The SPHINX simulations of the first billion years and reionisation

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with

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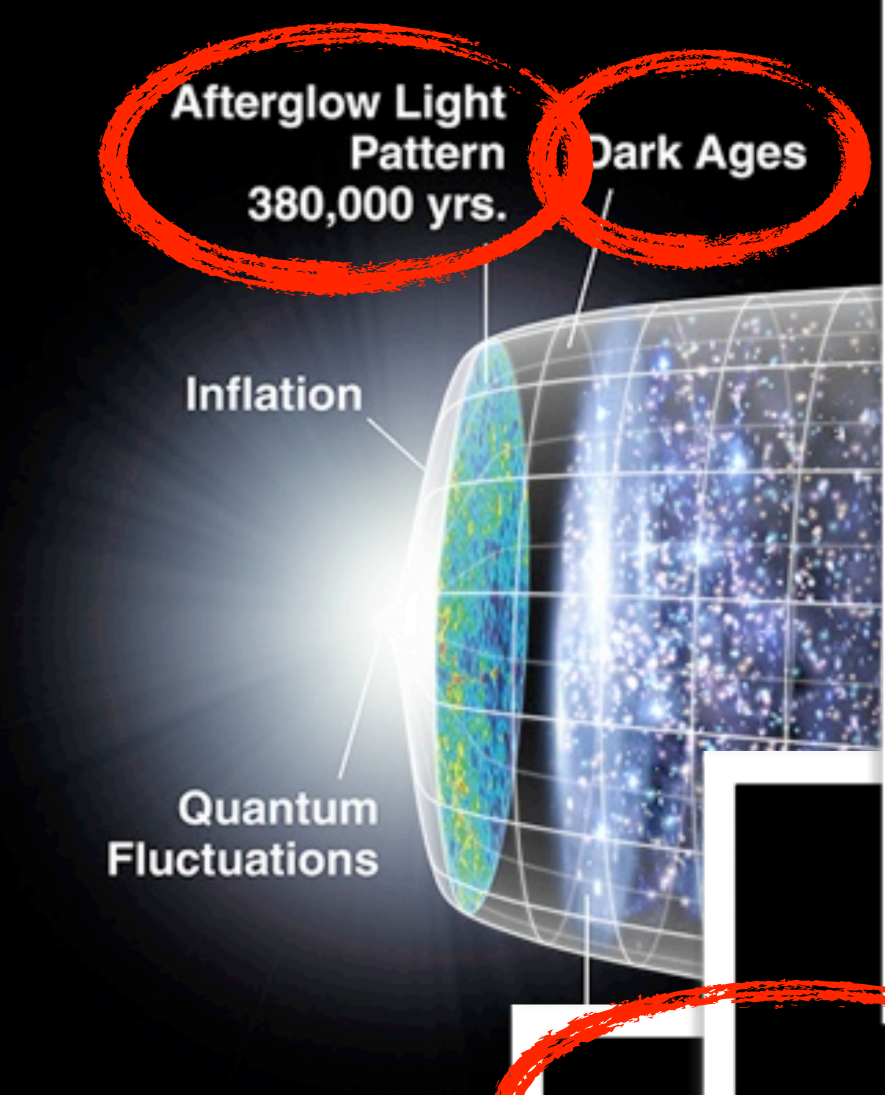
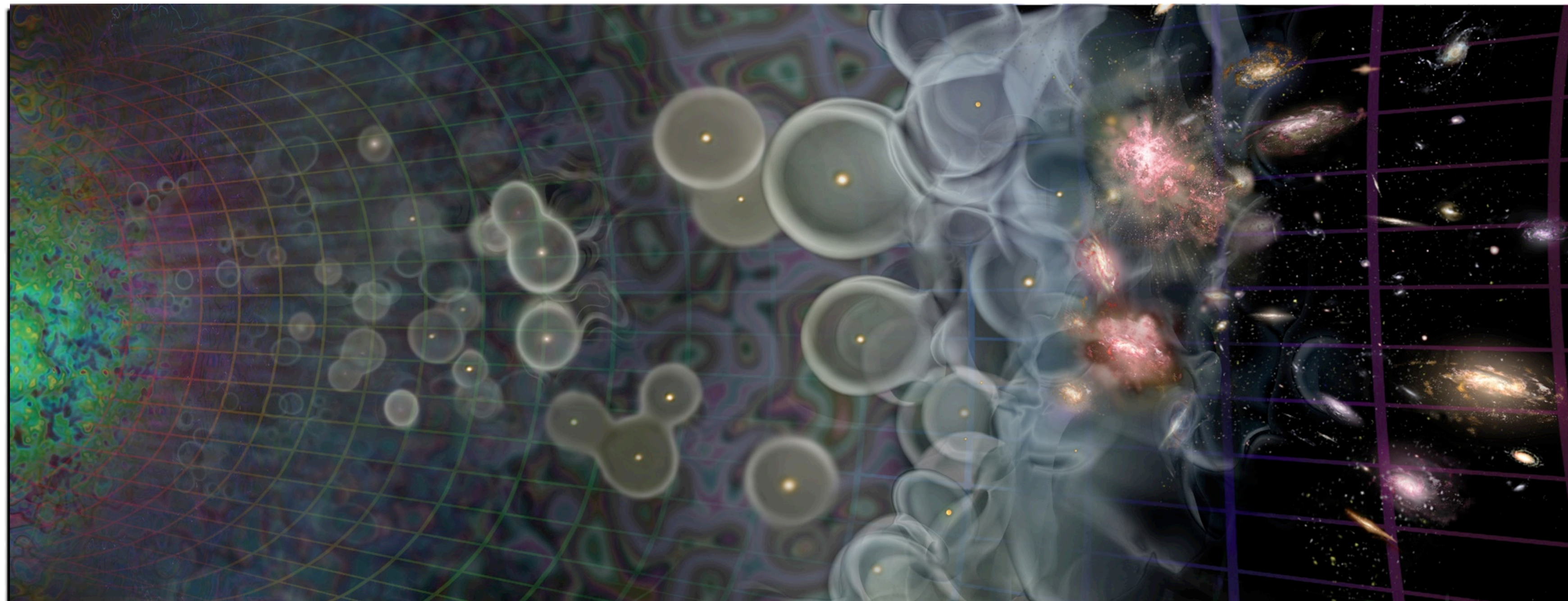
OCA Dec 5th 2017

Cosmological radiation-hydrodynamical simulations of reionisation to z=6, resolving the ISM of atomically cooling haloes

The first billion years

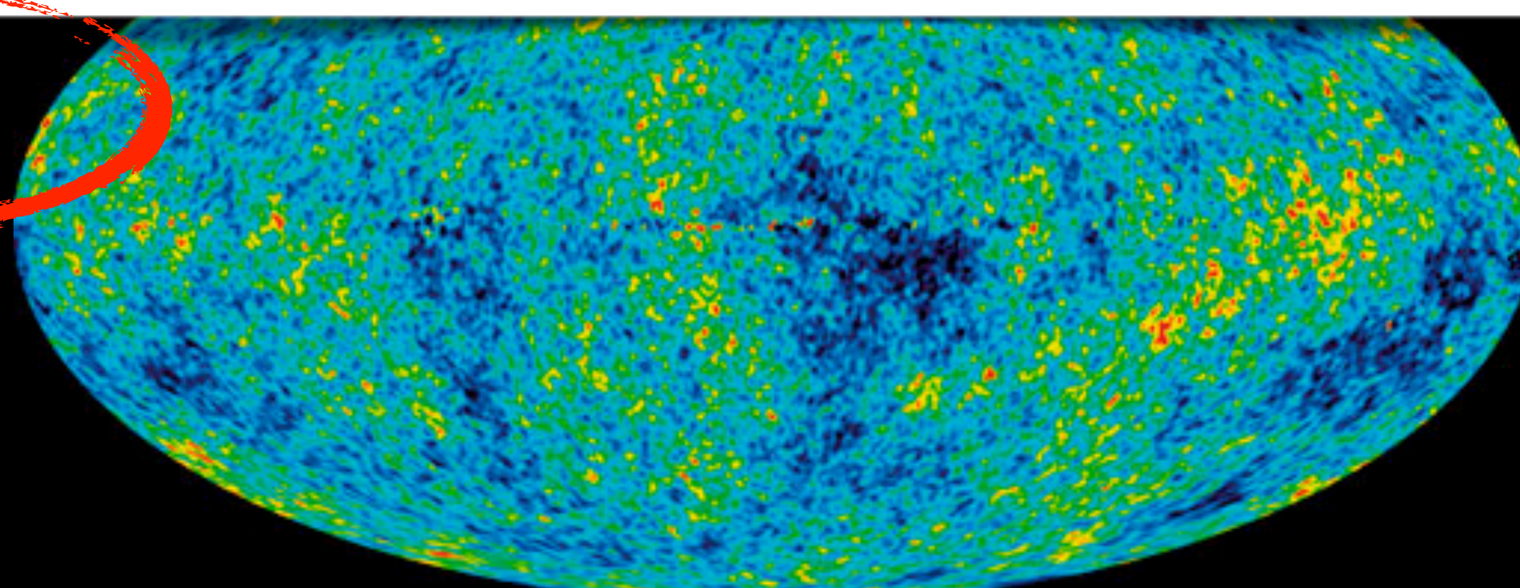




1st stars and reionization

- A neutral and metal-poor Universe becomes ionized and metal-rich
- We know it happened, but not so much how and when, even why

Credit: Abraham Loeb, Univ. Colorado



Cosmic microwave background, as observed by the WMAP satellite

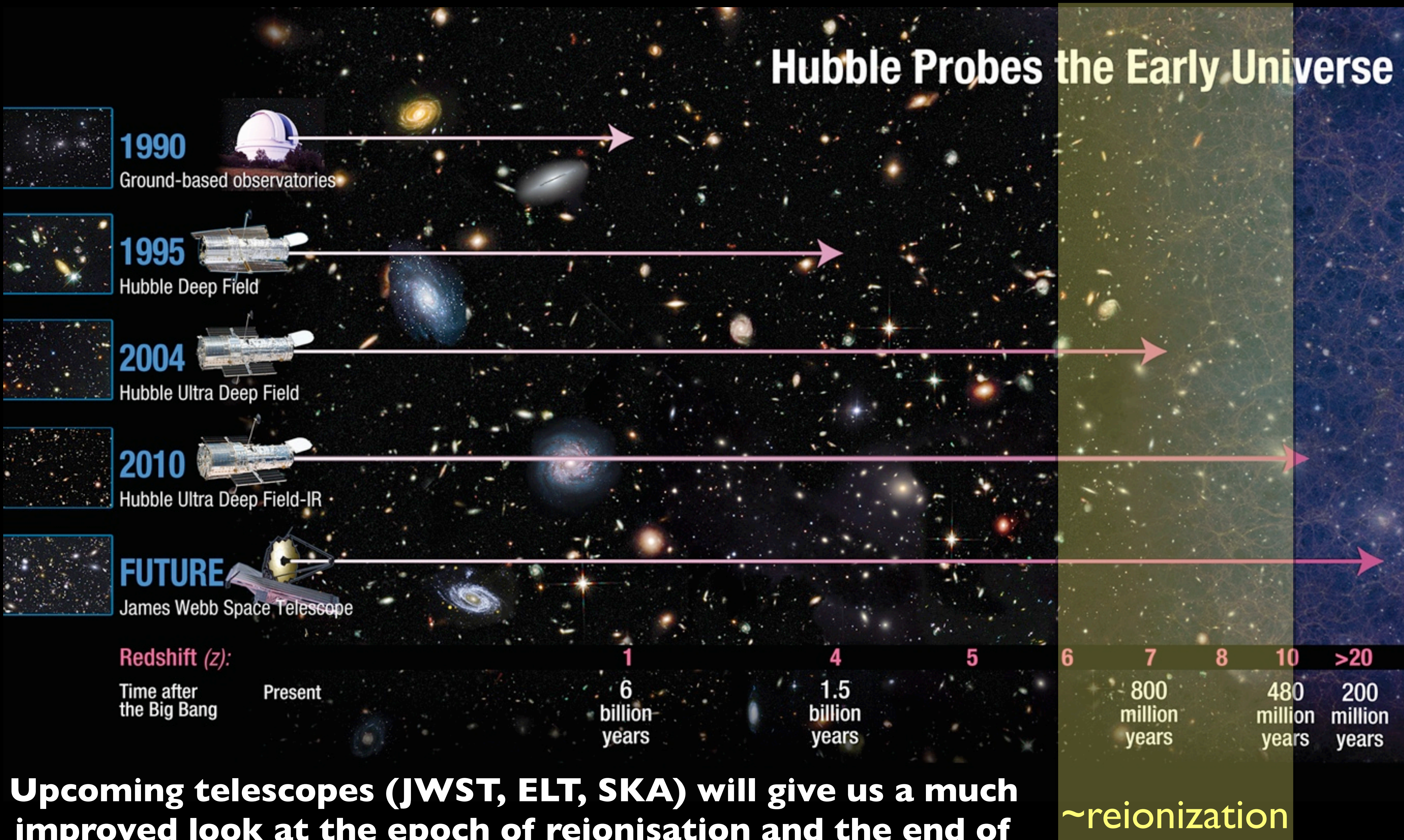
- Surface of last scattering: Atoms combined and Universe became transparent
- Tiny fluctuations in matter density
- Wealth of information about Universe: 1/6 baryons (atoms), 5/6 *dark matter*

Da

Ato

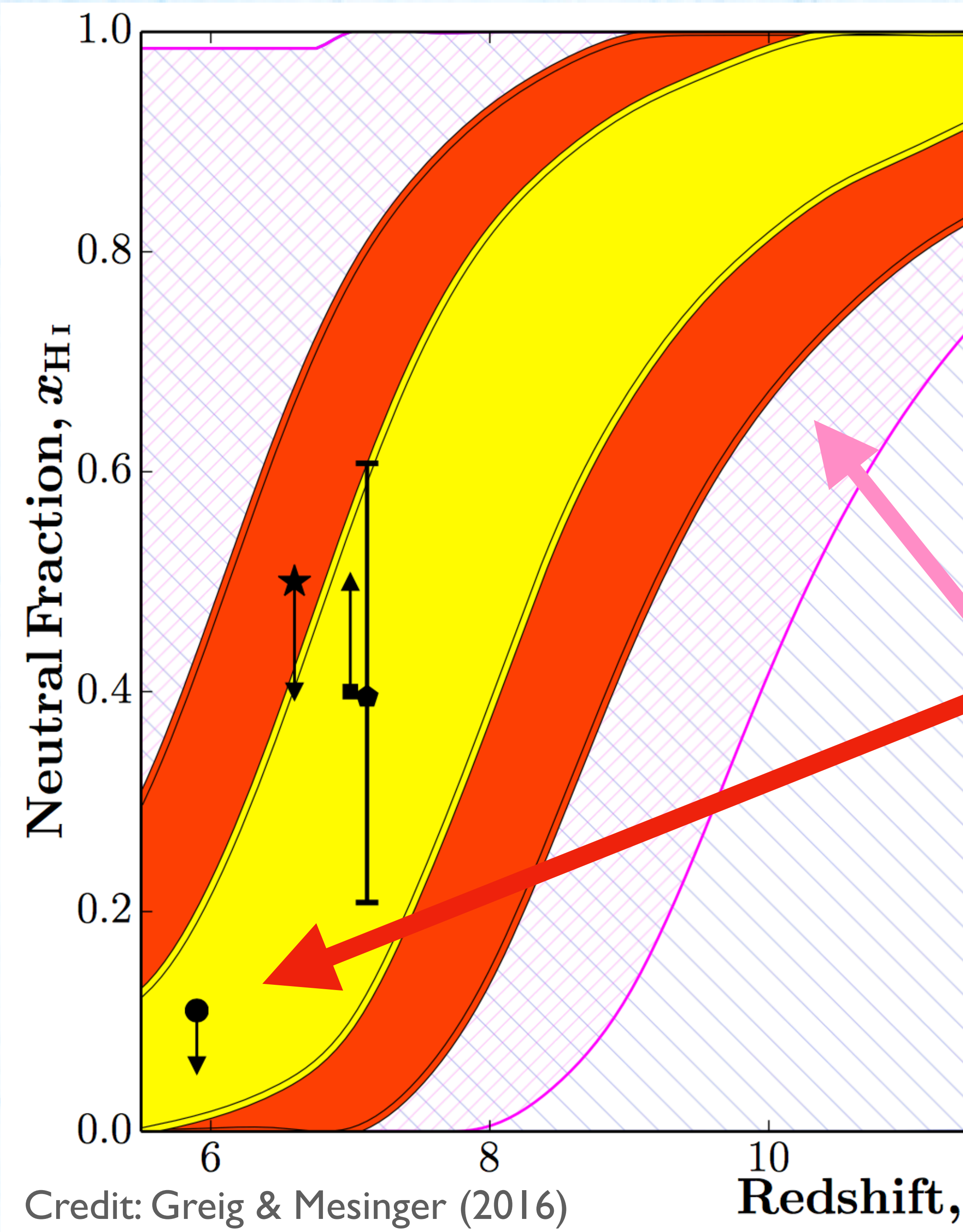
➔Fi

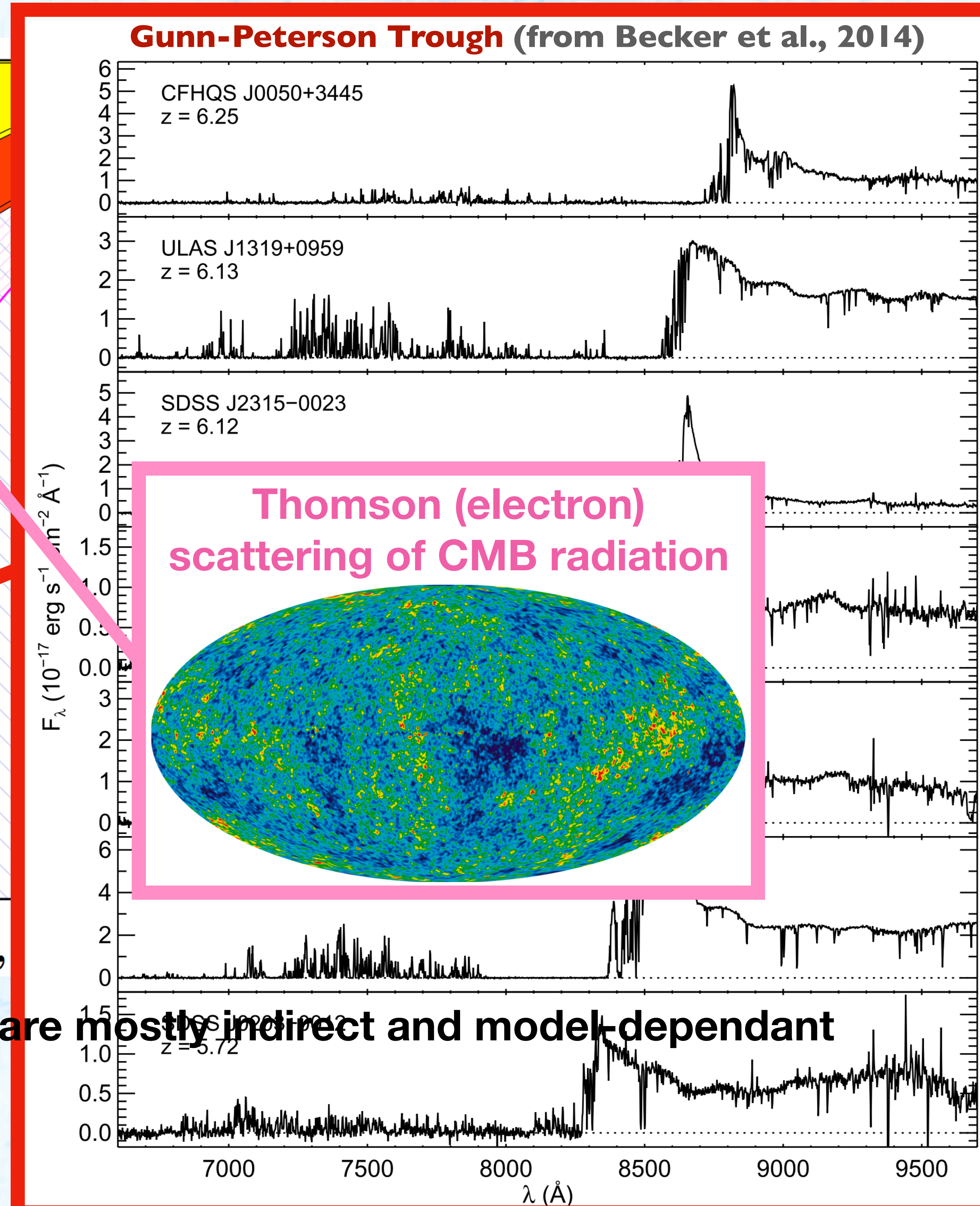
Observing the High-redshift Universe



Upcoming telescopes (JWST, ELT, SKA) will give us a much improved look at the epoch of reionisation and the end of the dark ages

Current observations of the EoR





Measures of the reionisation history are mostly indirect and model-dependant

What are the sources of reionsiation?

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

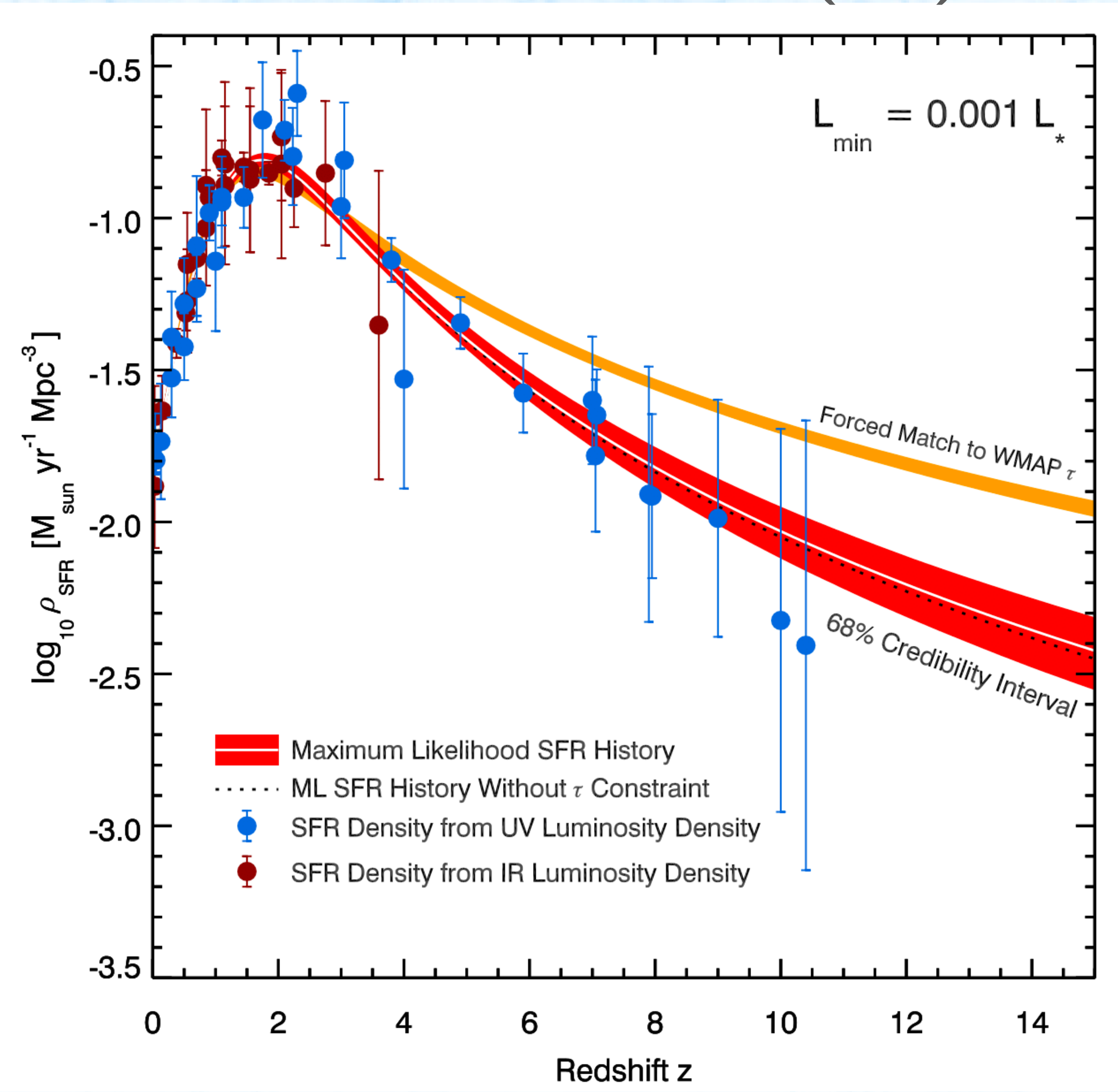
From Robertson et al. (2015)

Analytic models require an ionising radiation escape fraction of

$$f_{\rm esc} \gtrsim 20\%$$

Observationally it is impossible to measure $f_{\rm esc}$, but indirect measurements in the local Universe give

$$f_{\rm esc} \lesssim 1-3\%$$



Understanding the epoch of reionisation

To understand the complex interplay of galaxy formation, emission, propagation, and absorption of radiation which leads to reionisation, we need cosmological simulations, performed with radiation-hydrodynamics.

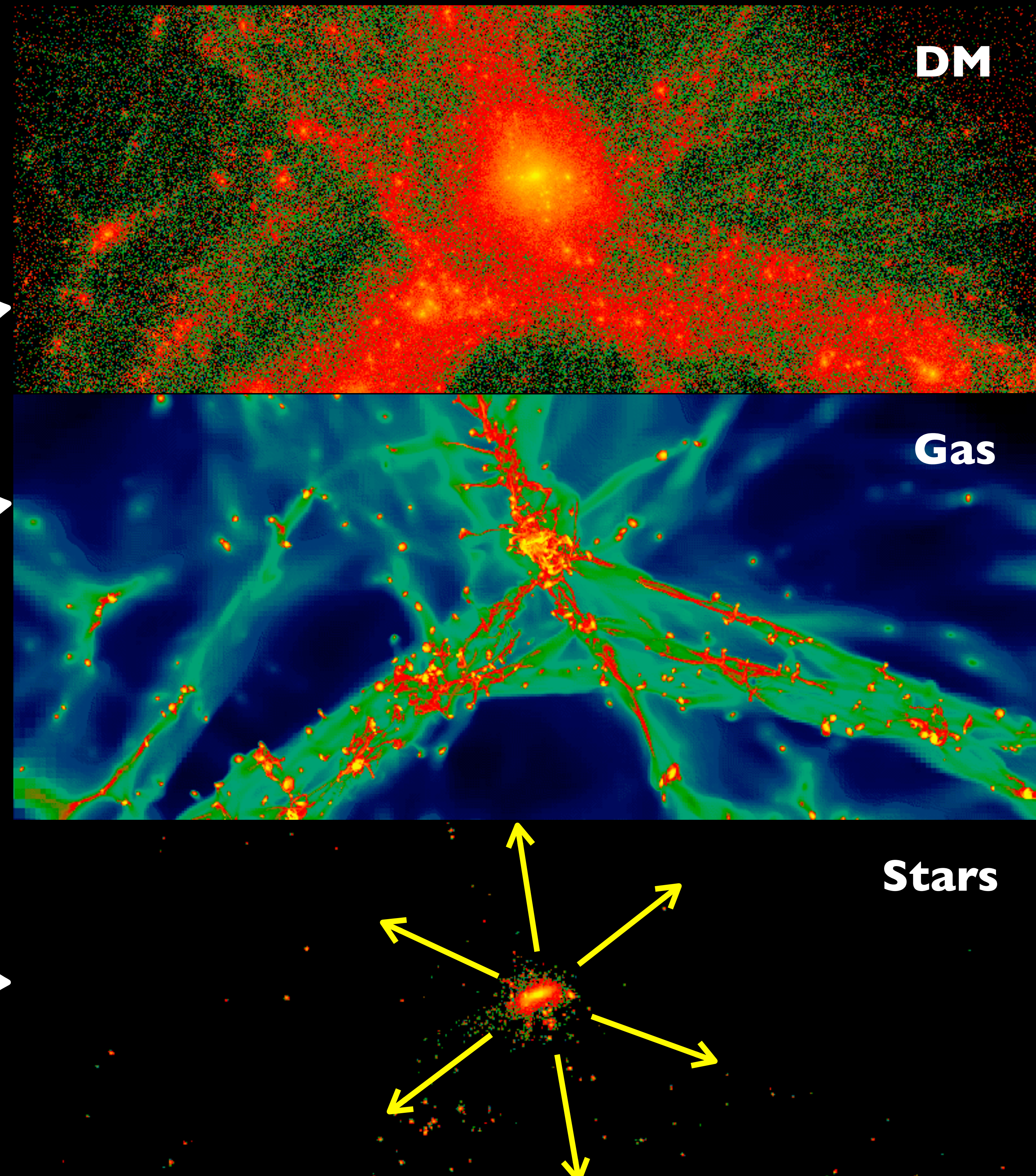
- ➡ f_{esc}
- ➡ sources of reionisation
- ➡ clustering of sources and patchiness of reionisation
- ➡ IGM temperature evolution
- ➡ interpretation of observations

Cosmological simulations

A few simulation codes are available on the 'market'

Included components:

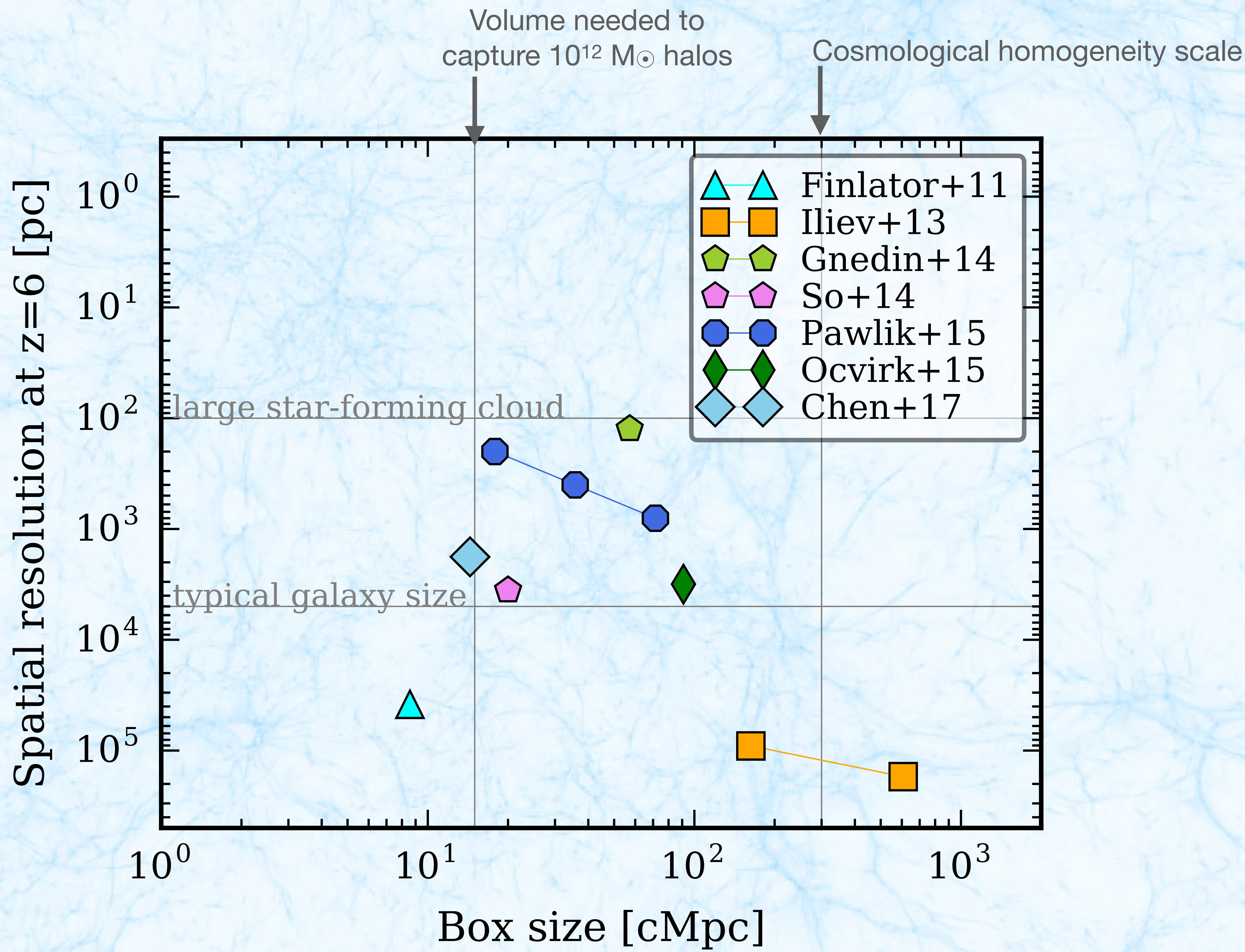
- Model of the cosmological expansion of a homogeneous Universe
- 3d evolution of:
  - **Dark matter**: gravity
  - **Baryonic gas:** (self-)gravity, hydrodynamics, radiative cooling, star formation
  - **Stars:** gravity, SNe feedback
  - **Ionsing radiation**



Two classes of reionisation simulations

Large volume with unresolved galaxies	**(Gap) So far impossible**	**Tiny volume with one or a few well resolved galaxies**
Representative volume on nearly homogeneous scale and statistical samples of (massive) halos. But galaxies are unresolved. f_{esc} is a free parameter. Low-mass halos are not captured. Good for the large-scale process, clustering, patchiness. Not-so-good for understanding the (unresolved) sources of ionisation.		Production of ionising radiation and f_{esc} resolved. But the large scale reionisation process is not captured (nor the actual contribution from individual sources).

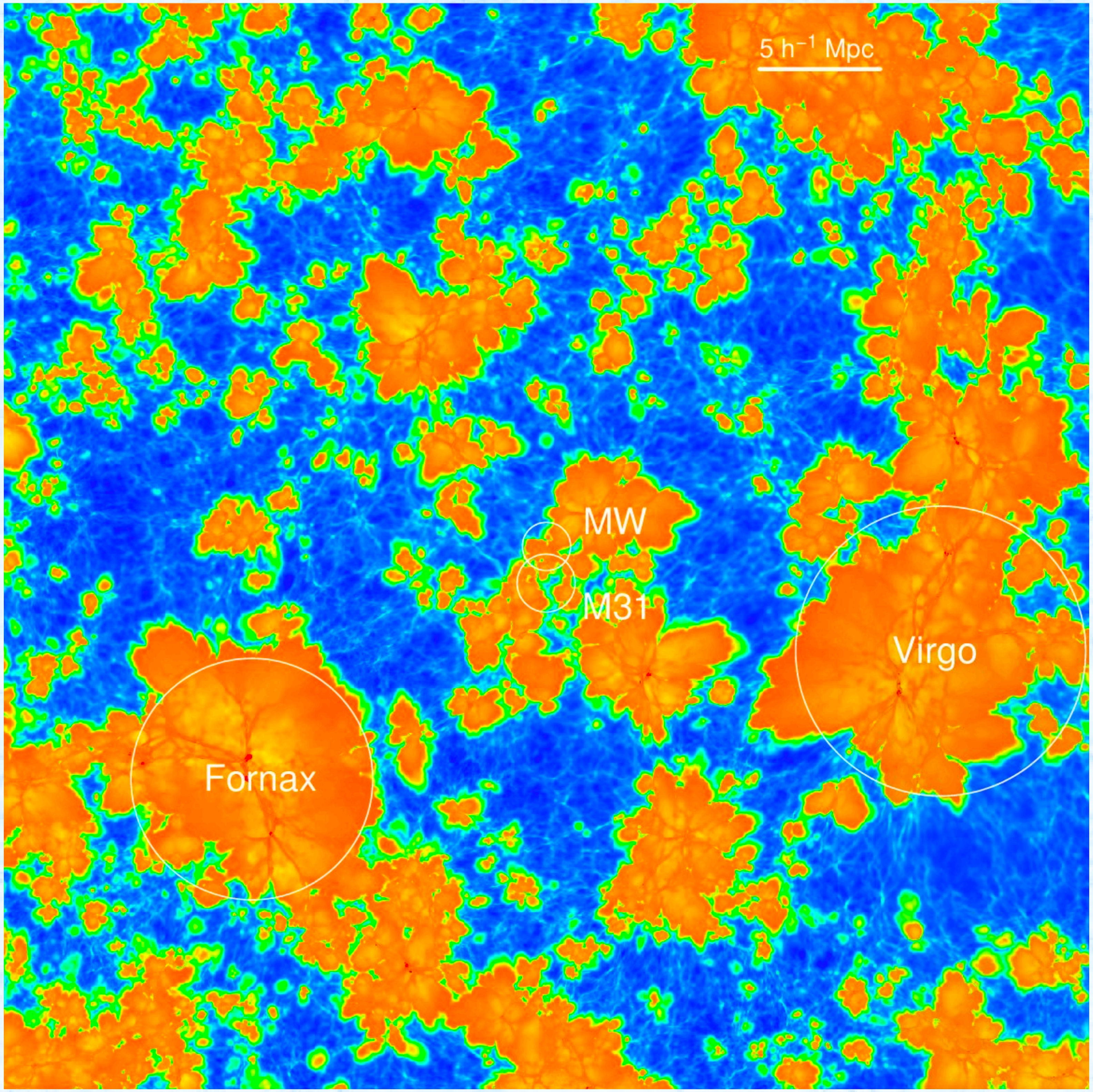
Large volume simulations of reionisation



Large volume simulations of reionisation

COsmic DAwn (CODA)
Ocvirk et al, 2015

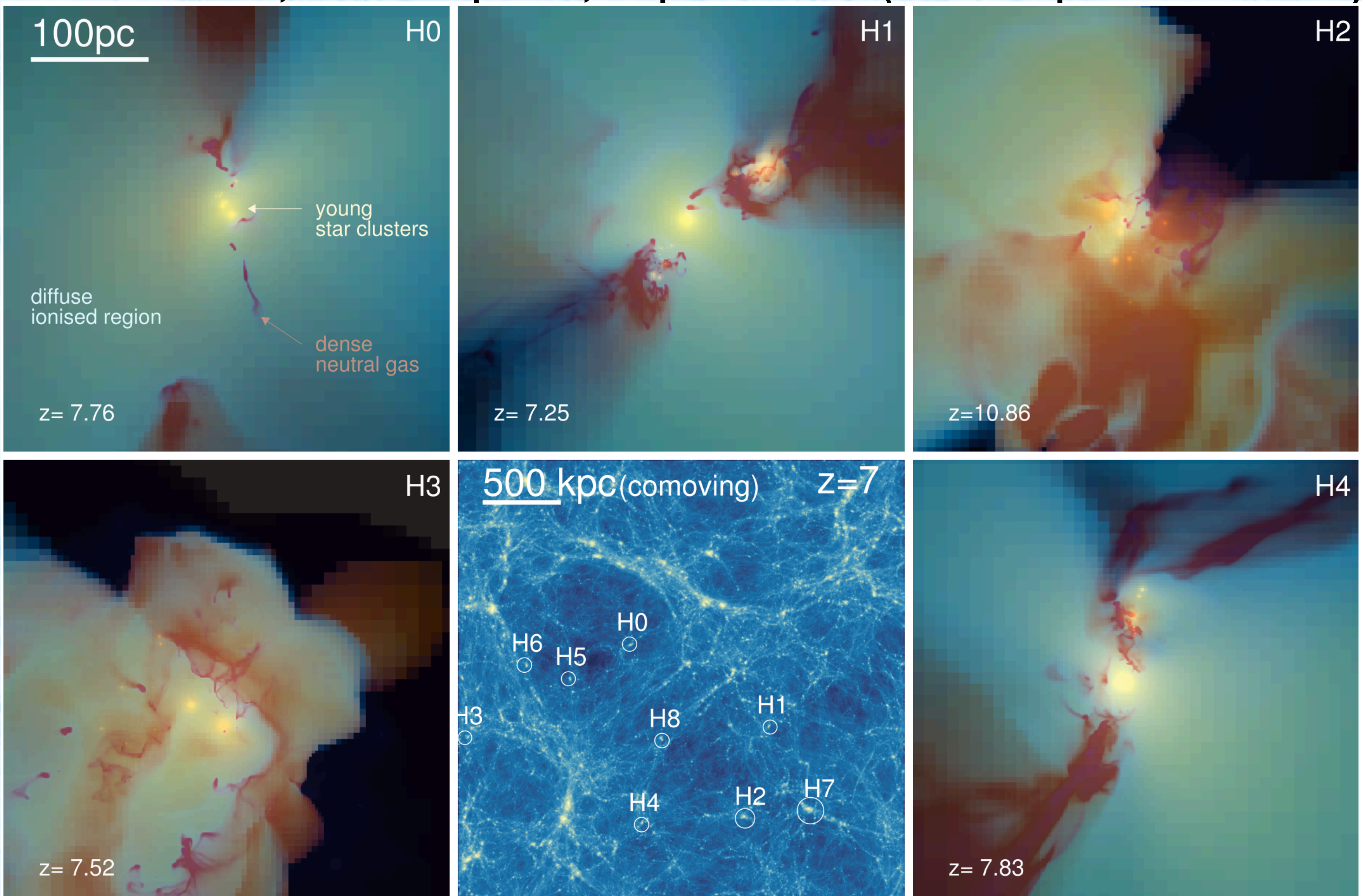
- f_{esc} calibrated to reproduce observed reionisation history
- Prediction of how the local volume was reionised
- Shapes of ionisation regions
- Suppression of star formation in low-mass haloes due to reionisation
- Ionisation state of cosmological filaments



Tiny volume simulations

Zoom technique to resolve one galaxy and its environment in a cosmological volume

From Kimm et al., 2017: 2 cMpc box, 0.7 pc resolution (in a small part of the volume)



Tiny volume simulations

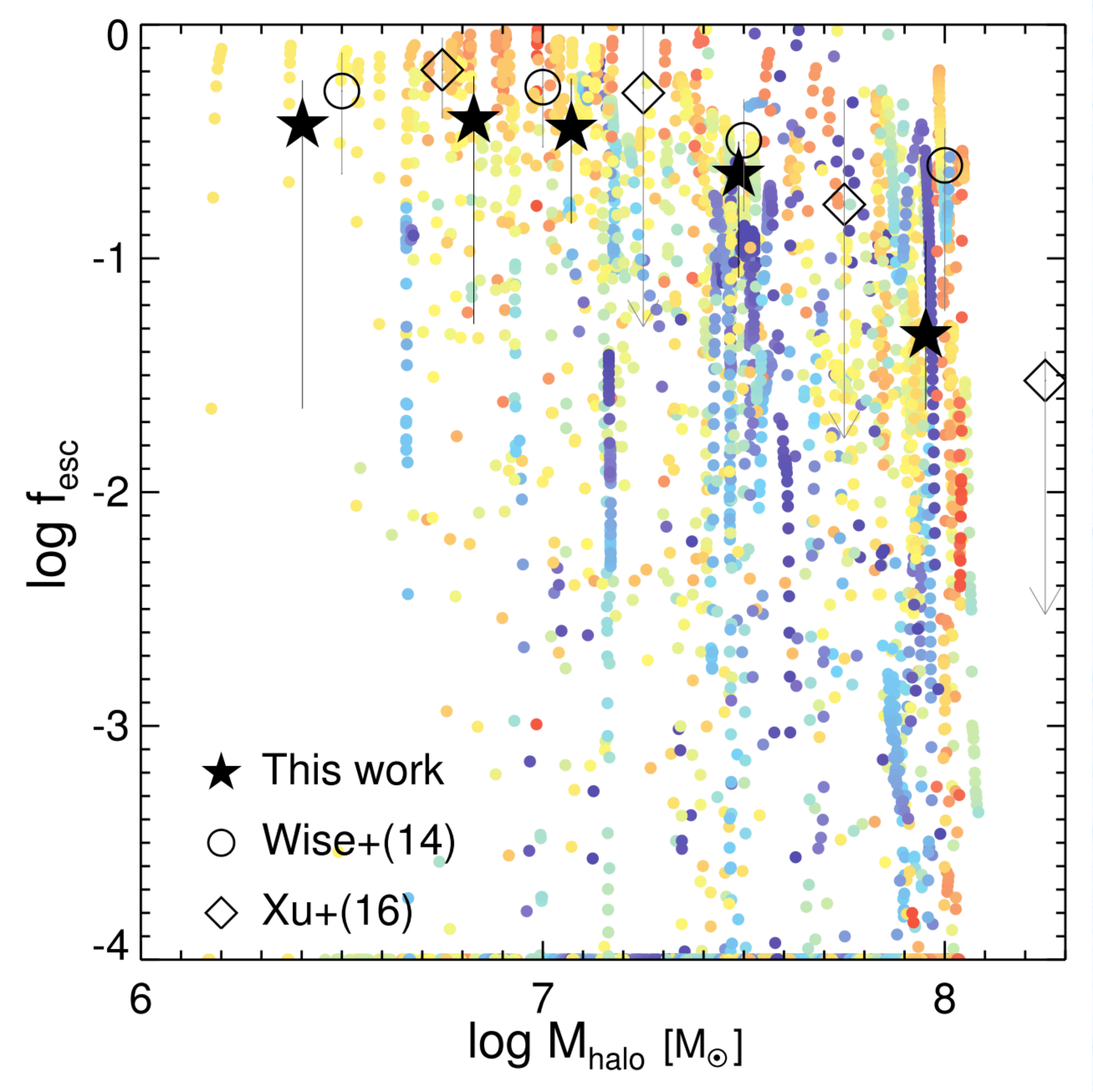
From Kimm et al., 2017: 2 cMpc box, 0.7 pc resolution (in a small part of the volume)

Kimm et al. studied f_{esc} from minihalos.

We found high escape fractions,

but these galaxies basically shut themselves down with radiation,

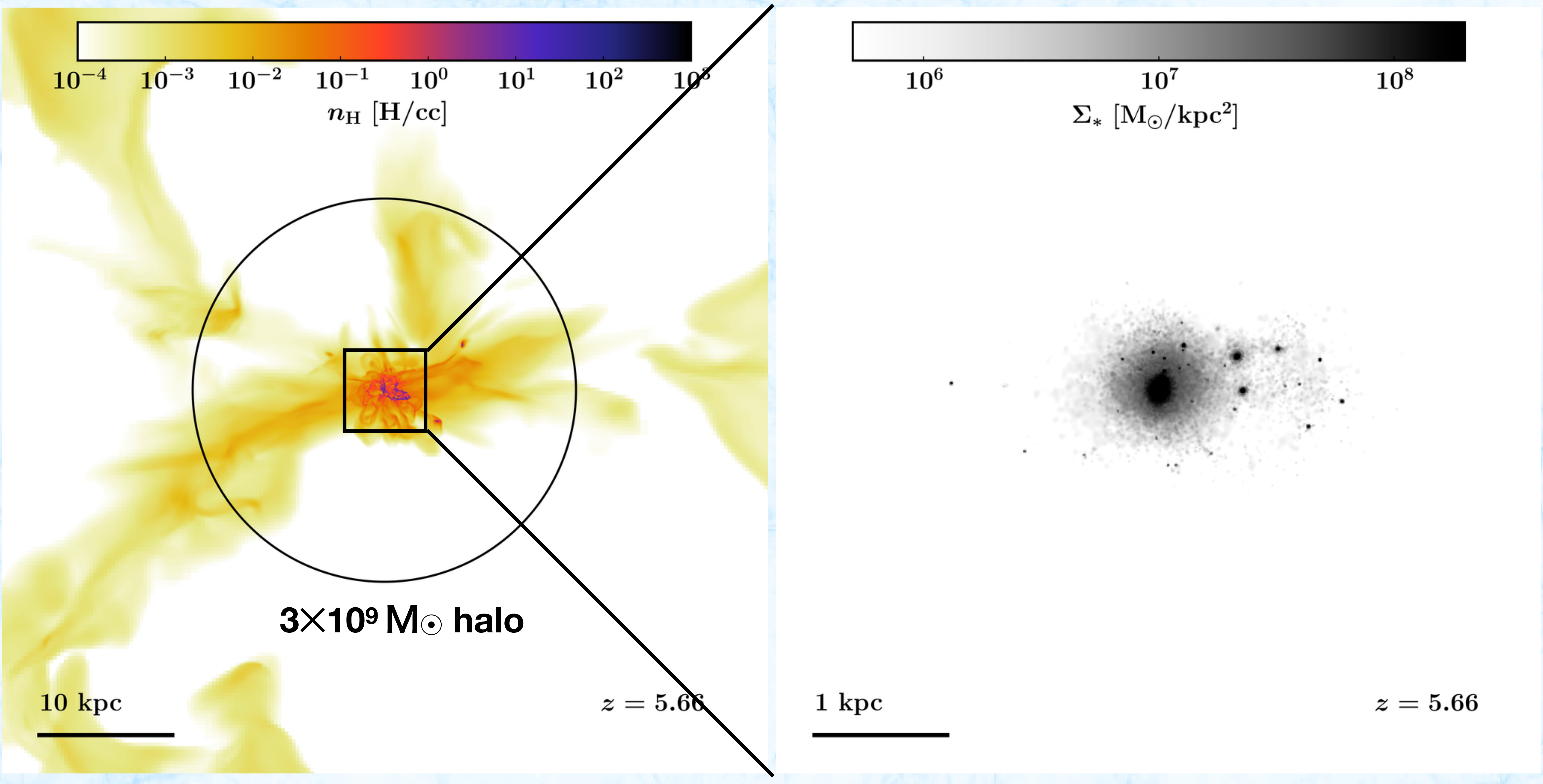
so they probably don't contribute much to reionisation.



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



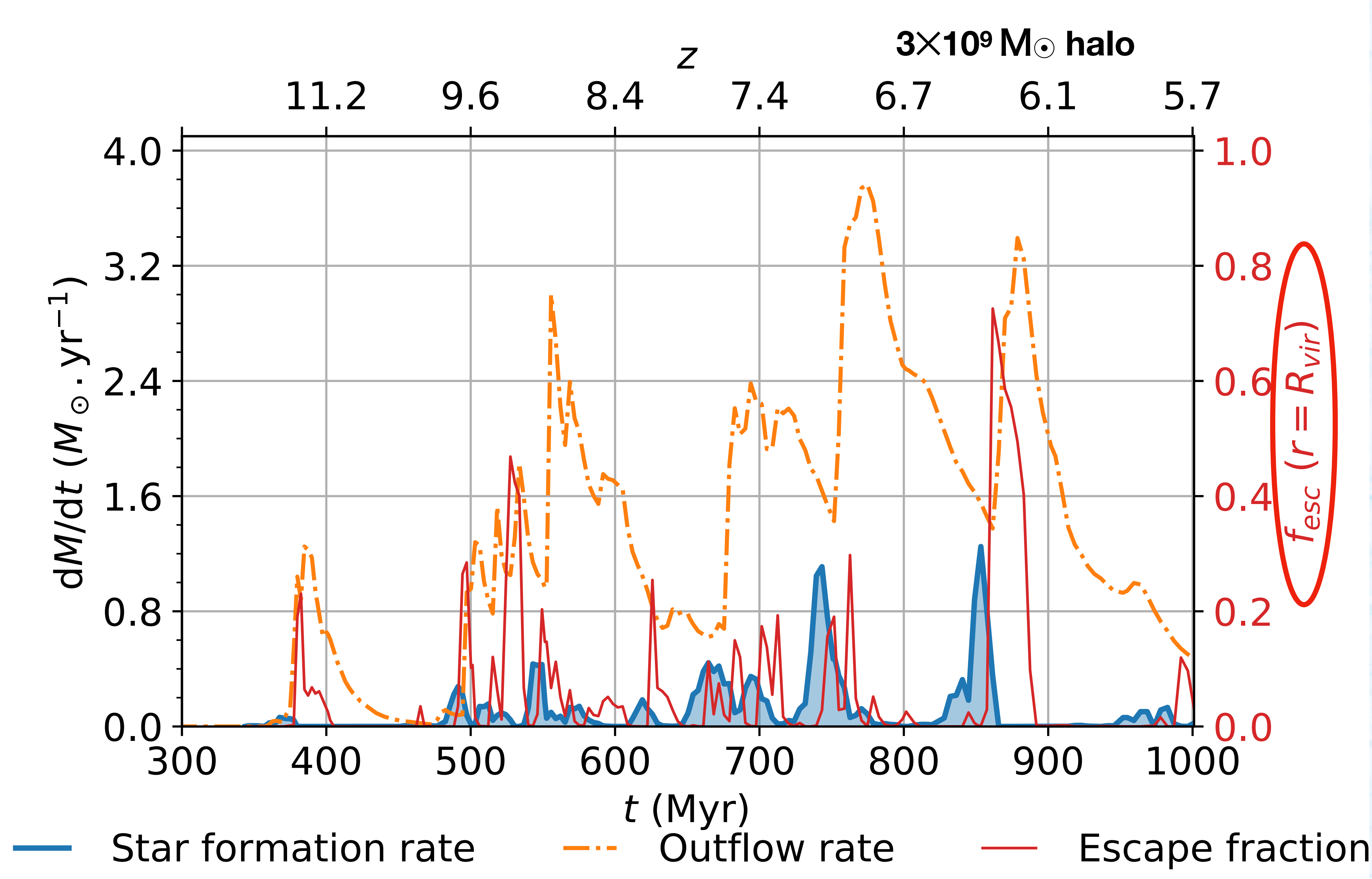
Tiny volume simulations

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:

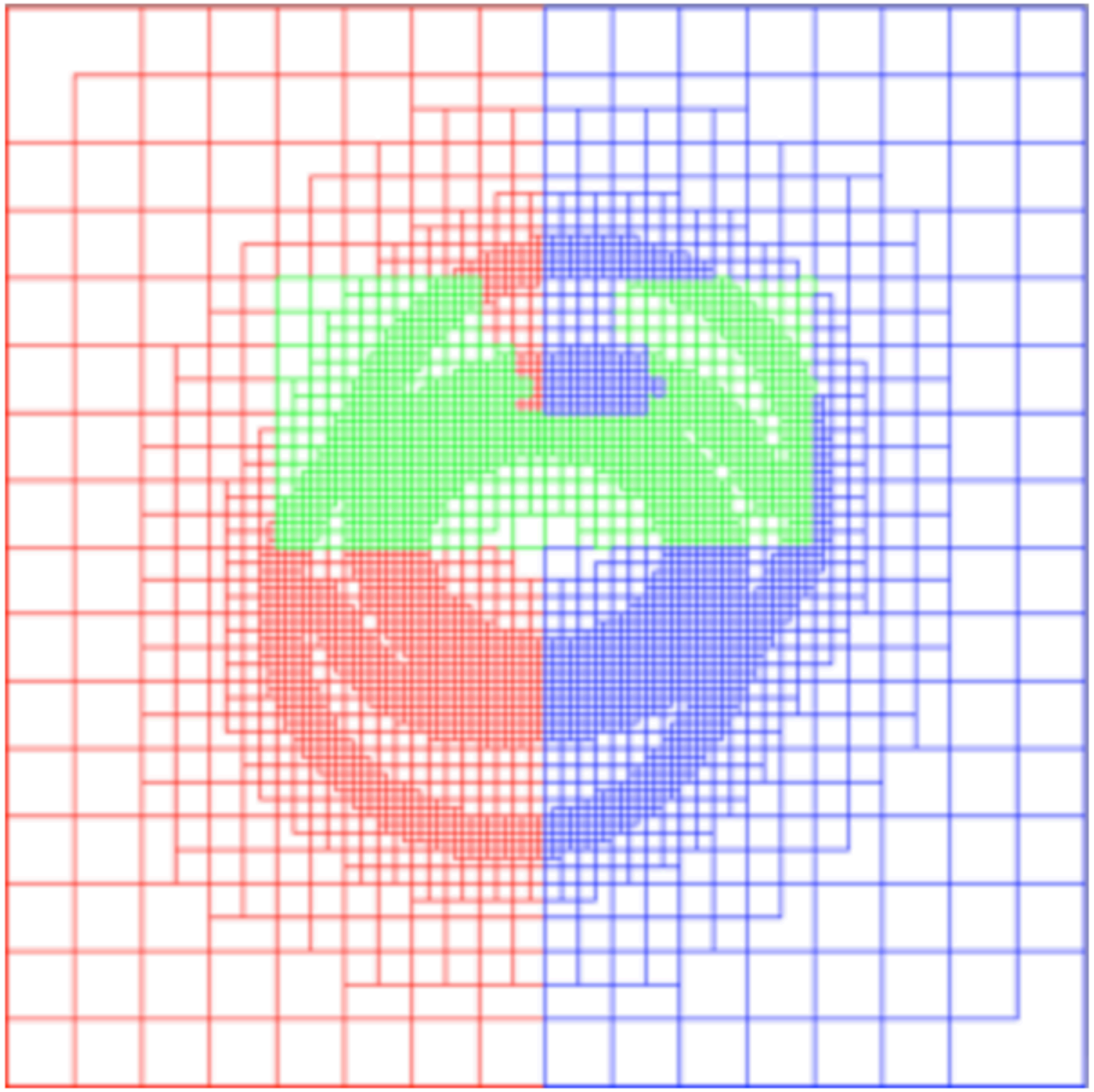
***f_{esc}* is far from constant and heavily regulated by supernova (SN) feedback**



How to perform radiation-hydrodynamical simulations of reionisation

RAMSES - my cosmological code of choice

Adaptive Mesh Refinement (AMR) for self-gravitating fluid flows



- AMR allows the calculation to be focused on regions of interest.
- The simulation volume can be split and run in parallel on thousands of CPUs
- Dark matter, gas, and stars are all included
- I spent my PhD on adding the propagation of *radiation* and its interactions with gas, see Rosdahl et al. (2013), Rosdahl & Teyssier (2015)

The challenges of adding radiation-hydrodynamics

The radiative transfer equation:

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

$I_\nu(\mathbf{x}, \mathbf{n}, t)$ intensity

$\kappa_\nu(\mathbf{x}, \mathbf{n}, t)$ absorption

$\eta_\nu(\mathbf{x}, \mathbf{n}, t)$ source function

Frequency

Location

Angle

Time

To solve this numerically, we need to overcome two main problems:

The challenges of adding radiation-hydrodynamics

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1. There are seven dimensions! Hydrodynamics has only four!

The challenges of adding radiation-hydrodynamics

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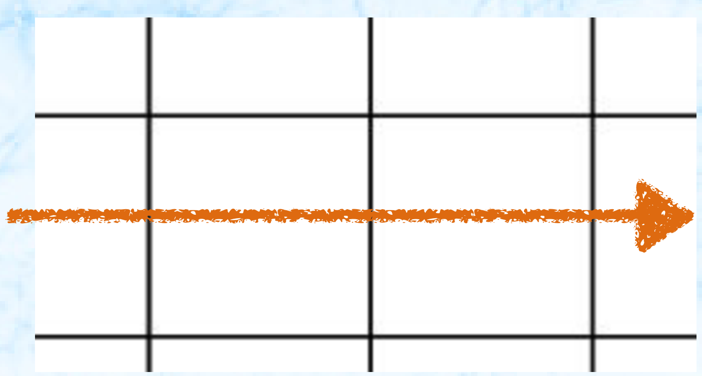
To solve this numerically, we need to overcome two main problems:

I. There are seven dimensions! Hydrodynamics has only four!

II. The timescale is ∝ u^{-1}, where u is *speed*, and $u_{\mathrm{light}} \sim 1000\ u_{\mathrm{gas}}$,
so ~ thousand radiation steps per hydro step!!



'Something' flowing at speed ***u***

$$\Delta t \lesssim \frac{\Delta x}{u}$$

Cell width

speed of flow

Timestep length

The challenges of adding radiation-hydrodynamics

The radiative transfer equation:

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

$I_\nu(\mathbf{x},\mathbf{n},t)$ intensity

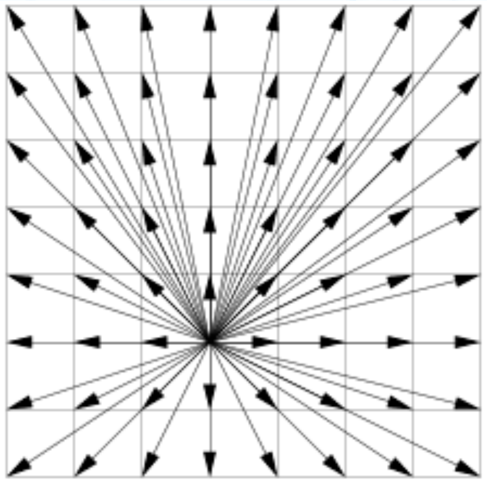
$\kappa_\nu(\mathbf{x},\mathbf{n},t)$ absorption

$\eta_\nu(\mathbf{x},\mathbf{n},t)$ source function

Two common strategies for radiative transfer:

I. *Ray tracing methods:* Cast a finite number of rays from a finite number of sources

- Simple and intuitive
- …but efficiently covering the volume can be tricky
- …and load scales with number of sources/rays



II. *Moment methods:* Convert the RT equation into a system of conservation laws that describe a *field* of radiation

- Not so intuitive, and *not rays*
- …but fits easily with a hydrodynamical solver for RHD
- …naturally takes advantage of AMR and parallellization
- …no problem with covering the volume
- …no limit to number of radiation sources

Moments of the radiative transfer equation

to 'reduce' the angular dimension

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

$I_\nu(\mathbf{x},\mathbf{n},t)$ intensity

$\kappa_\nu\,(\mathbf{x},\mathbf{n},t)$ absorbtion

$\eta_\nu\,(\mathbf{x},\mathbf{n},t)$ source function

Zeroth moment: $\oint f(\mathbf{n})\,d\Omega$

$$\frac{1}{c}\frac{\partial}{\partial t}\oint I_\nu\,d\Omega + \nabla\oint \mathbf{n}\,I_\nu\,d\Omega = -\kappa_\nu\oint I_\nu\,d\Omega + \eta_\nu\oint d\Omega$$

First moment: $\oint \mathbf{n}f(\mathbf{n})\,d\Omega$

$$\frac{1}{c}\frac{\partial}{\partial t}\oint \mathbf{n}\,I_\nu\,d\Omega + \nabla\oint \mathbf{n}\otimes\mathbf{n}\,I_\nu\,d\Omega = -\kappa_\nu\oint \mathbf{n}\,I_\nu\,d\Omega$$

These equations contain the first three moments of the intensity:

$$E_\nu = \frac{1}{c}\oint I_\nu\,d\Omega \qquad \text{(energy per volume and frequency)}$$

$$\mathbf{f}_\nu = \oint \mathbf{n}\,I_\nu\,d\Omega \qquad \text{(energy flux per area and time and frequency)}$$

$$\mathbb{P}_\nu = \frac{1}{c}\oint \mathbf{n}\otimes\mathbf{n}\,I_\nu\,d\Omega \qquad \text{(force per area and frequency)}$$

$$\boxed{\begin{aligned}\frac{\partial E_\nu}{\partial t} + \nabla\cdot\mathbf{f}_\nu &= -\kappa_\nu c E_\nu + S_\nu\\ \frac{\partial \mathbf{f}_\nu}{\partial t} + c^2\nabla\cdot\mathbb{P}_\nu &= -\kappa_\nu c\mathbf{f}_\nu\end{aligned}}$$

The challenges of adding radiation-hydrodynamics
part II: the impossibly large speed-of-light

Problem: the high speed of light requires a huge number of radiative transfer (RT) steps ➡ $$\Delta t_{\mathrm{RT}} \sim \frac{\Delta x}{c} \sim \frac{\Delta t_{\mathrm{HD}}}{1000}$$

Solution: **reduce the speed of light**
(see Gnedin & Abel, 2001)

$$c_{\mathrm{red}} = \frac{c}{1000} \quad ➡ \quad \Delta t_{\mathrm{RT}} \sim \frac{\Delta x}{c_{\mathrm{red}}} \sim \Delta t_{\mathrm{HD}}$$

➡ Only ~2X runtime increase, compared to pure hydrodynamics

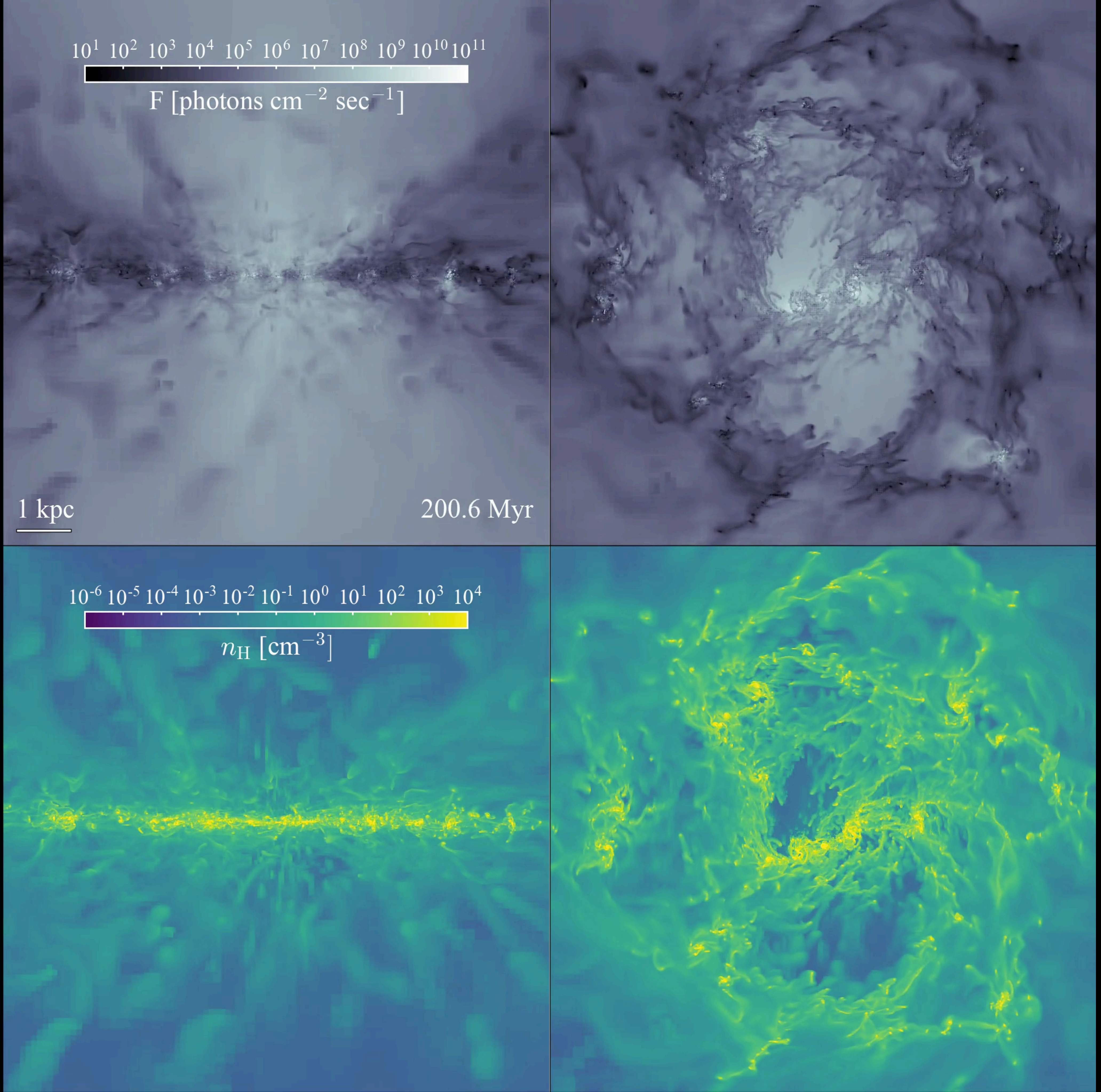
Not quite as bad as it sounds:
The dynamic speed in RHD simulations is that of *ionisation fronts*, not *c*.
We just want to get the front correct...

Radiation-hydrodynamics with RAMSES-RT

The full implementation of RHD in RAMSES-RT is described in Rosdahl et al. (2013) and Rosdahl & Teyssier (2015).

The RHD code is public and already well established in the community (20 publications, including the small volume reionisation simulations previously shown)

The important thing is that it is now possible to do radiation-hydrodynamics on galaxy scales with an unlimited number of radiation sources.



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
200.6 Myr
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 variable speed of light approximation

The main limitation for performing large-scale reionisation simulations was that reionisation of cosmological voids happens 'close' to the (real) speed of light.

We recently overcame this problem with a *variable speed of light approximation*, where *c* is slow in dense gas but speeds up in the diffuse IGM (see Katz et al, 2017).

Harley Katz

This makes it possible, for the first time, to fill the gap and perform large-scale reionsiation simulations that resolve individual galaxies.

The Sphinx project: simulating reionsiation and galaxy formation over the first billion years

Two classes of reionisation simulations

Large volume with unresolved galaxies

Representative volume ~~on nearly homogeneous scale and~~ statistical samples of (massive) halos.

~~But galaxies are unresolved.~~
~~f_{esc} is a free parameter.~~

~~Low mass halos are not captured.~~

Good for the large-scale process, ~~clustering~~, patchiness.

~~Not so good for understanding the (unresolved) sources of ionisation.~~

(Gap)

So far impossible

Sphinx

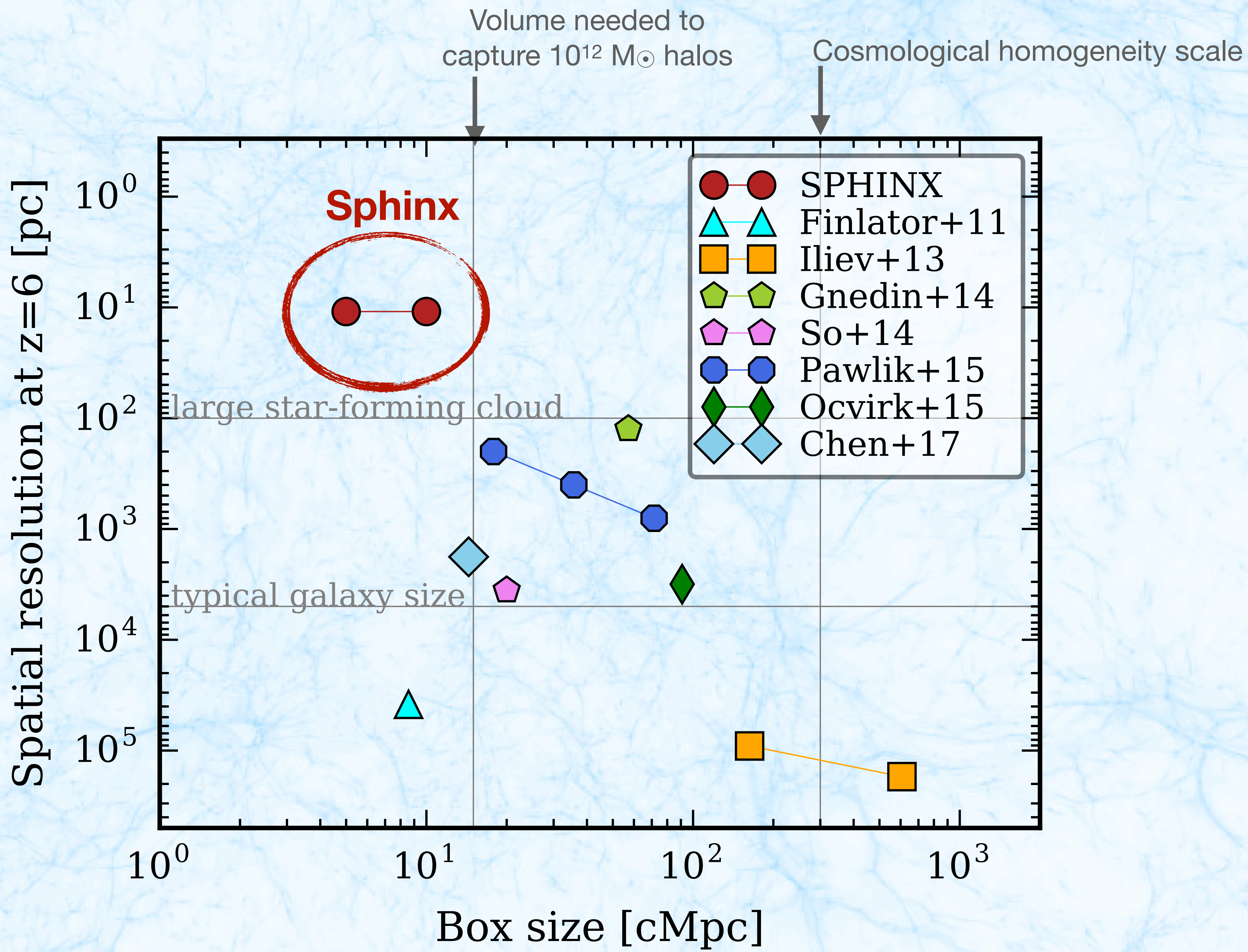
simulations

Tiny volume with one or a few well resolved galaxies

Production of ionising radiation and f_{esc} resolved.

~~But the large scale reionisation process is not captured (nor the actual contribution from individual sources).~~

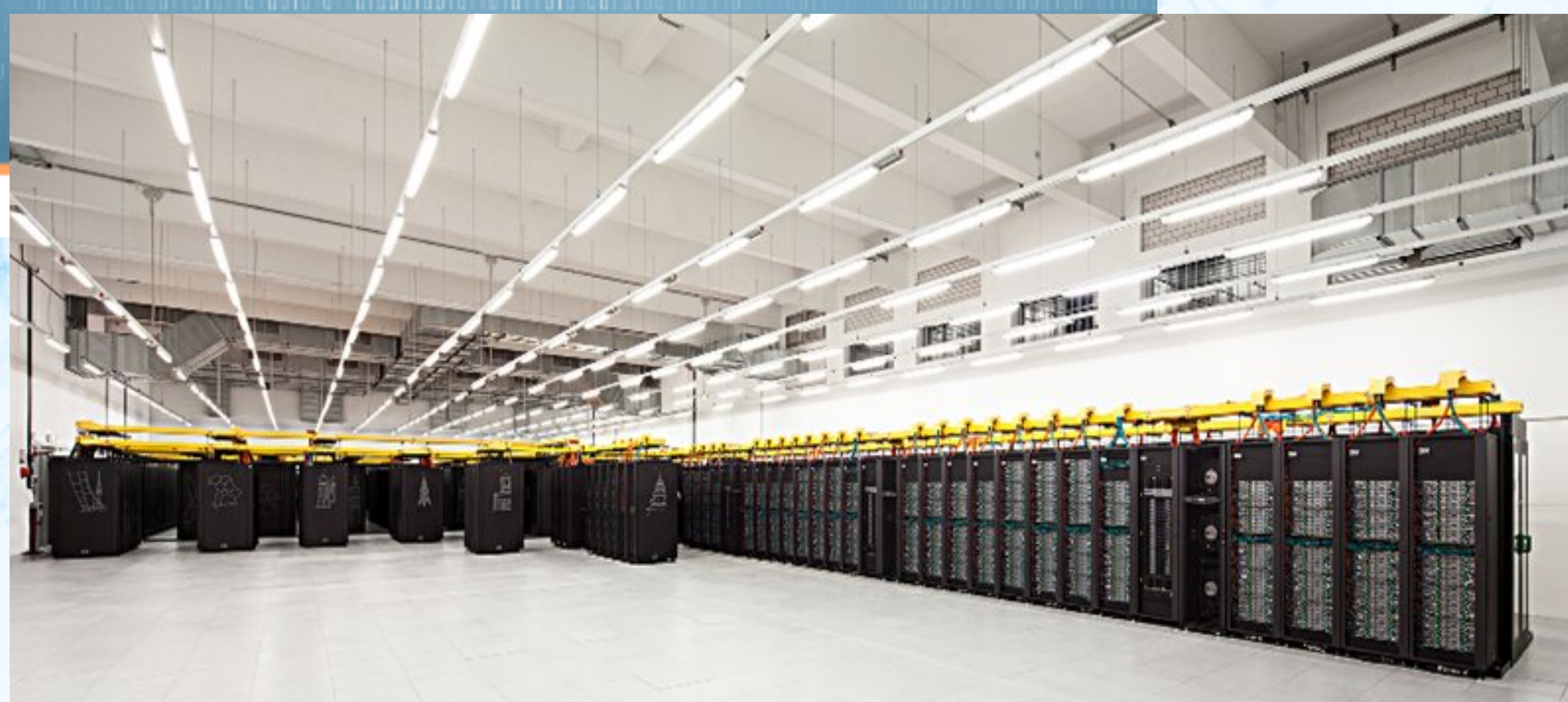
The Sphinx simulations in context



Computing resources

I applied for PRACE computing time last year and received 13.6 million cpu-hours to perform the Sphinx simulations on the SuperMUC supercomputer in Munich.

The main simulations run on 5600 cores and take about 3 million cpu-hours each



Project goals

- Understand the process and sources of reionisation
- Understand how patchy reionisation and metal enrichment suppresses or enhances the growth of satellite galaxies
- Model observational Lyman-alpha signatures produced by the various stages and environments during reionisation
- Predict luminosity function and galaxy distribution at extreme redshift for the JWST era
- Obtain statistical understanding about UV escape from the ISM (connection to feedback, halo mass)
    - First: What do binary stars have to do with reionisation?

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

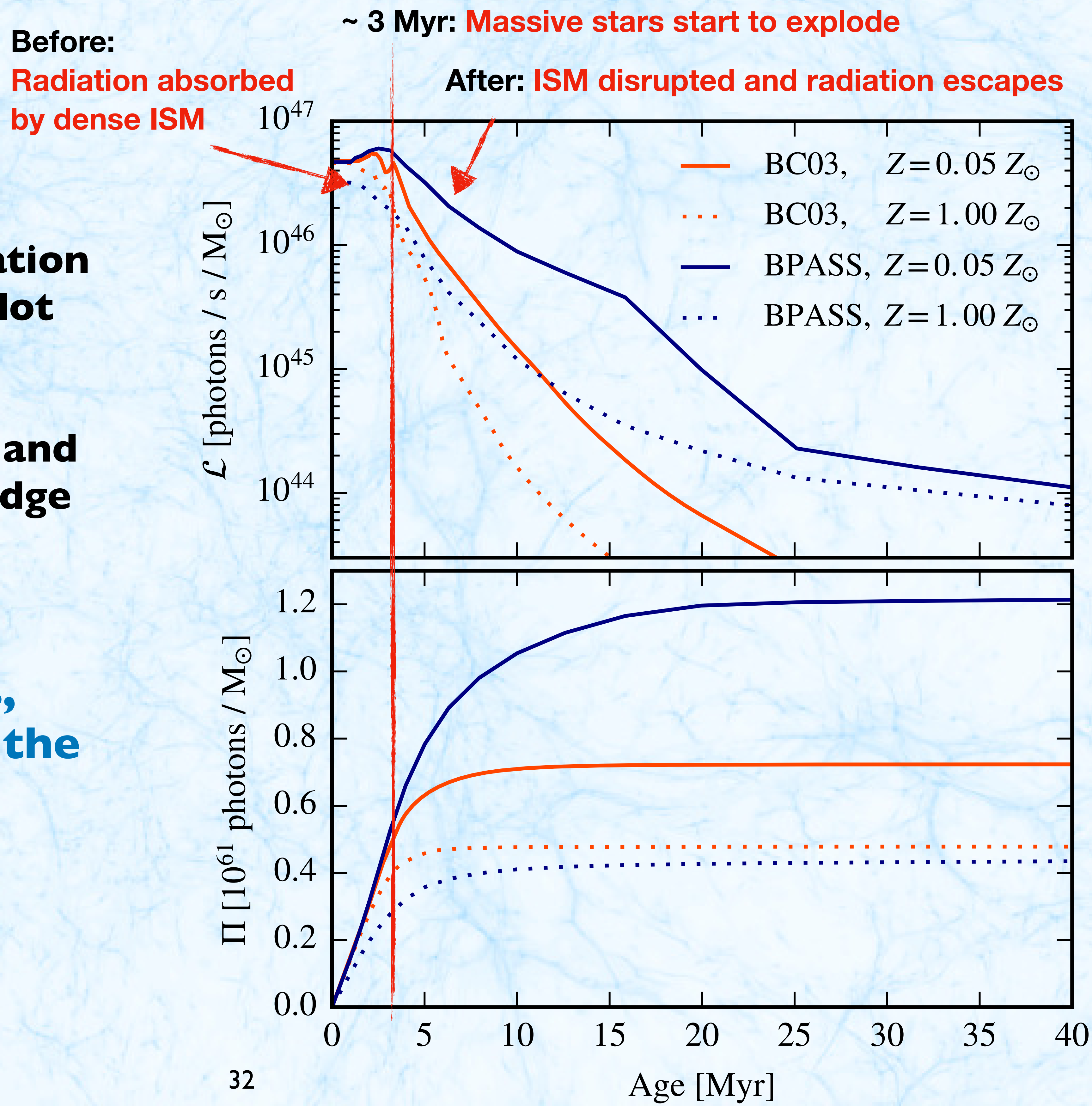
- The reason: longer and stronger radiation due to mass transfer and mergers in binary systems

SED models

Spectral Energy Distributions for stellar populations

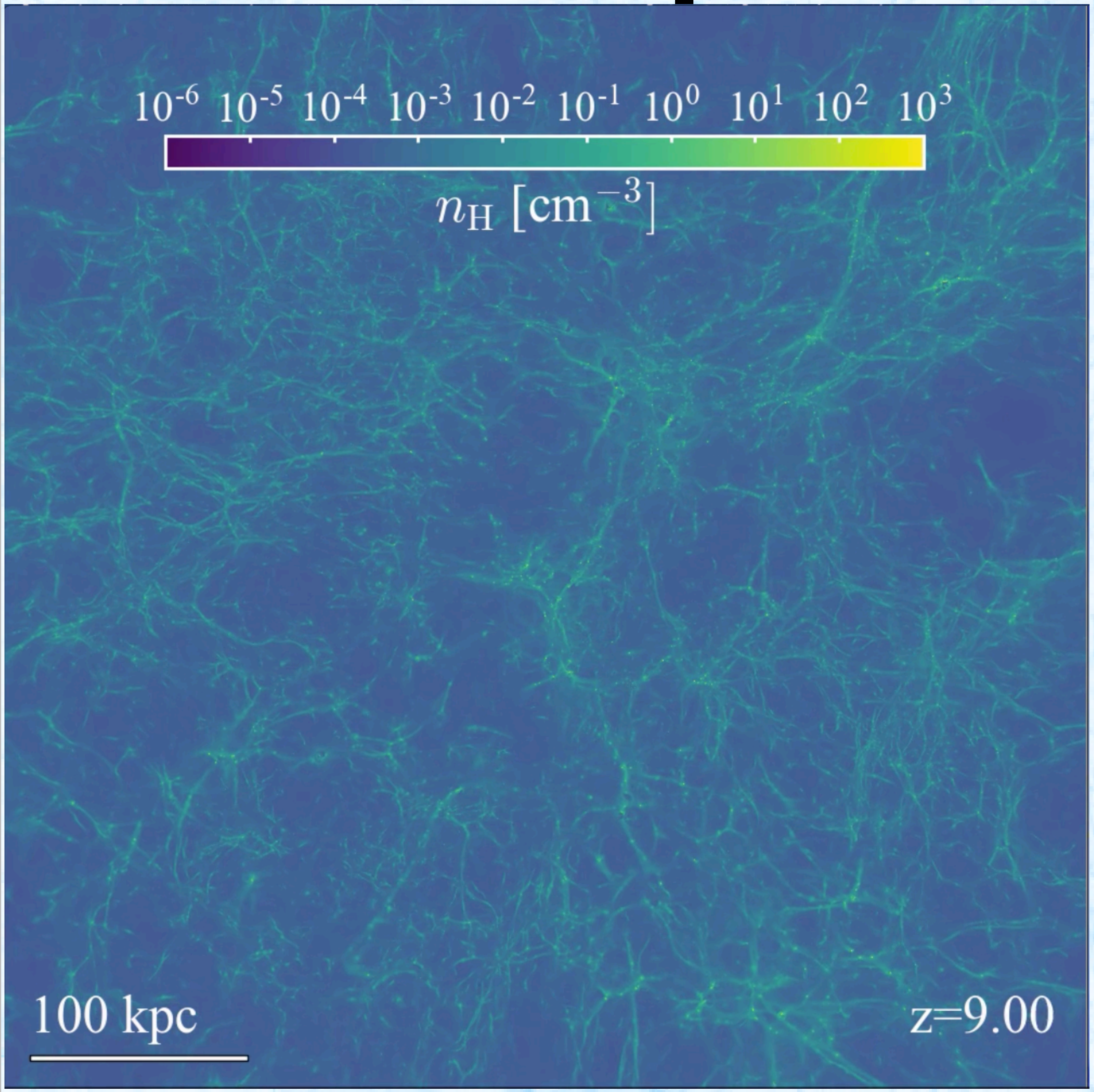
- **BC03 = Single stellar population model from Bruzual & Charlot (2003)**
- **BPASS = Binary Population and Spectral Syntesis from Eldridge et al.**

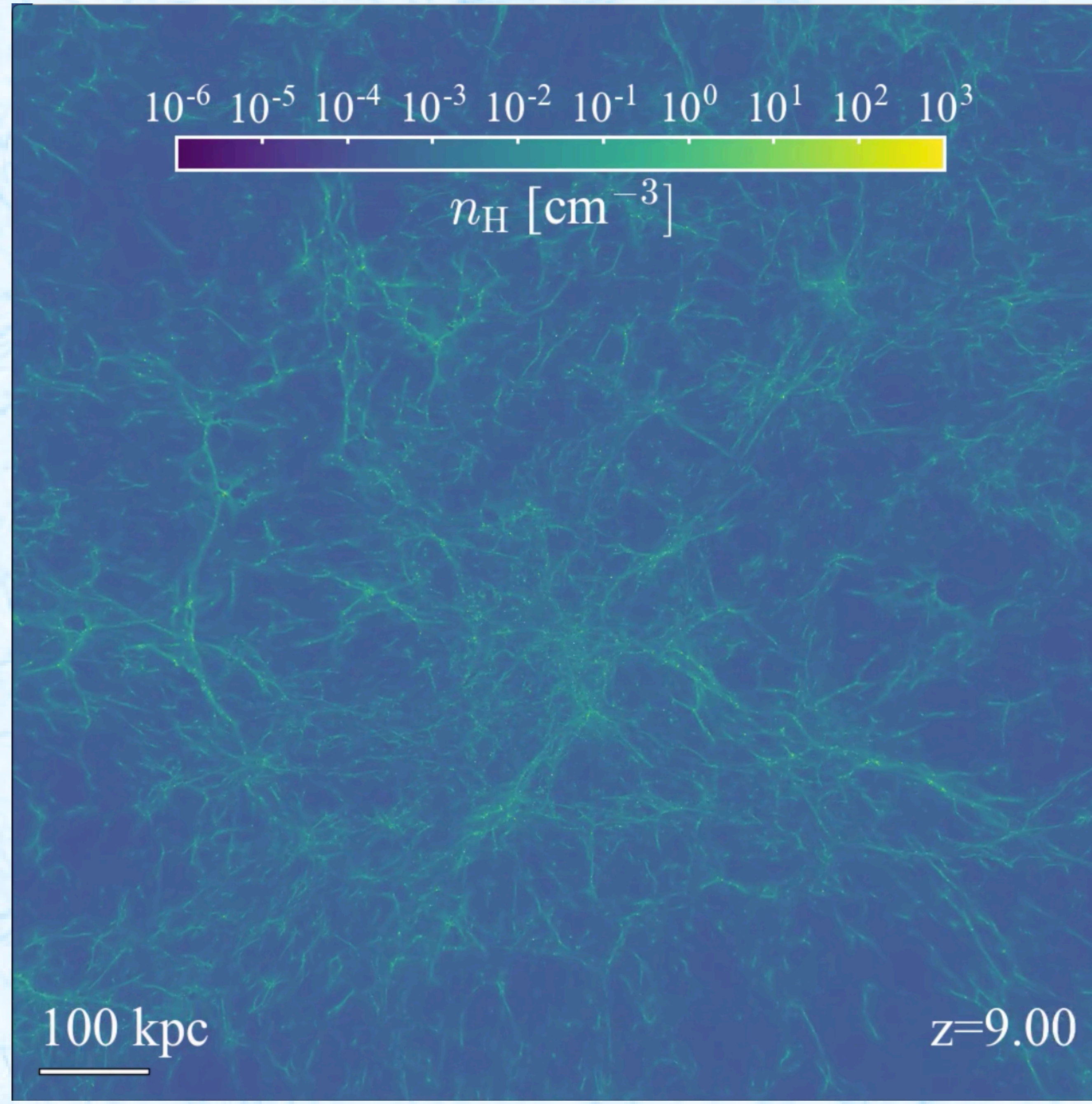
➡**SPHINX: using full RHD cosmological simulations, what does BPASS do for the reionsiation history?**



Setup of the Sphinx simulations

Sphinx simulations





5 cMpc box with high mass resolution

10 cMpc box with lower <u>mass</u> resolution (but same physical resolution)

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

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 (8 times less in 5 Mpc box).
  10^8 $M_\odot$ halo has 300 (2,500) particles ➢ all potential sources resolved.

- **Stellar particle resolution** of 10^3 $M_\odot$ (particle = a stellar population)

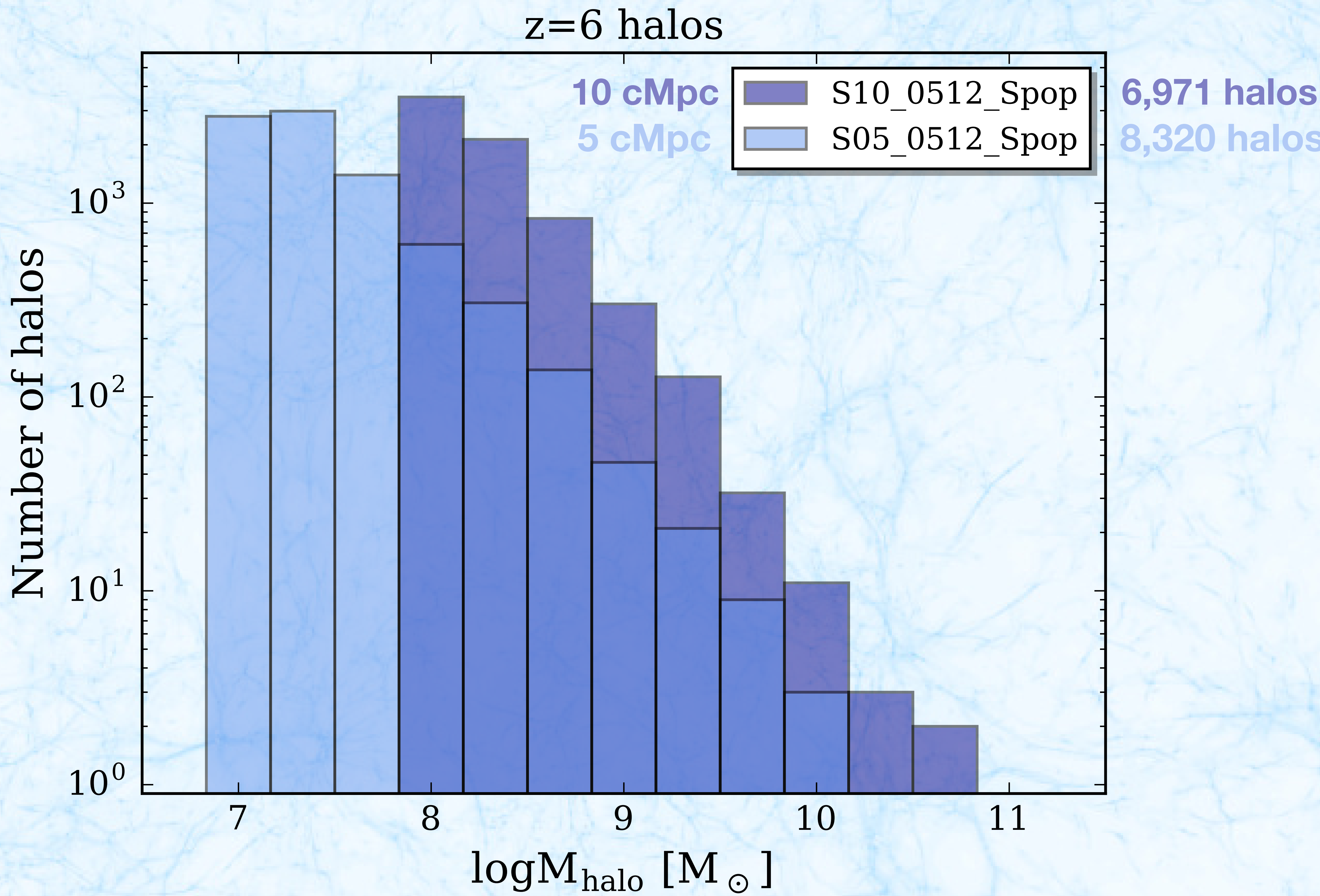
- *Bursty* turbulence-dependent **star formation** (Devriendt et al, <u>in prep</u>)

- **SN explosions** modelled with momentum kicks (Kimm et al., 2015)
  - We *calibrate* SN rates to reproduce a sensible 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 SED luminosity)

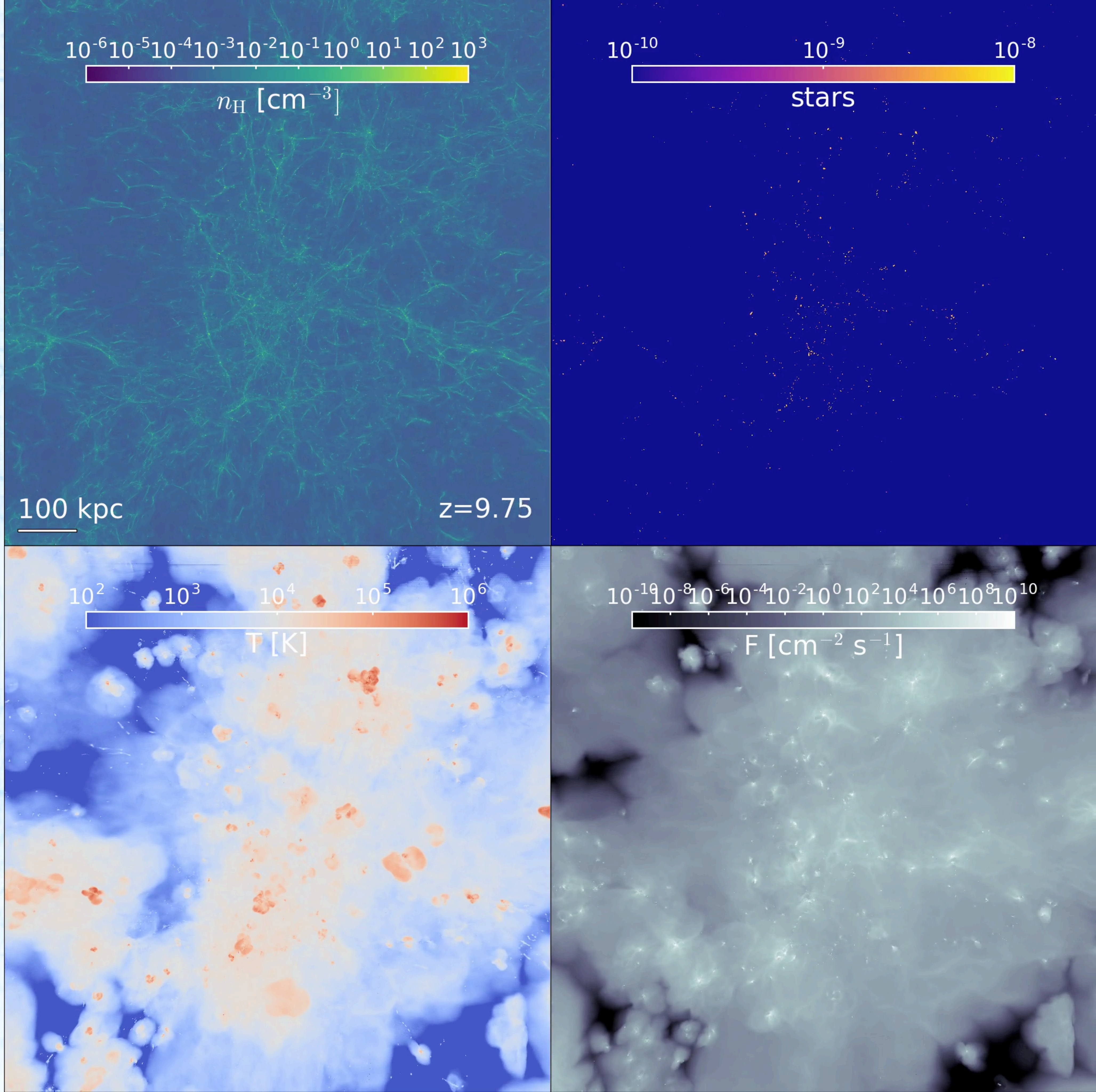
- We run with binary and single star SEDs

Sphinx simulations

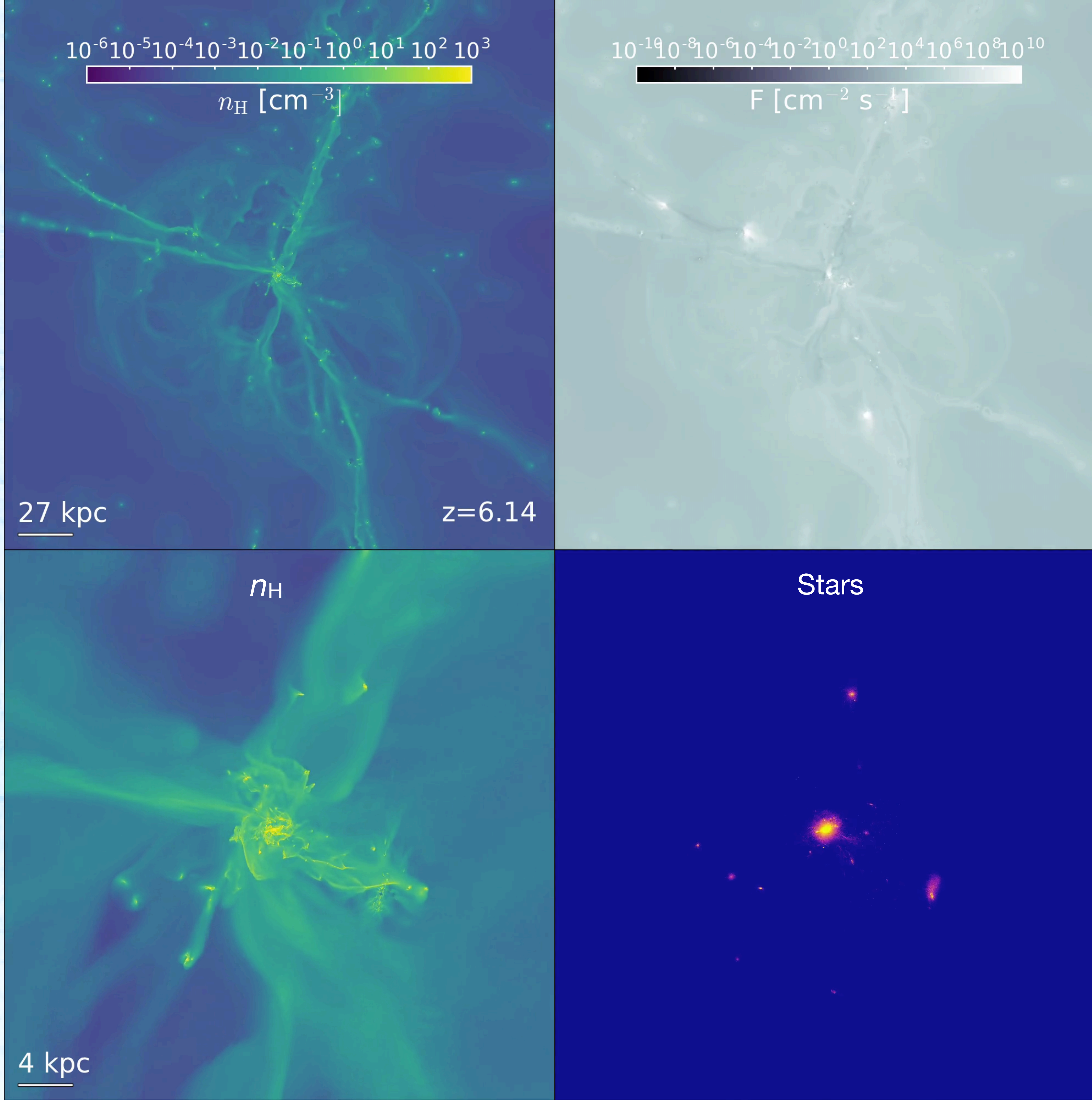


results

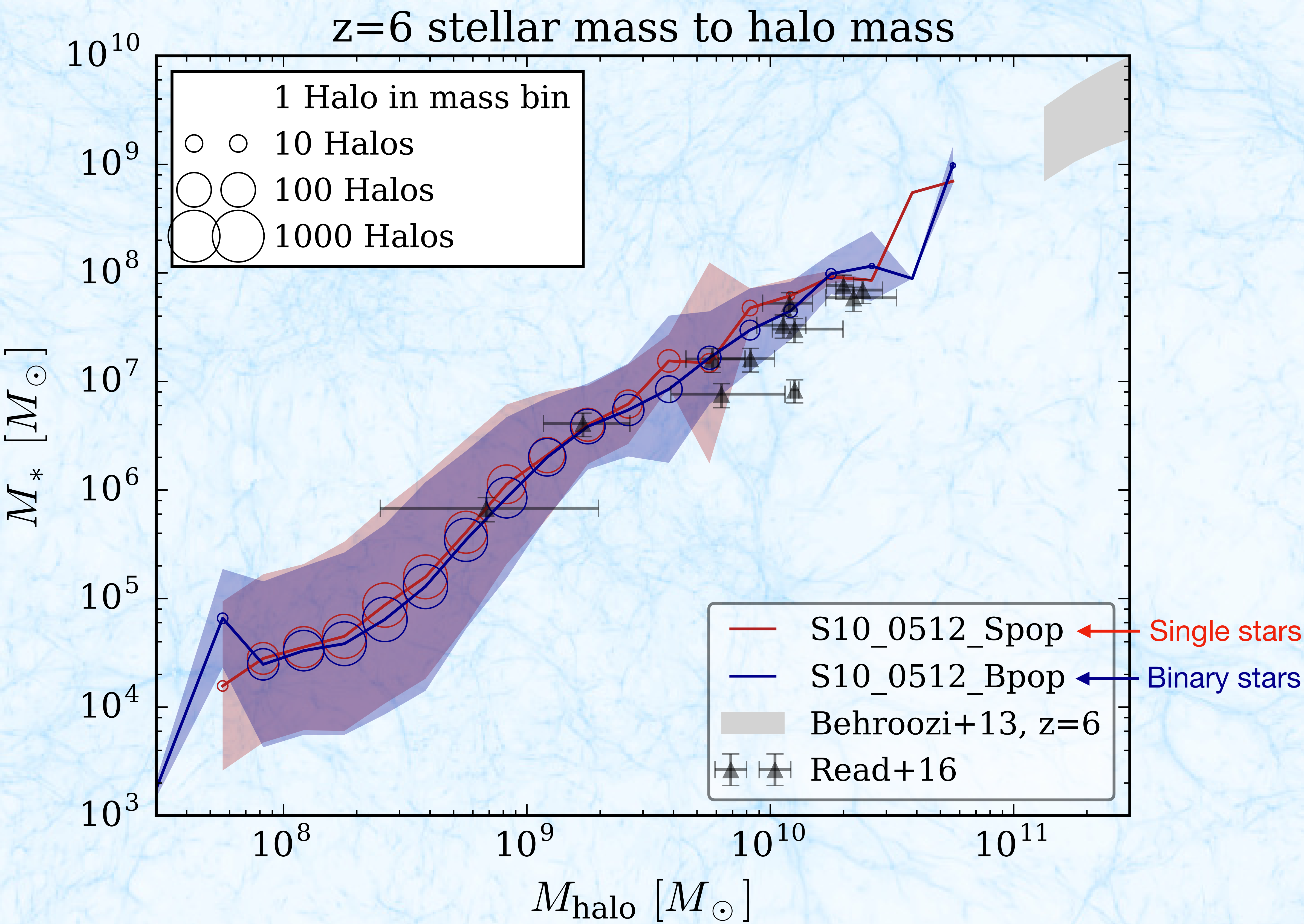
Full
10 cMpc box,
binary SED:



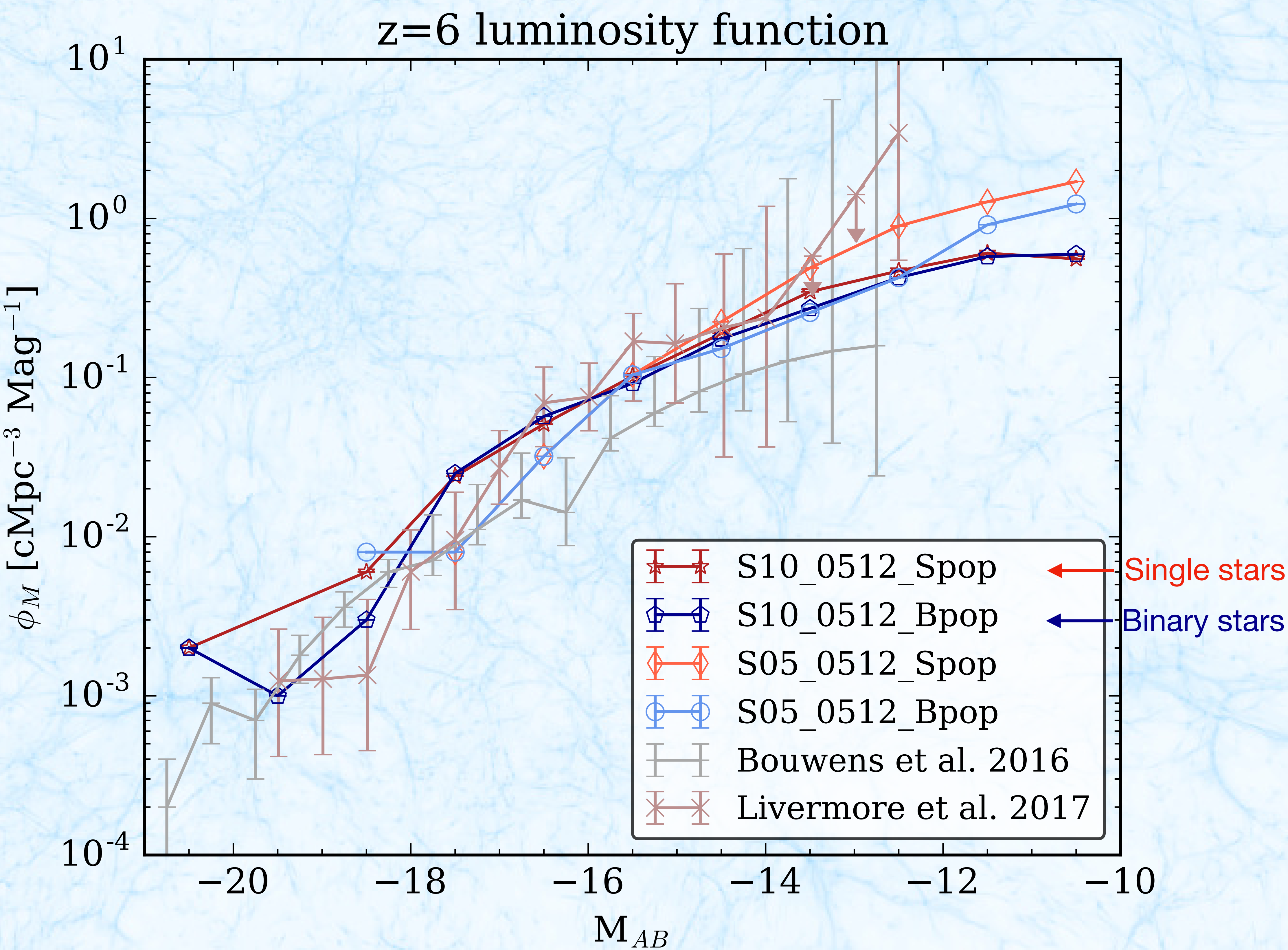
10 cMpc box, binary SED, a closer look



Stellar mass to halo mass

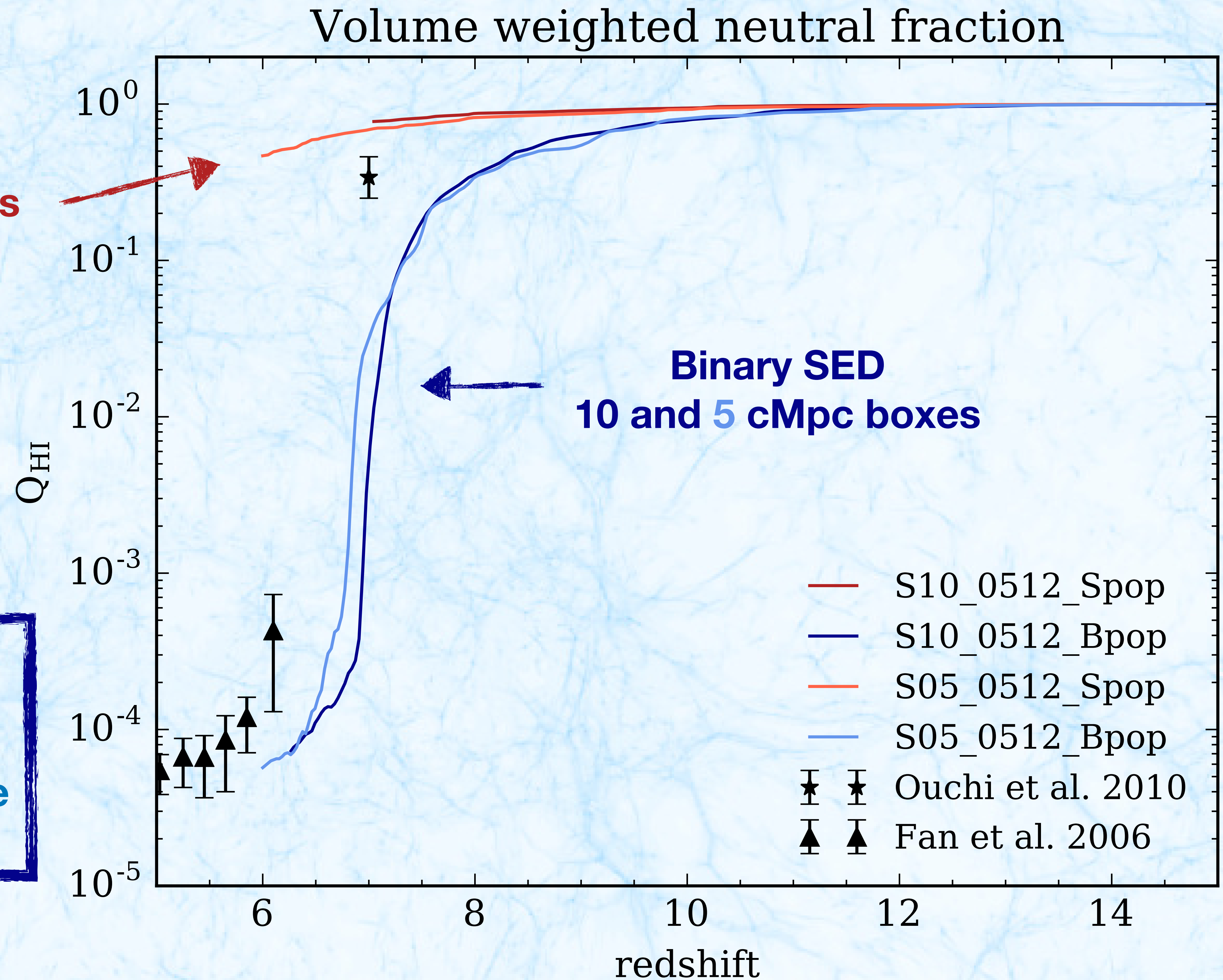


Luminosity function



Reionisation history
binary vs single SEDs

Single stars SED
10 and 5 cMpc boxes



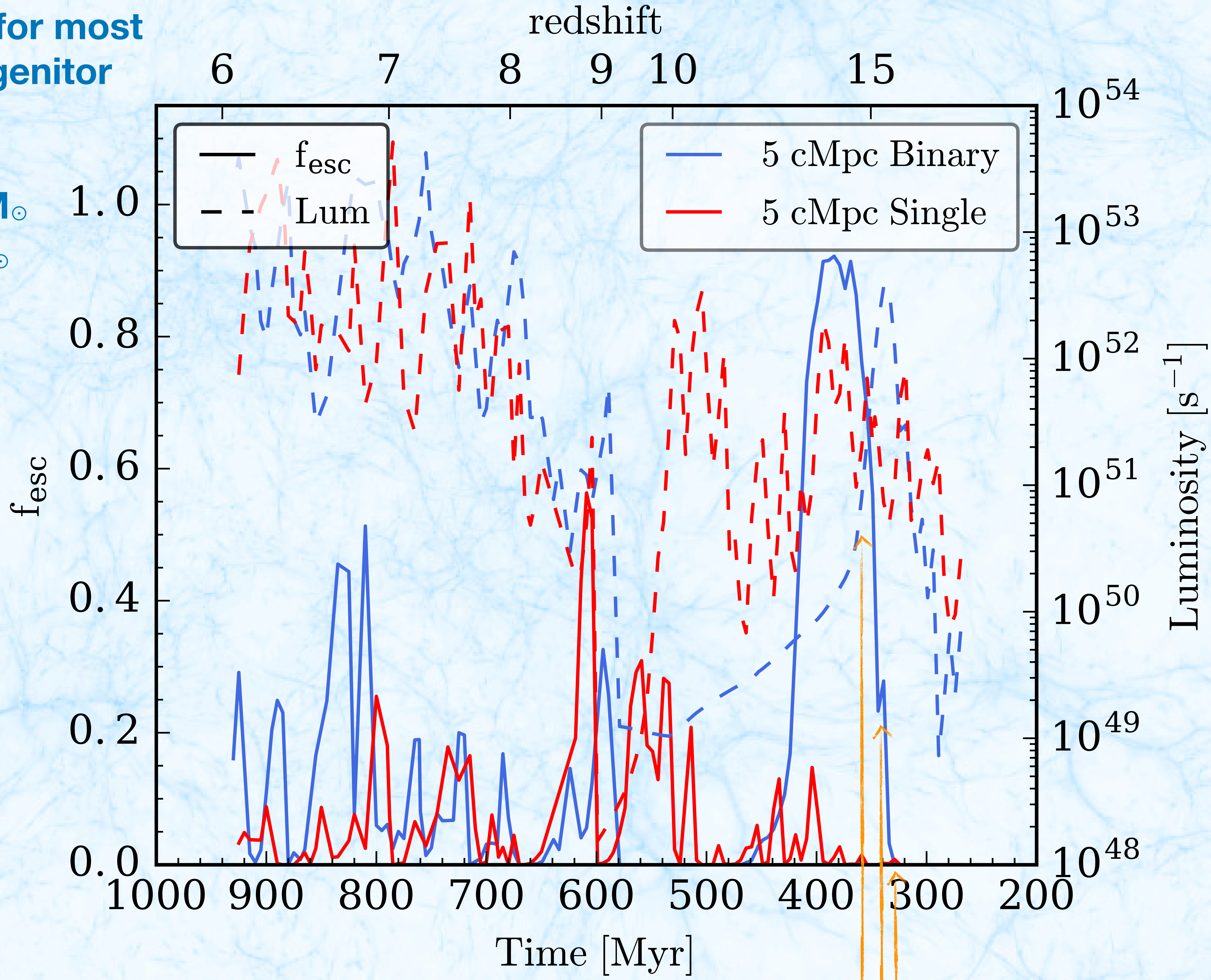
Binary SED
10 and 5 cMpc boxes

Much more efficient reionsiation with binary populations, independent of box size and mass resolution

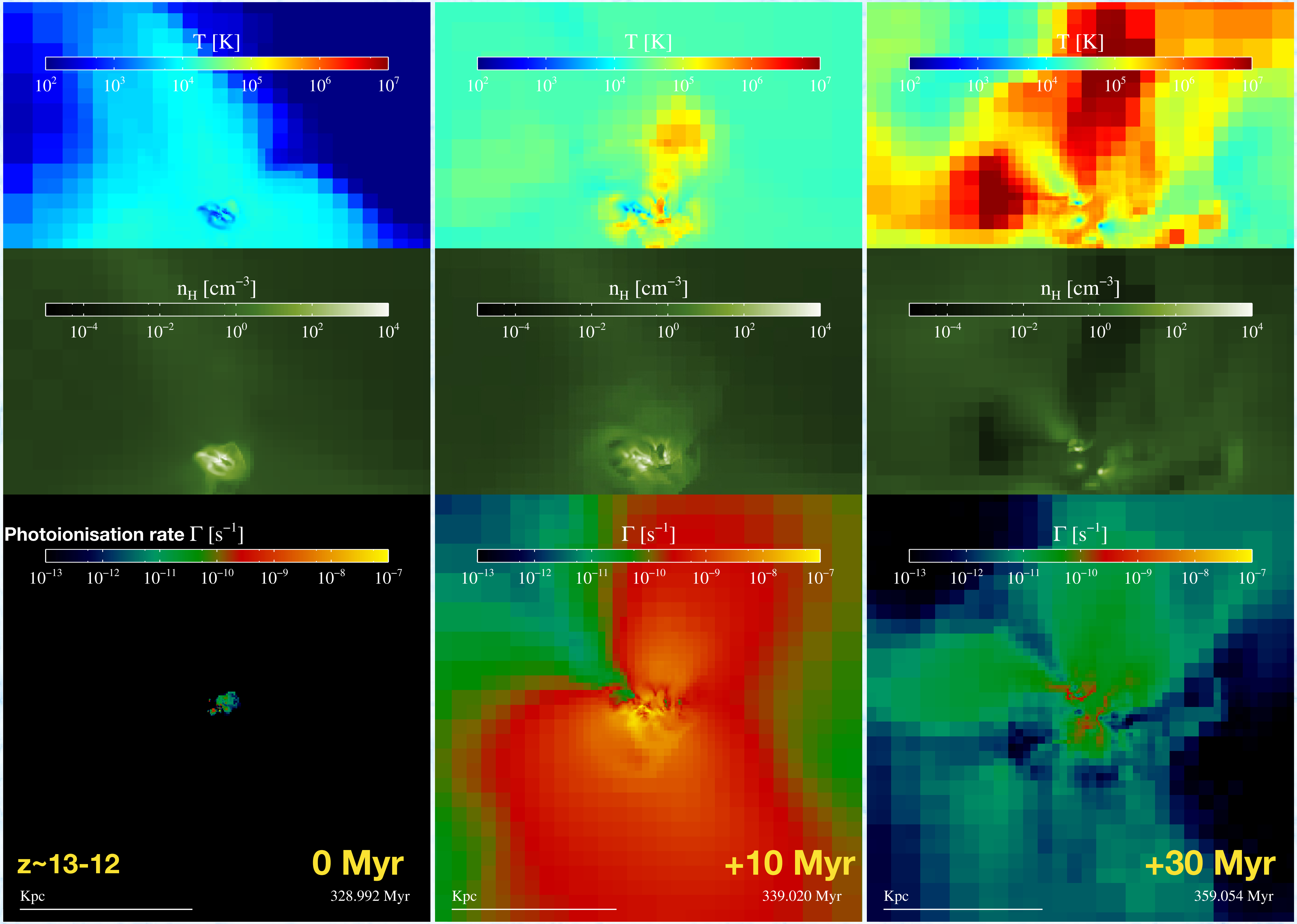
The interplay of feedback and f_{esc}

Escape fractions for most massive halo progenitor in smaller box

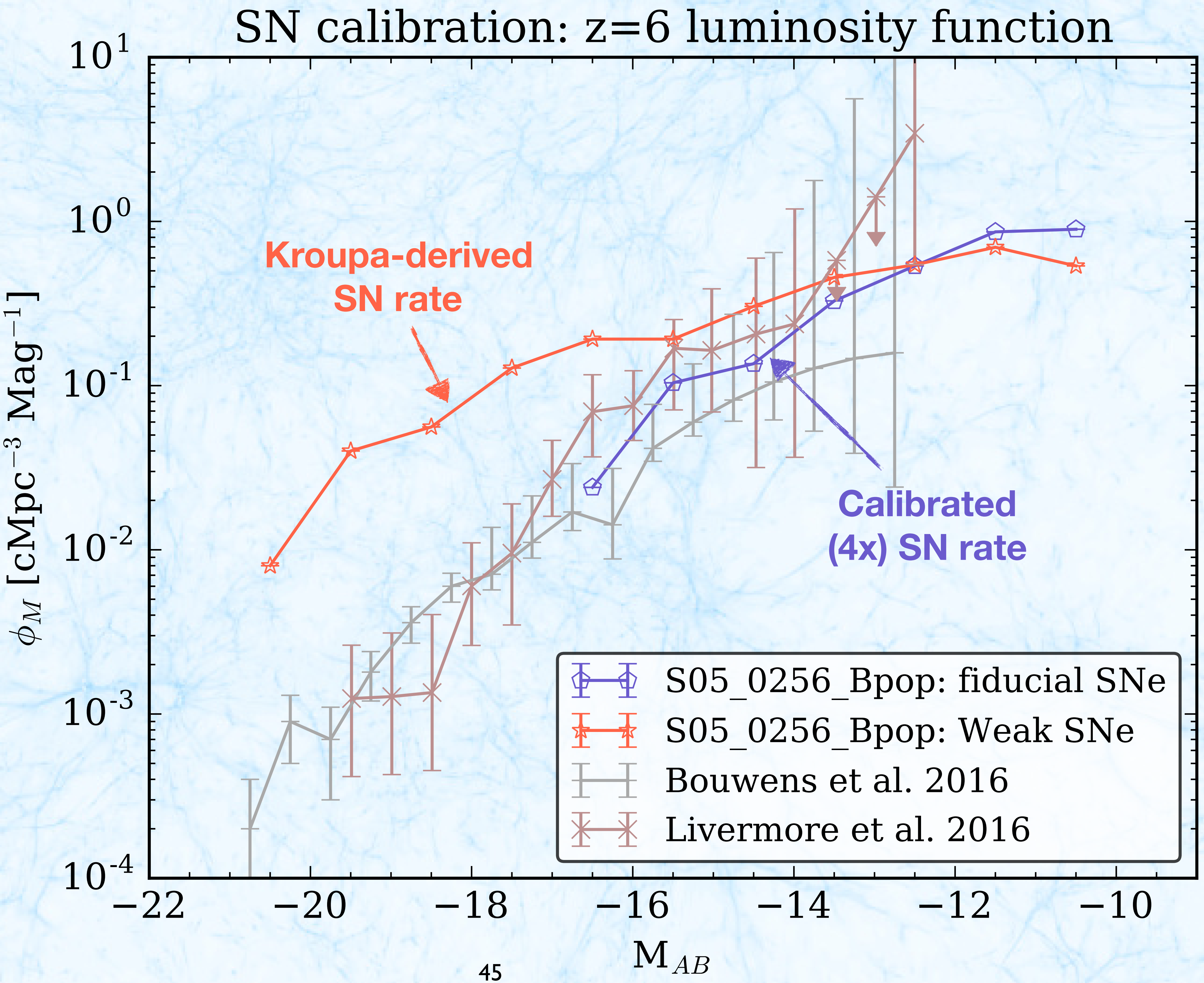
$M_{halo}(z=6) \sim 10^{10}\ M_\odot$
$M_{star}(z=6) \sim 10^{8}\ M_\odot$



The interplay of feedback and f_{esc}



The need for SN calibration



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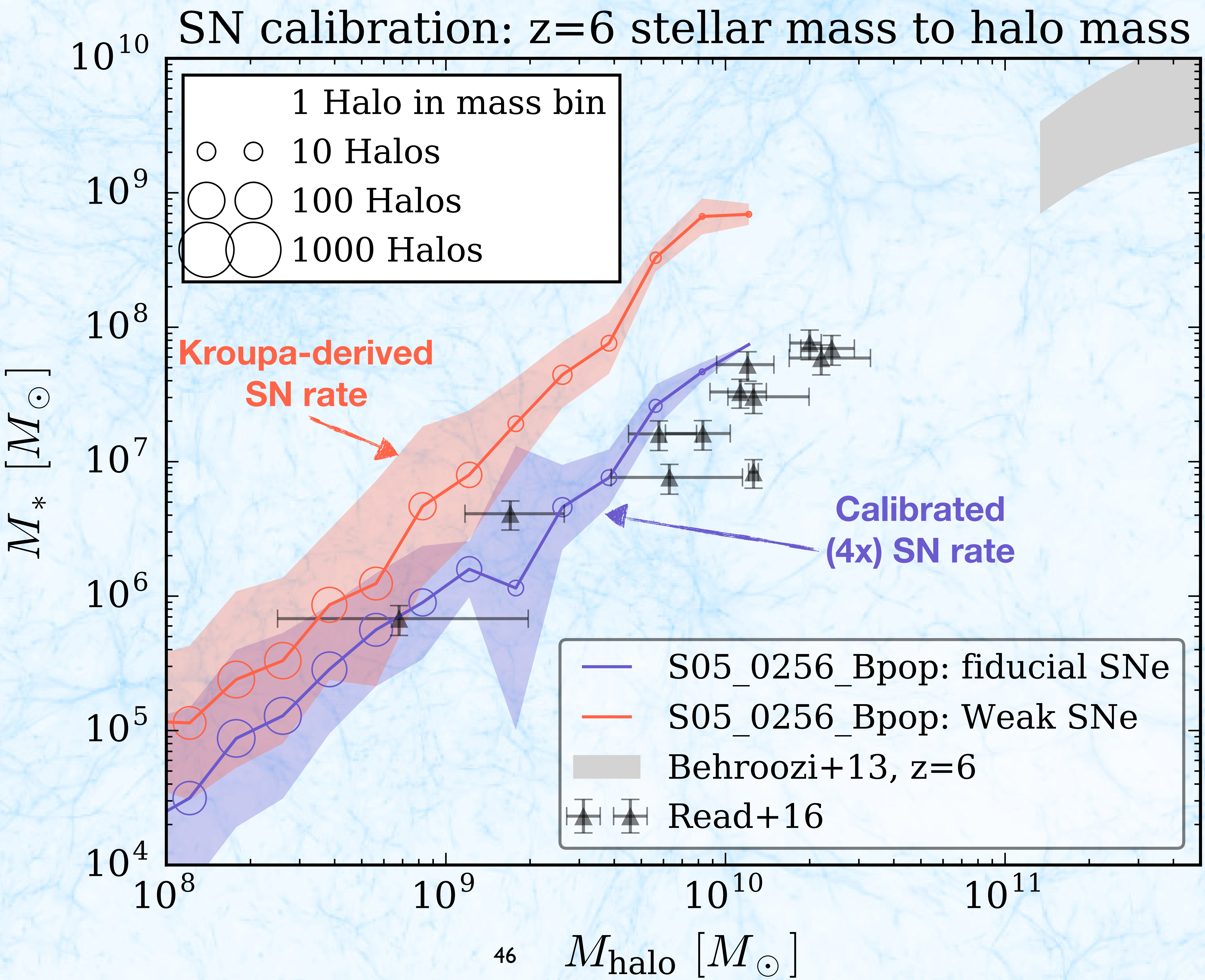
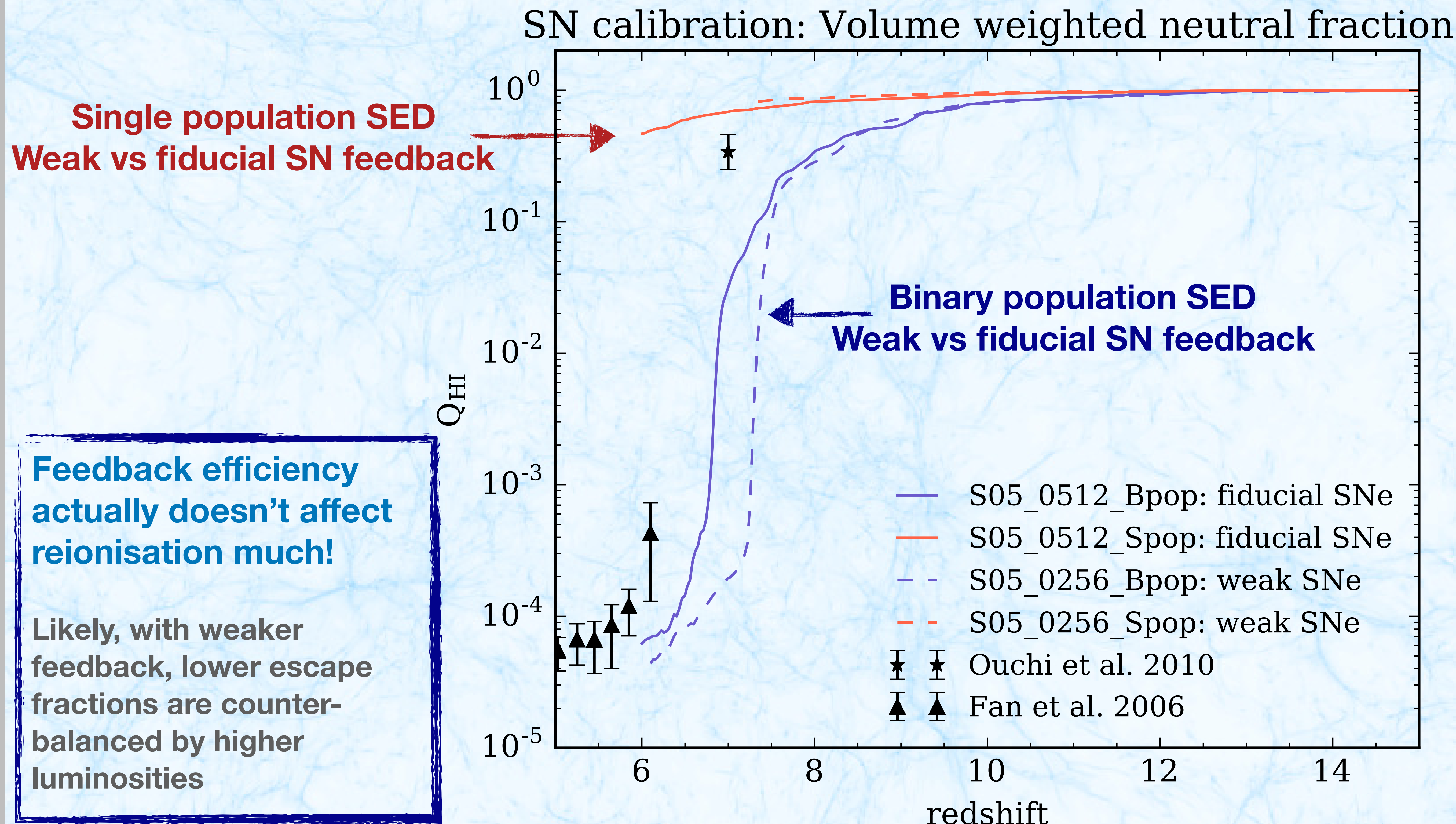


Reionisation history
with un-calibrated SN feedback

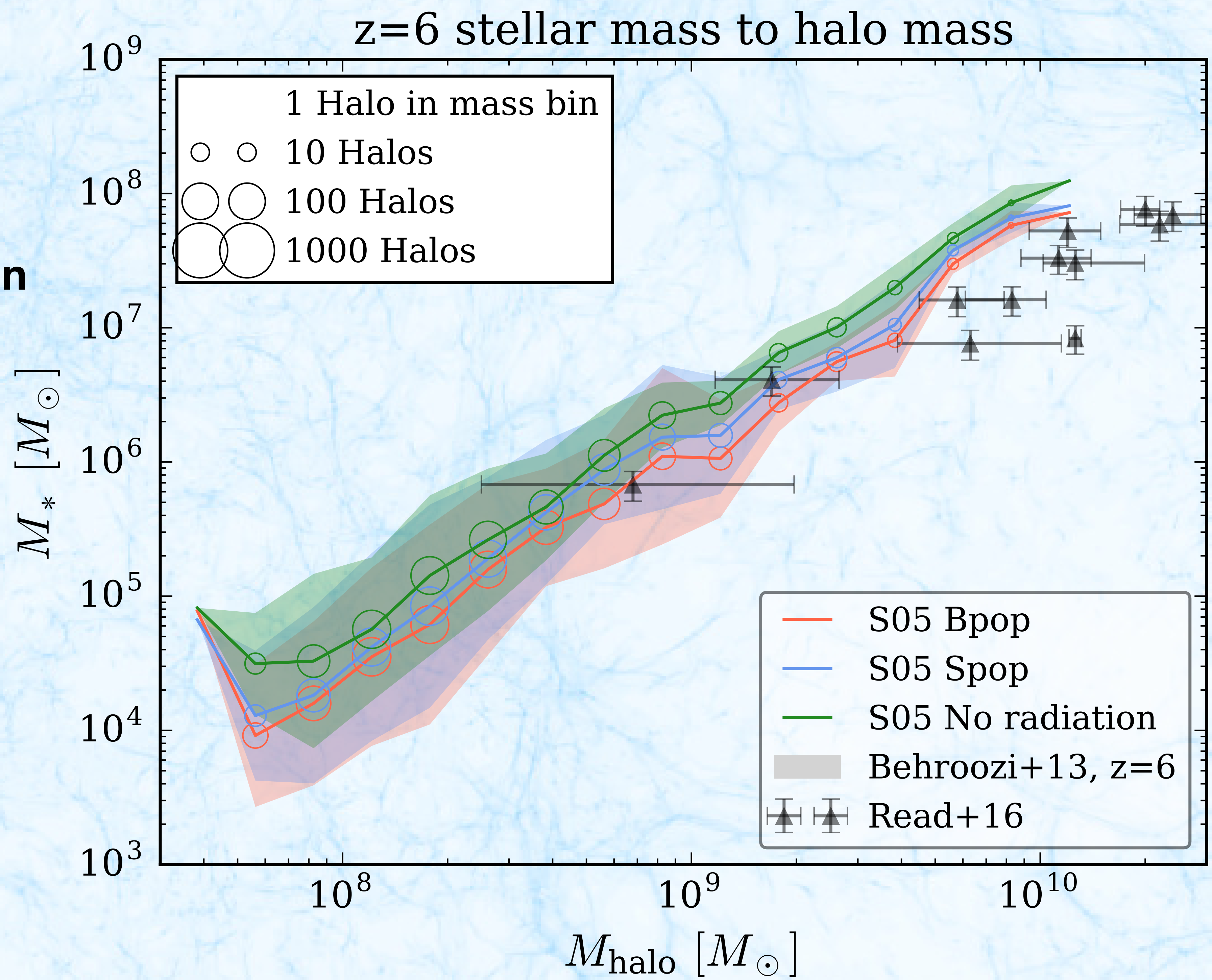


Feedback efficiency actually doesn't affect reionisation much!

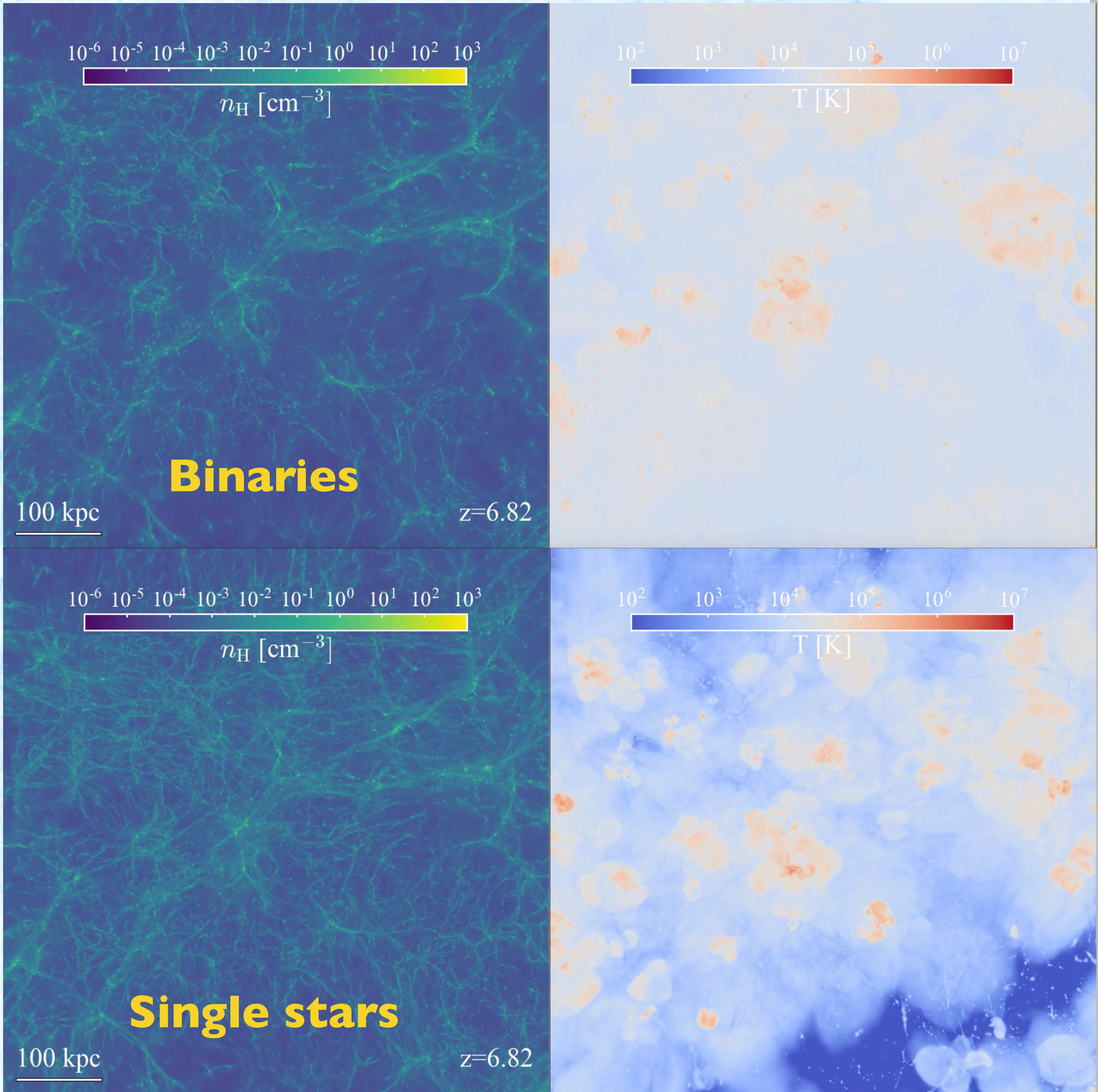
Likely, with weaker feedback, lower escape fractions are counter-balanced by higher luminosities

Radiation feedback

Radiation has some effect in suppressing star formation

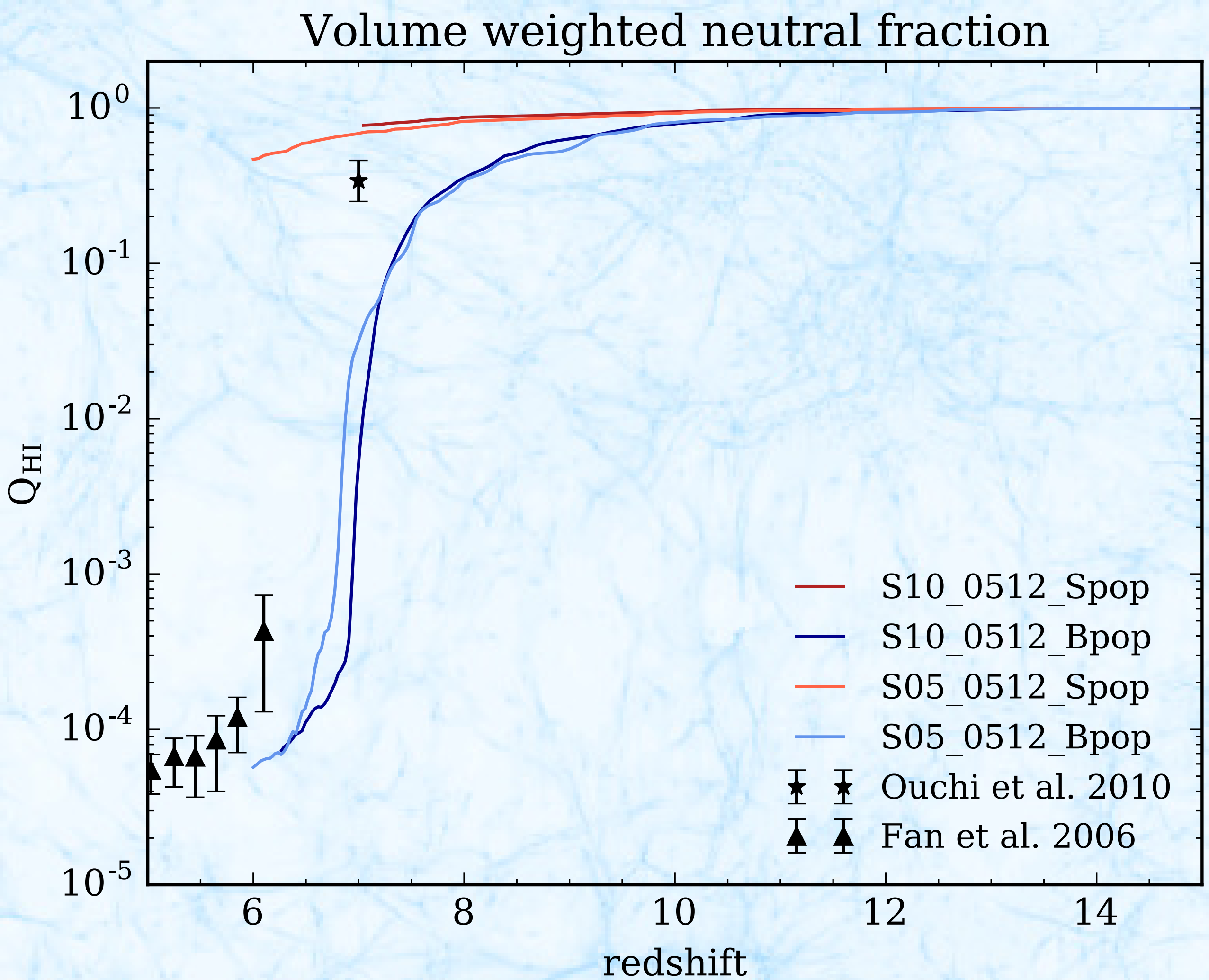


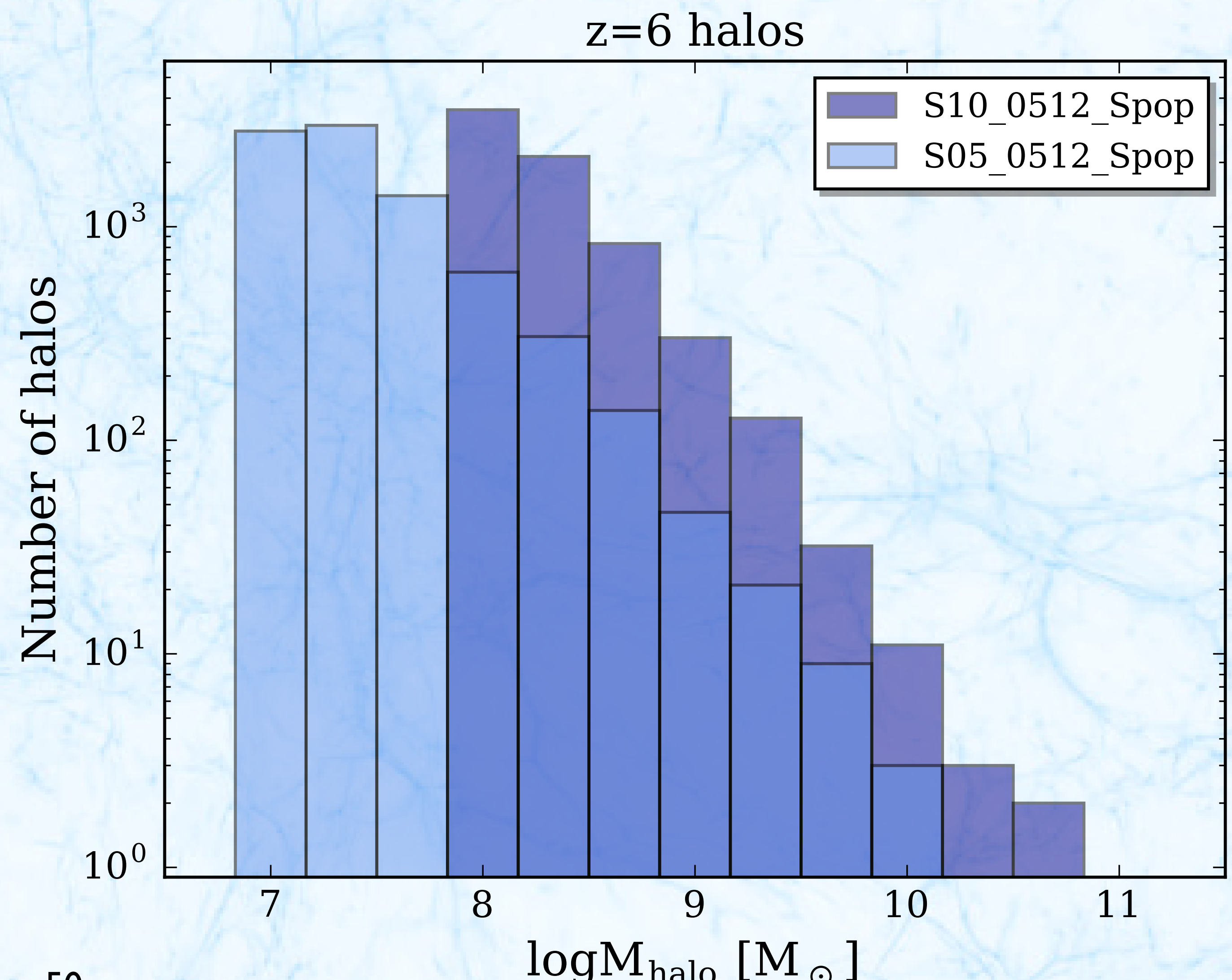
Effect of more IGM photons with binary populations



What are the sources of reionisation

Working on that, but first hypothesis is intermediate mass halos, since boxes of different sizes produce very similar reionisation histories





Summary and future

- The Sphinx simulations are the first cosmological RHD simulations of full reionisation that resolve the ISM of galaxies

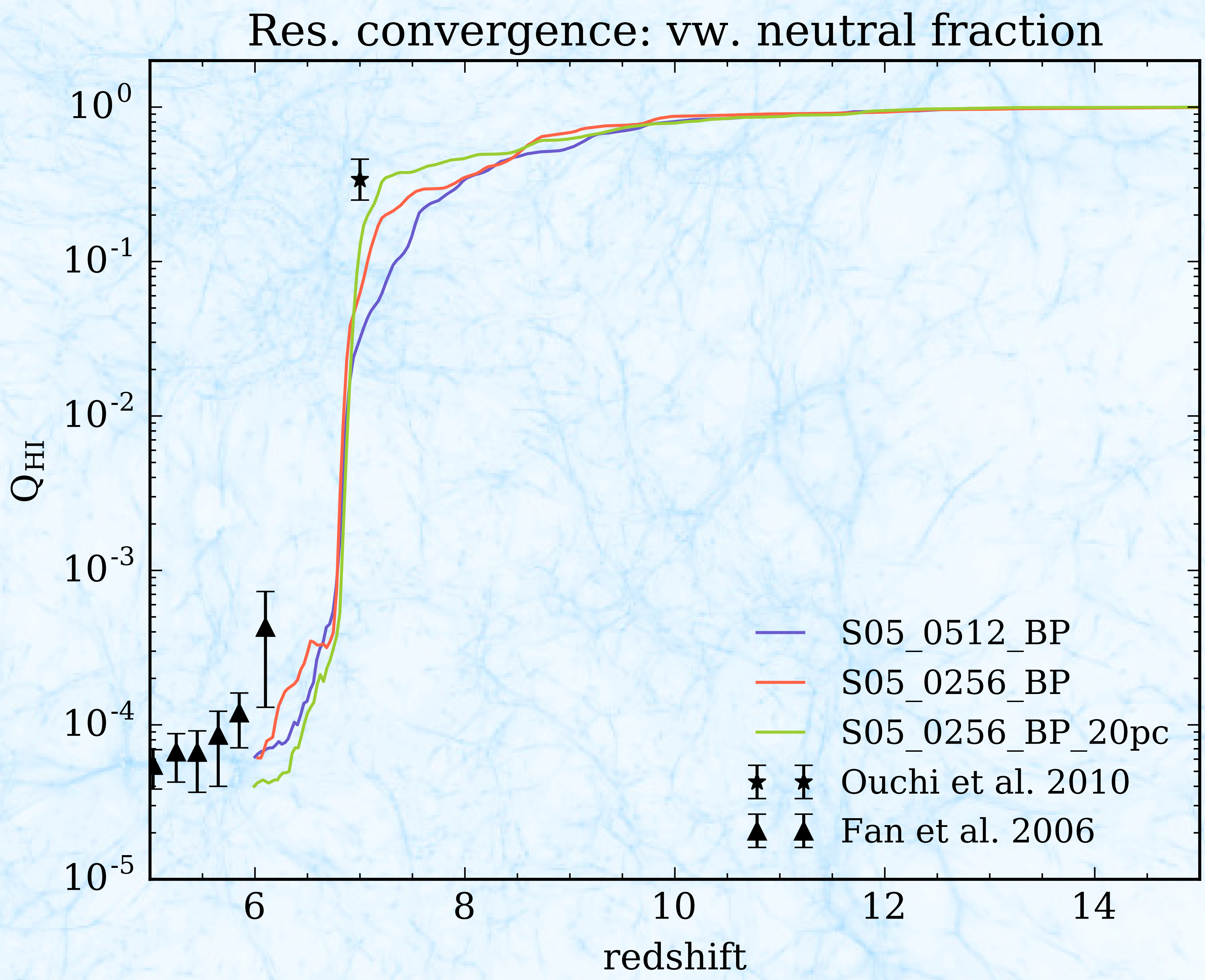
- Stay tuned for pilot paper:
    - Stellar populations with binary systems really speed up reionsiation!

- More papers to follow:
    - Lyman-alpha signatures of simulated galaxies
    - Which galaxies contribute to reionisation
    - Suppression of galaxy growth in ionisation bubbles
    - Metal-enrichment of the inter-galactic medium

- Then
    - Larger boxes: more and more massive galaxies

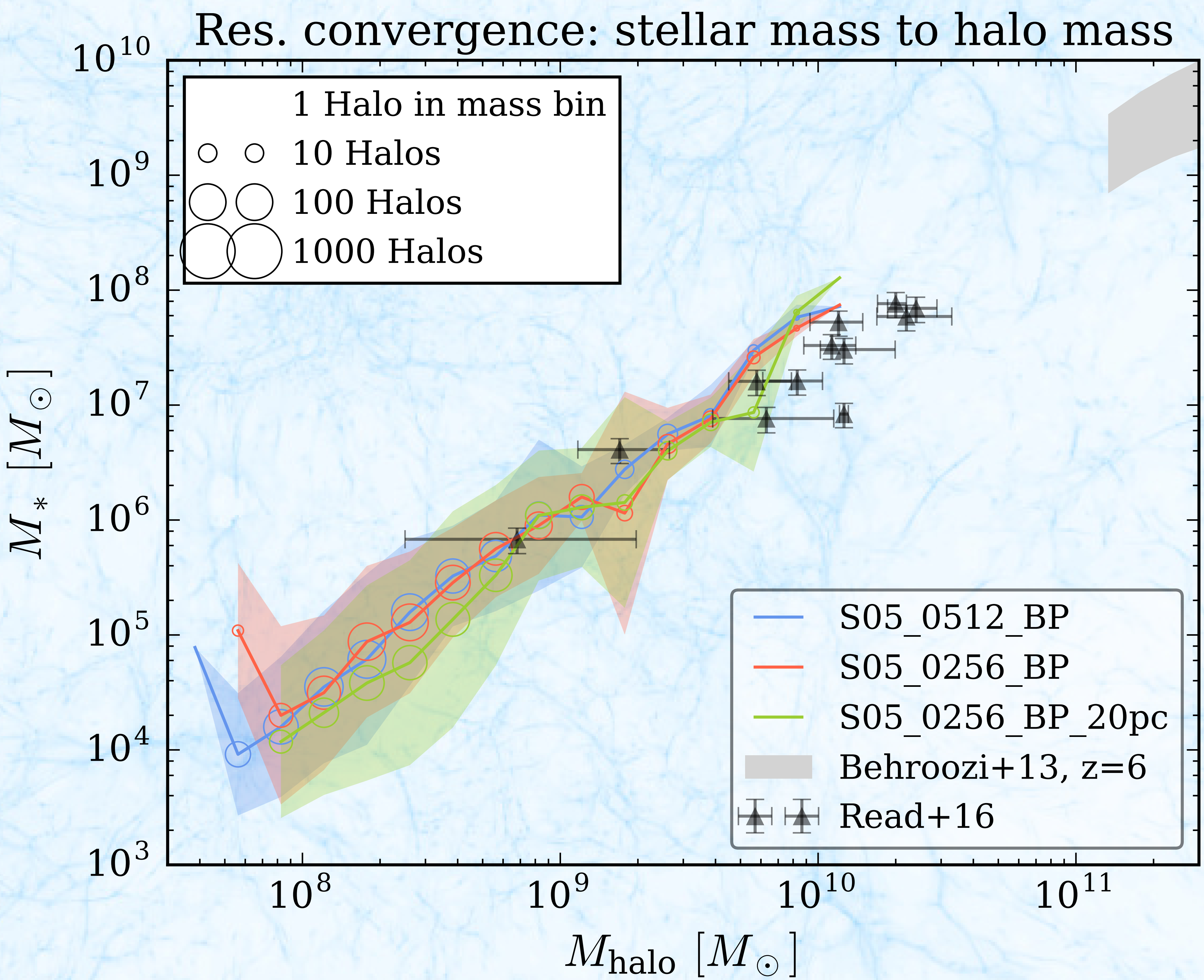
Resolution convergence

reionisation history



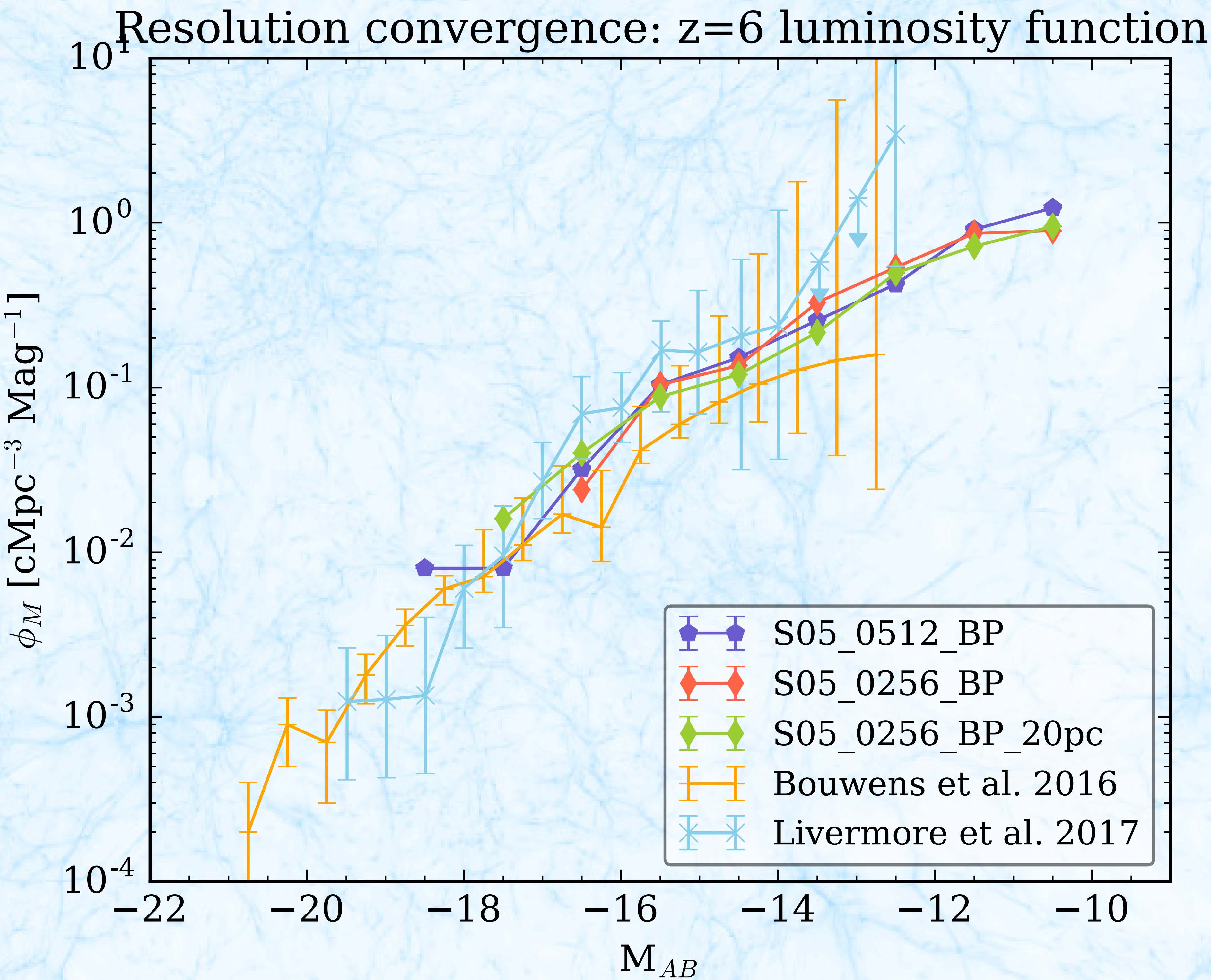
Resolution convergence

reionisation history



Resolution convergence

reionisation history



Resolution convergence

reionisation history