Cosmology from ACT: the small-scale CMB

Jo Dunkley

Oxford Astrophysics

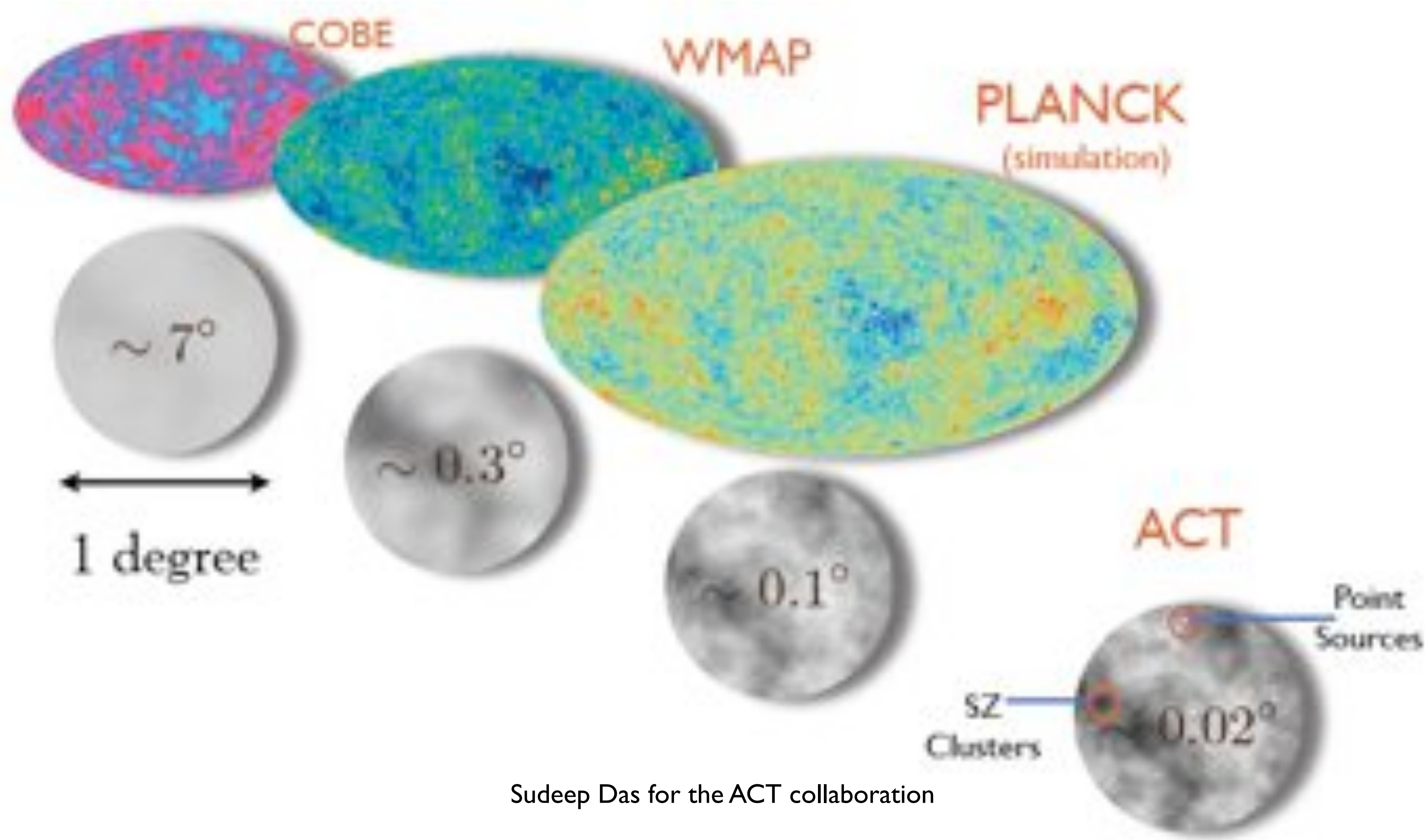
Ecole Chalonge, July 21

Atacama Cosmology Telescope

- Univ of British Columbia (Canada)
- Univ of Cape Town (S Africa)
- Cardiff University (UK)
- Columbia University (USA)
- Haverford College (USA)
- INAOE (Mexico)
- Univ of Kwa-Zulu Natal (S Africa)
- Univ of Massachusetts (USA)
- NASA/GSFC (USA)
- NIST (USA)
- Univ of Oxford (UK: Dunkley, Addison, Hlozek)
- Univ of Pennsylvania (USA)
- **Princeton University (USA) (PI L. Page)*
- Univ of Pittsburgh (USA)
- Pontifica Universidad Catolica (Chile)
- Rutgers University (USA)
- Univ of Toronto (Canada)
- Rome La Sapienza, MPI, Miami, Stanford, Berkeley (Das), Chicago, CfA, LLNL, IPMU Tokyo

→ ~ 90 collaborators

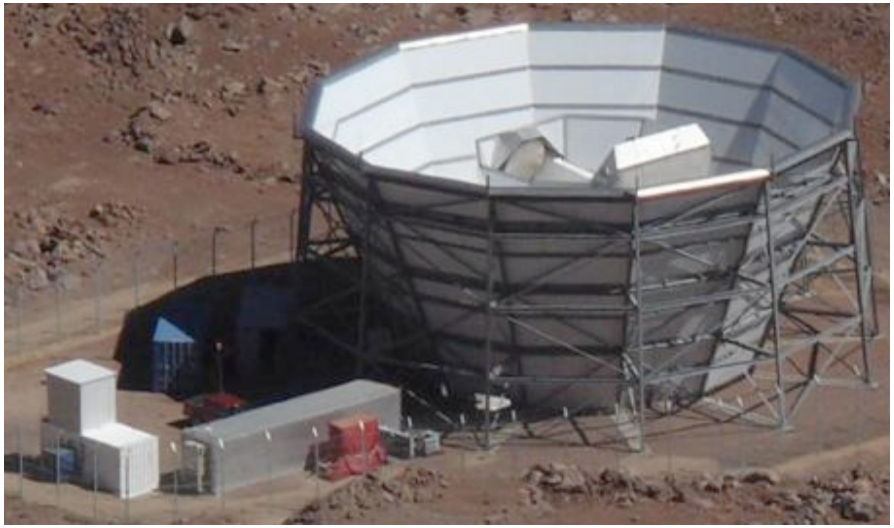
ACT probes new scales



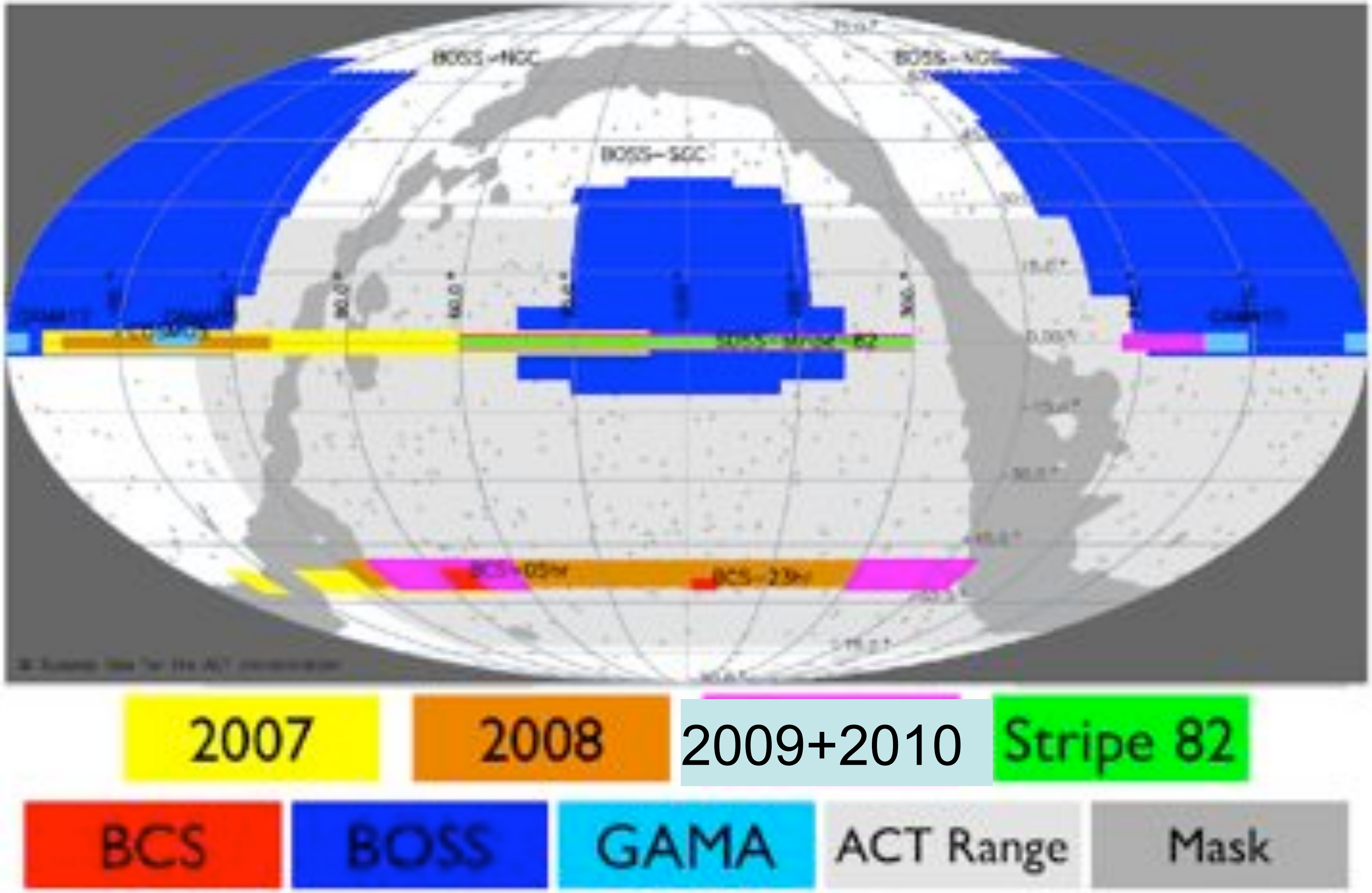
Sudeep Das for the ACT collaboration

ACT: the telescope

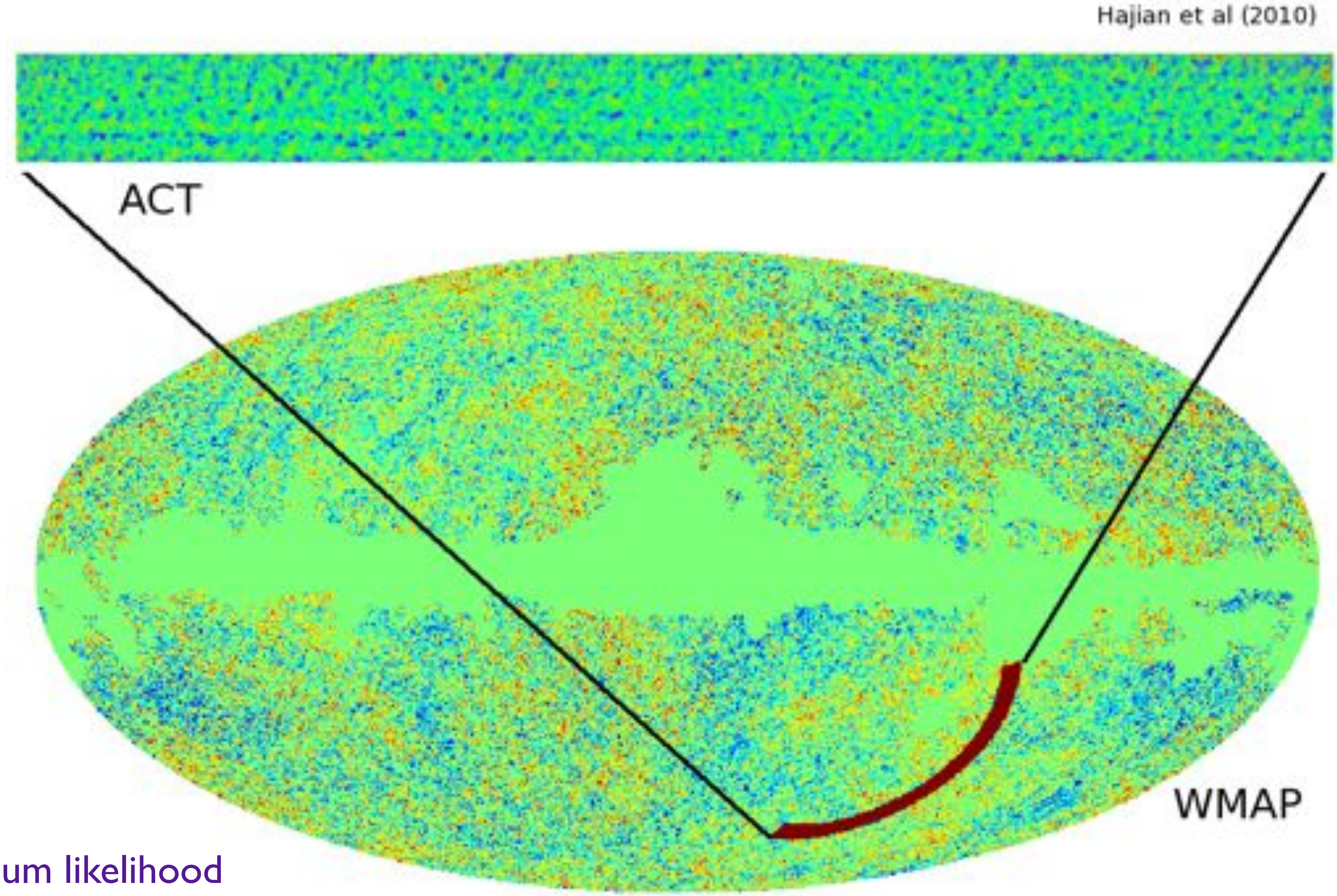
5200 meter elevation, one of driest places on planet
1° field of view, 6-meter primary, 2-meter secondary, 1.4’ resol
3 frequencies: 148, 220, 270 GHz, 3000 TES detectors



ACT Sky Coverage

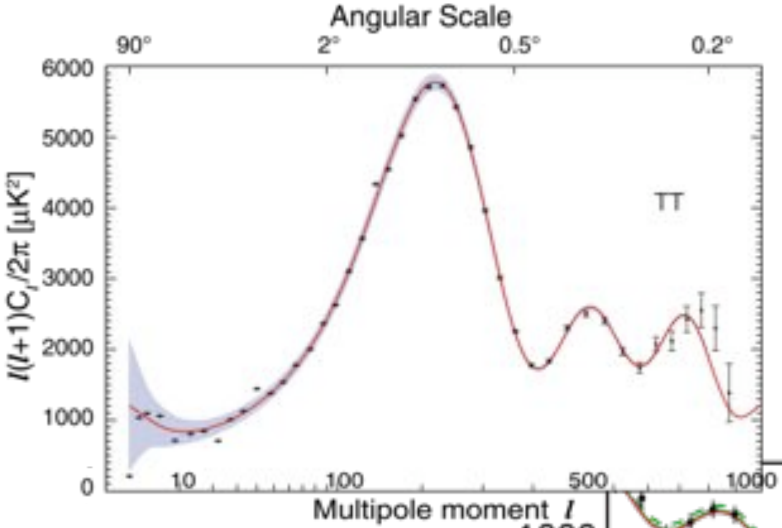


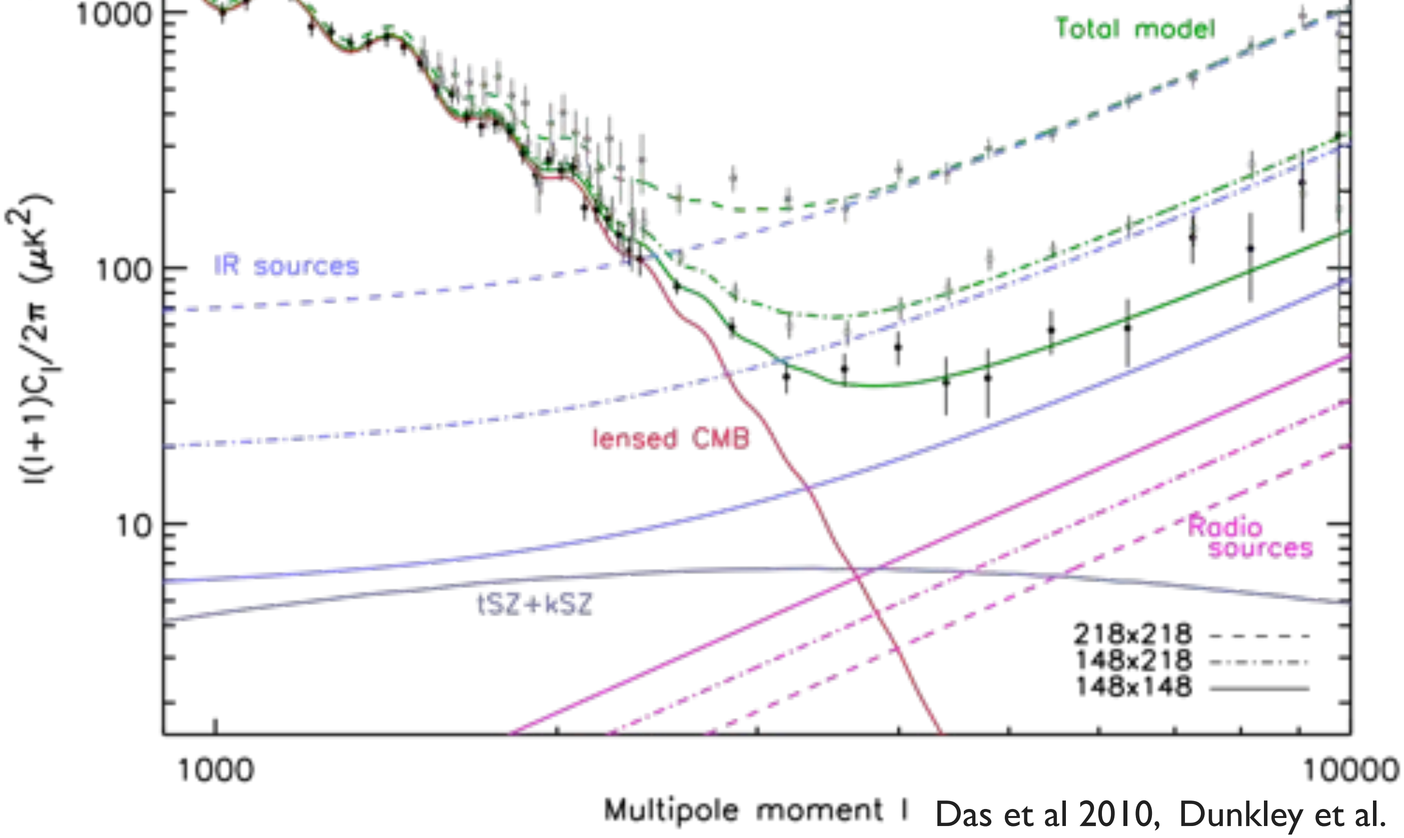
ACT southern field at 148 GHz



Maximum likelihood
map-maker

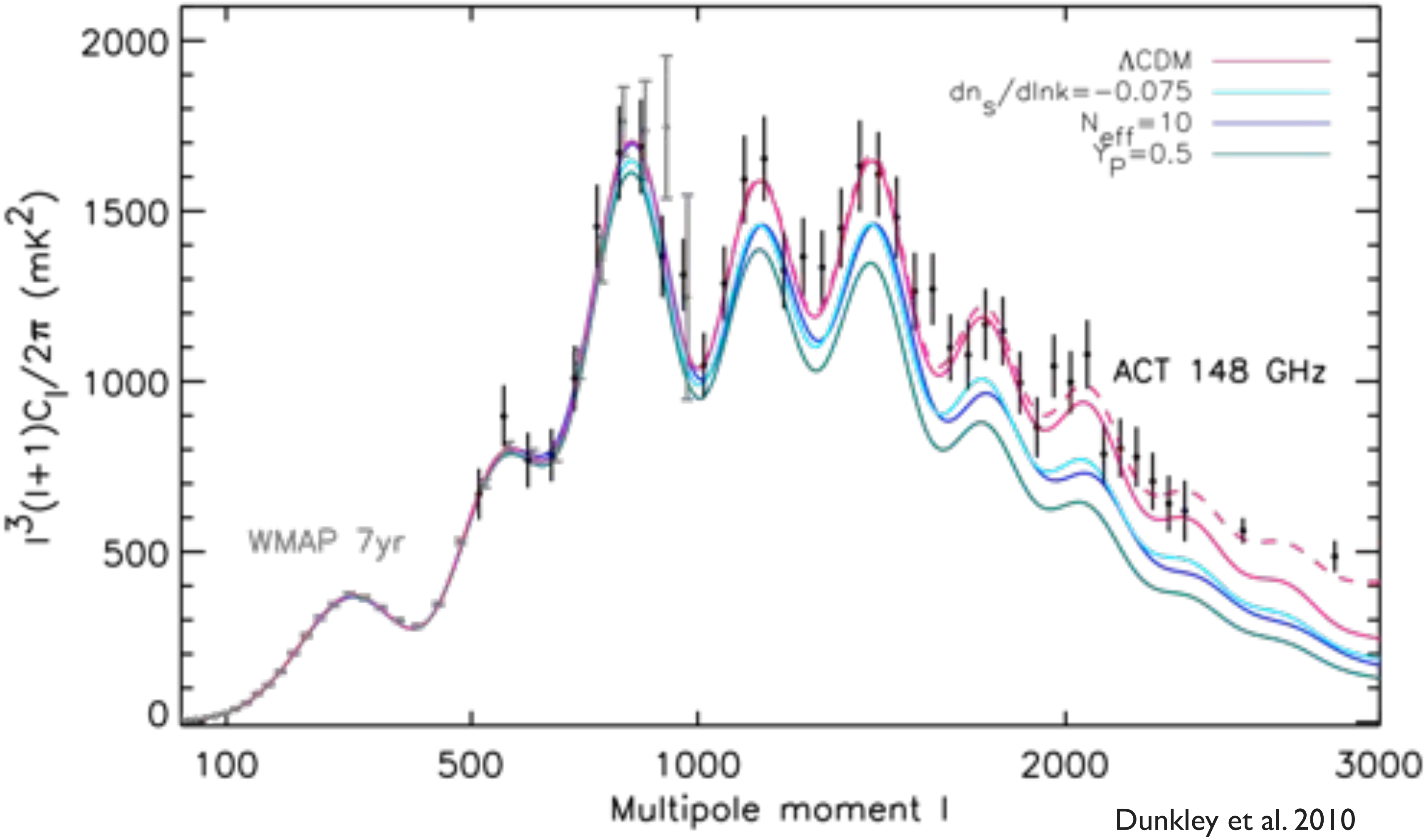
The small scale spectrum





Das et al 2010, Dunkley et al. 2010

(At least) seven acoustic peaks!



Dunkley et al. 2010

Inflation: limits from spectrum

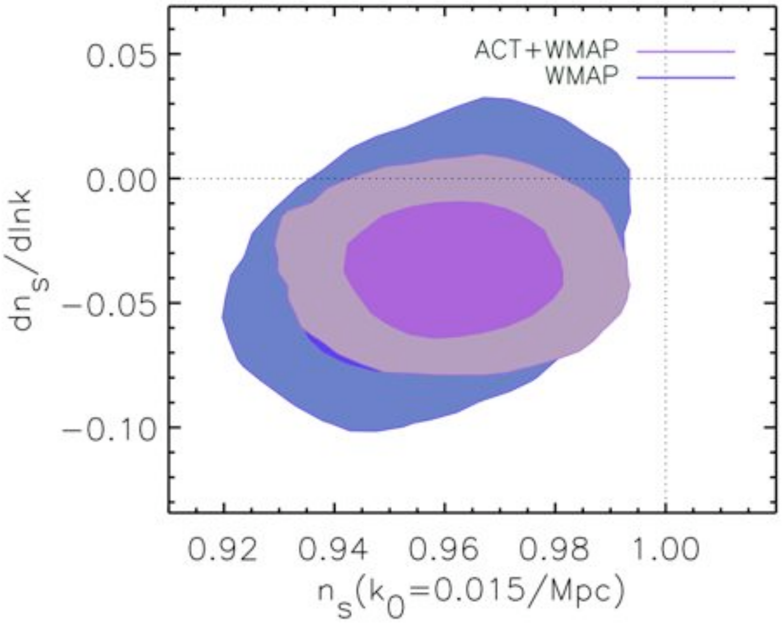
- Effective field theory, period of exponential expansion for > 60 e-folds.

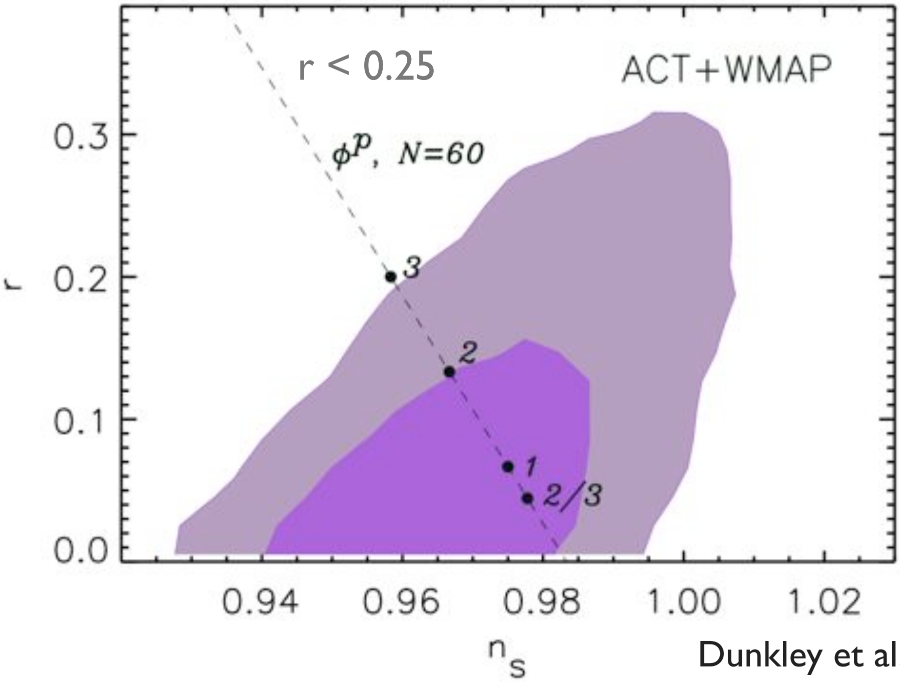
- Many models predicts spectra index <1. The index is still 3 sigma away.
- Running index, find $dn_s/d\ln k = -0.024 \pm 0.015$

  (ACT+WMAP+BAO+H0)

- New upper limit on tensors, find

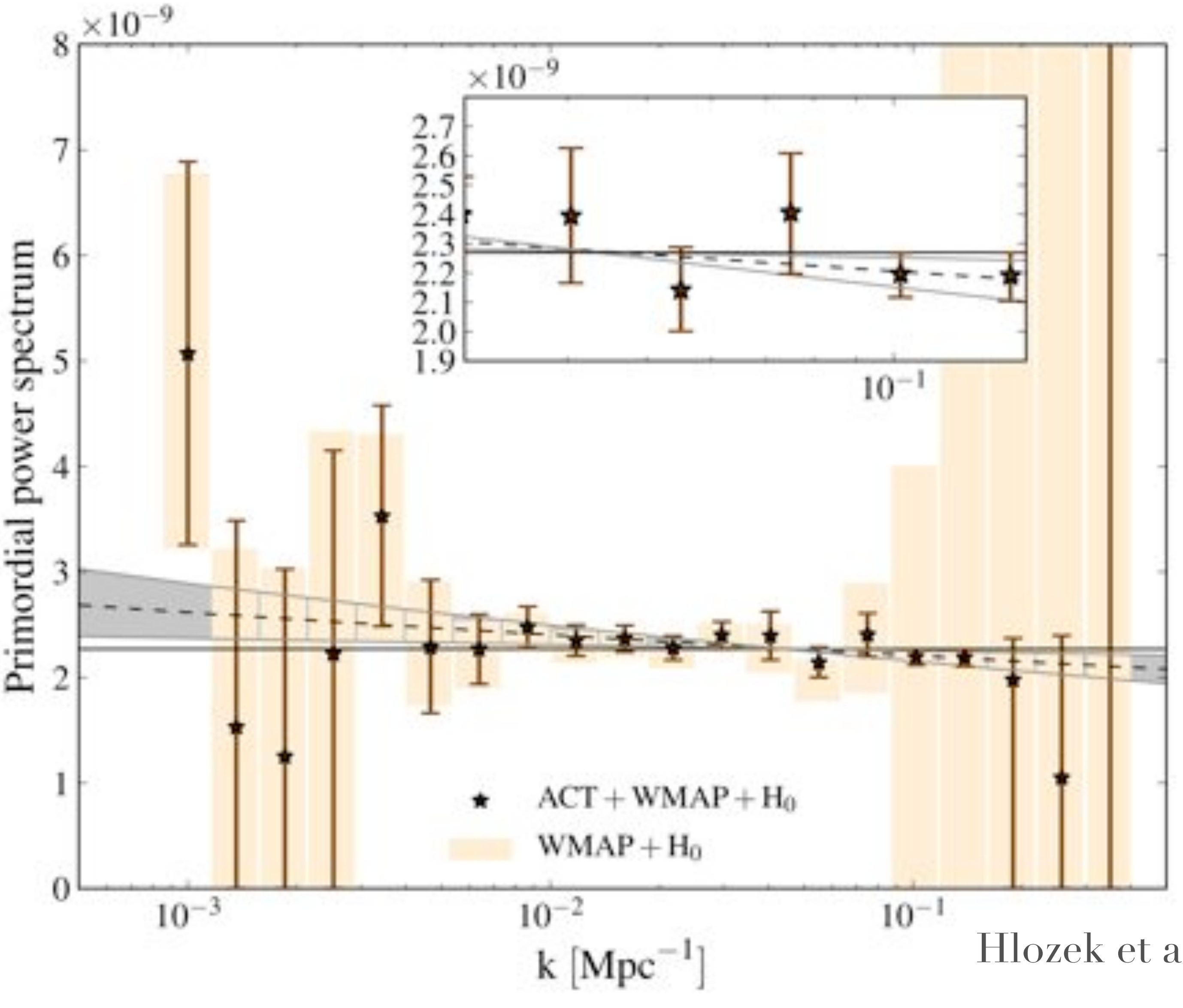
  $r < 0.19$ (95% CL, ACT+WMAP+BAO+H0)





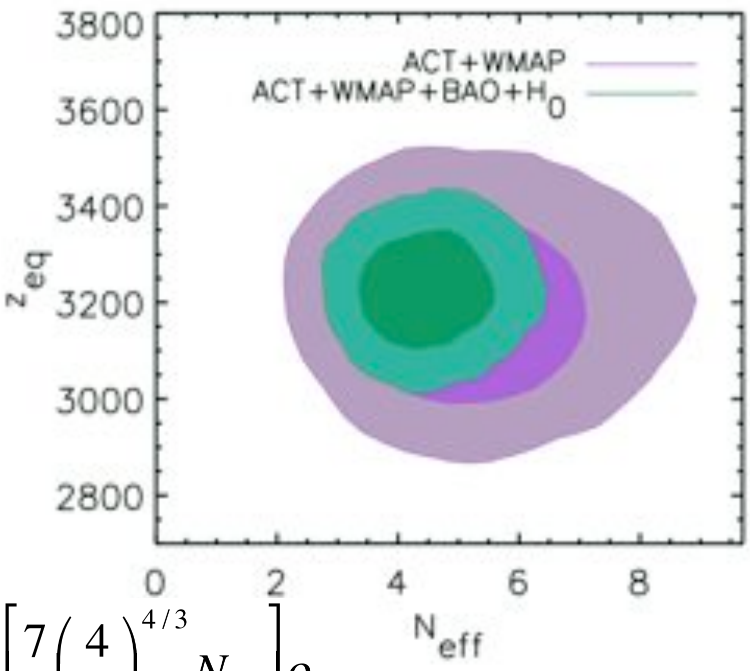
Dunkley et al. 2010

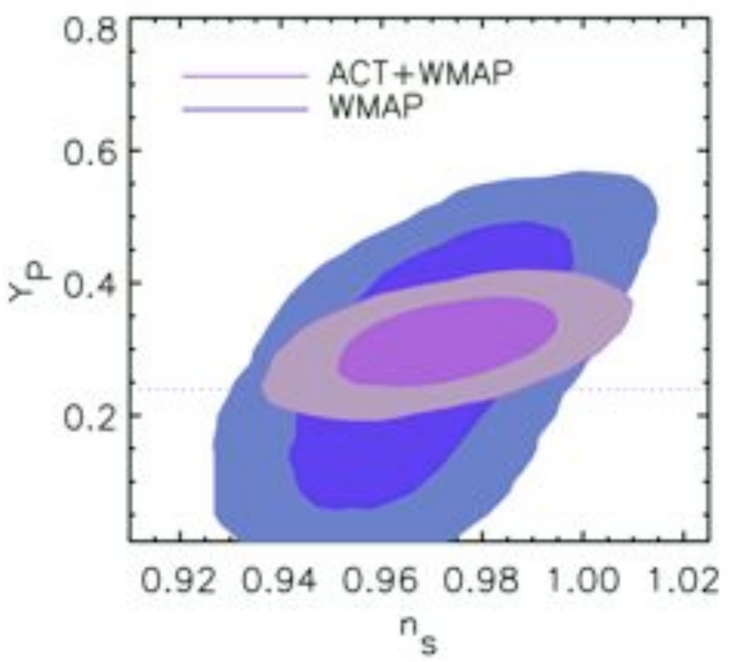
Primordial power spectrum



Hlozek et al. 2011

Early universe physics





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

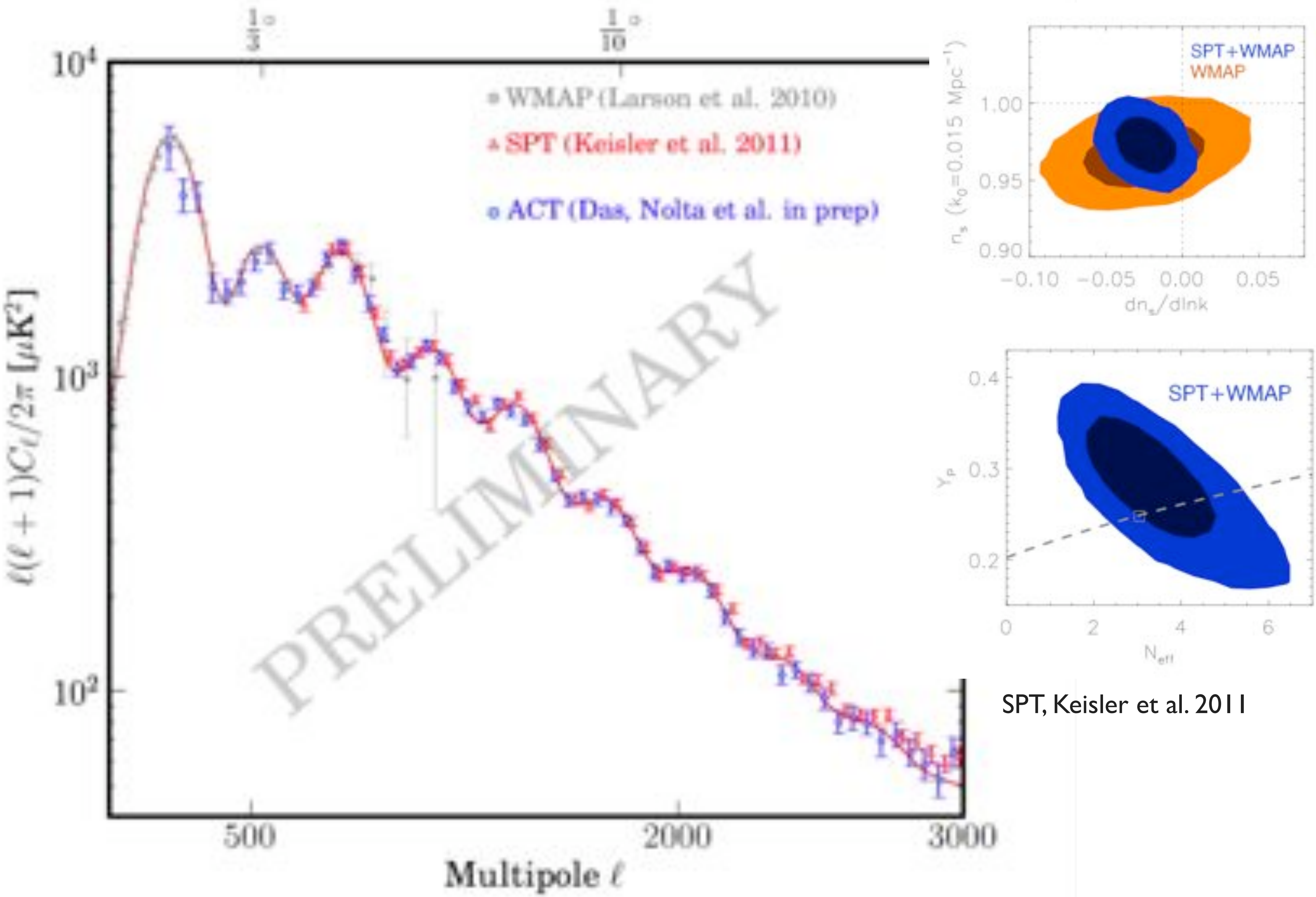
Dunkley et al. 2010

Neutrinos: More species, longer radiation domination. Changing Neff changes equality redshift.

Also - species suppress early acoustic oscillations in primary CMB, and phase shift in primary CMB.

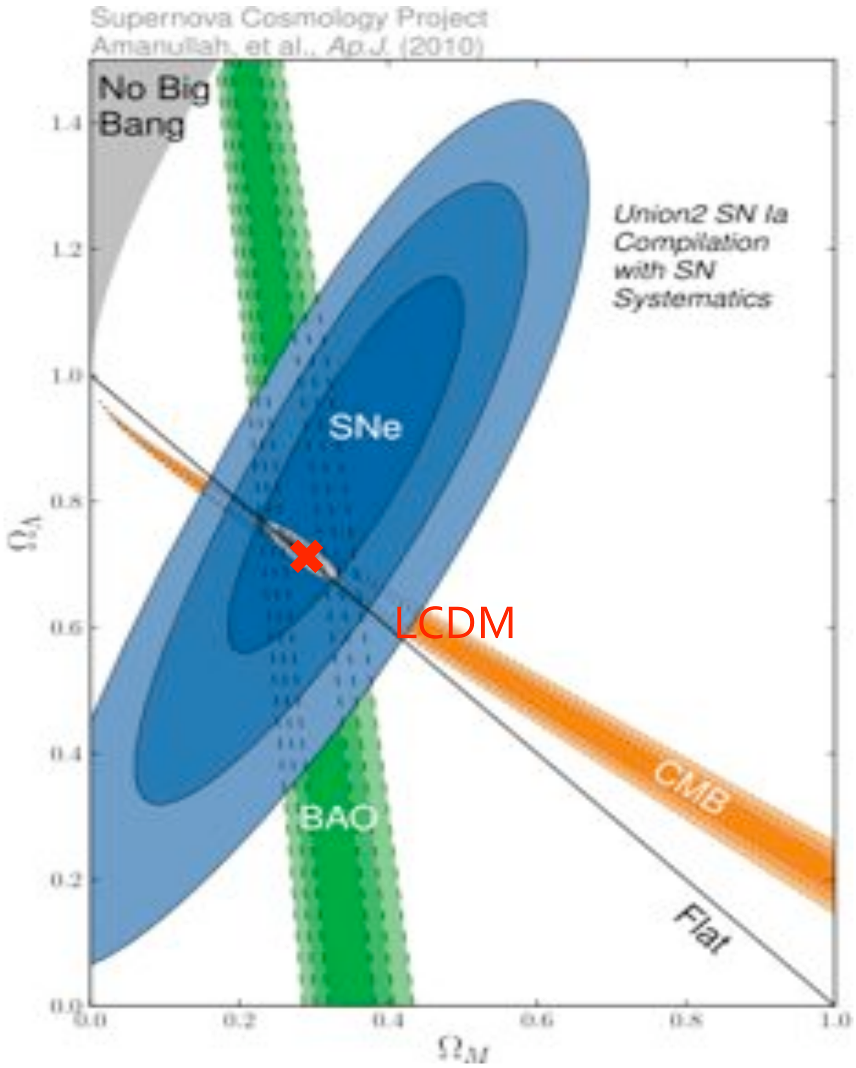
Helium: *Usually assume Y_P=0.24, predicted by BBN: Y_P = 0.2485+0.0016[(273.9$\Omega_b h^2$-6) +100 (S-1)]*

More helium decreases electron density, increasing damping. Find Y_p = 0.313 ± 0.044 from ACT.

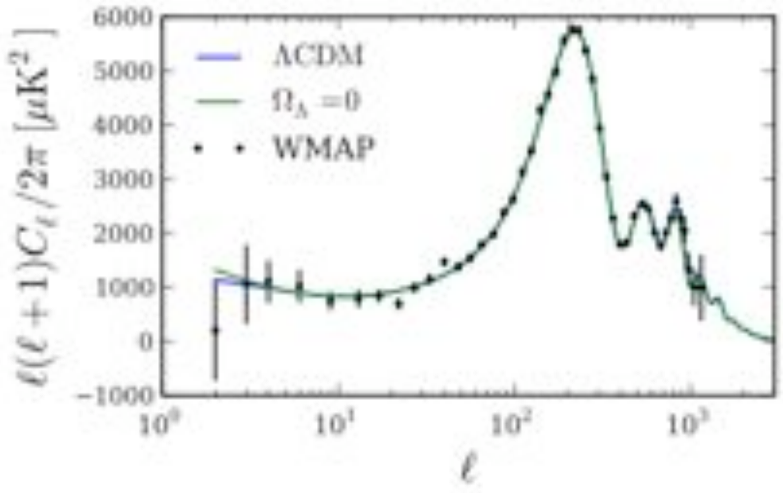


SPT, Keisler et al. 2011

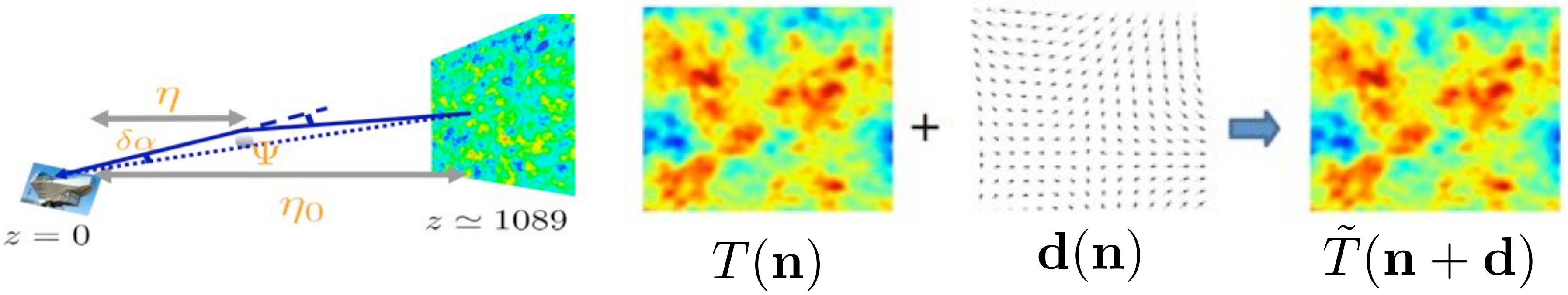
Limitations of primary CMB



- CMB geometric degeneracy: distance depends on contents, and expansion rate.
- Can balance distance with geometry to keep peaks in same place.
- Can't see late-time structure growth



The late universe: CMB lensing

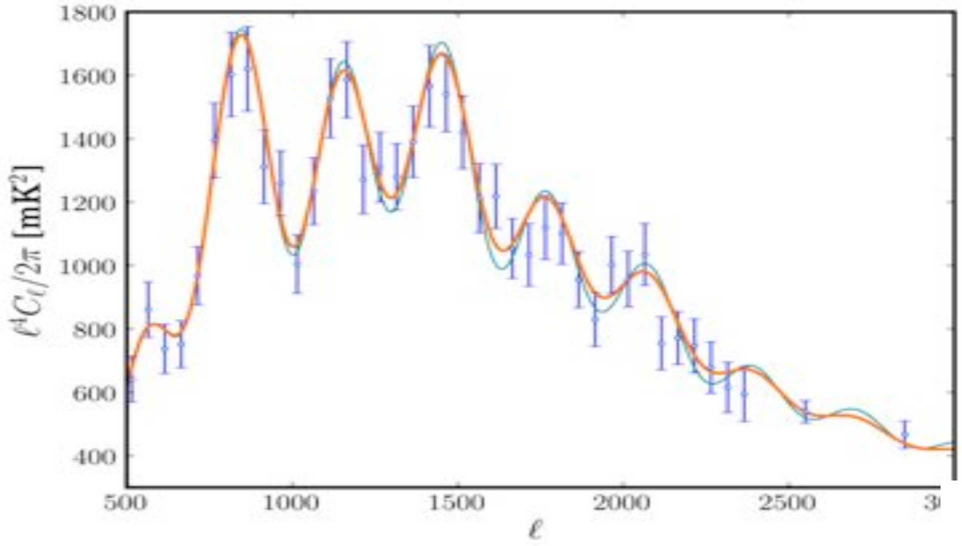


- Large scale structure potentials gravitationally deflect CMB photons by a lensing deflection angle d(n), typically few arcmins.

$$\begin{aligned} T(\mathbf{n})_{\text{lensed}} &= T(\mathbf{n}+\mathbf{d}(\mathbf{n}))_{\text{unl}} \\ &= T(\mathbf{n})_{\text{unl}} + d_i(\mathbf{n})\nabla_i T(\mathbf{n})_{\text{unl}} \end{aligned}$$

- Measurement of the deflection field is a measurement of matter fluctuations AND the geometry of the universe.

Lensing shows up in TT

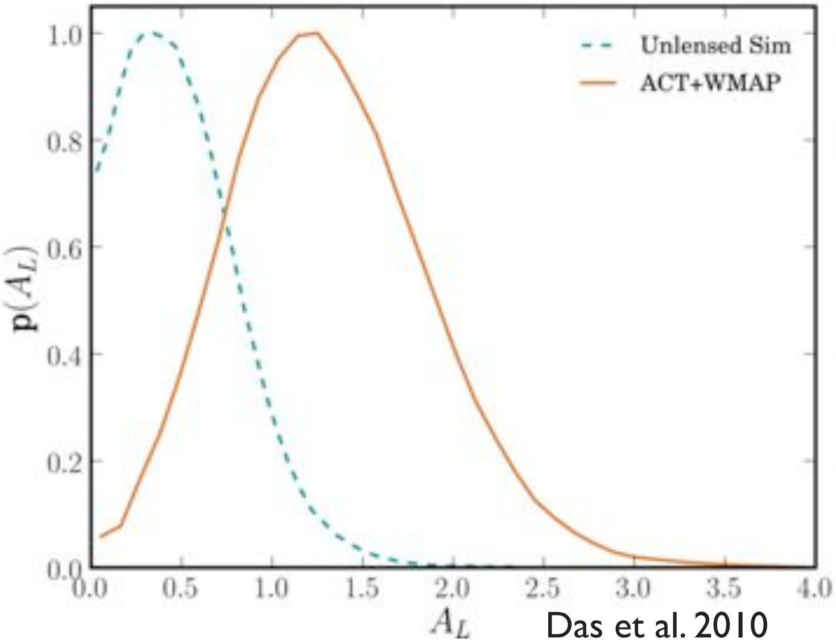


- An unlensed spectrum would have sharper features

- Test for lensing in spectrum by marginalizing over (unphysical) parameter A_L, scaling lensing potential. [Calabrese et al 2008]

- Expect A_L=1, and unlensed has A_L=0. See lensing at almost 3σ level:

$$A_L = 1.3 \pm 0.5^{+1.2}_{-1.0} \text{ (68, 95\% CL)}$$

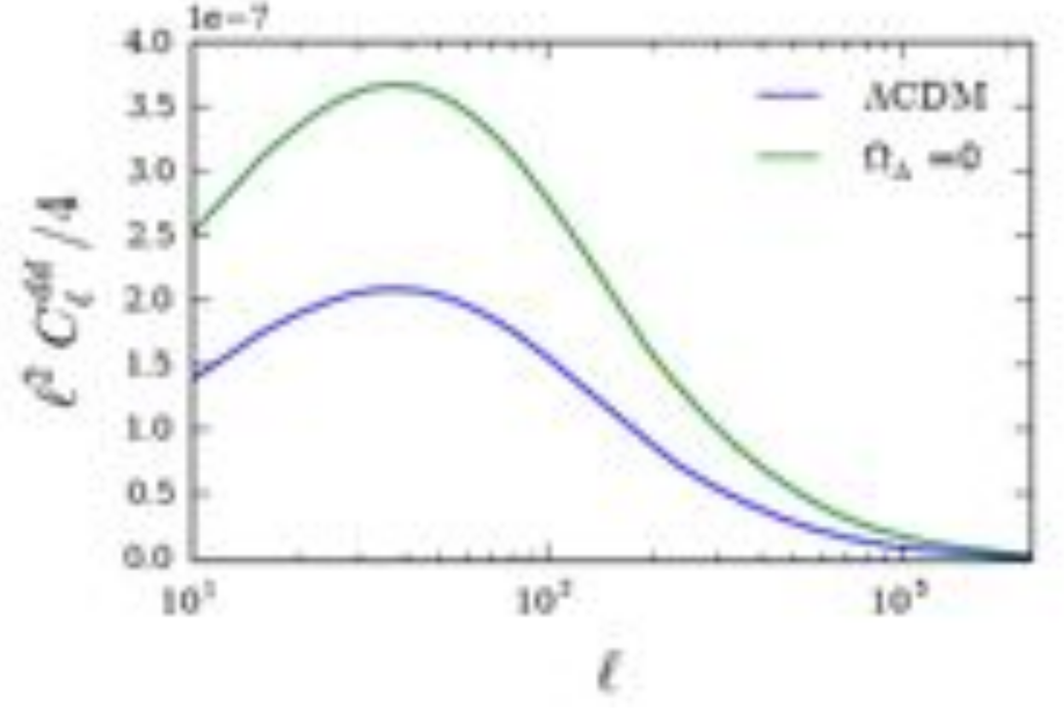


Das et al. 2010

Can lensing break the CMB degeneracy?

Measurement of the deflection field is a line of sight integral over matter fluctuations and the geometry of the universe:

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



Other late time cosmological parameters will also affect this spectrum

Reconstructing lensing from CMB maps

- Can estimate lensing deflection because it breaks Gaussianity
- Deflection spectrum ~ non-Gaussian part of lensed 4-point function

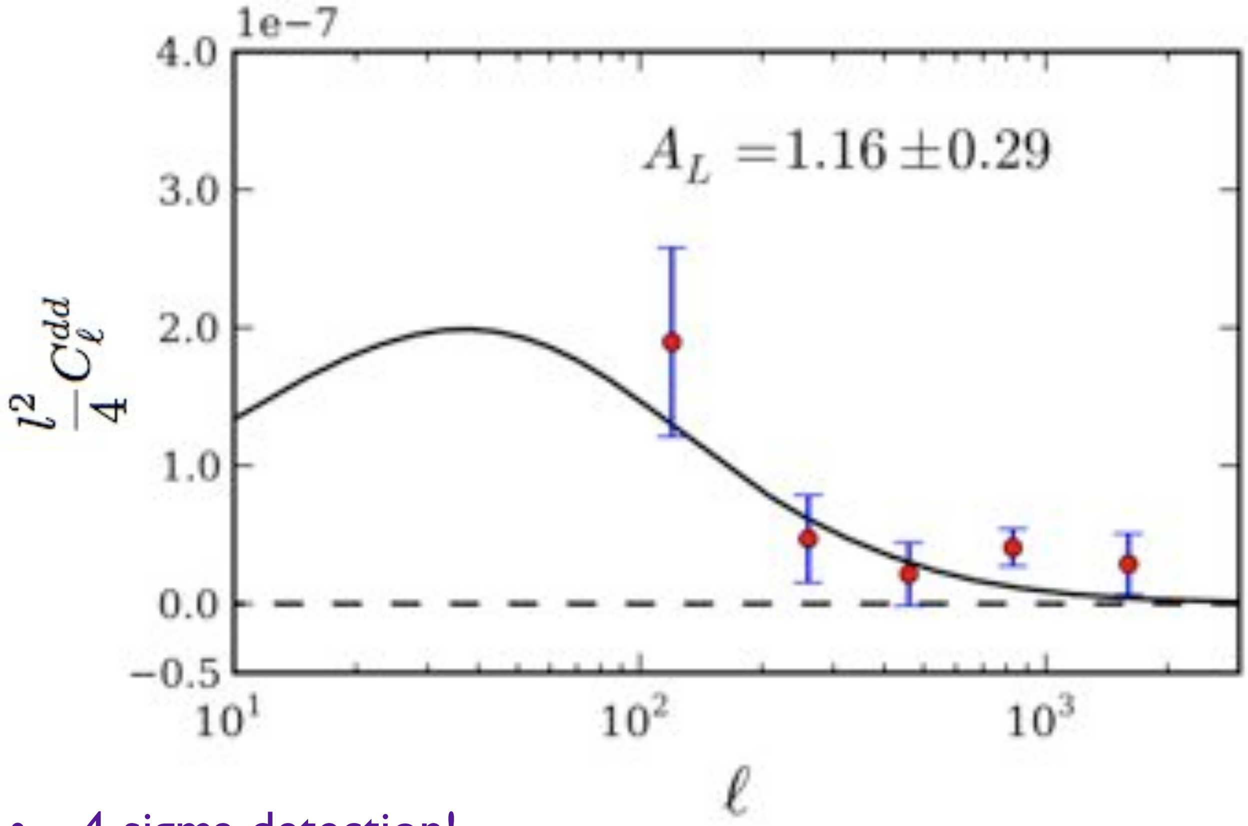
$$
\begin{aligned}
(2\pi)^2\delta(\mathbf{L}-\mathbf{L}')\,\hat{C}_L^{dd} = |N^{\kappa}(\mathbf{L})|^2 \int \frac{d^2\boldsymbol{\ell}}{(2\pi)^2} \int \frac{d^2\boldsymbol{\ell}'}{(2\pi)^2} |g(\boldsymbol{\ell},\mathbf{L})|^2 \\
\times \Big[T^*(\boldsymbol{\ell})\,T^*(\mathbf{L}-\boldsymbol{\ell})\,T(\boldsymbol{\ell}')\,T(\mathbf{L}'-\boldsymbol{\ell}') \\
- \langle T^*(\boldsymbol{\ell})\,T^*(\mathbf{L}-\boldsymbol{\ell})\,T(\boldsymbol{\ell}')\,T(\mathbf{L}'-\boldsymbol{\ell}')\rangle_{\text{Gauss}} \Big] \quad (1)
\end{aligned}
$$

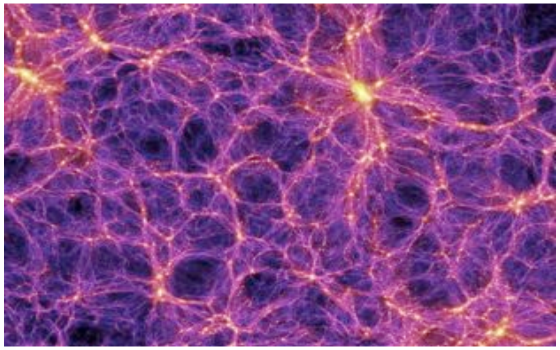
[Hu & Okamoto (2002), Kesden, Cooray, Kamionkowski (2003)]

•Must subtract off Gaussian part (= unconnected part)

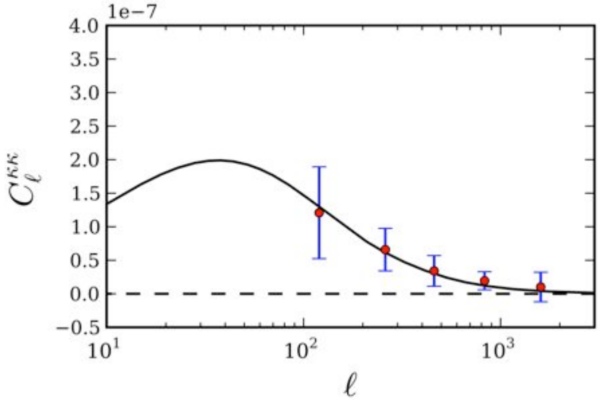
•Direct from data, obtain a ~Gaussian field with the same power spectrum from the observed one by randomizing phases of all the Fourier modes.

ACT detection of the lensing power spectrum



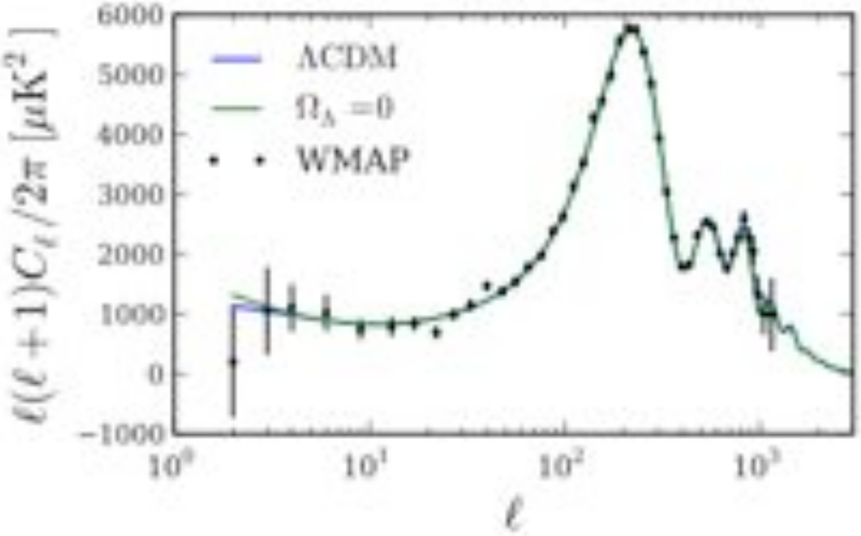


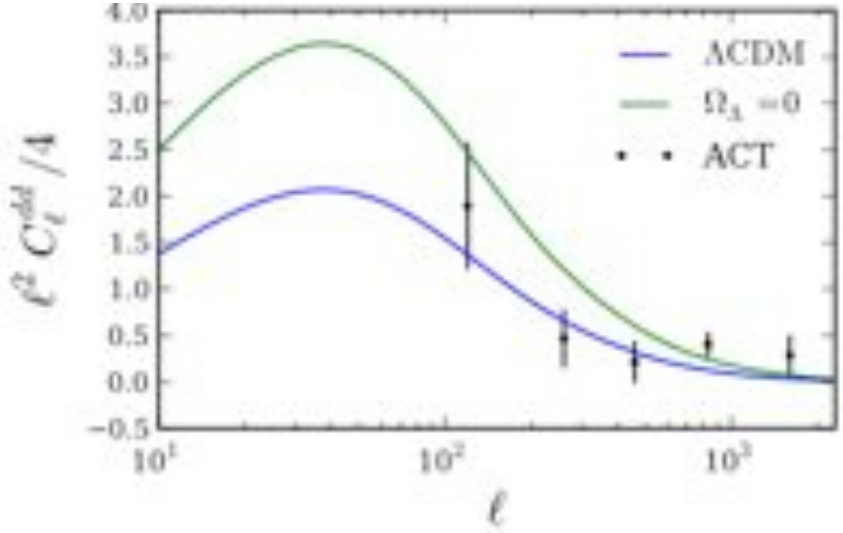
- 4-sigma detection!
- Constrains amplitude of matter fluctuations at z~0.5-3 to 12%.
- Direct gravitational probe of dark matter to z~1100



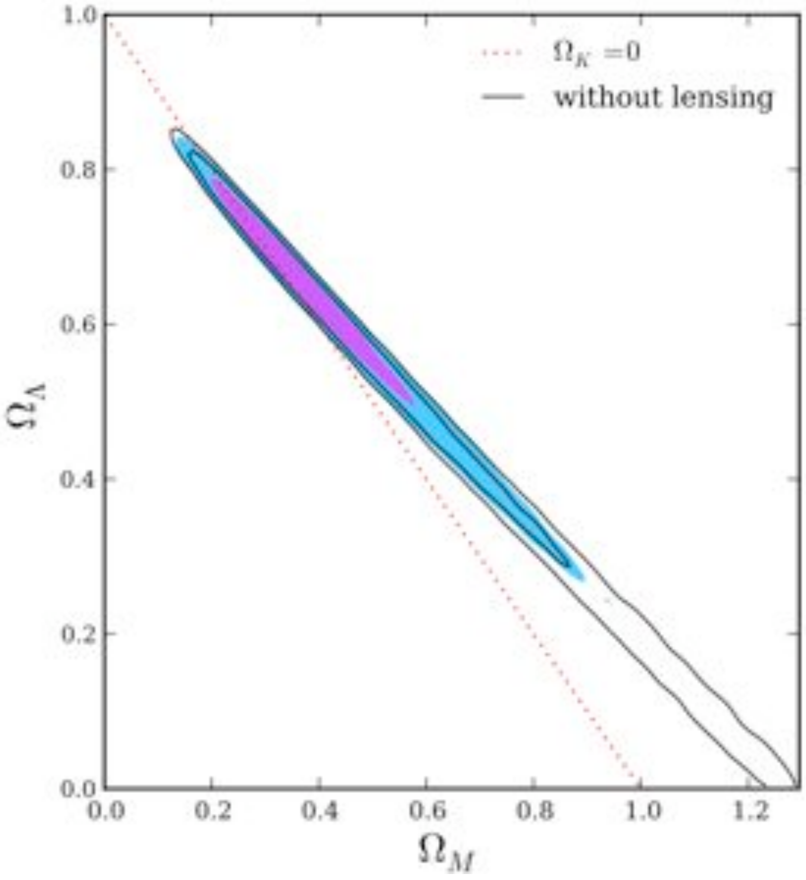
(Das, Sherwin et al. 2011)

CMB-only evidence for Λ!



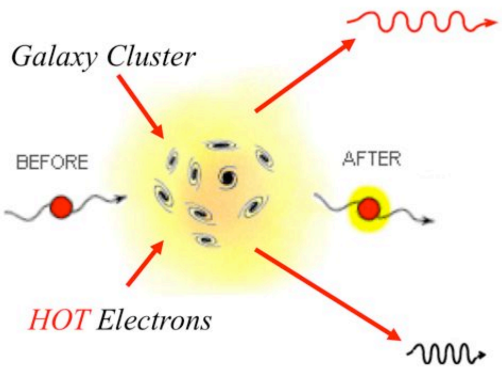


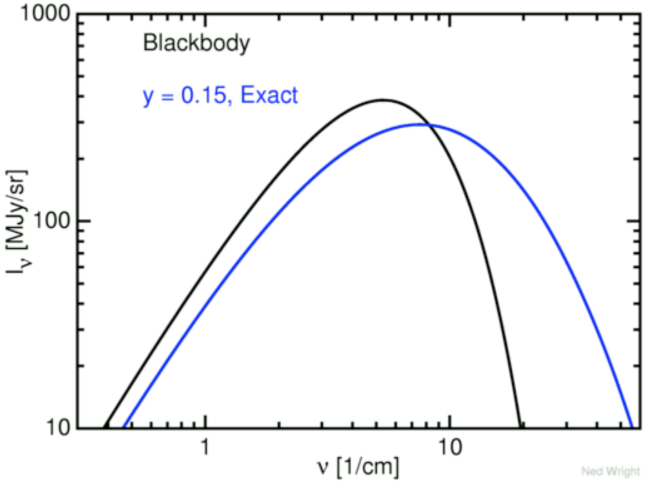
(Sherwin, Dunkley, Das 2011)



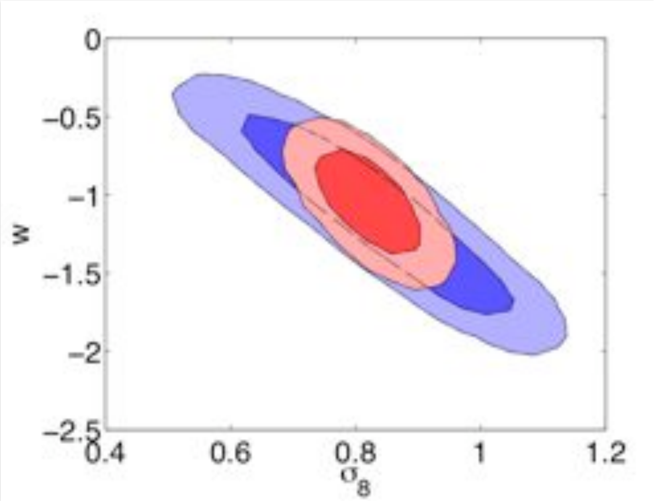
LCDM model favored at **3.2 sigma** over best model with no Λ

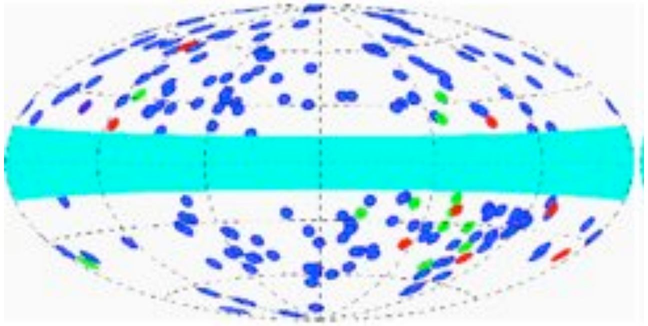
Sunyaev-Zel'dovich effect





- N(mass,z) is sensitive to dark energy and structure growth
- Big difficulty is getting mass from SZ decrement
- Also worry about source contamination

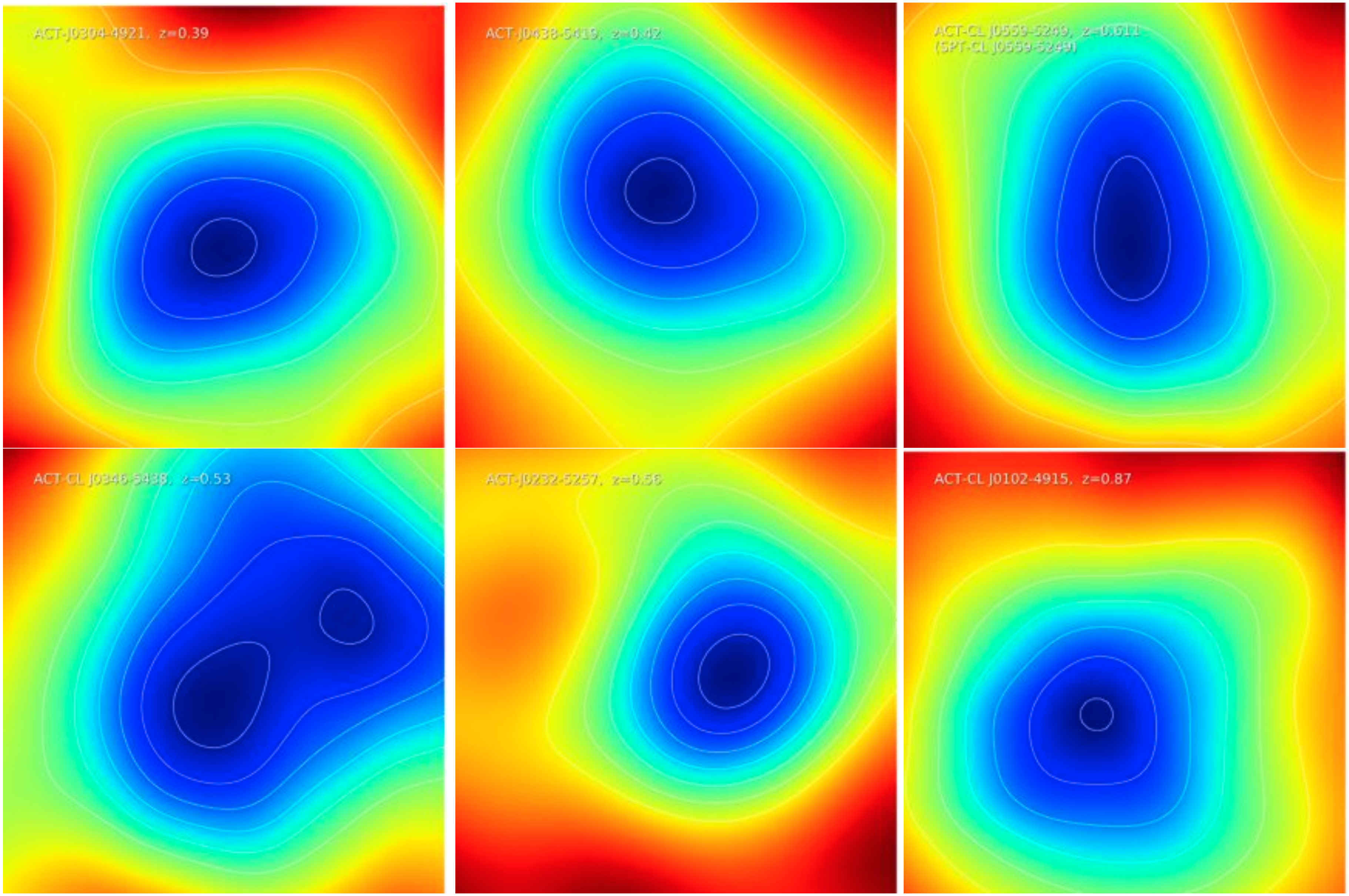




Planck collab 2011

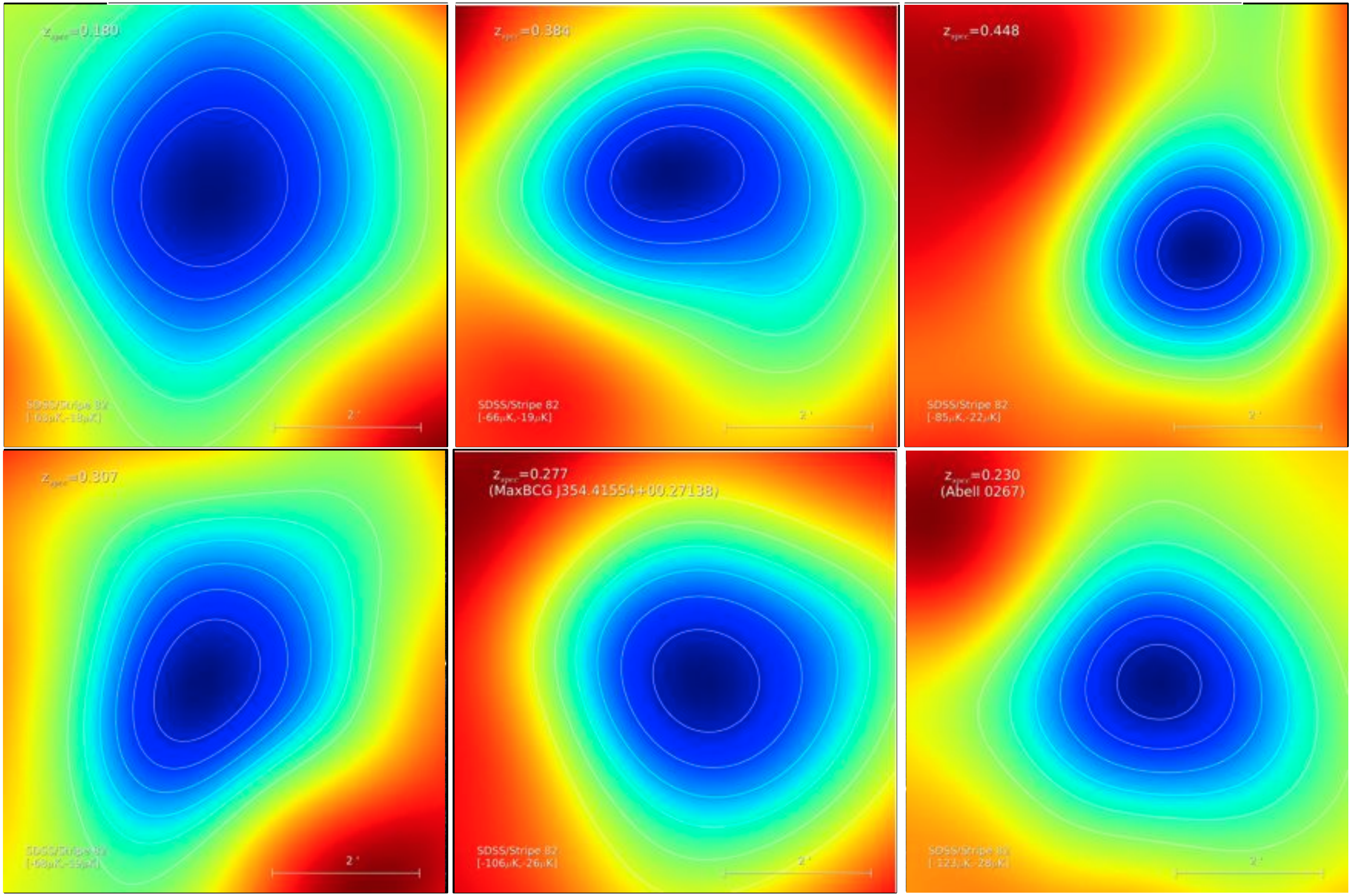
Sehgal et al 2010, assuming SZ-M relation

Some 2008 ACT SZ-discovered Clusters



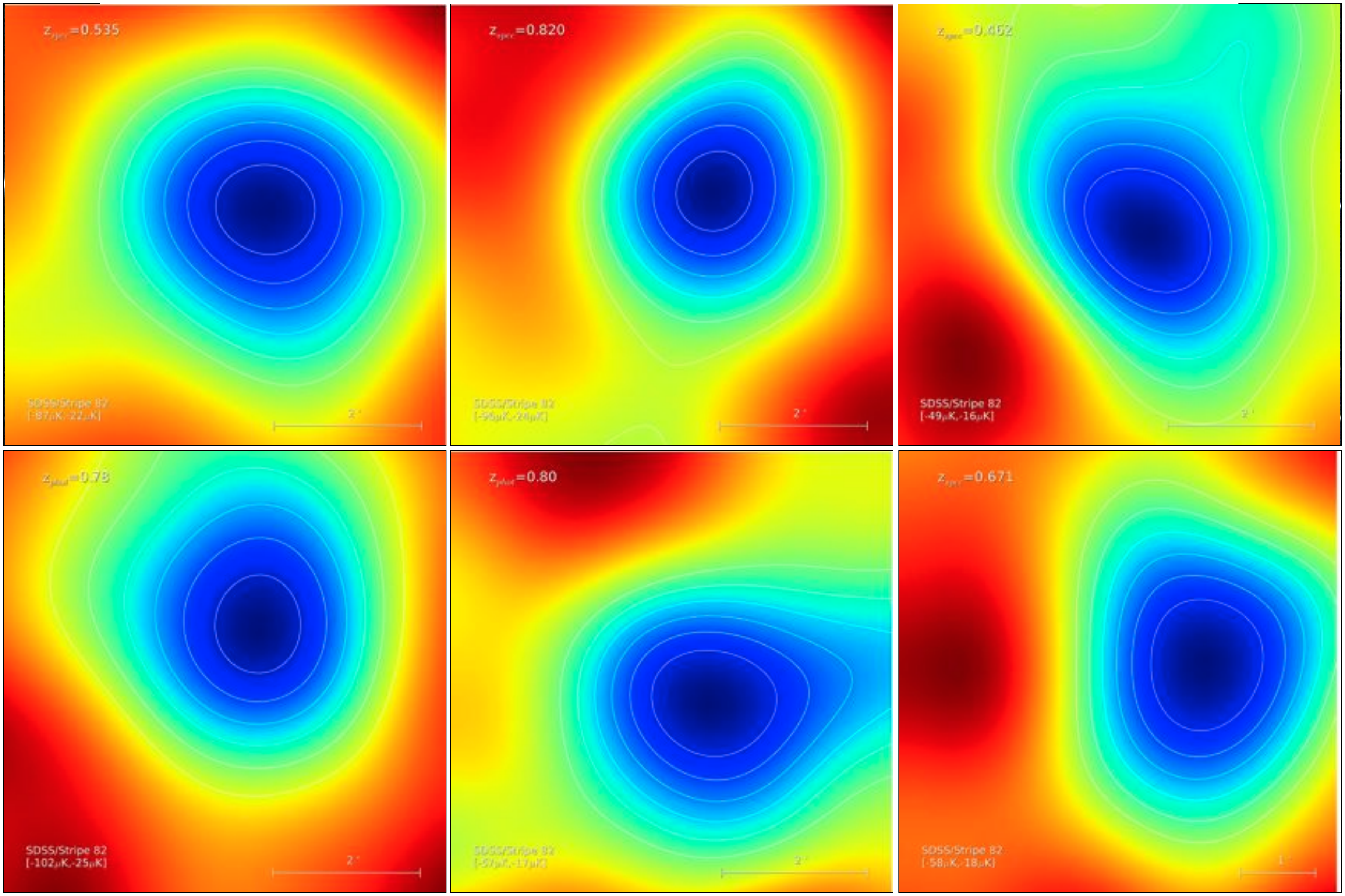
Menanteau et al. (2010), ApJ, 723,1523

Some New Clusters on SDSS/Stripe 82



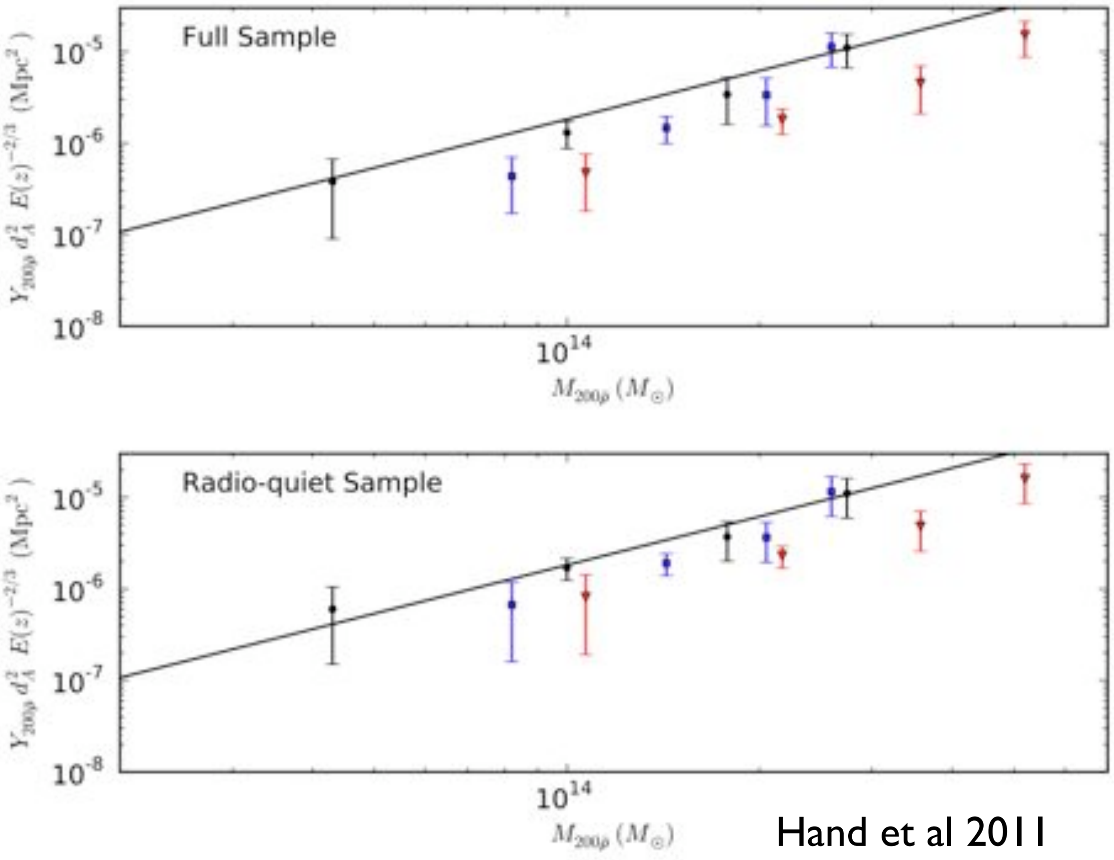
Menanteau et al. (in prep)

New Clusters on SDSS/Stripe 82

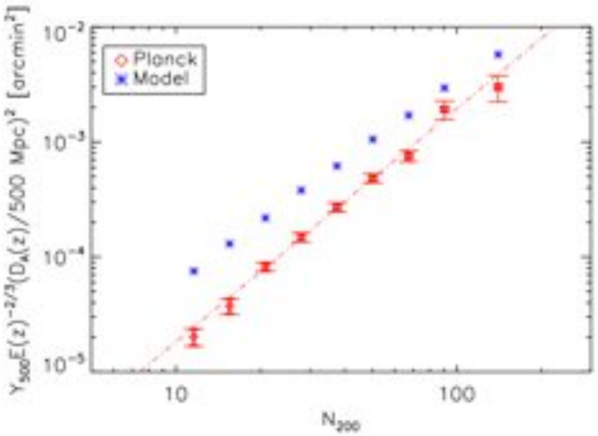


Menanteau et al. (in prep)

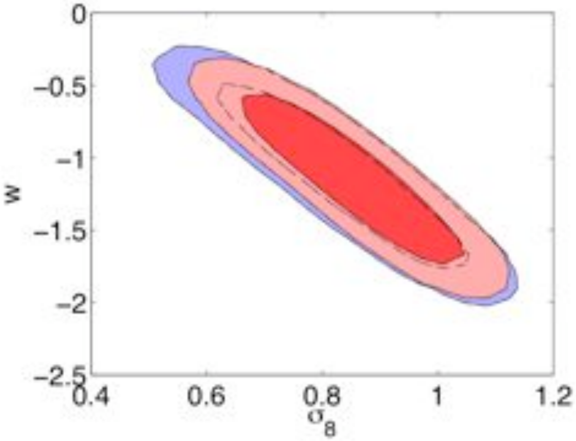
SZ-mass relation



Hand et al 2011

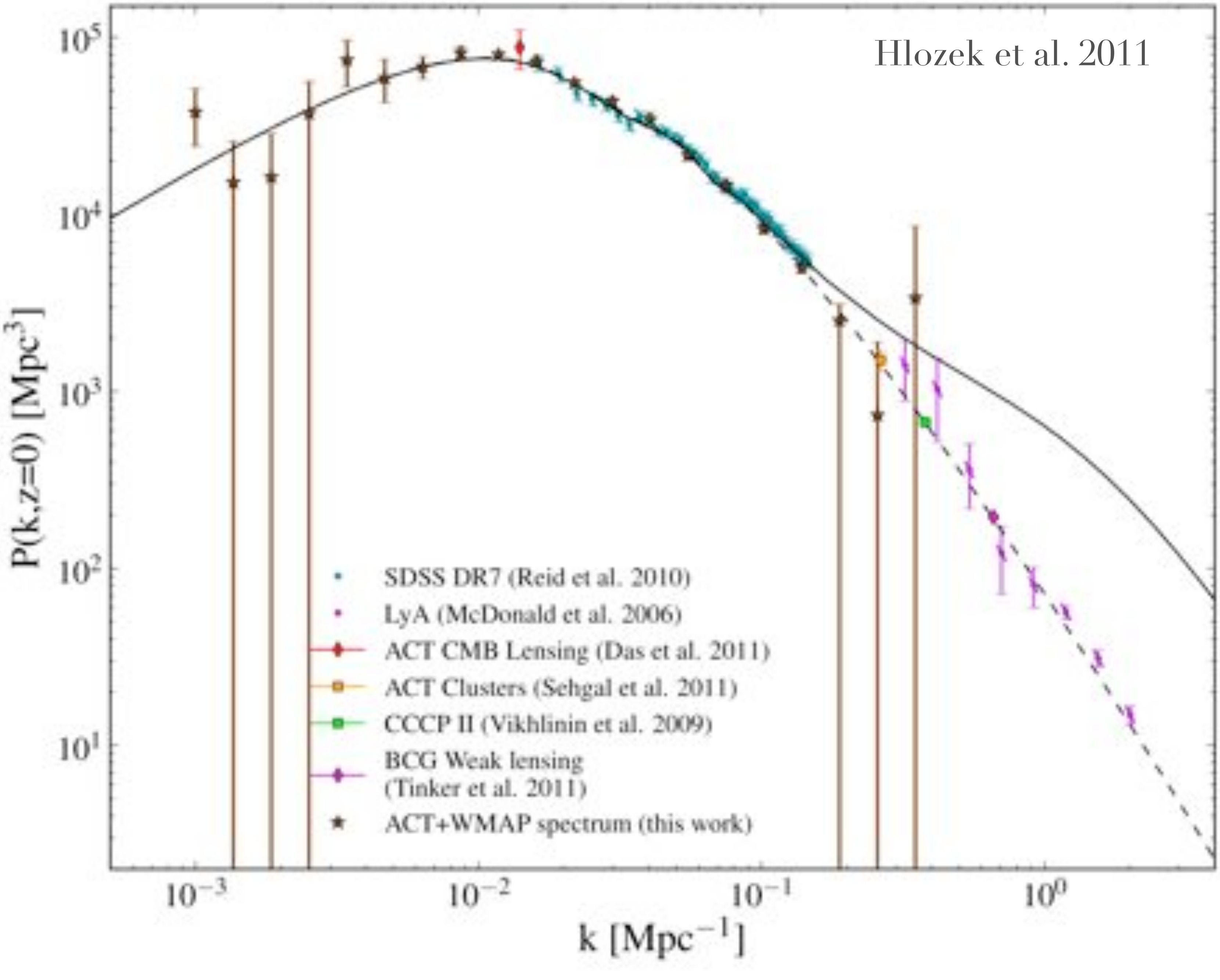


Planck collab 2011



Many 10-100s of clusters measured. Can we do cosmology yet?

Sehgal et al 2010



Hlozek et al. 2011
10^5
10^4
10^3
10^2
10^1
P(k,z=0) [Mpc^3]
10^{-3}
10^{-2}
10^{-1}
10^0
k [Mpc^{-1}]
SDSS DR7 (Reid et al. 2010)
LyA (McDonald et al. 2006)
ACT CMB Lensing (Das et al. 2011)
ACT Clusters (Sehgal et al. 2011)
CCCP II (Vikhlinin et al. 2009)
BCG Weak lensing (Tinker et al. 2011)
ACT+WMAP spectrum (this work)

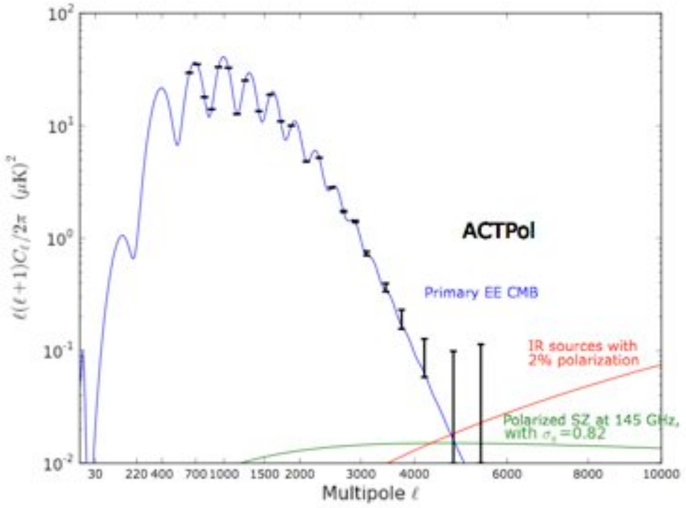
ACTPol: polarization

2012-2015 – measure temperature and polarization of CMB to arcminute scales over ~4000 deg^2, plus deep regions over ~300 deg^2.

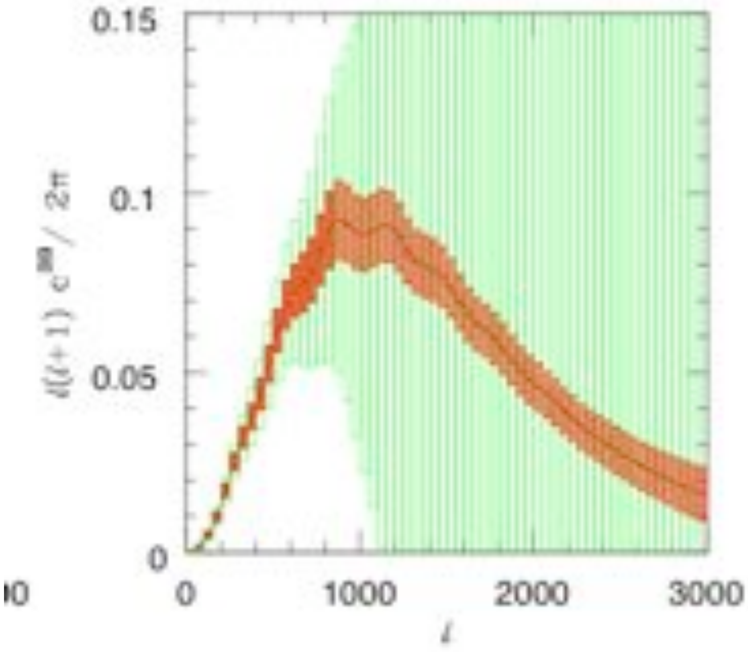
Measure primordial polarized spectrum (~15% pol) to l=3500. Low foreground contamination.

Measure lensing deflection field: distortion of CMB by large-scale structure.

Measure neutrino mass (to 0.07eV), unique probe of early dark energy and GR.



ACTPol, Niemack et al 2010



Summary

- There are multiple physical components in small-scale microwave sky. A simple model fits the ACT 148 and 218 GHz data, and is consistent with observations by SPT.

- The ΛCDM model continues to fit the data. ACT's longer level arm constrains inflationary parameters, and probes non-standard physics (relativistic species, primordial helium, cosmic strings).

- ACT has now detected the lensing deflection power spectrum. It allows us to see evidence for Dark Energy from the CMB alone.

- ACT cluster counts are also starting to show us the late-time universe.

- ACT has finish taking data, and the full analysis is underway. ACTPol due online next year!