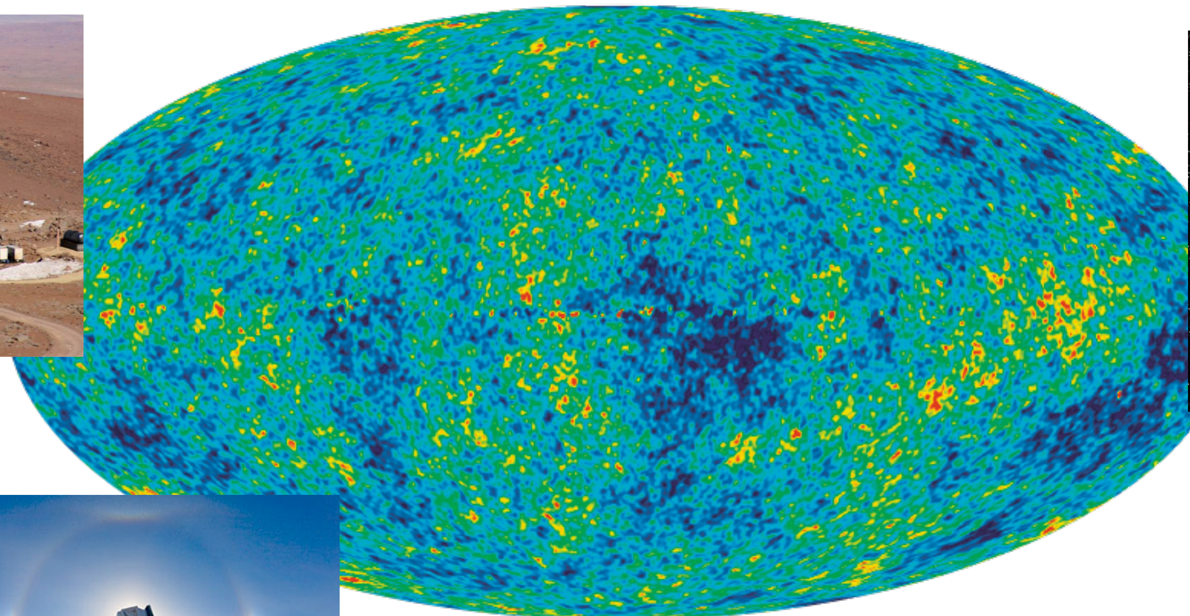
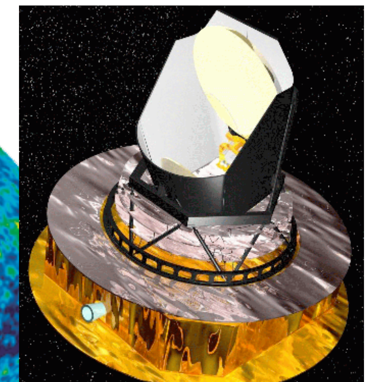
Dark Energy from the Cosmic Microwave Background



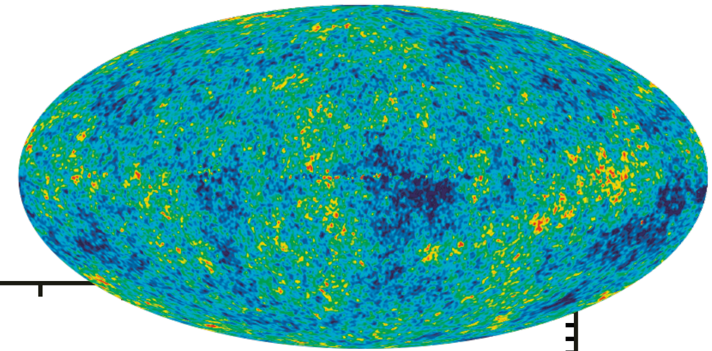


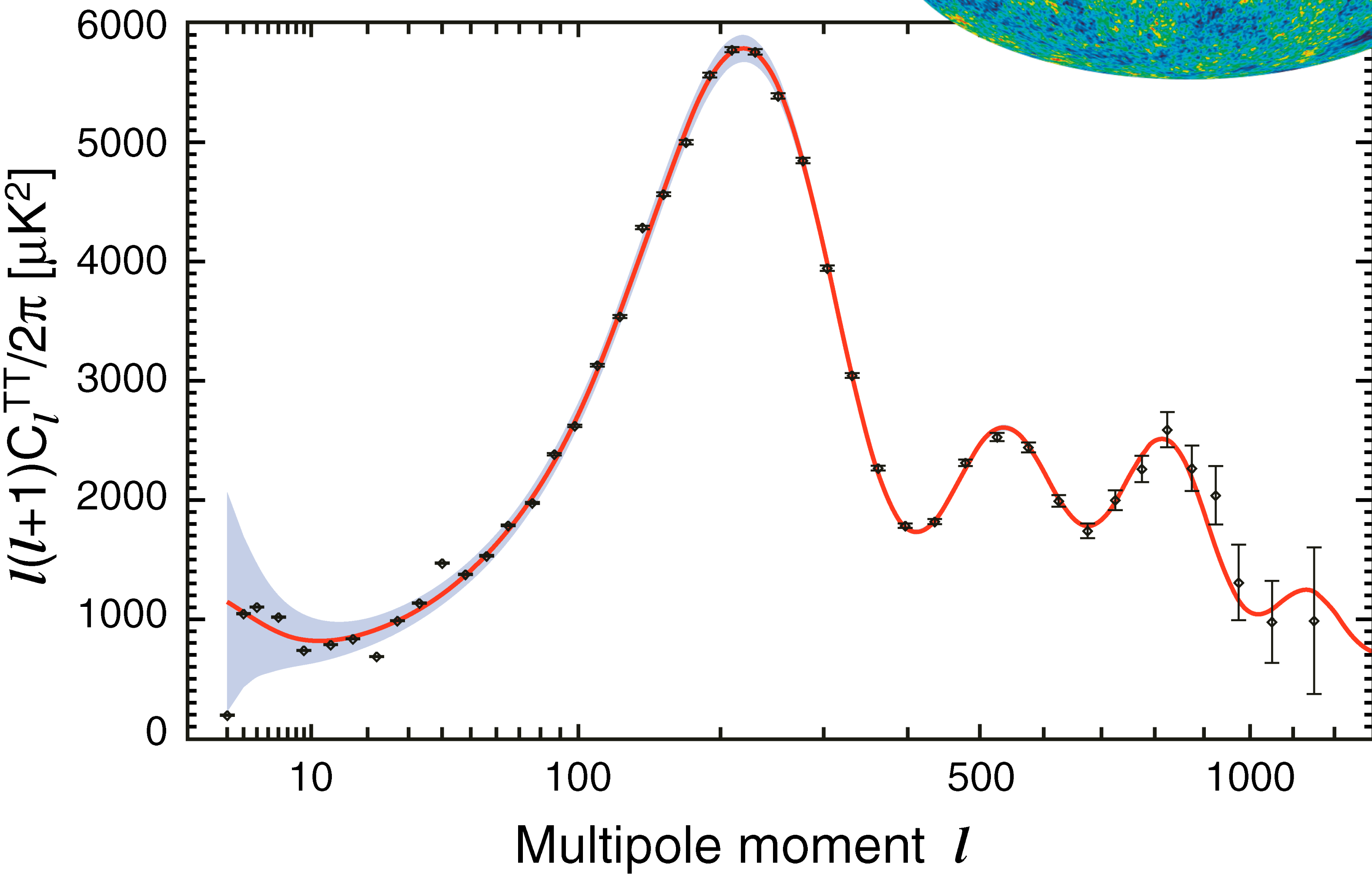
Jo Dunkley

Oxford Astrophysics

Trieste, Nov 10 2011

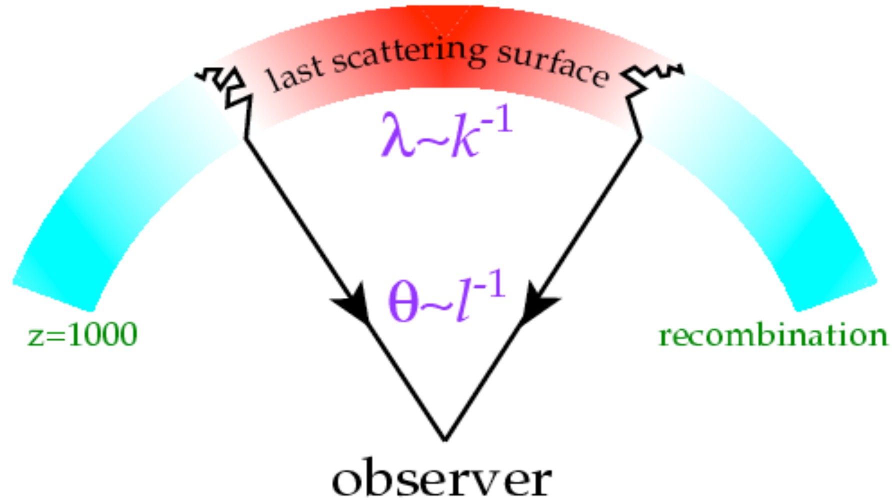
WMAP view of sky

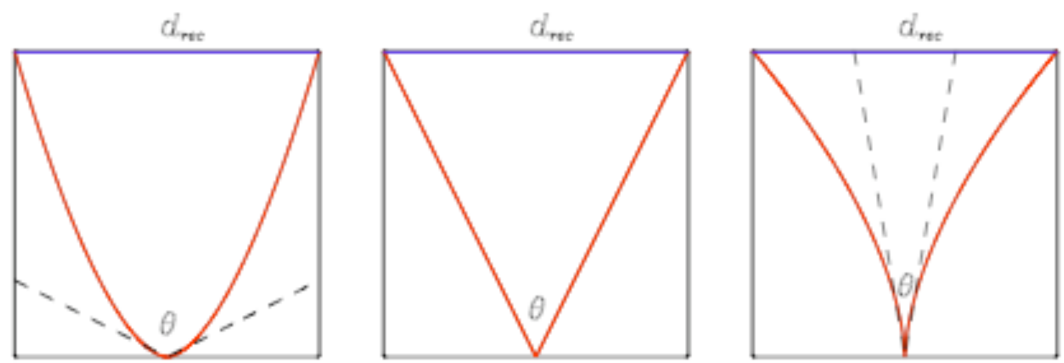




The CMB first peak, and ΛCDM

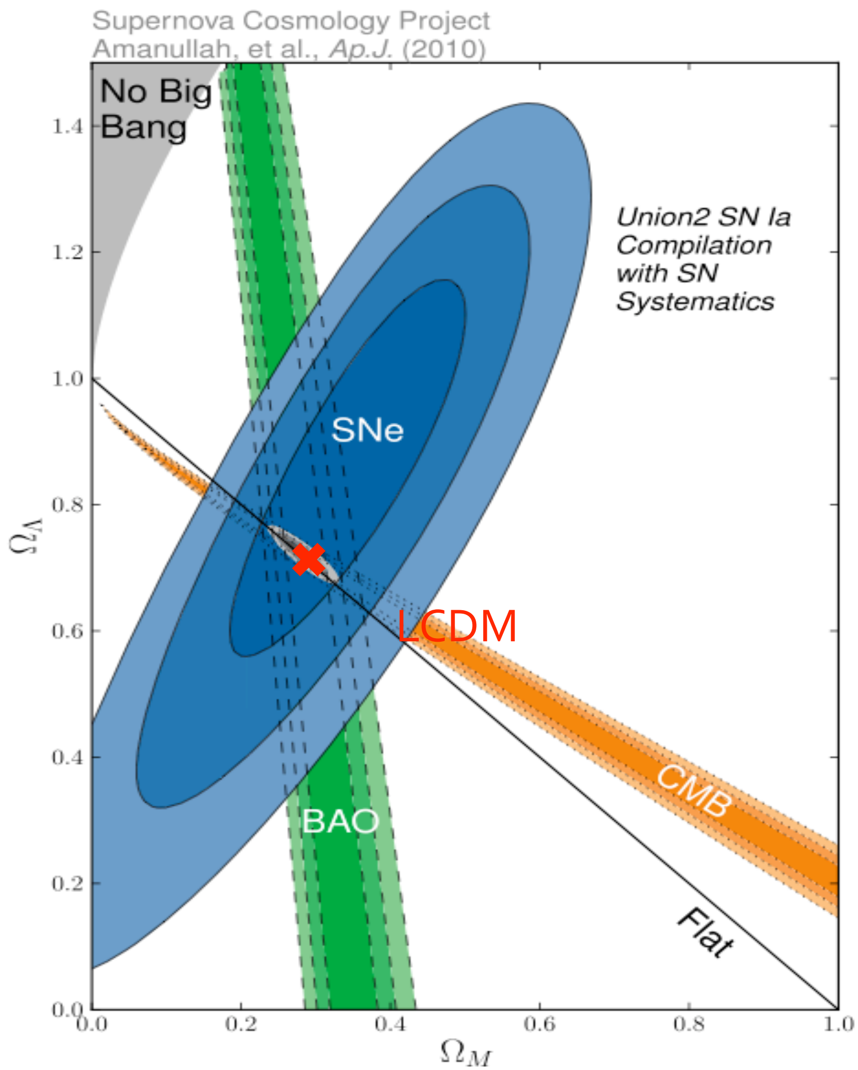
- Measure angular size of sound horizon, to work out geometry and contents.
- Peak is measured at l=220, by WMAP and before by Boomerang, Maxima, DASI.
- Assuming a distance to last-scattering, this tells us the universe is flat.
- Or, assuming flatness we measure Ω_Λ, helped by 3rd peak



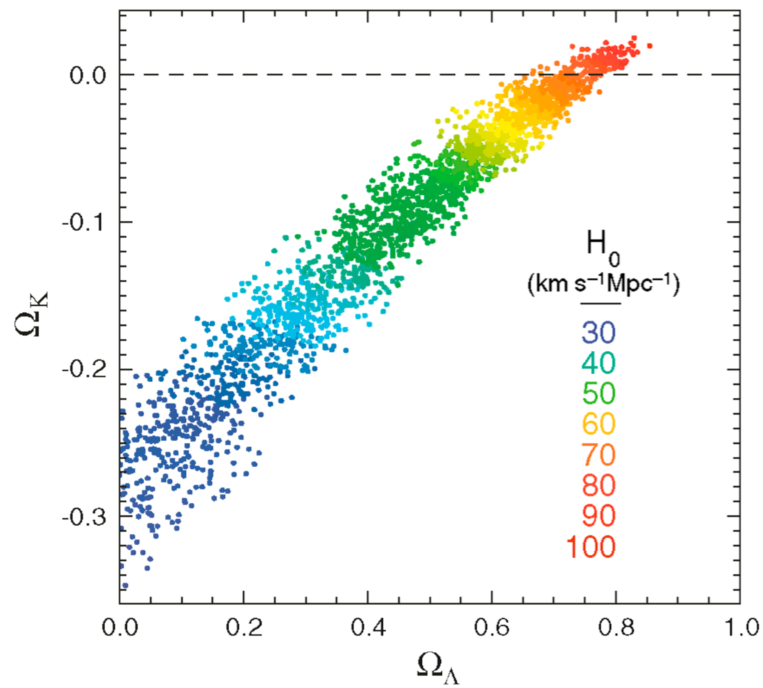


Closed $\Omega_k < 0$ flat $\Omega_k = 0$ open $\Omega_k > 0$

What do we really measure from the CMB?

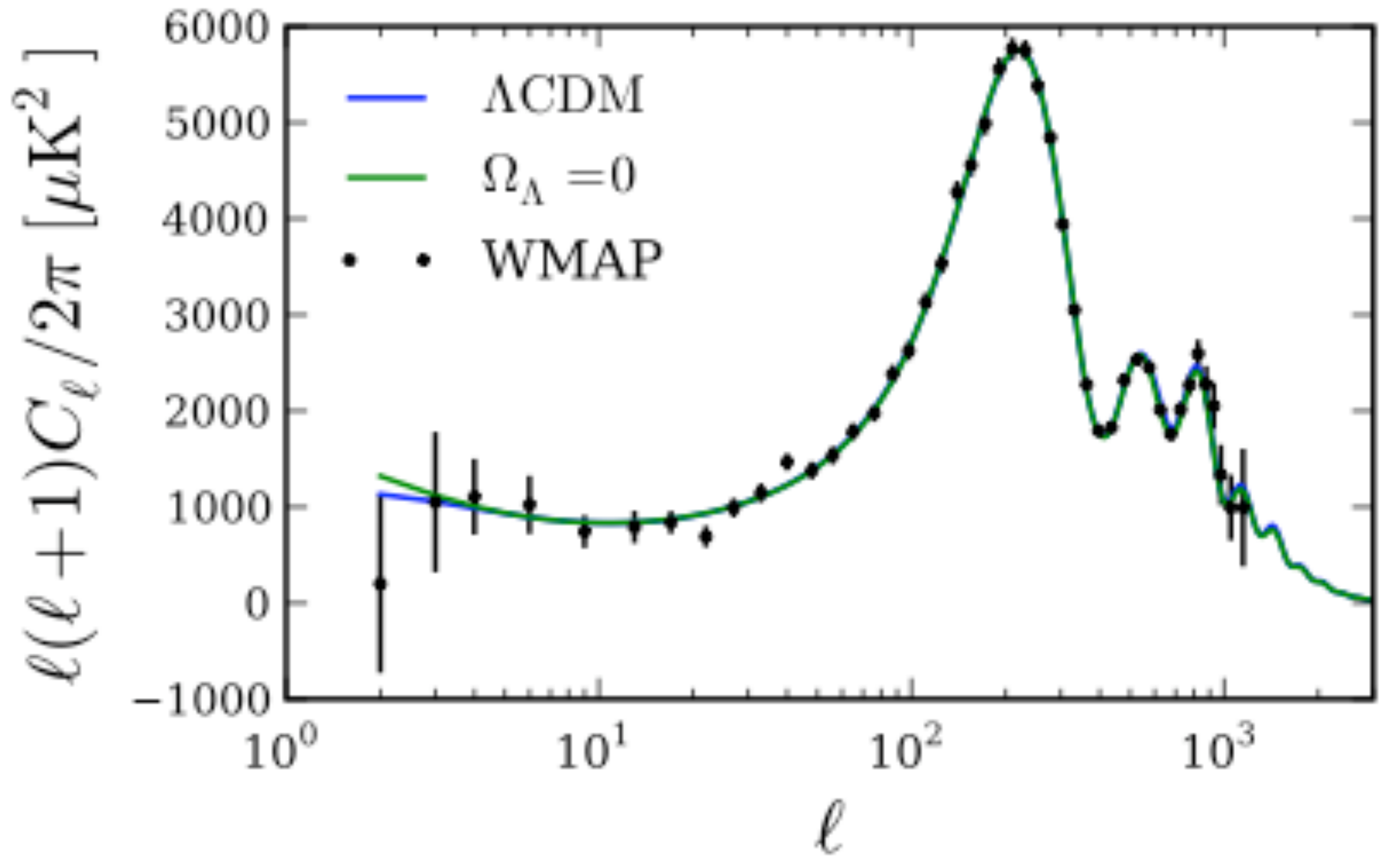


Geometric degeneracy: balance distance with geometry to keep first peak in same place



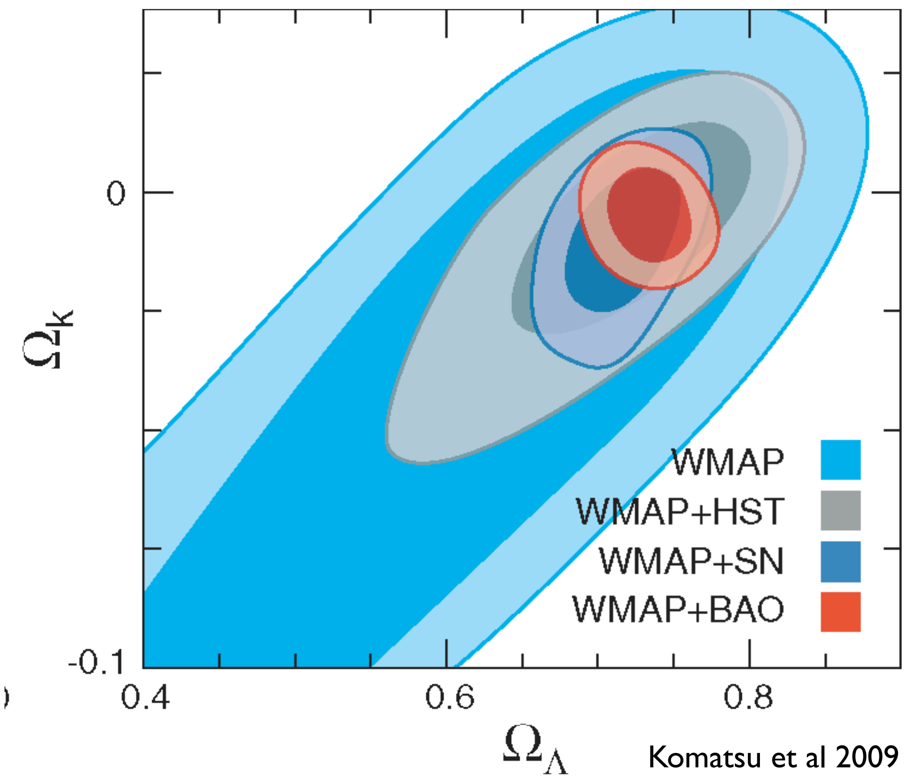
Dunkley et al 2009

A universe with no Λ looks like ΛCDM

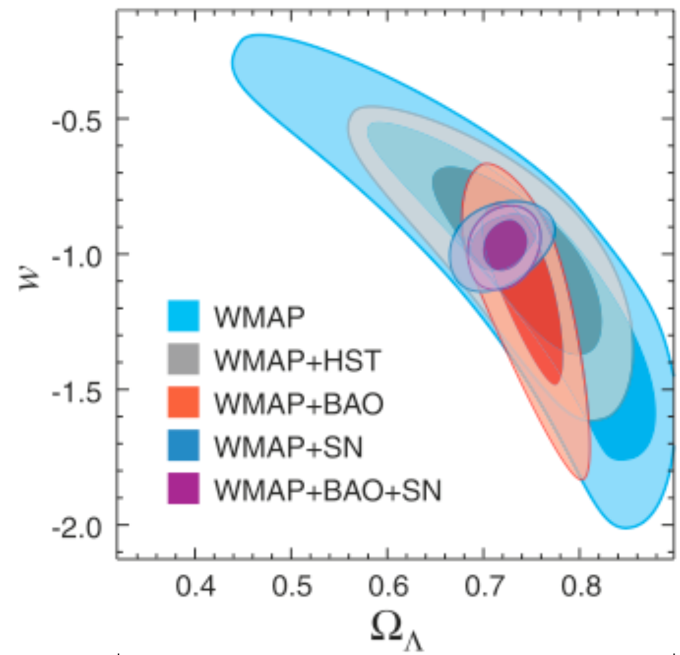


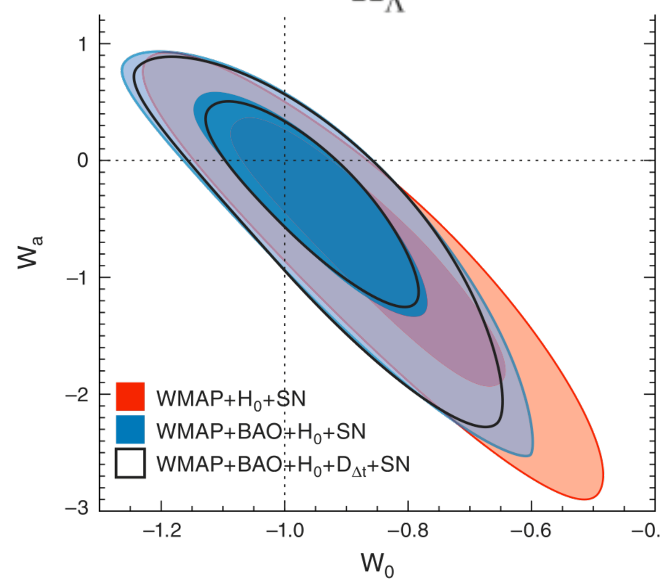
Sherwin, JD, Das et al 2011

Dark energy from combined probes



Komatsu et al 2009

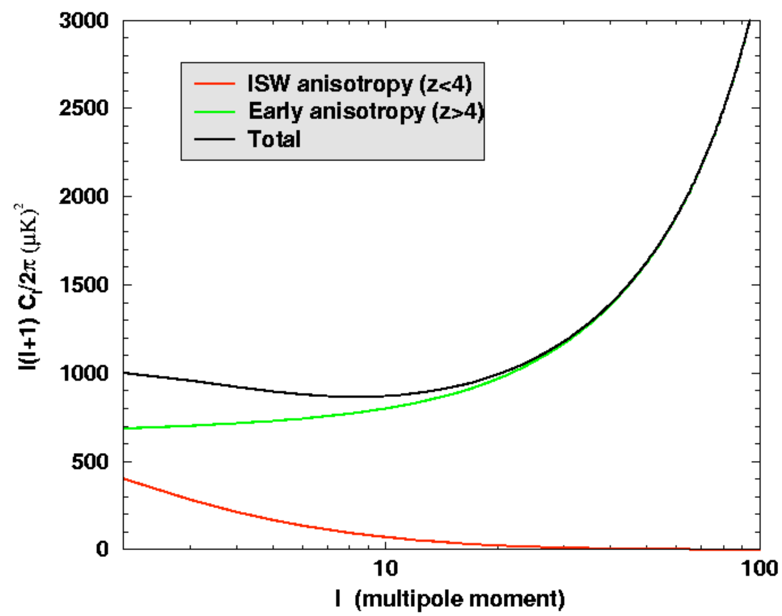




To determine nature of Dark Energy, primary CMB must be combined with other probes to constrain w(z) and test GR.

1. Integrated Sachs-Wolfe effect

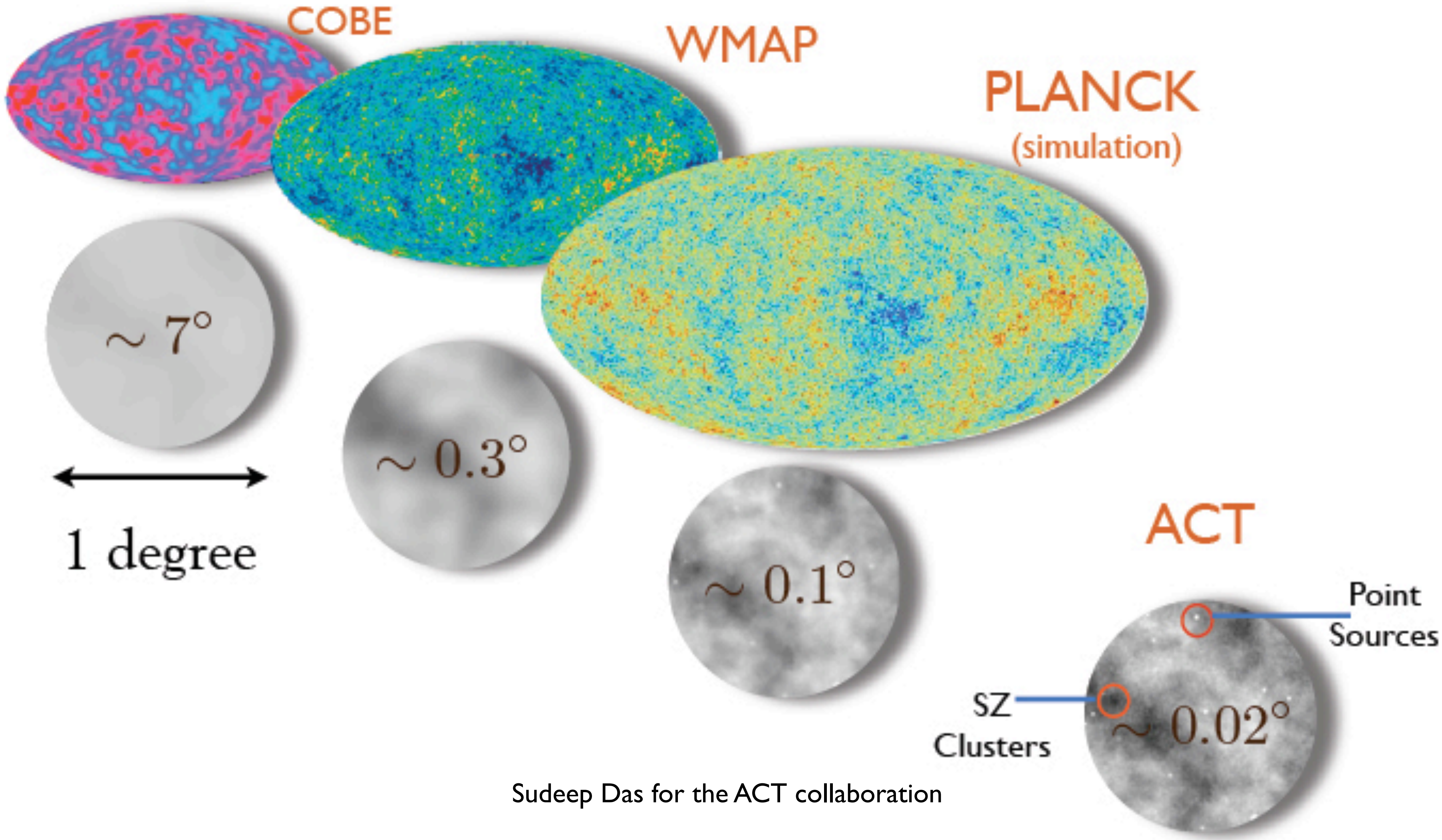
$$\frac{\delta T}{T} = -2\int \dot{\Phi}(\tau)d\tau$$



(From R Crittenden)

- CMB fluctuations are sum of two parts, one induced at low redshifts when DE or curvature contribute significantly.
- But, it is a large-scale effect, where cosmic variance dominates.
- Detected at ~4-sigma in cross-correlations with SDSS, NVSS, 2MASS *(including Ho et al 2008, Giannantonio et al 2008)*

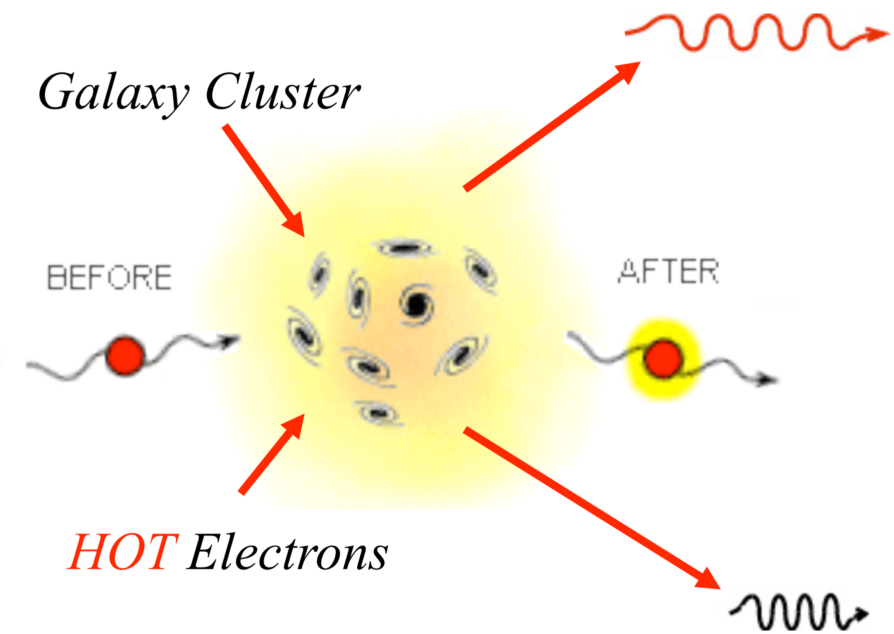
The CMB at smaller scales

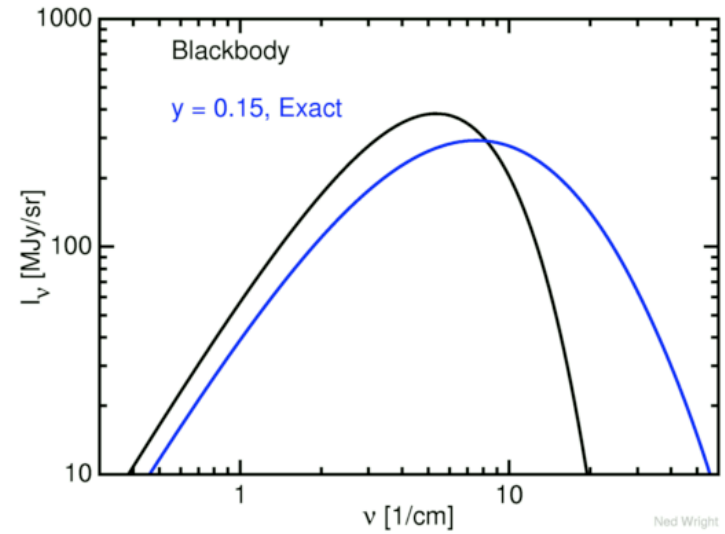


Sudeep Das for the ACT collaboration

Two arcminute expts: Atacama Cosmology Telescope, and South Pole Telescope

2. Sunyaev-Zel'dovich from clusters

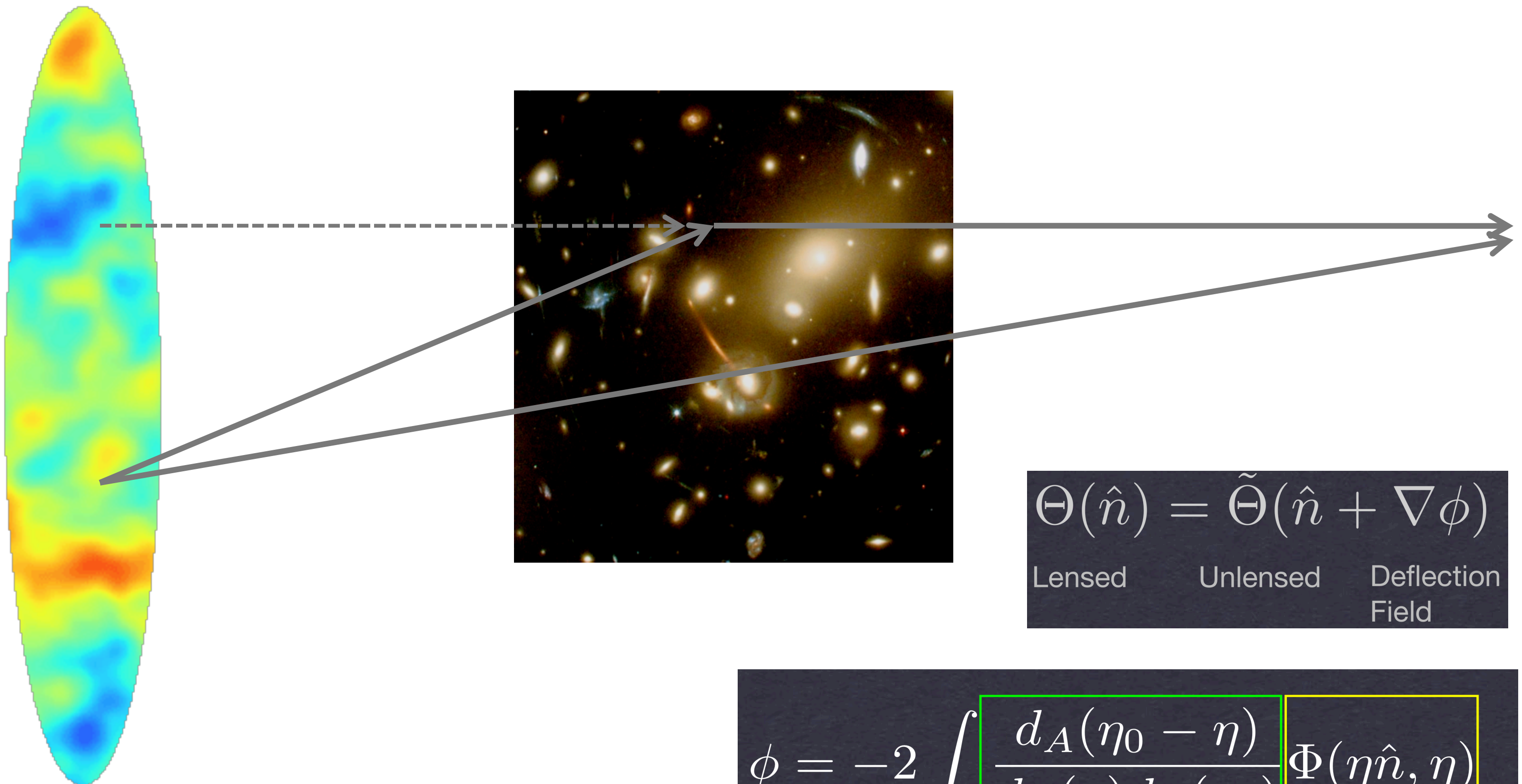




- Thermal SZ: inverse compton scattering from hot electrons
- See clusters with multi-wavelength observations
- N(mass,z) depends on cosmology

$$\frac{\Delta T}{T_{\rm CMB}} = f(x)\frac{k_B\sigma_T}{m_e c^2}\int n_e T_e {\rm d}l \equiv f(x)y,$$

3. Lensing of the CMB

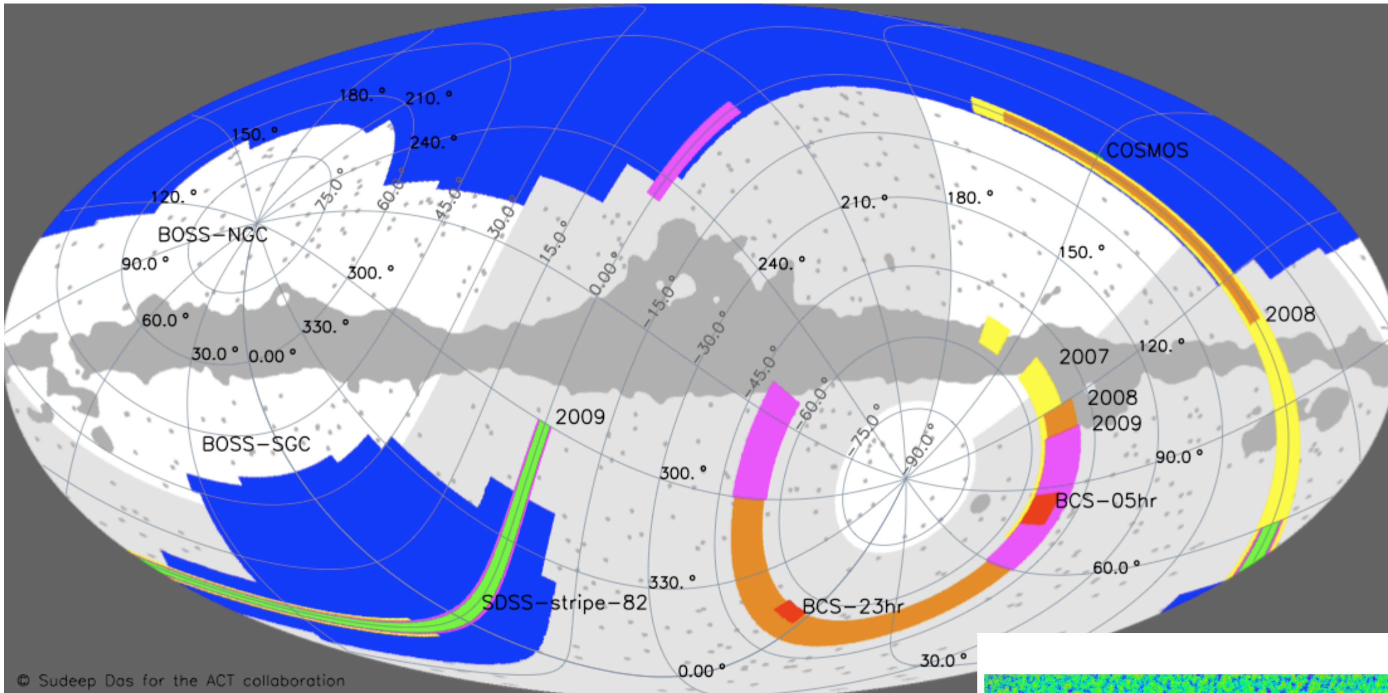


$$\underbrace{\Theta(\hat{n})}_{\text{Lensed}} = \underbrace{\tilde{\Theta}}_{\text{Unlensed}}(\hat{n} + \underbrace{\nabla\phi}_{\text{Deflection Field}})$$

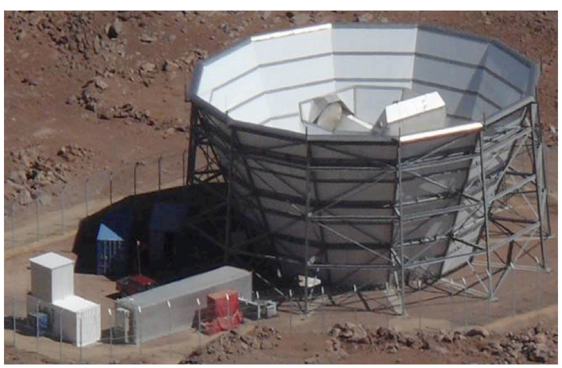
$$\phi = -2 \int \underbrace{\boxed{\frac{d_A(\eta_0 - \eta)}{d_A(\eta) d_A(\eta_0)}}}_{\text{Geometry}} \underbrace{\boxed{\Phi(\eta\hat{n}, \eta)}}_{\text{Matter potential}}$$

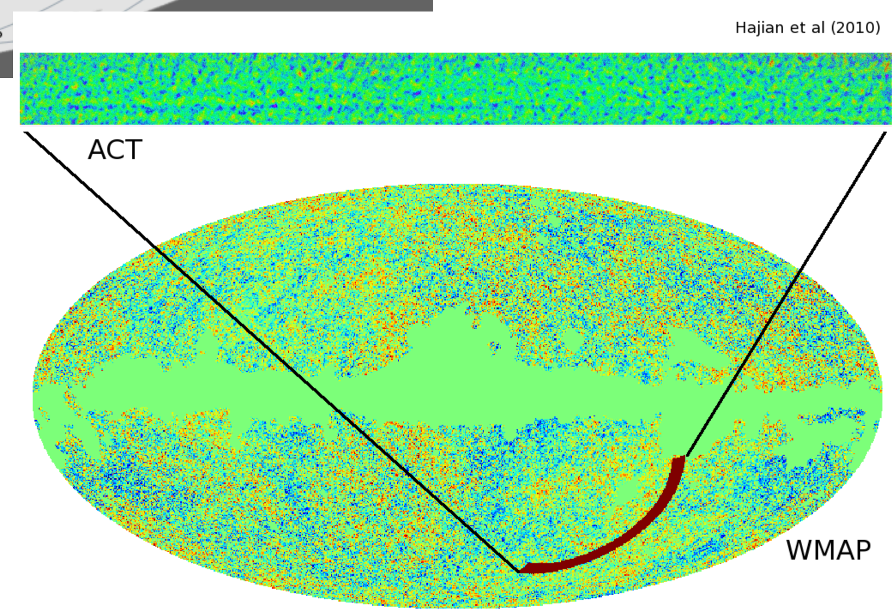
Measures integrated mass fluctuations along the line of sight, from fixed CMB source.

ACT observations (SPT in south)

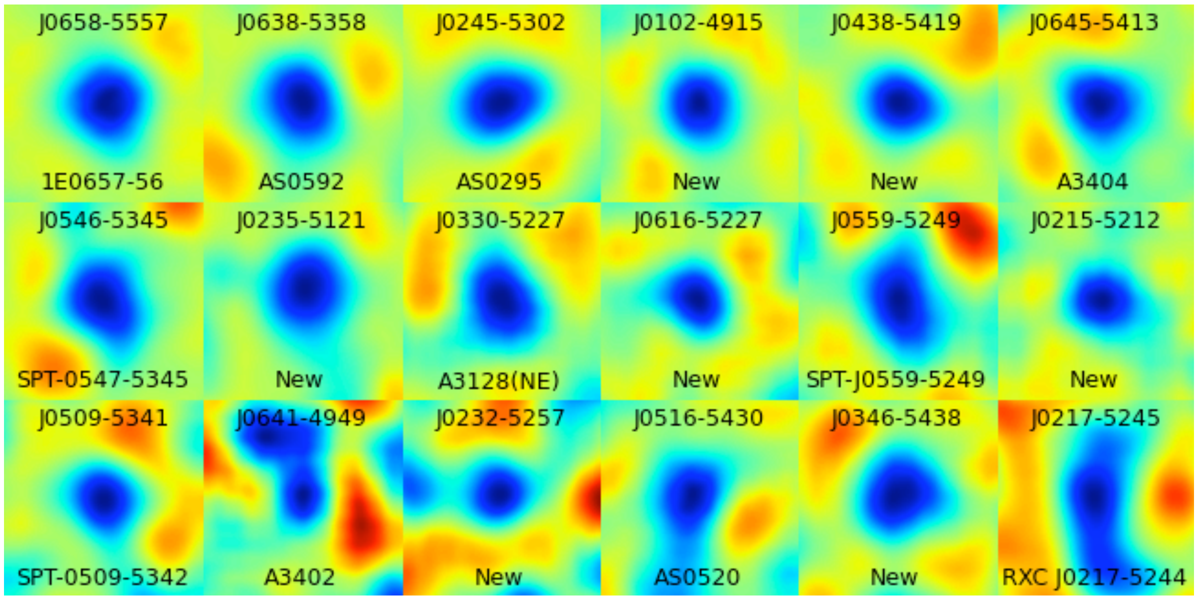


- ACT: led by Page in Princeton
- SPT: led by Carlstrom in Chicago



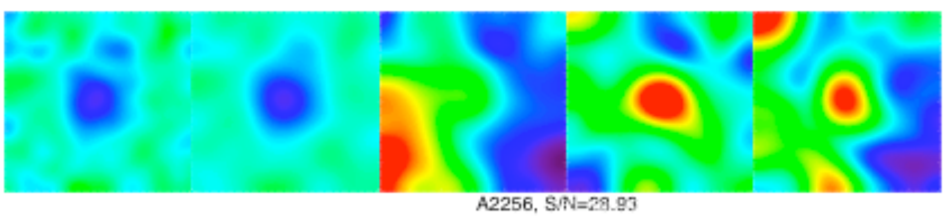


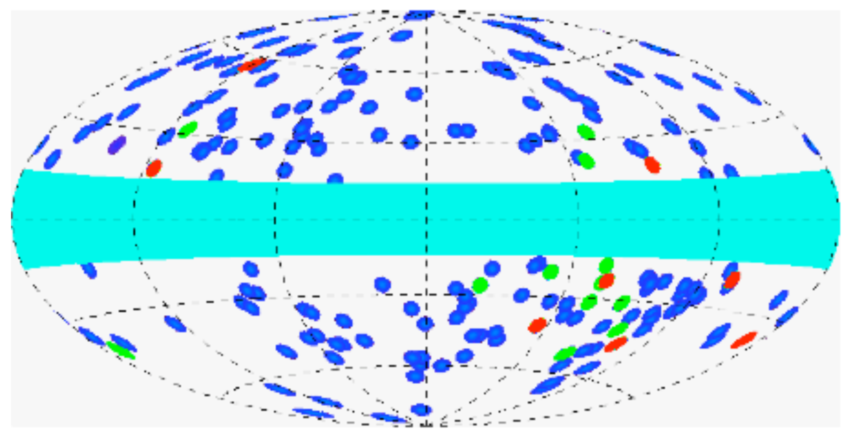
2. Sunyaev Zel'dovich clusters



Marriage et al. 2010, 23 clusters at >6σ

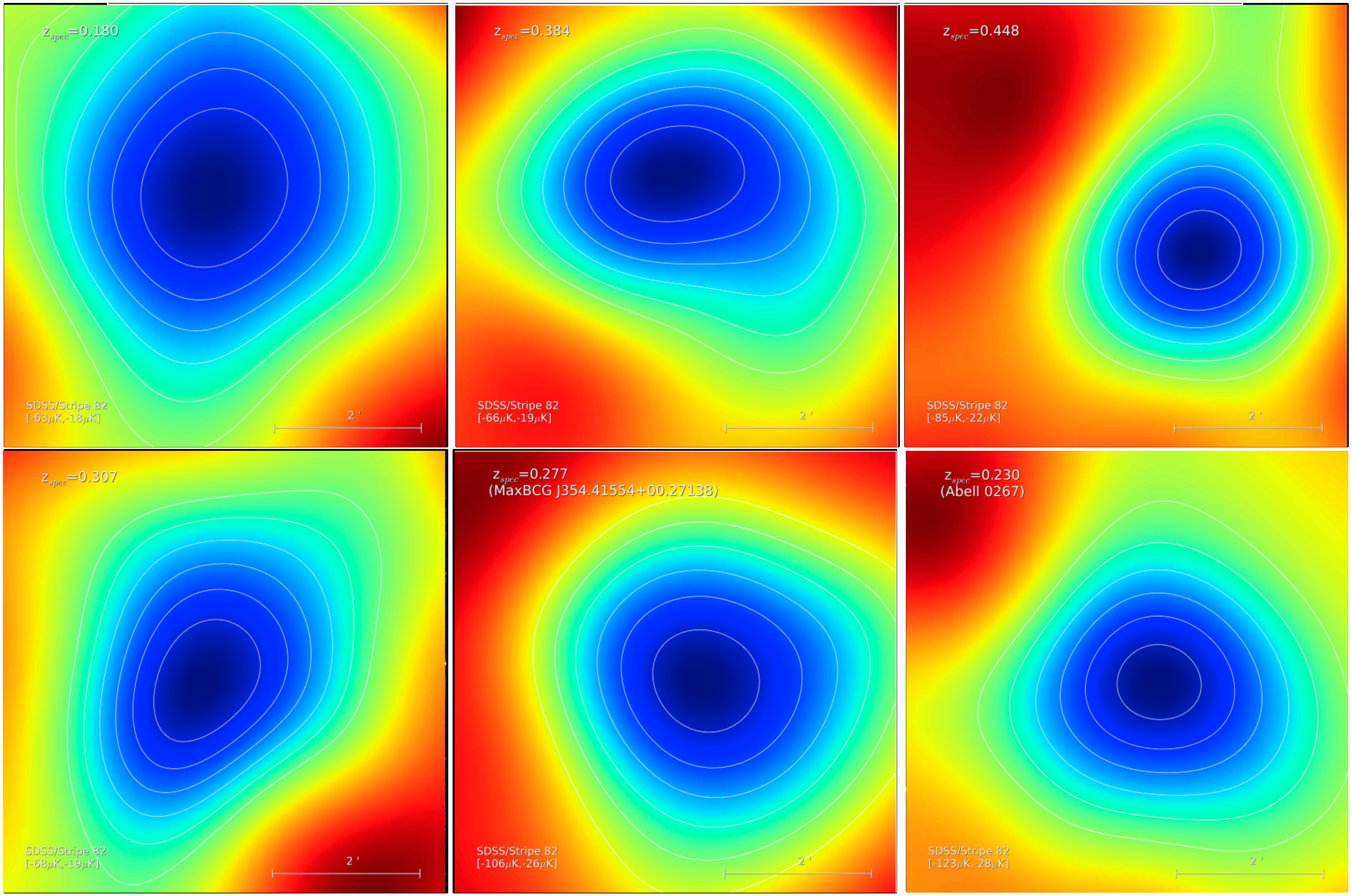
- 100+ clusters in ACT, median z~0.45
- First sample optically followed up (Menanteau et al 2010) and have redshift. to z~1.
- SPT: also 100+ in south





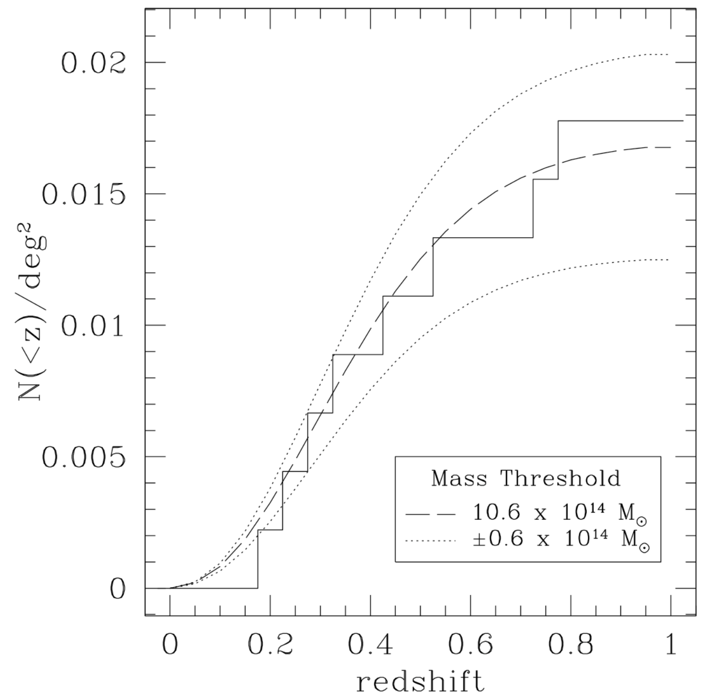
Planck collaboration 2011, 189 clusters, 20 new, 1-15e14 M, z<0.6

Some new clusters on SDSS/Stripe 82



Menanteau et al. (in prep)

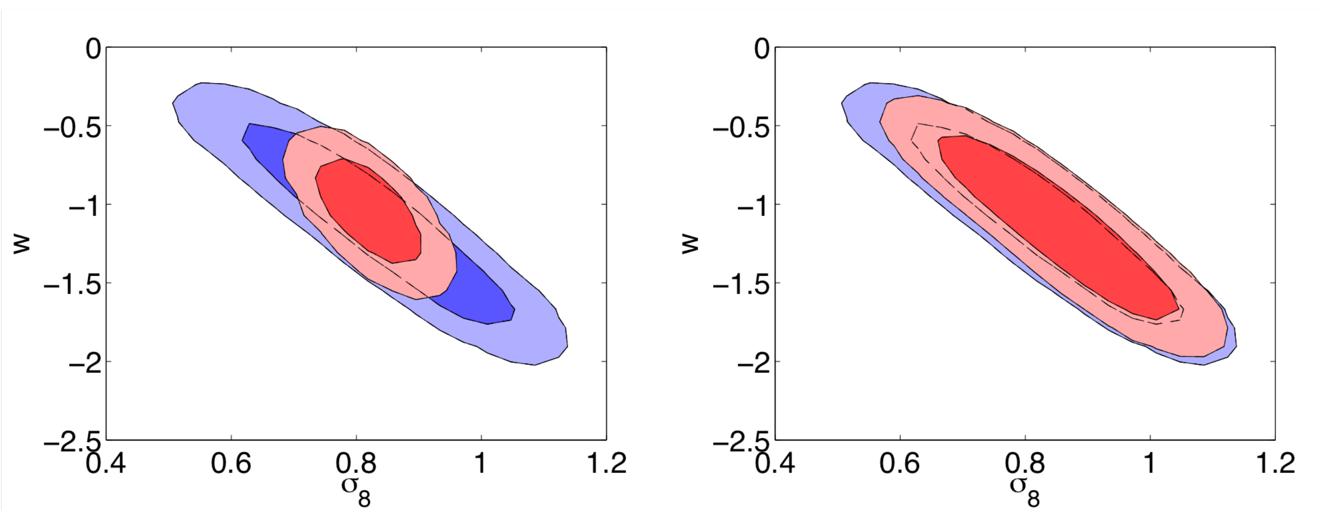
Dark energy from clusters?



Concordance cosmological model fits the N(z) data well.

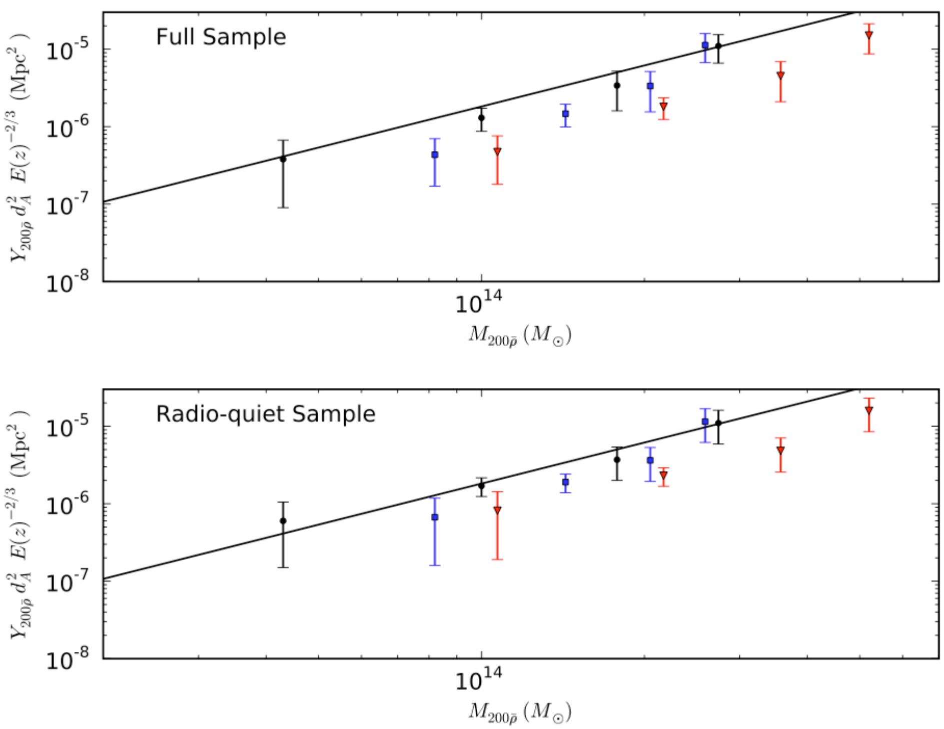
Want to use N(m,z) to test dark energy models. But we have N(Y,z) instead.

$$y^{\rm true} = A\left(\frac{M^{\rm true}}{M_0}\right)^B \left(\frac{1+z}{1+z_0}\right)^C.$$

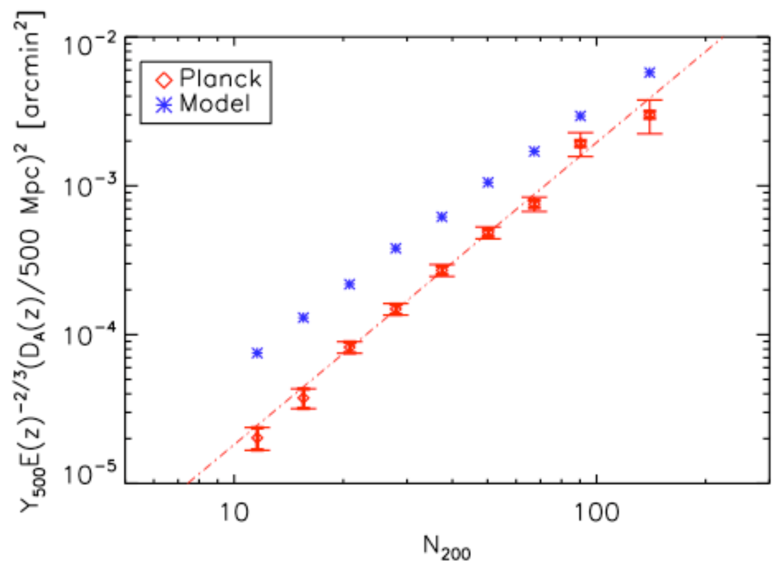


Sehgal et al 2010

What is the SZ-mass relation?



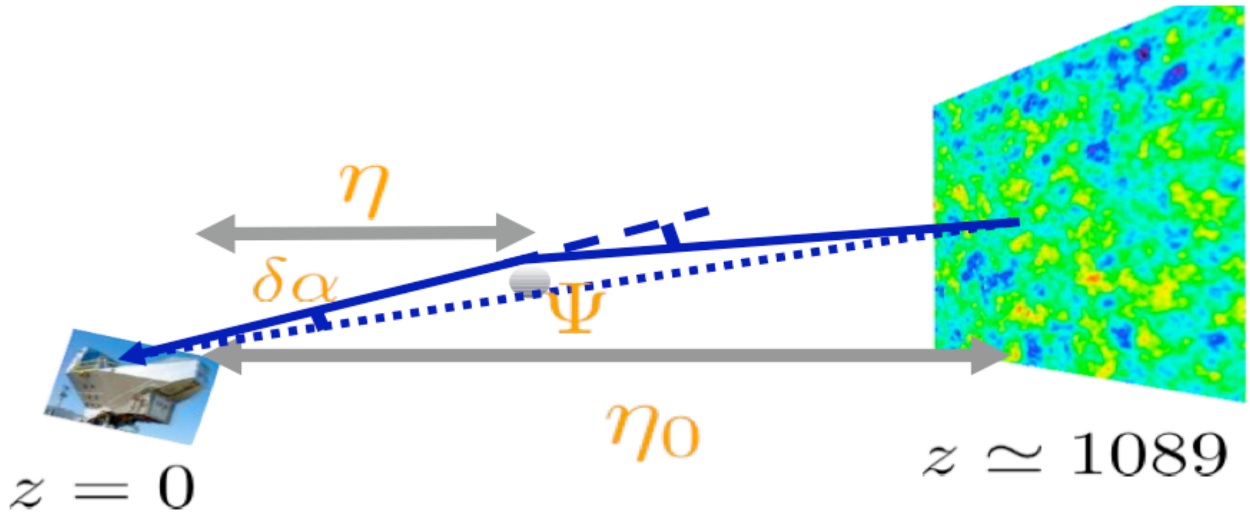
ACT, Hand et al 2011



Planck collaboration 2011

Stack up SZ signal using positions of LRGs from SDSS –optical sample of low mass clusters. Some evidence for scaling relation being low, and scatter. Limited by halo mass estimates. SZ clusters: not quite ready for precision dark energy constraints.

3. Lensing of the CMB

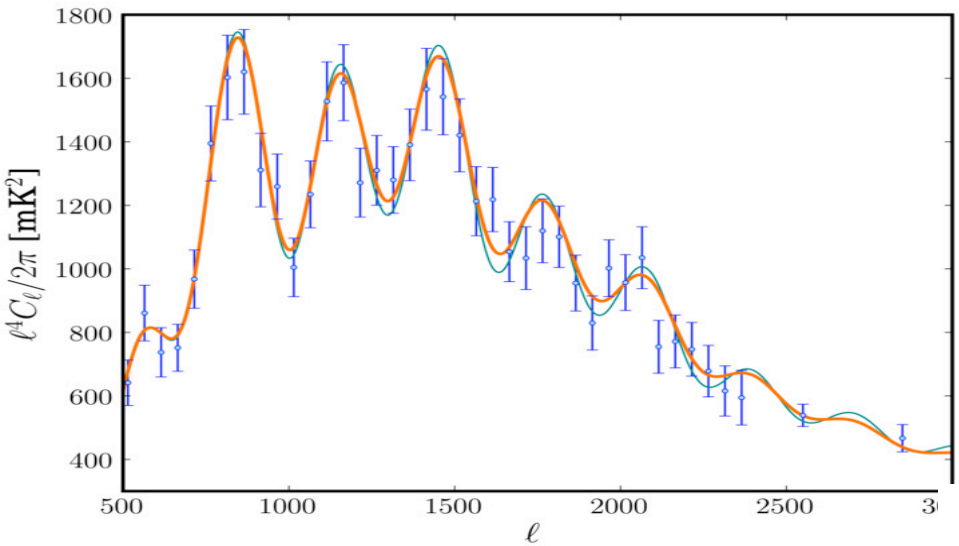


Large scale structure potentials gravitationally deflect CMB photons by a lensing deflection angle d(n), typically few arcmins.

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

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

Lensing shows up in TT



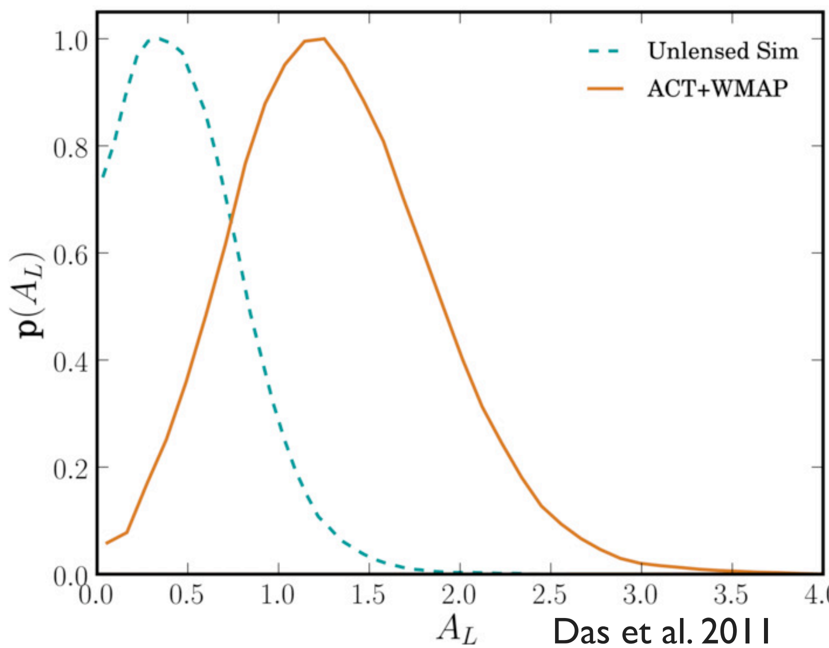
- An unlensed spectrum has sharper features

- Test for lensing by marginalizing over 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 in ACT:

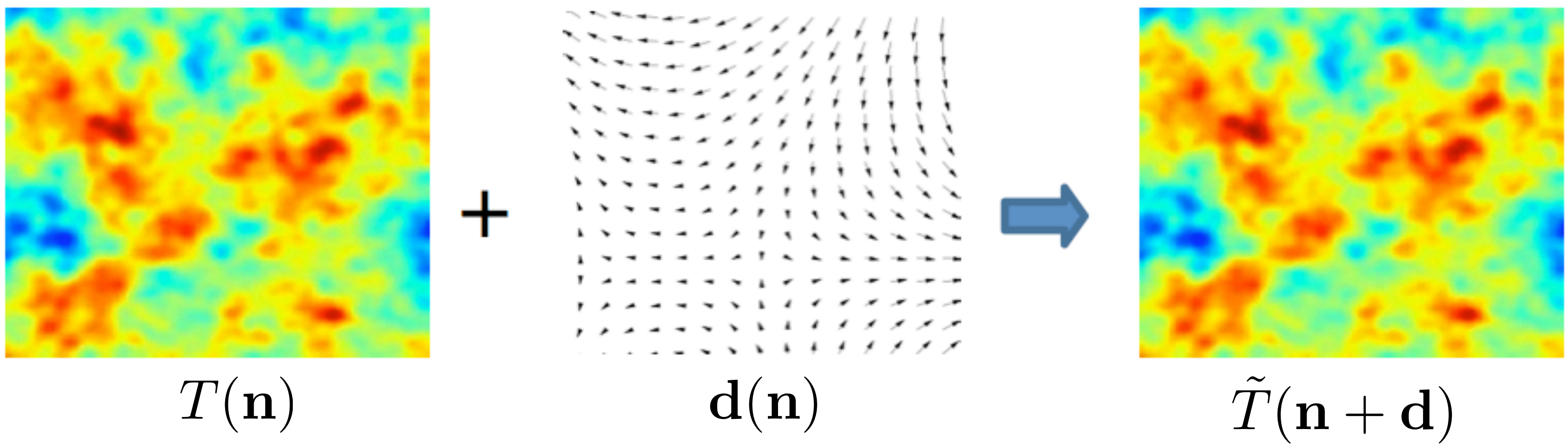
$$A_L = 1.3 \pm 0.5^{+1.2}_{-1.0} \text{ (68, 95\% CL)}$$

- Improved to 5-sigma detection from latest SPT (Keisler et al 2011)



Das et al. 2011

Better: try to estimate deflection



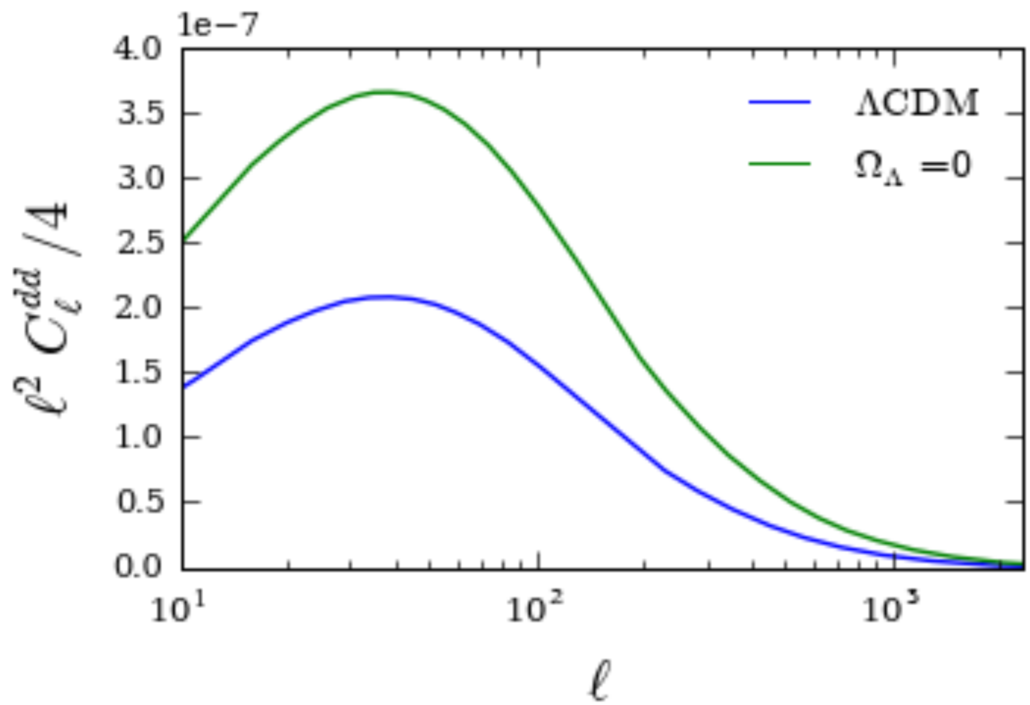
$$
\begin{aligned}
T(\mathbf{n})_{\text{lensed}} &= T(\mathbf{n}+\mathbf{d}(\mathbf{n}))_{\text{unl}} \\
&= T(\mathbf{n})_{\text{unl}} + d_i(\mathbf{n})\nabla_i T(\mathbf{n})_{\text{unl}} \quad \text{+ higher terms}
\end{aligned}
$$

Detection of deflection in cross-correlation of WMAP with NVSS and SDSS (Smith et al 2007, Hirata et al 2008)

Lensing as probe of Dark Energy

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

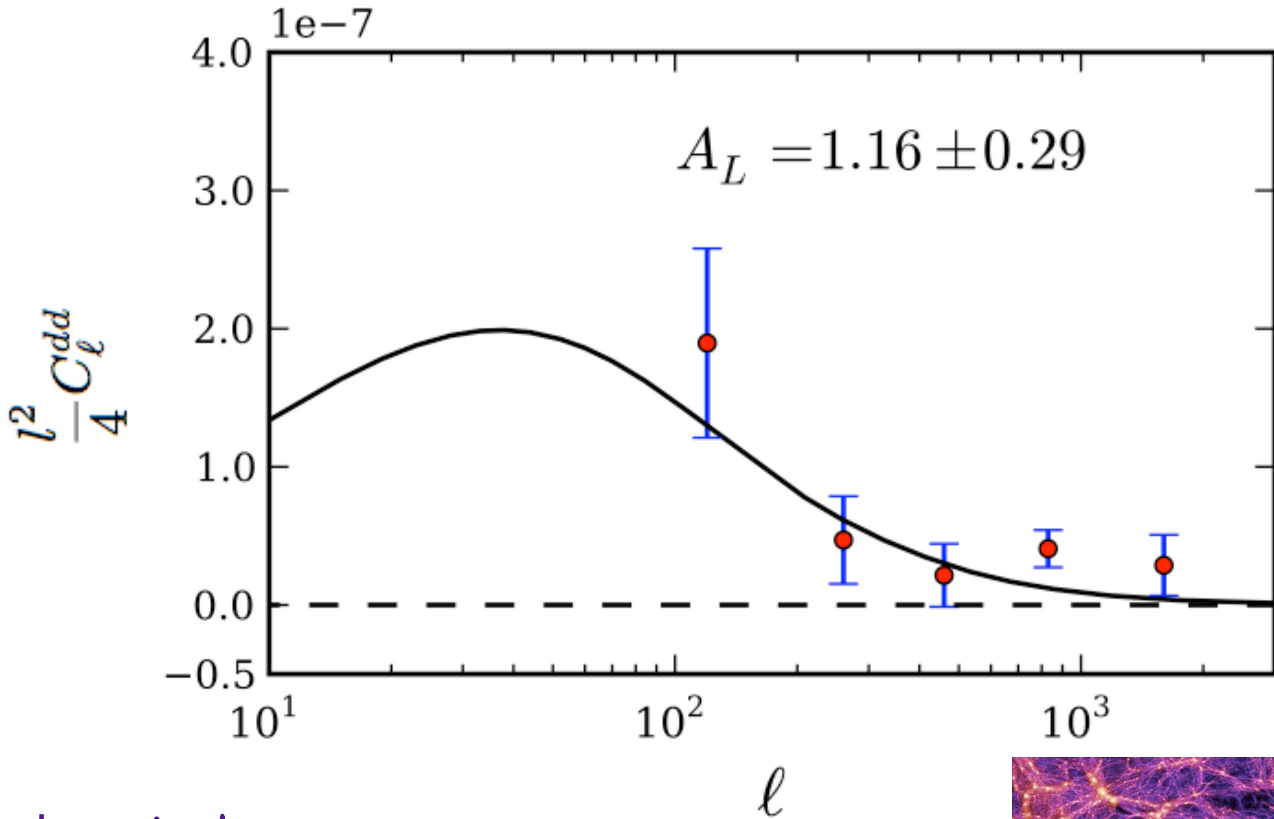
$$(2\pi)^2\delta(\mathbf{L}-\mathbf{L}')\,\hat{C}_L^{dd} = |N^\kappa(\mathbf{L})|^2 \int \frac{d^2\boldsymbol{\ell}}{(2\pi)^2} \int \frac{d^2\boldsymbol{\ell}'}{(2\pi)^2} |g(\boldsymbol{\ell},\mathbf{L})|^2$$
$$\times \Big[T^*(\boldsymbol{\ell})\, T^*(\mathbf{L}-\boldsymbol{\ell})\, T(\boldsymbol{\ell}')\,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

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

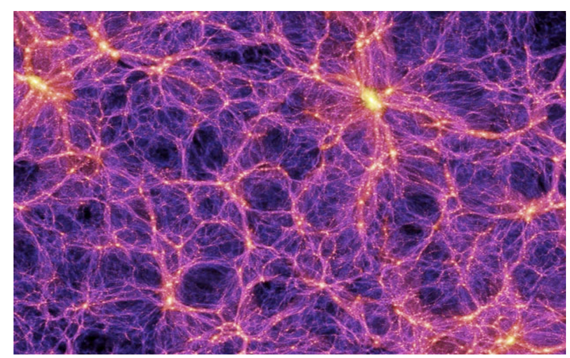
•Must subtract off Gaussian part (= unconnected part)

•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's direct detection of the lensing spectrum



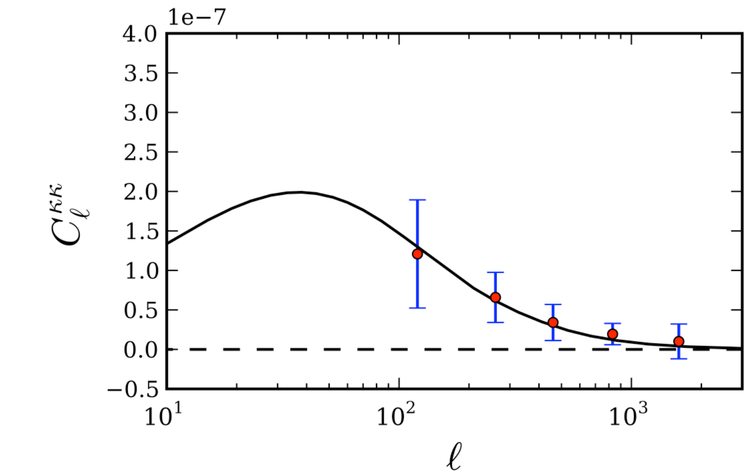
- 4-sigma detection!
- Constrains amplitude of matter fluctuations at z~0.5-3 to 12%.
- Direct gravitational probe of dark matter to z~1100

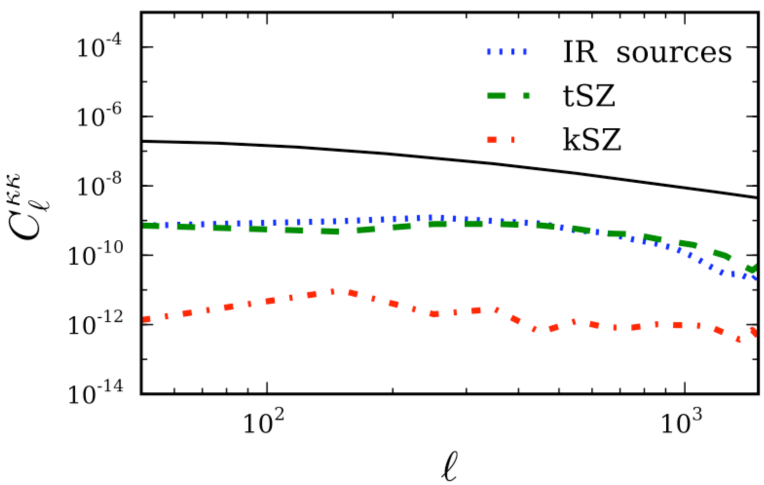


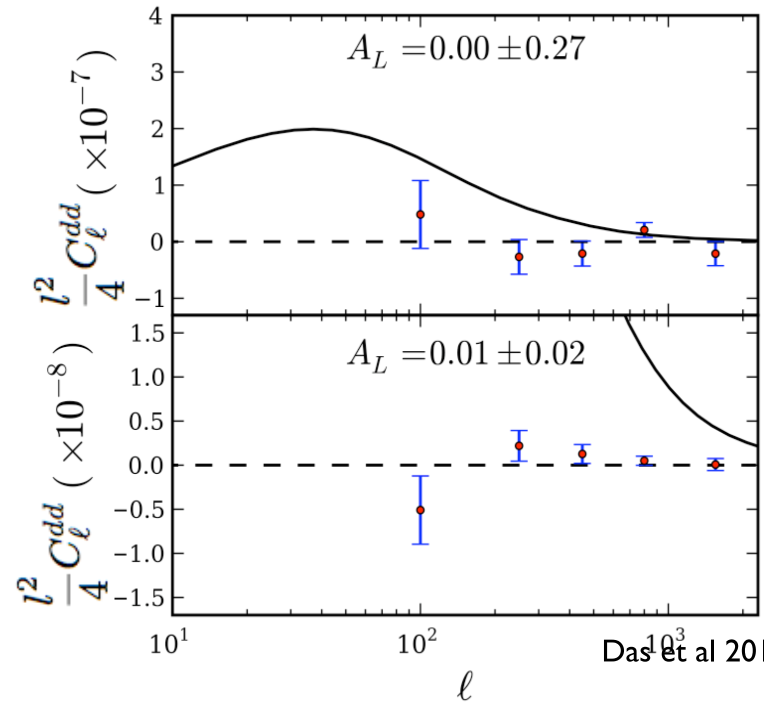
[Das, Sherwin et al. 2011, arXiv:1103.2124]

Sims, null tests, contaminants

- Remove low and high ell, fill in sources.
- Monte-Carlo tests on simulated data.
- Cross-correlate reconstruction on different patches, and on noise-only differenced maps.

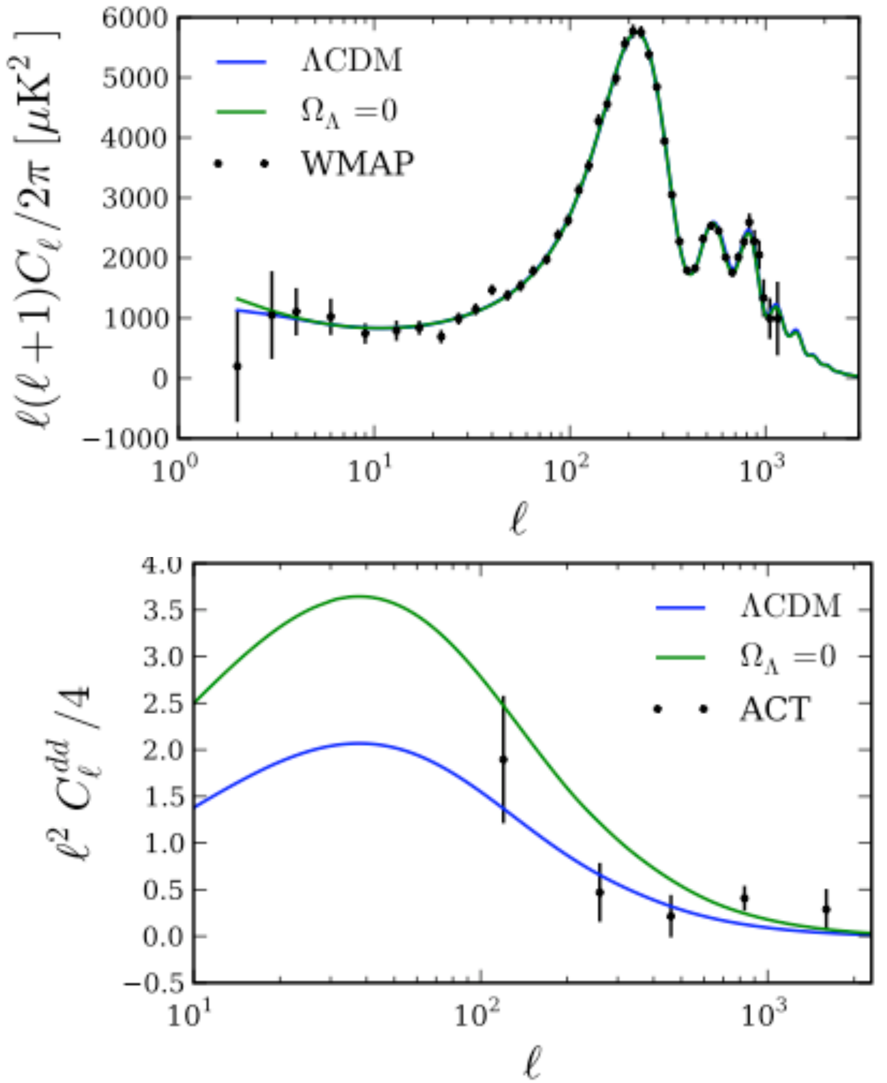


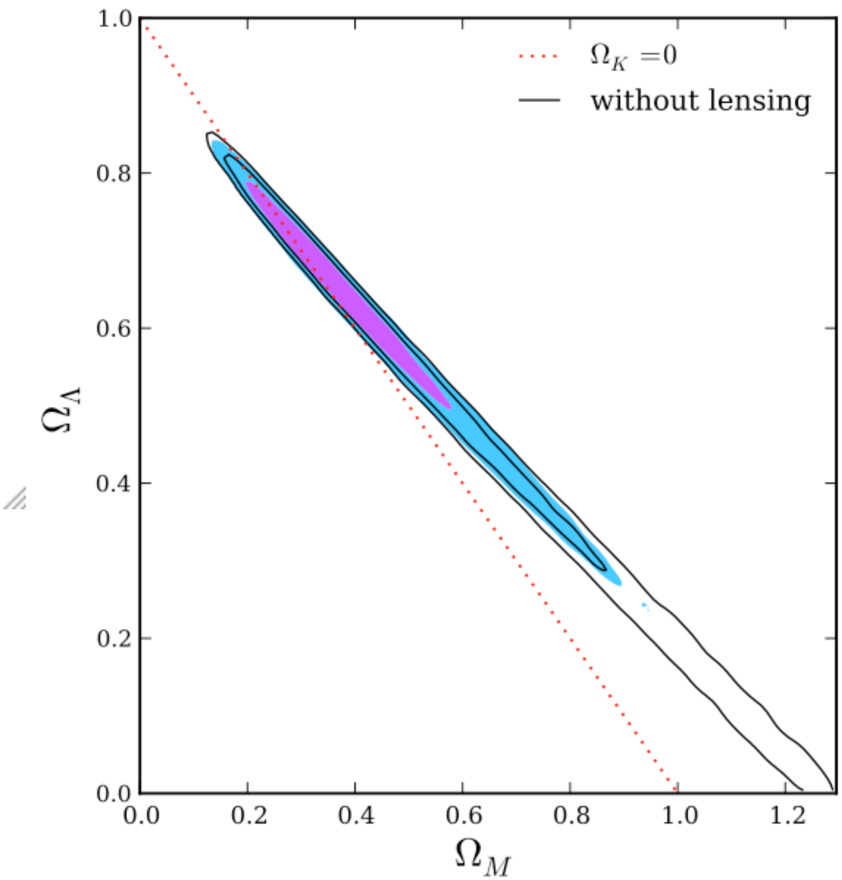




Das et al 2011

From ACT: CMB-only evidence for Λ





(Sherwin, Dunkley, Das 2011)

LCDM model favored at **>3 sigma** over best model with no Λ

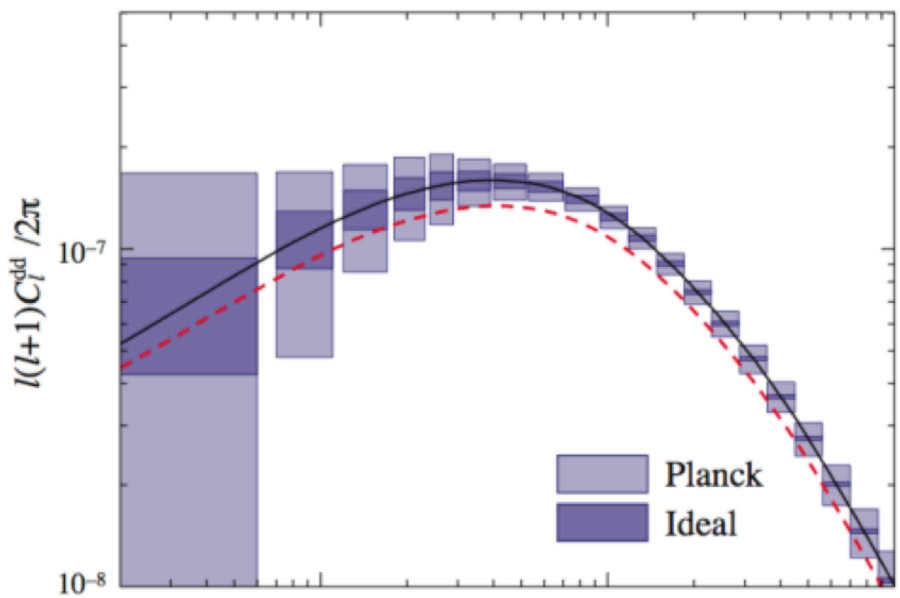
Next steps for lensing: SPT and Planck

SPT *expected to have ~10 sigma lensing detection from current data.*

Planck *first cosmology results due Jan 2013. Should measure higher acoustic peaks to better precision than ACT/SPT, over whole sky. Lensing detection forecast at ~ 25 sigma. ISW-lensing at 5-sigma.*

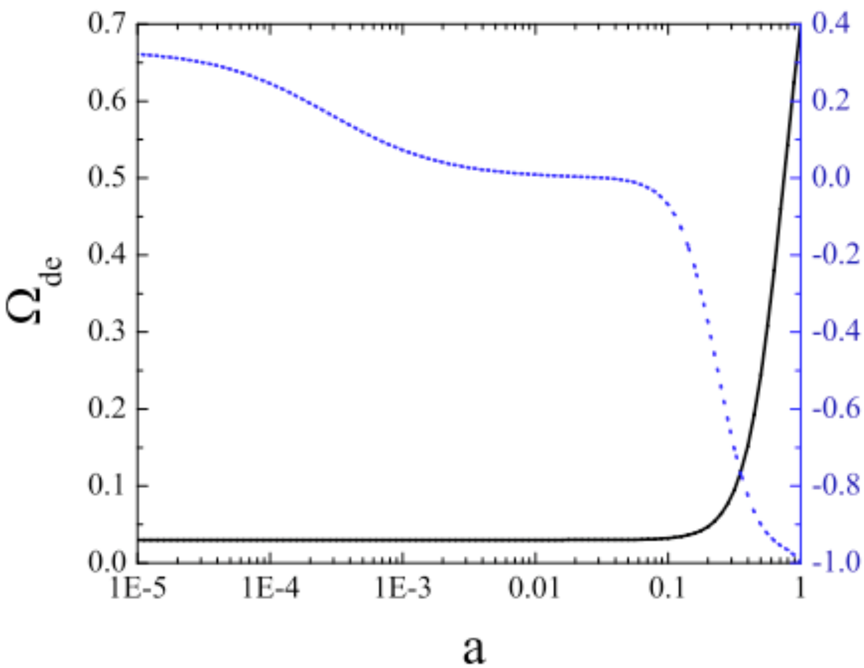
Probe dark energy and GR out to z~3 from lensing spectrum, also measure neutrino mass.

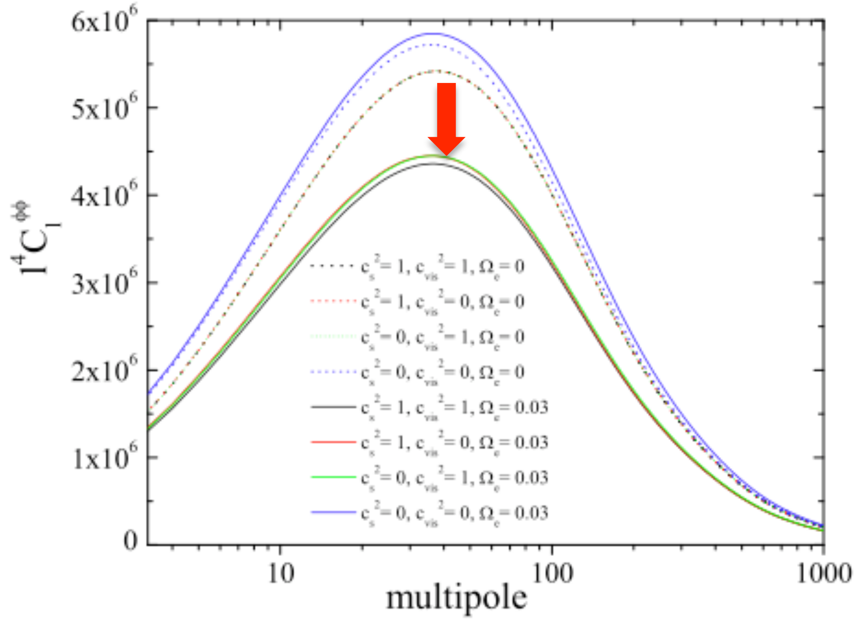
Cross-correlate CMB lensing maps with many LSS probes: galaxies, shear, quasars, CIB, SZ, Lyman-α



Early Planck forecast by Hu, 2001, two models are w=-1 and w=-2/3

E.g., early dark energy





Calabrese et al 2010

$$\Omega_{\rm de}(a) = \frac{\Omega^0_{\rm de} - \Omega_{\rm e}\left(1 - a^{-3w_0}\right)}{\Omega^0_{\rm de} + \Omega^0_m a^{3w_0}} + \Omega_{\rm e}\left(1 - a^{-3w_0}\right) \quad (1)$$

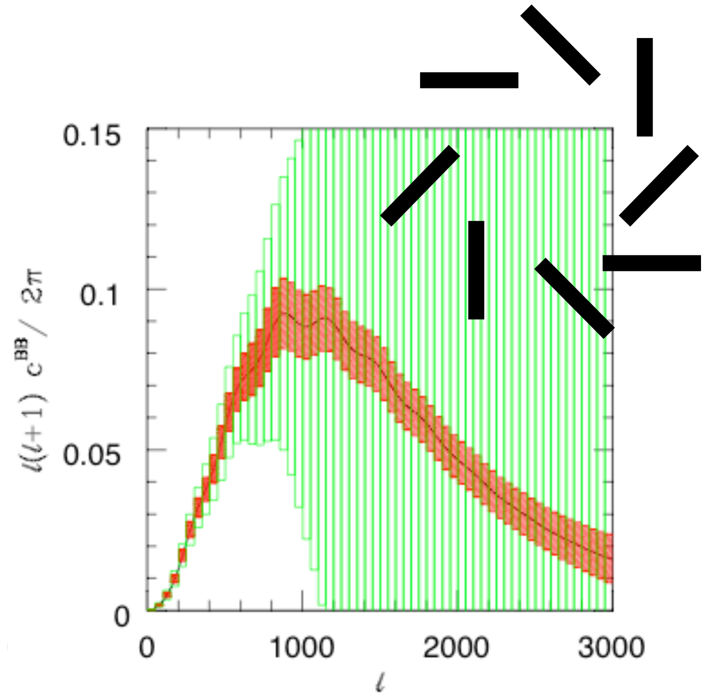
$$w(a) = -\frac{1}{3[1-\Omega_{\rm de}(a)]}\frac{d\ln\Omega_{\rm de}(a)}{d\ln a} + \frac{a_{eq}}{3(a+a_{eq})} \quad (2)$$

Then: ACTPol, SPTPol, PolarBear

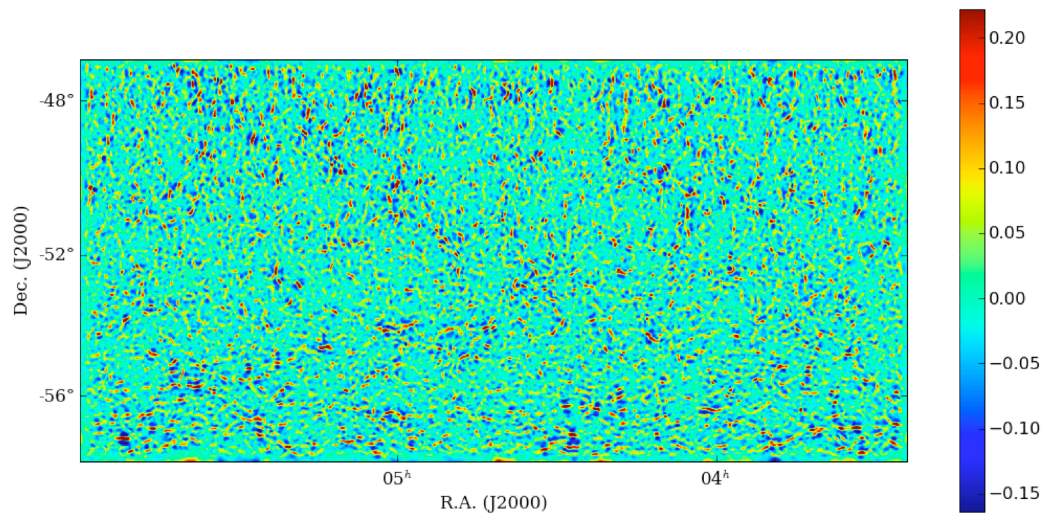
2012-2015 – ACTPol will measure polarization of CMB to arcminute scales over ~10% of sky. SPTPol coming too.

Lensing generates B-modes from E-modes. So – by measuring B-mode polarization we will better measure lensing deflection field:

- *Measure neutrino mass (to 0.1eV)*
- *Unique probe of dark energy and GR at z~1-3*
- *Wealth of cross-correlations*



Niemack et al 2010



Summary

- By combining primordial CMB with lower-redshift probes, get strongest current constraints on Dark Energy.

- Three ways to see dark energy effects in CMB at late times
  - Integrated Sachs-Wolfe, limited to large scales
  - SZ cluster counts, rely on Y-M relation
  - CMB lensing, directly probing dark matter distribution

- ACT has made first measurement of lensing power spectrum – robust 4-sigma detection, giving evidence for Lambda at >3 sigma from the CMB alone. SPT and Planck promise higher significance.

- To come: lensing from CMB B-mode polarization (ACTPol and SPTPol), and cross-correlations with LSS.