Expected Science from 21 cm Experiments

i. Ionization history
ii. Cosmology: Density field, ionization frac. Redshift distort, power spectrum
iii. High order statistics
iv. Mapping massive BH environment
v. First sources
vi. Cross correlation with other probes
vii. Dark ages and history of spin temperature.
viii. The future.

EoR & Dark Ages: Key Science Questions

- Global Evolution of the EoR. How did reionization proceed?
- What are the first sources?
  - → Stars: How did they form?
  - → The role of H_2 & HI cooling.
  - → Pop.II vs Pop III
  - → BH + mini-QSOs
  - → DM decay or annihilation.
- Topology of the IGM during the EoR.
- When reionization became complete?
- Individual Halos.

- Typical size of ionized regions as a function of redshift.
- Thermal history of the IGM
- Influence of the EoR on subsequent structure formation and evolution
- Do we know that reionization is photon starved? Is this a strong constraint of reionization?
- Cosmology:

PS, high-order statistics, cosmological PS, primordial non-Gaussianity, constrain DM candidates, Alcock Paczynski test, ...

Primary Science Goals of 1st generation experiments (e.g., LOFAR)

- Statistical detection of the global reionization history of the Universe as a function of redshift (rms as a function of z).
- The power spectrum of the underlying density fluctuations during the reionization.
- Measure higher order statistics of the EoR signal.
- Cross-correlating the EoR signal with other astrophysical observations.
- The 21 cm forest along the line of sight of very luminous high redshift radio sources.
- The study of individual ionization bubbles around very high redshift supermassive black holes or around clustered first stars.

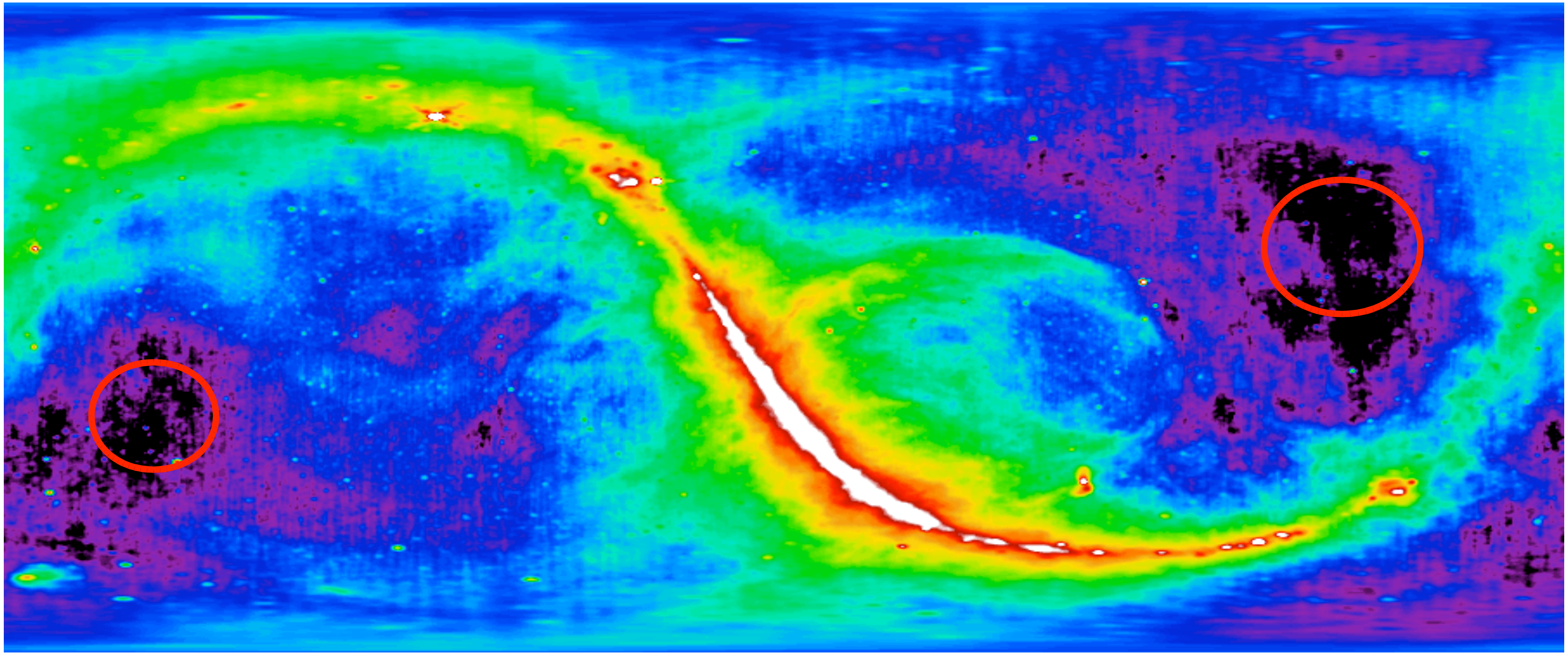
Please remember radio interferometers can't measure mean quantities but rather only variations on scales within the instruments field of view!

(Yesterday's question about CMB temp. and the 21 cm)

Extraction

$$T_{sys} = T_{sky} + T_{Receiver}$$

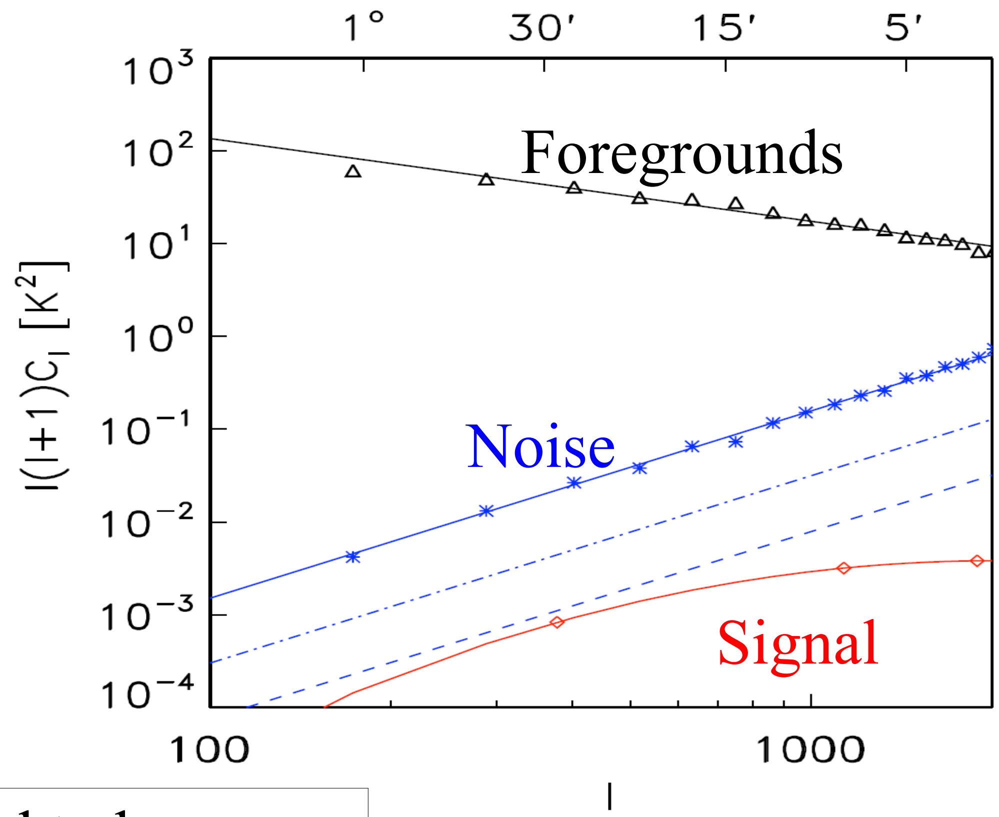
At 150 MHz $T_{sky} \sim 200K$



Radio sky at 408 MHz continuum

Haslam et al, 1982

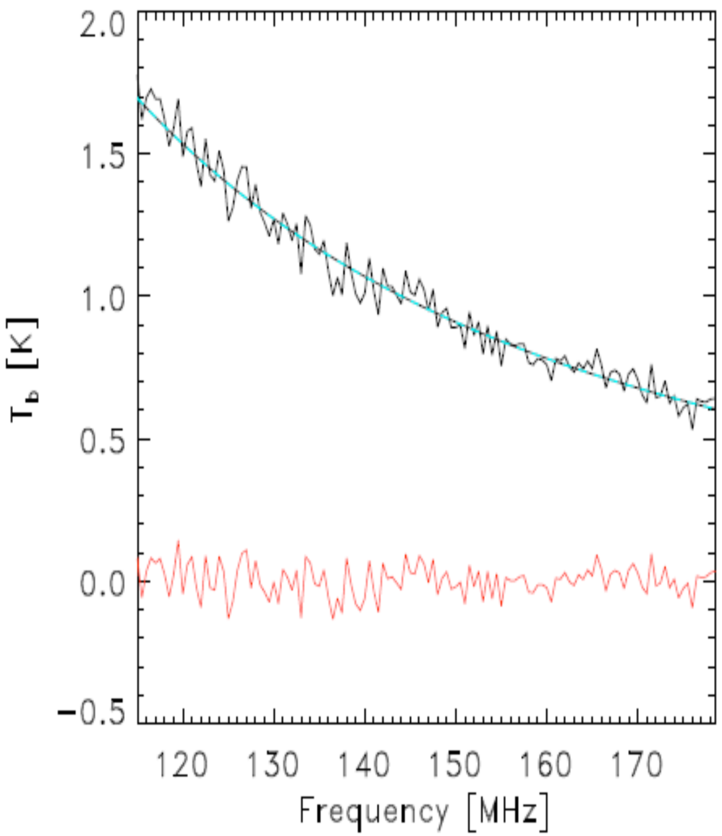
Angular power spectra of various contributions

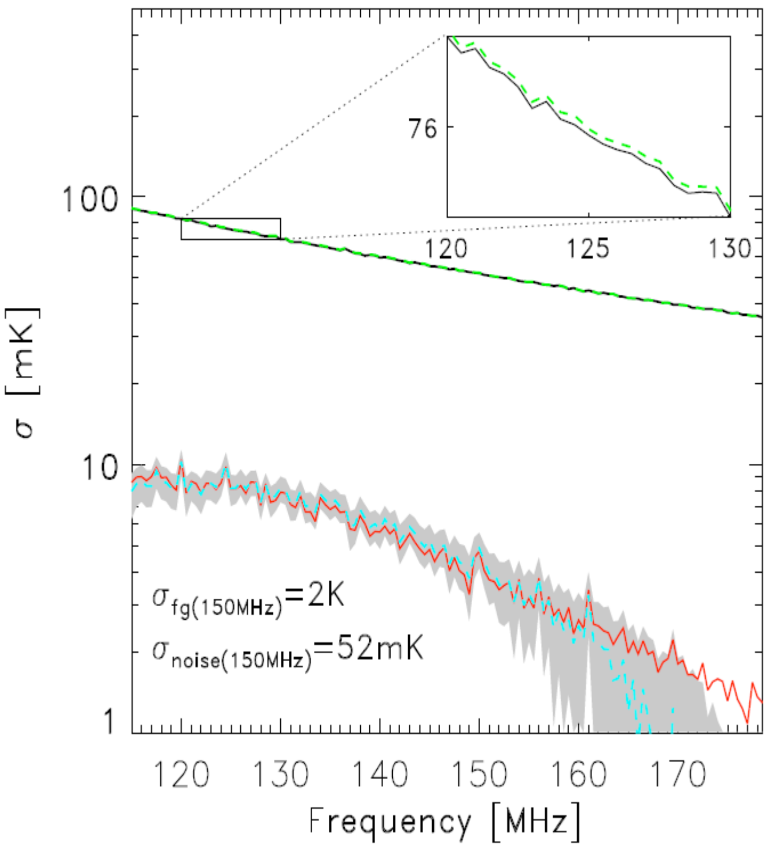


Fitting is expected to be worse at large scales (small *l*)

Santos et al.2006
Jelic at el. 2009

Extraction with Polynomials





Jelic et al. 2009

Wish list for a foreground fitting algorithm

- Algorithm should be accurate to better than 1/1000 per 1MHz.
- Should be Unbiased.
- Avoid under-fitting or over-fitting.
- Make minimal assumptions about the functional form of the foregrounds; i.e., exploit their smoothness directly.
- Robust against "systematic effects"
- Speed (less important since fitting is done once)

Statistical approach for FG fitting

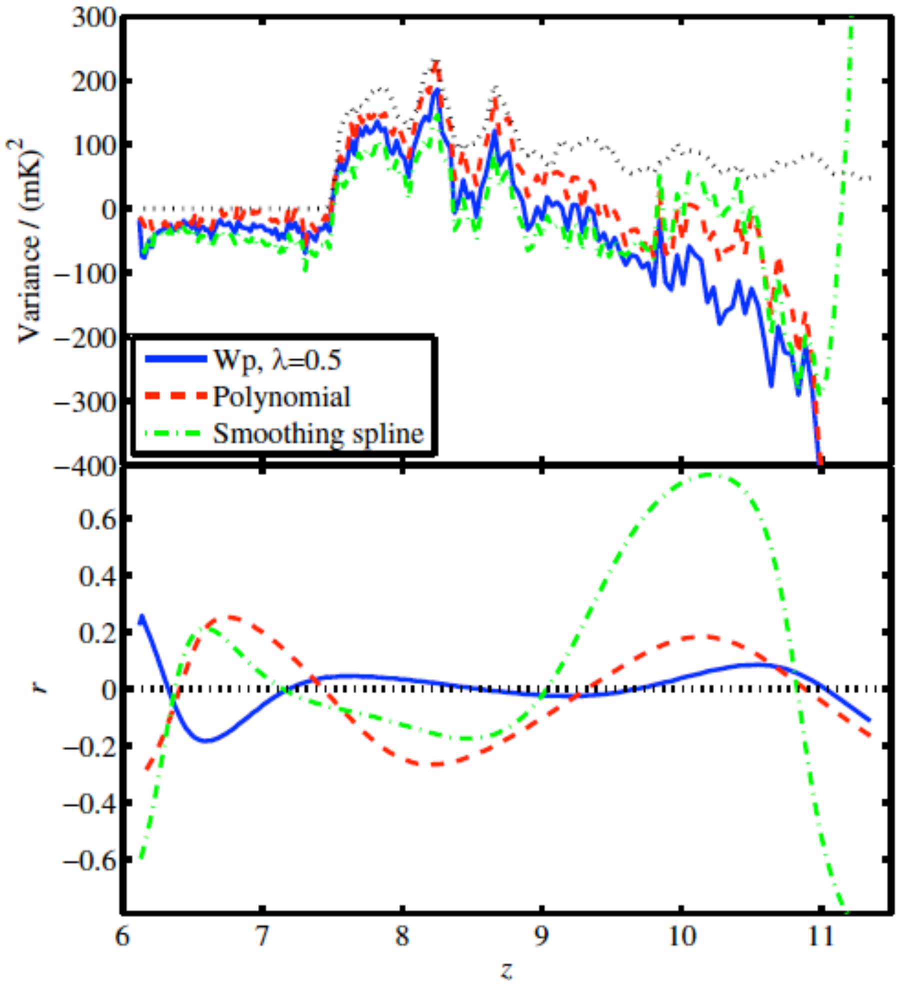
- Model data points (x_i ,y_i) by:

$$y_i = f(x_i) + \varepsilon_i, \; i = 1, \ldots, n$$

- Then we wish to solve the following problem:

$$\min_f \left\{ \underbrace{\sum_{i=1}^{n} \rho_i(y_i - f(x_i))}_{\text{"Least squares"}} + \underbrace{\lambda R[f]}_{\text{Roughness penalty}} \right\}$$

Cross-correlation of residuals with foregrounds

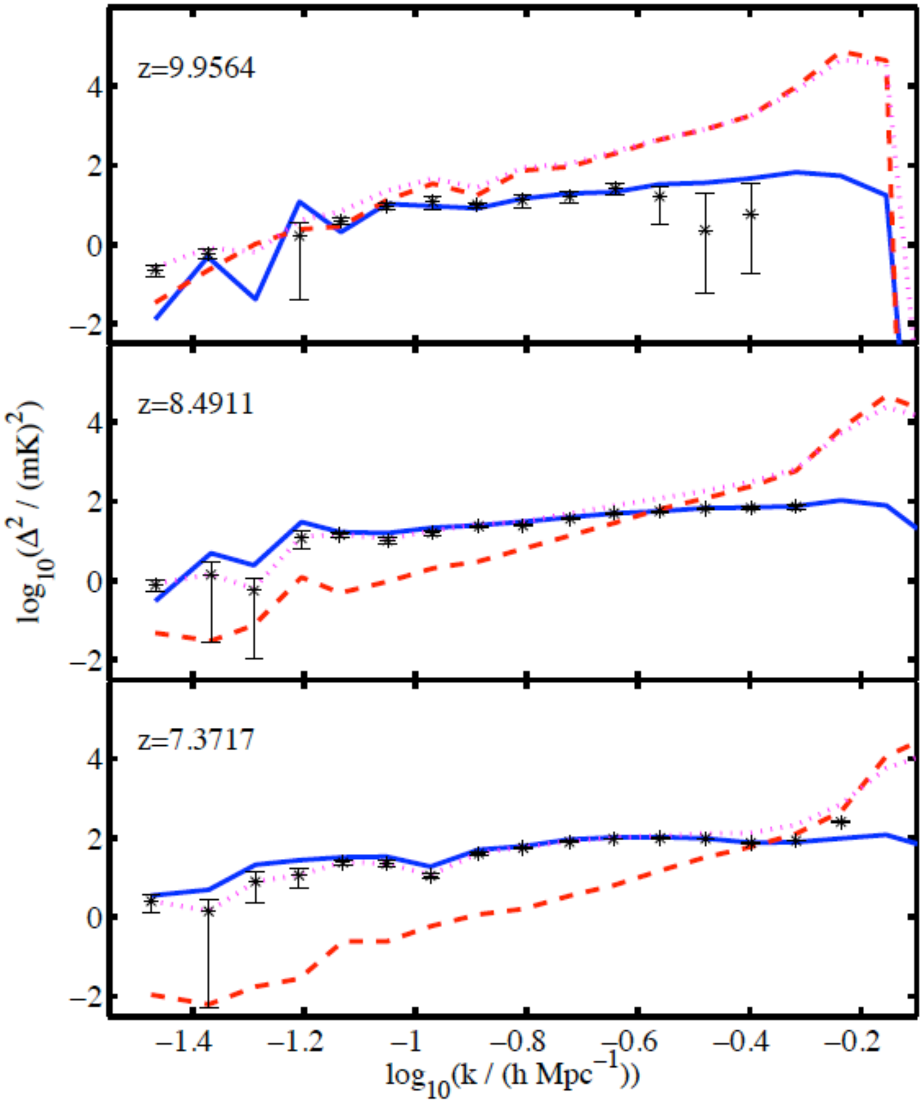


The fitting here is using a non-parametric algorithm called Wp which is well suited for this problem.

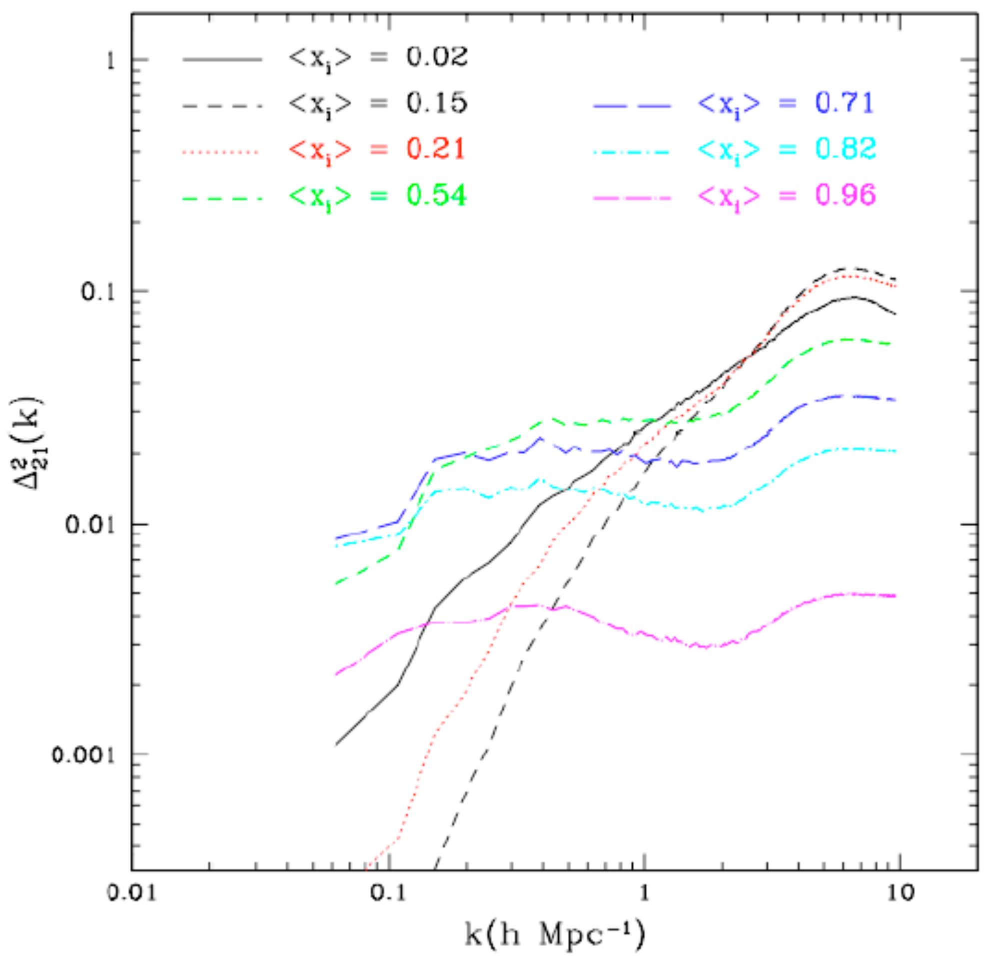
It avoids over- and under-fitting. It also minimizes the cross talk between the the fitted FG and the residuals.

Harker et al 2009

Power Spectrum Measurements



Harker et al.
2010



Lidz et al. (2007)

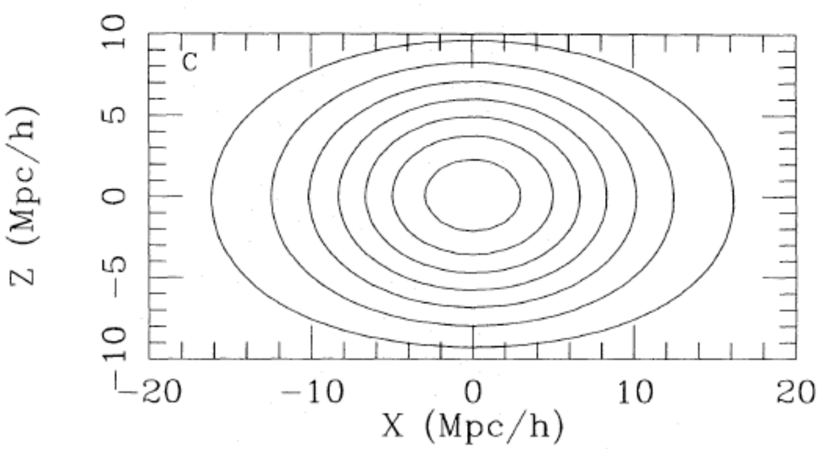
singer et al. 2010

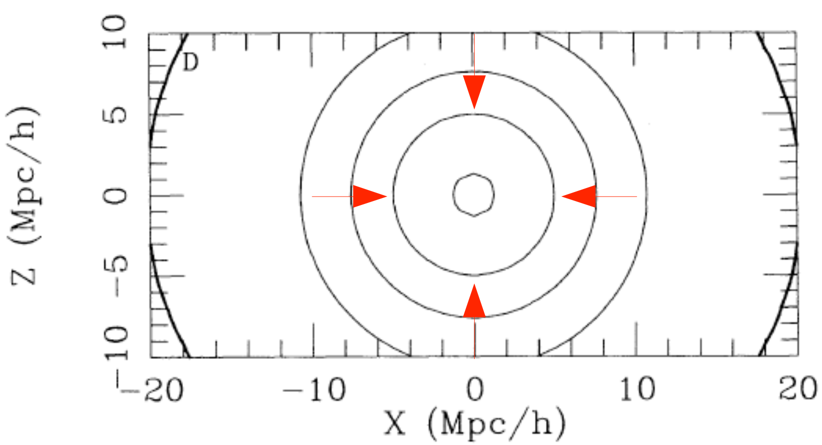
Redshift Space effect

$$P_s(\mathbf{k}) = P_r(\mathbf{k})(1+\Omega^{0.6}\mu^2)^2.$$

$$\mu_k = \hat{\mathbf{n}} \cdot \hat{\mathbf{k}}$$

Kaiser 1987





Zaroubi & Hoffman 1996

Linear power spectrum:

$$P_s(\mathbf{k}) = P_\Delta(k) + 2\mu_k^2 P_{\Delta v}(\mathbf{k}) + \mu_k^4 P_v(\mathbf{k})$$

astrophysics

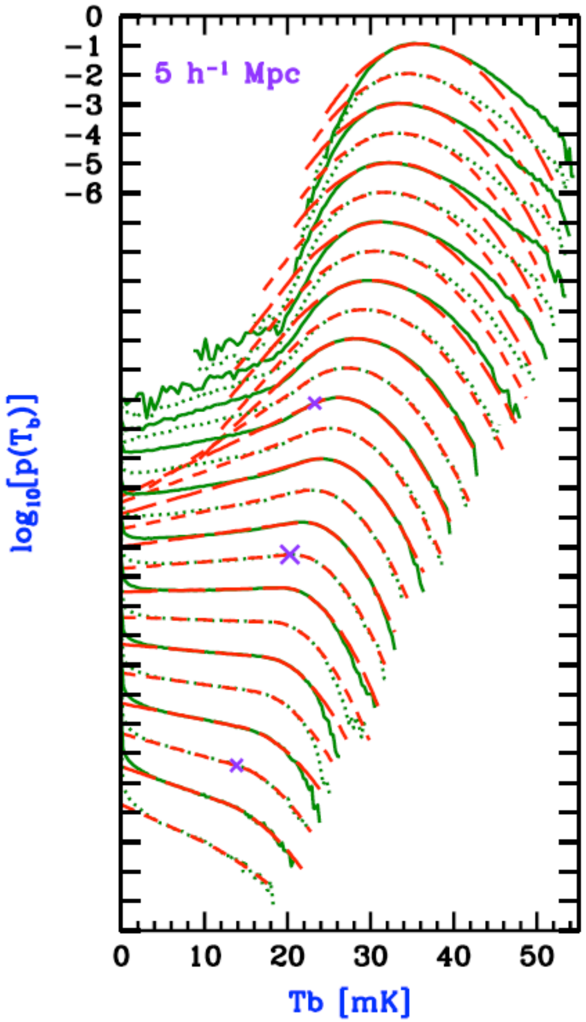
Velocities alone which give clean probe of cosmology

$(\mathbf{n}.\mathbf{k})^4$ component can be used for cosmology

Barkana & Loeb 2006

High Order Statistics

PDF of the brightness temp.

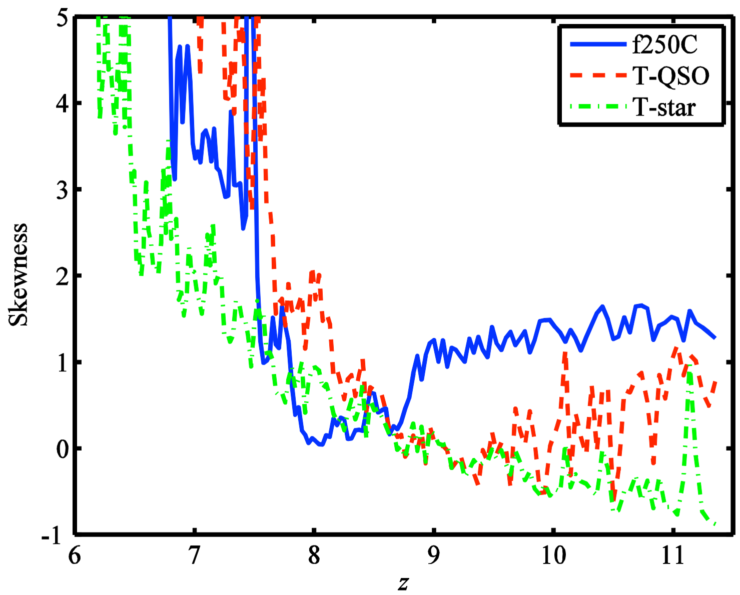


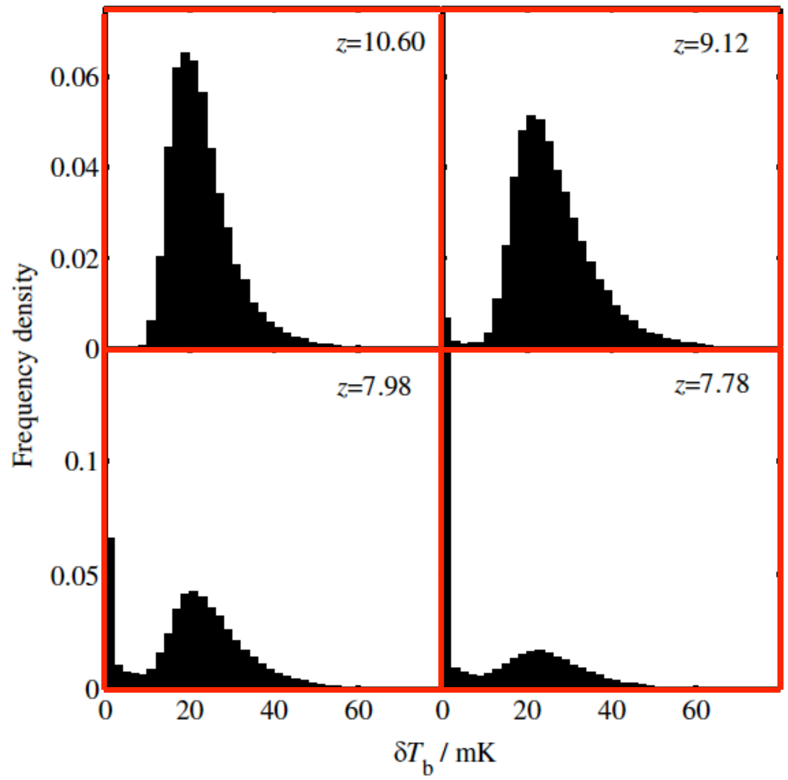
The evolution of the PDF of the brightness temp. as a function of redshift could be used to set constraint on reionization.

Ichikawa et al. 2010

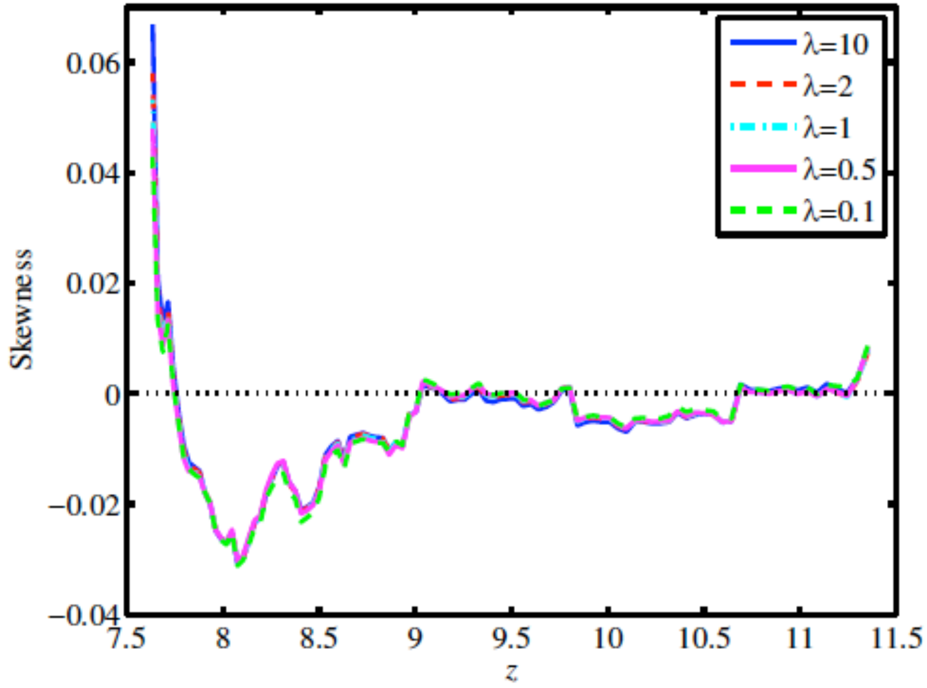
The Skewness

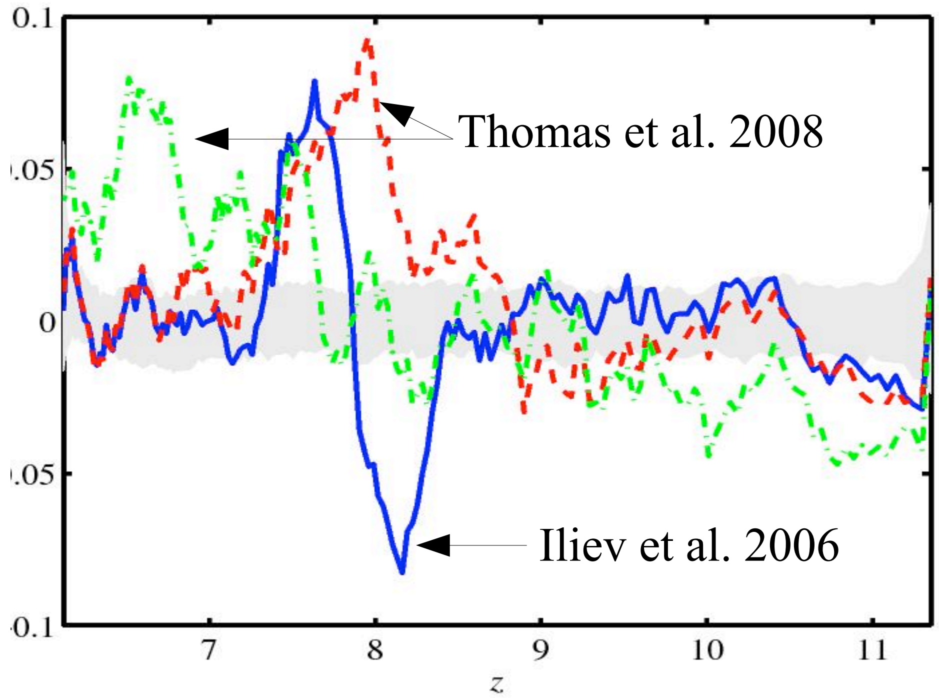
Original simulations





Extraction through the skewness

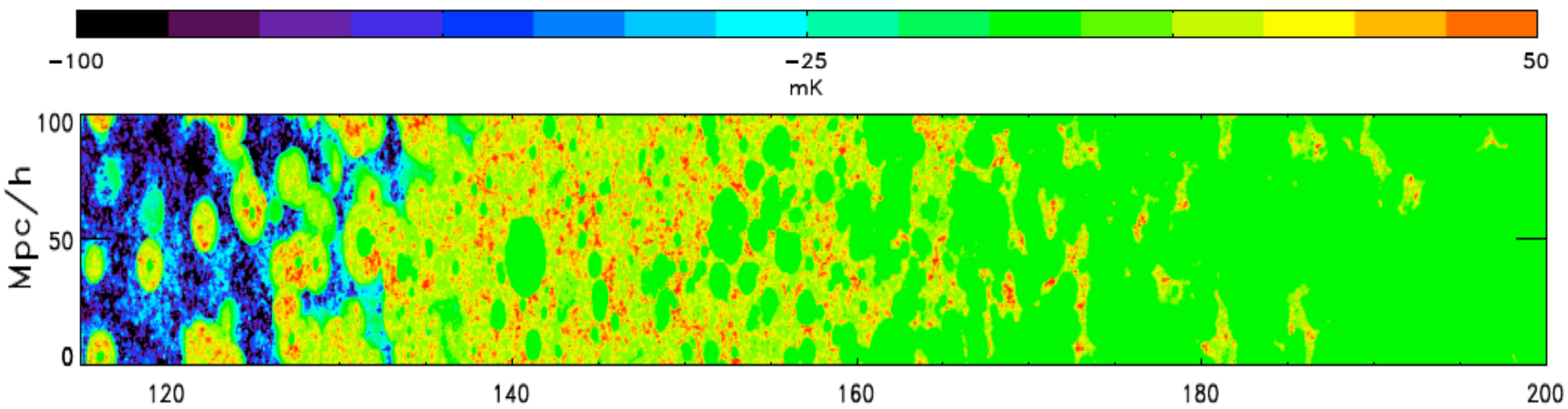




Harker et al. 2009

Spin Temperature issues

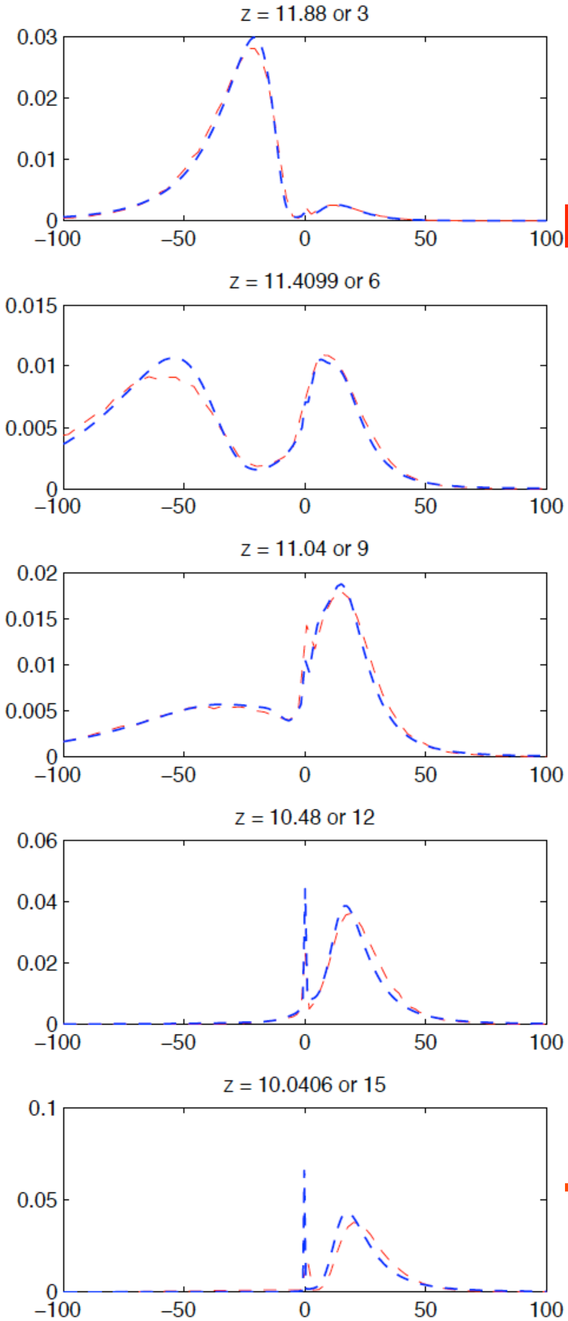
In case the spin temp. is of the order the CMB temp. or smaller an absorption signature is expected at high redshifts.



$$\delta T_b \approx 28\text{mK}\,(1+\delta)x_{HI}\frac{T_s - T_{CMB}}{T_s}\frac{\Omega_b h^2}{0.02}\left[\frac{0.24}{\Omega_m}\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}$$

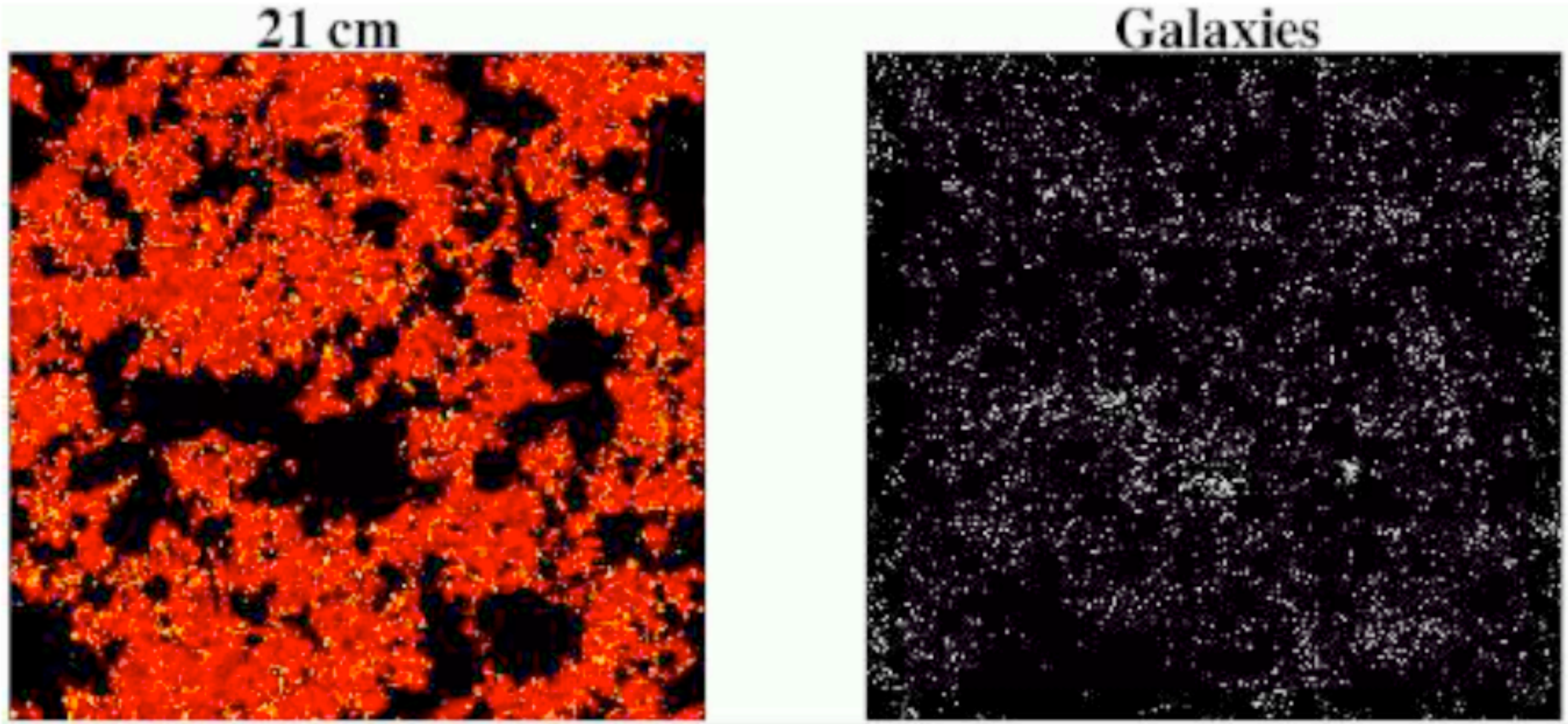
Thomas & Zaroubi 2010
See also Baek et al. 2010

The time dependent PDF for a simulations with evolving T_s



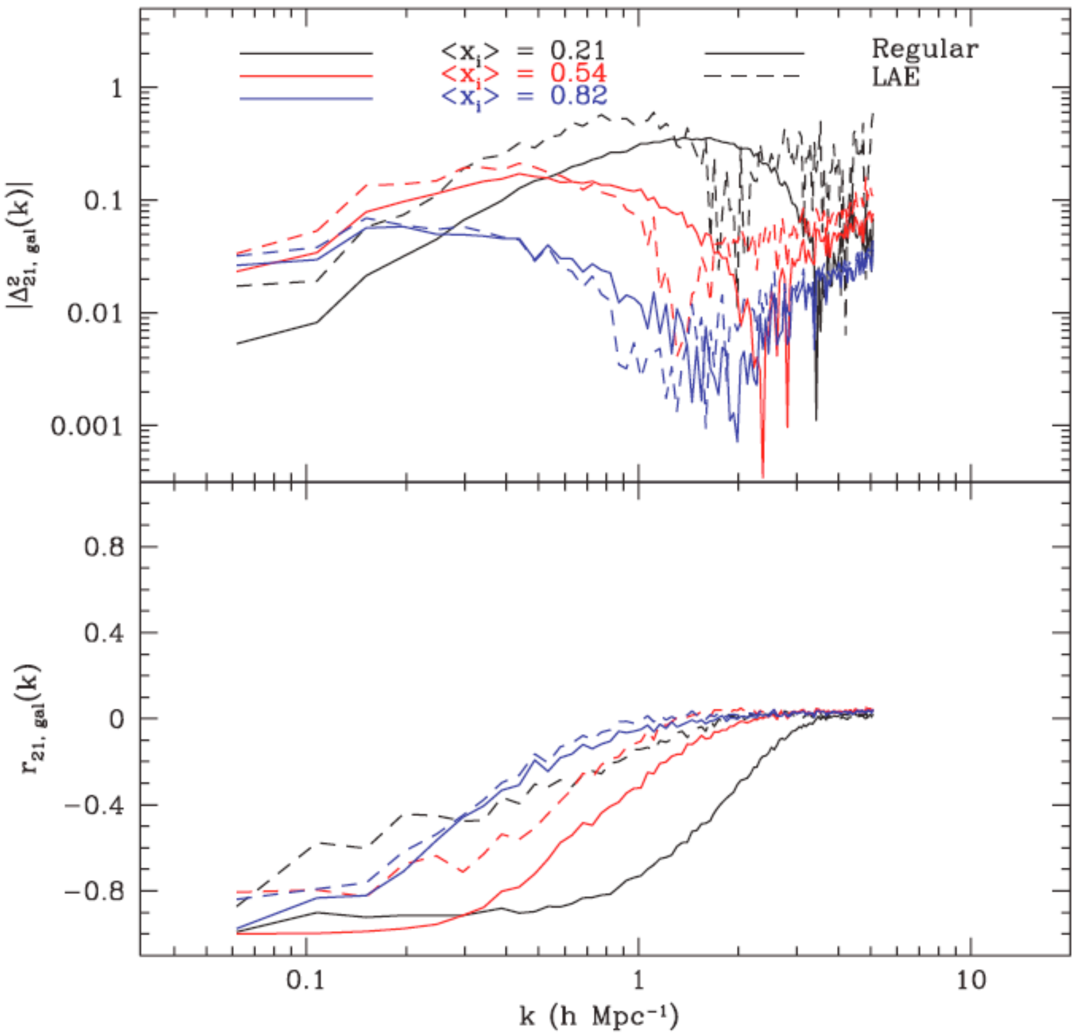
Jensma & Zaroubi, in prep.

Cross correlating 21 cm data with galaxy surveys

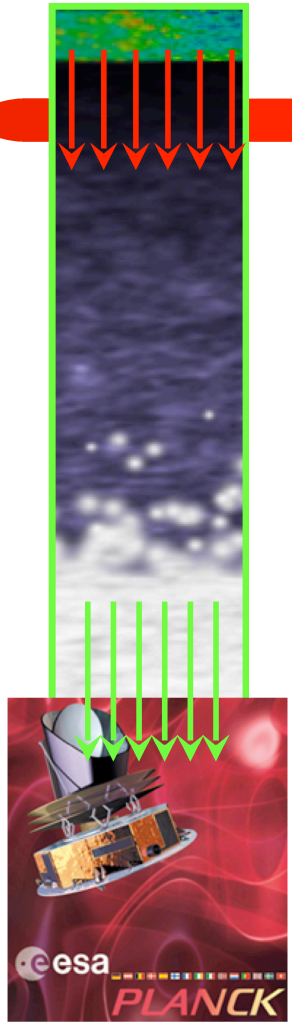


Lidz et al. 2009

21cm-galaxy cross power spectrum



CMB-21cm cross correlation



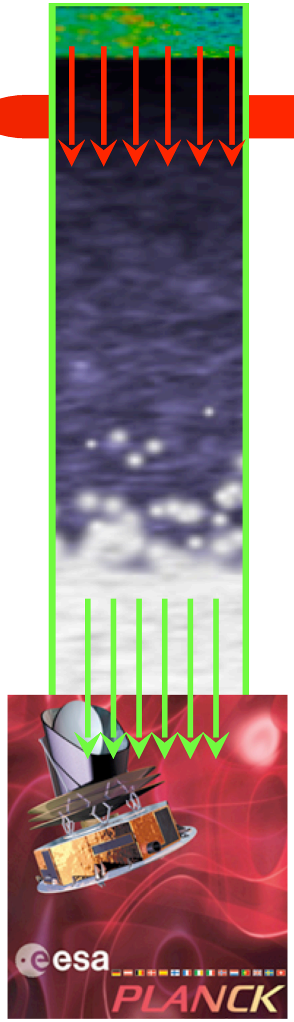
- CMB photons scatter off the ionized bubbles produced during the EoR ➔ secondary CMB anisotropies

- **thermal SZ effect**
  - **through inverse Compton scattering some of the energy of the electrons is transferred to the low energy CMB photons**

- **kinetic SZ effect**
  - **Doppler shift of the CMB photos due to bulk motions of the electrons**

- **imprint in polarization**
  - **through Thompson scattering the CMB is linearly polarized**

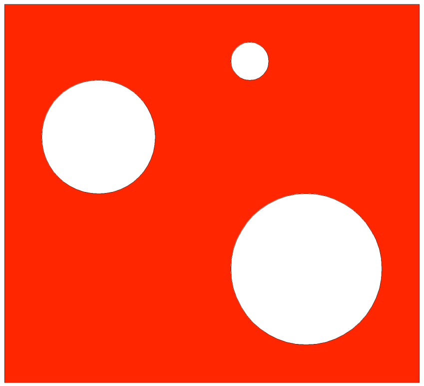
Introduction: basic idea

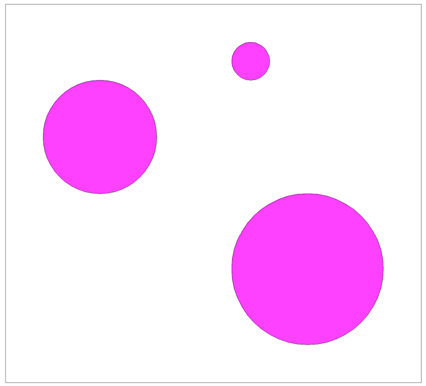


- the kSZ – the EoR map should anti-correlate

$n_e \cong 1 - n_H$

anti-correlation





- **kSZ from the EoR**
  - **semi-analytical model**: *Santos et al. 2003*
  - **simulations:** *McQuinn et al. 2005, Salvaterra et al. 2005, Zahn et al. 2005, Doré et al. 2007, Iliev et al. 2007, Jelic et al. 2009*

- **CMB-EoR cross-correlation**
  - **analytically**: *Cooray 2004, Alvarez et al. 2006, Slosar et al. 2007, Adshead & Furlanetto 2008, Lee 2009, Tashiro et al. 2009*
  - **simulations**: *Salvaterra et al. 2005, Jelic et al. 2009*

Simulations: kSZ maps

BEARS: density, neutral fraction & velocity cubes

$$\tau = c\sigma_T \int_0^z n_e \frac{(1+z)^2}{H} dz$$

$$\left(\frac{\delta T}{T}\right)_{kSZ} = -\sigma_T \int_0^{t_0} e^{-\tau} n_e (\hat{r} \cdot \vec{v}) dt$$

$$n_e = \bar{n}_n \bar{x}_e (1 + \delta + \delta_{x_e} + \delta\delta_{x_e})$$

$$\chi_e = 1 - \chi_n$$

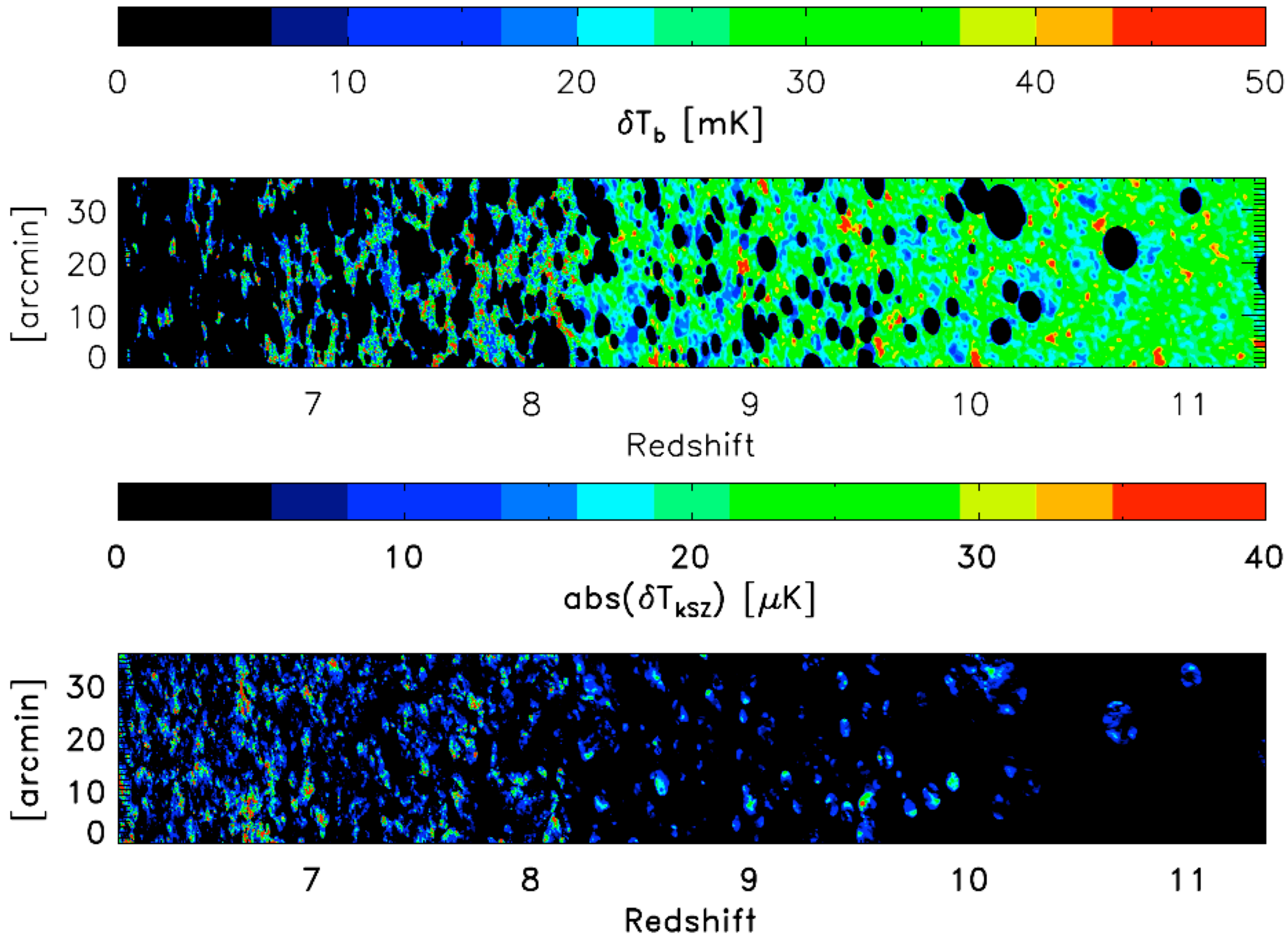
$$\left(\frac{\delta T}{T}\right)_{kSZ} = -\sigma_T \bar{n}_{n(0)} \int_{z_r}^{z_0} \frac{(1+z)^2}{H} e^{-\tau} \bar{x_e} \cdot (1 + \delta + \delta_{x_e} + \delta\delta_{x_e}) v_r dz$$

homogenous reionization term ($1 + \delta$)

patchy reionization term (δ_{x_e})

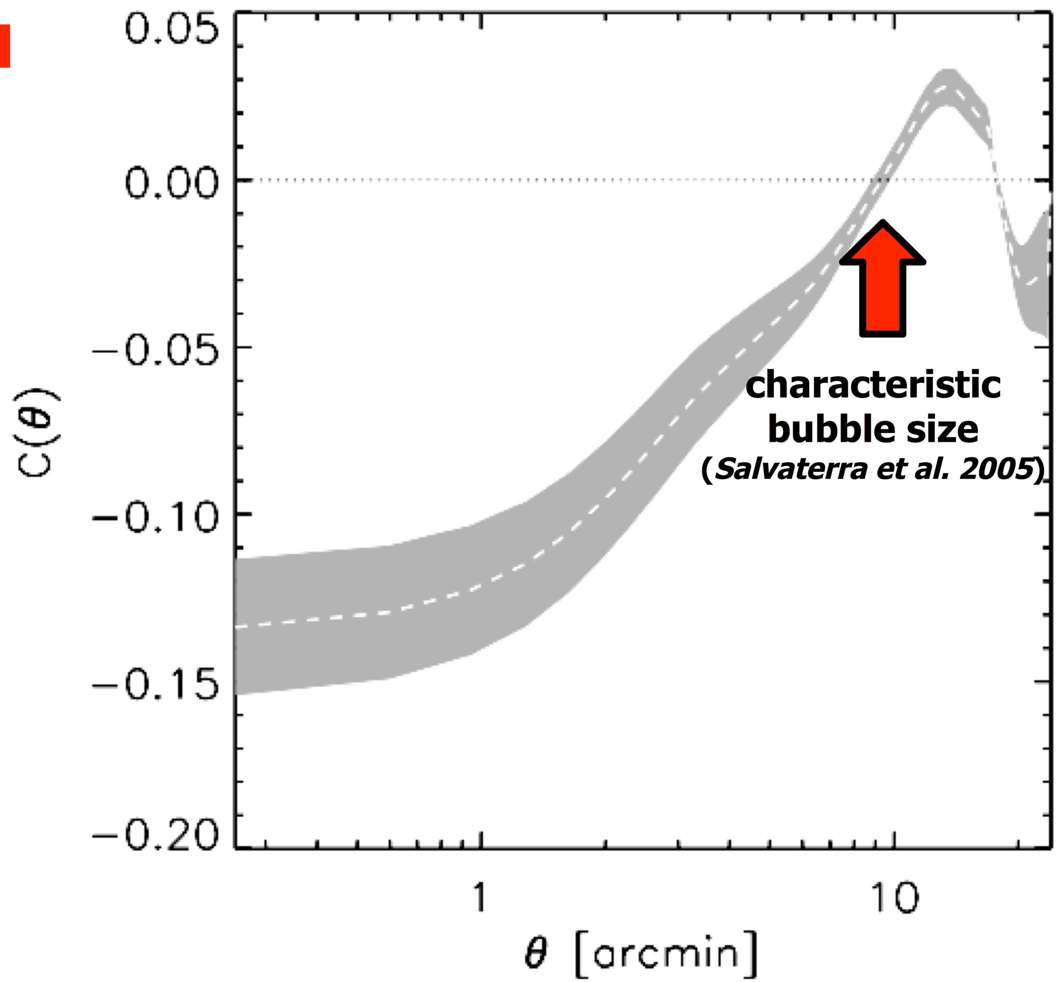
mixed term ($\delta\delta_{x_e}$)

Simulations results

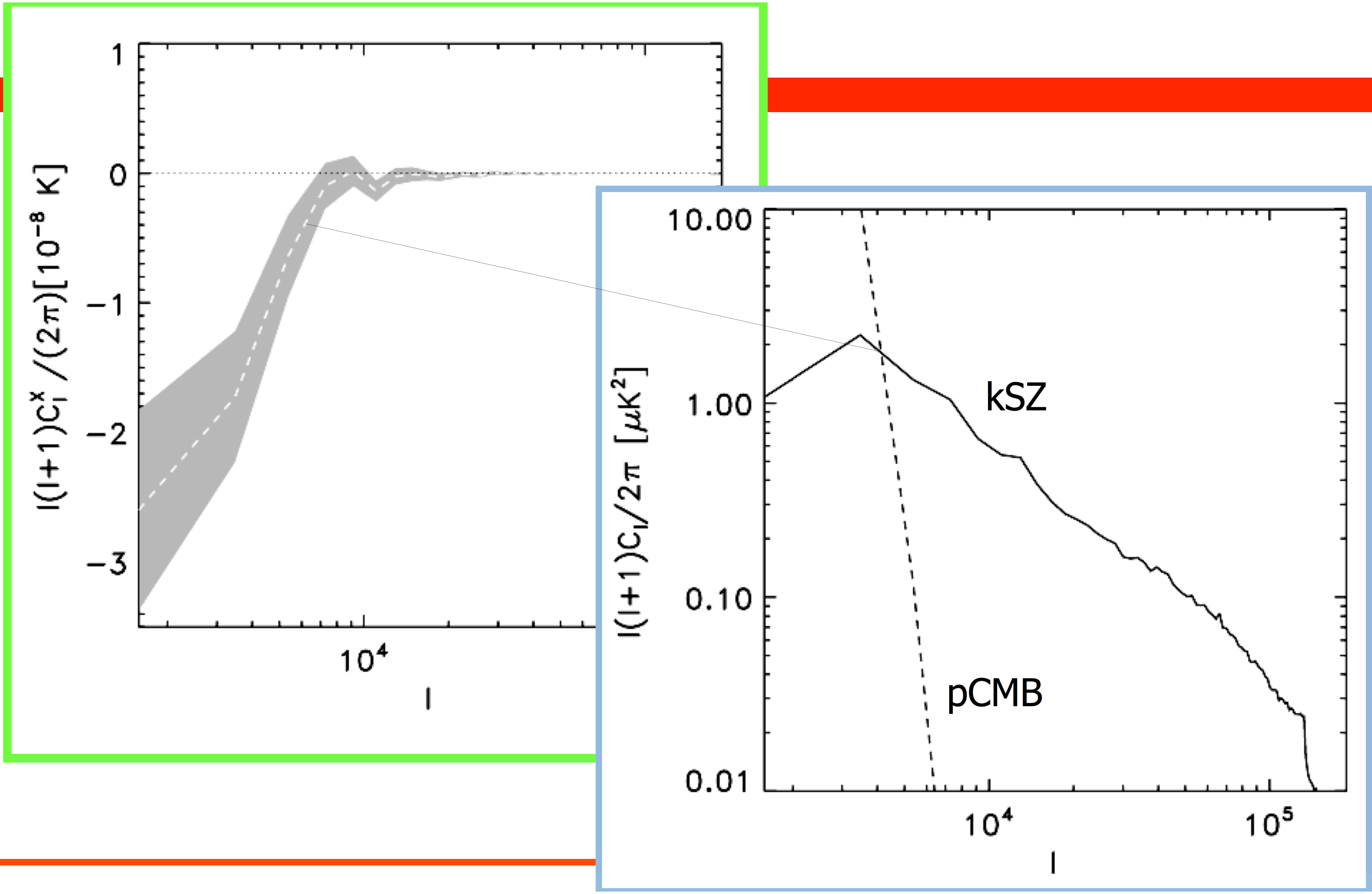


Cross-correlation as a function of lag

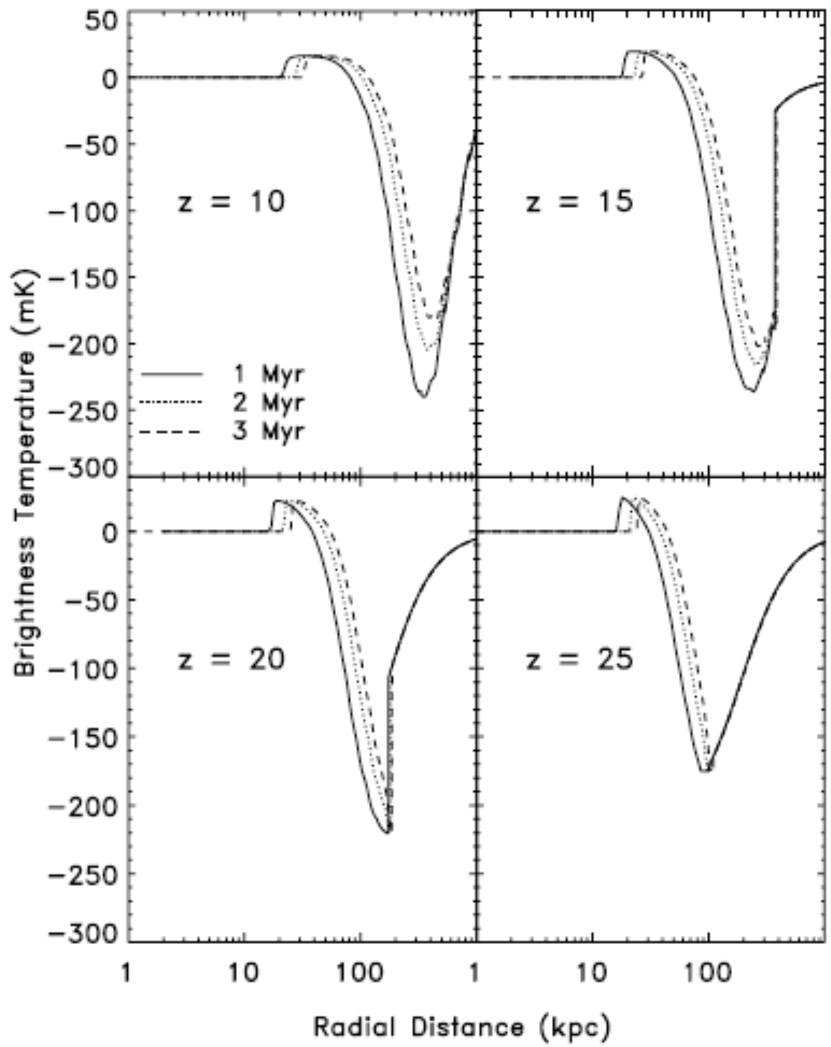
integ. kSZ & integ. EoR for Stars patch reion.



Influence of primary CMB



Bubbles around high z QSOs



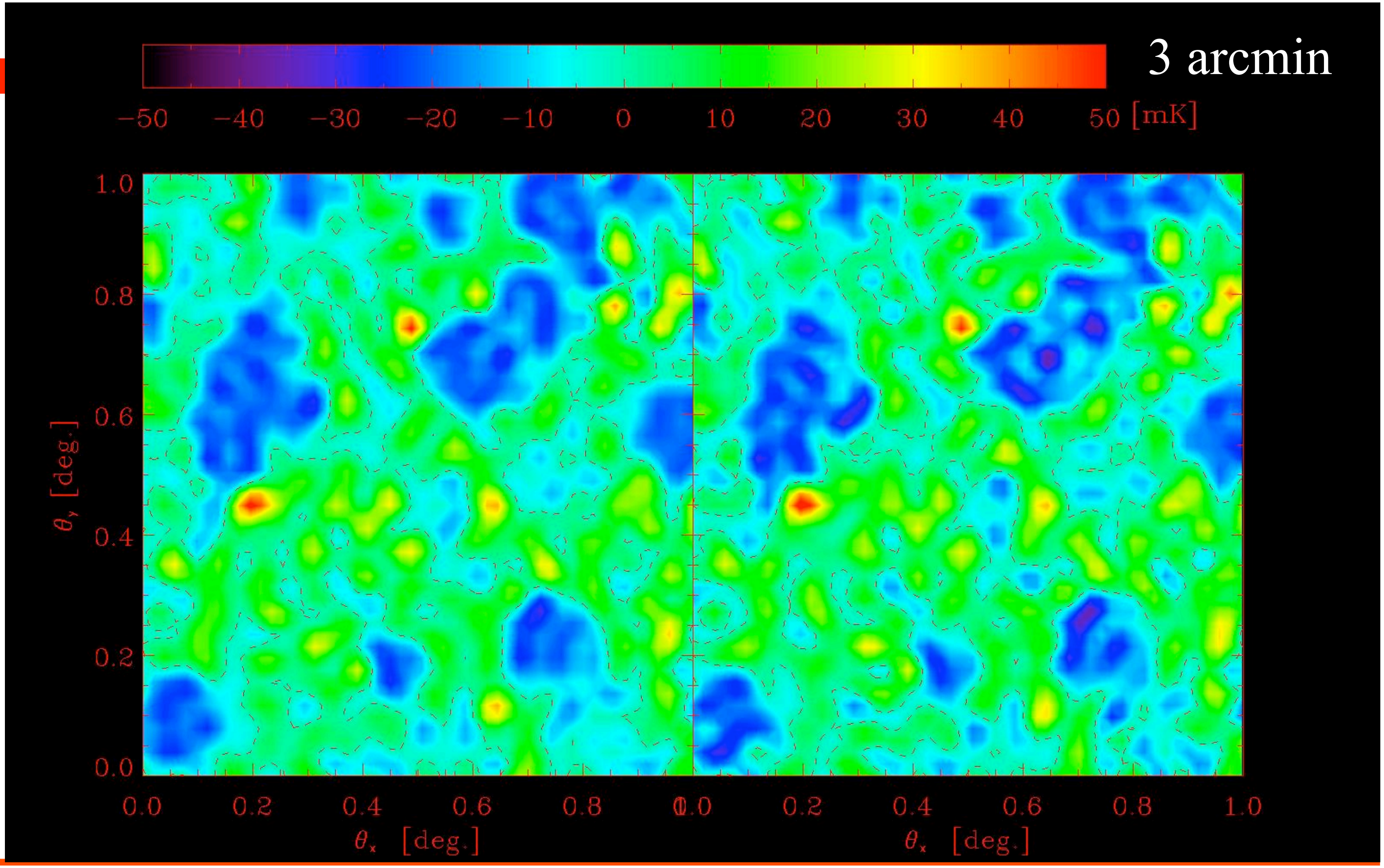
$M_{BH}=10^4\ M_{sun}$

The future:
SKA and the EoR

- SKA will have three main advantages over LOFAR:
  - Sensitivity (10-100 times more collecting area)
  - Frequency coverage (covers $z \sim 6-26$)
  - Resolution

  These advantages will allow addressing many issues that LOFAR won't be able to address.

Maps from SKA



Summary: the future is bright

- We are closing the gap in probing the the $z>6$ Universe. The EoR as probed by many future instruments should give a consistent picture.
- LOFAR will provide High sensitivity data in the frequency range 115-190MHz will in the near future.
- Extracting the EoR signal is challenging but doable and will usher us into a new era in studying the Universe.
- SKA will provide a another important jump in the quality of the 21 cm data from the EoR and the Dark Ages