Stellar Radiation Feedback in Galaxies

with Schaye, Teyssier, Perret

and

The Role of Feedback in Reionisation

with Blaizot, Chardin, Garel, Haehnelt, Katz, Keating,
Kimm, Michel-Dansac, Ocvirk, Teyssier

Joki Rosdahl

CRAL

CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

Potsdam Thinkshop, September 4th, 2018

Radiation feedback in galaxies
...and
the role of feedback in reionisation

Joki Rosdahl

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Potsdam, September 3rd, 2018

Double feature:

a) Multi-scattering radiation feedback in an optically thick ULIRG-like galaxy

with Schaye, Teyssier, Perret

b) On the importance of (SN) feedback for reionisation

with Blaizot, Chardin, Garel, Haehnelt, Katz, Keating, Kimm, Michel-Dansac, Ocvirk, Teyssier

Radiation feedback in galaxies

Stellar radiation feedback is a vital component in many models (FIRE, NIHAO, Vela)

- Suppresses SFR and generates outflows
- **BUT** done with sub-grid recipes and many assumptions

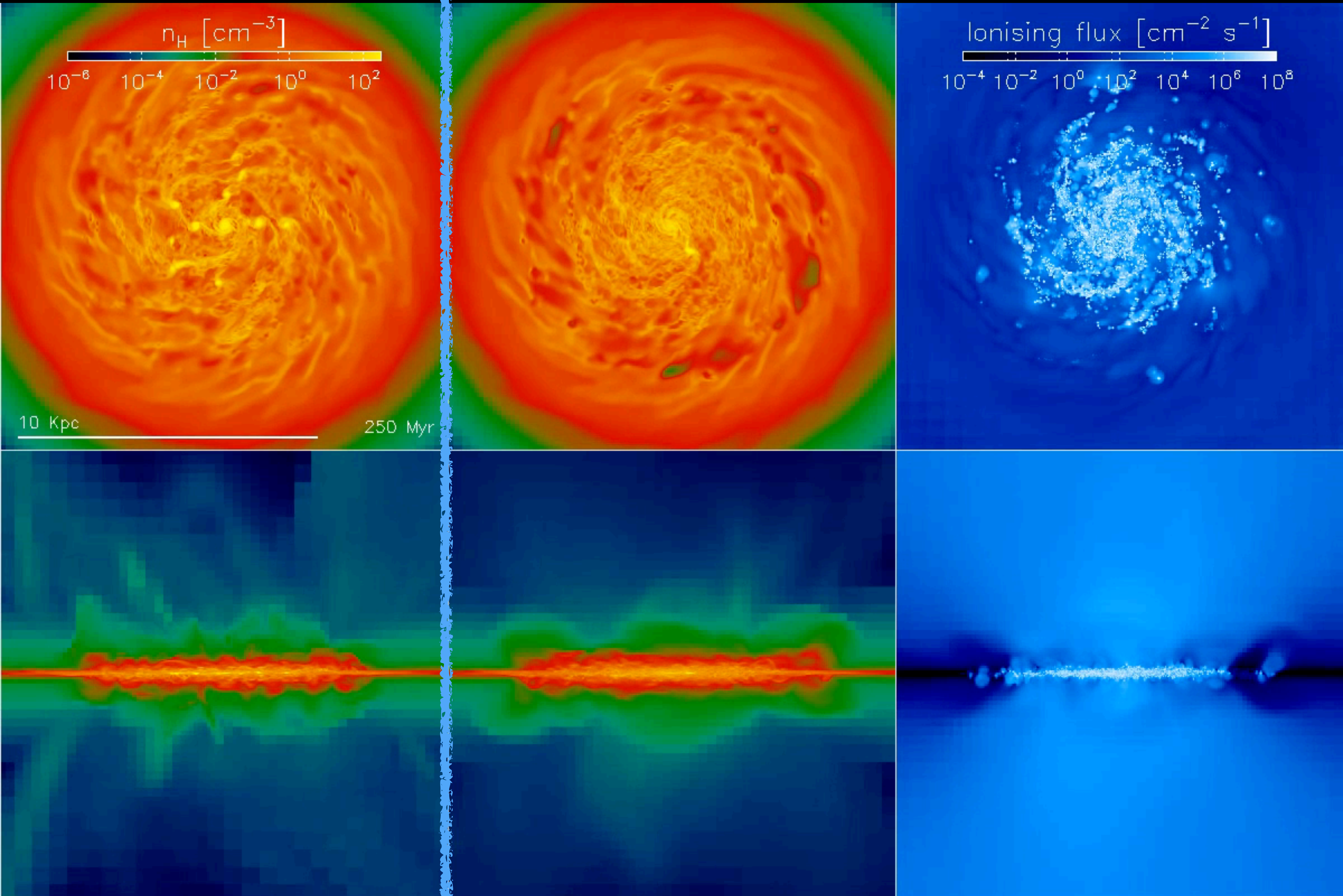
'Galaxies that shine: RHD simulations of disk galaxies'
Rosdahl, Schaye, Teyssier, & Agertz (2015)

We ran the first radiation-hydrodynamical simulations of galaxies that directly model photoionisation, radiation pressure and multi-scattering, using radiation-hydrodynamics (RHD)

Isolated MW-like galaxy

$M_{baryons} = 3.5 \times 10^9\ M_\odot$

SNe only | **SNe + Radiation**



'Galaxies that shine: RHD simulations of disk galaxies'

Rosdahl, Schaye, Teyssier, & Agertz (2015)

Results in short:

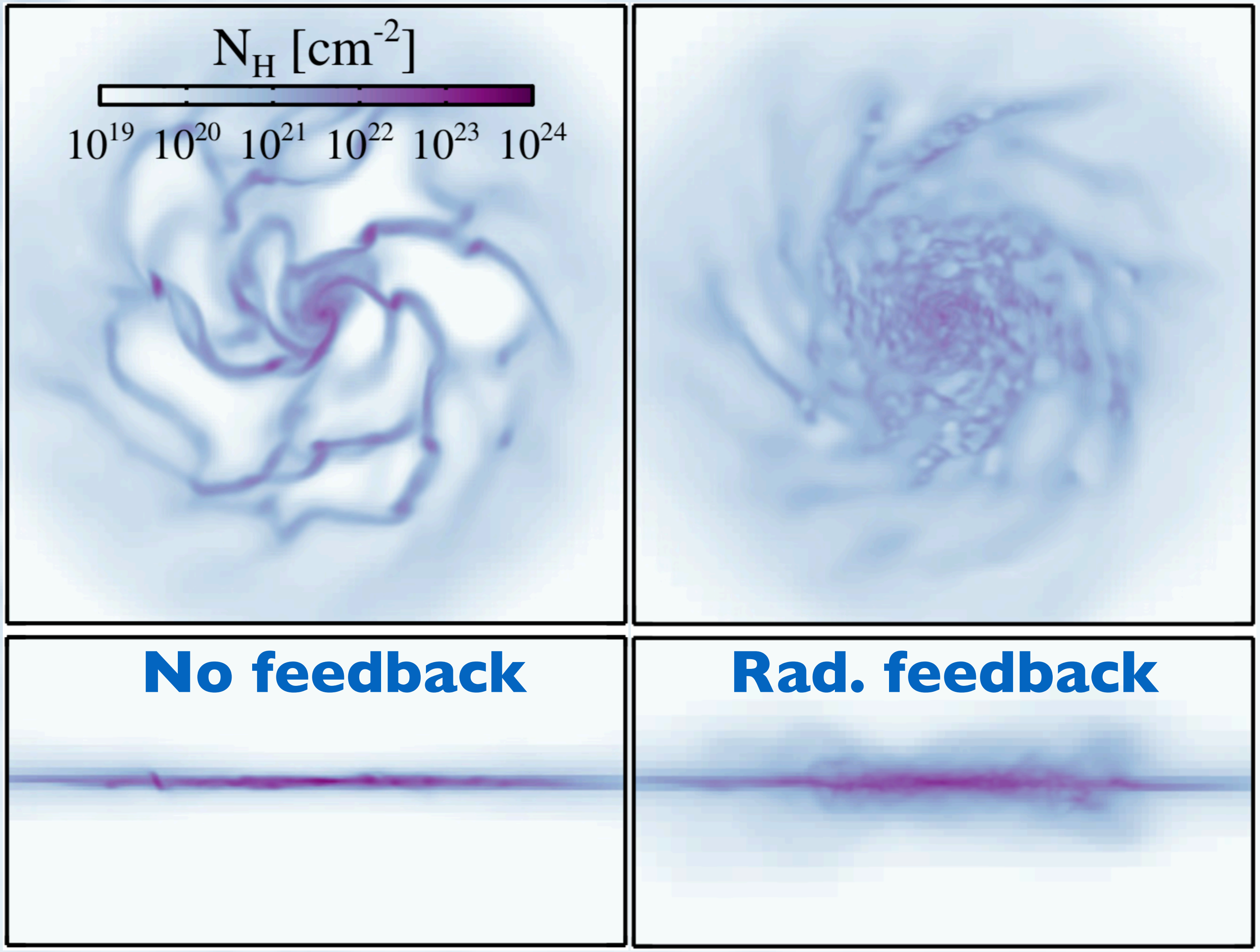
- significant effect from photoionisation in low-mass galaxies
- but little effect at ~MW mass
- radiation pressure did nothing

But: low optical depths ➡ little boost from multi-scattering IR radiation

$$\dot{p}_{\rm IR} = \frac{L}{c}\tau_{\rm IR}$$

➡What do we get in a `best-case' scenario of an optically thick ULIRG galaxy, with high optical depths?

$M_{\rm baryons} = 3.5 \times 10^8\ M_\odot (\approx 0.01\ M_{\rm MW})$



DRAMA simulations (in prep.)

Disks with RAdiation-MAtter interactions

Simulation setup

- Isolated compact ULIRG-like disk galaxy
- $\mathbf{M_{halo}} = 6\times10^{11}\ M_\odot$ $\mathbf{M_{baryons}} = 3\times10^{10}\ M_\odot$, 60% gas
- Max $\mathbf{\Delta x}$=5 pc resolution (1 kpc outside the ISM)
- Mass resolution of $\mathbf{m_{DM}} = 10^5\ M_\odot$ $\mathbf{m_{DM}} = 2\times10^3\ M_\odot$
- Metal mass fraction of $\mathbf{Z}$=0.01 (50% Solar metallicity)
- Individual 10^{51} erg SNe with momentum kicks (e.g. Kimm et al. 2015)
- *Bursty* star formation depends on local virial parameter and mach number (Federrath+Klessen 2012; similar to FIRE models)
  - Typical local star formation efficiency $\epsilon_{ff} \sim 0.5$

$$\dot{\rho}_* = \epsilon_{\rm ff}\,\rho / t_{\rm ff}$$

- Main differences from 'galaxies that shine':
  - More compact, gas rich
  - Burstier star formation in higher-density gas (optically thicker regions)

DRAMA Simulation setup

5 radiation groups extracted from Bruzual & Charlot (2003) stellar population model

Photon group	ϵ_0 [eV]	ϵ_1 [eV]	$\sigma_{\rm HI}$ [cm^2] ±5%	$\sigma_{\rm HeI}$ [cm^2] ±5%	$\sigma_{\rm HeII}$ [cm^2] ±5%	$\tilde{\kappa}$ [cm^2 g^{-1}]
IR	0.10	1.00	0	0	0	10
Opt	1.00	13.60	0	0	0	10^3
$\rm UV_{HI}$	13.60	24.59	3.3×10^{-18}	0	0	10^3
$\rm UV_{HeI}$	24.59	54.42	6.3×10^{-19}	4.8×10^{-18}	0	10^3
$\rm UV_{HeII}$	54.42	∞	9.9×10^{-20}	1.4×10^{-18}	1.3×10^{-18}	10^3

Group energy intervals

Photo-ionisation cross sections

Dust opacities, with $\kappa = \tilde{\kappa} \dfrac{Z}{Z_\odot}$

Dust-absorbed radiation is *reprocessed* into IR, which *multi-scatters* ➡ radiation pressure boost

Radiation hydrodynamics with RAMSES-RT

Rosdahl et al (2013), Rosdahl & Teyssier (2015)

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \boldsymbol{n}\cdot\nabla I_\nu = -\kappa_\nu I_\nu + \eta_\nu$$

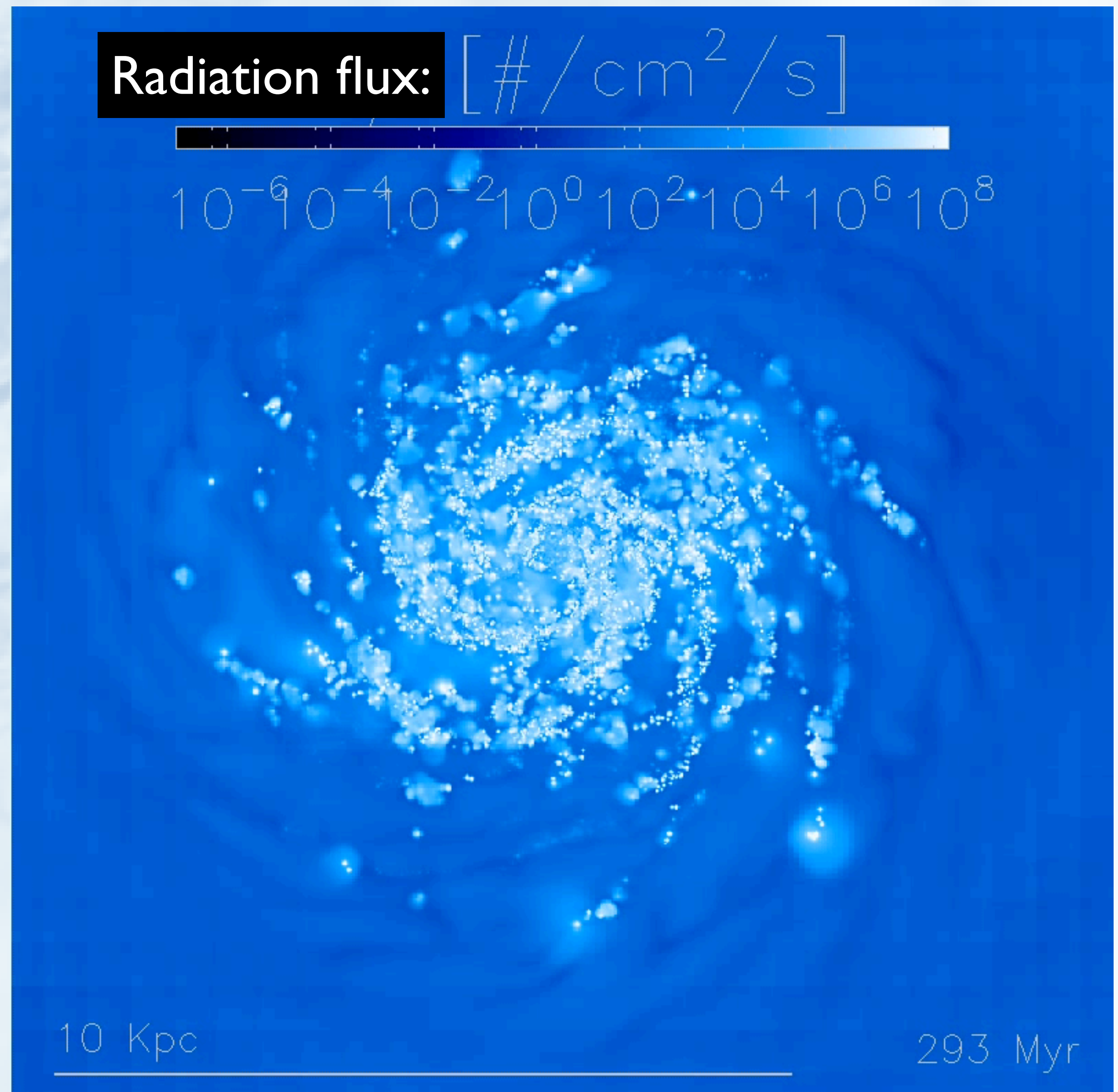
Beam intensity | Absorption | Emission

- Moment method for radiation
➡ unlimited number of sources

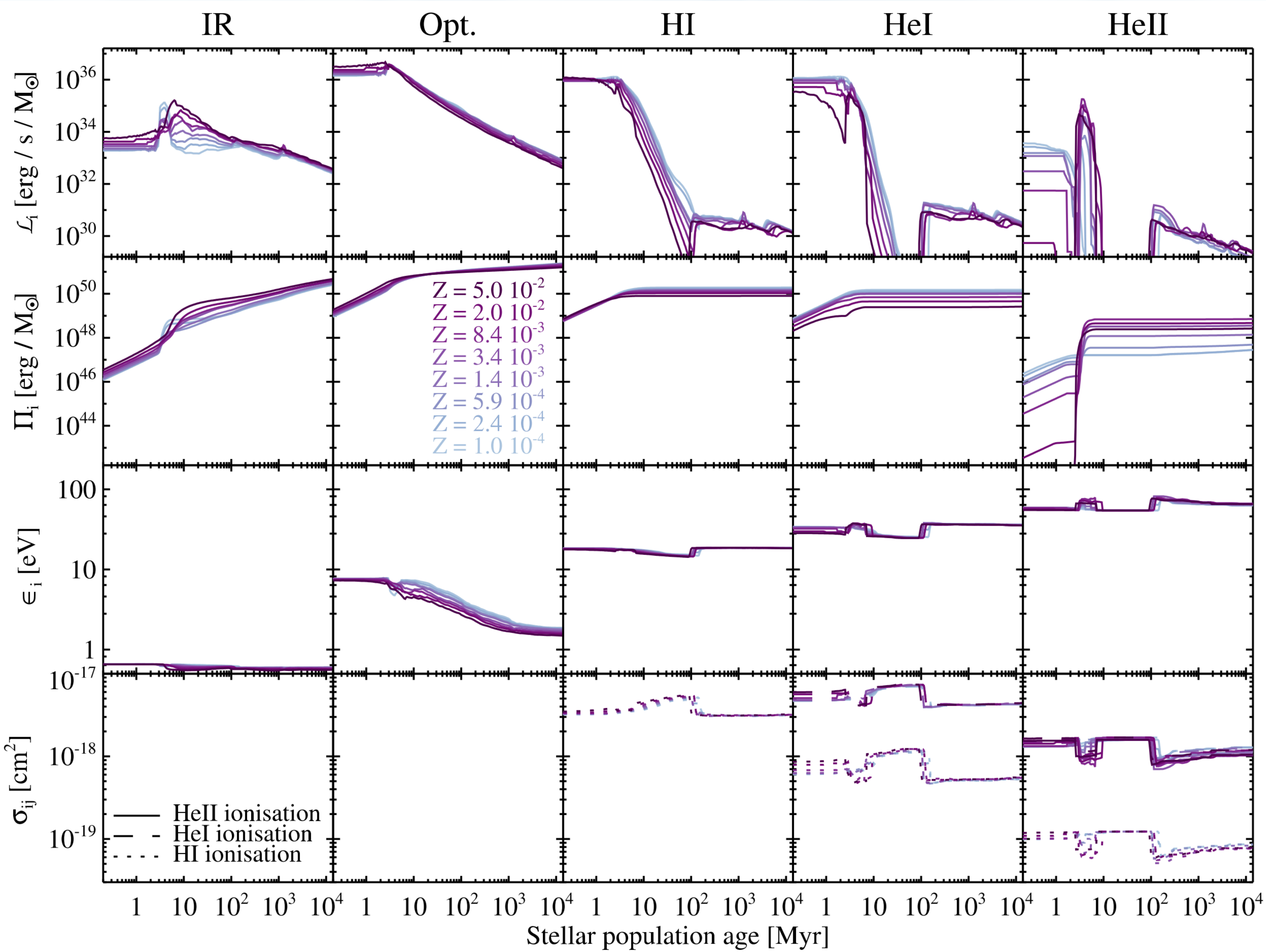
- Hydro-coupled
Photons emitted and propagated on-the-fly, ionising, heating, pushing, and multi-scattering on the gas

- Reduced speed-of-light to run in in feasible time

- Publicly available on bitbucket



BC03

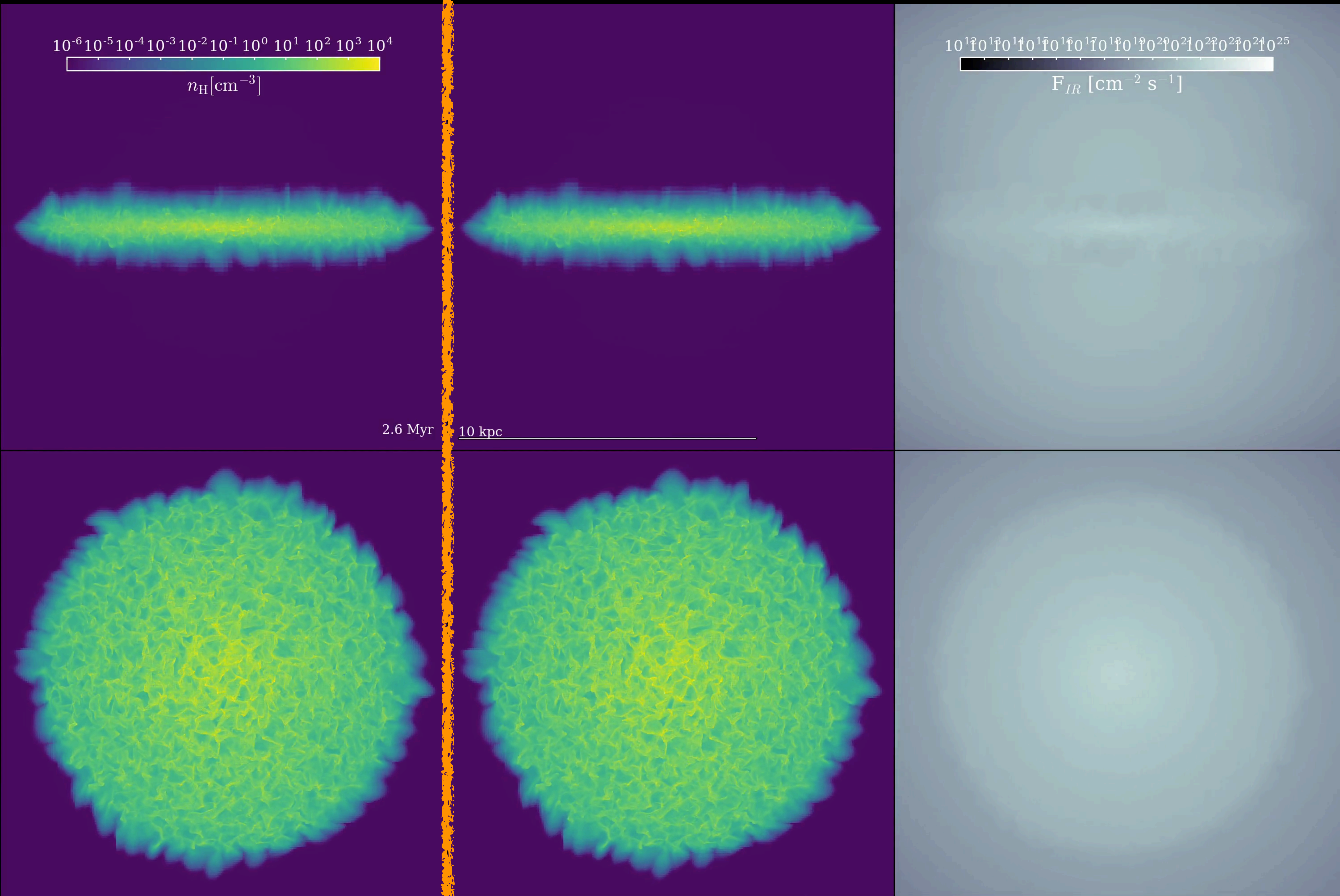


IR
Opt.
HI
HeI
HeII
$\mathcal{L}_i$ [erg / s / M$_\odot$]
Π_i [erg / M$_\odot$]
ϵ_i [eV]
σ_{ij} [cm^2]
Z = 5.0 10^{-2}
Z = 2.0 10^{-2}
Z = 8.4 10^{-3}
Z = 3.4 10^{-3}
Z = 1.4 10^{-3}
Z = 5.9 10^{-4}
Z = 2.4 10^{-4}
Z = 1.0 10^{-4}
HeII ionisation
HeI ionisation
HI ionisation
Stellar population age [Myr]

Joa

SNe+ionising radiation but no dust absorption

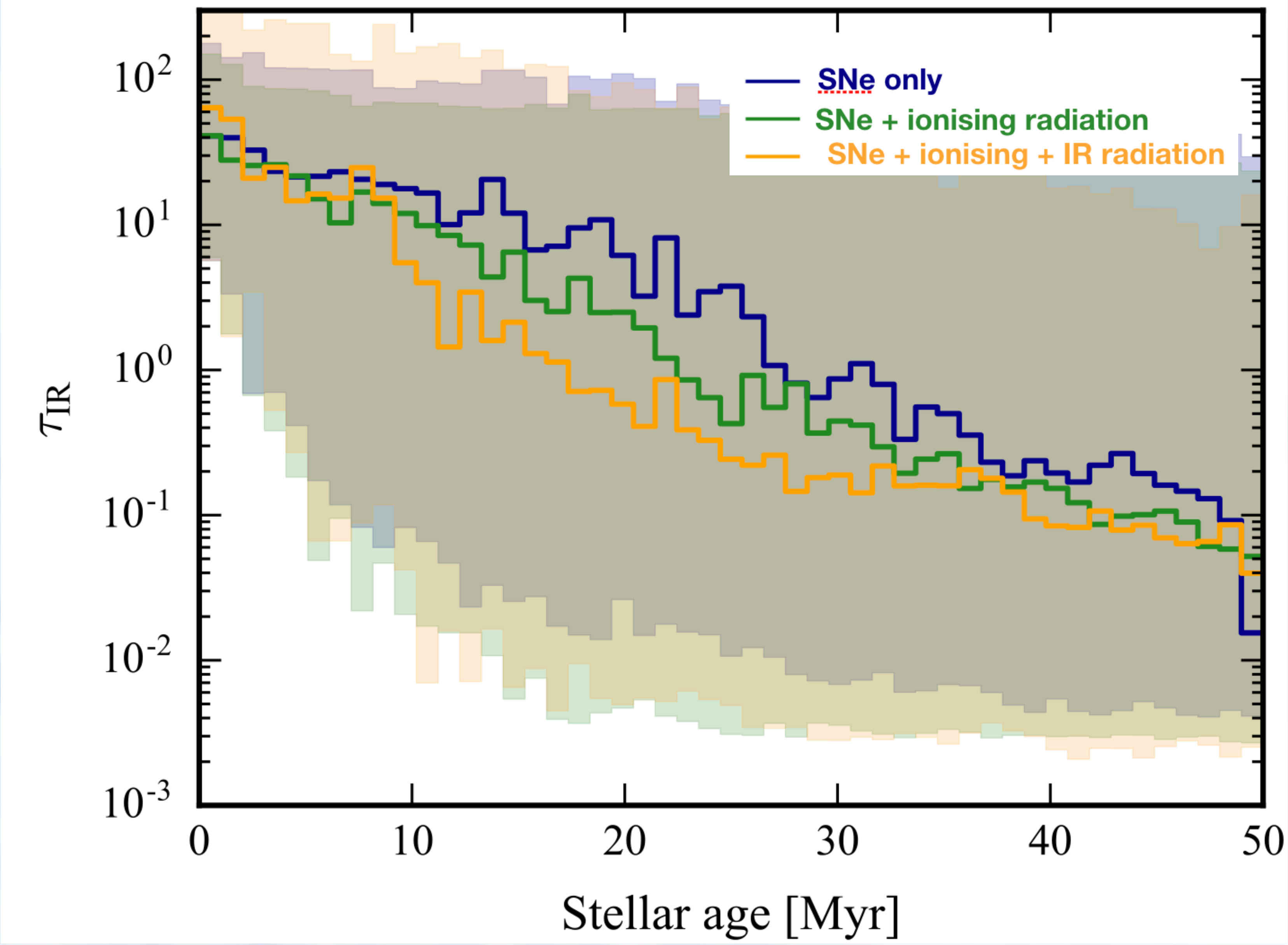
With dust absorption and scattering added



DRAMA: local optical depths

- Stars form at high optical depths; $\tau_{IR} \approx 10 - 100$
- Gas environment `diffuses' with stellar age
- Faster diffusion with IR radiation
- But stars form at higher densities with IR
    - Likely due to local IR pressure support, which delays star formation

Local IR optical depth vs stellar age



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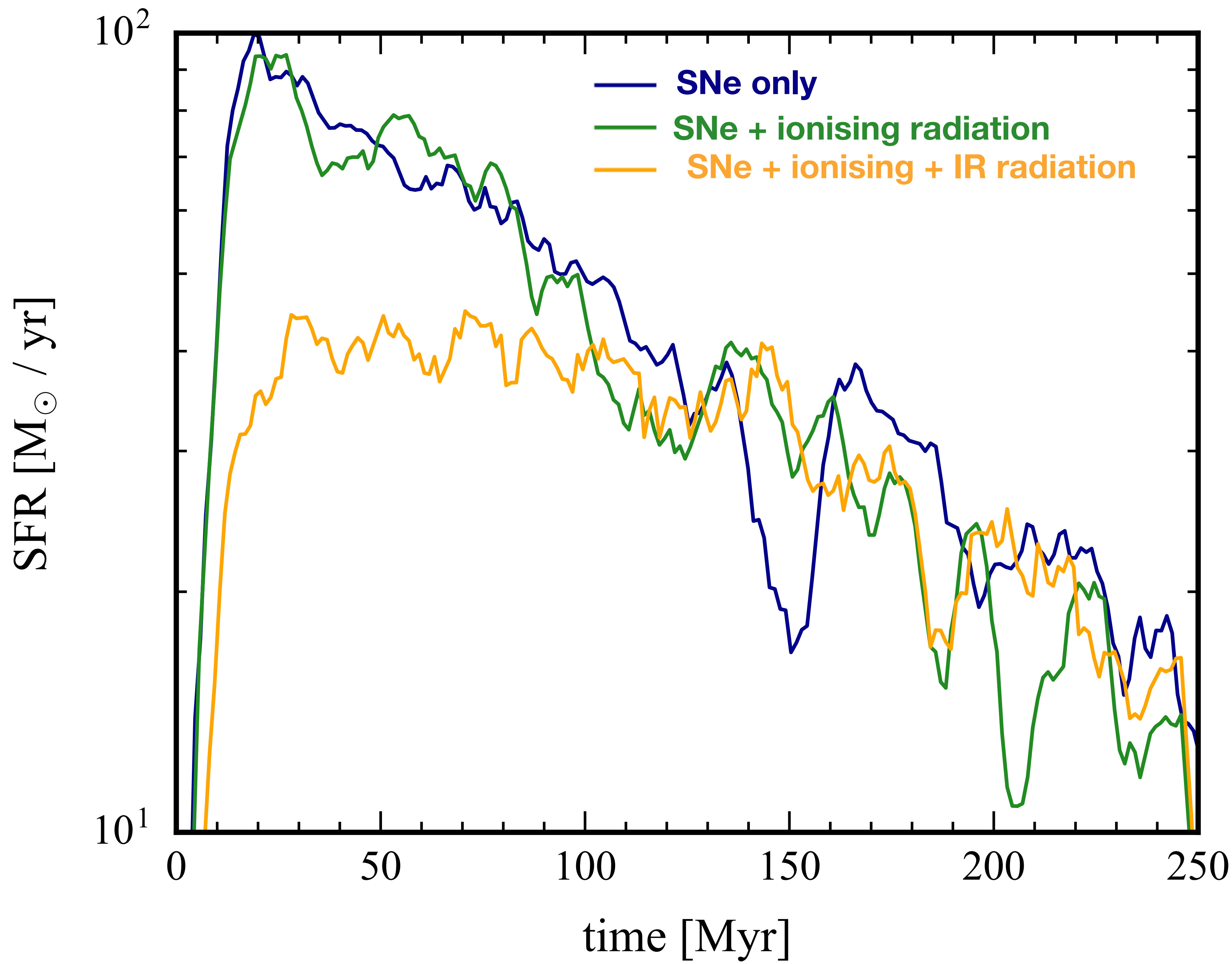
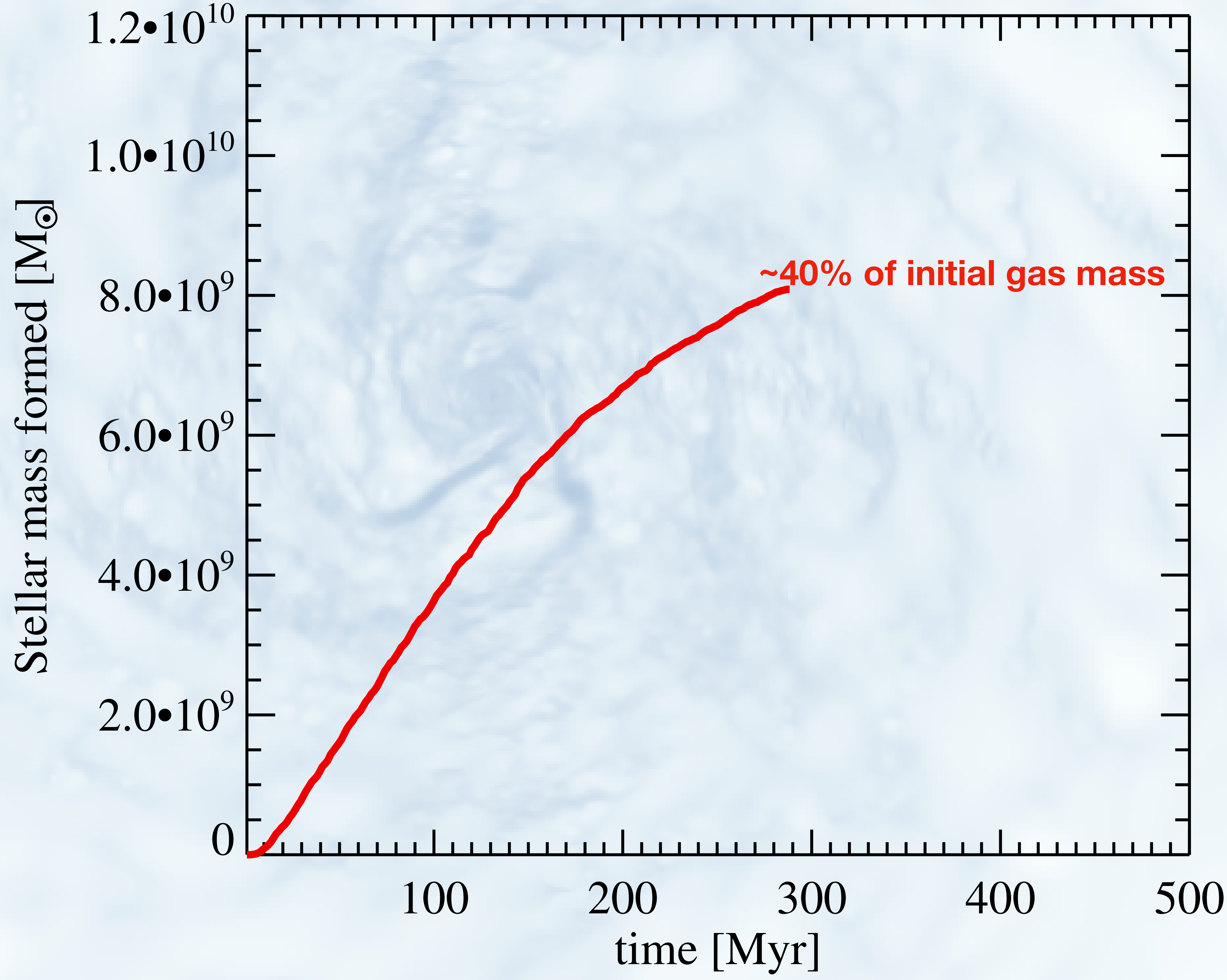
DRAMA Star formation

- IR radiation suppresses the initial starburst



Star formation

DRAMA: Disks with RAdiation-MAtter interactions



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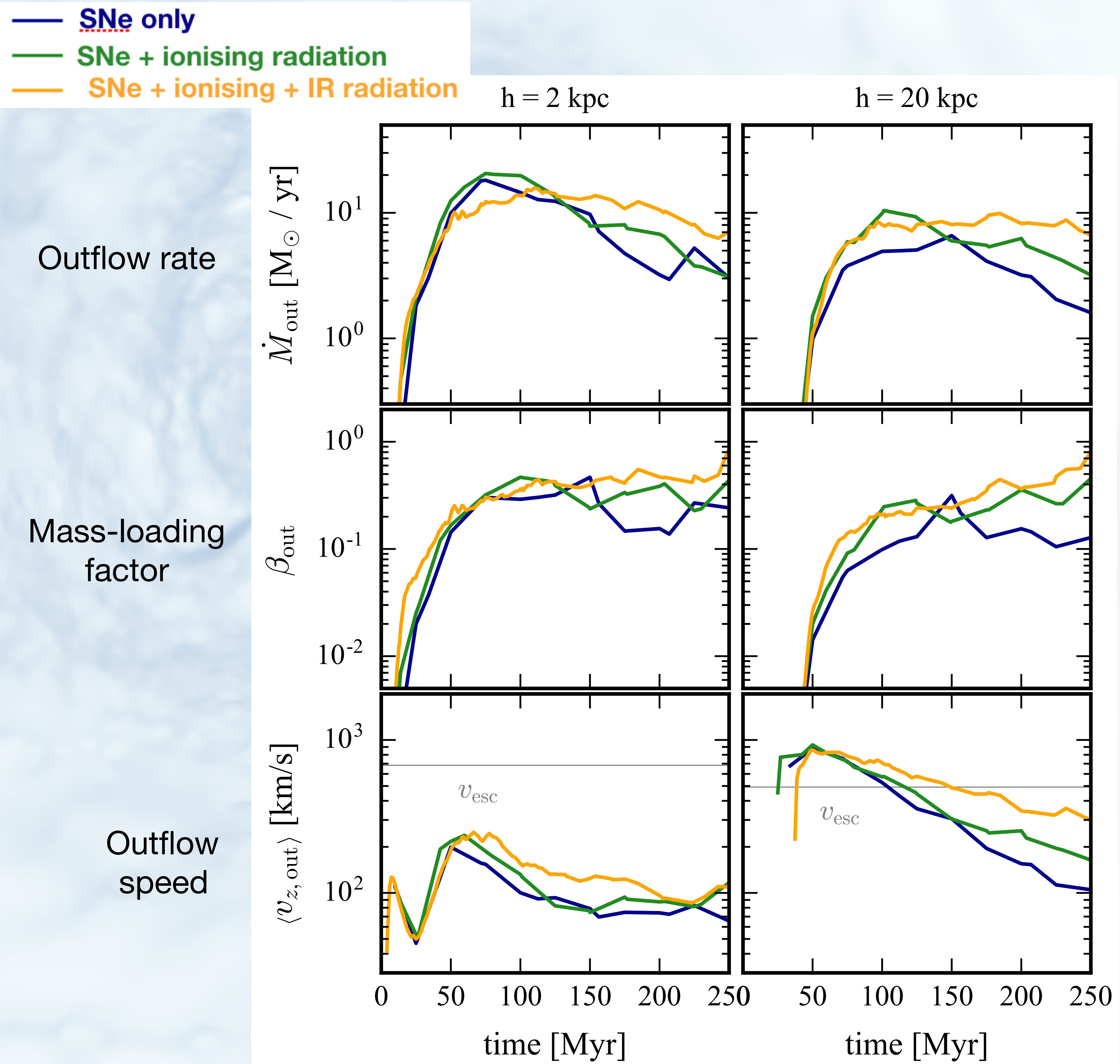
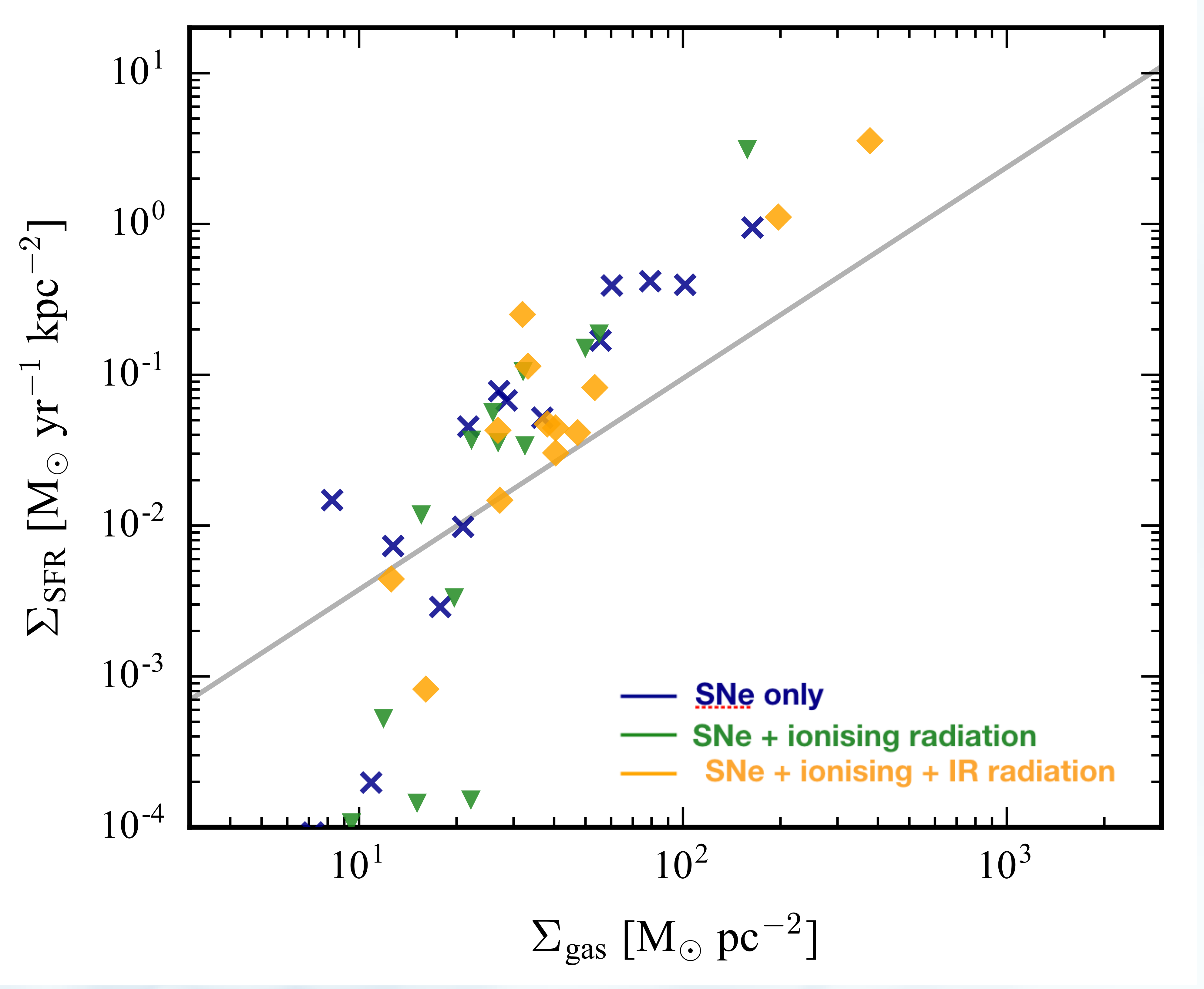
DRAMA Outflows

- Some increase in outflows due to IR radiation



DRAMA KS relation



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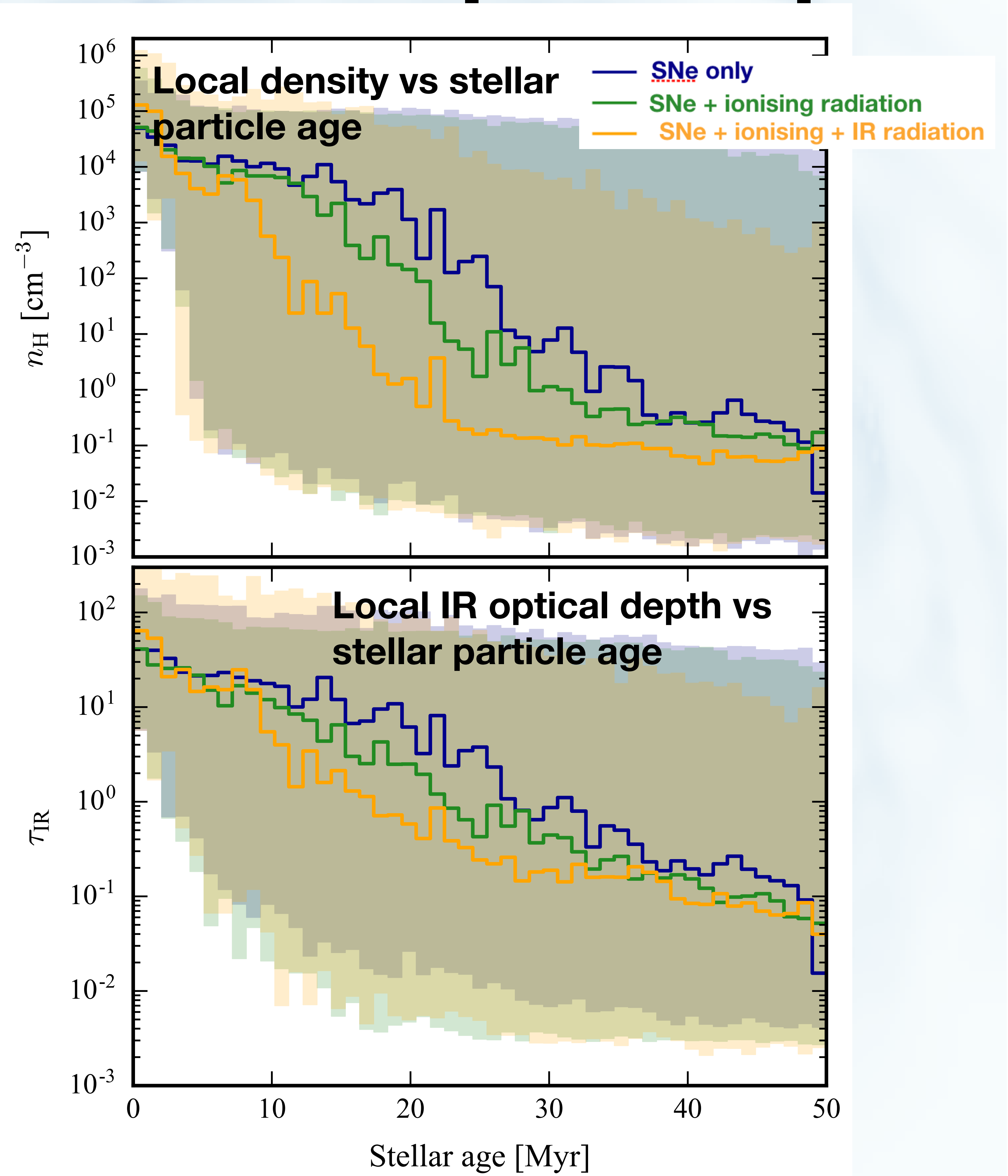
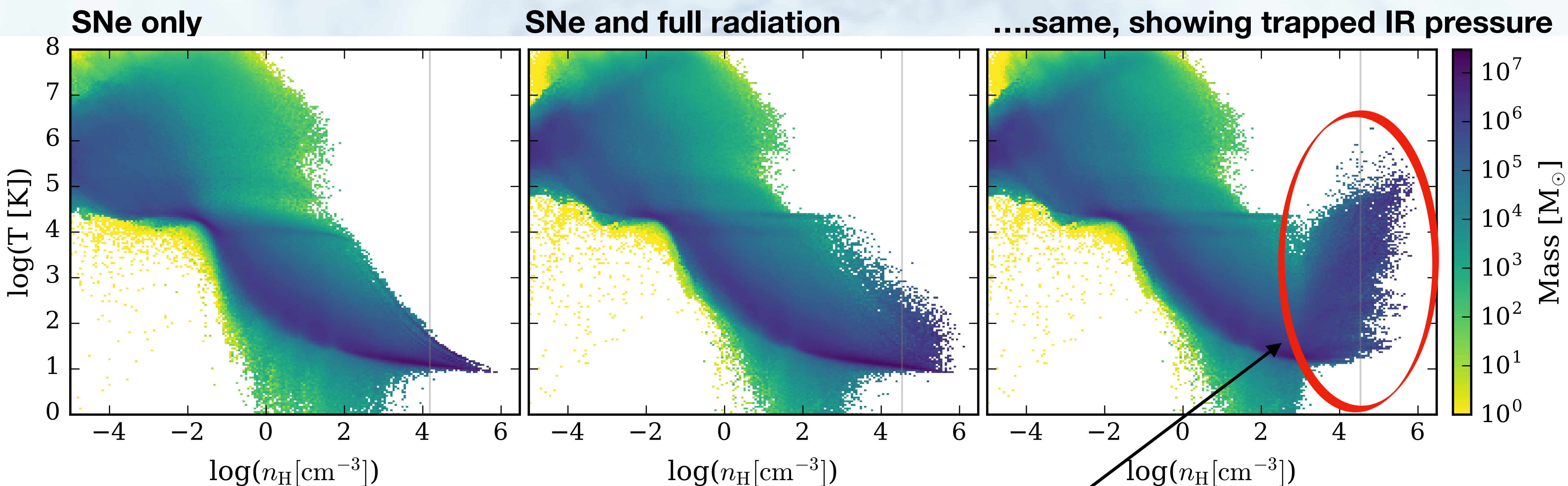


DRAMA: effect of IR radiation

Phase diagrams at 250 Myr



- Trapped, multi-scattering IR radiation pressurises the dense gas clumps

$$P_{\rm rad} = \frac{E_{\rm IR}^{\rm trapped}}{3}$$

➡Similar to a "classical" polytropic equation of state

Joakim Rosdahl

DRAMA: effect of IR radiation

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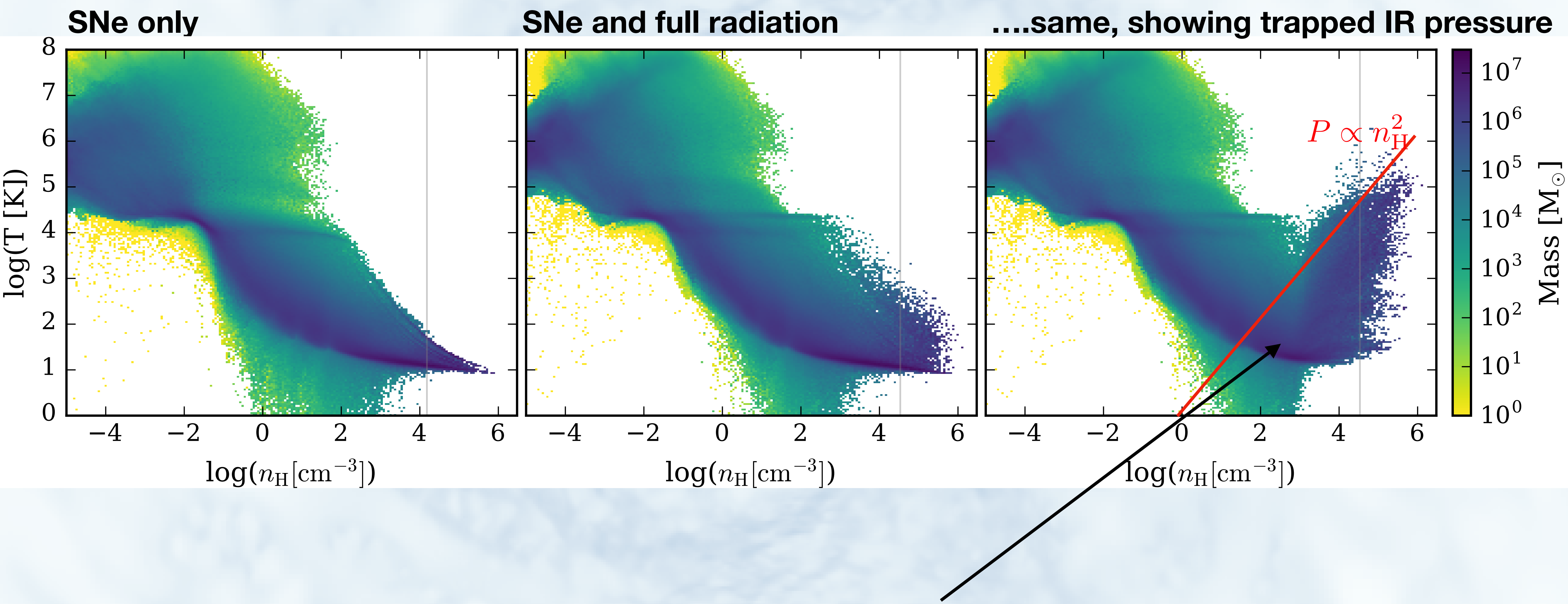

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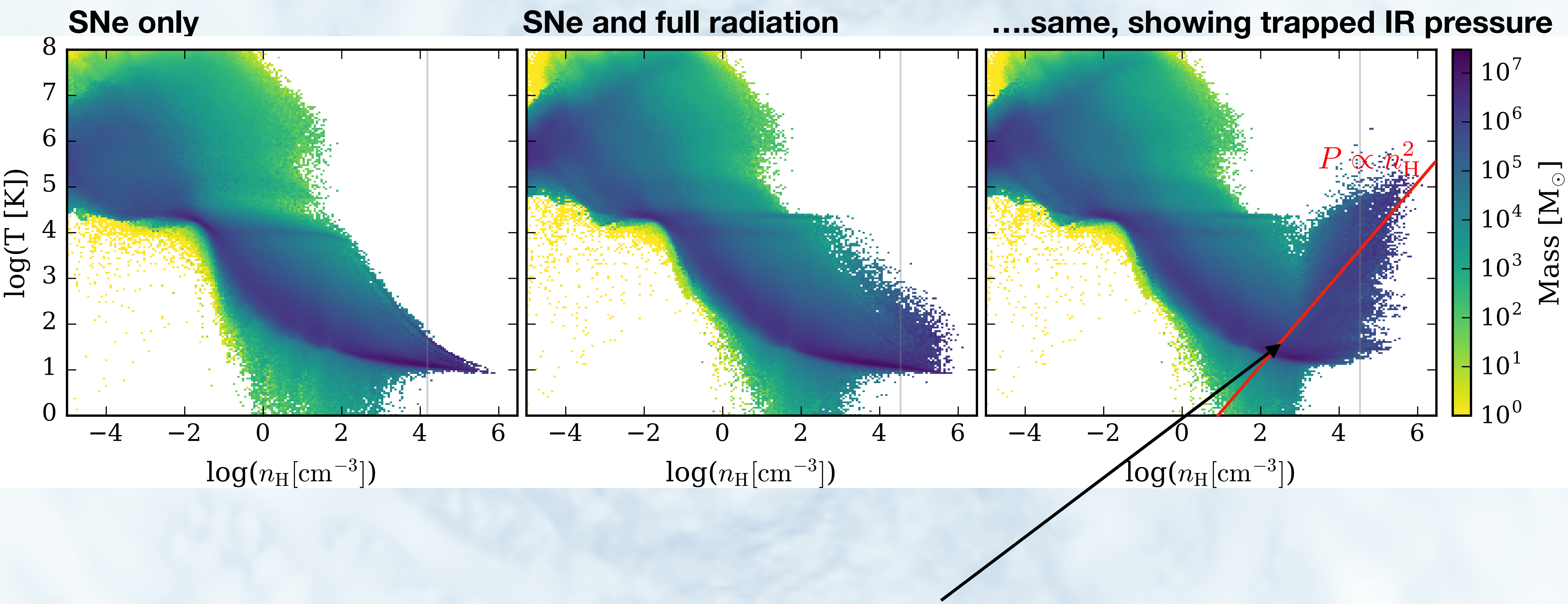

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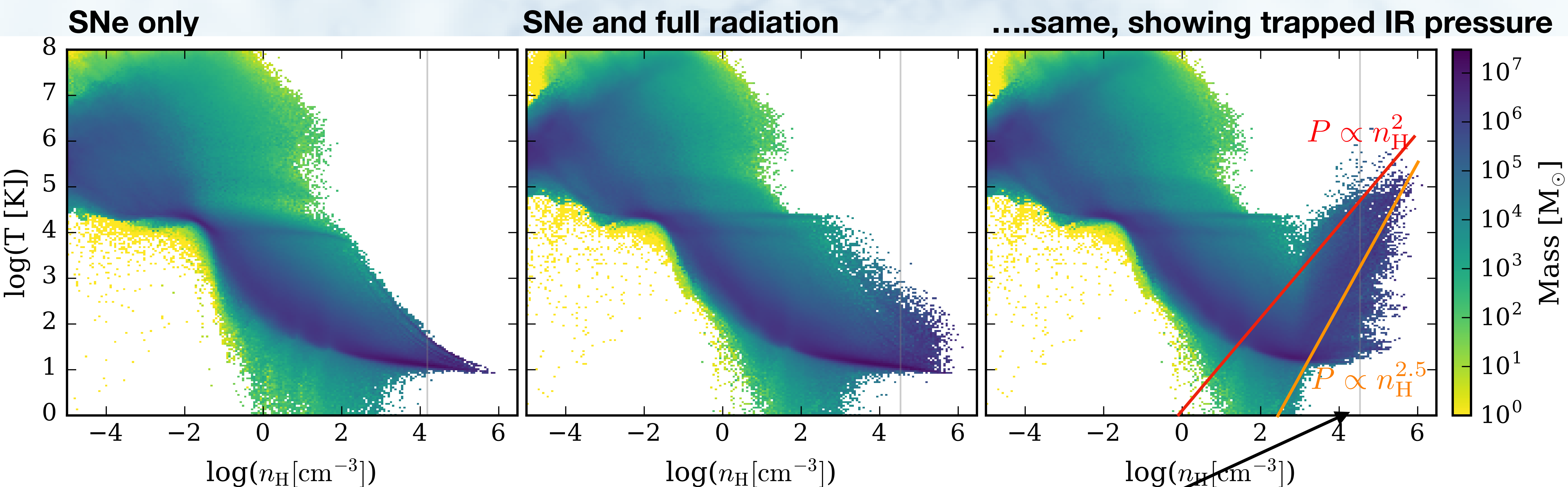

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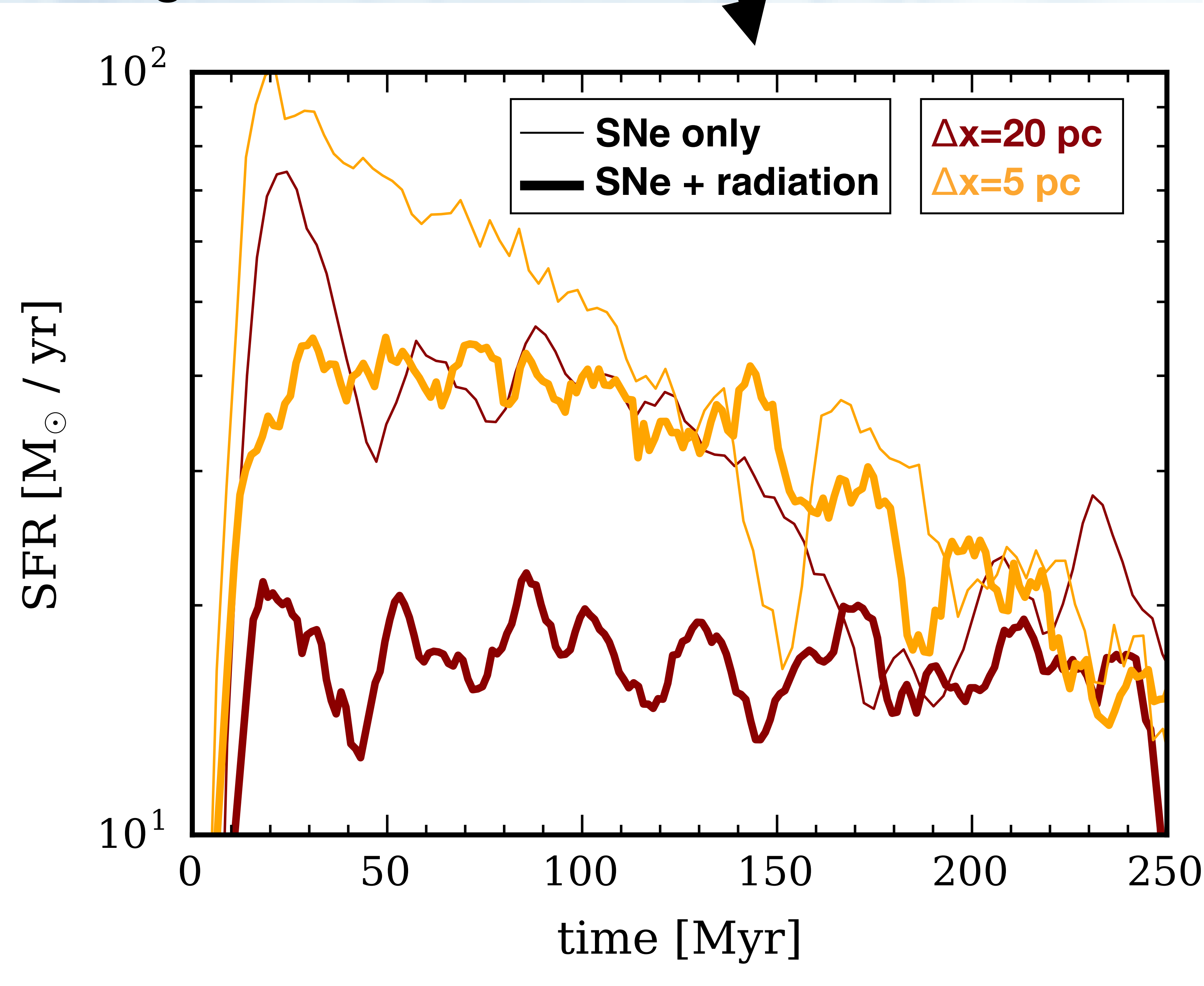
DRAMA simulations summary

- Multi-scattering IR radiation pressurises dense optically thick clumps, somewhat reducing star formation
- Mildly stronger outflows, compared to SN and photoionisation only

DRAMA simulations summary

- Multi-scattering IR radiation pressurises dense optically thick clumps, somewhat reducing star formation
- Mildly stronger outflows, compared to SN and photoionisation only
- Bad news: the effect of IR weakens with increasing resolution
    - More IR escape channels with higher resolution?



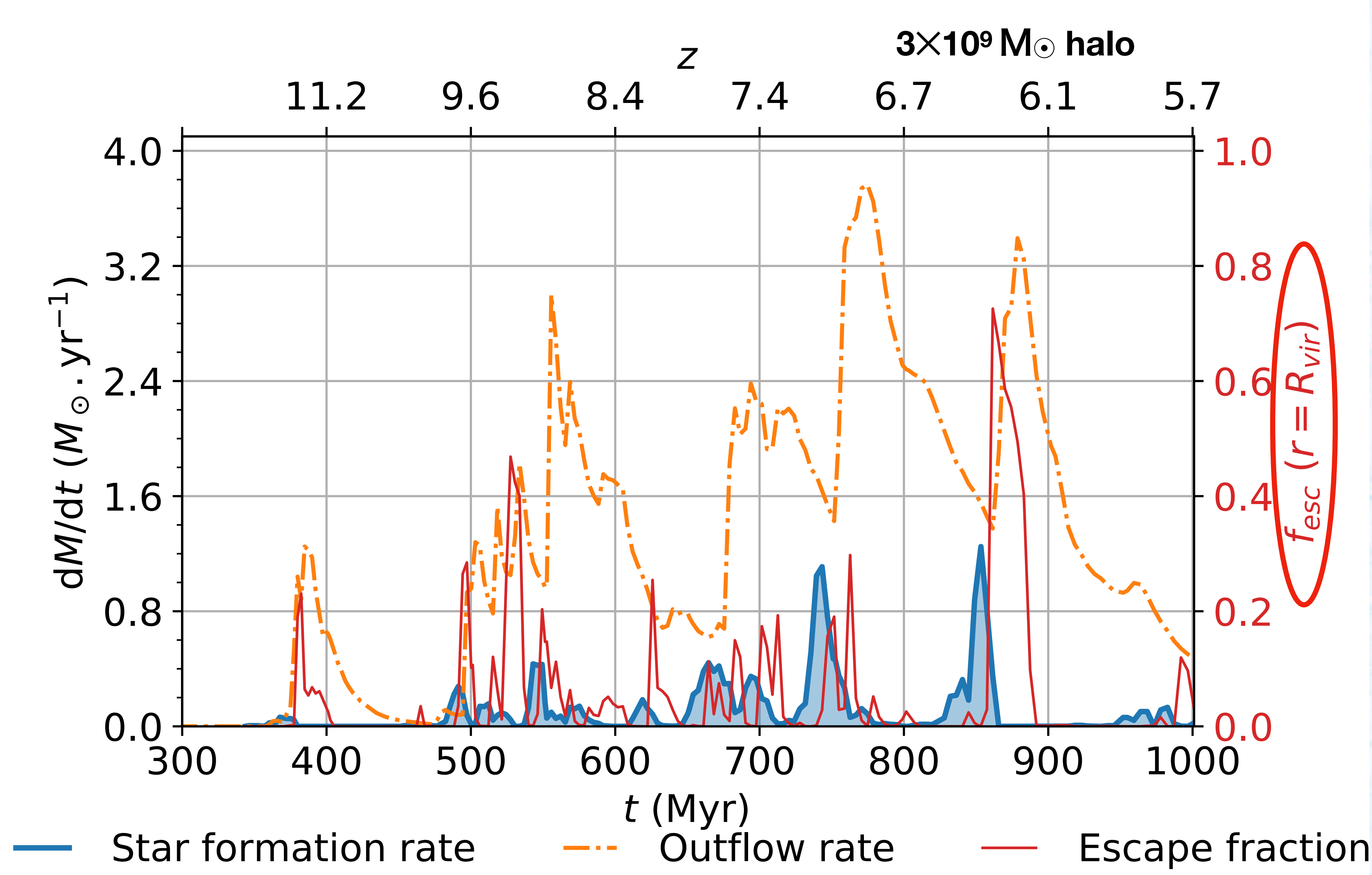
Tiny volume simulations

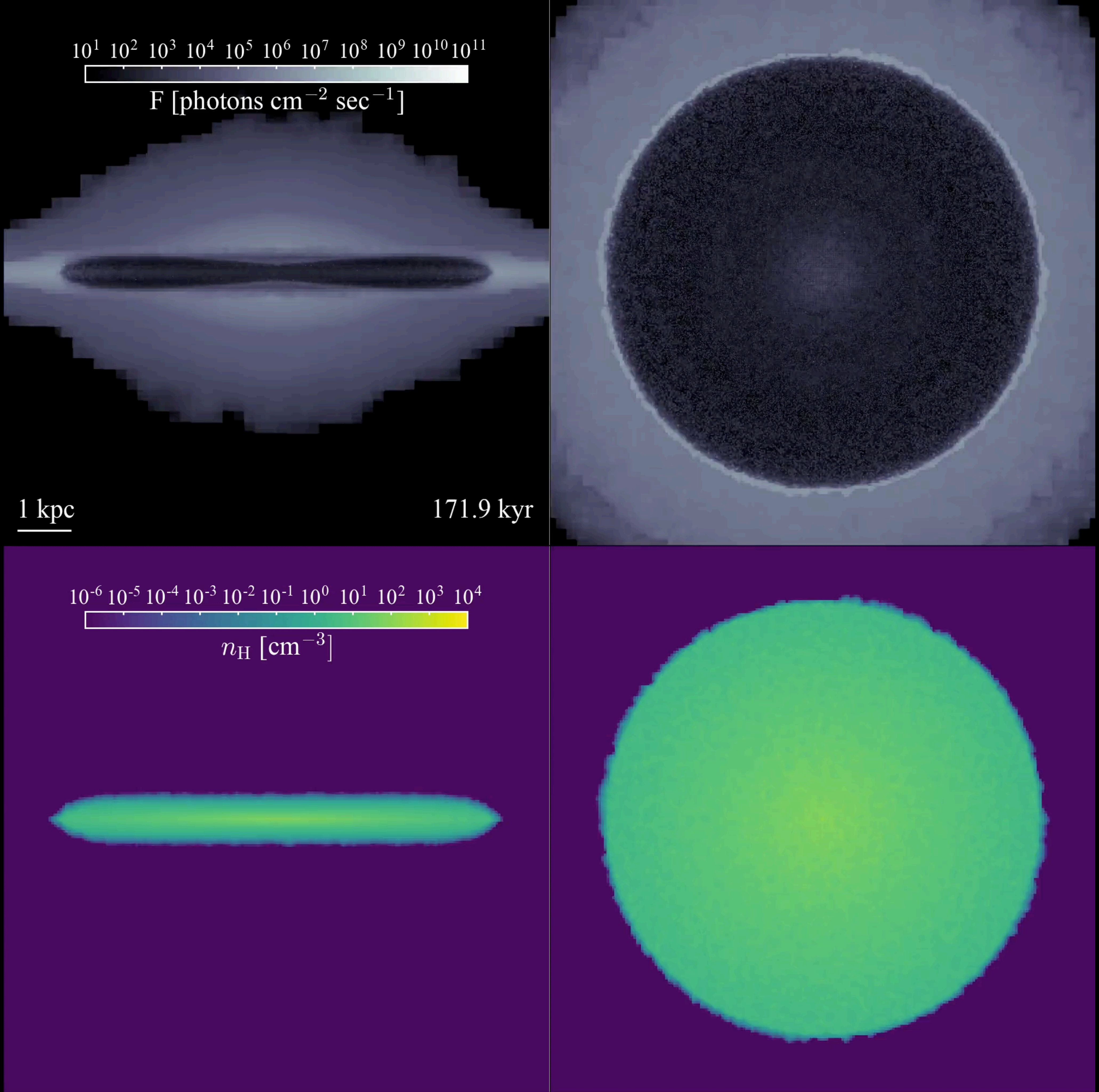
In **Trebitsch et al. (2017)** we studied f_{esc} from more massive halos.

Physical resolution of 7 pc in three targeted halos and their environments

Main result:

f_{esc} is far from constant and heavily regulated by supernova (SN) feedback





10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^10 10^11
F [photons cm^−2 sec^−1]
1 kpc
171.9 kyr
10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 10^0 10^1 10^2 10^3 10^4
n_H [cm^−3]

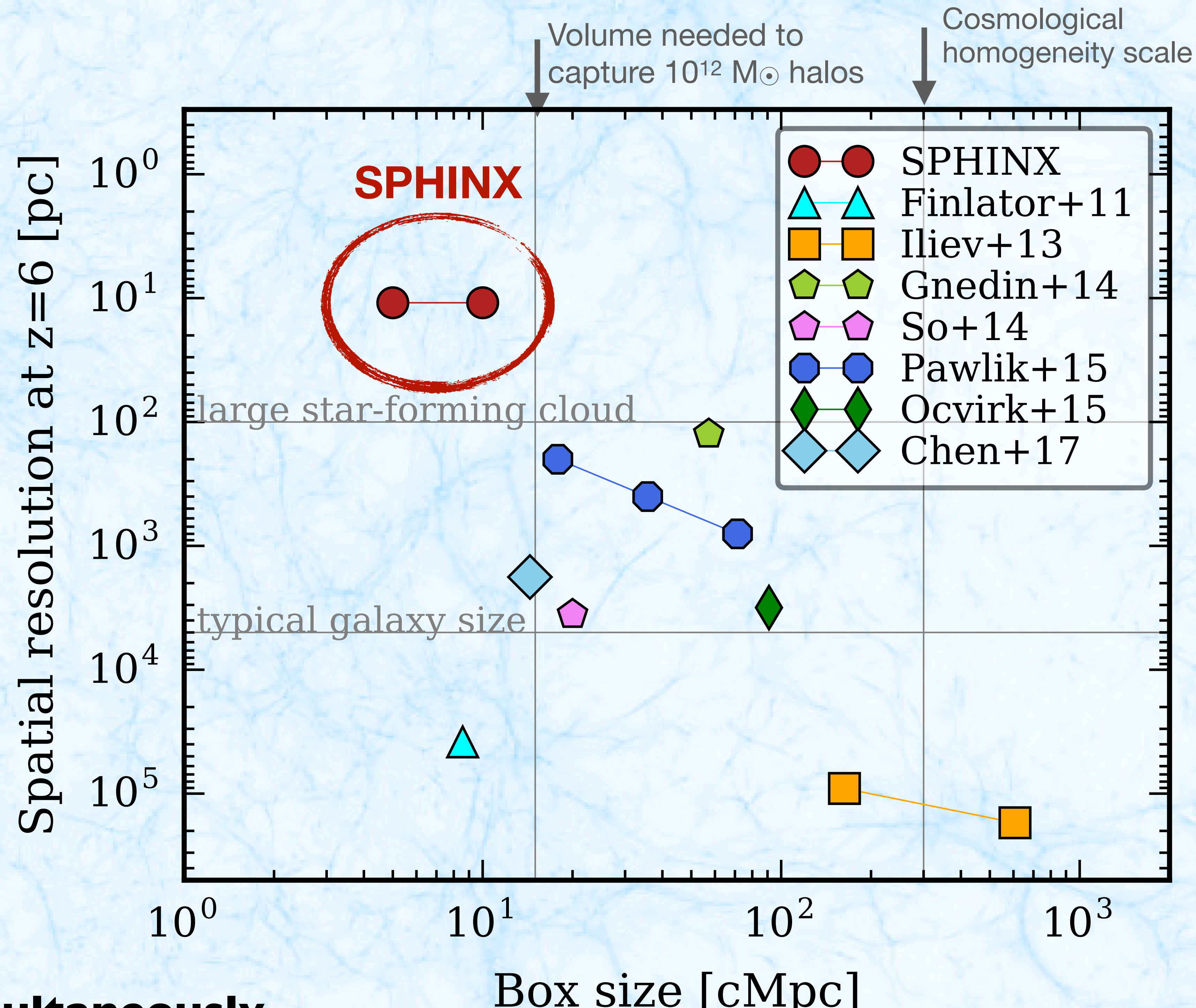
The role of (SN) feedback for reionisation

The SPHINX simulations project: simulating reionisation and galaxy formation over the first billion years

see arxiv:1801.07259

The SPHINX simulations in context

Showing RHD simulations with full cosmological (non-zoom) volumes



With SPHINX, we can simultaneously

• predict f_{esc} of ionising radiation from thousands of galaxies in one volume

➡predict the reionisation history

SED models

Spectral Energy Distributions for stellar populations

Binary Stars Can Provide the "Missing Photons" Needed for Reionization

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 pure-hydro zoom simulations, Ma et al. predict 4-10 times boosted f_{esc} (escape of ionising radiation) with a binary population SED

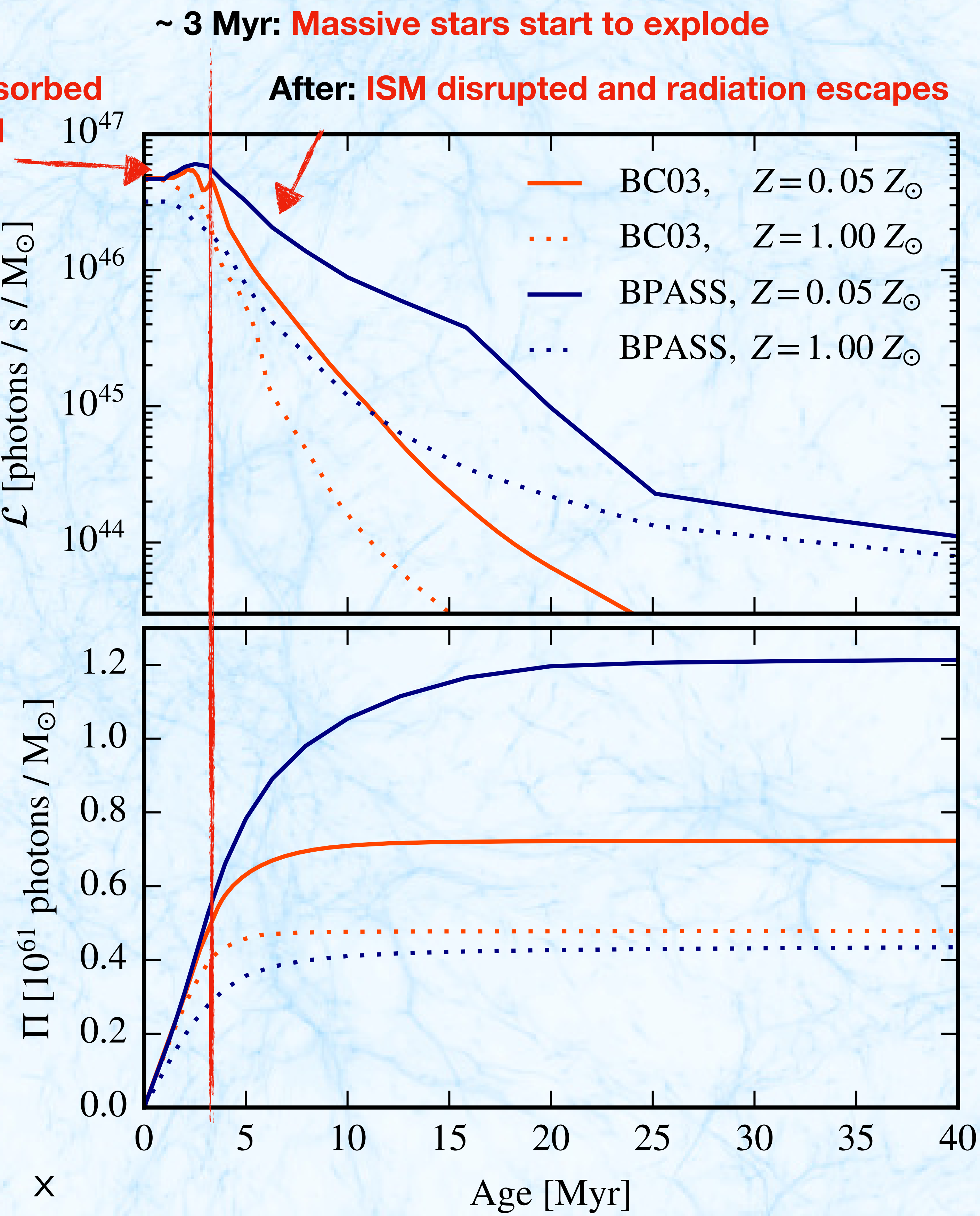
- The reason: longer and stronger radiation due to mass transfer and mergers in binary systems

SED models

Spectral Energy Distributions for stellar populations

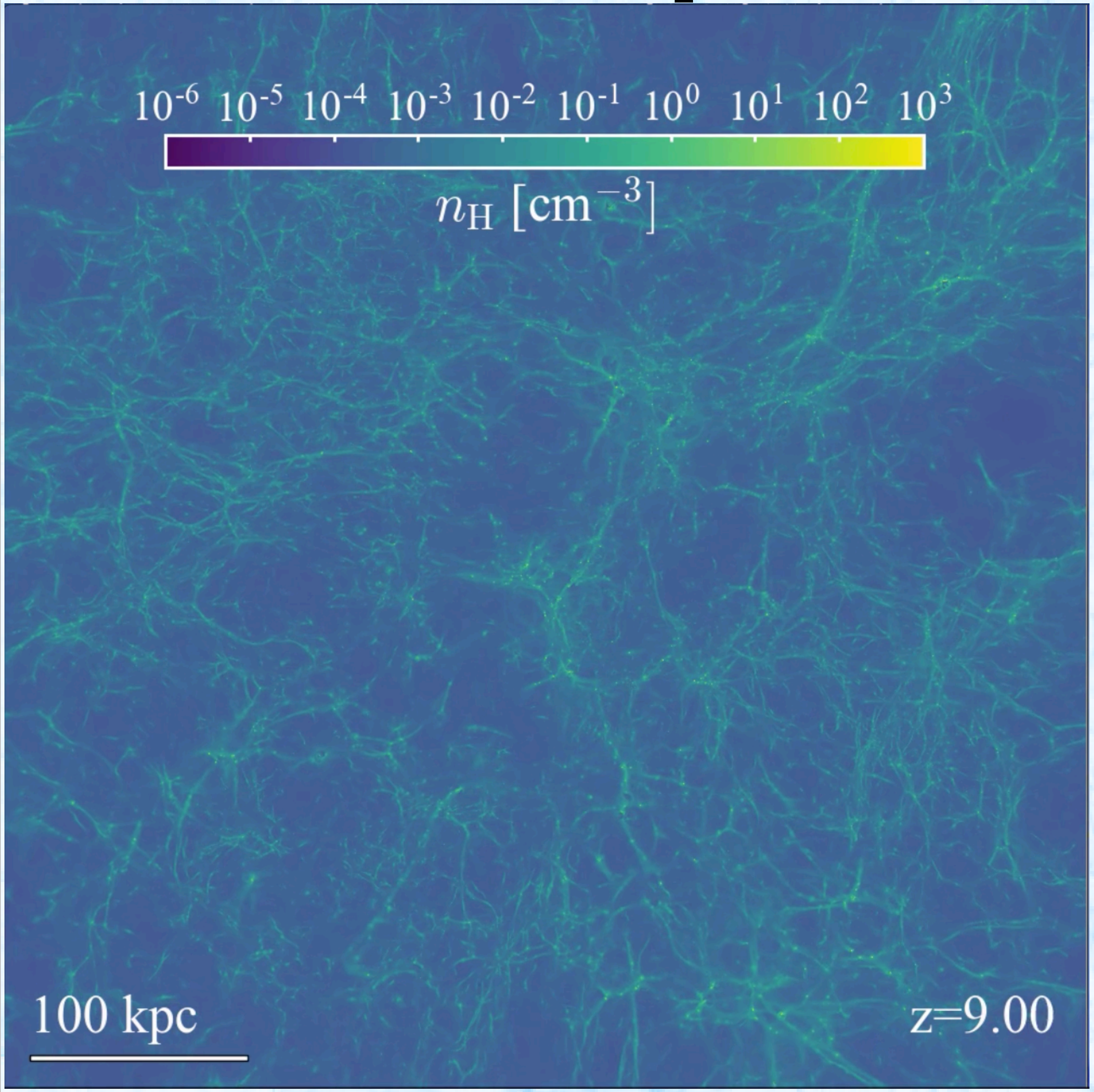
- **BC03 = Single stellar population model from Bruzual & Charlot (2003)**
- **BPASS = Binary Population and Spectral Syntesis from Eldridge et al.**

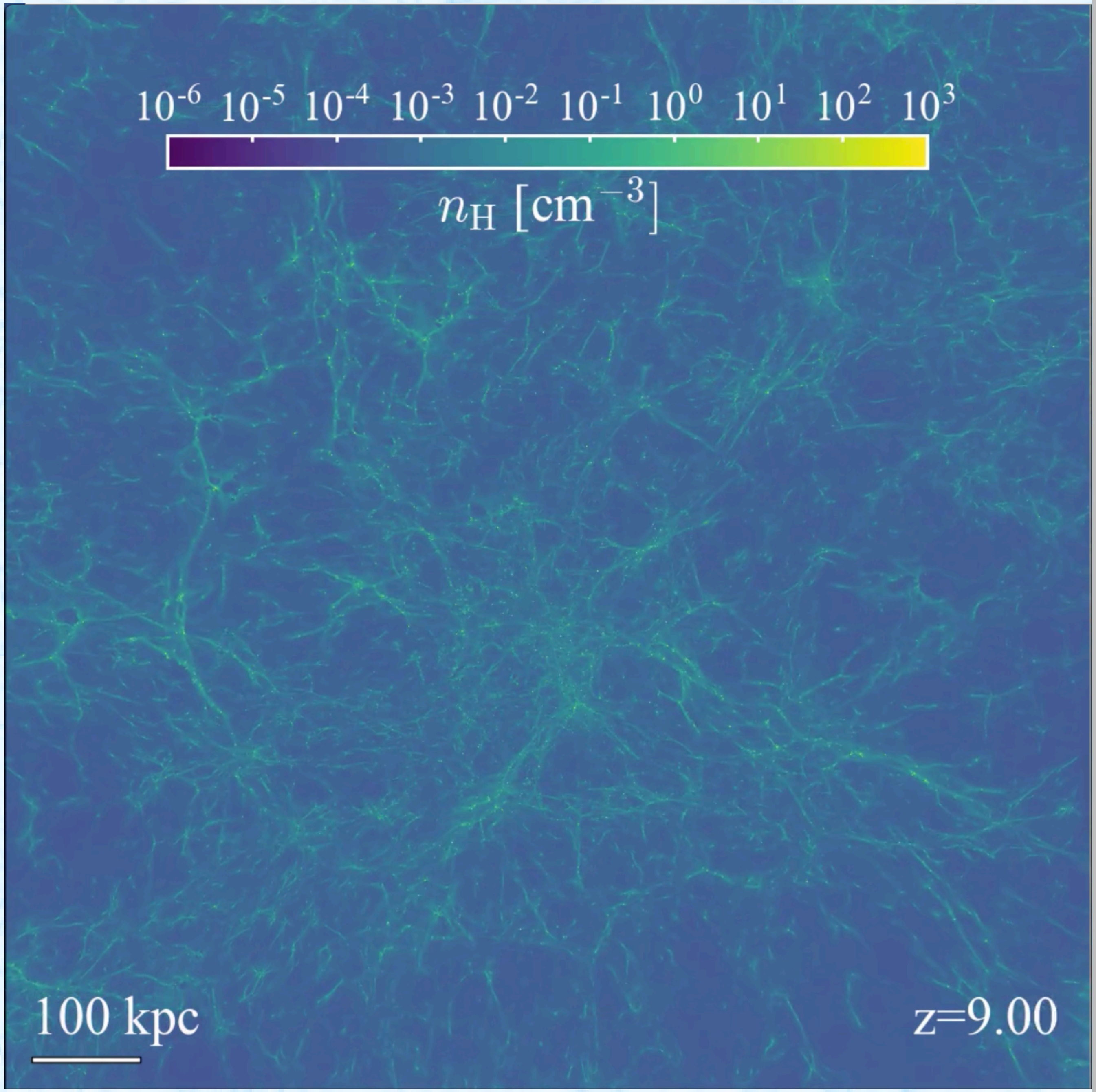
➡**SPHINX: using full RHD cosmological simulations, what does BPASS do for the reionsiation history?**



Setup of the Sphinx simulations

Sphinx simulations





5 cMpc box with high mass resolution

10 cMpc box with lower mass resolution (but same physical resolution)

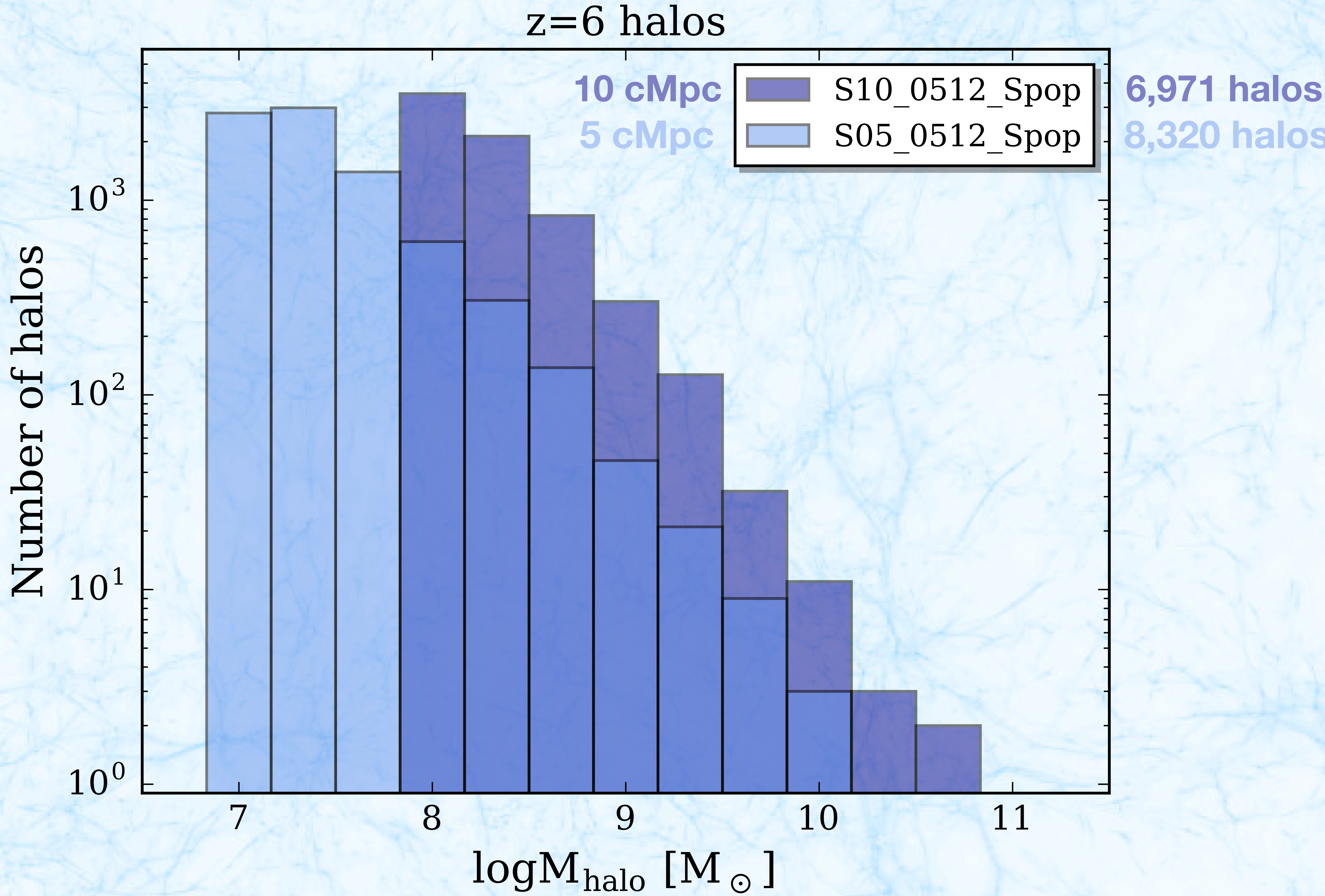
...plus many tiny 1.25-2.5 cMpc boxes for exploration and calibration

x

SPHINX setup

- **Physical resolution** max 10 pc, required to capture the escape of ionising radiation from galaxies (Kimm et al, 2017).
- **DM mass resolution** of 3×10^5 $M_\odot$
- **Stellar particle resolution** of 10^3 $M_\odot$
- *Bursty* turbulence-dependent **star formation**
- **SN explosions** modelled with momentum kicks (Kimm et al., 2015)
  - We *calibrate* SN rates to reproduce a realistic SF history (four times boosted SN rate derived from Kroupa initial mass function)
- **No calibration on unresolved f_{esc}** (i.e. we simply inject the [BPASS] SED luminosity)

Sphinx simulations



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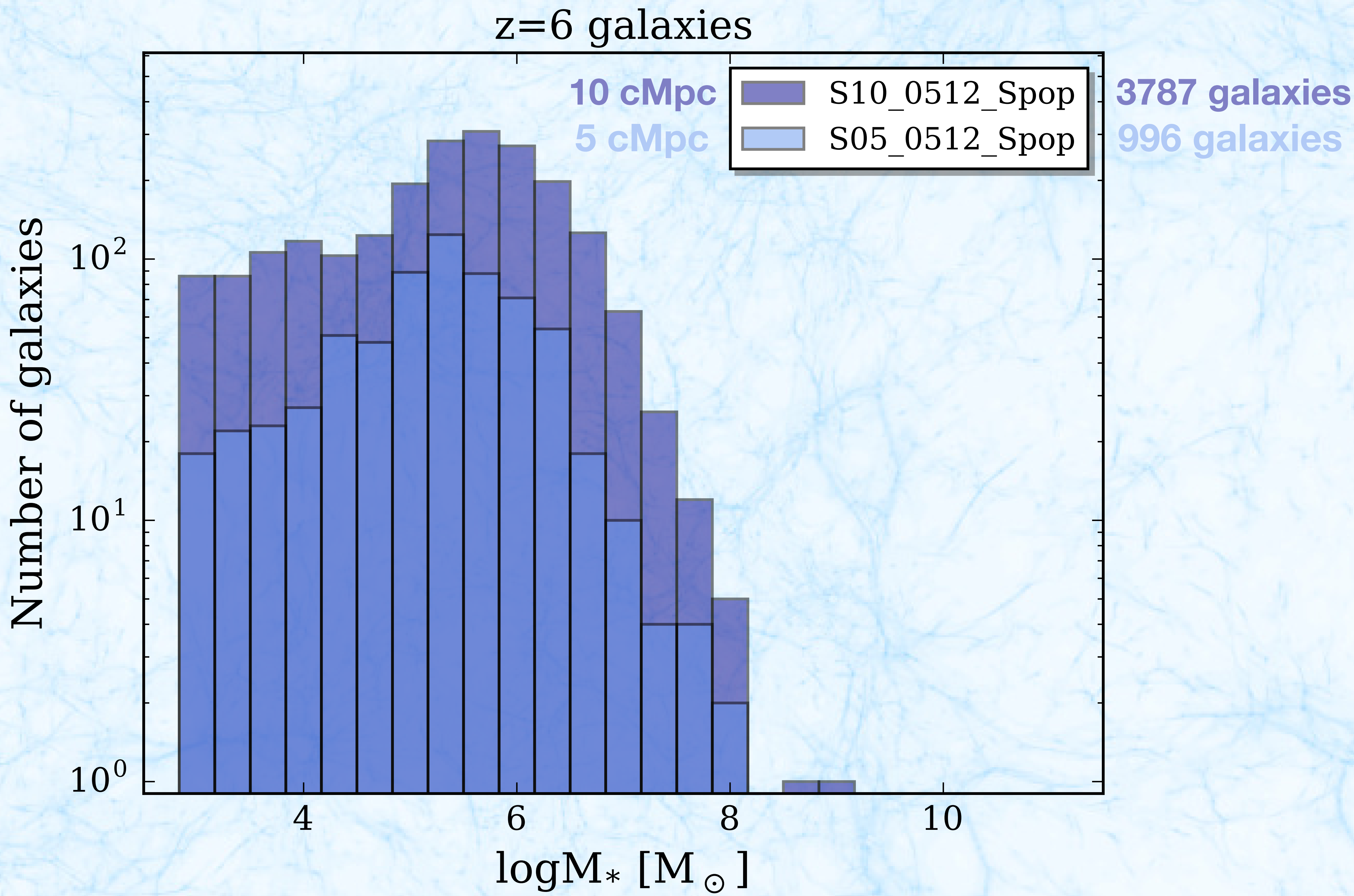
Sphinx simulations

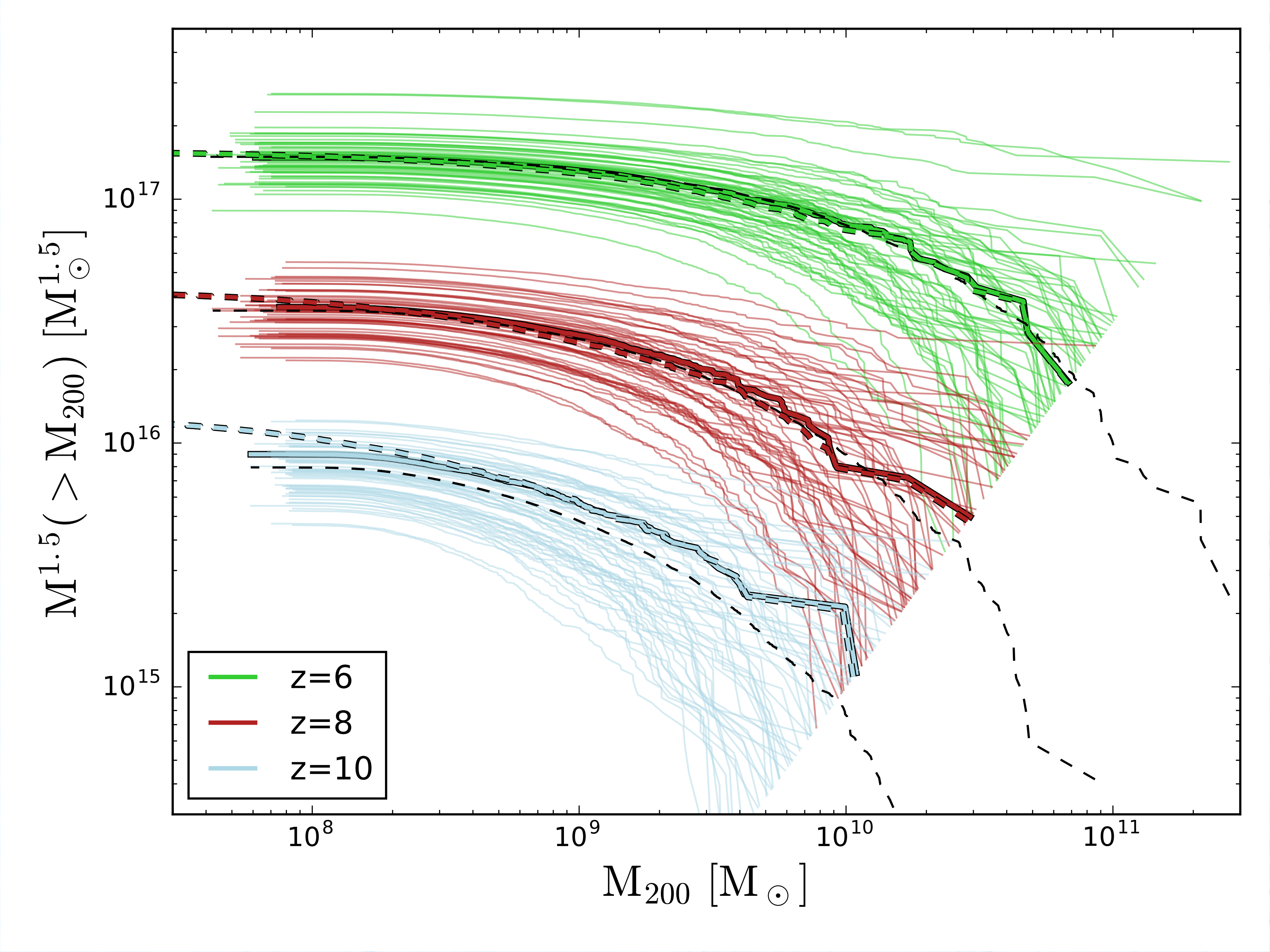


x

Selection of initial conditions

- **To minimise cosmic variance effects, we ran pure dark matter simulations from 60 (CMB) initial conditions and selected the 'best' halo mass function**
- **We're interested in the correct luminosity budget:**

$$\mathrm{Lum} \propto \mathrm{SFR} \propto M_{\mathrm{halo}}^{1.5}$$



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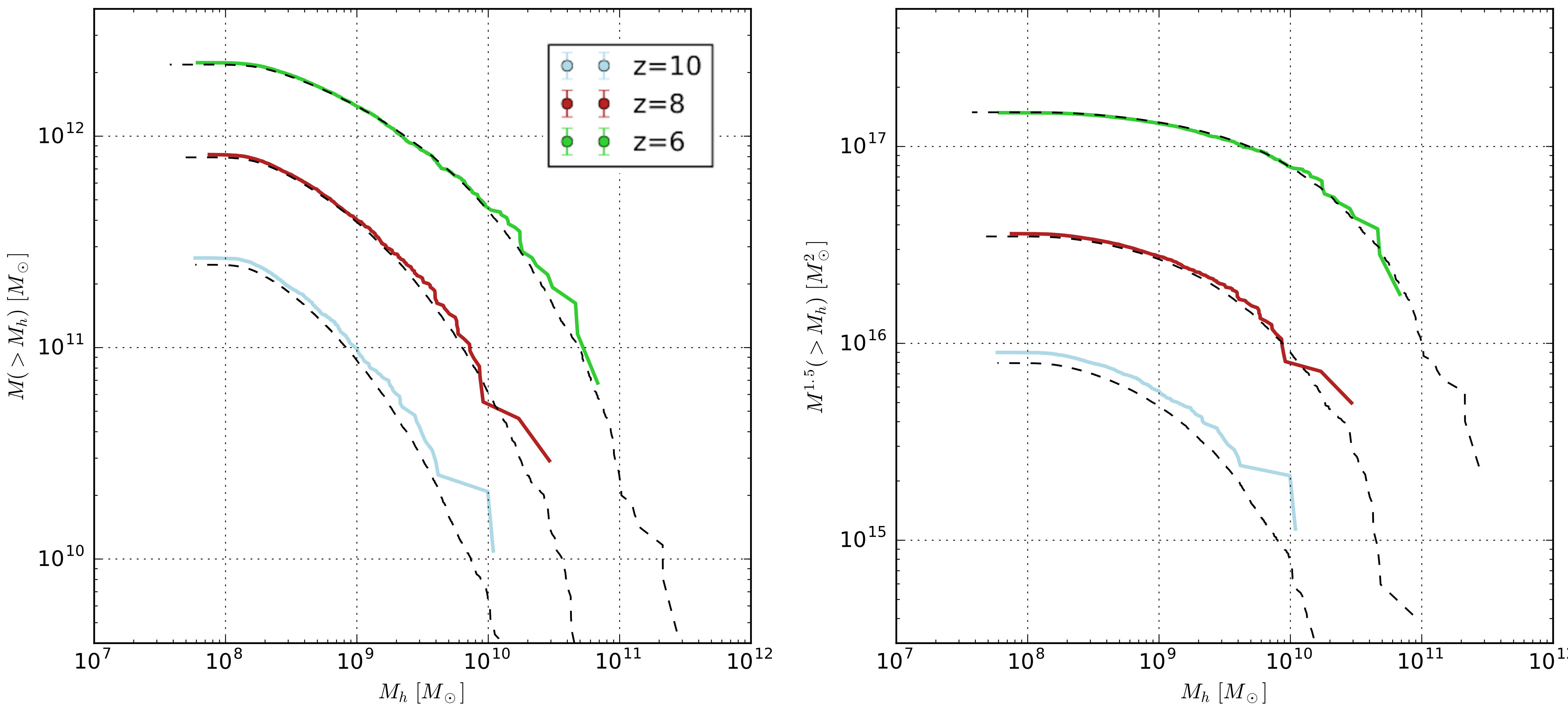
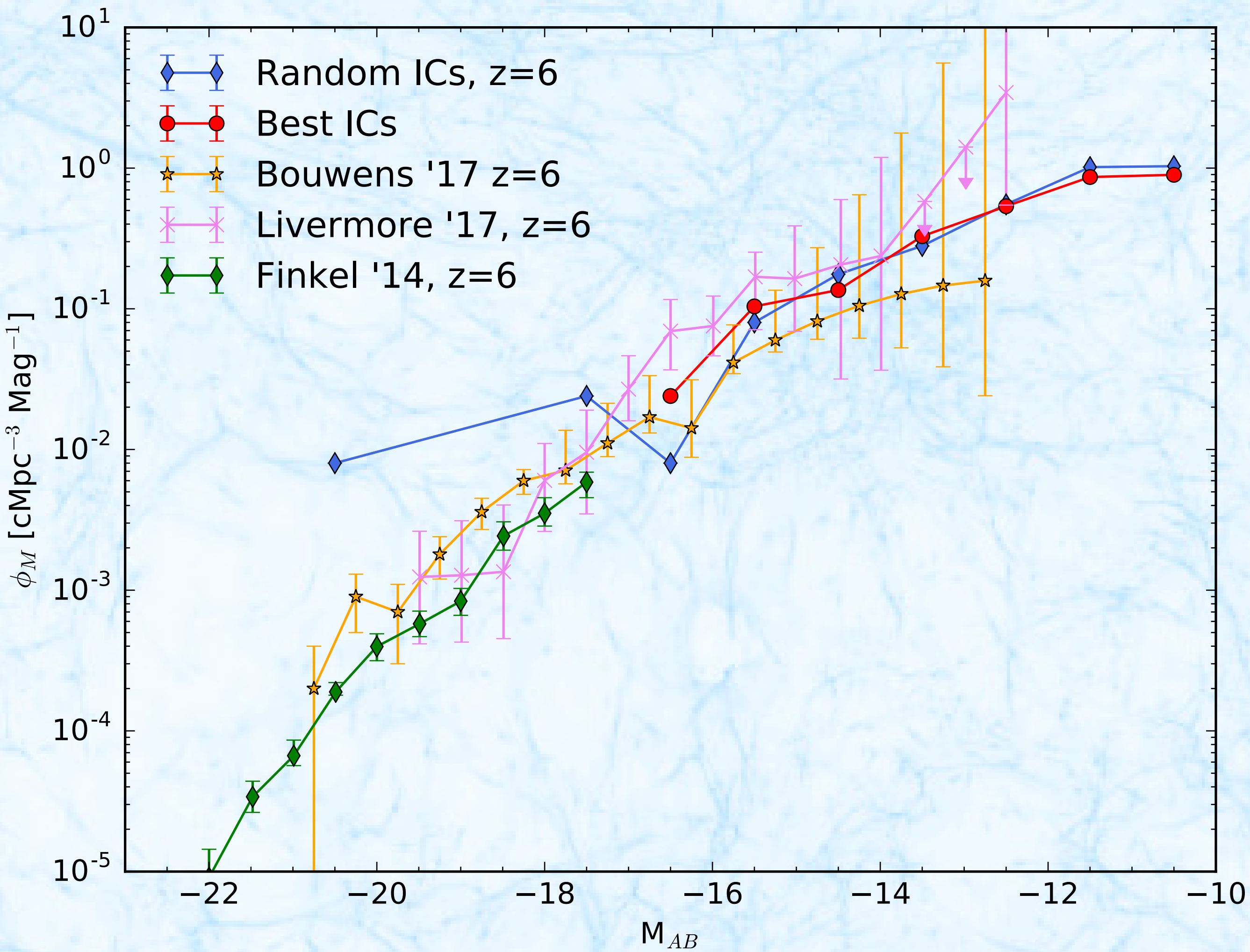
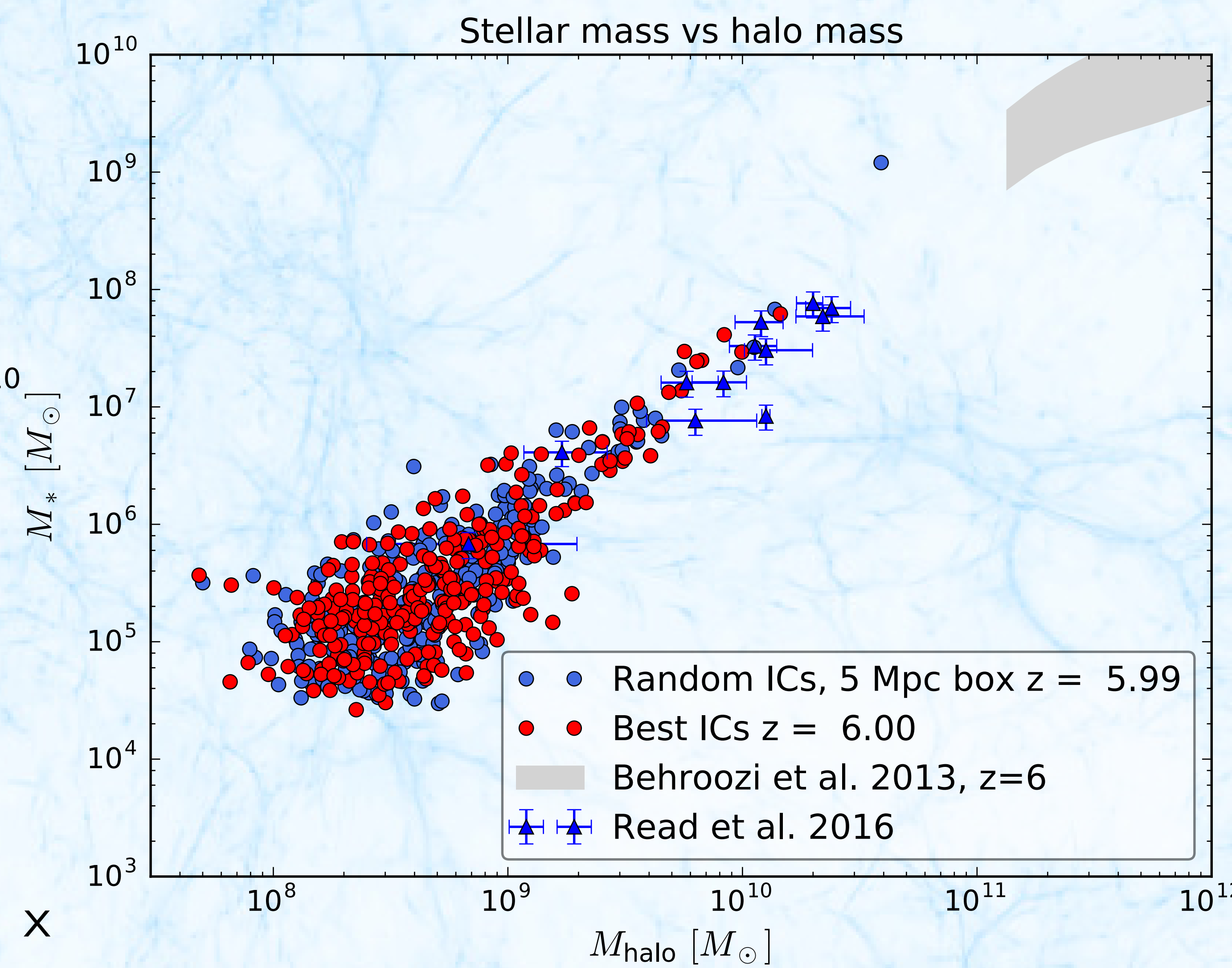


Selection of initial conditions

- **'Best' ICs give a better comparison to observations, given properly calibrated feedback**





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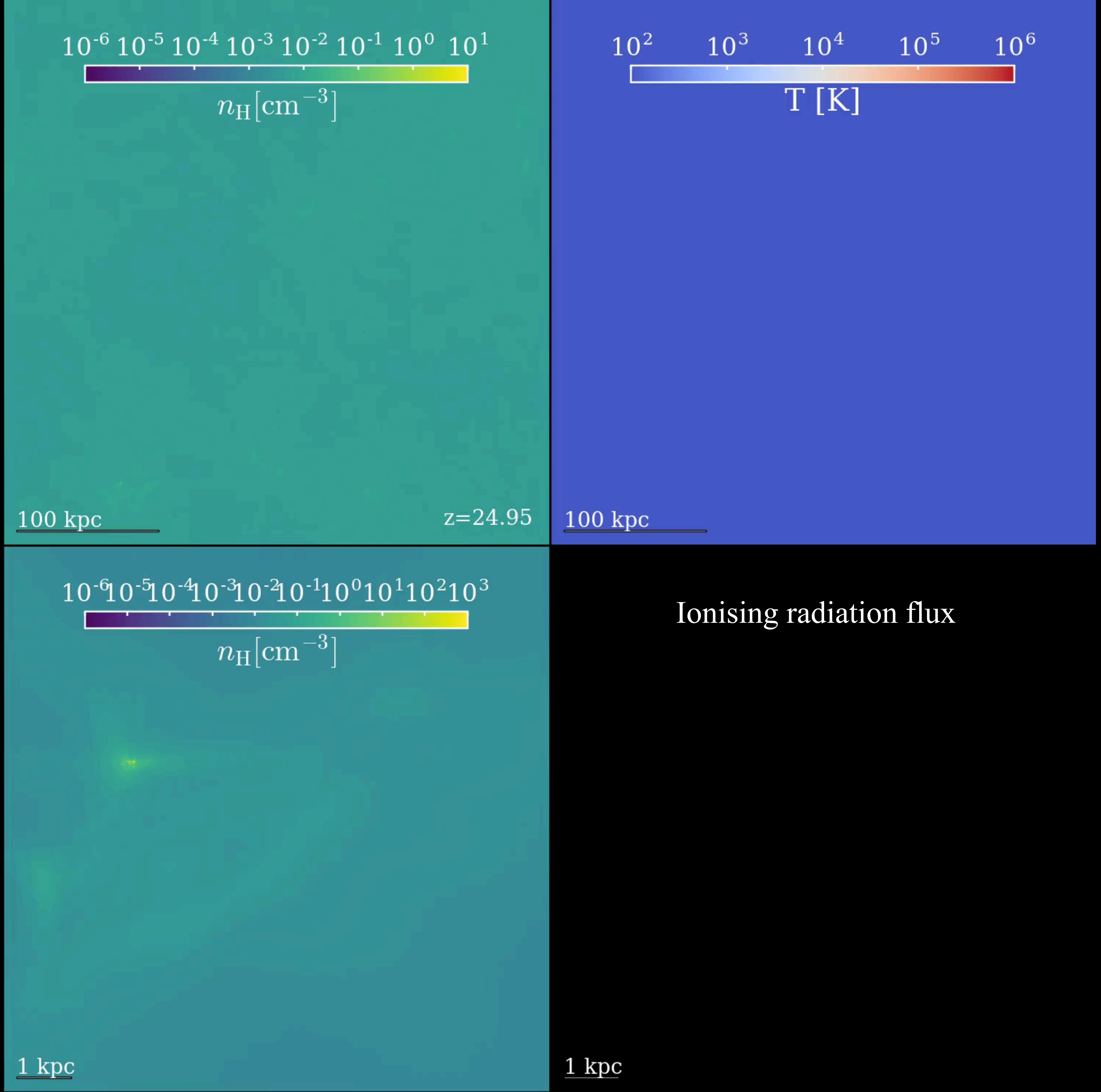
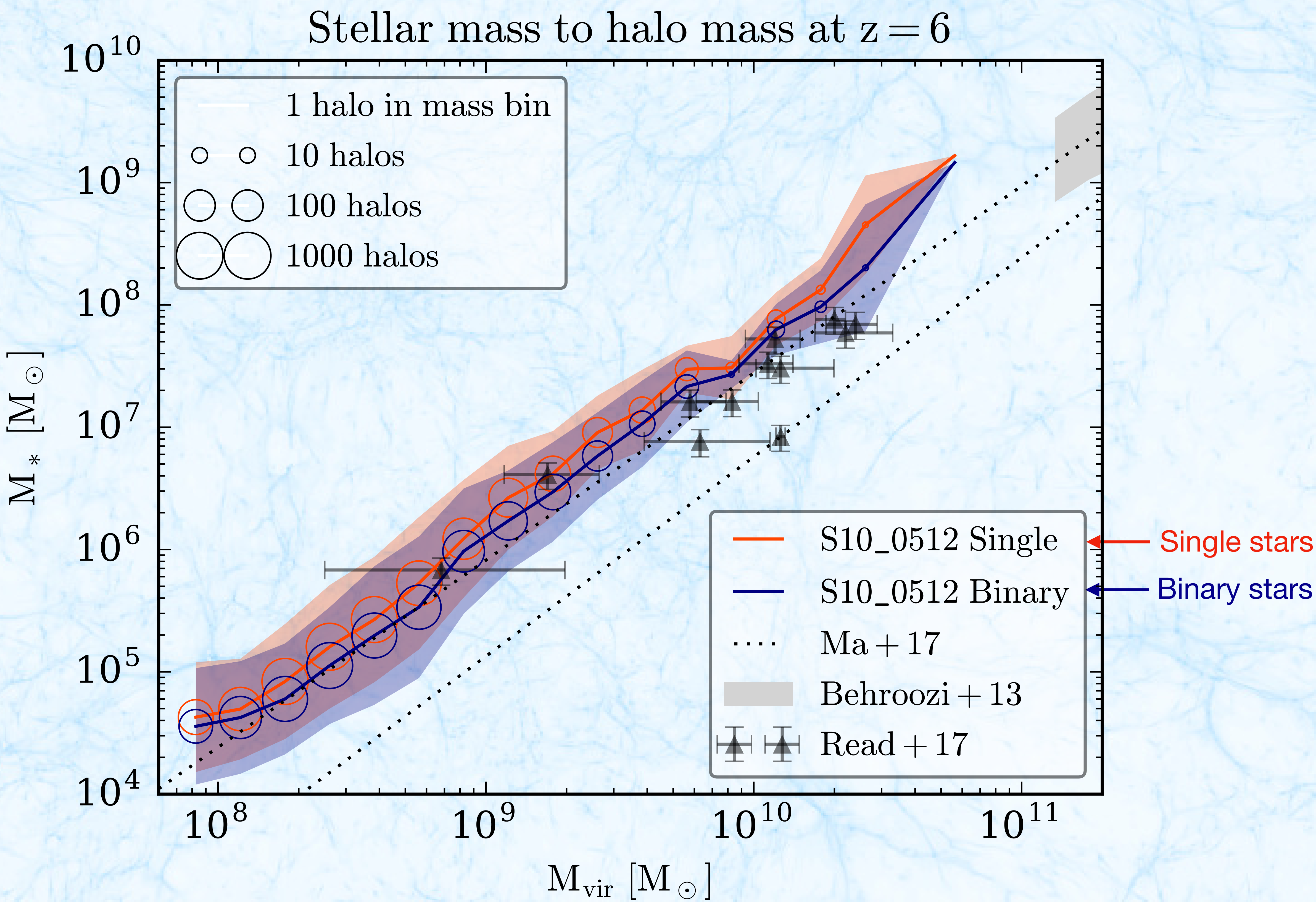


10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}
$n_{\rm H}[{\rm cm}^{-3}]$
100 kpc
z=24.95
10^{2} 10^{3} 10^{4} 10^{5} 10^{6}
T [K]
100 kpc
10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
$n_{\rm H}[{\rm cm}^{-3}]$
1 kpc
Ionising radiation flux
1 kpc

Stellar mass to halo mass



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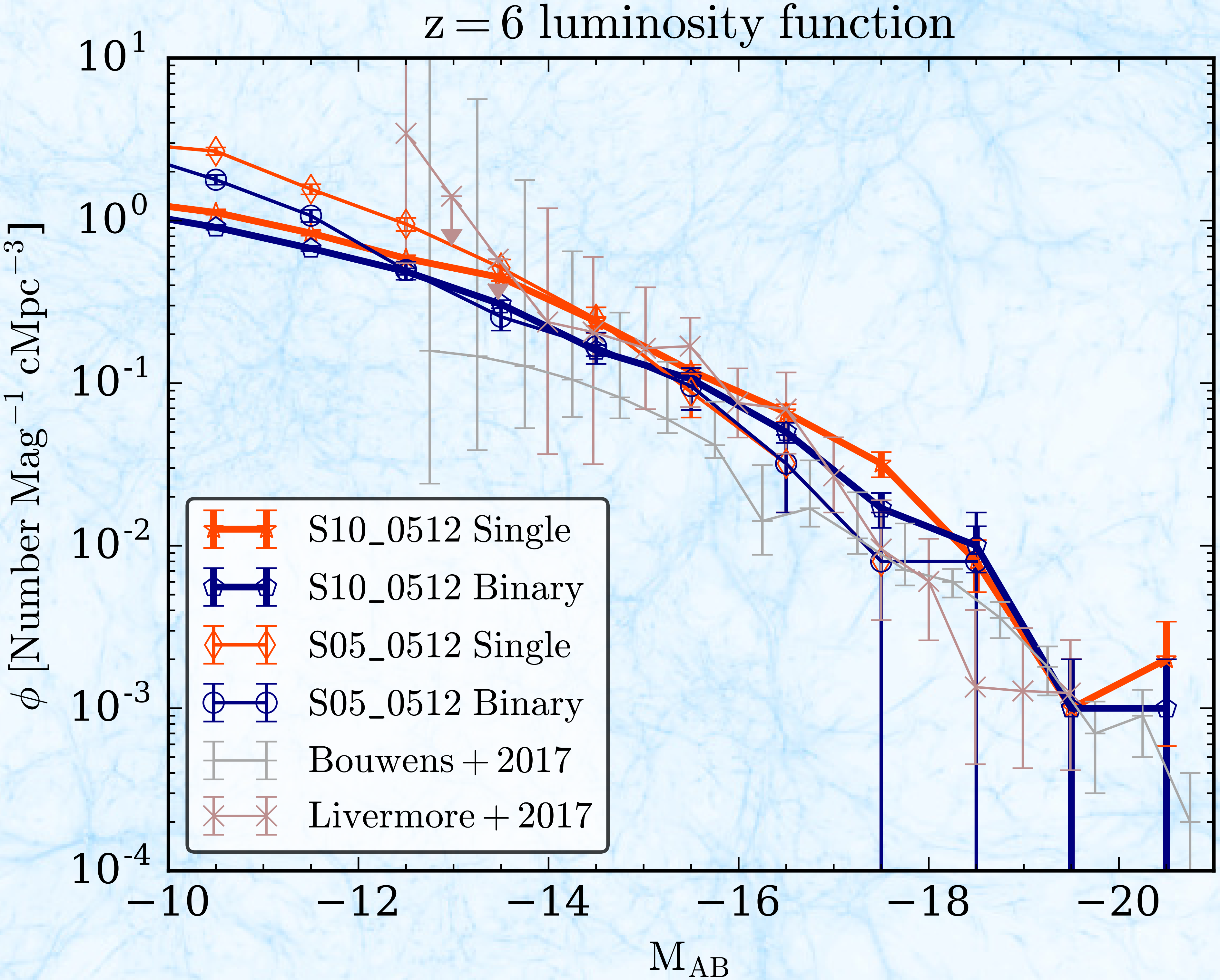
Luminosity function

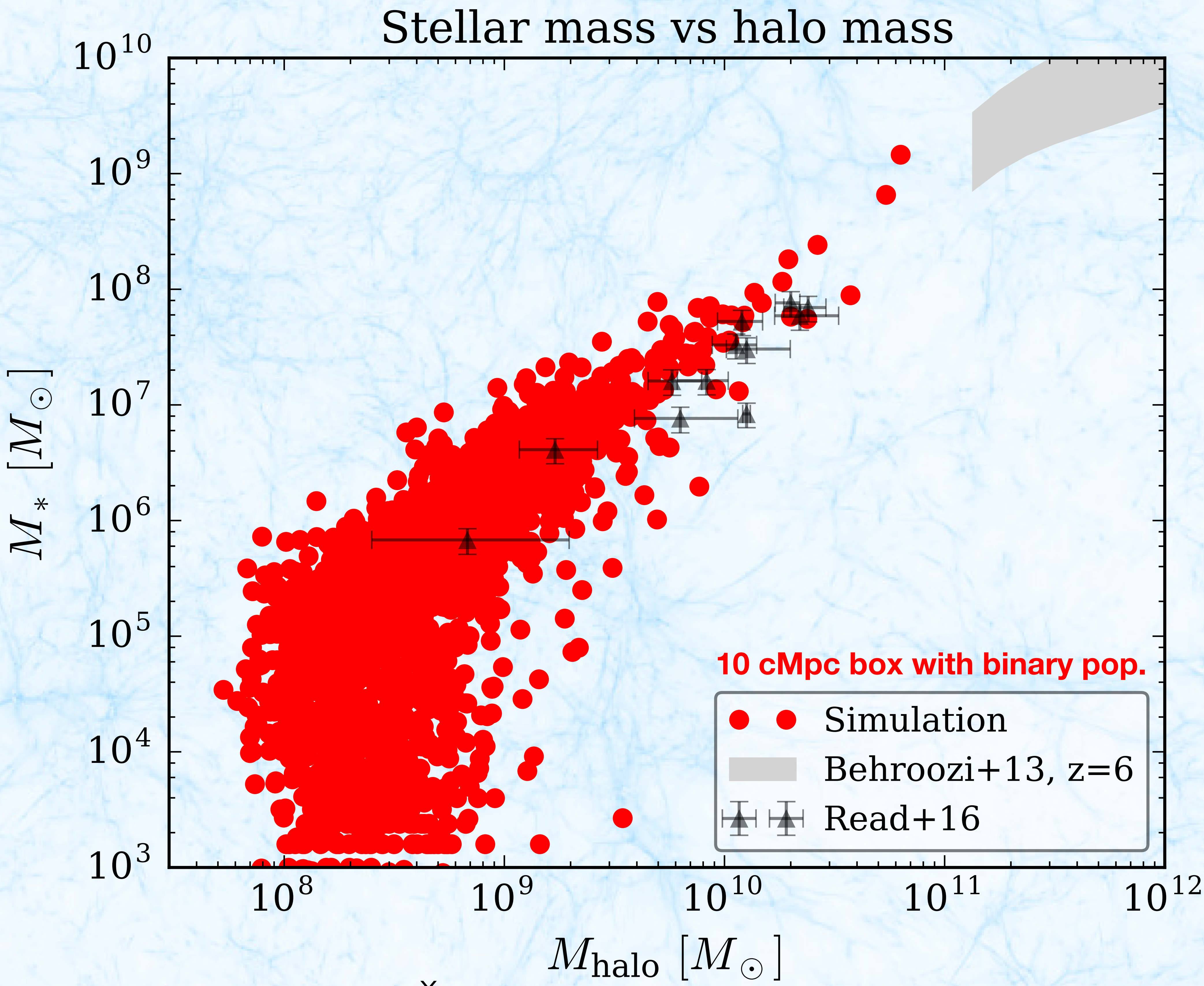


The agreement with observations is thanks to

- **Strong supernova feedback**
- **Careful selection of initial conditions to minimise cosmic variance**

x

Stellar mass to halo mass



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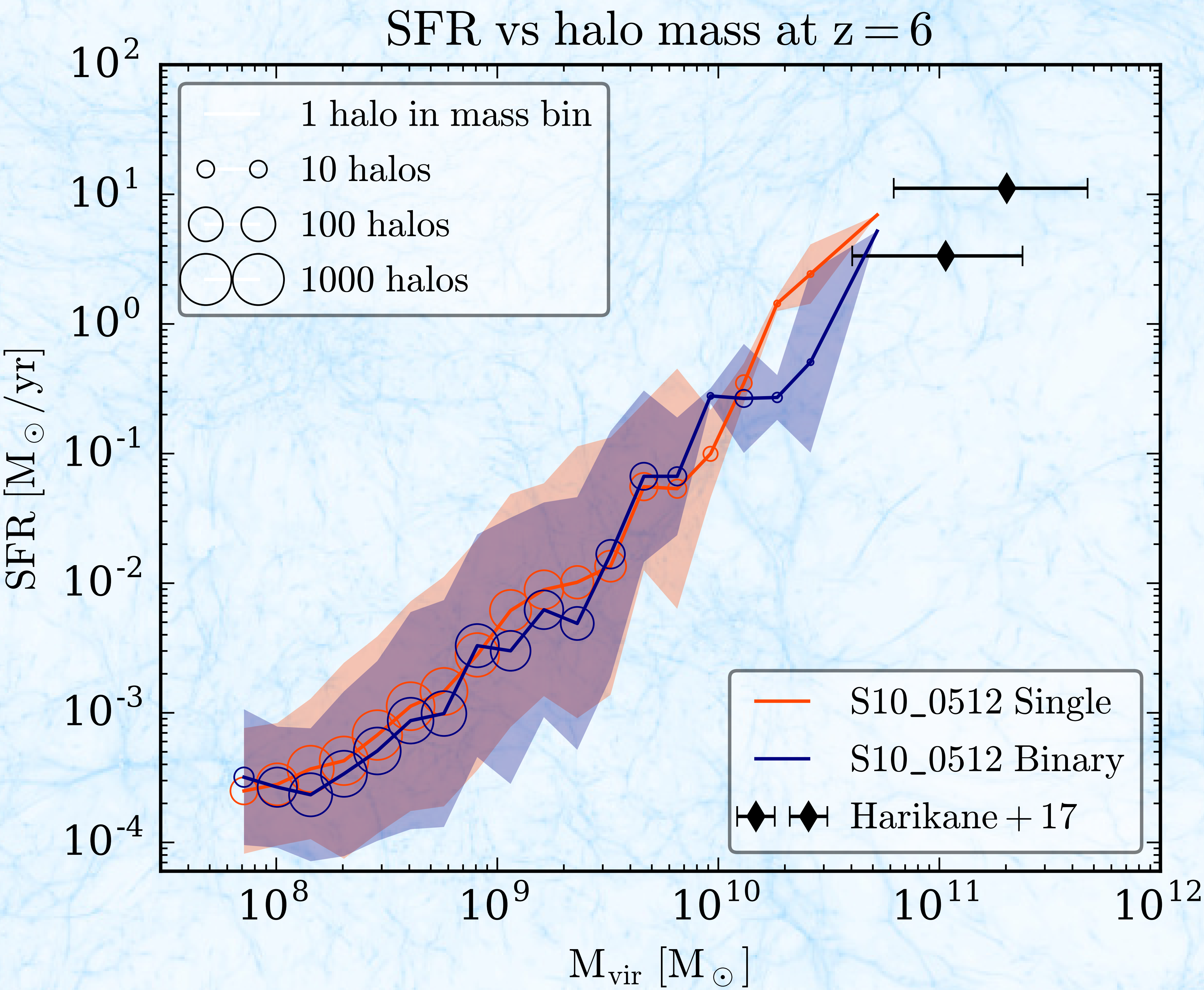

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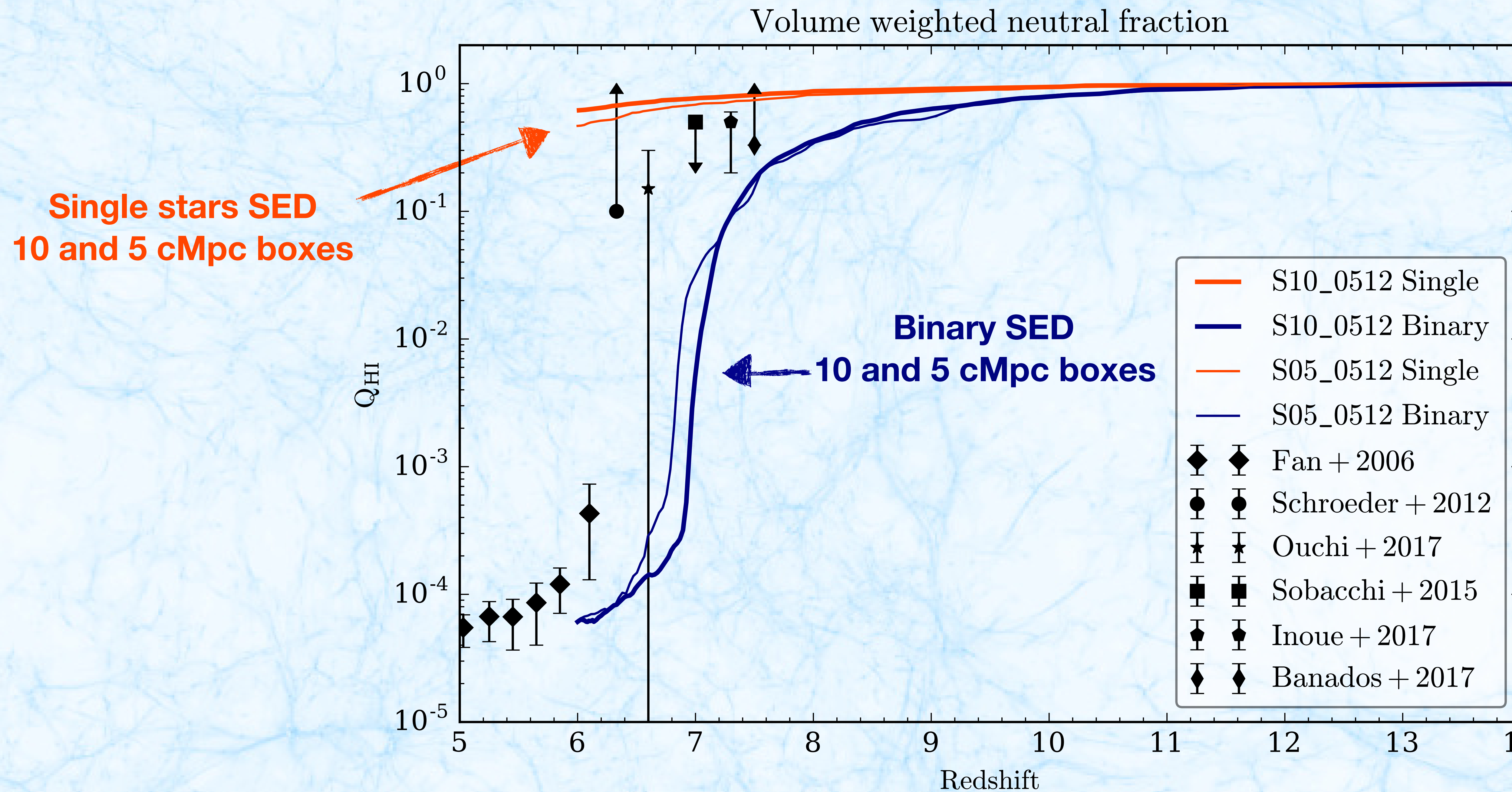
Reionisation history

binary vs single SEDs

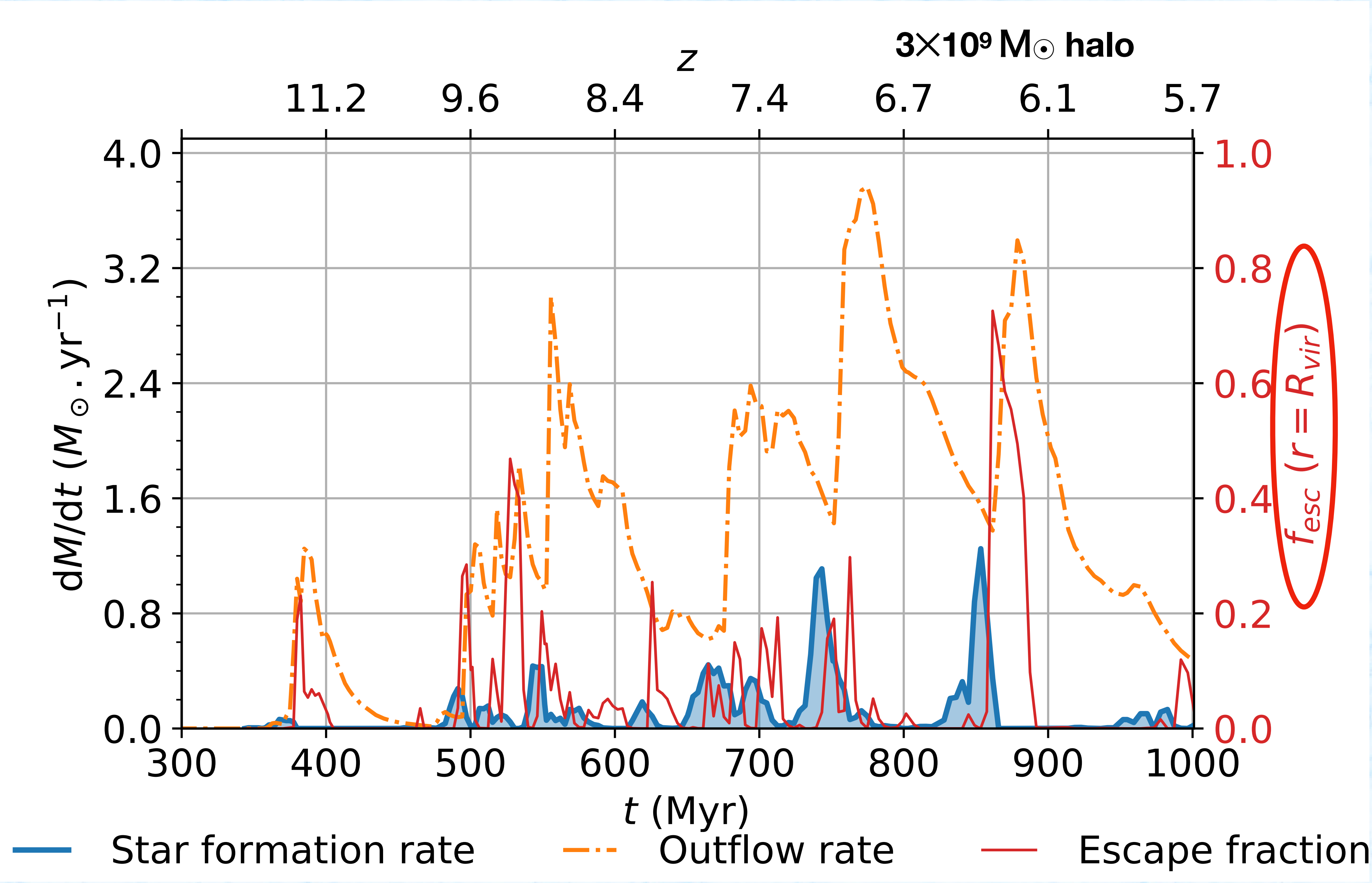


Much more efficient reionisation with binary populations, independent of volume size and mass resolution

x

The interplay of feedback and f_{esc}

I have not yet analysed the evolution of the escape fraction, but it looks a lot like our zoom simulations from Trebitsch et al (2017)

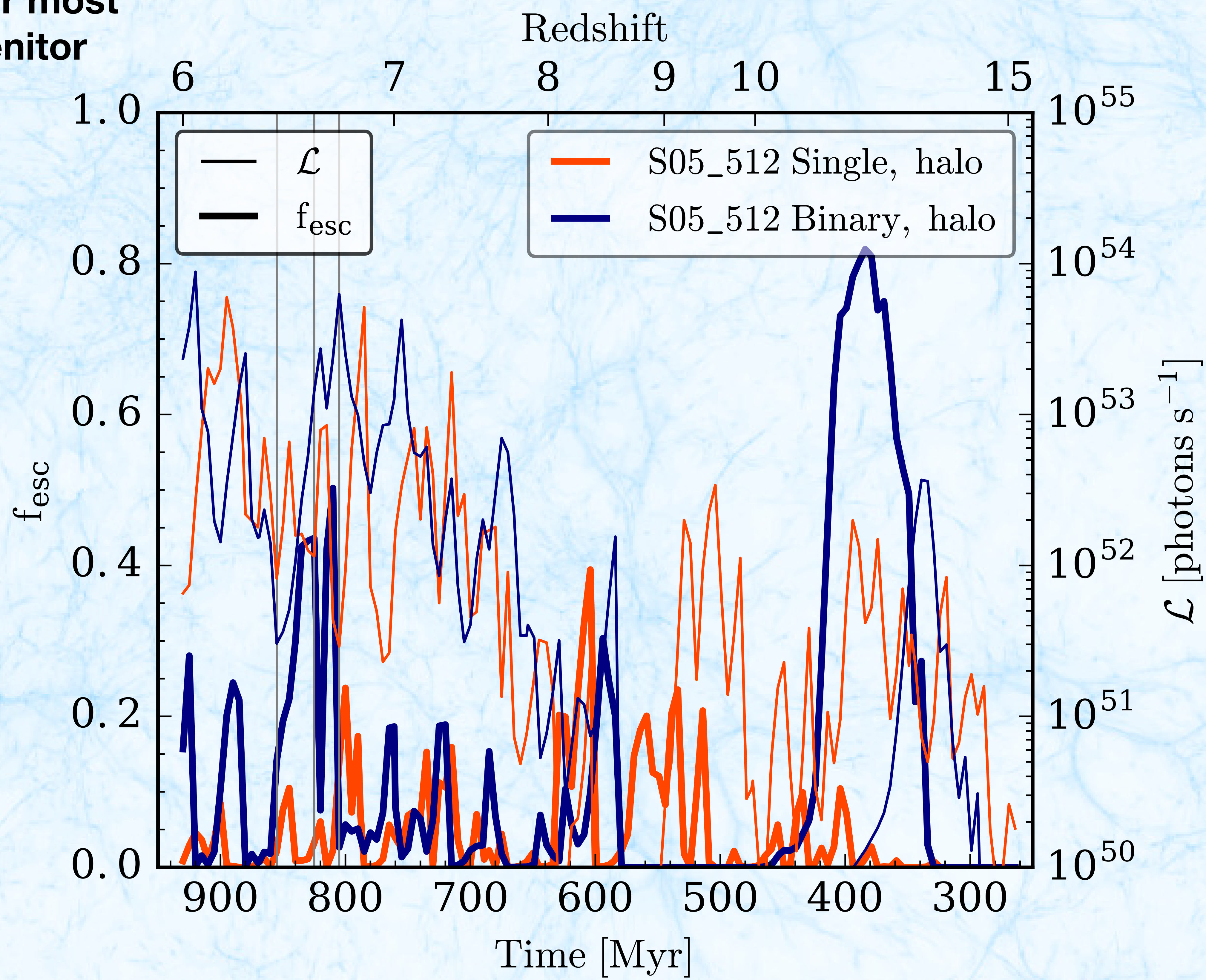


x

The interplay of feedback and f_{esc}

Escape fractions for most massive halo progenitor in smaller box

$M_{halo}(z=6) \sim 10^{10}\ M_{\odot}$
$M_{star}(z=6) \sim 10^{8}\ M_{\odot}$



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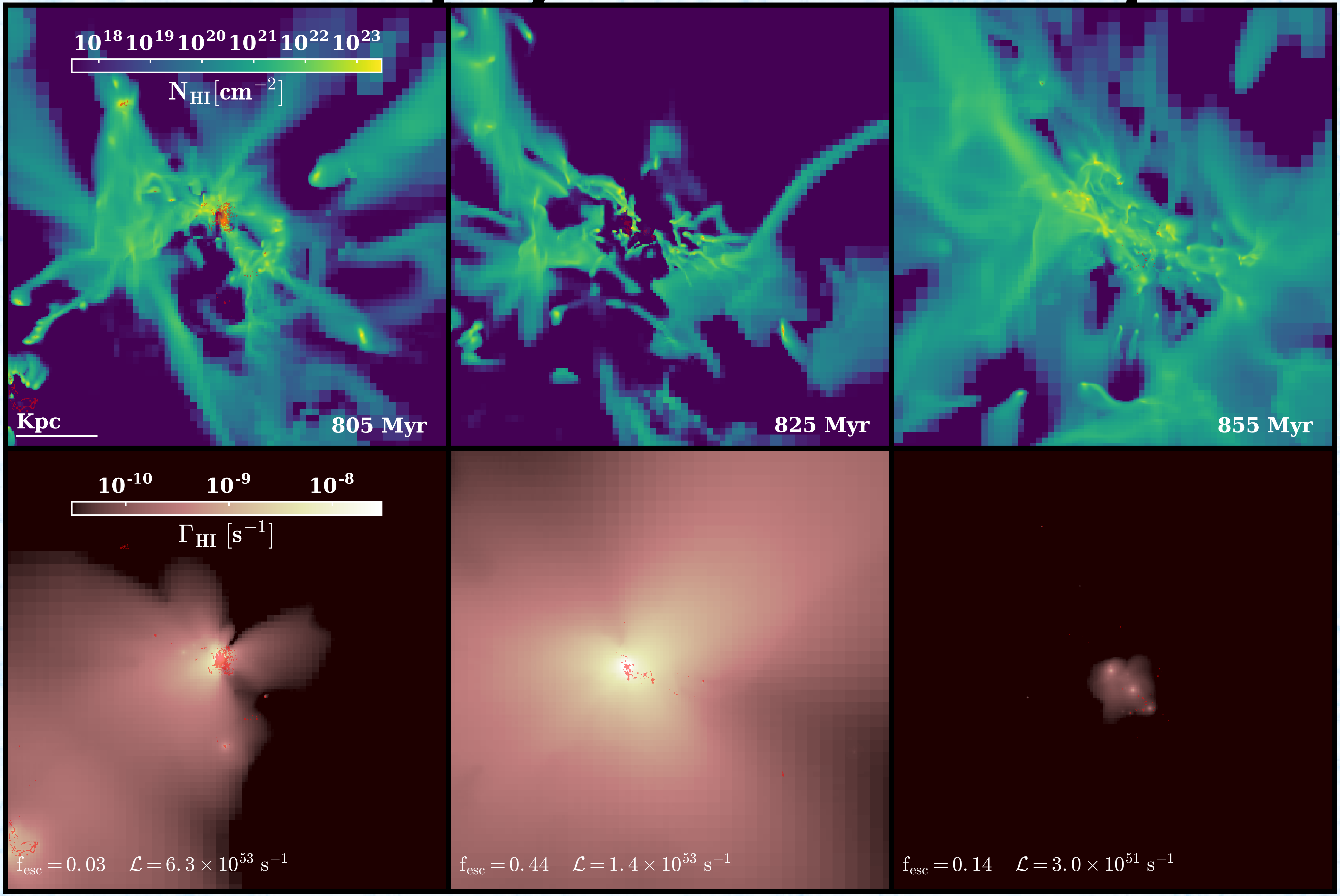
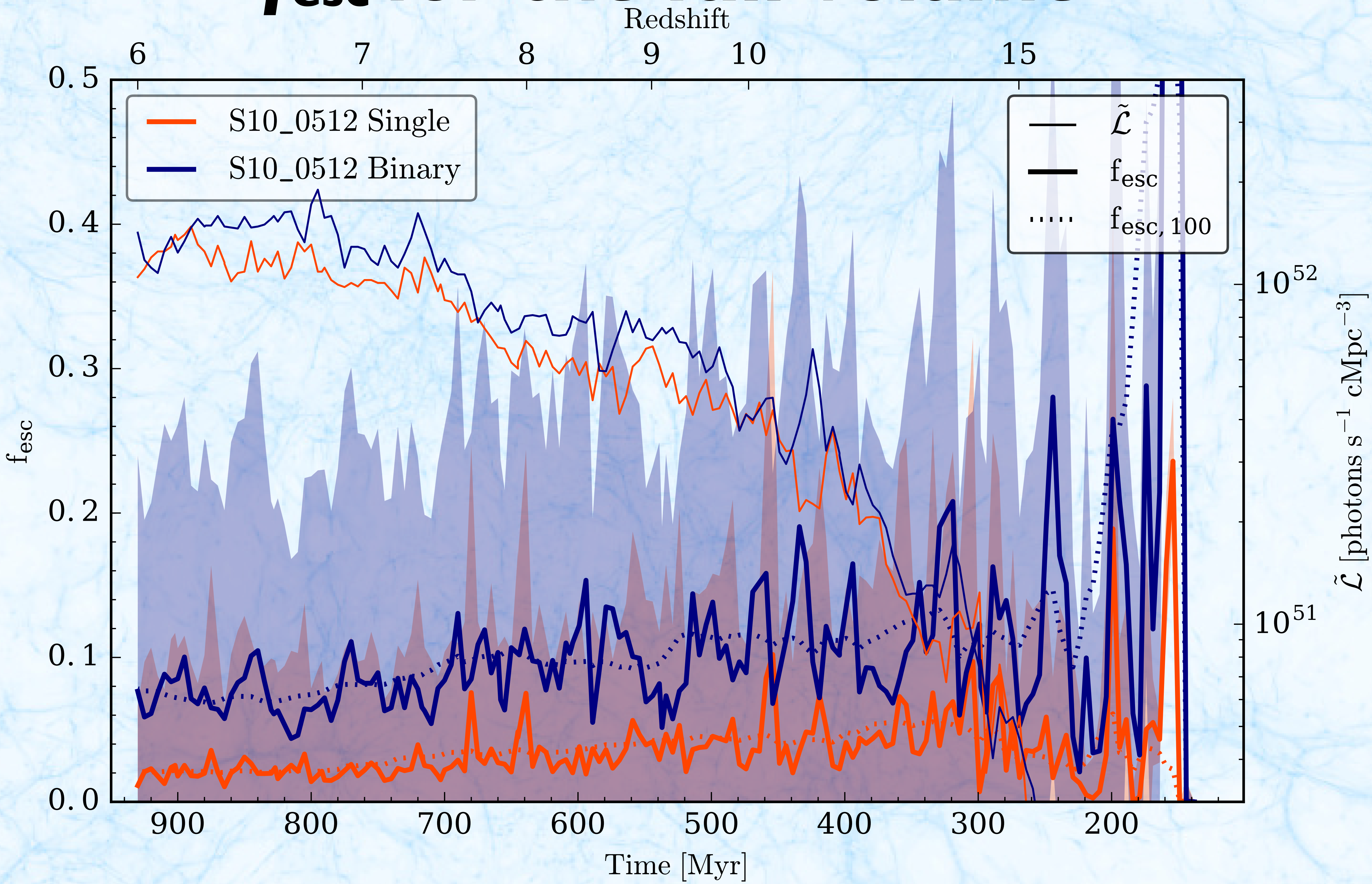
The interplay of feedback and f_{esc}



f_{esc} for the full volume

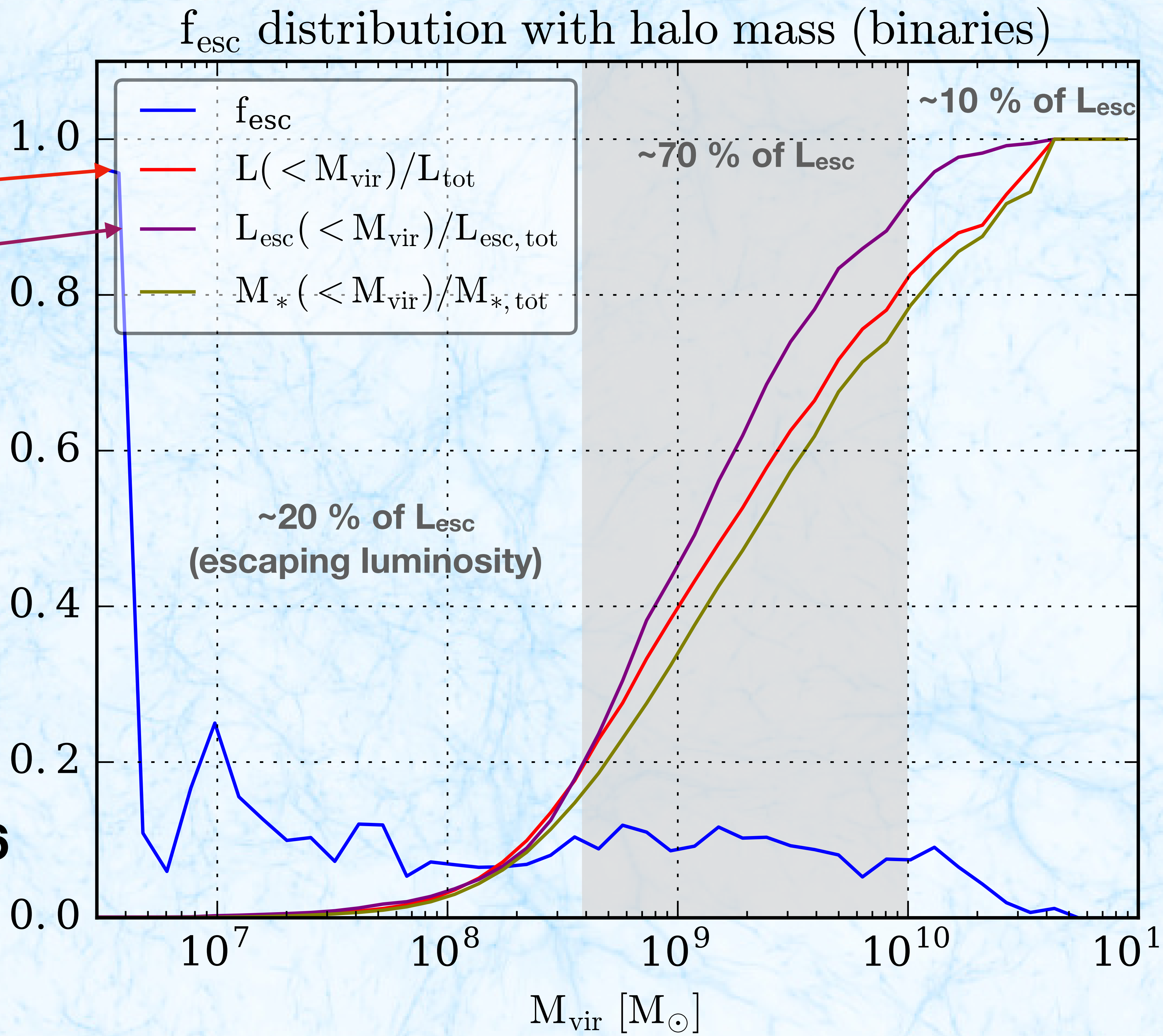


Escape fractions are systematically higher with binary stars !
Luminosities are somewhat higher too.

f_{esc} vs halo mass (with binaries)

Ionising luminosity

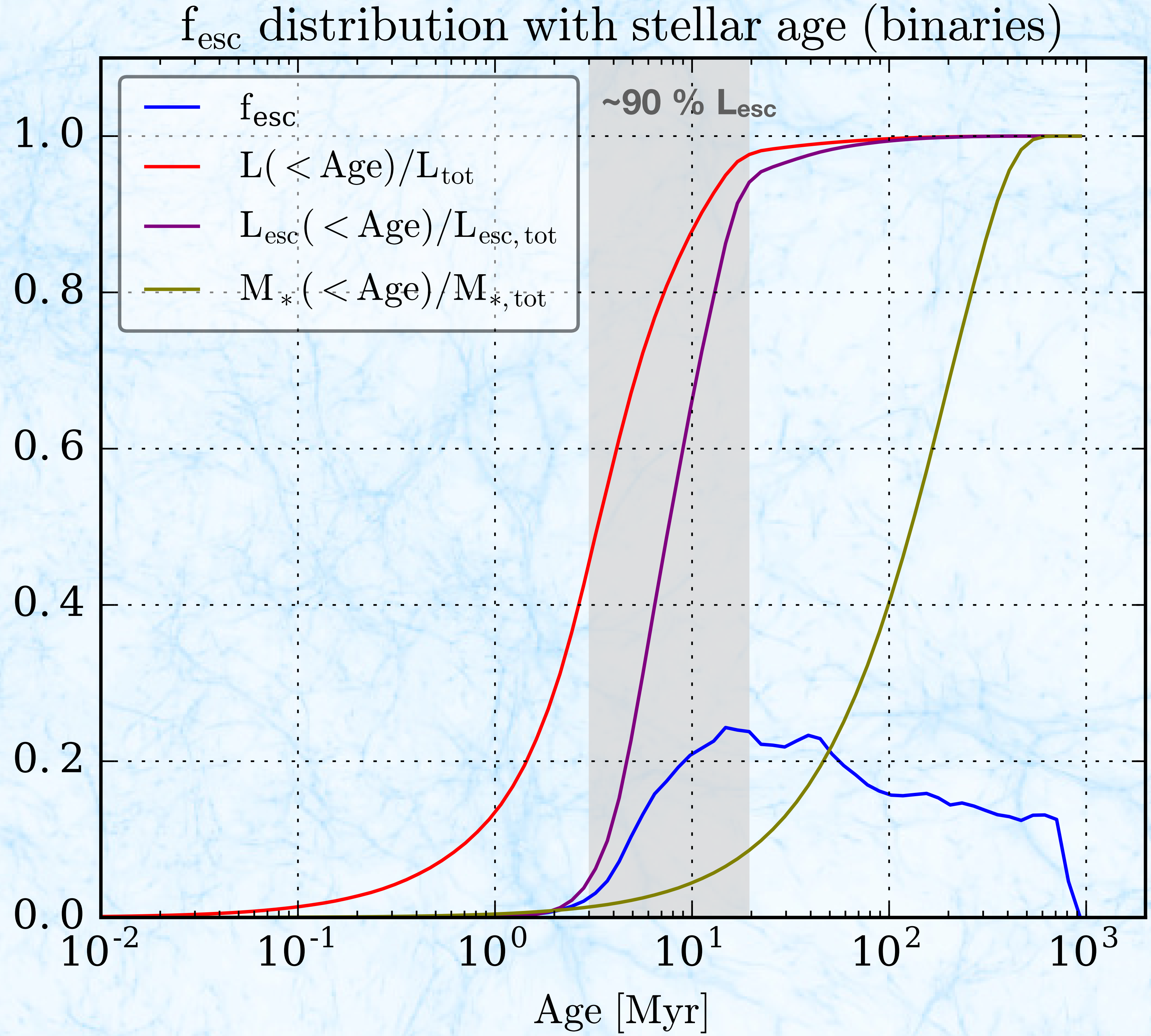
Escaping ionising luminosity



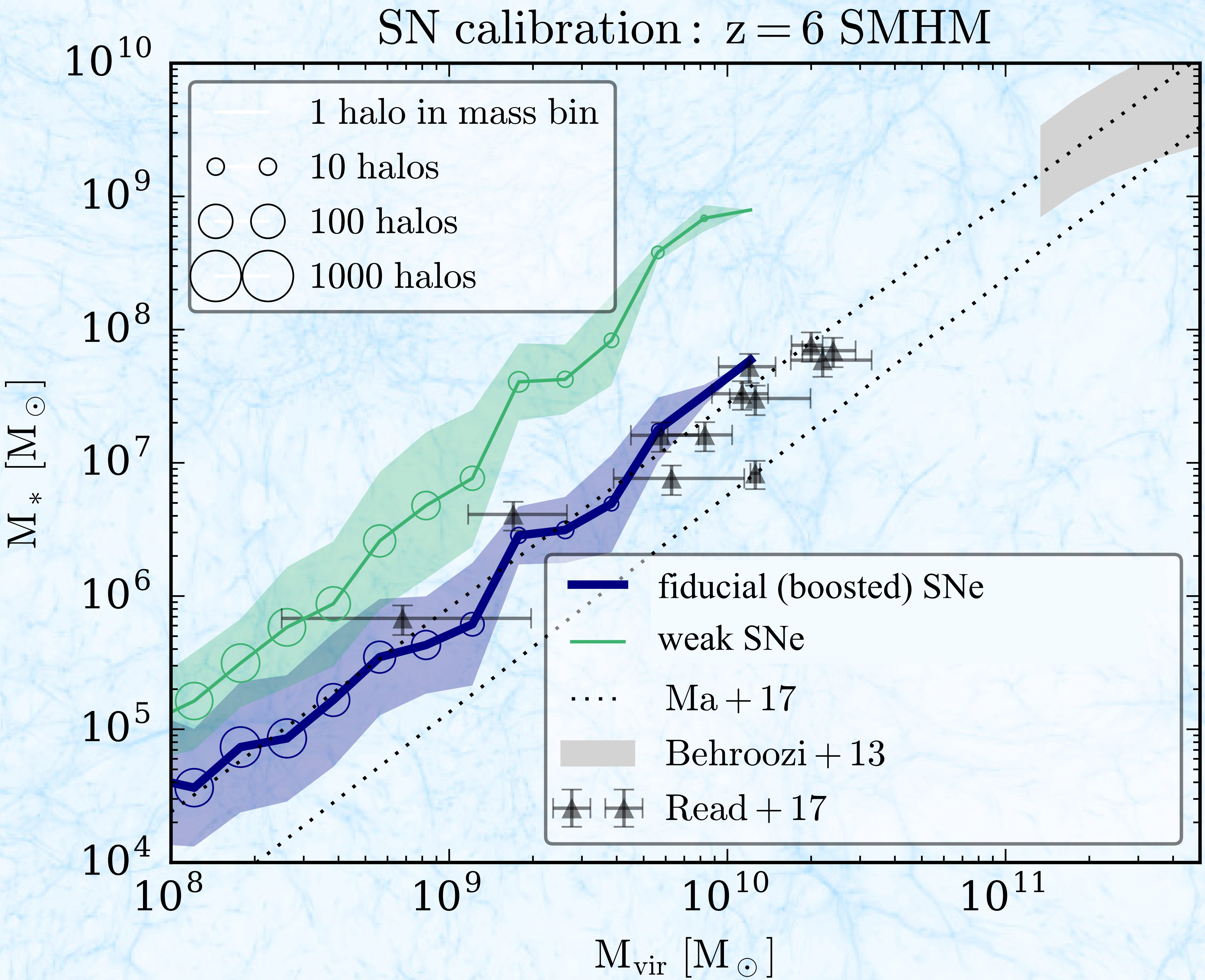
- Stacked data for z=9-6
- f_{esc} drops for $M_{halo} \gtrsim 10^{10}\ M_\odot$

f_{esc} vs stellar population age (with binaries)

- Stacked data for z=9-6
- 90% of escaping luminosity for 3-20 Myr

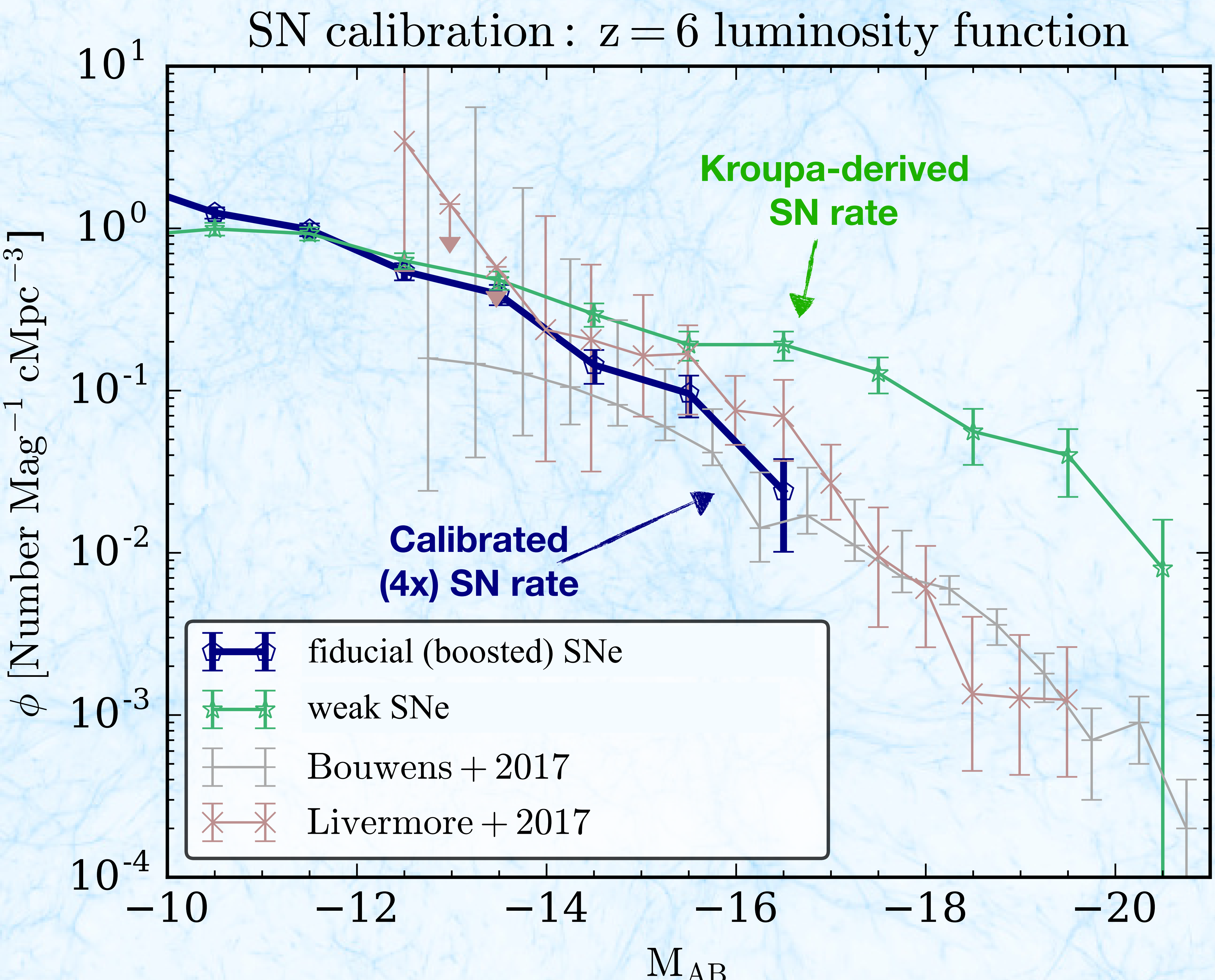


The need for SN calibration



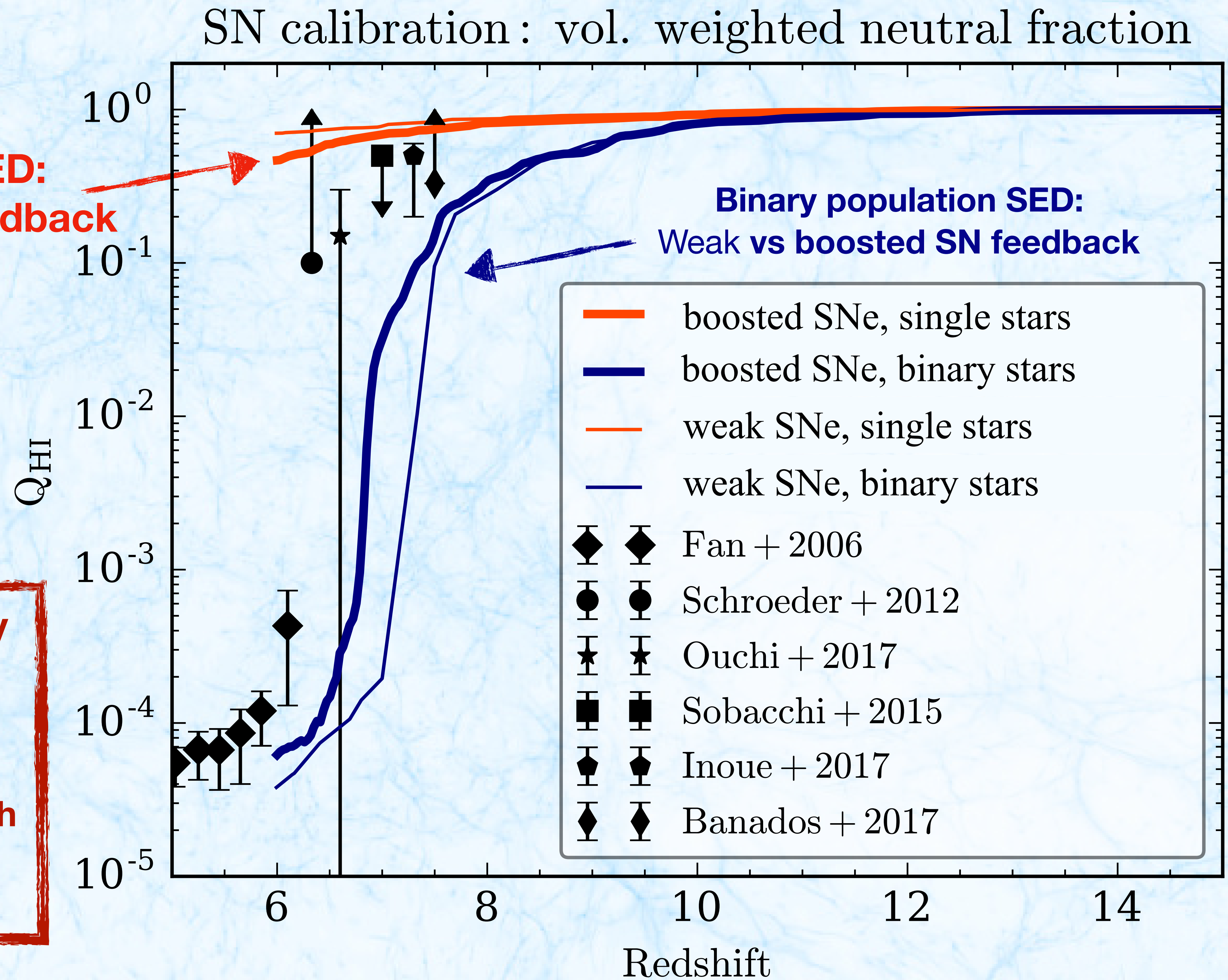
x

The need for SN calibration



Reionisation history

Single population SED:
Weak **vs boosted SN feedback**



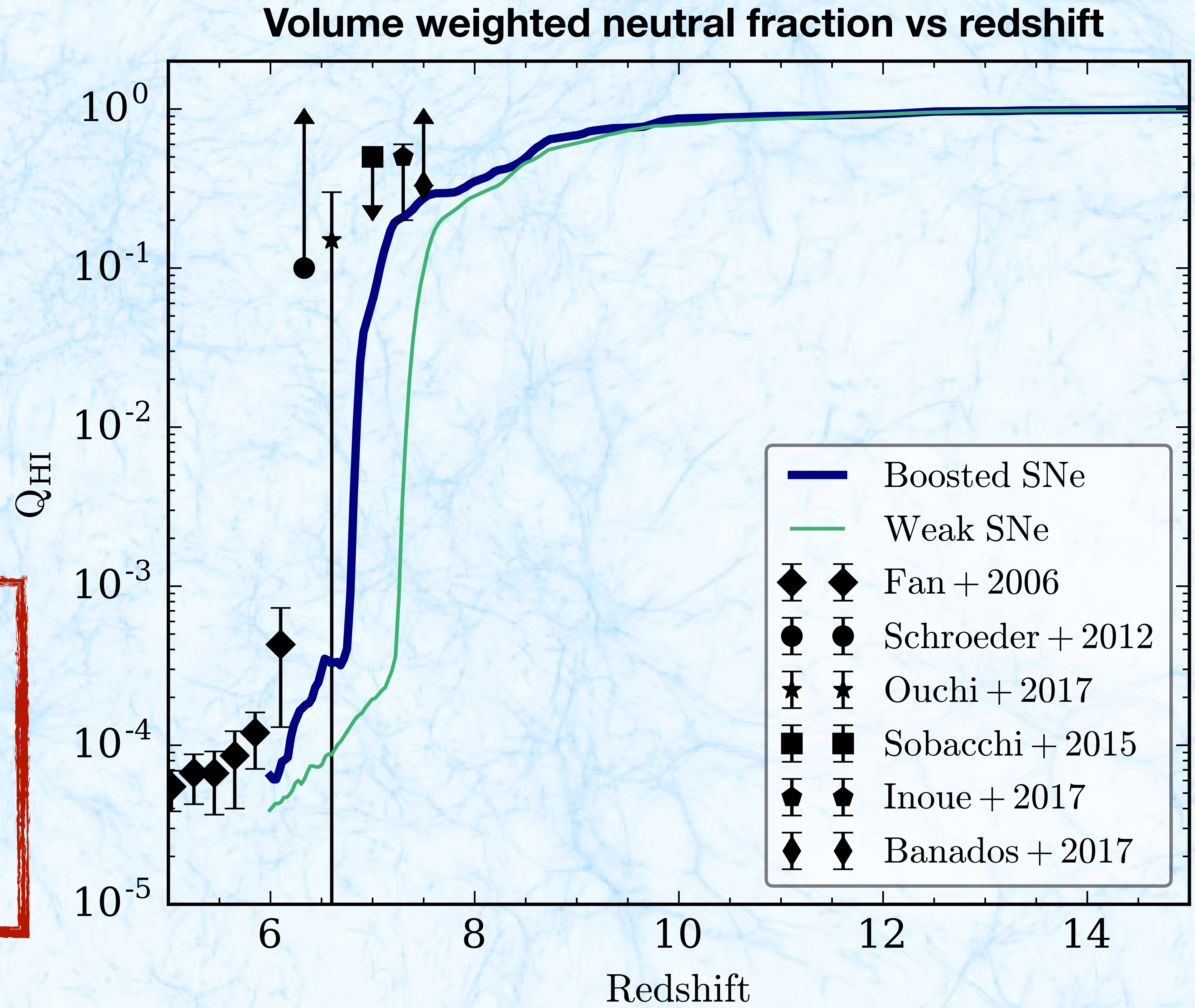
Binary population SED:
Weak **vs boosted SN feedback**

SN feedback efficiency doesn't affect reionisation much!

Surprising, given the much higher luminosities with weak feedback

x

Reionisation history



SN feedback efficiency does not affect reionisation much!

Surprising, given the much higher luminosities with weak feedback

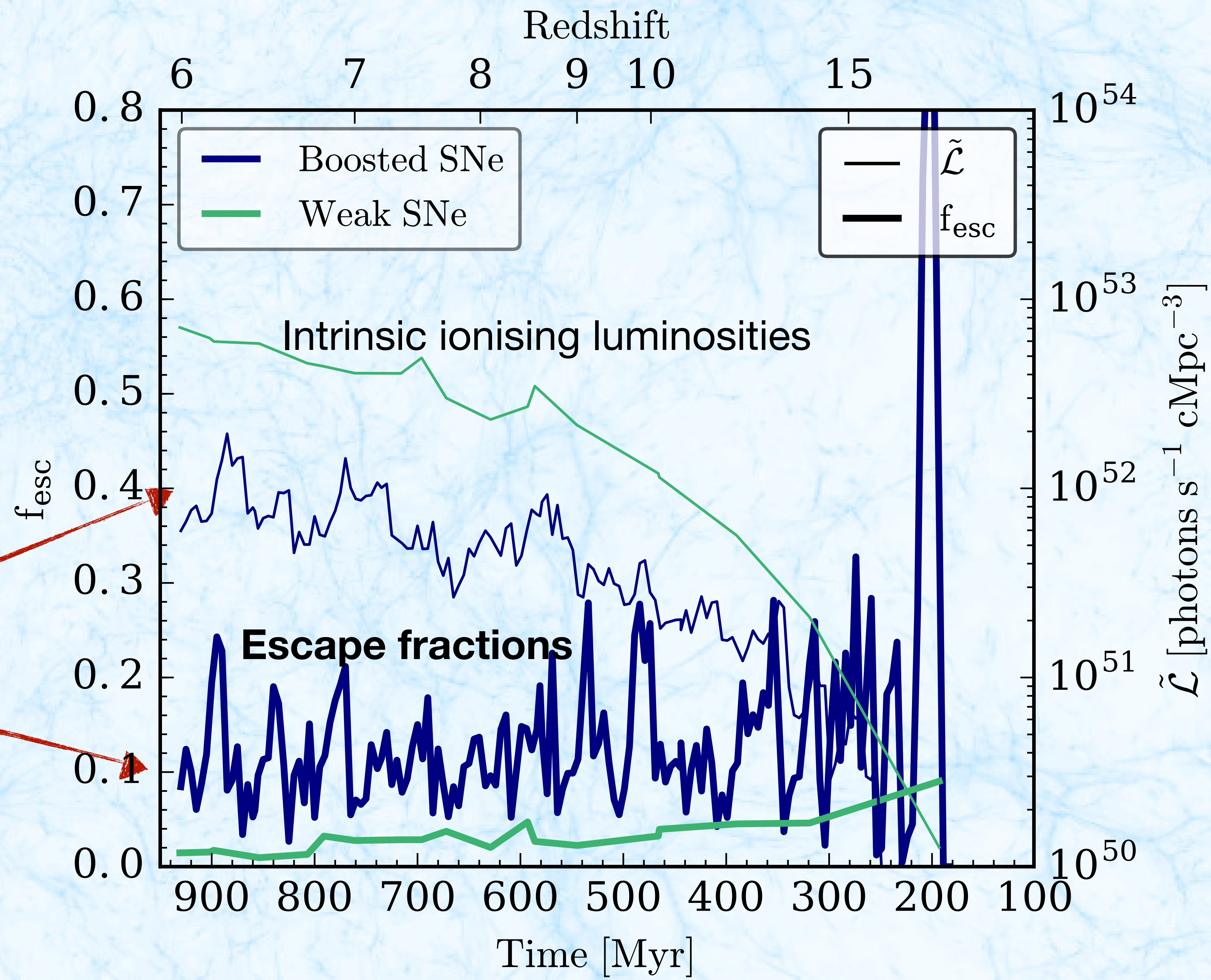
f_{esc} and feedback

fraction of ionising photons escaping from parent halo

Feedback efficiency does not affect reionisation much!

With strong feedback, lower luminosities are balanced by higher escape fractions

SN feedback helps the radiation get out

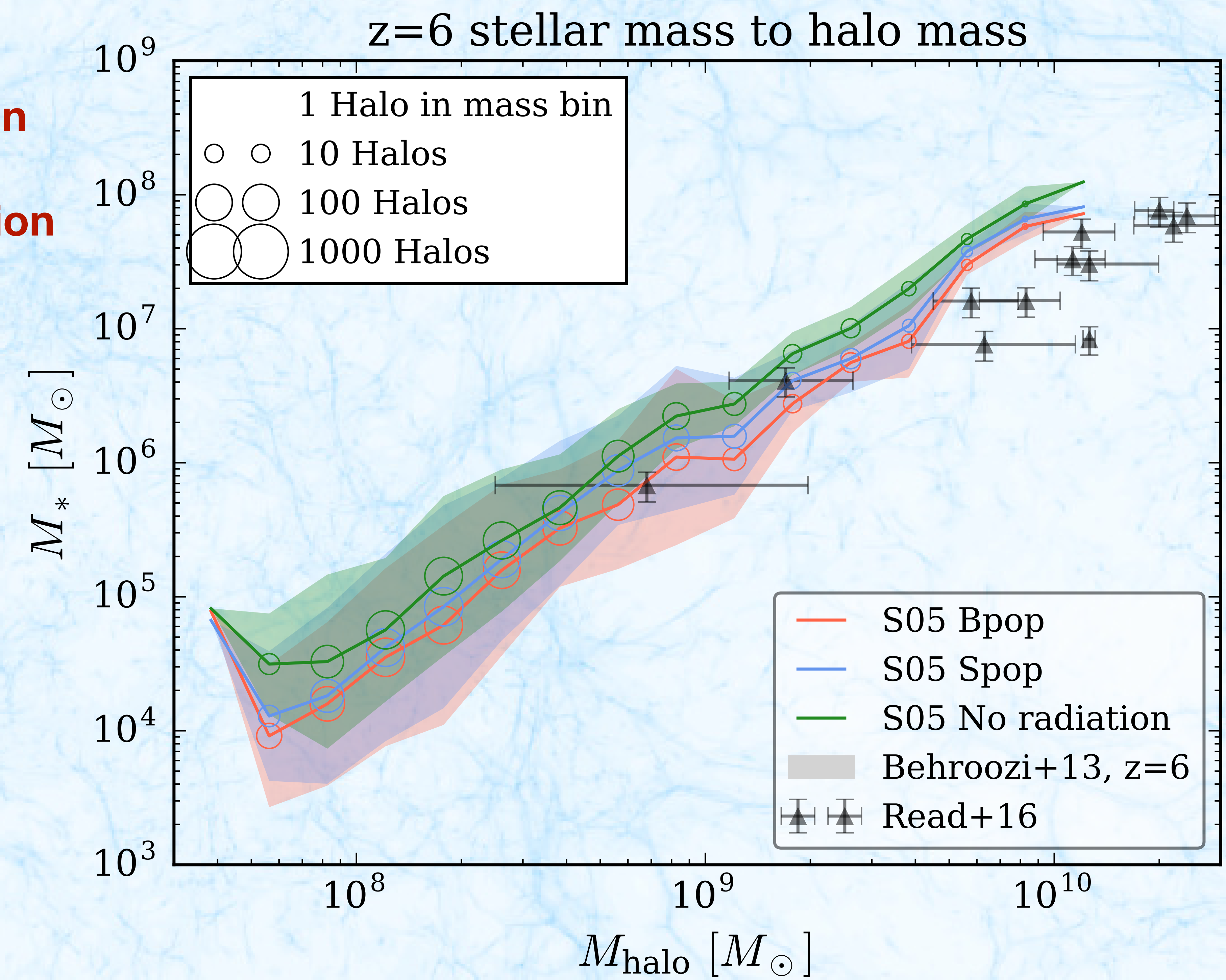


Radiation feedback

Radiation has a small effect in suppressing star formation

This is all from photoionisation

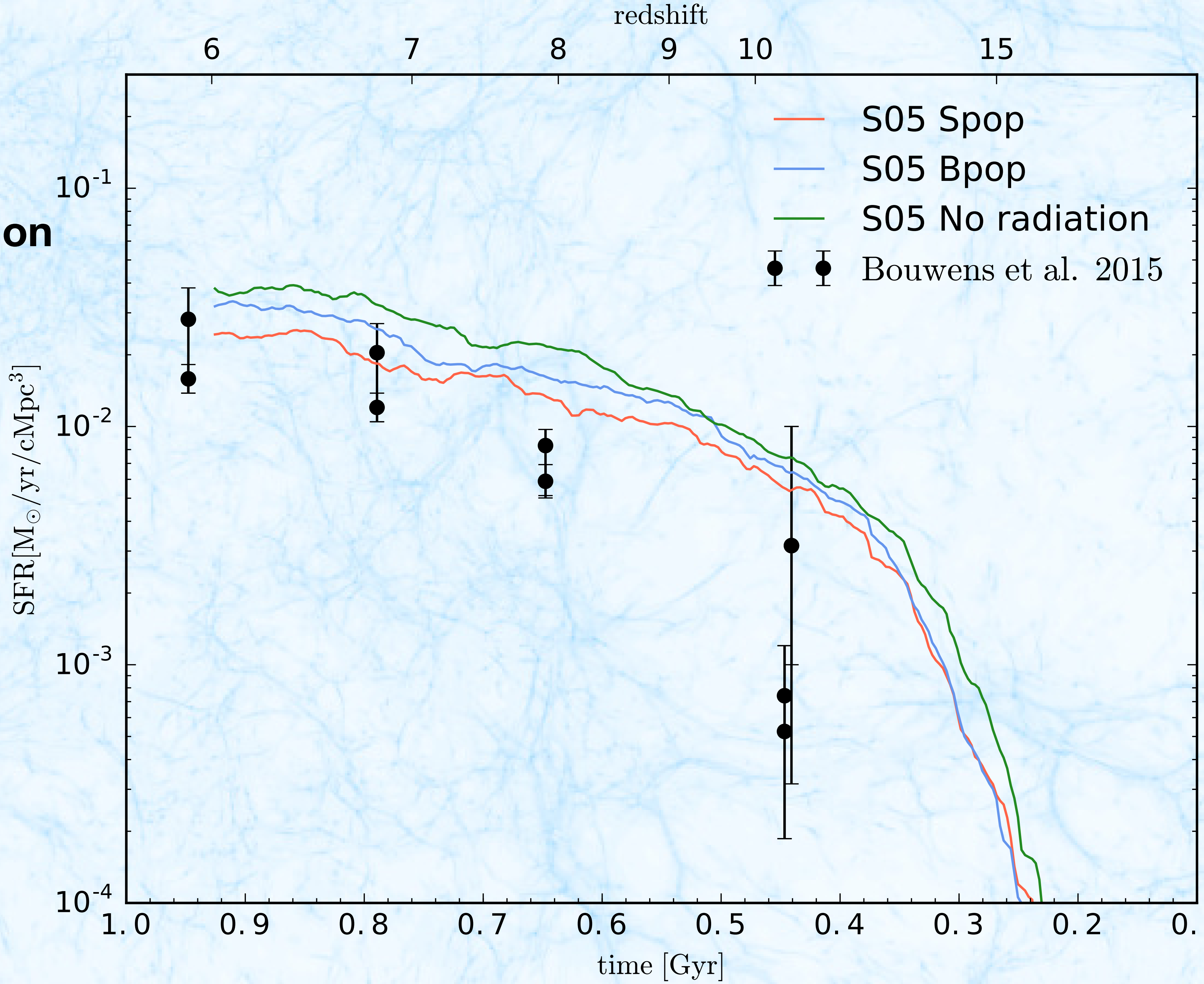
I ran a small-volume with IR radiation ➡ negligible effect



x

Radiation feedback

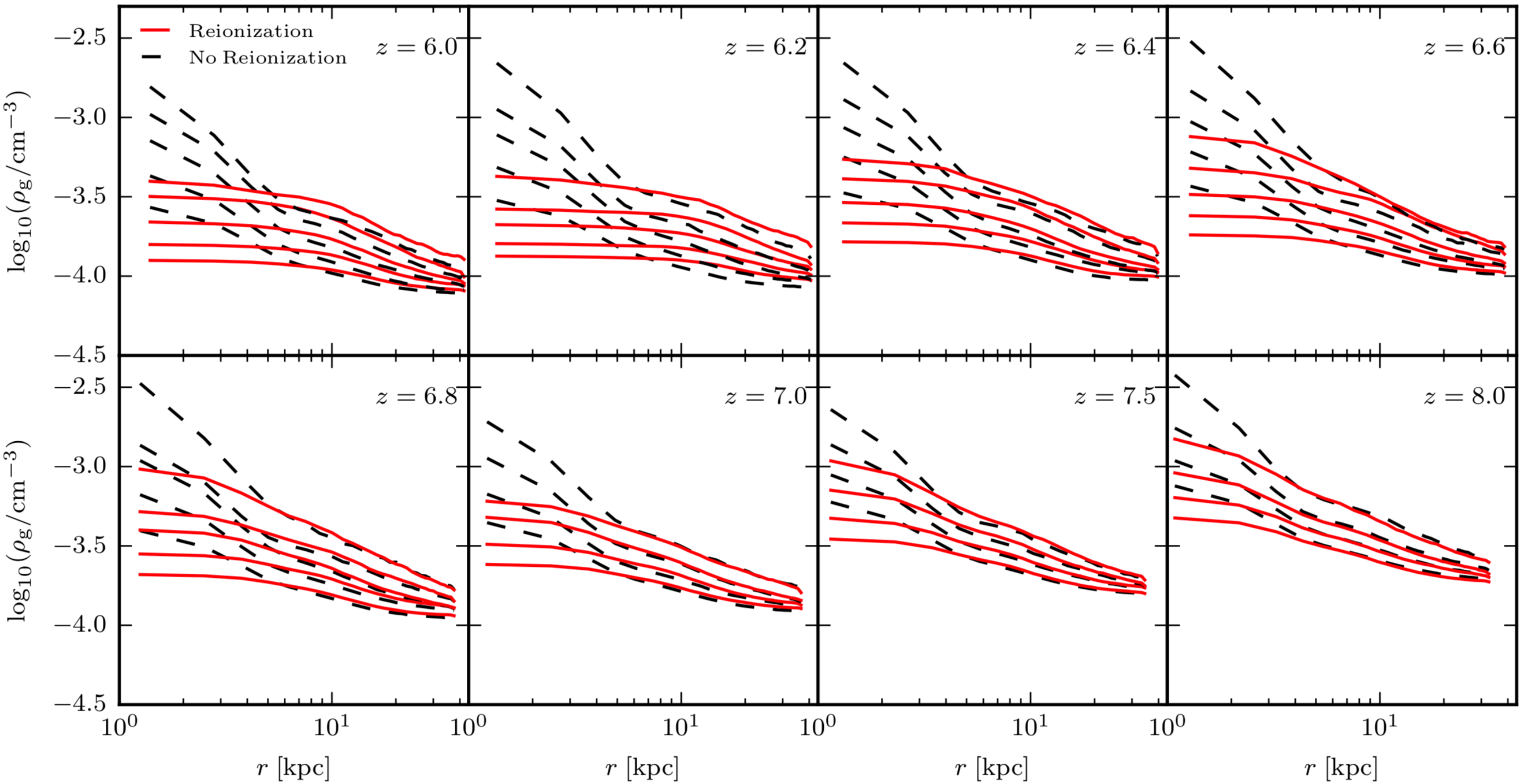
Radiation has some effect in suppressing star formation



x

Reionisation feedback

From upcoming paper by Harley Katz et al.:
Gas density profiles of IGM filaments with distance from central galaxies

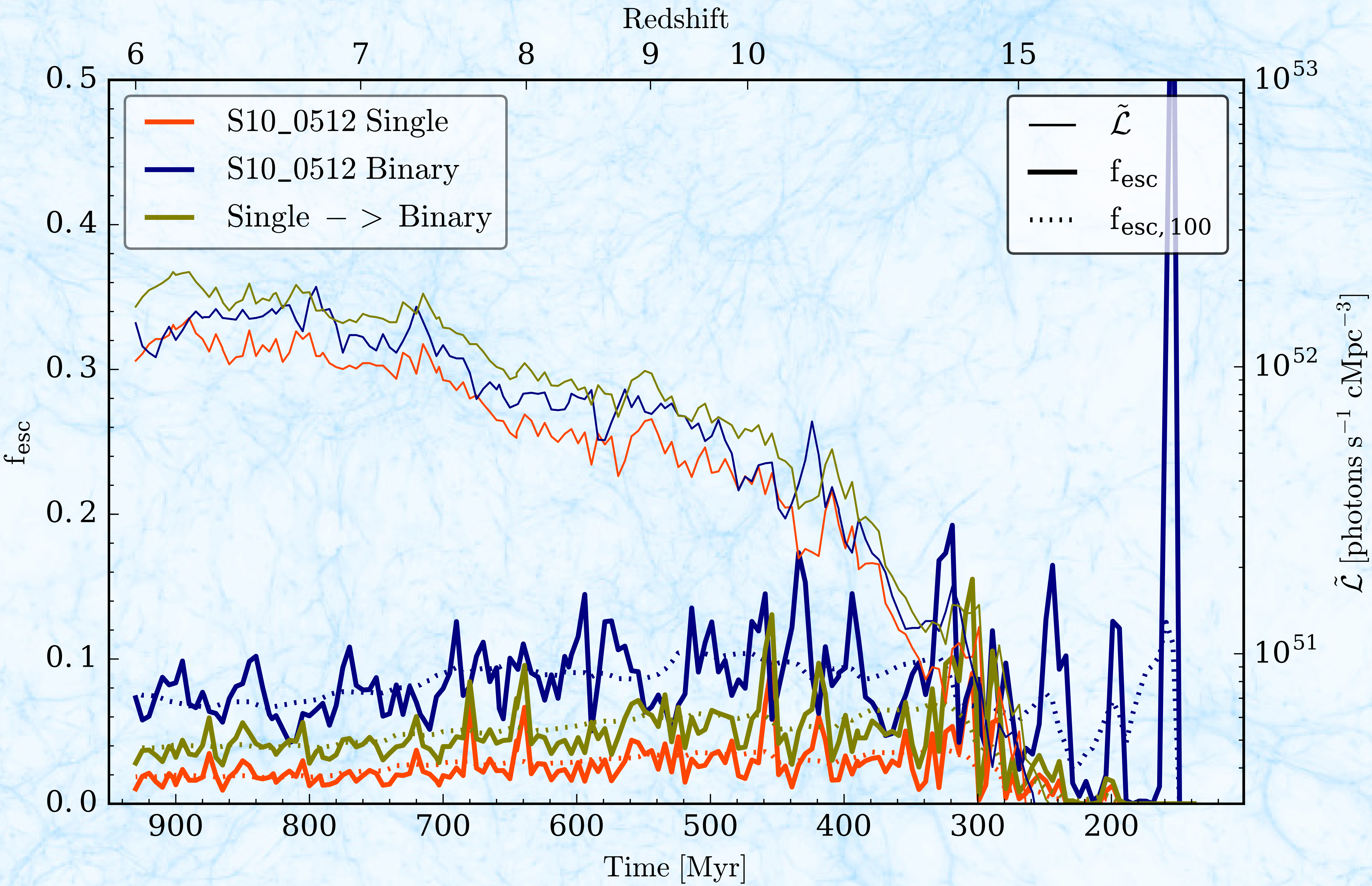


Reionisation suppresses (dwarf) galaxy growth by shutting down accretion

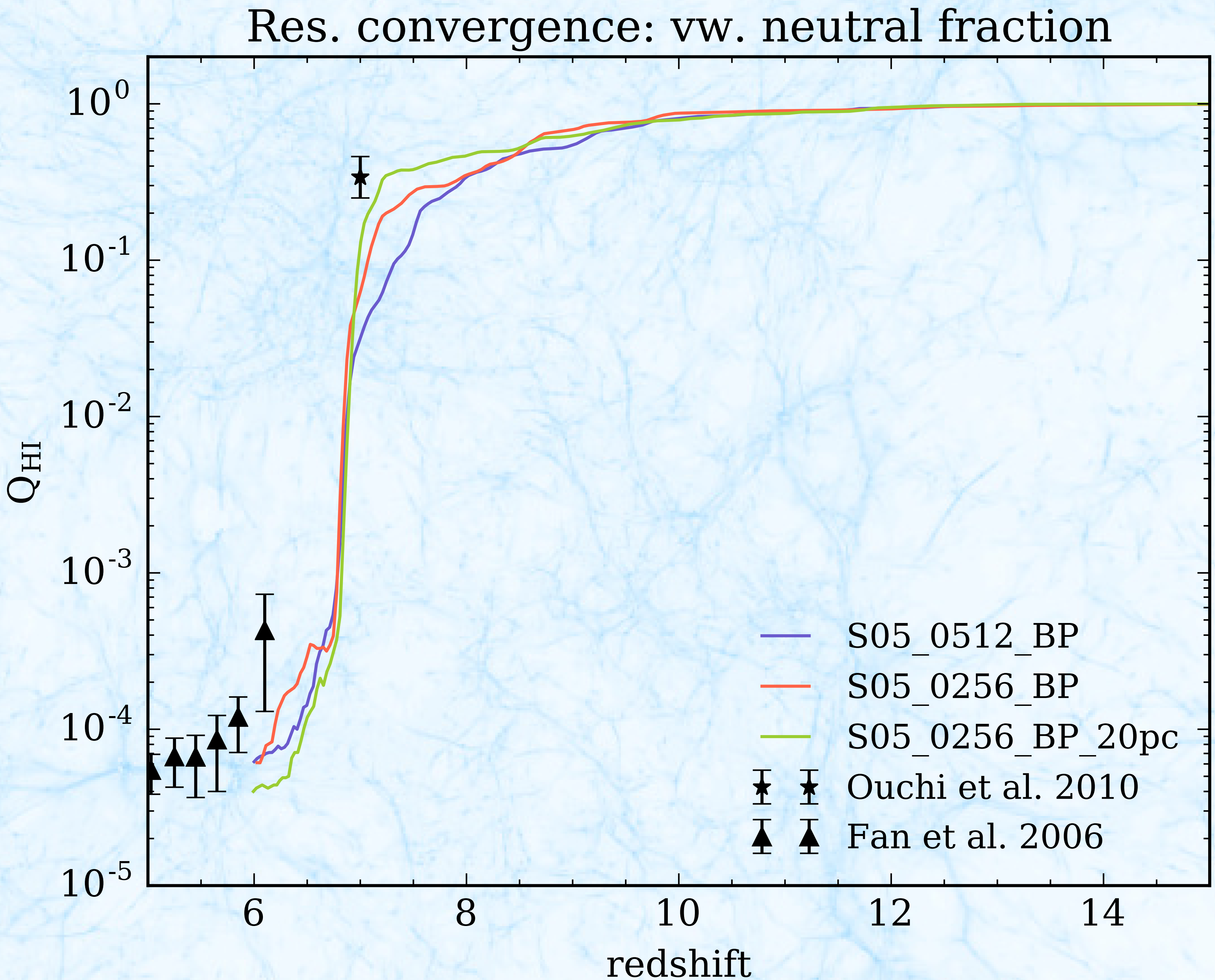
Summary

- **DRAMA isolated galaxy simulations**
  - IR radiation (still) not doing very much on the galactic scale
- **SPHINX reionisation simulations**
  - (SN) feedback suppresses intrinsic ionising luminosities of galaxies
  - But it also boosts the escape of the ionising radiation

➡Reionisation history is insensitive to SN feedback strength
- But what about other feedback physics?
- What do e.g. Cosmic Rays do to f_{esc} ?

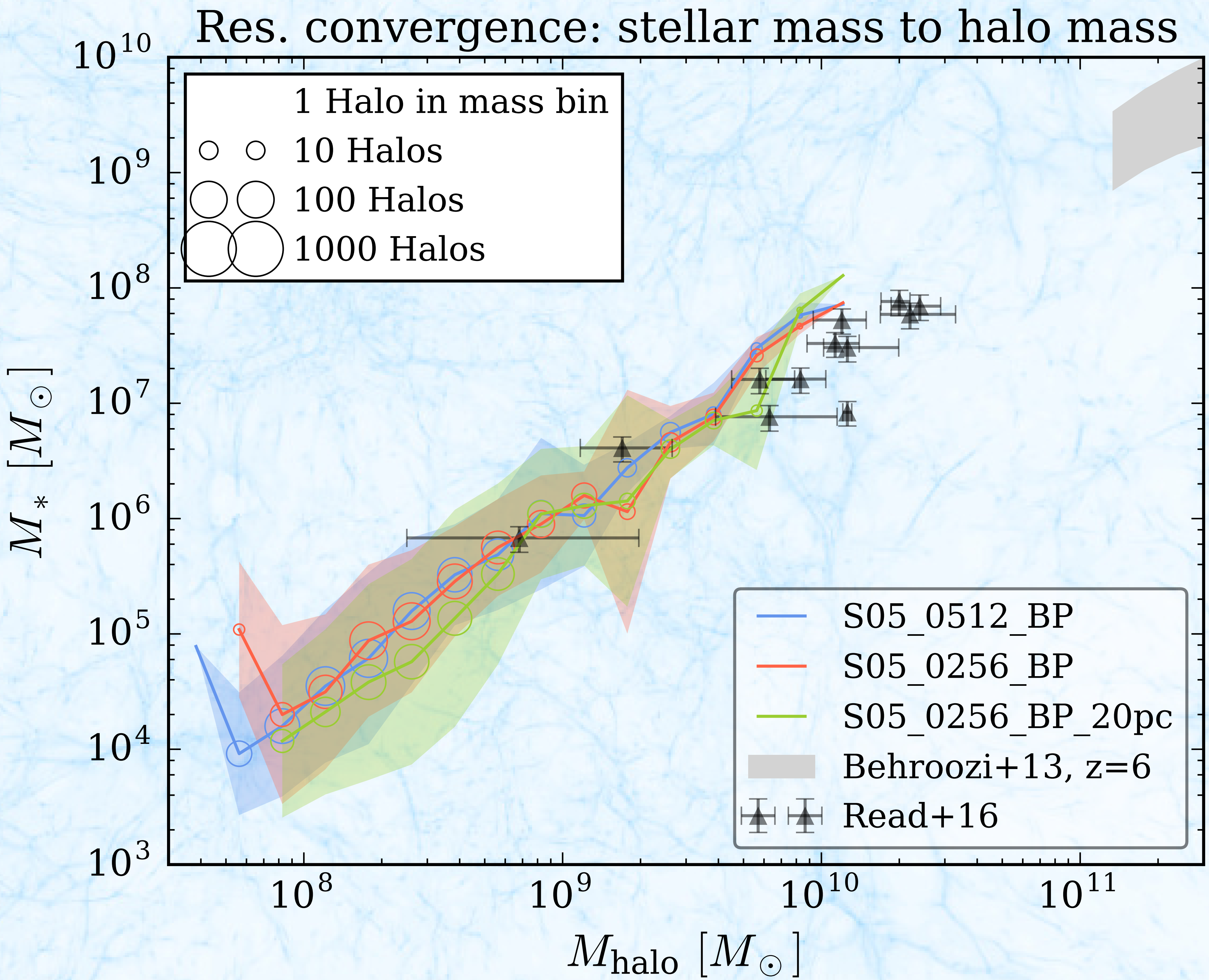

Redshift
6
7
8
9
10
15
0.5
0.4
0.3
0.2
0.1
0.0
10^{53}
10^{52}
10^{51}
S10_0512 Single
S10_0512 Binary
Single − > Binary
$\tilde{\mathcal{L}}$
f_{esc}
$f_{esc,\,100}$
f_{esc}
$\tilde{\mathcal{L}}$ [photons s^{-1} $cMpc^{-3}$]
900
800
700
600
500
400
300
200
Time [Myr]

Resolution convergence
reionisation history



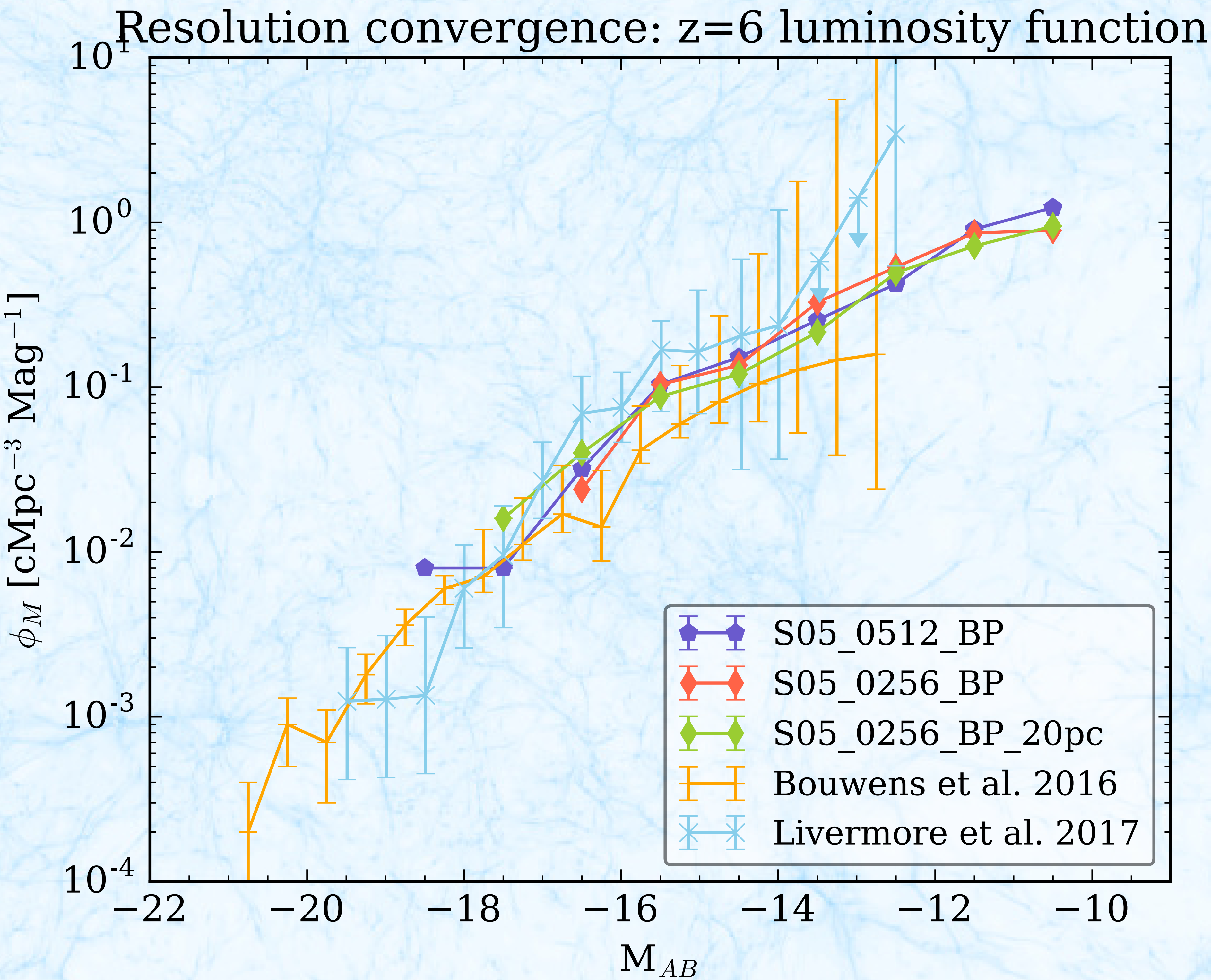
Resolution convergence

reionisation history

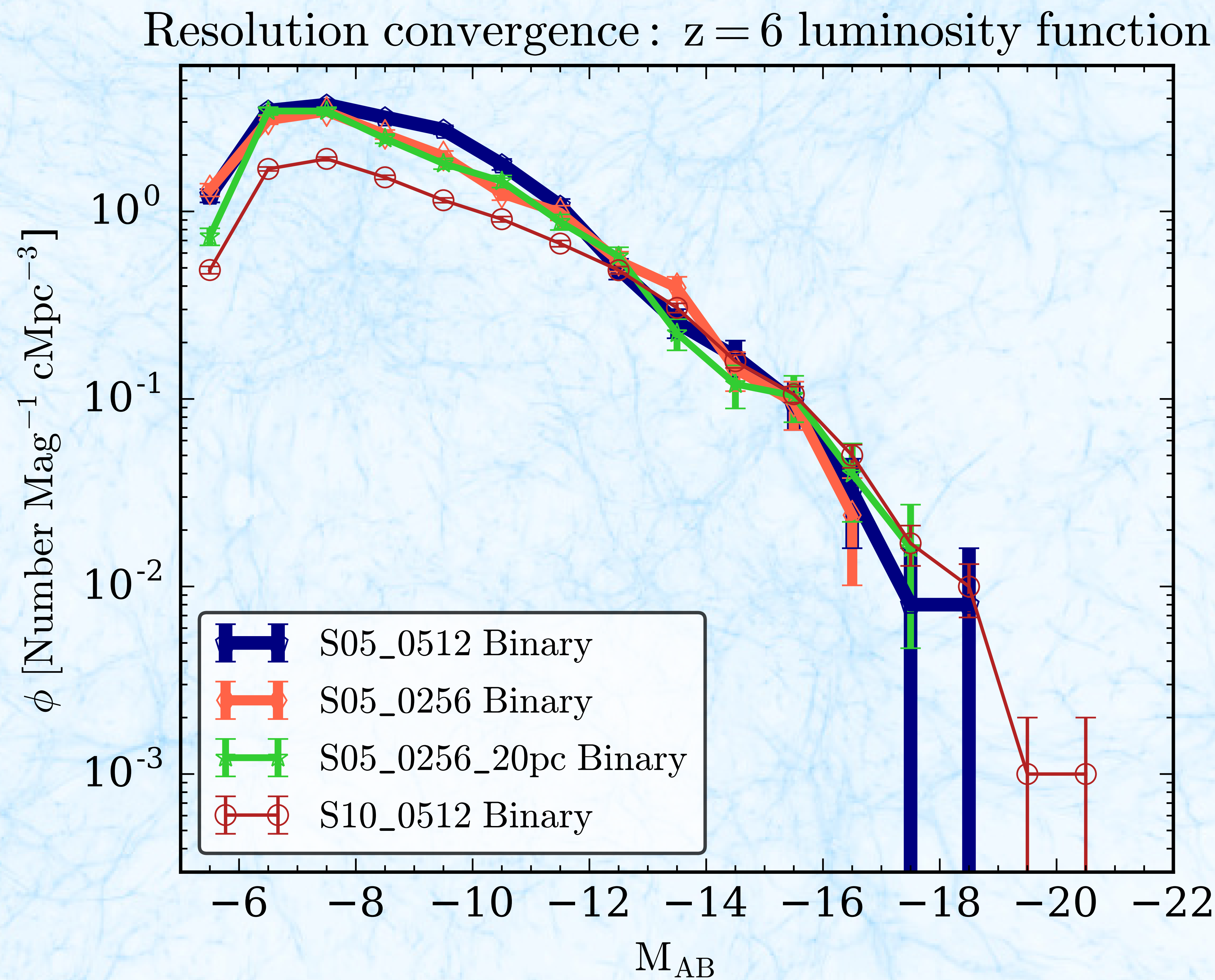


x

Resolution convergence
reionisation history



Resolution convergence



Resolution convergence
reionisation history