Radiation-hydrodynamics from Mpc to sub-pc scales with RAMSES-RT

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Davos, Feb 15th, 2017

What is RAMSES-RT?

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Multi-purpose radiation-hydrodynamics

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

- Part of the cosmological code RAMSES (Teyssier '01)
- Publicly available (www.bitbucket.org/rteyssie/ramses)

- Emission of photons from e.g. stars, AGN, gas
- Transport of photons through the 3D volume, on-the-fly with hydro, and in adaptive mesh refinement
- Hydro-coupled absorption and scattering by gas and dust
  - Photoionisation and heating of H and He
  - Radiation pressure, i.e. momentum transfer from photons to gas
  - Multi-scattering on dust

What is it for?

What is it for?

- Observable properties of gas in and around galaxies
  - E.g. diffuse Lyman-alpha emissivity (Rosdahl et al. ’12)
- Stellar/AGN radiation feedback (Rosdahl et al. ’15, Geen et al. ’15, Bieri et al. 2016, Gavagnin et al. 2016, Costa et al. in prep.)
- Ionising radiation escape from galaxies (Kimm & Cen ’14, Kimm et al. 2016)
- Large-scale reionisation (recently feasible with variable light speed)
- Protostar formation
- Molecule formation

…but not for…

- ‘Line’ (e.g. Lyman-alpha) radiative transfer
- Situations where strong shadows are imperative

Main features

Main challenges

M1 moment method

~~Reduced~~ Variable speed of light

Non-equilibrium thermochemistry

Radiation pressure and
multi-scattering

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

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

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

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

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The M1 moment method

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

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

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

- ➡ Take moments to get rid of angle dependency...
- ➡ ...and average over frequency
- ➡ giving the four-dimensional '*fluid*' equations:

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

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

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

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

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

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

The system is closed with an expression for $\mathbb{P}$ called the M1 closure (Levermore '84), which is *local* and retains a bulk directionality of the radiative field.

The M1 moment method

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

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

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

New cell variables in each cell

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

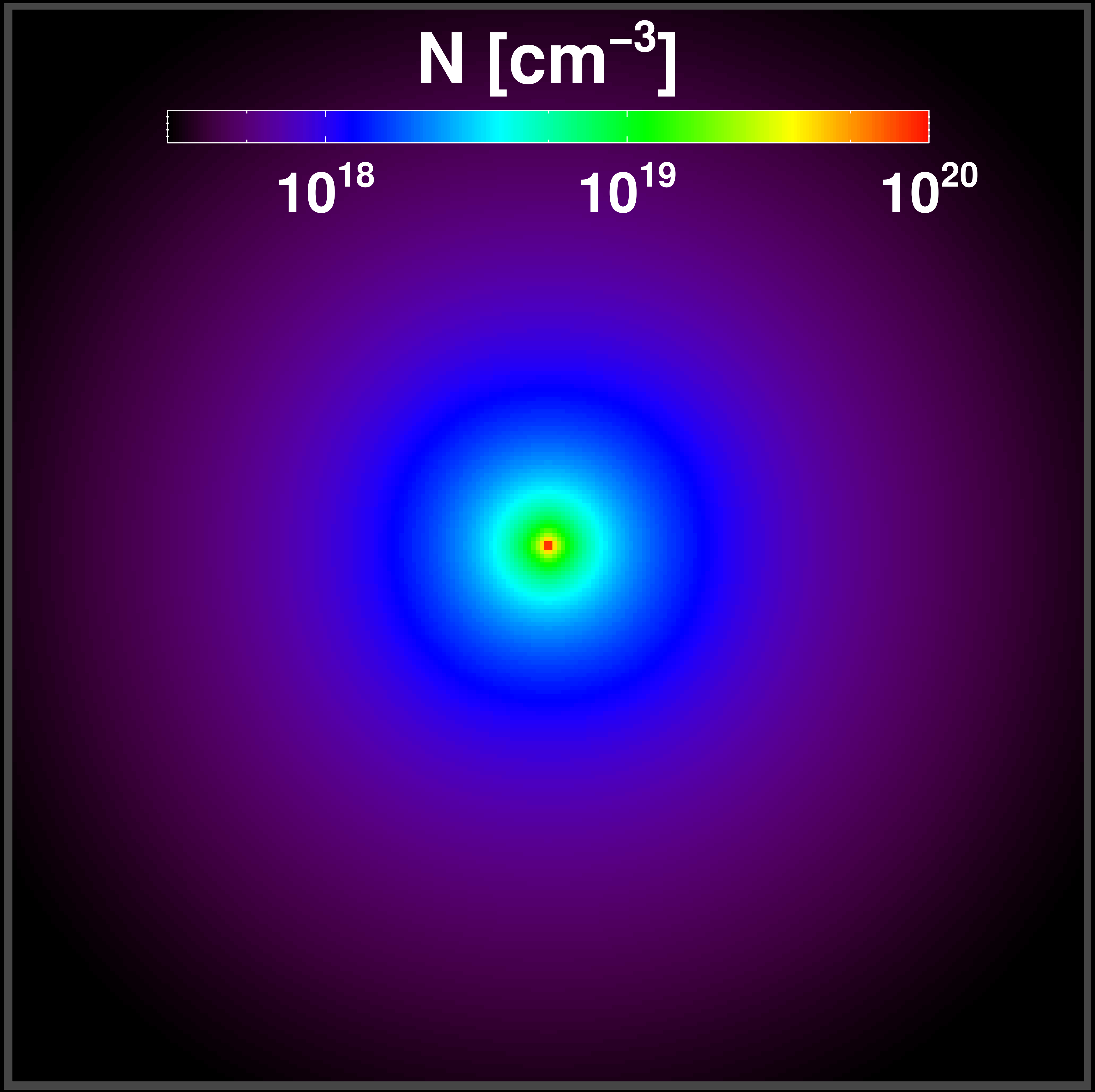
$\mathbf{F}(\mathbf{x}, t)$ photon flux

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

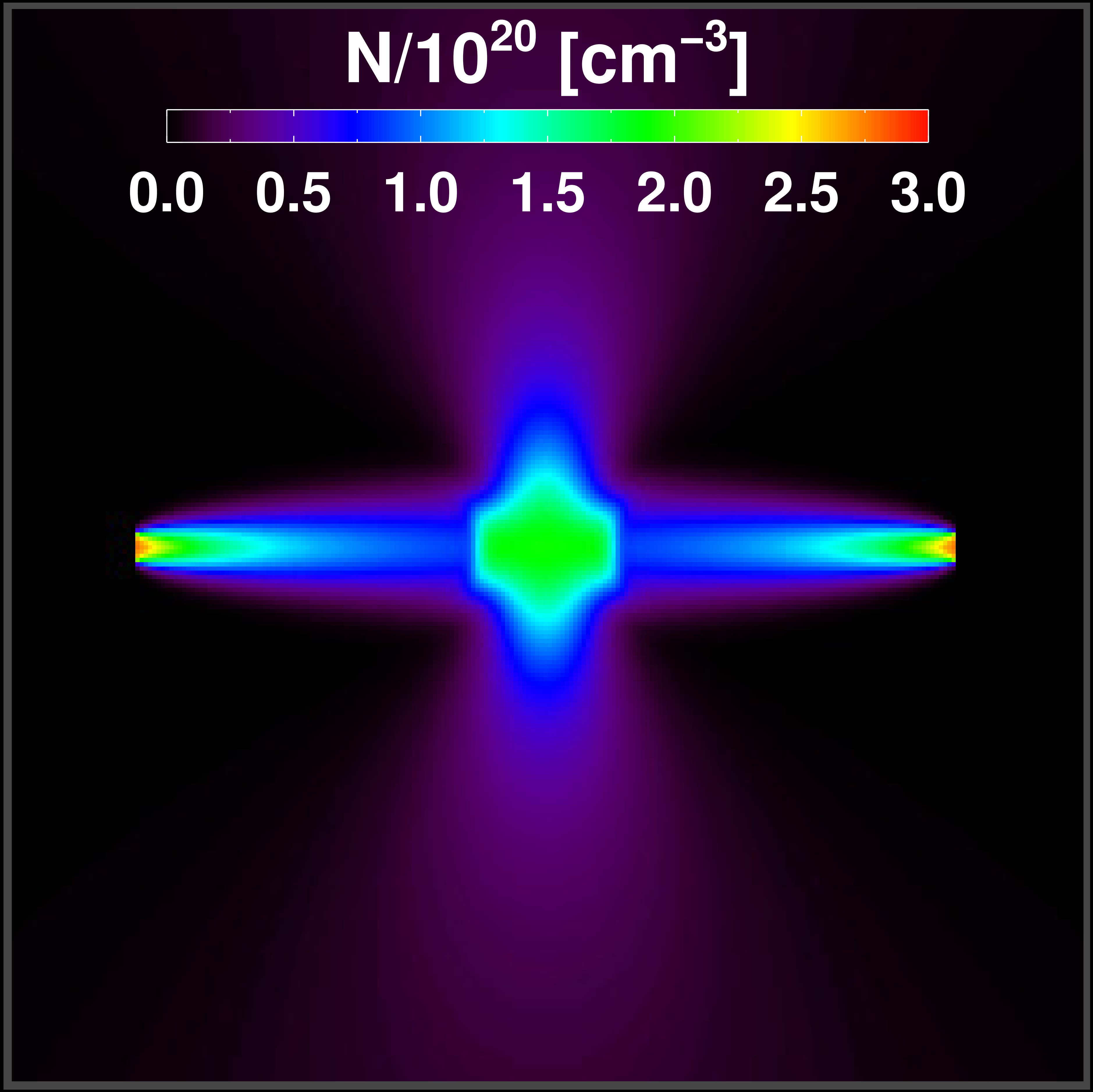
The moment equations are discretised on the AMR grid of RAMSES and integrated after each hydro step, *once for each radiation group* (e.g. IR, optical, UV).

The RT can be subcycled, with many RT steps per hydro-level-step, but the sacrifice is not quite perfect photon conservation

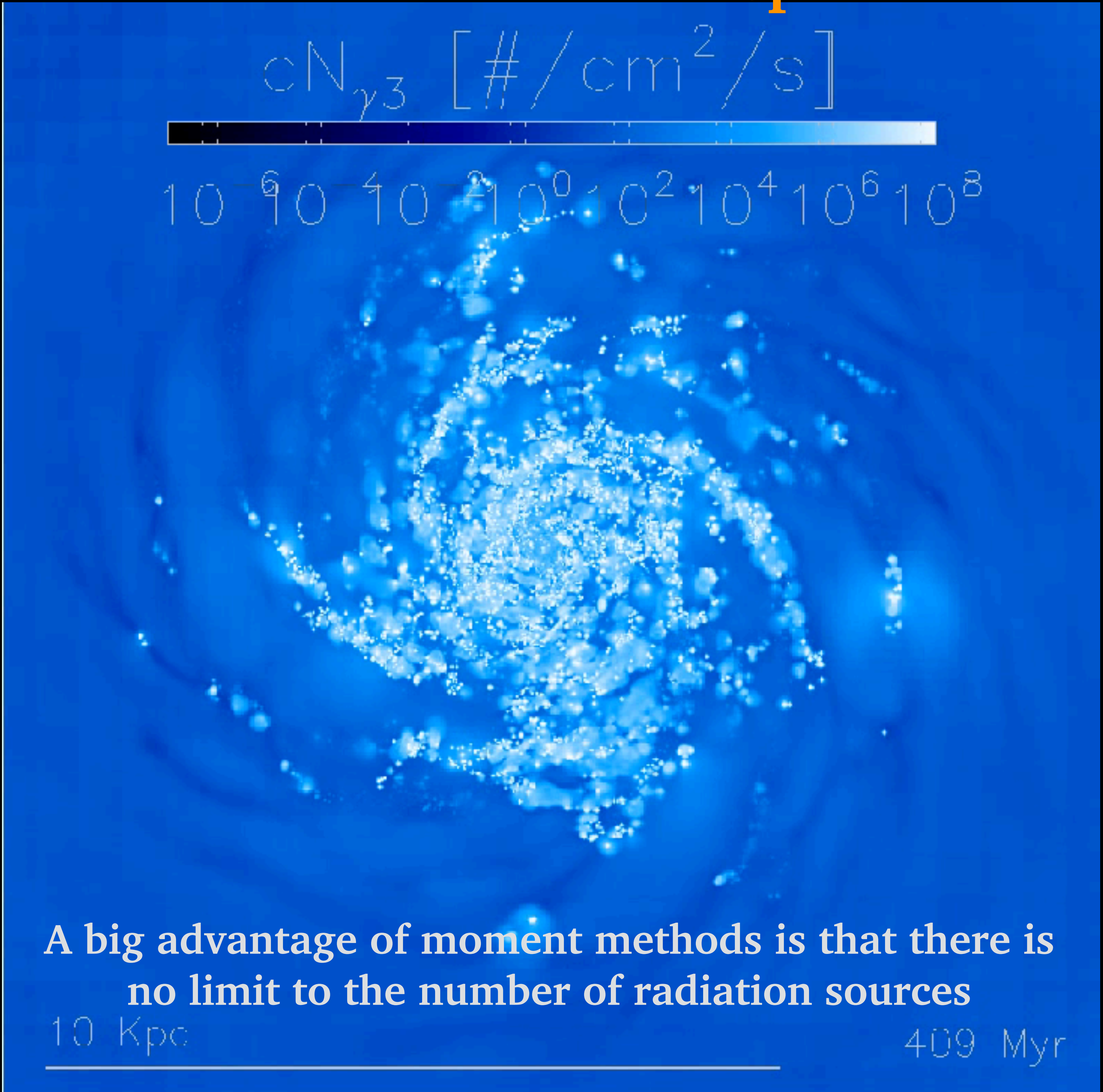
M1 radiation transport



M1 radiation transport



M1 radiation transport



Main features

M1 moment method

~~Reduced~~ Variable speed of light

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Radiation pressure and
multi-scattering

The speed of light problem

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

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

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

The radiation is advected between neighbouring cells in RT steps, using an *explicit* Godunov solver

The step length is $\Delta t_{\mathrm{RT}} \sim \frac{\Delta x}{c} \sim \frac{\Delta t_{\mathrm{HD}}}{1000}$

…implying a ~thousand-fold increase in runtime

The reduced speed of light approximation (RSLA)

Gnedin & Abel 2001

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The step length is $\Delta t_{\mathrm{RT}} \sim \frac{\Delta x}{c} \sim \frac{\Delta t_{\mathrm{HD}}}{1000}$

…implying a thousand-fold increase in runtime

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

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

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

Not as bad as it sounds:

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

We just want to get the front correct...

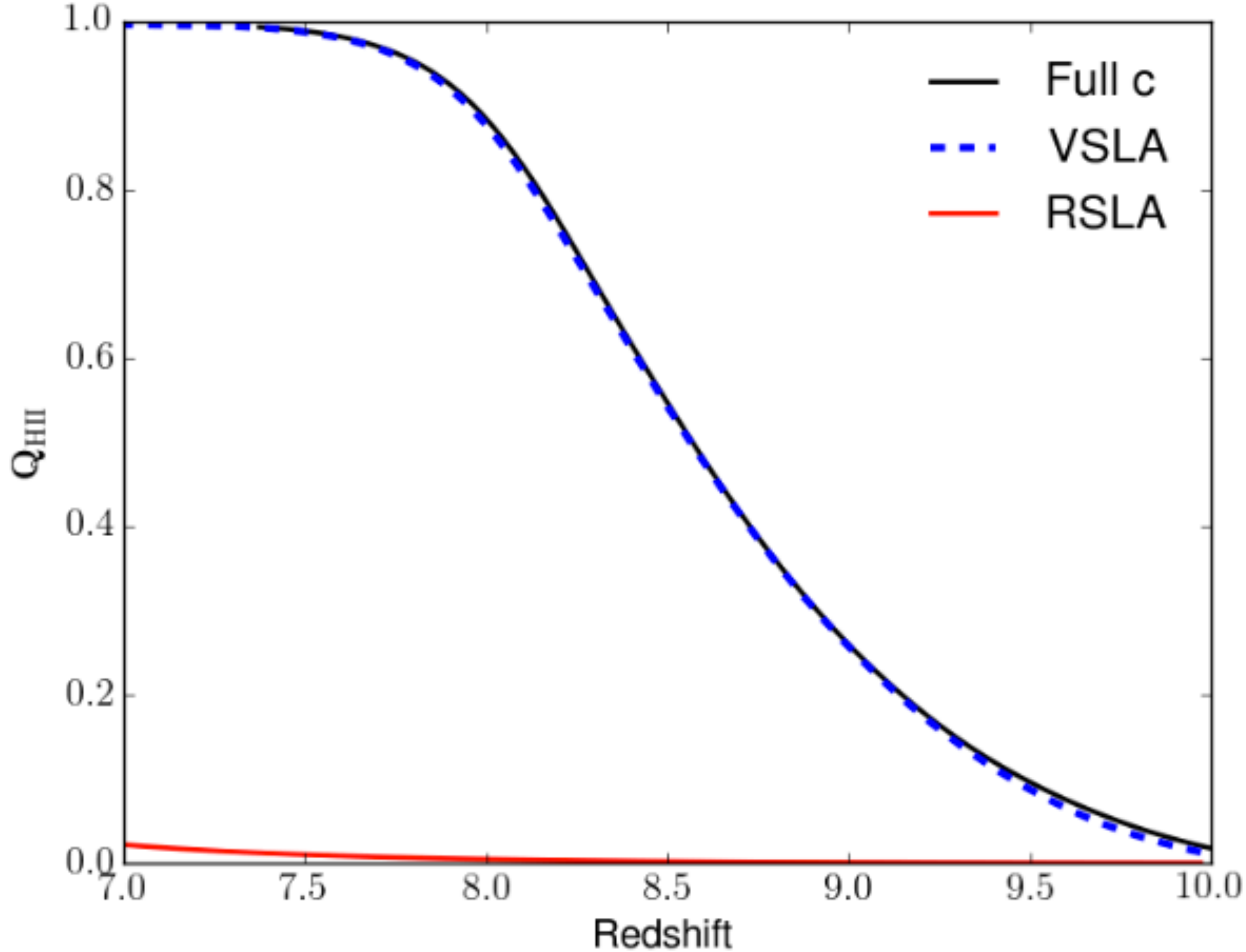
The variable speed of light approximation (VSLA)
Katz et al. 2017

- A ~full light speed matters most in diffuse ‘voids’ where I-fronts are *fast*.

- Taking advantage of this, Harley Katz implemented in Ramses-RT a variable light-speed, making reionisation simulations feasible with RAMSES-RT

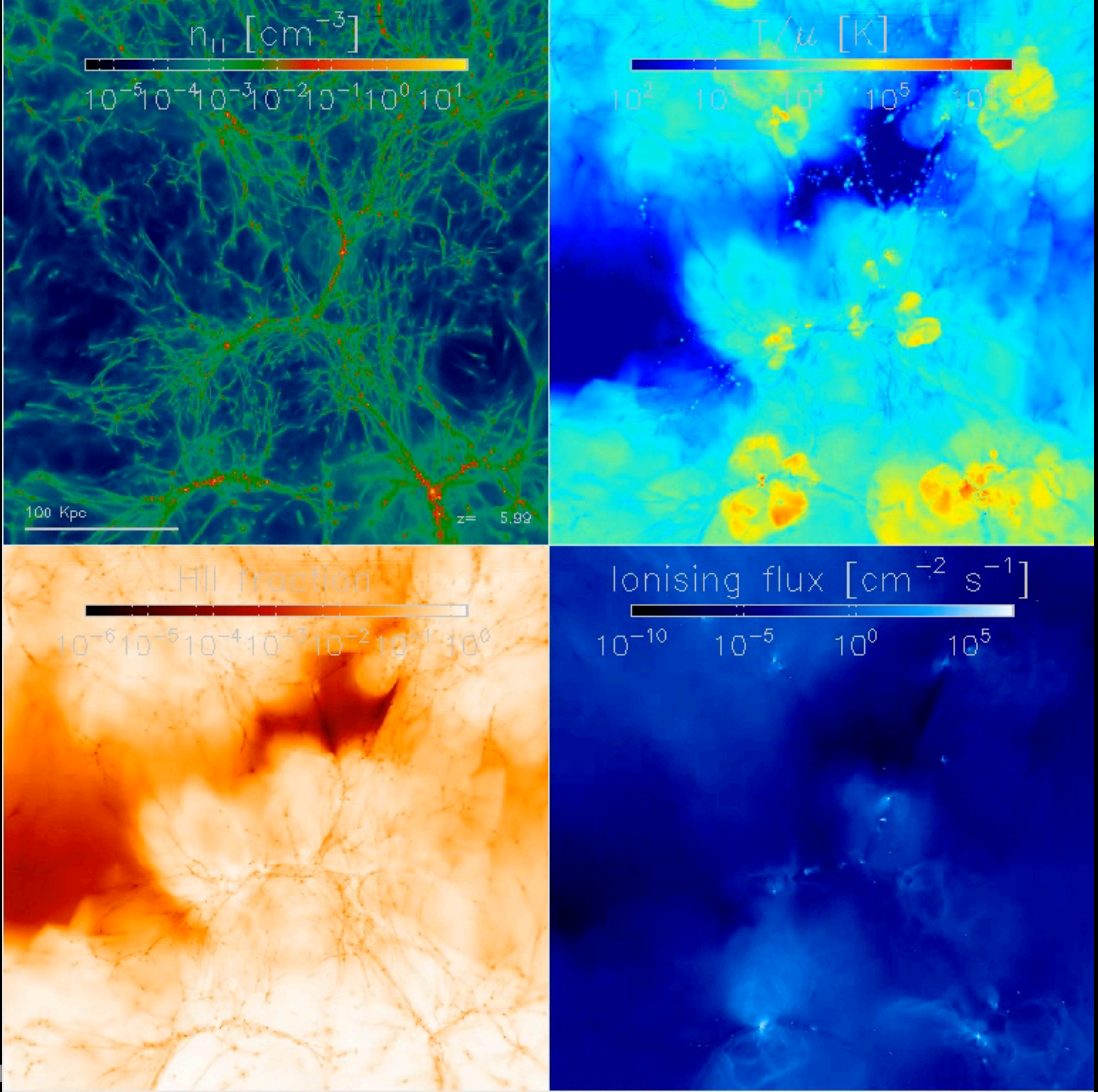
- Here, we use a slow light speed at the finest level and increase with each coarser level, towards a full light speed in the coarsest ‘voids’ (where there are ideally few cells).

The variable speed of light approximation (VSLA)



From Katz et al. 2017

Figure A6. Volume filling factor of HII as a function of redshift in a 230^3Mpc box using "Full c", VSLA, and RSLA. As this simulation is extremely low resolution, only massive galaxies form and very massive galaxies form with extremely massive and luminous star particles. This extreme choice is meant to mimic a quasar-dominated reionisation scenario and in this case VSLA works extremely well.



n_{II} [cm^{-3}]
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}
100 Kpc
z= 5.99
T/μ [K]
10^{2} 10^{3} 10^{4} 10^{5} 10^{6}
HII fraction
10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
Ionising flux [cm^{-2} s^{-1}]
10^{-10} 10^{-5} 10^{0} 10^{5}

Main features

M1 moment method

~~Reduced~~ Variable speed of light

Non-equilibrium thermochemistry

Radiation pressure and
multi-scattering

Non-equilibrium thermochemistry

- Thermochemistry is operator split from the advection of photons
- Hydro codes usually assume photoionisation equilibrium, where the gas ionisation state is a tabulated function of temperature
- Not a good idea if we want to conserve photons, and much harder to tabulate
- Therefore we store and evolve H and He ionisation fractions in each cell: $x_{\rm HII}, \quad x_{\rm HeII}, \quad x_{\rm HeIII}$
- Molecular hydrogen is coming soon (Sarah Nickerson & Romain)

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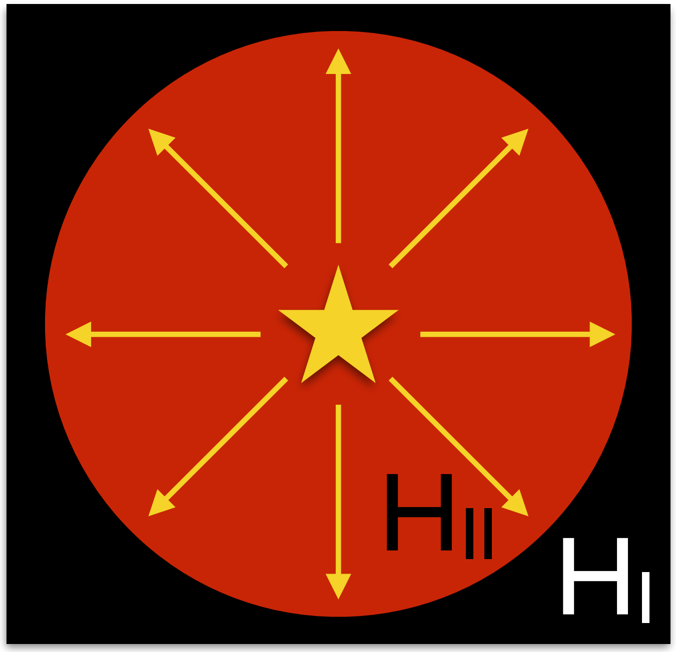
Radiation pressure

- May play a role in suppressing star formation and even generating outflows

- Cosmo simulations often include radiation pressure as a sub-grid recipe:



Stellar (UV) luminosity

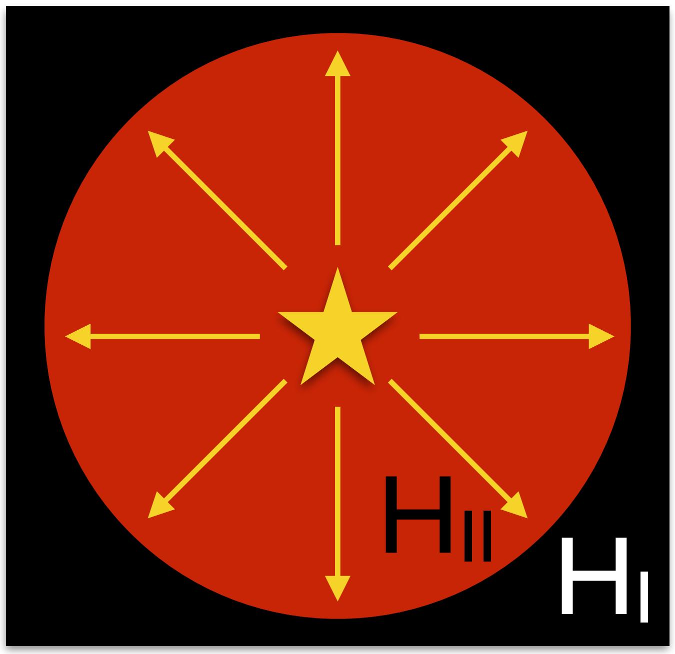
UV optical depth

$$\dot{p}_{\rm rad} = \frac{L_{\rm UV}}{c}\left(1 - e^{-\tau_{\rm UV}}\right) \approx \frac{L_{\rm UV}}{c}$$

Momentum absorption

Radiation pressure

- **We account for the absorbed momentum in every cell in each step:**



$$\dot{p}_{\rm rad} = \frac{L_{\rm UV}}{c}\left(1 - e^{-\tau_{\rm UV}}\right) \approx \frac{L_{\rm UV}}{c}$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} = \sum_{i}^{\rm groups} \frac{\boldsymbol{F}_i}{c} \left(\sum_{j}^{\rm H\,I, He\,I, He\,II} \sigma_{ij} n_j \right)$$

- **We can now start to assess these sub-grid recipes of radiation pressure feedback**

Multi-scattering

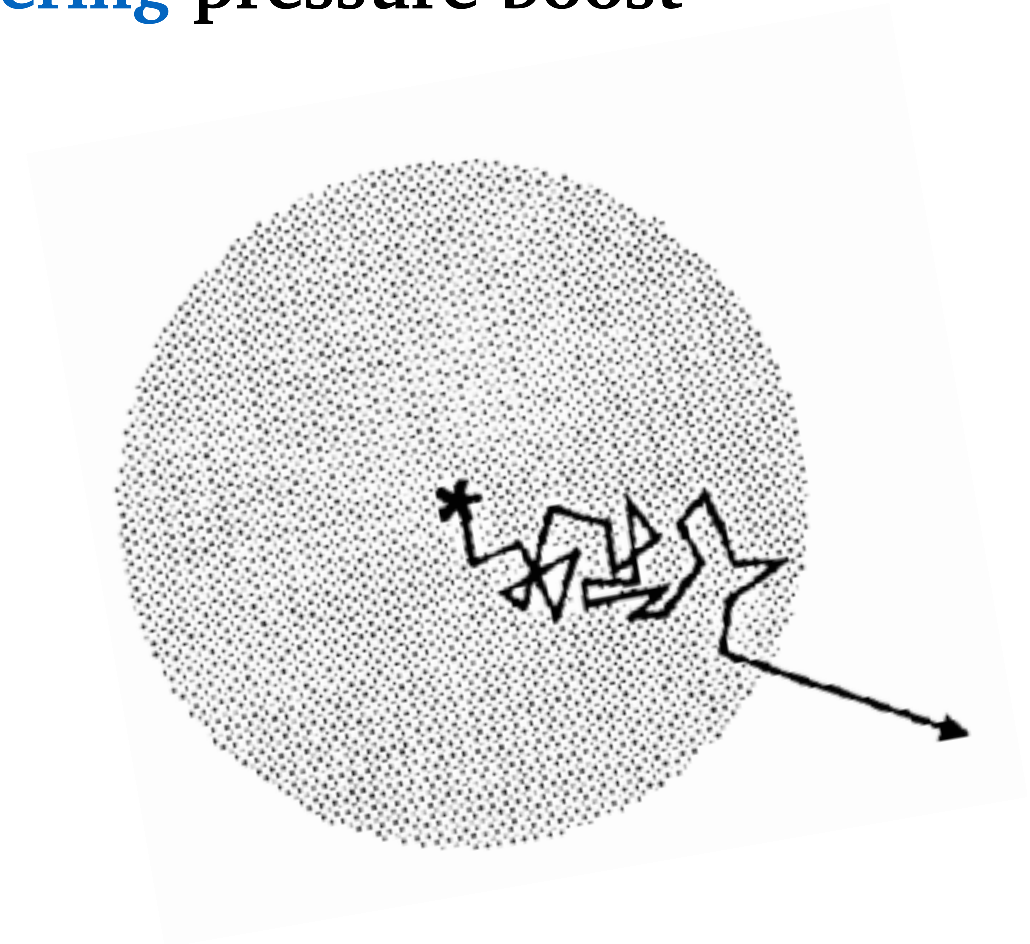
- Recently, we added dust absorption and scattering

$$\frac{\partial E_{\rm IR}}{\partial t} + \nabla \cdot \mathbf{F}_{\rm IR} = \kappa_{\rm P}\rho\left(caT^4 - \tilde{c}E_{\rm IR}\right) + \dot{E}_{\rm IR}$$

$$\frac{\partial \mathbf{F}_{\rm IR}}{\partial t} + \tilde{c}^2 \nabla \cdot \mathbb{P}_{\rm IR} = -\kappa_{\rm R}\rho\tilde{c}\mathbf{F}_{\rm IR}$$

- IR radiation pressure on dust may be important in galaxy evolution because of multi-scattering pressure boost

$$\dot{p}_{\rm rad} = \frac{L_{\rm Opt}}{c}\tau_{\rm IR}$$

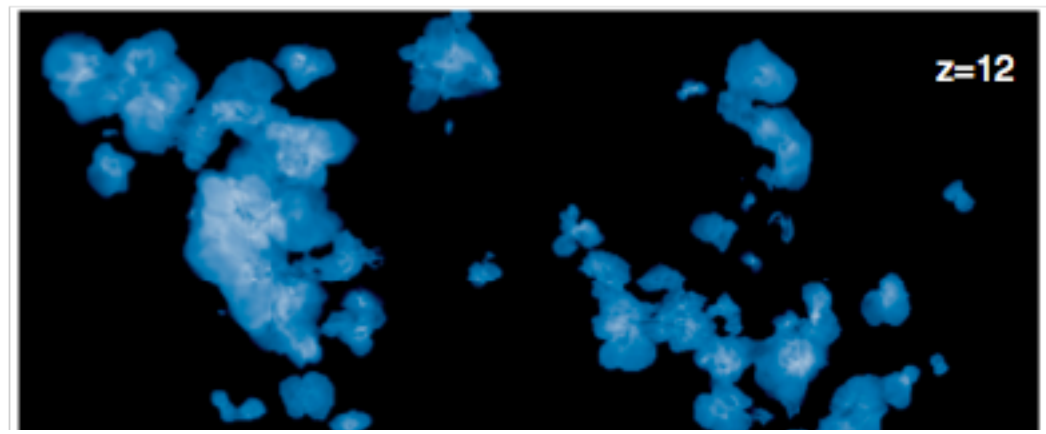


- For implementation details, see Rosdahl & Teyssier 2015

RHD science

Escape of ionising radiation from early galaxies

Kimm & Cen 2014, Kimm et al. 2016



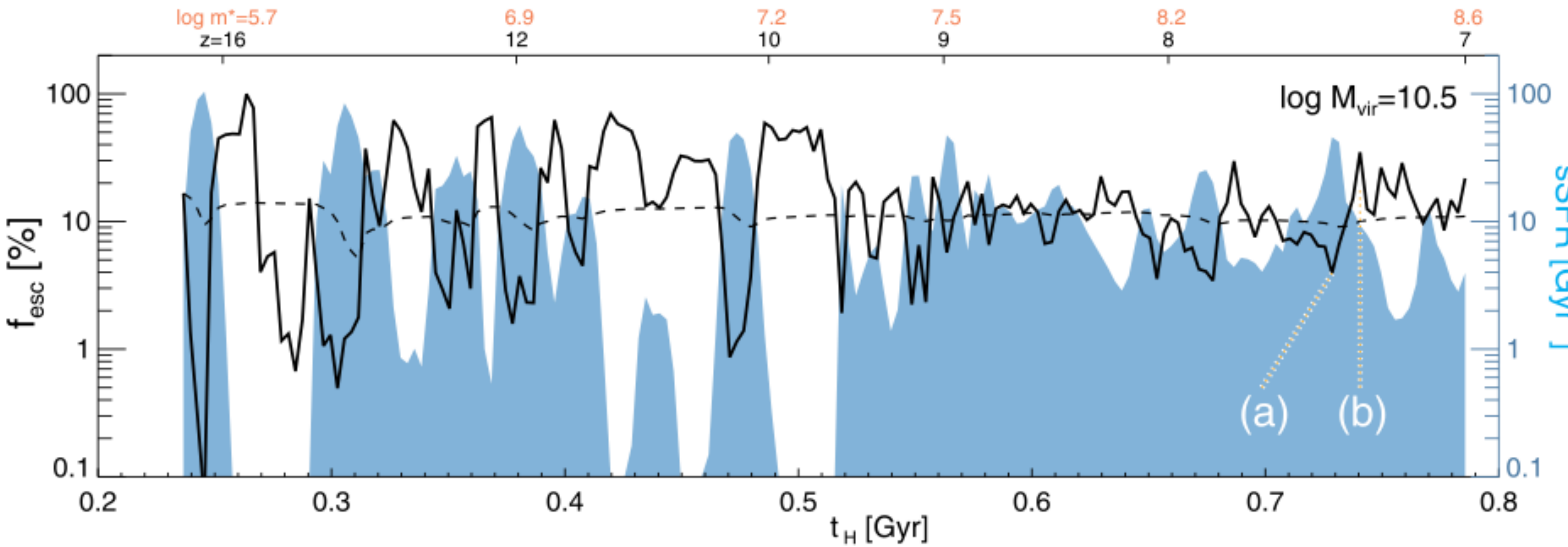


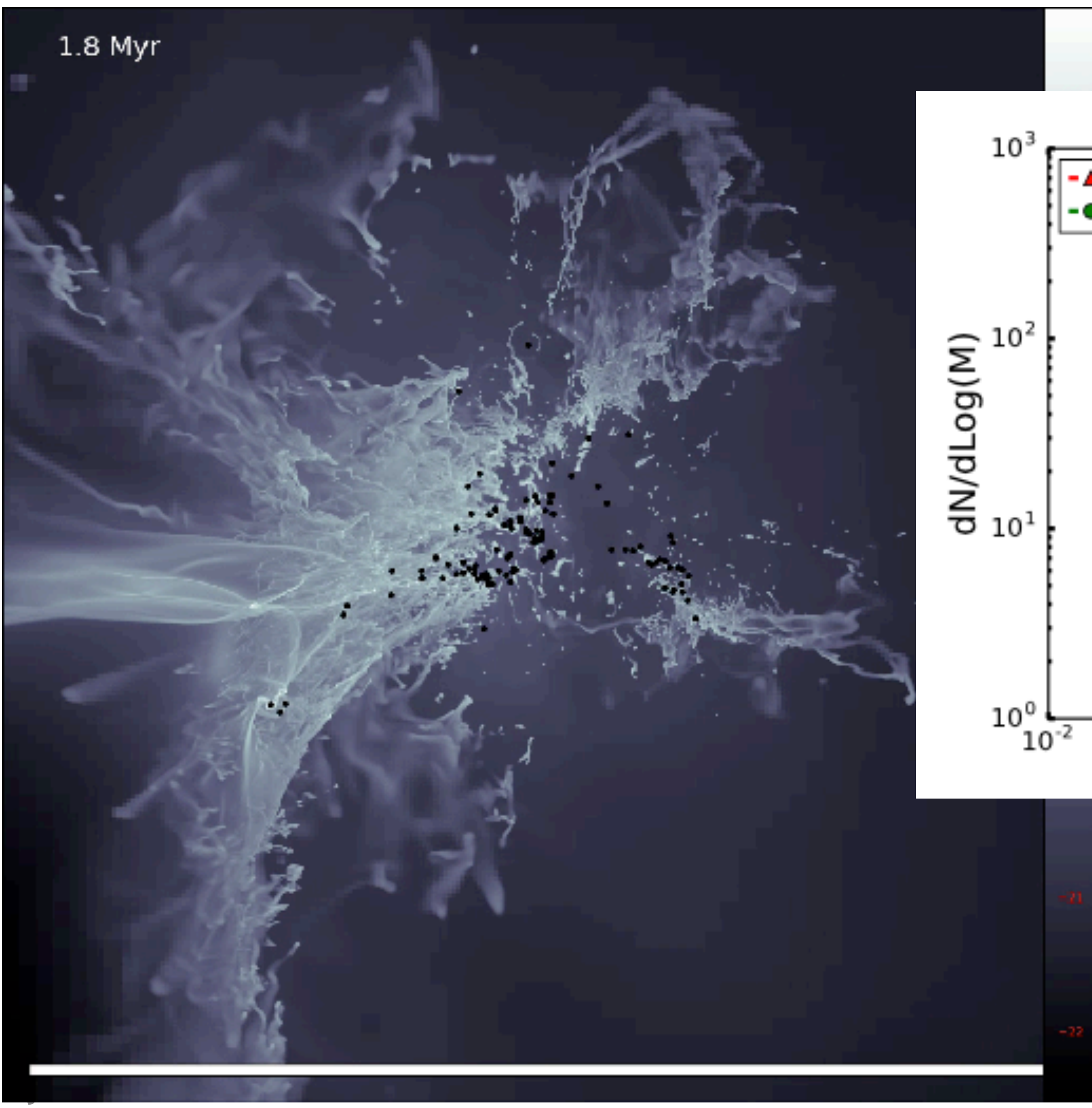
Figure 2. Expansion of the H II bubble in a cosmological simulation (FR). The three panels show the evolution of the density-weighted fraction of ionized hydrogen of the zoomed-in region. The horizontal size of the figure is 9.5 Mpc (comoving).

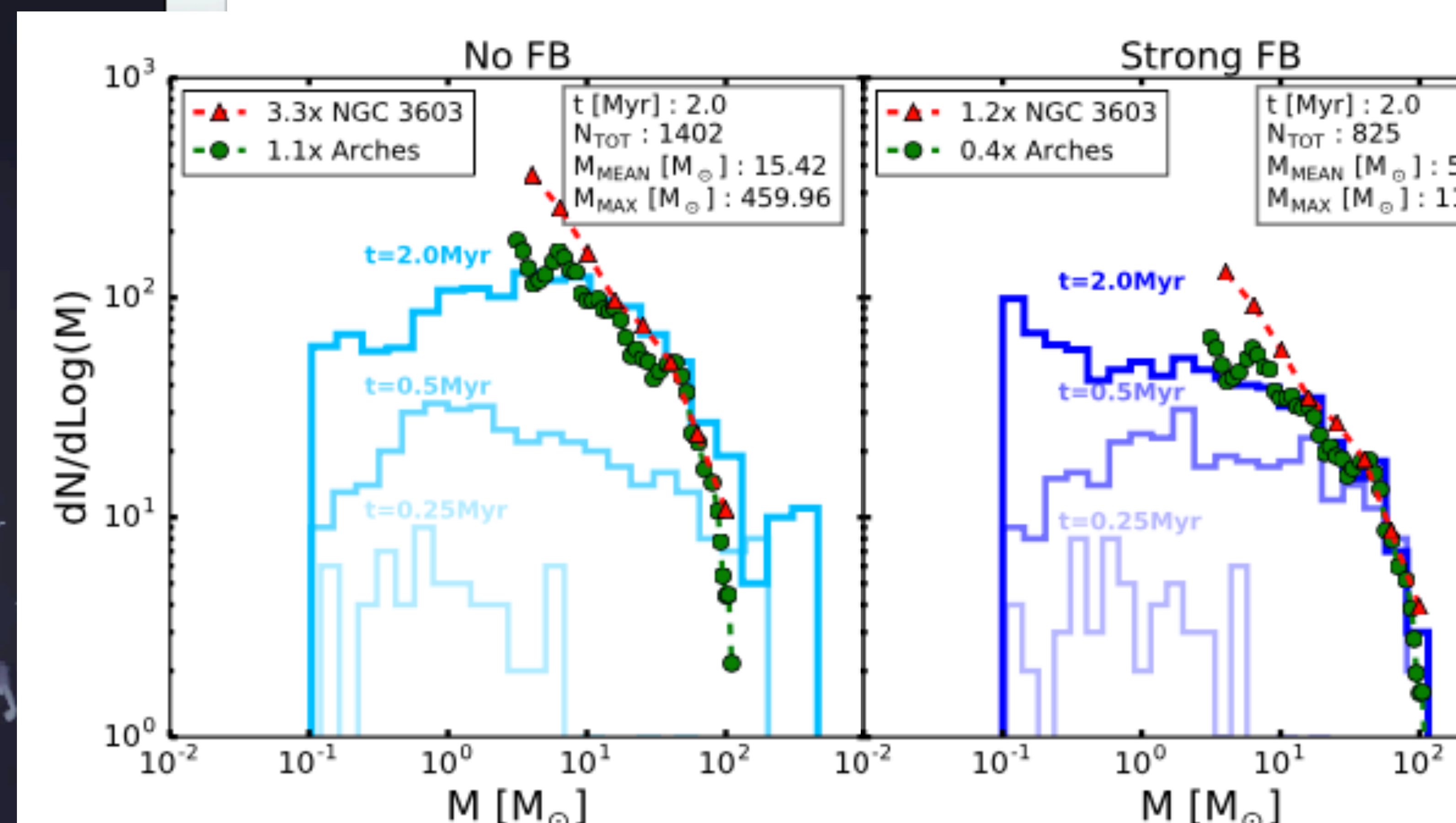
Photoionisation feedback in molecular clouds

Geen et al. (2013, 2015, 2016)

Gavagnin et al. (2017)

Studies of the photo-evaporation of star-forming clouds with sub-pc resolution: SN momentum boost, SF regulation and effects on the new-born stellar cluster dynamics





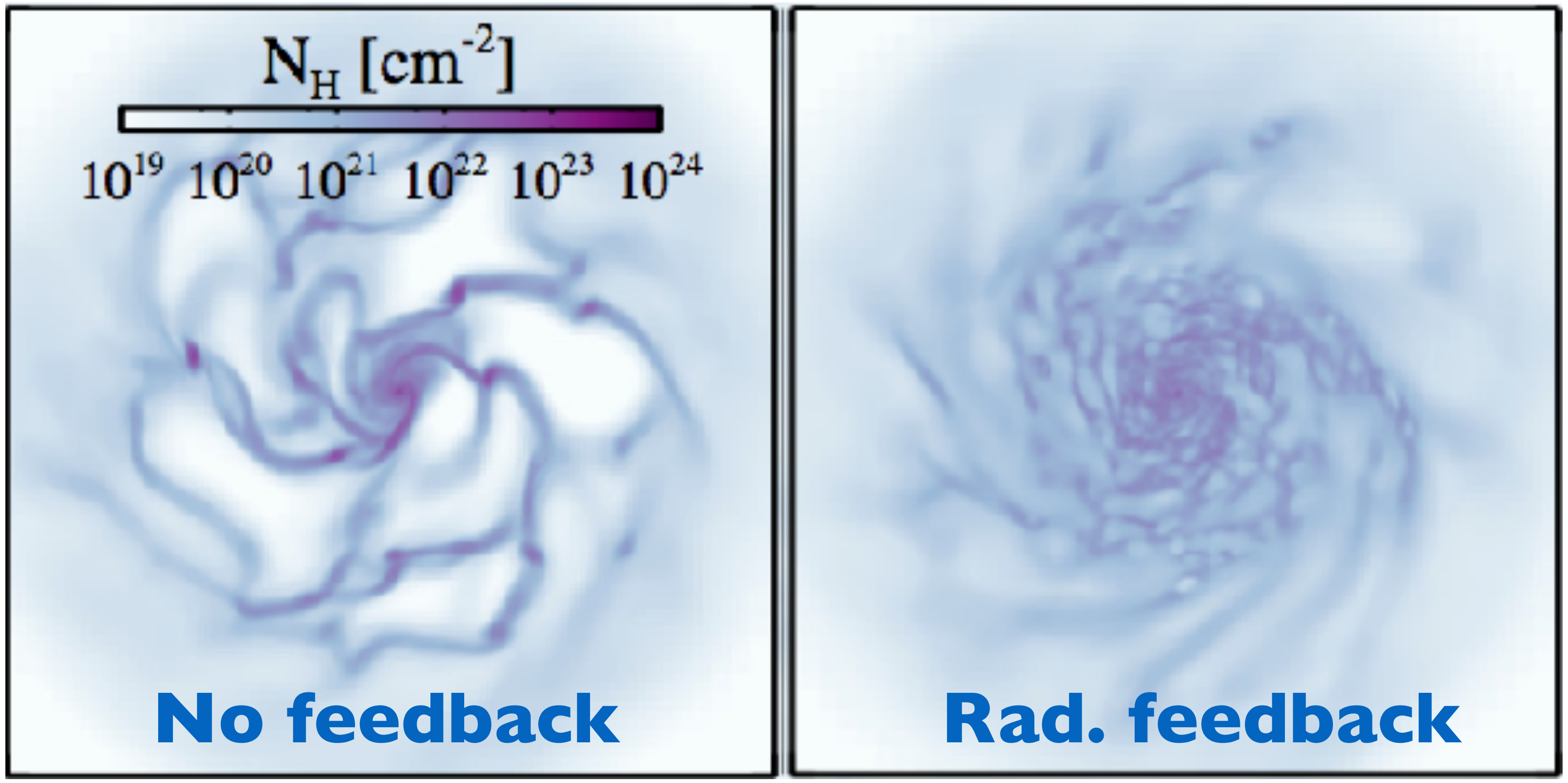
From Gavagnin et al. (2017)

Radiation feedback in isolated disk galaxies
Rosdahl et al. 2015

What is the role of stellar radiation feedback in galaxy evolution?

Results:

- Considerable effect in low-mass galaxies.
- Smoother gas distribution and reduced star formation.
- Photoionisation heating dominates over radiation pressure (optically thin disks).
- More coming soon for high-redshift ULIRGs



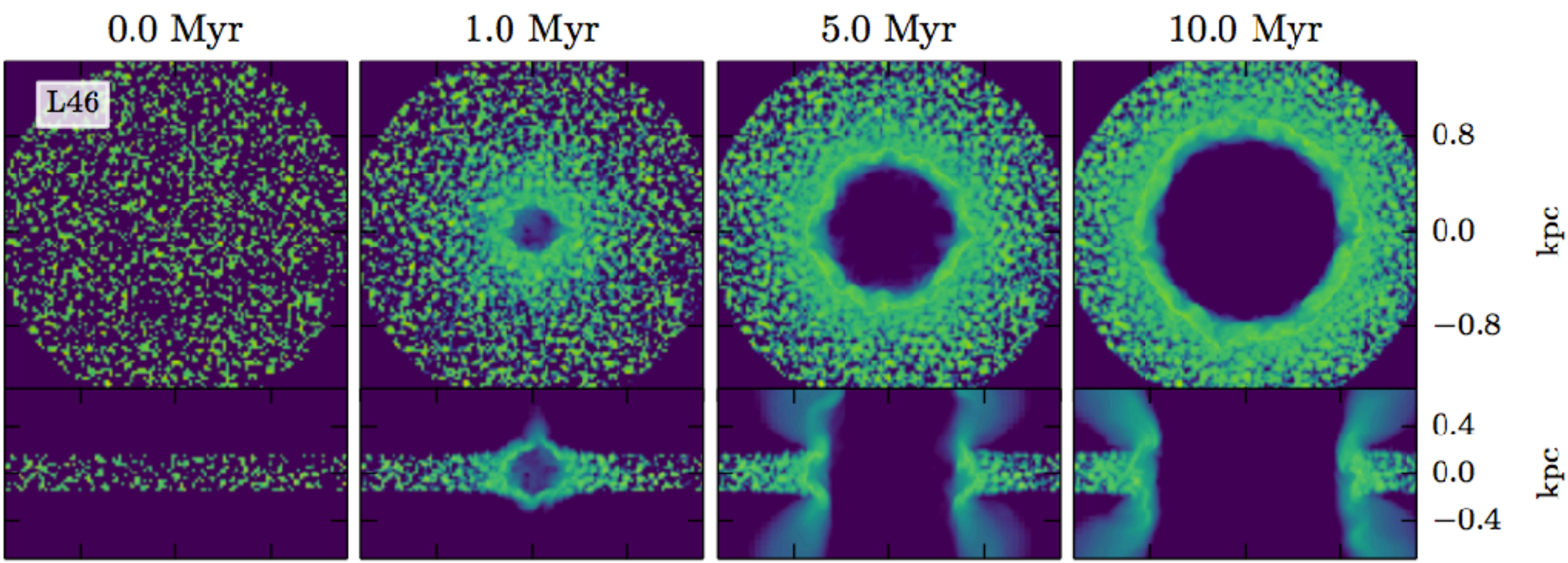
From Rosdahl et al. (2015)

Outflows driven by quasars via radiation pressure

Bieri et al. 2016

How efficiently can multiscattering IR radiation generate AGN outflows?

$$\dot{p}_{\rm rad} = \frac{L_{\rm Opt}}{c}\tau_{\rm IR} \quad ???$$



....see Yohan Dubois' talk tomorrow

Future developments in Ramses-RT

- Speedup:
  - GPUs?
  - Implicit RT solver to get rid of reduced light speed?
    - Not clear if there is always an advantage…the system should be 'slowly' evolving
- Coupling radiation with metal cooling
- H_2 chemistry - almost there
- Dust model, e.g. production, growth, destruction
  …the physics is complex and not well known

Summary

What is RAMSES-RT?

- Publicly available RHD extension of RAMSES
- On-the-fly radiation emission, transport, and absorption of H, He, and dust, using the M1 moment method
- Photoionisation, radiation pressure and dust scattering, correct in free-streaming *and* diffusion limits

Why?

- To predict observable properties of gas
- To study radiation feedback on (sub-) galactic scales
- To study reionisation and escape fractions