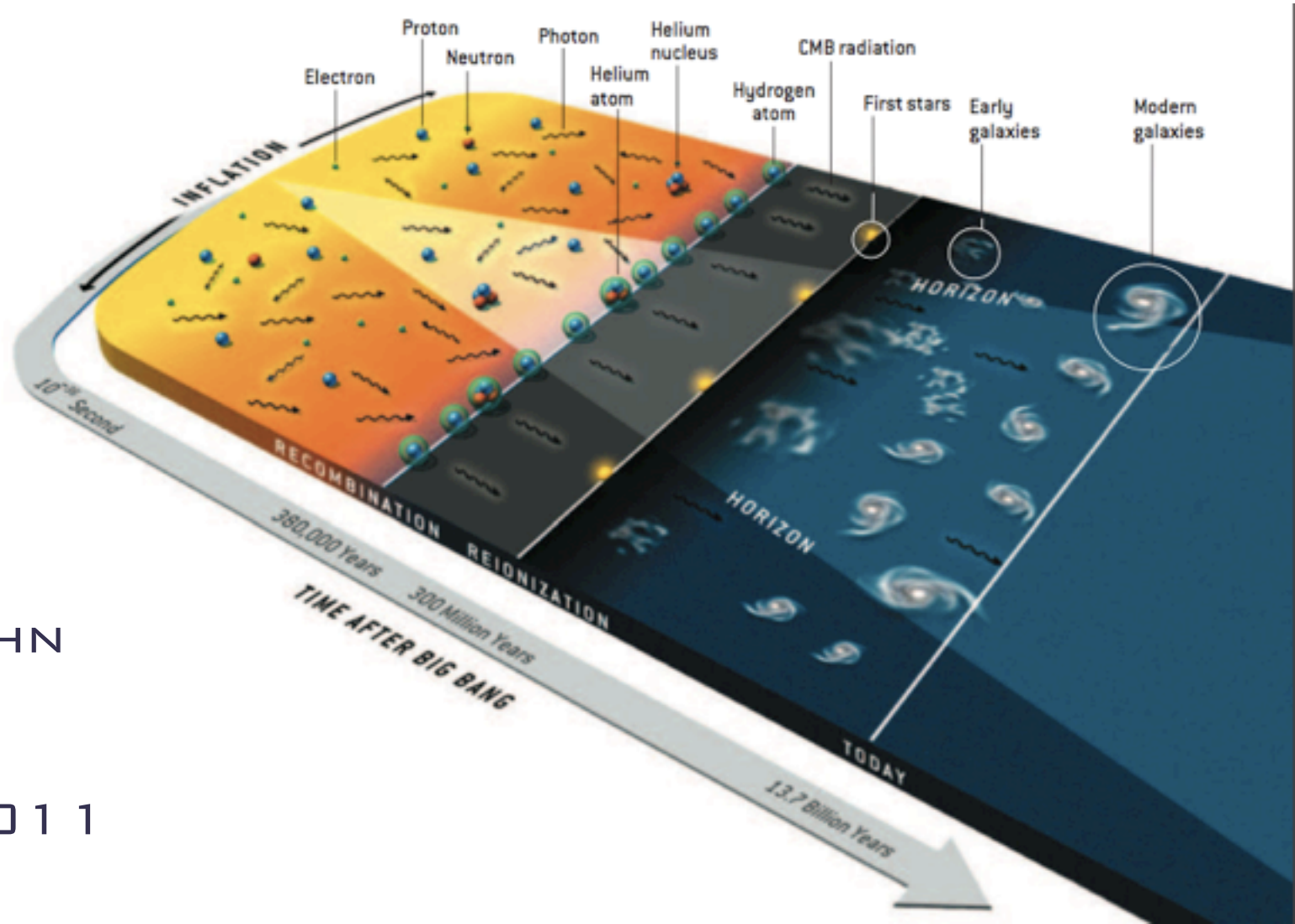
BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

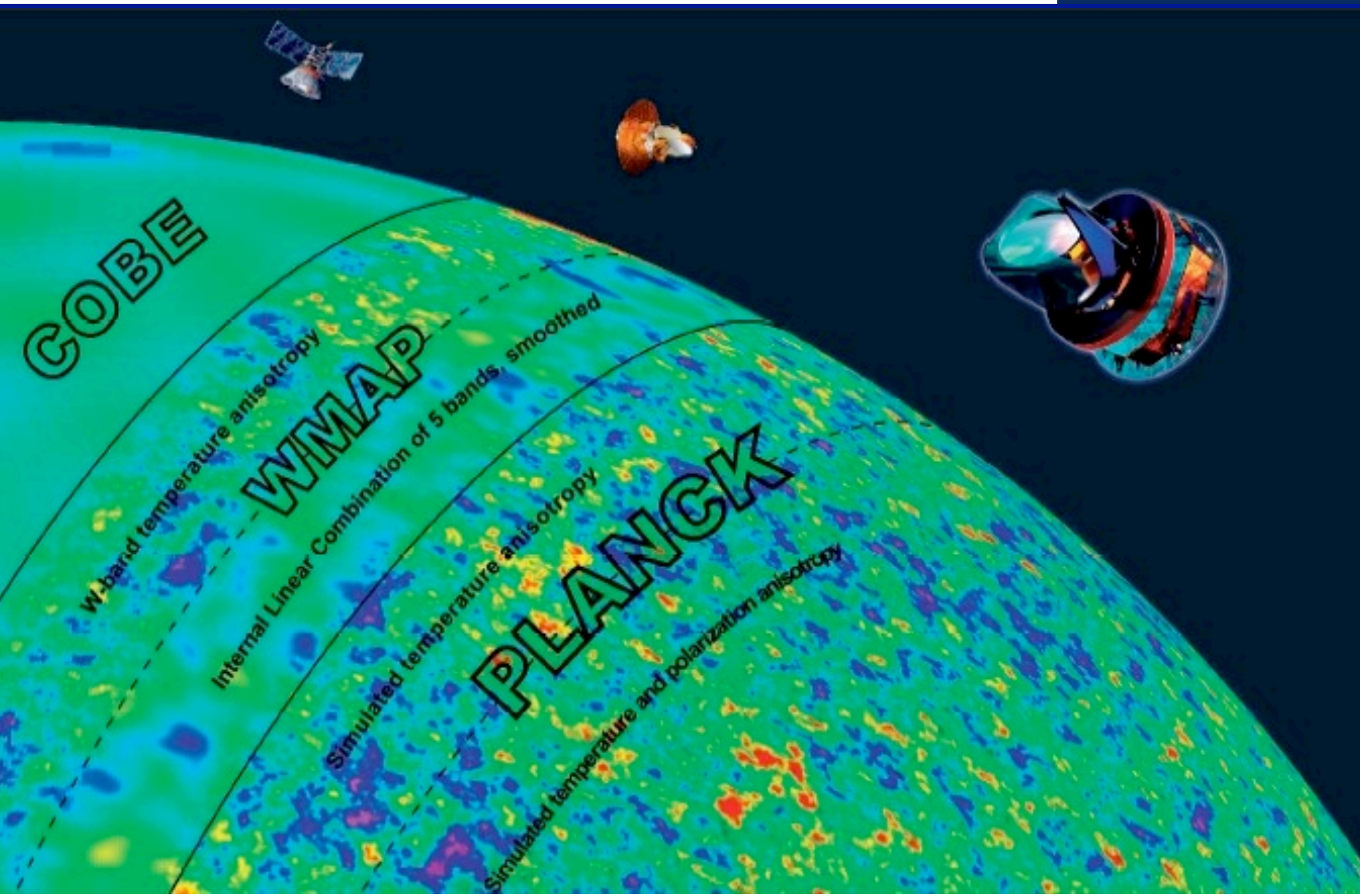
New Frontiers of Cosmic Microwave Background (CMB) research: Sunyaev-Zel'dovich effects and Lensing



Oliver Zahn

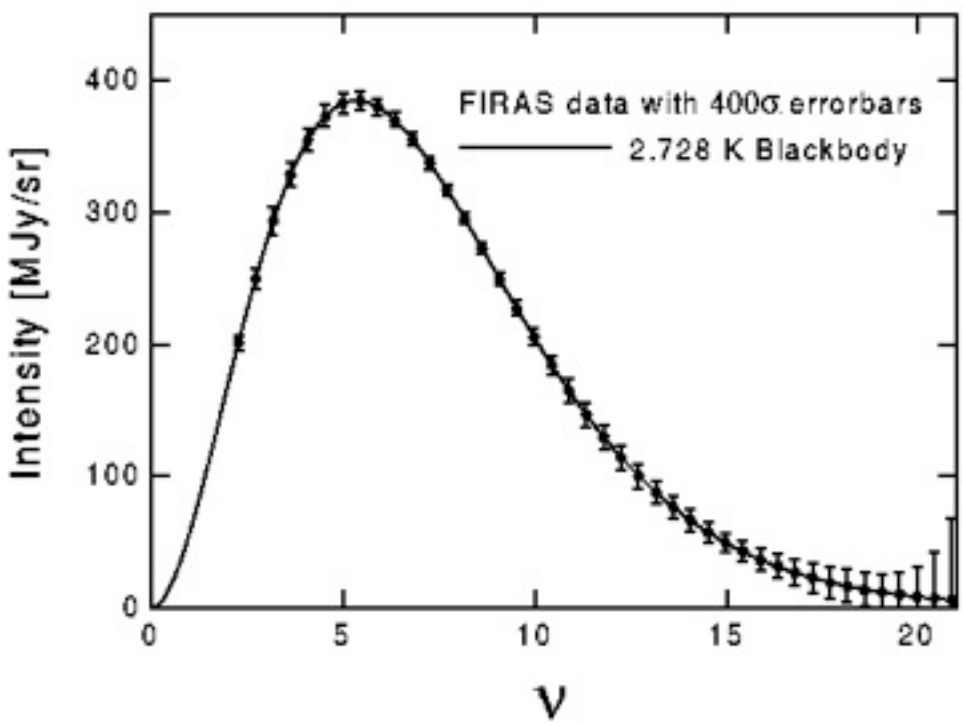
Puerto Vallarta school 2011

Connecting the Big Bang to Today

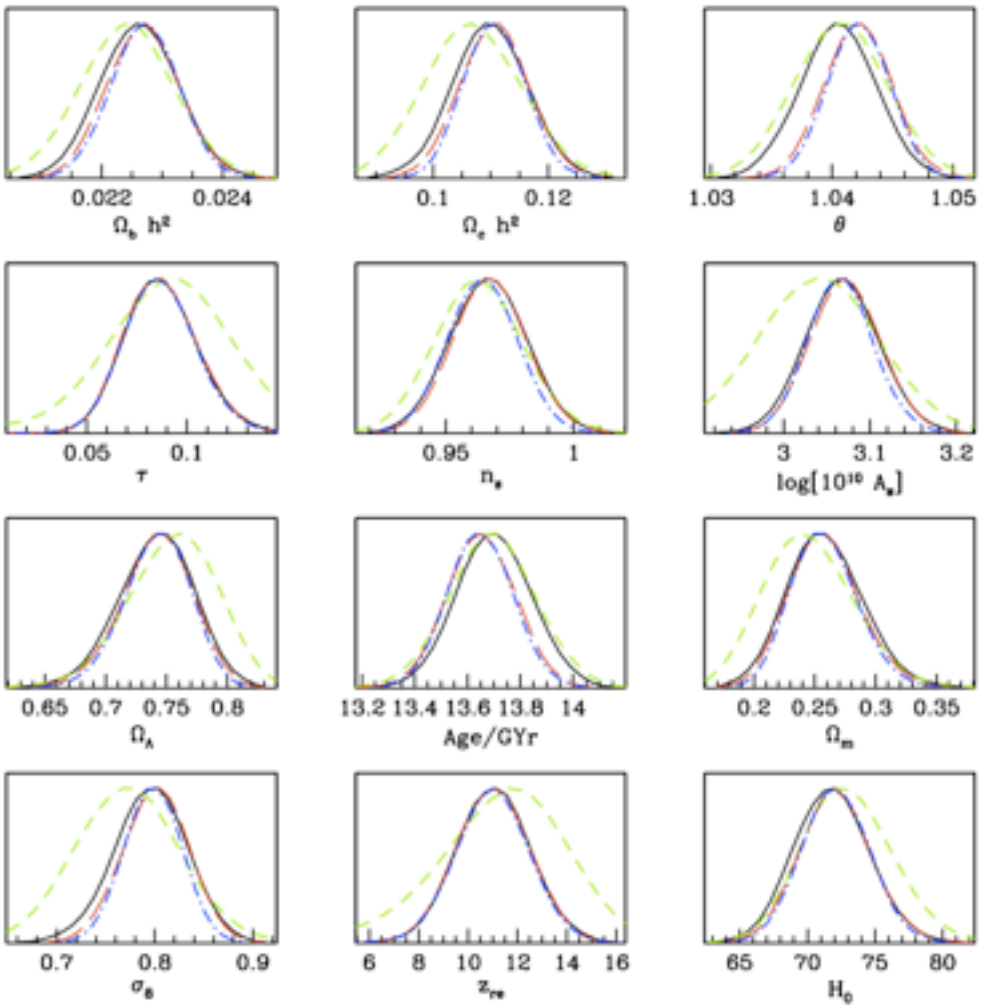


Primary well observed
Leading to new possibility

- CMB is the best measured black body radiator
- Angular distribution known with percent accuracy, and well-explained by inflation and LCDM theory.

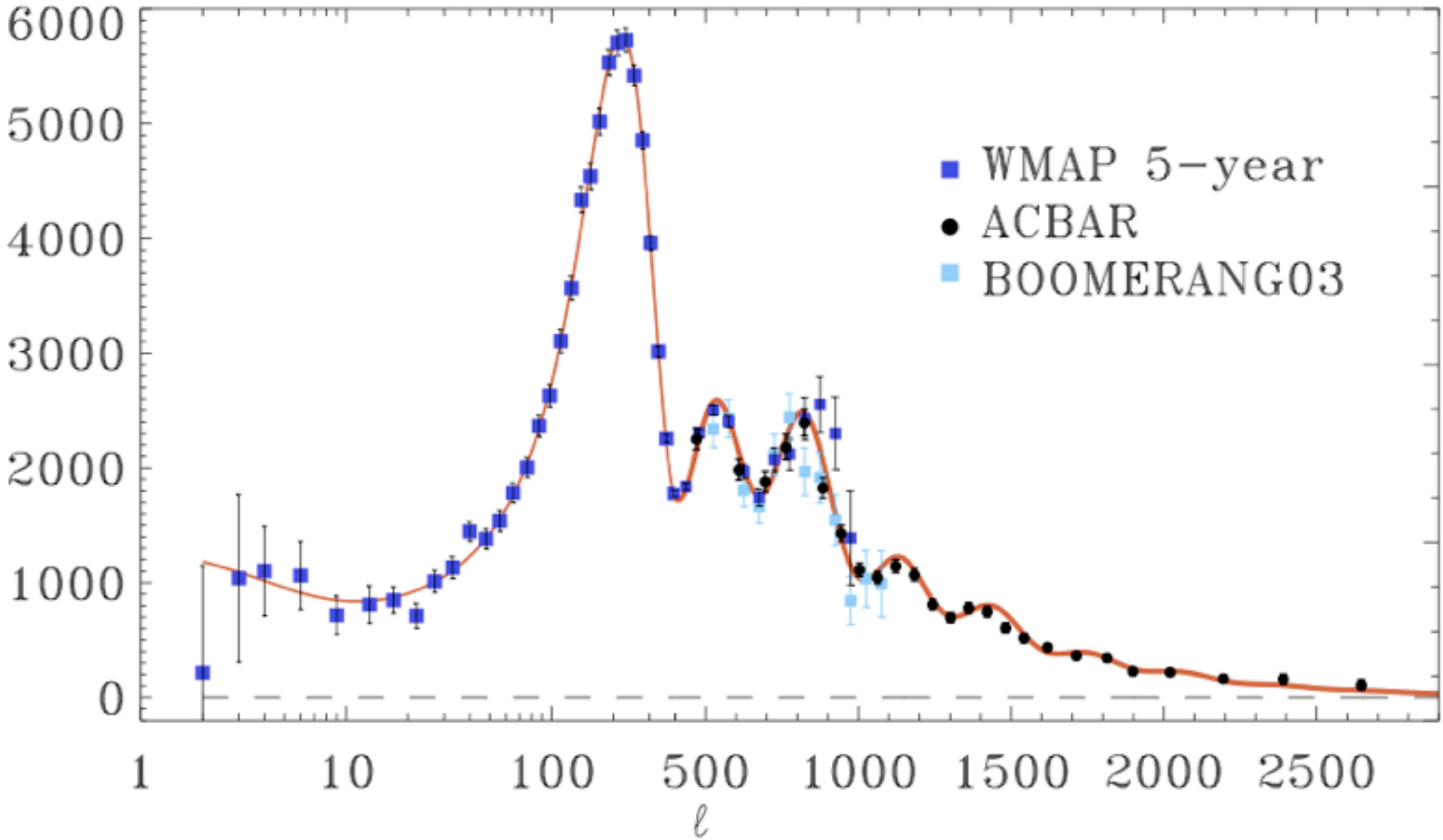


credits: COBE



credits: ACBAR

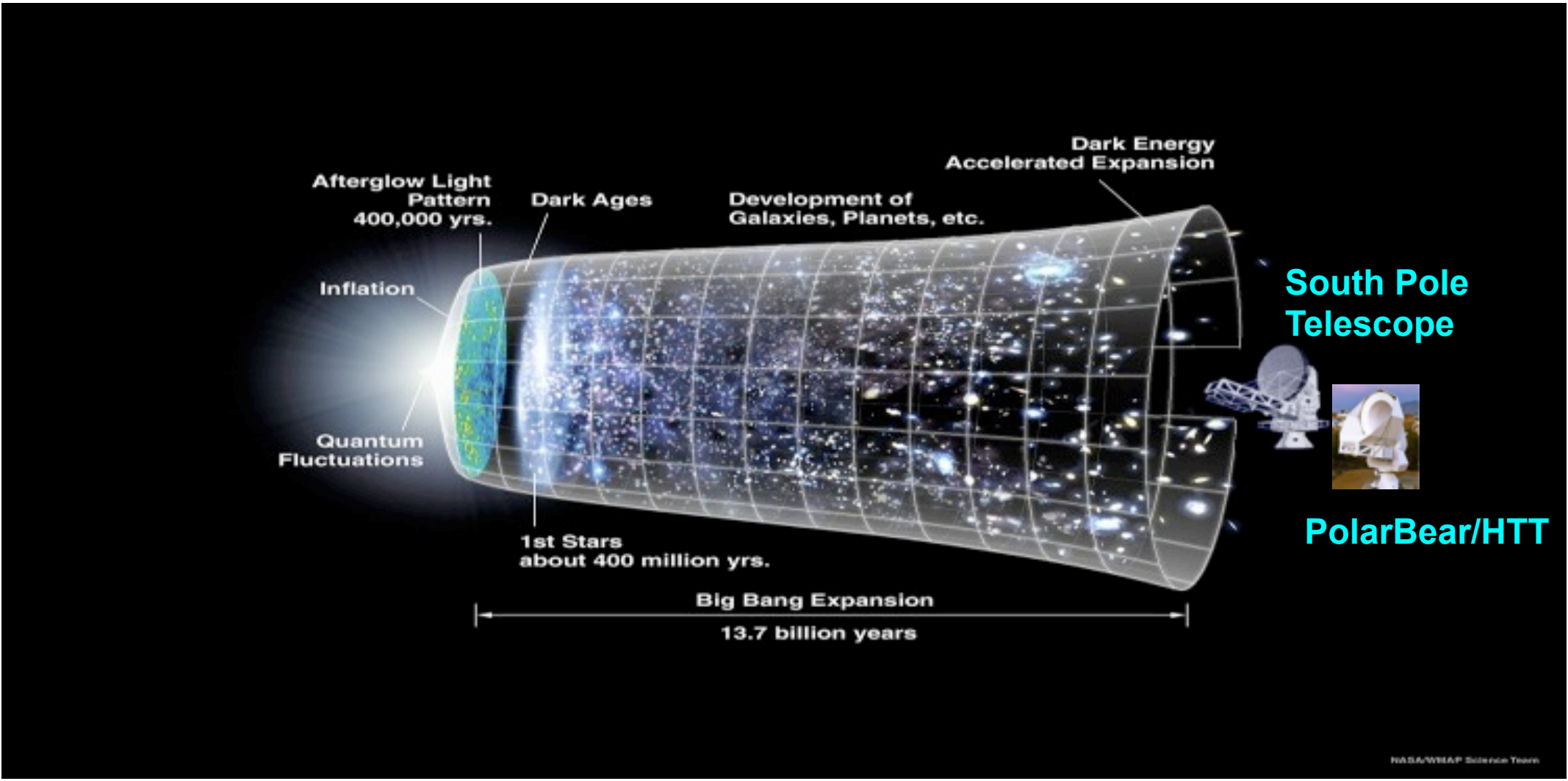
ACBAR/Planck=primary CMB nirvana



credits: ACBAR

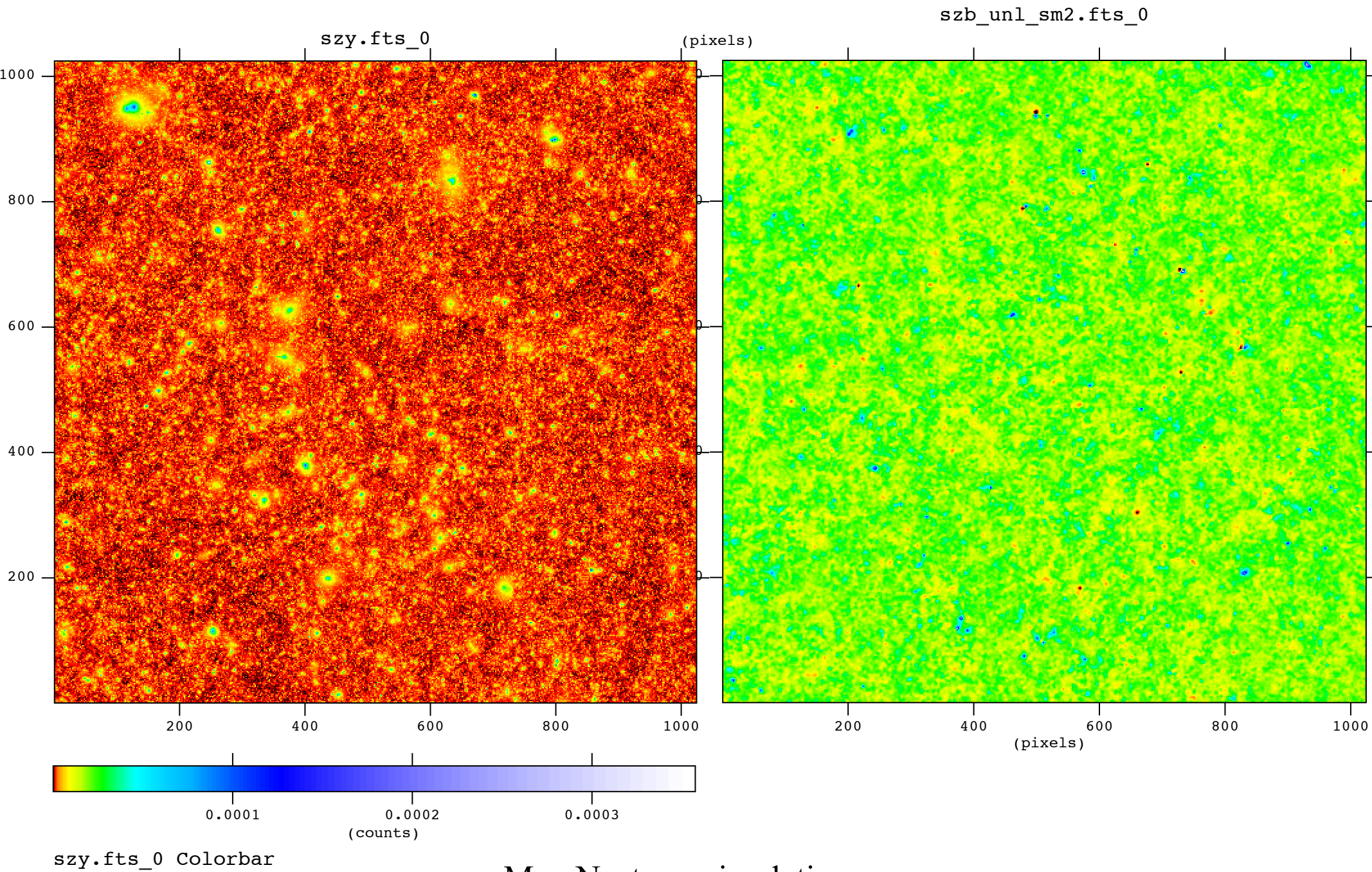
CMB photons trace through observable Universe, Creating Secondaries

Imagine using this well-understood most distant source as a background screen for understanding what happened since the big bang, along the light path of the CMB photons to us.



credit: WMAP science team/Princeton ;-)

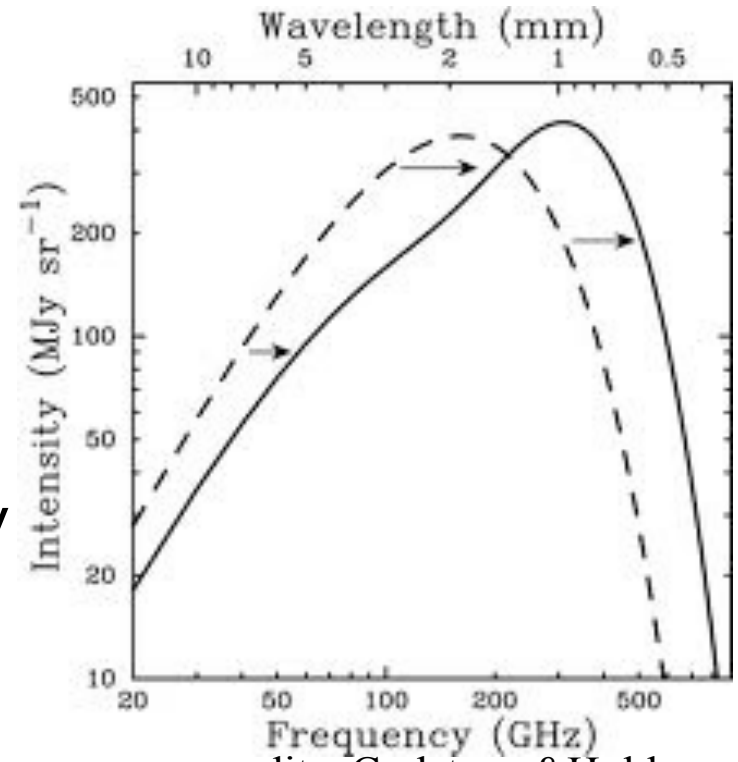
1) Sunyaev-Zel'dovich effects



MareNostrum simulation

Thermal Sunyaev-Zel'dovich effect

- CMB photons raining onto the hot gas in clusters of galaxies experience a shift of energy through inverse compton-scattering off relativistic electrons, which appears to observers as a temperature decrement at frequencies below 217 GHz, and an Increment above (Sunyaev&Zel'dovich 1972).

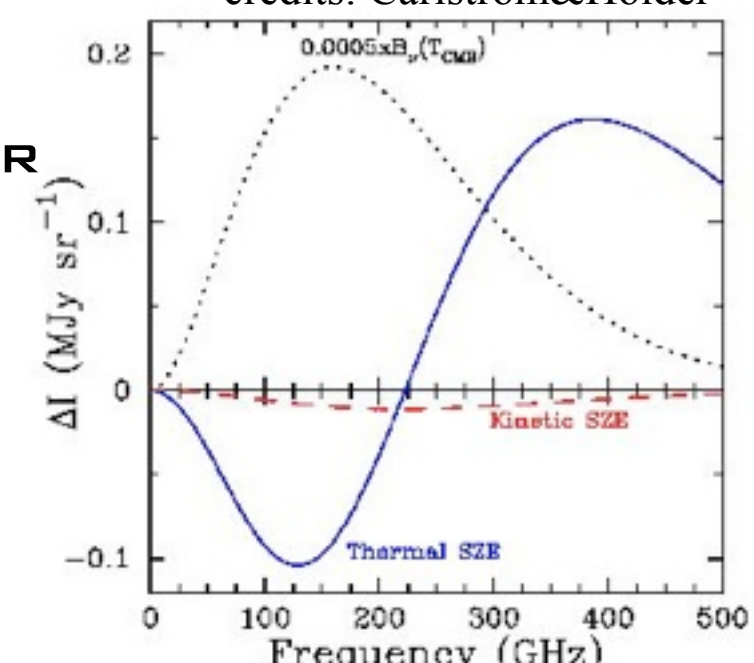


credits: Carlstrom&Holder

- By using both multi-frequency and angular information, clusters can be found and their ICM medium constrained.

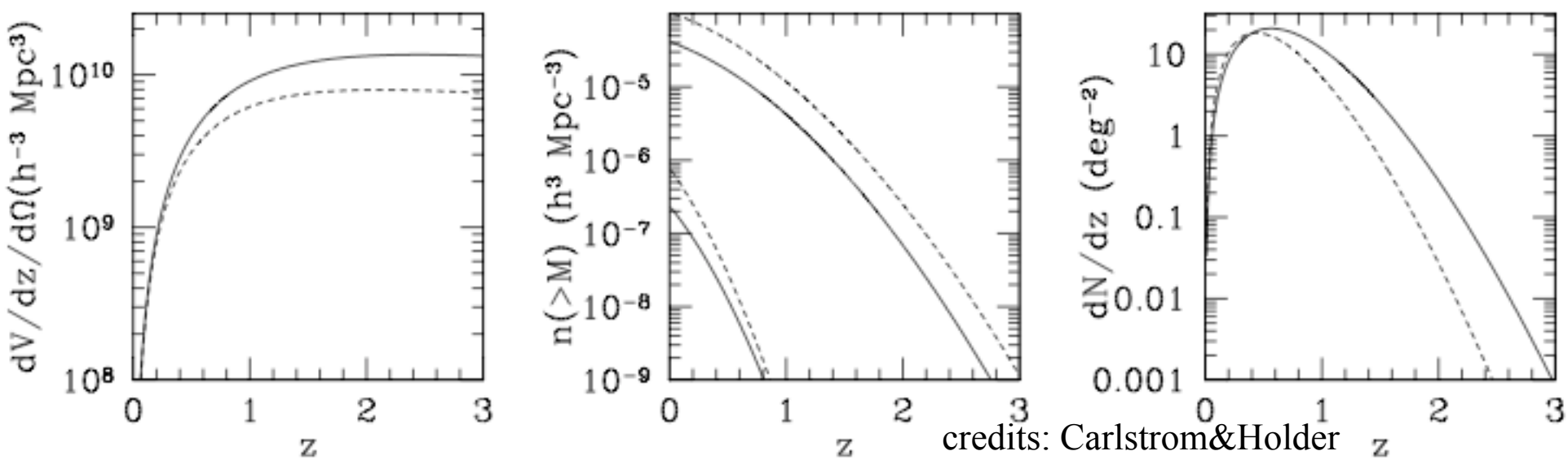
$$\frac{\Delta T_{SZE}}{T_{CMB}} = f(x)\ y = f(x) \int n_e \frac{k_B T_e}{m_e c^2} \sigma_T \, d\ell,$$

$$f(x) = \left(x \frac{e^x + 1}{e^x - 1} - 4 \right) (1 + \delta_{SZE}(x, T_e))$$



Redshift-independent tracer

- SZE allows studying clusters out to higher redshift than e.g. X-ray
- This property of SZE surveys is due to the fact that the SZE is a distortion of the cosmic microwave background (CMB)spectrum.
- While the CMB suffers cosmological dimming with redshift, the ratio of the magnitude of the SZE to the CMB does not; it is a direct, redshift independent measurement of the ICM column density weighted by temperature, i.e., the pressure integrated along the line of sight.



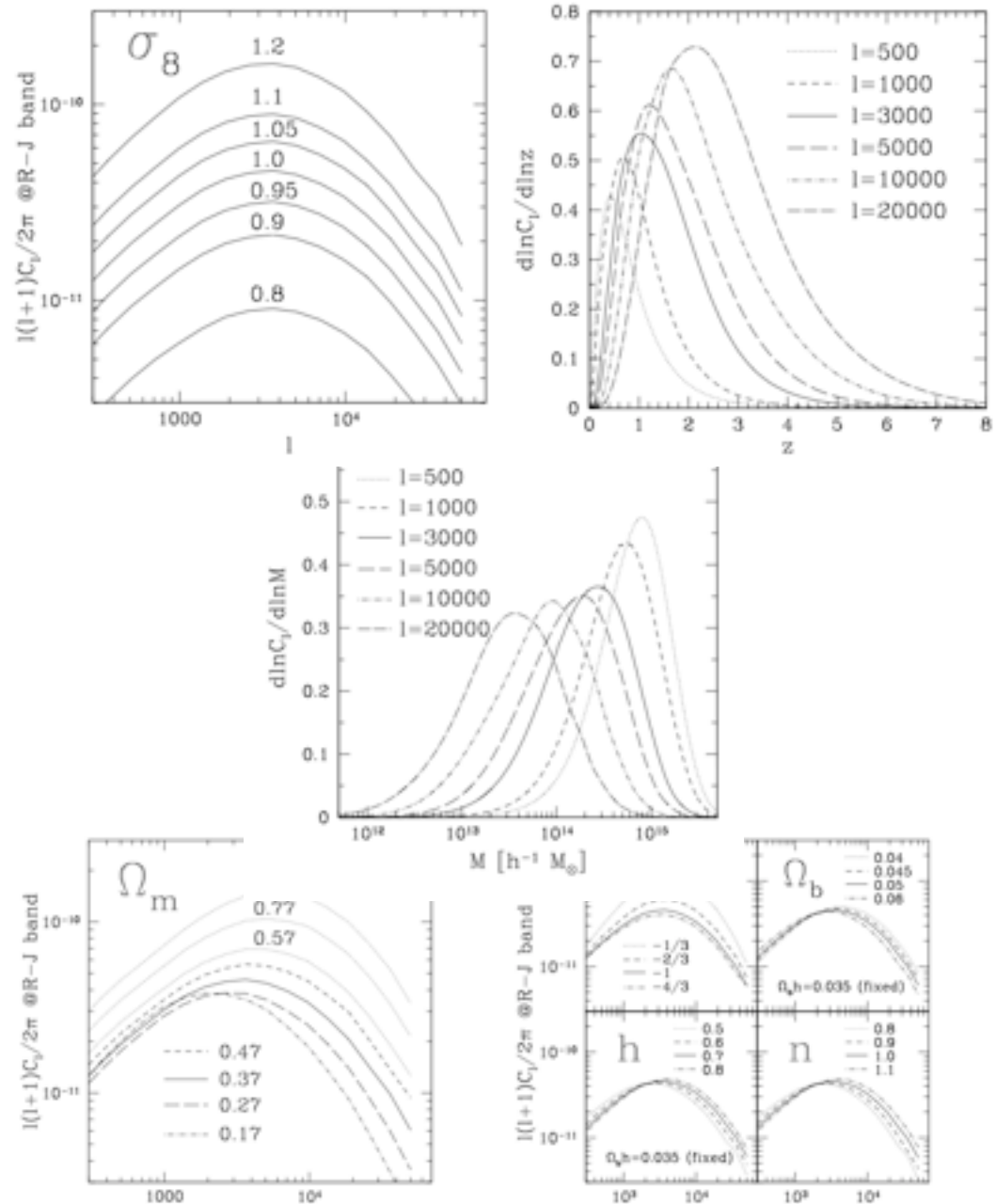
credits: Carlstrom&Holder

SZE as a cosmological probe

$$C_l = g_\nu^2 \int_0^{z_{\max}} dz \frac{dV}{dz} \int_{M_{\min}}^{M_{\max}} dM \frac{dn(M,z)}{dM} |\tilde{y}_l(M,z)|^2$$

Komatsu&Seljak '02

- SZE is highly sensitive to the normalization of the matter power. ~sigma8^7-8
- Decreases sharply at z>1
- depends on about a magnitude in mass from 10^14-10^15 Msol.
- Also depends on other cosmological quantities.



credits: Komatsu&Seljak

Modeling the CMB sky requires a large dynamic range

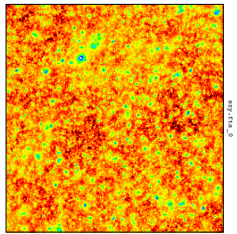
Need large dynamical range to:

- resolve smallest halos
- model variation of largest halos

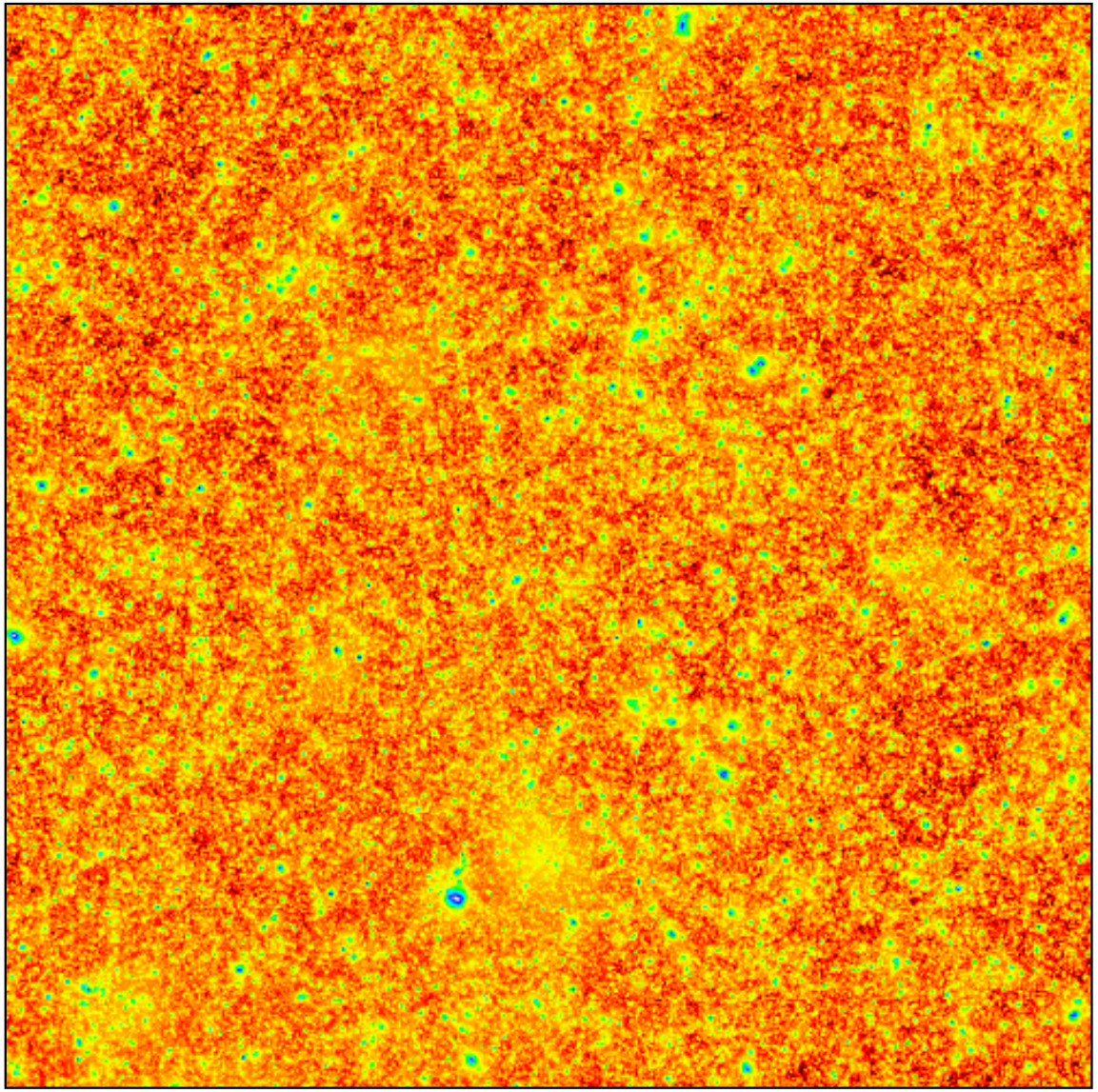
MareNostrum simulation

Gas physics is the mediator between Observations and Cosmology...

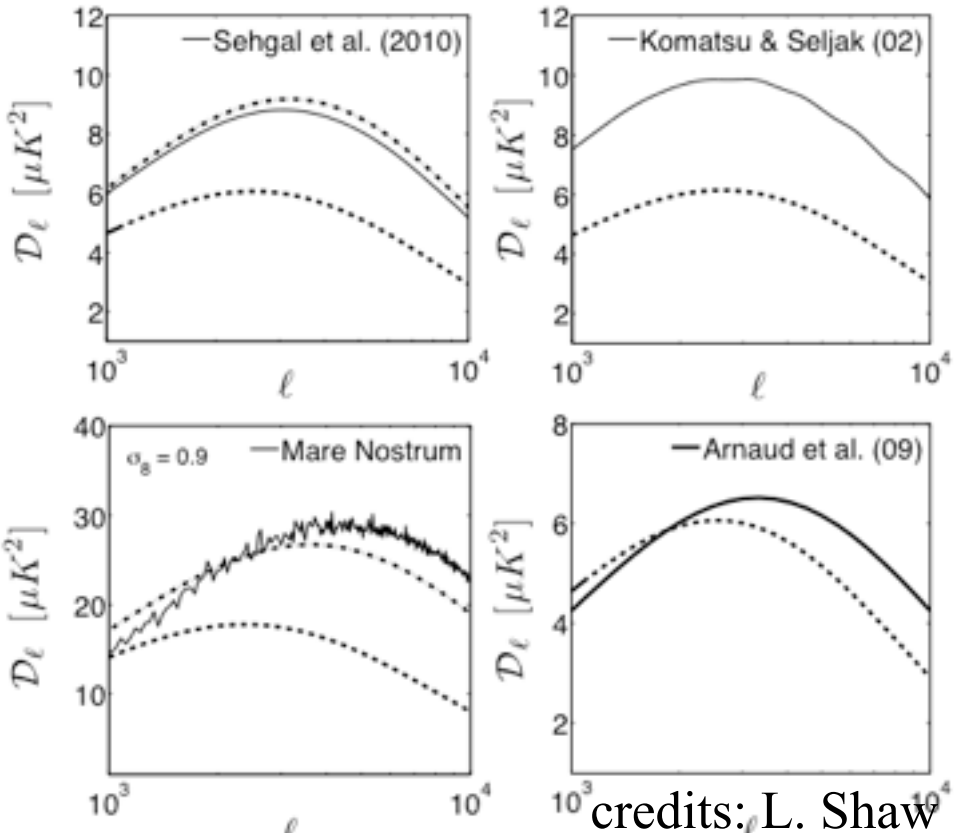
Previous simulations ~100 Mpc/h



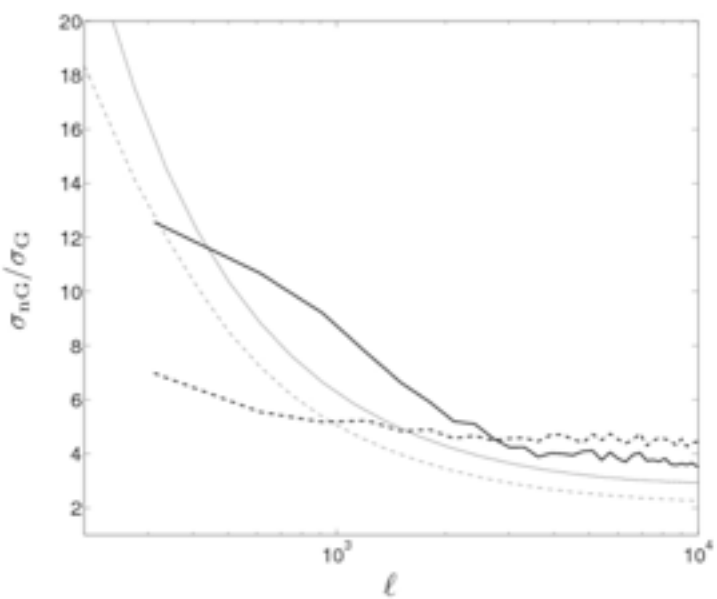
500 Mpc/h simulation



SZ theory: analytic versus simulation



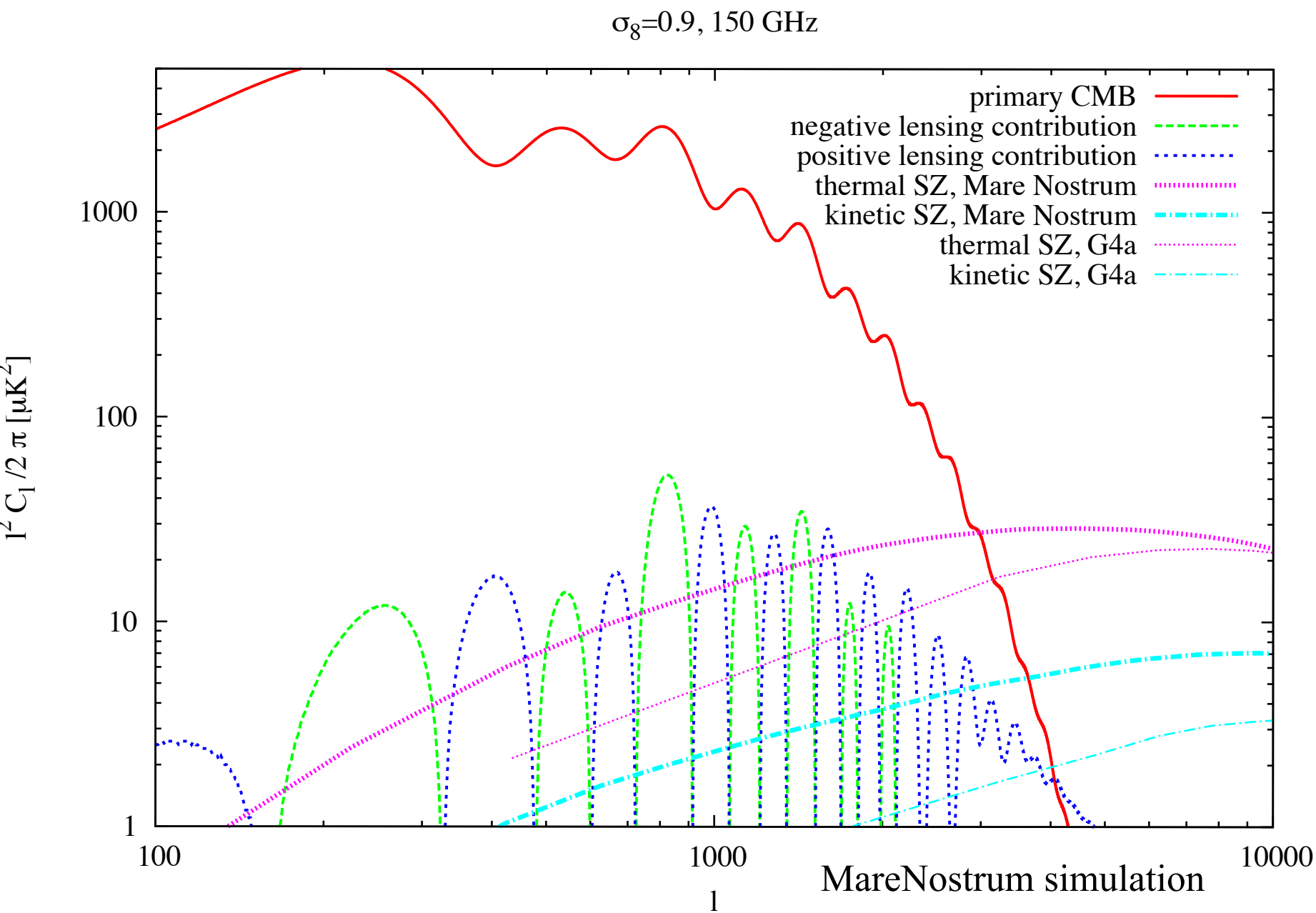
credits: L. Shaw



Bode&Ostriker model accounts for star formation and energy feedback (from supernovae and active galactic nuclei) as well as radially dependent non-thermal pressure support due to random gas motions, the latter calibrated by recent hydrodynamical simulations.

The simulation without star formation, cooling and feedback predicts a higher tSZ signal than the one that includes these processes. On small scales, this is principally due to the suppression of the SZ signal in the central regions of lower mass structures as gas is expelled by AGNs (Battaglia et al. 2010). On larger scales the difference is driven by differences in the cluster abundance.

- Importance of a large dynamical range

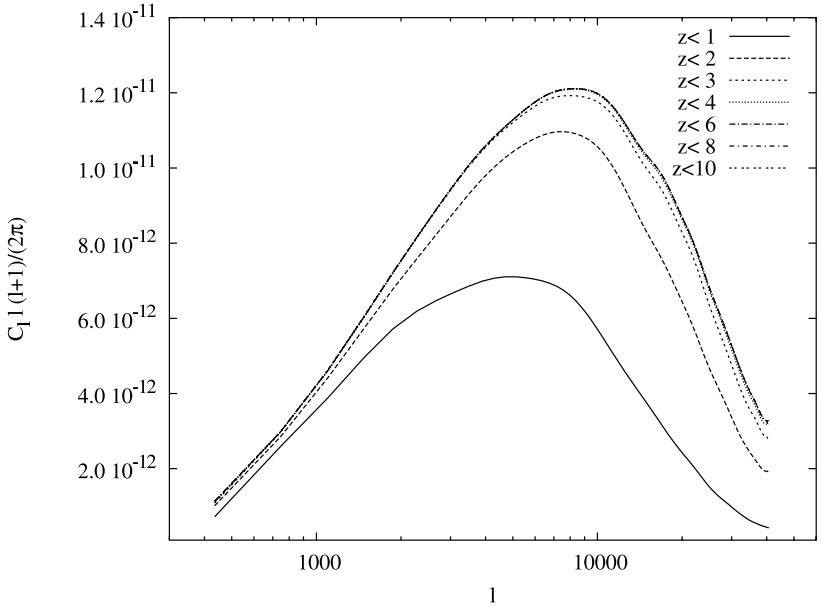


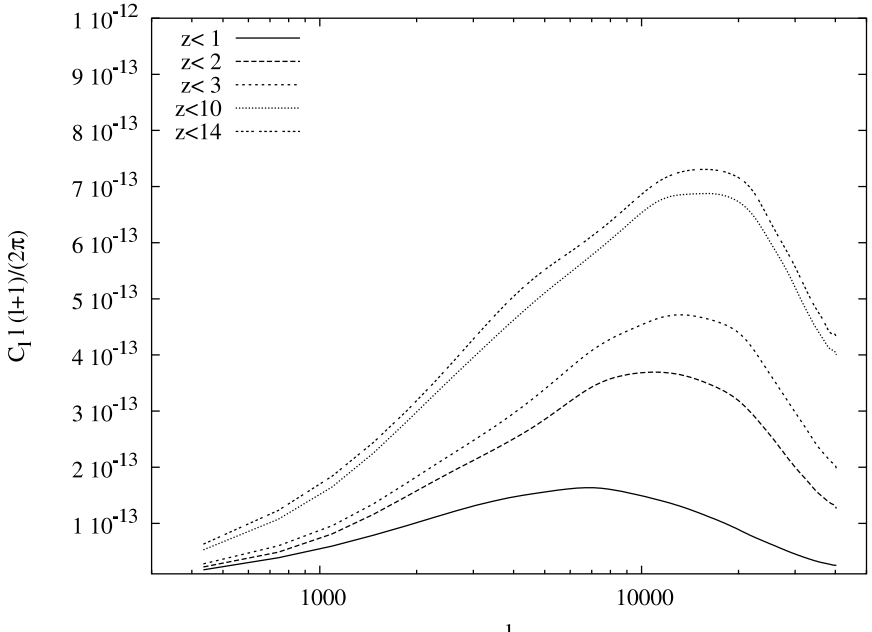
Kinetic SZE

- Owing to the peculiar motion of clusters and large scale structure, the CMB is Doppler shifted, which is called the kinetic SZE.
- Since the kSZ does not depend on the temperature of the free electrons, it has a different angular and redshift dependence as the tSZ. Specifically it has more large scale power and decays much slower with z.

$$\frac{\Delta T_{SZE}}{T_{CMB}} = -\tau_e \left(\frac{v_{pec}}{c}\right)$$

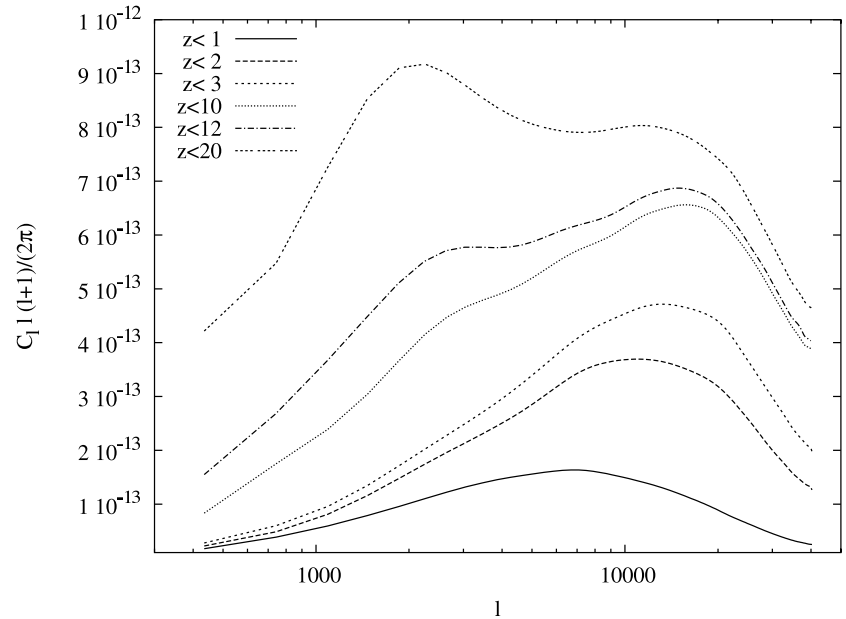
Zahn et al. 2006

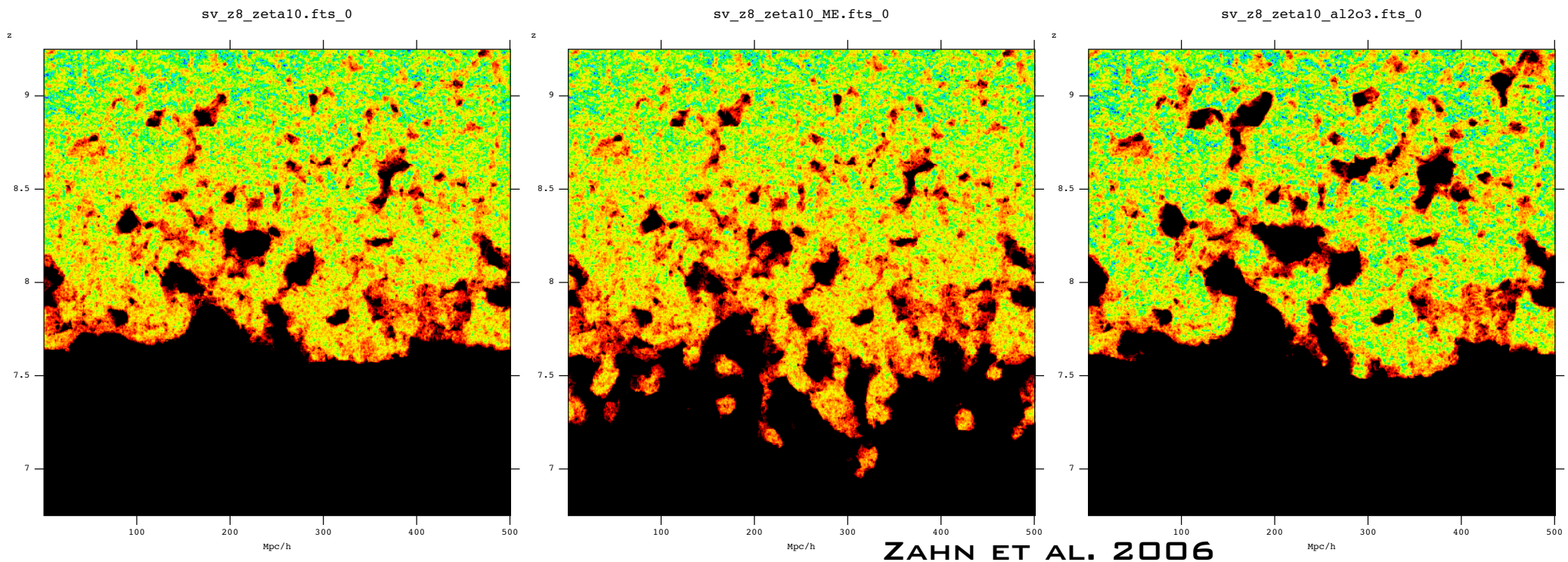




kSZ from reionization

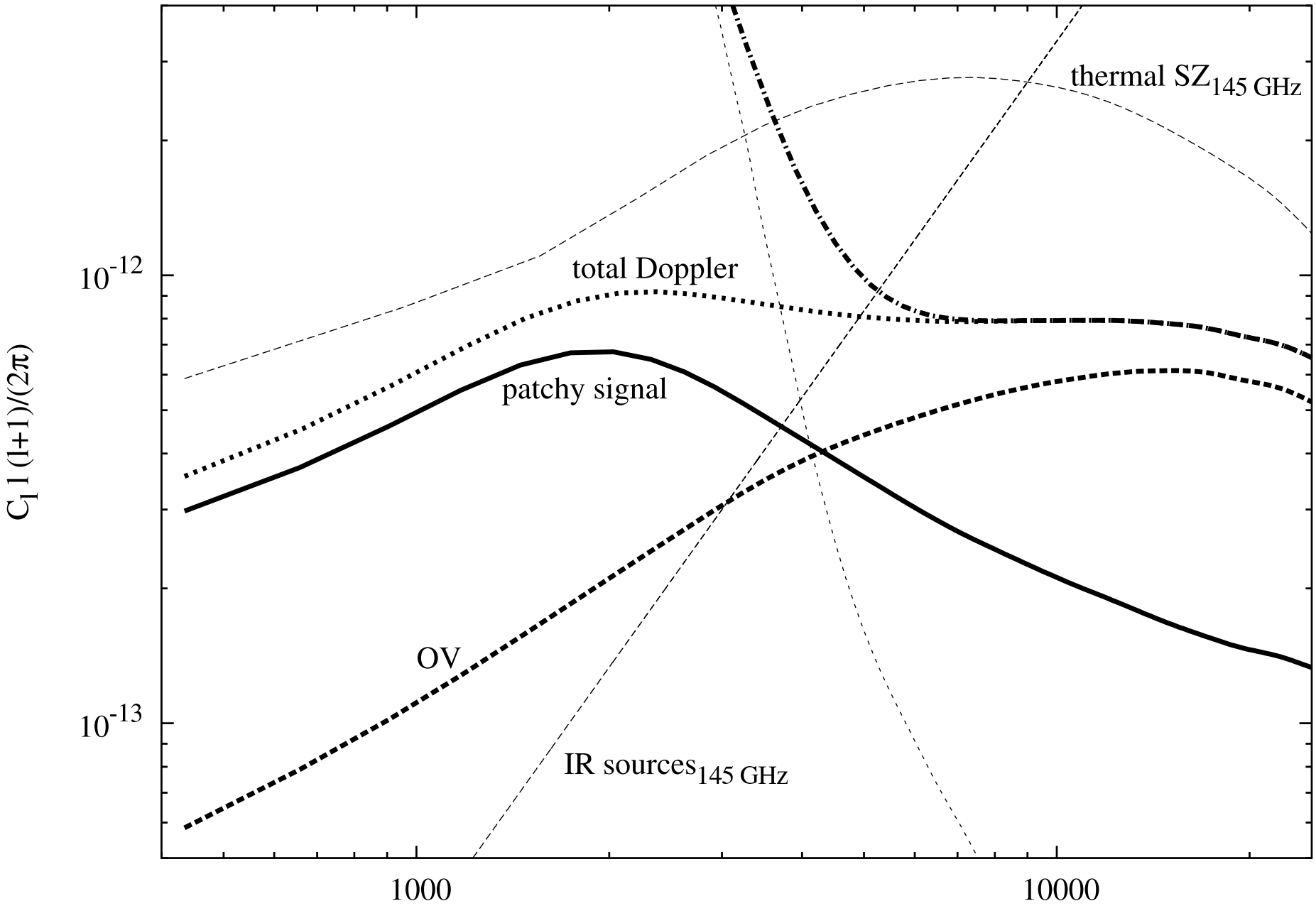
- kSZ is particularly slow-decaying if reionization is not homogenous, which we have ample reason to believe
- Large dynamic range important for bubbles and velocities





Zahn et al. 2006

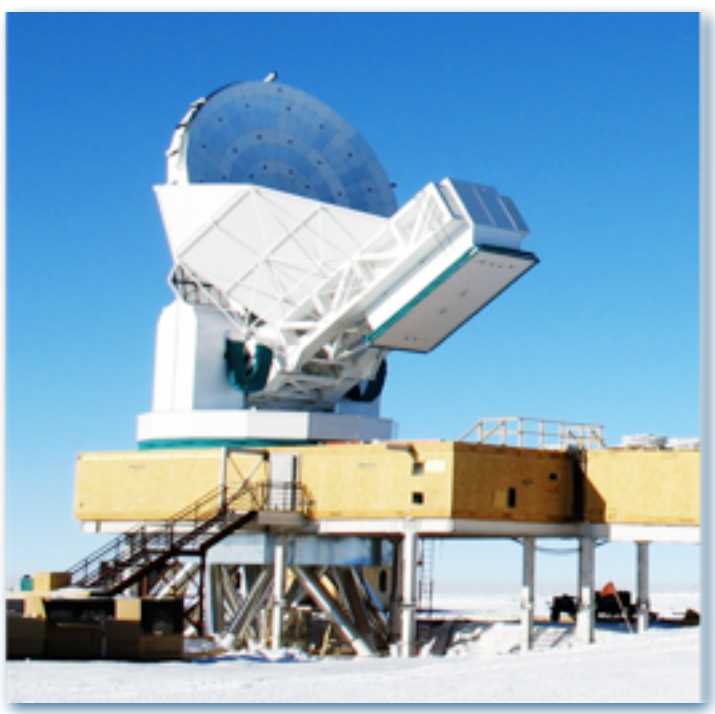
Various contributions to kSZ

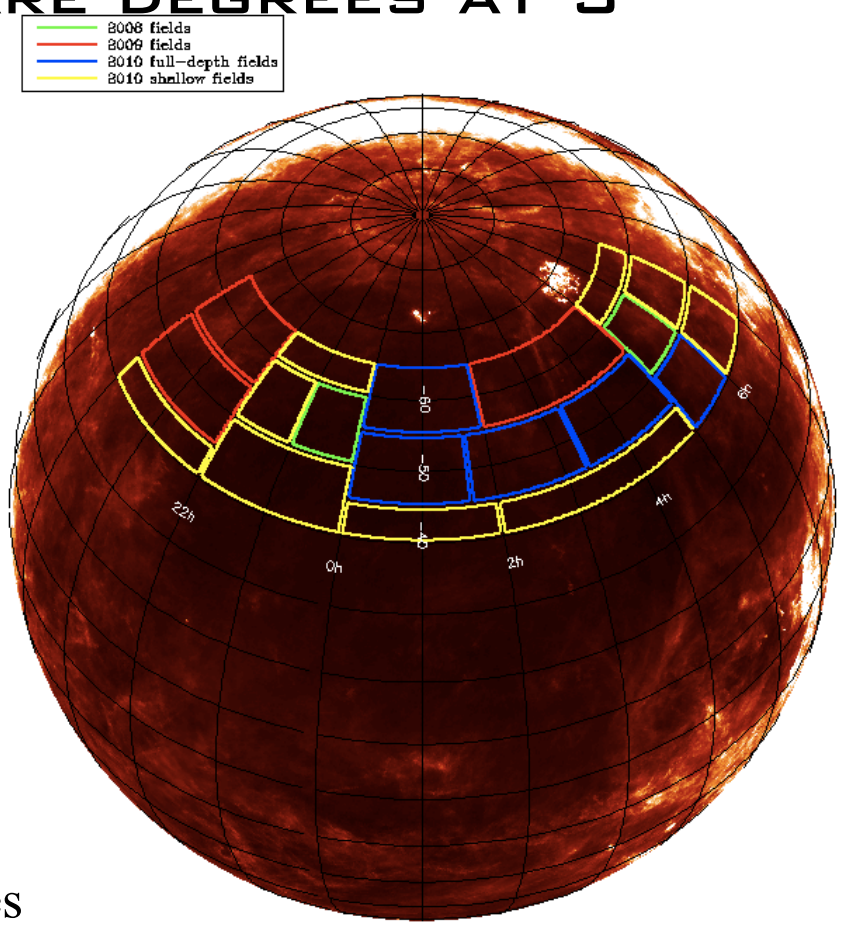


Zahn et al. 2006

The South Pole Telescope (SPT)

- Largest CMB telescope at 10 m, 960 detectors, each cooled to near absolute zero.
- Allows for imaging 1'=1/60th degree CMB structures=size of a large cluster at z=1. At South Pole (high altitude, dry atmosphere).
- Now surveyed 2600 square degrees at 3 frequencies





SPT images

The South Pole Telescope (SPT)

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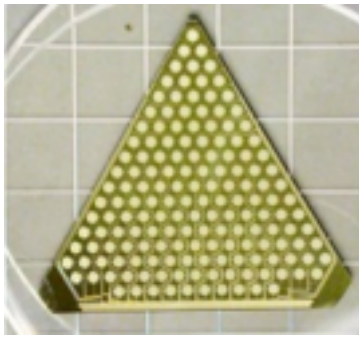
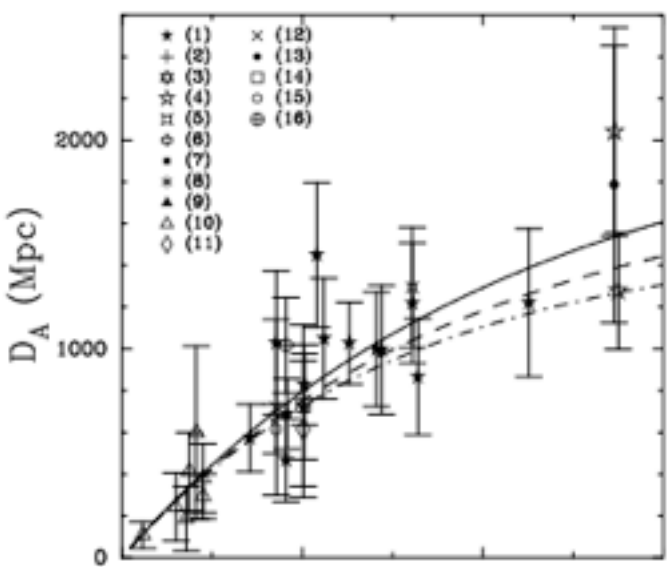
- Incredibly versatile experiment allows
  - —exploration of the properties of dark energy with catalogue of hundreds of newly detected galaxy clusters!
  - —statistical detection of Compton-scattering/SZ background&interpretation
  - —statistical detection of cluster peculiar velocities
  - —detection of gravitational lensing of the CMB and constraints on parameters

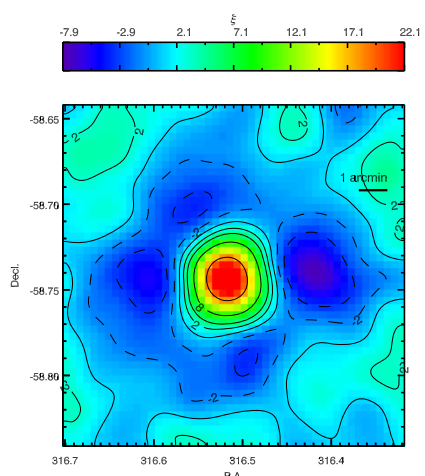


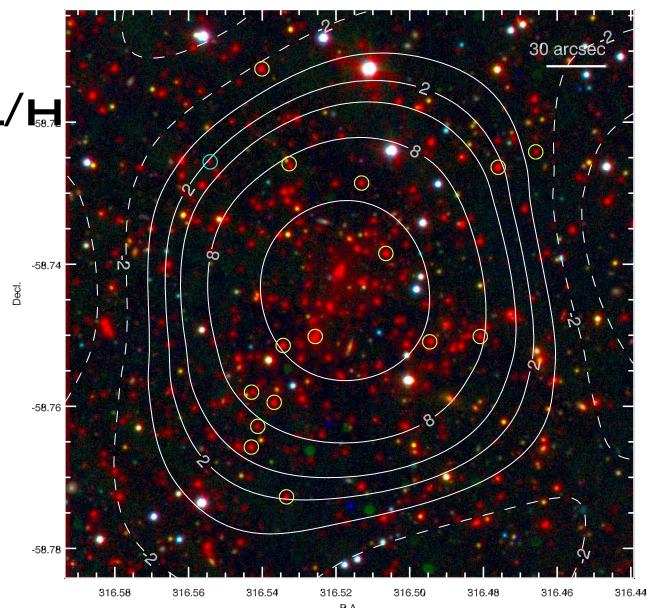
credits: Carlstrom&Holder



z=1.13

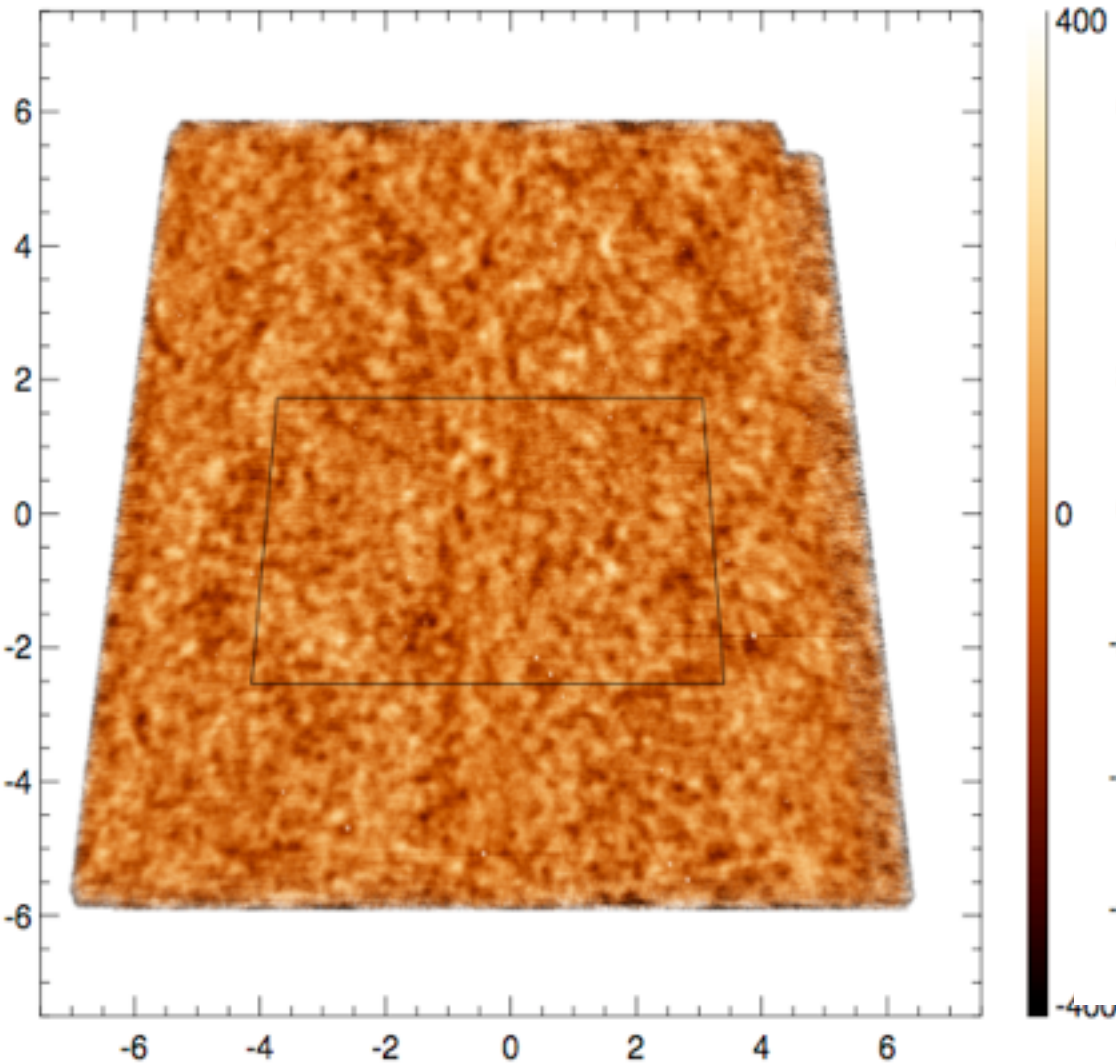
M=1.27e15 Msol/h



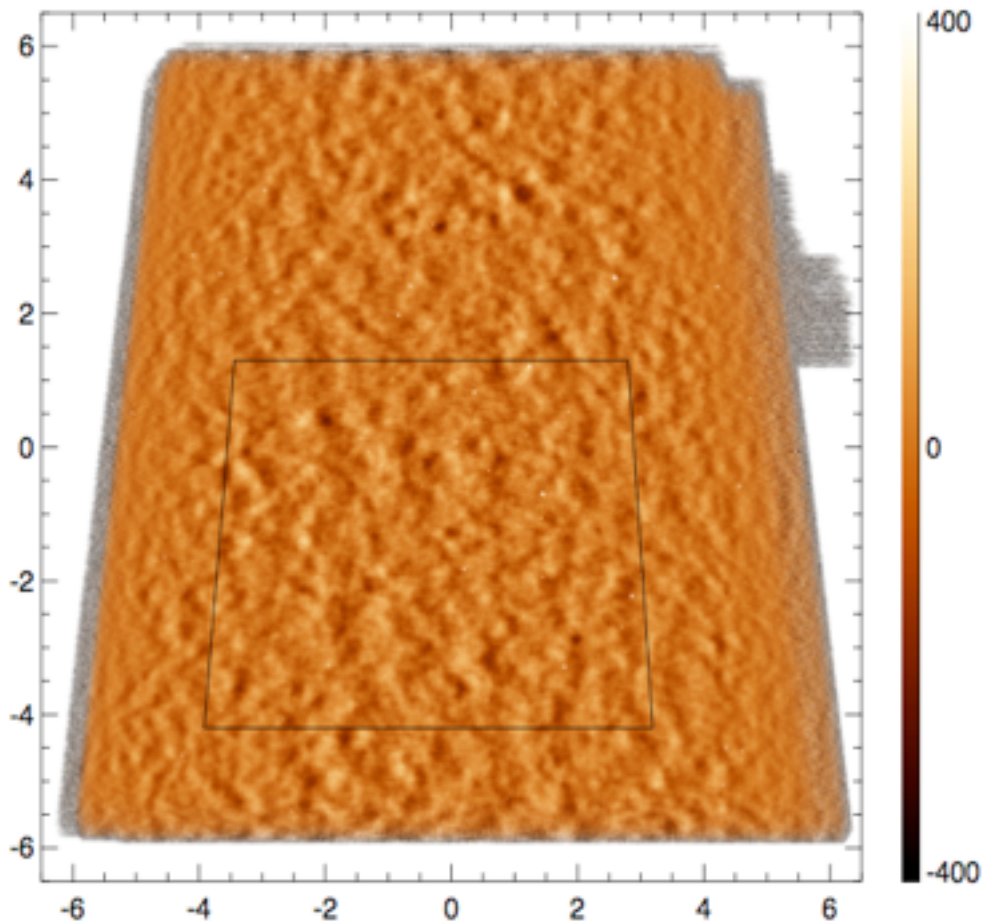


SPT - data

During 2008 SPT observed two 100 square degree fields overlapping the Blanco cosmology survey (BCS). These were fully analyzed in Lueker 09 and Shirokoff 10. By now1600 square degrees have been observed to the same depth

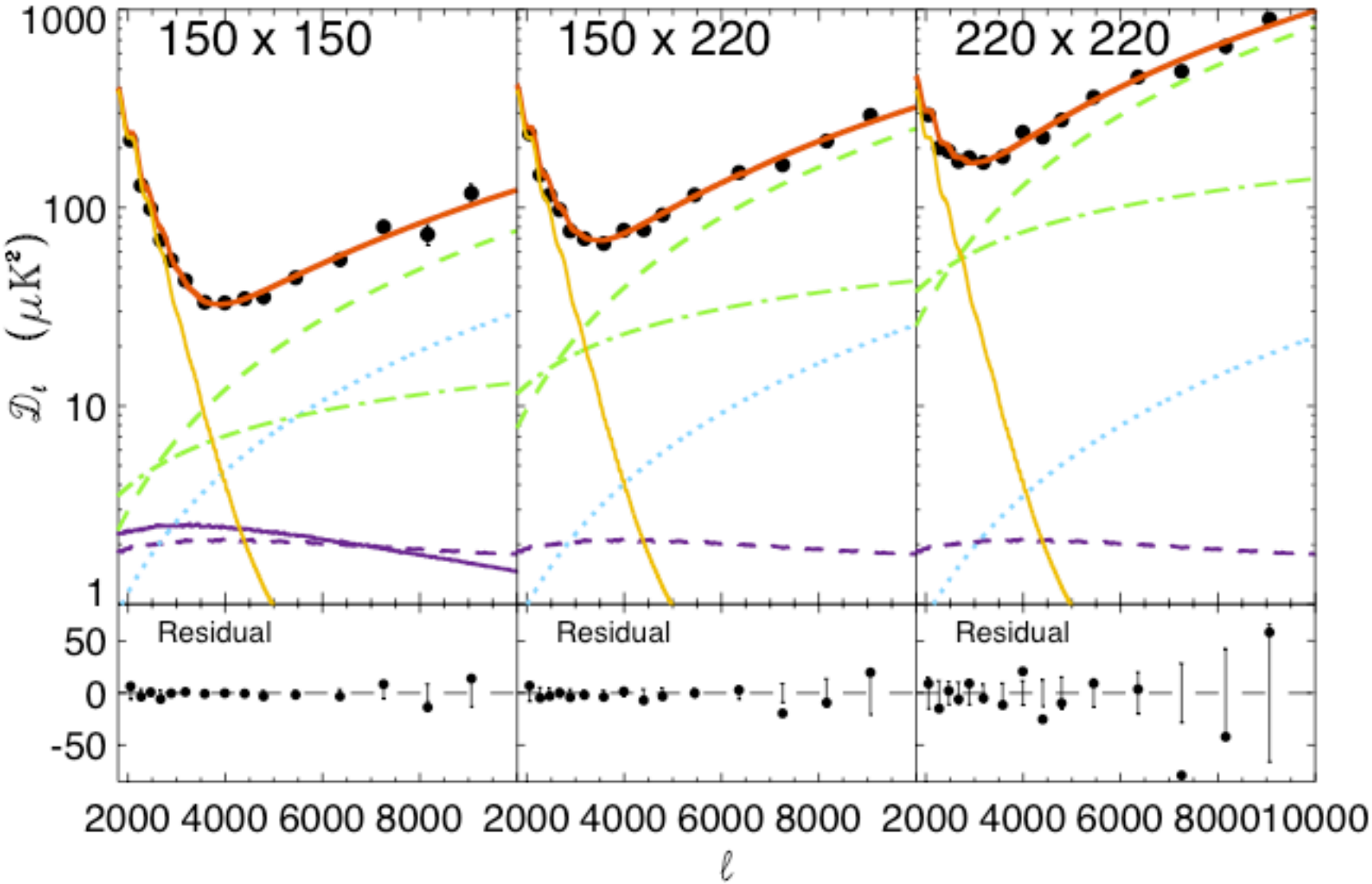


SPT collaboration



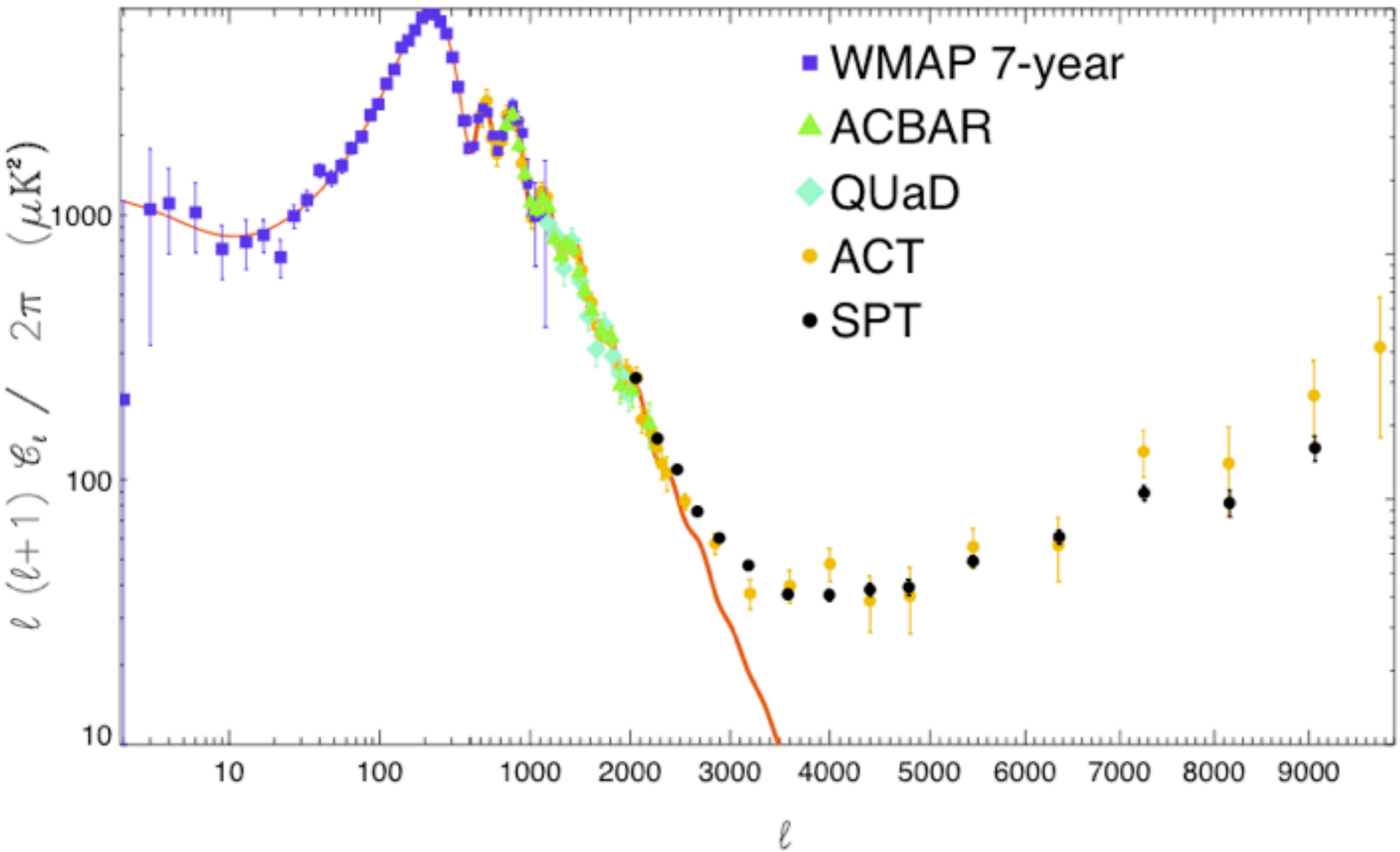
Shirokoff et al. 2010

- Full analysis of the 2x100 degrees observed in 2008 using all three frequencies. More detailed analysis of point sources.



Shirokoff et al. 2010

- CMB anisotropy now well understood over entire range from 1 arcminute to full sky



Dusty Star Forming Galaxies (DSFG)

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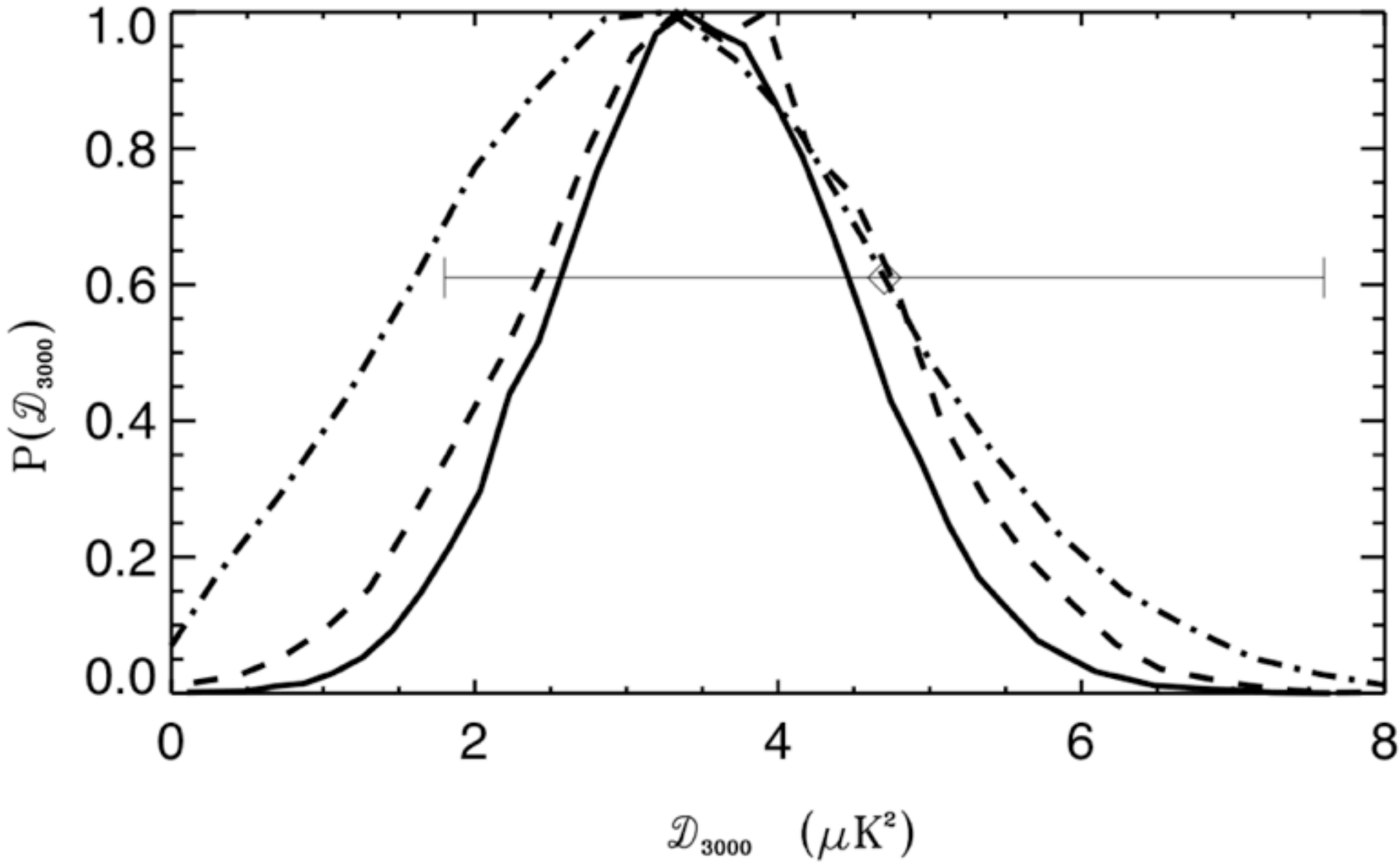
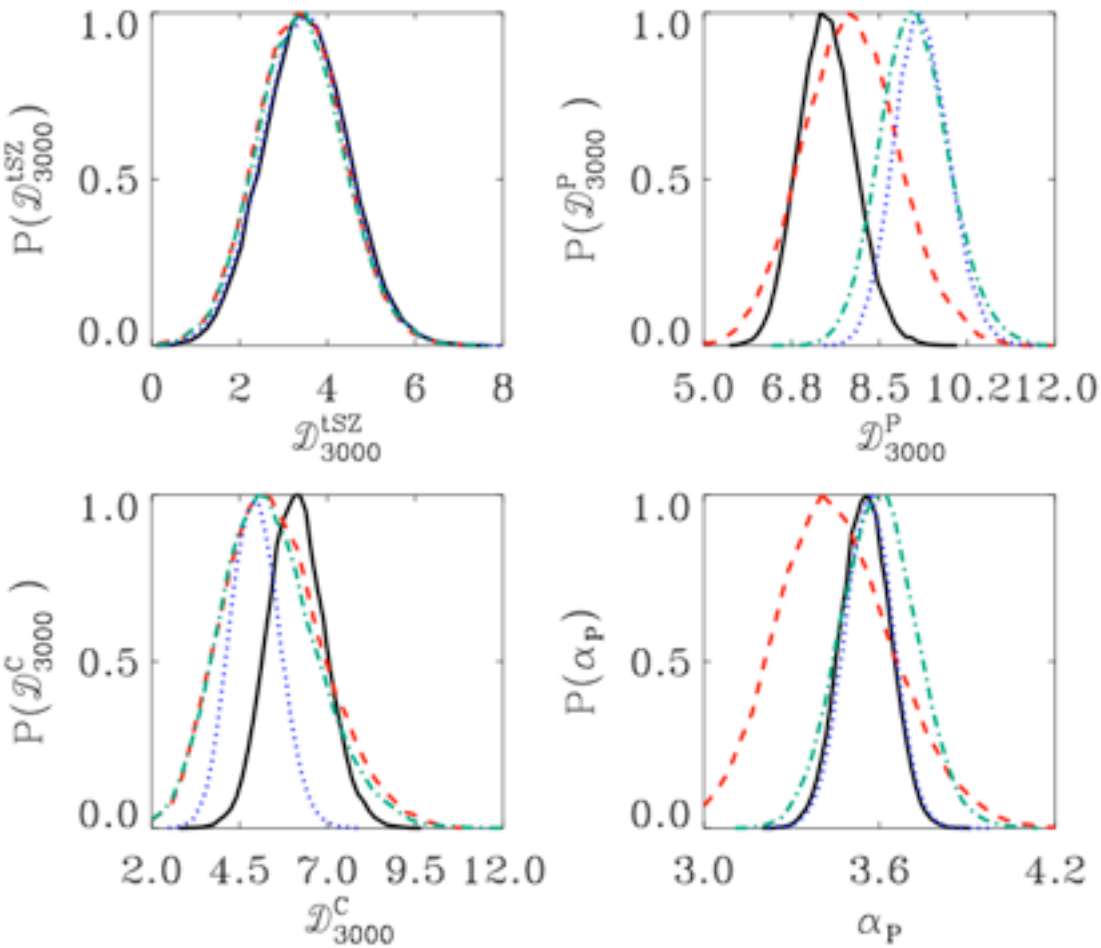
Shirokoff et al. 2010

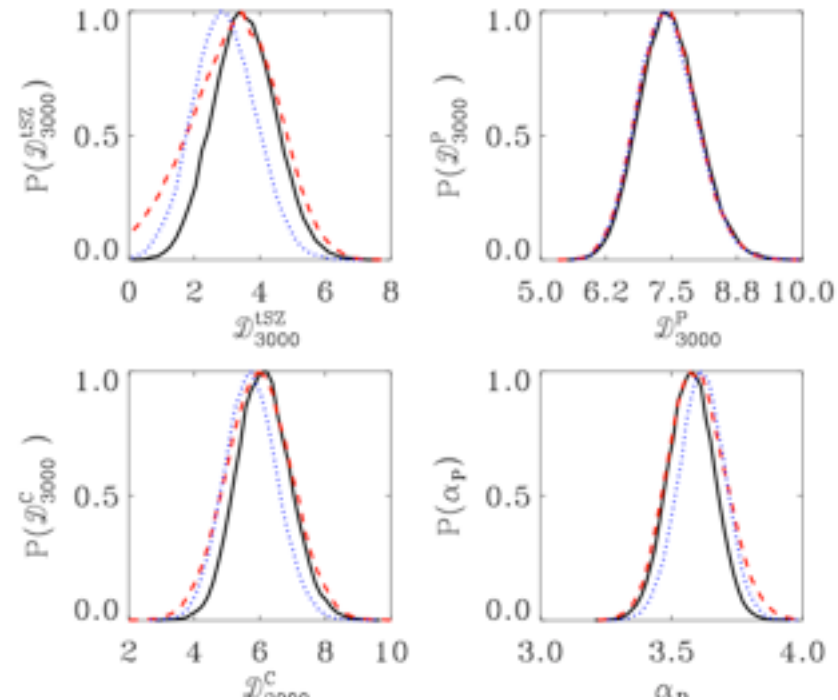


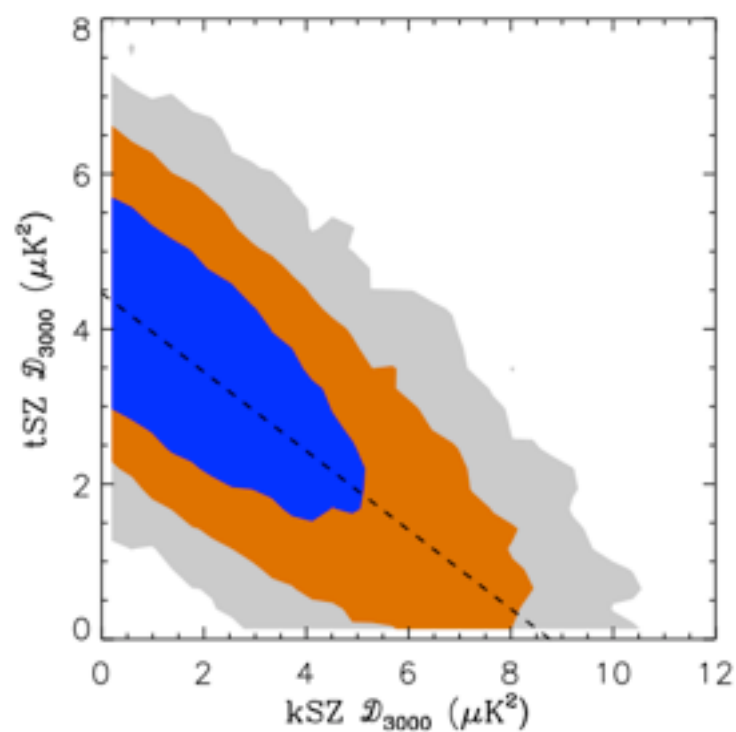
kSZ degeneracy

- kSZ on right
- DSFG on bottom

Shirokoff et al. 2010



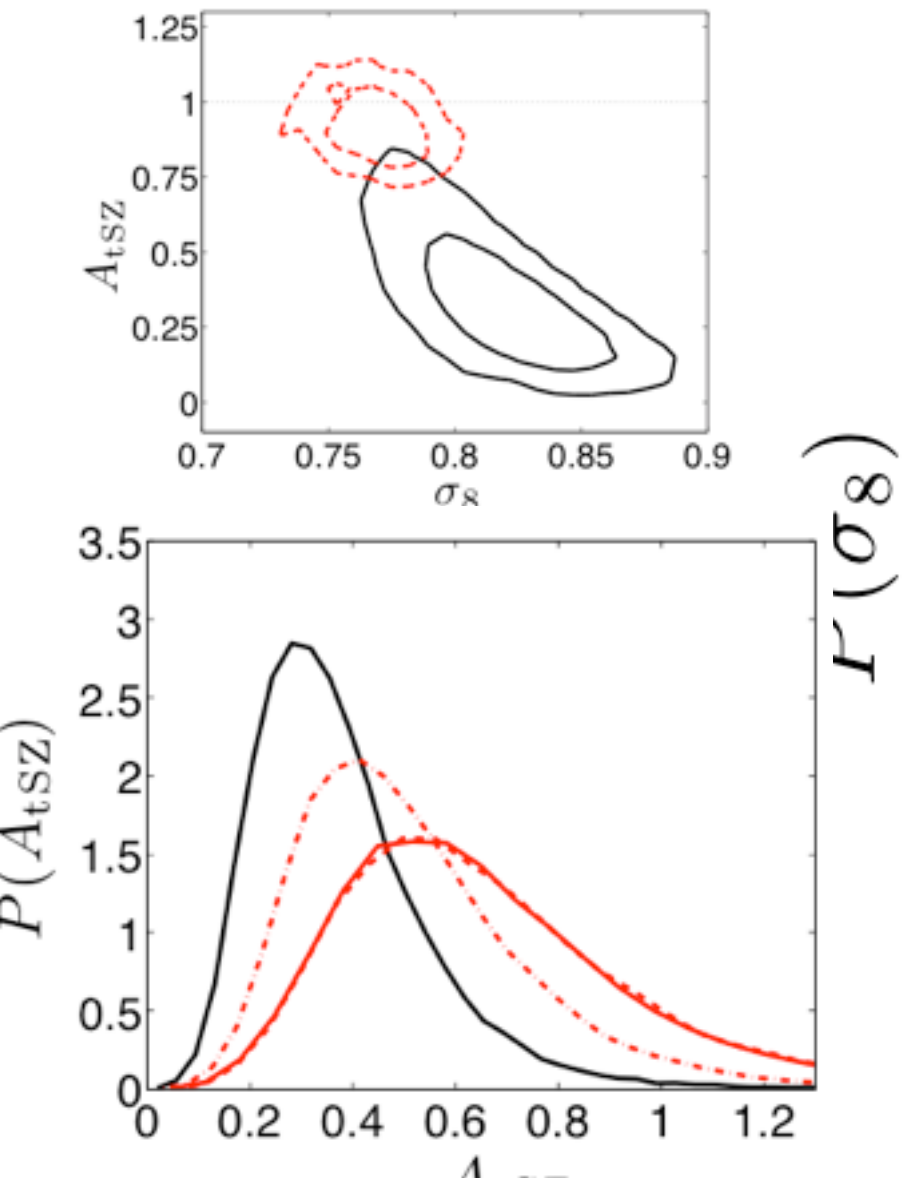


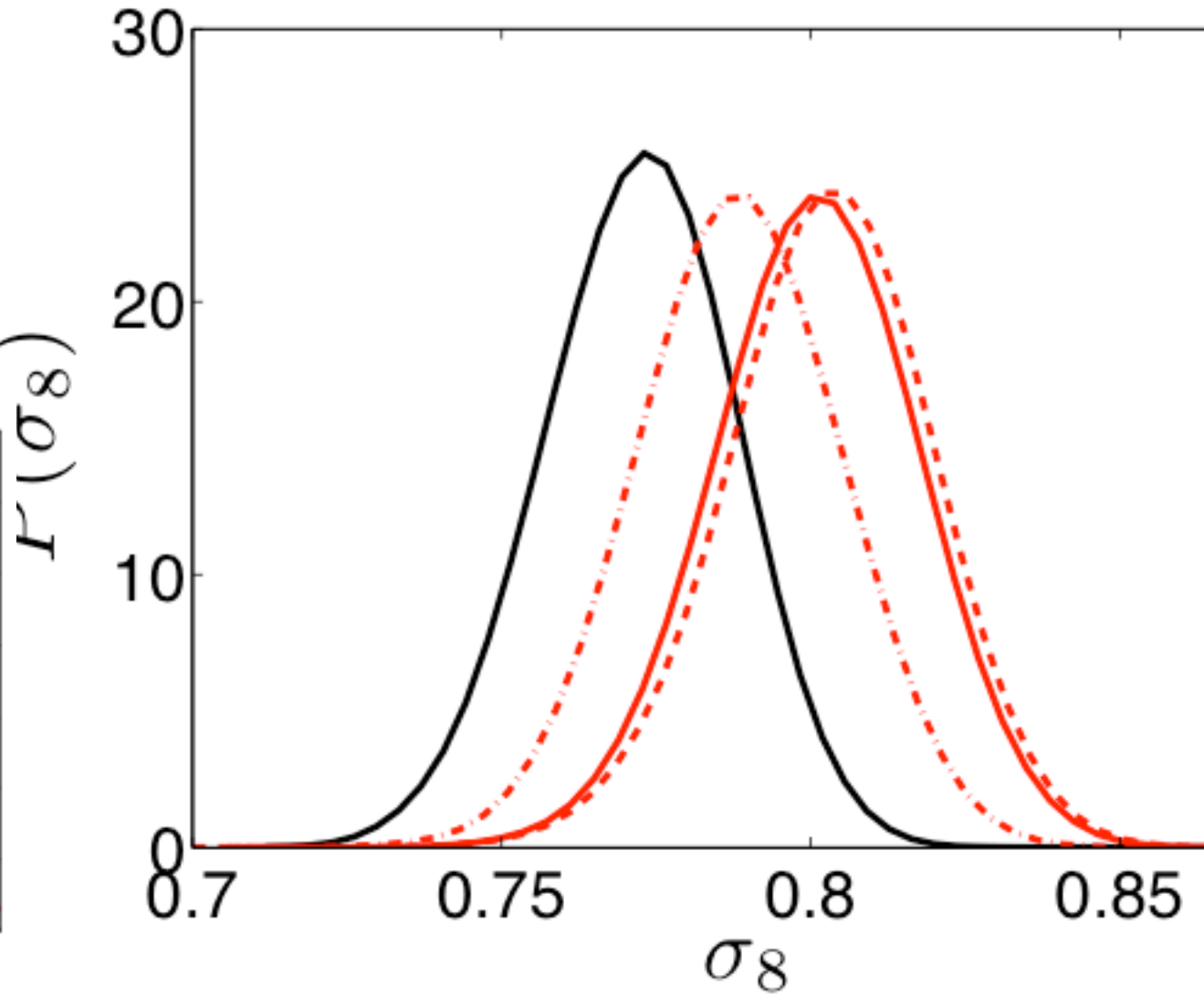


Uncertainty in tSZ modeling

- Symbiosis of simulations and analytic modeling: use for cosmological scaling of simulations.

Shirokoff et al. 2010





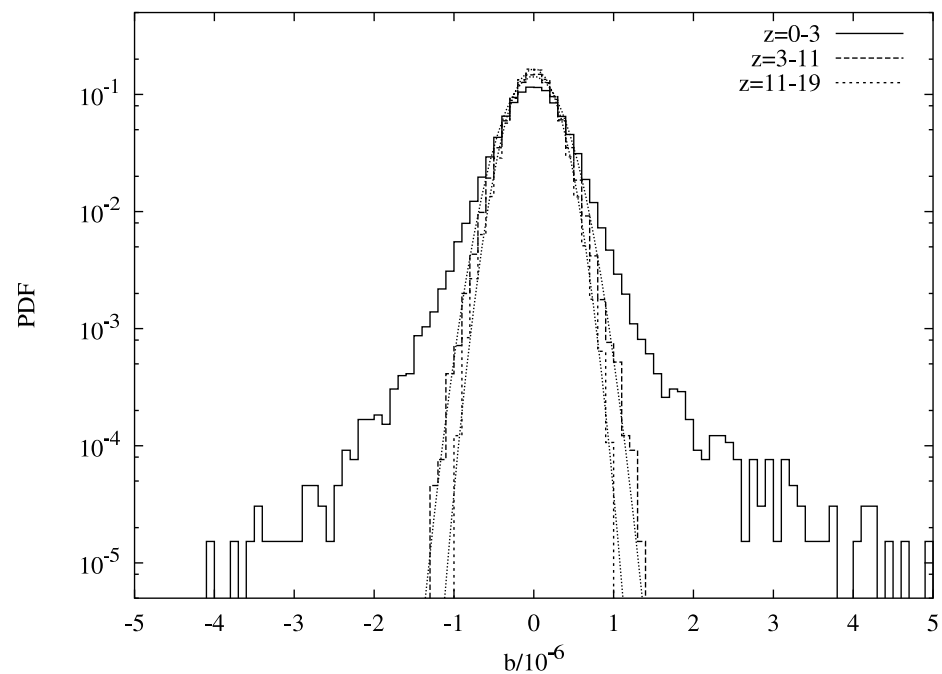
Biases and Detection of kSZ

- Planck may not be able to detect kSZ, however have to take it into account in constraints from primary power spectrum
- Interesting constraints in combination with SPT

model	τ_{ri}	Ω_Λ	ω_{dm}	ω_b	n_s	A_s
1σ	0.0035	0.010	0.0017	0.00018	0.0045	0.0050
A	0.40	1.18	-1.10	1.71	2.14	0.16
B	1.26	1.66	-1.54	2.40	3.05	0.78
C	2.25	2.89	-2.69	4.20	5.62	1.58

TABLE 1
Bias in units of the statistical error ($\mathcal{B}_i$) expected for cosmological parameter estimation with Planck, if temperature and polarization power spectra are used and the influences of kSZ/OV and patchy reionization are neglected in the power spectrum analysis. The maximum multipole in our analysis was $l = 4000$.

Zahn et al. 2006

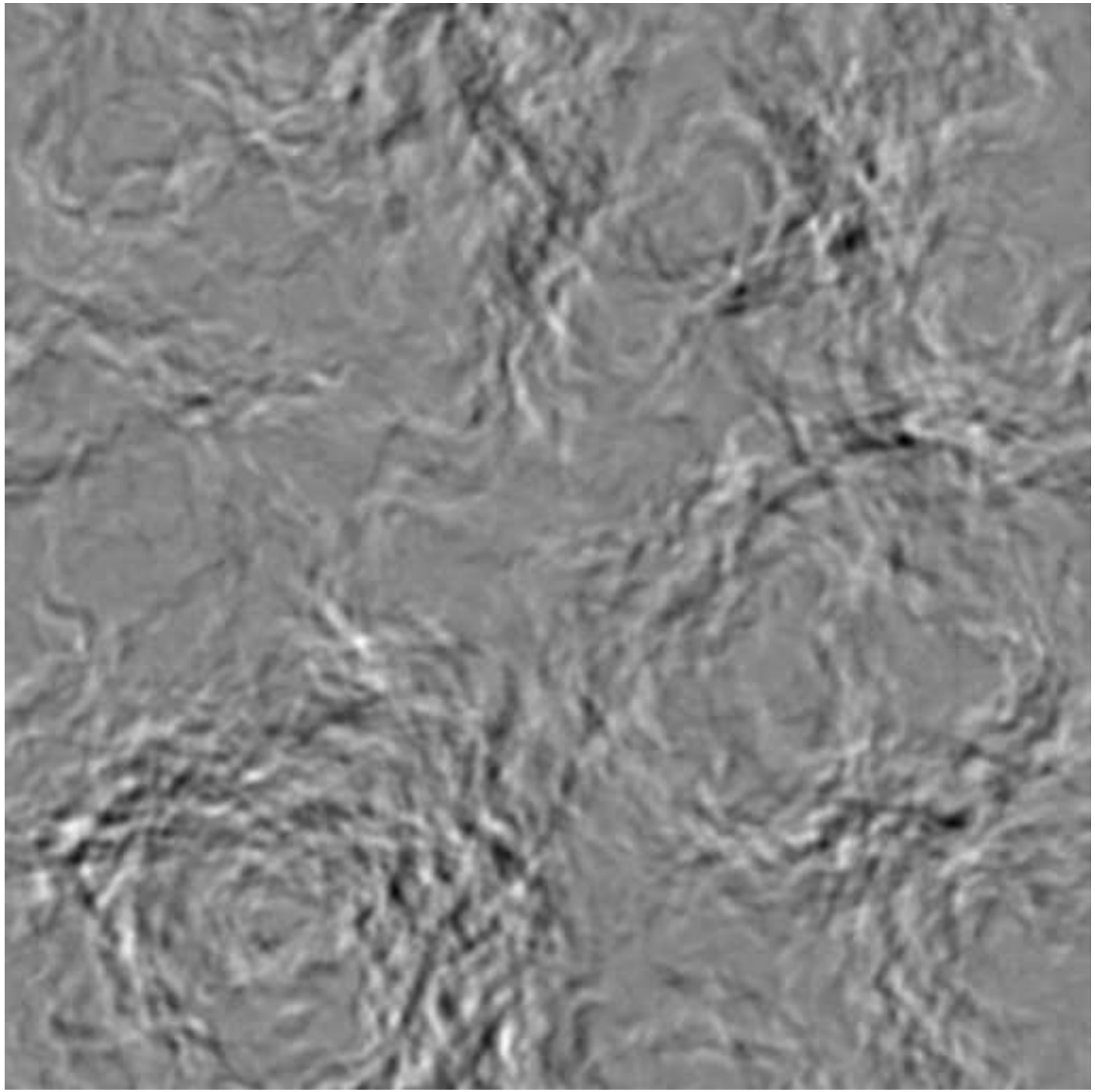


Zahn et al. 2006

SZ summary

- tSZ: What has been found:
  - —amazing high z objects
  - —lots more than anybody else in SZ (~700 clusters above 4.5 sigma in 2500 square degrees)
  - —>however normalization of matter power is smaller than expected=>less clusters and tSZ
  - —>turns out that clustered point sources are really problematic
  - —Modeling of kSZ will be more important for the full survey
- kSZ: interaction with tsz and PS
  - —herschel
  - —non-gaussian estimators
  - —cross-correlation with LSS

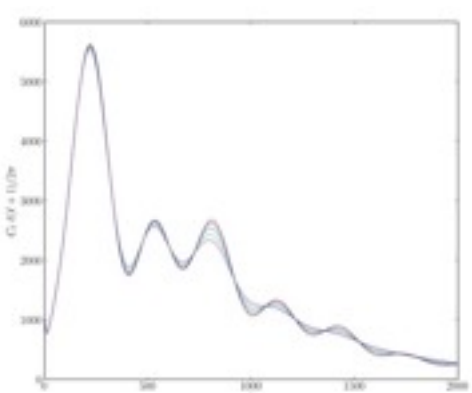
2) CMB lensing



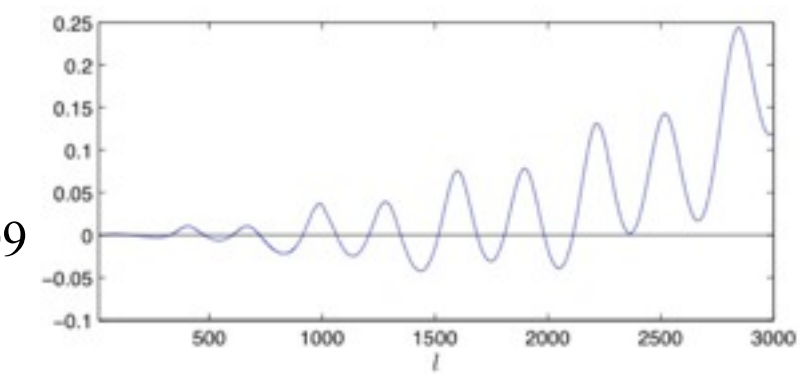
CMB lensing trivia

- Microwave Background is our most distant source, D=10 Gpc/h, z=1090. Its lensing can be used as ``scale" to weigh the Hubble volume (in case of an all sky survey).
- Order of magnitude of effect: last scattering surface 10,000 Mpc/h away, peak of matter power spectrum at ~200 Mpc/h
  - -for potential fluctuations on that scale, psi/c2~2e-5, deflection is according to GR 4 psi/c2~1e-4, corresponding to 20 arc seconds
  - -say overall there are 10,000/200=50 lens planes
  - -assume those planes independent => get total typical deflection of ~2.5 arcminutes from random walk.

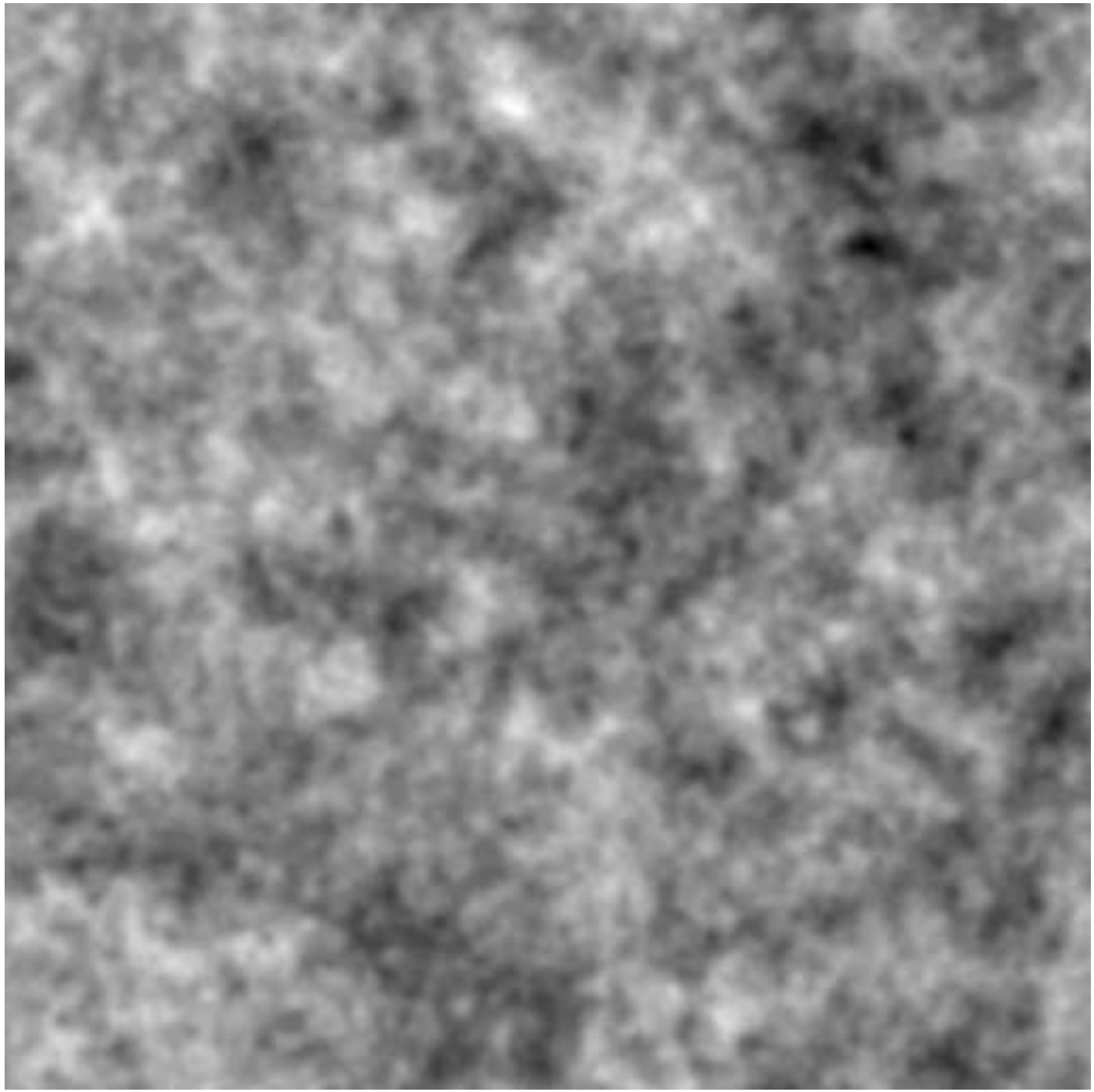
- Main statistical effects of CMB lensing:
  - -boost of power in T and P damping tail and "smearing" of peak structure
  - -characteristic angular size of potentials=200/10,000~2 deg. is the coherence scale of lensing=>hot/cold spots can get (de-)magnified by ~1%. Non-Gaussian signature gets imprinted in the CMB.



Calabrese et al 09



Simulation of lensing on 10 degree patch



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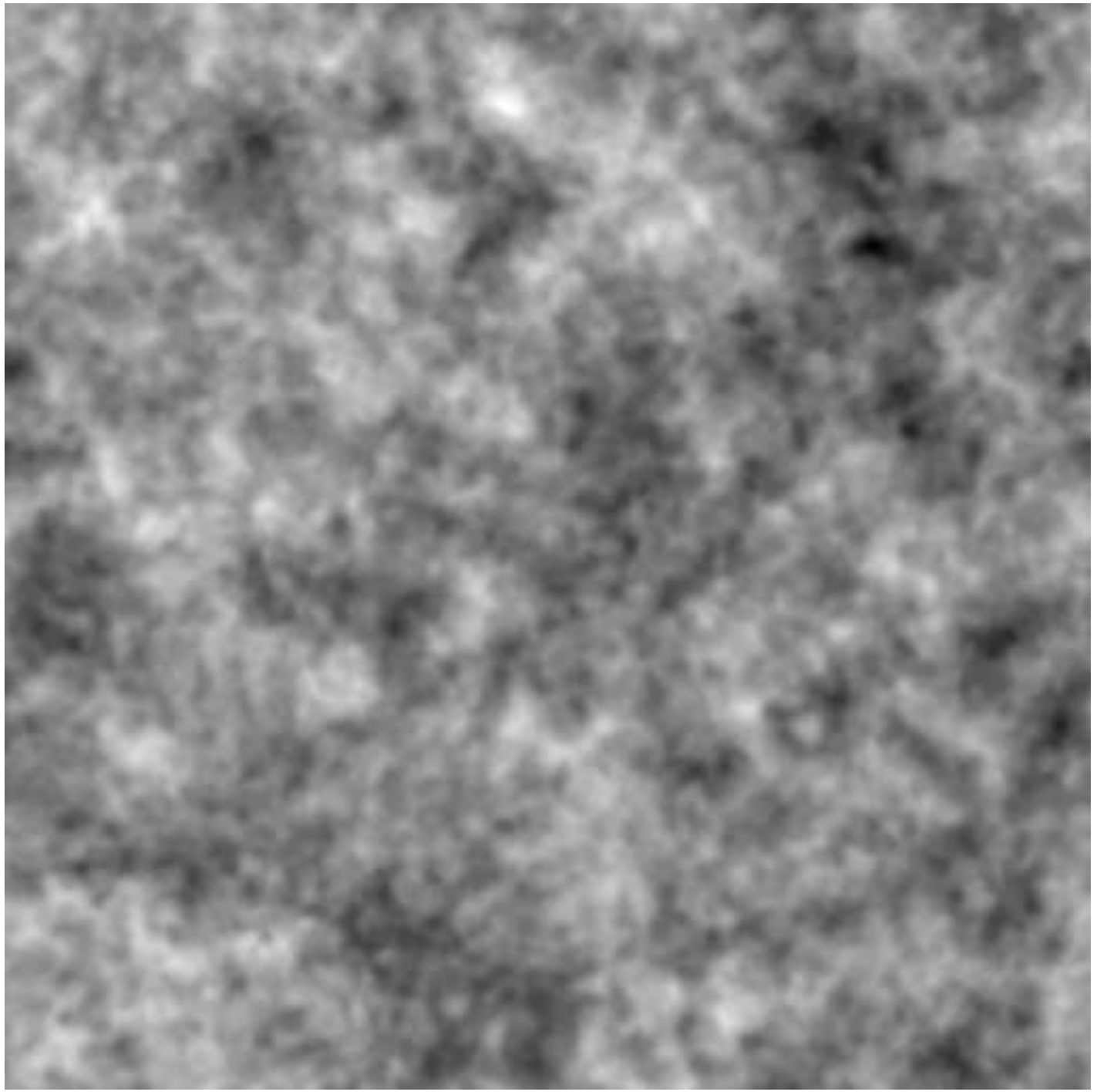

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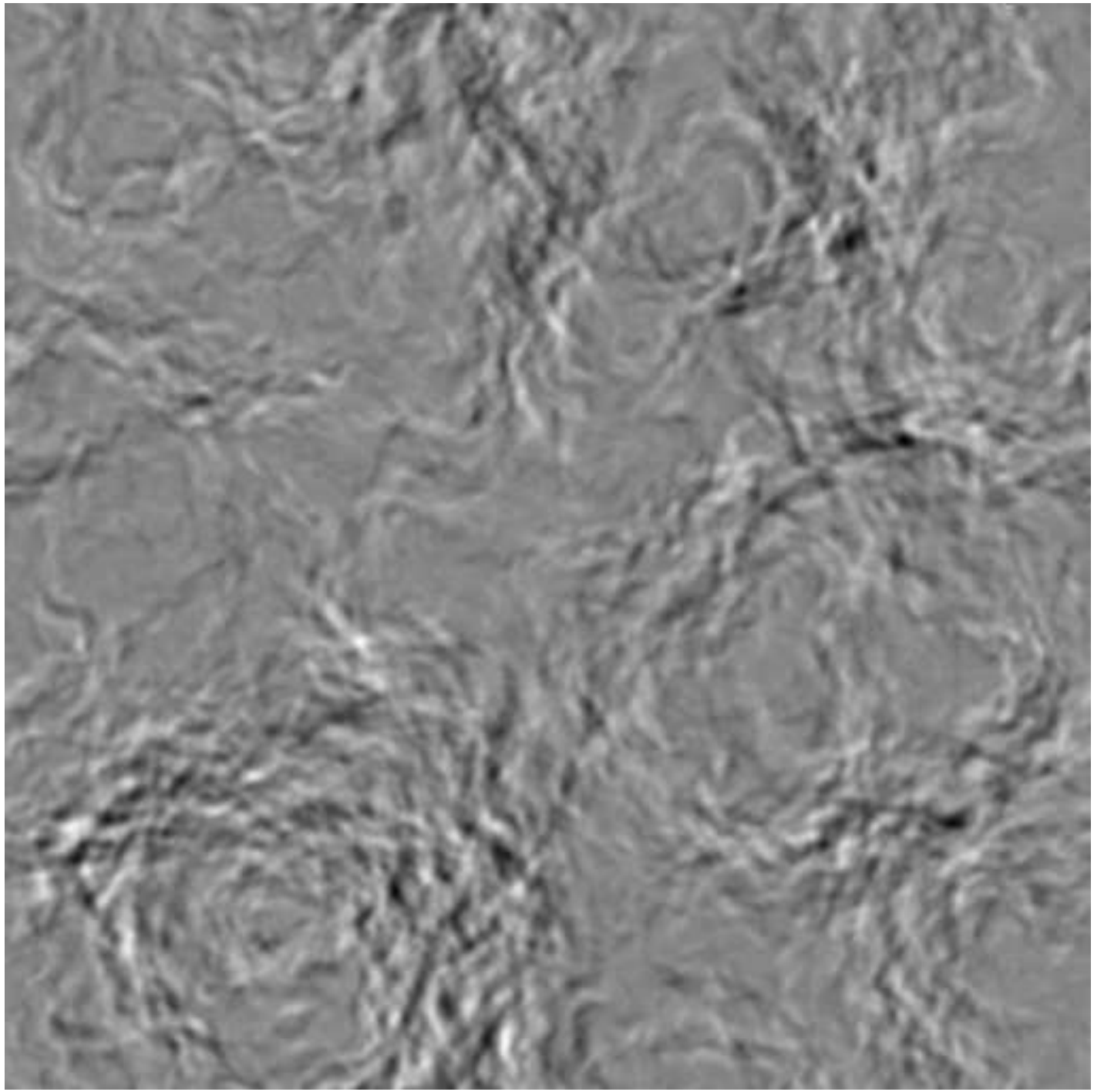

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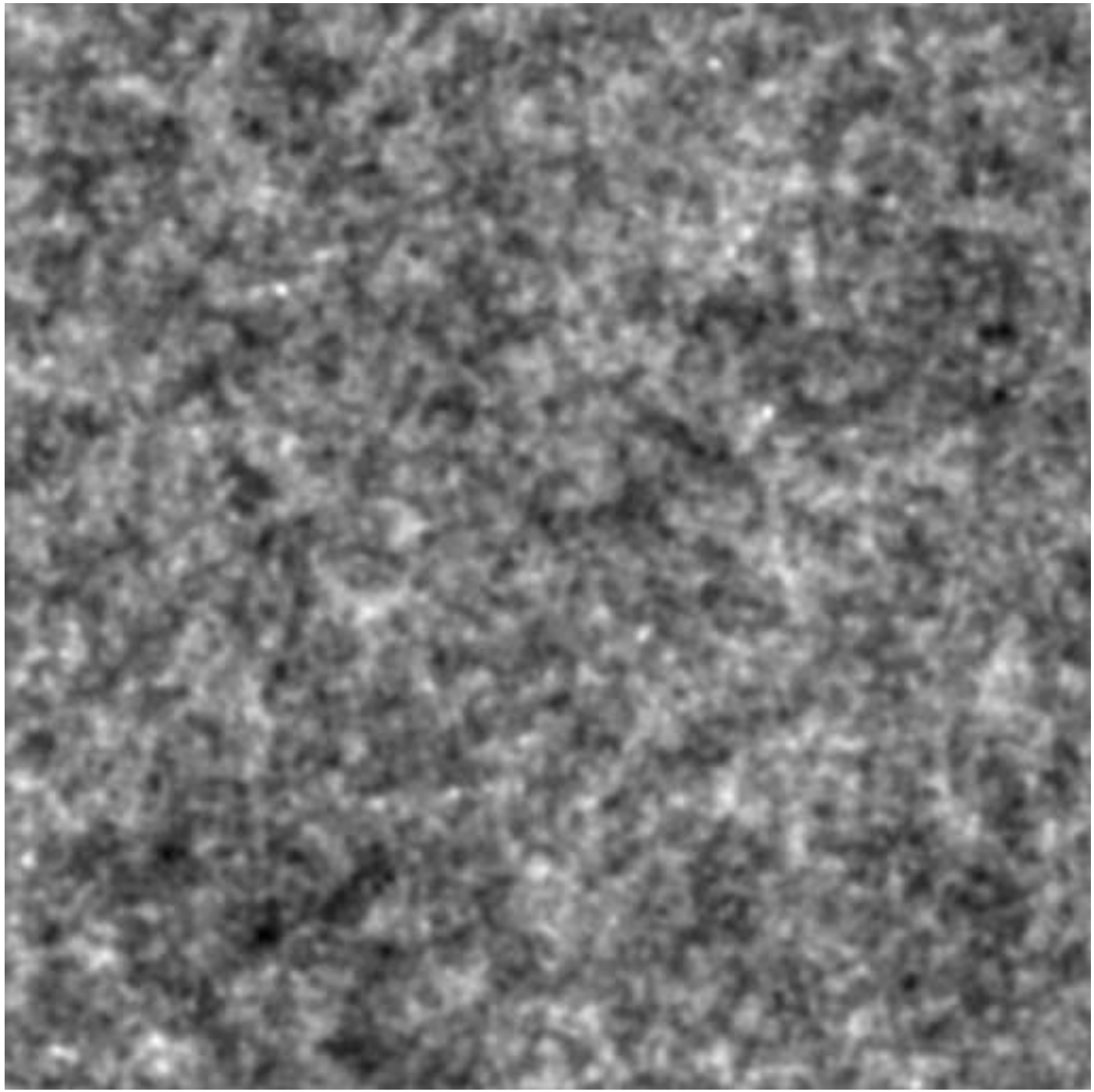
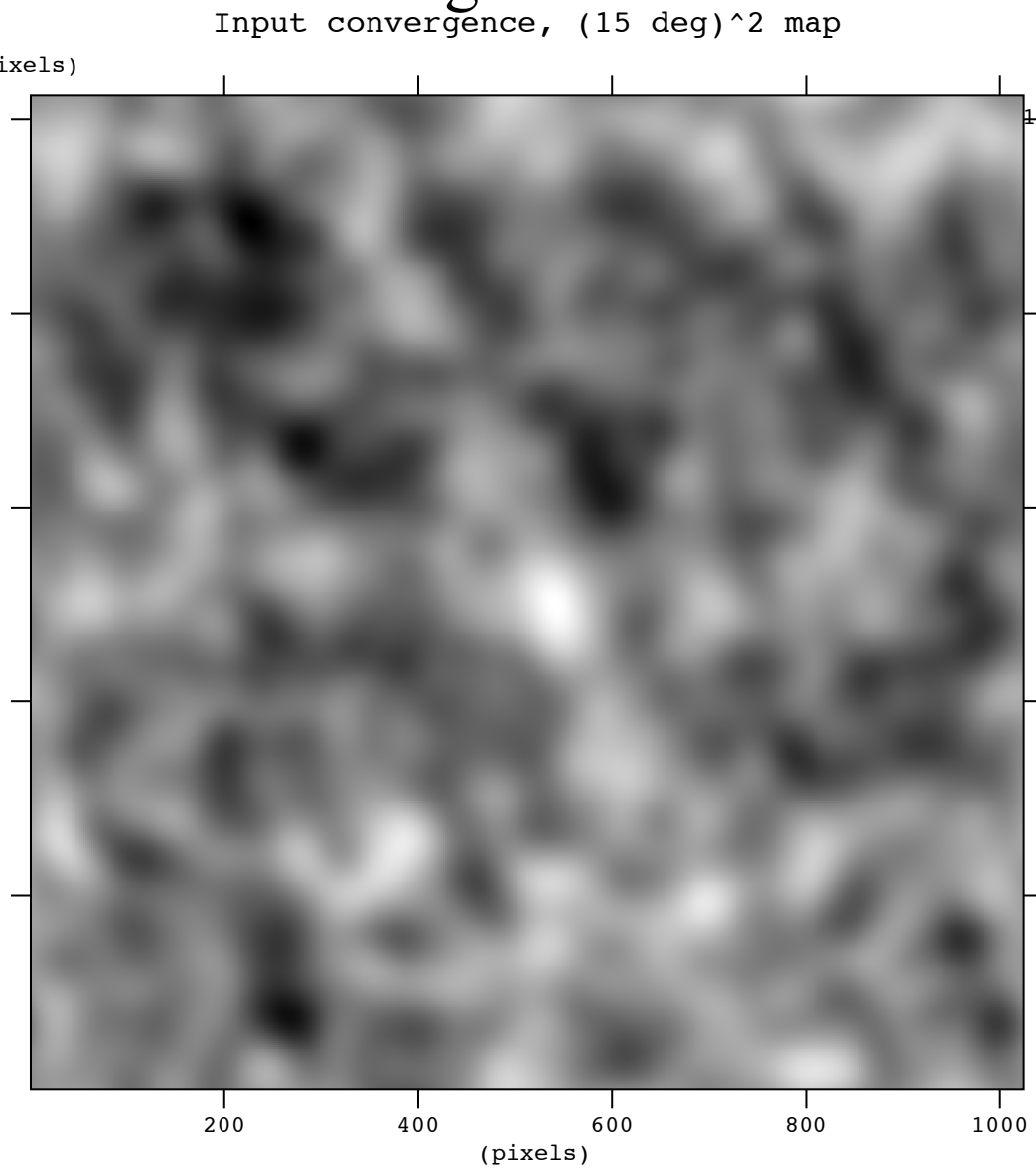
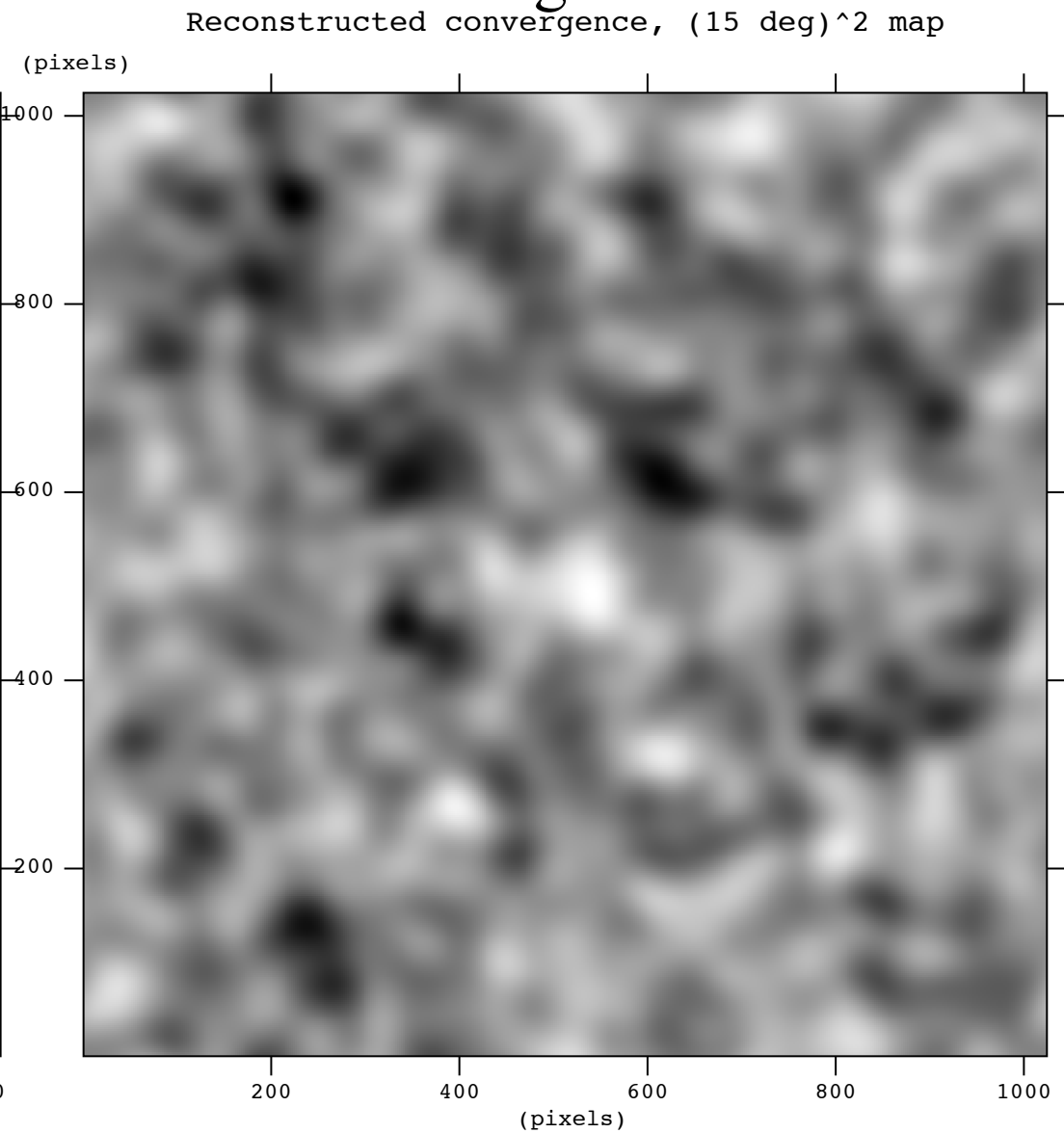


Input convergence



Reconstructed convergence



Application of CMB lensing

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•Lensing power spectrum is an integral over the mid-z universe and can be used to constrain neutrino absolute mass scale and dark energy models.

Constraints on differences of mass states presently:

$$\sqrt{\Delta m_{31}^2} \simeq 0.05\text{eV}, \quad \text{from atmospheric } \nu's$$

$$\sqrt{\Delta m_{21}^2} \simeq 0.009\text{eV}, \quad \text{from solar } \nu's$$

Tritium decay upper bound: 6 eV at 2 sigma

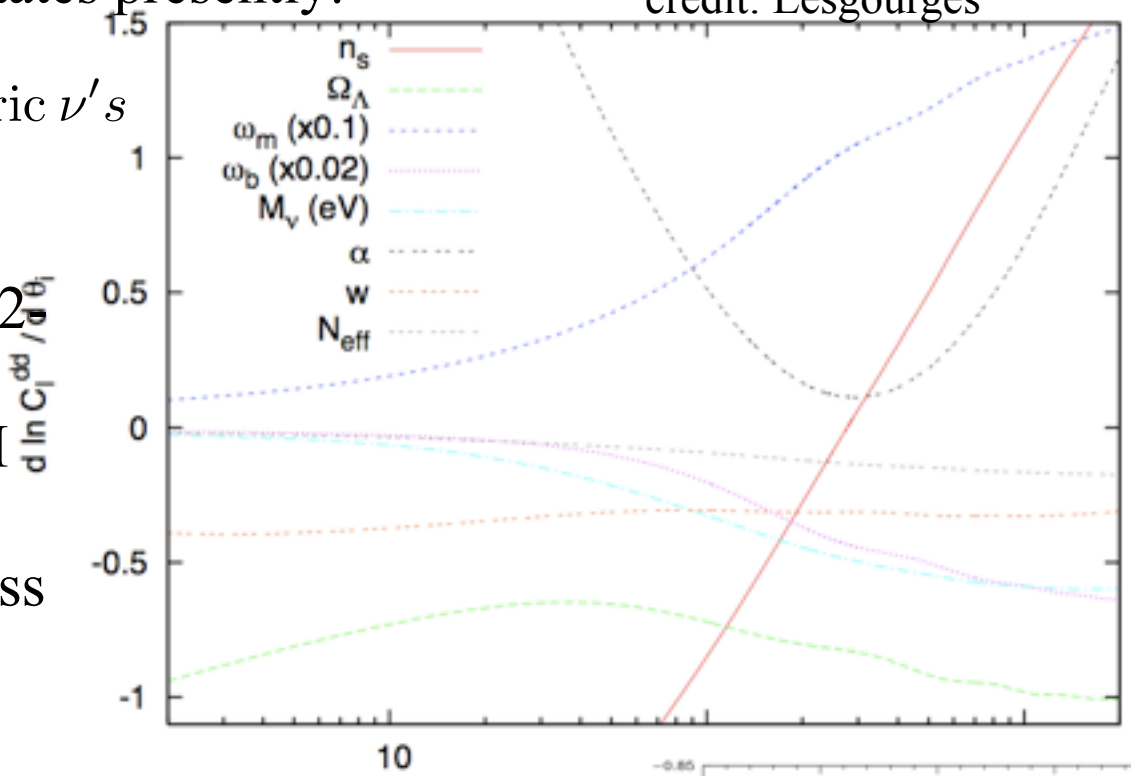
So nu's make up 0.5-50% of the DM

=> would like to fix the absolute mass scale

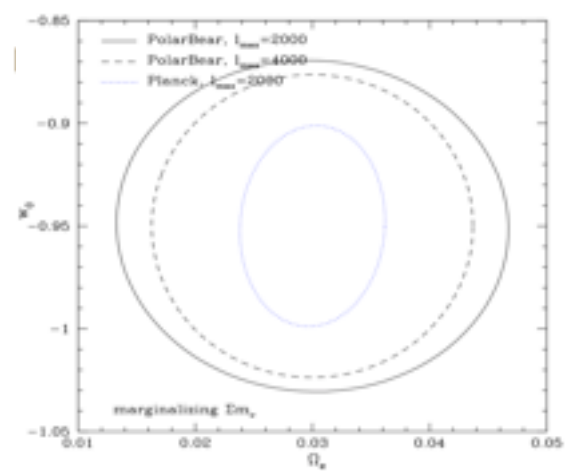
KATRIN promises to do~0.35 eV

Can we do better?

credit: Lesgourges



•Constraints on dark energy (esp. early) also interesting, see e.g. de Putter, Zahn, Linder 2009



Reconstructing the lensing potential using optimal quadratic estimator

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Looking for a quadratic estimator of the form:

$$\hat{\psi}(\mathbf{L}) = N(\mathbf{L}) \int \frac{d^2 l}{2\pi} \tilde{\theta}(\mathbf{L}-\mathbf{l}) \tilde{\theta}^*(\mathbf{l}) g(\mathbf{L},\mathbf{l})$$

First order expansion of deflection angle:

$$\tilde{\Theta}(\mathbf{l}) \approx \Theta(\mathbf{l}) - \int \frac{d^2\mathbf{l}'}{2\pi} \mathbf{l}' \cdot (\mathbf{l}-\mathbf{l}') \psi(\mathbf{l}-\mathbf{l}') \Theta(\mathbf{l}')$$

Requirements of no bias and minimum variance leads to (equivalent filter for E and B mode polarization):

$$g(\mathbf{L},\mathbf{l}) = \frac{(\mathbf{L}-\mathbf{l}) \cdot \mathbf{L} C^{\theta}_{|\mathbf{L}-\mathbf{l}|} + \mathbf{l} \cdot \mathbf{L} C^{\theta}_{l}}{2 \tilde{C}^{tot}_{l} \tilde{C}^{tot}_{|\mathbf{L}-\mathbf{l}|}}$$

Normalization

$$N(\mathbf{L}) = \left[\int \frac{d^2 \mathbf{l}}{(2\pi)^2} \frac{[(\mathbf{L}-\mathbf{l}) \cdot \mathbf{L} C^{\theta}_{|\mathbf{L}-\mathbf{l}|} + \mathbf{l} \cdot \mathbf{L} C^{\theta}_{l}]^2}{2 \tilde{C}^{tot}_{l} \tilde{C}^{tot}_{|\mathbf{L}-\mathbf{l}|}} \right]^{-1}$$

in other words

$$\hat{\psi}(\mathbf{L}) = N(\mathbf{L}) \, \mathbf{L} \cdot \int \frac{d^2 l}{2\pi} \frac{(\mathbf{L}-\mathbf{l}) C^{\theta}_{|\mathbf{L}-\mathbf{l}|} + \mathbf{l} C^{\theta}_{l}}{2 \tilde{C}^{tot}_{l} \tilde{C}^{tot}_{|\mathbf{L}-\mathbf{l}|}} \tilde{\theta}(\mathbf{l}) \tilde{\theta}^*(\mathbf{L}-\mathbf{l})$$

Lowest order noise determined by

$$\delta(\mathbf{0}) \langle |\hat{\psi}(\mathbf{L})|^2 \rangle^{-1} = N(\mathbf{L})^{-1} = \int \frac{d^2 \mathbf{l}}{(2\pi)^2} \frac{\left[(\mathbf{L}-\mathbf{l}) \cdot \mathbf{L} \, C^{\Theta}_{|\mathbf{l}-\mathbf{L}|} + \mathbf{l} \cdot \mathbf{L} \, C^{\Theta}_{l} \right]^2}{2 \tilde{C}^{tot}_{l} \tilde{C}^{tot}_{|\mathbf{l}-\mathbf{L}|}}$$

Hu&Okamoto, Lewis

Reconstructing the lensing potential using optimal quadratic estimator

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$$\langle\tilde{\Theta}(\mathbf{l})\tilde{\Theta}^*(\mathbf{l}-\mathbf{L})\rangle_\Theta = \delta(\mathbf{L})\,C_l^\Theta - \int\frac{\mathrm{d}^2\mathbf{l}'}{2\pi}\Big[\mathbf{l}'\cdot(\mathbf{l}-\mathbf{l}')\psi(\mathbf{l}-\mathbf{l}')\langle\Theta(\mathbf{l}')\Theta^*(\mathbf{l}-\mathbf{L})\rangle$$

$$+\mathbf{l}'\cdot(\mathbf{l}-\mathbf{L}-\mathbf{l}')\psi^*(\mathbf{l}-\mathbf{L}-\mathbf{l}')\langle\Theta(\mathbf{l})\Theta^*(\mathbf{l}')\rangle\Big] + \mathcal{O}(\psi^2)$$

$$= \delta(\mathbf{L})\,C_l^\Theta + \frac{1}{2\pi}\left[(\mathbf{L}-\mathbf{l})\cdot\mathbf{L}\,C^\Theta_{|\mathbf{l}-\mathbf{L}|} + \mathbf{l}\cdot\mathbf{L}\,C_l^\Theta\right]\psi(\mathbf{L}) + \mathcal{O}(\psi^2)$$

Combine T and P estimators

$$N_{\mathrm{mv}} = \frac{1}{\sum_{\alpha\beta}(\mathbf{N}^{-1})_{\alpha\beta}}$$

OQE application in practice. Rewrite e.g. 2nd term as

$$\hat{\psi}(\mathbf{L}) = N(\mathbf{L})\mathbf{L}\frac{1}{-i}\cdot\int\frac{d^2l}{2\pi}\left(\frac{-i\mathbf{l}C_l^\theta\tilde{\theta}(\mathbf{l})}{2\tilde{C}_l^{tot}}\right)\left(\frac{\tilde{\theta}(\mathbf{L}-\mathbf{l})}{\tilde{C}^{tot}_{|\mathbf{L}-\mathbf{l}|}}\right)$$

convolution->product in real space, so summation over l-pairs can be conveniently done via FFT's

$$\hat{\psi}(\mathbf{L}) = iN(\mathbf{L})\mathbf{L}\cdot\int\frac{d^2x}{2\pi}e^{-i\mathbf{L}\cdot\mathbf{x}}F_1(\mathbf{x})F_2(\mathbf{x})$$

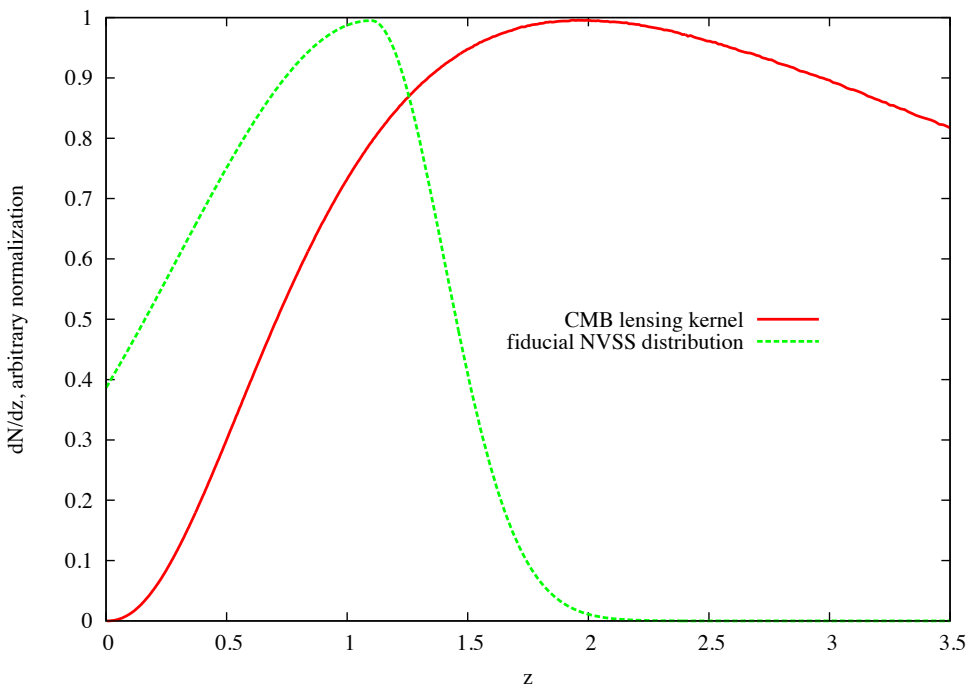
$$\mathbf{F}_1(\mathbf{l}) = \frac{-i\mathbf{l}C_l^\theta\tilde{\theta}(\mathbf{l})}{\tilde{C}_l^{tot}} \qquad F_2(\mathbf{L}-\mathbf{l}) = \frac{\tilde{\theta}(\mathbf{L}-\mathbf{l})}{\tilde{C}^{tot}_{|\mathbf{L}-\mathbf{l}|}}$$

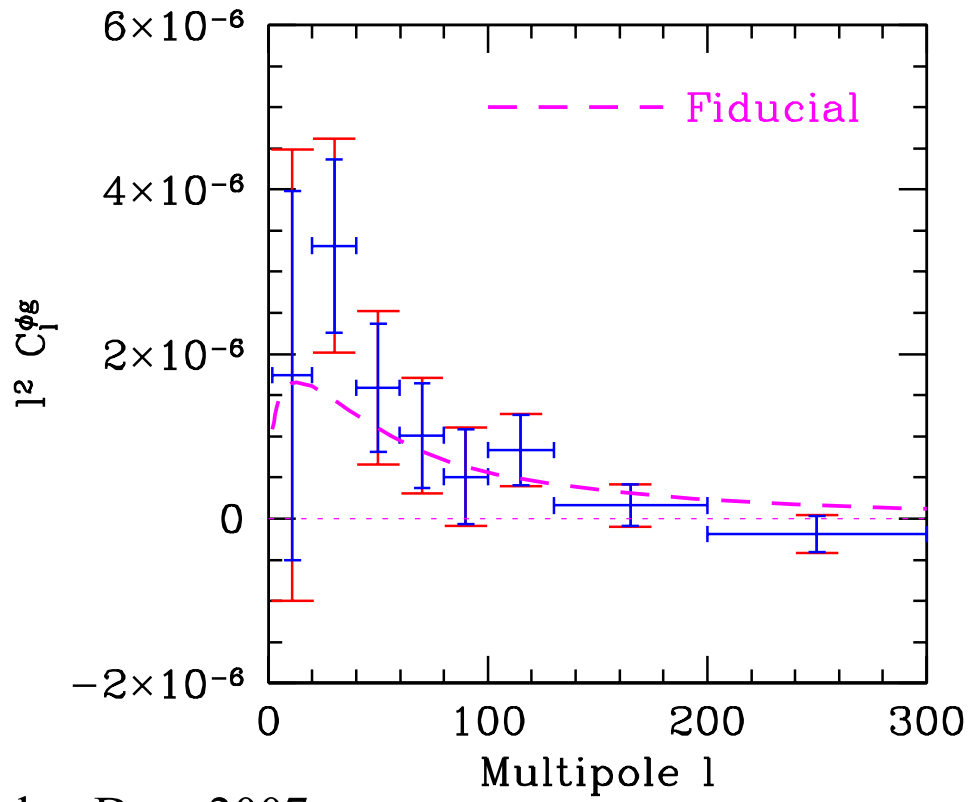
$$\hat{\kappa}(\mathbf{L}) = -\frac{1}{2}L^2\hat{\psi}(\mathbf{L})$$

Hu&Okamoto, Lewis

Lensing cross-correlation with LSS

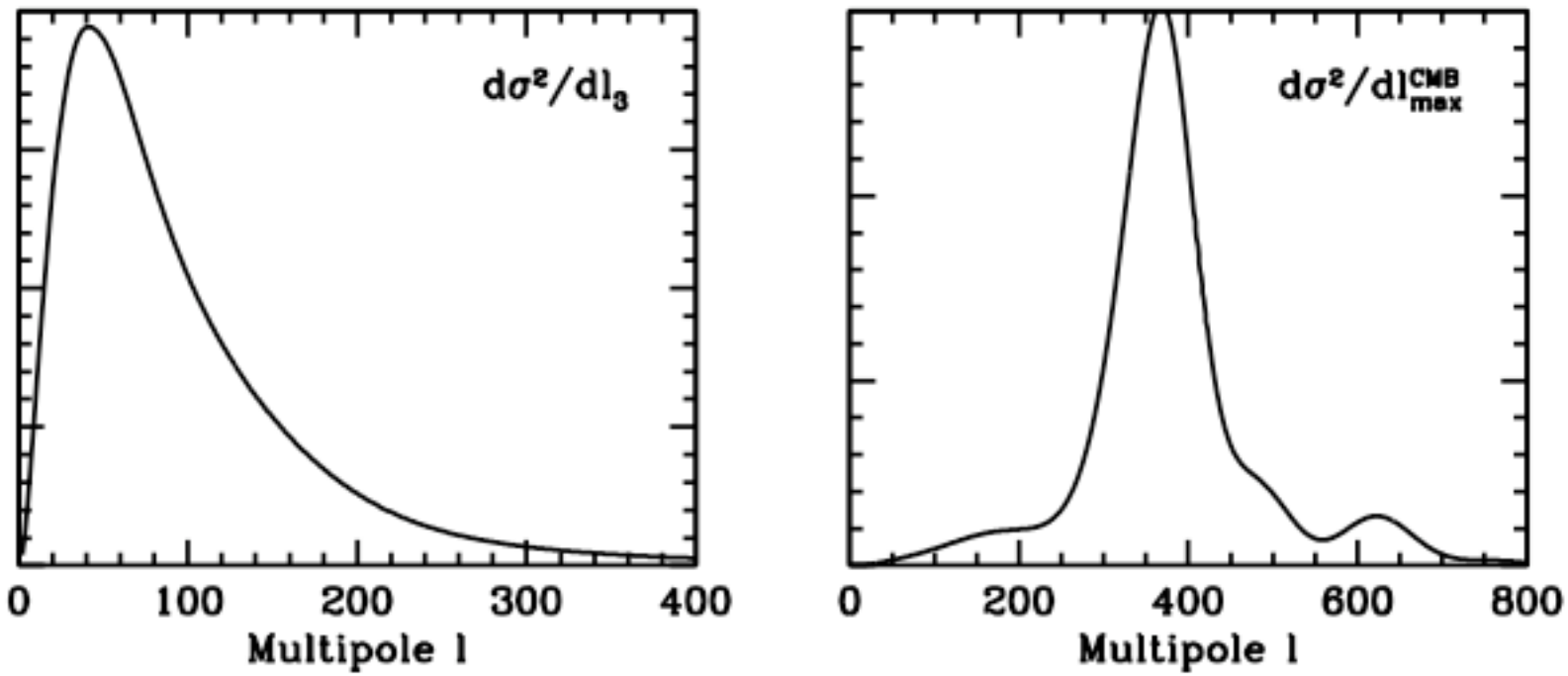
NRAO VLA All Sky Survey: 1.8 Million 1.4 GHz radio sources above 2.5 mJy, fsky=0.77, overlap with WMAP after masking is 0.58, ~4 sources per WMAP resolution element





Smith, Zahn, Dore 2007

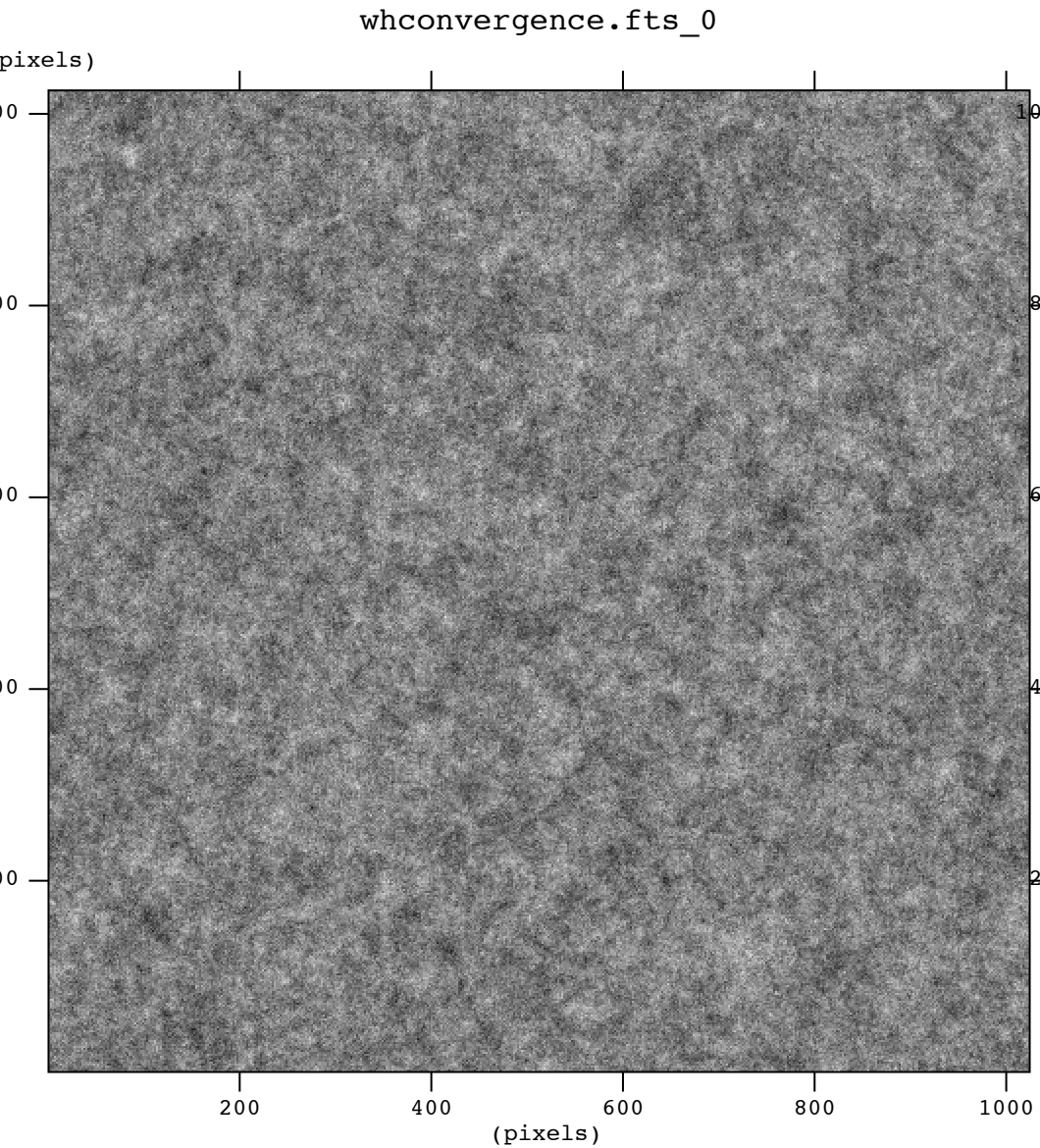
Contributions to the cross power estimator

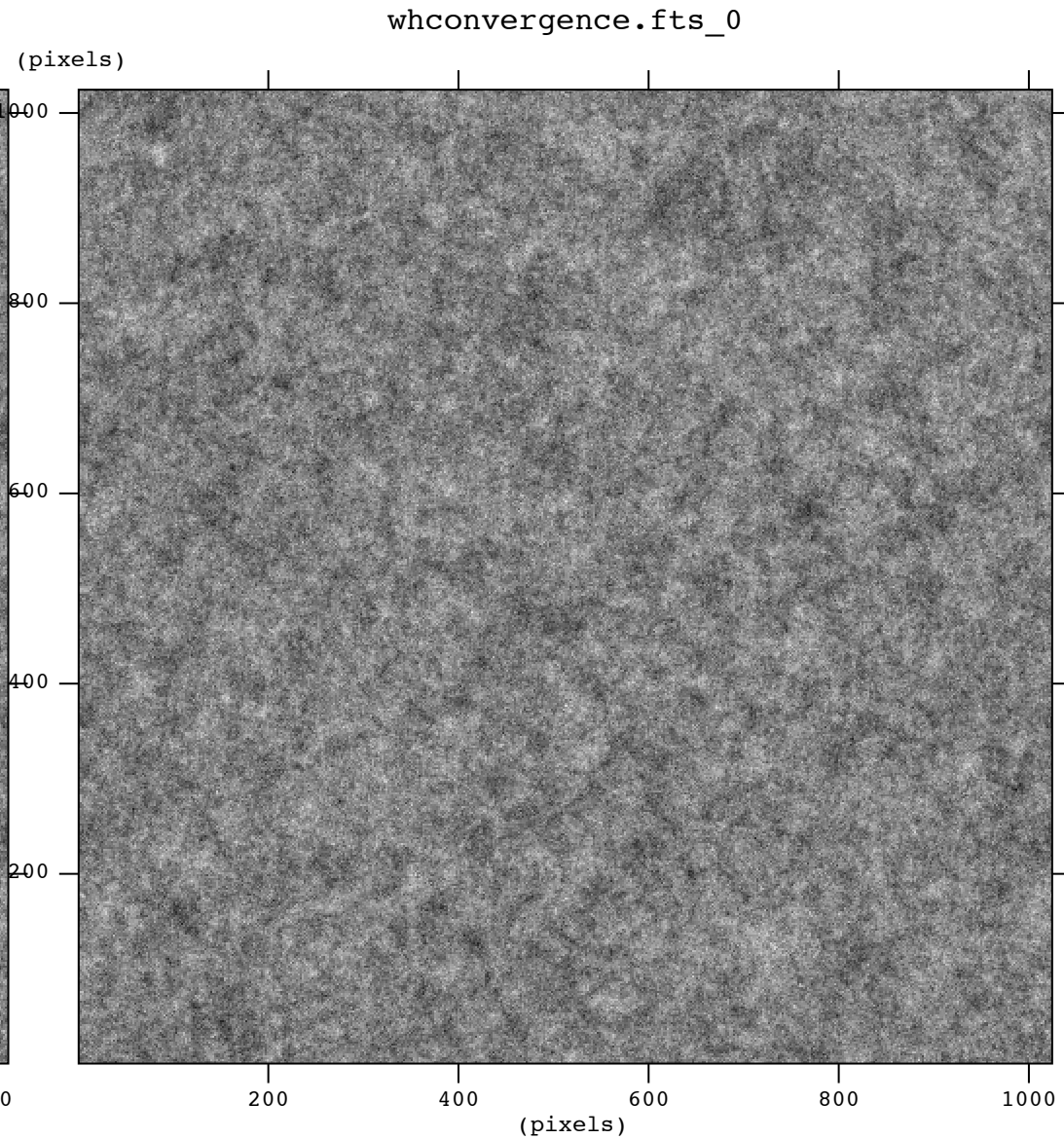


->3.4 sigma (Smith, Zahn, Dore, Nolta '07)

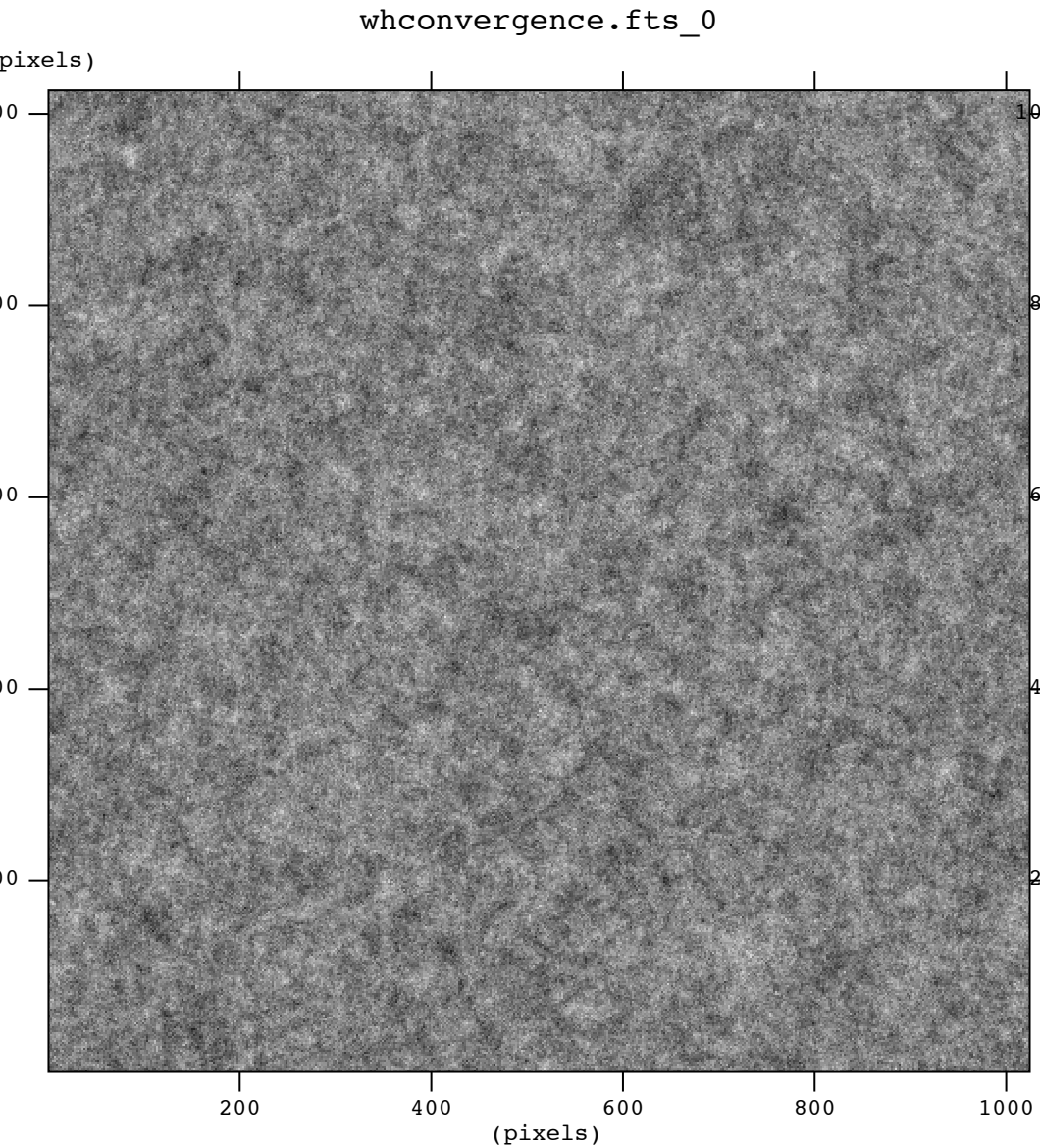
Gaussian random field reconstruction

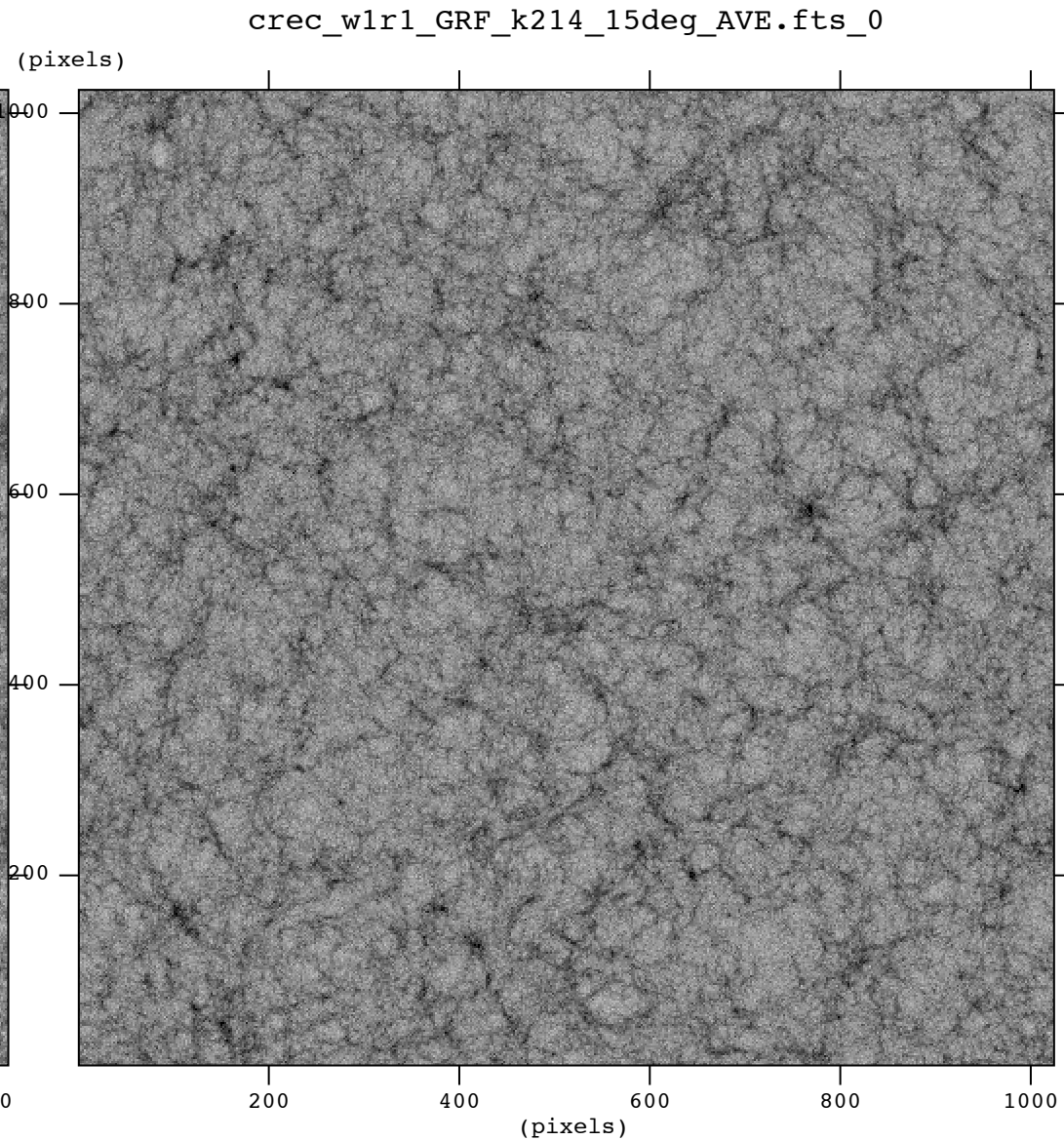
Lensing reconstruction bias



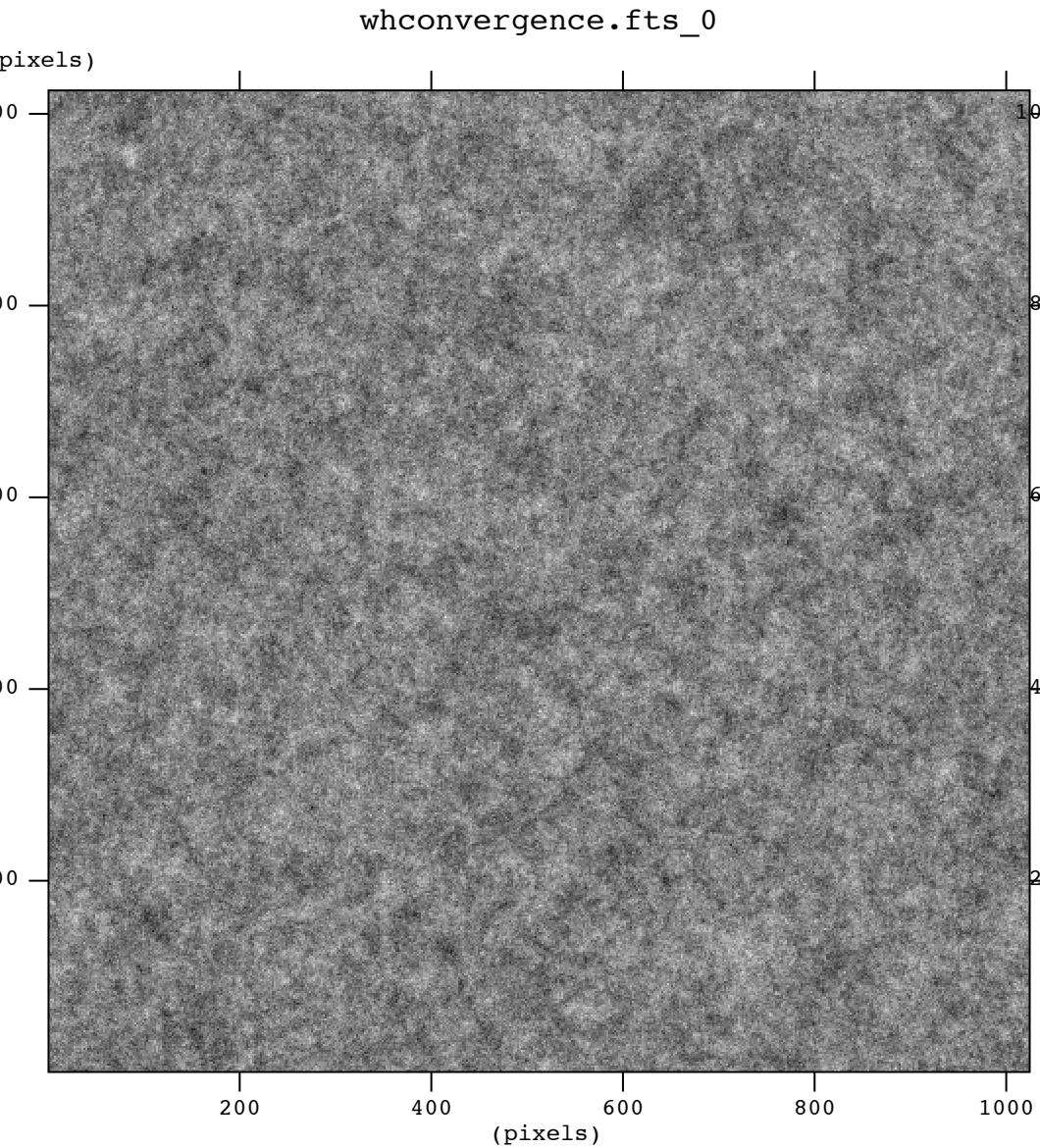


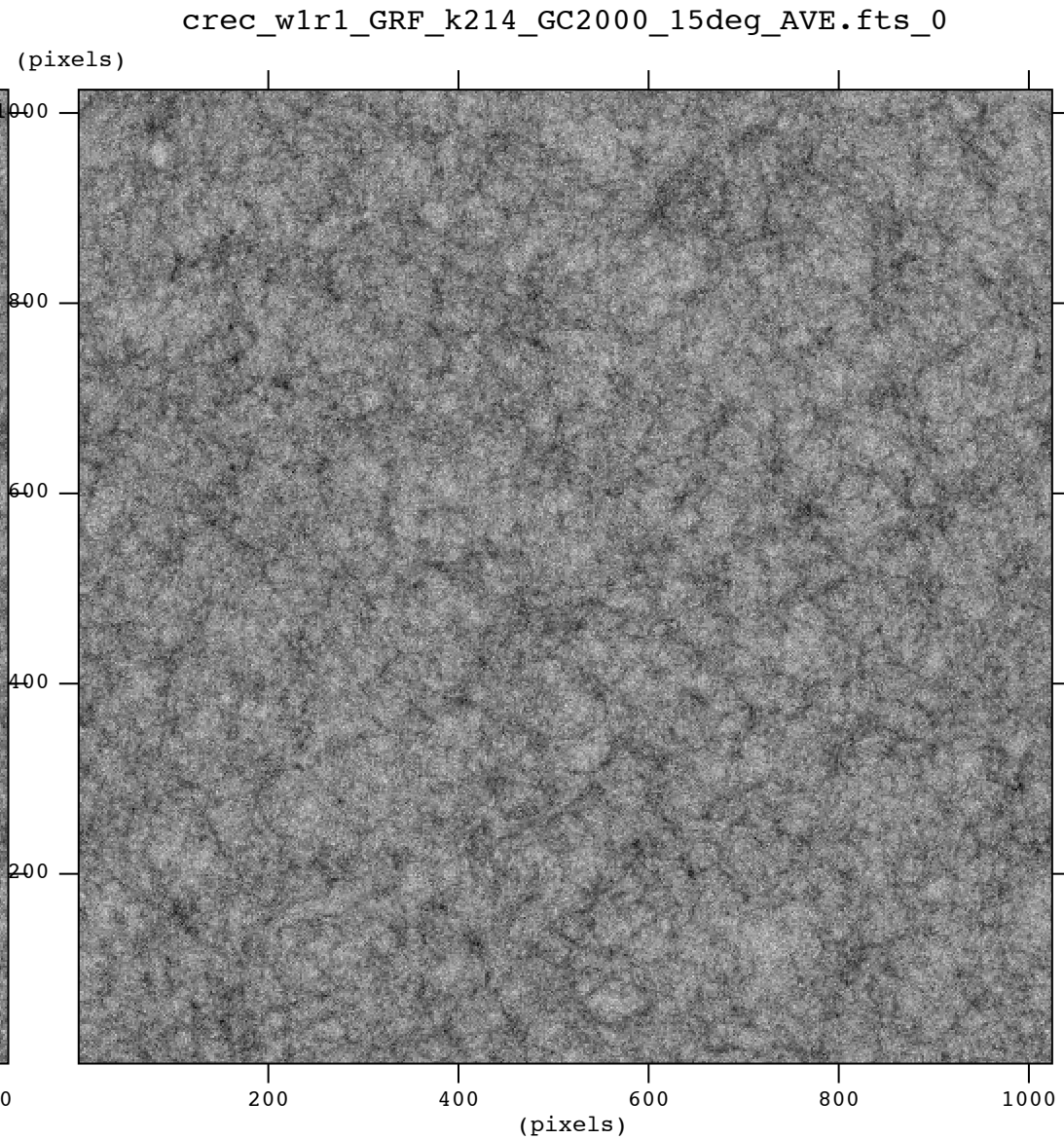
Lensing reconstruction bias





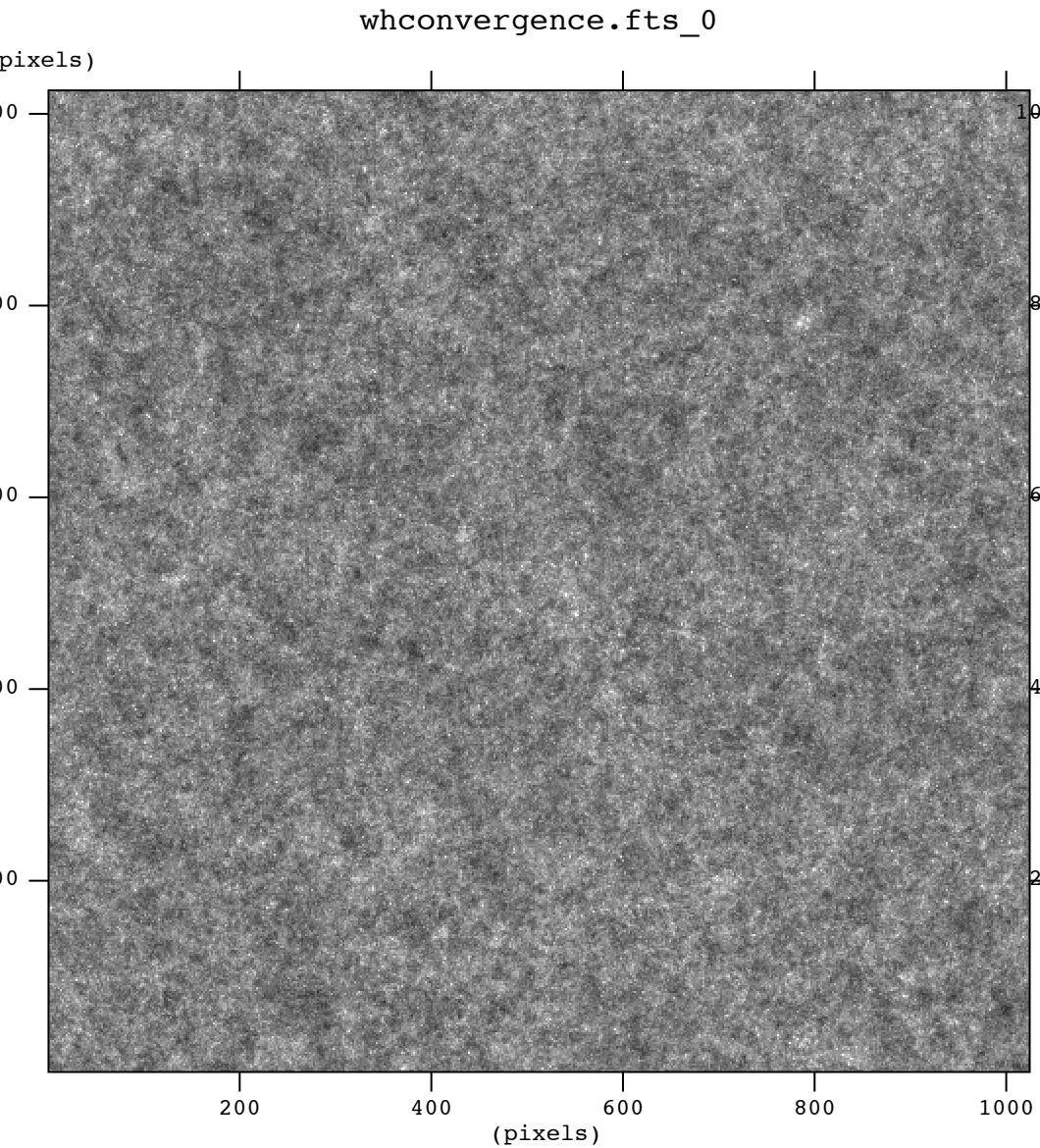
Lensing reconstruction bias

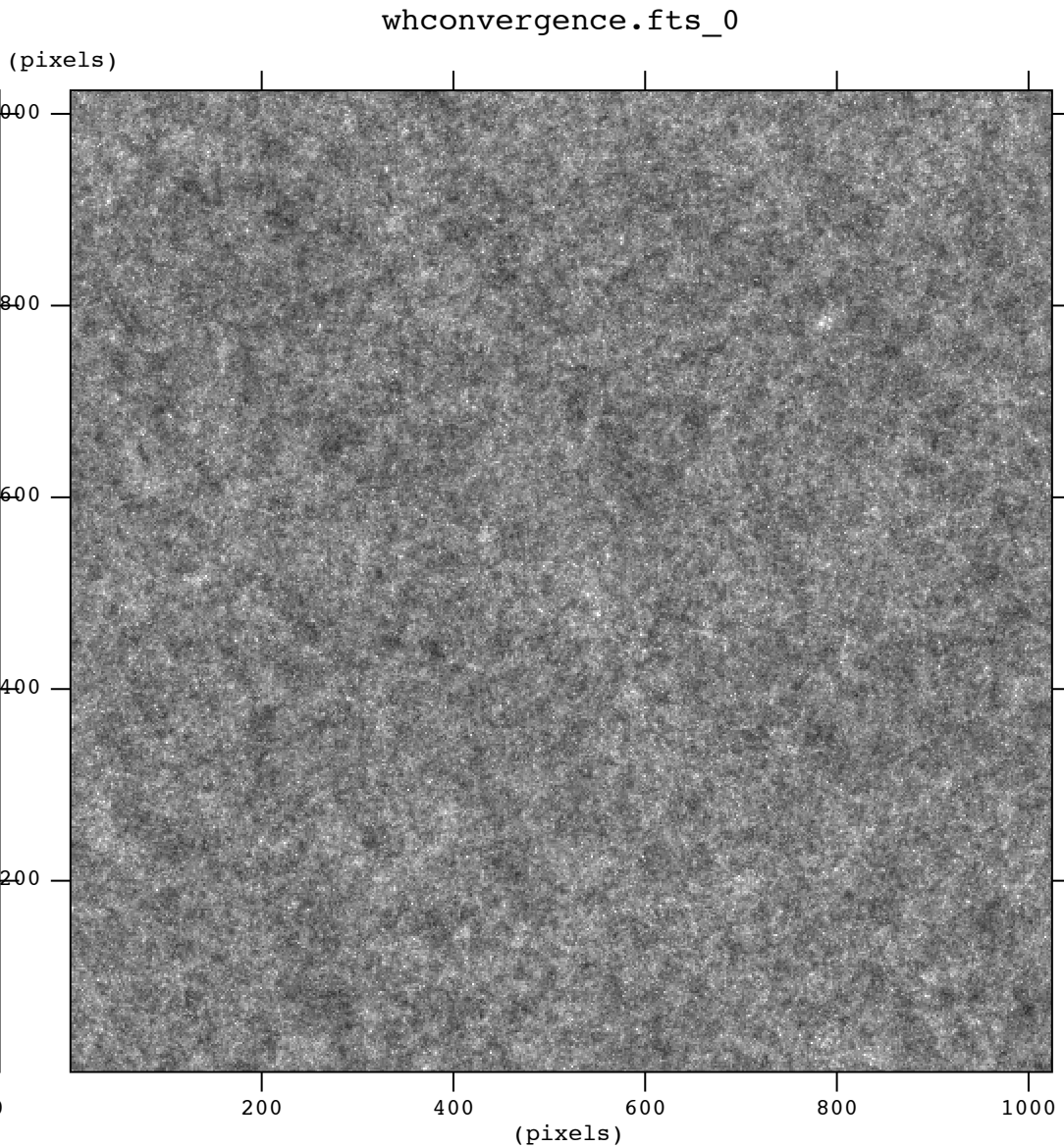




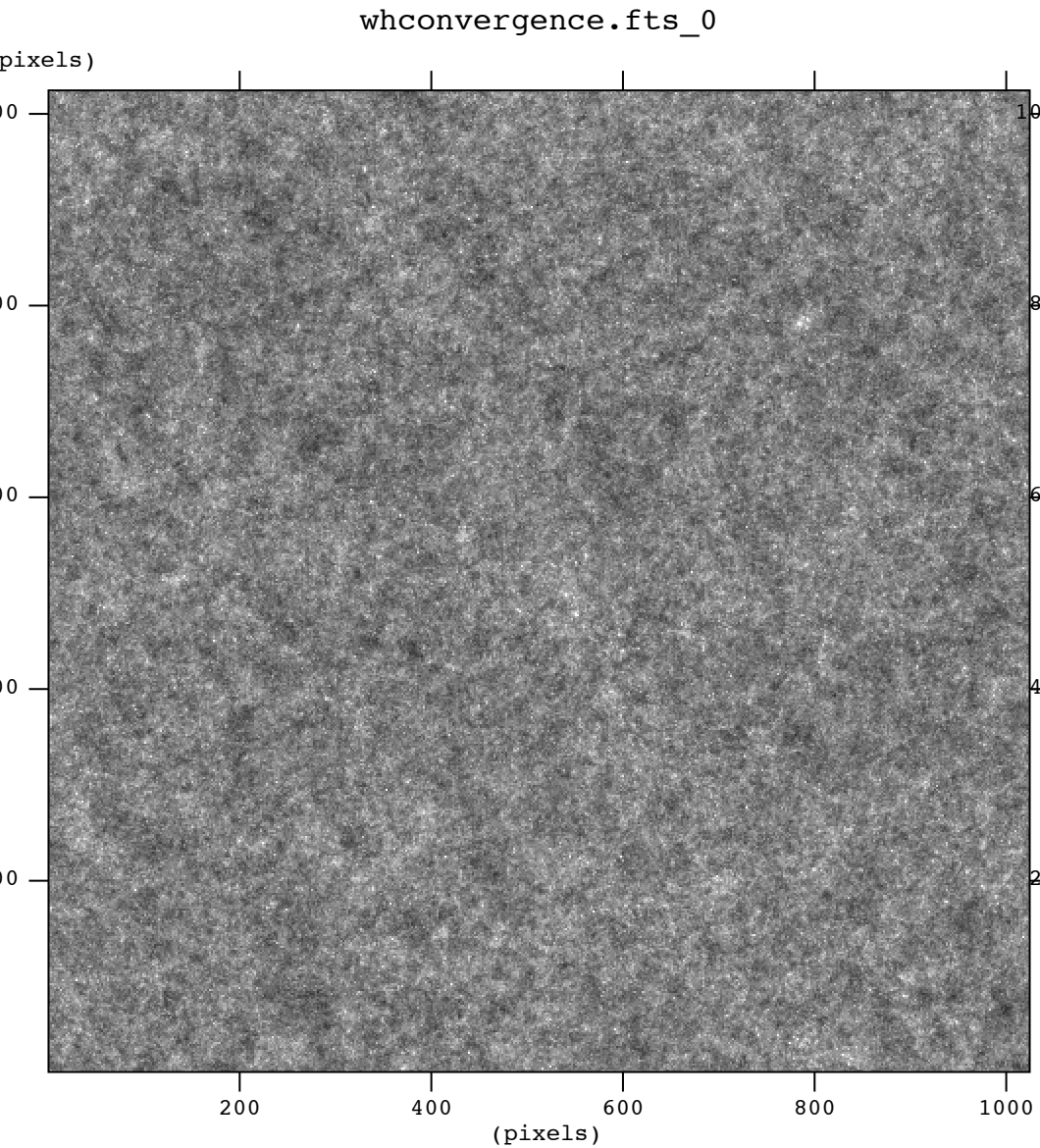
Simulation kappa field reconstruction

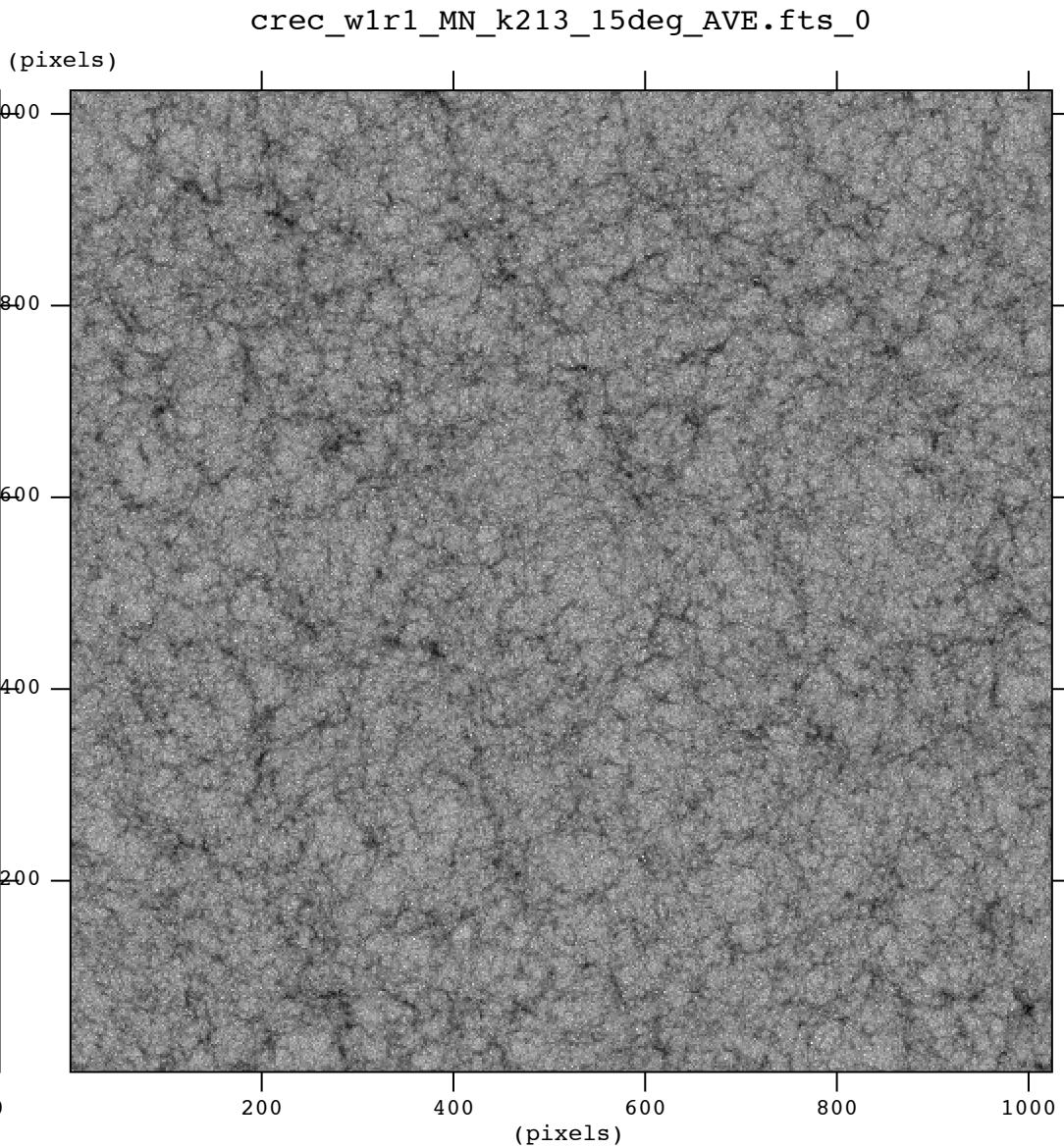
Lensing reconstruction bias



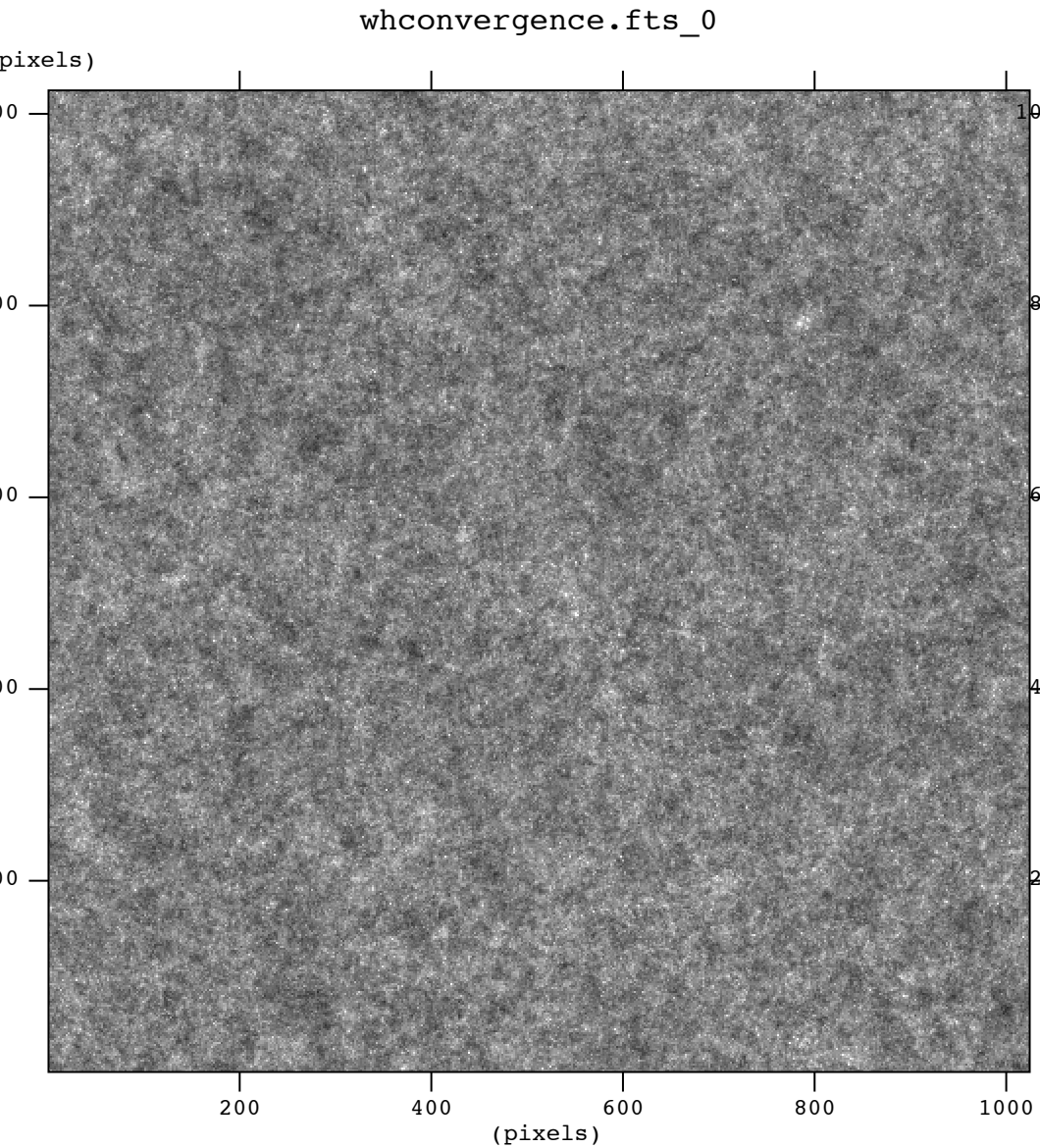


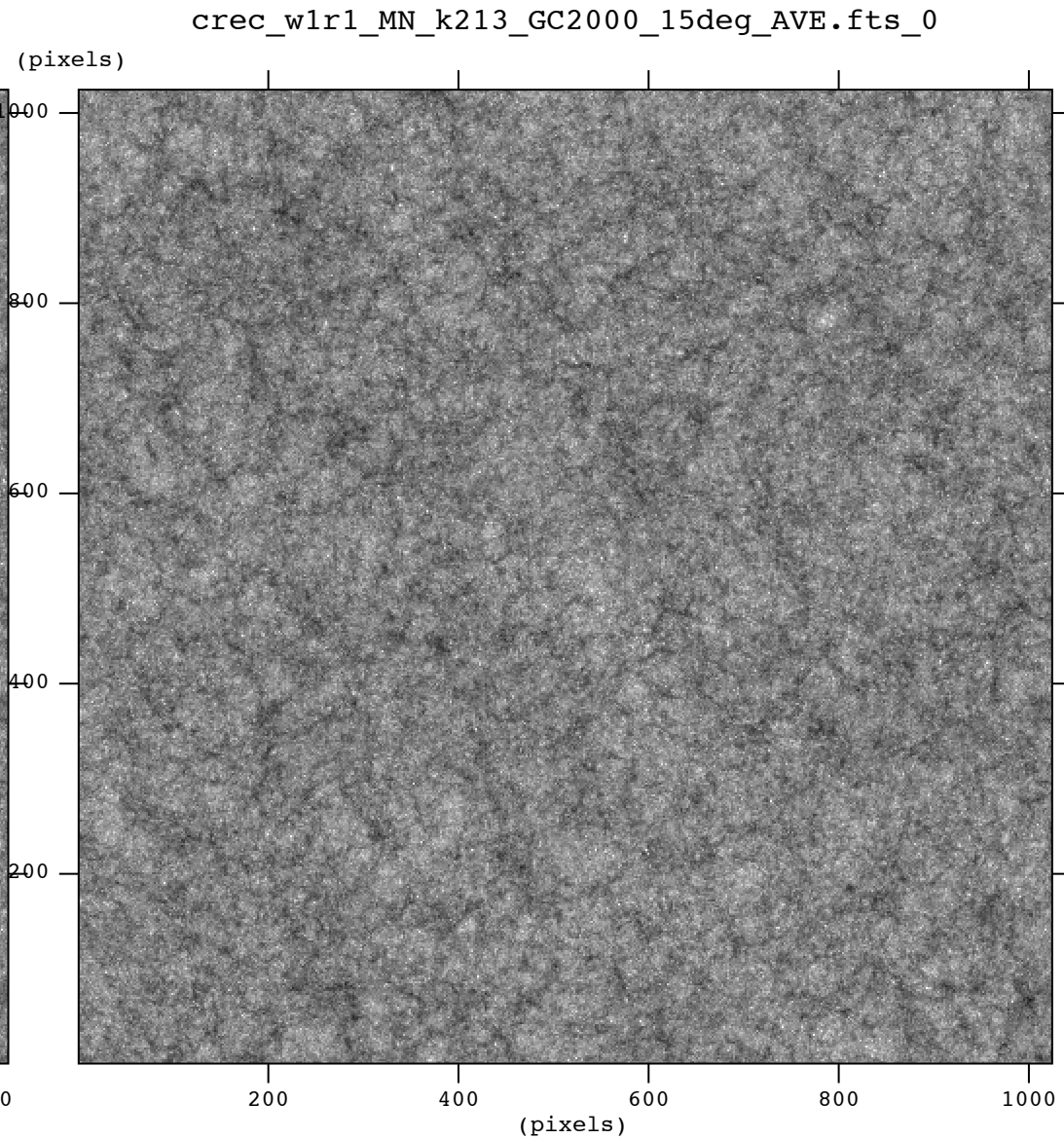
Lensing reconstruction bias





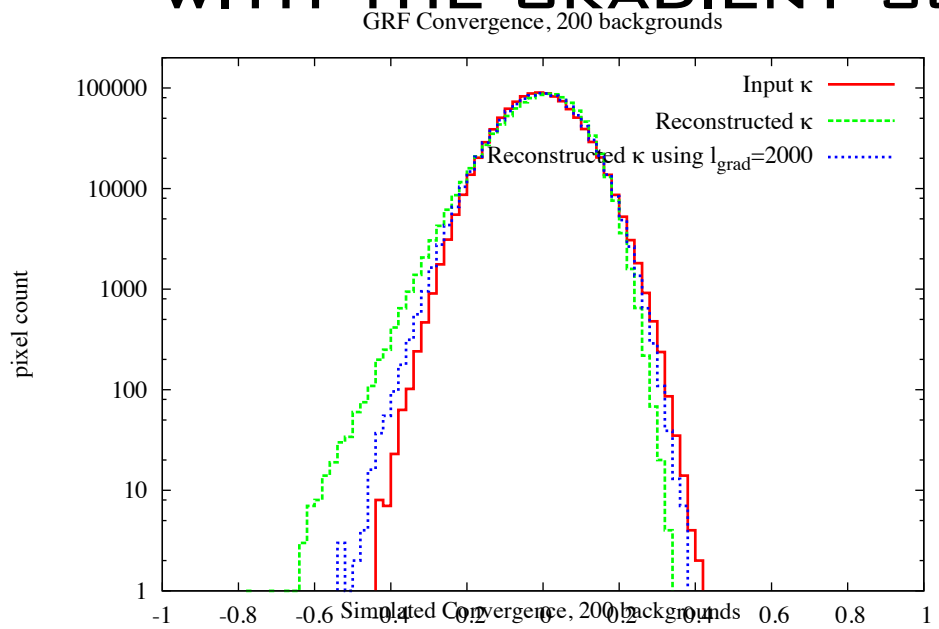
Lensing reconstruction bias

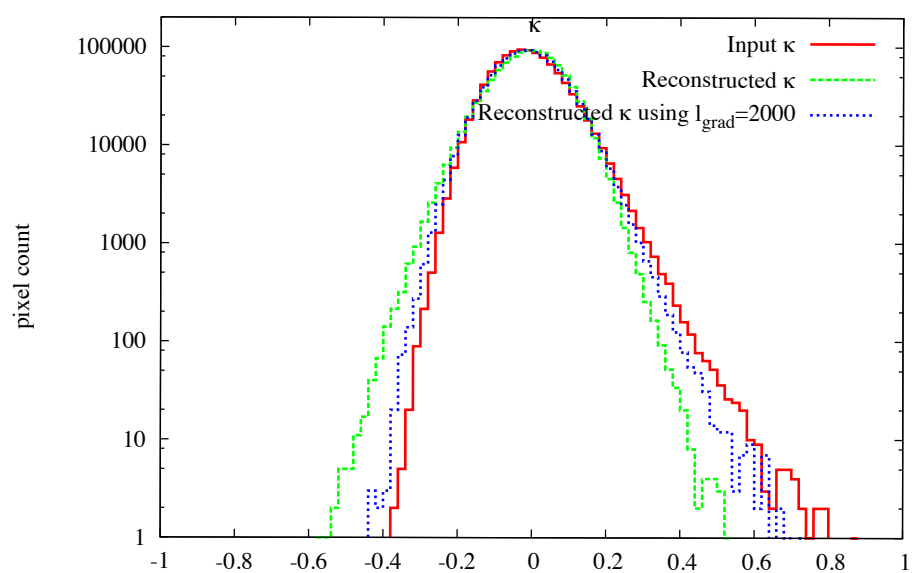




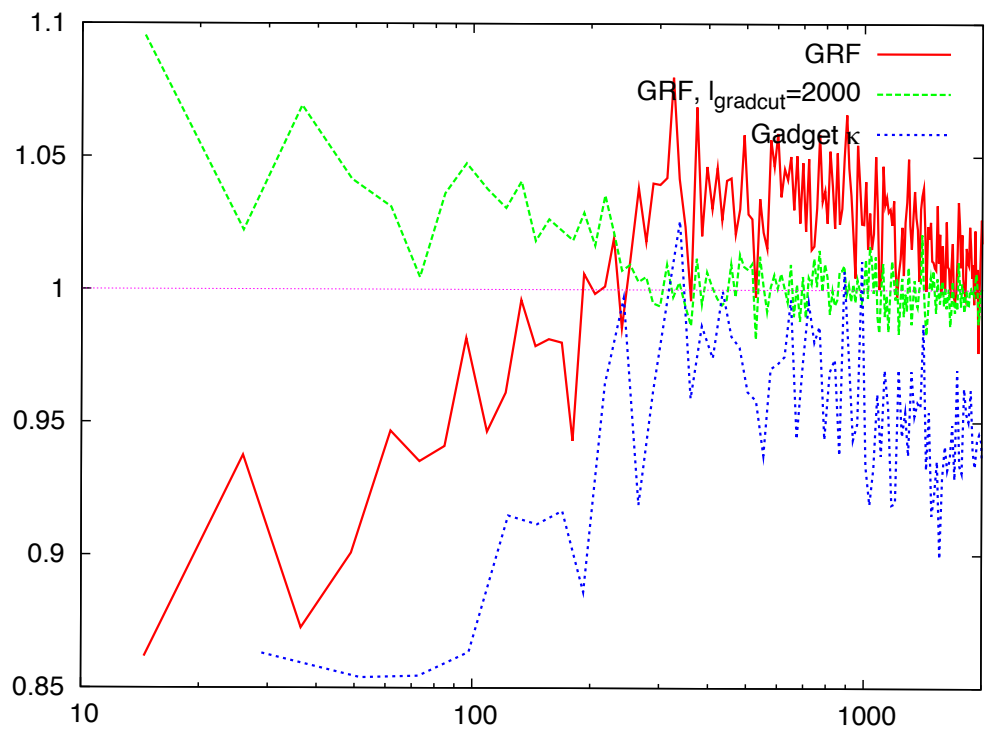
Biases in lensing reconstruction

- There arises a low bias in the lens reconstruction due to mixing of the lens with the gradient scale.

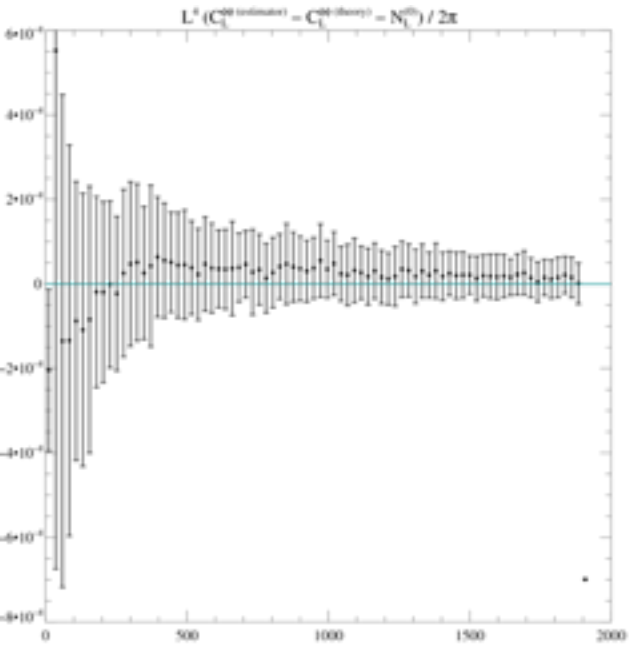


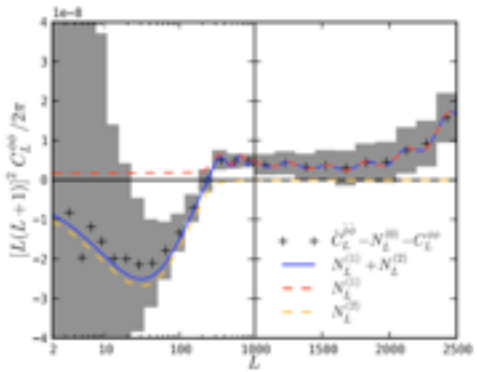


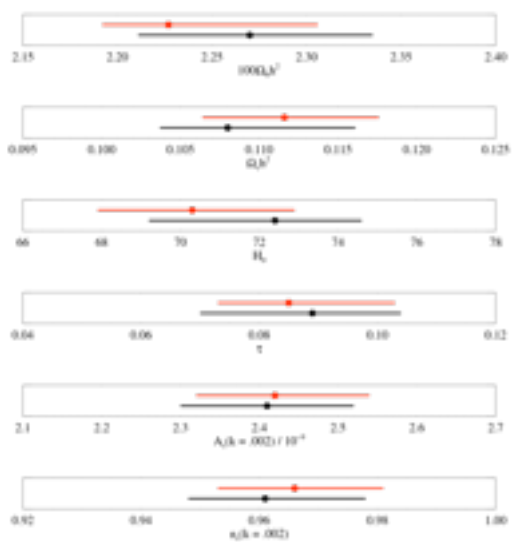
Zahn, Hu 2009 (unpublished)

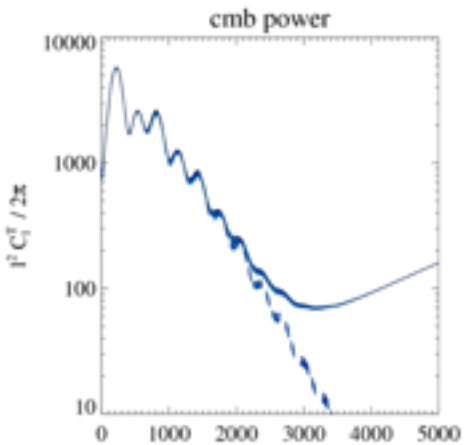


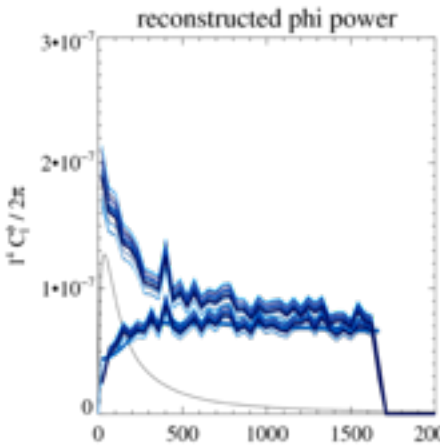
"Unknown Cosmology bias"

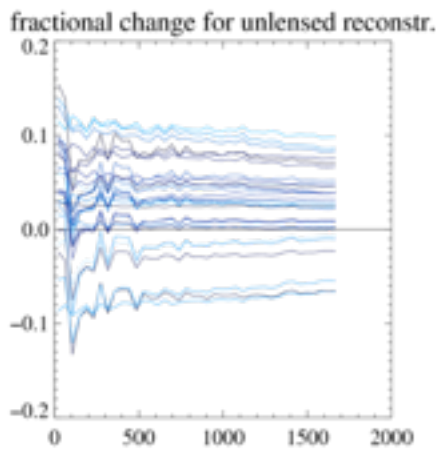


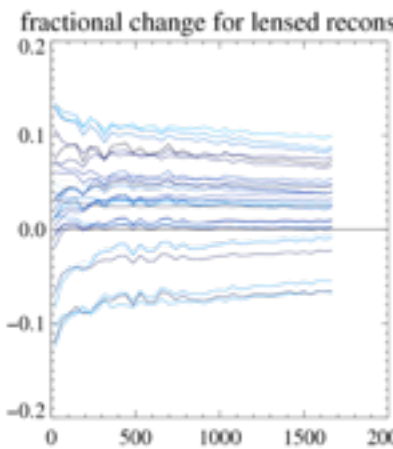












credit: Alexander van Engelen

Smidt, Cooray, et al. (2010)

- claim 2-sigma detection of lensing in WMAP-7 data, however at concordance phi incompatible with fisher analysis
- Appear to be combining A_L and Cl^phi estimators as independent observables.

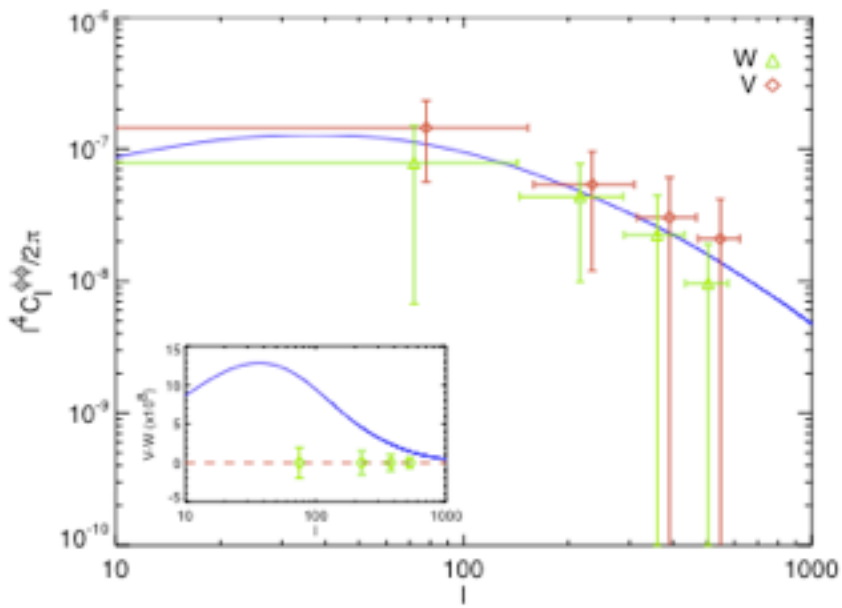


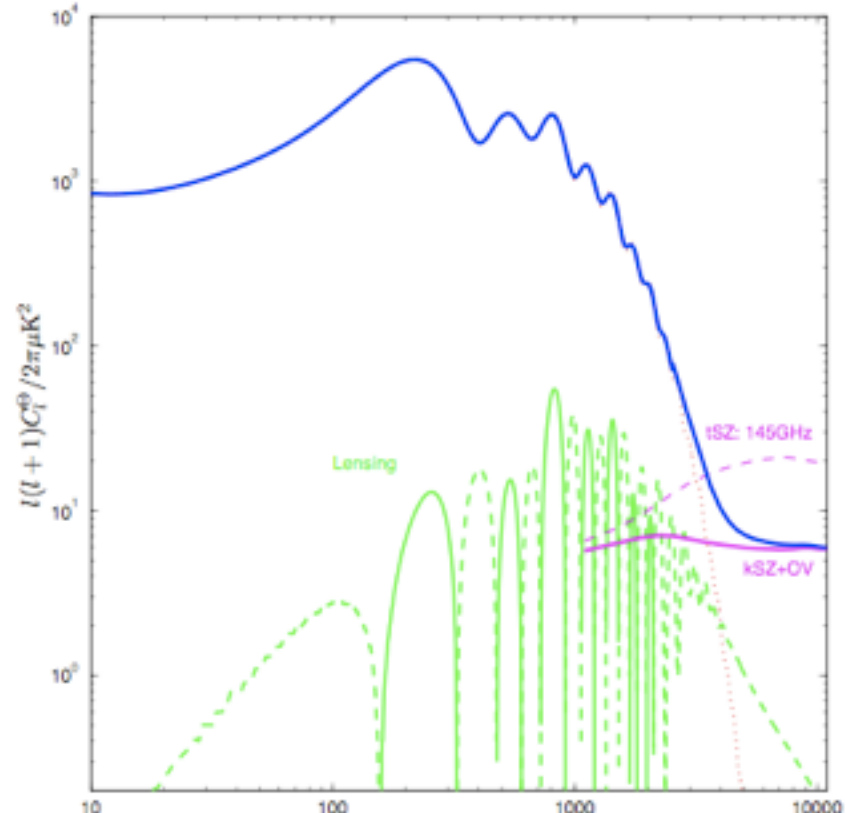
Fig. 2.— The constraints on $C_l^{\phi\phi}$ using the $\mathcal{K}^{(2,2)}$ estimator. In the larger plot, the red squares are the constraints by the V-band and the green circles are for the W-Band. The result of the null test is given in the smaller plot. These error bars represent 1σ errors.

Params.	WMAP7	WMAP7+A_L	WMAP7+A_L+$C_l^{\phi\phi}$
$10^3\Omega_b h^2$	22.51 ± 0.62	22.59 ± 0.63	22.60 ± 0.58
$10^2\Omega_{DM} h^2$	11.08 ± 0.57	11.04 ± 0.54	11.09 ± 0.54
τ	0.089 ± 0.016	0.090 ± 0.015	0.089 ± 0.015
n_s	0.967 ± 0.015	0.968 ± 0.014	0.968 ± 0.014
Ω_Λ	0.734 ± 0.031	0.737 ± 0.028	0.735 ± 0.027
Age/Gyr	13.8 ± 0.14	13.7 ± 0.14	13.7 ± 0.13
H_0^1	71.0 ± 2.7	71.3 ± 2.5	71.1 ± 2.4
$\mathbf{A_L}$	**1.0**	$\mathbf{0.87 \pm 1.05}$	$\mathbf{0.97 \pm 0.47}$

TABLE 1
Constraints on the cosmological parameters using CosmoMC. From left moving right: WMAP 7-year data only; WMAP7 with A_L allowed to run; WMAP7 with the constraints on $C_l^{\phi\phi}$ coming from our $\mathcal{K}_l^{(2,2)}$ estimator from the combined W-band and V-band data. The [1] Units on H_0 are (km s^{-1} Mpc^{-1}).

Temperature lensing systematics

- One way around it is to cross-correlate with LSS (only works on large scales)
- Or use 21 cm to beat shape noise to death by adding more and more smaller scales
- Notably, temperature reconstruction is relatively "dirty" because of gaussian noise
- Best foreseeable lensing reconstruction tool is polarization.

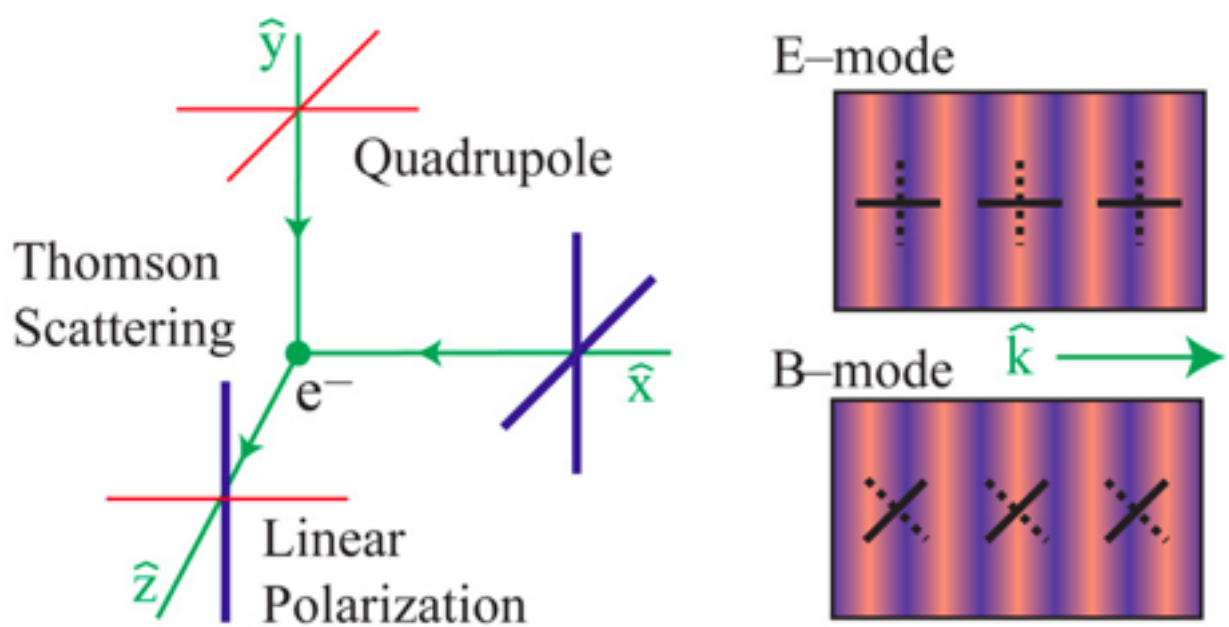


credit: Antony Lewis

Polarization of the CMB

- Quadrupole incident on free electrons during last 10% of recombination produces linear quadrupole

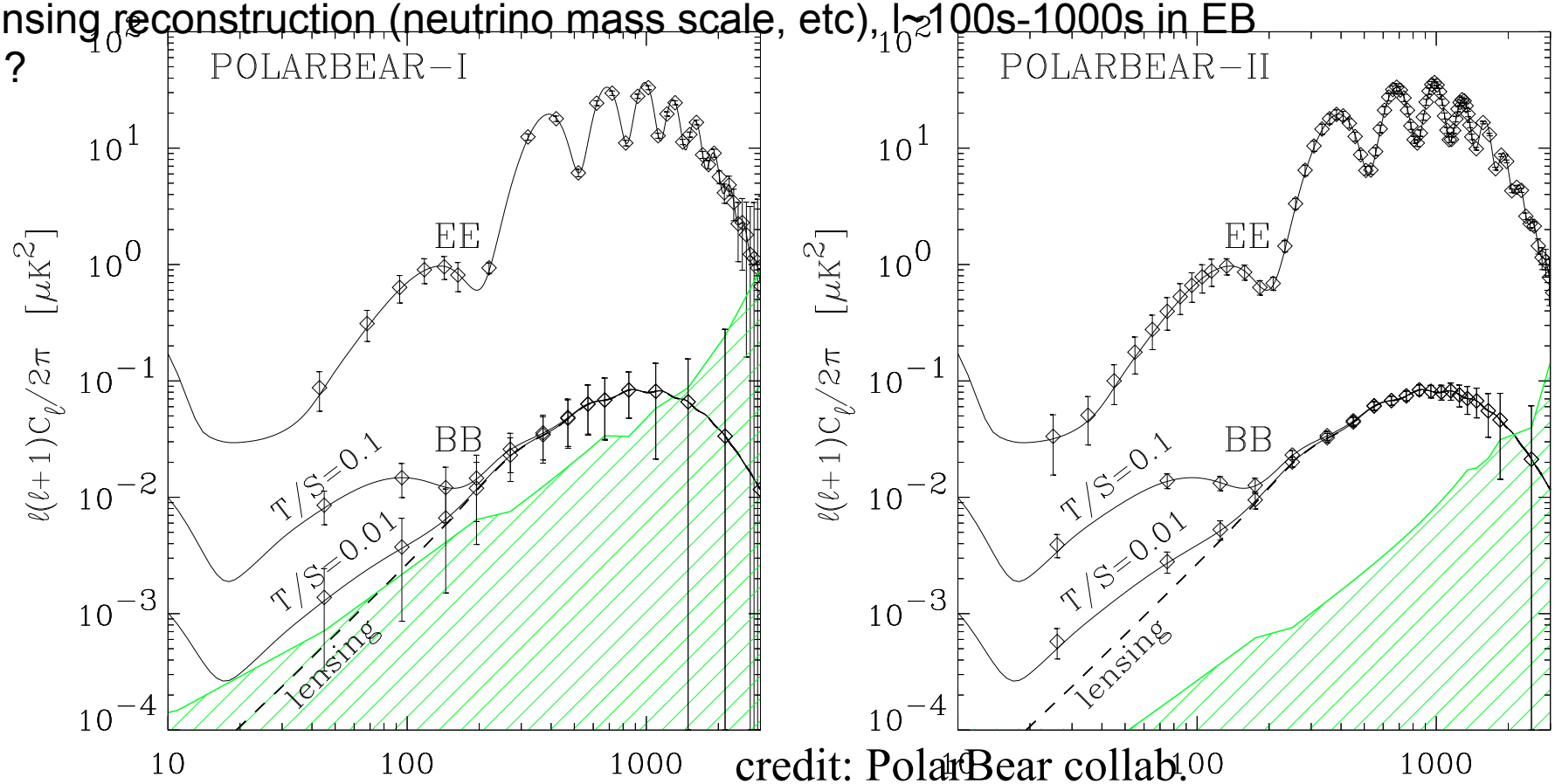
- This can be used as sensitive probe of recombination (e.g. Galli et al.) and because there is no primordial B, for lensing



credit: Wayne Hu

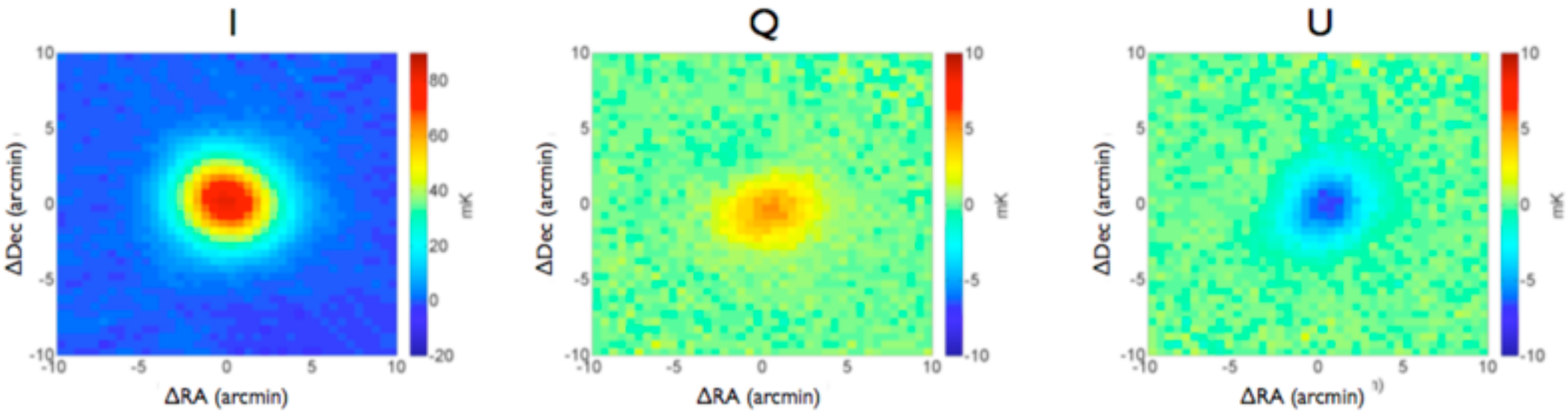
PolarBear (EBEX, etc)

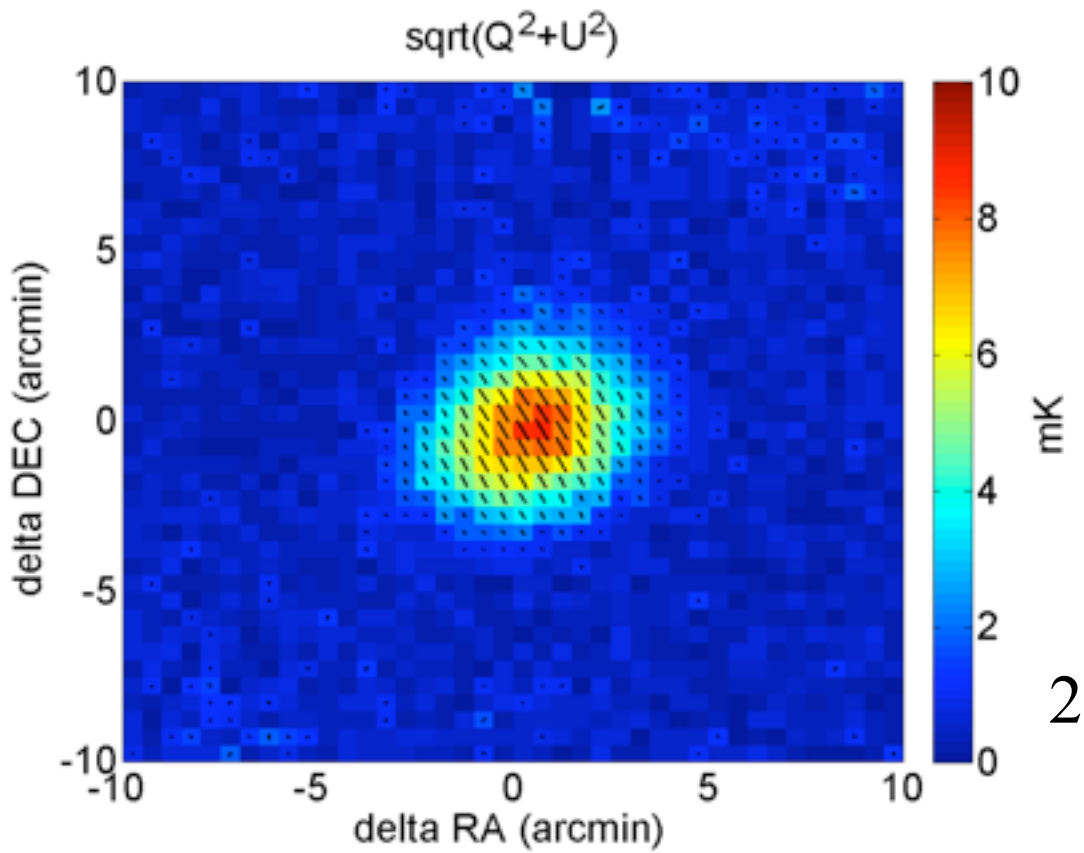
- Using all-sky data of the WMAP satellite, are able to find relatively weak evidence lensing, using the help of radio galaxies.
- Applying methods to SPT, lensing should be detectable *internally* at >10 sigma!
- PolarBear, a dedicated CMB polarization experiment, is aiming to constrain:
  - ✳cosmic reionization, l~2-20 in EE
  - ✳inflationary gravity waves, l~10s-200s in BB
  - ✳recombination science, l~100s-1000 in EE
  - ✳lensing reconstruction (neutrino mass scale, etc), l~100s-1000s in EB
  - ✳...?



credit: PolarBear collab.

POLARBEAR Measurements of TauA



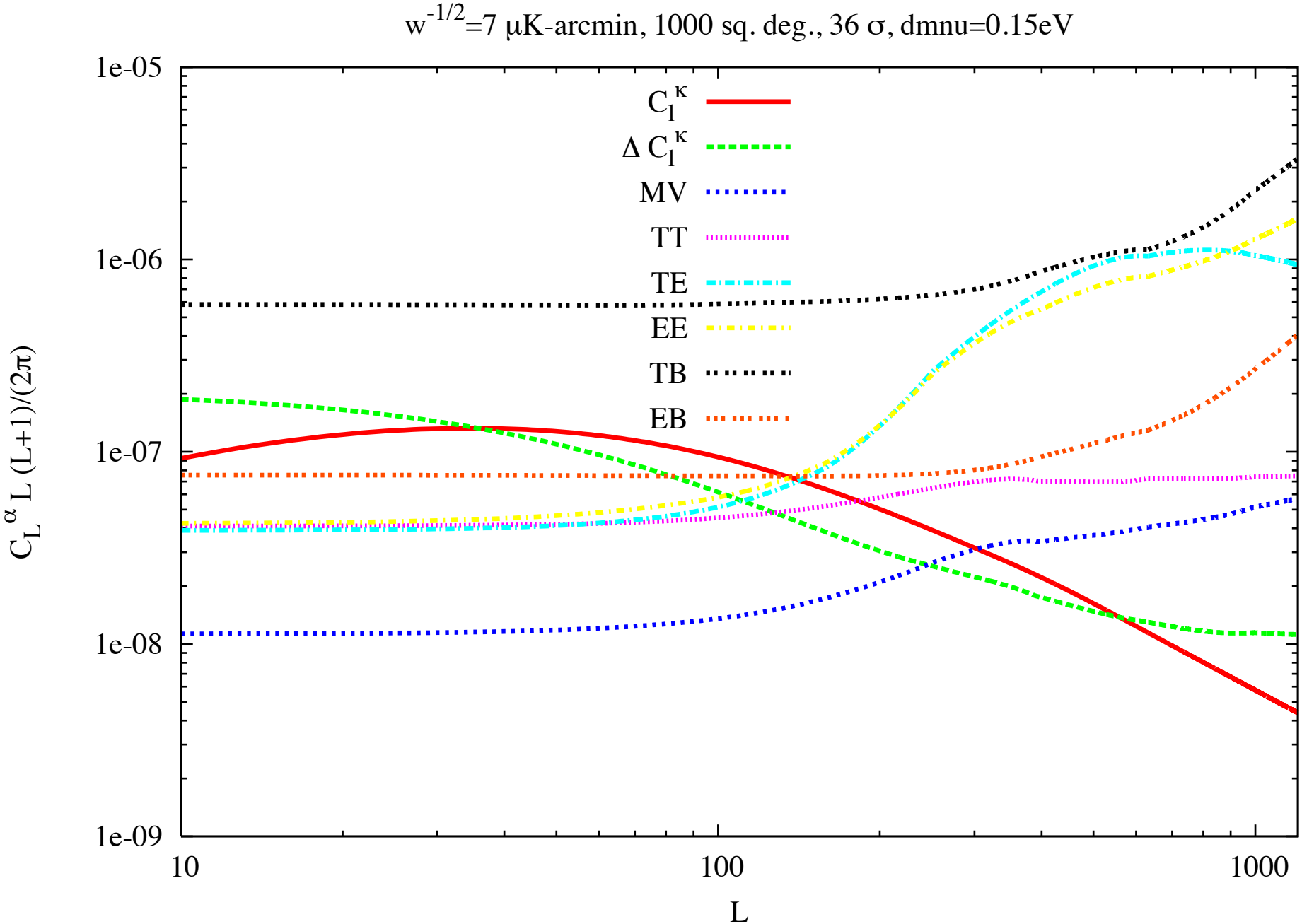


Pol. Angle + Fraction agree with Aumont et al.

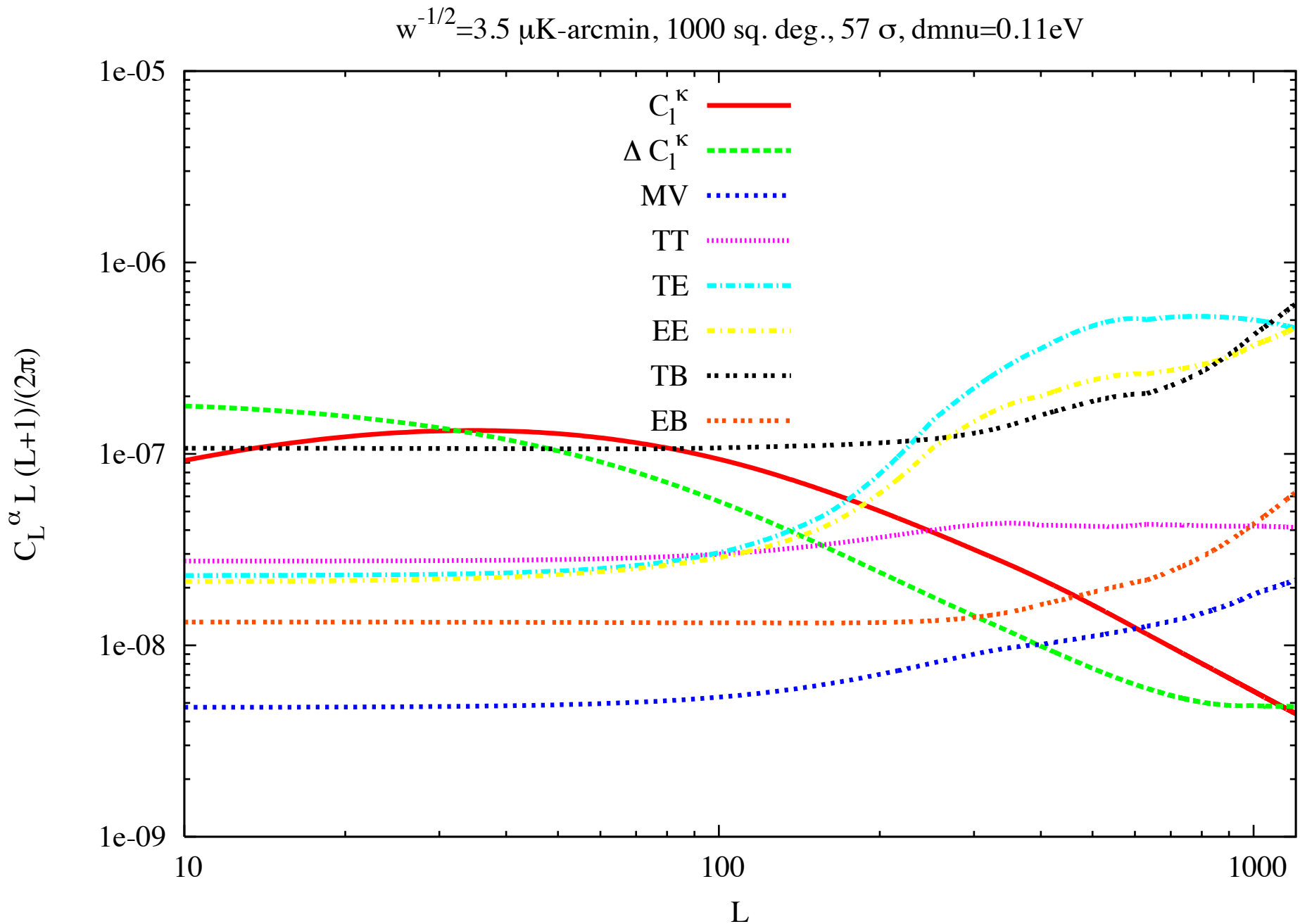
credit: PolarBear collab.

2 hours of data

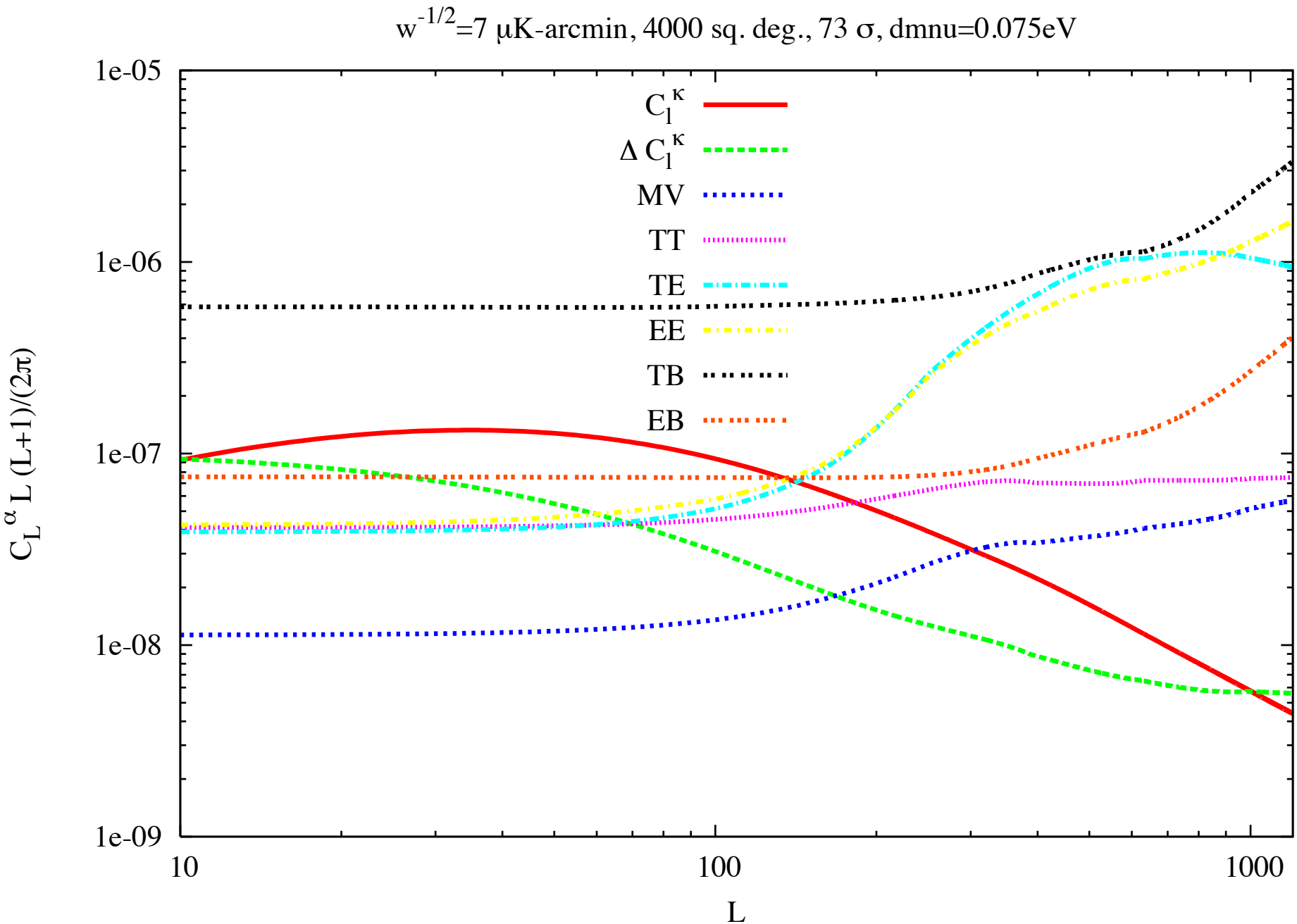
PB-I


w^-1/2=7 μK-arcmin, 1000 sq. deg., 36 σ, dmnu=0.15eV
C_l^κ
Δ C_l^κ
MV
TT
TE
EE
TB
EB
1e-05
1e-06
1e-07
1e-08
1e-09
10
100
1000
L
C_L^α L (L+1)/(2π)

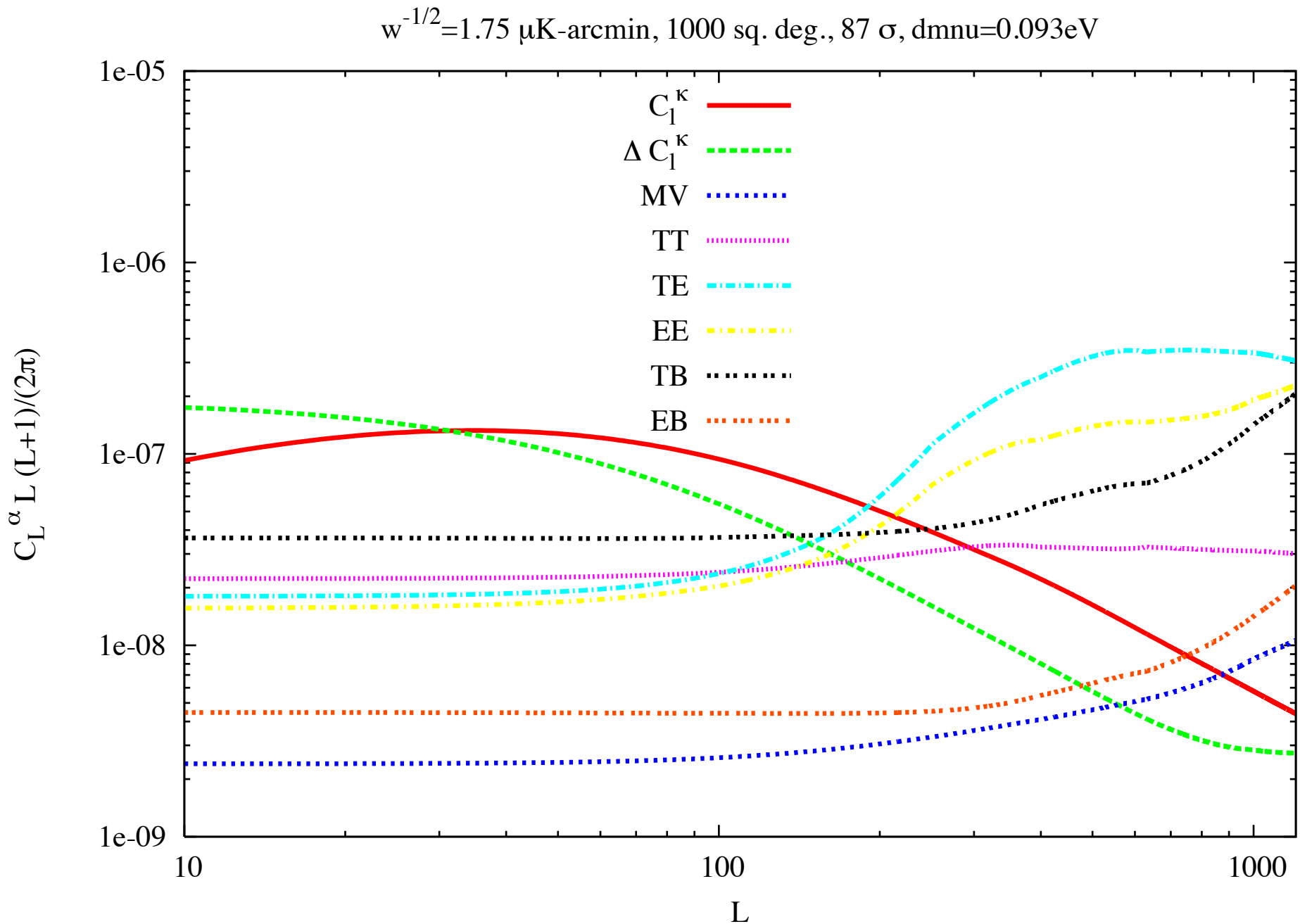
Polarbear-II deep



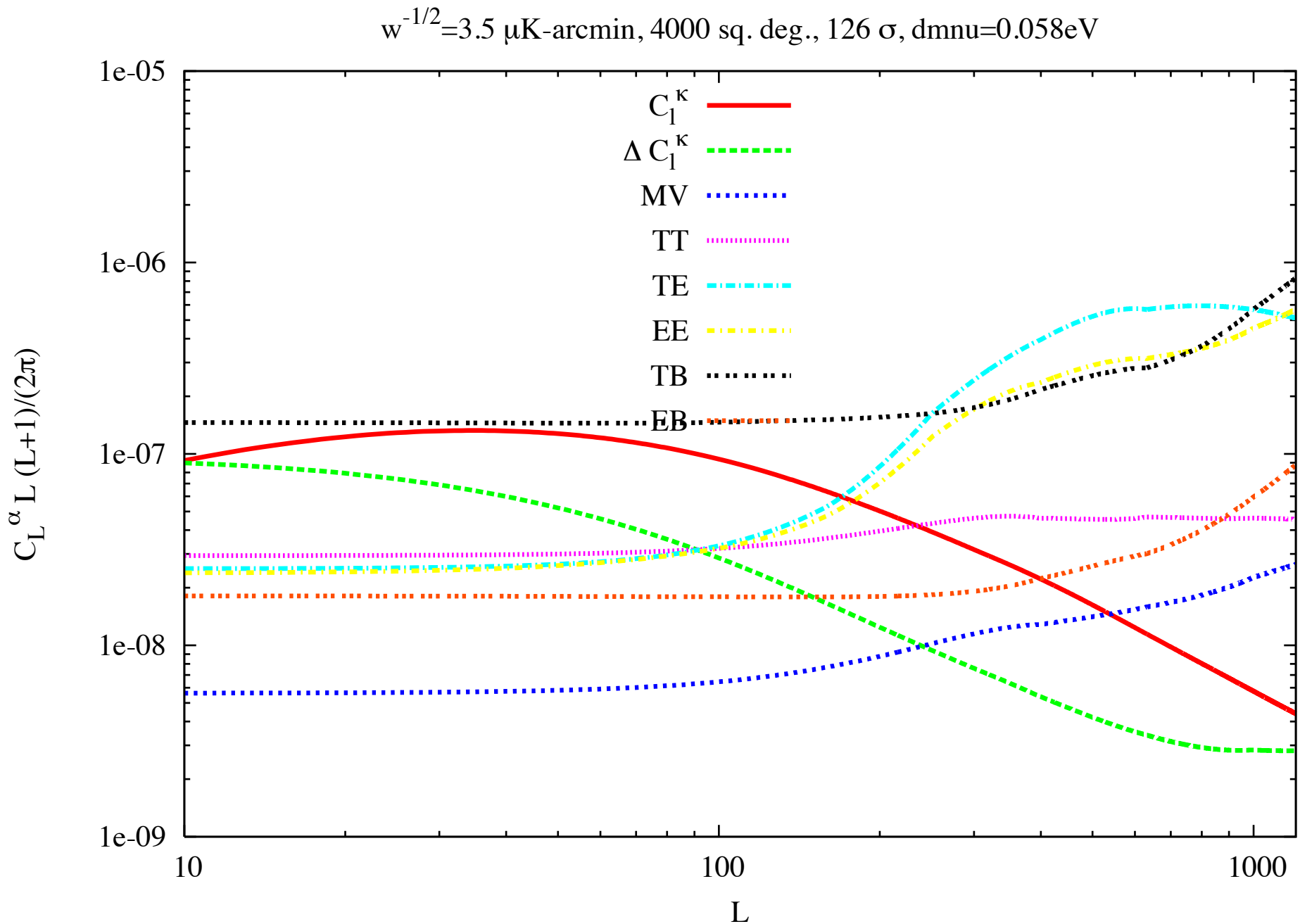
Polarbear-II wide



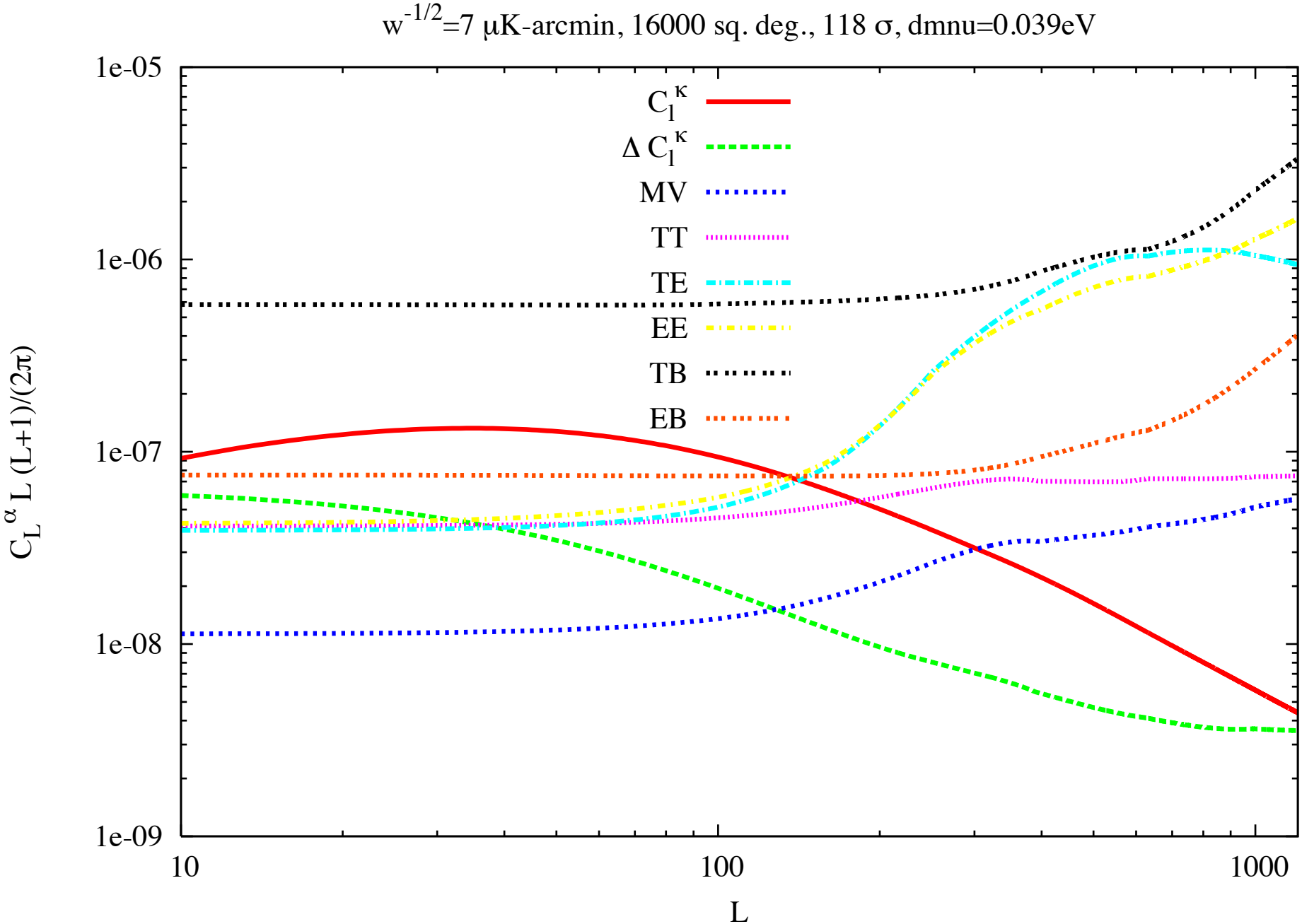
SuperPB deep



SuperPB mid

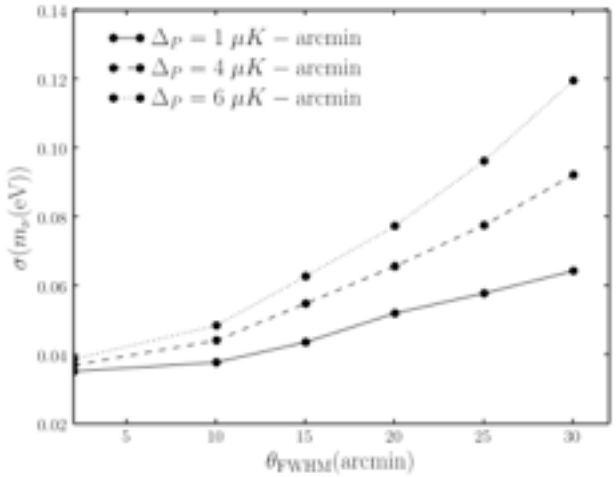

w^-1/2=3.5 μK-arcmin, 4000 sq. deg., 126 σ, dmnu=0.058eV
C_L^α L (L+1)/(2π)
L
1e-05
1e-06
1e-07
1e-08
1e-09
10
100
1000
C_l^κ
Δ C_l^κ
MV
TT
TE
EE
TB
EB

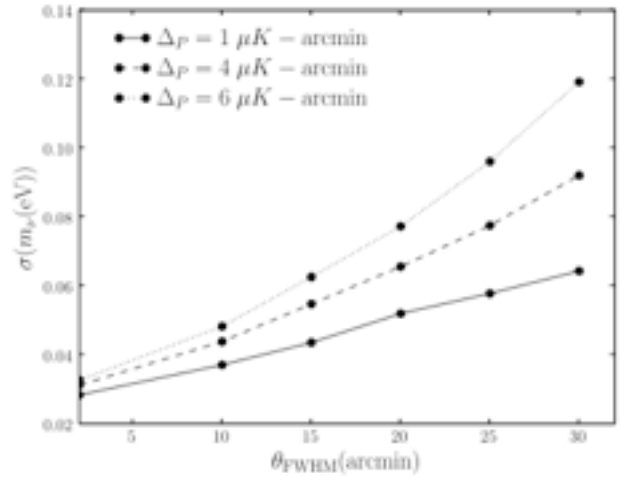
SuperPB wide

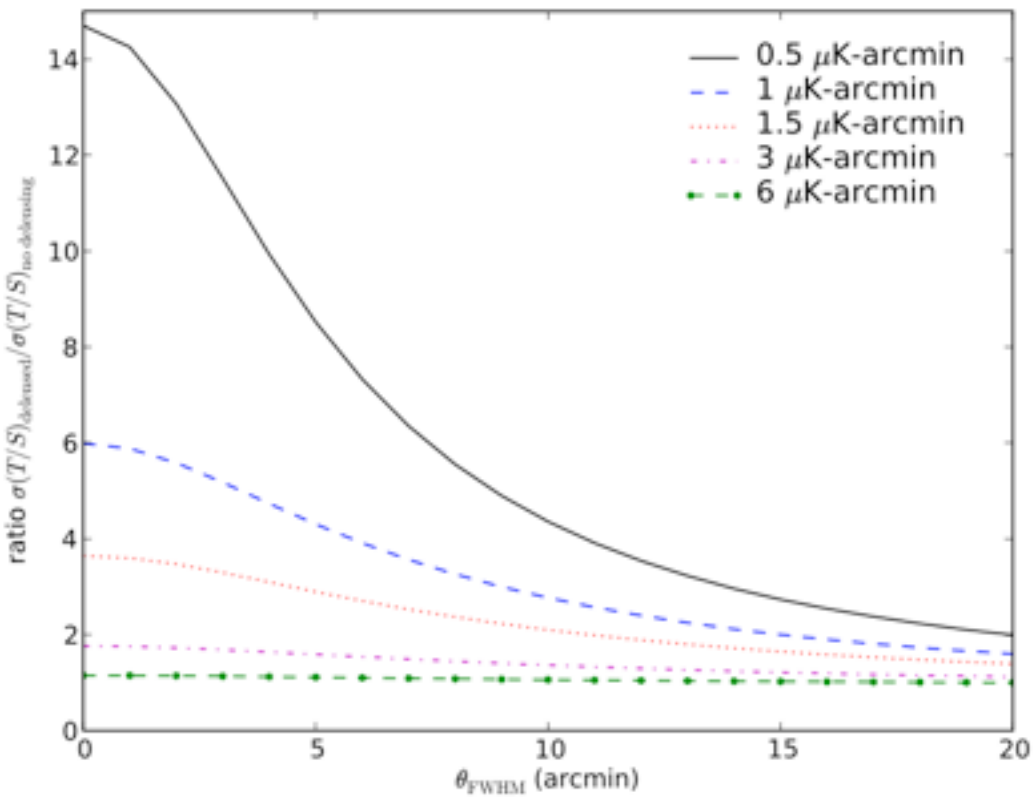


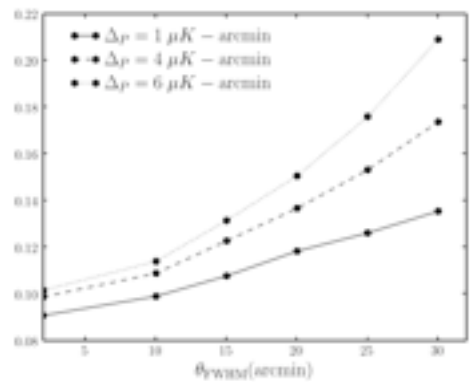
Silk-Damping

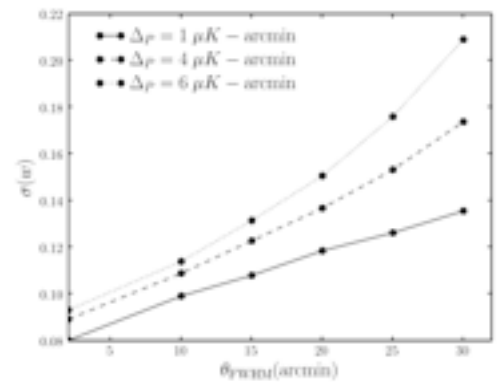
credit: Sudeep Das and Kendrick Smith

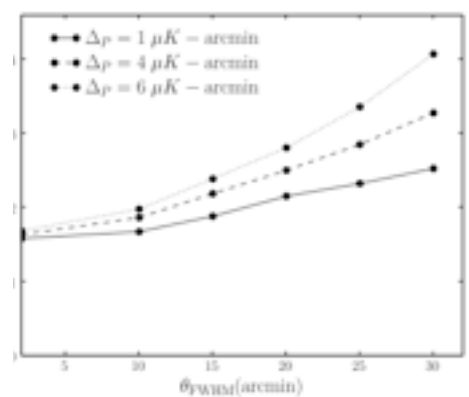


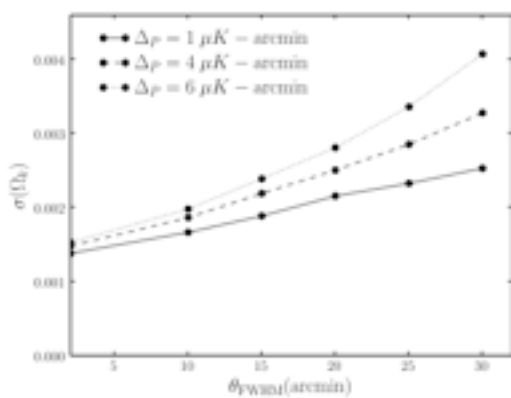












CMB lensing summary

- We have detected lensing at low significance in cross-correlation with LSS
- Have enough data to detect it at high significance internally with WMAP
- For cross-correlation studies advantageous to have large field
- Polarization is the best tool to detect and constrain CMB lensing:
  - ➡We don't expect small-scale primordial B-modes, hence there is no shape noise
  - ➡EB better than TT at PB-II level, huge S/N improvement
  - ➡There should be less astrophysical contamination (SZ, point sources)
  - ➡However Galactic foregrounds probably more important, as well as experimentals
  - ➡SuperPB could be the definitive CMB lensing experiment!