High-z cosmological structure formation and reionization

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with

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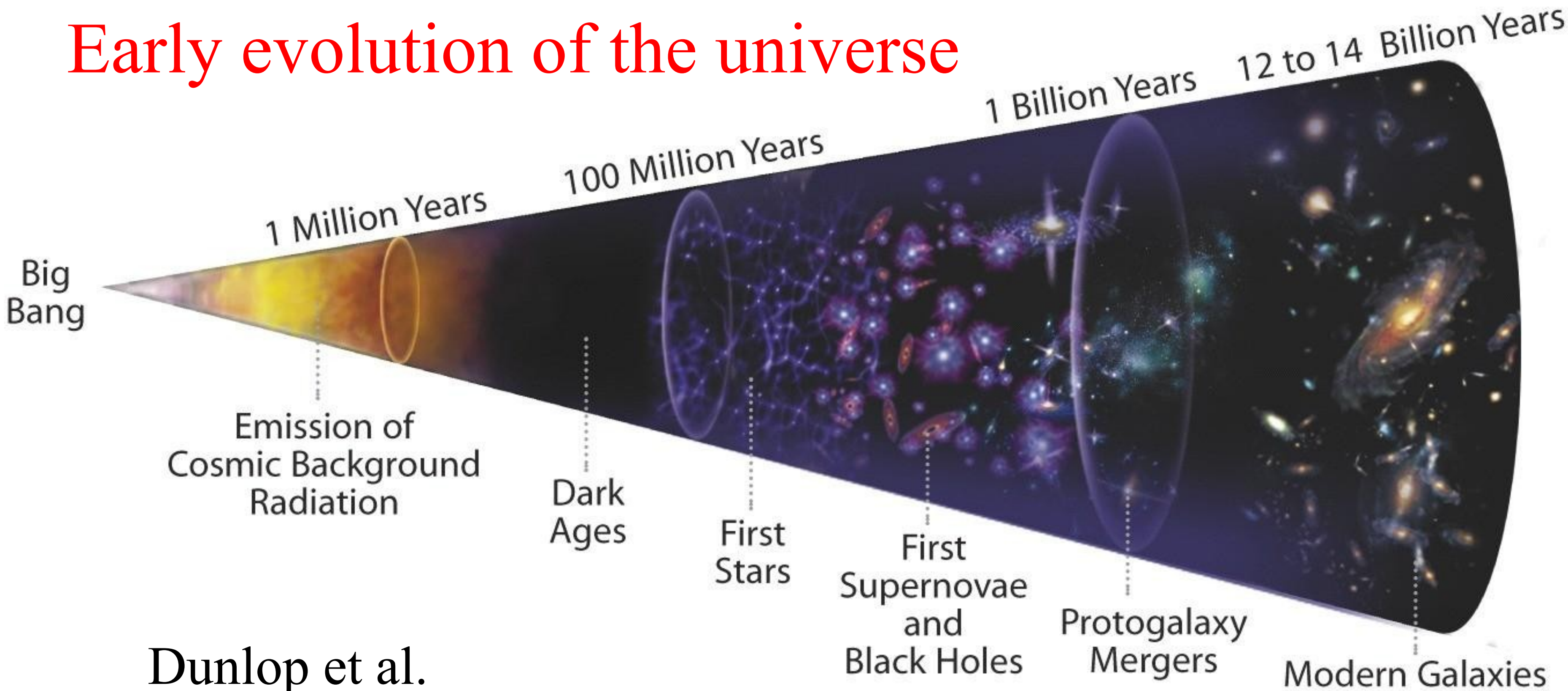
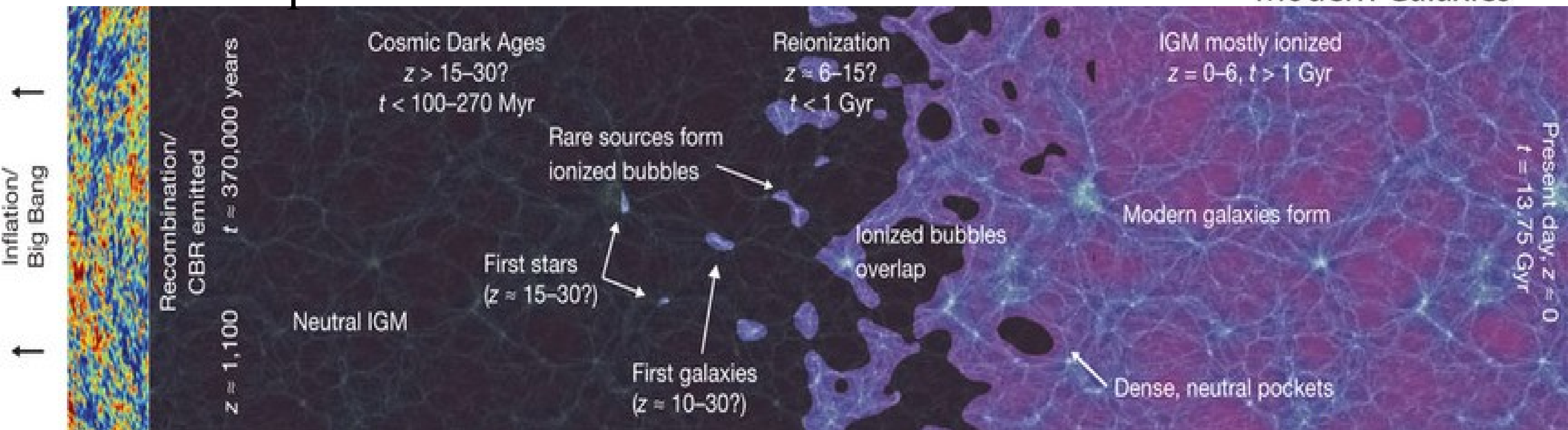
Early evolution of the universe



Dunlop et al.

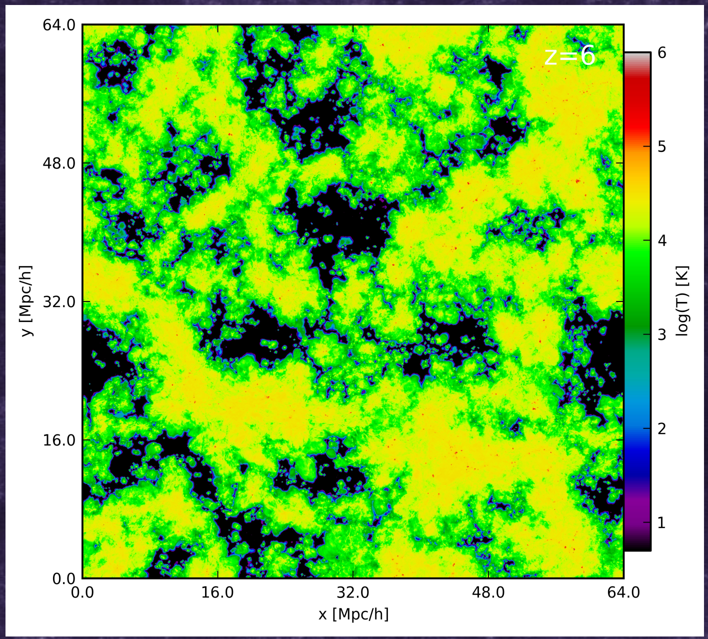


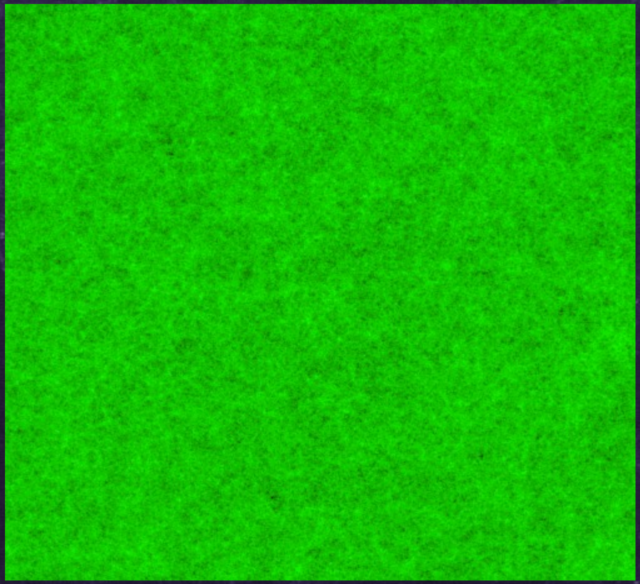
Progress of reionization: 3D view

The Program

- INCITE (DOE), PRACE:
- Cosmological radiative hydro
- 40M +3.5M core-h, CPU+GPU
- 64 Mpc/h, constrained realiz.
- 4096^3 grid, 4096^^{3} particles
- Goals: detailed modelling of gas effects; LG reionization

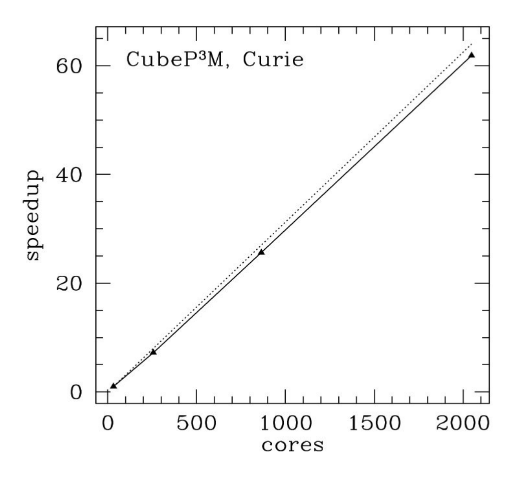
- PRACE (Tier-0, Tier-1): PRACE4LOFAR and LocalUniverse projects
- N-body+RT
- 26M+22M+11M core-h
- 6.3Mpc/h-500 Mpc/h
- 1728^3-6912^3 particles
- Goals: Large-scale EoR, LOFAR models, param. studies

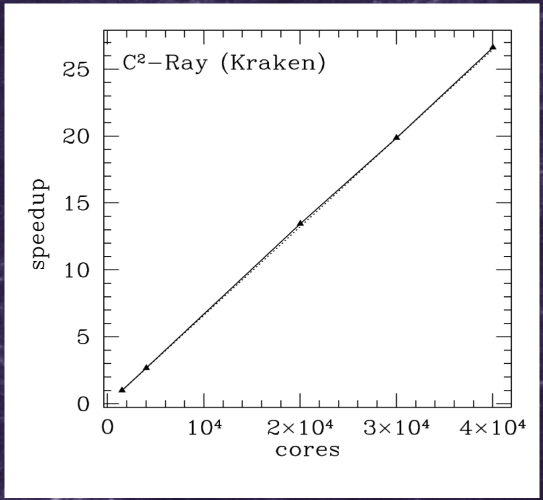


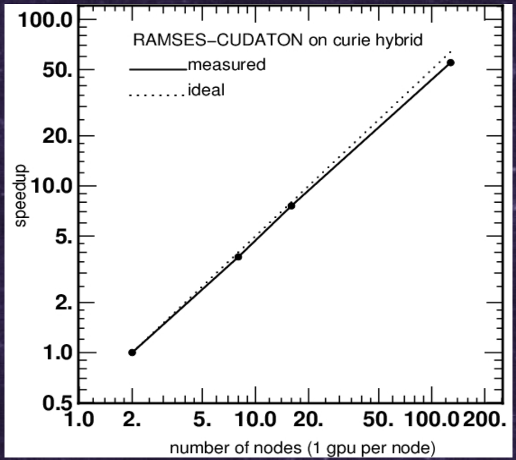


Codes scaling

(Iliev et al. 2012, Harnois-Deraps et al. 2012, Ocvirk et al., in prep.)







- N-body
- Scales to 27k+ cores

- RT (ray tracing)
- Scales to 40k+ cores

- N-body radiative hydro (CPU+GPU)
- Scales to 132k+ cores & 8192 GPUs

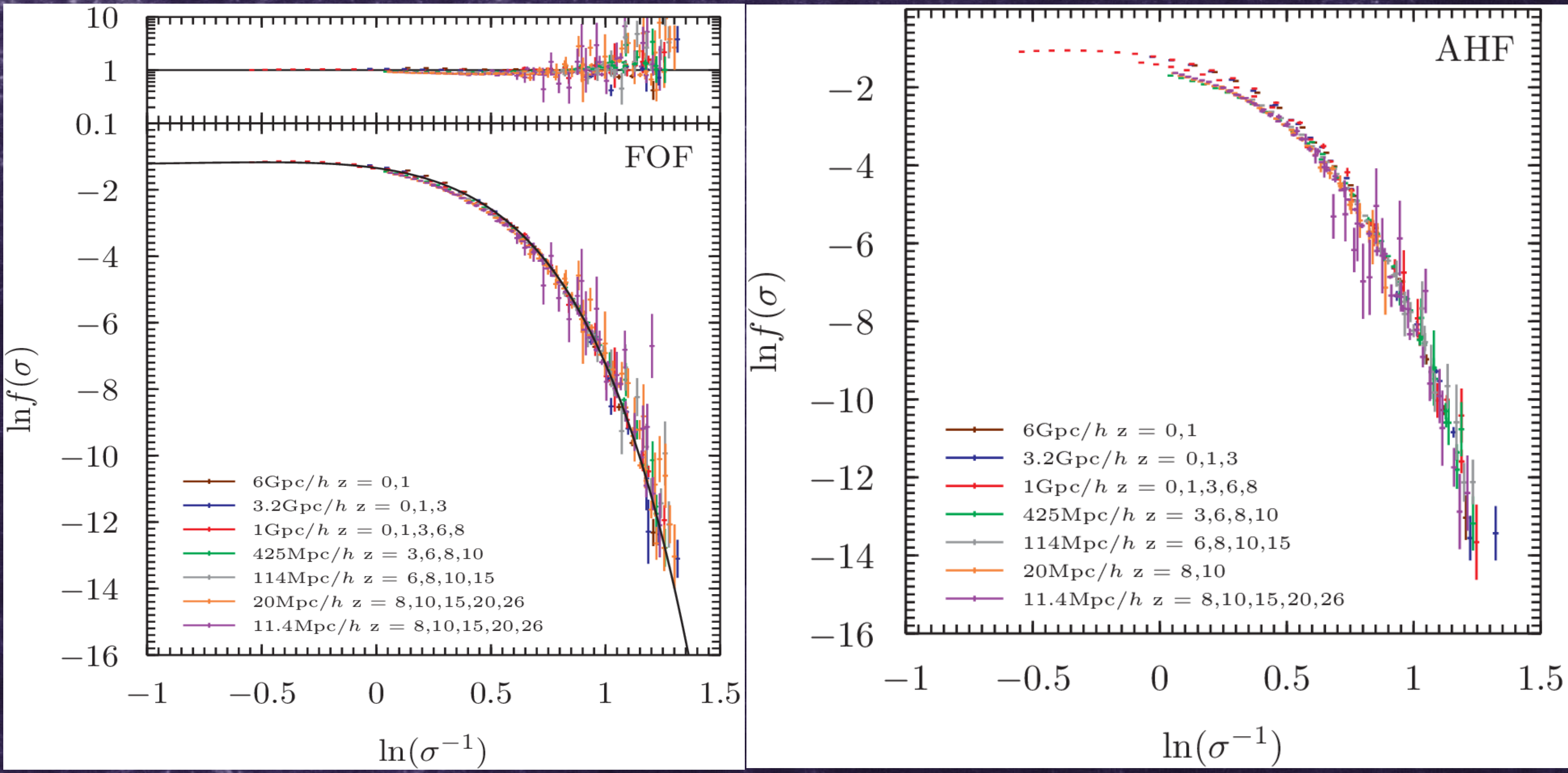
N-body simulations

Box Size h^{-1}Mpc	N_{part}	Mesh	Resolution h^{-1}kpc	$m_{particle}$ $h^{-1}M_\odot$	$M_{halo,min}$ $h^{-1}M_\odot$	z_{in}
11.4	3072^3	6144^3	0.18	3.63×10^3	7.63×10^4	300
20	5488^3	10976^3	0.18	3.63×10^3	7.63×10^4	300
114	3072^3	6144^3	1.86	3.83×10^6	7.63×10^7	300
425	5488^3	10976^3	3.87	3.69×10^7	7.35×10^8	300
1000	3456^3	6912^3	14.47	1.96×10^9	3.85×10^{10}	150
3200	4000^3	8000^3	40.00	4.06×10^{10}	8.12×10^{11}	120
6000	6000^3	12000^3	50.00	7.49×10^{10}	1.50×10^{12}	100
500	6912^3	13824^3	~2	~4e7	1e9	150

- WMAP 5 Cosmology ($\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$)
- CUBEP^{3}M Code (Harnois-Deraps et al 2013)
- Runs done at TACC, Texas (Ranger) and Juelich, Germany (Juropa)
- Newer runs and tests done on PRACE Petascale facilities Curie (France) and SuperMUC (Germany)

Halo mass function through the cosmic ages

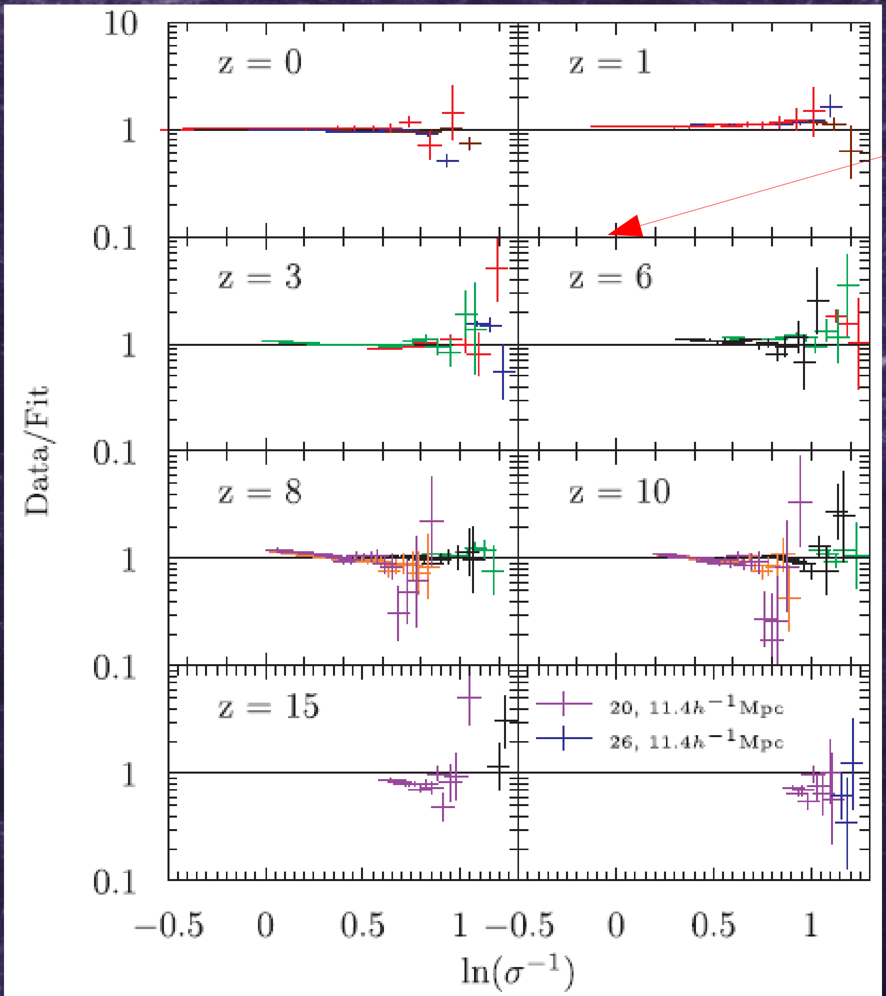
(Watson et al., 2013a, MNRAS,433,1230)



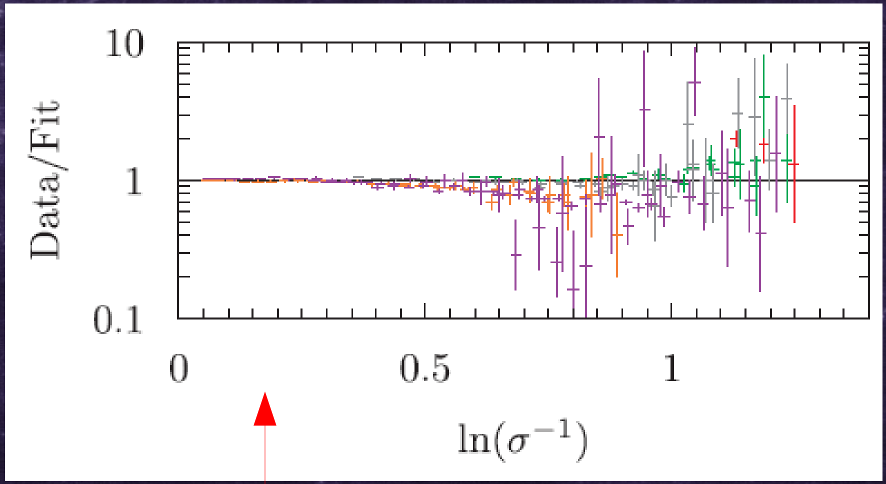
FOF: universal shape SO: redshift- and Ω-dependent

Accurate MF fits provided in paper, both over all z's and for high-z.

Halo mass function through the cosmic ages
(Watson et al., 2013, MNRAS,433,1230)



- Derived fits match data well from very high-z to the present (0<z<26).

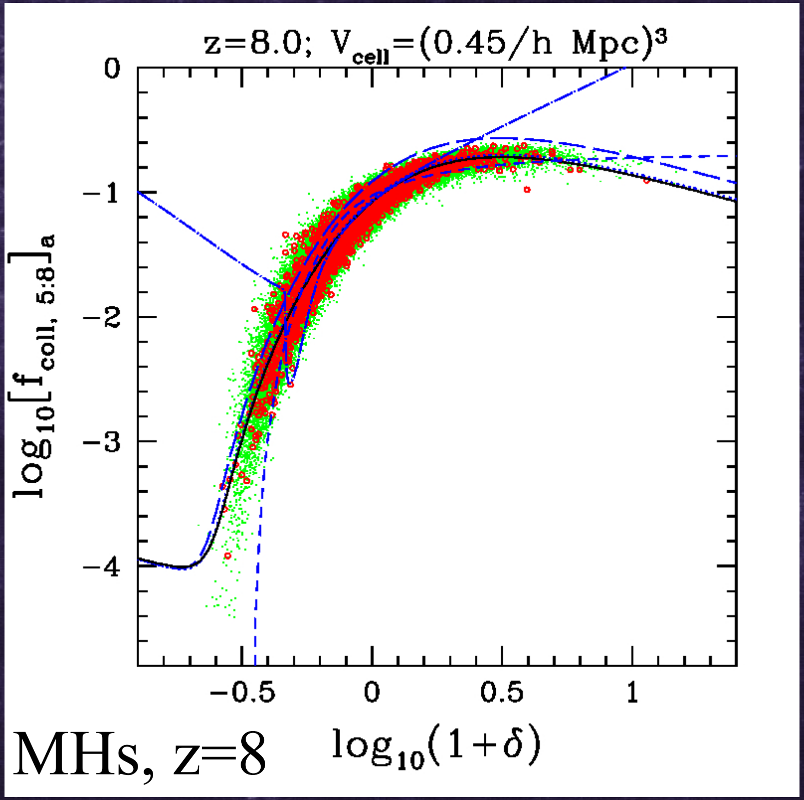


- Separate fits provided for high-z (6<z<26).

Modelling the small-scales

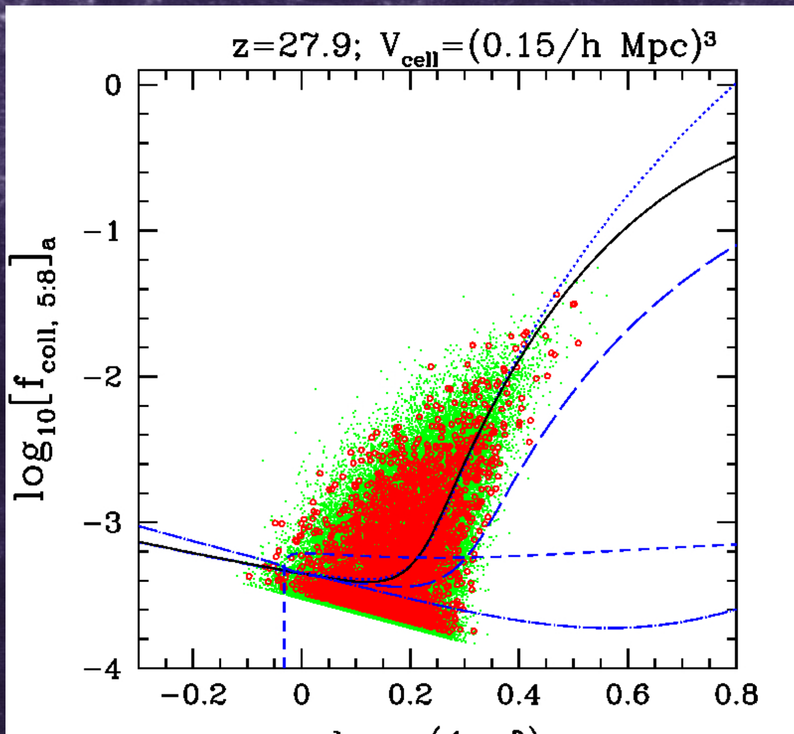
(Ahn et al., submitted; Koda et al., in prep.; Shukla, Mellema & Iliev, in prep.)

- The vast range of relevant structure formation scales require sub-grid modelling.
- Fits based on very high-resolution simulations and observational data + theoretical models used:
  - Local halo mass function and bias
  - Local gas clumping
  - LLS absorbers

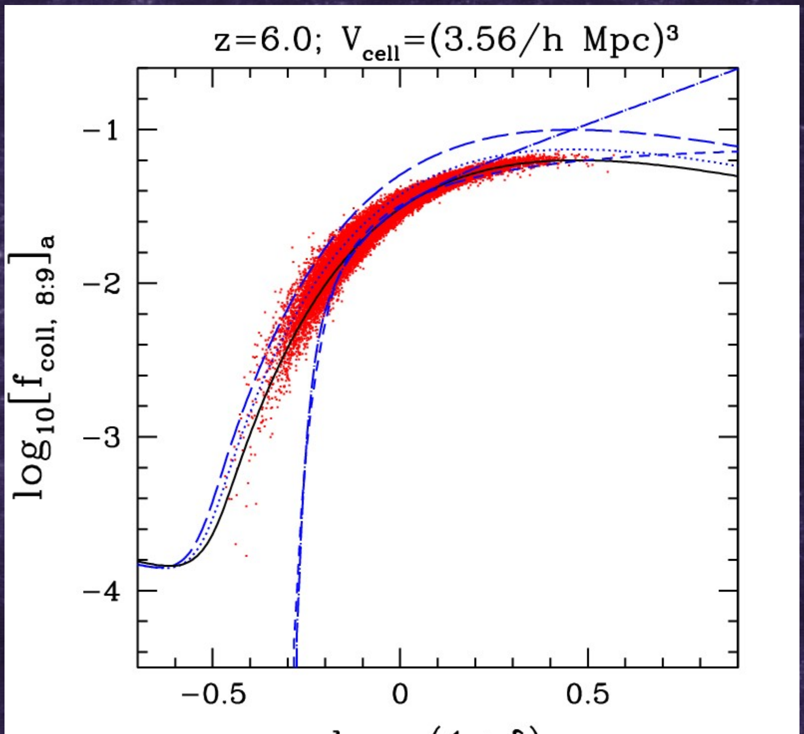


Modelling the small-scales

(Ahn et al., submitted)



MHs, z=27.9



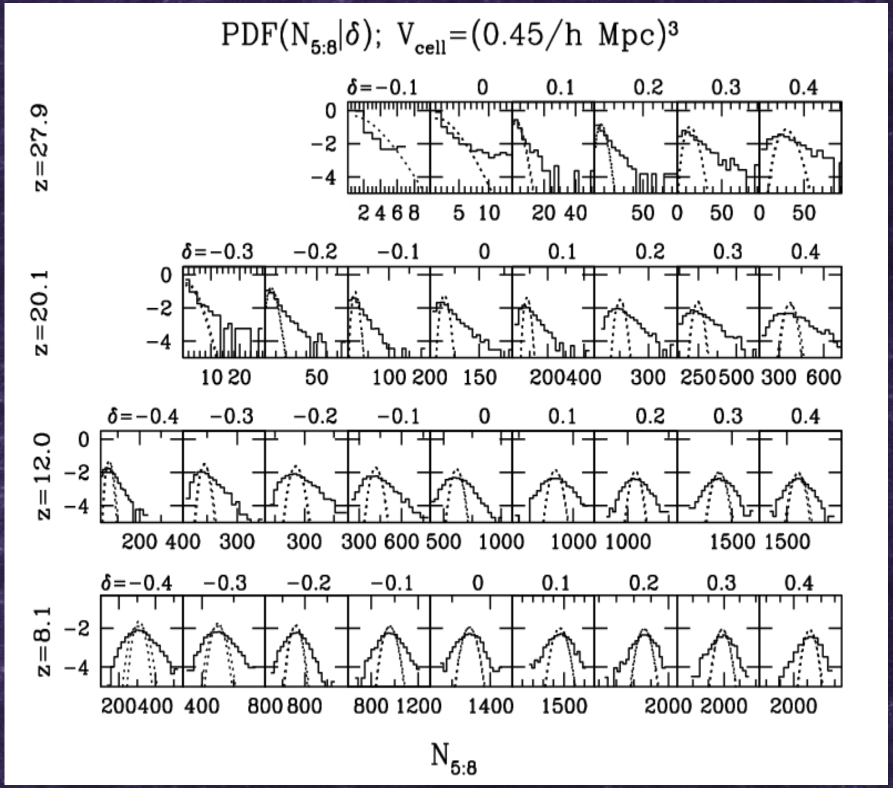
ACHs, z=6

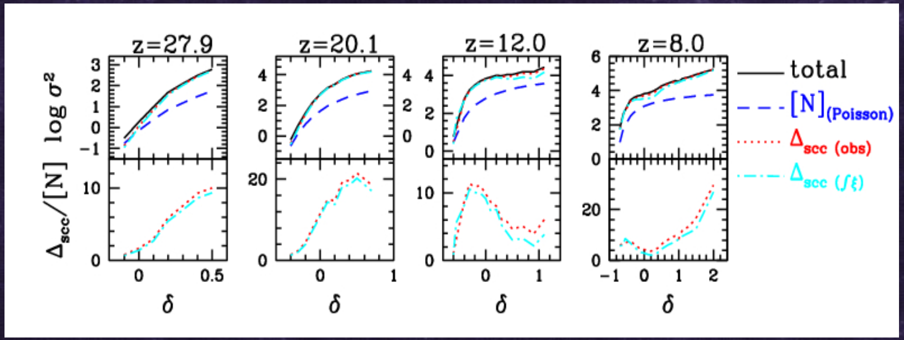
The mean halo collapsed fraction-local density relation is best matched by simulated halo mass function + (nonlinear) Eulerian halo bias for wide redshift and halo mass range. Linear bias and/or more approximate MFs are not a good fit.

Modelling the small-scales

(Ahn et al., submitted)

- Relation scatter is larger than Poisson
- Due to local sub-grid halo clustering
- Well matched by such a model

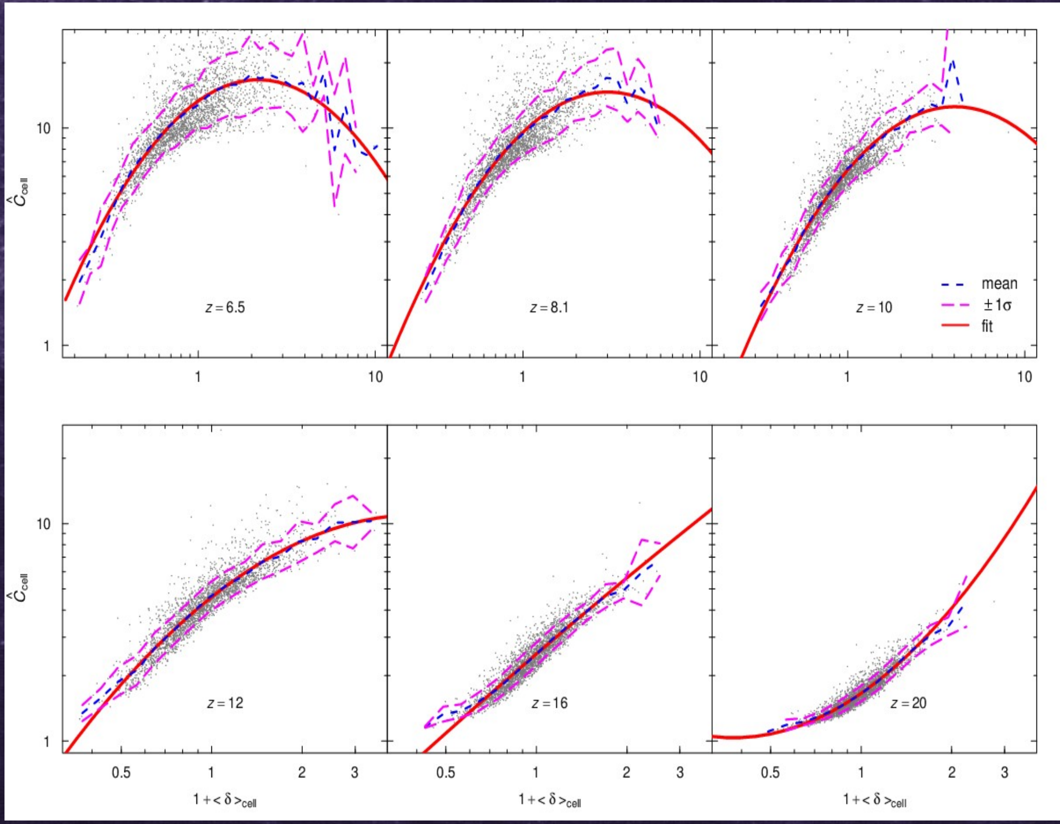




Modelling the small-scales: gas clumping

(Koda et al., in prep.)

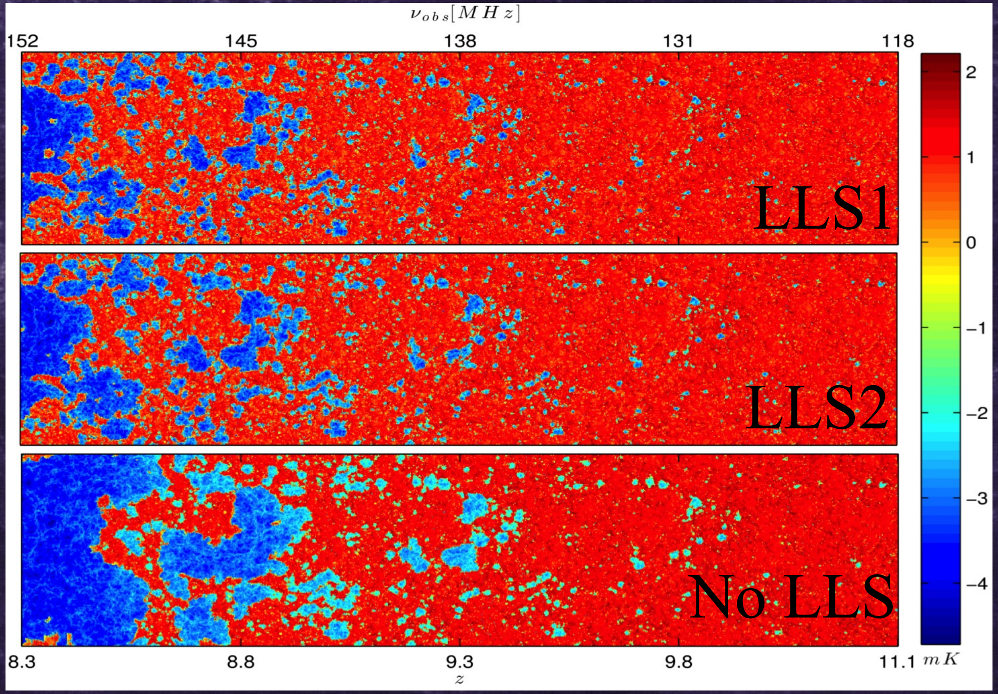
- Strong correlation with local density
- Fits derived based on high-res simulations and used in large-scale ones



Modelling the small-scales: LLSs

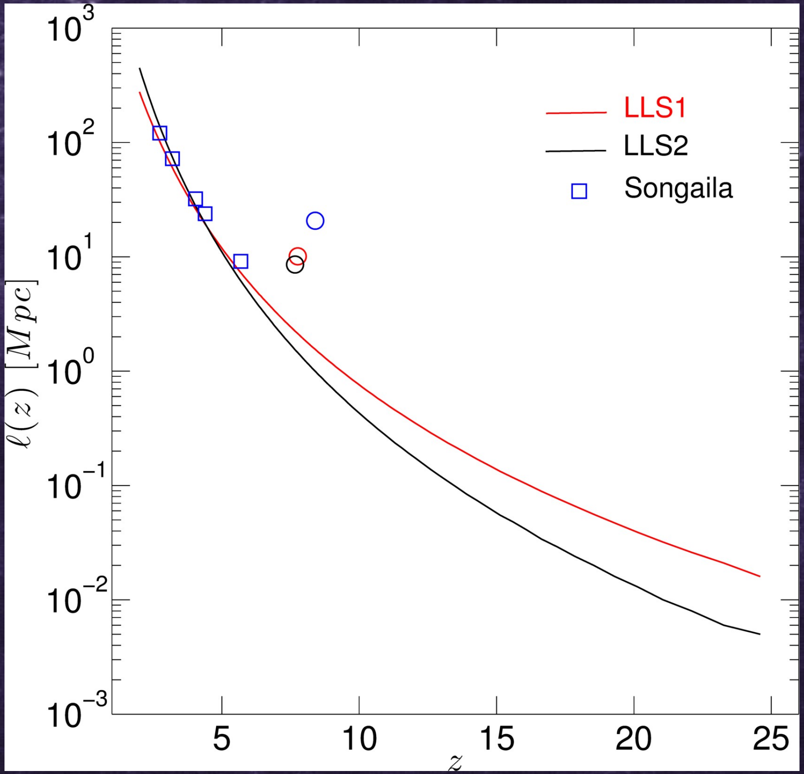
(Shukla, Mellema & Iliev, in prep.)

- Lyman-Limit systems (moderate HI column) control the continuum photons mean free path after reionization
- During reionization their effects are more subtle
- Process slowed down, smaller ionized patches
- Suppressed large-scale power

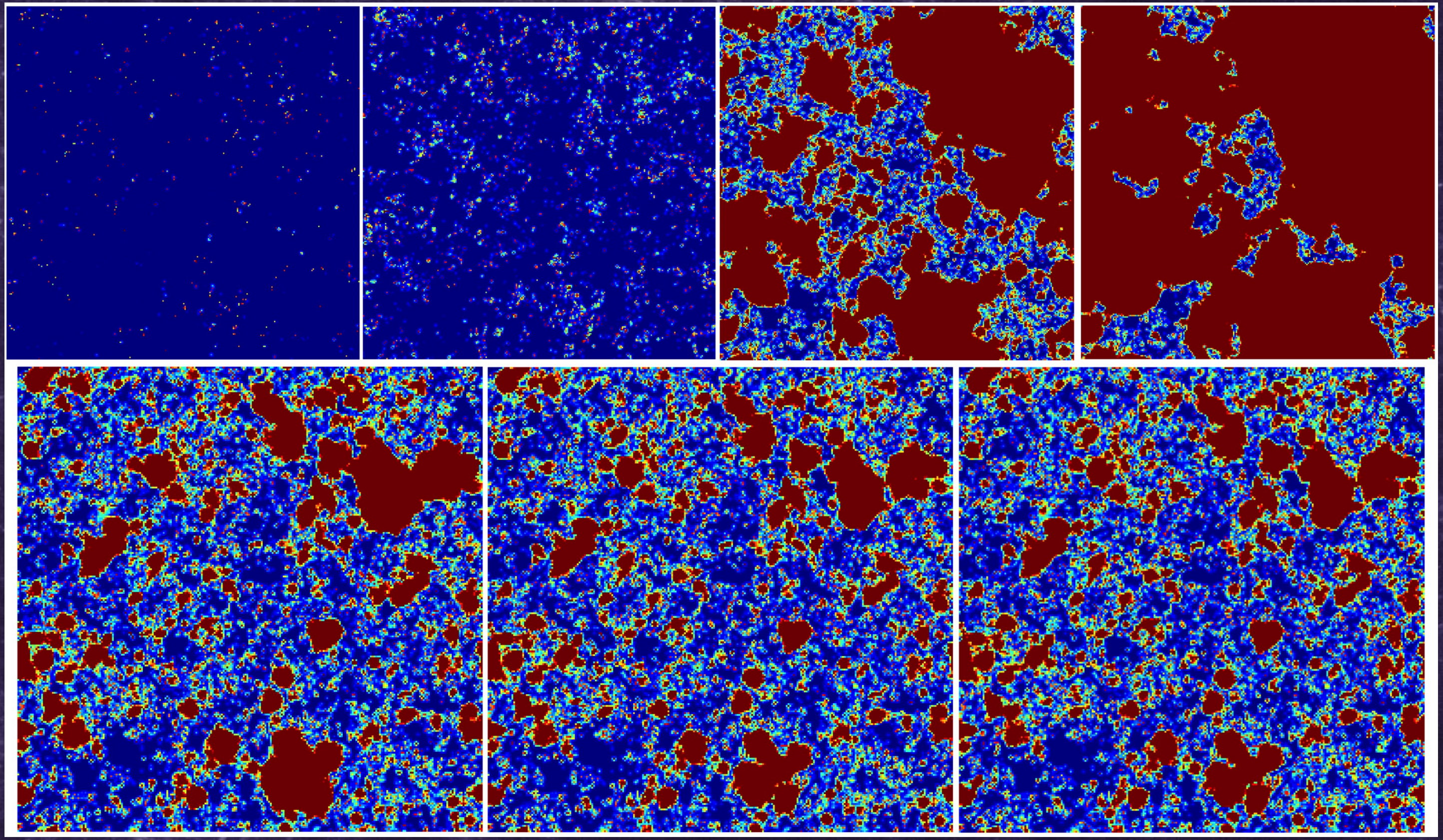


Ionizing photons: mean free path

- Early the mfp is dictated by the neutral patches
- Later the neutral patches and residual neutral fraction are insufficient and LLS take over.

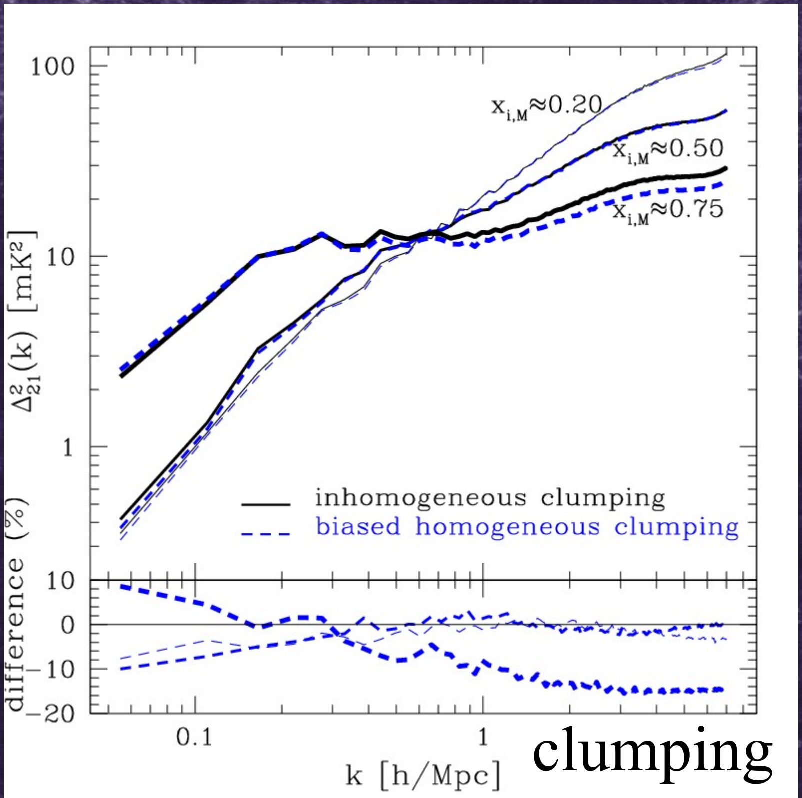


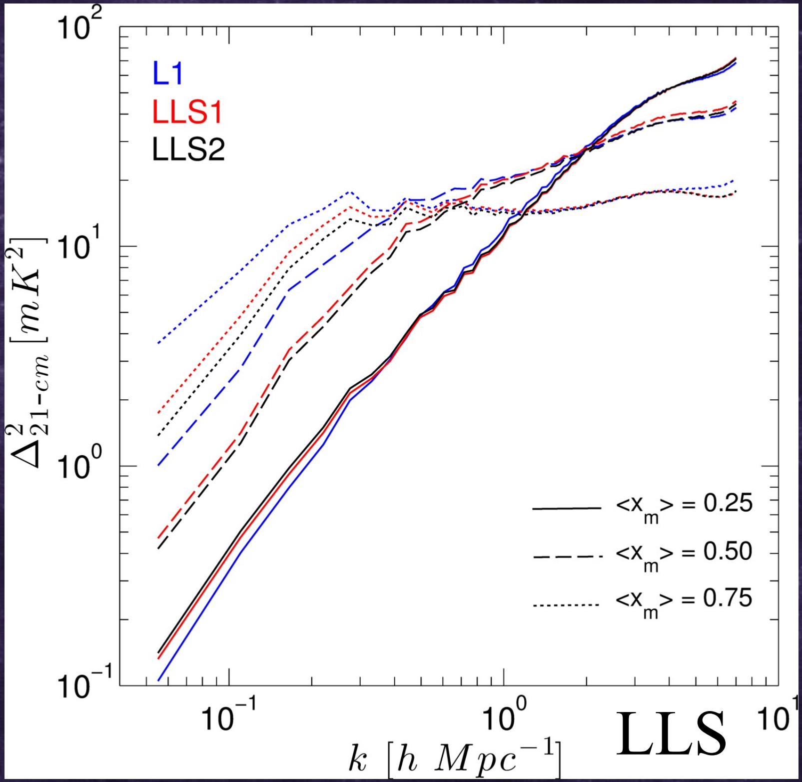
Effect of LLS on reionization geometry



No LLS LLS1 LLS2

Small-scale structures and HII region growth

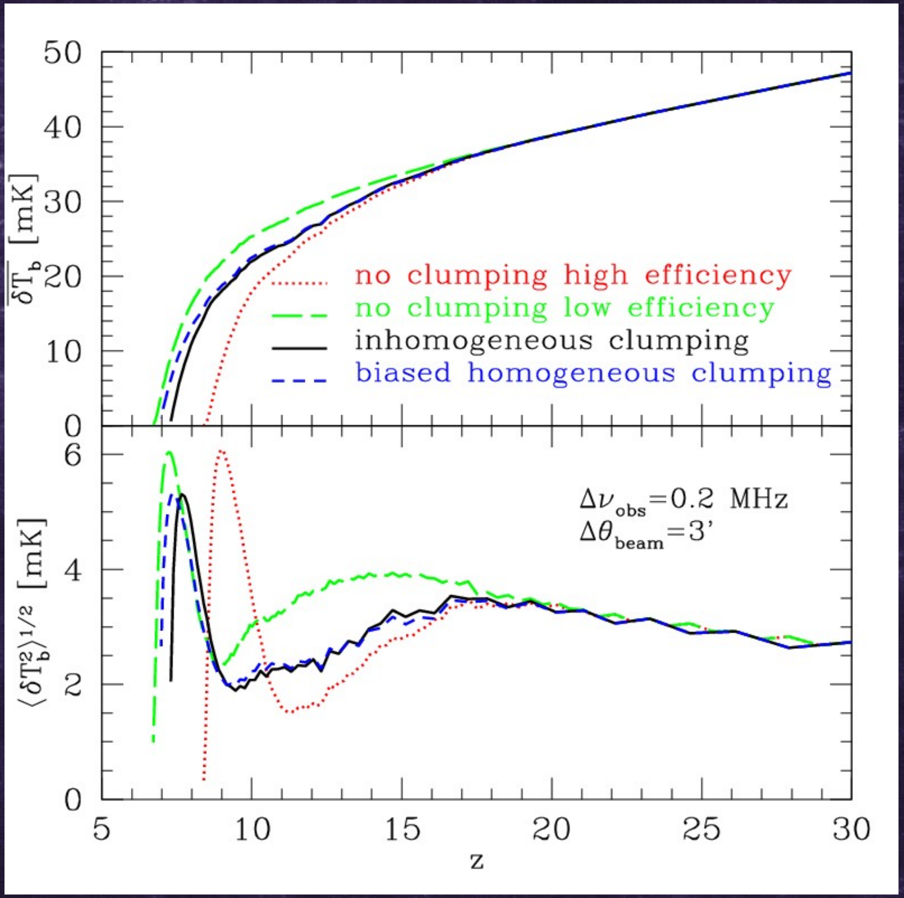




Small-scale structures limit the growth of HII regions
→ suppress power at large scales

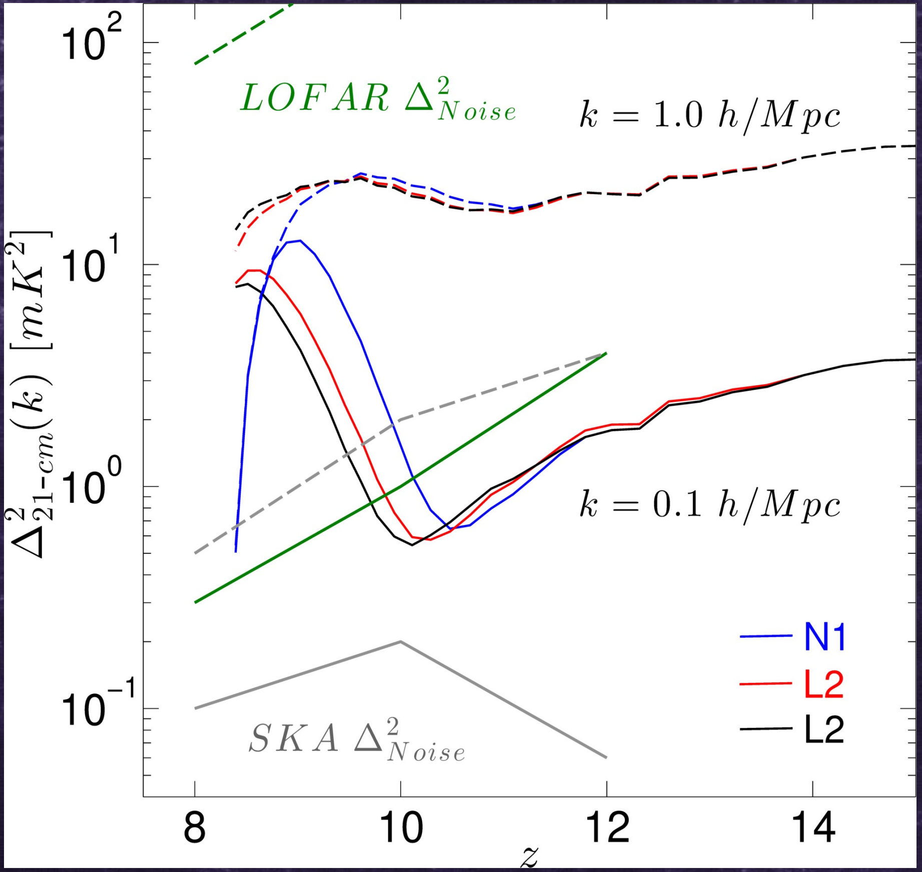
Effect of clumping on 21-cm rms

- Gas clumping enhances the local recompination rate, slowing down reionization.
- Results are not equivalent to lower source efficiencies, however.
- Details of modelling have small effect on the results.

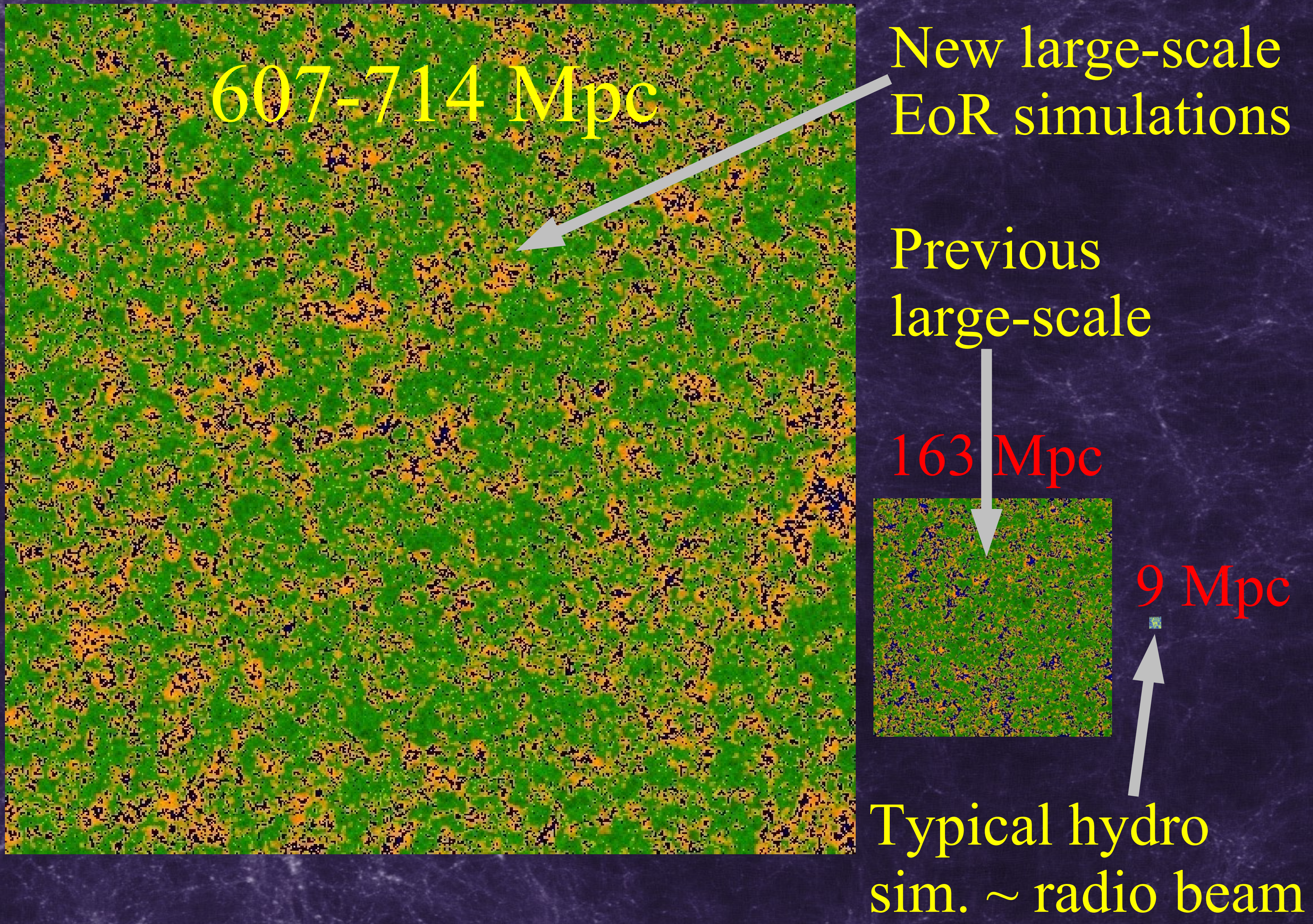


Detectability at 21-cm

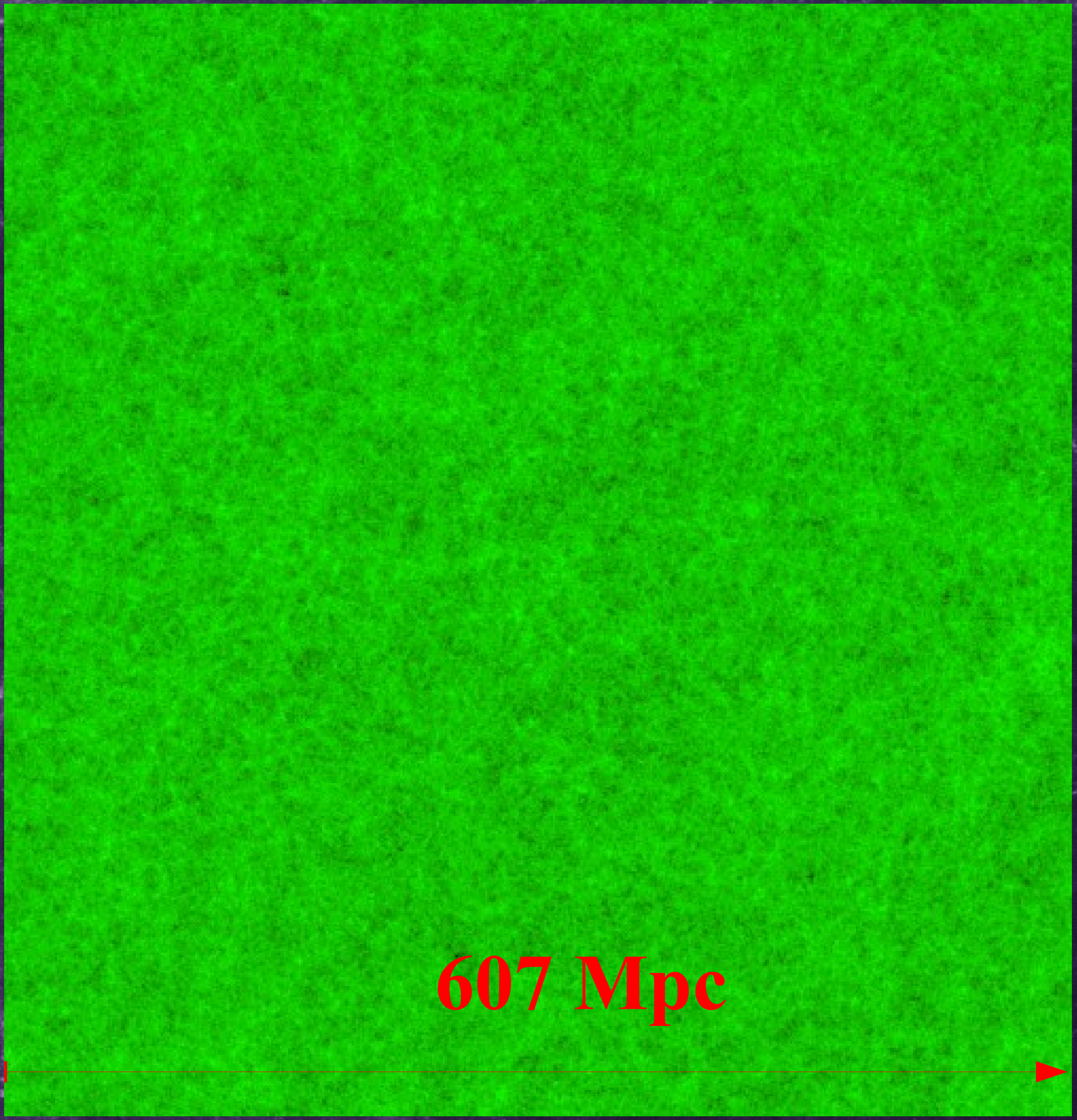
- Effects of LLS are significant at large scales and late times
- Should be detectable by LOFAR
- Easily detectable with SKA



Scales of reionization



Large-scale reionization: movie

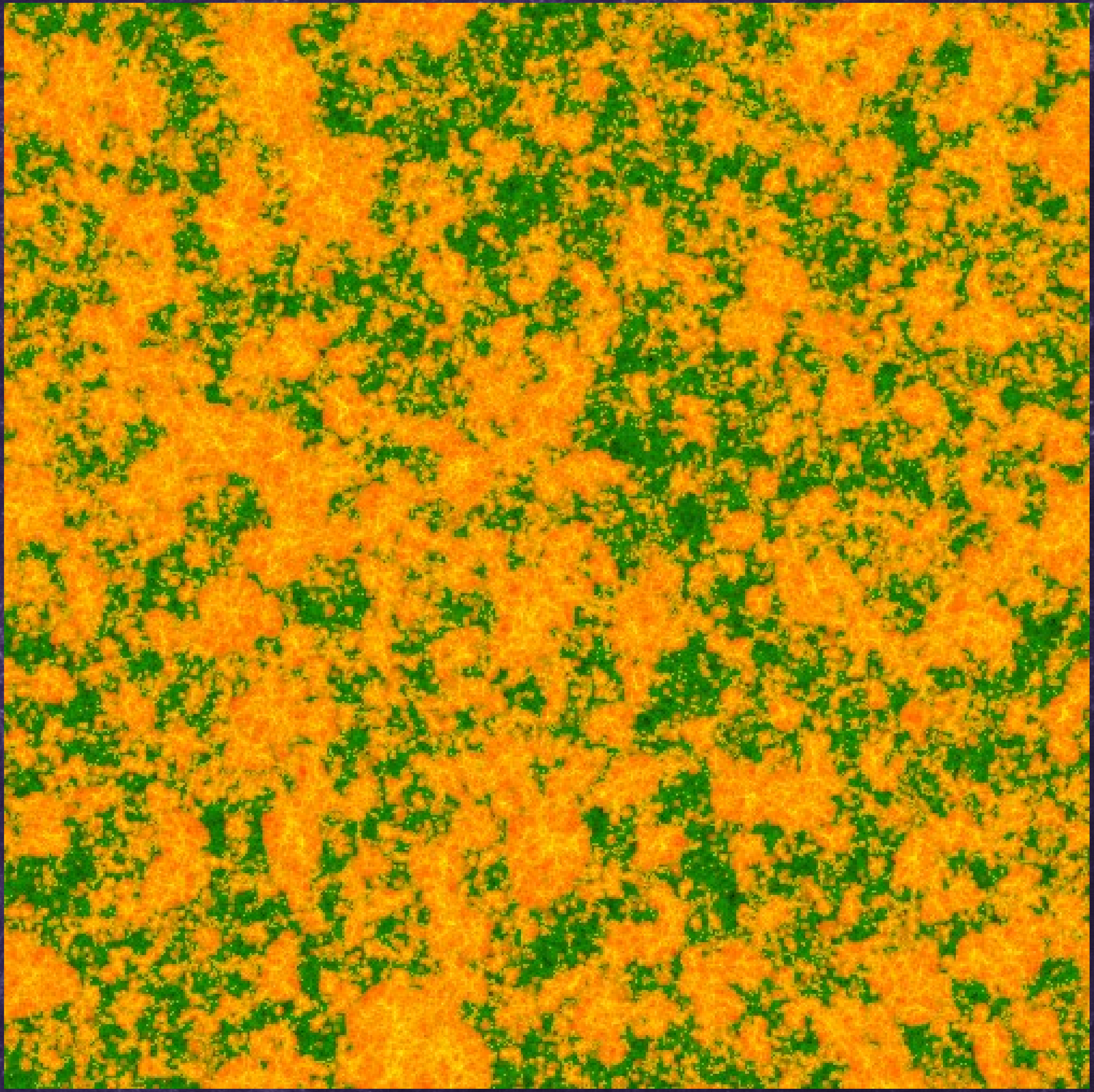


Large-scale Structure of Reionization

(Iliev et al, 2013)

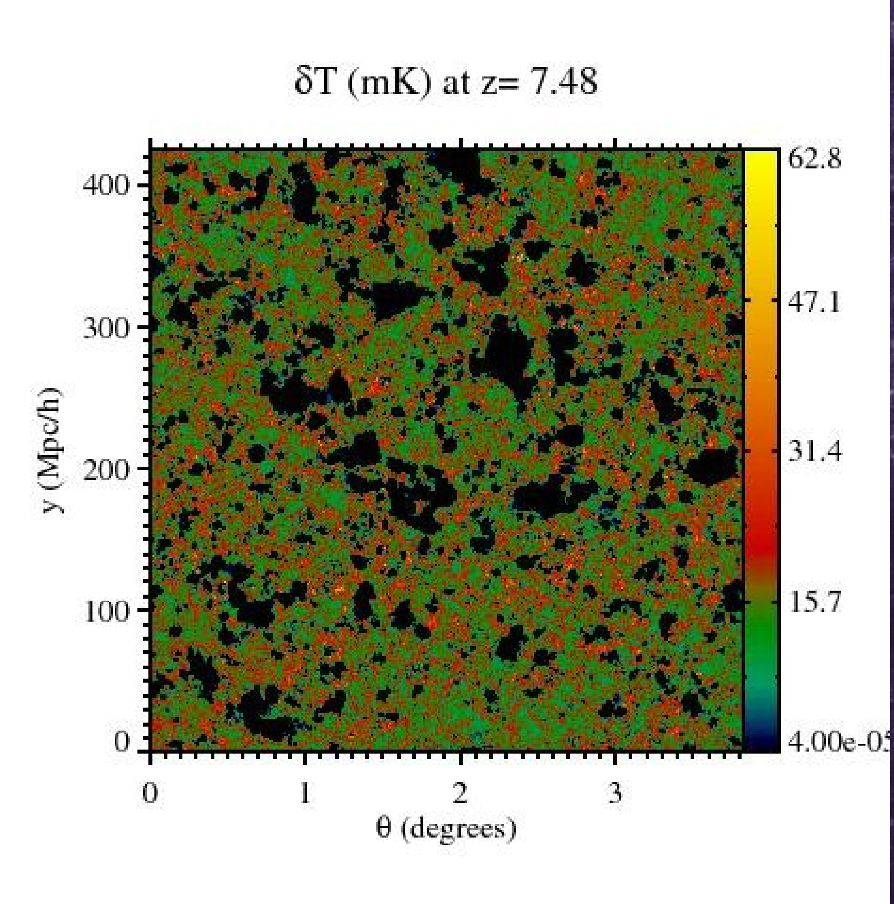
$z=7.35$
$x_m \sim 0.5$

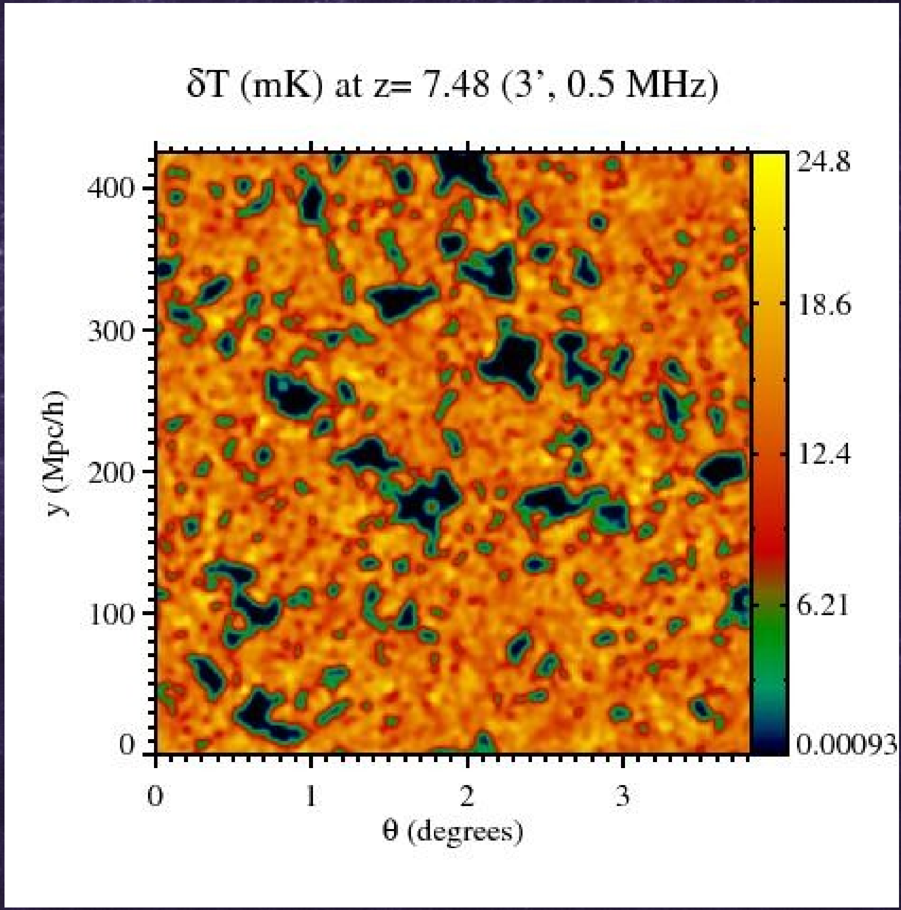
425 Mpc/h
504^3 RT



LOFAR resolution

(Iliev et al, 2013)



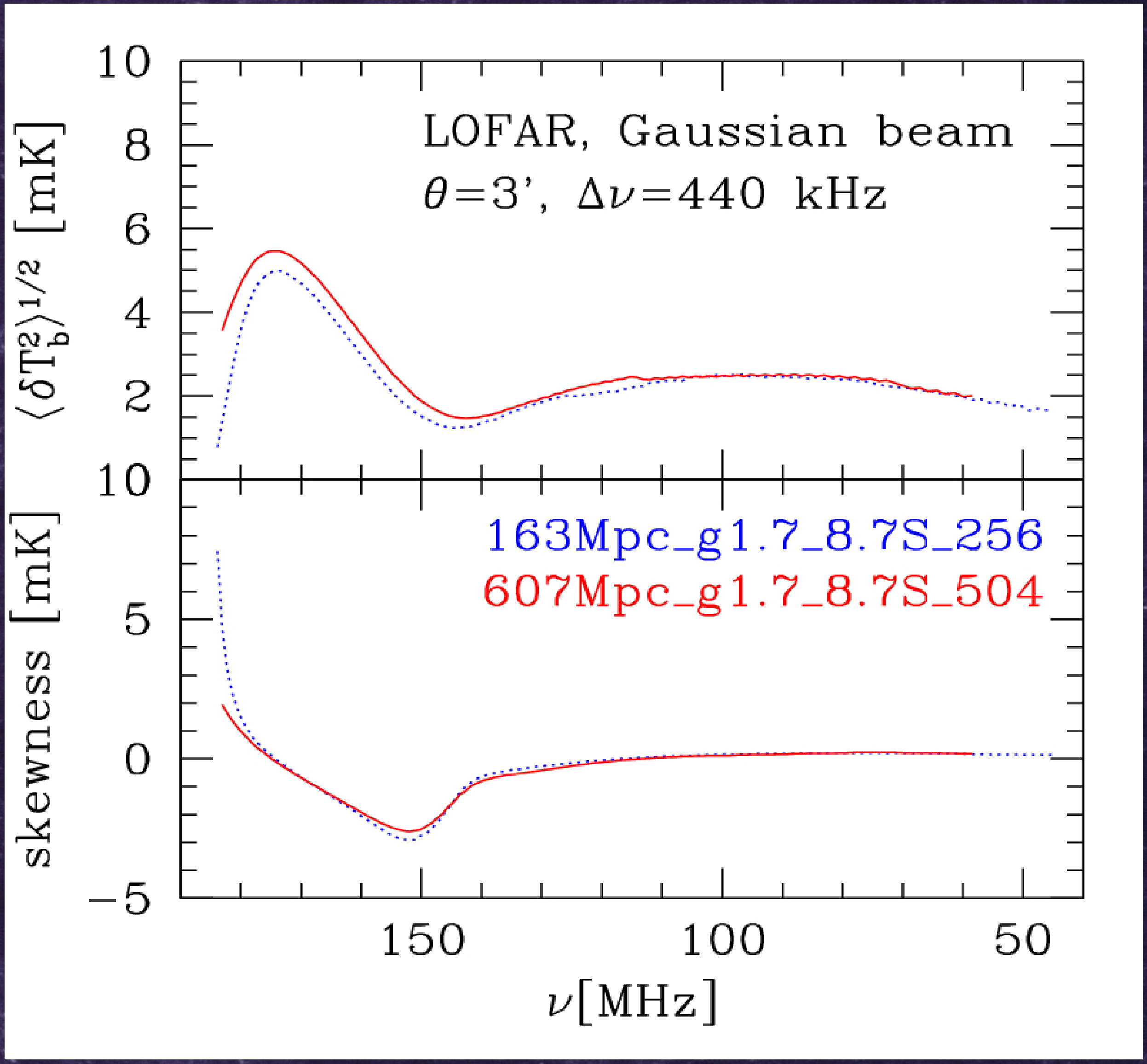


At the (rough) LOFAR resolution large-scale patchiness is still clearly seen, though small-scale structure is smoothed away.

21-cm fluctuations: rms and skewness

(Iliev et al, 2013)

Additional power also seen in (beam- and bandwidth-smoothed) 21-cm rms fluctuations, but not in non-Gaussian measures like PDF skewness.

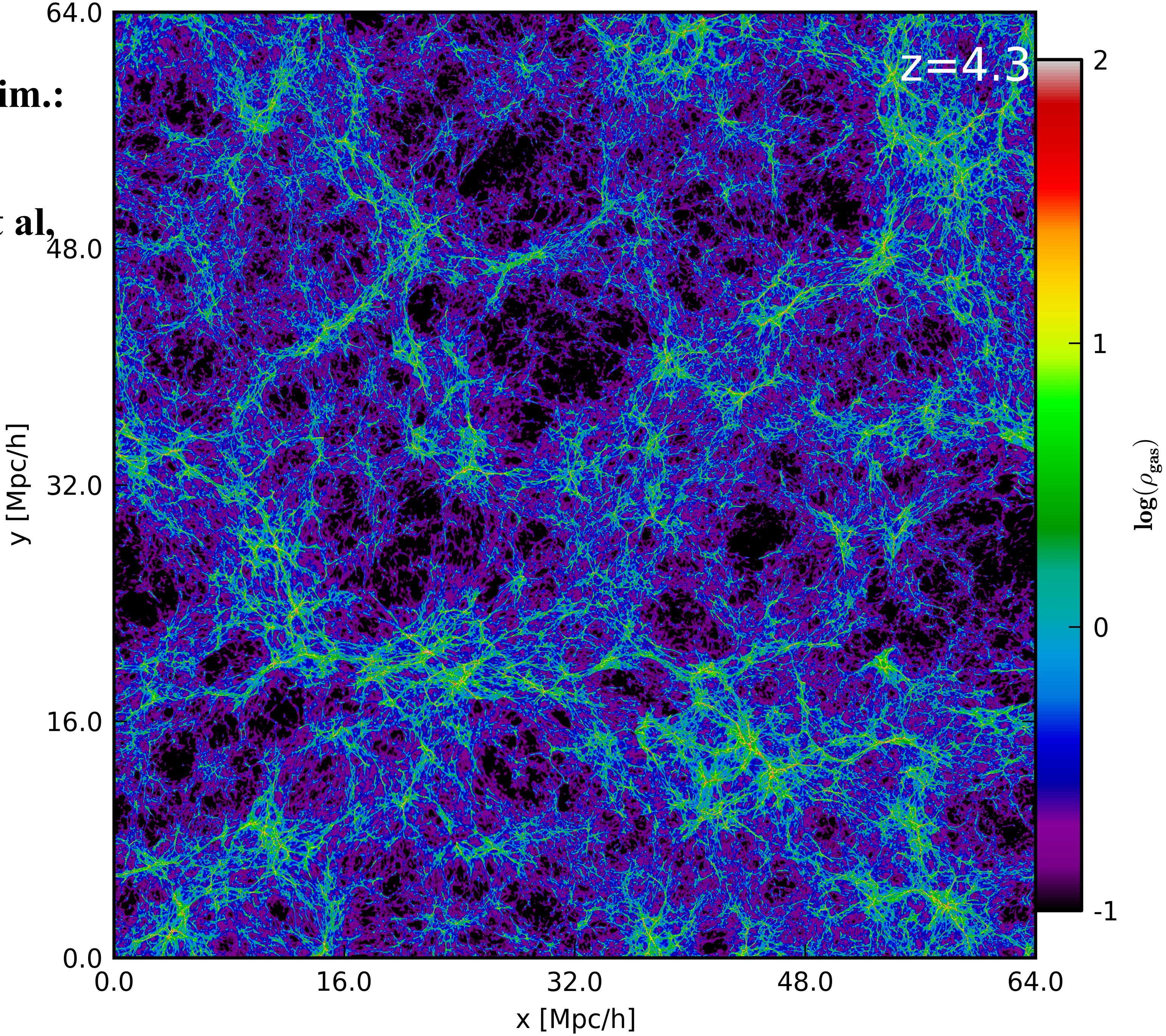


Radiative feedback during reionization

- Ionizing UV: short mean free path; suppresses star formation in low-mass galaxies, resulting in self-regulation → main focus of this talk.
- Soft UV (Lyman-Werner band radiation): long (~100 Mpc) mean free path; destroys H_2 molecules, suppressing or delaying star formation in very low-mass halos (minihalos), particularly important for First Stars → will cover if there is time (ask me if interested).
- X-rays: very long mean free paths (~hundreds of Mpc) heating of the neutral IGM, resulting in suppression of gas infall on very low-mass halos. Sometimes might stimulate star formation → work in progress.

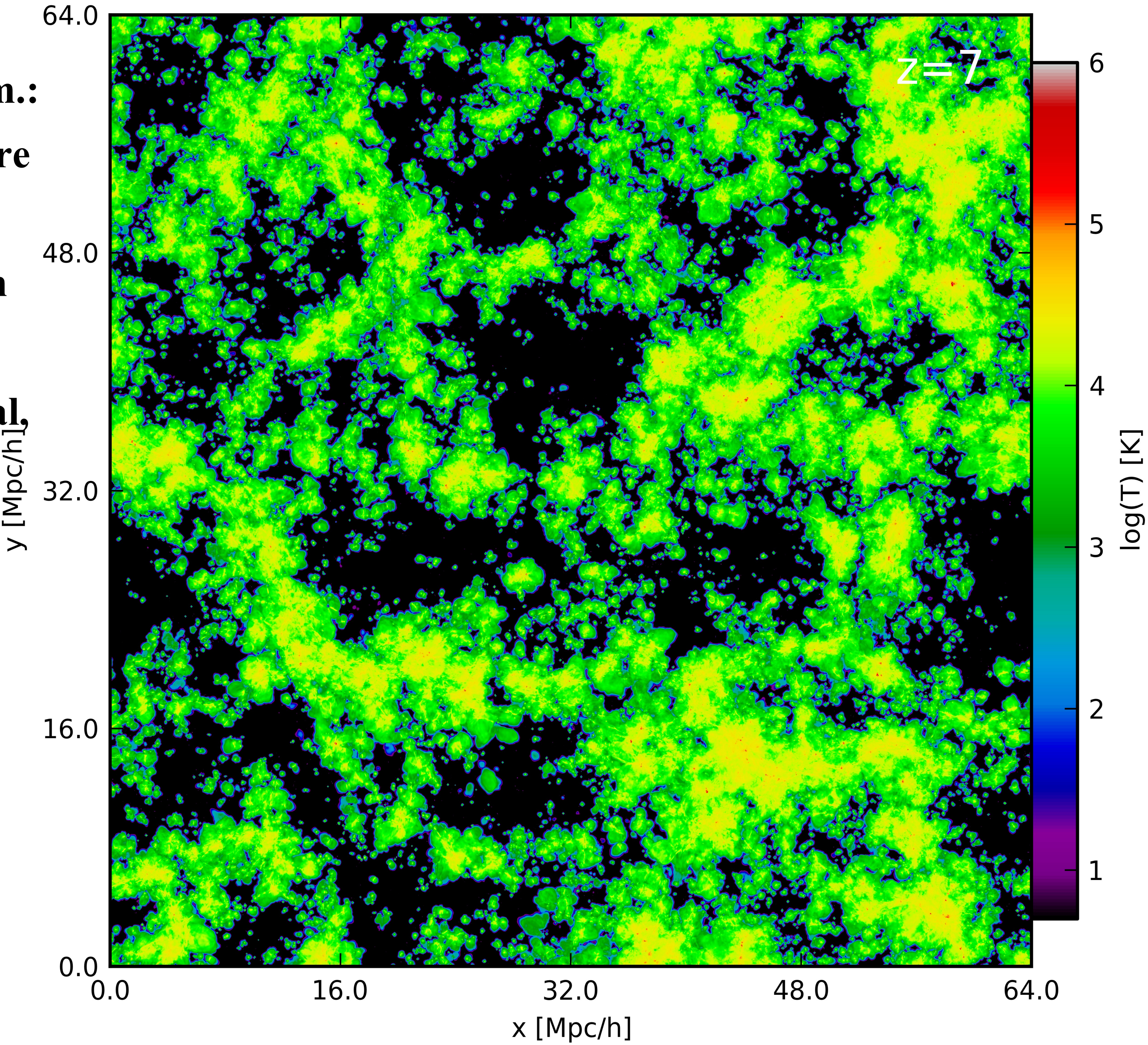
INCITE simulation, Ocvirk et al,in prep.

INCITE sim.: Density (Ocvirk et al, in prep.)



INCITE sim.: Temperature during reionization

(Ocvirk et al, in prep.)

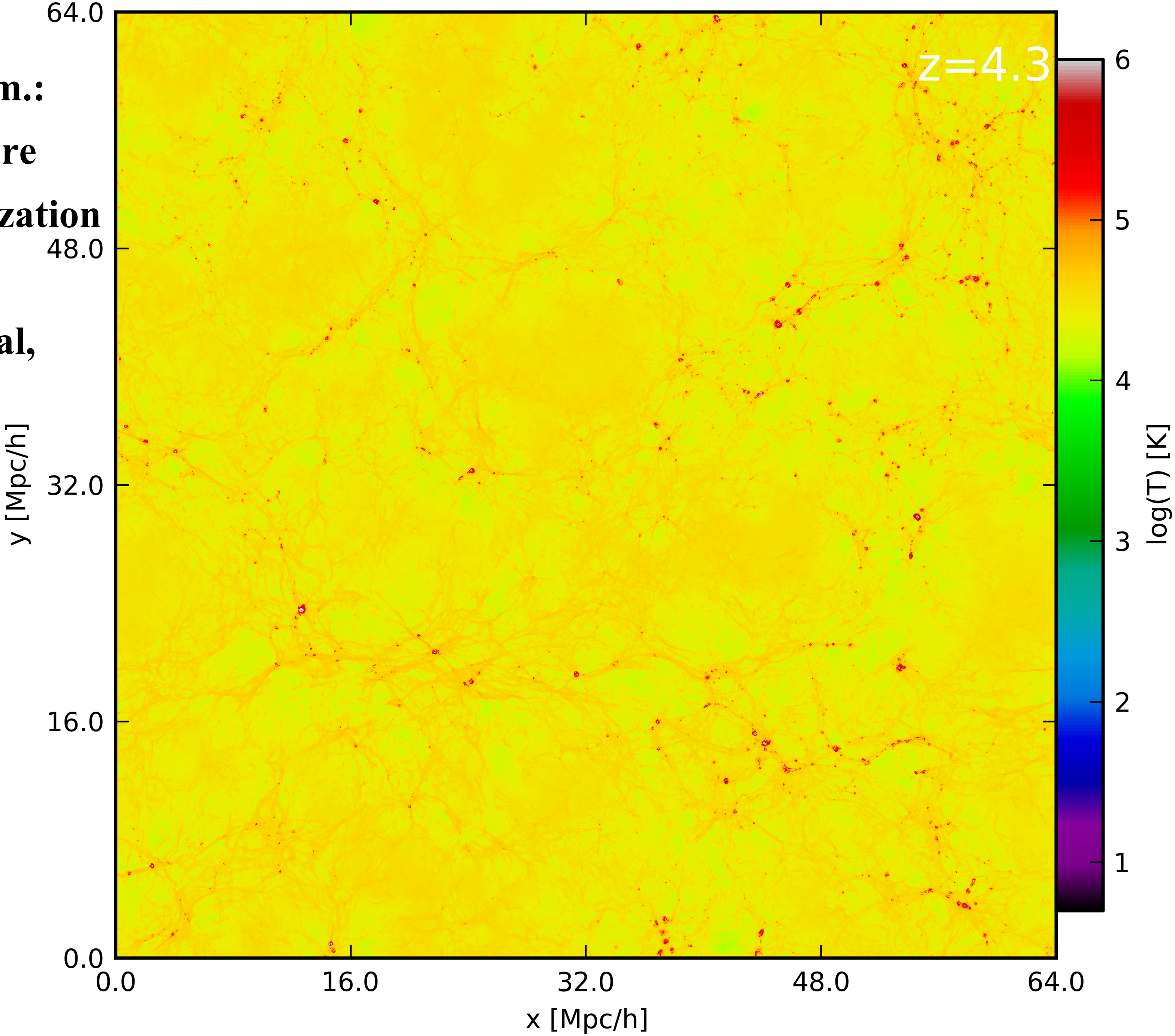


INCITE sim.:

Temperature

Post-reionization

(Ocvirk et al, in prep.)



Filtering Mass

- Takes into account full thermal history of the gas – Gnedin & Hui 98
- Sets the scale below which gas can fragment **prior** to reionization

$$\frac{1}{k_F^2(t)} = \frac{1}{D_+(t)} \int_0^t dt' a^2(t') \frac{\ddot{D}_+(t') + 2H(t')\dot{D}_+(t')}{k_J^2(t')} \int_{t'}^t \frac{dt''}{a^2(t'')}$$

$$k_J \equiv \frac{a}{c_S} \sqrt{4\pi G \bar{\rho}}$$

$$c_S^2 = \frac{5}{3} \frac{k_B \langle T \rangle_V}{\mu m_p}$$

$$M_F \equiv \frac{4\pi}{3} \bar{\rho} \left(\frac{2\pi a}{k_F} \right)^3$$

The Characteristic Mass - M_C

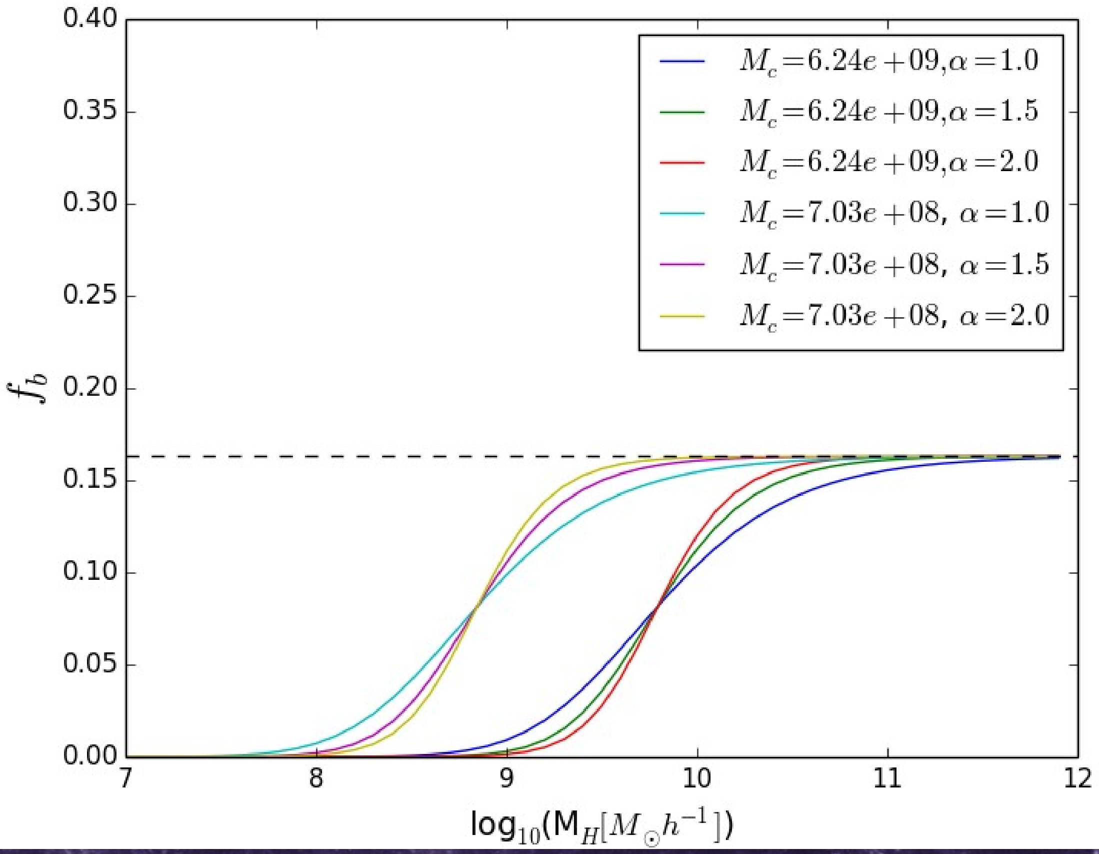
- Fitting function (Gnedin 00) for the baryon fraction in halos of mass M:

$$f_{\rm b}(M,z) = \langle f_{\rm b} \rangle \left\{ 1 + (2^{\alpha/3} - 1) \left(\frac{M}{M_{\rm c}(z)} \right)^{-\alpha} \right\}^{-\frac{3}{\alpha}}$$

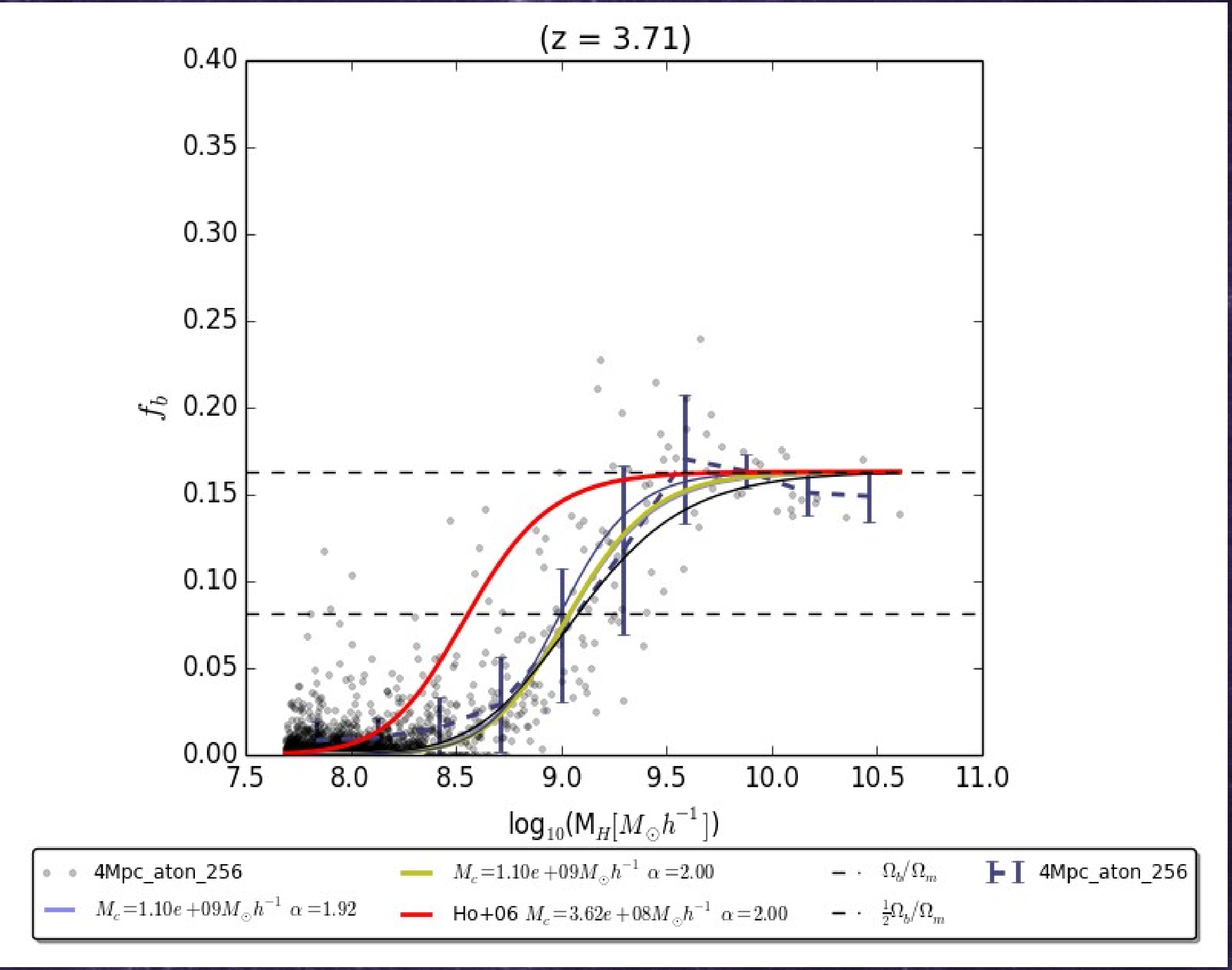
- $M_c(z)$ sets the halo mass at which the gas fraction is half the cosmic mean
- Gnedin 00 found that the filtering mass, M_F, gave a good fit to M_c
- The exponent α controls steepness of the transition between baryon poor/rich halos – a value of 2 is found to fit well in the literature

Effect of Altering Mc and α

$$f_{\rm b}(M,z) = \langle f_{\rm b}\rangle \left\{1 + (2^{\alpha/3}-1)\left(\frac{M}{M_{\rm c}(z)}\right)^{-\alpha}\right\}^{-\frac{3}{\alpha}}$$

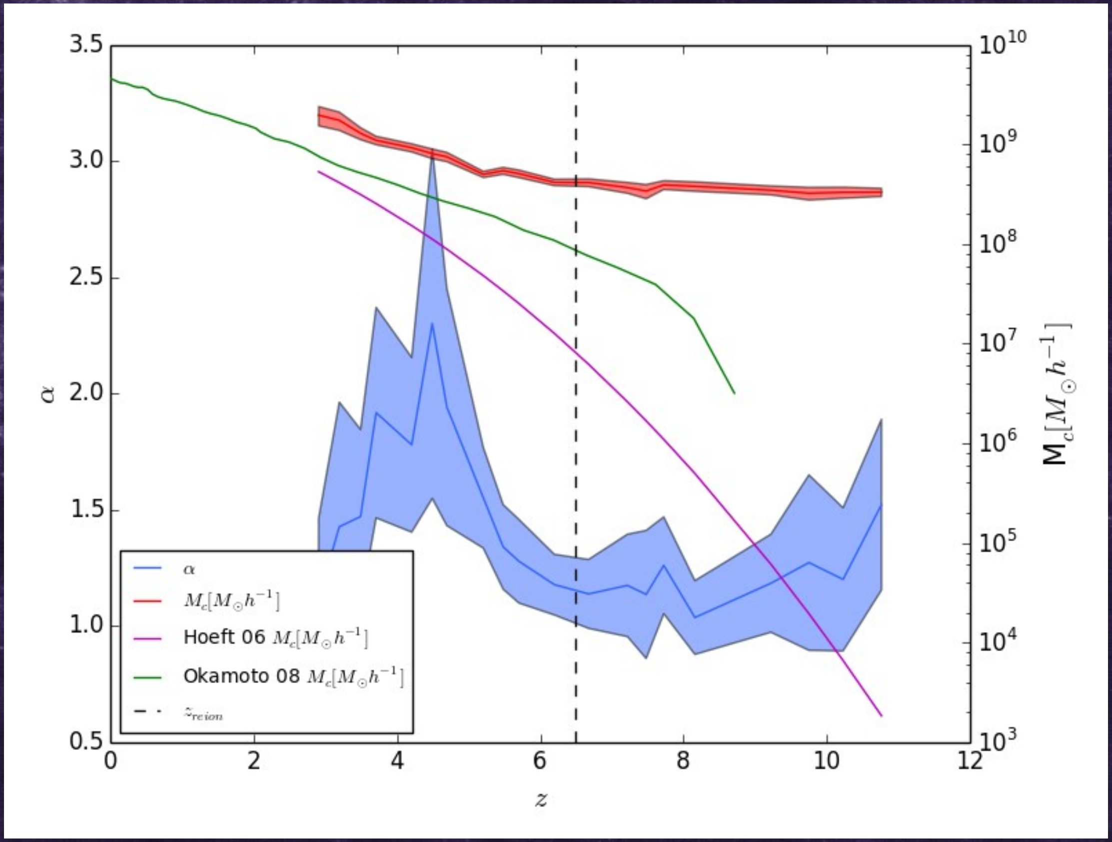


Distinct Halos Only…



M_c and α vs redshift

- Larger than Hoeft+ 06 & Okamoto+ 08 predictions (although former tuned to match voids) – preferentially heat dense gas



Evolution of the equation of state

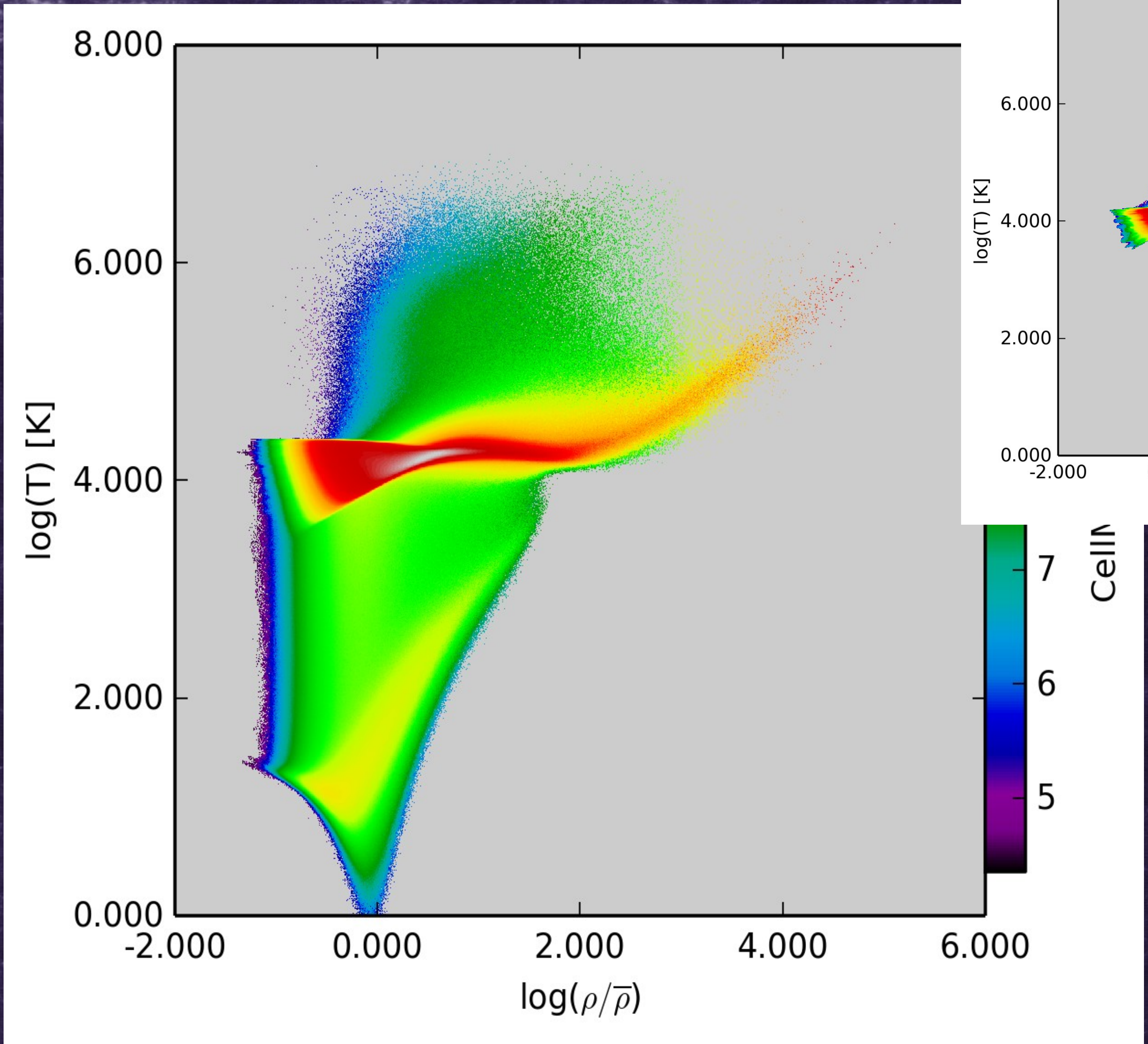
Equation of state: effect of the photoionization and heating

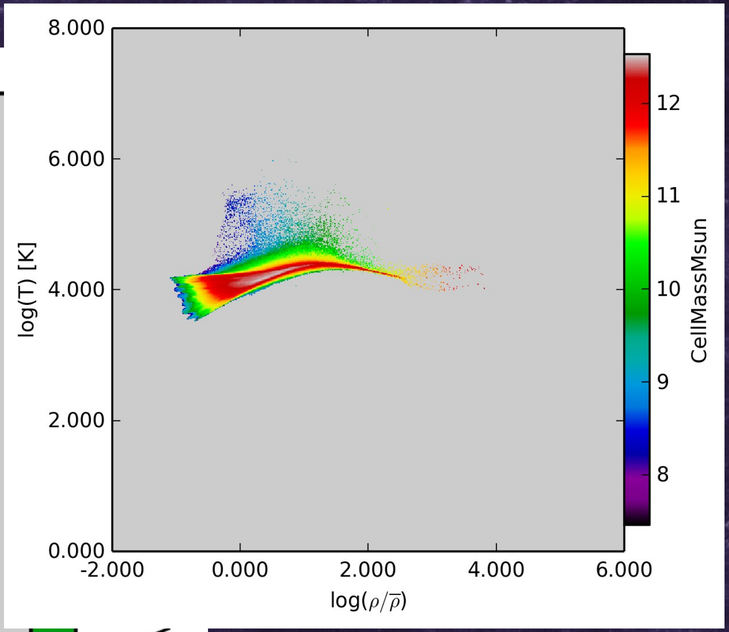
(Sullivan et al., in prep.)

Gas density: effect of photoionization and heating

(Sullivan et al., in prep.)

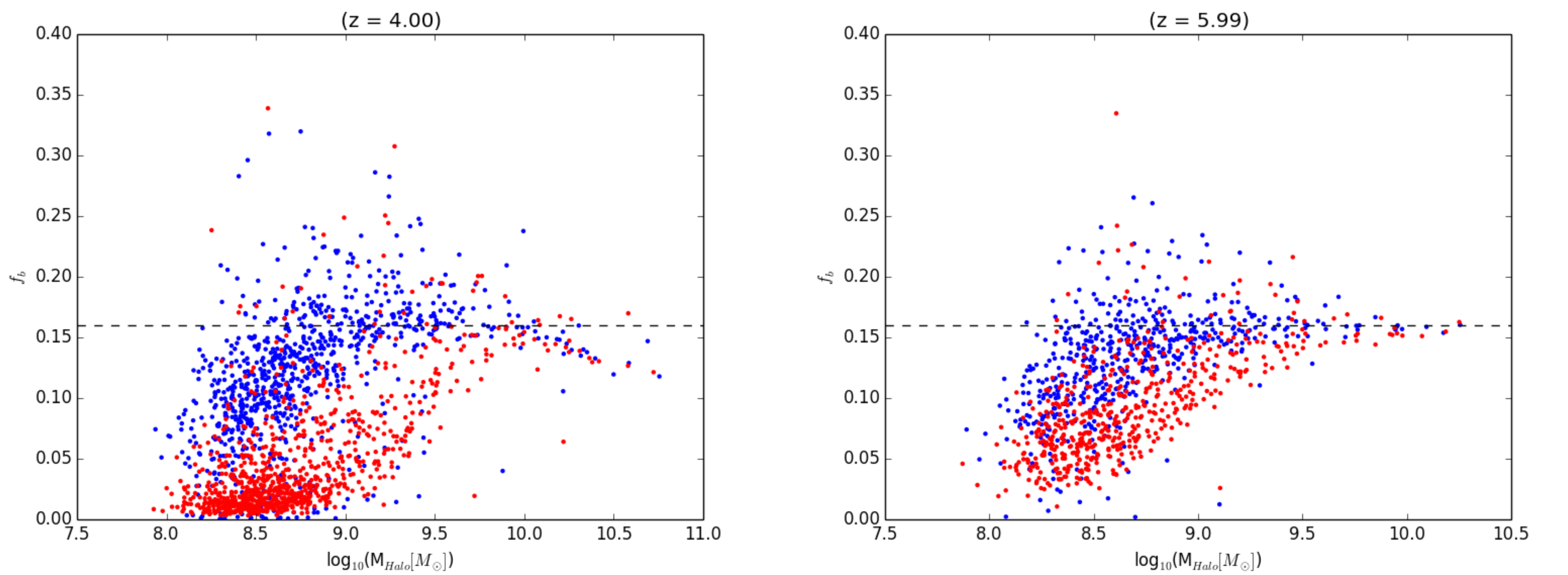
Equation of state: INCITE run





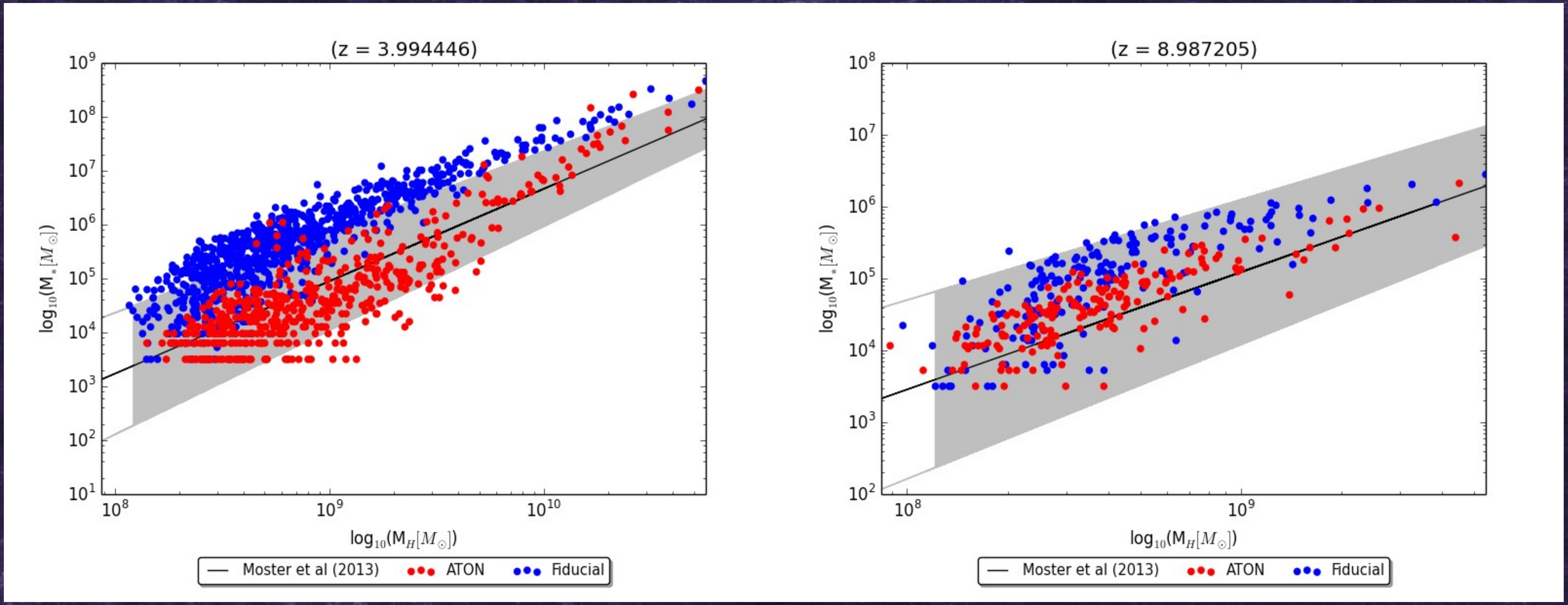
Gas fraction: effect of photoionization and heating

(Sullivan et al., in prep.)



Star formation rates: with and without photoheating

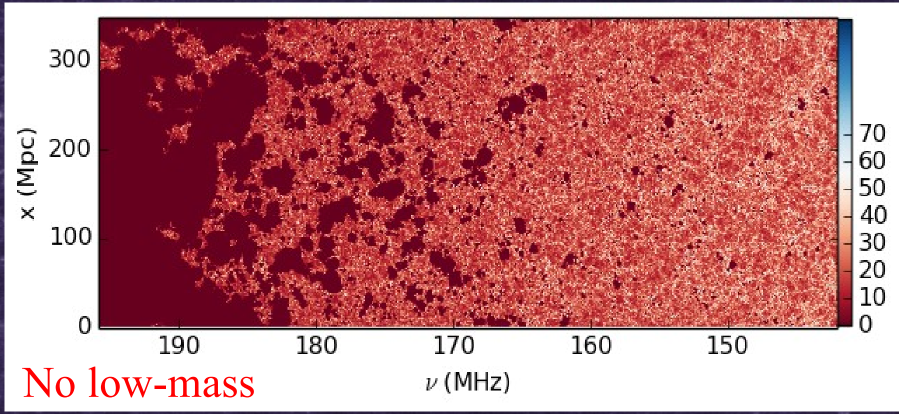
(Sullivan et al., in prep.)

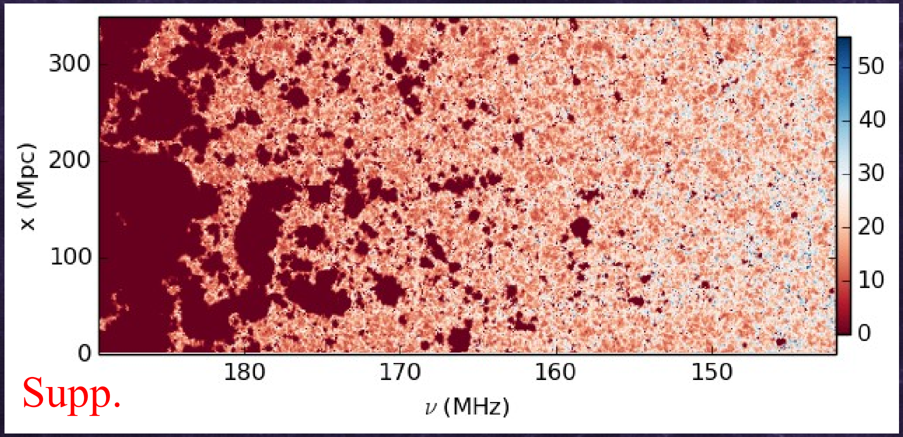


Effect of suppression on large scales

(Dixon et al. in prep.)

- Photon output during reionization is dominated by low-mass galaxies.
- Radiation photoheating rises temperature to $>10^4$ K → Jeans mass becomes $\sim 10^9$ M_solar.
- This strongly modifies the reionization geometry and duration.
- Details of the suppression are not yet fully understood.

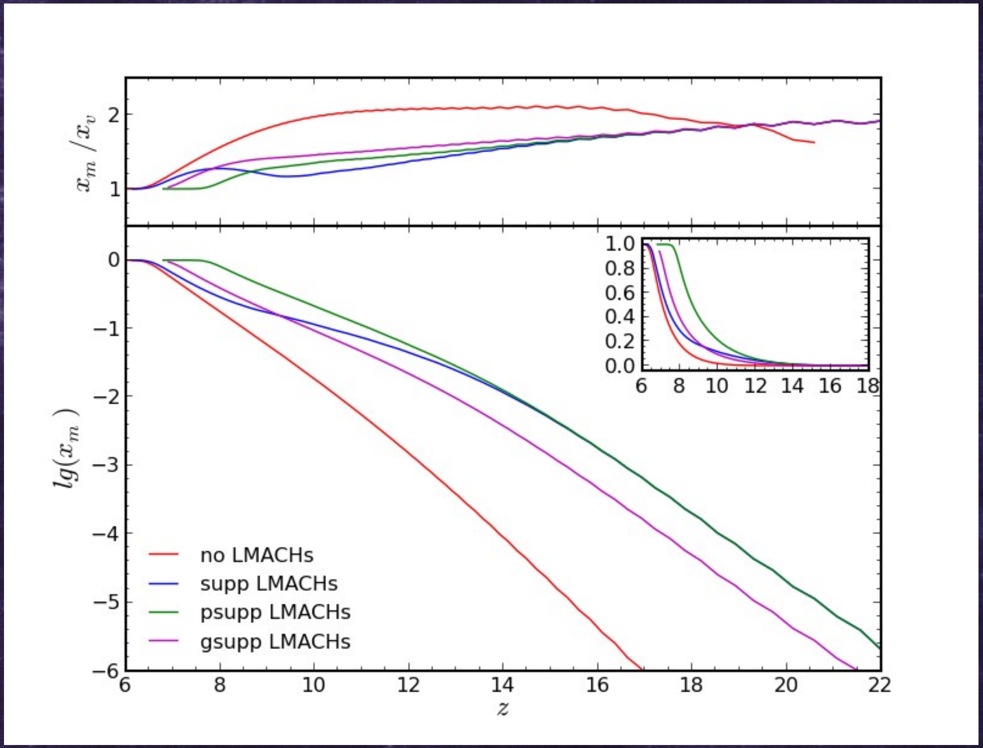




Different source suppression models

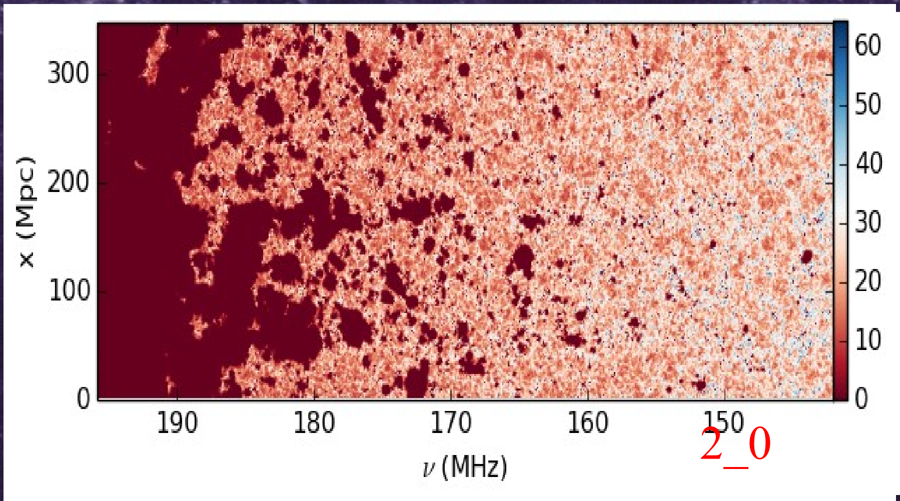
(Dixon et al. in prep.)

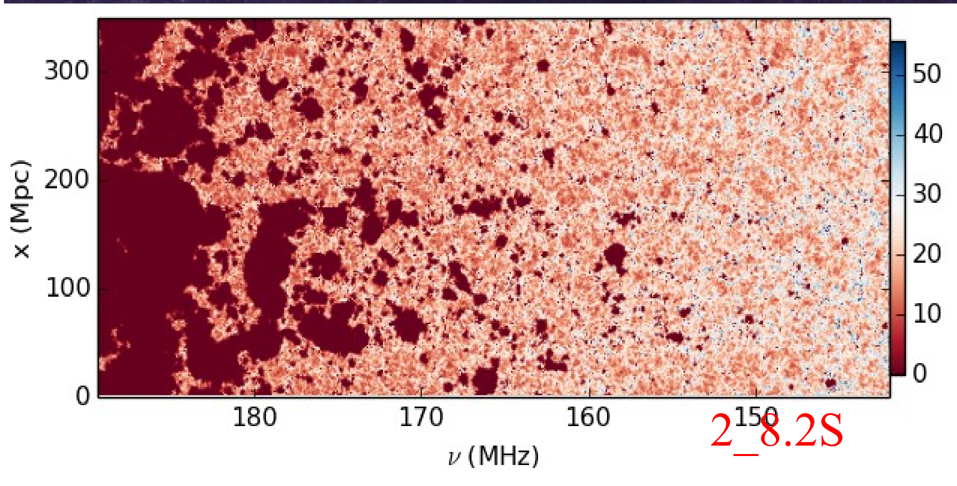
- Extended reionization history → higher τ, while still same z_{ov}.
- Suppression results in self-regulation.
- 4 suppression models compared:
  - No low-mass
  - Full suppression
  - Partial suppression
  - Gradual suppression

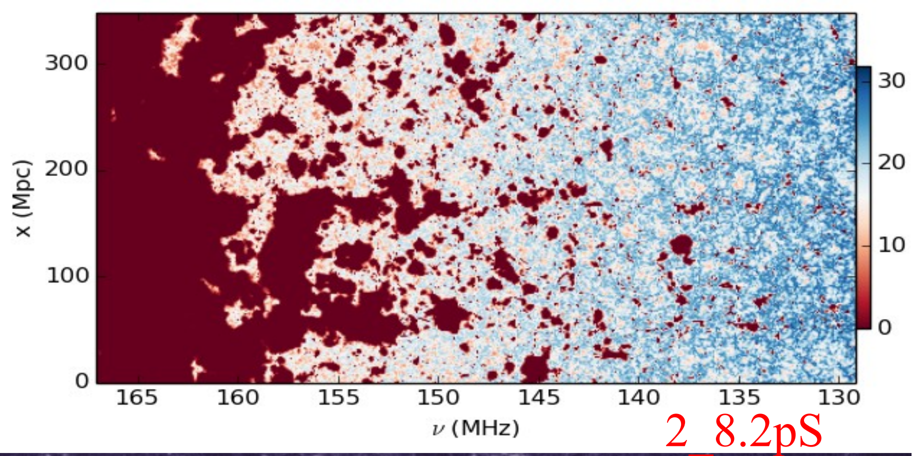


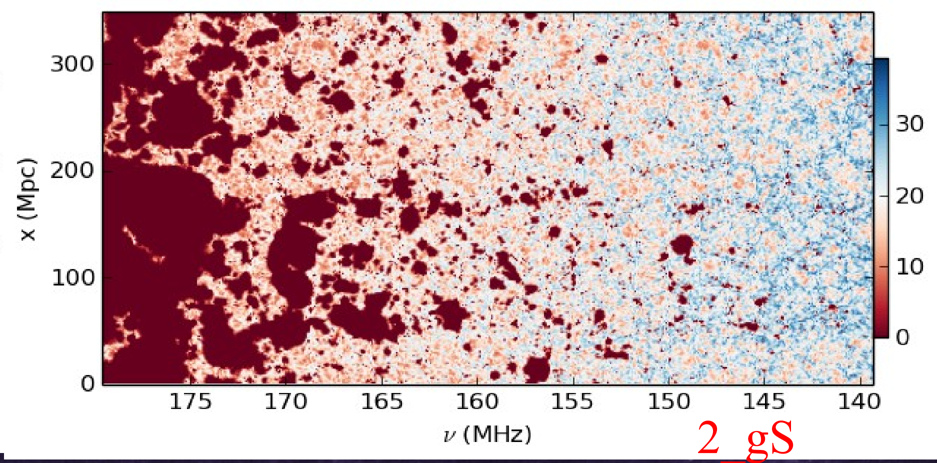
Different low-mass source suppression models: 21-cm

(Dixon et al. in prep.)



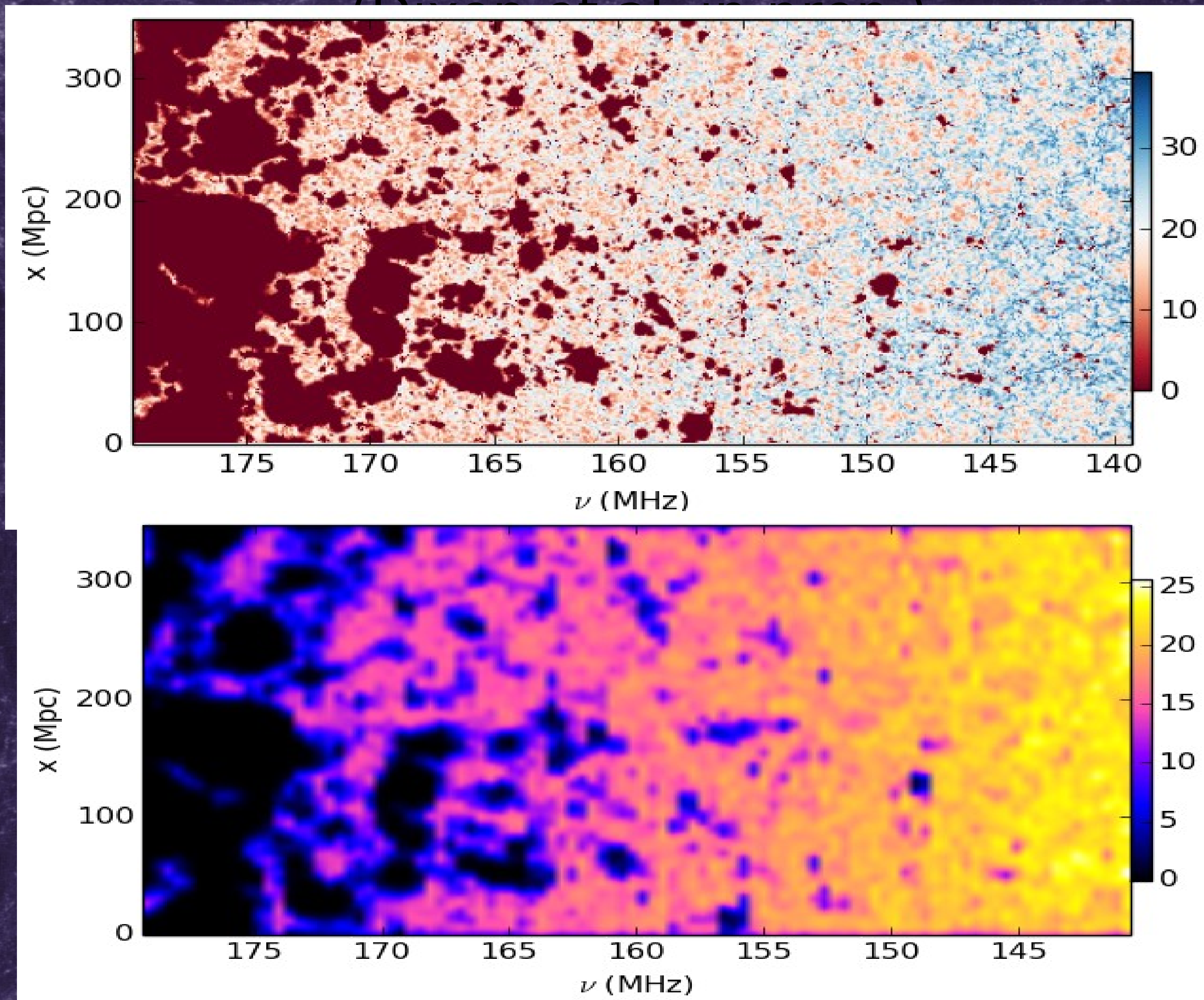






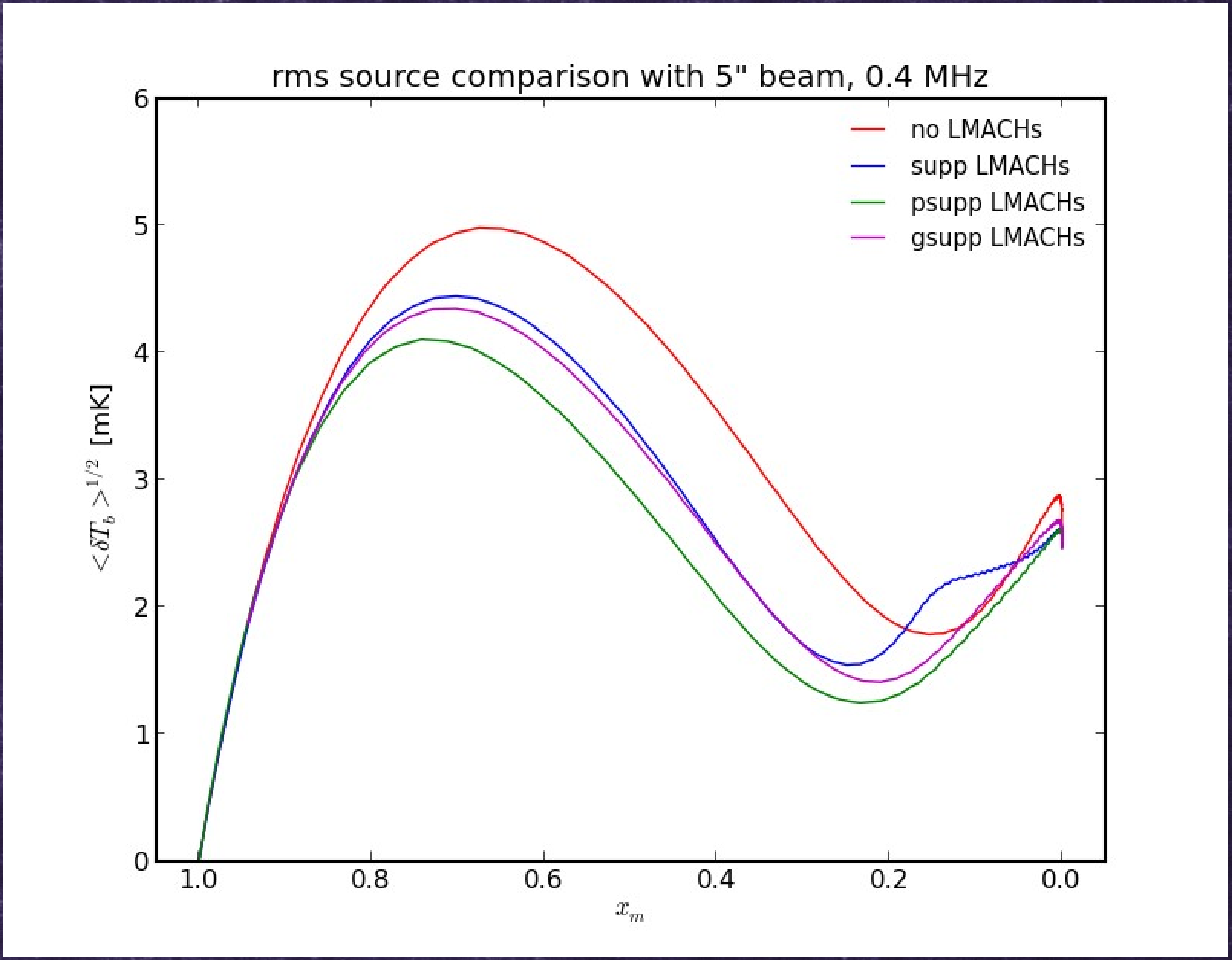
21-cm: effect of resolution (beam and bandwidth)

(Dixon et al. in prep.)



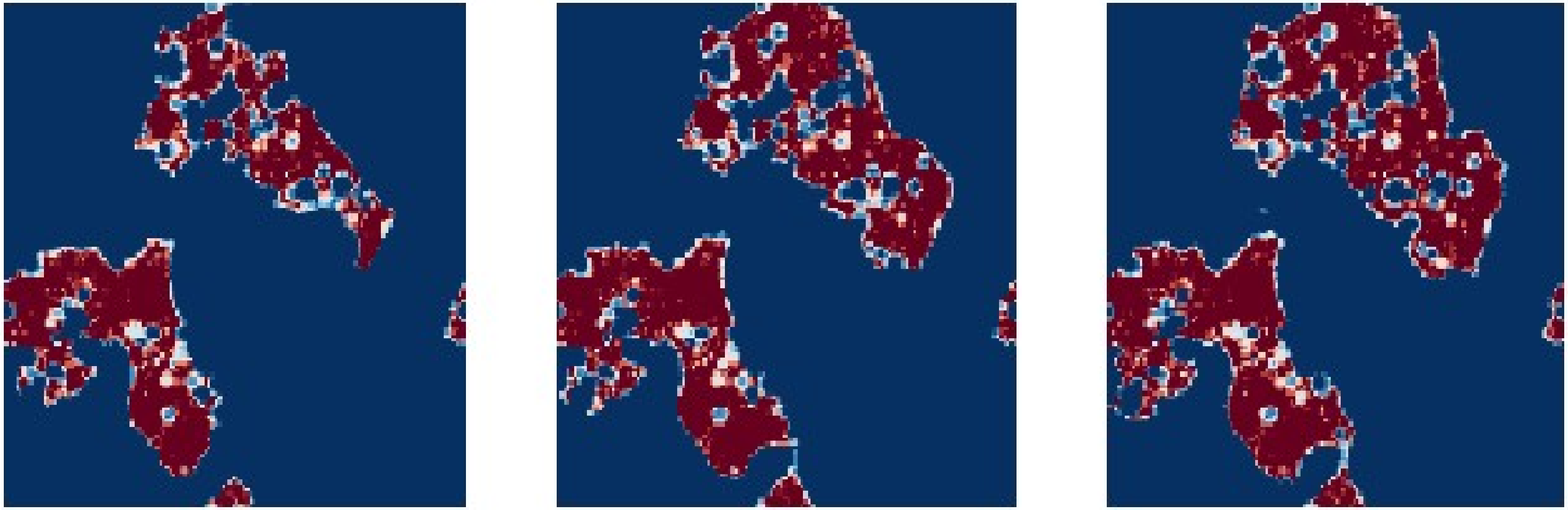
21-cm rms fluctuations

(Dixon et al. in prep.)



Source suppression models and star formation history

(Srisawat et al, in prep.)

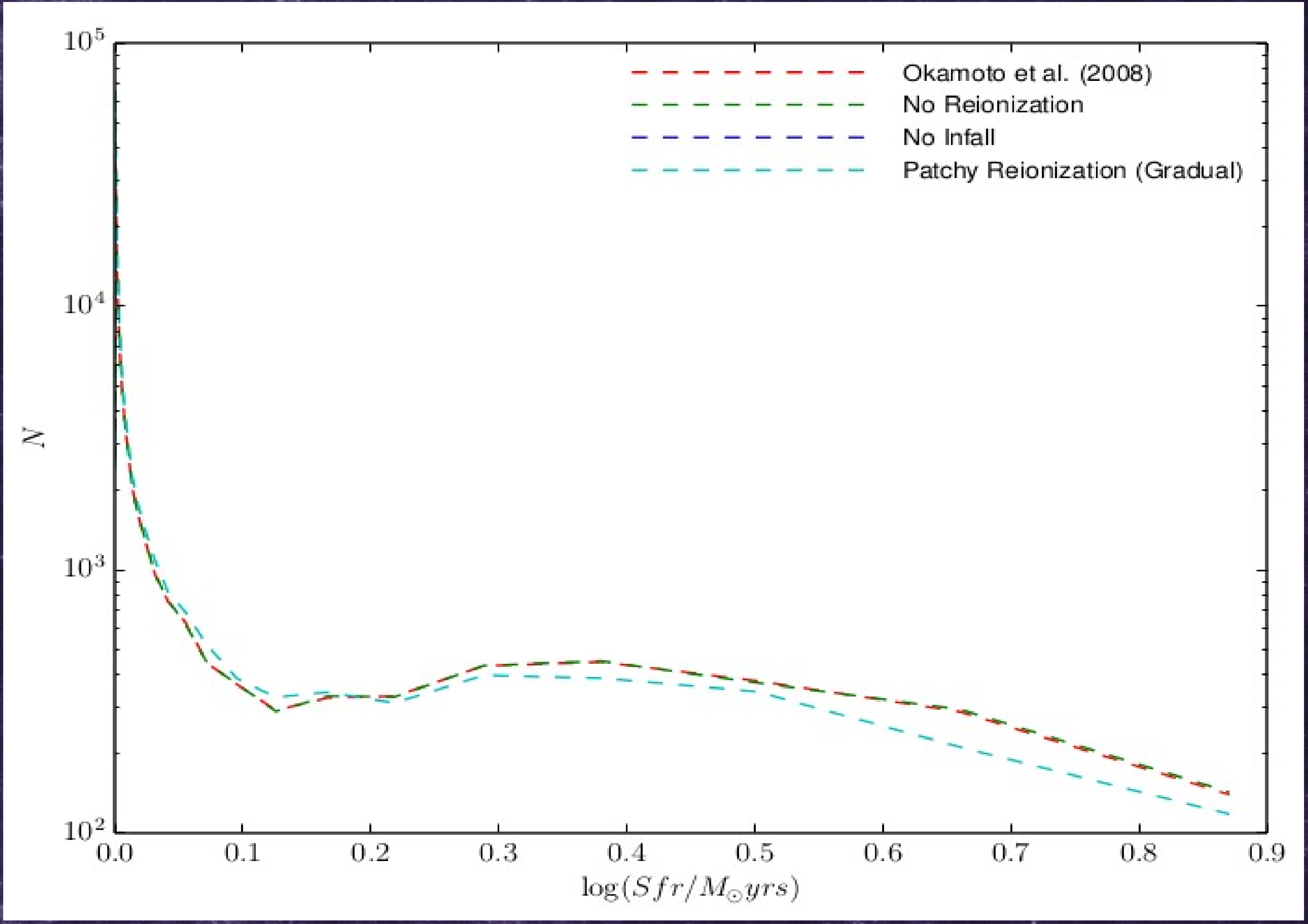


No suppression Okamoto et al. Gradual supp. model

The vast parameter space can be explored quickly using semi-analytical galaxy formation models (L-Galaxies) and semi-numerical reionization modelling (Majumdar et al.).

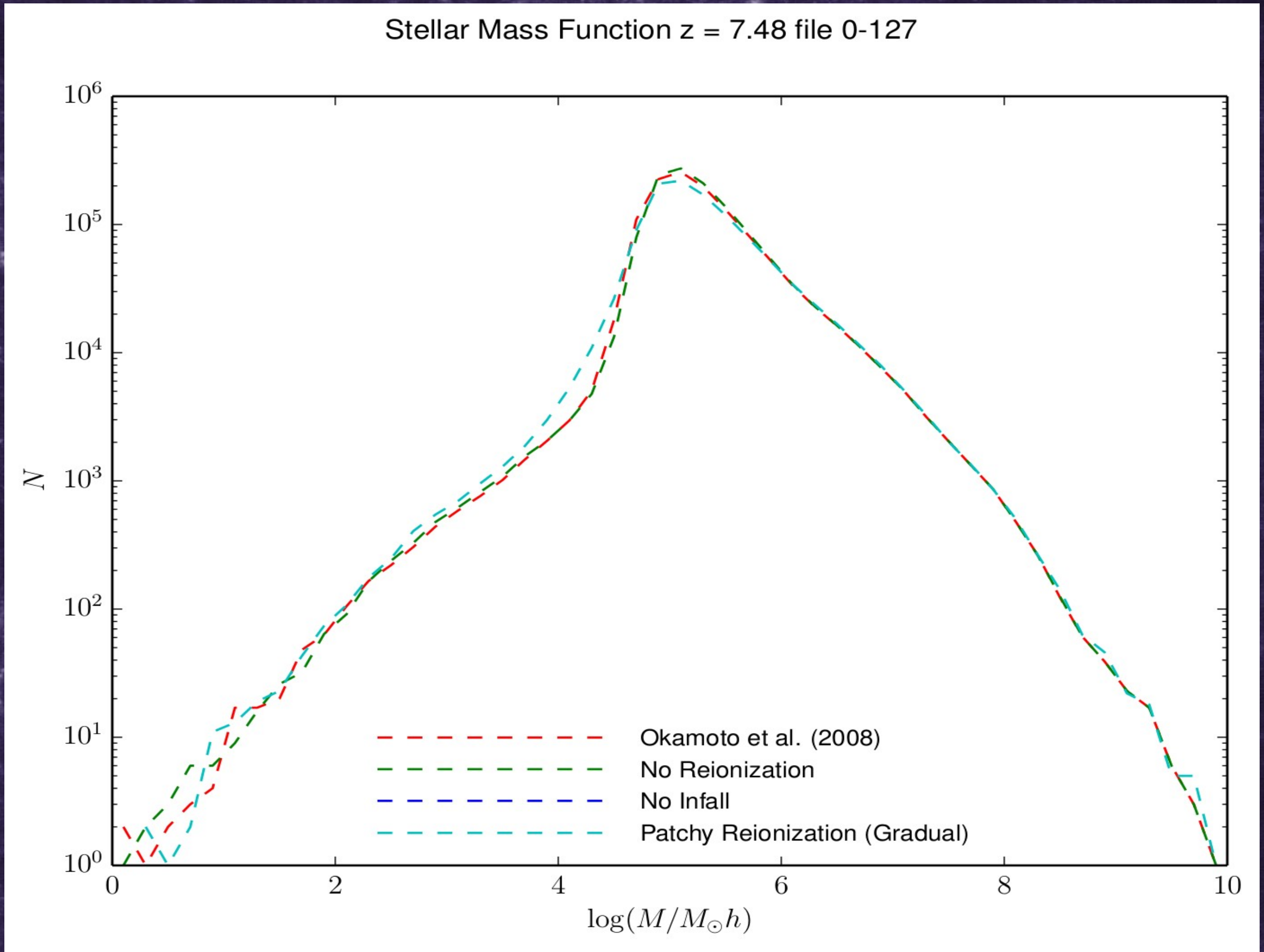
Star Formation Rate PDF

(Srisawat et al, in prep.)



Stellar Mass Function vs Stellar Mass

(Srisawat et al, in prep.)



Summary

- Structure formation at high-z is quite different from low-z.
- Precision mass function fits good to very high redshift are now available. Local nonlinear halo bias also available and behaviour (mean and scatter) understood.
- Very long wavelength density fluctuations significantly increase reionization patchiness and 21-cm signal.
- Large FOV (multiple degrees) is required for LOFAR, SKA and other future experiments.
- Reionization feedback significantly affects early galaxy formation (cold gas fraction and star formation). Detailed radiative hydrodynamics required for reliable modelling.
- The most extreme EoR models should be possible to discriminate with first generation of 21-cm experiments (e.g. LOFAR), much more will be achieved by SKA.