Joakim Rosdahl

Lyon->Leiden

Cosmological simulations with *radiation-hydrodynamics*

Collaborators:

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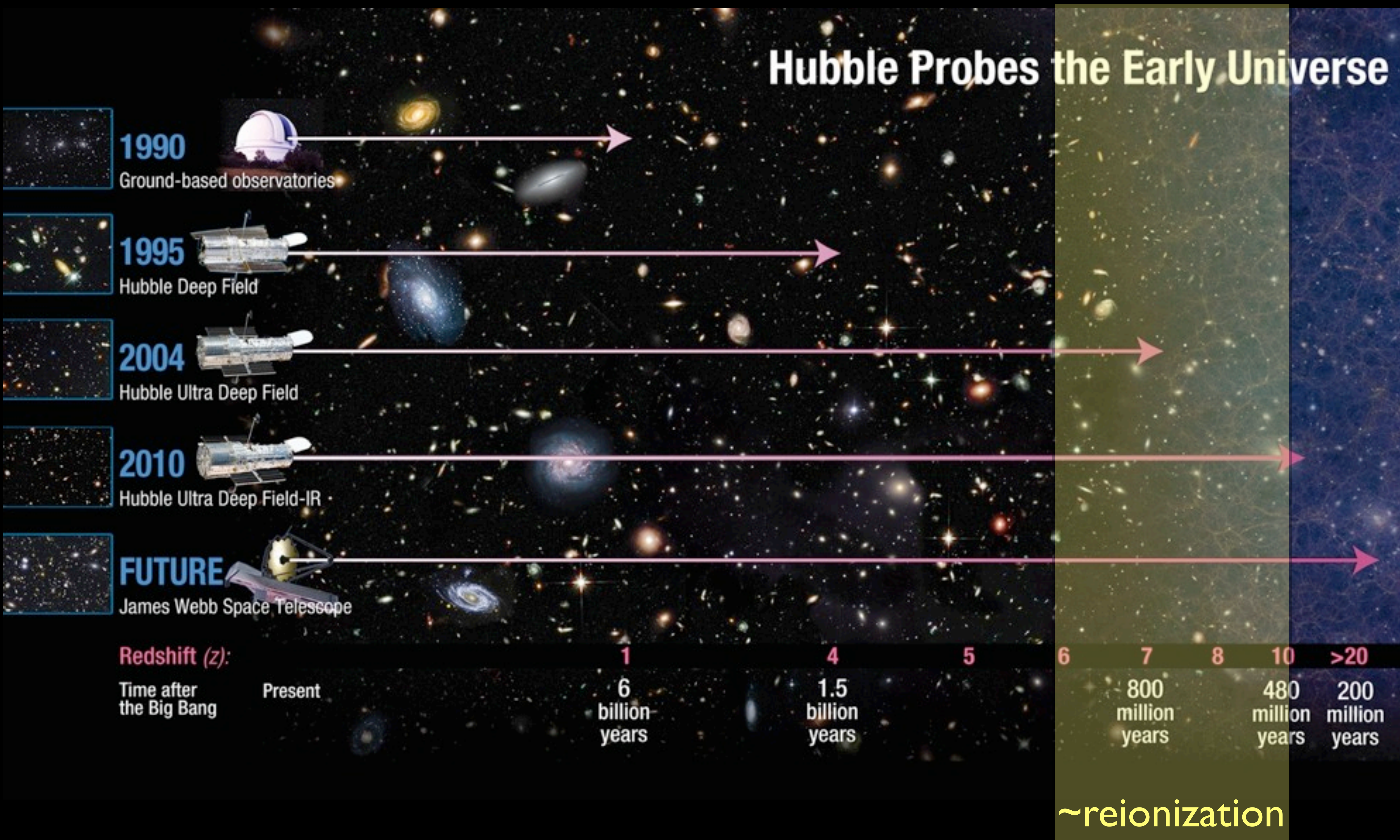
observatoire de Lyon

Final ELIXIR meeting,
Leiden, Nov 12th 2012

ELIXIR

Observing the Universe



The JWST will give us a *first* look at the epoch of reionization and the end of the dark ages

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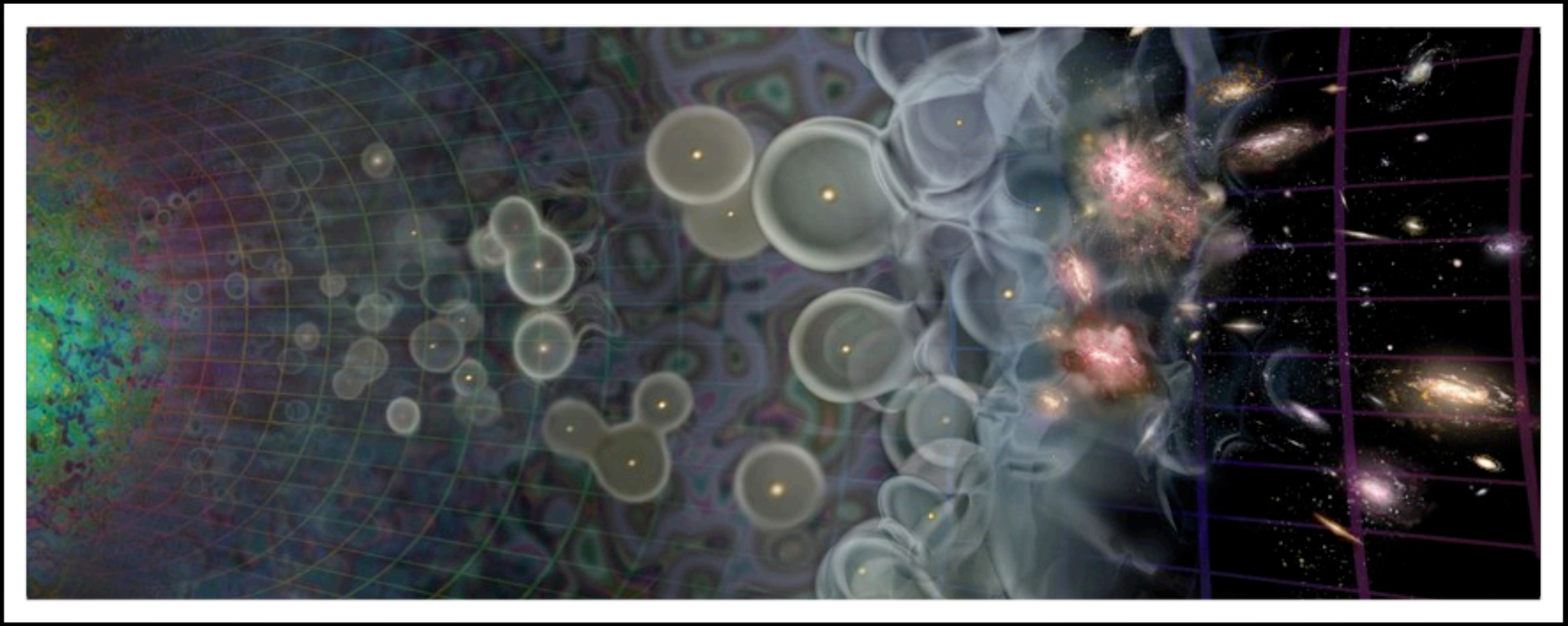
My motivations



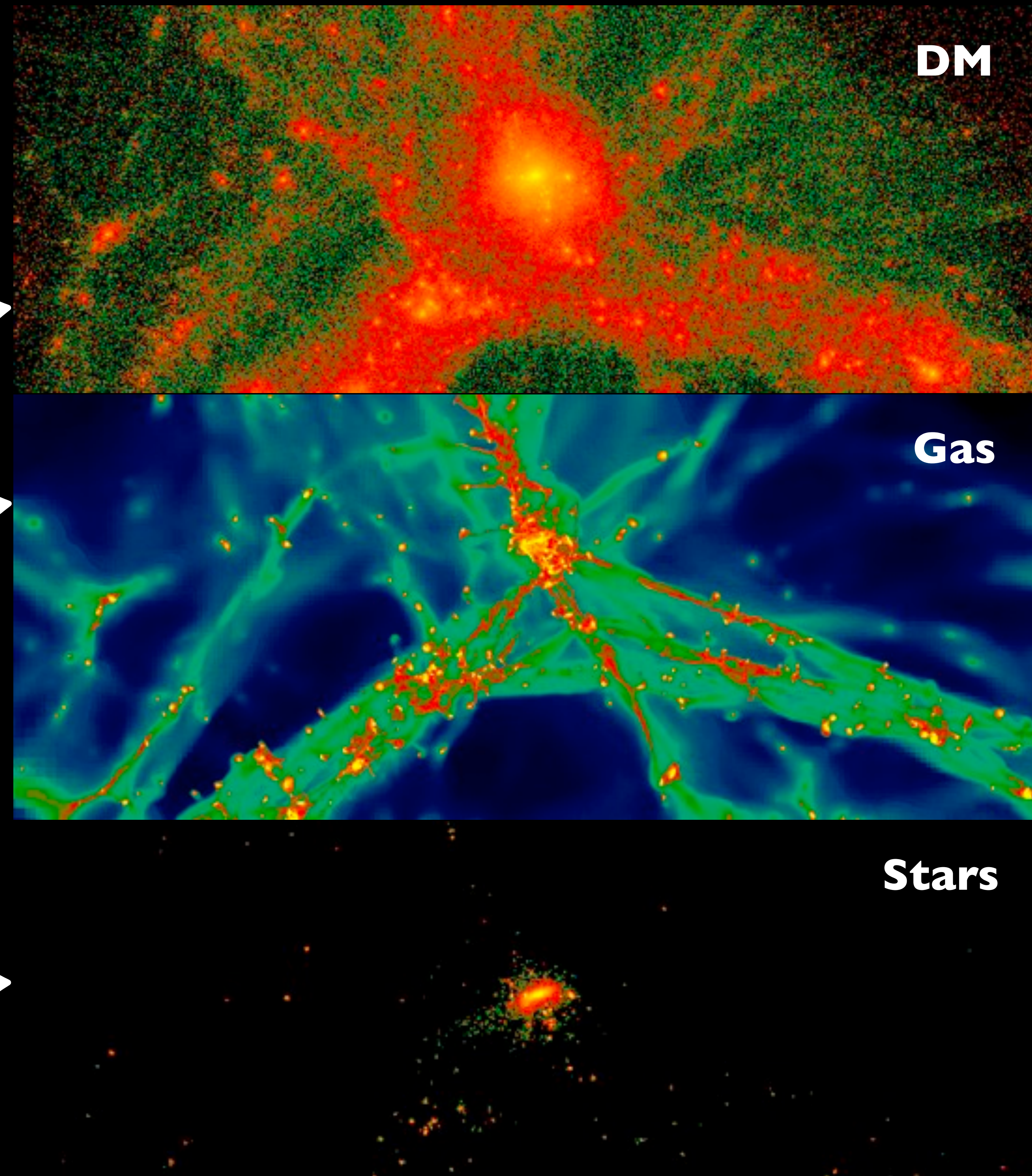
- Upcoming observations call for theory
- How did early structures form, evolve and interact with their surroundings?
- A study of this involves complex interplay of many factors
- *Simulations* are the only way to gain a detailed understanding

Cosmological simulations

A few simulation codes are available on the market

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



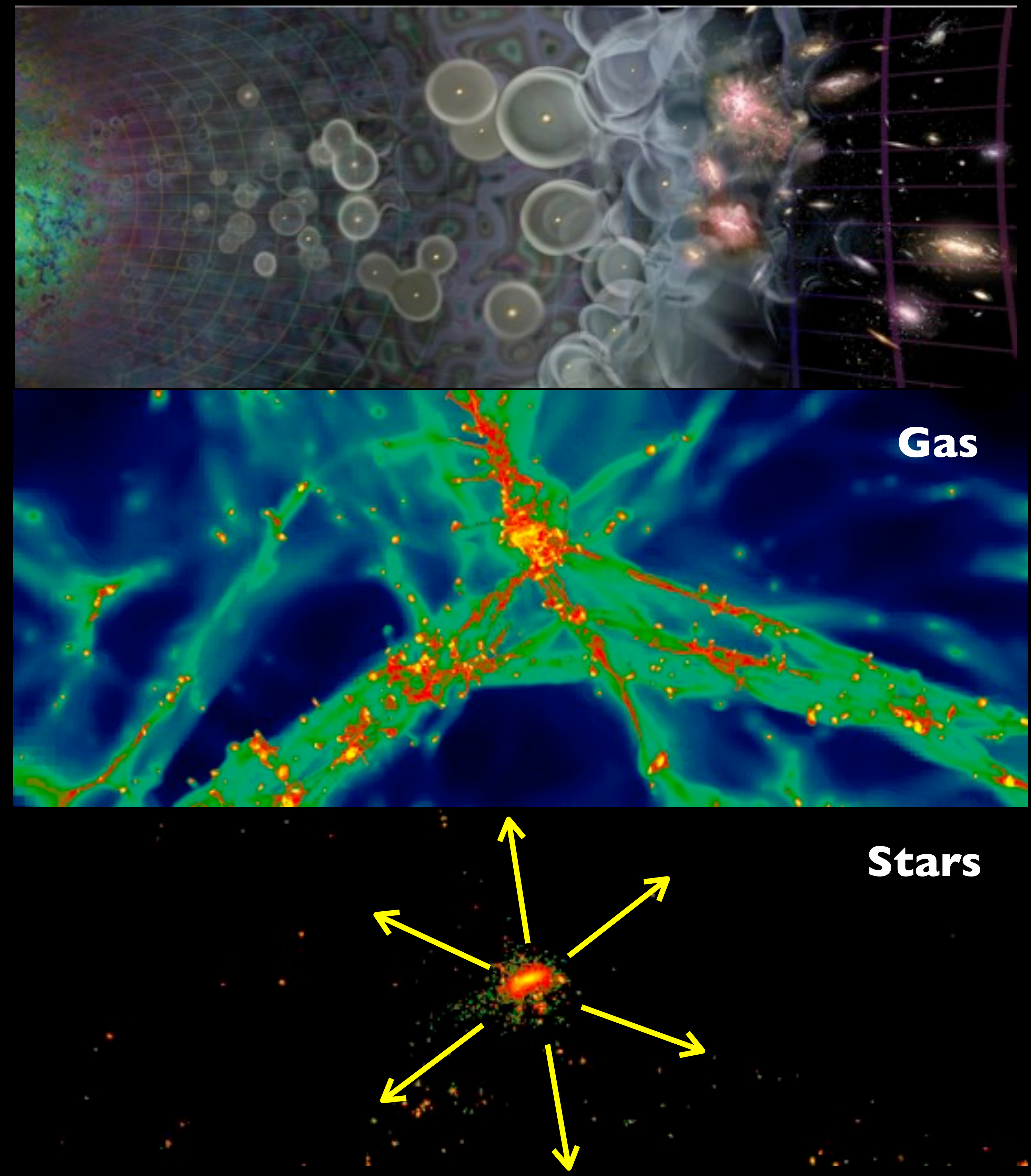
Cosmological simulations

A Fresh ingredient:
Ionizing radiation

- Especially relevant before and during reionization

- Has been neglected so far
  - Second-order component?
  - Complicated and expensive
  - ...but is on the rise, partly driven by the advent of JWST

- To simulate early galaxies, I have developed a coupled description of galaxies and light, i.e. **radiation-hydrodynamics (RHD)**



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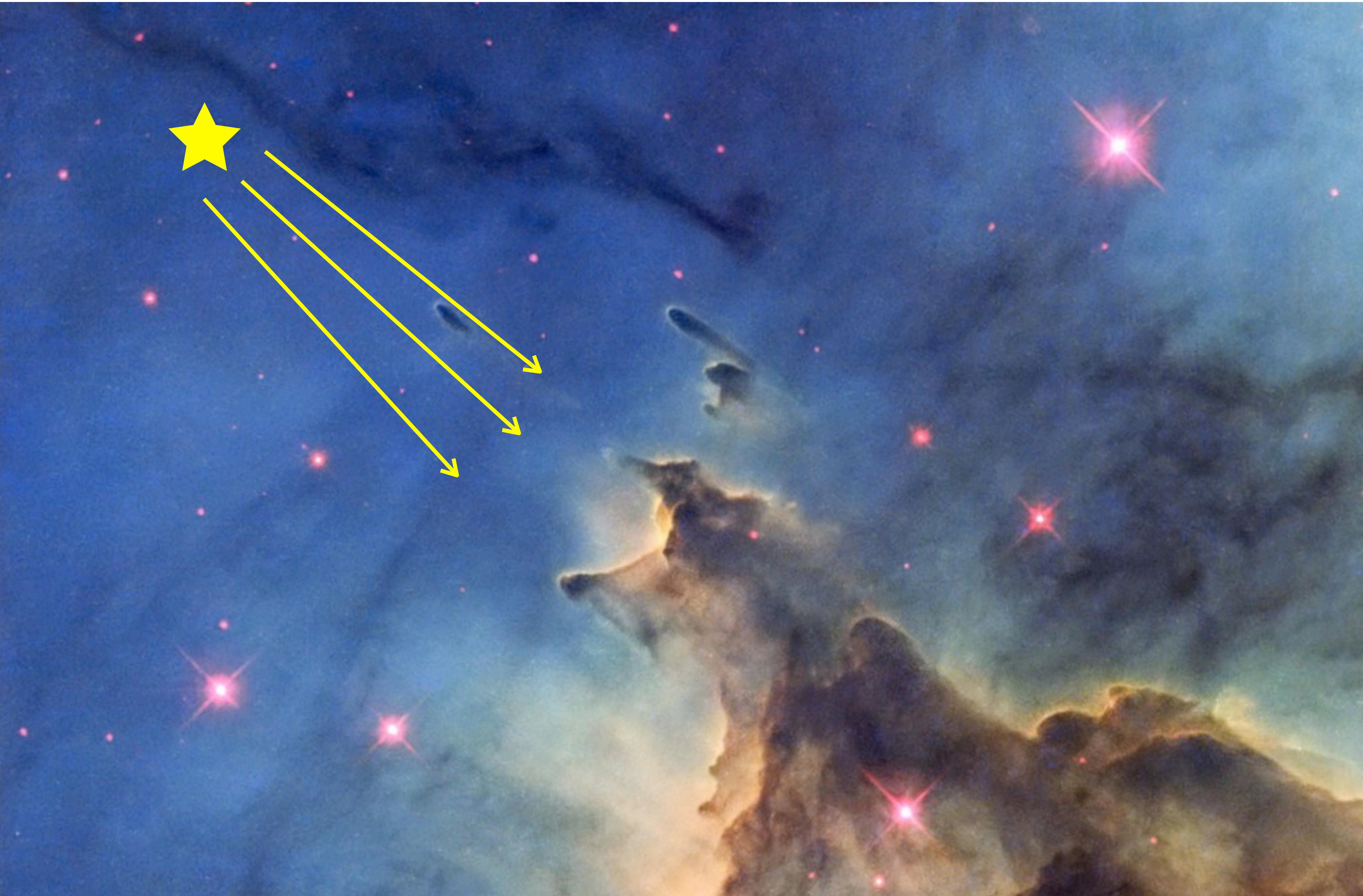
How do photons interact with gas?

photoionization, heating, pressure



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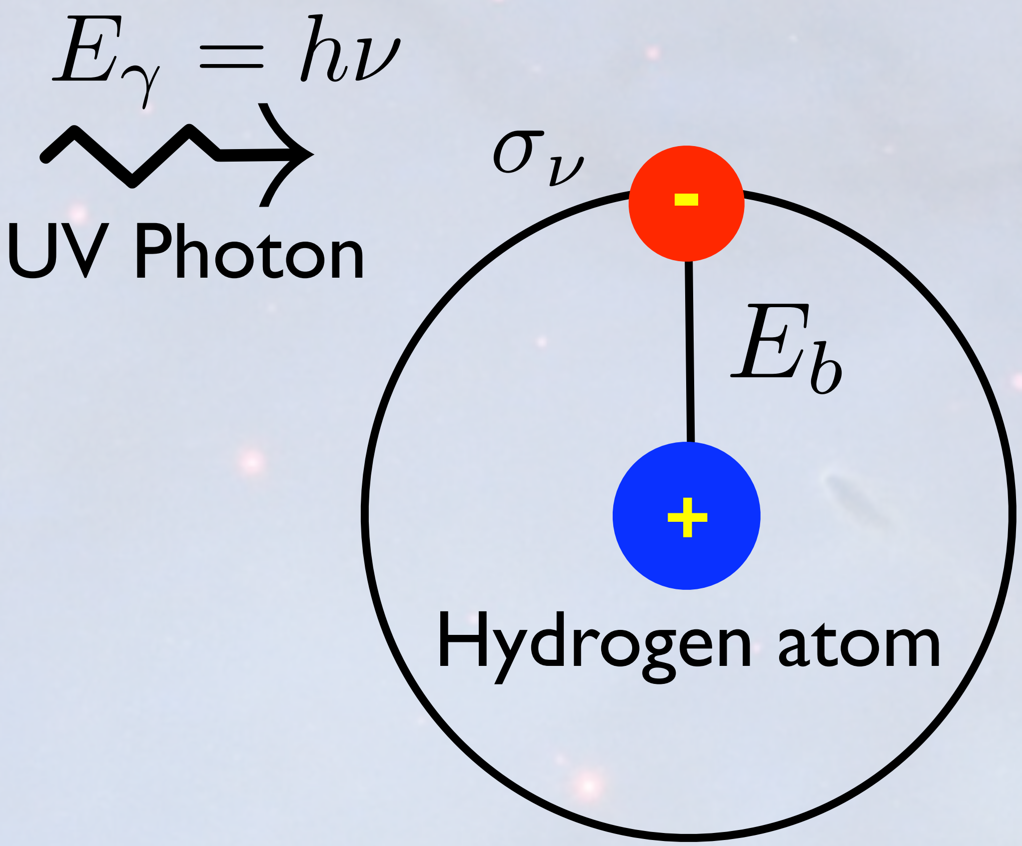


Photionizations change the ionization state

$$\frac{\partial n_{\rm HII}}{\partial t} = \int_\Omega \int_\nu F_{\nu\Omega} \sigma_\nu n_{\rm HI} \, d\nu \, d\Omega$$

heat the gas,

$$\frac{\partial \varepsilon_{\rm gas}}{\partial t} = \int_\Omega \int_\nu F_{\nu\Omega} \sigma_\nu n_{\rm HI} \left(h\nu - E_b \right) \, d\nu \, d\Omega$$

Recombinations cool the gas
and send off photons

and push the gas

$$\frac{\partial \mathbf{p}_{\rm gas}}{\partial t} = \int_\Omega \int_\nu F_{\nu\Omega} \sigma_\nu n_{\rm HI} \, \hat{\mathbf{r}} \frac{h\nu}{c} \, d\nu \, d\Omega$$

Putting all this into simulations

...

first we need to pick a known and robust cosmological simulations code (DM, stars, gas)

...

then we need to come up with a numerical RT method which is both cheap and accurate

...

and then mesh it into the code -> RHD

The Ramses cosmological code

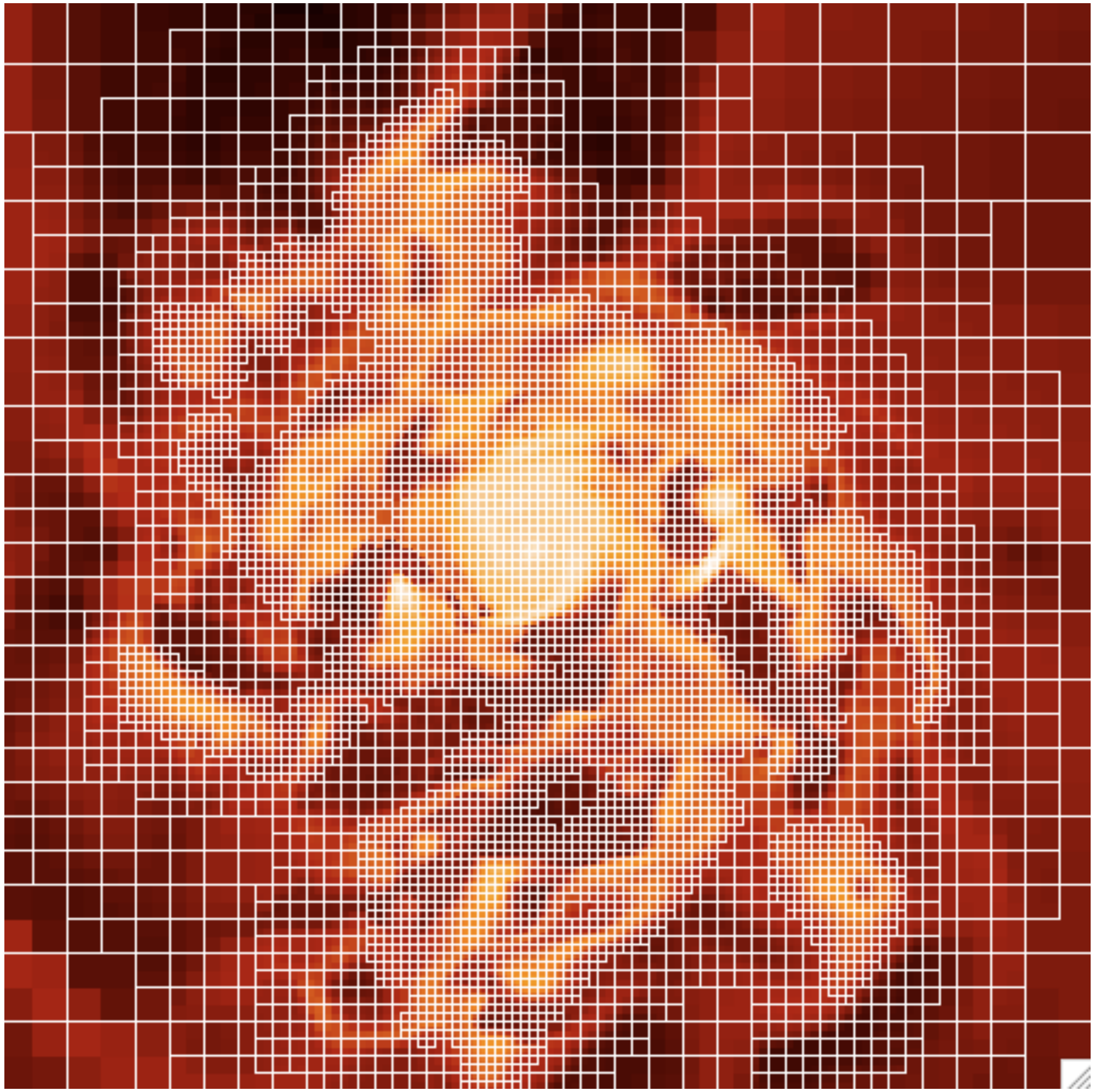
the 'host' of my RHD implentation
i.e. the cosmology, DM and gas

Two 'selling points':

<u>AMR: Adaptive Mesh Refinement</u>
i.e. cells of different sizes. Resolution adapts locally on structures, while uninteresting regions are coarsely refined

- Saves time and allows higher *effective* resolution than a homogeneous grid
- But also more complicated

<u>Massively parallel:</u>
The AMR grid can be split between hundreds of processors, to share the load (ok, this exists in most codes, but it's *very efficient* in Ramses)



Gas density in a simulated galaxy, with AMR cells overplotted (Credit: Y.Dubois)

The radiative transfer equation

and numerical strategies

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

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

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

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

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

I. There are seven dimensions! HD has only four!

II. The timescale is $\propto u^{-1}$, where u is *speed*, and speed of light is ~1000x faster than typical gas speeds

➡We need a combination of approximations and a fast solver

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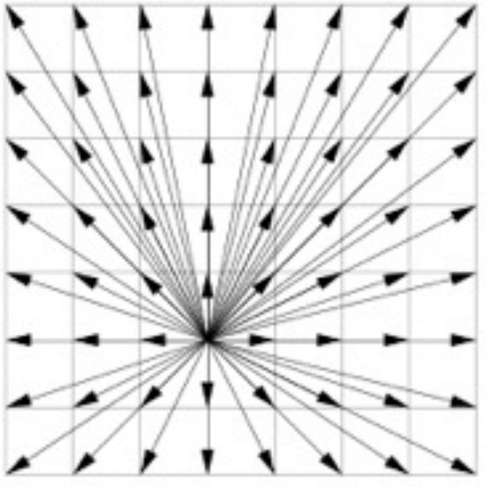
Two common strategies:

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

- Simple and intuitive
- but load scales with number of sources/rays



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

- Not so intuitive
- but no limit to number of sources
- no problem with covering the volume
- fits easily with a hydrodynamical solver
- naturally takes advantage of AMR and parallellization

The M1 moment method

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

$I_\nu(\mathbf{x},\mathbf{n},t)$ intensity
$\alpha_\nu(\mathbf{x},\mathbf{n},t)$ absorbtion
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➡ Take moments to get rid of angle dependency...
➡ ...and average over frequency
➡ giving the four-dimensional equations:

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

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

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

$N(\mathbf{x},t)$ 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, which is *local* and retains a bulk directionality of the radiative field.

Solving the RT moment equations on a grid

For simplification, separate into three 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 tasks, in each timestep:

I. Injection into cells

II. Photon transport between adjacent cells

III. Thermochemistry in every cell

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

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

$$\mathbb{P}_i = \mathbb{D}_i N_i,$$

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

The speed of light problem

- When coupling RT (light) with HD (gas), there is a thousand-fold increase in runtime

- No information can cross more than one cell width in one timestep: $\Delta t_{\mathrm{RT}} \sim \frac{\Delta x}{c} \sim \frac{\Delta t_{\mathrm{HD}}}{1000}$

- To relieve this we use the *reduced speed of light approximation:*

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

➡ No runtime increase!

- Not as bad as it sounds: In practise, the dynamic speed in RHD simulations is the speed of ionization fronts, not the speed of light.

RHD in Ramses

main tasks in the implementation

- Advecting photons on an *adaptive grid*
- *Multifrequency* approximation ➜ Handful of photon groups
- *Non-equilibrium* thermochemistry of hydrogen *and helium*
- *On-the-fly* photon emission - from stars or continuous regions, using SED/ UV background models
- Coupling RT with hydrodynamics on an AMR grid

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

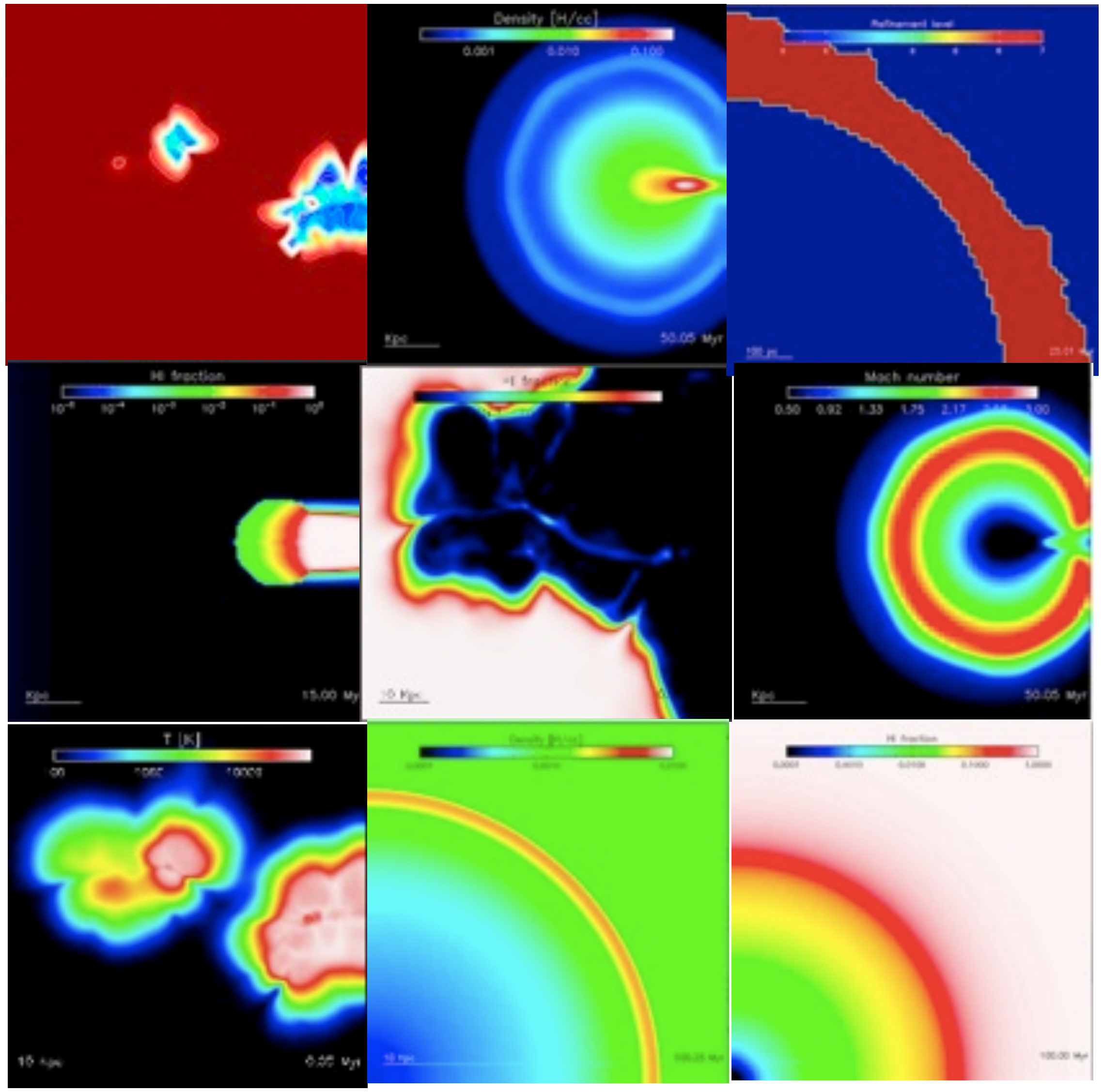
Pure RT:

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

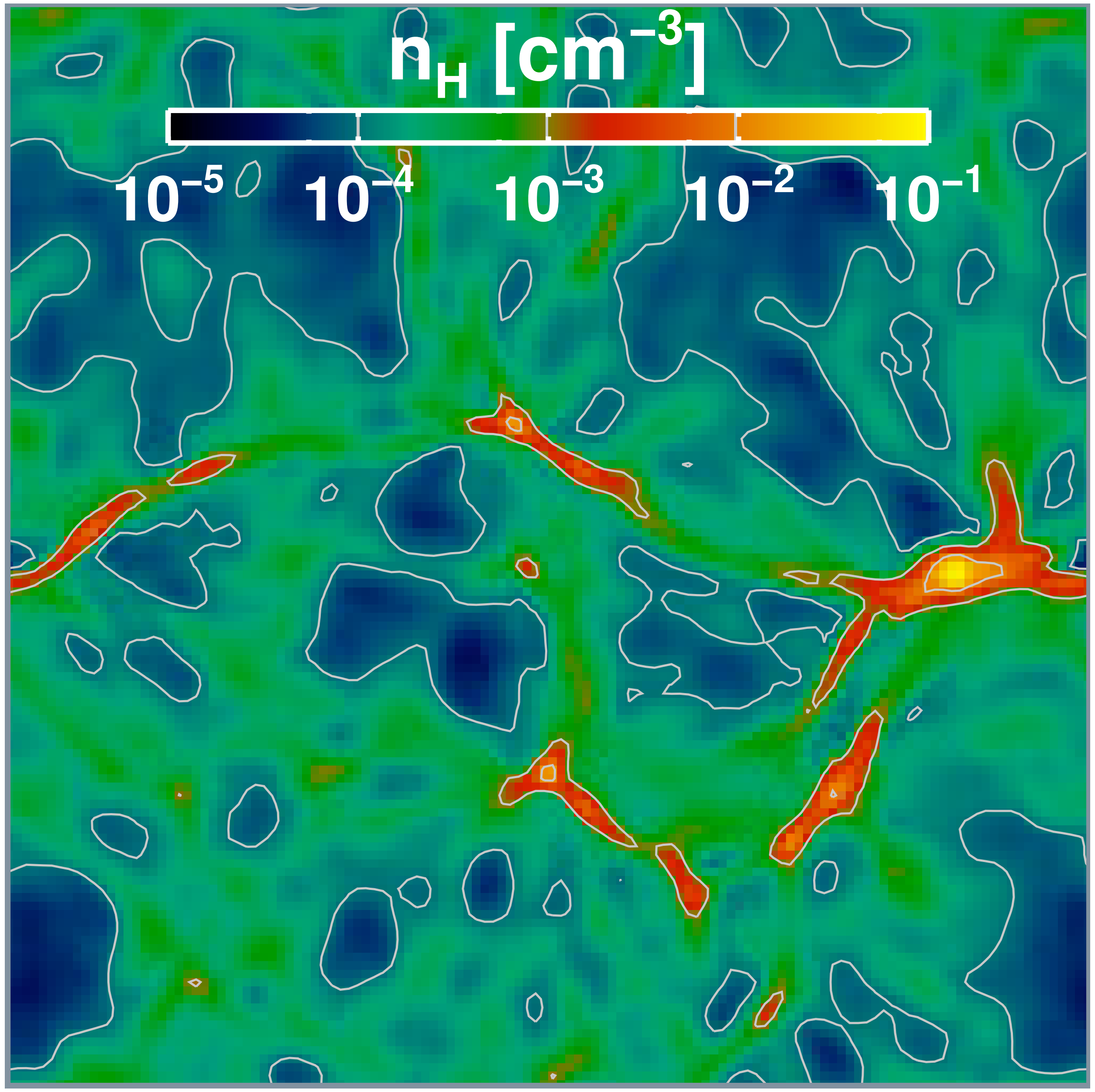
RHD:

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

- Comparison good, except for 4)



Iliev 4: Ionizing a cosmological volume



- Density field from a cosmological simulation (z=9)
- 16 radiative sources (Blackbodies)
- Ionize the volume for 0.4 Myrs
- Compare the result to other RT codes

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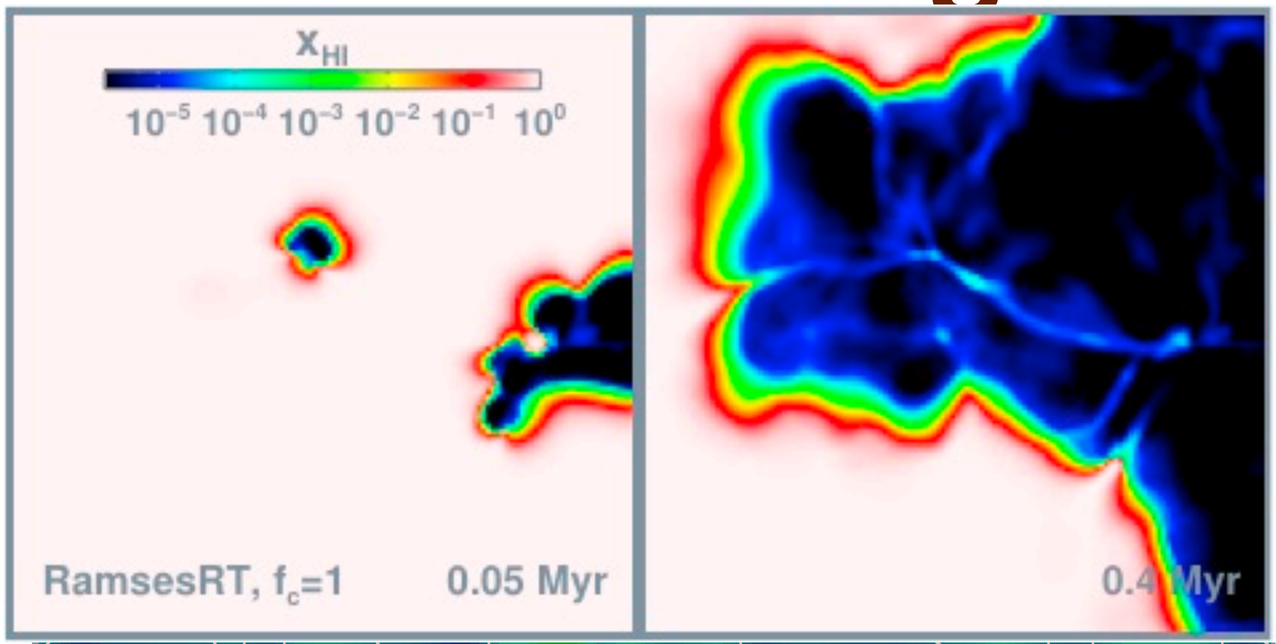

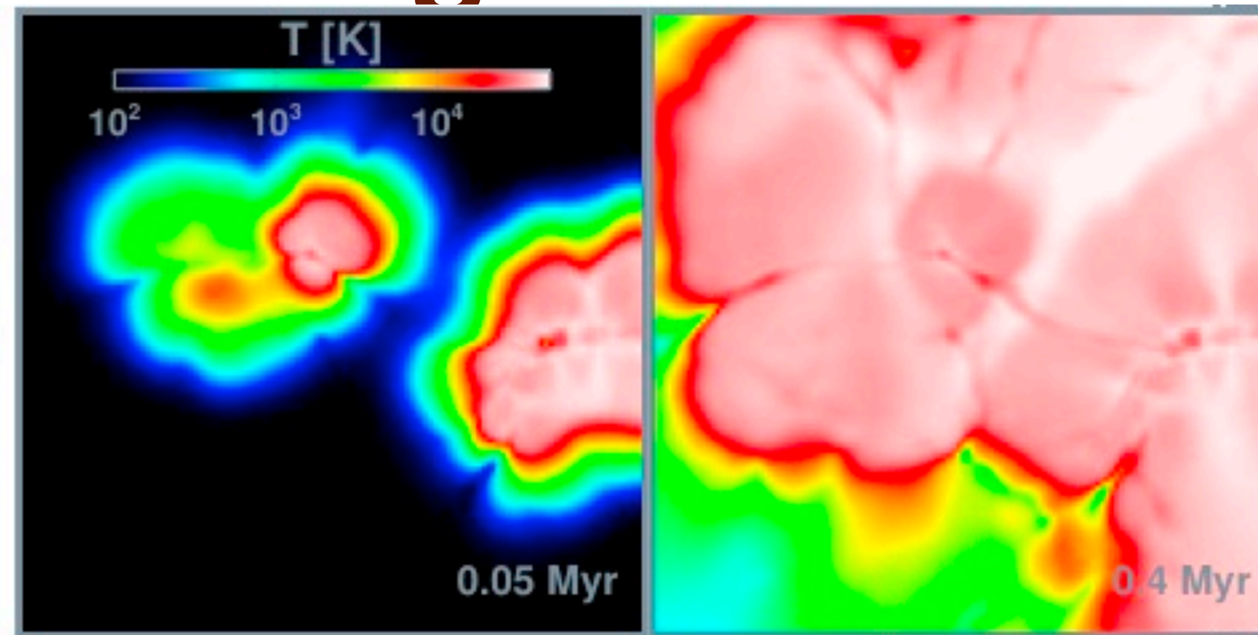

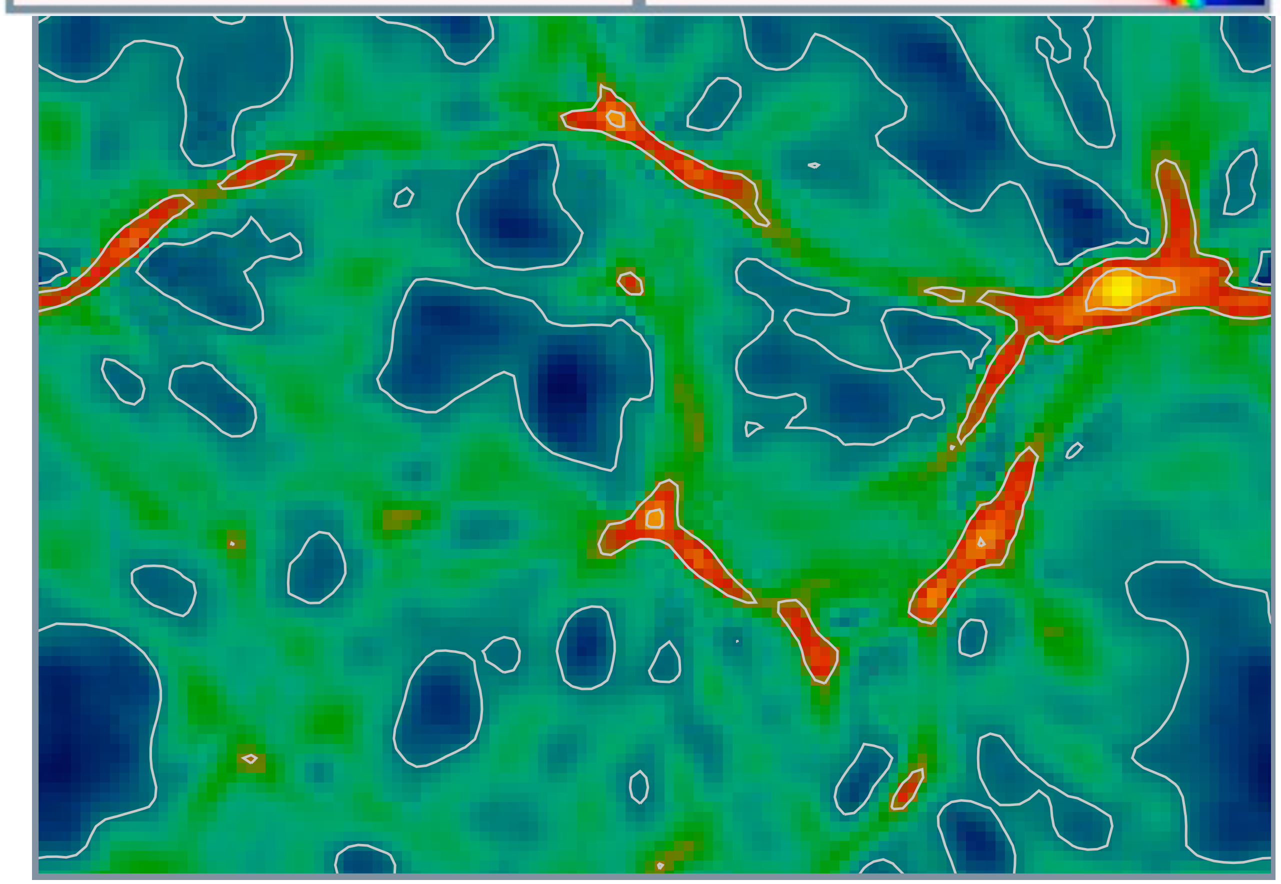

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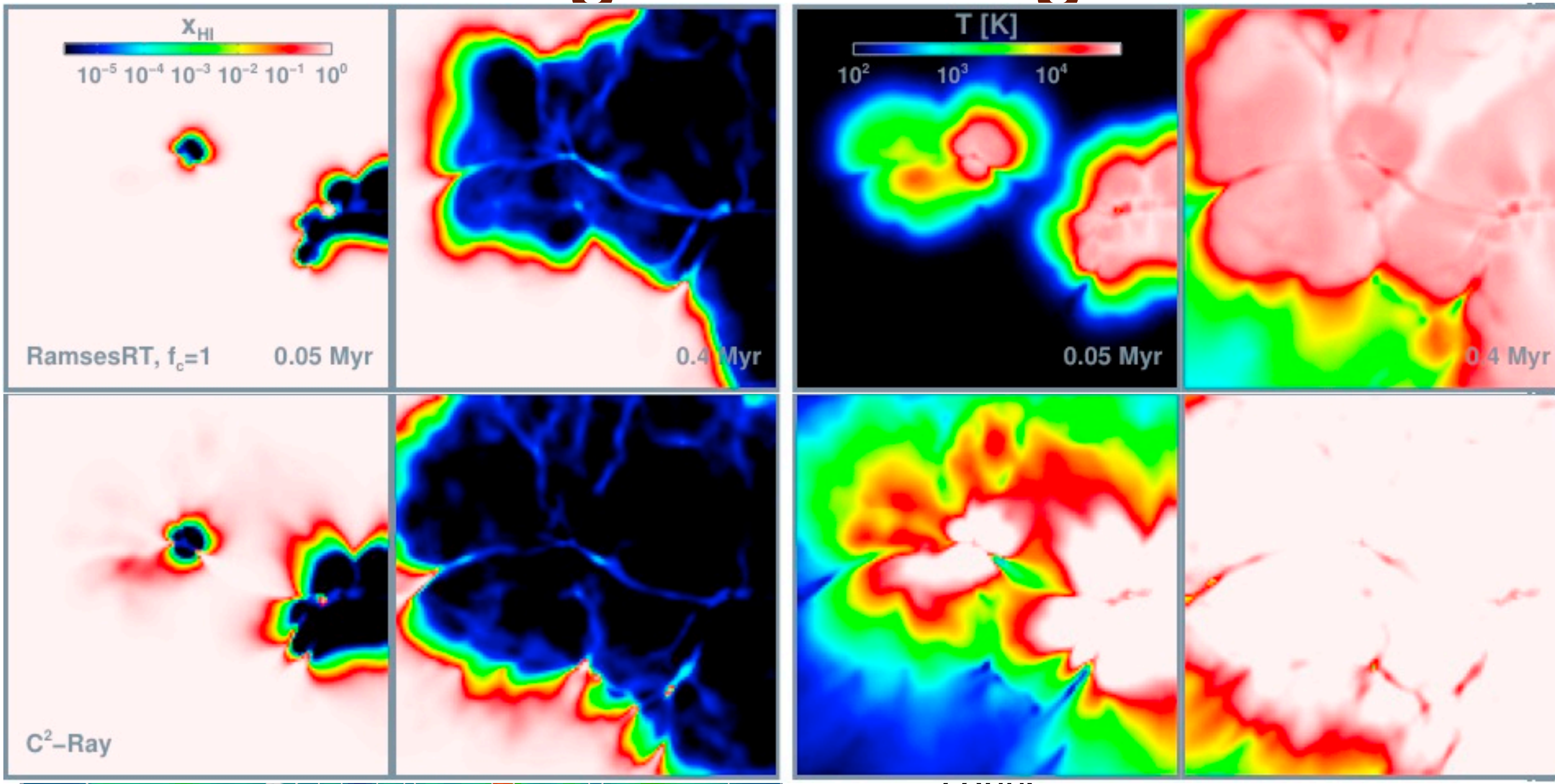

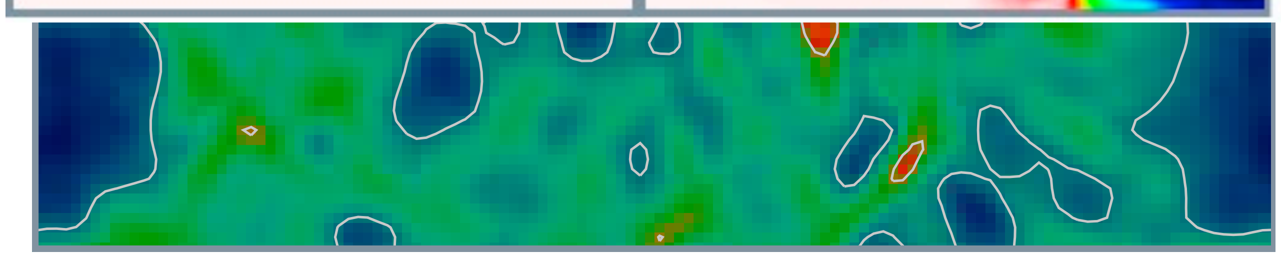

codes

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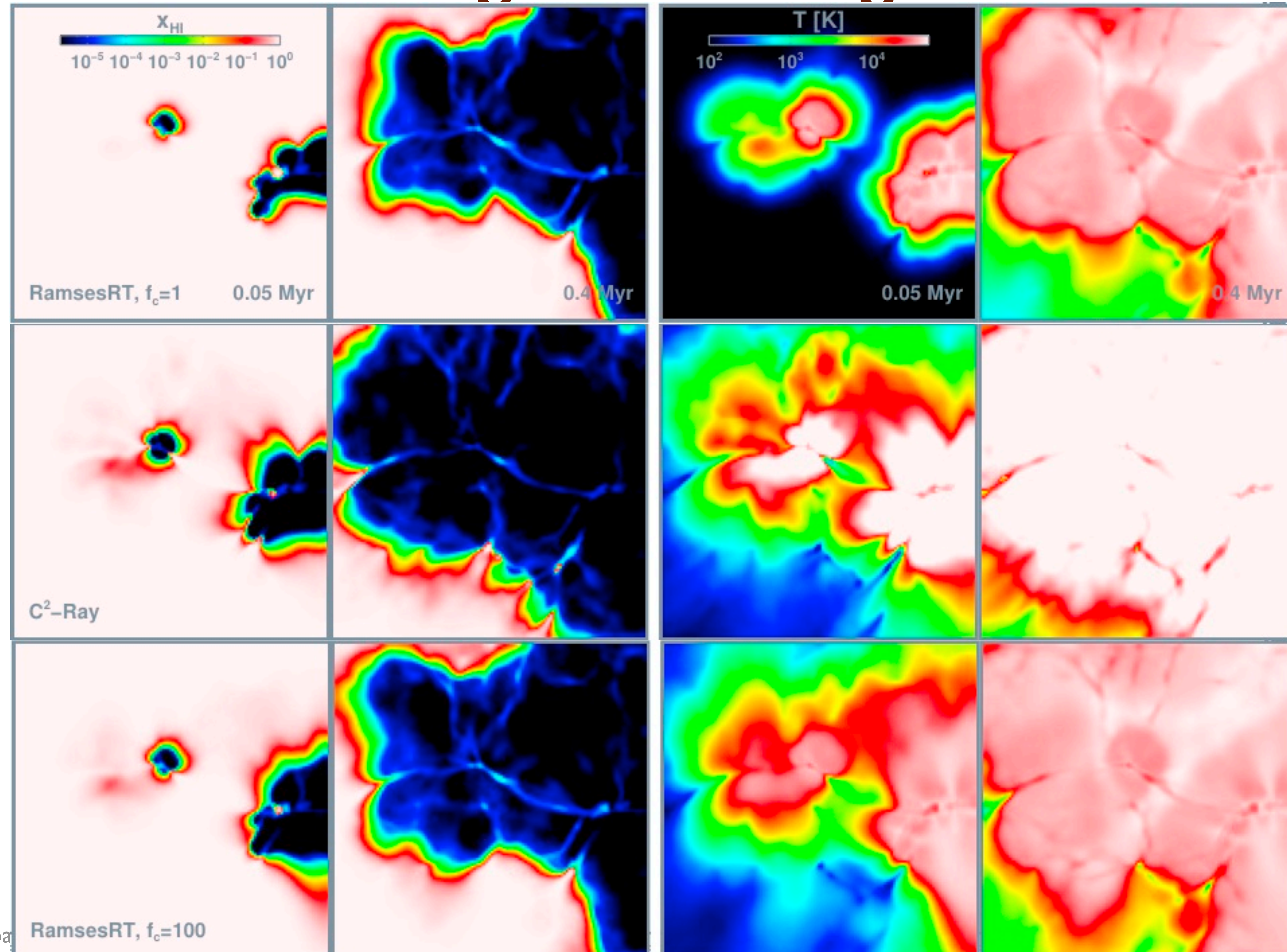


OK, now some simulations!

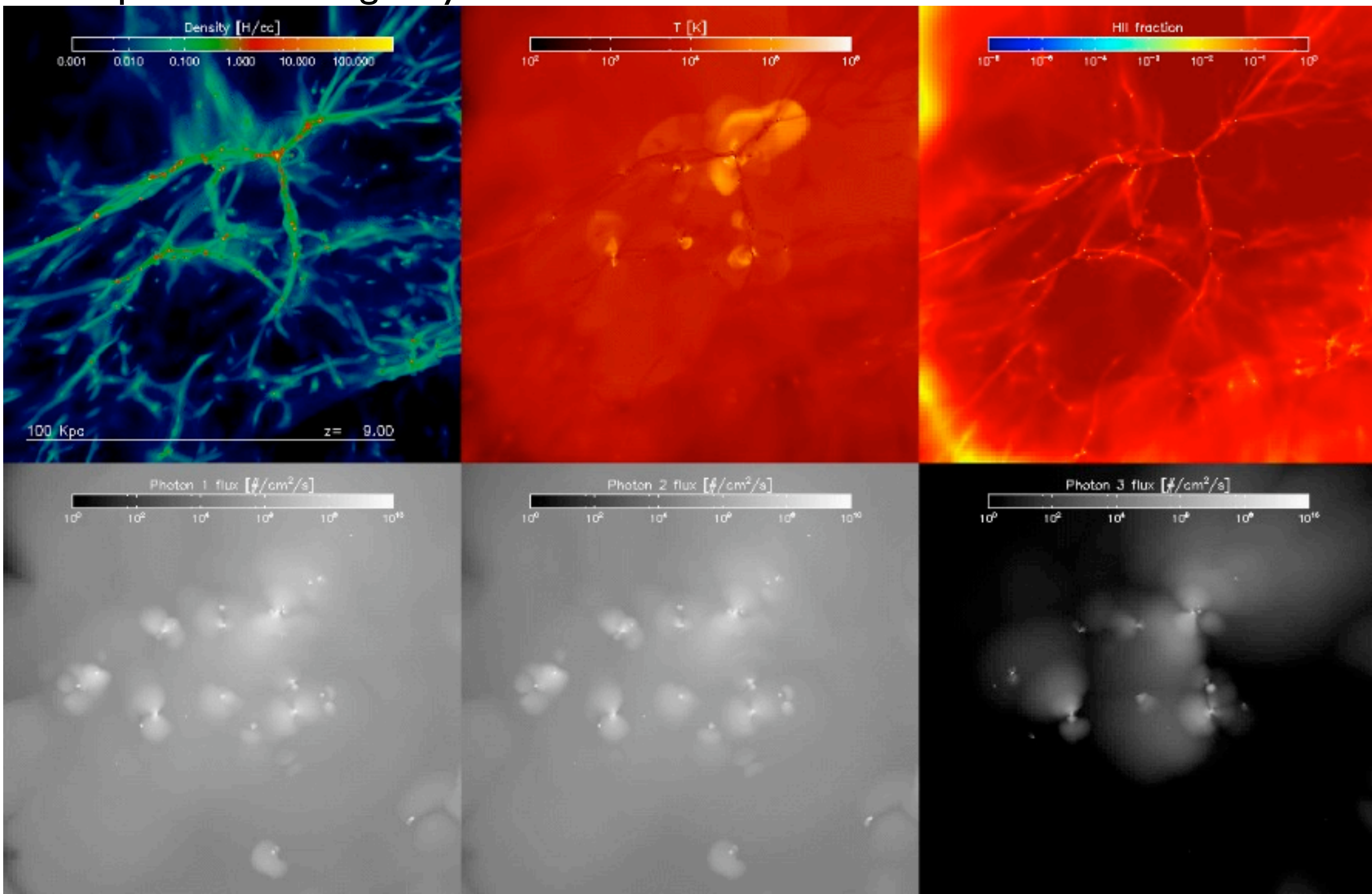
...

Some RHD simulations

with RamsesRT

UV emission from star-forming regions at high redshift

- Photoheating of the galaxy
- Escape of UV photons from galaxy -> reionization



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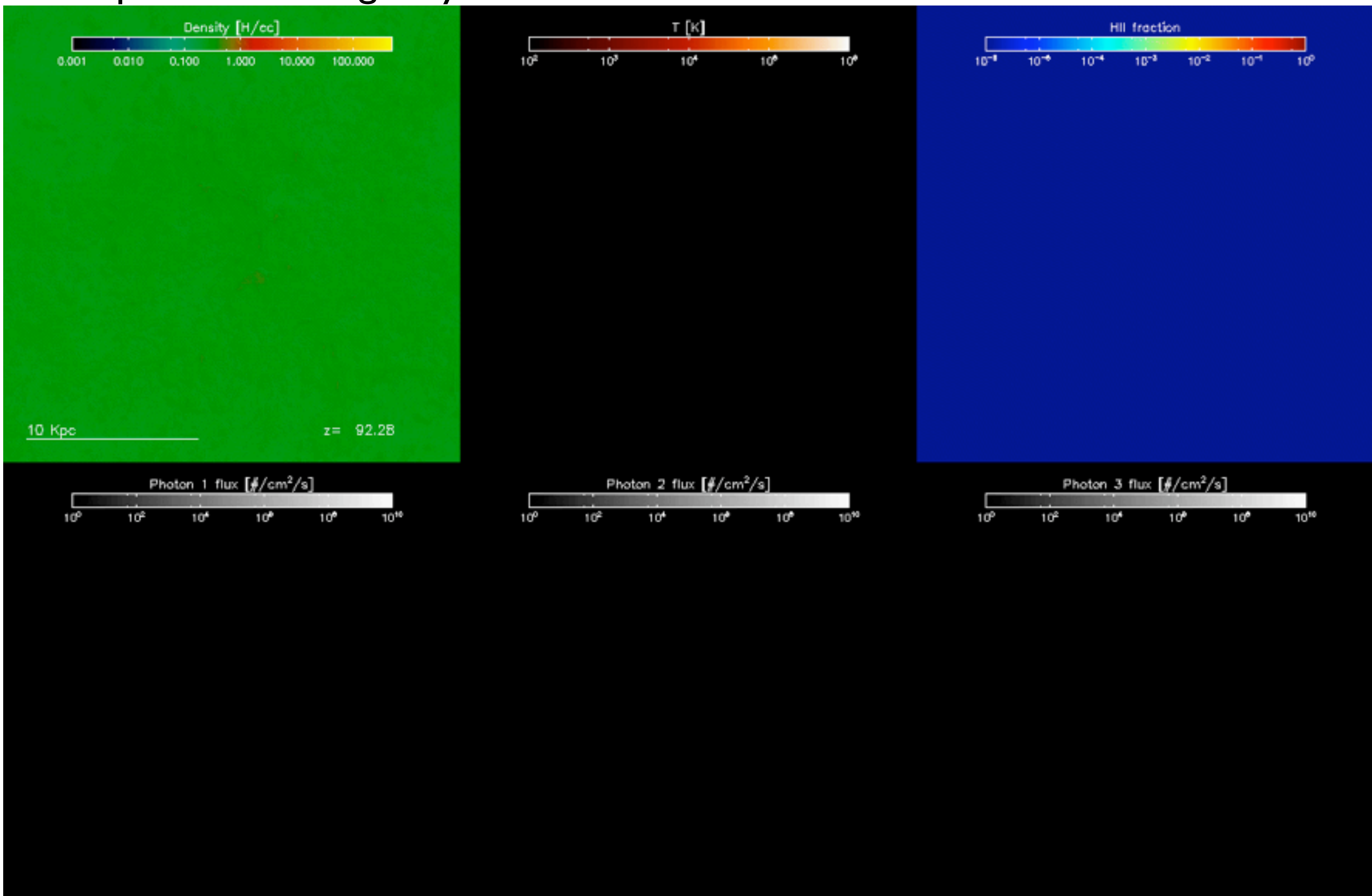

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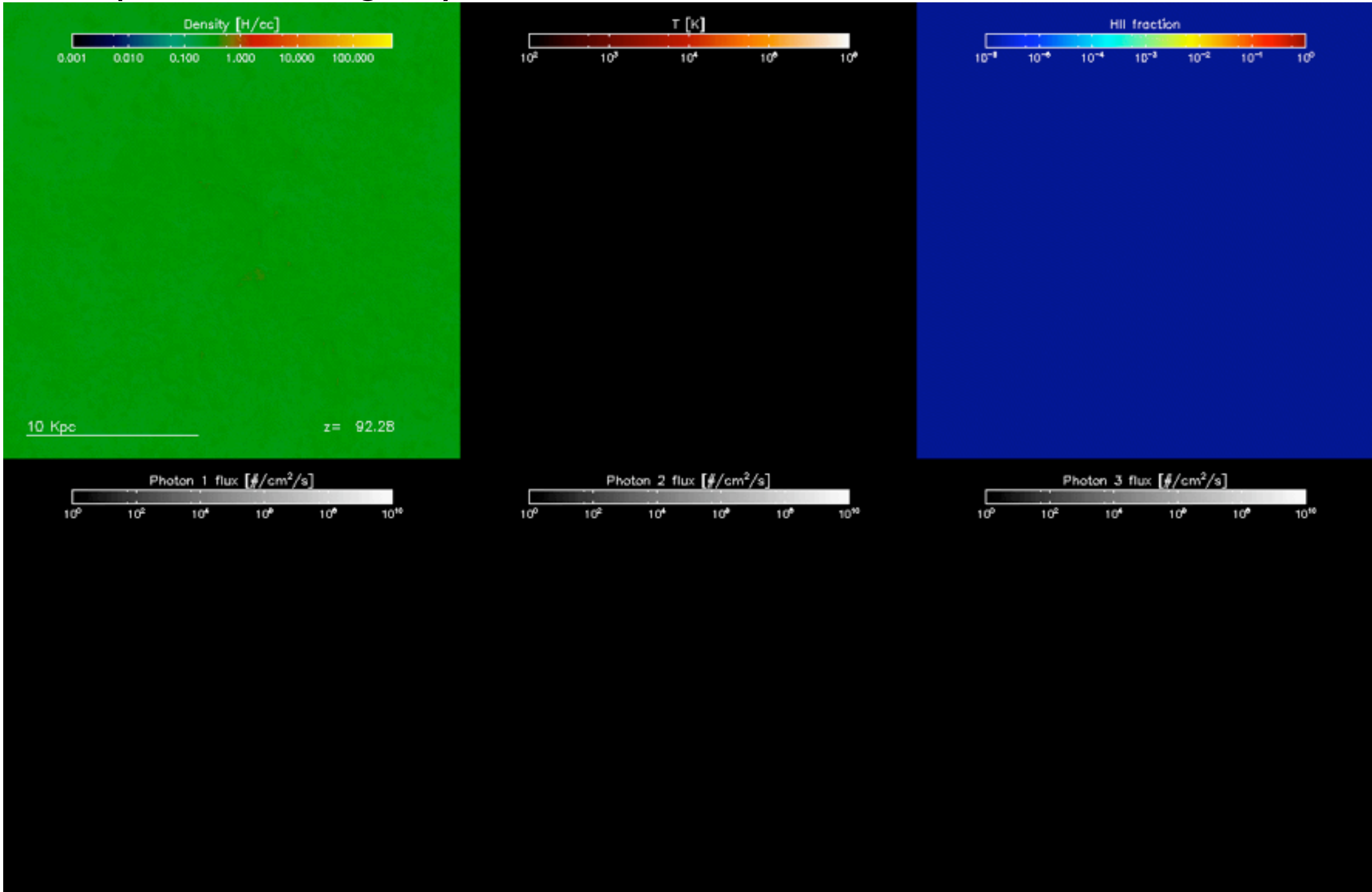

Some more simulations

with RamsesRT

Radiation feedback from stars

- Helps regulate star-formation via gas heating
- Important to map out the HI/HII regions in the galaxy, for mock observations
- Pressure from photons on gas -> may impact the morphology

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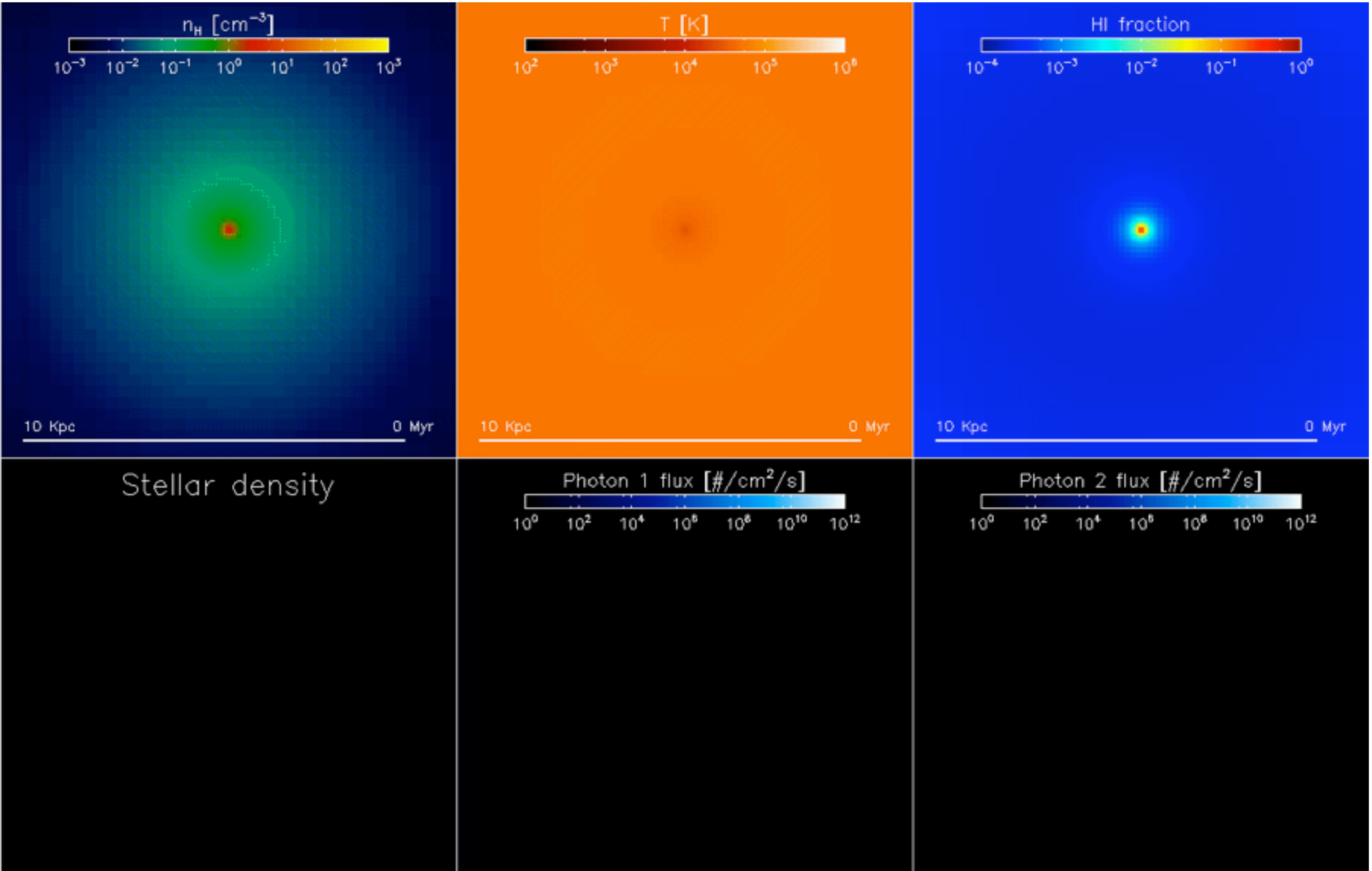

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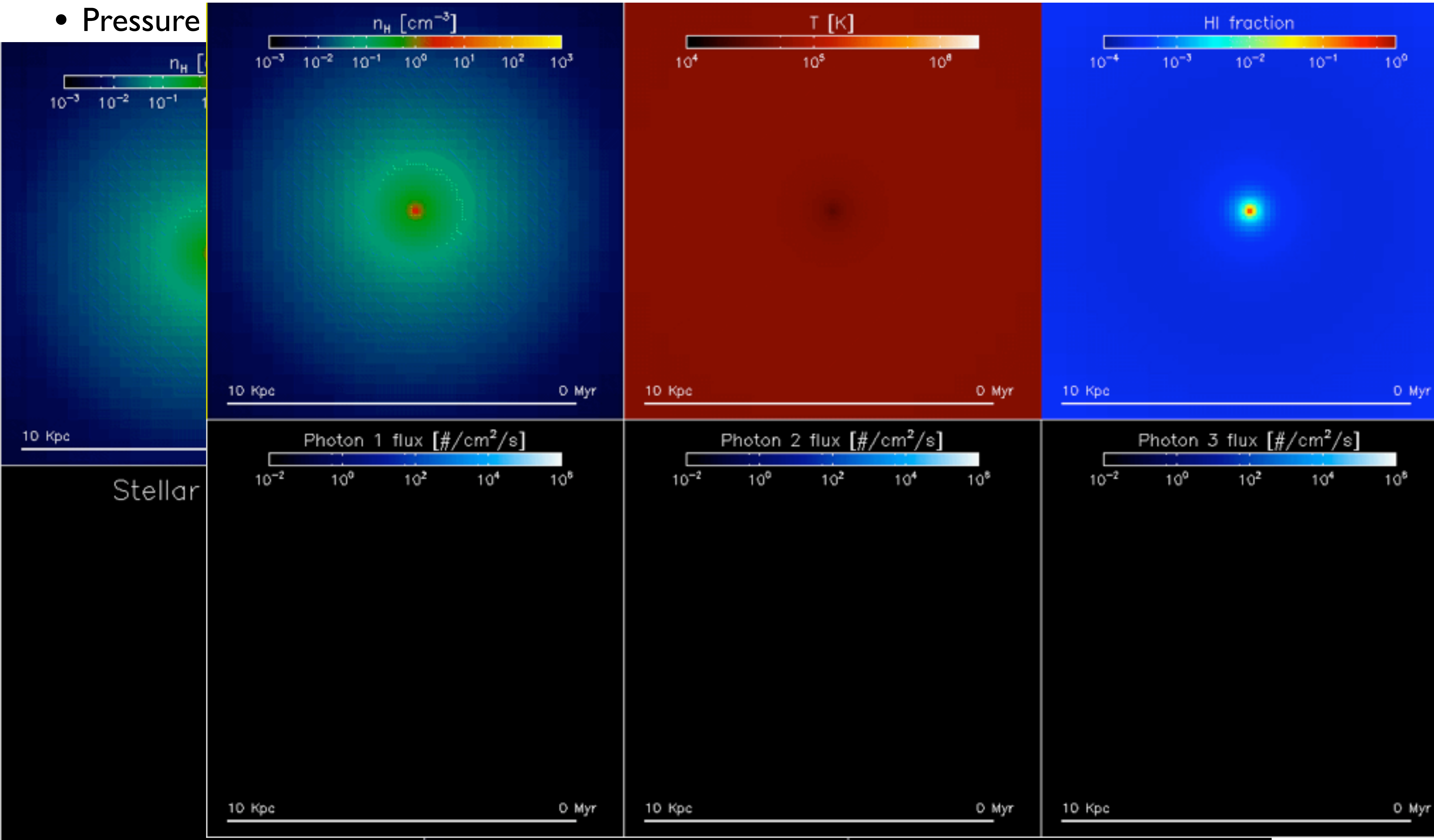

UV 'shielded' cosmological structures

Γ = UV photoionization rate

- Dense clouds/filaments are self-shielded from the UV radiation
- Important to interpret and predict absorption and emission properties of those structures, because their HI/HII content is very dependent on the UV radiation.

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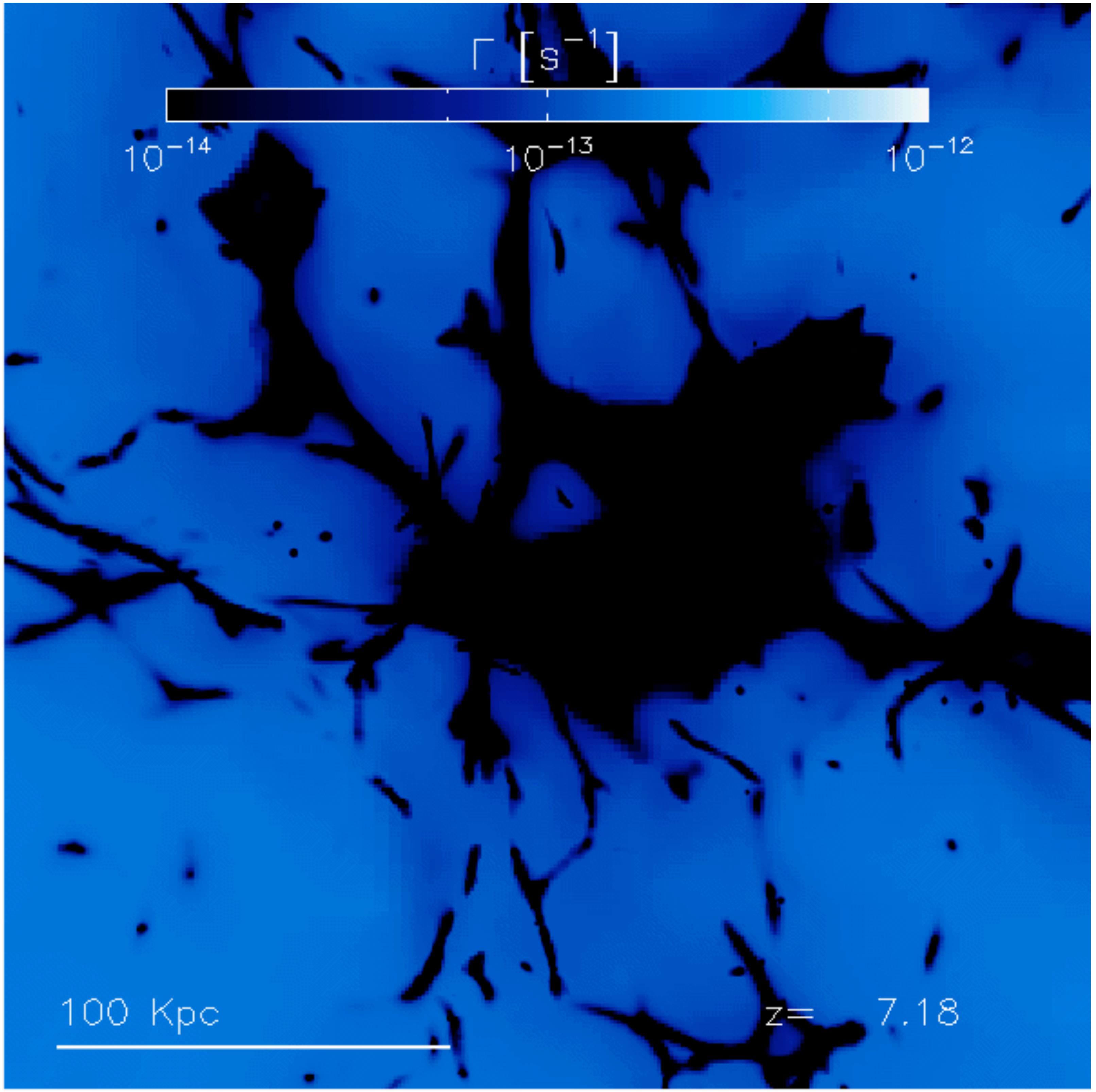

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Conclusions and future directions

- RamsesRT is robust and needs to be put to some use:
- Now I want to pursue the PhD topic: ‘Cosmological RHD simulations of early galaxy formation’
- Continue with the study of extended Lyα emission (last year’s talk)
- Improved subgrid-recipes for stellar feedback (with S. Geen)
- Lyα signatures of compact galactic sources (with A. Verhamme, Y. Dubois)
- Radiative pressure feedback in galaxies (with O. Agertz, R. Teyssier)
- AGN radiative feedback (with Y. Dubois)
- Improved thermochemistry, tracking molecular and metal species (with A. Richings)

Time to wake up!

Thanks for listening