Reionization, small-scale structure and feedback

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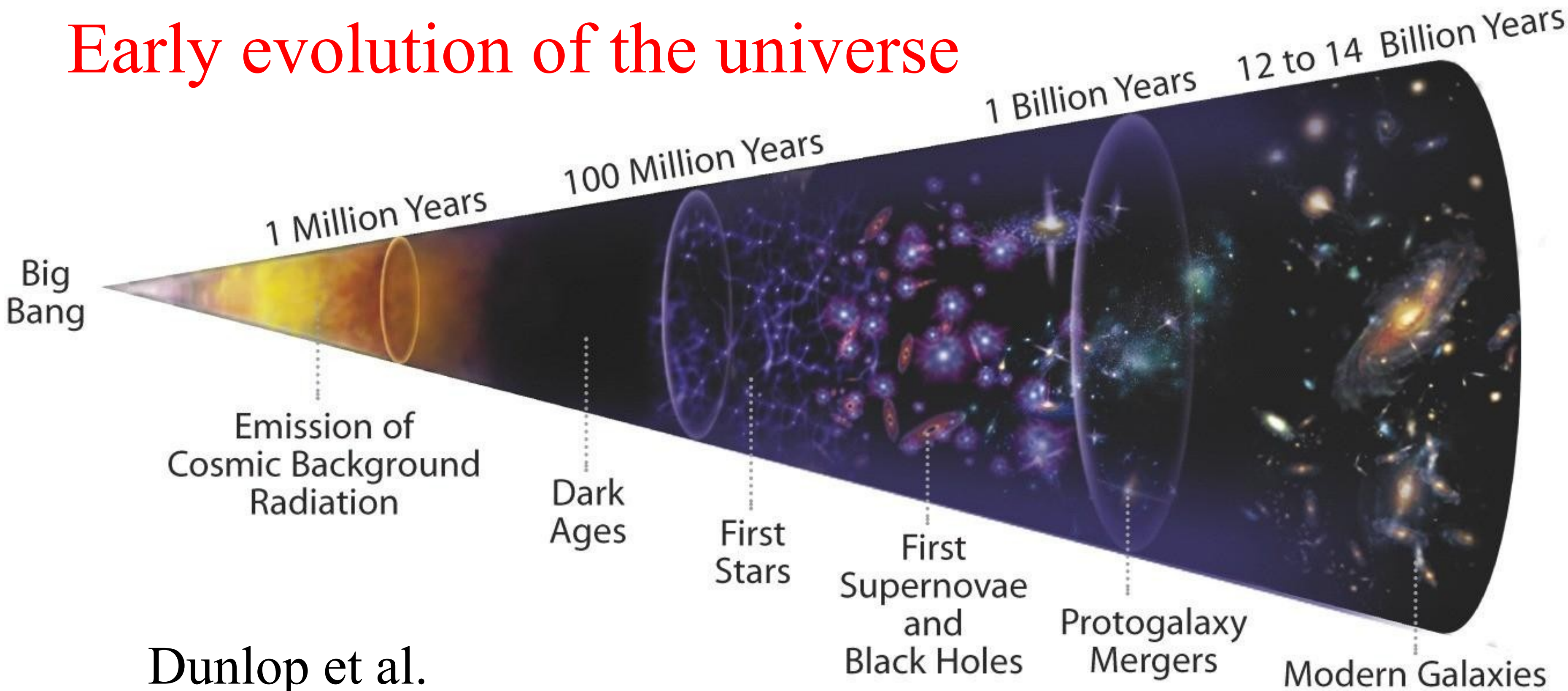
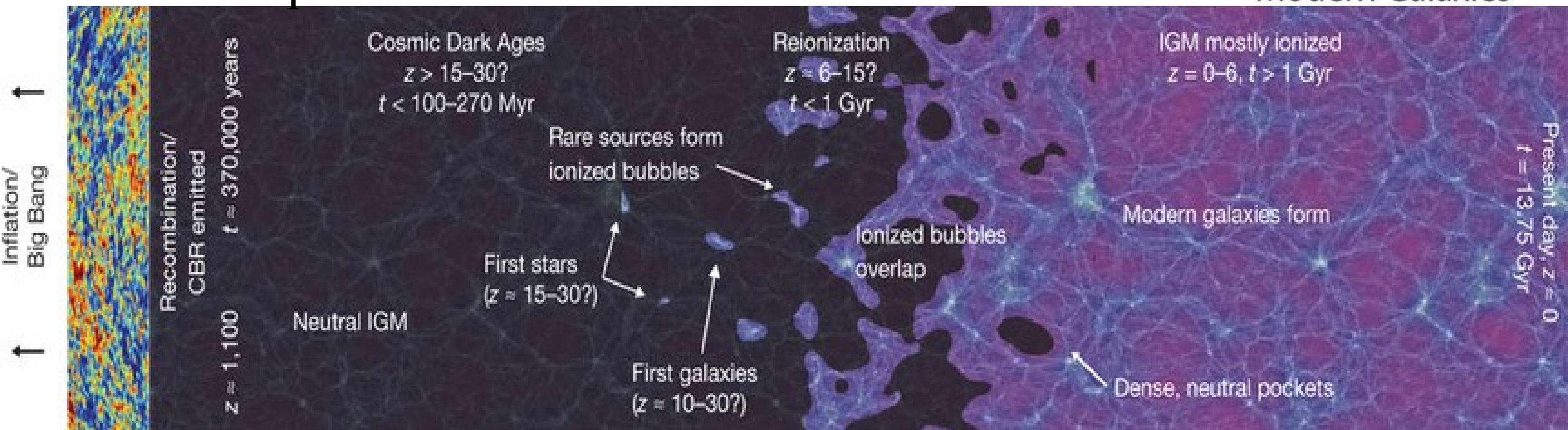
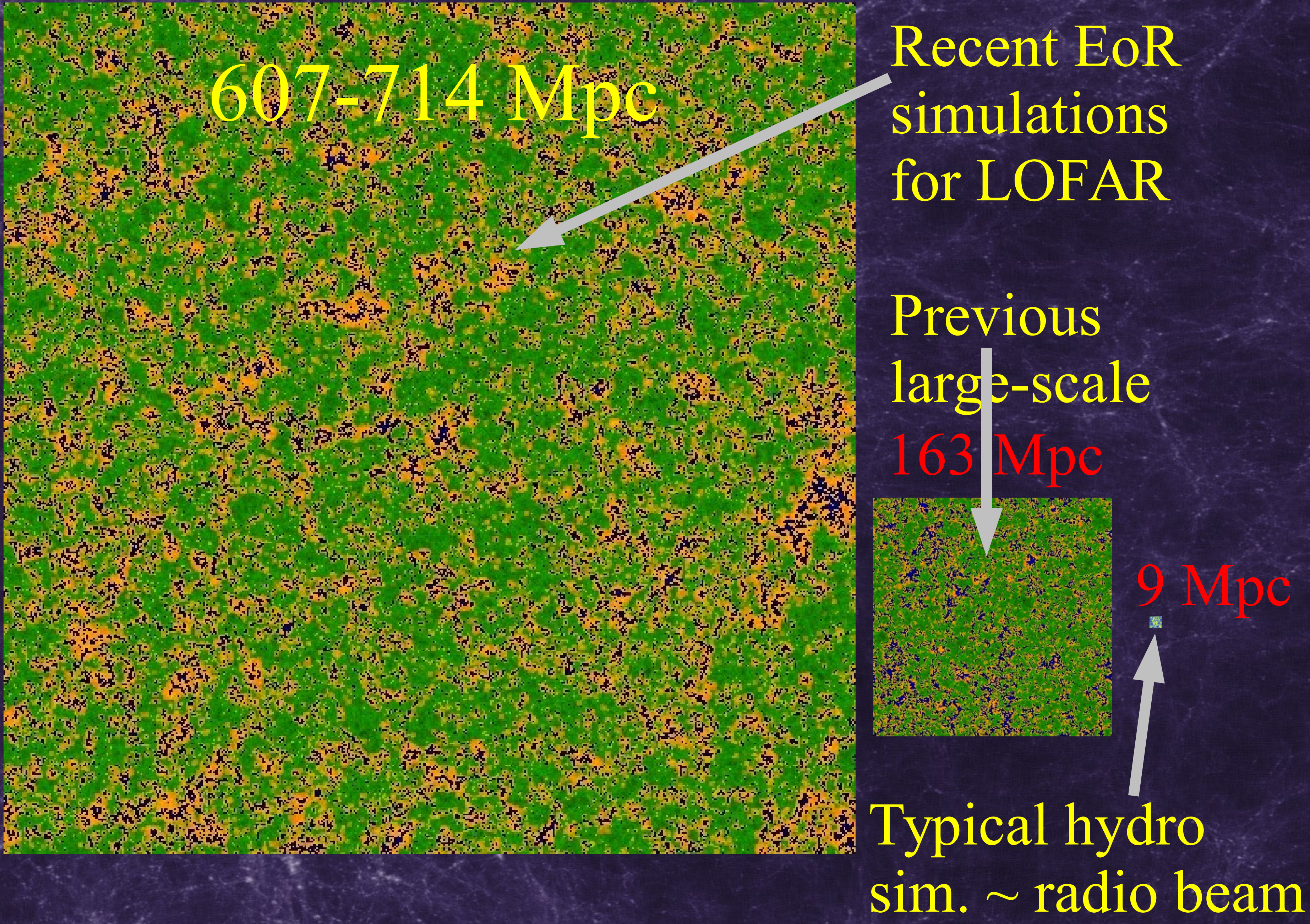
Early evolution of the universe



Dunlop et al.



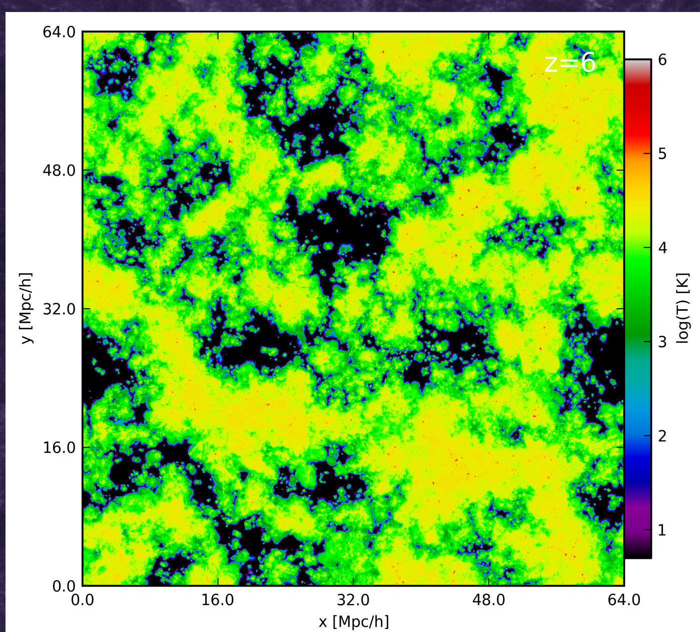
Scales of reionization

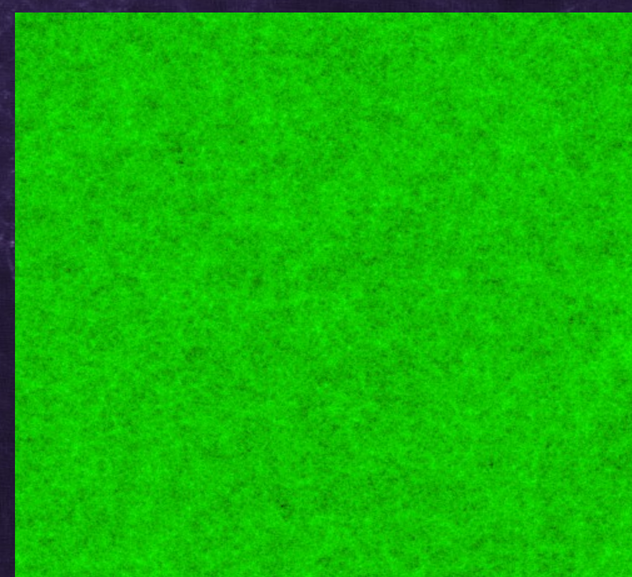


The Program

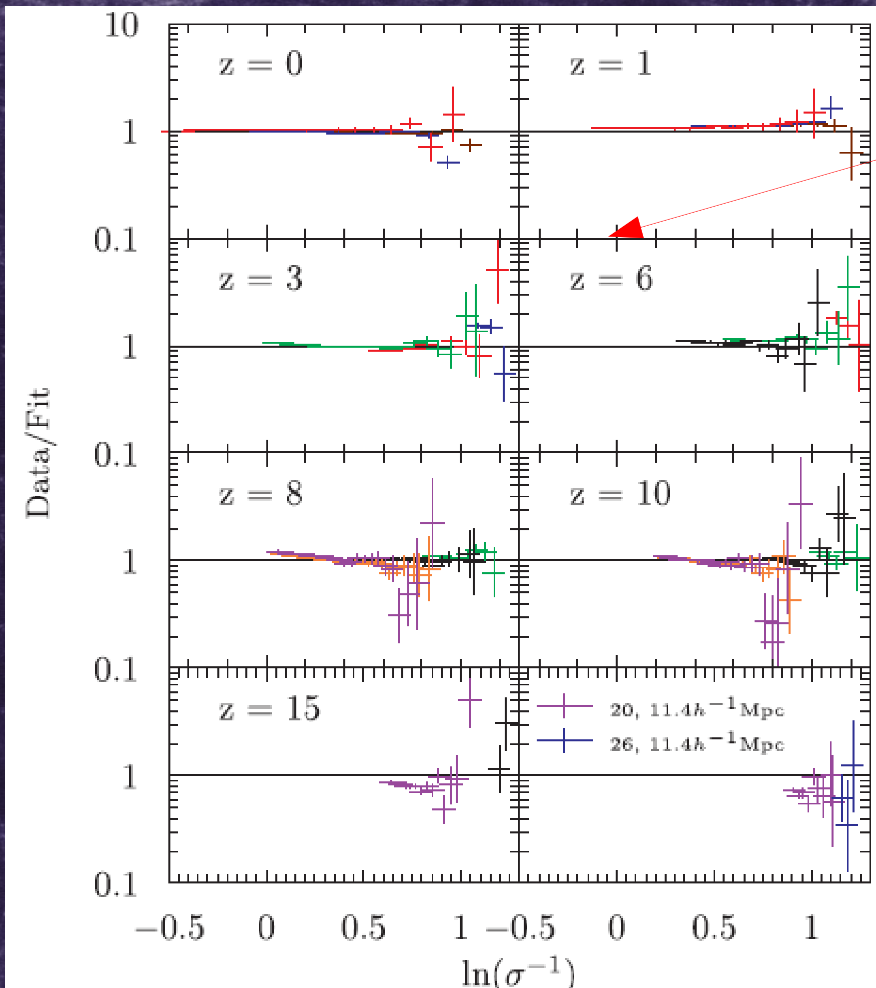
- INCITE (DOE), PRACE (Multi-scale Reionization project):
- Cosmological radiative hydro
- 60M +21M + 3.5M core-h, CPU+GPU, AMR
- 16-64 Mpc/h
- 4096^3 grid, 4096^3 part.+AMR sims
- Goals: detailed modelling of gas effects; LG reionization

- 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

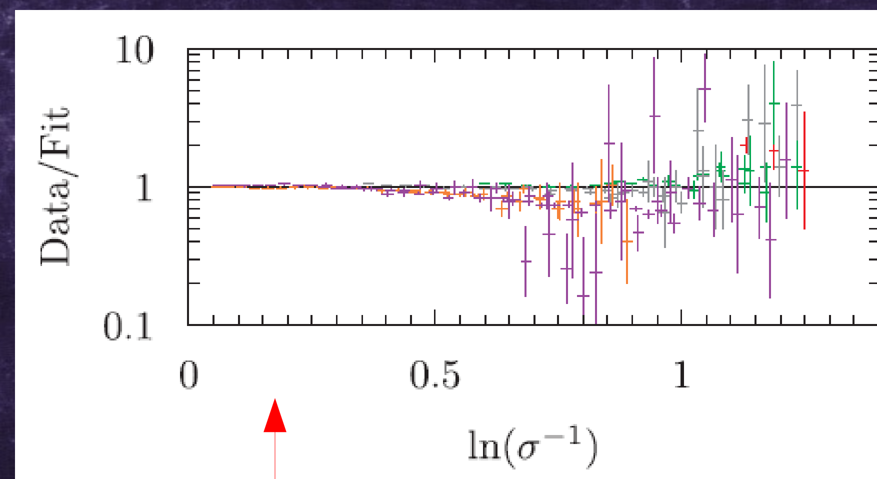




Halo mass function through the cosmic ages
(Watson et al., 2013, MNRAS,433,1230)



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

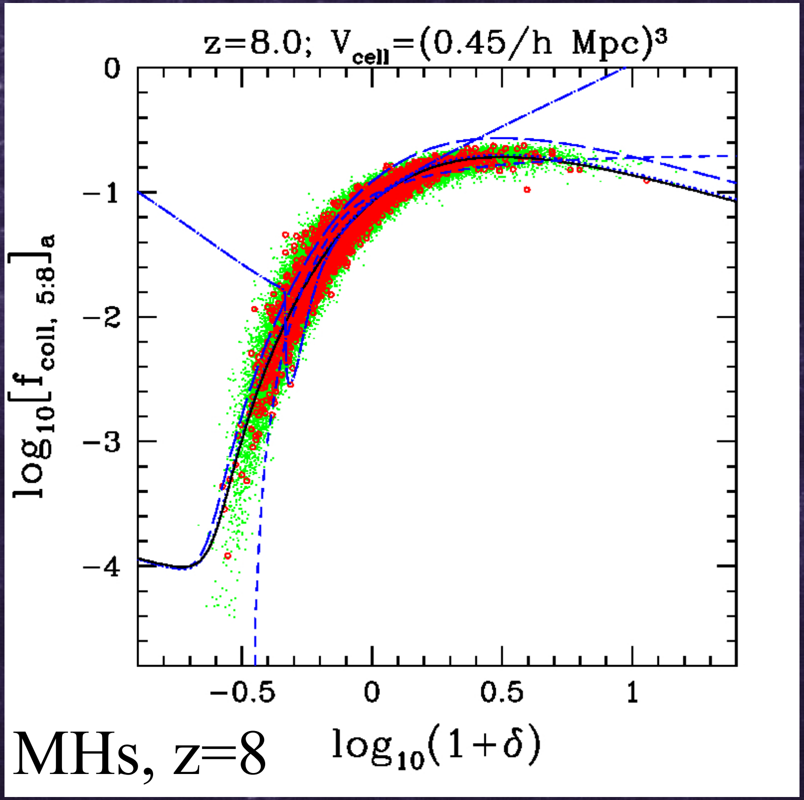


- Separate fits provided for high-z (6<z<26).

Modelling the small-scales

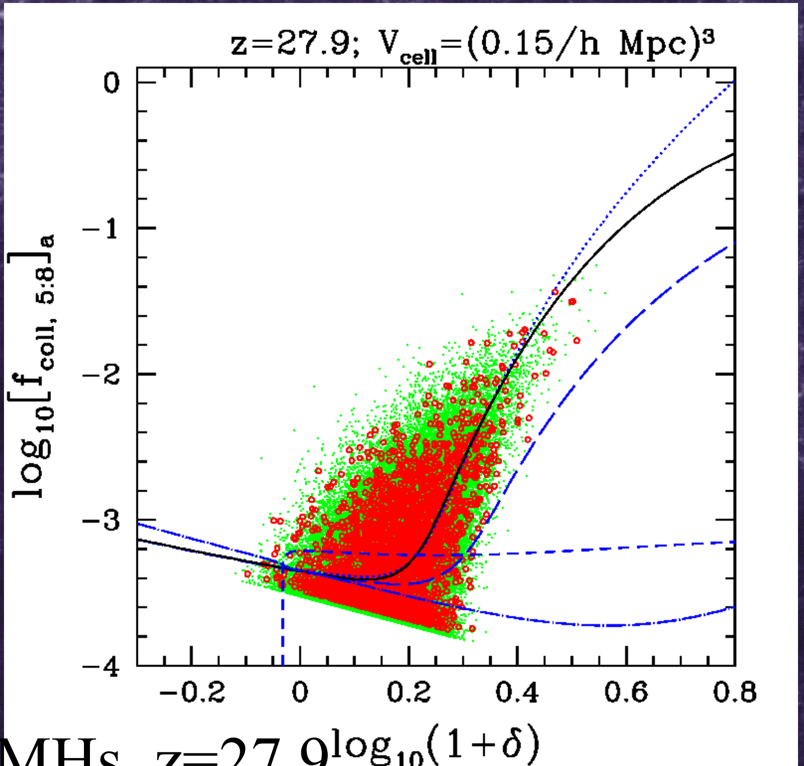
(Ahn et al., submitted; Koda et al., in prep.; Shukla, Mellema & Iliev, in prep.)

- 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

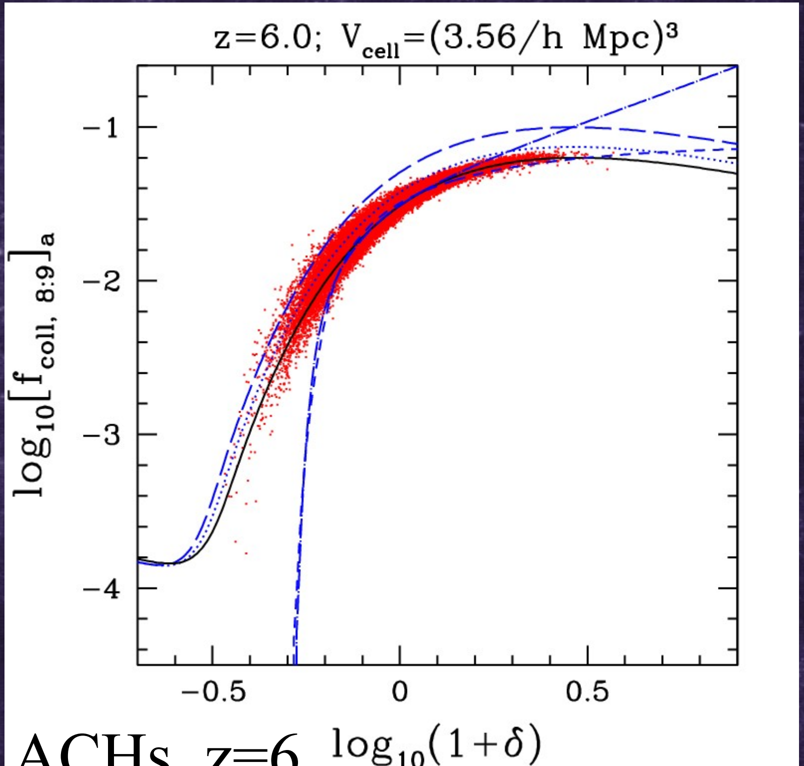


Modelling the small-scales

(Ahn et al., submitted)



MHs, z=27.9



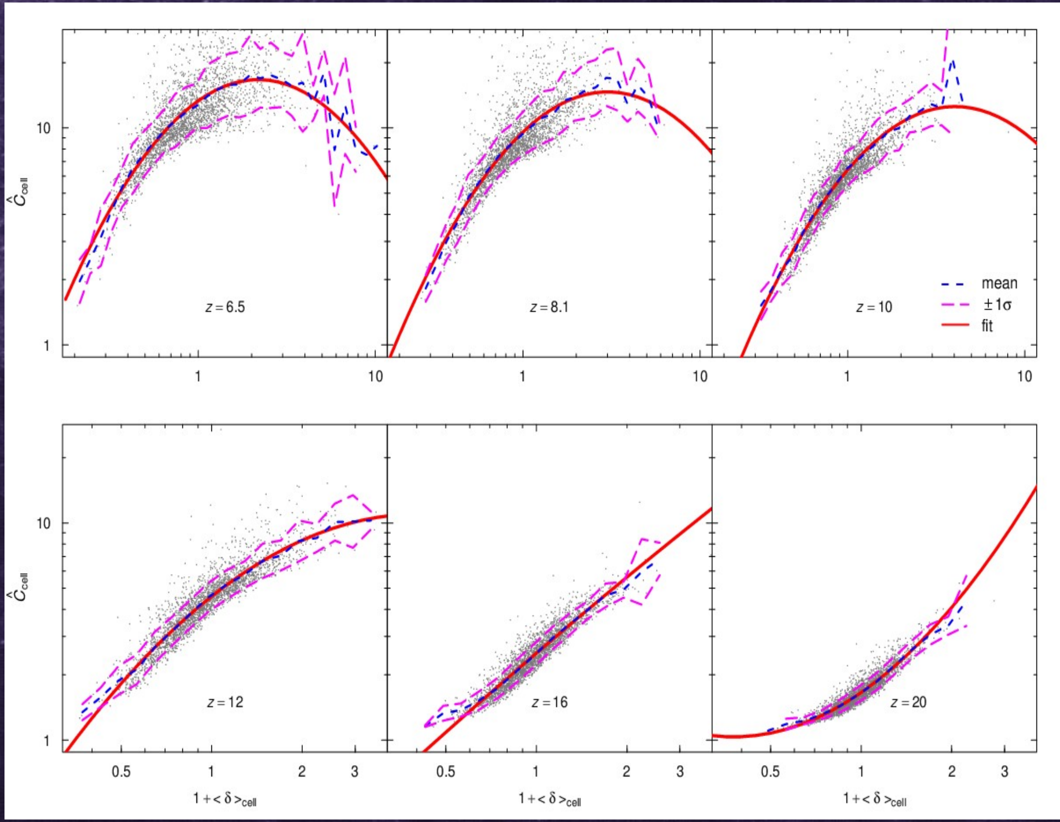
ACHs, z=6

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: gas clumping

(Koda et al., in prep.)

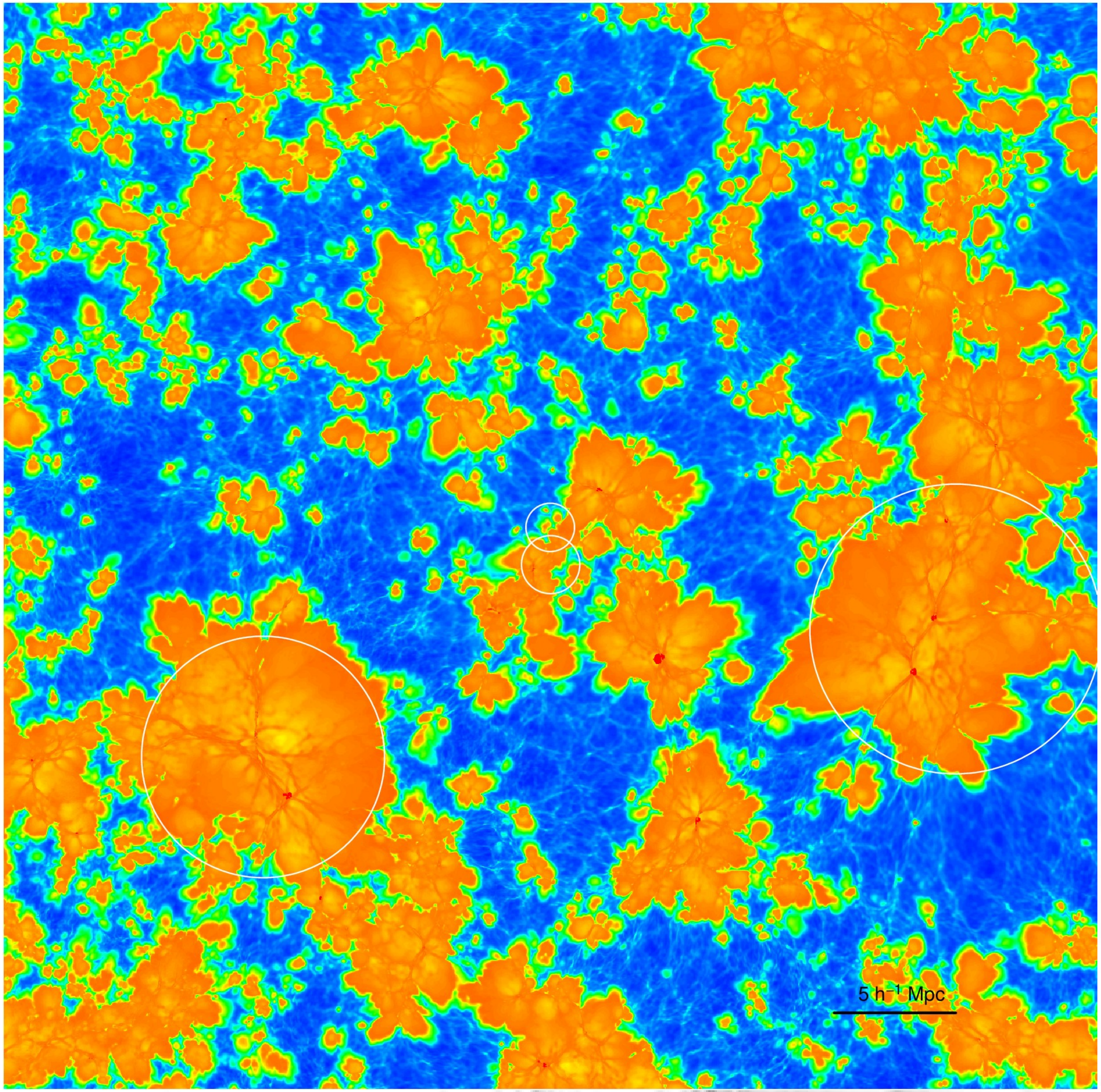
- Strong correlation with local density
- Fits derived based on high-res simulations and used in large-scale ones



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.
- 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.

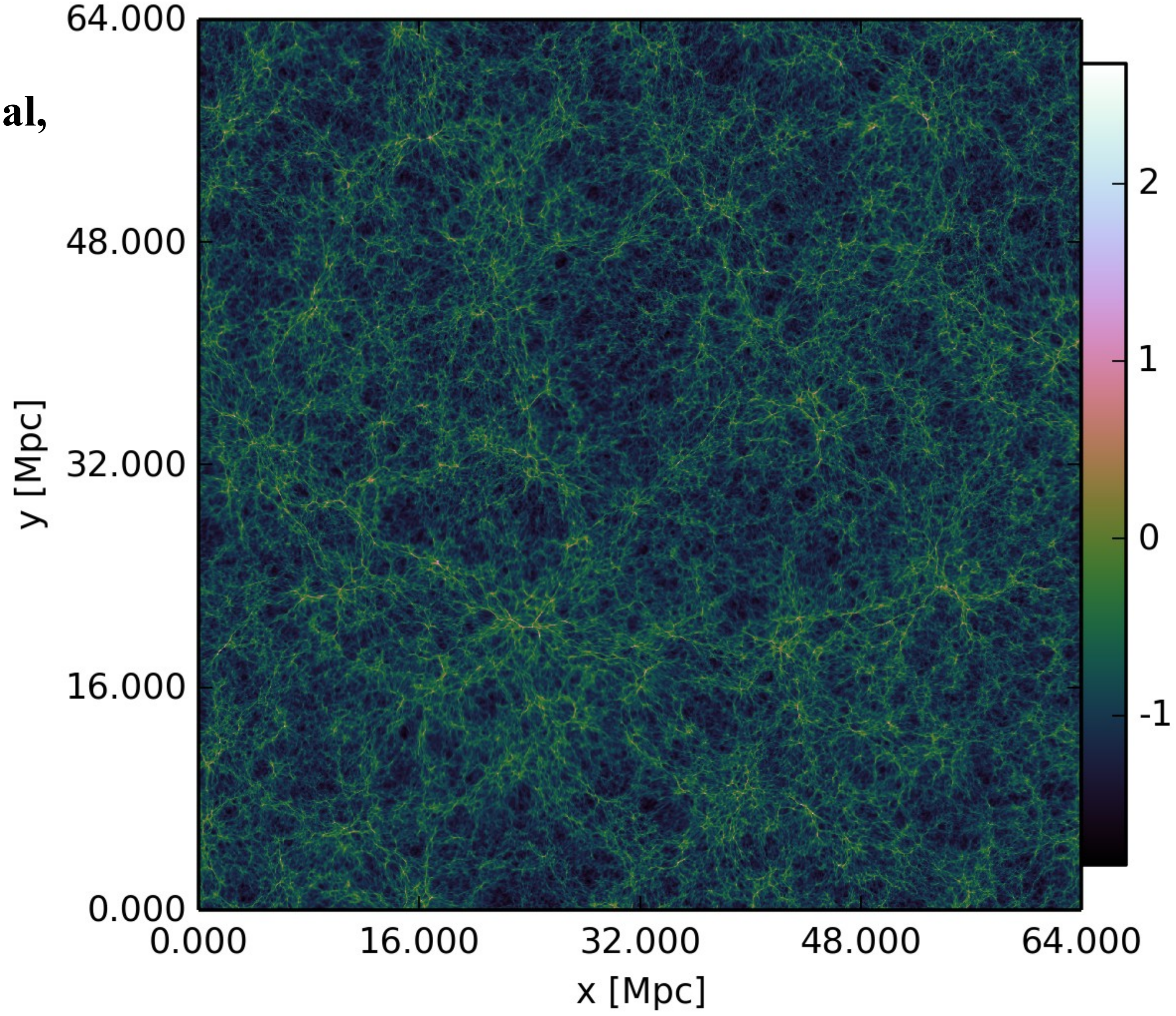
Cosmic Dawn simulation: reionization of the Local Group



Cosmic Dawn simulation, Ocvirk et al, in prep.

Gas overdensity evolution

Cosmic Dawn simulation (Ocvirk et al, in prep.)



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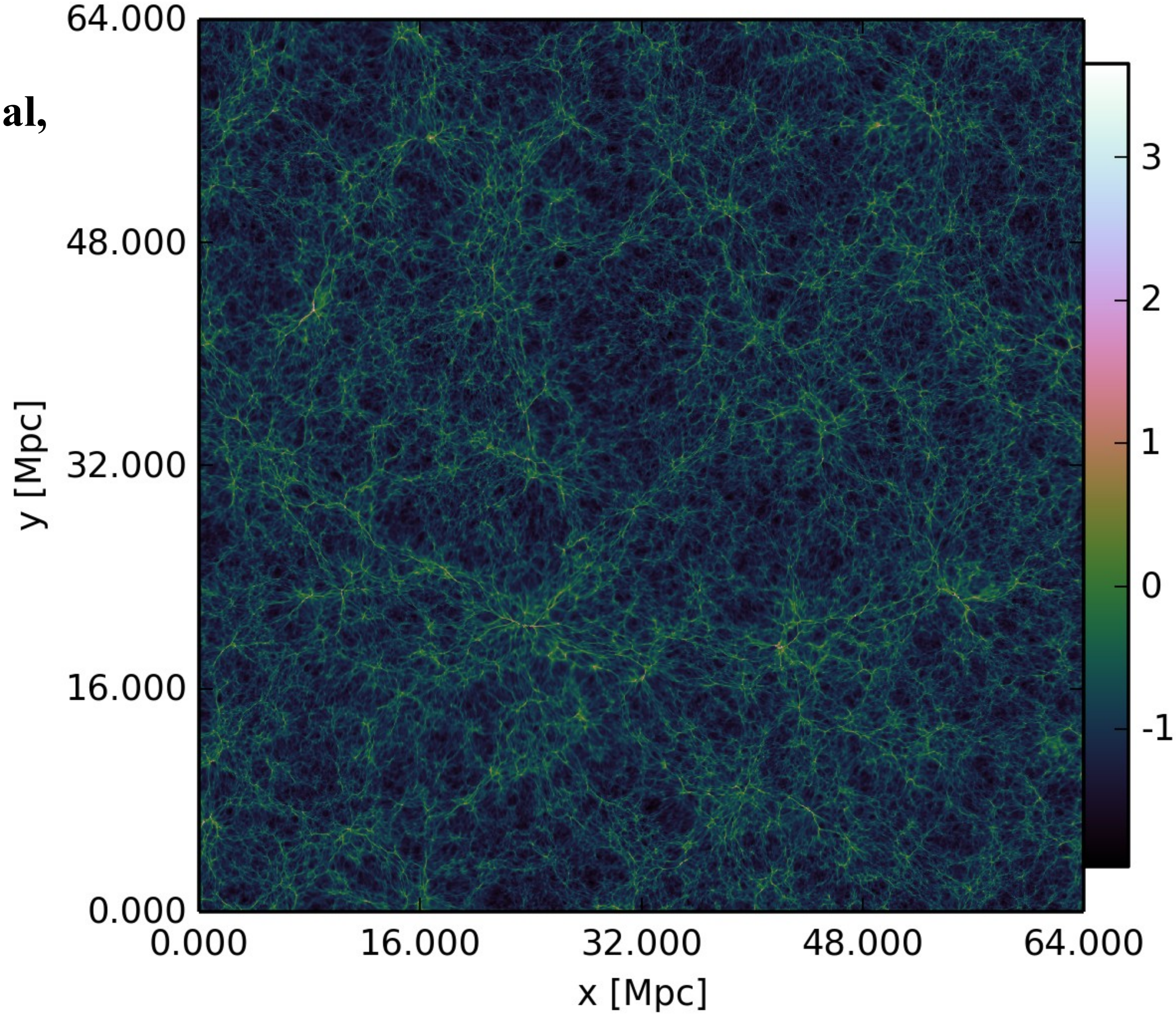

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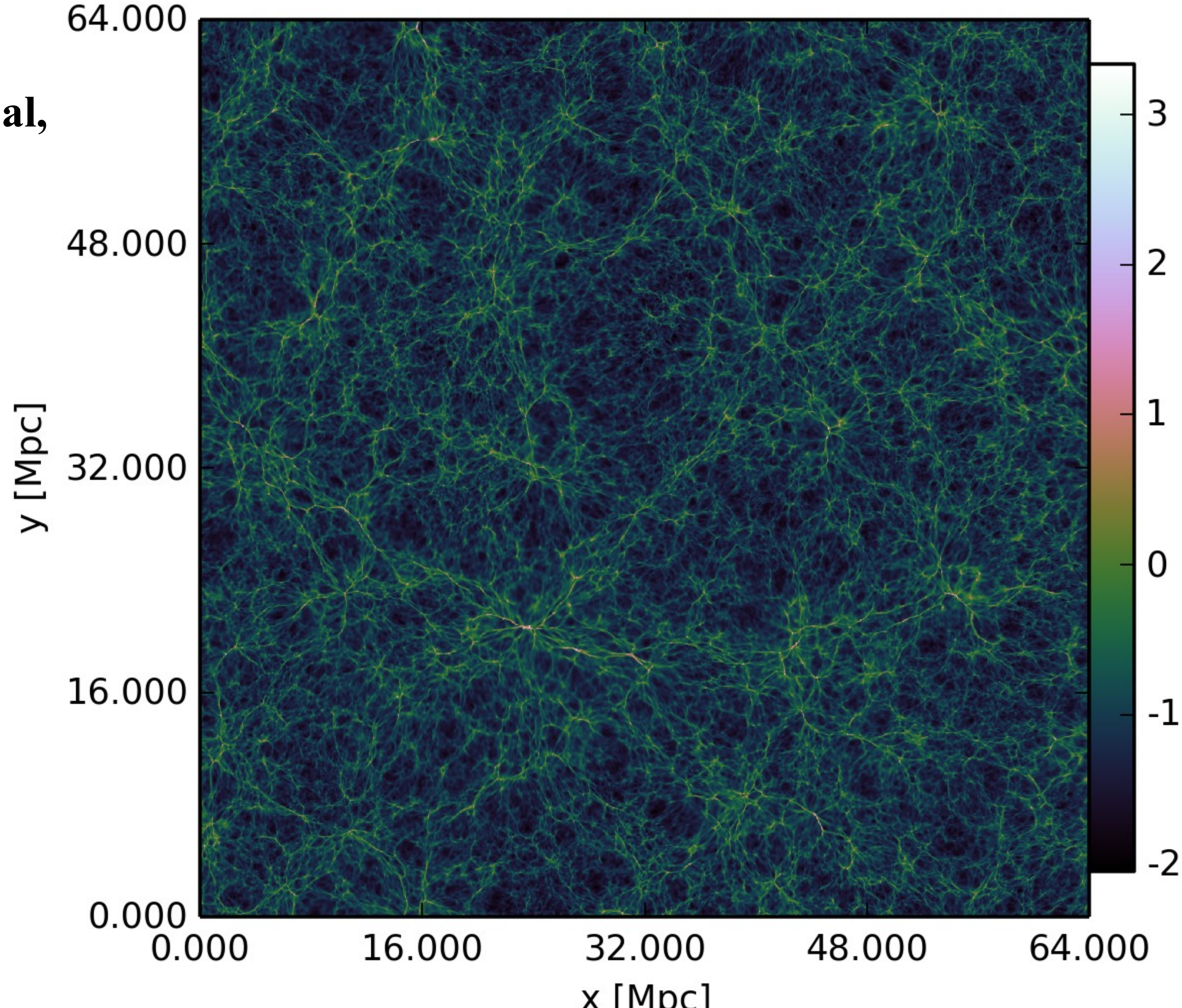
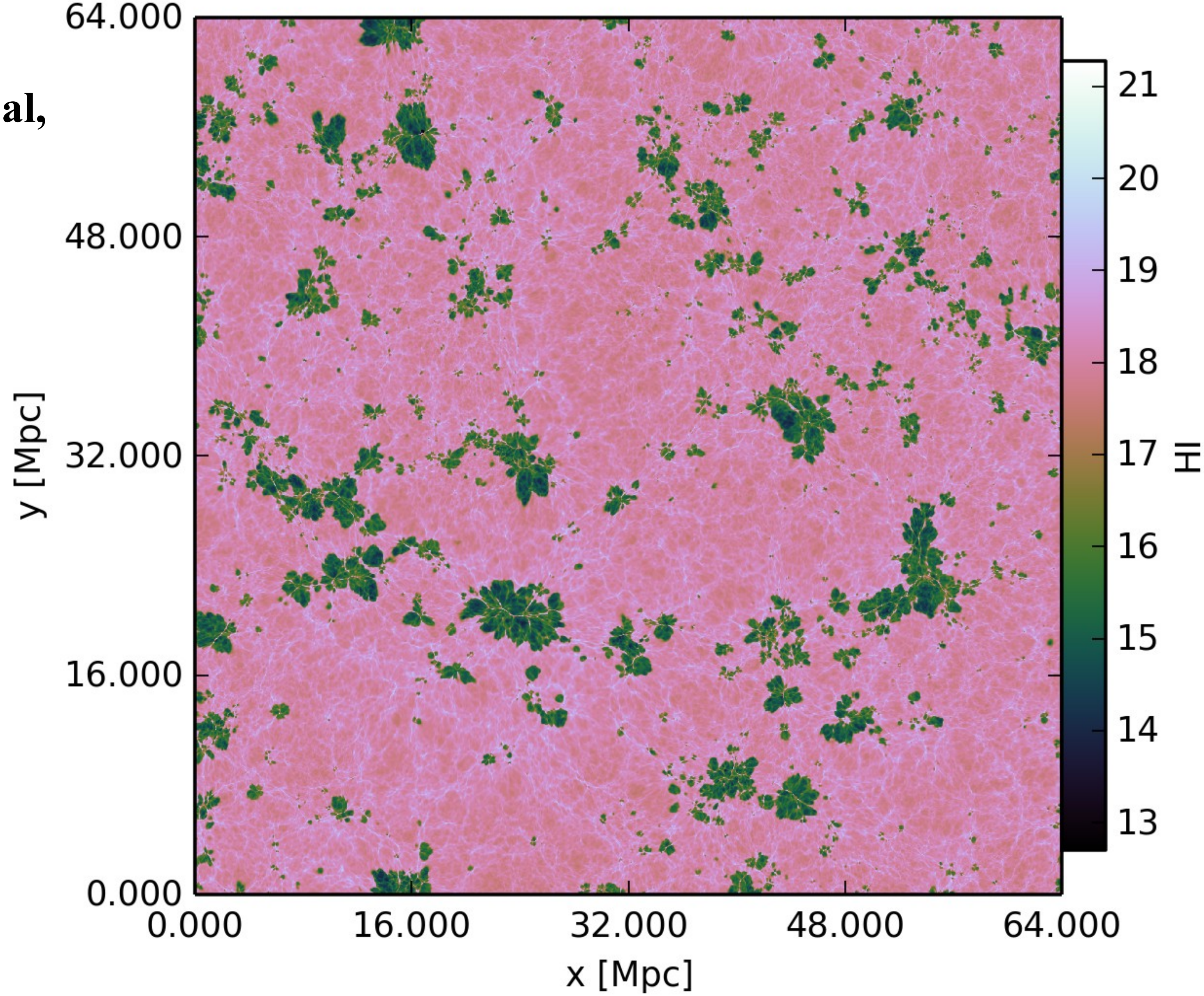


HI column density evolution

Cosmic Dawn simulation (Ocvirk et al, in prep.)



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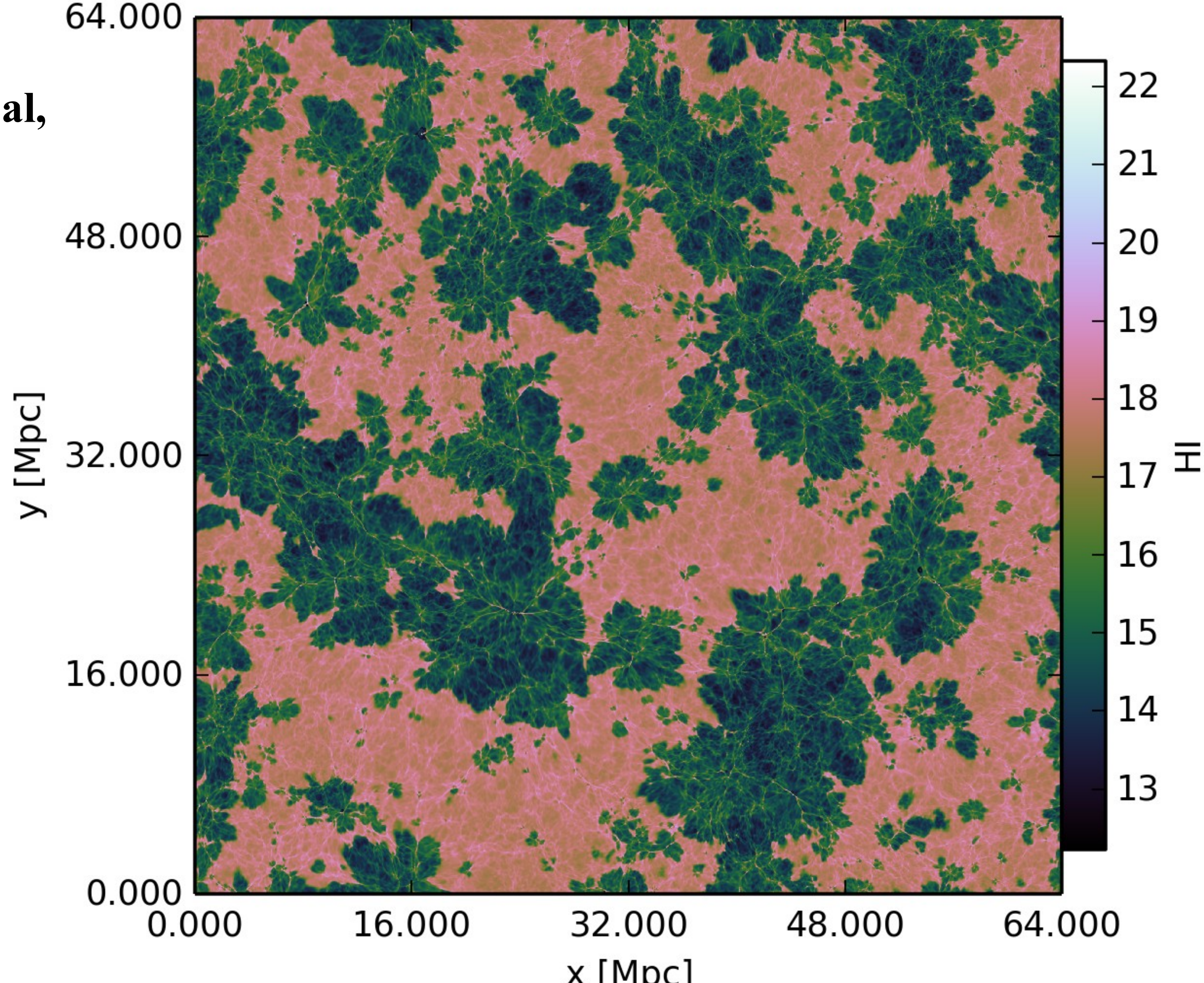

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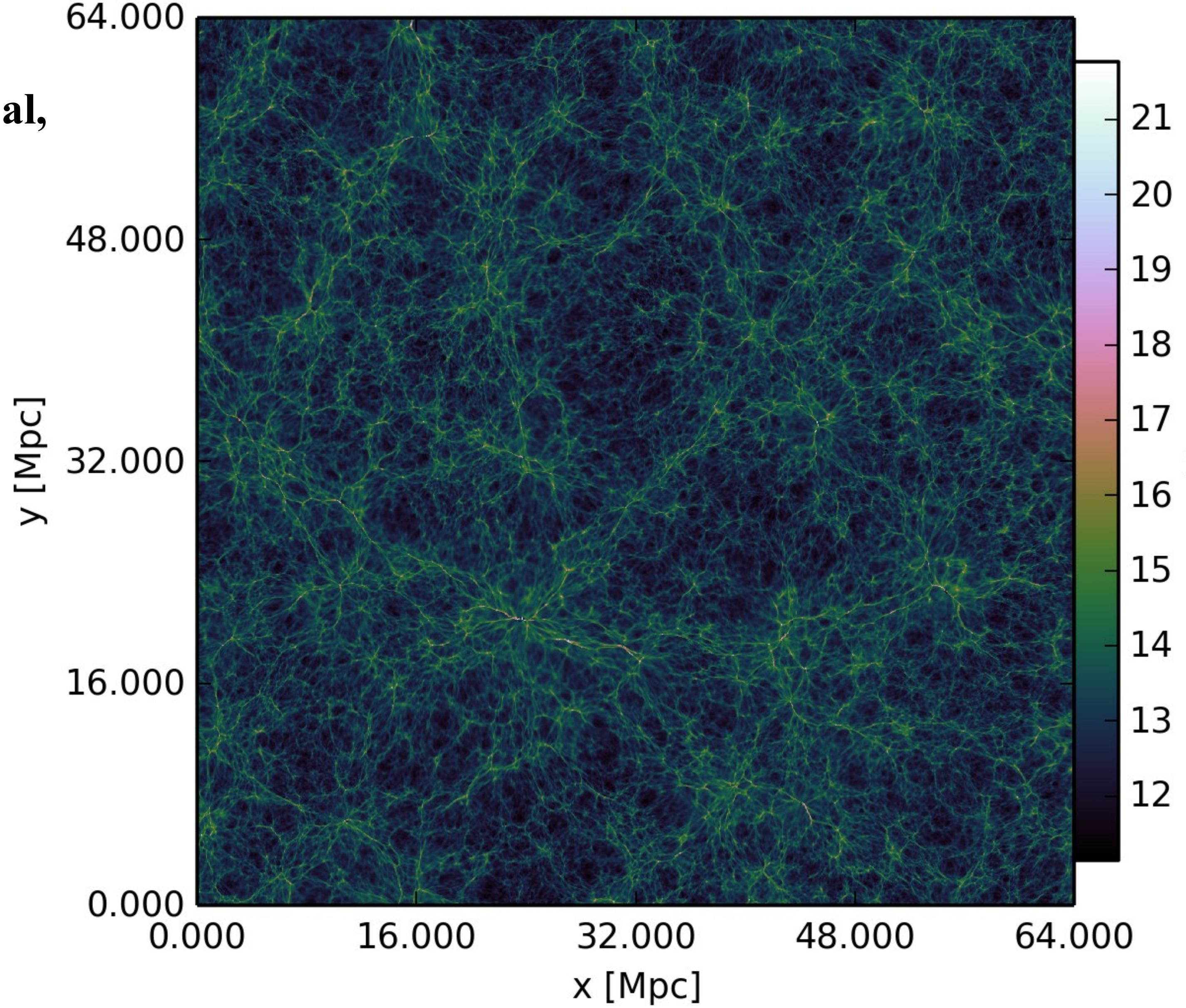
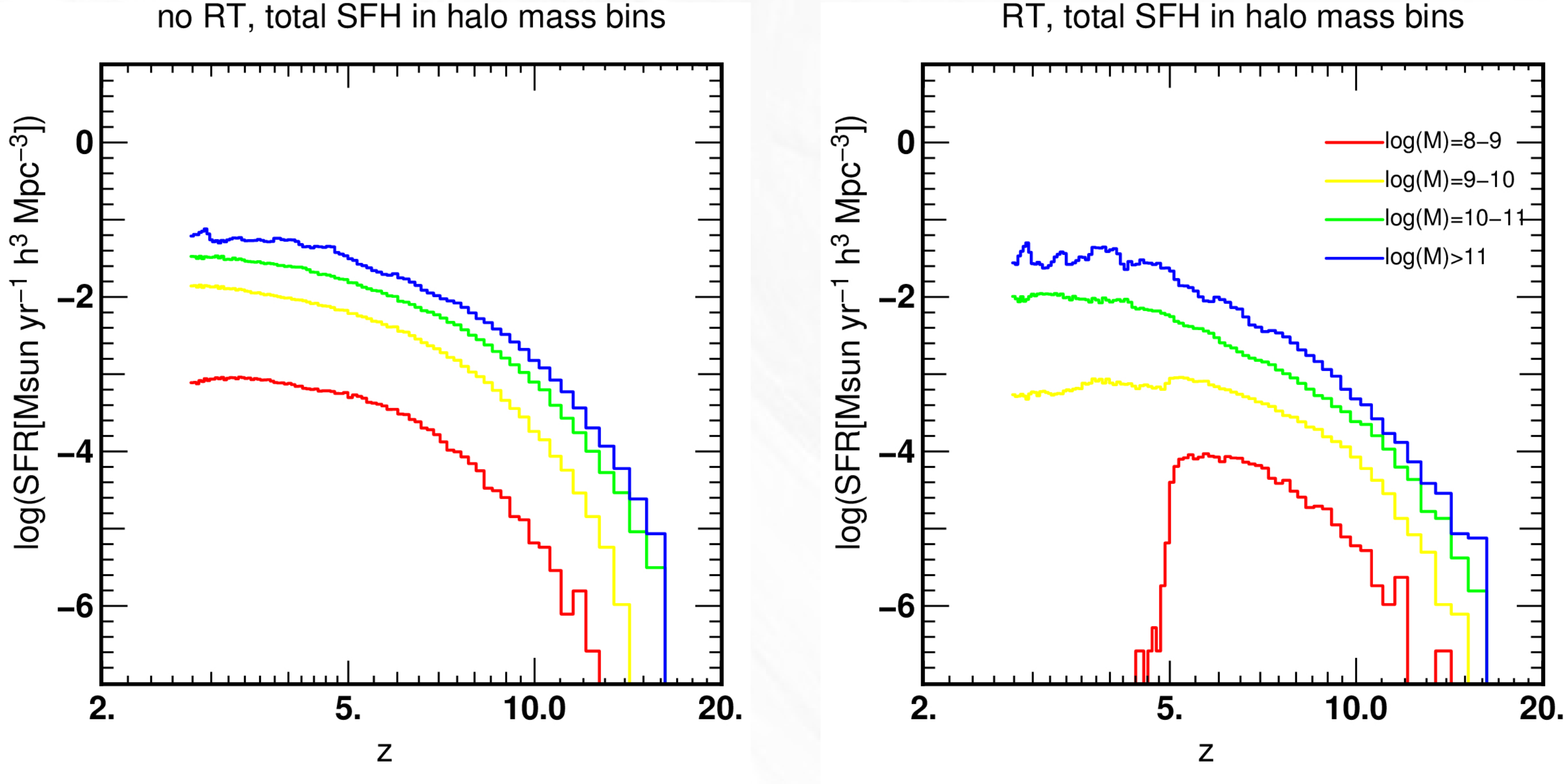
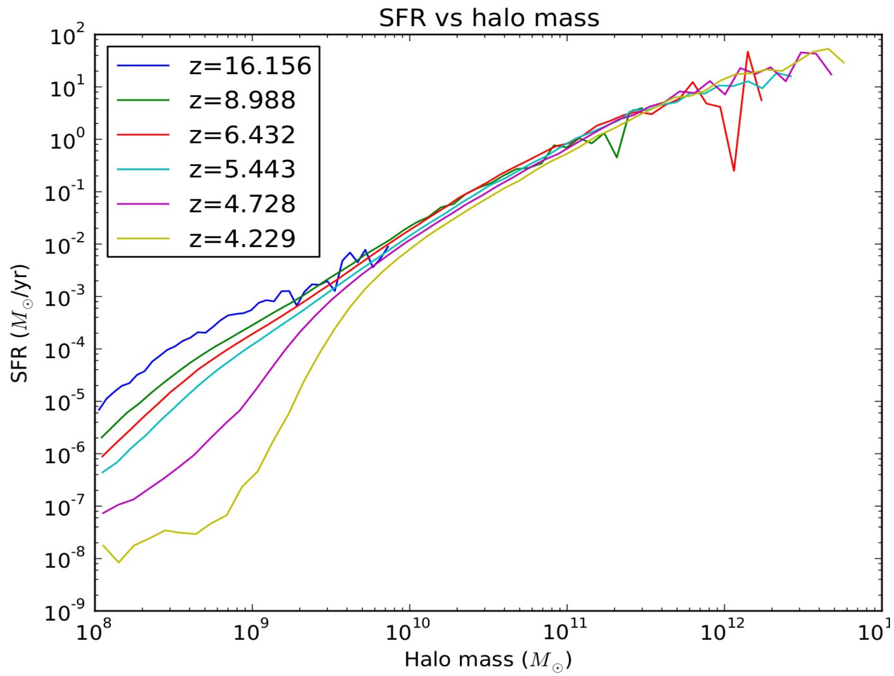


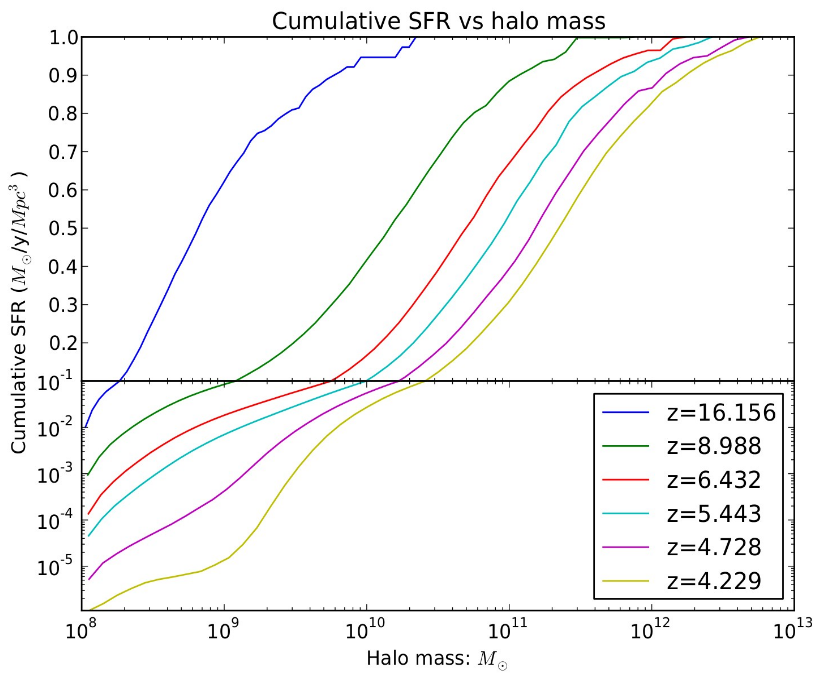
SFR and radiative feedback



Cosmic Dawn simulation (Ocvirk et al, in prep.)

SFR dependence on halo mass

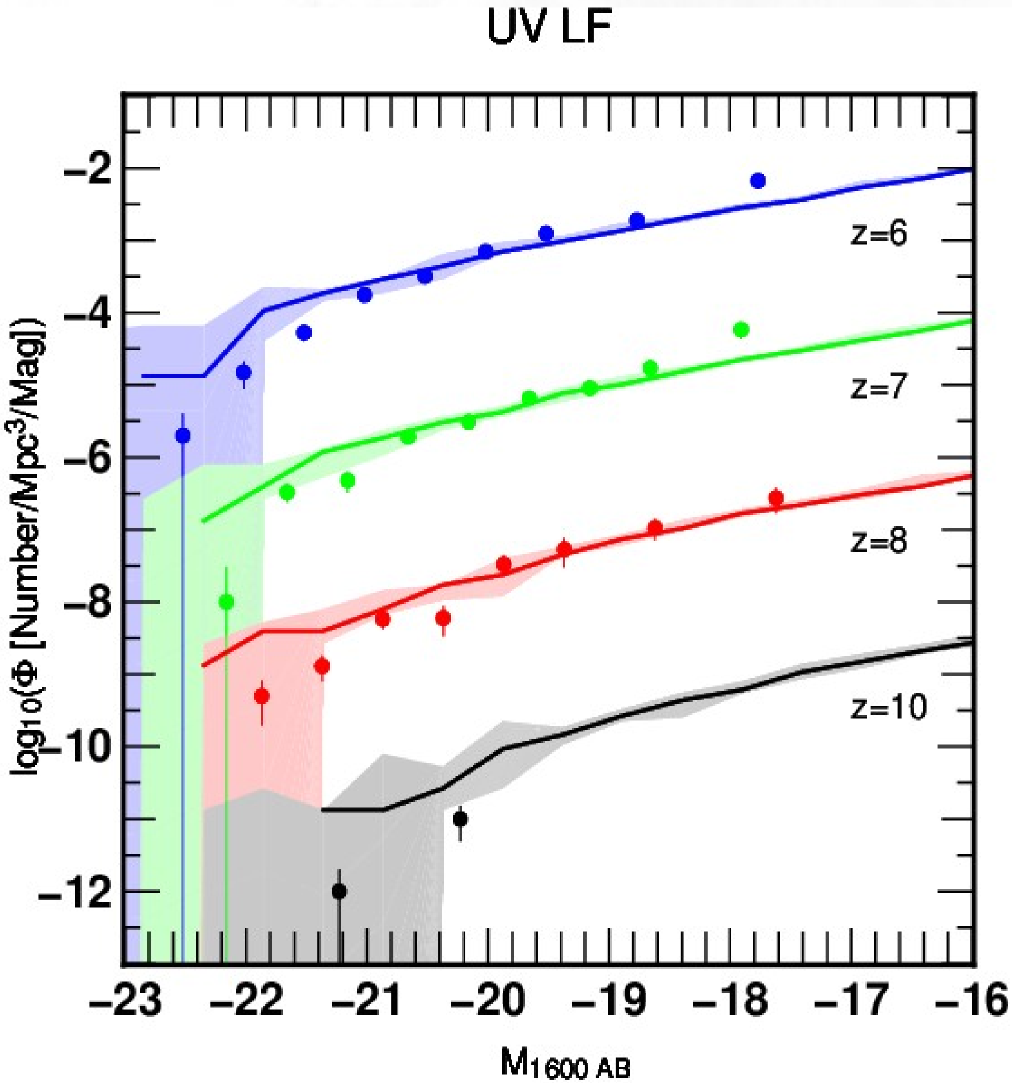




Cosmic Dawn simulation

(Ocvirk et al, in prep.)

Cosmic Dawn: Galaxy UV luminosity function



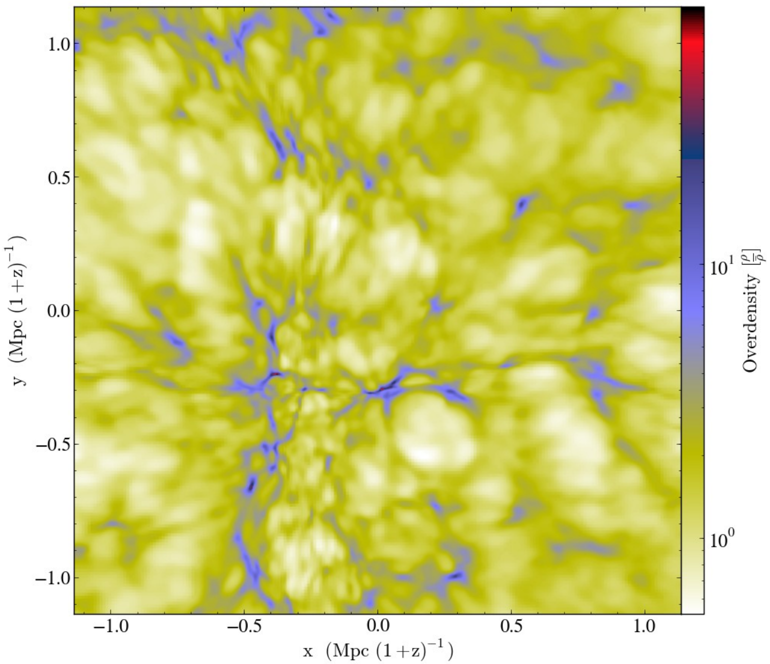
Cosmic Dawn simulation (Ocvirk et al, in prep.)

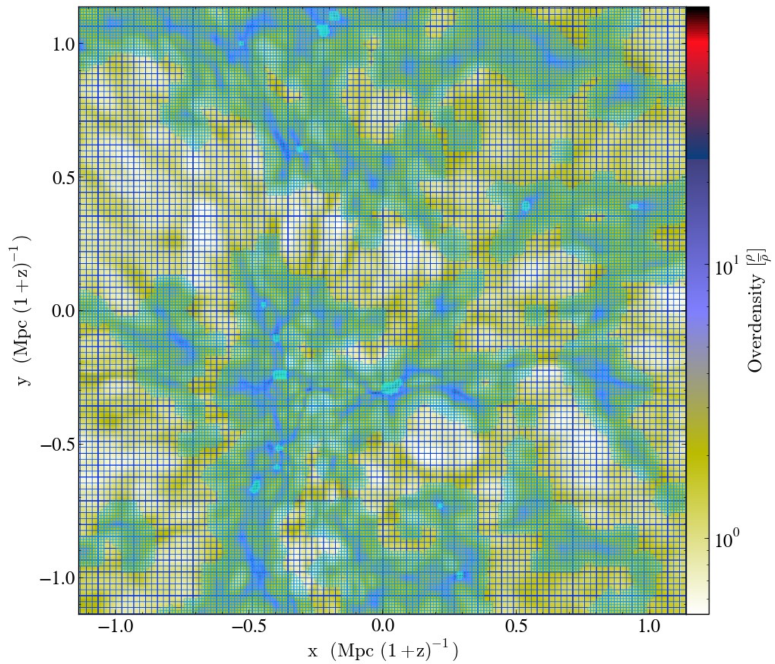
Data: Bouwens et al. 2014

M_{1600AB} based on lowest-metallicity models of Bruzual and Charlot 2003

Shaded = 5 independent 50/h Mpc^3 sub-volumes of the simulation, similar to CANDELS-DEEP field

The very small scales: cosmological zoom (AMR) simulations





(Sullivan et al., in prep.)

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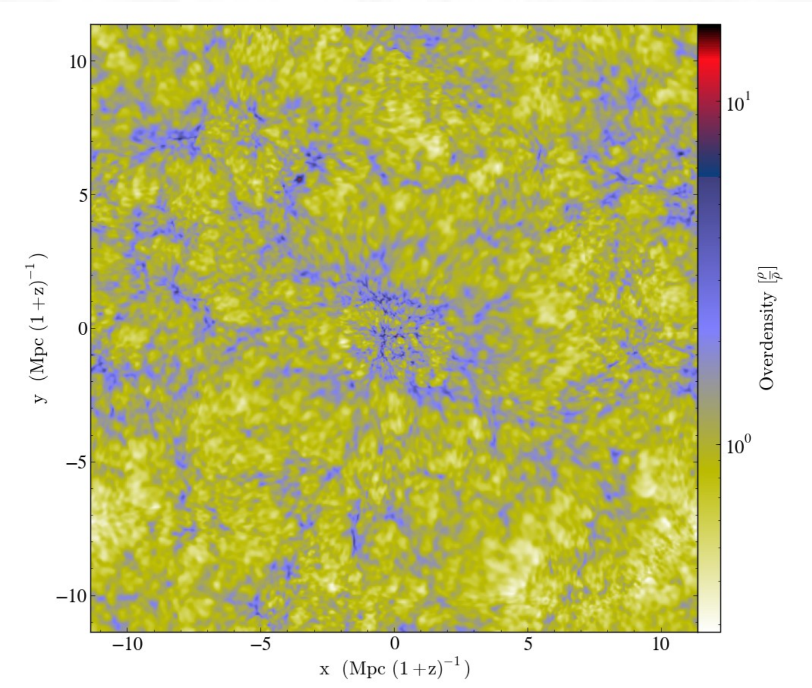
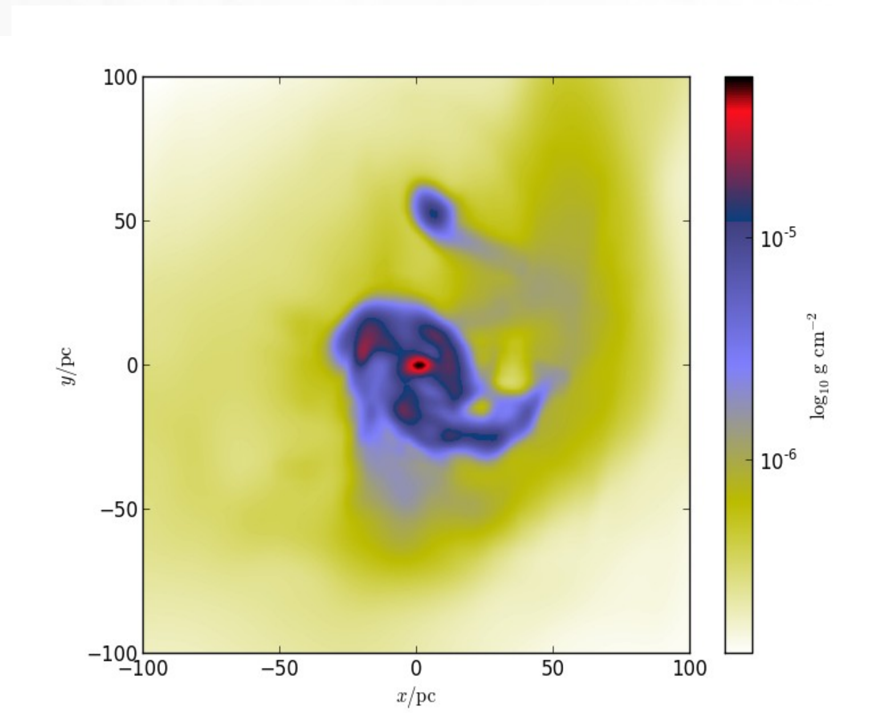




Full box: 16 Mpc/h

Zoom: 2.7 pc (proper) resolution

(Sullivan 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

(Sullivan et al., in prep.)

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

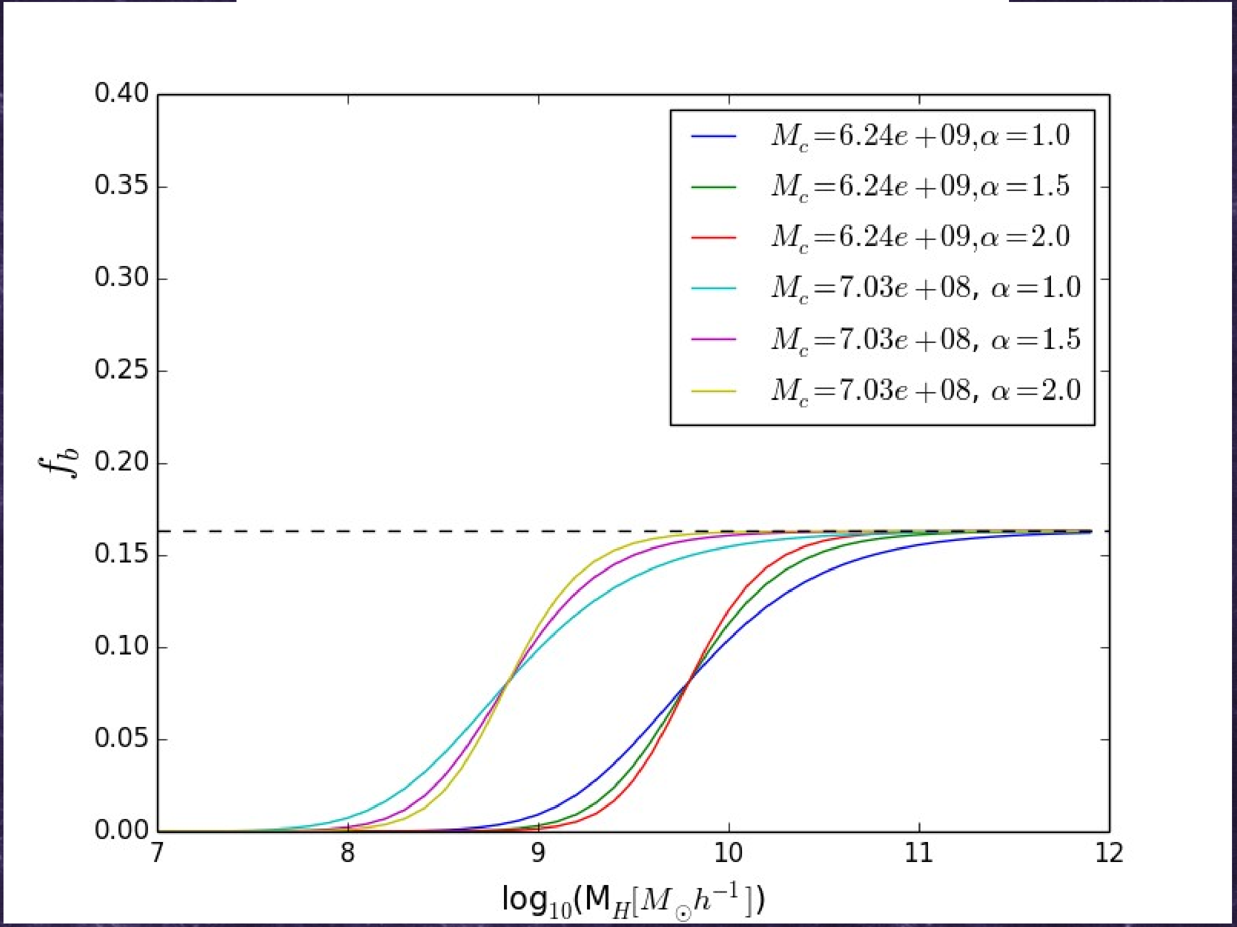
$$f_{\rm b}(M,z) = \langle f_{\rm b}\rangle \left\{1 + (2^{\alpha/3} - 1)\left(\frac{M}{M_{\rm c}(z)}\right)^{-\alpha}\right\}^{-\frac{3}{\alpha}}$$

- $M_c(z)$ 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

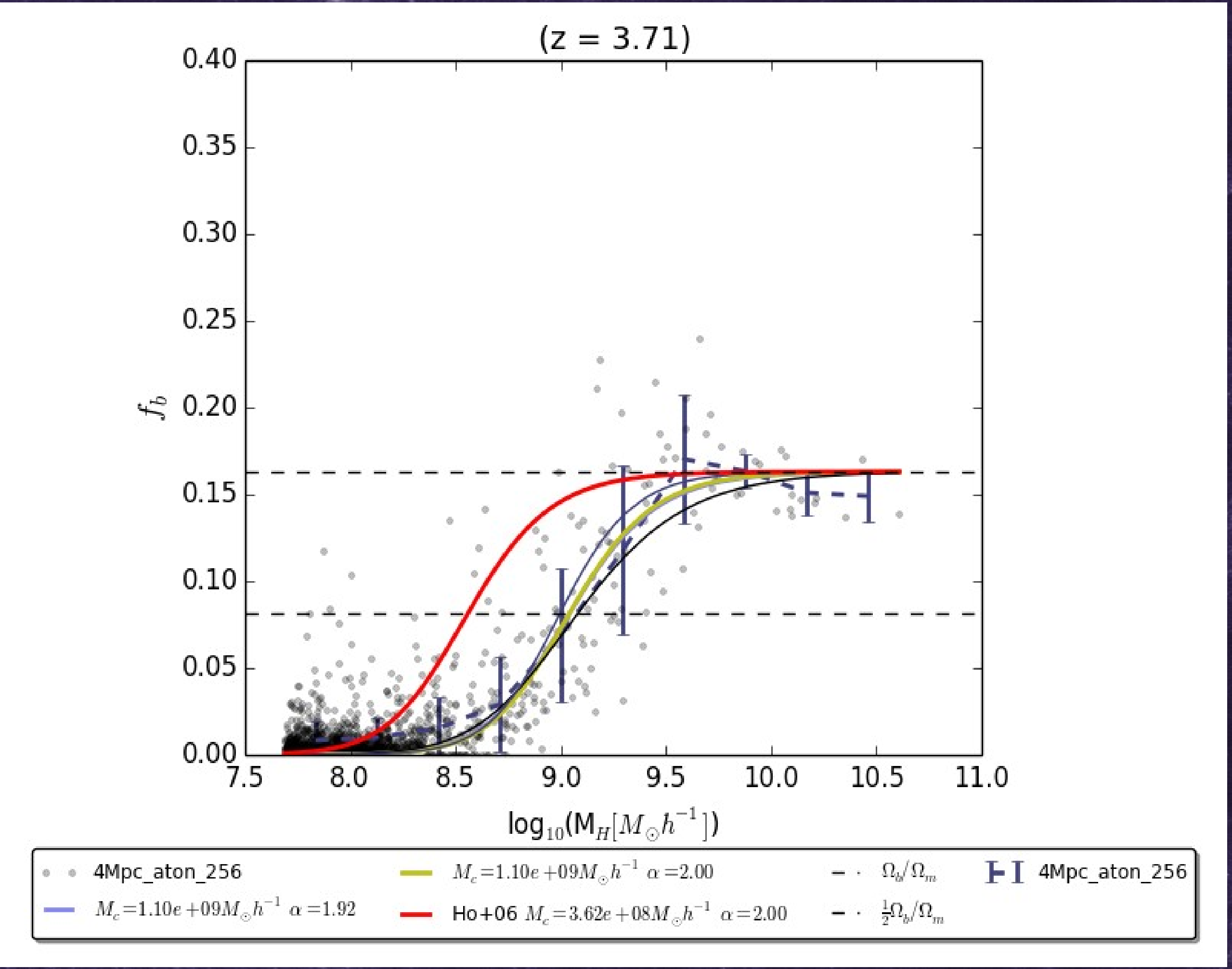
(Sullivan et al., in prep.)

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



Distinct Halos Only...

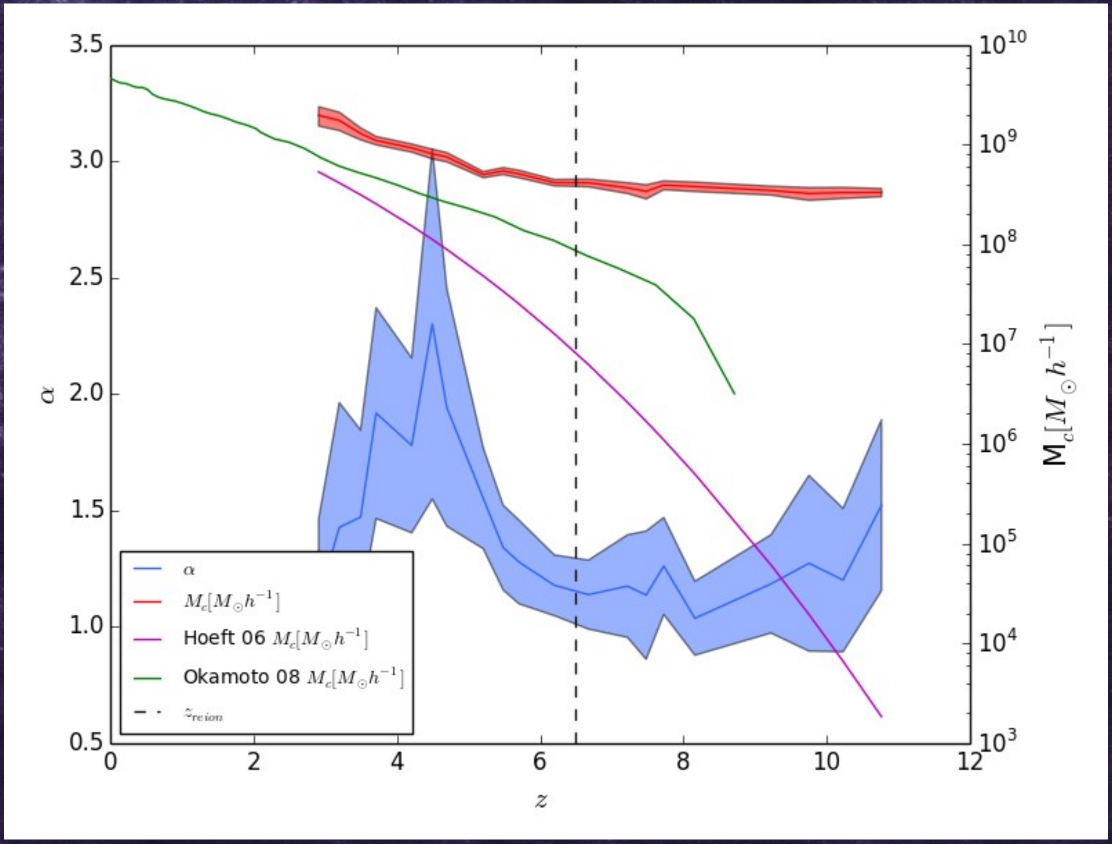
(Sullivan et al., in prep.)



M_c and α vs redshift

(Sullivan et al., in prep.)

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



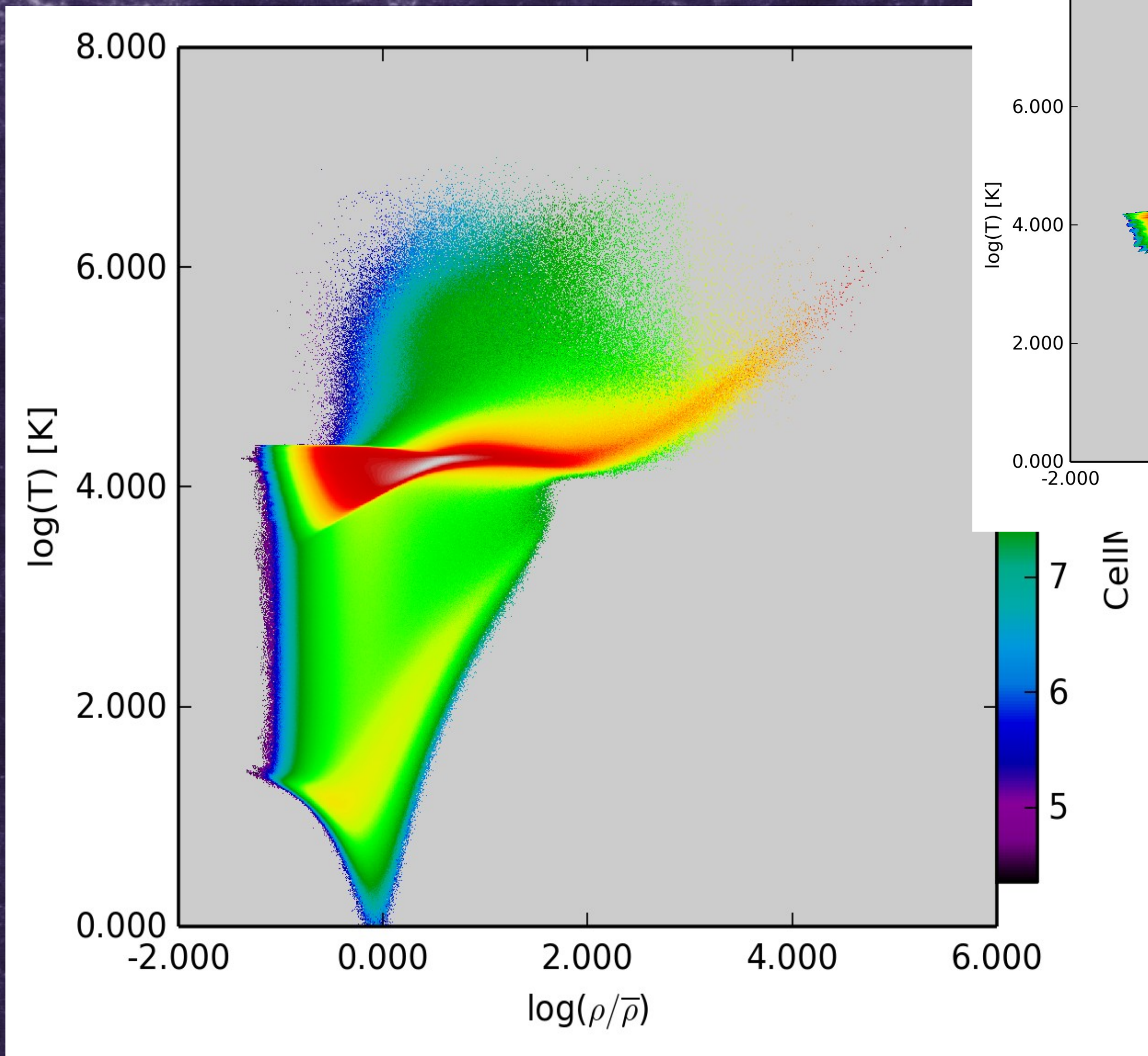
Equation of state: effect of the photoionization and heating

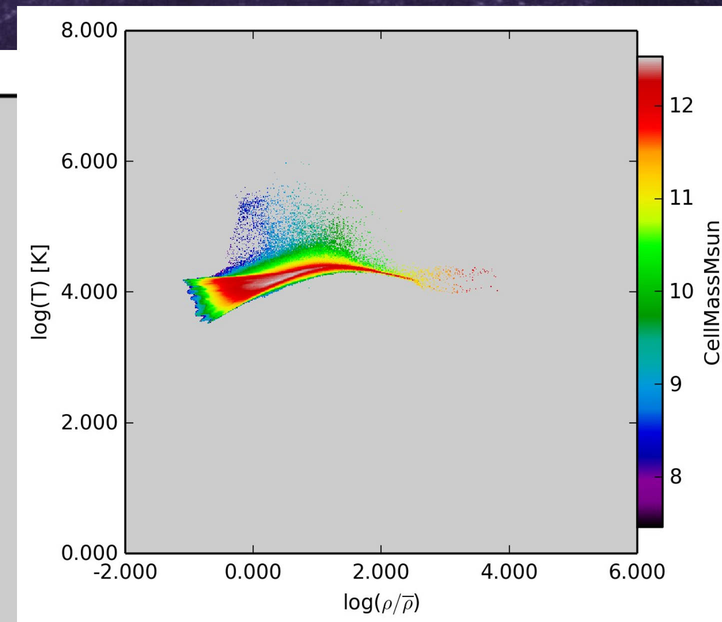
(Sullivan et al., in prep.)

Gas density: effect of photoionization and heating

(Sullivan et al., in prep.)

Equation of state: Cosmic Dawn run

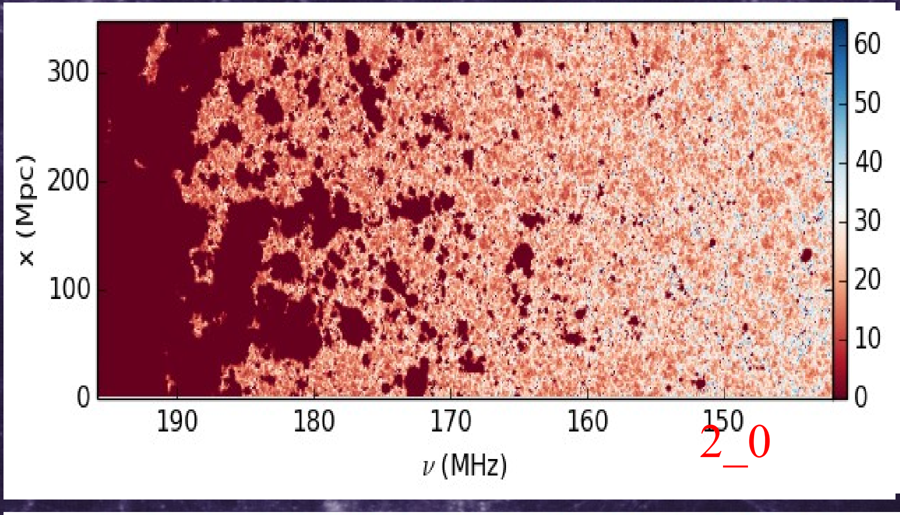


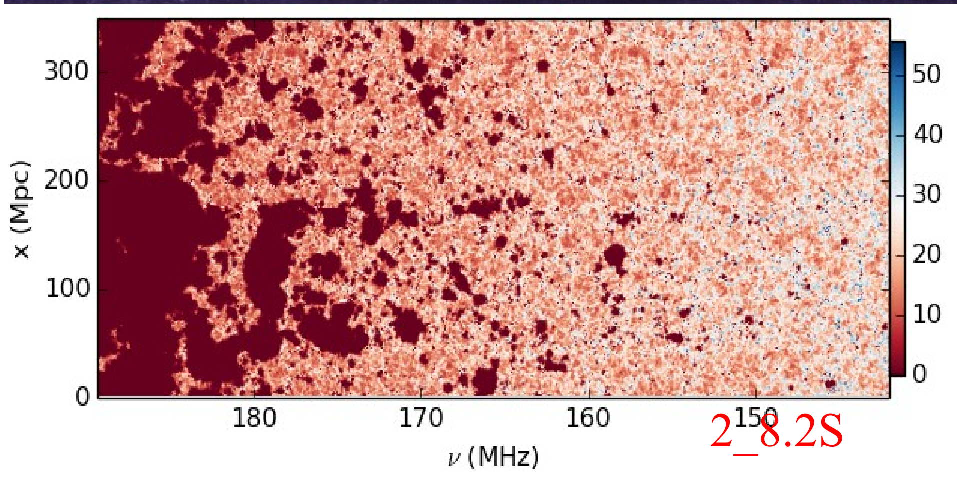


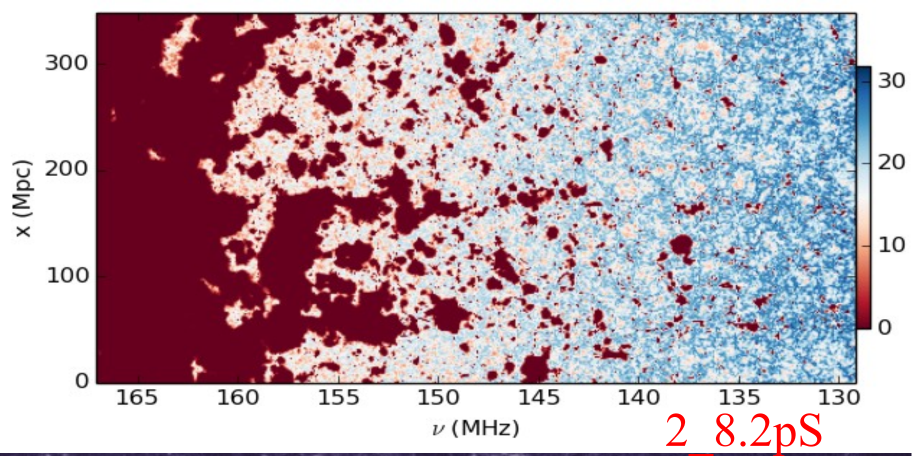
(Ocvirck et al., in prep.)

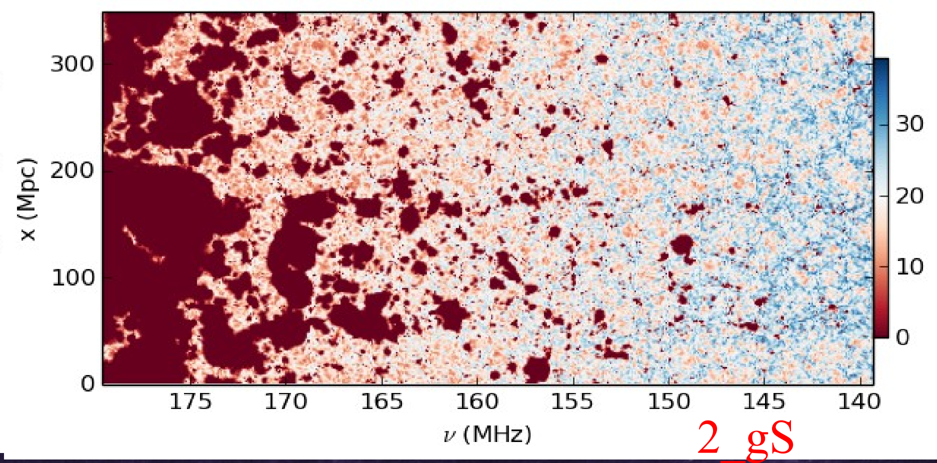
Different low-mass source suppression models: 21-cm

(Dixon et al. in prep.)

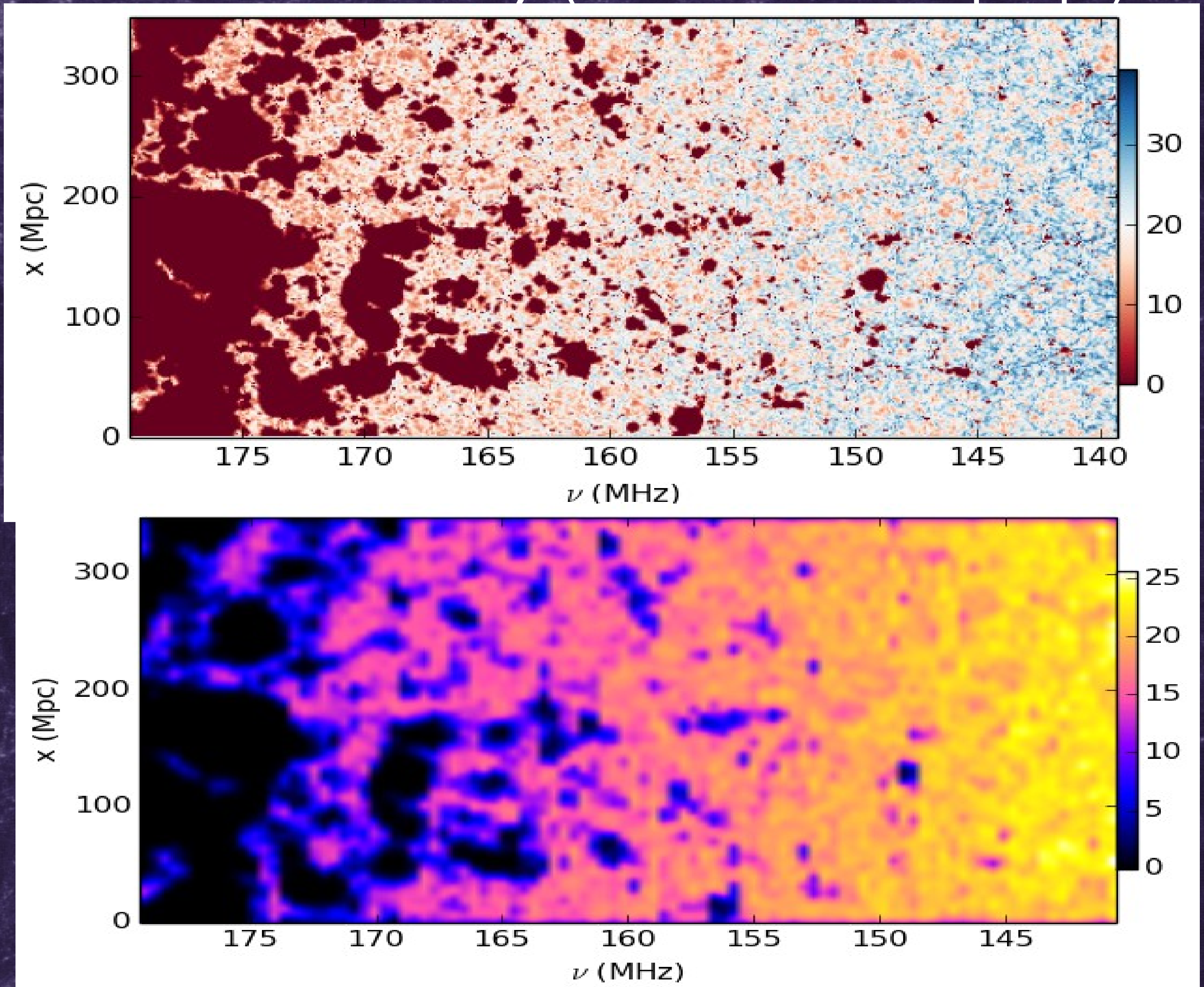






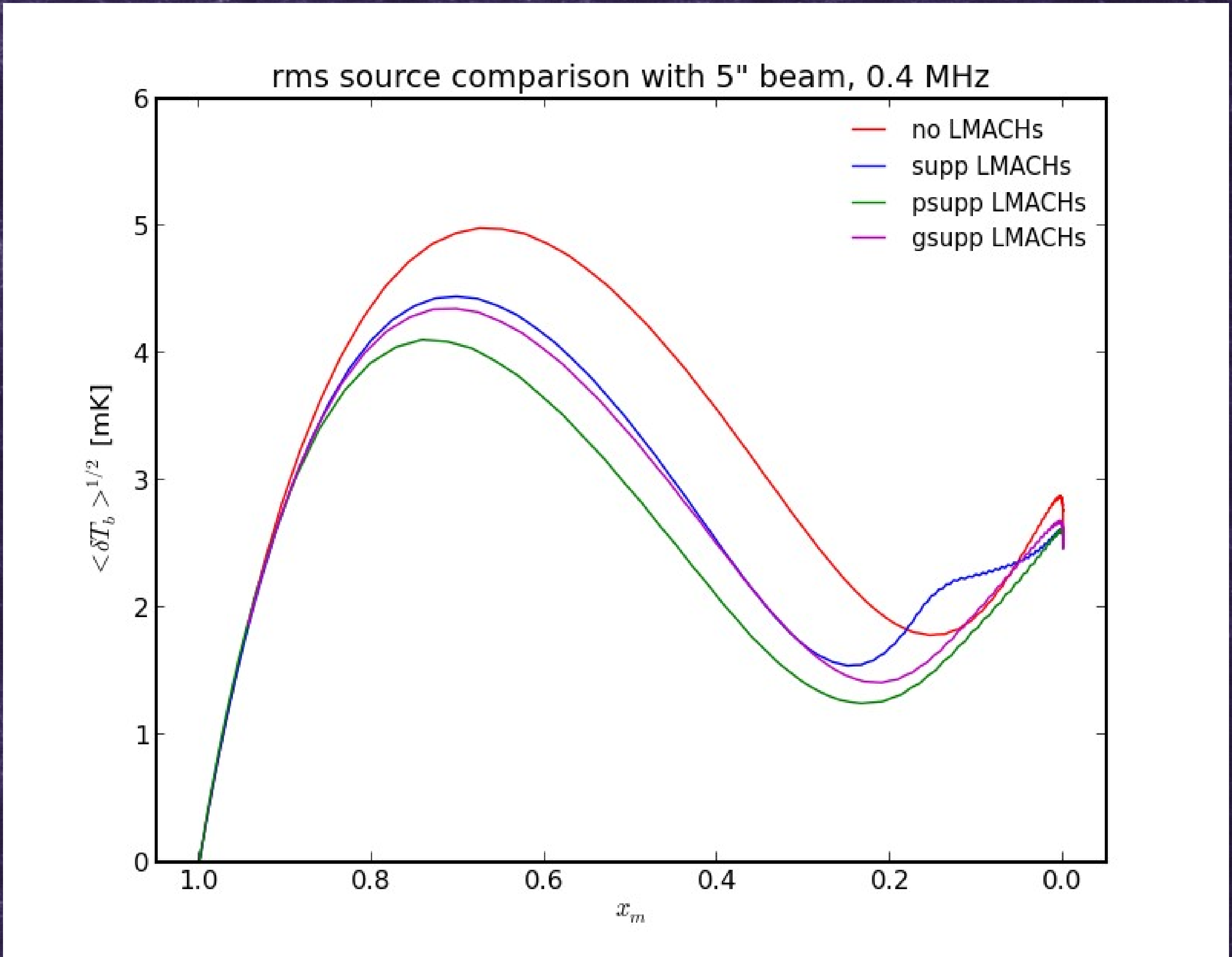


21-cm: effect of resolution (beam and bandwidth) (Dixon et al. in prep.)



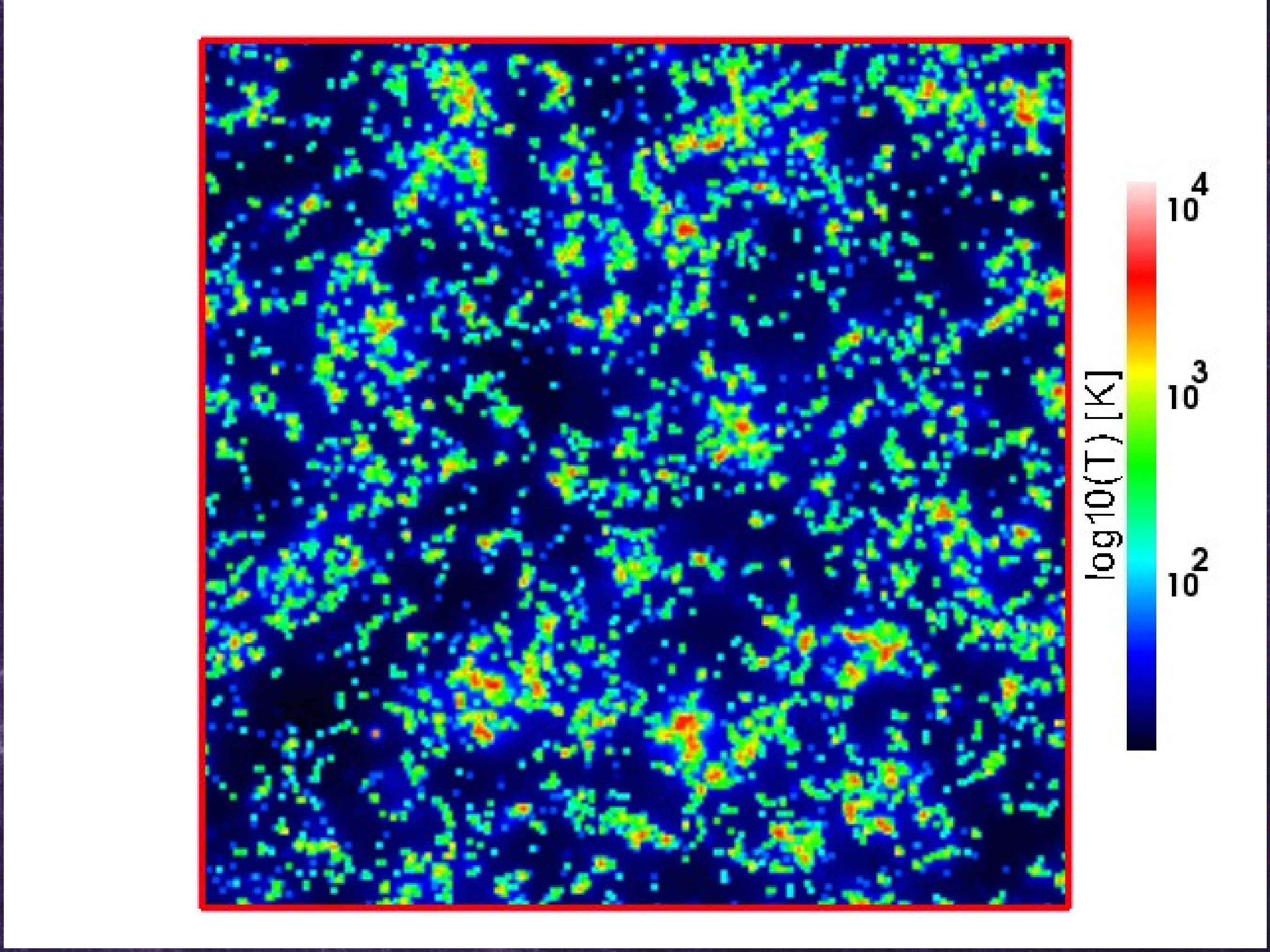
21-cm rms fluctuations

(Dixon et al. in prep.)



Early Inhomogeneous X-ray heating

(Ross et al., in prep.)



Summary

- Reionization is inherently multi-scale — pc to 100s Mpc.
- Large scales are needed for observations, small scales is where most physics happens.
- Small-scale physics could be included in large volume simulations using detailed sub-grid models.
- Precision mass function fits good to very high redshift are now available. Local nonlinear halo bias also available and behaviour (mean and scatter) understood.
- Reionization feedback significantly affects early galaxy formation (cold gas fraction and star formation). Detailed radiative hydrodynamics required for reliable modelling.
- Such simulations are quite expensive, but are becoming possible with current advanced techniques and petascale computers → first such simulations are being performed.