The SPHINX simulations of the first billion years and reionisation

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with

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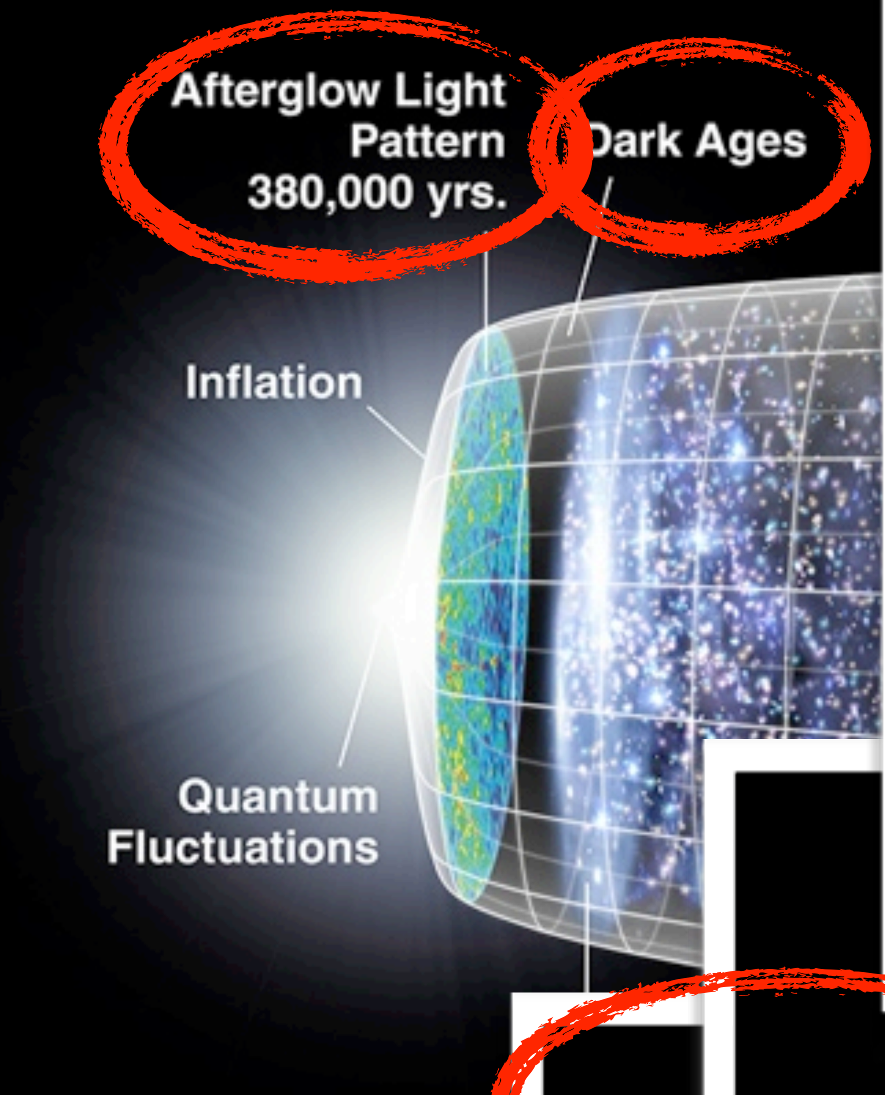
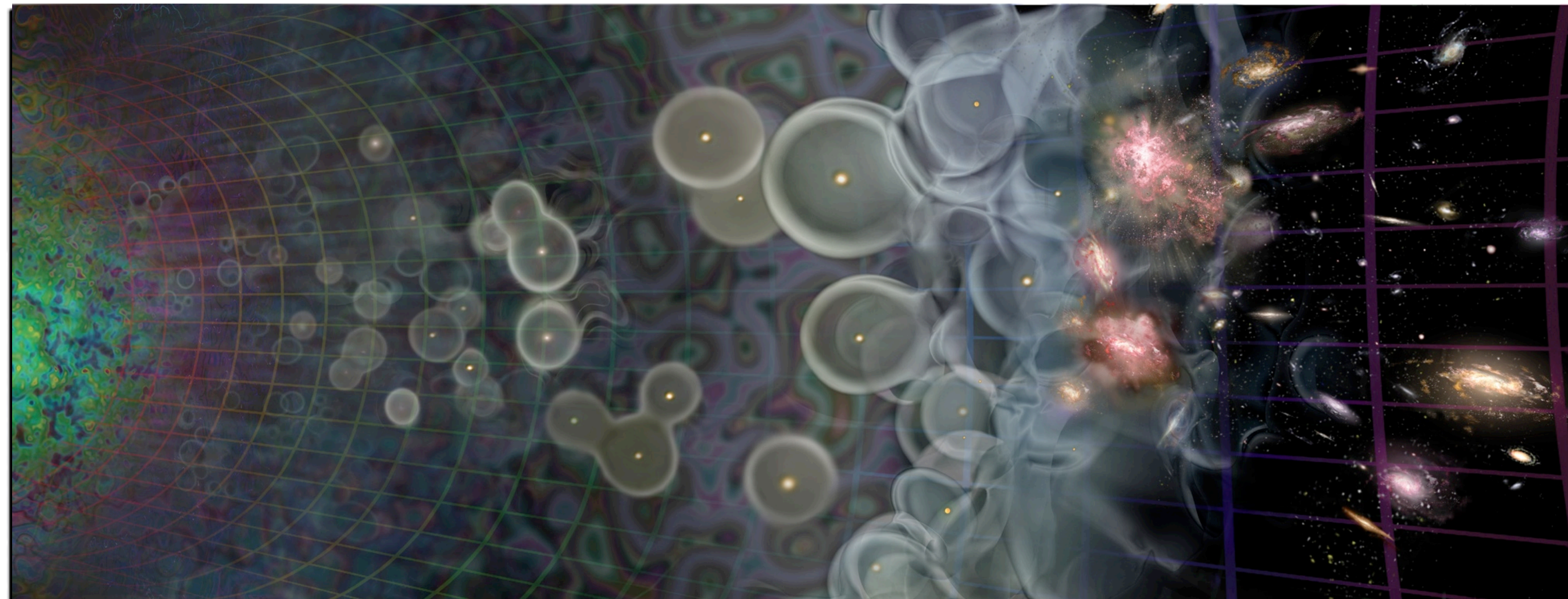
PNCG 2017

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

13.6 million cpu-hours allocated by PRACE in April 2017 — we are finishing the main simulations

The first billion years

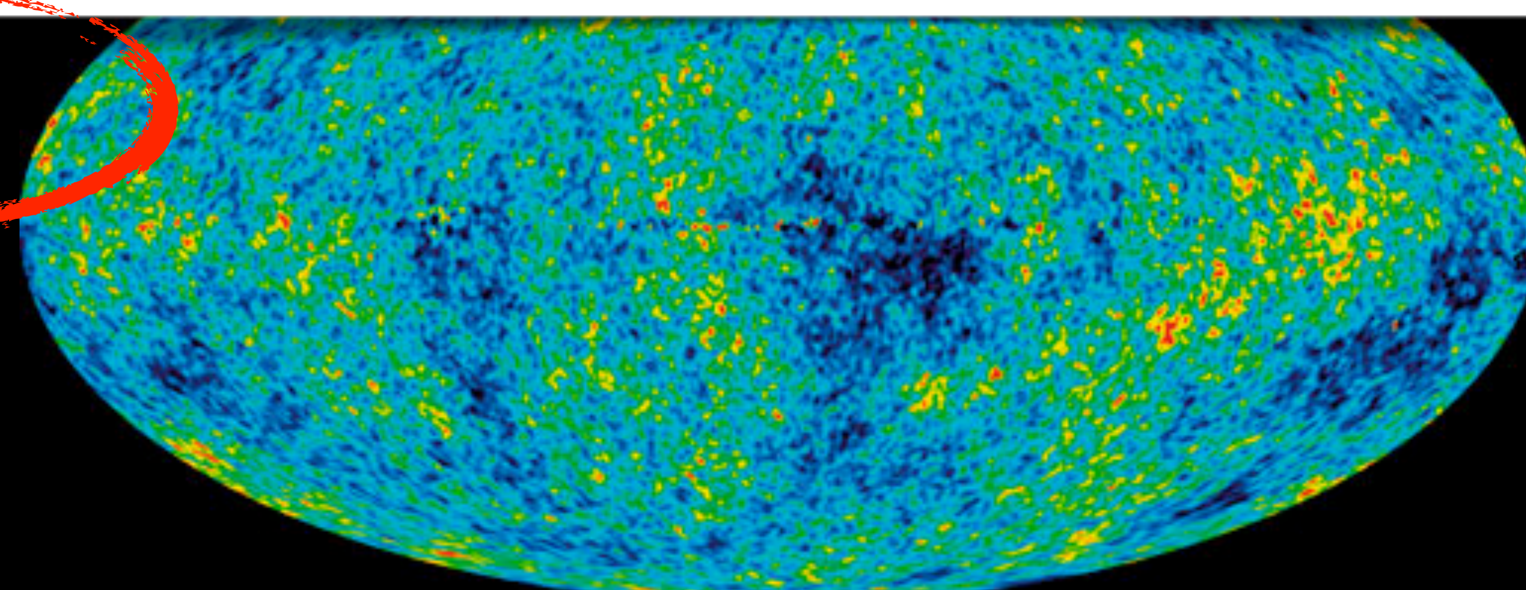




1st stars and reionization

- 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

Project goals

- Understand the process and sources of reionisation
- Understand how patchy reionisation affects the growth of satellite galaxies
- Model observational Lyman-alpha signatures of galaxies (➠ RASCAS..see earlier talk by J.Blaizot)
- Predict luminosity function and galaxy distribution at extreme redshift for the JWST era
- Obtain statistical understanding about radiation 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 in binary systems

SED models

Spectral Energy Distributions for stellar populations

- **BC03 = Single stellar population model from Bruzual & Charlot (2003)**

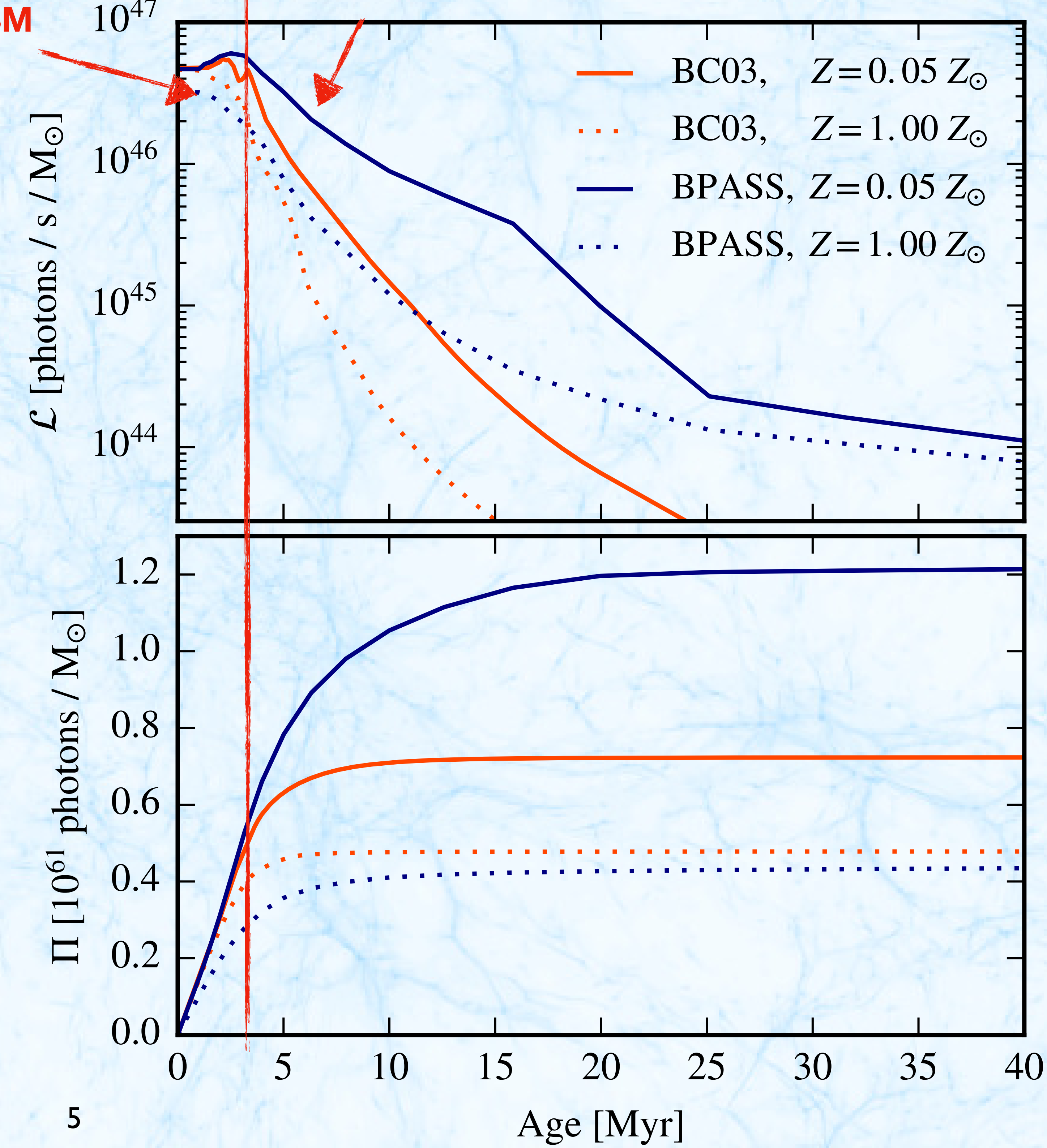
- **BPASS = Binary Population and Spectral Syntesis from Eldridge et al.**

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

~ 3 Myr: Massive stars start to explode

Before: Radiation absorbed by dense ISM

After: ISM disrupted and radiation escapes

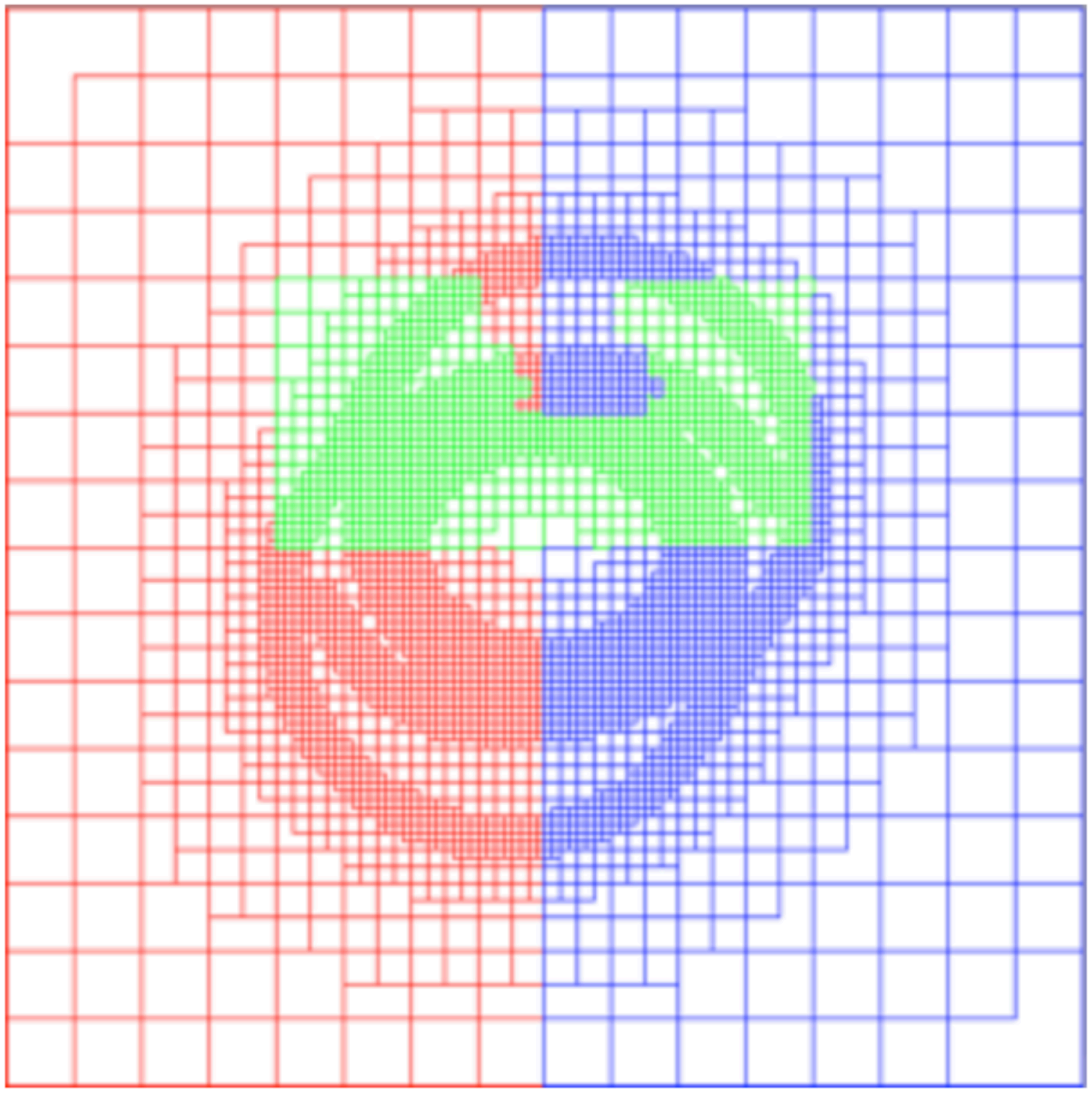


SPHINX
simulation code and setup

Cosmological code: RAMSES

Teyssier (2002)

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

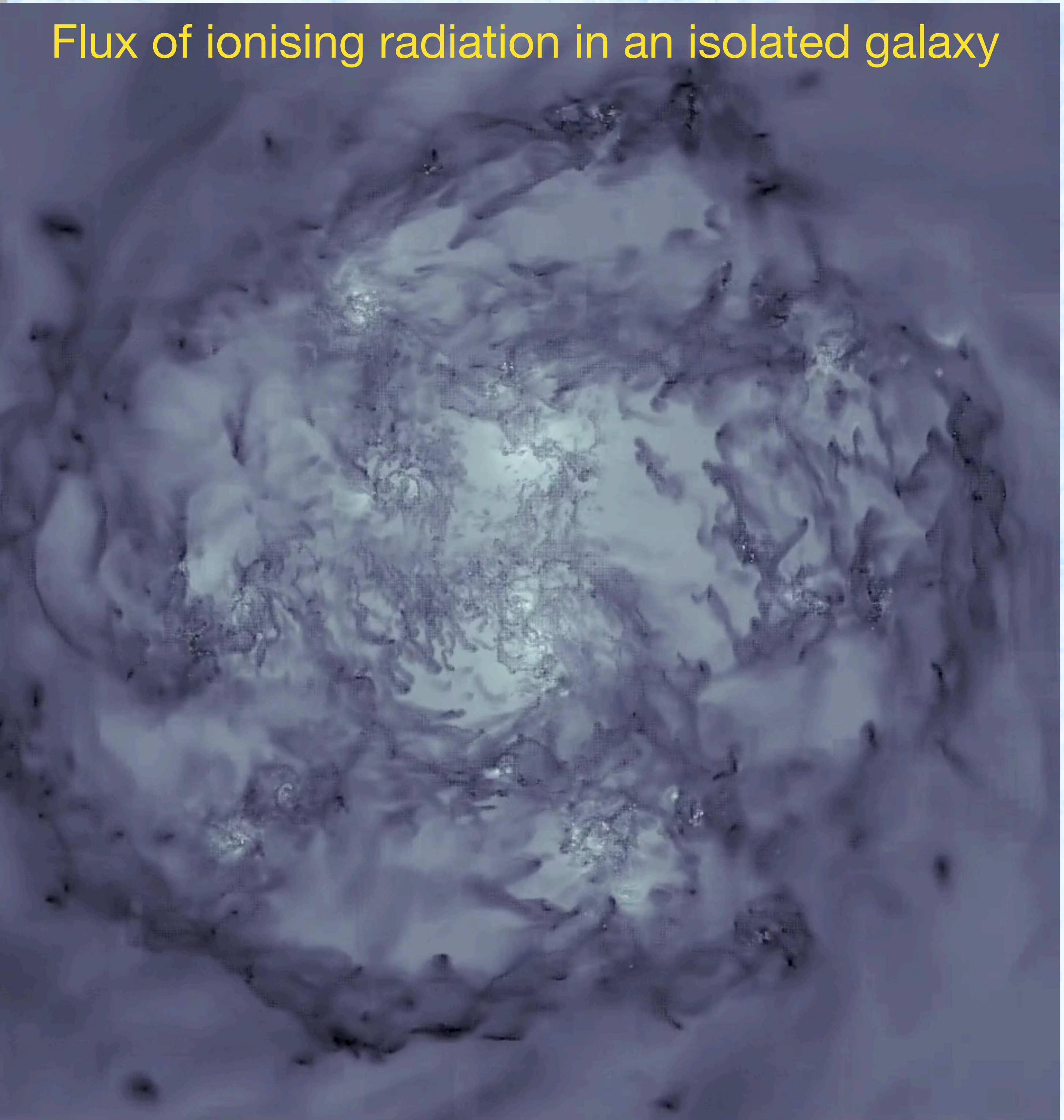


- AMR allows the calculation to be focused on regions of interest.
- The simulation volume can be split and run in parallel on thousands of CPUs
- Cosmology, dark matter, gas, and stars are included
- I spent my PhD on adding the propagation of *radiation* and its interactions with gas,
  see Rosdahl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

RAMSES-RT

Radiation Hydrodynamics in RAMSES

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

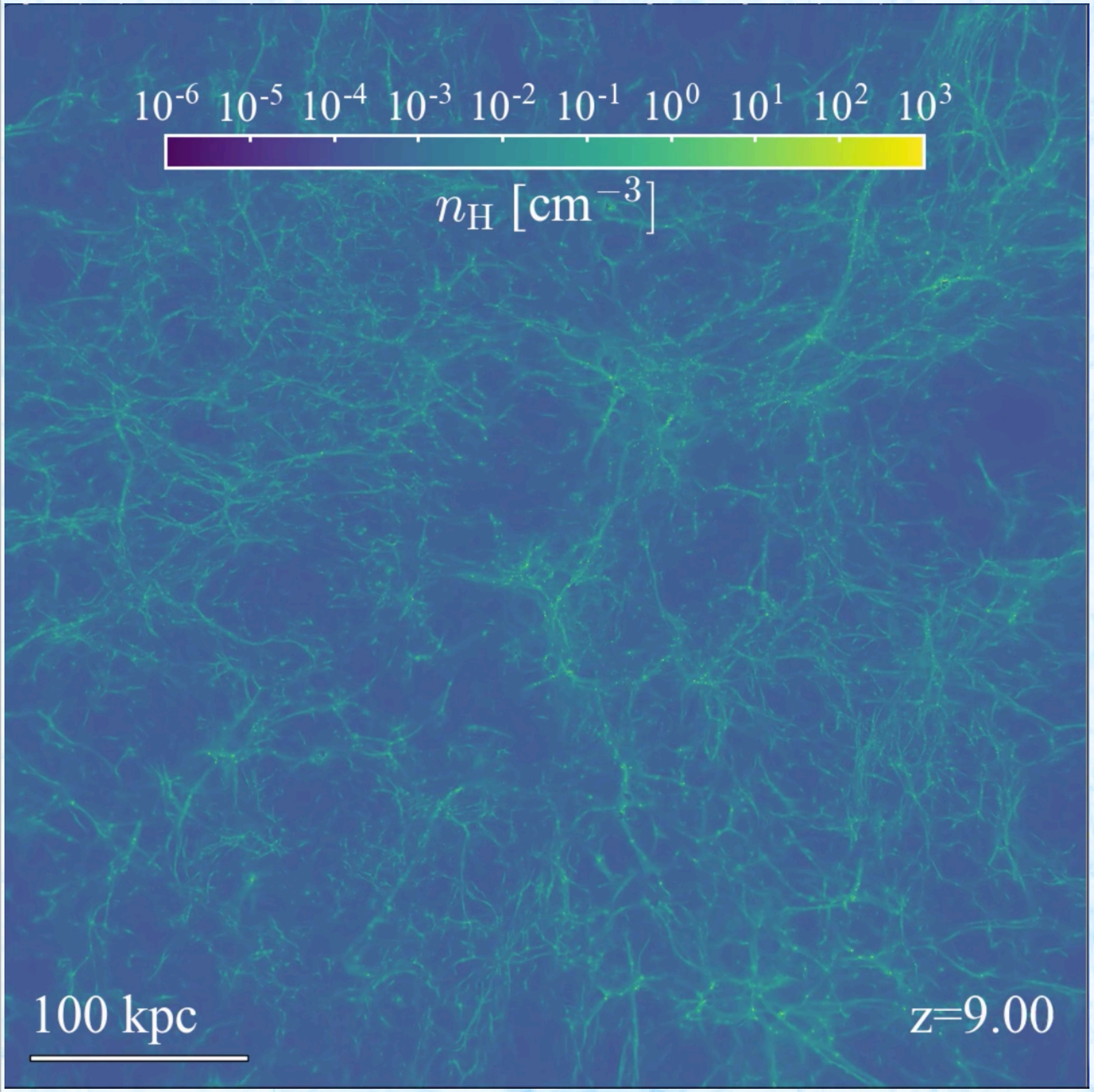


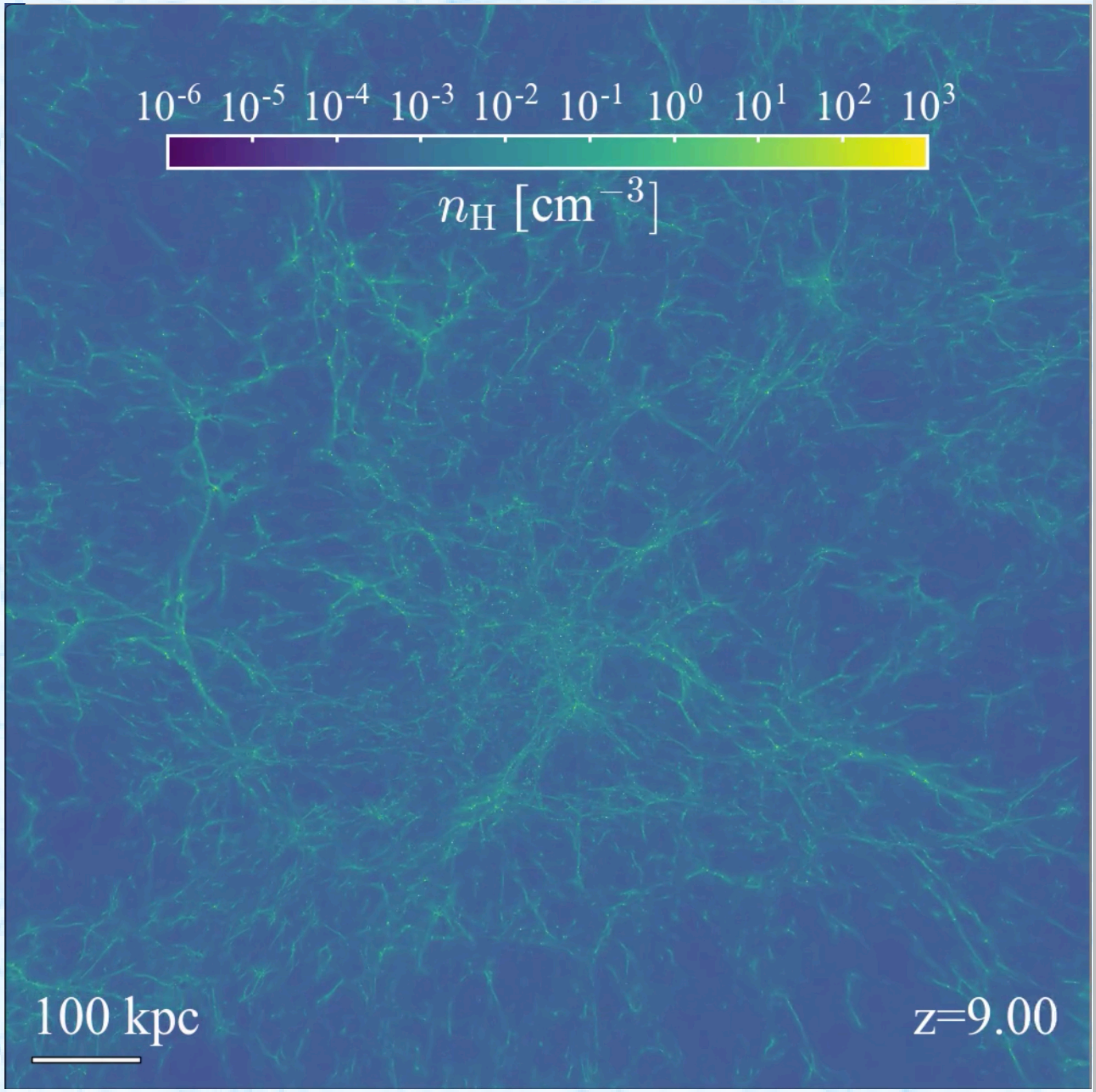
- Moment method to propagate photons, allowing an **unlimited number of sources**
- Photons are emitted and propagated on-the-fly. They **ionise, heat, and push** the gas, and **multi-scatter** on dust
- Variable speed-of-light and subcycling of radiation makes for enormous efficiency

➡ **Only** existing code that can simulate large-scale reionisation while resolving individual galaxies

- Public, as part of RAMSES, and used in over 20 papers

SPHINX simulations





5 cMpc box with high mass resolution

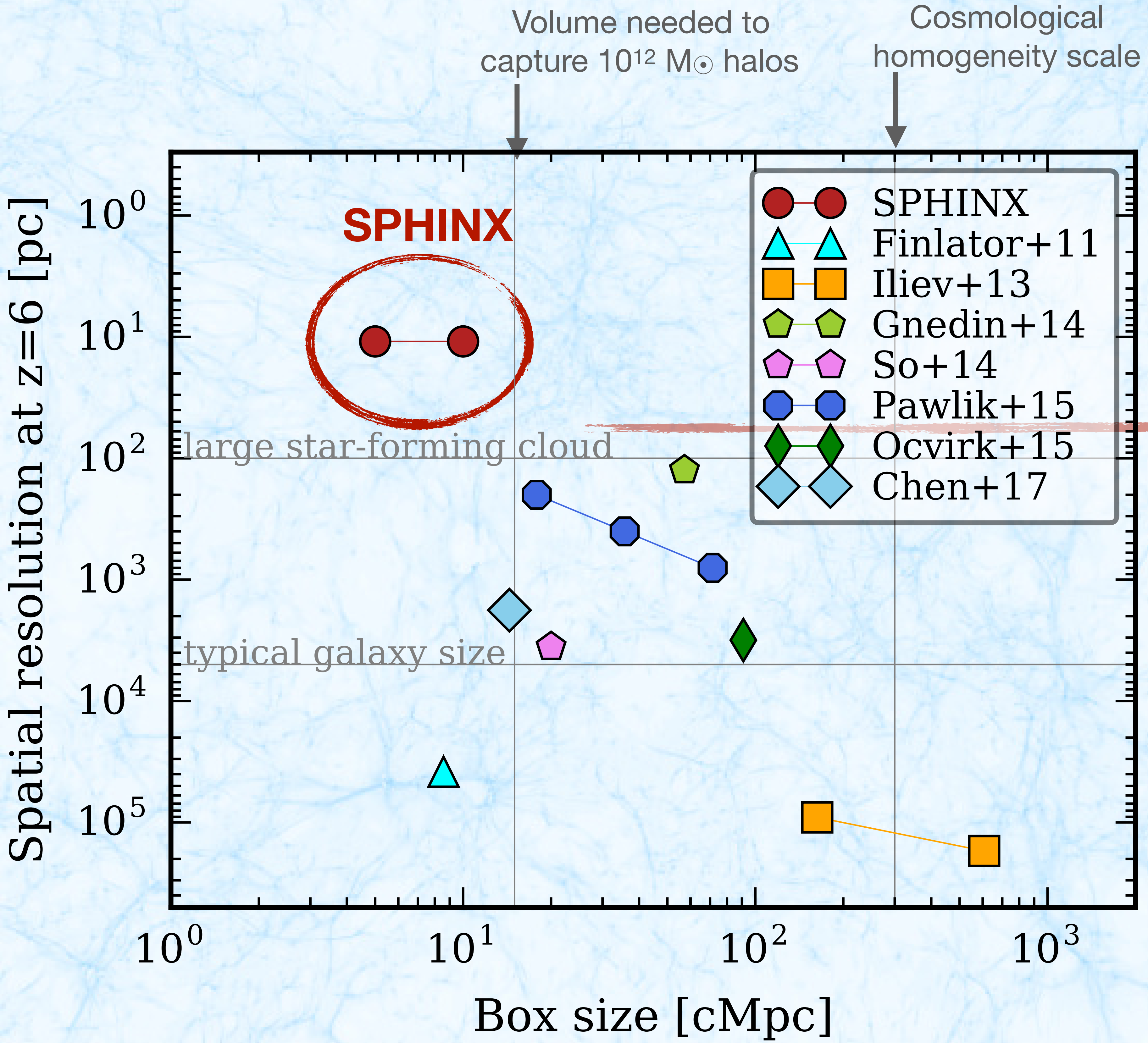
10 cMpc box with lower <u>mass</u> resolution (but same physical resolution)

...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 reionisation sources are resolved.
- **Stellar particle resolution** of 10^3 $M_\odot$ (particle = a stellar population)
- *Bursty* turbulence-dependent **star formation** (Devriendt et al, in prep)
- **SN explosions** modelled with momentum kicks (Kimm et al., 2015)
- **No calibration on unresolved** f_{esc} (i.e. we simply inject the SED luminosity)
- We run with binary and single star SEDs

SPHINX compared to previous reionisation works

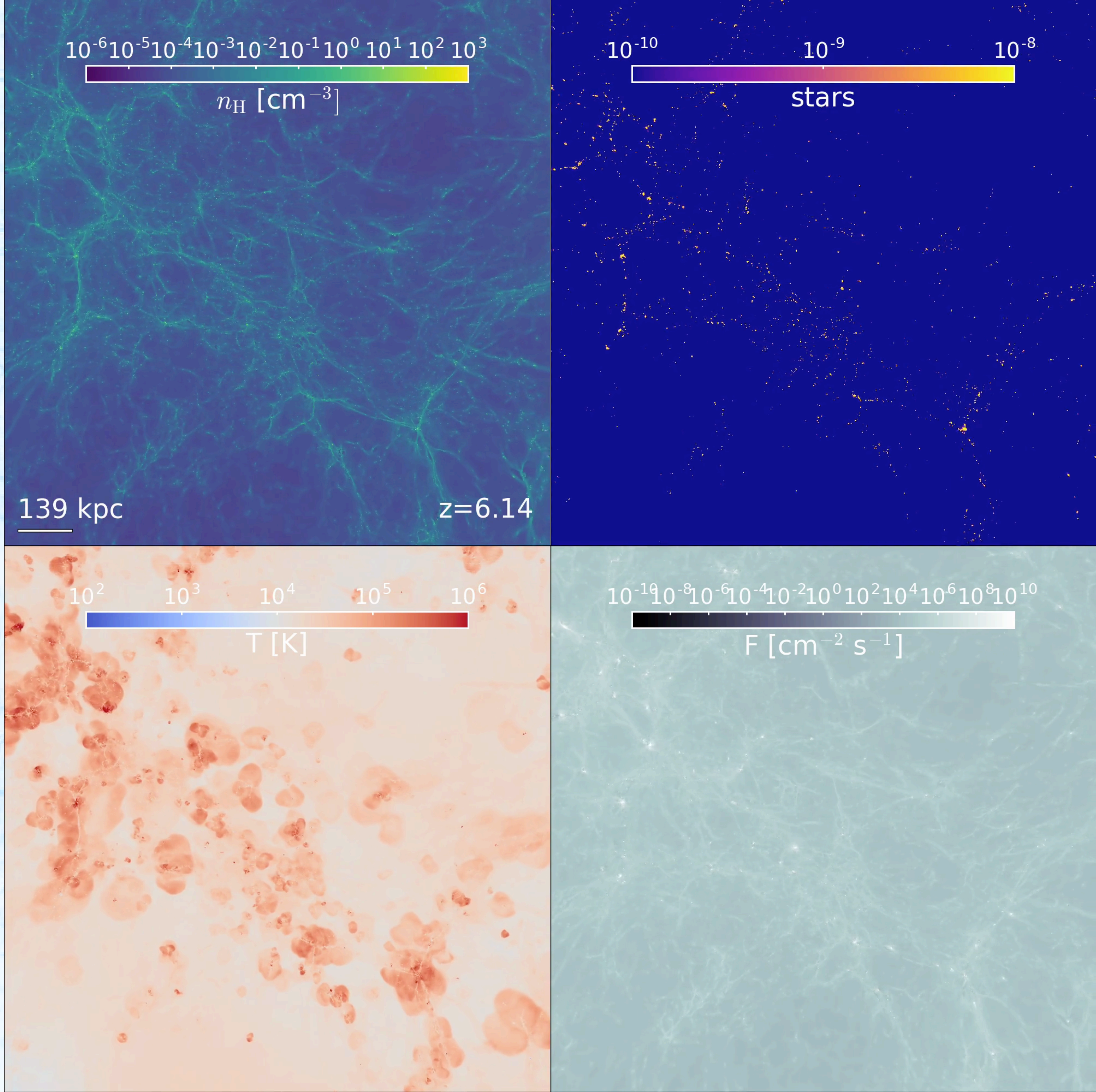


High resolution: f_{esc} can be predicted

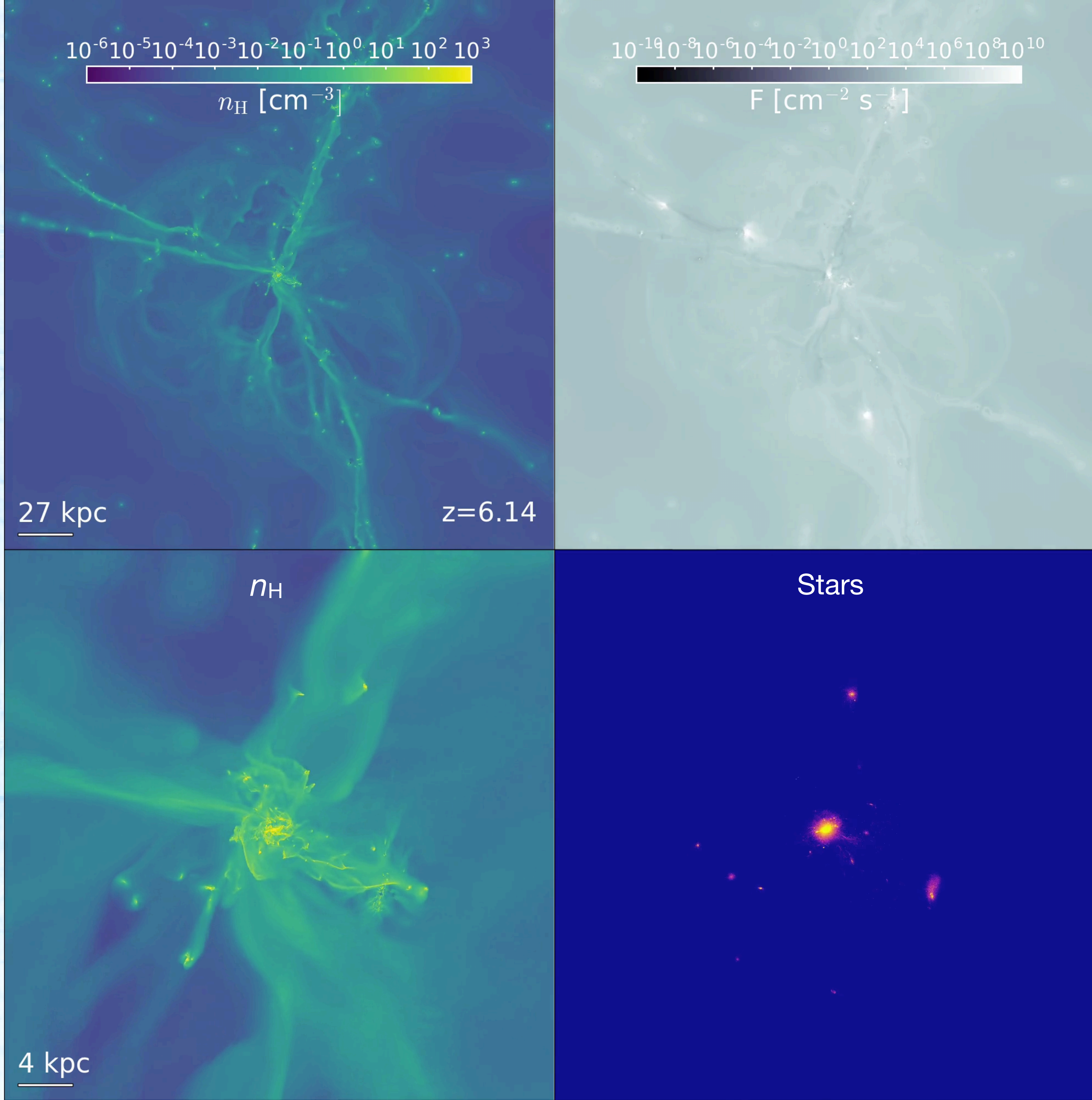
Low resolution: f_{esc} is a calibrated parameter

SPHINX
results

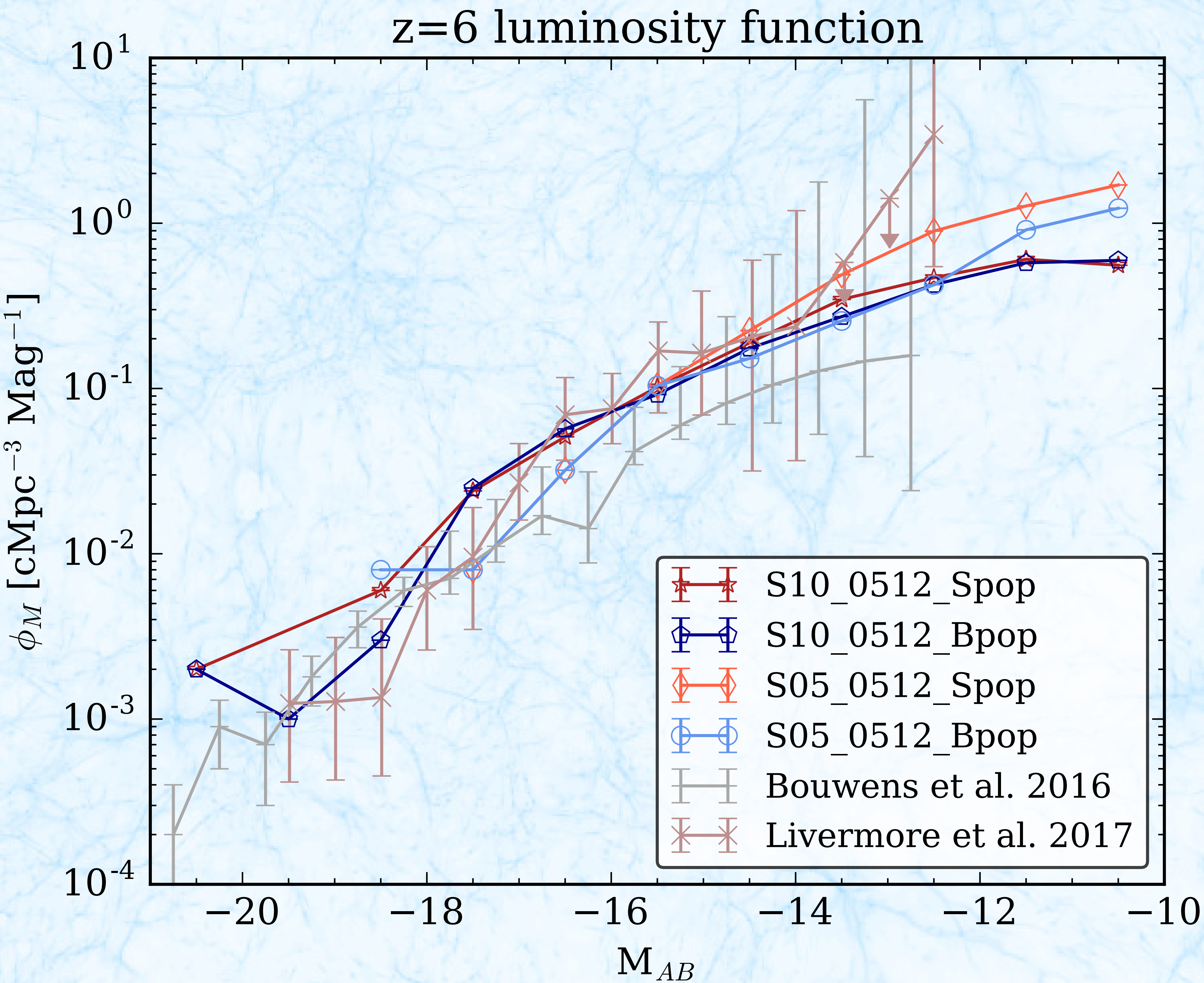
Full
10 cMpc box, binary SED:



10 cMpc box, binary SED, a closer look



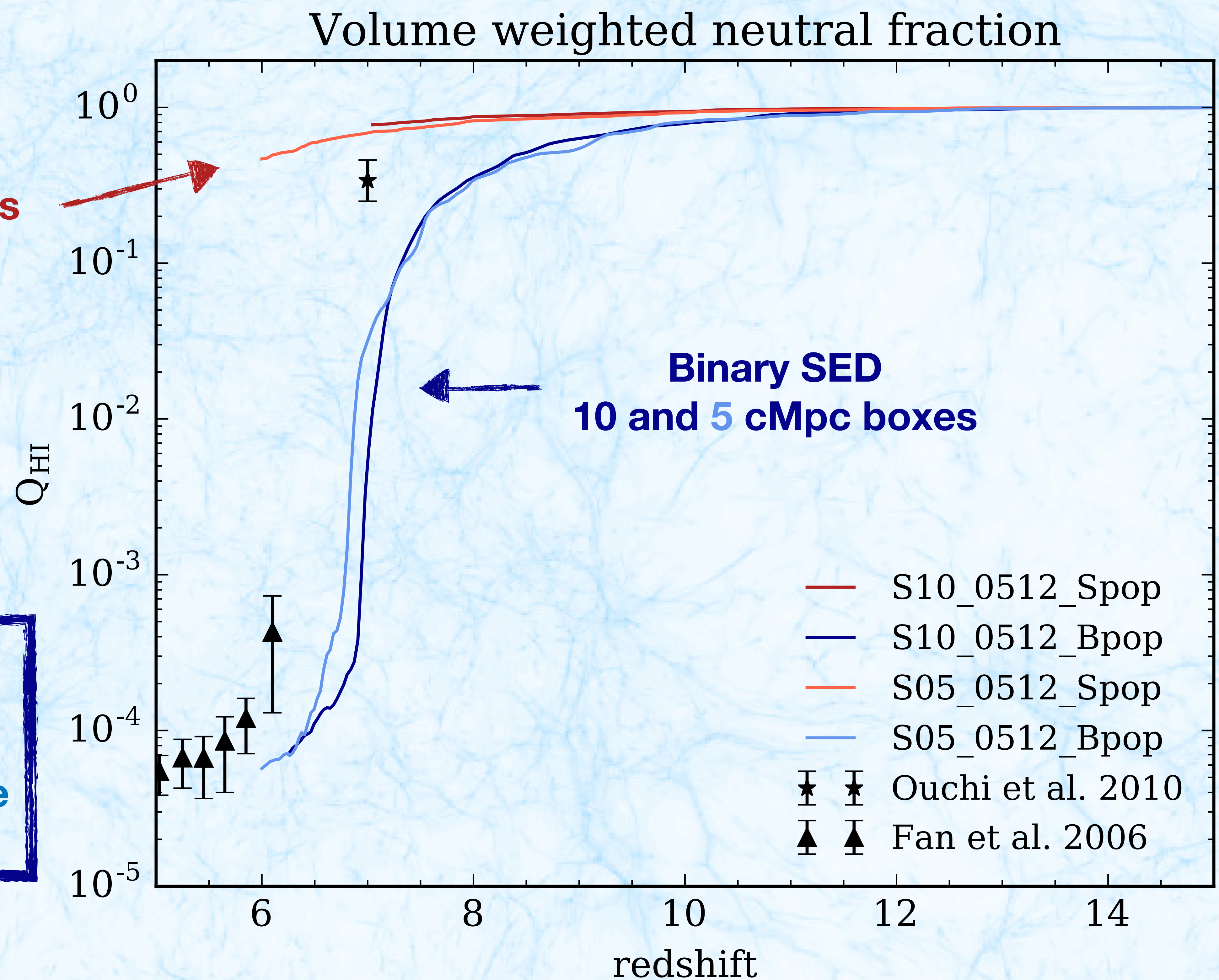
Luminosity function



Reionisation history

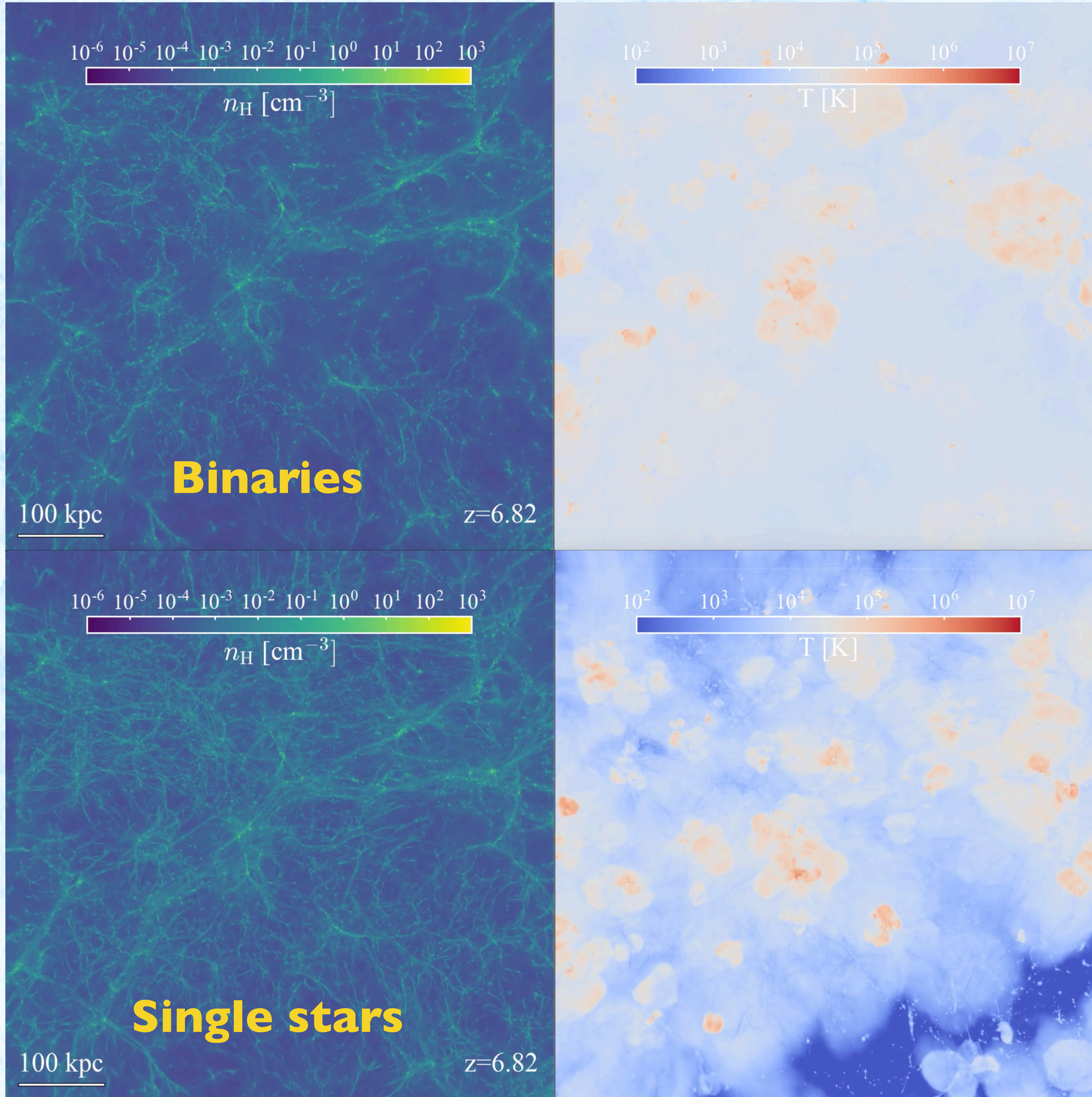
binary vs single SEDs

Single stars SED
10 and 5 cMpc boxes



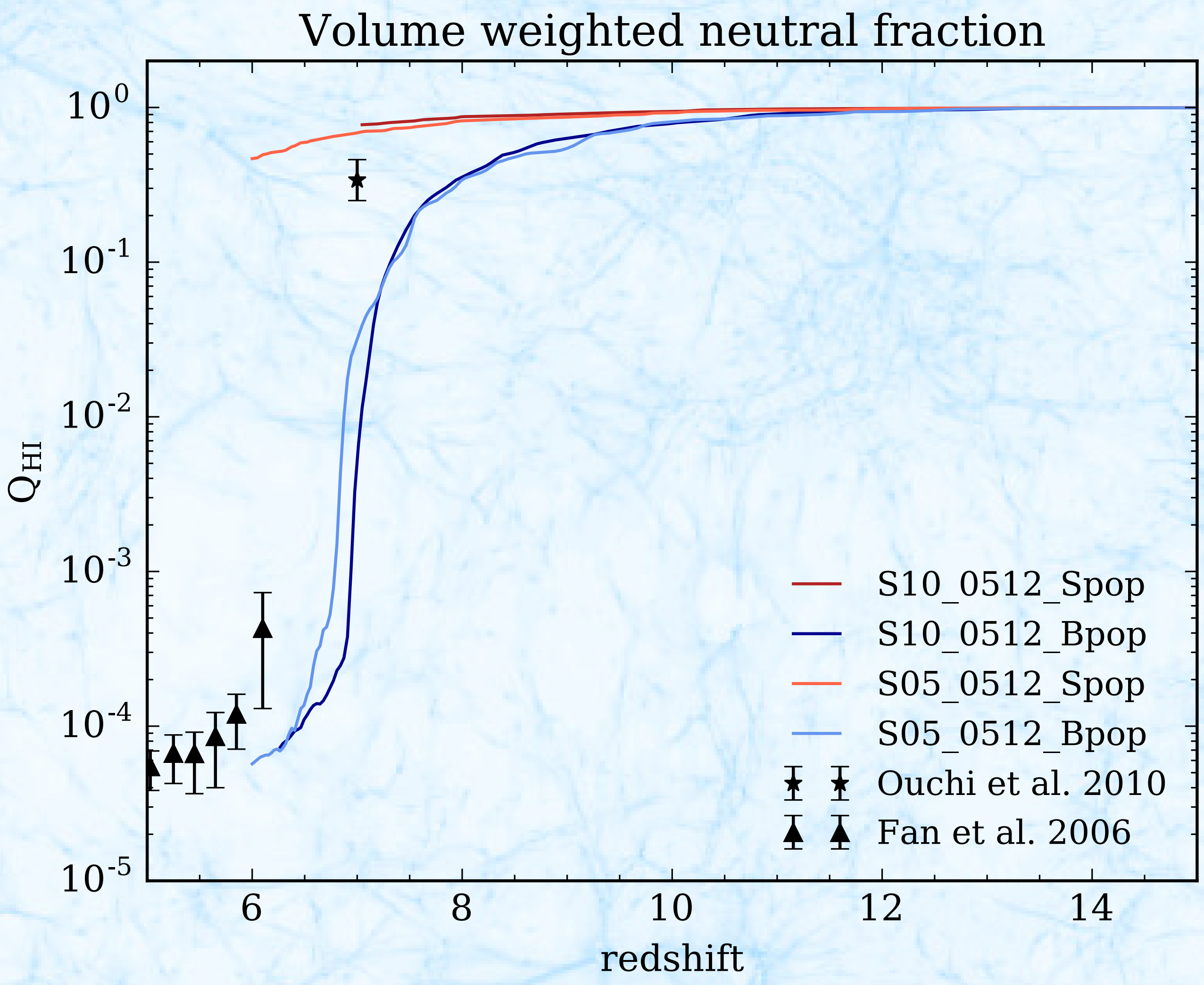
Much more efficient reionsiation with binary populations, independent of box size and mass resolution

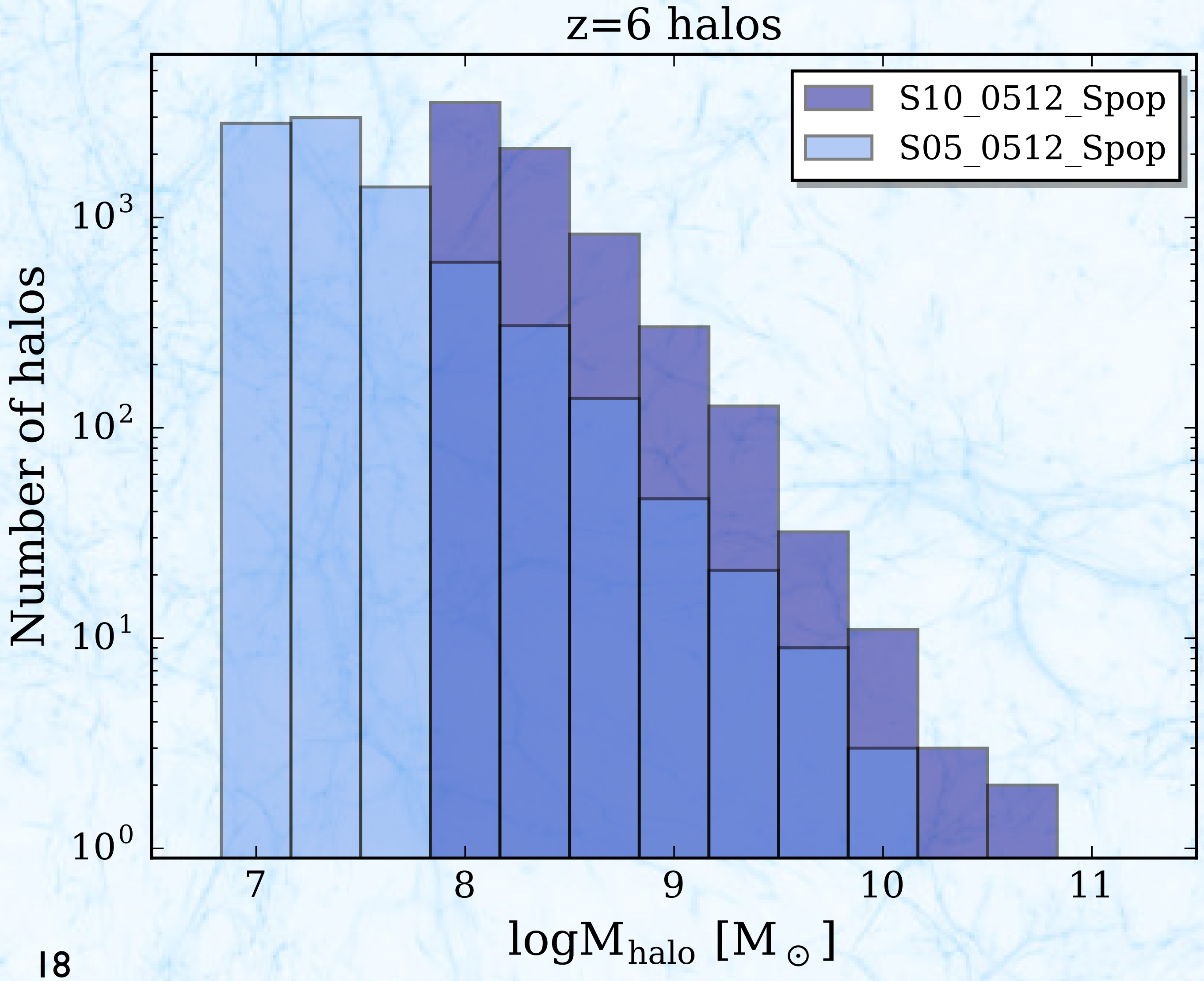
Effect of more IGM photons with binary populations



What are the sources of reionisation?

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





Summary and future

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

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

- More papers to follow:
  - Lyman-alpha signatures of simulated galaxies
  - Statistical analysis of escape fractions
  - 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