Reionisation with cosmological radiation-hydrodynamics using RAMSES-RT

CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

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With

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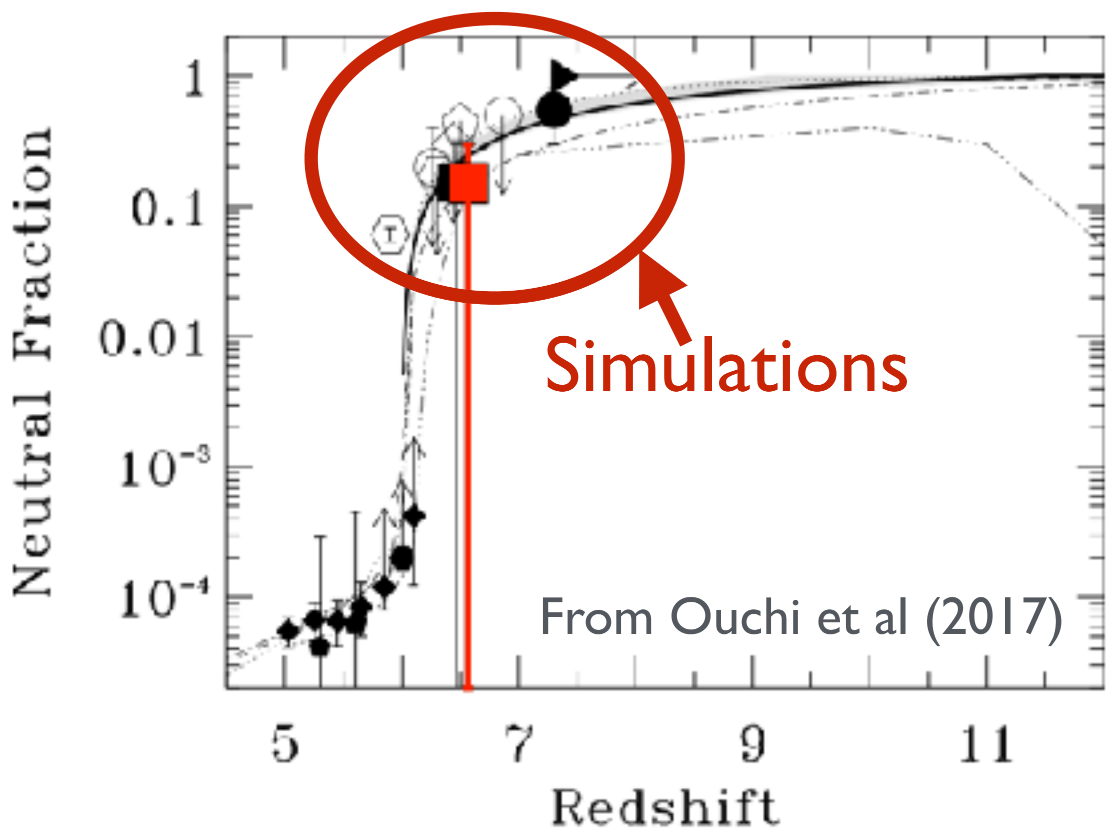
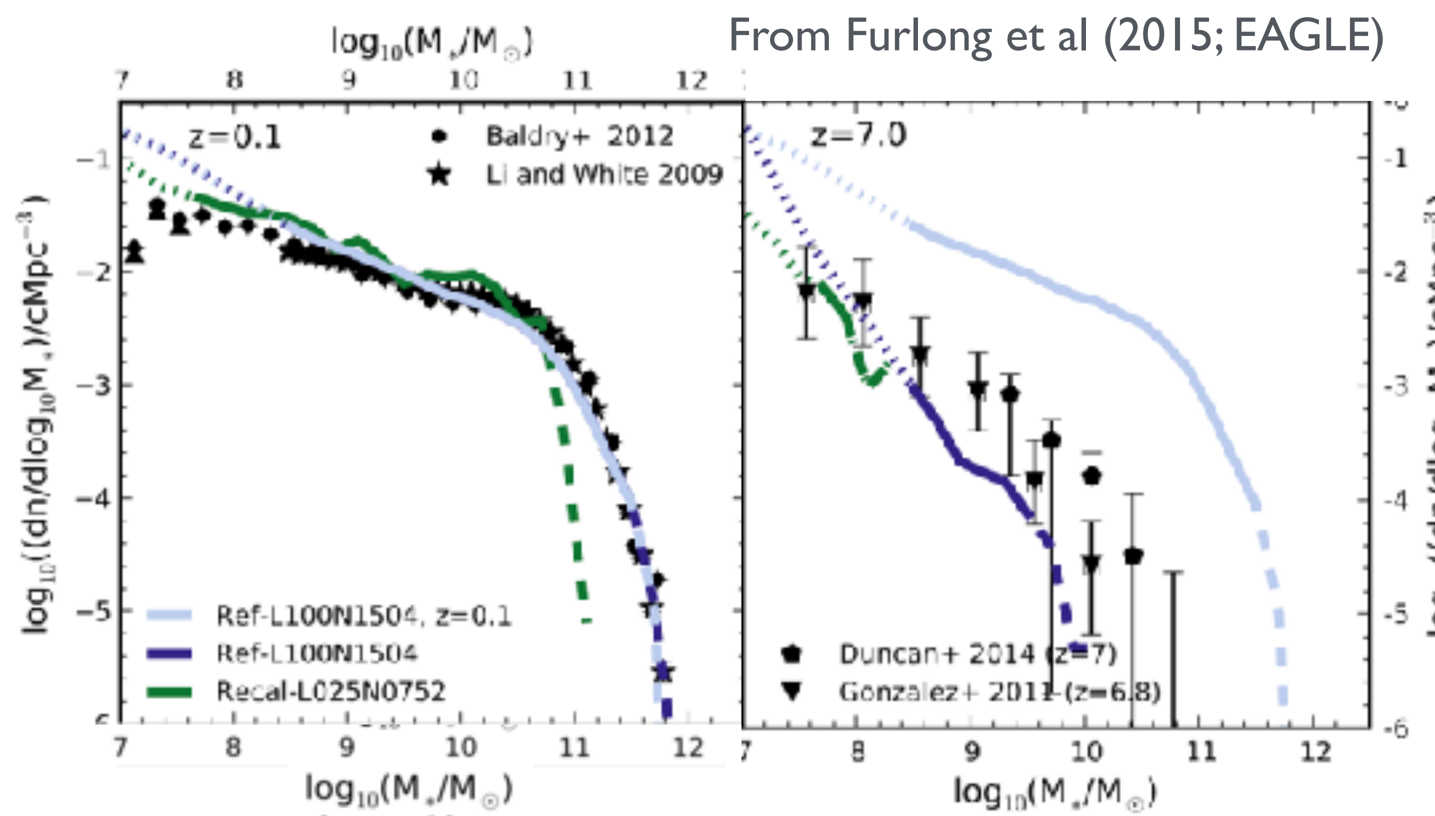
Why simulations of reionisation?

- Galaxy formation and reionisation are really hard to describe analytically, because they are:
  - highly non-linear and three-dimensional
  - multi-physical (gravity, hydrodynamics, thermochemistry, radiative transfer)
  - multi-scale (from AU-scale stellar sources to Mpc inter-galactic medium)



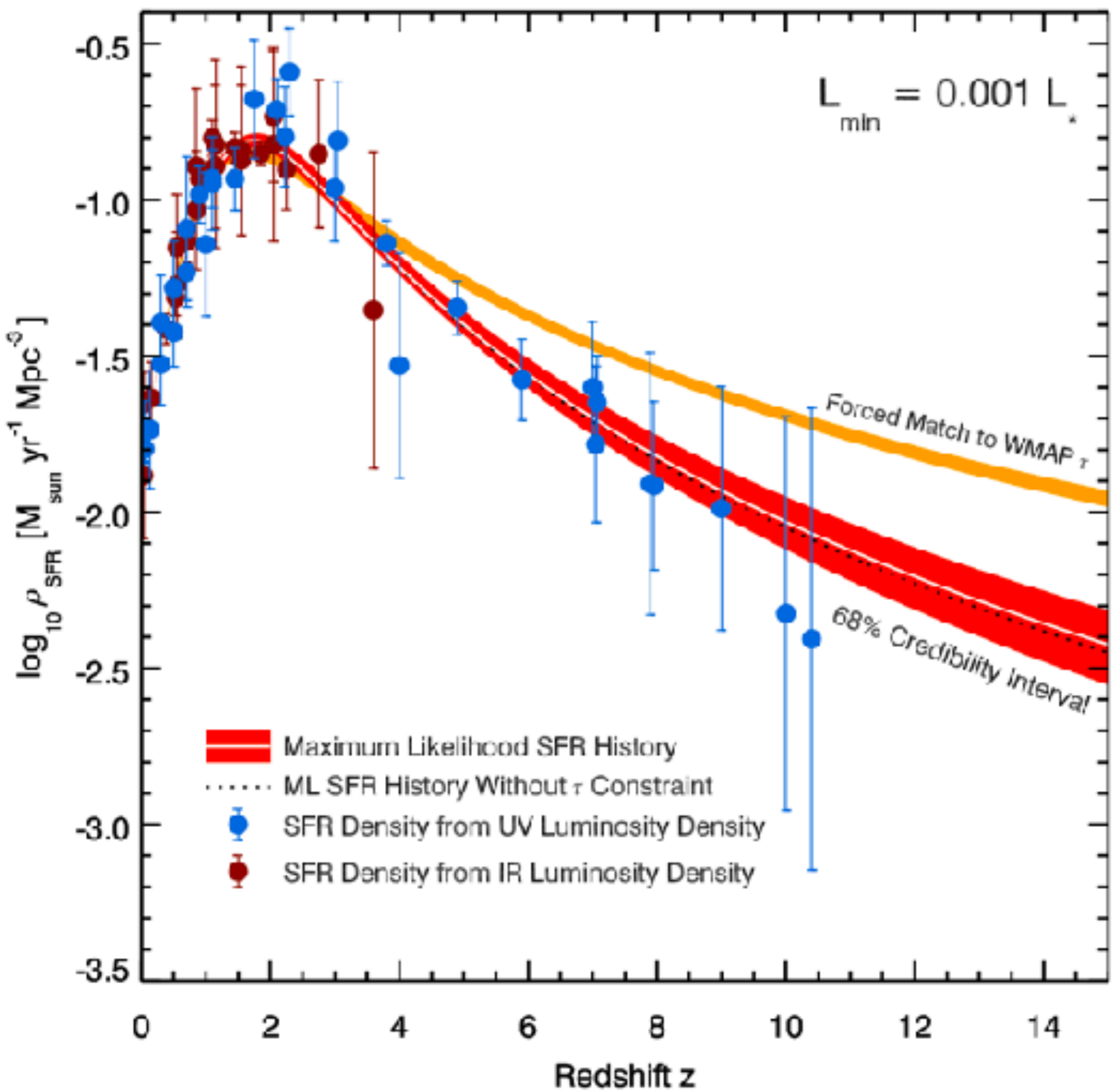


- We need a theory of high-z galaxy evolution and reionisation to:
  - understand and interpret (and prepare for) observations
  - understand the physics (e.g. feedback) at play

What are the sources of reionisation?

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

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

Observationally it is impossible to measure $f_{\rm esc}$, but indirect measurements in the local Universe give

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

We use simulations to try and understand these discrepancies

What can we learn from simulations?

➡ Escape of radiation from galaxies; f_{esc}

➡ Sources of reionisation

➡ Clustering of sources and patchiness of reionisation

➡ Outside-in vs inside-out scenarios

➡ IGM temperature evolution

How do we simulate reionisation?

a: we first spend 10 years writing a code
b: we use an existing cosmological code

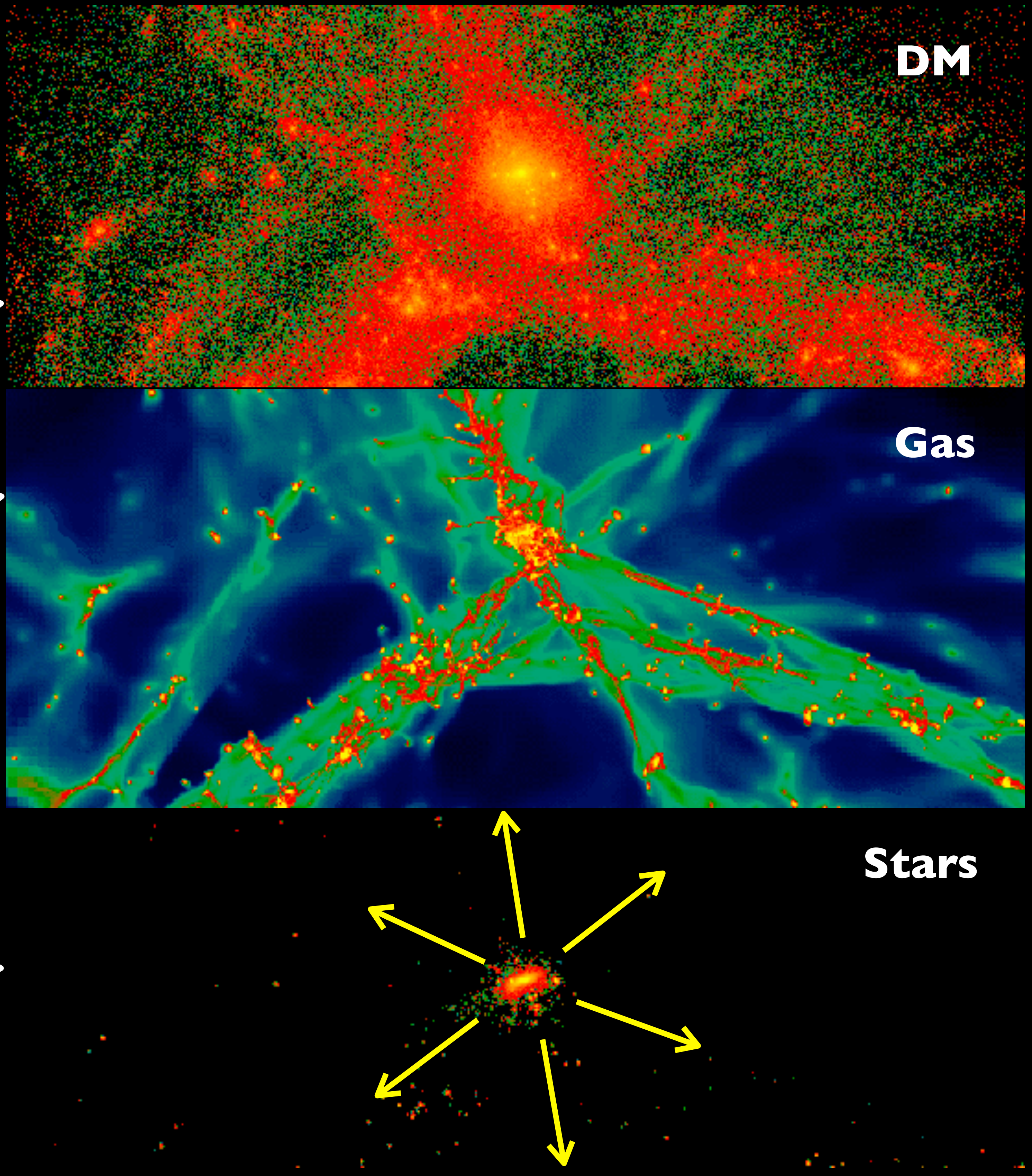
- Arepo (not public)
- ART
- **ENZO** (with RHD)
- **Gadget**
- **Gasoline / ChaNGa**
- **Gizmo**
- **<u>RAMSES</u>** (with RHD, and the focus of this talk)

Cosmological simulations

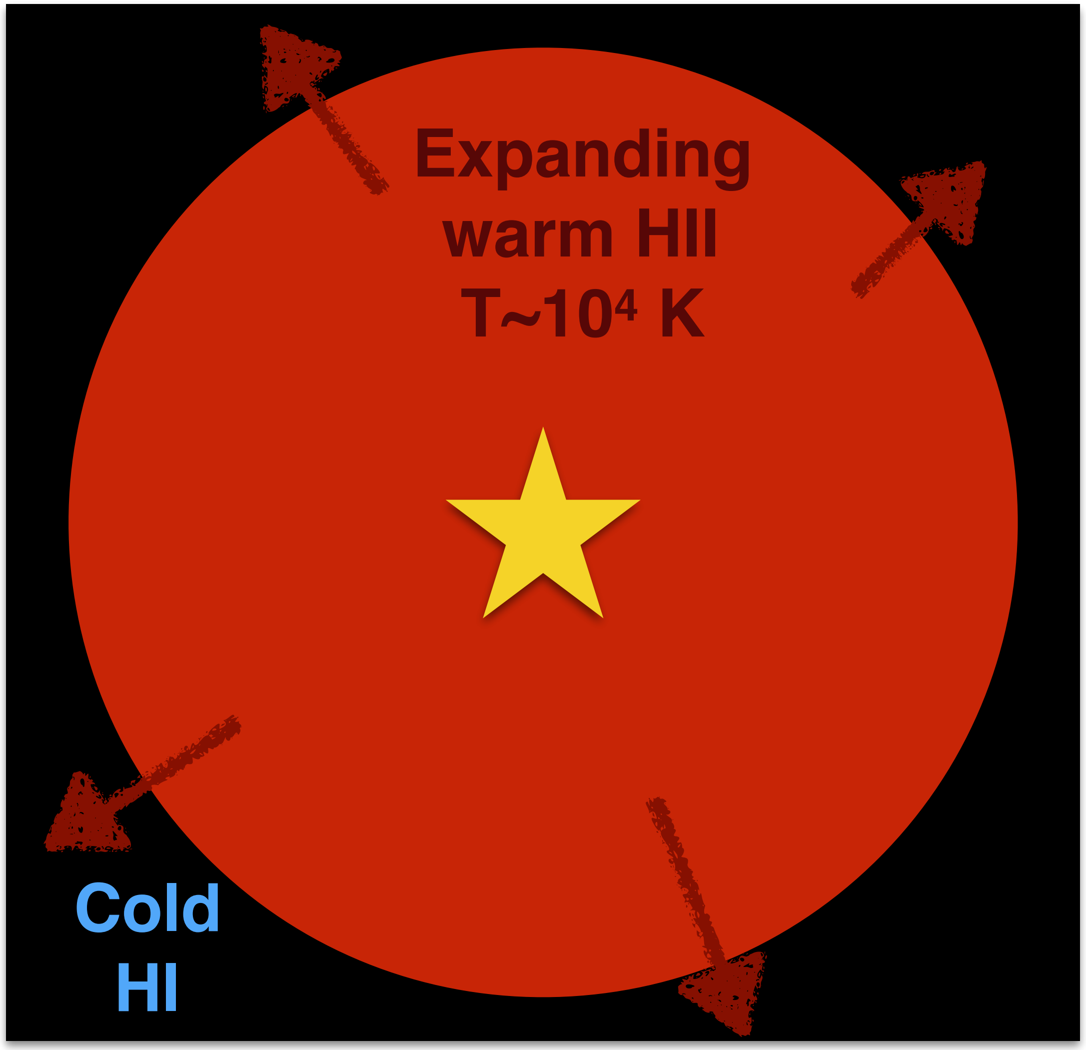
All available codes have the same components

Included components:

- Model of the cosmological expansion of a homogeneous Universe
- 3d evolution of:
  - **Dark matter**: gravity
  - **Baryonic gas:** (self-)gravity, hydrodynamics, radiative cooling, star formation
  - **Stars:** gravity, SNe feedback
  - **Ionsing radiation**



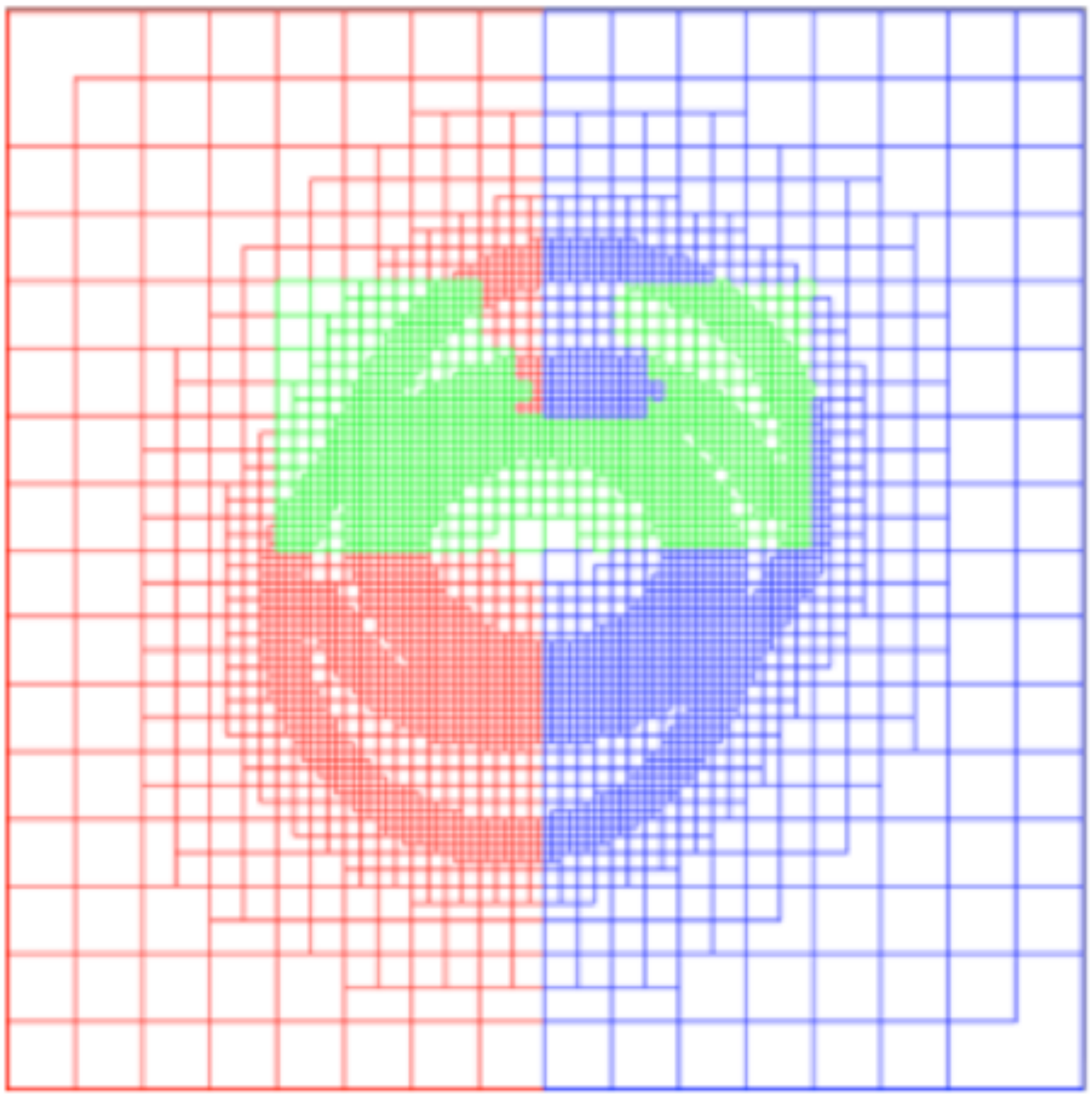
The impact of radiation is mainly via photoionisation heating



There is also radiation pressure, but this is not very important for reionisation

RAMSES - my cosmological code of choice

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
- Dark matter, gas, and stars are all included
- I spent my PhD adding the propagation of *radiation* and its interactions with gas, see Rosdahl et al. (2013), Rosdahl & Teyssier (2015)
- RAMSES-RT is one of two cosmological codes with publicly available radiation-hydrodynamics (RHD)

Overview

- Challenges in numerical radiative transfer
- Main features of RAMSES-RT
  - M1 moment radiative transfer
  - Reduced and variable speed of light
  - Coupling to AMR hydrodynamics
- Tests
- Reionisation with RAMSES-RT

The radiative transfer equation

main challenges in numerical approaches

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \mathbf{n} \cdot \nabla I_\nu = -\kappa_\nu I_\nu + \eta_\nu$$

$I_\nu(\mathbf{x}, \mathbf{n}, t)$ intensity

$\kappa_\nu(\mathbf{x}, \mathbf{n}, t)$ absorption

$\eta_\nu(\mathbf{x}, \mathbf{n}, t)$ source function

Frequency

Location

Angle

Time

To solve this numerically, we need to overcome two main problems:

The radiative transfer equation

main challenges in numerical approaches

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \mathbf{n}\cdot\nabla I_\nu = -\kappa_\nu I_\nu + \eta_\nu$$

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Frequency

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Angle

Time

To solve this numerically, we need to overcome two main problems:

I. There are seven dimensions! Hydrodynamics have only four!

The radiative transfer equation

main challenges in numerical approaches

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \mathbf{n}\cdot\nabla I_\nu = -\kappa_\nu I_\nu + \eta_\nu$$

$I_\nu(\mathbf{x}, \mathbf{n}, t)$ intensity

$\kappa_\nu\,(\mathbf{x}, \mathbf{n}, t)$ absorption

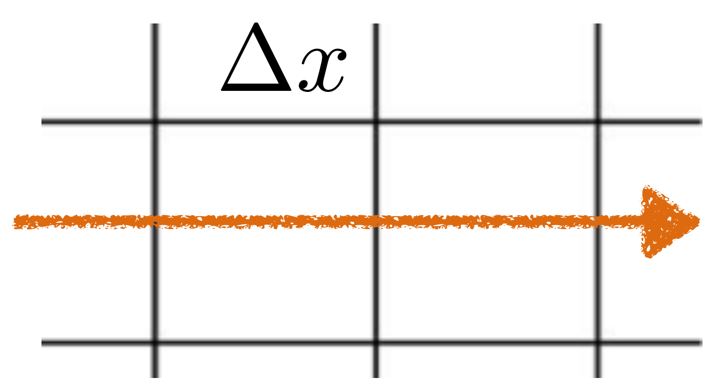
$\eta_\nu\,(\mathbf{x}, \mathbf{n}, t)$ source function

Frequency, Location, Angle, Time

To solve this numerically, we need to overcome two main problems:

I. There are seven dimensions! Hydrodynamics have only four!

II. The timescale is ∝ u^{-1}, where u is *speed*, and $u_{\mathrm{light}} \sim 1000\ u_{\mathrm{gas}}$, so ~ thousand RT steps per hydro step!!



'Something' flowing at speed ***u***

$$\Delta t \lesssim \frac{\Delta x}{u}$$

Cell width (Δx); speed of flow (u); Timestep length (Δt)

The radiative transfer equation

main challenges in numerical approaches

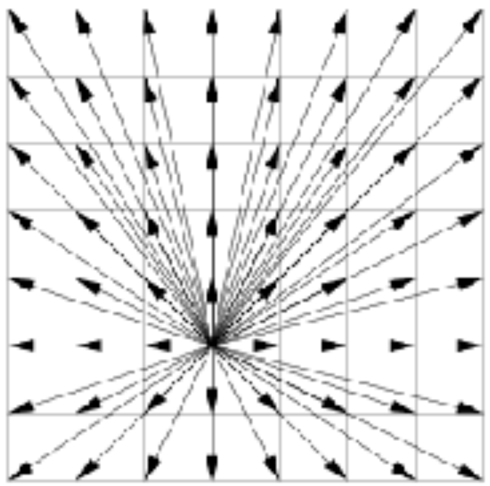
$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \mathbf{n}\cdot\nabla I_\nu = -\kappa_\nu I_\nu + \eta_\nu$$

$I_\nu(\mathbf{x},\mathbf{n},t)$ intensity
$\kappa_\nu(\mathbf{x},\mathbf{n},t)$ absorption
$\eta_\nu(\mathbf{x},\mathbf{n},t)$ source function

Two common strategies for radiative transfer:

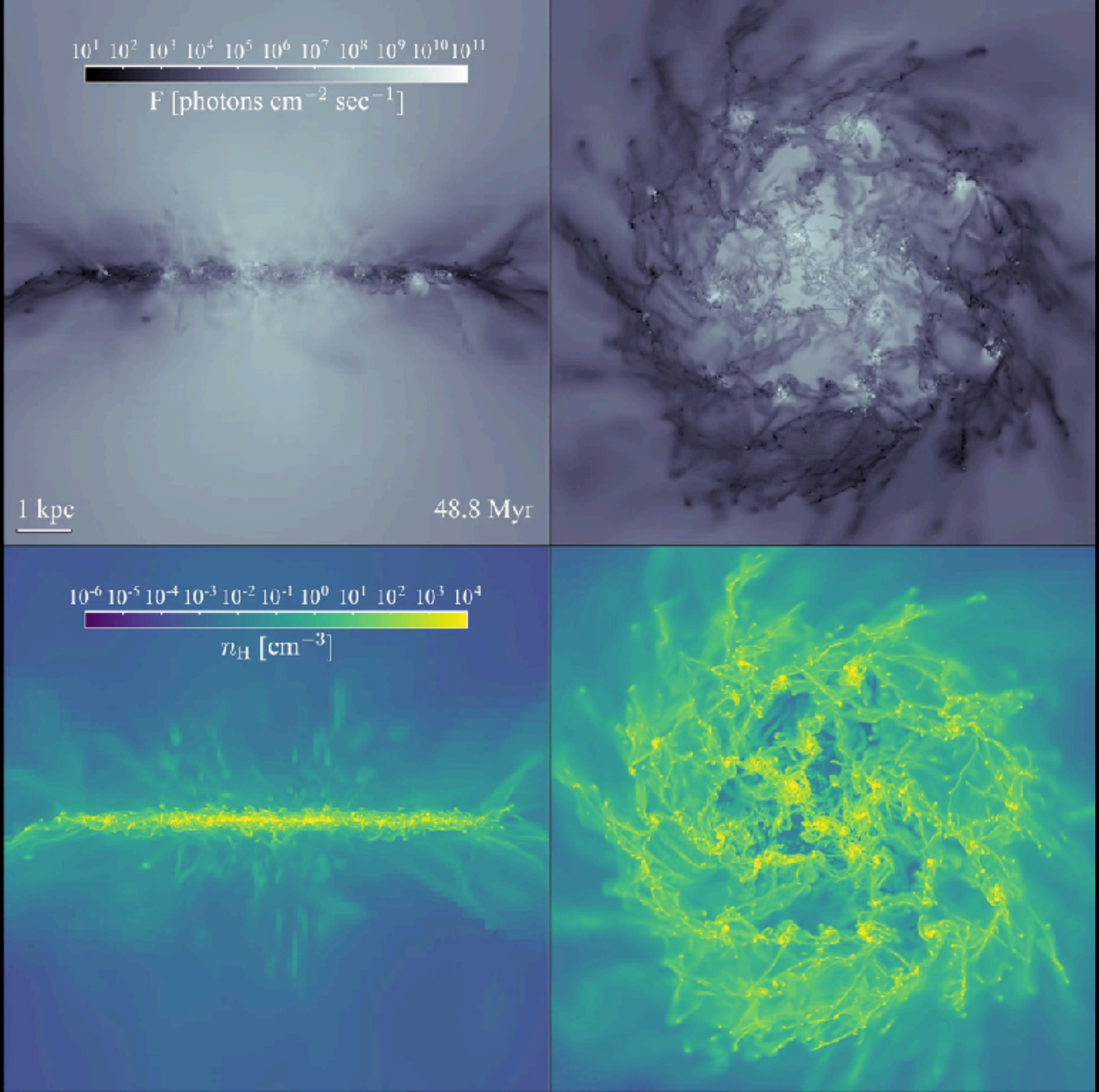
I. *Ray tracing methods:* Cast a finite number of rays from a finite number of sources

- Simple and intuitive
- …but efficiently covering the volume is tricky
- …and load scales with number of sources/rays



II. *Moment methods:* Convert the RT equation into a system of conservation laws that describe a *field* of radiation

- Not so intuitive, and *not rays*
- …but fits easily with a hydrodynamical solver for RHD
- …naturally takes advantage of AMR and parallellization
- …no problem with covering the volume
- …no limit to number of radiation sources


10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10⁷ 10⁸ 10⁹ 10¹⁰ 10¹¹
F [photons cm⁻² sec⁻¹]
1 kpc
48.8 Myr
10⁻⁶ 10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 10⁰ 10¹ 10² 10³ 10⁴
n_H [cm⁻³]

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Moments of the RT equation

to get rid of the angular dimension

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \mathbf{n}\cdot\nabla I_\nu = -\kappa_\nu I_\nu + \eta_\nu$$

$I_\nu(\mathbf{x},\mathbf{n},t)$ intensity

$\kappa_\nu(\mathbf{x},\mathbf{n},t)$ absorbtion

$\eta_\nu(\mathbf{x},\mathbf{n},t)$ source function

Zeroth moment: $\oint f(\mathbf{n})\, d\Omega$

$$\frac{1}{c}\frac{\partial}{\partial t}\oint I_\nu\, d\Omega + \nabla\oint \mathbf{n}\, I_\nu\, d\Omega = -\kappa_\nu\oint I_\nu\, d\Omega + \eta_\nu\oint d\Omega$$

First moment: $\oint \mathbf{n} f(\mathbf{n})\, d\Omega$

$$\frac{1}{c}\frac{\partial}{\partial t}\oint \mathbf{n}\, I_\nu\, d\Omega + \nabla\oint \mathbf{n}\otimes\mathbf{n}\, I_\nu\, d\Omega = -\kappa_\nu\oint \mathbf{n}\, I_\nu\, d\Omega$$

These equations contain the first three moments of the intensity:

$$E_\nu = \frac{1}{c}\oint I_\nu\, d\Omega \quad \text{(energy per volume and frequency)}$$

$$\mathbf{f}_\nu = \oint \mathbf{n}\, I_\nu\, d\Omega \quad \text{(energy flux per area and time and frequency)}$$

$$\mathbb{P}_\nu = \frac{1}{c}\oint \mathbf{n}\otimes\mathbf{n}\, I_\nu\, d\Omega \quad \text{(force per area and frequency)}$$

$$\frac{\partial E_\nu}{\partial t} + \nabla\cdot\mathbf{f}_\nu = -\kappa_\nu c E_\nu + S_\nu$$

$$\frac{\partial \mathbf{f}_\nu}{\partial t} + c^2\nabla\cdot\mathbb{P}_\nu = -\kappa_\nu c\mathbf{f}_\nu$$

Moment RT equations

$$\frac{\partial E_\nu}{\partial t} + \nabla \cdot \mathbf{f}_\nu = -\kappa_\nu c E_\nu + S_\nu$$
$$\frac{\partial \mathbf{f}_\nu}{\partial t} + c^2 \nabla \cdot \mathbb{p}_\nu = -\kappa_\nu c \mathbf{f}_\nu$$

$E_\nu = \frac{1}{c}\oint I_\nu \, d\Omega$ (energy per volume and frequency)

$\mathbf{f}_\nu = \oint \mathbf{n} \, I_\nu \, d\Omega$ (energy flux per area and time and frequency)

$\mathbb{p}_\nu = \frac{1}{c}\oint \mathbf{n} \otimes \mathbf{n} \, I_\nu \, d\Omega$ (force per area and frequency)

With ionising radiation, it makes more sense to keep track of *photon number density* than energy density

$$\frac{\partial N_\nu}{\partial t} + \nabla \cdot \mathbf{F}_\nu = - \sum_j^{\mathrm{HI,HeI,HeII}} n_j c \sigma_{\nu j} N_\nu + \dot{N}_\nu^* + \dot{N}_\nu^{rec}$$
$$\frac{\partial \mathbf{F}_\nu}{\partial t} + c^2 \nabla \cdot \mathbb{P}_\nu = - \sum_j^{\mathrm{HI,HeI,HeII}} n_j c \sigma_{\nu j} \mathbf{F}_\nu$$

$N(\mathbf{x}, t)$ photon density

$\mathbf{F}(\mathbf{x}, t)$ photon number flux

$\mathbb{P}(\mathbf{x}, t)$ photon ‘pressure’

Frequency binning

We separate the RT equations into M *sets, or photon groups*, that discretise the frequency continuum

➡M (a handful of) separate radiation fields, one per frequency bin, with average photon energies and cross sections

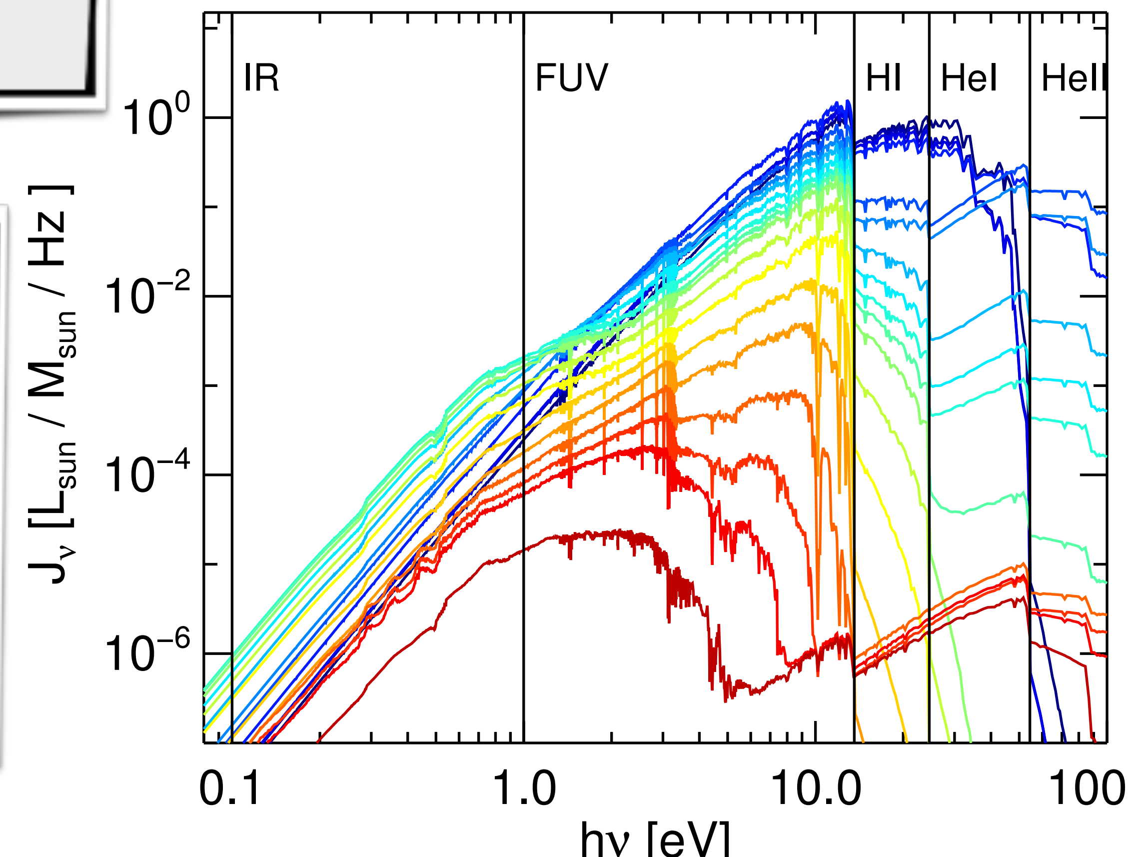
$$\frac{\partial N_\nu}{\partial t} + \nabla \cdot \mathbf{F}_\nu = -\sum_j^{\mathrm{HI,HeI,HeII}} n_j c \sigma_{\nu j} N_\nu \quad + \dot{N}_\nu^* + \dot{N}_\nu^{rec}$$

$$\frac{\partial \mathbf{F}_\nu}{\partial t} + c^2 \nabla \cdot \mathbb{P}_\nu = -\sum_j^{\mathrm{HI,HeI,HeII}} n_j c \sigma_{\nu j} \mathbf{F}_\nu$$

$$\frac{\partial N_i}{\partial t} + \nabla \cdot \mathbf{F}_i = -\sum_j^{\mathrm{HI,HeI,HeII}} n_j c \sigma_{ij} N_i \quad + \dot{N}_i^* + \dot{N}_i^{rec}$$

$$\frac{\partial \mathbf{F}_i}{\partial t} + c^2 \nabla \cdot \mathbb{P}_i = -\sum_j^{\mathrm{HI,HeI,HeII}} n_j c \sigma_{ij} \mathbf{F}_i$$

A SED of stellar populations is used to characterise frequencies and energies of the photon groups



Radiation variables, stored in each cell

one set per photon group (neglecting the i-index)

$$\frac{\partial N}{\partial t} + \nabla \cdot \mathbf{F} = - \sum_j^{\text{HI,HeI,HeII}} n_j \sigma_j c N \quad + \dot{N}^{\star} + \dot{N}^{rec}$$

$$\frac{\partial \mathbf{F}}{\partial t} + c^2 \nabla \cdot \mathbb{P} = - \sum_j^{\text{HI,HeI,HeII}} n_j \sigma_j c \mathbf{F}$$

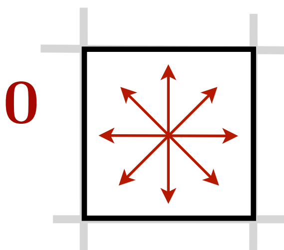
$N(\mathbf{x})$ **photon density**

$\mathbf{F}(\mathbf{x}) = (F_x, F_y, F_z)$

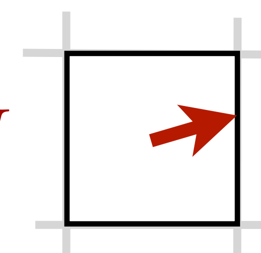
photon flux

Describe isotropic plus directed radiation in each volume element (cell)

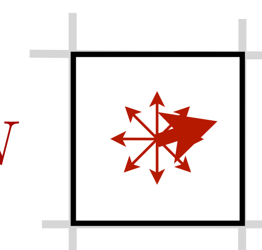
Diffusion limit (isotropic): $\mathbf{F} = \mathbf{0}$



Transport limit (directed): $|\mathbf{F}| = cN$



A combination: $0 < |\mathbf{F}| < cN$



The 'directionality' can be described by the **reduced flux**: $f \equiv \frac{|\mathbf{F}|}{cN}, \qquad 0 \leq f \leq 1$

We almost have usable expressions - we 'only' need to close the equations

Closing the moment RT equations

$$\frac{\partial N}{\partial t} + \nabla \cdot \mathbf{F} = - \sum_{j}^{\mathrm{HI,HeI,HeII}} n_j \sigma_j c N + \dot{N}^{\star} + \dot{N}^{rec}$$

$$\frac{\partial \mathbf{F}}{\partial t} + c^2 \nabla \cdot \mathbb{P} = - \sum_{j}^{\mathrm{HI,HeI,HeII}} n_j \sigma_j c \mathbf{F}$$

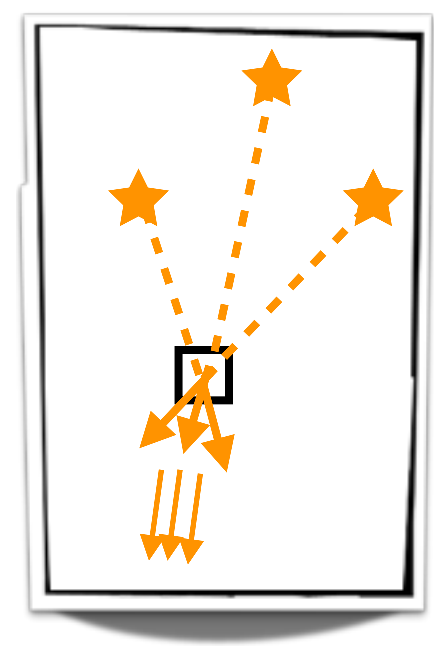
$\mathbb{P} = \mathbb{D} N$ Eddington tensor

$N(\mathbf{x}, t)$ photon density
$\mathbf{F}(\mathbf{x}, t)$ photon flux
$\mathbb{P}(\mathbf{x}, t)$ photon 'pressure'

Three closures:

I: Flux limit diffusion: Radiation flows in the direction of less radiation
Good description in the optically thick limit

II: (OT)VET: (Optically thin) variable Eddington tensor:
The tensor (direction of flow) is made from the sum of all sources
Nonlocal expression, so computationally challenging.



III: M1 closure (Levermore 1984): The tensor is composed out of the ***local*** *quantities N and* ***F*** *only*

M1 closure - a warning

The loss of the angular dimension combined with the locality of M1 results in peculiar radiation propagation

For speed, we sacrifice the collision-less nature of photons

$$\frac{\partial N}{\partial t} + \nabla \cdot \mathbf{F} = - \sum_{j}^{\text{H\,I,He\,I,He\,II}} n_j \sigma_j c N \quad + \dot{N}^{\star} + \dot{N}^{rec}$$

$$\frac{\partial \mathbf{F}}{\partial t} + c^2 \nabla \cdot \mathbb{P} = - \sum_{j}^{\text{H\,I,He\,I,He\,II}} n_j \sigma_j c \mathbf{F}$$

$$\mathbb{P} = \mathbb{D} N$$

Solving the M1 moment RT equations on a uniform grid

Solving the RT moment equations on a grid

Operator splitting: separate into **3 steps** that can be solved in order over one discrete timestep at a time:

$$t^n \rightarrow t^{n+1} = t^n + \Delta t$$

3 steps, at each Δt:

I. Photon transport between adjacent cells

II. Injection into cells

III. Thermochemistry in every cell

$$\frac{\partial N}{\partial t} + \nabla \cdot \mathbf{F} = -\sum_{j}^{\text{HI,HeI,HeII}} n_j \sigma_j c N + \dot{N}^{\star} + \dot{N}^{rec}$$

$$\frac{\partial \mathbf{F}}{\partial t} + c^2 \nabla \cdot \mathbb{P} = -\sum_{j}^{\text{HI,HeI,HeII}} n_j \sigma_j c \mathbf{F}$$

$$\mathbb{P} = \mathbb{D} N$$

$$\frac{\partial \varepsilon}{\partial t} = \Lambda\left(\rho, \varepsilon, n_j, N_i\right)$$

Photon transport

$$\frac{\partial N}{\partial t} + \nabla \cdot \mathbf{F} = - \sum_{j}^{\mathrm{HI,HeI,HeII}} n_j \sigma_j c N + \dot{N}^{\star} + \dot{N}^{rec}$$

$$\frac{\partial \mathbf{F}}{\partial t} + c^2 \nabla \cdot \mathbb{P} = - \sum_{j}^{\mathrm{HI,HeI,HeII}} n_j \sigma_j c \mathbf{F}$$

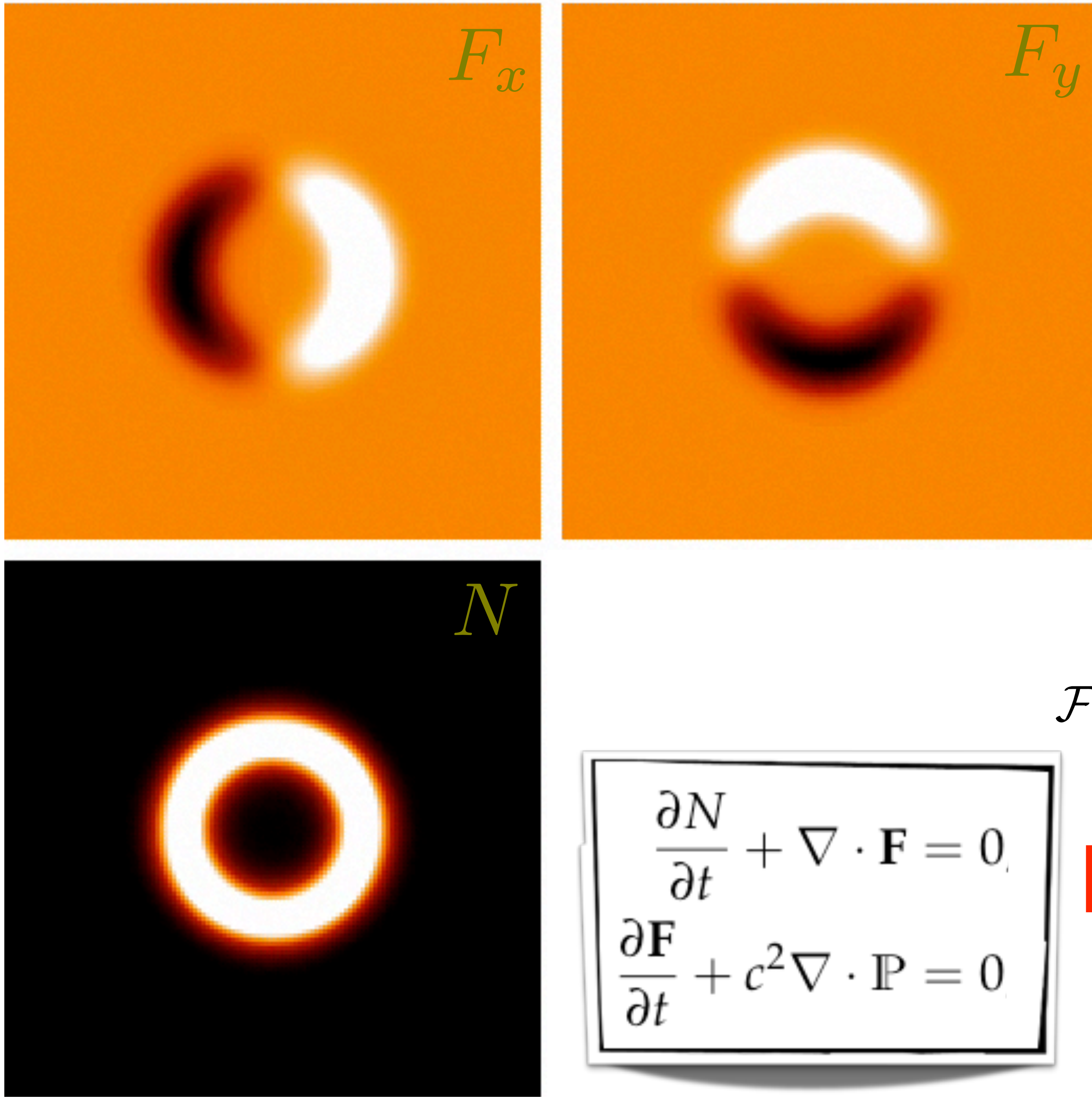
$$\mathbb{P} = \mathbb{D} N$$

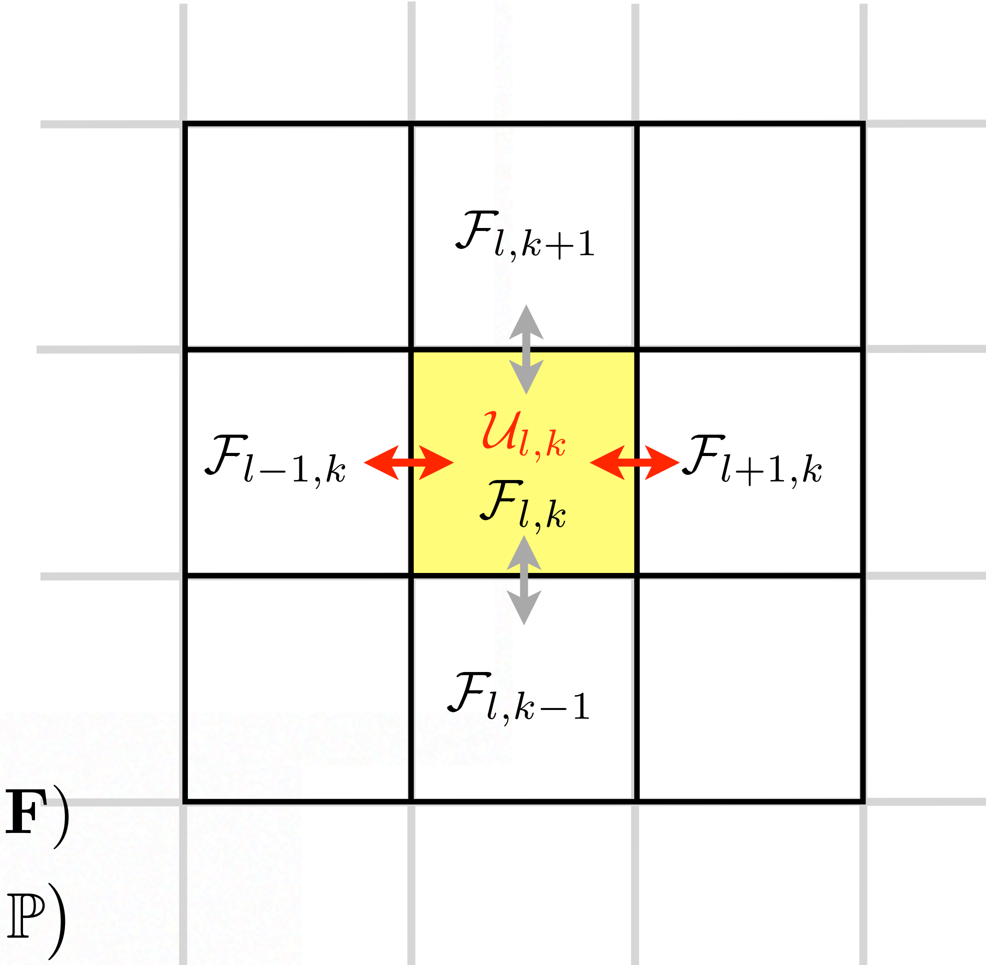
$$\frac{\partial \varepsilon}{\partial t} = \Lambda \left(\rho, \varepsilon, n_j, N_i \right)$$

$$\frac{\partial N}{\partial t} + \nabla \cdot \mathbf{F} = 0,$$

$$\frac{\partial \mathbf{F}}{\partial t} + c^2 \nabla \cdot \mathbb{P} = 0,$$

Photon transport





$$\mathcal{U} \equiv (N, \mathbf{F})$$

$$\mathcal{F} \equiv \left(\mathbf{F}, c^2\mathbb{P}\right)$$

$$\frac{\partial N}{\partial t} + \nabla \cdot \mathbf{F} = 0$$

$$\frac{\partial \mathbf{F}}{\partial t} + c^2 \nabla \cdot \mathbb{P} = 0$$

$$\frac{\partial \mathcal{U}}{\partial t} + \nabla \mathcal{F}(\mathcal{U}) = 0$$

Explicit time discretisation: $t^{n+1} = t^n + \Delta t$

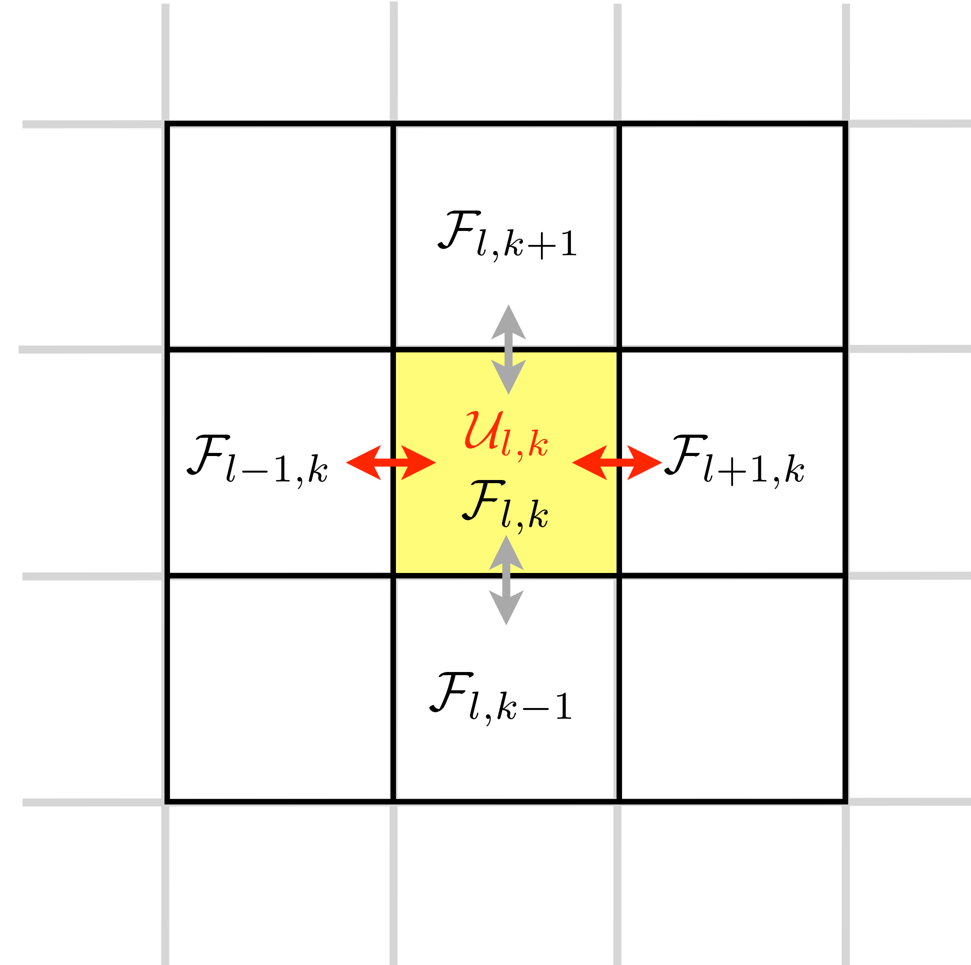
$$\mathcal{U}_l^{n+1} = \mathcal{U}_l^n + \frac{\Delta t}{\Delta x}\left(\mathcal{F}_{l-1/2}^n - \mathcal{F}_{l+1/2}^n\right)$$

Intercell flux function

$$\mathcal{U}_l^{n+1} = \mathcal{U}_l^n + \frac{\Delta t}{\Delta x}\left(\mathcal{F}_{l-1/2}^n - \mathcal{F}_{l+1/2}^n\right)$$

$$\mathcal{U} \equiv (N, \mathbf{F})$$

$$\mathcal{F} \equiv \left(\mathbf{F}, c^2\mathbb{P}\right)$$



How do we pick $\mathcal{F}_{\ell+1/2}$??

~~Simplest case is average between cells:~~

$$\mathcal{F}_{l+1/2} = \frac{\mathcal{F}_l + \mathcal{F}_{l+1}}{2}$$

$$\mathcal{U}_l^{n+1} = \mathcal{U}_l^n + \frac{\Delta t}{\Delta x}\left(\mathcal{F}_{l-1} + \mathcal{F}_{l+1}\right)$$

Harten-Lax-van Leer - **HLL**:

$$\mathcal{F}_{l+1/2} = \frac{\lambda^+\mathcal{F}_l - \lambda^-\mathcal{F}_{l+1} + \lambda^+\lambda^-\left(\mathcal{U}_{l+1} - \mathcal{U}_l\right)}{\lambda^+ - \lambda^-}$$

$$\lambda^+ = \max(0, \lambda_l^{\max}, \lambda_{l+1}^{\max})$$
$$\lambda^- = \min(0, \lambda_l^{\min}, \lambda_{l+1}^{\min})$$

= angle-dependent 'speeds' = eigenvalues of $\frac{\partial \mathcal{F}}{\partial \mathcal{U}}$

a simpler flux function

HLL: $$\mathcal{F}_{l+1/2} = \frac{\lambda^+ \mathcal{F}_l - \lambda^- \mathcal{F}_{l+1} + \lambda^+ \lambda^- \left(\mathcal{U}_{l+1} - \mathcal{U}_l\right)}{\lambda^+ - \lambda^-}$$

A stable alternative is not to bother with eigenvalues at all. In the Global Lax Friedrich function, or **GLF**, we make the approximation that

$$\lambda^+ = -\lambda^- = c$$

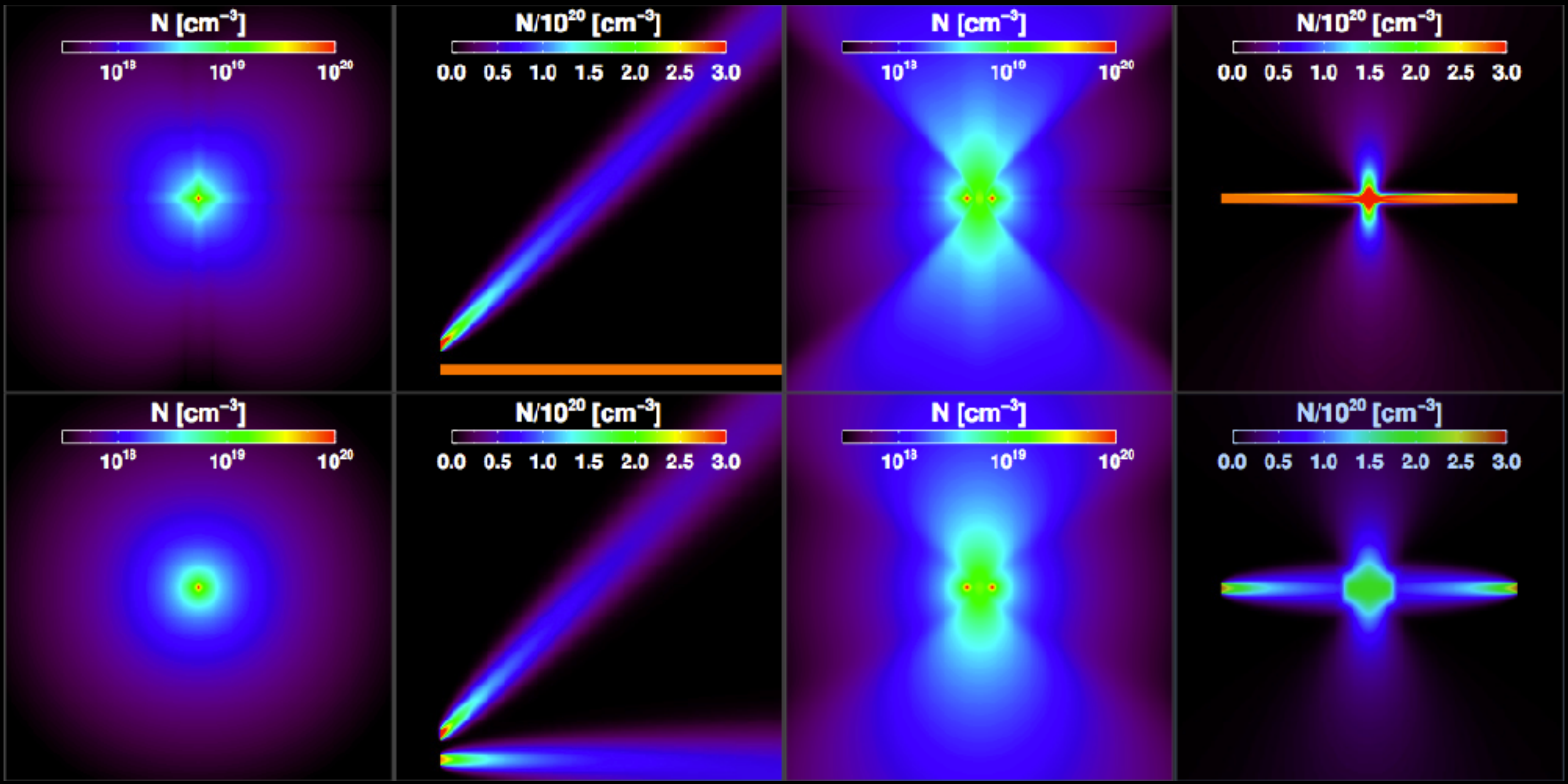
which gives

GLF: $$\mathcal{F}_{l+1/2} = \frac{\mathcal{F}_l + \mathcal{F}_{l+1}}{2} - \frac{c}{2}\left(\mathcal{U}_{l+1} - \mathcal{U}_l\right)$$

The resulting photon transport is more diffusive than HLL, which is both good and bad

HLL vs GLF transport of photons

HLL



GLF

...I generally prefer GLF

Thermochemistry

$$\frac{\partial N}{\partial t} + \nabla \cdot \mathbf{F} = -\sum_{j}^{\text{HI,HeI,HeII}} n_j \sigma_j c N + \dot{N}^{\star} + \dot{N}^{rec}$$

$$\frac{\partial \mathbf{F}}{\partial t} + c^2 \nabla \cdot \mathbb{P} = -\sum_{j}^{\text{HI,HeI,HeII}} n_j \sigma_j c \mathbf{F}$$

$$\mathbb{P} = \mathbb{D} N$$

$$\frac{\partial \varepsilon}{\partial t} = \Lambda \left(\rho, \varepsilon, n_j, N_i\right)$$

- **Hydro codes usually assume photoionisation equilibrium (PIE) where the gas ionisation fractions are a tabulated function of temperature and density**
- **Not ideal if we want to conserve photons**
- **Therefore we store and evolve ionisation fractions in each cell:**

$$x_{\text{HII}}, \quad x_{\text{HeII}}, \quad x_{\text{HeIII}}$$

- **Molecular hydrogen was added last week** **(Nickerson, Teyssier, & Rosdahl, 2018)**

Overview

Challenges in numerical radiative transfer

Main features of RAMSES-RT

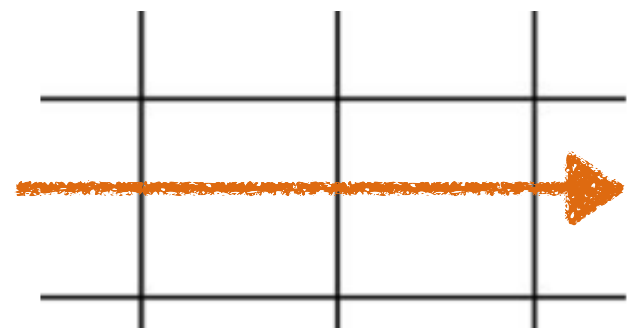
- M1 moment radiative transfer
- Reduced and variable speed of light
- Coupling to AMR hydrodynamics

Tests

Reionisation with RAMSES-RT

The speed of light problem

The explicit advection of radiation across cells makes us slaves to the Courant condition



'Something' flowing at speed ***u***

$$\Delta t \lesssim \frac{\Delta x}{u}$$

$$\Delta t_{\rm RT} \sim \frac{\Delta x}{c} \sim \frac{\Delta t_{\rm HD}}{1000}$$

The reduced speed of light approximation (RSLA)

Gnedin & Abel 2001

To cheat death we use the reduced speed of light approximation (Gnedin & Abel 2001):

$$c_{\rm red} = \frac{c}{1000} \quad \Rightarrow \quad \Delta t_{\rm RT} \sim \frac{\Delta x}{c_{\rm red}} \sim \Delta t_{\rm HD}$$

➡ Only ~2X runtime increase, compared to pure hydro

Not as dramatic as it sounds:

The dynamic speed in RHD simulations is that of *ionisation fronts*, not *c*.

We just want to get the front correct...

Setting the reduced speed of light

Assuming a constant luminosity in a homogeneous medium…

Regime	n_H (cm^{-3})	$\dot{N}$ (s^{-1})	r_S (kpc)	t_{cross} (Myr)	t_{rec} (Myr)	τ_{sim} (Myr)	$f_{c,\,min}$
MW ISM	10^{-1}	2×10^{50}	0.9	3×10^{-3}	1.2	1	3×10^{-2}
MW cloud	10^{2}	2×10^{48}	2×10^{-3}	6×10^{-6}	1×10^{-3}	0.1	6×10^{-4}
Iliev tests 1, 2, 5	10^{-3}	5×10^{48}	5.4	2×10^{-2}	122.3	10	2×10^{-2}
Iliev test 4	10^{-4}	7×10^{52}	600	2	1200	0.05	1

Reionisation

$$f_c = \min(1; \sim 10 \times t_{cross}/\tau_{sim})$$

These are suggestive values…
Light speed convergence tests are the best final verdict.

Great for ISM and CGM simulations, but death for reionisation (of cosmological voids) 😫

The variable speed of light approximation (VSLA)

Katz et al. 2017

The main limitation for performing large-scale reionisation simulations was that reionisation of cosmological voids happens 'close' to the (real) speed of light.

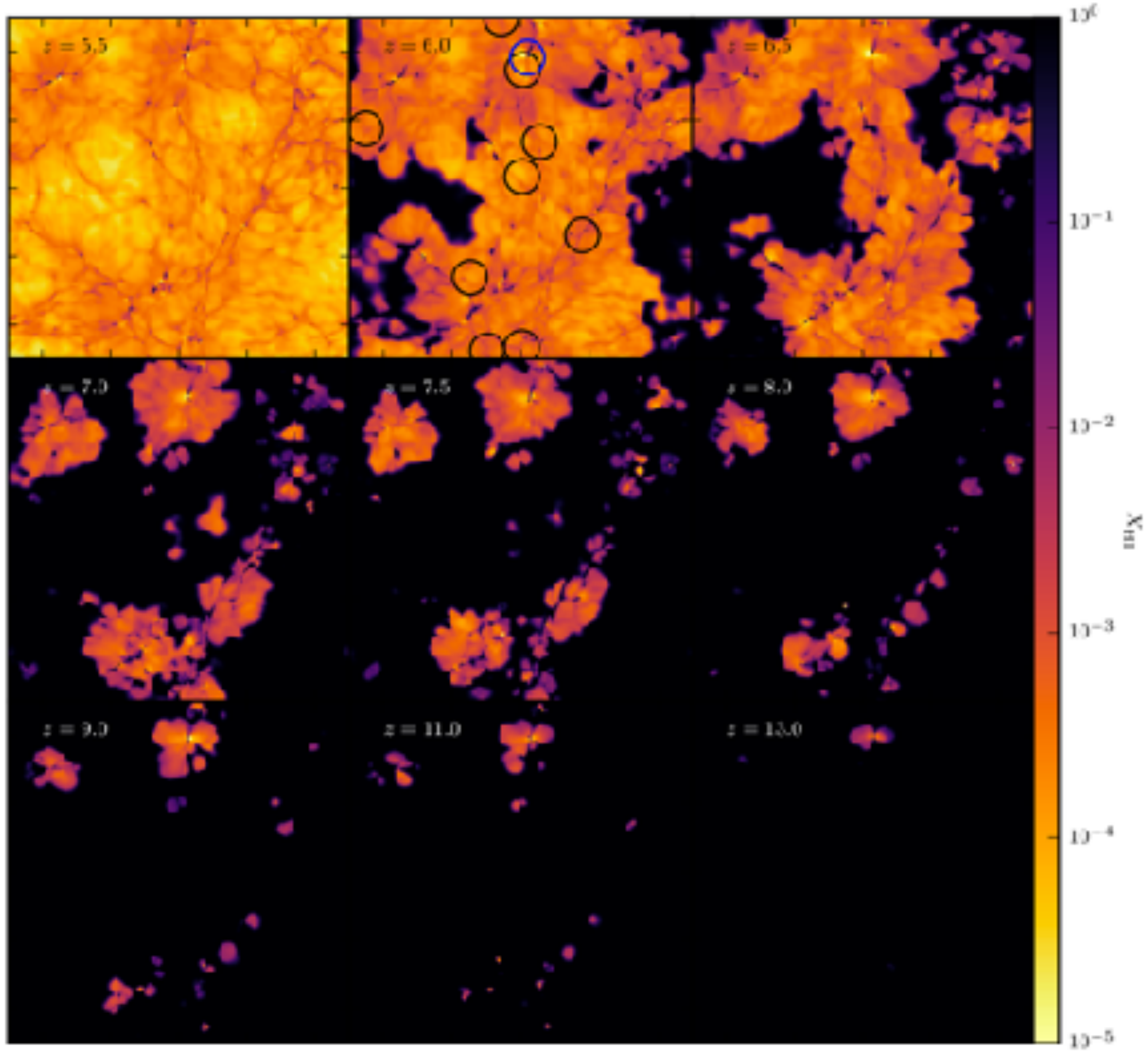
We recently overcame this problem with a *variable speed of light approximation*, where *c* is slow in dense gas but speeds up in the diffuse IGM (see Katz et al, 2017).

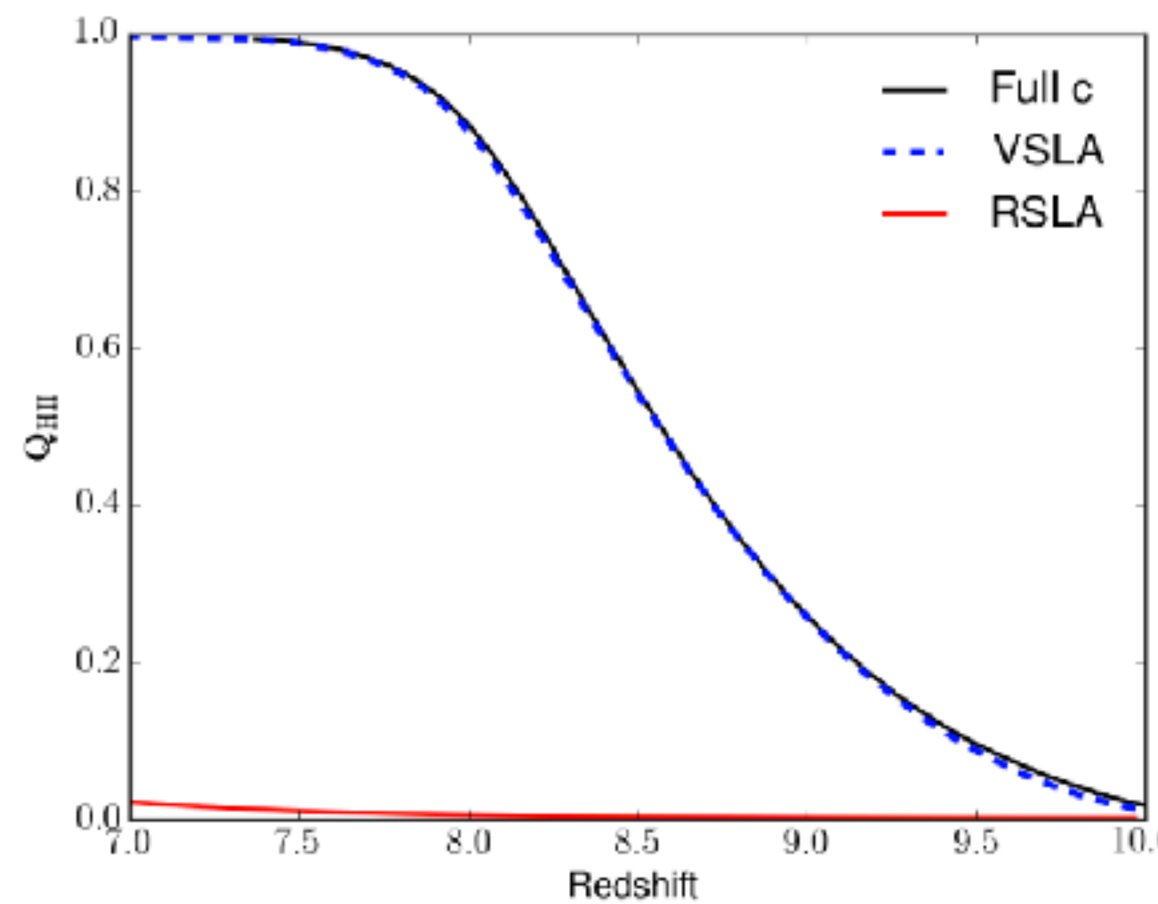
Harley Katz

This makes it possible, for the first time, to perform large-scale reionsiation simulations that resolve individual galaxies.

The variable speed of light approximation (VSLA)

From Katz et al. 2017





3-100 %
3%
light speed

Overview

Challenges in numerical radiative transfer

Main features of RAMSES-RT

- M1 moment radiative transfer
- Reduced and variable speed of light
- Coupling to AMR hydrodynamics

Tests

Reionisation with RAMSES-RT

Ramses hydrodynamics

Conservation of mass:	$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$
Conservation of momentum:	$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) + \nabla p = \rho \nabla \phi$
Conservation of energy:	$\frac{\partial \mathcal{E}}{\partial t} + \nabla \cdot (\mathcal{E} + p)\, \mathbf{u} = -\rho \mathbf{u} \cdot \nabla \phi + \Lambda(\rho, \varepsilon)$
Closure: Equation of state:	$p = (\gamma - 1)\varepsilon$
Kinetic vs. thermal energy:	$\mathcal{E} = \frac{1}{2}\rho u^2 + \varepsilon$

- Gravitational potential ϕ is imprinted on the AMR grid with a Poisson equation solver
- Mass, momentum and energy are advected with a second-order Godunov solver
- Operator splitting: Radiative cooling Λ is subcycled on every gravito-hydro timestep

RHD: Coupling hydrodynamics and RT

HD equations solved in Ramses:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) + \nabla p = \rho \nabla \phi$$

$$\frac{\partial \mathcal{E}}{\partial t} + \nabla \cdot (\mathcal{E} + p)\, \mathbf{u} = -\rho \mathbf{u} \cdot \nabla \phi + \Lambda(\rho, \varepsilon)$$

$$p = (\gamma - 1)\varepsilon$$

$$\mathcal{E} = \frac{1}{2}\rho u^2 + \varepsilon$$

RT equations:

$$\frac{\partial N}{\partial t} + \nabla \cdot \mathbf{F} = -\sum_j^{\text{HI,HeI,HeII}} n_j \sigma_j c N + \dot{N}^\star + \dot{N}^{rec}$$

$$\frac{\partial \mathbf{F}}{\partial t} + c^2 \nabla \cdot \mathbb{P} = -\sum_j^{\text{HI,HeI,HeII}} n_j \sigma_j c \mathbf{F}$$

$$\mathbb{P} = \mathbb{D} N$$

$$\frac{\partial \varepsilon}{\partial t} = \Lambda\left(\rho, \varepsilon, n_j, N_i\right)$$

HD and RT couple where photons interact with gas

Considerations:

- $\Delta t_{\text{hydro}} >> \Delta t_{\text{RT}} >> \Delta t_{\text{chemistry}}$
- The coupling happens in Λ (i.e the thermochemistry)

➡ **Operator splitting:**
The thermochemistry is sub-cycled within the RT, which is subcycled within the hydrodynamics.

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Reionisation with RAMSES-RT

Overview

Challenges in numerical radiative transfer

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- M1 moment radiative transfer
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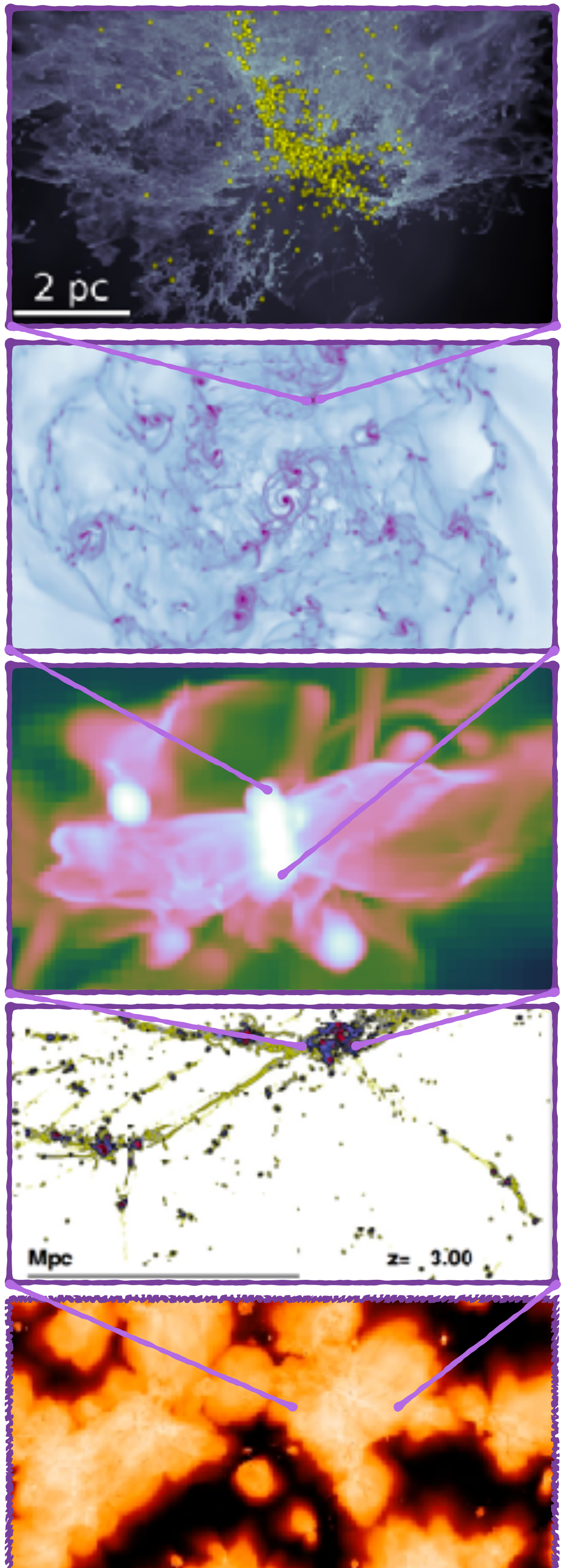
Tests

Reionisation with RAMSES-RT

Science with RAMSES-RT on many scales



- **Molecular clouds**, sub-pc to pc scales
  Gavagnin, Bleuler, Rosdahl, & Teyssier (2017)
  Kimm, Cen, Rosdahl, & Yi (2016)
  Geen, Hennebelle, Tremblin, & Rosdahl (2015, 2016)
  Geen, Rosdahl, Blaizot, Devriendt, & Slyz (2015)
  Geen, Soler, & Hennebelle (2017)

- **Galaxy-scale stellar feedback**, pc to kpc scales
  Butler, Tan, Teyssier, Rosdahl, van Loo, & Nickerson (2017)
  Rosdahl, Schaye, Teyssier, & Agertz (2015)
  Rosdahl & Teyssier (2015)

- **Feedback from active galactic nuclei**, pc to kpc scales
  Trebitsch et al. (2018)
  Costa, Rosdahl, Sijacki, & Haehnelt (2017a,b)
  Bieri, Dubois, Rosdahl, Wagner, Silk, & Mamon (2016)

- **Properties of the circum-galactic medium**, kpc to Mpc scales
  Rosdahl & Blaizot (2012)
  Trebitsch, Verhamme, Blaizot, & Rosdahl (2016)

- **Reionisation and escape of ionising photons**, pc to Mpc scales
  Kimm & Cen (2014)
  Trebitsch, Blaizot, Rosdahl, Devriendt, & Slyz (2017)
  Kimm, Katz, Haehnelt, Rosdahl, Devriendt, & Slyz (2017)
  Katz, Kimm, Sijacki, Haehnelt (2017)
  Rosdahl et al. (2018)

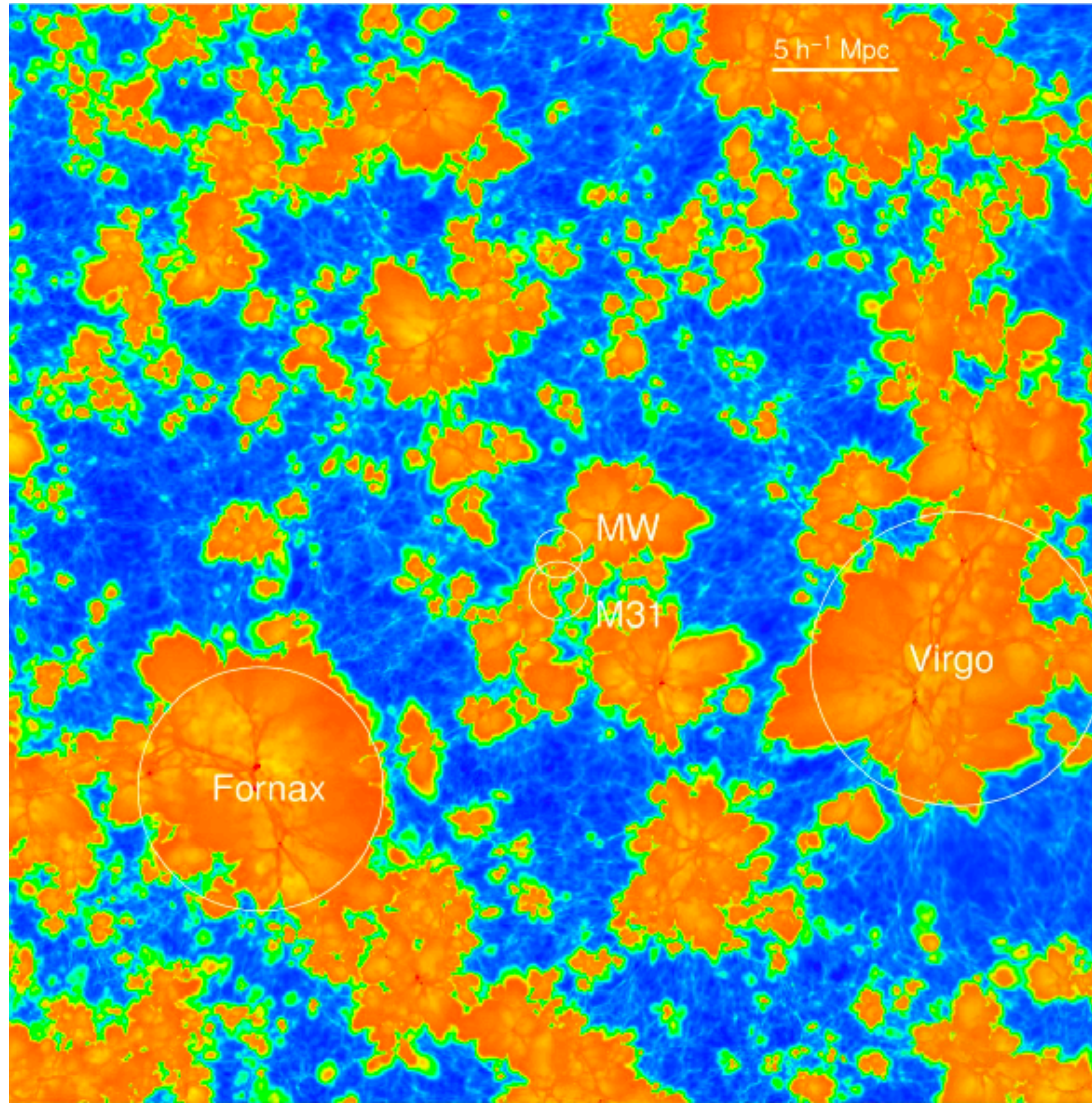
Two classes of reionisation simulations

Large volume with unresolved galaxies	(Gap) So far impossible	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. f_{esc} is a free parameter. Low-mass halos are not captured. Good for the large-scale process, clustering, patchiness. Not-so-good for understanding the (unresolved) sources of ionisation.		Production of ionising radiation and f_{esc} resolved. But the large scale reionisation process is not captured (nor the actual contribution from individual sources).

Large volume simulations of reionisation

COsmic DAwn (CODA)
Ocvirk et al, 2015

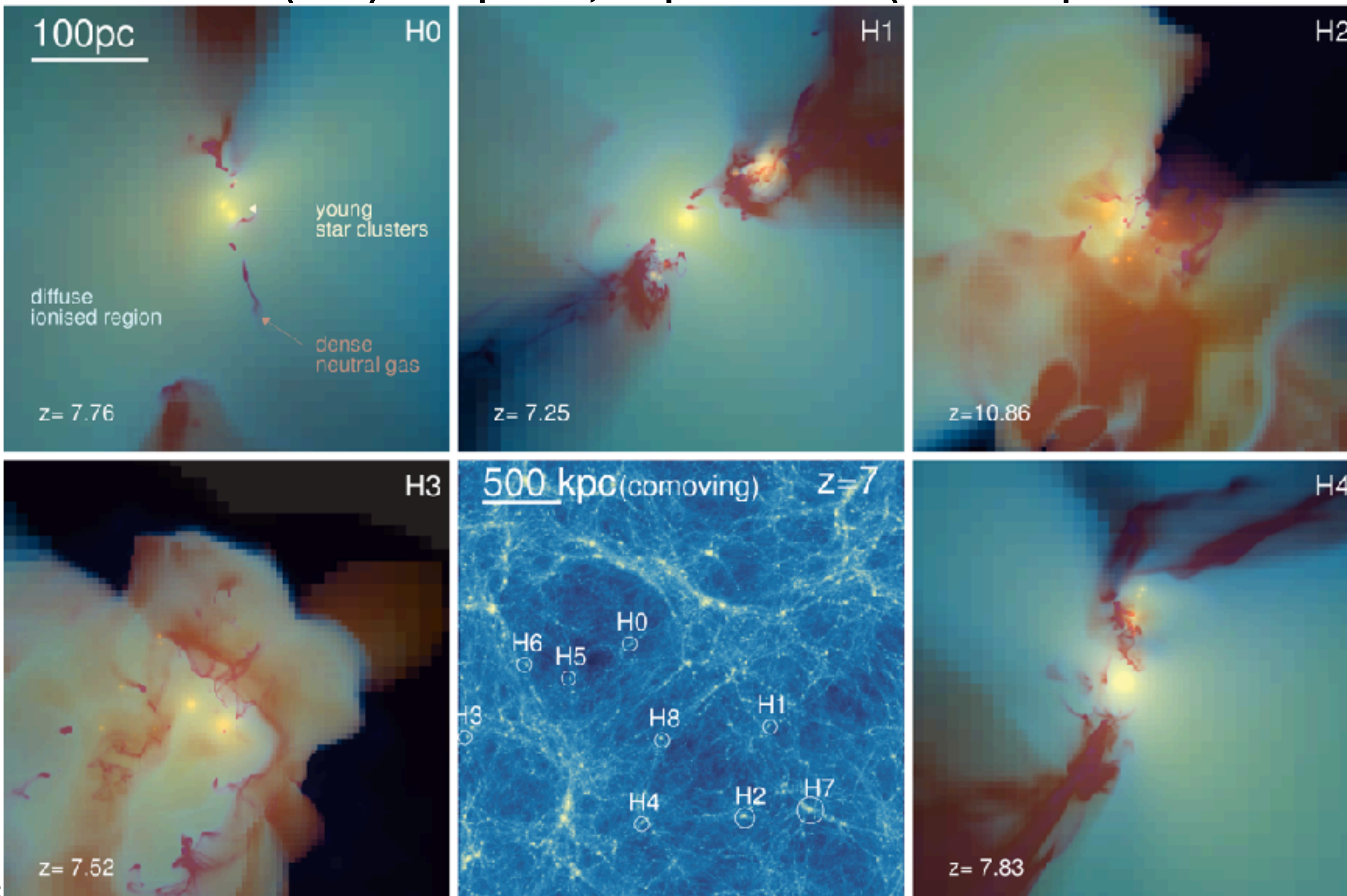
- f_{esc} calibrated to reproduce observed reionisation history
- Prediction of how the local volume was reionised
- Shapes of ionisation regions
- Suppression of star formation in low-mass haloes due to reionisation
- Ionisation state of cosmological filaments



Tiny volume simulations with RAMSES-RT

Zoom technique to resolve one galaxy and its environment in a cosmological volume

From Kimm et al. (2017): 2 cMpc box, 0.7 pc resolution (in a small part of the volume)



Tiny volume simulations with RAMSES-RT

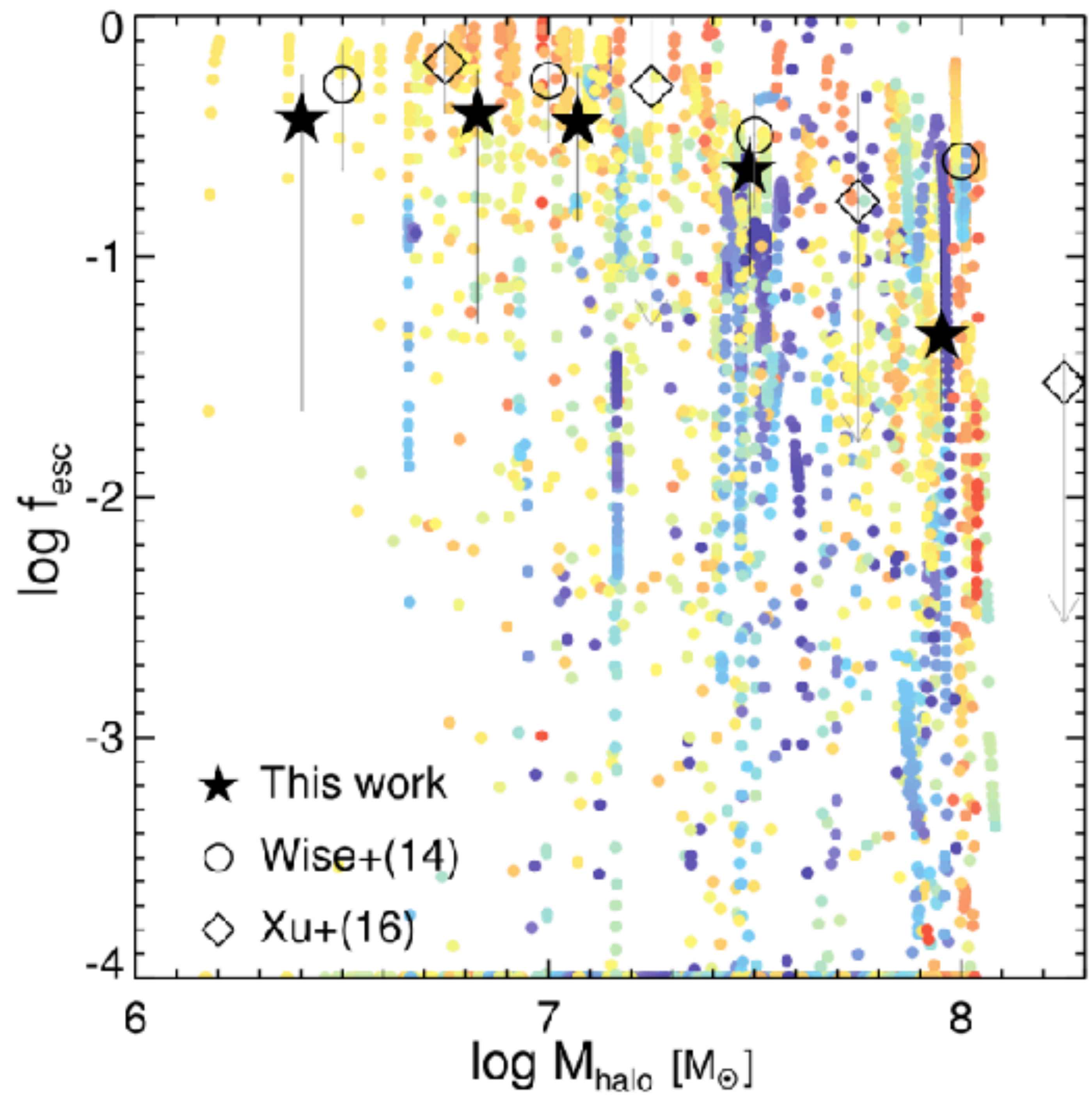
From Kimm et al., 2017: 2 cMpc box, 0.7 pc resolution (in a small part of the volume)

Kimm et al. studied f_{esc} from minihalos.

We found high escape fractions,

but these galaxies basically shut themselves down with radiation,

so they probably don't contribute much to reionisation.



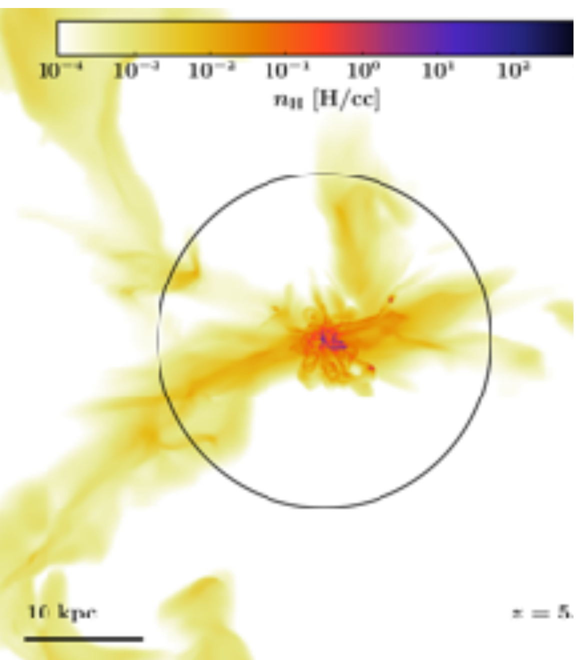
Tiny volume simulations with RAMSES-RT

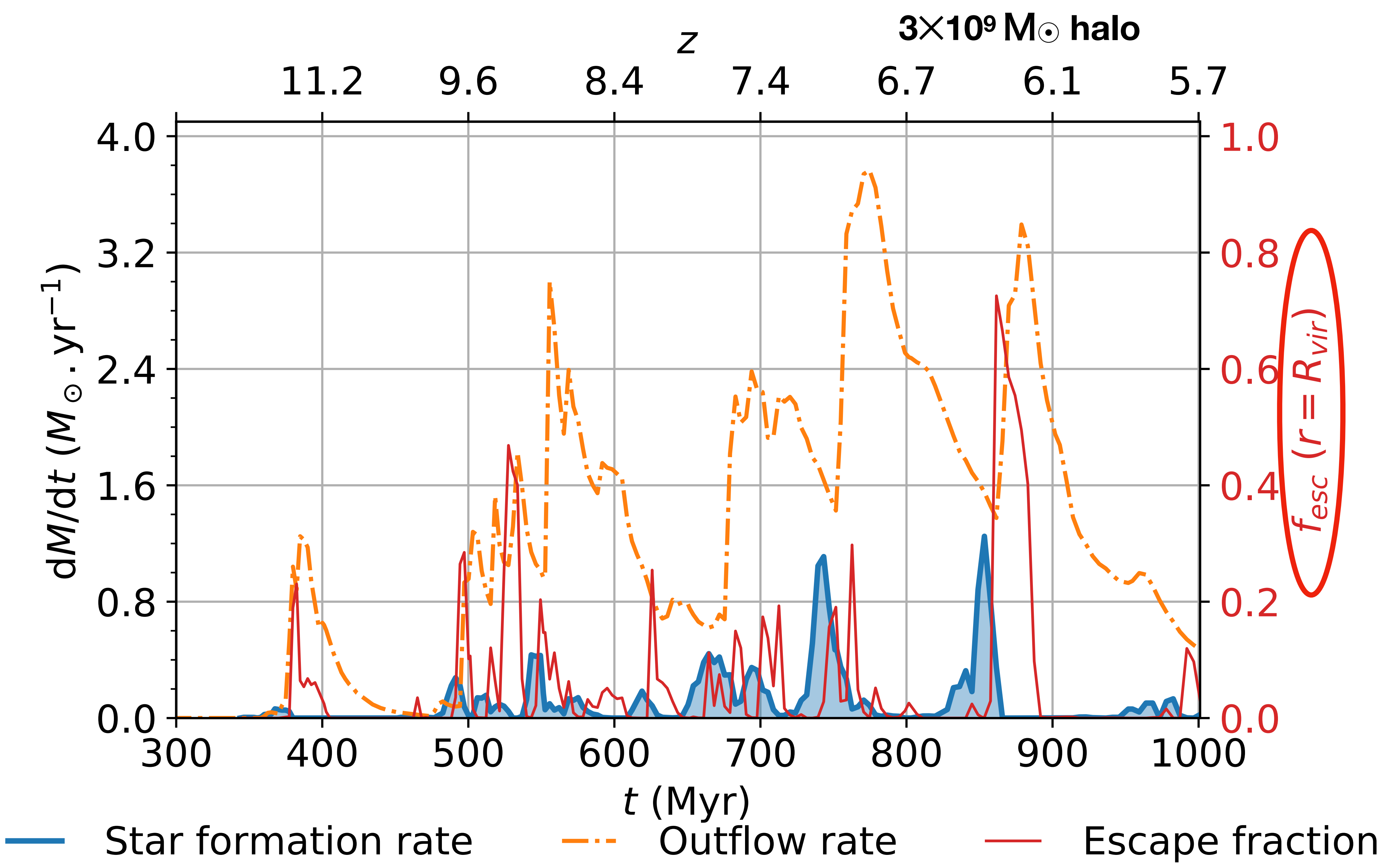
From **Trebitsch et al. (2017):**

Physical resolution of 7 pc in three targeted halos and their environments

Main result:

f_{esc} is far from constant and heavily regulated by supernova (SN) feedback





Two classes of reionisation simulations

Large volume with unresolved galaxies	(Gap) So far impossible Sphinx simulates	Tiny volume with one or a few well resolved galaxies
Representative volume ~~on nearly homogeneous scale and~~ statistical samples of (massive) halos.		Production of ionising radiation and f_{esc} resolved.
~~But galaxies are unresolved.~~ ~~f_{esc} is a free parameter.~~		~~But the large scale reionisation process is not captured (nor the actual contribution from individual sources).~~
~~Low mass halos are not captured.~~		
Good for the large-scale process, ~~clustering~~, patchiness.		**Sphinx is mainly made possible by moment-based RT and the variable speed-of-light**
~~Not so good for understanding the (unresolved) sources of ionisation.~~		

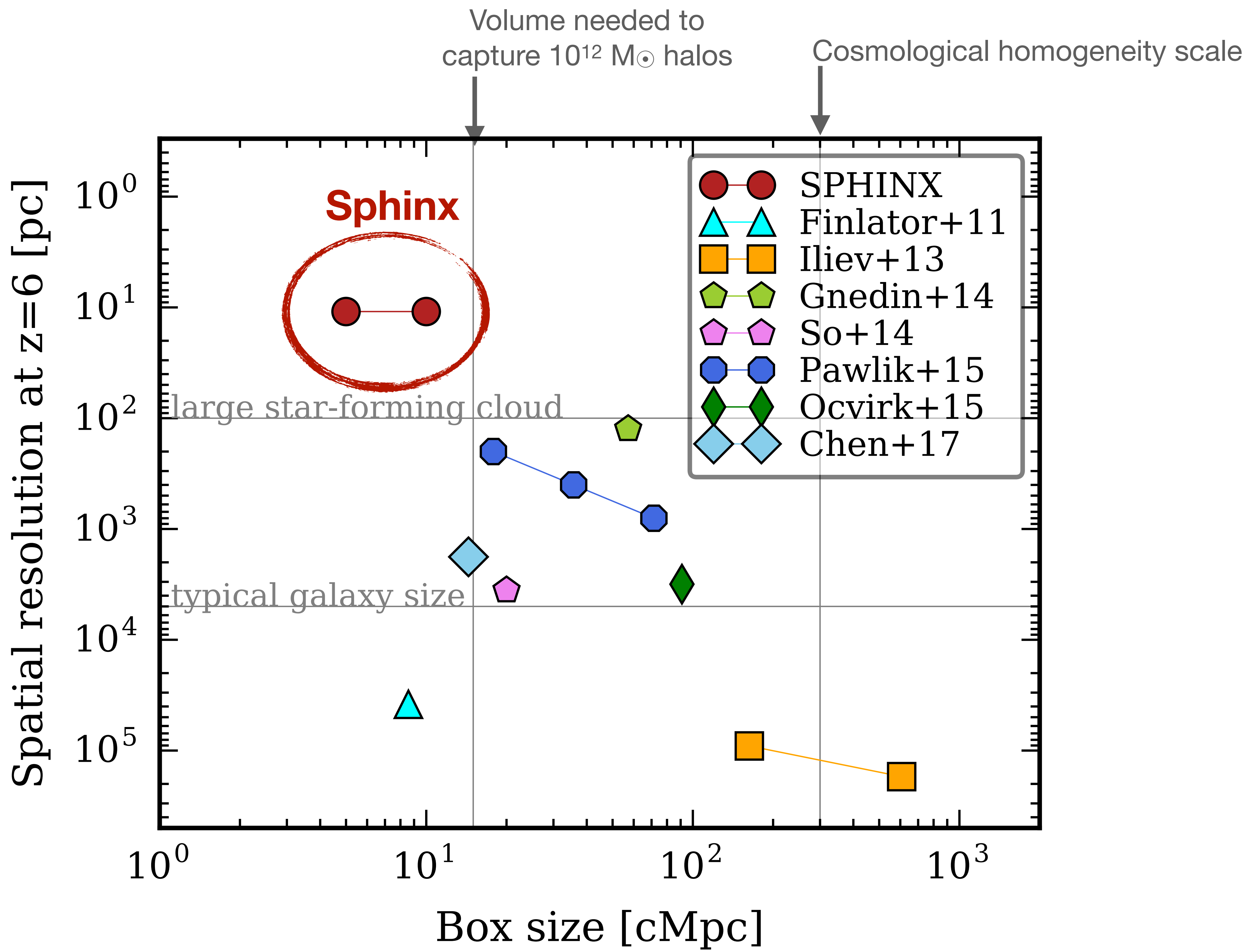
arXiv:1801.07259

The SPHINX Cosmological Simulations of the First Billion Years: the Impact of Binary Stars on Reionization*

Joakim Rosdahl[1]†, Harley Katz[2,3], Jérémy Blaizot[1], Taysun Kimm[4,3], Léo Michel-Dansac[1], Thibault Garel[1], Martin Haehnelt[3], Pierre Ocvirk[5], and Romain Teyssier[6].

[1] *Univ Lyon, Univ Lyon1, Ens de Lyon, CNRS, Centre de Recherche Astrophysique de Lyon UMR5574, F-69230, Saint-Genis-Laval, France*
[2] *Sub-department of Astrophysics, University of Oxford, Keble Road, Oxford OX1 3RH, UK*
[3] *Kavli Institute for Cosmology and Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK*
[4] *Department of Astronomy, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 03722, Republic of Korea*
[5] *Observatoire Astronomique de Strasbourg, Université de Strasbourg, CNRS UMR 7550, 11 rue de l'Université, 67000 Strasbourg, France*
[6] *Institute for Computational Science, University of Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland*

The Sphinx simulations in context



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?**

Binary stars ?

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]

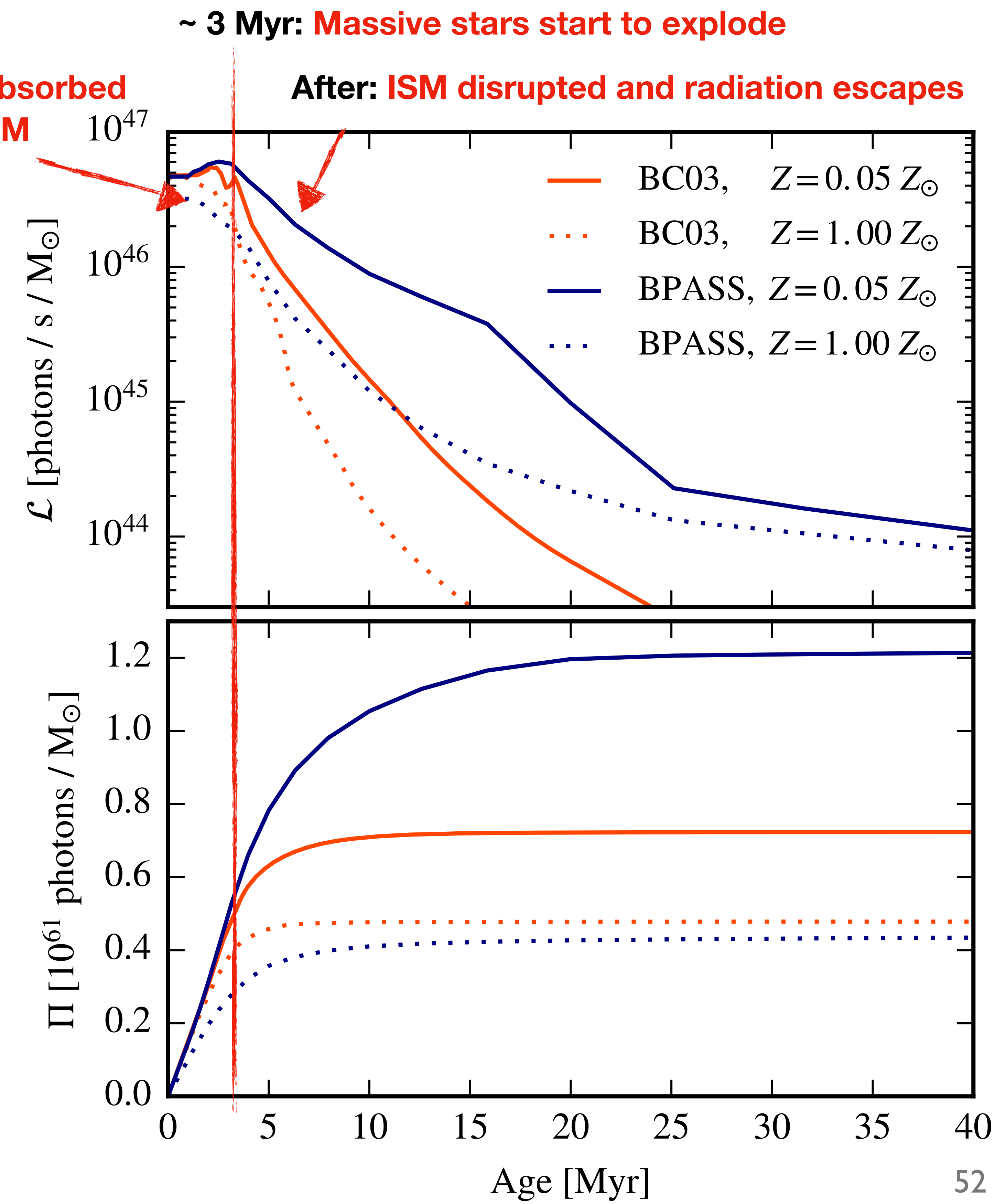
- Post-processing pure-hydro zoom simulations, Ma et al. (2016) predict 4-10 times boosted f_{esc} (escape of ionising radiation) with a binary population SED
- The reason: longer and stronger radiation due to mass transfer and mergers in binary systems

SED models

Spectral Energy Distributions for stellar populations

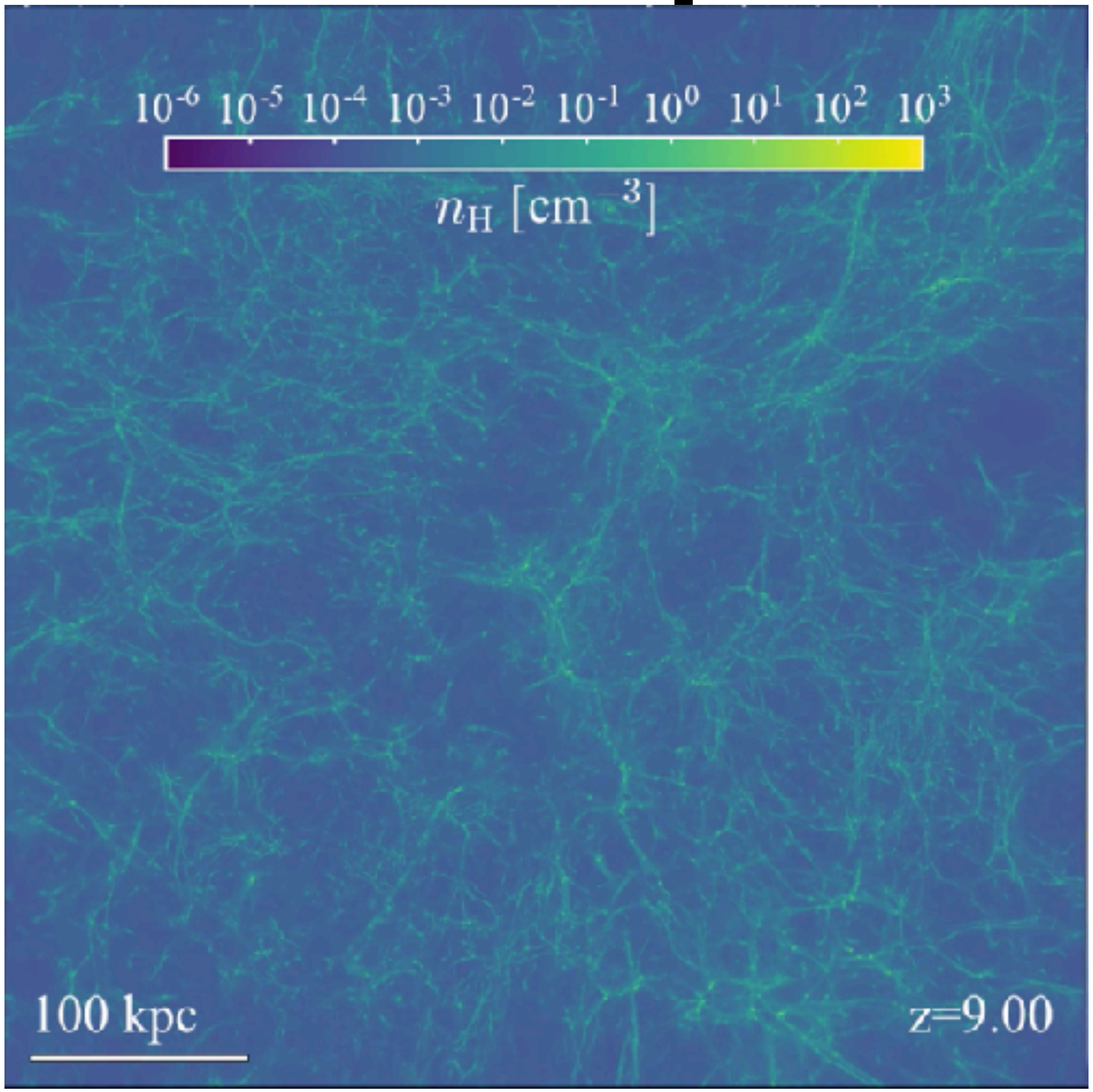
- **BC03 = Single stellar population model from Bruzual & Charlot (2003)**
- **BPASS = Binary Population and Spectral Syntesis from Eldridge et al.**

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

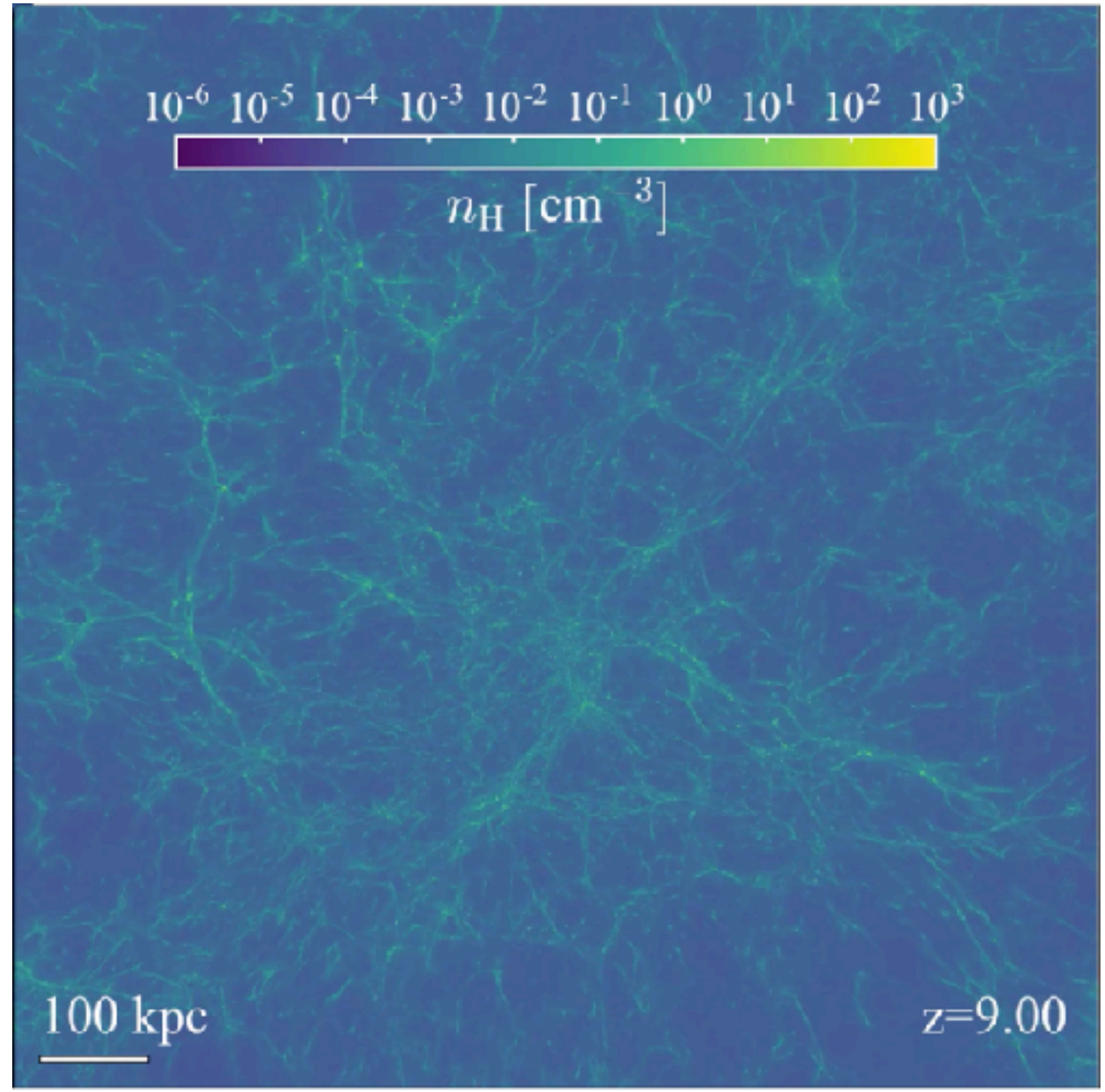


Setup of the Sphinx simulations

Sphinx simulations



5 cMpc box with
high mass resolution



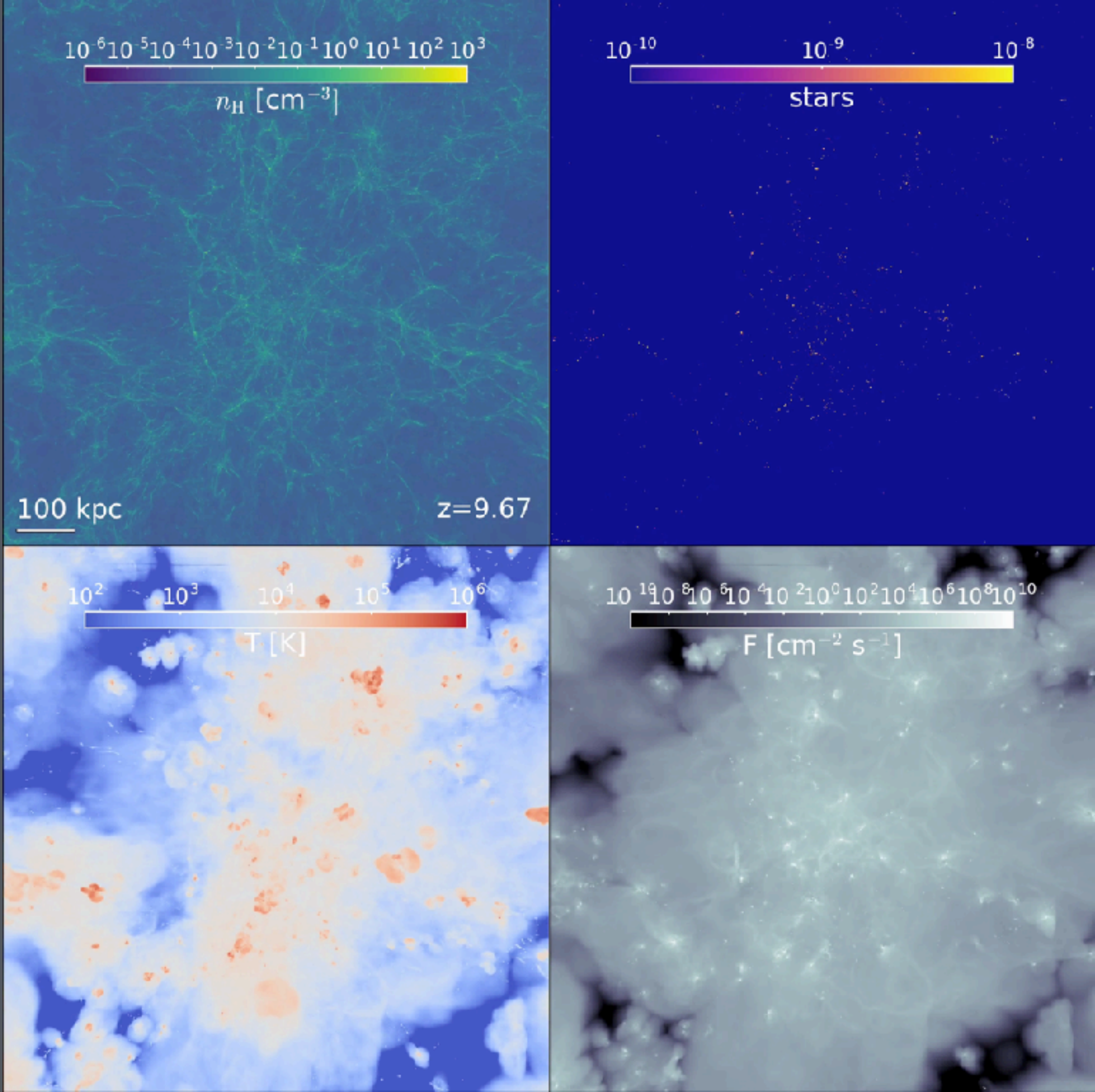
10 cMpc box with
lower <u>mass</u> resolution
(but same physical resolution)

...plus many tiny 1.25-2.5 cMpc boxes
for exploration and calibration

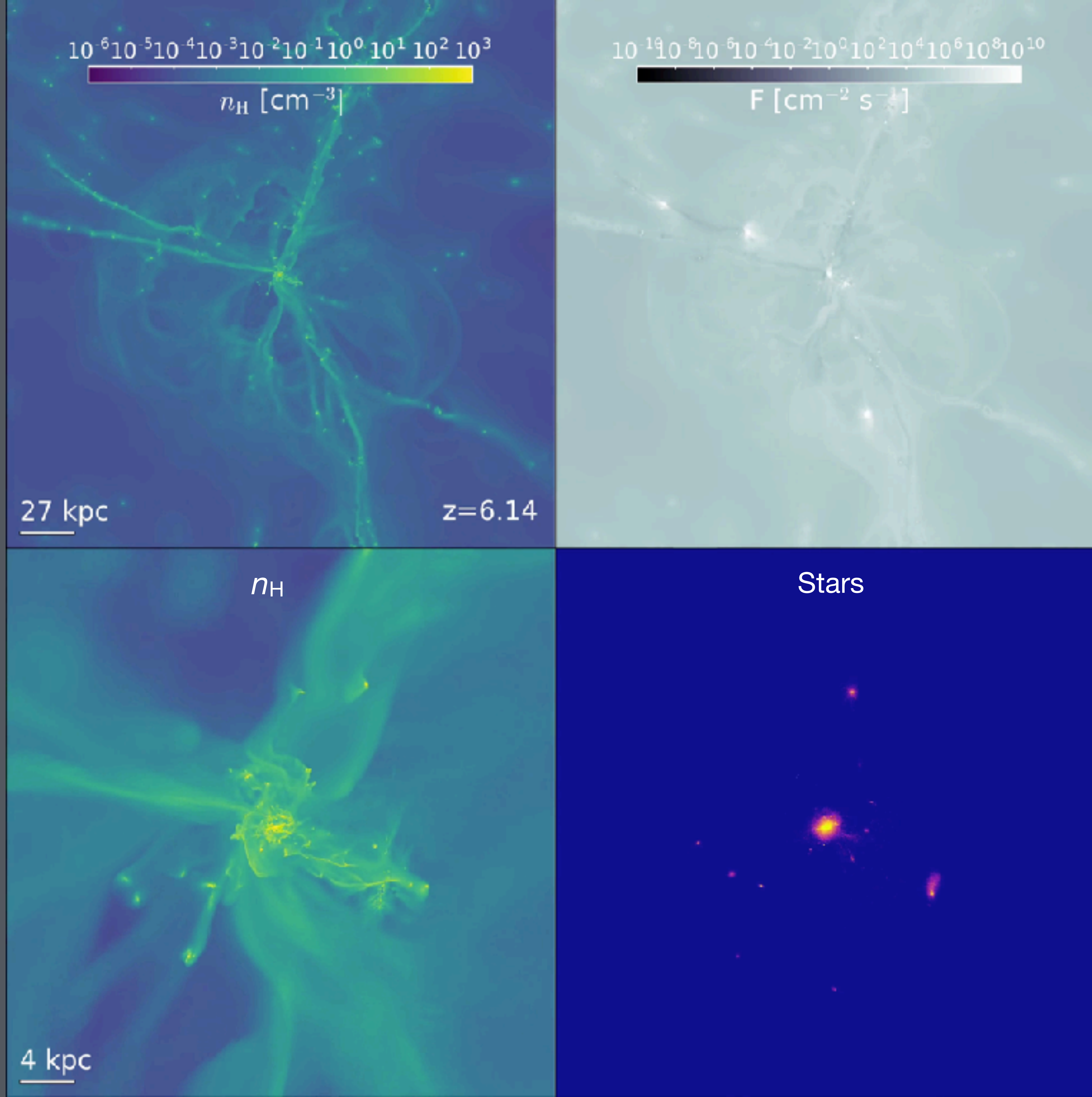
SPHINX setup

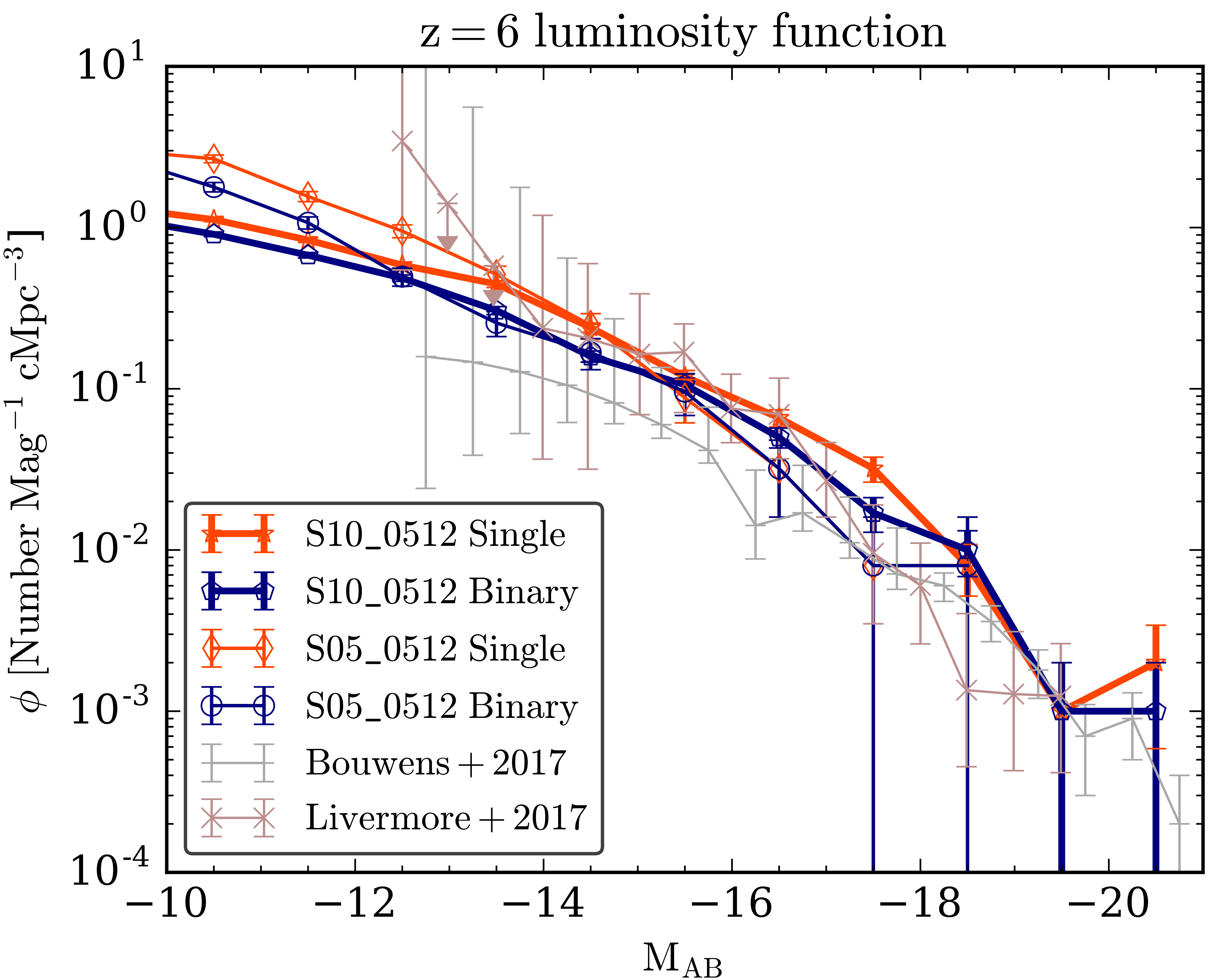
- **Physical resolution** max 10 pc, required to capture the escape of ionising radiation from galaxies (Kimm et al, 2017).
- **DM mass resolution** of 3×10^5 (8 times less in 5 Mpc box).
  10^8 $M_\odot$ halo has 300 (2,500) particles ➢ all potential sources resolved.
- **Stellar particle resolution** 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)
  - We *calibrate* SN rates to reproduce a sensible SF history
    (four times boosted SN rate derived from Kroupa initial mass function)
- **No calibration on unresolved f_{esc}** (i.e. we simply inject the SED luminosity)
- We run with binary and single star SEDs

Full
10 cMpc box, binary SED:



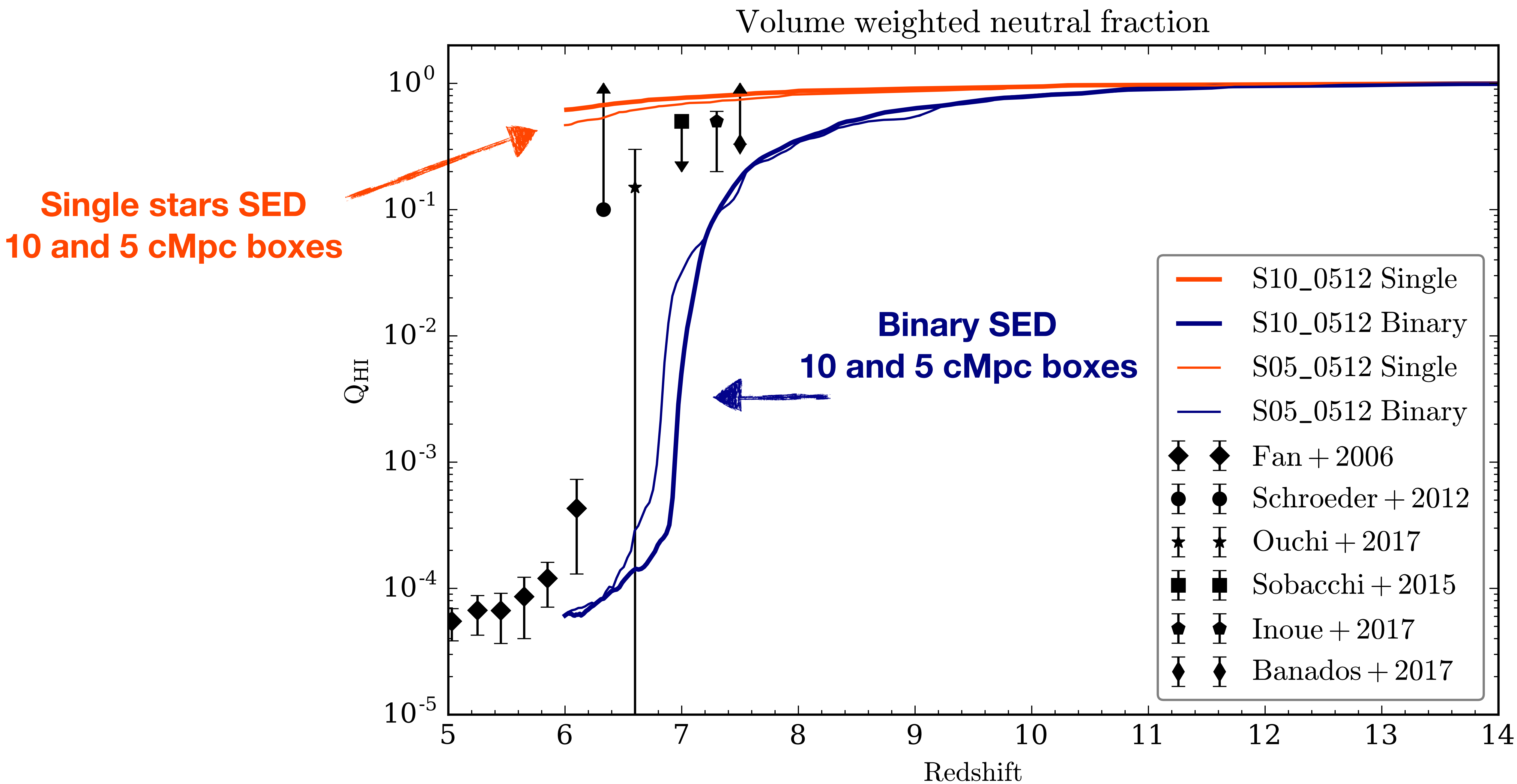
10 cMpc box, binary SED, a closer look




z = 6 luminosity function
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
ϕ [Number Mag^{-1} cMpc^{-3}]
−10
−12
−14
−16
−18
−20
M_{AB}
S10_0512 Single
S10_0512 Binary
S05_0512 Single
S05_0512 Binary
Bouwens + 2017
Livermore + 2017

Reionisation history

binary vs single SEDs

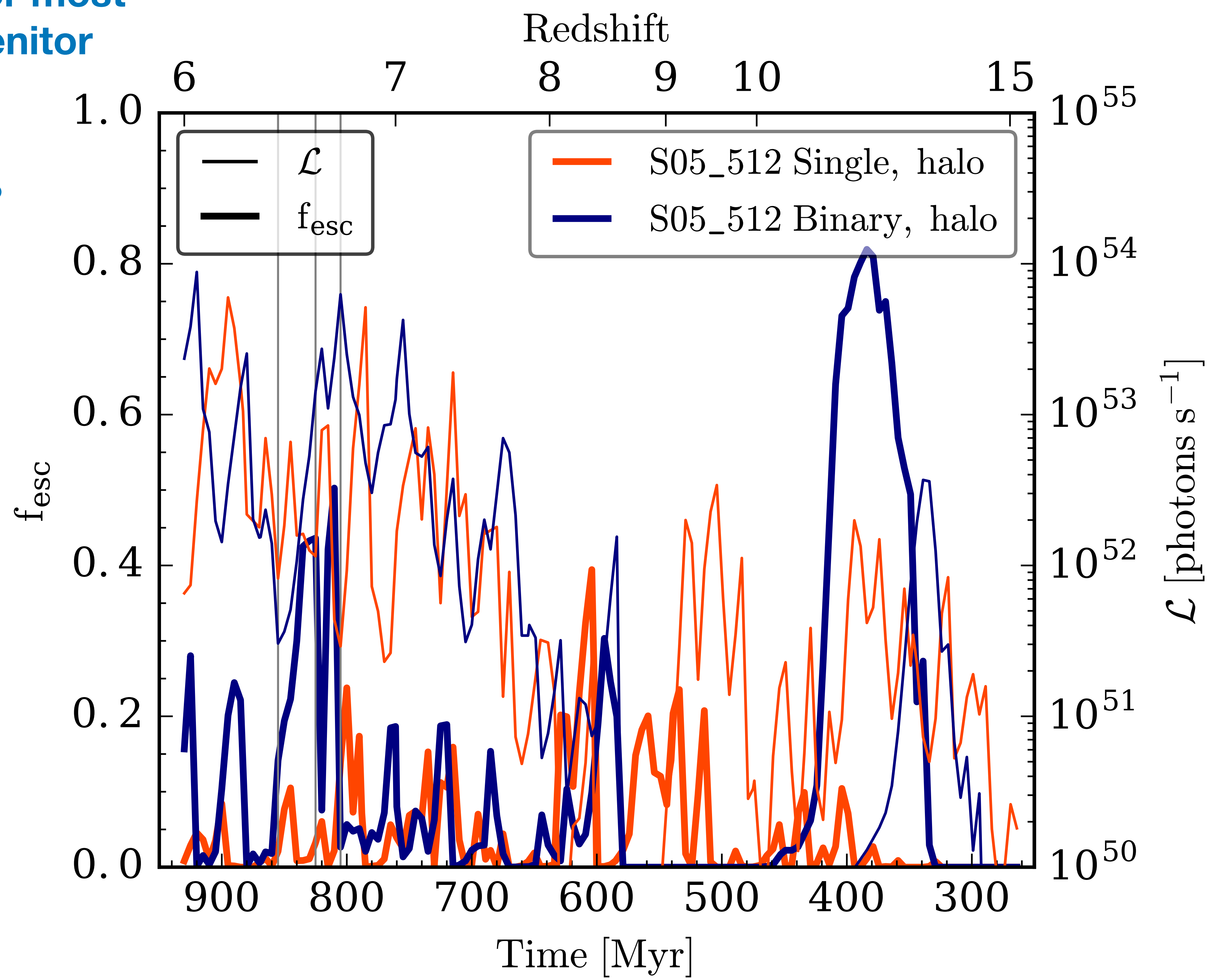


Much more efficient reionsiation with binary populations, independent of volume size and mass resolution

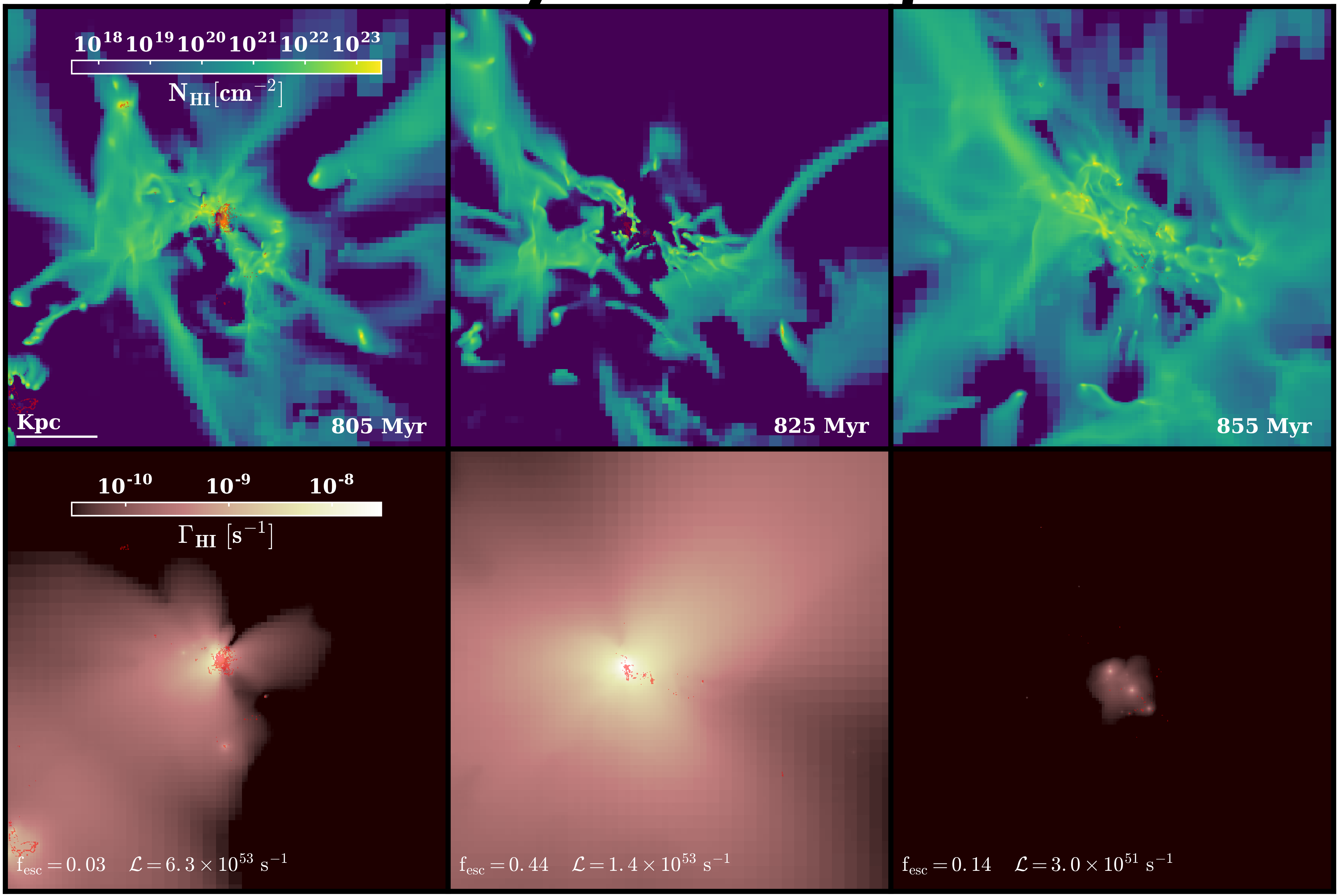
Binary stars and f_{esc}

Escape fractions for most massive halo progenitor in smaller box

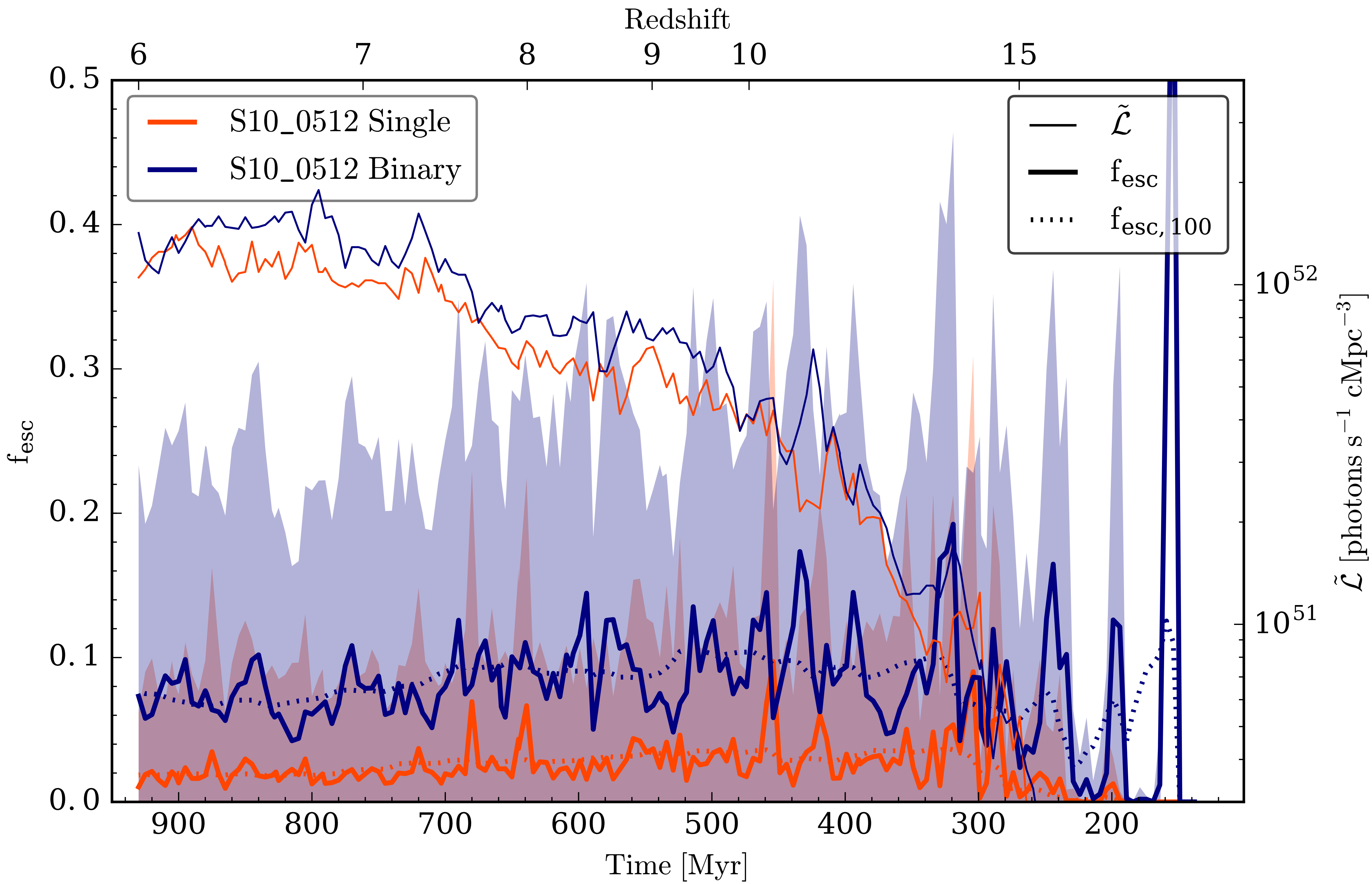
$M_{halo}(z=6) \sim 10^{10}\ M_\odot$
$M_{star}(z=6) \sim 10^{8}\ M_\odot$



Binary stars and f_{esc}



f_{esc} for the full volume



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

Summary

- **Cosmological simulations of reionisation are necessary for understanding observations and the high-z universe**

- **But they are expensive to run due to the radiative transfer (many dimensions, speed of light)**

- **RAMSES-RT is one of two public radiation-hydrodynamical codes with which you can run your own reionisation simulations**

- **The Sphinx simulations (run with RAMSES-RT) are the first full cosmological RHD simulations of reionisation that resolve f_{esc} from galaxies**

- **Pilot Sphinx paper is just out:**
  - **Stellar populations with binary systems really affect reionsiation, due to the interplay of feedback and f_{esc}!**
  - **Much more to come**