FiBY

The escape of ionising radiation from galaxies during the epoch of reionisation

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Stars are believed to be the main source of ionising photons during reionisation

Contribution of stars depends on:

- Star formation rate
- Fraction of photons that escape the host galaxy

Escape fraction is a key parameter in studies of reionisation

Observations of escape fractions:

Milky Way: ~1-2% (e.g. Bland-Hawthorn et al. 1999)

Local starbursts: < 1 - 6% (e.g. Heckman et al. 2001)

Galaxies around redshift 1: < 1-2 % (e.g. Siana et al. 2010)

Higher redshifts: increasing towards <10% (e.g. Shapley et al. 2006)

Direct measurements complicated

- Compare flux at Lyman limit to frequency at which intrinsic luminosity is inferred
- Need model description of star formation history

Samples are small

- Low redshift counterparts of high redshift galaxies may not have been targeted yet
- High redshift objects may be untypical bright objects

Modelling of escape fractions:

1-3% with almost no redshift dependence between $3 < z < 9$ — Gnedin et al. (2008)

1-2% (z~2), 8-10% (z~3), 80% (z~10) — (Razoumov et al. 2006,2007,2010)

40 - ~90% for dwarf galaxies at $8 < z < 10$ — (Wise & Cen 2009)

7 - 70% with almost no redshift dependence — (Yajima et al. 2011)

Key is to understand the physical meaning behind this large scatter in values

Two approaches:

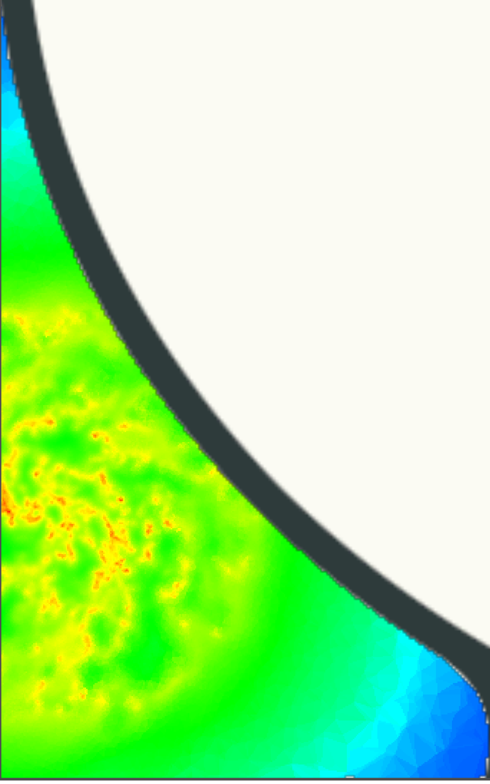
I Study galaxies in isolation and concentrate on physical processes inside galaxies

II Use simulation of cosmological structure formation to obtain large sample

- **Study galaxies in isolation and concentrate on physical processes inside galaxies**

Drawback: no interaction with environment, important at high redshift

JPP, Pelupessy, Altay & Kruip (2011)



Models

Isolated models

SPH code follows gas and star particles

Supernova and stellar wind feedback taken into account using pressure particles

Model for 2-phase ISM similar to Wolfire et al. (2003)

Salpeter IMF

Initial conditions

Dark matter halo with NFW profile

Disk of stars and disk of gas

Different models to do parameter study of

mass $10^8 - 10^9 M_\odot$

spin parameter $\lambda = \frac{L|E|^{1/2}}{GM_{vir}^{5/2}} = 0.025 - 0.1$

gas fraction $f_{gas} = 0.2 - 0.8$

Radiative Transfer

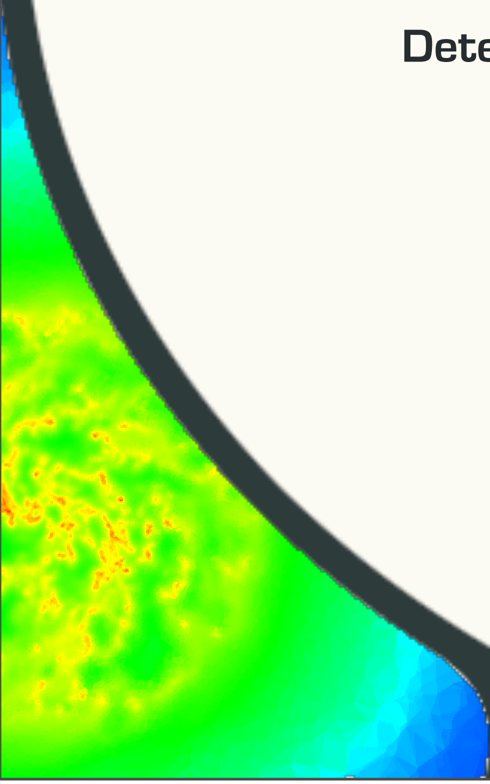
Radiative transfer in post-processing with radiative transfer algorithm SimpleX

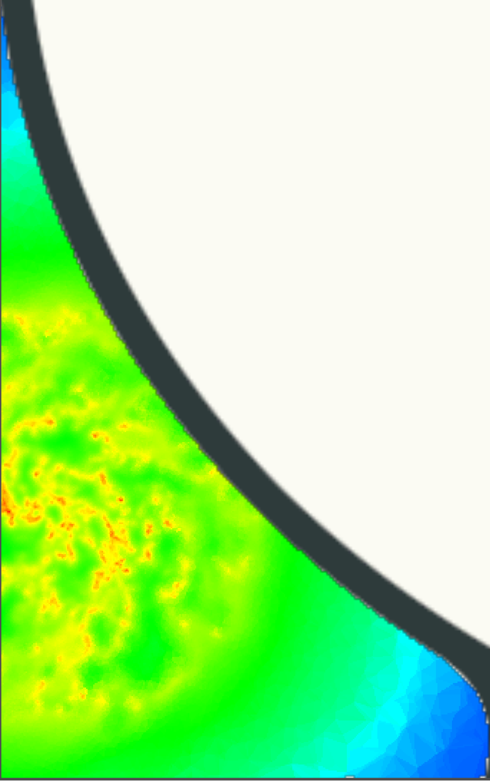
Ionising luminosities from updated version of Bruzual&Charlot (1993)

Consider only hydrogen (and dust)

Determine the fraction of produced photons that reach virial radius

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



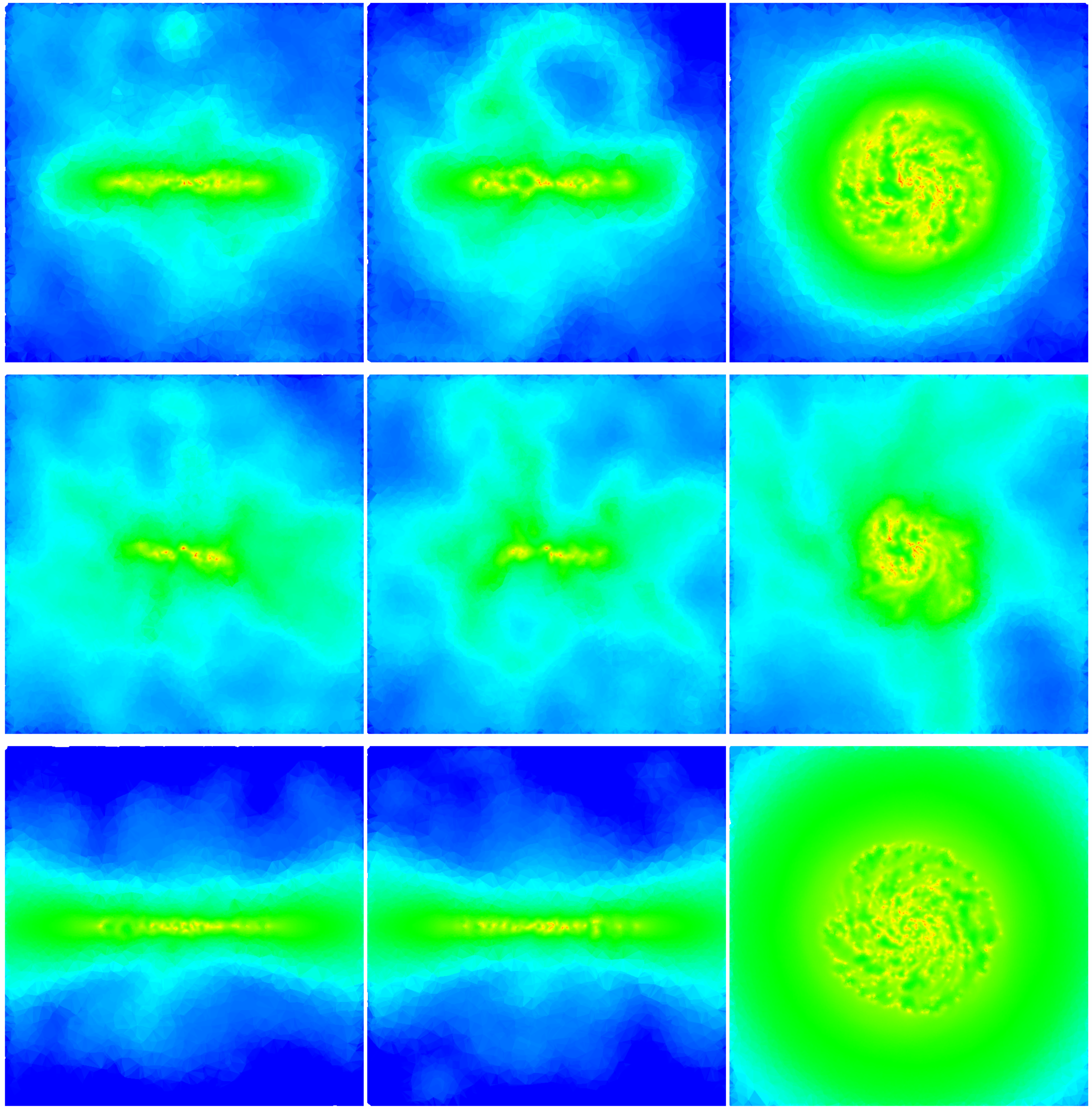


Galaxy morphologies

Irregular dwarf galaxies

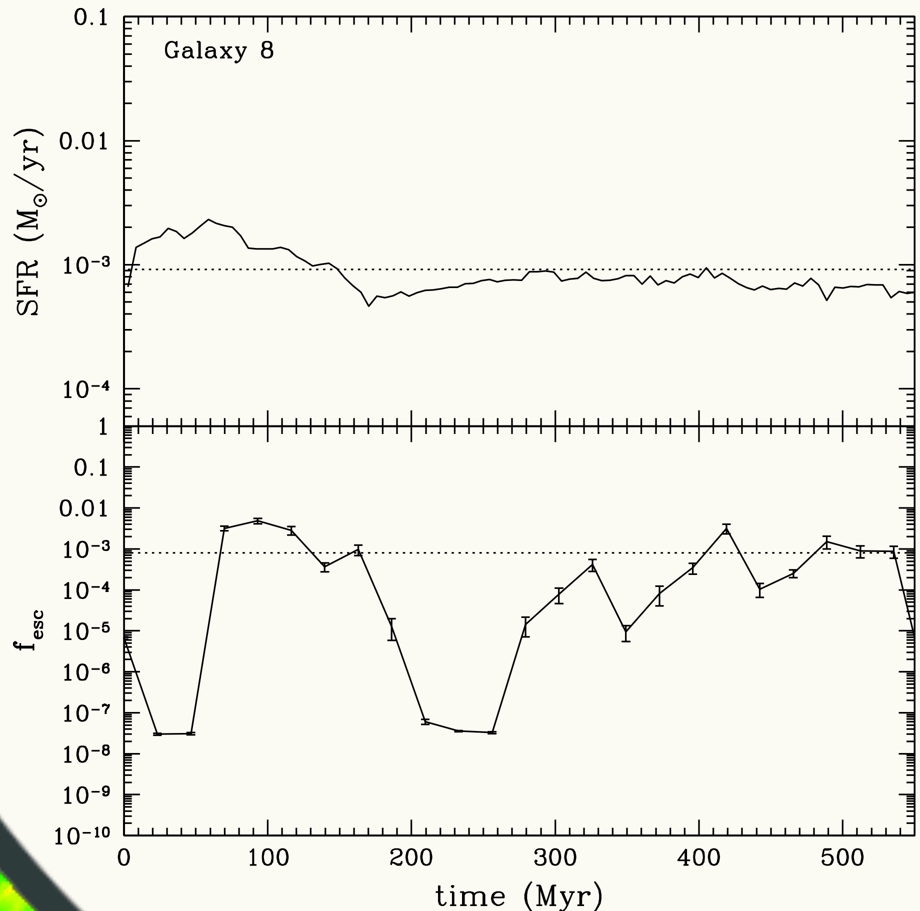
Gas confined in disc

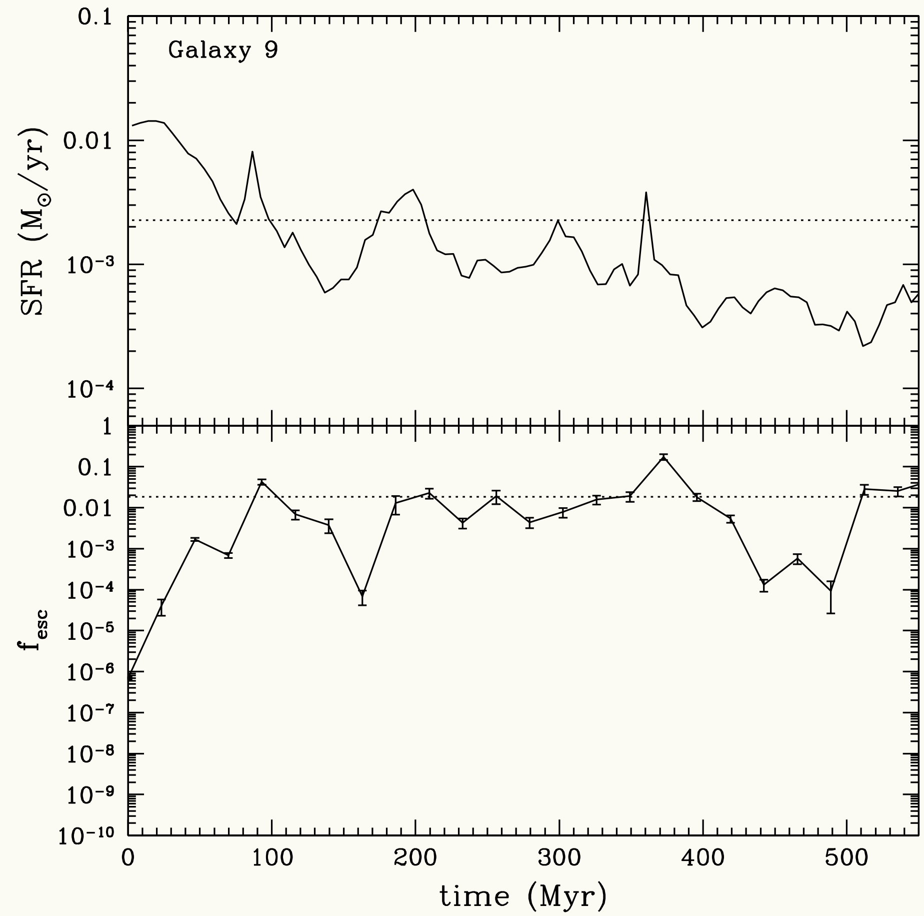
Stars form in high-density knots



Star formation rate and escape fraction of 1e9 solar mass galaxies

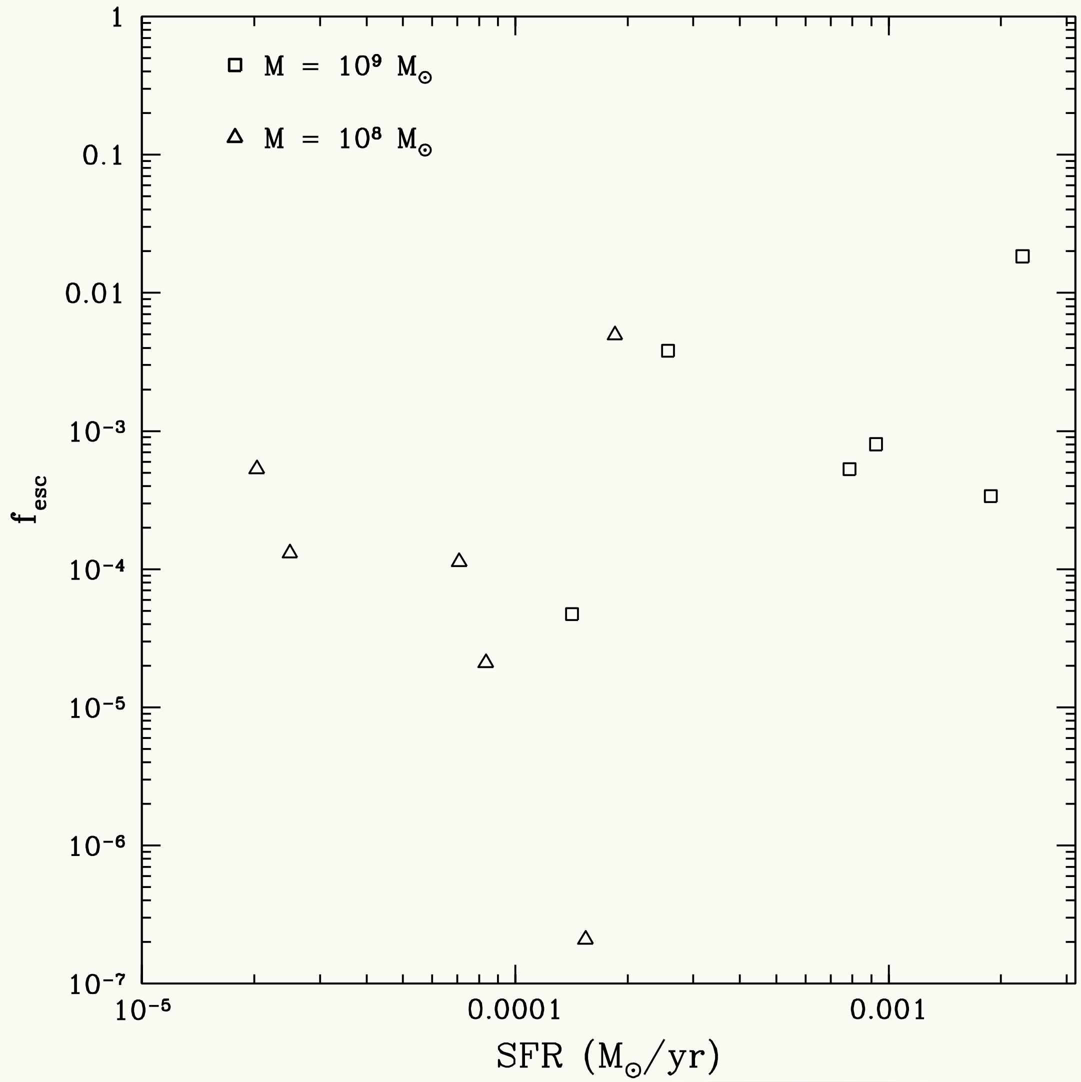
Peak in star formation rate causes peak in escape fraction





Escape fractions

Escape fraction and star formation rate are not tightly coupled



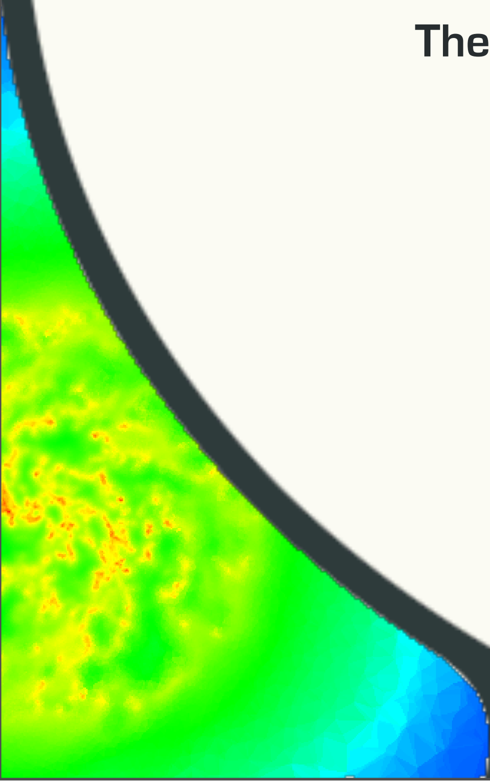
Escape fractions

The sites of star formation are so dense that no UV radiation can escape

Ionising radiation escapes primarily through holes blown by supernovae

Escape of UV radiation highly inhomogeneous

The local gas complexes are the main constraint on escape fraction



Numerics

This implies that numerical treatment is important!

High resolution to resolve gas clumps around sources

Feedback implementation plays important role

Abundant low luminosity sources need to be taken into account

Detailed modelling of processes that shape the local ISM is essential

II Use simulation of cosmological structure formation to obtain large sample

Realistic formation scenario of galaxies from cosmological initial conditions

Large sample

Drawback: detailed modelling of the ISM not possible

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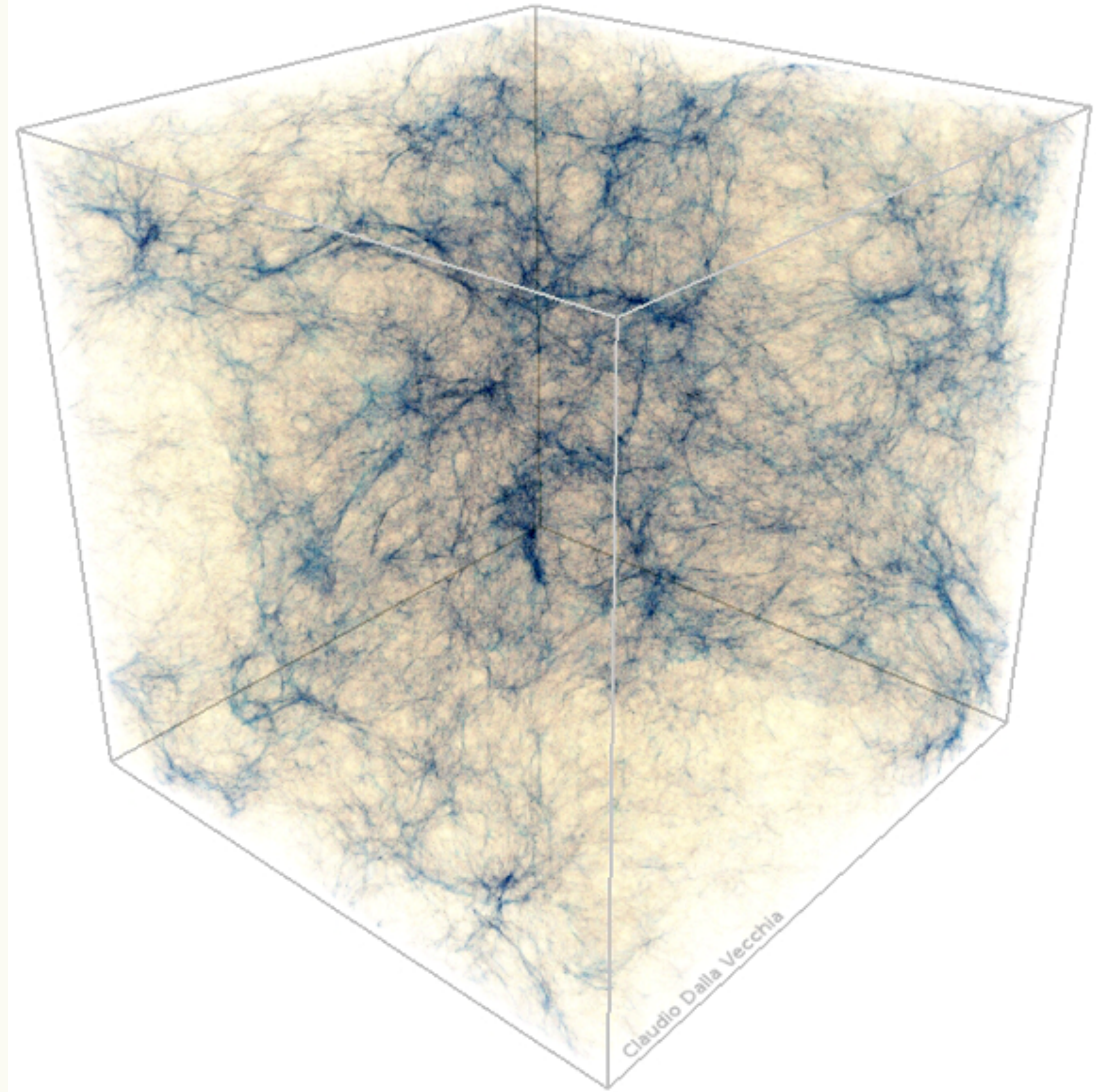
First Billion Years simulations

- 4 Mpc box
- 1250 solar mass particles
- 2 x 684^3 particles

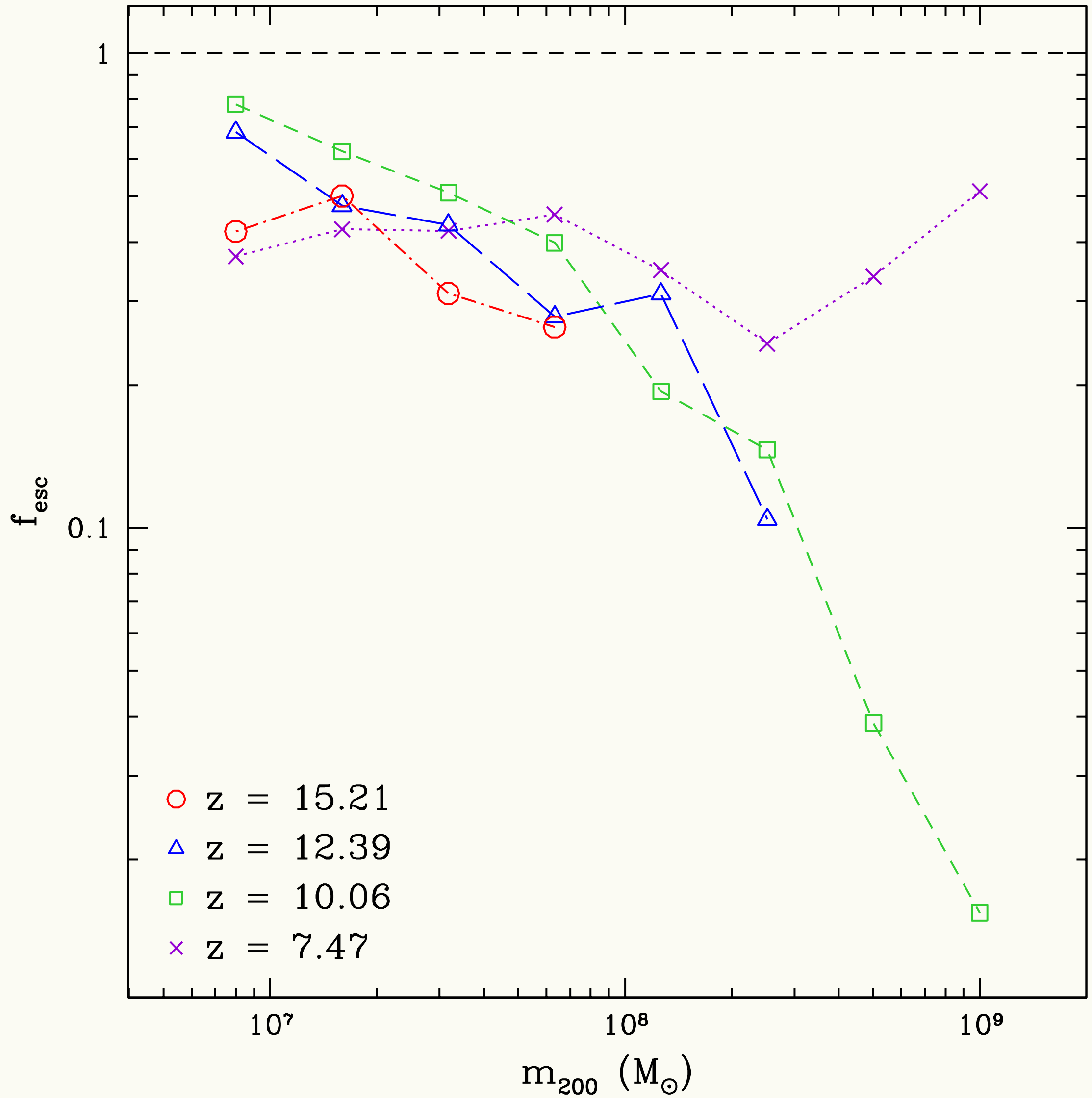


Extract all haloes that are resolved with at least 1000 dark matter particles

Focus on 4 redshifts: in total 1200 haloes

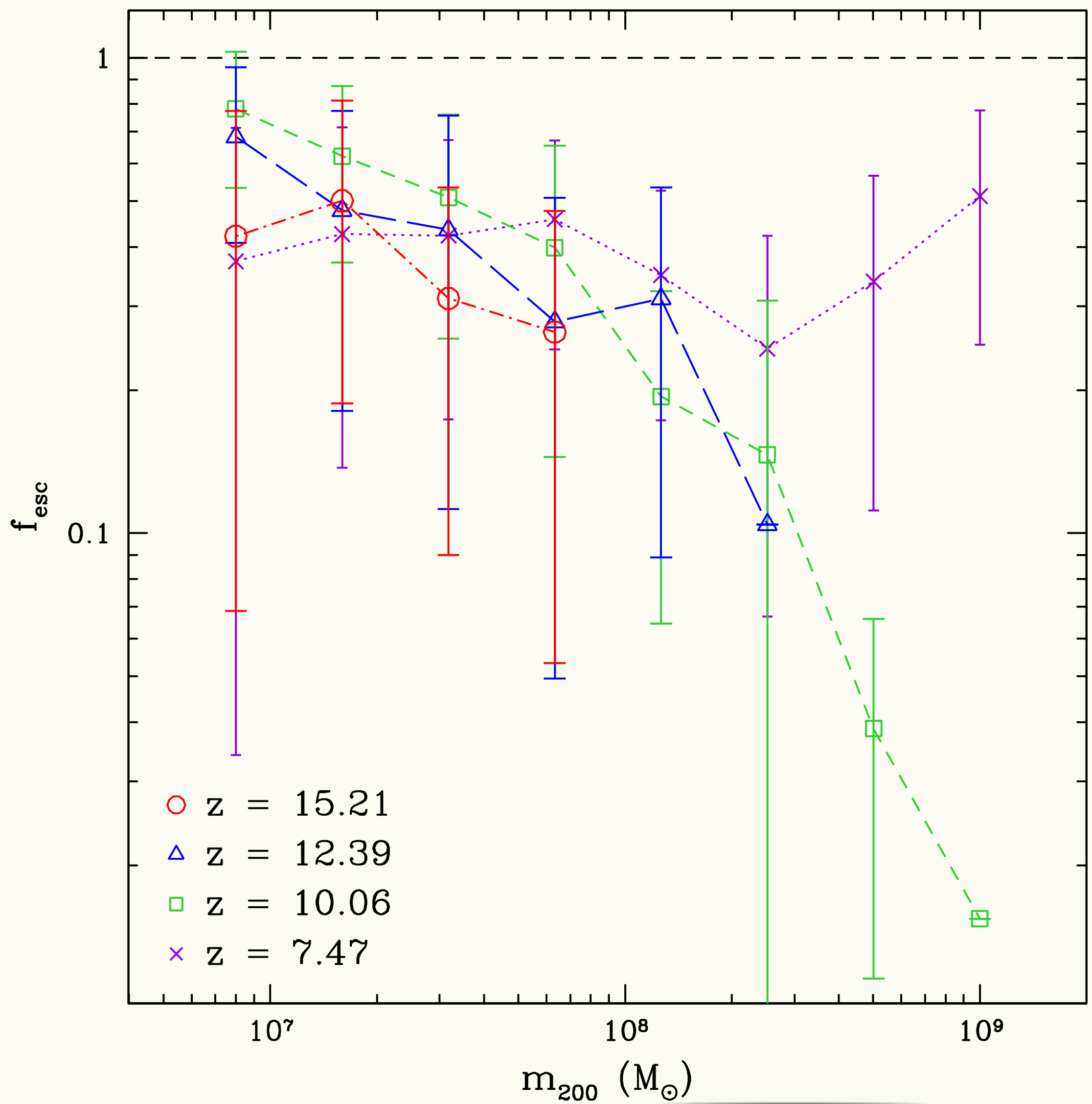
First results

Escape fraction from cosmological haloes significantly higher



First results

Important: scatter!



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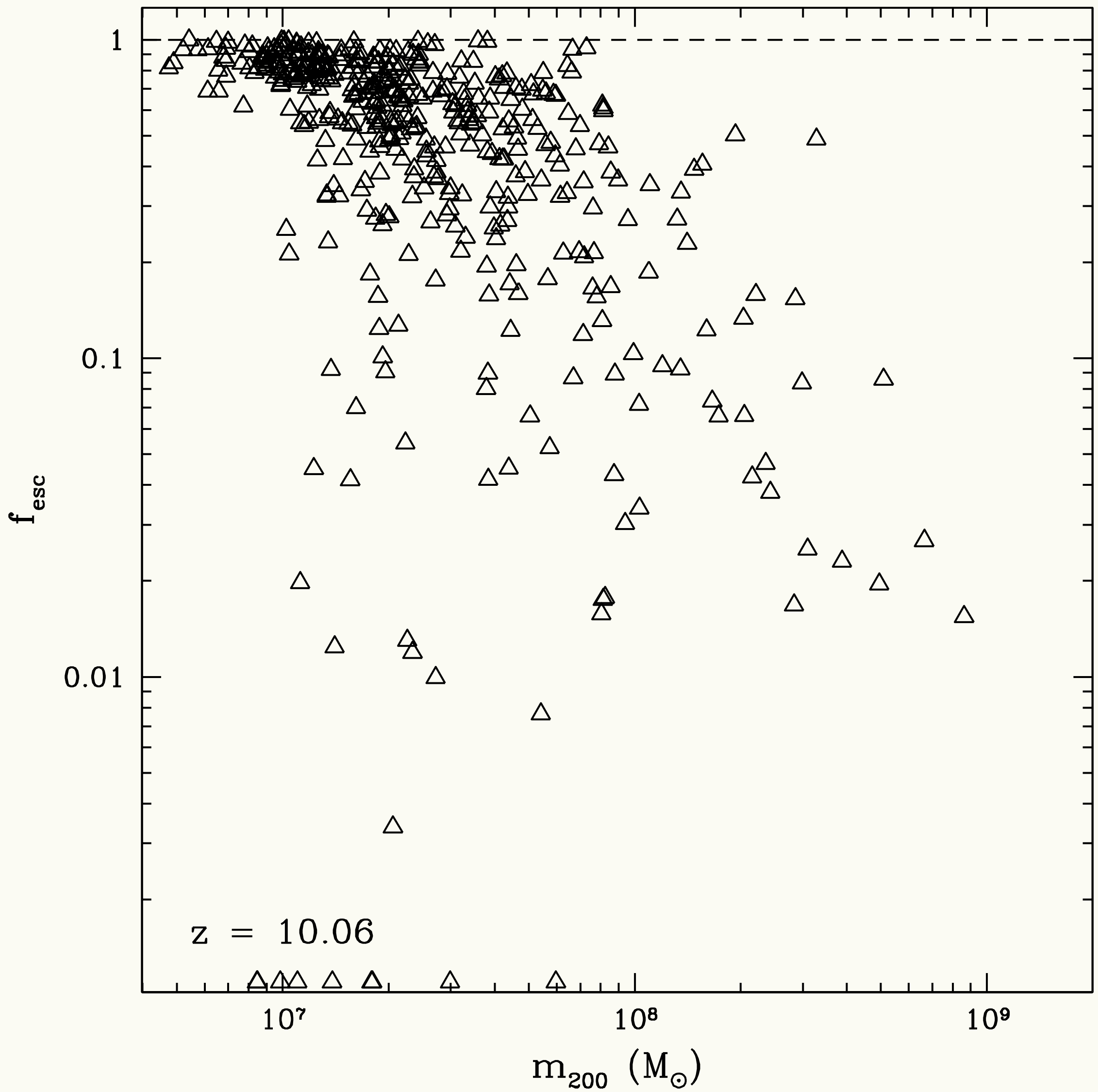
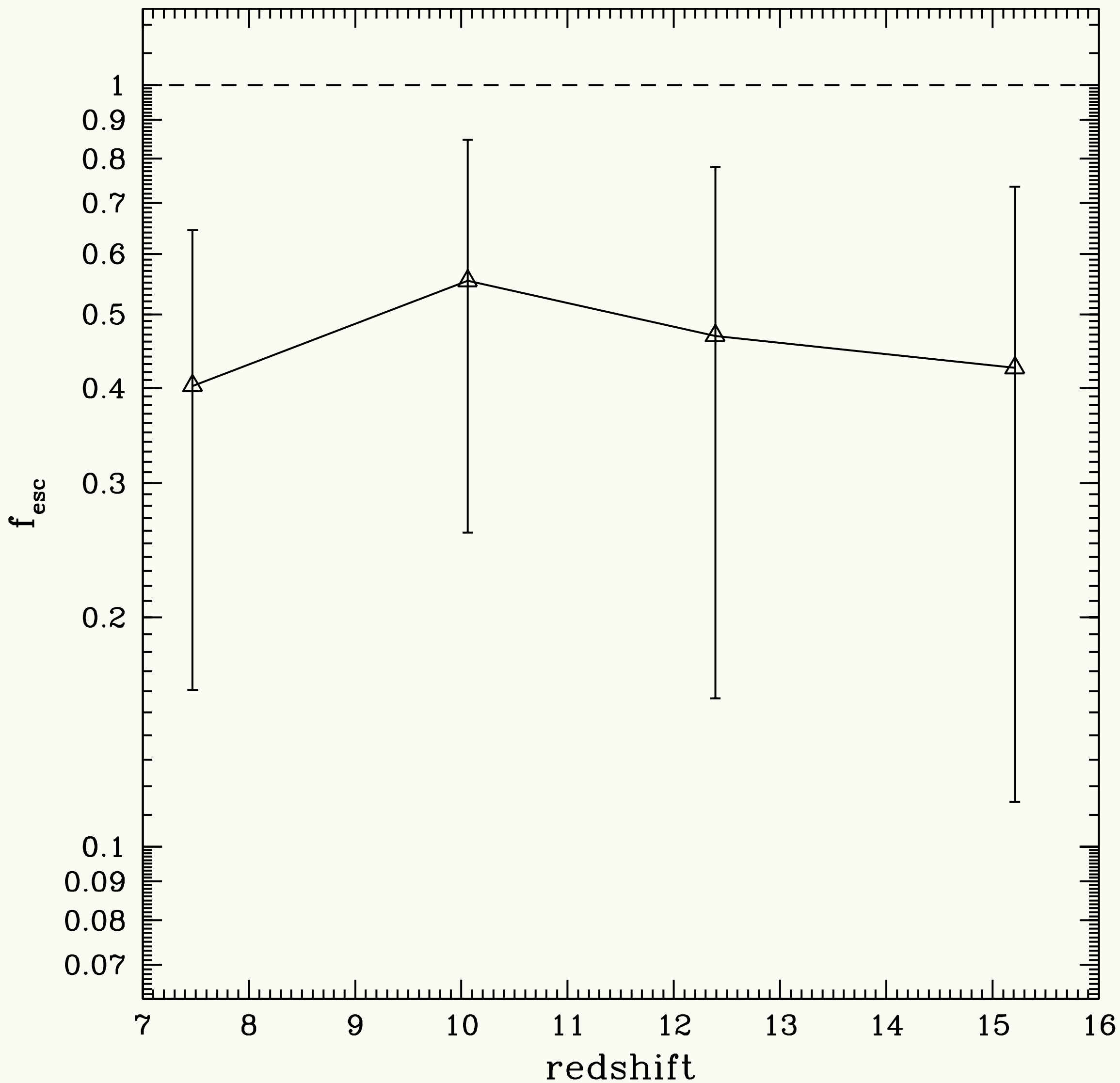
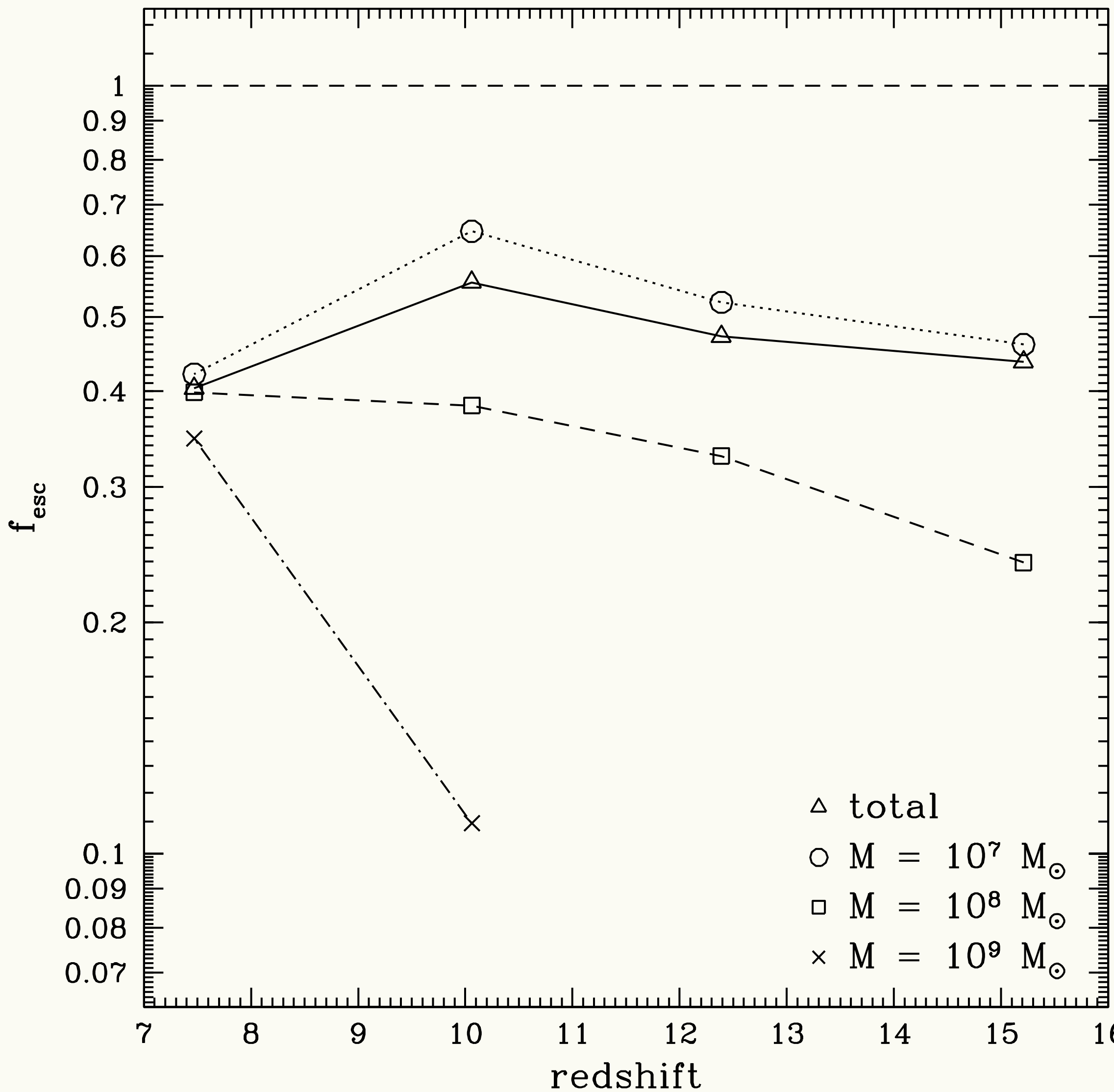


Redshift evolution



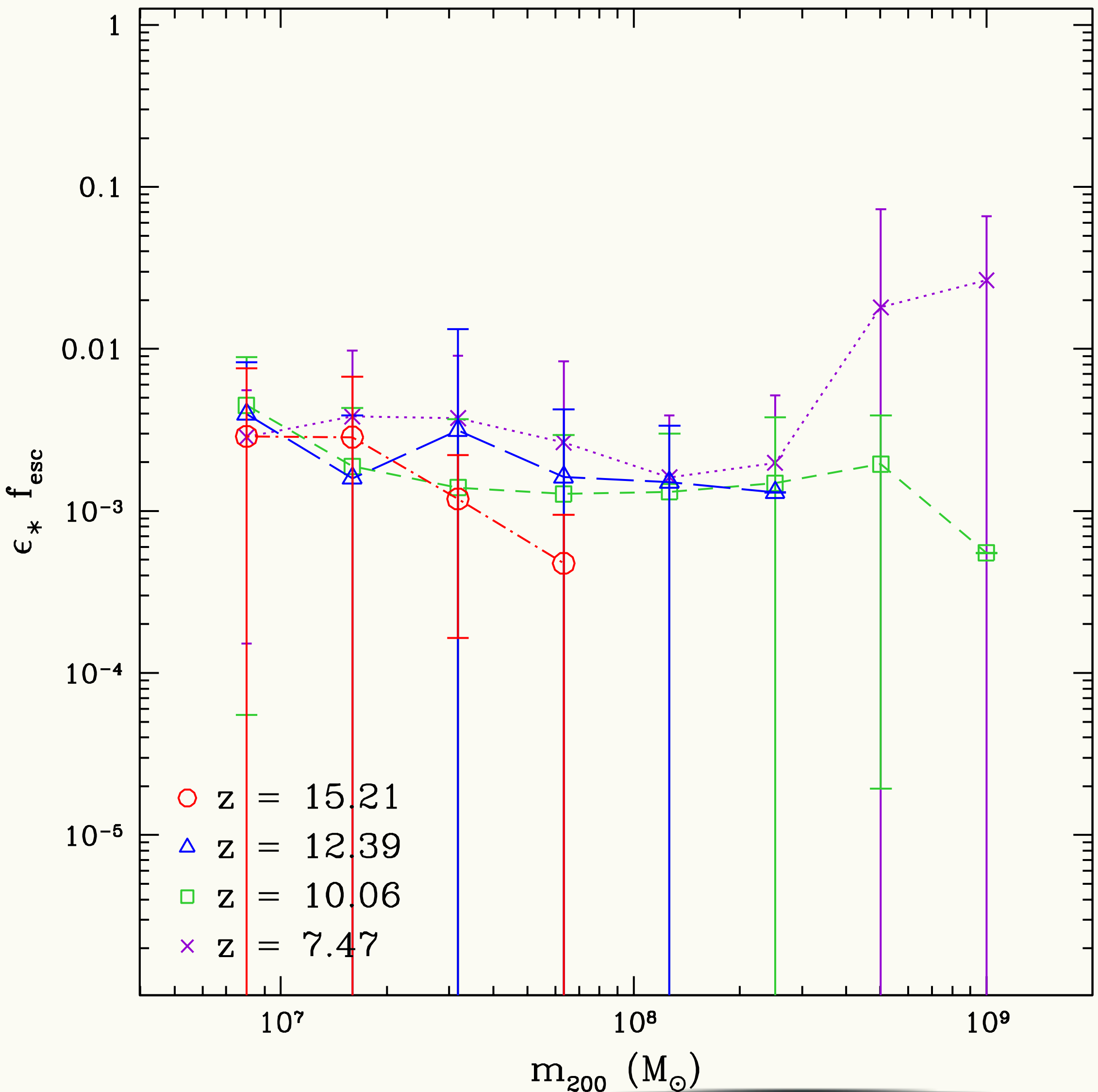
First results

Redshift evolution

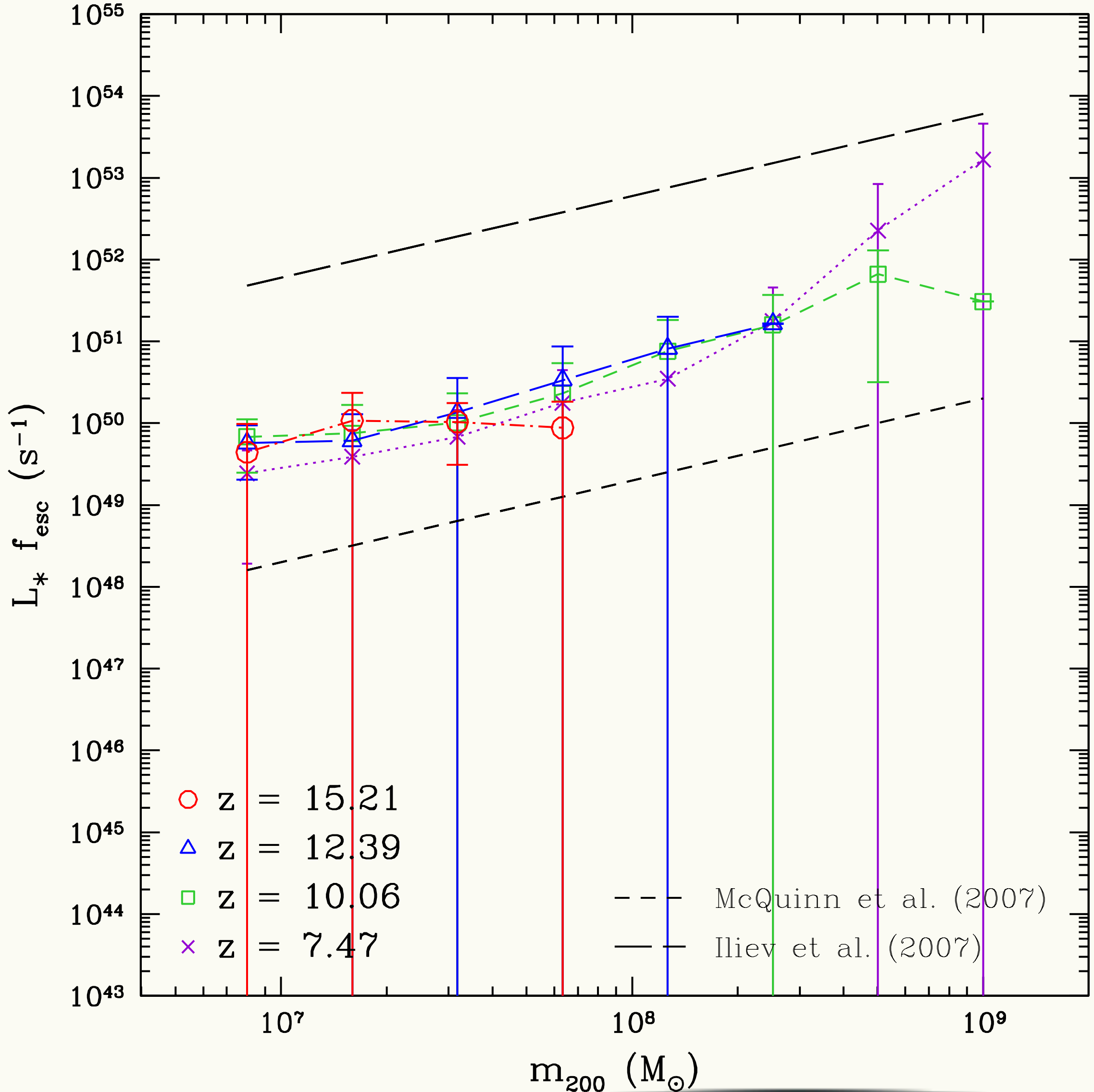


First results

Consequences for reionisation: semi-analytical models



Consequences for reionisation: numerical simulations



These large samples allow us to study the physical origin of this scatter

- clustering of haloes
- merger history
- star formation history

More detailed radiative transfer in SimpleX

- Helium
- Pop III
- Multi-frequency transport

Conclusions

Isolated disk models

Local gas complexes are main constraint for the escape fraction

Feedback of the stellar population on the gas important

Cosmological models

Large sample shows large scatter

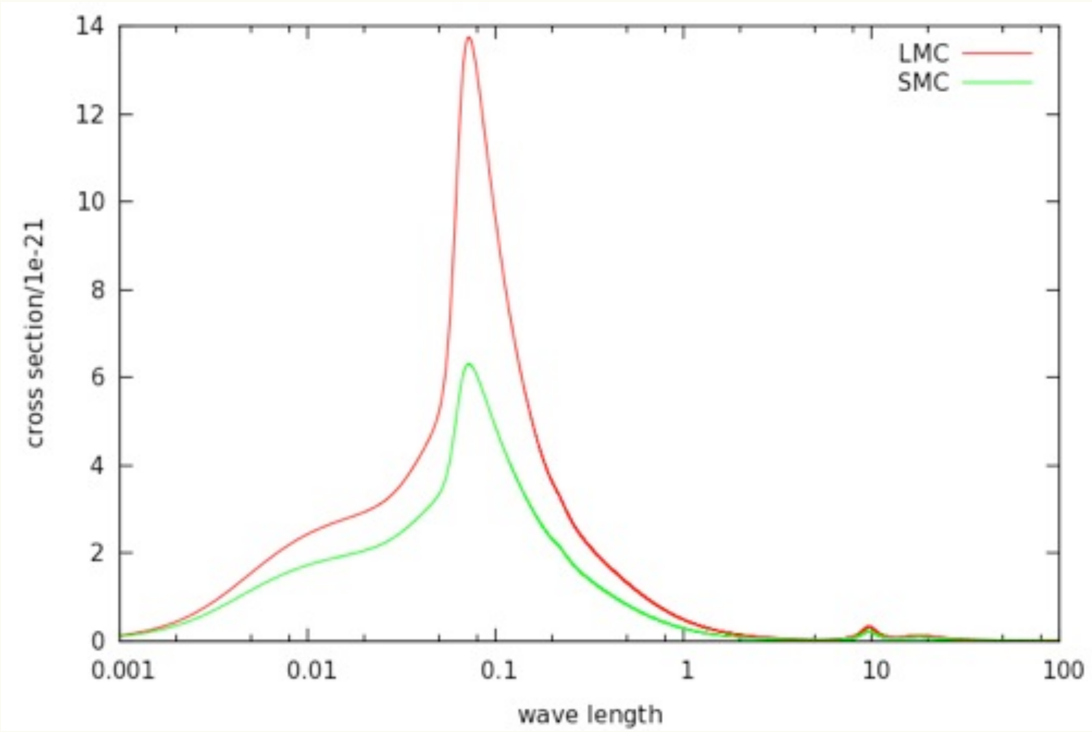
We need to understand the physical origin (if any) of this scatter

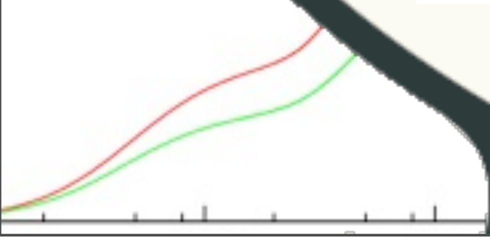
THE escape fraction does not exist

Dust model similar to Gnedin et al. (2008)

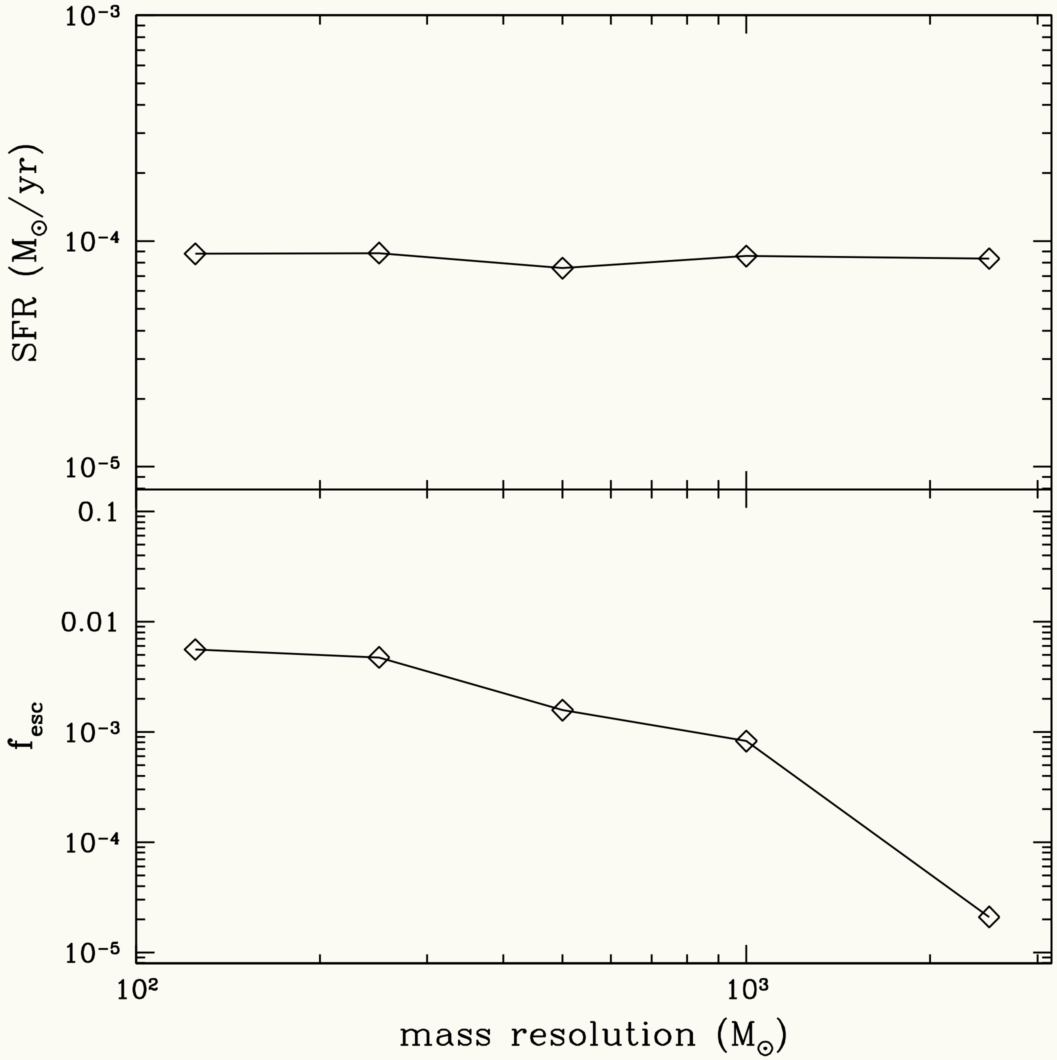
Express dust cross section as effective cross section per hydrogen atom

Use fit to the observed extinction curves of SMC and LMC

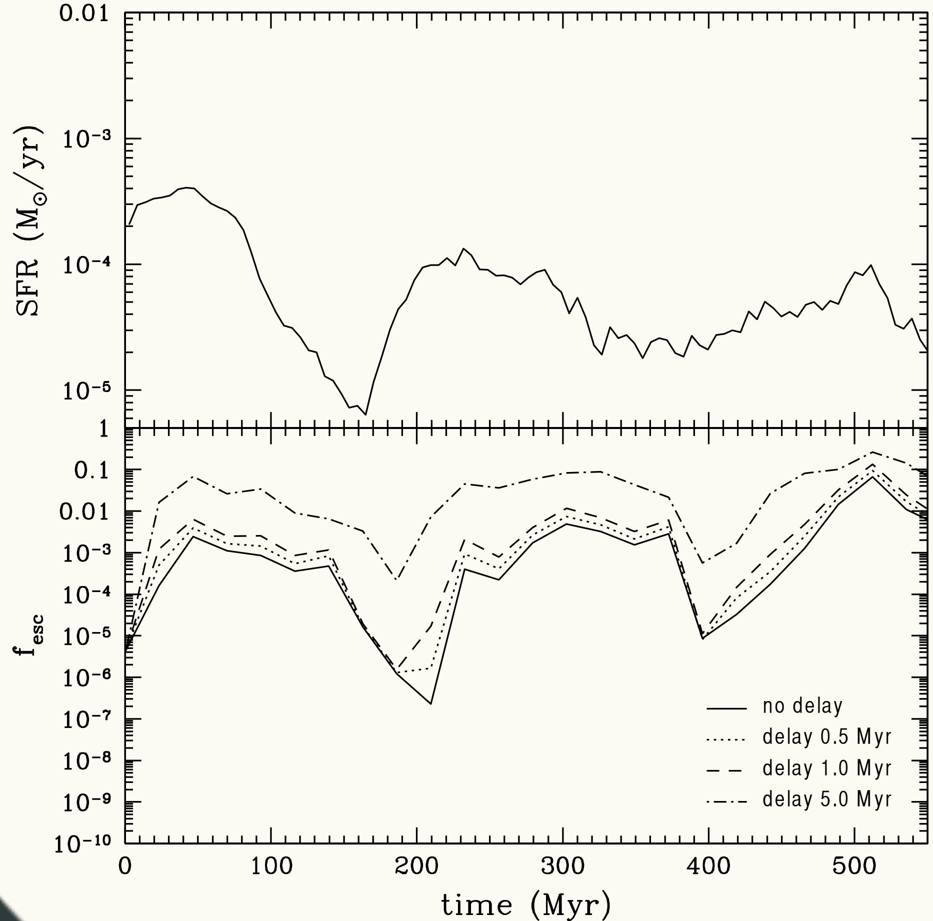


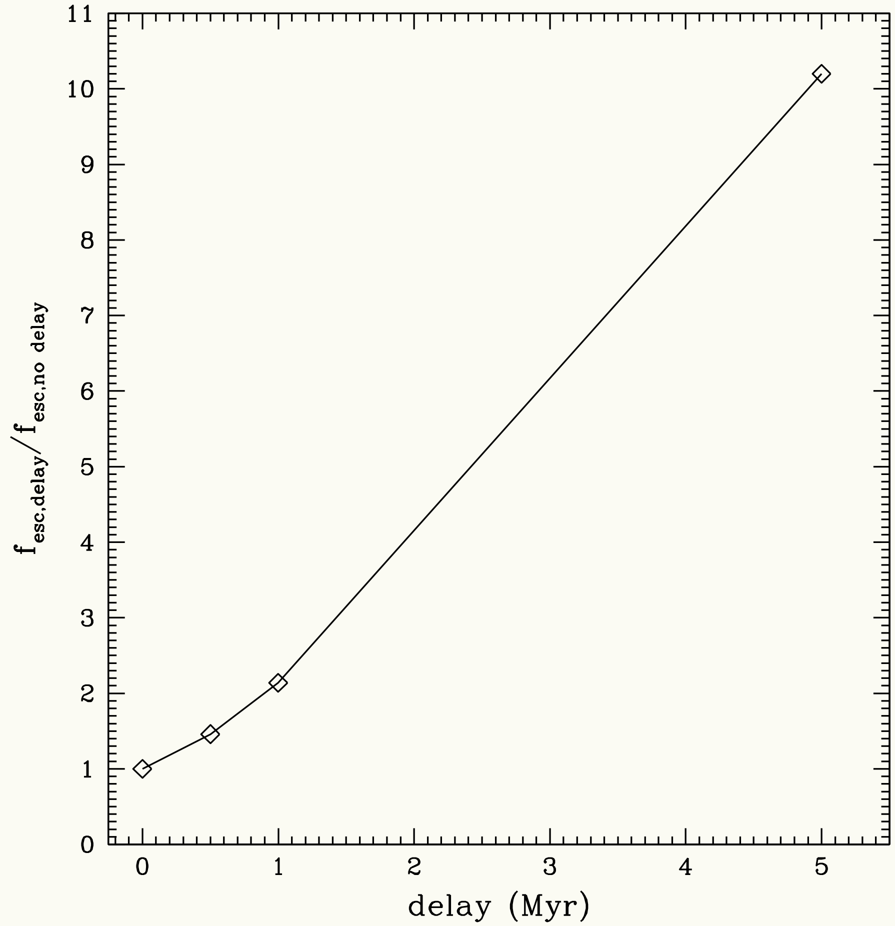


High resolution to resolve gas clumps around sources



Feedback implementation plays important role





Consequences for reionisation: numerical simulations