Fundamental Characteristics and Observability of the Epoch of Reionization

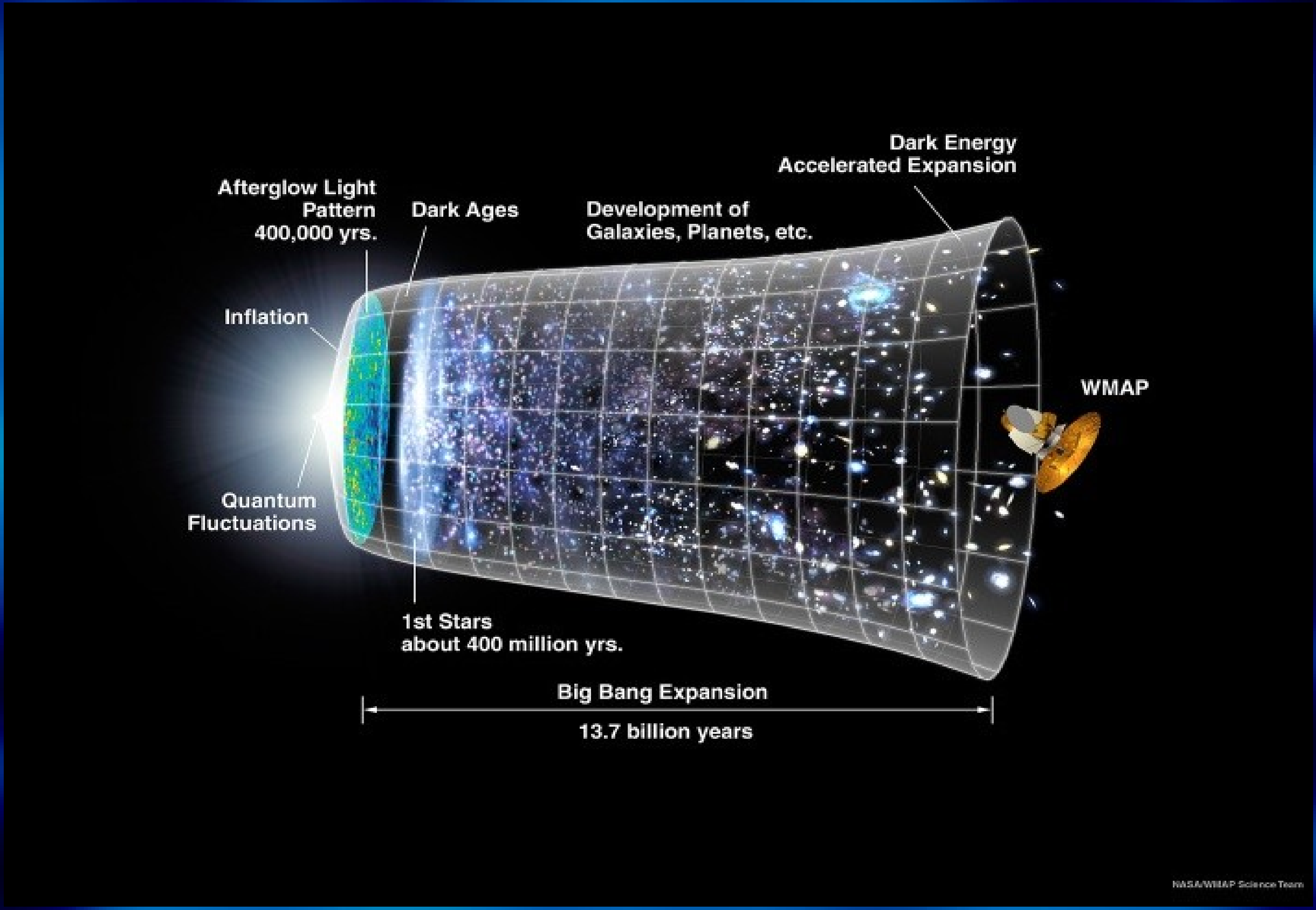
Ilian T. Iliev

University of Zurich

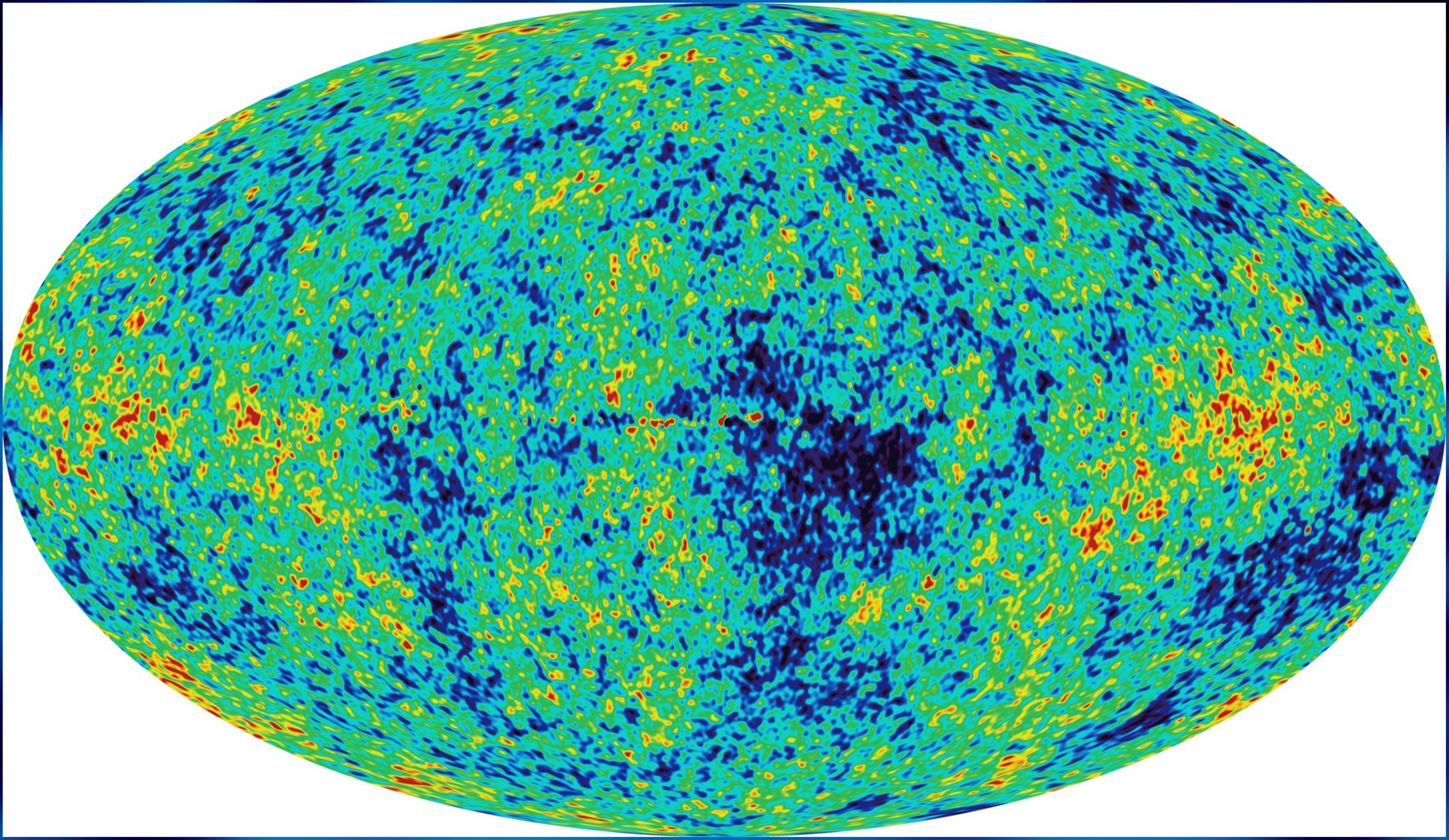
with

Garrelt Mellema (Stockholm), Paul Shapiro, K. Ahn (Austin), Ue-Li Pen, Dick Bond, Pat McDonald, Olivier Dore (CITA), Ben Moore (Zurich), G. Yepes (Madrid), S. Gottloebber (AIP)

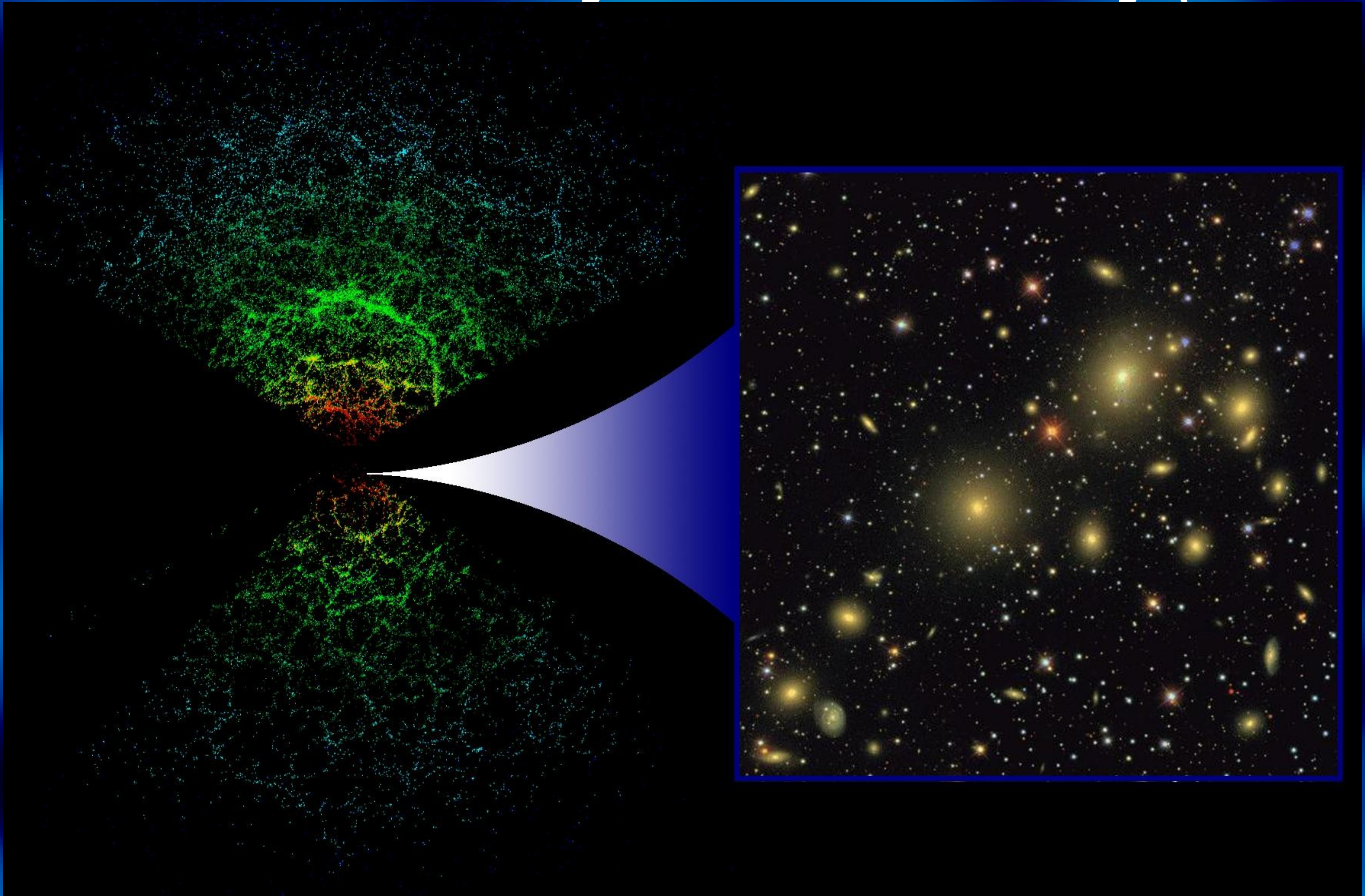
History of the Universe



Primordial density fluctuations as seen by WMAP satellite

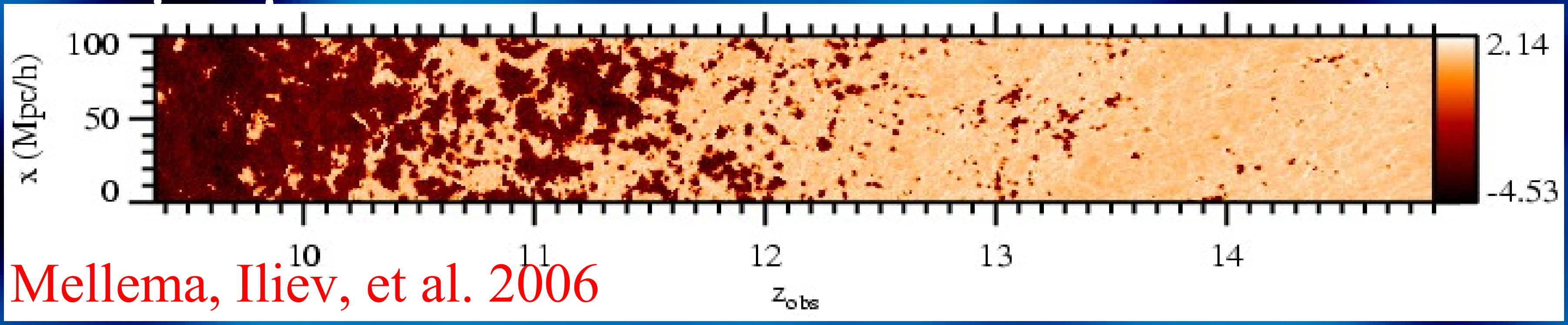


Cosmological Structure Formation: The Cosmic Web seen by the Sloan Survey (SDSS)



The importance of Reionization

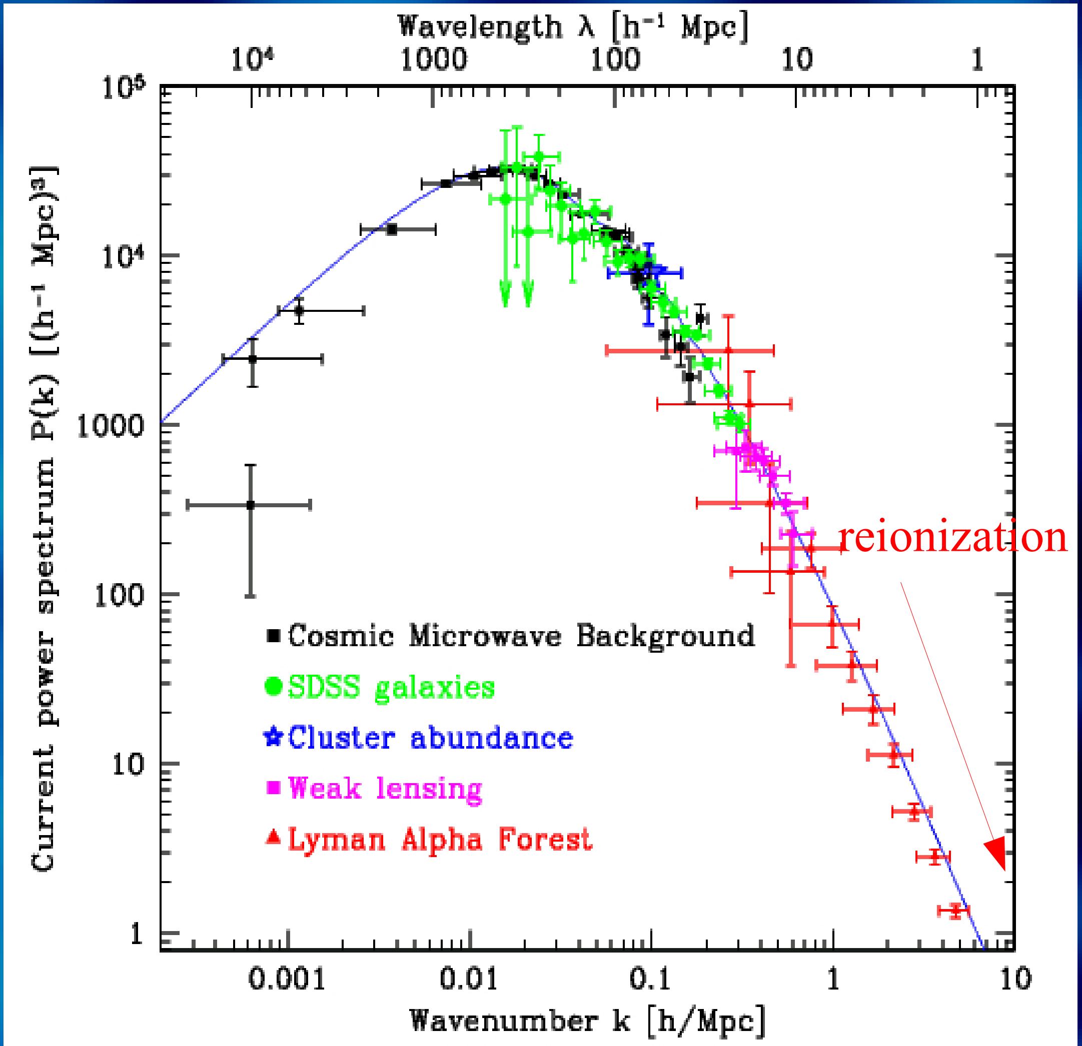
- Epoch of Reionization (EOR): the last global transition of the IGM, from neutral to highly-ionized, which occurred due to the ionizing radiation from the first galaxies, with profound effects on the state of the IGM and the subsequent galaxy and star formation.
- Significant, important and poorly-understood period in the history of the Universe (age ~100 Myr to 1 Gyr). Complex, patchy evolution.
- Currently very little observational data is available (τ and z of overlap) - difficult to constrain models of reionization. It is important to make reliable predictions for a number of upcoming experiments: EOR is one of the Key Science Projects for both SKA and LOFAR (pathfinder for SKA), and for other current and planned



Mellema, Iliev, et al. 2006

Primordial power spectrum of density fluctuations and the EOR

Reionization depends mostly on scales k>>1/Mpc, a part of the P(k) density power spectrum well below the scales currently probed by other methods



EOR Simulations: Requirements

- *Large* scale simulations.
  - Observationally needed: radio observations will have ~degree fields of view and low resolution ~1' (sensitivity).
  - Fundamentally required: size of HII regions >10 Mpc, long-wavelength density perturbations.
- *Large* dynamic range simulations.
  - Dominant contributors to reionization were small (dwarf and sub-dwarf) galaxies. Ideally need to resolve collapsed halos of mass $10^8 M_{solar}$ and up.
  - Low dynamic range imposes artificial cut-offs on density fluctuations.

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.

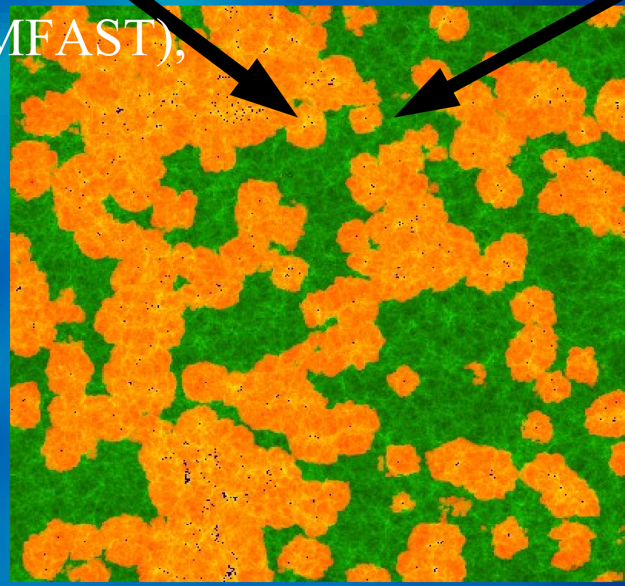
Large-Scale Simulations of Reionization

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

- N-body:
  - PMFAST:1624^3 part. (4.3 billion)
  - CubeP^{3}M:1728^3 part. (5.2 billion) or more - 2048^3-4000^3(8.6-64 billion)
- density slices
- velocity slices
- halo catalogues-sources

- 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 4000 cores).

100/h or 35/h Mpc box (PMFAST), 64-144/h Mpc (CubeP^{3}M)
resolving 10^8 M_{solar} halos
up to few x 10^6 sources
50-100 dens. snapshots
simple source models
sub-grid clumping
no hydro – large scales.

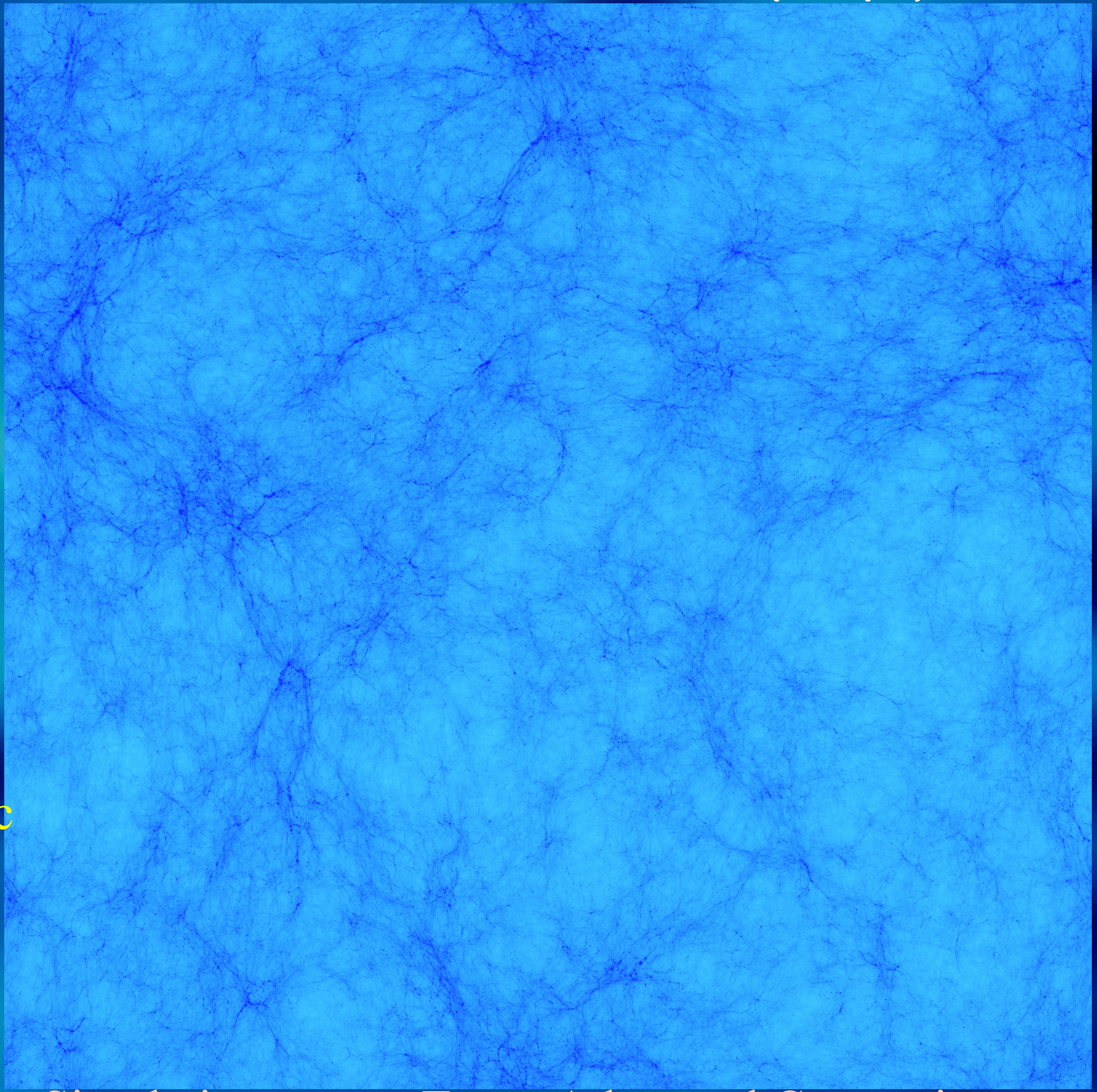


The Formation of Early Cosmic Structures
(Iliev et al., 2006a, MNRAS, 369, 1885; Iliev et al. in prep.)

64/h Mpc box @ z=6
1728^3 particles (5.2 billion),
3456^3 cells

29 billion (3072^3) and
64 billion (4000^3)-particle
simulations are under way;
10^{12} ($10,000^3$=trillion)-particle
simulations are now within reach.

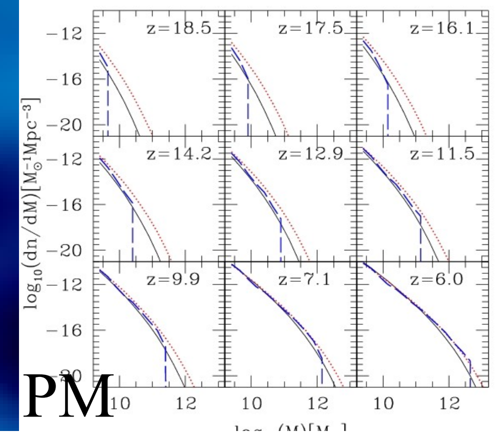
These sizes allow resolving all halos down to atomically-cooling limit (10^8 M_{solar}) in 100-150/h Mpc boxes, as well as simulating the whole volume of a large galaxy survey (multiple Gpc^3) with the appropriate resolution (i.e. resolving L* or better).



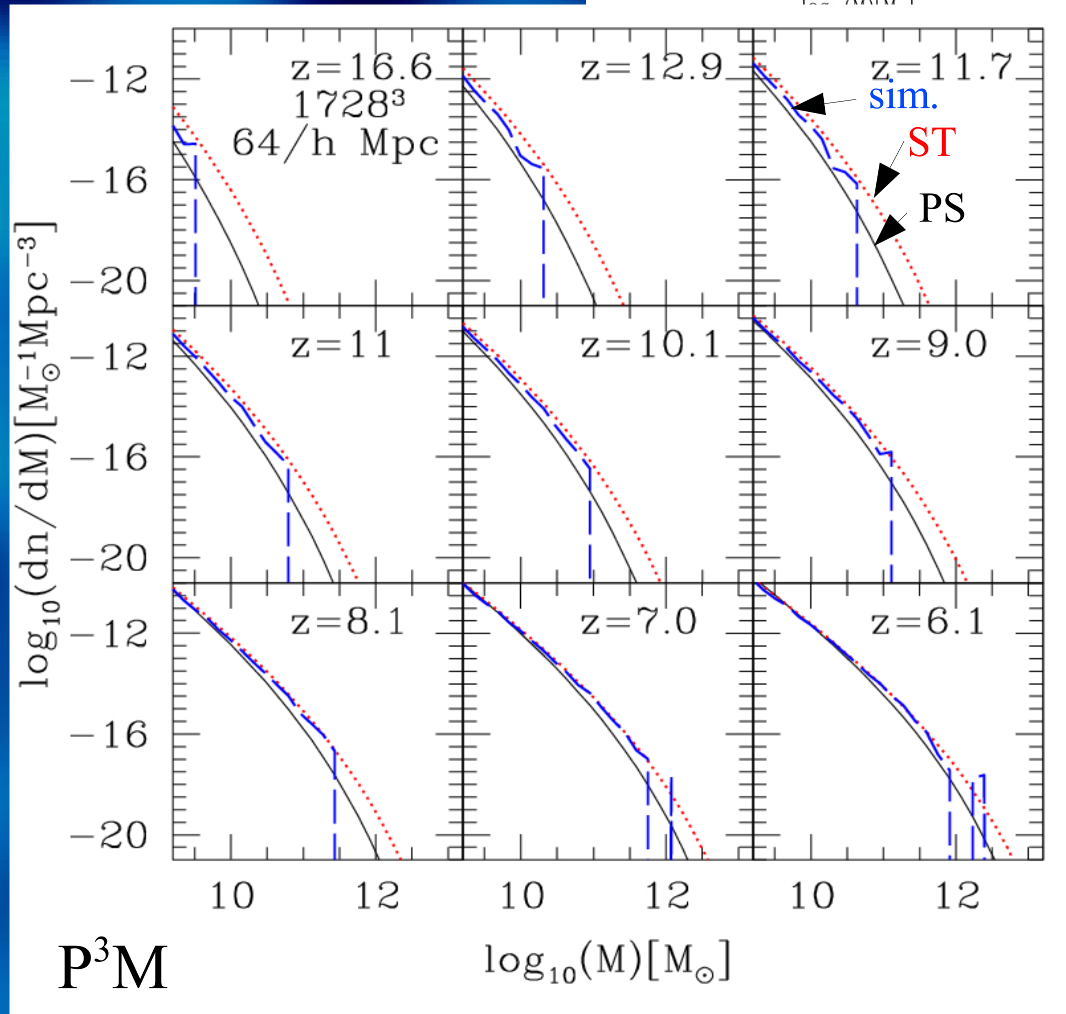
Simulations ran at Texas Advanced Computing Center, each taking few days on 432 - 4000 cores.

The high-z halo mass function

(Iliev et al., 2006a, MNRAS, 369,1625; Iliev et al, in prep.)



- Up to ~2 million (PM) and ~4 million (P^3M) halos identified.
- The simulated halo mass function at high-z does not agree well with either Sheth-Tormen (ST), or Press-Schechter (PS) analytical models.
- However, at later times ST is in resonable agreement with simulations.
- -> Originally shown by our PM simulations and now confirmed by current high-res P^3M data, as well as by other groups).

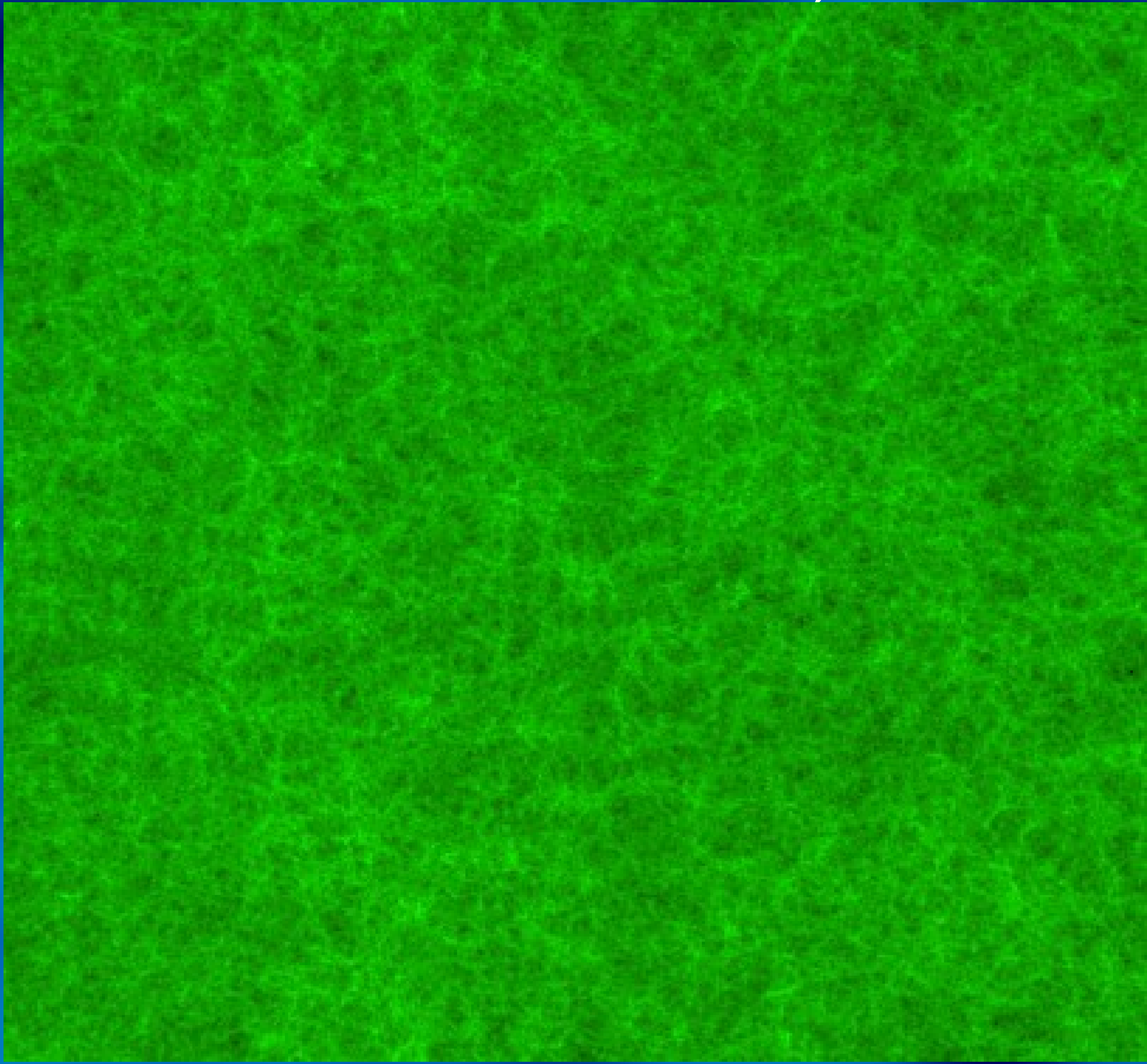


Dark Ages and Epoch of Reionization

(Iliev et al. 2006a, MNRAS, 369, 1885)

100/h Mpc box,
WMAP1
406^3 radiative
transfer simulation
Evolution: z=22 to 12.

Strong halo clustering (bias), quick local percolation, large H II regions with complex geometry.



Reionization history of sub-regions the highly-patchy nature of reionization

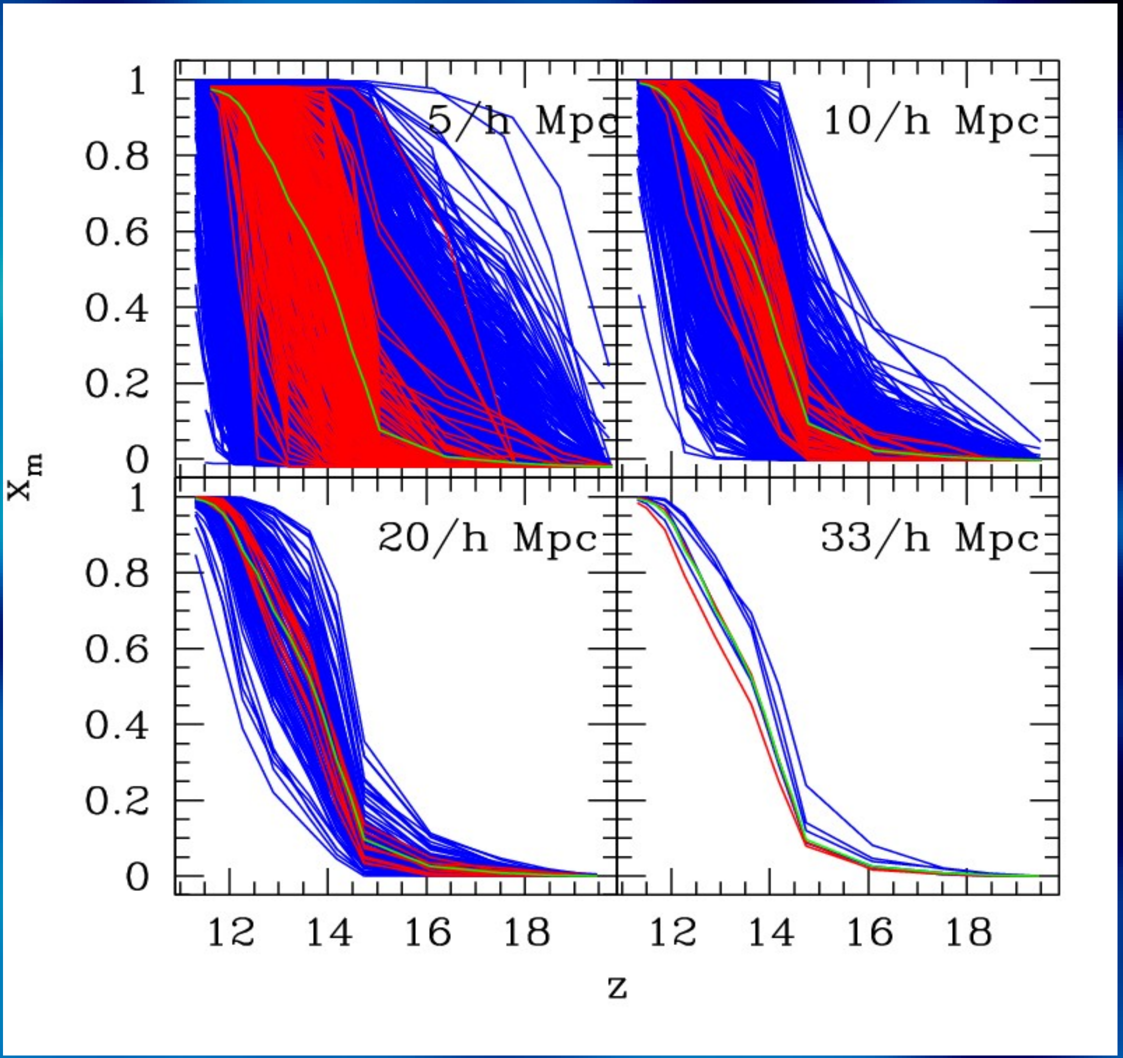
(Iliev et al., 2006a, MNRAS, 369,1625)

green = total mean

red = mean-density subregions

blue = all sub-regions

For small regions there is huge scatter and overlap epoch cannot be determined well. Only sufficiently large regions (>20 Mpc) describe the mean evolution well (though still larger volumes needed for e.g. HII regions size distribution).

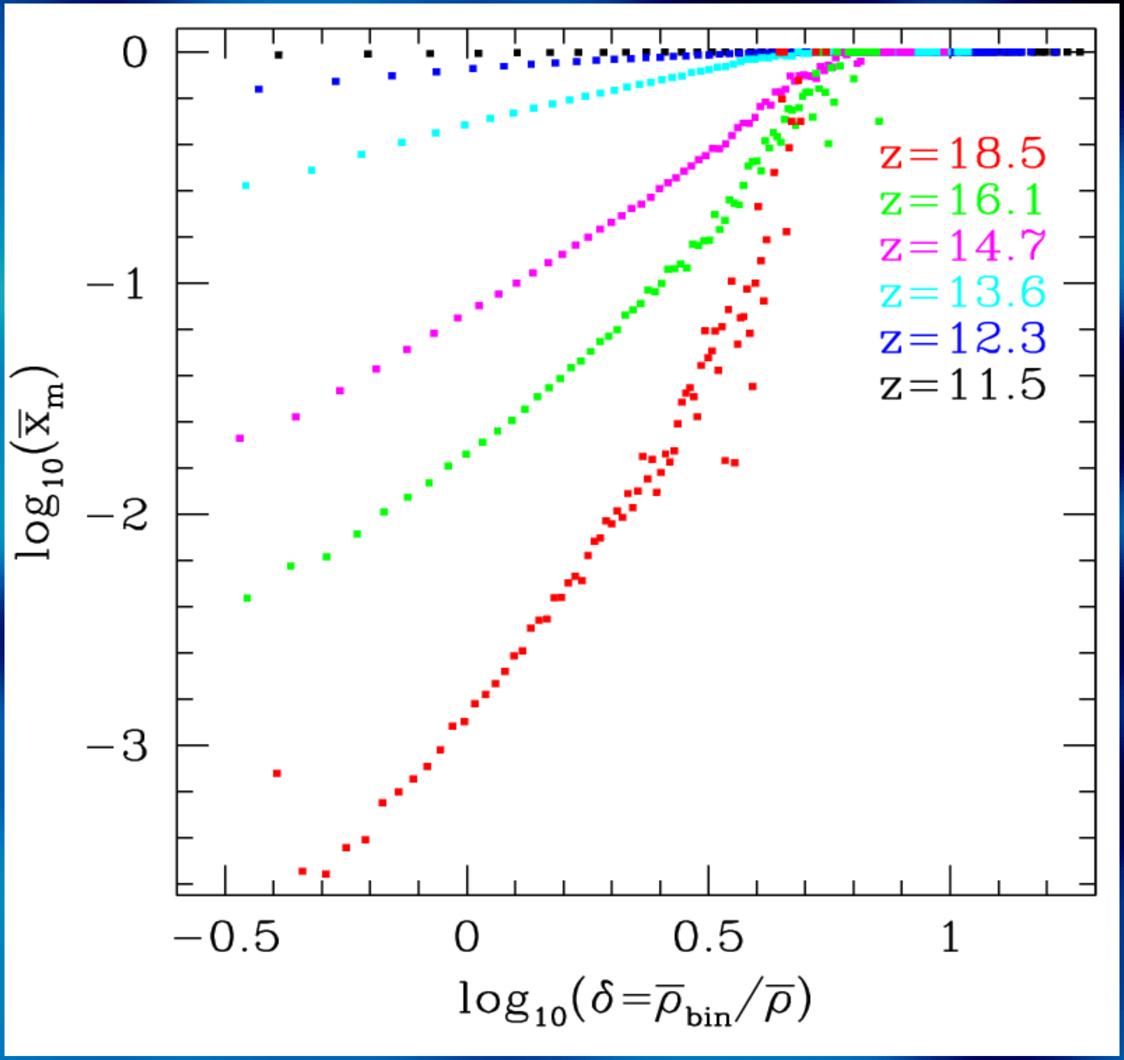


Mean Ionized Fractions vs. Density: Inside-Out Reionization

(Iliev et al., 2006a, MNRAS, 369,1625)

x_m=mean mass-weighted ion. fraction in a density bin

The highly overdense regions get ionized earliest, the lower the density, the later on average a region gets ionized.



Self-Regulated Reionization

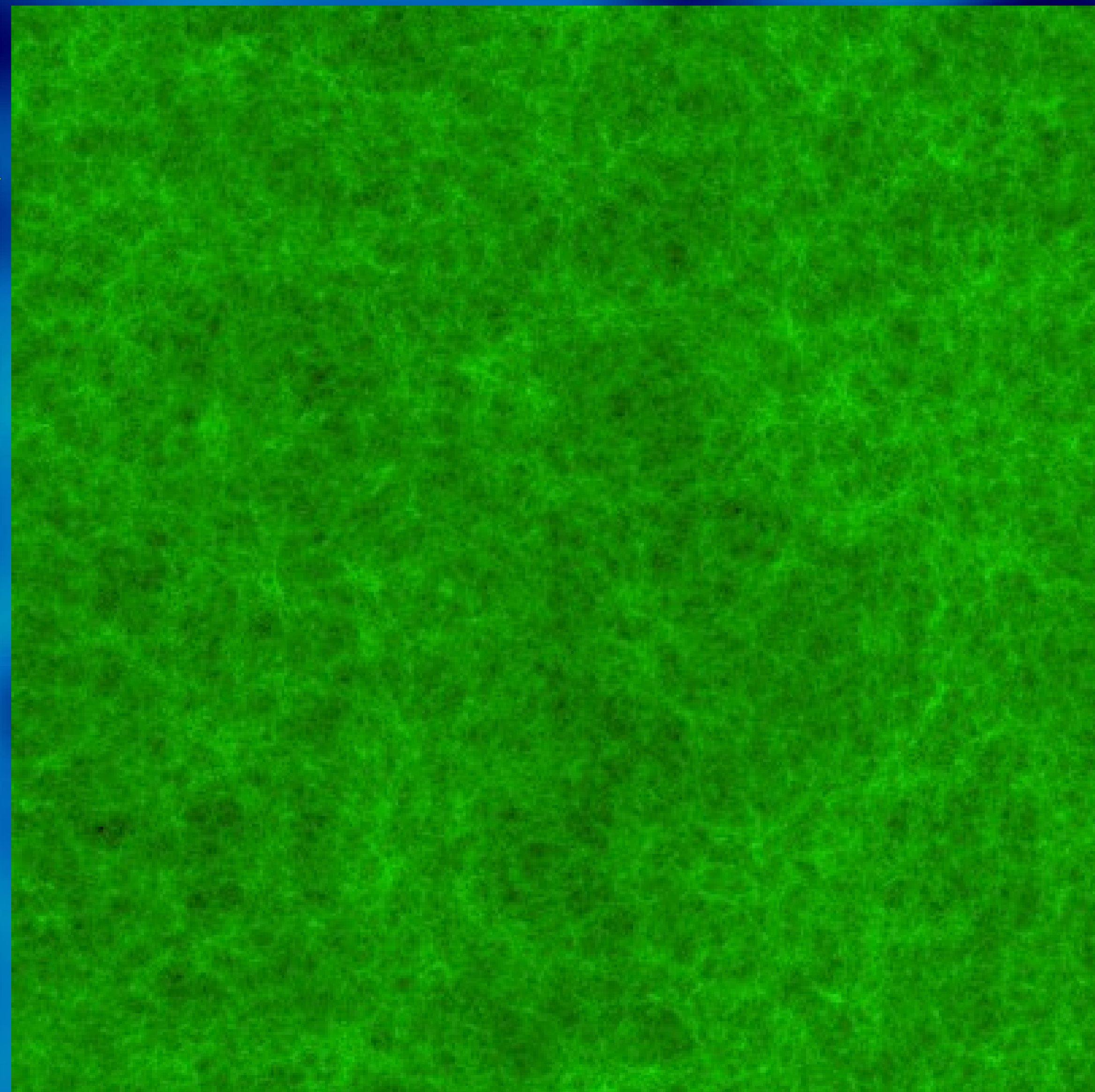
(Iliev et al. 2007a, MNRAS, 376, 534)

35/h Mpc box,
WMAP3 cosmology 406^3 radiative transfer simulation
Evolution: z=20 to 7.

$>10^8$ solar mass halos resolved (i.e. all atomically-cooling halos)-Jeans mass filtering

Lower efficiency for the low-mass sources does not extend reionization appreciably (but decreases τ).

Reionization is self-regulated!



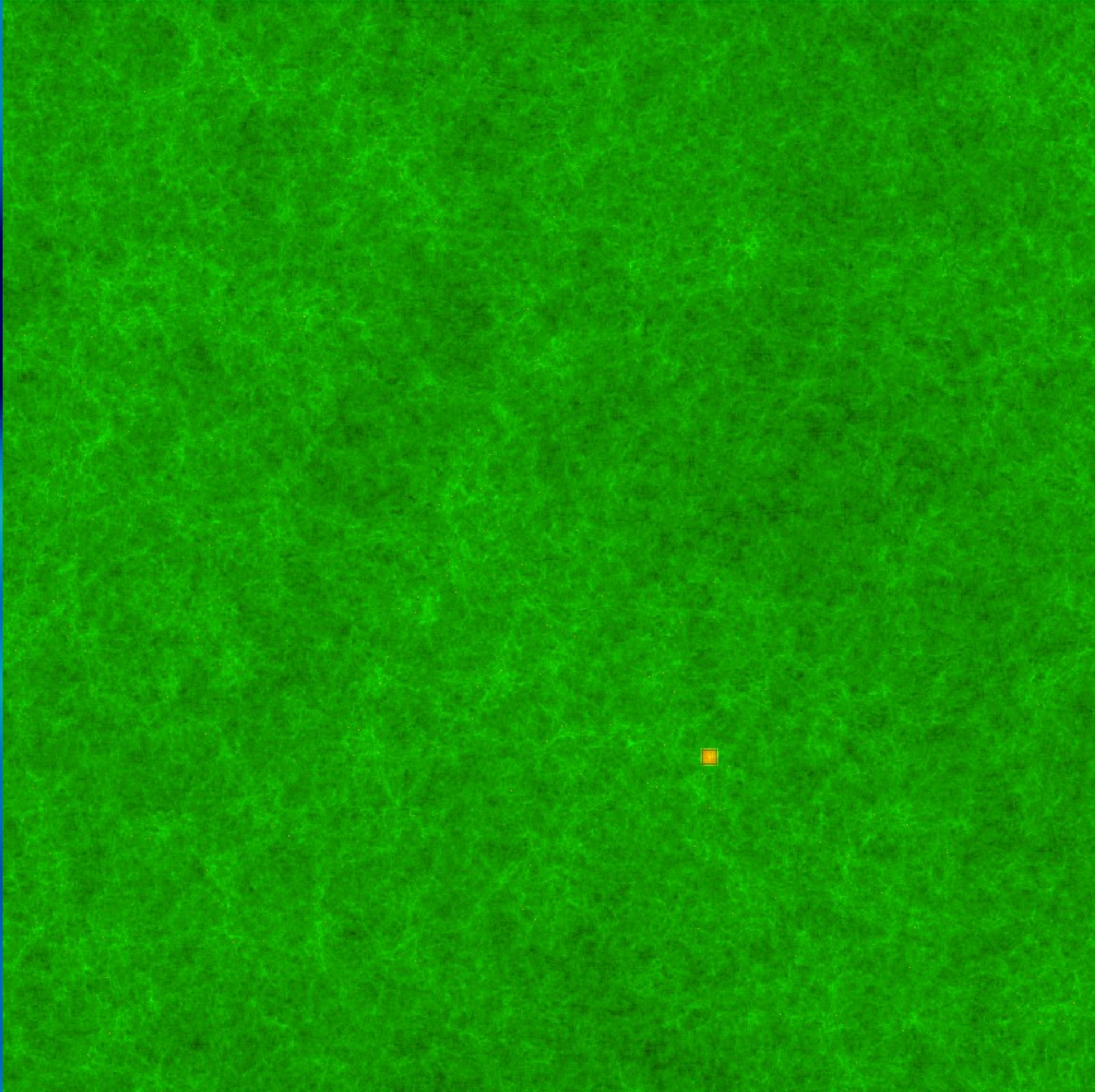
Self-Regulated Reionization

(the new generation)

(Iliev et al., in prep.)

64/h Mpc box, WMAP3+ cosmology, 216^3 radiative transfer simulation (432^3 under way)
Evolution:
z=30 to 7.

>10^8 solar mass halos resolved



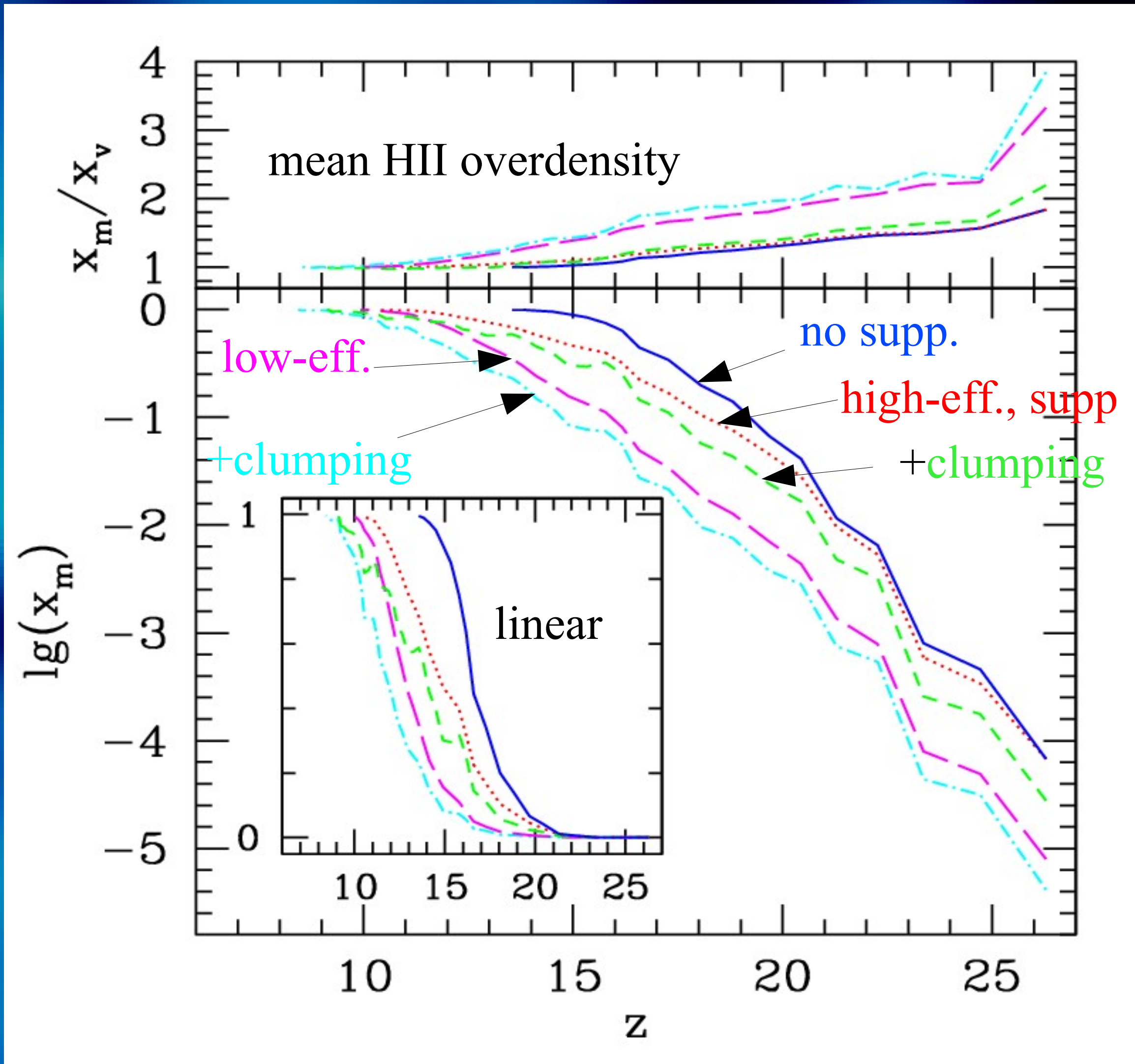
Self-Regulated Reionization II

(Iliev et al., 2007a, MNRAS, 376, 534)

Lower large-source efficiencies, Jeans-mass filtering of small sources and time-increasing sub-grid gas clumping all extend reionization and delay overlap.

However:

Lower small-source efficiency does not extend reionization appreciably (but decreases τ). Reionization is self-regulated.



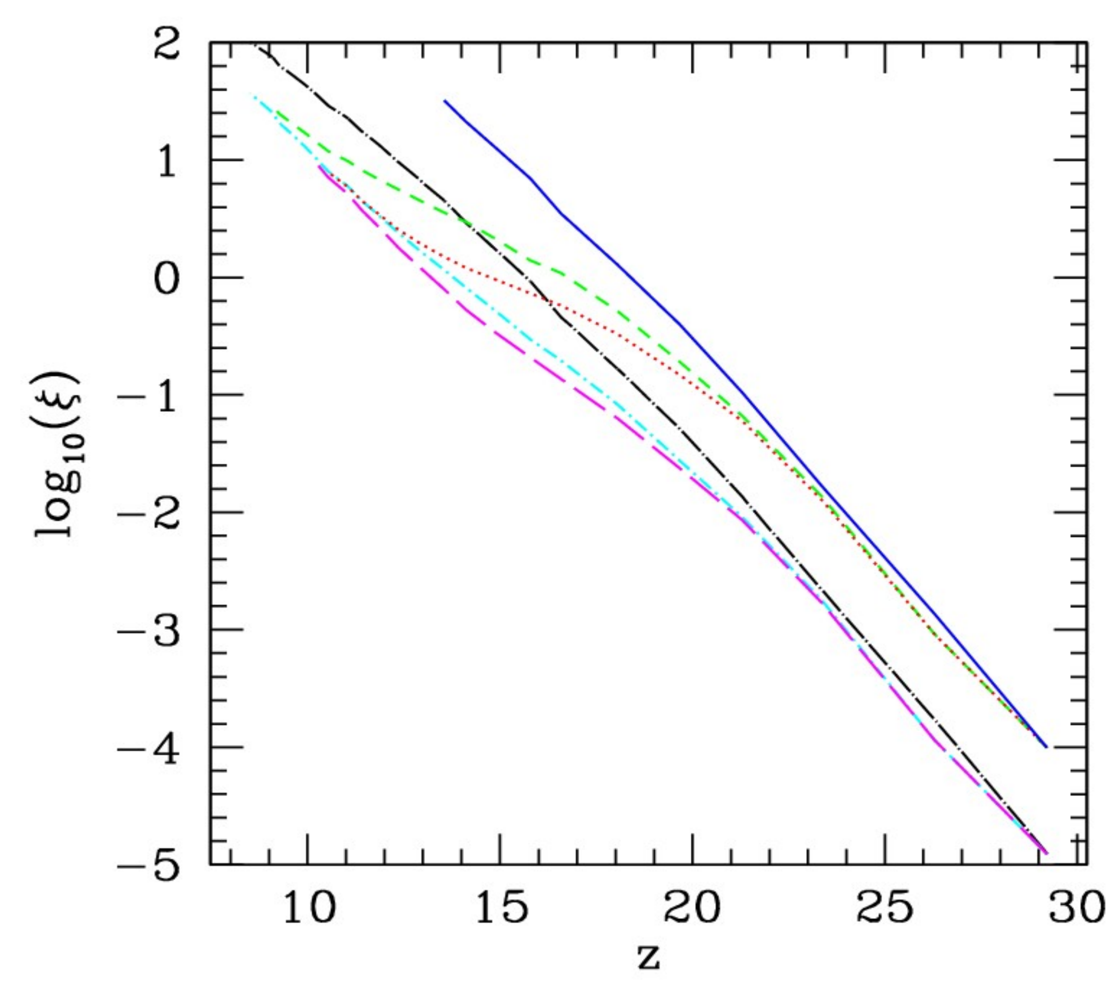
Self-Regulated Reionization III

(Iliev et al., 2007a, MNRAS, 376, 534)

Jeans-mass filtering of small sources suppresses the total emissivity by order of magnitude or more.

However:

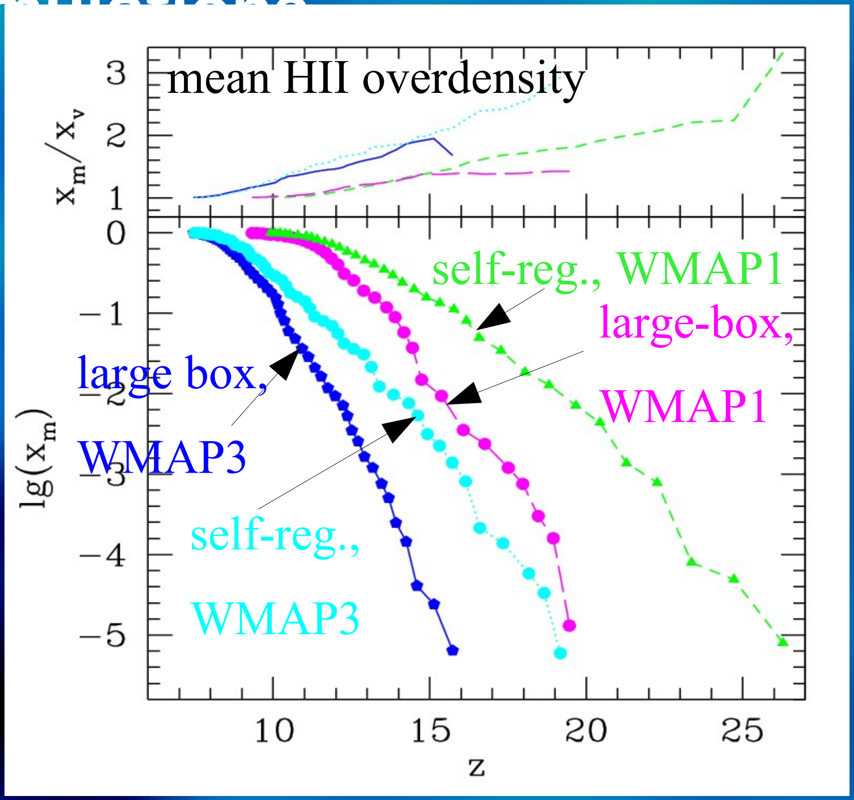
The epoch overlap is determined by the level of sub-grid clumping and the large, unsuppressed sources alone.

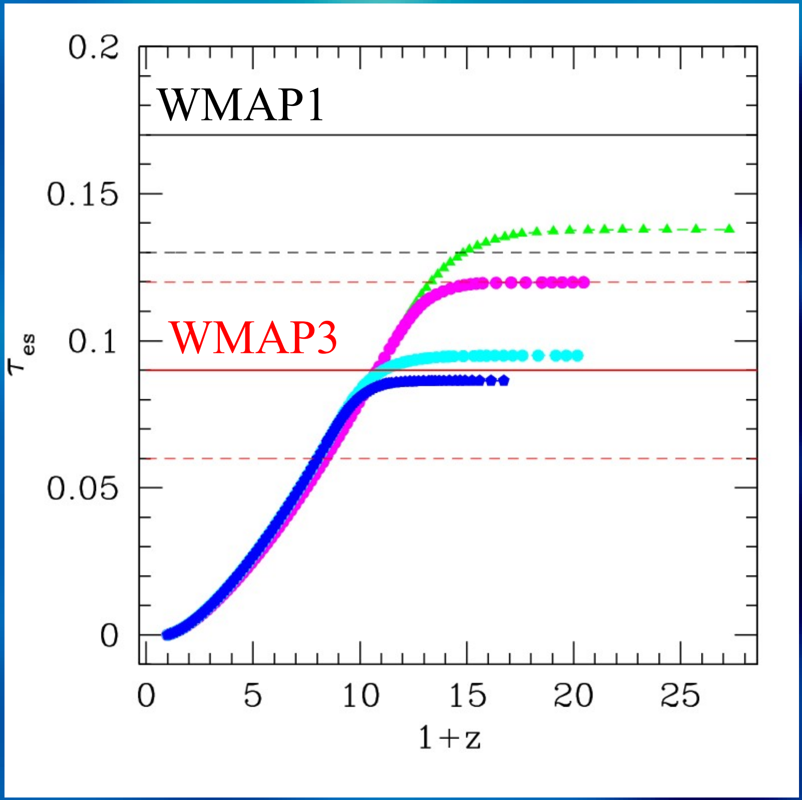


Reionization: WMAP1 vs. WMAP3

(Alvarez et al. 2006, ApJL, 644,101; Iliev et al., 2007a, MNRAS, 376, 534)

In WMAP3 cosmology reionization is delayed by 1.3-1.4 in 1+z, just enough to compensate for the new value of τ. Originally shown analytically, now confirmed by simulations

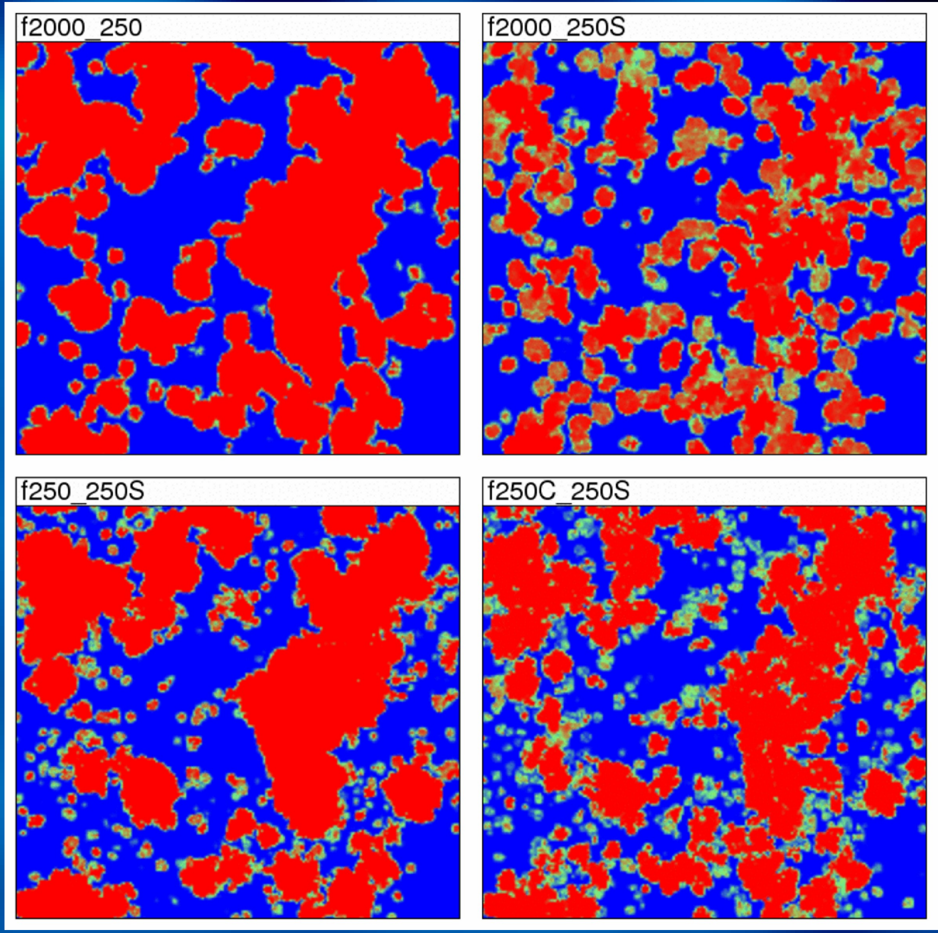




Characteristic scales of reionization and their dependence on the reionization scenario

(Alvarez, Shapiro, Iliev et al. 2007, in prep.)

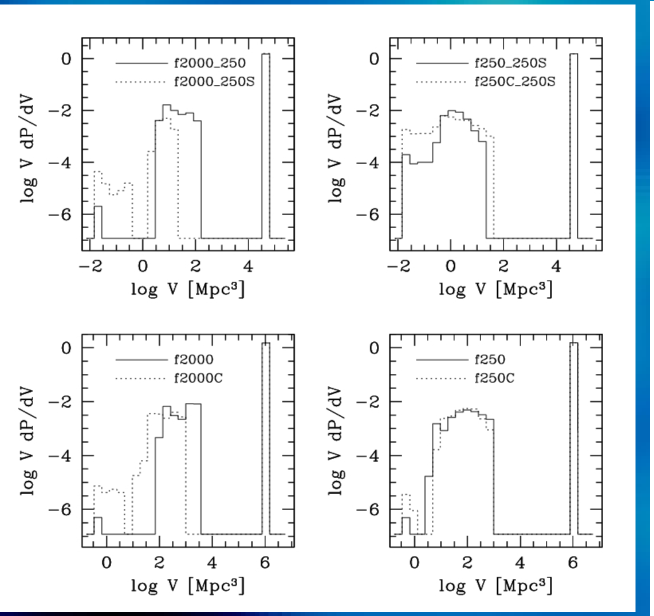
- Reionization is very inhomogeneous and patchy process.
- The sizes of the ionized and neutral patchess influence the fluctuations of all observables.
- There are different ways to describe the scales of the patches...



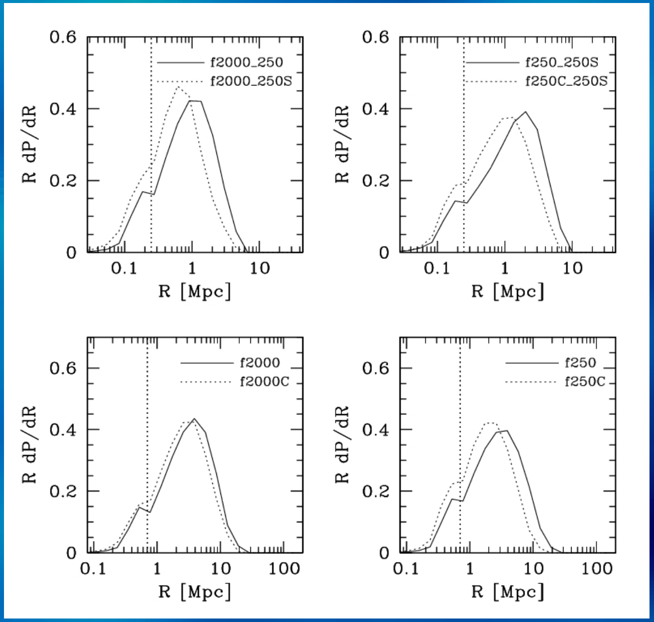
Characteristic scales of reionization and their dependence on the reionization scenario

(Alvarez, Shapiro, Iliev et al. 2007, in prep.)

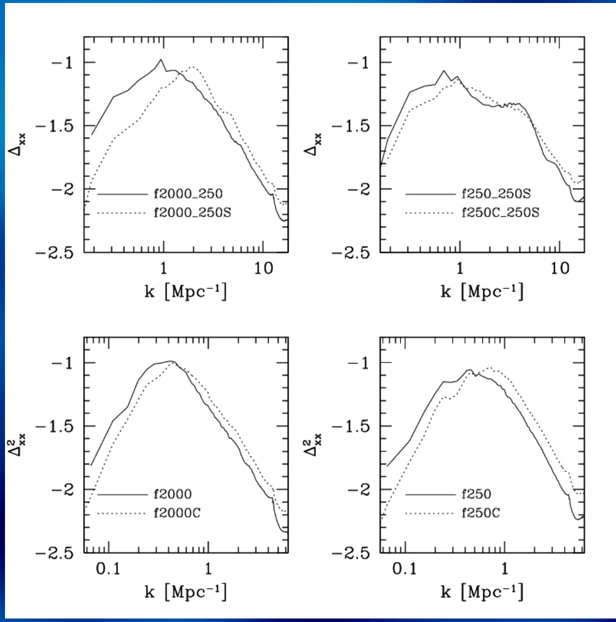
- 3 ways: connected (friends-of-friends, FOF); above threshold (spherical average; SA); 3D power spectra.
- All show characteristic scales, albeit varying between methods. Each reflects different features of the ionization field.



FOF



SA

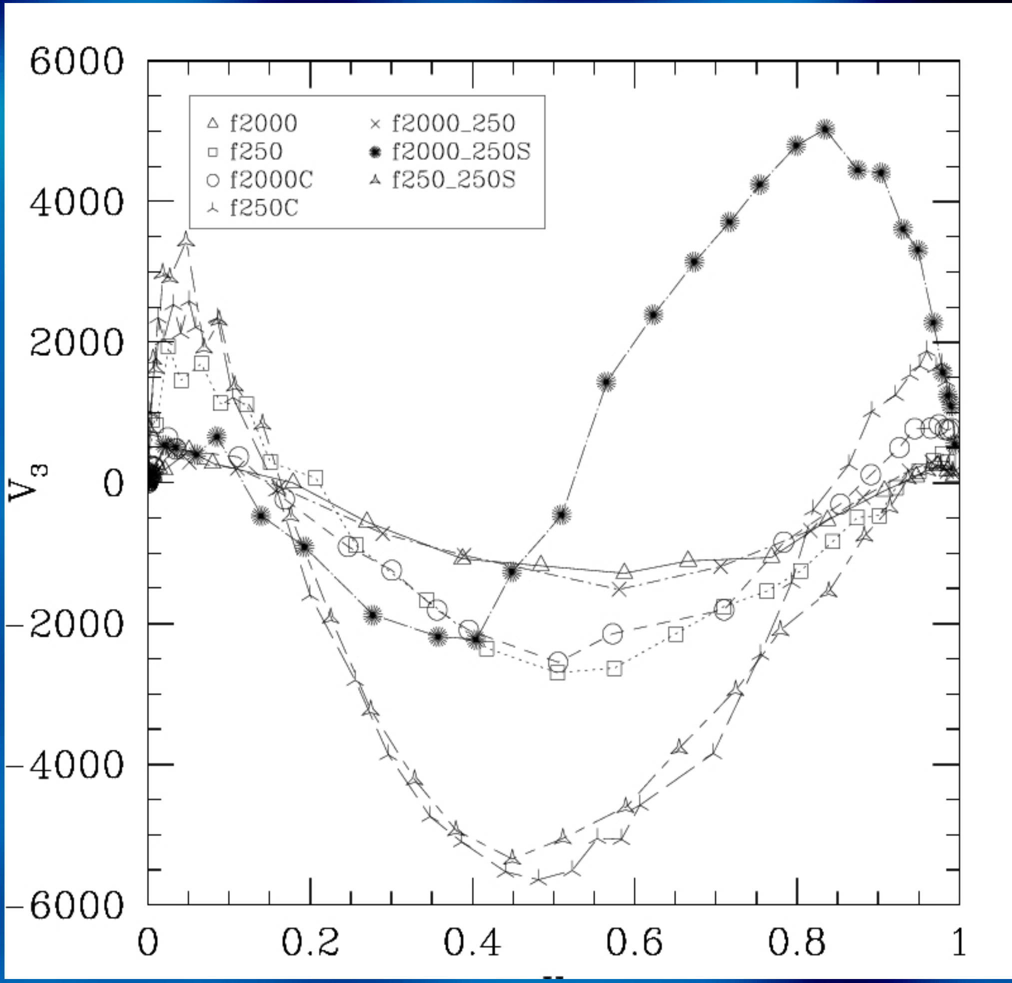


$\Delta(k)$

Reionization Topology

(Alvarez, Shapiro, Iliev et al. 2007, in prep.)

- Topological measures provide a complementary method to study the patchiness.
- The Minkovski functional V_3=integral of Gaussian curvature over surface =1-g, where g = genus = # of separate parts - # of tunnels.
- Indicates the complexity of the ionization surface topology.
- Proves sensitive to the efficiency of the low-mass, suppressible sources.



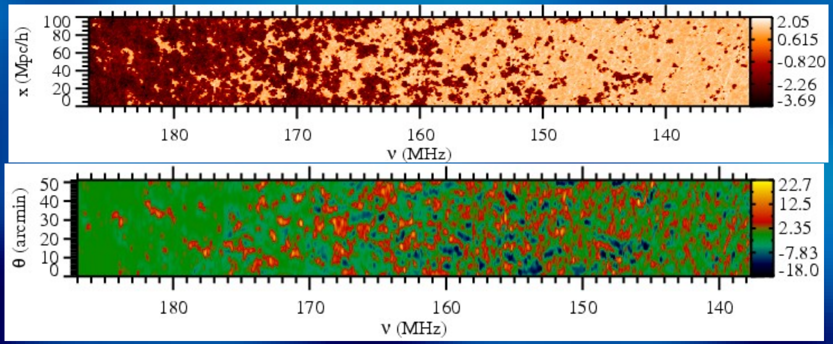
Key Results

(also summarized in recent astro-ph/0708.3846)

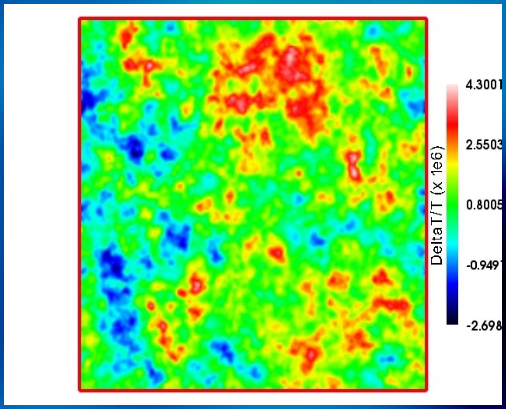
arXiv:0708.3846

- 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 faithful representation (long-wavelength density modes key for source bias).

Observing the Reionization Epoch

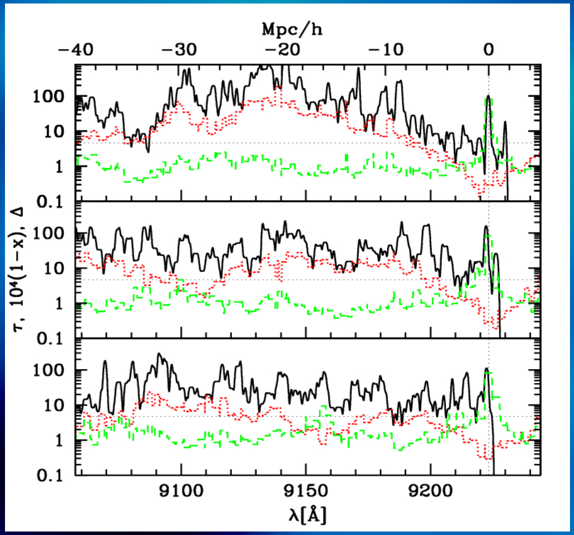


redshifted 21-cm (LOFAR, MWA,GMRT,SKA)

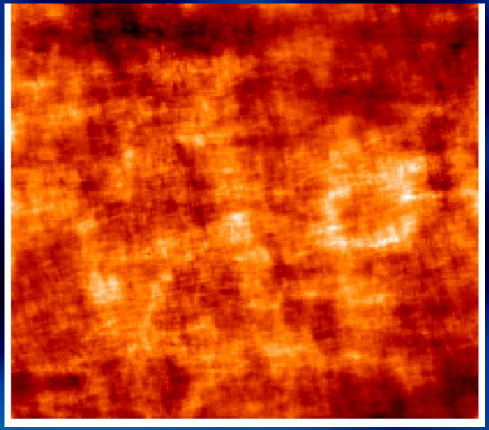


kinetic Sunyaev-Zeldovich effect (kSZ;ACT, SPT)

Ly-α sources



CMB polarization

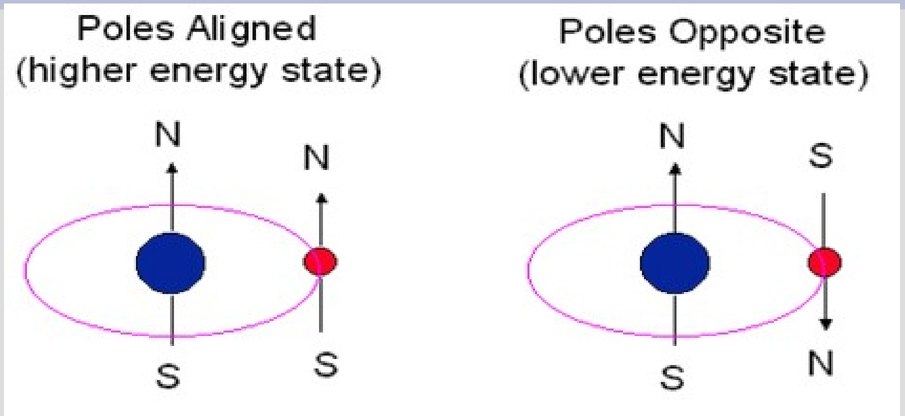


BB

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

21-cm Line of Atomic Hydrogen

- H atom ground state is split into two energy levels by electron-proton spin interaction.Emission or absorption of a photon of 21-cm wavelength and 1.42 GHz frequency will cause transition between these hyperfine levels.



$$\frac{n_2}{n_1} = 3 \exp\left(-\frac{h\upsilon_0}{kT_{spin}}\right)$$

Level populations

Seeing Invisible Light From the Dark Ages

- Hydrogen atoms in the early universe can be detected in absorption or emission against the Cosmic Microwave Background (CMB) at redshifted radio wavelength 21 cm.
- Halos formed during the dark ages are dense and hot enough to appear in emission.
- The intergalactic medium, too, can appear in either emission or absorption.
- Future radio astronomy antenna arrays are being designed to detect this 21 cm emission.

21-cm Radiation Background

- Foreground emission or absorption by H atoms at redshift z seen against CMB at redshifted wavelength 21(1+z) cm.

Emission ↔ $T_{spin} > T_{CMB}$

Absorption ↔ $T_{spin} < T_{CMB}$

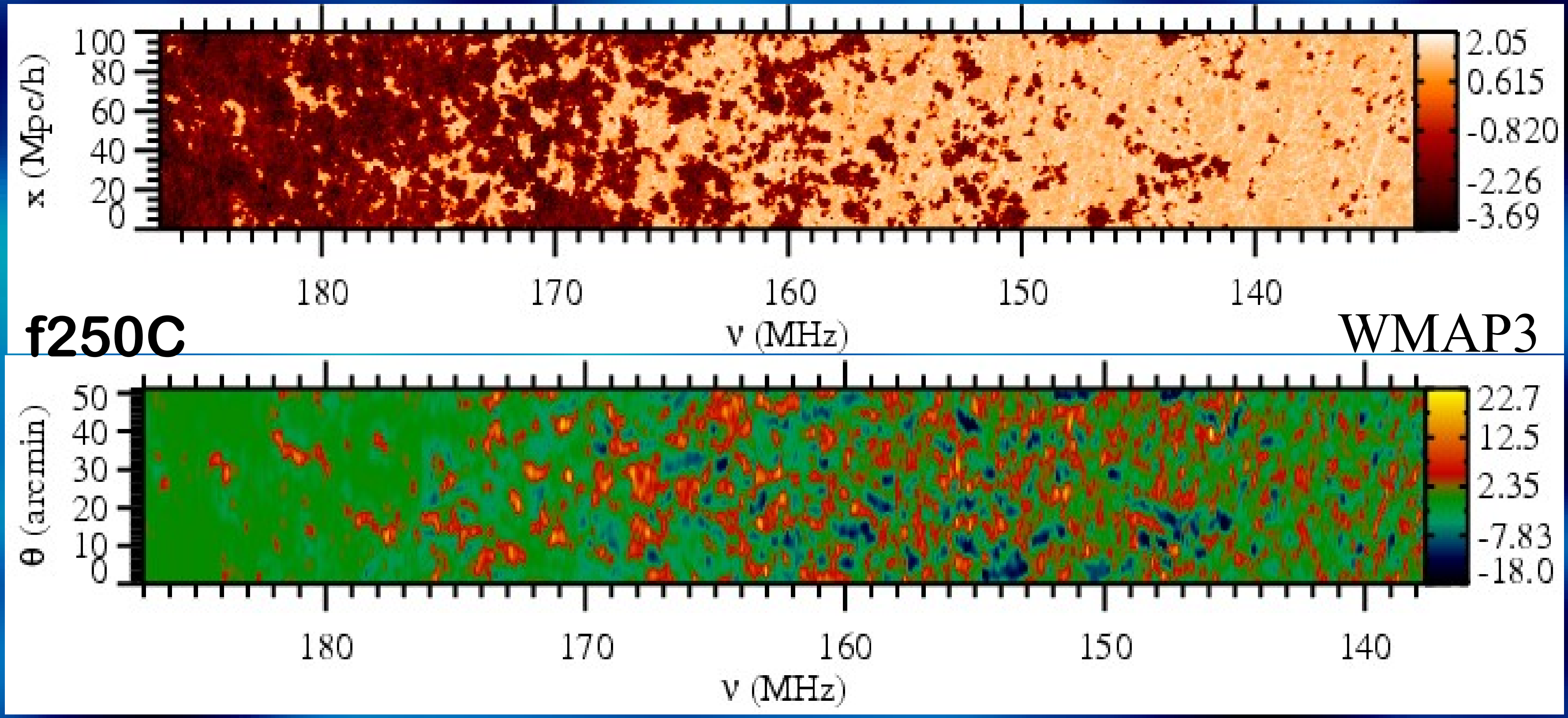
Transparent ↔ $T_{spin} = T_{CMB}$

3 Ways to Change the 21-cm Level Population:

- Absorb a 21-cm photon from the CMB (CMB Pumping)
- Collide with another atom (Collisional Pumping)
- Absorb a UV photon at 1215 Angstrom to make Lyman alpha transition of H atom, then decay to one of 21-cm levels (Lyman Alpha Pumping)

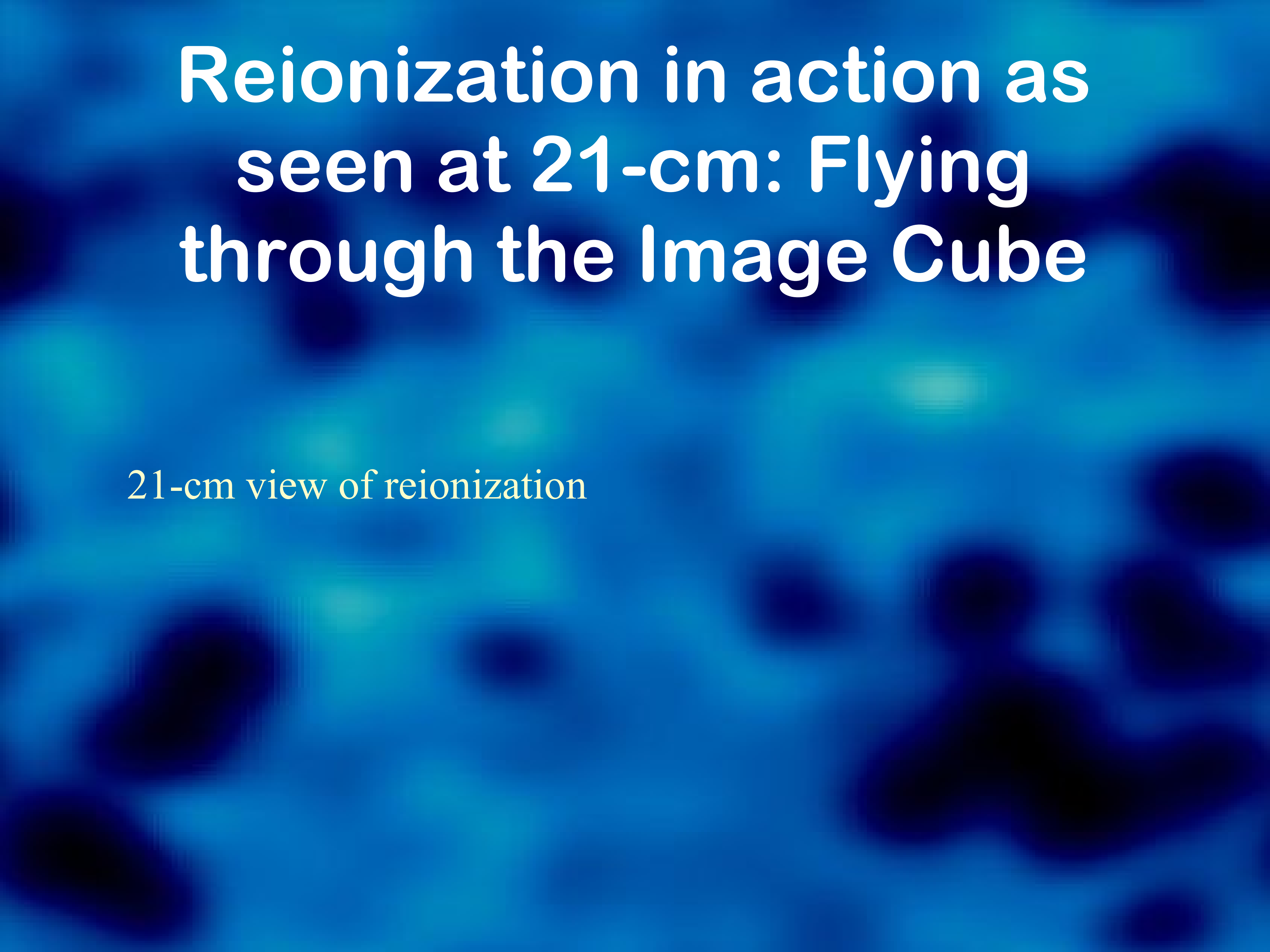
Evolution Slices at 21-cm line

(Mellema, Iliev, et al. 2006; Iliev et al. 2007b)



Shown is (log/linear) differential (to CMB) brightness temperature: top: high-res; bottom: beam- and bandwidth-smoothed (LOFAR: will see large ion. bubbles!).

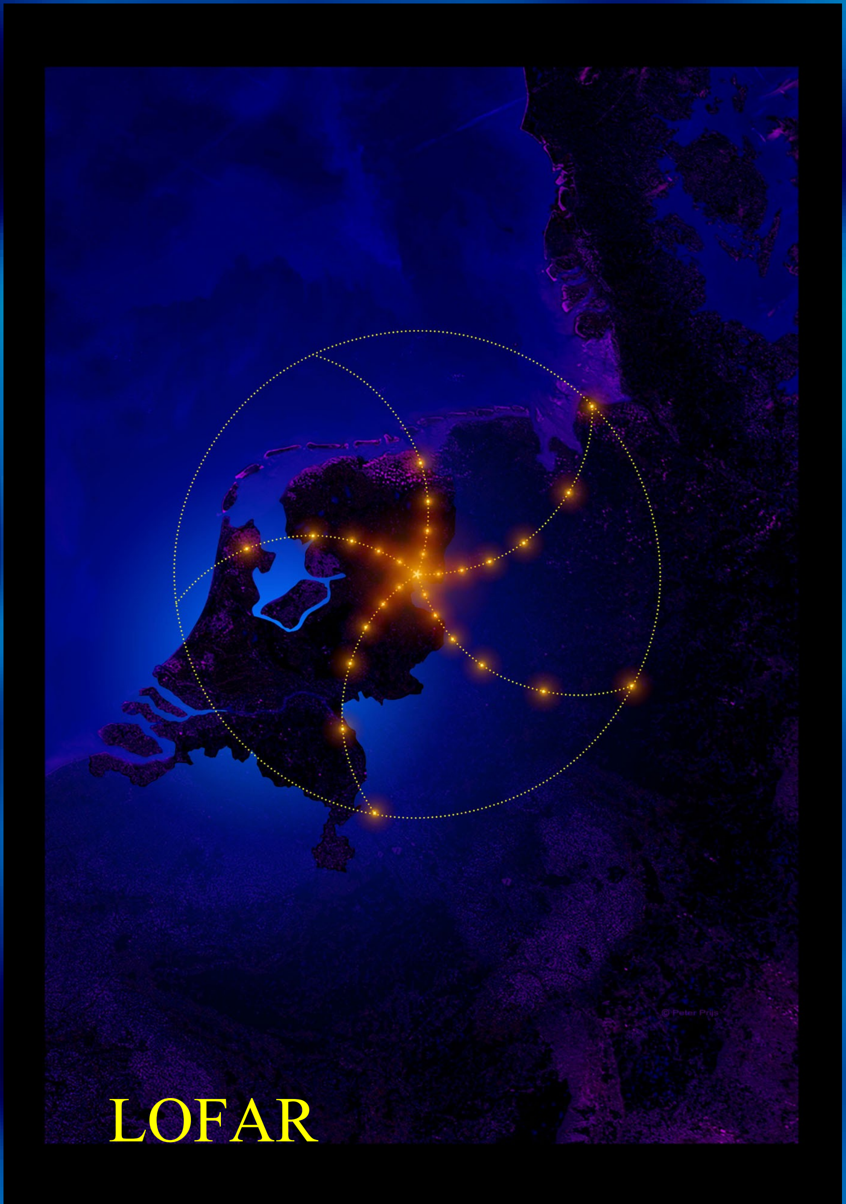
Reionization in action as seen at 21-cm: Flying through the Image Cube



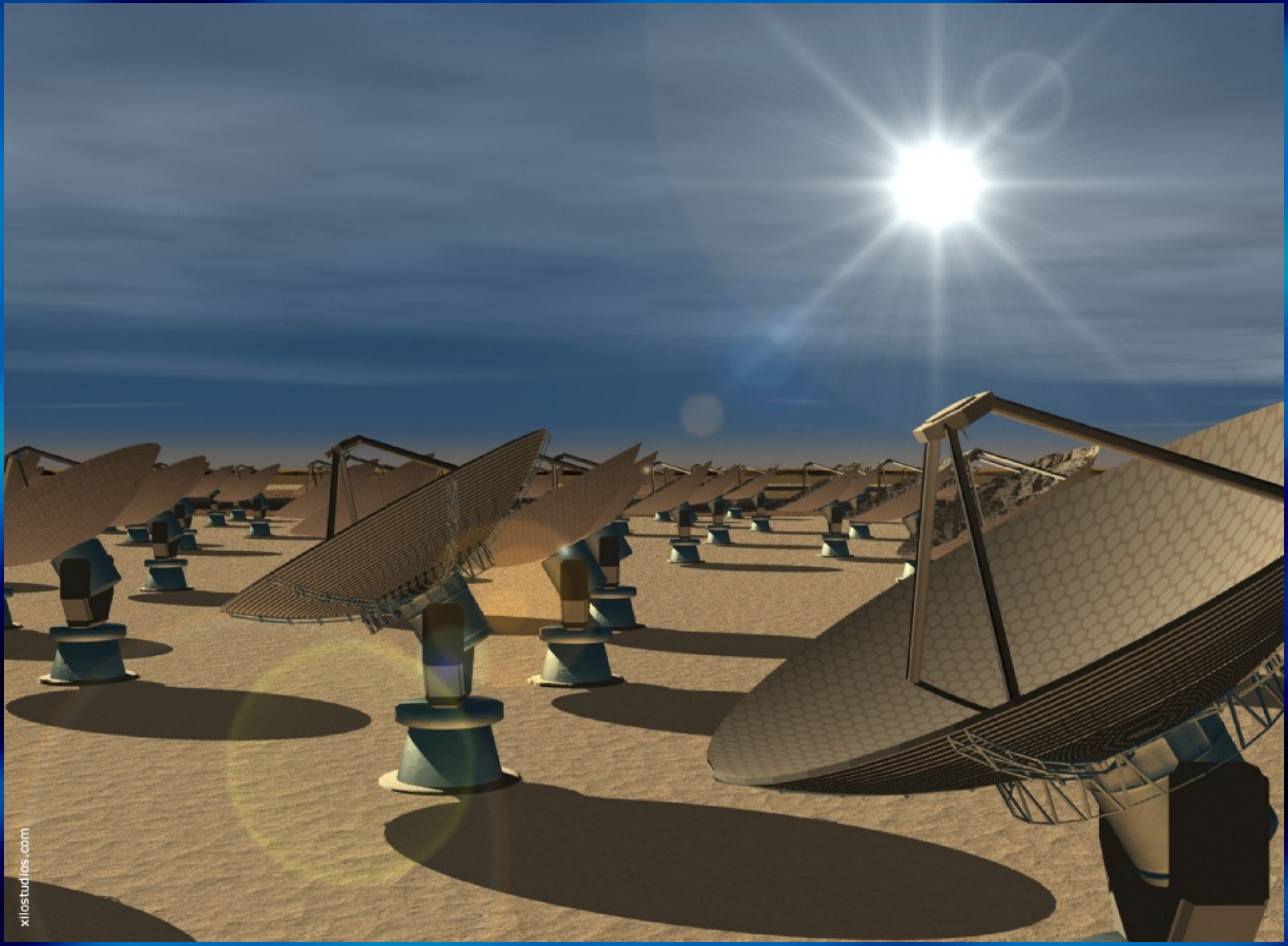
21-cm view of reionization

How are we going to observe that signal?

Giant Radio Arrays!

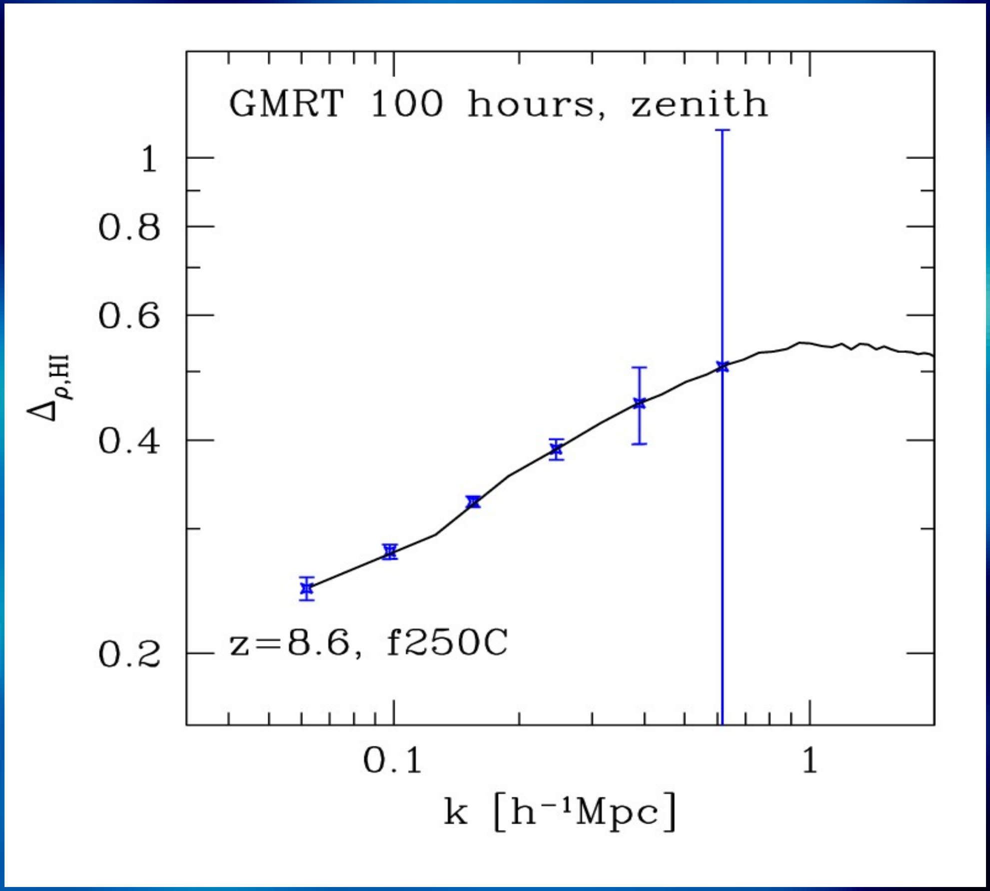


The Future: SKA



Detectability of 21-cm

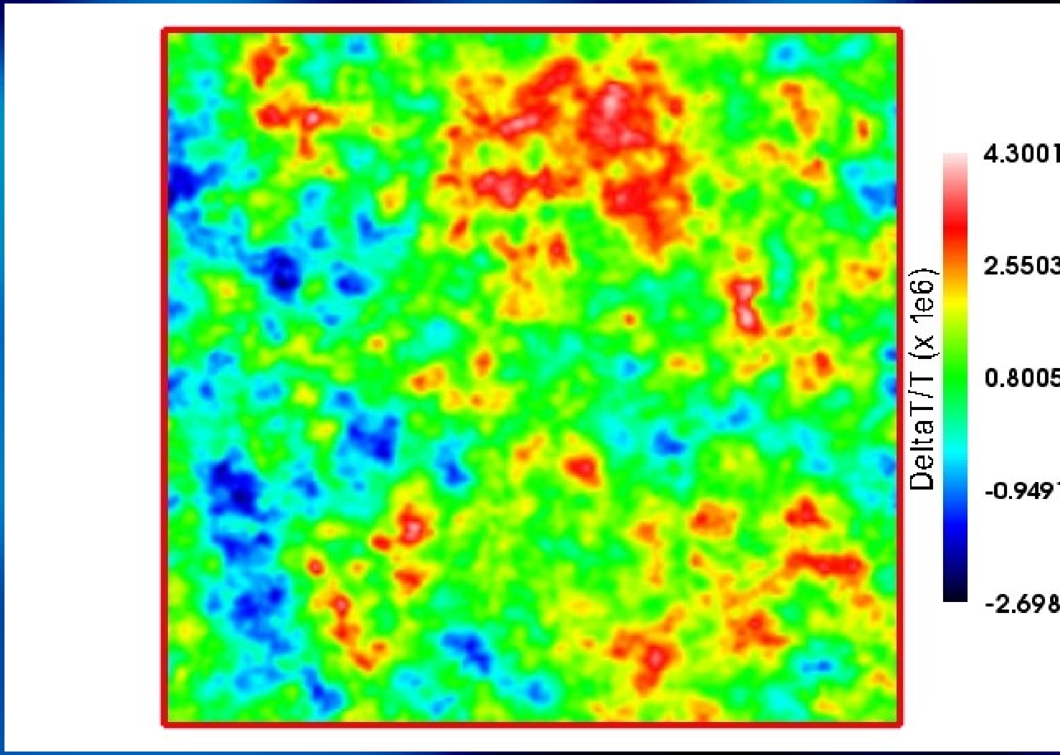
(Iliev et al, 2008, MNRAS, 384, 863)



- 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).

Kinetic Sunyaev-Zeldovich (kSZ) effect from patchy reionization (Iliev et al. 2006, ApJ)

kSZ effect is due to Thomson scattering of CMB photons on moving electrons.

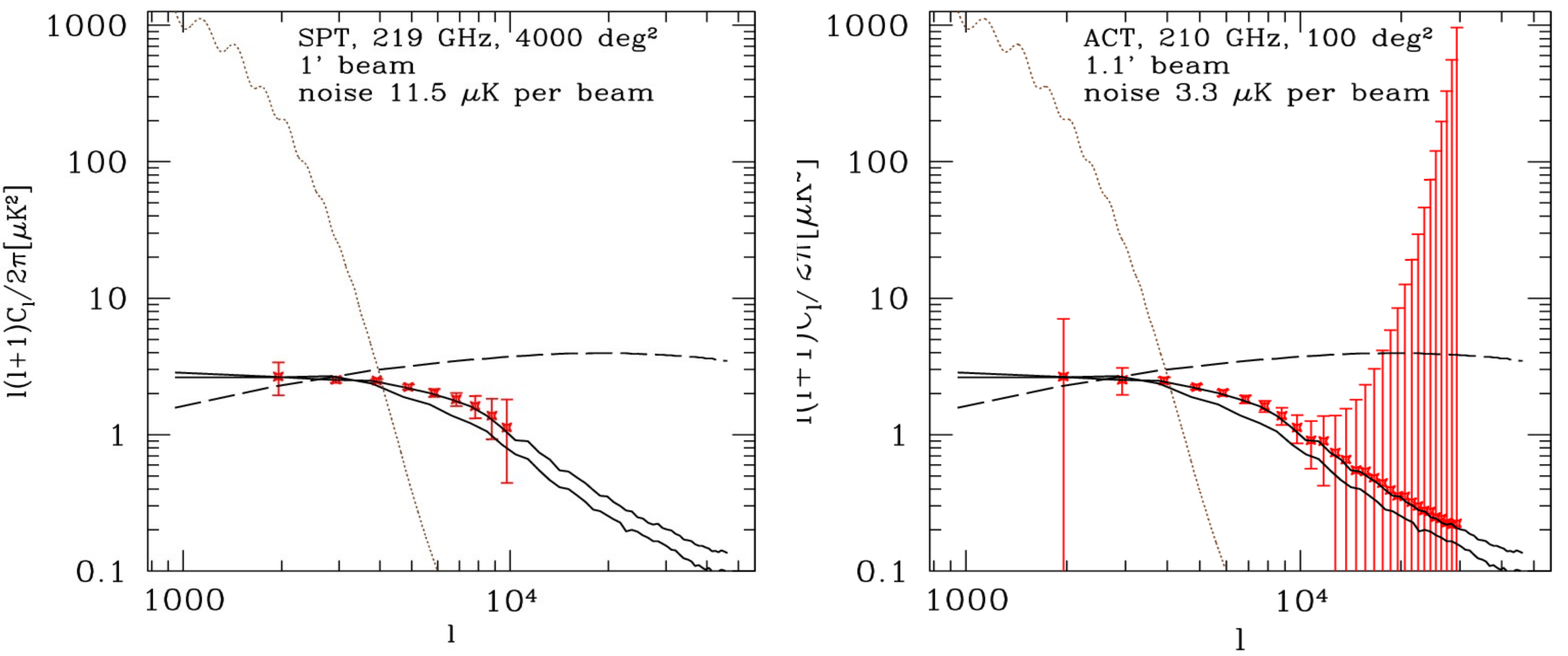


Several upcoming experiments (ACT, SPT) aim to detect this signal.

CMB telescopes: kSZ effect

Detectability of kSZ

(Iliev et al, 2008, MNRAS, 384, 863)



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 assumed subtracted.

Cosmological Structure Formation: The Cosmic Web

(Iliev et al., 2006a, MNRAS, 369, 1885; Iliev et al. in prep.)

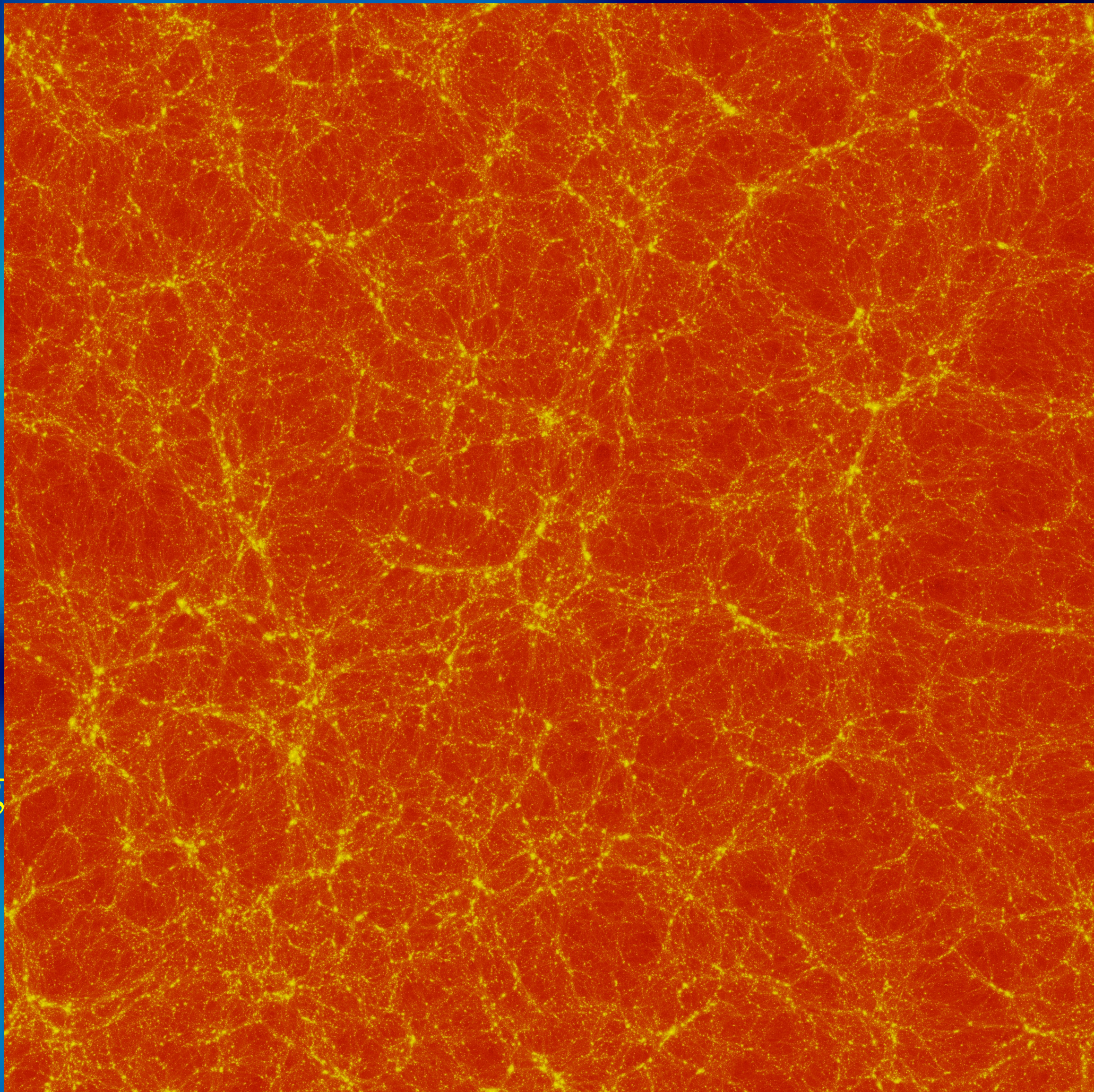
500/h Mpc box; z=0

1624^3 particles

(4.3 billion), 3248^3 cells

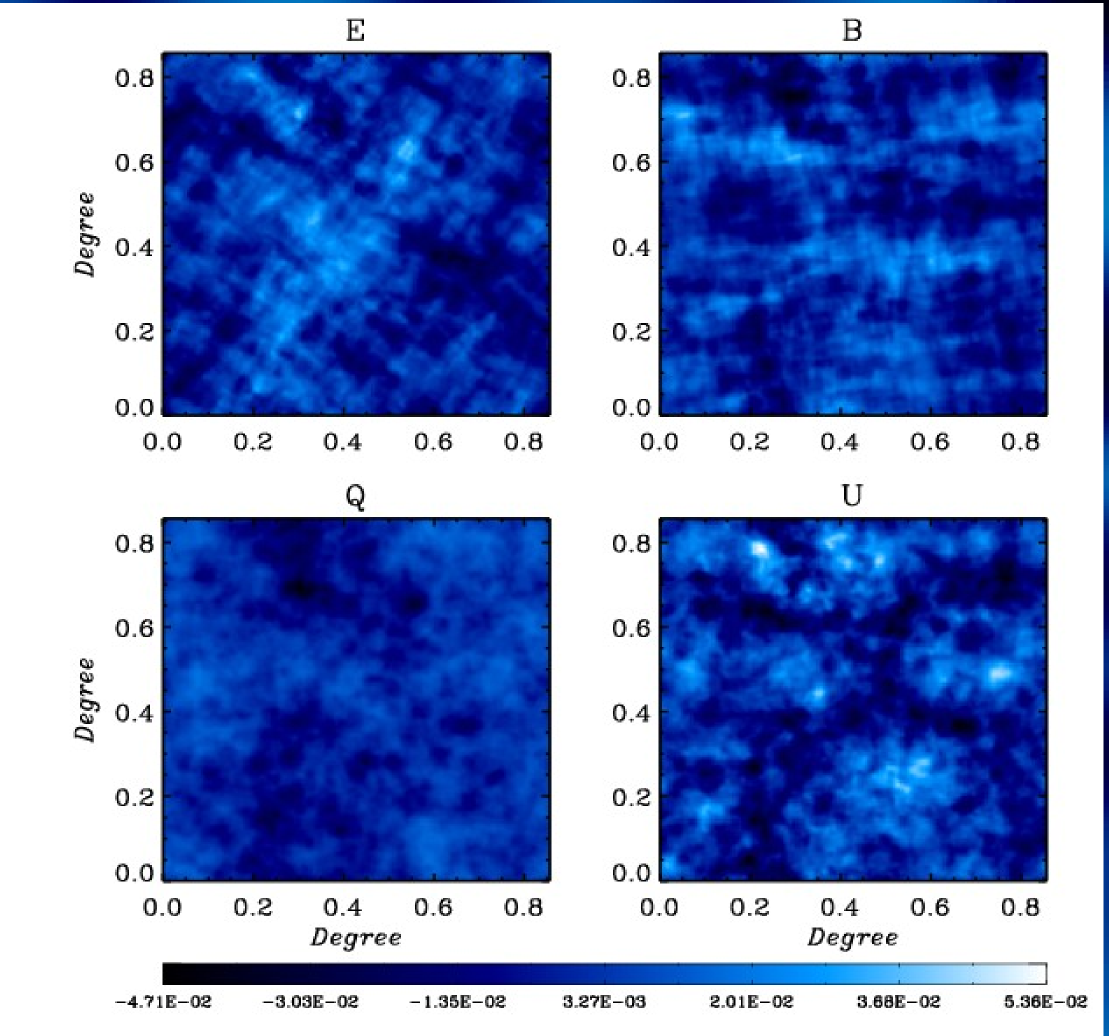
64 billion-particle (4000^3) simulations expected to be run shortly; 10^{12} particles ($10{,}000^3$) simulations are now within reach.

These sizes allow simulating the whole volume of a large survey (few Gpc^3) with the appropriate resolution.



CMB polarization signatures from patchy reionization
(Dore et al. 2007, PhysRev D, submitted)

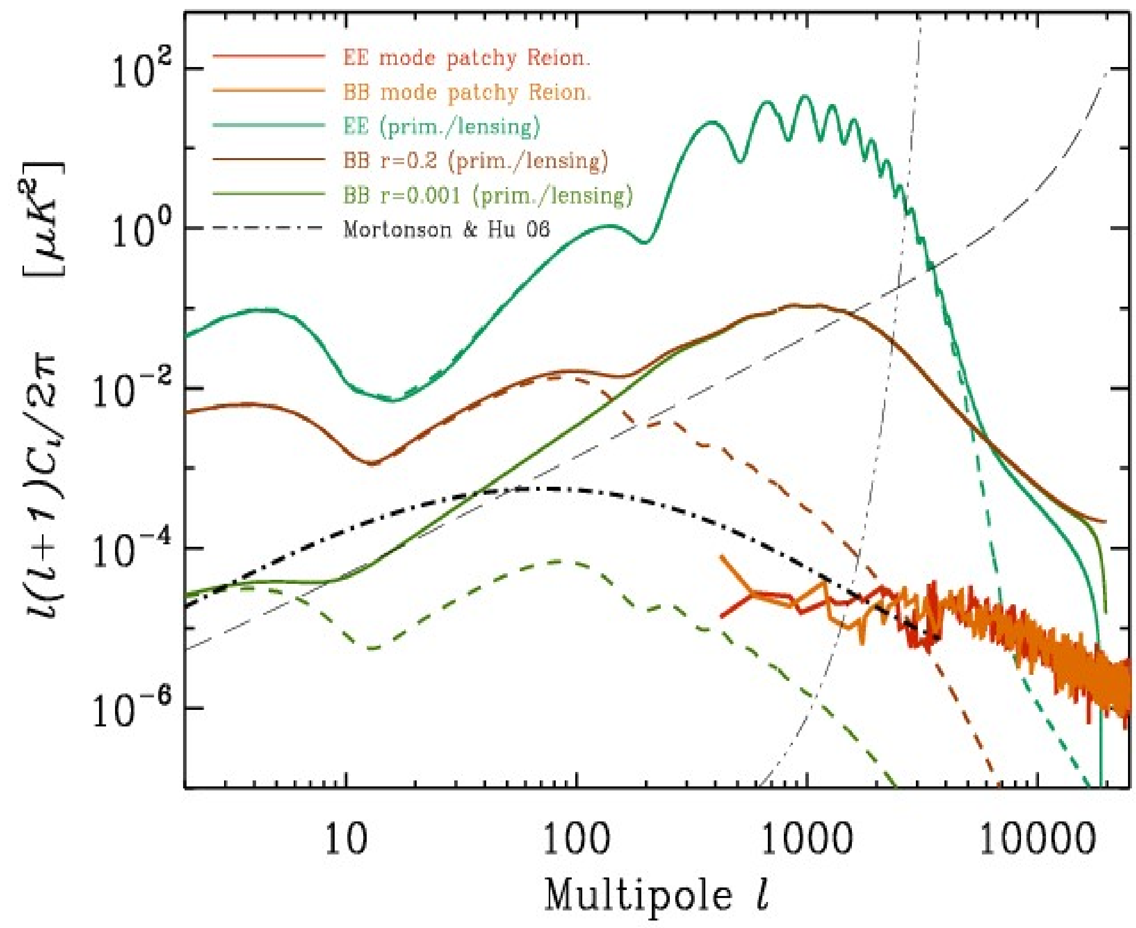
- The EoR patchiness yields significant fluctuations of τ at arcminute scales.
- This creates characteristic signatures in CMB polarization at



CMB polarization signatures from patchy reionization II

(Dore et al. 2007, PhysRev D, submitted)

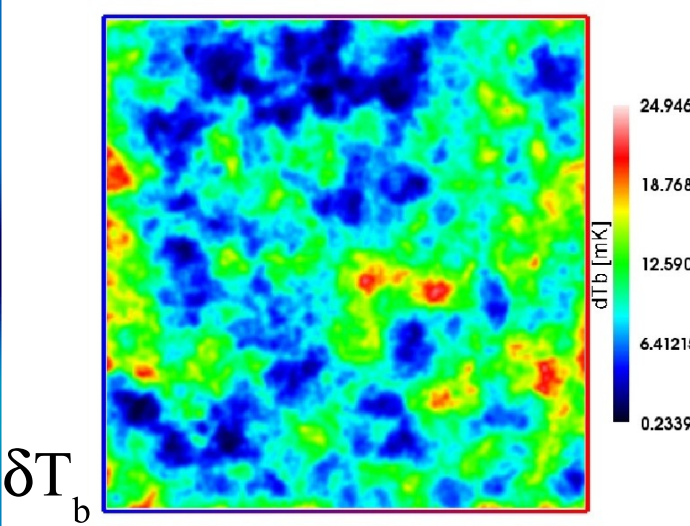
- EoR and lensing are main sources of BB polarization at small scales.
- Signals are weak and the lensing one dominates, but both might still be detectable with future

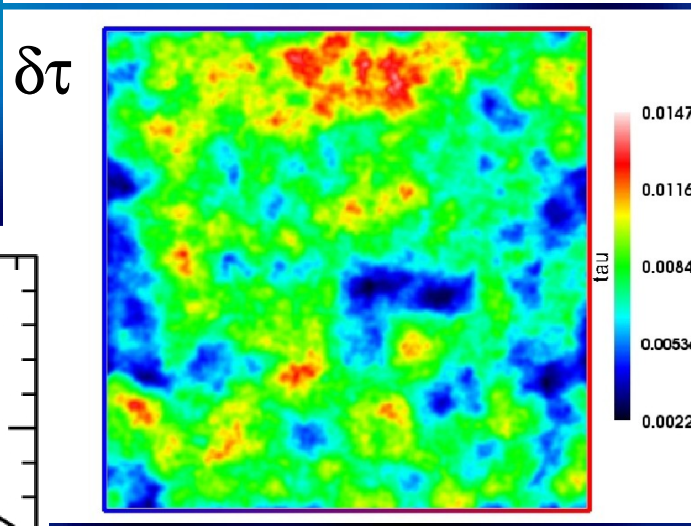


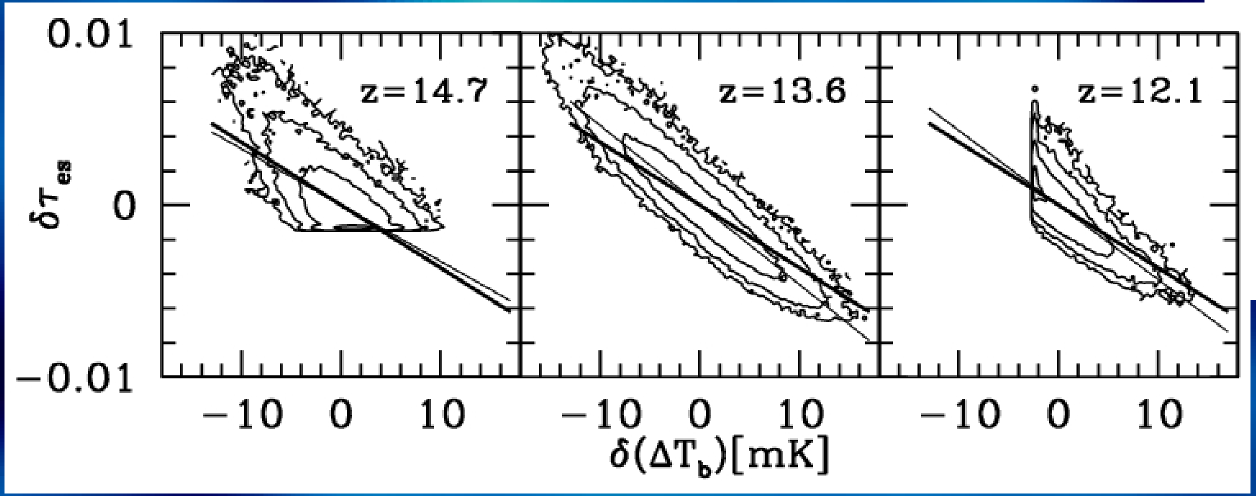
Reconstructing the Thomson Optical Depth due to Patchy Reionization with 21-cm Fluctuation Maps

(Holder, Iliev, Mellema, ApJL, submitted)

wide-band (6 MHz) 21-cm maps are an almost perfect negative image of Thomson optical depth maps -> small-scale CMB polarization features could



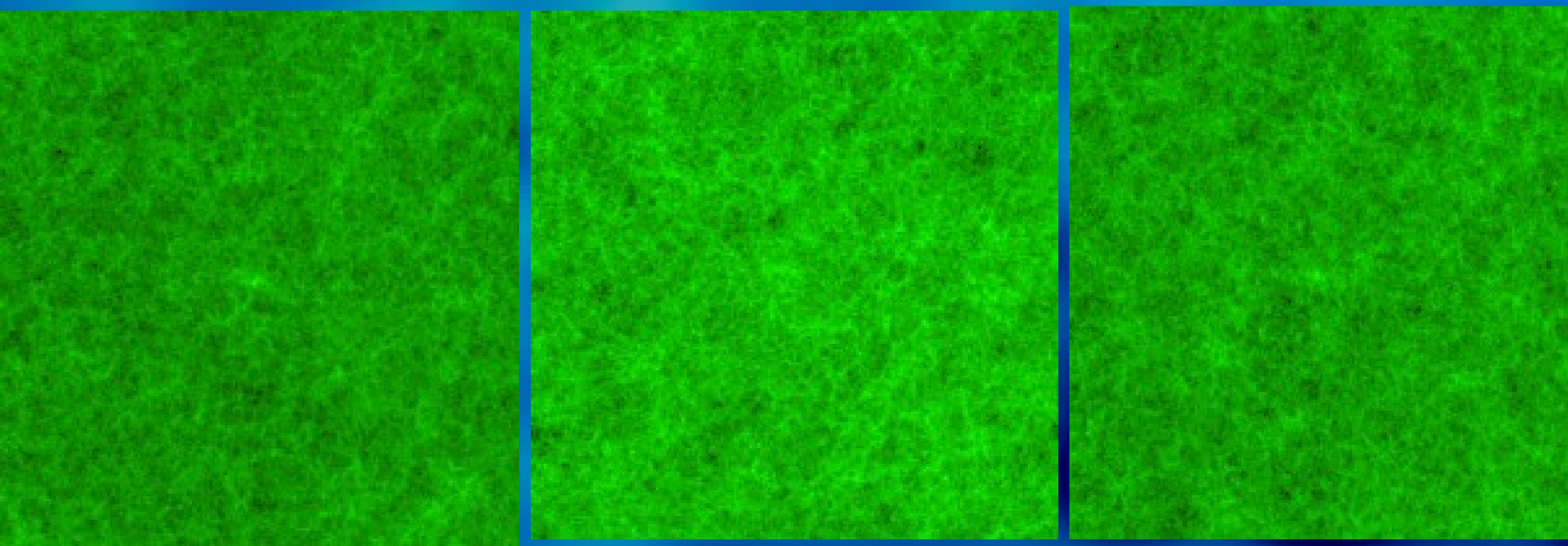




Luminous sources at the end of reionization: animations

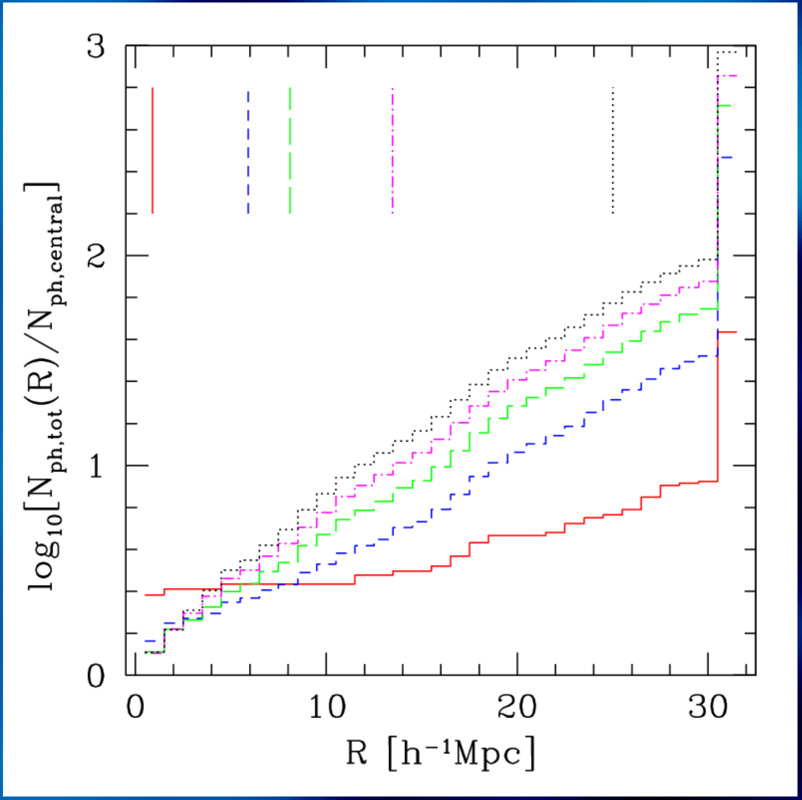
(Iliev et al. 2007c, MNRAS submitted, astro-ph/0711.2944)

- The most massive source at z~6 is in 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.



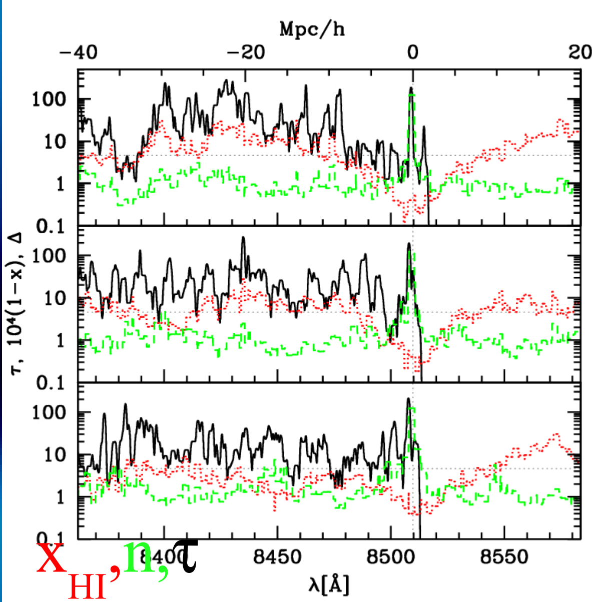
Dominant contribution of ionizing photons

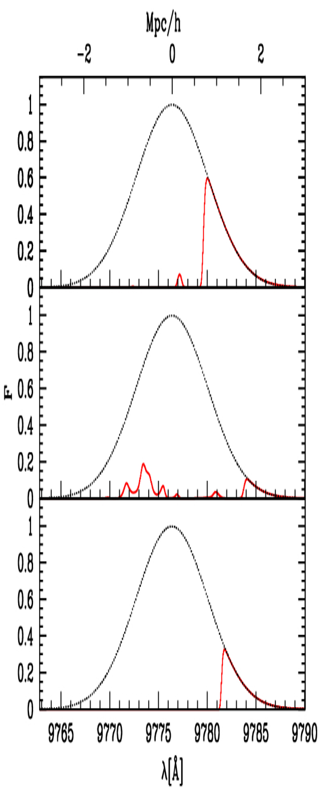
For a cluster of ionizing sources around a high density peak the majority of the ionizing photons (by up to 2 orders of magnitude) are contributed by the clustered small sources, rather than by the central massive galaxy.

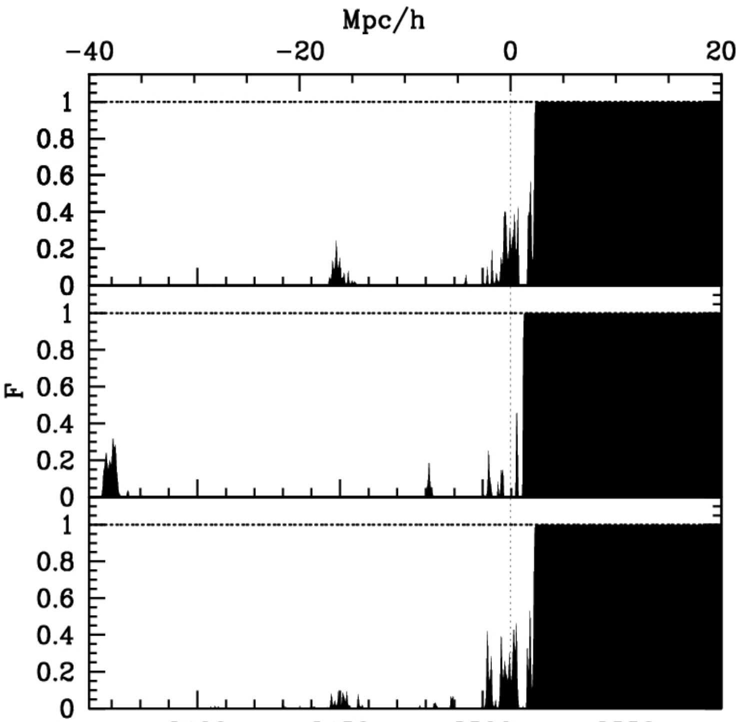


Luminous sources at the end of reionization: Ly-α spectra

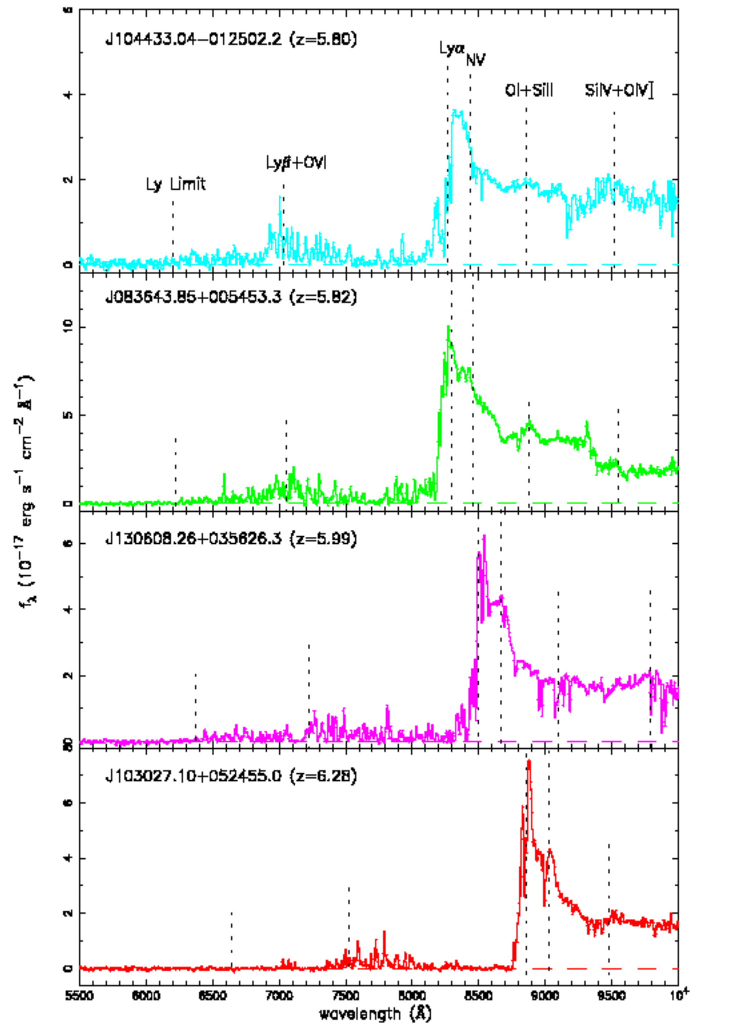
(**Iliev** et al. 2007c, MNRAS subm., astro-ph/0711.2944)







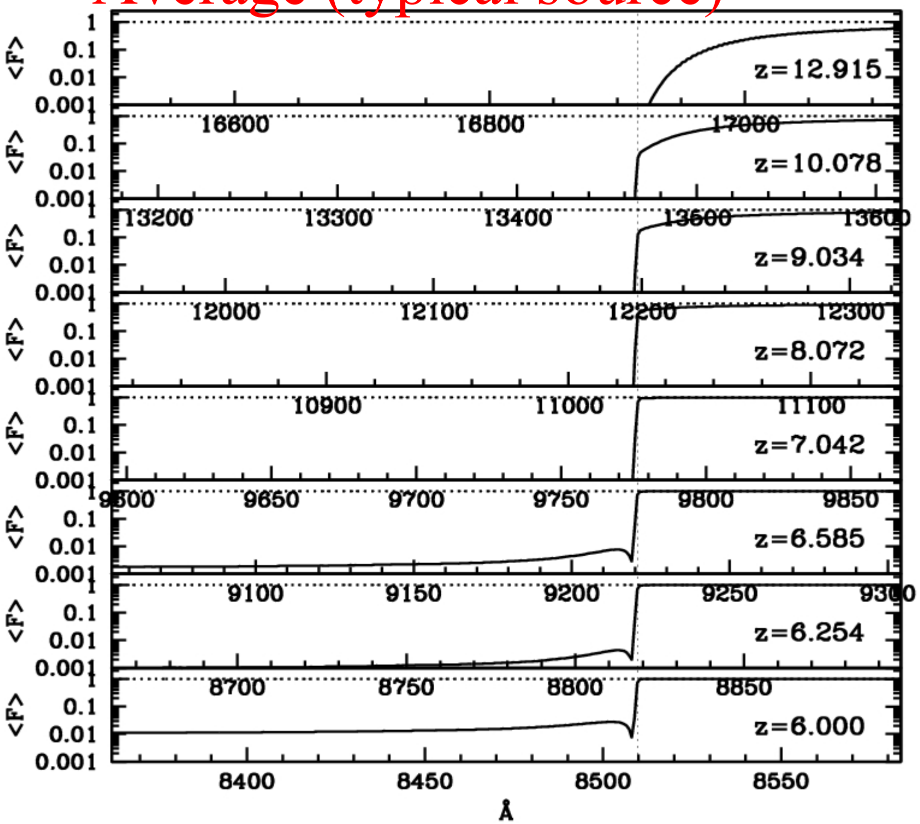
z=6



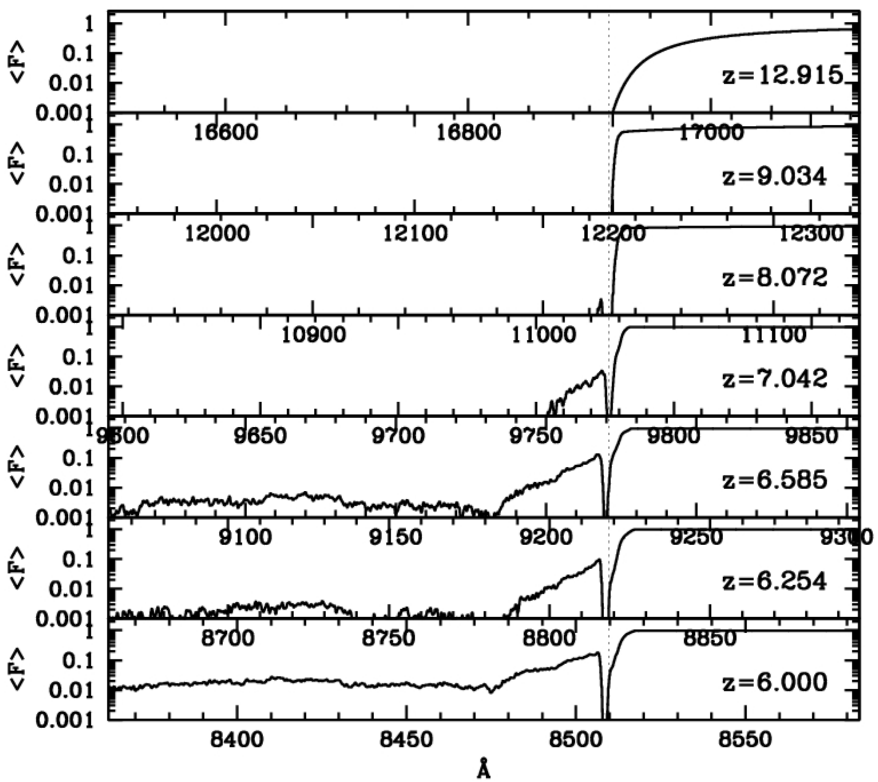
Mean Ly-α transmission vs. z

- Stong damping wing at z>10, only minor differences between average and luminous source.
- Some transmission at blue side of line, as IGM slowly becomes transparent; large proximity transmission region

Average (typical source)



Luminous source

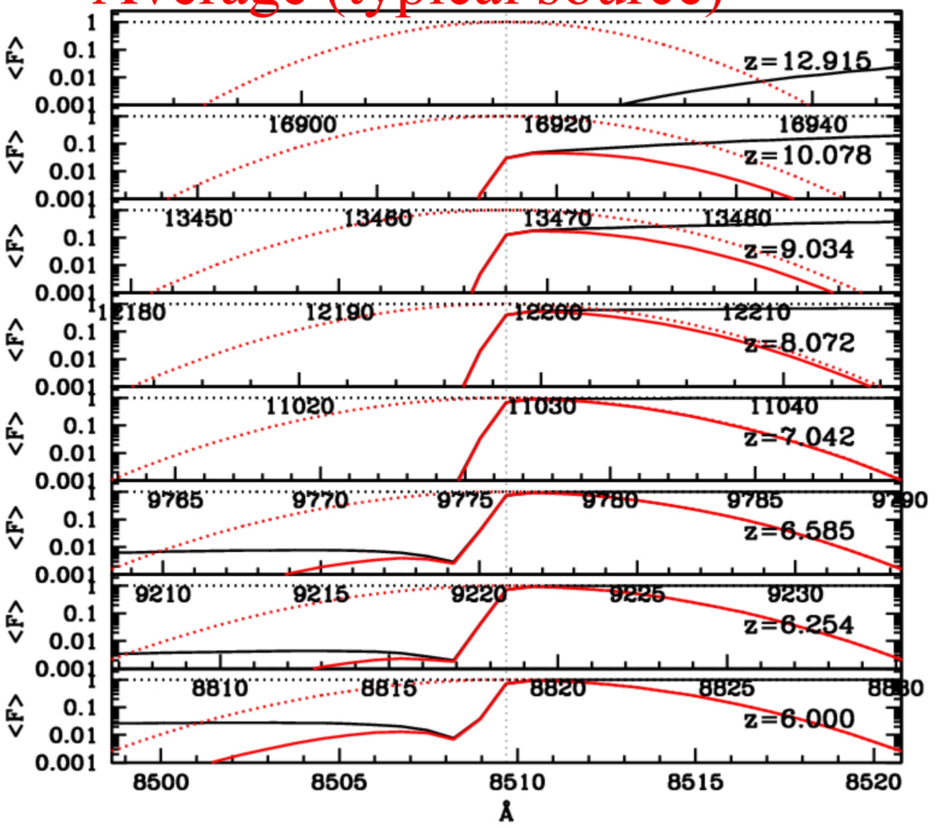


Mean Ly-α line shape vs. z

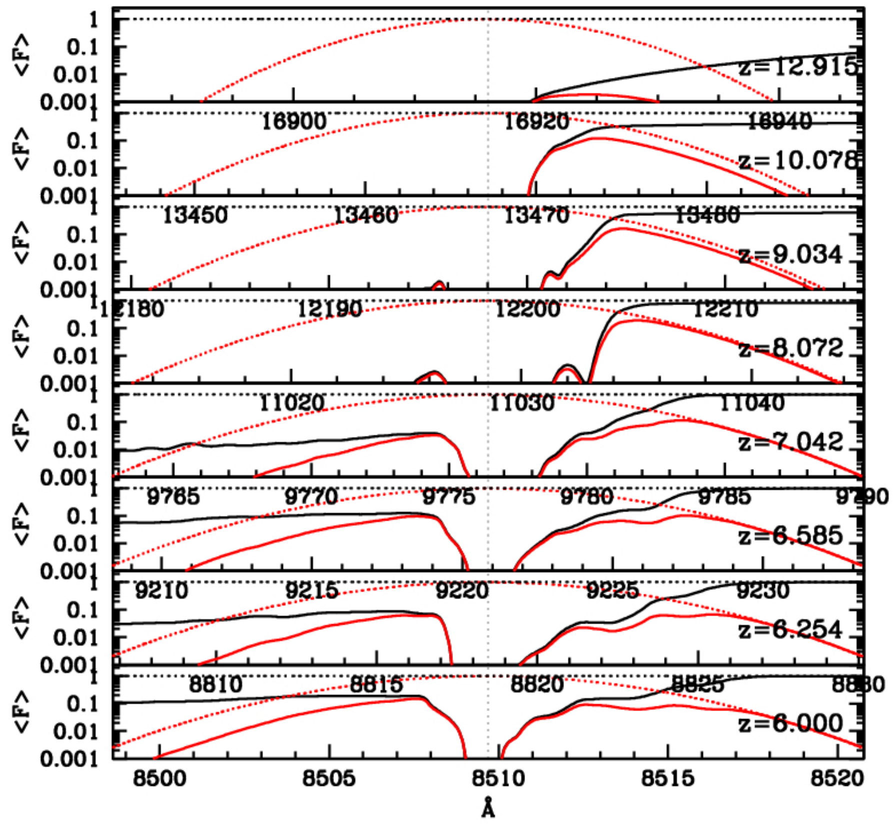
(Iliev et al. 2007c, MNRAS submitted, astro-ph/0711.2944)

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

Average (typical source)

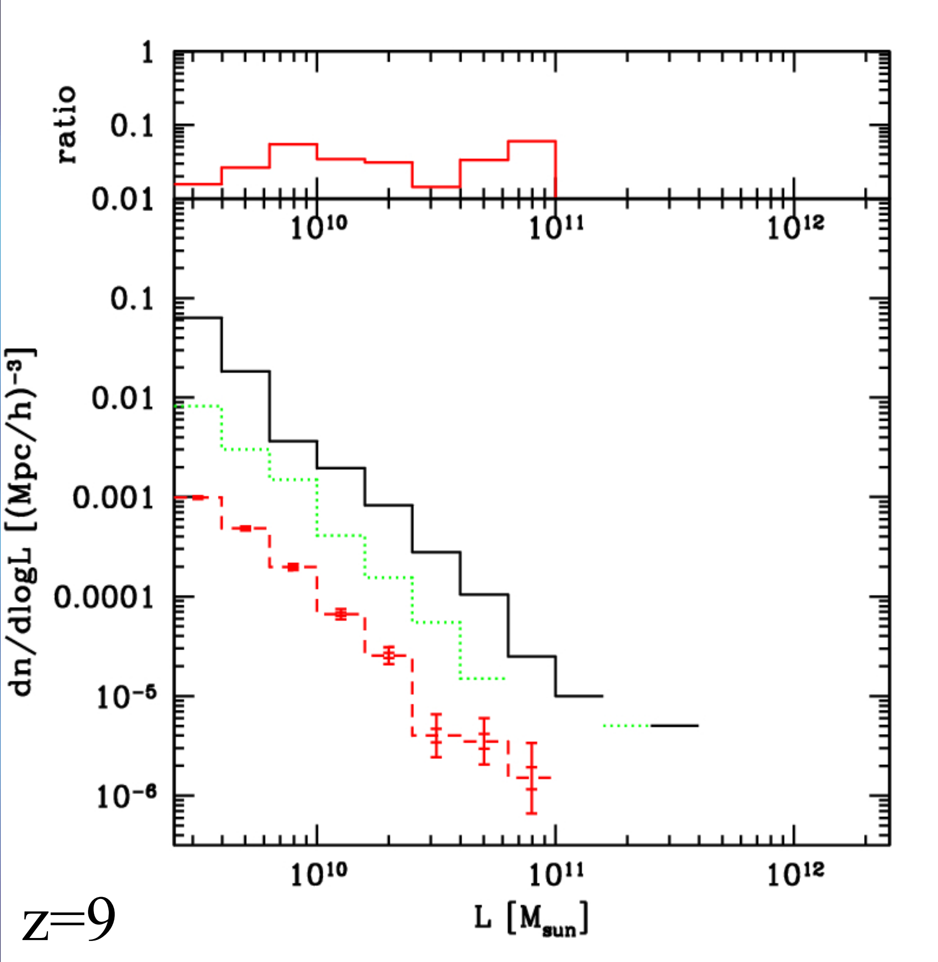


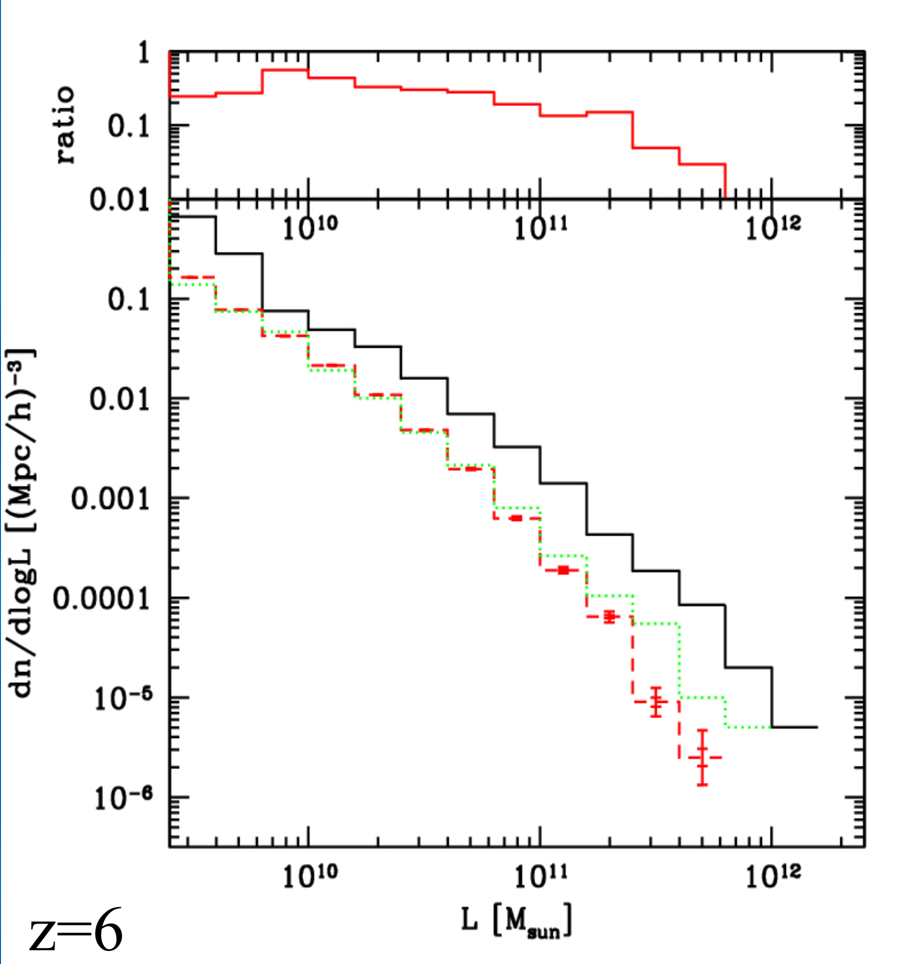
Luminous source



Ly-a Luminosity Functions

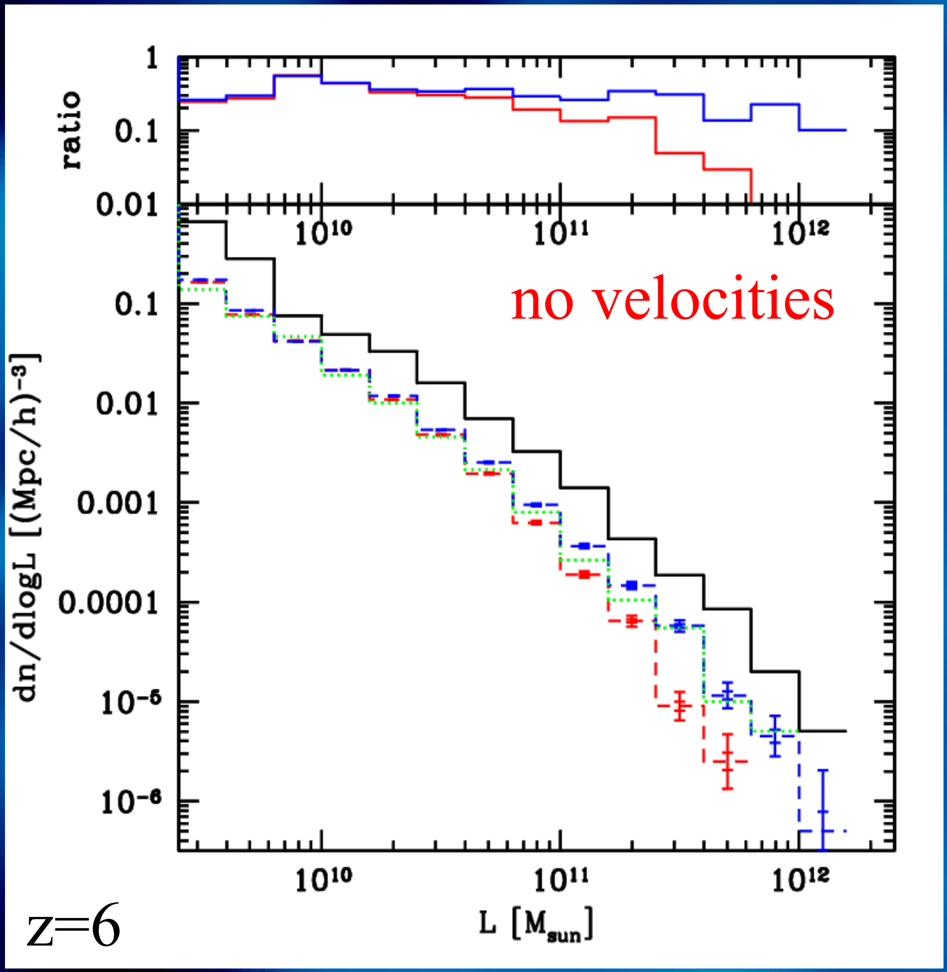
(Iliev et al. 2007, MNRAS, submitted, astro-ph/0711.2944)

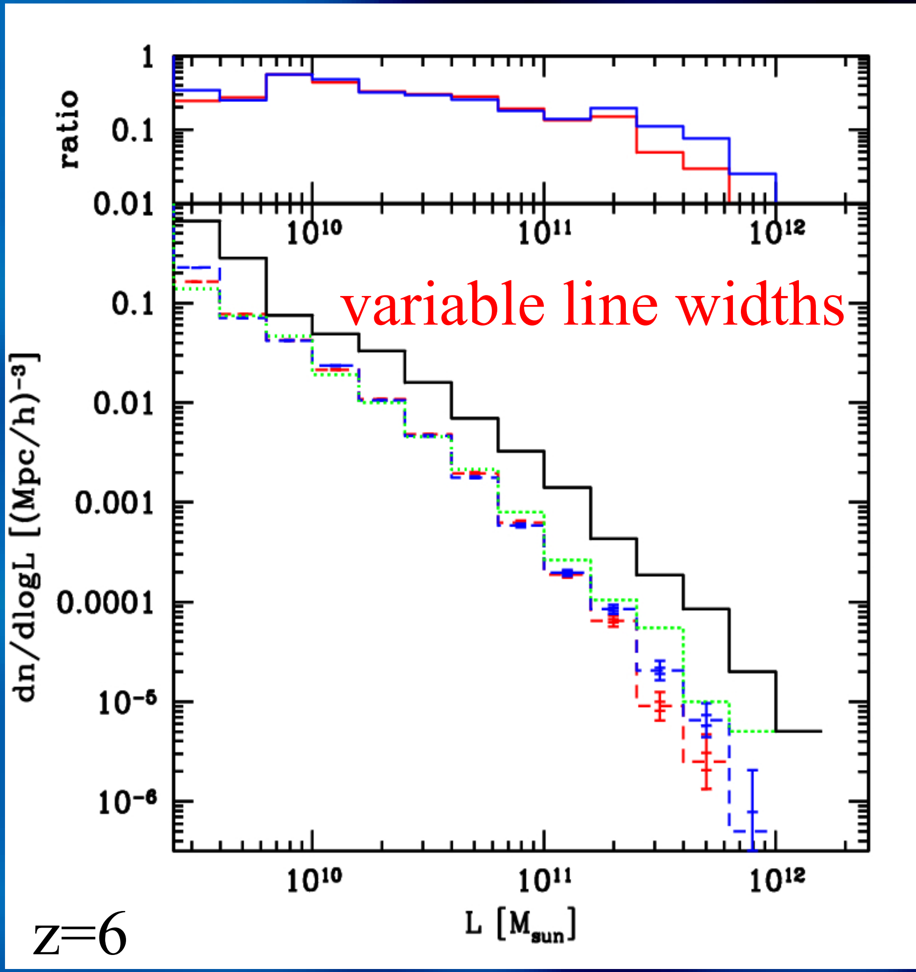




Ly-a Luminosity Functions: effects of velocities and line widths

(Iliev et al. 2007c, MNRAS submitted, astro-ph/ 0711.2944



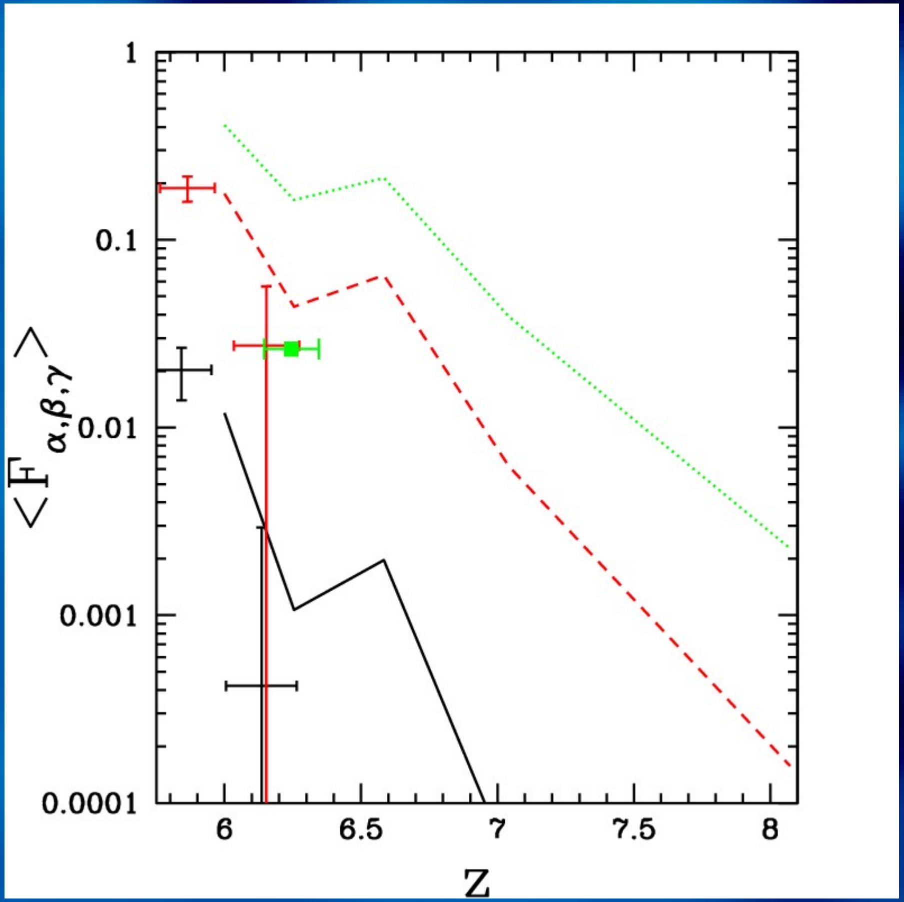


IGM transmission: simulation vs. data

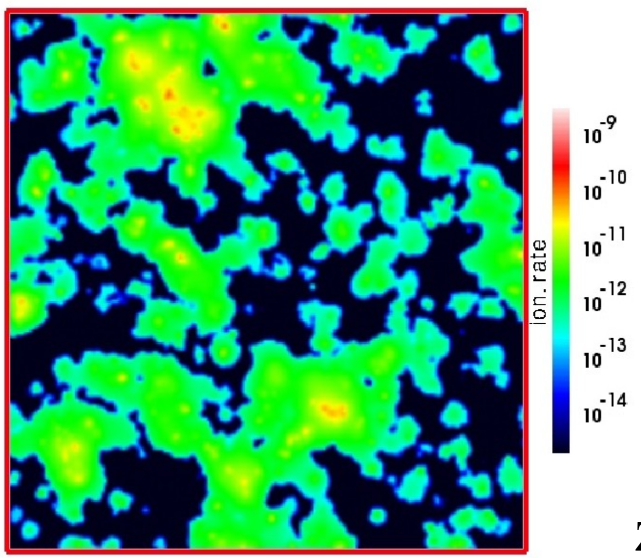
(Iliev et al. 2007c, submitted,astro-ph/0711.2944)

The averaged IGM transmission at Ly-α,β,γ is somewhat higher than the observation data (Fan et al.) -» lower source efficiencies are required for a better fit.

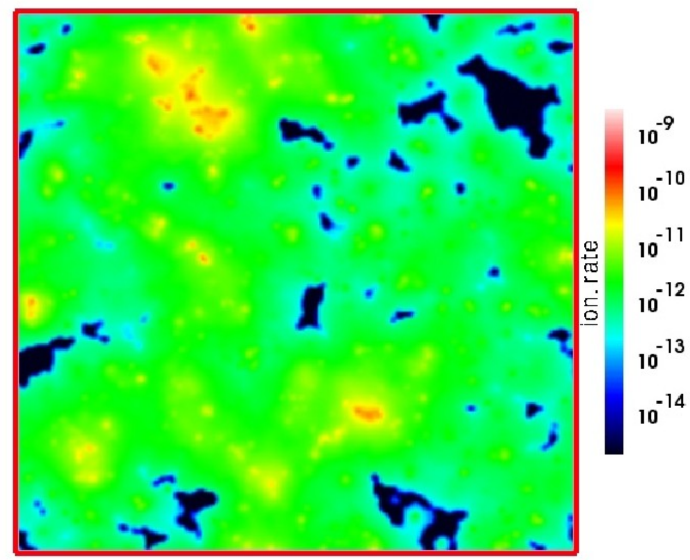
Higher-z data can be used to constrain reionization parameters better.



Photoioinization rates



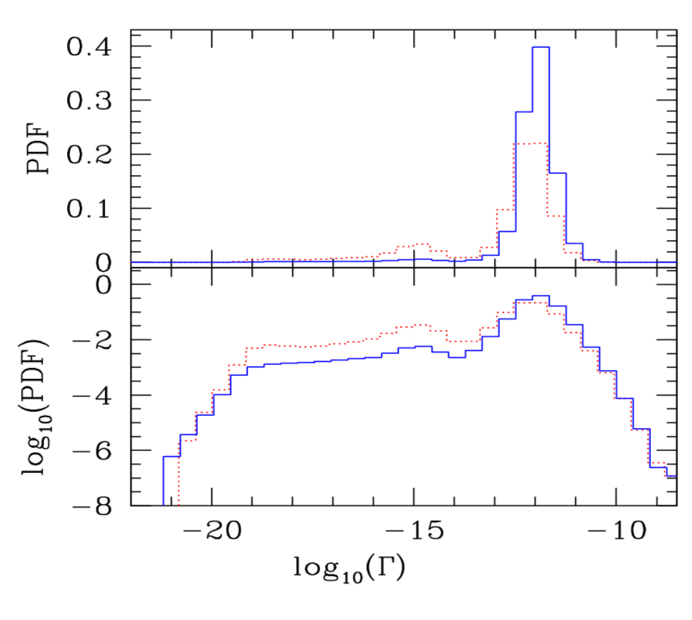
z=8



z=7

Photoionization rates:

- highly inhomogeneous spatially
- non-equilibrium behind I-fronts
- Peak at Γ_{-12}~1

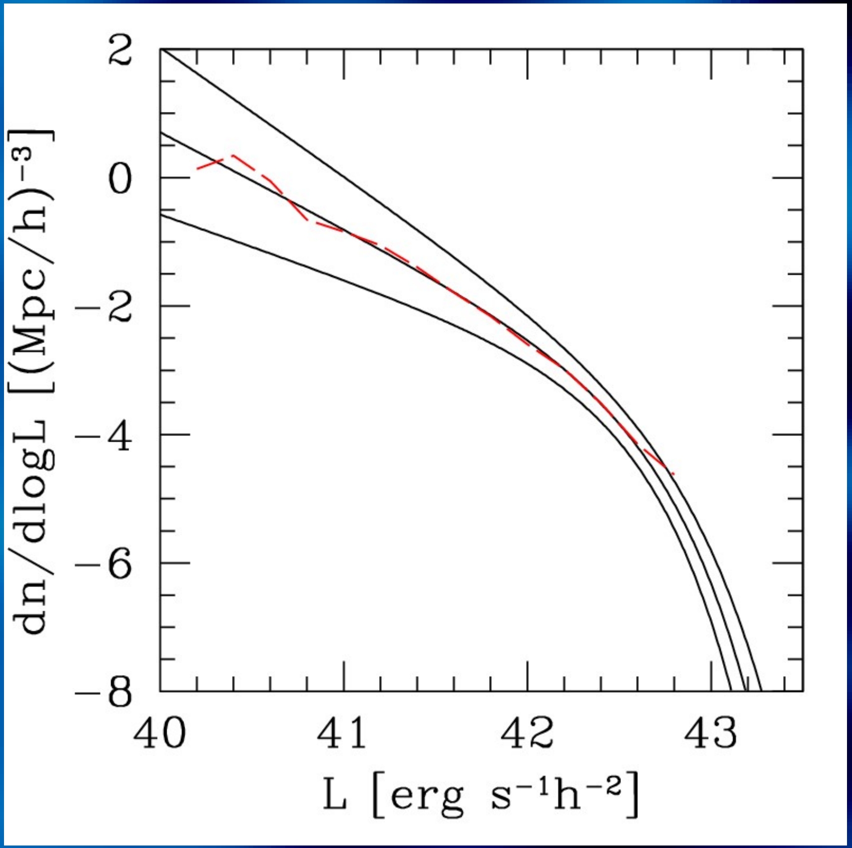


Luminosity function: simulations vs. observations

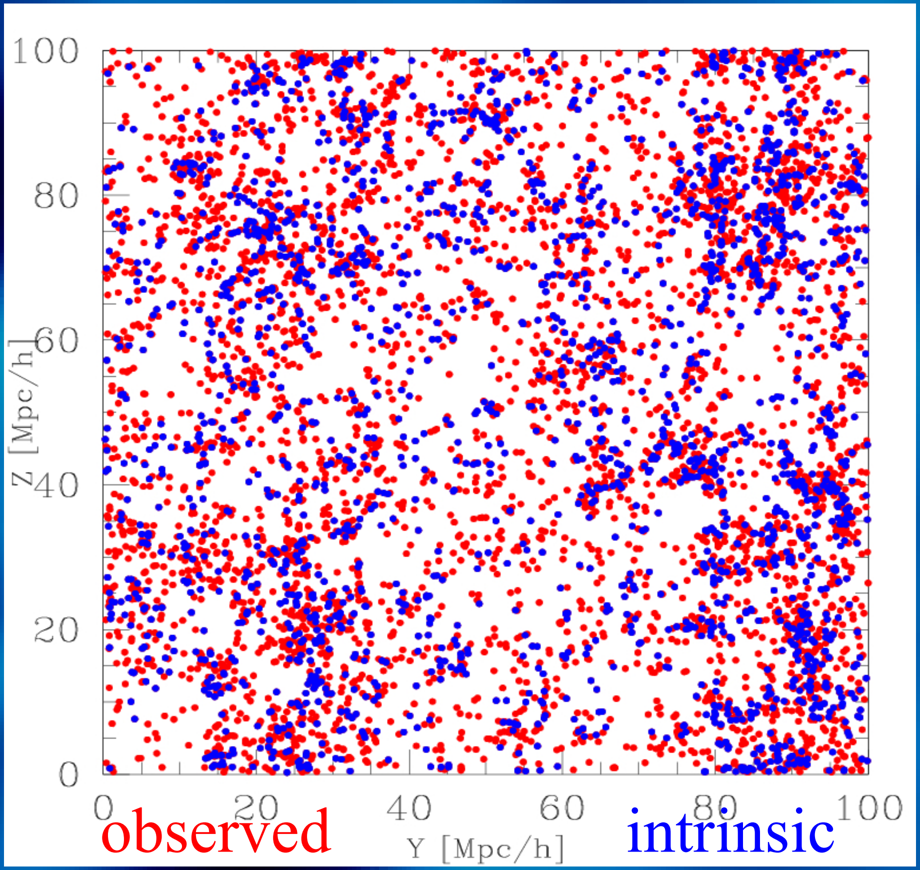
(Iliev et al. 2007c, submitted,astro-ph/0711.2944)

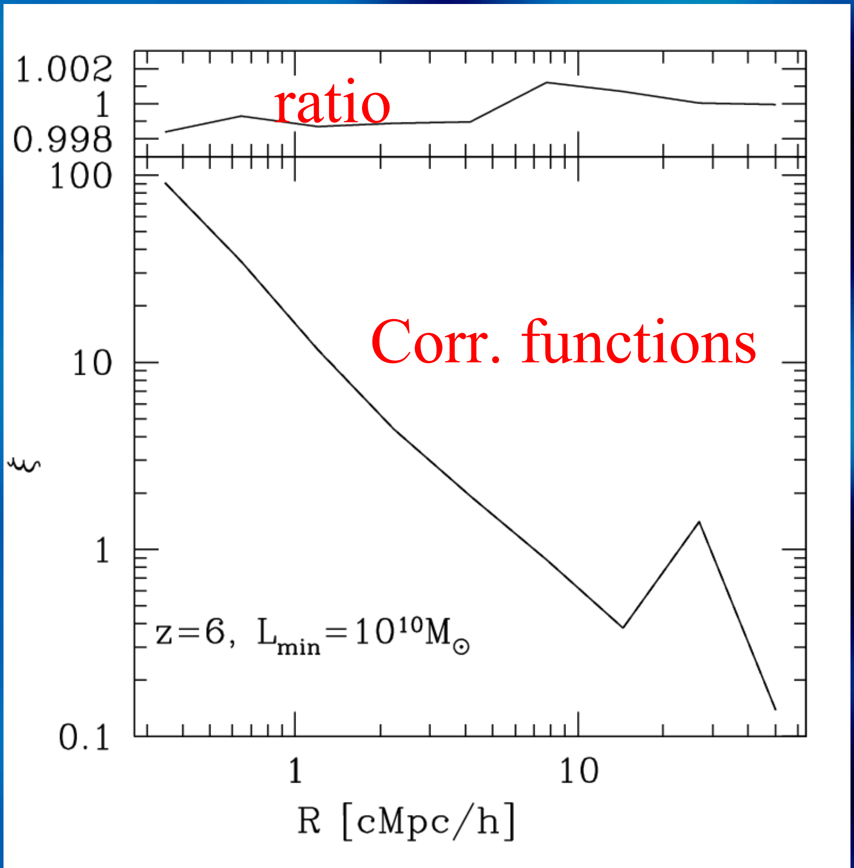
LF normalization: set by matching the number density of sources in simulations to the observed one (by Kashikawa et al. 2006). Excellent match of the shape, for an assumed faint-end slope of -1.5 for the fit to the observations.

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



Correlation functions of Ly-α sources



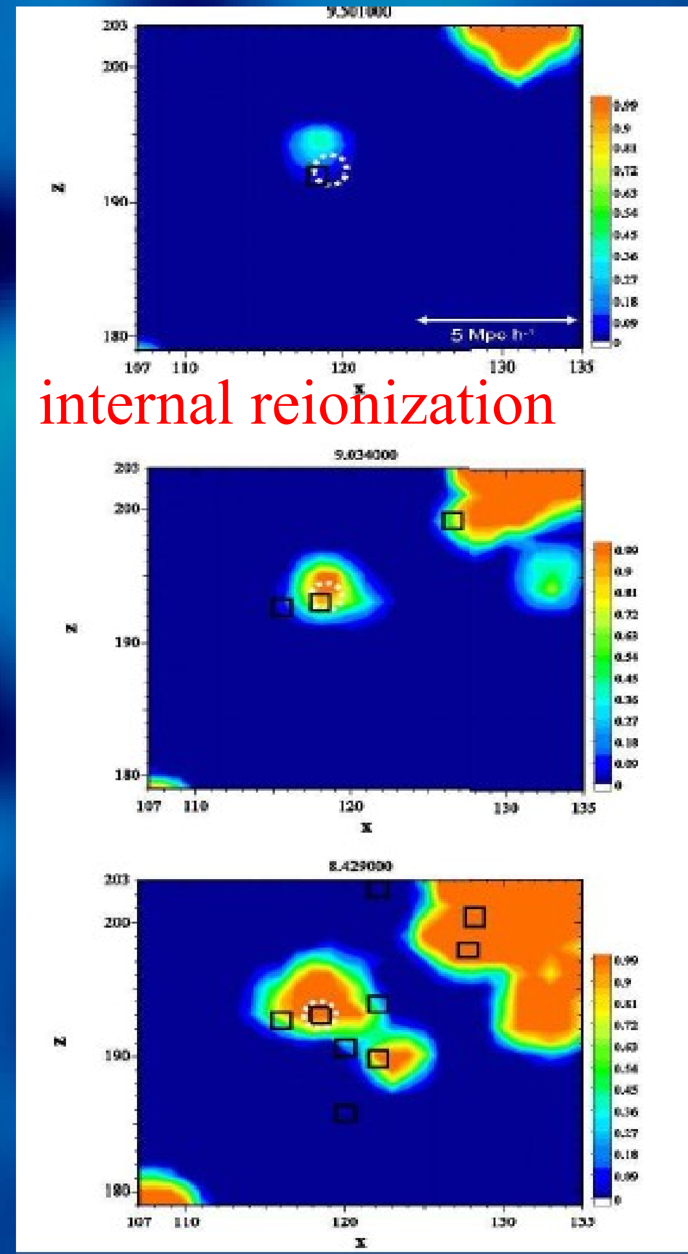


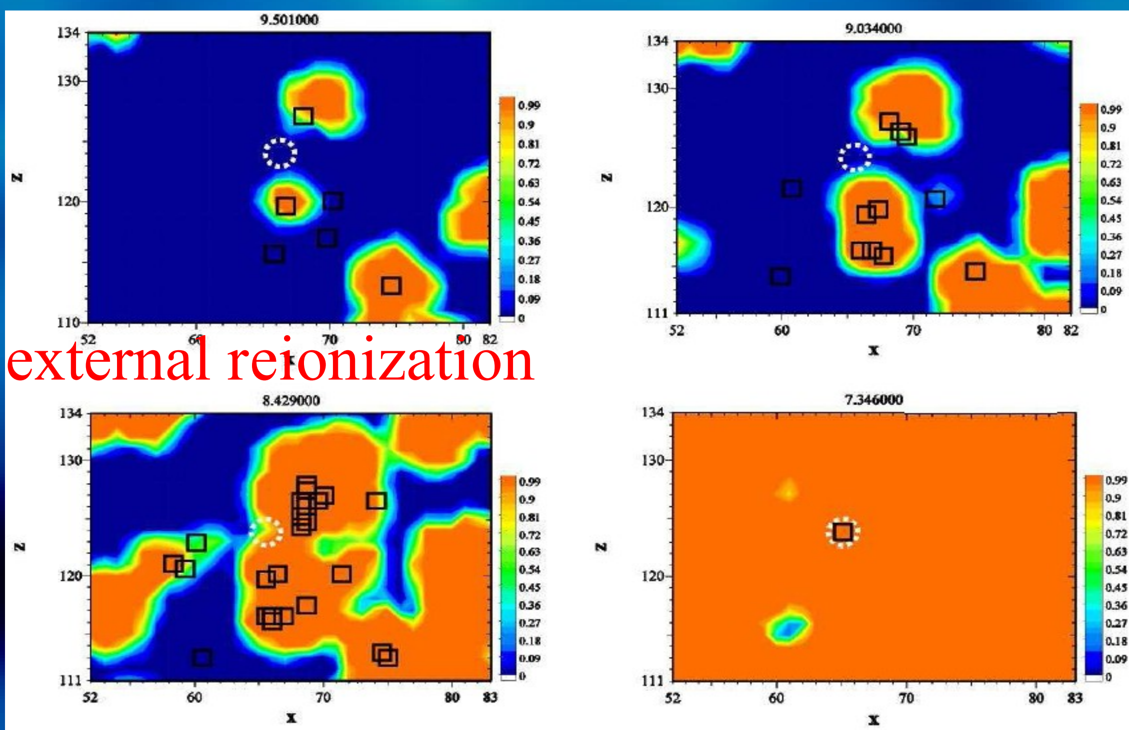
For a given (e.g. observed) **number density** of sources their clustering is largely **unaffected** by reionization patchiness (max 10% difference at small scales and at high-z, decreasing later).

Dependence of Reionization history on Galactic Morphology and Environment

(Weinmann et al., astro-ph/0705.0530)

Internal (self-) reionization vs. external one: important consequences for SF, dwarf population, globular clusters: How does it correlate with the galactic morphology and environment?





Results: reionization history vs. morphology

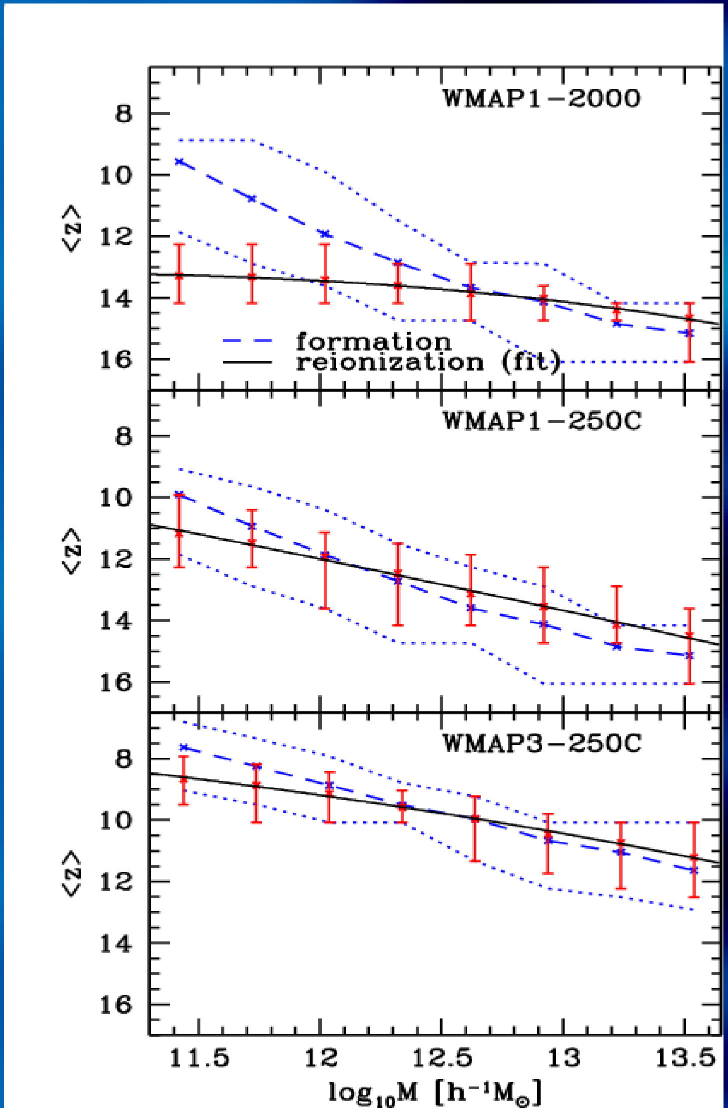
- 4 types of halos considered:
  - field: 40-80% external
  - L*: mostly external for early reion., mostly internal for extended reionization
  - cD's: always internal
  - LG-like binary groups: similar to

	z_f	z_r	$z_{70\%}$	$f_{\rm ext}$	Δt	Δt^*
WMAP1-f2000						
field haloes	10.8	13.4	13.1	0.79	-114	-0.237
L* halo sample	12.6	13.6	12.85	0.62	-36	-0.075
central cDs	16.7	15.5	14.1	0.0	26	0.055
LG sample	12.8	13.3	12.9	0.44	-21	-0.044
WMAP1-f250C						
field haloes	11.0	11.7	10.4	0.4	-33	-0.053
L* halo sample	12.6	12.4	10.9	0.17	8	0.013
central cDs	16.7	15.5	11.8	0.0	26	0.042
LG sample	12.8	12.4	10.8	0.1	13	0.021
WMAP3-f250C						
field haloes	8.2	8.9	8.2	0.56	-60	-0.062
L* halo sample	9.3	9.4	8.6	0.27	-9	-0.009
central cDs	13.0	12.6	9.6	0.0	15	0.016
LG sample	9.1	9.2	8.3	0.24	-8	-0.008

Reionization history vs. present-day mass

- Present-day groups and clusters were predominantly internally-reionized.
- L* galaxies: mostly externally-reionized for early reionization, but self-reionized for extended scenarios.

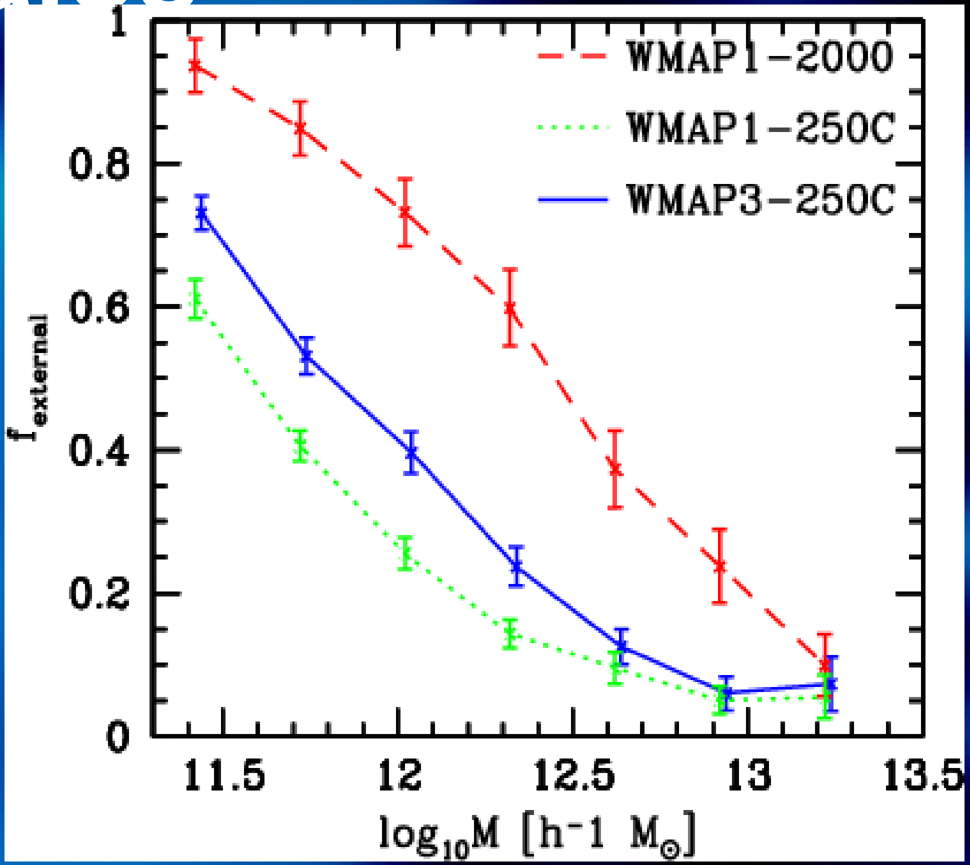
Low-mass galaxies were predominantly



f_{ext} vs. Halo Mass for Field Halos

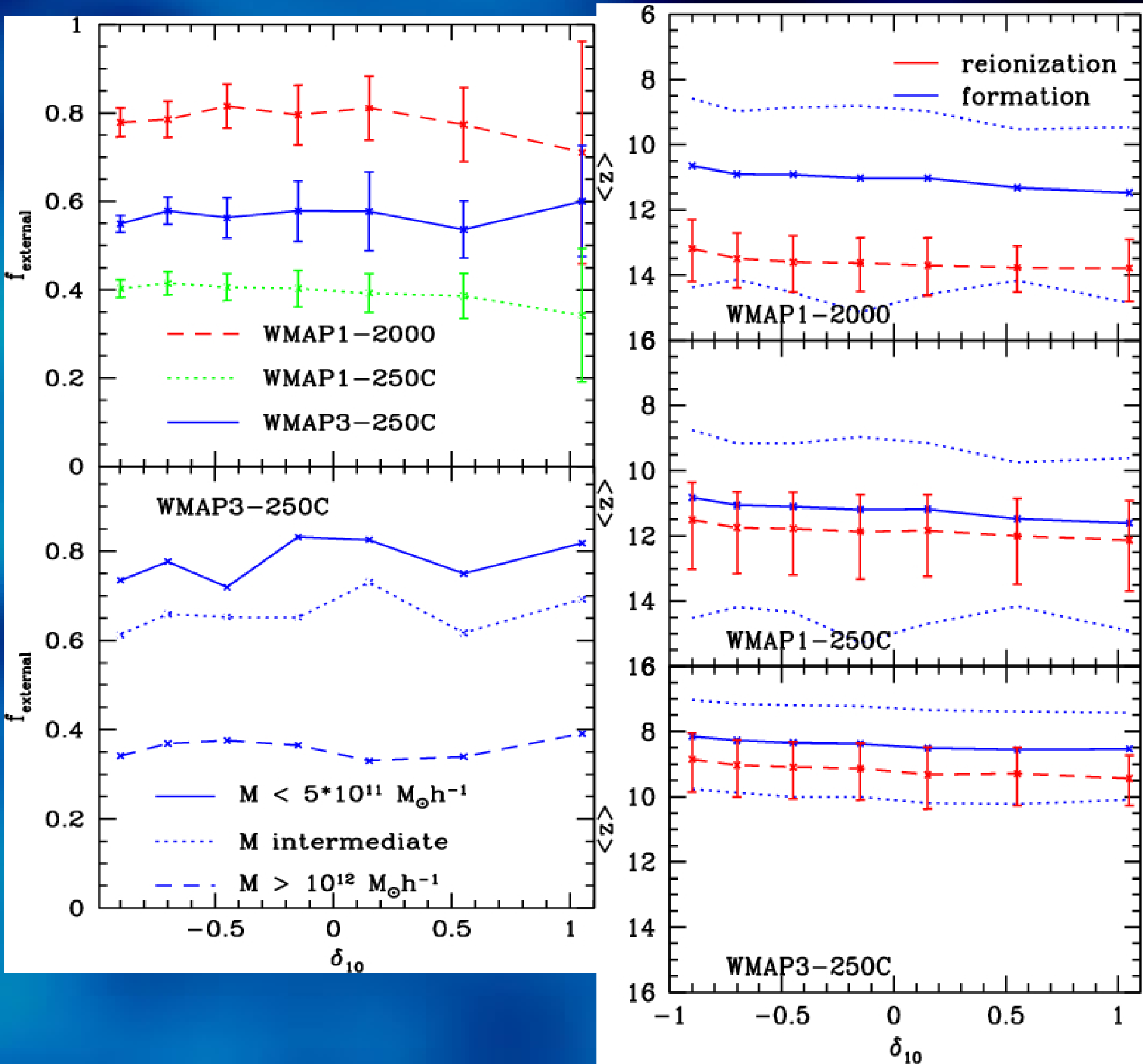
Fraction of externally-reionized field halos is strongly mass-dependent.

Significantly different for early (WMAP1-2000) and extended reionization scenarios.



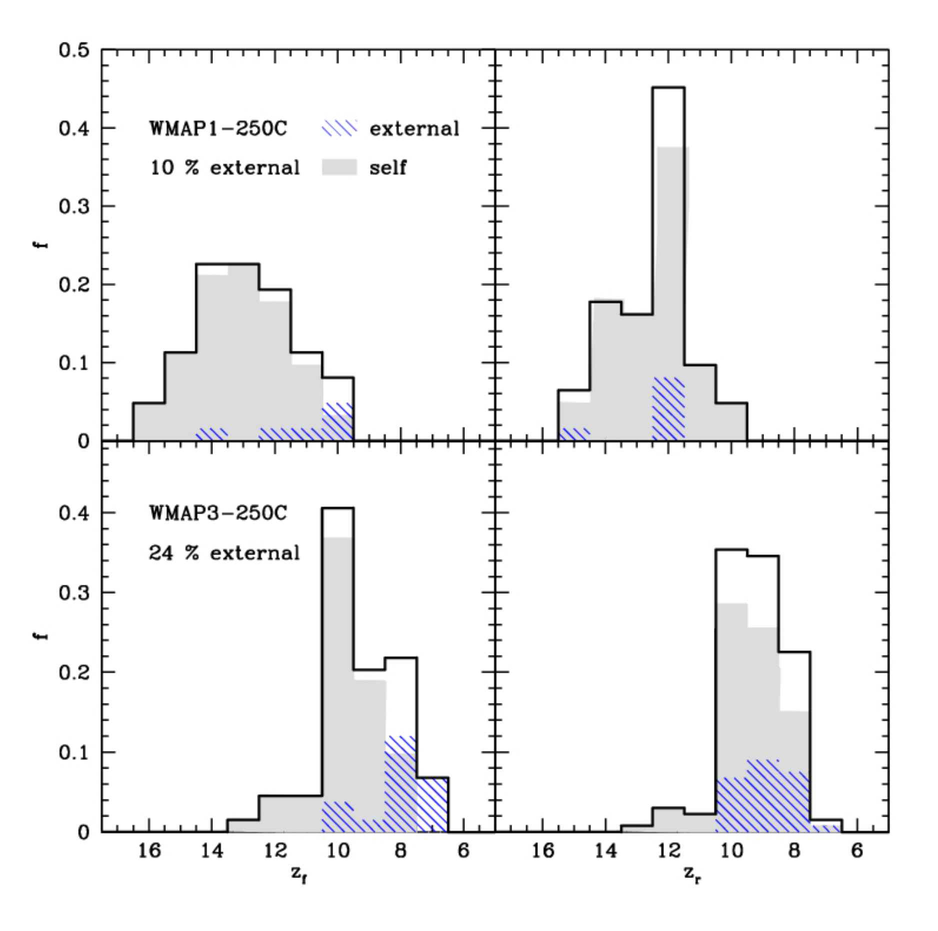
Reionization history vs. environment

The fraction of externally-reionized halos is largely uncorrelated with local overdensity, regardless of reionization scenario or halo mass, at least for relatively isolated galaxies, not necessarily the case for galaxies in



Reionization of the Local Group: extended reionization scenarios

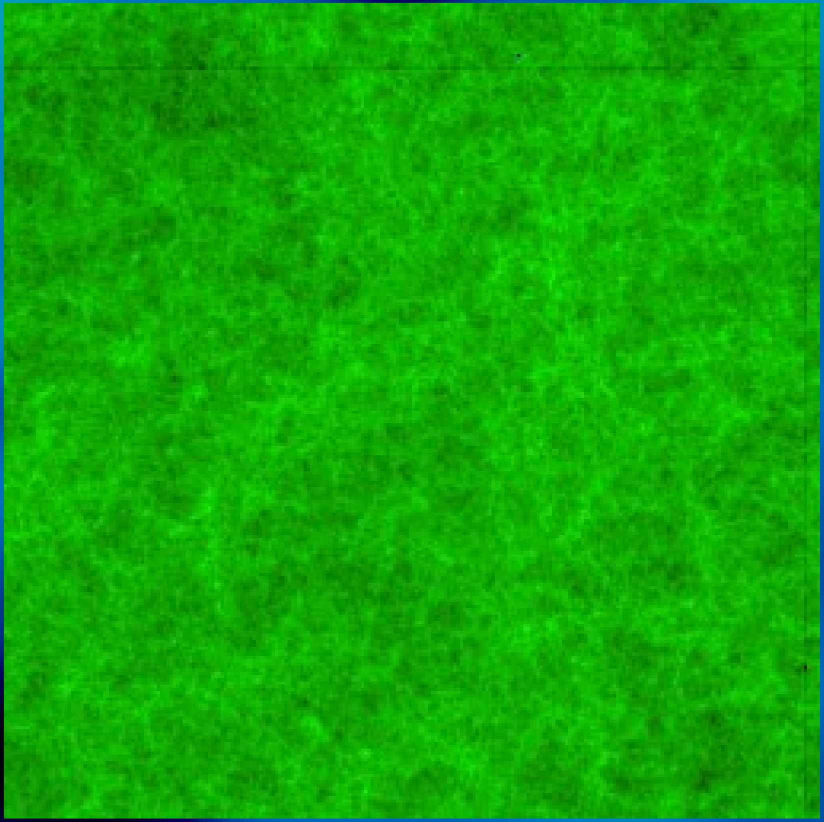
- LG-like systems have reionization histories similar to L*'s.
- Formation times peak at z~13 (10) for WMAP1 (WMAP3), but externally-reionized ones form much later.
- Reionization times have very similar distributions for either externally or internally reionized cases.



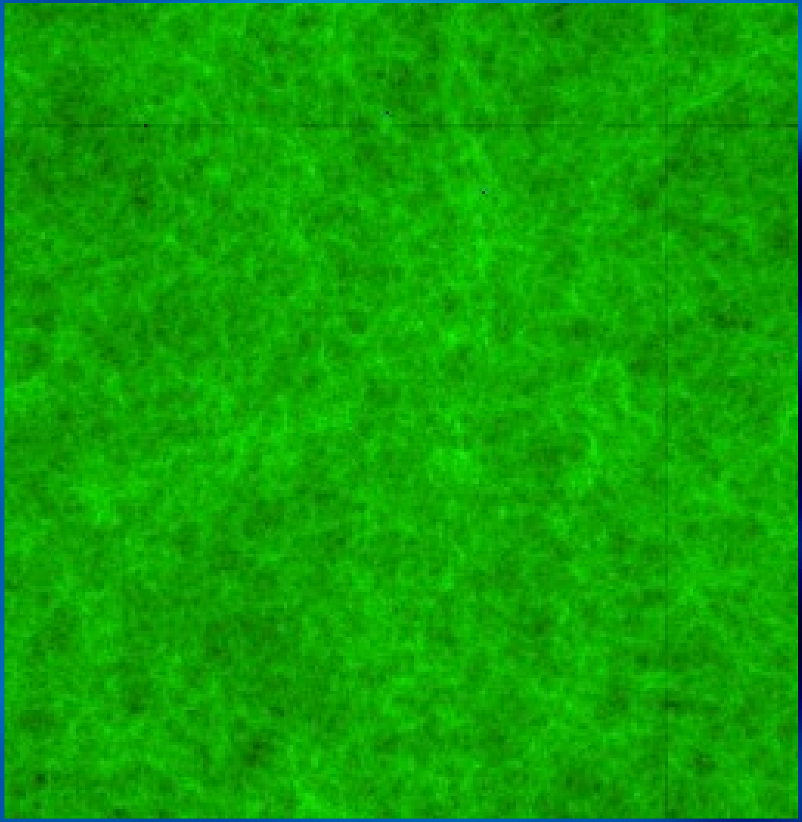
Reionization of the Local Group

(w/B. Moore, G. Yepes, S Goetlobber, G. Mellema; work in progress)

Constrained simulations of the formation of the LG and its neighbourhood (GADGET, 64/h Mpc box, 1024^3 particles) post-processed with radiative transfer (on 256^3 grid), same setup as above.



Milky Way



Virgo