The SPHINX simulations of the first billion years and reionisation

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With

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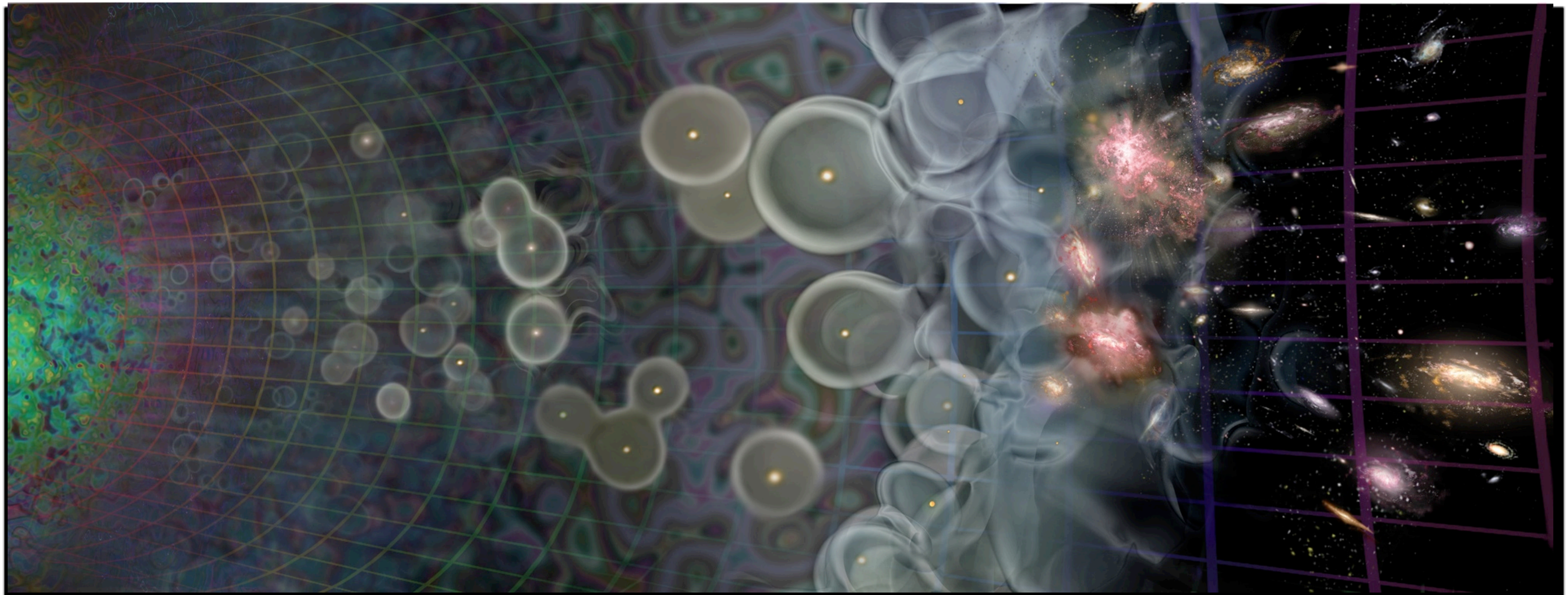
The first billion years and reionisation



1st stars and reionisation

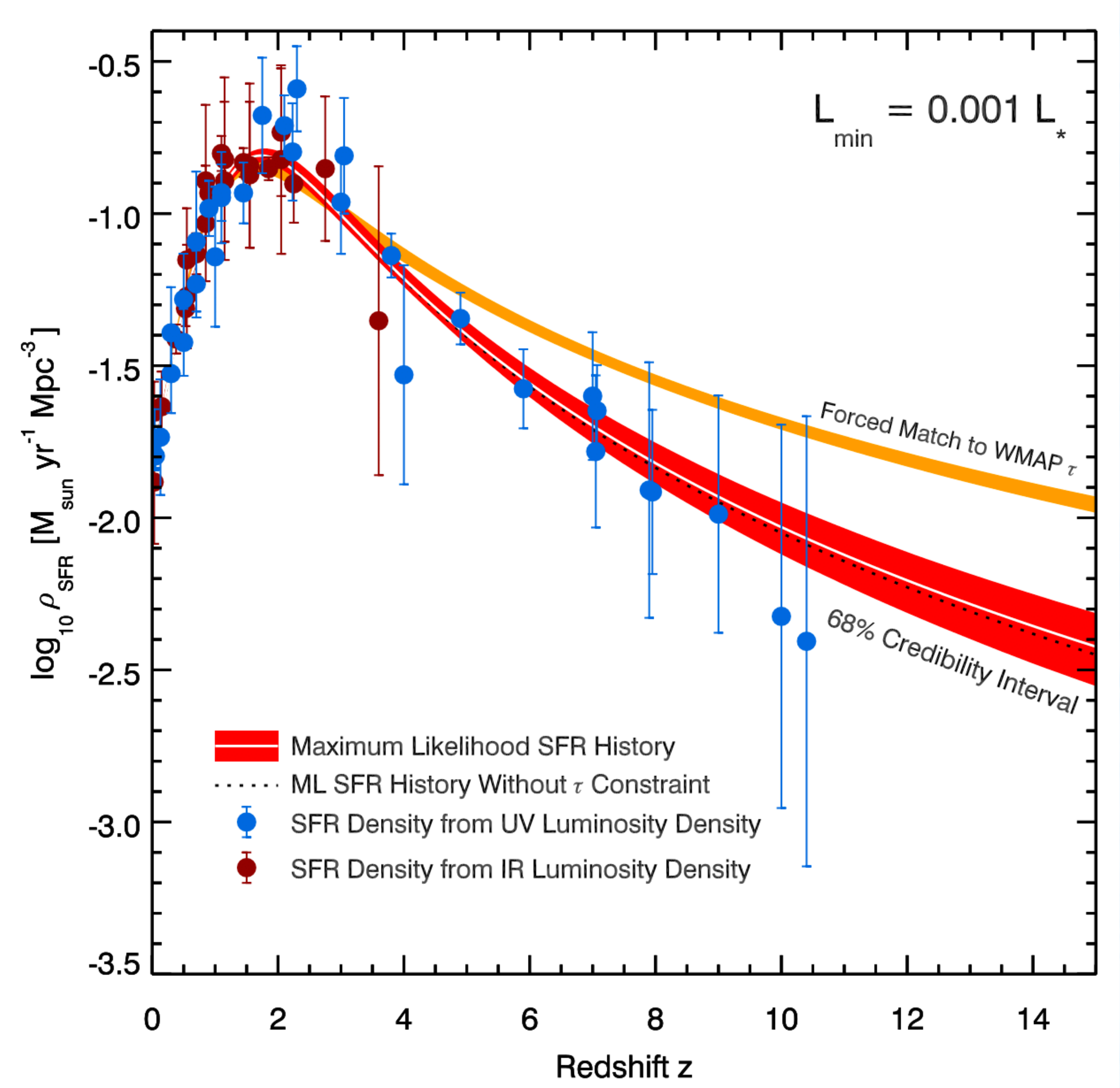
- A neutral and metal-poor Universe becomes ionized and metal-rich
- We know it happened, but not so much how and when, and what sources powered it
- For this non-linear, multi-scale, multi-physics problem, simulations are the best way to gain an understanding

Credit: Abraham Loeb, Univ. Colorado

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

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

Observationally it is very hard to measure f_{esc}, but indirect measurements in the local Universe give

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

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

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

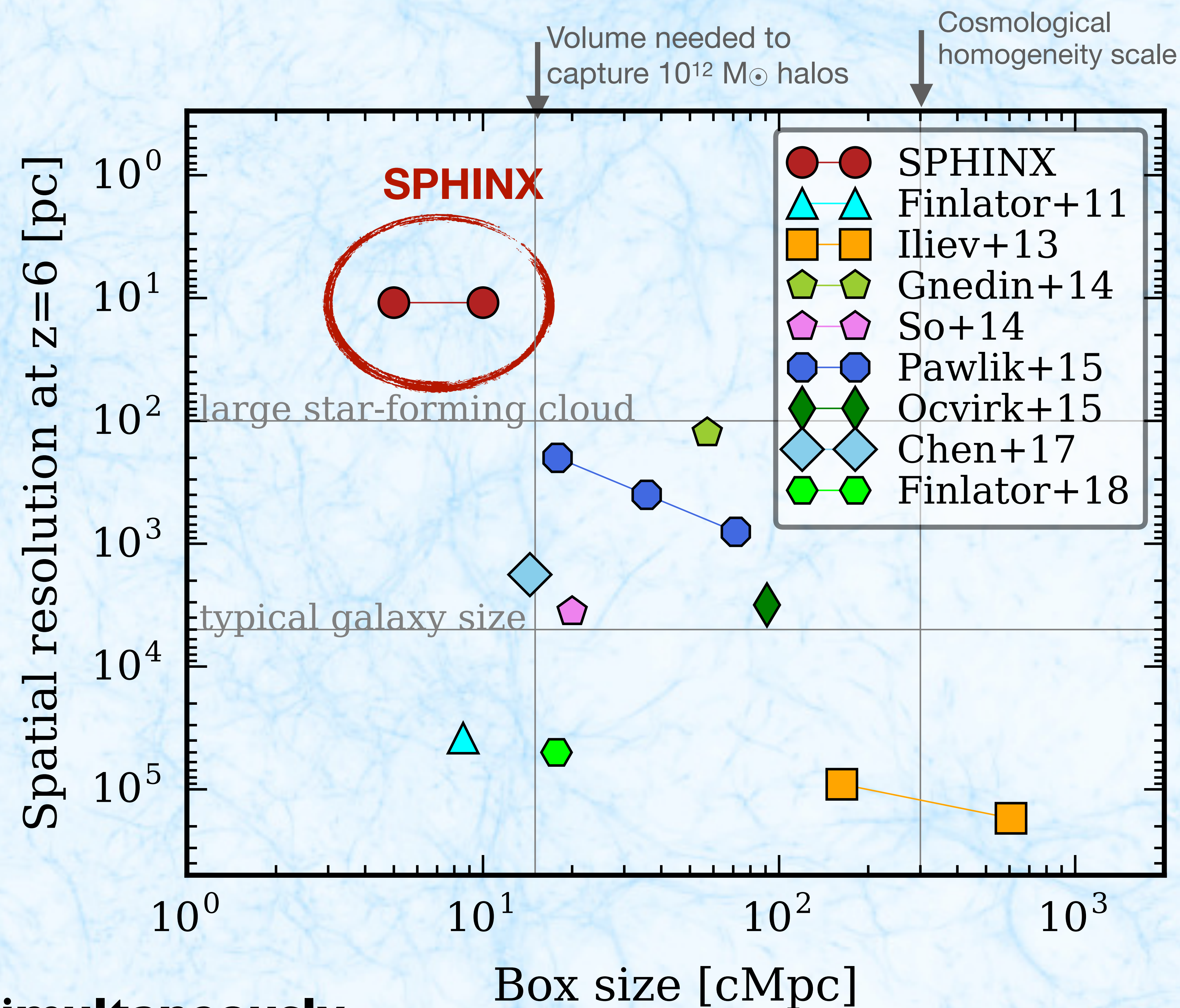
Two classes of reionisation RHD simulations

Radiation-hydrodynamics

Large volume with unresolved galaxies	Hard to do large volumes with resolved galaxies	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. Ionising escape fraction (f_{esc}) is a free parameter. Low-mass halos are not captured. Good for the large-scale reionisation process, clustering, patchiness. Not-so-good for understanding the (unresolved) sources of ionisation.	**SPHINX simulations**	Production of ionising radiation and f_{esc} resolved. But the large scale reionisation process is not captured (nor the actual contribution from individual sources).

SPHINX in the context of cosmological RHD simulations

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



With SPHINX, we can simultaneously

- **resolve f_{esc} from thousands of galaxies in one volume**
- **predict the reionisation history**

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

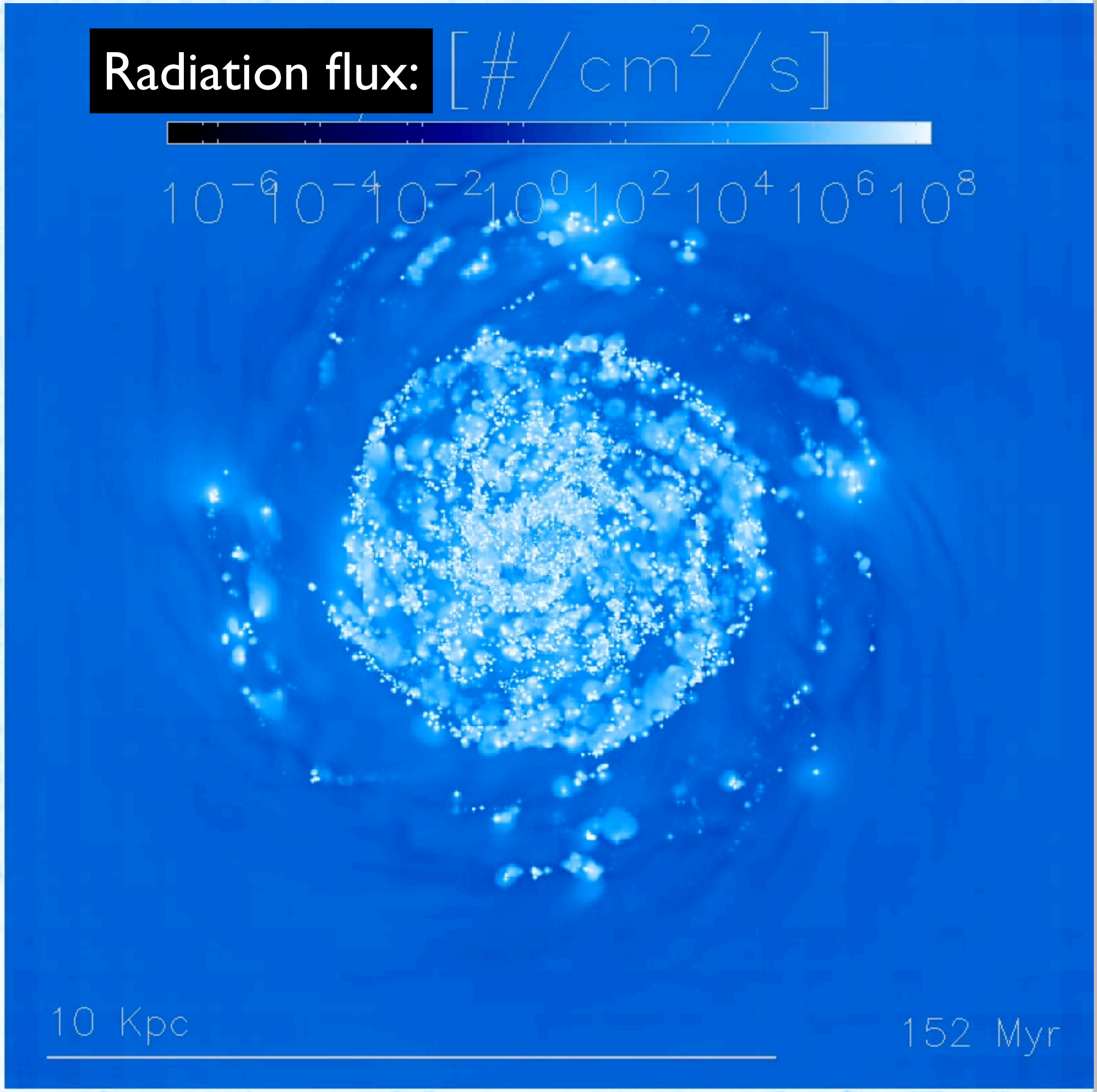
7 dimensions!!
position, time, frequency, angle

- Moment method for radiation to reduce the angular dimensions
➡ unlimited number of sources

- Reduced light-speed to speed up implicit RT-solver

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

- Publicly available



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. This is incompatible with the reduced speed-of-light approach.

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 perform large-scale reionisation simulations that resolve individual galaxies.

Computing resources

I applied for PRACE time in 2016 and received 13.6 million cpu-hours to perform the Sphinx simulations on the SuperMUC supercomputer in Munich.

The main simulations ran on 5600 cores in ~3 M cHrs each.
Each output is ~200 GB. Total storage is ~40 TB per simulation

PRACE
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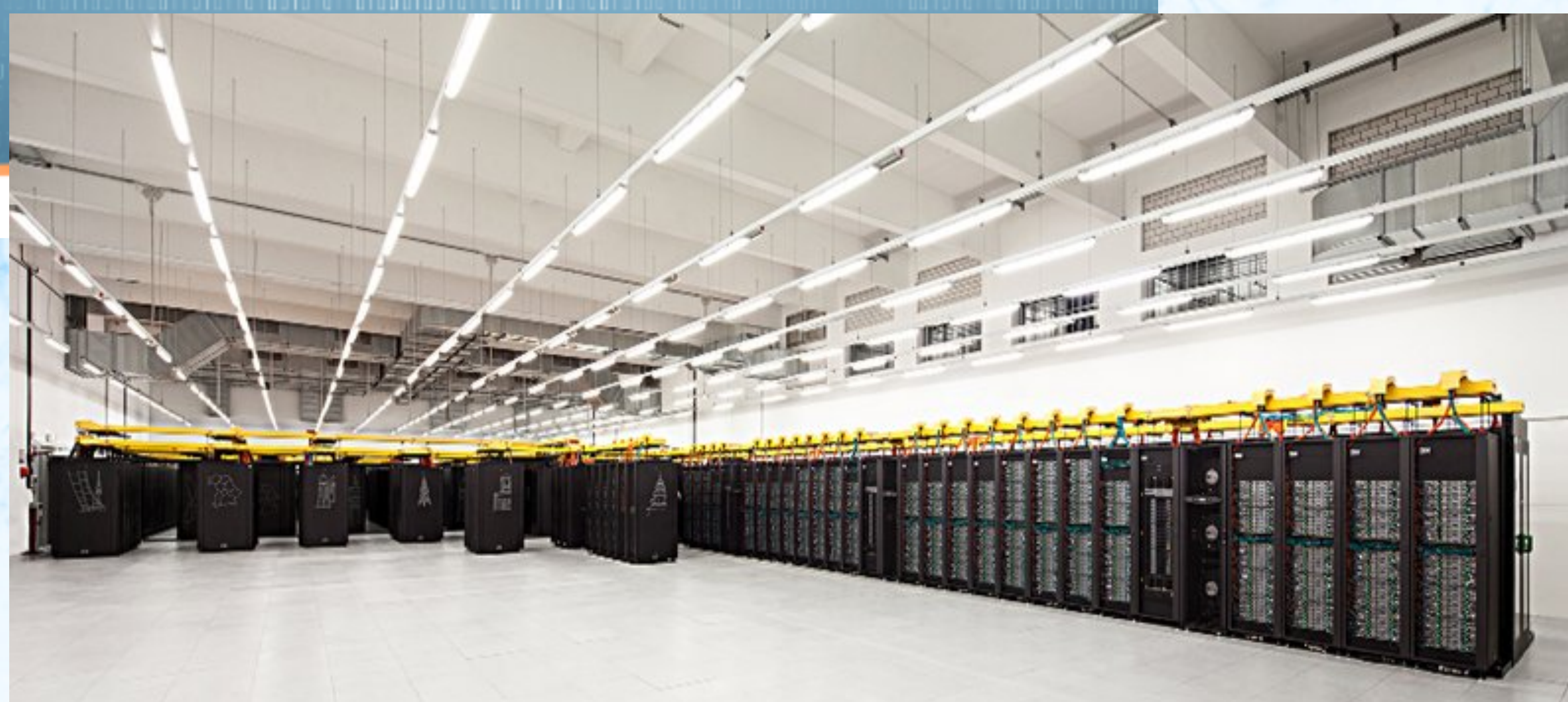


Project goals

- 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? (Rosdahl et al., MNRAS.479..994R)

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

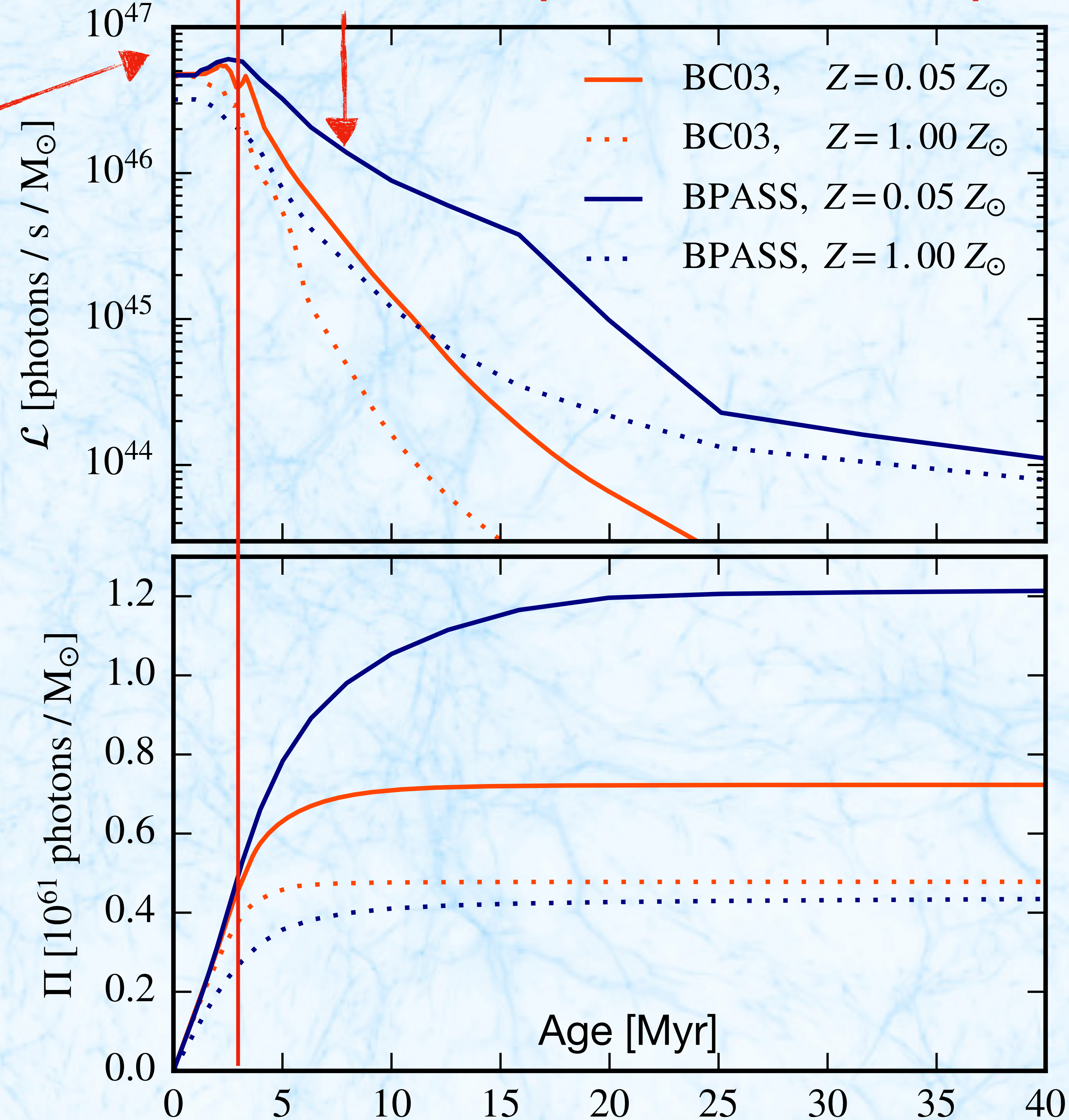
- The reason: longer and stronger radiation due to mass transfer and mergers in binary systems

SEDs (Spectral Energy Distribution models for stellar populations)

~ 3 Myr:
massive stars start to explode

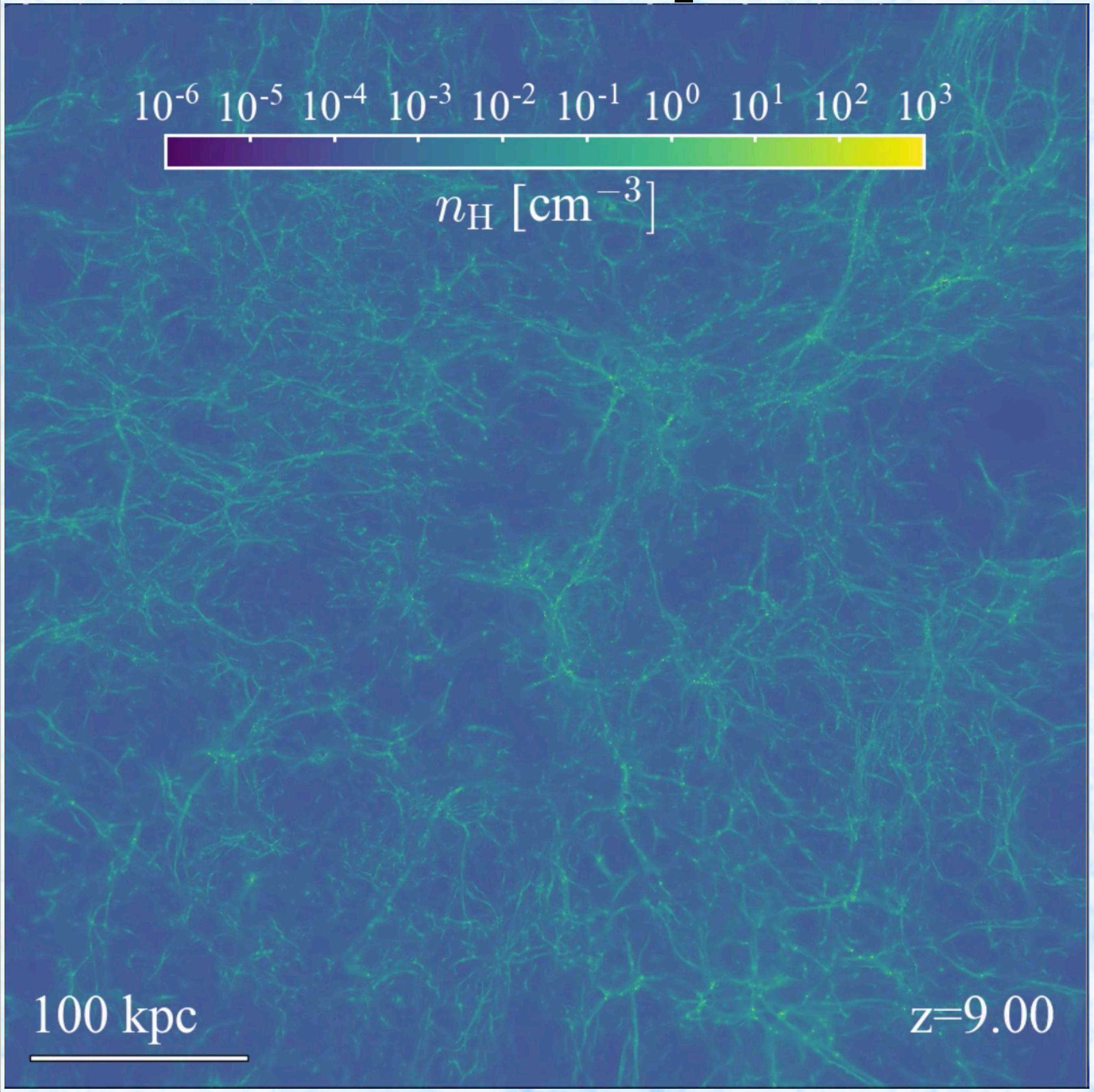
After ~ 3 Myr:
cloud disrupted and radiation escapes

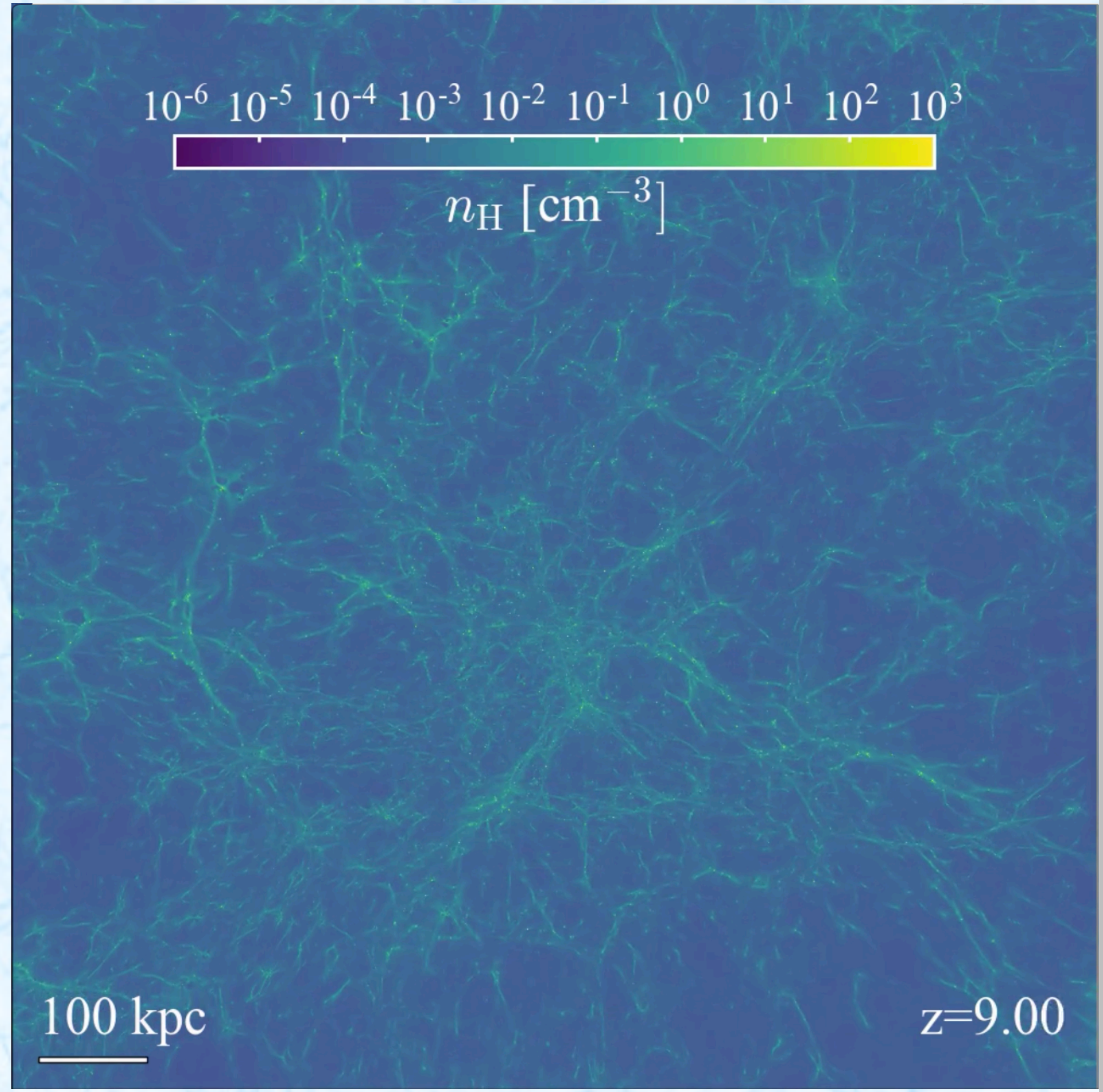
Before ~ 3 Myr:
radiation absorbed by dense ISM



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

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

SPHINX setup

- **Physical resolution** $\Delta x > 10$ pc

- **DM mass resolution** of $3\times10^4\ M_\odot$ per particle
  $10^7\ M_\odot$ halo has 300 particles ➢ all potential sources resolved.

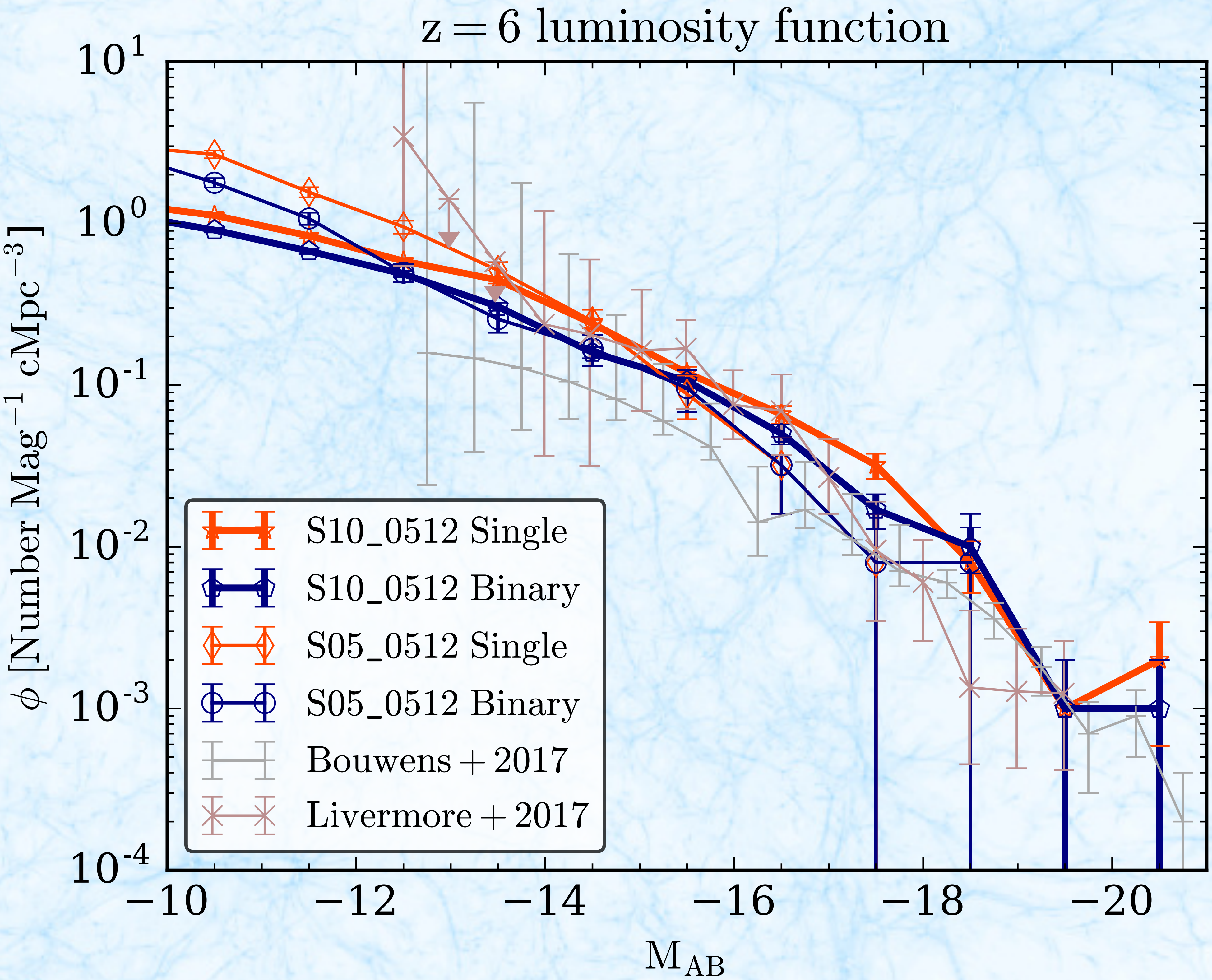
- **Stellar particle resolution** of $10^3\ M_\odot$ (particle = a stellar population)

- *Bursty* **star formation** depends on local virial parameter and mach number
  - Typical local star formation efficiency $\epsilon_{ff} \sim 0.5$ $\dot{\rho}_* = \epsilon_{\rm ff}\rho/t_{\rm ff}$

- **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 compared to Kroupa initial mass function)

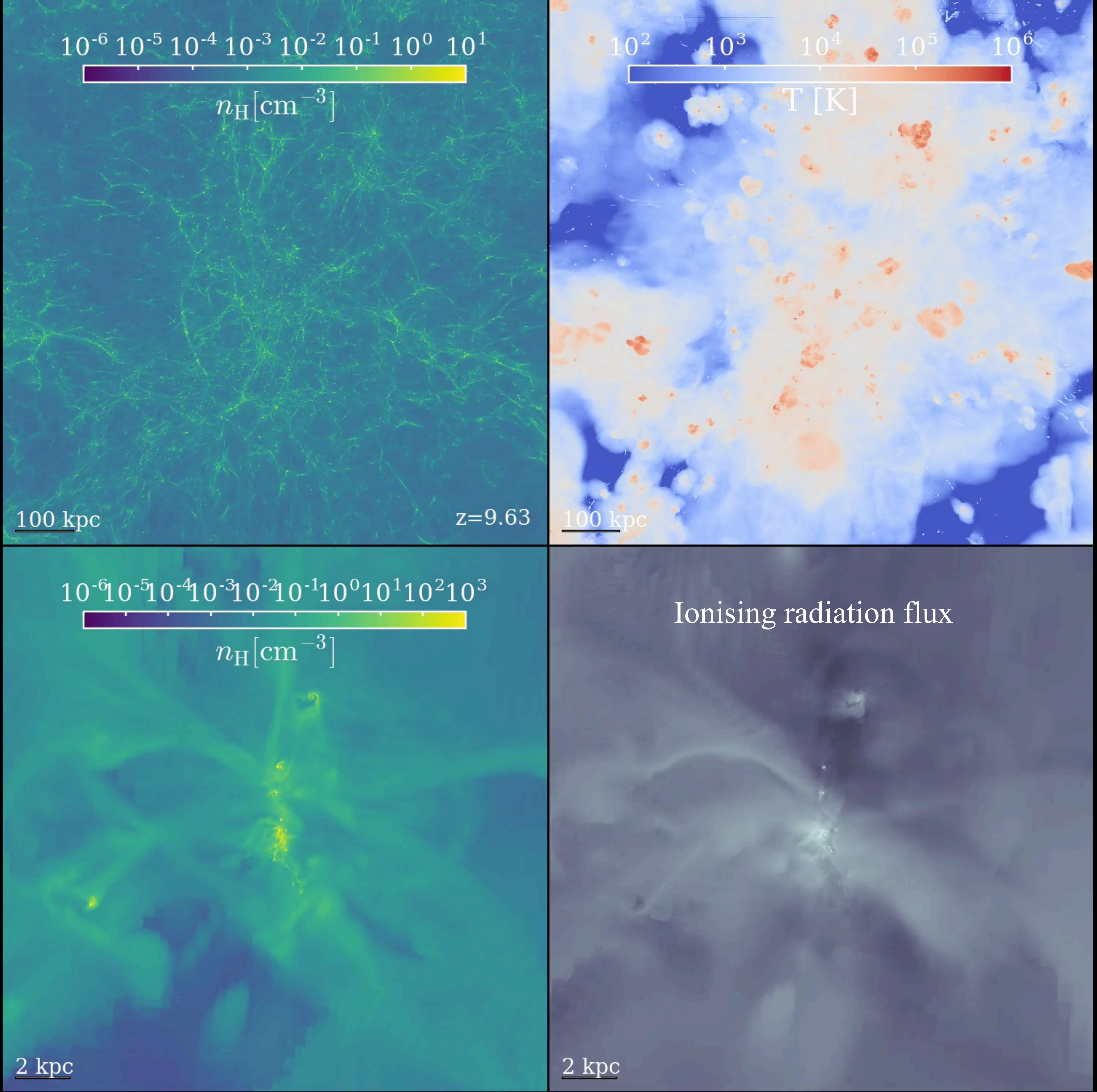
- **No calibration on unresolved f_{esc}** (i.e. we inject the SED luminosity)

- We run with binary and single star SEDs



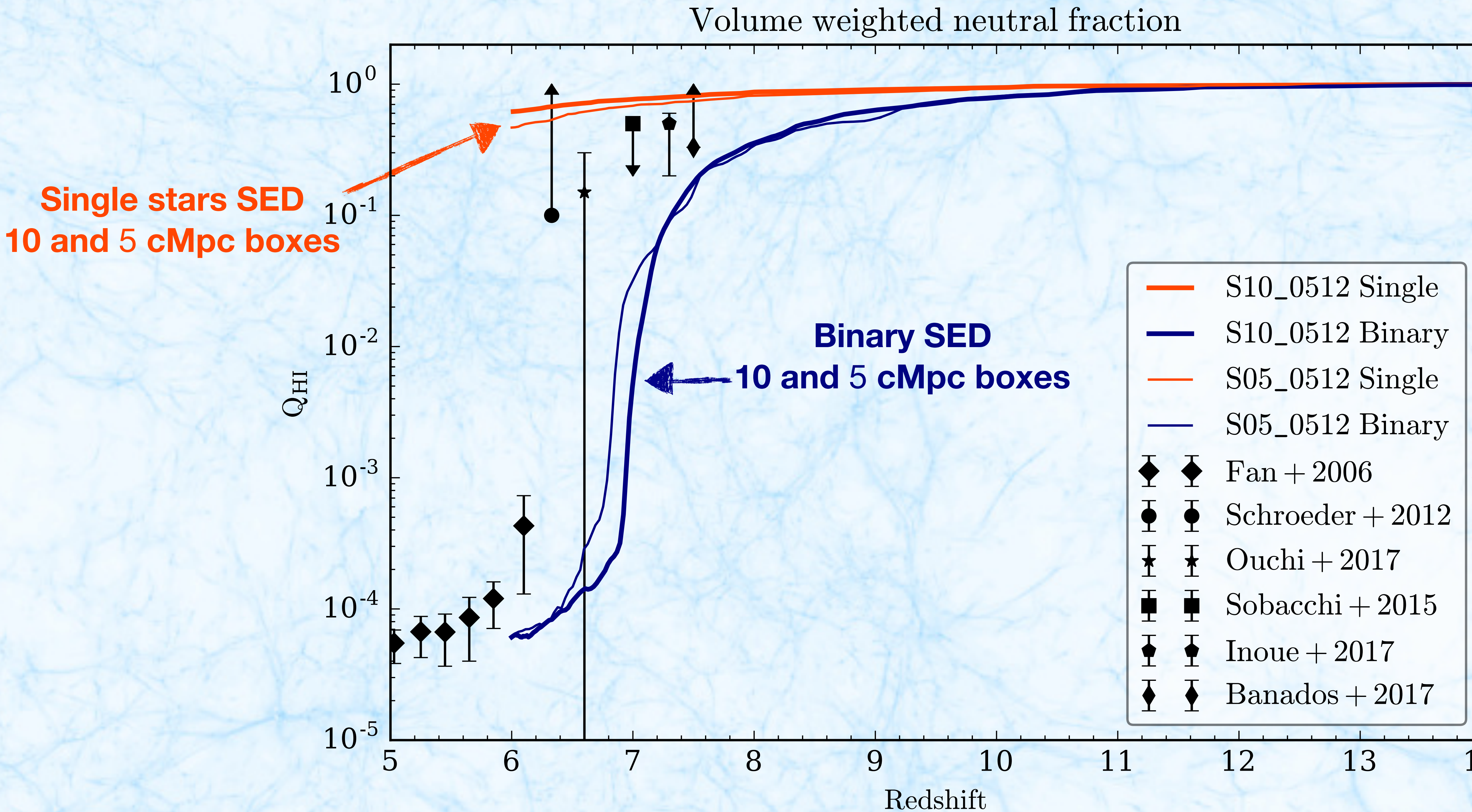
The agreement with observations is thanks to

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



10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}
$n_H [cm^{-3}]$
100 kpc
z=9.63
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}
$n_H [cm^{-3}]$
2 kpc
Ionising radiation flux
2 kpc

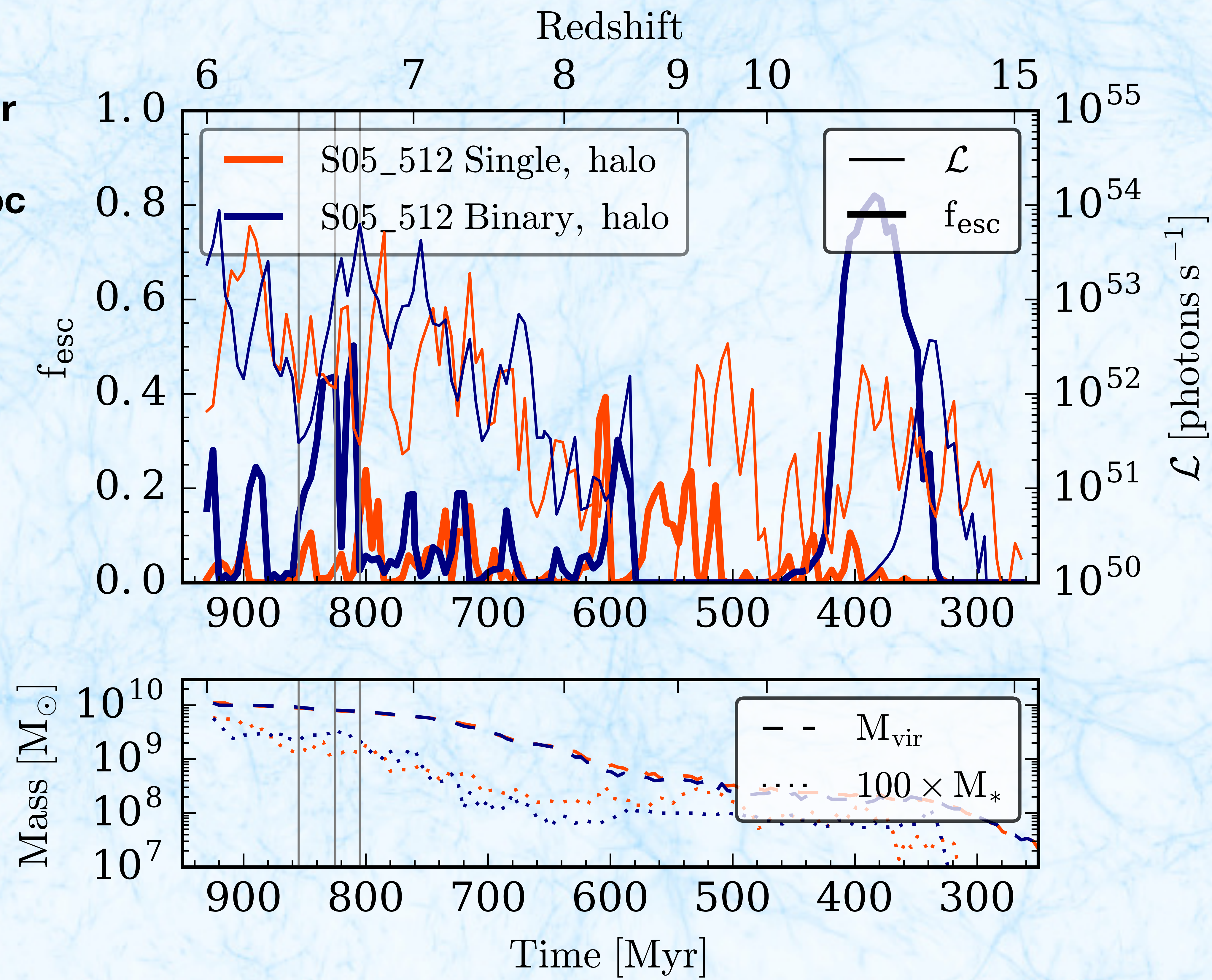
Reionisation history
binary vs single SEDs



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

f_{esc} for a single halo

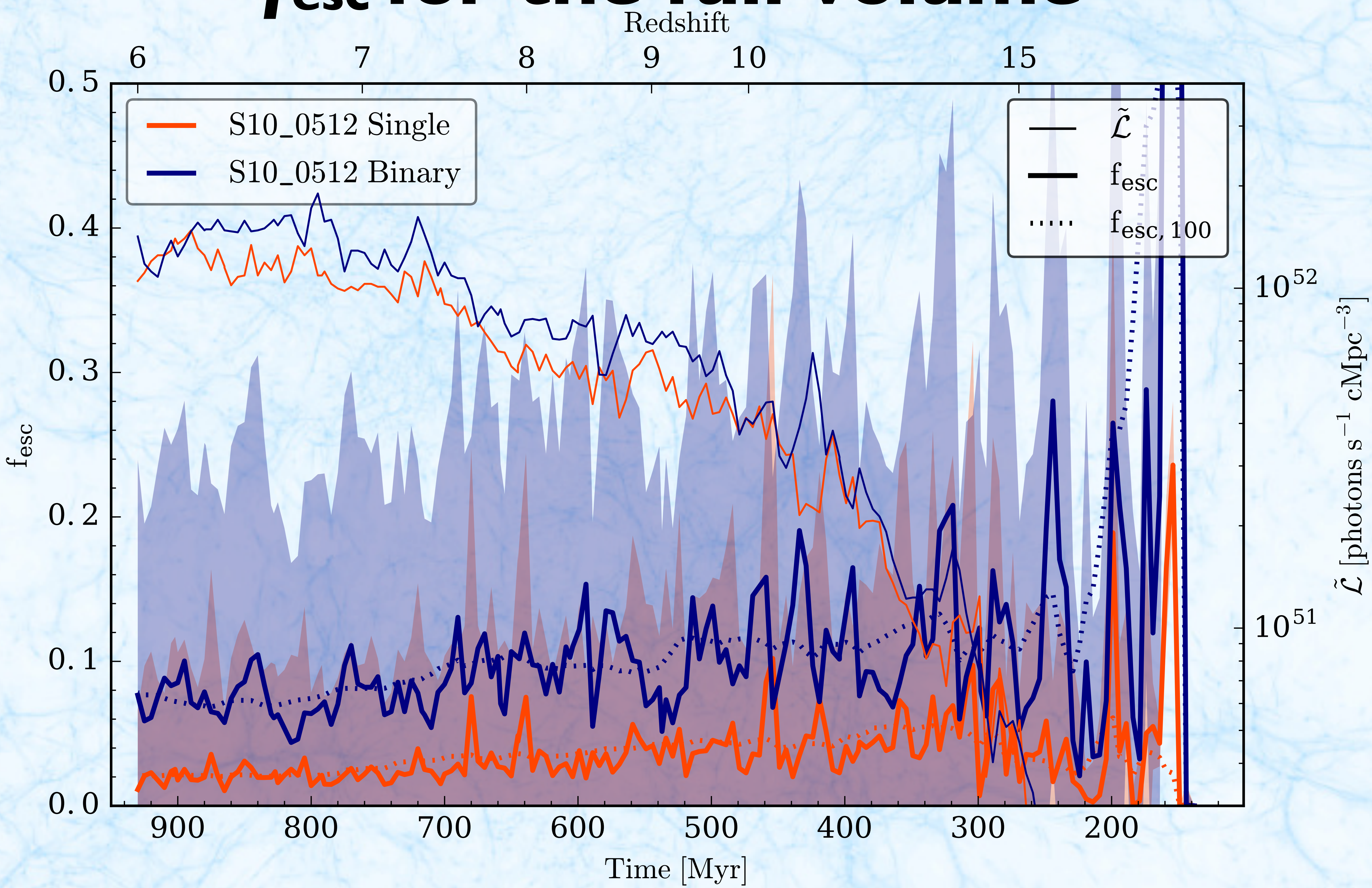
Escape fractions for most massive halo progenitor in 5 cMpc volume



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

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

f_{esc} for the full volume

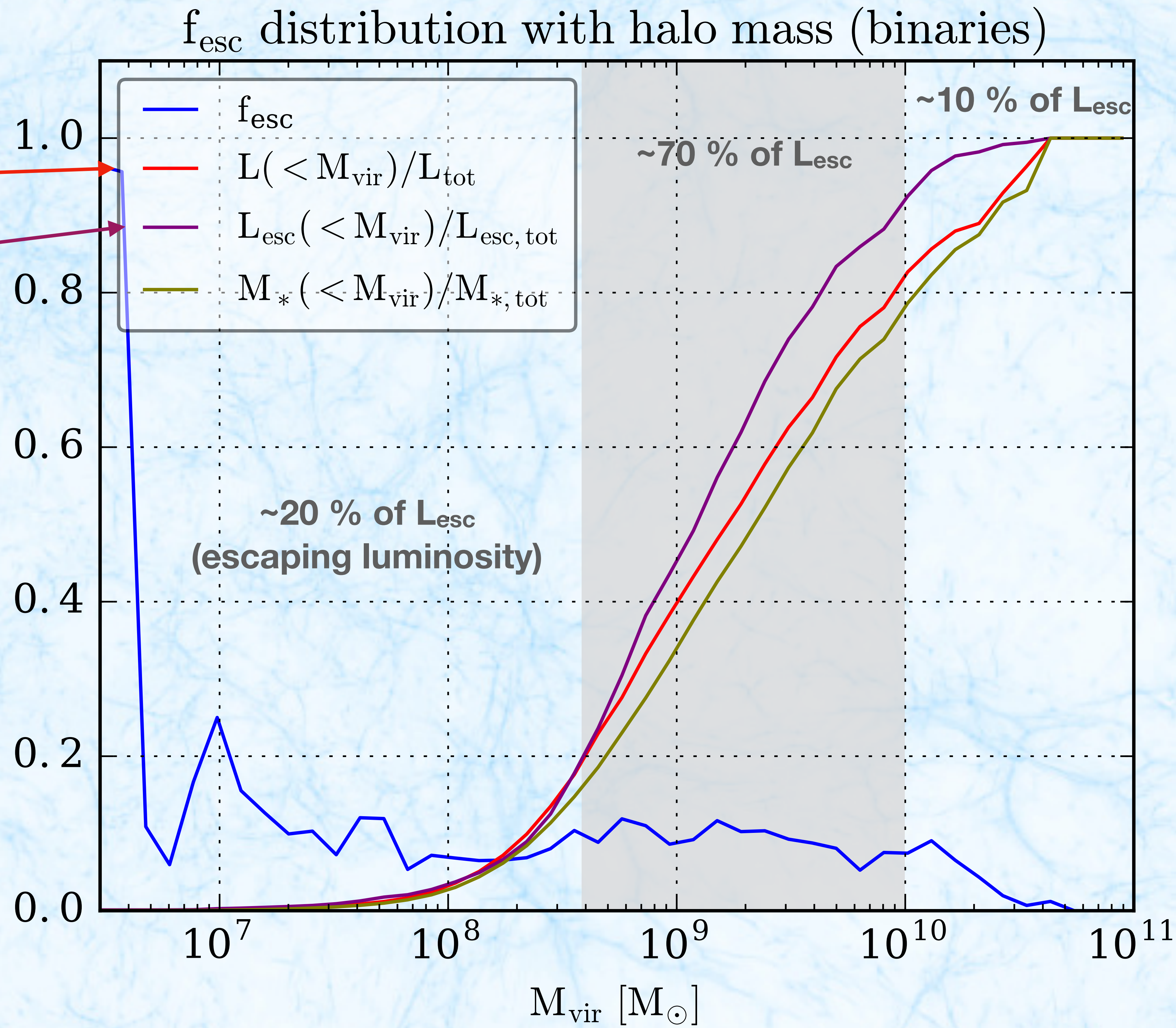


Escape fractions are systematically higher with binary stars !
Luminosities are somewhat higher too.

f_{esc} vs halo mass (with binaries)

Intrinsic ionising luminosity

Escaping ionising luminosity



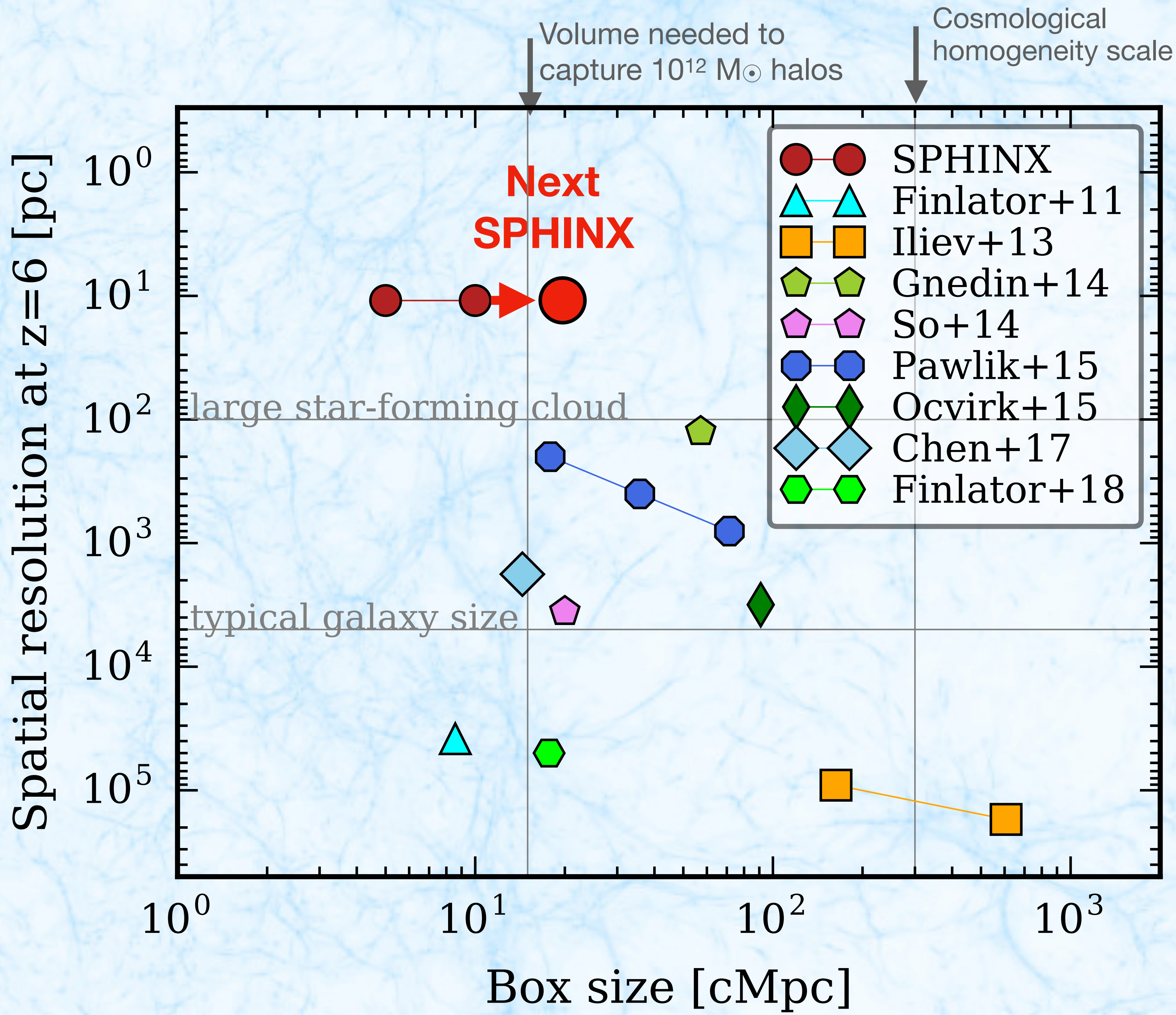
- **Stacked data for z=9-6**
- ***f_{esc}* drops for $M_{halo} \gtrsim 10^{10}\ M_\odot$**
- **But very few galaxies at those masses**

Next … more PRACE time !

We have received 5McHrs on JUWELS for 8 times larger volume

➡**Contribution from massive galaxies**

➡**Less noise in (very stochastic) f_{esc}**



Catch: JUWELS provides 2 GB per core, too little for RHD simulations

➡**Single precision RHD?**

Summary and future

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

- Pilot Sphinx paper in MNRAS (Rosdahl et al., 2018)
    - Stellar populations with binary systems really speed up reionsiation!

- More to follow:
    - Observational signatures of simulated galaxies (w RASCAS)
    - Which galaxies contribute to reionisation
    - Suppression of galaxy growth in ionisation bubbles

- And more simulations:
    - Larger volume: more galaxies, and more massive
    - More physics: what really regulates SFR and f_{esc} ?