Simulating the redshifted 21cm Signal from Reionization

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Contents

- The simulations
- The geometry of reionization
- The redshifted 21cm signal

- Iliev, GM, Pen, Shapiro, Alvarez, 2006, MNRAS 369, 1625
- GM, Iliev, Pen, Shapiro, 2006, MNRAS 372, 679
- Iliev, GM, Shapiro, Pen, 2007, MNRAS 376, 534
- Iliev, Pen, Bond, GM, Shapiro, 2007, astro-ph/0609592
- Iliev, GM, Pen, Bond, Shapiro, 2007, astro-ph/0702099

- The simulations
- Simulation geometry results
- Redshifted 21cm results

Simulations: Requirements

- *Large* scale simulations.
  - Observationally needed (LOFAR observations will have ~several degree fields of view).
  - Theoretically needed (cosmic variance, size of HII regions >>10 Mpc). See poster.
- *Large* dynamic range simulations.
  - Dominant structures in early universe were small collapsed `halos´ (dwarf proto-galaxies).
  - Preferably resolve collapsed structures of $10^8\ M_\odot$ and up.

Simulations: How?

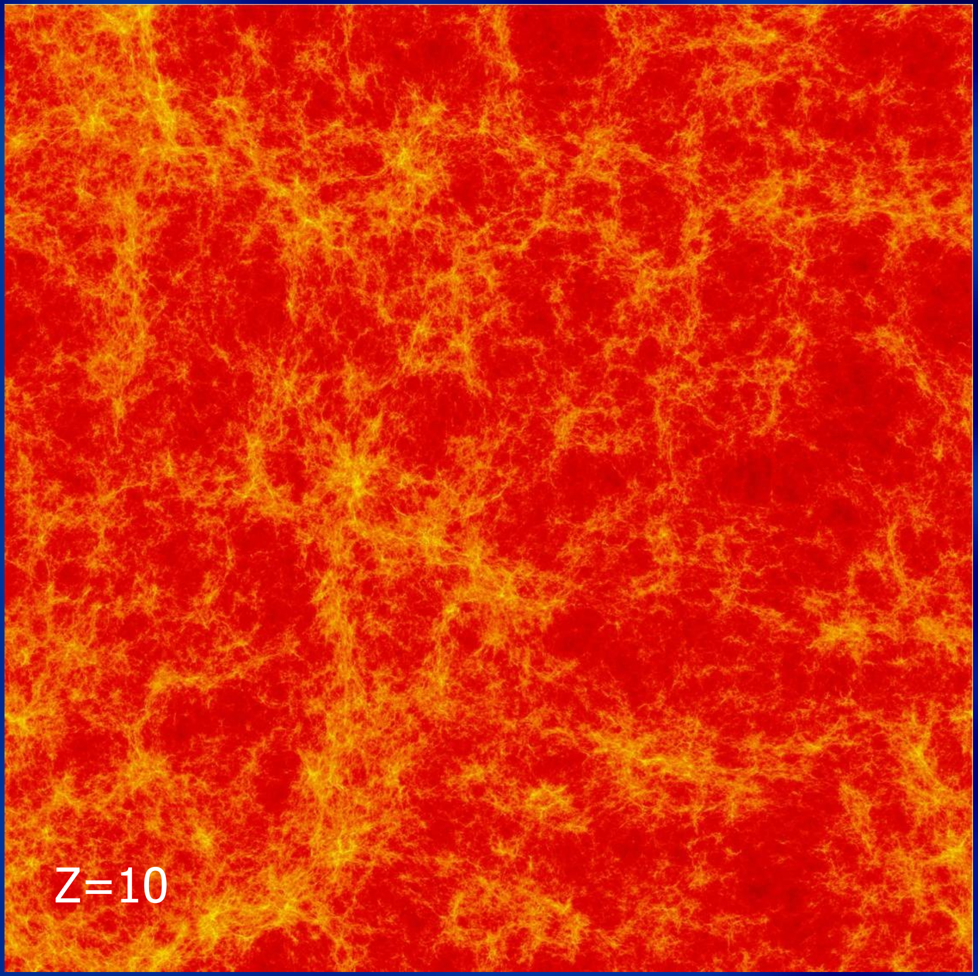
- Two separate steps:
  - **PMFAST** (Merz, Pen, Trac 2005) simulations (3248^3 mesh, with 1624^3 (4.3 billion) particles):

    ΛCDM (WMAP)

    - Evolving density field (snapshots)
    - Collapsed halo list sources
    - Smallest scale structures: clumping factor C(z) $(\langle n^2\rangle/\langle n\rangle^2)$
  - **C^2-Ray** (GM et al. 2006) postprocessing (203^3, 406^3 meshes):
    - Ionized hydrogen fraction
- Note: no hydrodynamics, and photo-ionization as post-processing (no feedback): justified by the large scale.

PMFAST Structure Formation

- Example of density field (WMAP3).
- L=100/h Mpc
- 4.3 billion particles.
- $M_{min}=2.2 \times 10^9 M_\odot$
- First collapsed halos at $z \approx 16$.
- 600,000 sources at z=6.



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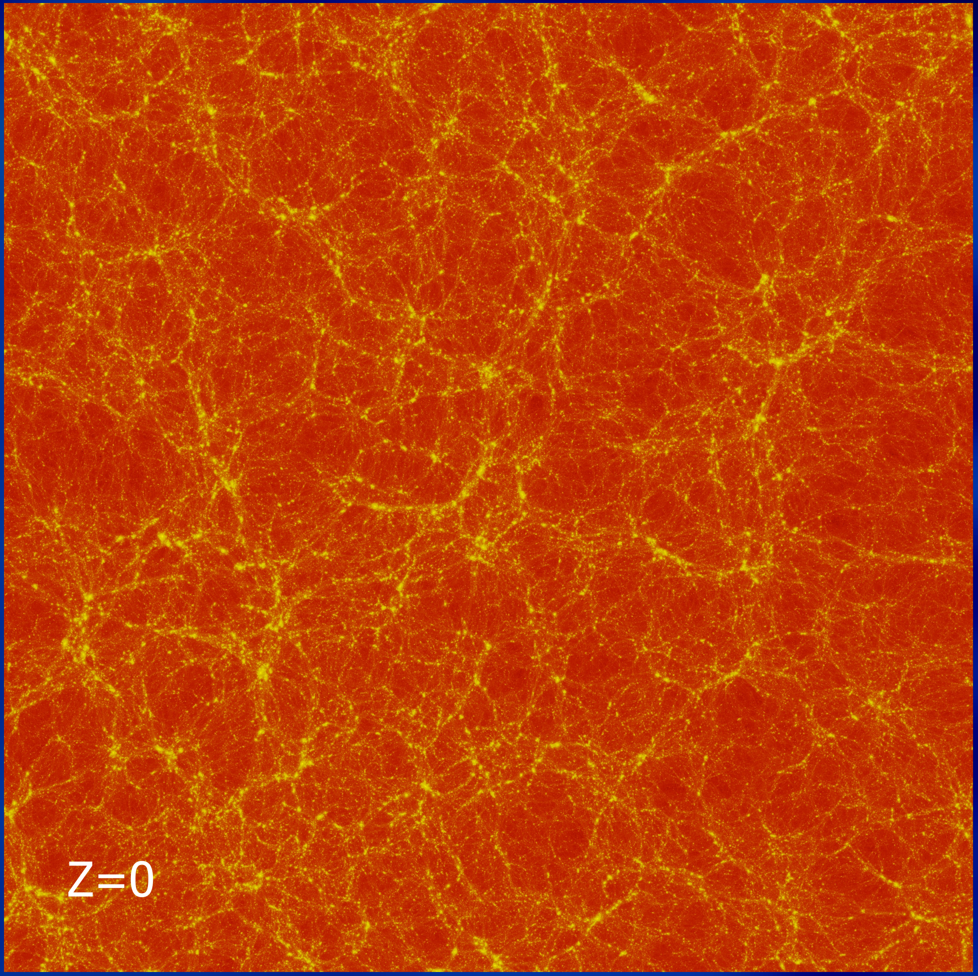
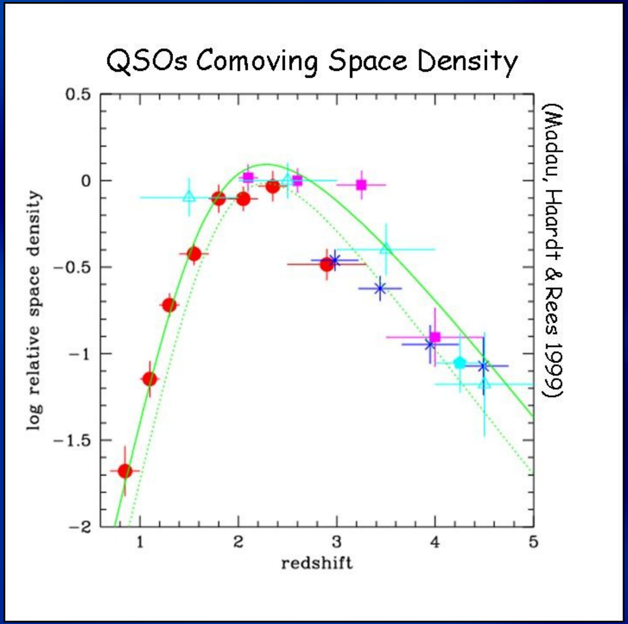


Sources of Reionization

- There are several candidates for the cause of reionization
  - Stars: metal abundance and 'old' stellar populations in galaxies at redshift ~6 suggest early star formation.
  - Quasars: too few?
  - Mini-quasars: no direct evidence?
  - Particle decay: speculative
- Conservative approach: Stars in atomically cooling halos ($M>10^8\,M_\odot$).



Halos as Sources

- Conservative approach: Stars in atomically cooling halos ($M>10^8 M_\odot$).
- Assumptions:
  - M/L=const.
  - fixed ionizing photons/atom escaping: $f = f_{SF} \times f_{esc} \times N_{photon}$ per epoch (2×10^6 year) (Iliev, Scannapieco & Shapiro 2005).
  - Spectrum: 50,000 K Black body.
- f=250:
  - f_{SF} =16% , f_{esc} =16%, N_{photon}=10,000 (Top-heavy/PopII)
  - f_{SF} =20% , f_{esc} =25%, N_{photon}=5,000 (Salpeter/PopII)

- The simulations
- The geometry of reionization
- The redshifted 21cm signal

Global Parameters

Sim	f	clumping	Z(50%)	Z(99%)	τ_{es}
f250	250	1	8.9	7.5	0.086
f250C	250	C(z)	8.4	6.5	0.08

(WMAP 3: τ_{es}= 0.09 ± 0.03)

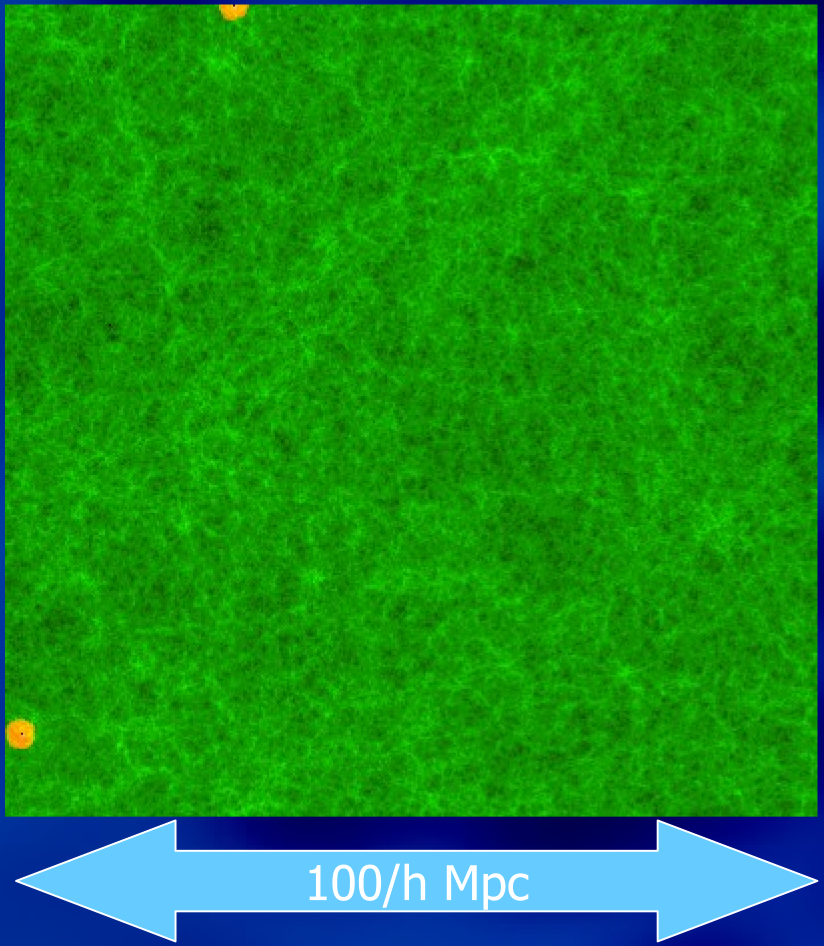
Volume: 100/h Mpc
$M_{min}=2.2\times10^9\ M_\odot$

⇨ A normal stellar population (with efficient SFR & UV escape efficiency) can reionize the universe before z=6, and produce a τ consistent with WMAP3.

Results: Evolution

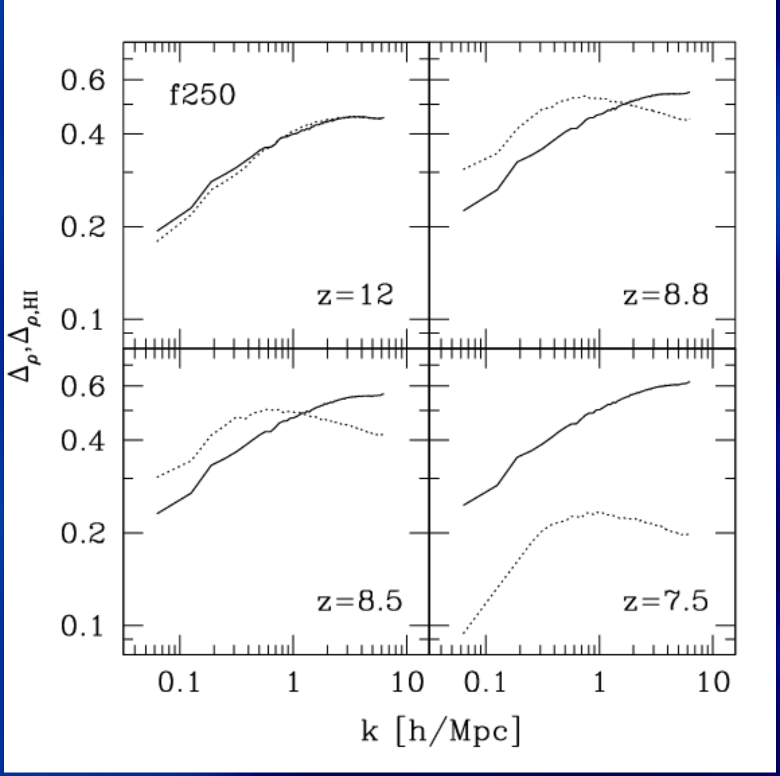
- Animation of the evolution of (a slice of) the density field and HII regions
- Green: neutral
- Orange: ionized
- Black dots: sources

- Note: clustering & overlap.
- Inside-out reionization.
- Simulation with f=2000 in 406^3 (evolution from z=14 to 8).



Geometry: Power Spectra

- 3D powerspectra:
  - Poisson noise at largest scales
  - Clear peak at some (time-dependent) characteristic scale.
  - Strongest peak at 50% ionization: average distance between larger clusters.



Full density ———

Neutral density ········

- The simulations
- The geometry of reionization
- The redshifted 21cm signal

Observing Reionization

Directly: Hydrogen
(lines → redshift information)

- Emission:
  - **21cm** (if $T_{spin} > T_{CMB}$)
- Absorption:
  - **21cm**: Against radio galaxies / Cosmic Microwave Background: (if $T_{spin} < T_{CMB}$)
  - **Lyα**: Against QSOs, starbursts, or gamma-ray bursts

Indirectly: Effects on the CMB
(integrated along the line of sight).

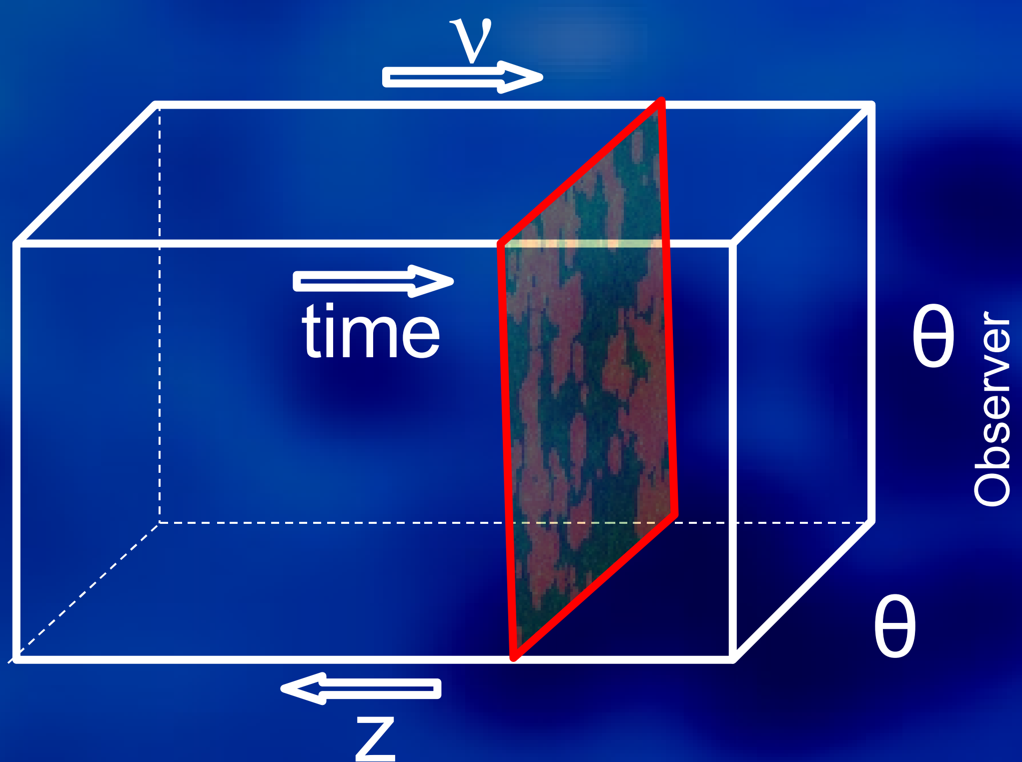
- **CMB Polarization**:
  τ_{es} between us and the CMB + small scale variations.
  - B-mode polarization.
- **Kinetic Sunyaev-Zel'dovich effect** (inverse Thomson scattering against moving electrons).

Constructing the 21cm Signal

- The differential brightness temperature of the 21cm signal can be written as
$$\delta T(z) \approx 28\text{mK}\, x_{HI}\, (1 + \delta)\, (1-T_{CMB}/T_s)\, [(1+z)/10]^{1/2}$$
(for WMAP3 cosmological parameters).
- For $T_{spin} >> T_{CMB}$, it depends *only* on overdensity (δ) and neutral fraction (x_{HI}), and can be easily constructed from simulation results.
- Here we assume that the neutral IGM has $T_{spin}>>T_{CMB}$:
  - IGM heated by X-rays and/or shocks.
  - T_{spin} coupled to T_{kin} by Lyα scattering (Ciardi & Madau 2004).

The Image Cube

- Frequency ⟷ Redshift ⟷ Time.
- Observations of fields $\Delta\theta$ by $\Delta\theta$ over $\Delta\nu$: image cube.

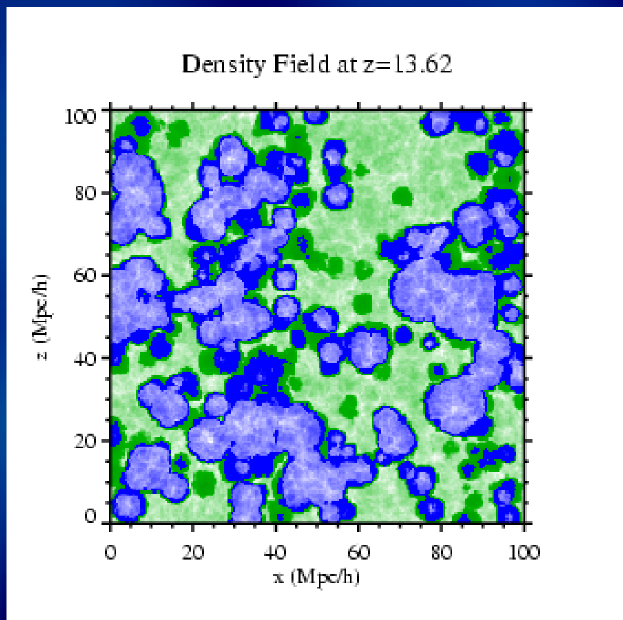


Flying through the Image Cube

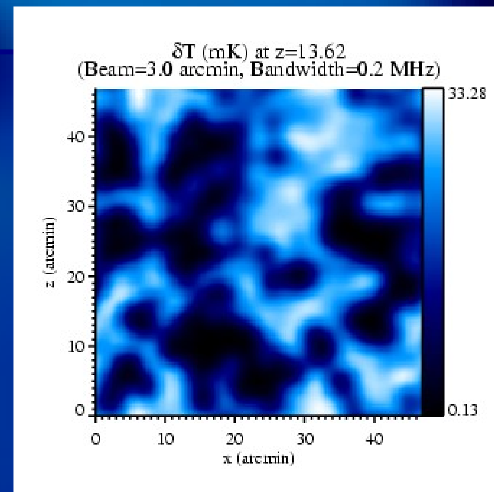
- As we fly through frequency/redshift space, structure formation raises the intensity level, and the contrast.
- Reionization removes 21cm: dark spots.
- Movie generated by using the periodicity of the volume, but rotating it to avoid passing through the same structures.

Simulation f250C

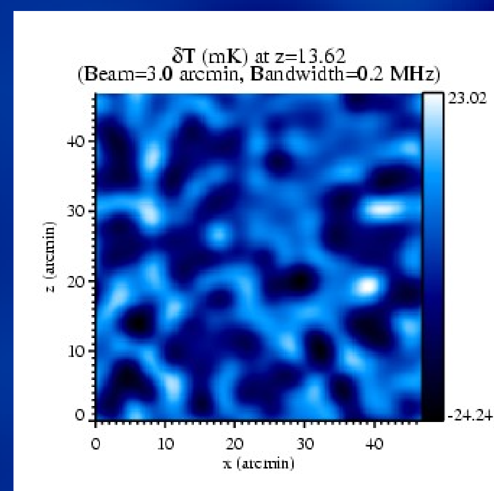
Different Beam shapes



f2000 (WMAP1)

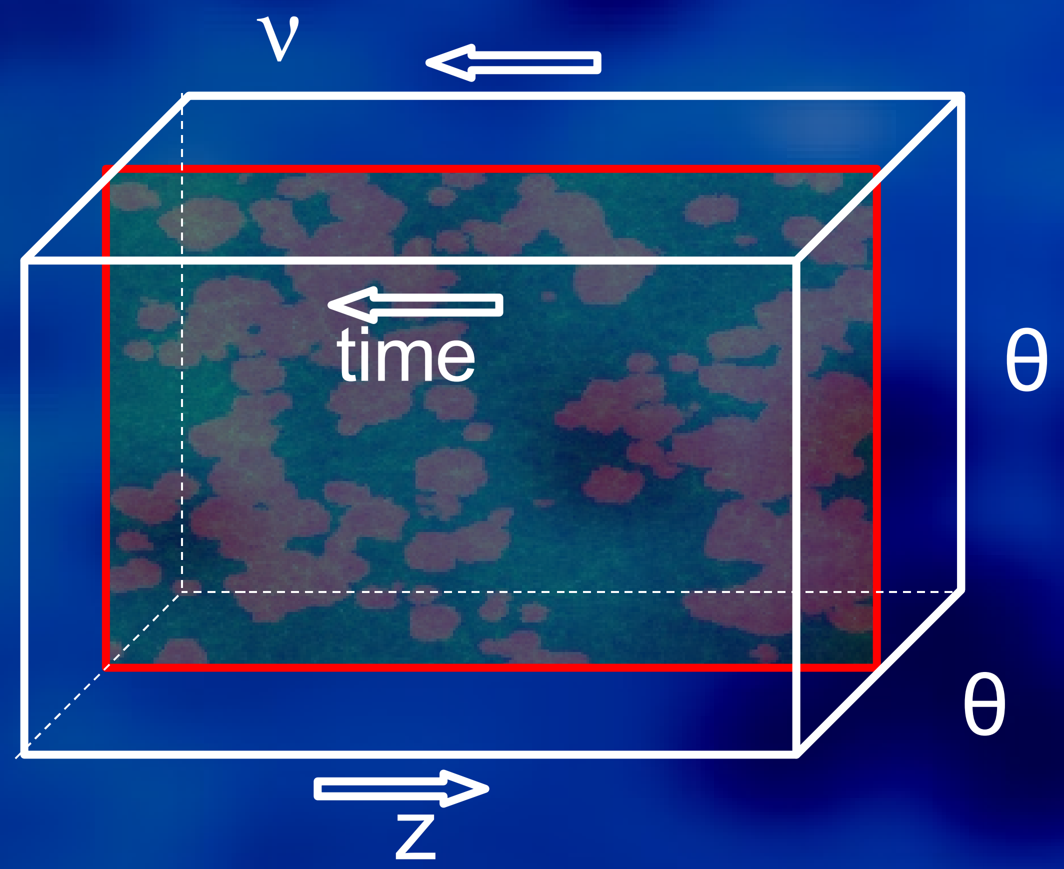


Gaussian Beam



Compensated Gaussian Beam

Image Cube: Redshift Slice

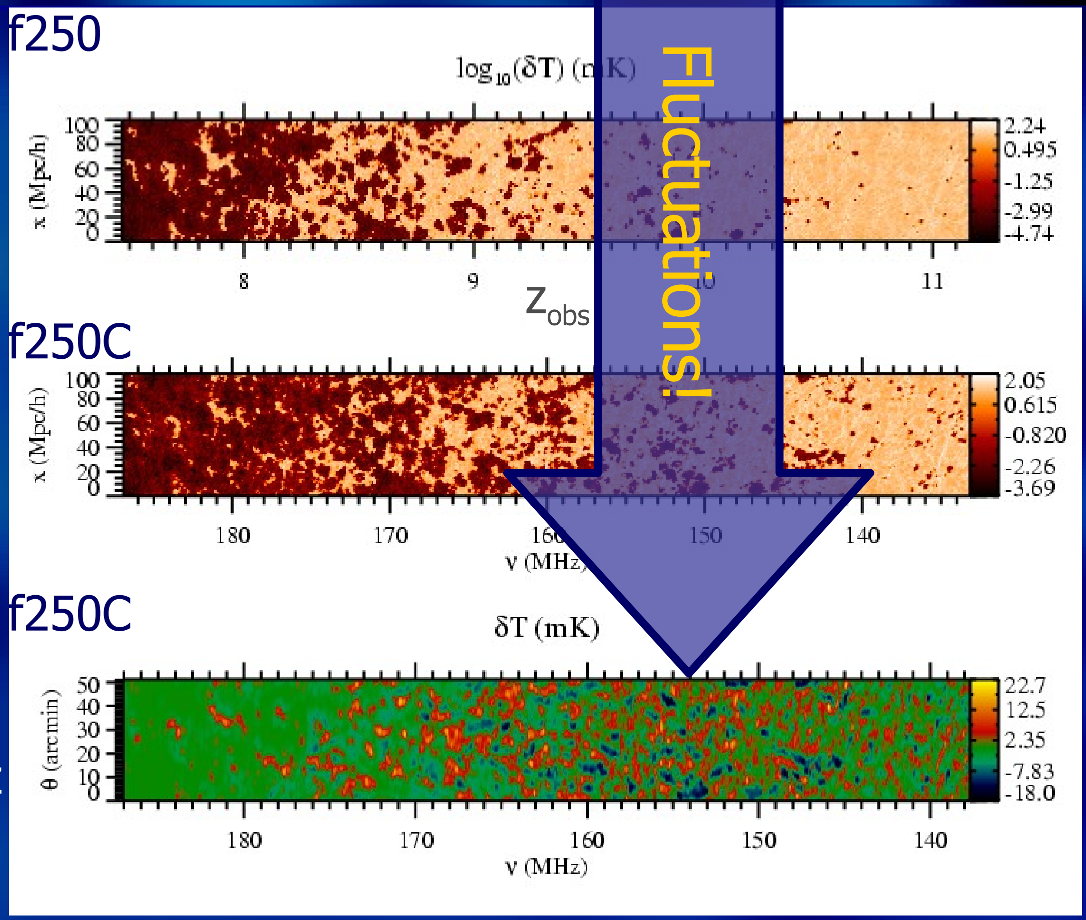


LOS Reionization Histories

- Reionization histories along the line of sight.
- Frequency direction contains evolutionary, geometrical and velocity information.

3′ interferometer beam and 200kHz bandwidth

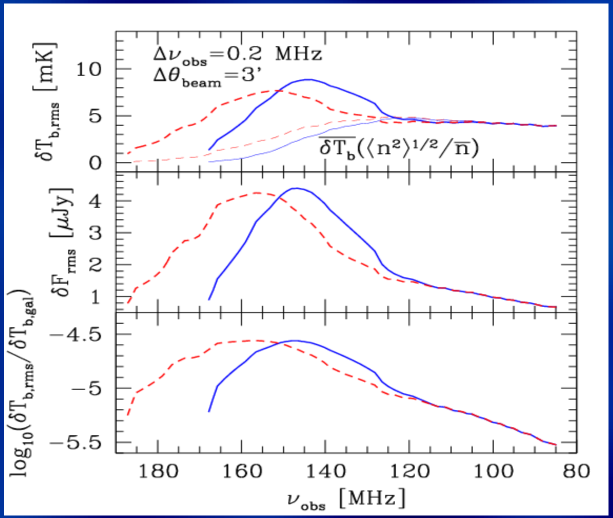
(LOFAR core-like)



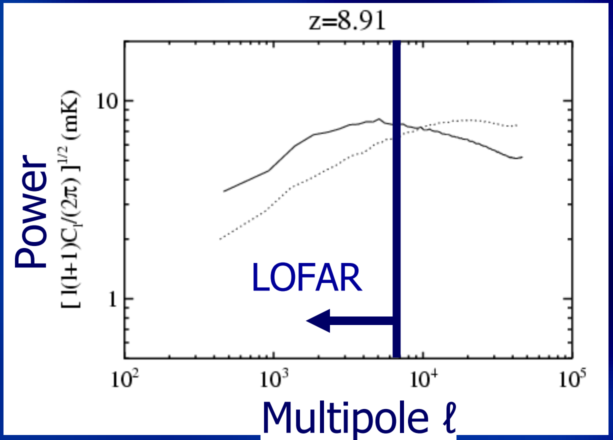
Includes redshift distortions due to peculiar velocities

Statistical Measurements

- LOFAR EoR experiment sensitivity will (initially) be too low (< 20 mK) to image 21cm emission pixel by pixel: Statistical measurements needed.
  1. measure noise level as function of redshift.
  2. measure 21cm power spectrum on the sky as function of redshift (given directly by interferometer 'visibilities': Fourier transform of the sky).



RMS noise level at redshifted 21cm



Z(50%)

Conclusions

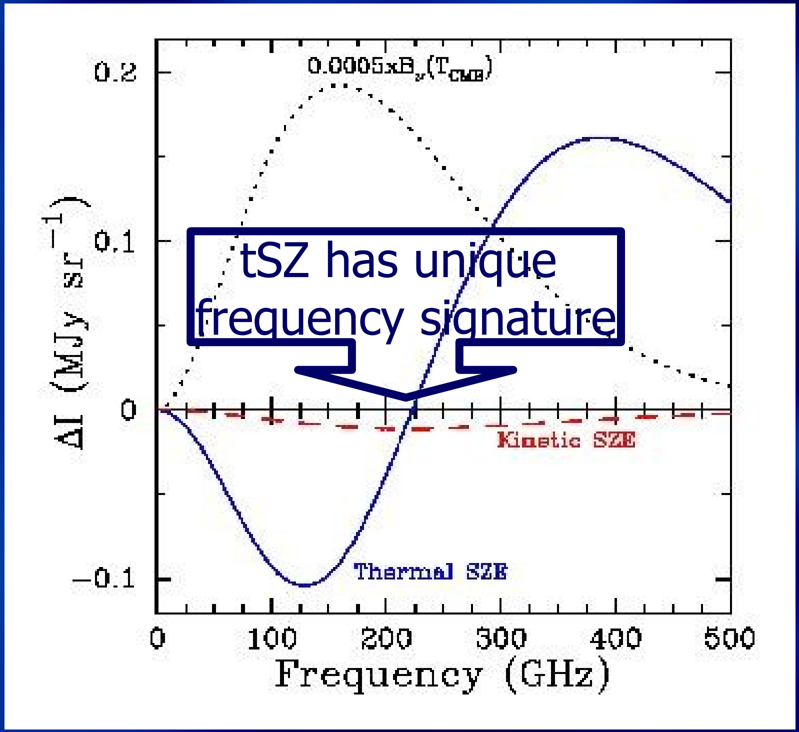
- Large scale, large dynamic range simulations needed for reionization.
- Normal stellar population can explain reionization.
- Reionization produces a clear signature in the rms noise level and in the power spectra of redshifted 21cm, which is measurable by LOFAR.
- Start, end and duration of reionization will give exciting clues about earliest galaxy/star formation.

Caveats

- LOFAR will have to deal with serious foreground emission, 10^5 times above the EoR signal (galactic & extragalactic).
- Our star formation recipe gives a few times higher values than estimates from z~6.
- Finite resolution affects the geometry of reionization (but not by much, cf. Ritzerveld 2007).

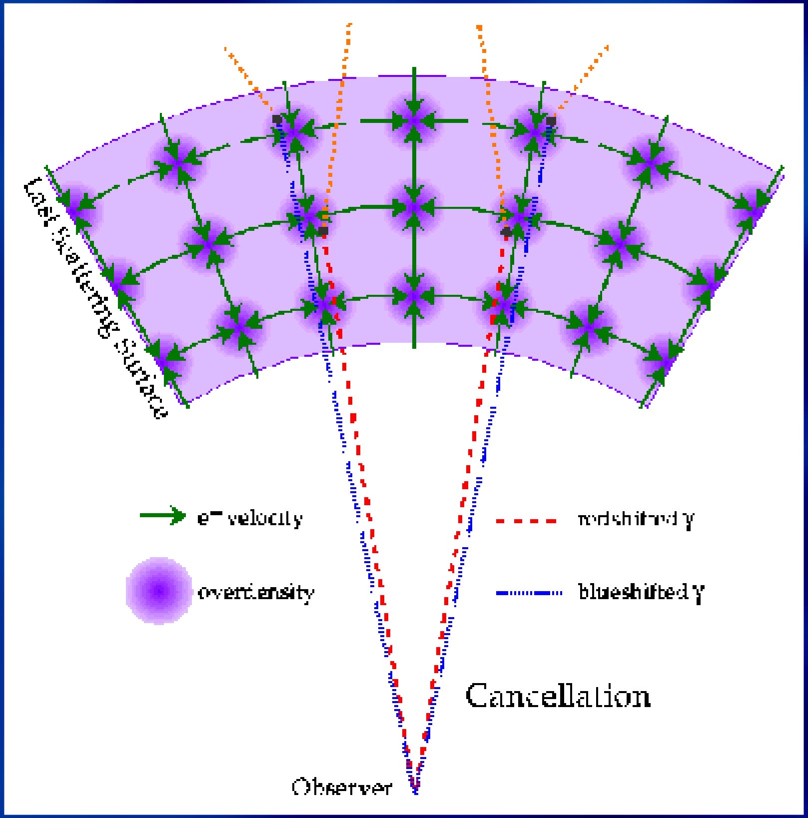
Sunyaev Zel'dovich Effects

- Photons travelling from the CMB to us are scattered by free electrons, this can change their energies.
- There are *two* effects:
  - Thermal SZ: in hot cluster gas (10^8 K) the photons inverse Compton scatter and the average photon energy increases.
  - Kinetic SZ: in any ionized region the photons scatter against moving electrons and lose or gain energy depending on the motion of the electrons.



Kinetic SZ Effect

- To first order the kinetic scatterings cancel out.
- Electron density fluctuations needed:
  - Linear density fluctuations in IGM (Ostriker-Vishniac or OV effect).
  - Non-linear density fluctuations in clusters (kSZ in narrow sense)
  - Patchy reionization



Relevance and Previous Work

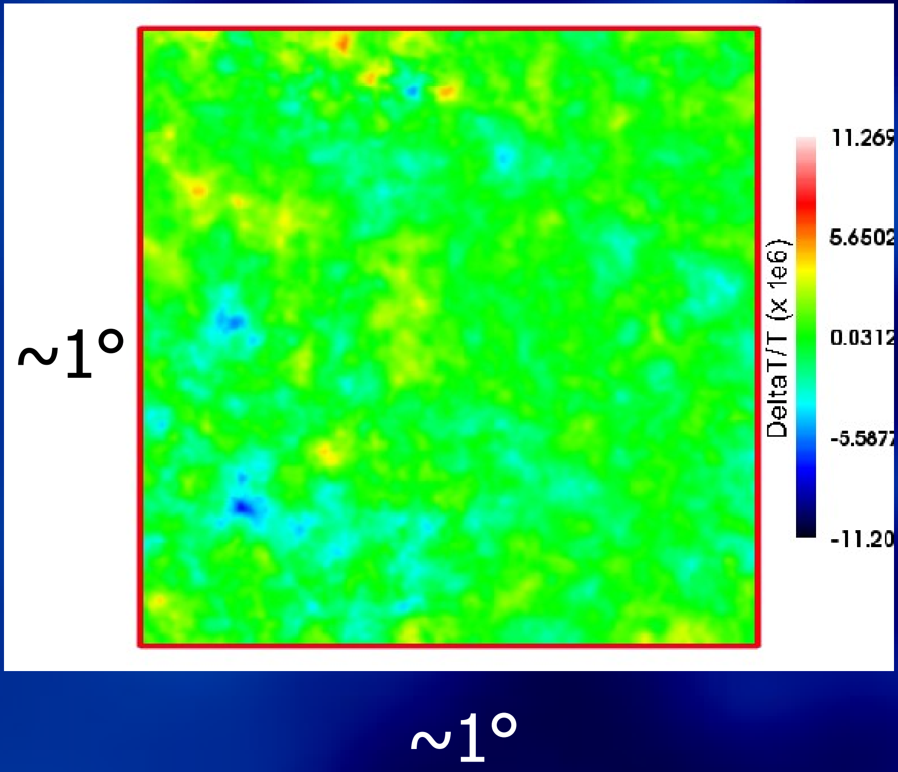
- The kSZ effect is one of the targets for upcoming CMB experiments: Atacama Cosmology Telescope (ACT), South Pole Telescope (SPT).
- Analytical estimates (Gruzinov & Hu 1998, Santos et al. 2003, McQuinn et al. 2005, Zahn et al. 2005): disagreement on strength and scales.
- Numerical estimates (Gnedin & Jaffe 2001, Salvaterra et al. 2005): considered small volumes.

Sample kSZ map from patchy reionization

- Sample kSZ map (100/h Mpc, f=250).
- Temperature variations given by LOS integral:

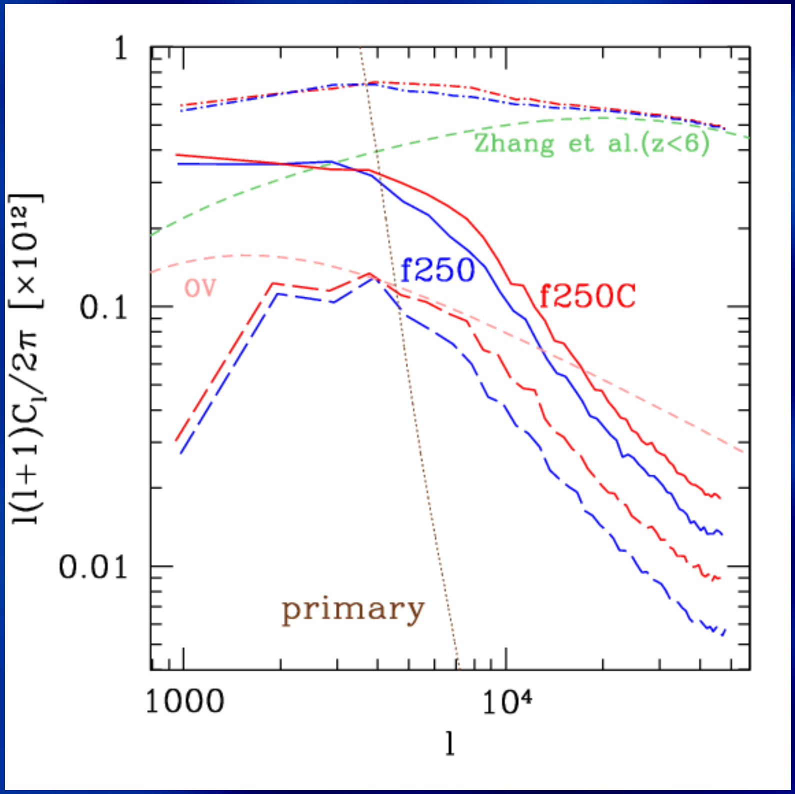
$$\frac{\Delta T}{T}(\hat{\mathbf{n}})_{\rm kSZ} = \sigma_T \int d\eta\, e^{-\tau(\eta)} a n_e \hat{\mathbf{n}} \cdot \mathbf{v},$$

- Fluctuations range $\Delta T/T = -10^{-5}$ to 10^{-5} , i.e. ΔT max/min are in the tens of μK at ~arcmin scales.



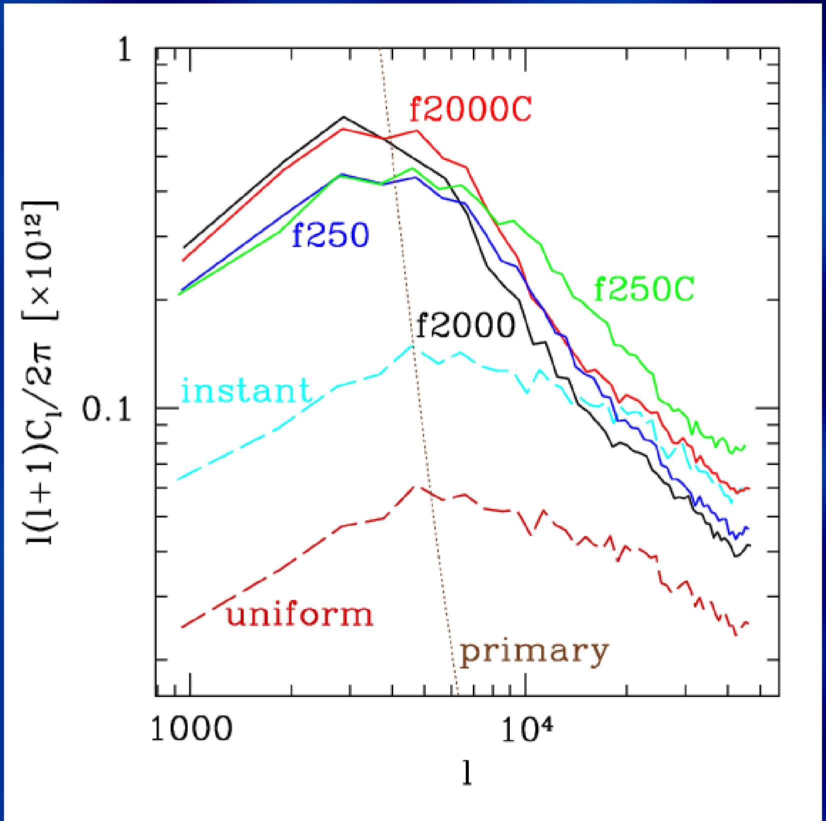
kSZ Power Spectra

- Power spectra from patchy reionization peak at ℓ~3000-5000, with a peak value ~1 μK.
- Below ℓ~10^4 patchy reionization dominates over OV-effect.
- Above ℓ~3000 never stronger than post-reionization non-linear kSZ (Zhang et al.).



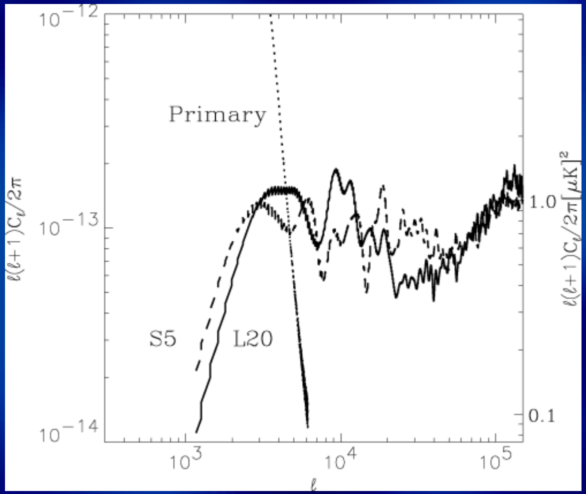
Importance of Patchiness

- We compare to instant and uniform reionization histories with the same τ_{es}.
- Instant:
  - order of magnitude less power for l~2000-10^4, but same large-l behaviour.
- Uniform:
  - much less power on all scales.
- Note: results without the correction for the missing velocity modes.

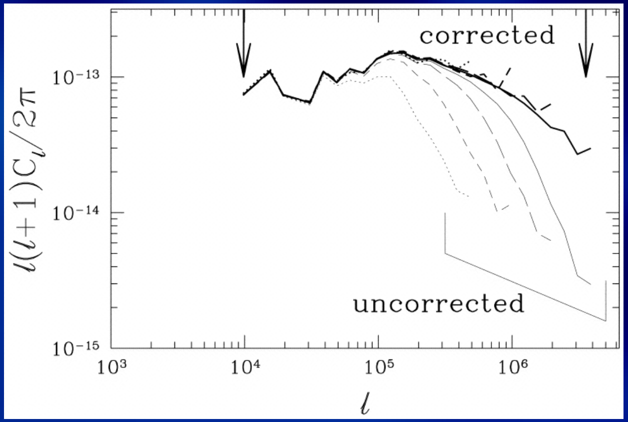


Previous Simulations

- Previous numerical simulations on smaller volumes:
  - 4/h Mpc (Gnedin & Jaffe 2001)
  - 20/h Mpc (Salvaterra et al. 2005)
- Much lower amplitudes: missing large scale power in velocity field.

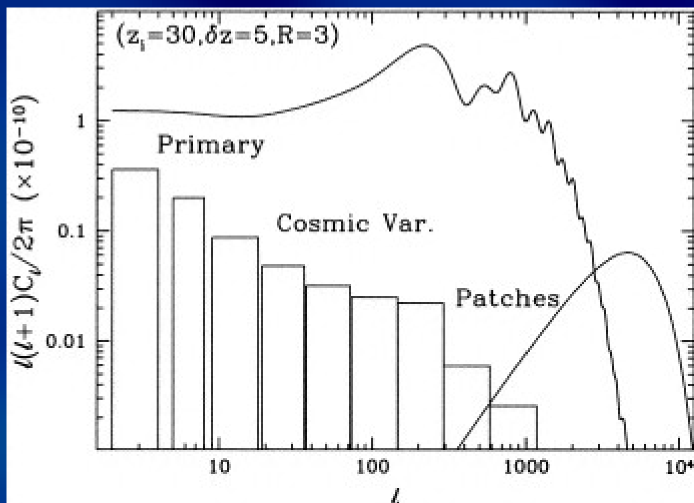


Salvaterra et al. 2005

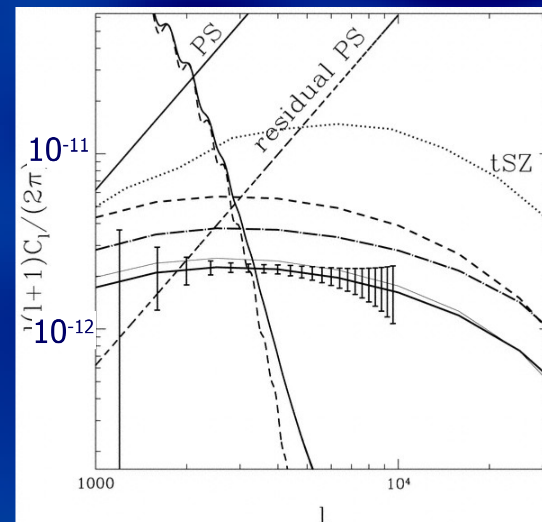


Gnedin & Jaffe 2001

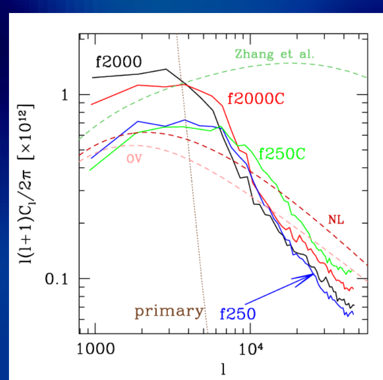
Analytical Estimates



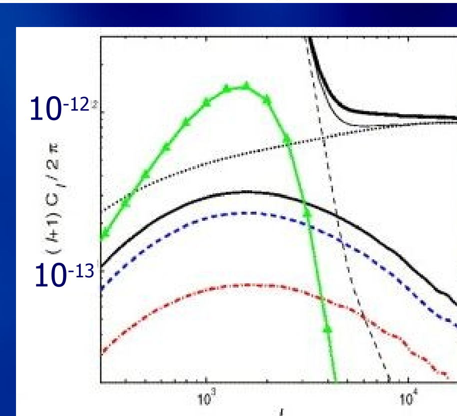
Gruzinov & Hu 1998



Santos et al. 2005



Our results



McQuinn et al. 2005

Analytical Estimates

- None of the existing analytical & numerical estimates matches our results (nor each other!!):
  - different amplitudes
  - shapes of the power spectrum (sharper or shallower)
  - ℓ-value of peak
- kSZ observations should give interesting clues about reionization!

35/h Mpc Simulations

Sim	f_{low}	f_{high}	clumping	Z(50%)	Z(99%)	τ_{es}
f2000_250	2000	250	1	16.2	13.5	0.197
f2000_250S*	2000	250	1	14.5	10.4	0.167
f2000C_250S	2000	250	C(z)	13.8	9.1	0.151
f250_250S	250	250	1	12.6	9.9	0.138
f250C_250S	250	250	C(z)	11.6	8.4	0.122

* also done at 406^3

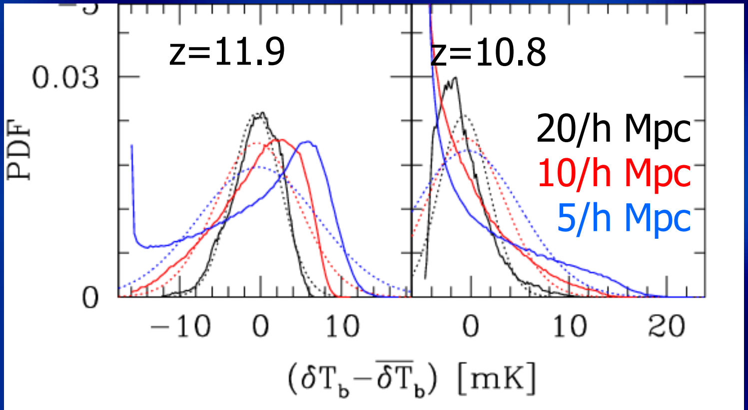
1st year WMAP cosmological parameters

Low mass halos: $10^8 < M < 10^9 M_\odot$, 'S': suppressed in ionized regions.

High mass halos: $M > 10^9 M_\odot$

Statistics

- The 21cm signal is strongly non-gaussian.



LOFAR EoR Experiment

- The plan is to observe three different fields of 2° by 2° for 100 nights with the 'virtual core', starting in 2008.
- After initial calibration at 1 s and 1 kHz resolution, the observations will be saved at 10 s and 10 kHz resolution for further processing. Total storage ~1PB.
- The final sensitivity should be of order 20-30 mK per beam.
- Resolution will be ~3′, or ℓ~7000.

21cm Challenge: Foregrounds

- Continuum Foregrounds:
  - Galactic Synchrotron (~100K)
  - Radio Galaxies (~10K)
  - Radio Halos & Relics (~10K)
  - Galactic & Extragalactic free-free emission (~1K)
- Smooth continuum should allow subtraction. Complications: foreground polarization, angular variations.
- Radio recombination lines.
- Ongoing observation campaign with WSRT/LFFE to characterize the foregrounds.

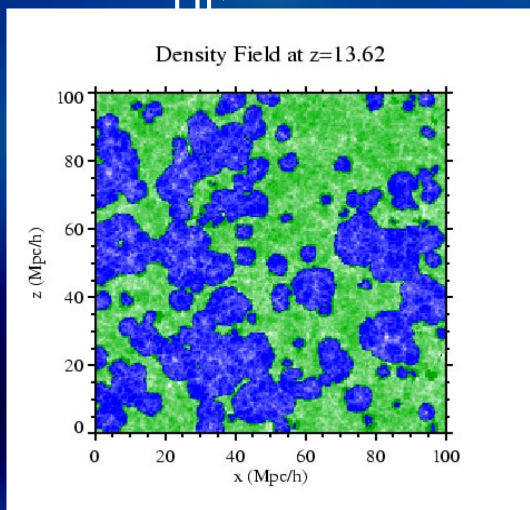
Implications for LOFAR

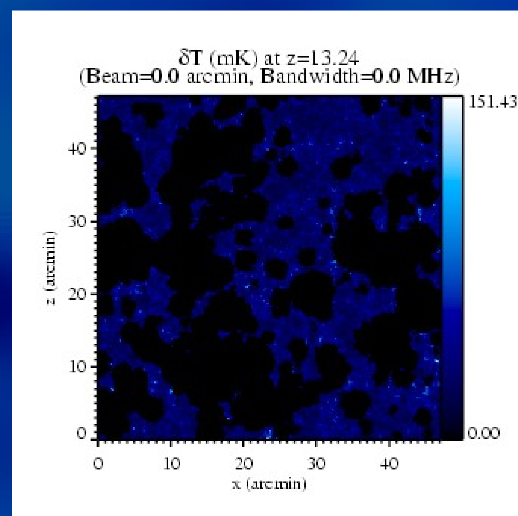
- LOFAR noise level will not allow imaging of redshifted 21cm.
- Analysis will be done on statistical data such as fluctuations as a function of frequency, and 2D (3D) power spectra.
- Perhaps some extreme peaks/valleys can be picked up, but only at the 2σ level.
- Maximum resolution (ℓ~7000) does capture the peak of the power spectrum; its location is slightly dependent on source efficiency.

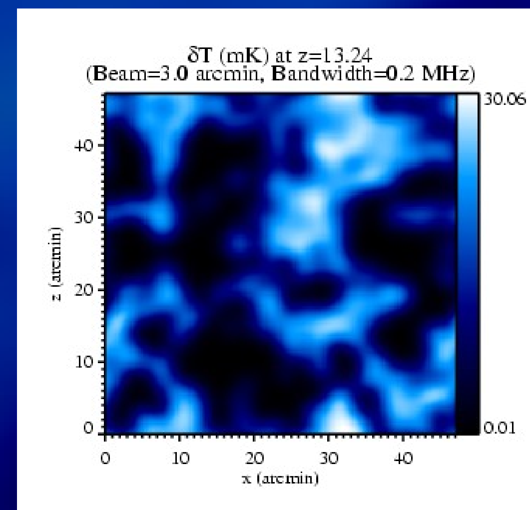
Image Slice

$T_S >> T_{CMB}$ $\quad$ $W(\delta\theta, \delta\nu)$

x_{HI}, δ $\quad$ δT







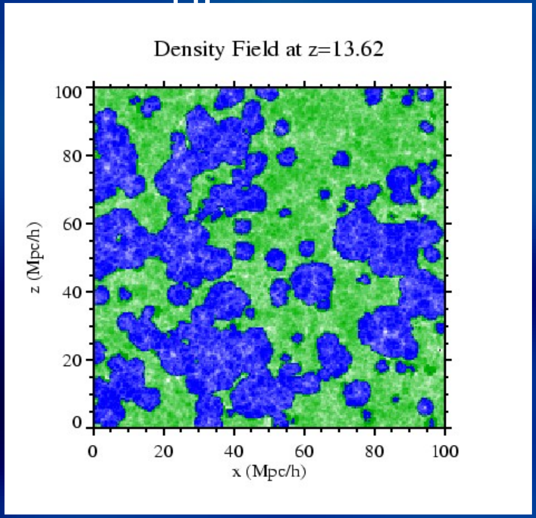
f2000

Image Slice

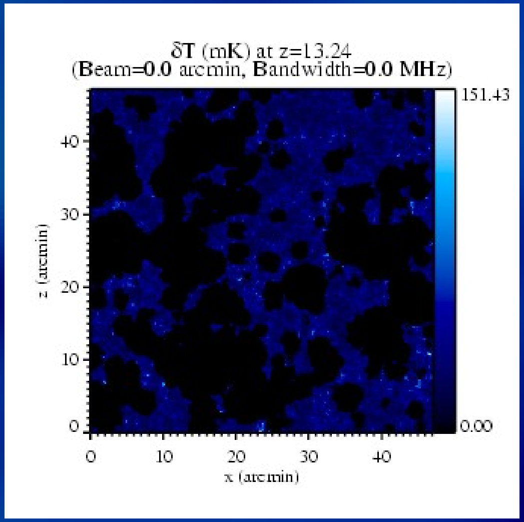
$T_S >> T_{CMB}$

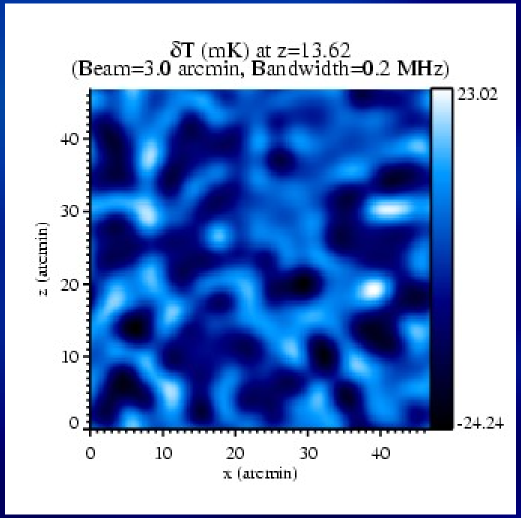
$W_{interferometer}$ $(\delta\theta, \delta\nu)$

x_{HI}, δ



δT





f2000