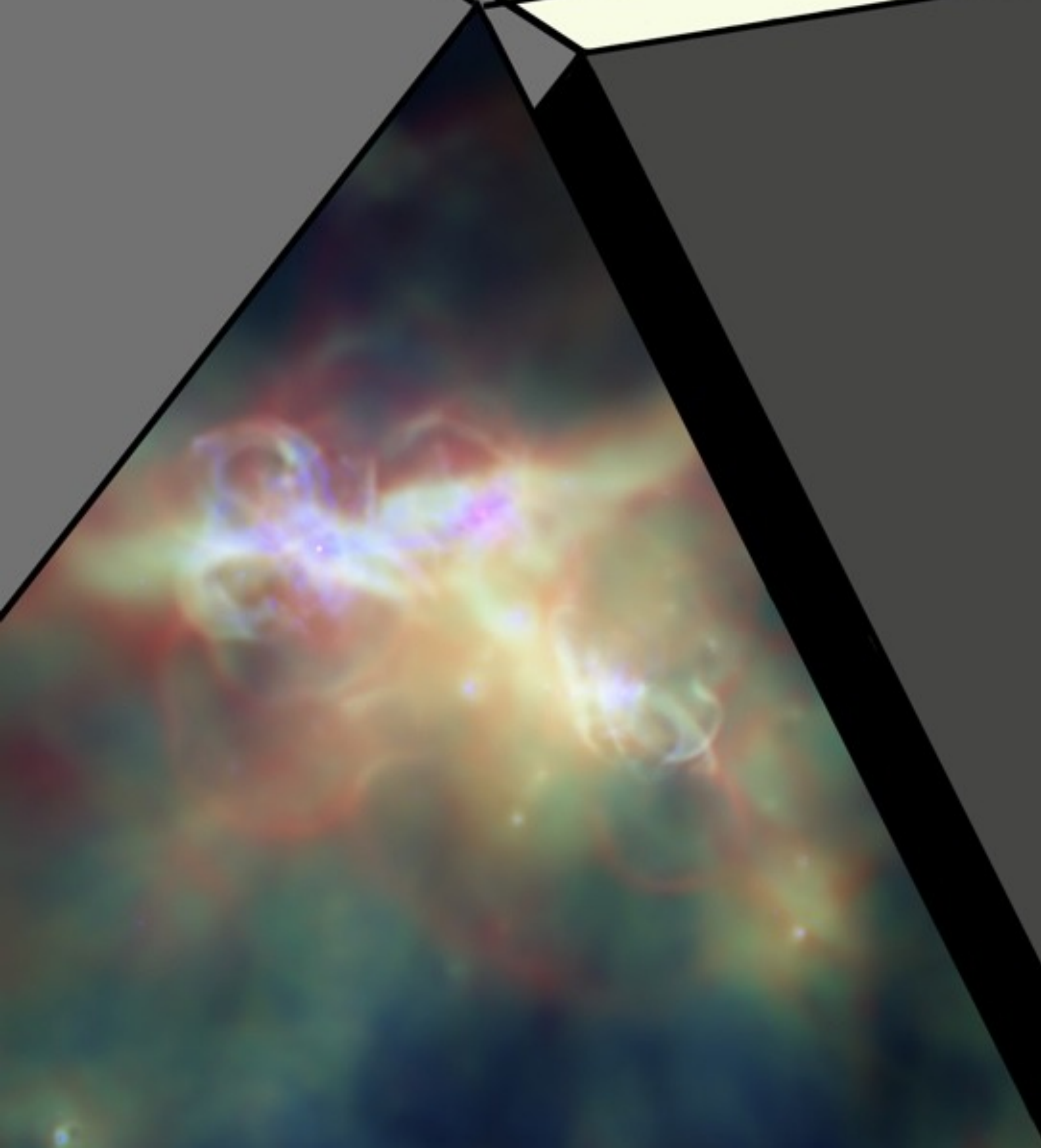
Simulating the sources of reionisation with SimpleX



Jan-Pieter Paardekooper

MPE Garching

Claudio Dalla Vecchia
Sadegh Khochfar
TMoX Group

Theoretical Modeling of Cosmic Structures

Outline

SimpleX: radiative transfer on an unstructured grid

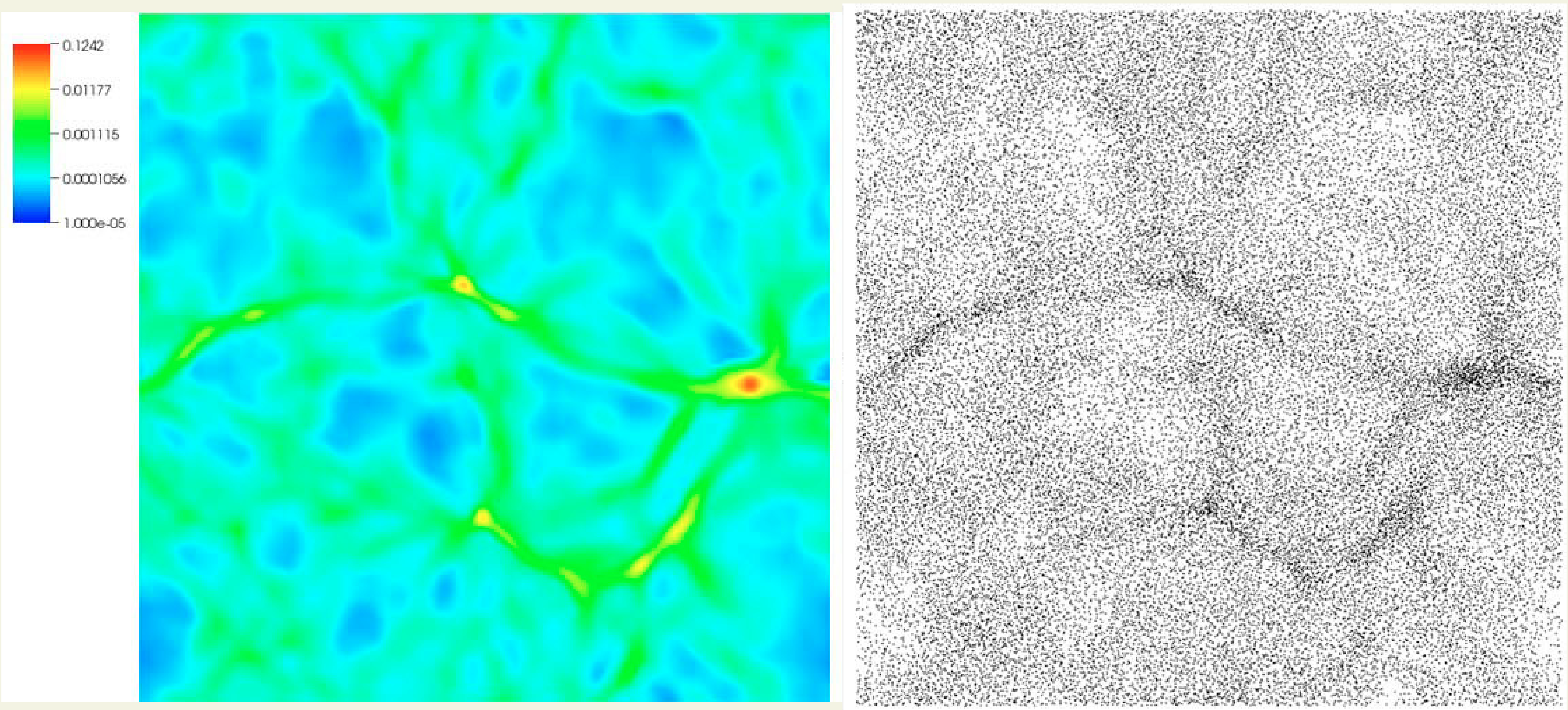
Simulating the sources of reionisation

SimpleX

- Radiative transfer equation solved on unstructured grid
- Grid points connected by Delaunay triangulation
- Photons are transported along triangulation edges
- Interaction takes place at every vertex

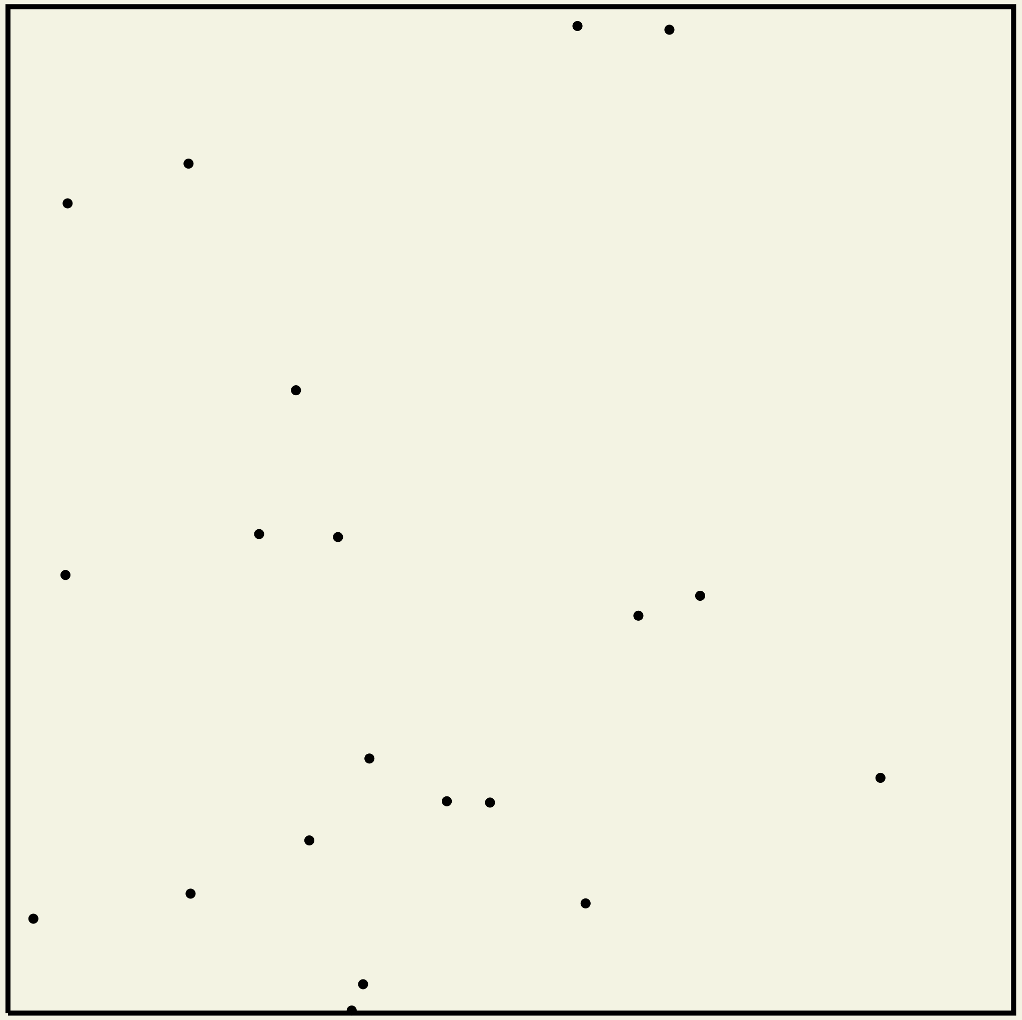
Grid Points

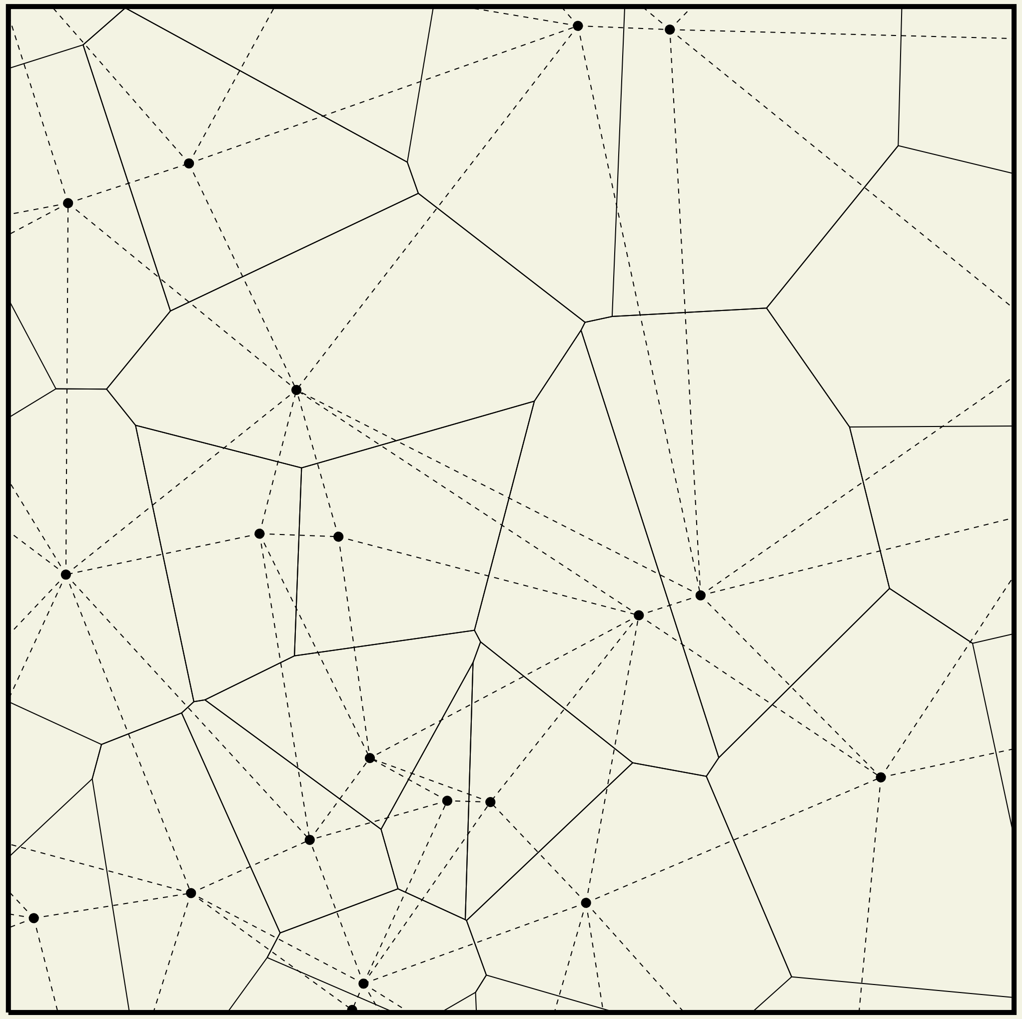
Grid points follow the density distribution



Delaunay Triangulation

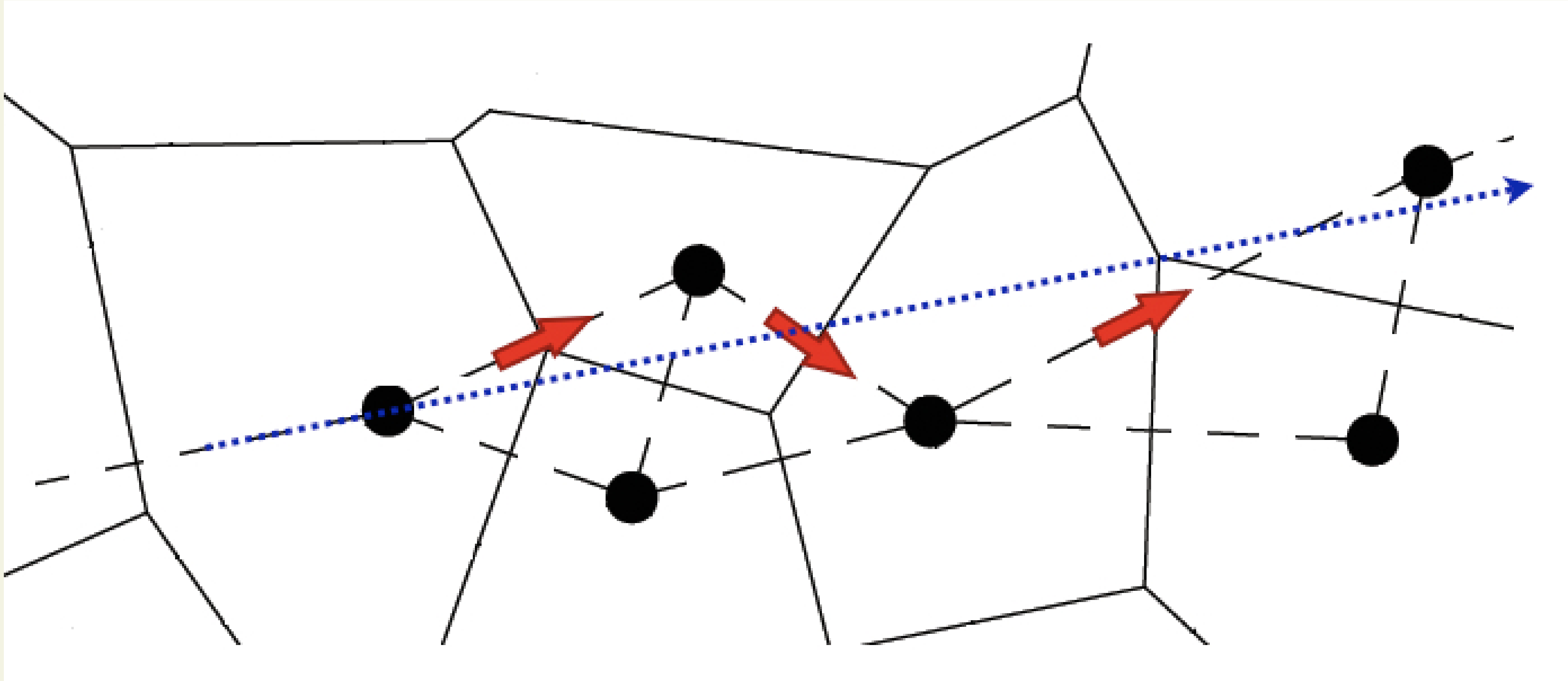
Grid points connected using Delaunay triangulation





Photon Transport

Photons travel along edges of triangulation

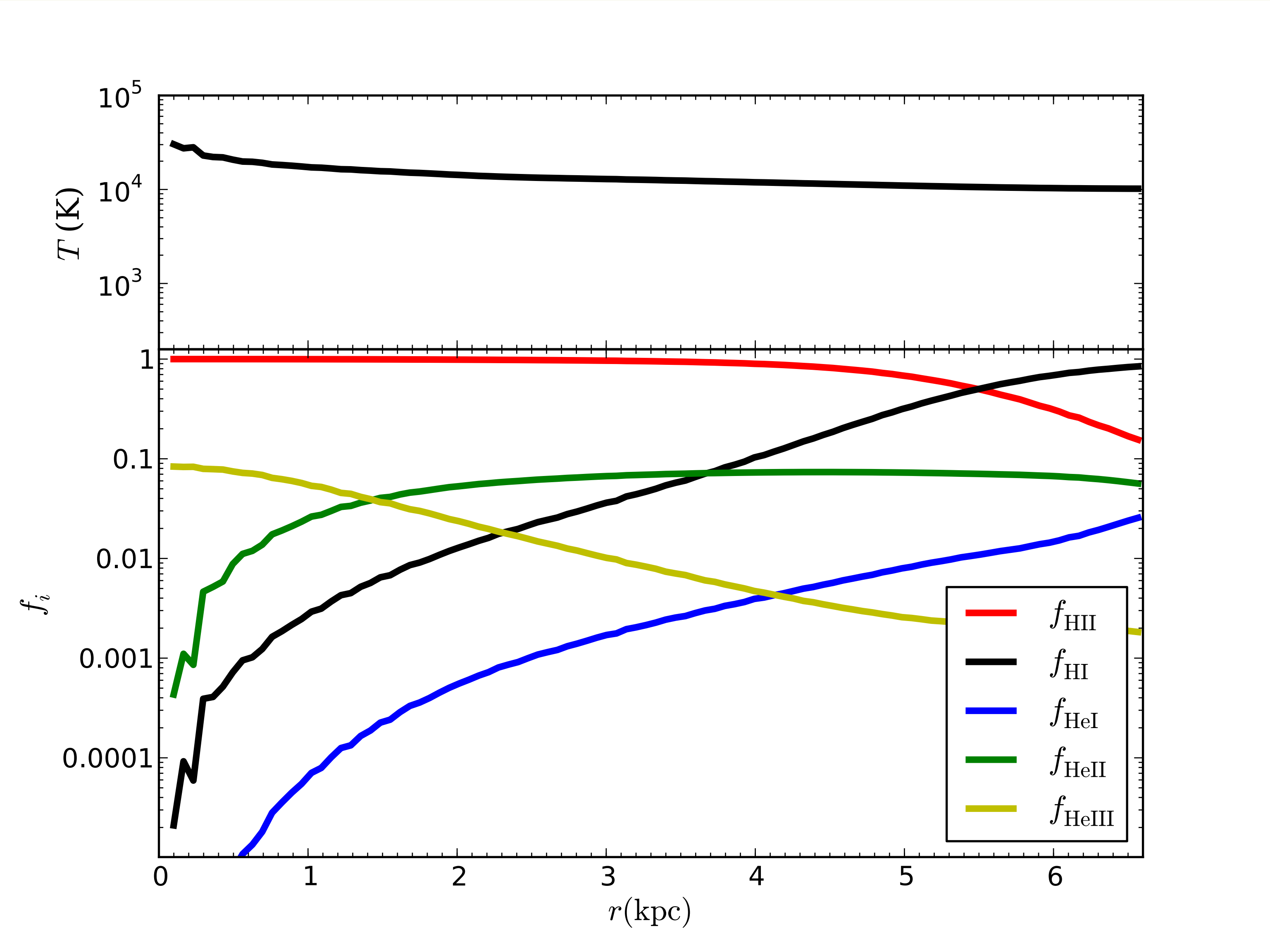


Ionisation Physics

Species: Hydrogen and Helium

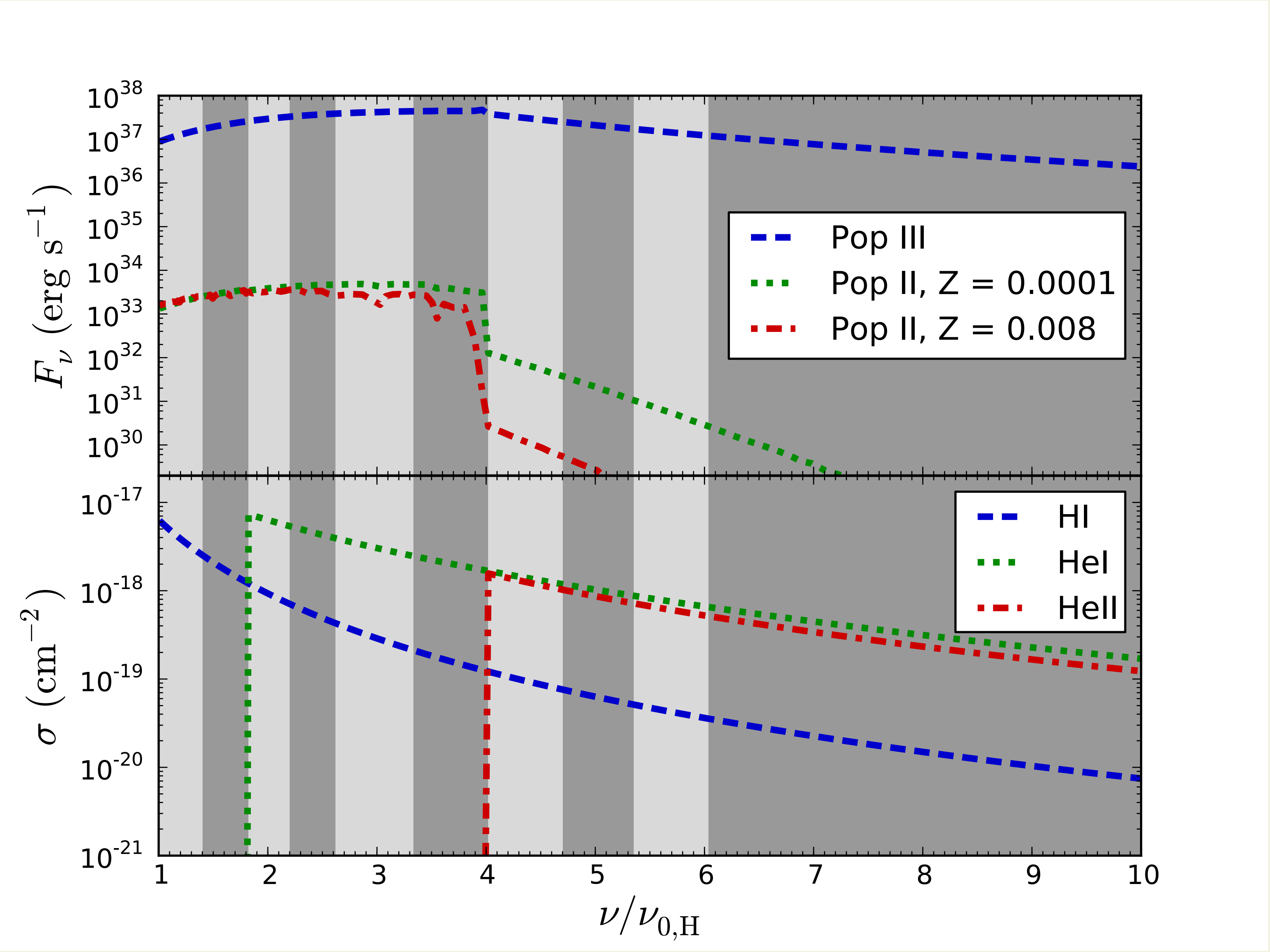
Solvers: Low ionisation rate: subcycling (Pawlik&Schaye 2008)

High ionisation rate: iterative (Mellema et al. 2006, Altay et al. 2008, Friedrich et al. 2012)



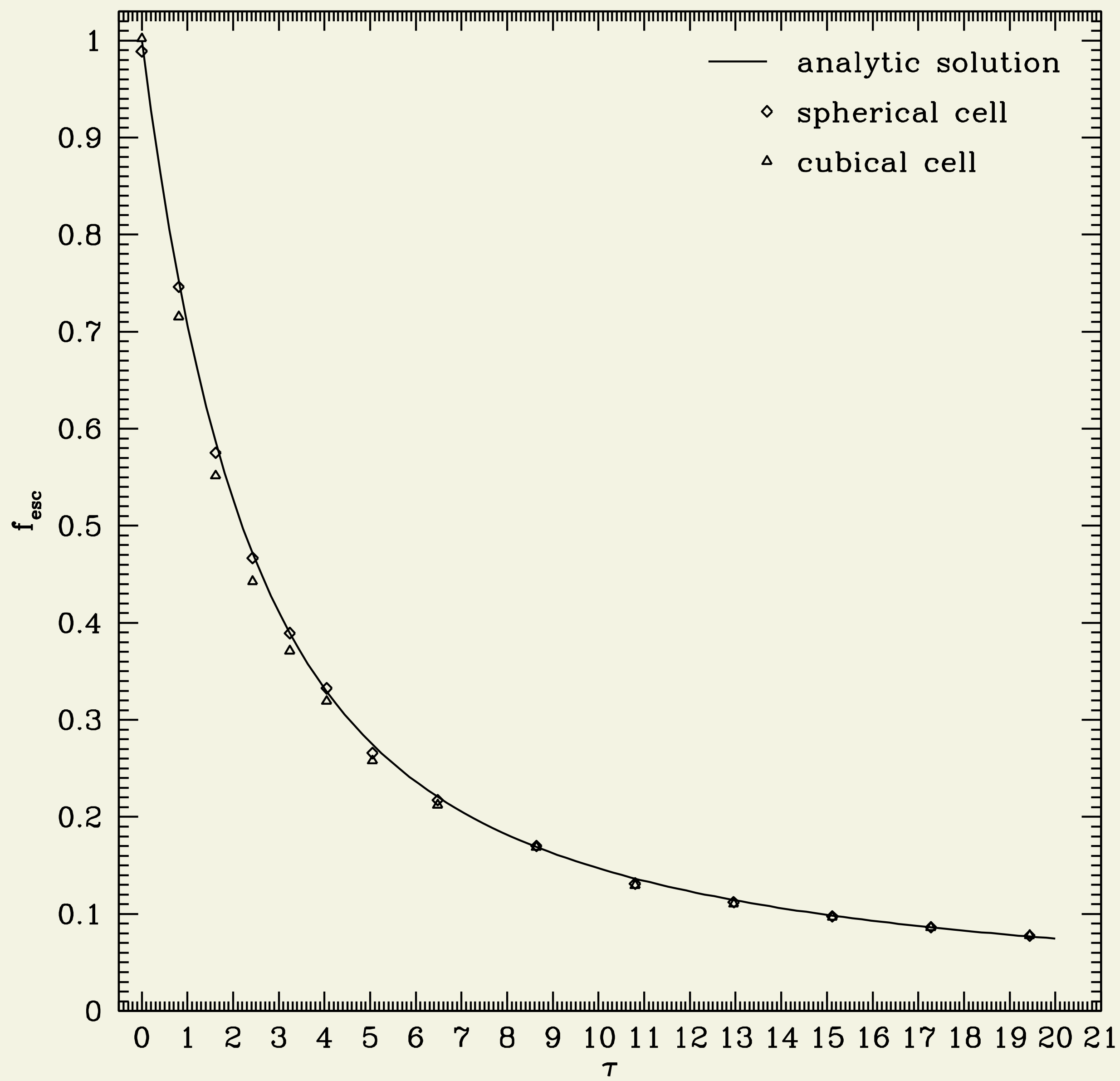
Sources

Monochromatic
Black body
Pop III and Pop II



Recombinations

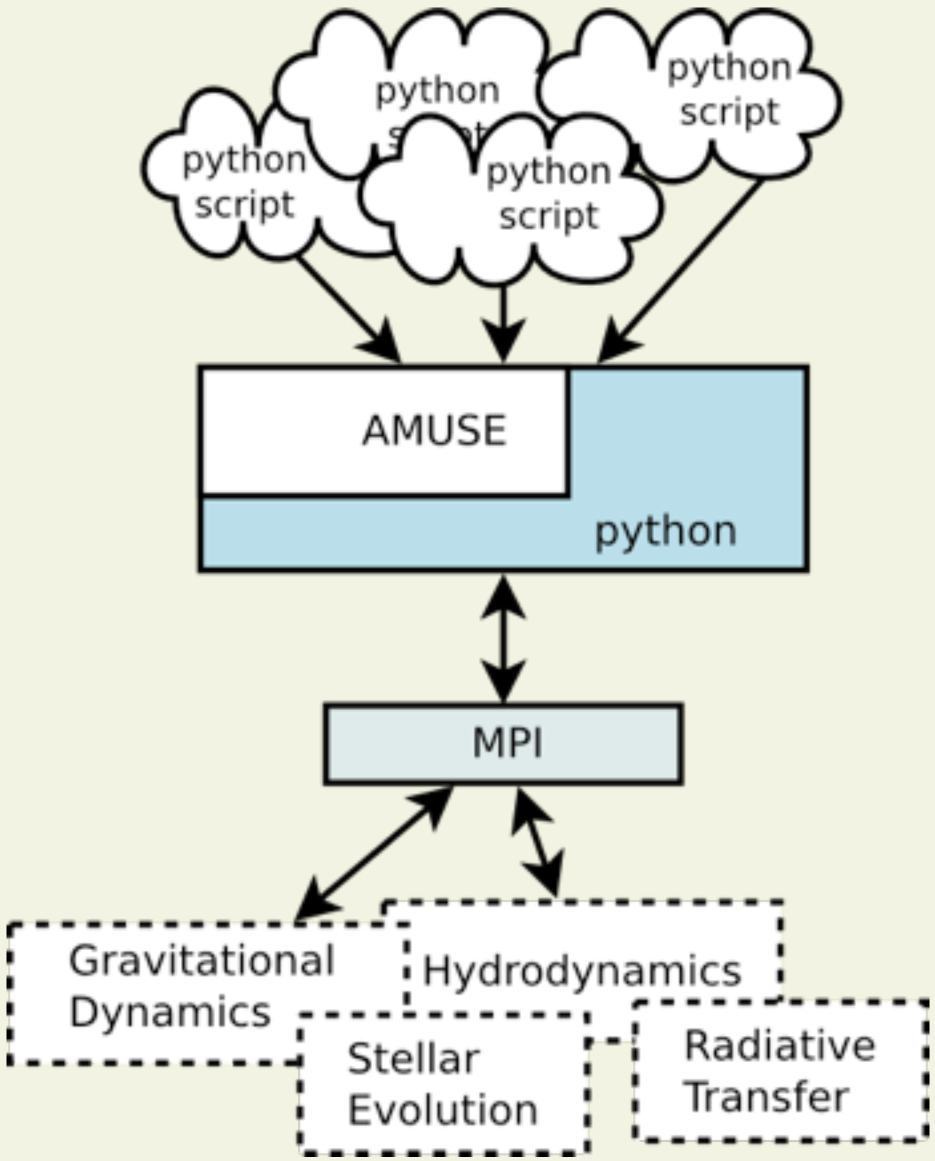
On-the-spot approximation
Radiative transfer of recombination photons



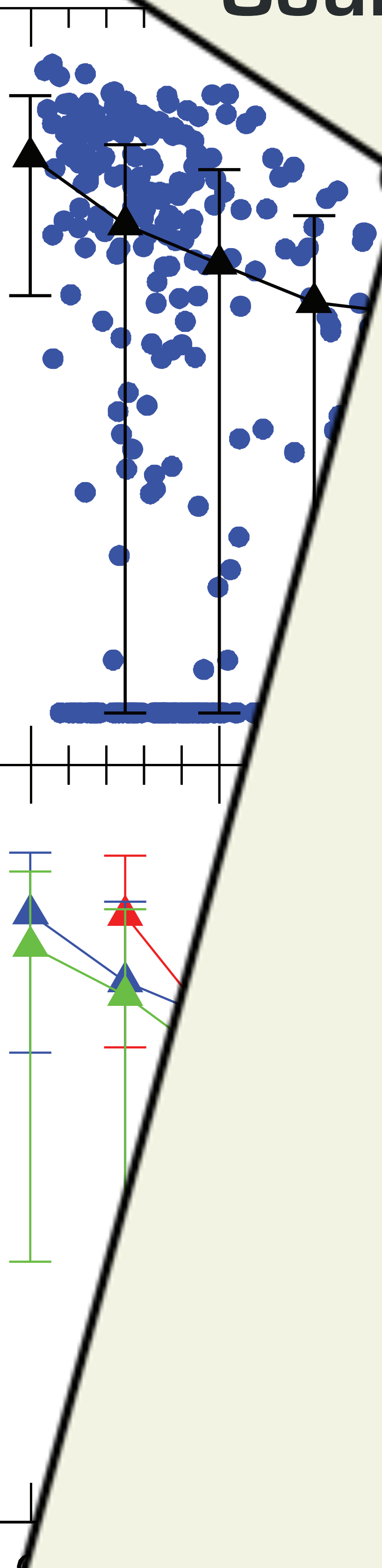
Radiation Hydrodynamics

SimpleX is part of Amuse (Astrophysical Multi-Scale Environment)

www.amusecode.org



Sources



Simulations of reionisation do not resolve sources

Subgrid model: assume emissivity scales linearly with halo mass

Iliev et al: $\dot{N}_\gamma \propto f_\gamma M_\mathrm{h}$ with $f_\gamma = f_\mathrm{esc} f_\star N_\star$

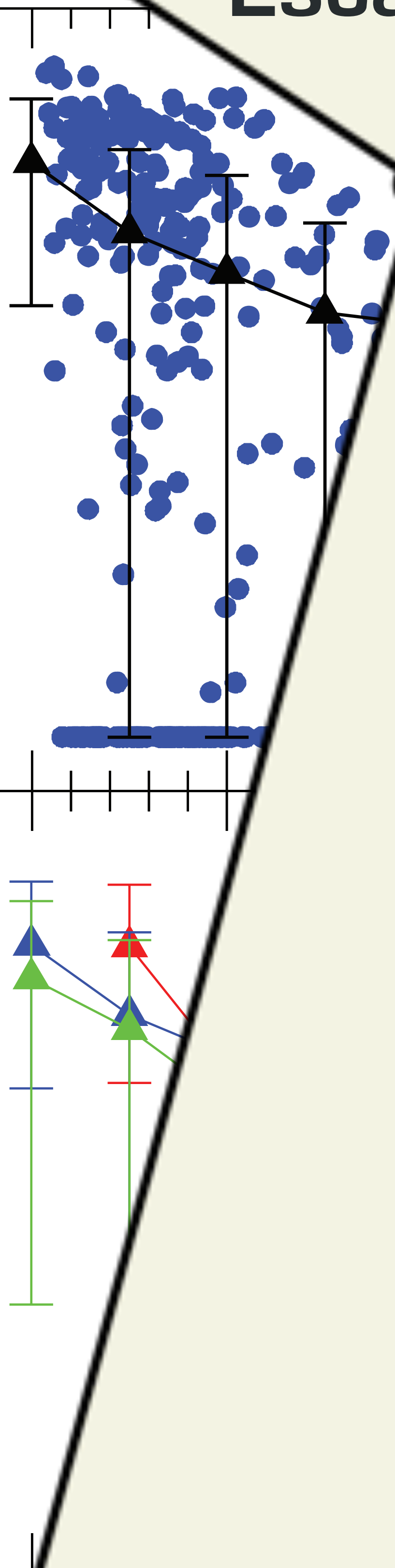
This is a reasonable approximation for the intrinsic emissivity

Escape fraction is not the same for different halo masses

Part II

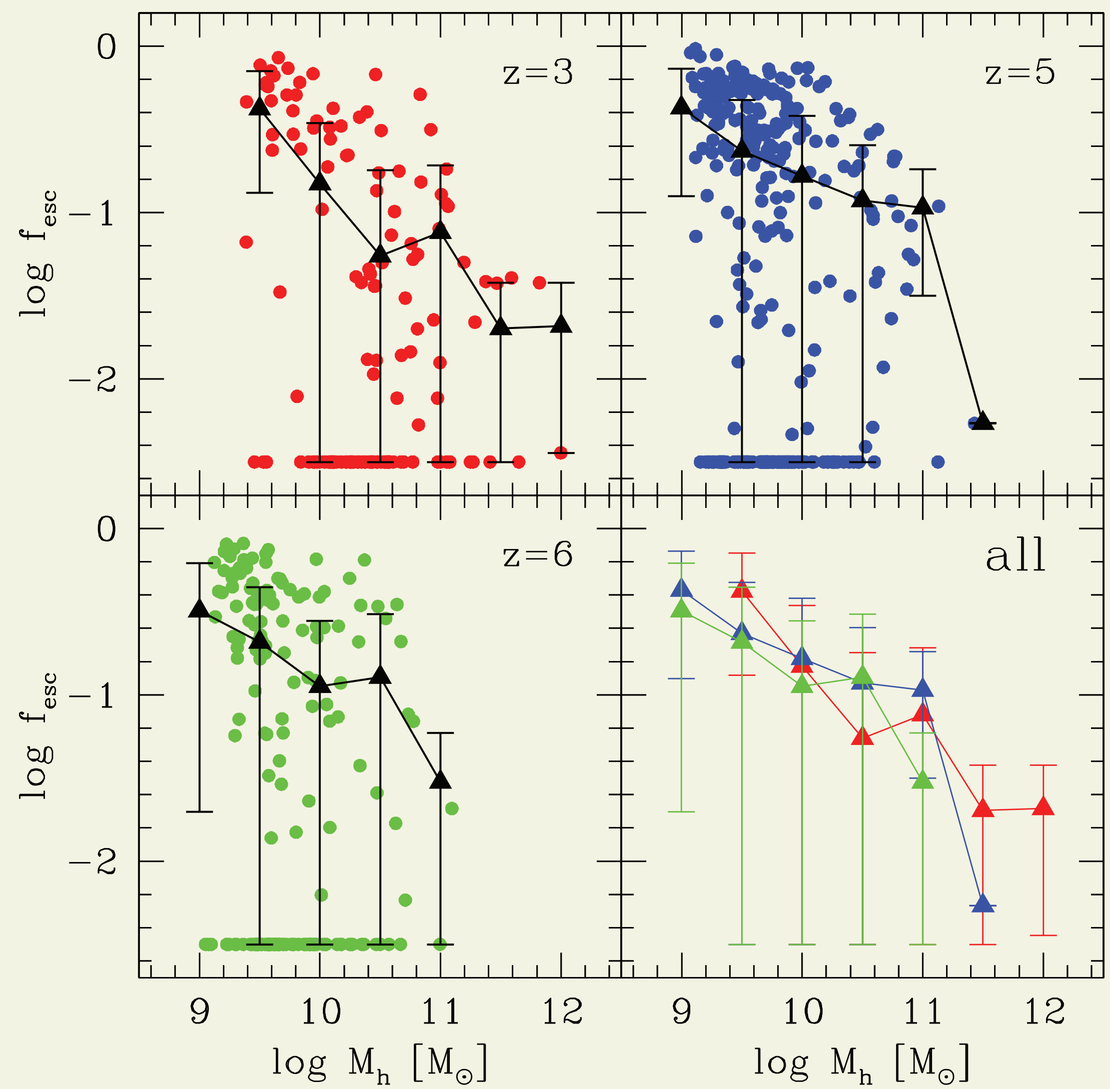
The sources of reionisation

Escape Fraction



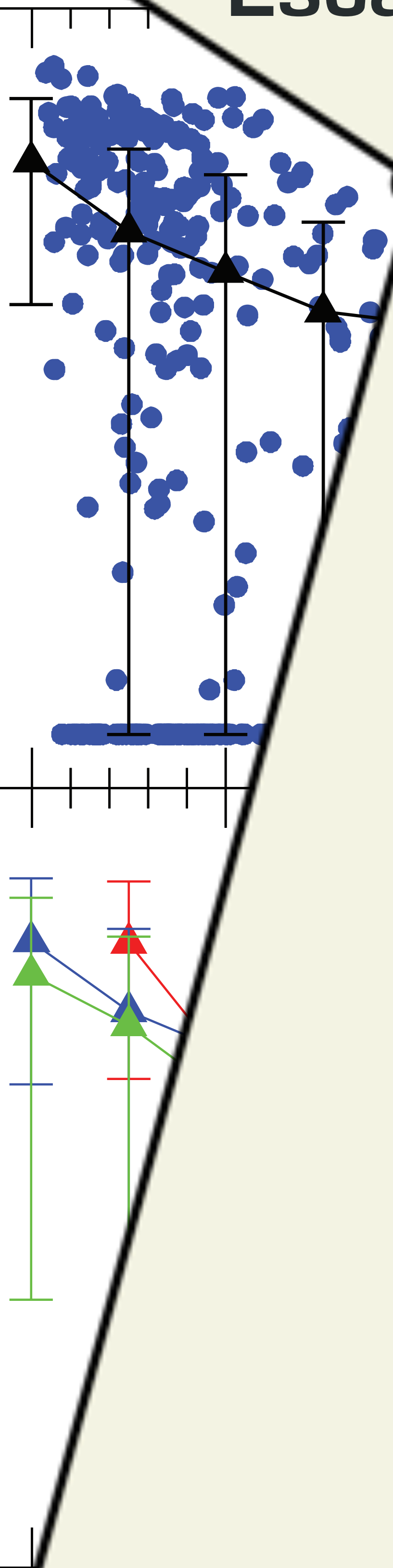
Depends strongly on galaxy morphology

Strong dependence on halo mass



Yajima et al. (2010)

Escape fraction



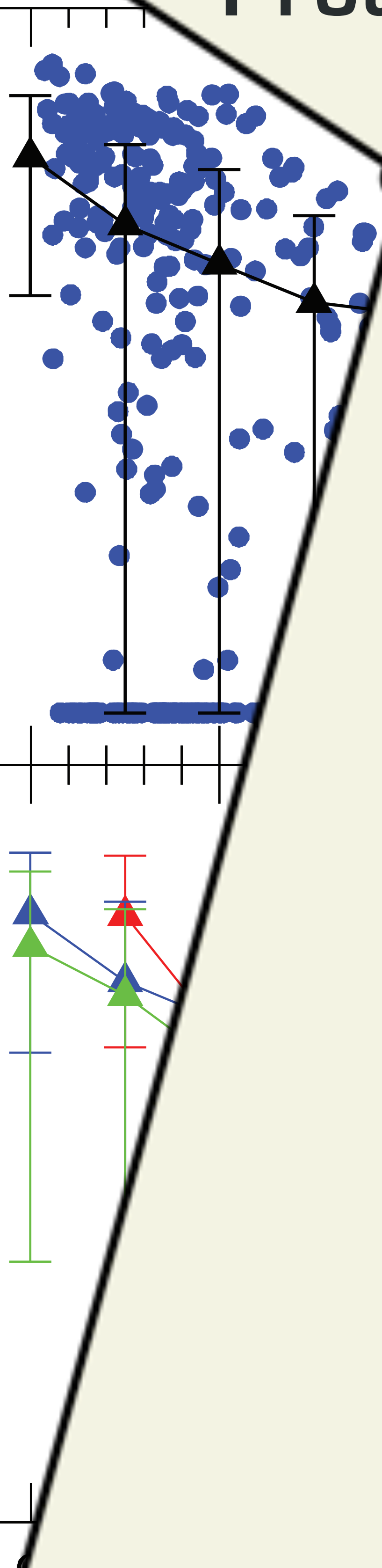
Sites of star formation are so dense that no ionising radiation escapes

Ionising radiation escapes primarily through holes blown by supernovae

Escape highly inhomogeneous

The local gas complexes are the main constraint on escape fraction

Proto-galaxies



(Proto-)galaxy population during reionisation

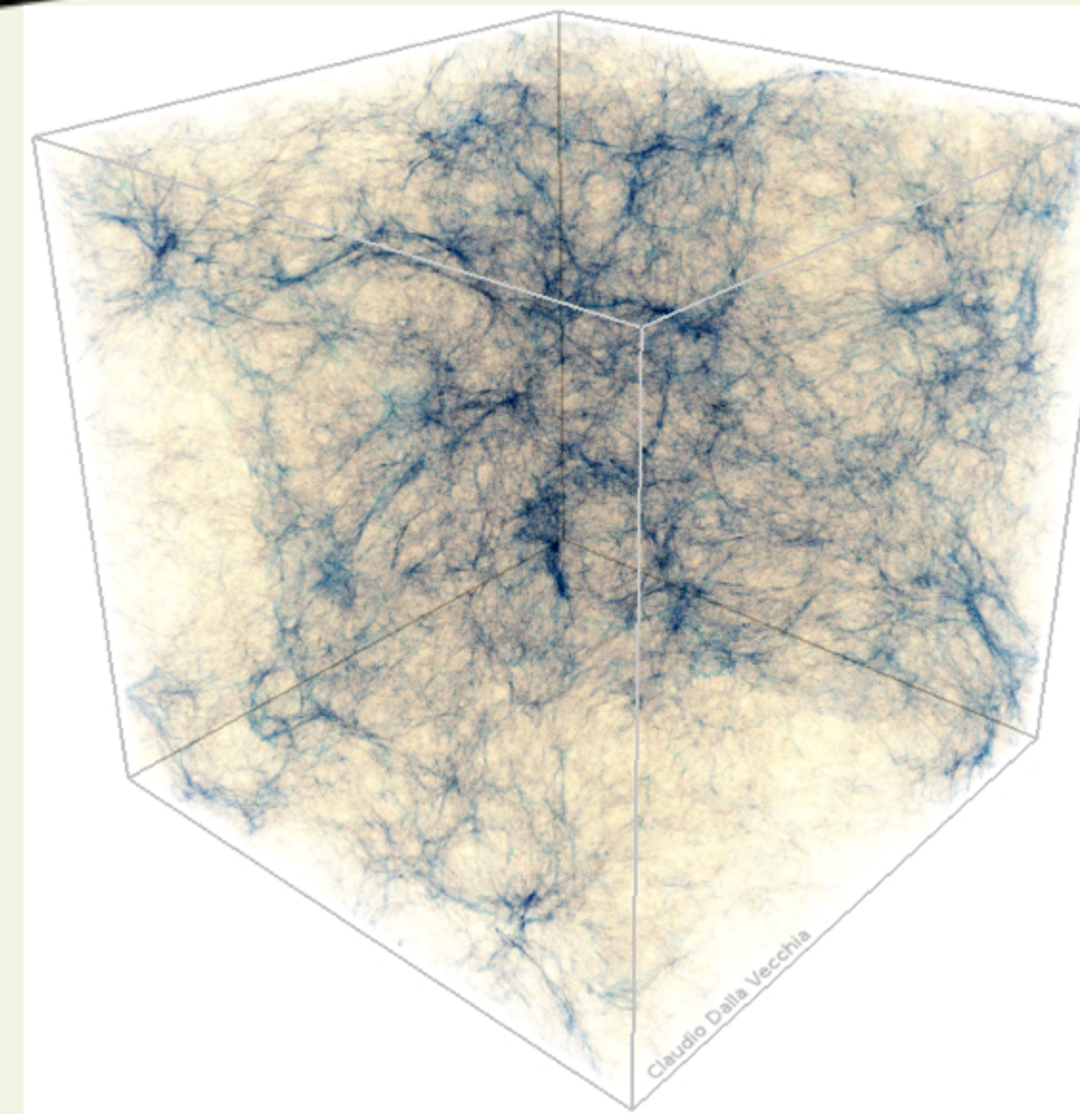
Relevant mass range: $10^8 - 10^9 \, \mathrm{M}_{\odot}$

1) Low mass ➡ efficient feedback ➡ high escape fraction?

2) Star formation suppressed in ionised regions of the Universe

Do these sources produce enough photons?

FiBY simulation



First Billion Years project

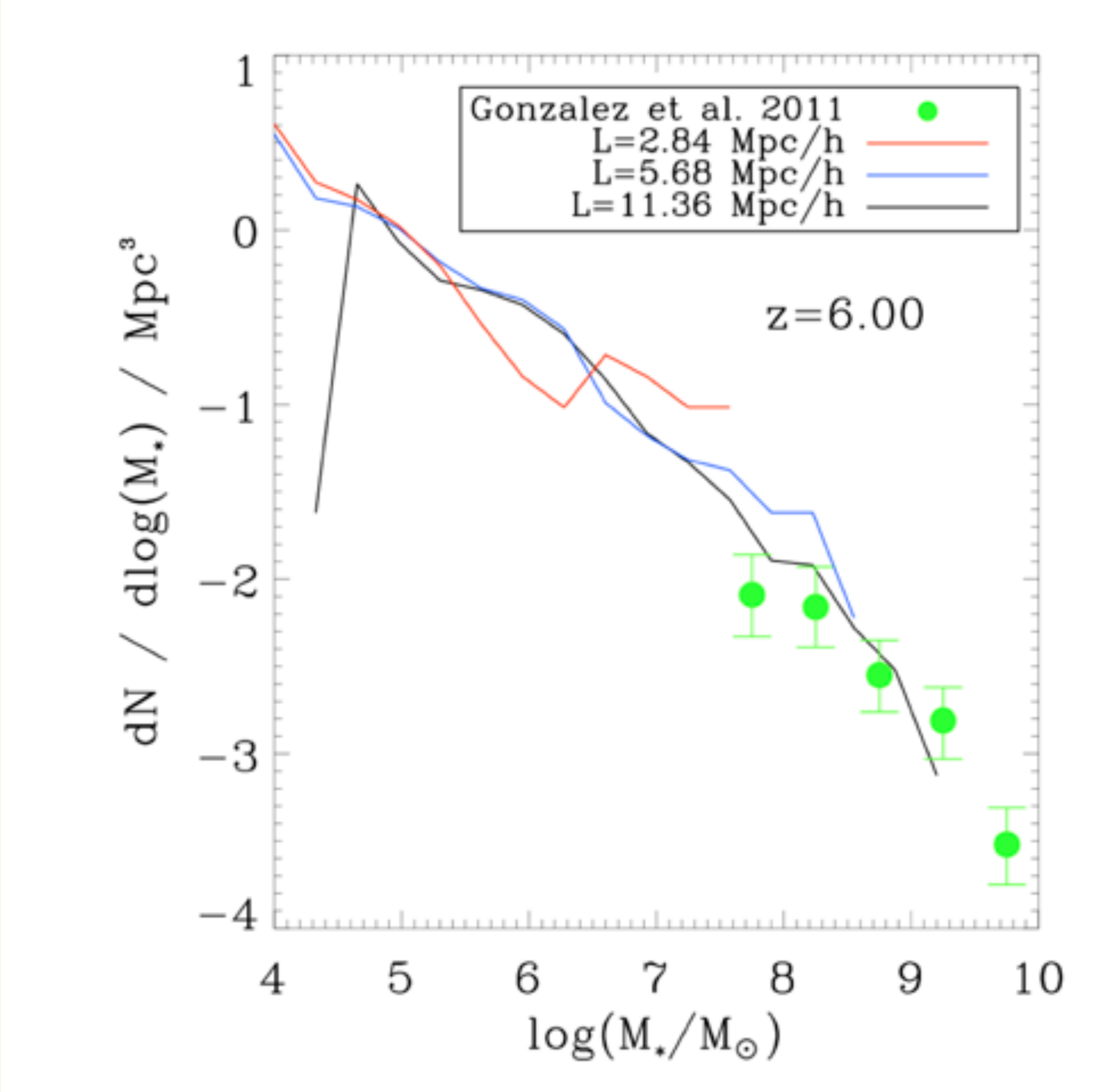
box size: $4\,(8, 16)\,\mathrm{Mpc}$

number of particles: 2×684^3

gas particle mass: $1250\,\mathrm{M}_\odot$

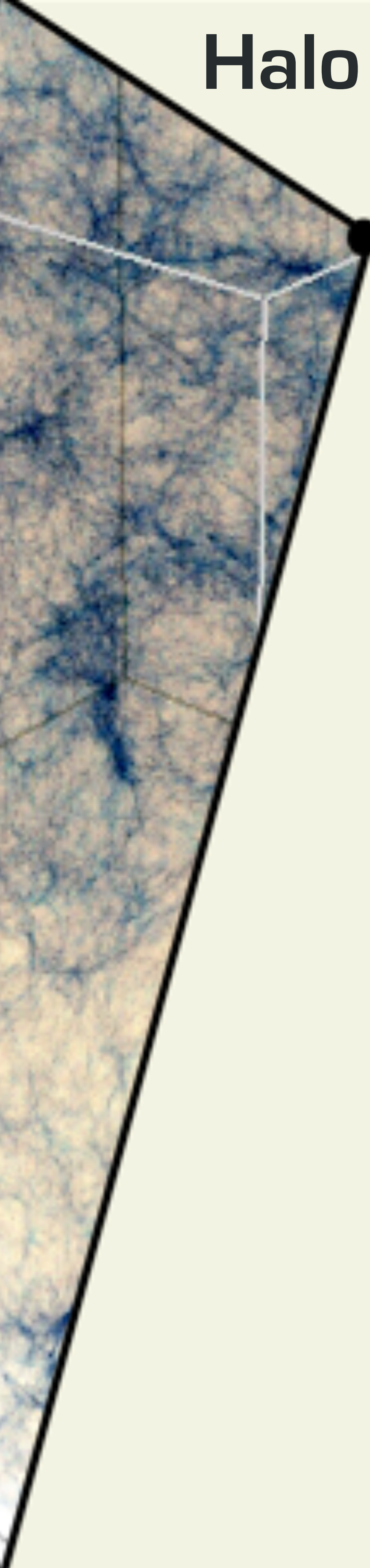
Khochfar et al. in prep
Dalla Vecchia et al. in prep

Mass function



Khochfar et al. in prep

Halo sample



Select all haloes with at least 1 star particle and 1000 dm particles

> 11,000 haloes in redshift range 6 < z < 22

number of star particles in each halo: few - >80,000

Determine the fraction of produced photons that reach virial radius

$$f_{\mathrm{esc}}(t) = \frac{N_{\mathrm{phot}}(r > r_{200}, t)}{N_{\mathrm{emitted}}(t)}$$

Radiative transfer

Radiative transfer in post-processing

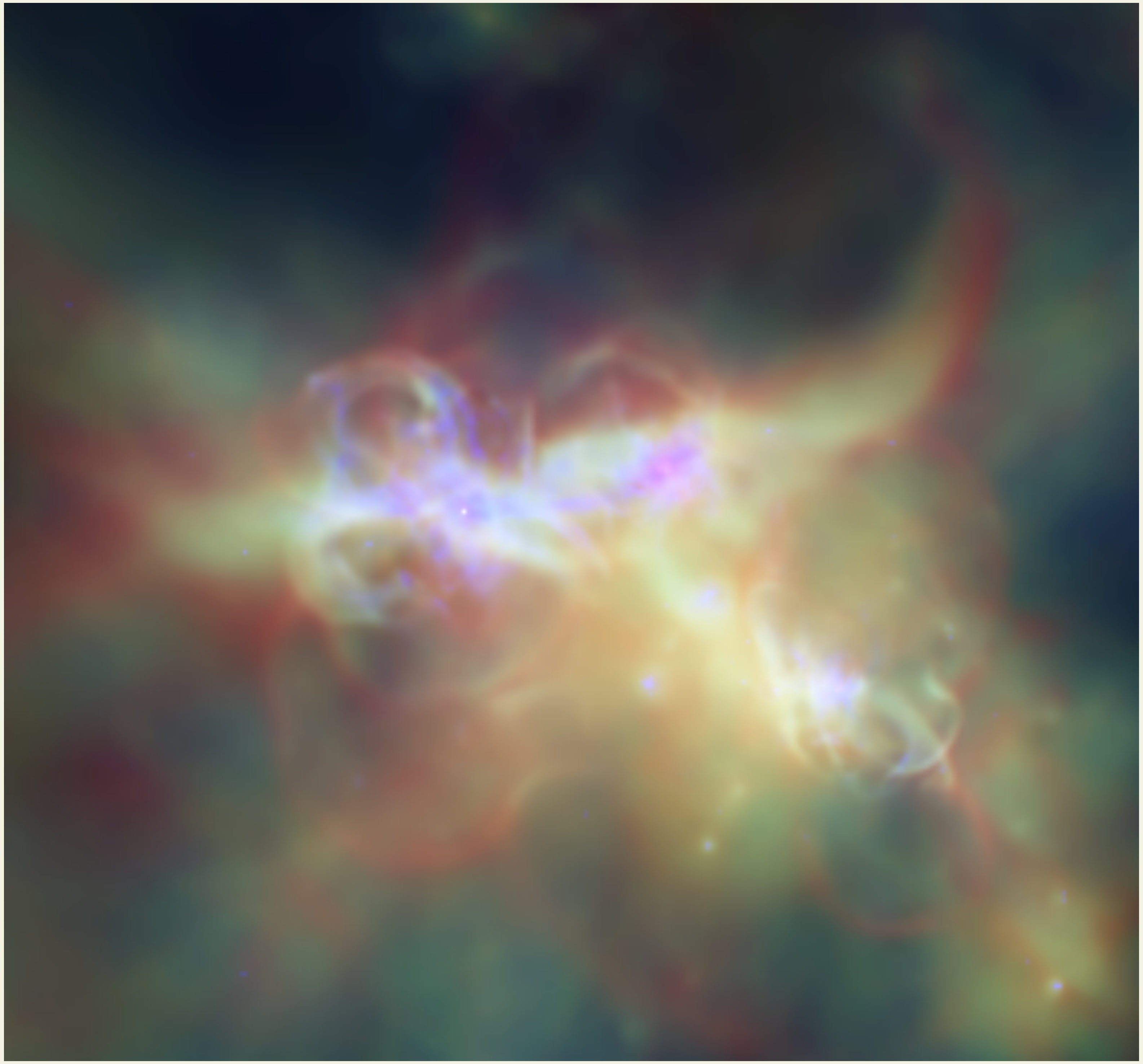
Follow photons from Pop III and Pop II stars

Spectra from stellar synthesis models
(Raiter et al. 2010; Bruzual&Charlot 2003)

Absorption by hydrogen and helium

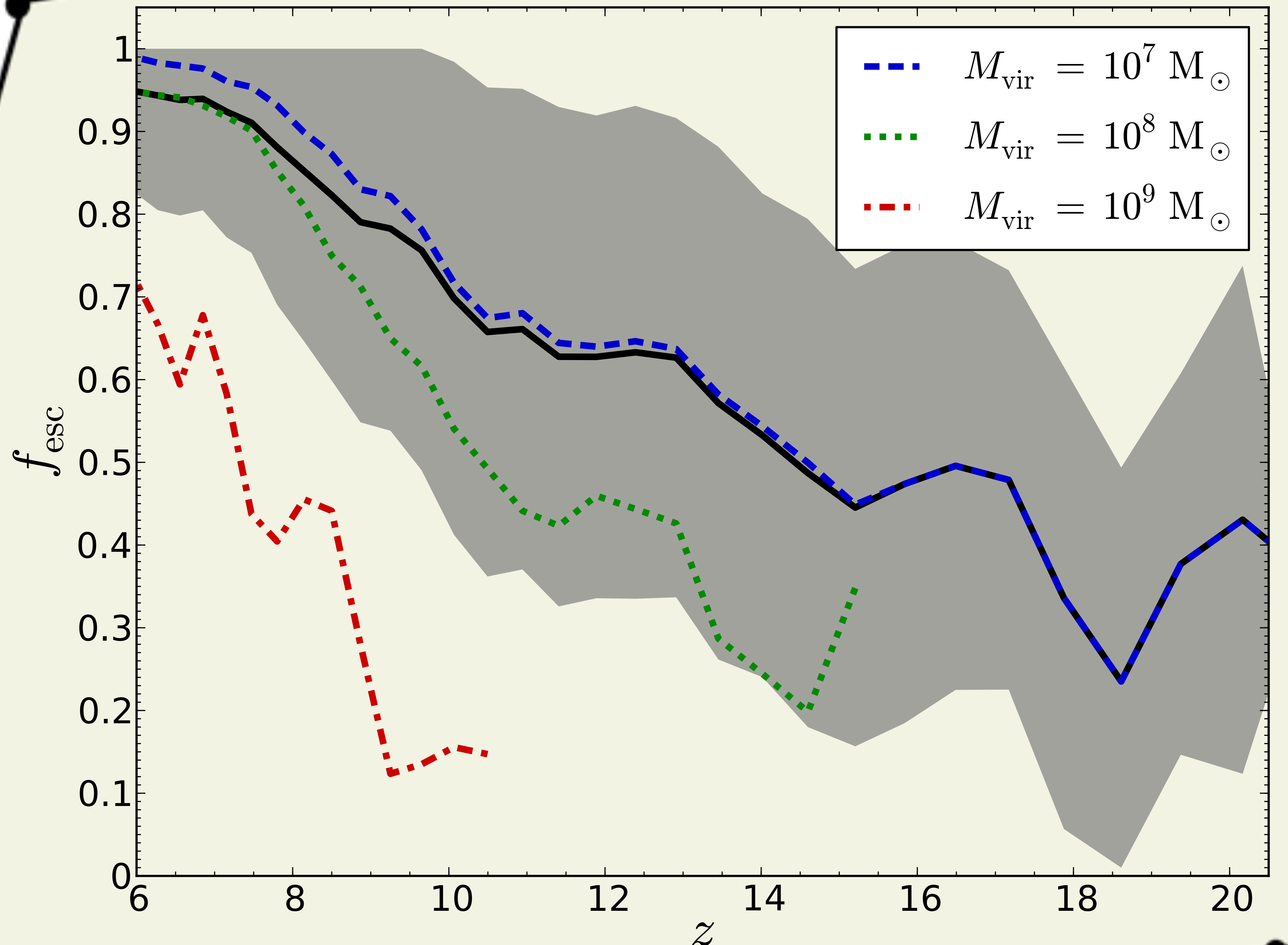
Multi-frequency approach including relevant heating and cooling processes

Galaxy



C. Dalla Vecchia

Escape fraction



Reionisation model

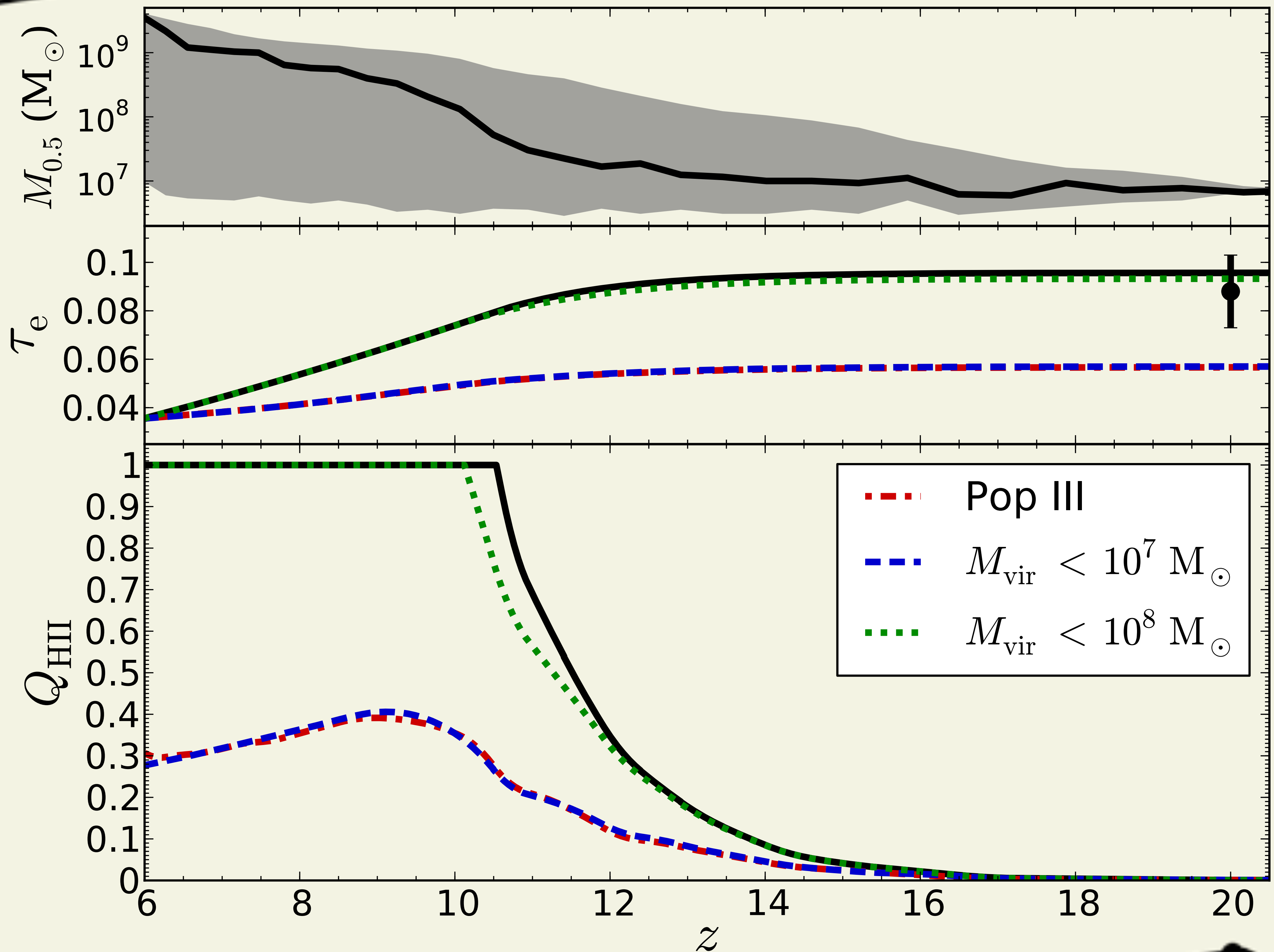
$$\frac{\mathrm{d}Q_{\mathrm{H\,II}}}{\mathrm{d}t} = \frac{\dot{N}_{\mathrm{ion}}}{\bar{n}_{\mathrm{H},0}} - Q_{\mathrm{H\,II}}\, C\, \bar{n}_{\mathrm{H},0}\, \alpha(T)\, (1+z)^3$$

Observations: $Q_{\mathrm{H\,II}} = 1$ for $z \lesssim 6.5$

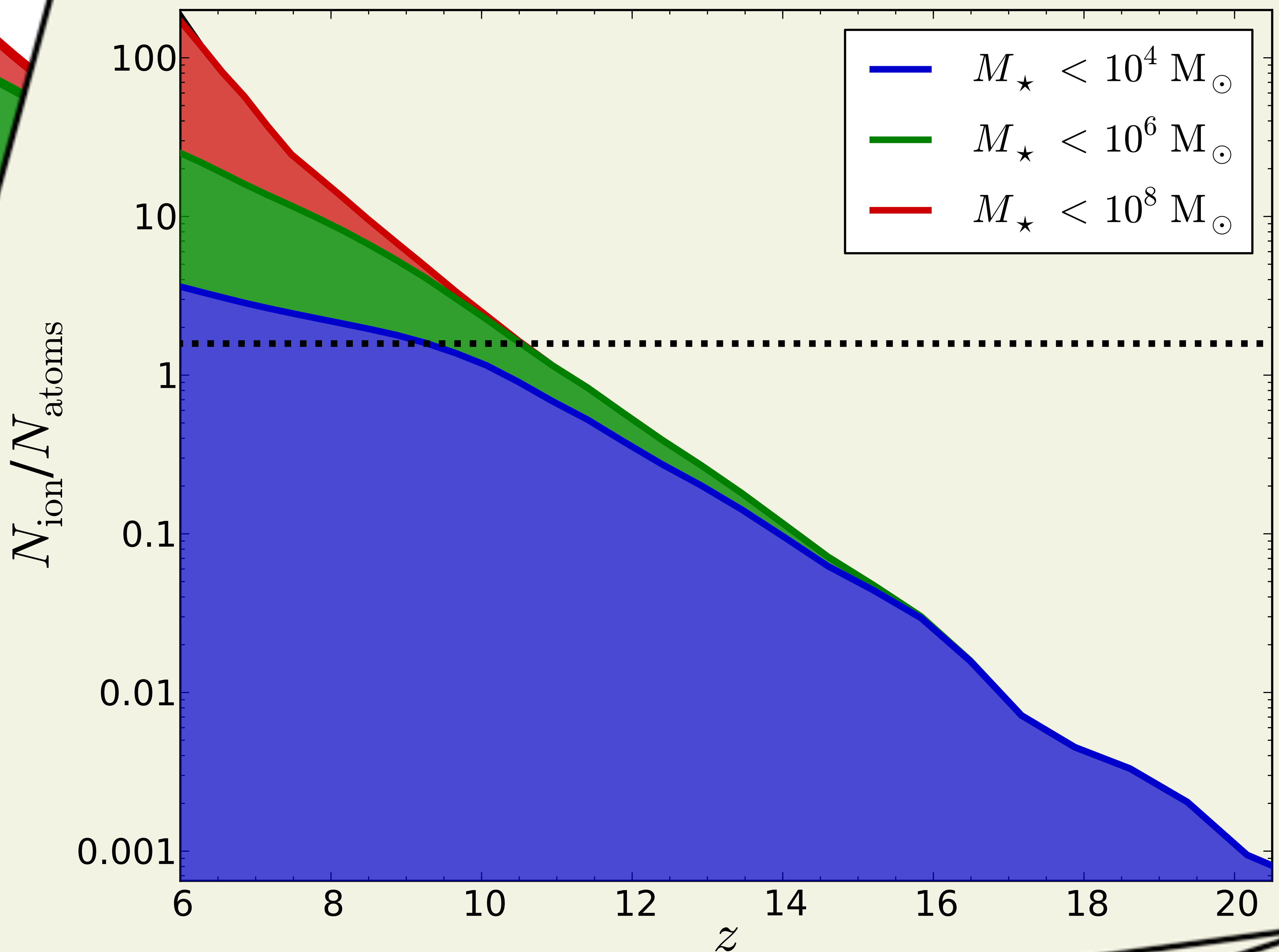
$$\tau_{\mathrm{e}} = \int_0^{z_{\mathrm{rec}}} \mathrm{d}z \left| \frac{\mathrm{d}t}{\mathrm{d}z} \right| c\, Q_{\mathrm{H\,II}}(z)\, \bar{n}_{\mathrm{H},0}\, (1+z)^3\, \sigma_{\mathrm{T}}$$

Observations: $\tau_{\mathrm{e}} = 0.088 \pm 0.015$

Reionisation results



Proto-galaxies



Proto-galaxies

These proto-galaxies are susceptible to feedback

- Star formation suppressed by external UV feedback
- Suppression probably underestimated in our simulations

Our simulations do not include the most massive haloes

- Box size is limited due to resolution requirements
- Contribution of these sources is small

Conclusions

Escape fraction is important parameter in reionisation studies

Escape fraction depends strongly on the halo mass

Proto-galaxies at $z > 10$ emit enough photons for reionisation

Star formation in these haloes is suppressed after reionisation

Topology of reionisation different from current scenarios