Simulating cosmic reionization at large scales

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Simulating cosmic reionization at large scales:

- 1. The geometry of reionization
  - Trying to understand the size and spatial distribution of the ionized and neutral patches and their evolution
- 2. The 21-cm emission features and statistical signals
  - Approach for direct detection of the epoch of reionization

1. Geometry of reionization

- Previous reionization simulations only small volumes, not exceeding 20 h^{-1} commoving Mpc.
- Need to resolve small galaxy which dominate at early times
- Most methods are based on ray-tracing radiative transfer method, which grows proportionally to number of ionizing sources, limiting size.

New Simulation

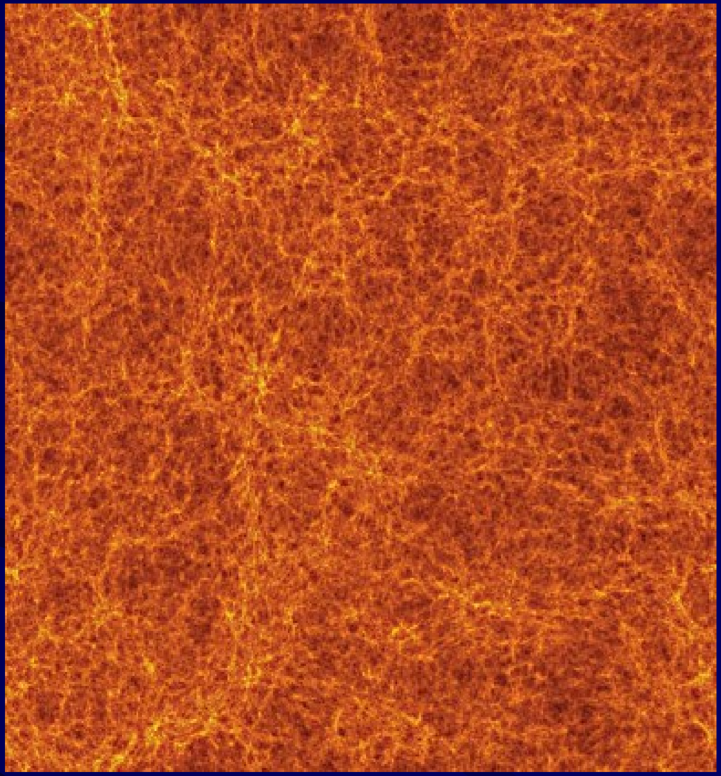
- They create the first large-scale radiative transfer simulation with a volume of $(100\ h^{-1}\ \mathrm{Mpc})^3$
- Use codes PMFAST and C^2-RAY to do a N-body simulation that can resolve down to dwarf galaxies
- New Ray-tracing radiative transfer method, correctly track ionization fronts

Assumptions

- Gas closely follows dark matter distribution
- Flat ΛCDM with:
  - $\Omega_m = 0.27$
  - $\Omega_\Lambda = 0.73$
  - $\Omega_b = 0.044$
  - $h = 70$ km s^{-1} Mpc^{-1}
  - $\sigma_8 = 0.9$
  - $n = 1$

N-body Simulation

- Resolution: 1624^3 = 4.28 billion dark matter particales and 3248^3 computational cells.
- Particle mass: 2.5 x 10^7 M_Θ
- Only deal with haloes of 100 or more particles



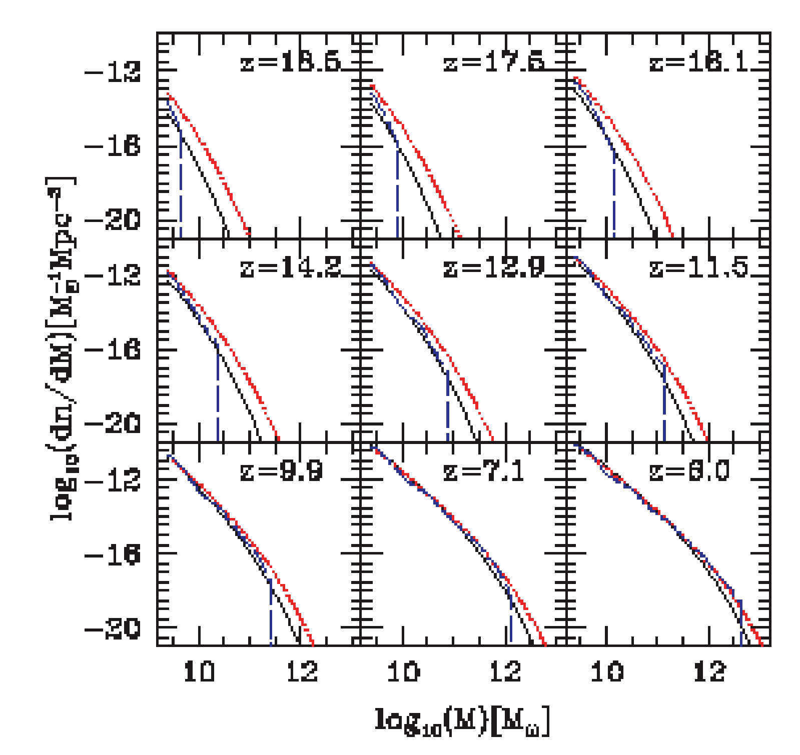
Early structure formation at z = 10

N-body Simulation

- Minimum halo mass of $2.5 \times 10^9\ M_\Theta$, which would be a dwarf galaxy
- The first haloes form at $z \approx 21$, reaching 85,000 haloes by $z \approx 11$, and 0.8 million by $z = 6$.

Halo Mass Functions

- At lower redshifts (z≤10) it agrees with Sheth-Tormen (ST) mass function, but overestimates number of haloes at high redshift
- The Press-Schechter (PS) approximation underestimates the number of rare haloes in the exponential tail



Blue - Halo mass function

Black - PS

Red - ST

Simulation

- Assume a fixed temperature of 10^4 K everywhere.
- Ionizing sources are based on haloes from simulation. Sources falling within the same cell of the radiative transfer grid are combined together.

Ionizing Flux

$$\dot{N}_\gamma = f_\gamma \frac{M\Omega_{\rm b}}{\Delta t_i \Omega_0 m_{\rm p}},$$

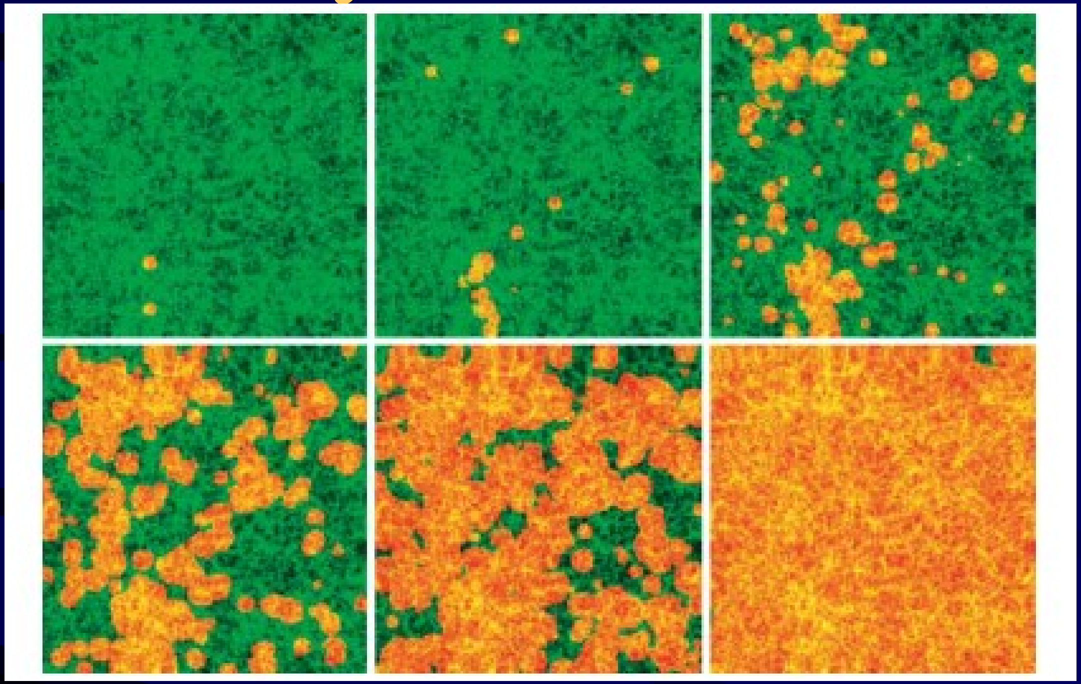
$$f_\gamma = f_* f_{\rm esc} N_i$$

- f_γ is the efficiency factor
- N_γ is the number of ionizing photons emitted by source per unit time
- N_i is the total photon production per stellar baryon
- f_* is the star formation efficiency
- f_{esc} is the ionizing photon escape fraction

Ionizing Flux

- They adopt a $f_{\gamma} = 2000$
  - either top-heavy intial mass function of N_i = 50,000, f_*=0.2 and f_{esc}= 0.2
  - or Salpeter IMF with N_i = 10,000, f_*=0.4 and f_{esc}= 0.5

Geometry of Reionization



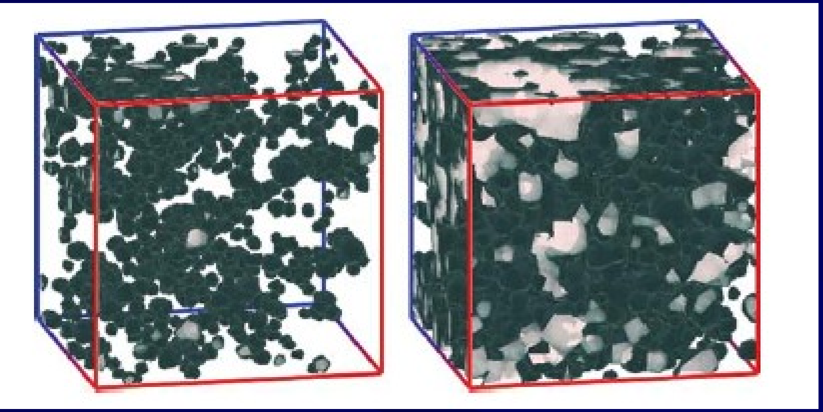
- Slices through simulation volume at z = 18.5, 16.1, 14.5, 13.6, 12.6, and 11.3, neutral = green, ionized = yellow, H_{II} = red

Geometry of Reionization

- First H_{II} regions appear at z~21.5, and expand to a few comoving Mpc by z~18
- Highly clustered and quickly merge into larger regions
- Early ionization is dominated by local source clustering.
- http://www.cita.utoronto.ca/~iliev/xy_f2000_406_5mpc_thick_thin.gif

Geometry of Reionization

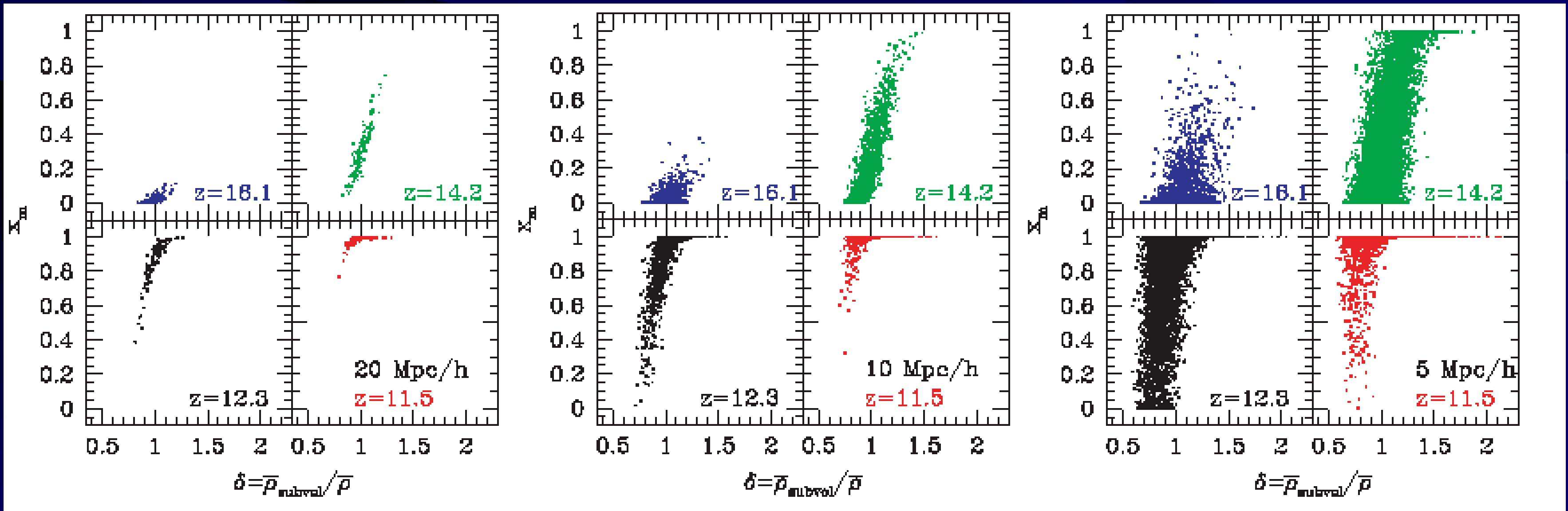
- As reionization progresses regions become less clustered and have local overlap
- Whole box ionized by z~11.3



Volume with H_{II} regions at redshifts z=14.74 and z=13.62

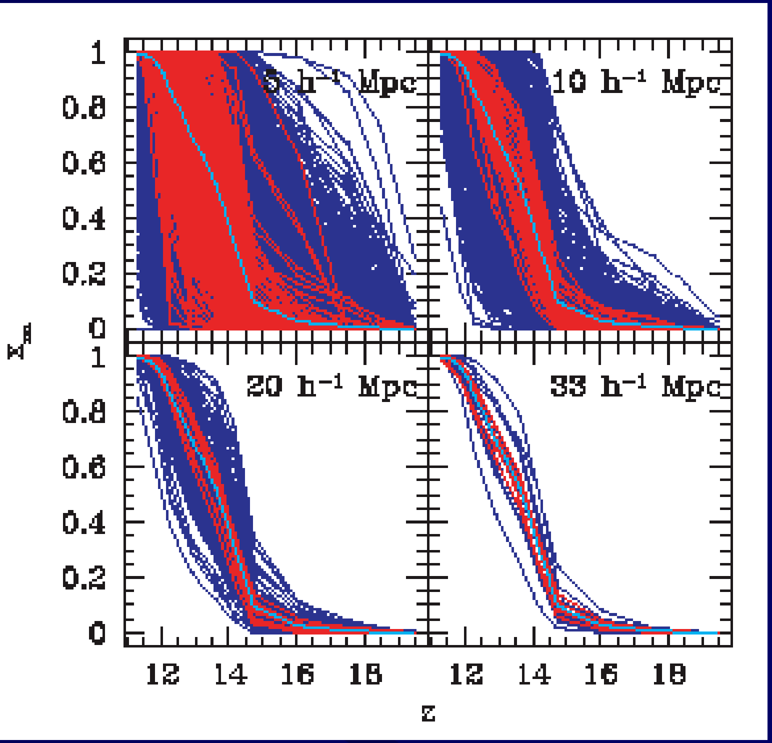
Density and Ionization

- No simple relation between mean density of a region and its reionization history, but most overdense regions become ionized first.
- Graph of mass-weighted ionized fraction vs. average density at different redshifts

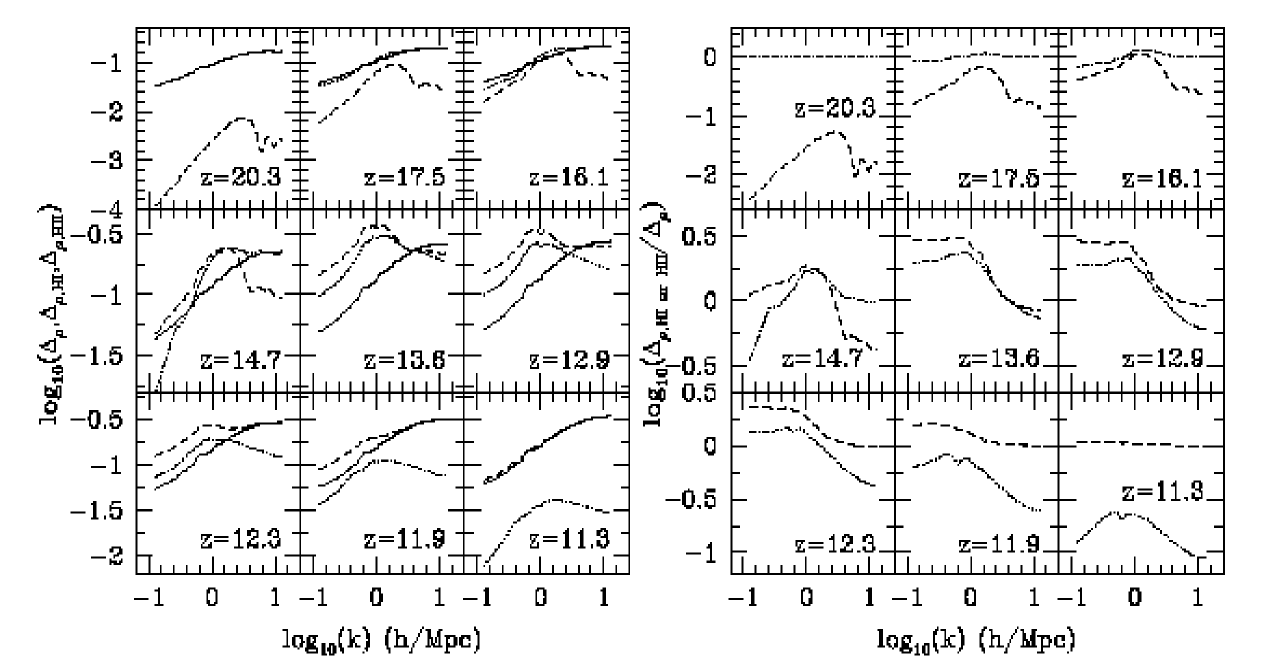


Density and reionization

- Blue = Evolution of mass-weighted ionized fraction in non-overlapping cubical subregions of different sizes.
- Red = Mean density
- Cyan = global evolution of mass ionized fraction



Power Spectra



Dotted = Variance of 3D power spectra of neutral gas denisty

Solid = Total density

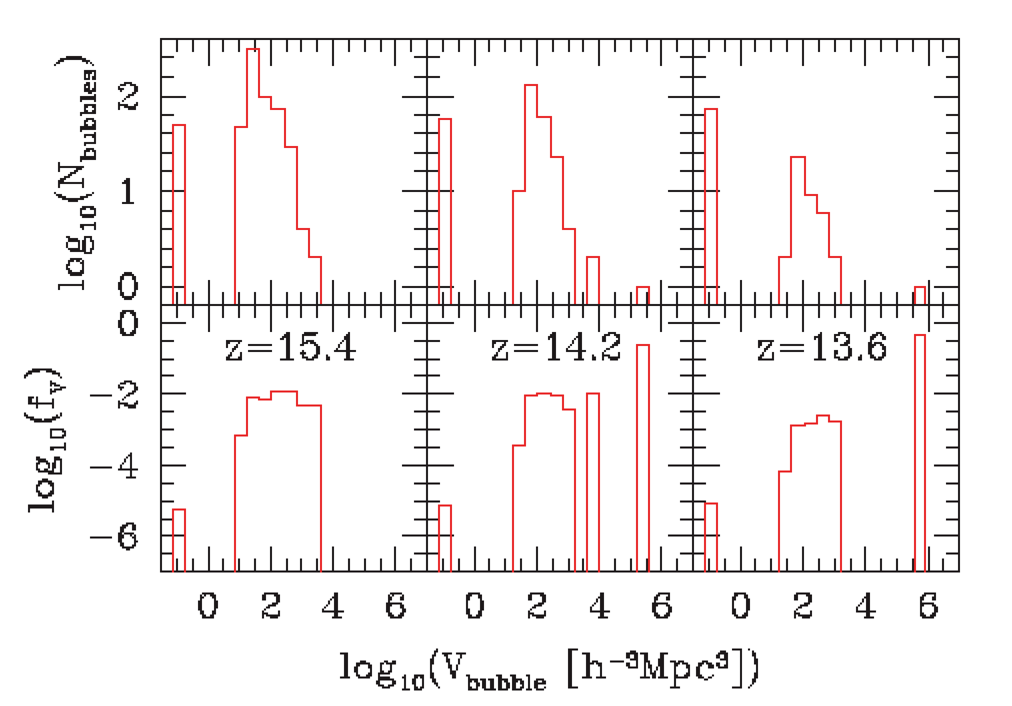
Dashed = ionized gas density

“Friends-of-Friends”

- To find individual ionized regions used a “Friends-of-friends” algorithm
  - 2 cells are linked together if their ionized fractions are larger than 0.5
  - This lets them catalogue the H_{II} bubbles and their merger history

Size Distribution

- Total bubbles
- At higher redshifts, no large bubbles, and more small-medium sized
- At lower redshifts, mostly dominated by large bubbles



Top - number of H_{II} bubbles of that size

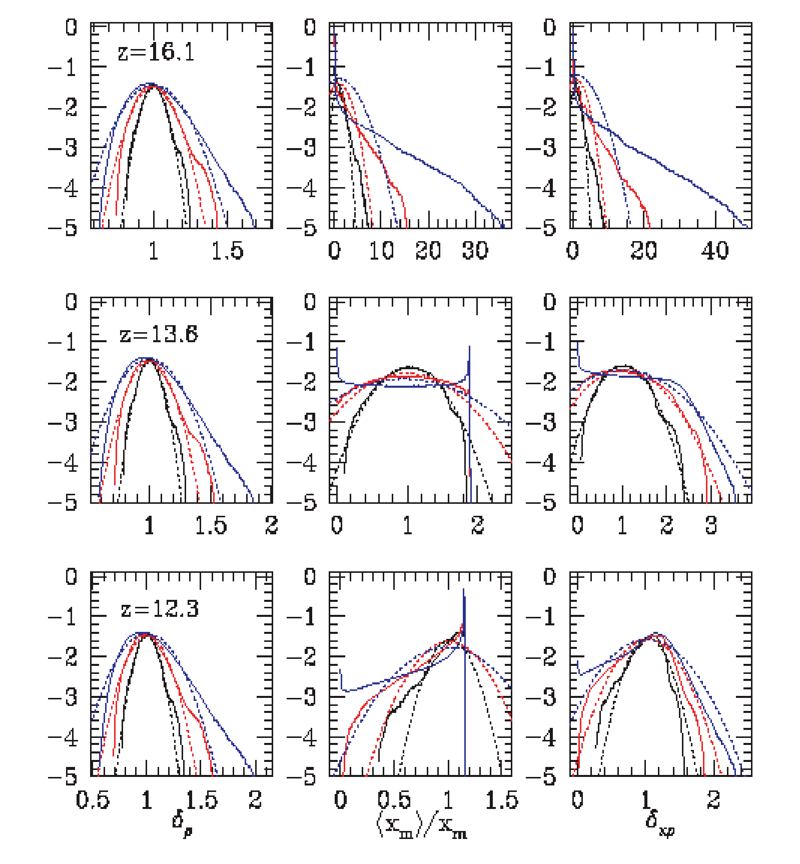
Bottom - volume filling factor of the bubbles

Size Distribution

- By redshift z~14.2 there are three H_{II} regions larger than 10^4 $(h^{-1}\ \mathrm{Mpc})^3$ and each occupies a few percent of the total volume
- By z~13.6 they become one large bubble which occupies half the total volume
- By z~11.5, one big large bubble

Non-Gaussian nature of Reionization

- Probability Distribution Functions
- Left: density in mean density
- Middle: mass ionized fraction
- Right: density in mean ionized density



2. The 21-cm emission features

- Observations of 21-cm line of hydrogen could be a good approach for direct detection of the epoch of reionization
- The 21-cm radio line is due to a spin-flip transition of neutral hydrogen.
- Needs to be decoupled from the CMB

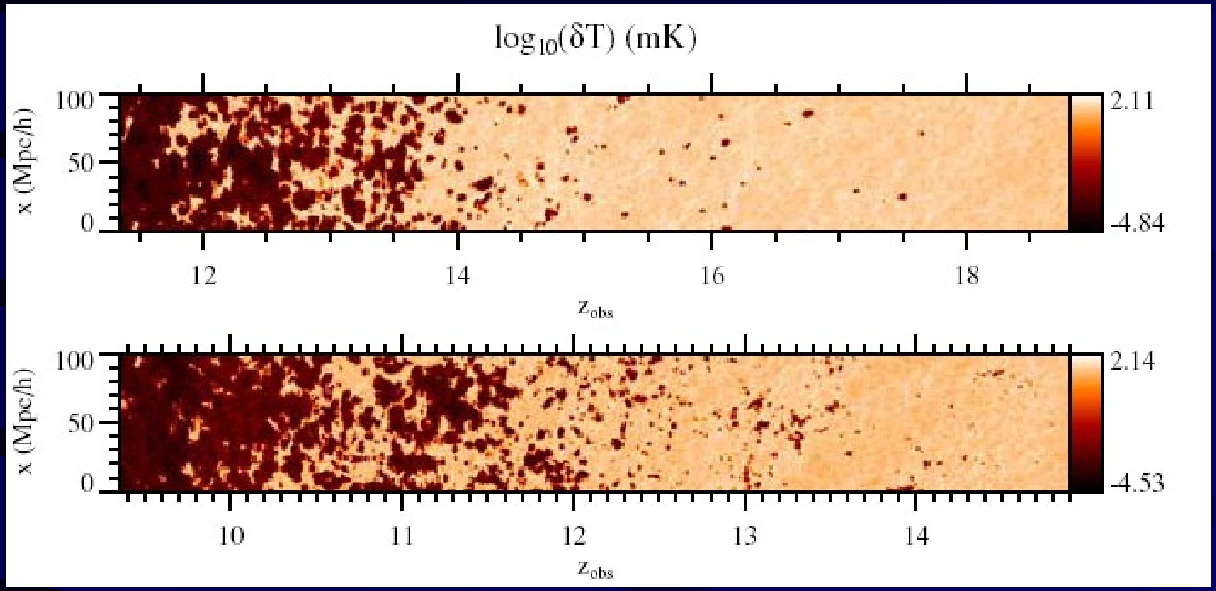
Models

Table 1. Simulation parameters and global reionization history results.

	f2000	f2000_406	f250	f2000C	f250C
Mesh	203^3	406^3	203^3	203^3	203^3
f_γ	2000	2000	250	2000	250
$C_{\rm subgrid}$	1	1	1	$C(z)$	$C(z)$
$z_{50\,\rm per\,cent}$	13.6	13.5	11.7	12.6	11.0
$z_{\rm overlap}$	11.3	$\sim$11	9.3	10.15	8.2
$\tau_{\rm es}$	0.145	$\sim$0.14	0.121	0.135	0.107

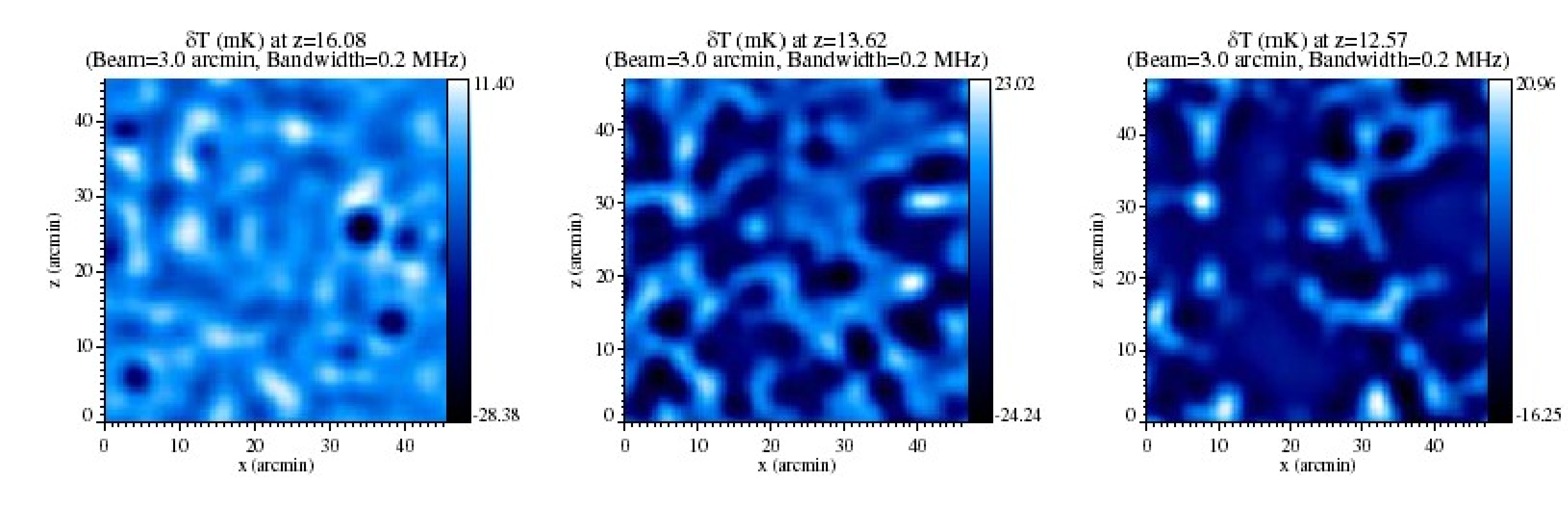
- f2000- model from paper 1
- f250 - efficiency factor of 250
- C add subgrid gas inhomogeneities - with clumping factors - improved small scale clumping

Comparing the models



- Top - f2000, bottom - f250
- Observationally they correspond to slices through and image-frequency volume
- Reionization occurs at higher redshifts for f2000

Sky Maps



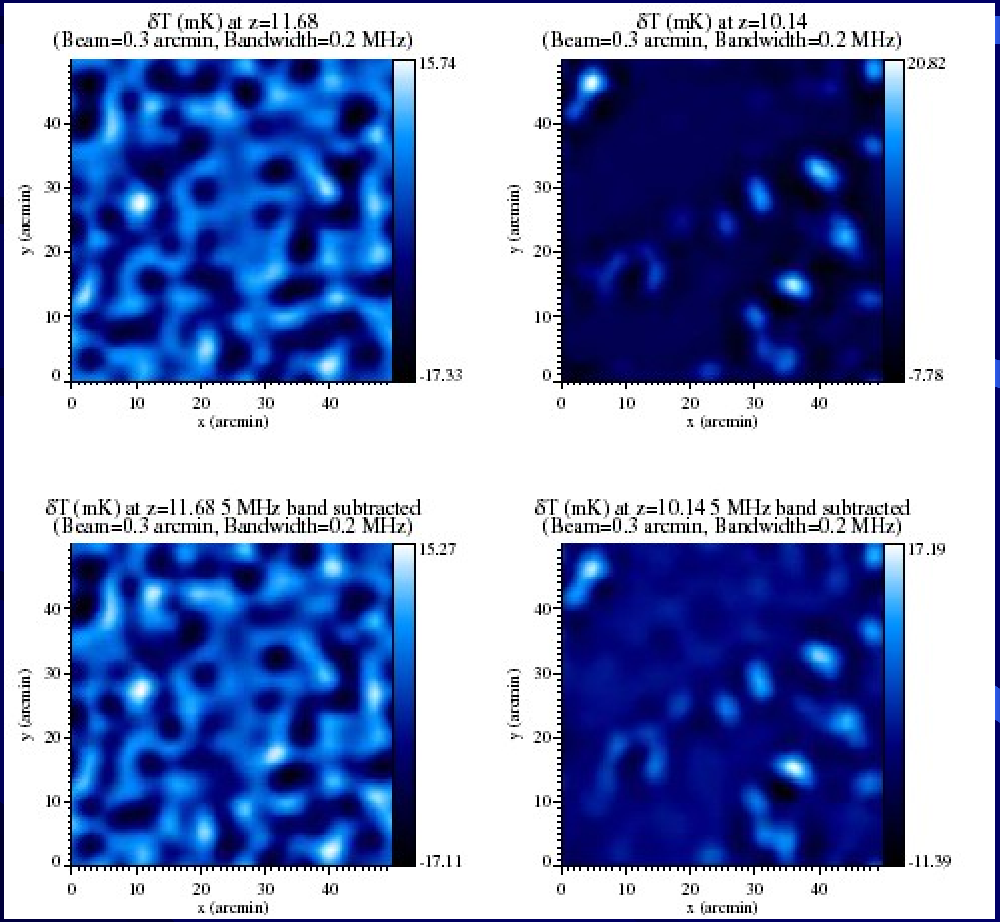
- Sky map as seen at redshifted 21 cm line
- With 3-arcmin FWHM compensated Gaussian beam and 0.2-MHz bandwidth
- Large H_{II} regions are apparent as holes in the radiation map.

Sky Maps

- Although obtaining images of 21-cm emission would be ideal, its unlikely in the near term because of sensitivity limits and dominate foregrounds.
- Can approximate foregrounds with a slowly varying power law in frequency, subtract signal over a bandwidth, they use 5 MHz

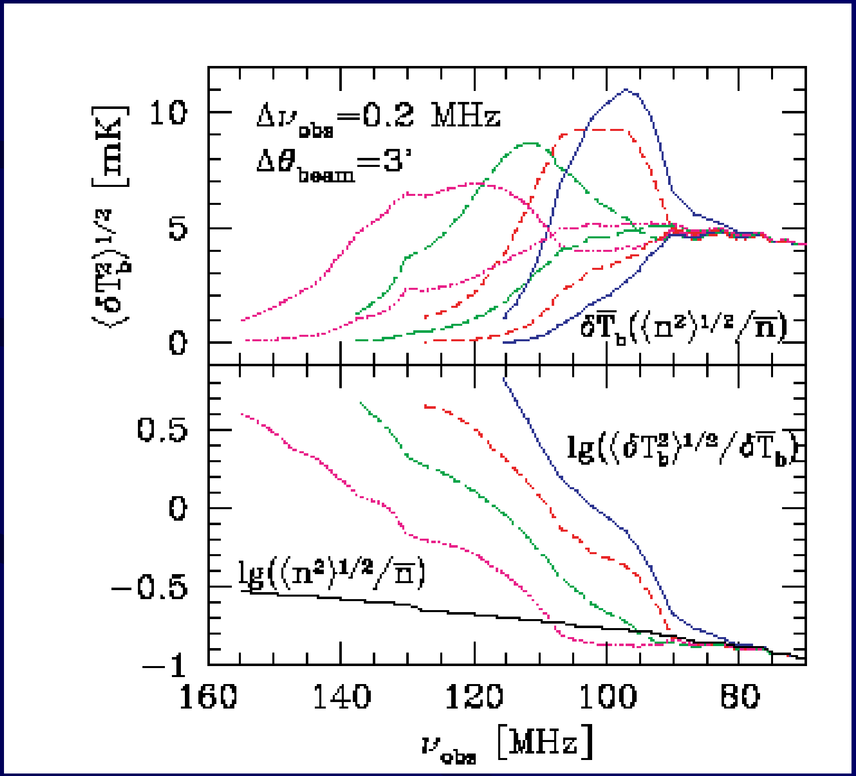
Sky Maps

- Top - sky map
- Bottom - sky map with subtracted a wide 5Mhz band to remove foreground



Rms Fluctuations

- Top - rms fluctuations of the differential brightness temperature versus observed frequency
- Could be something to be observed and see which model is closest
- Peak - univserse is 50% ionized by mass



Blue - f2000

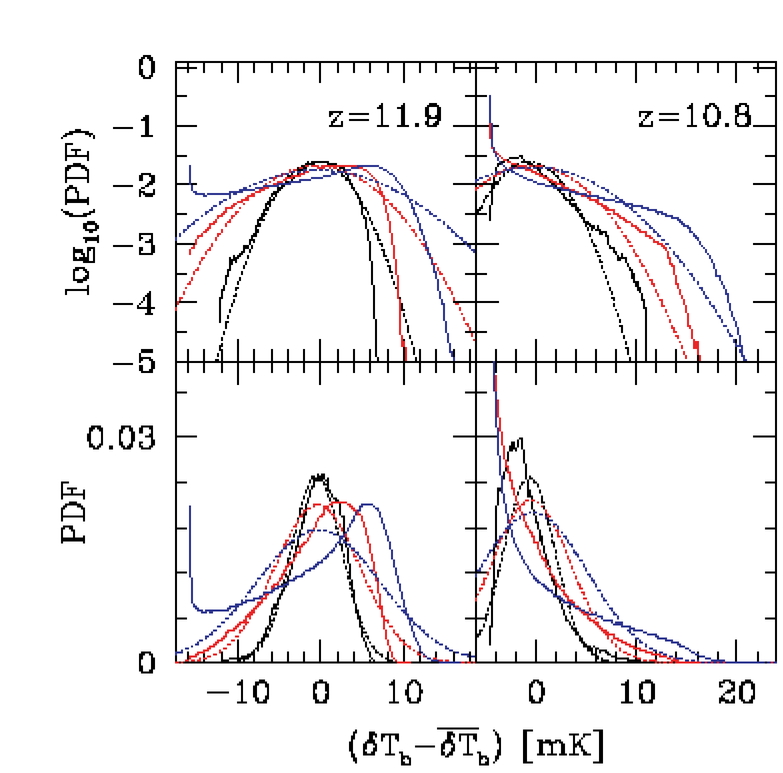
Red - f2000C

Magenta - f250C

Green - f250

Non-Gaussianity

- 21-cm signal is also non-Gaussian



Upcoming missions

- PAST
  - Primeval Structure Telescope
- MWA
  - Murchison Widefield Array
- LOFAR
  - Low Frequency Array
- SKA
  - Square Kilometre Array
- GMRT

MWA

SKA

Summary

- First large-scale radiative transfer simulation, showing final overlap at z~11
- Denser/clumpier gas has shorter recombination times\
- Complex relation between density of a region and its ionization state.
- Probability distribution functions are Non-Gaussian, for all models

Summary

- Gradual transition in the 21-cm signal from neutral gas being ionized
- The large-scale geometry of reionization is well resolved in the 21-cm sky map, especially if you subtract out a large-frequency band to eliminate foreground
- Rms fluctuations hit a maximum at 50% ionization by mass.

- http://www.cita.utoronto.ca/~iliev/xy0_evol.gif
- http://www.cita.utoronto.ca/~iliev/dokuwiki/doku.php?id=simulations