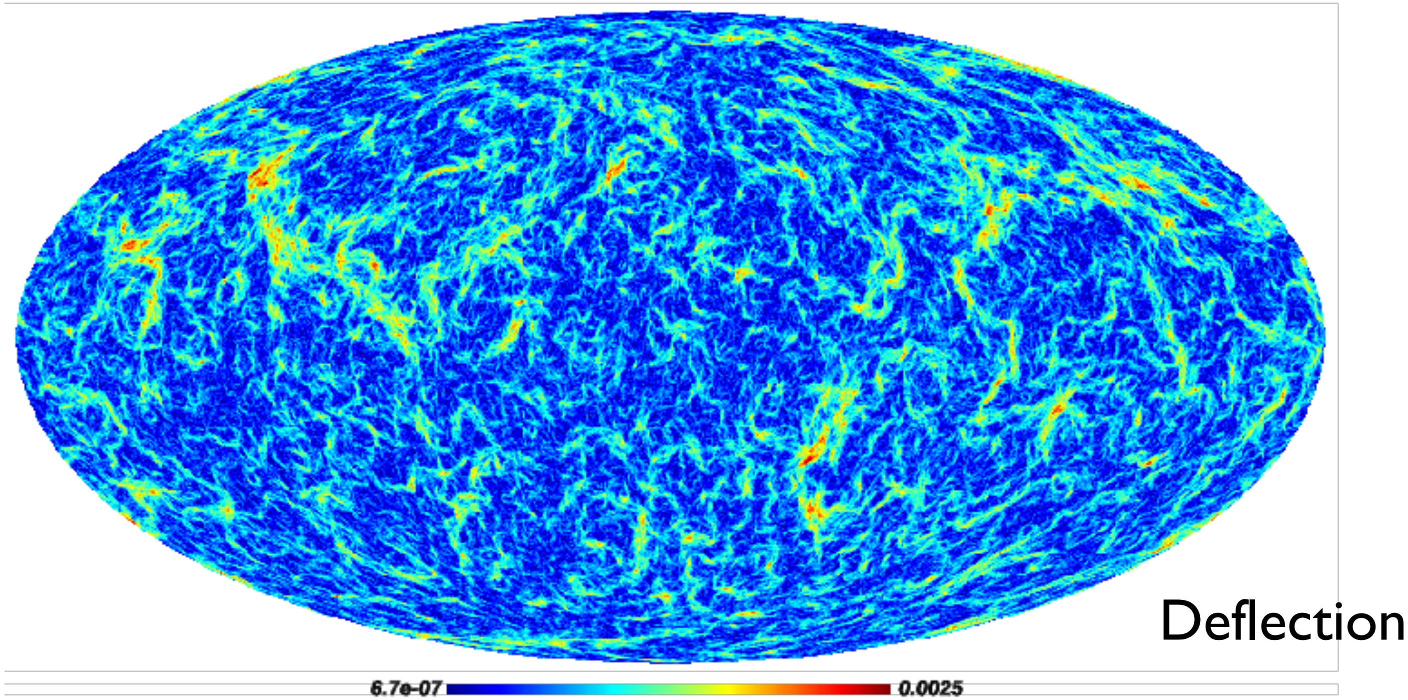
$$\Theta(\hat{n}) = \tilde{\Theta}(\hat{n} + \nabla\phi)$$

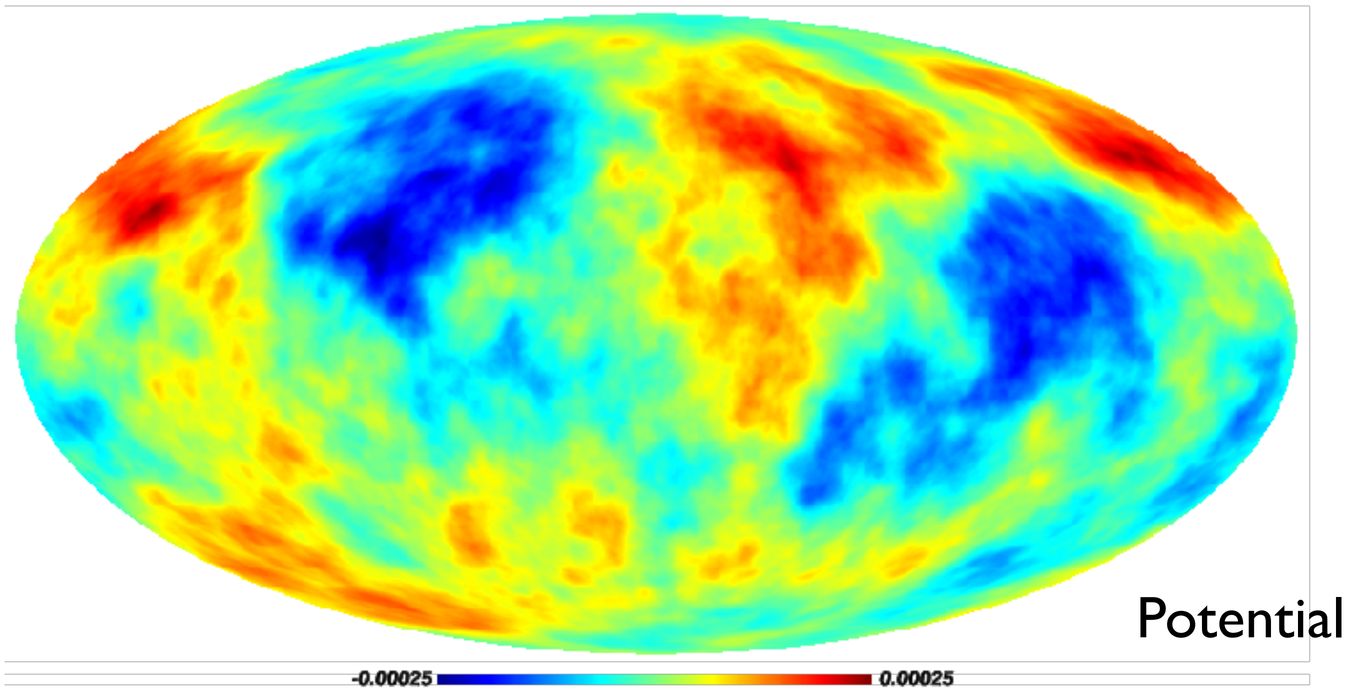
$$\frac{\ell^2}{4} C_\ell{}^{dd} = \int_0^{\eta_*} \mathrm{d}\eta \, \underbrace{W^2(\eta)}_{\text{geometry}} \, \underbrace{P\left(k = \frac{\ell + 1/2}{d_A(\eta)}, \eta\right)}_{\text{matter}}$$

Integrated mass fluctuations along the line of sight
Deflection is a couple of arcminutes, but coherent on degree scales.

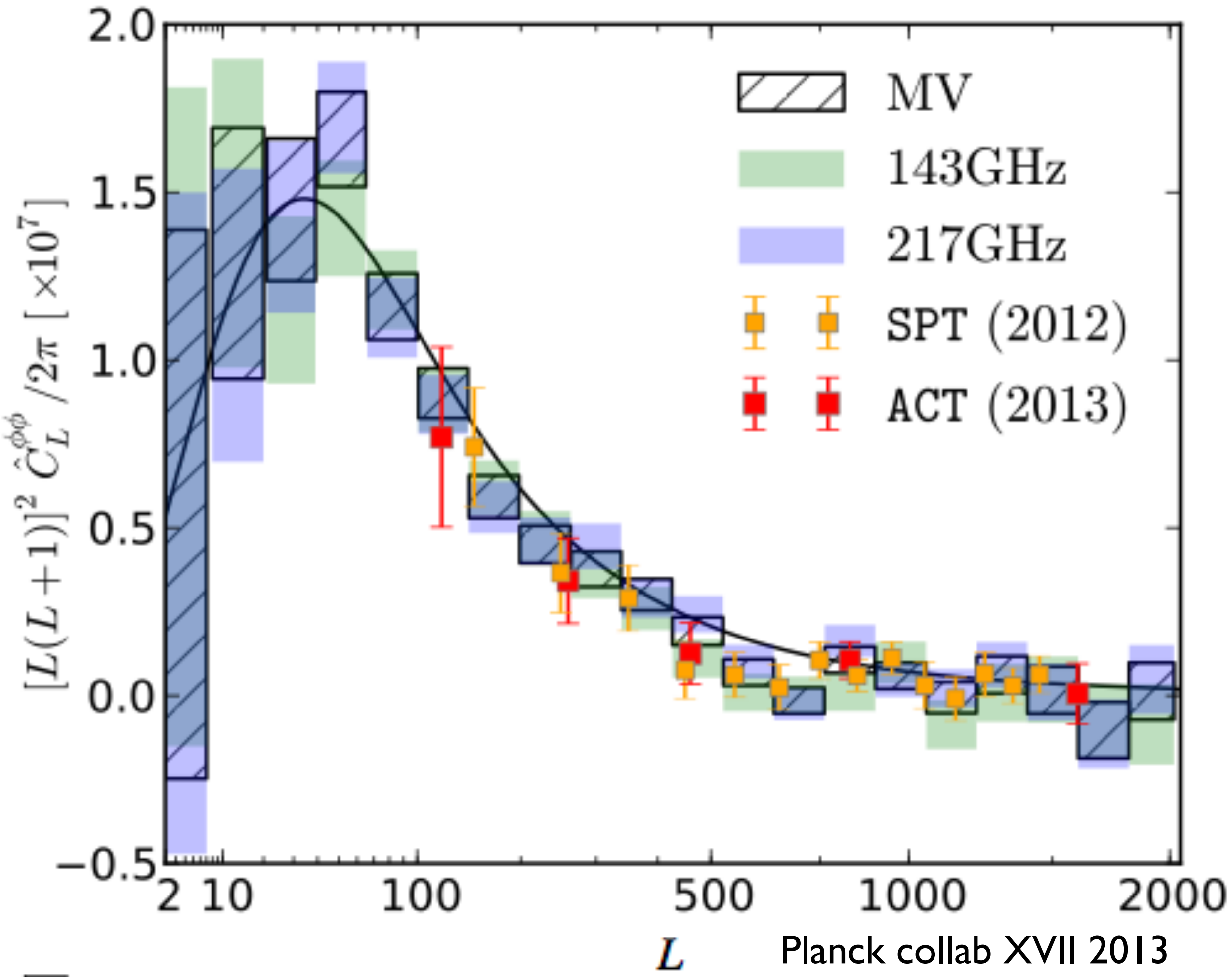

Unlensed
Lensed
2.5°


Lensed
Lensed
2.5°


Deflection
6.7e-07
0.0025


Potential
-0.00025
0.00025

CMB lensing measurements



Planck collab XVII 2013

First direct measurement: ACT 2011, 4σ (Das et al, update in 2013)

Then SPT in 2012 (Van Engelen et al, 6σ)

Now Planck in 2013 (Planck Collab XVII, 25σ)

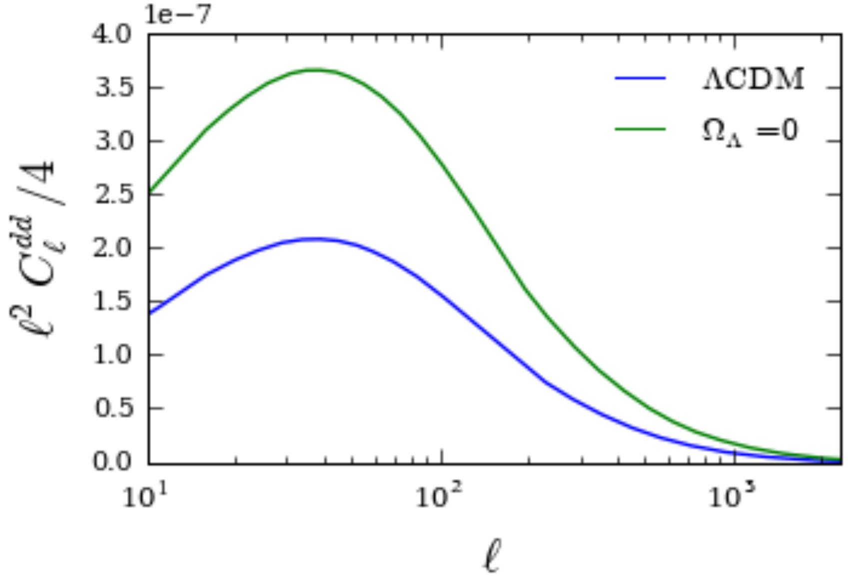
$$\Psi(\boldsymbol{L}) \propto T(\boldsymbol{\ell})T^*(\boldsymbol{L}-\boldsymbol{\ell})$$

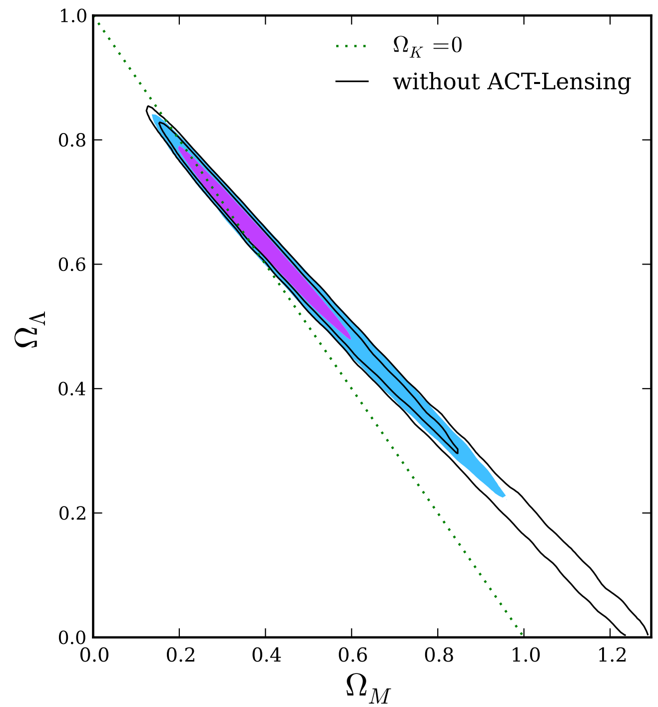
Late-time physics

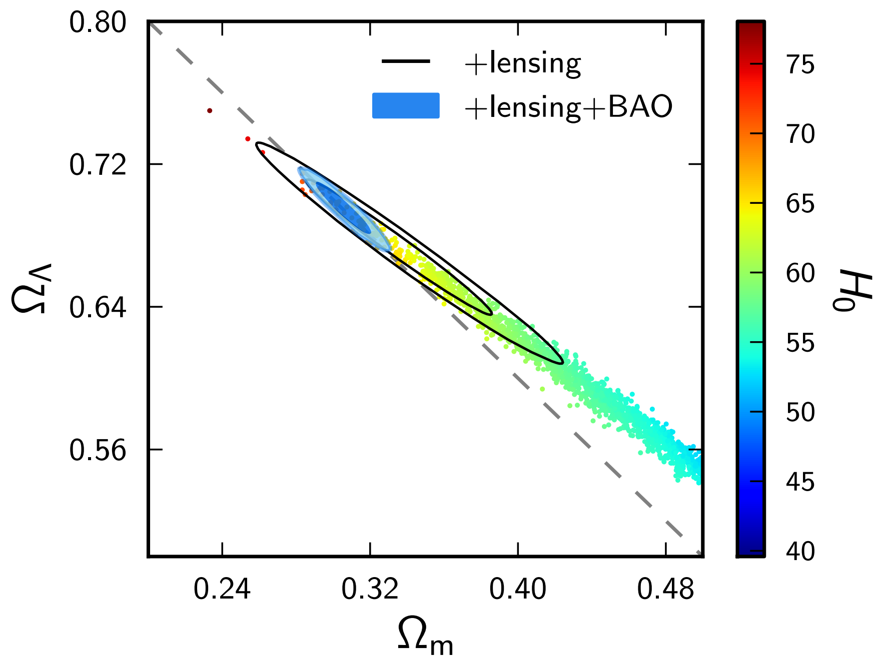
With primary CMB, cannot measure curvature.

Planck measures curvature through lensing (more closed, less dark energy → more lensing)

Similarly, probes neutrino mass and dark energy



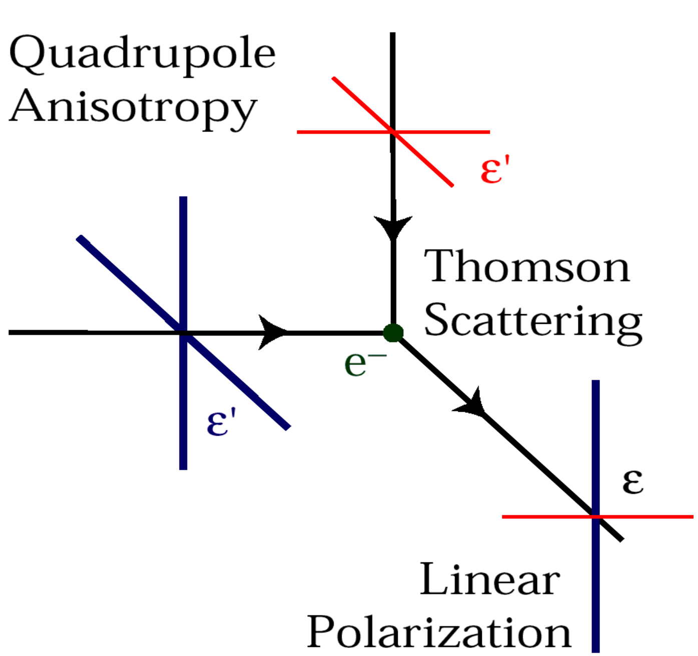


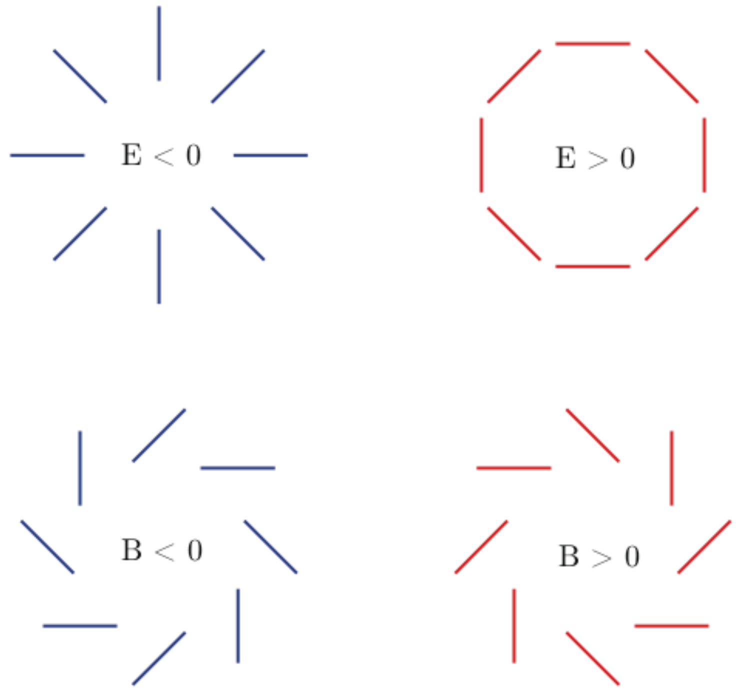


Planck Collab XVII 2013

Sherwin, Dunkley, Das et al 2011

CMB polarization

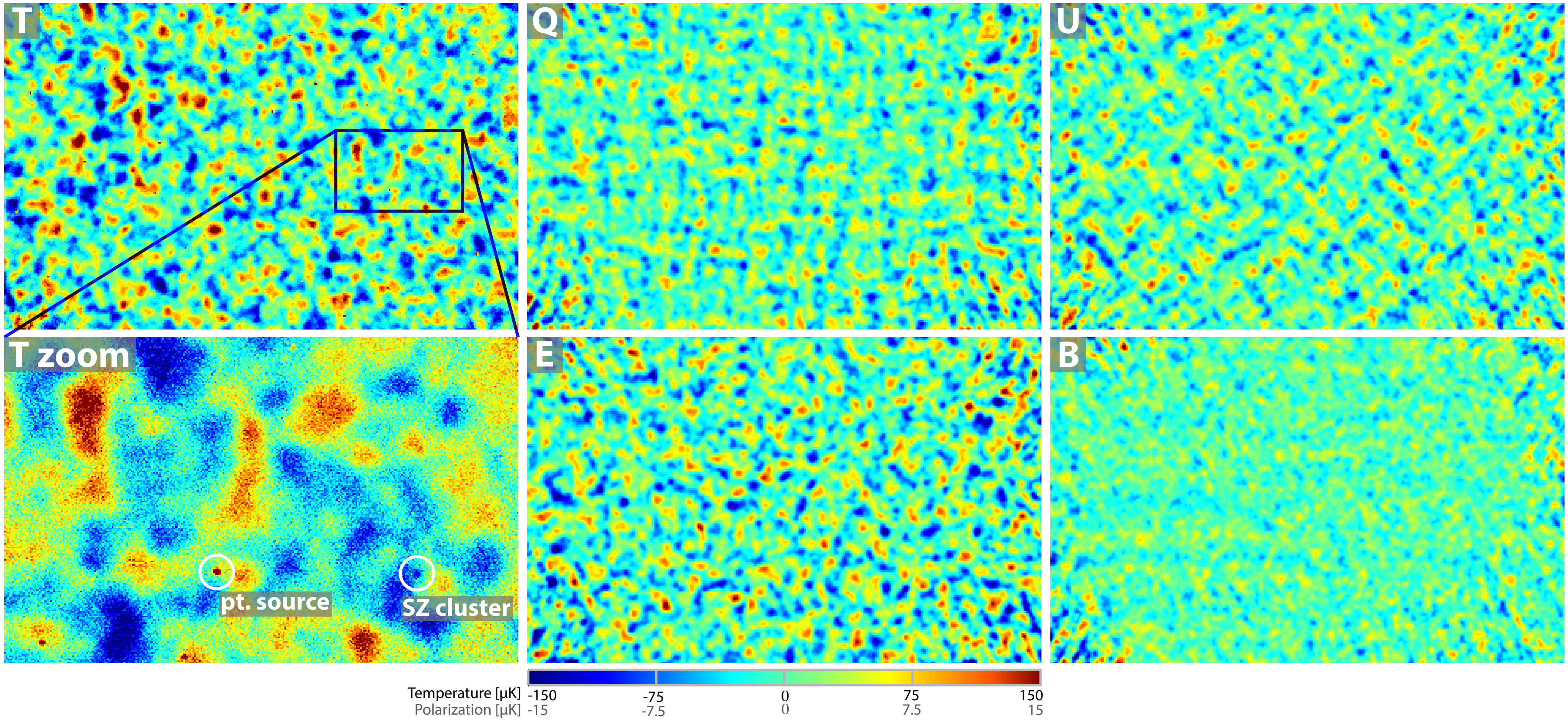




Generated at recombination from velocity of photon-baryon fluid (E-modes) and gravitational waves (E, B-modes)

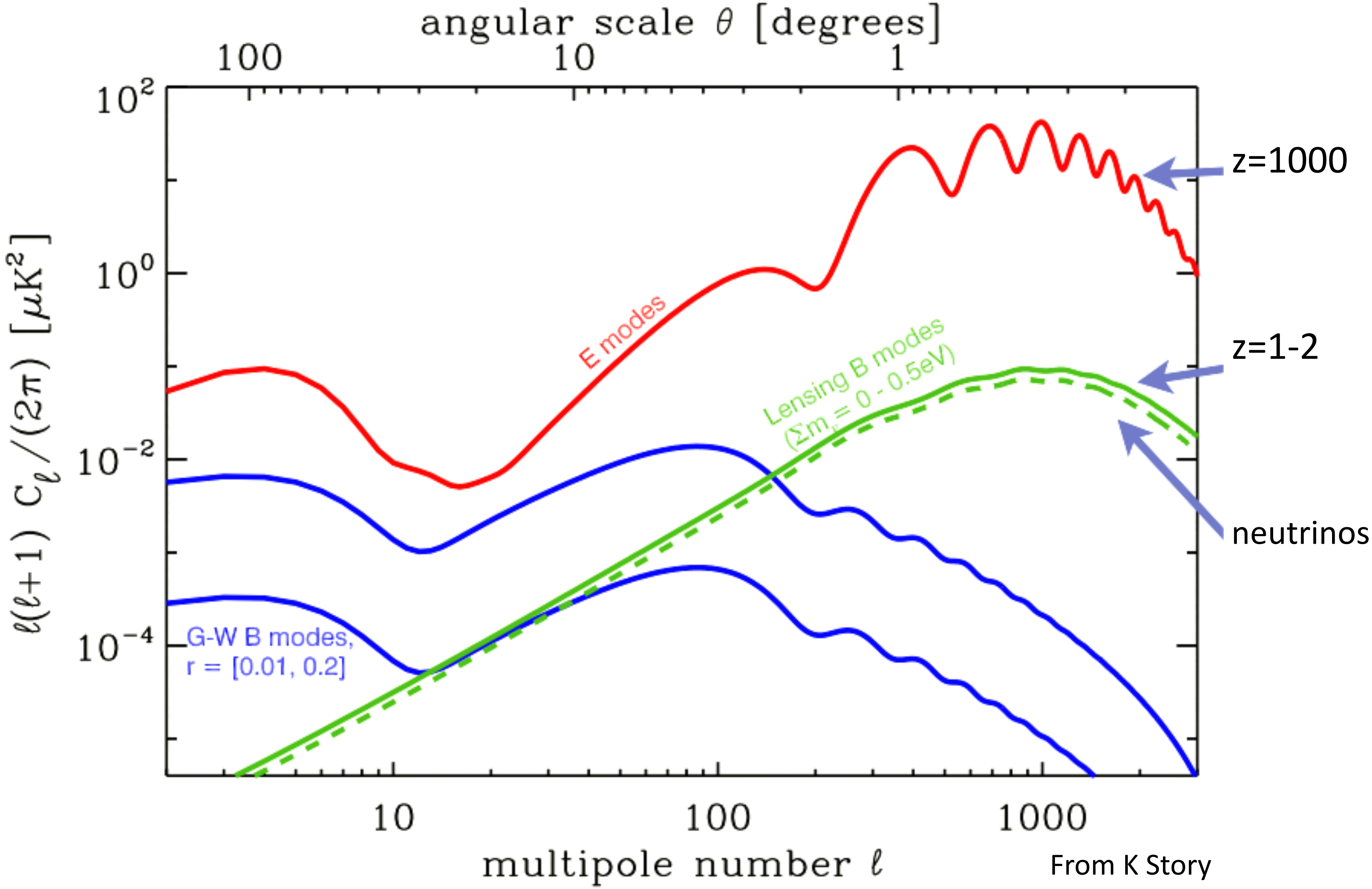
Generated at reionization by quadrupole scattering

Lensing mixes E/B



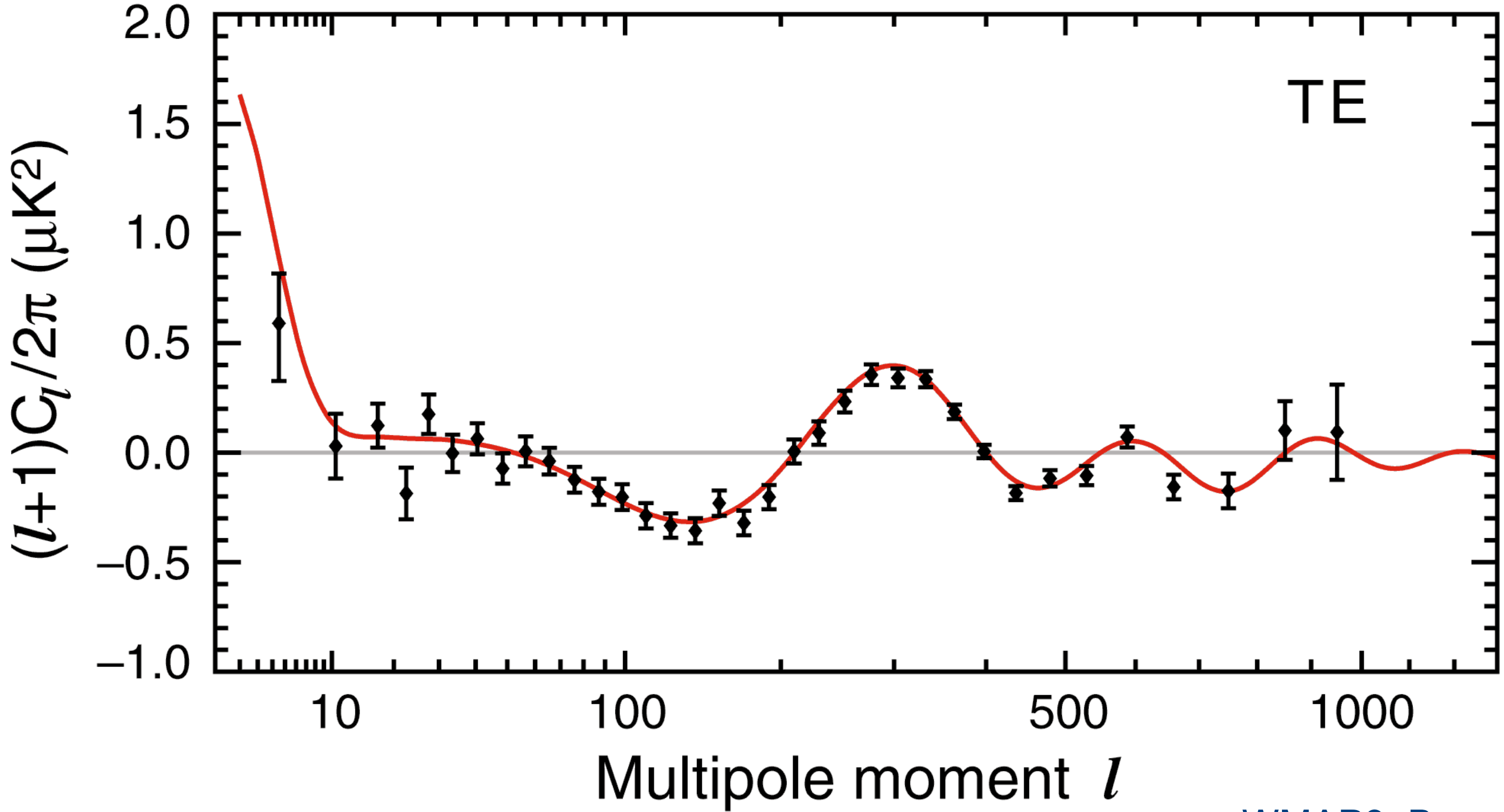
ACTPol maps, Naess et al 2014

The landscape of CMB polarization



From K Story

Polarization acoustic peaks



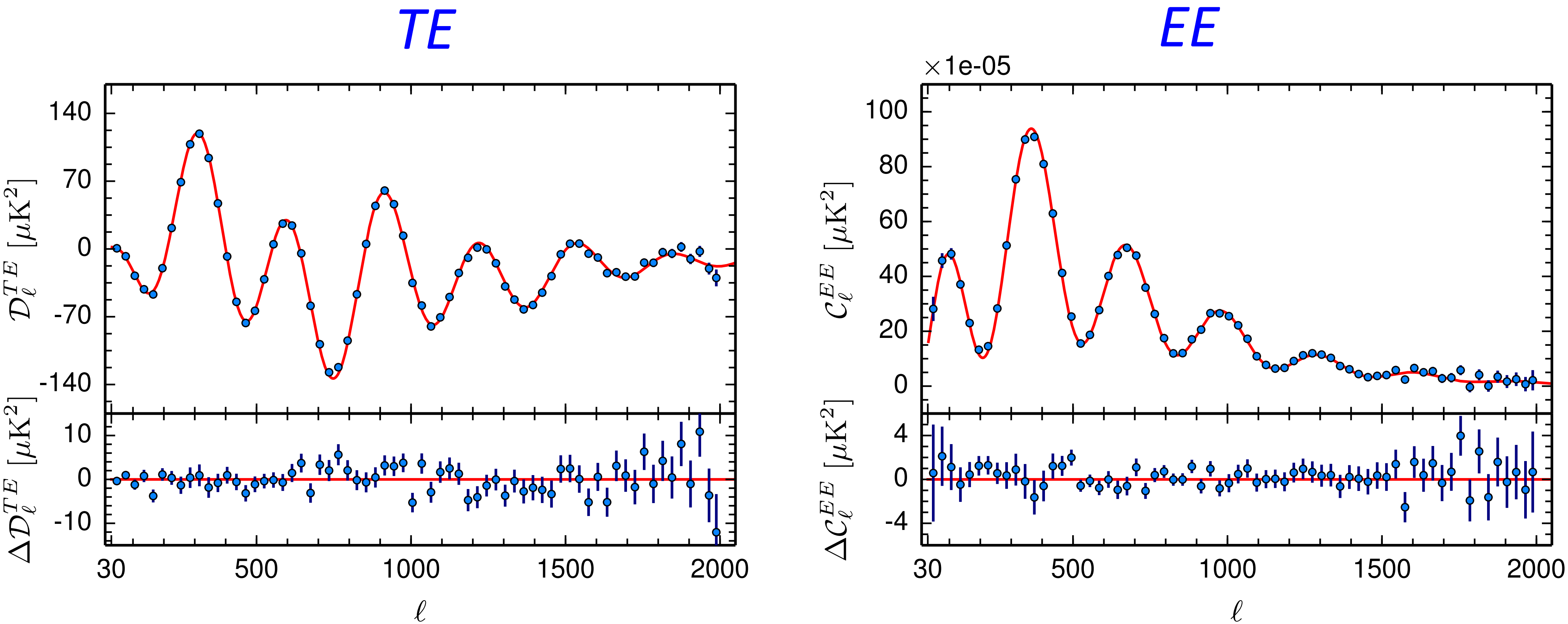
WMAP9, Bennett et al 2012

TE correlation measured by WMAP and ground-based expts

Validates ΛCDM model. Evidence for superhorizon fluctuations.

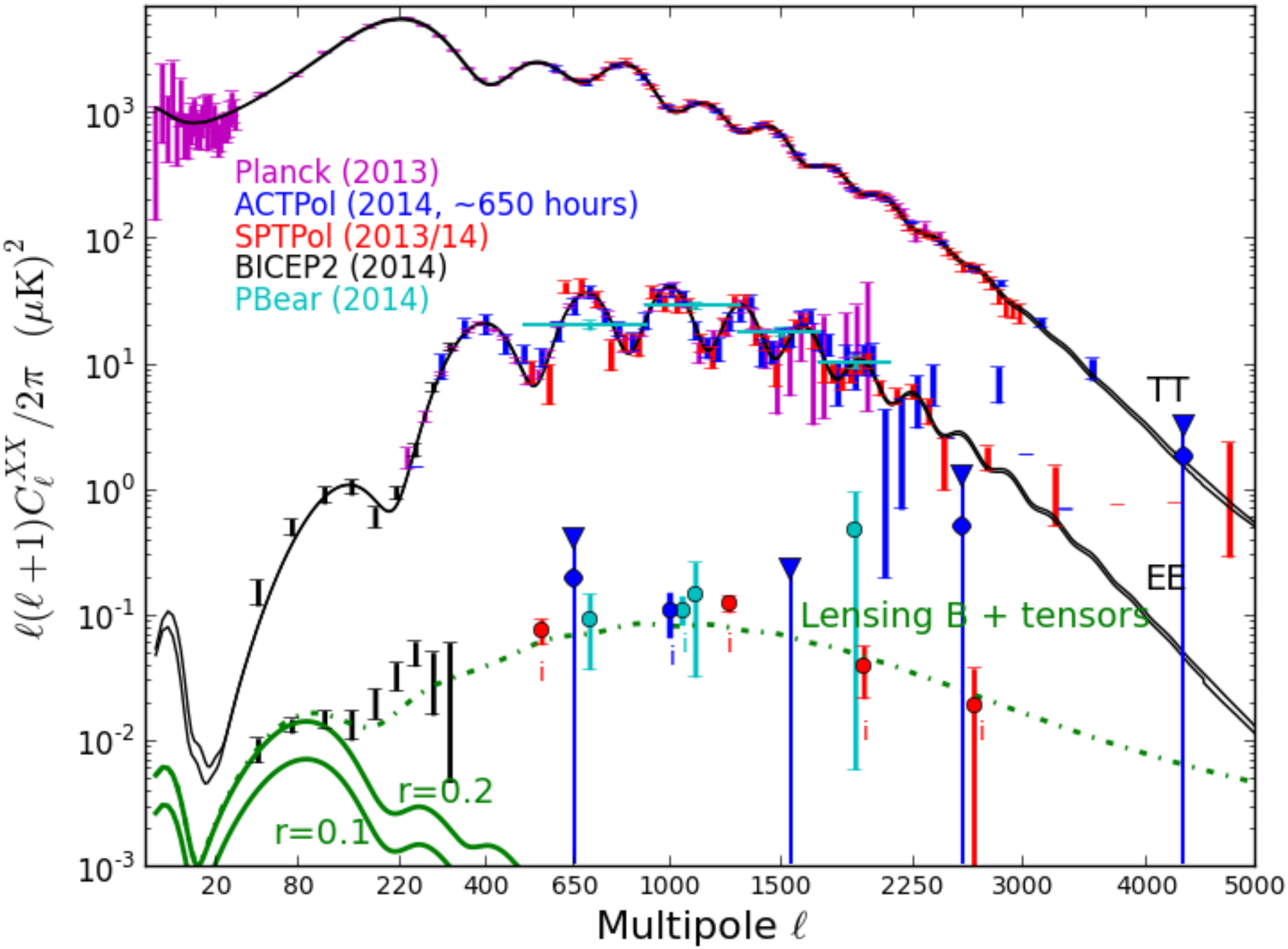
– TE+EE promises better limits on neutrino number, isocurvature fluctuations etc.

Planck 2014 (preliminary)



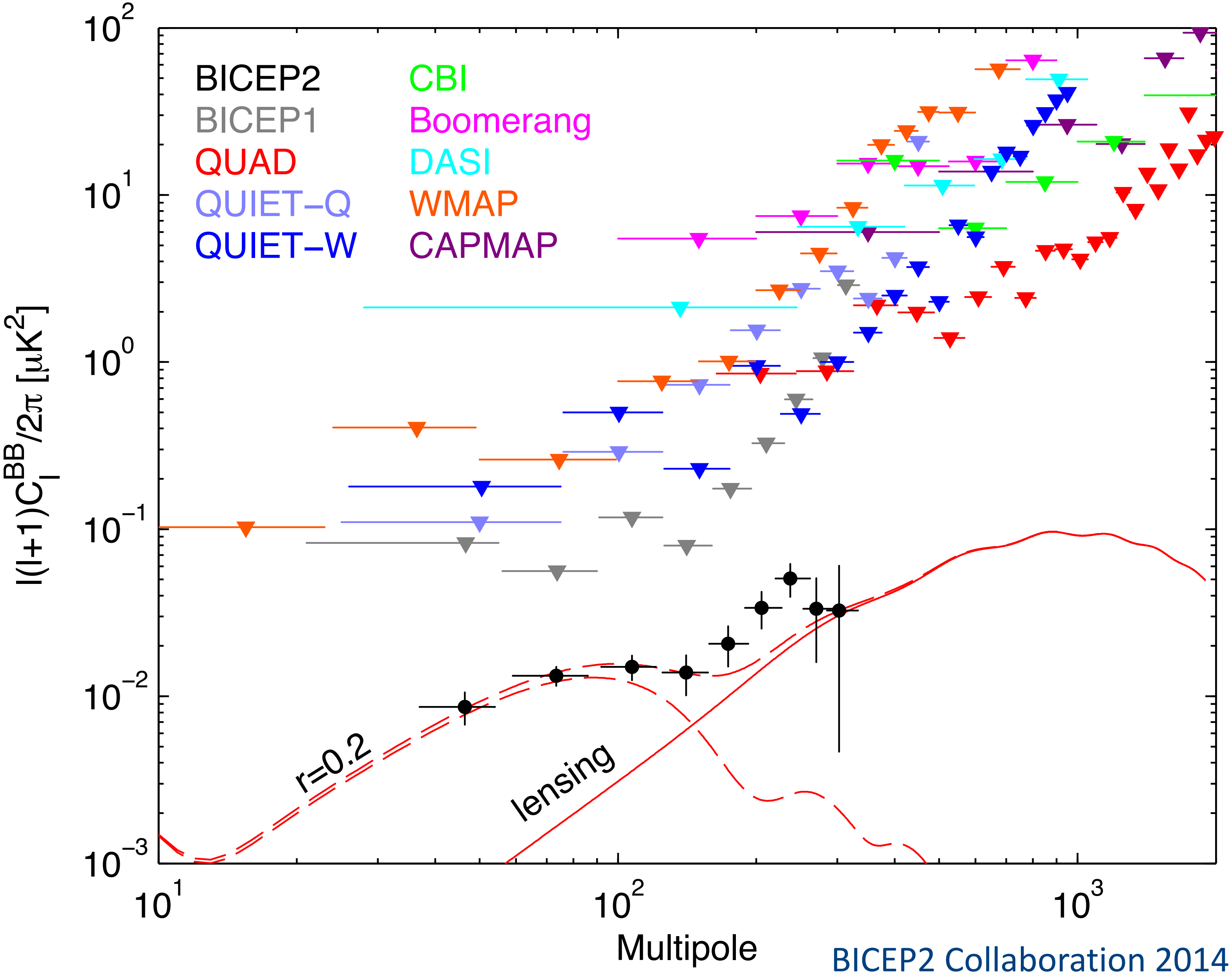
Planck Collaboration 2015, prep
from Efstathiou Ferrara talk

Polarization spectra from ACTPol/SPTPol



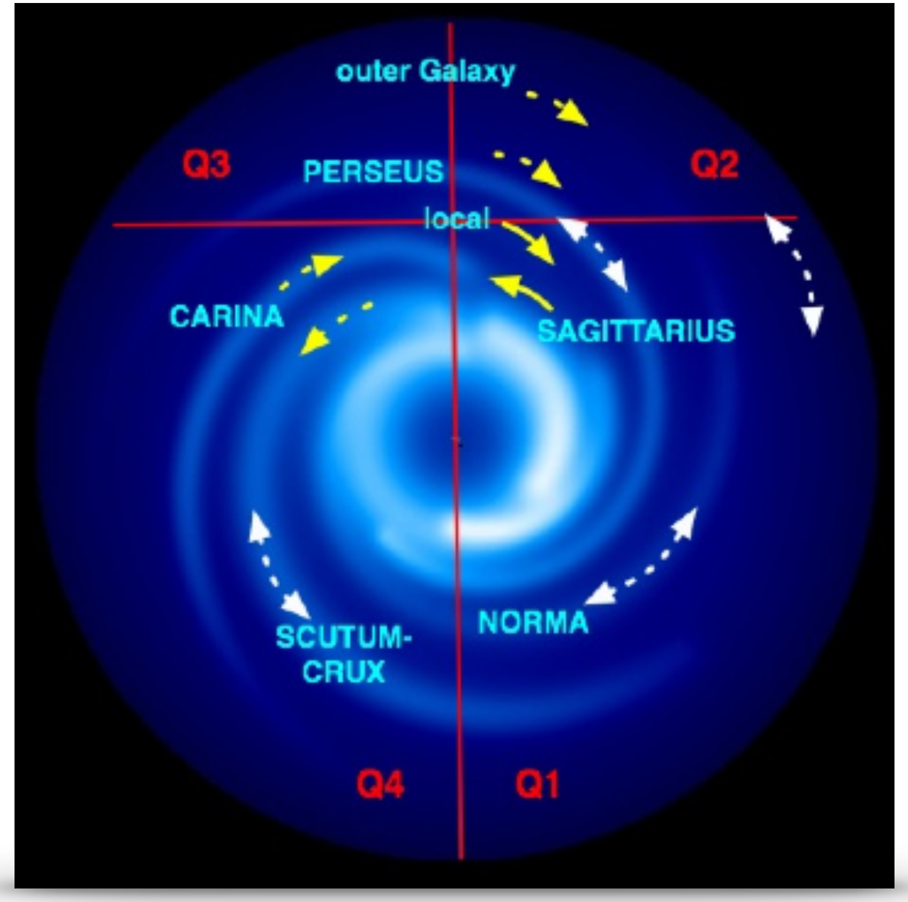
L. Page, results from Naess et al 2014

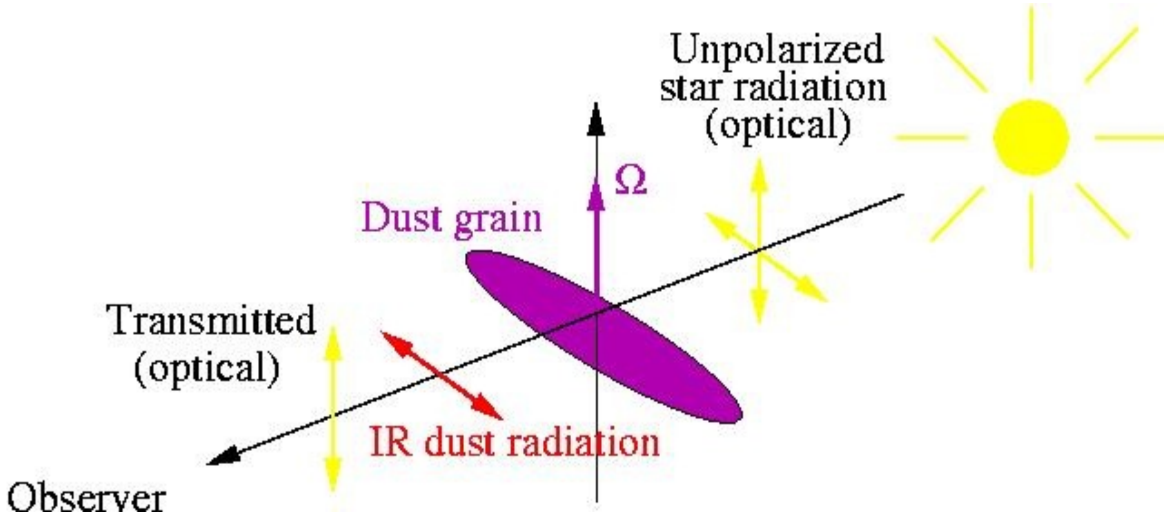
BICEP2 measured a B-mode signal



BICEP2 Collaboration 2014

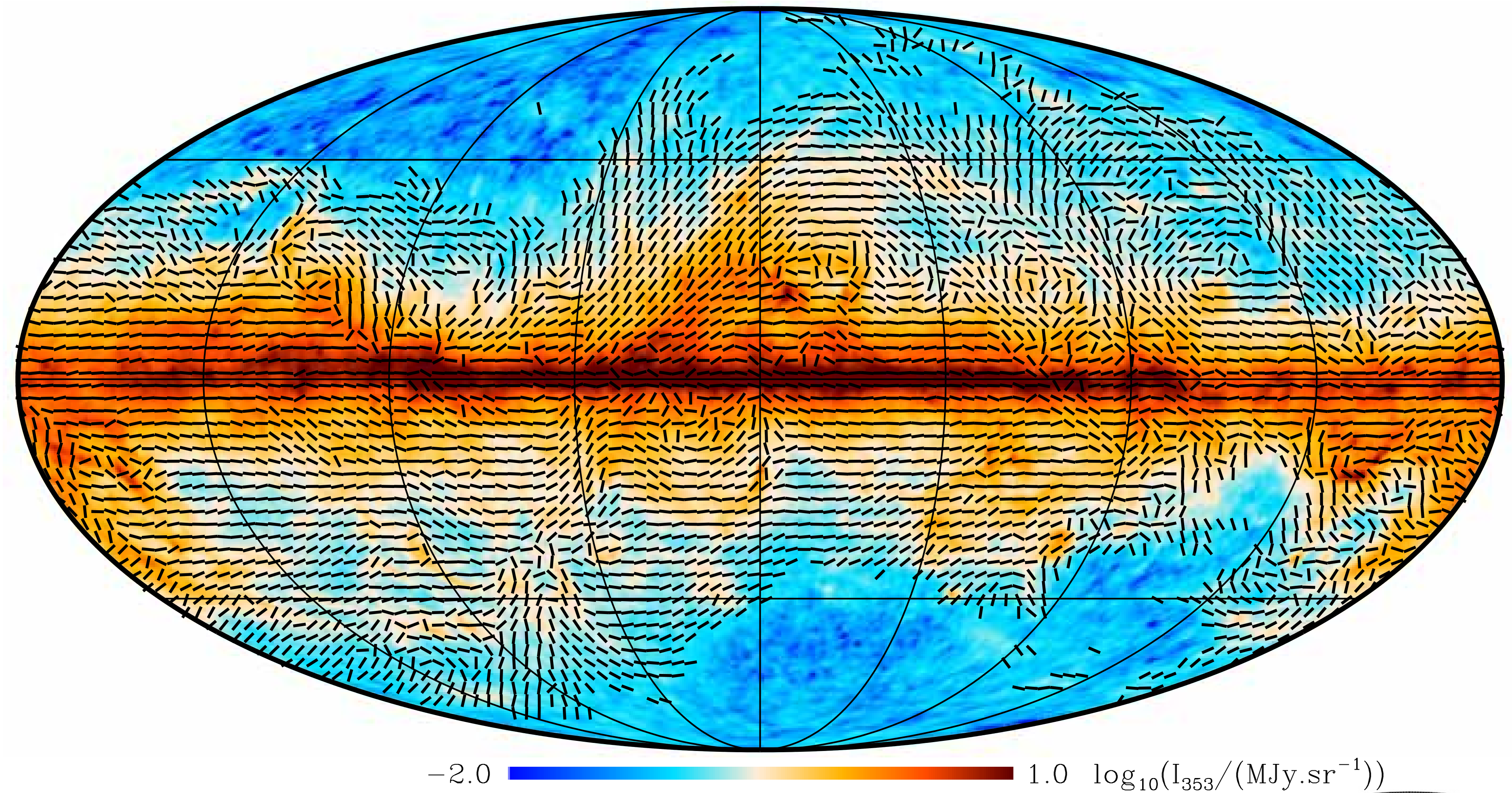
How polarized is the Galaxy?

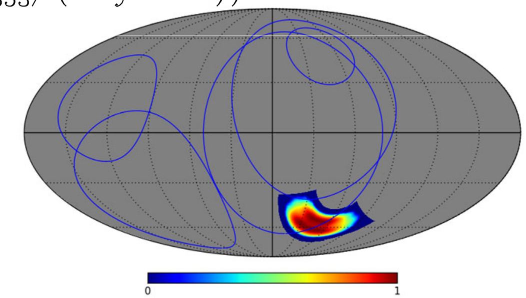




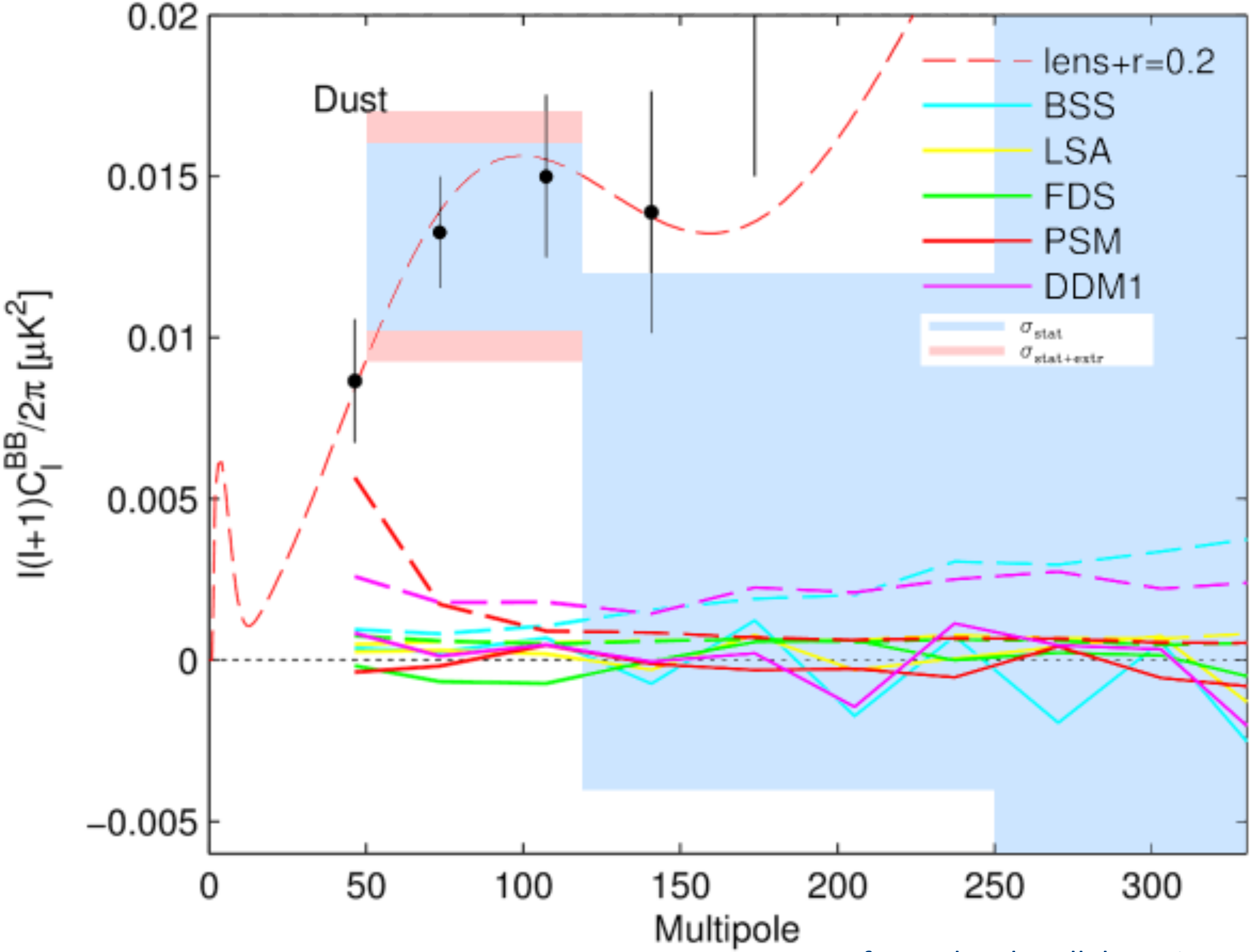
- Grains align perpendicular to magnetic field - likely radiative torque. Preferentially emit along their long axis (so need some asphericity to generate polarization).
- Simple models say intrinsic polarization <~15%, then reduced due to line-of-sight averaging.

Dust polarization measured by Planck



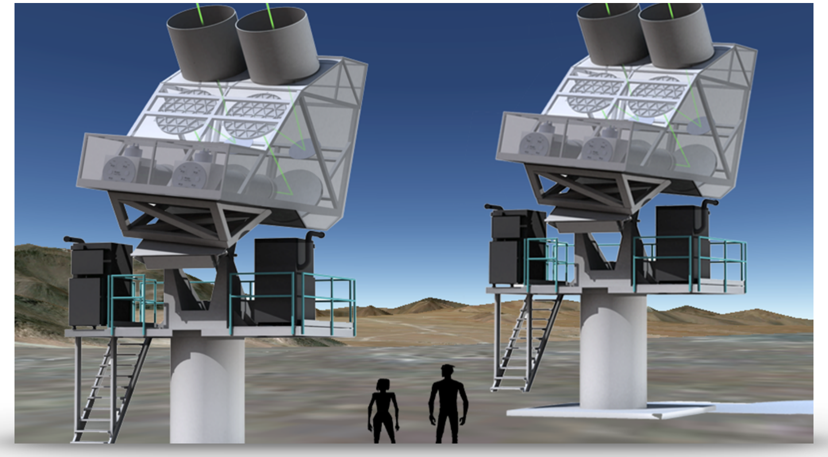


Planck Collaboration 2014
Dust scales roughly nu^1.7, mapped at 353 GHz



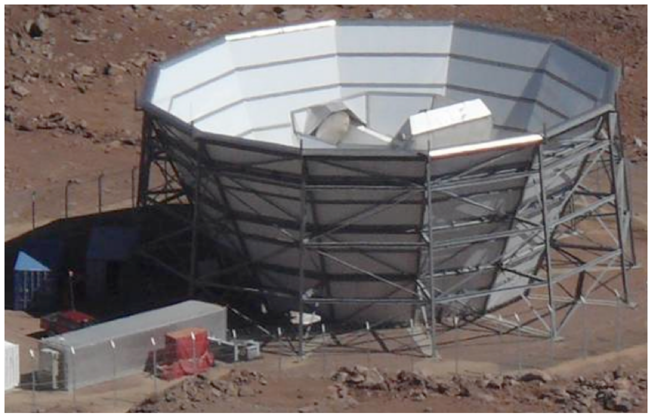
Data from Planck Collaboration 2014

Outlook for coming few years



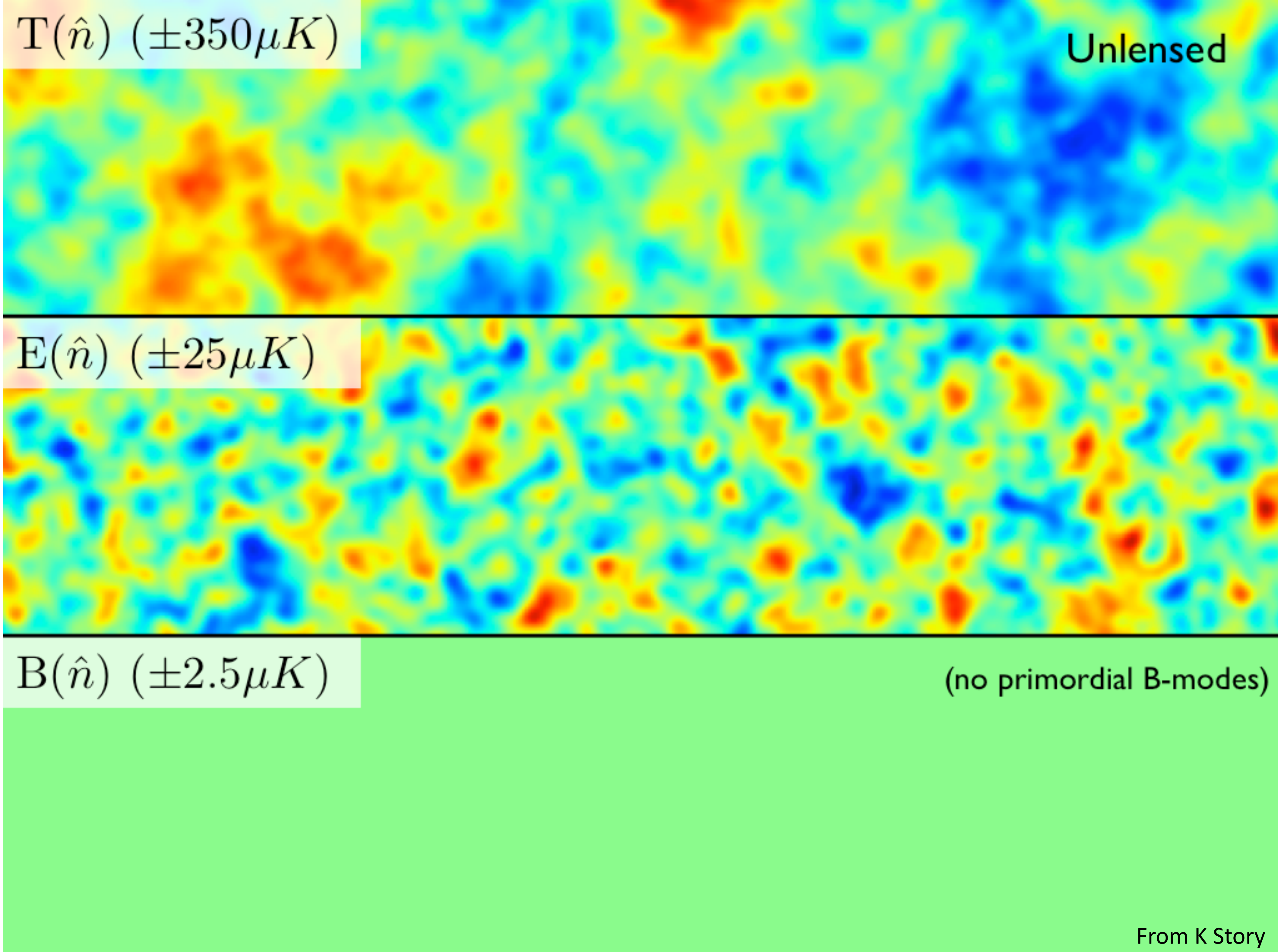
CLASS deploy 2015 - Atacama

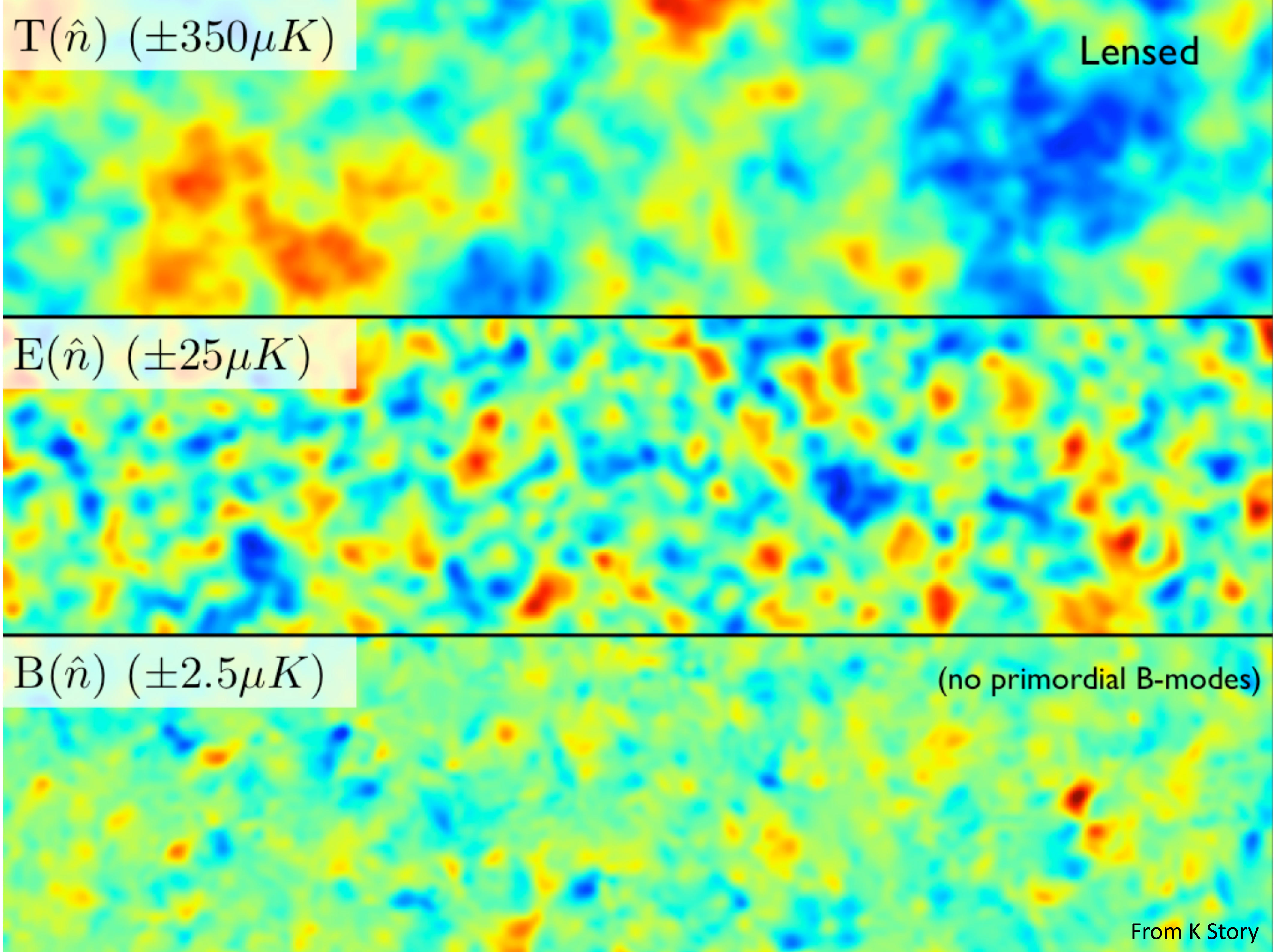
Keck Array 2014+
South Pole



AdvACT begin
2016- Atacama

SPIDER launched Jan 1 2015!

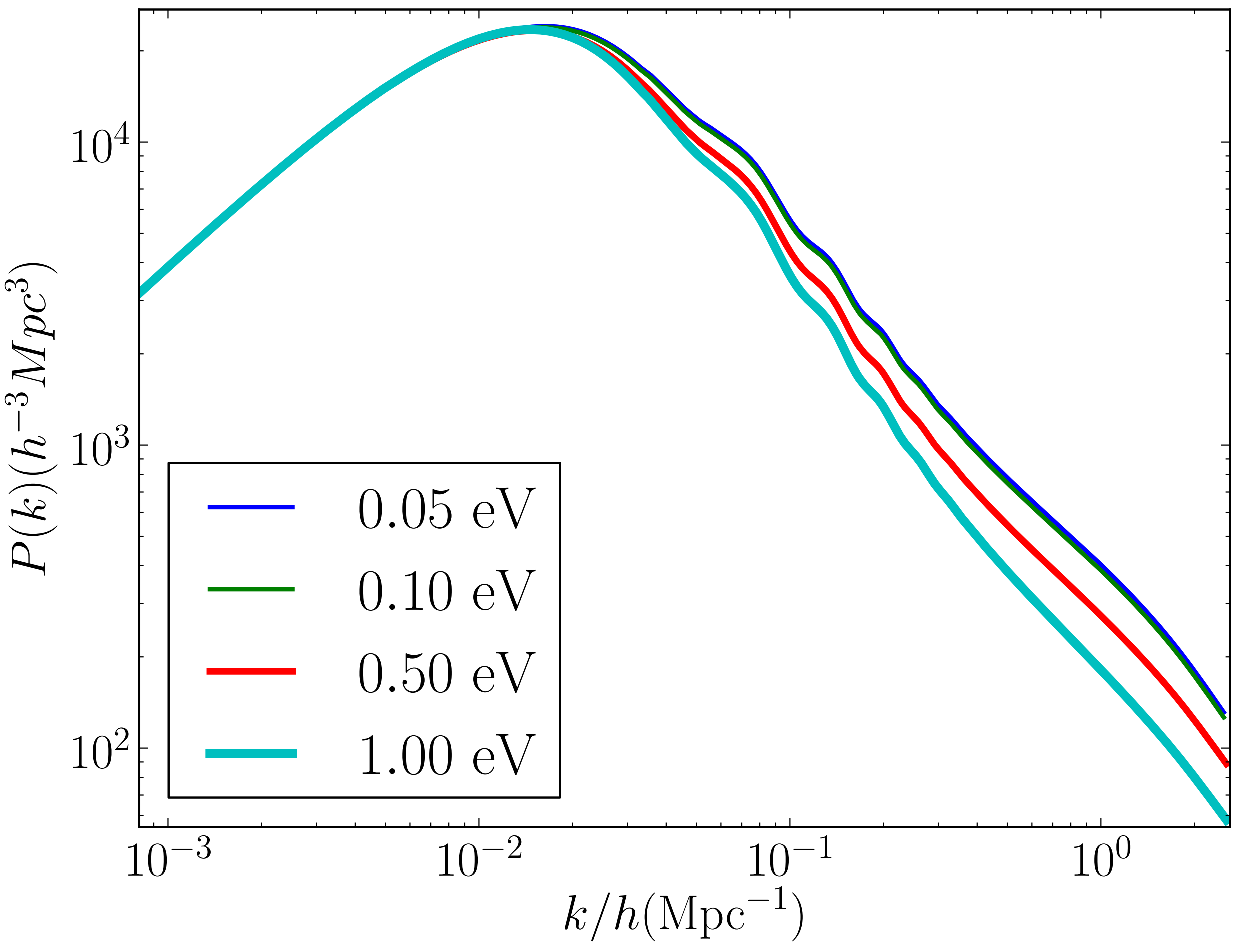

$\mathrm{T}(\hat{n})\ (\pm 350\mu K)$
Unlensed
$\mathrm{E}(\hat{n})\ (\pm 25\mu K)$
$\mathrm{B}(\hat{n})\ (\pm 2.5\mu K)$
(no primordial B-modes)
From K Story

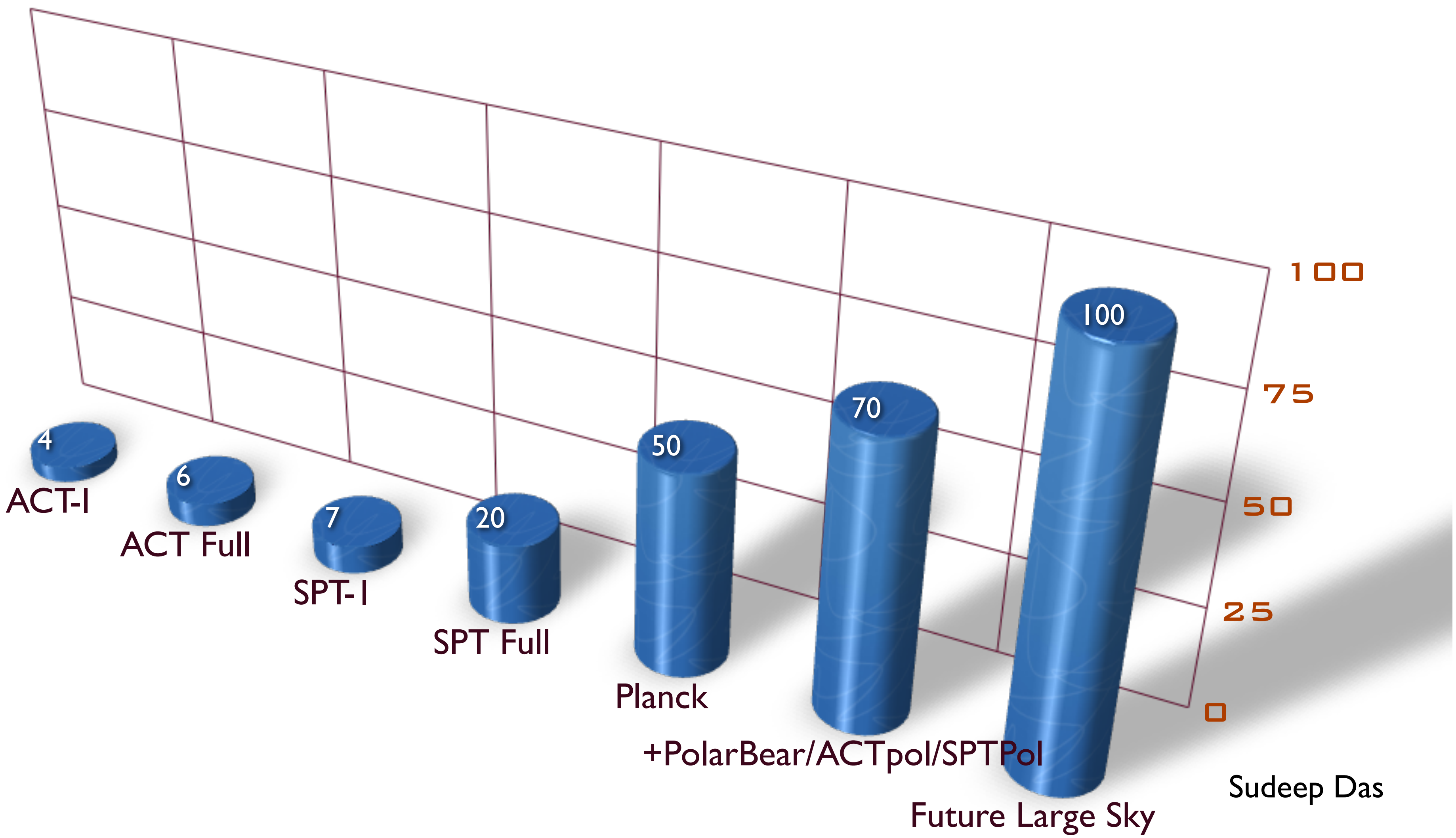


$T(\hat{n})$ $(\pm 350\mu K)$
Lensed
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
(no primordial B-modes)
From K Story

Lensing: probe of neutrino mass

- Neutrinos free-stream when relativistic, and reduce damping of photon-baryon oscillations
- smears out matter clustering on scales where relativistic.
- In decade CMB lensing should reach detection of 0.05 eV





Cross-correlations of CMB lensing also made with radio galaxies, quasars, optical galaxies…

Summary

- CMB temperature measurements
  - Planck satellite measures 7 acoustic peaks (2013). Also limits 3-pt function.

- ΛCDM model tightly constrained; deviations are now strongly limited (e.g. likely no additional neutrino species)

- CMB polarization measurements: many underway. WMAP still provides large-scale measurement for optical depth. Planck measured TE/EE acoustic peaks. The future is in polarization (large and small scale).

- CMB lensing is fast-growing! It probes clustering of matter and expansion rate. Detected in ACT, SPT, PolarBear and Planck. Dark energy now required just from the CMB. Looking to neutrino mass detection.

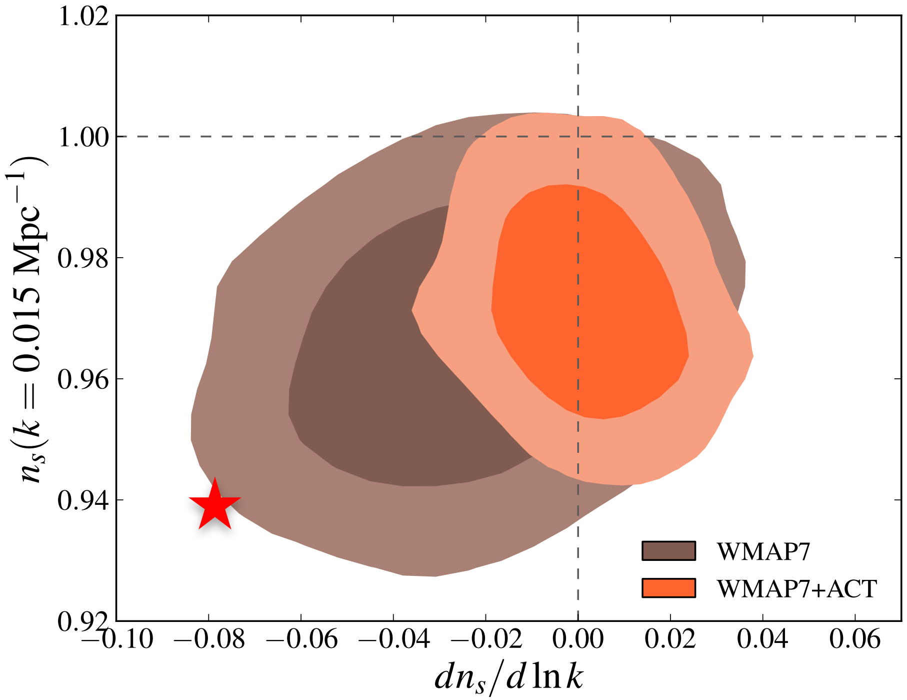
(2) Primordial spectrum: running

- Test inflation: period of exponential expansion for > 60 e-folds.
- Fluctuations expected almost power law. Running index, expected ~0.001.

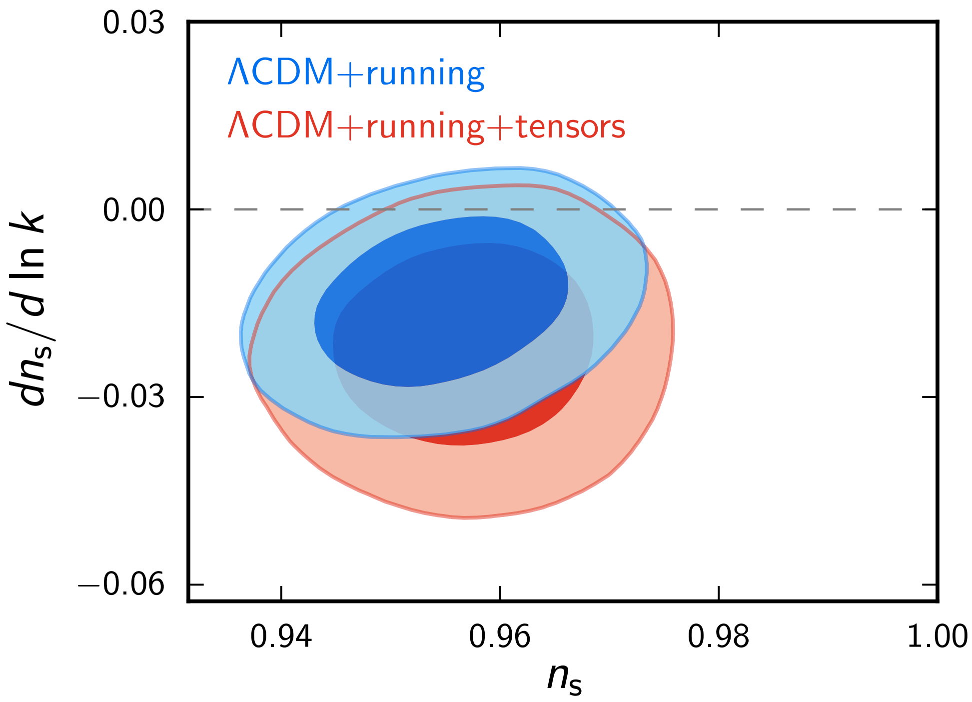
  $dn_s/d\ln k = -0.004 \pm 0.012$ (ACT+WMAP7)

  $dn_s/d\ln k = -0.015 \pm 0.009$ (Planck+)

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



Sievers, Hlozek et al. 2013



Planck Collab XVI 2013