Cosmological reionization simulations: all halos great and small

Ilian T. Iliev

University of Sussex

with

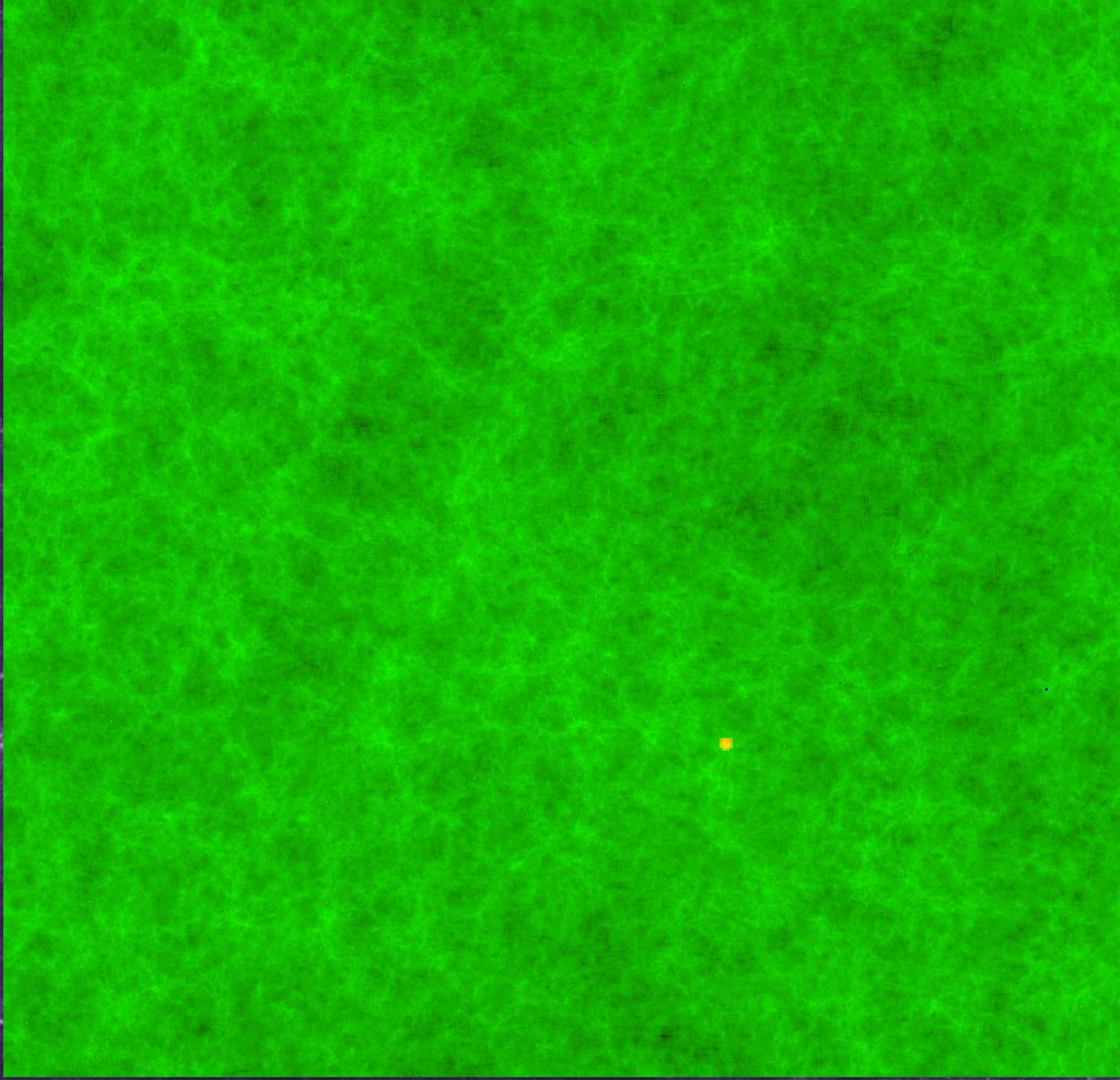
Garrelt Mellema (Stockholm), Paul Shapiro (Austin), Kyugjin Ahn (Chosun), Ue-Li Pen, Dick Bond, Pat McDonald, Olivier Dore (CITA), Ben Moore, Uros Seljak, Vincent Desjacques (Zurich), Gustavo Yepes (Madrid), Stefan Gottloeber (AIP), Yehuda Hoffman (Jerusalem)

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

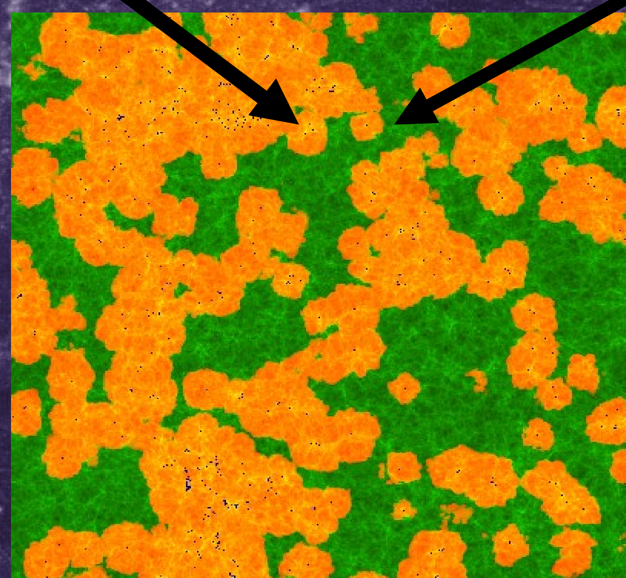
[Iliev et al. 2006a, 2007a; Mellema, Iliev, et al. 2006; and in prep.]

- 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 up to 21,952
- cores

- C^2-Ray code
(Mellema, Iliev, et al. 2006)
- radiative transfer
  - noneq. chemistry
  - precise
  - highly efficient
  - coupled to gasdynamics
  - massively parallel (ran on over 10,000 cores).

Coupled to hydro

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.

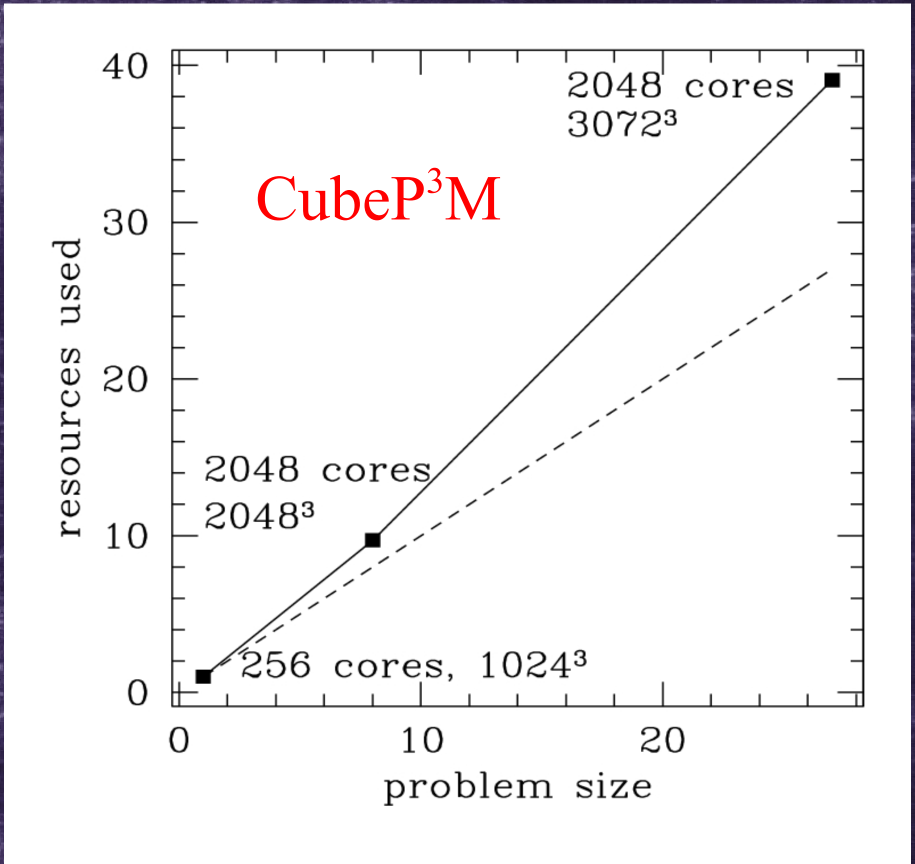


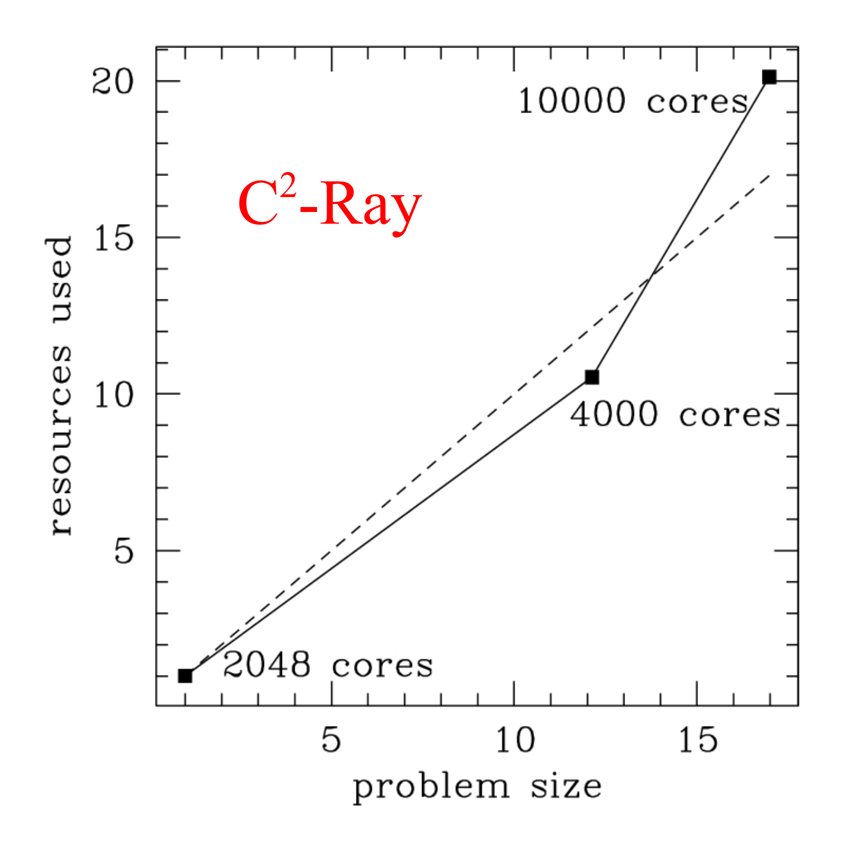
Code Scaling

(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!





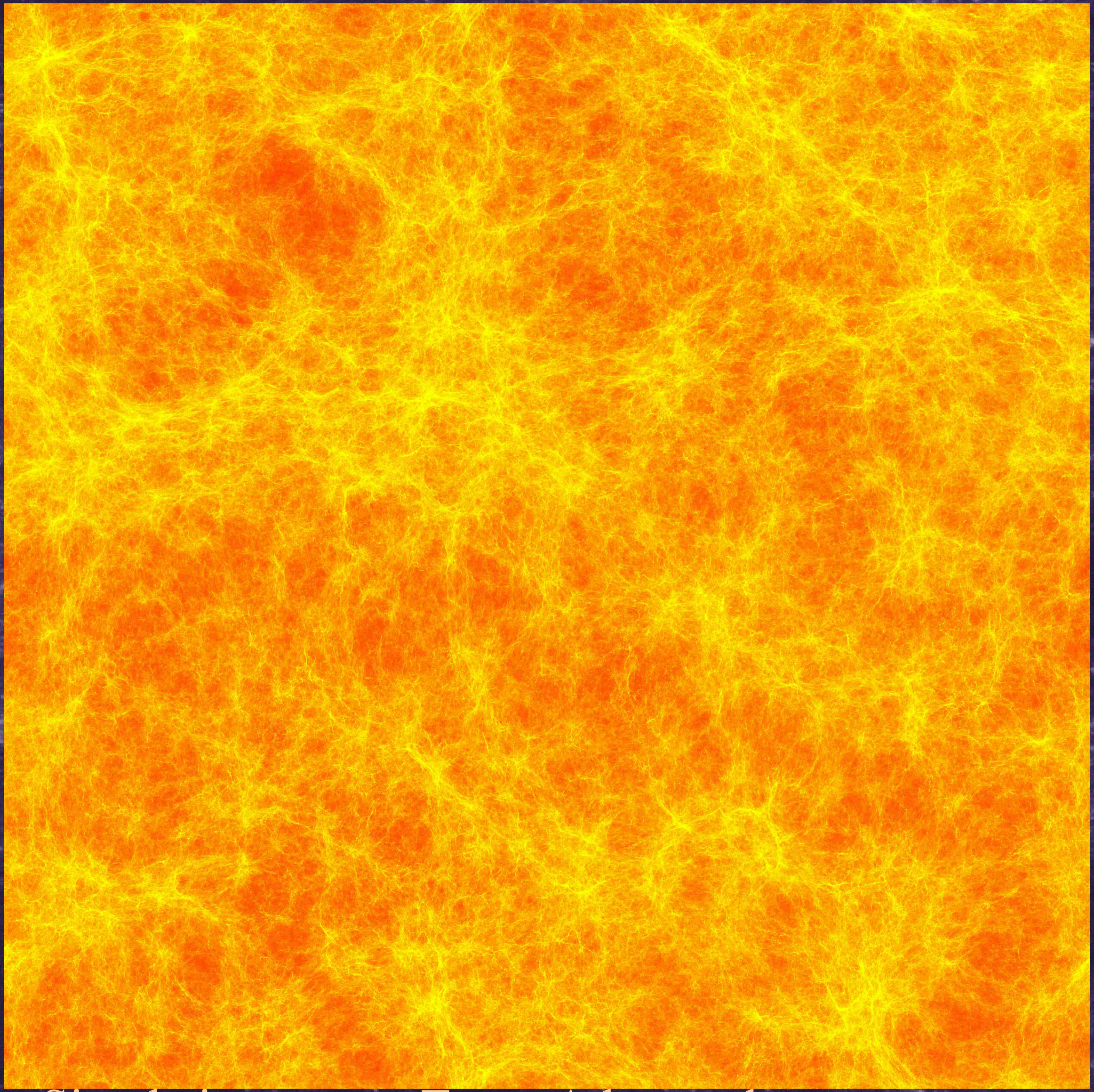
The Formation of Early Cosmic Structures

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 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

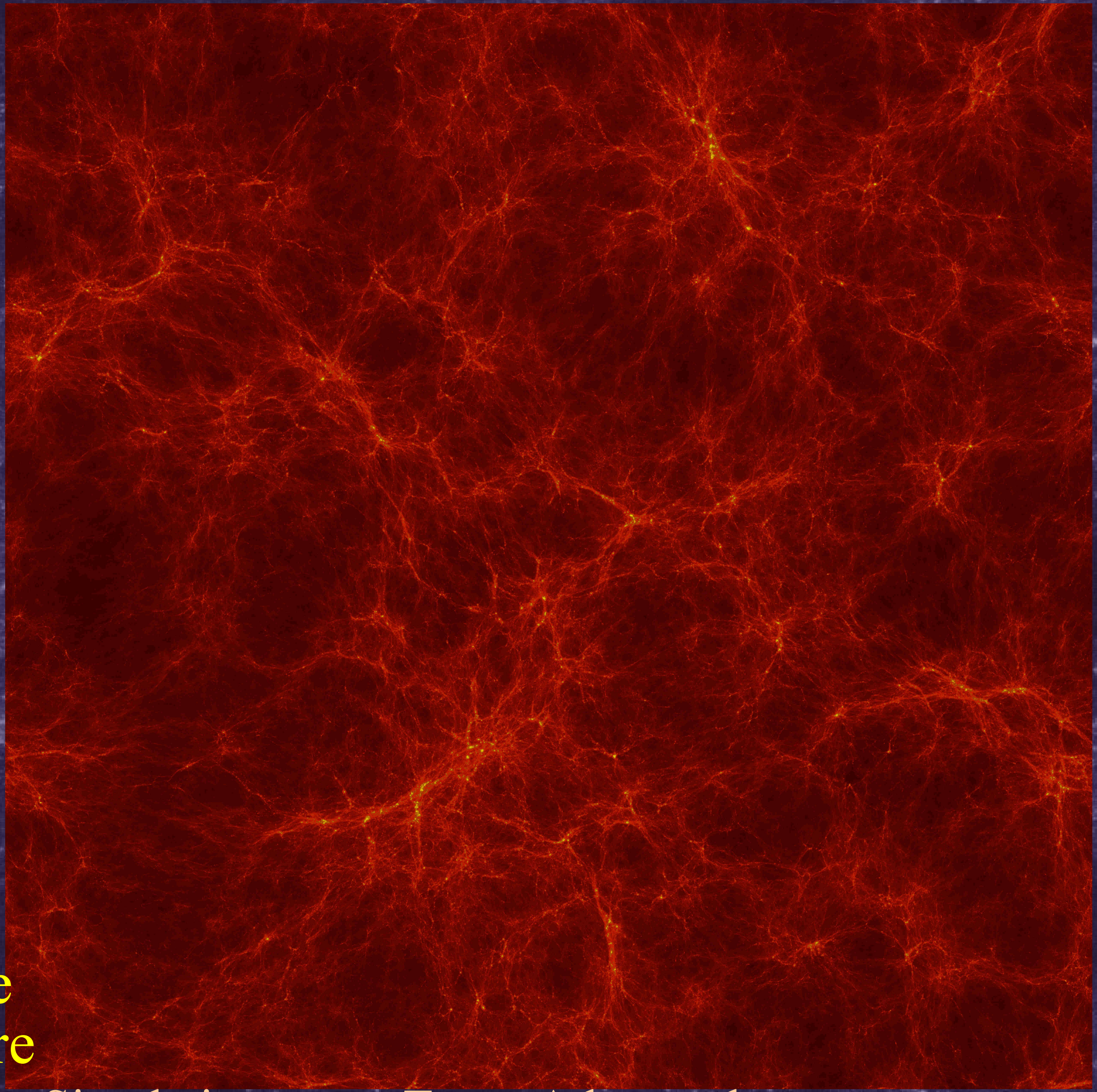
Resolves all halos down to small minihalos (10^5 M_{solar}).

Structures are highly biased! Extend to extremely small scales.

First resolved halos form at z=40.

>21 million halos at z=8.

Very useful for modelling the effects of small-scale structure and 21-cm absorption.



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

The Formation of Early Cosmic Structures: The Very Small Scales

(Iliev, et al., work in progress)

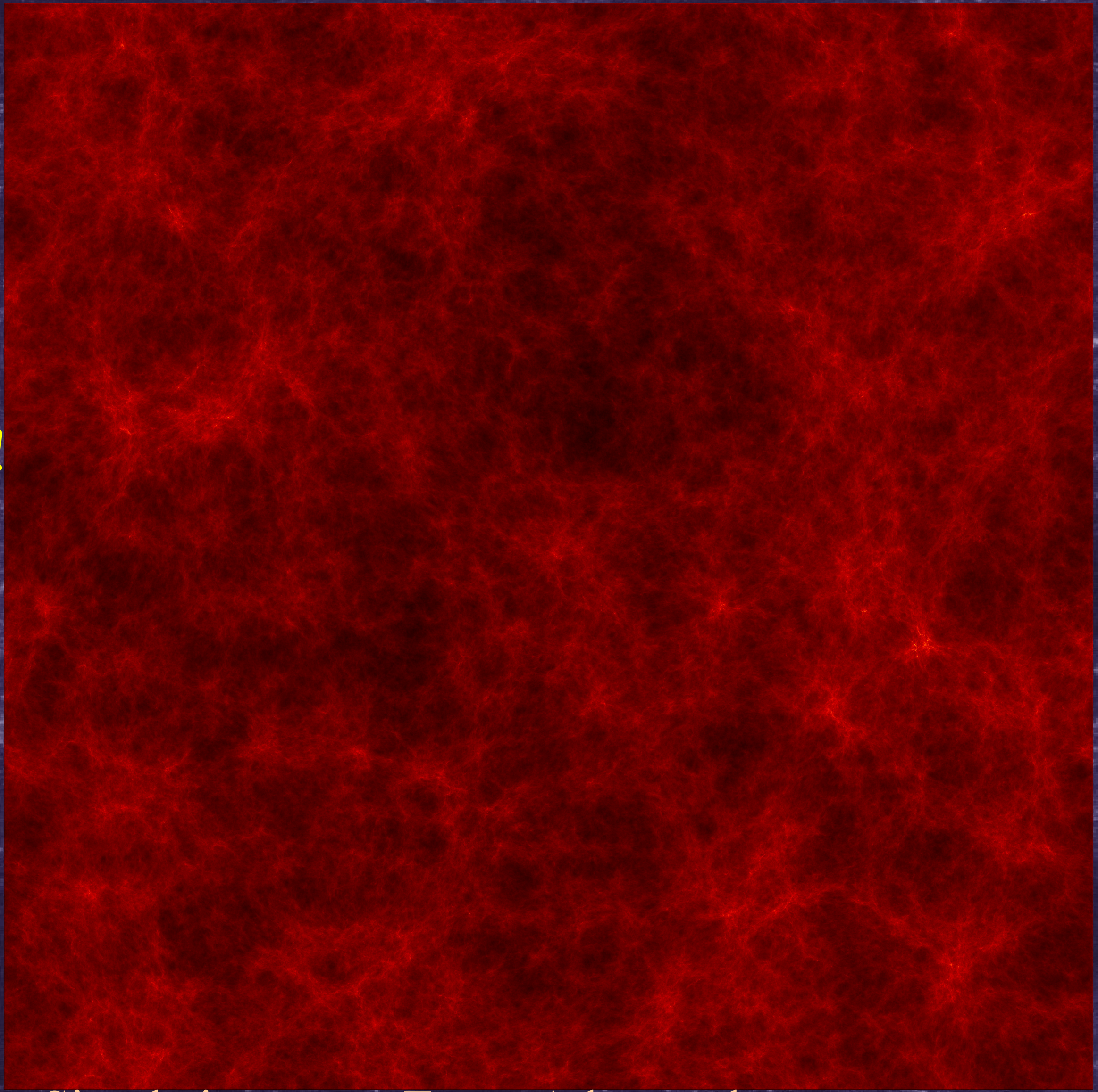
20/h Mpc box @ z=20
5488^3 particles (165 billion),
10976^3 cells, P^3M simulation

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 182 pc!)

First resolved halos form at z=43.

>40 million halos at z=14.7 (still running).



Simulation ran at Texas Advanced Computing Center on 21952 cores.

Universe in a Box: Simulating the Observable Universe

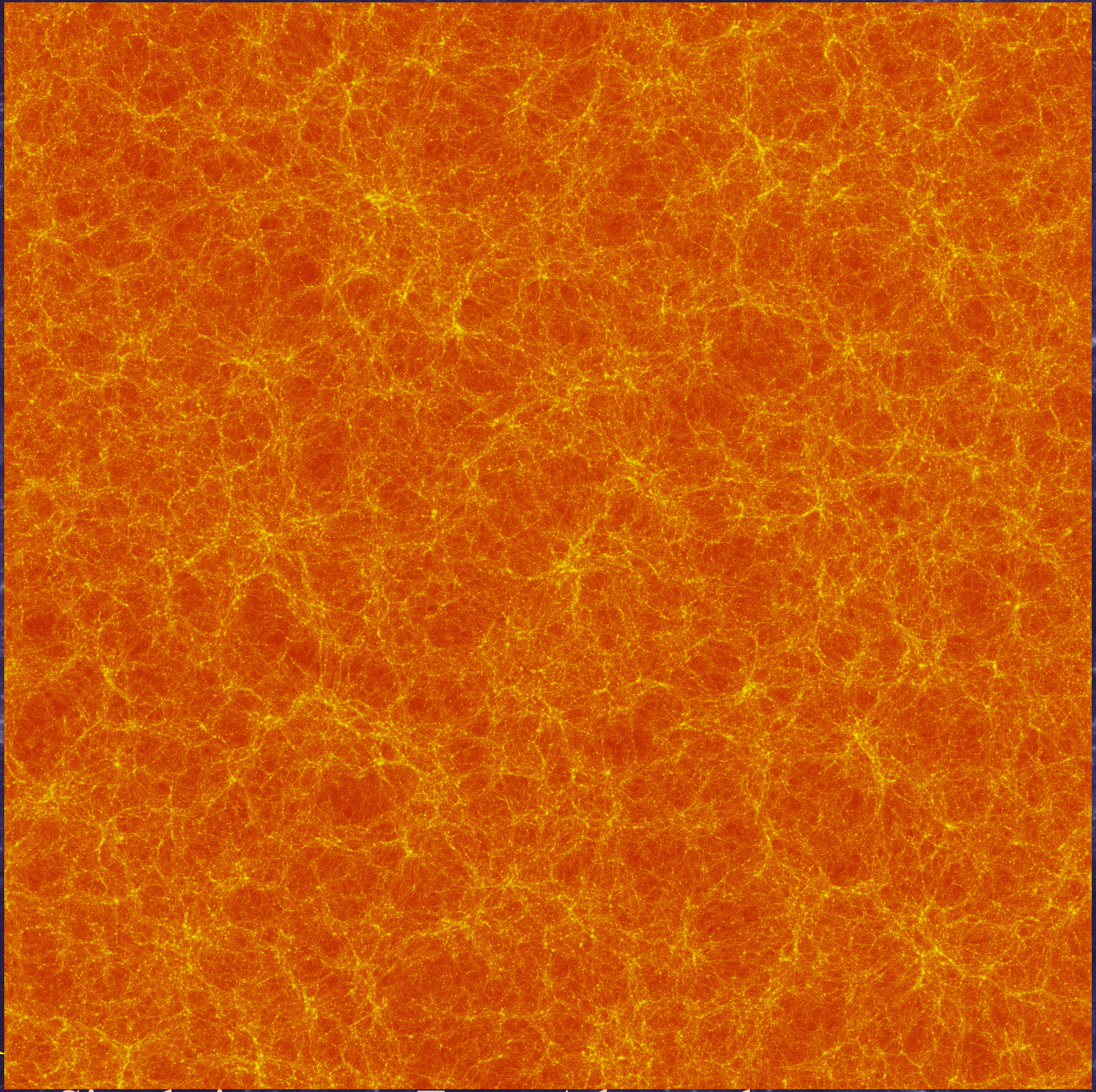
(Desjacques, Seljak & Iliev 2008, and in prep.)

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) and 3.2 Gpc/h box is in progress

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).

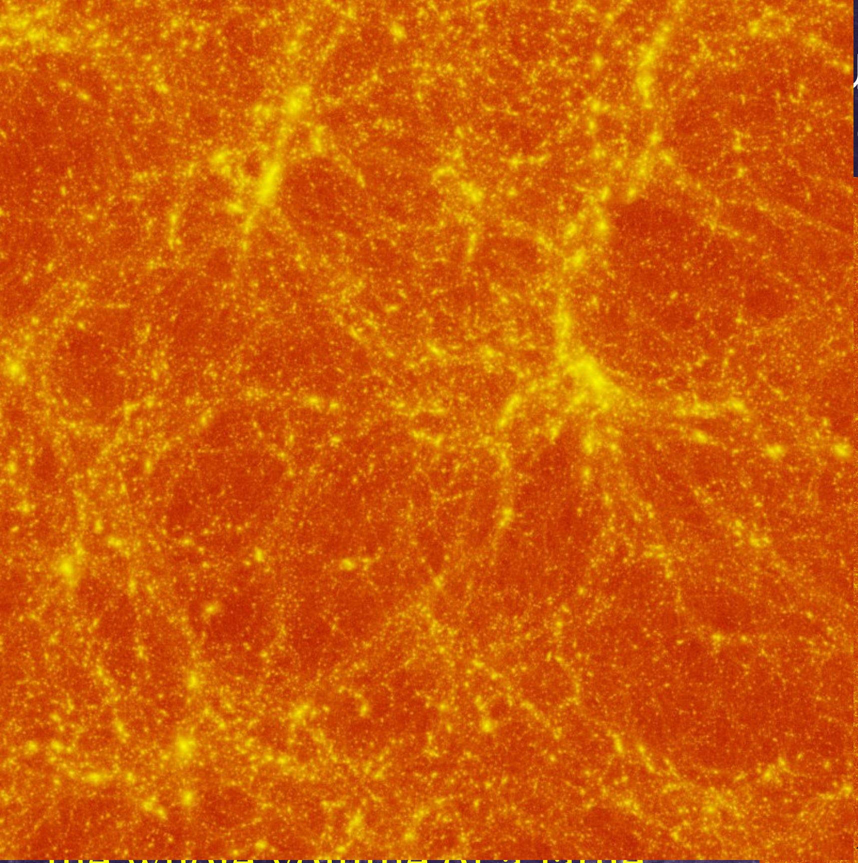
Useful also for modelling LOFAR foregrounds (5x5 deg FOV)

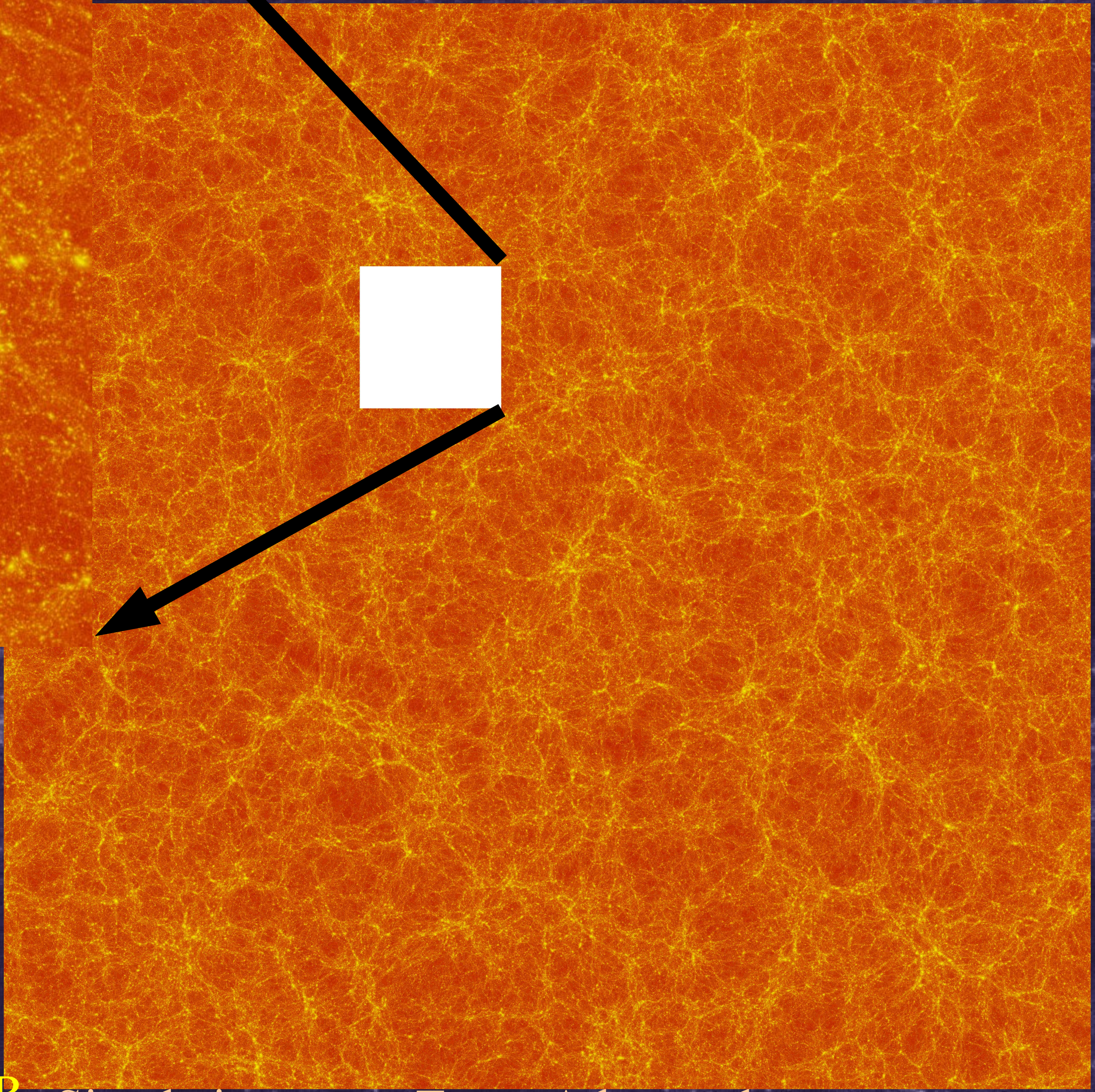


Simulation ran at Texas Advanced Computing Facility on 2048 cores.

ulating the Observable Universe

ck & Iliev 2008, and in prep.)





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).

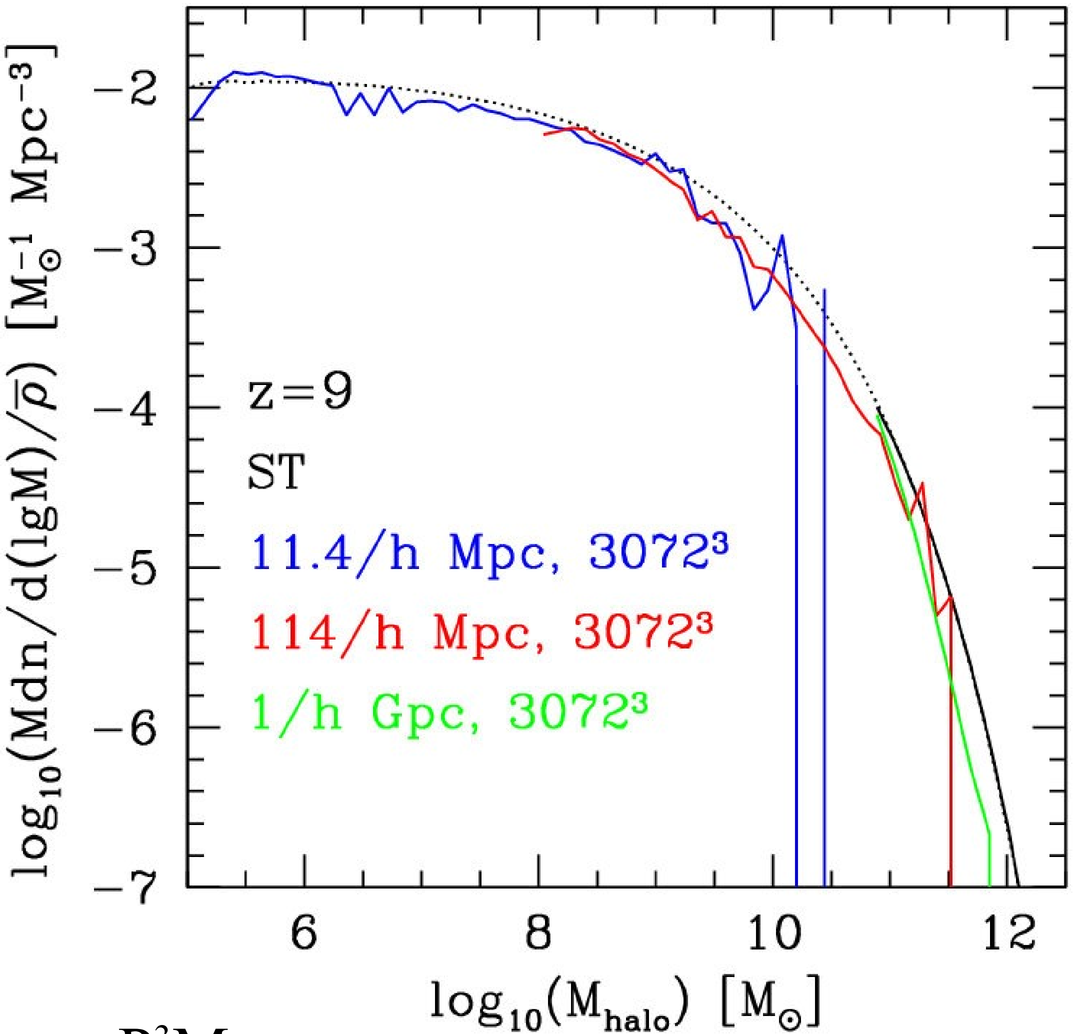
Useful also for modelling LOFAR foregrounds (5x5 deg FOV)

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.

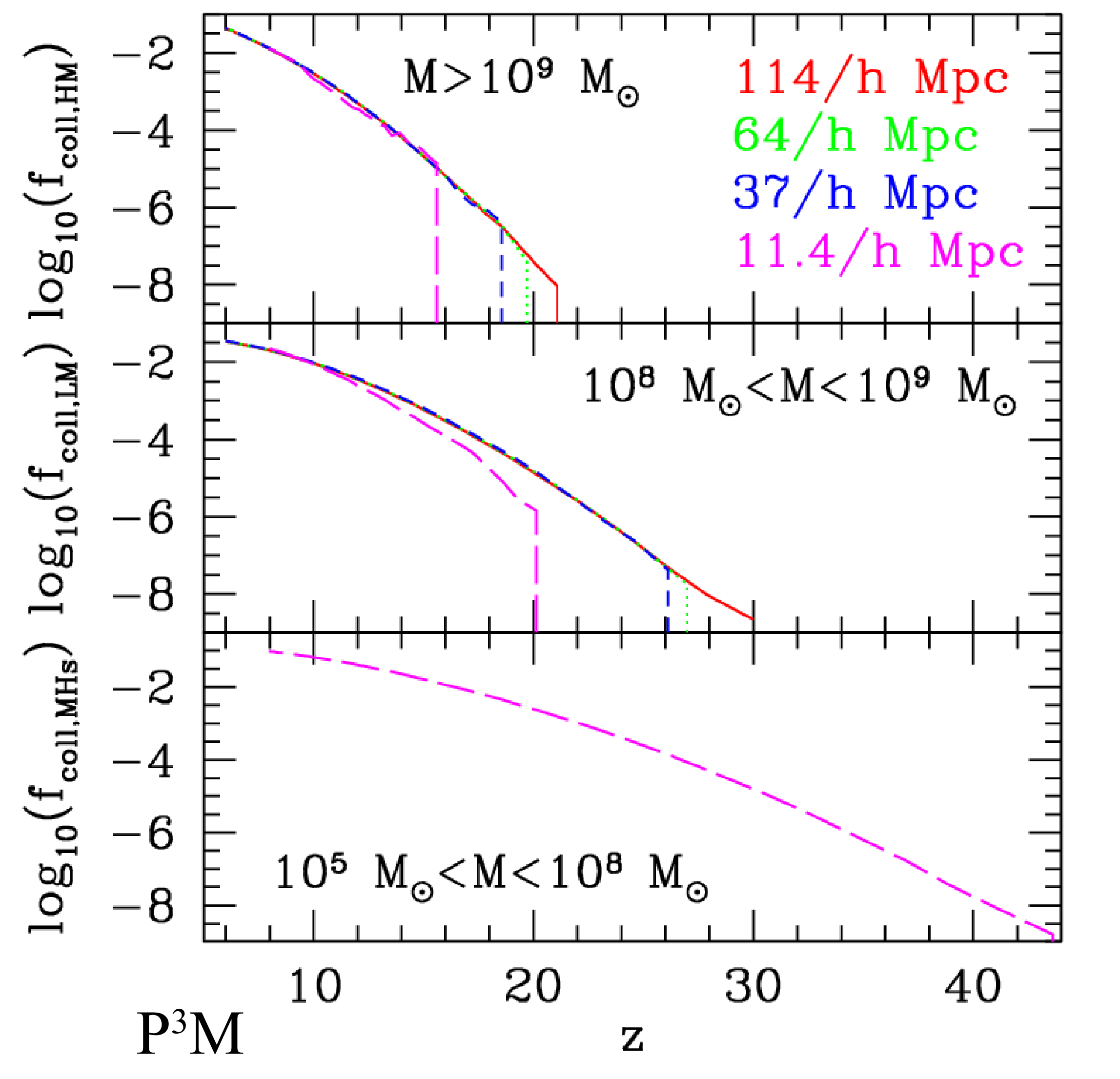
Results show good agreement with each other, but differ from the Sheth-Tormen mass function (black).



P^{3}M

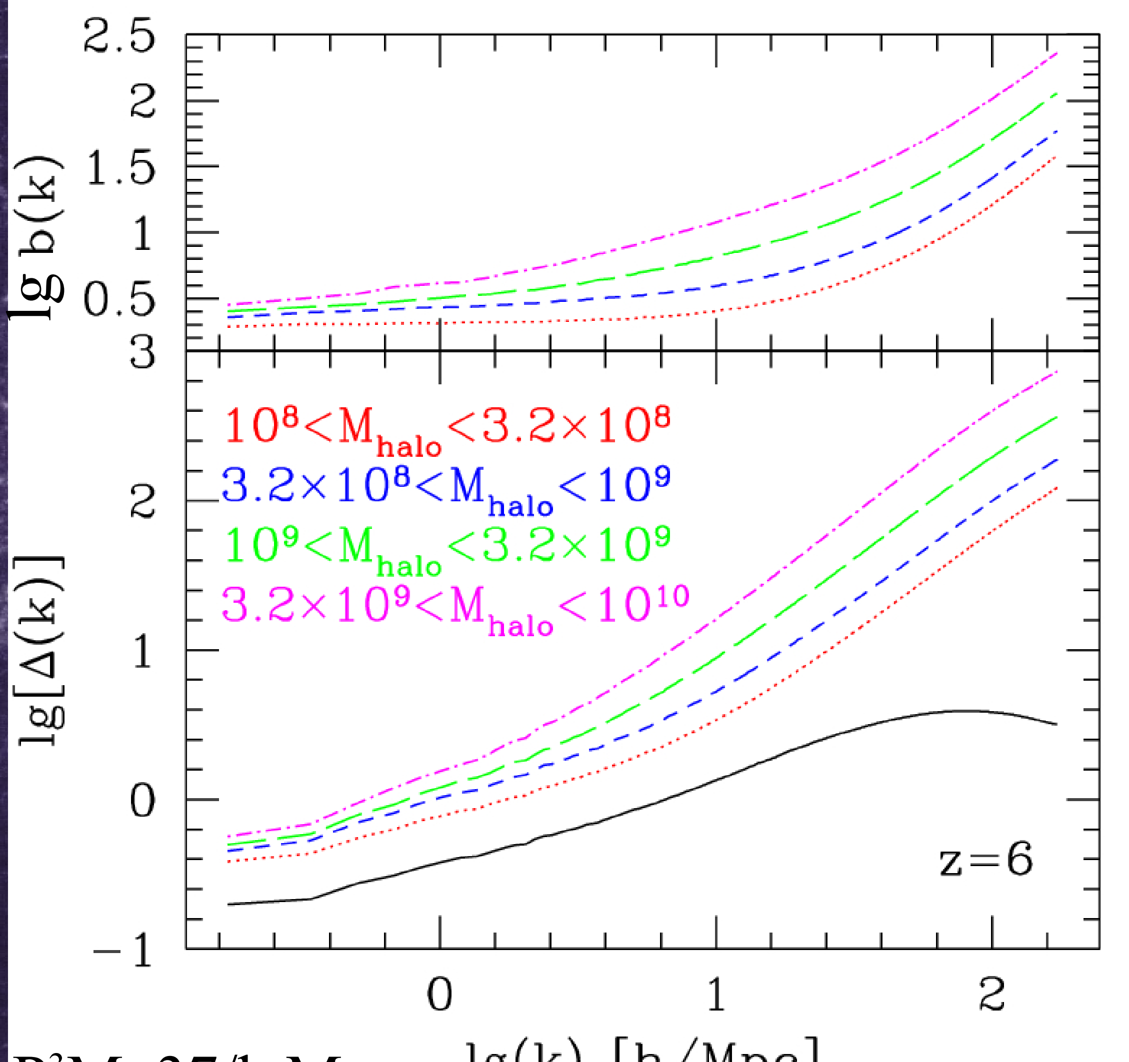
The high-z collapsed fractions
(work in progress)

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^{3}M, 37/h Mpc

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

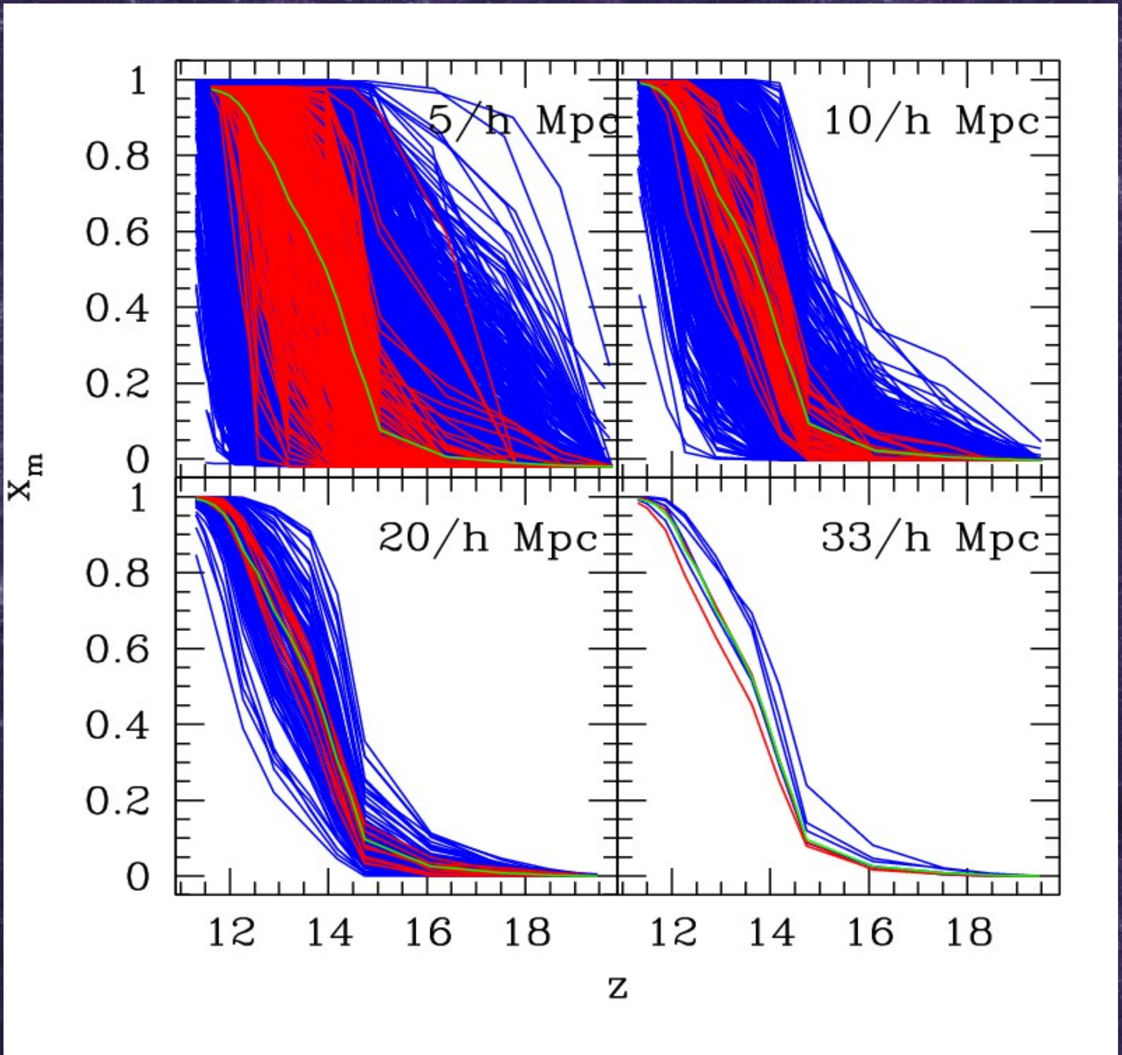
(Iliev, Mellema, Pen, Merz, Shapiro, Alvarez 2006, MNRAS, 369,1625)

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).



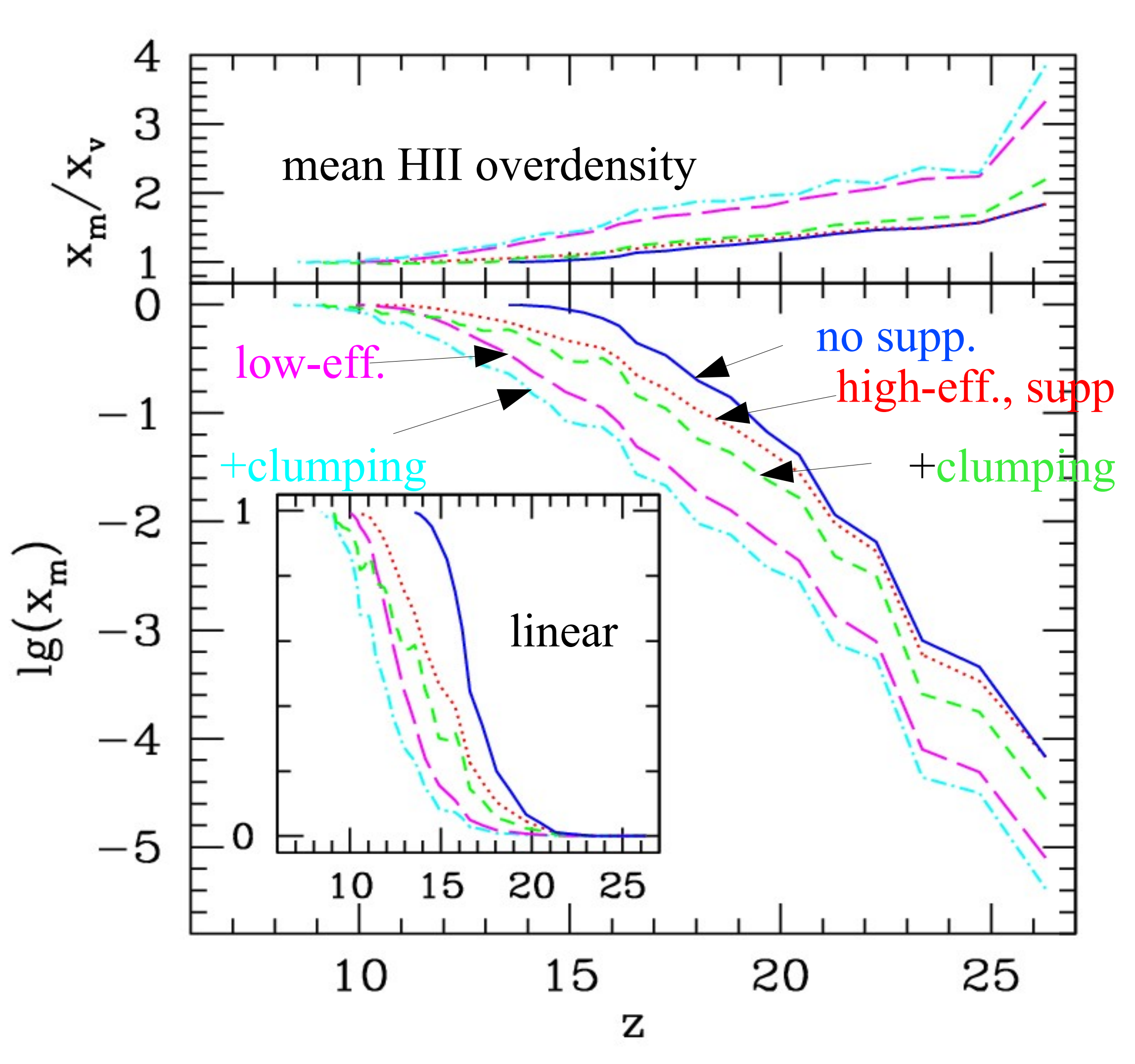
Self-Regulated Reionization

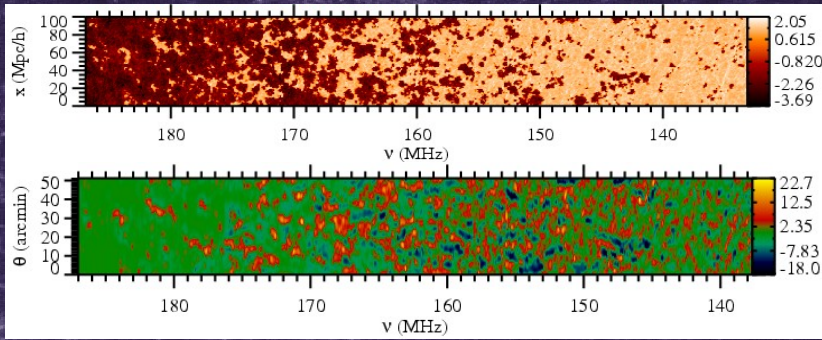
(Iliev, Mellema, Shapiro and Pen 2007a, MNRAS, 376, 534)

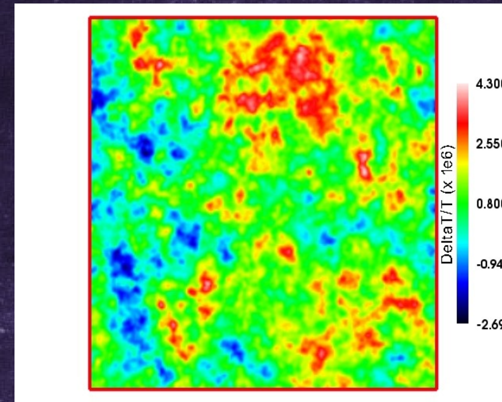
Lower large-source efficiencies, Jeans-mass filtering of small sources and time-increasing sub-grid gas clumping all extend reionization and delay overlap.

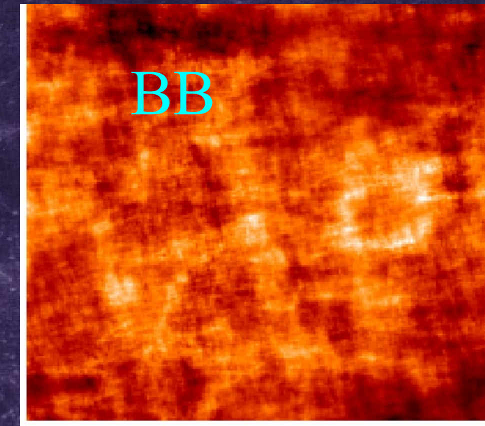
More/less efficient low-mass sources result in more/less suppression of same sources =>

Reionization is self-regulated.









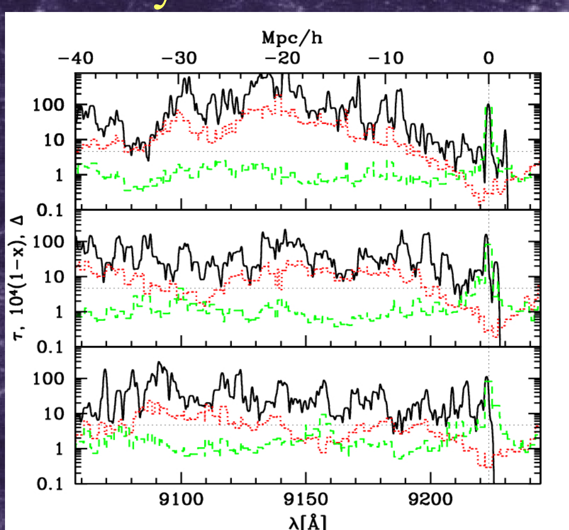
redshifted 21-cm

kinetic Sunyaev-Zeldovich effect (kSZ)

CMB polarization

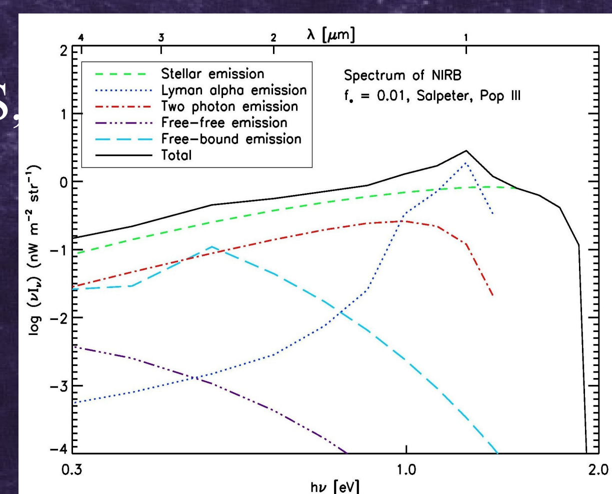
Observing the Reionization Epoch

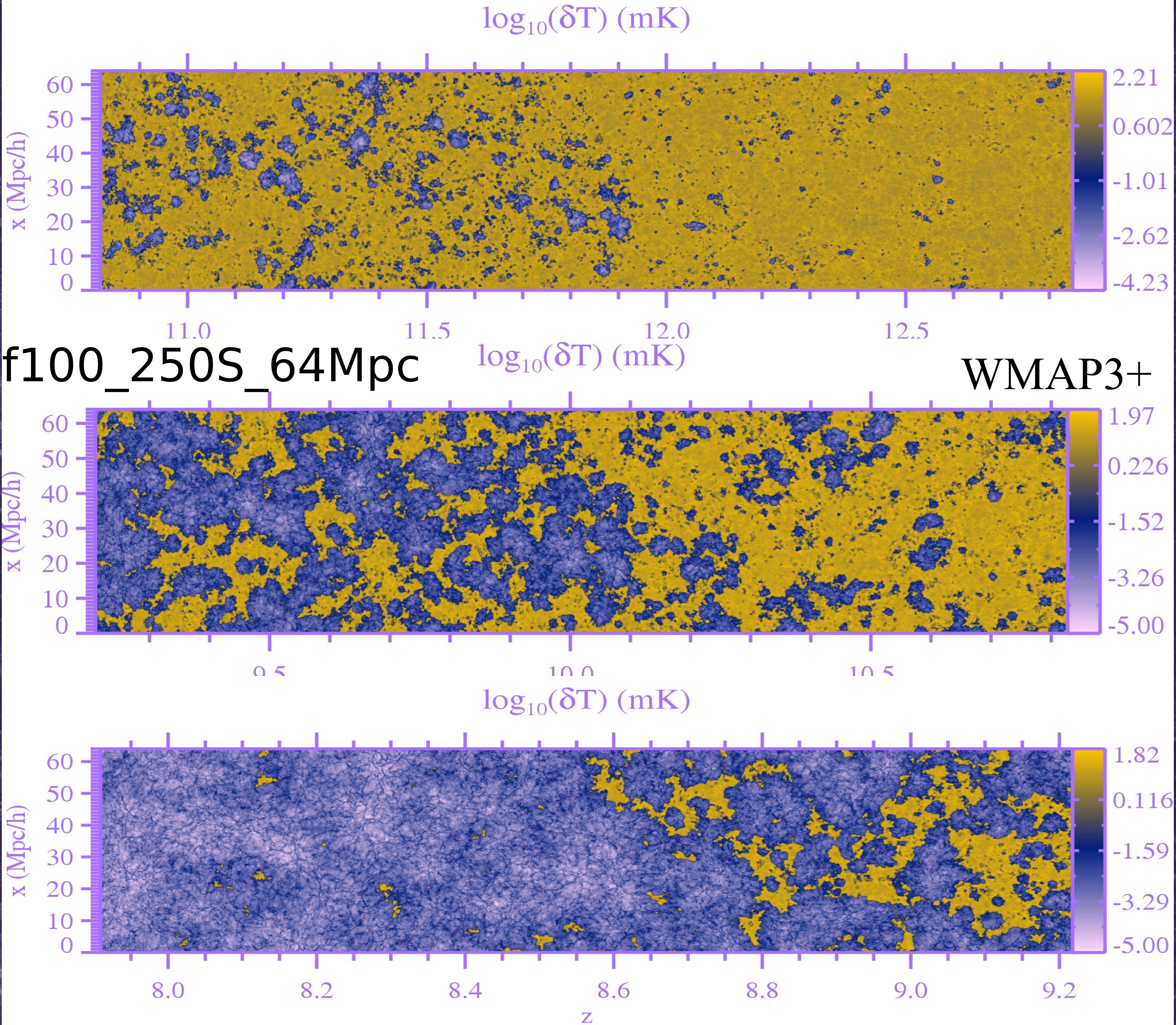
Ly-α sources



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





f100_250S_64Mpc

WMAP3+

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

21-cm view of EOR

LOS spectra: redshift space distortions

(Mellema, Iliev, Pen, Shapiro MNRAS, 2006)

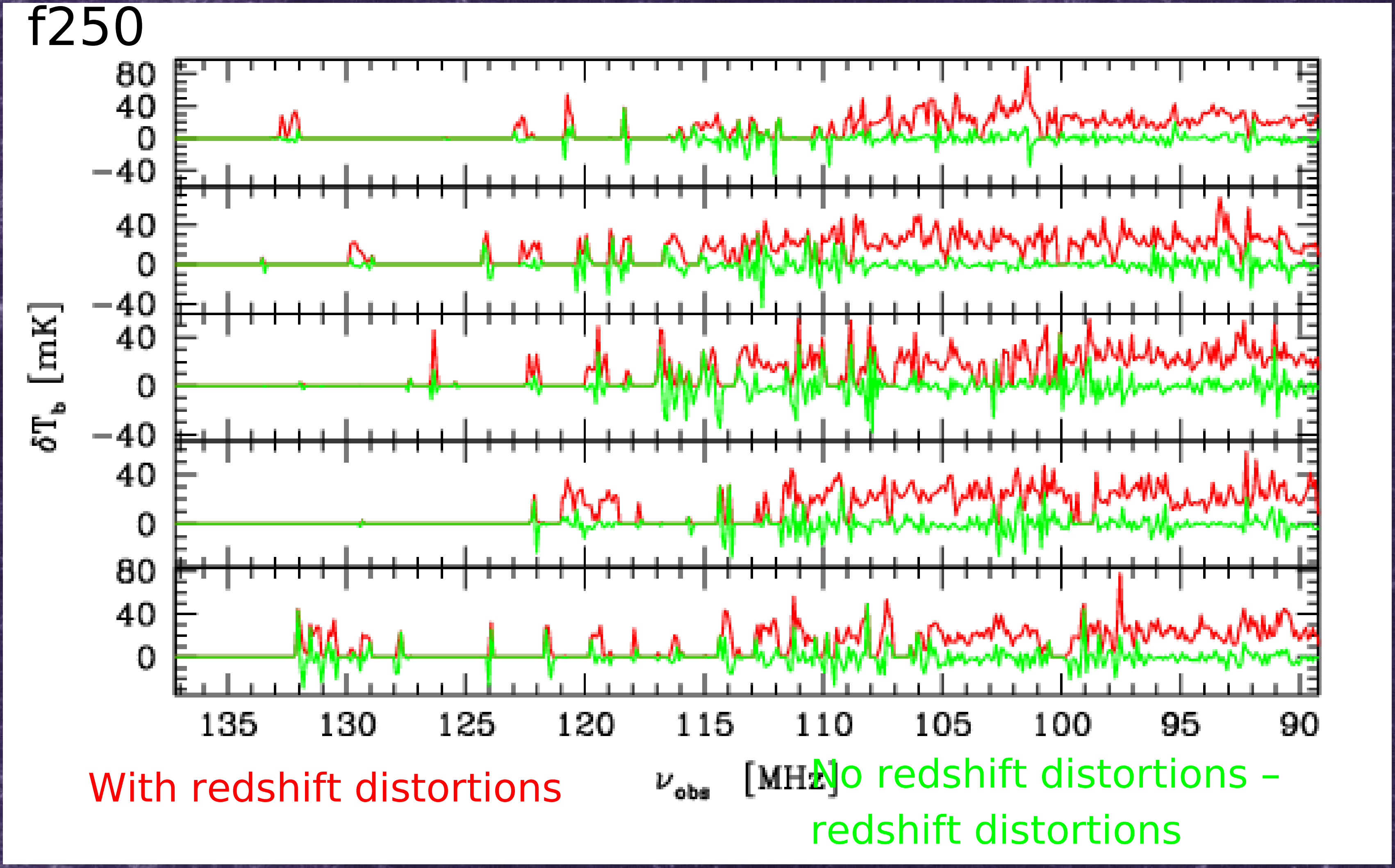


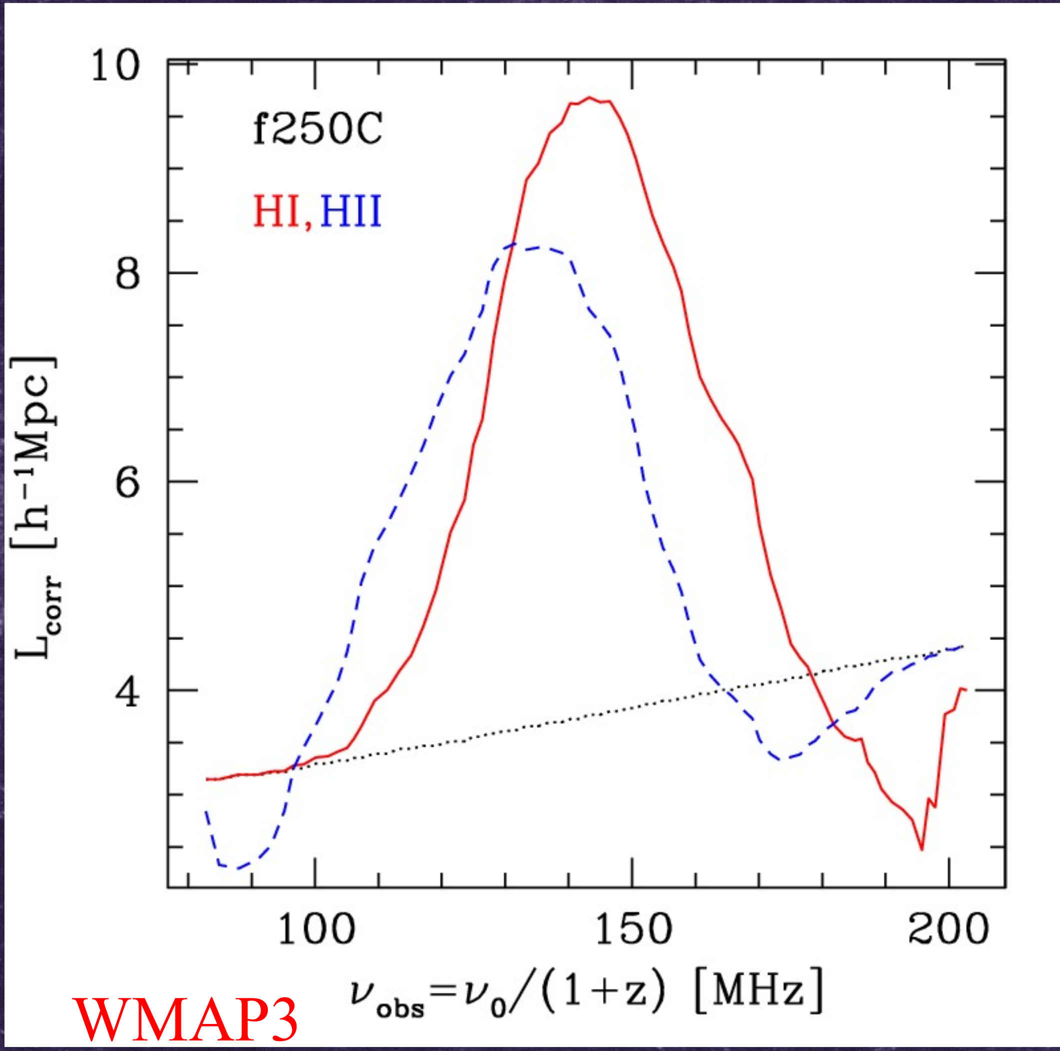
Image correlations

(Iliev, Mellema, Pen, Shapiro, arXiv/0712.1356, PoS)

The correlation lengths between images (freq. slices) show strong evolution, mirroring the characteristic patch size evolution.

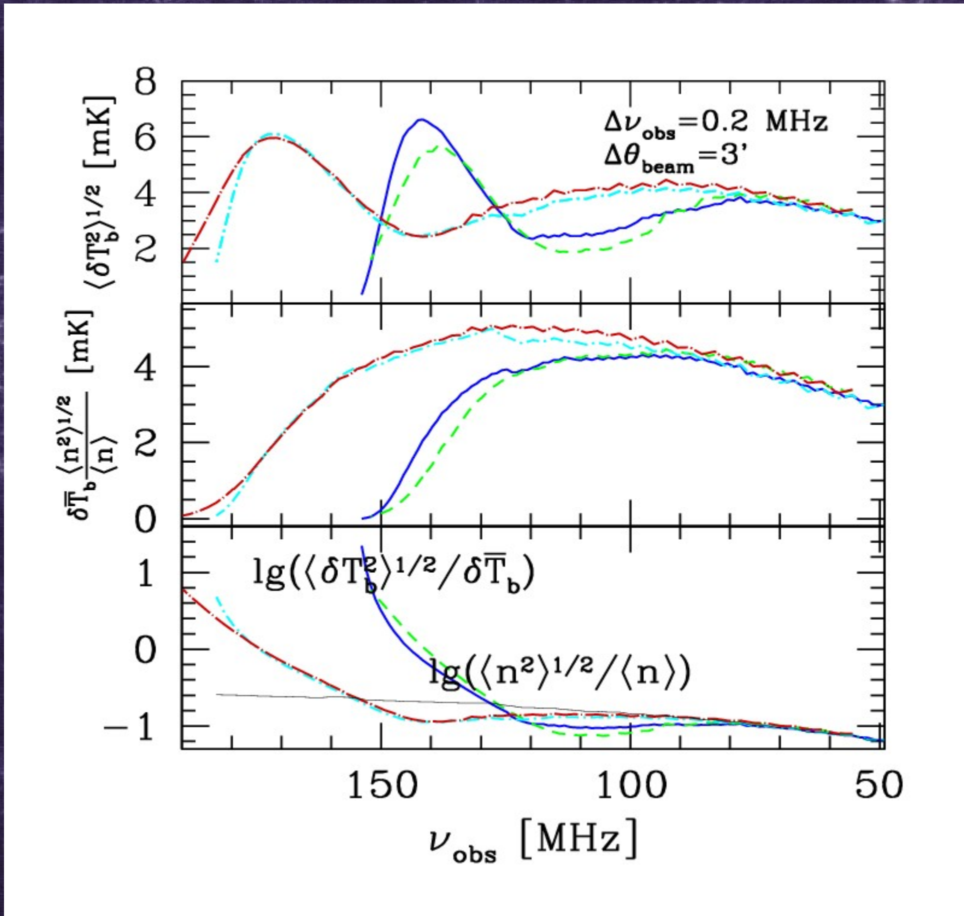
Ionized bubble correlations peak earlier than the ones for the neutral patches.

Useful check on the observations – if the EOR signal is real.

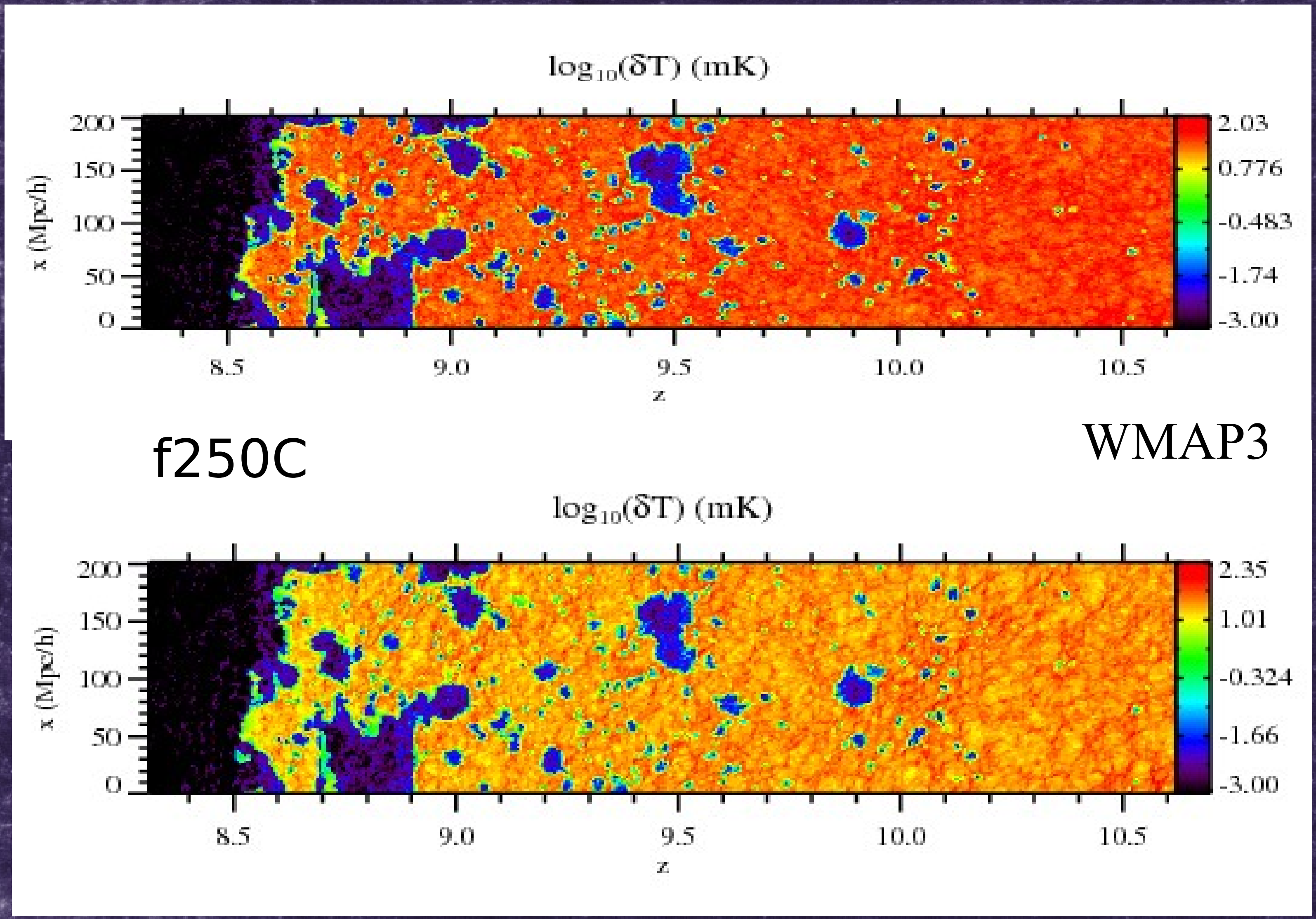


21-cm rms fluctuations: extended vs. early reionization

- Significant boost of fluctuations due to patchiness.
- Similar peak levels, 6-7 mK at LOFAR-like resolution, but at very different frequencies - ~140 vs. ~170 MHz.
- Small box supresses fluctuations noticeably for early reionization, but not for extended one.

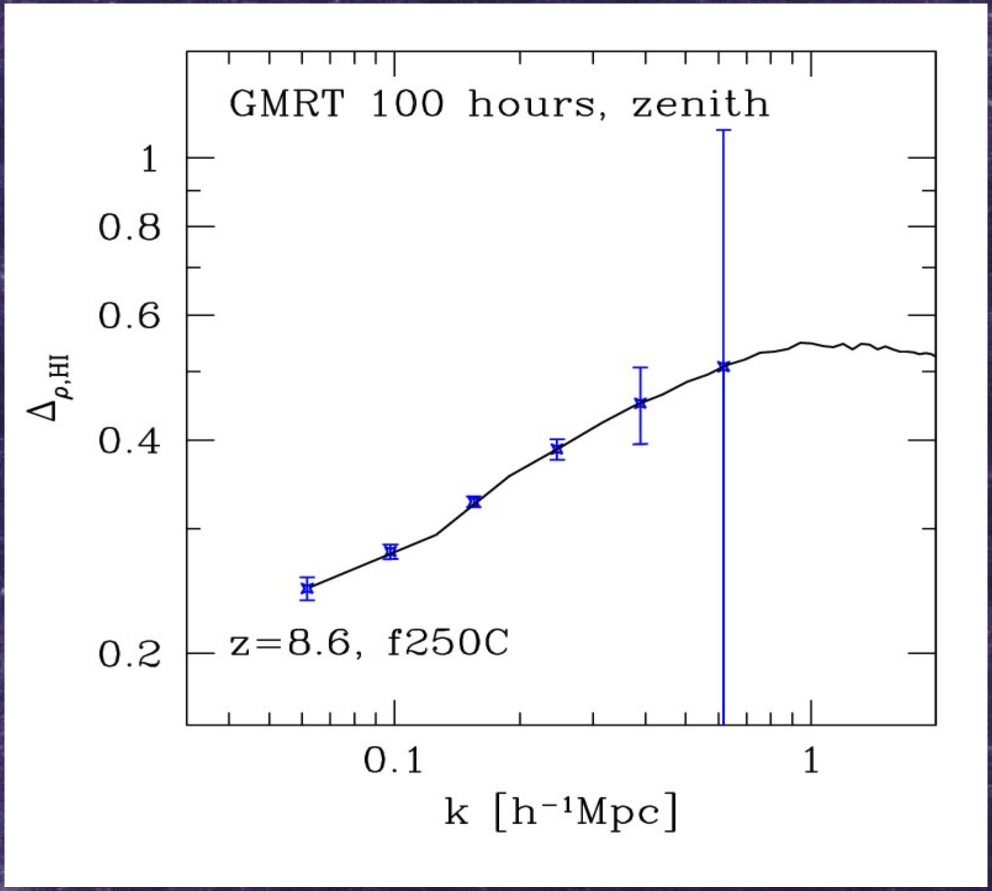


Evolution Slices at 21-cm line: redshift-space distortions and Kaiser effect



Detectability of 21-cm

(Iliev, Mellema, Pen, Bond, Shapiro, 2007)



- 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).

Beyond Gaussian statistics

(Mellema, Iliev, et al. 2006)

- What is the brightest point in our volume at a given redshift?

$\langle \delta T \rangle$

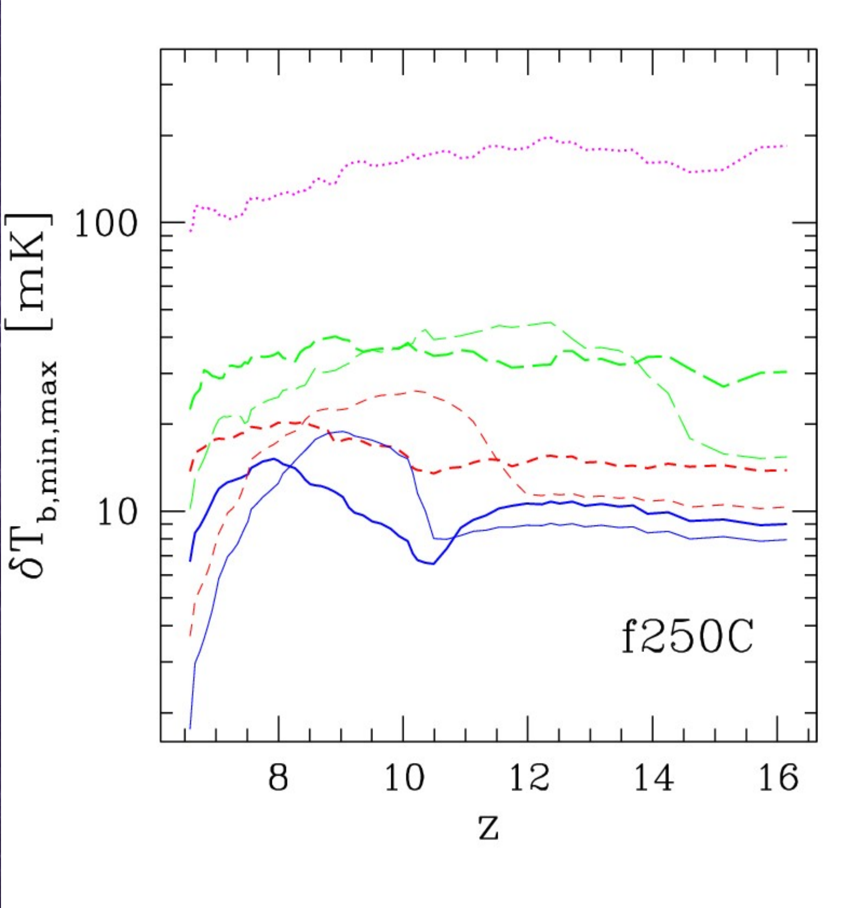
thin: min, thick: max

δT_{max} (full resolution)

δT_{max} (1’, 0.1 MHz)

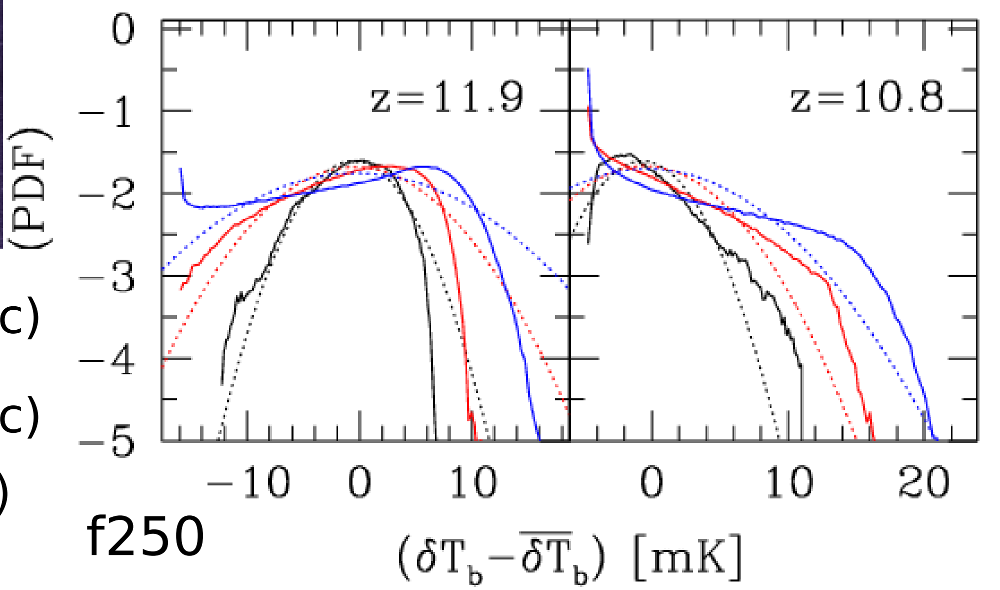
δT_{max} (3’, 0.2 MHz)

δT_{max} (6’, 0.4 MHz)



Probability Distribution Functions
(Mellema, Iliev, et al. 2006; Iliev et al. 2008a)

Distribution of δ T is highly non-Gaussian, especially at late times.



Gaussian PDF (20/h Mpc)

Gaussian PDF (10/h Mpc)

Gaussian PDF (5/h Mpc)

PDF (20 Mpc/h)

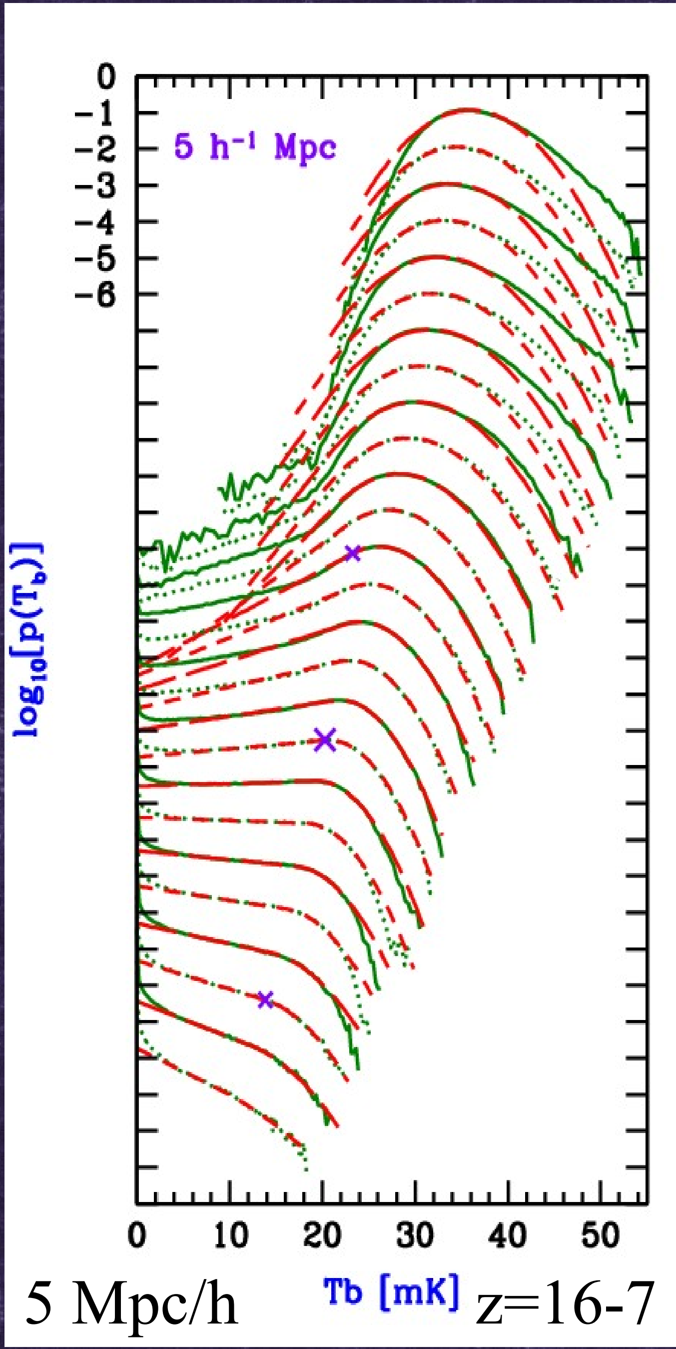
PDF (10 Mpc/h)

PDF (5 Mpc/h)

Measuring EoR History using 21-cm PDF

(Ichikawa, Barkana, Iliev, Mellema, Shapiro, submitted, arXiv/0907.2932)

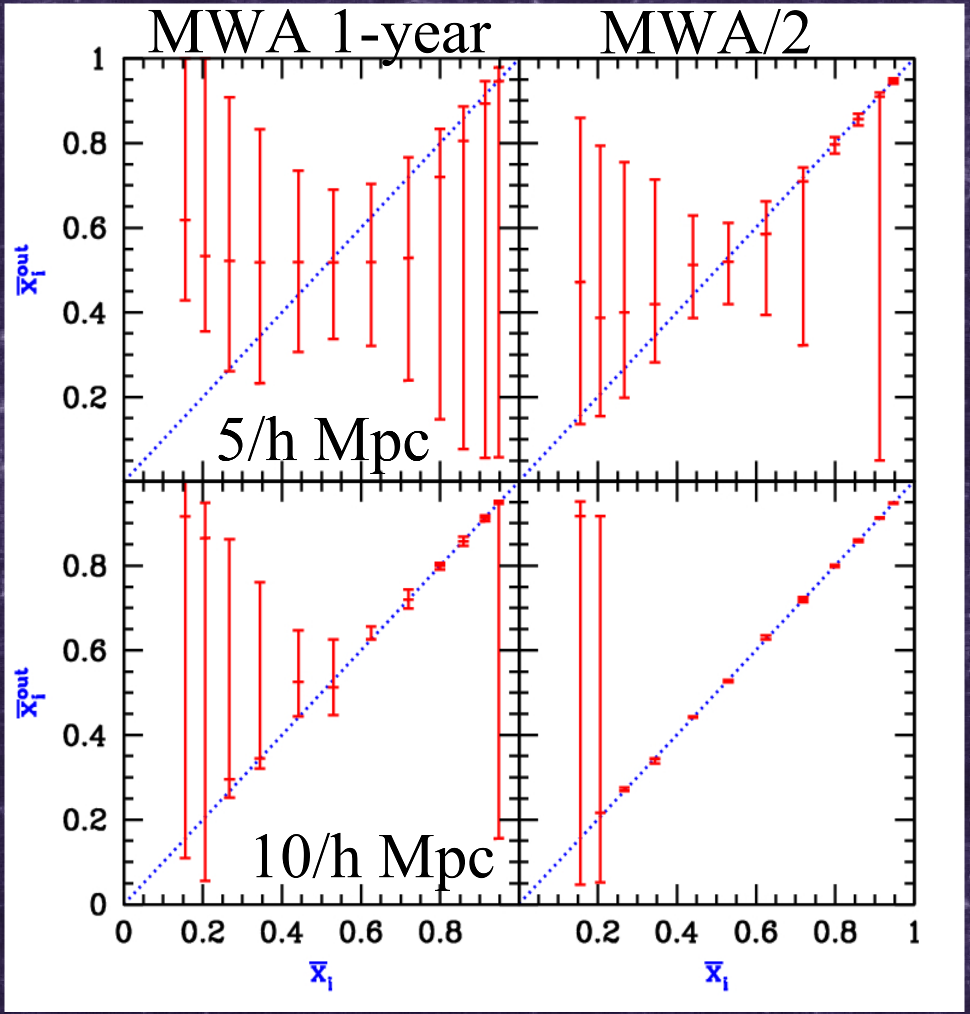
- PDFs are highly non-Gaussian.
- Intermediate PDFs (x=0.16-95) are well-fit by exp+Gaussian with 4 free parameters.



Measuring EoR History using 21-cm PDF

(Ichikawa, Barkana, Iliev, Mellema, Shapiro, submitted, arXiv/0907.2932)

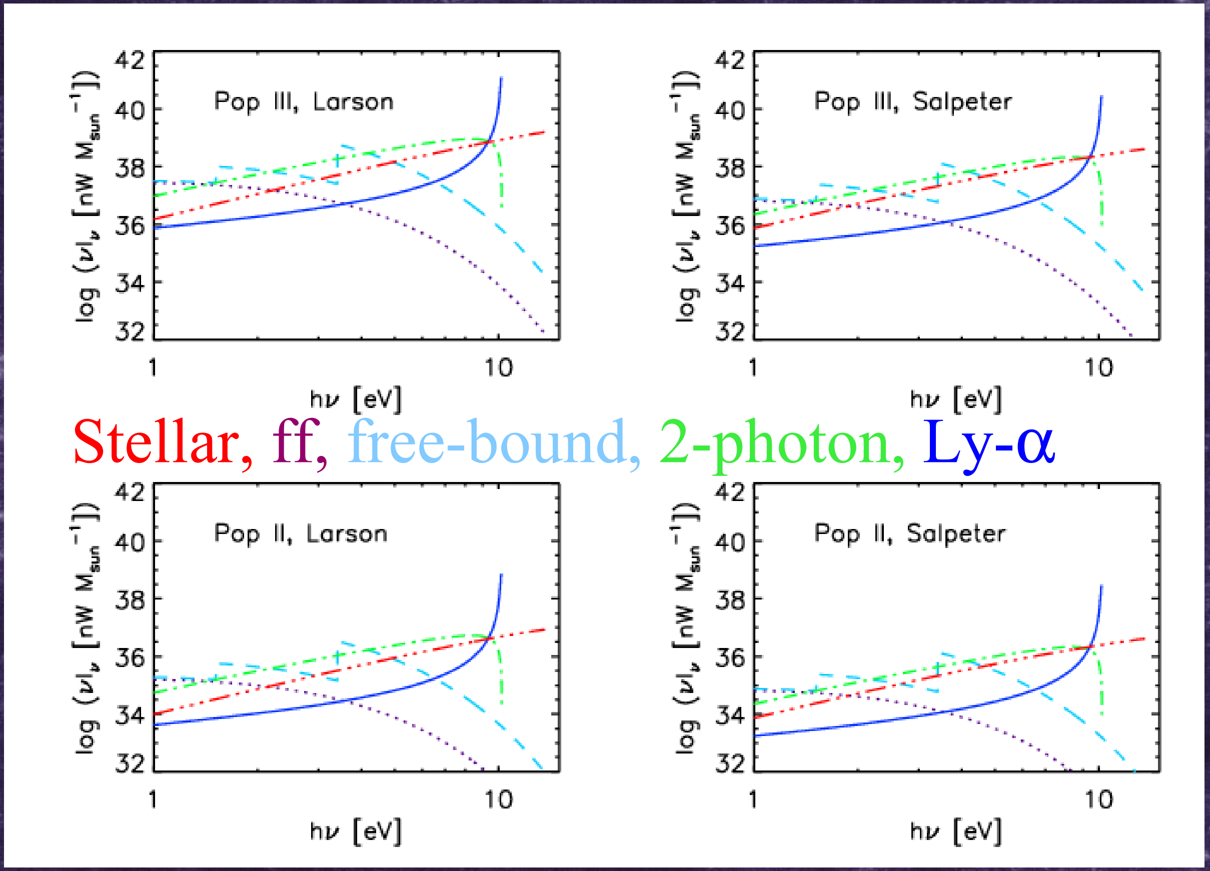
- PDF fits could be used to reconstruct the reionization history:
- E.g. assume PDFs vary with x as in simulations (1-parameter model).
- We generate N_p data points (pixels) with Gaussian noise per pixel.
- Resulting Monte-Carlo generated 'observed' PDF is compared to the model with C-statistics to find the best-fit (see paper for details).



Cosmic Infrared Background Fluctuations

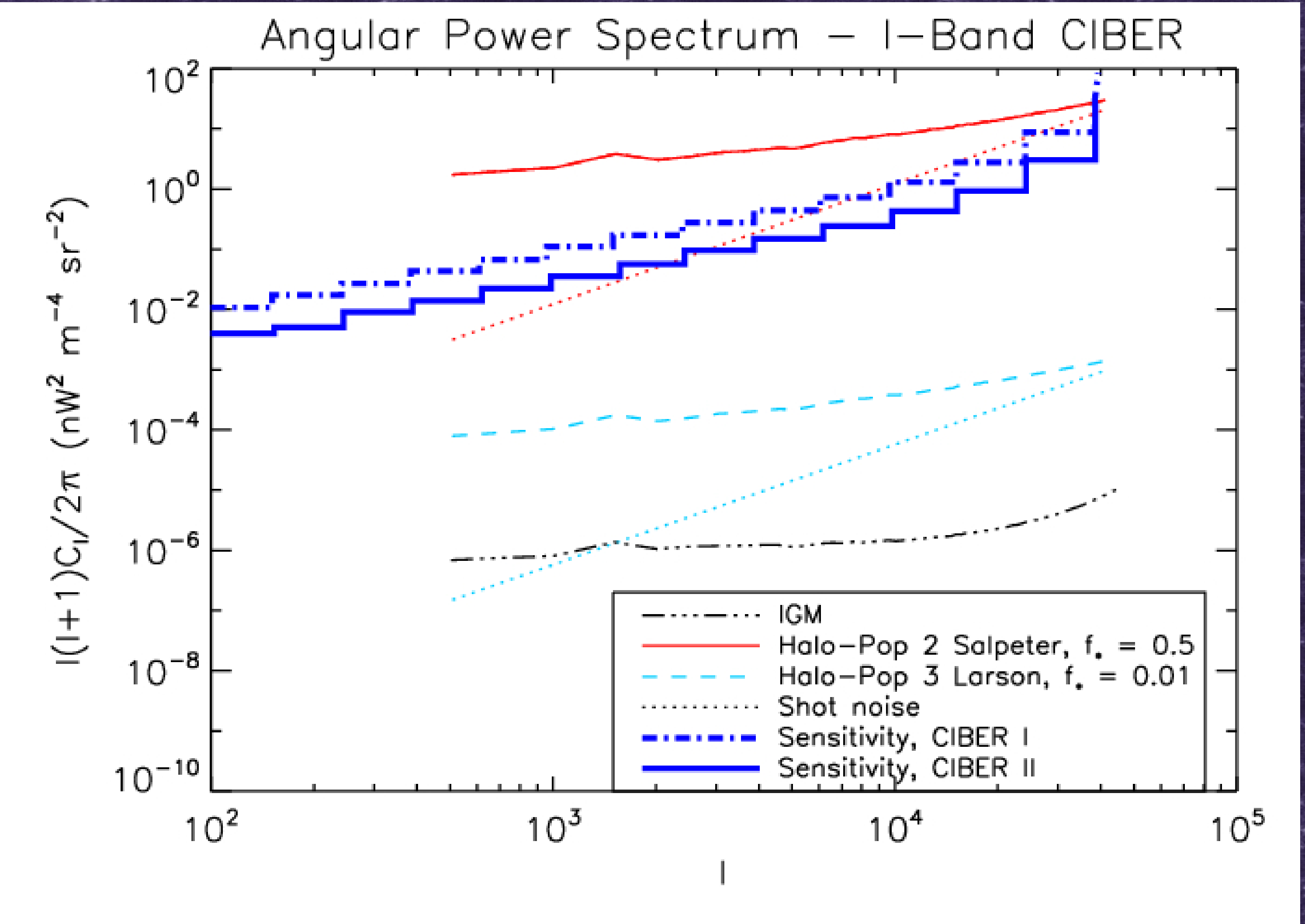
(Fernandez, Komatsu, Iliev & Shapiro, submitted, arXiv/0906.4552)

- N-body+RT data is combined with analytical model for luminosity of early structures (halos+IGM) under different assumptions for the stellar IMF, SF efficiency and escape fractions.



Cosmic Infrared Background Fluctuations: Observability

(Fernandez, Komatsu, Iliev & Shapiro, submitted, arXiv/0906.4552)



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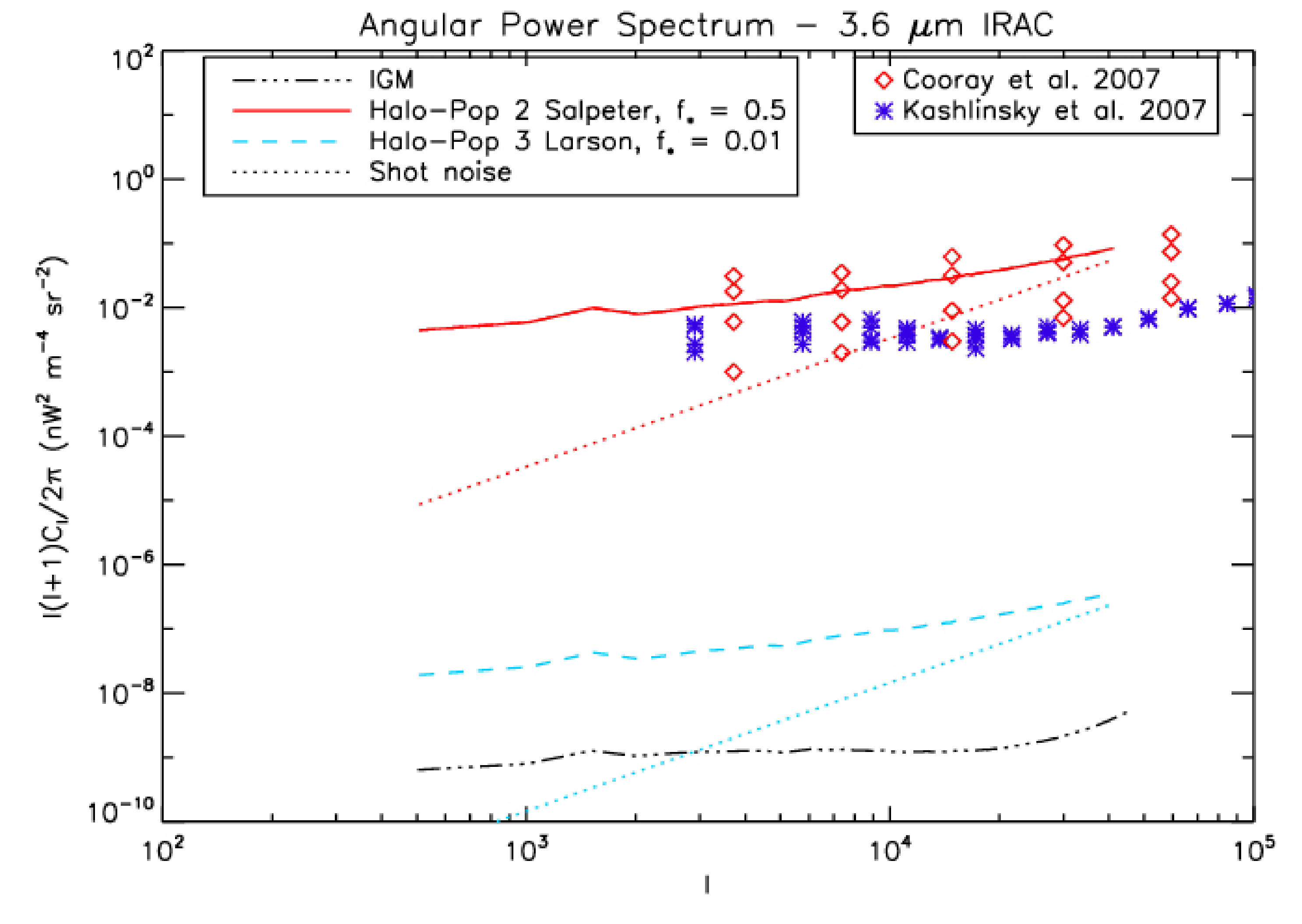
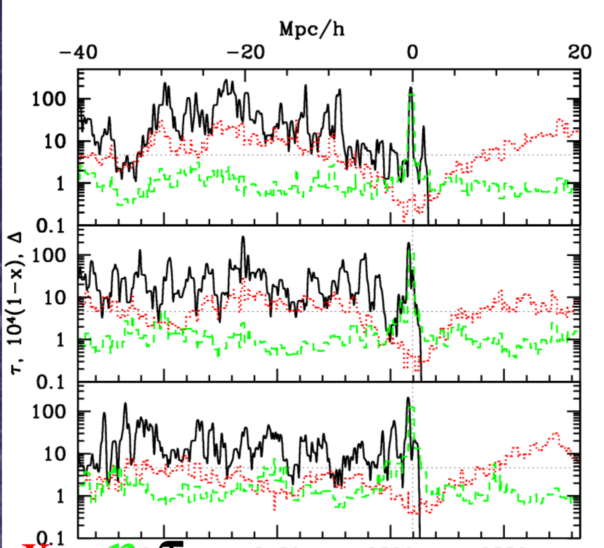
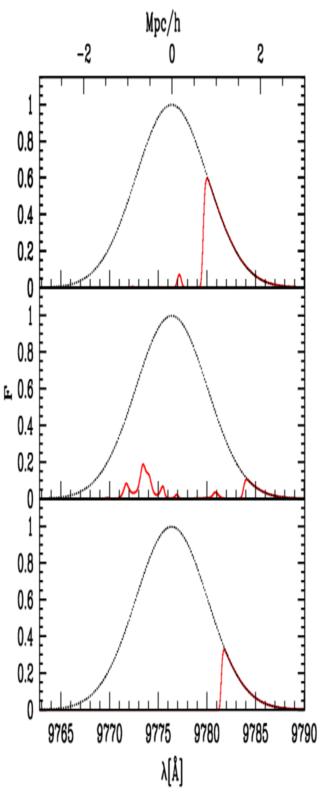


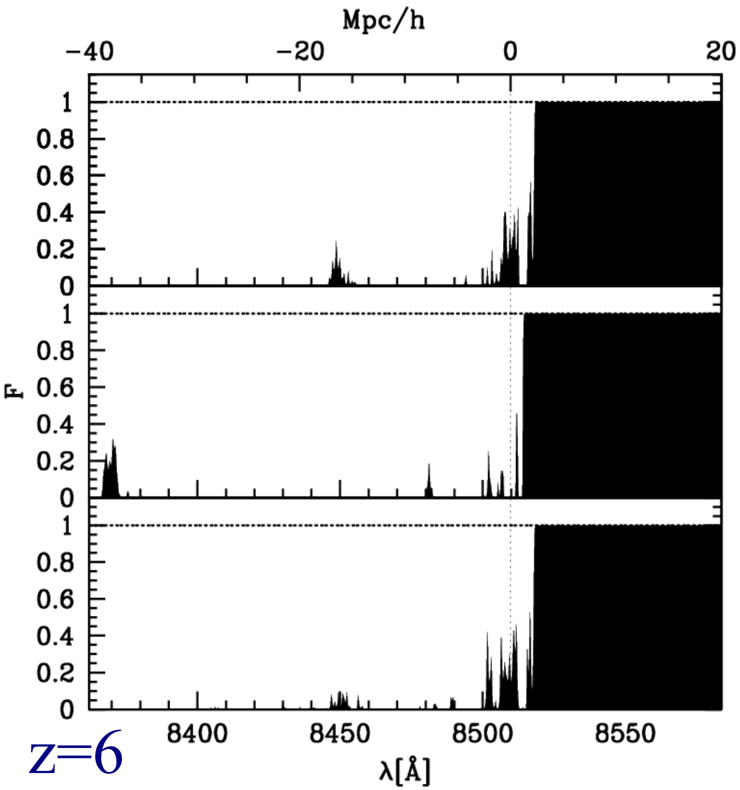
Luminous sources at the end of reionization: Ly-α spectra

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

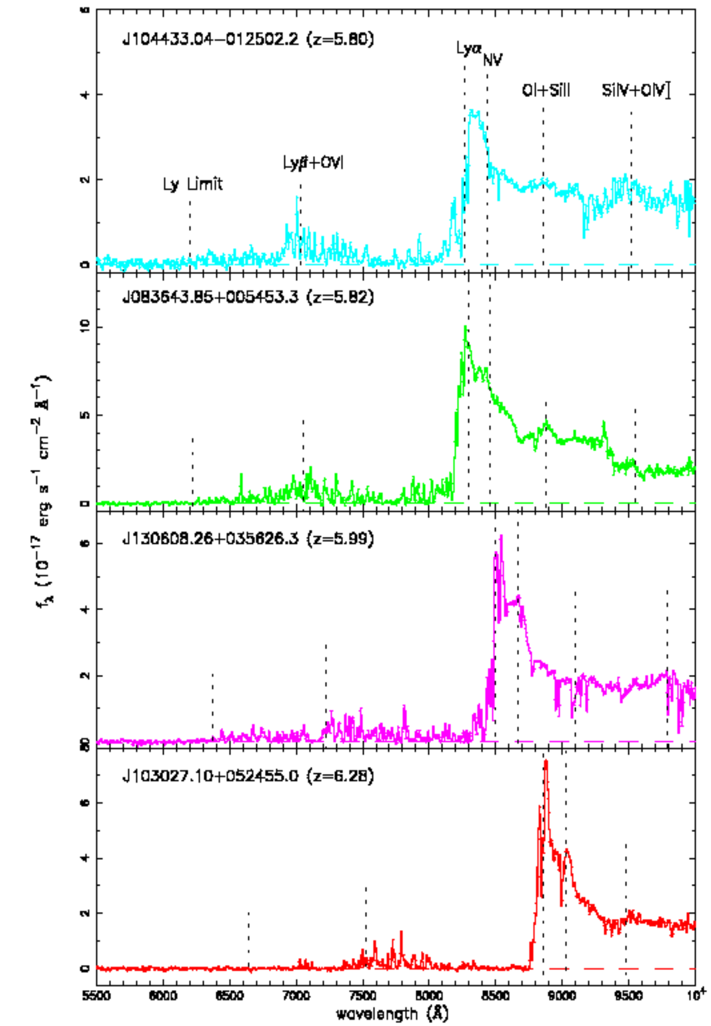


x_{HI}, n, τ





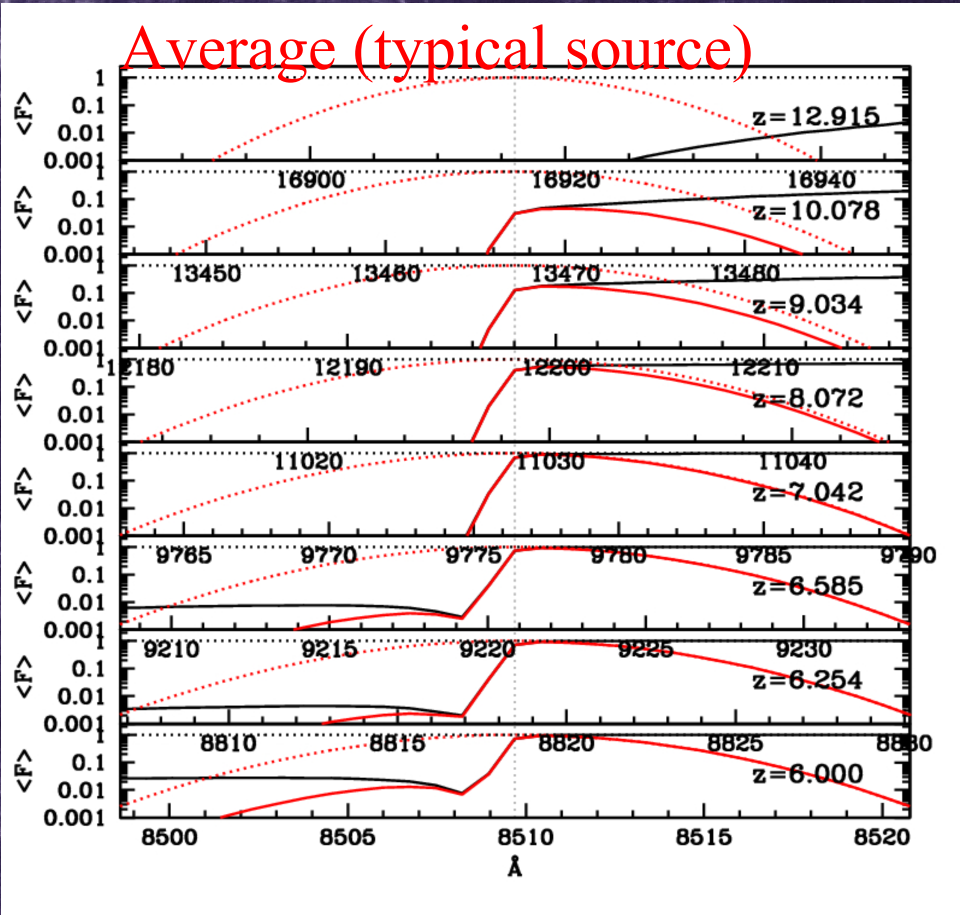
z=6

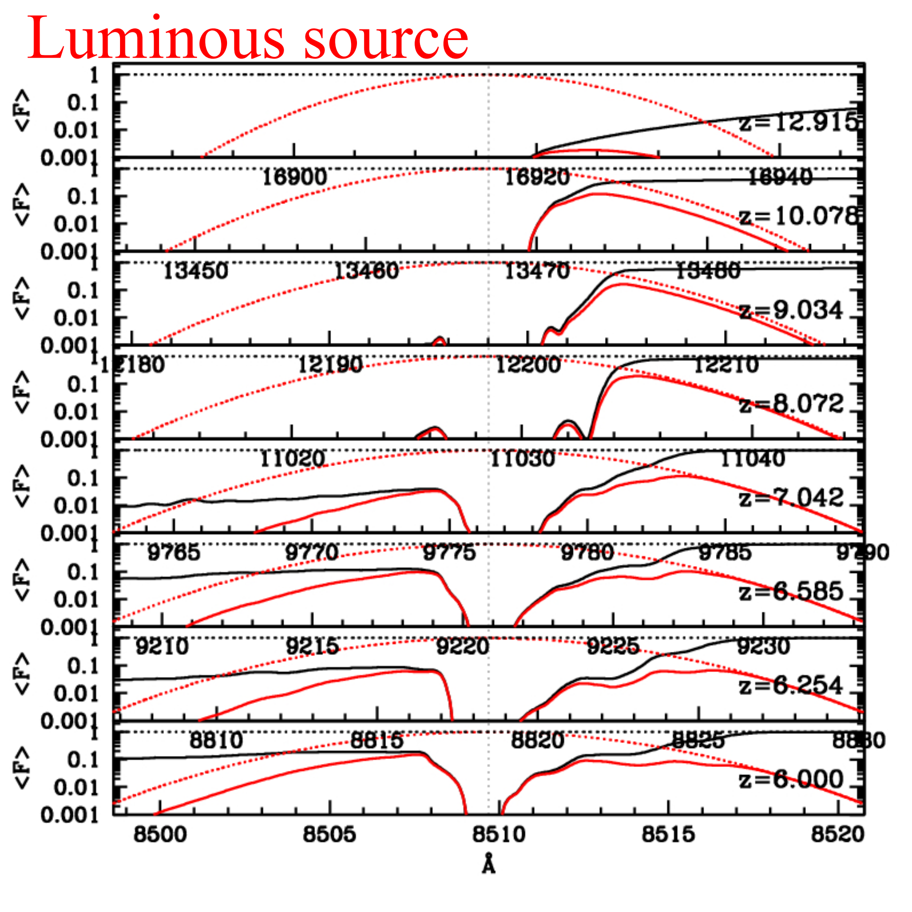


Mean Ly-α line shape vs. z

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

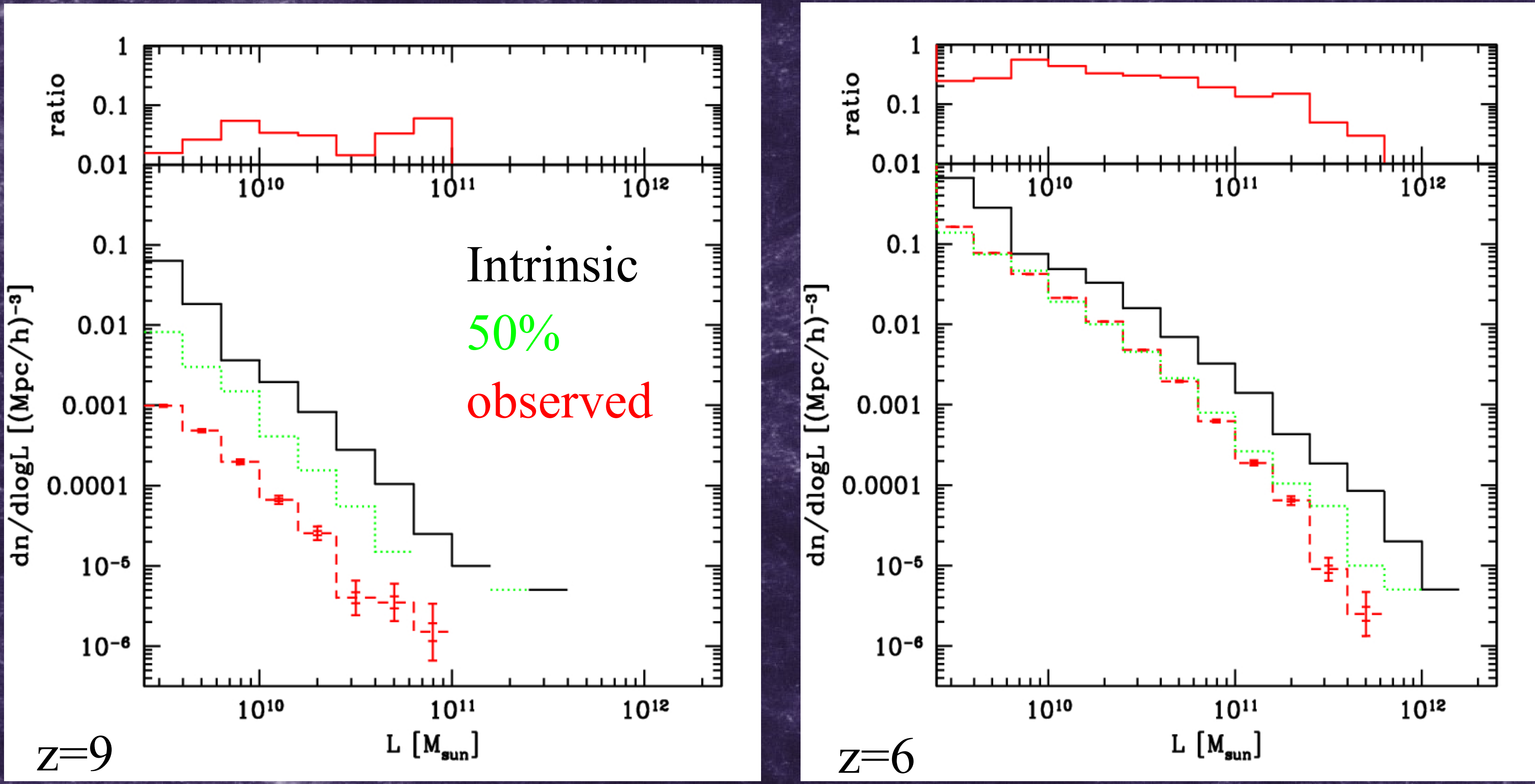
- Mostly the red wing comes through (but damped at z>10).
- Infall more important for luminous sources, changes the line shape.





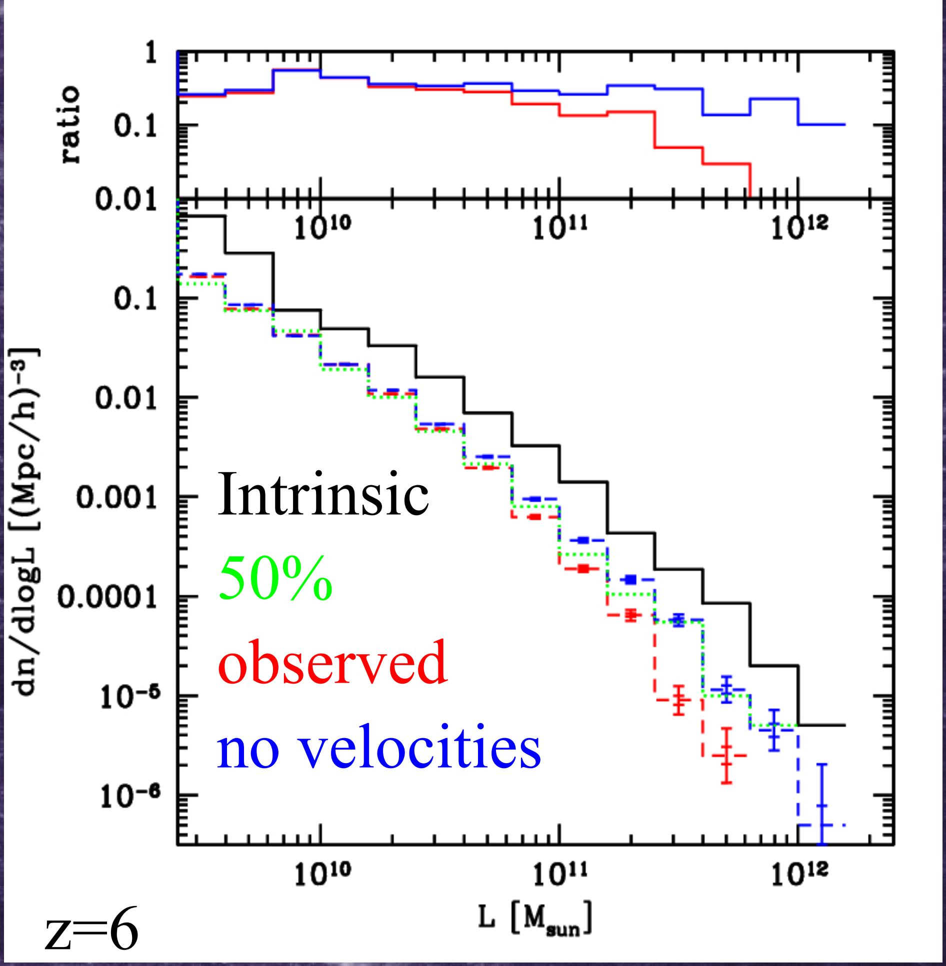
Ly-a Luminosity Functions

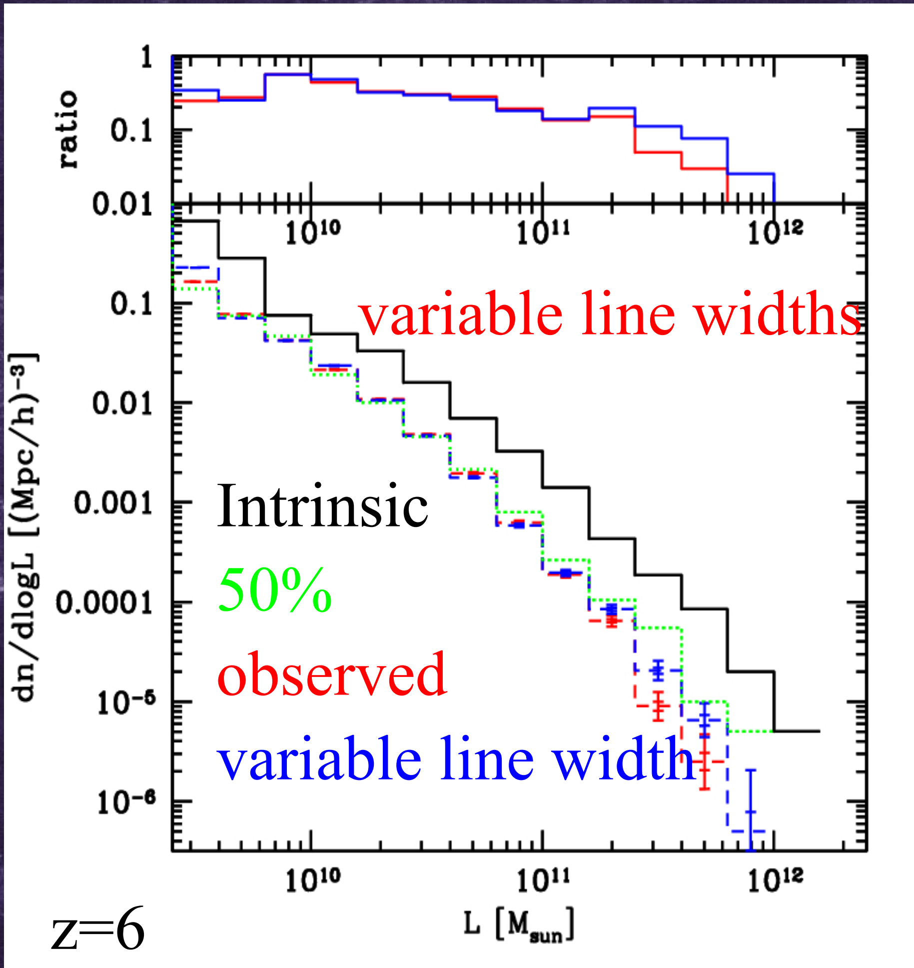
(Iliev et al. 2008, MNRAS, 391, 63)



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

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



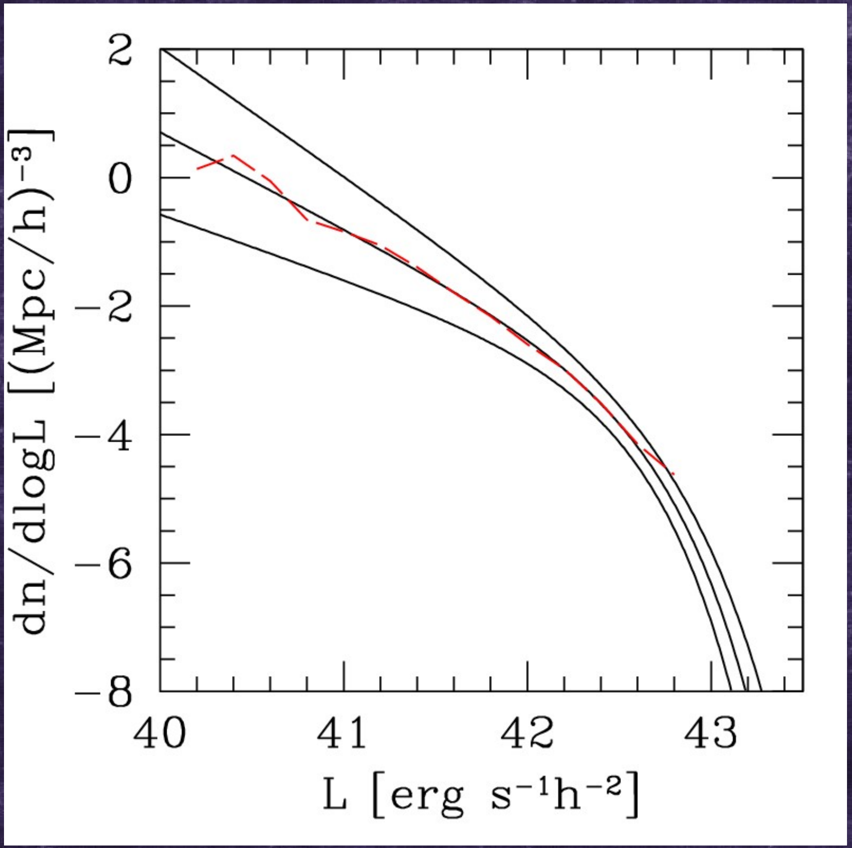


Luminosity function: simulations vs. observations

(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.

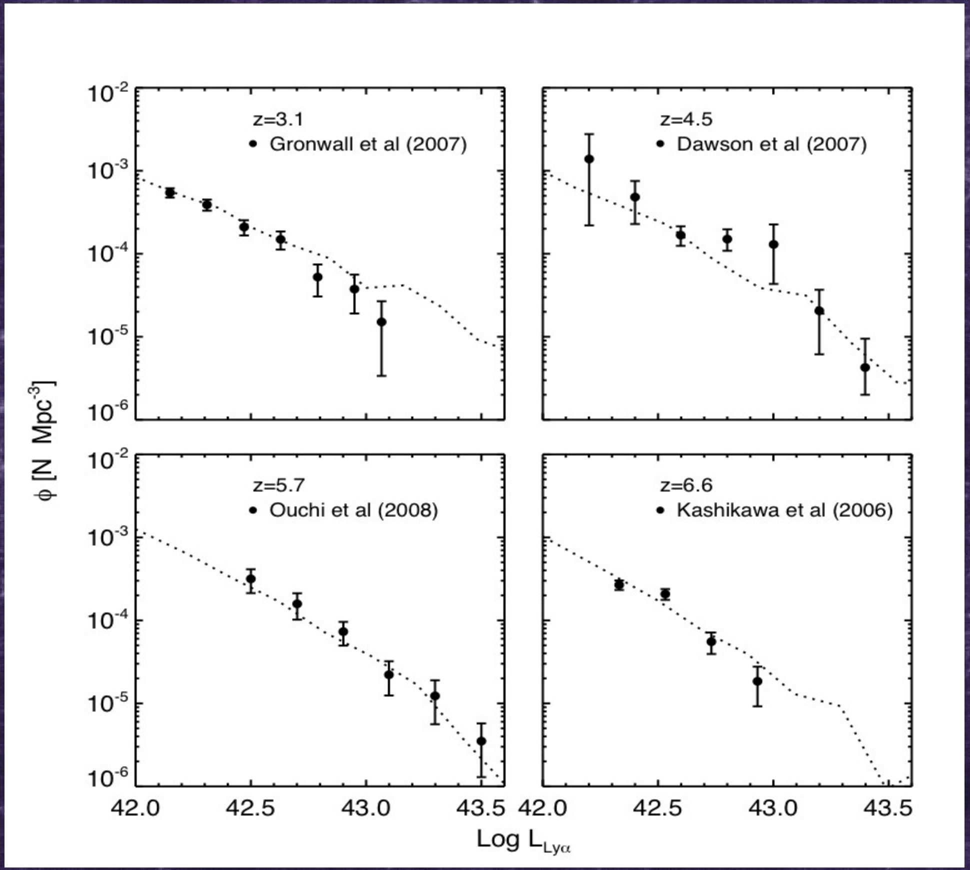
-> the majority of sources responsible for reionization are too faint to be observed at present.



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

(Tilvi, Malhotra, Rhoads, Scannapieco, Thacker, Iliev & Mellema, 2008, submitted, arXiv/0906.5159)

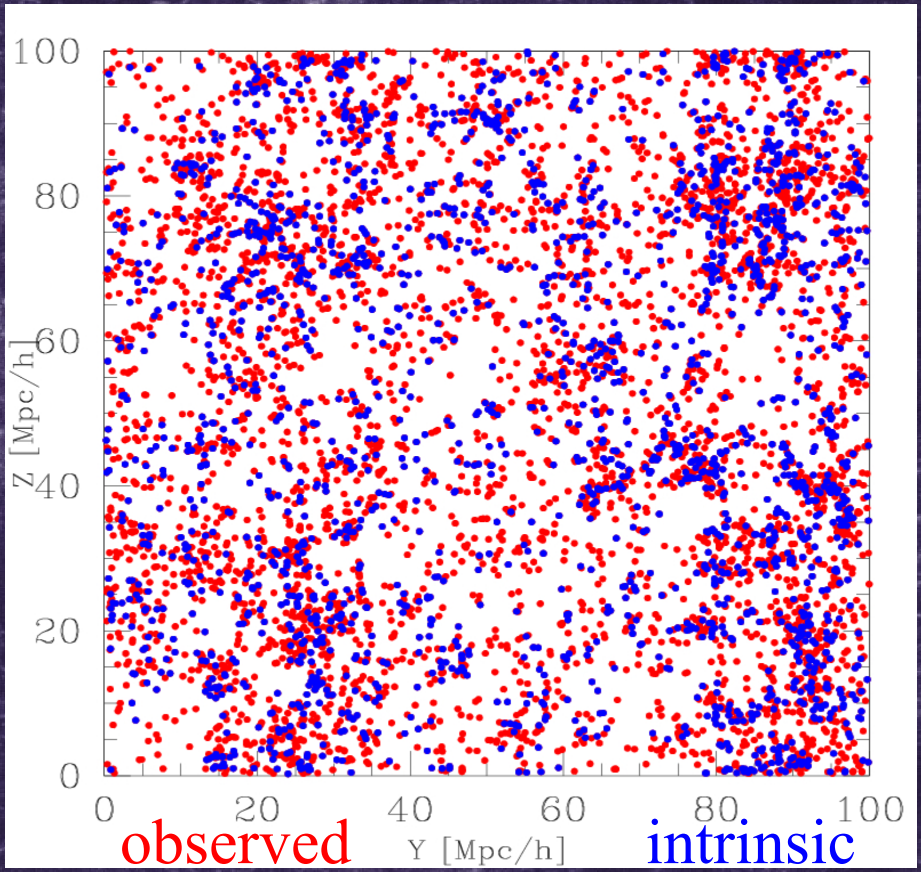
- A simple, 1-parameter model.
- Based on assumption that Ly-a luminosity is proportional to halo mass growth.
- Matches well the Ly-a LF data at z=3-6.6.
- Introduces naturally a duty cycle.
- Source clustering agrees well with observed one.

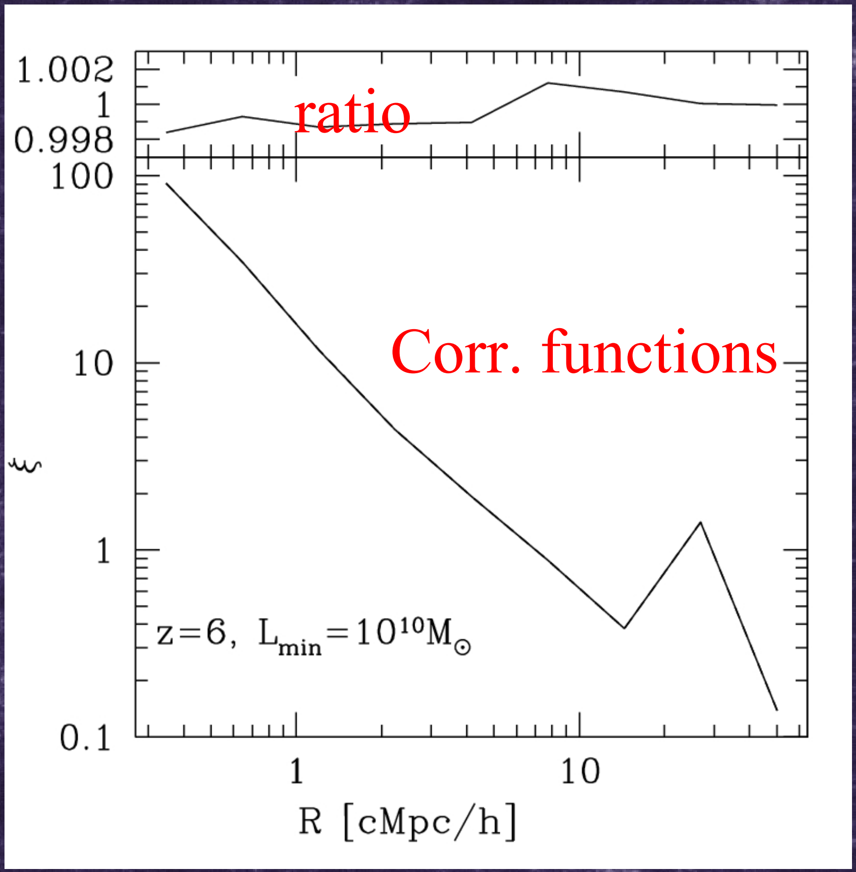


For more details see paper.

Correlation functions of Ly-α sources

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



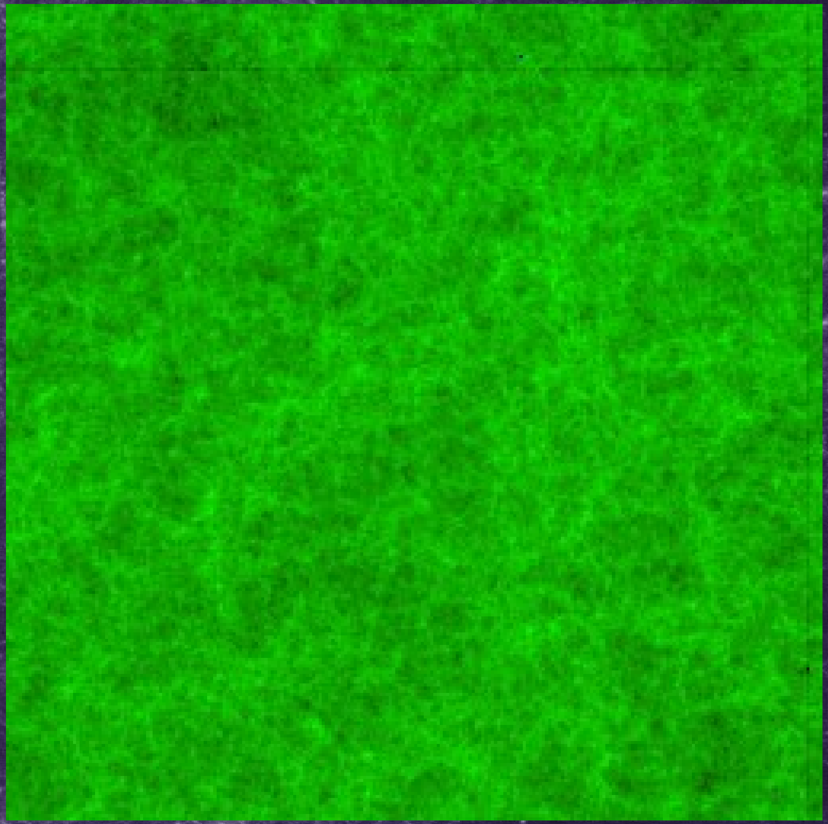


For a given (e.g. observed) number density of sources their clustering is largely unaffected by reionization patchiness (max 10% difference at small scales and at high-z, decreasing later).

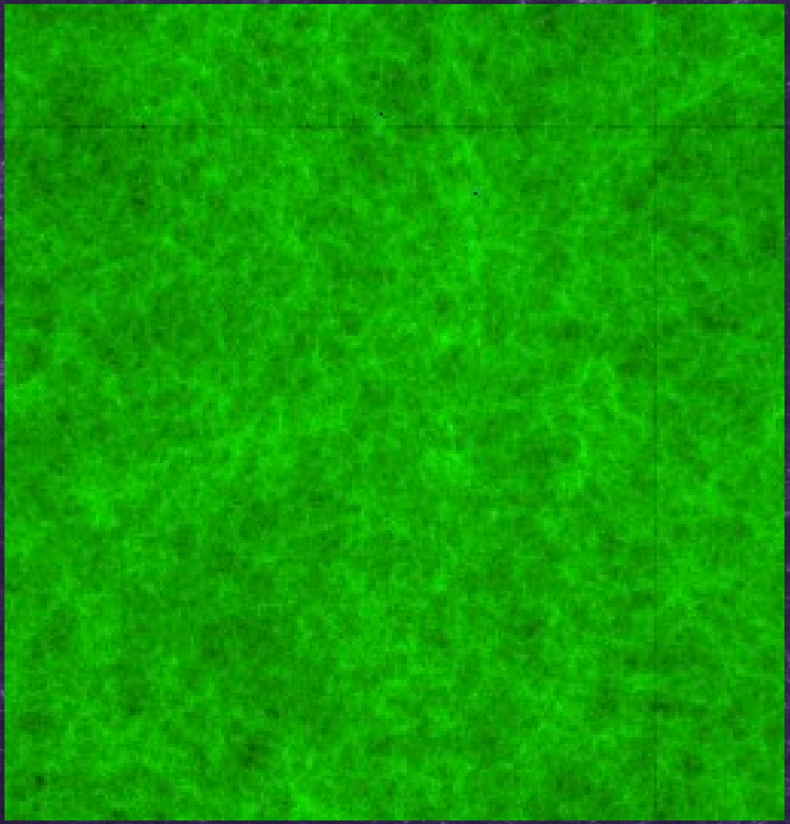
Reionization of the Local Group

(w/B. Moore, G. Yepes, S Goettlober, Y. Hoffman, 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 method.

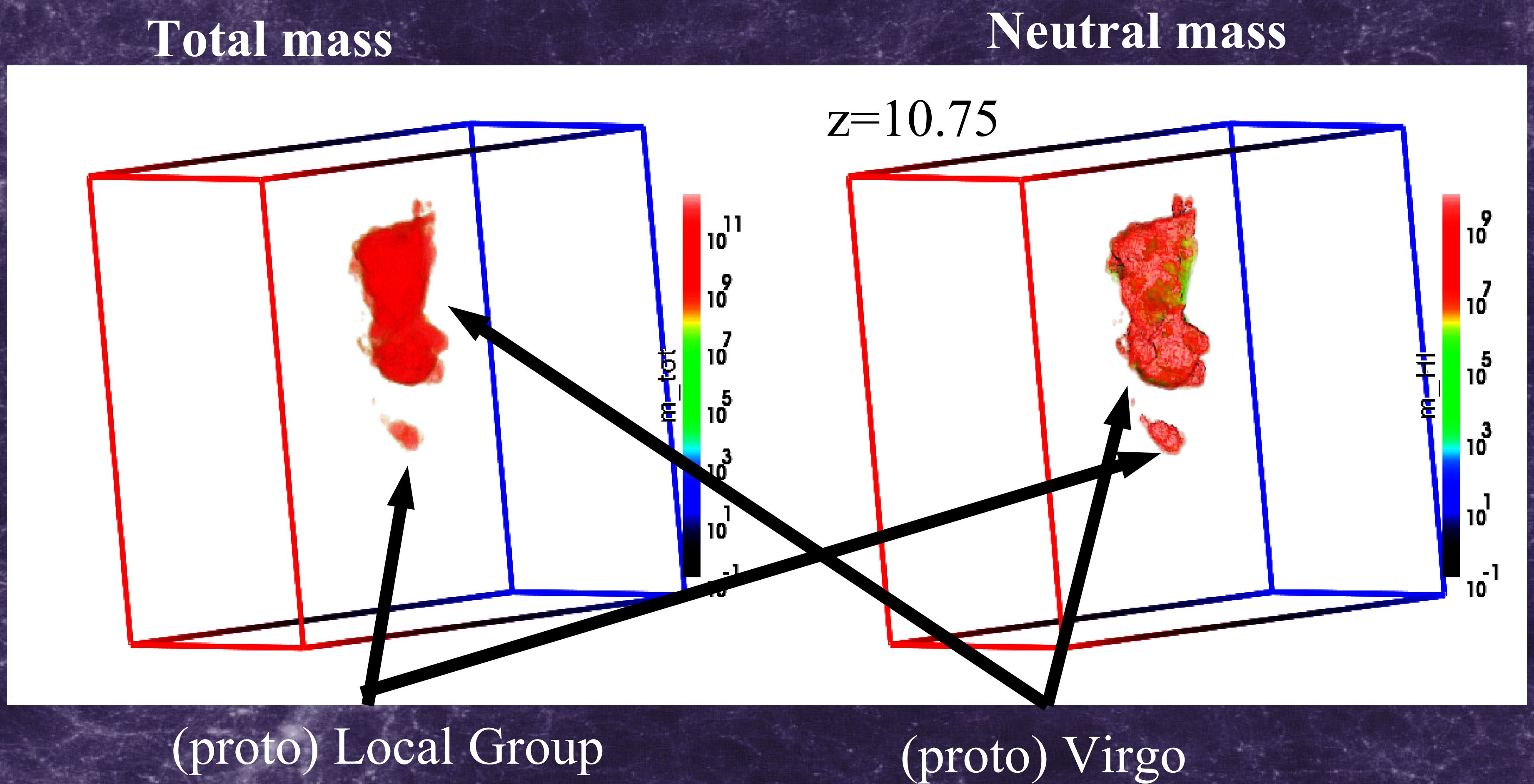


Milky Way

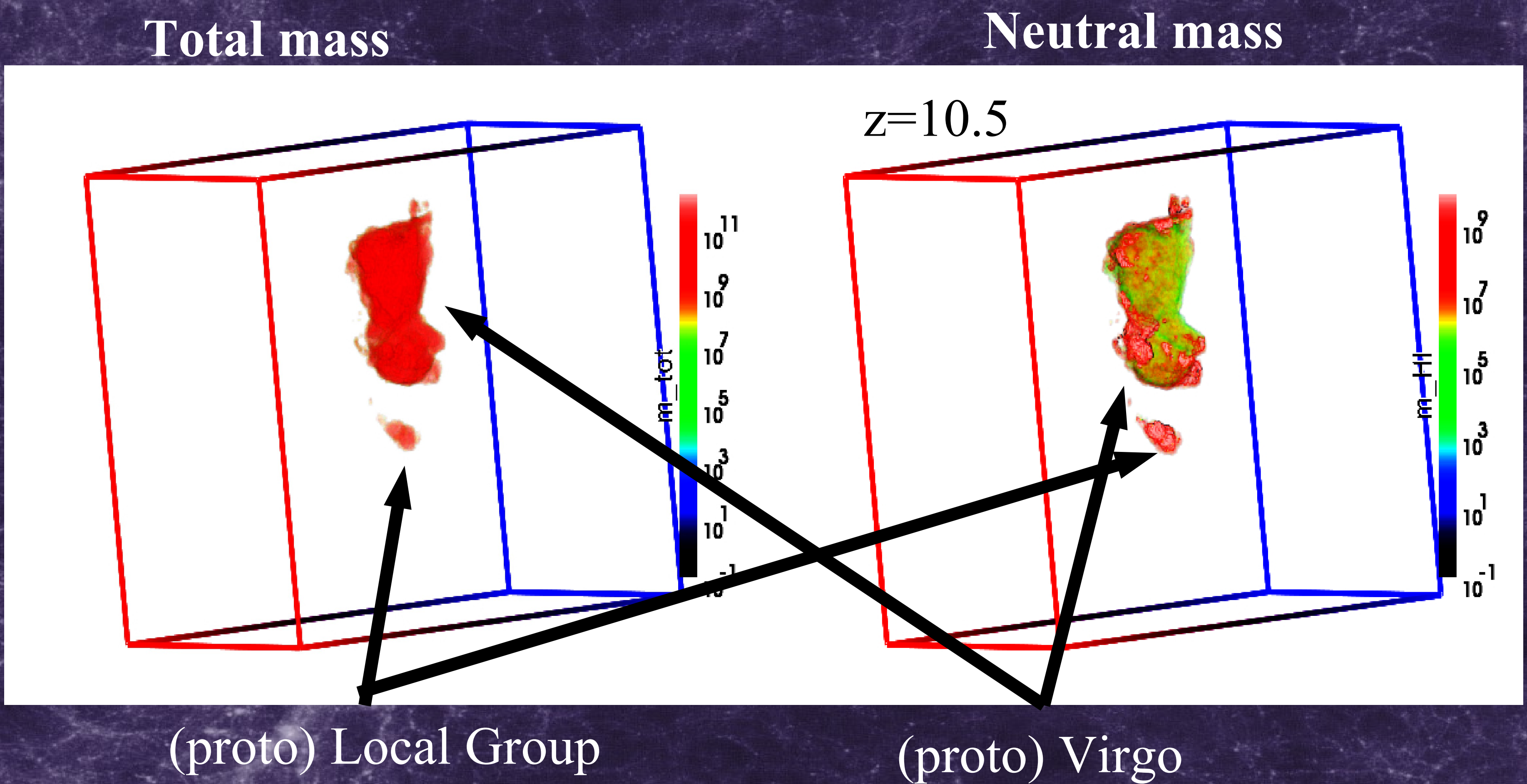


Virgo

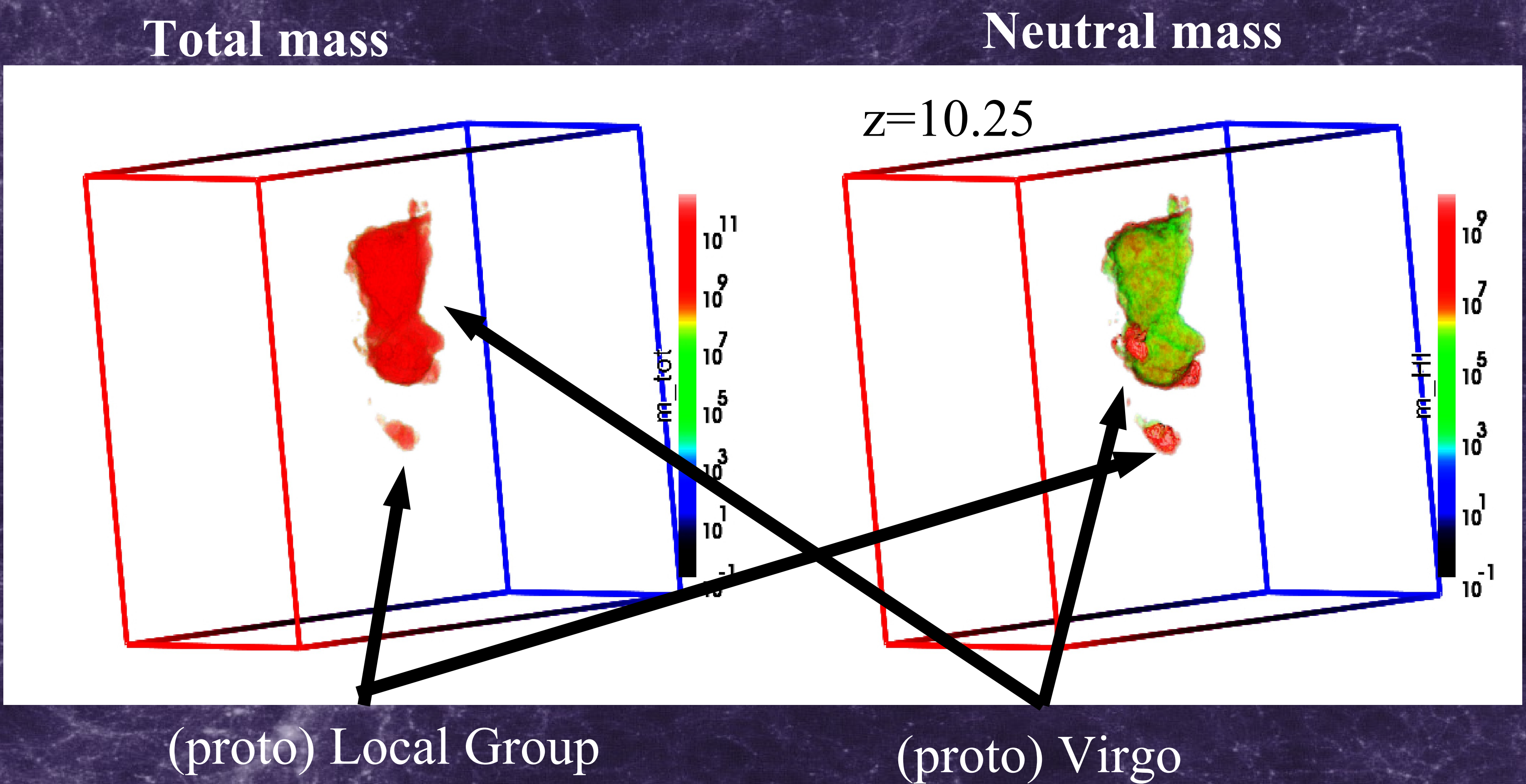
Reionization of the Local Group: the evolution



Reionization of the Local Group: the evolution

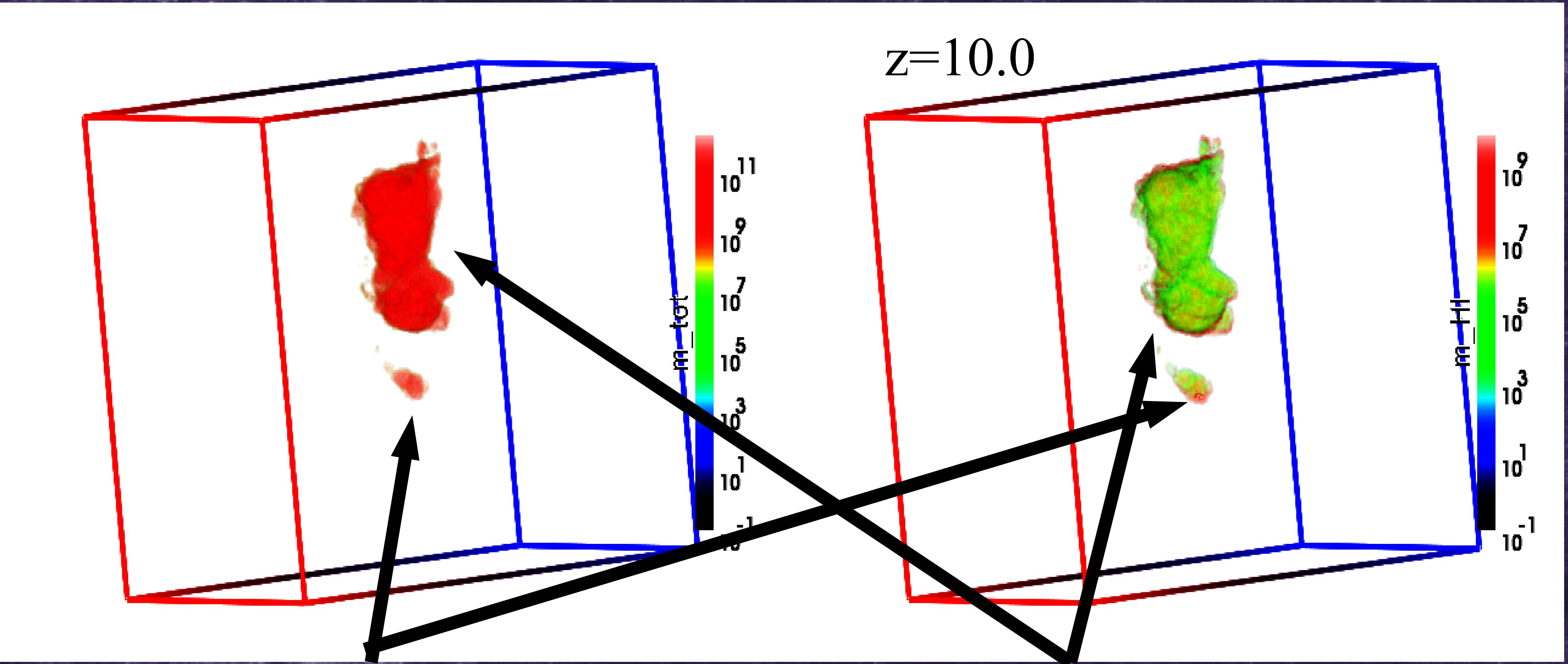


Reionization of the Local Group: the evolution



Reionization of the Local Group: the evolution

Total mass **Neutral mass**

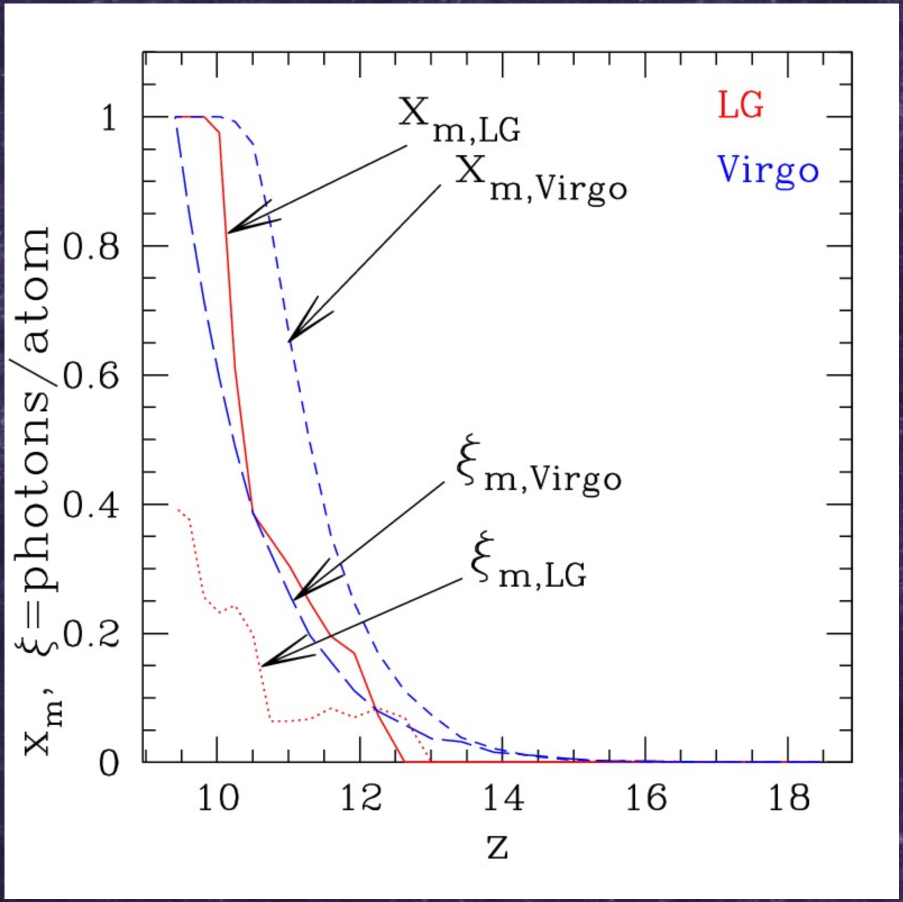


(proto) Local Group

(proto) Virgo

Reionization of the Local Group: the Photon Budget

- Both (pre-)LG and Virgo reionize at z~10.
- At the time of LG reionization internal sources have produced just ~0.2 ionizing photons/atom => mostly external reionization
- Virgo constituents have produced ~0.6 photons/atom by z~10 and 1 photon/atom by z~9.5, i.e. its reionization is primarily, but not completely, internal



Thank you for your attention!

Time for questions...