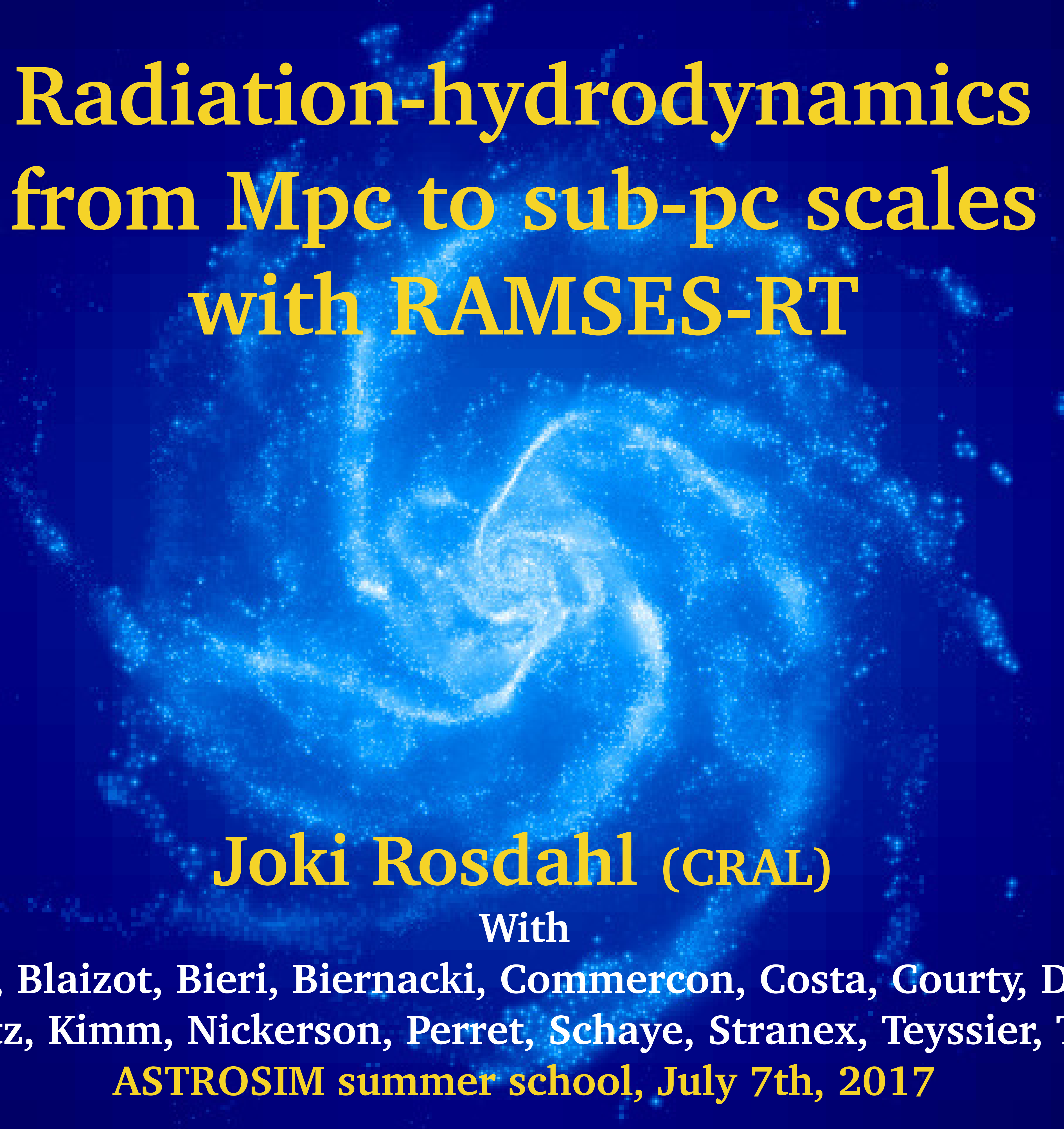


Radiation-hydrodynamics from Mpc to sub-pc scales with RAMSES-RT

Joki Rosdahl (CRAL)

With

Aubert, Blaizot, Bieri, Biernacki, Commercon, Costa, Courty, Dubois, Geen, Katz, Kimm, Nickerson, Perret, Schaye, Stranex, Teyssier, Trebitsch

ASTROSIM summer school, July 7th, 2017

What is RAMSES-RT?

What is RAMSES-RT?

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, He, H_2 (and eager to add more!)
  - Radiation pressure, i.e. momentum transfer from photons to gas
  - Multi-scattering on dust

How do ionising photons interact with primordial gas?

photoionisation, heating, pressure, recombinations

What is RAMSES-RT for?

What is RAMSES-RT for?

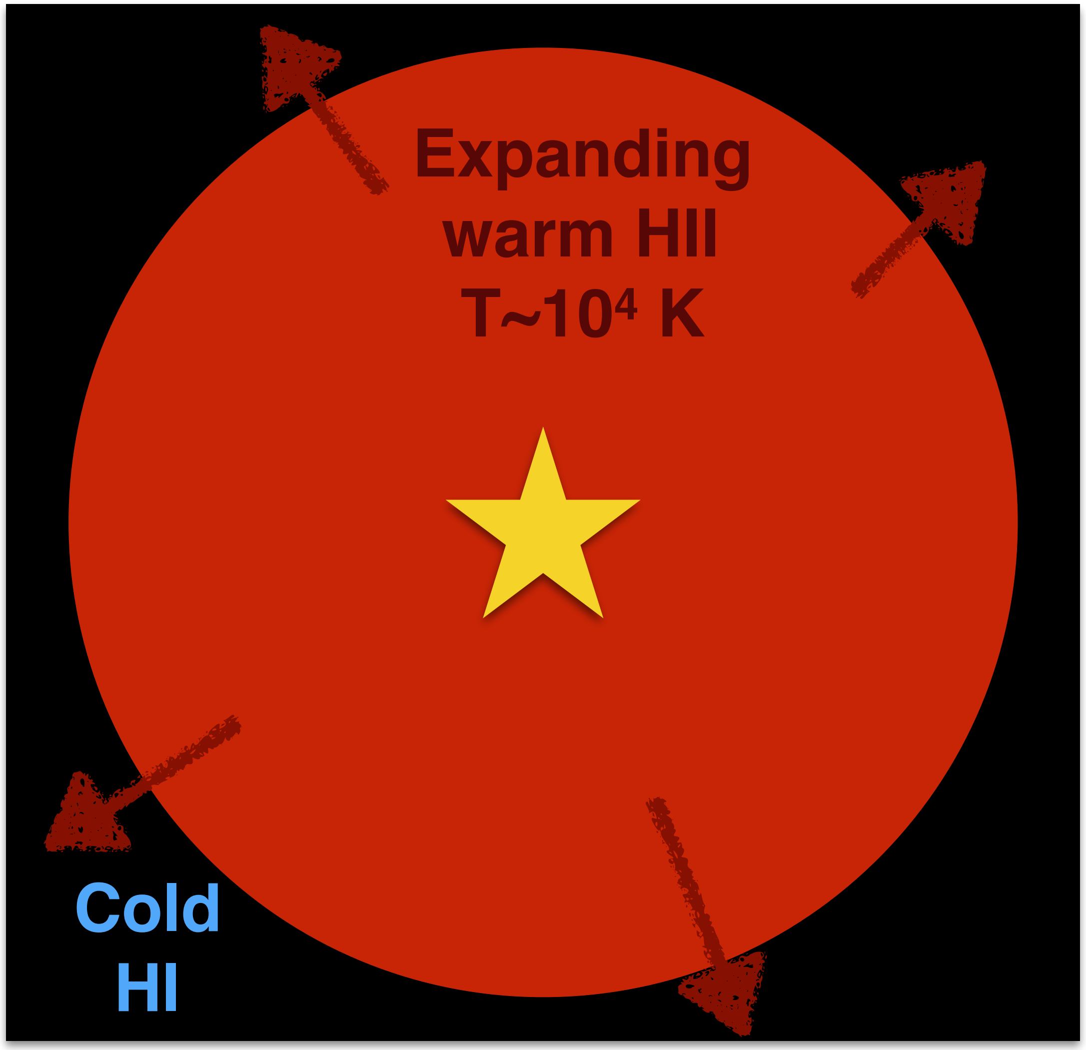
- **Observable properties of gas in and around galaxies** Rosdahl+12, Katz+17
- **Stellar/AGN radiation feedback** Rosdahl+15, Geen+15-16-17, Bieri+16, Gavagnin+17, Costa+17
- **Ionising radiation escape from galaxies** Kimm+14, Kimm+17, Trebitsch+17, Katz+17
- **Large-scale reionisation** (recently feasible with variable light speed)
- **H_2 formation and destruction** Butler+17
- **Protostar formation**

…but not for…

- **'Line' radiative transfer and PDR diagnostics** ☛ Monte Carlo
- **Situations where strong shadows are important**

➡ **More about dynamical effects of radiation than diagnostics**

Photoionisation heating



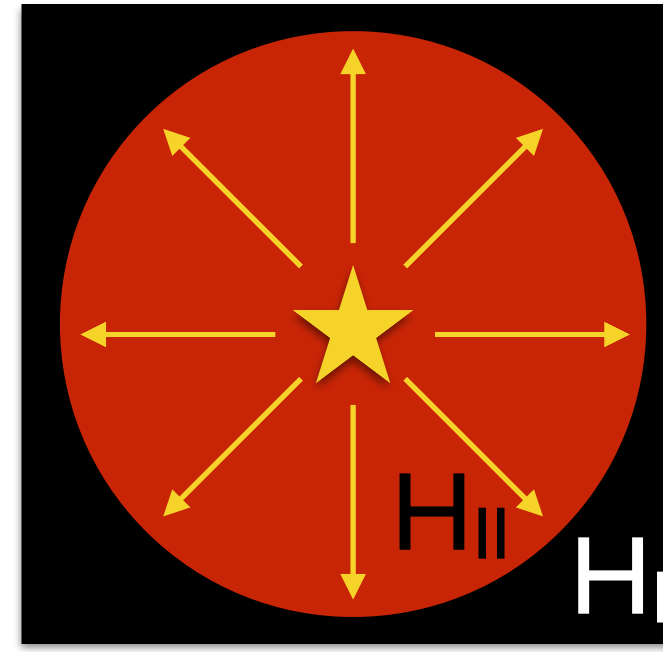
Radiation pressure

Momentum absorption

Stellar UV luminosity

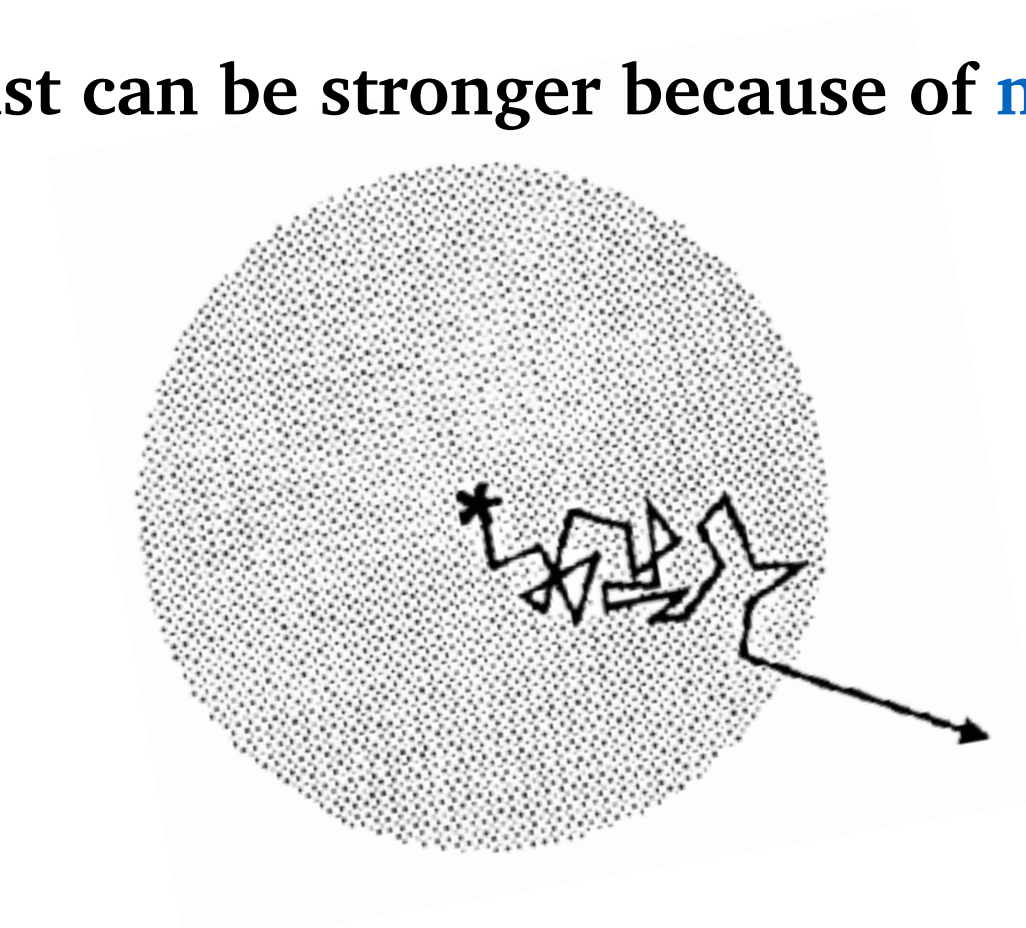
UV optical depth

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



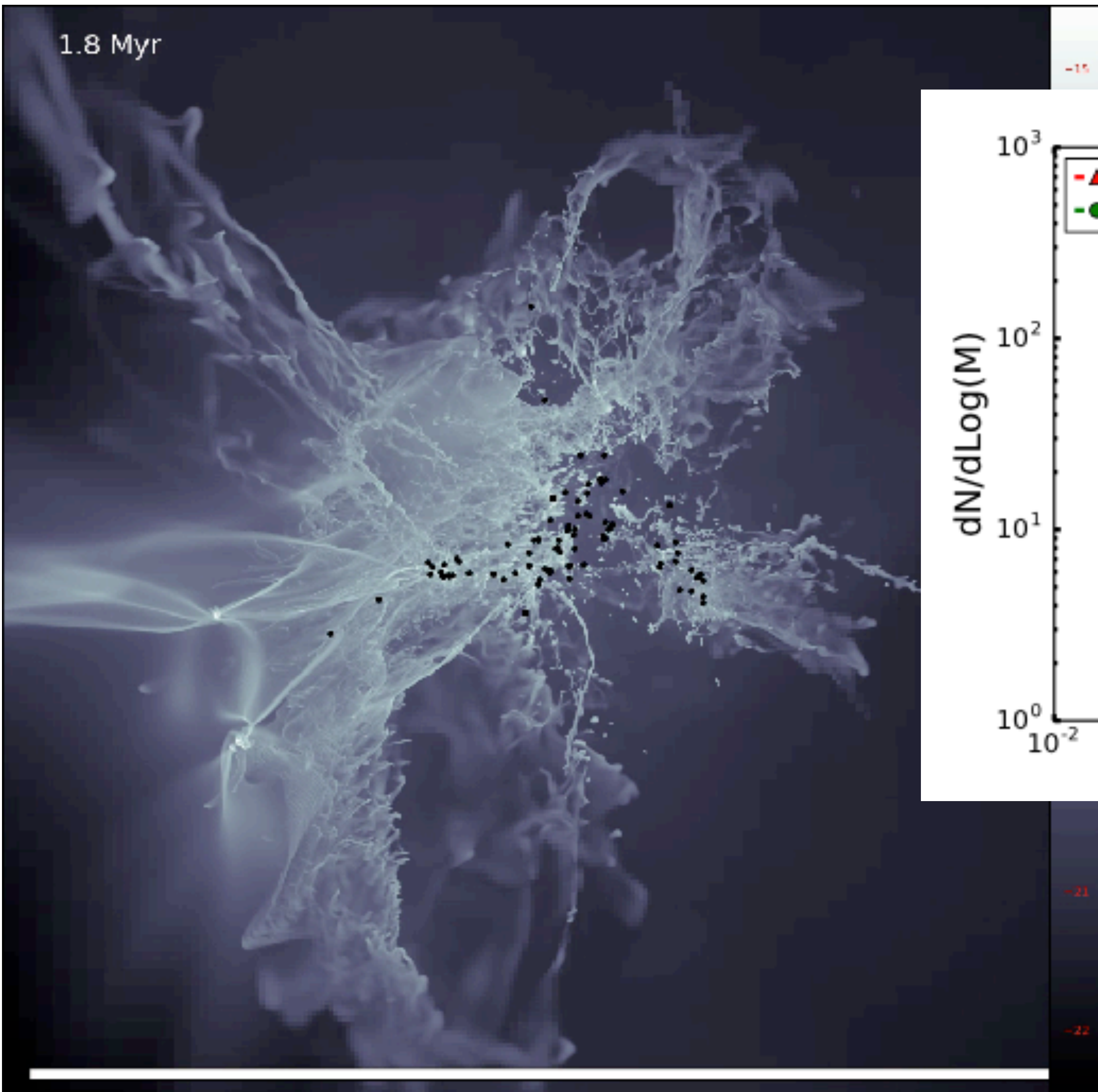
IR radiation pressure on dust can be stronger because of multi-scattering pressure boost

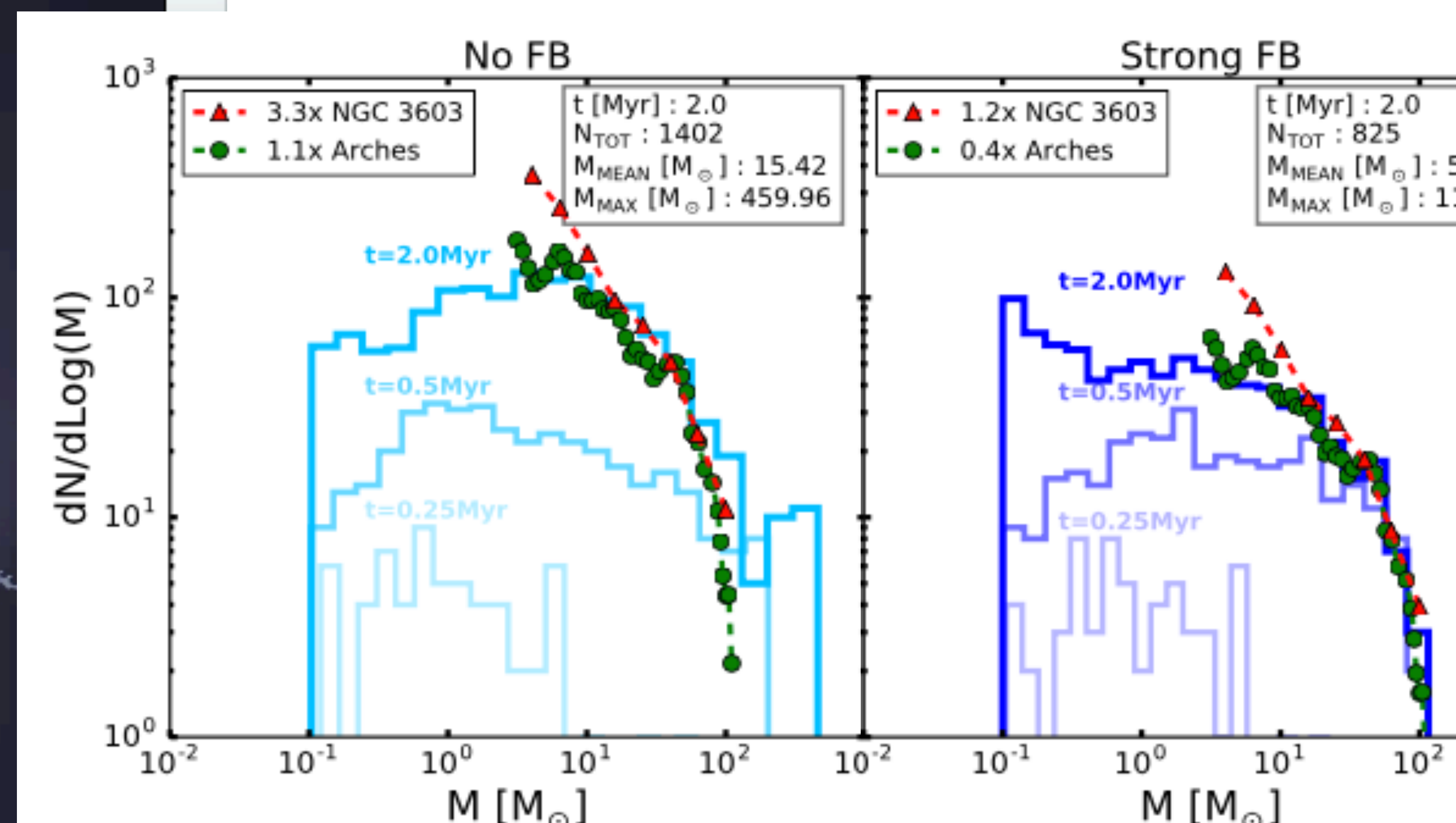
$$\dot{p}_{\rm rad} = \frac{L_{\rm Opt}}{c}\tau_{\rm IR}$$



Photoionisation feedback in molecular clouds with RAMSES-RT
Gavagnin et al. (2017)

Effect of ionising radiation on emerging stellar population and runaway stars





From Gavagnin et al. (2017)

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
  - Radiation pressure and multi-scattering
- Tests
- Science 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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$\eta_\nu(\mathbf{x}, \mathbf{n}, t)$ 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!

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

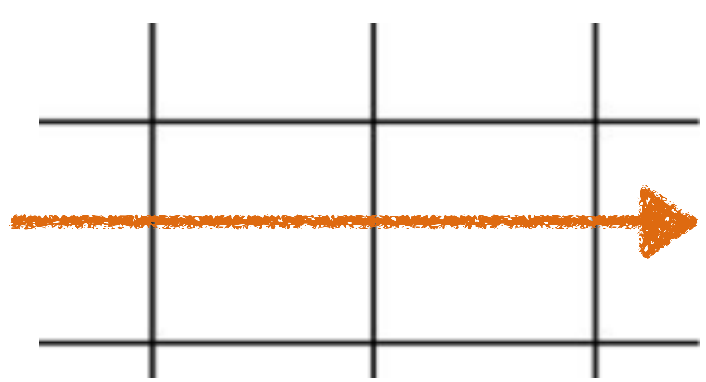
Angle

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 $u_{\text{light}} \sim 1000\ u_{\text{gas}}$, so ~ thousand RT steps per hydro step!!



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

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

Cell width

speed of flow

Timestep length

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

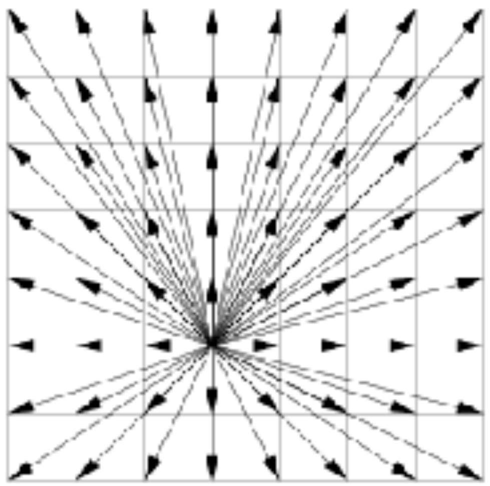
$\kappa_\nu\,(\mathbf{x}, \mathbf{n}, t)$ absorption

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

Two common strategies for radiative transfer:

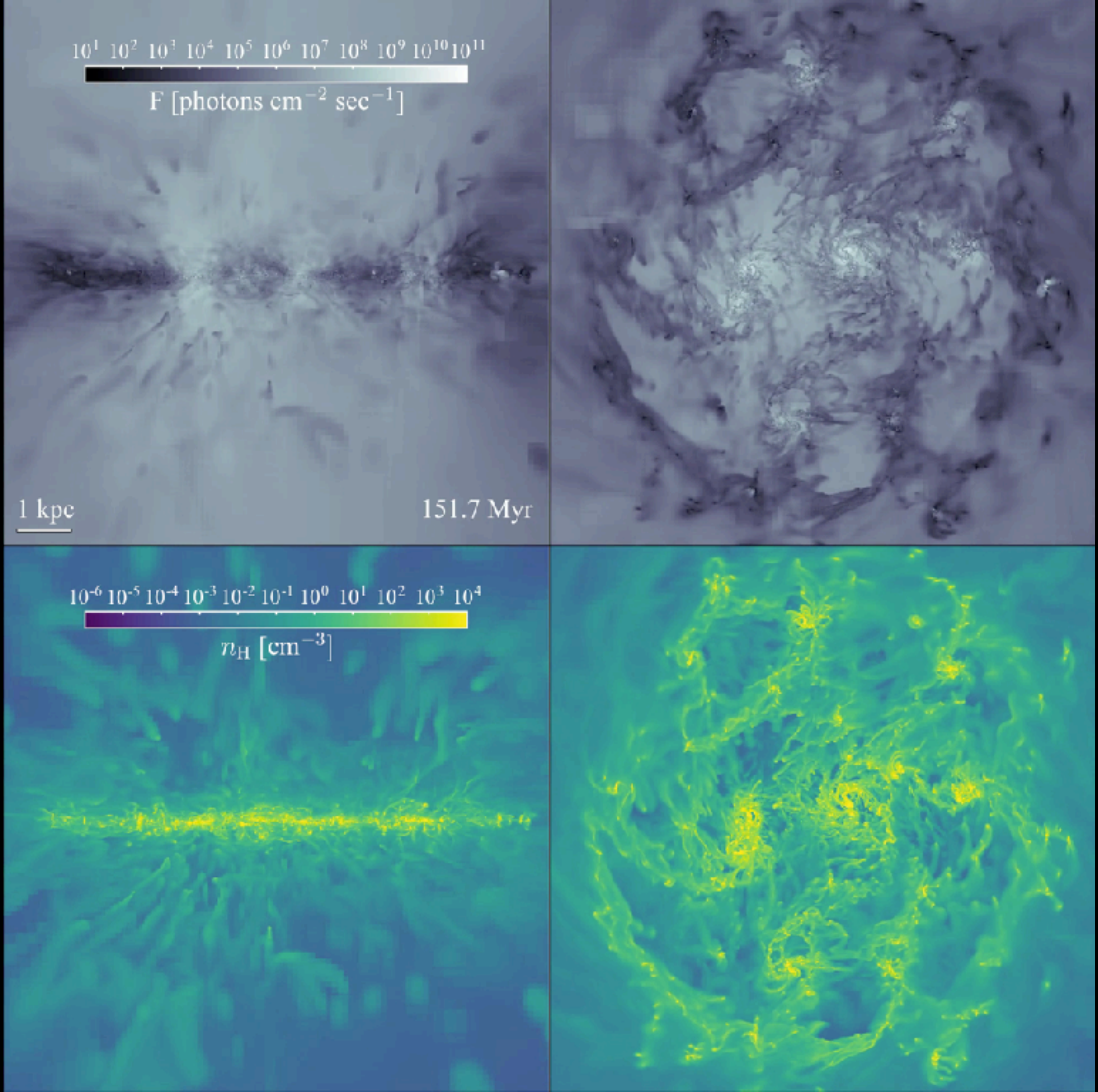
I. *Ray tracing methods:* Cast a finite number of rays from a finite number of sources

- Simple and intuitive
- …but efficiently covering the volume can be 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
151.7 Myr
10⁻⁶ 10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 10⁰ 10¹ 10² 10³ 10⁴
n_H [cm⁻³]

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
- Radiation pressure and multi-scattering

Tests

Science with RAMSES-RT

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

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

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

$N(\mathbf{x}, t)$ 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 <u>photon groups</u>*, that discretise the frequency continuum

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

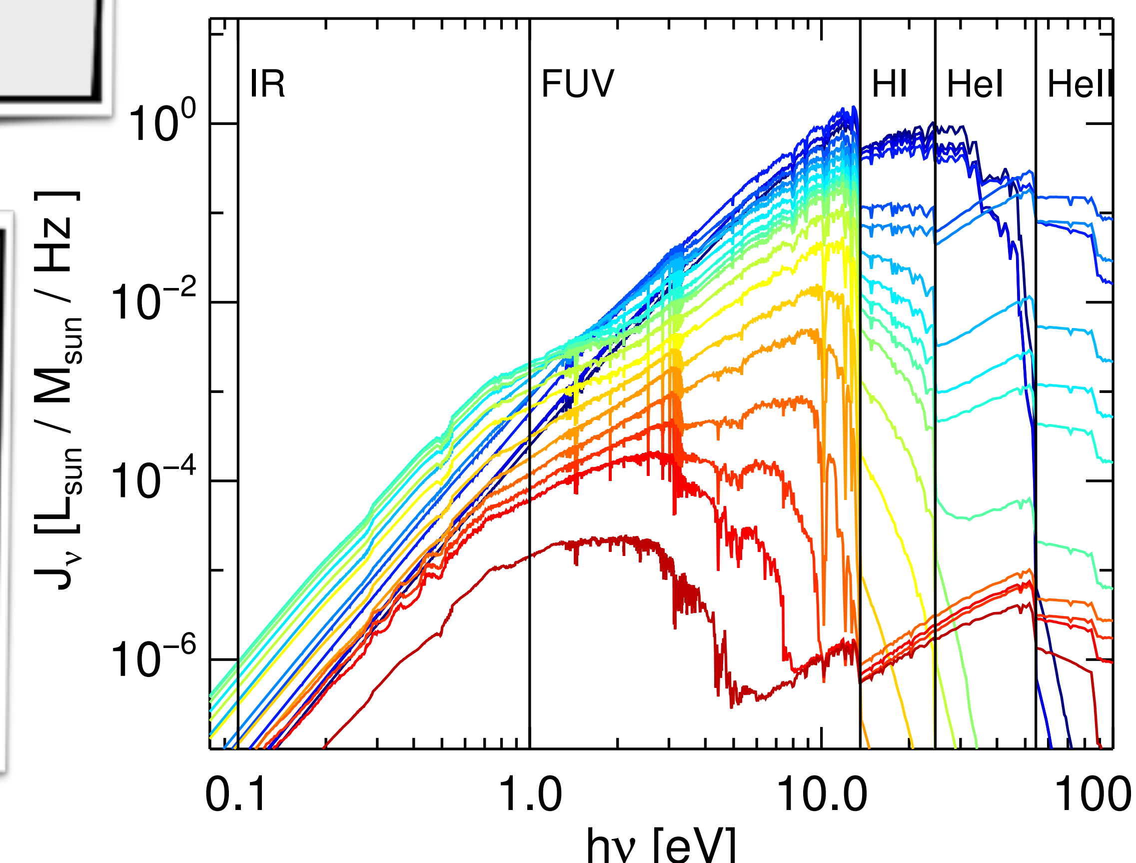
$$\frac{\partial N_\nu}{\partial t} + \nabla \cdot \mathbf{F}_\nu = - \sum_j^{\mathrm{H\,I,He\,I,He\,II}} n_j c \sigma_{\nu j} N_\nu \quad + \dot{N}_\nu^* + \dot{N}_\nu^{rec}$$

$$\frac{\partial \mathbf{F}_\nu}{\partial t} + c^2 \nabla \cdot \mathbb{P}_\nu = - \sum_j^{\mathrm{H\,I,He\,I,He\,II}} n_j c \sigma_{\nu j} \mathbf{F}_\nu$$

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

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

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)

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

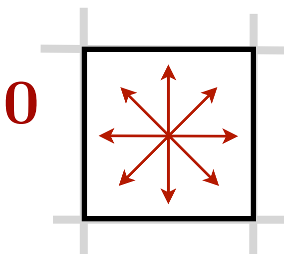
$$\frac{\partial \mathbf{F}}{\partial t} + c^2 \nabla \cdot \mathbb{P} = - \sum_{j}^{\mathrm{HI,HeI,HeII}} n_j \sigma_j c \mathbf{F}$$

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

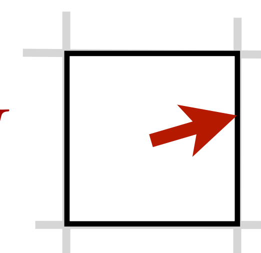
$\mathbf{F}(\mathbf{x}) = (F_x, F_y, F_z)$ **photon flux**

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

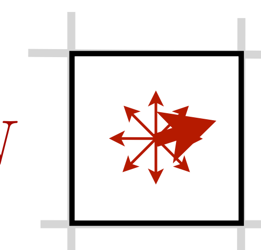
Diffusion limit (isotropic): $\mathbf{F} = \mathbf{0}$



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

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

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

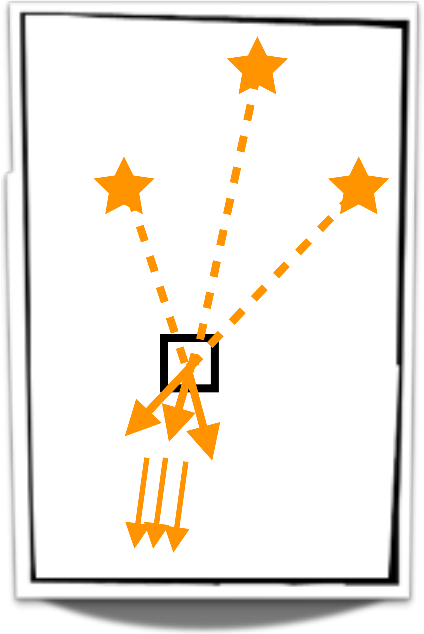
$\mathbb{P} = \mathbb{D} N$ Eddington tensor

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

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

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

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

An expression for $\mathbb{D}$ must conserve photons and preserve flux.
Should also be local (i.e. derived only from quantities within the cell).

Levermore 1984:

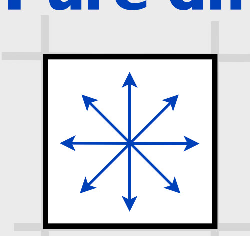
$$\mathbb{D} = \frac{1-\chi}{2}\mathbf{I} + \frac{3\chi - 1}{2}\frac{\mathbf{F}\otimes\mathbf{F}}{|F|^2}$$

$$\chi = \frac{3 + 4f^2}{5 + 2\sqrt{4 - 3f^2}}$$

$$f \equiv \frac{|\mathbf{F}|}{cN}$$

Examples

Pure diffusion:



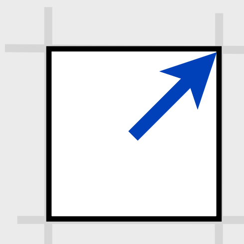
$$\mathbf{F} = \mathbf{0}$$

$$f = 0$$

$$\chi = 1/3$$

$$\Rightarrow \mathbb{P} = \begin{bmatrix} N/3 & 0 & 0 \\ 0 & N/3 & 0 \\ 0 & 0 & N/3 \end{bmatrix}$$

Pure transport:



$$\mathbf{F} = cN\left(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, 0\right)$$

$$f = 1$$

$$\chi = 1$$

$$\Rightarrow \mathbb{P} = \begin{bmatrix} N/2 & N/2 & 0 \\ N/2 & N/2 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

M1 closure - a warning

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

<u>We sacrifice the collision-less nature of photons</u>

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

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

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

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

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

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

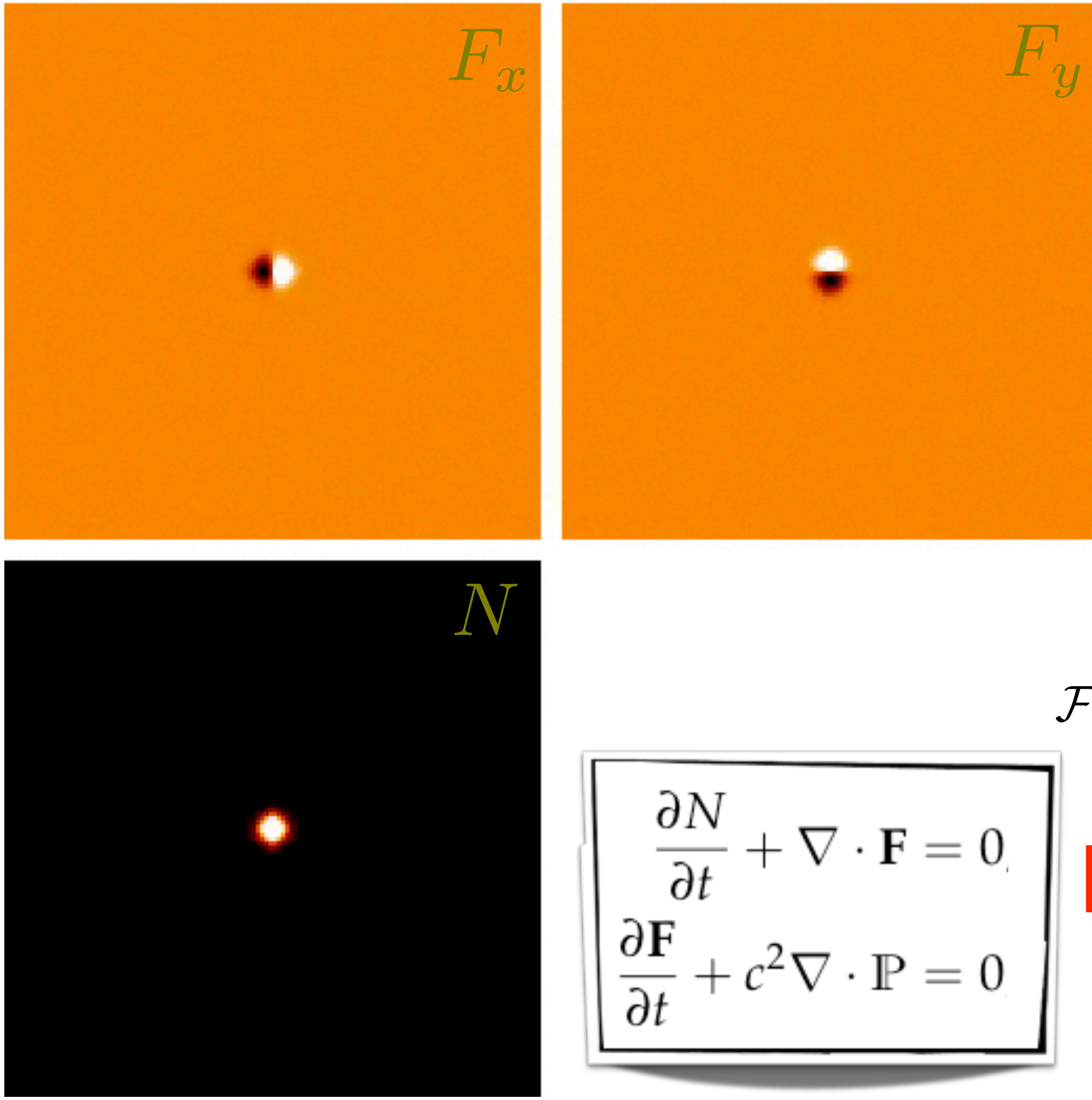
$$\mathbb{P} = \mathbb{D} N$$

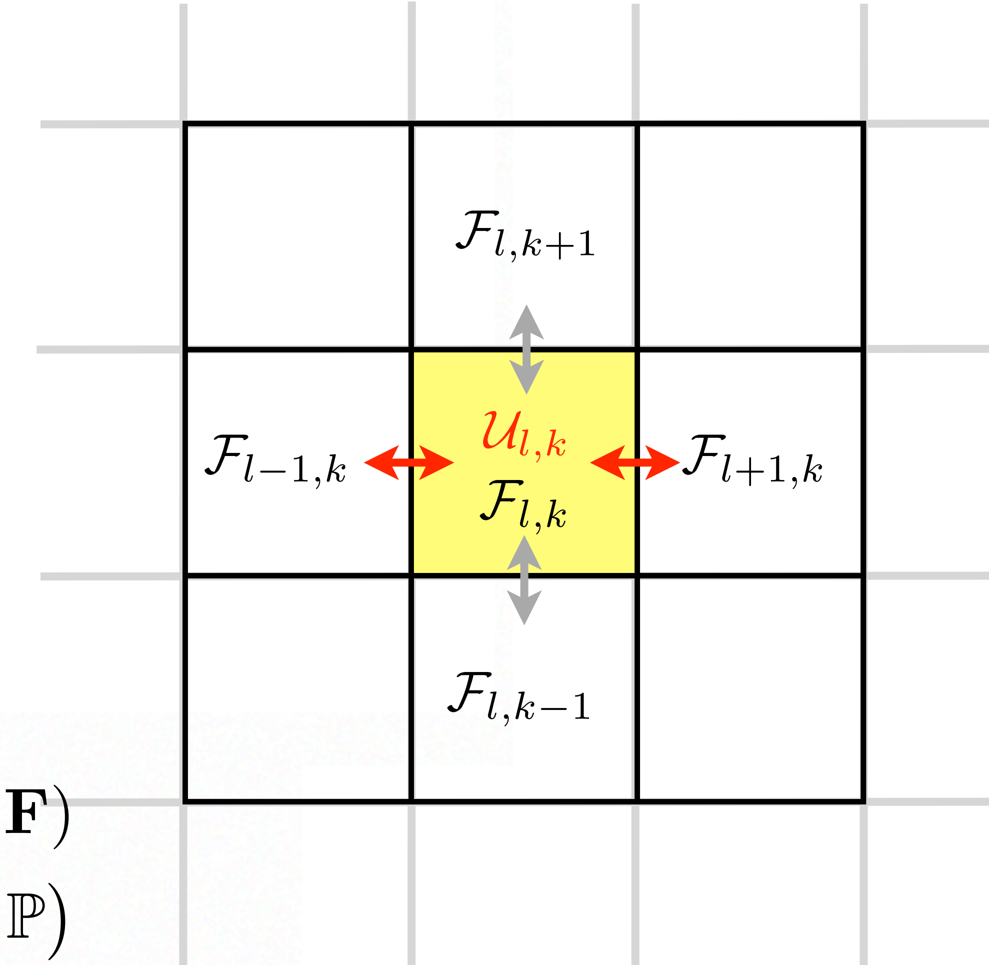
$$\frac{\partial \varepsilon}{\partial t} = \Lambda\left(\rho, \varepsilon, n_j, N_i\right)$$

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

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

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

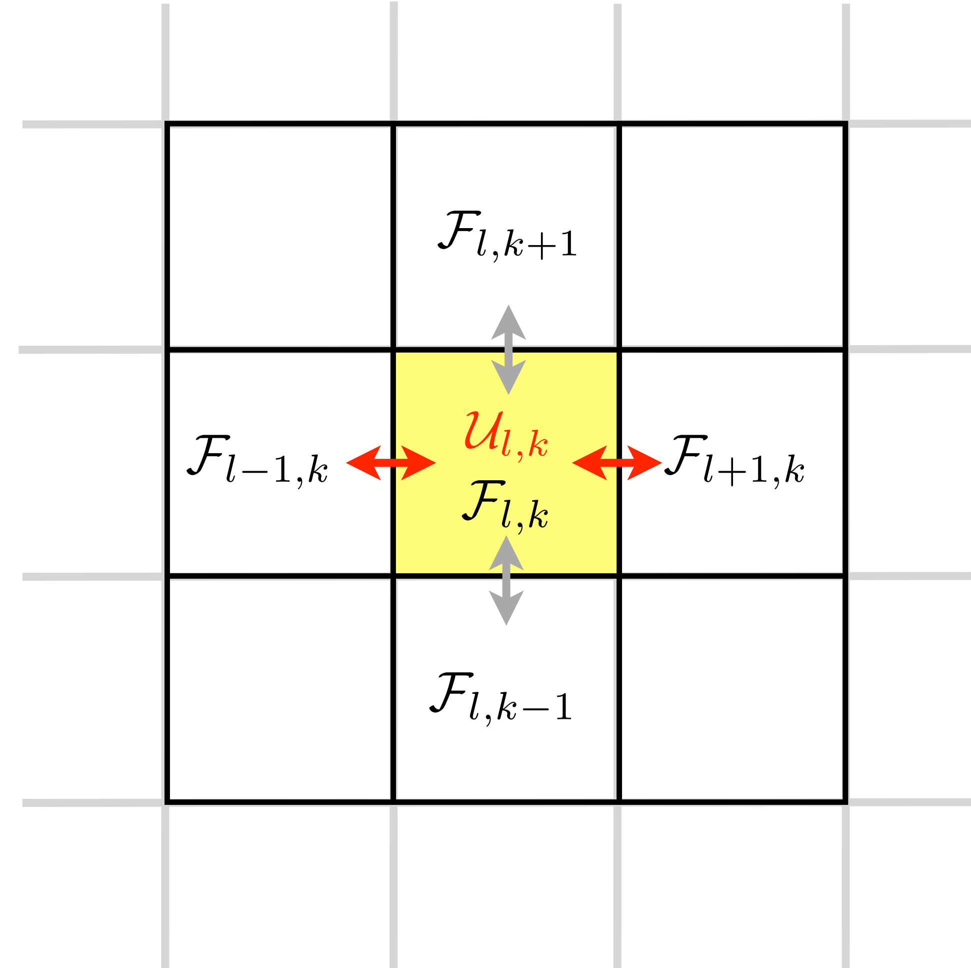
$$\mathcal{U}_l^{n+1} = \mathcal{U}_l^n + \frac{\Delta t}{\Delta x}\left(\mathcal{F}_{l-1/2}^n - \mathcal{F}_{l+1/2}^n\right)$$

(Implicit is also possible, has pros and cons)

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:~~

Harten-Lax-van Leer - HLL:

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

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

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

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

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

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

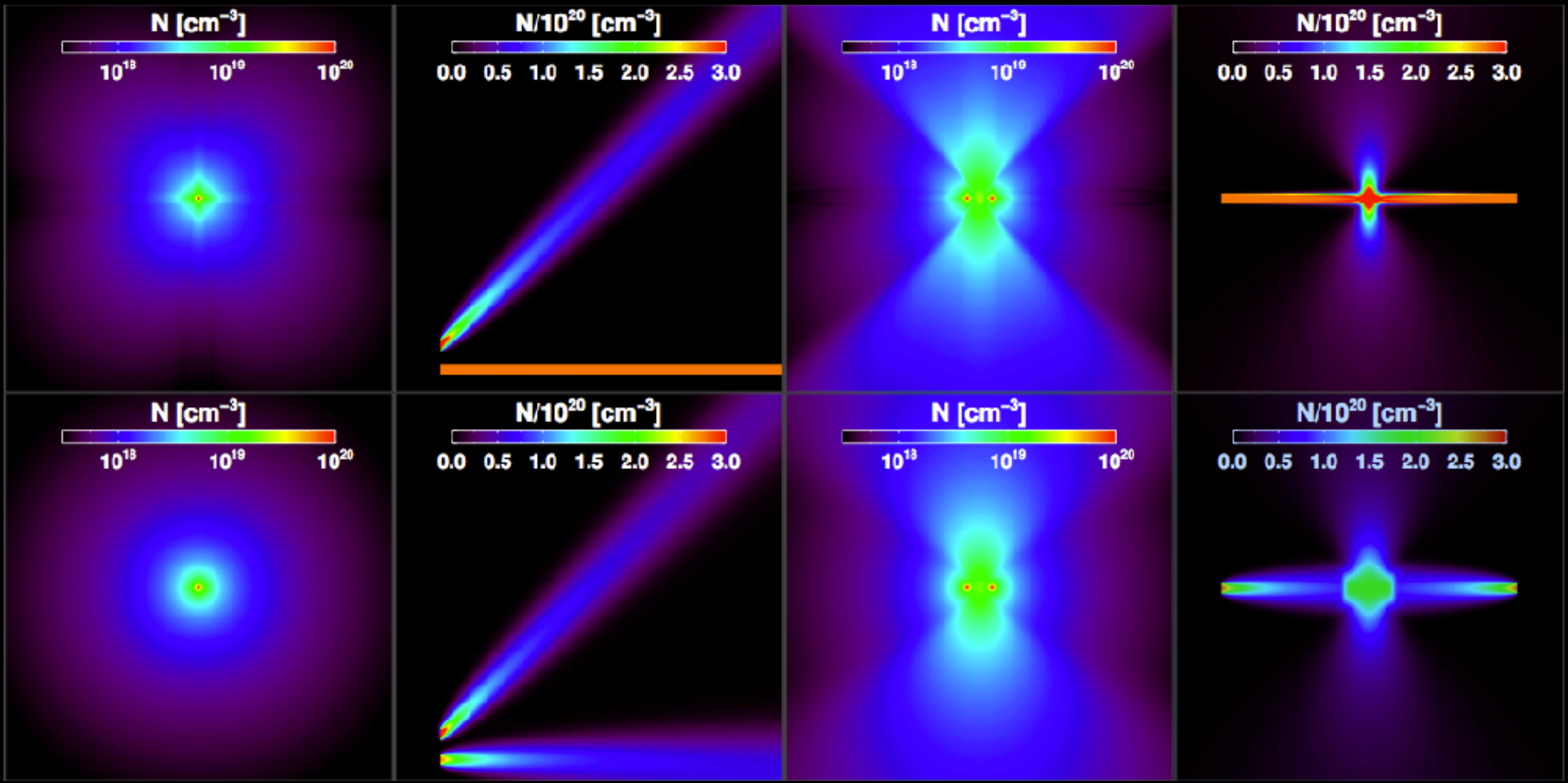
which gives

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 is coming soon

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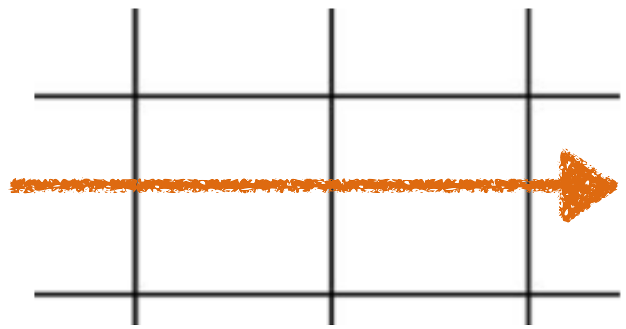
The speed of light problem

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



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

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

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 quite 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...

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) 😫

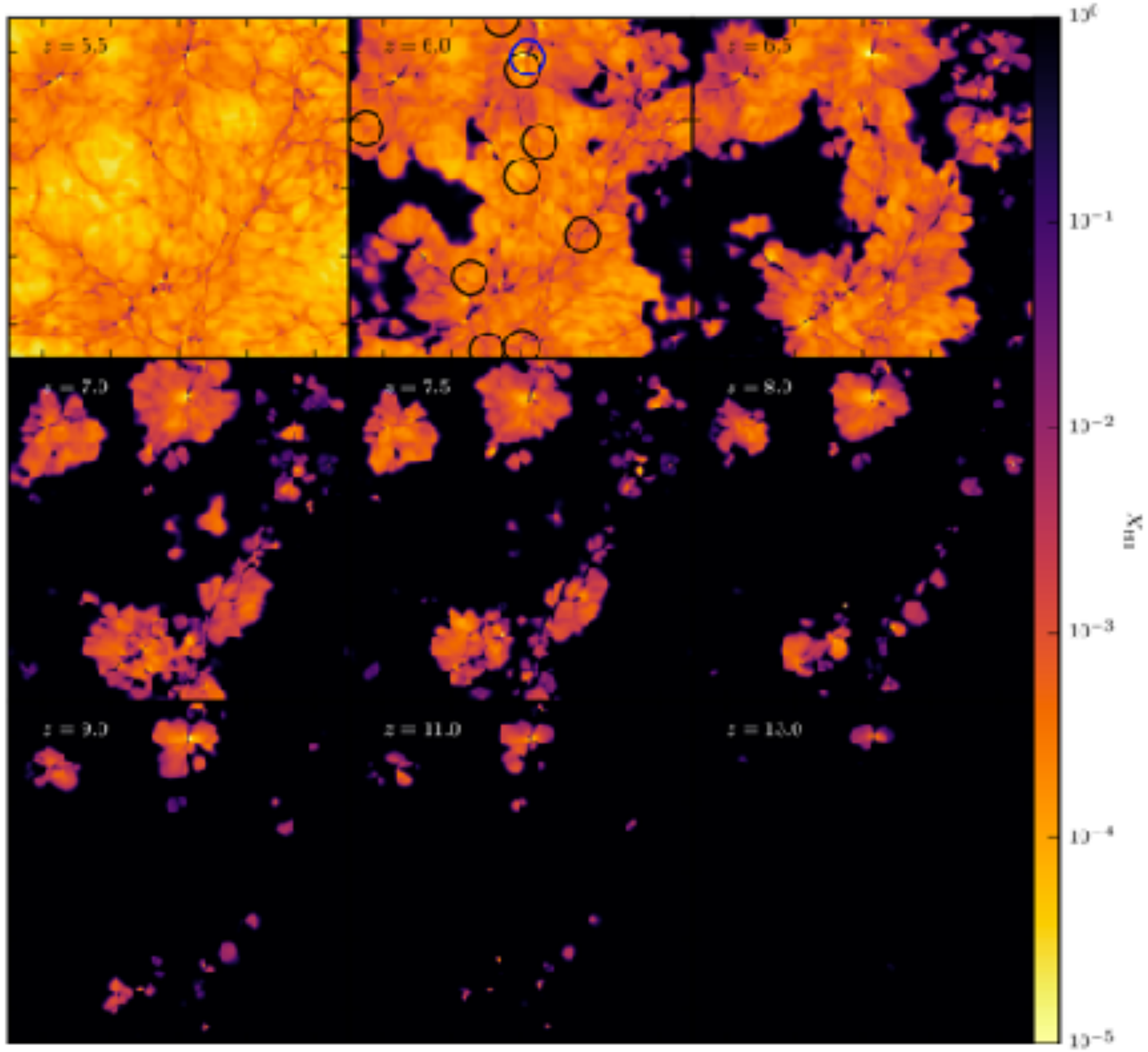
The variable speed of light approximation (VSLA)

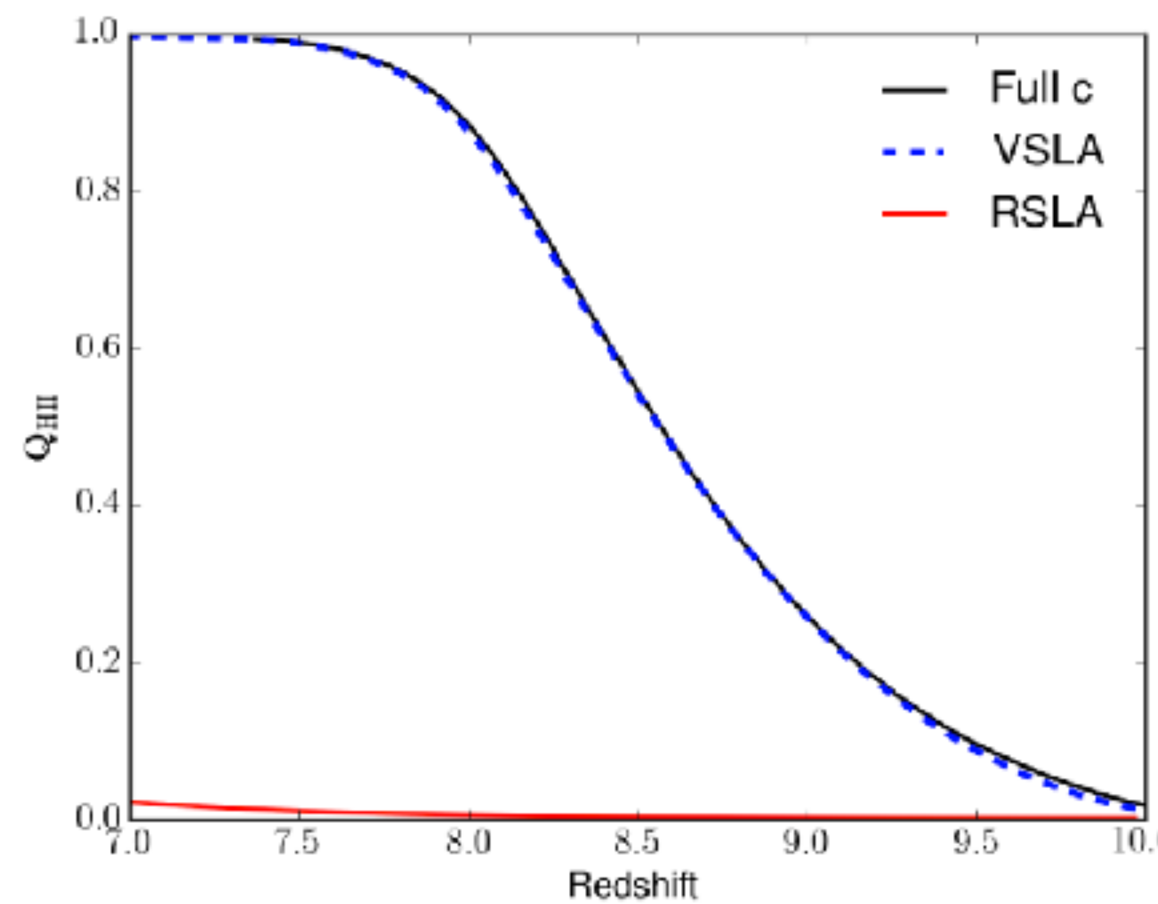
Katz et al. 2017

- 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 AMR 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)

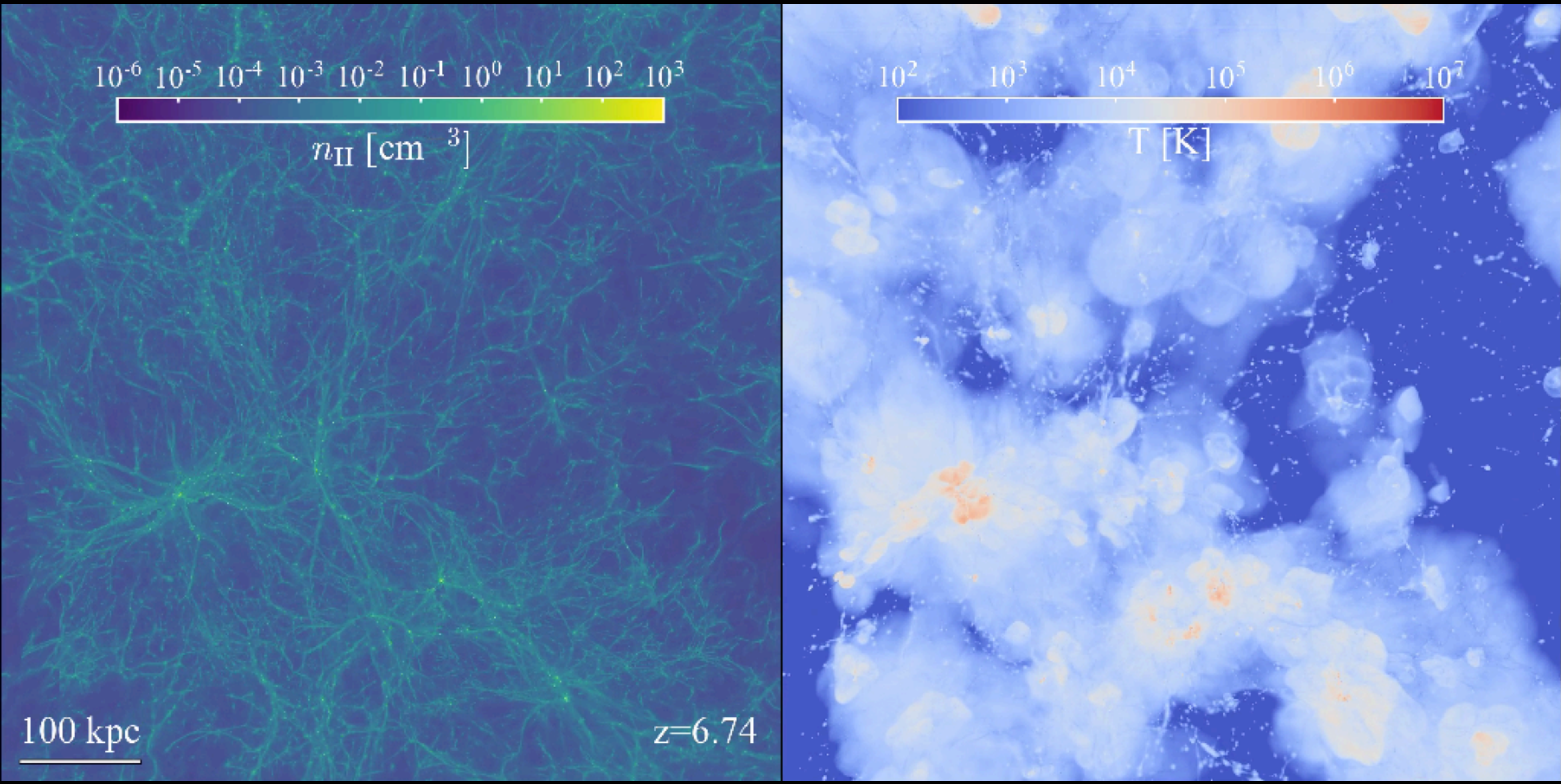
From Katz et al. 2017





3-100 %
3%
light speed

Using the VSLA for high resolution reionsiation simulations



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
  - Radiation pressure and multi-scattering
- Tests
- Science with RAMSES-RT

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:

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

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

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

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

HD and RT couple where photons interact with gas

Considerations:

- We should explicitly keep track of ionization fractions,

➡ Non-equilibrium thermochemistry of hydrogen and helium, with local photoheating

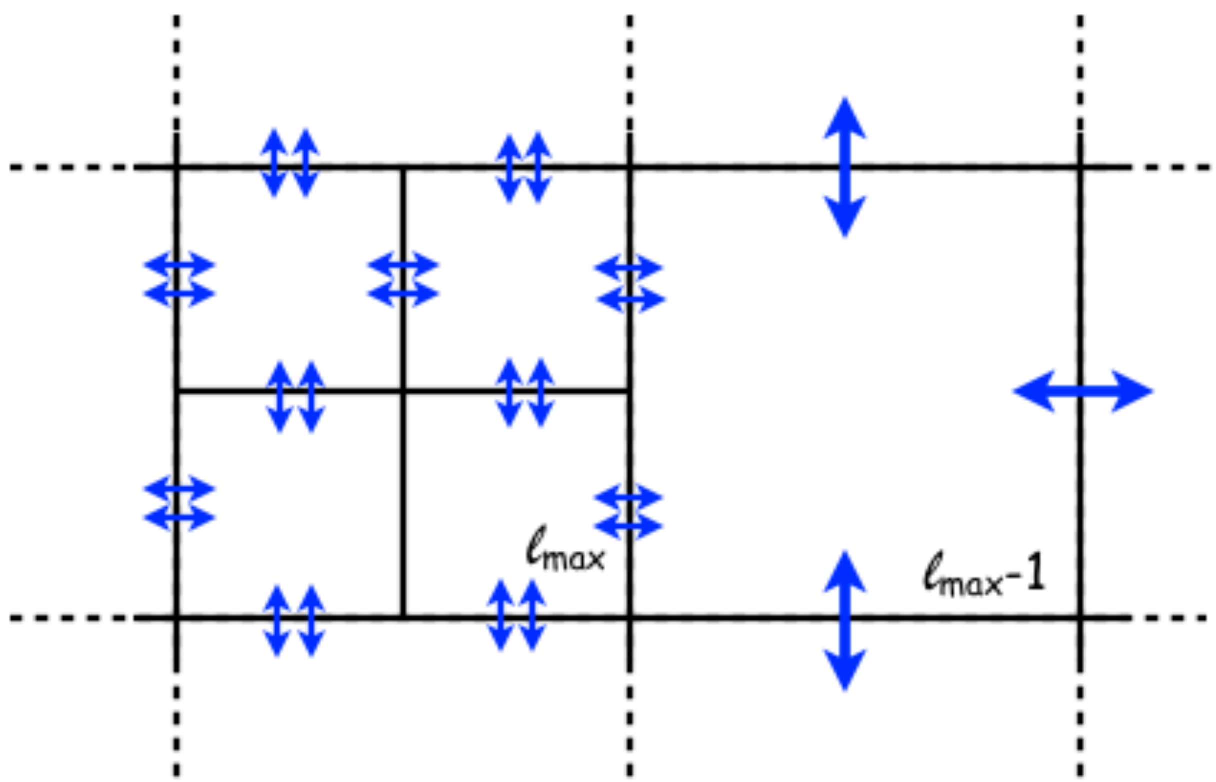
- ...which should be done on the shorter RT timescale

➡ HD is left virtually unchanged, and RT is subcycled after HD timestep
= **Operator splitting**

- ...but AMR subcycling makes this tricky

The AMR timestep in Ramses

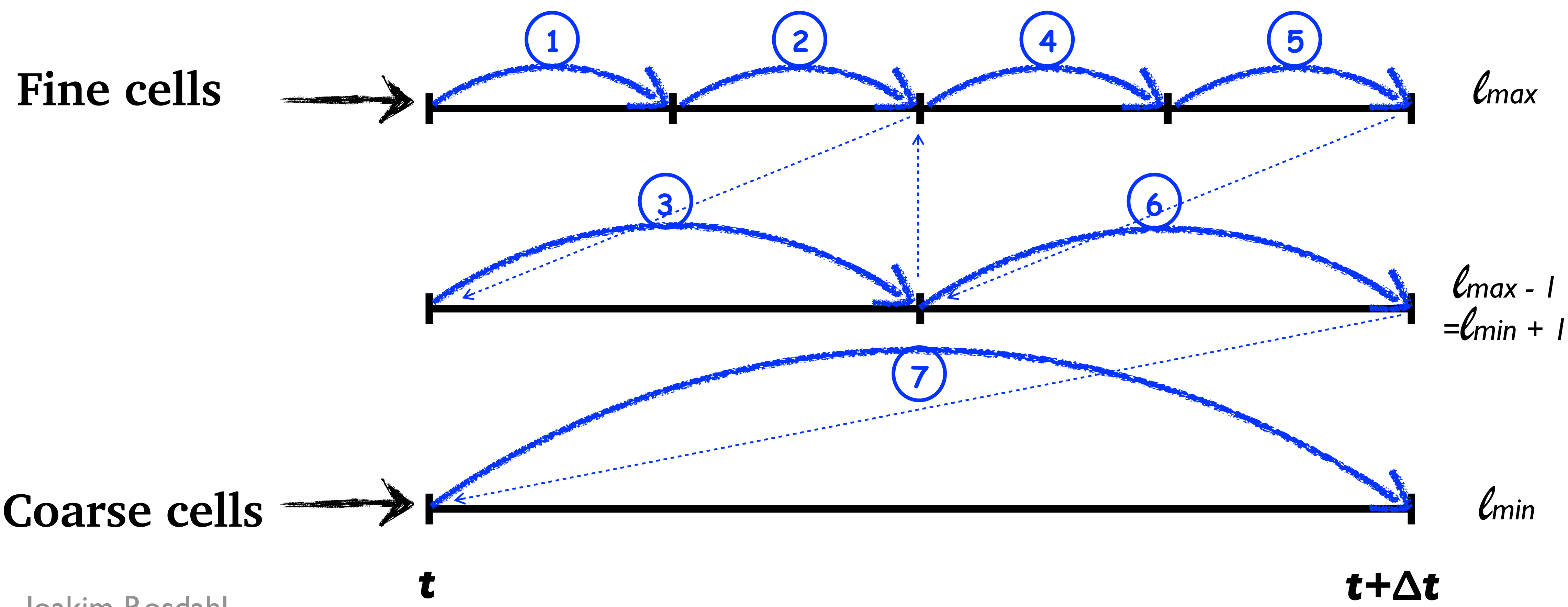
Adaptive resolution both in space and time



The timestep length is a cell crossing time (Courant condition):

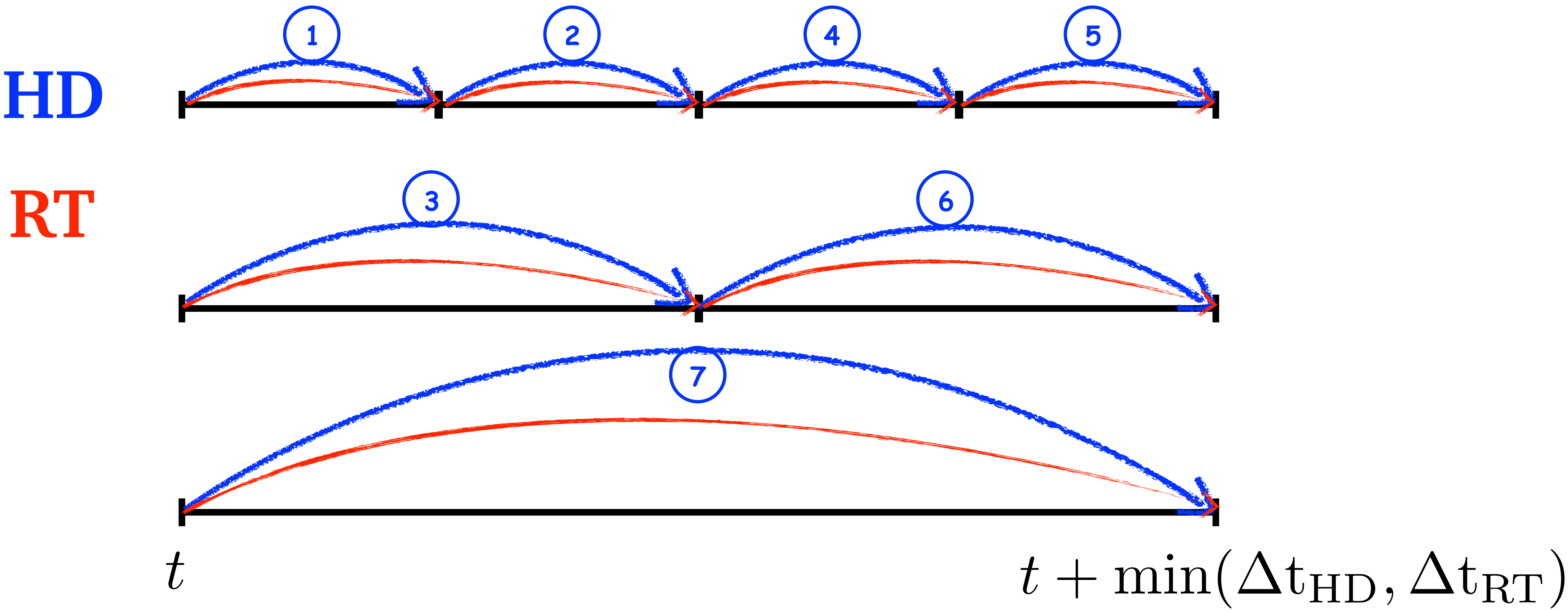
$$\Delta t_l \approx \frac{\Delta x_l}{u}$$

➜The levels are multistepped in time when solving HD -- one coarse step per two fine steps



Where does the RT fit in?

Approach a): Do a single RT step after HD on each level



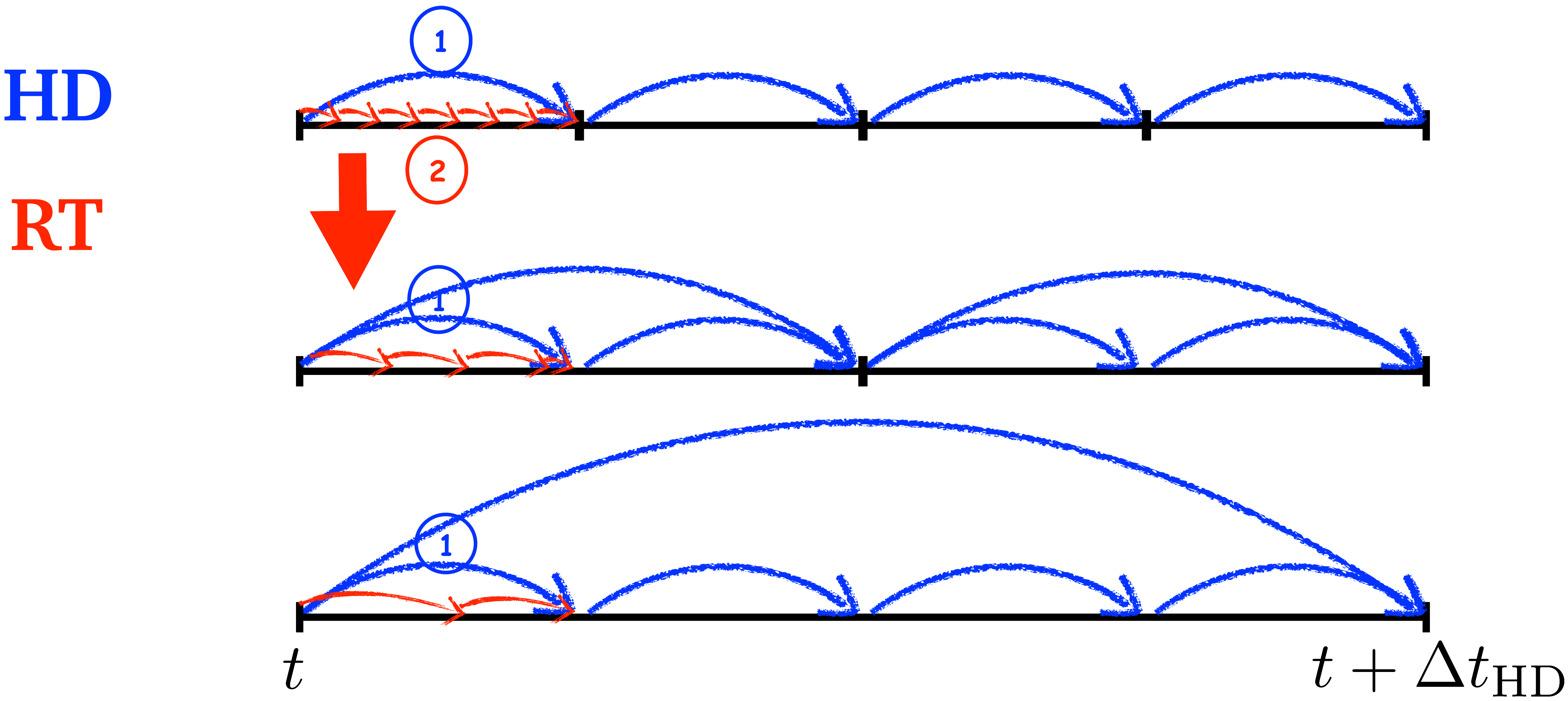
$$\Delta t_{\rm HD} \sim \frac{\Delta x}{u}$$

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

Orders of magnitude shortening of the HD timestep

Where does the RT fit in?

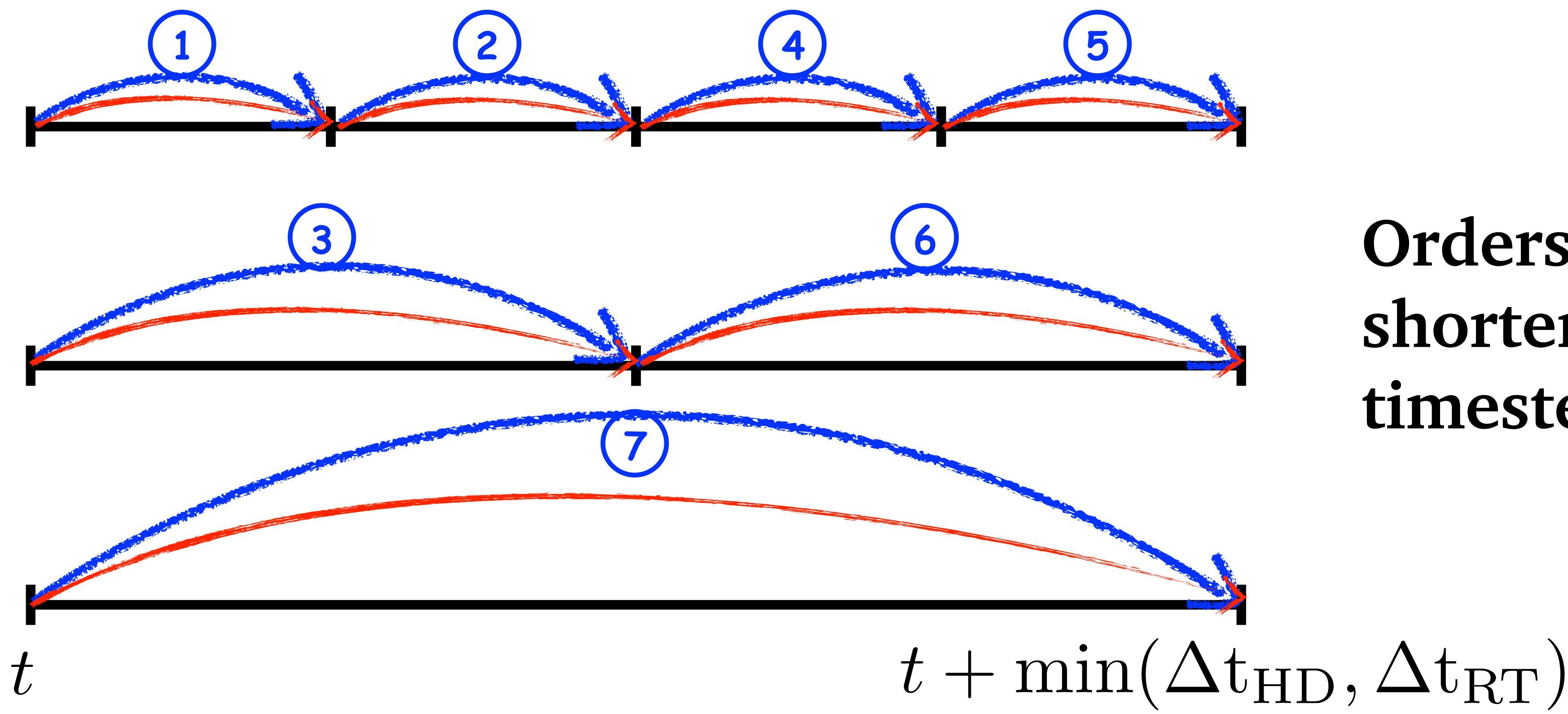
Approach b): Many RT steps after HD on each level



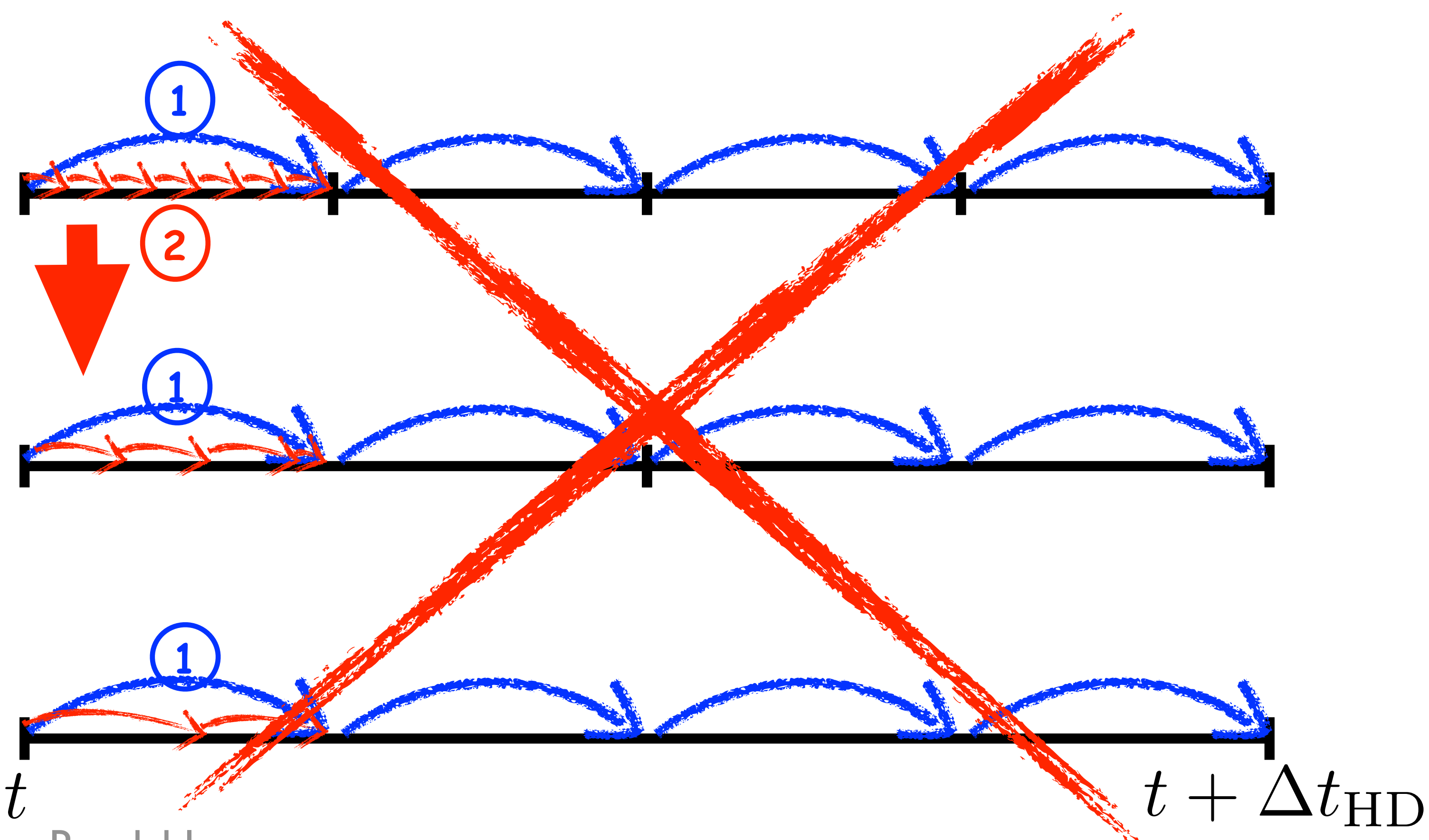
No HD multistepping (no time refinement)

Where does the RT fit in?

a) vs b)



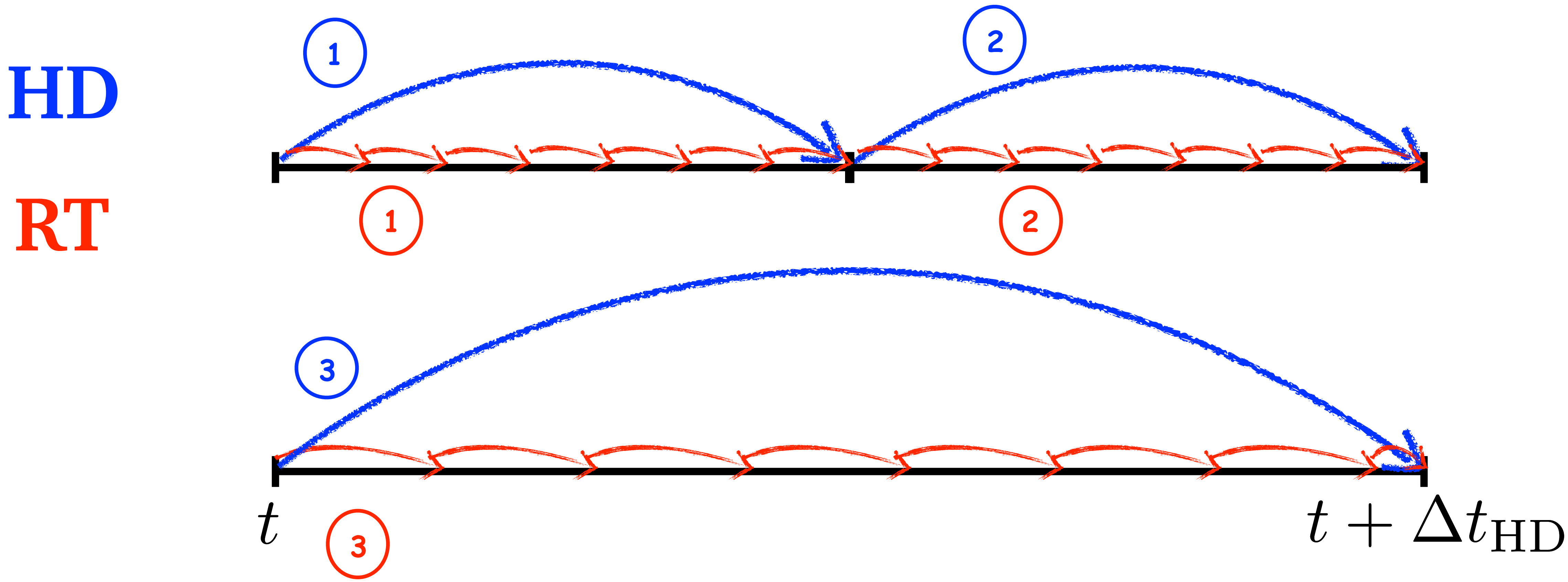
Orders of magnitude shortening of the HD timestep



No HD multistepping (<u>no time refinement</u>)

Plan c: rt_subcycle

Approach c): Many RT steps after HD on each level and lose photons across boundaries

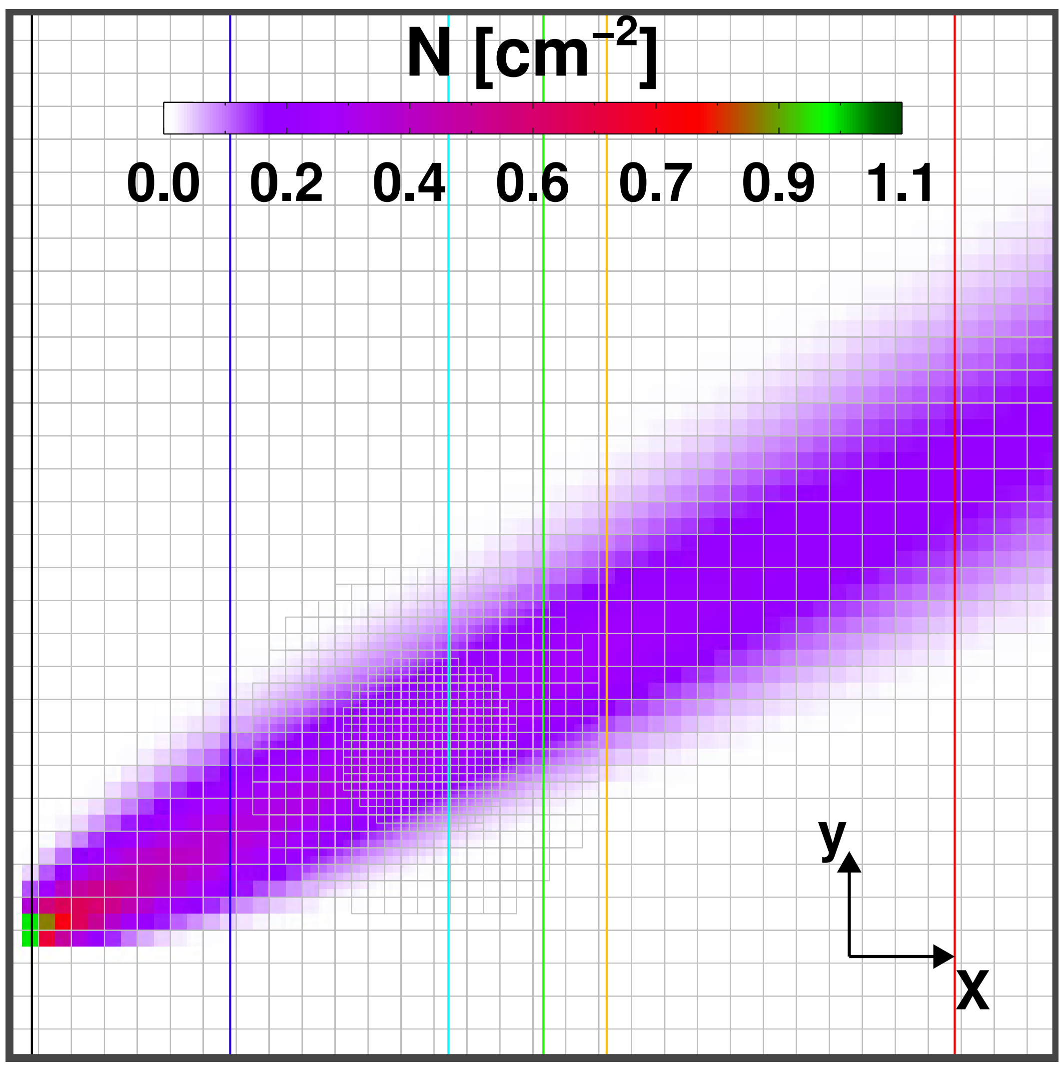


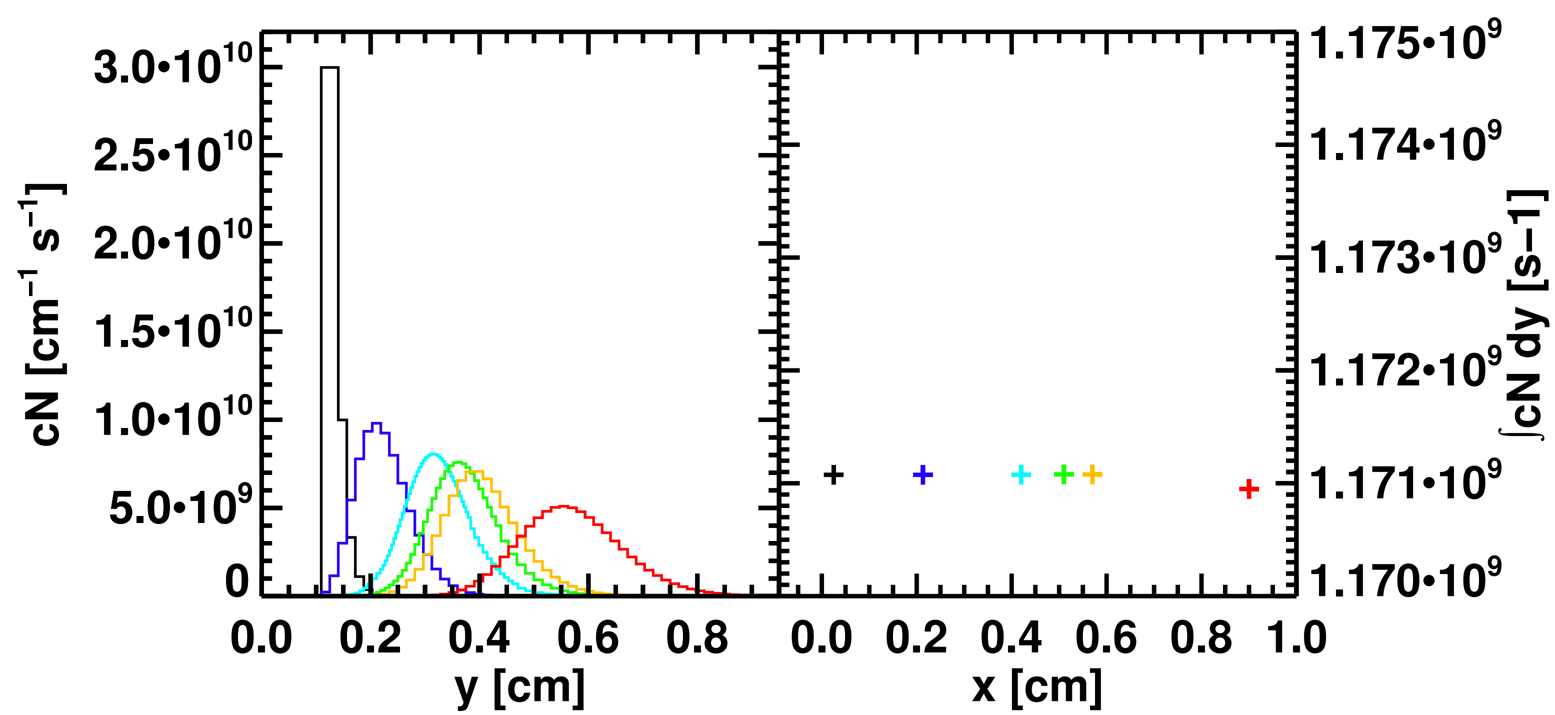
Keep HD multistepping and time refinement, while subcycling RT

Sacrifice perfect photon conservation across level boundaries

Radiation transport across an AMR grid

- RT variables are stored in cells, in just the same way as hydro variables
- So there's not much to do here but just take advantage of native AMR strategy and interpolation schemes already in place in Ramses
- In the same way, the RHD is fully MPI parallel, as is the rest of RAMSES





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Challenges in numerical radiative transfer

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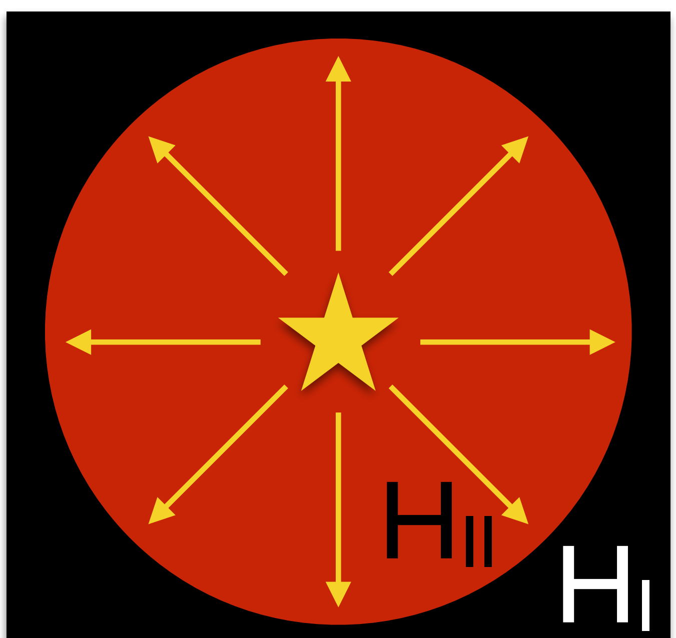
Radiation pressure

- 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

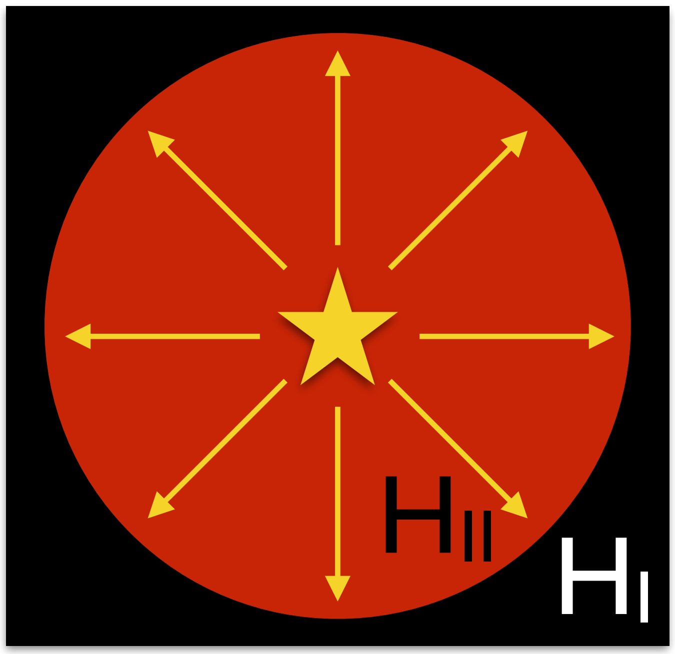
UV optical depth

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

Momentum absorption

Radiation pressure

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



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

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

Multi-scattering

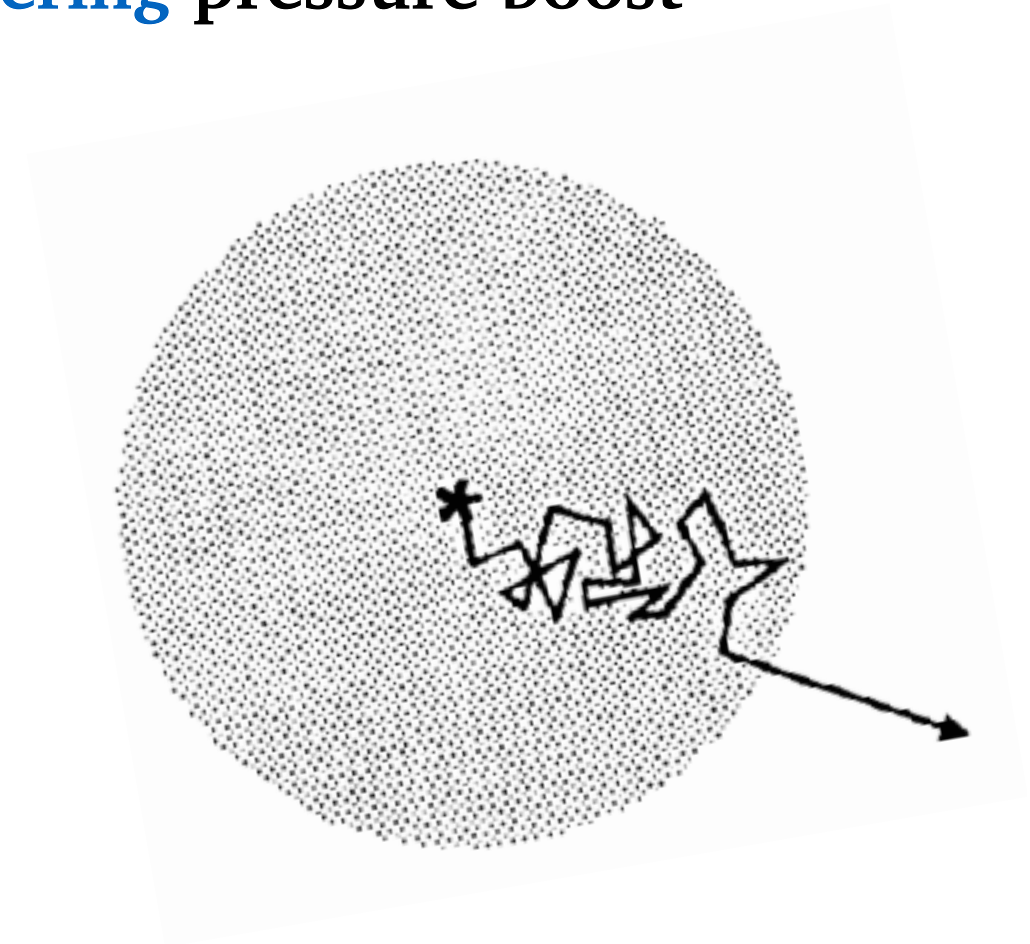
- Recently, we added dust absorption and scattering

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

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

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

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



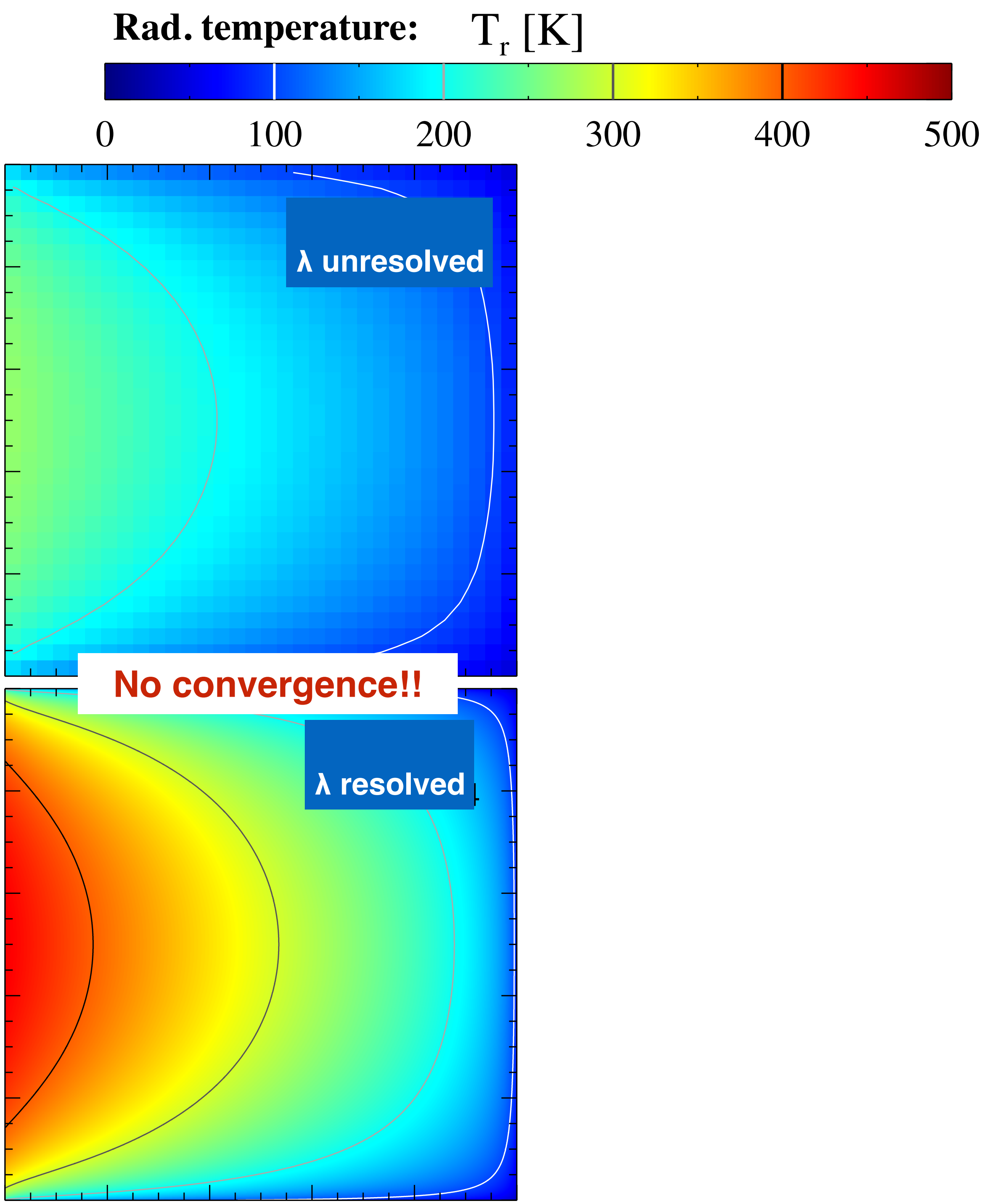
- For implementation details, see Rosdahl & Teyssier 2015

Diffusion of radiation in optically thick gas

- **The challenge is to model IR radiation in both the optically thin and thick limits**

- **The de-facto mean free path is**

$$\lambda_{\text{eff}} = \max\left(\lambda, \Delta x\right)$$



From Rosdahl & Teyssier, 2015

Diffusion of radiation in optically thick gas

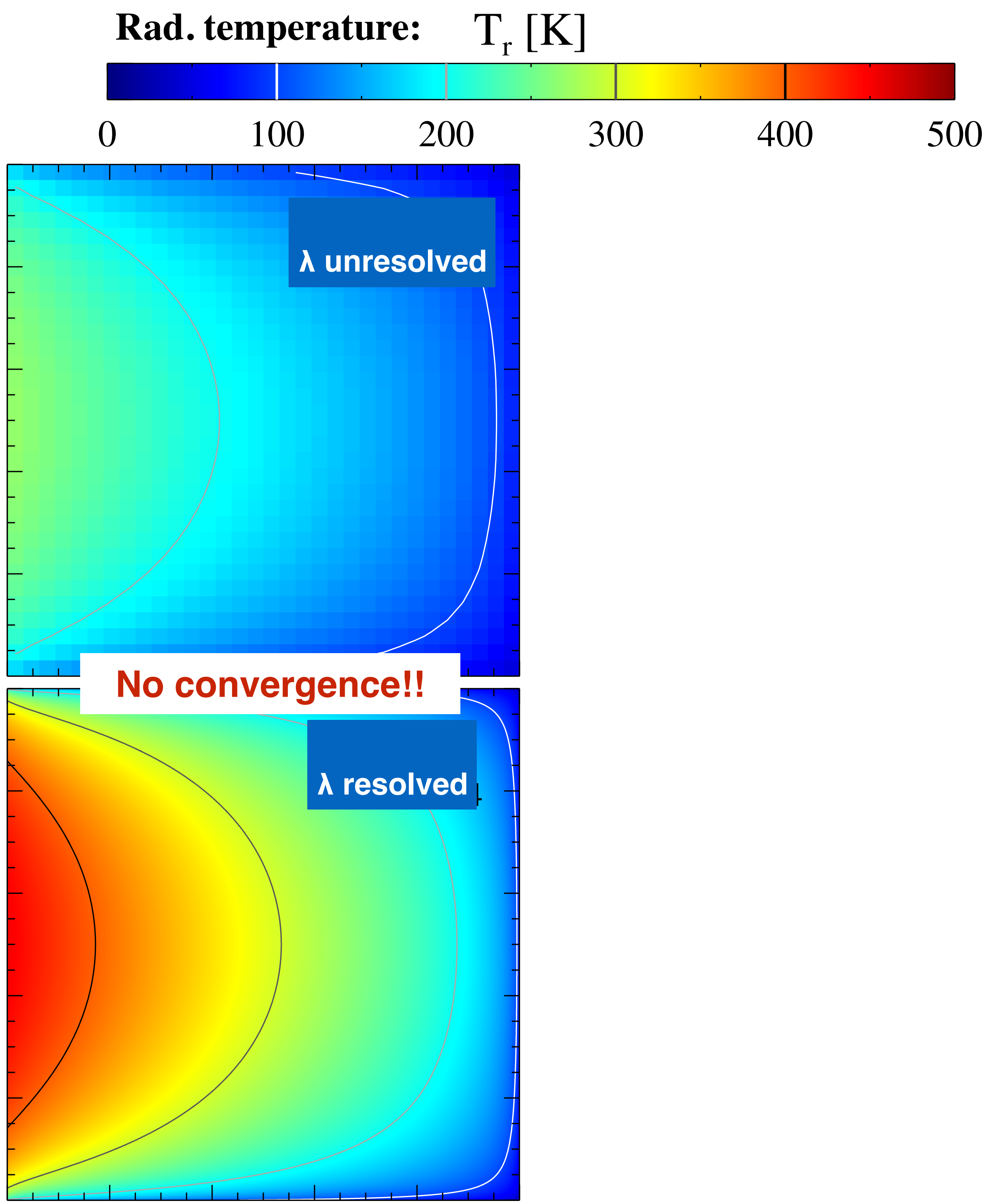
We divide the IR photons into trapped and streaming components in each cell, with

$$f_{\text{trapped}} = \exp\left(\frac{2}{3\tau_{\text{cell}}}\right)$$

We then recover the correct diffusion limit when the mean free path is unresolved, i.e.

$$\mathbf{F}_{\text{rad}} = -\frac{c\lambda}{3}\nabla E_{rad}$$

➡ **Radiative transfer is accurate both in the diffusion and free-streaming limits (but at a reduced light speed)**



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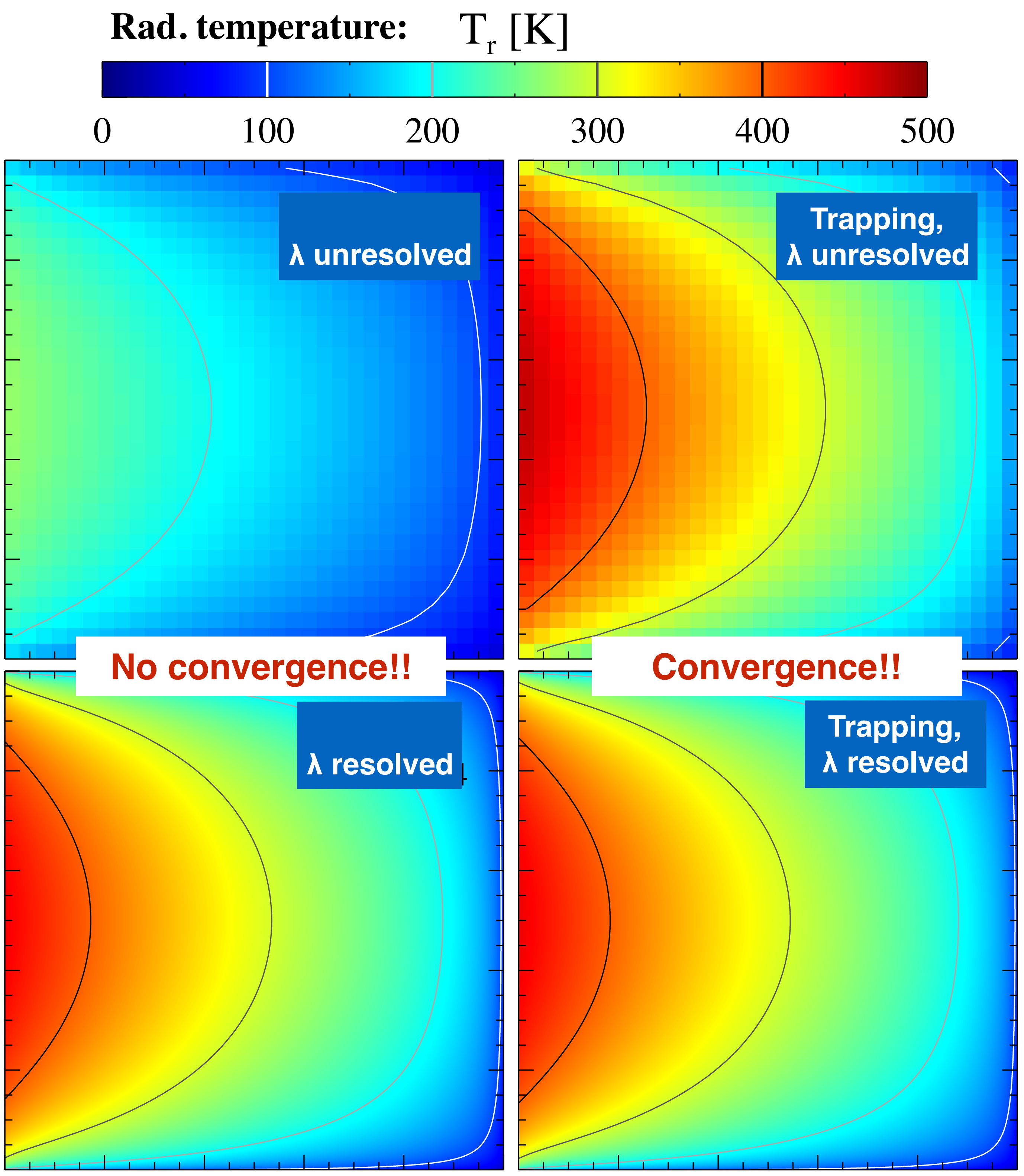

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Validation tests for RamsesRT

Thermochemistry tests

- Convergence of temperature and ionization states
- Stability
- Tests turn out ok

Iliev et al's 'RT codes comparison project'

- Compare against other codes results

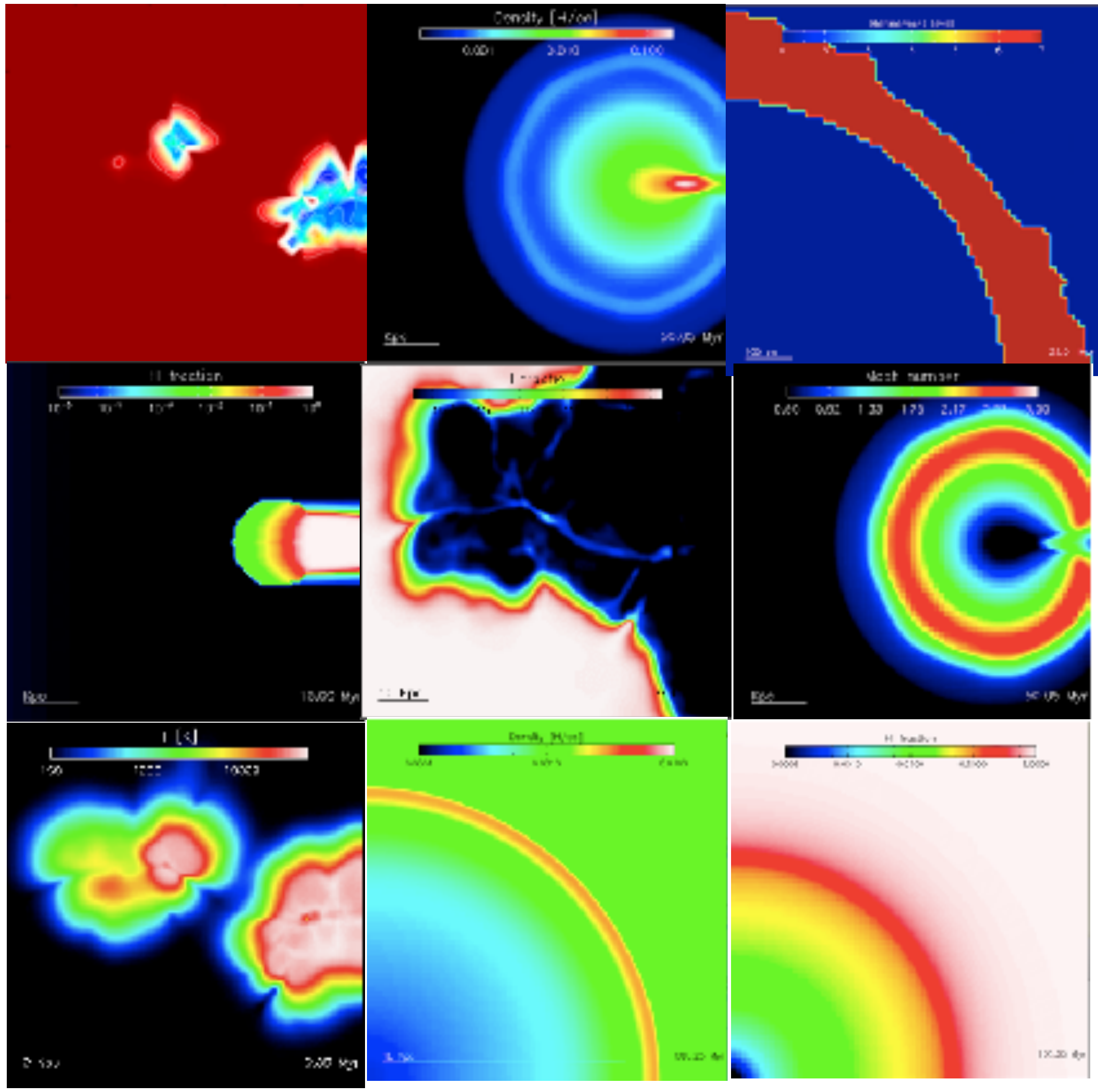
Pure RT:

1) Isothermal HII region expansion
2) HII region expansion with cooling
3) Shadow test
4) Ionizing a cosmological volume

RHD:

5) HII D-type expansion
6) HII expansion in a r^{-2} density profile
7) Photo-evaporation of a dense clump

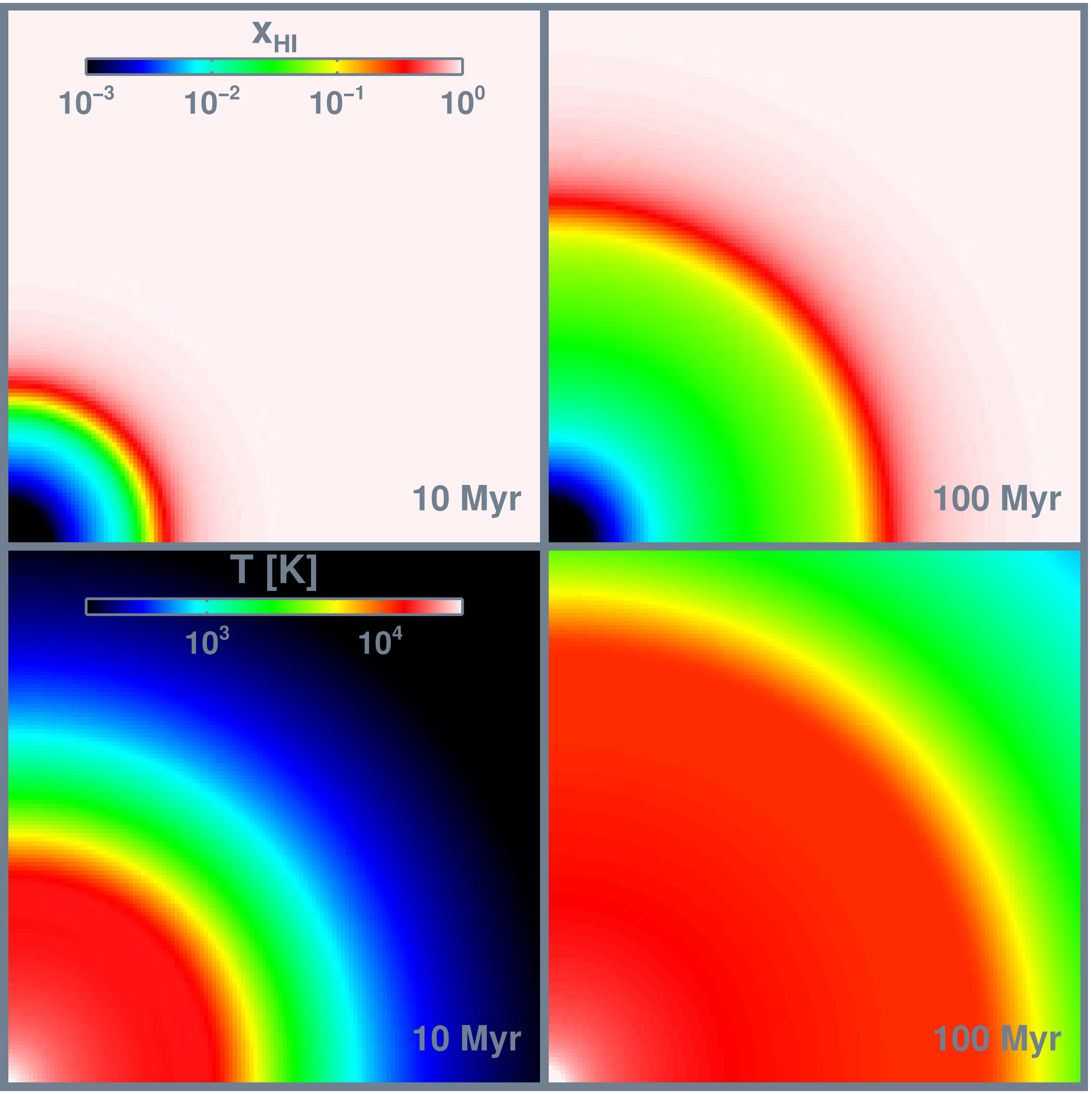
- Comparisons good, except for 4)

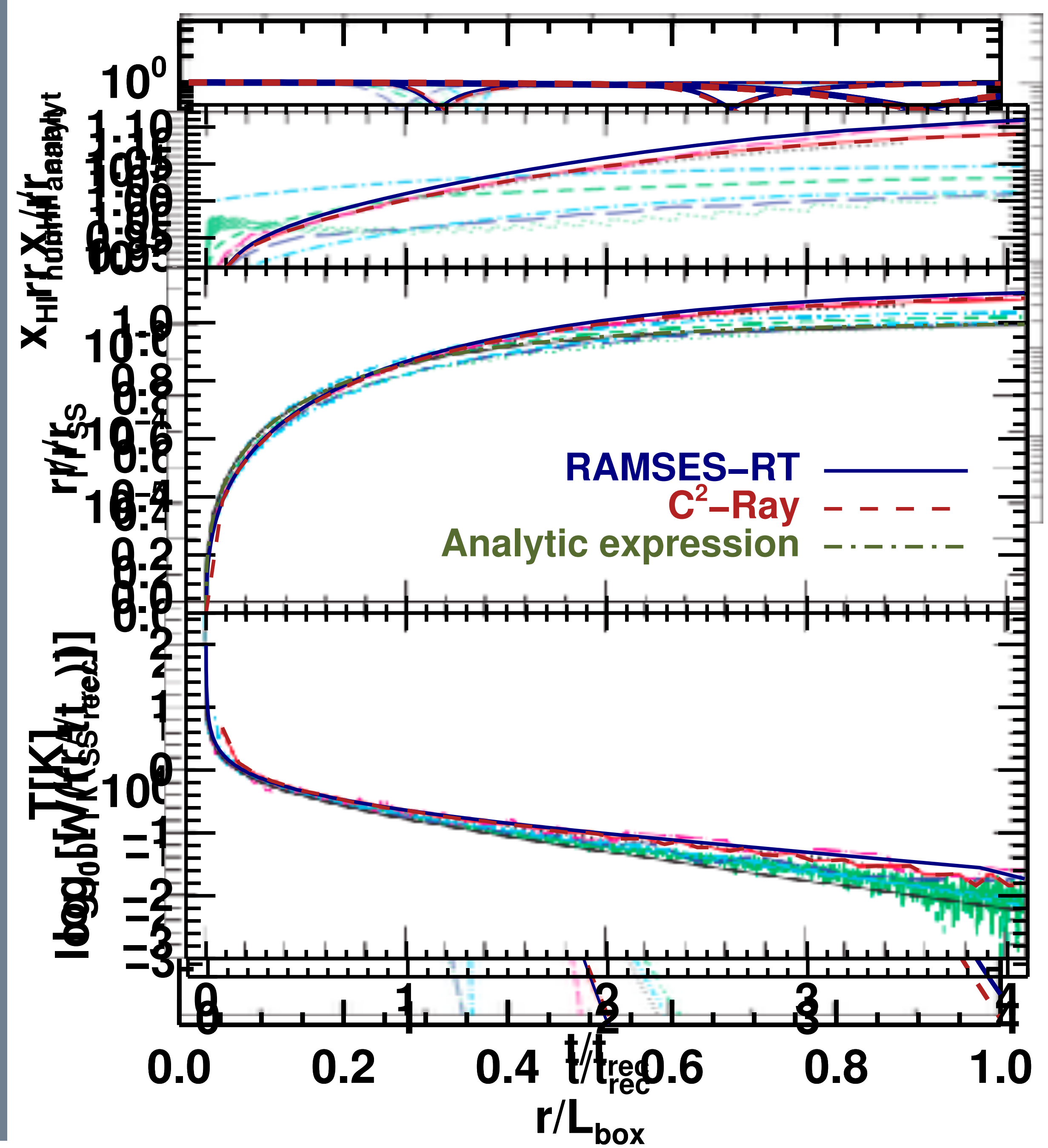


Validation tests for RamsesRT

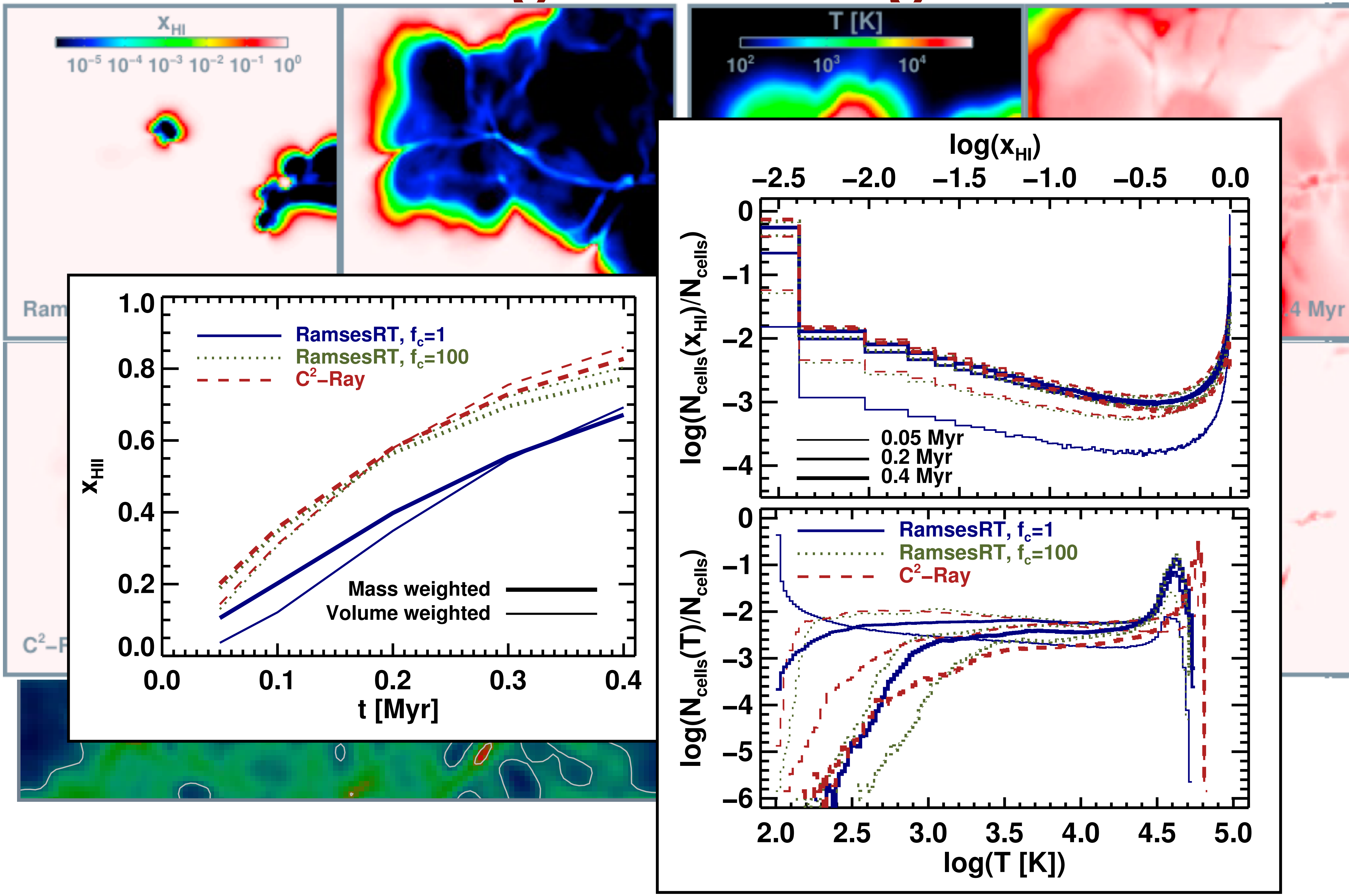
- For complete descriptions, see
  - Rosdahl et al. 2013: Standard Iliev tests
  - Rosdahl & Teyssier 2015: Radiation pressure and diffusion
  - Bisbas et al. 2015: Starbench code comparison project

Iliev 2: HII region expansion





Iliev 4: Ionizing a cosmological volume



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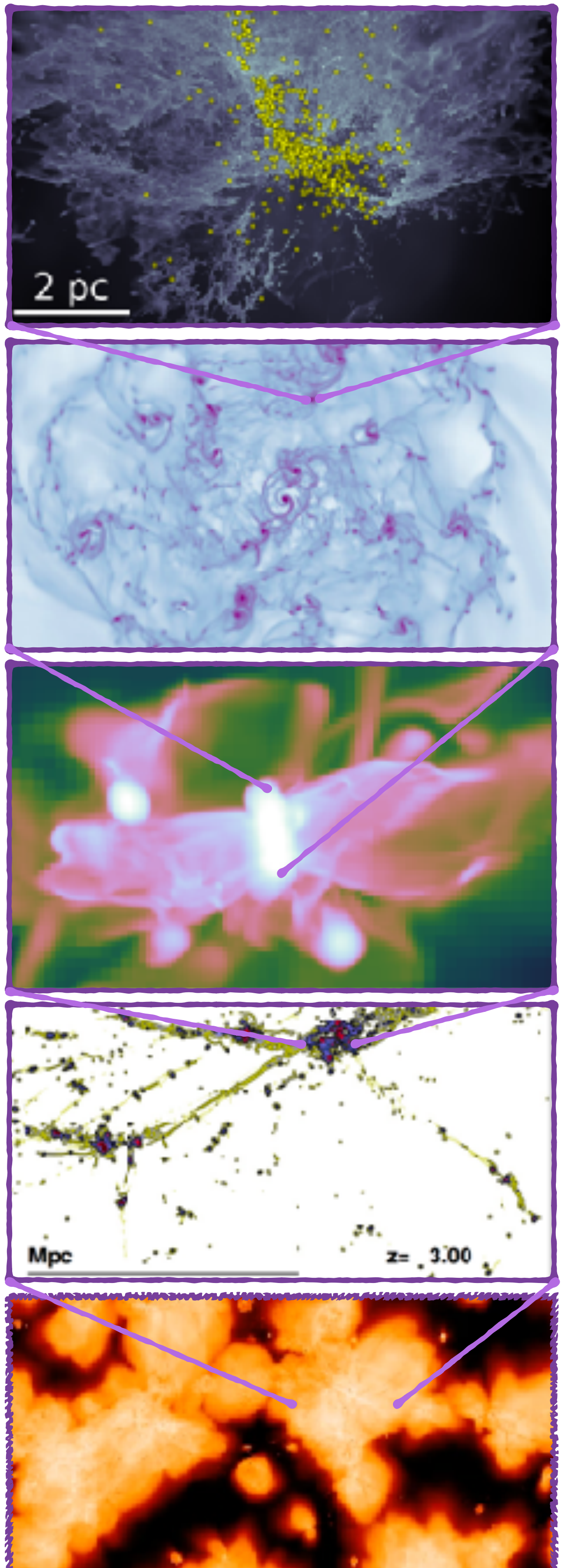
Science with RAMSES-RT



- **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)

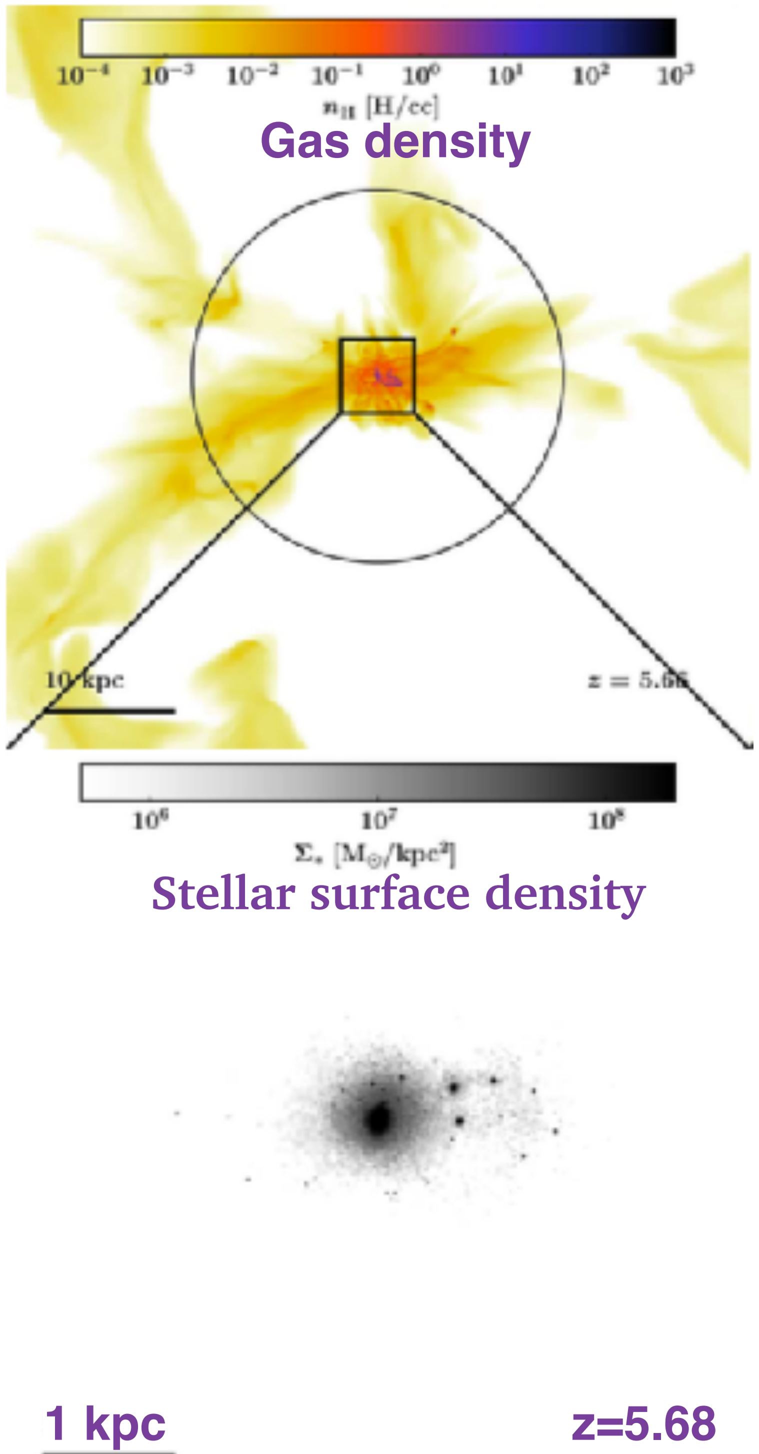
- **Feedback from active galactic nuclei**, pc to kpc scales
  Costa, Rosdahl, Sijacki, & Haehnelt (2017a,b)
  Roos, Bournaud, Renaud, Gabor, Dubois, Rosdahl, Perret, & Teyssier (2017)
  Bieri, Dubois, Rosdahl, Wagner, Silk, & Mamon (2016)

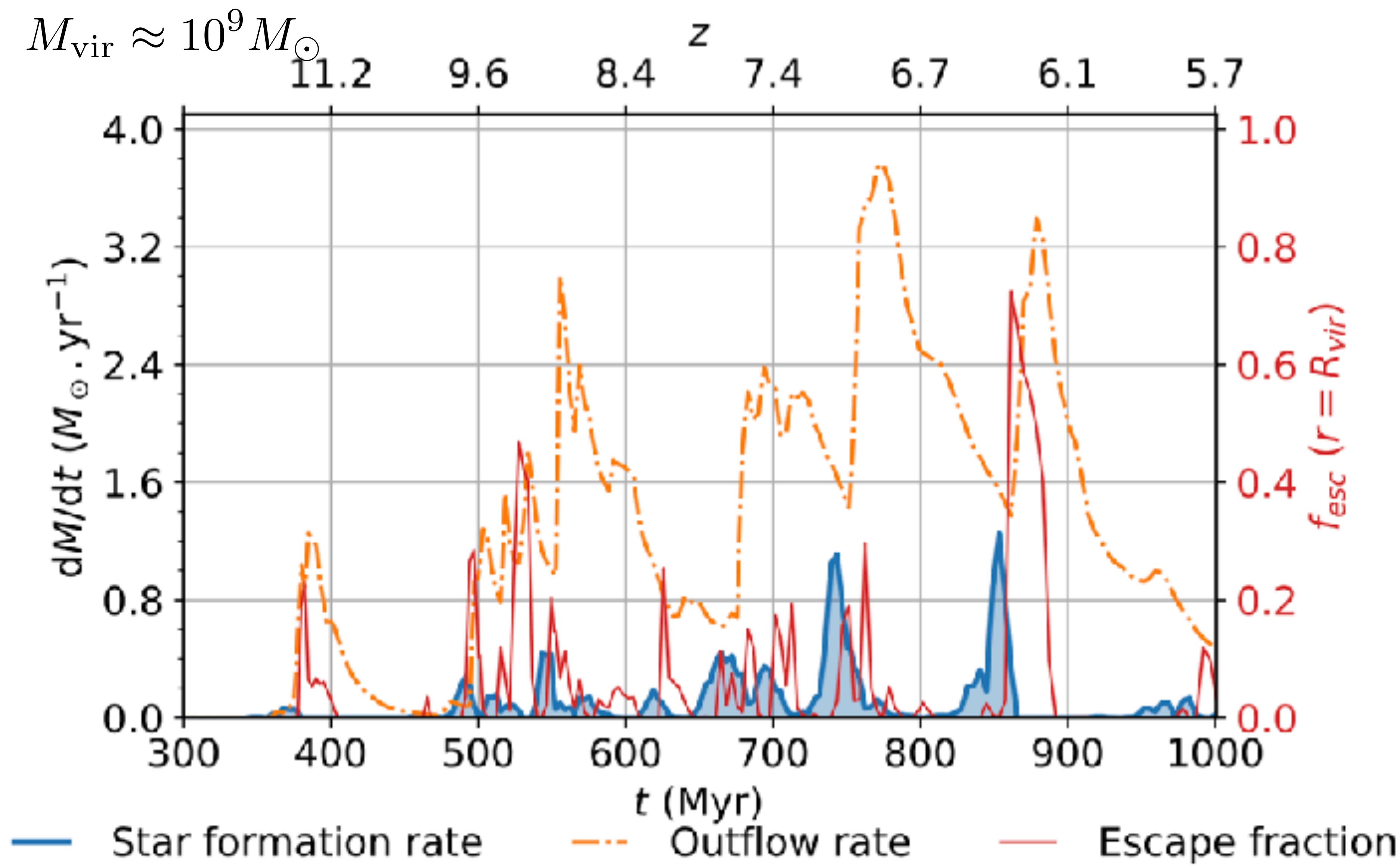
- **Properties of the circum-galactic medium**, kpc to Mpc scales
  Rosdahl & Blaizot (2012)
  Trebitsch, Verhamme, Blaizot, & Rosdahl (2016)

- **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)

UV escape from galaxies during reionisation

Trebitsch, Blaizot, Rosdahl, Devriendt, & Slyz (2017)





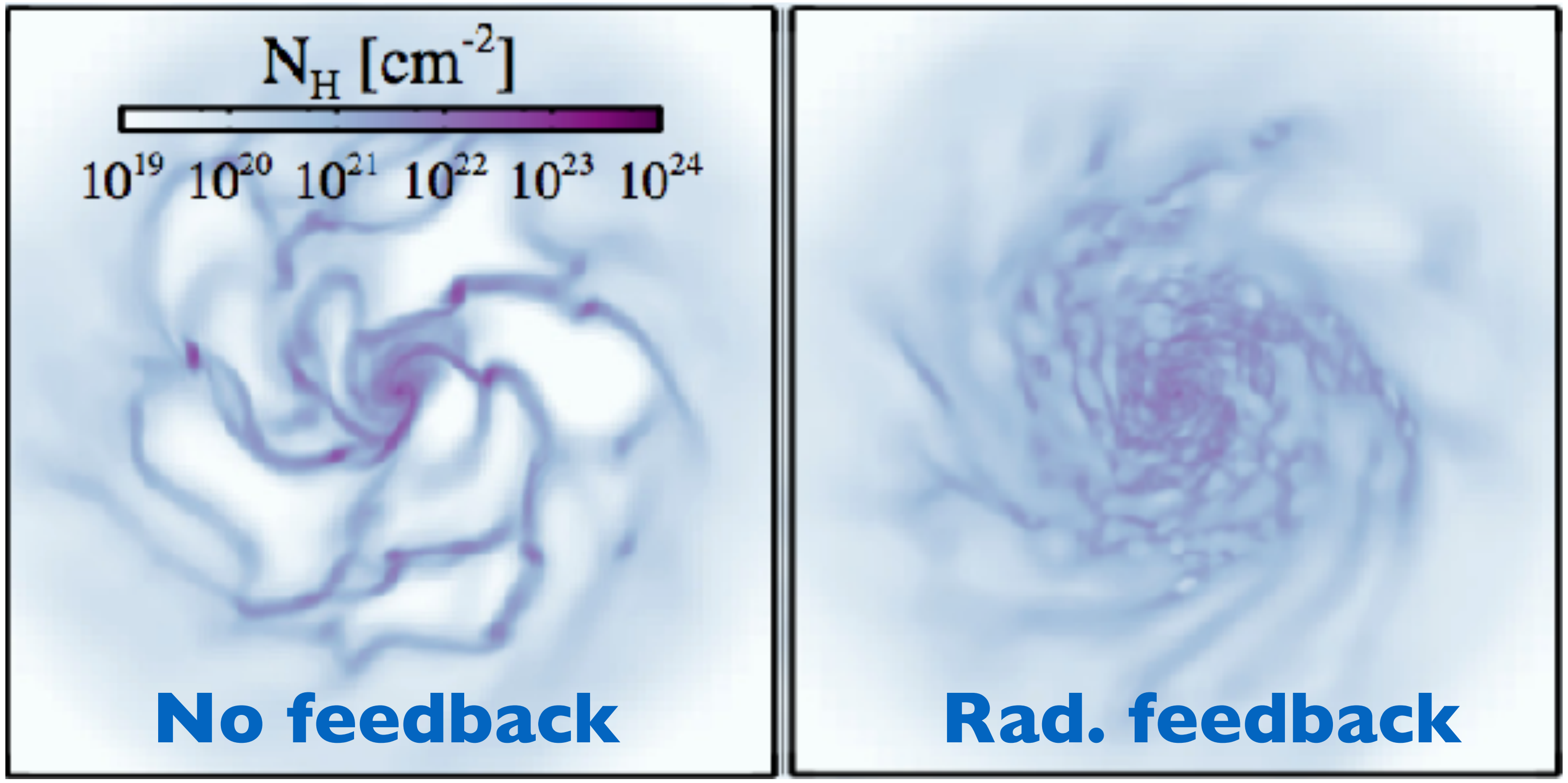
Low *average* escape fractions, *regulated* by SN explosions

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

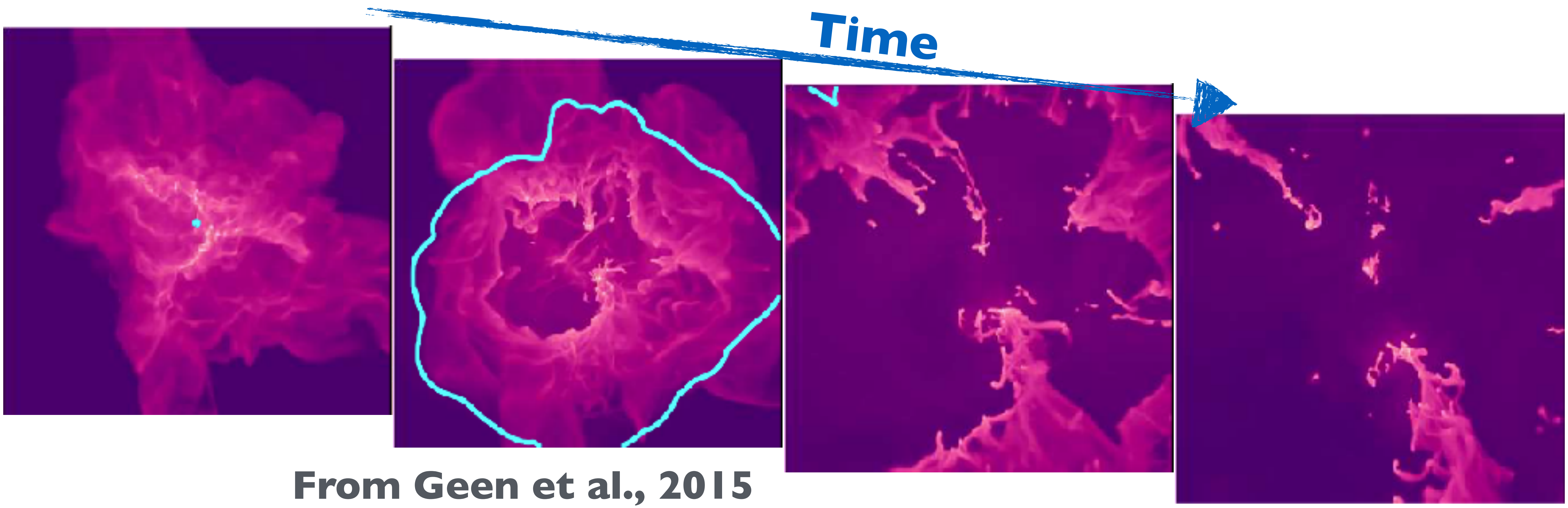


From Rosdahl et al. (2015)

Photoionisation feedback in a stellar nursery

Geen et al., 2013, 2015, 2016, 2017
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



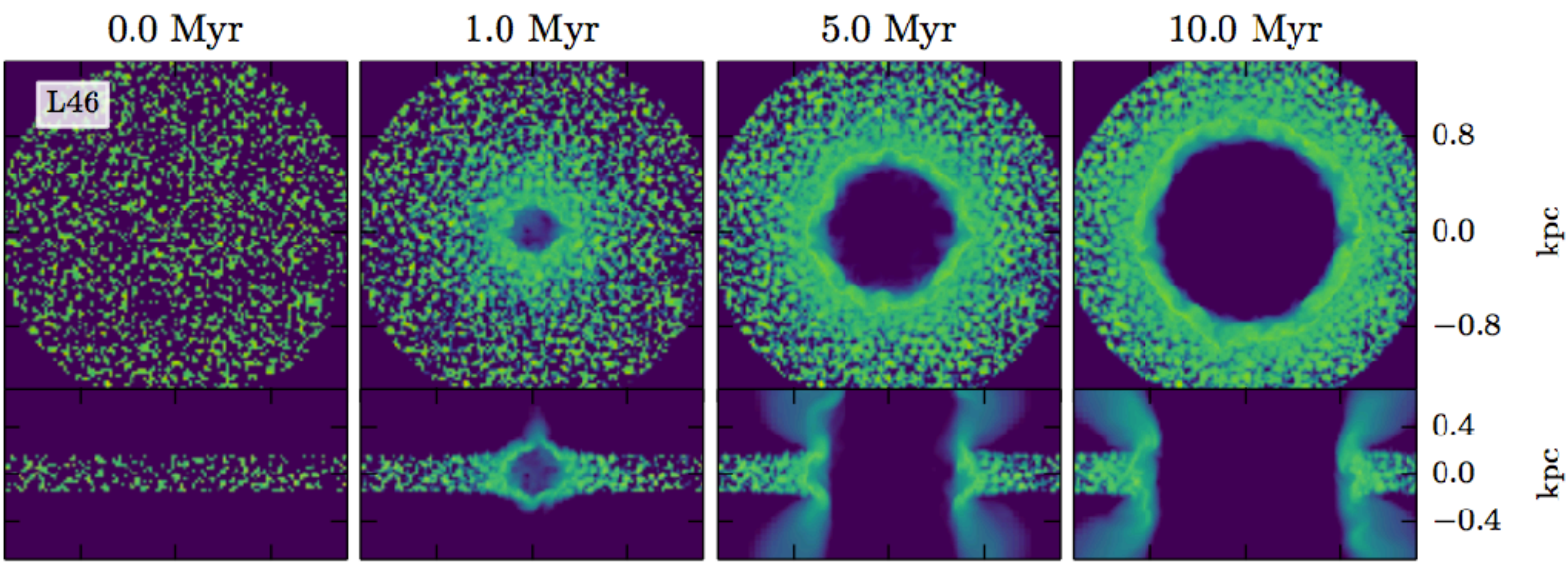
From Geen et al., 2015

Outflows driven by quasars via radiation pressure

Bieri et al. 2016

How efficiently can multiscattering IR radiation generate AGN outflows?

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



The radiation can push out fast winds, but the boost is much weaker than tau.

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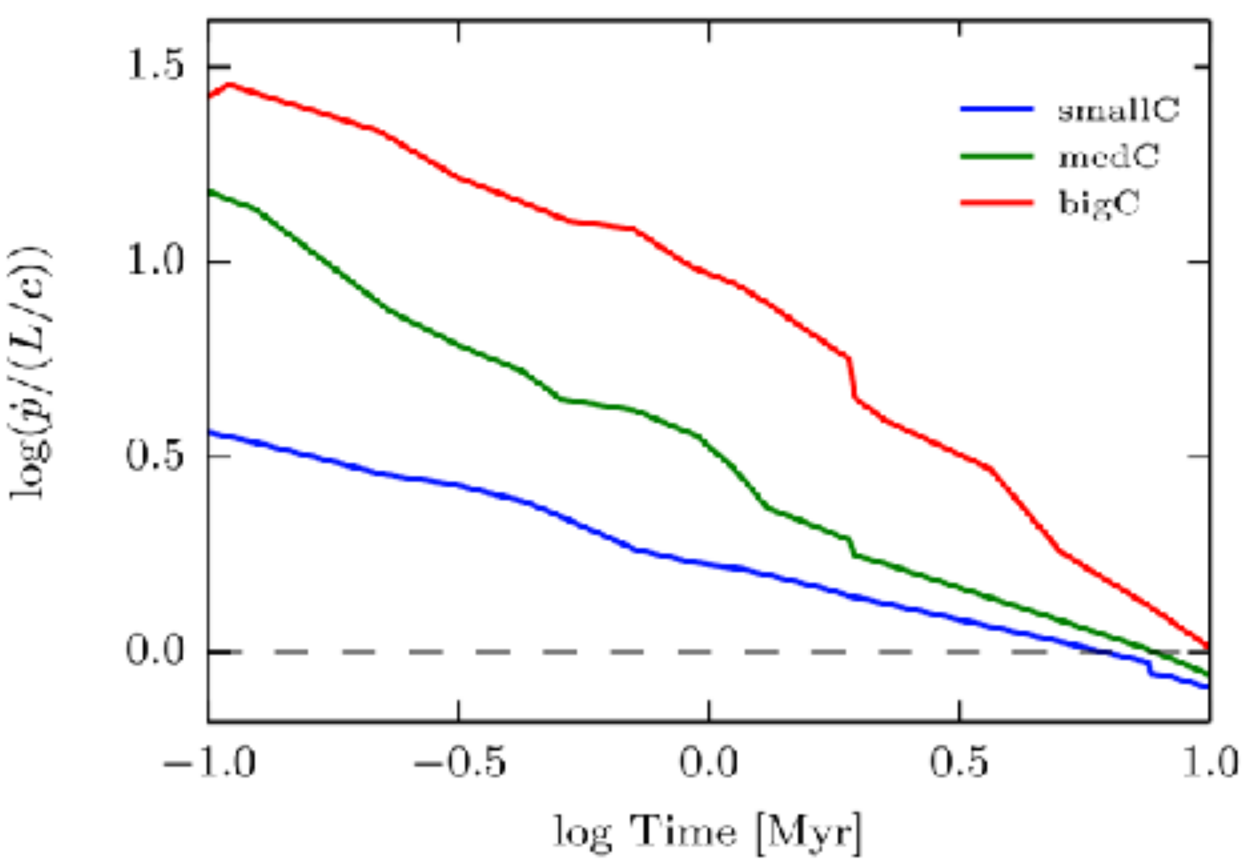

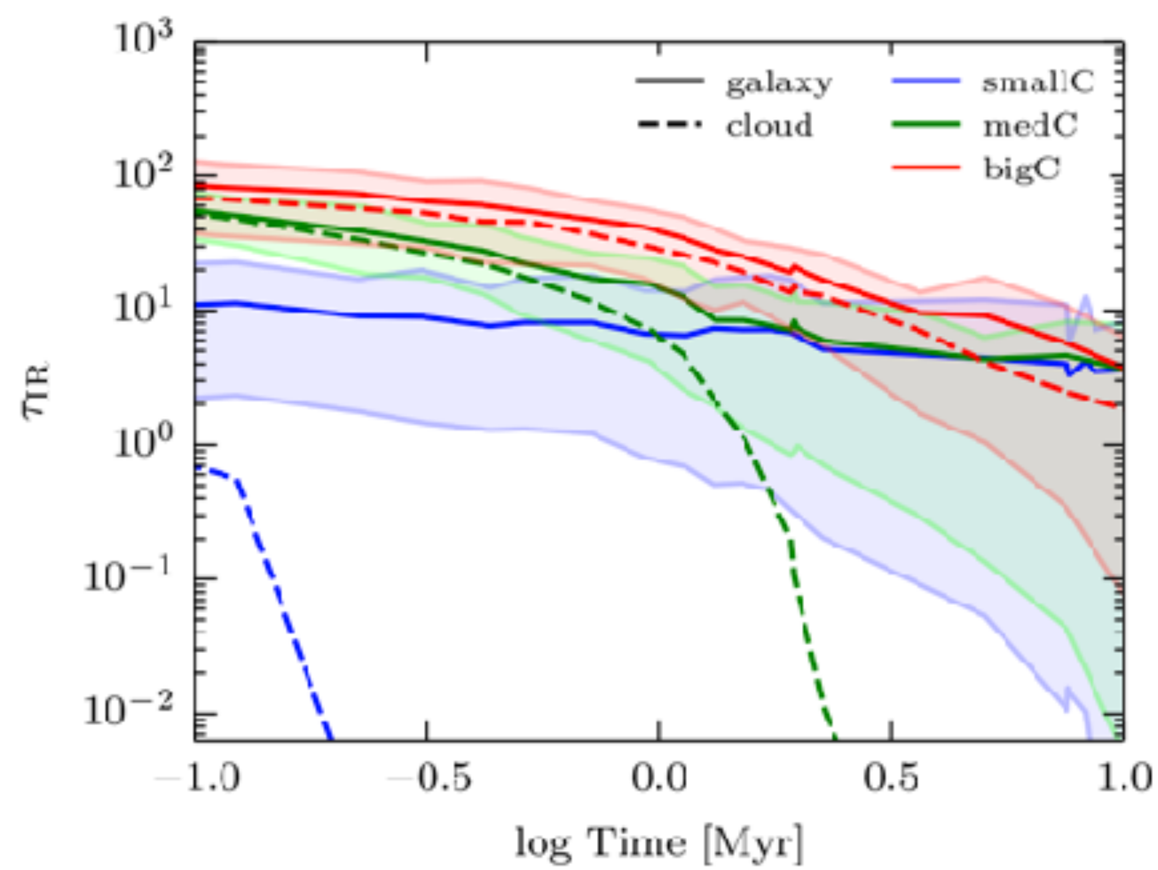

The radiation can push out fast winds, but the boost is much weaker than tau.

Future developments in Ramses-RT

- Speedup:
  - Implicit RT solver to get rid of reduced light speed?
    - Not clear if there is always an advantage…the system should preferrably 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