Effects of Reionization on the observability of Ly-a emitters

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with

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Reionization in Action:From the Dark Ages to Reionized Universe

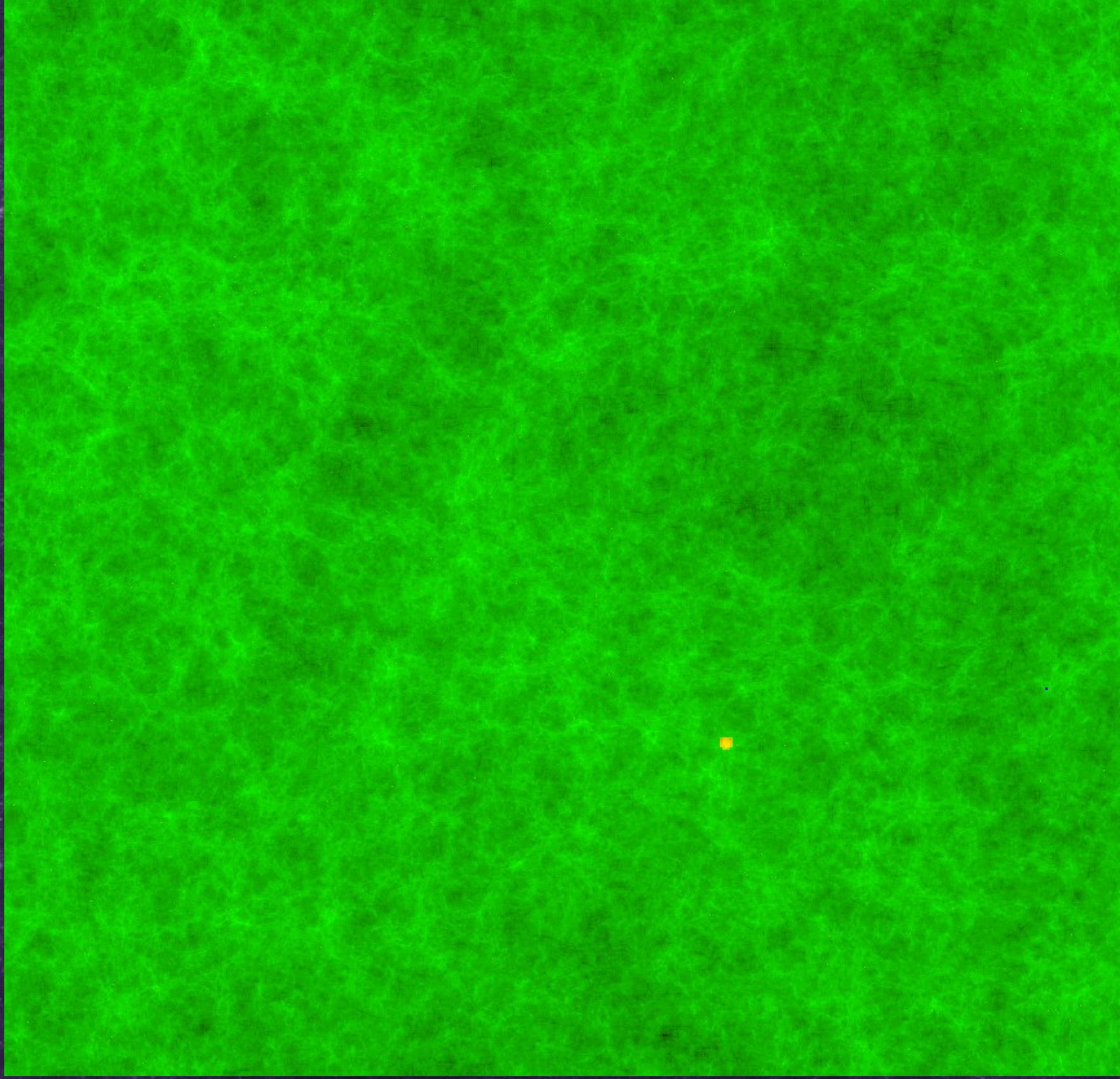
-Strong halo clustering

-quick local percolation

-large H II regions with complex geometry.

64/h Mpc box, WMAP3+ cosmology, 432^3 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

EOR Simulations: High Requirements

- *Large* scale simulations: needed both observationally (radio observations will have multiple degree FOV) and fundamentally (size of HII regions >10 Mpc, long-wavelength density perturbations crucial).
- *Large* dynamic range simulations:dominant contributors to ionizing flux are small (dwarf and sub-dwarf) galaxies. Ideally need to resolve collapsed halos of mass $>10^8 M_{solar}$ (atomic cooling).Low dynamic range also imposes artificial cut-offs on density fluctuations.
- Fast, precise radiative transfer.

Ours are the first ever reionization simulations to satisfy these requirements. Based on them we have now produced the first realistic predictions of the EOR character and observable signatures.

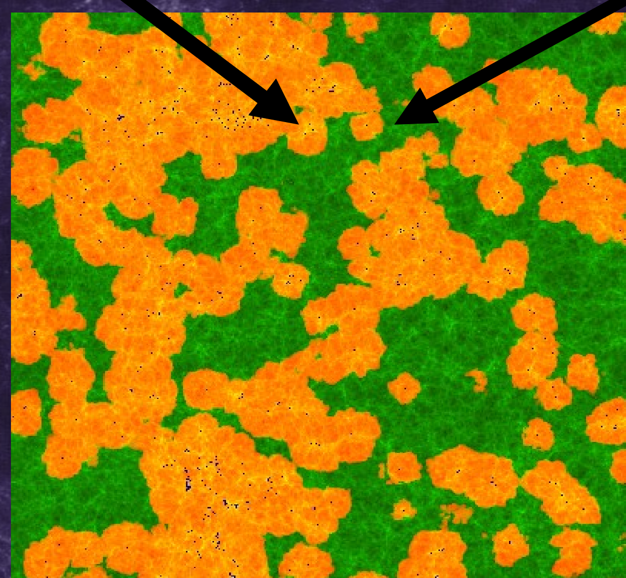
Large-Scale Simulations of Reionization

[Iliev et al. 2006a, 2007a; Mellema, Iliev, et al. 2006; and in prep.]

- N-body: CubeP^{3}M
1728^3-3072^3 part.
(5.2 to 29 billion) or more -
4000^3-5488^3 (64-165 billion)
- density slices
- velocity slices
- halo catalogues-sources
- Scales well at least up to 10976 cores

- C^2-Ray code
(Mellema, Iliev, et al. 2006)
- radiative transfer
  - noneq. chemistry
  - precise
  - highly efficient
  - coupled to gasdynamics
  - massively parallel (ran on up to 10240 cores).

35-114/h Mpc (CubeP^{3}M)
resolving 10^8 M_{solar} halos
up to 21 x 10^6 sources
50-100 dens. snapshots
simple source models
sub-grid clumping
no hydro – large scales.



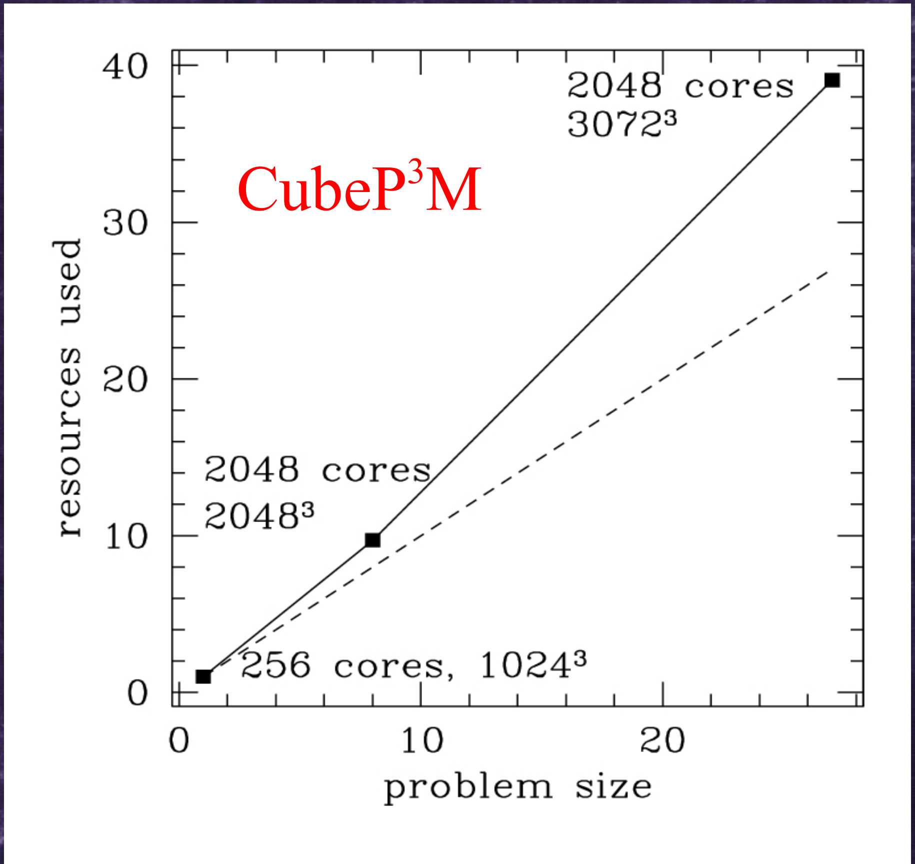
Coupled to hydro

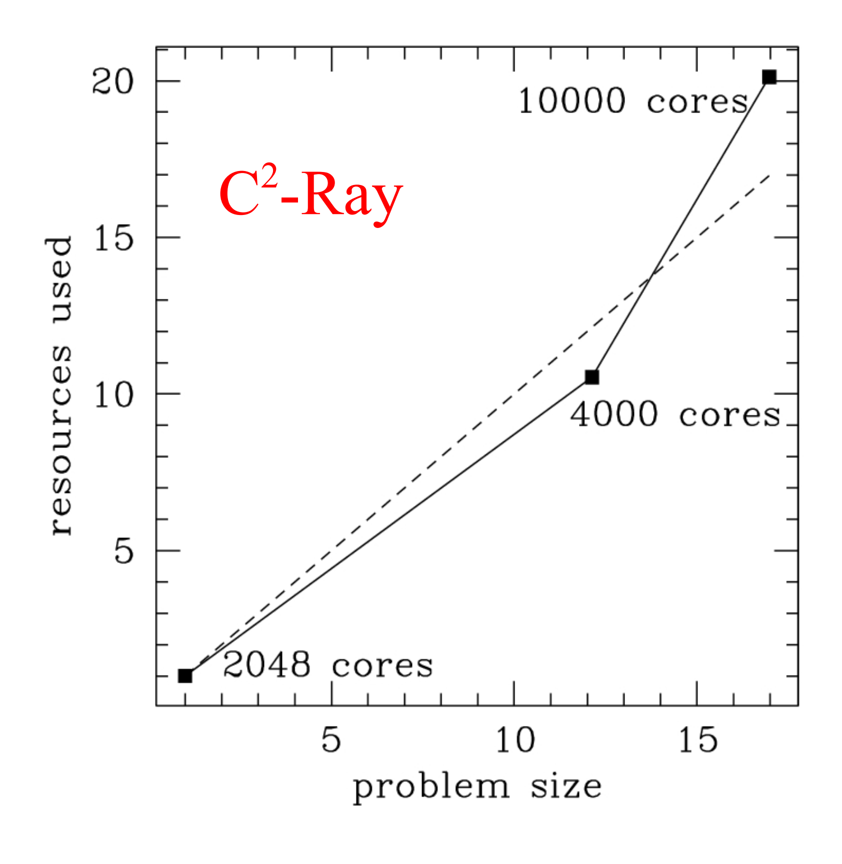
Code Scaling

(Iliev, Mellema, Merz, Shapiro, Pen 2008 in TeraGrid08 proceedings)

Both N-body and radiative transfer codes are massively parallel and scale (weakly) up to thousands of processors.

Full, detailed radiative transfer|: Petascale-size problem!





Key Results

- Reionization proceeds inside-out and is highly patchy in nature.
- HII regions are large, with a pronounced characteristic scale (5-20 Mpc) imprinted on all observables.
- Reionization is strongly self-regulated through Jeans-mass filtering of low-mass sources.
- Current constraints on reionization parameters (source efficiencies, gas clumping) are weak; τ_{es} and overlap epoch are readily reproduced.
- Small-box/low dynamic range simulations are inadequate for a faithful representation.

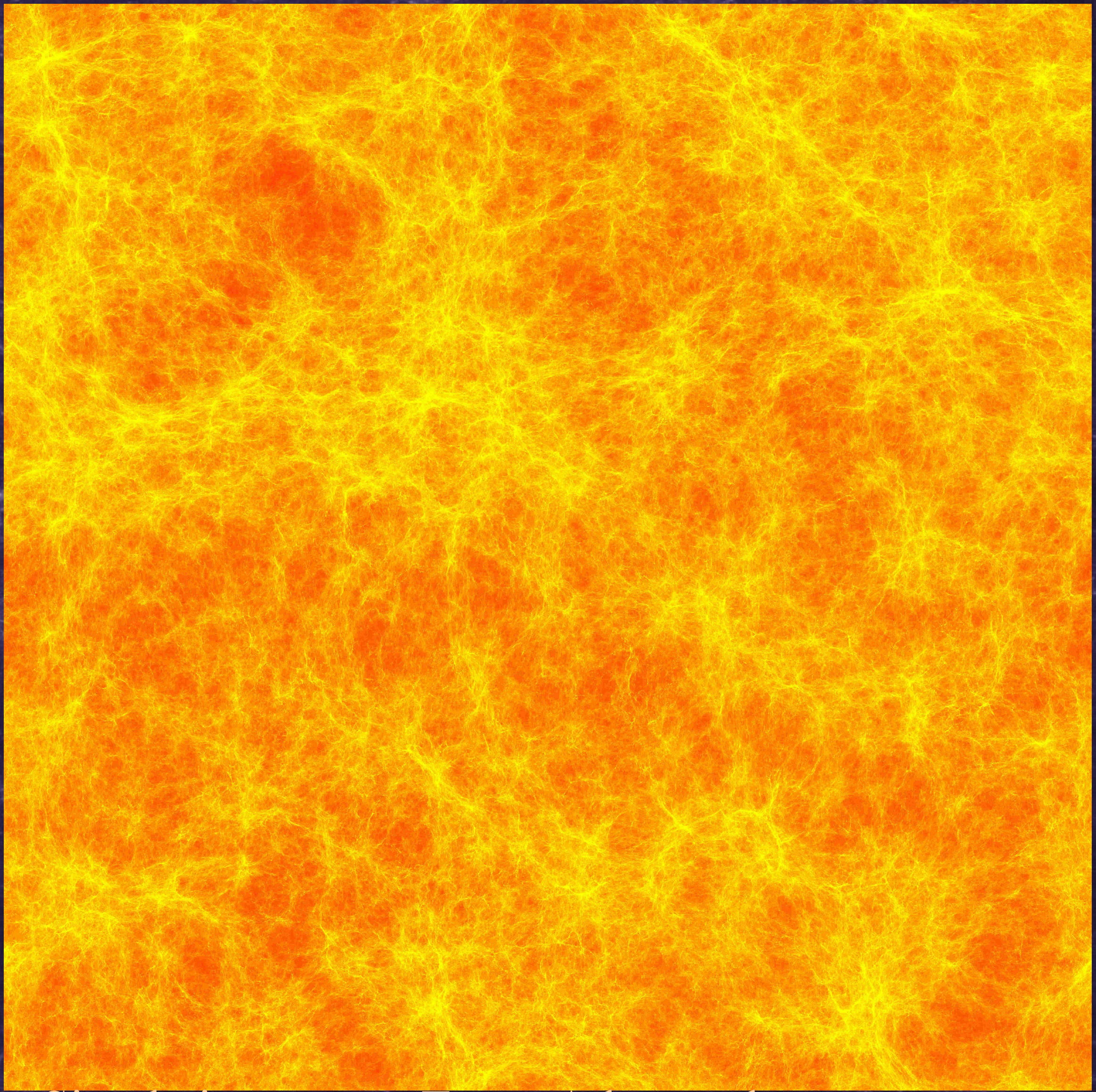
The Formation of Early Cosmic Structures

Iliev, Mellema, Pen, Merz, Shapiro, Alvarez 2006a, MNRAS, 369, 1885, and in progress)

114/h Mpc box @ z=6
3072^3 particles (29 billion),
6144^3 cells, P^3M simulation

We have now ran simulations with 1024^3, 1500^3, 1728^3, 2048^3 and 3072^3 particles in boxes of 37/h-114/h Mpc. Still larger simulations are possible on current hardware, with 64-300 billion particles (6x-30x the Millenium simulation) 165 billion (5488^3;on 10,976 cores) is presently running ; 10^{12} ($10{,}000^3$= trillion)-particle simulations are now within reach..

These sizes allow us to resolve all halos down to the atomically-cooling limit (10^8 M_{solar}) in 100-150/h Mpc boxes - the ultimate goal for this type of simulations.



Simulations ran at Texas Advanced Computing Facility on 432 to 2048 cores.

The Formation of Early Cosmic Structures: The Very Small Scales

(Iliev, et al., work in progress)

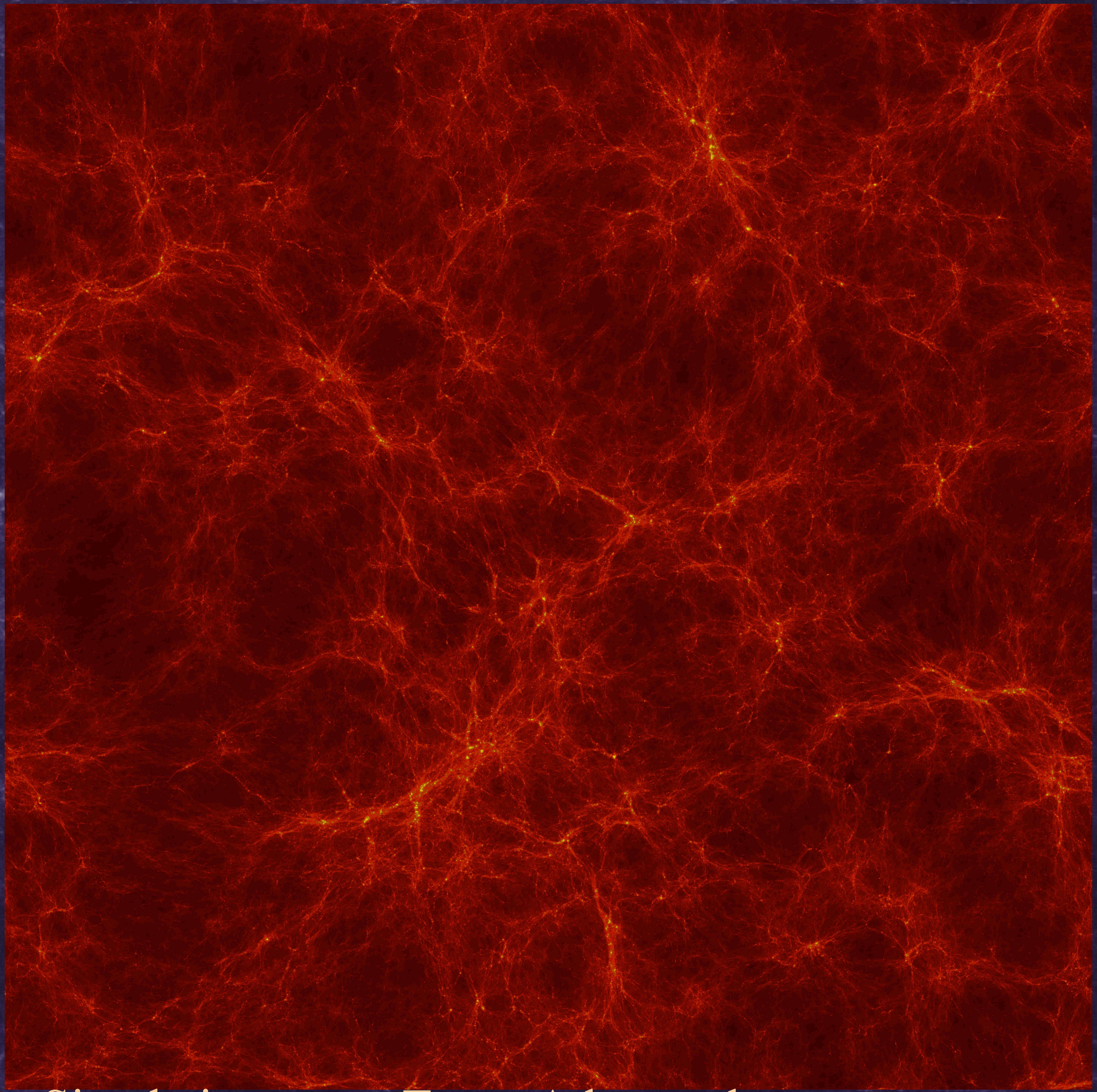
11.4/h Mpc box @ z=8
3072^3 particles (29 billion),
6144^3 cells, P^3M simulation

Resolves all halos down to small minihalos (10^5 M_{solar}).

Structures are highly biased! Extend to extremely small scales (resolution of this simulation is 186 pc!)

20/h Mpc box with 5488^3 particles is running now on 10,976 cores.

First resolved halos form at Z=40 (z=43 for 20/h Mpc)
>21 million halos at z=8.



Simulation ran at Texas Advanced Computing Center on 2048-4096 cores.

Universe in a Box: Simulating the Entire Observable Universe

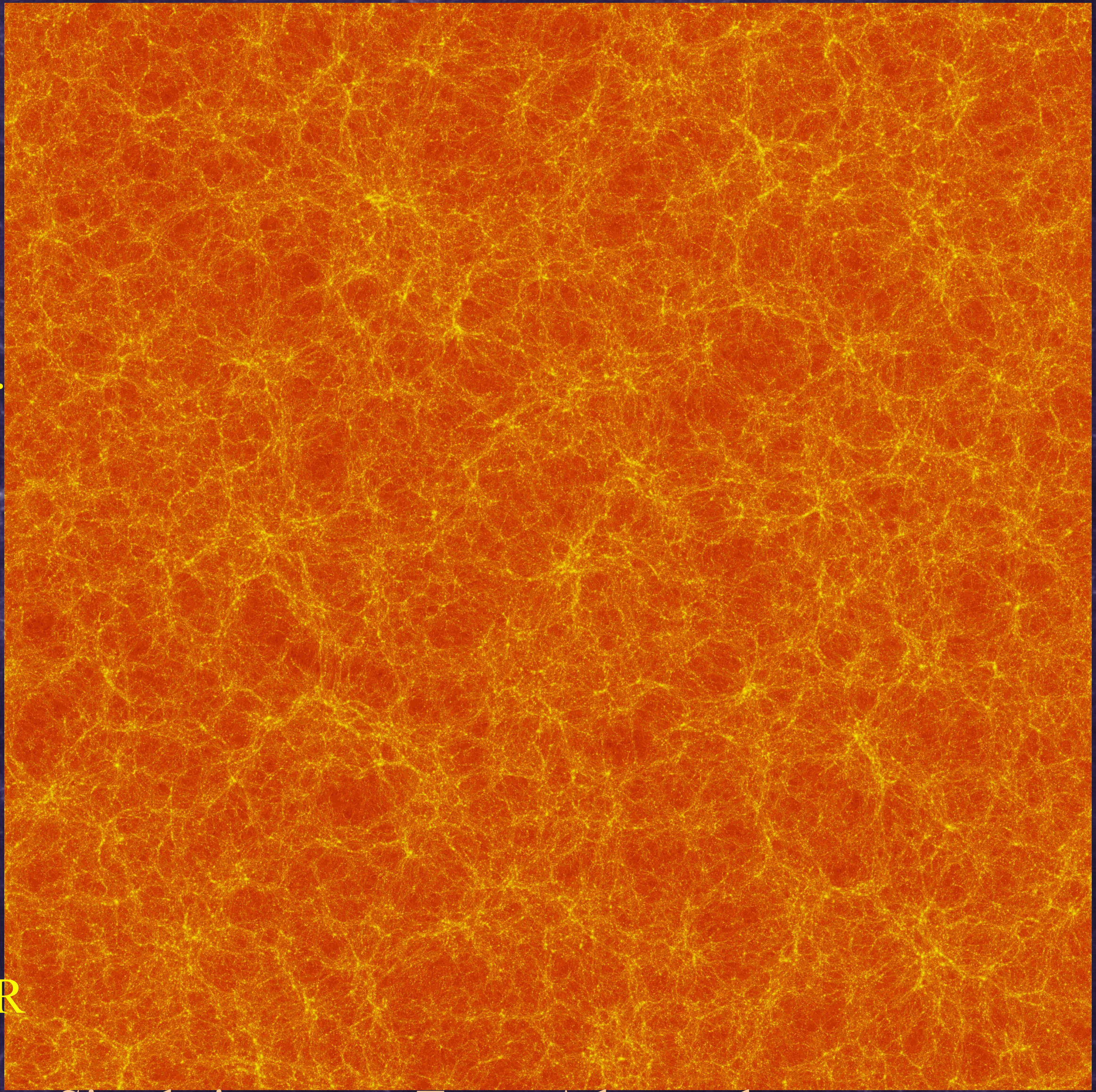
(Desjacques, Seljack & Iliev 2008, and in prep.)

1/h Gpc box @ z=0.28
3072^3 particles (29 billion),
4096^3 cells, P^3M simulation
over 40 million halos at low z's

Series of sims with 64 billion (4000^3) particles (on 4000 cores).

These sizes allow simulating the whole volume of a large galaxy survey (multiple Gpc^3) with the appropriate resolution (i.e. resolving L* or better) – up to 1 billion galaxies! Ideal for LOFAR/SKA HI surveys (BAO, nonlinear bias, non-gaussianity).

Useful also for modelling LOFAR foregrounds (5x5 deg FOV)

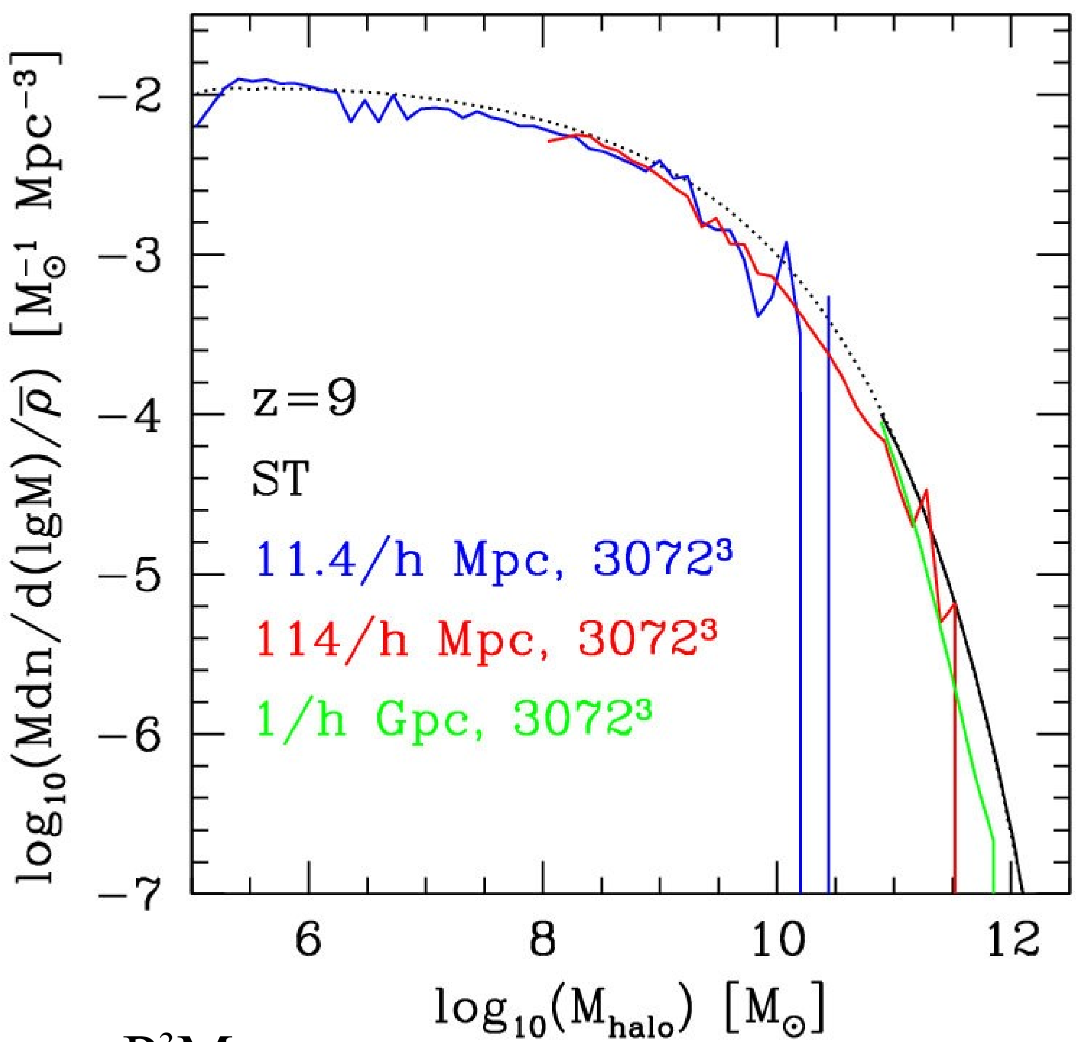


Simulation ran at Texas Advanced Computing Facility on 2048 cores.

The high-z halo mass function
(work in progress)

Up to ~38 (21,21) million halos identified by z=0 (6,8) for 1Gpc/h, 114 Mpc/h, 11.4 Mpc/h.

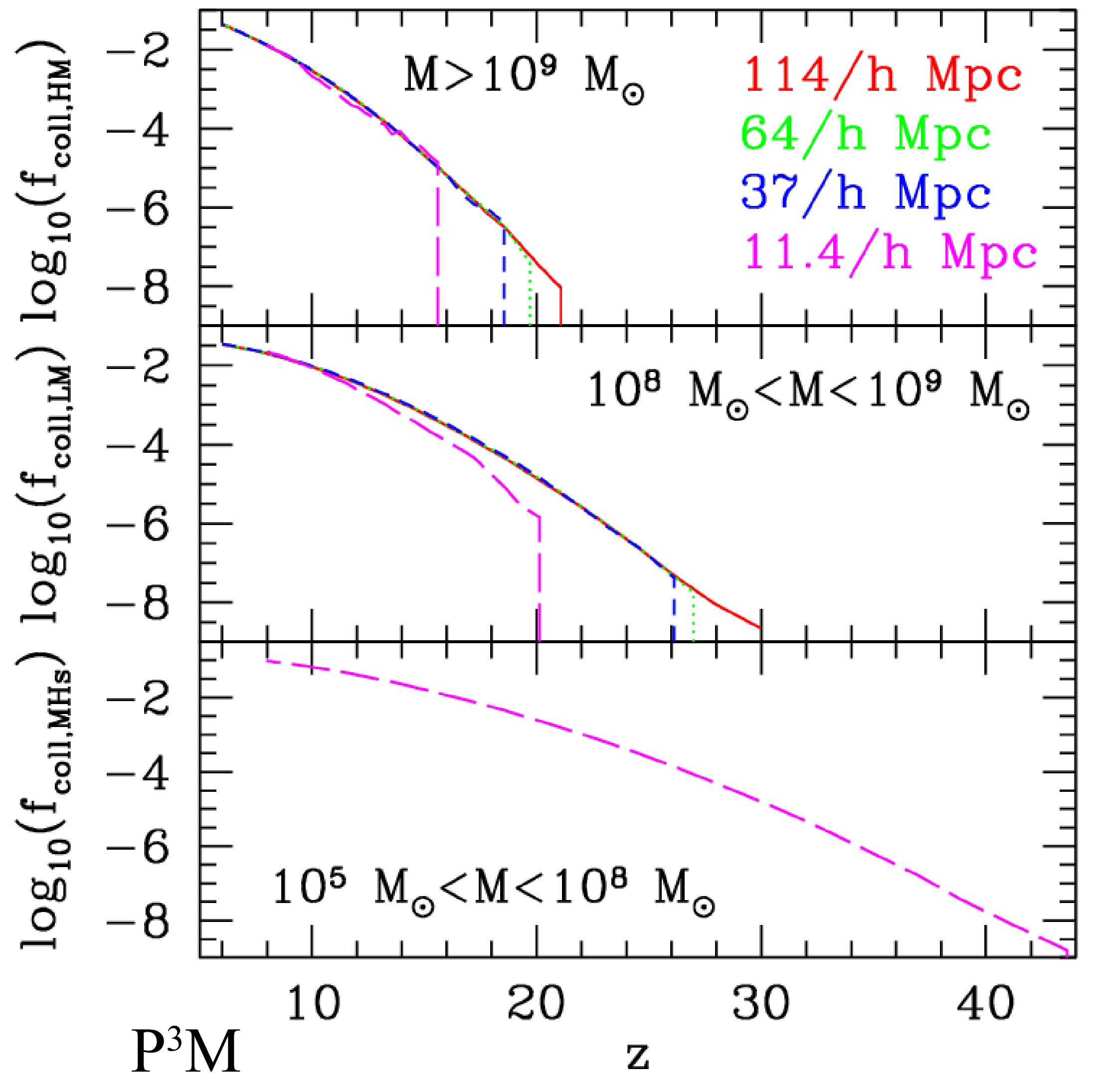
Results show good agreement with each other, but differ from the Sheth-Tormen mass function (black).



P³M

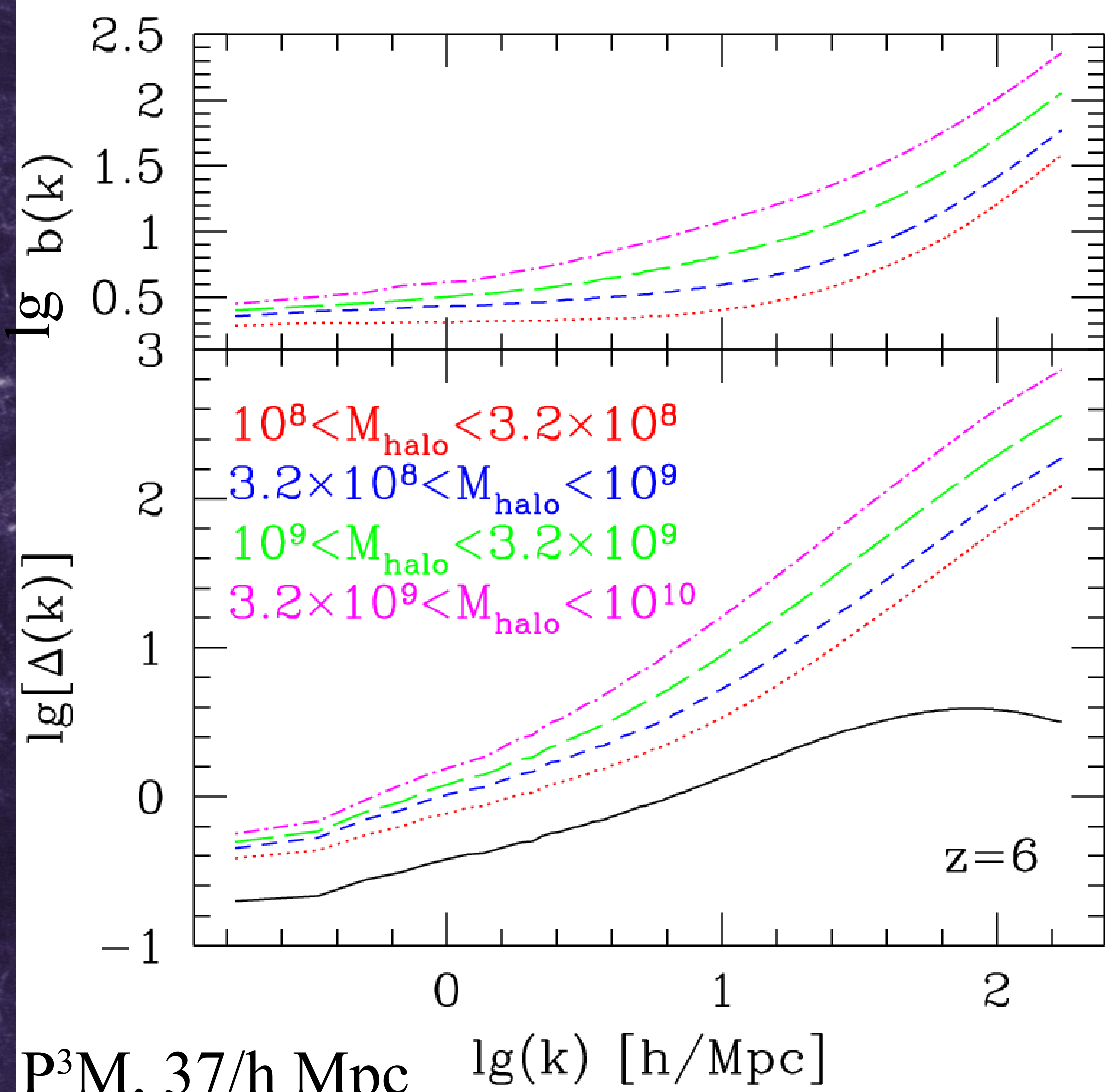
The high-z collapsed fractions
(work in progress)

Halo collapsed fractions agree quite well for a range of box sizes from 114 Mpc/h to 11.4 Mpc/h. Defficiency of large halos for the smallest box due to poor statistics.



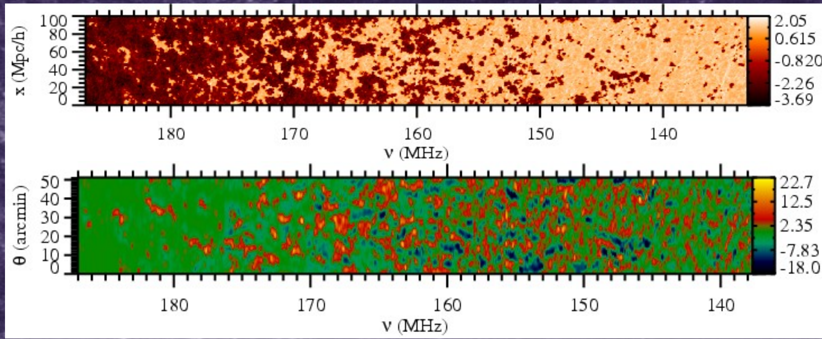
The high-z halo bias
(work in progress)

- Halos at high-z are strongly biased.
- Bias increases strongly with halo mass and can reach a few hundred in the nonlinear regime.
- Scale at which bias becomes linear varies significantly with halo mass.

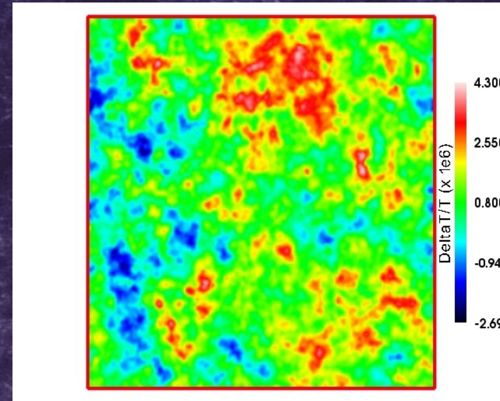


P^3M, 37/h Mpc

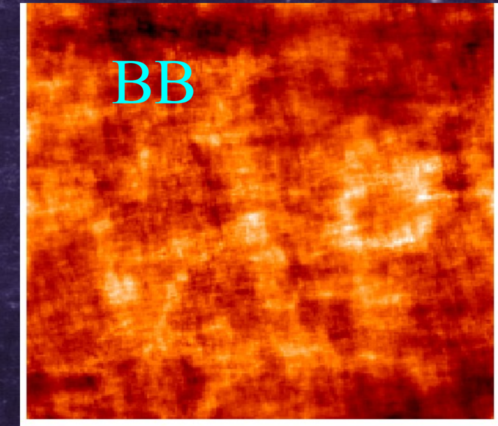
Observing the Reionization Epoch



redshifted 21-cm

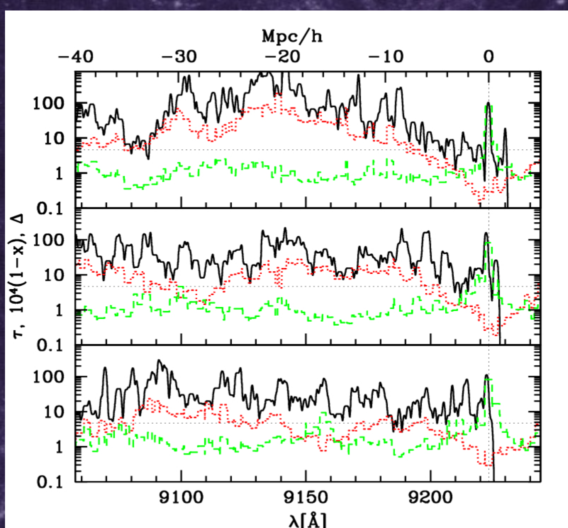


kinetic Sunyaev-Zeldovich effect (kSZ)

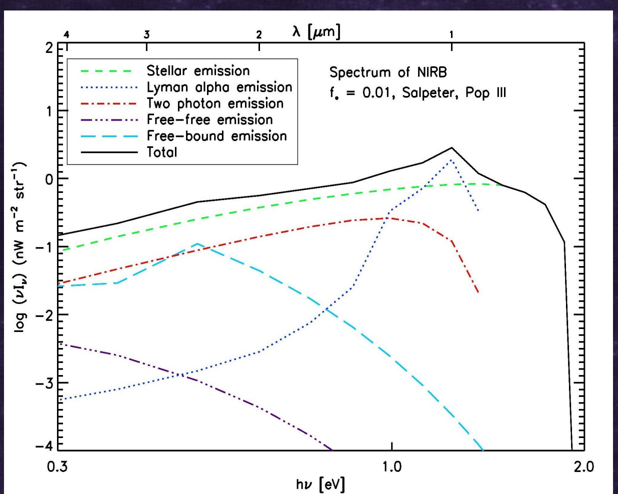


CMB polarization

Ly-α sources



NIR fluctuations

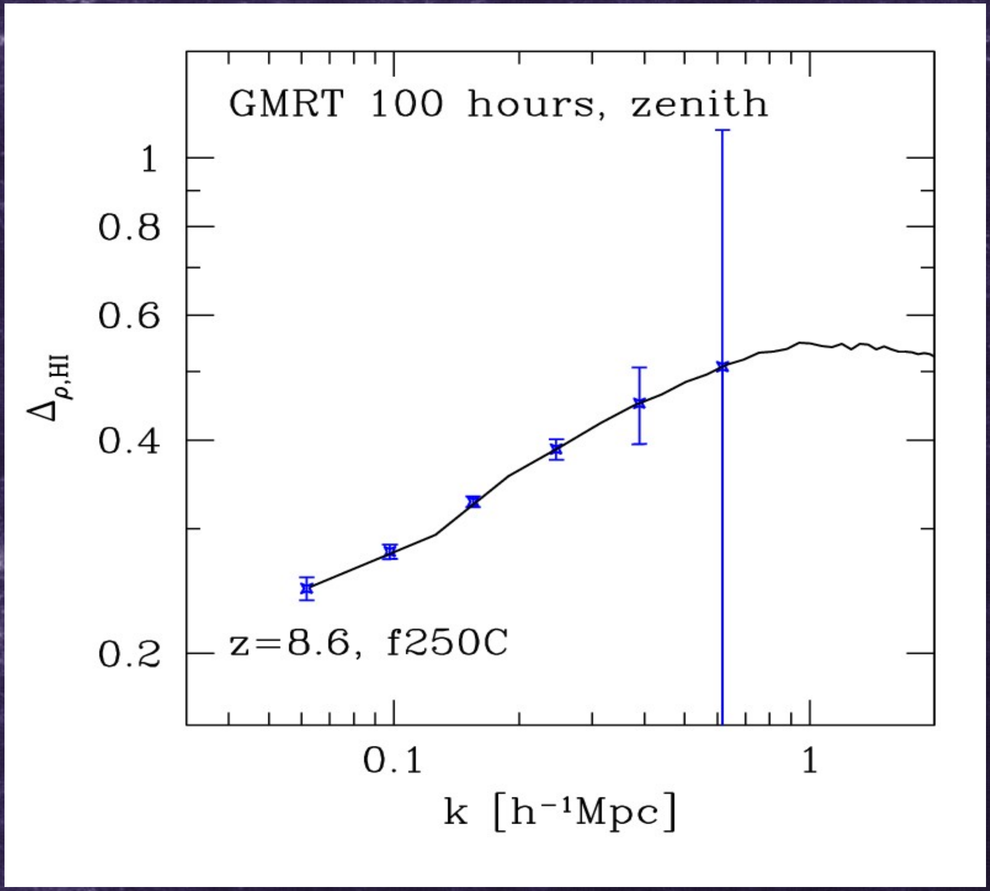


Iliev et al. 2006a, MNRAS; 2007(a,b,c,d),2008 MNRAS, ApJ, Mellema et al. 2006, MNRAS; Dore et al., 2006, Phys. Rev. D; Holder, Iliev & Mellema 2006 ApJ, Fernandez et al. 2009, Tilvi et al. 2009, submitted

Reionization in action as seen at 21-cm: Flying through the Image Cube

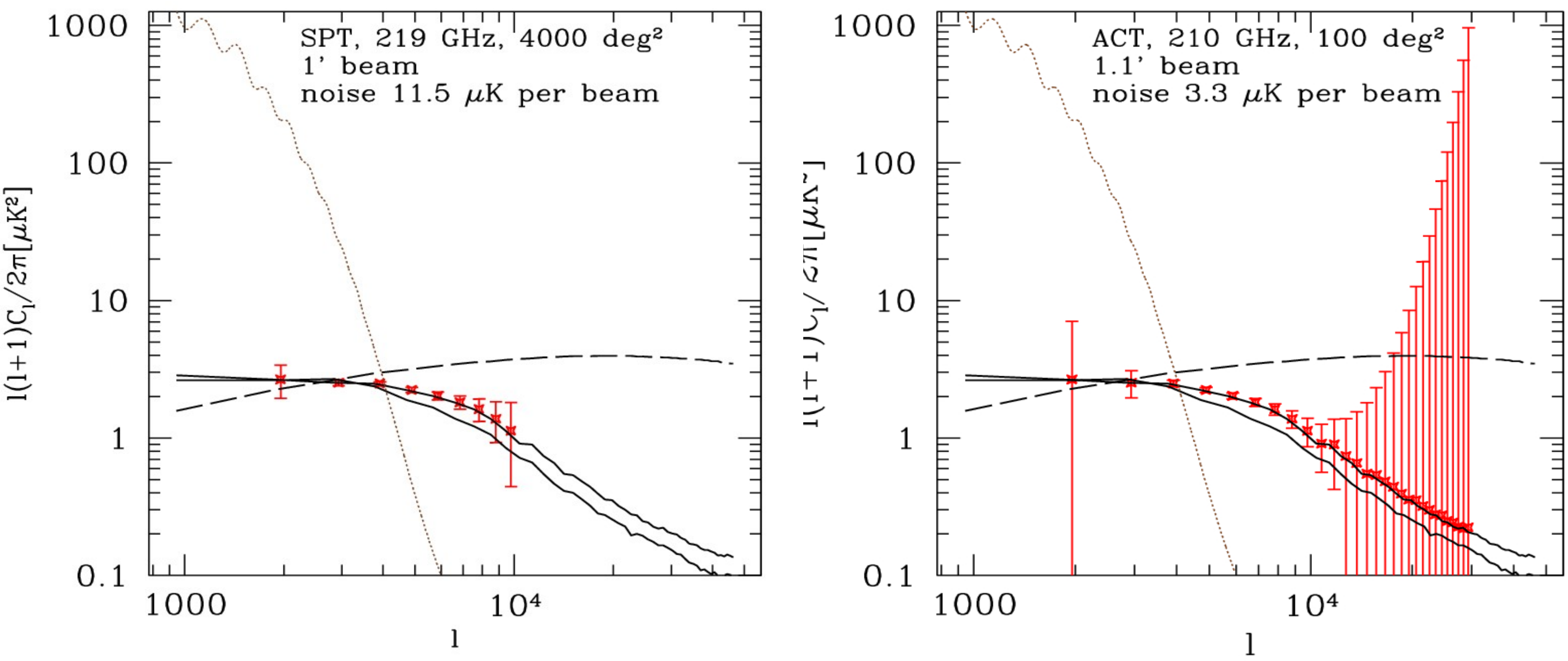
21-cm view of reionization

Detectability of 21-cm
(Iliev et al, 2006d, MNRAS, submitted)



- **3D power spectra of the EoR 21-cm signal (neutral density) vs. noise level of GMRT. Foregrounds will increase error bars at large scales (small k's).**

Detectability of kSZ
(Iliev et al, 2006d, MNRAS, submitted)

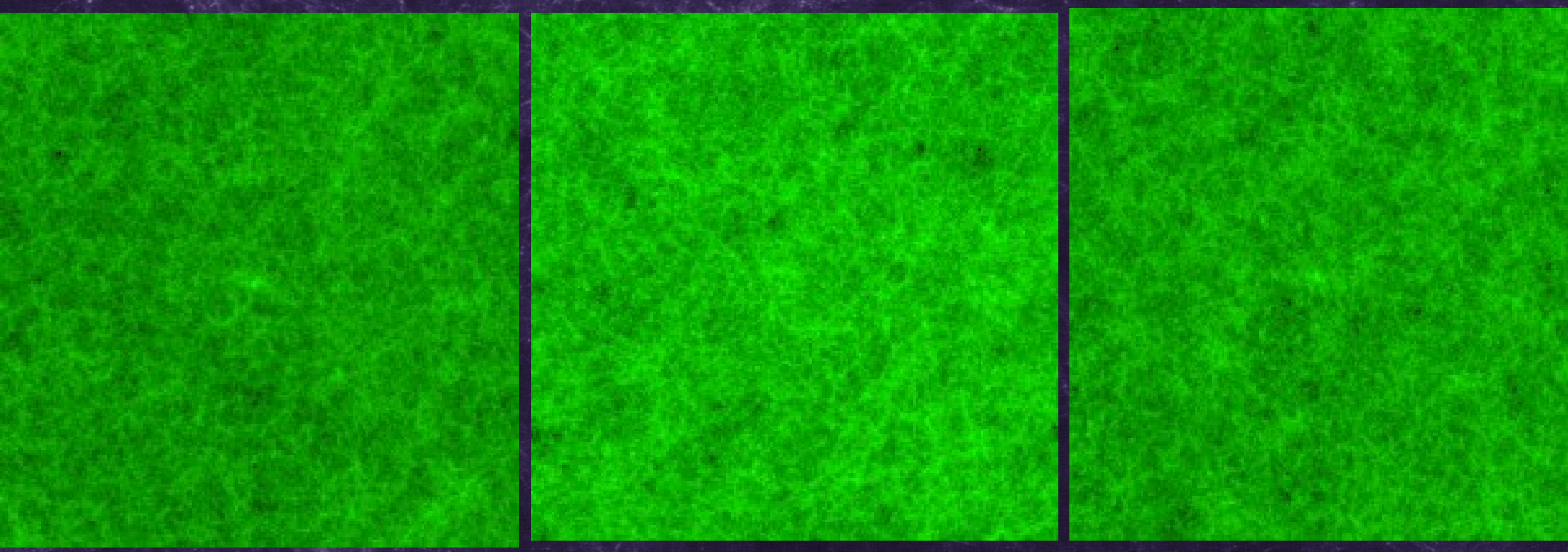


- Sky power spectra of patchy EoR kSZ vs. expected noise levels of SPT and ACT. Includes noise from primary CMB and post-EoR kSZ (shown). tSZ is

Luminous sources at the end of reionization: animations

(Iliev et al. 2008, MNRAS, 391, 63)

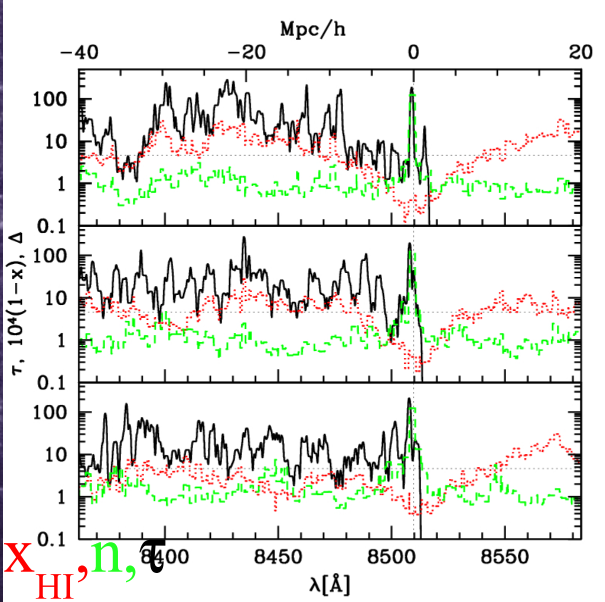
- The most massive source at z~6 is at the center
- HII region around it forms early (z~16) and grows quite large
- ... but even at the end (z~6.6) many patches remain neutral.

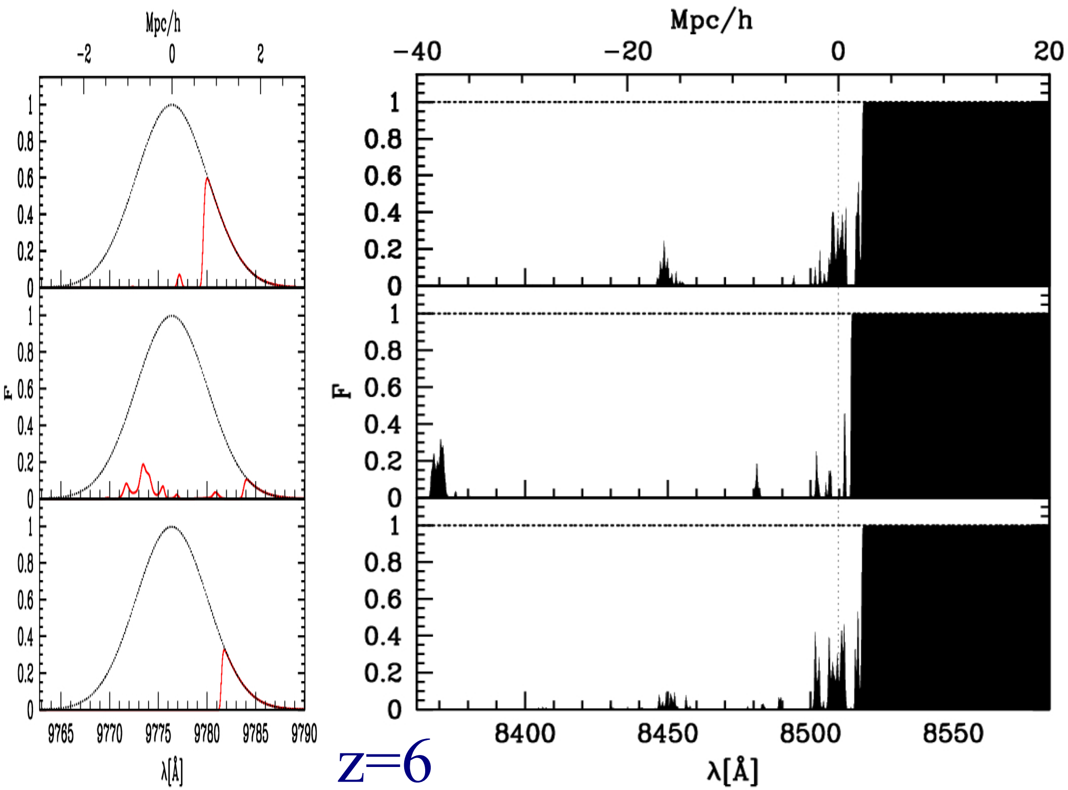


xz xy 100 Mpc/h yz

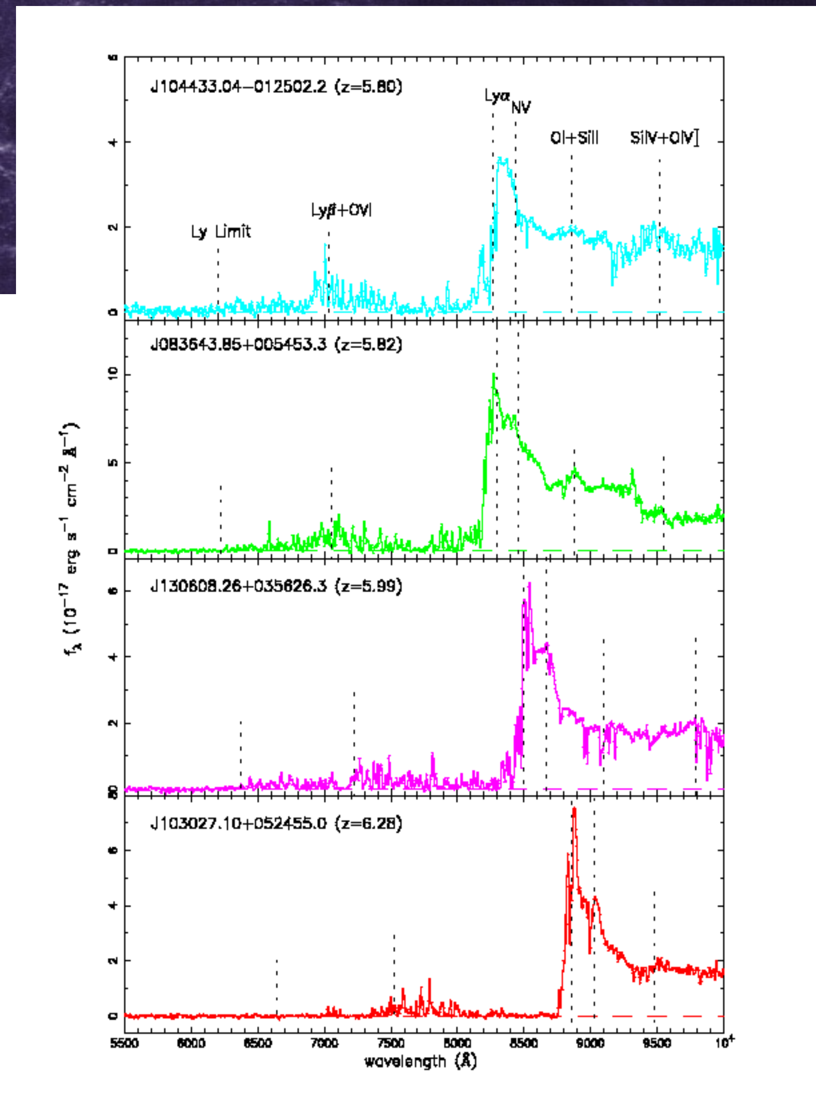
Luminous sources at the end of reionization: Ly-α spectra

(Iliev et al. 2008, MNRAS, 391, 63)





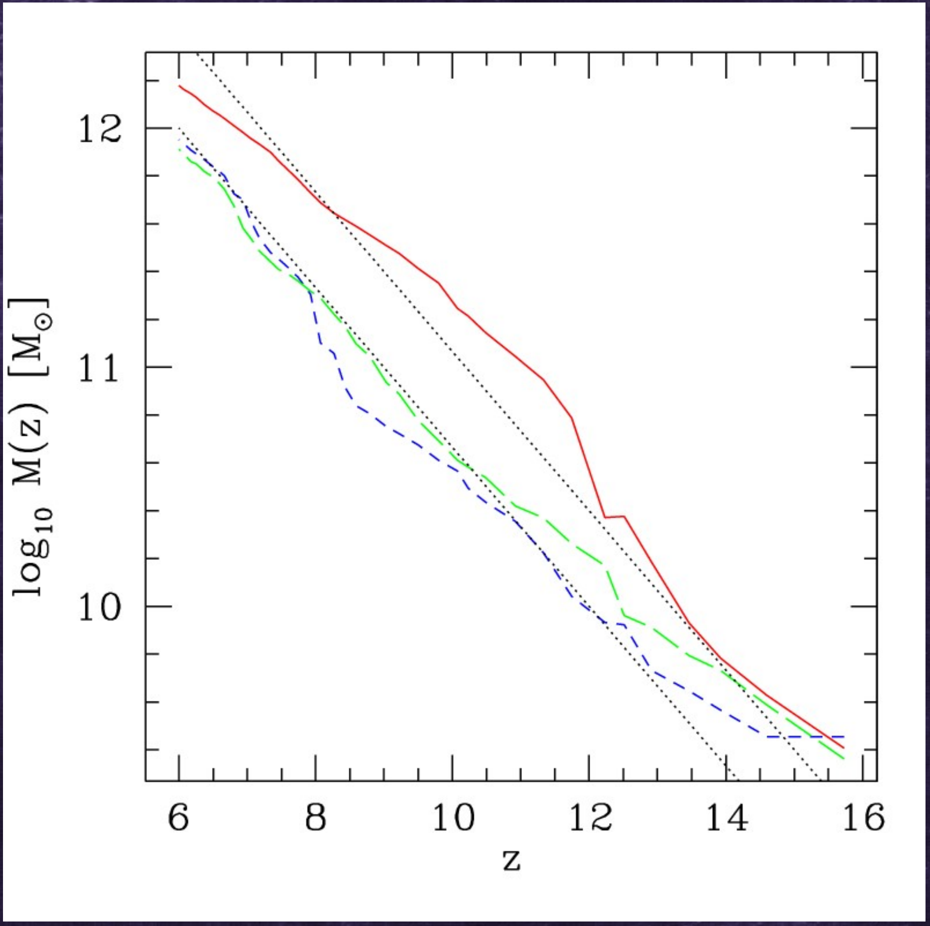
z=6



Luminous sources at the end of reionization

(Iliev et al. 2008, MNRAS, 391, 63)

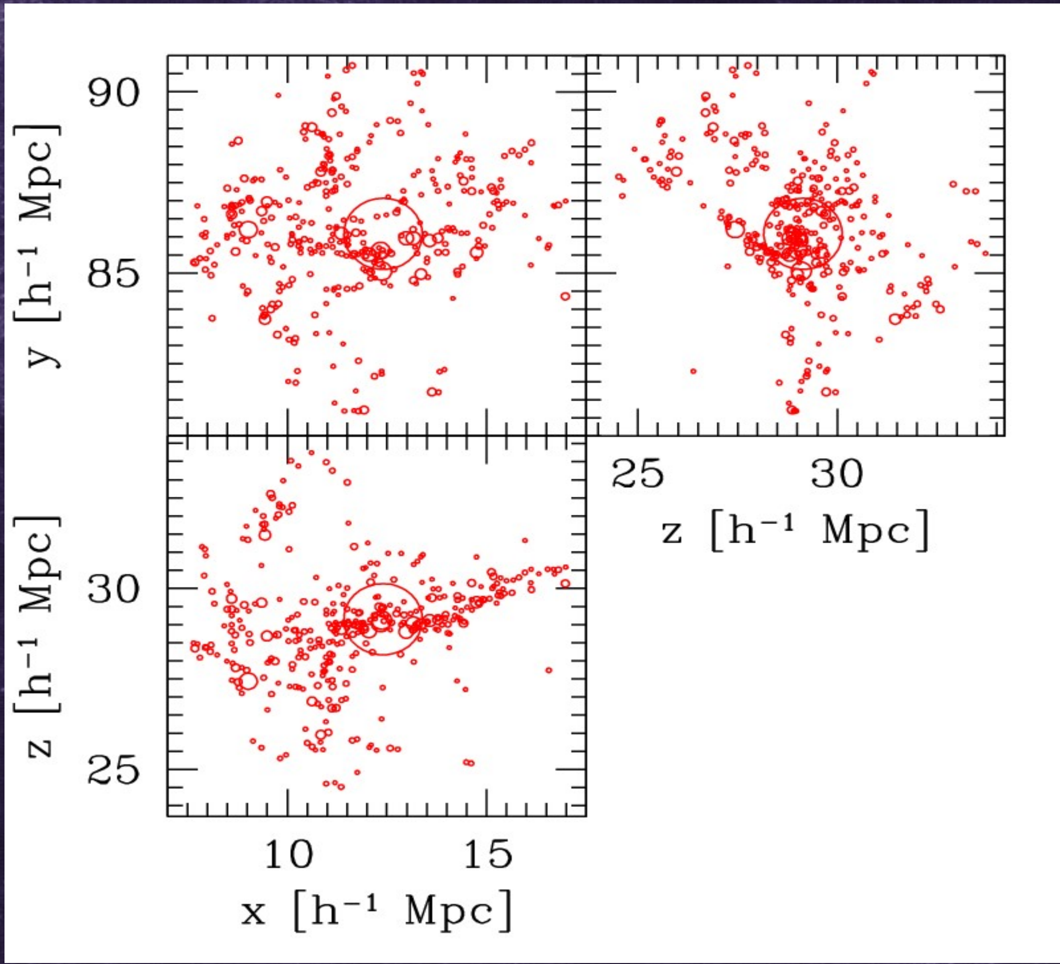
- The first sources detected at the reionization tail-end (z~6) are among the brightest galaxies and QSOs (e.g. in SDSS)
- Rare, high peaks of the density
- Strongly clustered sources
- Most massive galaxies in our box ~1.5e12 M_{solar} at z=6 (5-σ peak), mass accretion history of the 3 most massive shown (approx. exponential with z).



The neighbourhood of a high-density peak

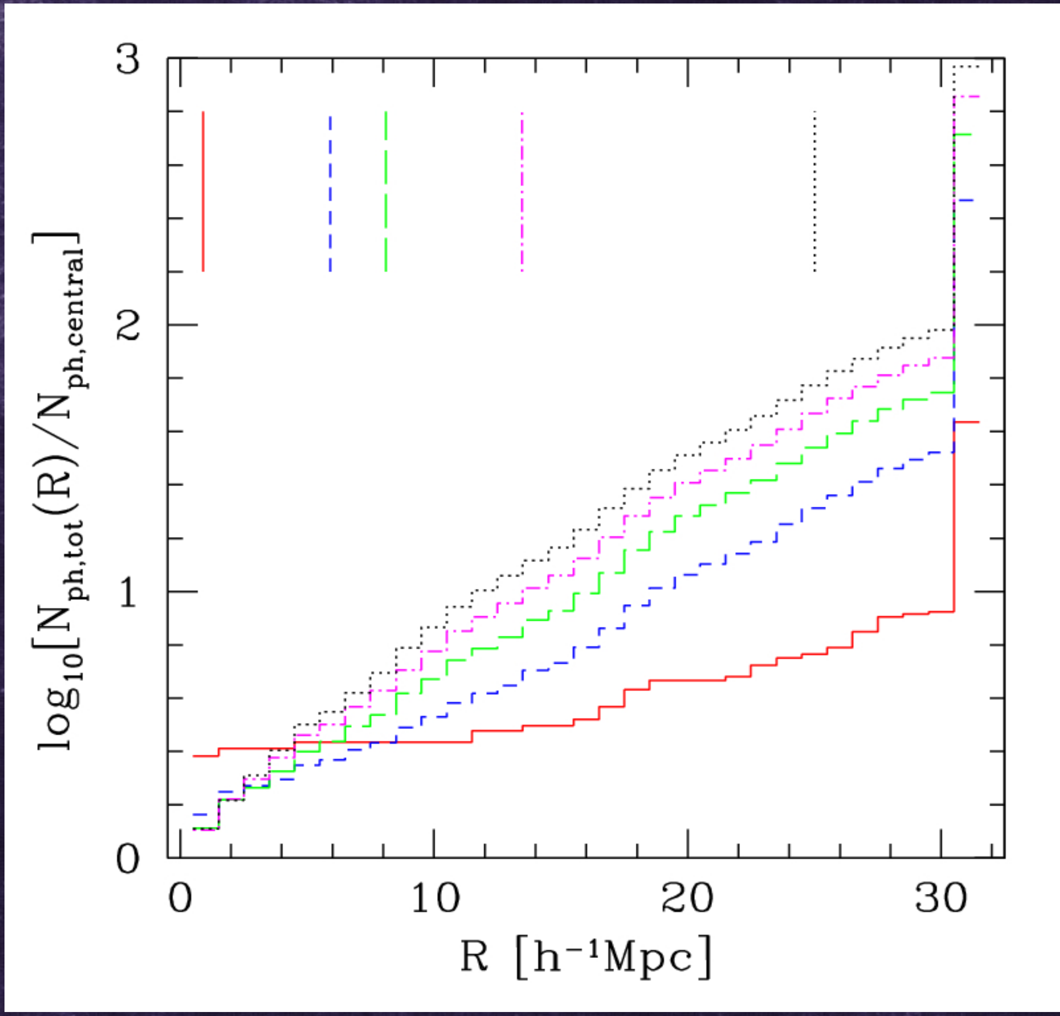
(Iliev et al. 2008, MNRAS, 391, 63)

Each massive galaxy resides in a high-density peak, with many sources clustered around it (Gaussian peak statistics)



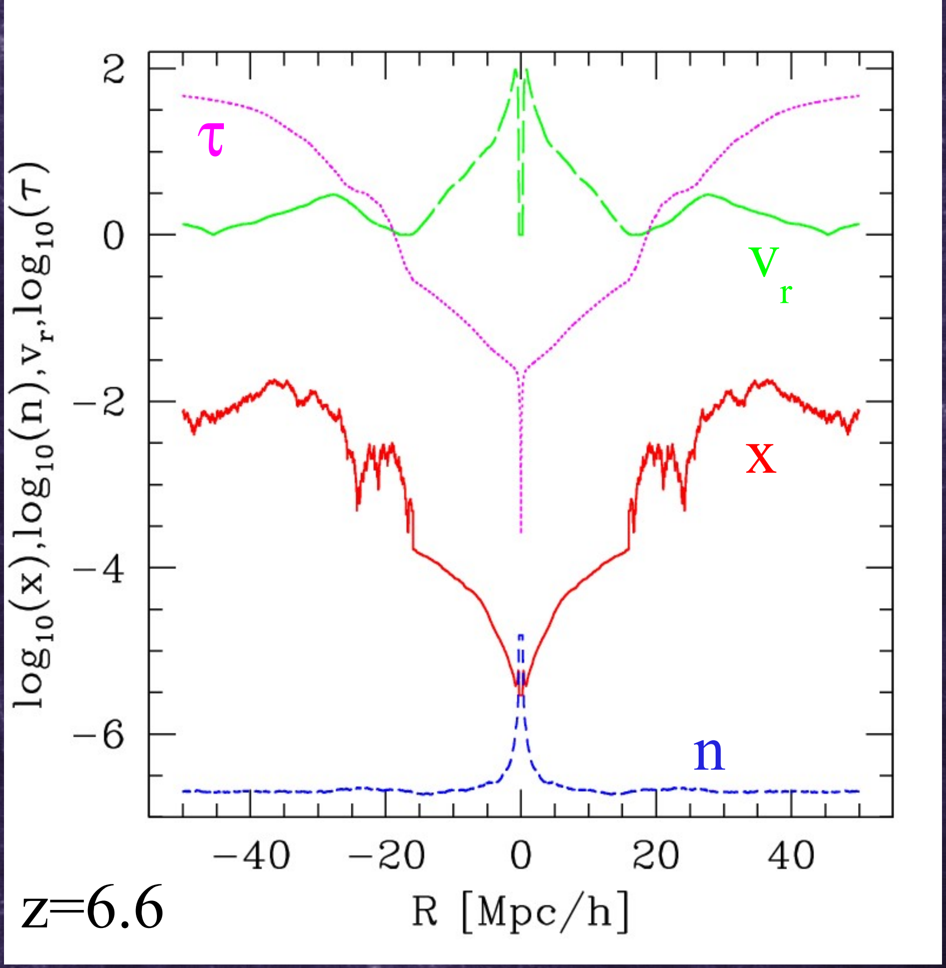
Luminosity of central source vs. surrounding ones
(Iliev et al. 2008, MNRAS, 391, 63)

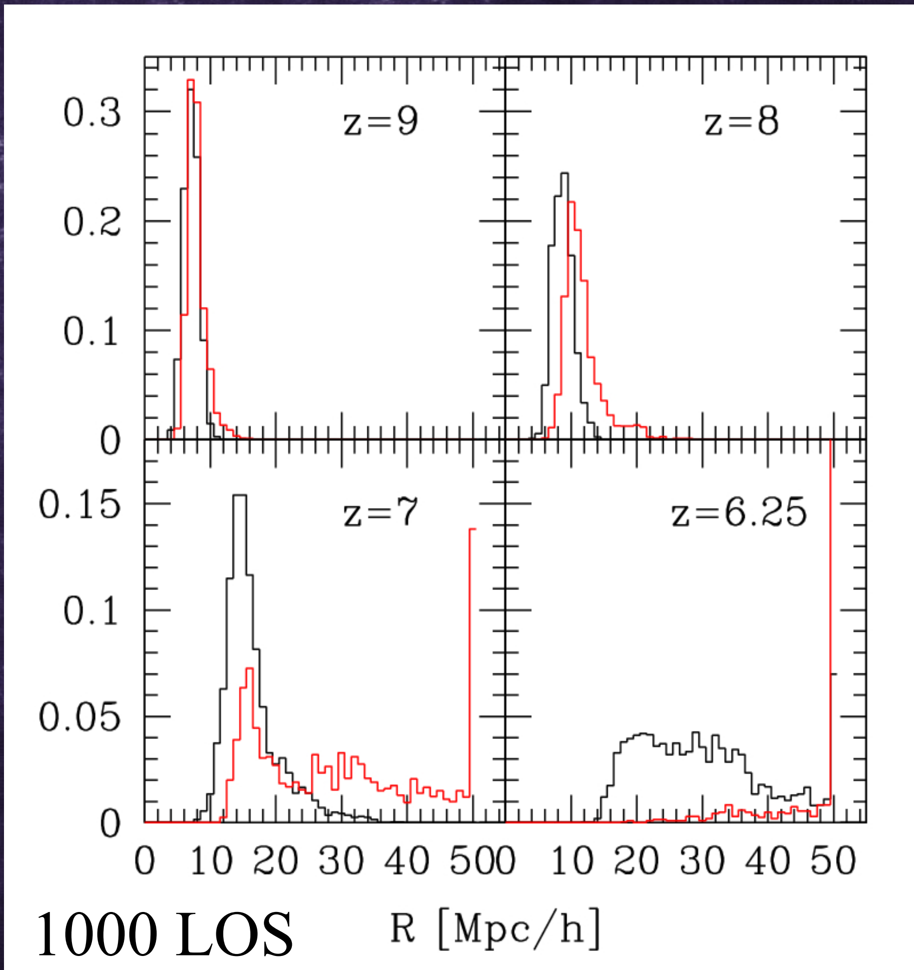
- The central, luminous galaxy dominates the total emissivity only within a very small volume, <1 Mpc.
- The photon emissivity from the small sources in the same HII region dominates by factor of 10-100 (redshift-dependent, higher at later times)



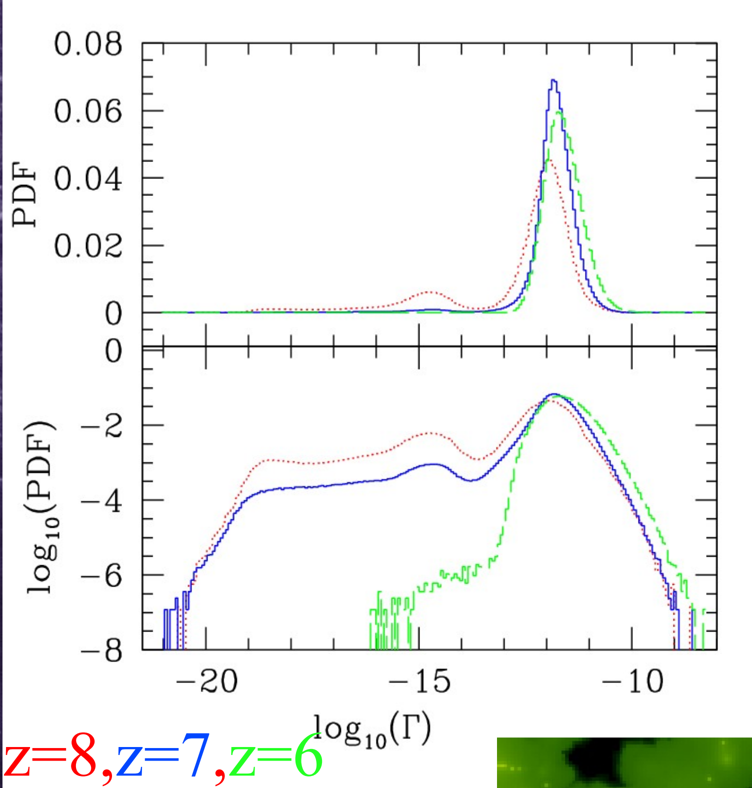
Luminous sources at the end of reionization: average profiles and LOS variations

(Iliev et al. 2008, MNRAS, 391, 63)



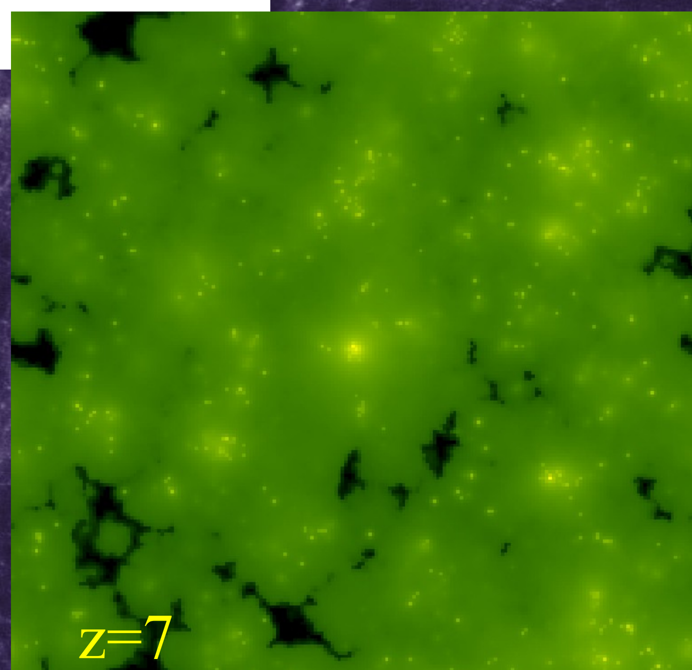


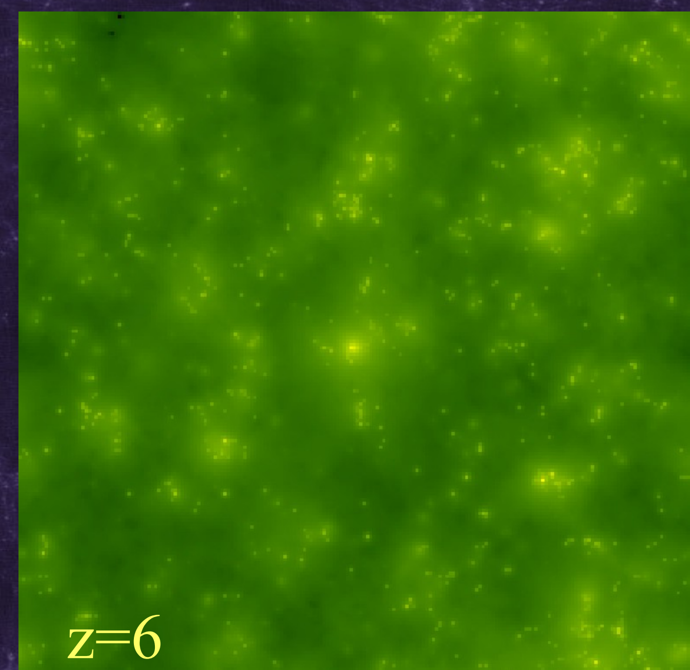
black: τ=1, red: τ=4.6 (99% absorp.)



Photoionization rates during reionization: non-equilibrium and very inhomogeneous

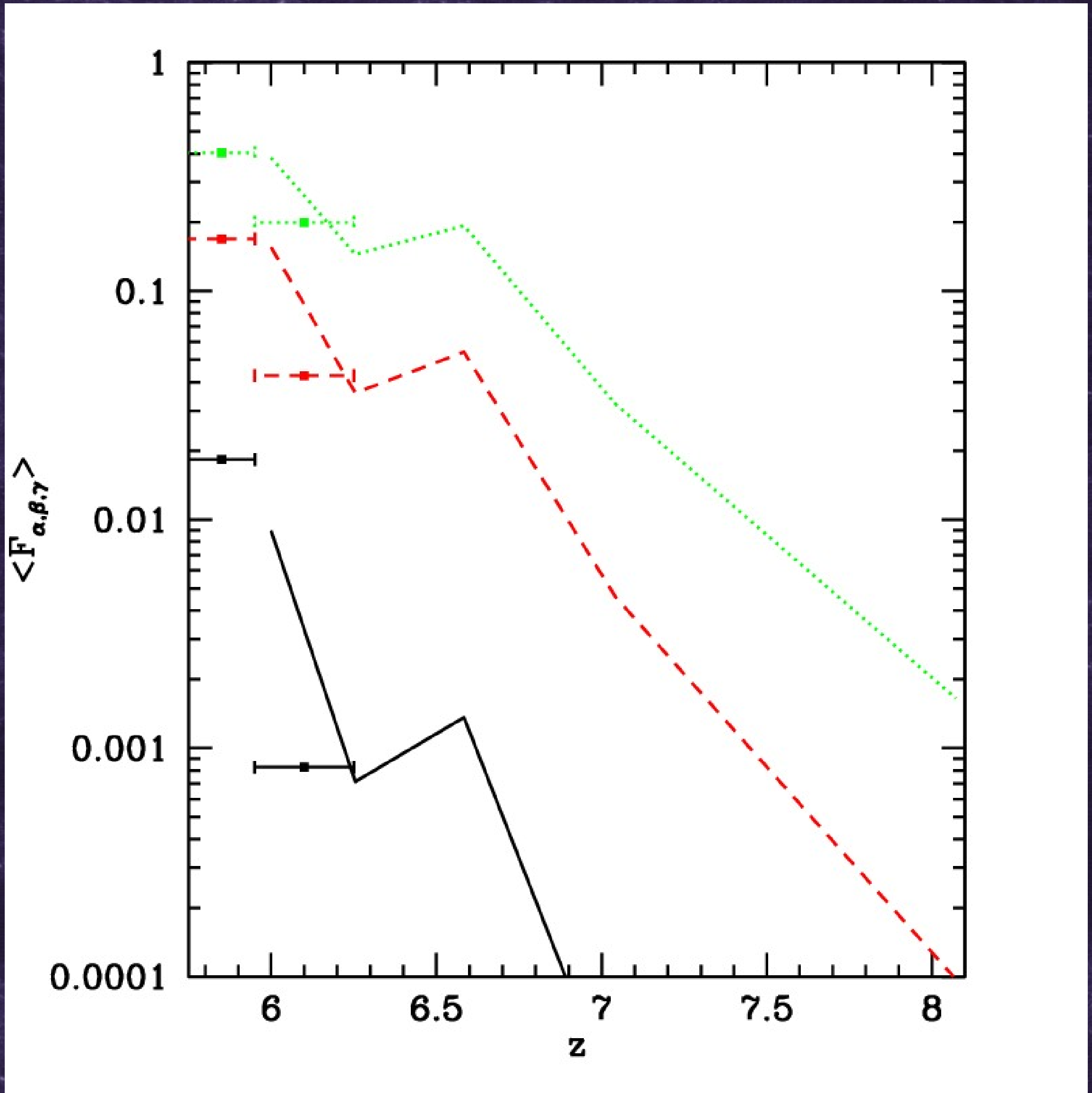
(Iliev et al. 2008, MNRAS, 391, 63)





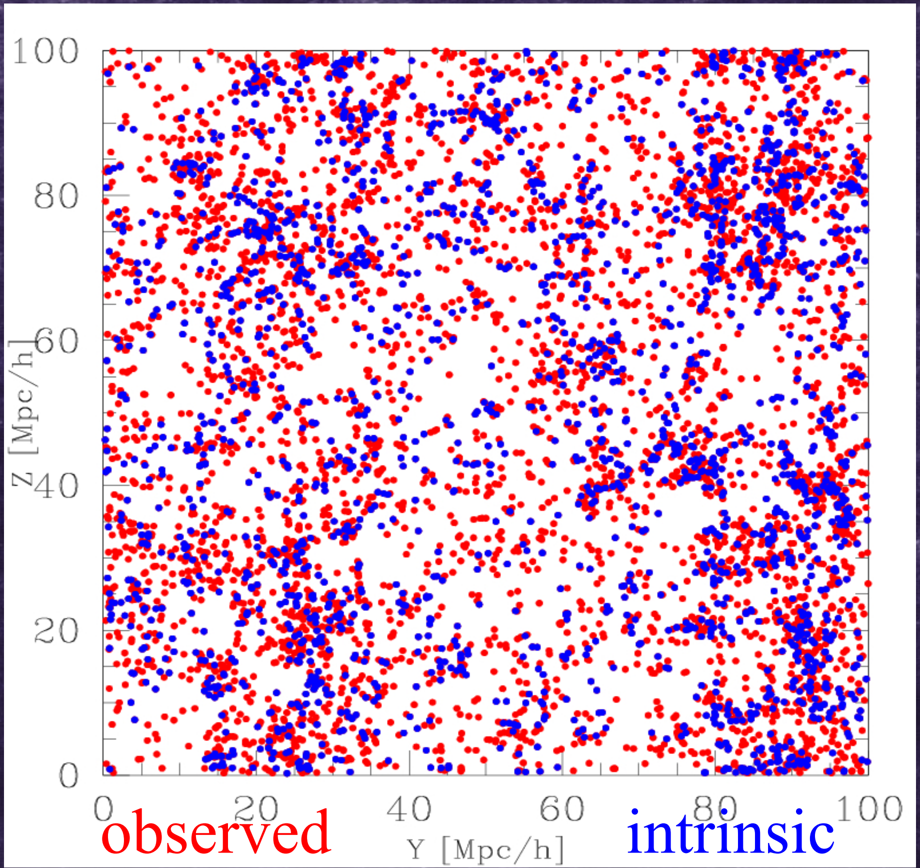
Ly-α,β,γ: IGM Transmissivity

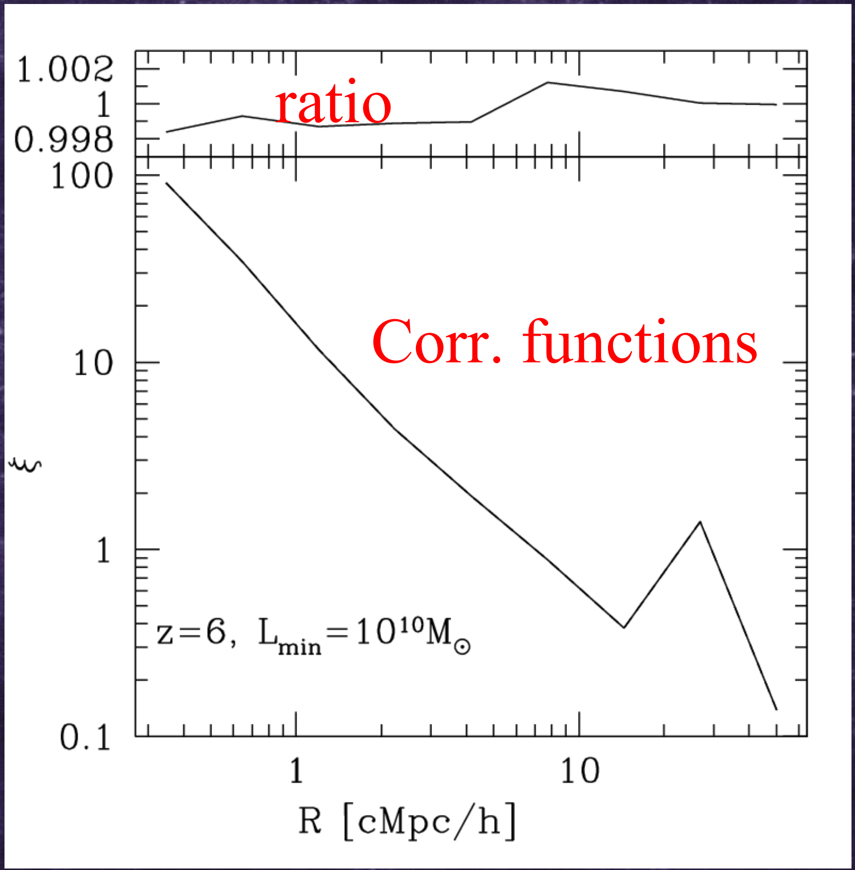
(Iliev et al. 2008, MNRAS, 391, 63)



data: Fan et al. 2006

Correlation functions of Ly-α sources
(Iliev et al. 2008, MNRAS, 391, 63)



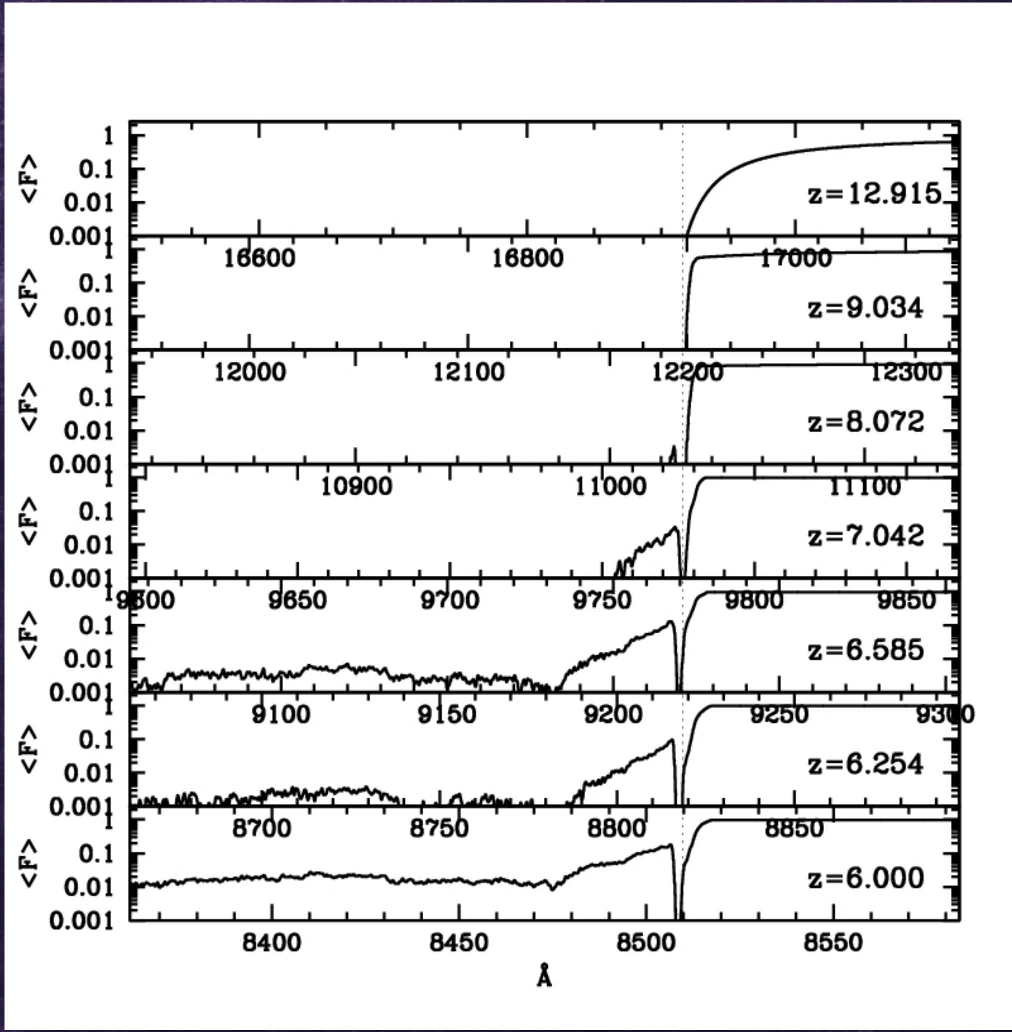


For a given (e.g. observed) **number density** of sources their clustering is largely **unaffected** by reionization patchiness (max 10% difference at small scales and at high-z, decreasing later).

Mean Ly-a transmission vs. z

(Iliev et al. 2008, MNRAS, 391, 63)

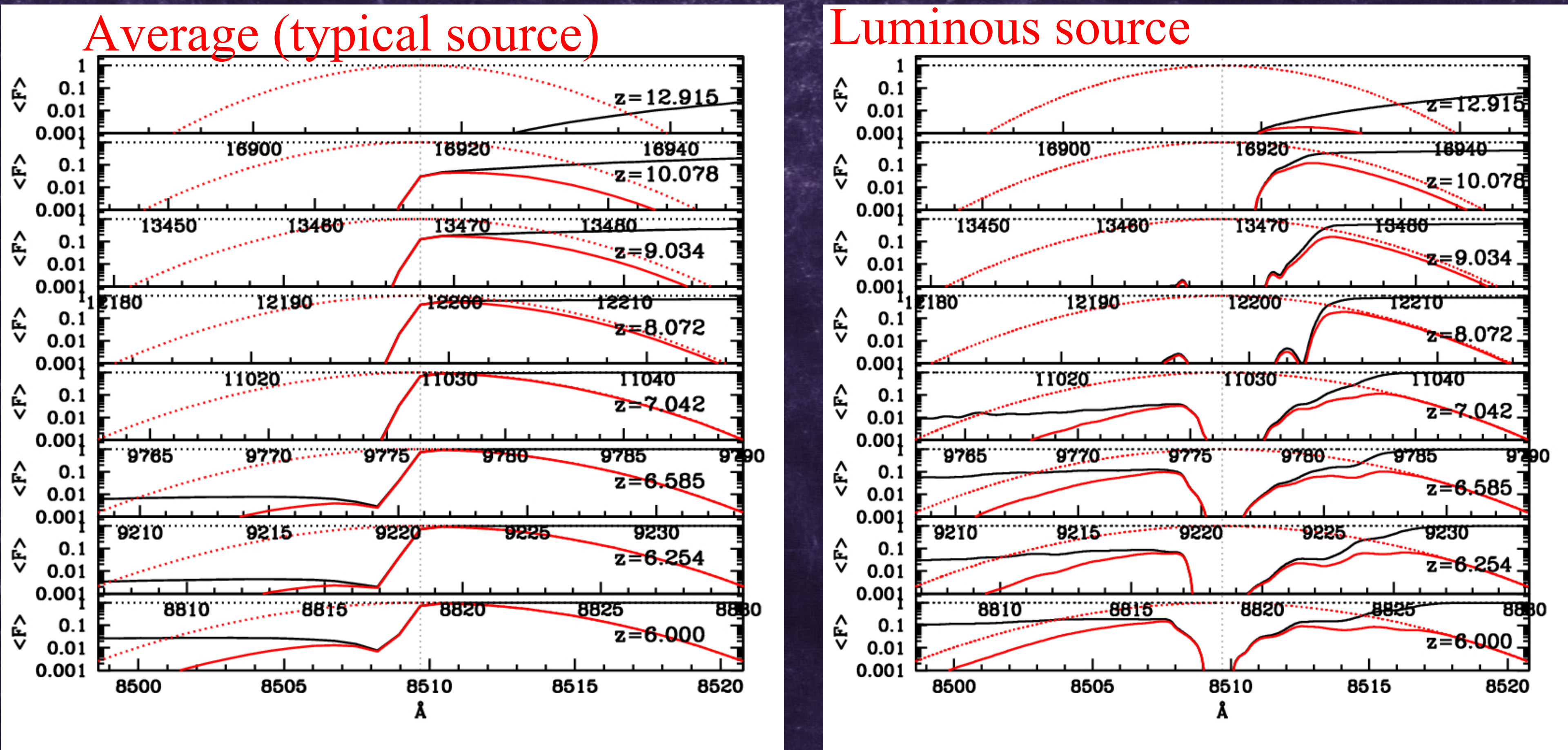
- Stong damping wing at z>10
- Red side of line is visible at z<10
- Some transmission at blue side of line, first in proximity region, later throughout, as IGM slowly becomes transparent.



Mean Ly-α line shape vs. z

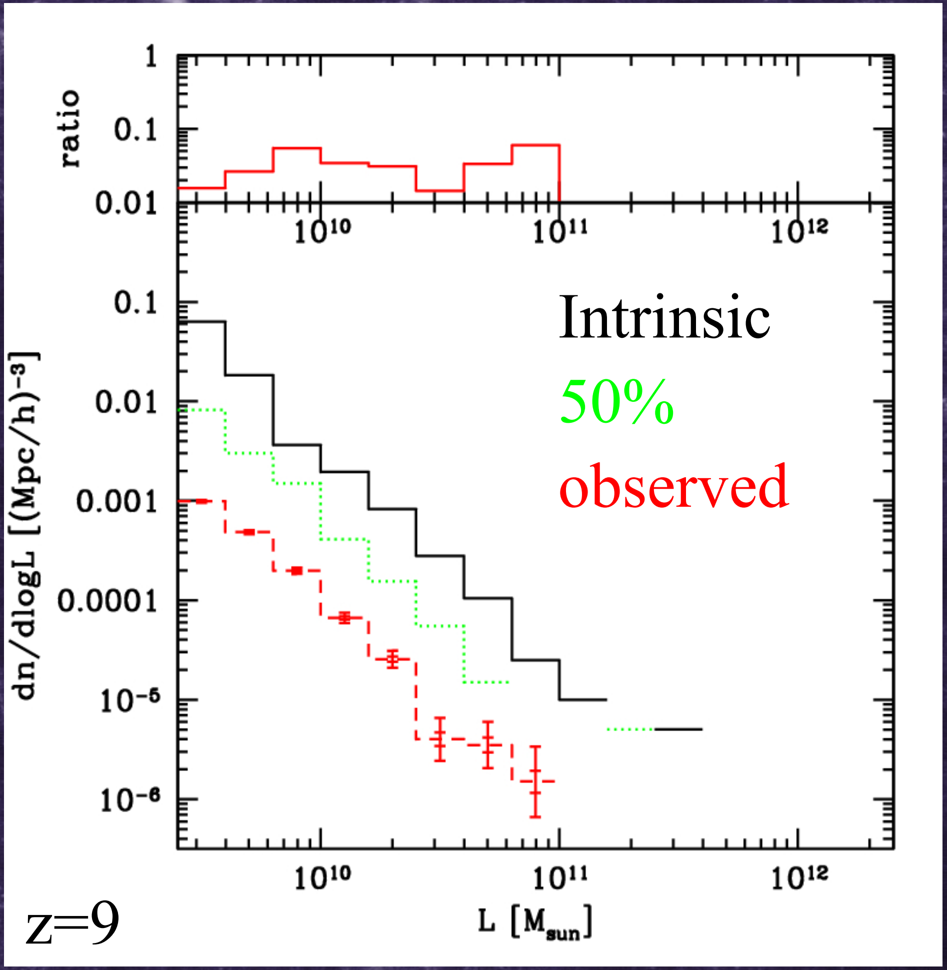
(Iliev et al. 2008, MNRAS, 391, 63)

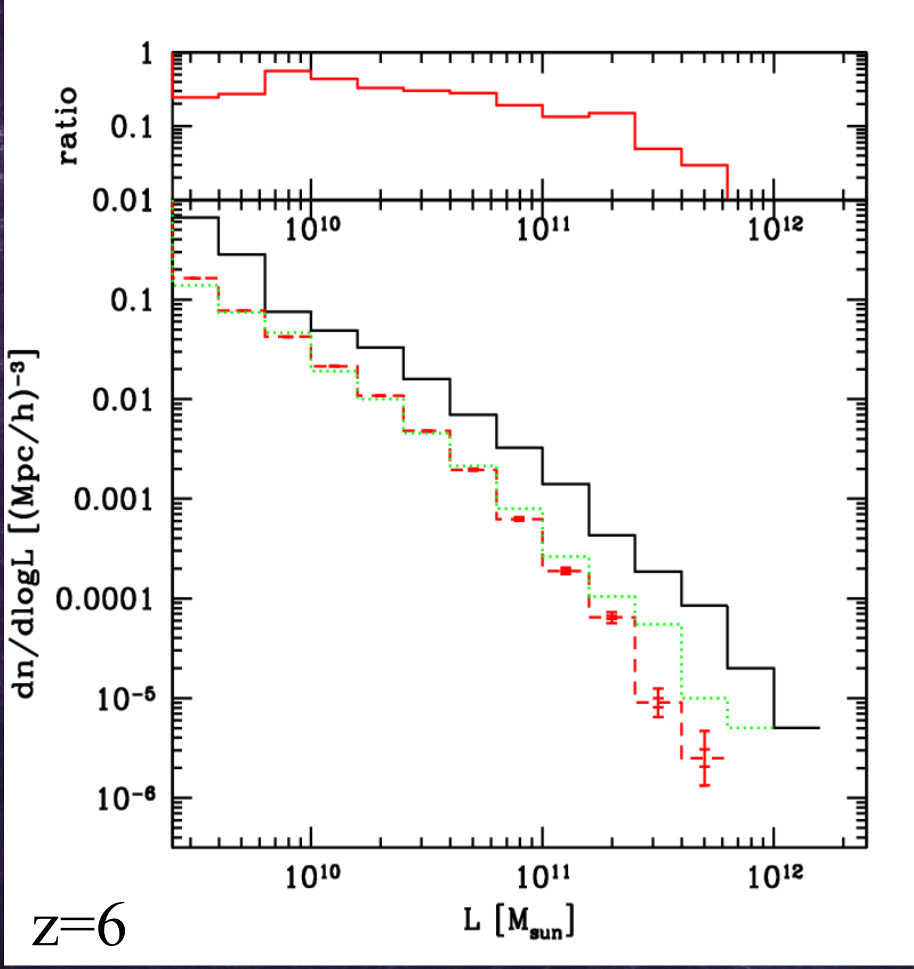
- Mostly the red wing comes through (but damped at z>10).
- Infall more important for luminous sources, changes the line shape.



Ly-a Luminosity Functions

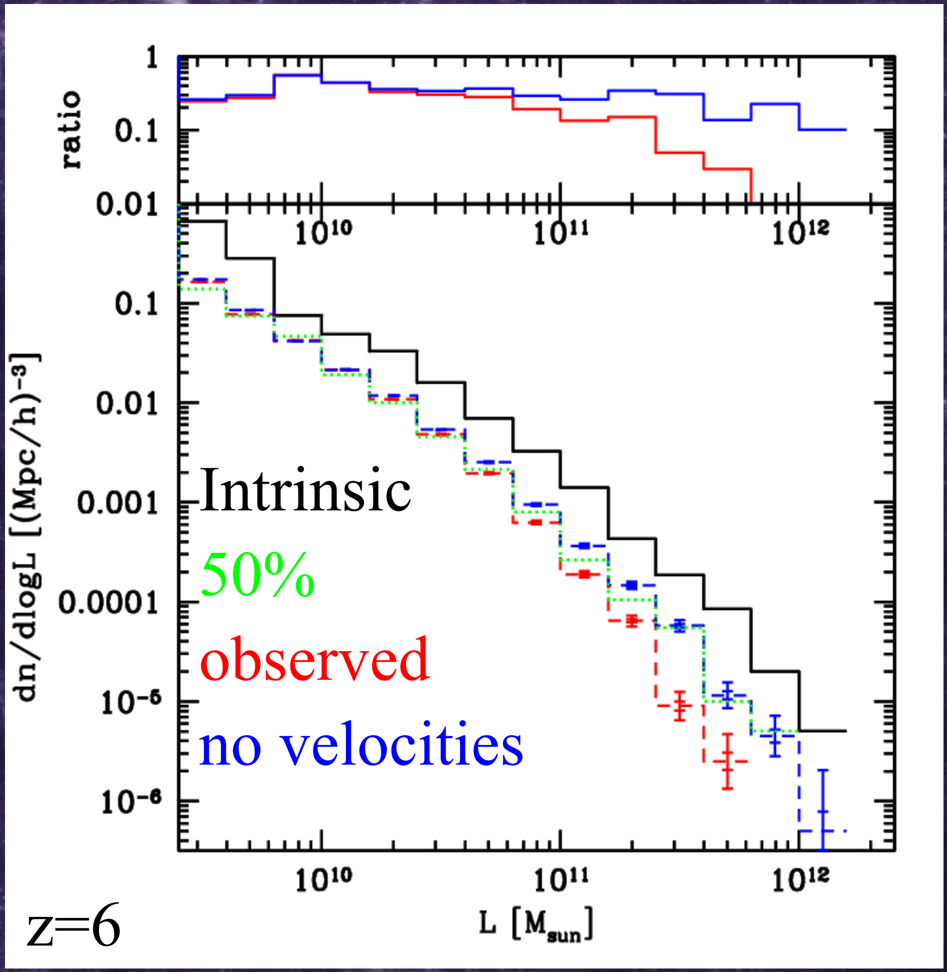
(Iliev et al. 2008, MNRAS, 391, 63)

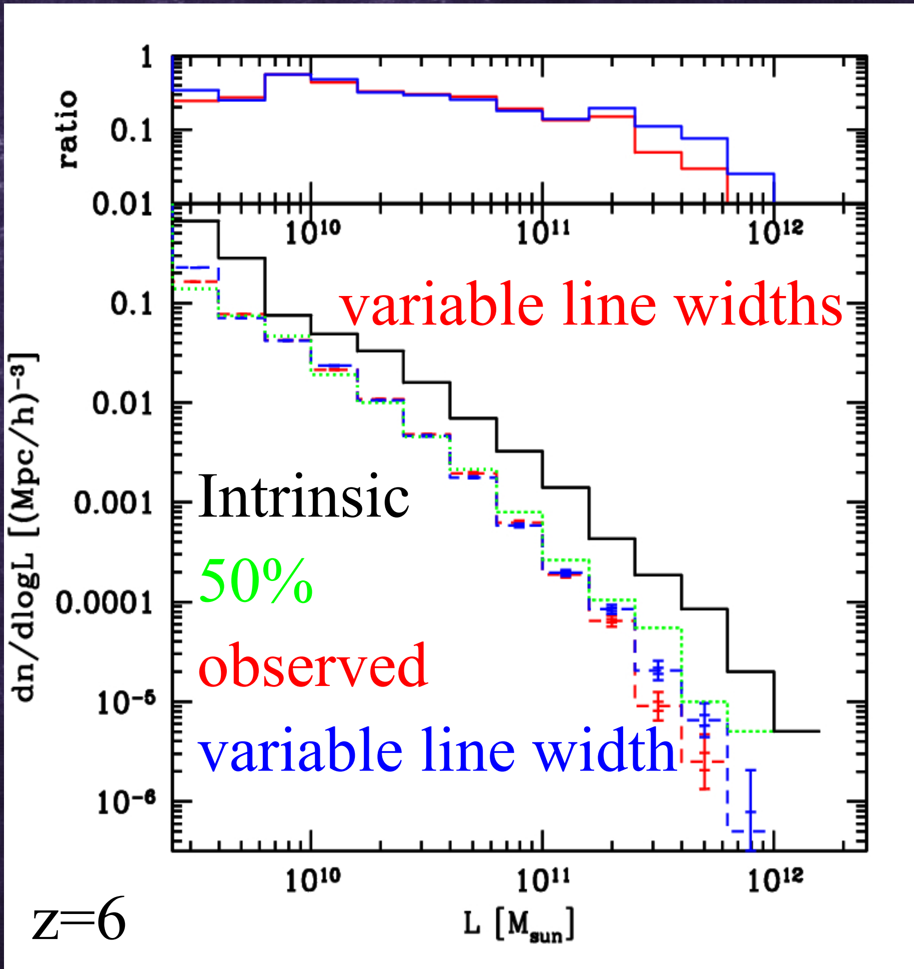




Ly-a Luminosity Functions: effects of velocities and the assumed line widths

(Iliev et al. 2008 MNRAS, 391, 63)

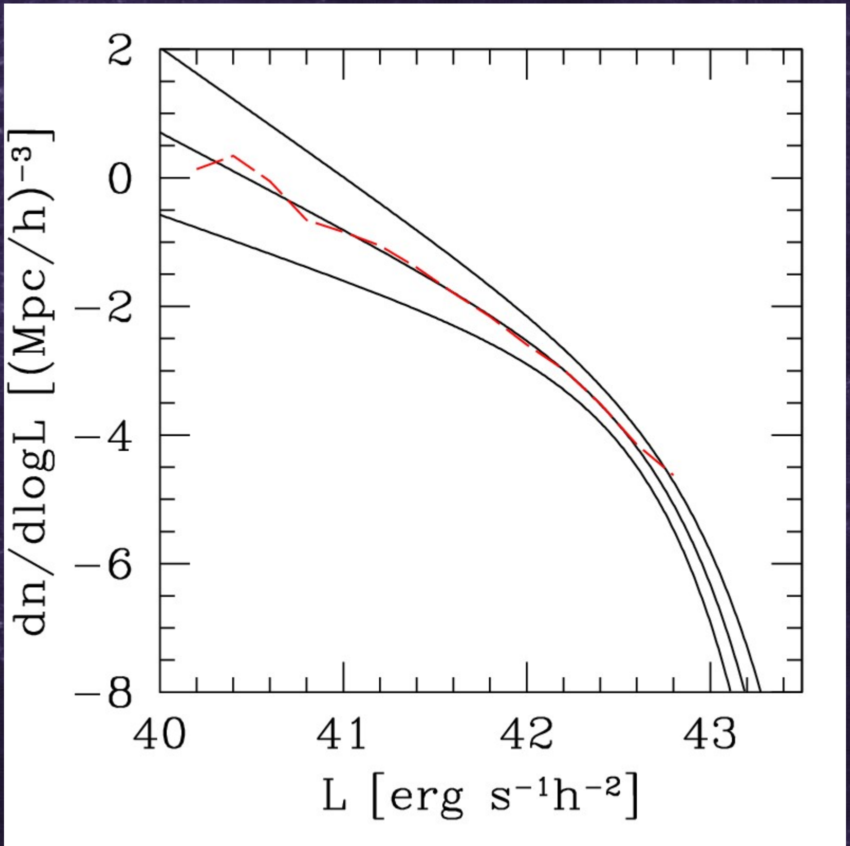




Luminosity function: simulations vs. observations
(Iliev et al. 2008, MNRAS, 391, 63)

LF normalization: set by matching the number density of sources in simulations to the observed one (by Kashikawa et al. 2006). Excellent match of the shape, for an assumed faint-end slope of -1.5 for the fit to the observations.

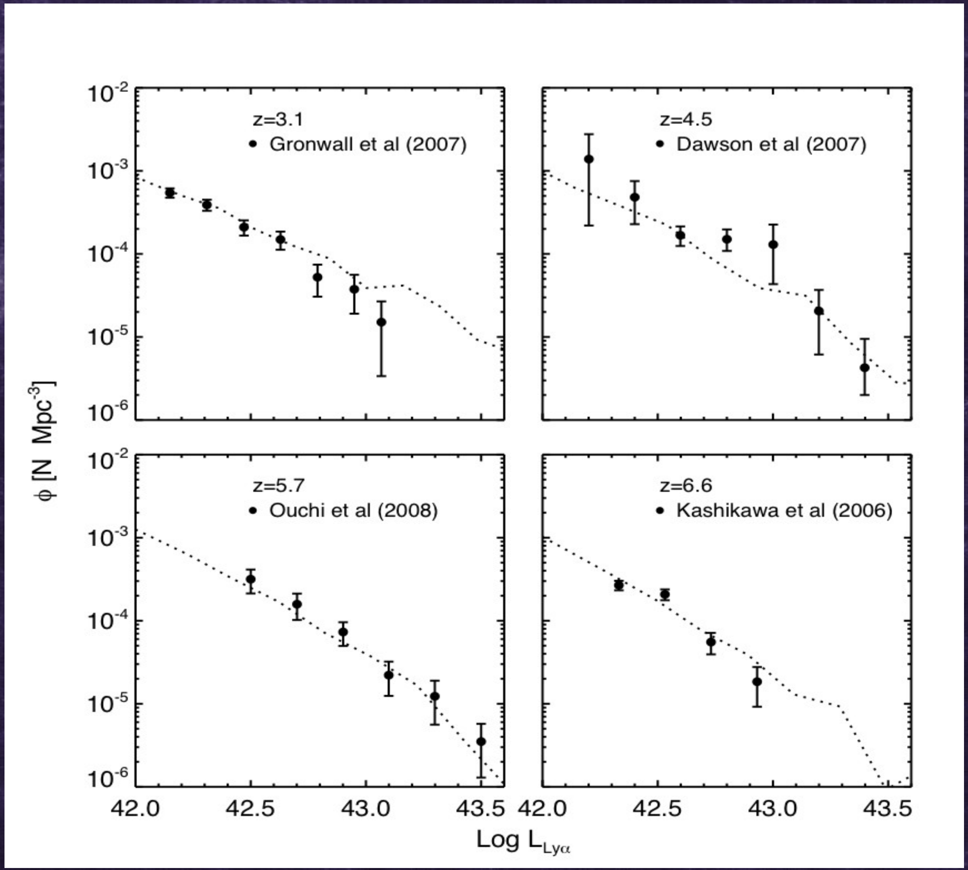
→ the majority of sources responsible for reionization are too faint to be observed at present.



A simple physical model for the luminosity function of Ly-a sources

(Tilvi, Malhotra, Rhoads, Scannapieco, Thacker, Iliev & Mellema, 2008, submitted)

- A simple, 1-parameter model.
- Based on assumption that Ly-a luminosity is proportional to halo mass growth.
- Matches well the Ly-a LF data at z=3-6.6.
- Introduces naturally a duty cycle.
- Source clustering agrees well with observed one.



For more details see poster, preprint and talk to authors present here.

Summary

- Large-scale, accurate and detaled structure formation and radiative transfer simulations of the epoch of reionization at the large scales relevant to observations are now possible.
- Sources are strongly clustered, resulting in large HII regions, each carved by large number of sources. Even bright sources do not dominate their HII regions.
- Local IGM properties (density, ionization, velocity) have huge impact on the observability of Ly-a sources, and have to be modelled correctly and in detail.
- Velocity effects are particularly important for luminous sources. Line profiles are generally double-peaked.
- The currently-detected sources are at the bright end of the luminosity function and are not the ones responsible for emitting the majority of the ionizing radiation.
- Photoionization rates are highly spatially inhomogeneous and non-equilibrium.

Thank you for your attention!

Time for questions...