How useful are simulations for understanding the sources of reionization?

Can we predict the escape of LyC radiation from galaxies with simulations?

Joki Rosdahl

CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

Cosmic Dawn at high latitudes, June 2024

What are the sources of reionization?

Most likely massive young stars emitting ionising radiation that **leaks** out of the inter-stellar medium (ISM) of galaxies

Knowing the emissivity of these young stars in the early Universe allows us to model reionization:

volume-filling factor of HII

emissivity per volume of ionising photons

$$\frac{dQ_{\mathrm{HII}}}{dt} = \frac{\dot{n}_{\mathrm{ion}}}{\langle n_{\mathrm{H}} \rangle} - \frac{Q_{\mathrm{HII}}}{\langle t_{\mathrm{rec}} \rangle}$$

average density of IGM

recombination time

What are the sources of reionization?

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emissivity per volume of ionising photons

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average density of IGM

recombination time

The main ingredient is the emission of radiation from galaxies

Observed f_{esc} is very low at low z, and unknown at z≳5 so *almost* a free parameter

➡simulations are needed

$$\dot{n}_{\rm ion}(z) = \underbrace{SFRD(z)}_{\simeq\text{known}} \times \underbrace{\ell}_{\simeq\text{known}} \times f_{\rm esc}(z)$$

star formation rate density

number of photons per stellar mass formed

escape fraction of ionising radiation from galaxies

Can we predict LyC escape fractions with simulations?

I: ’ancient’ history

ESCAPE OF IONIZING RADIATION FROM HIGH-REDSHIFT GALAXIES

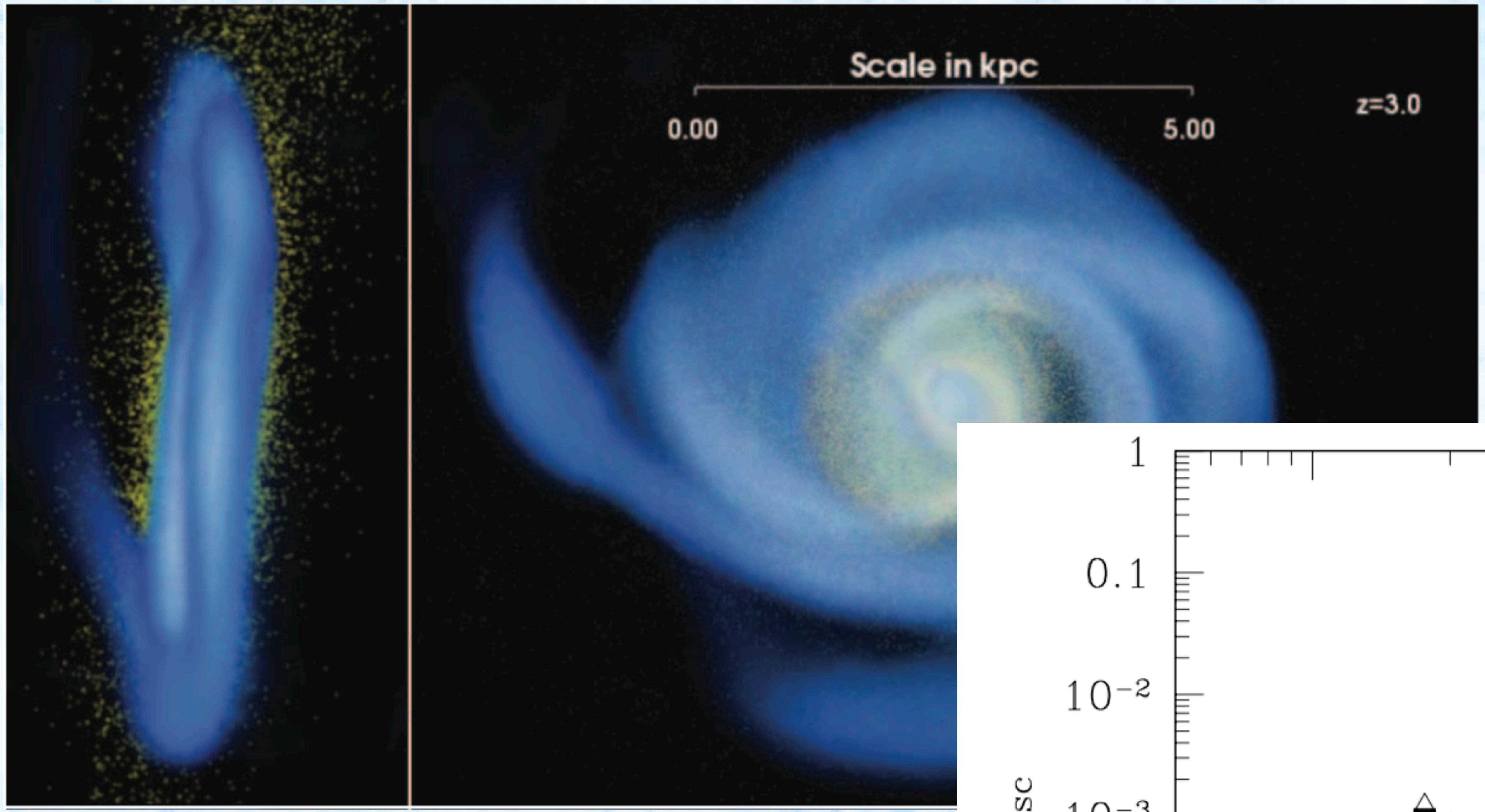
NICKOLAY Y. GNEDIN,[1,2,3] ANDREY V. KRAVTSOV,[2,3,4] AND HSIAO-WEN CHEN[3]

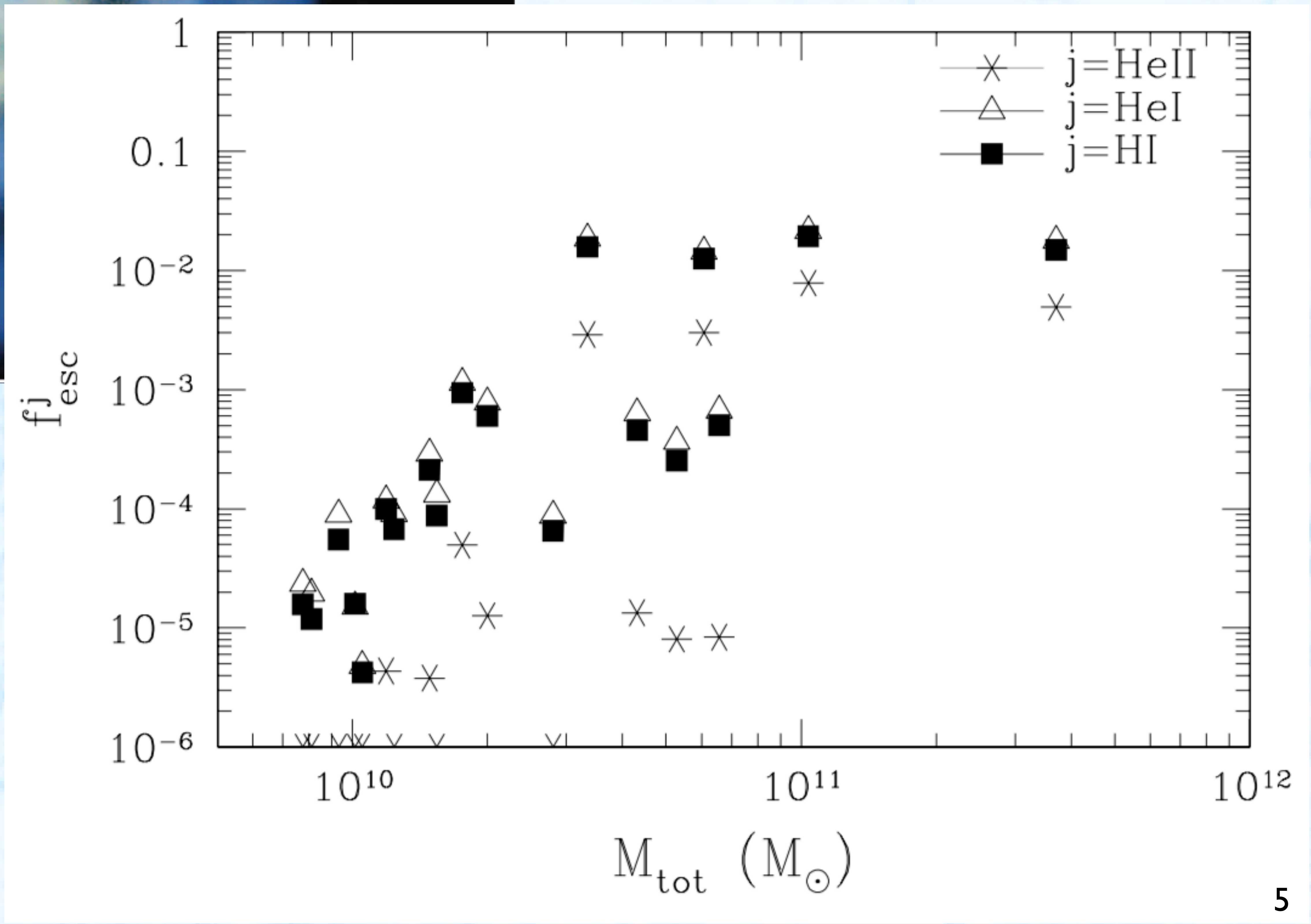
Received 2007 July 6; accepted 2007 September 23

Cosmological RHD zoom simulation

$M_{halo} \lesssim 10^{11}\ M_\odot$ at z=3

Physical resolution
$\Delta x > 40$ pc

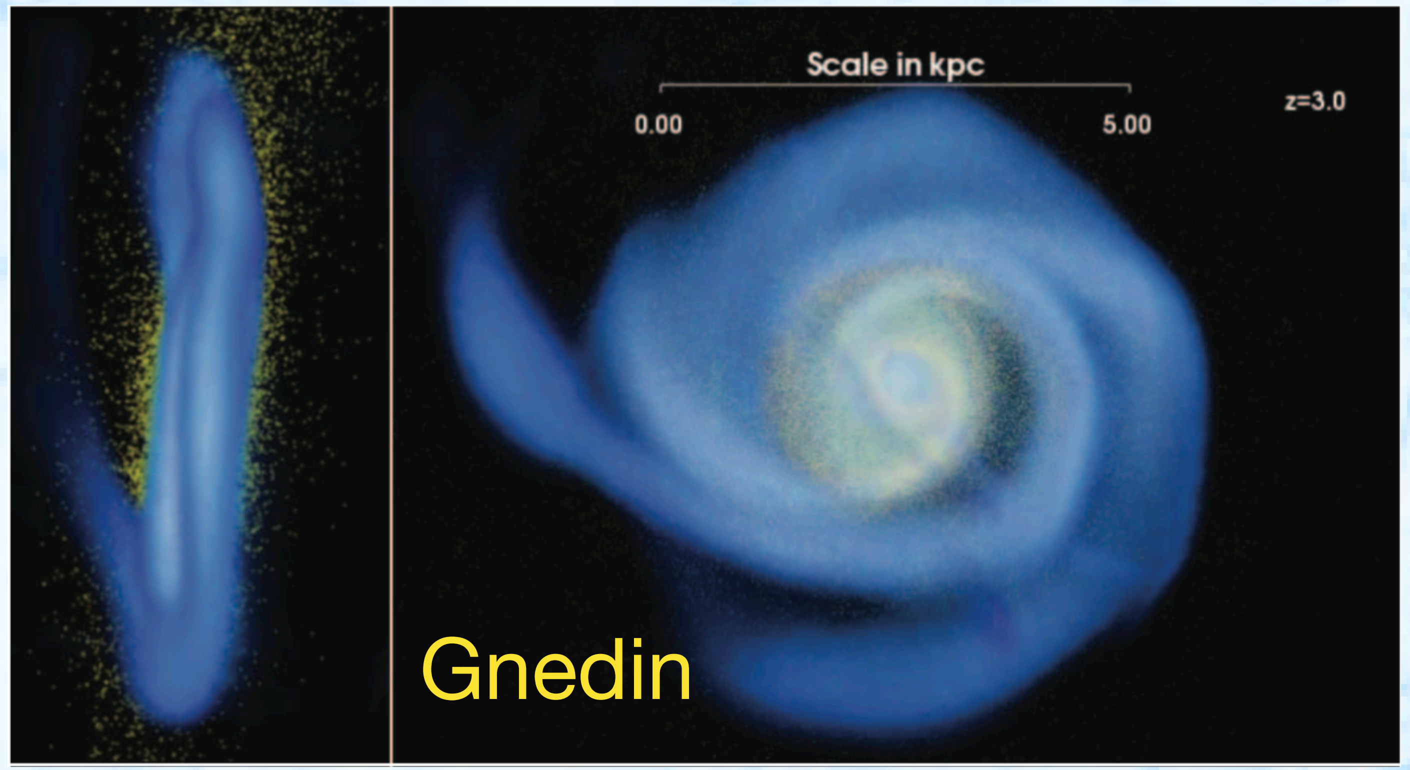


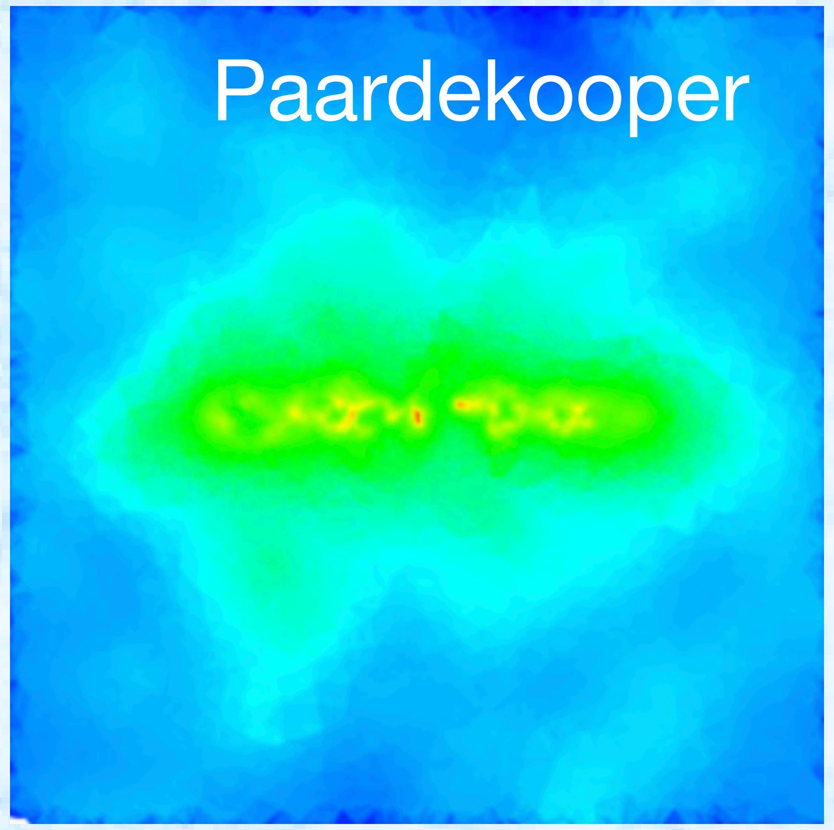


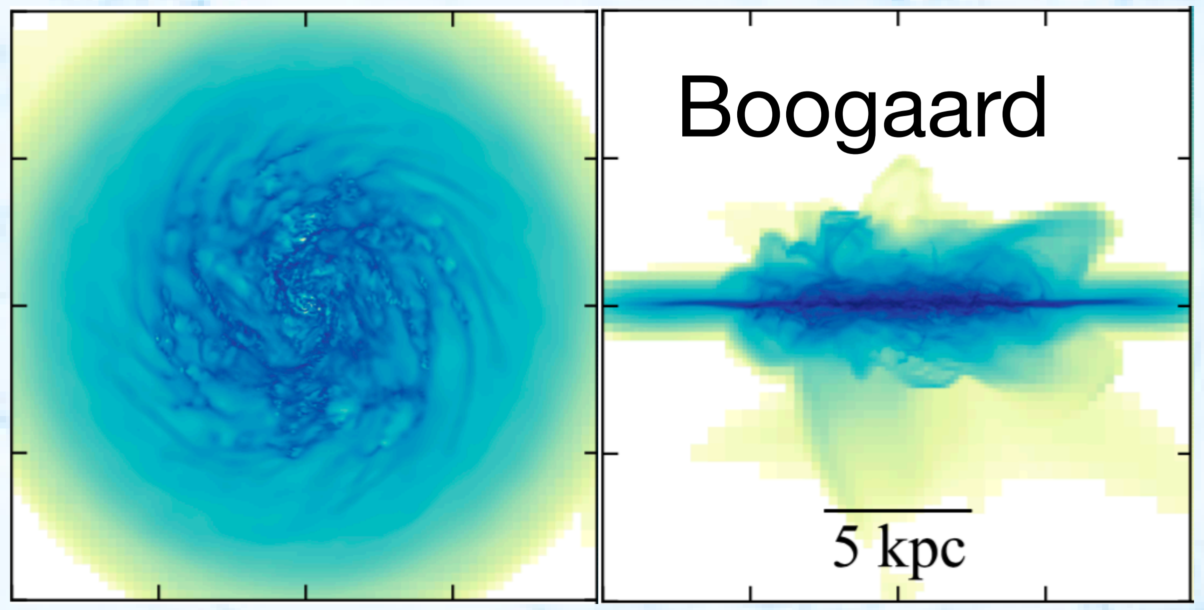
Low escape fractions !

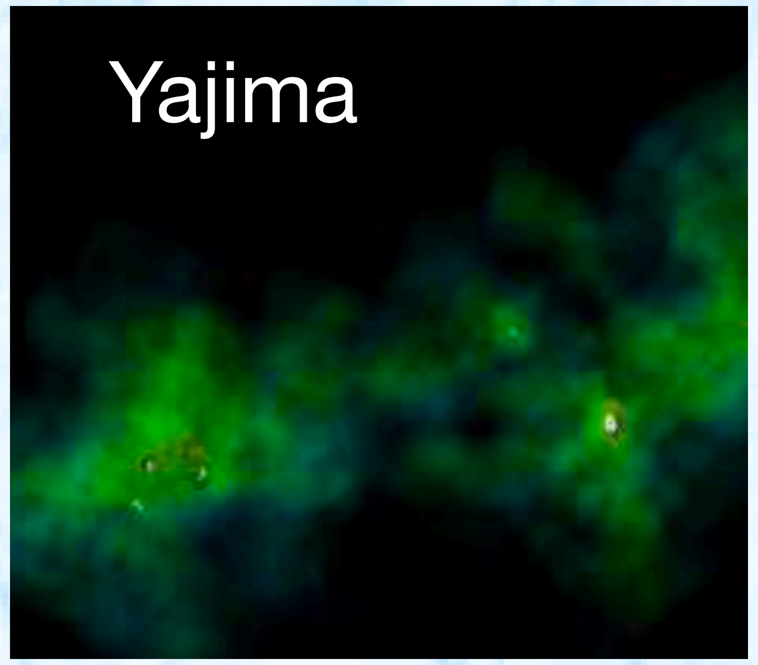
Similar results were found in other simulation works at the time, e.g. Razoumov & Sommer-Larsen (2006)

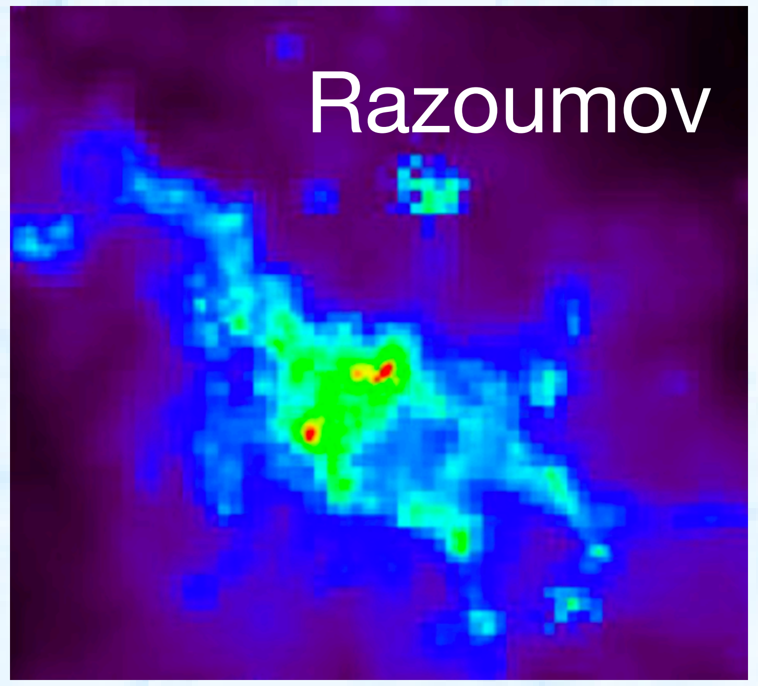
f_{esc} all over the place!

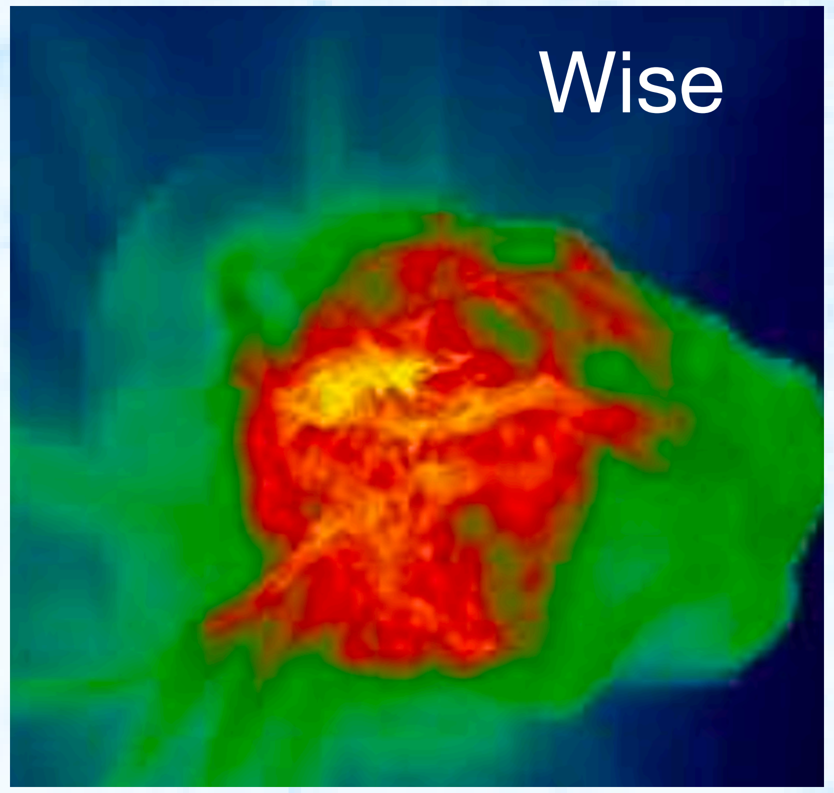












Low f_{esc}:

- Gnedin+07
- Razoumov & Sommer-Larsen 06
- Paardekooper+11
- Ma+15
- Boogaard+16

High f_{esc}:

- Wise&Cen 08
- Yajima+11
- Razoumov&Sommer-Larsen 10

Feedback-regulated f_{esc}

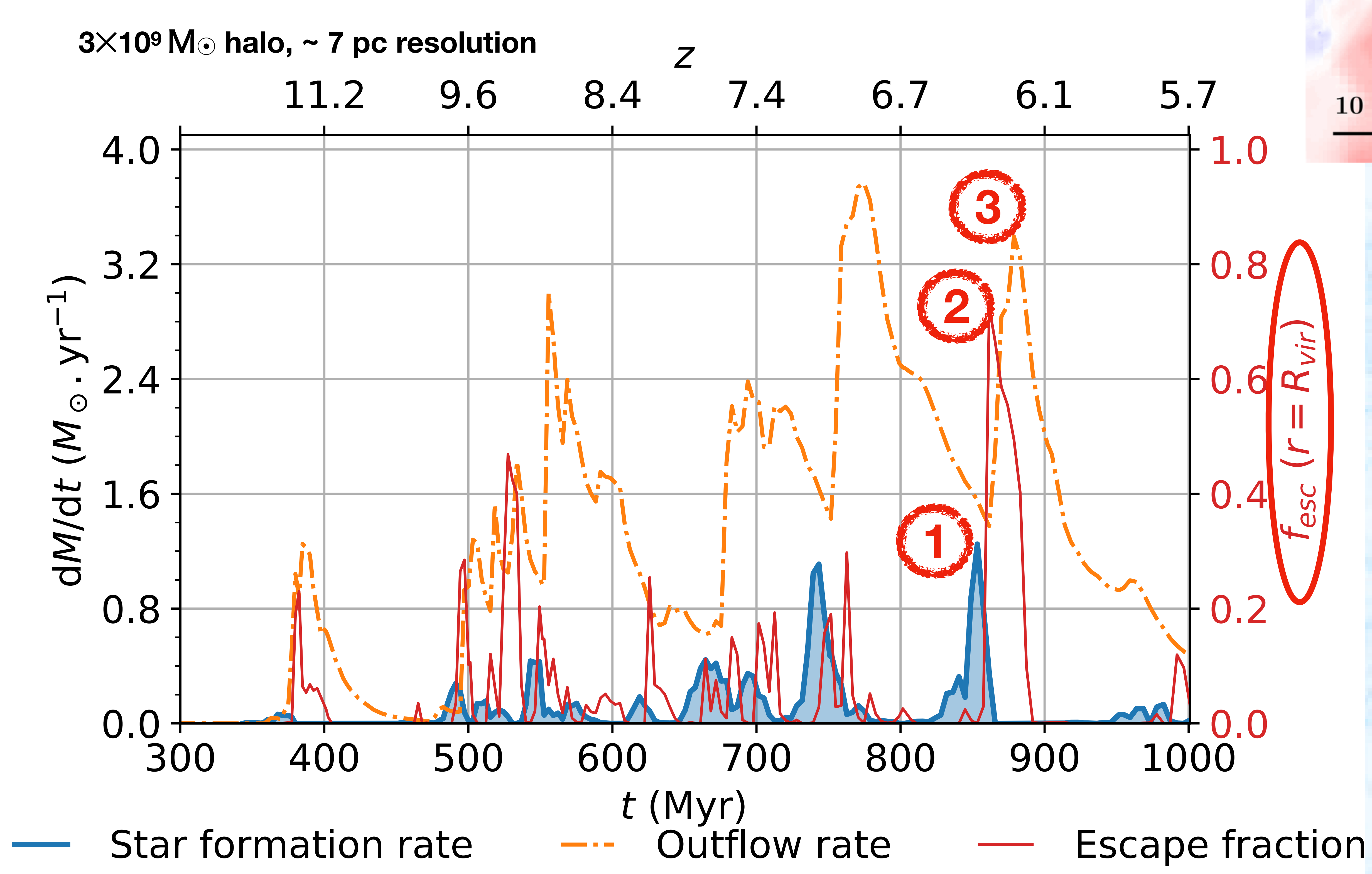
Kimm&Cen14, Wise+14, Paardekooper+15, Xu+16, Ma+15, Trebitsch+17

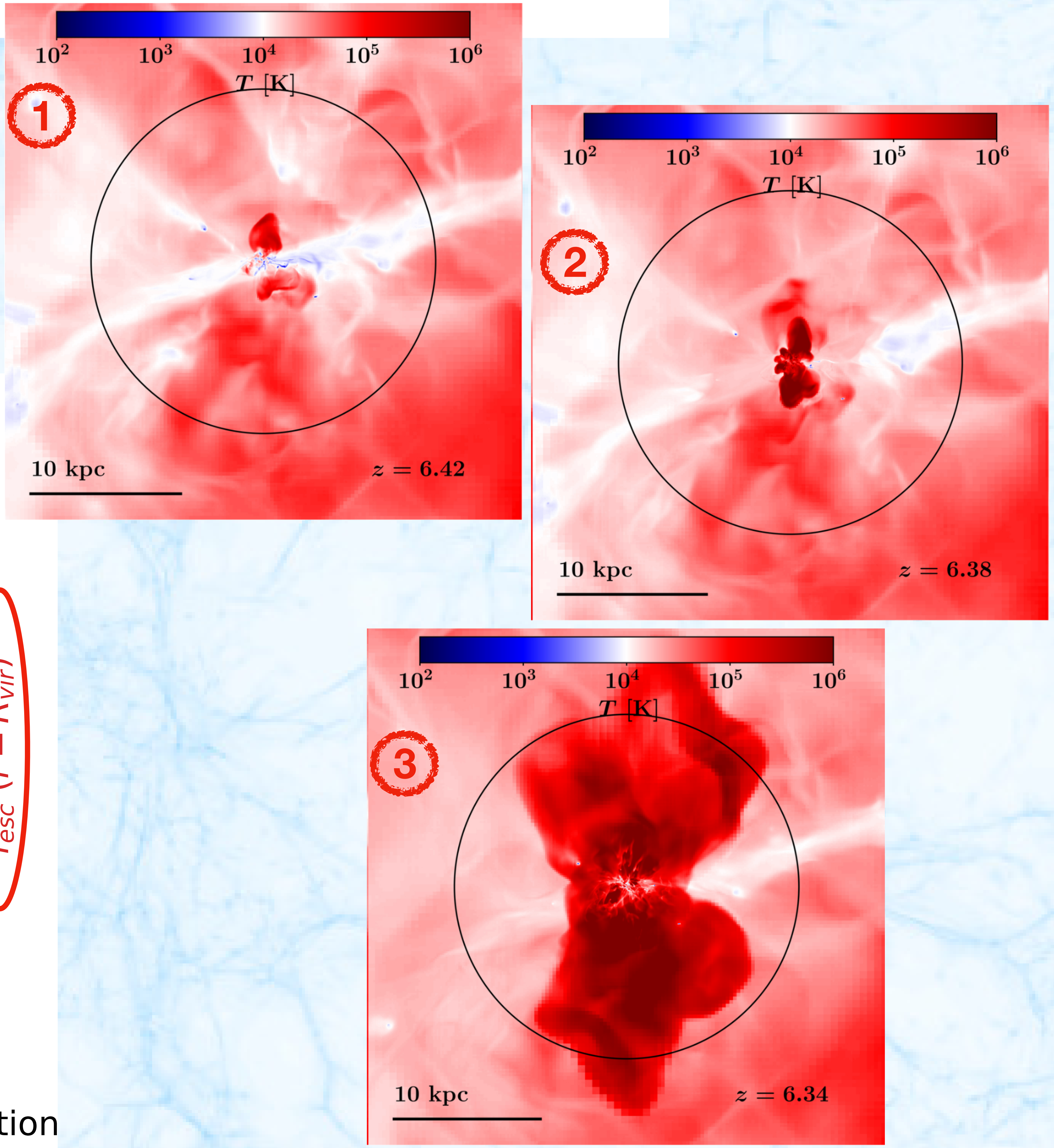
Fluctuating feedback-regulated escape fraction of ionizing radiation in low-mass, high-redshift galaxies (2017)

Maxime Trebitsch[1,2]★, Jérémy Blaizot[2], Joakim Rosdahl[2,3], Julien Devriendt[2,4] and Adrianne Slyz[4]

Study of f_{esc} from 3 high-z halos with 7 pc resolution

➡f_{esc} is highly variable and SN-regulated



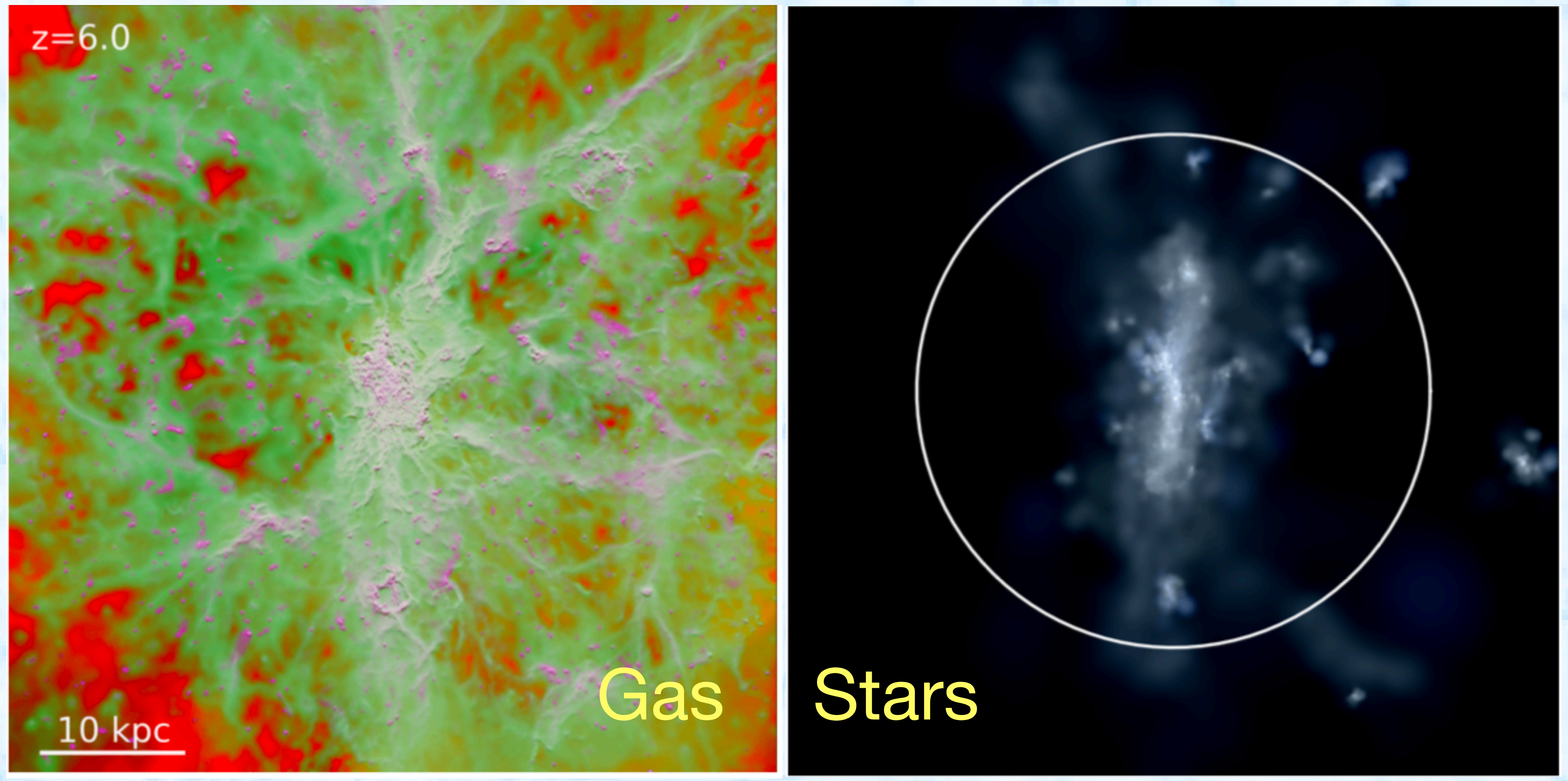


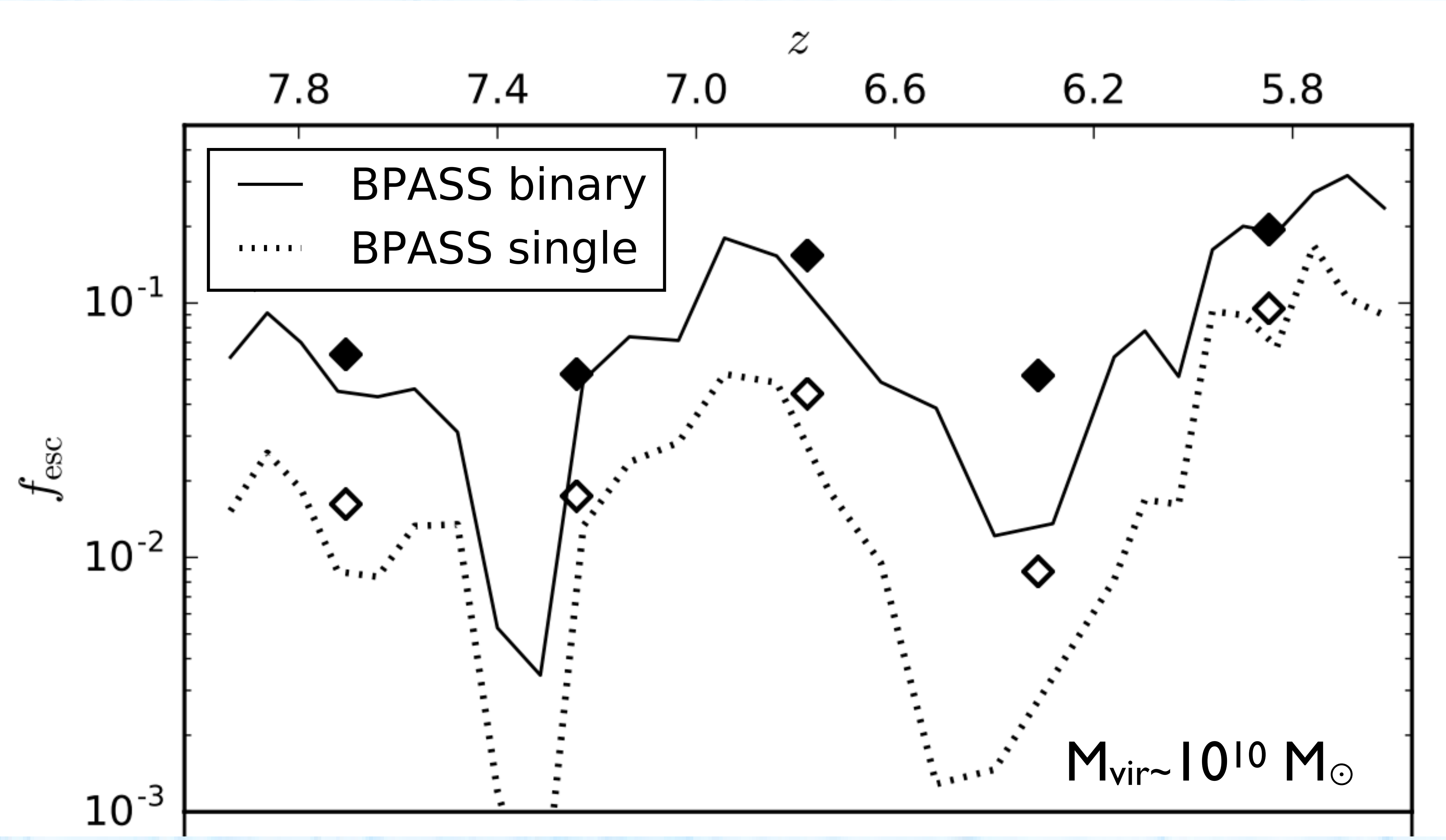
Coupling feedback to stellar evolution

Binary Stars Can Provide the "Missing Photons" Needed for Reionization (2016)

Xiangcheng Ma,[1]∗ Philip F. Hopkins,[1] Daniel Kasen,[2,3] Eliot Quataert,[2] Claude-André Faucher-Giguère,[4] Dušan Kereš[5] Norman Murray[6]† and Allison Strom[7]

- Post-processing of cosmological zoom simulations, tracing rays from stellar sources, using binary and single SEDs

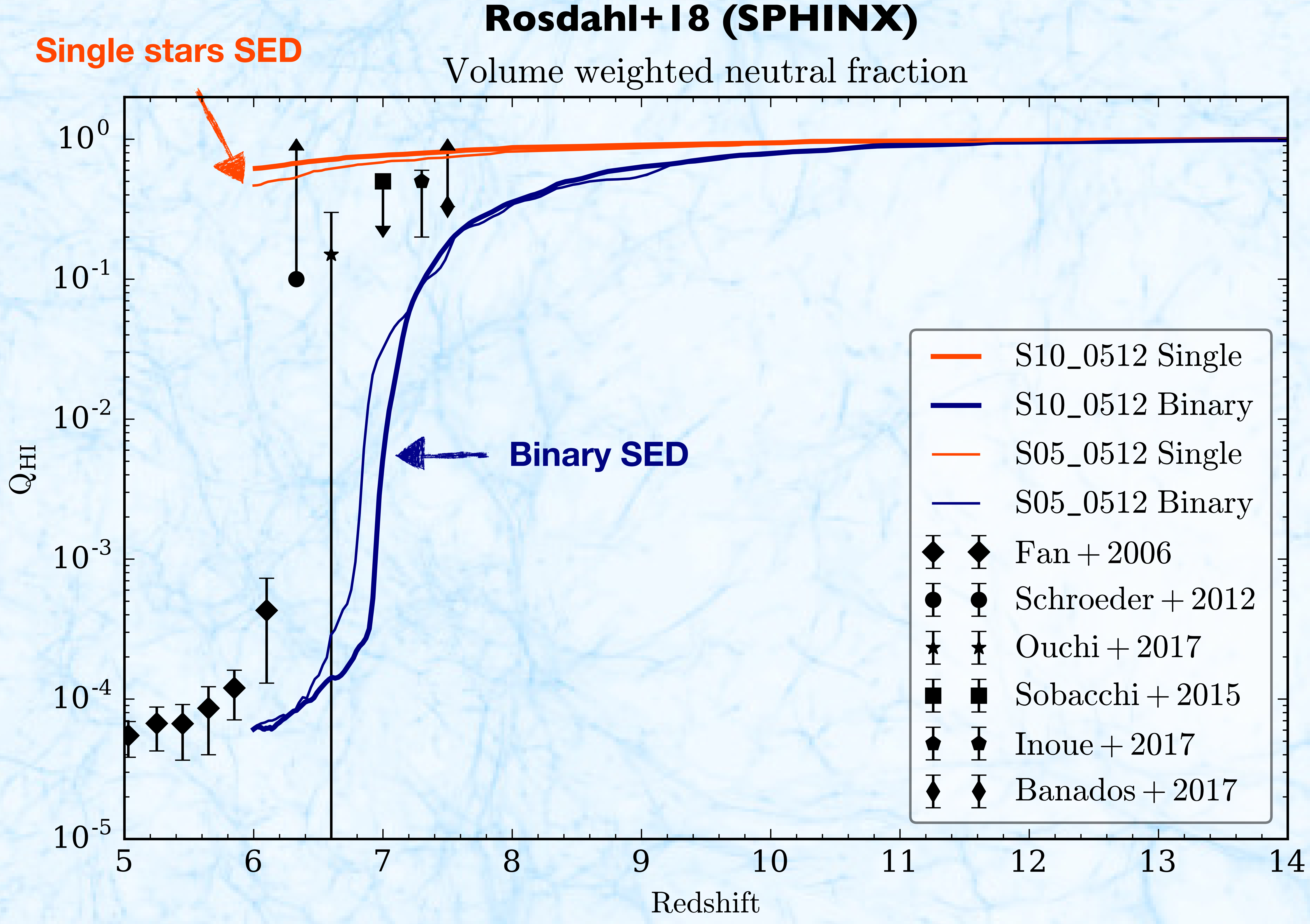




- Factor-few boost in fesc with binaries !

Coupling feedback to stellar evolution

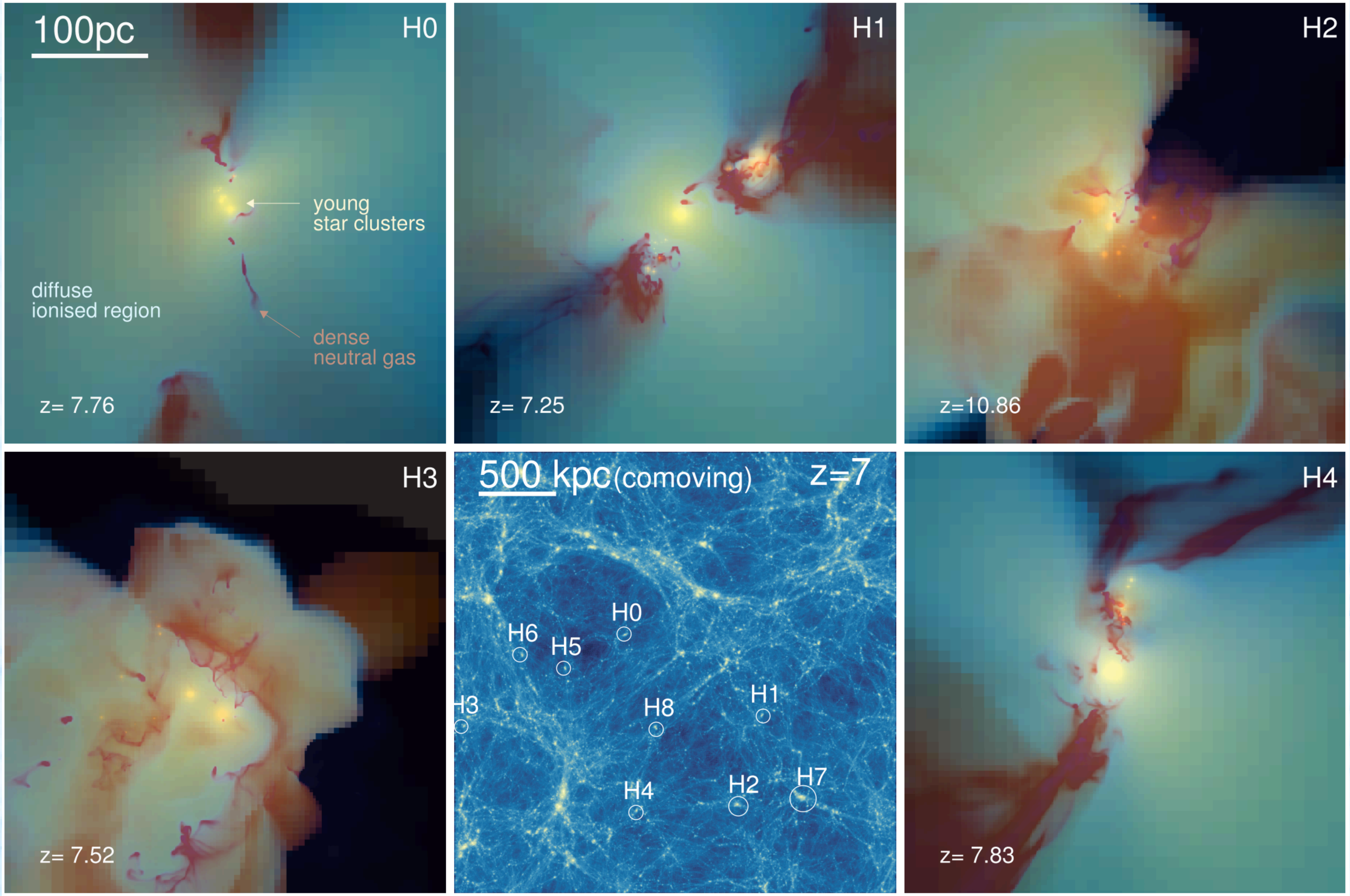
This difference in escape fractions (and hence reionization history) is due to late time (≳5 Myr) boost in LyC luminosities of binary stars with exposed helium cores



Radiation- Feedback-regulated star formation and escape of LyC photons from mini-haloes during reionisation (2017)

Taysun Kimm[1*], Harley Katz[1], Martin Haehnelt[1], Joakim Rosdahl[2], Julien Devriendt[3,4], Adrianne Slyz[3]

'Zoomed' 2 cMpc wide volume, 0.7 pc resolution, allowing for resolved HII regions



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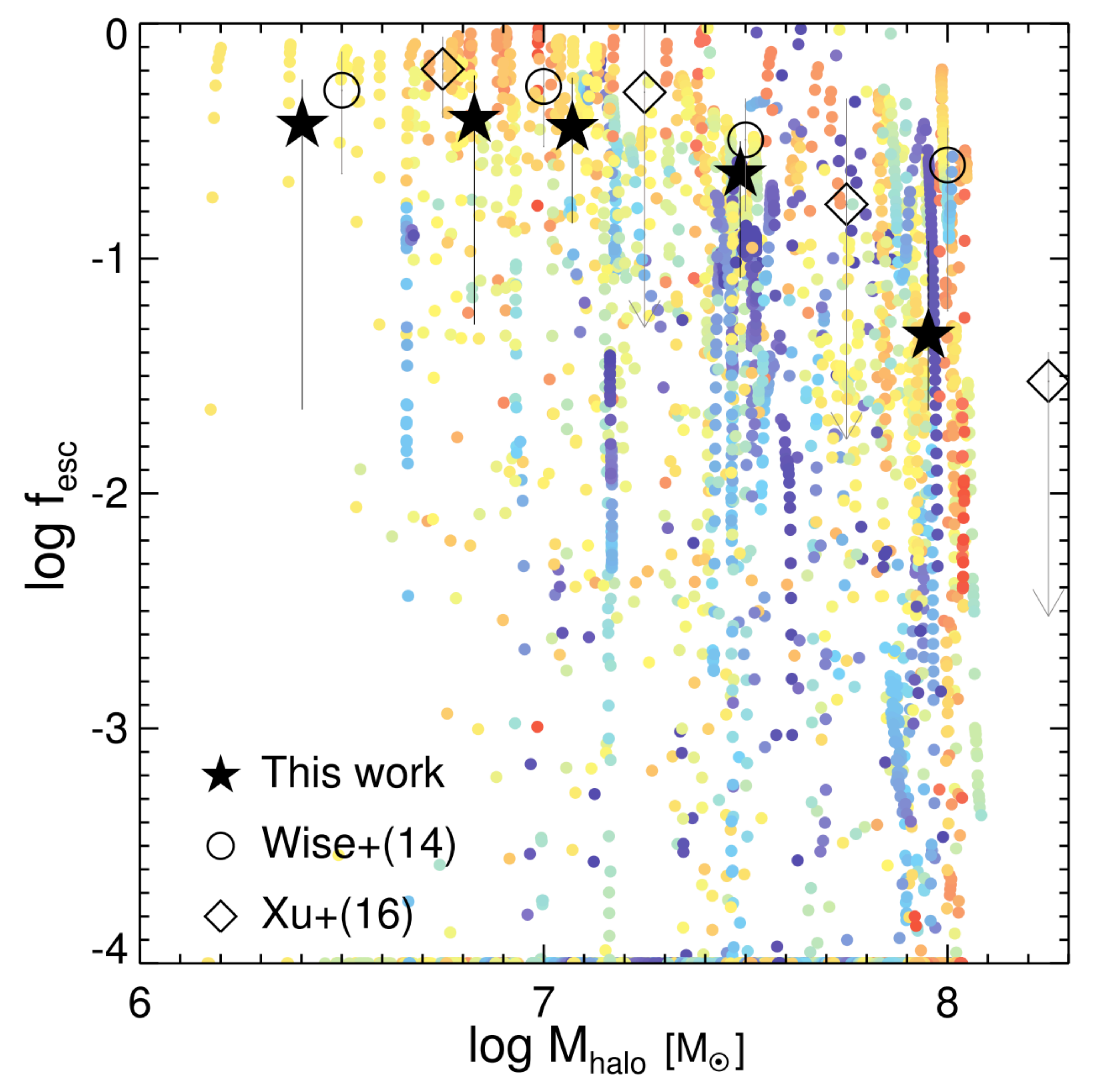
Taysun Kimm[1*], Harley Katz[1], Martin Haehnelt[1], Joakim Rosdahl[2], Julien Devriendt[3,4], Adrianne Slyz[3]

'Zoomed' 2 cMpc wide volume, 0.7 pc resolution (in a small part of the volume)

- Mini-halos have high f_{esc},
- but these galaxies shut themselves down with their own radiation,
- so not much contribution to reionization.



Towards newer and larger simulations

How do LyC escape fractions correlate with galaxy properties?

What do simulations find, and do they agree?

The Key Players

(From Garaldi et al. 2024)

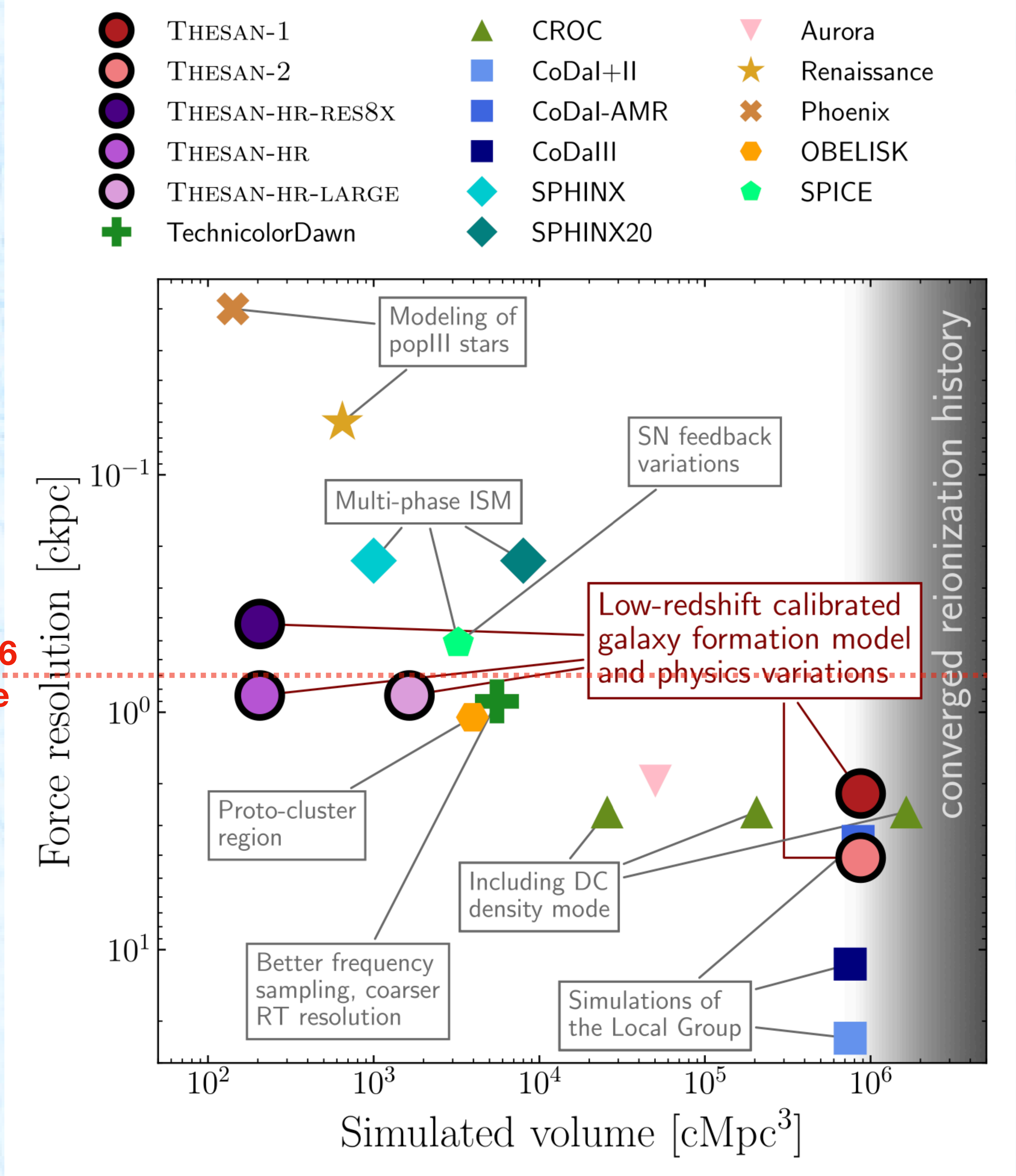
Strong trade-off between resolution and statistics — and we need both!

This is restricted to cosmological radiation-hydrodynamical simulations

Other non-RHD cosmological simulations are used to probe correlations of f_{esc} with galaxy properties, e.g.:

- FiBy (Paardekooper+15)
- FIRE (Ma+16,20)
- IllustrisTNG (Kostyuk+24)

100 pc at z=6 (size of large SF clouds)

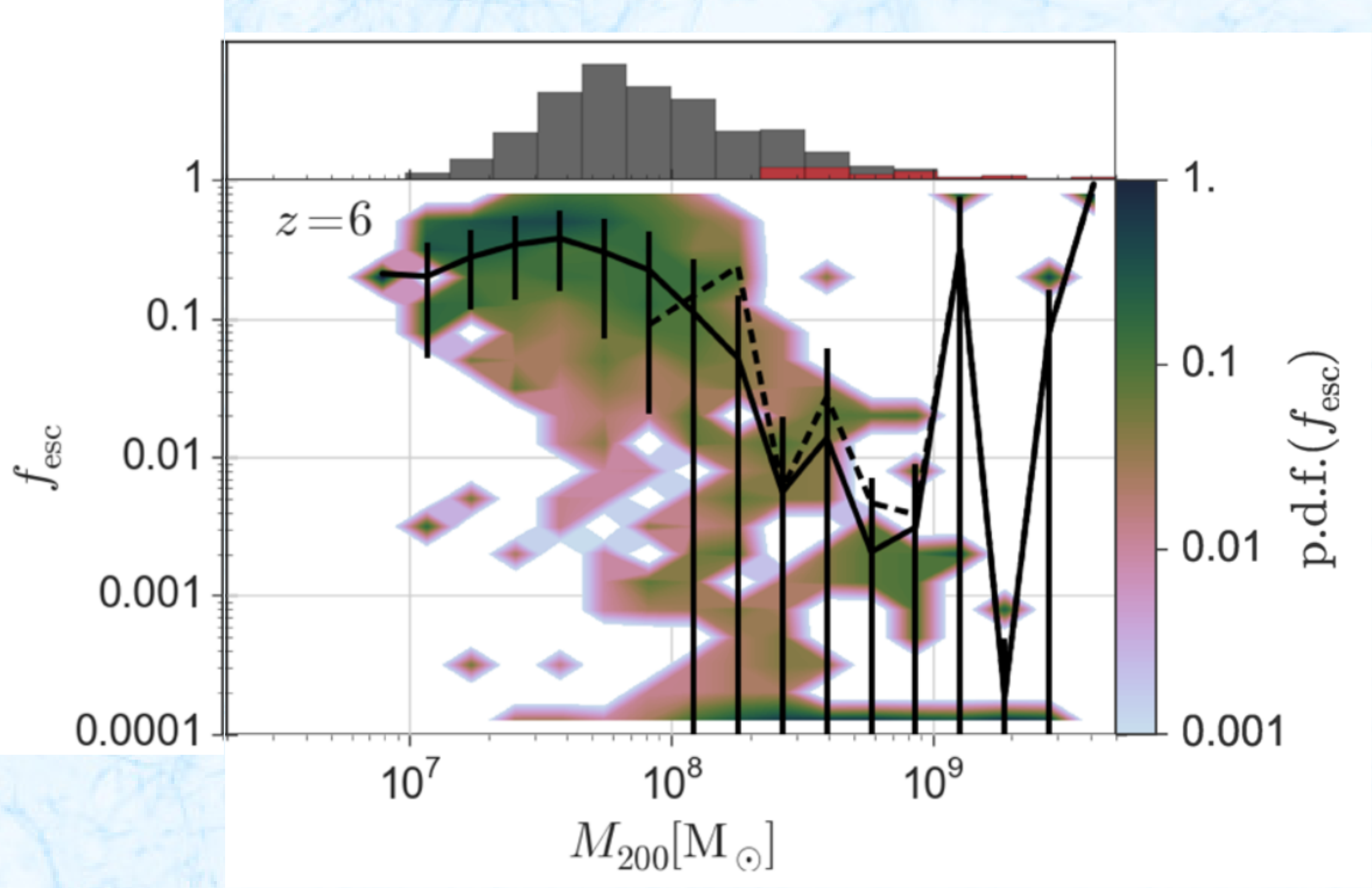


$\langle f_{esc} \rangle$ vs halo mass

Paardekooper+15 (FiBy, pure hydro cosmo-sim)

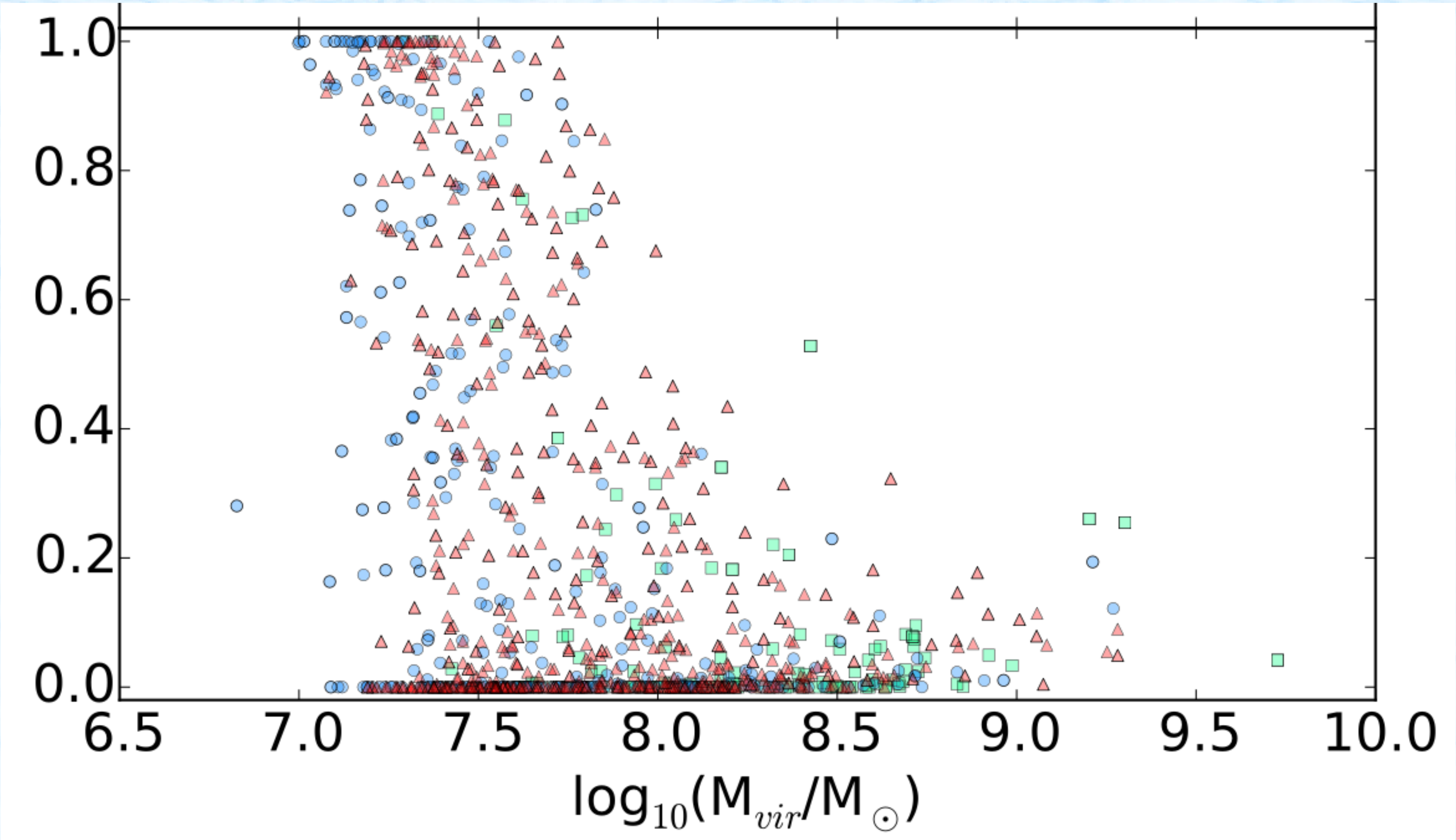
Decrease of <u>mean</u> f_{esc} with halo mass, for $M_{halo} \gtrsim 10^8\ M_\odot$

(and a lot of noise)



f_{esc} vs halo mass

Xu+16 (Renaissance)



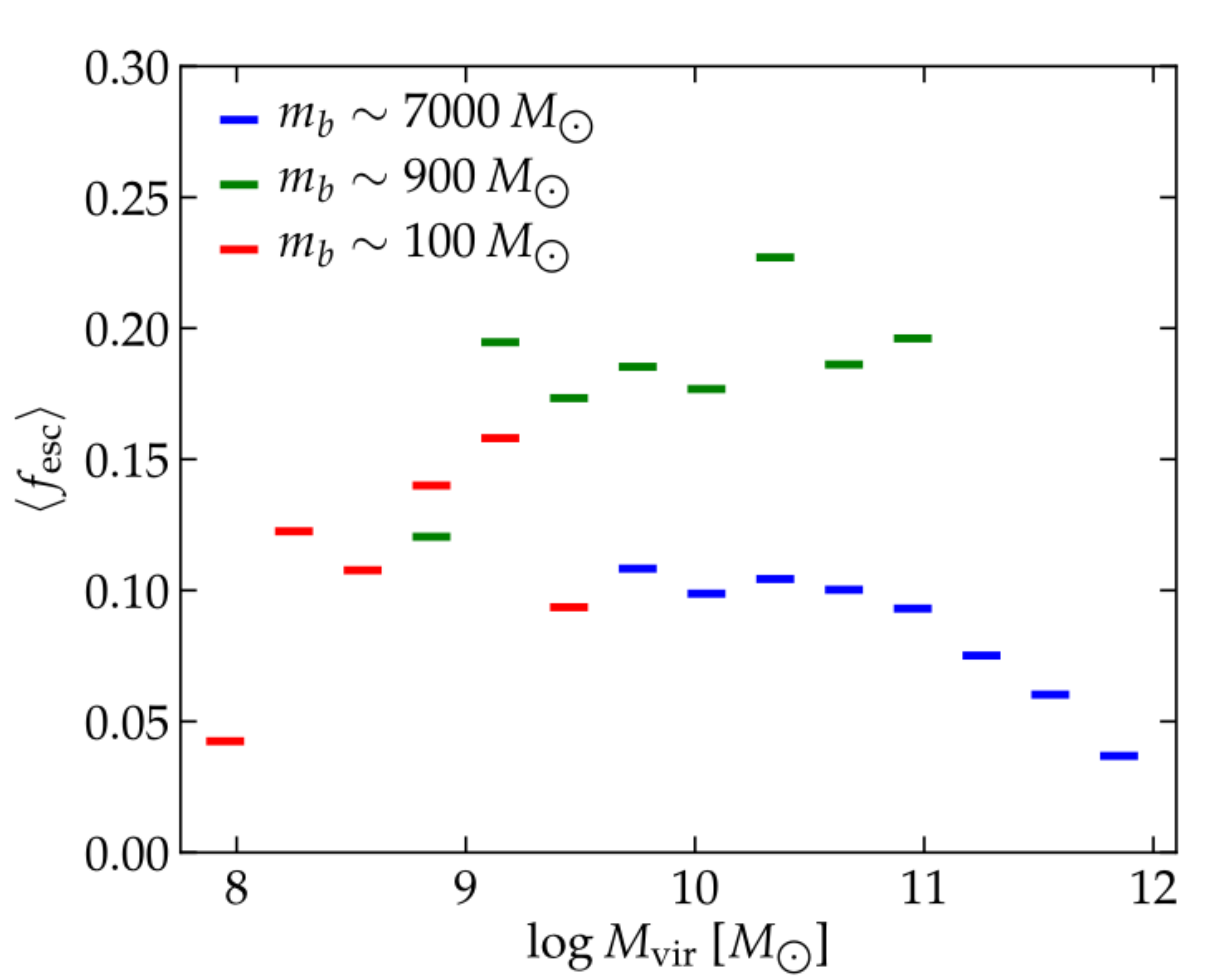
Decrease with halo mass, for $M_{halo} \gtrsim 10^8\ M_\odot$

$\langle f_{esc} \rangle$ vs halo mass

Ma+20 (FIRE, pure hydro cosmo-zooms)

Decrease of L_{LyC}-weighted f_{esc} with halo mass, for $M_{halo} \gtrsim 10^{11}\ M_\odot$, depending on resolution

Very strong feedback in FIRE

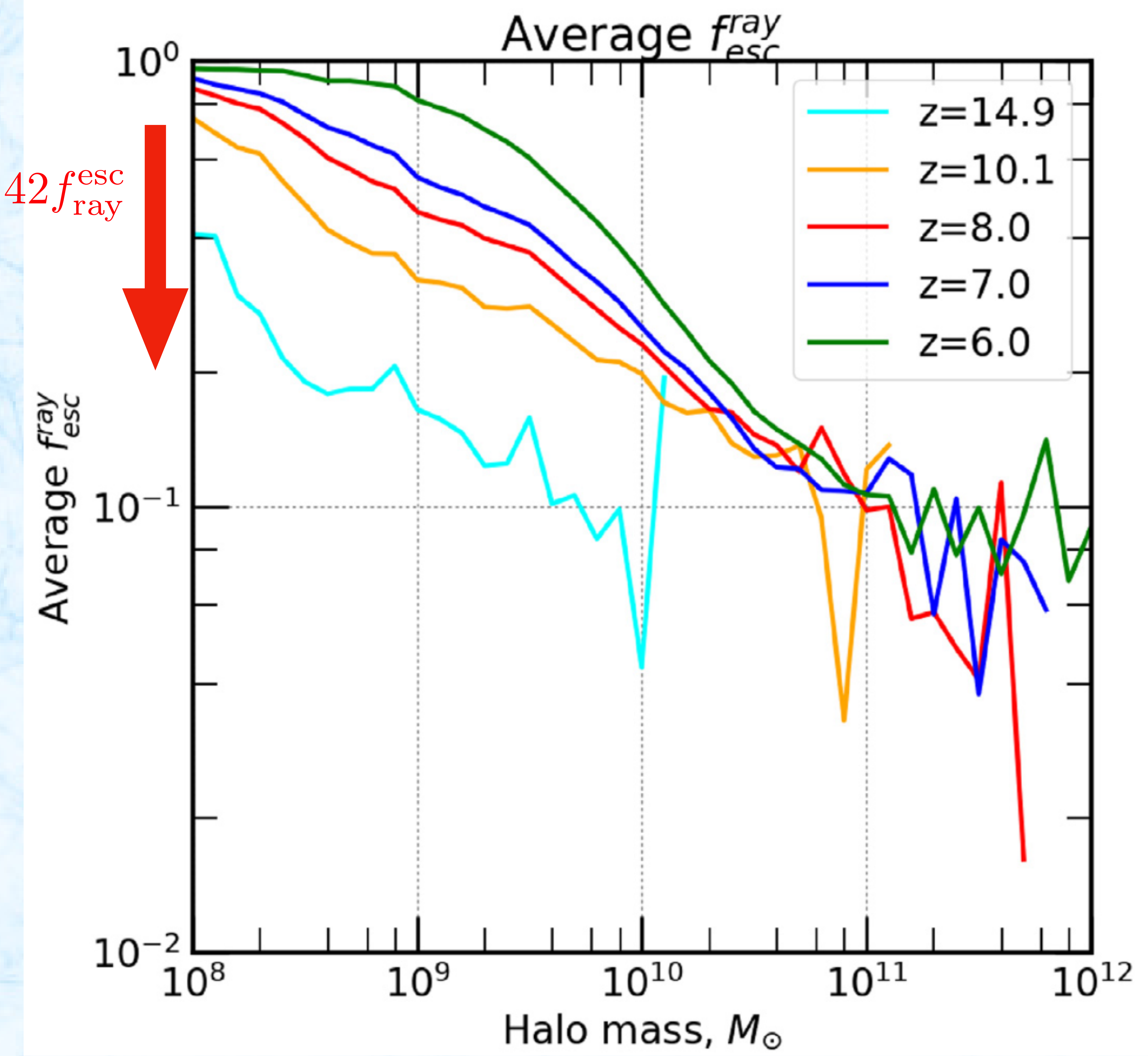


$\langle f_{esc} \rangle$ vs halo mass

Lewis+22 (CoDa cosmological RHD simulation)

Decrease of $\langle f_{esc} \rangle$ with halo mass, for $M_{halo} \gtrsim 10^9\, M_\odot$

$$f_{\rm net}^{\rm esc} = 0.42 f_{\rm ray}^{\rm esc}$$

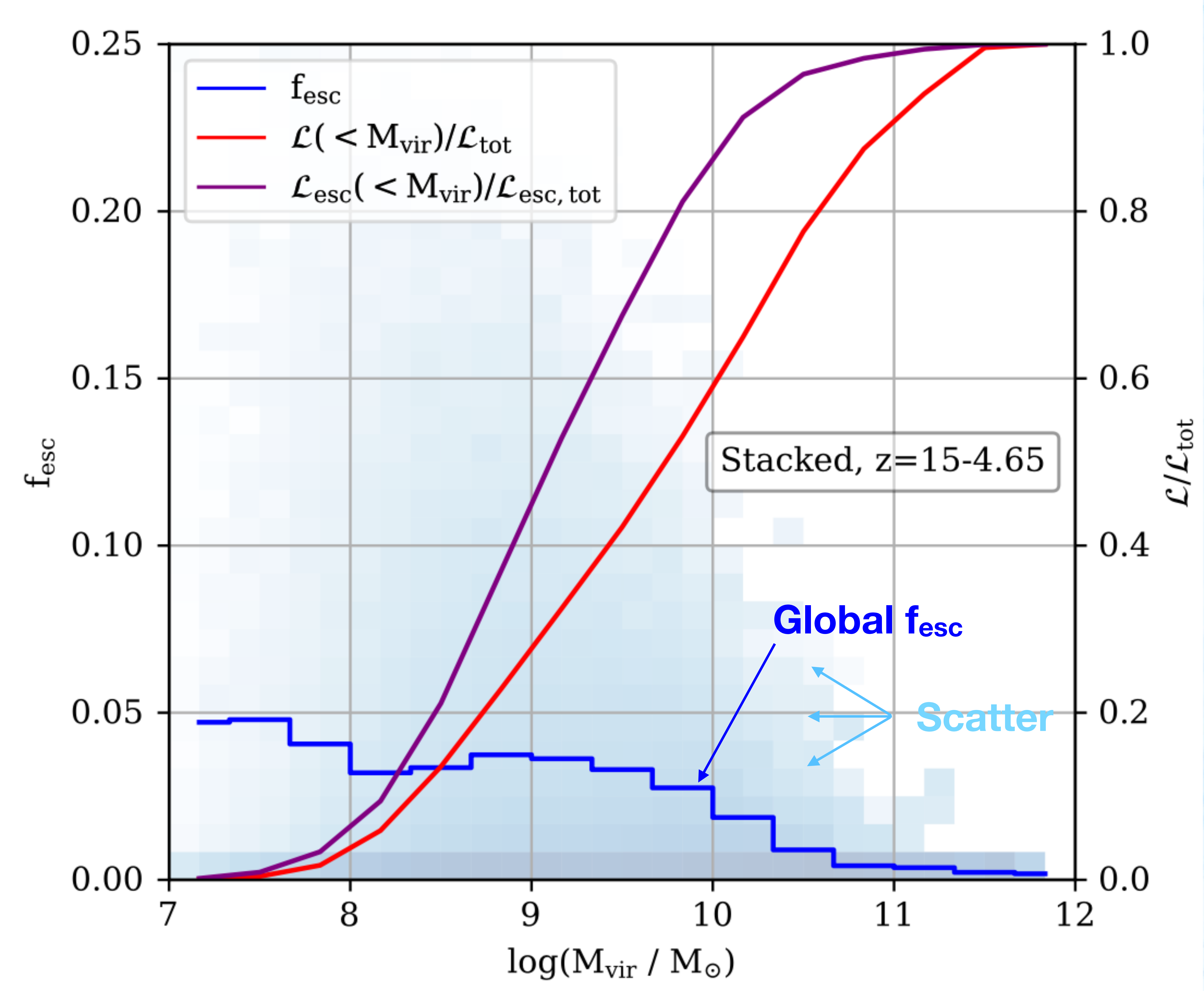


$\langle f_{esc} \rangle$ vs halo mass

Rosdahl+22 (SPHINX)

Decrease with halo mass, for $M_{halo} \gtrsim 10^9\,M_\odot$

Similar trend to CoDa, even if ~100 times higher ISM resolution



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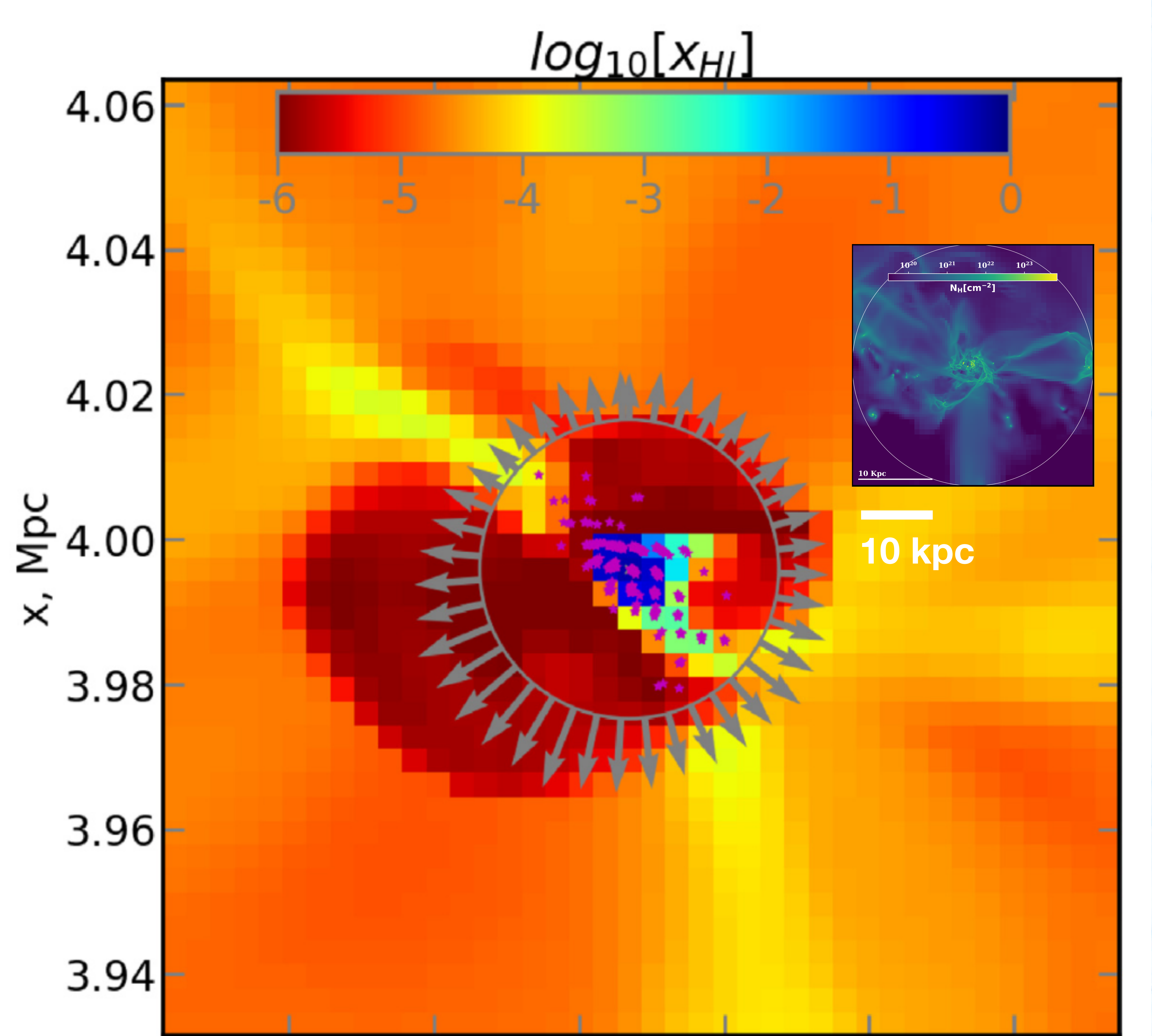
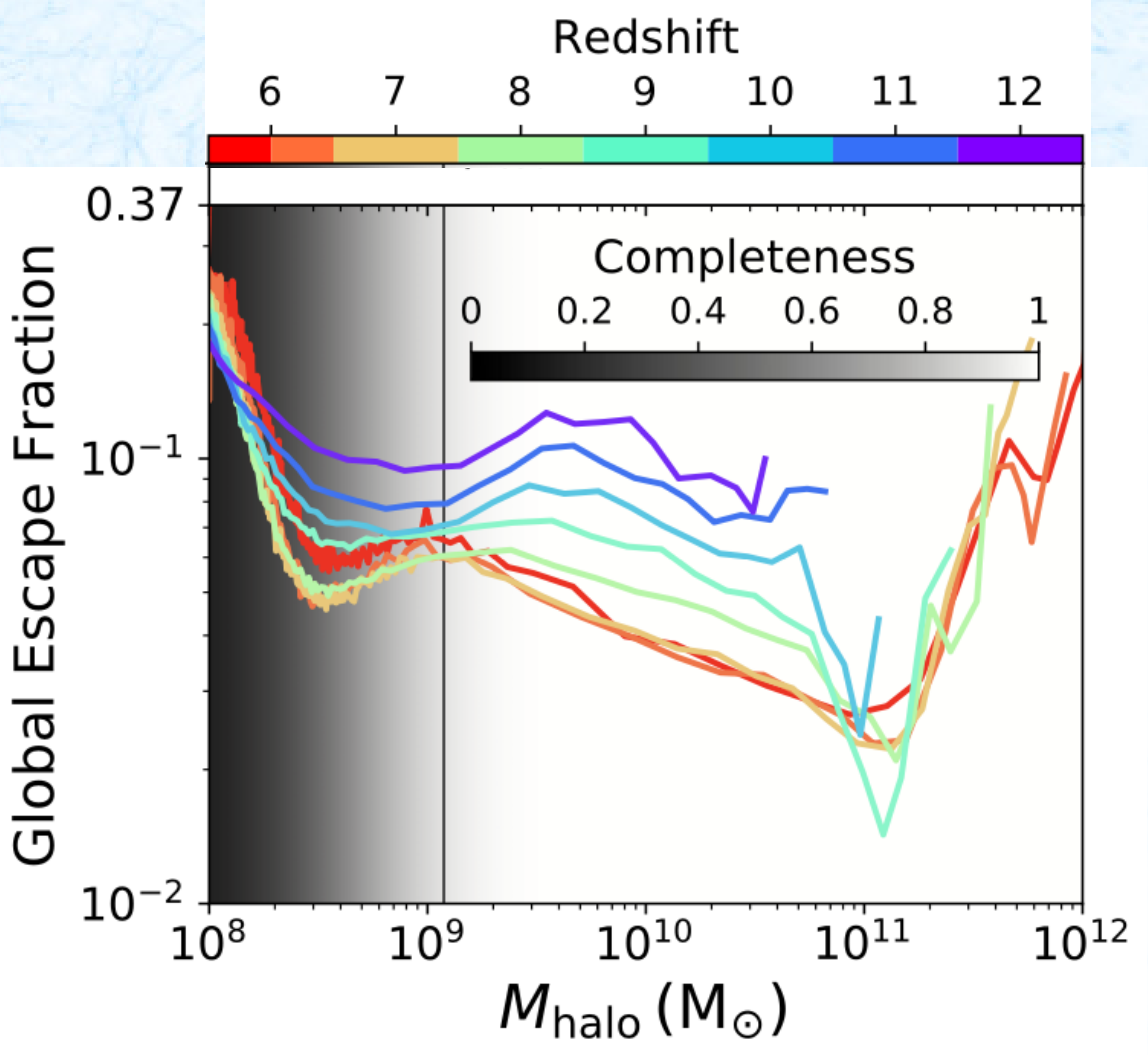


$\langle f_{esc} \rangle$ vs halo mass

Yeh+22 (THESAN)

Usual trend for global f_{esc} at lower masses: decrease with halo mass for $M_{halo} \sim 10^9$ - 10^{11} $M_\odot$

But sharp increase in massive halos. AGN or sub-grid feature?
➡we will know in THESAN-TNG



f_{esc} vs halo mass

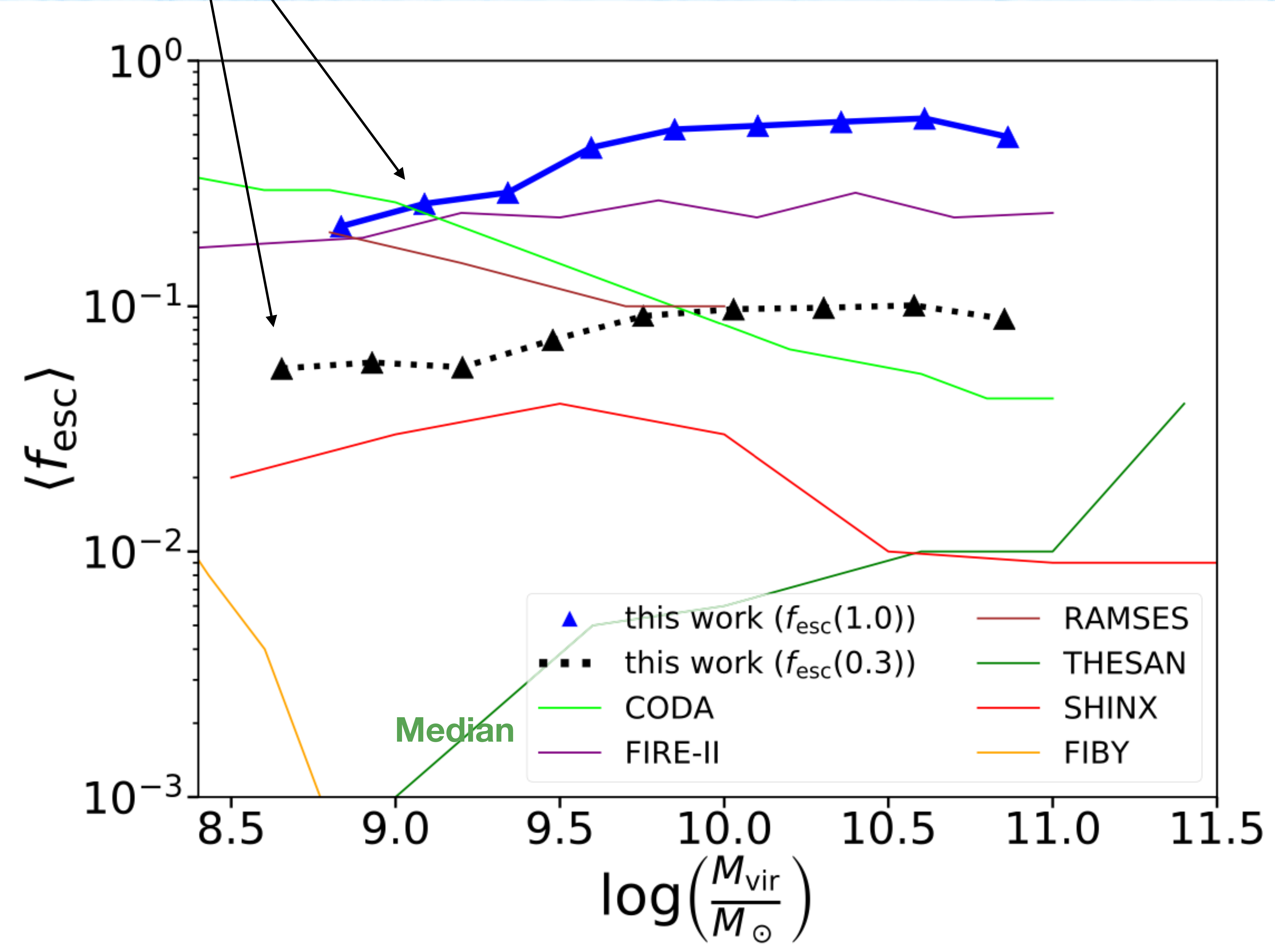
Kostyuk+23 (IllustrisTNG)

What to make of this?😳

Reasons for discrepancies:
- different definitions of <f_{esc}>
- different resolutions and sub-grid models

Yet same models in THESAN and TNG produces quite different f_{esc}

CODA, THESAN, SPHINX all produce reasonable reionization histories, UV luminosity functions, and Thomson optical depths, due to large uncertainties in observations and trade-off between SFR and f_{esc}



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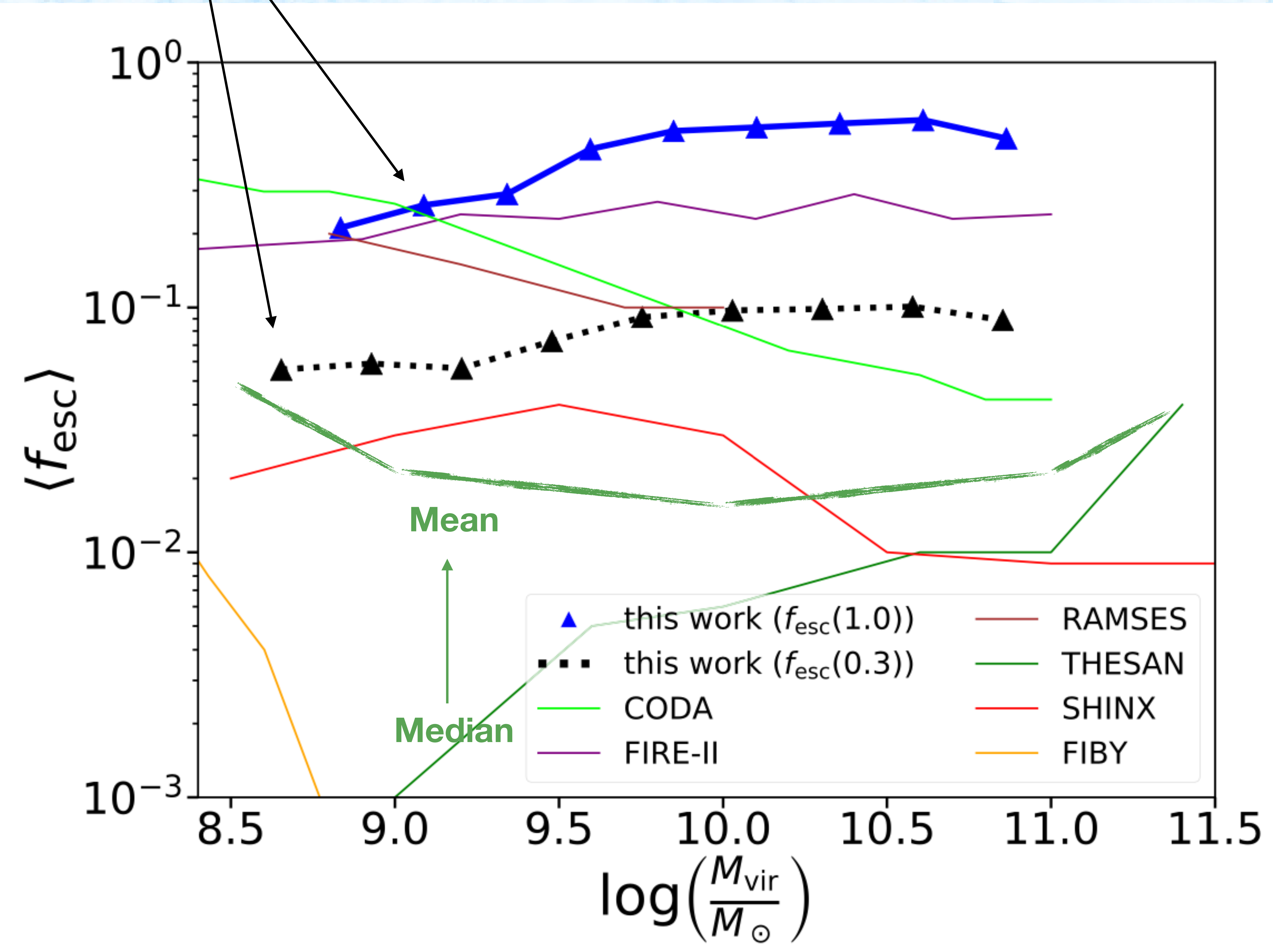
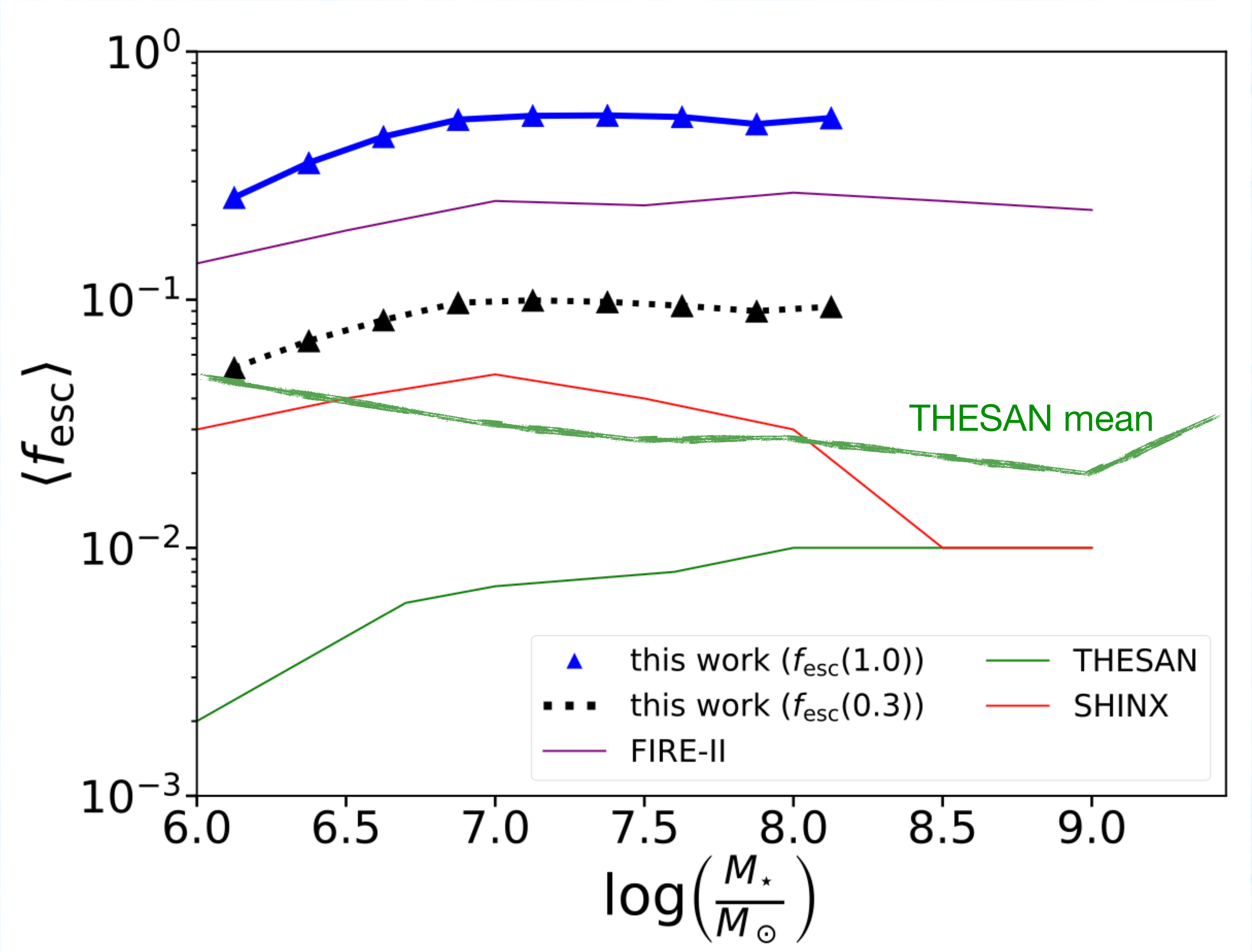


f_{esc} vs galaxy mass
Overview from Kostyuk+23

- Also all over the place, but
- SPHINX, FIRE, THESAN all hint at f_{esc} dropping with M_*



f_{esc} vs mass in observations

Saxena+22

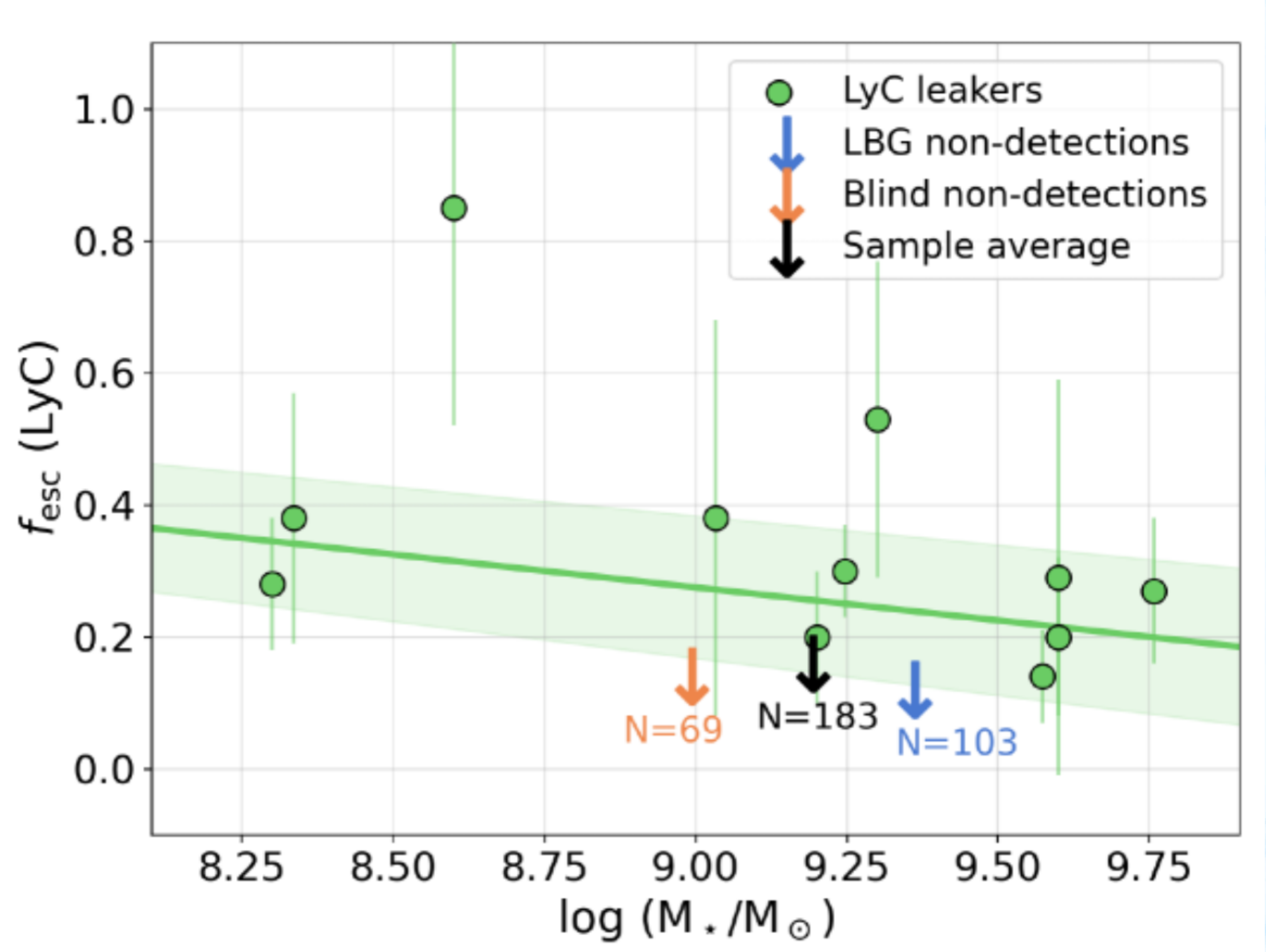
183 galaxies at z~3.5 (GOODS-S)

Direct LyC signals in 11 galaxies

No significant trend

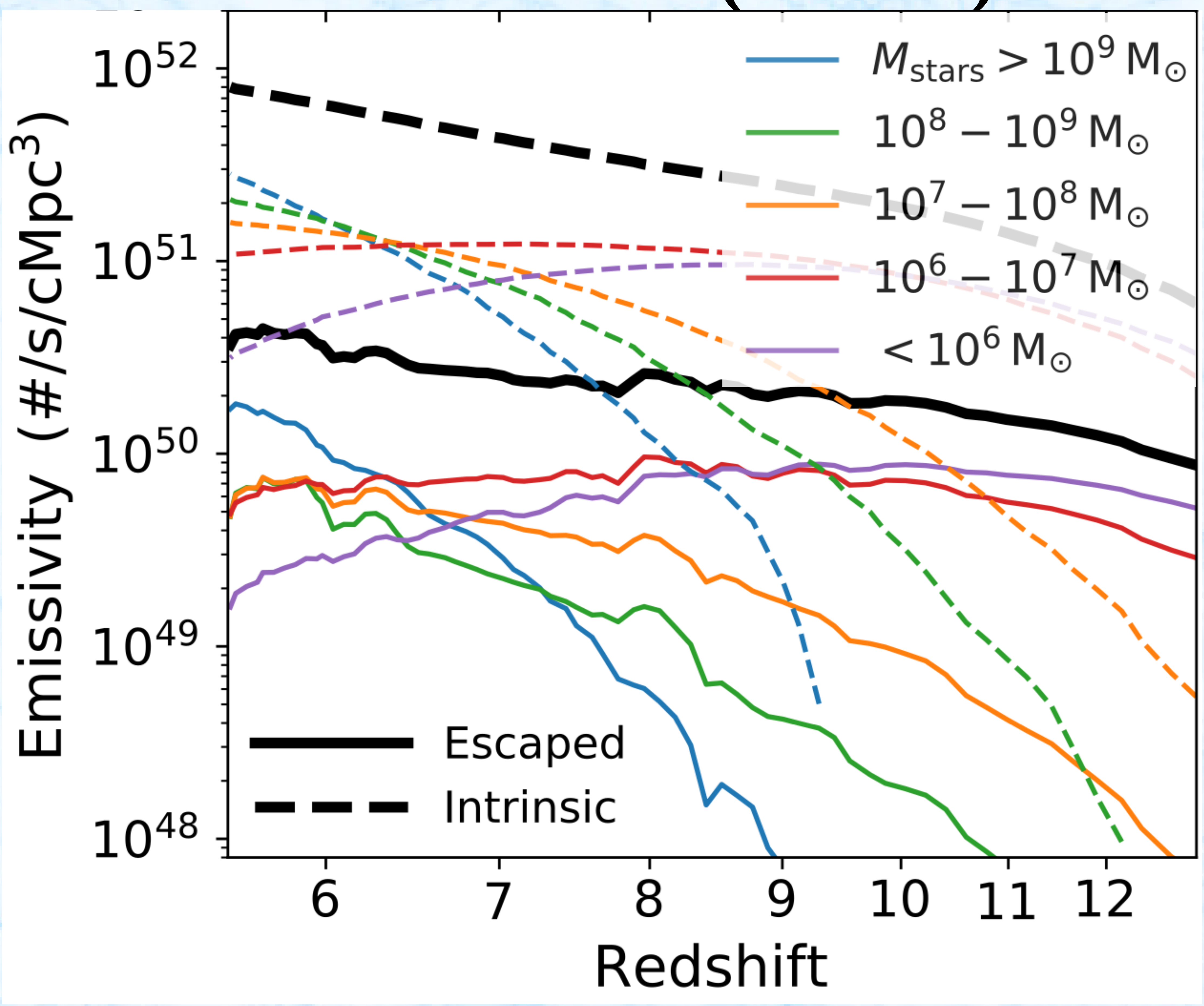
But…..
- Bright and leaking galaxies
- Low redshift
- These are LOS escape fractions

We should apply similar selections to our simulations for comparison

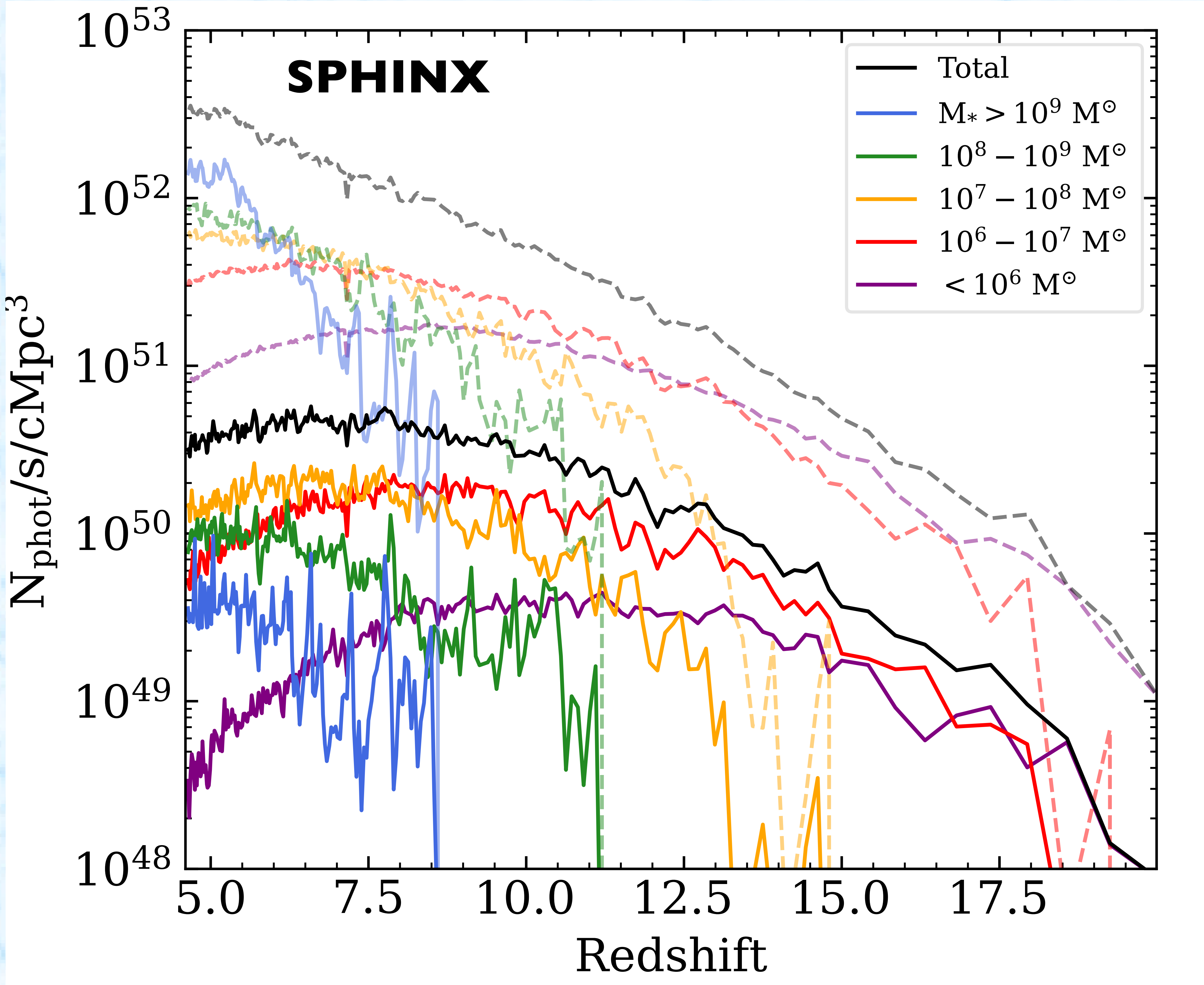


Contributions to reionization

From Yeh+15 (THESAN)



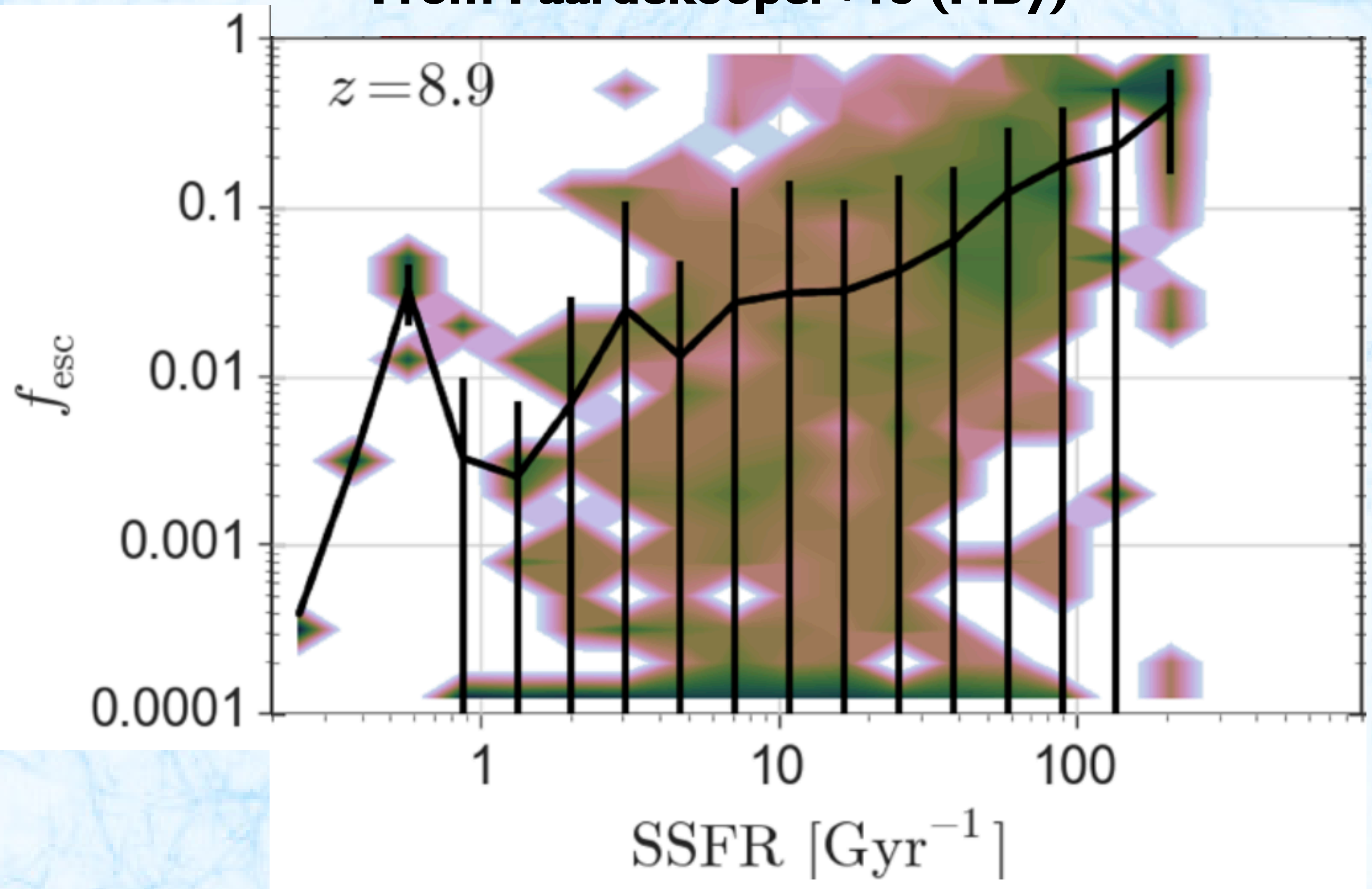
- THESAN oligarchs start to rule after Z~6
- SPHINX is more middle-classy
- These differences are due to different mass-f_{esc} correlations

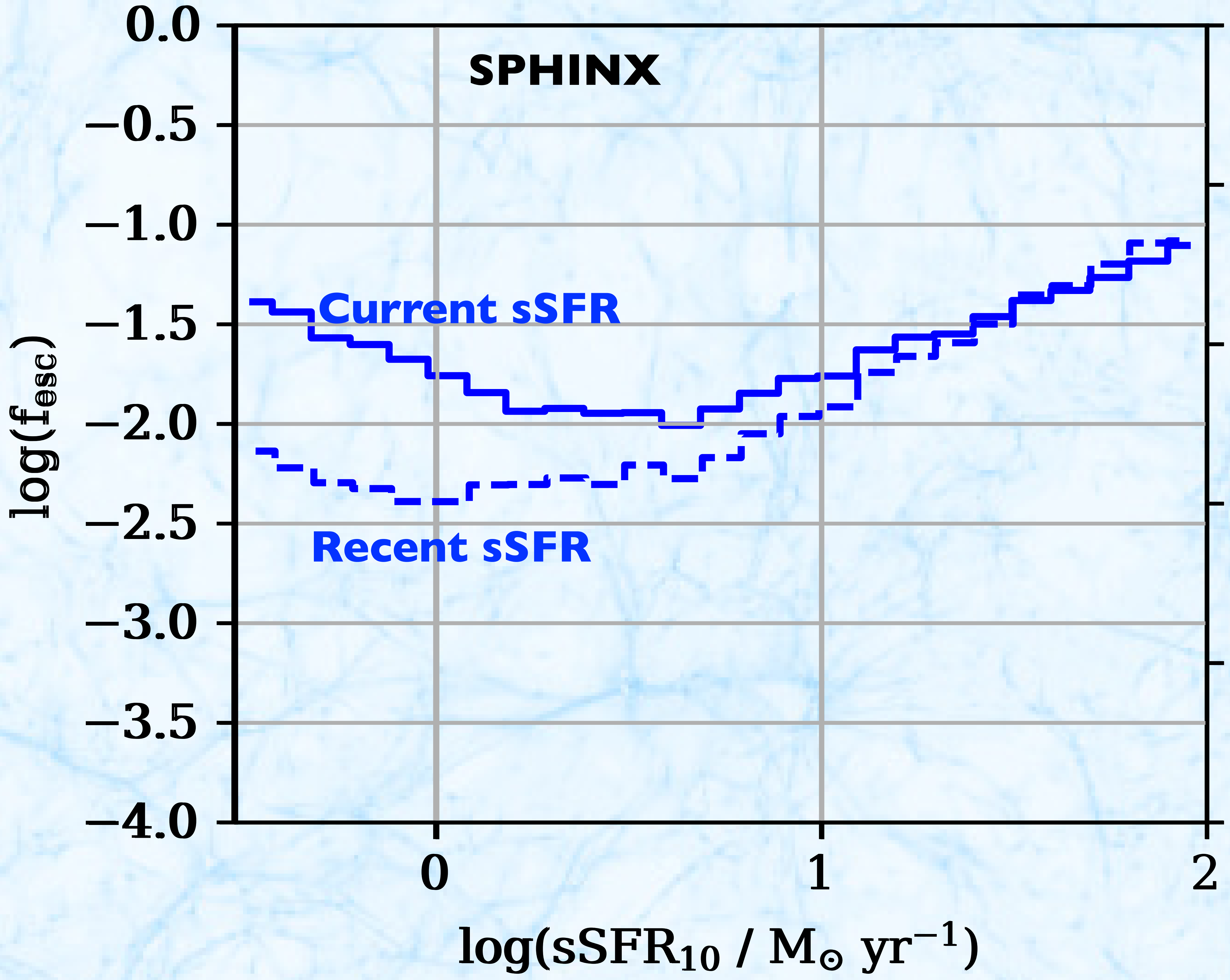


f_{esc} vs specific SFR

- sSFR = SFR/M* is a measure of star formation burstiness

From Paardekooper+15 (FiBy)

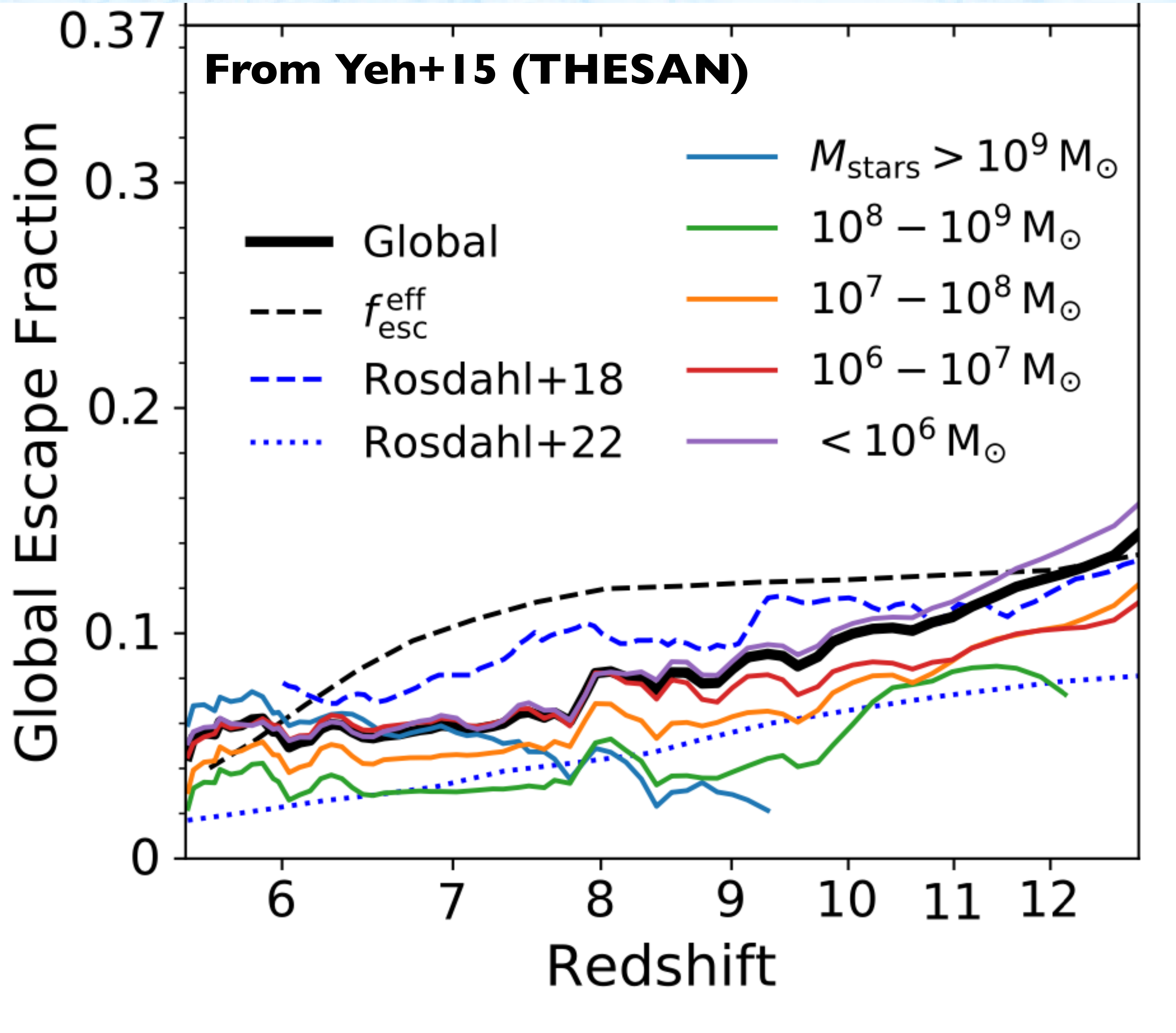




- Galaxies with current or recent starbursts have high escape fractions, due to strong feedback

Evolution of f_{esc} with redshift

- Both SPHINX and THESAN find that f_{esc} decreases globally with redshift
- In SPHINX, this can be traced directly to decreasing sSFR — i.e. decreasing star formation burstiness — with redshift
- CoDa simulations find f_{esc} *increasing* with redshift



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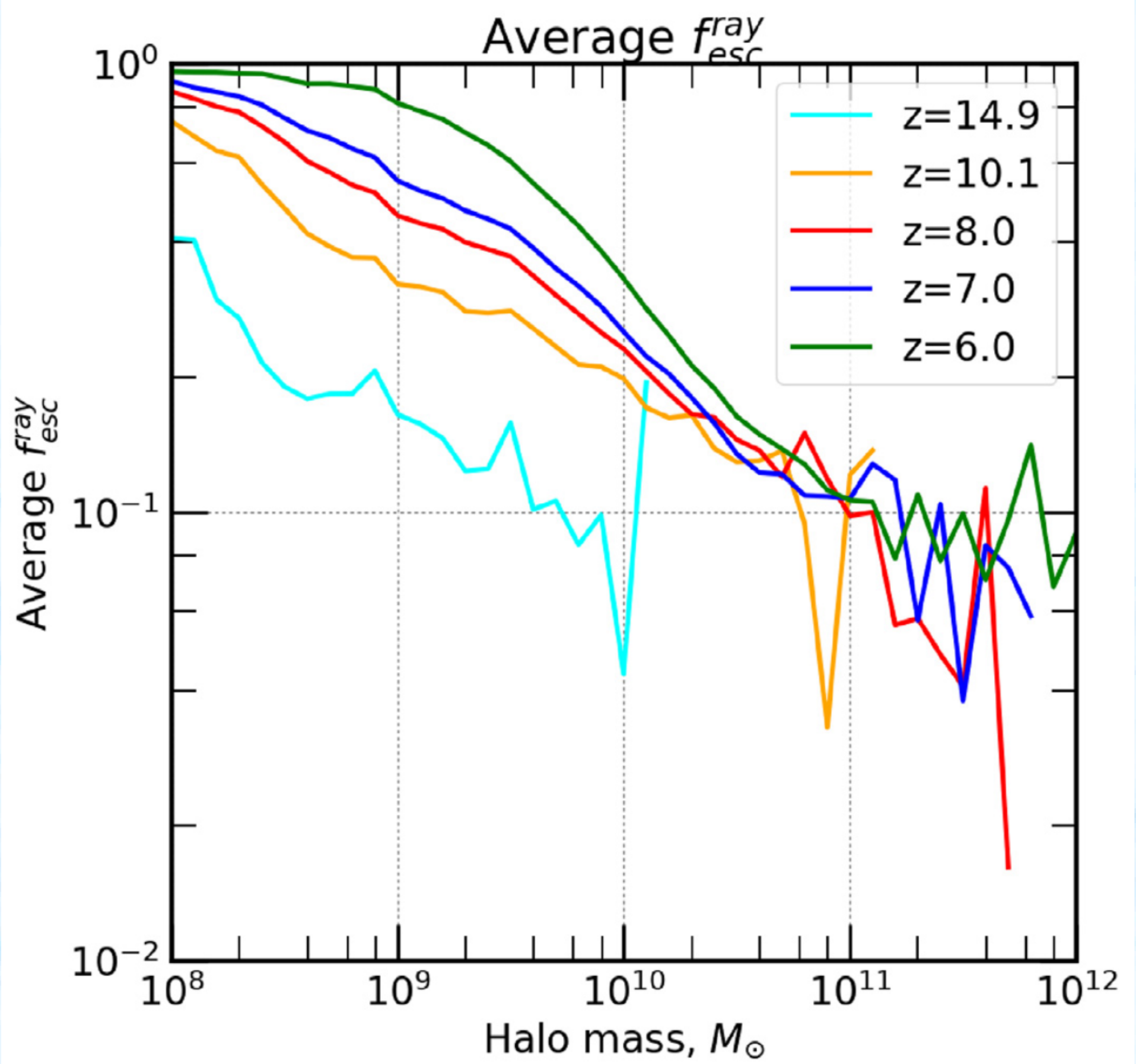
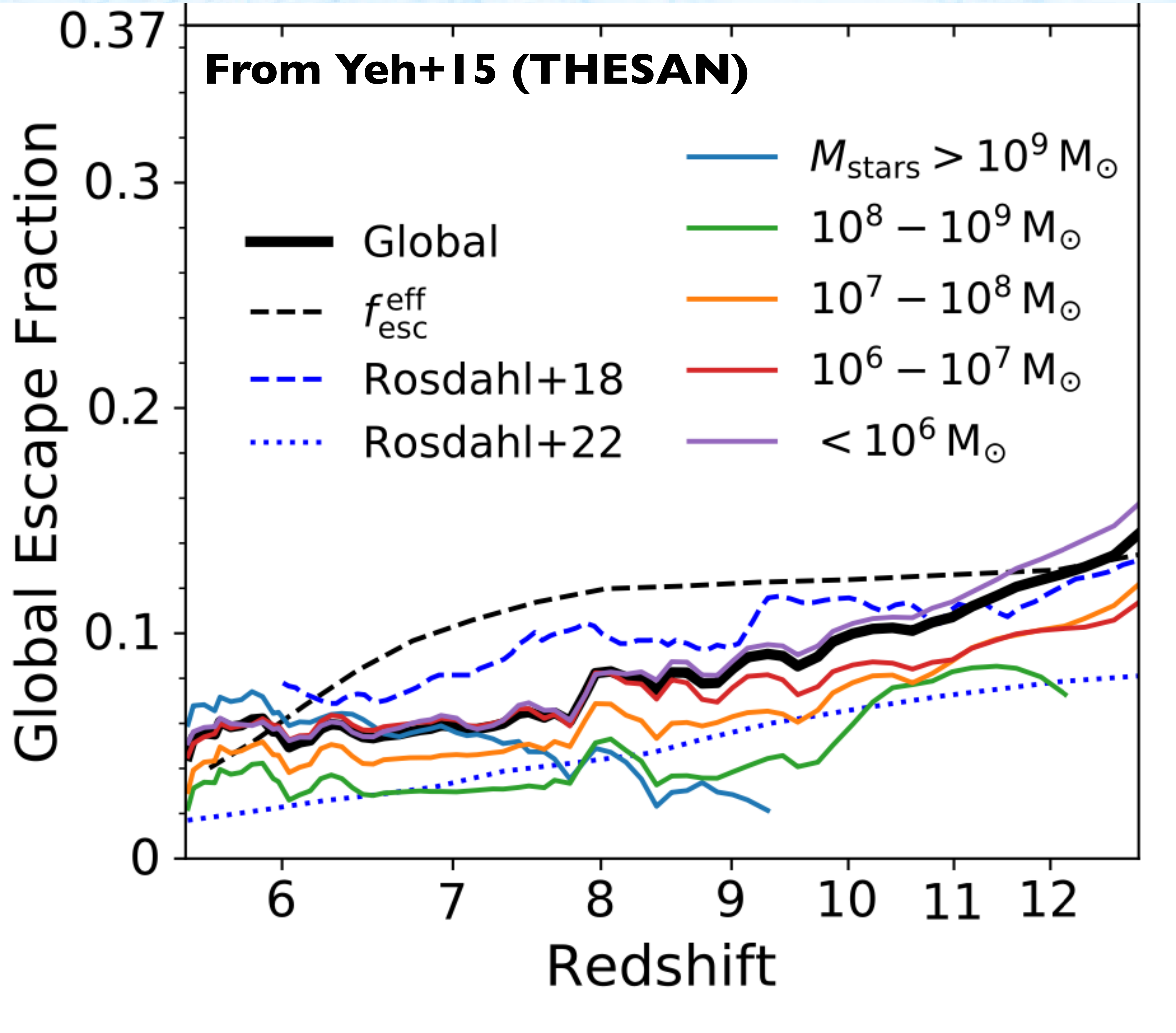
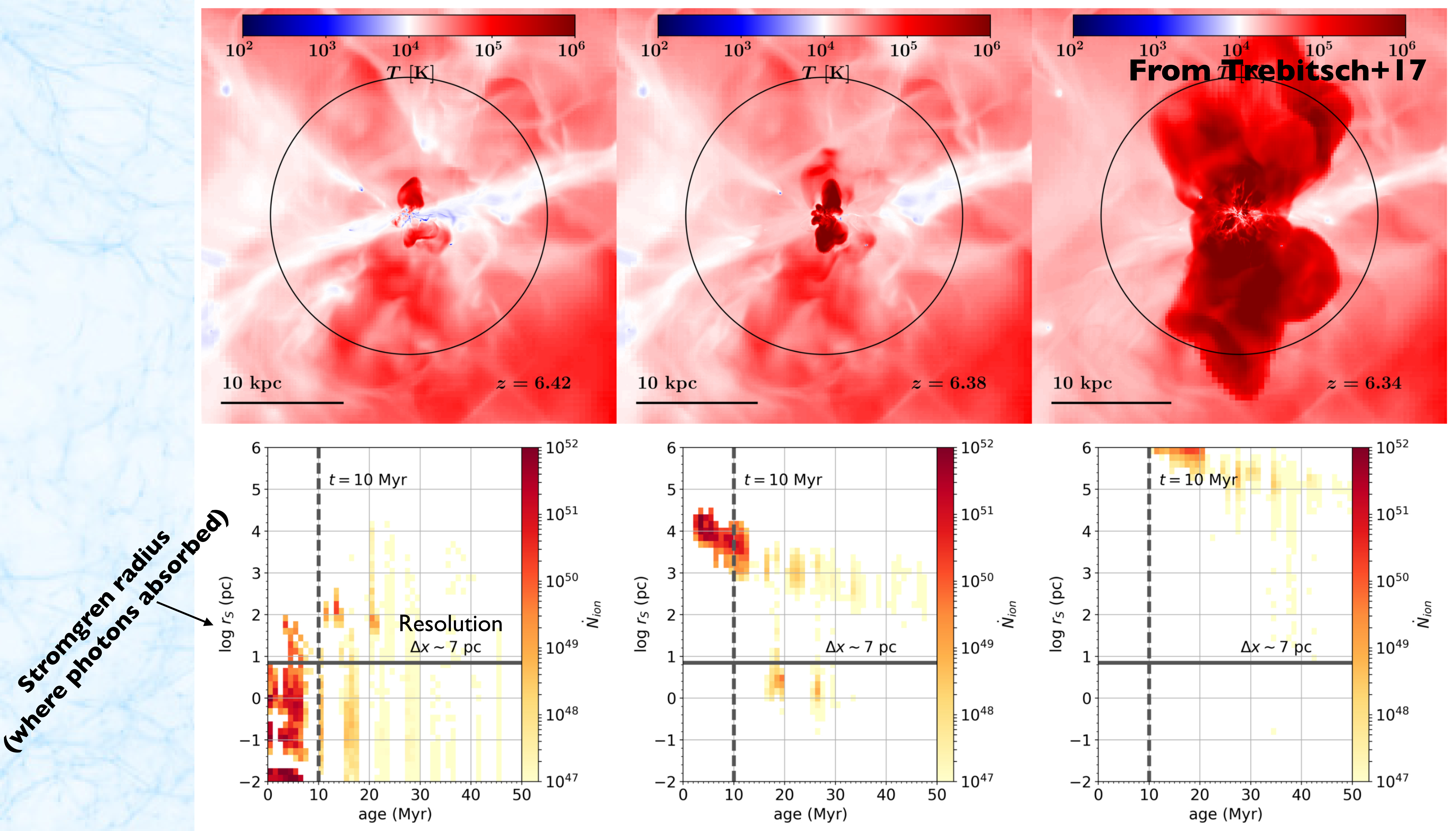




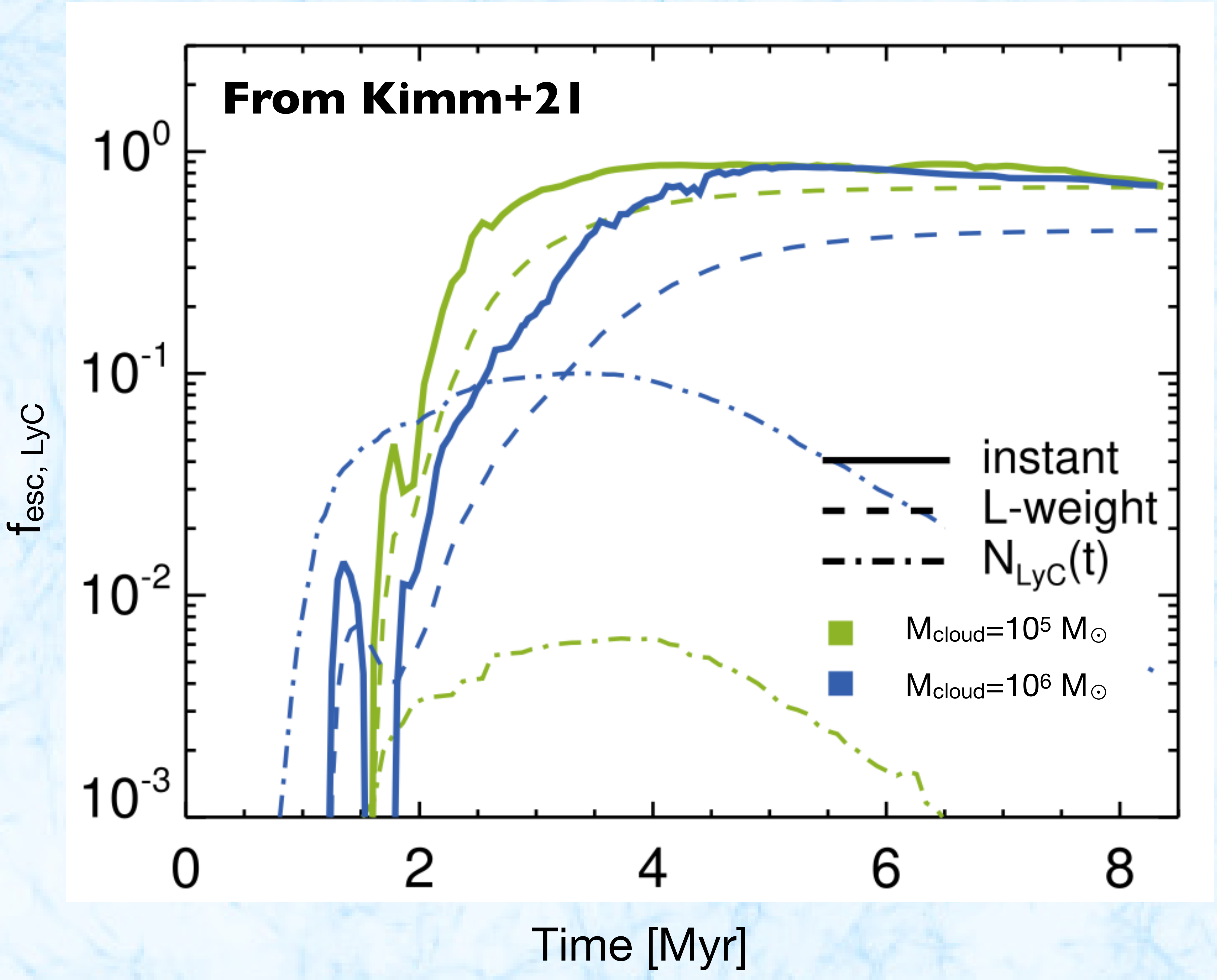
f_{esc} is ***not resolved*** in cosmological simulations

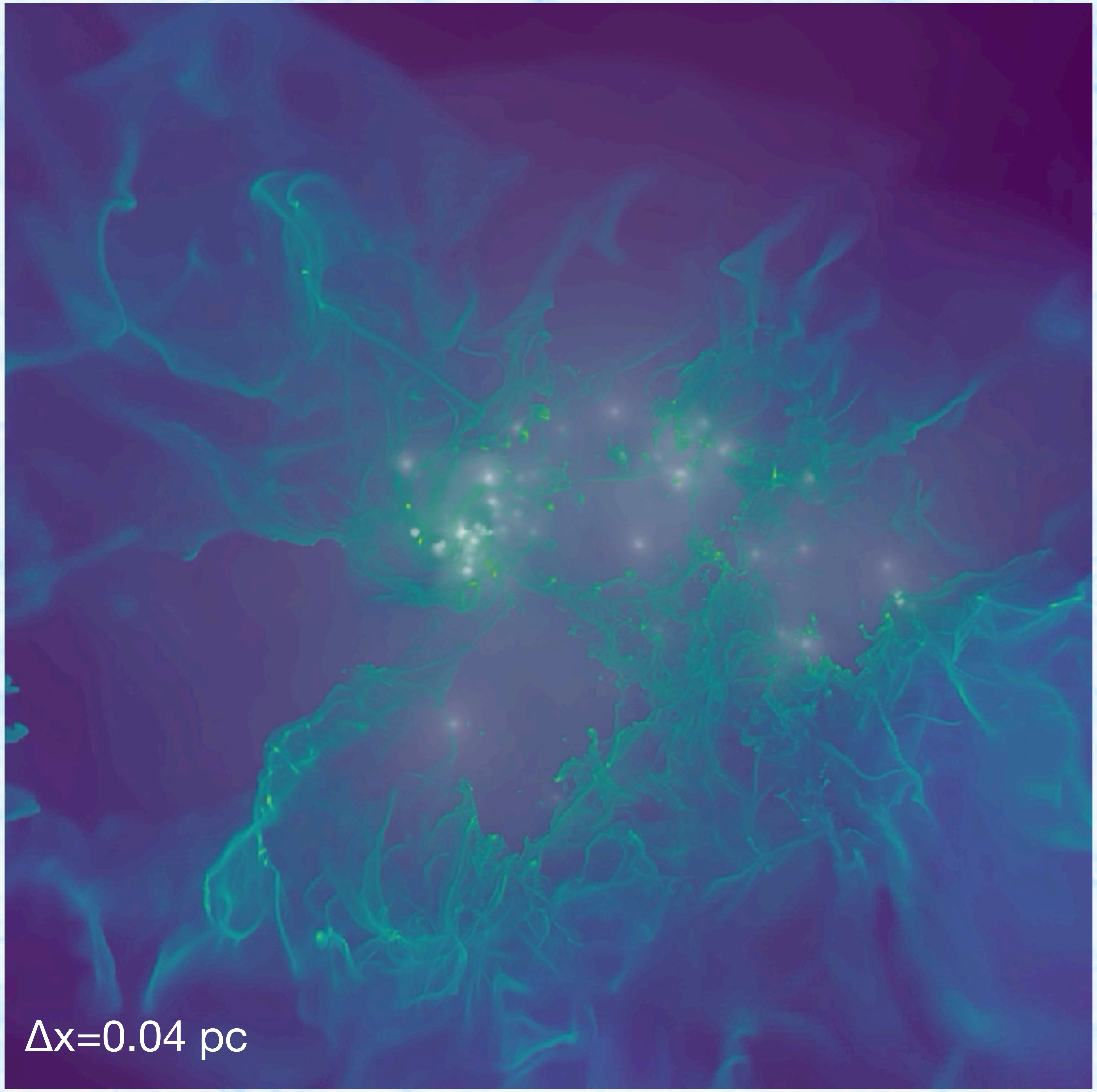
- HII regions are *mostly unresolved*, even in highest-resolution cosmological sims

➡Radiation feedback is underestimated and likely so is f_{esc}



What happens at much better resolution?



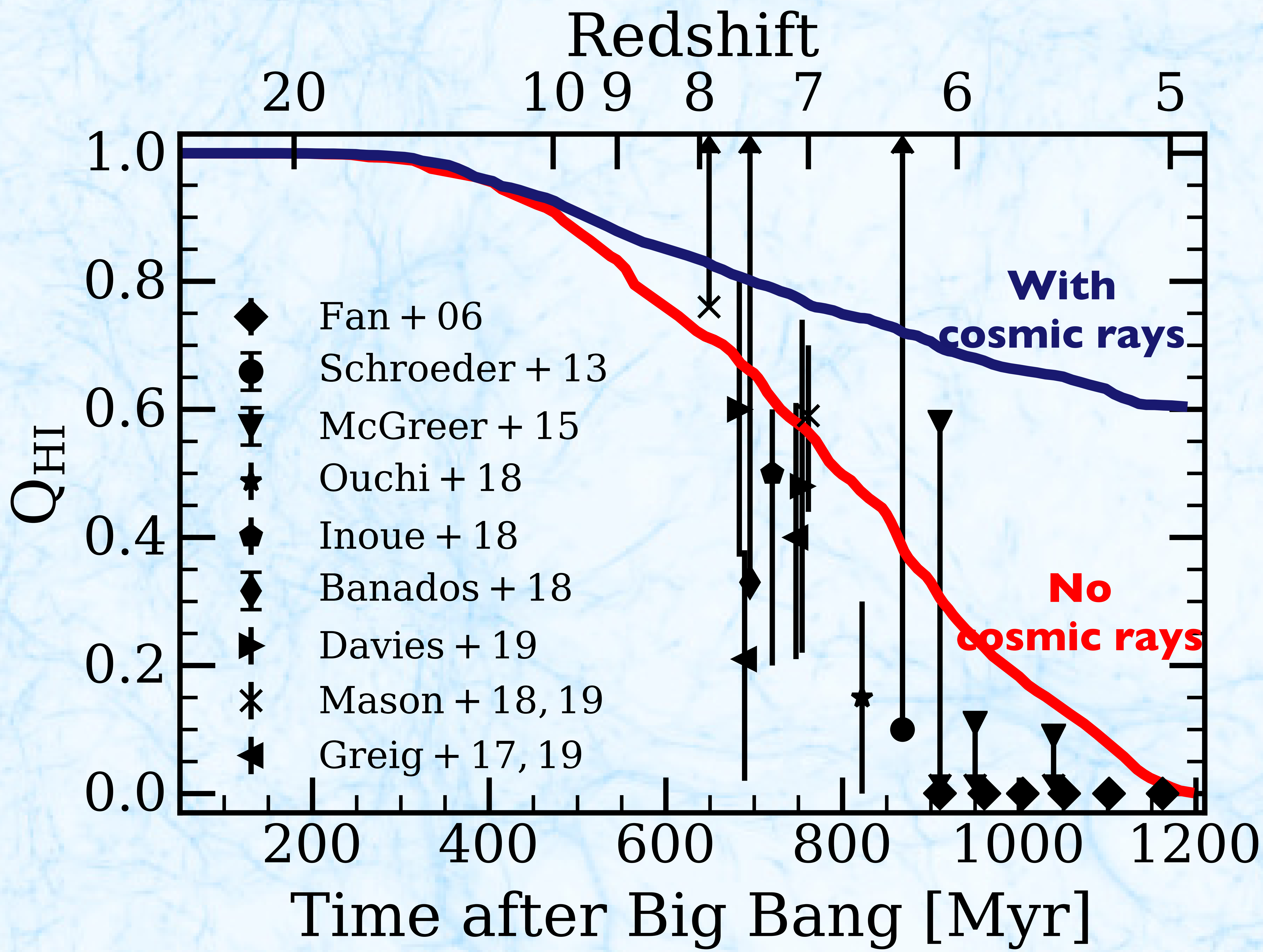


- *A* lot of the radiation escapes *before SN explosions, due to radiation feedback*
- We need to capture this in galaxy simulations, with sub-pc resolution and samples of thousands of galaxies!!

Missing physics

- Cosmic rays prevent escape (Farcy)
- Stellar winds prevent escape (Geen+22)
- Magnetic fields — ?
- Stellar rotation in SEDs
- AGN (➡Yeh, Trebitsch)
- …

Borrowed from Marion Farcy



So are simulations useful for LyC escape?

- At the moment they are better for increasing confusion than understanding
- Simulations are not very converged
- But it is a relatively new business to predict escape fractions
- With more simulations, better models and resolution, we will likely converge to something
- Also, this talk was quite narrowly about LyC escape and simulations are very useful in many aspects for reionization
  - SPHINX and THESAN data releases are surely useful to many of you (mock observables, SFHs, escape fractions, ...)