ACT(POL)

Sudeep Das

BERKELEY CENTER FOR COSMOLOGICAL PHYSICS

THE SUB-MILLIMETER UNIVERSE: THE CCAT VIEW.
CORNELL UNIVERSITY
NOV 12-13, 2010

The Atacama Cosmology Telescope (ACT)

The **Atacama Cosmology Telescope** (**ACT**) is a six-metre telescope on Cerro Toco in the Atacama Desert in the north of Chile. It is designed to make high-resolution, microwave-wavelength surveys of the sky in order to study the cosmic microwave background radiation (CMB). At an altitude of 5190 metres (17030 feet), it is currently the highest permanent, ground-based telescope in the world.

- 6 m primary mirror. Off-axis Gregorian telescope
- ~1 arcmin resolution
- 148, 218, 277 GHz channels
- 3000 detector elements

Swetz et al. (2010)

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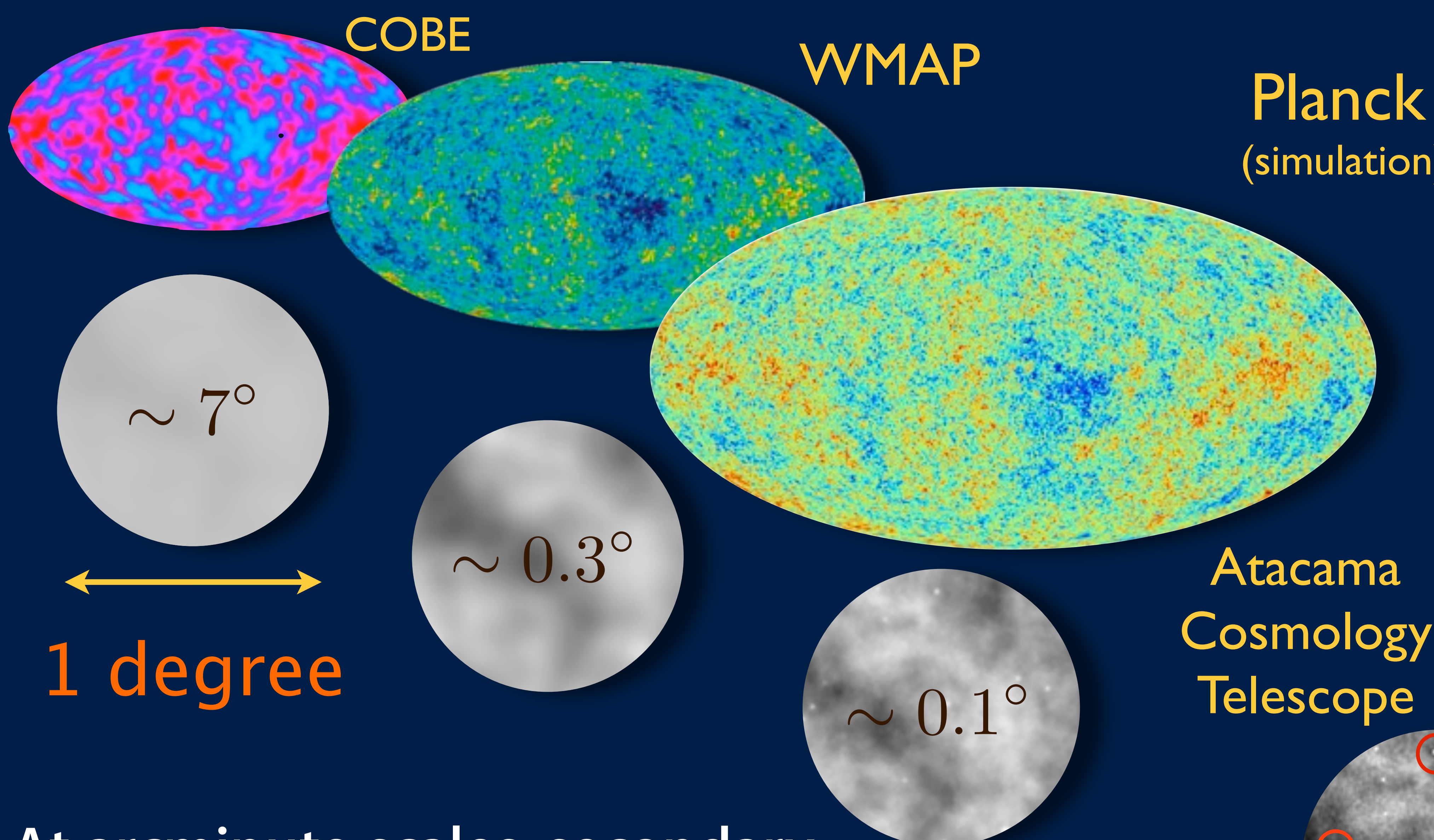
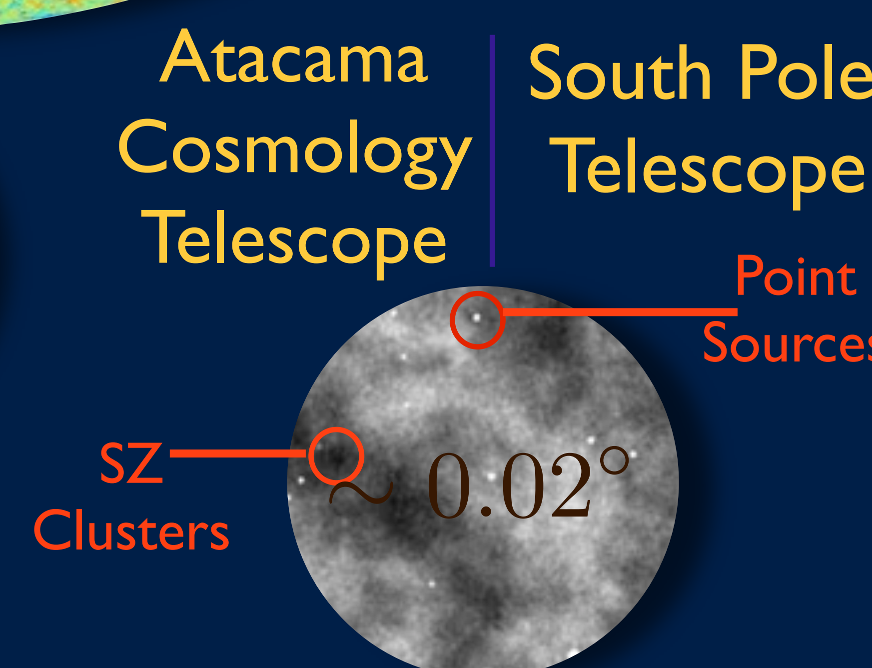
New view of the CMB





At arcminute scales, secondary anisotropies become important and bring us in contact with astrophysics.

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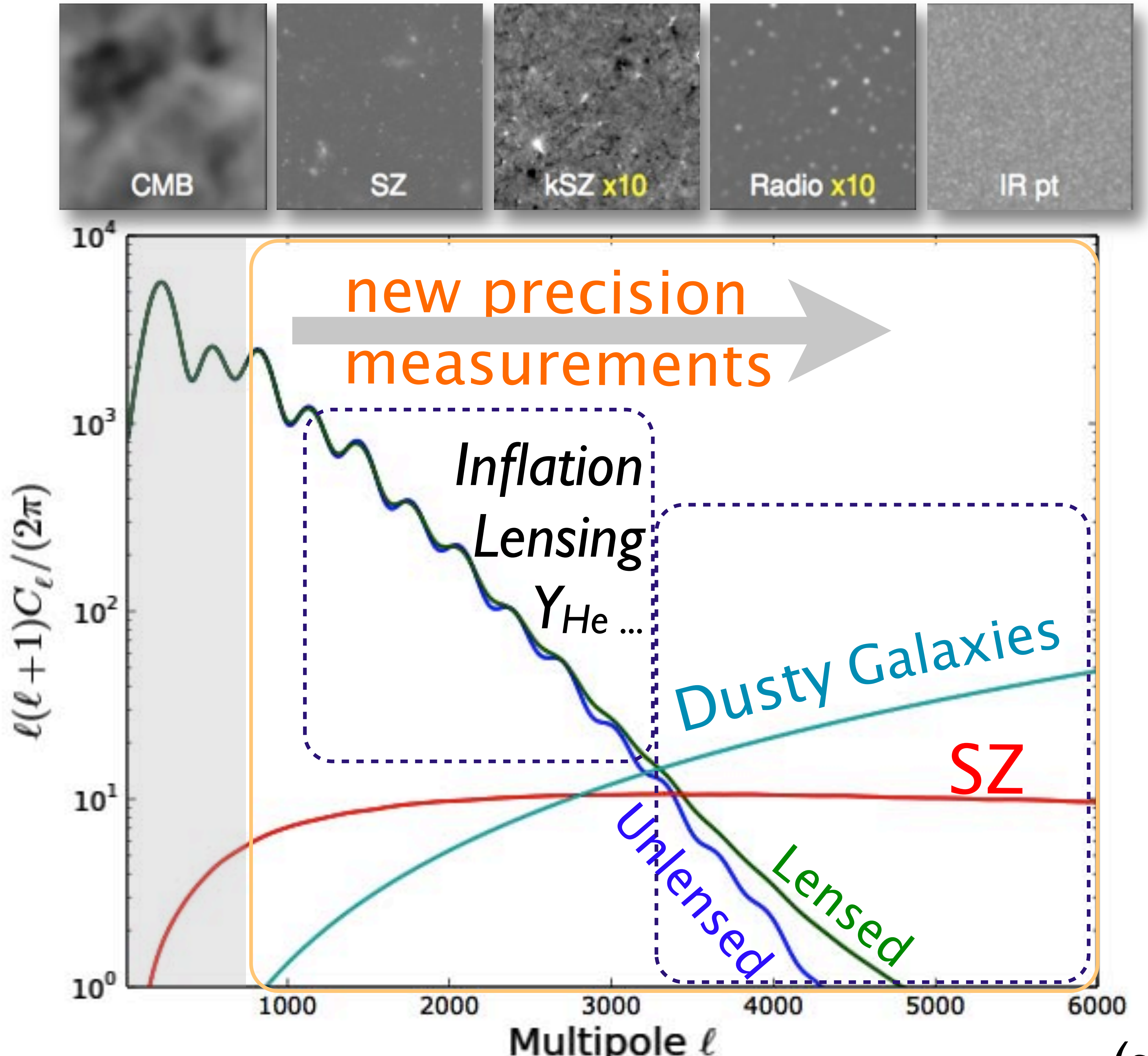
NEW VIEW OF THE CMB



Higher order peaks give leverage on cosmology.

Secondary anisotropies (SZ, lensing) lets us probe geometry, growth, reionization, etc ...

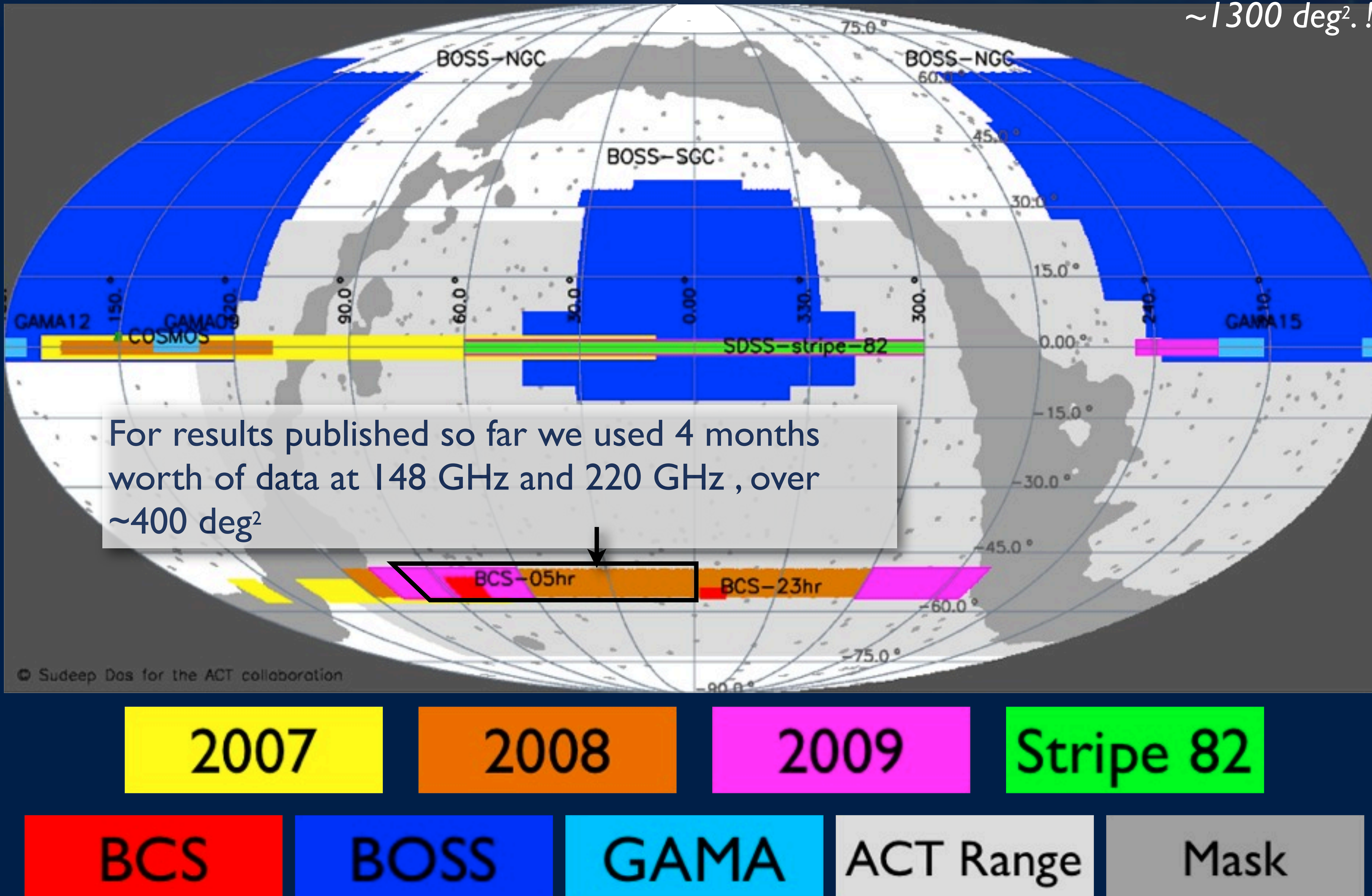
Dusty galaxies give a window into high-z galaxy clustering and evolution.

(see, e.g. Galli et al. 2010)

ACT
The Present

Observations

ACT has taken 18 months of data at 3 frequencies already, over ~1300 deg^2. !



For results published so far we used 4 months worth of data at 148 GHz and 220 GHz , over ~400 deg^2

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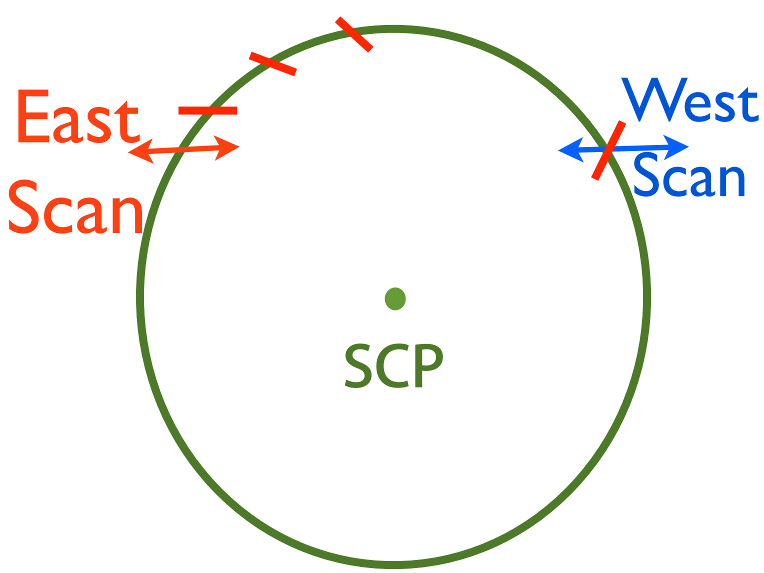
Publications

Instrument	Swetz et al. (2010)	arXiv: 1007.029
WMAP calibration	Hajian et al. (2010)	arXiv: 1009.0777
Power Spectrum and Parameters	Fowler et al. (2010)	arXiv: 1001.2934
	Das et al. (2010)	arXiv: 1009.0847
	Dunkley et al. (2010)	arXiv: 1009.0866
SZ clusters - detection, followup, and cluster cosmology	Hincks et al (2010)	arXiv: 0907.0461
	Marriage et al. (2010a)	arXiv: 1010.1065
	Menanteau et al. (2010)	arXiv: 1006.5126
	Sehgal et al. (2010)	arXiv: 1010.1025
Point Source Catalog	Marriage et al. (2010b)	arXiv: 1007.5256

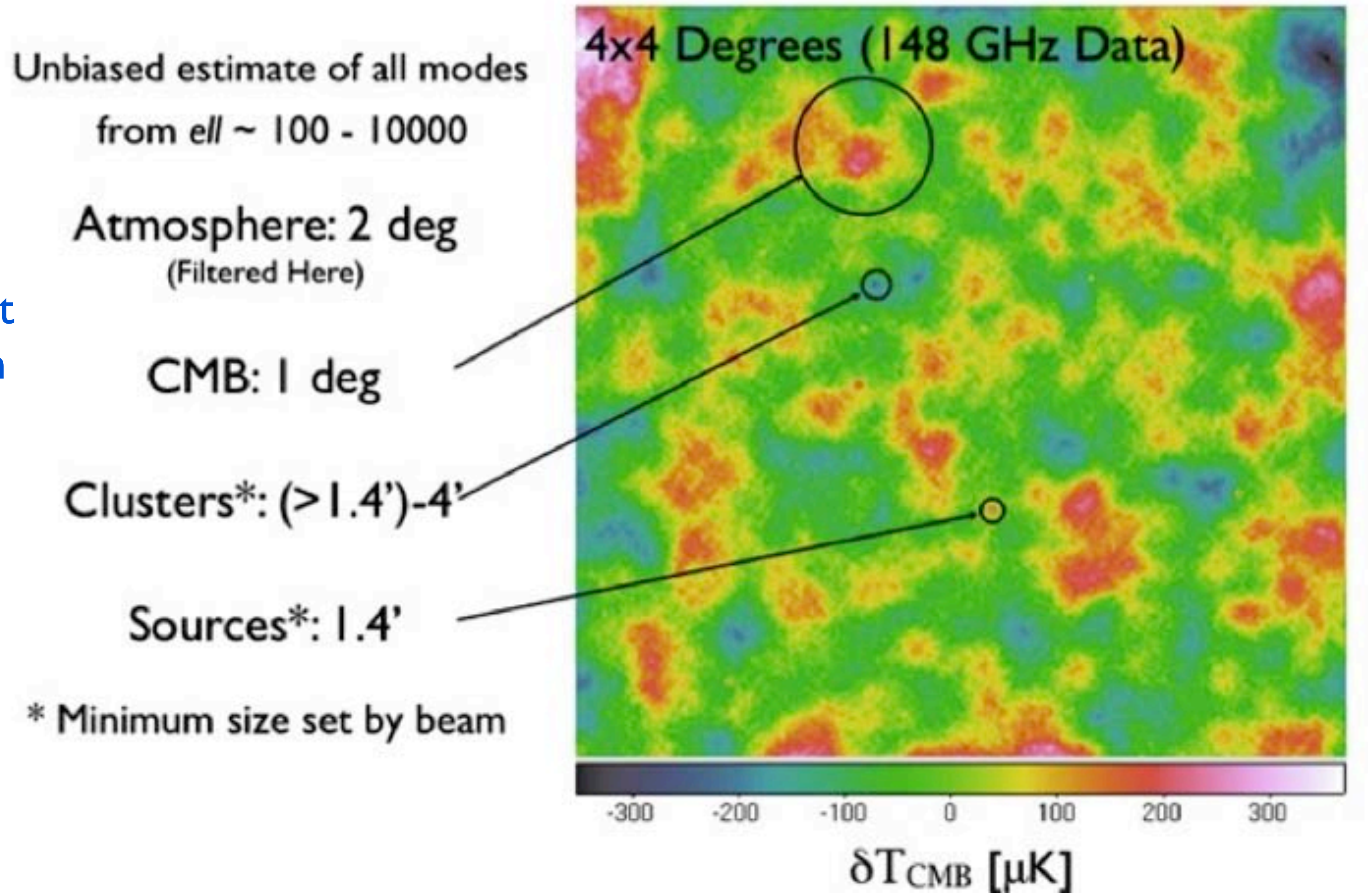
Data reduction and Map Making

- Relative Calibration
- Pointing and Astrometry
- Data Selection

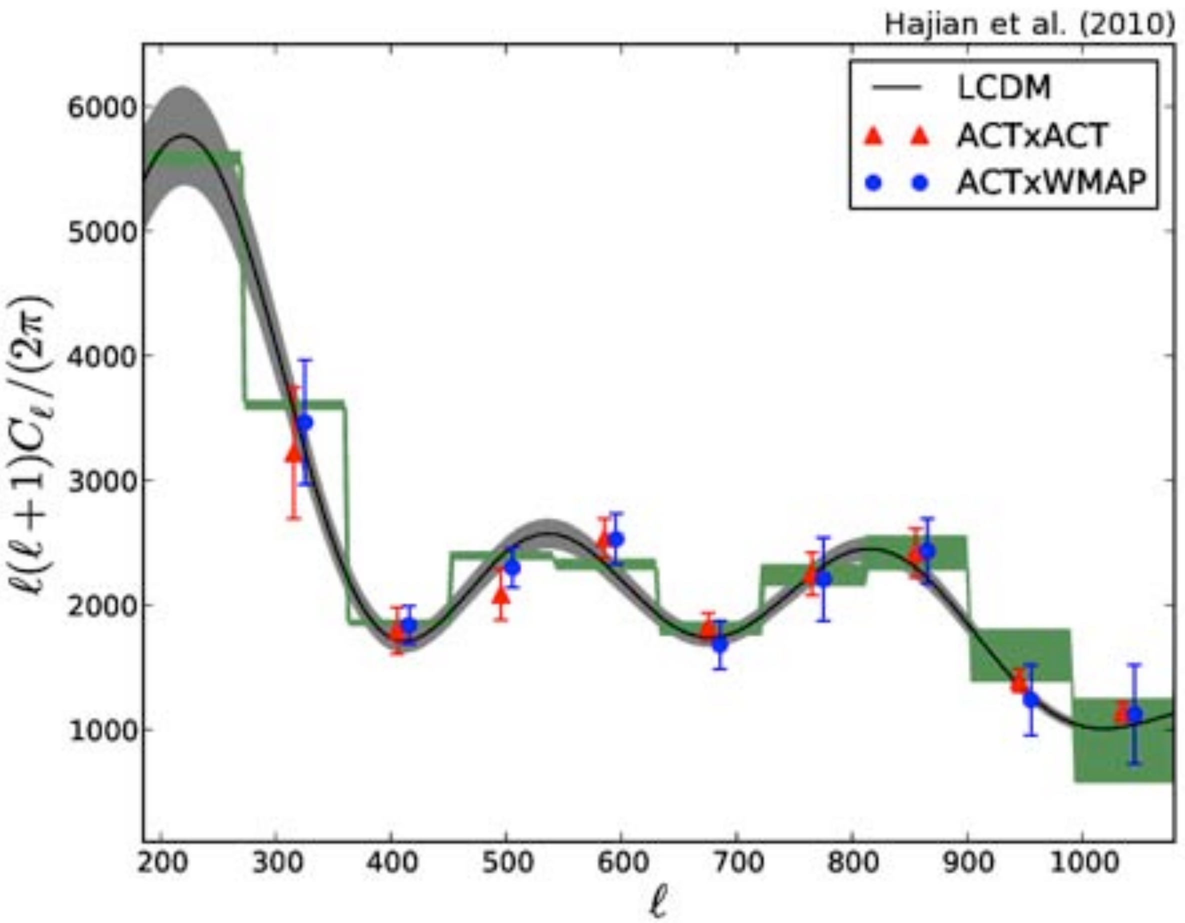
- **Map-making:** Cross-linked observations help us solve for the maximum-likelihood map: true representation of the sky. Gain back modes suppressed by filtering through iteration. For one season of data, needs 100,000 CPU hours (lead: J. Sievers)



Cross-linking

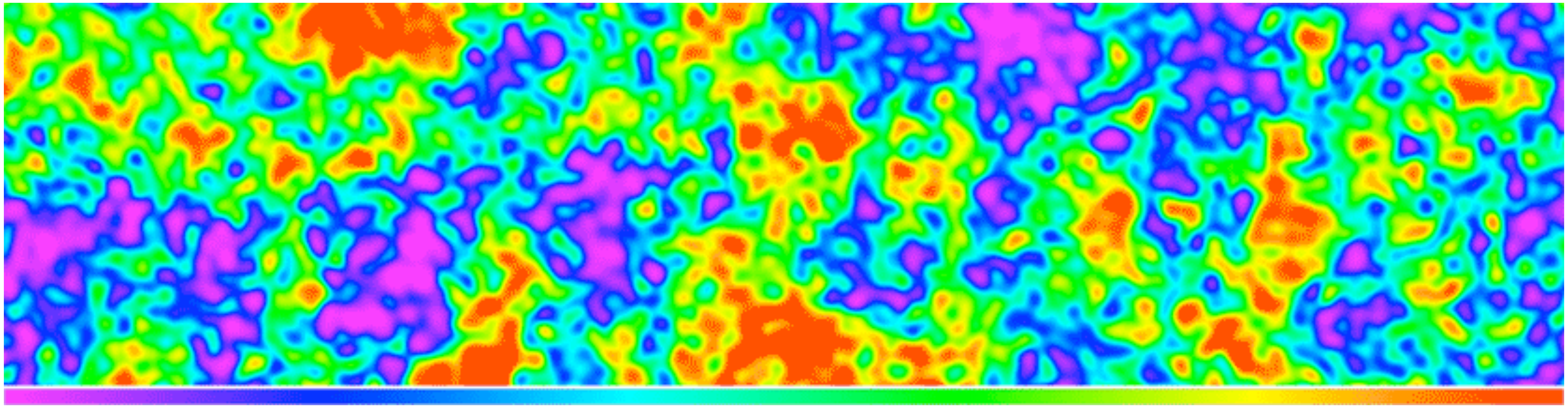


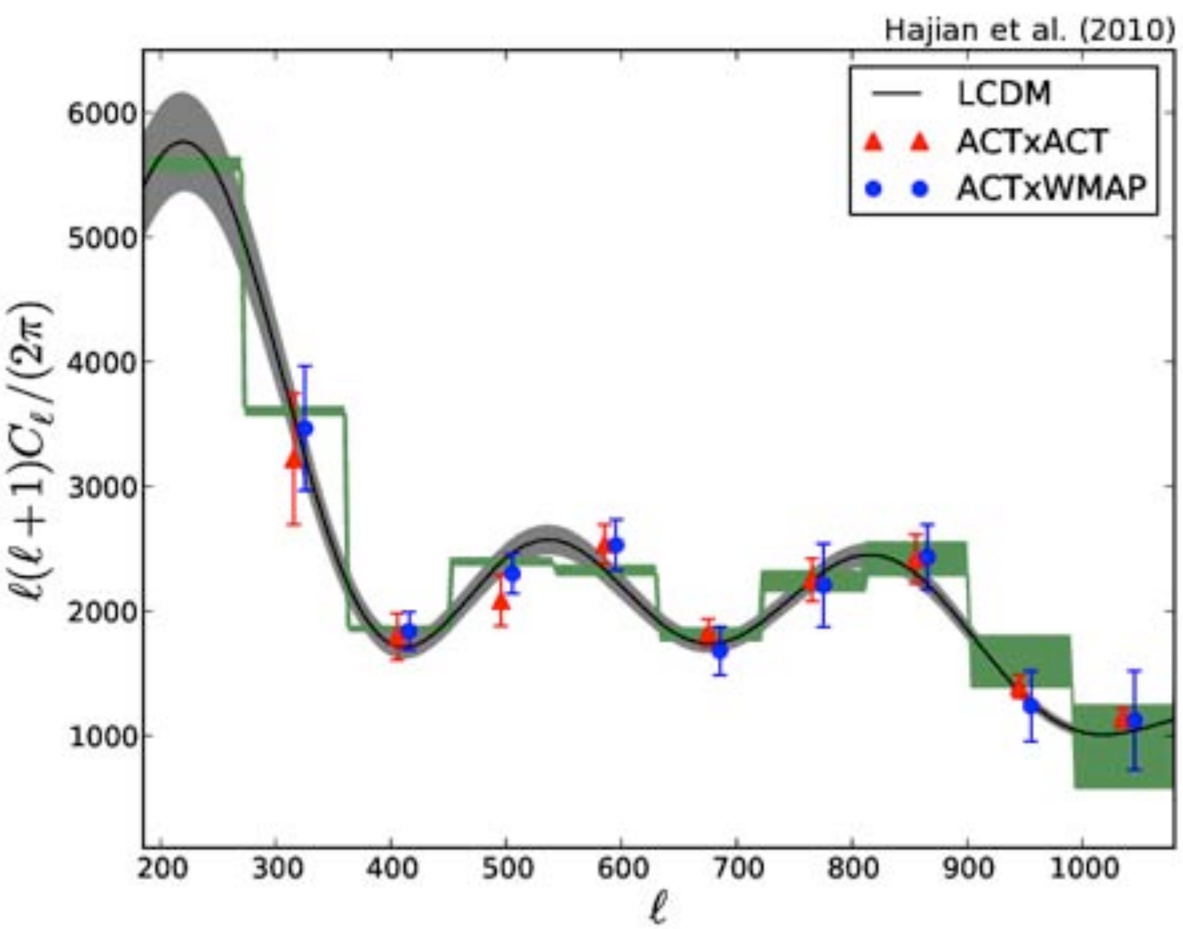
WMAP AND ACT



- ACT sees the same hot and cold spots as WMAP, but at a much higher angular resolution.
- We cross-correlate ACT maps with WMAP maps to estimate the absolute calibration for the ACT maps.
- For our148 GHz maps, we achieve a 2% calibration uncertainty.

WMAP and ACT





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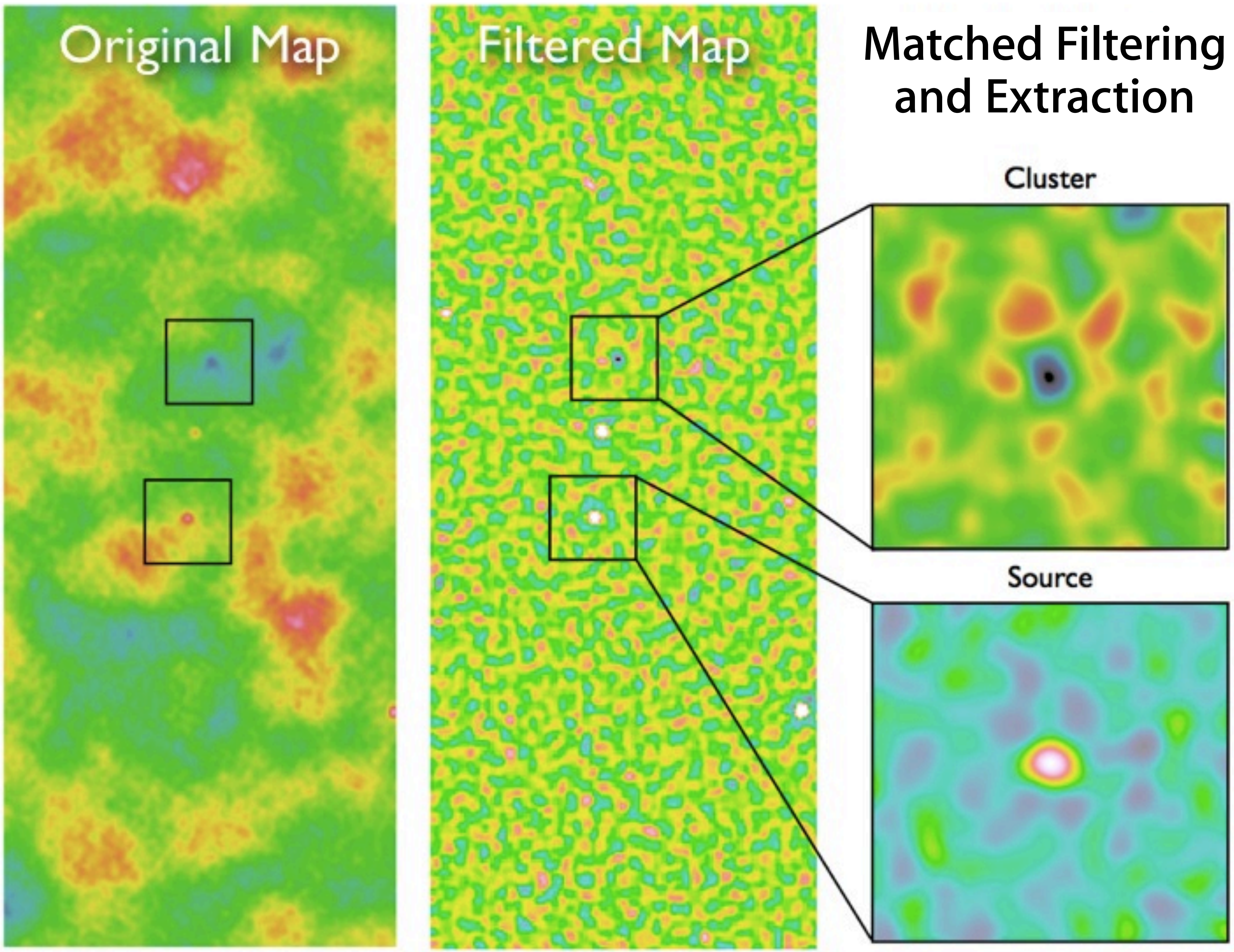
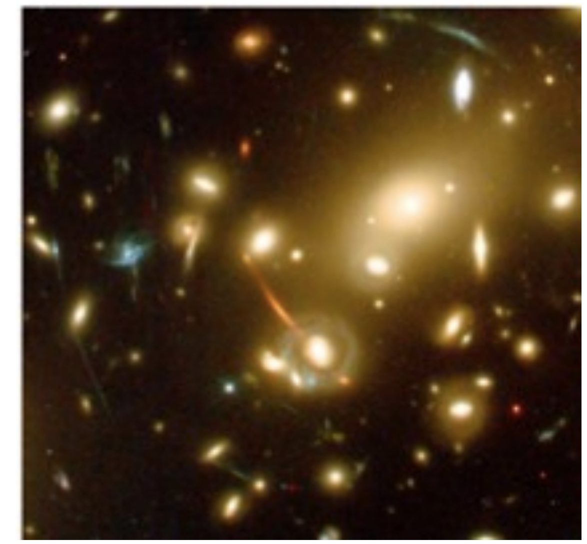
Hajian et al. (2010)

Smallest Scales: Point Sources & Clusters



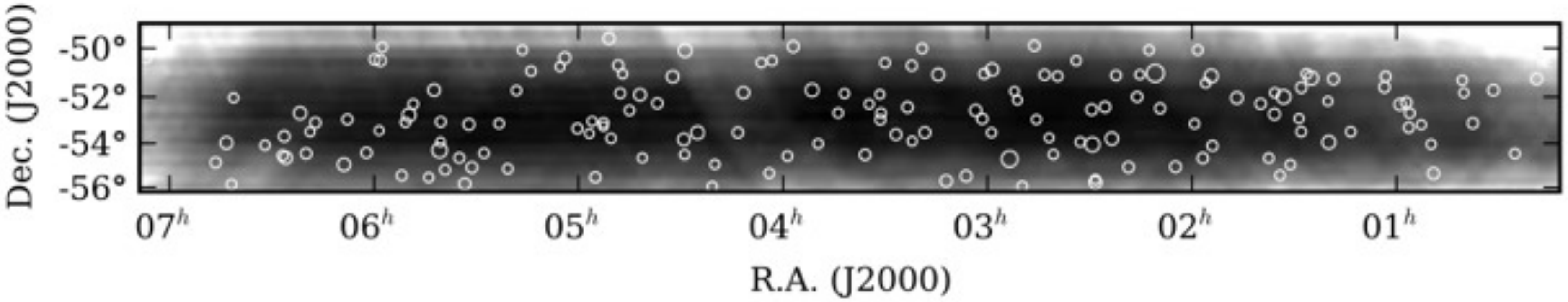
Matched Filtering and Extraction

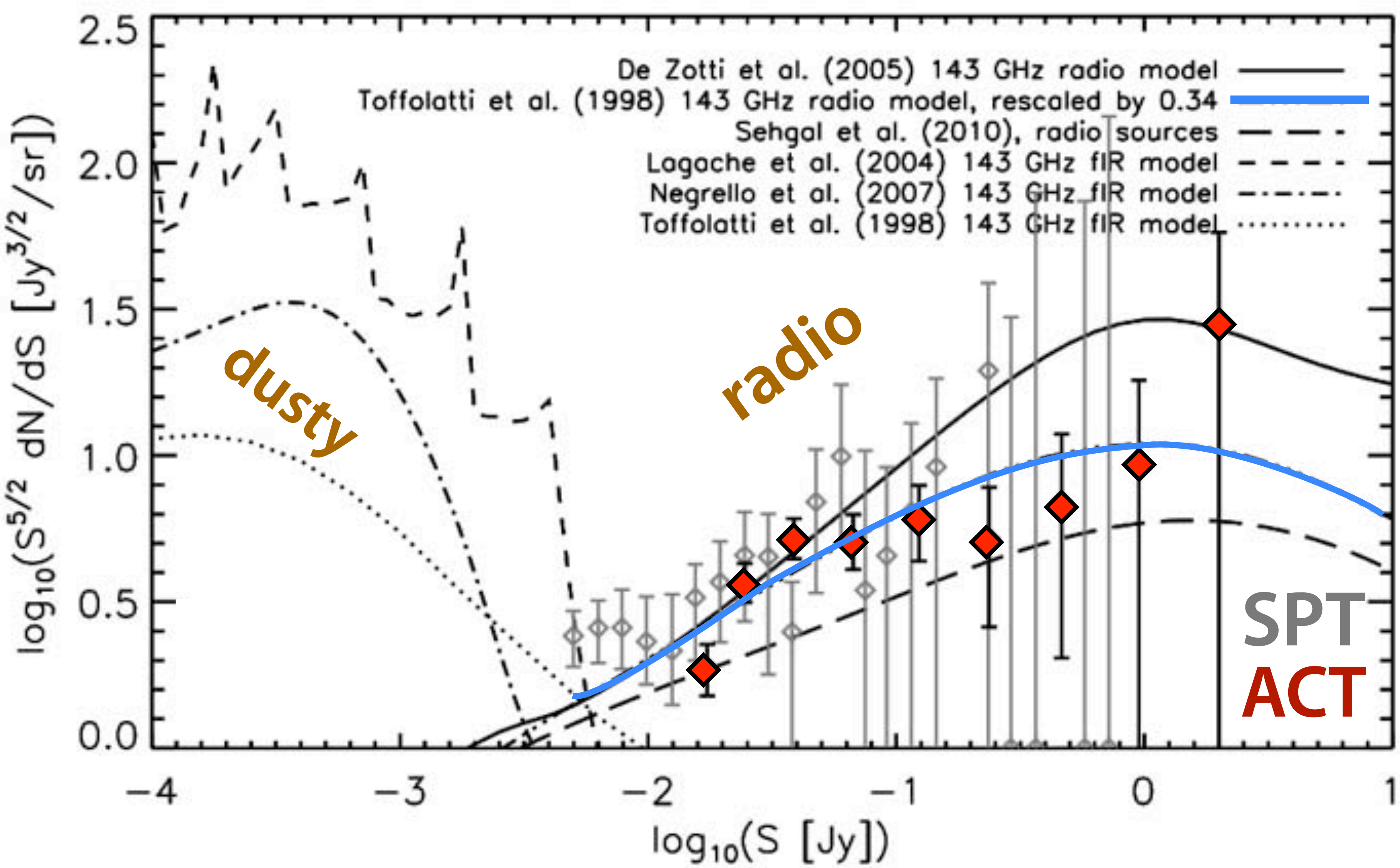


Flat Sprectrum Radio Sources

Cen A, LABOCA

Extragalactic point sources @ 148 GHz

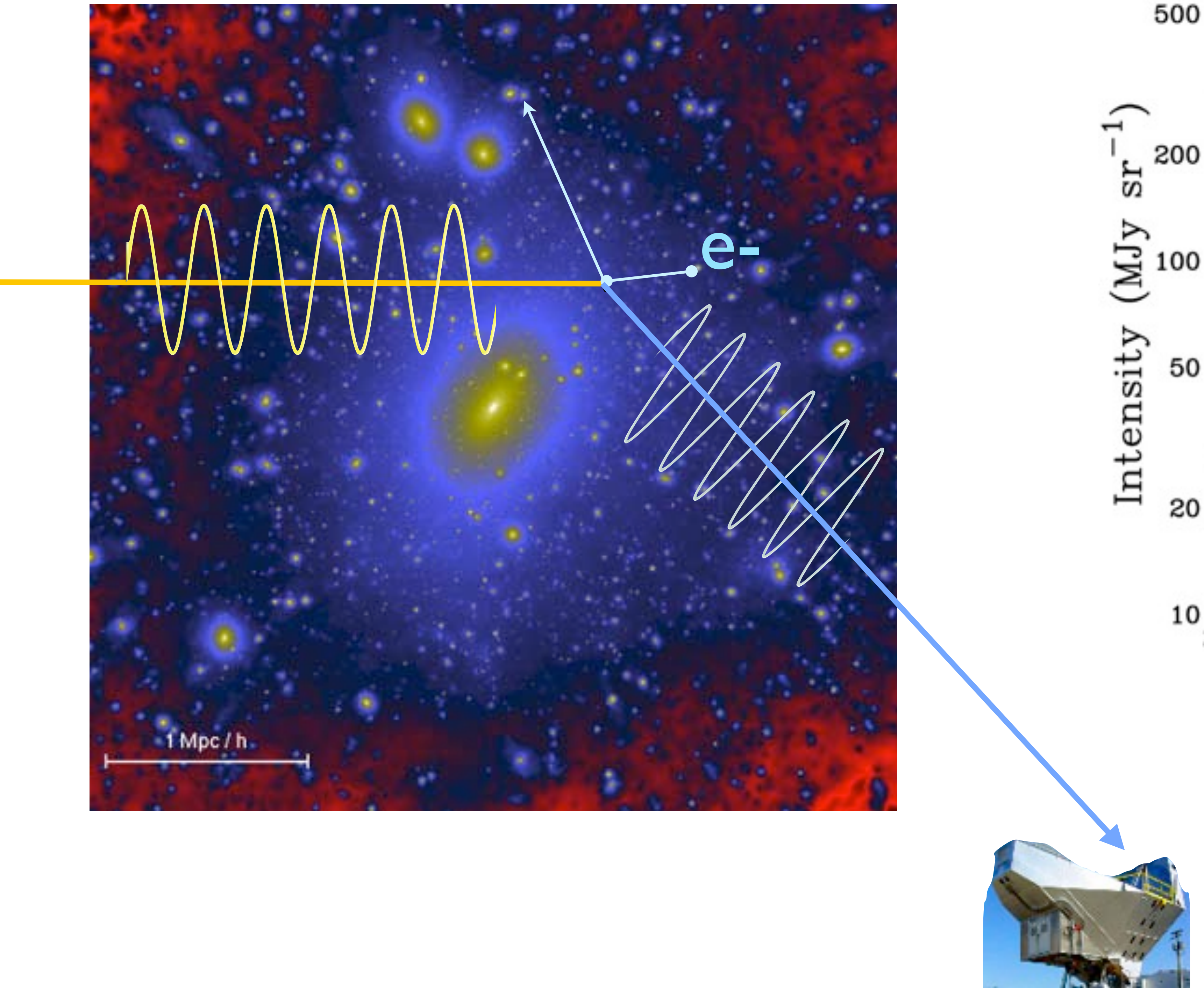


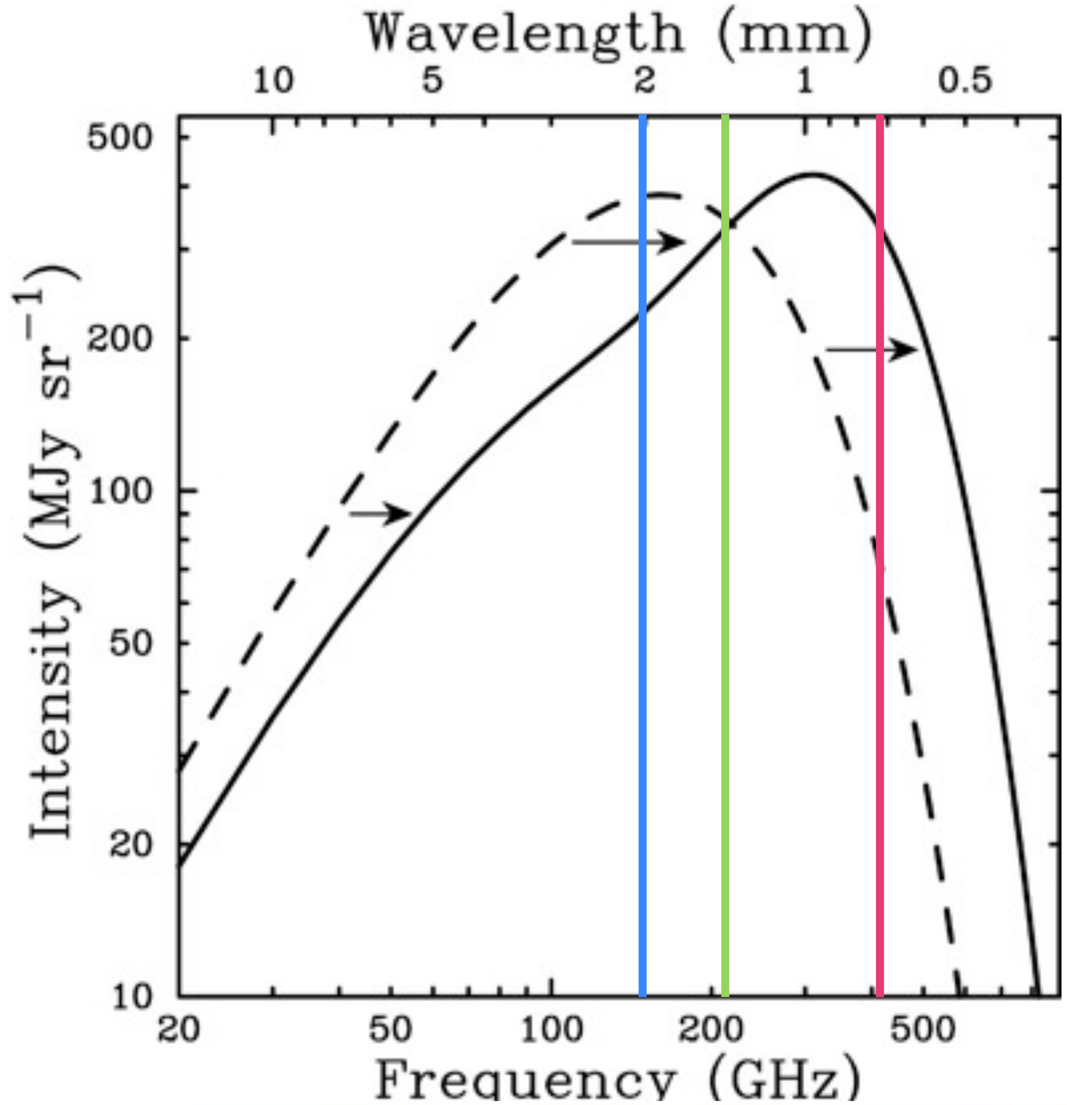


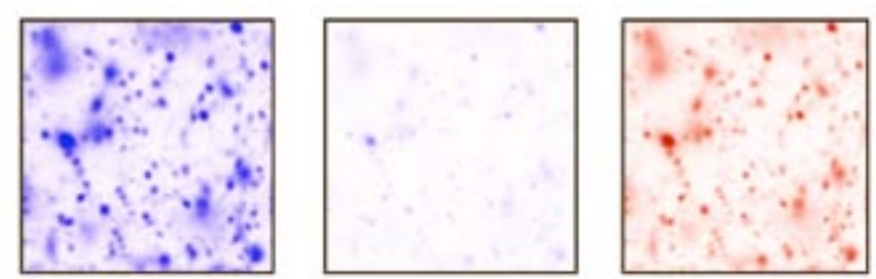
- Detect 157 sources in 455 sq. deg. (15-1500 mJy)
- Majority are known radio galaxies.
- Find evidence for steepening of spectral index between 5,20 and 148 GHz
- Number counts consistent with SPT (Vieira et al. 2009), and prefers the Toffolatti et al. (1998) model.

Marriage et al. (2010)

THE SUNYAEV-ZELDOVICH EFFECT



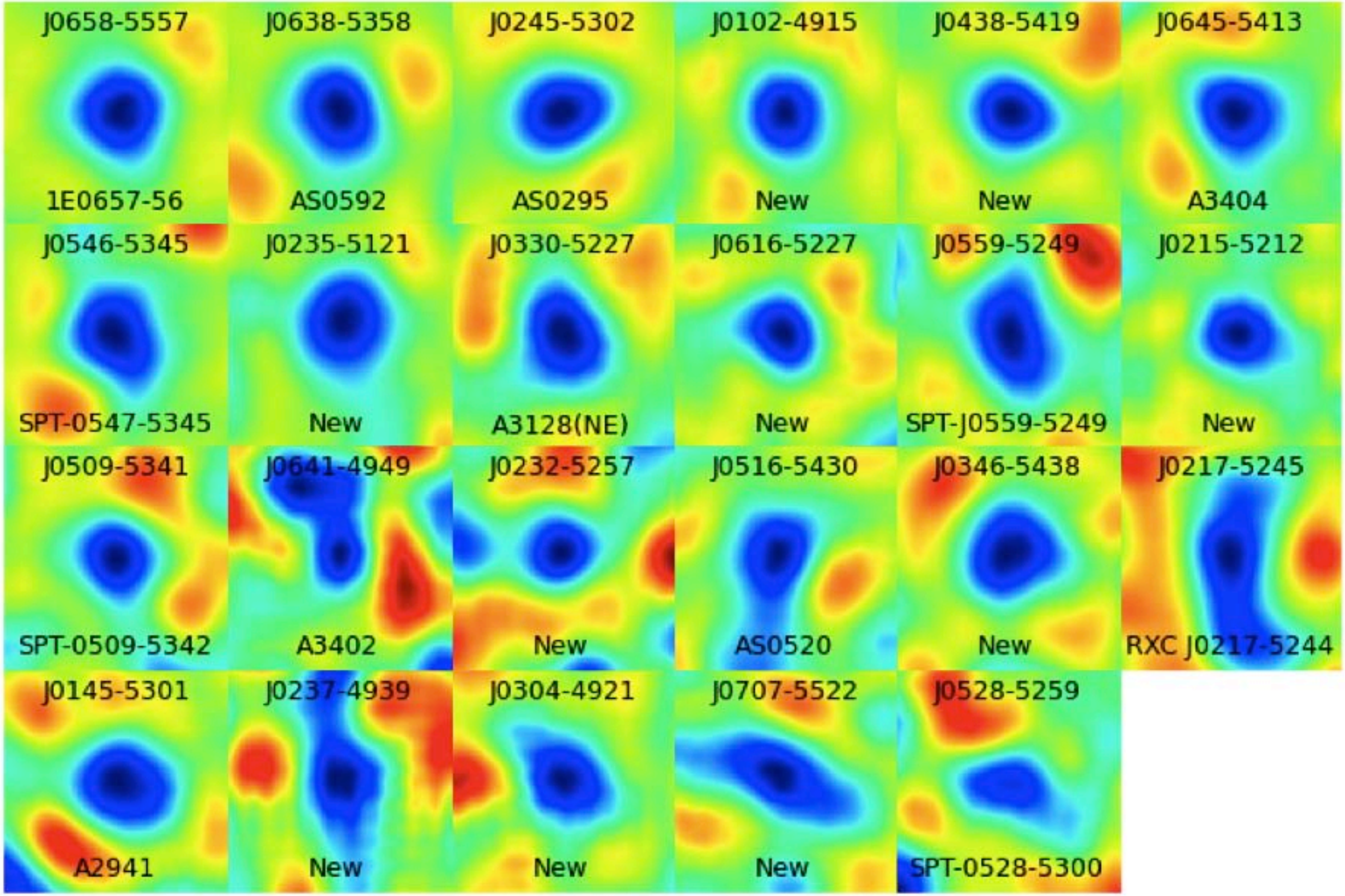




150 GHz decrement | 220 GHz null | 280 GHz increment

see, e.g., Carlstrom et al. (2002)
Reese (2003)

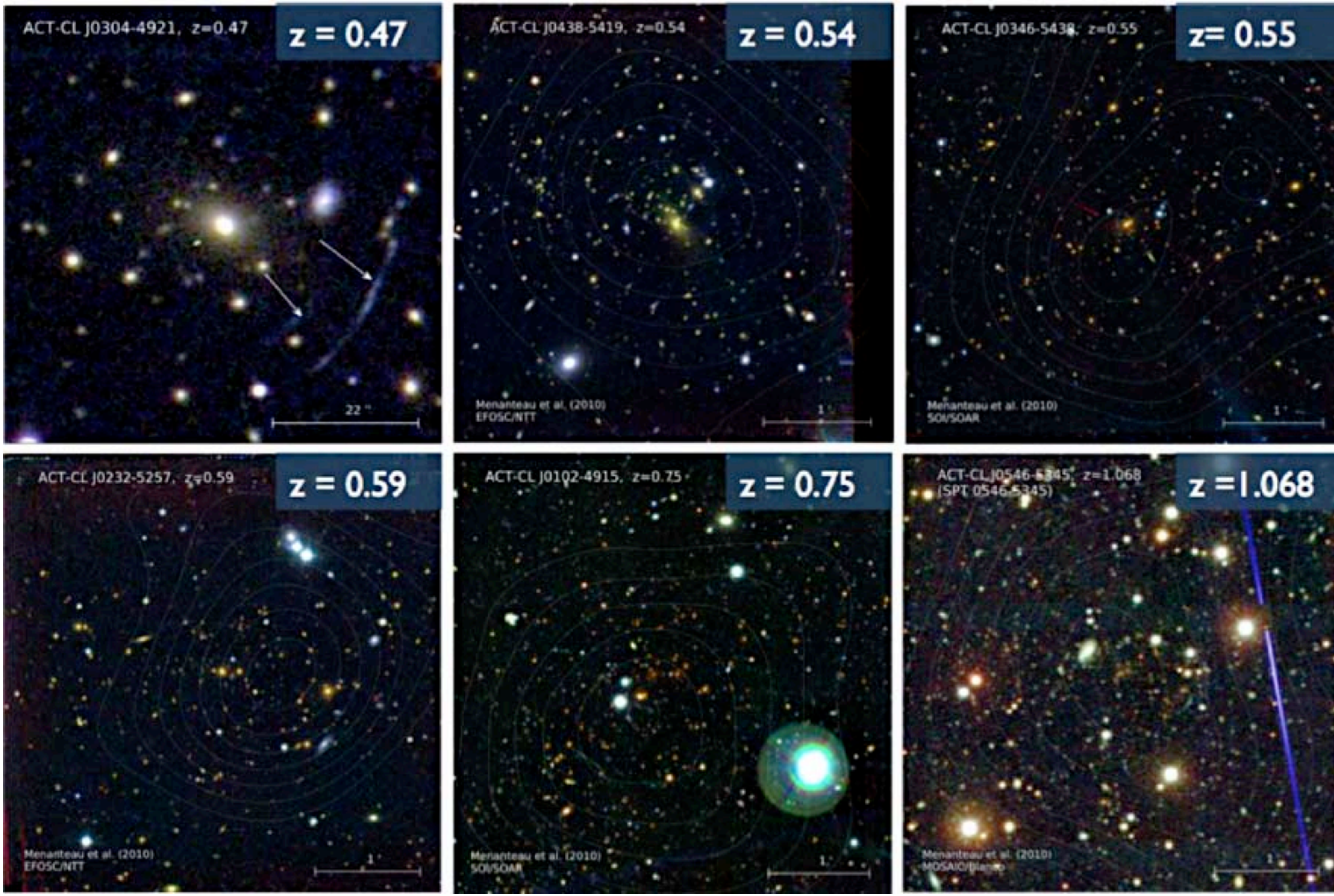
Galaxy Clusters @ 148 GHz



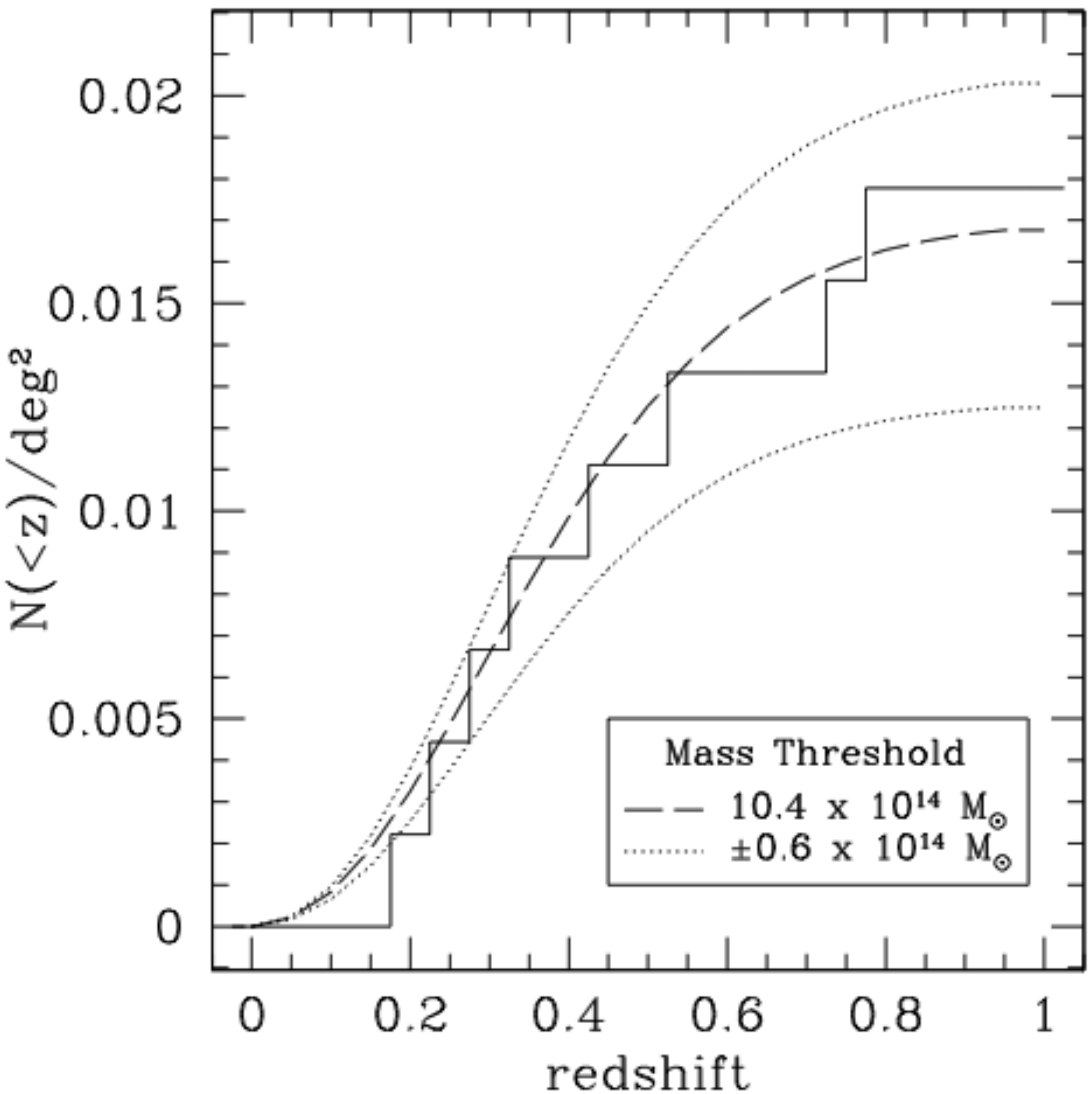
Marriage et al. (2010b)
See, also, Vanderlinde et al. (2010)

Cluster Follow-up

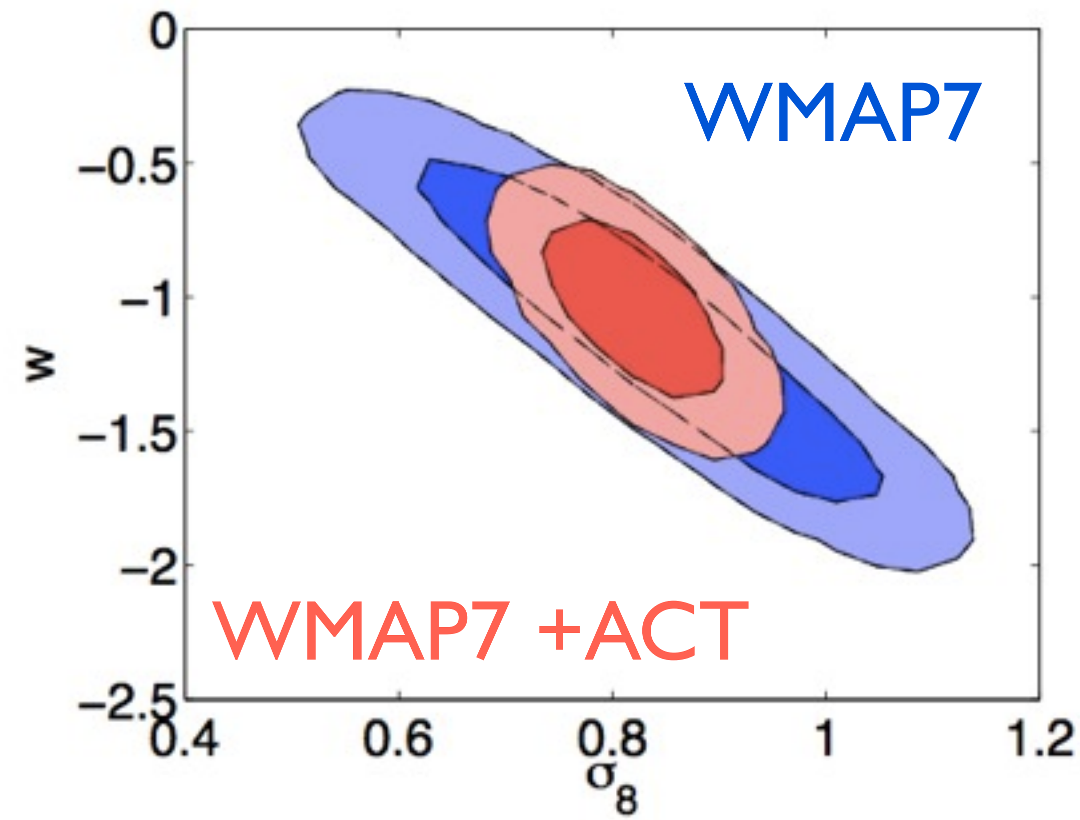
Optical Observations with Blanco, NTT and SOAR



Menanteau et al. (2010)
See, also, High et al. (2010)

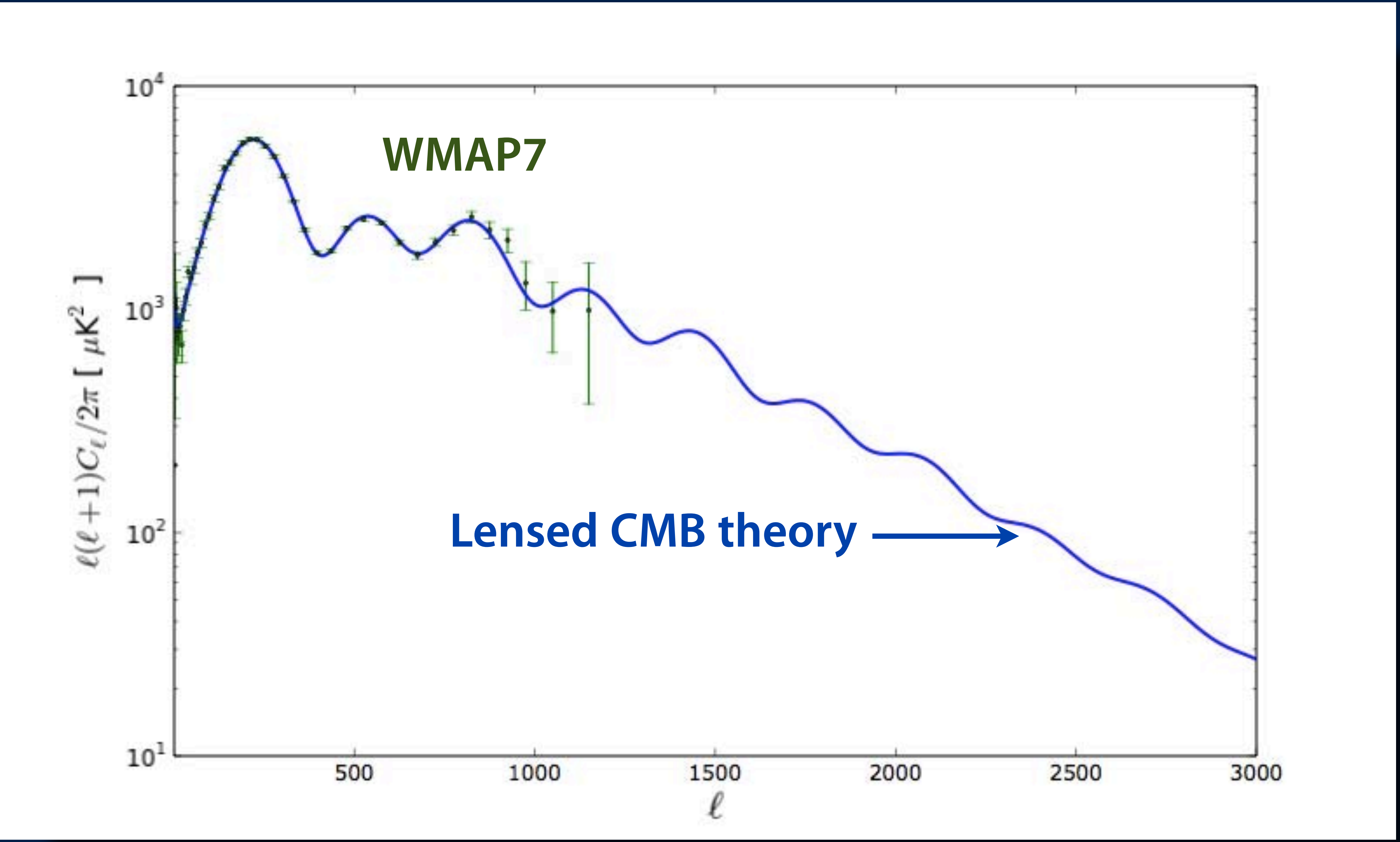


For high significance clusters, concordance cosmological model fits the data well for a given mass limit.



Sehgal et al. (2010)
See, also, Vanderlinde et al. (2010)

The Angular Power Spectrum



Das et al. (2010)

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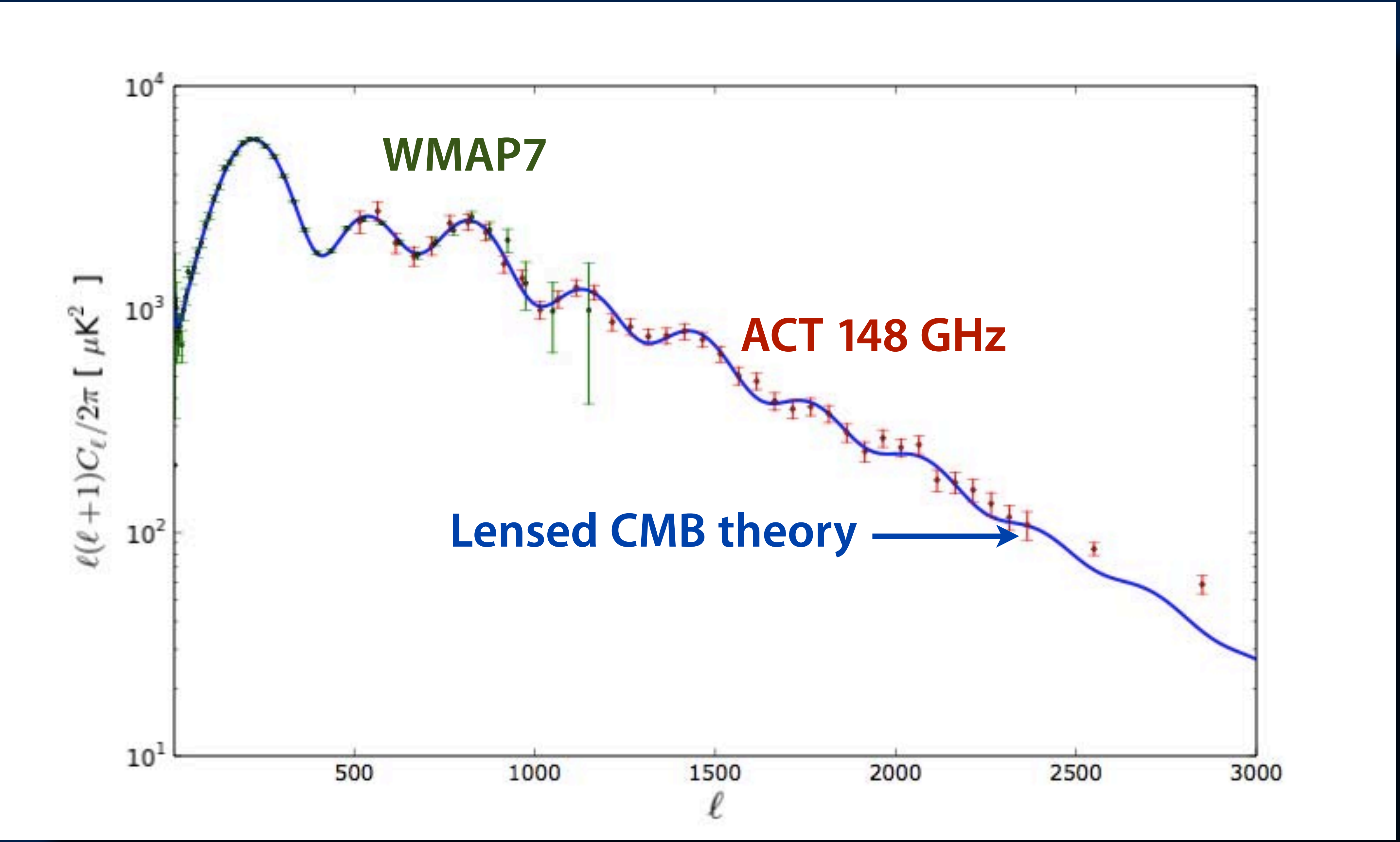
The Angular Power Spectrum



Das et al. (2010)

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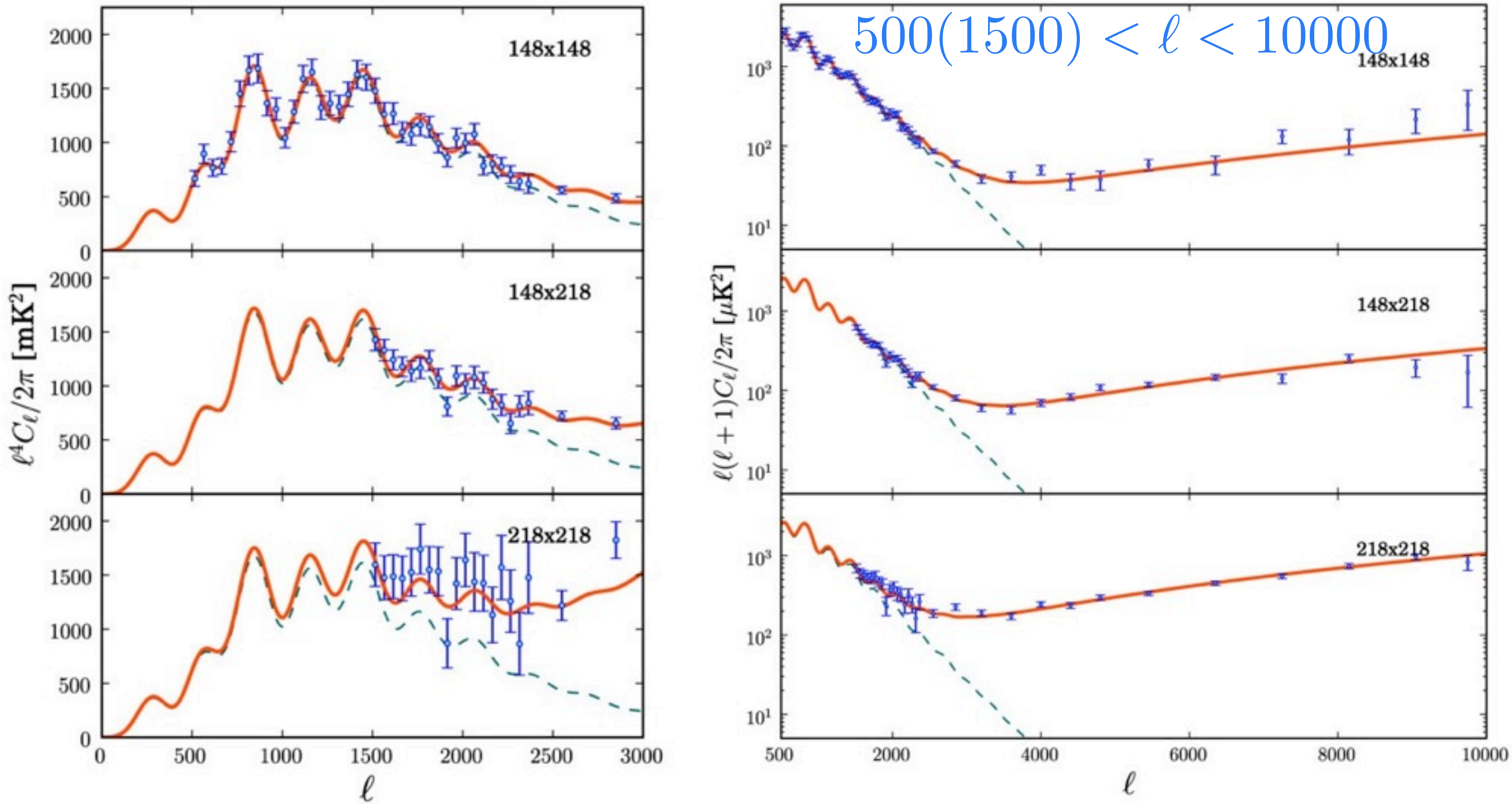
Multifrequency Power Spectra

Zoom in with ℓ^4 scaling

Full dynamic range

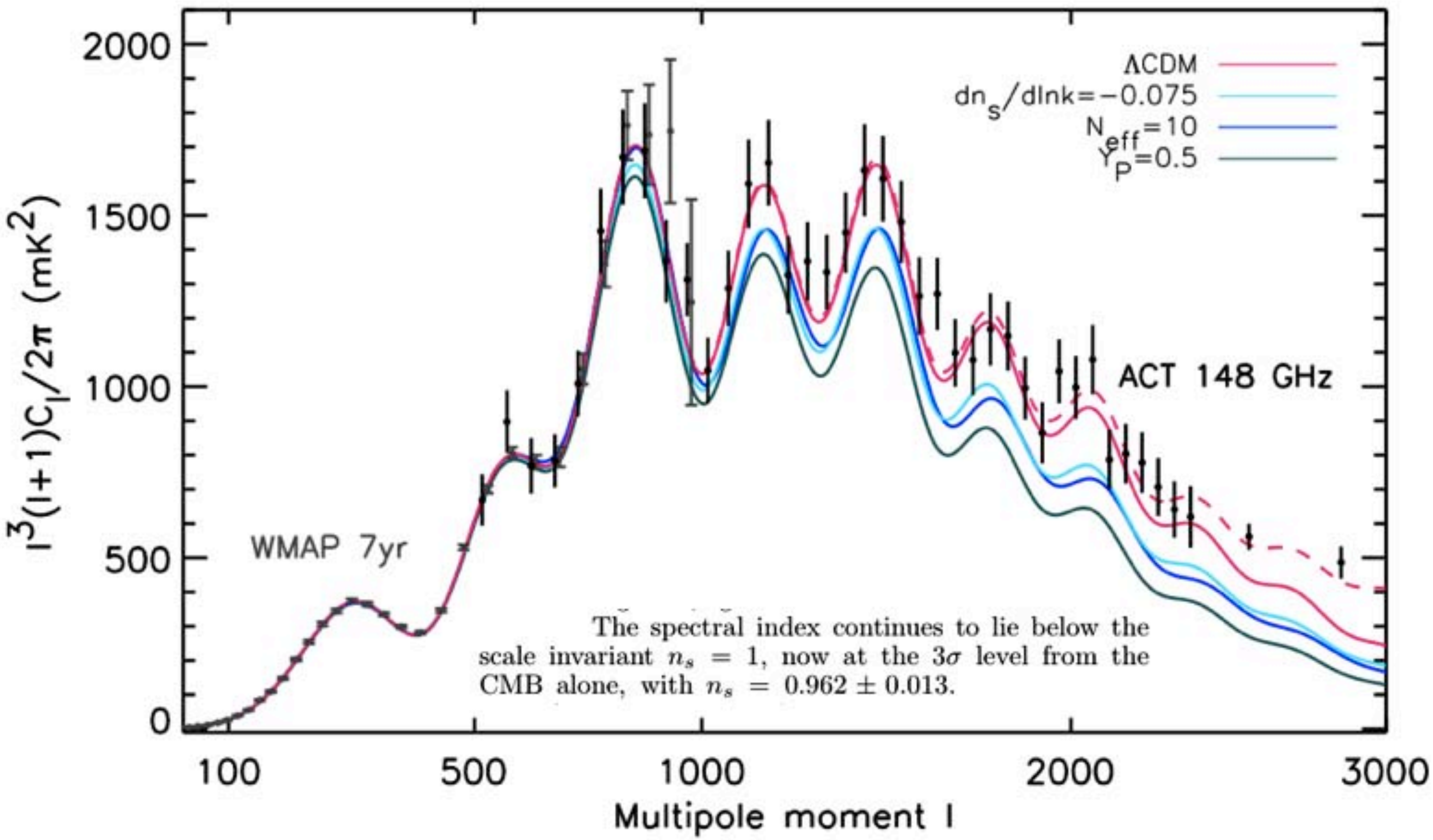
$500(1500) < \ell < 10000$



Das et al. (2010)

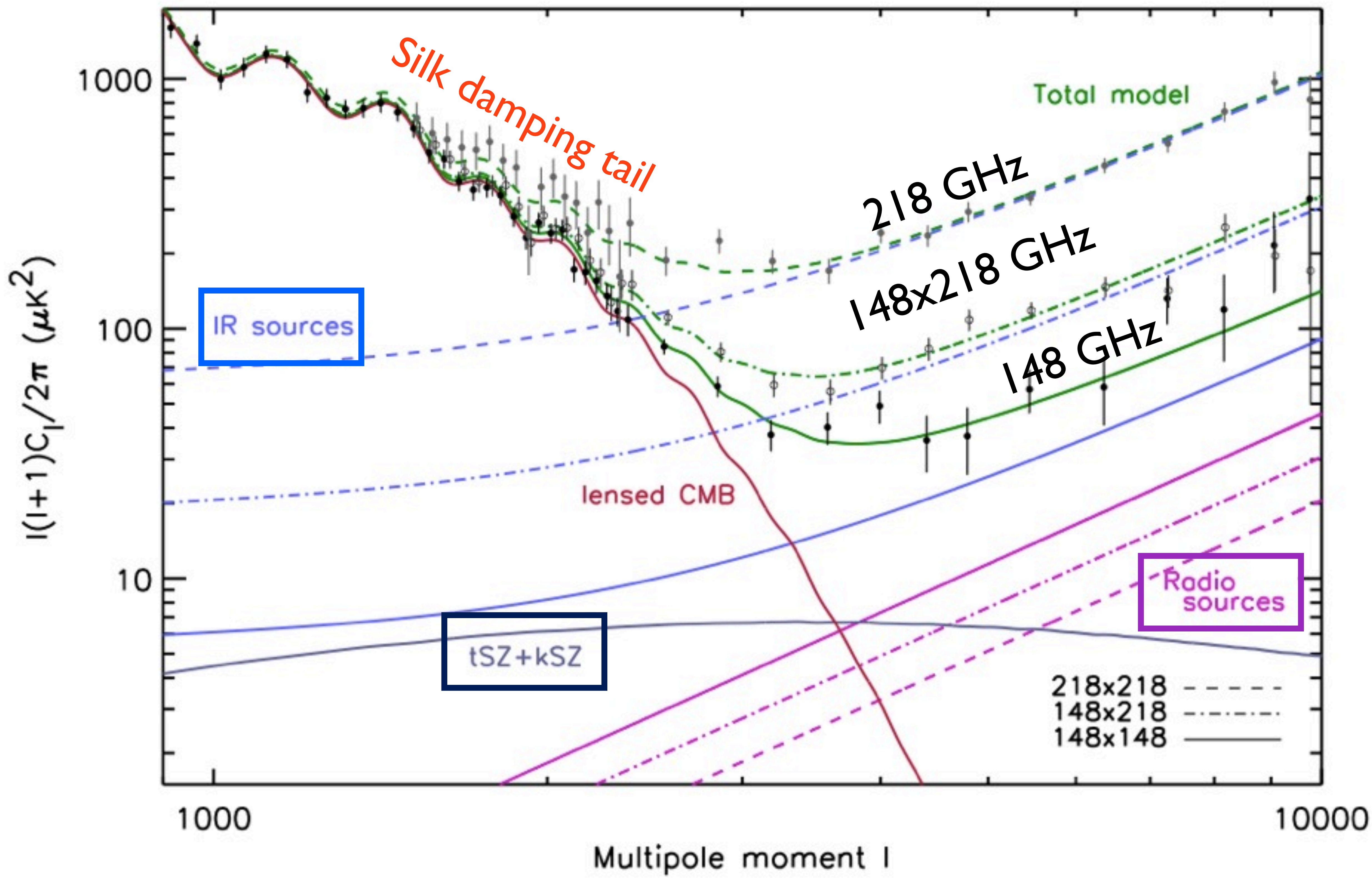
THE "LOW-MULTIPOLE" PARAMETERS

- The low-multipole spectra (l<3000 @148 GHz and l<2000 @218 GHz) are in excellent agreement with the 6-parameter ΛCDM model.
- The higher order peaks provide some of the tighest CMB-only constraints on (beyond-)ΛCDM parameters.



Dunkley et al. (2010)

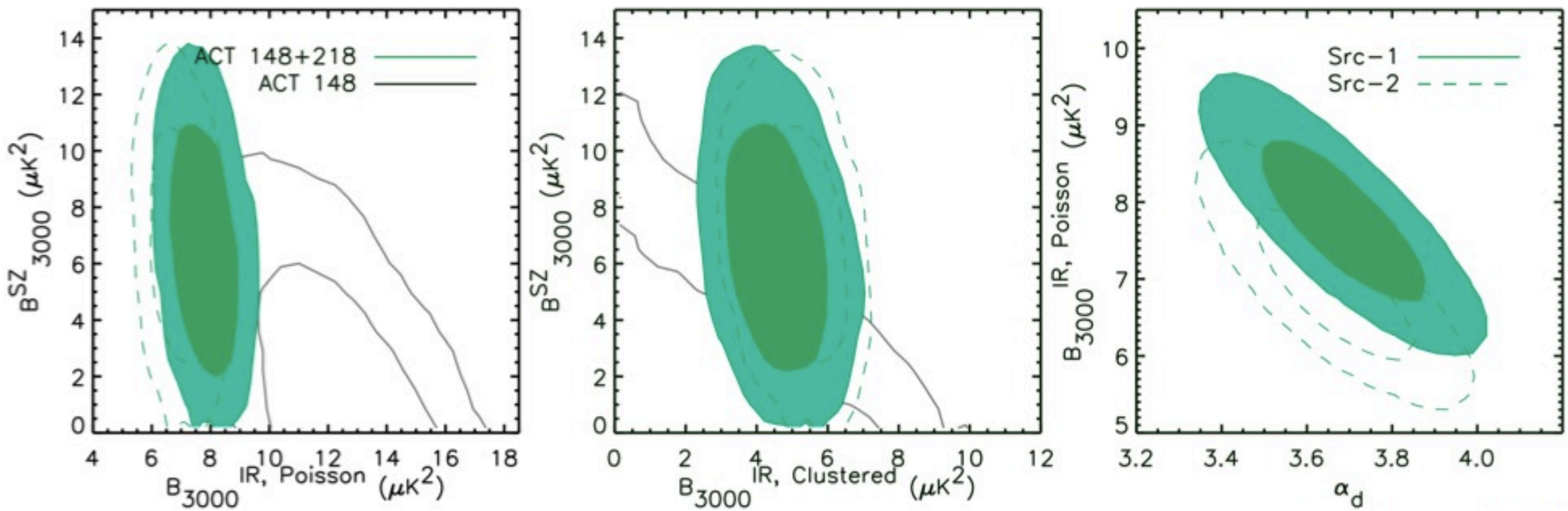
Interpreting The "High-multipole" Spectra



Dunkley et al. (2010)

Infrared source power

$$B_{3000} = \ell(\ell+1)C_\ell/2\pi|_{\ell=3000}$$

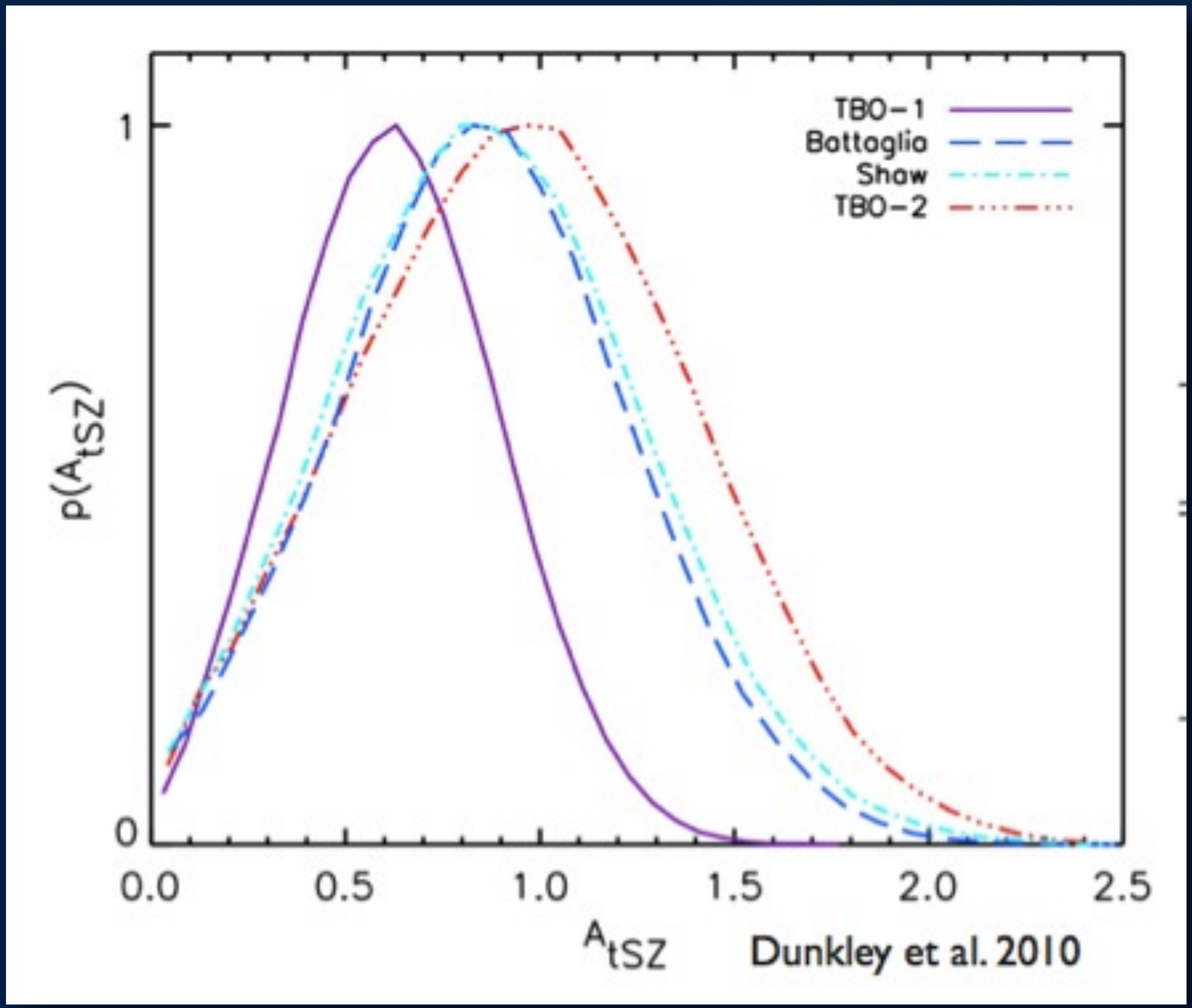


- Clustered IR sources required at 5-sigma.
- IR index (1.5-2.0) consistent with that of dusty star-forming galaxies at z=2-4
- 218 GHz data breaks point sourec SZ degeneracy

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

Dunkley et al. (2010); see also Hall et al. (2010)

Sunyaev-Zel'dovich power



- An SZ component is required at 95% confidence.
- Observed SZ power is consistent with SPT.
- Various SZ models were considered --- the power at l=3000 is independent of the template.
- Kinetic SZ upper limit < 8 μK^2 at l=3000.

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

Dunkley et al. (2010); see also Hall et al. (2010)

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The Future

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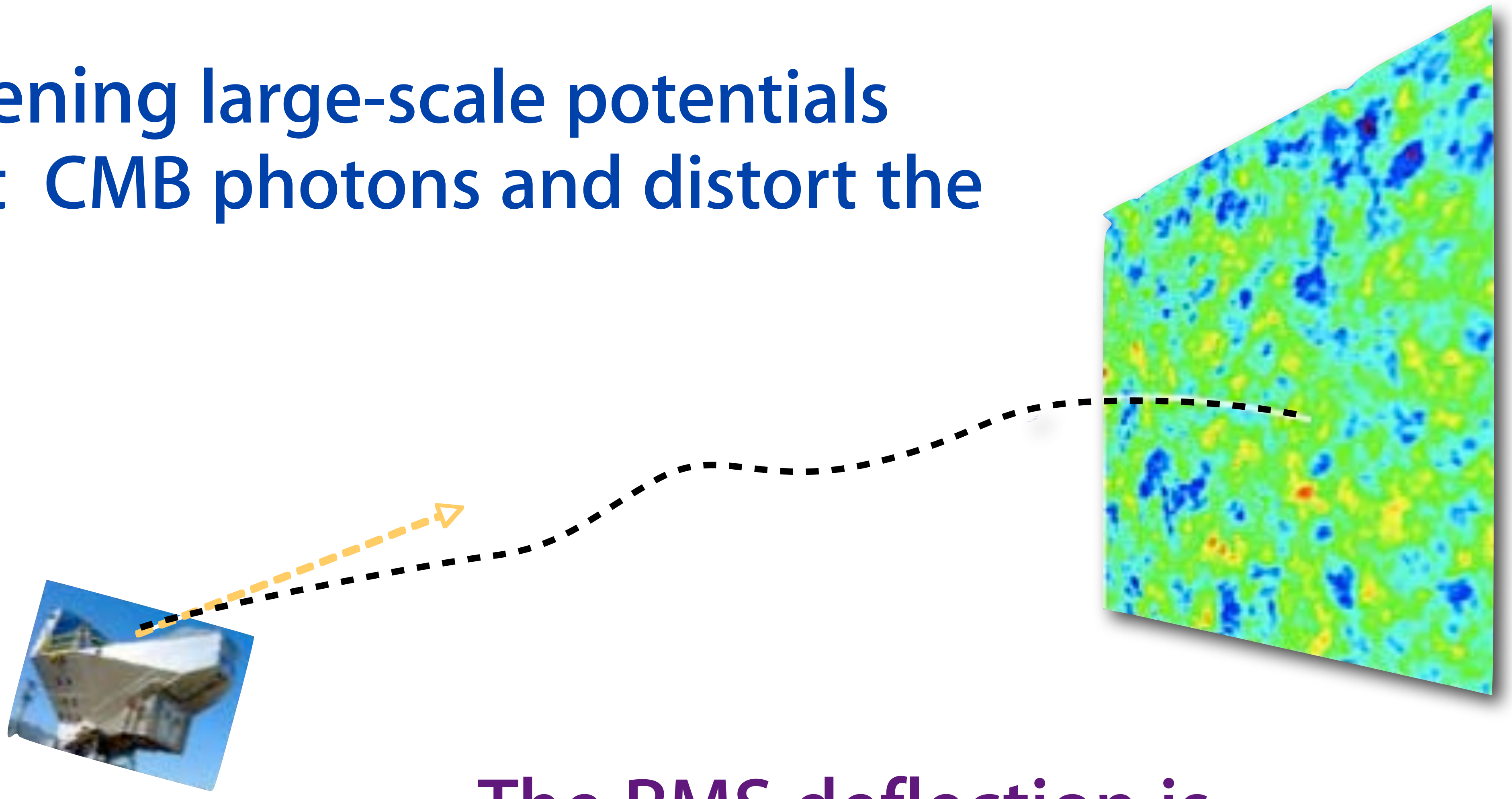
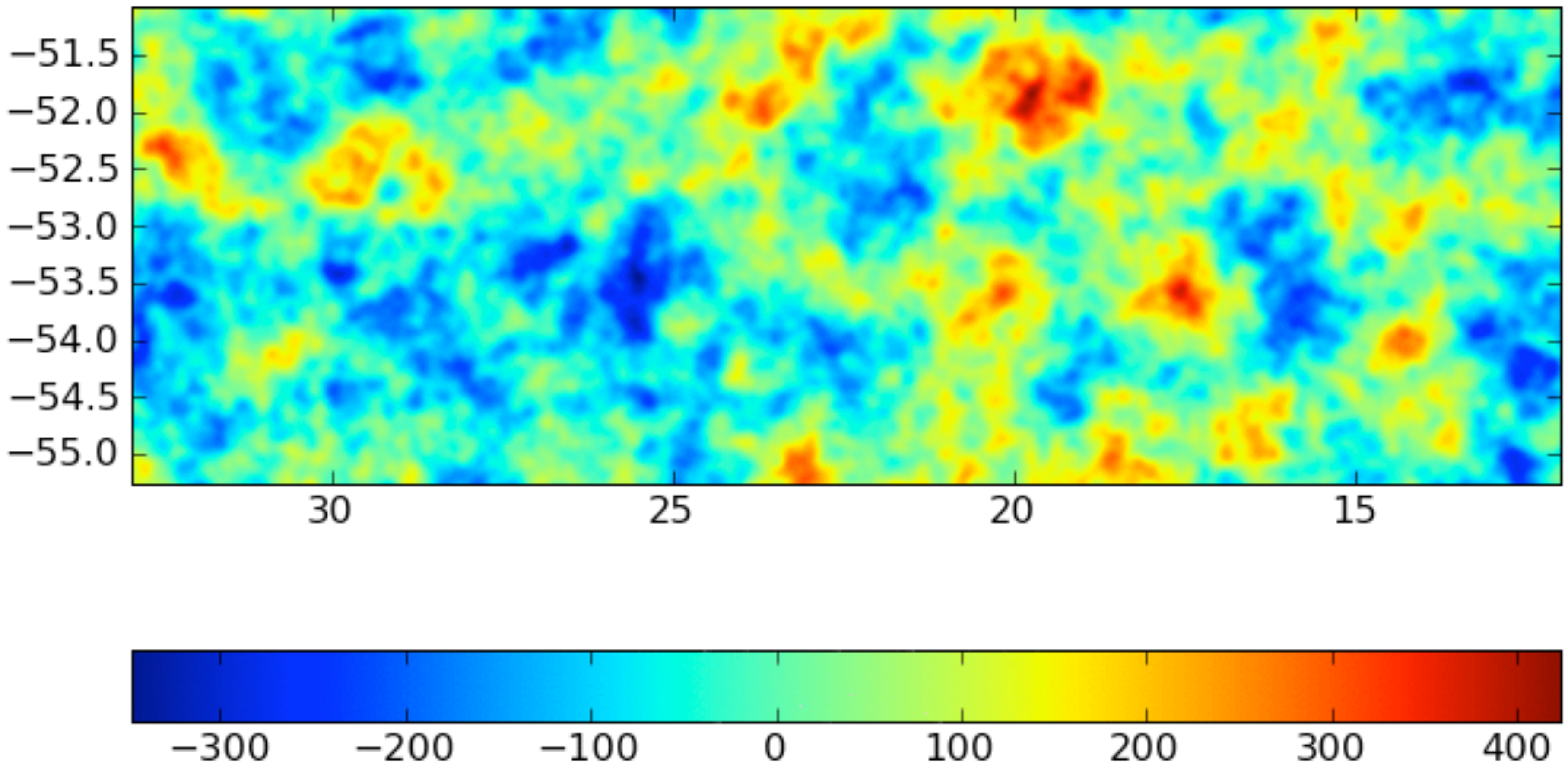
Intervening large-scale potentials deflect CMB photons and distort the CMB.



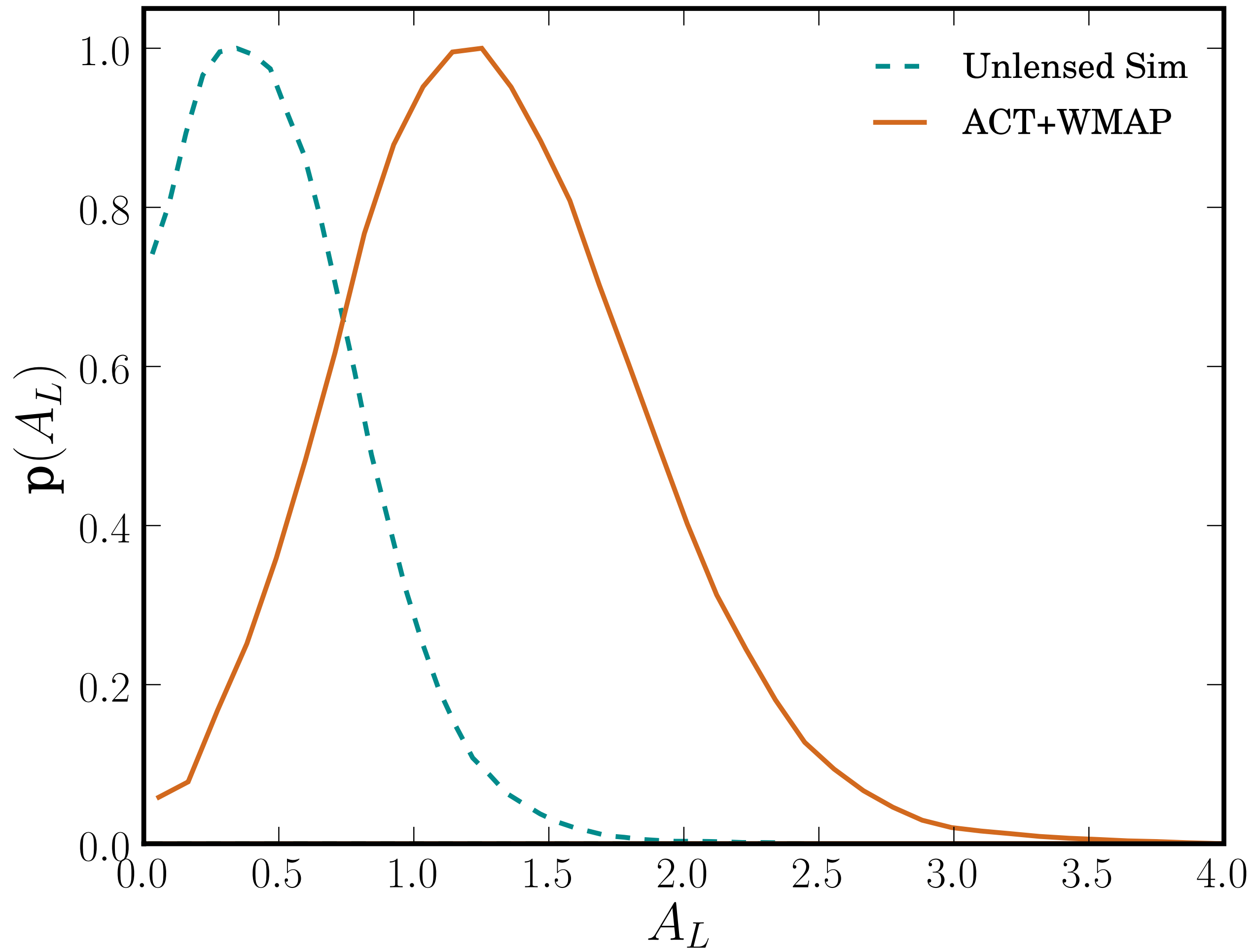
The RMS deflection is about 2.7 arcmins, but the deflections are coherent on degree scales.

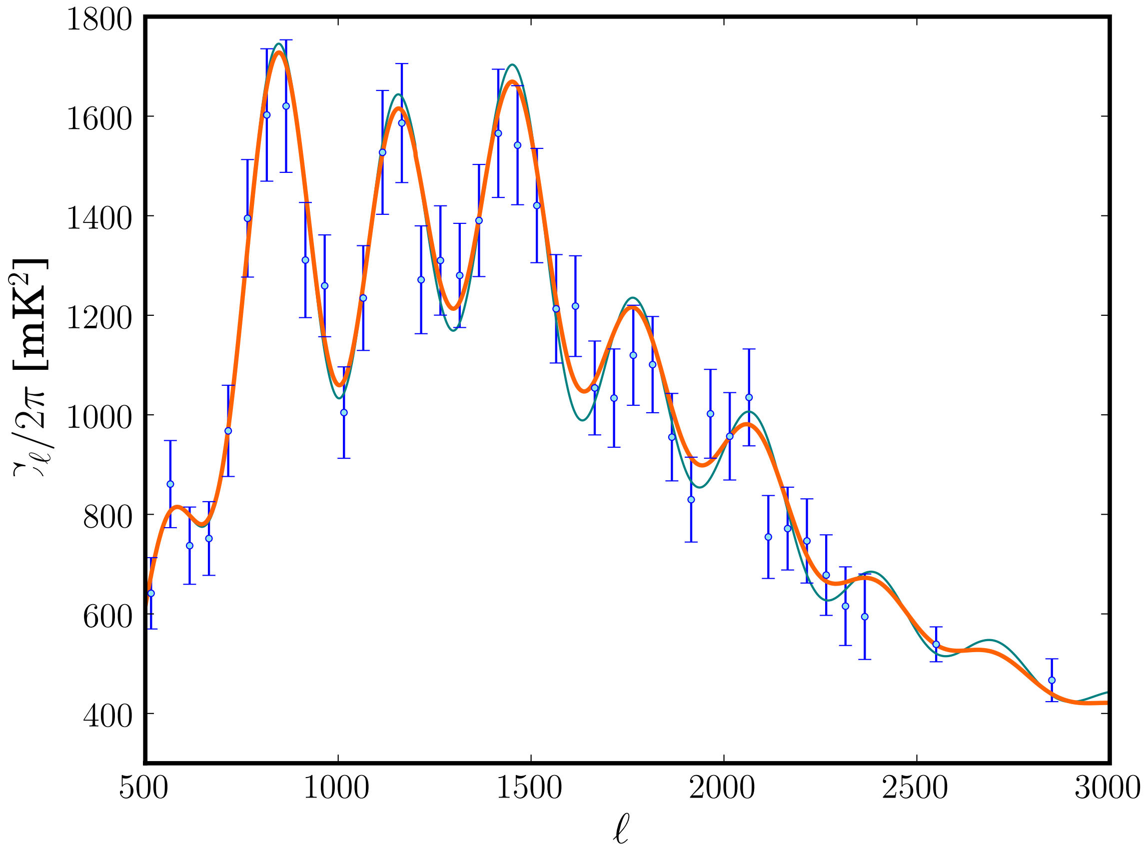
A patch from a lensing simulation



Lensing smoothes acoustic peaks

$$C_\ell^{\phi\phi} \rightarrow A_L C_\ell^{\phi\phi}$$



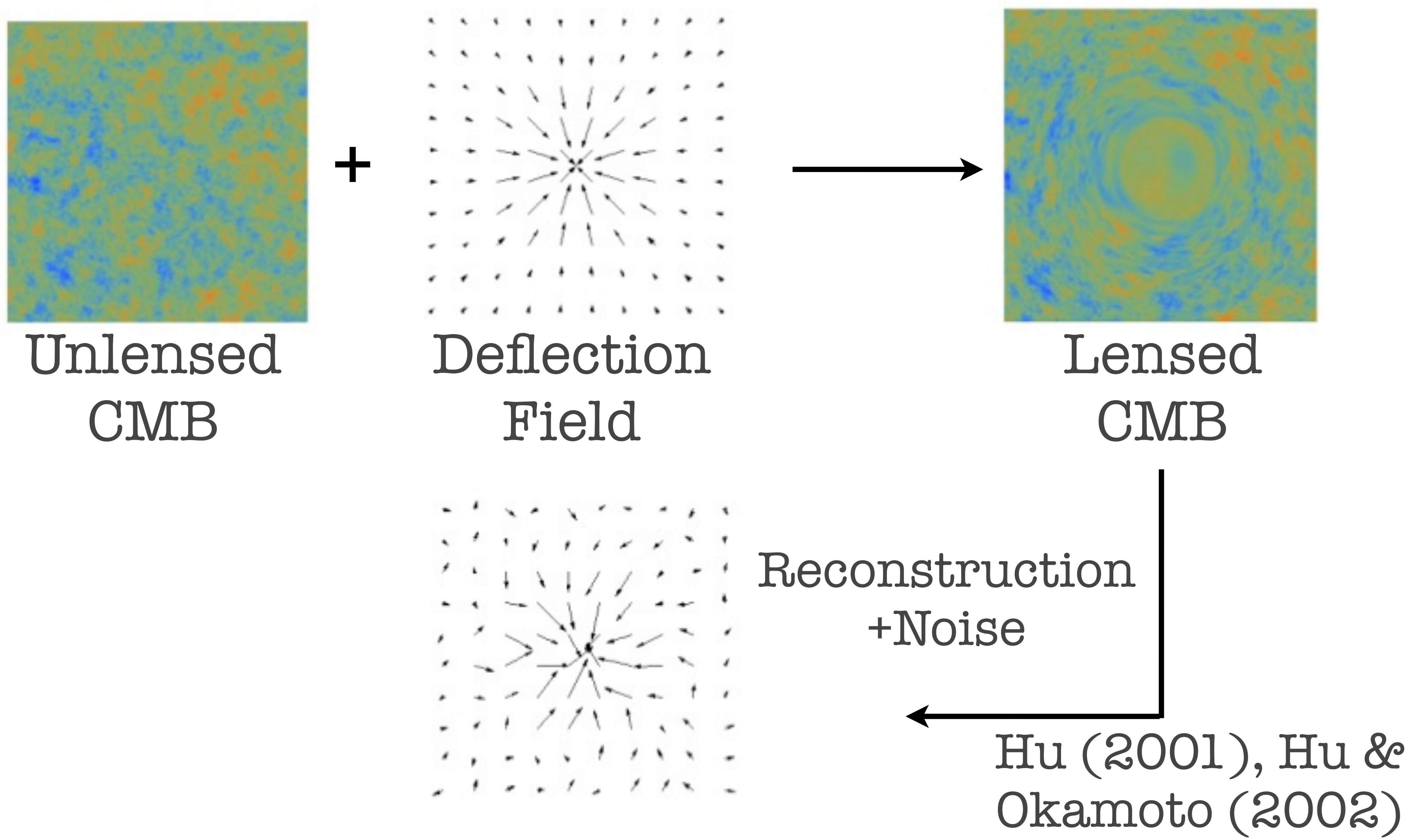


- Test for lensing in spectrum by marginalizing over (unphysical) parameter A_L, scaling lensing potential. [Calabrese et al 2008]
- Expect A_L=1, and unlensed has A_L=0. See lensing at almost 3σ level.
- Find $A_L = 1.3 \pm 0.5^{+1.2}_{-1.0}$ (68, 95% CL)

Das et al. (2010)

Lensing Reconstruction

Given only the lensed CMB sky, can we estimate the deflection field?



Why polarization helps ...

Gravitational lensing remaps the primordial CMB temperature and polarization fields through the deflection field d(n):

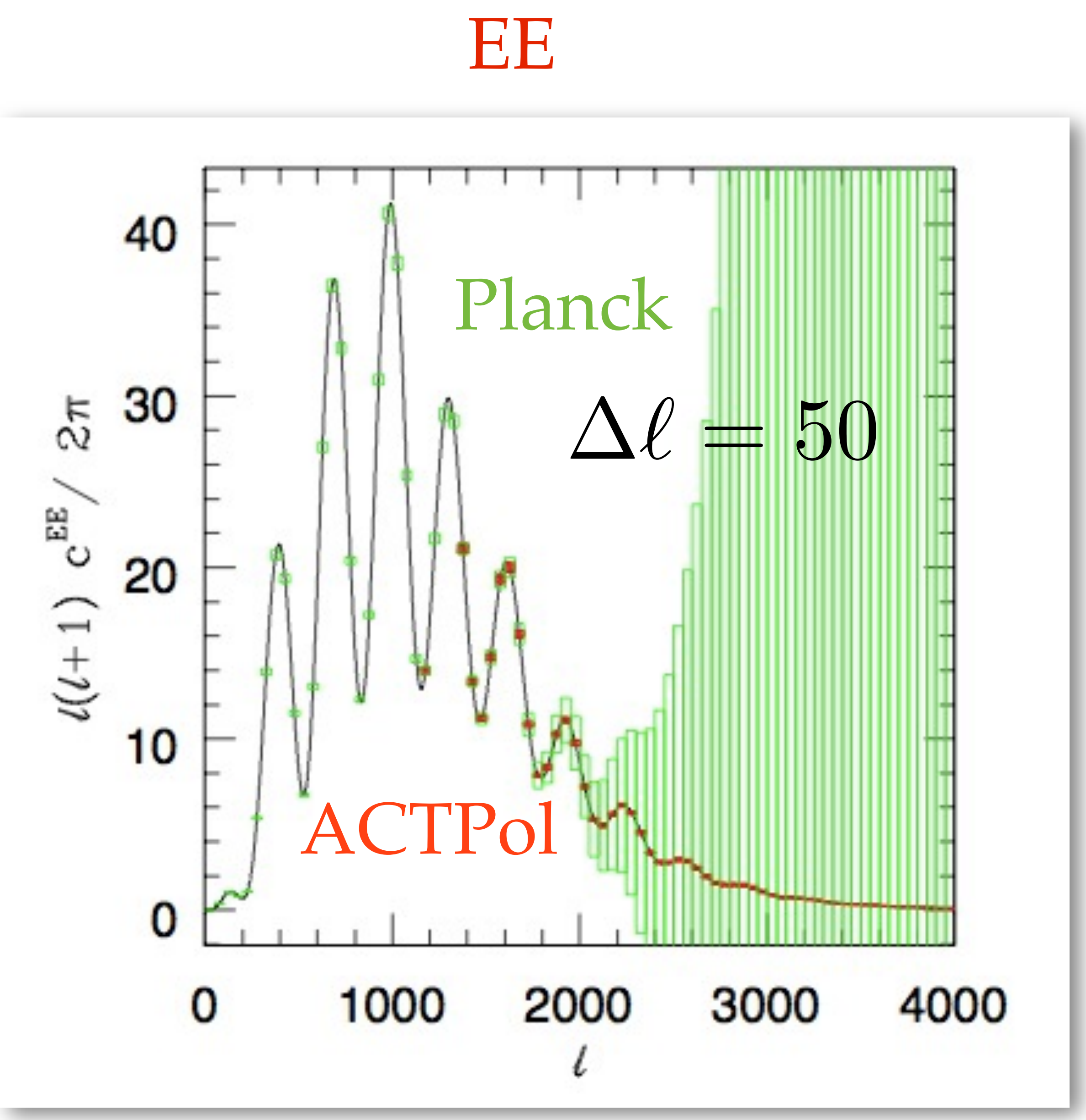
$$\tilde{T}(\hat{\mathbf{n}}) = T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))$$
$$[\tilde{Q} \pm i\tilde{U}](\hat{\mathbf{n}}) = [Q \pm iU](\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))$$

In the Fourier space, lensing introduces correlations between different Fourier modes $\boldsymbol{\ell},\ \boldsymbol{\ell}'$, which are uncorrelated for the primordial signals. This correlation is used to write down an estimator of the deflection field from the observed fields. Schematically:

$$\hat{\mathbf{d}}_{XY}(\mathbf{L}) \propto \tilde{X}(\boldsymbol{\ell})\tilde{Y}(\mathbf{L} - \boldsymbol{\ell})$$

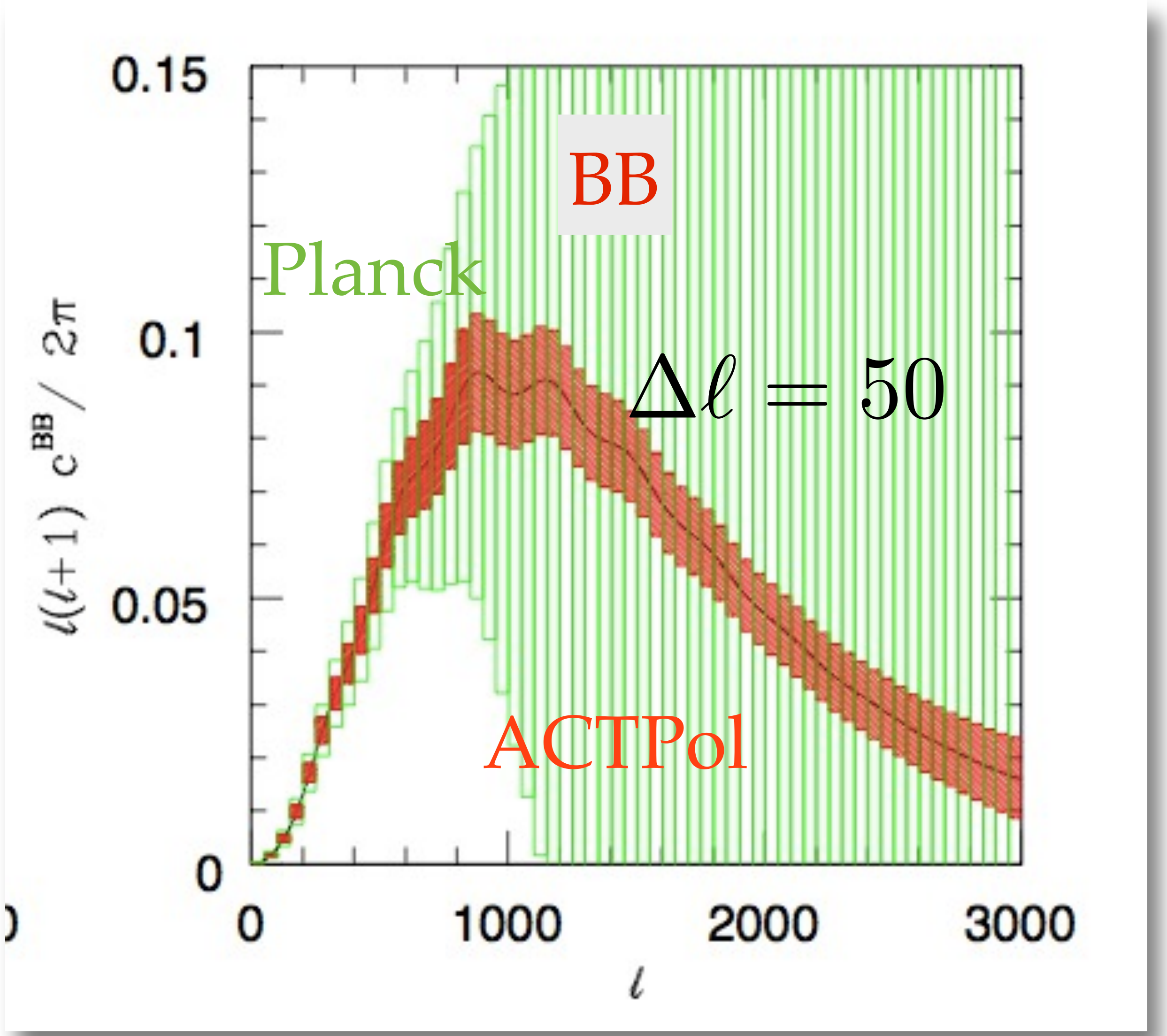
where $X, Y \in (\tilde{T}, \tilde{E}, \tilde{B})$

We are interested in the power spectrum C_ℓ^{dd} of d, which is sensitive to growth of structure and hence to neutrino mass and dark energy.



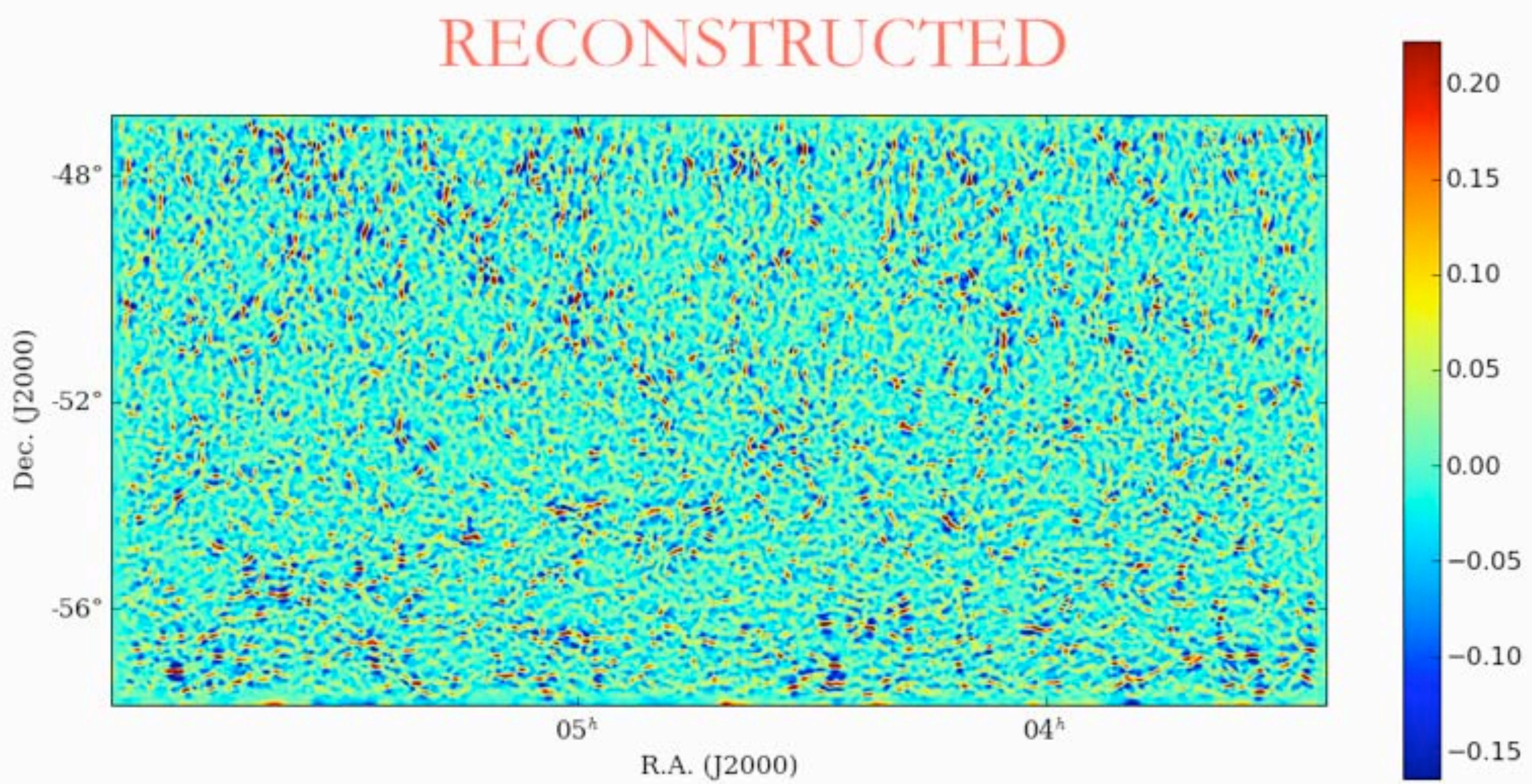
ACTPol will make precise measurements of the high-l polarization spectrum, probing the spectral index and inflationary physics.

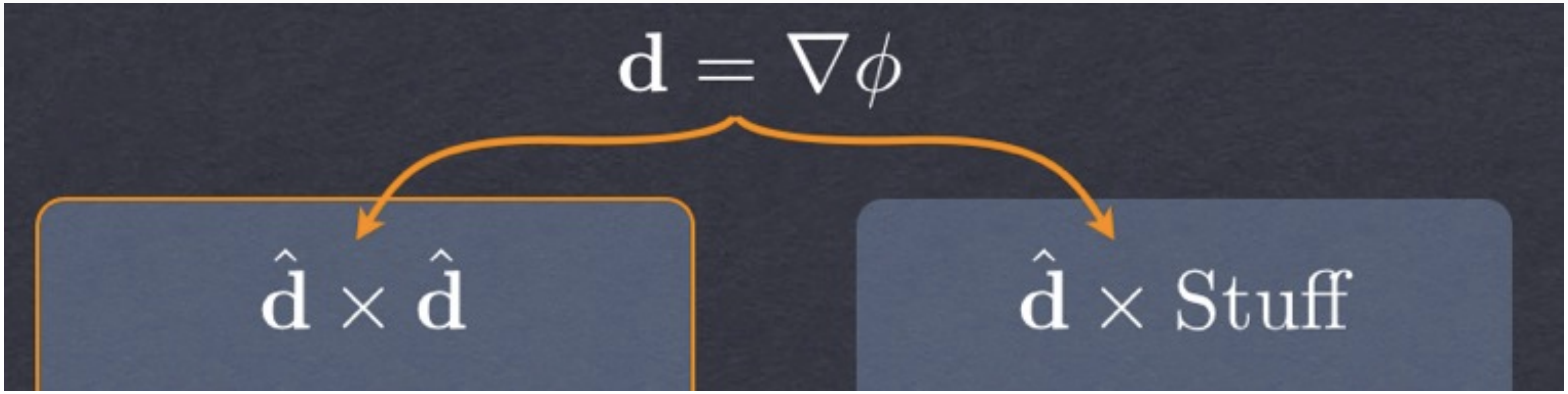
For BB, the high-l spectrum comes primarily from lensing of E-modes.



See Niemack et al (2010) and his poster here!

From reconstruction to science





Geometry and Growth

CMB lensing can be fully described via the deflection field:

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

Lensed — Unlensed — Deflection Field

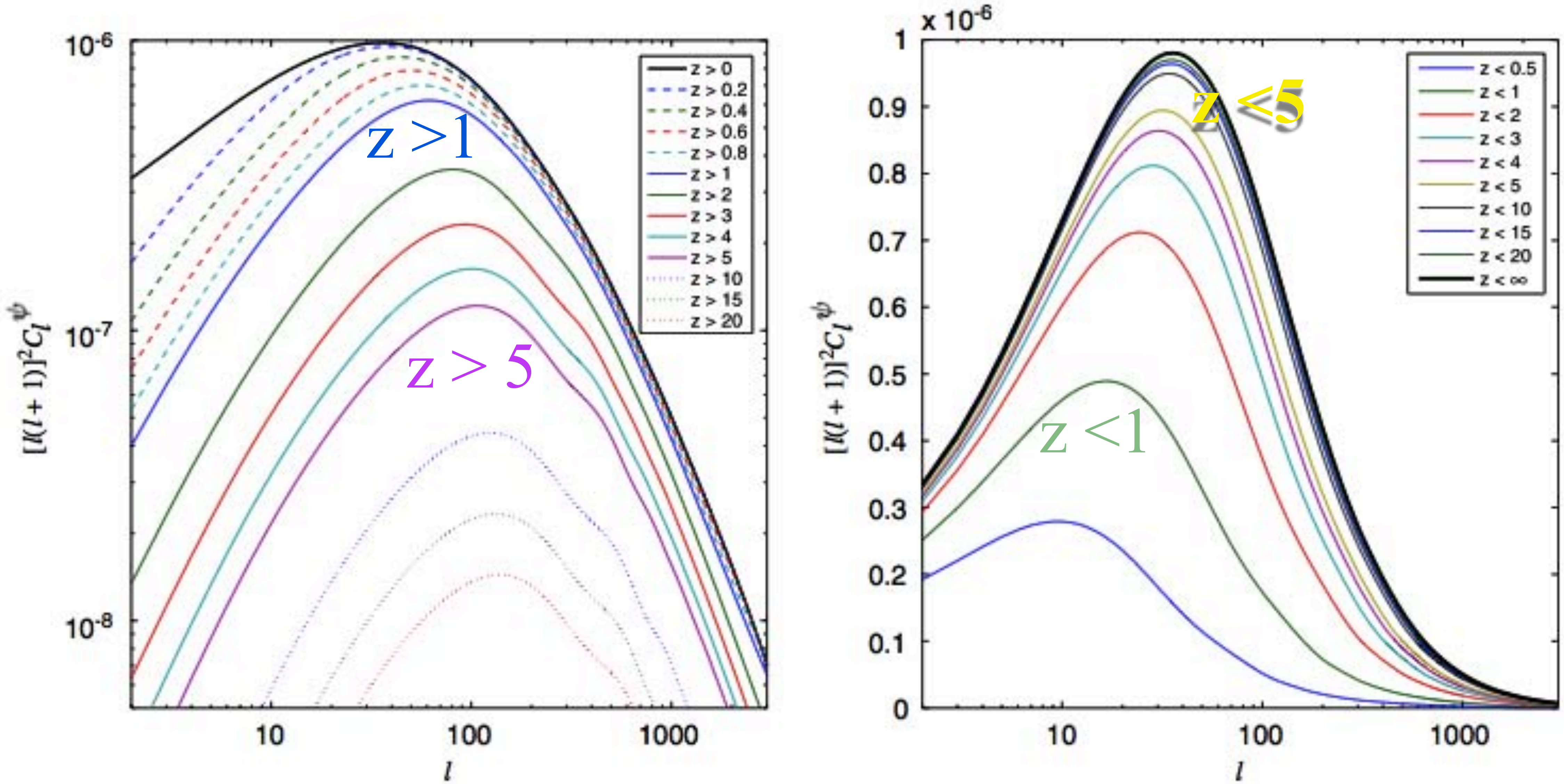
$$\phi = -2 \int \frac{d_A(\eta_0 - \eta)}{d_A(\eta)\, d_A(\eta_0)} \Phi(\eta\hat{n}, \eta)$$

Effective Lensing Potential — Geometry — Matter potential

Affected by parameters that affect distance scales and growth of structure in the late universe.

For high z lenses (clusters, galaxies) CMB is the only source !

Redshift sensitivity

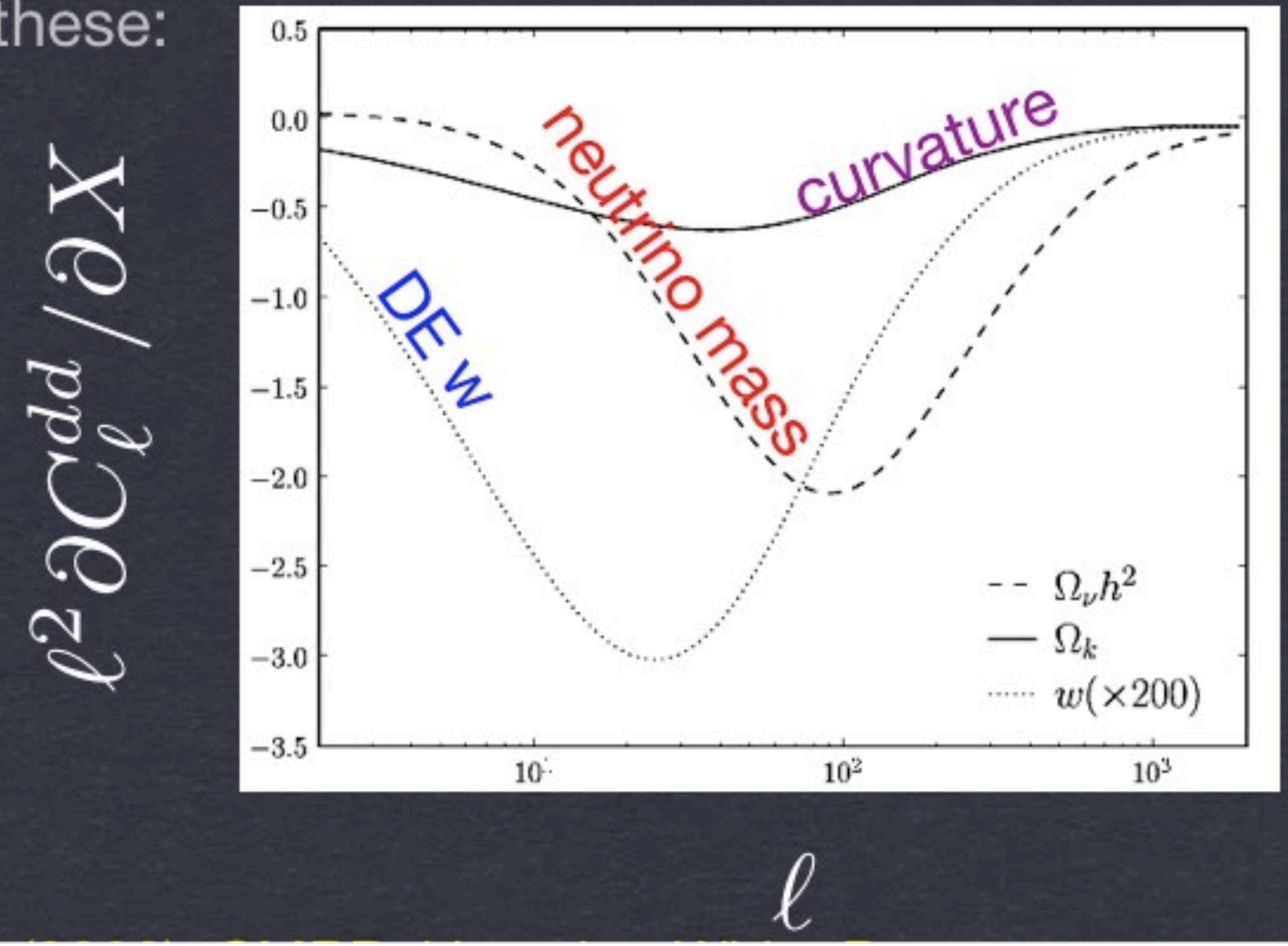


The deflection field receives most contribution from a wide range of redshifts: 0.5 <z <5.

Breaking Degeneracies

The primary CMB can be kept nearly unchanged under variations of neutrino mass, dark energy equation of state or curvature. But the deflection field cares about these:

Lensing breaks the angular diameter distance degeneracy!



Smith, Cooray, Das, Dore et al., CMBPOL Lensing White Paper (2009)

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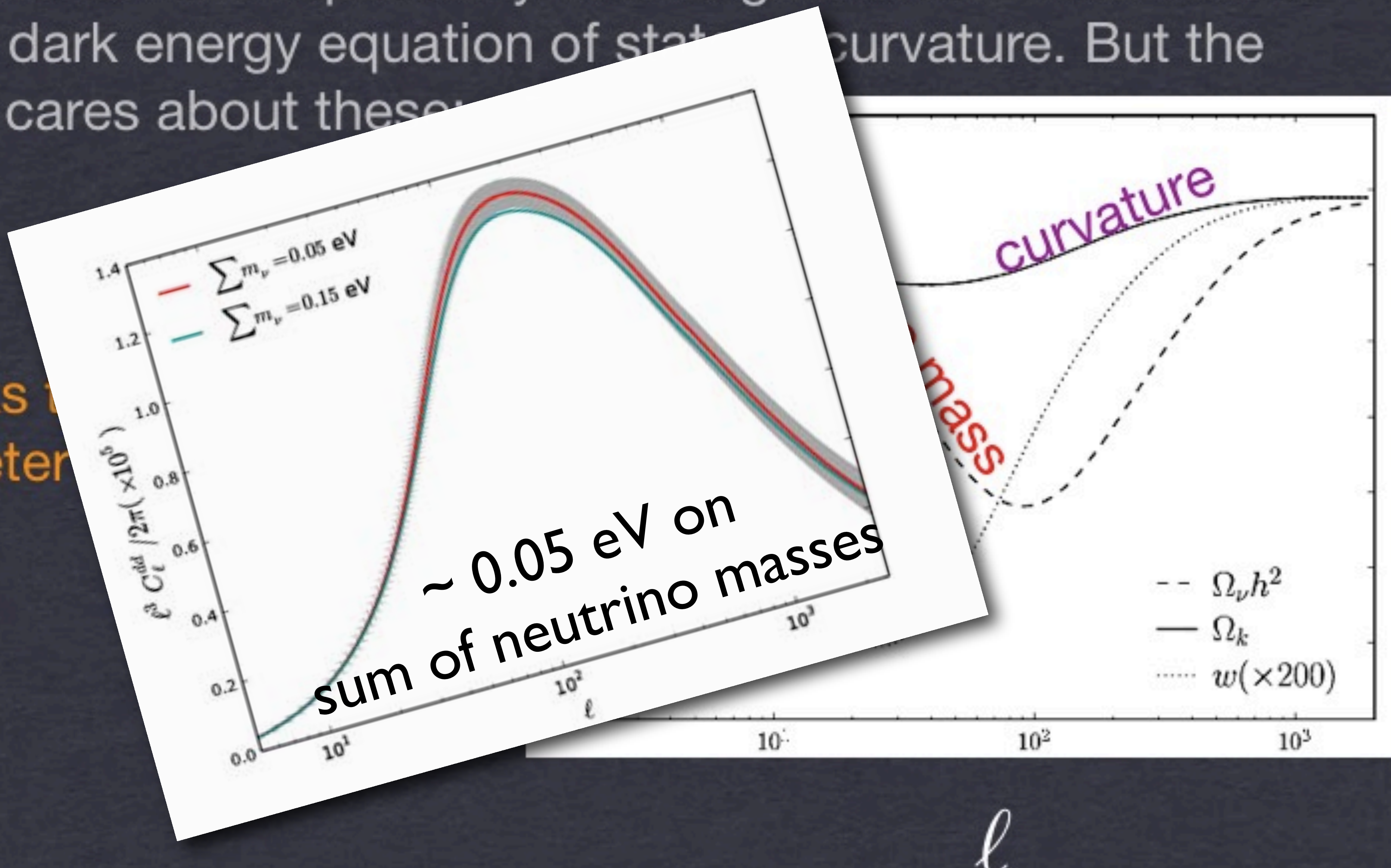
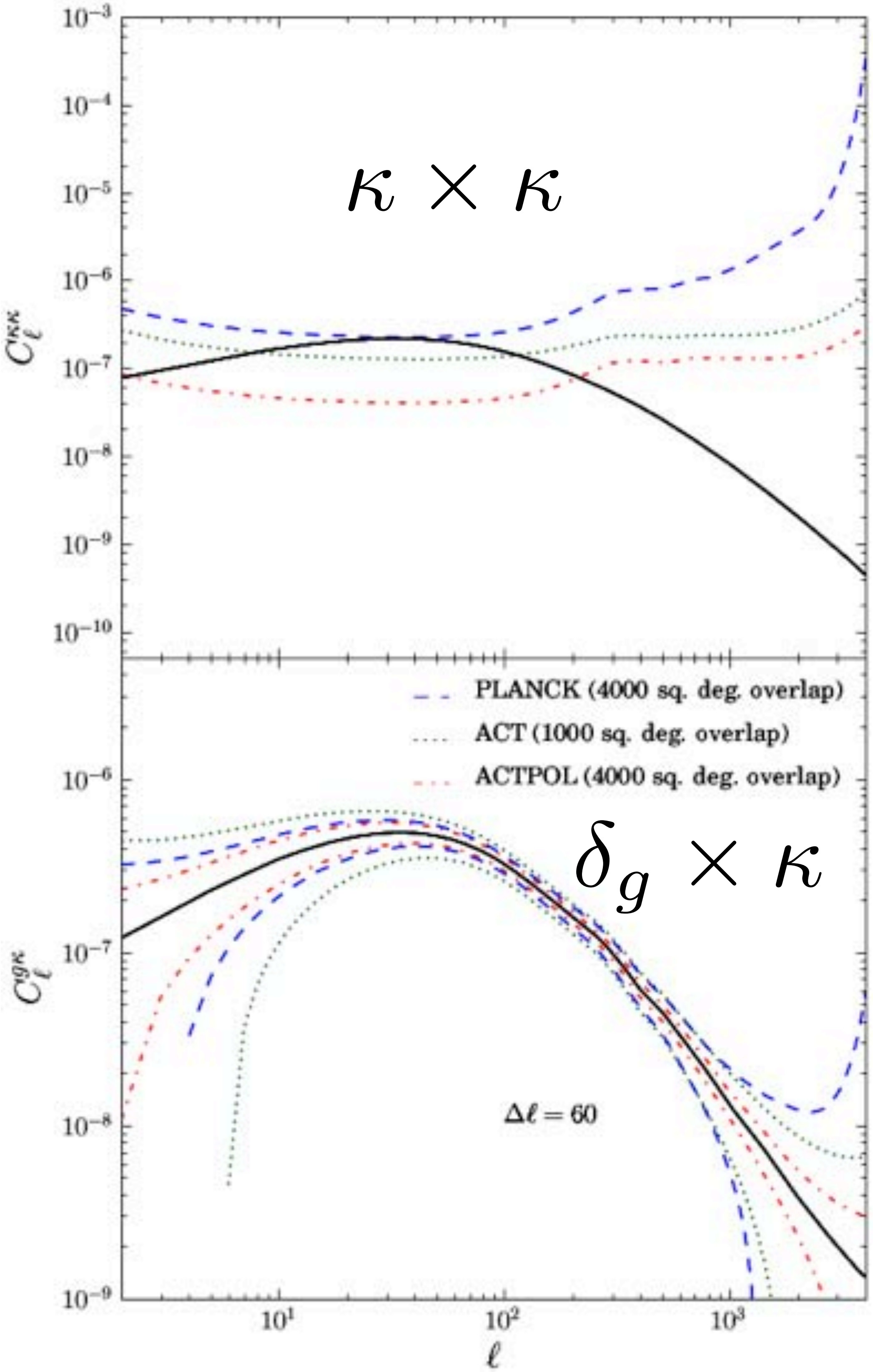


Smith, Cooray, Das, Dore et al., CMBPOL Lensing White Paper (2009)

Convergence - Galaxy cross correlation



- CMB lensing reconstruction yields a map of projected density.
- This can be cross-correlated with galaxy density maps to learn how galaxies relate to the underlying dark matter.
- This is specially important for high-z sub-mm galaxies (Herschel/WFIRST/CCAT) due to their high-z location and high magnification bias.
- The bias of these sources will simply fall out once the signal is measured. Percent accuracy on bias is possible.

Das and de Putter (in prep.)

See also, Namikawa et al (2010)

Measuring galaxy bias

Great Signal-to-noise!

Galaxy Survey	$\hat{n}$	$A/10^3$	z_c	b	CMB Expt.	(S/N)	$\Delta b/b(\%)$
SDSSLRG	12.4	3.8	0.31	2	PLANCK	5.8	17.3
					PACT	11.4	8.8
					IDEAL	20.4	4.9
BOSS1	40.	10	0.3	2	PLANCK	10.8	9.3
					PACT	25.5	3.9
					IDEAL	52.5	1.9
BOSS2	110.	10	0.6	2	PLANCK	17.0	5.9
					PACT	39.4	2.5
					IDEAL	78.2	1.3
ADEPT	3500	27	1.35	1	PLANCK	52.8	1.9
					PACT	107.5	0.9
					IDEAL	228.3	0.4

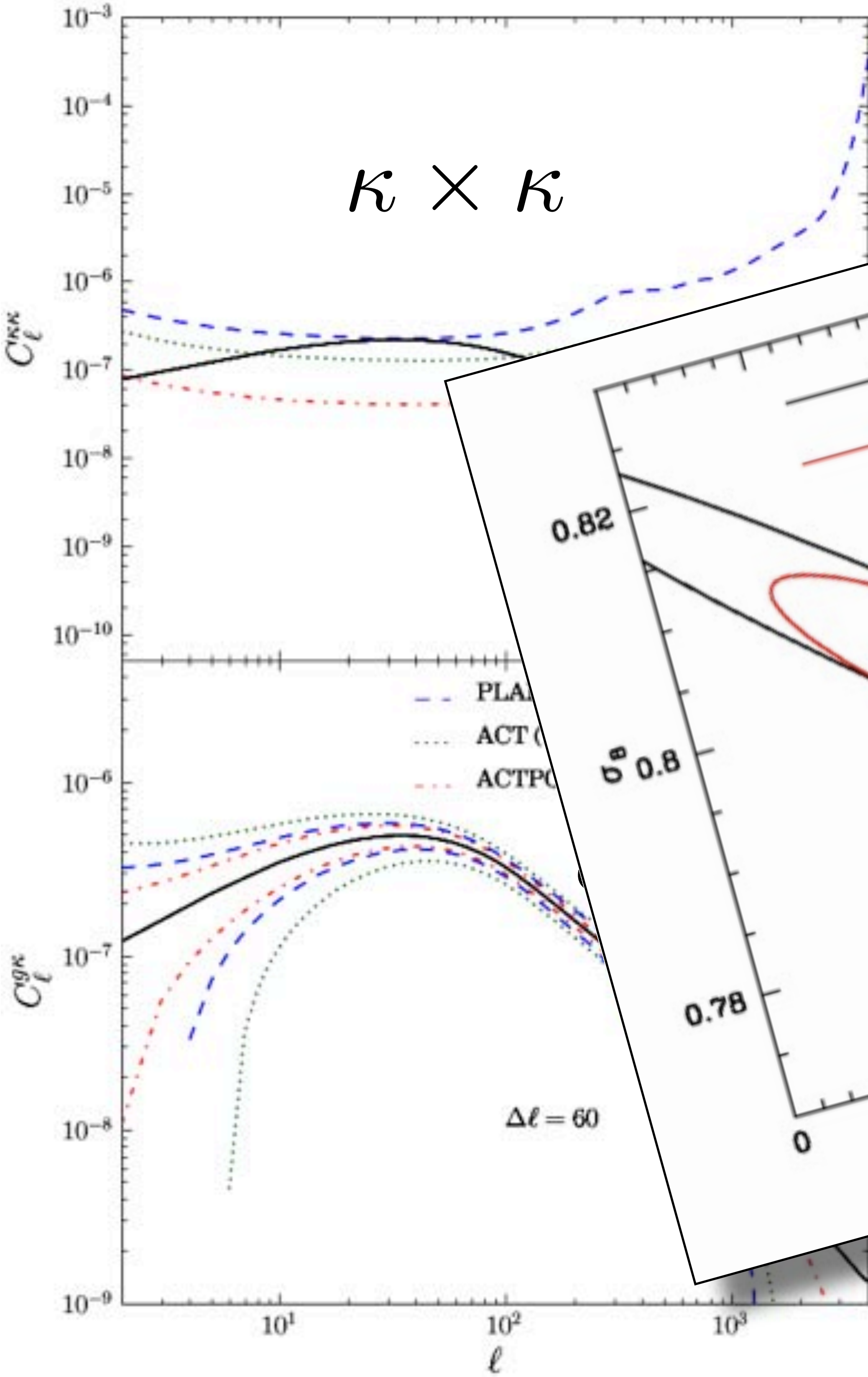
Acquavivia, Hajian, Spergel and Das, PRD 78, 043514 (2008)

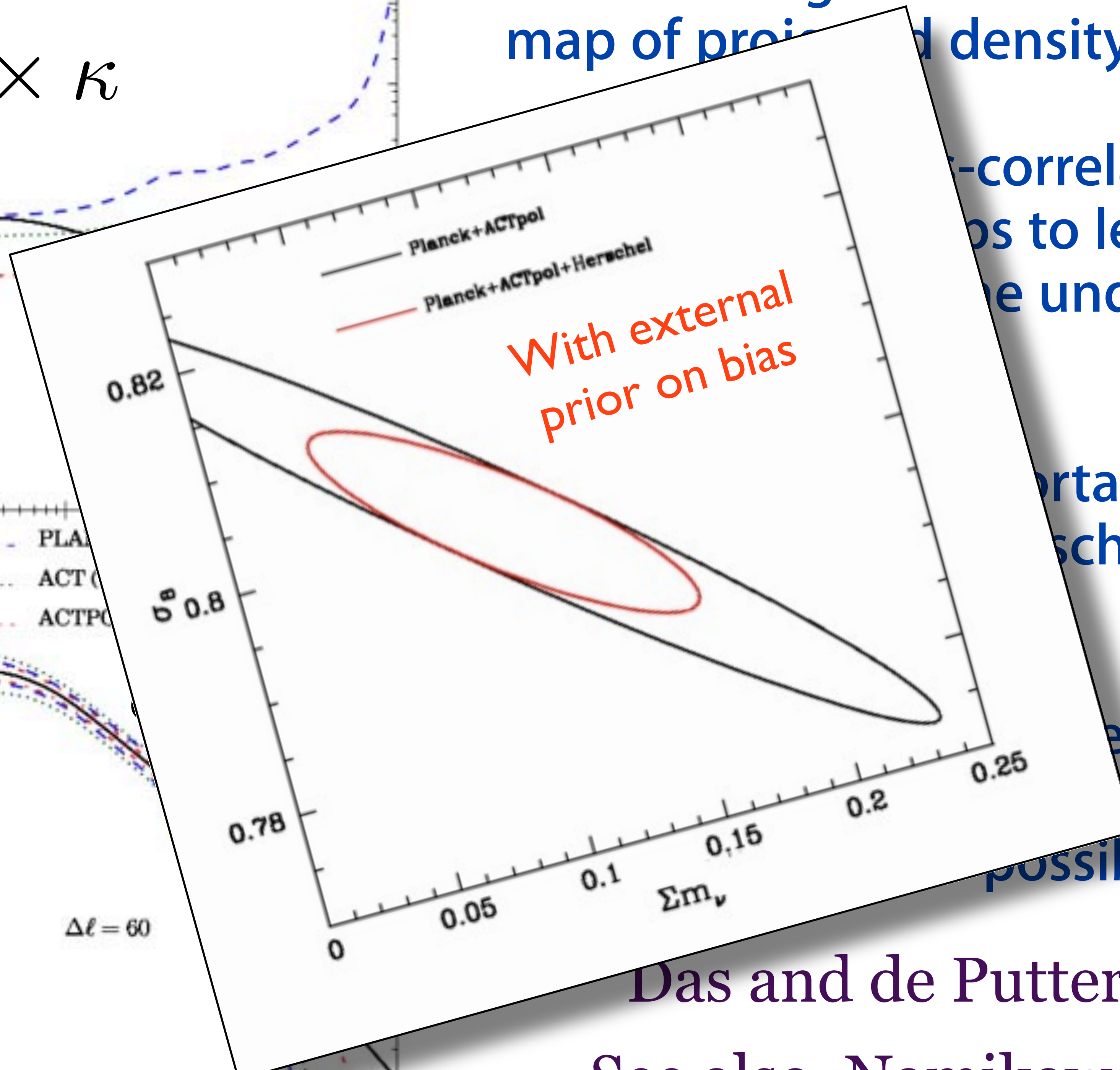
With their strong -ve K corrections, and high mag-bias, sub-mm galaxies are the golden candidates for cross-correlation with CMB lensing.

	Experiment	S/N	$\Delta b/b(\%)$
HSLS x	Planck	20	5.0
	ACT	16	6.2
	ACTPol	42	2.3

Cooray et al. (2010), HSLS White Paper

CONVERGENCE - GALAXY CROSS CORRELATION





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…-correlated with …s to learn how …e underlying dark

…rtant for high-z …schel/WFIRST/

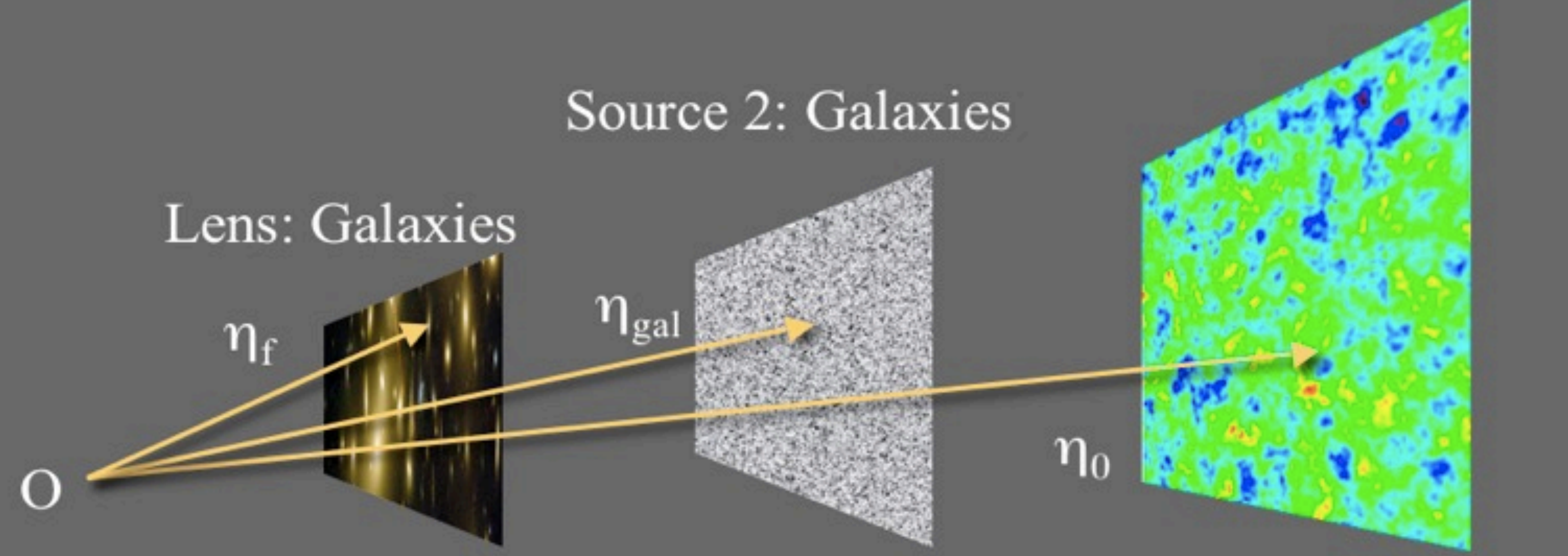
…es will simply fall …asured. Percent …possible.

Das and de Putter (in prep.)

See also, Namikawa et al (2010)

Measuring distances

Should be doable on Stripe-82 (CFHTLS);
also with Subaru HSC



$$r \equiv \frac{C_\ell^{\kappa_{\rm CMB}\Sigma}}{C_\ell^{\kappa_{\rm gal}\Sigma}} \simeq \frac{d_A(\eta_0 - \eta_f)\, d_A(\eta_{\rm gal})}{d_A(\eta_{\rm gal} - \eta_f)\, d_A(\eta_0)}.$$

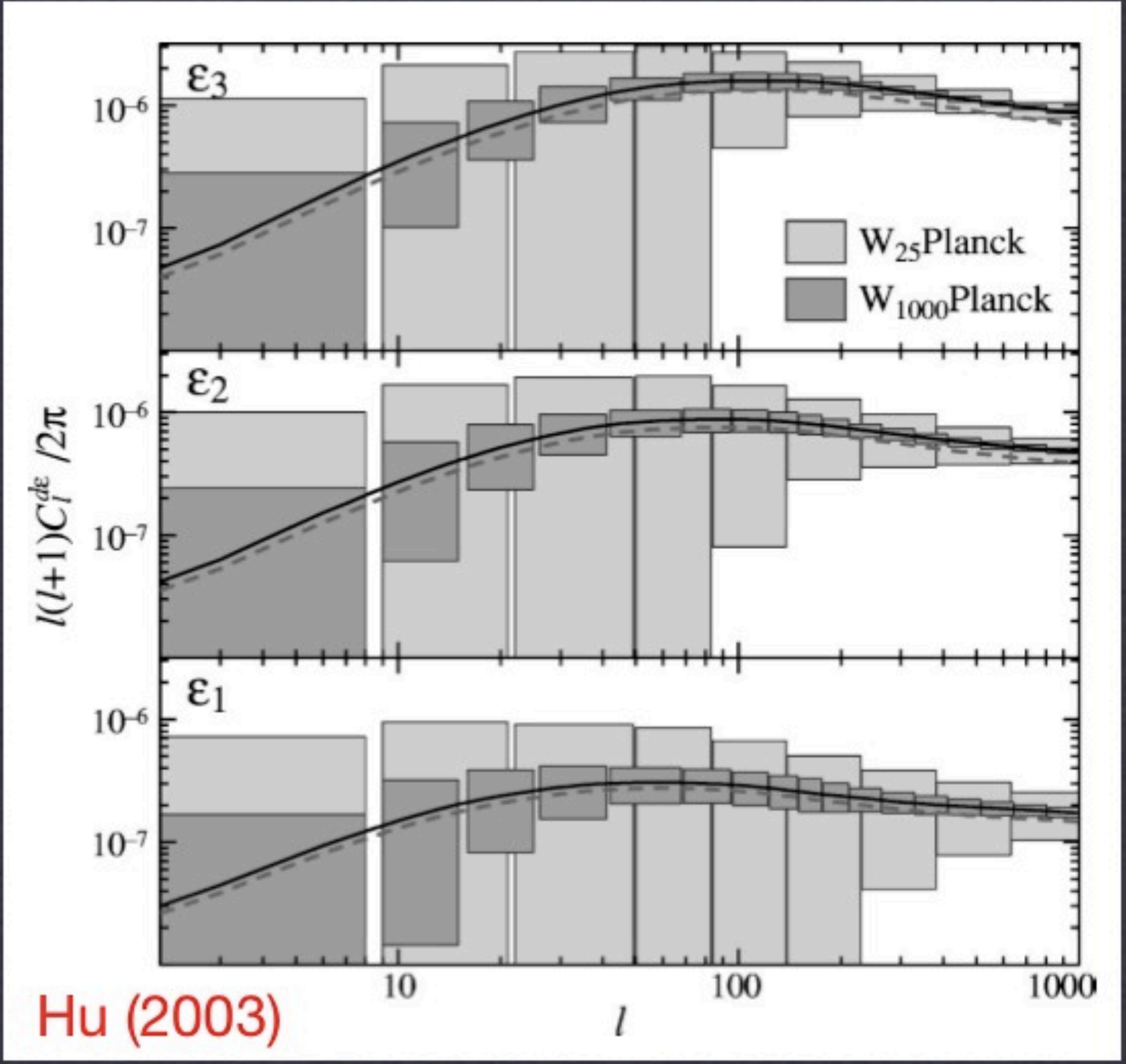
Das and Spergel (2008)

Measuring Growth

Cross-correlating CMB lensing with cosmic shear in redshift slices will probe growth of structure directly!

Deviations from GR?

Das, de Putter, et al in prep



These are exciting times!

• Arcminute scales CMB experiments are bringing new insights into cosmology and astrophysics through precision measurements of the primary and secondary anisotropies.

• The Atacama Cosmology Telescope is one such experiment which is already producing valuable results, informing cosmology, galaxy cluster and sub-mm galaxy physics.

• There is a lot of potential in the gravitational lensing of the CMB, and efforts to extract this signal are underway.

• A large array of cross-correlation projects are upcoming, where we expect to witness a very productive interplay of CMB physics and astrophysics (synergies with Herschel and CCAT).

• Small-scale polarization experiments like ACTPol, POLARBear and SPTPol will open up new windows into cosmology and astrophysics.