21cm Radiation from Reionization, the View from Simulations

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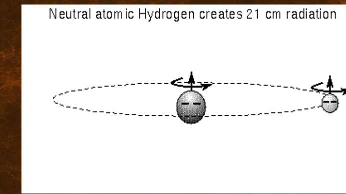
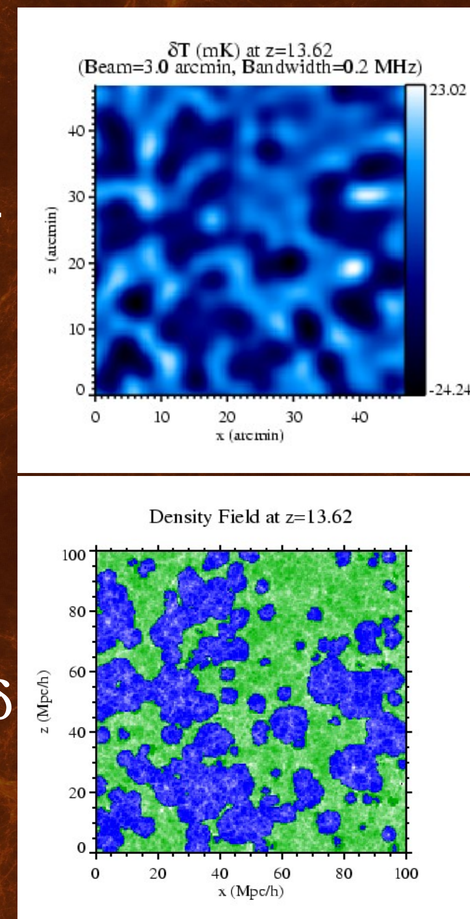
Redshifted 21cm Emission



- Observing the 21cm spin-flip transition of HI directly will probably provide the best probe of the when and how of reionization.
- In addition we may get data on the density power spectrum of the intergalactic medium (IGM).
- Attempts underway with GMRT, 21CMA, LOFAR, MWA.

δT

x_{HI}, δ



Mellema et al. (2006)

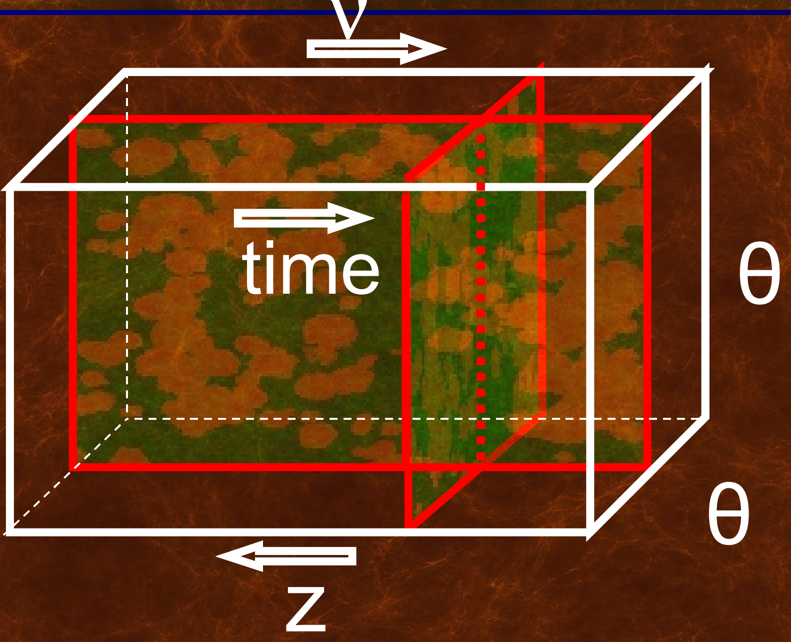
LOFAR
HBA Antennas

The Redshifted 21cm Signal

- The measured radio signal is the differential brightness temperature $\delta T_b = T_b - T_{CMB}$:

  $\delta T(z) \approx 27 \mathbf{x_{HI}} (1 + \delta)(1 - T_{CMB}/\mathbf{T_s})[(1+z)/10]^{1/2}$ mK

  (for WMAP3 cosmological parameters).
- Depends on:
  - x_{HI}: neutral fraction
  - δ: overdensity
  - T_s: spin temperature
- For $T_s \gg T_{CMB}$, the dependence on T_s drops out
- The signal is *line* emission: carries spatial, temporal, and velocity information.



The image cube: images stacked in frequency space

Simulation Methodology

- We rely on the paradigm of hierarchical structure formation in ΛCDM cosmology (using cosmological parameters, e.g. WMAP).
- Three steps:
  - Evolution of IGM density (δ) & (proto-)galaxies from a cosmological simulation.
  - Assign EUV luminosity to (proto-)galaxies.
  - Transfer EUV radiation through the IGM (x_{HI}).
- For large scale simulations galaxy formation is unresolved and baryons and dark matter have the same distribution:
  - Cosmological N-body simulation (for DM).
  - Transfer of EUV radiation can be done in postprocessing mode.

Cosmological Simulations

- We need
  - *Large* scale simulations.
    - Observationally needed (~degree fields of view).
    - Theoretically needed (cosmic variance, HII regions >>10 Mpc).
  - *Large* dynamic range simulations.
    - Dominant structures were *small* dwarf proto-galaxies.
    - Preferably resolve collapsed structures (`halos´) of **10^8 $M_\odot$** and up.
- This implies `Millenium-size´simulations (>10 billion particles).
- For example: 114/h Mpc box resolving $M_{halo} > 10^8 M_\odot$: **2/3** of halos have $M_{halo} < 10^9 M_\odot$ at z~9.

DM Halos as EUV Sources

- We have concentrated on stellar populations as sources of EUV radiation.
- Parameters:
  - Initial Mass Function
  - Star formation rate
  - EUV escape efficiency (10-20%)

ESO338-IG04

- Options:
  - Simple parametrization ($L \propto M_{DM}$, #photons per baryon).
  - Galaxy evolution models (DM + hydro, semi-analytical models): GADGET, GALFORM.
- If (lower mass) sources are missing: boost the luminosity of available sources (but this does influence the results!).

Simulation Characteristics

- I will concentrate on 21cm results from a range of our simulations.
- Three generations of simulations:
  - WMAP1 (100/h Mpc)
  - WMAP3 (100/h Mpc, 35/h Mpc)
  - WMAP3+ (114/h Mpc, 64/h Mpc)

- WMAP3 simulations have constant particle *number* (35/h Mpc: $M_{min}=10^8\ M_{¤}$, 100/h Mpc: $M_{min}=2\ 10^9\ M_{¤}$).

- New WMAP3+ simulations have constant particle *mass* ($M_{particle}=5\ 10^7\ M_{¤}$, so $M_{min}=10^8\ M_{¤}$).

Simulation Characteristics (2)

- We distinguish between low and high mass sources, the boundary lies at $M = 10^9 M_{\odot}$.
  - Low and high mass sources can have different photon producing efficiencies.
  - Low mass sources can be suppressed in ionized regions (feedback of reionization on galaxy formation), `Jeans mass filtering´.

- A redshift dependent (global) clumping factor can be used. This increases the recombination rates, and leads to later reionization.

Notation

- Our simulations are characterized by

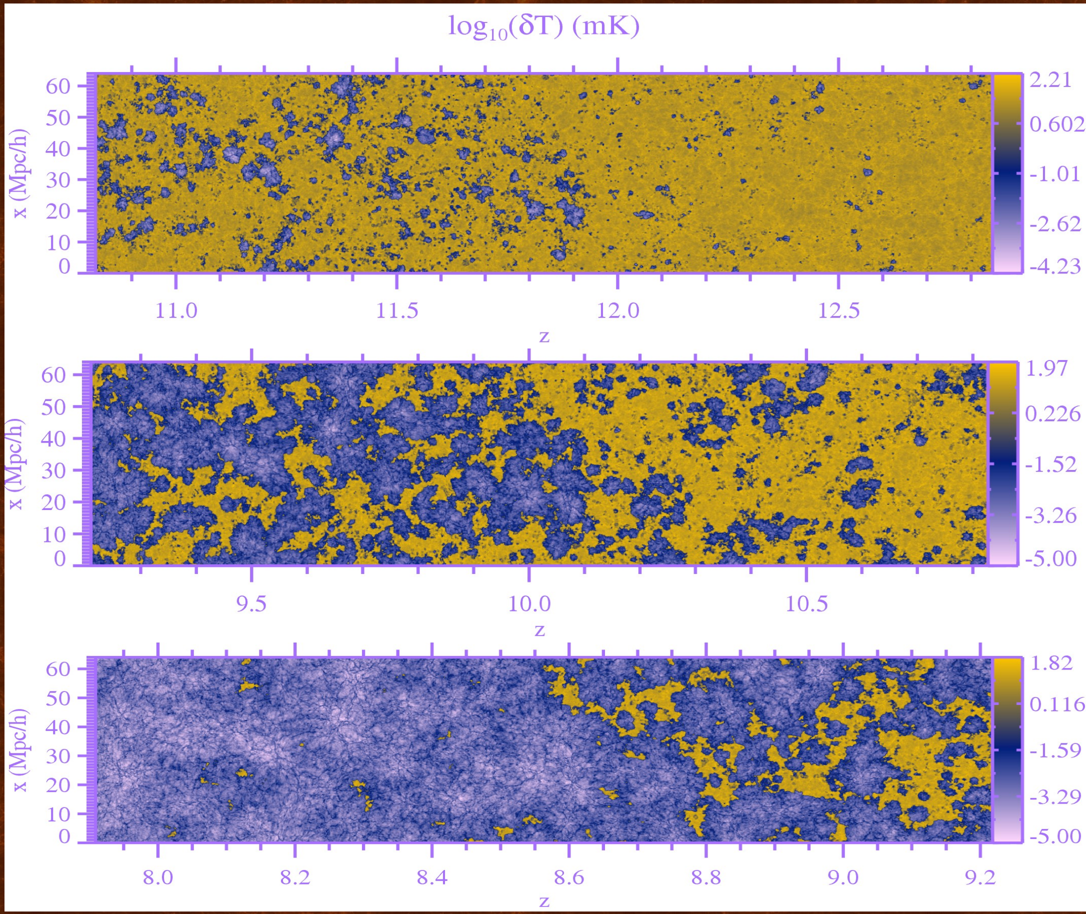
64Mpc_f100C_f250S_432

- 64Mpc: Boxsize = 64/h Mpc
- f100: High mass sources efficiency
- C: Clumping
- f250: Low mass sources efficiency
- S: Low mass sources suppression
- 432: RT grid = 432^3

21cm LOS Reionization History

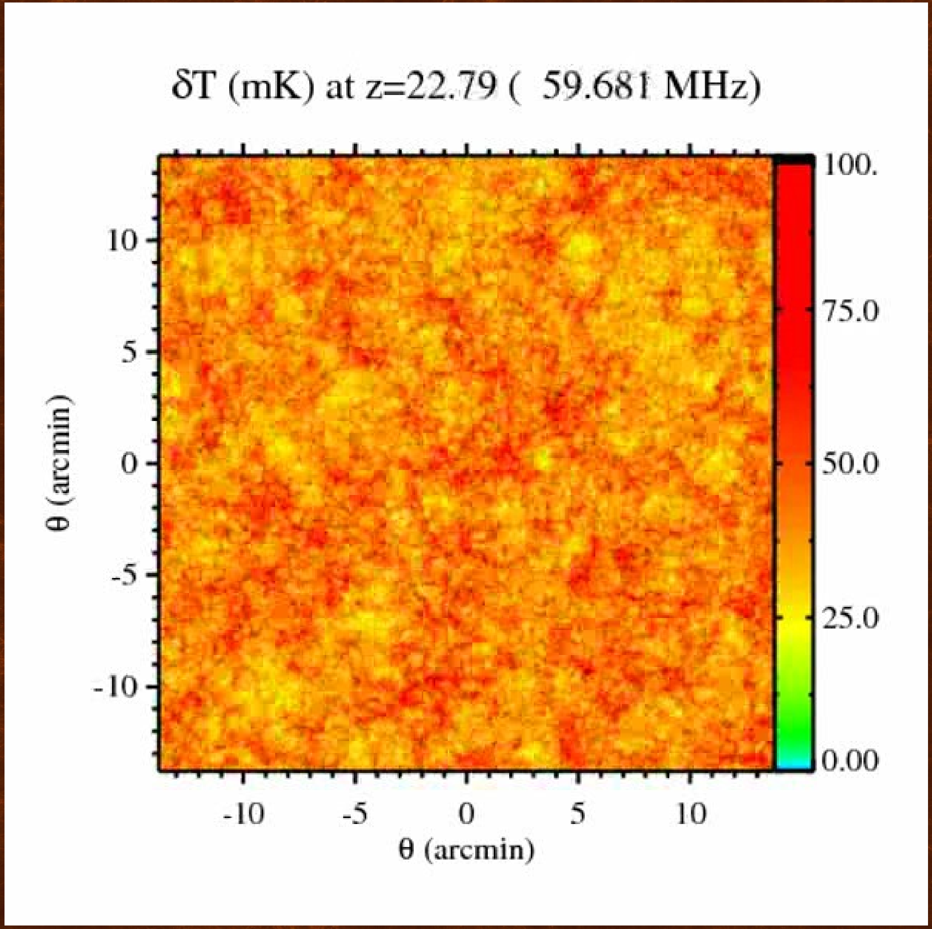
- Reionization histories along the line of sight.
- Frequency/redshift direction contains evolutionary, geometrical and velocity information.

- Simulation: 64Mpc_f100_f250S_432 (64/h Mpc, $M_{halo} > 10^8$ $M_\odot$), with feedback on low mass sources.



Flying through Time and Space

- Reionization has a complex geometry of growing and overlapping bubbles.
- Here illustrated with the redshifted 21cm signal:
  - High density neutral regions are red
  - Ionized regions are black.
- Movie generated by using the periodicity of the volume, but rotating it to avoid passing through the same structures.



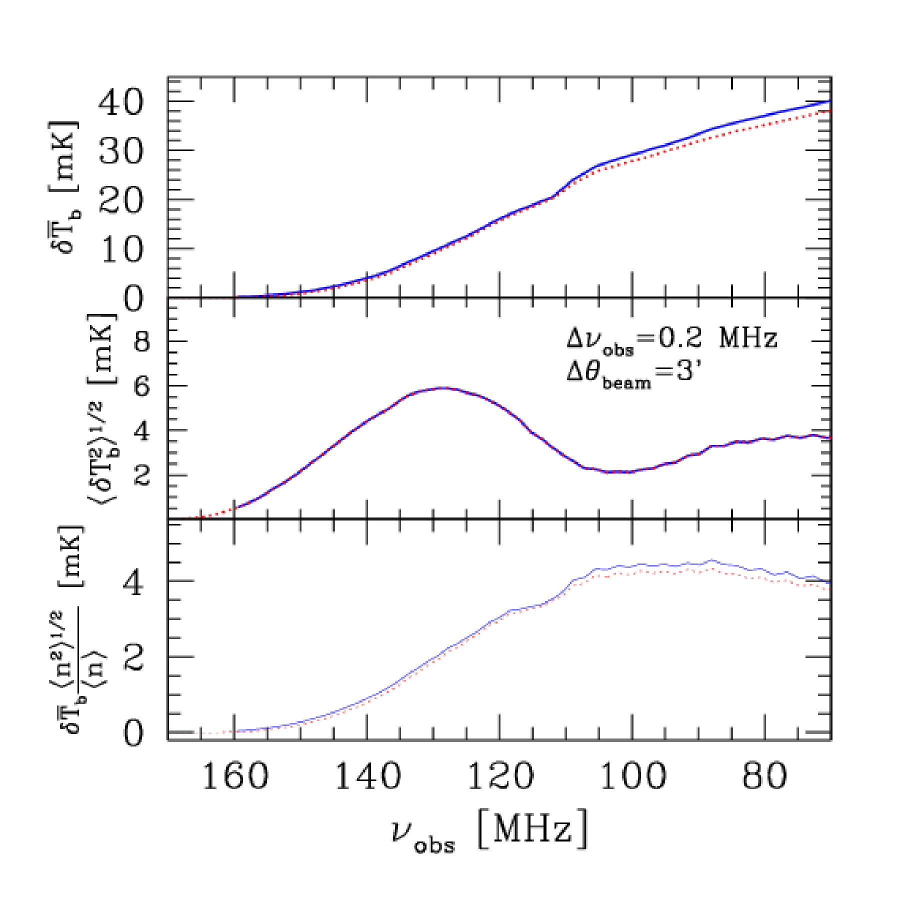
Simulation 64Mpc_f100_f250S_432

Statistical Measurements

- The sensitivity of the upcoming EoR experiments will be too low to image 21cm from reionization pixel by pixel: Statistical measurements needed.
  - **First goal**: to reliably detect signatures from reionization (and separate them from foreground and instrumental effects).
  - **Second goal**: to interpret them in terms of astrophysics (source population and properties).
- Luckily, the 21cm line signal is rich in properties:
  1. Global signals: mean signal, fluctuations.
  2. Angular properties: power spectra
  3. Frequency properties: correlation length, Kaiser effect
  4. Non-Gaussianity.

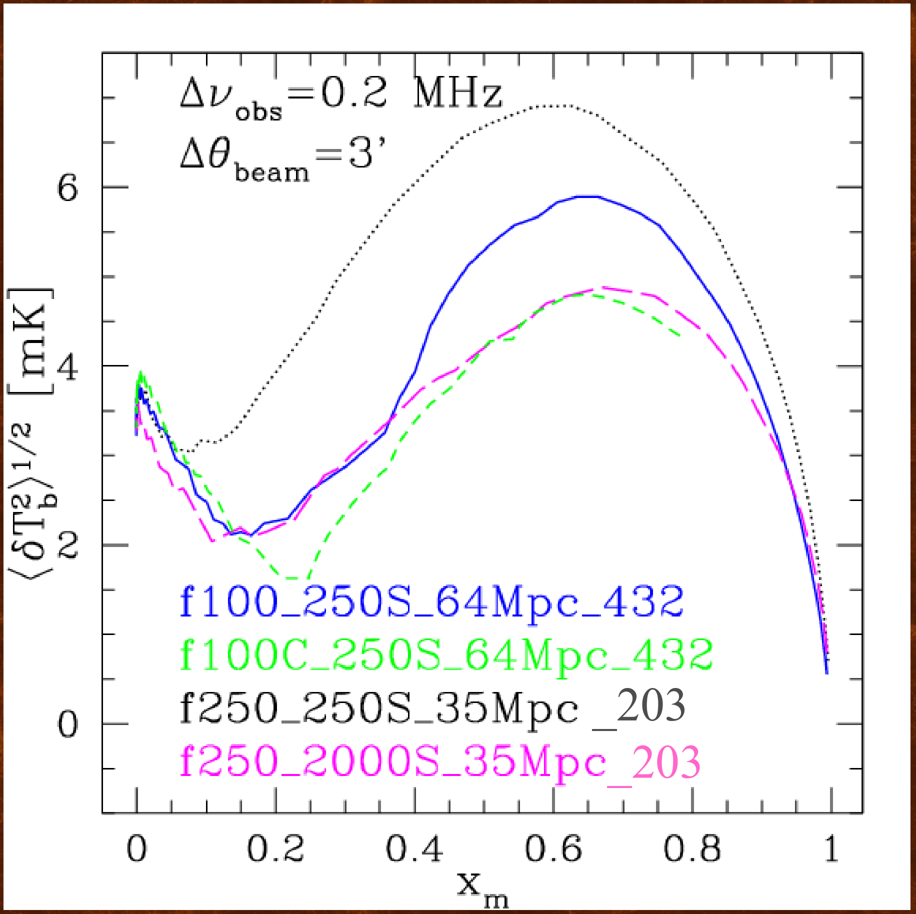
Global Signals

- A single dish telescope could measure the change of the global signal with frequency: simulations do not show a sharp transition.
- The corresponding measurement by an interferometer would be the change of the 21cm (rms) fluctuations.
- Simulations: 64Mpc_f100_f250S_432 and 64Mpc_f100_f250S_216



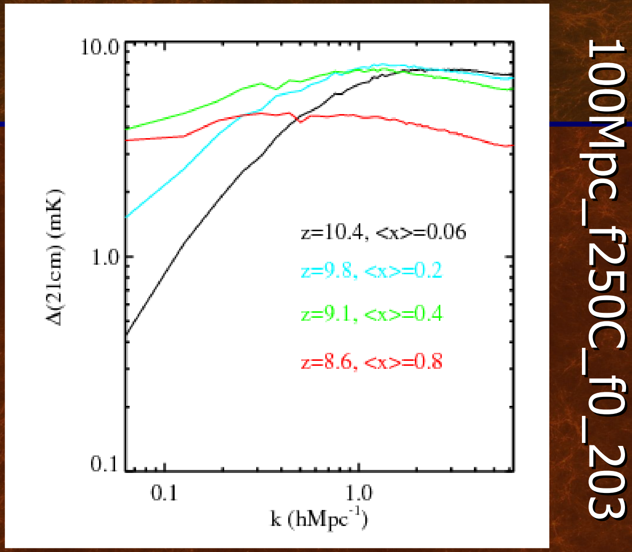
Evolution of Fluctuations

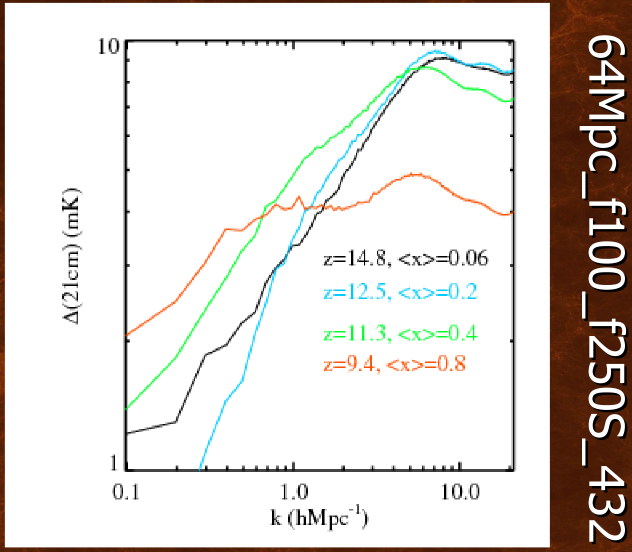
- When plotted against the mean mass-weighted ionization fraction x_m(HII), for late times the evolution of fluctuations shows roughly similar behaviour for different (simulation) resolution and source parameters, but the amplitude differs.
- Peak around x_m(HII)~0.6-0.7 (shifts to lower values for higher angular resolution).



Power Spectra

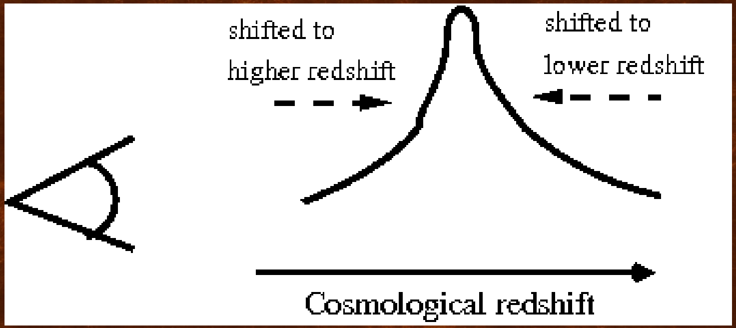
- Information about the length scales can be obtained from the power spectra.
- Simulations show clear trends of shifting power to larger scales as reionization progresses, and a flattening of the power spectra.
- Note that the angular power spectrum is measured directly by an interferometer, the multipole l is equivalent to $\sqrt{(u^2+v^2)}$ in a visibility map.





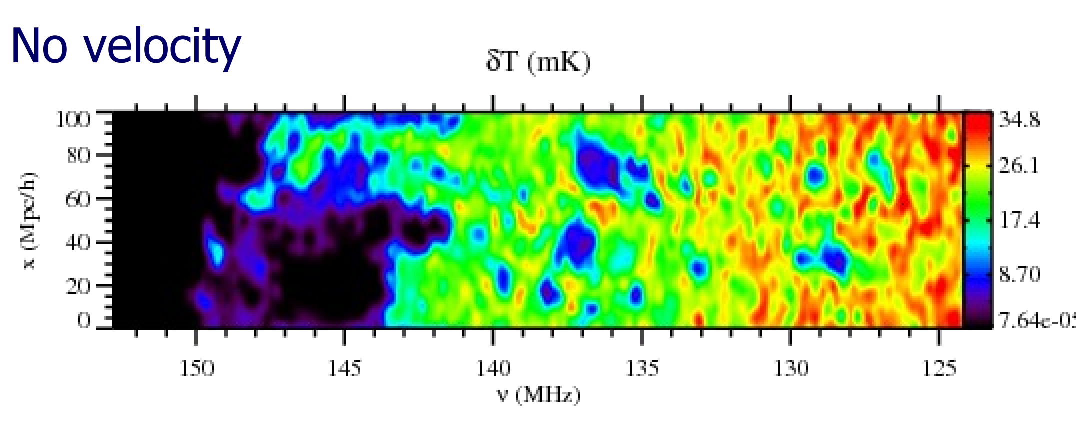
Velocity Distortions

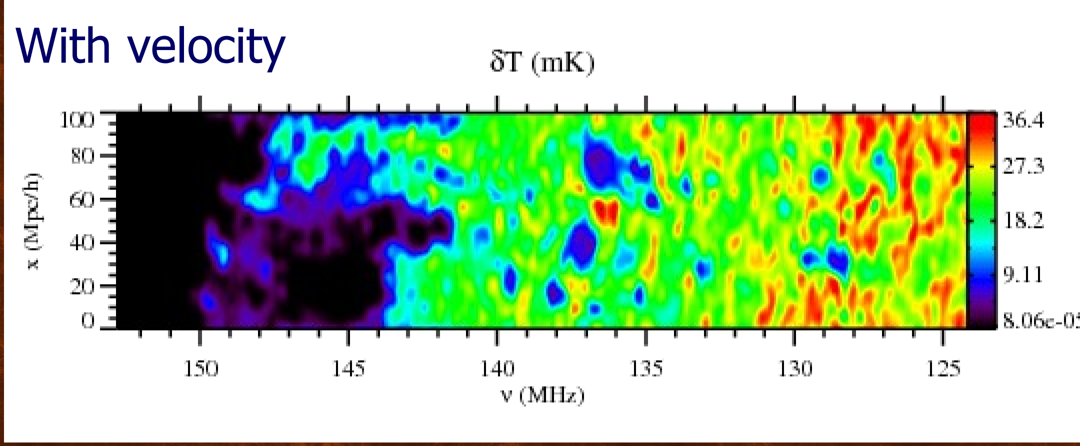
- Due to the peculiar velocity field, the signal can be displaced from its cosmological redshift.
- `Kaiser effect´ or `velocity compression´: due to infall, signal concentrates at the high density peaks.
- This is clearly seen in the simulations and gives ~30% increase in fluctuations (and up to a factor of 2).
- This shows that fluctuations calculated from density and ionization fractions alone miss some power → better to use image cubes.



Effect of the Velocity Field

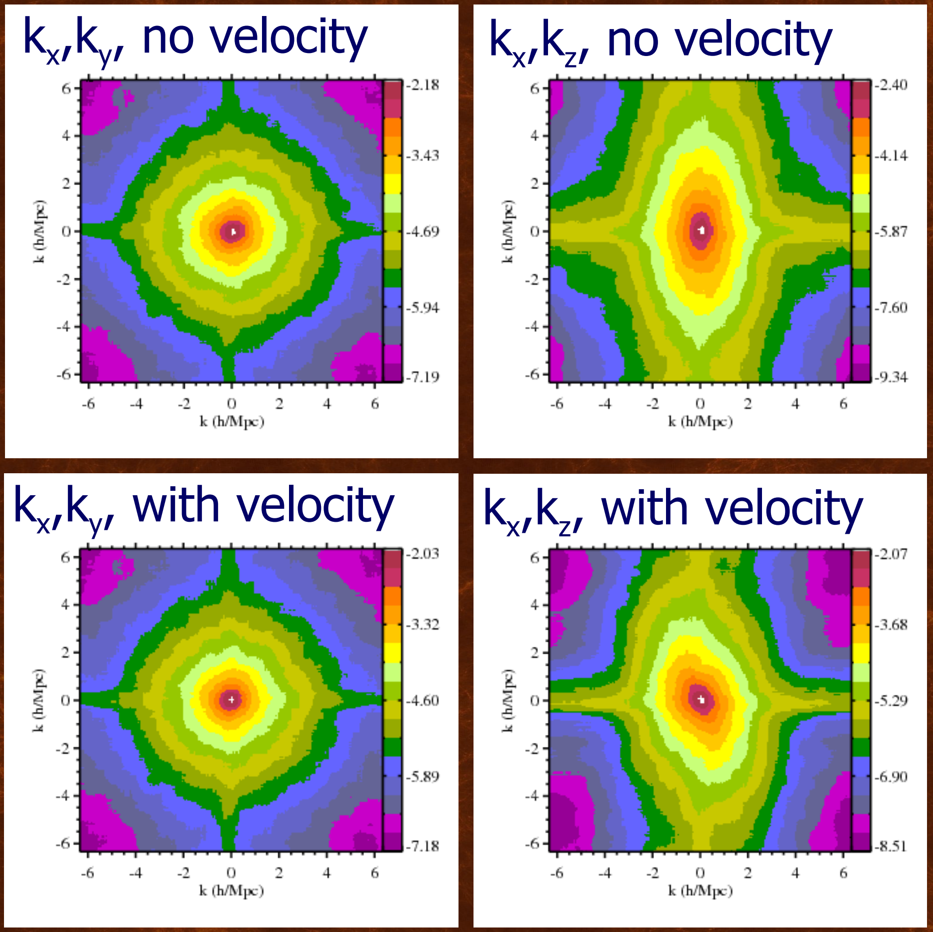
- Adding the velocity distortions visibly increases the fluctuations in the neutral medium.
- Maximum value also larger.
- The effect remains noticeable even at LOFAR-like resolution (3′, 200 kHz).
- Simulation: 100Mpc_f250C_f0_203.





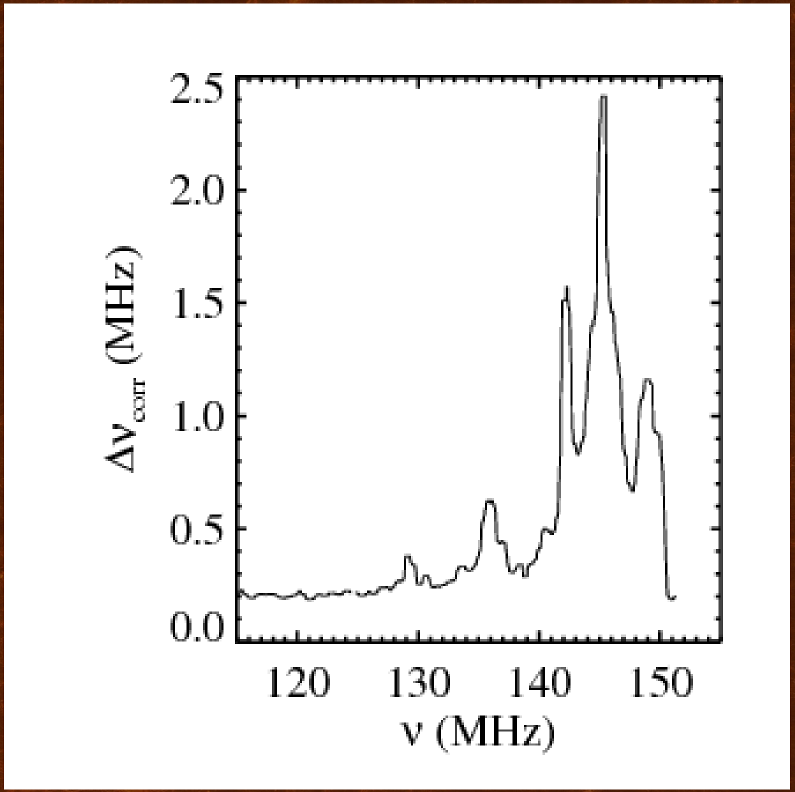
And in Fourier Space...

- Since the velocity gradients responsible for the distortions are related to the density field, one can write P(**k**) in terms of a polynomial in $\mu=\cos(\theta_k)$, the angle between the LOS and the **k** vectors (see Barkana & Loeb 2005).
- This results in warped contours in Fourier space when looking along the z-axis.
- Should allow direct characterization of density power spectrum.



Correlation Length

- Reionization changes the correlation length along the frequency axis in a characteristic way: formation of large HII regions increases correlation length from ~200 kHz to ~1 MHz.
- Still substantially shorter than for the continuum foregrounds, so it could be used as a test for proper foreground subtraction.

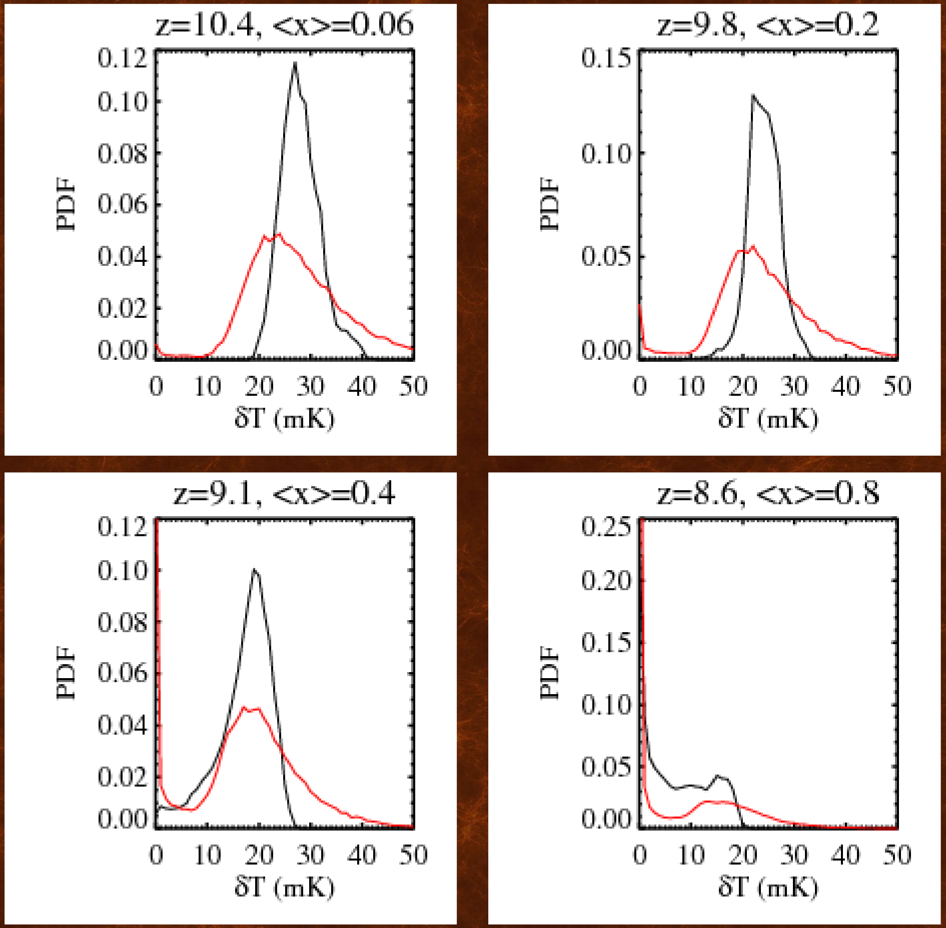


Simulation 100Mpc_f250C_f0_203

Non-Gaussianity

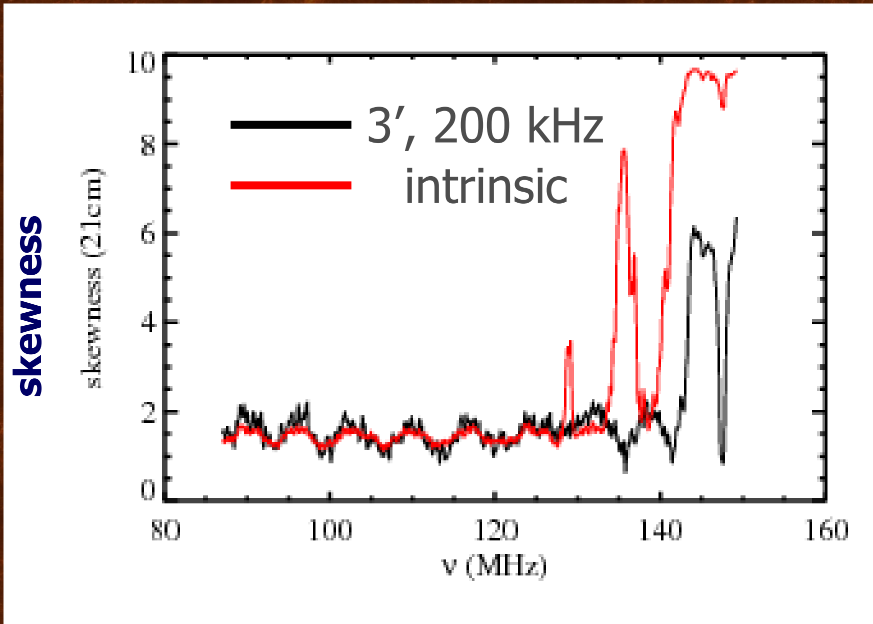
Simulation 100Mpc_f250C_f0_203

- Probability distribution functions of the 21cm signal are clearly non-Gaussian.
- Limited resolution reduces the effect somewhat, but still noticeable.
- Towards the end of reionization the effect is largest.



Skewness

- Non-Gaussianity suggests that measuring the skewness could be an interesting diagnostic.
- The simulations show a clear evolution of skewness with increasing ionization, with some differences between different simulations.
- Finite resolution modifies skewness, but does not remove it.
- Skewness may offer an good way to detect the signal, if remnants of foreground subtractions and other effects are dominantly Gaussian (cf. Harker et al. 2008).



Conclusions

- Numerically modelling reionization is challenging, requiring large dynamic range simulations.
- The 21cm signal has a rich set of properties which should help in recognizing it in the data of upcoming EoR experiments.
- The later stages of the EoR are characterized by increases in the
  - rms fluctuations
  - skewness
  - correlation length in frequency direction
- Power spectra also show a characteristic evolution to flatter structures, as well as warped contours in the redshift/frequency direction due to velocity compression.