Reionisation with cosmological radiation-hydrodynamics using RAMSES-RT

Joki Rosdahl

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

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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

Analytic models require an ionising radiation escape fraction of

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

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

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

We use simulations to try and understand these discrepancies

From Robertson et al. (2015)
What can we learn from simulations?

- Escape of radiation from galaxies; $f_{\text{esc}}$
- 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
- RAMSES (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.

Expanding warm HII
T\sim10^4 \text{ K}

Cold HI

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

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

To solve this numerically, we need to overcome two main problems:
The radiative transfer equation
main challenges in numerical approaches

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

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

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

- \( I_{\nu}(x, n, t) \): intensity
- \( \kappa_{\nu}(x, n, t) \): absorption
- \( \eta_{\nu}(x, n, t) \): 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 \( \sim \) thousand RT steps per hydro step!!
The radiative transfer equation
main challenges in numerical approaches

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

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 parallelization
   • …no problem with covering the volume
   • …no limit to number of radiation sources
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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
\( \kappa_\nu (\mathbf{x}, \mathbf{n}, t) \) absorption
\( \eta_\nu (\mathbf{x}, \mathbf{n}, t) \) source function

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

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

These equations contain the first three moments of the intensity:

\[ \frac{1}{c} \frac{\partial}{\partial t} \int I_\nu \, d\Omega + \nabla \int \mathbf{n} I_\nu \, d\Omega = -\kappa_\nu \int I_\nu \, d\Omega + \eta_\nu \int \, d\Omega. \]

\[ \frac{1}{c} \frac{\partial}{\partial t} \int \mathbf{n} I_\nu \, d\Omega + \nabla \int \mathbf{n} \otimes \mathbf{n} I_\nu \, d\Omega = -\kappa_\nu \int \mathbf{n} I_\nu \, d\Omega. \]

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

\[ f_\nu = \int \mathbf{n} I_\nu \, d\Omega \] (energy flux per area and time and frequency)

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

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

\[ \frac{\partial \mathbf{f}_\nu}{\partial t} + c^2 \nabla \cdot \mathbf{p}_\nu = -\kappa_\nu c \mathbf{f}_\nu \]
With ionising radiation, it makes more sense to keep track of *photon number density* than energy density.
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.

\[
\frac{\partial N_\nu}{\partial t} + \nabla \cdot F_\nu = - \sum_{j} n_j c \sigma_{\nu j} N_\nu + \dot{N}_\nu^* + \dot{N}_\nu^{rec}
\]

\[
\frac{\partial F_\nu}{\partial t} + c^2 \nabla \cdot P_\nu = - \sum_{j} n_j c \sigma_{\nu j} F_\nu
\]

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

\[
\frac{\partial N_i}{\partial t} + \nabla \cdot F_i = - \sum_{j} n_j c \sigma_{ij} N_i + \dot{N}_i^* + \dot{N}_i^{rec}
\]

\[
\frac{\partial F_i}{\partial t} + c^2 \nabla \cdot P_i = - \sum_{j} n_j c \sigma_{ij} F_i
\]
Radiation variables, stored in each cell
one set per photon group (neglecting the i-index)

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

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

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

A combination:

The ‘directionality’ can be described by the reduced flux:

\[ f \equiv \frac{|\mathbf{F}|}{cN}, \quad 0 \leq f \leq 1 \]

We almost have usable expressions - we ‘only’ need to close the equations
Closing the moment RT equations

\[
\frac{\partial N}{\partial t} + \nabla \cdot F = - \sum_{j} n_j \sigma_j c N + \dot{N}^* + \dot{N}^{rec}
\]

\[
\frac{\partial F}{\partial t} + c^2 \nabla \cdot P = - \sum_{j} n_j \sigma_j c F
\]

\[
P = DN \quad \text{Eddington tensor}
\]

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

\( N(x, t) \) photon density
\( F(x, t) \) photon flux
\( P(x, t) \) photon ‘pressure’
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*
Solving the M1 moment RT equations on a uniform grid

\[
\frac{\partial N}{\partial t} + \nabla \cdot \mathbf{F} = - \sum_{j} n_j \sigma_j c N + \dot{N}^* + \dot{N}^{rec}
\]

\[
\frac{\partial \mathbf{F}}{\partial t} + c^2 \nabla \cdot \mathbf{P} = - \sum_{j} n_j \sigma_j c \mathbf{F}
\]

\[
\mathbf{P} = \mathbb{D} N
\]
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** \( \Delta t \):

I. **Photon transport** between adjacent cells

II. **Injection into cells**

III. **Thermochemistry in every cell**
Photon transport

\[
\frac{\partial N}{\partial t} + \nabla \cdot \mathbf{F} = - \sum_j n_j \sigma_j c N + \dot{N}^\star + \dot{N}^{rec}
\]

\[
\frac{\partial \mathbf{F}}{\partial t} + c^2 \nabla \cdot \mathbf{P} = - \sum_j n_j \sigma_j c \mathbf{F}
\]

\[
\mathbf{P} = DN
\]

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

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

\[
\frac{\partial \mathbf{F}}{\partial t} + c^2 \nabla \cdot \mathbf{P} = 0,
\]
Photon transport

\[ \mathcal{F}_{l,k+1} \]
\[ \mathcal{F}_{l-1,k} \]
\[ \mathcal{U}_{l,k} \]
\[ \mathcal{F}_{l,k-1} \]

\[ \mathcal{U} \equiv (N, \mathbf{F}) \]
\[ \mathcal{F} \equiv (\mathbf{F}, c^2 \mathbb{P}) \]

\[
\begin{align*}
\frac{\partial N}{\partial t} + \nabla \cdot \mathbf{F} &= 0 \\
\frac{\partial \mathbf{F}}{\partial t} + c^2 \nabla \cdot \mathbb{P} &= 0
\end{align*}
\]

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

Explicit time discretisation:

\[ t^{n+1} = t^n + \Delta t \]

\[ \mathcal{U}^{n+1}_l = \mathcal{U}^n_l + \frac{\Delta t}{\Delta x} \left( \mathcal{F}^n_{l-1/2} - \mathcal{F}^n_{l+1/2} \right) \]
Intercell flux function

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

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

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

How do we pick \( \mathcal{F}_{l+1/2} \)?

Simplest case is average between cells:

Harten-Lax-van Leer - HLL:

\[ \mathcal{F}_{l+1/2} = \frac{\mathcal{F}_{l+1} + \mathcal{F}_{l+1}}{2} \]

\[ \mathcal{F}_{l+1/2} = \frac{\mathcal{F}_{l+1} + \mathcal{F}_{l+1}}{2} \]

\[ \lambda^+ = \max(0, \lambda_l^{\text{max}}, \lambda_{l+1}^{\text{max}}) \]

\[ \lambda^- = \min(0, \lambda_l^{\text{min}}, \lambda_{l+1}^{\text{min}}) \]

\( \lambda^+ \) = angle-dependent ‘speeds’ = eigenvalues of \( \frac{\partial \mathcal{F}}{\partial \mathcal{U}} \)
a simpler flux function

**HLL:** \[ \mathcal{F}_{l+1/2} = \frac{\lambda^+ \mathcal{F}_l - \lambda^- \mathcal{F}_{l+1} + \lambda^+ \lambda^- (U_{l+1} - U_l)}{\lambda^+ - \lambda^-} \]

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:** \[ \mathcal{F}_{l+1/2} = \frac{\mathcal{F}_l + \mathcal{F}_{l+1}}{2} - \frac{c}{2} (U_{l+1} - U_l) \]

The resulting photon transport is more diffusive than HLL, which is both good and bad.
HLL vs GLF transport of photons

...I generally prefer GLF
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: $x_{\text{HII}}, x_{\text{HeII}}, x_{\text{HeIII}}$.

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

\[ \Delta t \lesssim \frac{\Delta x}{u} \]

\[ \Delta t_{RT} \sim \frac{\Delta x}{c} \sim \frac{\Delta t_{HD}}{1000} \]
The reduced speed of light approximation (RSLA)  
Gnedin & Abel 2001

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

\[ c_{\text{red}} = \frac{c}{1000} \quad \Rightarrow \quad \Delta t_{\text{RT}} \sim \frac{\Delta x}{c_{\text{red}}} \sim \Delta t_{\text{HD}} \]

\[ \Rightarrow \text{Only } \sim 2 \times \text{ runtime increase, compared to pure hydro} \]

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...

<table>
<thead>
<tr>
<th>Regime</th>
<th>$n_H$ (cm$^{-3}$)</th>
<th>$\dot{N}$ (s$^{-1}$)</th>
<th>$r_S$ (kpc)</th>
<th>$t_{\text{cross}}$ (Myr)</th>
<th>$t_{\text{rec}}$ (Myr)</th>
<th>$\tau_{\text{sim}}$ (Myr)</th>
<th>$f_{c, \text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW ISM</td>
<td>$10^{-1}$</td>
<td>$2 \times 10^{50}$</td>
<td>0.9</td>
<td>$3 \times 10^{-3}$</td>
<td>1.2</td>
<td>1</td>
<td>$3 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$10^2$</td>
<td>$2 \times 10^{48}$</td>
<td>$2 \times 10^{-3}$</td>
<td>$6 \times 10^{-6}$</td>
<td>$1 \times 10^{-3}$</td>
<td>0.1</td>
<td>$6 \times 10^{-4}$</td>
</tr>
<tr>
<td>Iliev tests 1, 2, 5</td>
<td>$10^{-3}$</td>
<td>$5 \times 10^{48}$</td>
<td>5.4</td>
<td>$2 \times 10^{-2}$</td>
<td>122.3</td>
<td>10</td>
<td>$2 \times 10^{-2}$</td>
</tr>
<tr>
<td>Iliev test 4</td>
<td>$10^{-4}$</td>
<td>$7 \times 10^{52}$</td>
<td>600</td>
<td>2</td>
<td>1200</td>
<td>0.05</td>
<td>1</td>
</tr>
</tbody>
</table>

Reionisation

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

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 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).

This makes it possible, for the first time, to perform large-scale reionisation simulations that resolve individual galaxies.
The variable speed of light approximation (VSLA)

From Katz et al. 2017

3-100 %
3%
light speed
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### Ramses hydrodynamics

<table>
<thead>
<tr>
<th>Conservation of mass:</th>
<th>$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conservation of momentum:</td>
<td>$\frac{\partial}{\partial t} (\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) + \nabla p = \rho \nabla \phi$</td>
</tr>
<tr>
<td>Conservation of energy:</td>
<td>$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot (\varepsilon + p) \mathbf{u} = -\rho \mathbf{u} \cdot \nabla \phi + \Lambda(\rho, \varepsilon)$</td>
</tr>
</tbody>
</table>

**Closure:**
- Equation of state: $p = (\gamma - 1)\varepsilon$
- Kinetic vs. thermal energy: $\varepsilon = \frac{1}{2}\rho \mathbf{u}^2 + \varepsilon$

- Gravitational potential $\phi$ 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 $\Lambda$ is subcycled on every gravito-hydro timestep.
RHD: Coupling hydrodynamics and RT

HD equations solved in Ramses:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) &= 0 \\
\frac{\partial}{\partial t} (\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) + \nabla p &= \rho \nabla \phi \\
\frac{\partial \mathcal{E}}{\partial t} + \nabla \cdot (\mathcal{E} + p) \mathbf{u} &= -\rho \mathbf{u} \cdot \nabla \phi + \Lambda(\rho, \mathcal{E}) \\
p &= (\gamma - 1) \mathcal{E} \\
\mathcal{E} &= \frac{1}{2} \rho \mathbf{u}^2 + \mathcal{E}
\end{align*}
\]

Considerations:
- \( \Delta t_{\text{hydro}} >> \Delta t_{\text{RT}} >> \Delta t_{\text{chemistry}} \)
- The coupling happens in \( \Lambda \) (i.e., the thermochemistry)

\[\Rightarrow \text{Operator splitting:} \]
The thermochemistry is subcycled within the RT, which is subcycled within the hydrodynamics.

RT equations:

\[
\begin{align*}
\frac{\partial N}{\partial t} + \nabla \cdot \mathbf{F} &= - \sum_{j}^{\text{H}_1, \text{He}_1, \text{He}_\text{II}} n_j \sigma_j c N + \dot{N}^* + \dot{N}^{\text{rec}} \\
\frac{\partial \mathbf{F}}{\partial t} + c^2 \nabla \cdot \mathbf{P} &= - \sum_{j}^{\text{H}_1, \text{He}_1, \text{He}_\text{II}} n_j \sigma_j c \mathbf{F} \\
\mathbf{P} &= \mathbb{D} N \\
\frac{\partial \mathcal{E}}{\partial t} &= \Lambda(\rho, \mathcal{E}, n_j, N_i)
\end{align*}
\]
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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)
  Rosdahl et al. (2018)
Two classes of reionisation simulations

**Large volume with unresolved galaxies**
- Representative volume on nearly homogeneous scale and statistical samples of (massive) halos.
- But galaxies are unresolved. $f_{\text{esc}}$ 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.

**Tiny volume with one or a few well resolved galaxies**
- Production of ionising radiation and $f_{\text{esc}}$ resolved.
- But the large scale reionisation process is not captured (nor the actual contribution from individual sources).

(Gap) So far impossible
Large volume simulations of reionisation

**COsmic DAwn (CODA)**
Ocvirk et al, 2015

- $f_{\text{esc}}$ 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 $f_{\text{esc}}$ 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:

$f_{\text{esc}}$ is far from constant and heavily regulated by supernova (SN) feedback
Two classes of reionisation simulations

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<th>(Gap) [ \text{So far simulations} ]</th>
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</table>

Sphinx is mainly made possible by moment-based RT and the variable speed-of-light
The SPHINX Cosmological Simulations of the First Billion Years: the Impact of Binary Stars on Reionization

Joakim Rosdahl\textsuperscript{1,\dagger}, Harley Katz\textsuperscript{2,3}, Jérémie Blaizot\textsuperscript{1}, Taysun Kimm\textsuperscript{4,3}, Léo Michel-Dansac\textsuperscript{1}, Thibault Garel\textsuperscript{1}, Martin Haehnelt\textsuperscript{3}, Pierre Ocvirk\textsuperscript{5}, and Romain Teyssier\textsuperscript{6}.

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The Sphinx simulations in context

Volume needed to capture $10^{12}$ M\(\odot\) halos

Cosmological homogeneity scale

The plot shows the spatial resolution at $z=6$ [pc] versus the box size [cMpc]. The data points represent various simulations including SPHINX, Finlator+11, Iliev+13, Gnedin+14, So+14, Pawlik+15, Ocvirk+15, and Chen+17. The plot also highlights large star-forming clouds and typical galaxy sizes.
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?**
• Post-processing pure-hydro zoom simulations, Ma et al. (2016) predict 4-10 times boosted $f_{\text{esc}}$ (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 Synthesis from Eldridge et al.

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

*Graph showing the comparison of light curves for different models and metallicities.*

Before: Radiation absorbed by dense ISM

After: ISM disrupted and radiation escapes

~ 3 Myr: Massive stars start to explode
Setup of the Sphinx simulations
Sphinx simulations

5 cMpc box with high mass resolution

10 cMpc box with lower mass 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 $3 \times 10^5$ (8 times less in 5 Mpc box).
  $10^8 M_\odot$ halo has 300 (2,500) particles $\gg$ 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 $f_{\text{esc}}$** (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
Reionisation history
binary vs single SEDs

Much more efficient reionisation with binary populations, independent of volume size and mass resolution
Binary stars and $f_{\text{esc}}$

Escape fractions for most massive halo progenitor in smaller box

$M_{\text{halo}}(z=6) \sim 10^{10} \, M_\odot$

$M_{\text{star}}(z=6) \sim 10^{8} \, M_\odot$
Binary stars and $f_{\text{esc}}$
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 $f_{\text{esc}}$ from galaxies

• Pilot Sphinx paper is just out:
  • Stellar populations with binary systems really affect reionisation, due to the interplay of feedback and $f_{\text{esc}}$!
  • Much more to come