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Blown away

relative velocities and the first galaxies

Luke Conaboy

with thanks to Ilian Iliev (Sussex), Anastasia Fialkov (Cambridge),
Keri Dixon (NYUAD) and David Sullivan (Sussex)

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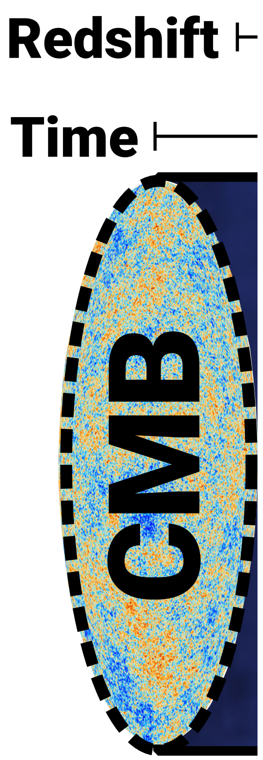
Brief history



John H. Wise (Georgia Tech)

Wise (2019)

- Hydrogen recombines at $z \approx 1090$
- Prior to this, baryons are tightly coupled to photons in a plasma
- Dark matter free to gravitationally collapse

Brief history

John H. Wise (Georgia Tech)

Wise (2019)

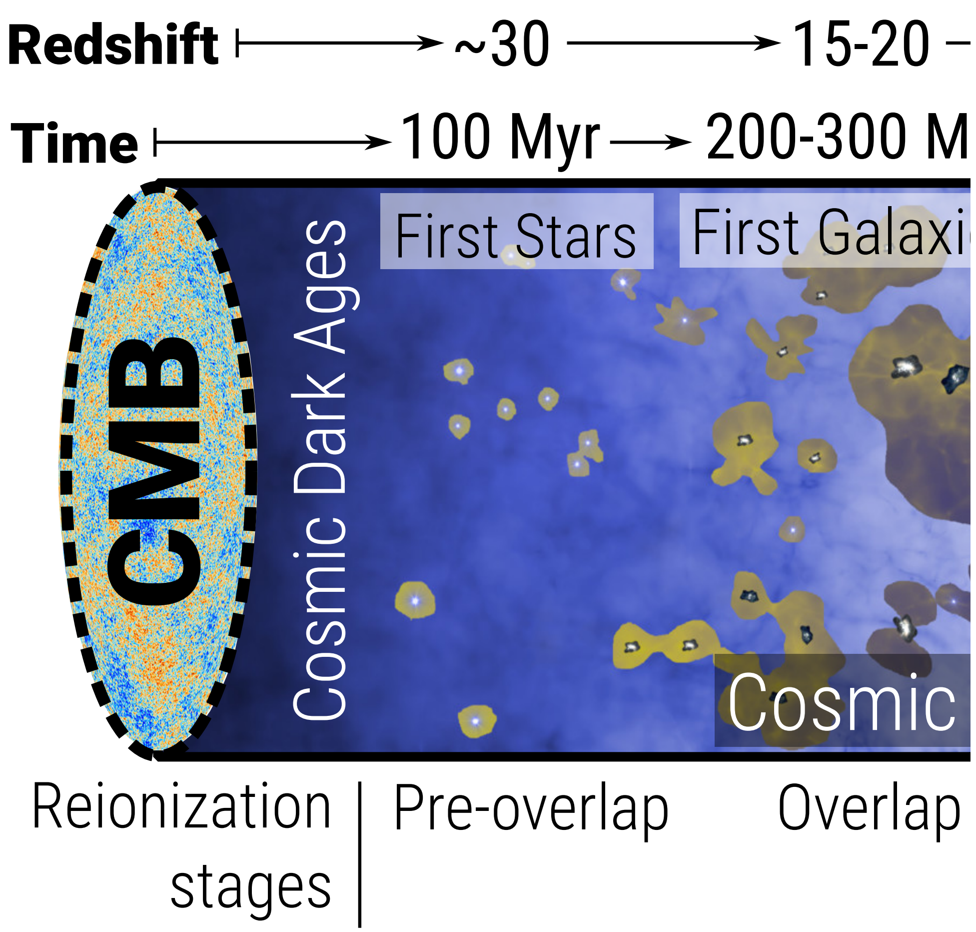
- After recombination, we enter the Dark Ages
- Baryons begin falling into dark matter potential wells

Brief history

Wise (2019)

- First luminous sources form at $z \sim 30 - 15$
- This first generation of stars likely live in molecular-cooled minihaloes and are very short lived

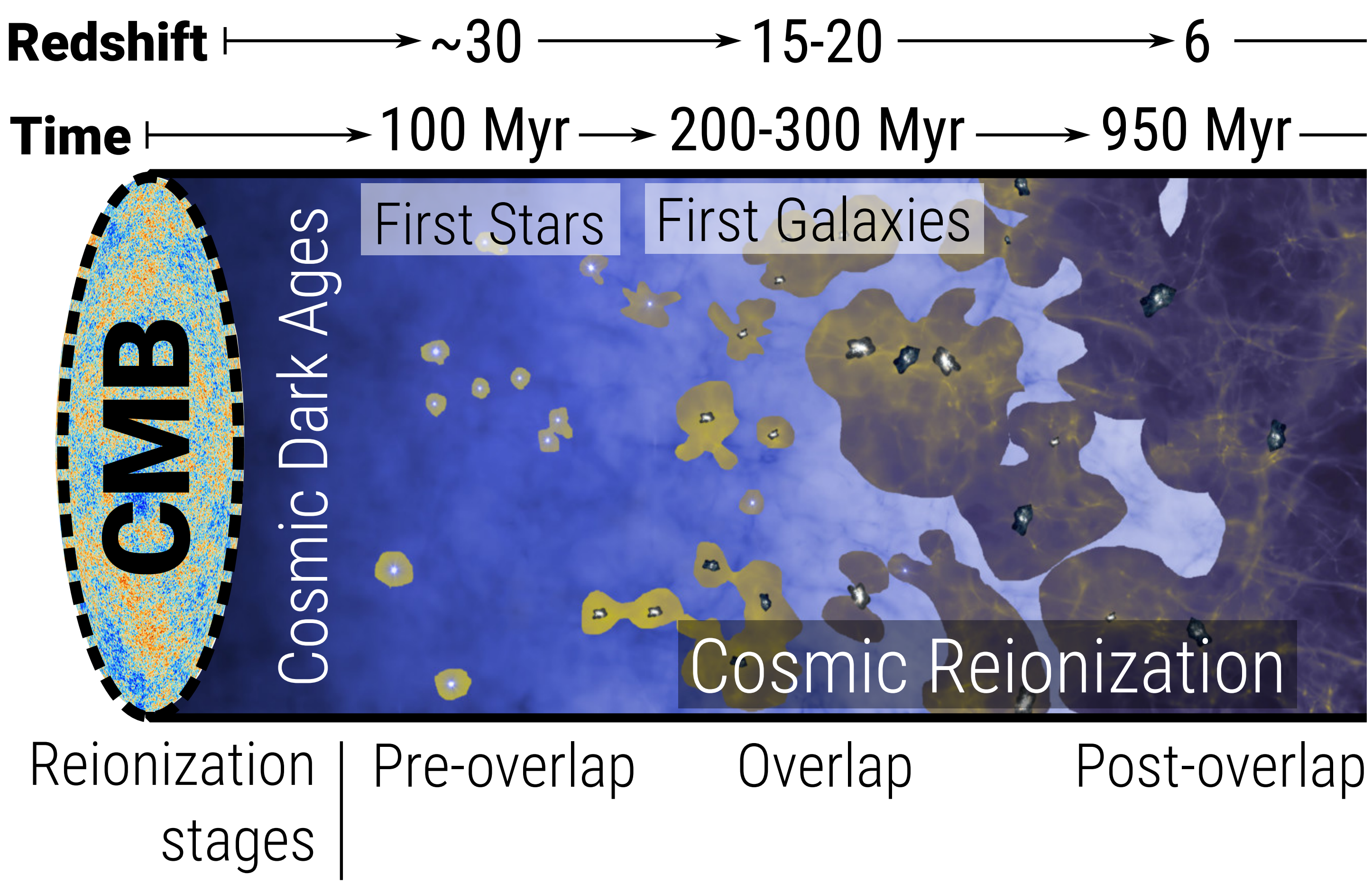
Brief history



Wise (2019)

- First galaxies form in $\sim 10^8\ \mathrm{M}_\odot$ atomic-cooling haloes
- Begin to ionise the neutral hydrogen gas in earnest

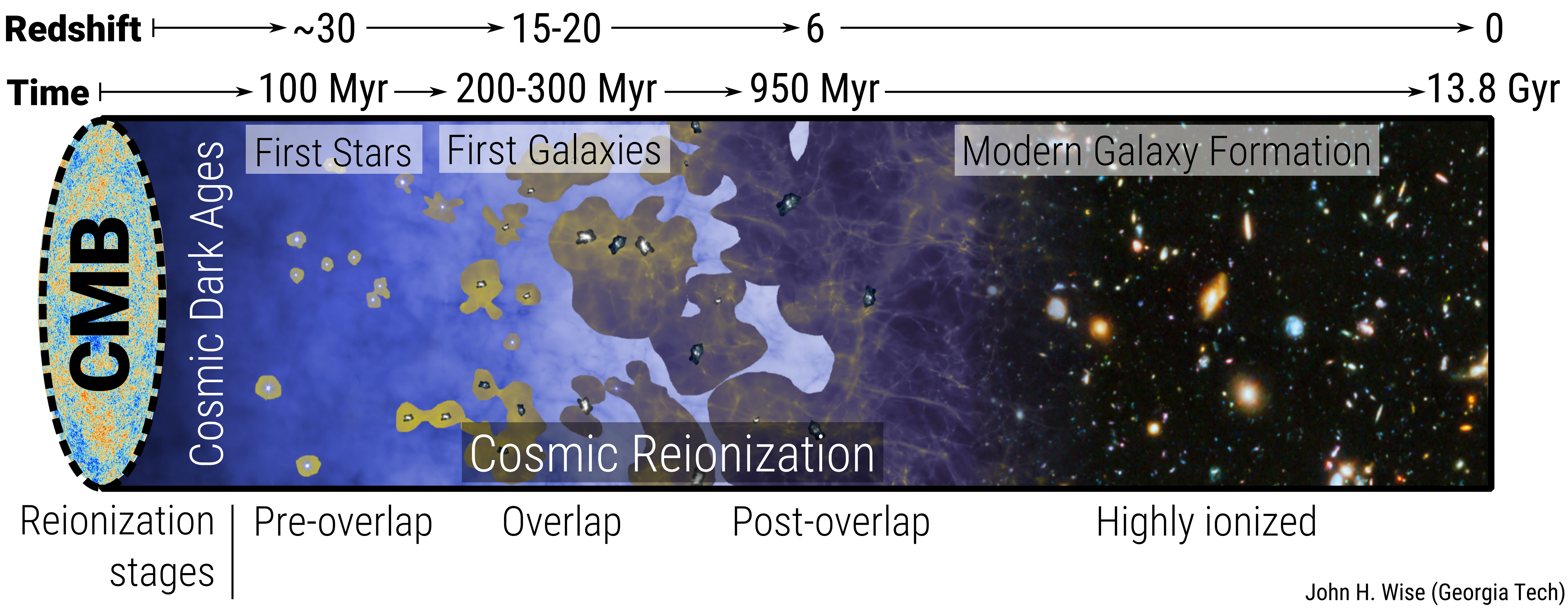
Brief history



Wise (2019)

- Ionised bubbles overlap at $z \sim 6$ and the Universe is now almost totally ionised

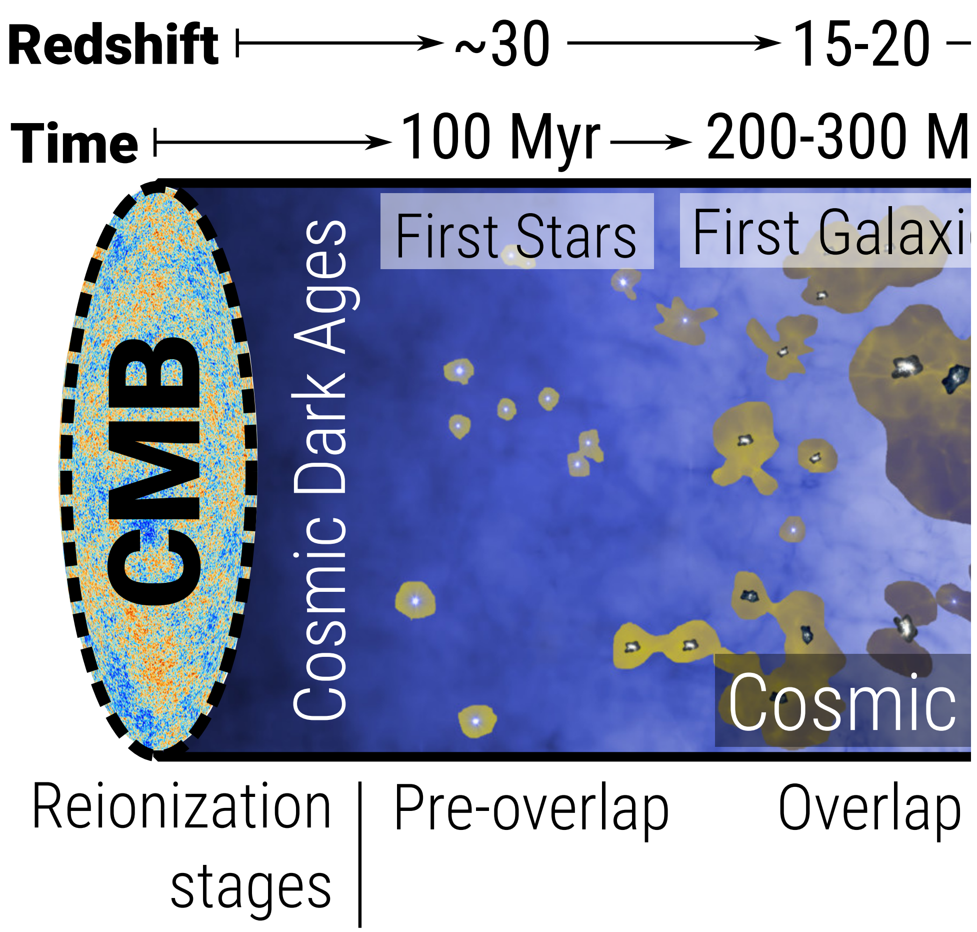
Brief history



Wise (2019)

- Ionisation maintained for the rest of cosmic history by metagalactic UV background

Brief history

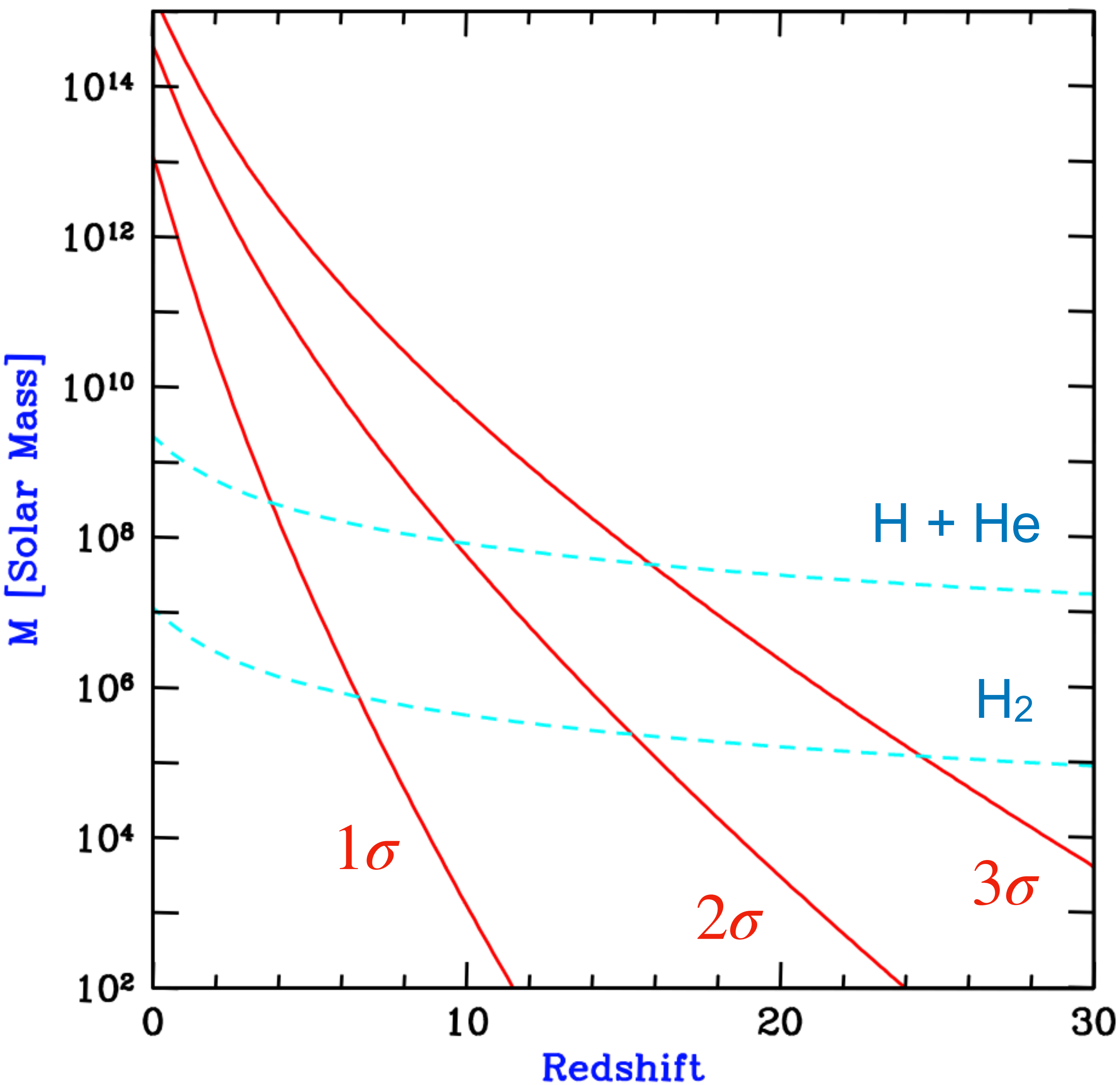


John H. Wise (Georgia Tech)

Wise (2019)

- Today, we will focus on the period from recombination to $z \approx 10$

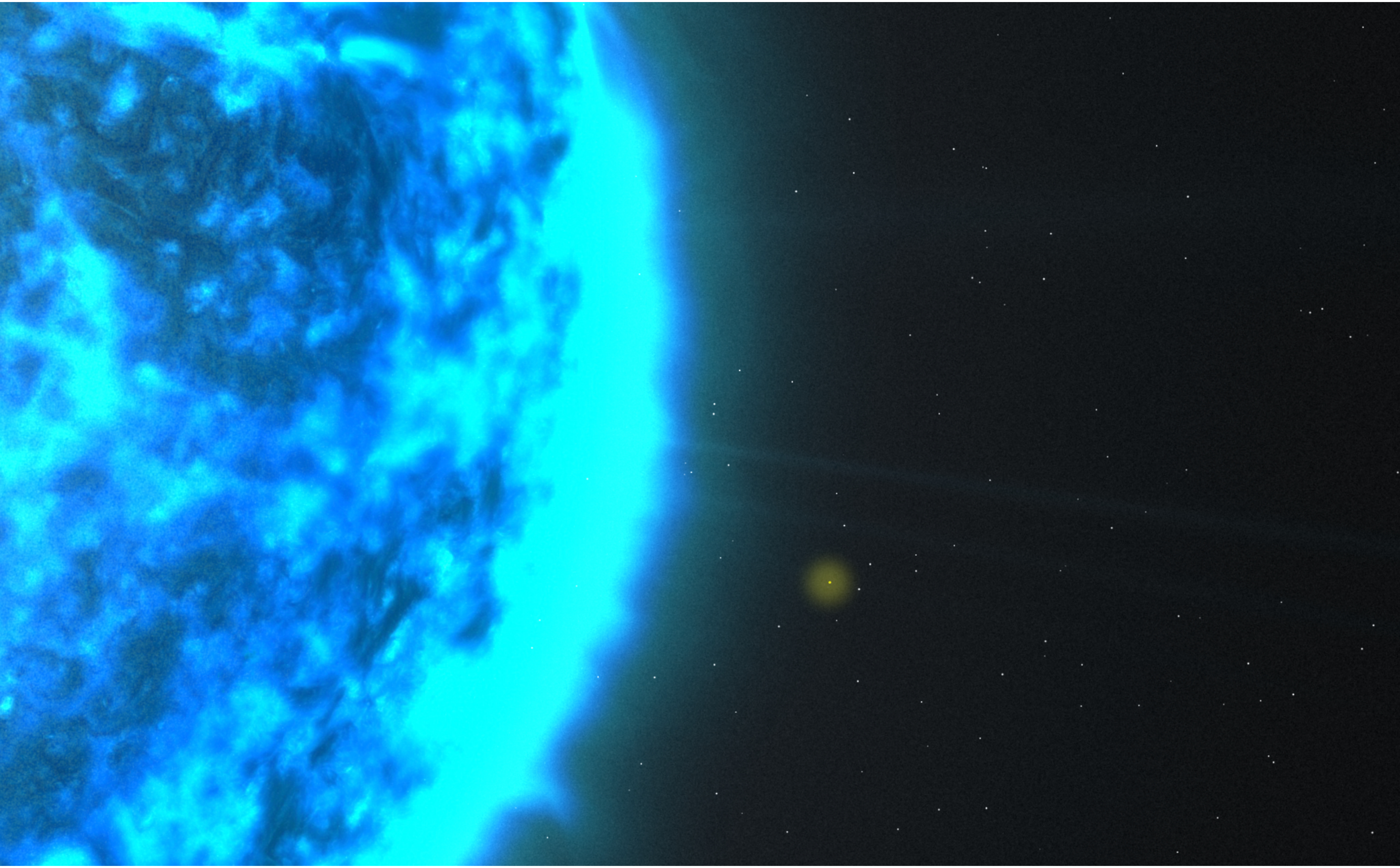
First structures



- First haloes to form are low mass
- Primordial gas mostly atomic H and He
- He and H cannot cool efficiently below ~10^4 K, but H_2 can
- First galaxies likely form in molecular cooling haloes

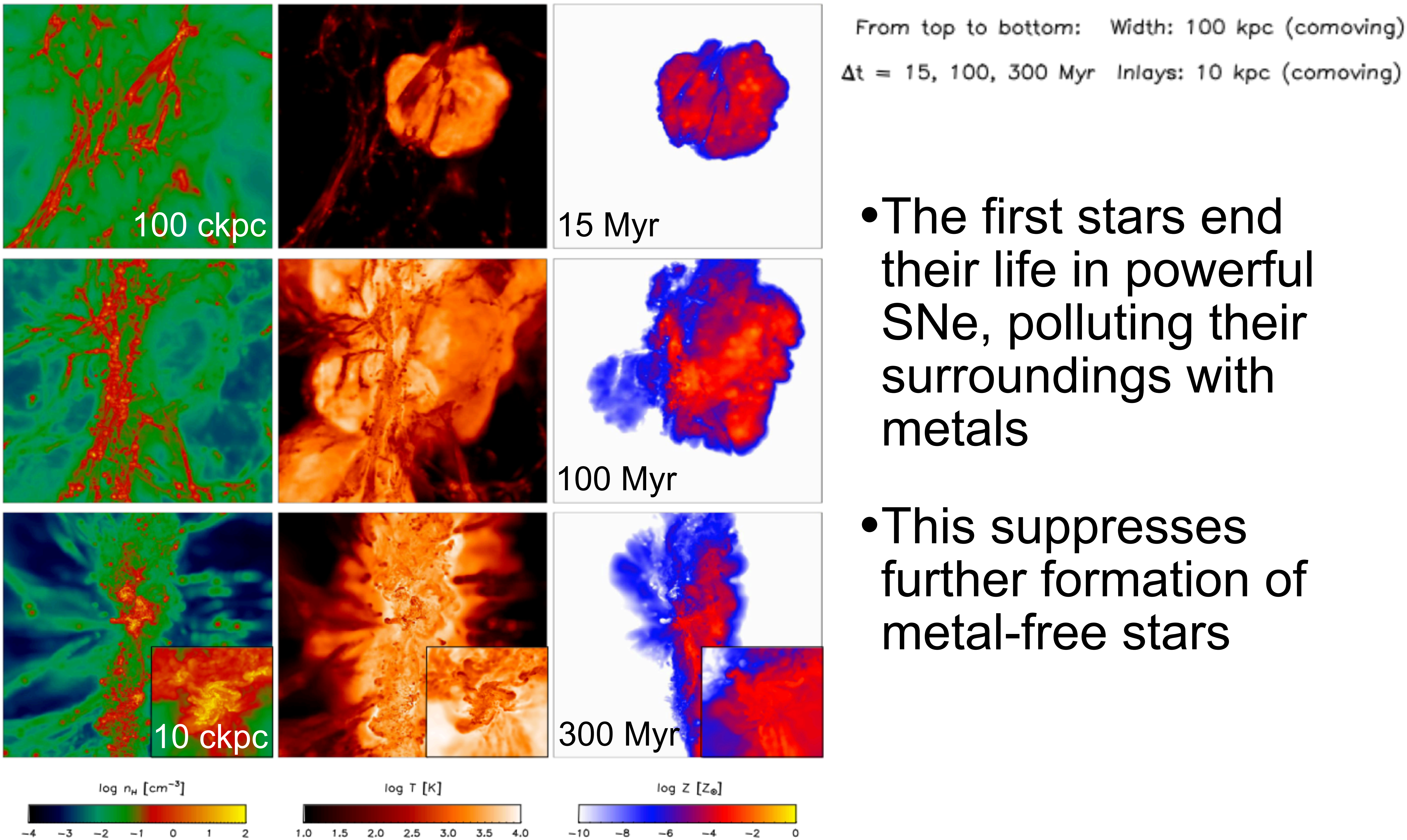
Barkana & Loeb (2001)

First stars



NASA Goddard, Wiessinger

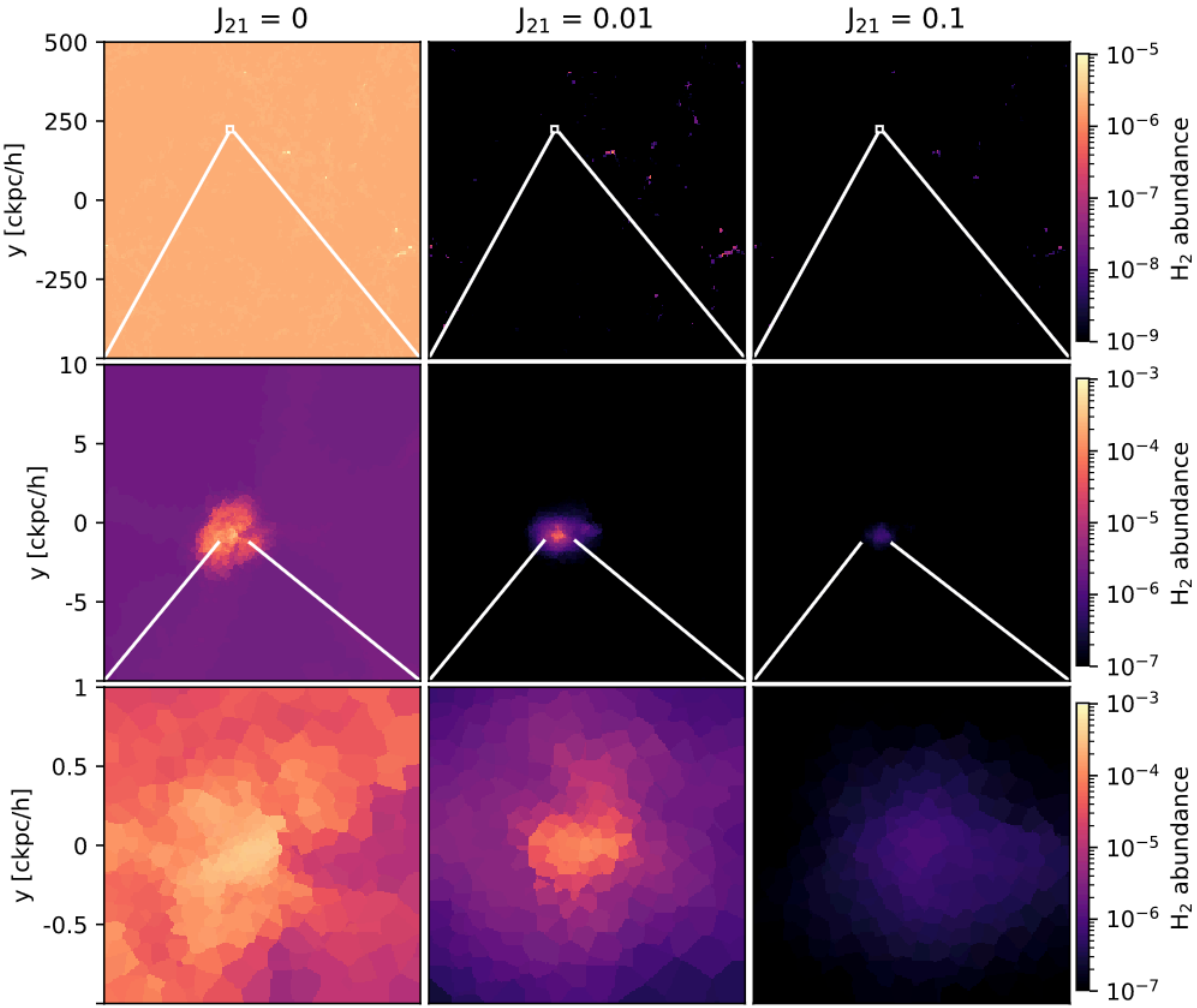
Feedback



- The first stars end their life in powerful SNe, polluting their surroundings with metals
- This suppresses further formation of metal-free stars

Greif+ (2010)

Feedback

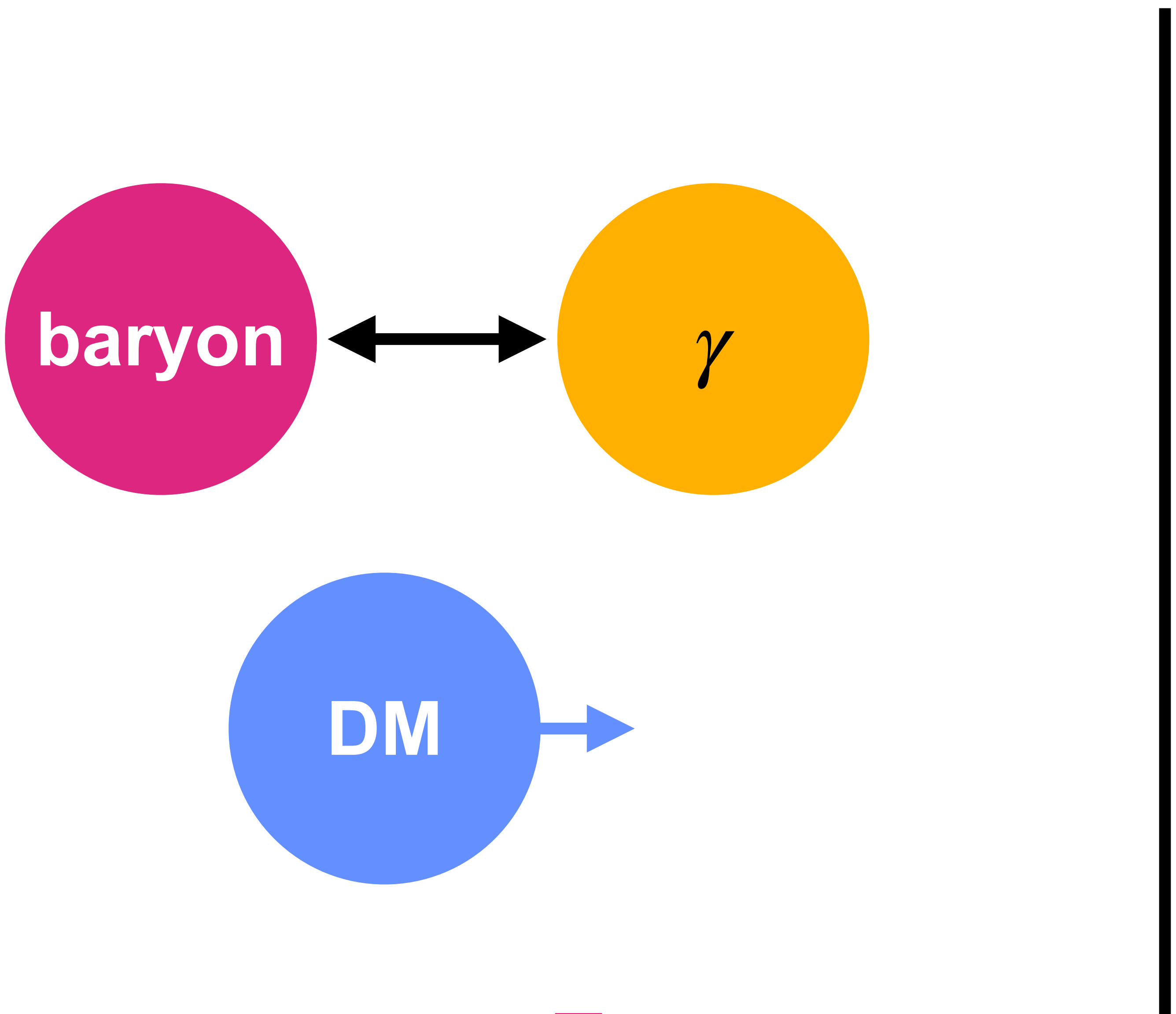


Schauer+ (2021)

- First stars also produce H_2-dissociating Lyman-Werner radiation
- Prevent cooling in low-mass haloes

Origin of $v_{\rm bc}$

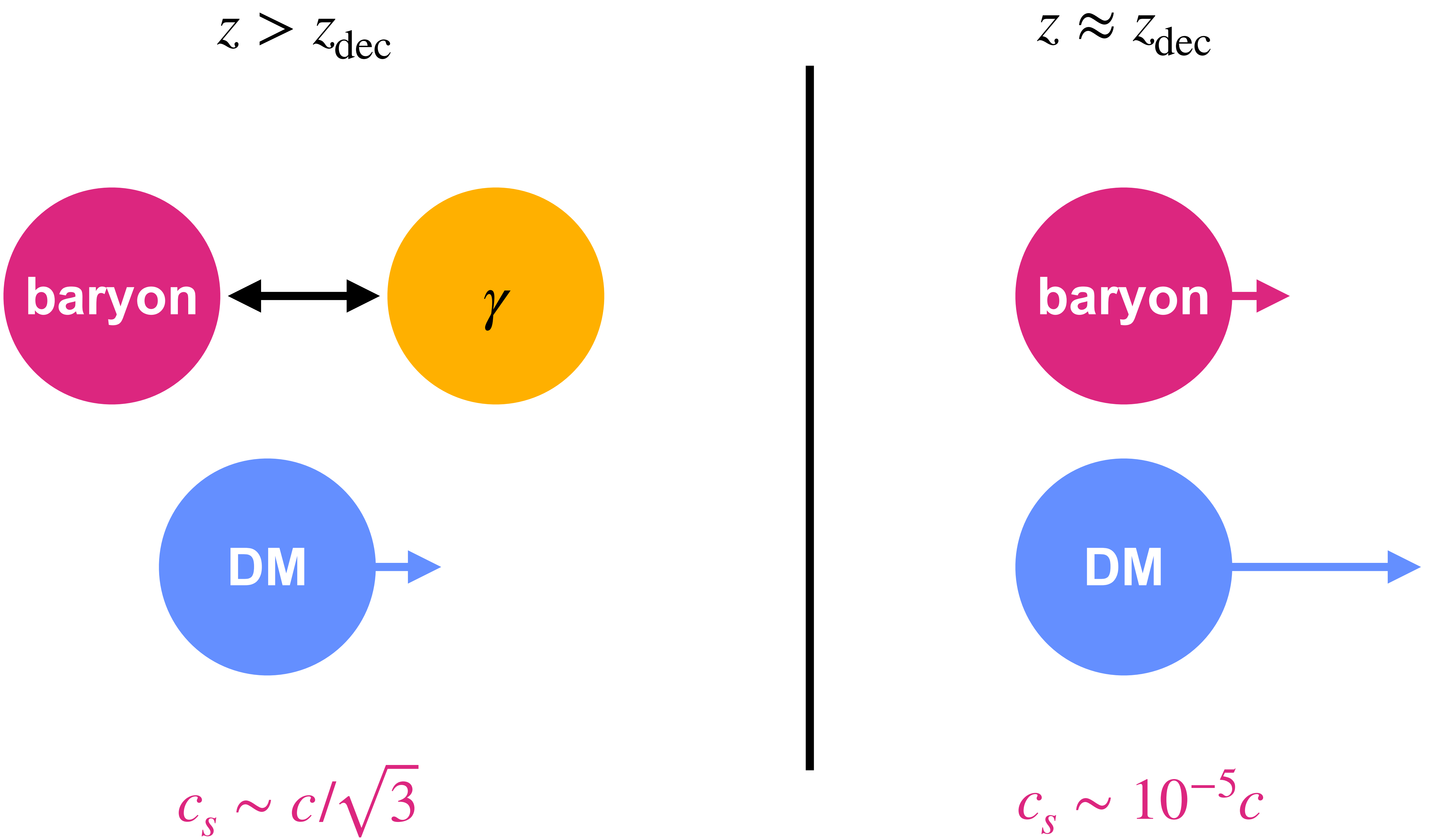
$z > z_{\rm dec}$



$c_s \sim c/\sqrt{3}$

not to scale!

Origin of $v_{\rm bc}$

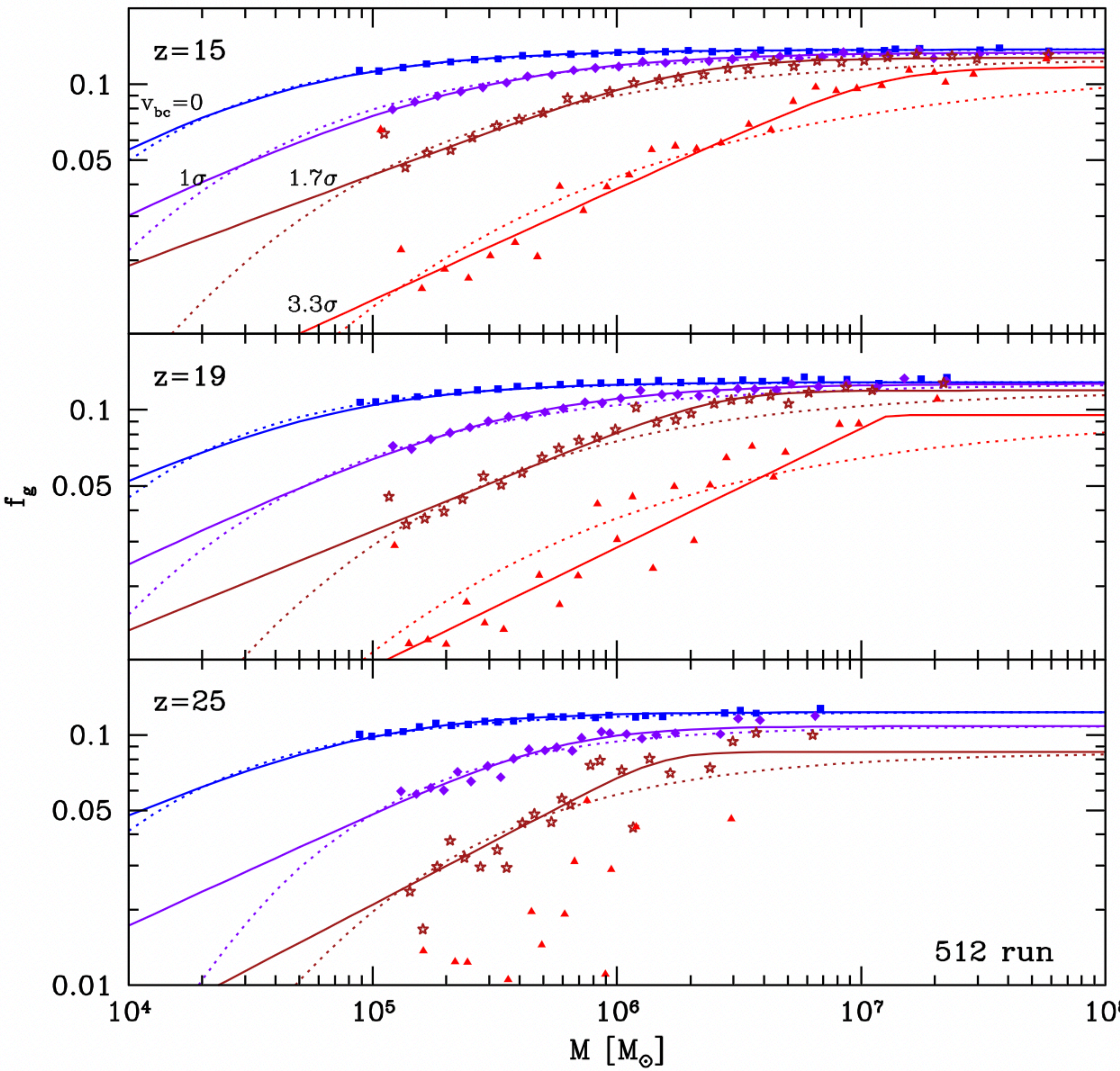


$$v_{\rm bc} = |\mathbf{v}_{\rm b} - \mathbf{v}_{\rm c}| \quad \mathscr{M} = v_{\rm bc}/c_s \sim 5$$

not to scale!

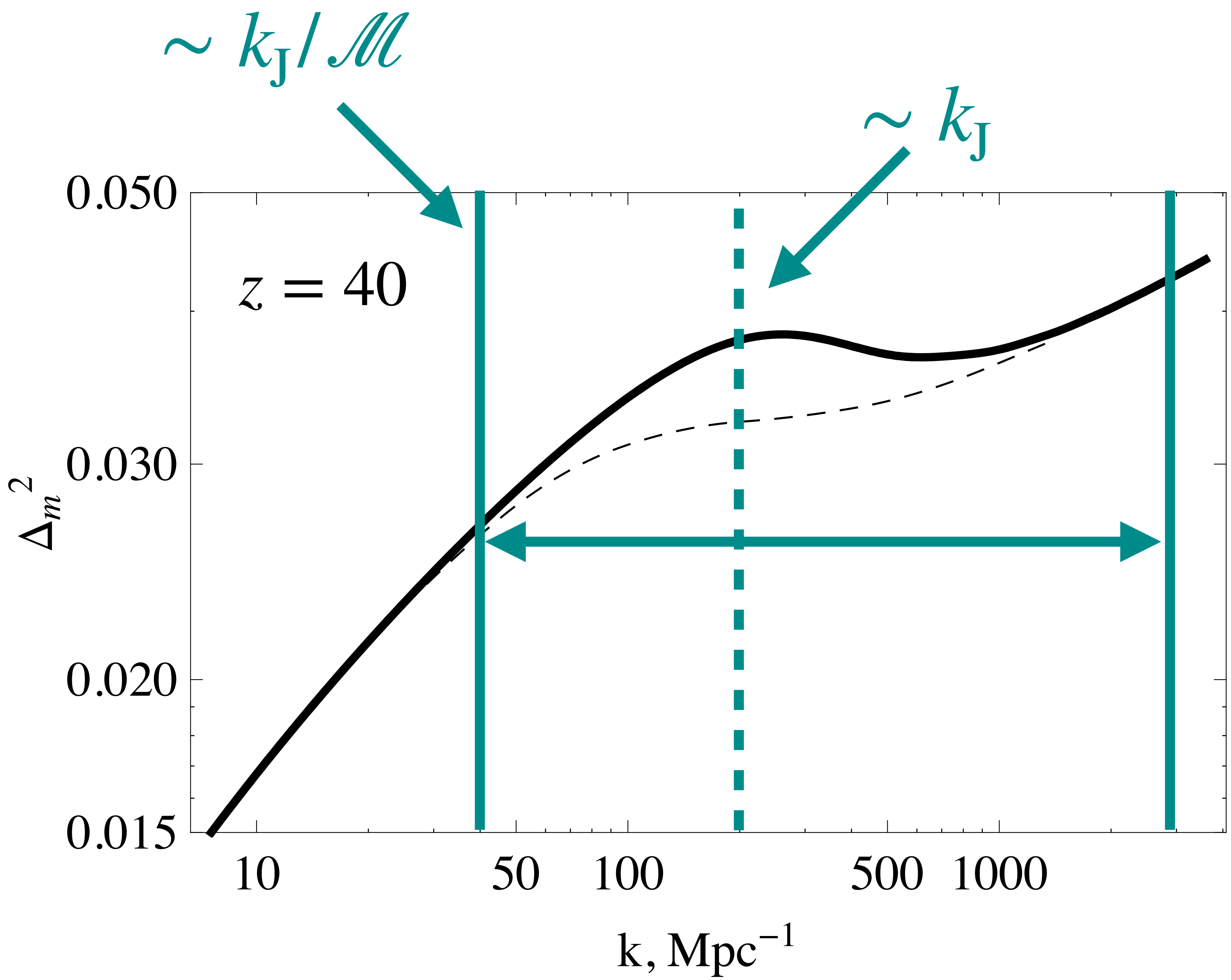
Suppression

- Baryons advect out of potential wells created by dark matter, raising minimum halo mass for gas-rich haloes



Naoz, Yoshida & Gnedin (2013)

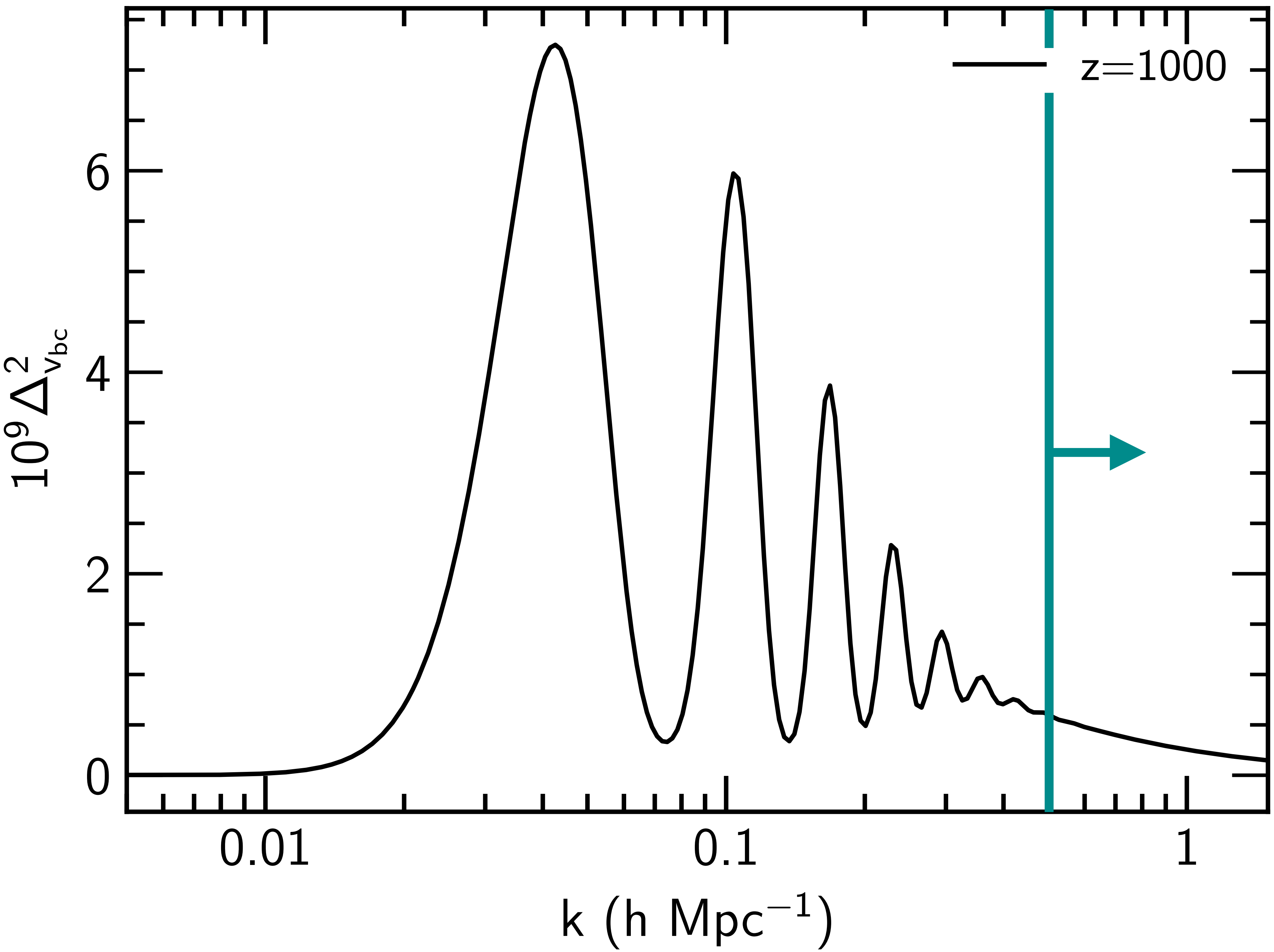
Suppression



Tseliakhovich & Hirata (2010)

- $v_{bc} = |\mathbf{v}_b - \mathbf{v}_c|$ smooths out baryonic fluctuations over $40 \lesssim k \lesssim 3000\ \mathrm{Mpc}^{-1}$
- most suppression at $k_J = 2\pi/\lambda_J \sim 200\ \mathrm{Mpc}^{-}$ where $\lambda_J(\delta = 0) \approx 30\ \mathrm{kpc}$

Scale of the problem

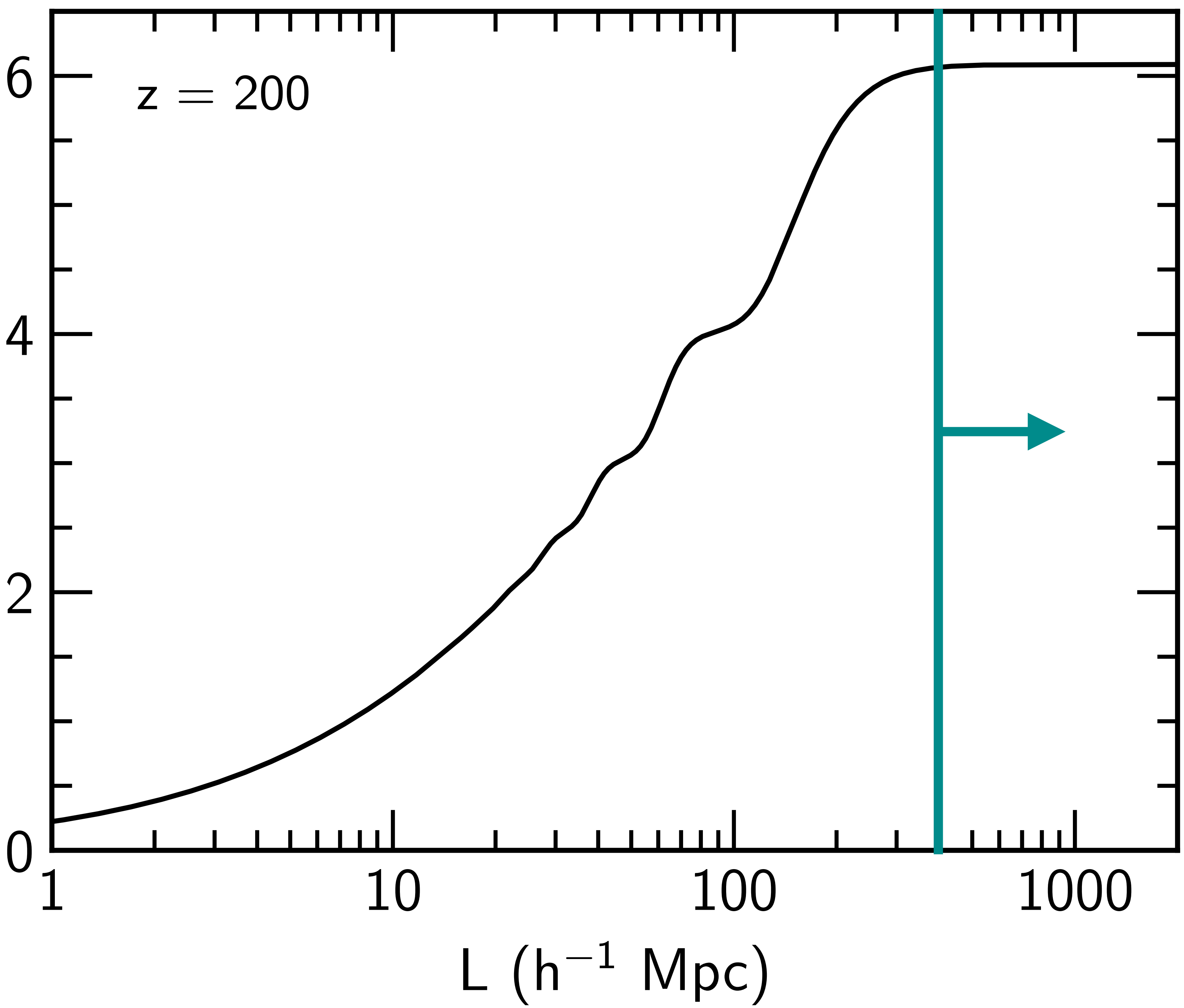


power drops off rapidly for $k \gtrsim 0.5\ h\ \mathrm{Mpc}^{-1}$

so v_{bc} coherent over $L \lesssim 10\ h^{-1}\ \mathrm{Mpc}$

v_{bc} variance per $\ln k$ from CAMB (see Tseliakhovich & Hirata 2010)

Scale of the problem

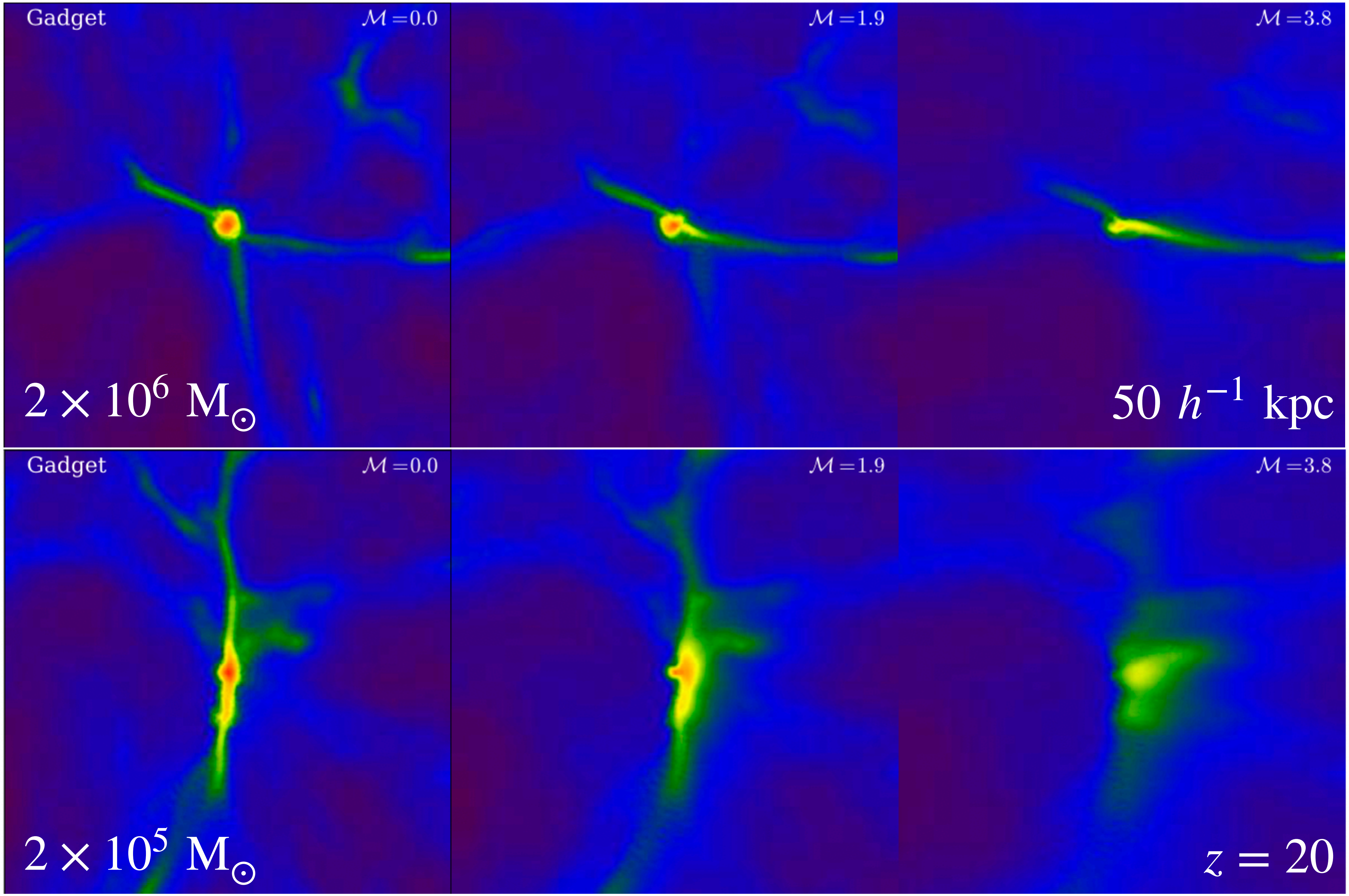


$$\langle v_{\rm bc}^2 \rangle_L^{\frac{1}{2}} = \int_{k_{\rm min}}^{\infty} \frac{\mathrm{d}k}{k} \Delta^2_{v_{\rm bc}}$$

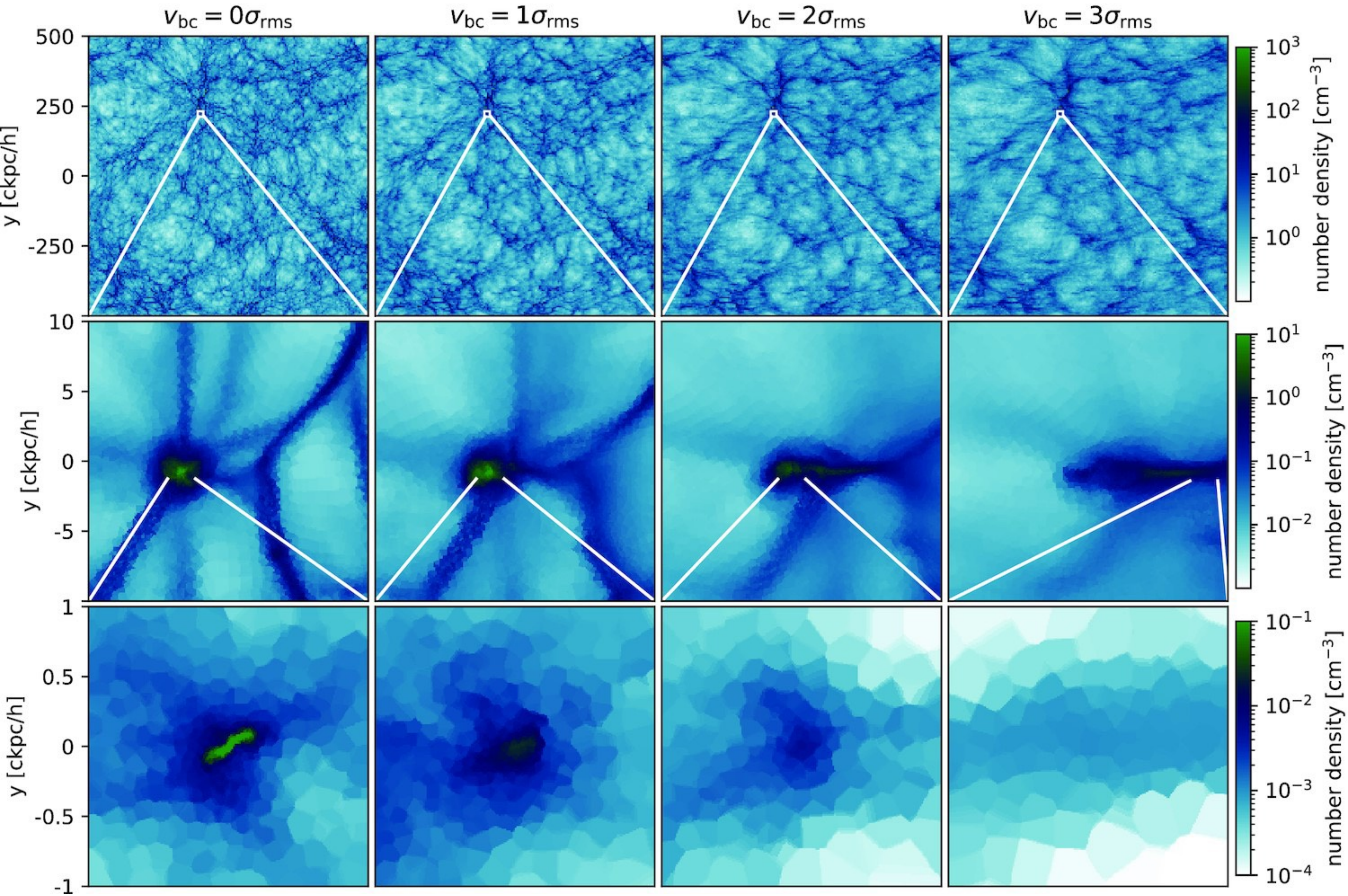
$$k_{\rm min} = \frac{2\pi}{L}$$

$L \gtrsim 400\ h^{-1}$ Mpc

cf. Pontzen+ (2020)



O'Leary & McQuinn (2012)

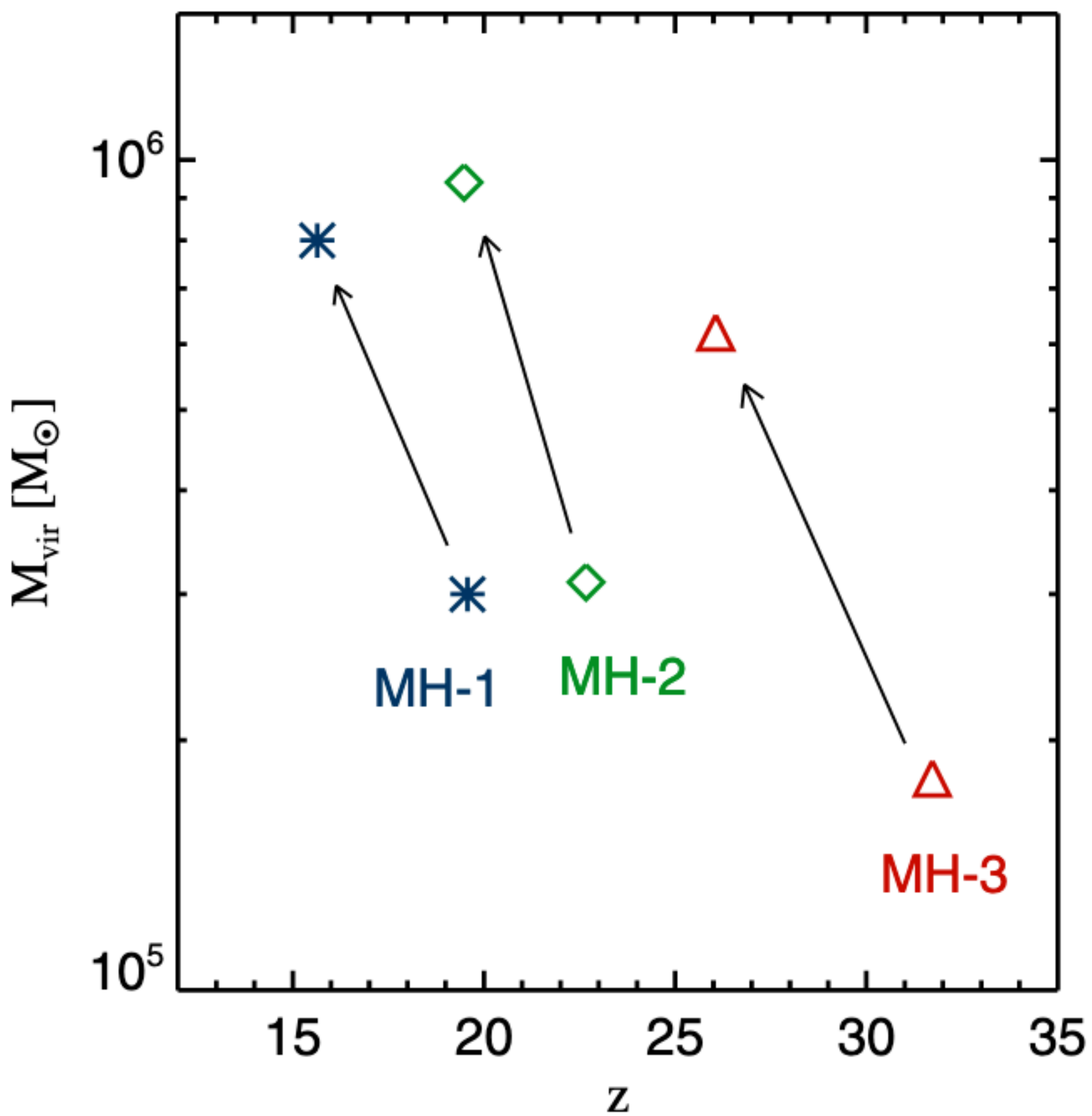


Schauer, Glover, Klessen & Clark (2021)

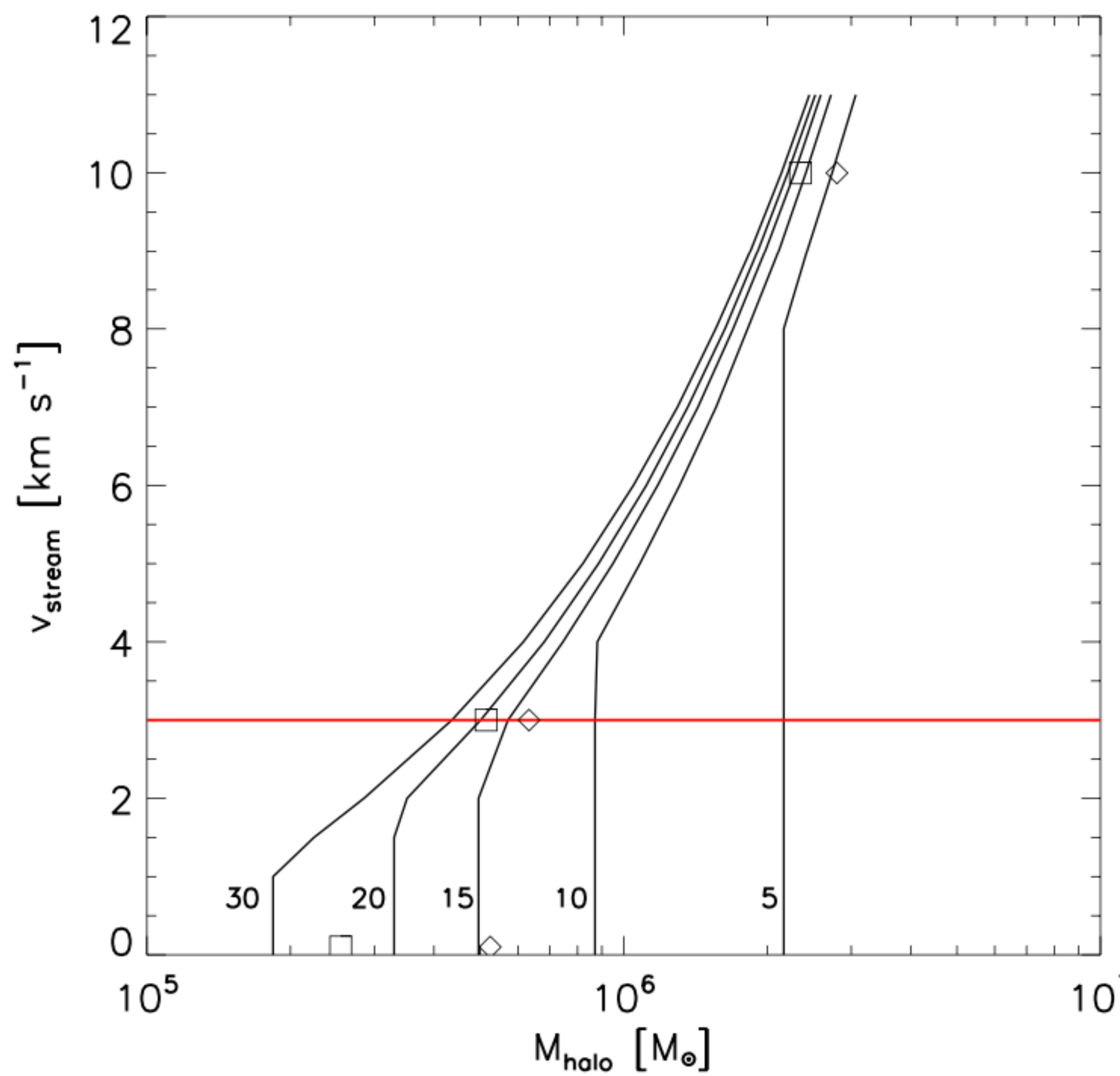
$z = 15$

First stars

- Raises minimum mass of star-forming haloes, particularly important for large $v_{\rm bc}$ at high-z

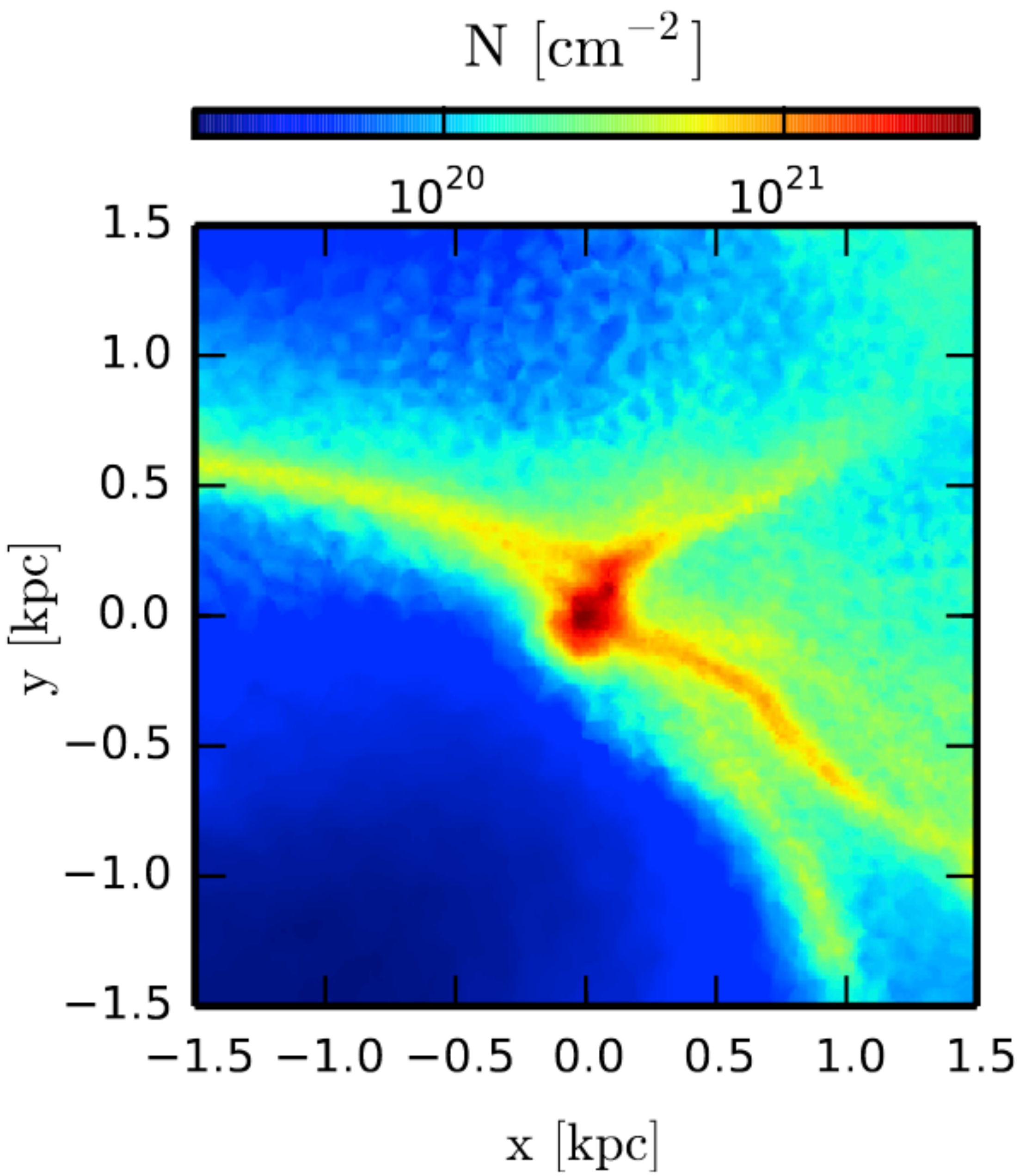


Greif, White, Klessen & Springel (2011)



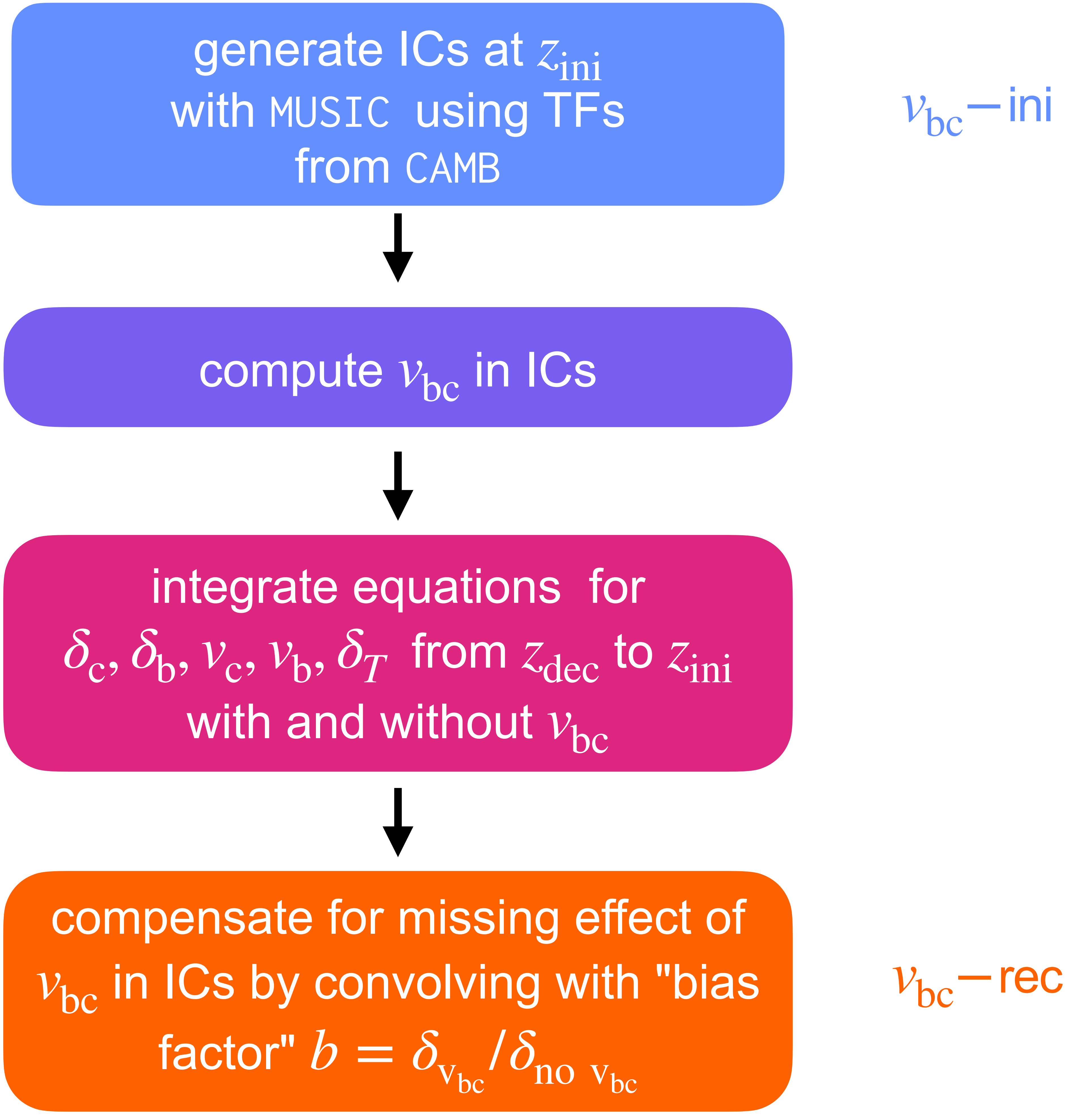
Stacy, Bromm & Loeb (2011)

Gas-rich objects



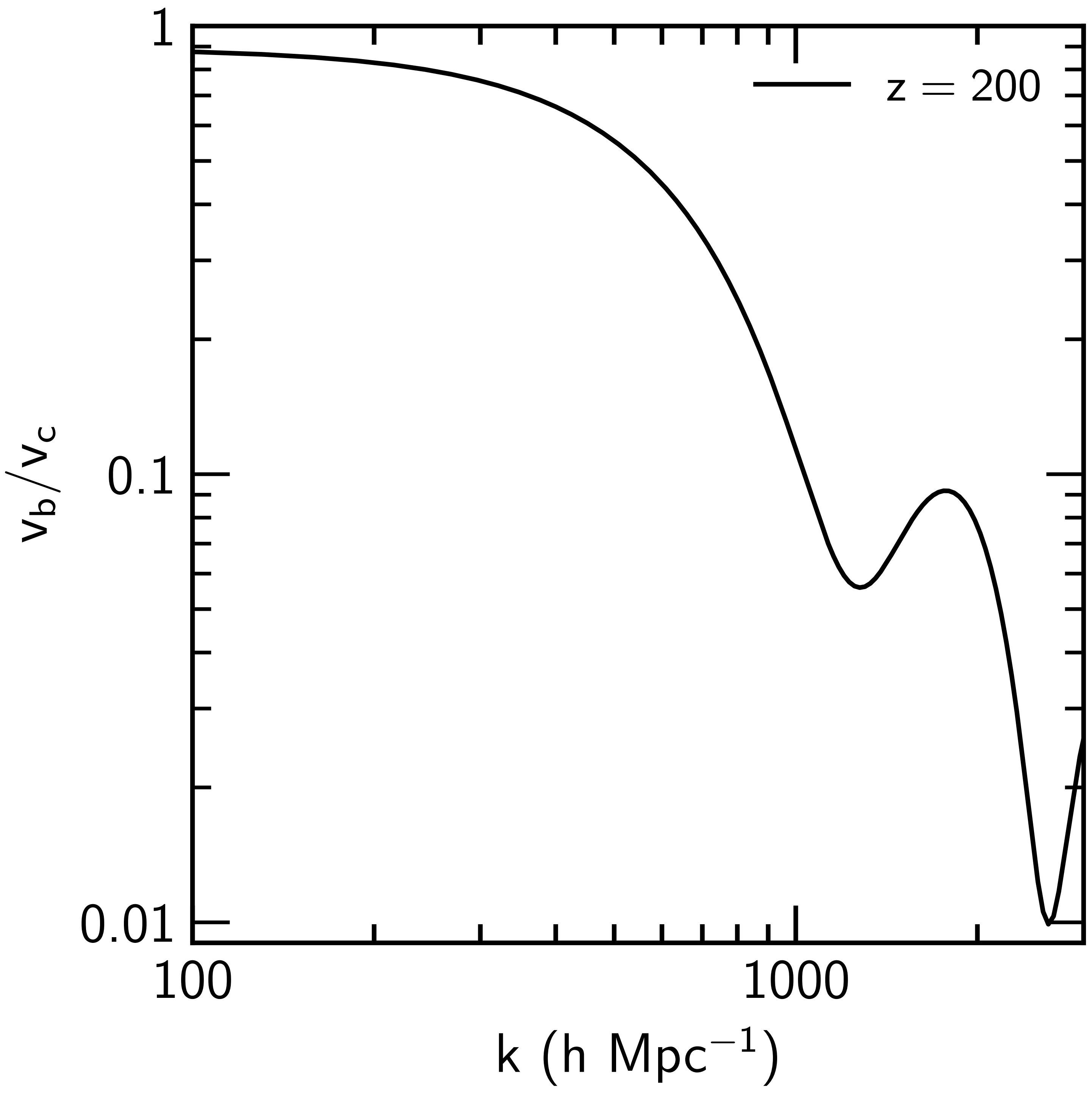
Popa, Naoz, Marinacci & Vogelsberger (2015)

- Can induce the formation of bound gas-rich objects outside of a host DM halo


generate ICs at z_{ini} with MUSIC using TFs from CAMB
compute v_{bc} in ICs
integrate equations for $\delta_{\mathrm{c}}, \delta_{\mathrm{b}}, v_{\mathrm{c}}, v_{\mathrm{b}}, \delta_T$ from z_{dec} to z_{ini} with and without v_{bc}
compensate for missing effect of v_{bc} in ICs by convolving with "bias factor" $b = \delta_{\mathrm{v_{bc}}} / \delta_{\mathrm{no\ v_{bc}}}$
v_{bc}—ini
v_{bc}—rec

v_{bc}–ini

- Generating ICs using transfer functions with separate amplitudes for baryons and dark matter gives v_{bc} *but only from the start time of the simulation*
- Effect on perturbations

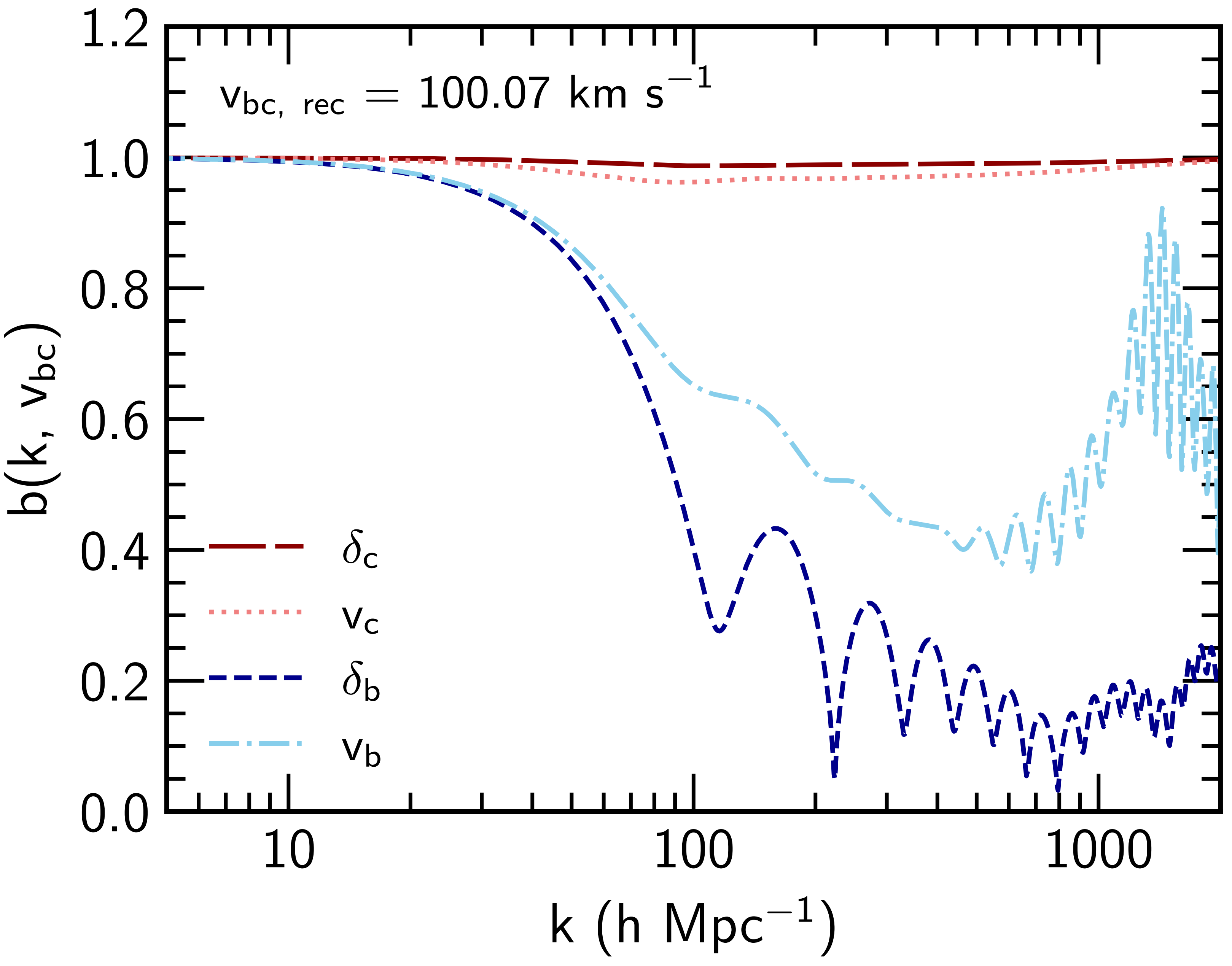


Ratio of velocity transfer functions from CAMB

- now we have v_{bc} at the simulation start time (v_{bc}—ini), but what about suppression throughout Dark Ages?
- we compute an (isotropic) bias factor to compensate for the missing baryon suppression in ICs (v_{bc}—rec)

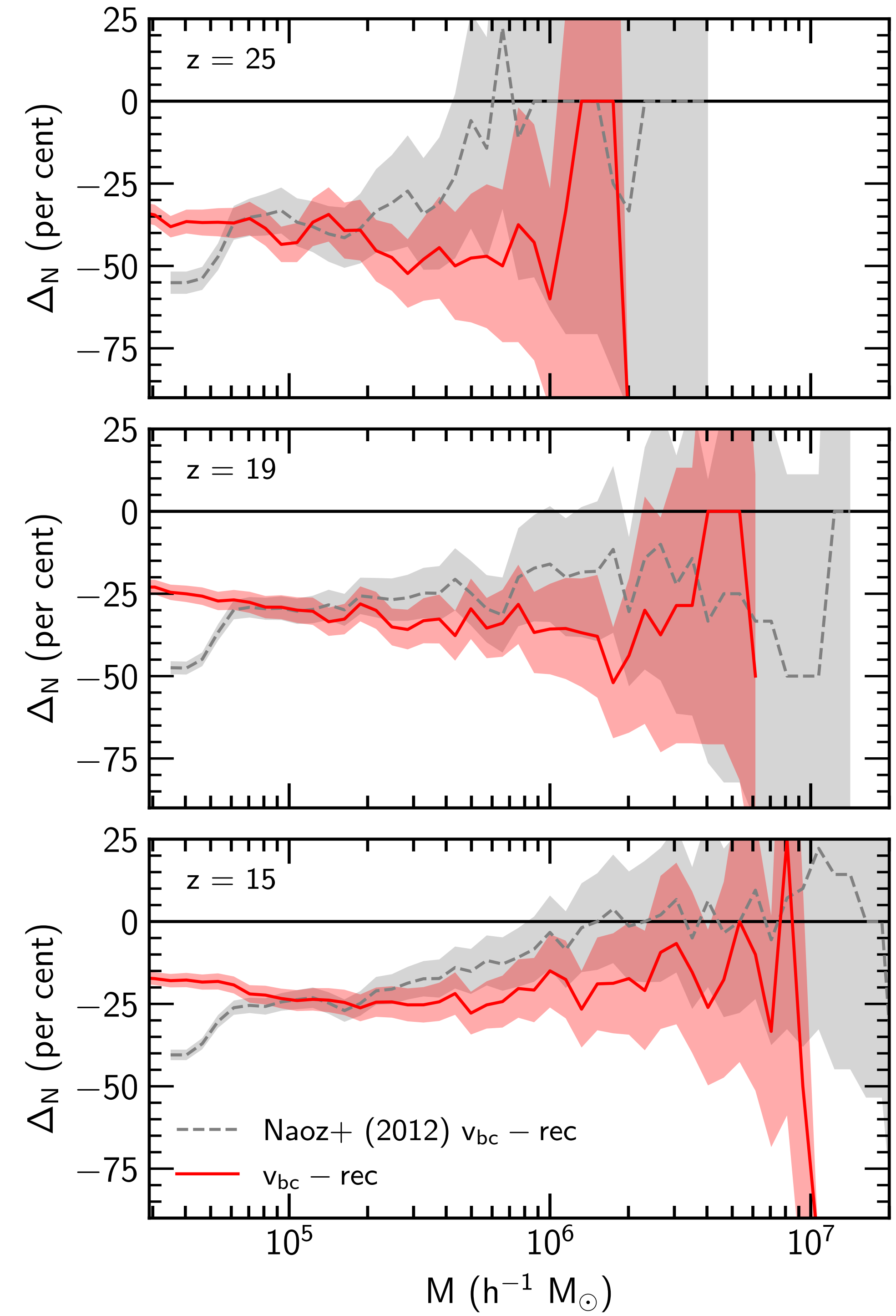
$$b_{X_{\mathrm{b}}}(k, v_{\mathrm{bc}}) = \frac{\delta_{X_{\mathrm{b}}}(k, v_{\mathrm{bc}})}{\delta_{X_{\mathrm{b}}}(k, v_{\mathrm{bc}} = 0)}$$

$$\hat{X}_{\mathrm{b}}(k) = b_{X_{\mathrm{b}}}(k, v_{\mathrm{bc}}) \cdot X_{\mathrm{b}}(k)$$



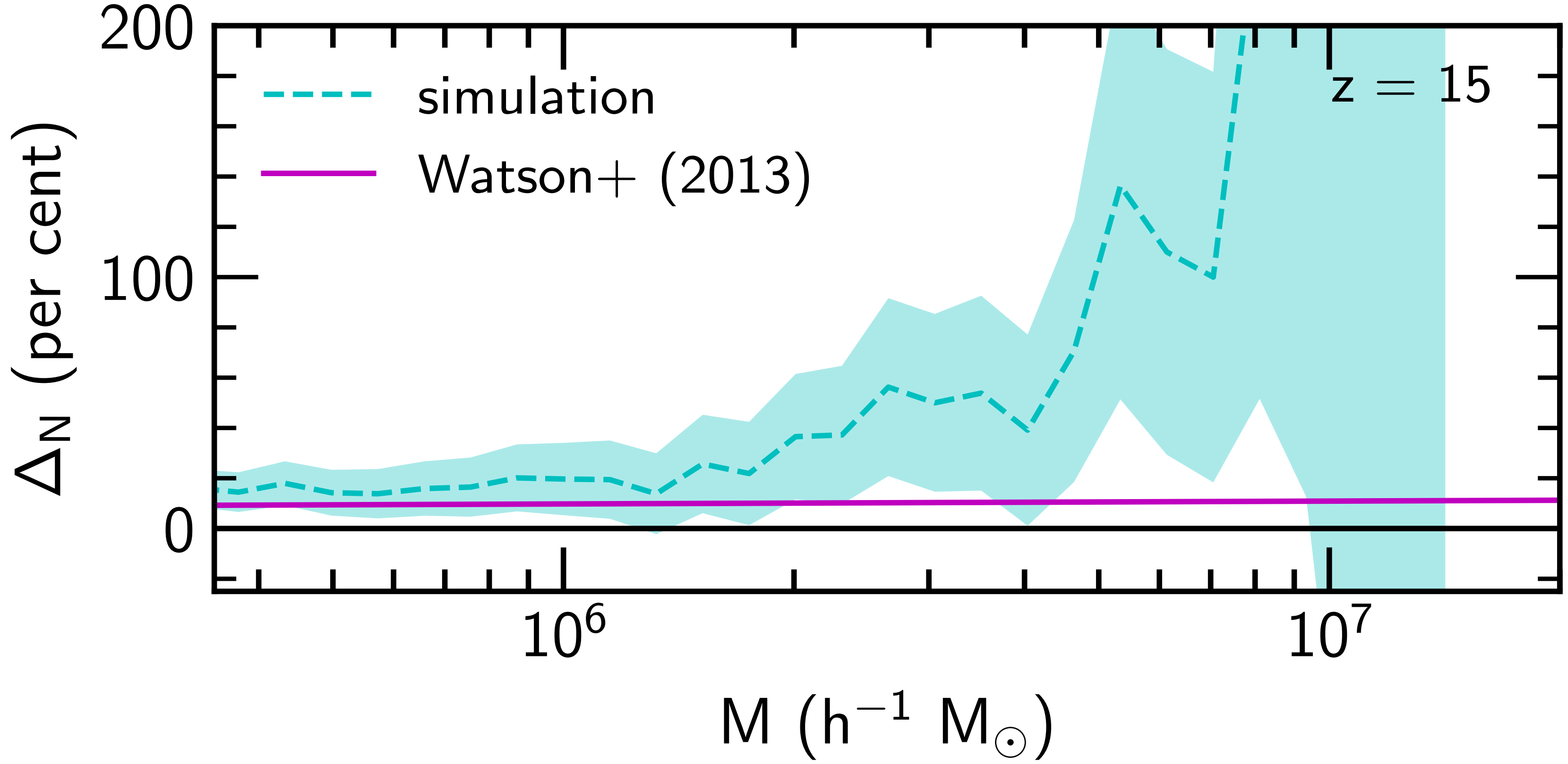
Comparison to previous works (HMF)

- 512^3 particles in 700 kpc box, boosted $\sigma_8 = 1.4$
- Apply $v_{\rm bc}$ as a uniform wind across the box
- Compute decrement as $\Delta_N = N_{v_{\rm bc}}/N_{\rm no\ v_{bc}} - 1$ where $N = N(>M)$ is the cumulative mass function
- Good agreement to within 1σ Poisson uncertainties (shaded)



Grey: Naoz, Yoshida & Gnedin (2012)
Red: LC+ (2023)

Comparison to previous works (HMF)

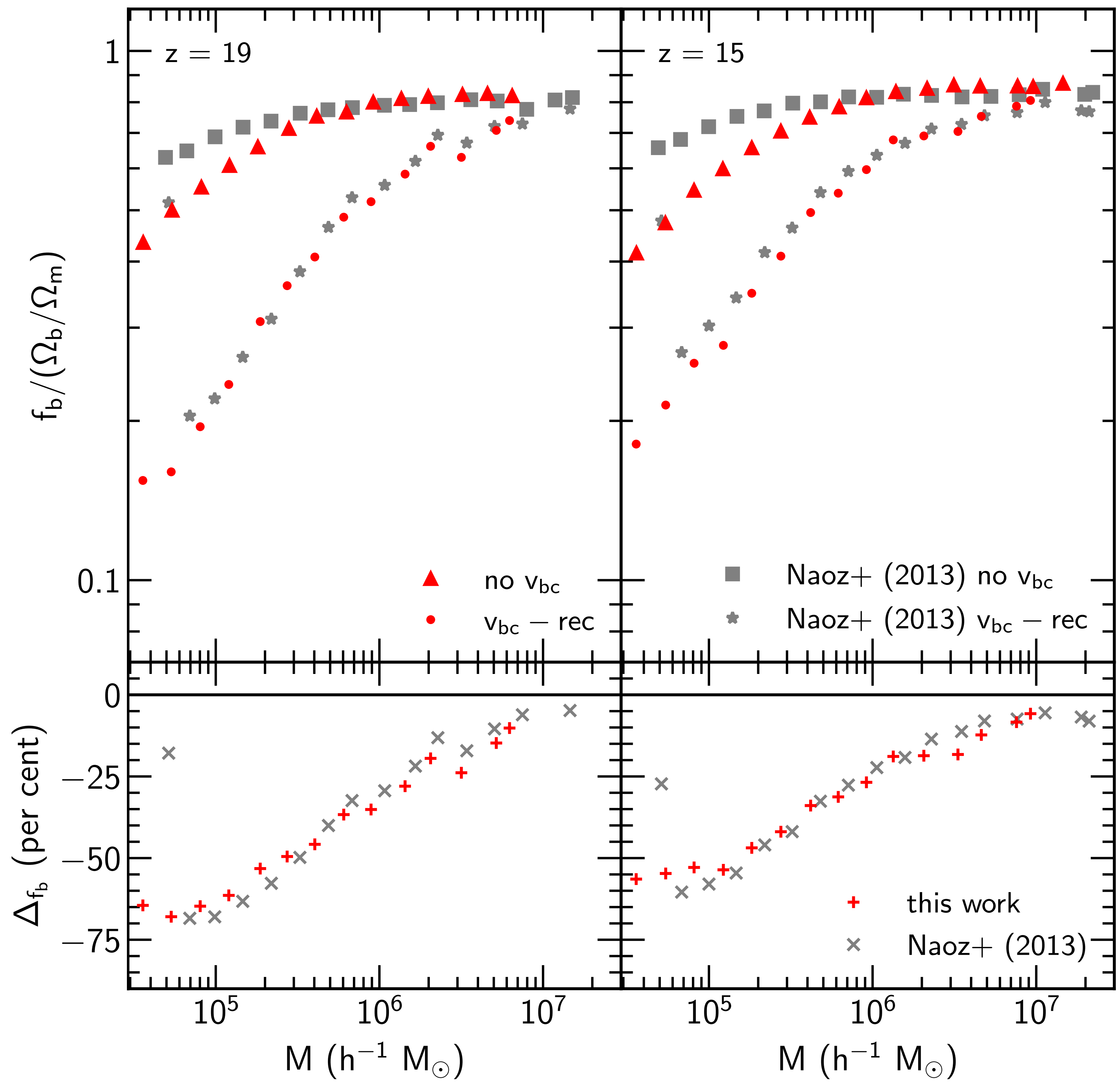


- Slight difference in shape may be due (at least in part) to slightly different choices in cosmology

- Watson+ (2013) is a functional form of HMF fit to *N*-body simulations over range of mass scales and redshifts and $\Delta_N = N_{\mathrm{NGY12}}/N_{\mathrm{ours}} - 1$

Comparison to previous works (f_b)

- Same simulation as for HMF, this time looking at baryon fraction
  $f_b = M_g / M_{tot}$
- Good agreement, though some deviation at low masses (could be due to AMR v SPH, FoF/SO vs AHF halo finding, …?)



Grey: Naoz, Yoshida & Gnedin (2013)
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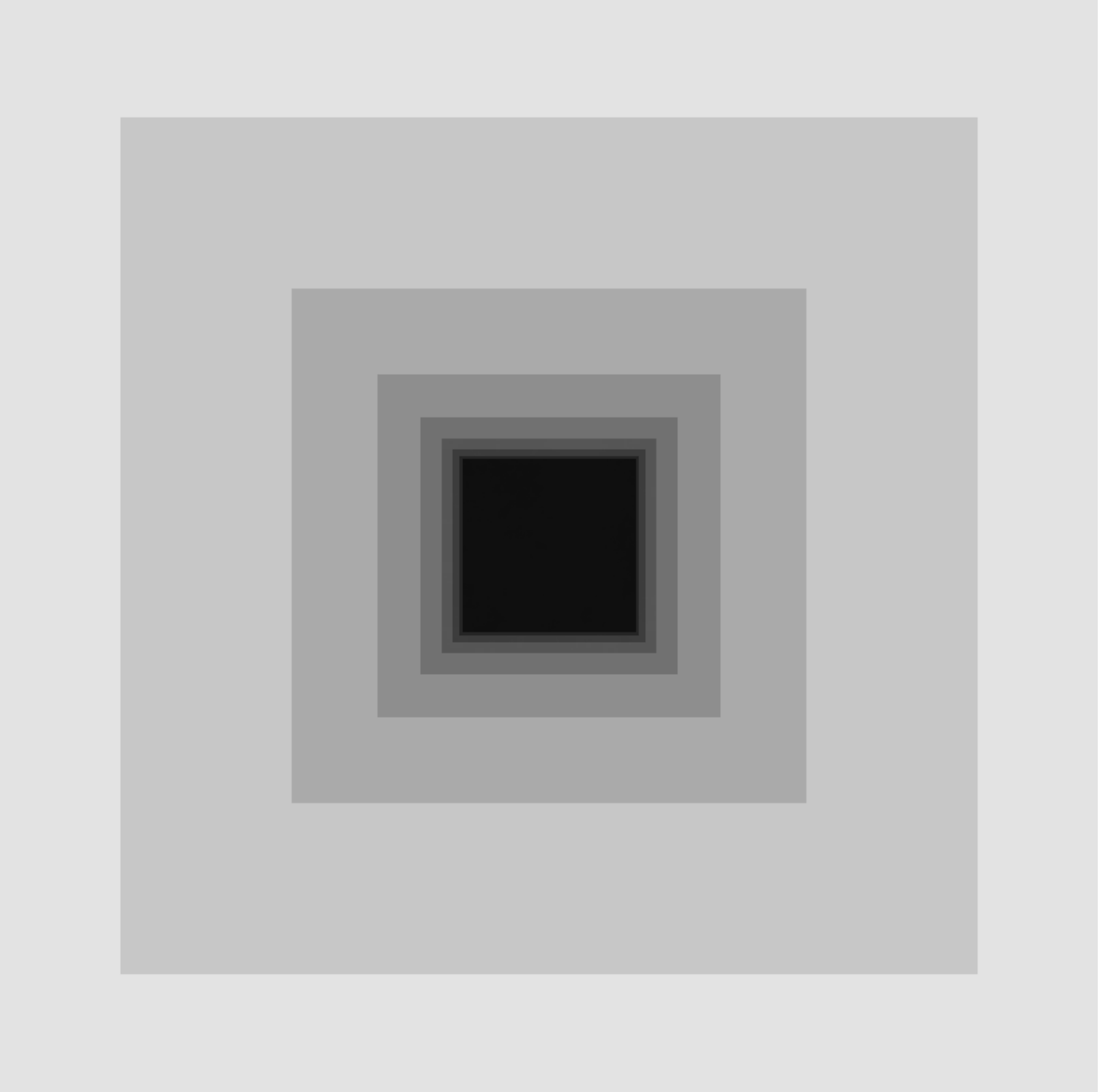
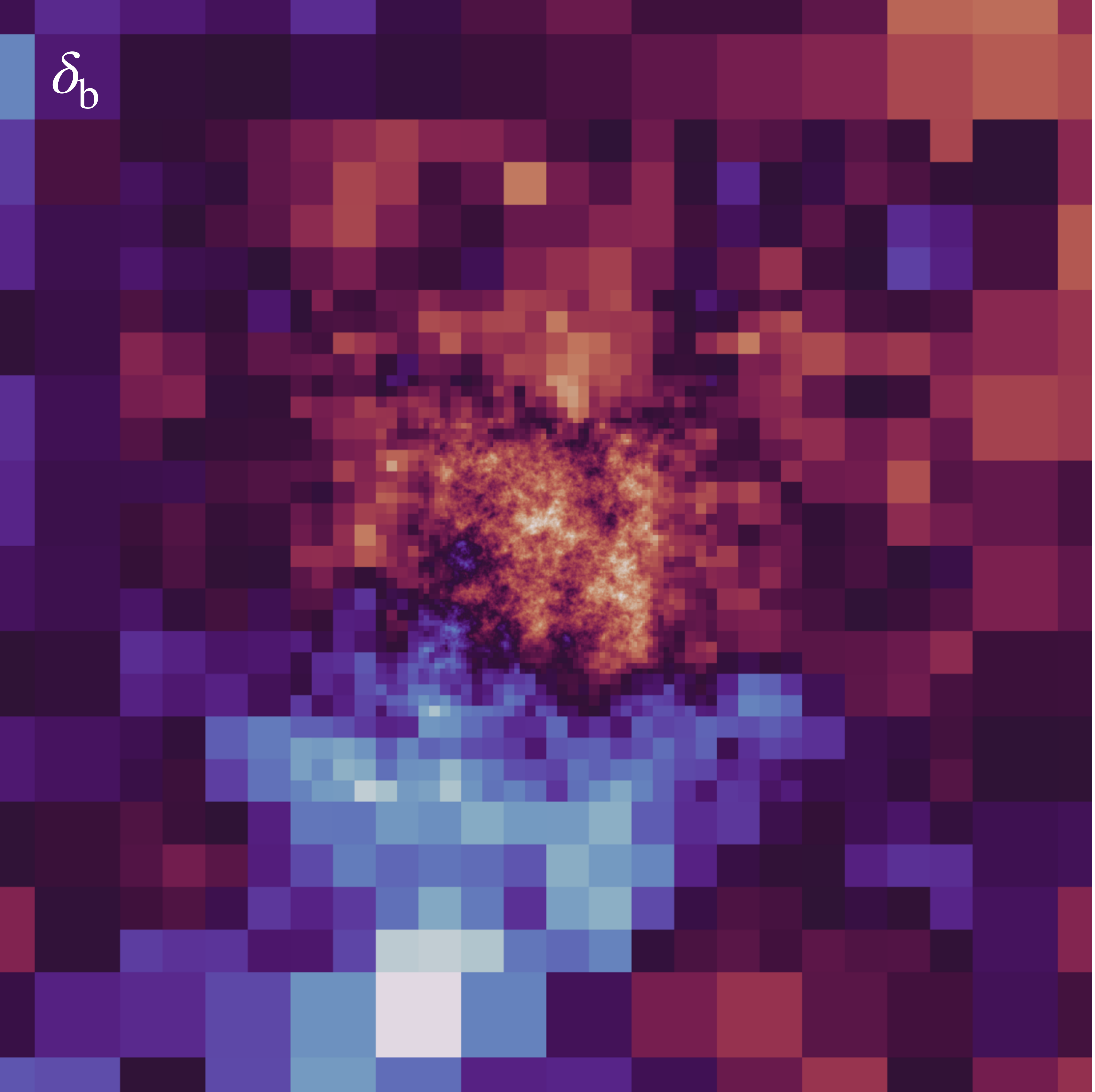


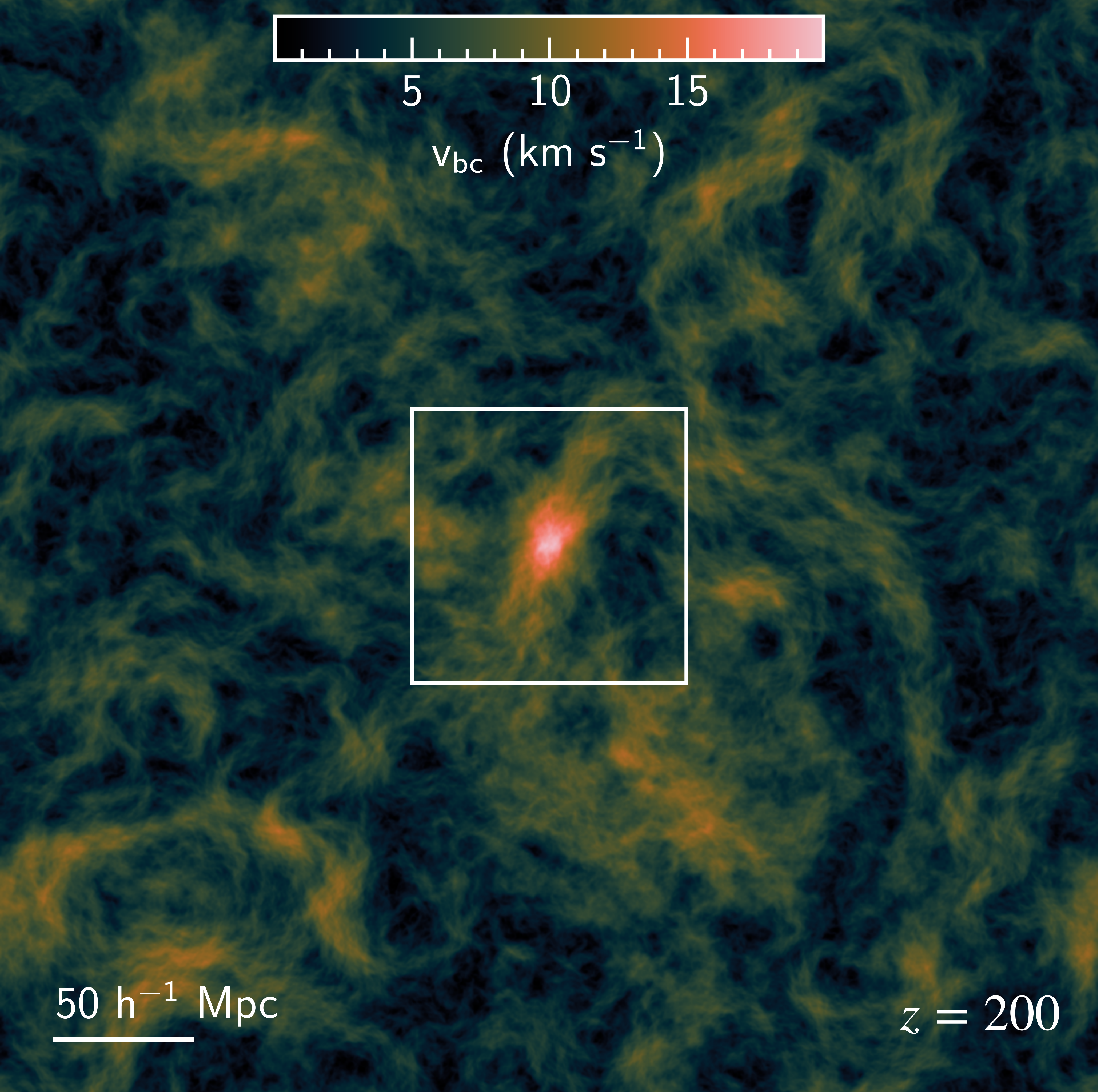
low resolution

high resolution



low resolution

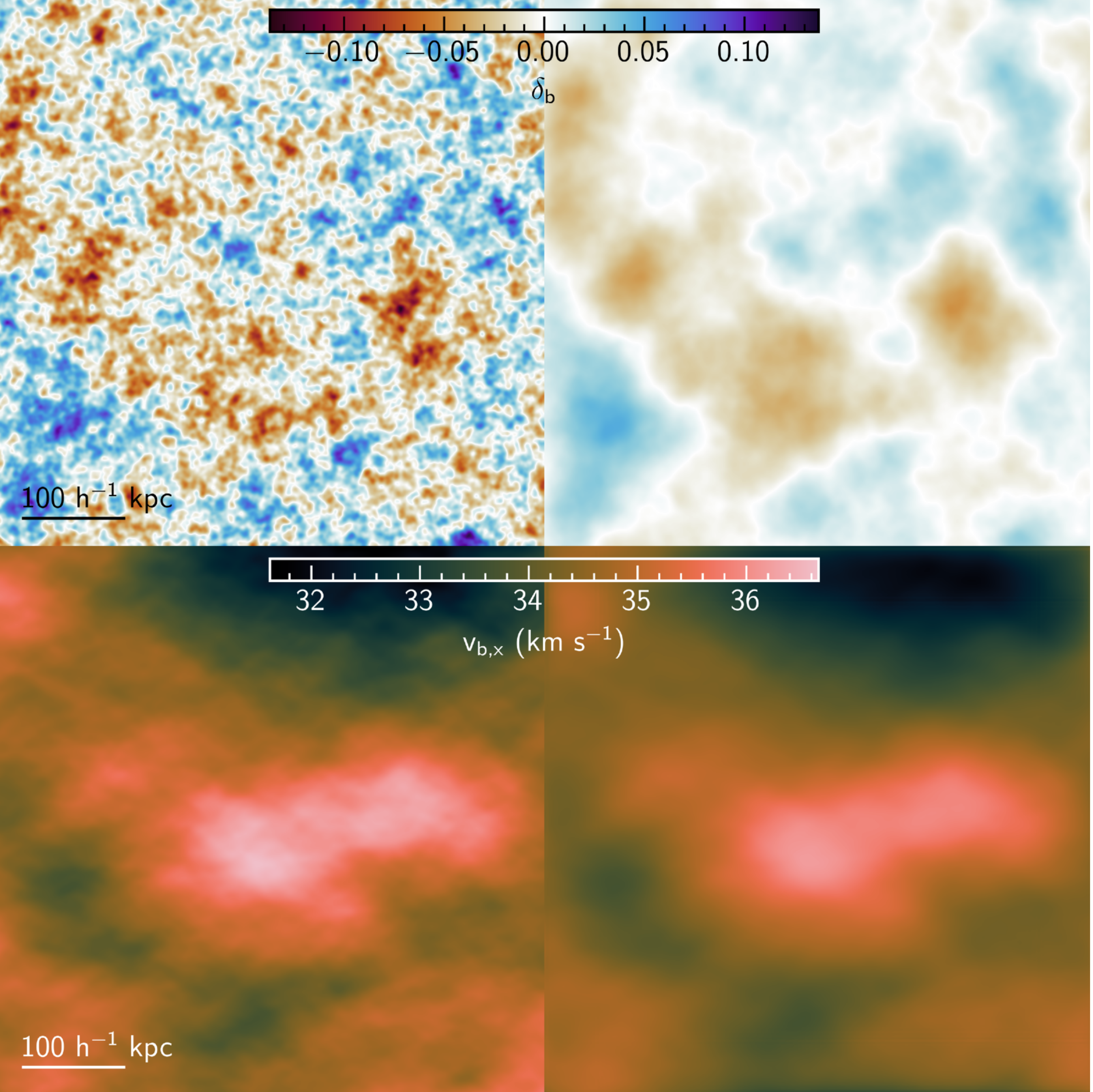
high resolution



400 h^{-1} Mpc
parent box

100 h^{-1} Mpc
sub-box

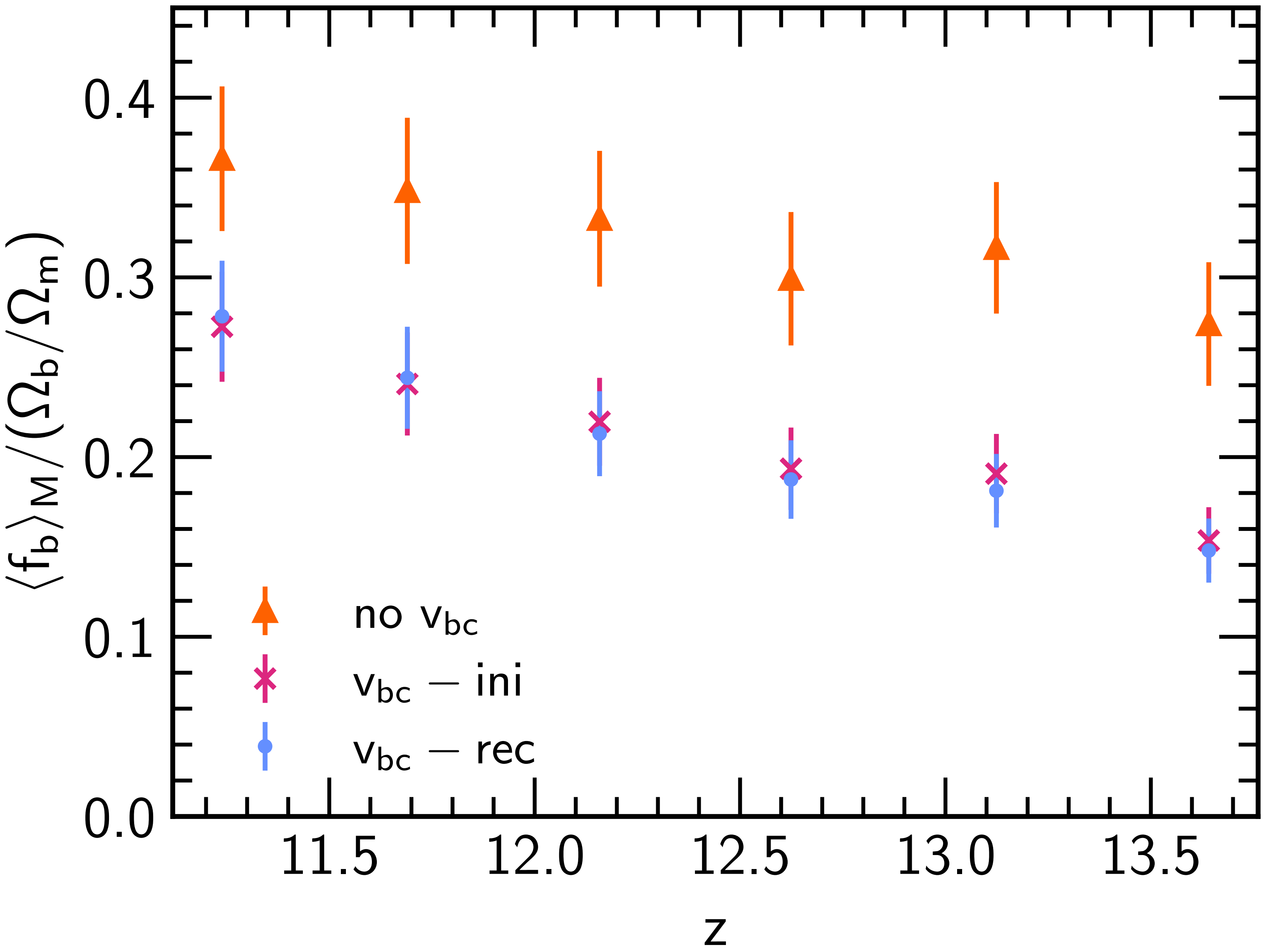
< 1 h^{-1} Mpc
zoom region



small-scale fluctuations in δ_b get washed out

less dramatic for v_i since most power is in large scales

Baryon fraction



$$f_b = \frac{M_g + M_\star}{M_d + M_g + M_\star}$$

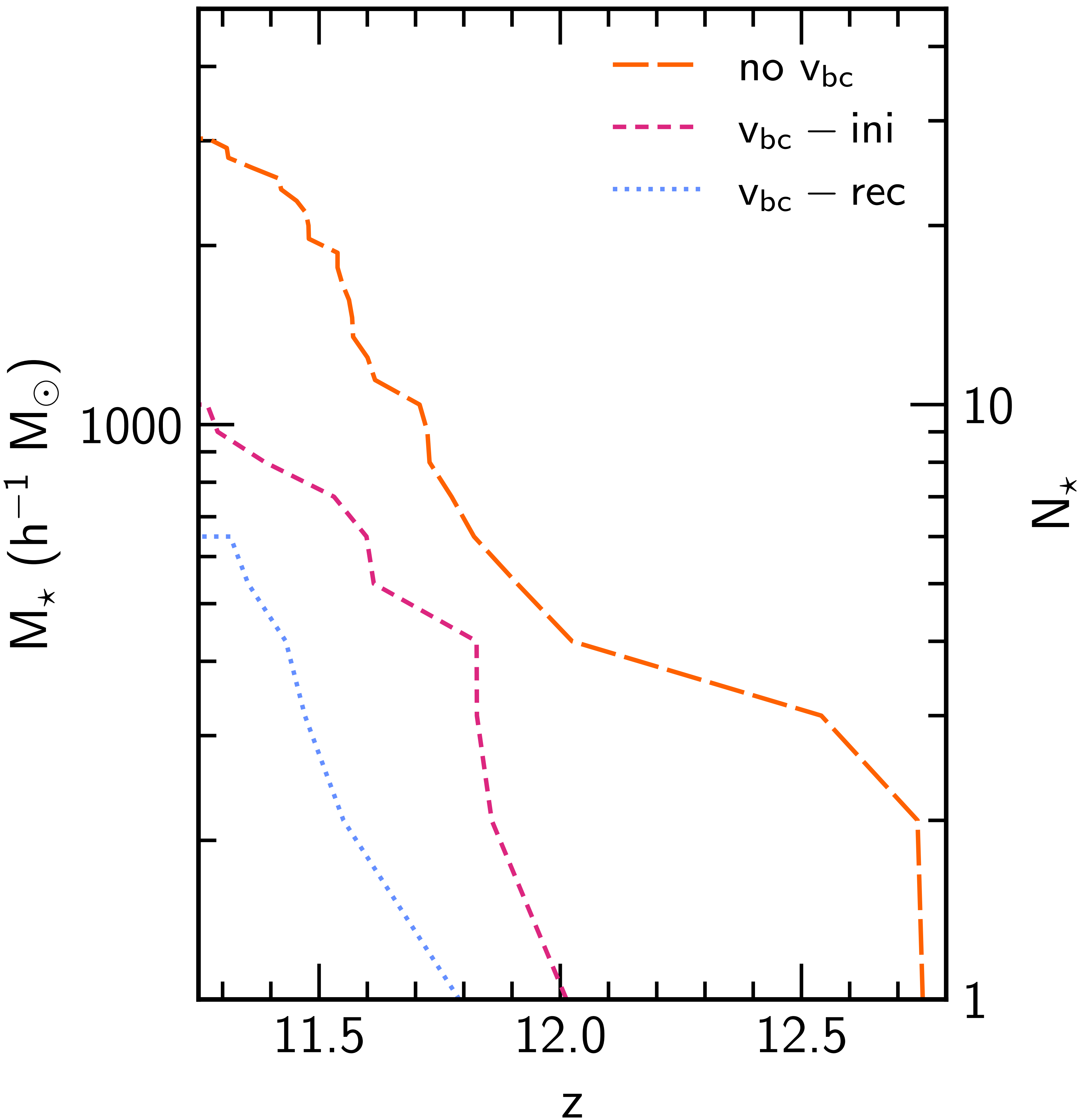
$$\langle f_b \rangle_M = \frac{\sum_i f_{b,i} M_i}{\sum_i M_i}$$

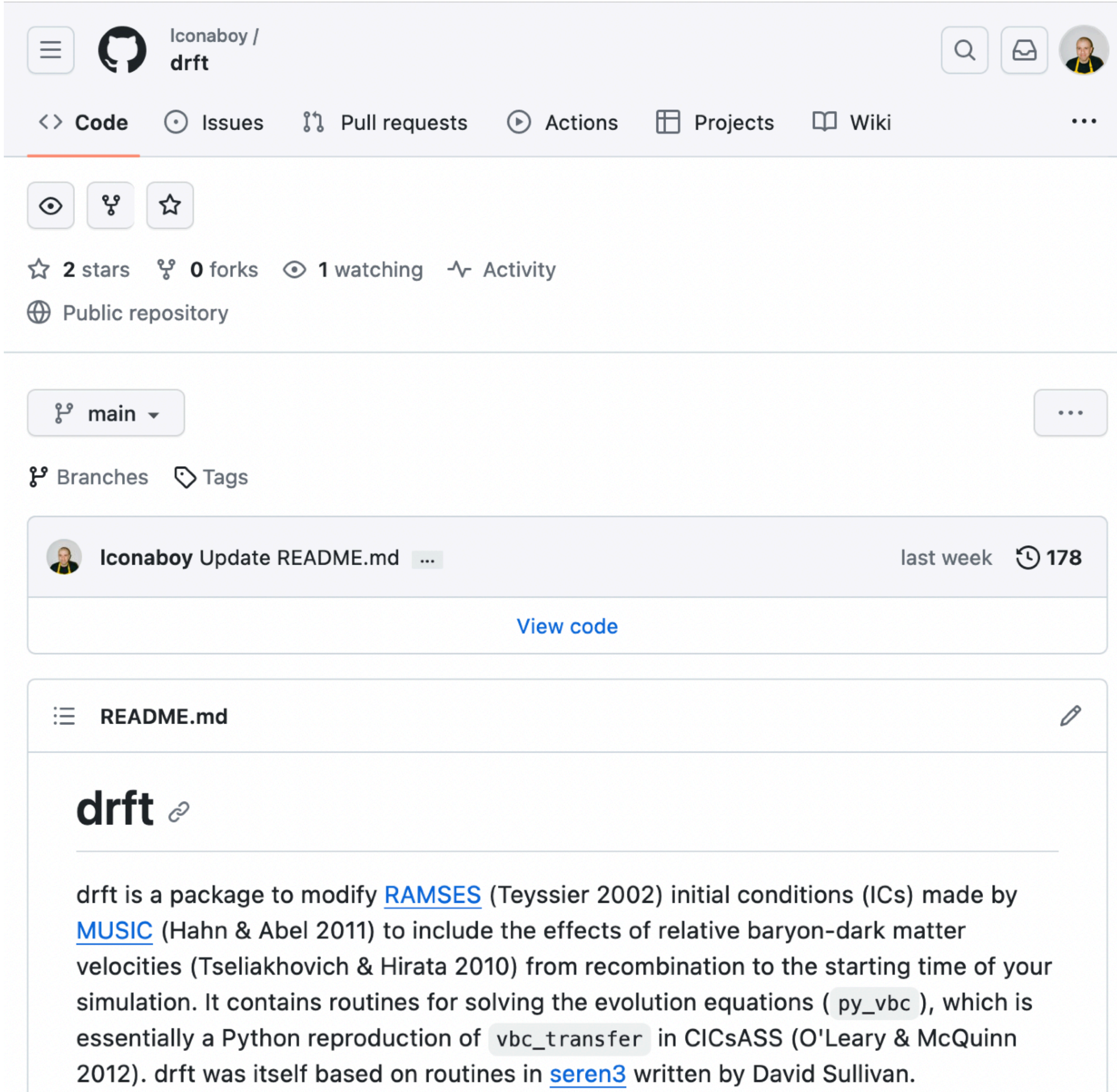
- suppression of 46% at high-z, decreases to 23% by $z \approx 11$

- average delay in formation of nth star particle

- v_{bc}—ini: 19 Myr
- v_{bc}—rec: 35 Myr

- of order the lifetime of a $9\ M_\odot$ Population III star (~20 Myr)




Iconaboy / drft

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View code

README.md

drft

drft is a package to modify RAMSES (Teyssier 2002) initial conditions (ICs) made by MUSIC (Hahn & Abel 2011) to include the effects of relative baryon-dark matter velocities (Tseliakhovich & Hirata 2010) from recombination to the starting time of your simulation. It contains routines for solving the evolution equations (`py_vbc`), which is essentially a Python reproduction of `vbc_transfer` in CICsASS (O'Leary & McQuinn 2012). drft was itself based on routines in seren3 written by David Sullivan.

Iconaboy/drft

Summary

- We performed the first cosmological zoom simulations to self-consistently sample v_{bc} from a large box
- We found that baryon fraction and star formation is suppressed in the case where v_{bc} is included, consistent with results in the literature
- This methodology could be used to explore the effect of variation in v_{bc} local variation on e.g. star formation and chemical enrichment