kSZ effect from patchy reionization

Ilian T. Iliev

University of Sussex

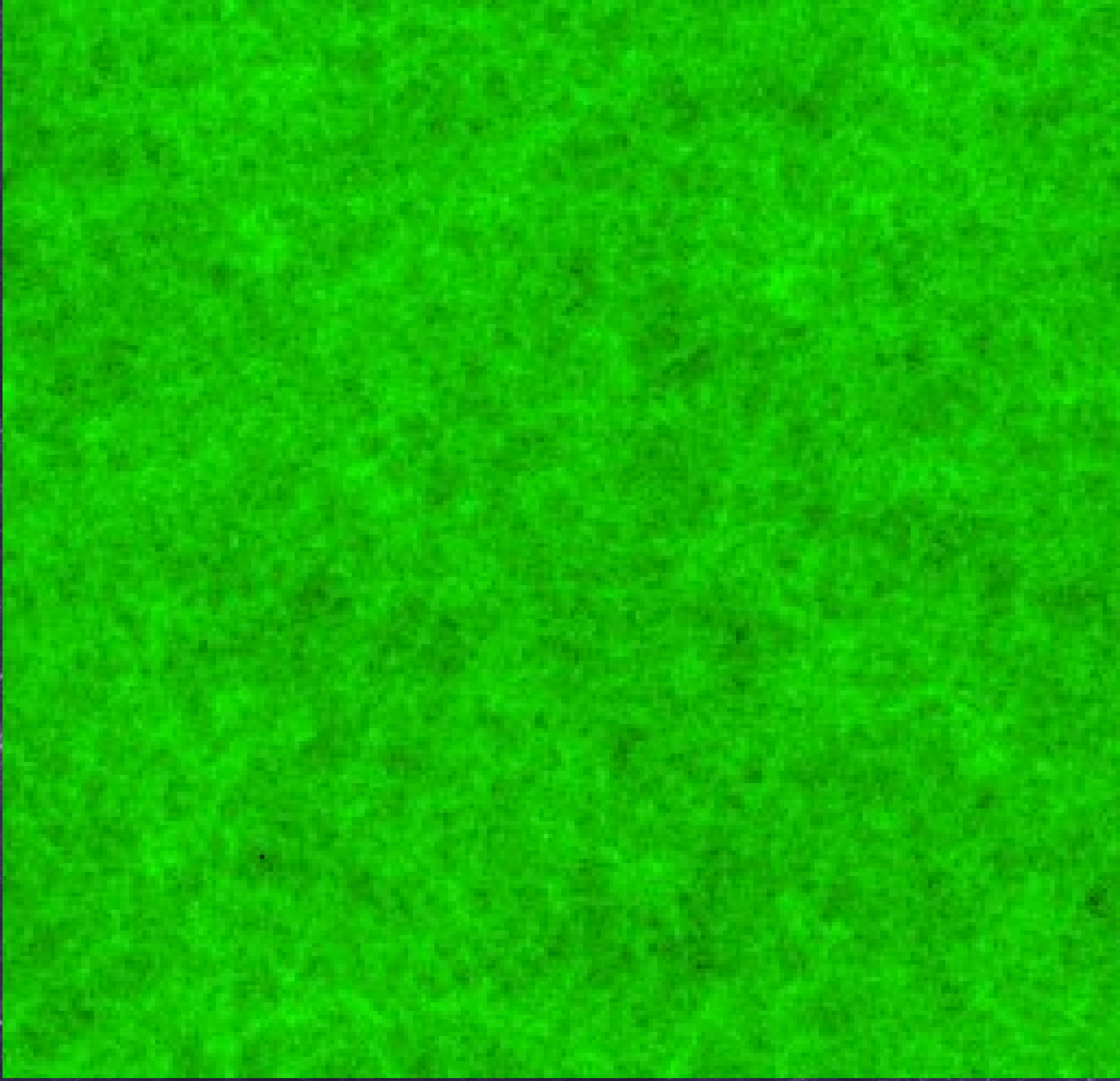
Reionization in Action:From the Dark Ages to Reionized Universe

-Strong halo clustering

-quick local percolation - large H II regions with complex geometry.

114/h Mpc box, WMAP3+ cosmology, 256^3 radiative transfer simulation. Evolution: z=30 to 7.

$>10^8$ solar mass halos resolved



Simulations ran at Texas Supercomputing Center on up to 10,000 cores

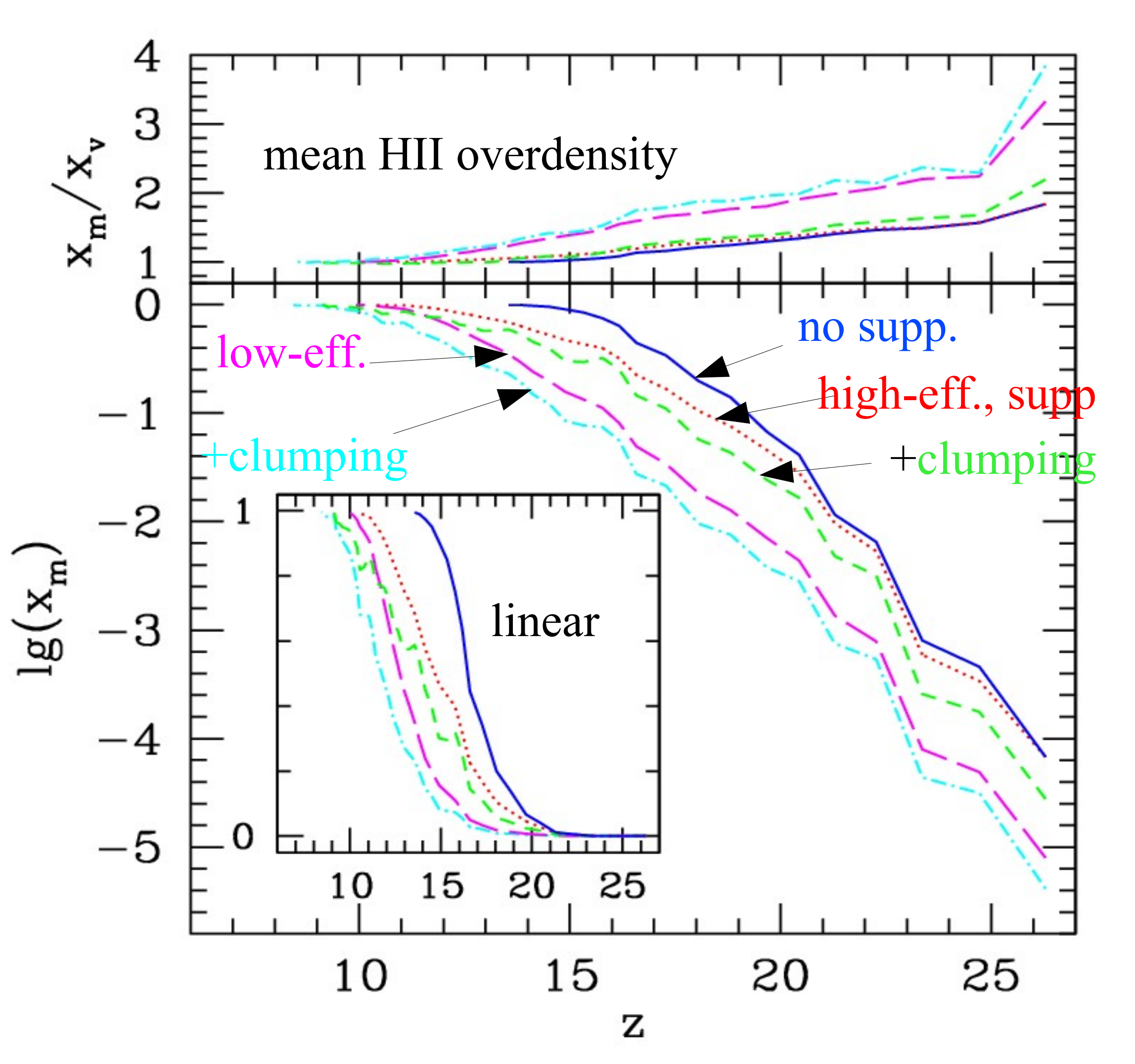
Self-Regulated Reionization

(Iliev, Mellema, Shapiro and Pen 2007a, MNRAS, 376, 534)

Lower large-source efficiencies, Jeans-mass filtering of small sources and time-increasing sub-grid gas clumping all extend reionization and delay overlap.

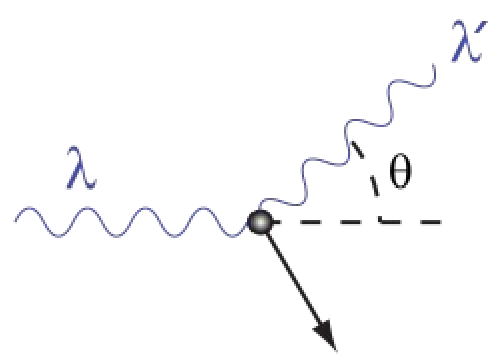
More/less efficient low-mass sources result in more/less suppression of same sources =>

Reionization is self-regulated.



SZ effect
(Sunyaev & Zel'dovich 1970)

- Due to inverse Compton scattering of CMB photons on moving electrons, whic transfers some energy between them.
- This causes small temperature fluctuations of the CMB — secondary fluctuation anisotropies at small scales.



Thermal SZ effect

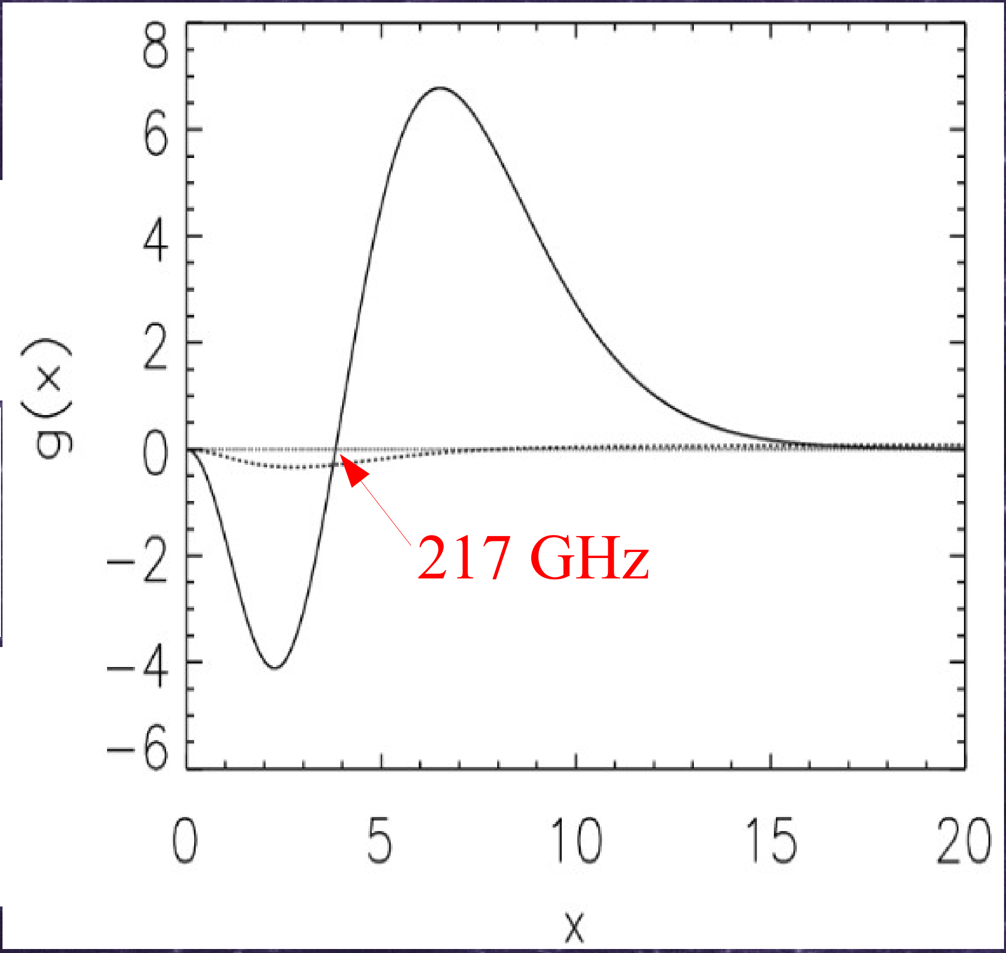
Scattering of CMB on thermally-distributed electrons. Important for high T (galaxy clusters).

$$\Delta I_{\rm nr} = i_{\rm o} y g(x),$$

$$y = \int \left(\frac{kT_e}{mc^2}\right) n_e \sigma_T dl,$$

$$g(x) = \frac{x^4 e^x}{(e^x - 1)^2}\left[\frac{x(e^x + 1)}{e^x - 1} - 4\right]$$

$$x = h\nu/kT$$



Kine(ma)tic SZ effect

- Temperature variations given by LOS integral:

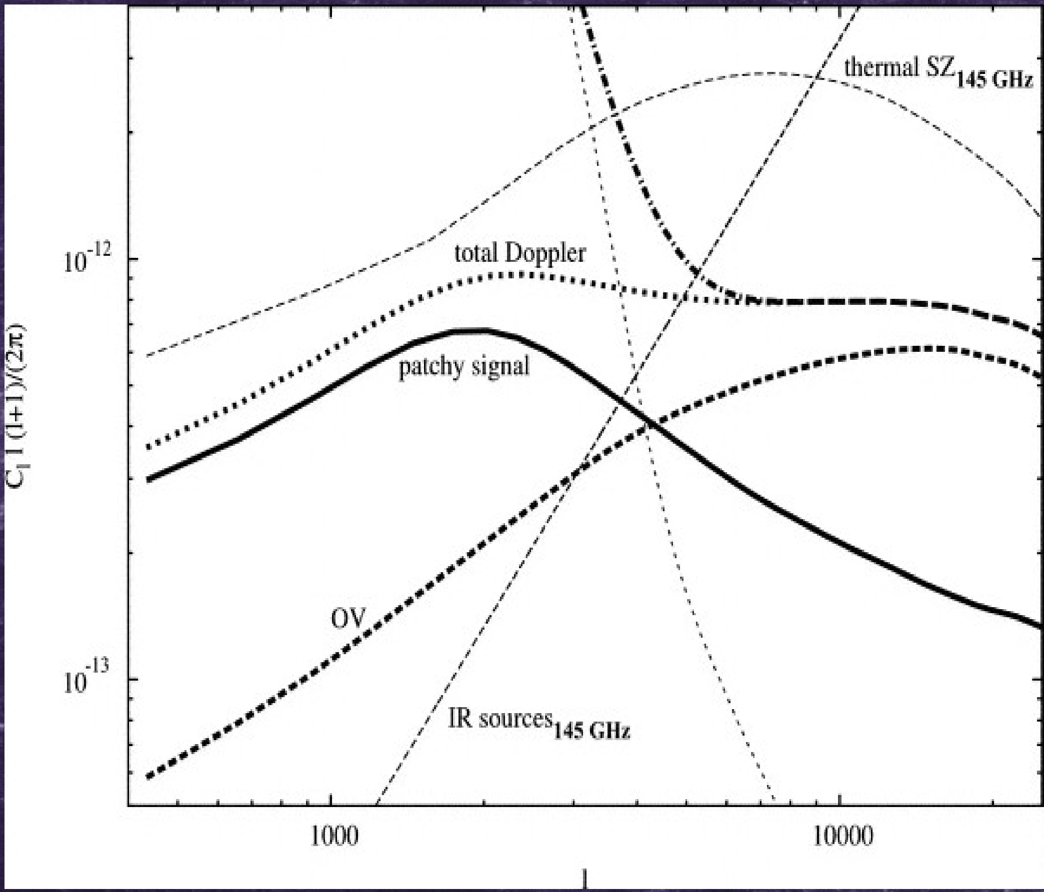
$$\frac{\Delta T}{T}(\hat{\mathbf{n}})_{\mathrm{kSZ}} = \sigma_T \int \mathrm{d}\eta \mathrm{e}^{-\tau(\eta)} a n_e \hat{\mathbf{n}} \cdot \mathbf{v},$$

- Spectrum is black-body (no spectral distortions of original CMB.
- Both density and velocity distributions are important, with ionization imposing additional fluctuations during EoR.
- Dominated by IGM during EoR and by clusters later-on.

Different SZ signals: example

- CMB primary drops fast at l~few 1000s
- tSZ is largest, but

  could be subtracted due to its charachteristic spectrum and zero point.
- Patchy and post-EOR kSZ dominate high l's after tSZ subtraction, but have same spectrum and similar magnitude — difficult to disentangle.



kSZ from patchy reionization: extraction from simulations

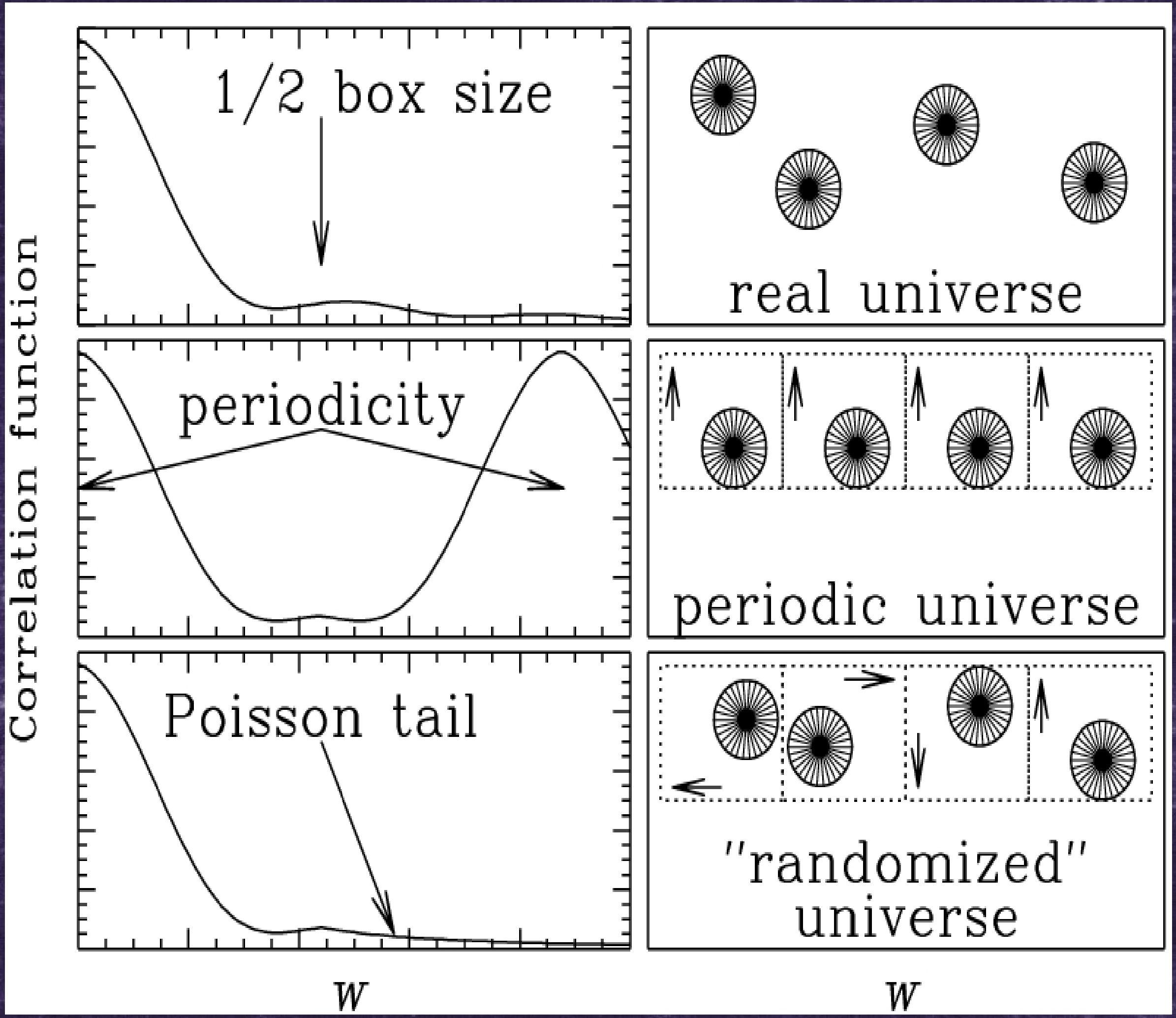
- (Iliev, Pen, Mellema, Bond, Shapiro, 2007)

$$\frac{\Delta T}{T}(\hat{\mathbf{n}})_{\mathrm{kSZ}} = \sigma_T \int \mathrm{d}\eta \mathrm{e}^{-\tau(\eta)} a n_e \hat{\mathbf{n}} \cdot \mathbf{v},$$

- **Method:**
  - find all integrals along LOS for available outputs
  - every light-crossing time interpolate between closest two outputs
  - to avoid periodicity artefacts change directions (x-y-z) and do random shifts (using box periodicity) and/or 90 degree rotations.

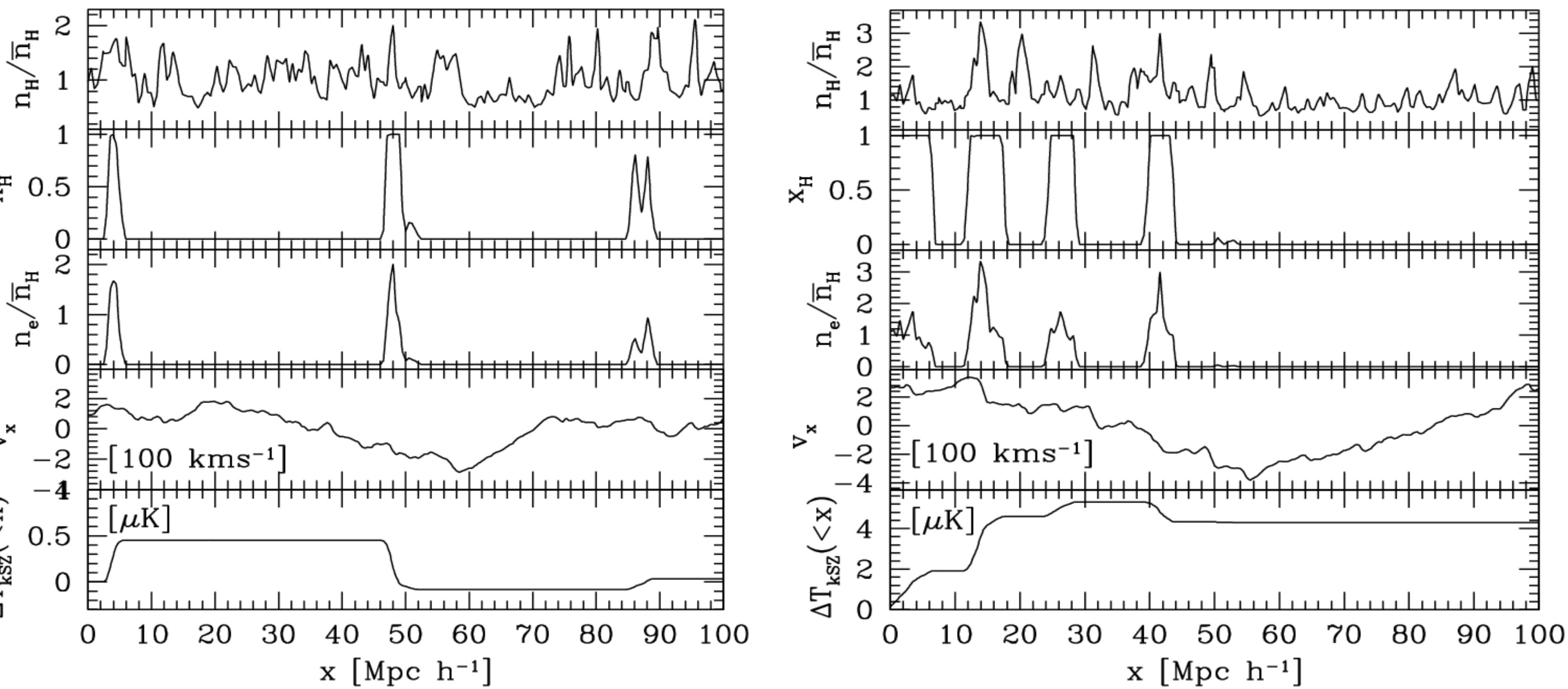
Randomization

- Simulation volumes are relatively small — many are traversed by each LOS.
- This demands randomization, so that repeated structures do not artificially boost the signal



Gnedin & Jaffe 91

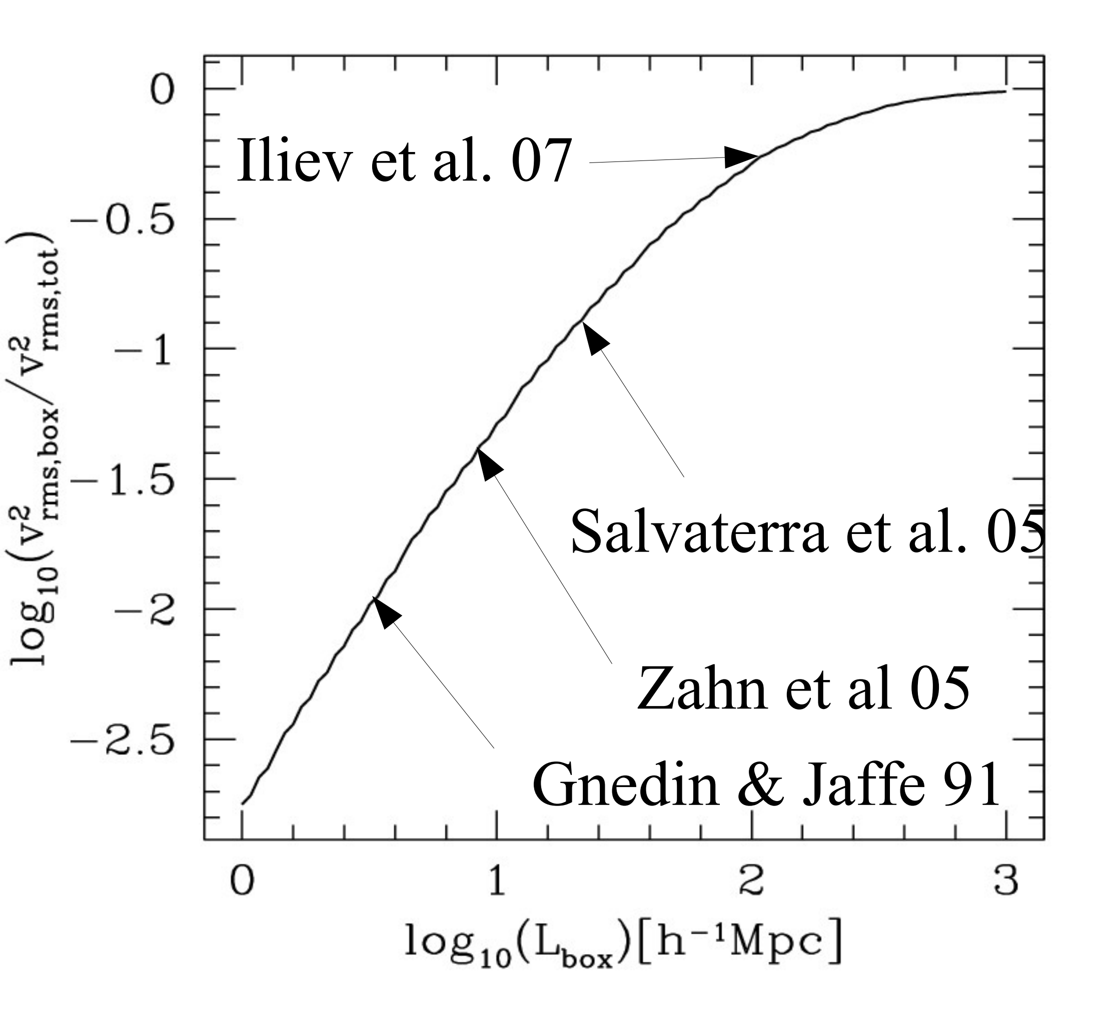
KSZ from reionization: composition of the signal



Iliev et al. 2007

Large-scale velocities

- The coherent bulk motions due to cosmic structure formation peak at very large scales — hundreds of Mpc (missing rms power vs. boxsize shown).
- Fortunately, those large-scale motions are linear and can be (statistically) corrected for (Iliev et al. 2007).



Large-scale velocities correction:algorithm

(Iliev, Pen, Bond, Mellema & Shapiro 2007)

- First, the missing velocity power is calculated based on the linear theory for the simulation boxsize and cosmology.
- Then, the full computational volume is assumed to be moving with the same coherent velocity, v_{box}, in which case:

$$\left(\frac{\Delta T}{T_{\rm CMB}}\right)_{\rm tot}(z) = \left(\frac{\Delta T}{T_{\rm CMB}}\right)_{\rm box}(z) + \tau_{\rm es}(z)\frac{\bar{v}_{\rm box}(z)}{c}$$

- Here, the velocity v_{box} is chosen with random amplitude and direction using

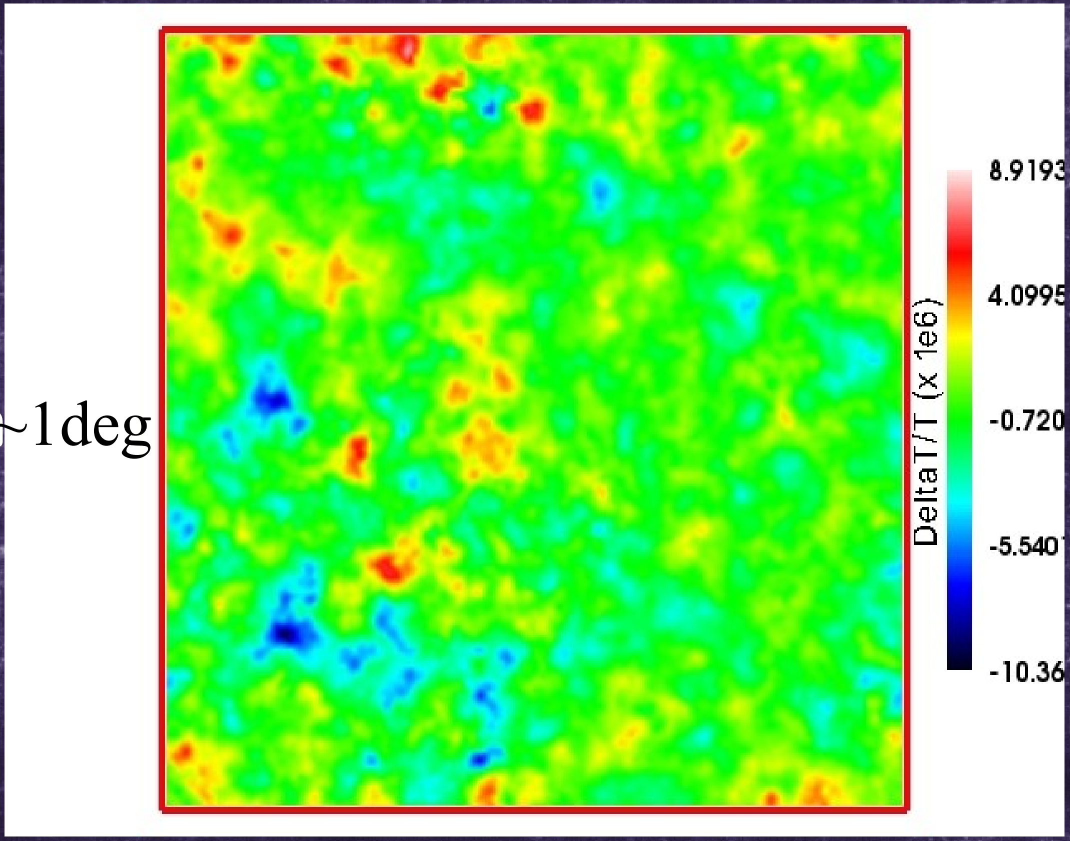
$$\bar{v}_{\rm box}(z) = v_{\rm rms,missing}(-2\ln q)^{1/2}\cos(2\pi\theta)$$

where q and t are uniformly-distributed random numbers between 0 and 1, which guarantees Gaussian-distributed v_{box} with zero mean (Box & Mueller 1958).

Sample kSZ map from patchy reionization

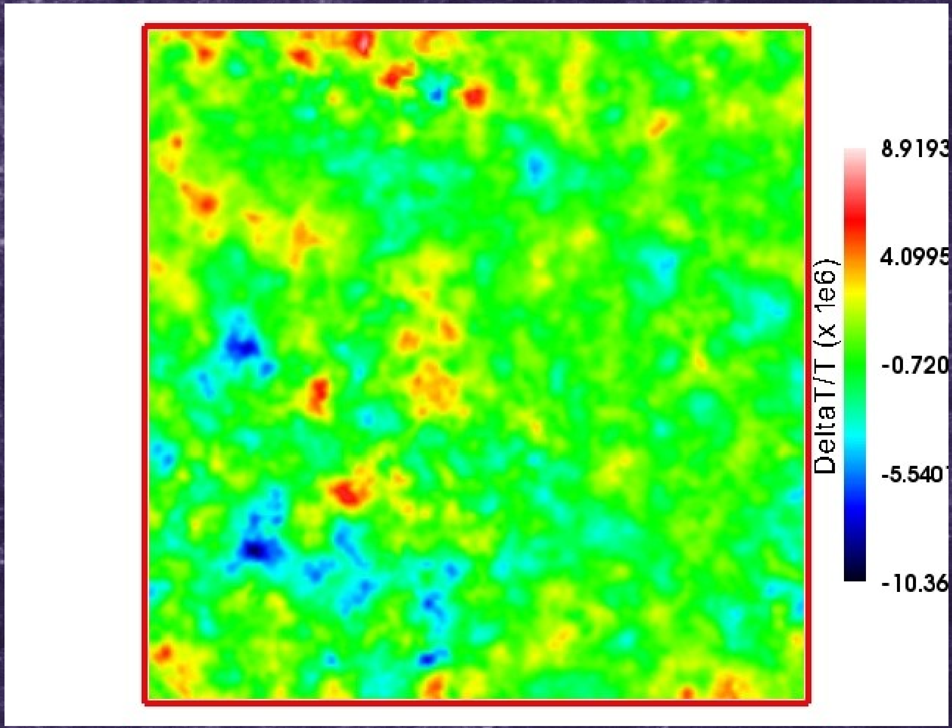
- Sample kSZ map (run f250).
- range of pixel values is $\Delta T/T=-10^{-5}$ to 10^{-5}, i.e. ΔT max/min are in the tens of μK at ~ arcmin scales.

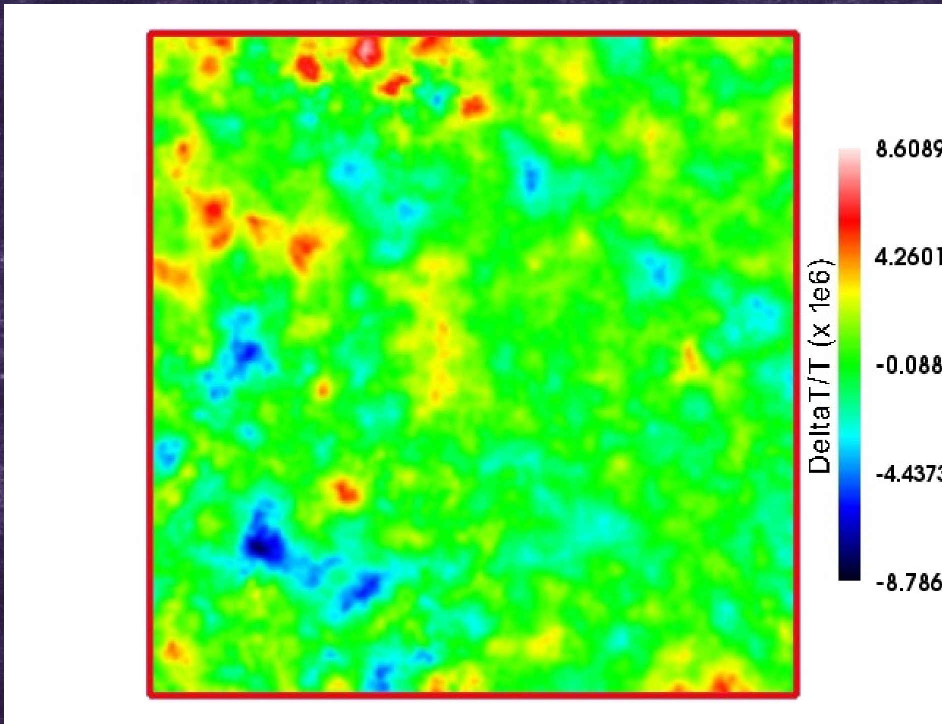
~1deg



~1 deg

kSZ sky maps: early vs. extended reionization

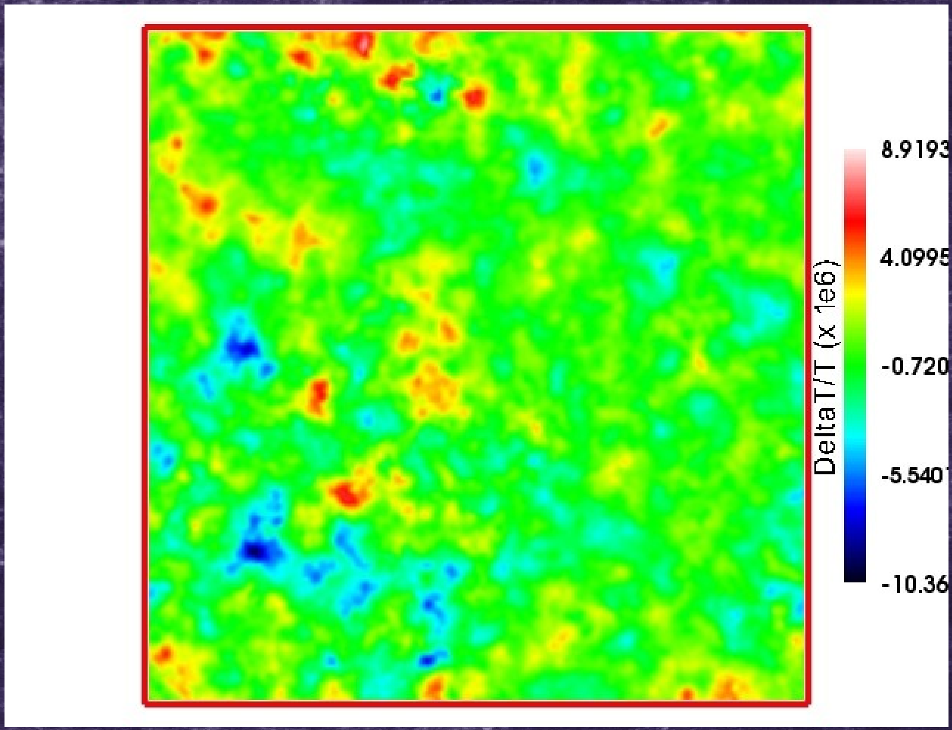


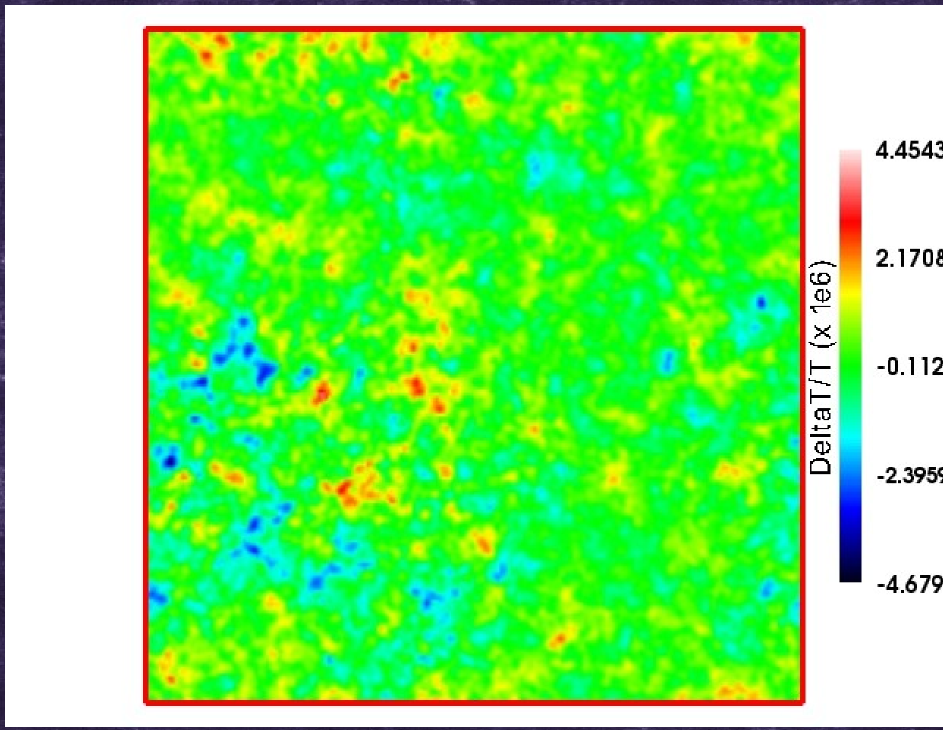


f250

f2000

kSZ sky maps: extended vs. instant reionization

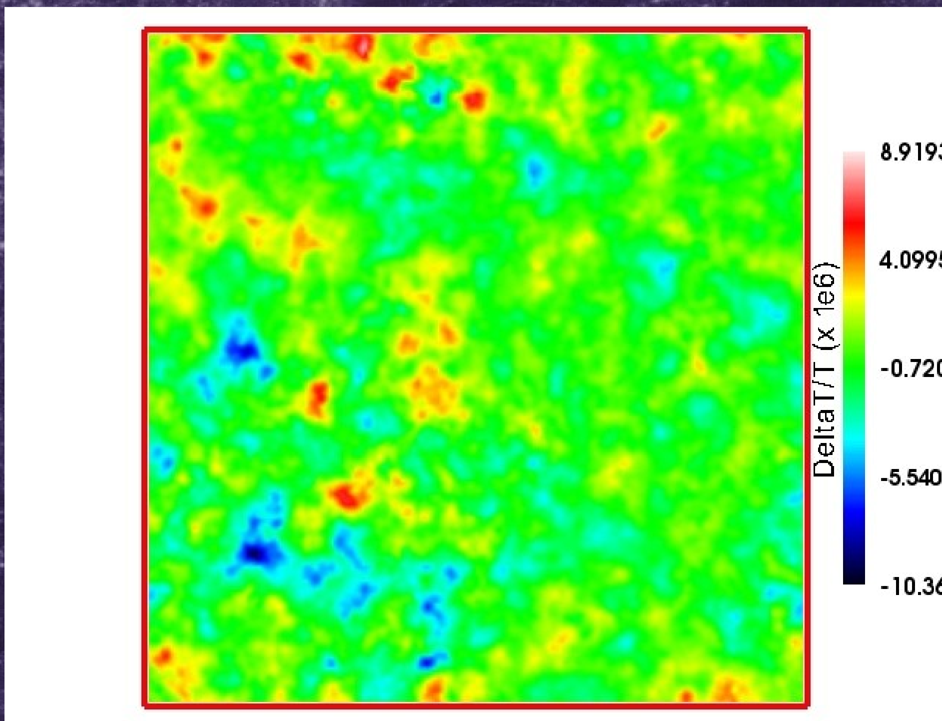


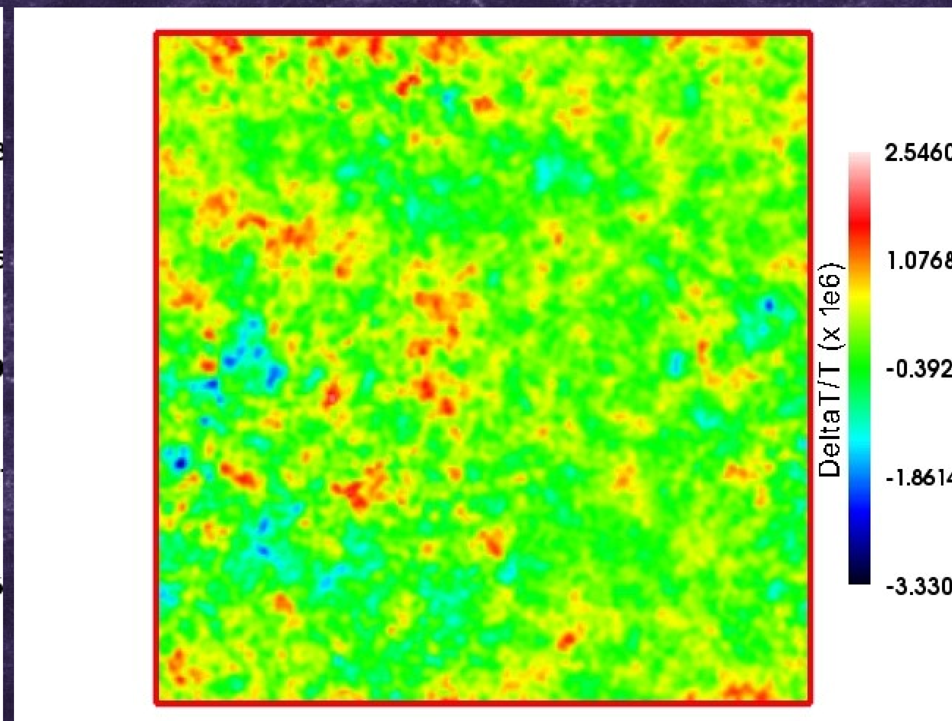


f250

instant reionization, same τ

kSZ sky maps: patchy vs. uniform reionization



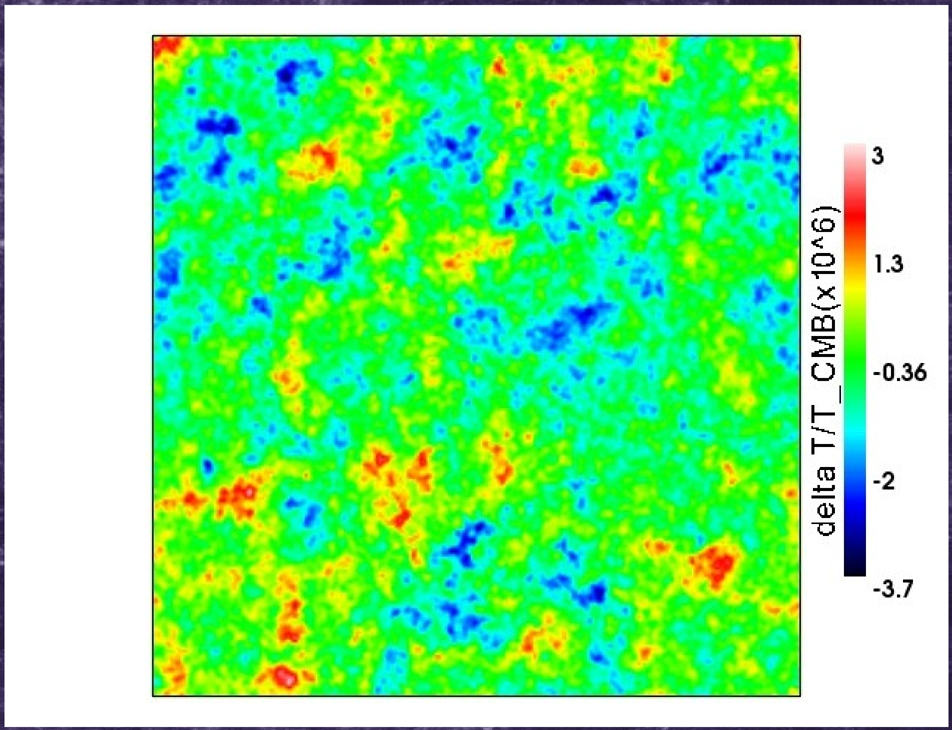


f250

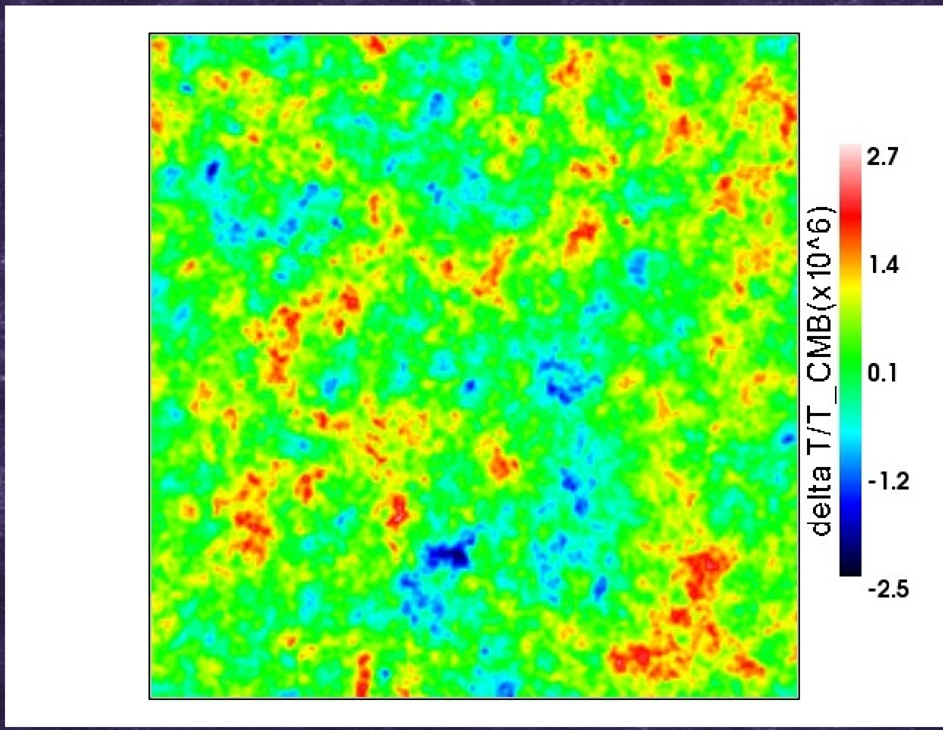
uniform reionization, same x_m (and, thus τ)

kSZ sky maps: self-regulated reionization

(work in progress)



Early reionization scenario

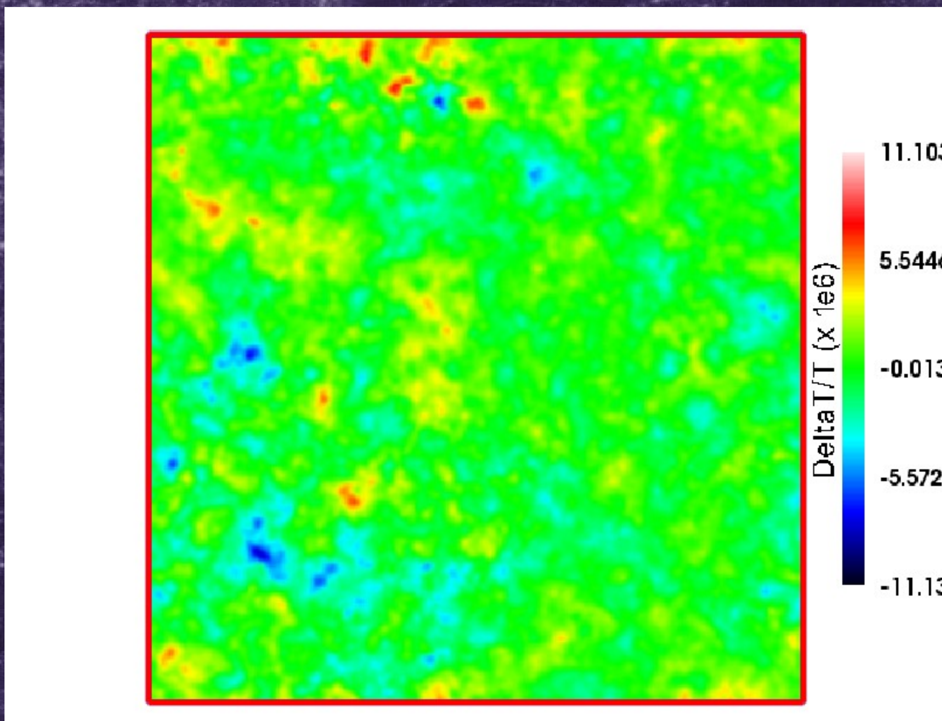


Extended reionization scenario

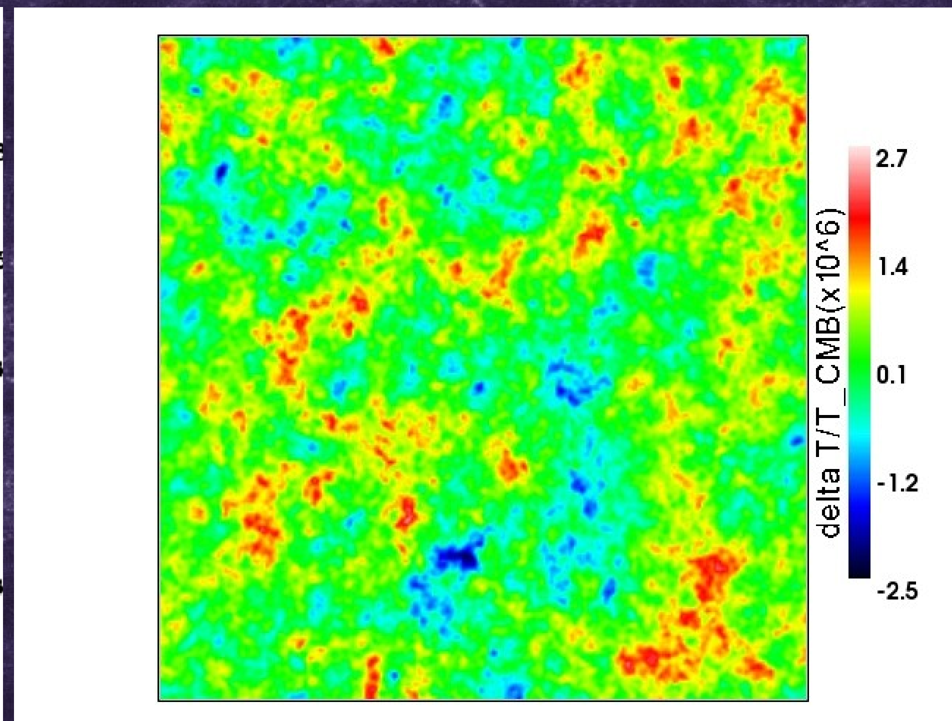
114/h Mpc box, overlap at z~8.3 (early) and z~6.5 (extended), τ=0.08 (early) and τ=0.06 (extended).

kSZ sky maps: self-regulated reionization vs. non-regulated

(work in progress)



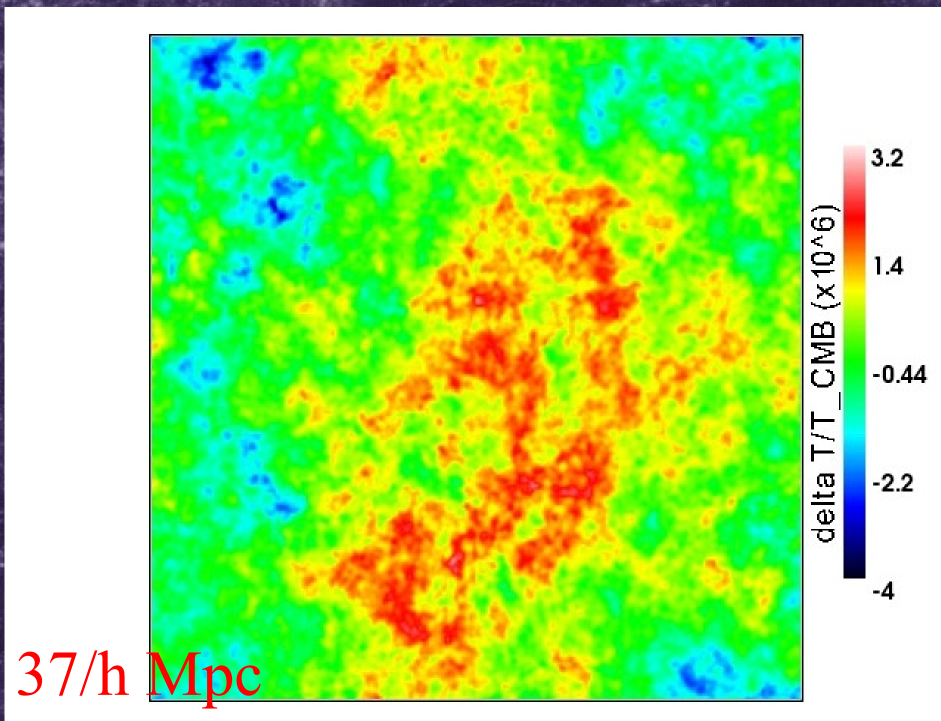
Non-regulated (f250C), 100/h Mpc

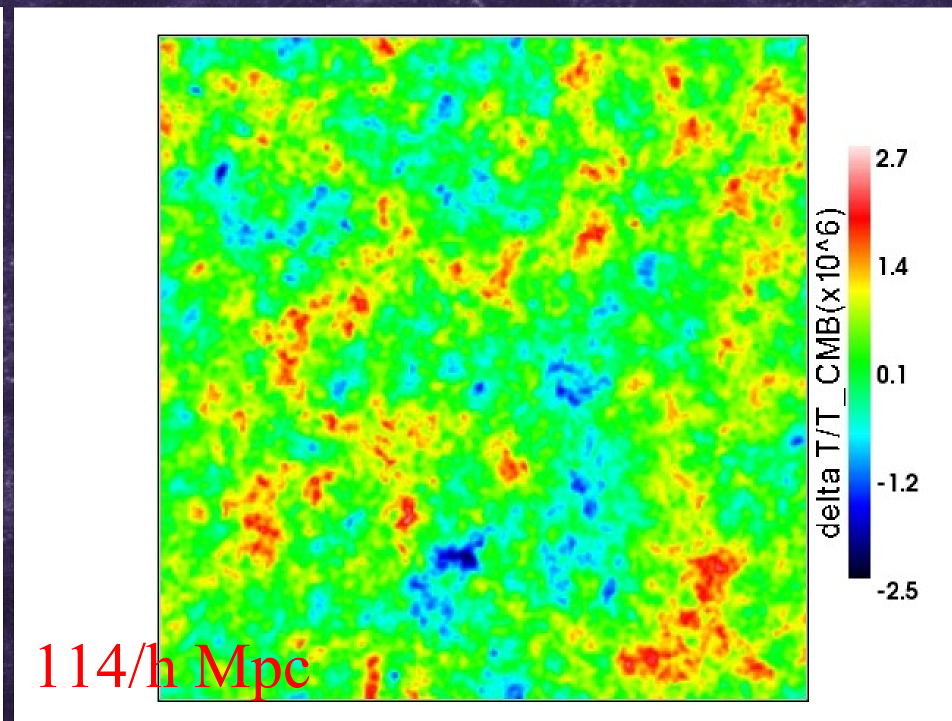


Extended reionization scenario

kSZ sky maps: effect of box size

(work in progress)

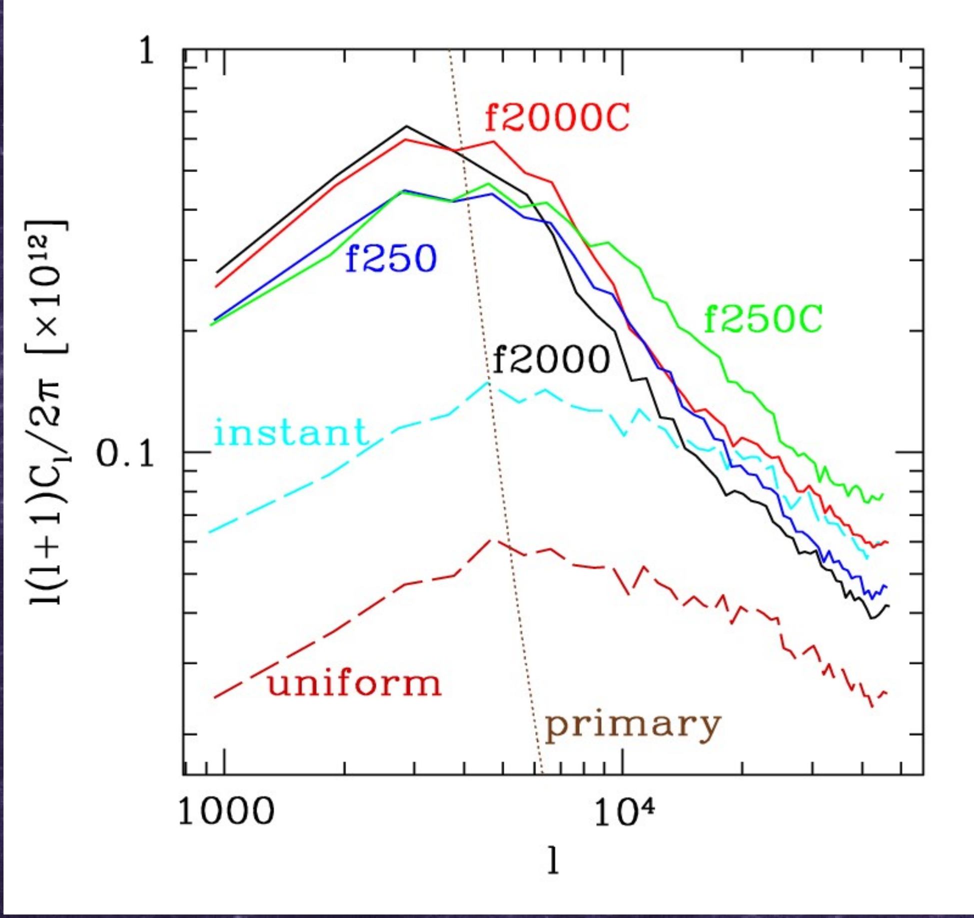




Extended reionization scenario, same reionization history.

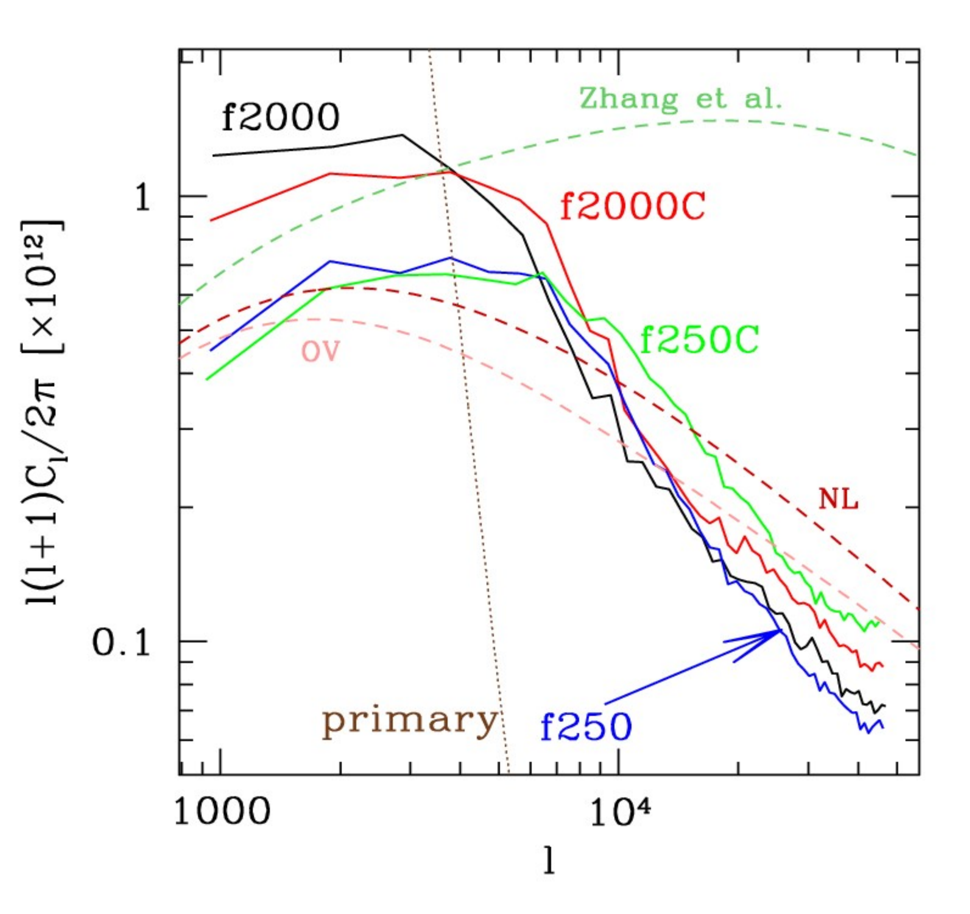
kSZ sky power spectra

- Power spectra peak at l~3000-5000, with a peak value >1 μK
- Early and late reionization scenarios (f2000 and f250) would be difficult to distinguish (some differences for l~3000-20,000)
- Instant reionization (at z~13, same τ as f250) has ~ order of magnitude less power for l~2000-8000, but same large-l behaviour.
- Uniform reionization (same x_m as f250) has much less power on all scales.



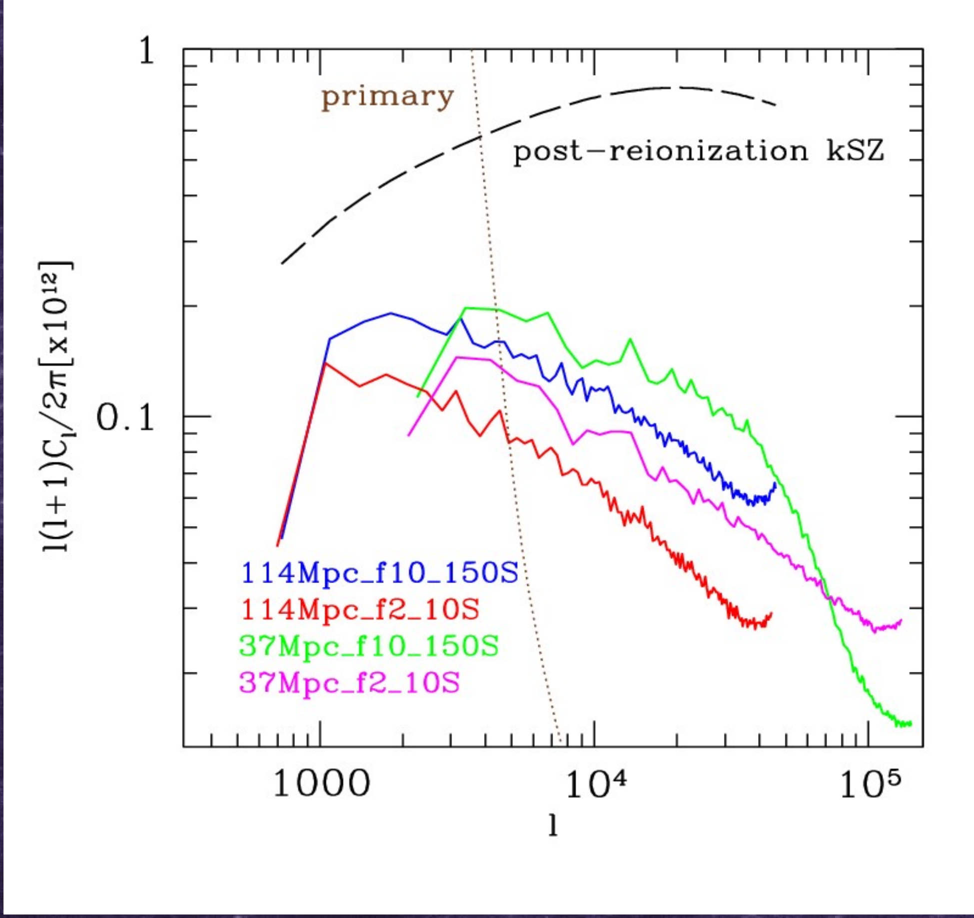
kSZ sky power spectra with large-scale velocity correction

- Power spectra peak at l~3000-5000, with a peak value >1 μK
- Early and late reionization scenarios (f2000 and f250) would be difficult to distinguish (some differences for l~3000-20,000)

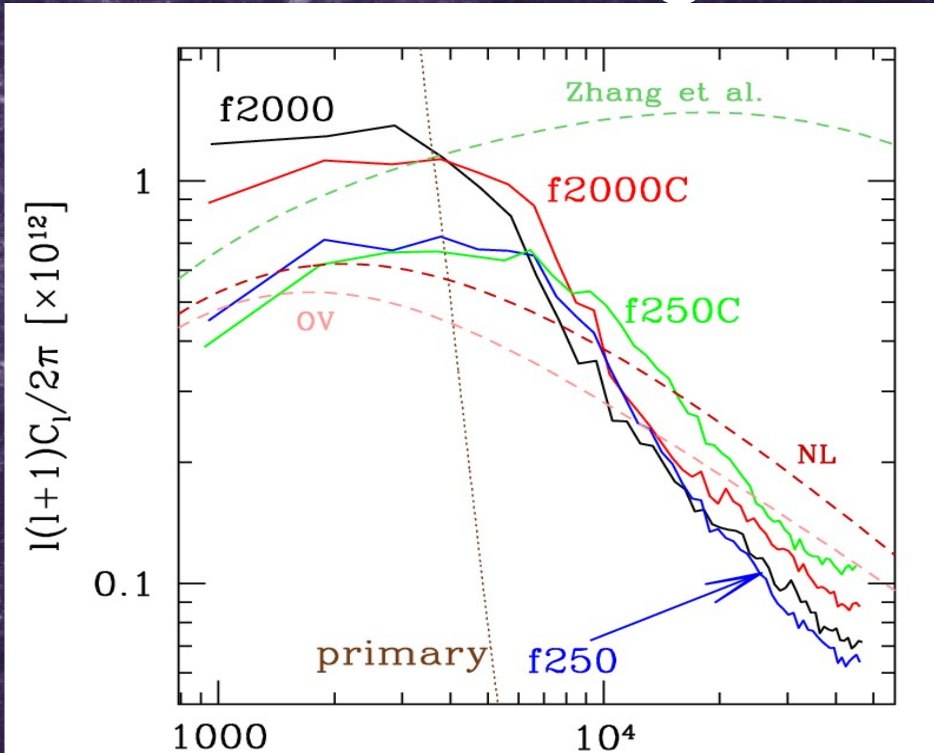


kSZ sky power spectra with self-regulation vs. no regulation

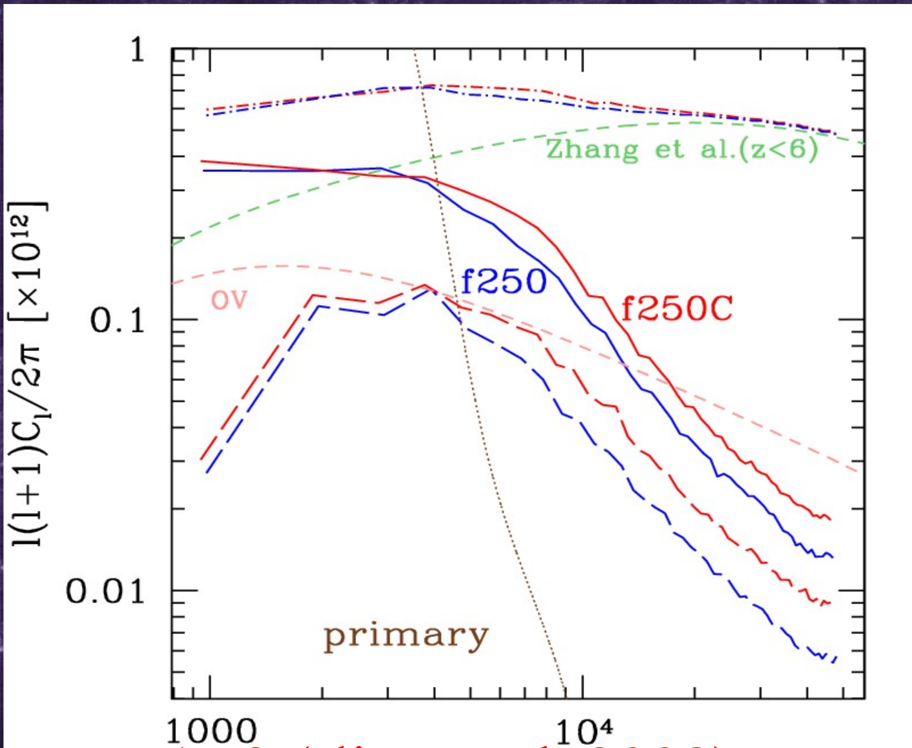
- Power spectra peak at l~3000-5000, with a peak value >1 μK
- Early and late reionization scenarios (f2000 and f250) would be difficult to distinguish (some differences for l~3000-20,000)
-



kSZ sky power spectra: effect of background cosmology



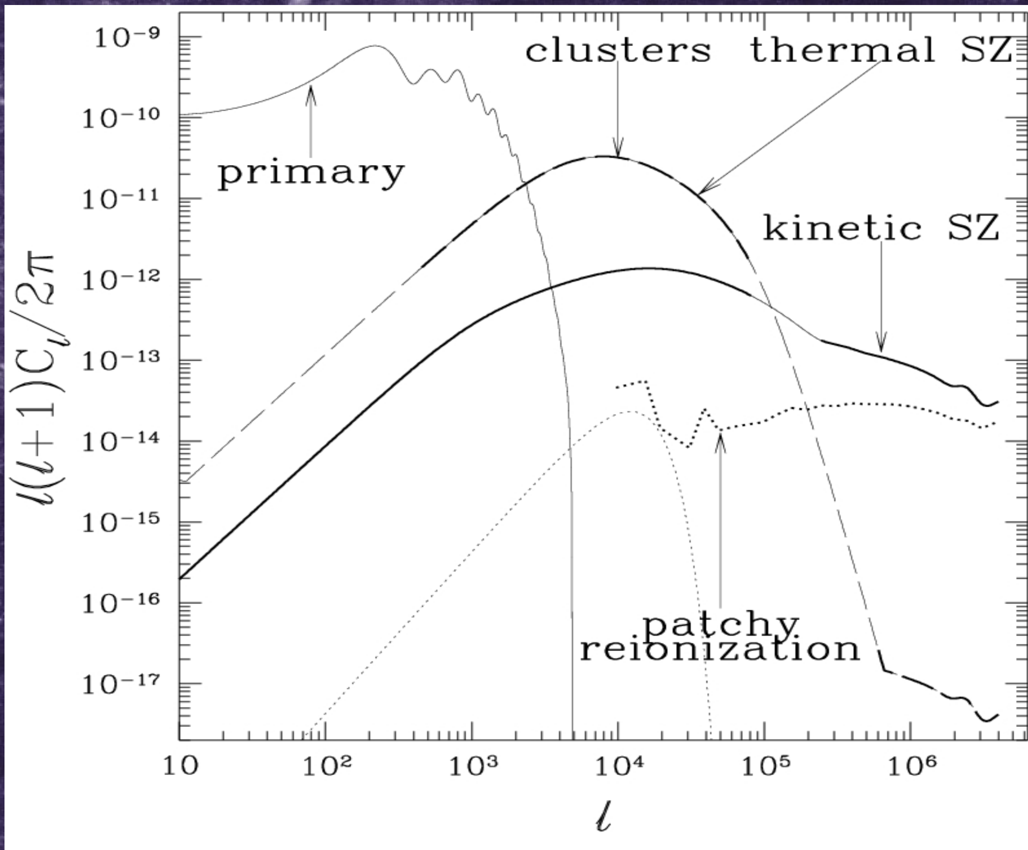
WMAP1 (Iliev et al. 2007)

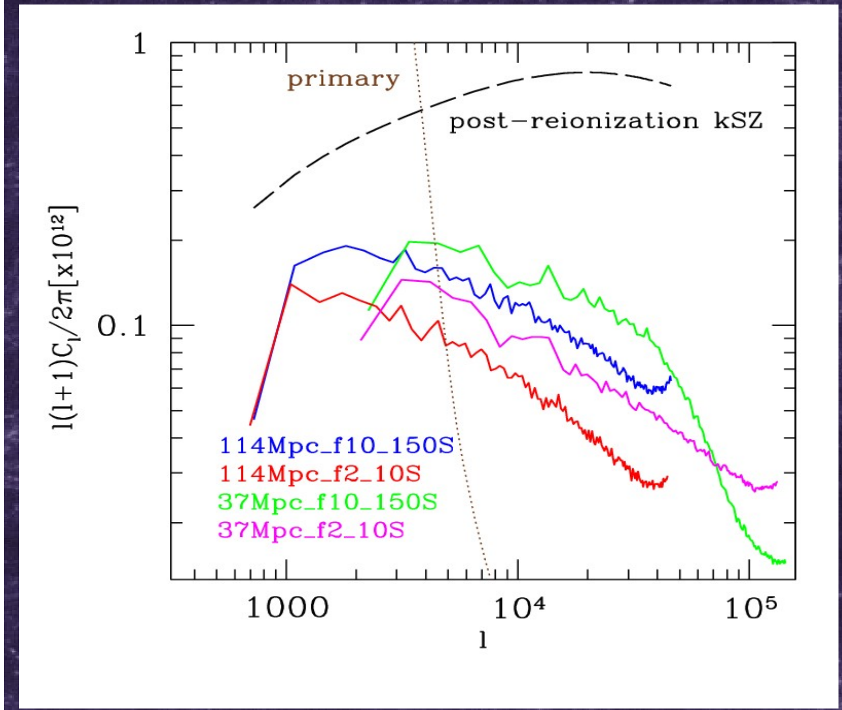


WMAP3 (Iliev et al. 2008)

Low power spectrum normalization/tilt (WMAP3) decrease the patchy signal by factor of ~2 compared to high one (WMAP1). The post-reionization signal scales down as $\sigma_8^5 \sim (0.9/0.74)^5 \sim 2.7$.

kSZ sky power spectra: Gnedin & Jaffe 2001

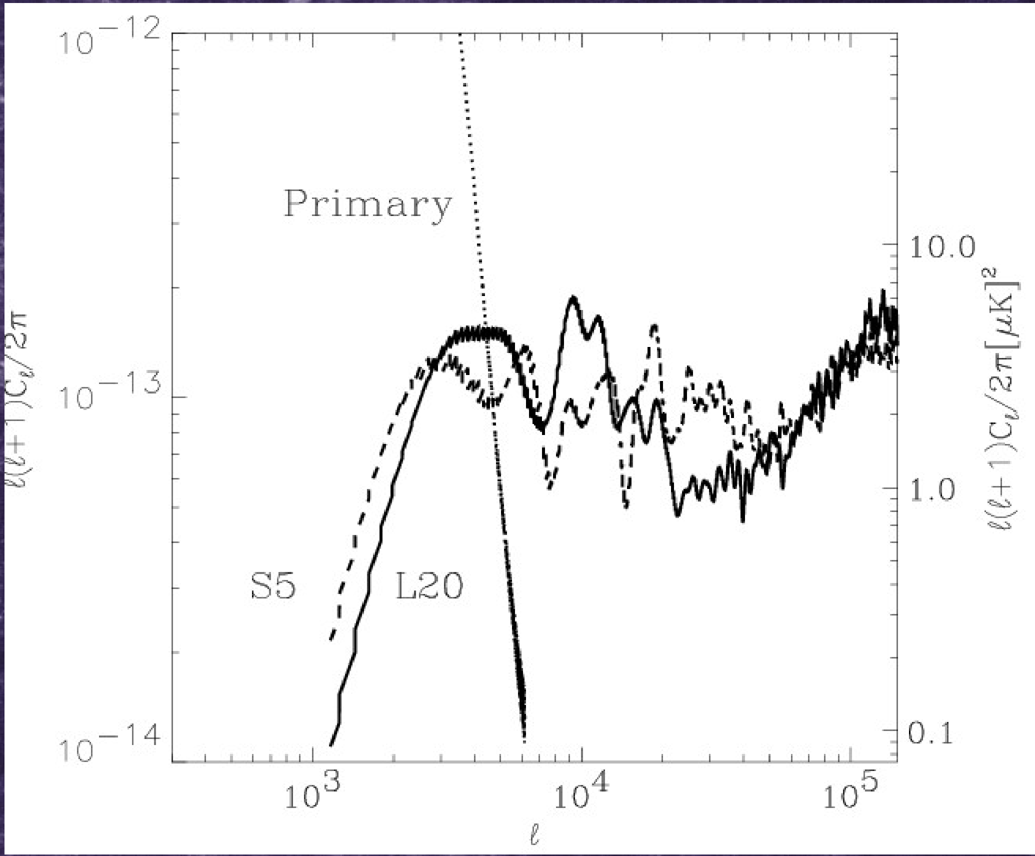


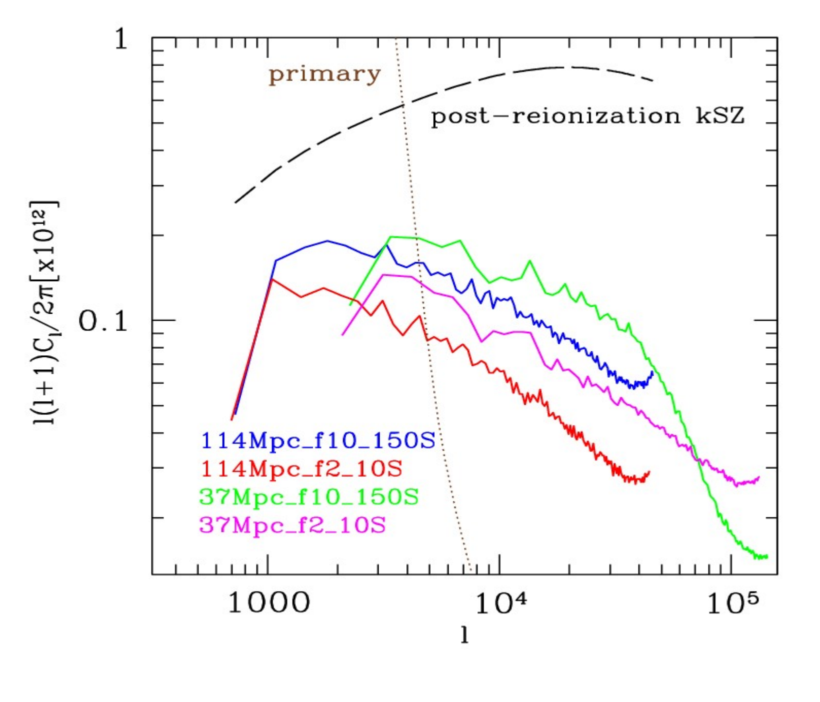


Self-reulated models

Gnedin & Jaffe 01 (first EoR kSZ calculation from simualtions?) found much lower signal due to their small (4 Mpc/h) boxsize — too small to properly reflect EoR patchiness and no correction for missing large-scale velocities.

kSZ sky power spectra: Salvaterra et al. 2005

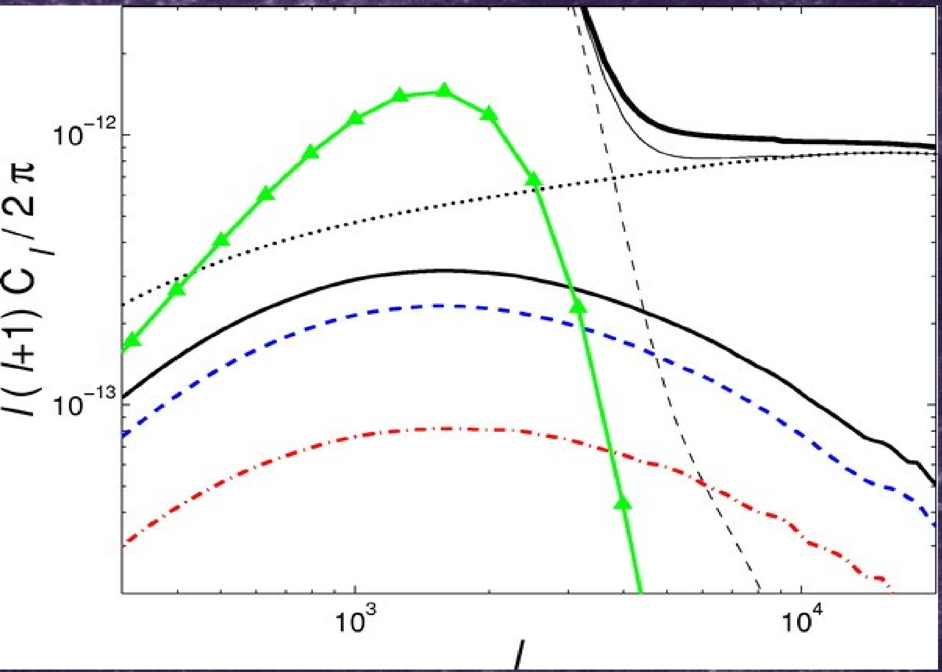


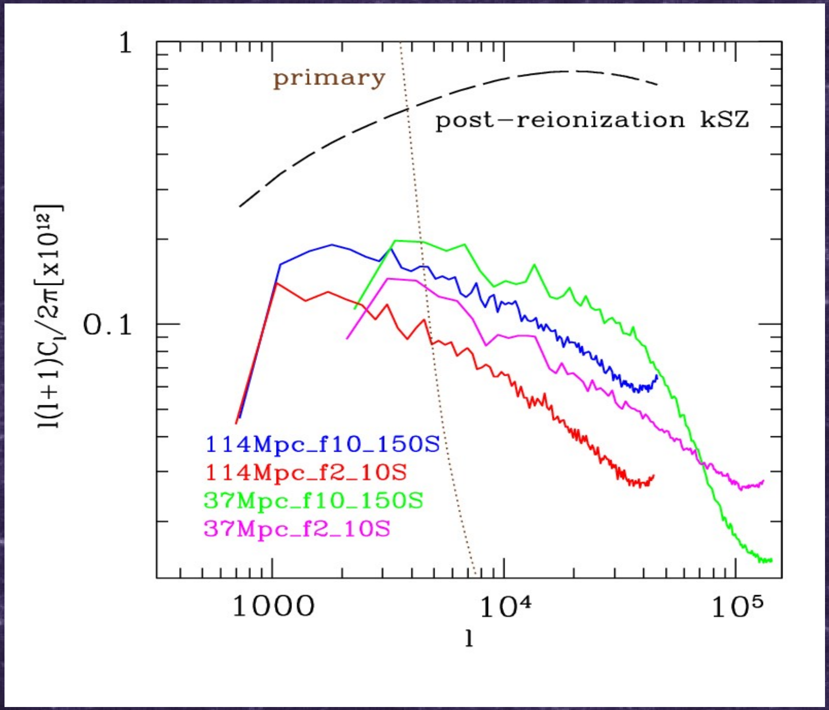


Self-reulated models

Salvaterra 05 (20/h Mpc box) found similar amplitude, but very different shape. Boxsize still somewhat small compared to EoR patchiness scales and different cosmology parameters and missing velocity power again affect the results.

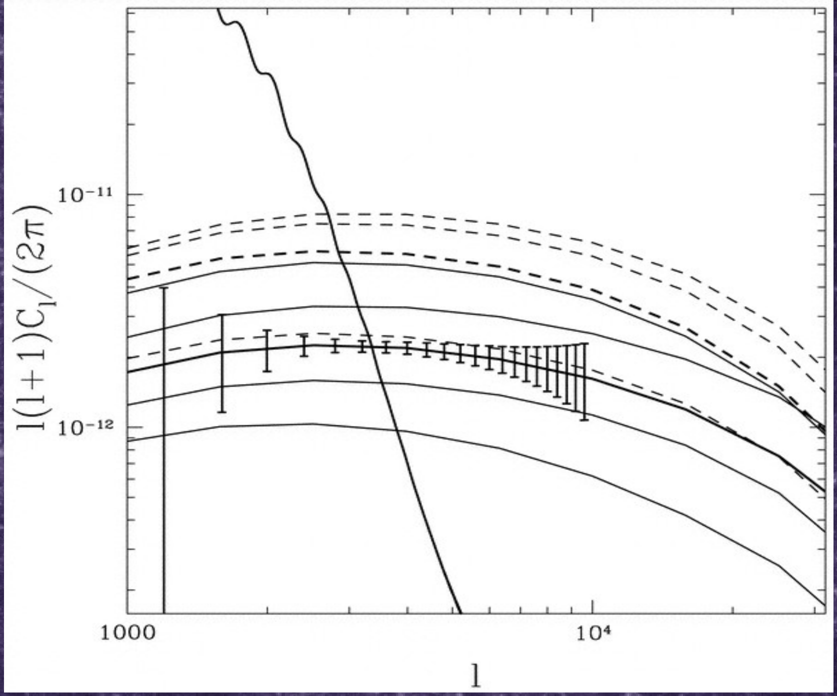
kSZ sky power spectra: comparison with analytical results

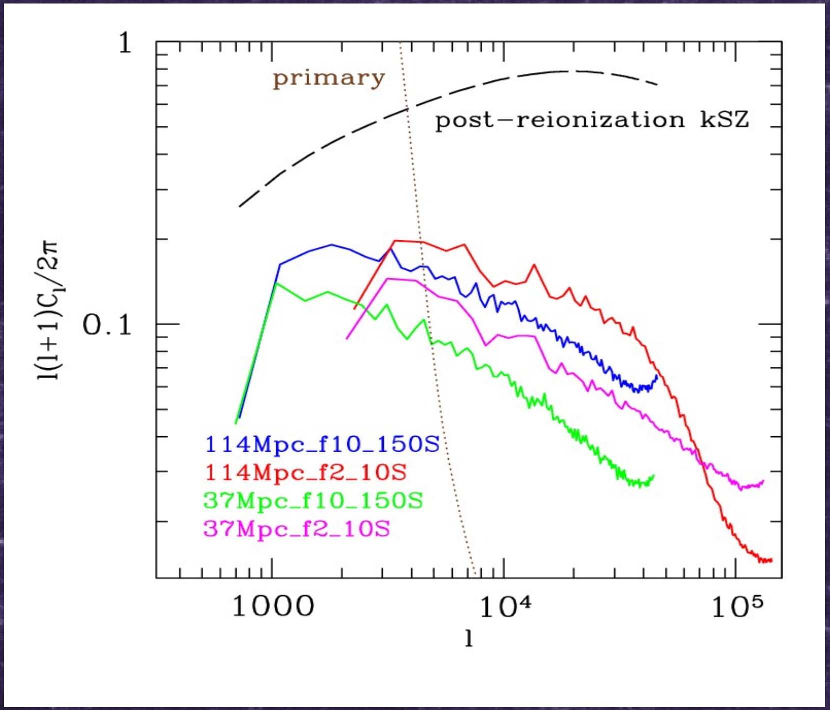




McQuinn et al. and Zahn et al. (black solid; based on Furlanetto et al.'s semi-analytical model) find a signal that is similar in both magnitude and shape. Simple model of Hu and Gruzinov 98 (green) has a somewhat similar shape to signal from Iliev et al 07, but peaks at significantly larger scales and drops steeply at large l's.

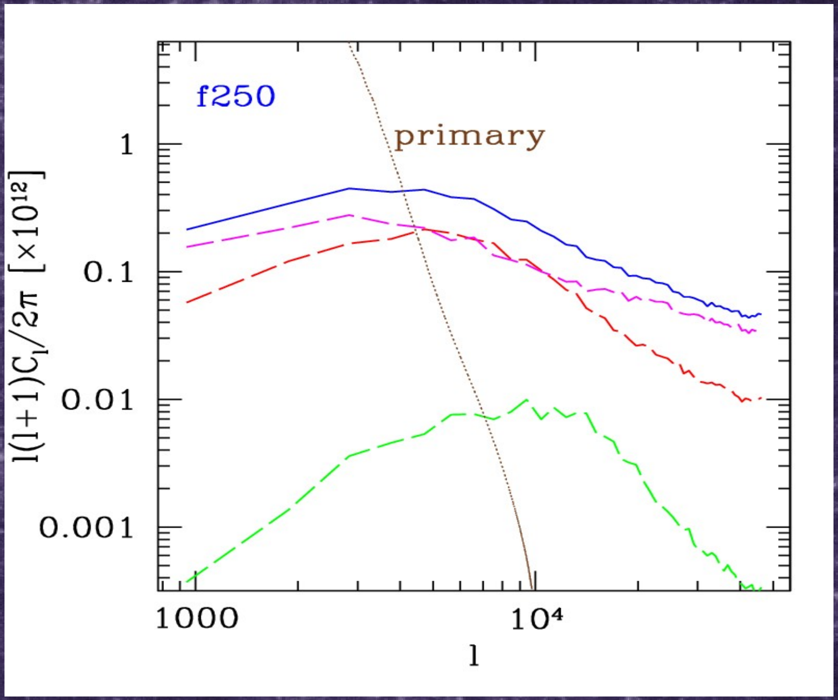
kSZ sky power spectra: comparison with analytical results II



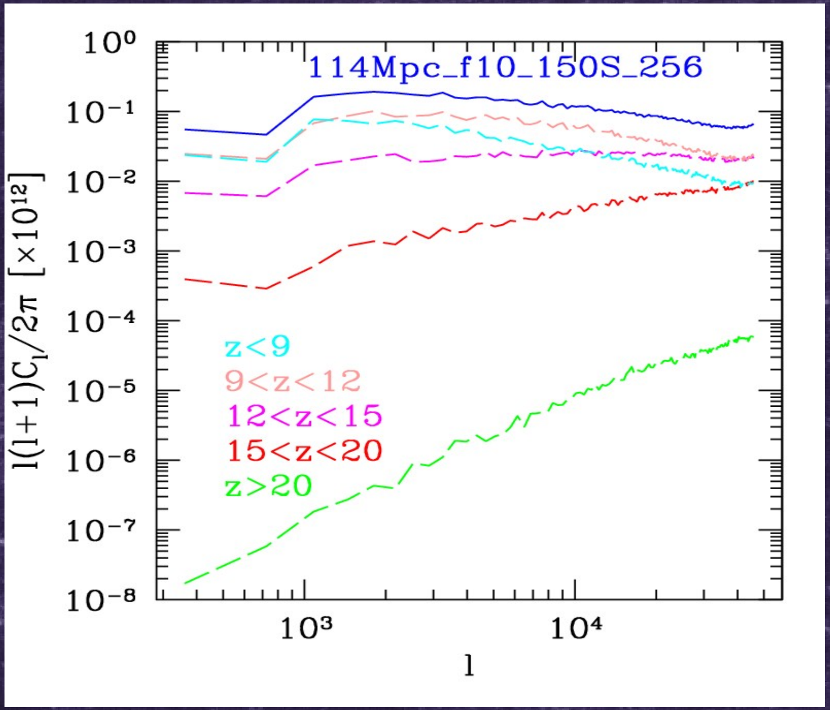


Santos et al. (solid, left) find a signal with flatter shape, and higher amplitude due to their different underlying assumptions and background cosmology.

kSZ sky power spectra: contributions by epoch



Not self-regulated



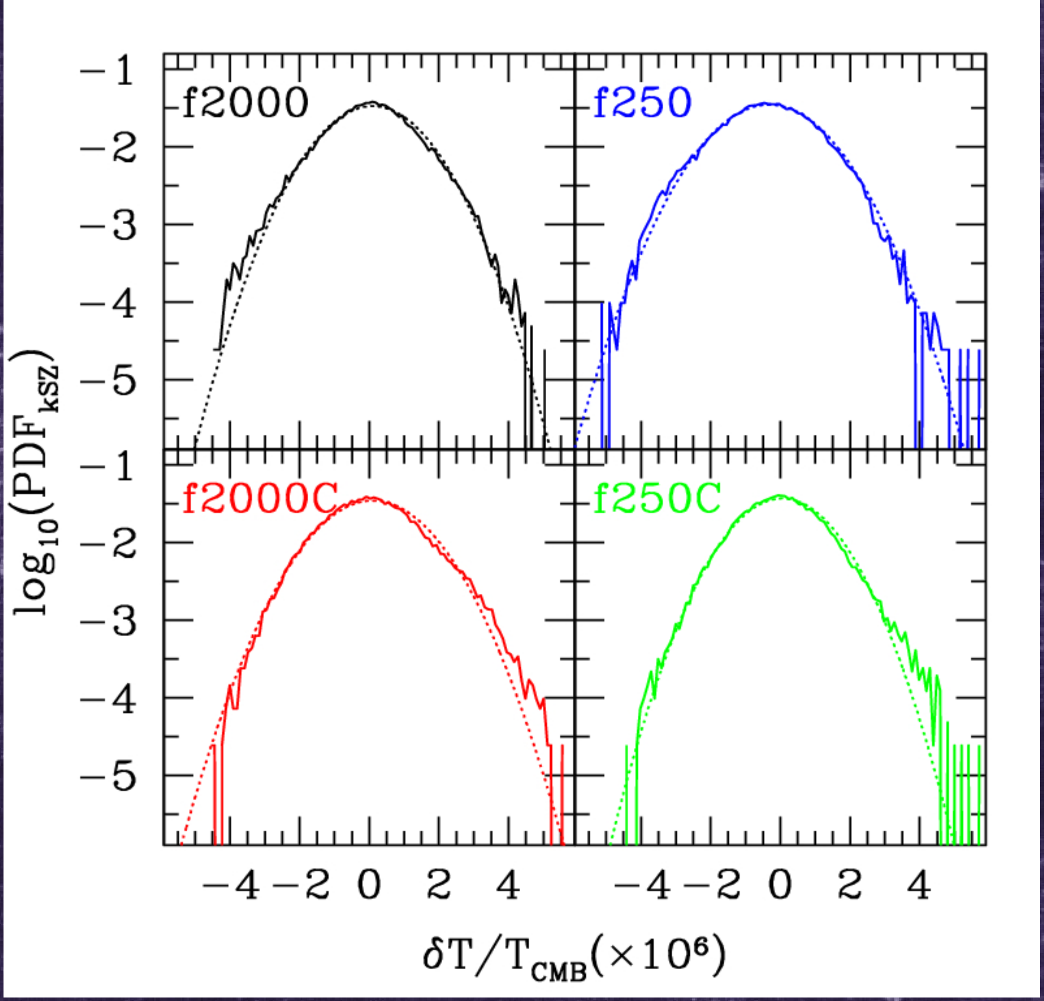
Self-regulated

kSZ non-Gaussianity?

- Not really! Maps are highly Gaussian

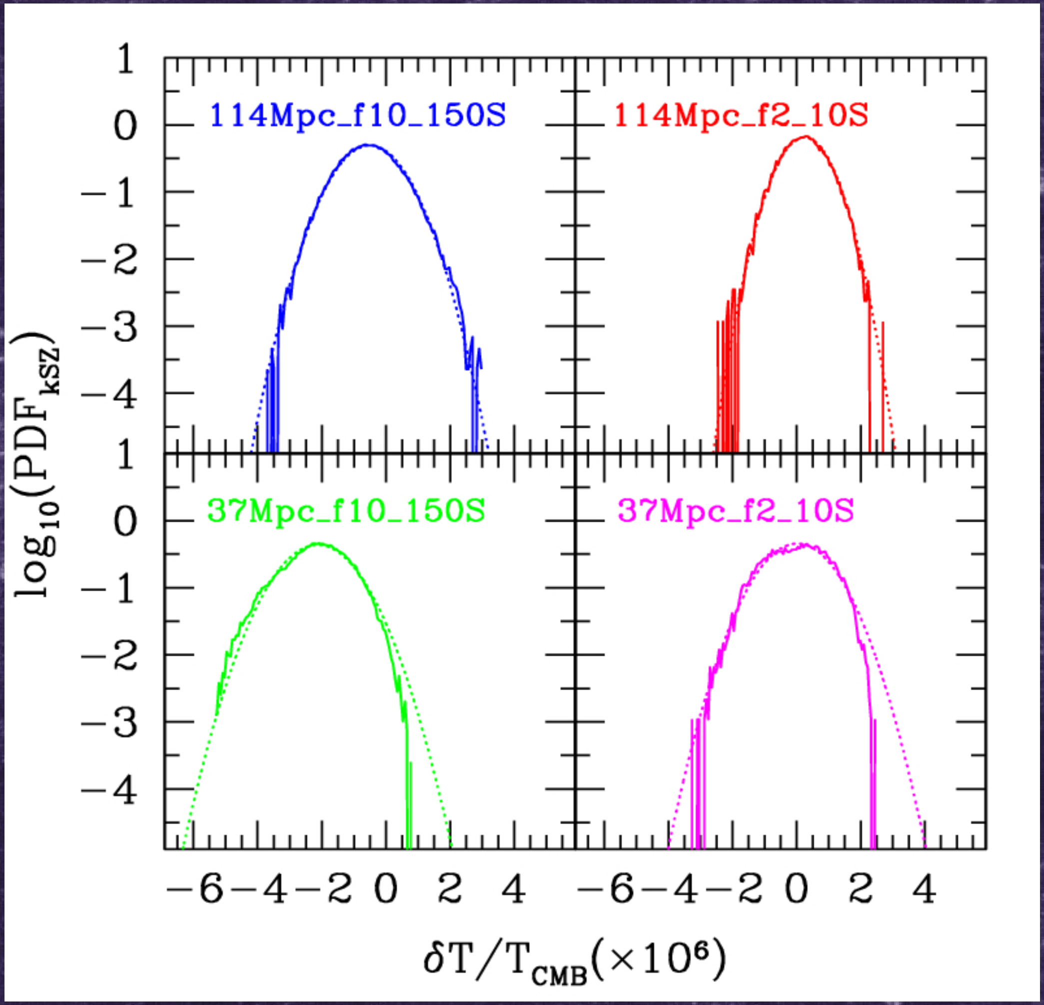
solid: f250 simulation

dotted: Gaussian with same mean and rms



KSZ PDFs: self-regulated models

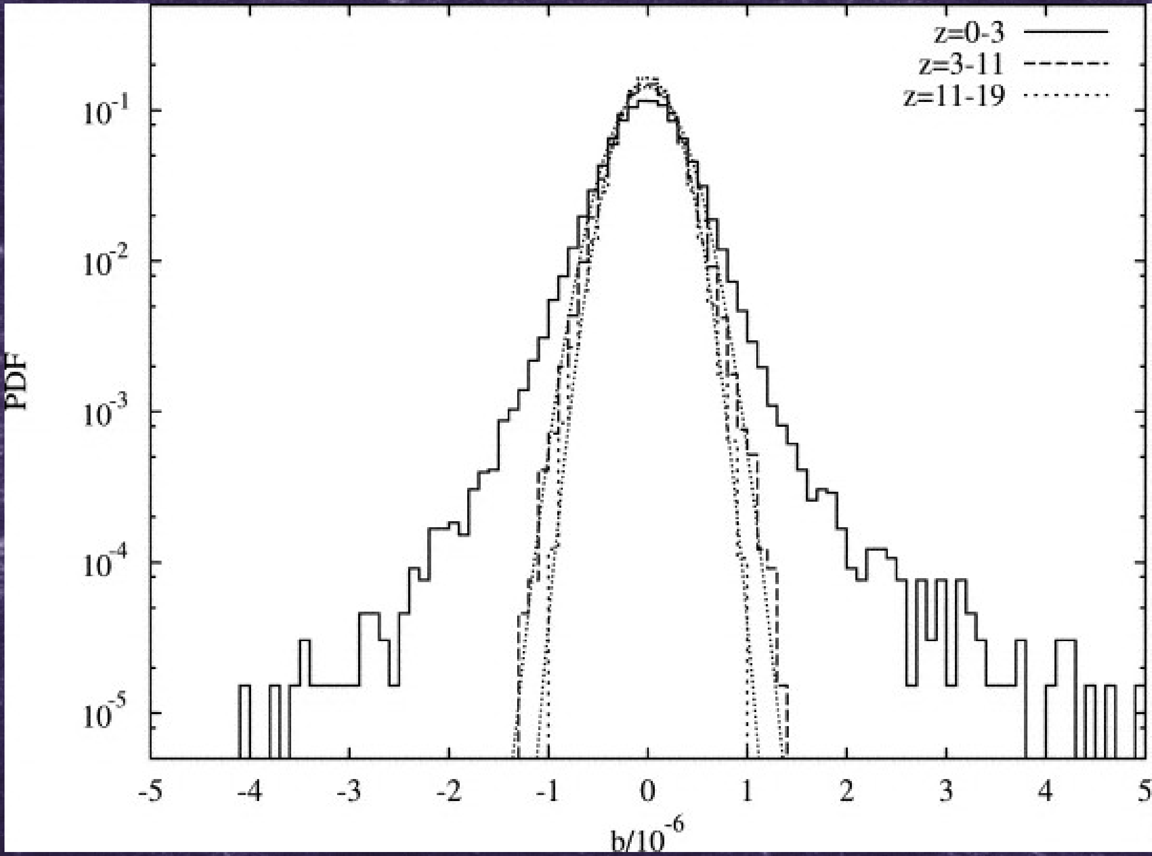
Maps are still largely Gaussian, with some departures at wings. Extended reionization scenarios yield somewhat less wide PDFs.



Non-Gaussianity: analytical

Semi-analytical models yield even more Gaussian PDFs,

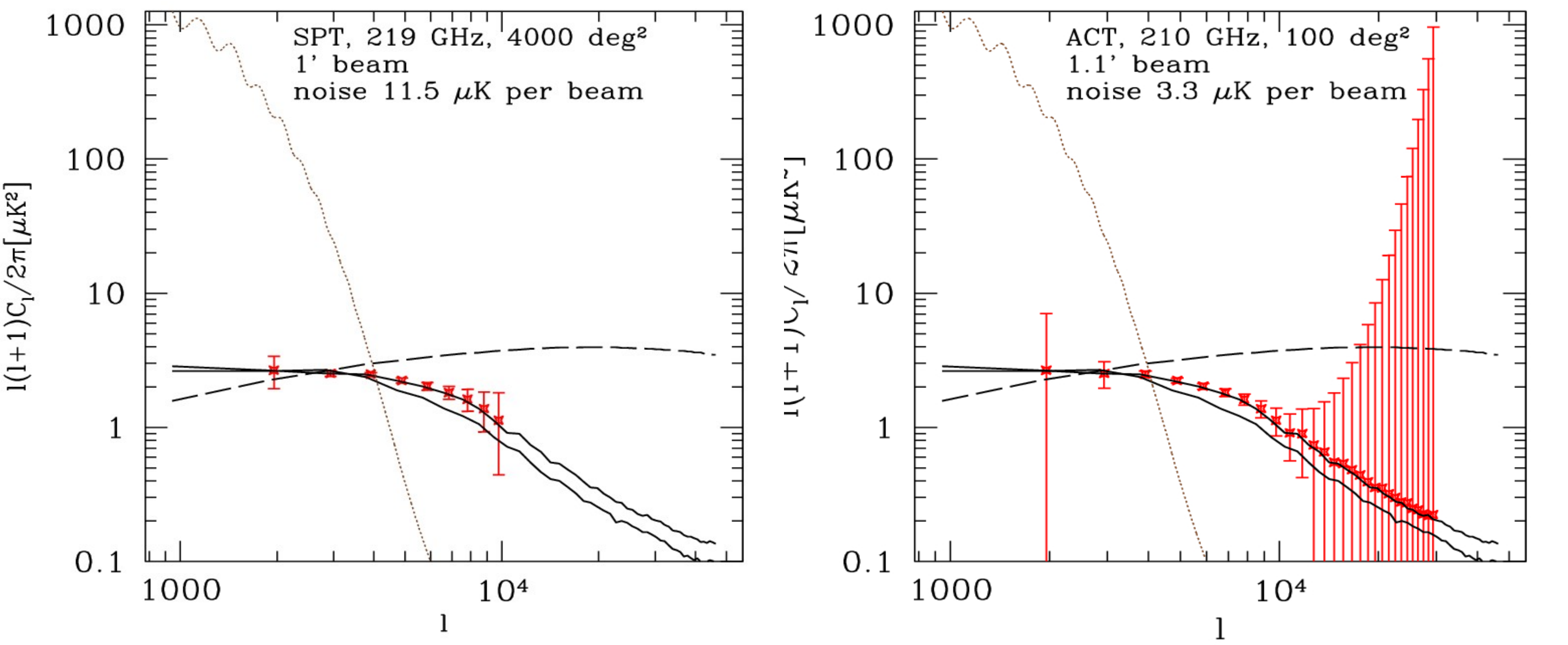
Which develop non-Gauissian tails only at very late times, well after overlap.



Zahn et al. 2005

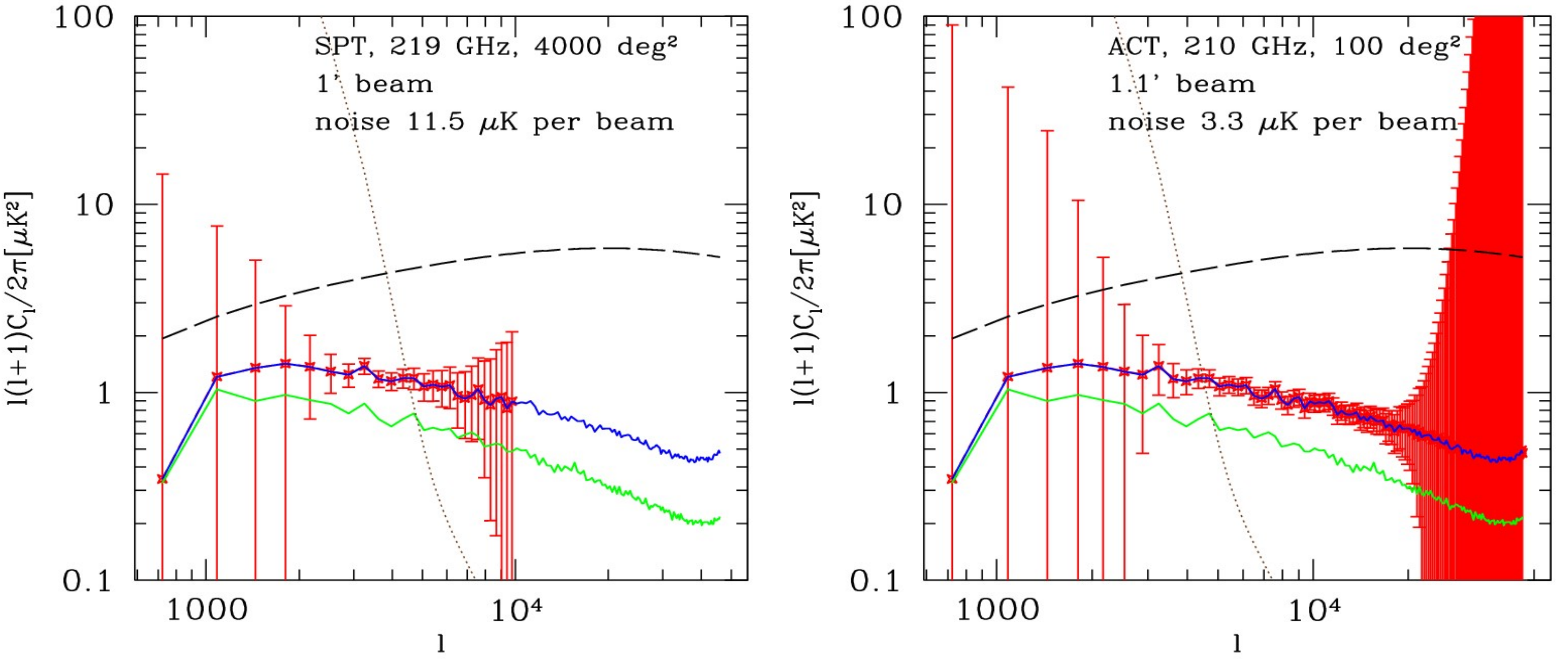
Detectability of kSZ

(Iliev, Mellema, Pen, Bond, Shapiro, 2008, MNRAS, 384, 863)



Sky power spectra of patchy EoR kSZ vs. expected noise levels of SPT and ACT. Includes noise from primary CMB and post-EoR kSZ (shown). tSZ is assumed subtracted.

Detectability of kSZ: self-regulated
(work in progress)

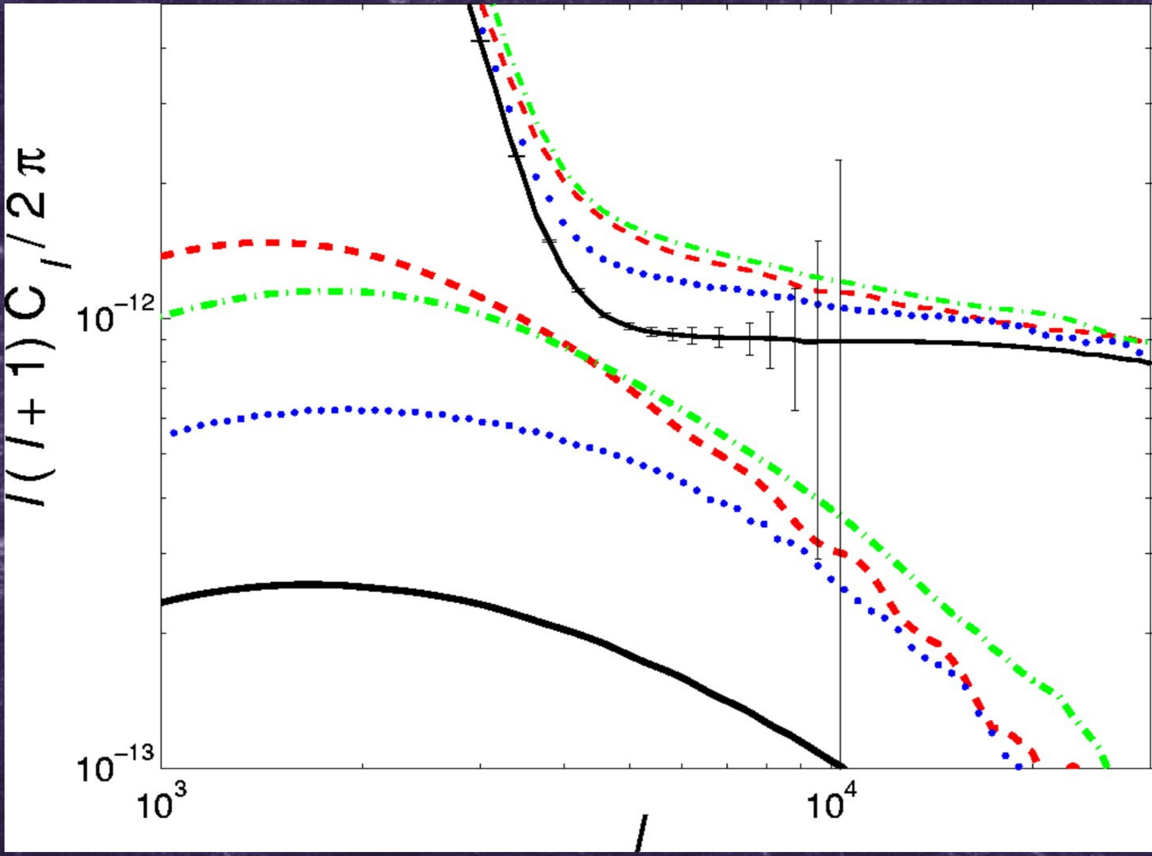


Sky power spectra of patchy EoR kSZ with expected noise levels of SPT and ACT. Includes noise from primary CMB and post-EoR kSZ (shown). tSZ is assumed subtracted. Early and extended scenarios are clearly distinguishable for l>5000.

Observability: analytical

Semi-analytical models yield similar best range for observations l~5000-10,000.

(shown are extended reionization scenarios, ACT error bars)



McQuinn et al. 2005

Conclusions

- We now can do sufficiently large (100/h Mpc size or more) radiative transfer simulations of reionization to reliably derive the kSZ effect due to ionized patches.
- The derived sky power spectra peak strongly to > 10 $(\mu K)^2$ at l~few thousand (dependent on details of reionization). The corresponding maps are quite Gaussian. Large-scale bulk velocities are important.
- The patchy signal is much stronger than the signals from either instant reionization or uniform one.
- Realistic reionization scenarios could be distinguished from each other based on the kSZ signal, but only if tSZ and post-EoR signals are separated to a high precision.
- Semi-analytical results roughly agree with the simulations, but differ in many details.