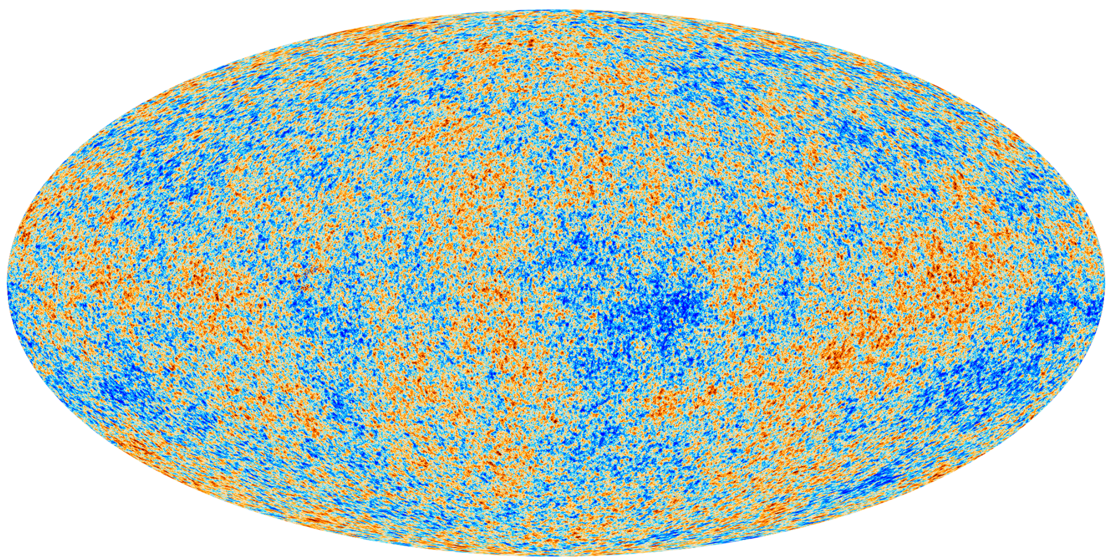
The Cosmic Microwave Background



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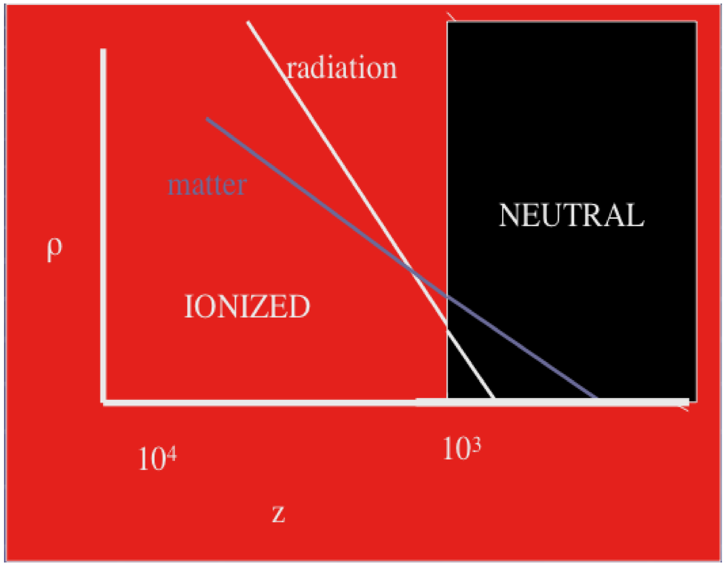
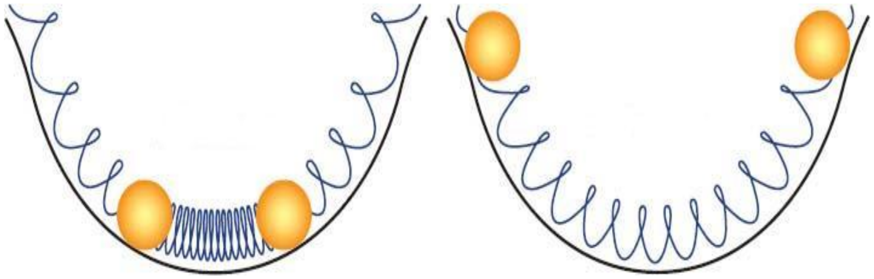
Ripples in the Cosmos, July 22

Seeds of structure

1. Inflation (?) imprints quantum fluctuations.
2. Space expands, regions enter into causal contact and start to evolve.
3. Coupled baryons and photons produce oscillations in plasma.



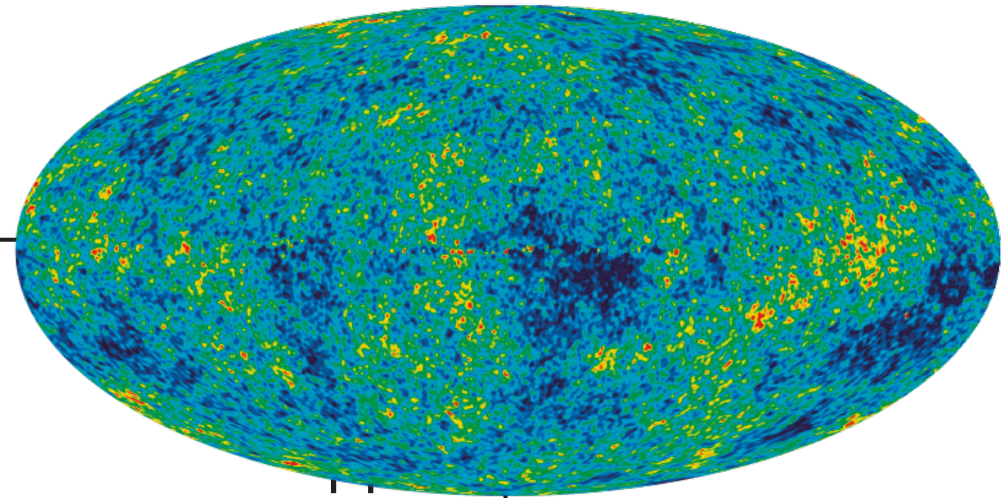


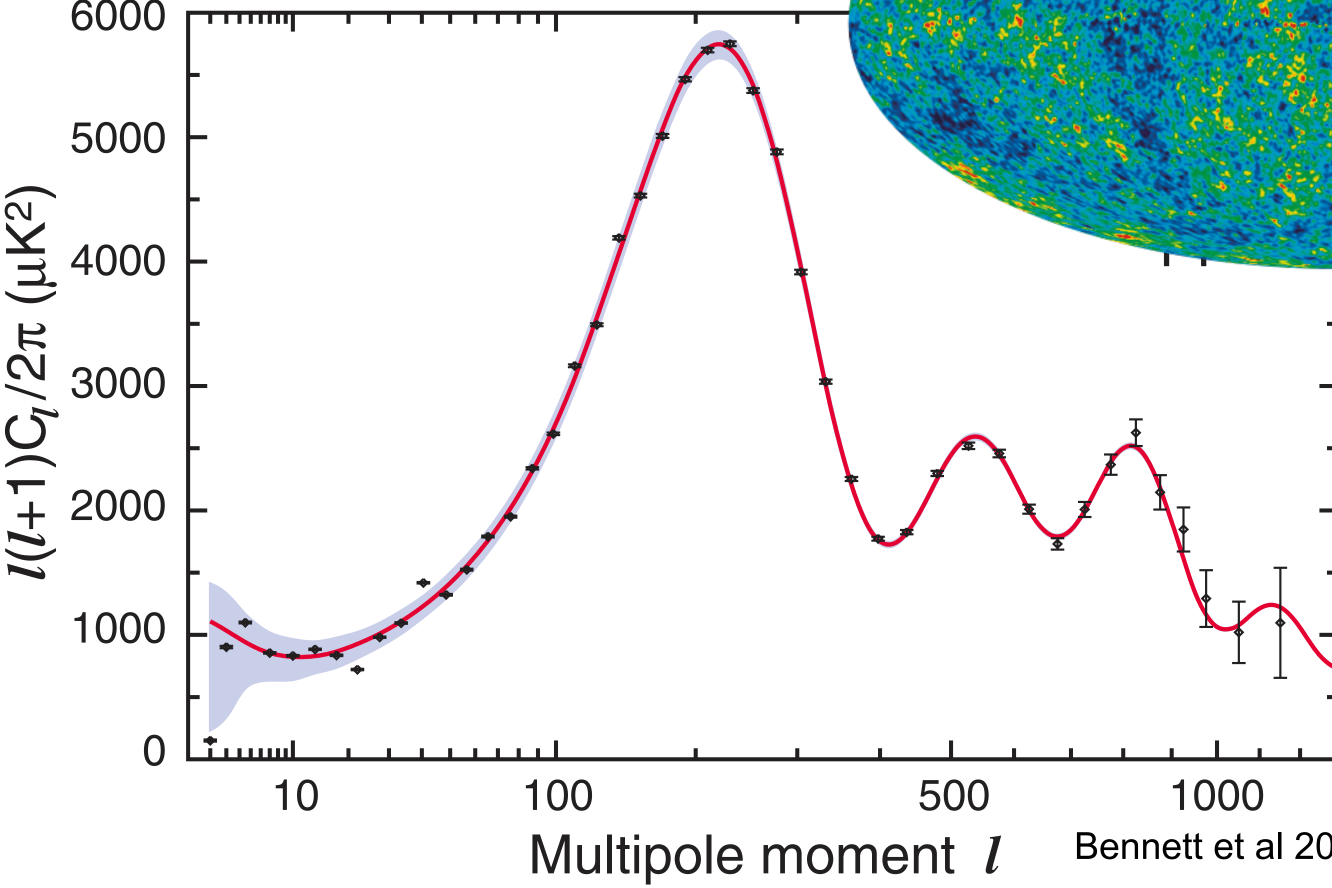
After 380,000 years the fluctuations have evolved, and we see a snapshot of them as anisotropies in Cosmic Microwave Background.

Linearity → anisotropies used to infer initial fluctuations and contents of the Universe.

We now also have to account for journey of photons to us, and obscuration.

WMAP: 2001-12





Bennett et al 2012

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

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

Established/constrained 6-parameter ΛCDM model (contents plus power-law fluctuations)
In combination with other data, limits deviations from ΛCDM

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

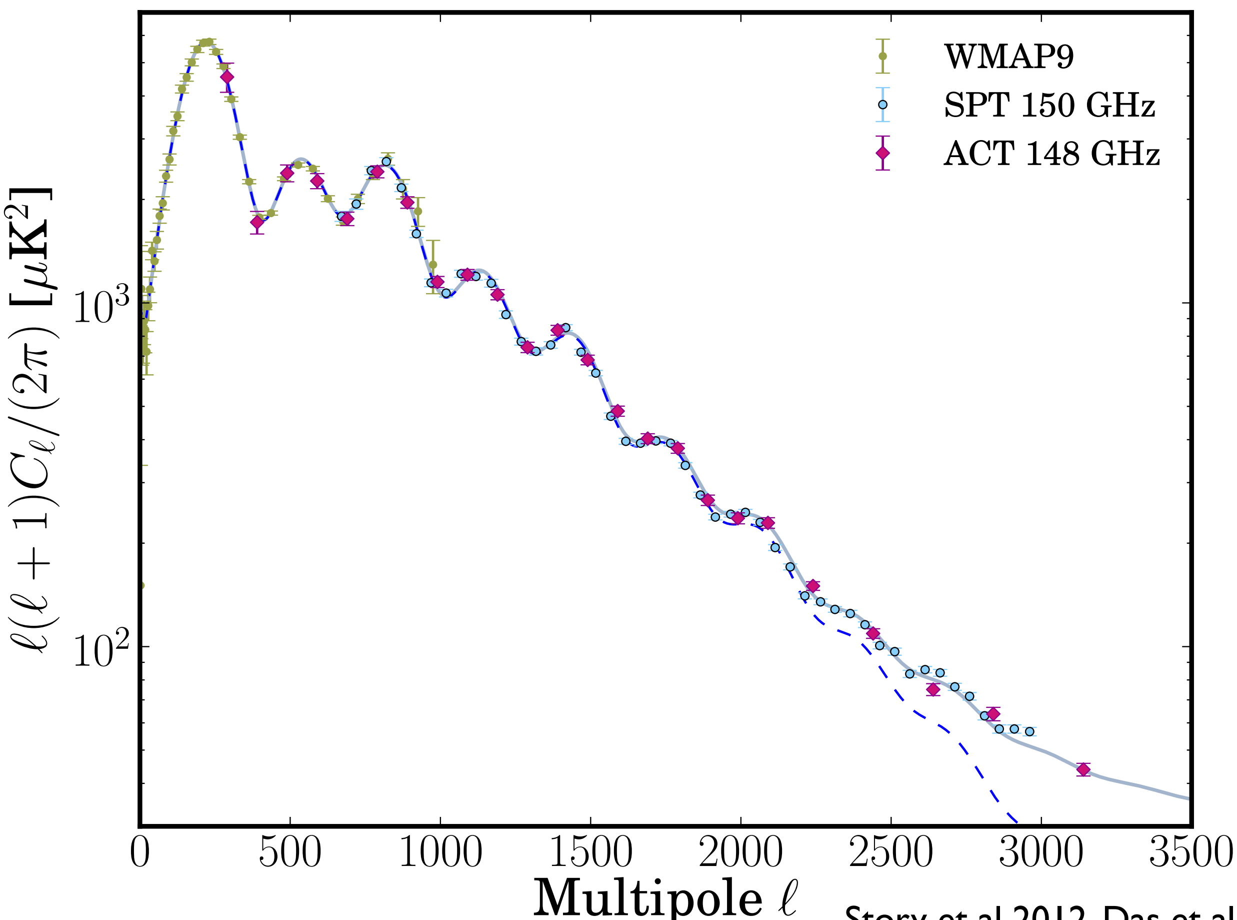
(3) Reionization

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

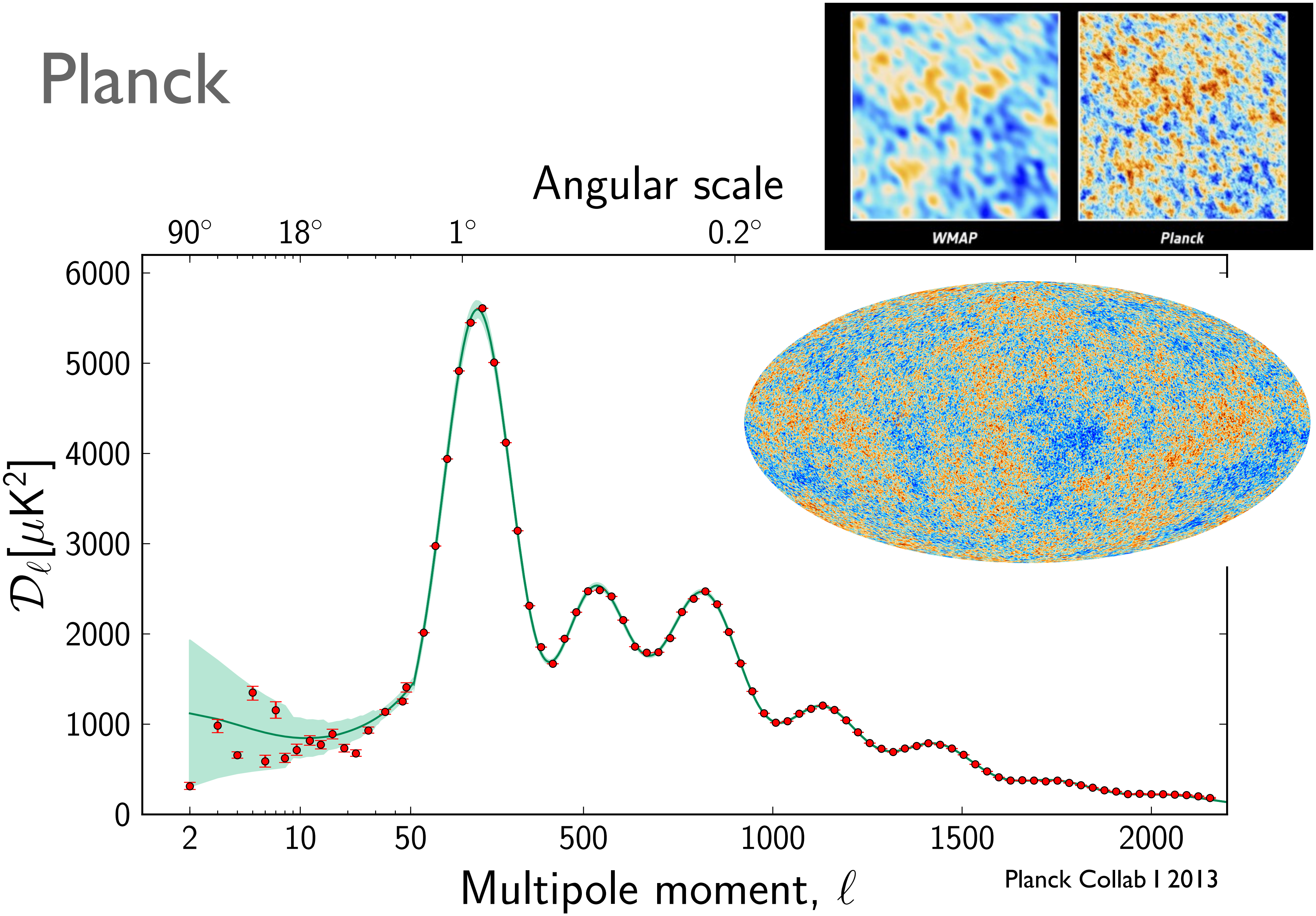
Measured to smaller scales by ACT & SPT (2007-11)



Story et al 2012, Das et al 2013

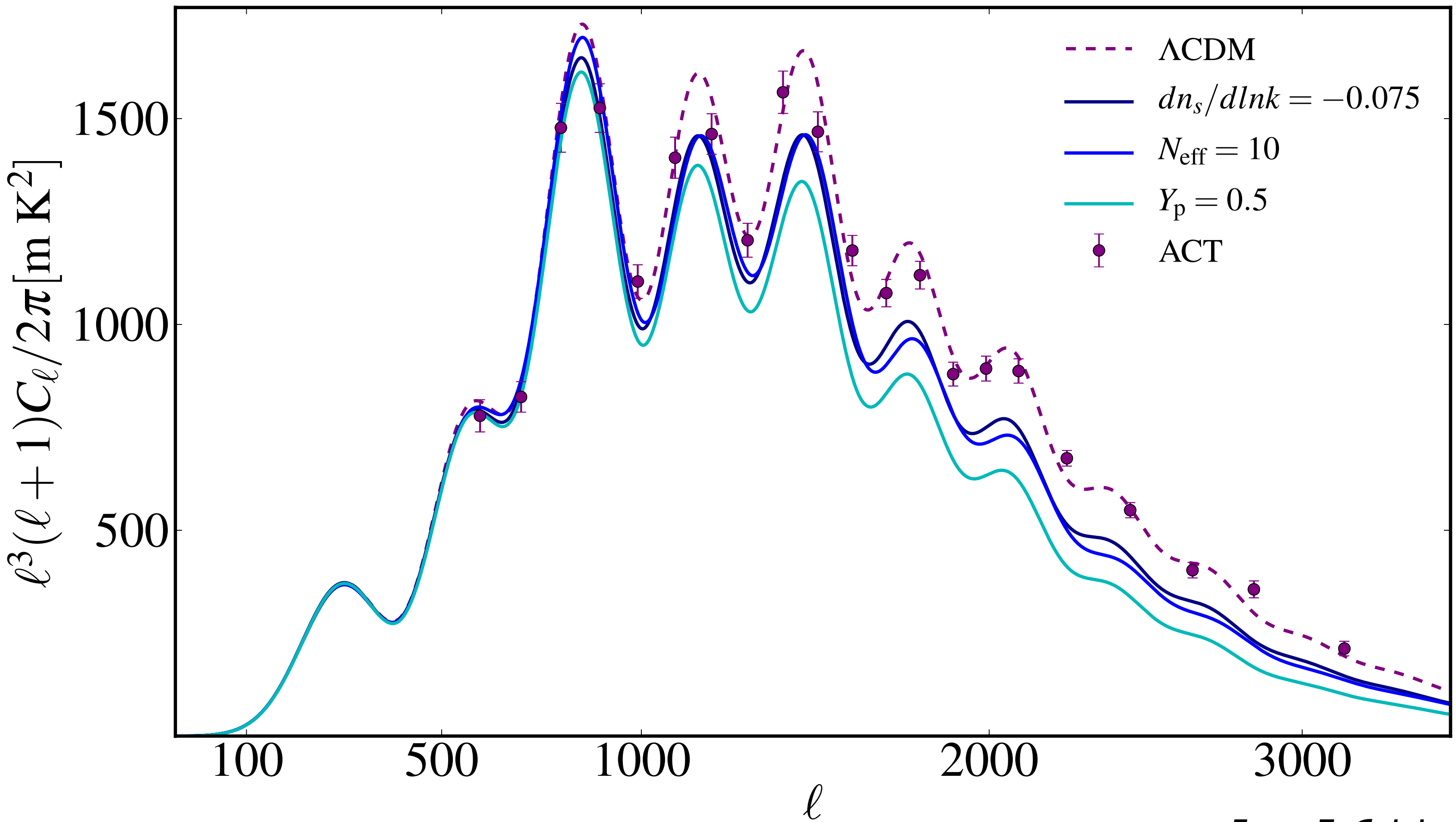
Clearly any deviations from the concordance model would have to be small
Power of these data are to limit extensions to ΛCDM

Planck



Typically half limits on 6-parameter ΛCDM model and detects n<1 (see Efstathiou talk).

Cosmology from the higher acoustic peaks

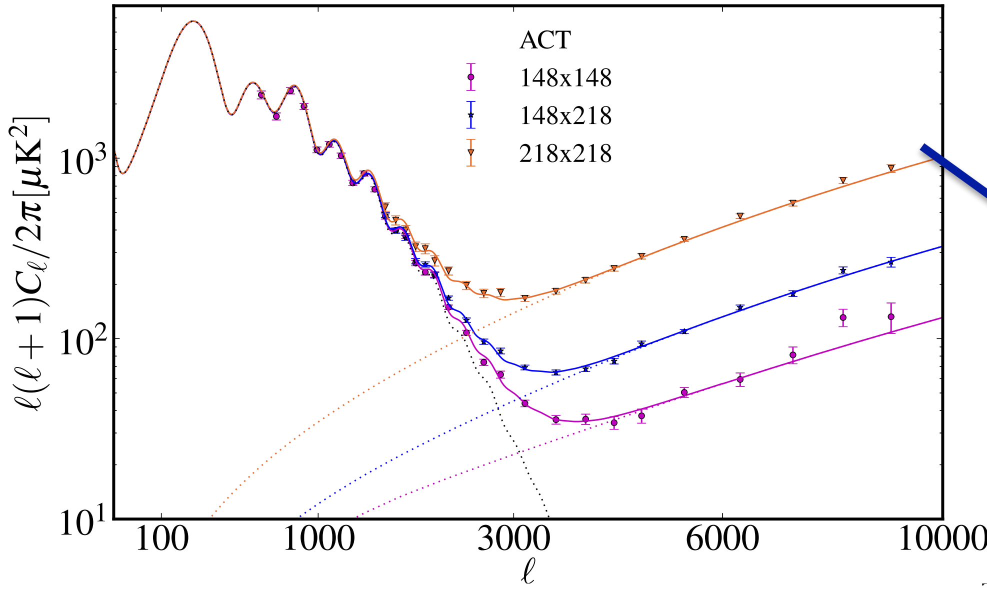


From E. Calabrese, for ACT

Limits on neutrino species, Helium fraction, running of the index, cosmic string tension, variation in alpha, early dark energy, isocurvature etc

Pre-Planck: no deviations from ΛCDM seen (had been 2σ hints from SPT)

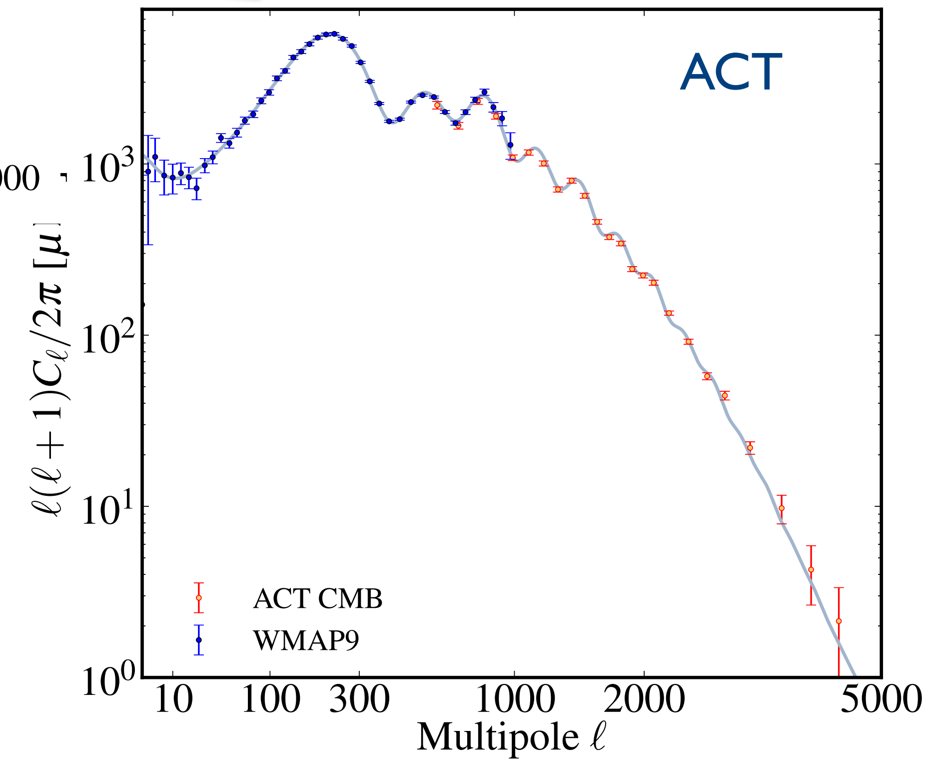
Now have to model foregrounds



Dunkley et al 2013, Sievers et al 2013

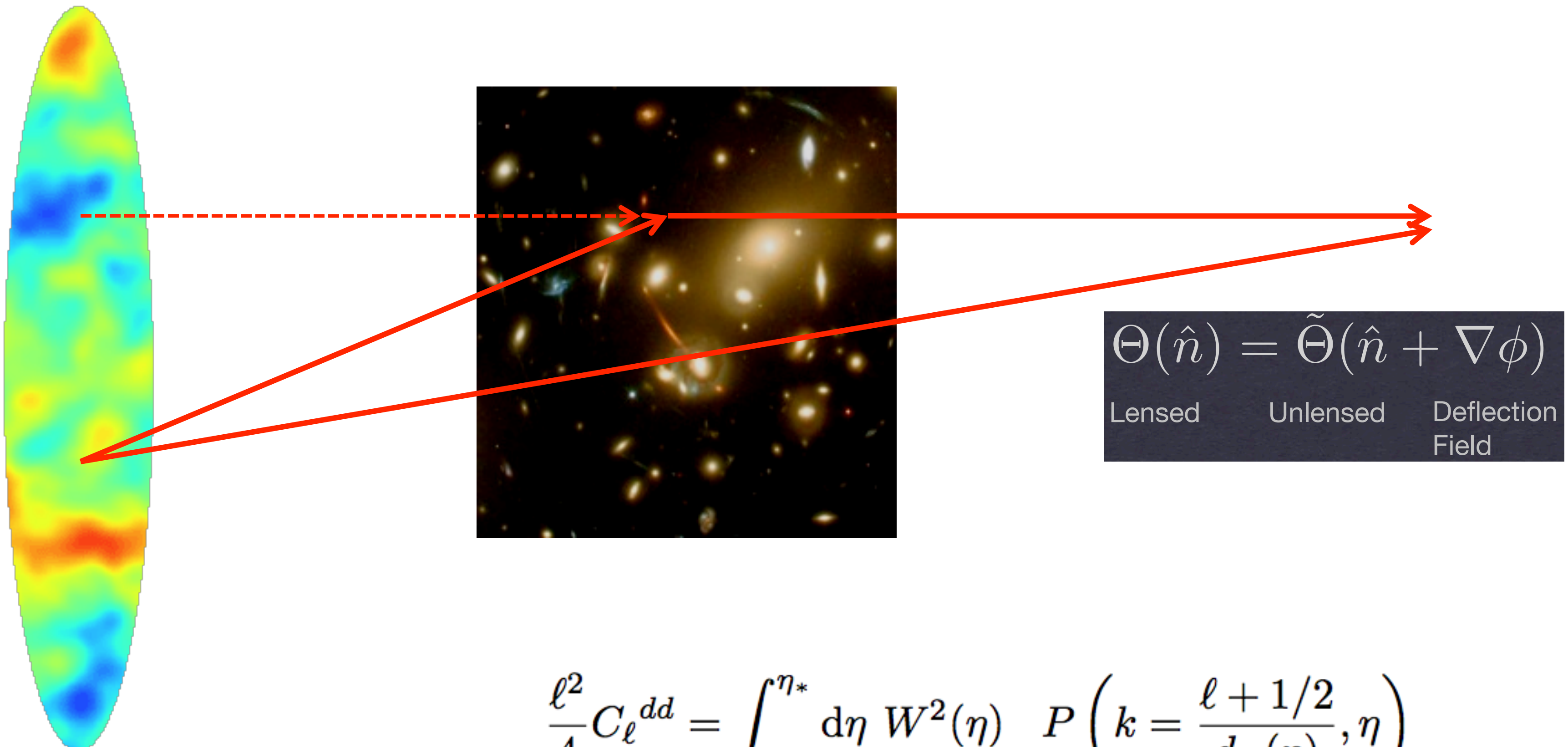
1. Model spectra at multiple frequencies
2. Include point sources, Sunyaev-Zel'dovich effects, Galactic cirrus.
3. Marginalize over non-CMB power using ~10-20 parameters

Used for ACT and SPT, now Planck too.



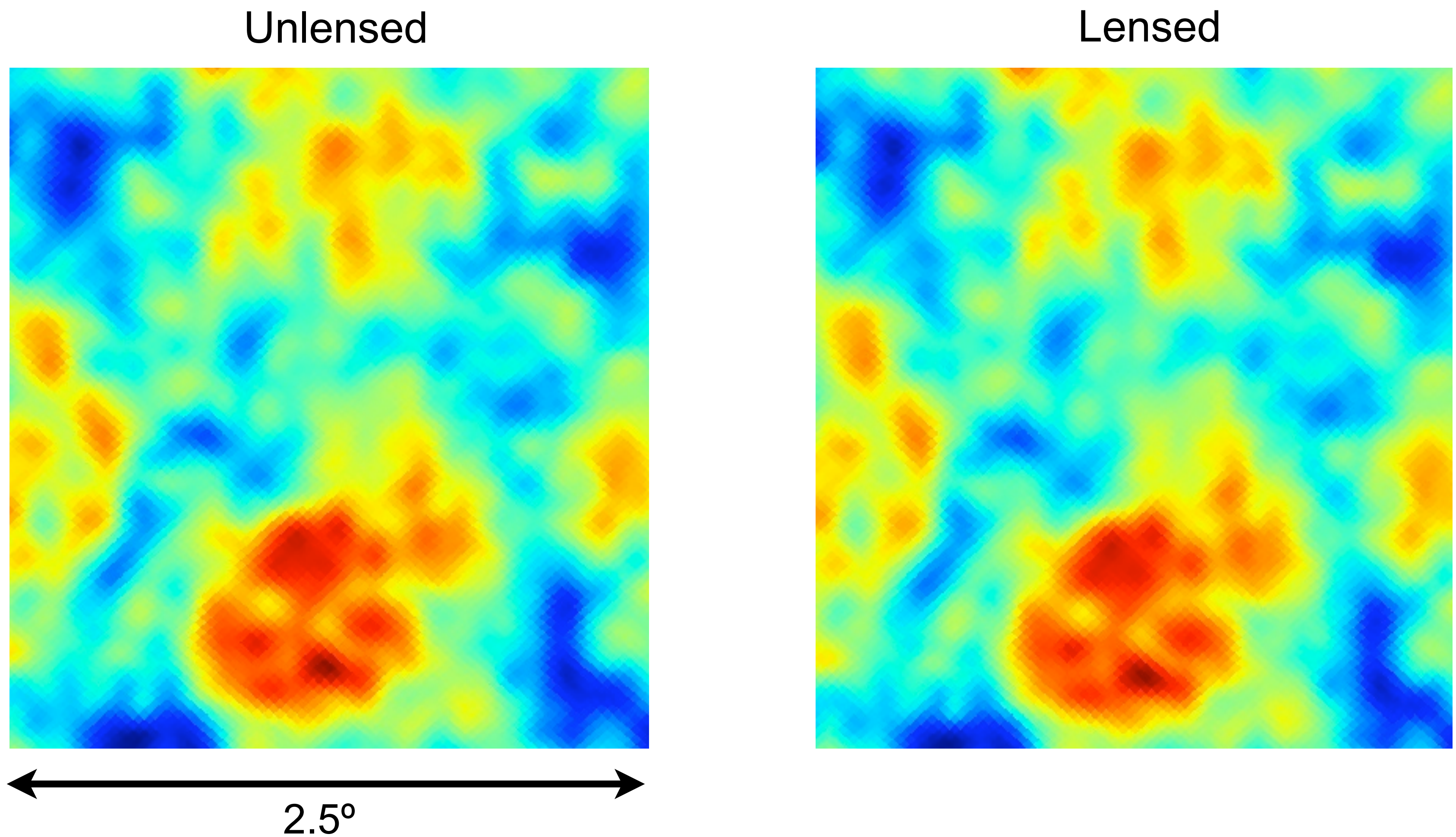
Das et al 2013, Dunkley et al 2013

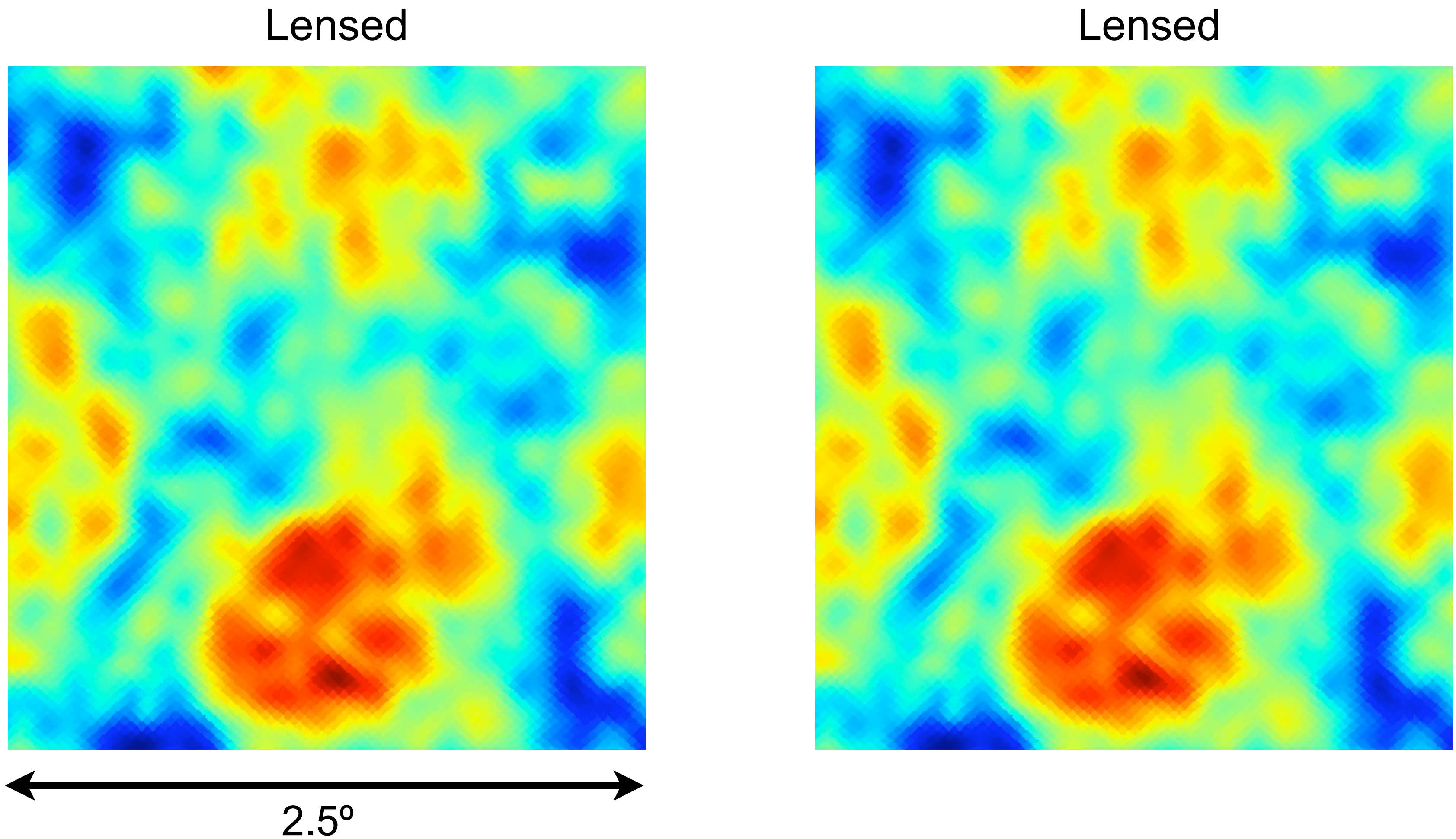
Lensing of the CMB



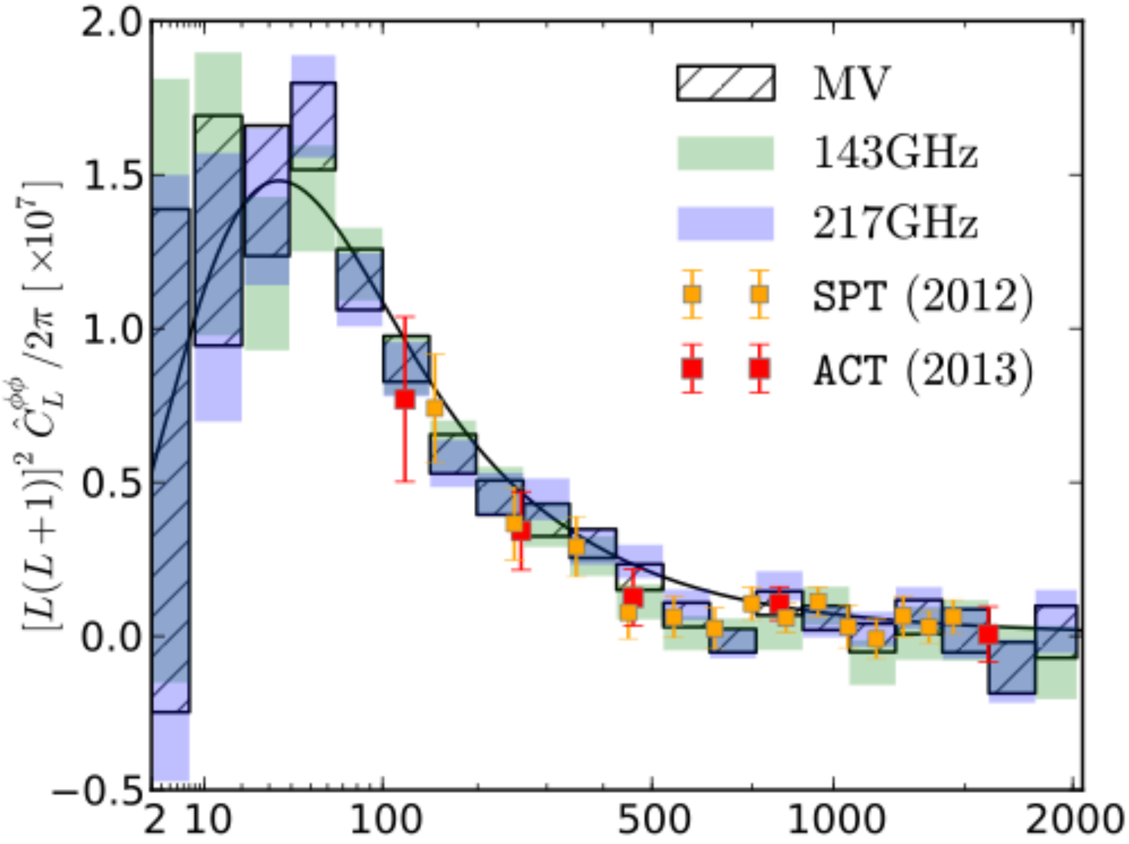
$$\frac{\ell^2}{4} C_\ell^{dd} = \int_0^{\eta_*} \mathrm{d}\eta \, \underbrace{W^2(\eta)}_{\text{geometry}} \; \underbrace{P\left(k = \frac{\ell + 1/2}{d_A(\eta)}, \eta\right)}_{\text{matter}}$$

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


Unlensed
Lensed
2.5º


Lensed
Lensed
2.5º

CMB lensing measurements



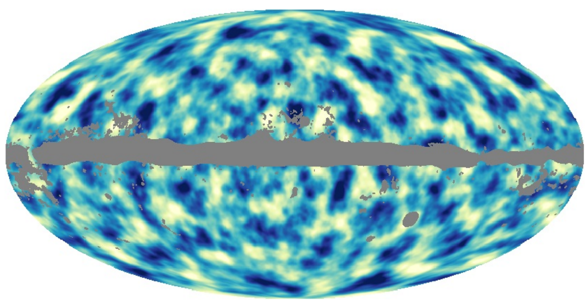
Planck collab XVII 2013

Lensing estimator $\hat{\phi}_{\ell m} \propto \left[(C^{-1}T)\nabla(SC^{-1}T)\right]_{\ell m}$

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

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

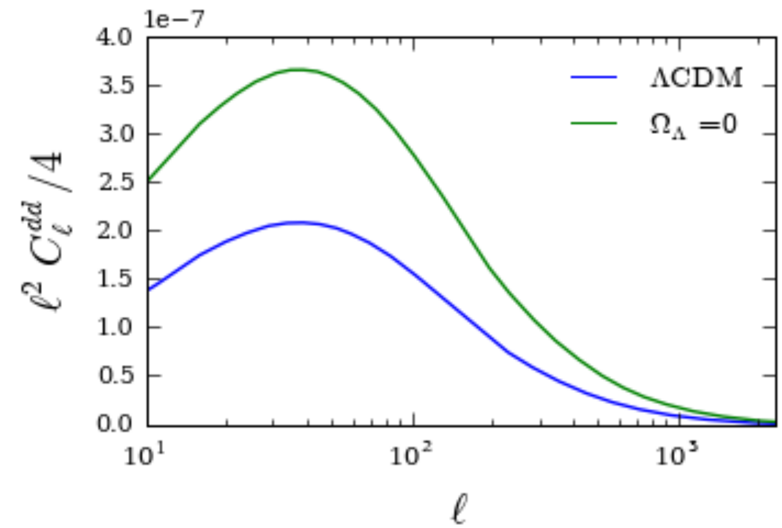
Now Planck in 2013 (Planck Collab XVII, 25σ)

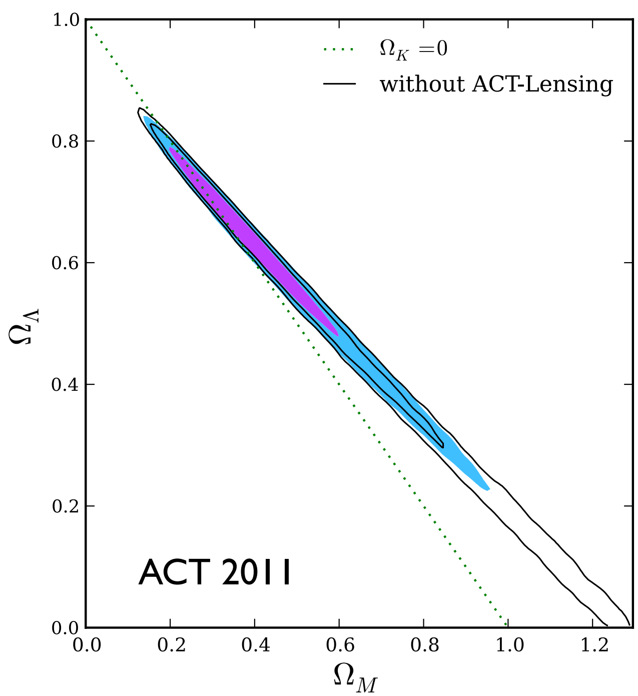


Late-time physics

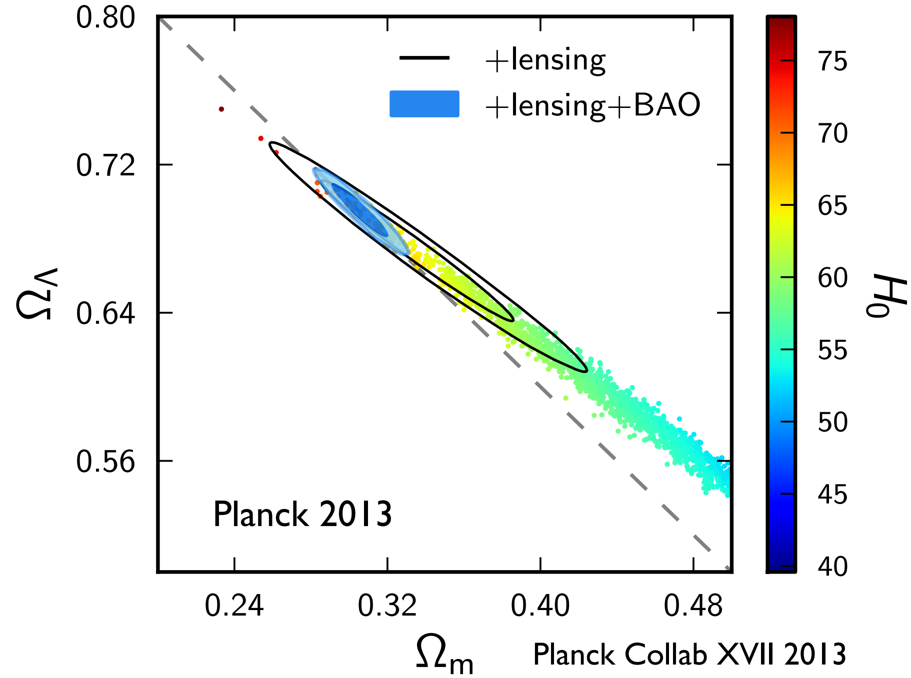
With primary CMB, cannot measure curvature.

Planck measures curvature through lensing
(more closed, less dark energy → more lensing)
Similarly, probes neutrino mass and dark energy



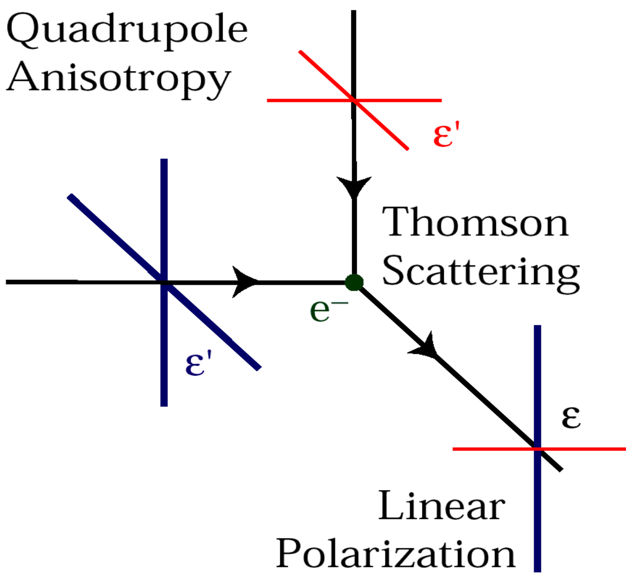


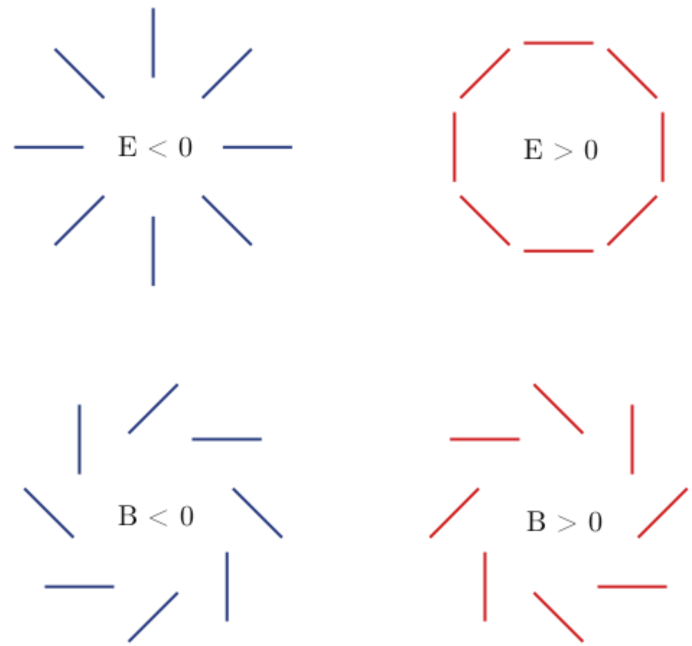
Sherwin, Dunkley, Das et al 2011



Planck Collab XVII 2013

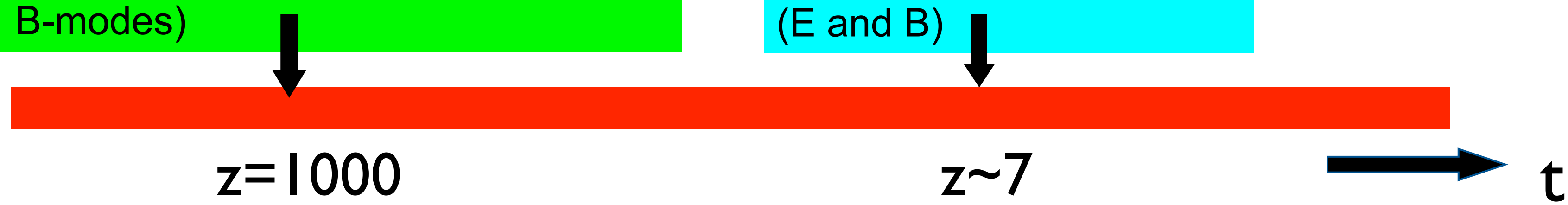
CMB polarization



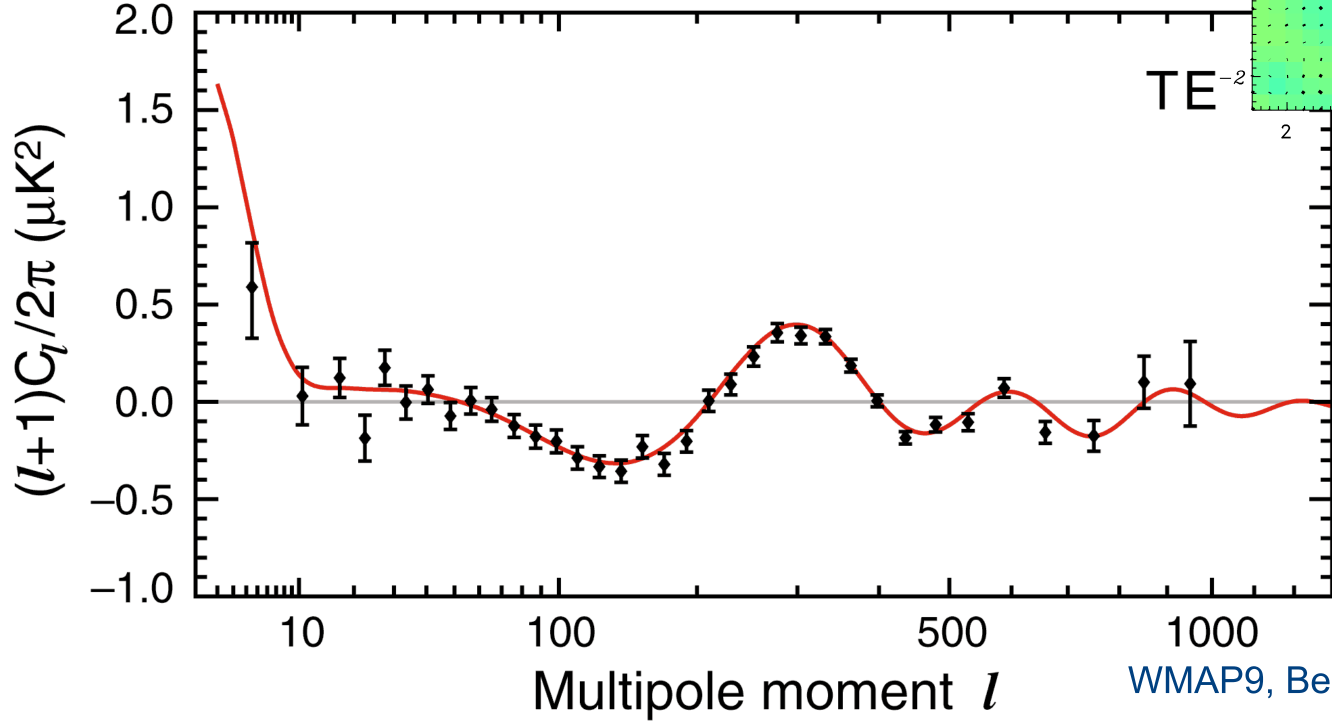


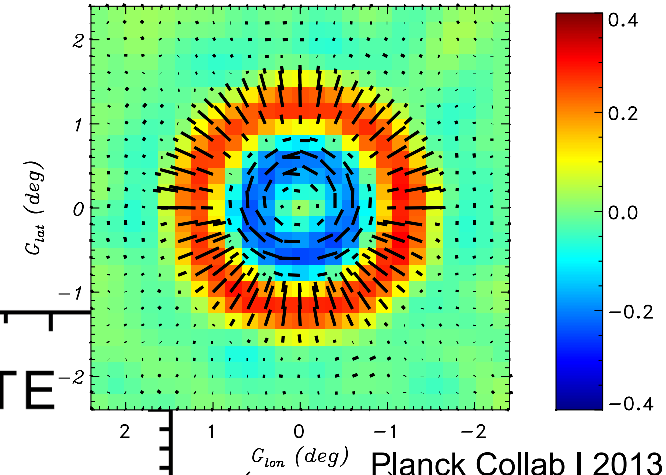
Generated at recombination from velocity of photon-baryon fluid (E-modes) and gravitational waves (E, B-modes)

Generated at reionization by quadrupole scattering (E and B)



Polarization acoustic peaks





Planck Collab I 2013

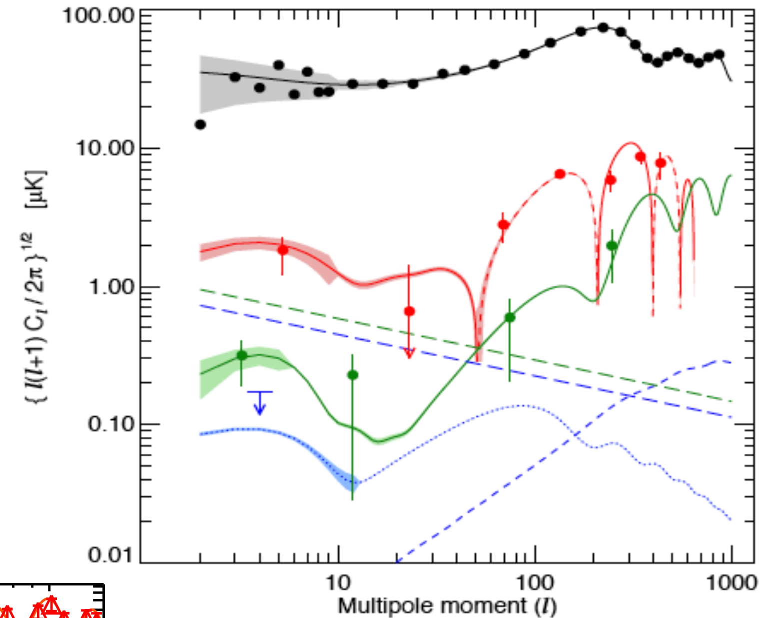
WMAP9, Bennett et al 2012

TE correlation measured by WMAP, and TE/EE by incl QUAD, QUIET, and Planck.

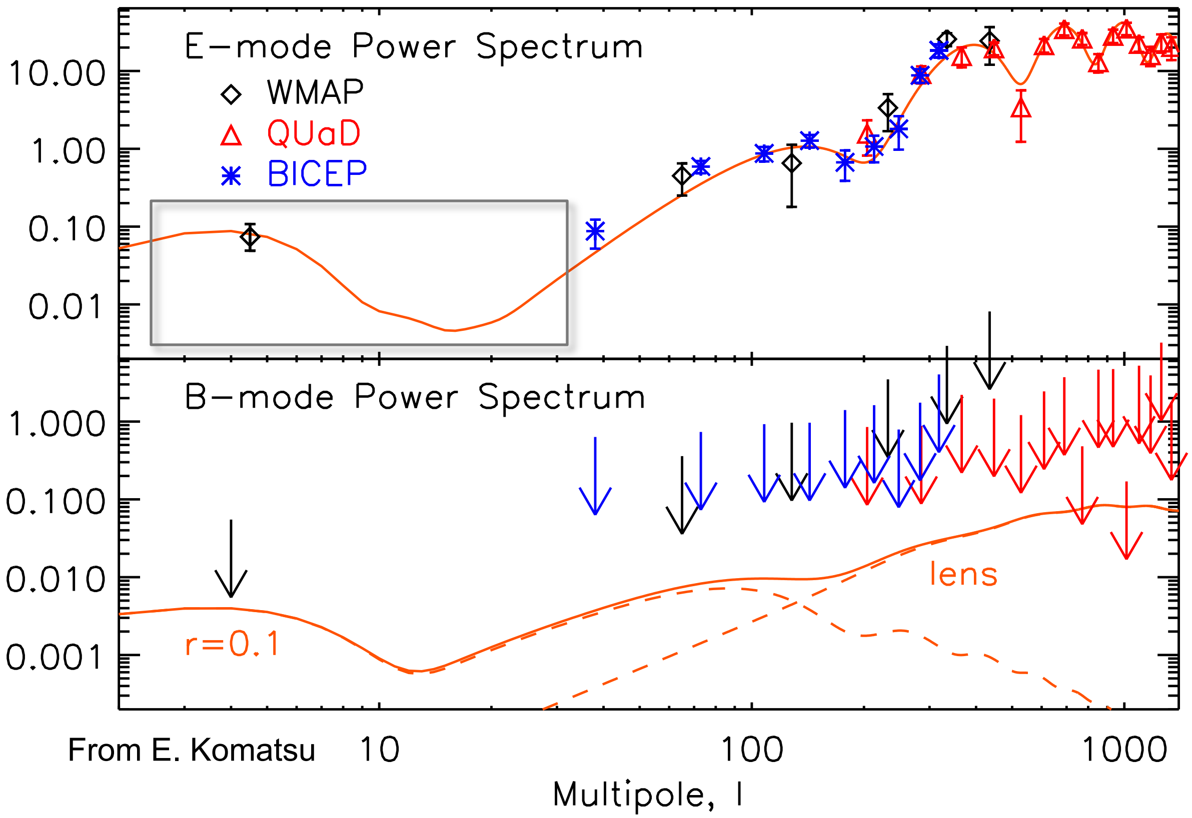
- Validates ΛCDM model. Evidence for superhorizon fluctuations.
- TE+EE promises better limits on neutrino number, isocurvature fluctuations etc.
- See Efstathiou for Planck latest on TE and EE.

Large scale polarization

E-mode power constrains optical depth: best limit still from WMAP9 (Hinshaw et al 2012)



WMAP, Page et al 2007



From E. Komatsu

B-mode still upper limits:

BICEP: r< 0.73

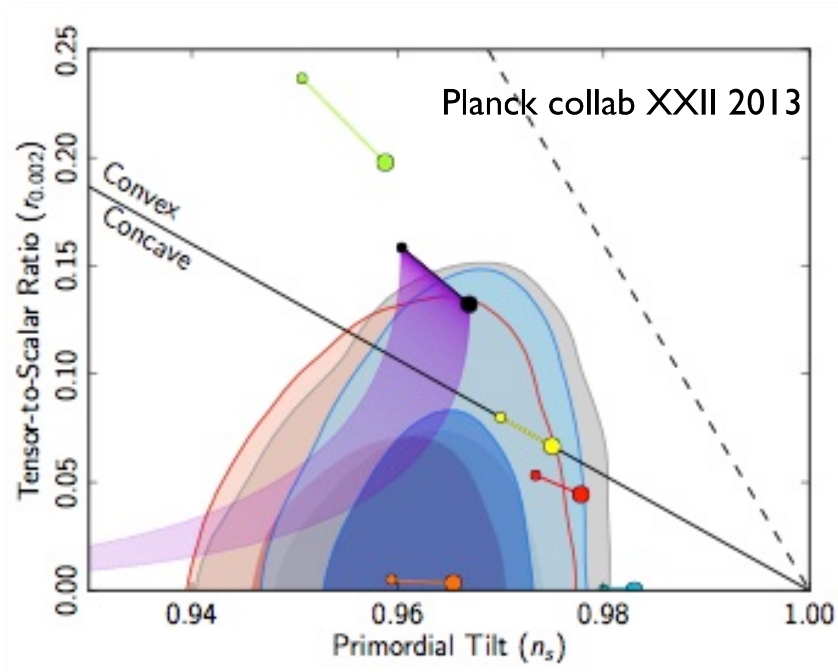
Chiang et al 2009

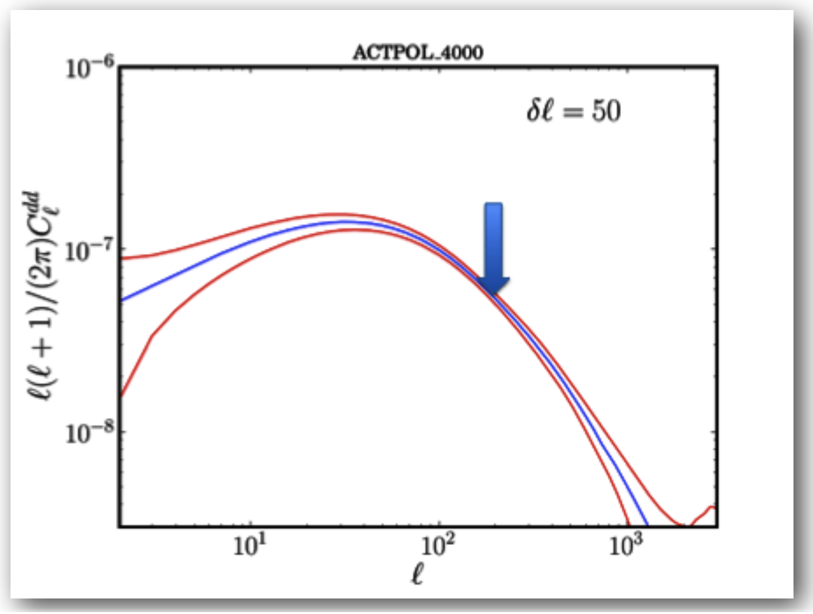
QUIET: r<2.7

QUIET collab 2012

The future

- E-mode oscillations
  - Planck, ACTPol, SPTPol
- Large-scale B-mode for inflation
  - Keck Array, EBEX, SPIDER, ABS, QUIJOTE, CLASS, PIPER… Aiming at r=0.1-0.01
  - Future satellites?: LiteBIRD, PRISM,PIXIE
- Lensing from small-scale T, E, B
  - SPTPol, ACTPol, PolarBear
  - Aiming for neutrino mass limits of 0.1 -0.05eV (5% change for 0.1eV)
  - Unique probe of z~2 dark energy
  - Strong cross-correlation capabilities





From B. Sherwin for ACTPol

Summary

- CMB temperature measurements
  - WMAP completed its 9-year survey (2012)
  - Ground-based experiments ACT and SPT measure CMB temperature at high resolution
  - Planck satellite measures 7 acoustic peaks (2013). Also limits 3-pt function.

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

- CMB lensing is fast-growing! It probes clustering of matter and expansion rate. Detected in ACT, SPT, and Planck. Dark energy now required just from the CMB. SZ number counts also probe dark energy and matter growth.

- CMB polarization measurements: many underway. WMAP still provides large-scale measurement for optical depth. The future is in polarization (large and small scale).