The Atacama Cosmology Telescope: results from the 2008 survey

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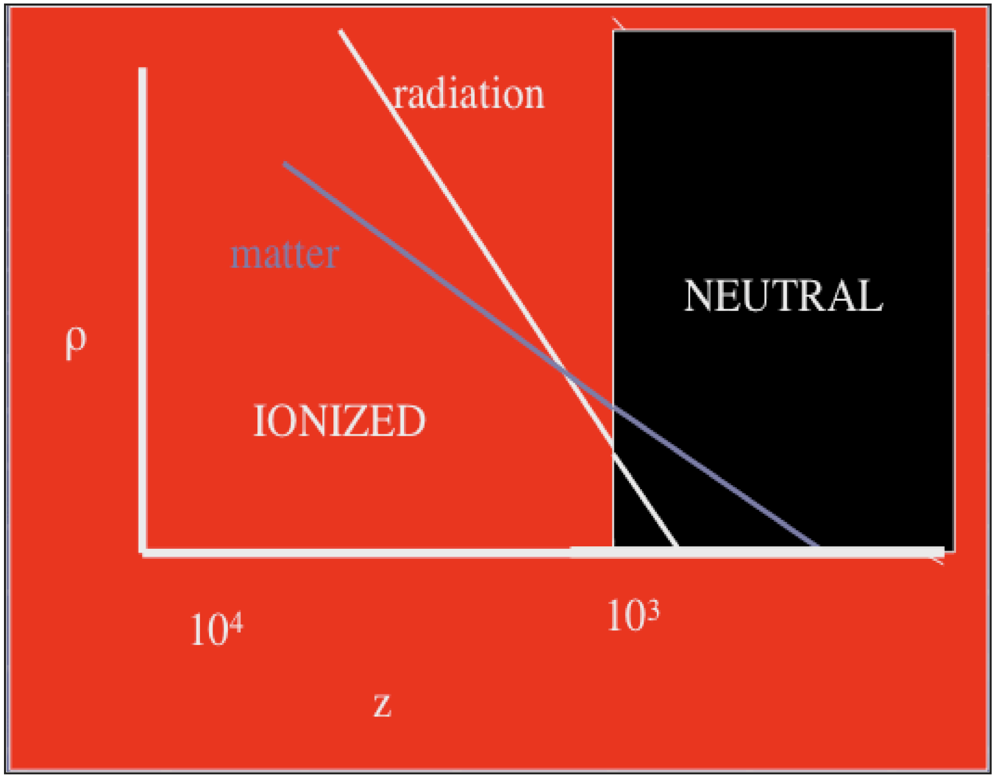
Oxford Astrophysics

APC, Sep 21, 2010

The Cosmic Microwave Background

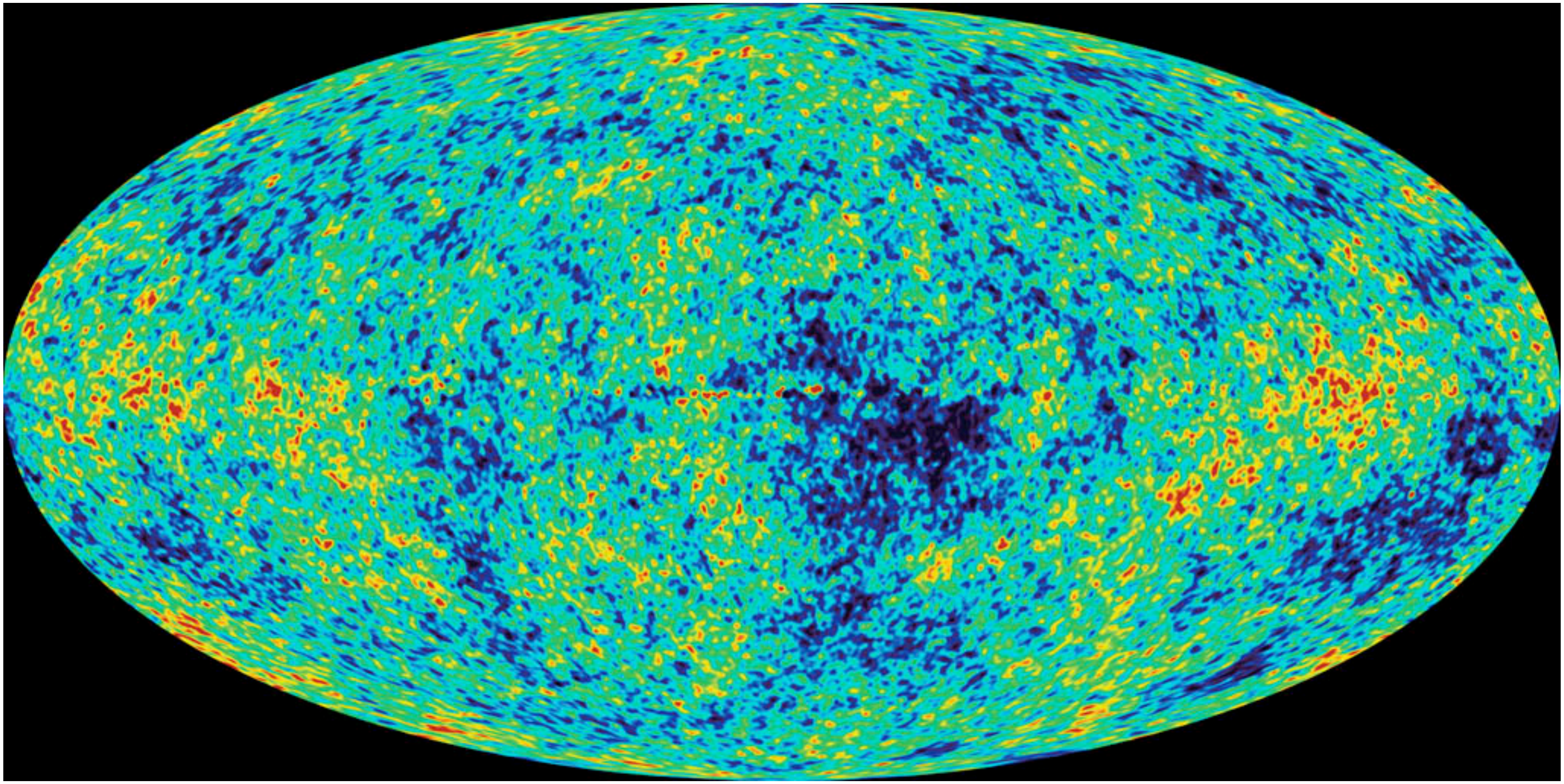


- Linear theory (at early times)
- Basic elements are well understood. Initial fluctuations evolve.
- Numerical codes predict power spectrum in a given universe.

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

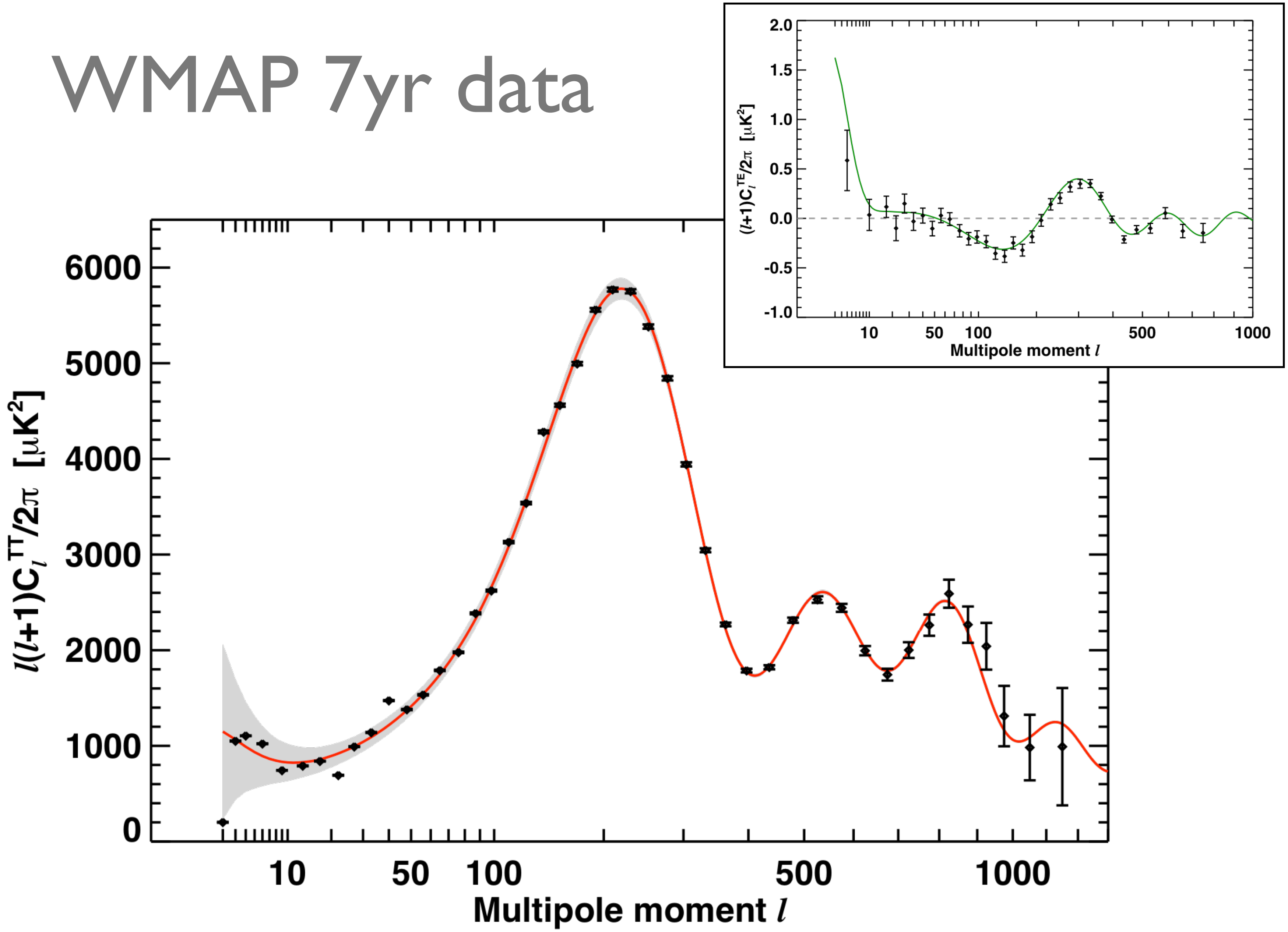
$$c_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

CMB fluctuations



WMAP7, Hinshaw et al 2008, Jarosik et al 2010

WMAP 7yr data



Larson, JD et al 2010

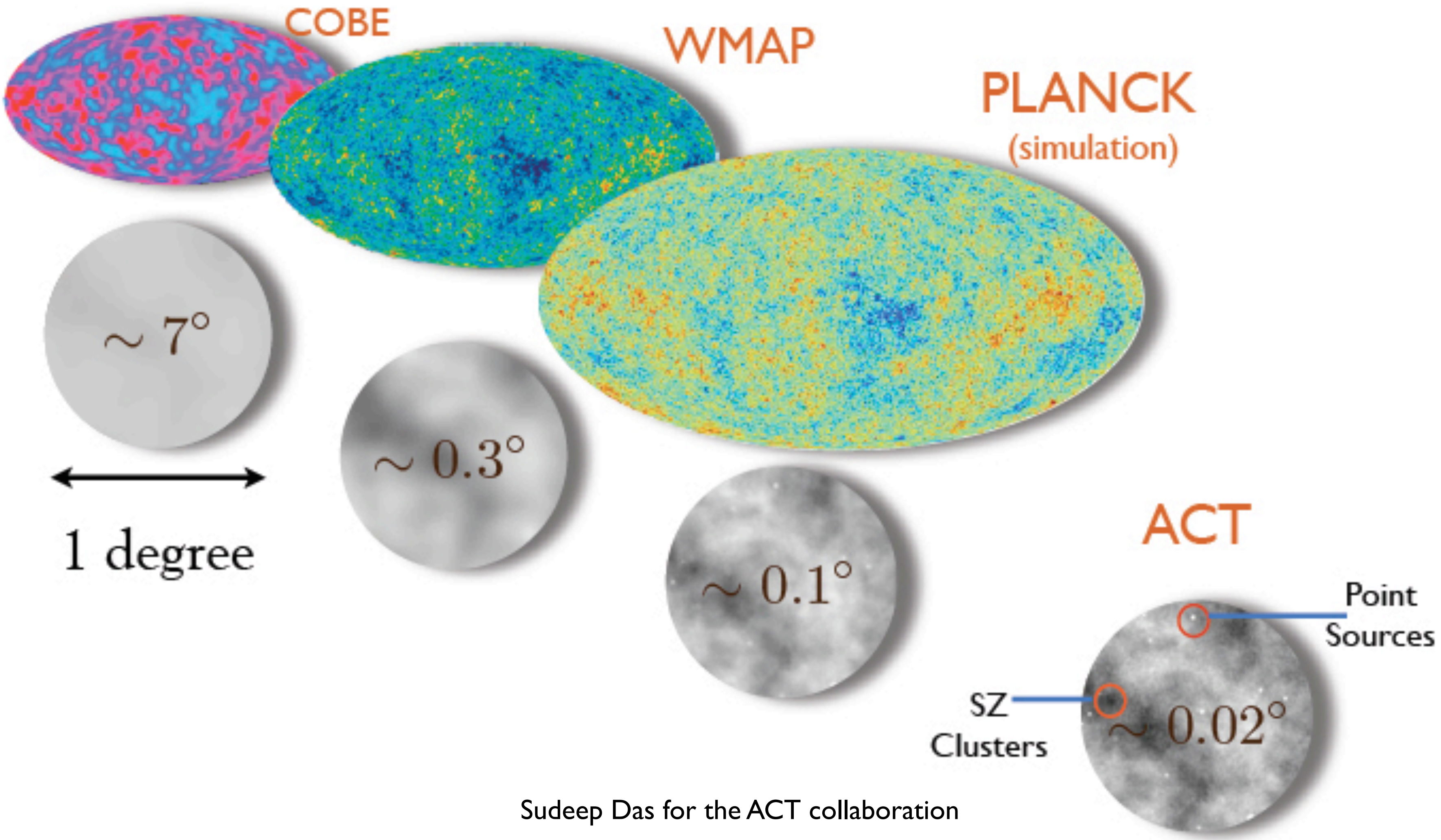
Constrained 6-parameter lcdm cosmological model

Atacama Cosmology Telescope

- Barcelona ICE
- 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, 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)
- Collaborators at La Sapienza, MPI, Miami, Stanford, Berkeley, Chicago, CfA, LLNL, IPMU Tokyo

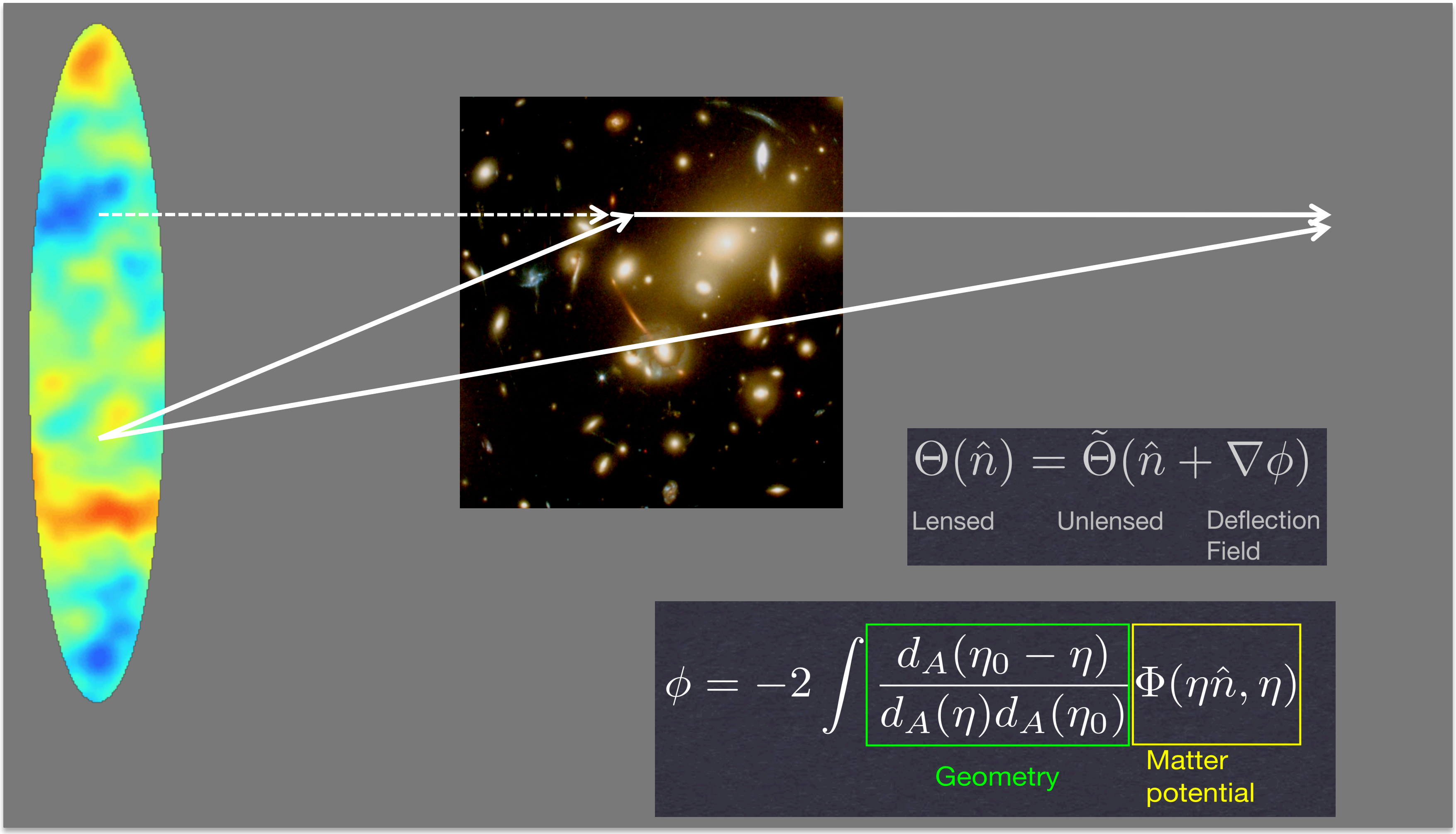
→ ~ 90 collaborators

ACT probes new scales



Sudeep Das for the ACT collaboration

CMB lensing



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

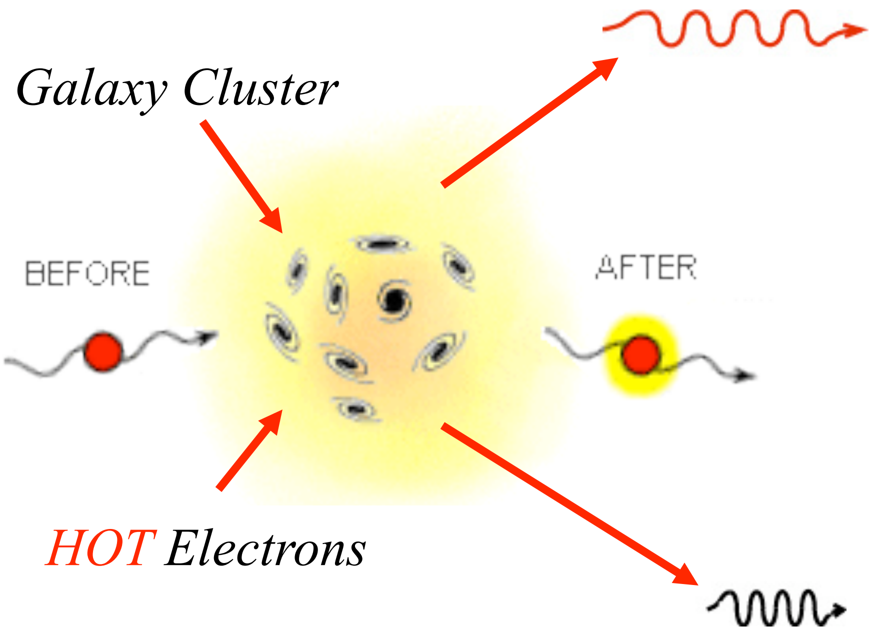
Lensed   Unlensed   Deflection Field

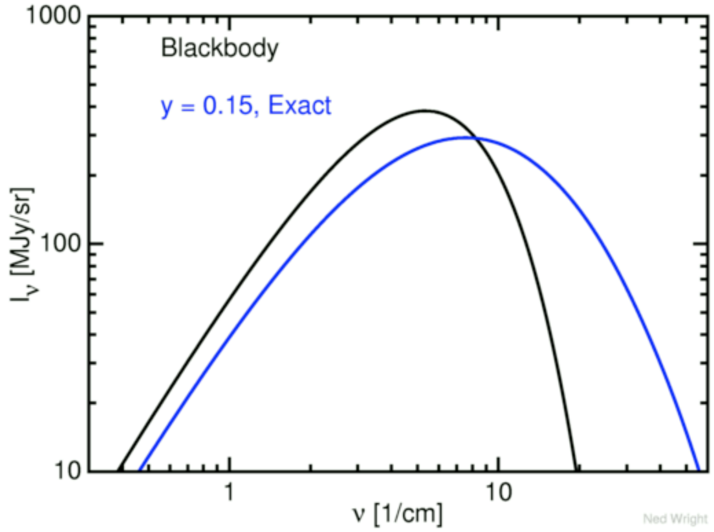
$$\phi = -2\int \boxed{\frac{d_A(\eta_0 - \eta)}{d_A(\eta)d_A(\eta_0)}}\boxed{\Phi(\eta\hat{n}, \eta)}$$

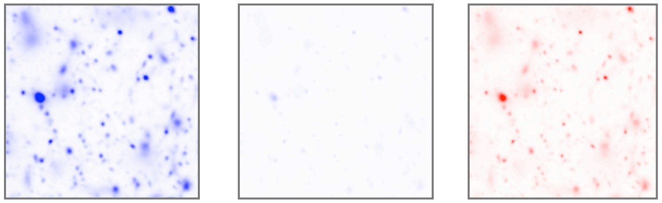
Geometry   Matter potential

Integrated mass fluctuations along the line of sight, from fixed CMB source. Kernel peaks at z=2-3.Ulimately use TT (and E/B) to reconstruct deflection power spectrum.

Sunyaev-Zeldovich from clusters

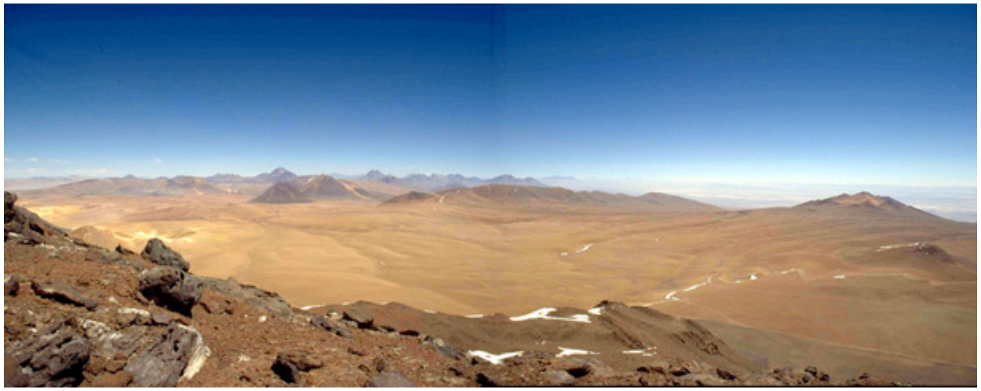






- Thermal Sunyaev-Zeldovich: inverse compton scattering from hot electrons
- Identify and measure clusters with multi-wavelength observations
- Derive science from N(mass,z)

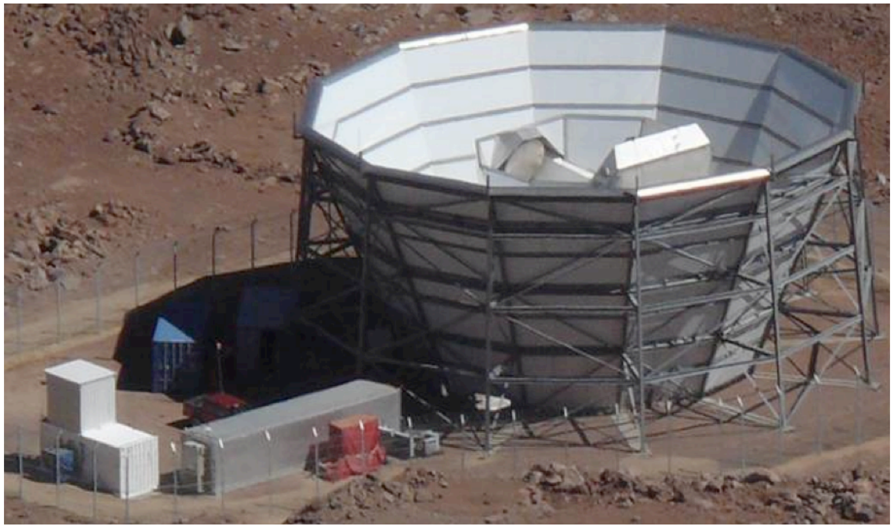
ACT: the telescope



5200 meter elevation, one of driest places on planet

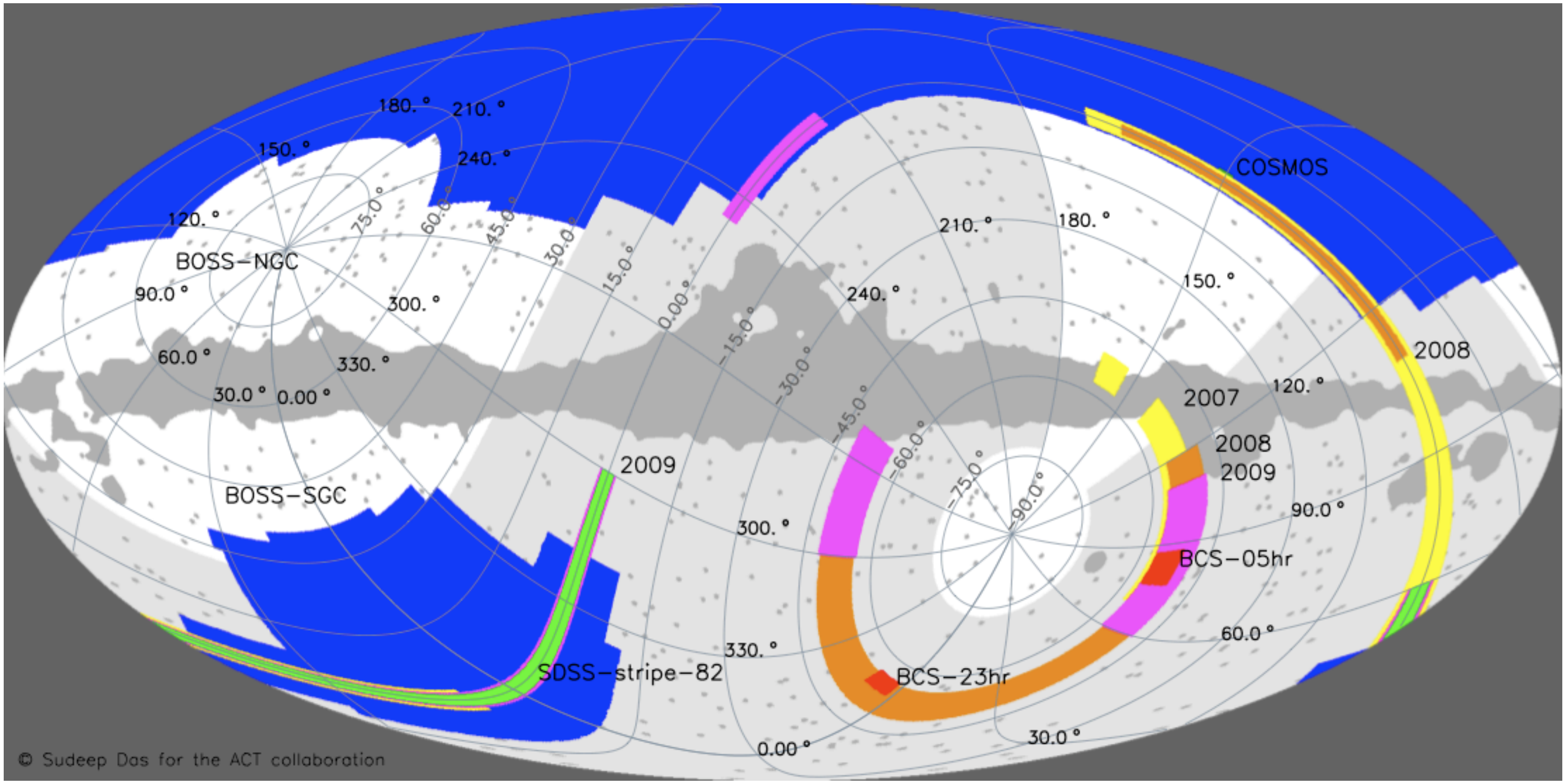
1° field of view, 6-meter primary, 2-meter secondary, 1.4’ resol

3 frequencies: 148, 220, 270 GHz, 3000 TES detectors



ACT sky coverage

To date ACT has taken ~17 months of data in 3 frequency bands, over ~1300 deg^2



© Sudeep Das for the ACT collaboration

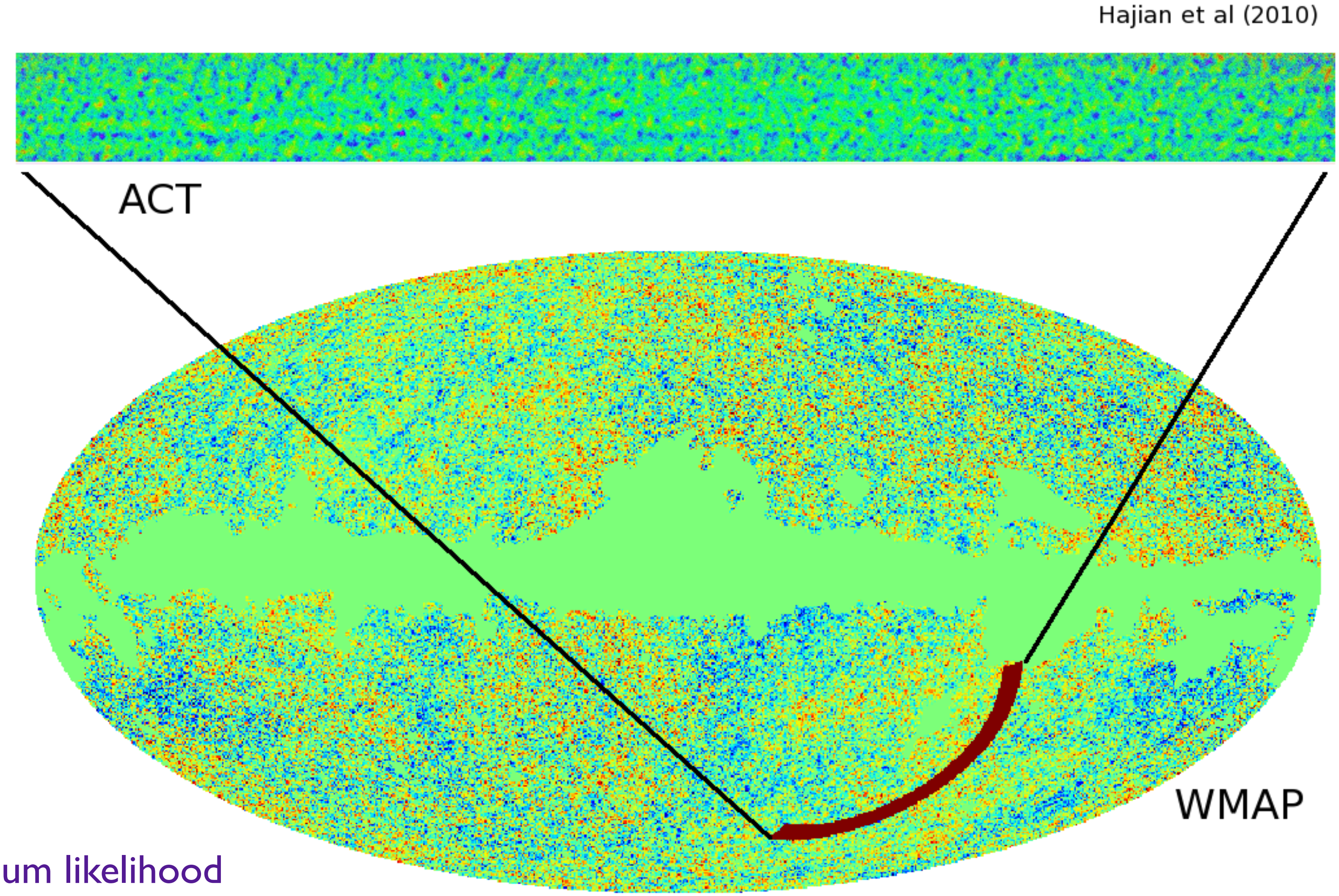
Observe mainly at night: 20:30 – 09:30 local time

Fixed elevation of 53° South. Rapid scanning: 6 degrees every 8 seconds

Cross-linking: observe each patch twice per night

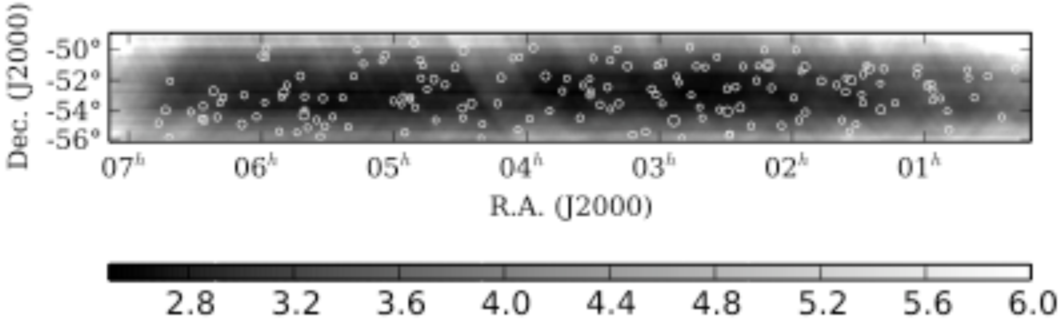
Showing today: ~ 4 months in 2008, 2 frequencies, 300 deg^2

ACT southern field at 148 GHz



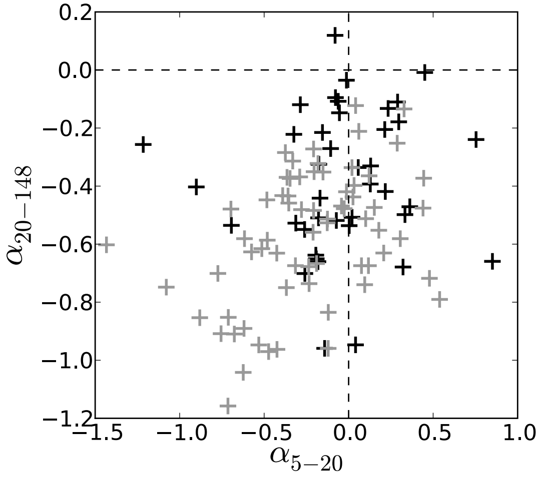
Maximum likelihood
map-maker

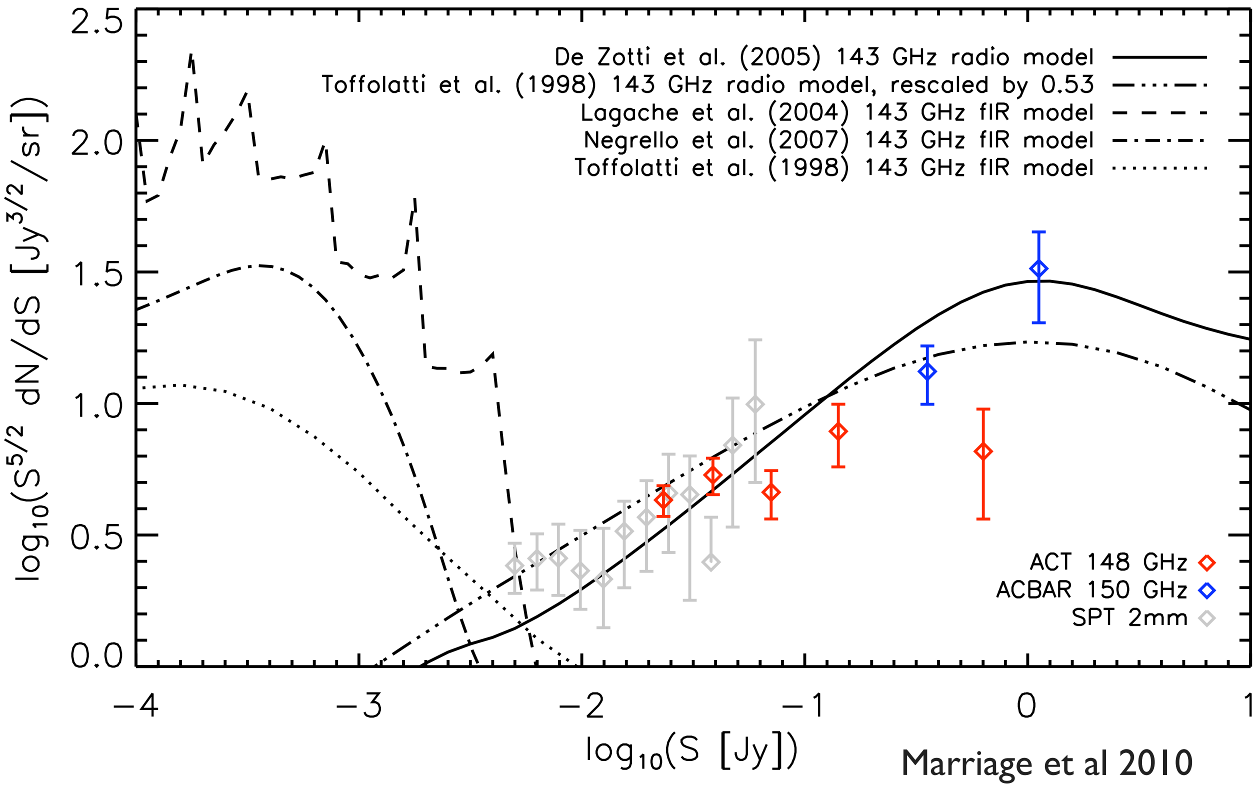
Radio galaxy detections at 148 GHz



157 sources 15-1500 mJy (5 sigma)

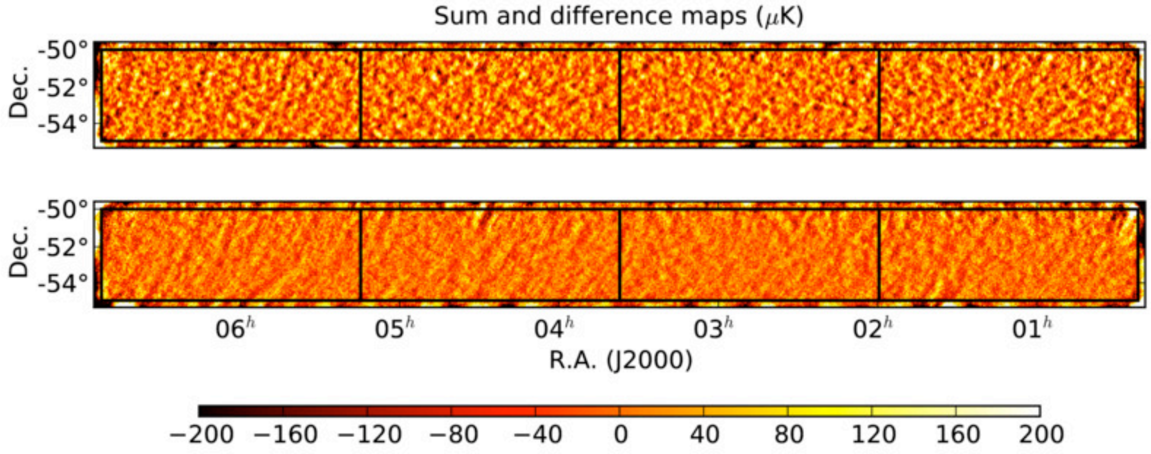
98% known radio sources

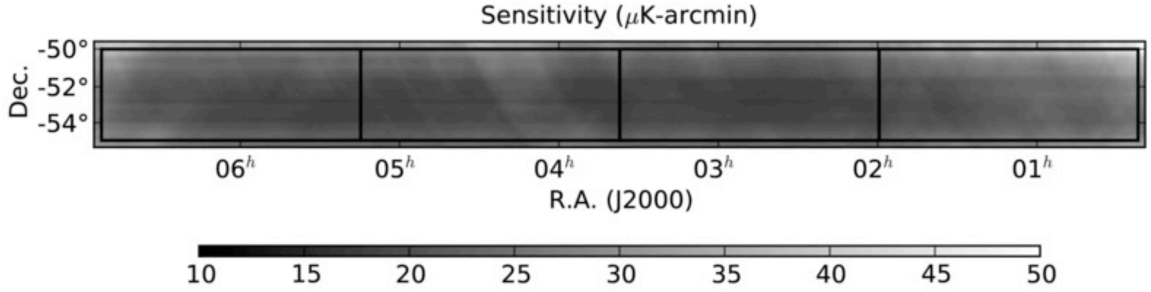


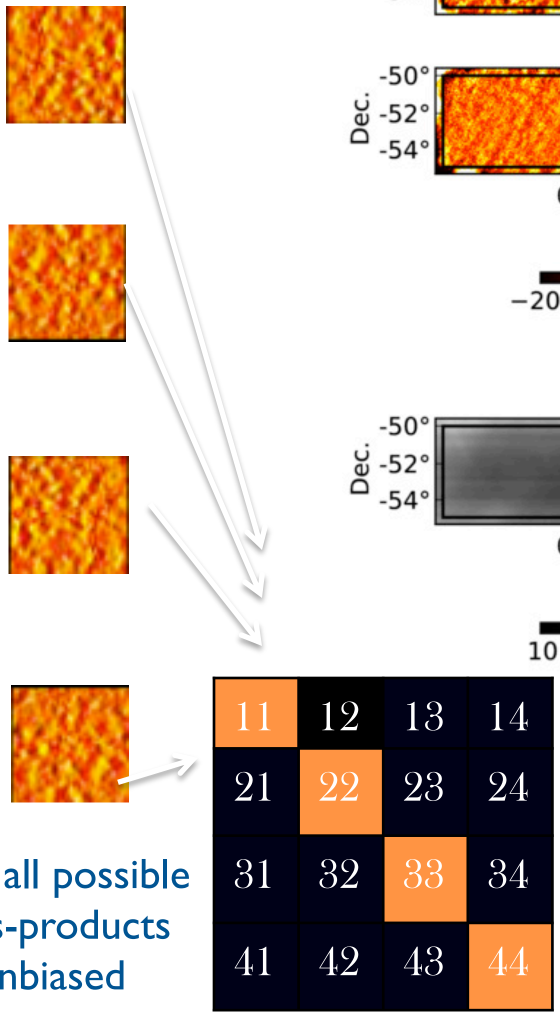


Marriage et al 2010

Computing power spectrum







11	12	13	14
21	22	23	24
31	32	33	34
41	42	43	44

Take all possible cross-products for unbiased spectra

Take four 5x15 degree patches, and also make four data splits for cross-spectra (and null tests).

First, filter l<500, pre-whiten, mask out bright sources
Take flat-sky tapered 2D pseudo-Cls
Take angular-weighted annular average → 1D pseudo-Cl

ACT 148-218 GHz power spectra

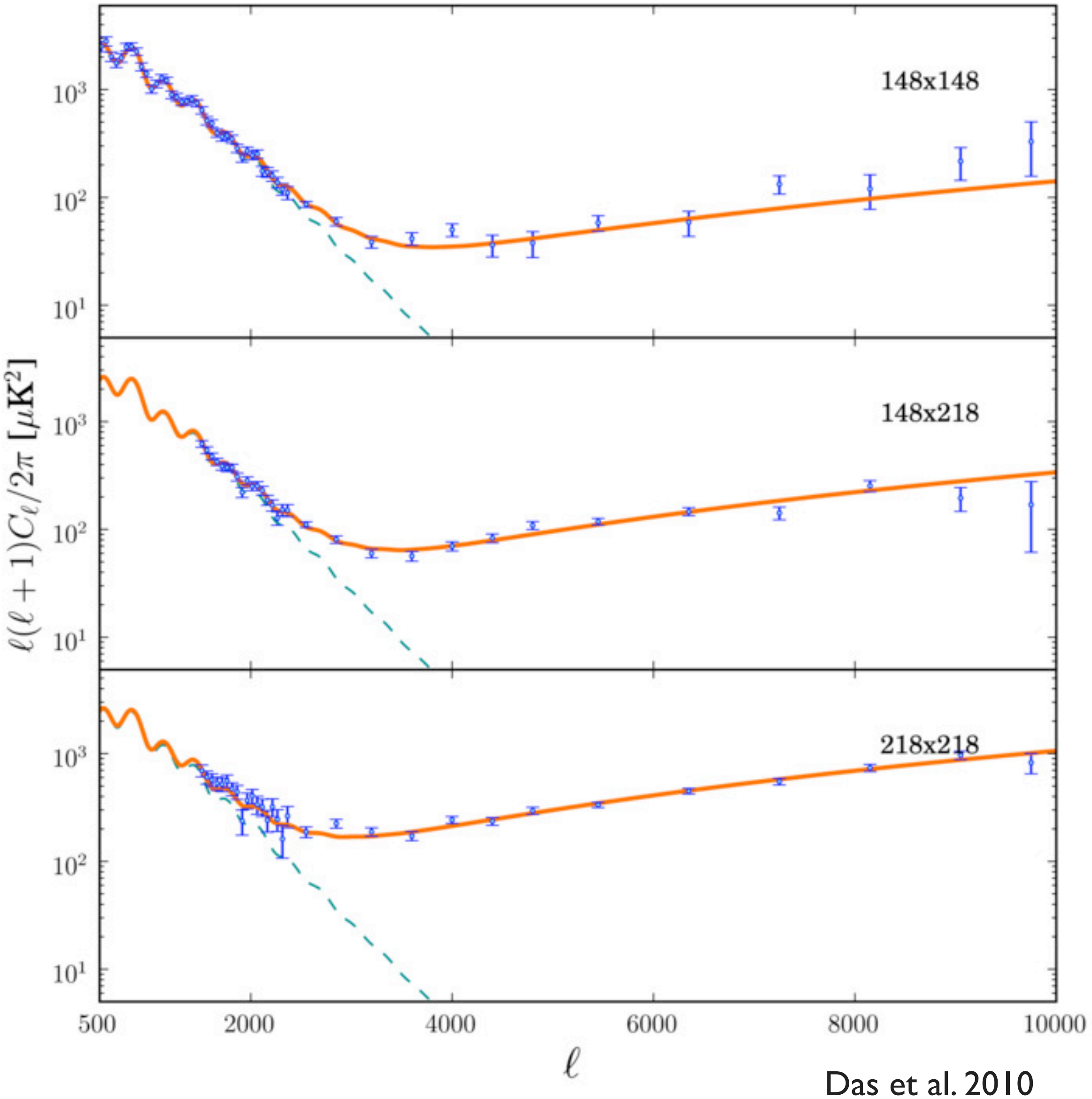
•WMAP extends to l=1000; ACT spans 500<l<10000 range for 148 GHz, 1500<l<10000 for 218 GHz

• Higher acoustic peaks and Silk damping tail probed

• CMB dominates out to l~3000 for 148 GHz, and l~2000 for 218 GHz

• CMB only about 15% by l=3000 at 218 GHz.

• Will use l=3000 as useful reference scale.

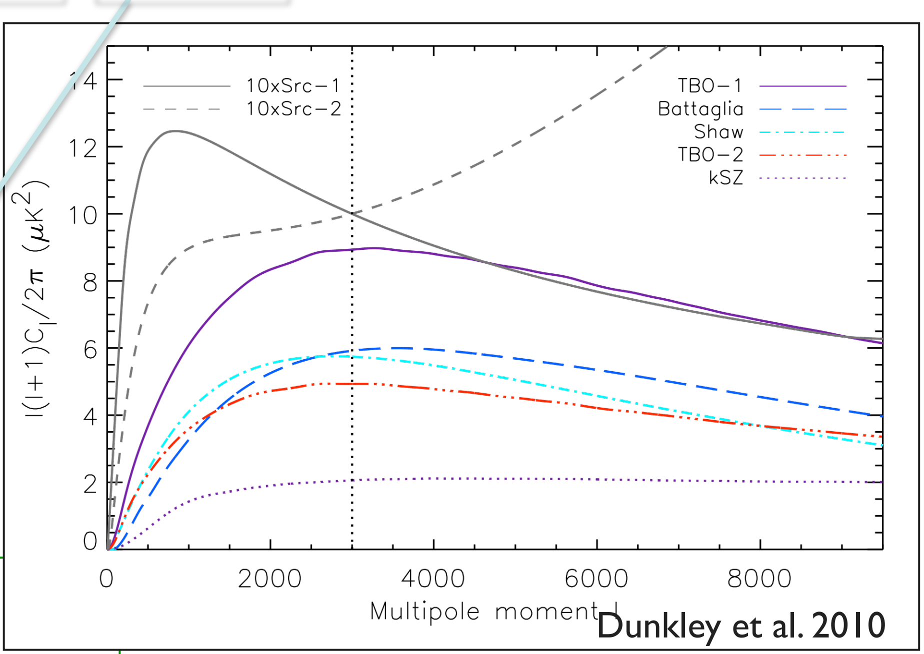


Das et al. 2010

High-ell model

$$\mathcal{B}_\ell^{\rm th,ij} = \mathcal{B}_\ell^{\rm CMB} + \boxed{\mathcal{B}_\ell^{\rm tSZ,ij} + \mathcal{B}_\ell^{\rm kSZ,ij}} + \boxed{\mathcal{B}_\ell^{\rm IR,ij}} + \mathcal{B}_\ell^{\rm rad,ij} + \mathcal{B}_\ell^{\rm Gal,ij} \quad (5)$$

$$\boxed{\mathcal{B}_\ell^{\rm SZ,ij} = A_{\rm tSZ} \frac{f(\nu_i)}{f(\nu_0)} \frac{f(\nu_j)}{f(\nu_0)} \mathcal{B}_{0,\ell}^{\rm tSZ} + A_{\rm kSZ} \mathcal{B}_{0,\ell}^{\rm kSZ}.}$$

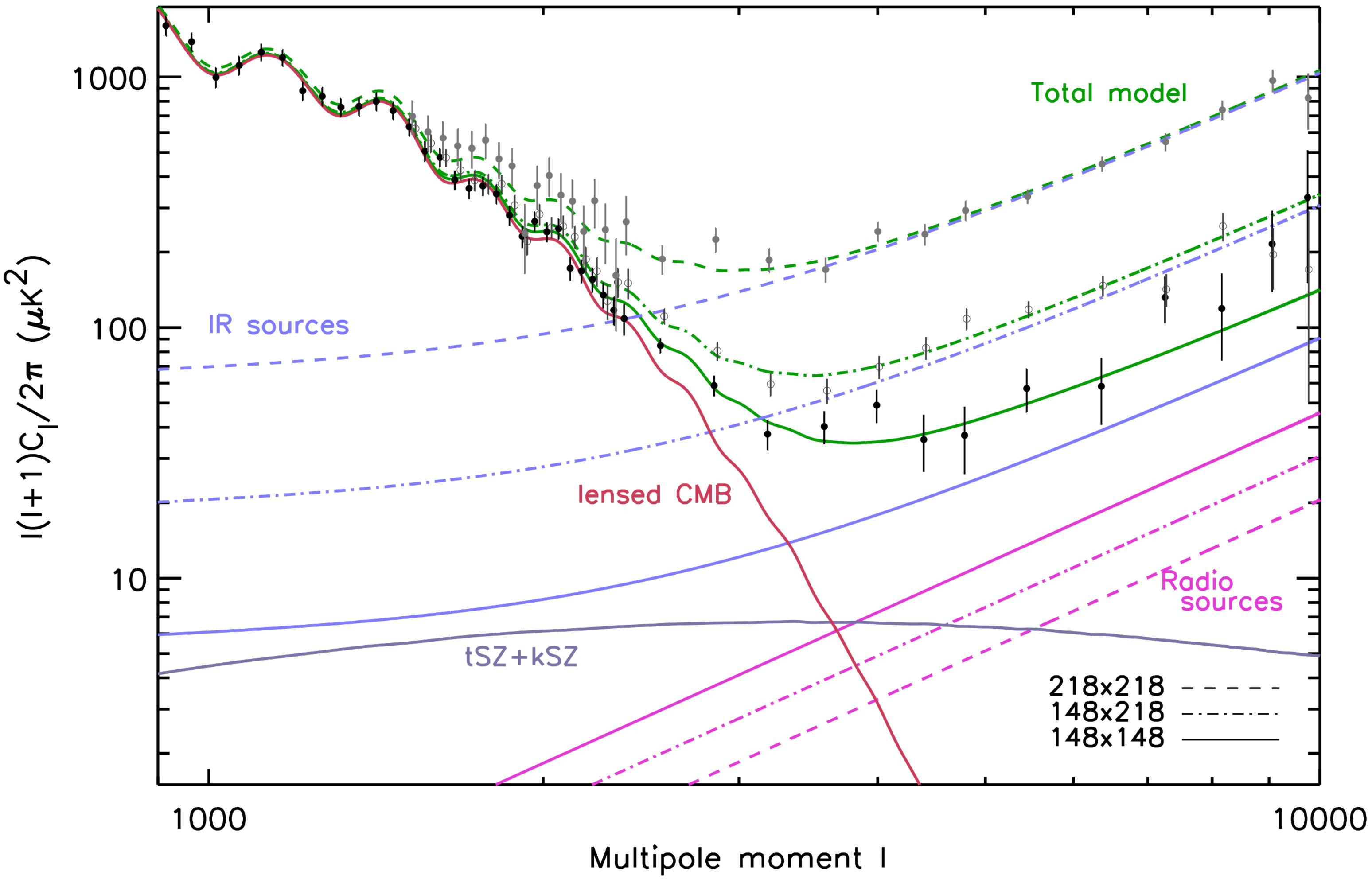


Dunkley et al. 2010

$$\mathcal{B}_\ell^{\rm IR,ij} = \left[A_d \left(\frac{\ell}{3000}\right)^2 + A_c \mathcal{B}_{0,\ell}^{\rm clust}\right] \frac{g(\nu_i)}{g(\nu_0)} \frac{g(\nu_j)}{g(\nu_0)} \left(\frac{\nu_i}{\nu_0}\frac{\nu_j}{\nu_0}\right)^{\alpha_d - 2} \quad (9)$$

$$\mathcal{B}_\ell \equiv \ell(\ell+1)C_\ell/2\pi.$$

Simple model fits small scales



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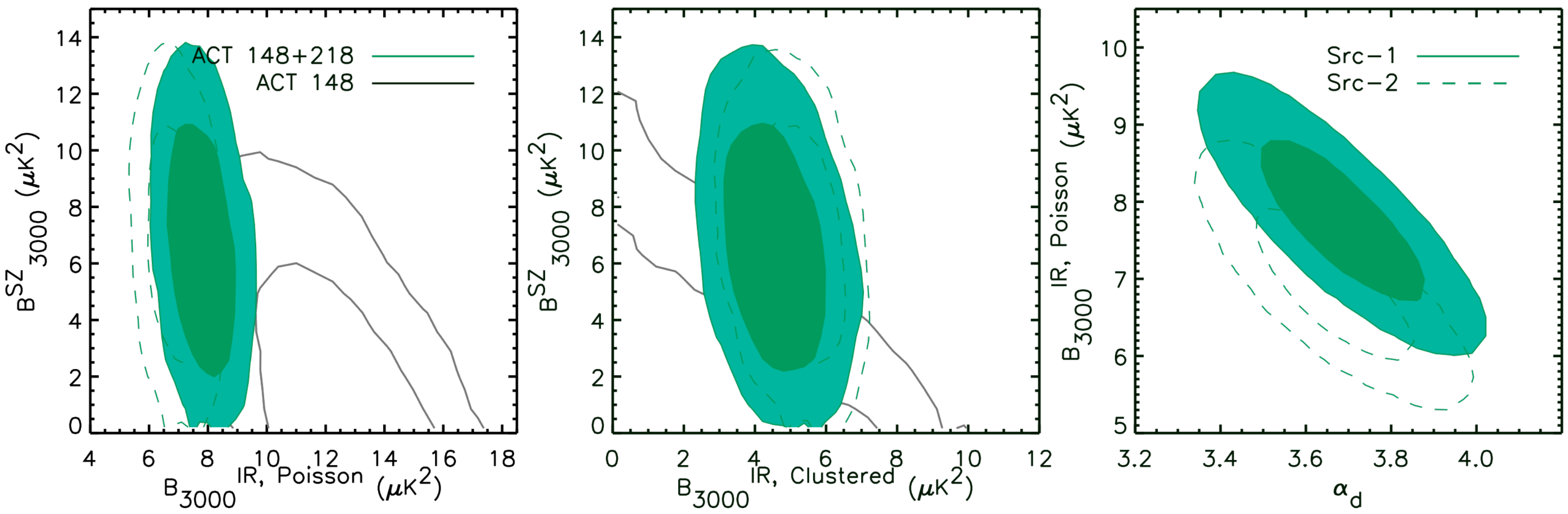
Secondary parameters



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- Simple model fits 3 spectra
- Clustered IR sources required at 5 sigma

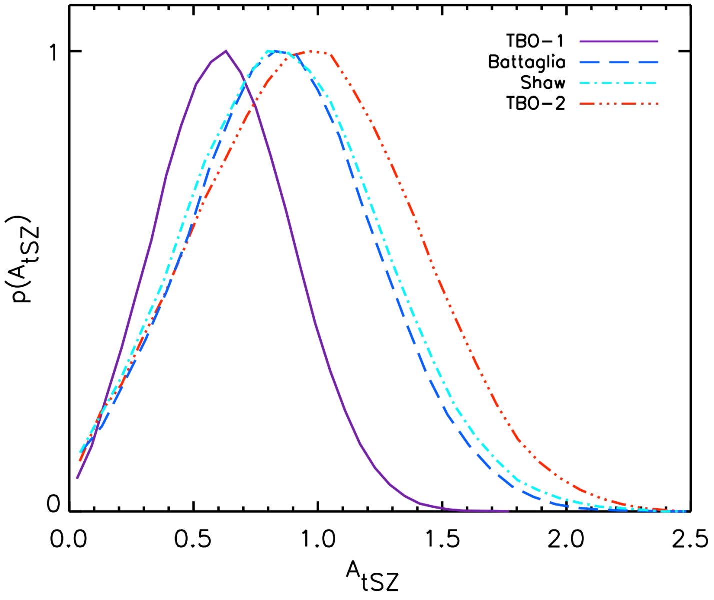
- At 148 GHz we separate radio and IR with prior from detected radio sources.
- Index consistent with dusty galaxies z=2-4

TABLE 3

Derived constraints on unresolved IR source emission[a]

		148 GHz	218 GHz
Poisson	$\mathcal{B}_{3000}$ $(\mu\mathrm{K}^2)$[b]	$7.8 \pm 0.7 \pm 0.7$	$90 \pm 5 \pm 10$
	$C_\ell(\mathrm{nK}^2)$	$5.5 \pm 0.5 \pm 0.6$	$63 \pm 3 \pm 6$
	C_ℓ $(\mathrm{Jy}^2\,\mathrm{sr}^{-1})$	$0.85 \pm 0.08 \pm 0.09$	$14.7 \pm 0.7 \pm 1.8$
Clustered	$\mathcal{B}_{3000}$ $(\mu\mathrm{K}^2)$[c]	$4.6 \pm 0.9 \pm 0.6$	$54 \pm 12 \pm 5$
Total IR	$\mathcal{B}_{3000}$ $(\mu\mathrm{K}^2)$	12.5 ± 1.2	144 ± 13

Sunyaev-Zeldovich power



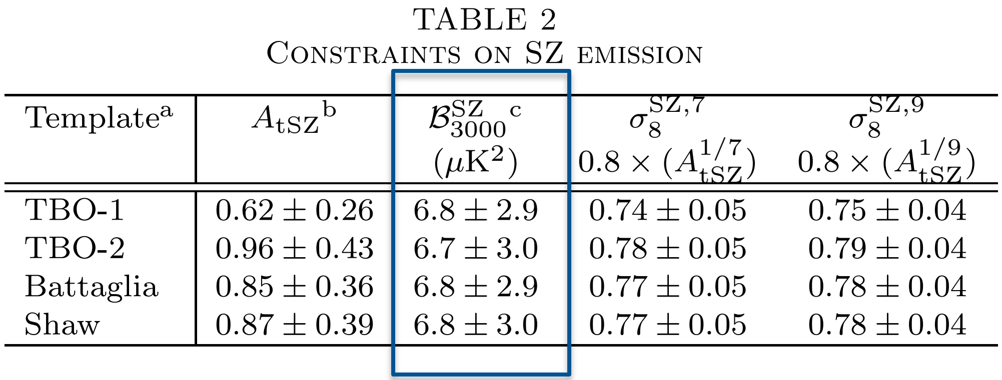


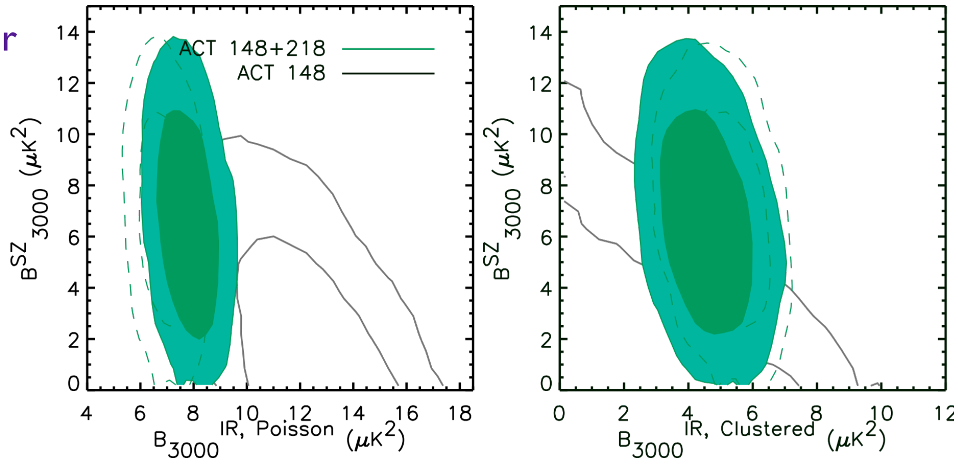
TABLE 2
CONSTRAINTS ON SZ EMISSION

Template[a]	A_{tSZ}[b]	$\mathcal{B}^{SZ}_{3000}$[c] (μK^2)	$\sigma_8^{SZ,7}$ $0.8 \times (A_{tSZ}^{1/7})$	$\sigma_8^{SZ,9}$ $0.8 \times (A_{tSZ}^{1/9})$
TBO-1	0.62 ± 0.26	6.8 ± 2.9	0.74 ± 0.05	0.75 ± 0.04
TBO-2	0.96 ± 0.43	6.7 ± 3.0	0.78 ± 0.05	0.79 ± 0.04
Battaglia	0.85 ± 0.36	6.8 ± 2.9	0.77 ± 0.05	0.78 ± 0.04
Shaw	0.87 ± 0.39	6.8 ± 3.0	0.77 ± 0.05	0.78 ± 0.04

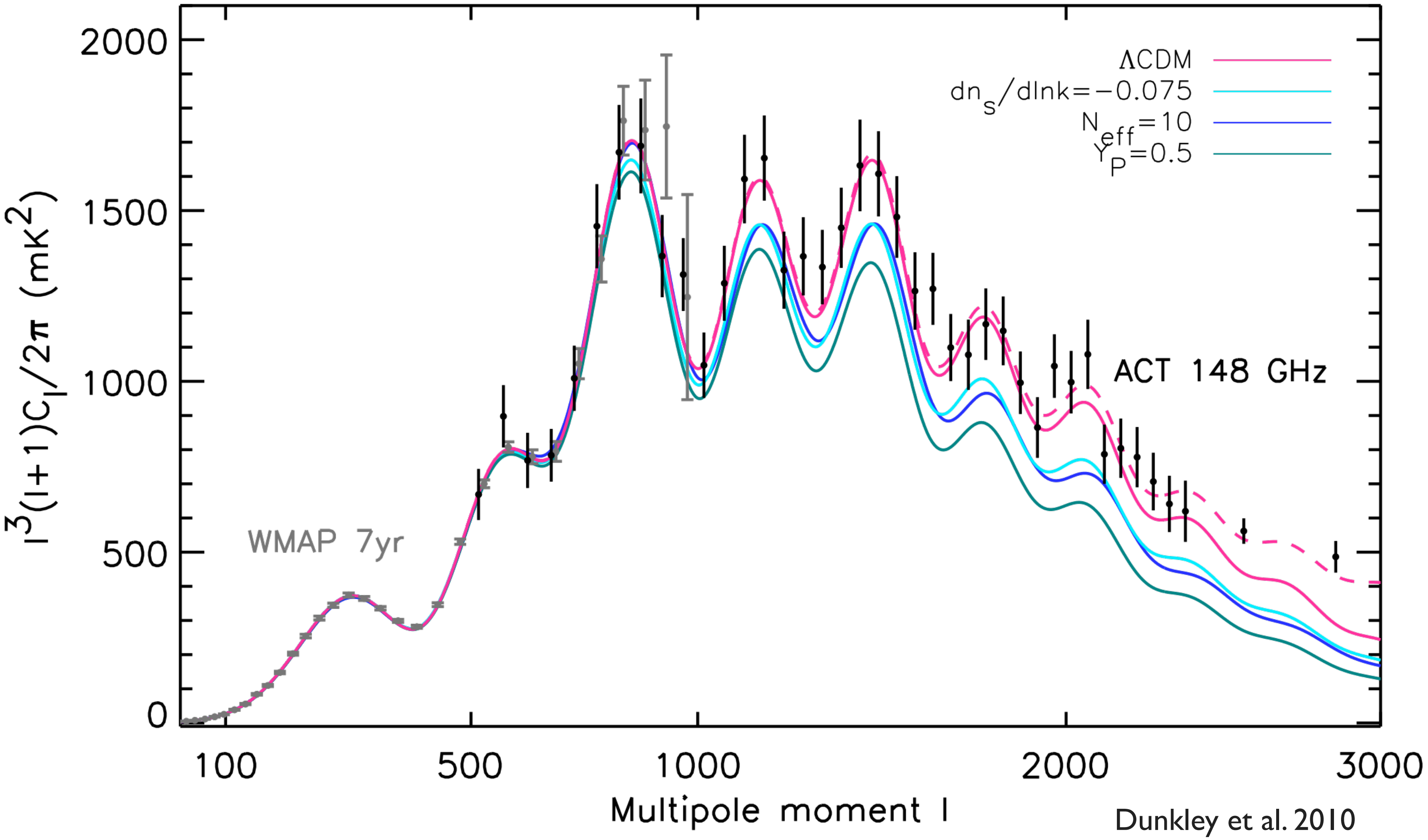
- SZ required at 95% level. Atsz=1 is prediction for σ8=1.
- ACT sees consistent power with SPT (0.4+-0.2) but also with simple gas model templates.
- Power at l=3000 is independent of template

- kSZ upper limit: <8 μK^2 at l=3000.
- With 218 GHz the SZ power is not strongly correlated with IR source power

Dunkley et al. 2010



ACT ‘low-ell’ power spectrum



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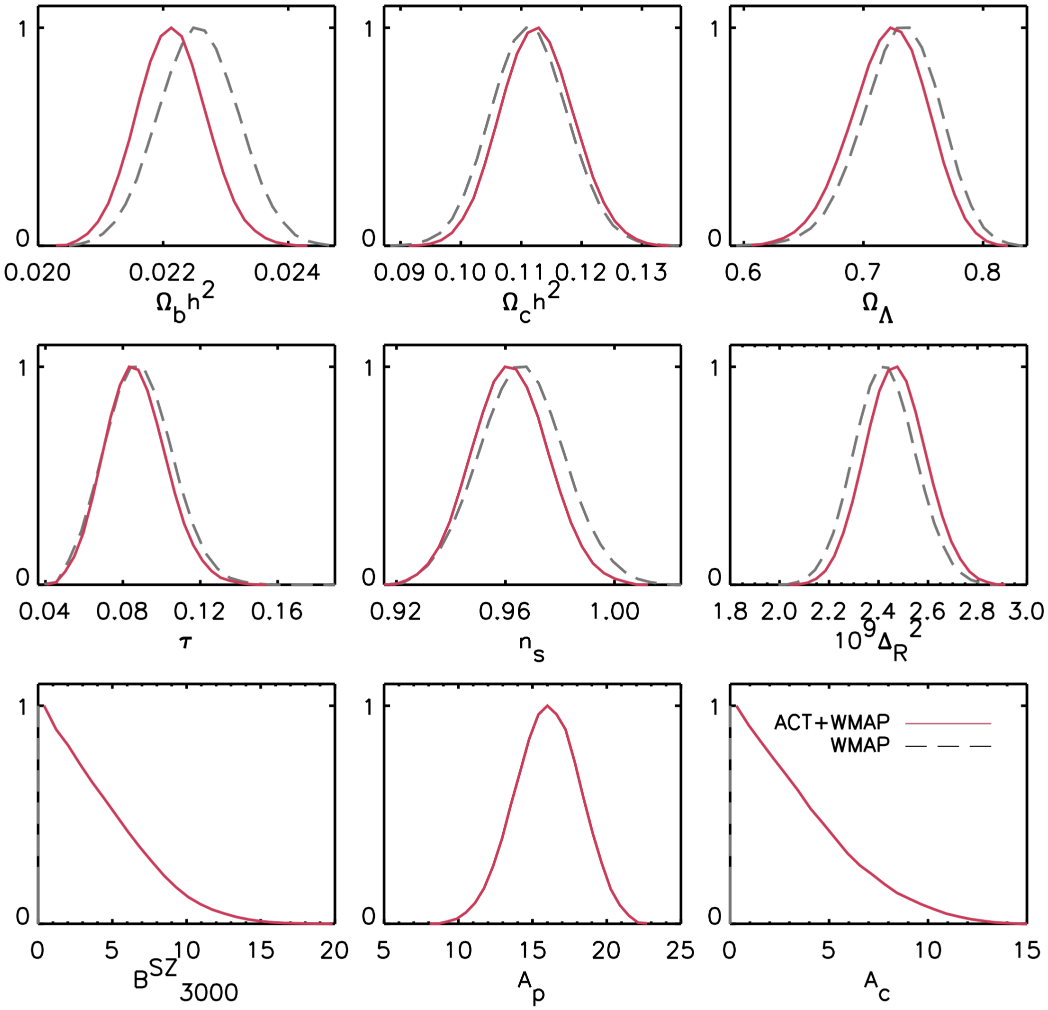
ΛCDM Parameters

- 6-parameter LCDM continues to fit the data well
- Scale invariant ns=1 now disfavored at 3σ from CMB data alone, in support of inflation.

- Simple secondary parameter model captures high ell behavior.



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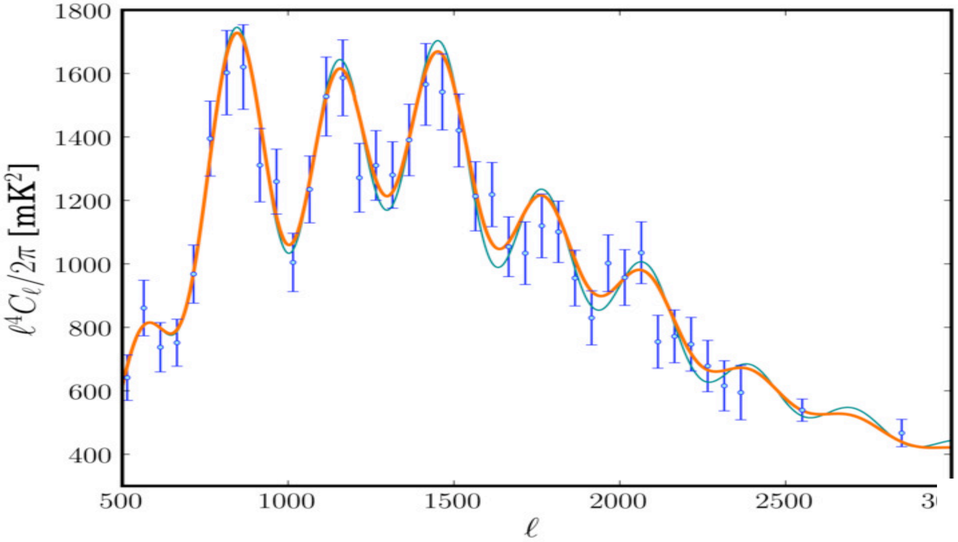
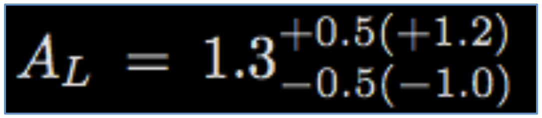
Gravitational lensing



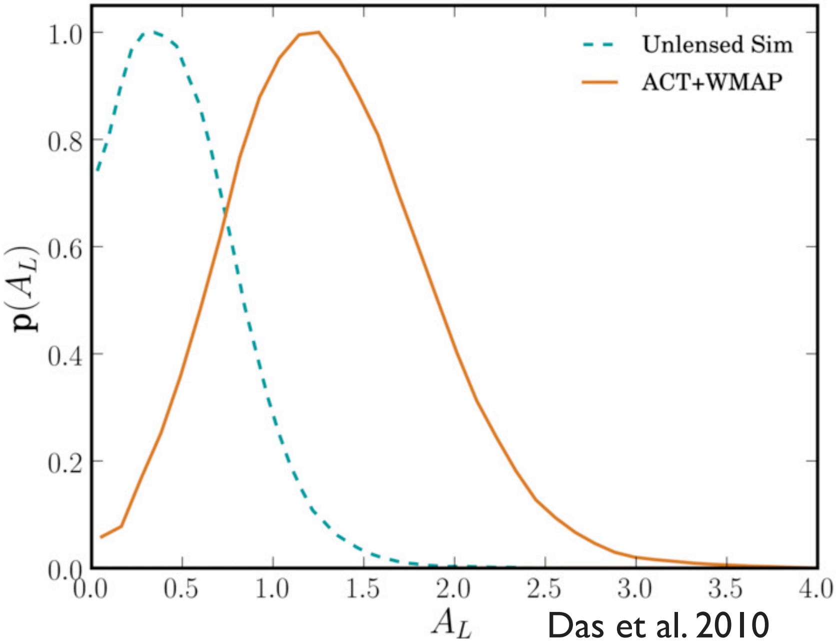
Usually assume lensing signal as standard. An unlensed spectrum would have sharper features. *(2-pt function not best lensing statistic, but provides first check)*

- 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.



$$A_L = 1.3^{+0.5(+1.2)}_{-0.5(-1.0)}$$



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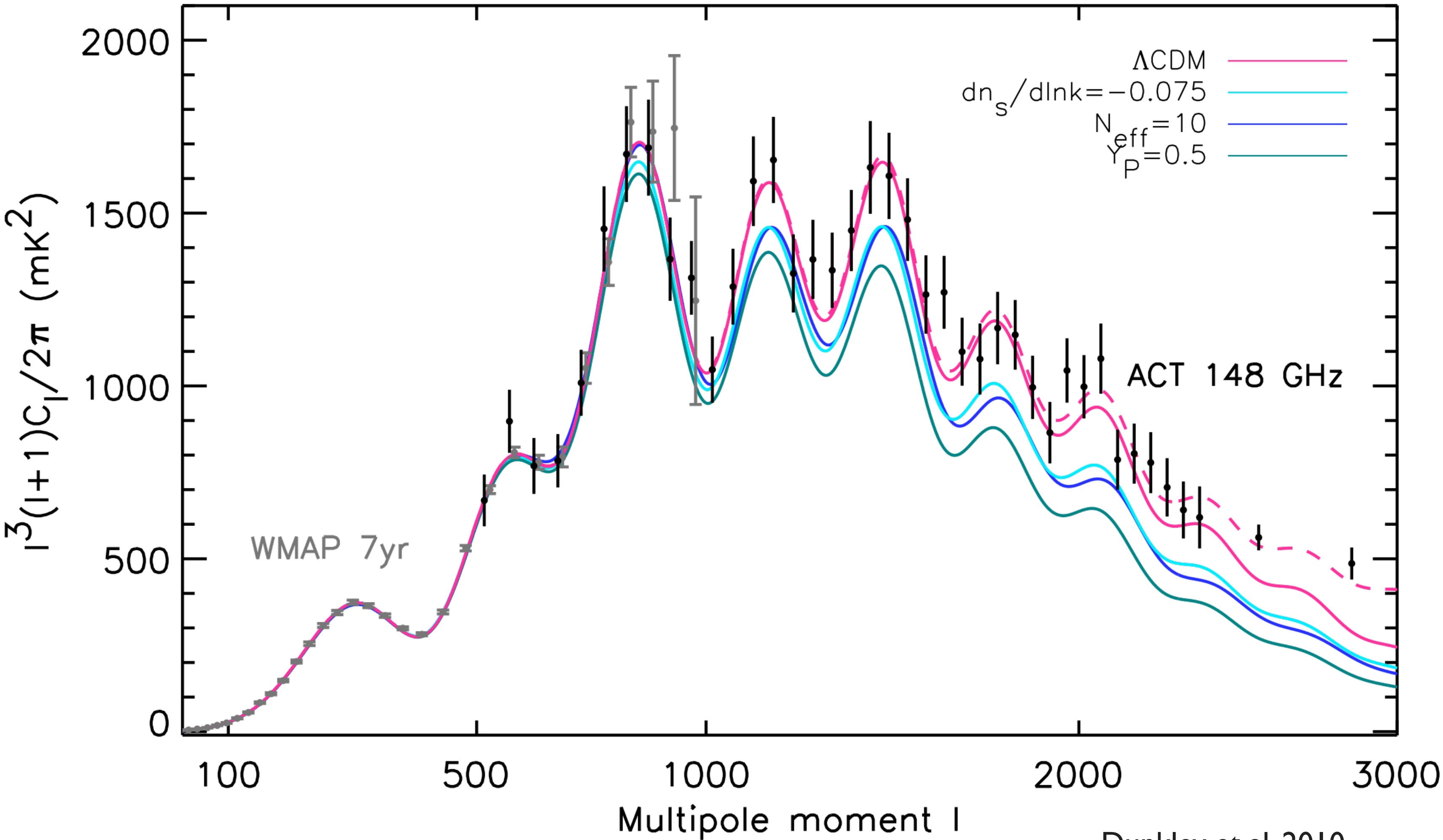
Beyond the standard model



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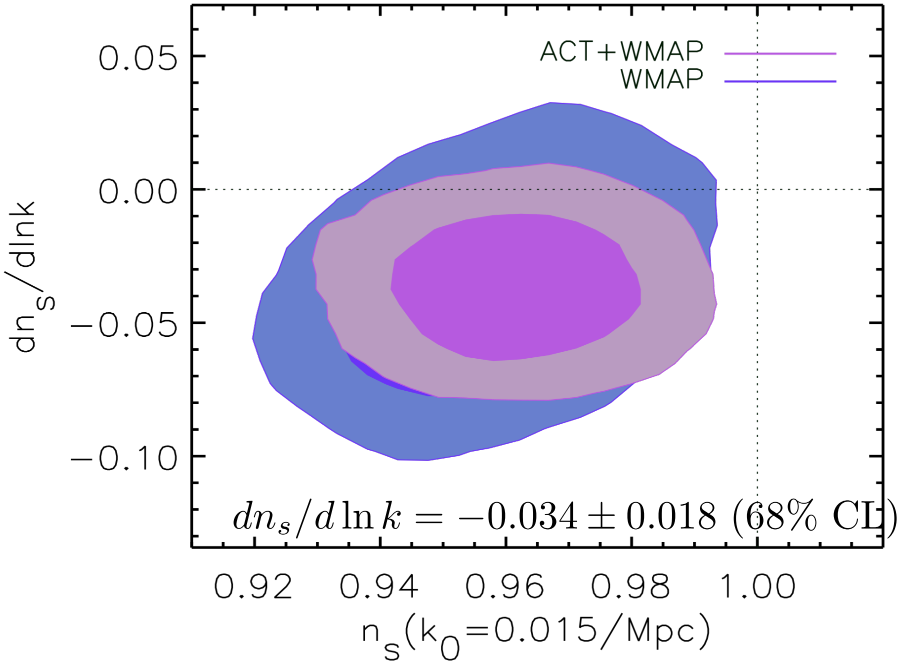
Inflation

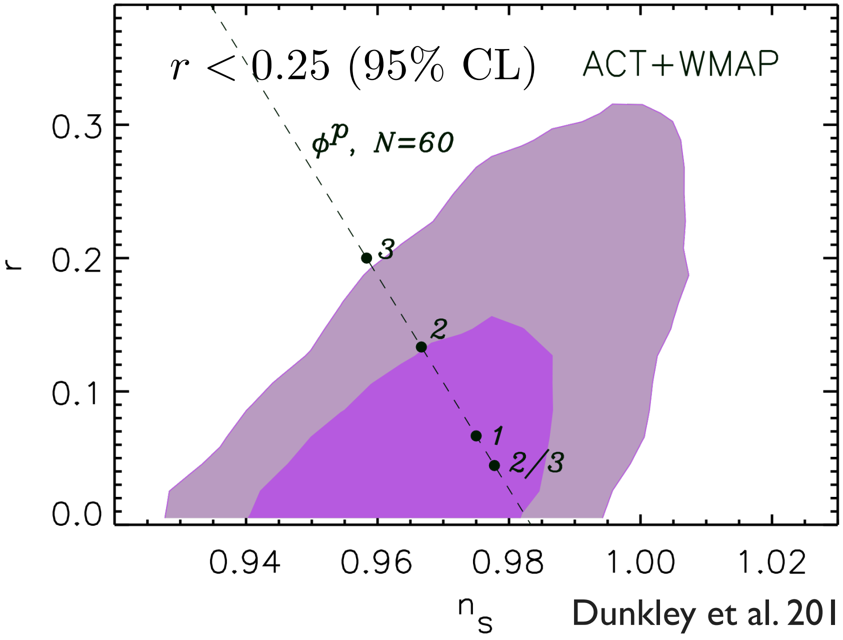
- Effective field theory, period of exponential expansion for > 60 e-folds
- Provides mechanism for seeding cosmic structure
- Look for
    - *Index deviating from 1*
    - *Running index*
    - *Gravitational waves*
    - Isocurvature fluctuations
    - Non-Gaussian signatures

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

$$dn_s/d\ln k = -0.024 \pm 0.015$$

$r < 0.19$ ACT+all





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Relativistic species

'Assume' N=3 neutrino species.

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

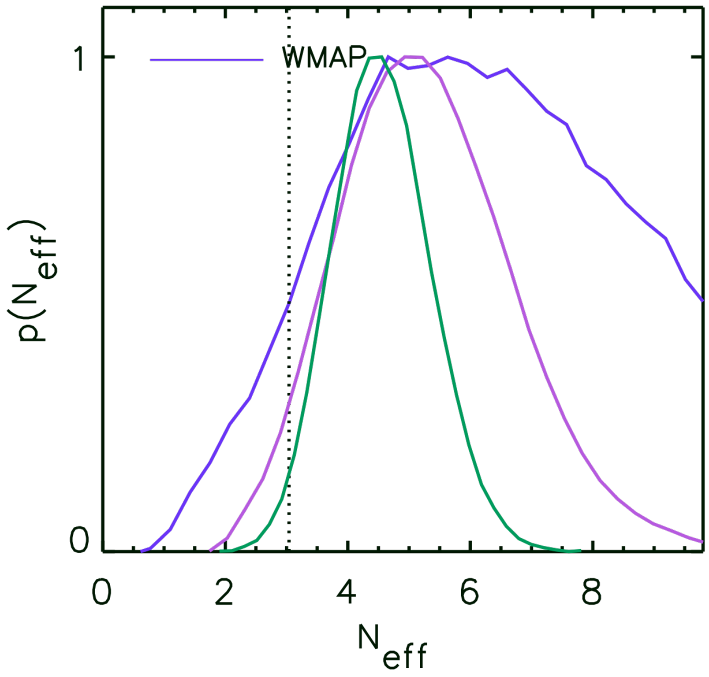
More species, longer radiation domination.
Changing Neff changes equality redshift.

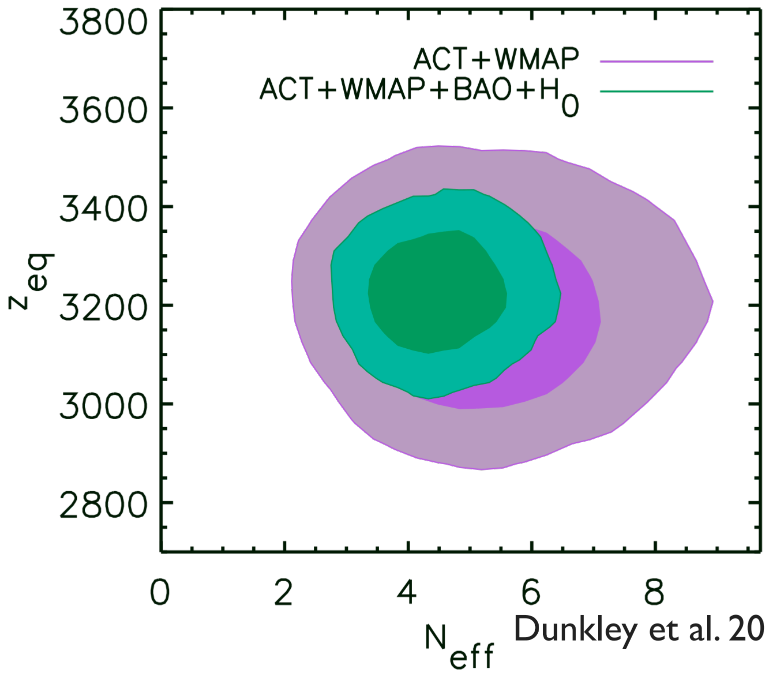
Also - species suppress early acoustic oscillations in primary CMB, and phase shift in primary CMB. Distinct to zeq.

For ACT+WMAP we find:

$$\boxed{N_{\rm eff} = 5.3 \pm 1.3 \ (68\% \ \mathrm{CL})}$$

Errors reduced to 0.75 with BAO and H0 measures. Mean value higher than 3.04 but N=3 still fits data well!





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Primordial Helium

Assume Yp=0.24, predicted by BBN.

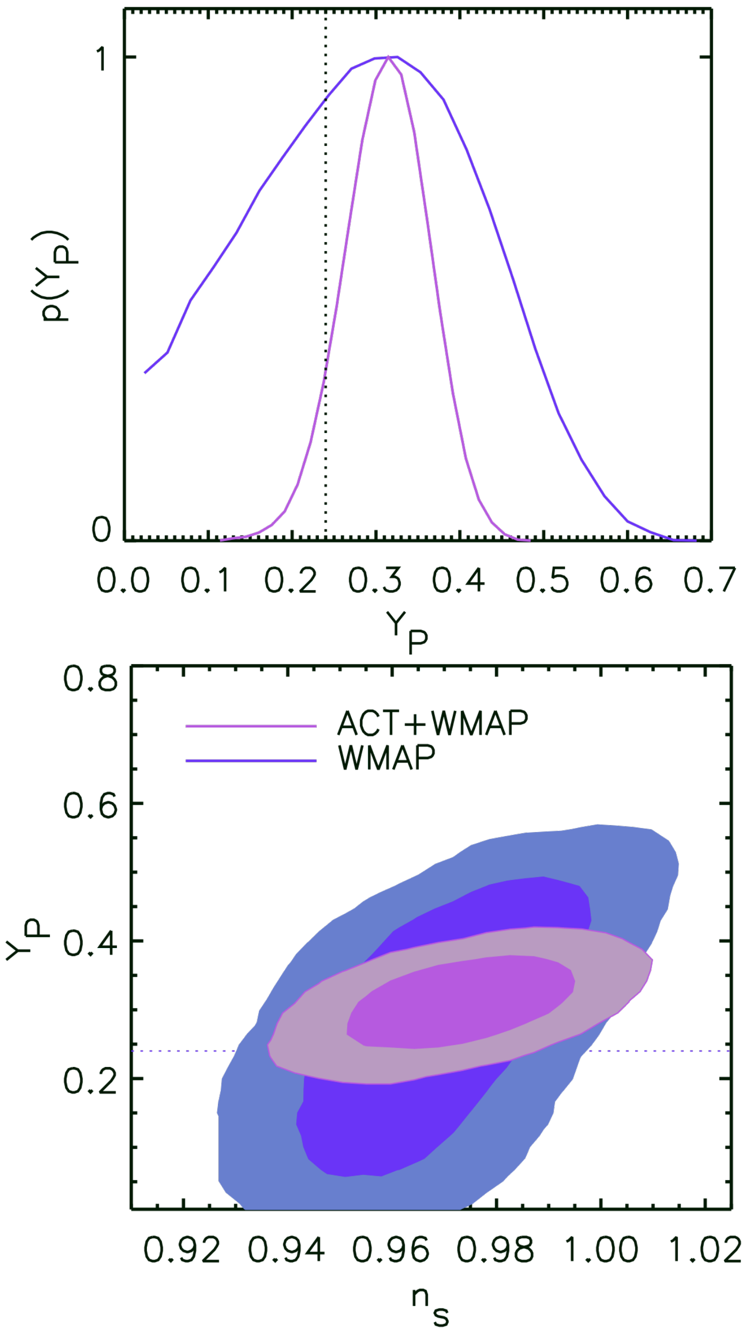
$$Y_P = 0.2485 + 0.0016[(273.9\Omega_b h^2 - 6) + 100(S - 1)], \quad (27)$$

where $S^2 = 1 + (7/43)(N_{\rm eff} - 3)$ (see e.g., Kneller & Steigman 2004; Steigman 2007; Simha & Steigman 2008).

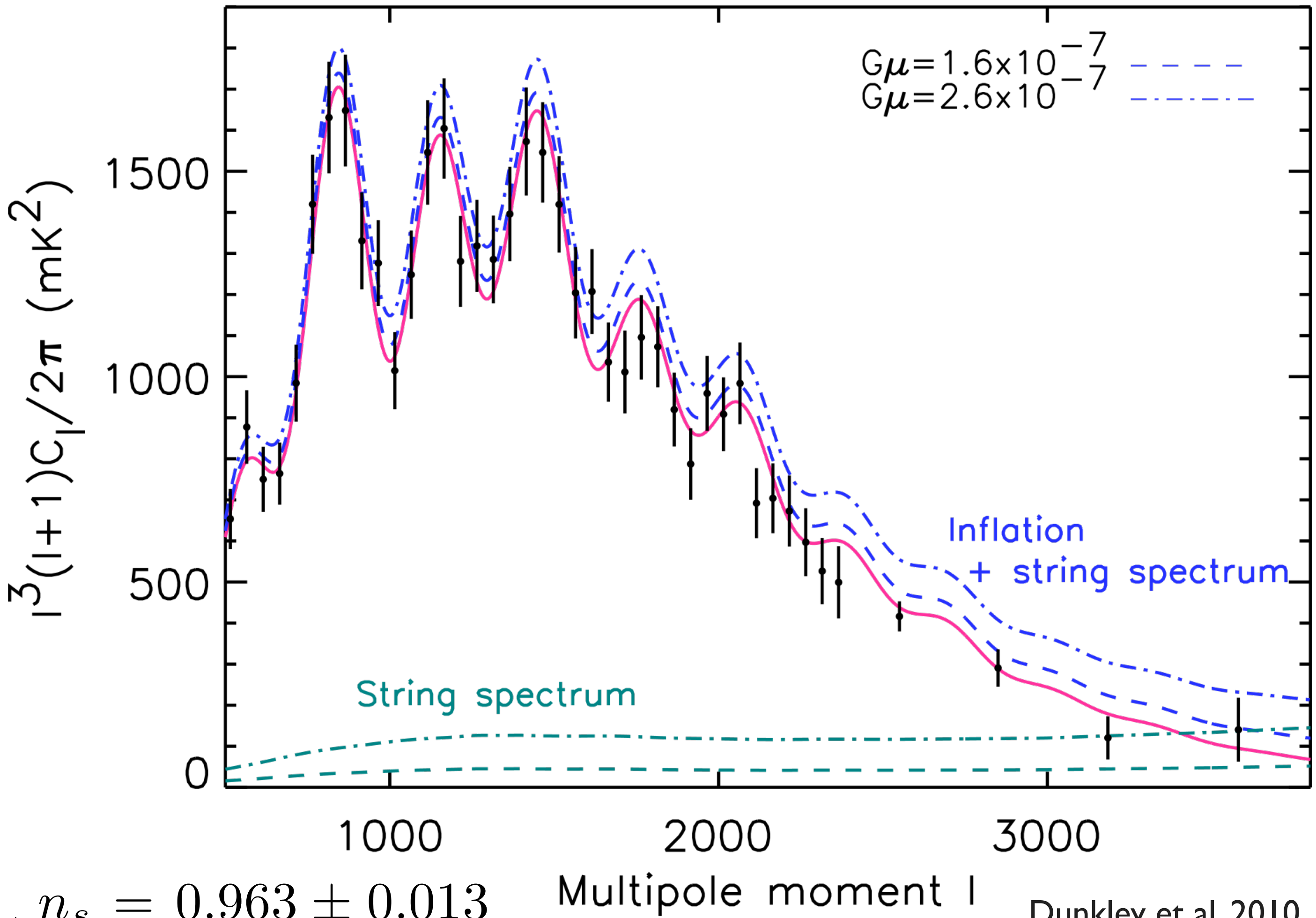
- More helium decreases electron density, increasing damping.
- A universe with no Helium is now ruled out at 6 sigma from ACT+WMAP – it would produce too much small scale power.

$$Y_P = 0.313 \pm 0.044 \ (68\% \ \mathrm{CL})$$

Dunkley et al. 2010



Cosmic strings? – tighter bounds



$n_s = 0.963 \pm 0.013$

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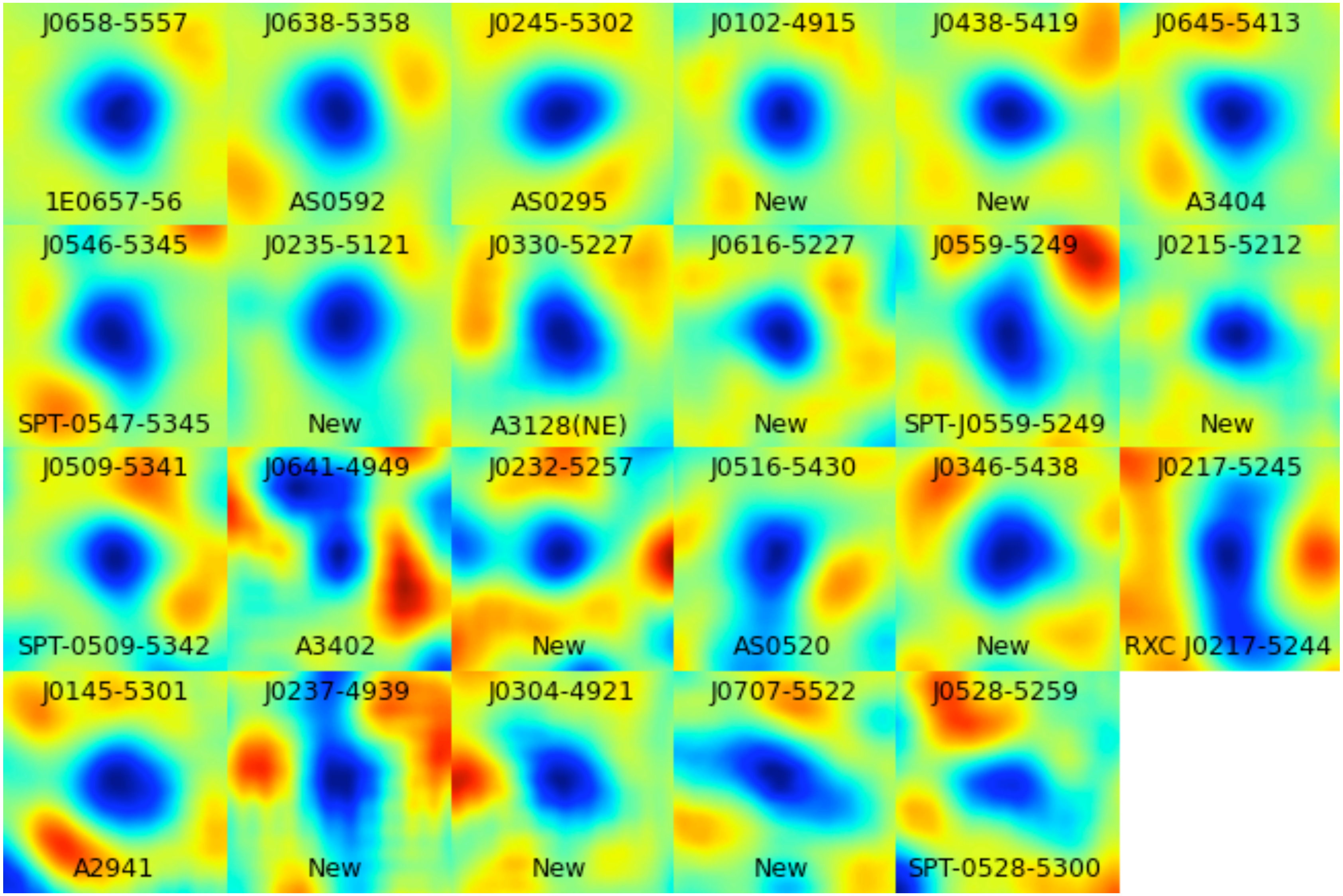
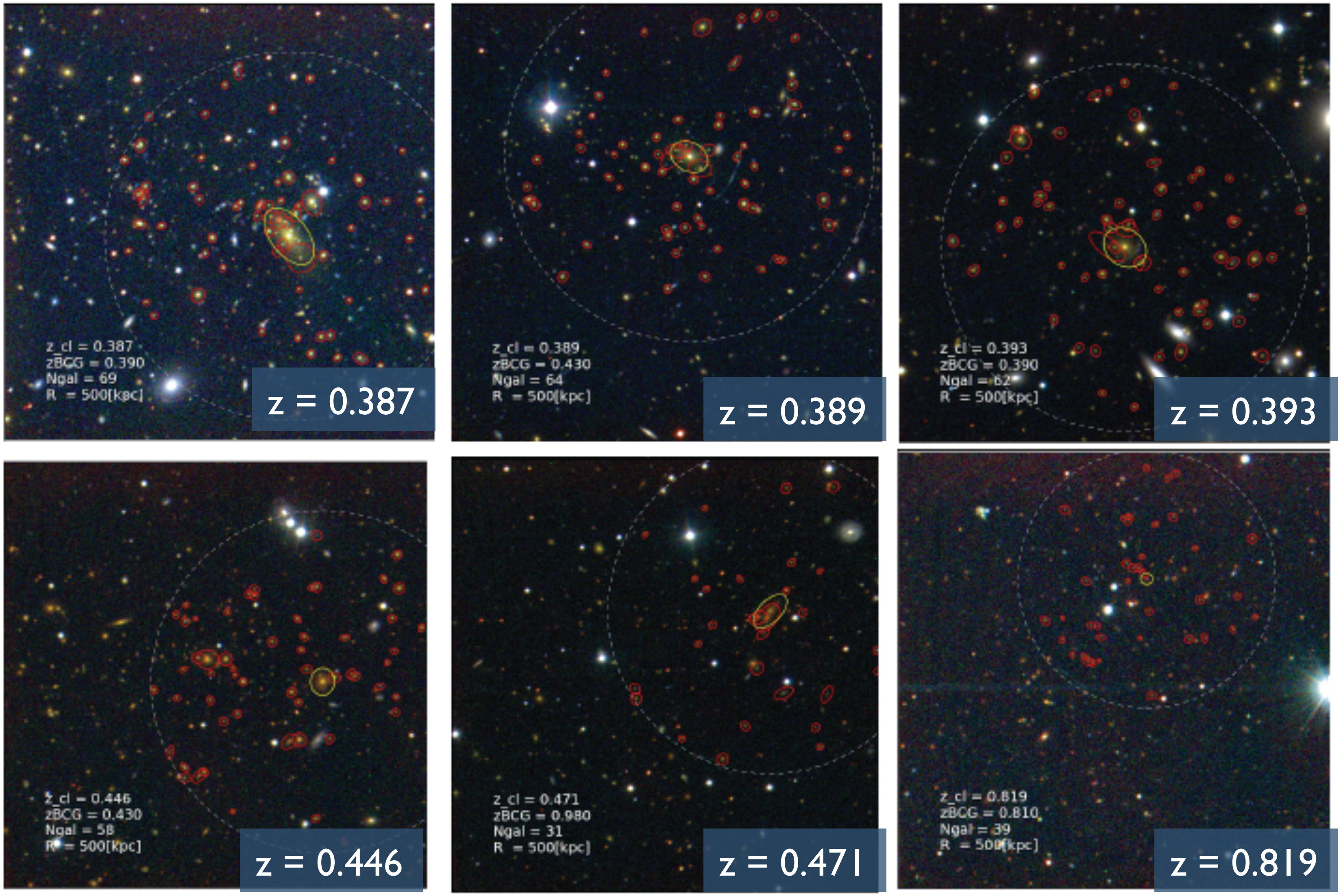
SZ cluster detections



Marriage et al. 2010 in prep

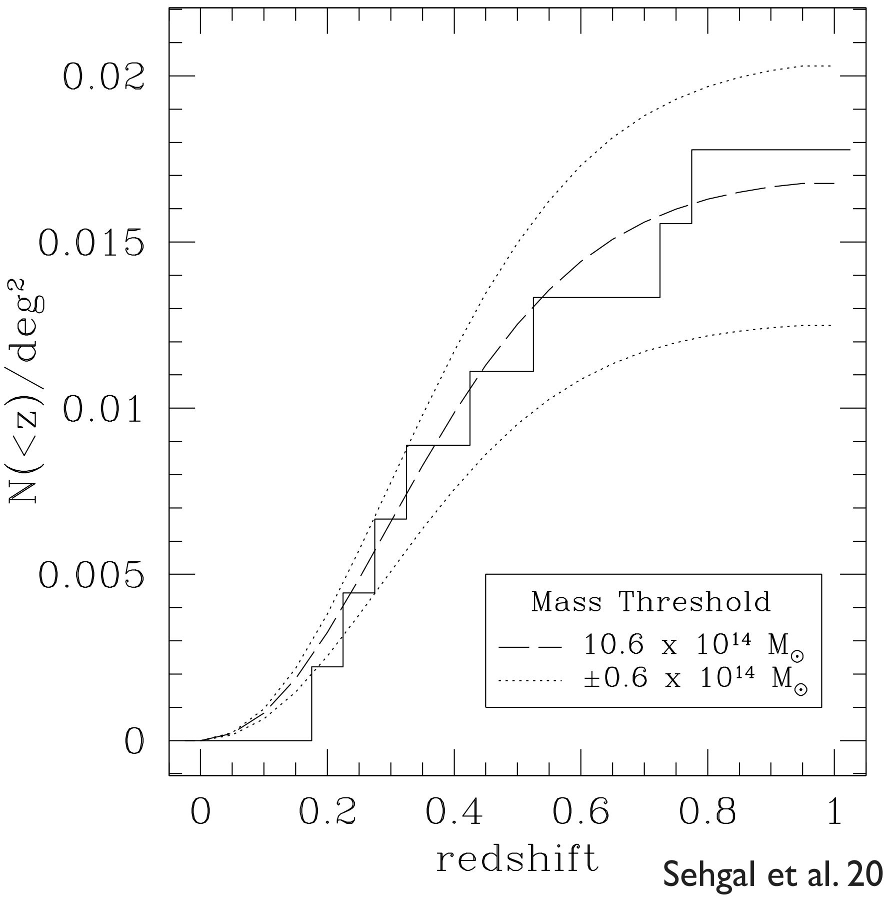
Optical follow-up with NTT



Menanteau et al. 2010

Cluster number counts

Concordance cosmological model fits the data well for a given mass limit



Sehgal et al. 2010 in prep

Summary

- There are multiple physical components in small-scale microwave sky. A simple model fits the ACT 148 and 218 GHz data.

- Clustering of unresolved IR sources is needed; and a preference for non-zero SZ power from galaxy clusters, consistent with expectations.

- The ΛCDM model continues to fit the data, and lensing of the CMB is preferred at almost 3σ; ACT's longer level arm gives stronger new constraints on inflationary parameters, and probes non-standard physics through testing relativistic species, detecting primordial helium at 6σ, and constraining cosmic string contributions.

- ACT continues to work with 1000s detectors on the sky. Taken ~18 months of data over ~1300 sq deg, and will stop end of 2010 to make way for the funded ACTPol.