High-redshift radiation-hydrodynamics simulations of galaxy formation

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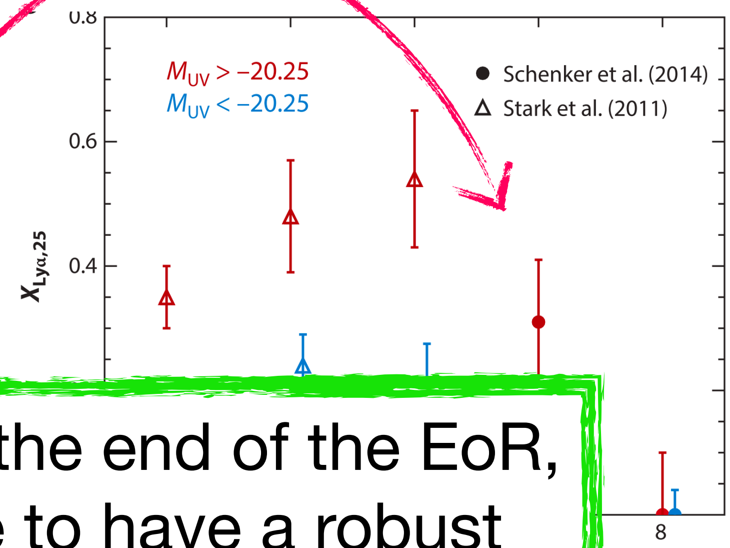
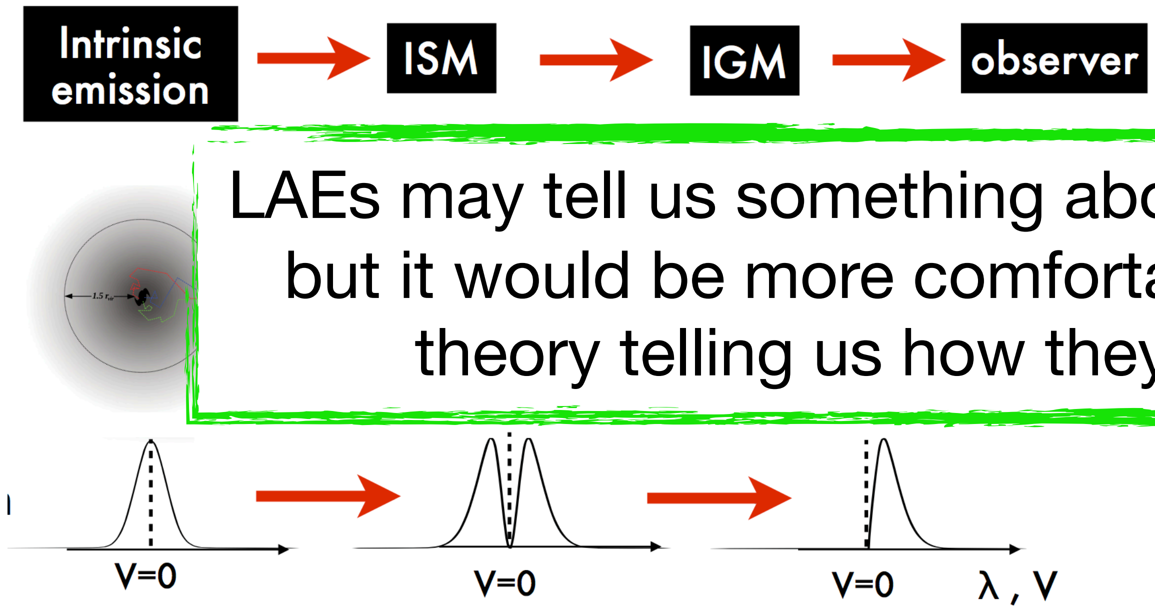
Lyman-alpha emitters as probes of reionisation

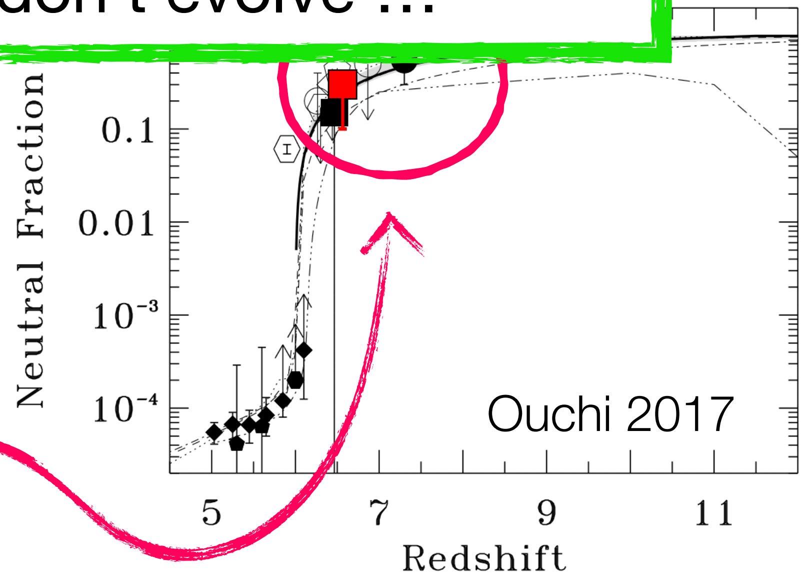
A partially neutral IGM will reduce the visibility of LAEs

Stark 2016





LAEs may tell us something about the end of the EoR, but it would be more comfortable to have a robust theory telling us how they don't evolve …



A partially neutral IGM will boost the clustering signal of LAEs

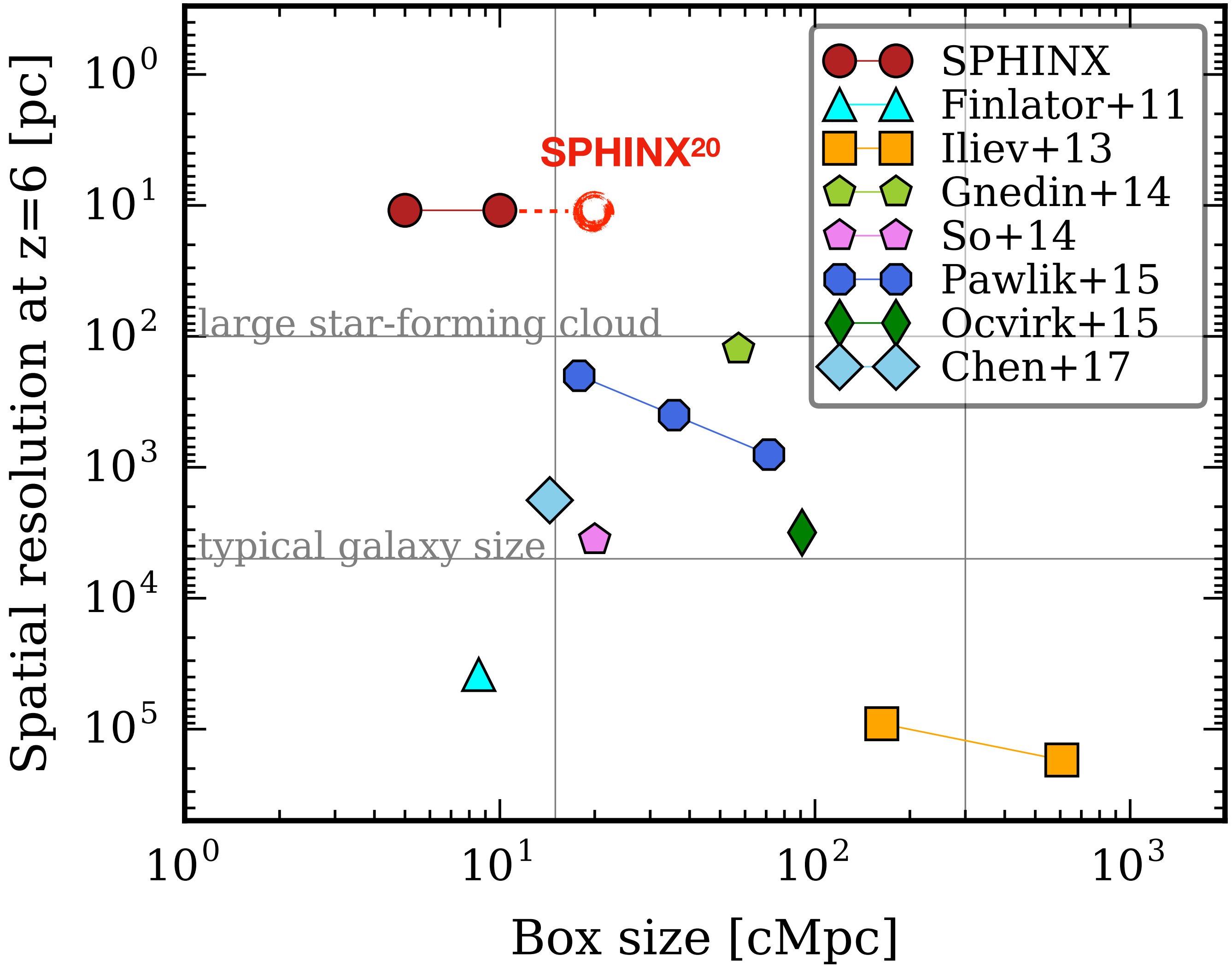
(see also Garel+12,15,16)

Predicting Lya emission from simulated galaxies

- **Full Radiation-hydrodynamics** : ionisation of the IGM **and** Lyman-alpha emissivity of galaxies.
- **High resolution** : resolve everywhere the cooling time + resolve small-scale ISM structure (see *Verhamme+12*).
- **Dust model** : e.g. from metallicity & HI distributions (***Laursen+09***)
- **Lya RT** : this is a problem solved…
- Large volume with **consistency between the IGM large-scale ionisation state and the activity of galaxies**, taking into the full complexity of the cosmological context (clustering, clumping, …)

Simulations of galaxy formation during the EoR: The SPHINX project.

Simulations with resolution < 10pc are predictive in terms of escape give access to essential observational probes (absorption/emission lines)

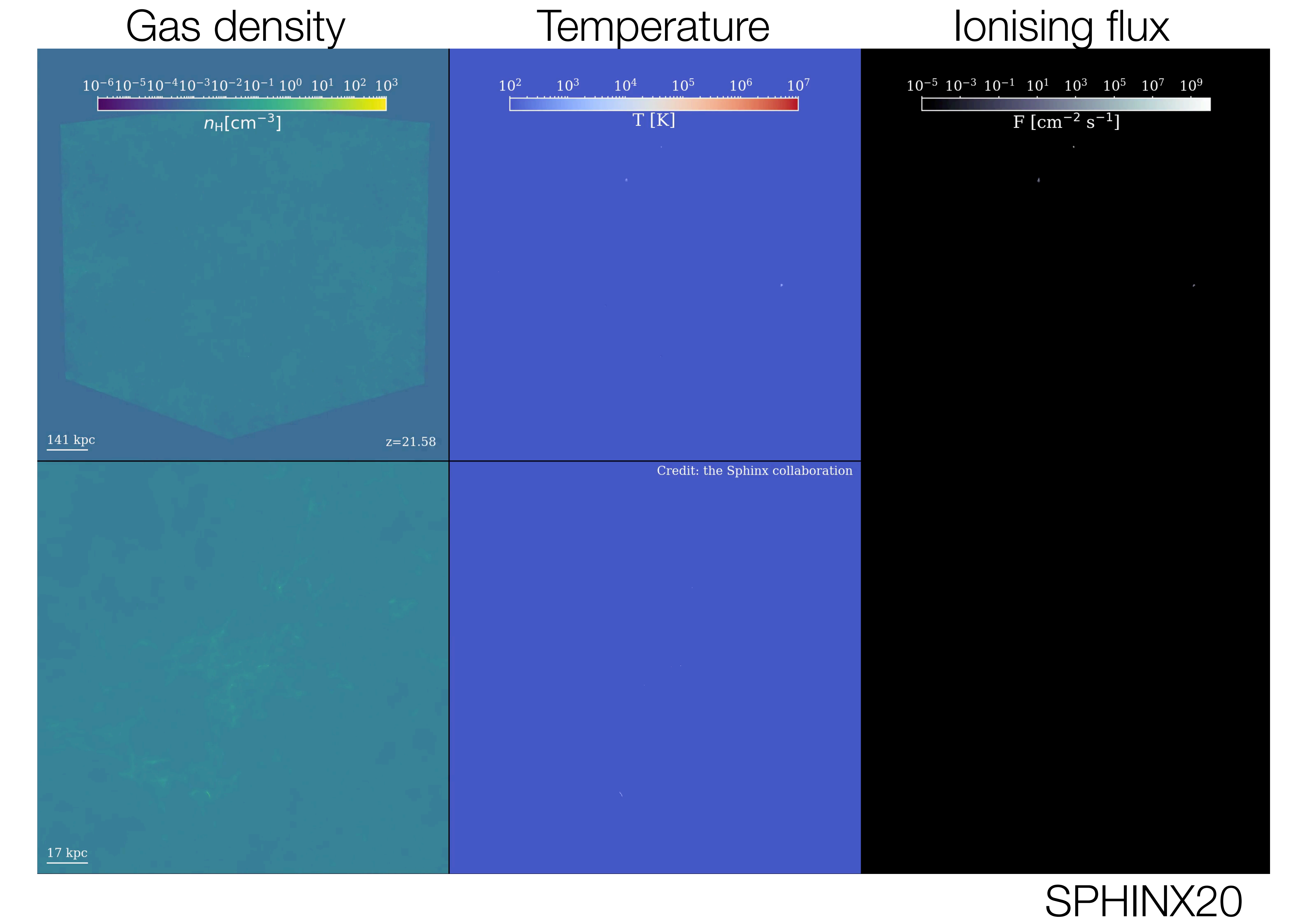


SPHINX setup

- **Volume widths** of 5 and 10 cMpc … larger volumes to come
- **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** with local efficiency that decreases with virial parameter and increase with mach number
- **SN explosions** modelled with momentum kicks (Kimm et al., 2015)
  - We *calibrate* SN rates with 4-fold boost for realistic luminosity function
- **No calibration on unresolved f_{esc}** (i.e. we inject the SED luminosity)
- We run with **binary and single star SEDs**

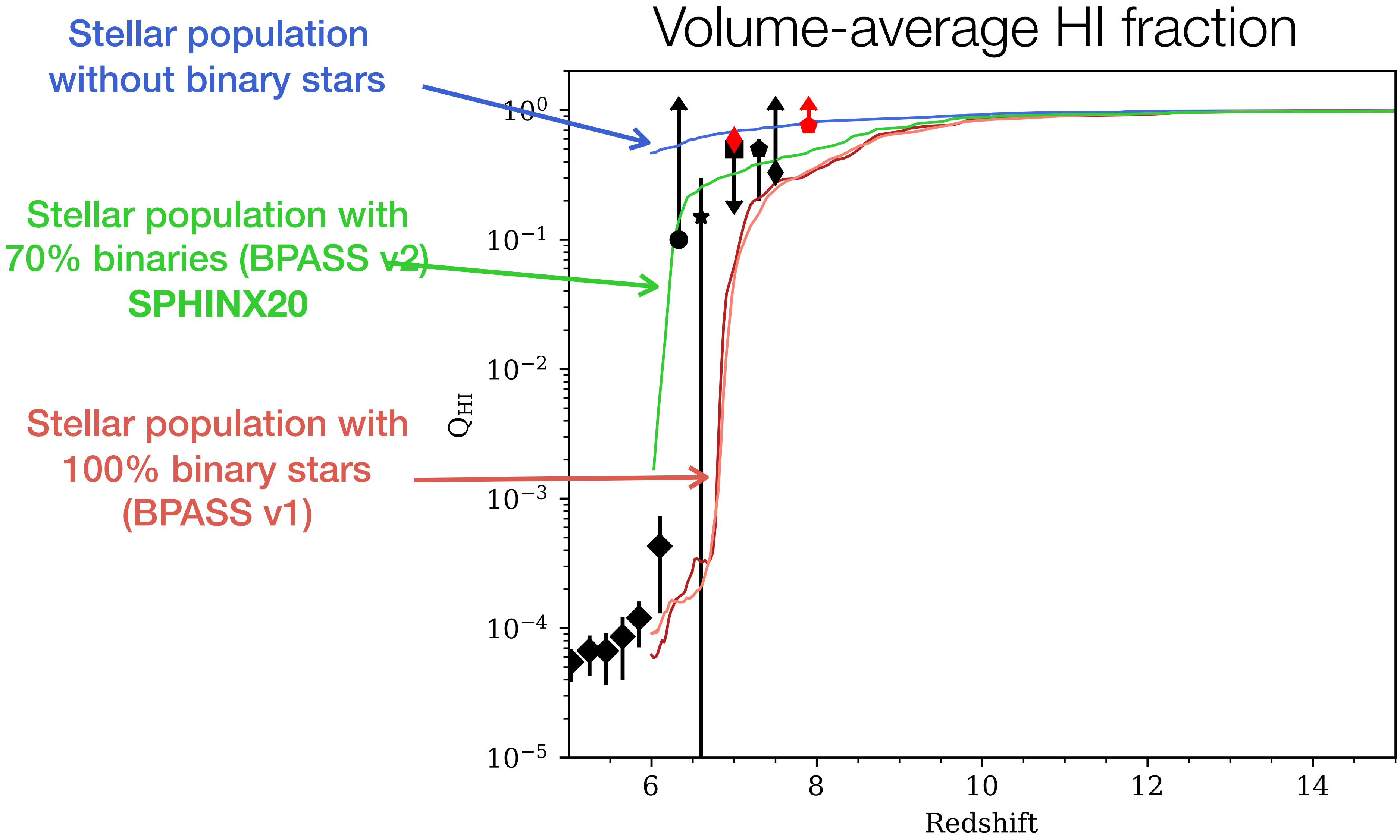
1. Results from SPHINX simulations



Gas density
Temperature
Ionising flux
10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
$n_{\mathrm{H}}[\mathrm{cm}^{-3}]$
10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}
T [K]
10^{-5} 10^{-3} 10^{-1} 10^{1} 10^{3} 10^{5} 10^{7} 10^{9}
F $[\mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$
141 kpc
z=21.58
Credit: the Sphinx collaboration
17 kpc
SPHINX20

Rosdahl+18

Reionisation history: changing stellar populations

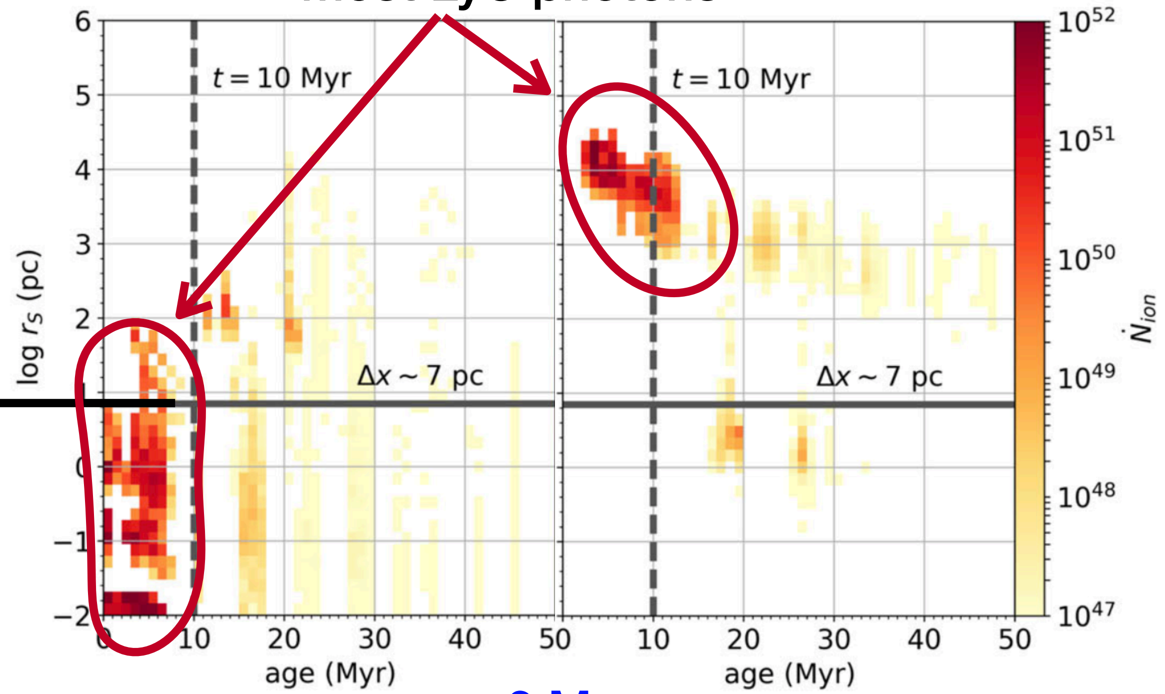


Fesc is regulated by SN explosions

Young stars that contribute most LyC photons

Transparent environment

Opaque environment



3 Myr

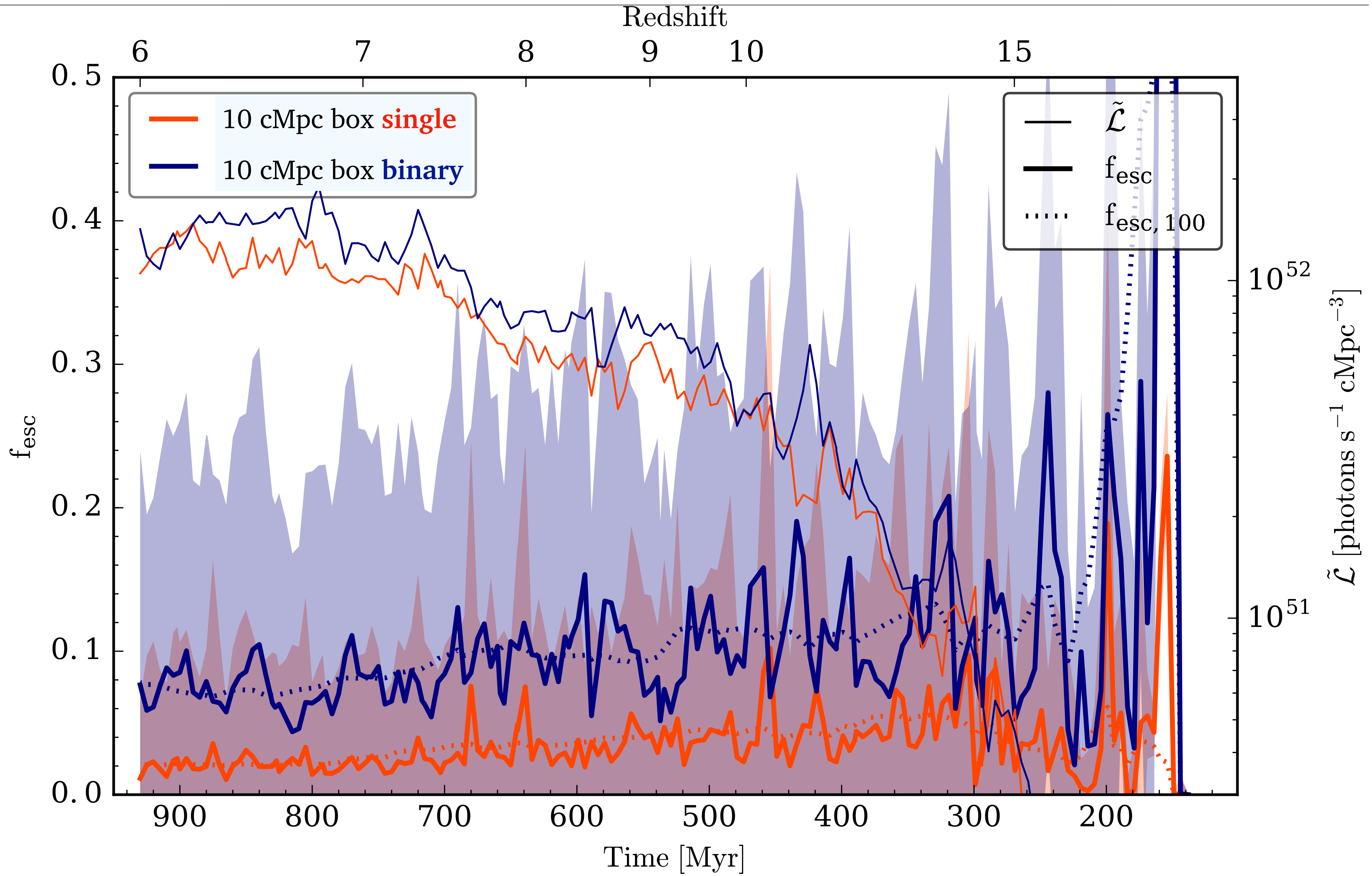
Trebitsch+17: SN explosions clear star-forming clouds and allow the escape of LyC photons

(See also Kimm+14, Kimm+19)

Binary stars still produce ionising photons after the SN explosions clear the way for escape. Models with such stars are more efficient at ionising the IGM.

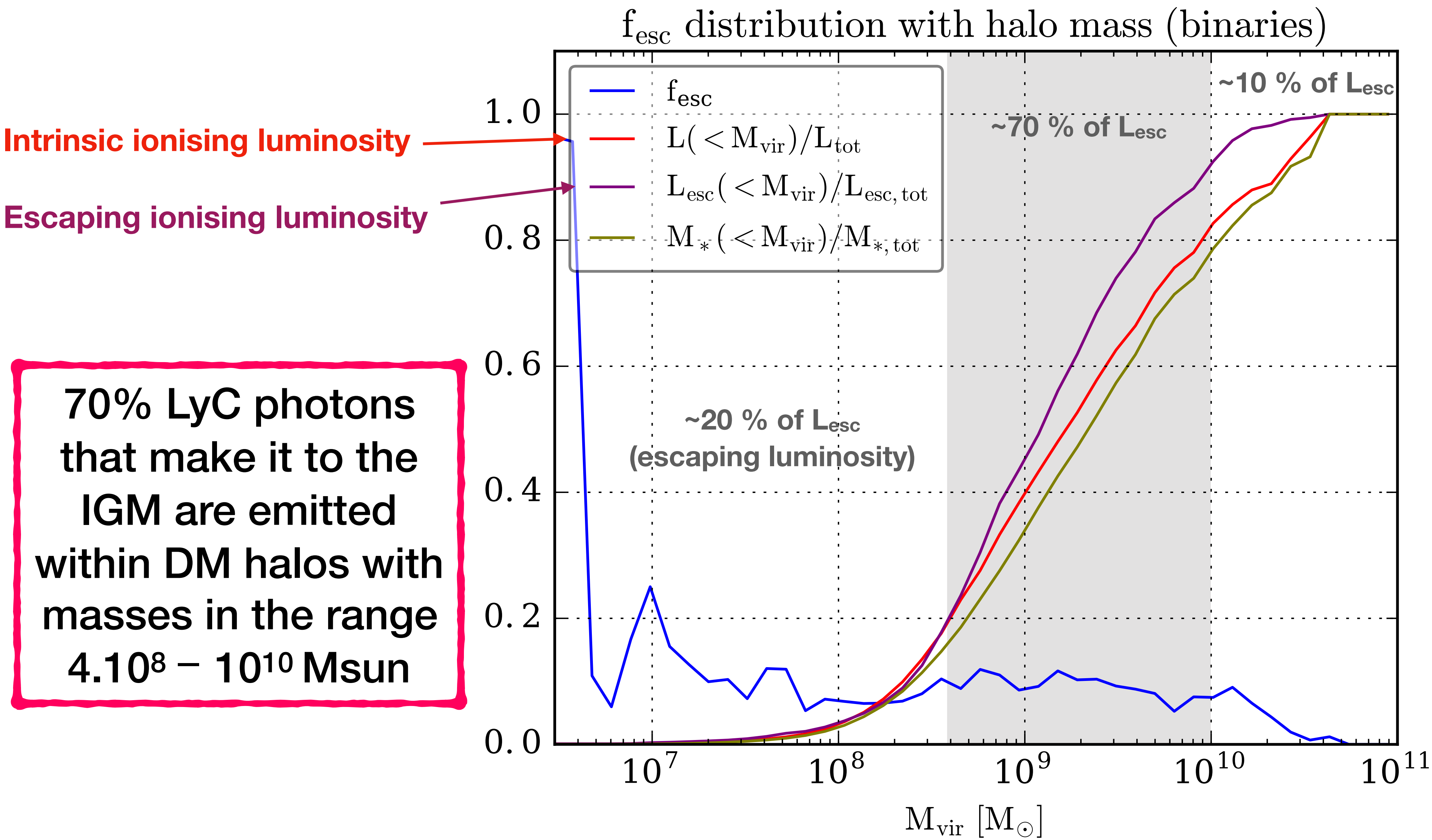
Rosdahl + 18

Stars alone can ionise the IGM …
With a relatively low escape fraction (~10%)



Rosdahl+20

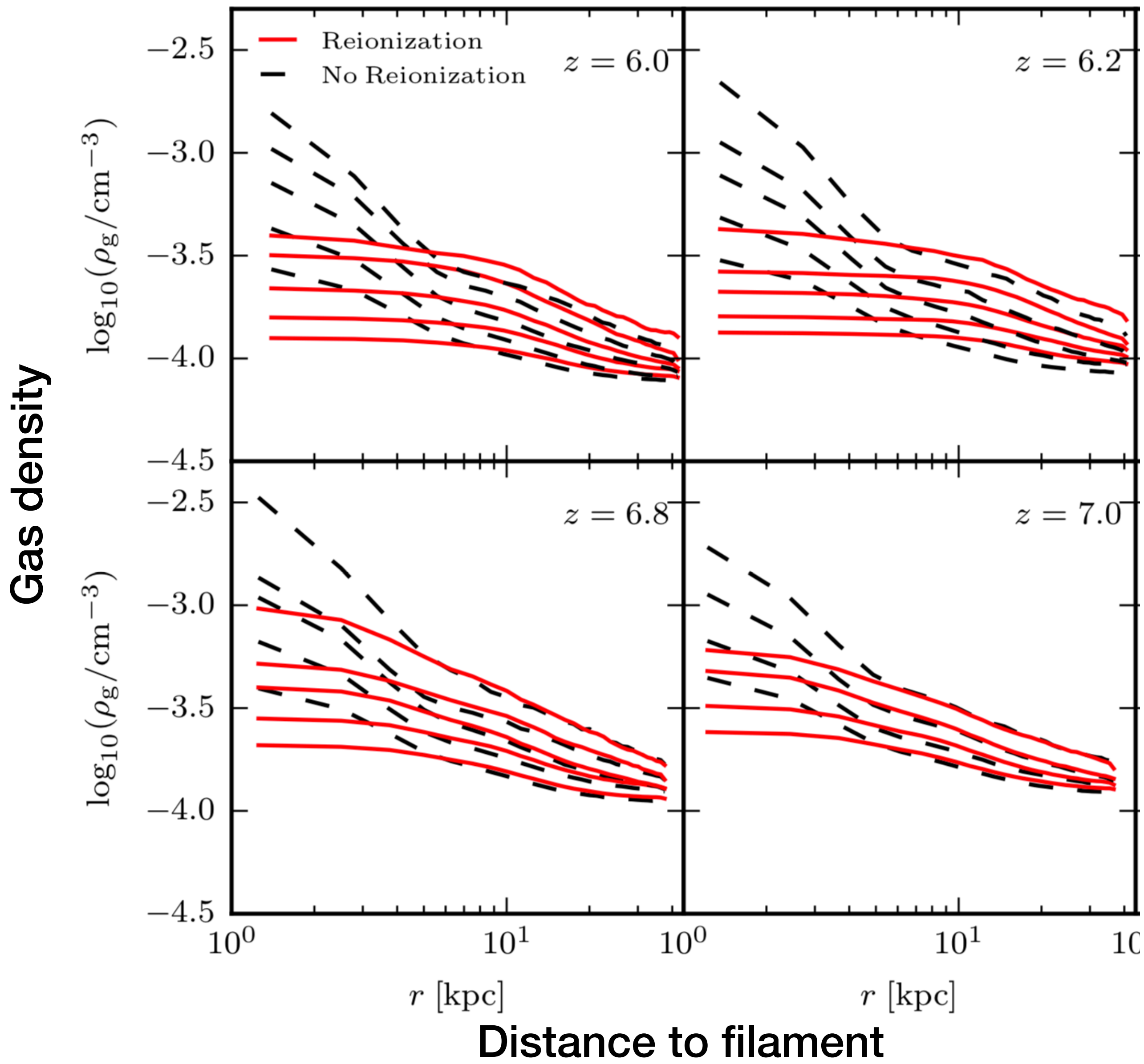
Which galaxies contribute most to reionisation ?



70% LyC photons that make it to the IGM are emitted within DM halos with masses in the range 4.10⁸ – 10¹⁰ Msun

Katz+19

Reionisation feedback

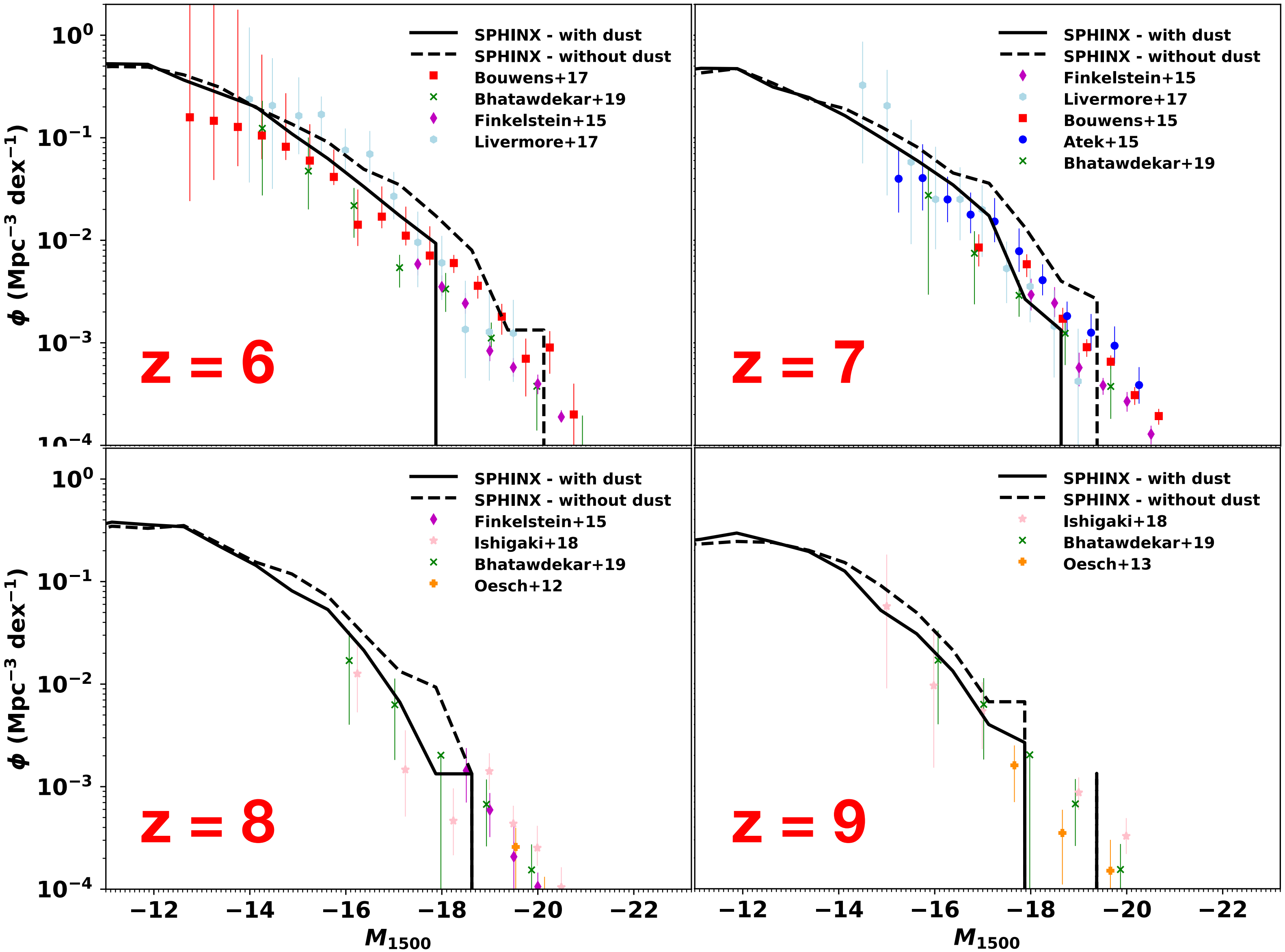


Reionisation diffuses filaments, turning off growth source for low-mass galaxies

2. Observations of the SPHINX simulations

Thibault Garel

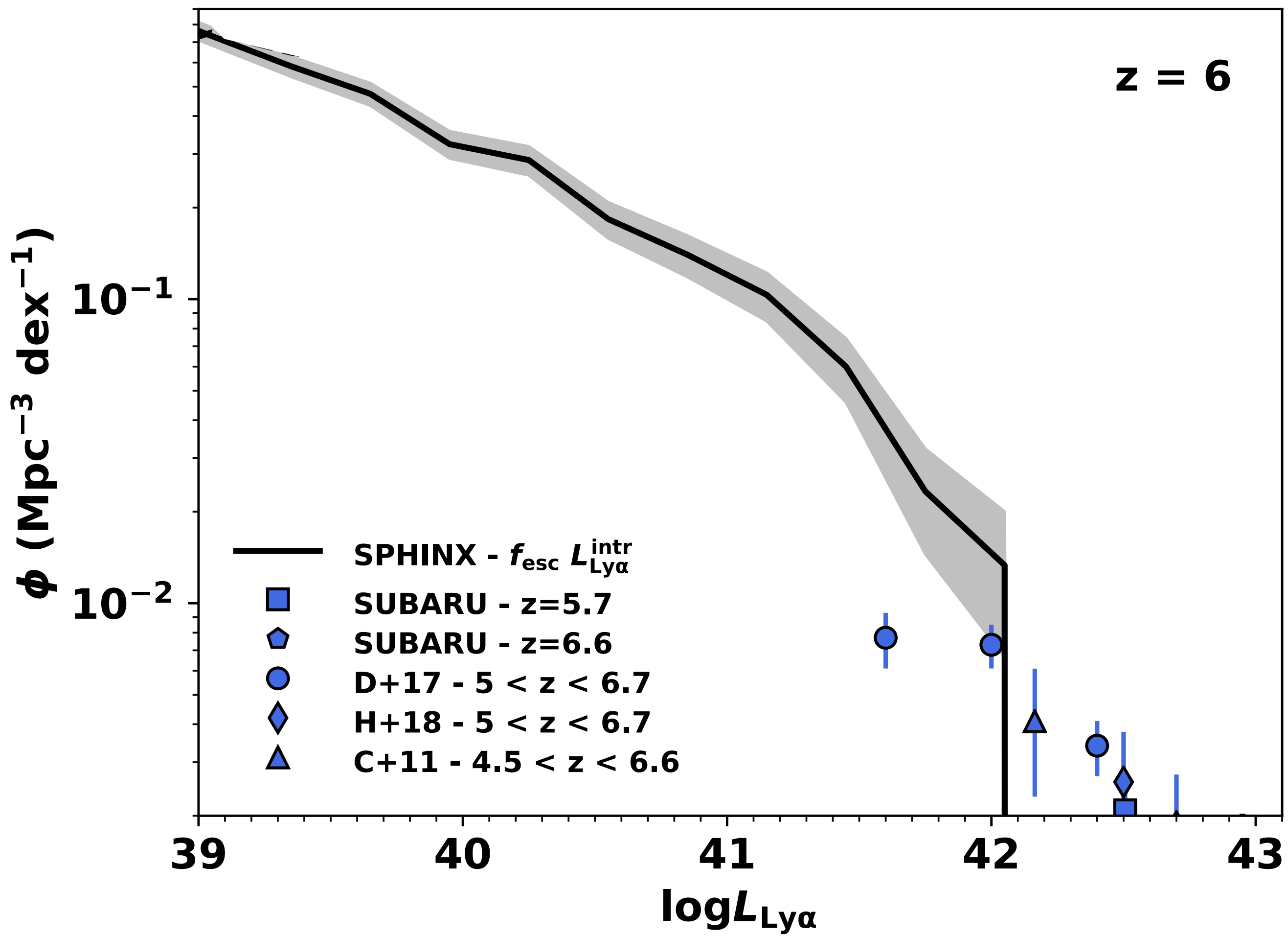
SPHINX UV Luminosity functions z = 6 to 9



Thibault Garel

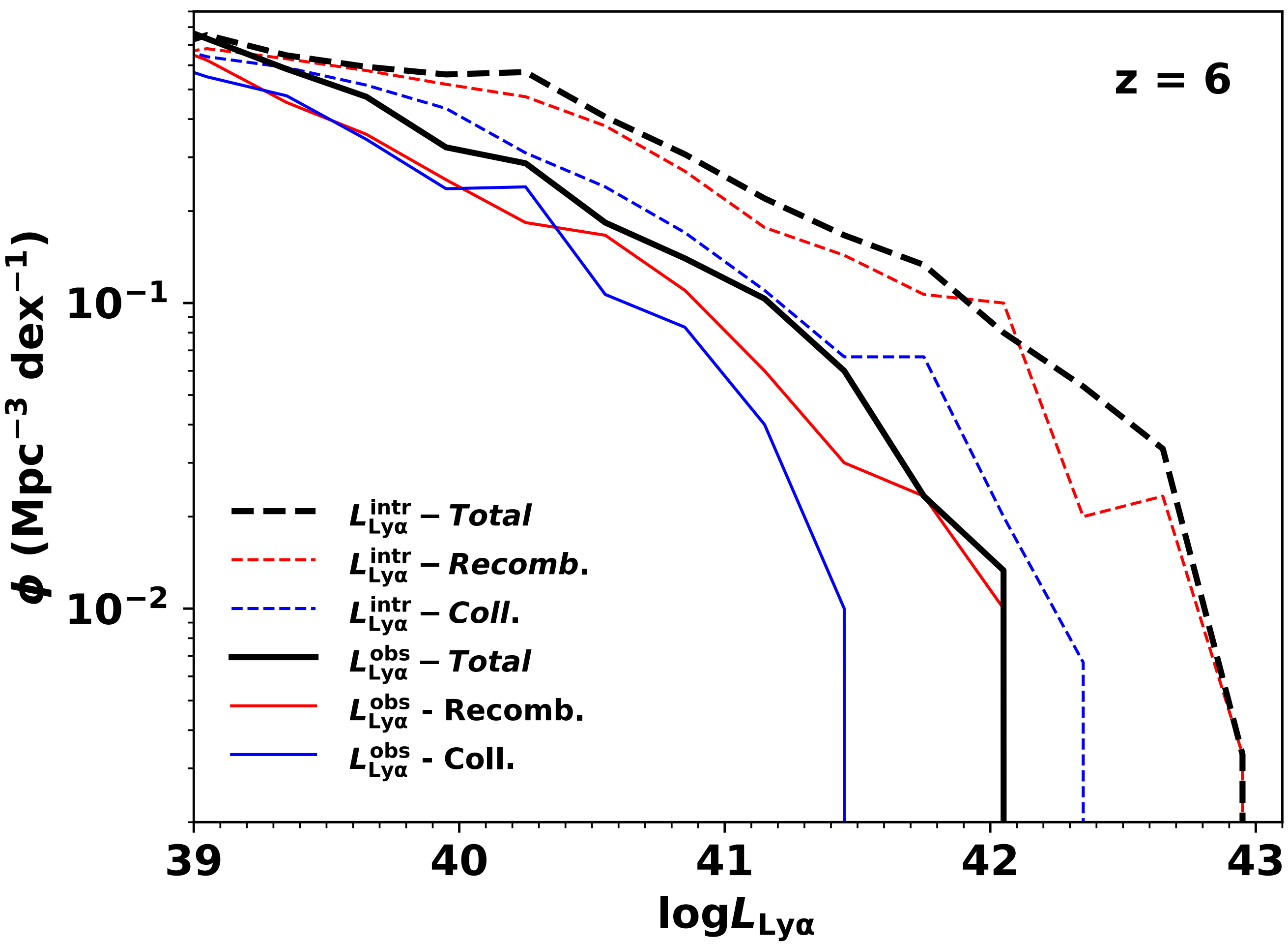
SPHINX Lyman-alpha Luminosity function (z = 6)

Rascas

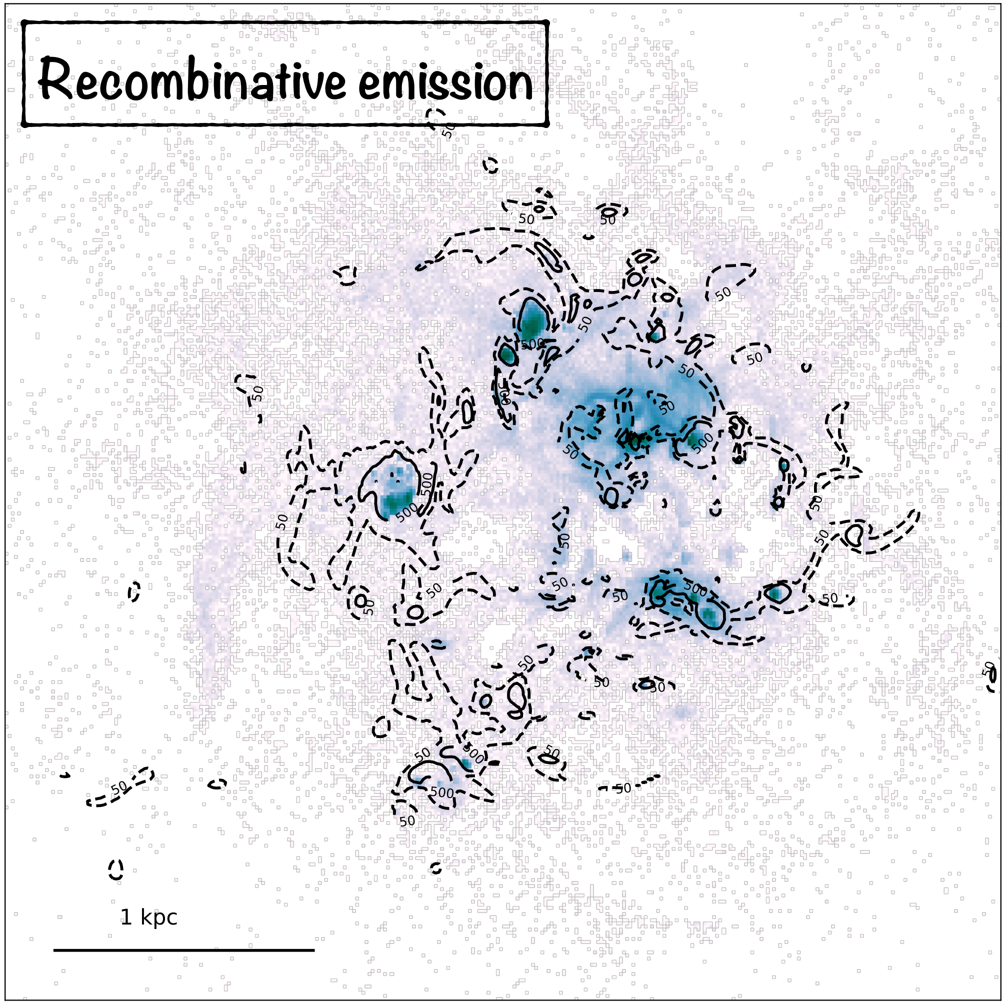


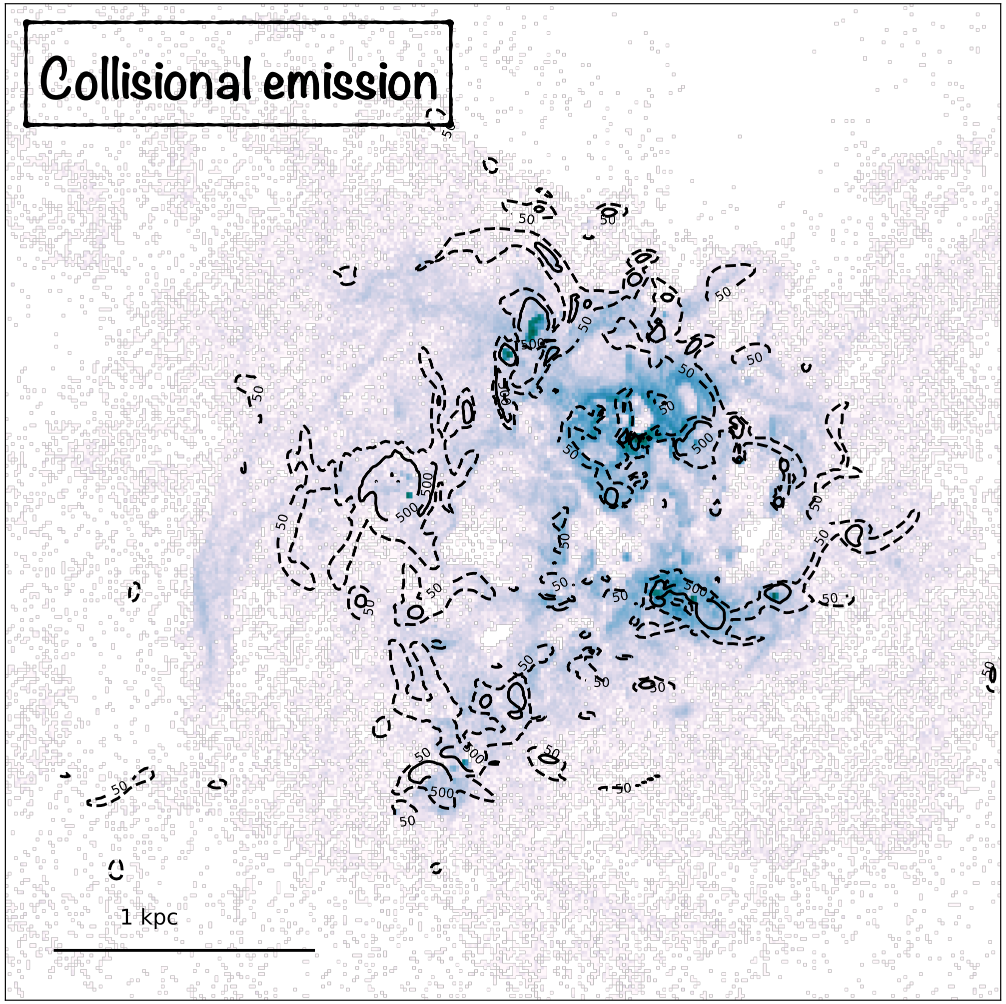
Thibault Garel

SPHINX Lyman-alpha Luminosity function (z = 6)



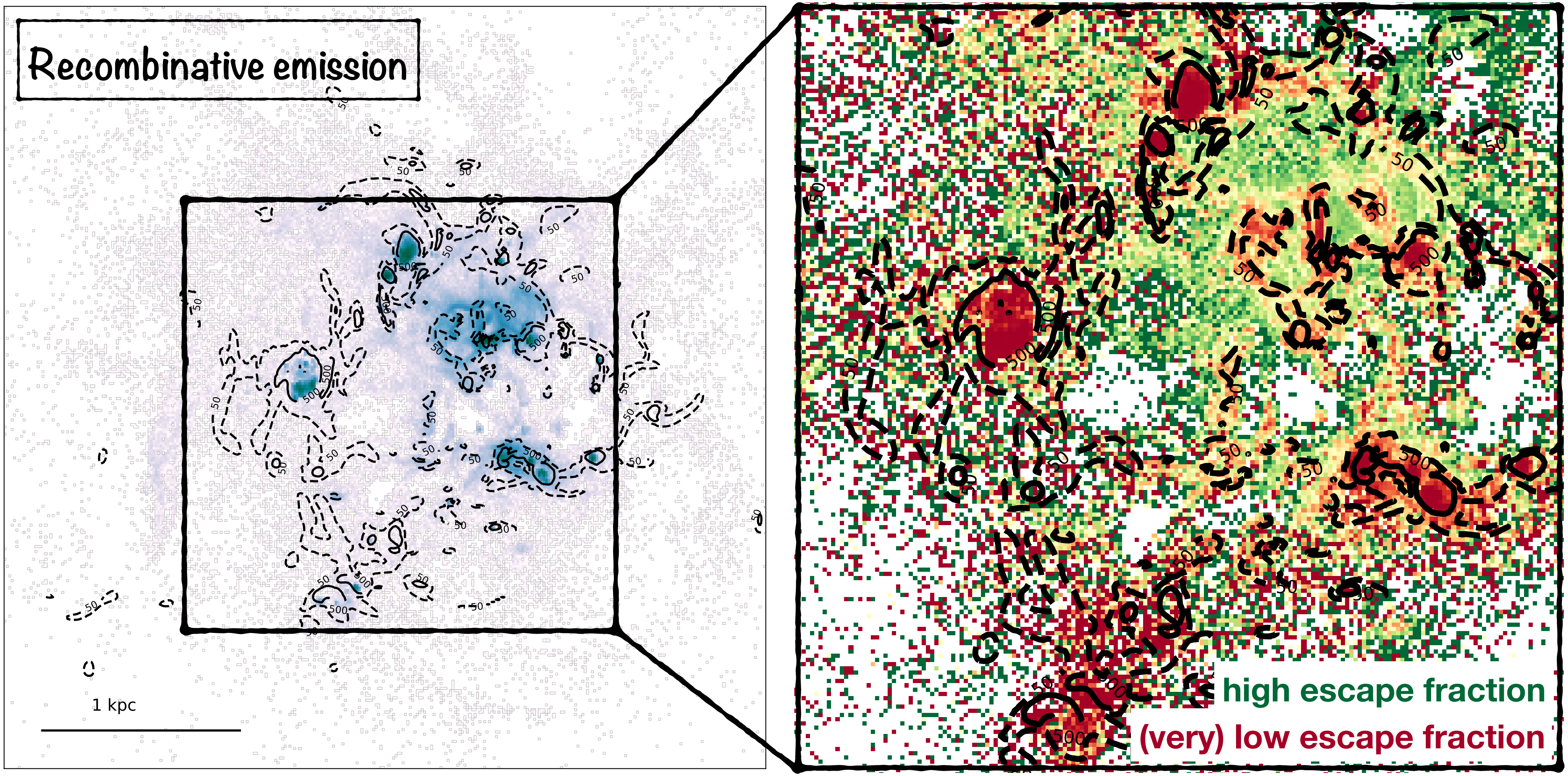
Where are photons emitted …





Collisional emission comes from warm (~10^4K) relatively diffuse gas, whereas **recombinations** *also* come from cold and dense (100s K, nHI > 500 #/cm3) star-forming clouds.

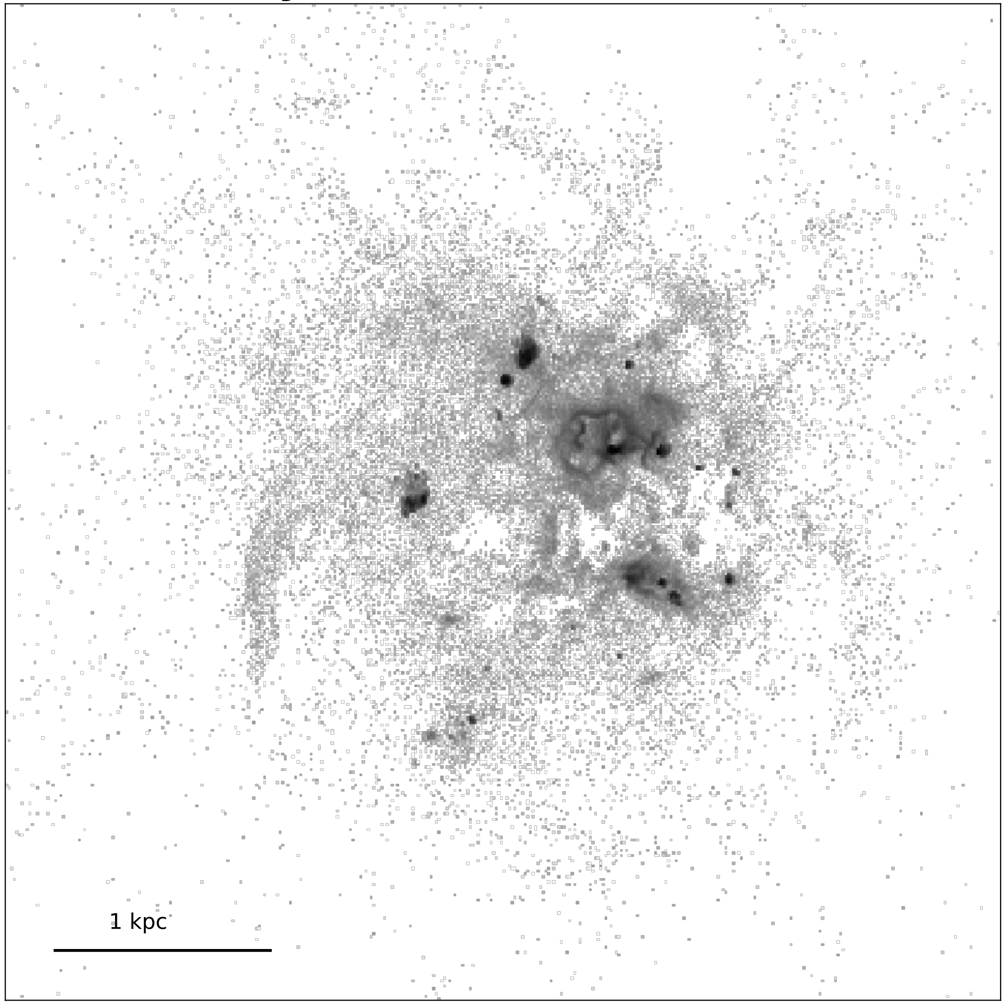
Where are photons absorbed …



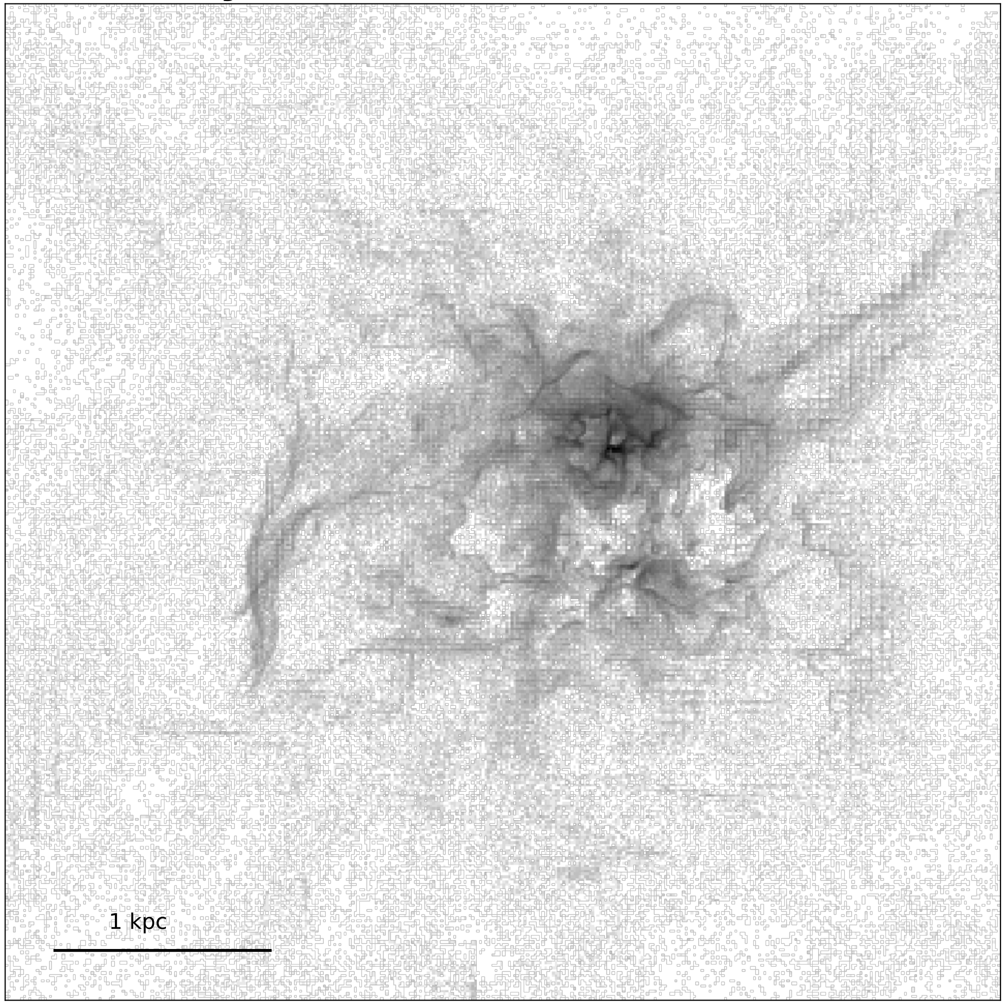
Escape from star-forming clouds is very hard before they are dispersed by SN explosions. Recombination photons are preferentially lost there.

Where are photons seen …

Before Lya RT



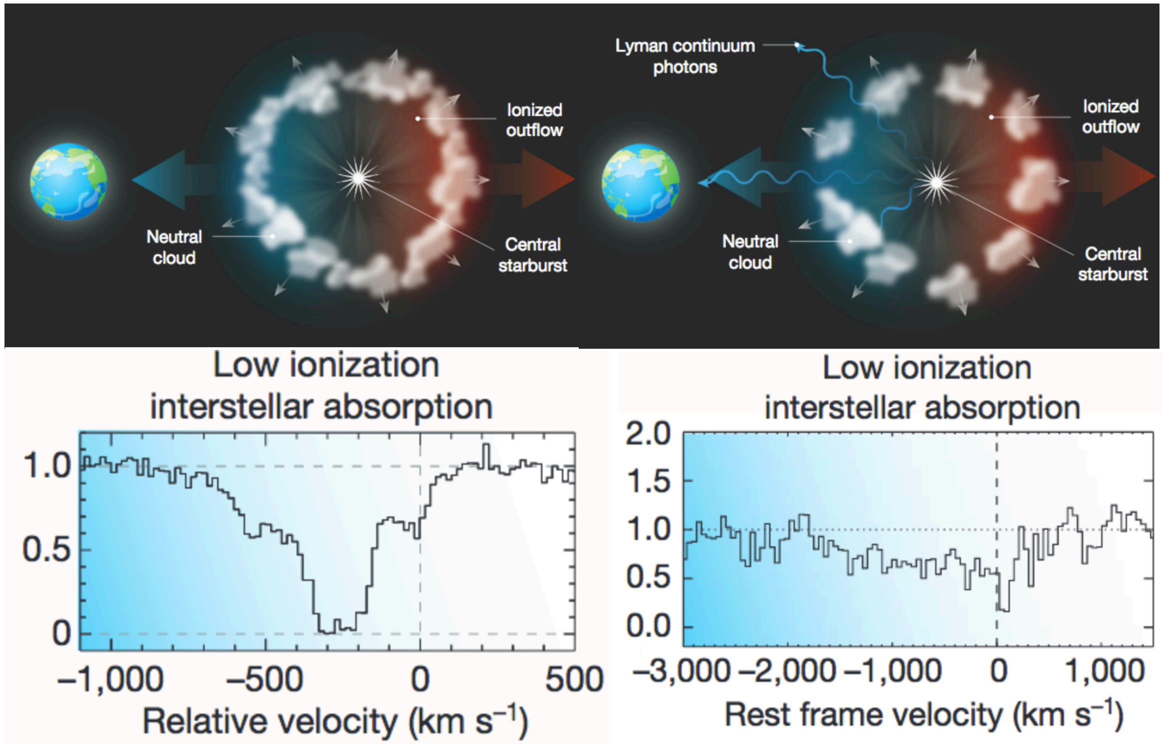
After Lya RT

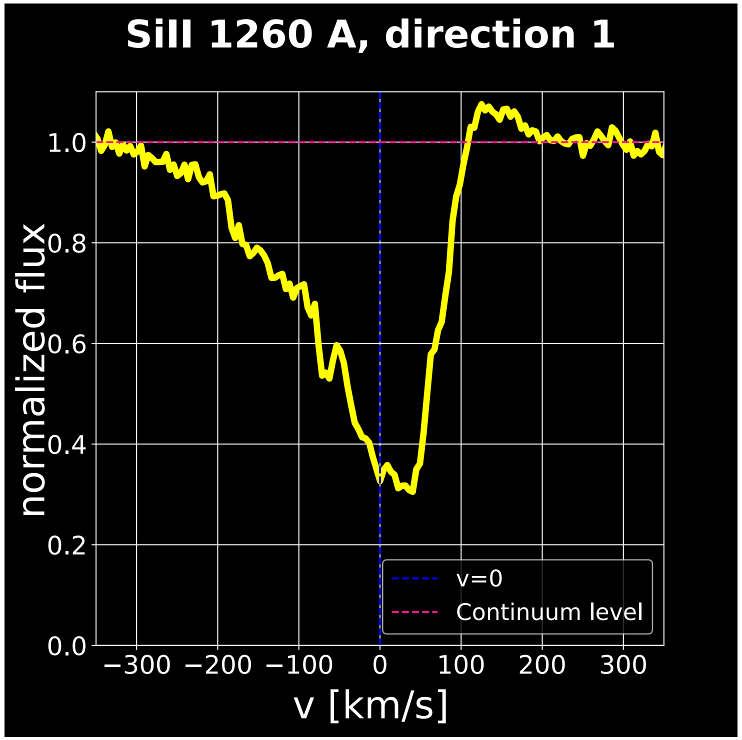


Valentin Mauerhofer

Absorption lines: can we infer LyC leakage ?

One expects that the depth of absorption lines due to cold gas would be a good indicator of the escape fraction of ionising photons… is that so ?

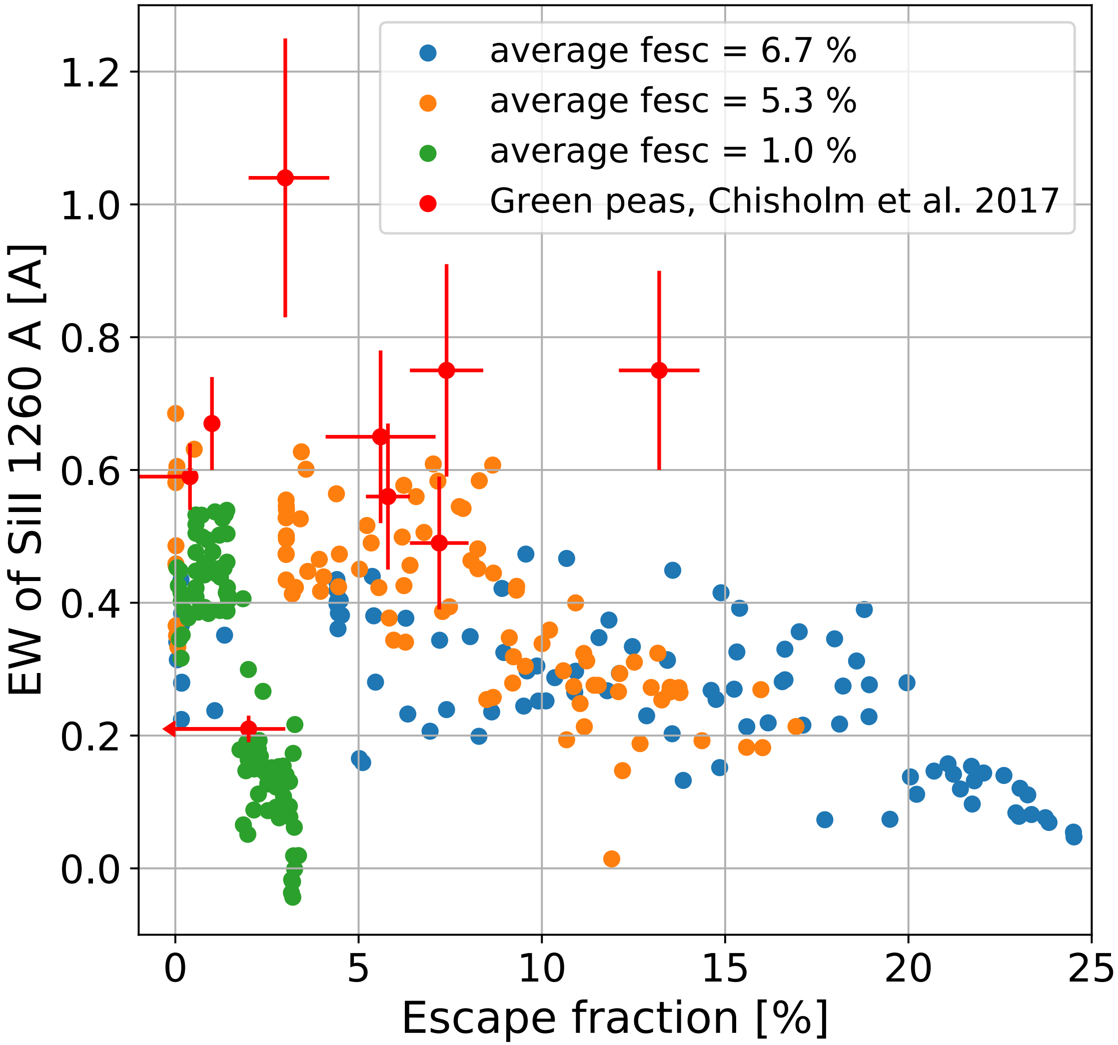




Mock spectrum from a SPHINX zoom-in simulation

Valentin Mauerhofer

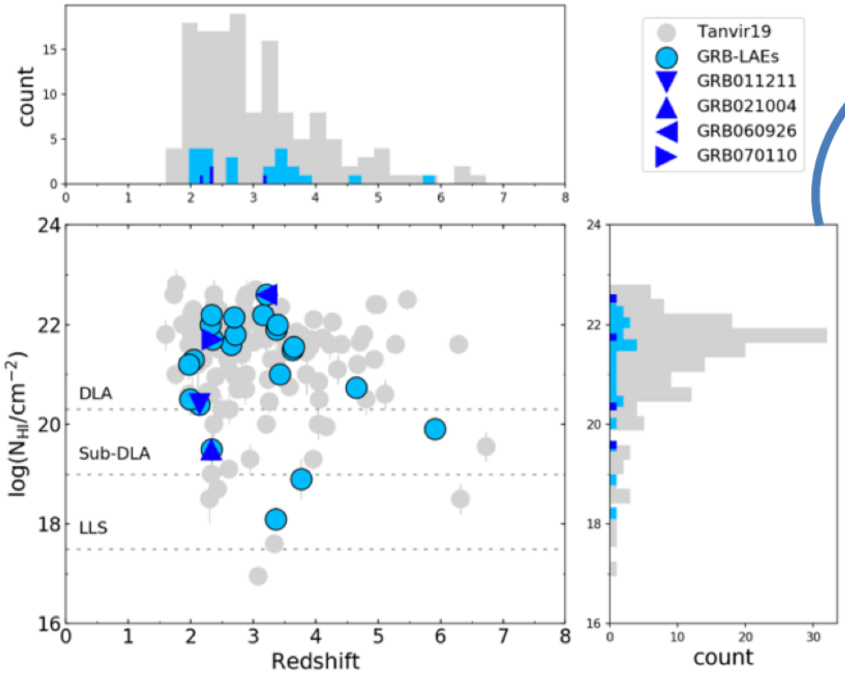
Absorption lines: can we infer LyC leakage ?

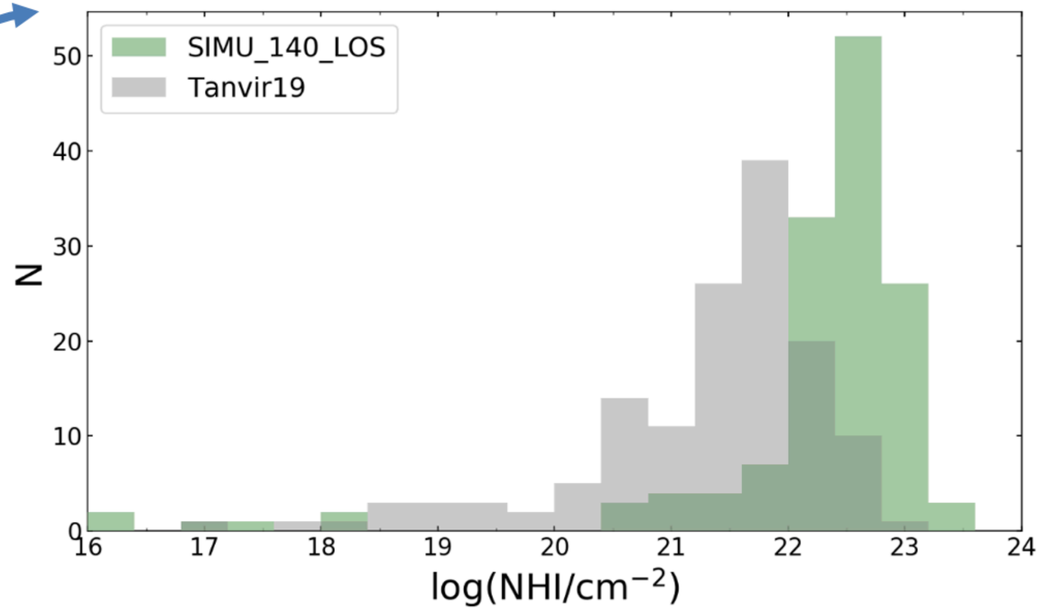


We find no clear correlation between the escape fraction of ionising photons and the equivalent width or the residual flux of LIS absorption lines

Jean-Baptist Vielfaure

GRBs as a probe of the ISM ?





Comparison of the NHI distribution for 140 GRBs (Tanvir et al. 2019) with NHI distribution of 140 LOS calculated from the GRB position in the simulation

Conclusions

- **High-resolution** (<10pc) **radiation-hydrodynamics cosmological simulations of galaxy formation** have reached a high level of maturity.
- They produce **realistic ISM** for large populations fo galaxies.
- **Reionisation happens naturally** at roughly the right time, with no free parameter (ahem …). Small (but not too small) galaxies are responsible for this.
- Such simulations can be used to **test complex observing strategies** (e.g. using GRBs) and **help their interpretation**.
- Not in this talk: emission lines from galaxies and their CGM work well too !
- More to come: (1) more physics (cosmic rays, MHD, …), (2) larger volumes & zooms on more massive objects.