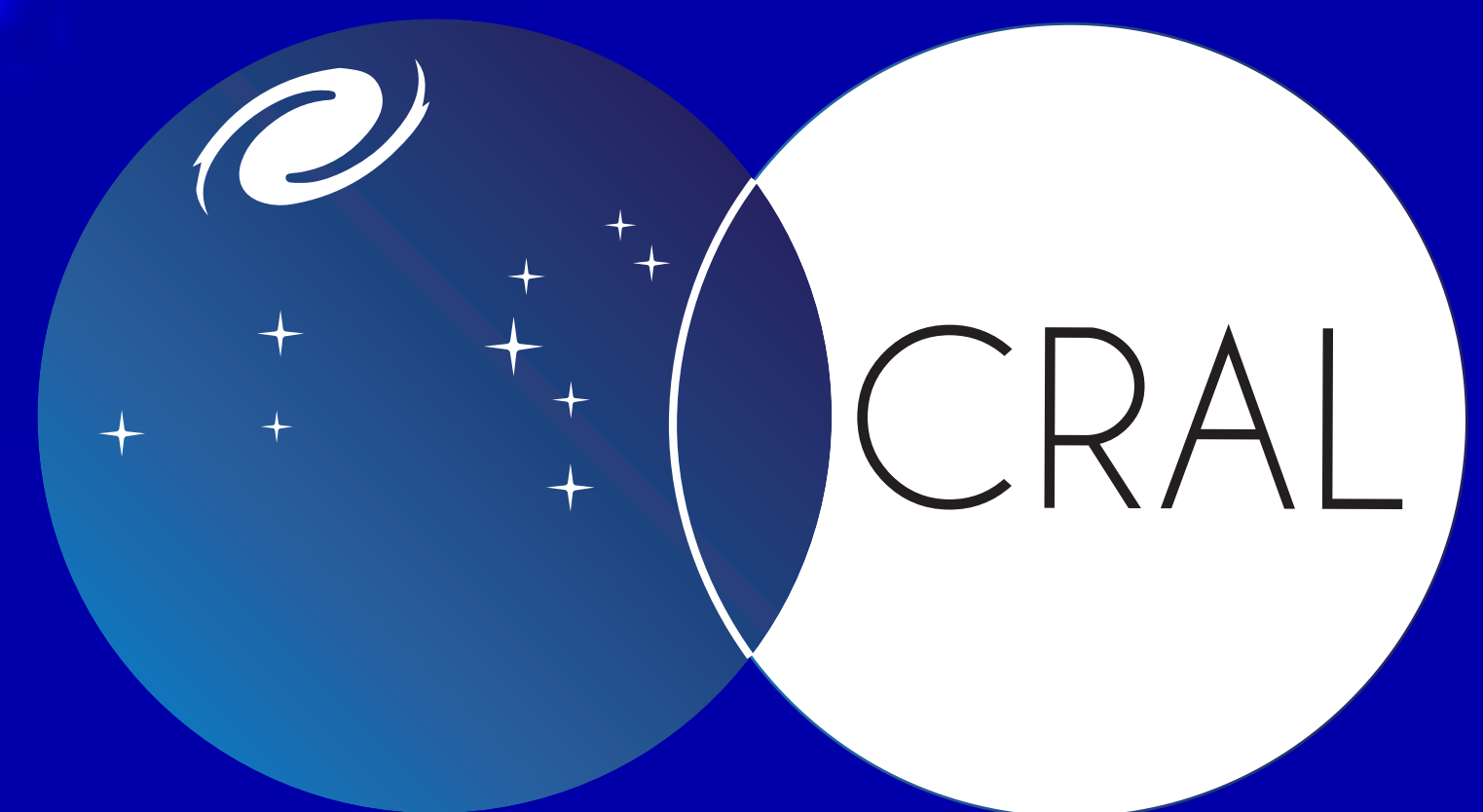
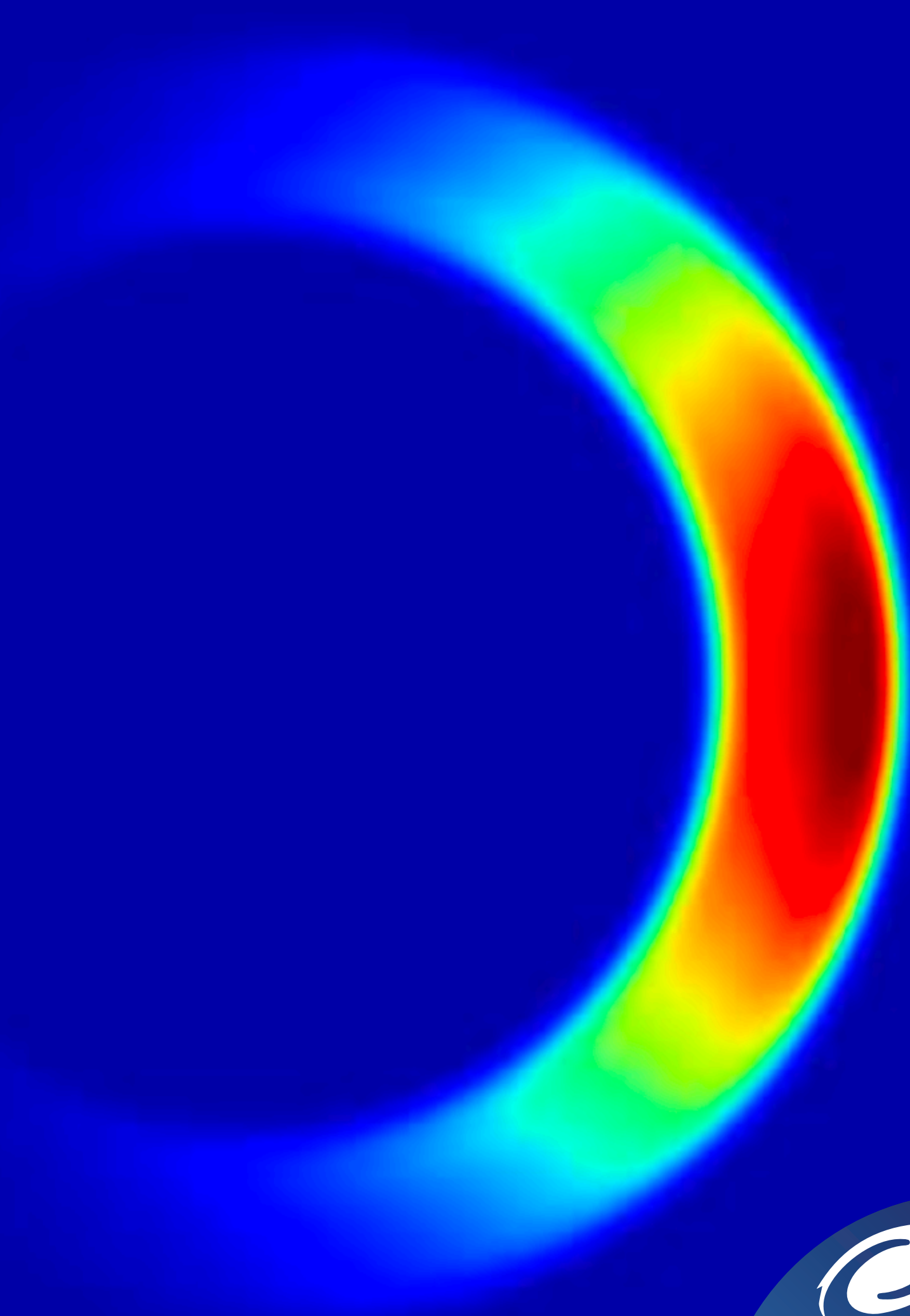


Two-moment Cosmic Rays in **RAMSES** (arXiv 2509.19447)

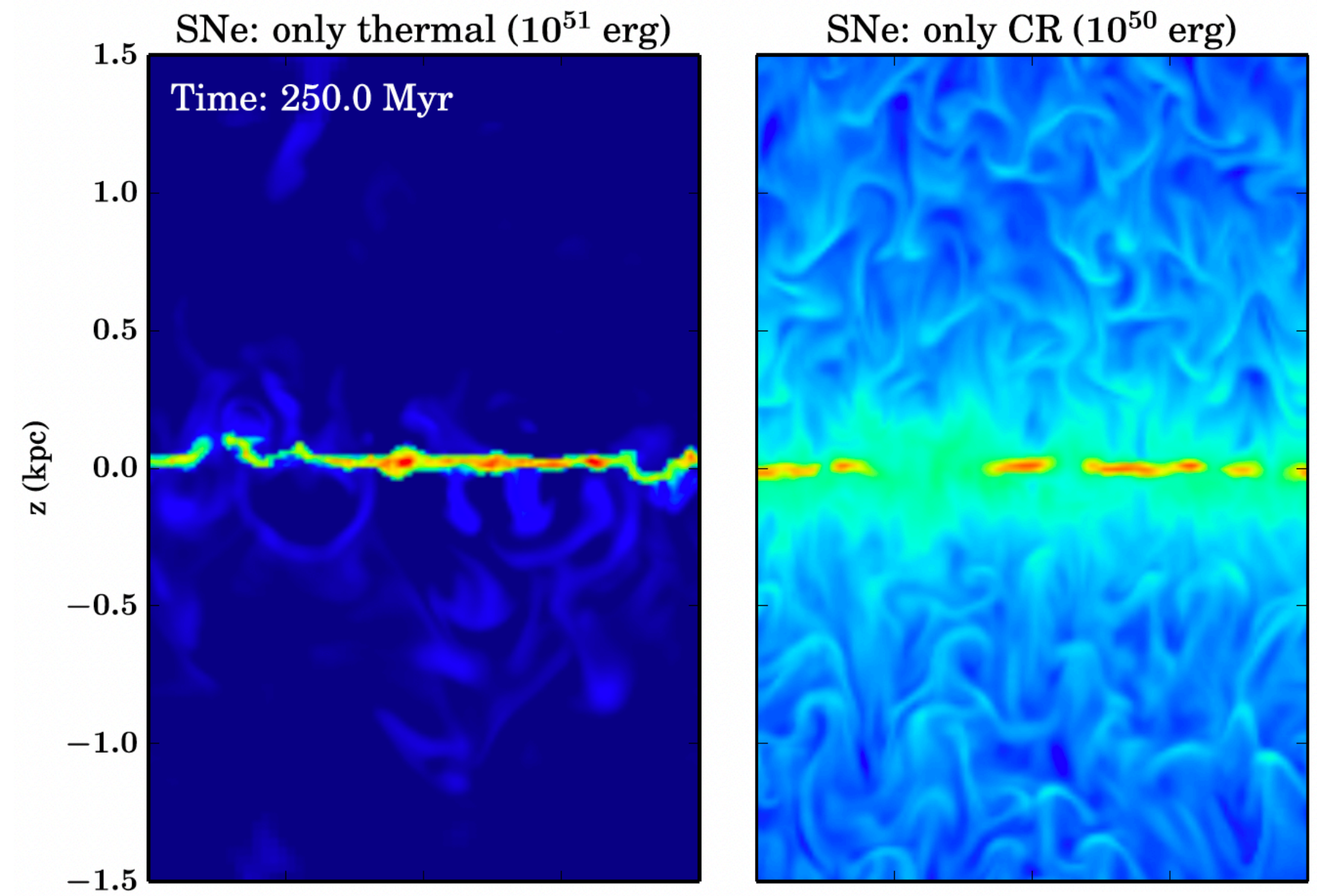
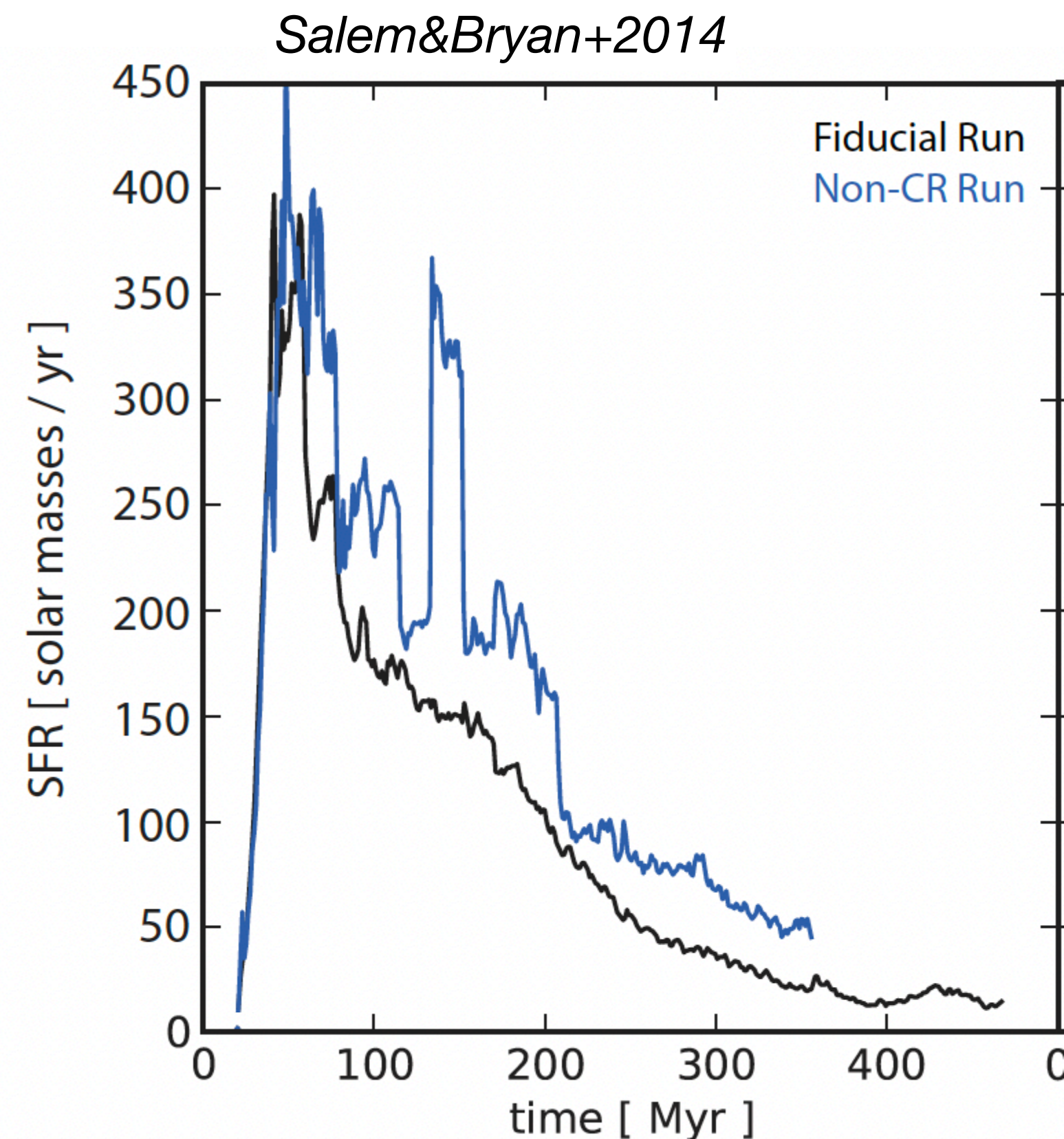
Joki Rosdahl (CRAL)
with Commerçon, Dubois,
Marcowith, Diallo, Lin

The RUM, April 27th 2026



Why (and what are) cosmic rays?

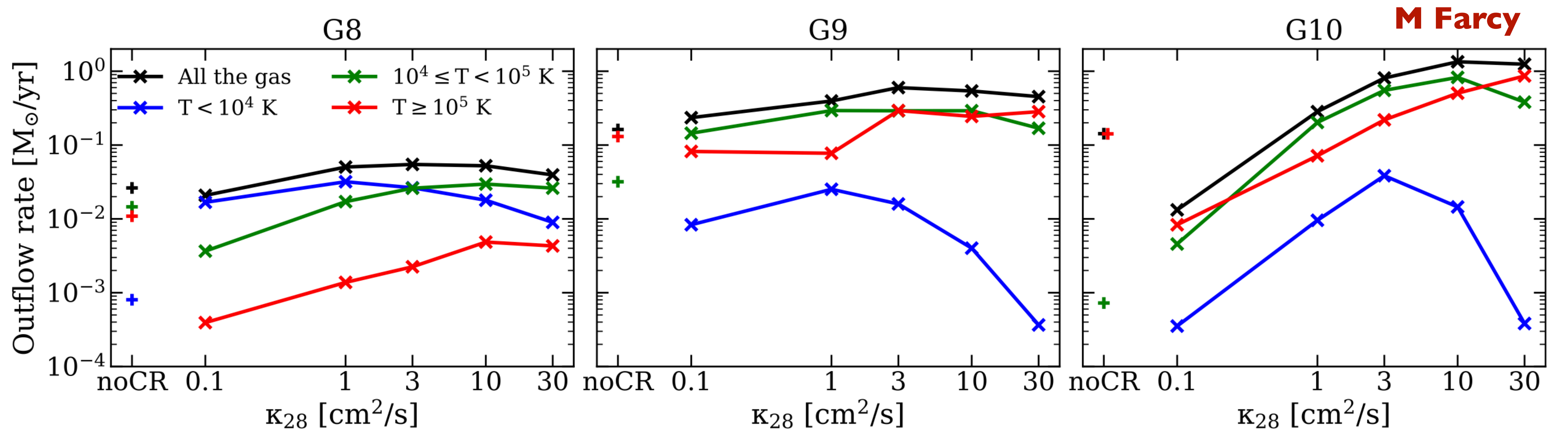
- Cosmic rays (CRs) are charged energetic particles, mostly electrons and protons
- Injected mostly via shocks (SN remnants, AGN, ...)
- CRs are in energy equipartition with thermal and magnetic energy in galaxies
- CRs are an important component of galaxy evolution



Girichidis+16

Uncertainties in...

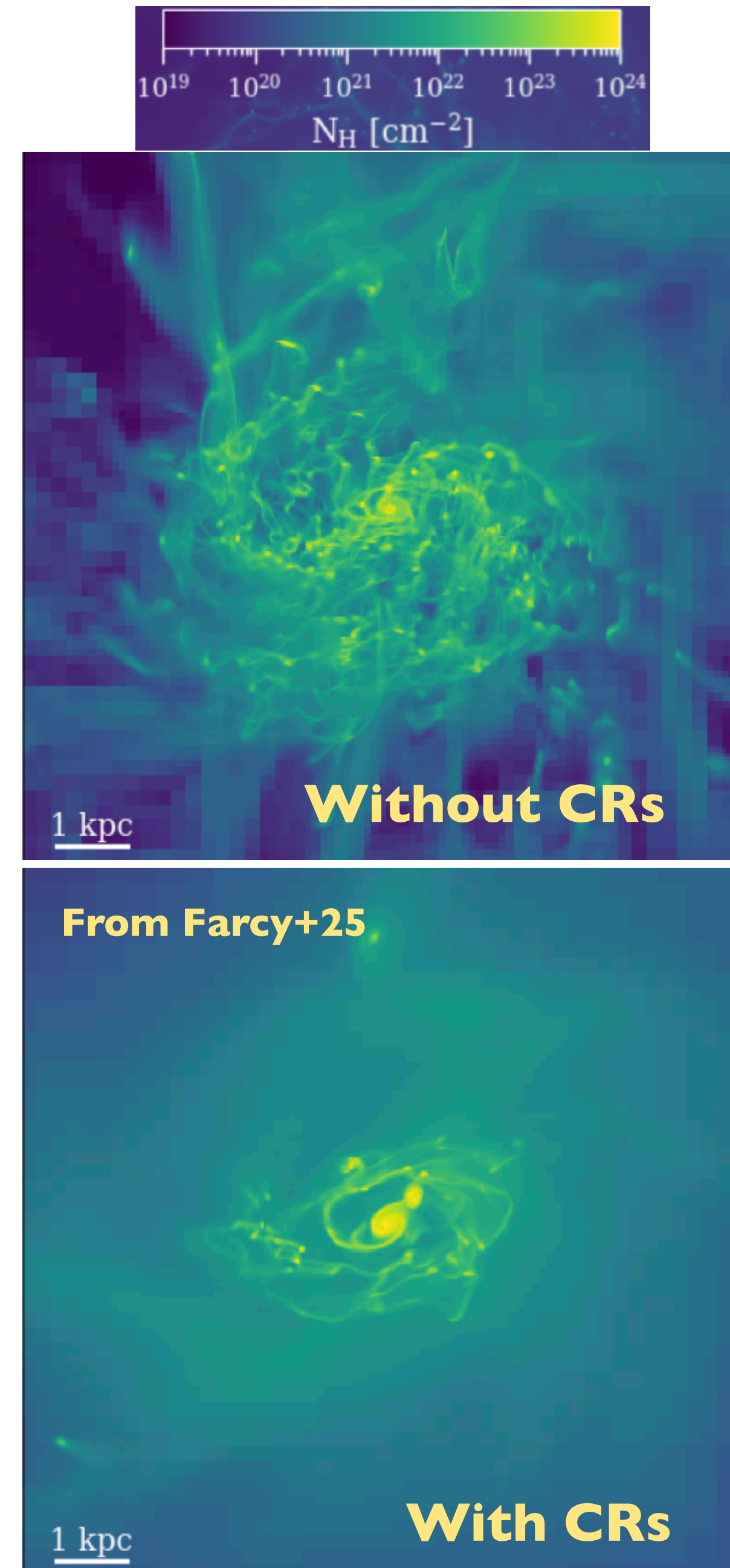
- the amount of energy injected around SN remnants ($\sim 10\text{-}20\%$)
- their diffusion coefficient κ [cm^2/s]



Farcy+2022, see also Dashyan&Dubois 2020 (both with RAMSES)

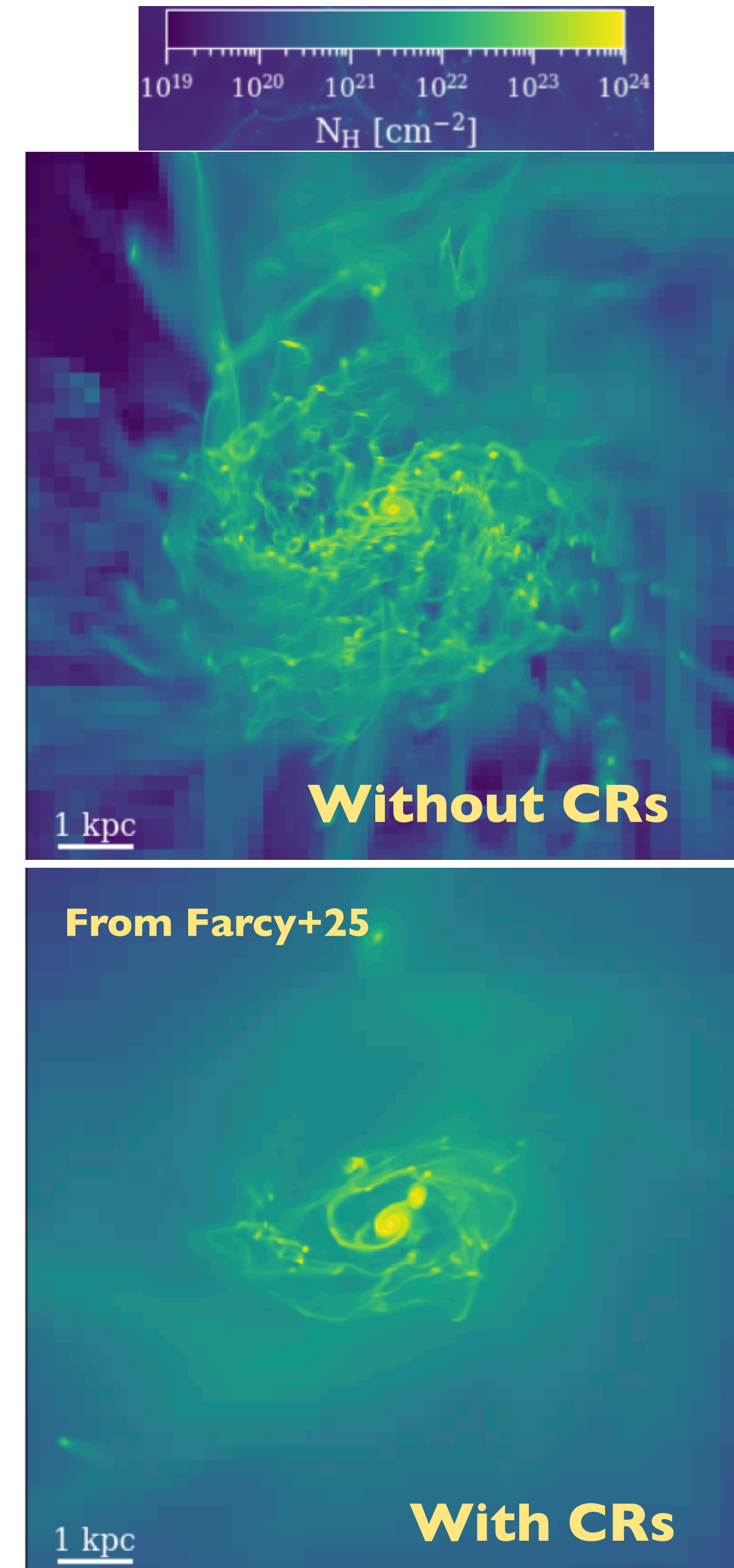
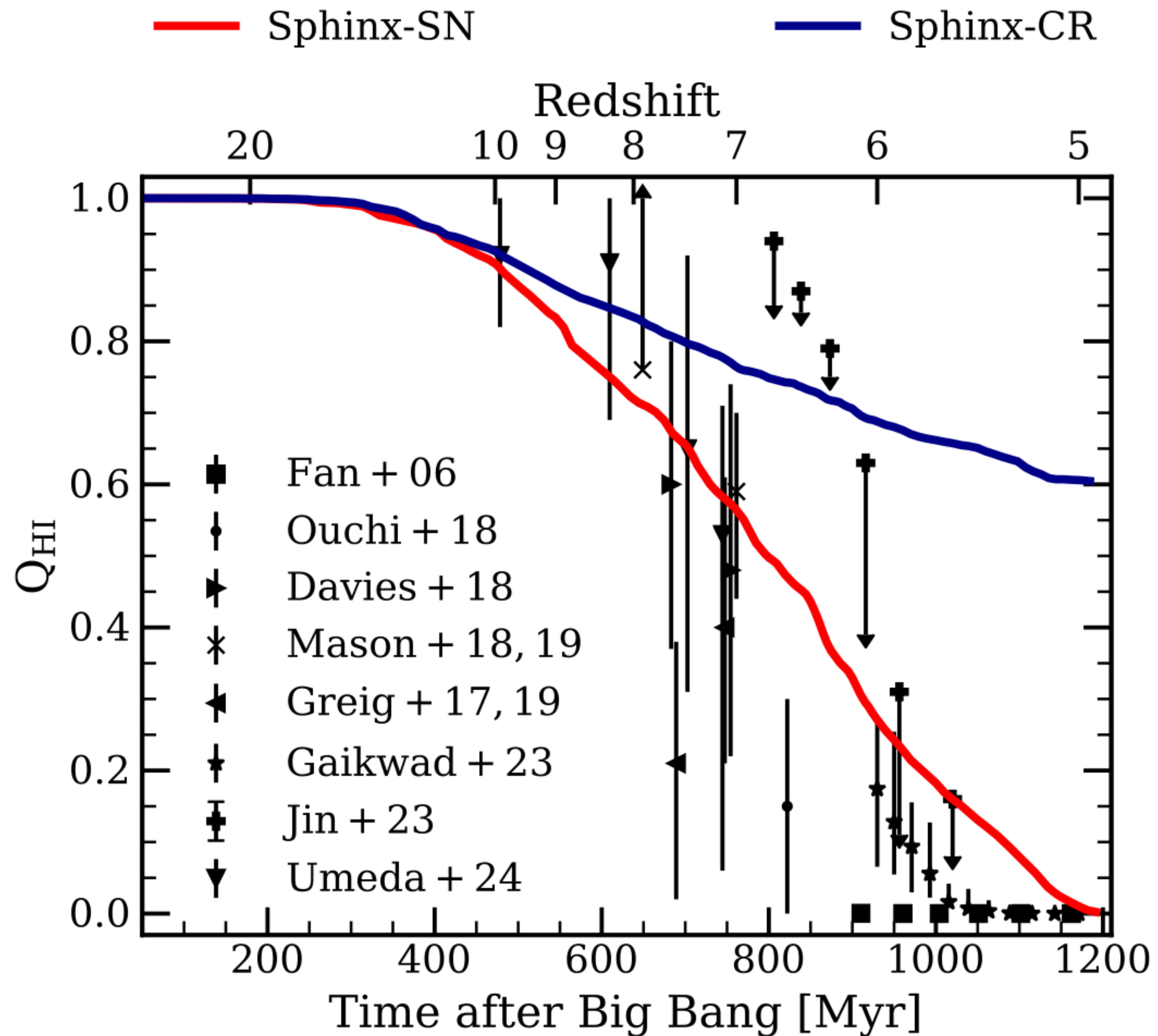
CRs can have a big impact

- For 'efficient' diffusion coefficients, they can suppress and 'smooth out' star formation



M Farcy

But beware of side effects!



M Farcy

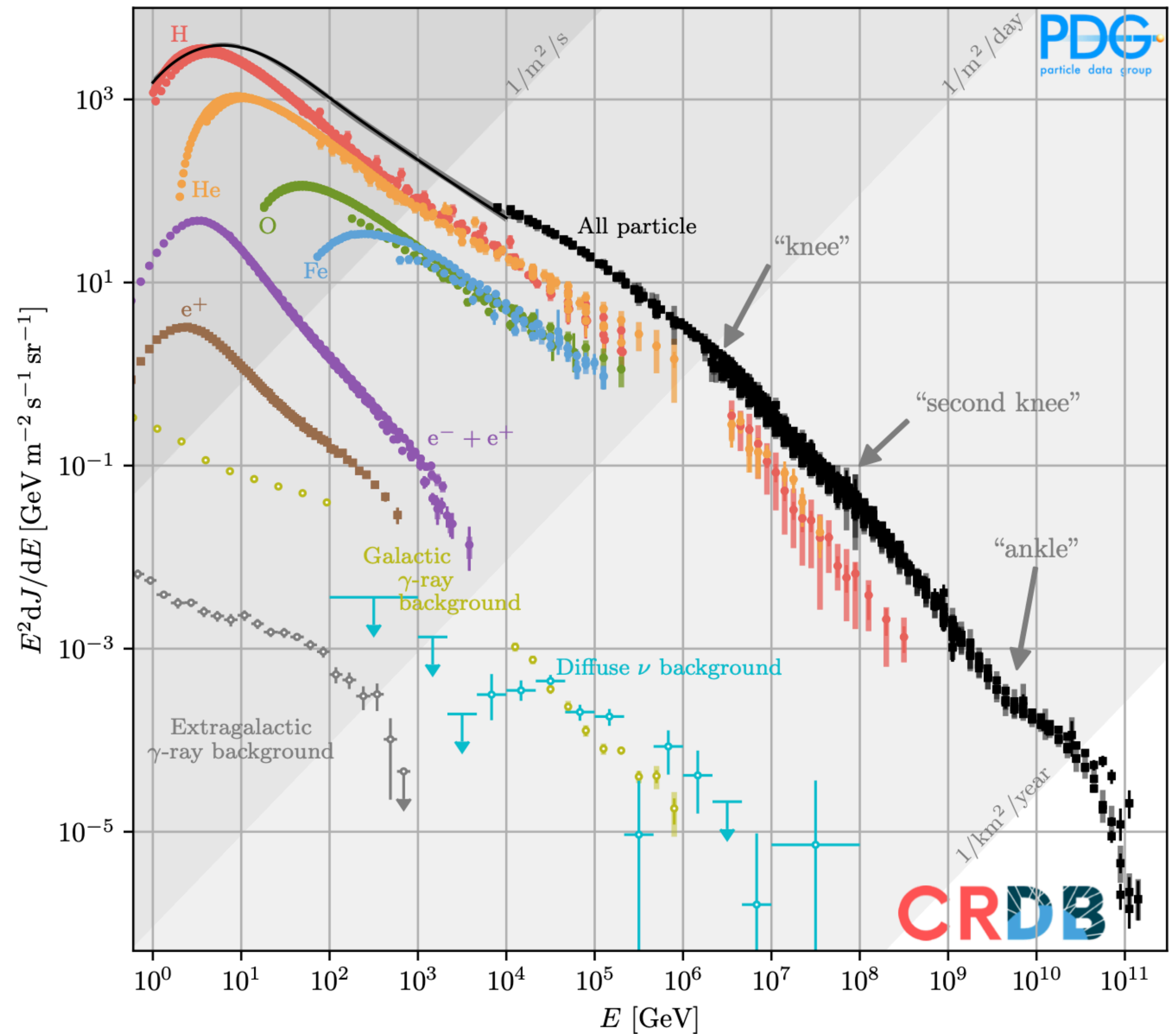
Farcy+2025, with RAMSES

What is the reality?

- A spectrum of energies and diffusion coefficients

$$\kappa \sim 10^{28} - 10^{29} \text{ cm}^2/\text{s} \left(\frac{E}{\text{GeV}} \right)^{0.5}$$

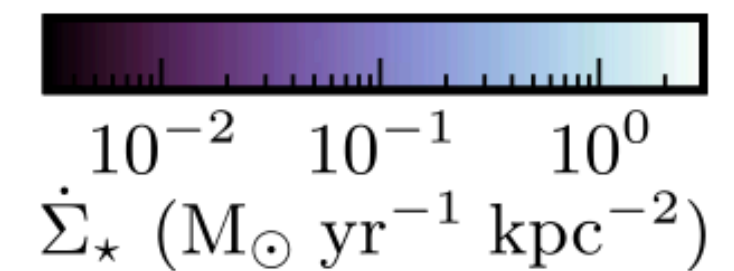
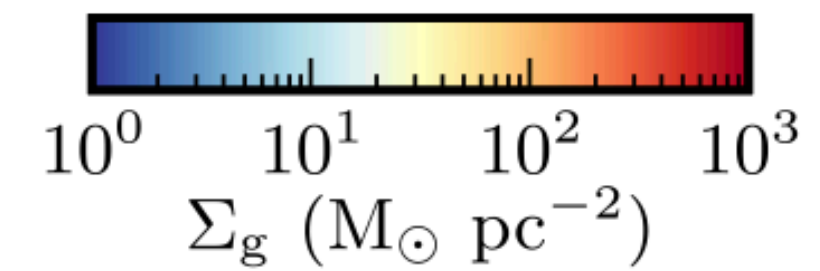
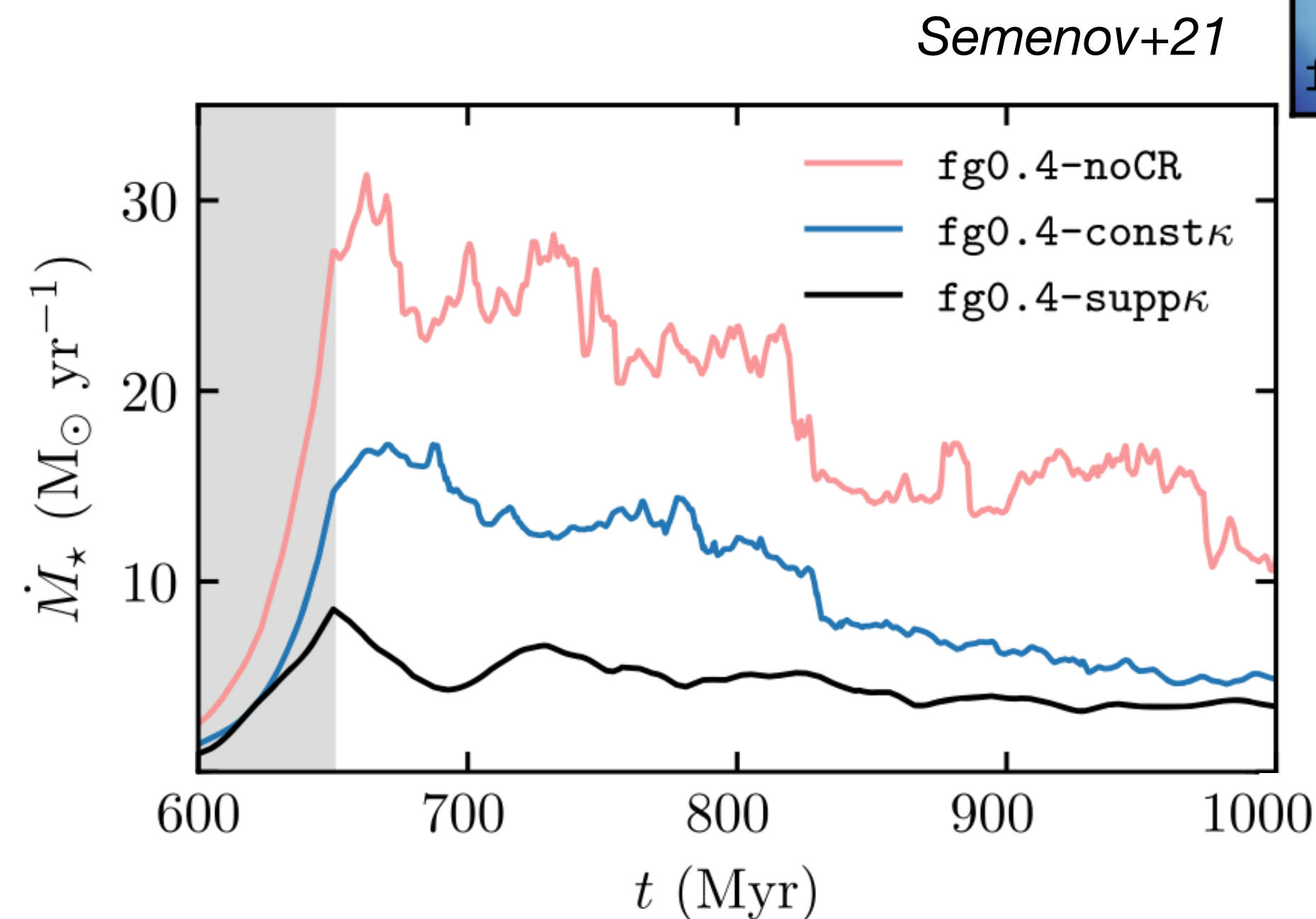
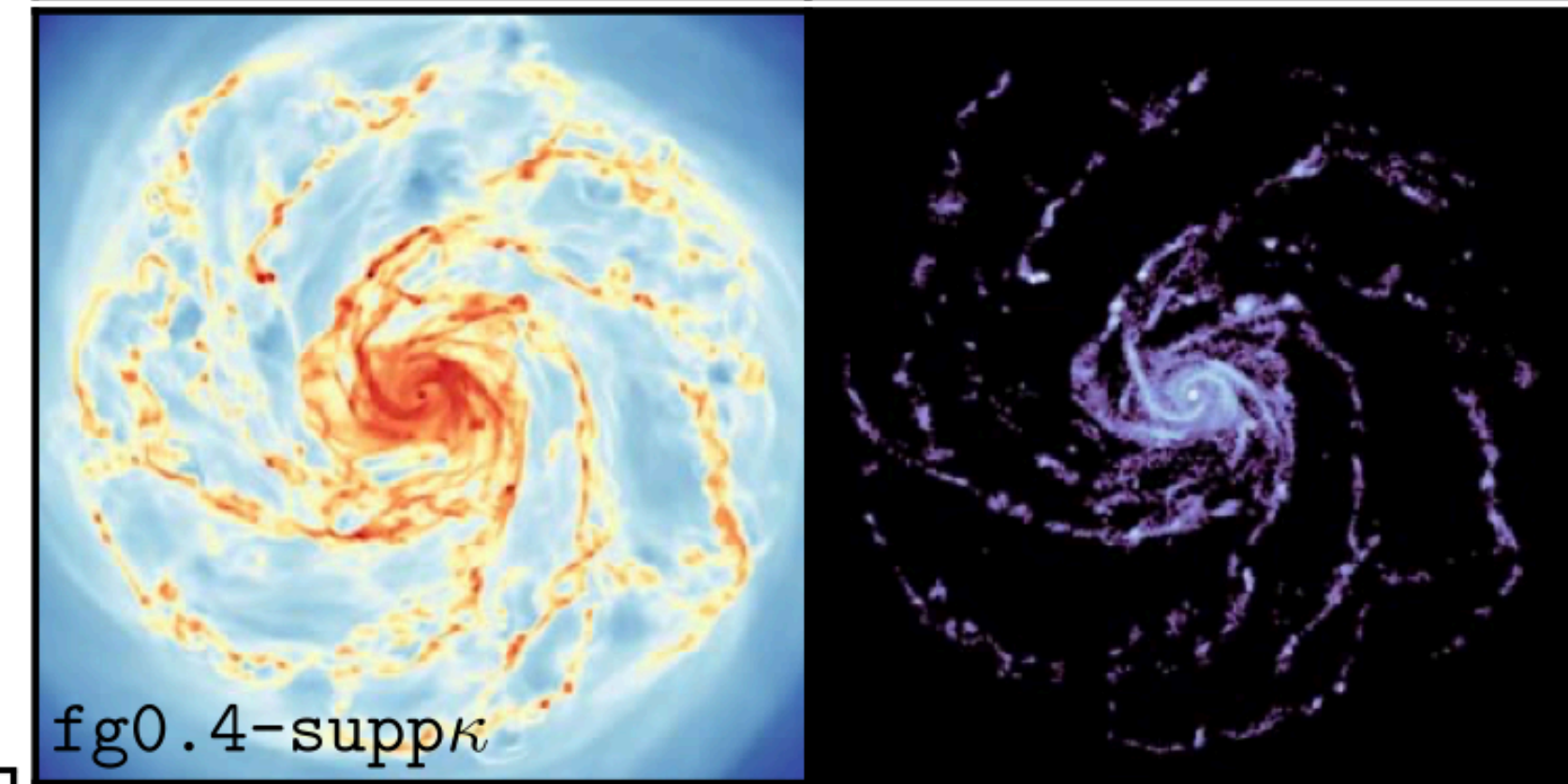
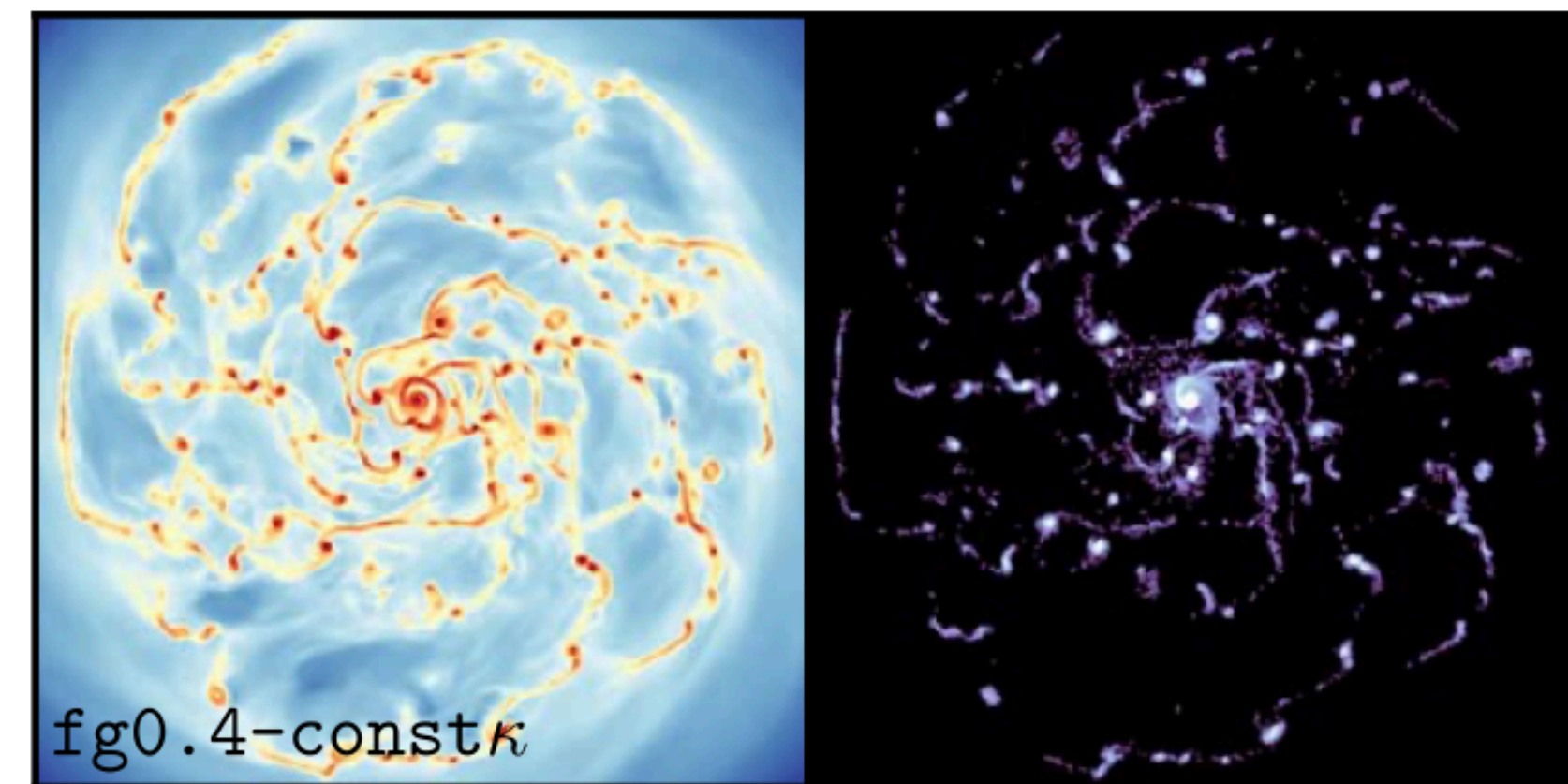
- And they can *stream* along **B**



What is the reality?

- CRs can also be trapped in turbulent regions around star formation (i.e. suppressed κ)

- To advance our understanding of CR feedback, it is vital to model multiple CR energies and varying κ



Cosmic rays in RAMSES, since 2015

1-moment, or “zeroth-moment”, already in RAMSES (Dubois&Commercon 2015)

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

$$\frac{\partial(\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v} - \mathbf{B} \mathbf{B} + \mathbf{P}^*) = \nabla \cdot \mathbf{P}_C$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P^*) \mathbf{v} - \mathbf{B}(\mathbf{B} \cdot \mathbf{v})] = -(\mathbf{v} + \mathbf{v}_s) \cdot (\nabla \cdot \mathbf{P}_C),$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0,$$

$$\frac{\partial E_c}{\partial t} + \nabla \cdot \mathbf{F}_c = (\mathbf{v} + \mathbf{v}_s) \cdot (\nabla \cdot \mathbf{P}_c) + Q,$$

$$\mathbf{F}_c = (E_c + P_c) (\mathbf{v} + \mathbf{v}_s) \quad \leftarrow \text{Advection}$$

$$\quad - \kappa \mathbf{b} (\mathbf{b} \cdot \nabla E_c) \quad \leftarrow \text{Diffusion}$$

- Zeroth moment drawbacks:

- severe timestepping condition (-> implicit)

$$\Delta t < C_{\text{cour}} \Delta x^2 / \kappa,$$

- overly diffusive

- problems with diffusion-streaming transition, varying diffusion coefficients, and multi-group transport

New: 2-moment CRs in RAMSES!

Rosdahl+25, Diallo+26

based on Jiang&Oh (2017) in ATHENA, and similar to Chan et al. (2019) and others

$$\begin{aligned}\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0, \\ \frac{\partial(\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v} - \mathbf{B} \mathbf{B} + \mathbf{P}^*) \\ &= \nabla \cdot \mathbf{P}_c \\ \frac{\partial E}{\partial t} + \nabla \cdot [(E + P^*) \mathbf{v} - \mathbf{B}(\mathbf{B} \cdot \mathbf{v})] \\ &= -(\mathbf{v} + \mathbf{v}_s) \cdot (\nabla \cdot \mathbf{P}_c), \\ \frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) &= 0,\end{aligned}$$

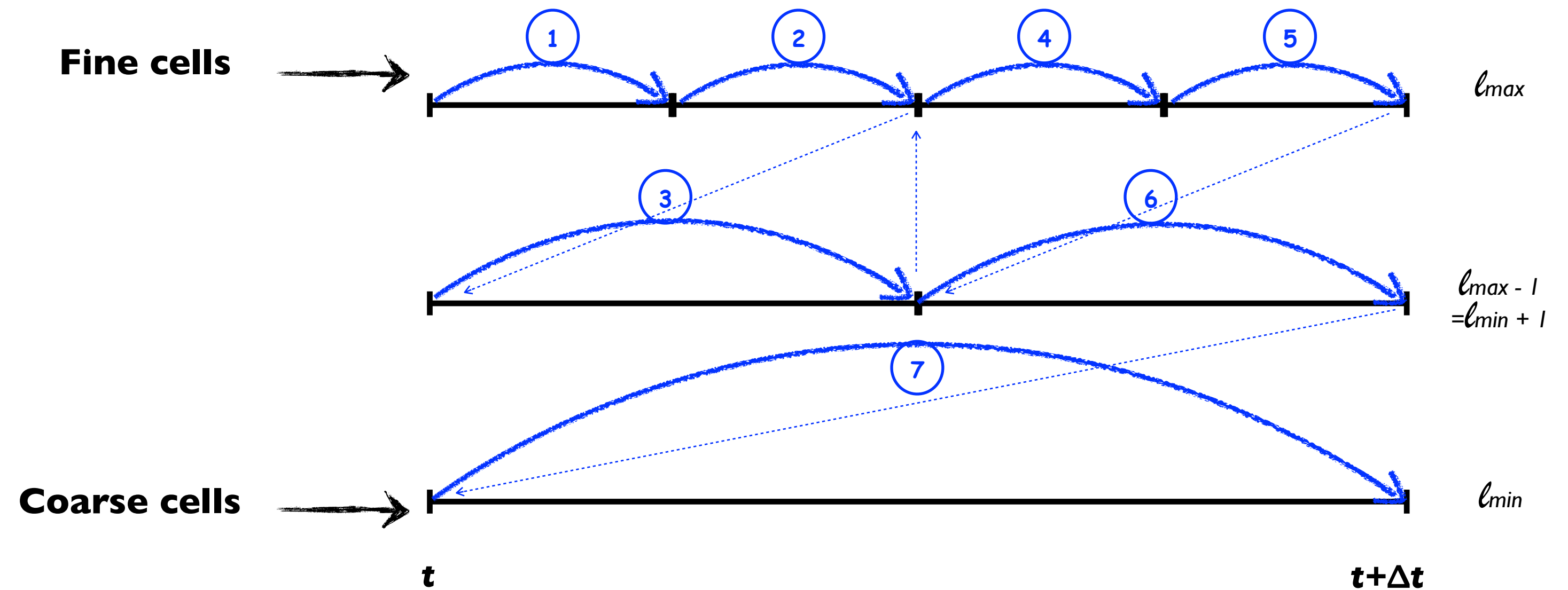
$$\begin{aligned}\frac{\partial E_c}{\partial t} + \nabla \cdot \mathbf{F}_c \\ &= (\mathbf{v} + \mathbf{v}_s) \cdot (\nabla \cdot \mathbf{P}_c) + Q, \\ \frac{1}{V_m^2} \frac{\partial \mathbf{F}_c}{\partial t} + \nabla \cdot \mathbf{P}_c \\ &= -\kappa^{-1} [\mathbf{F}_c - \mathbf{v} \cdot (E_c \mathbf{I} + \mathbf{P}_c)].\end{aligned}$$

- \mathbf{F}_c becomes an extra vector variable
- **Explicit solver:** no problem with multi-group or varying diffusion
- V_m is a *maximum* CR speed (or “reduced light speed”)
- Limits the time-step with the usual Courant condition, i.e.
$$\Delta t \approx \Delta x / V_m$$
- V_m **must** be larger than the gas speed and *preferentially* larger than the streaming speed and diffusion speed

Adding 2mom CRs to RAMSES

Hydro only

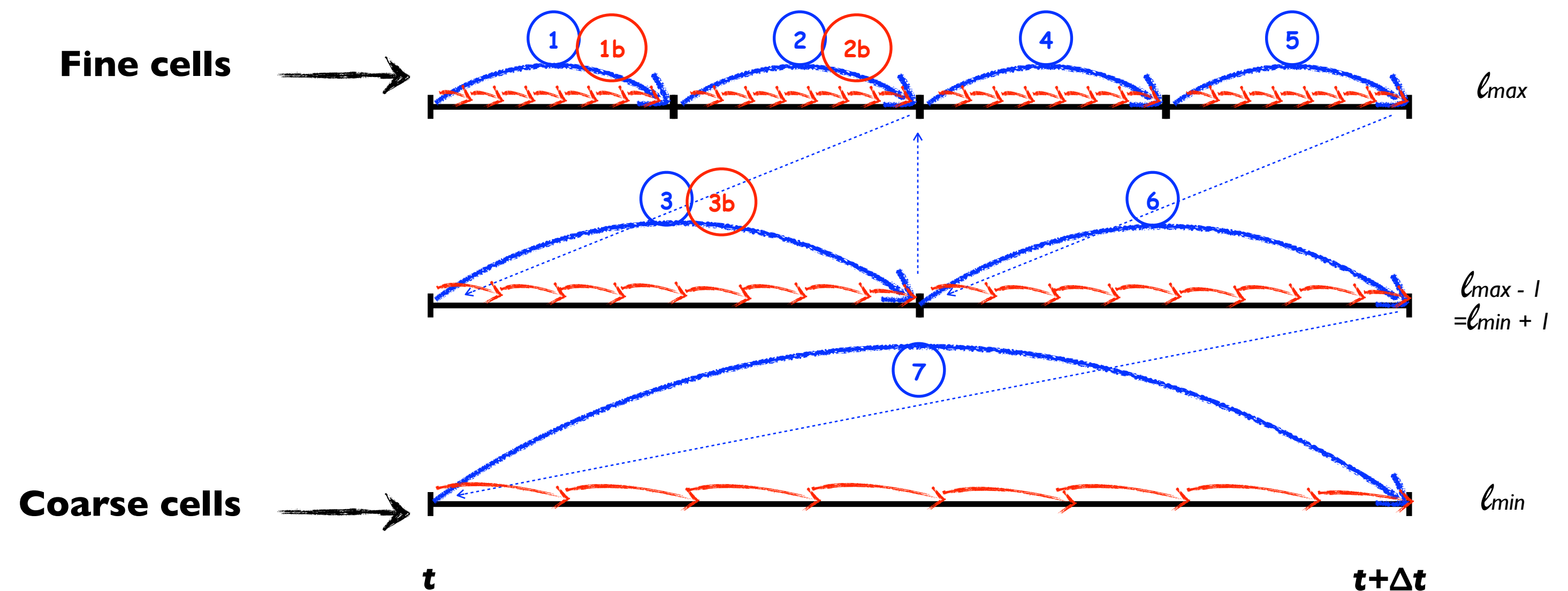
- Two fine steps for every coarse steps, starting at finest level



Adding 2mom CRs to RAMSES

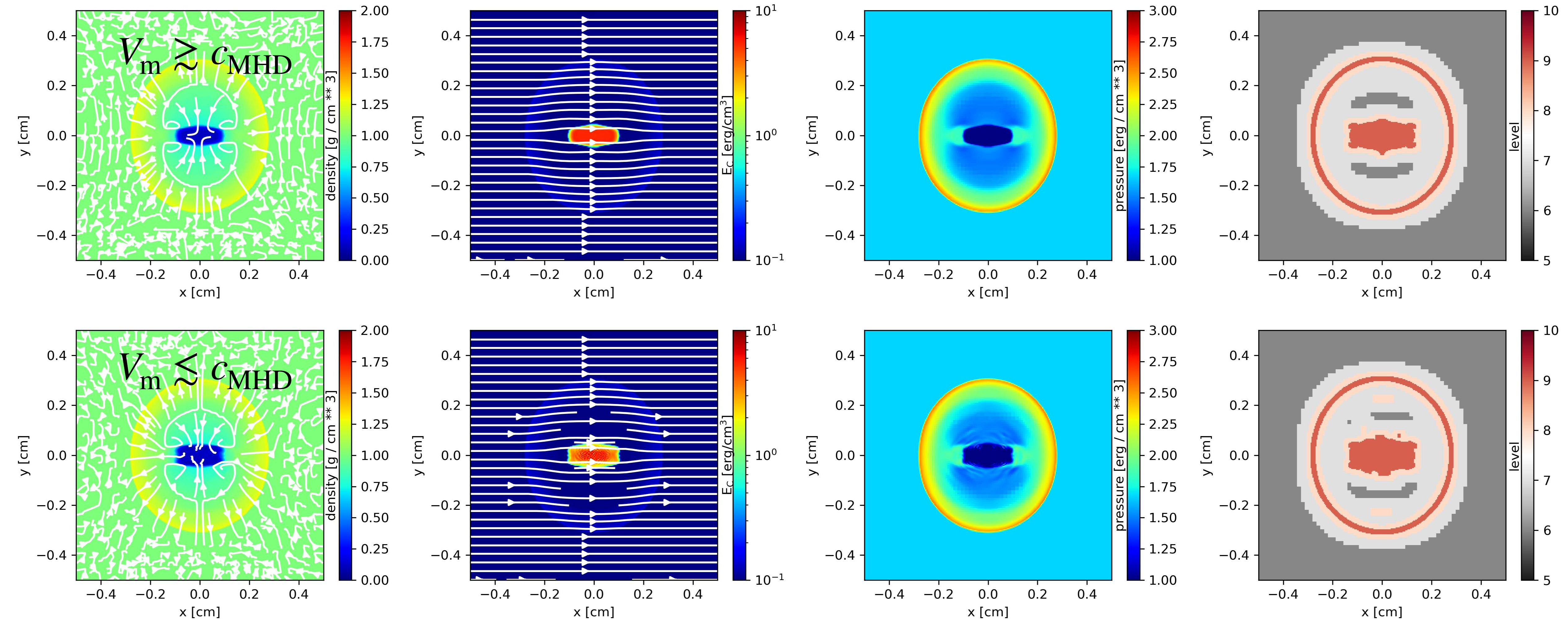
Hydro + CRs

- CRs **sub-cycled** on each level
- Almost all the additions are in `cr_godunov_fine.f90` and `cr_flux_module.f90`
- Call to `crmom_step` inside the `amr_step` routine
- CR sub-cycling precludes exact CR energy conservation across refinement boundaries



Reduced speed of light

- We must have $V_m > c_{\text{MHD}}$, otherwise things break down



Variable speed of light

- We must have $V_m > c_{\text{MHD}}$
- It's difficult to know in advance what will be the maximum c_{MHD} , so we use a variable light-speed, setting in every MHD step in every refinement level:

$$V_m = N c_{\text{MHD}}$$

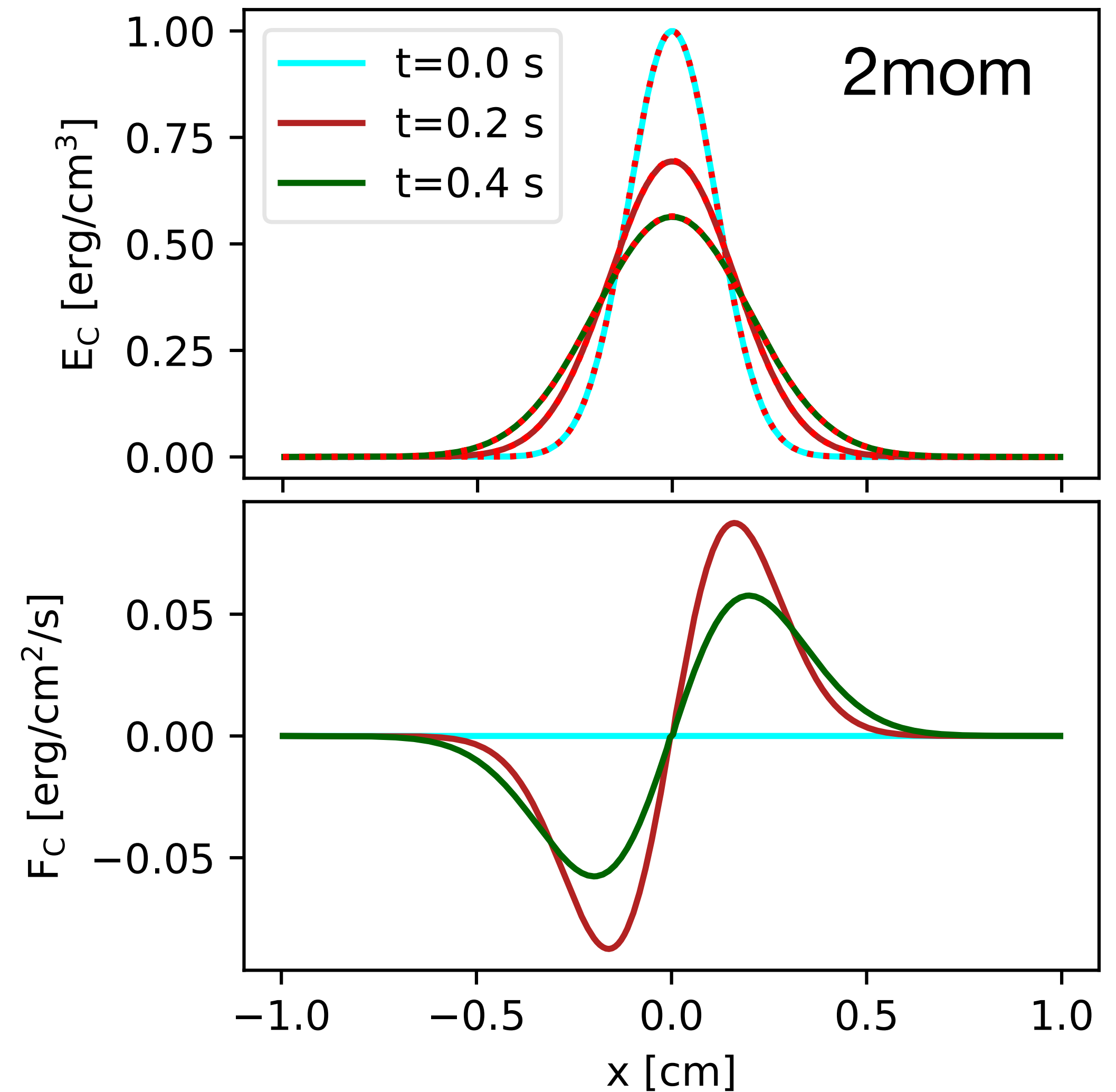
- For the tests, we typically need $N \gtrsim 10$
- But for isolated galaxy test, the results are converged with $N \gtrsim 3$

Tests

Tests

Pure diffusion in 1d

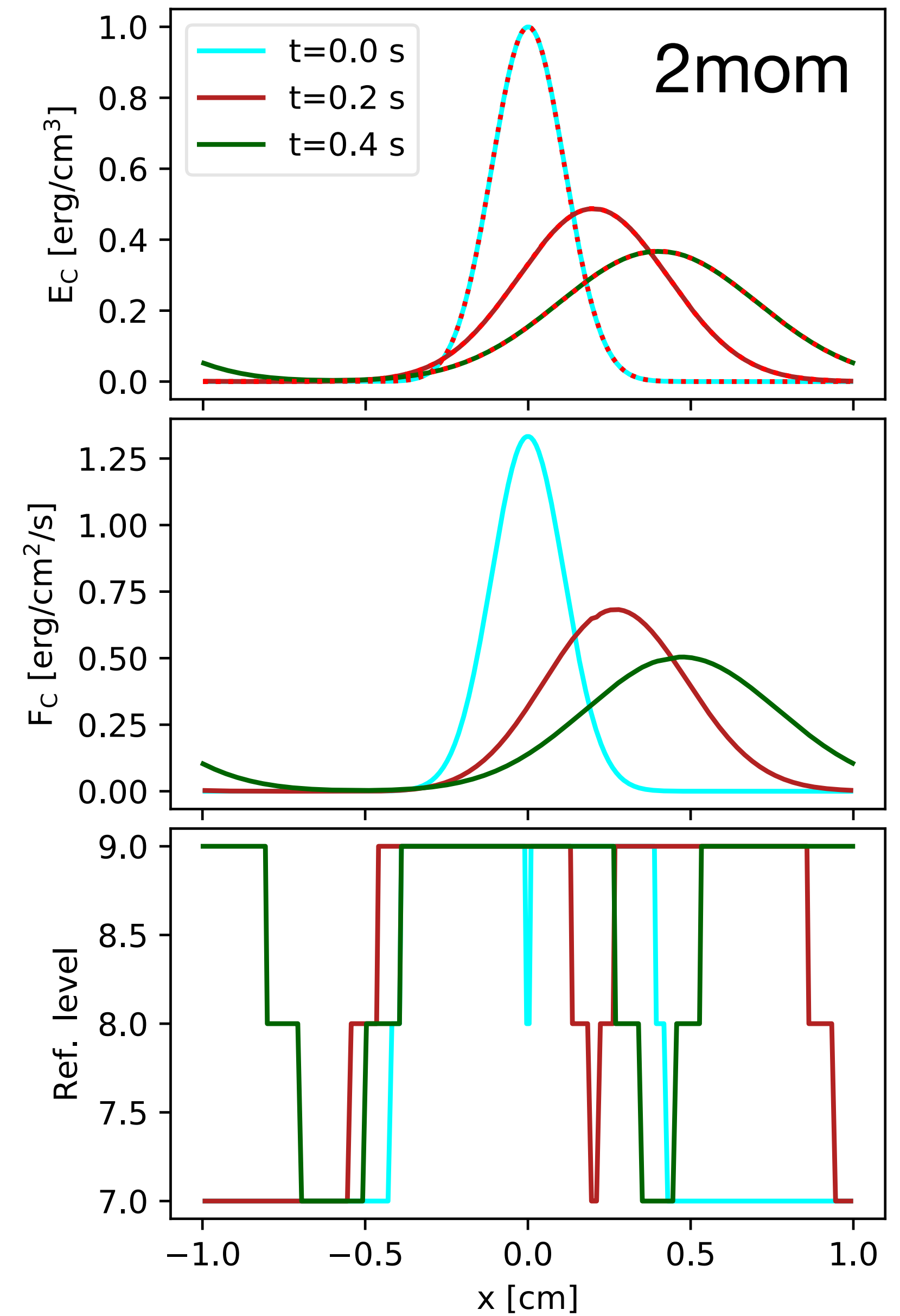
- Diffusion can be compared to analytic expression, in dotted curves



Tests

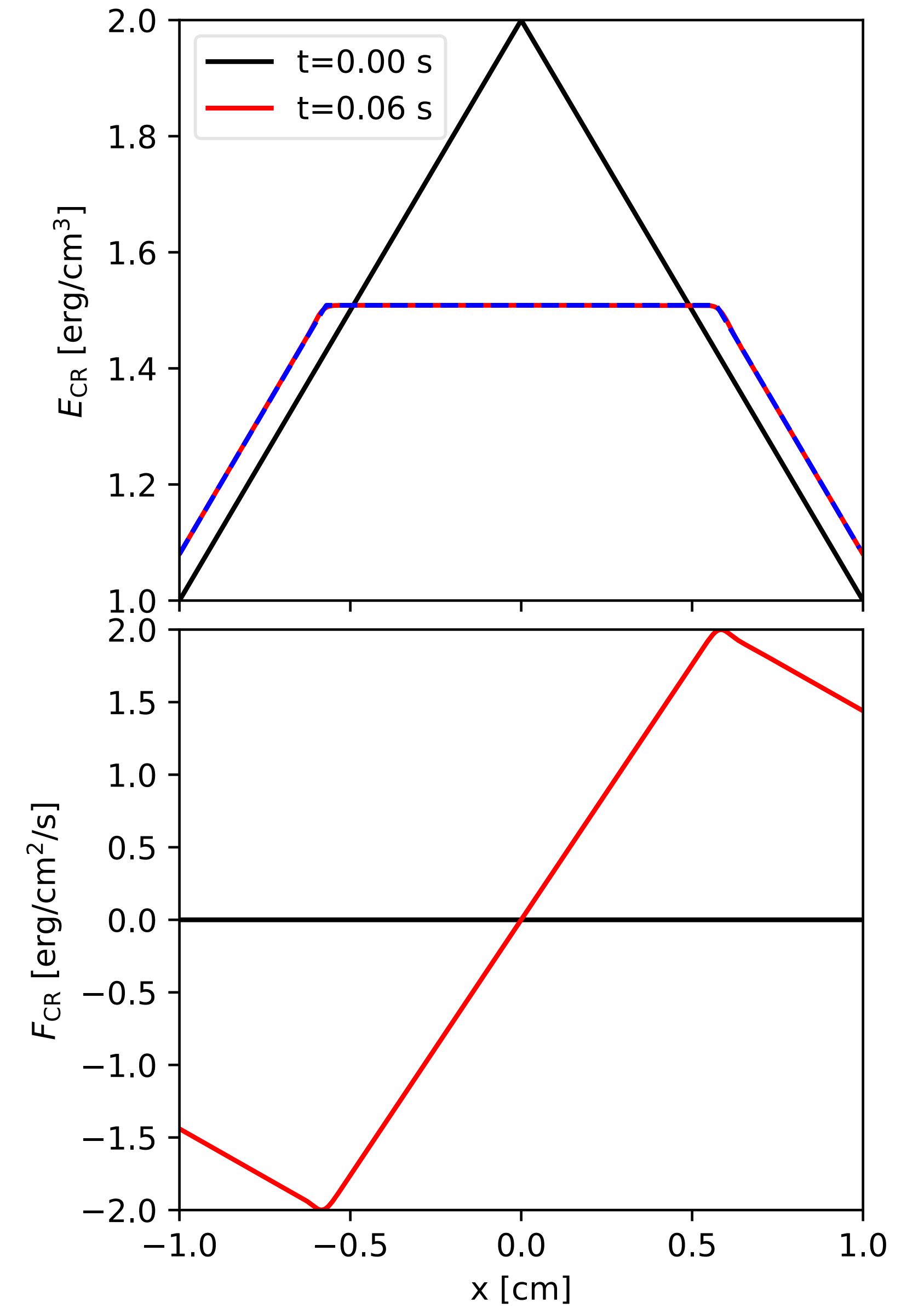
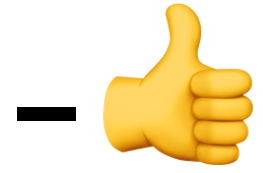
Pure diffusion in 1d

- Diffusion can be compared to analytic expression, in dotted curves
- With AMR and moving gas
- 👍



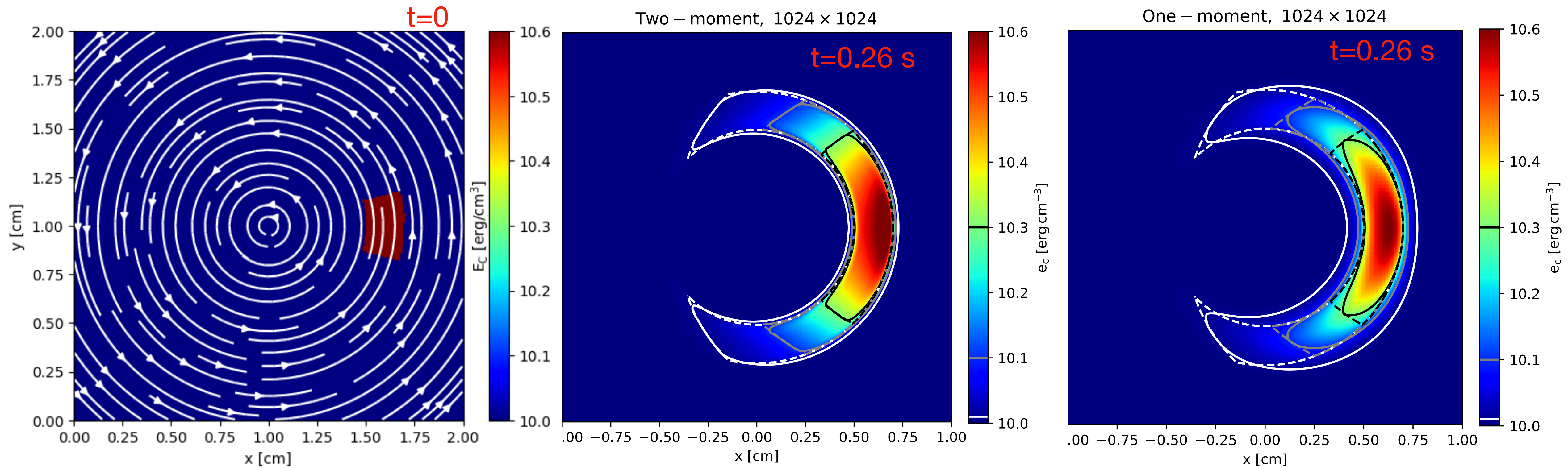
Tests

Pure streaming in 1d



Tests

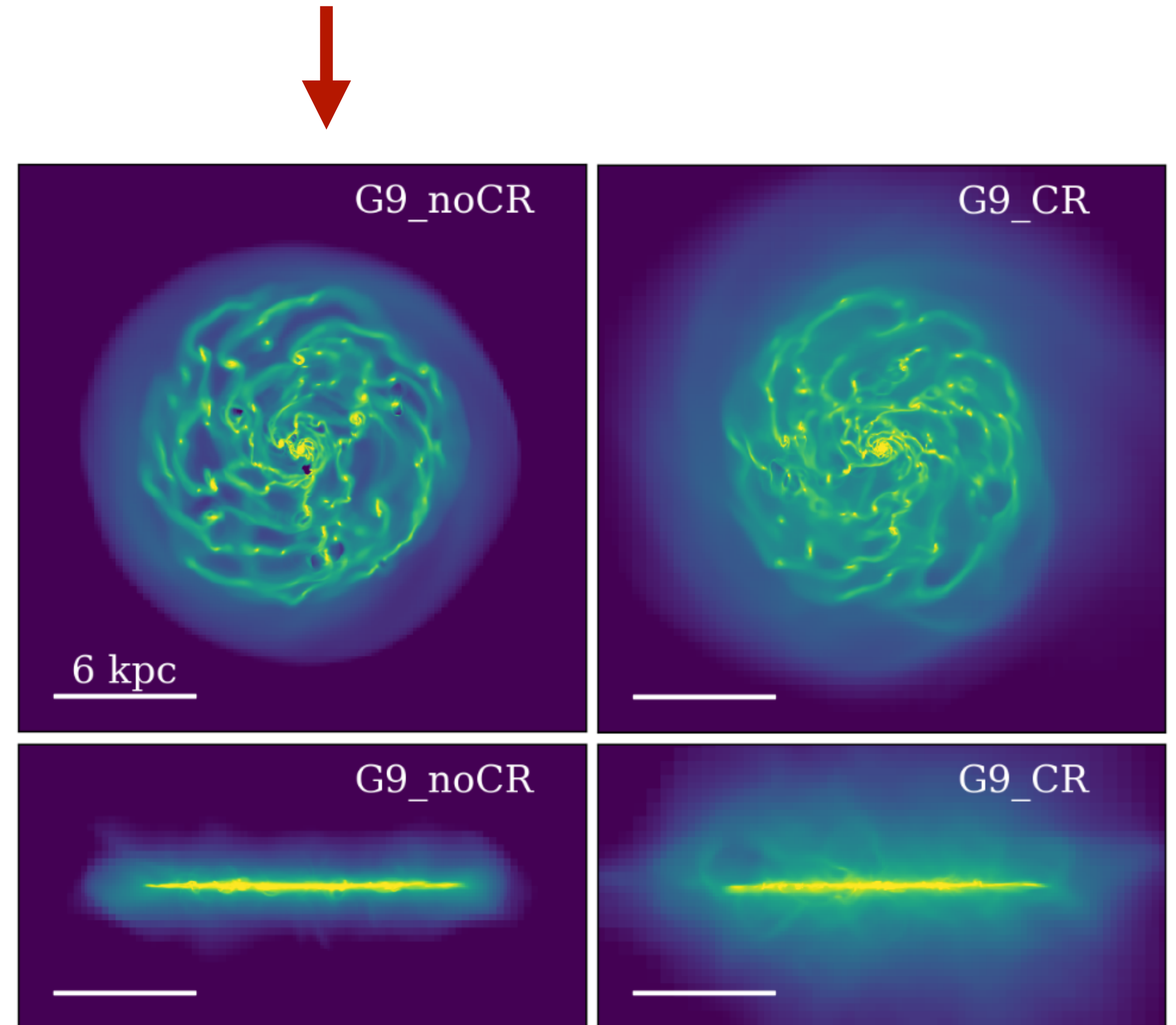
Anisotropic diffusion



Tests

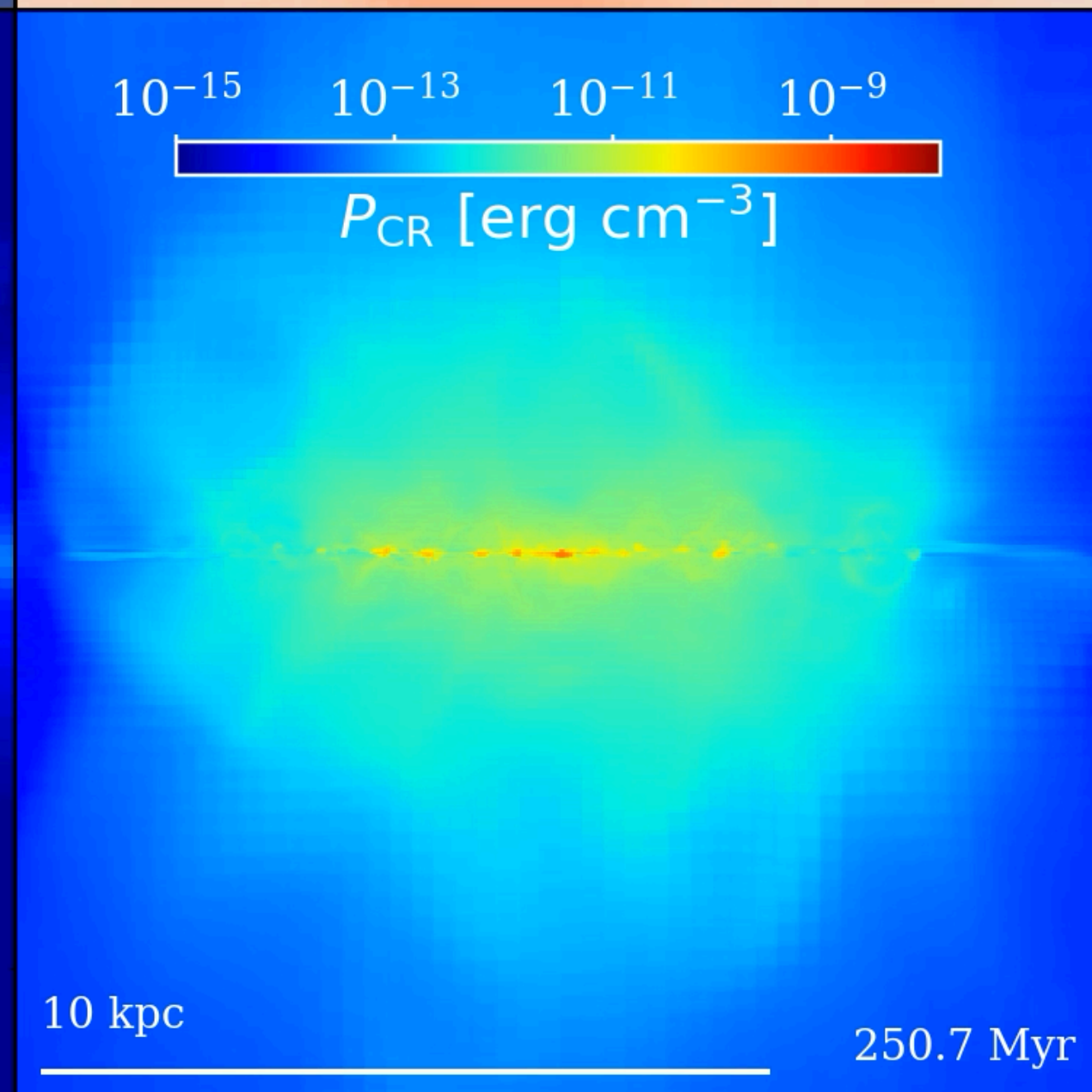
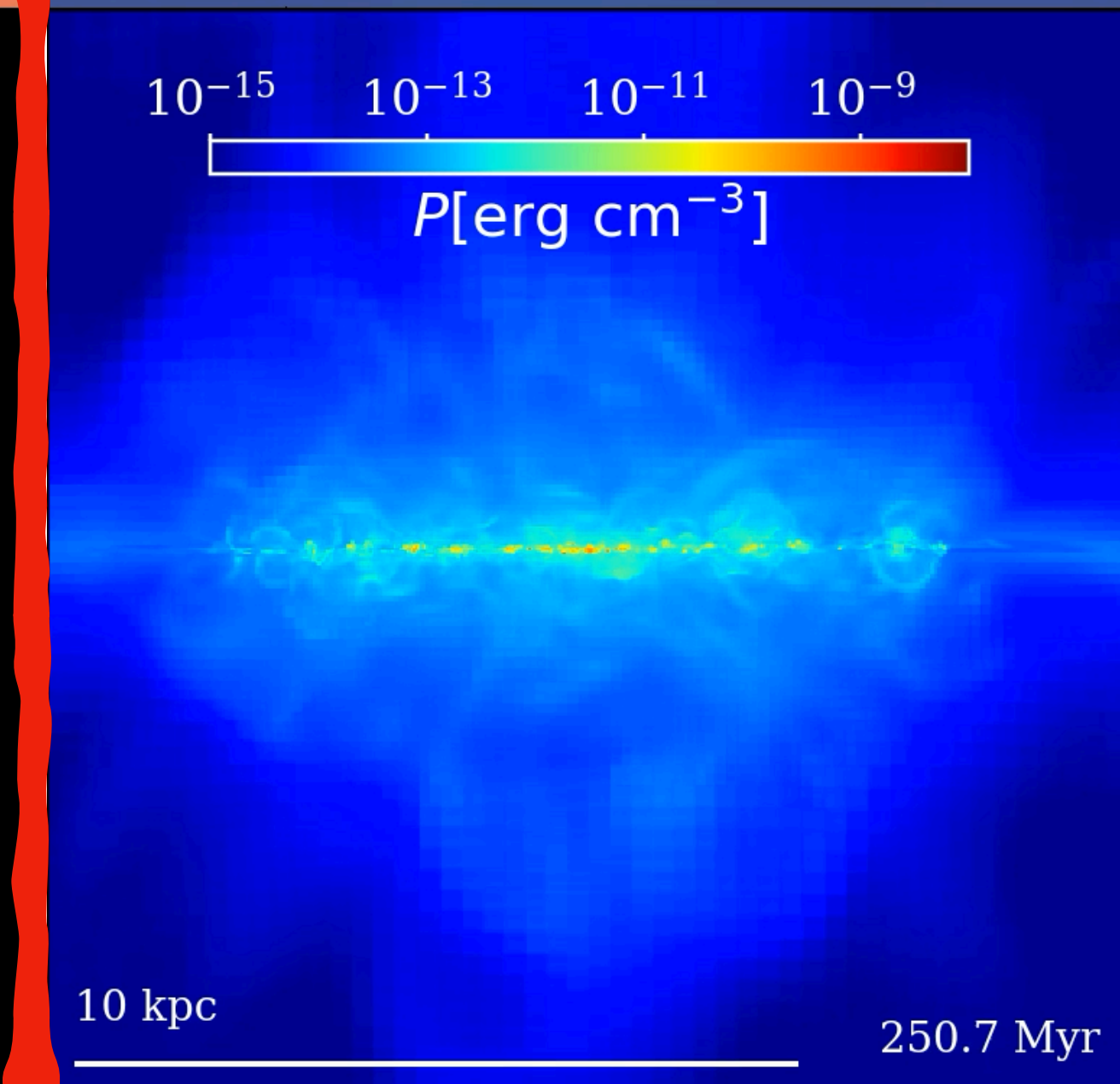
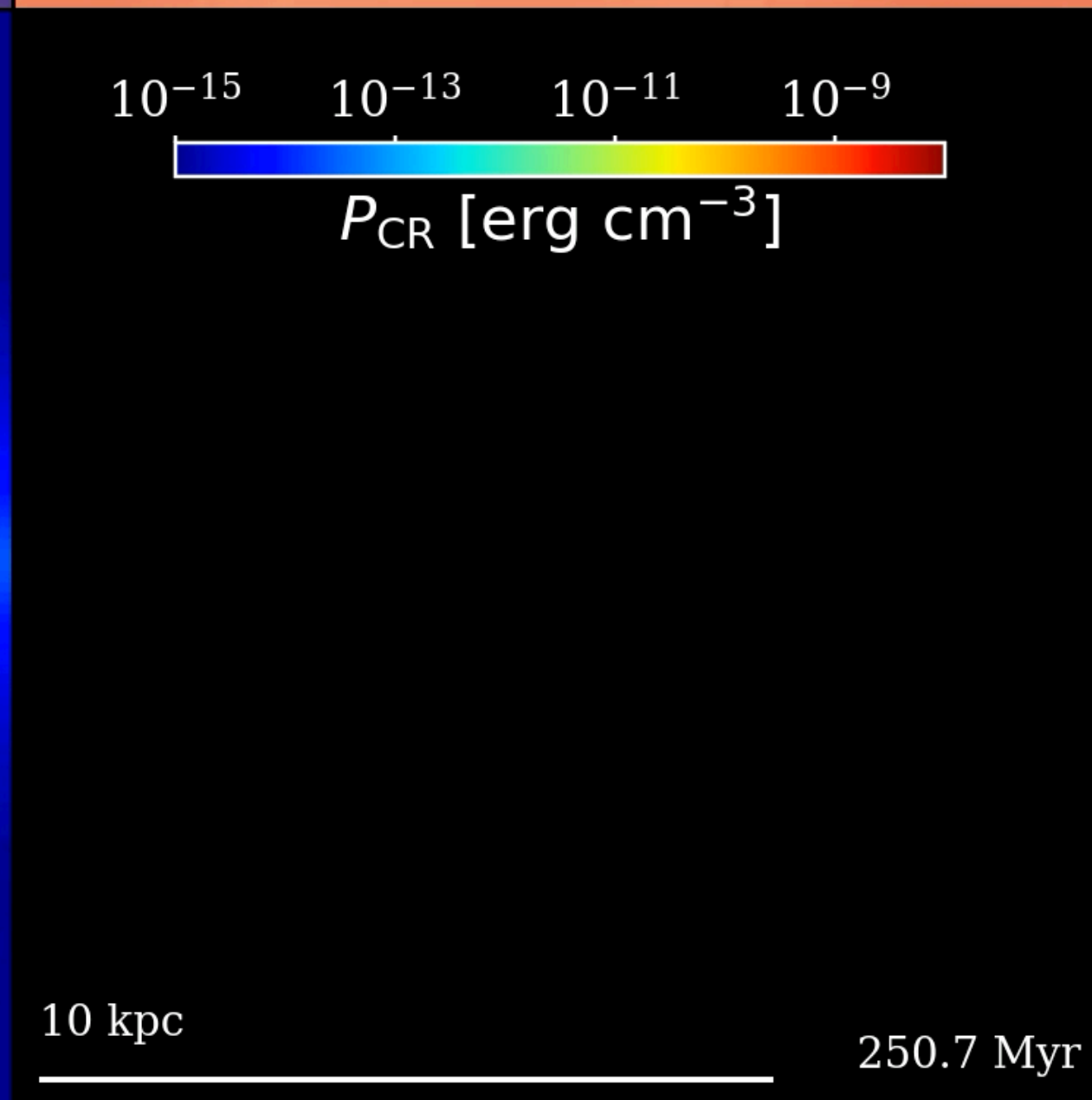
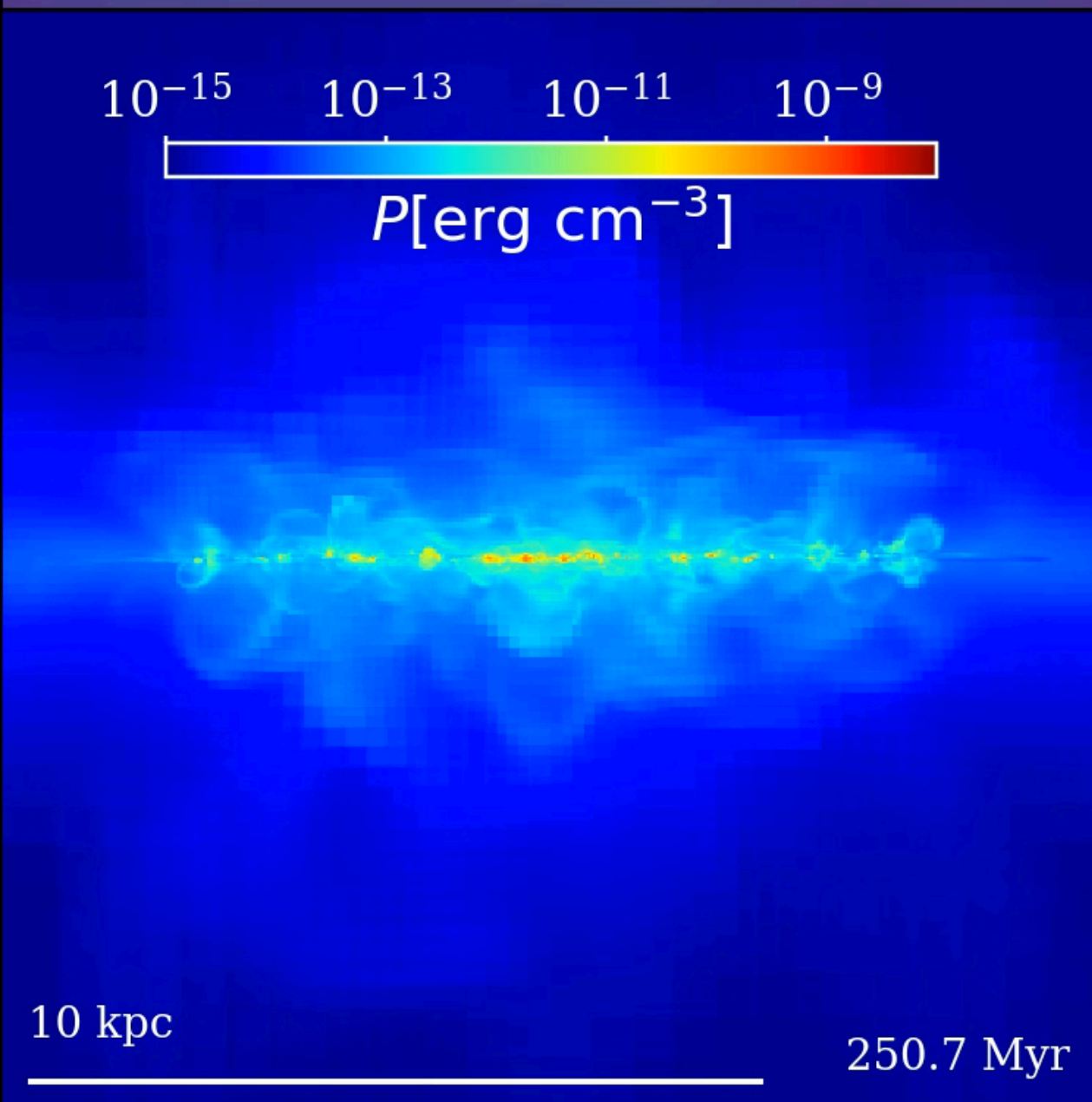
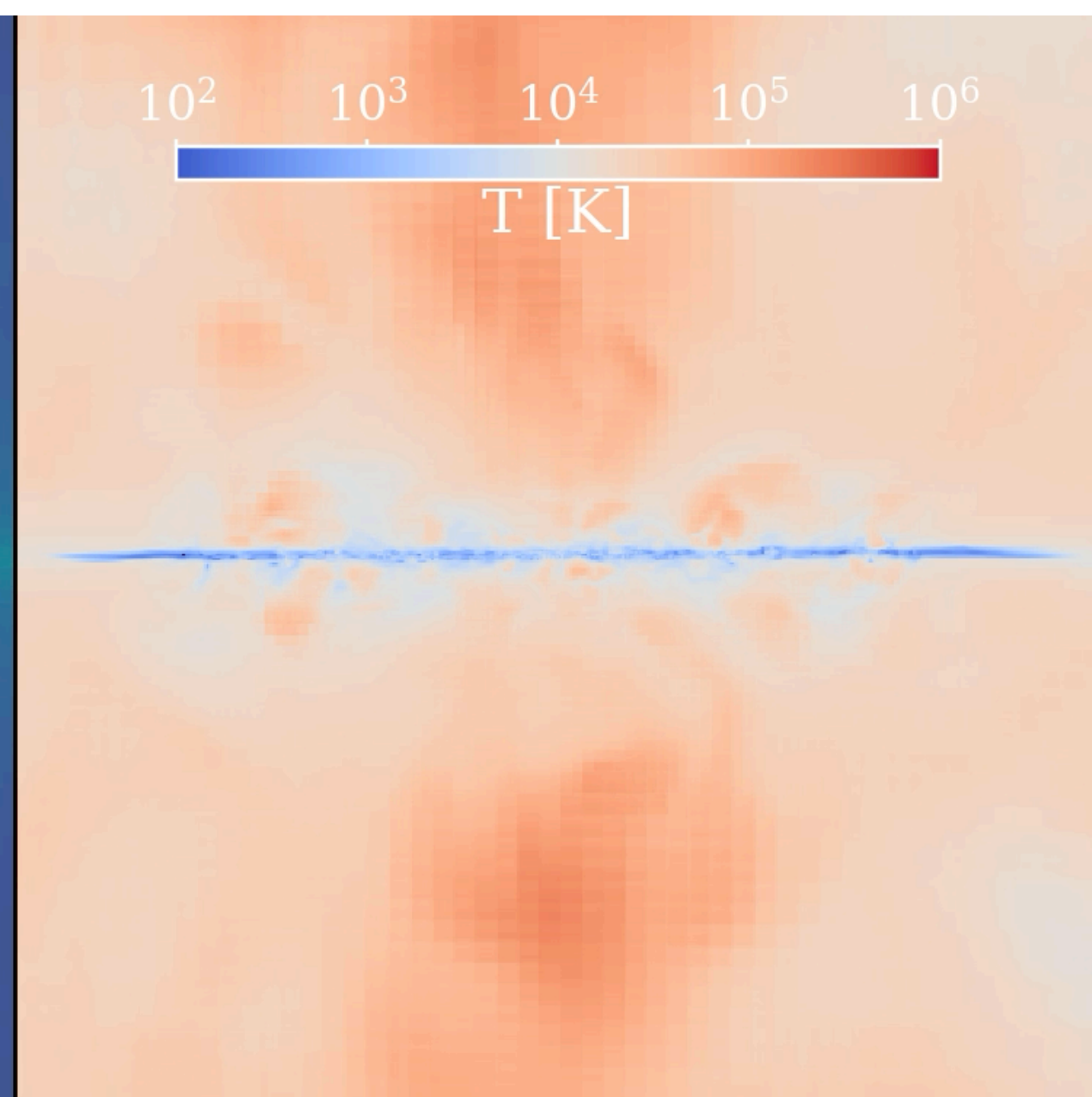
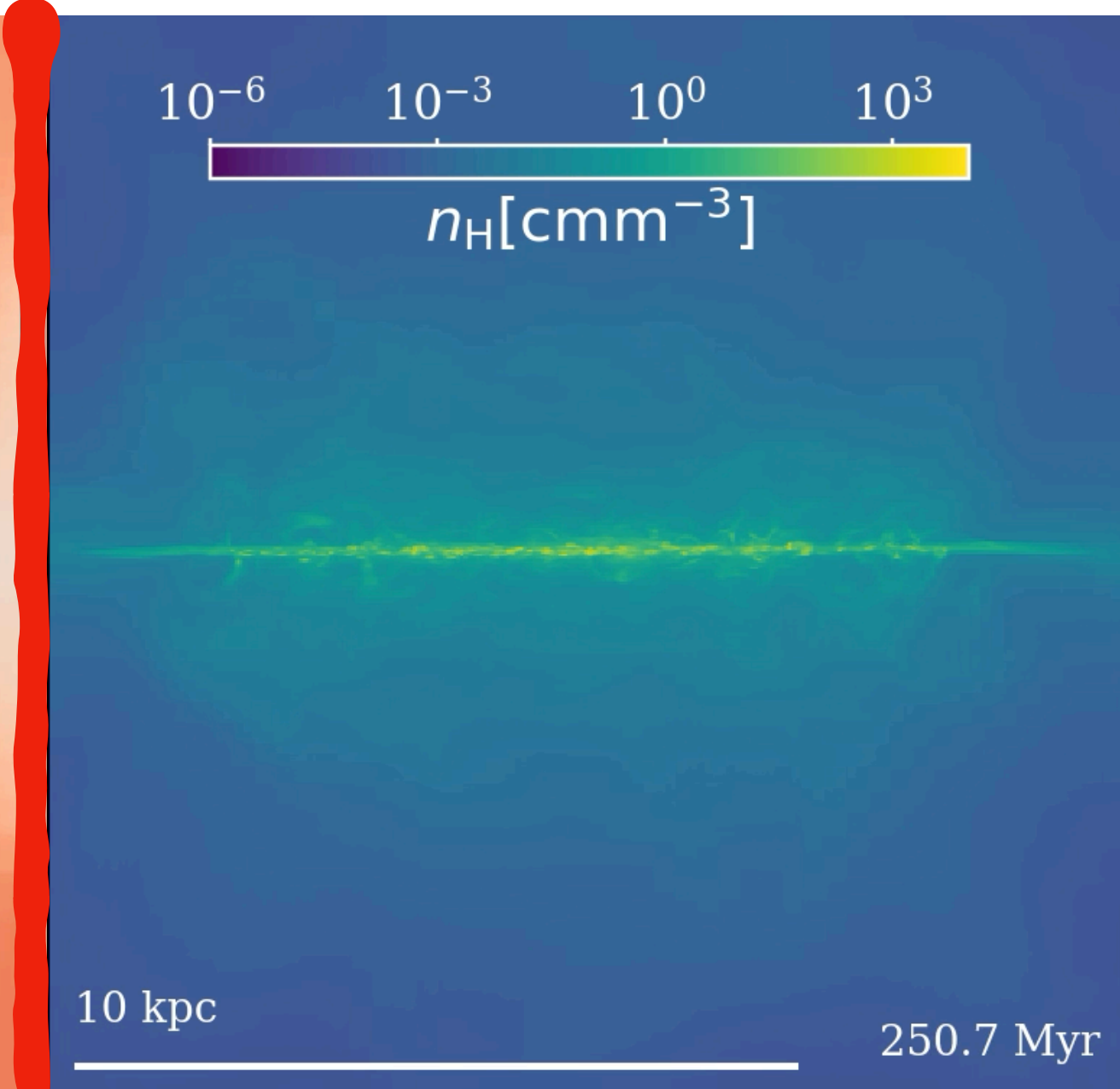
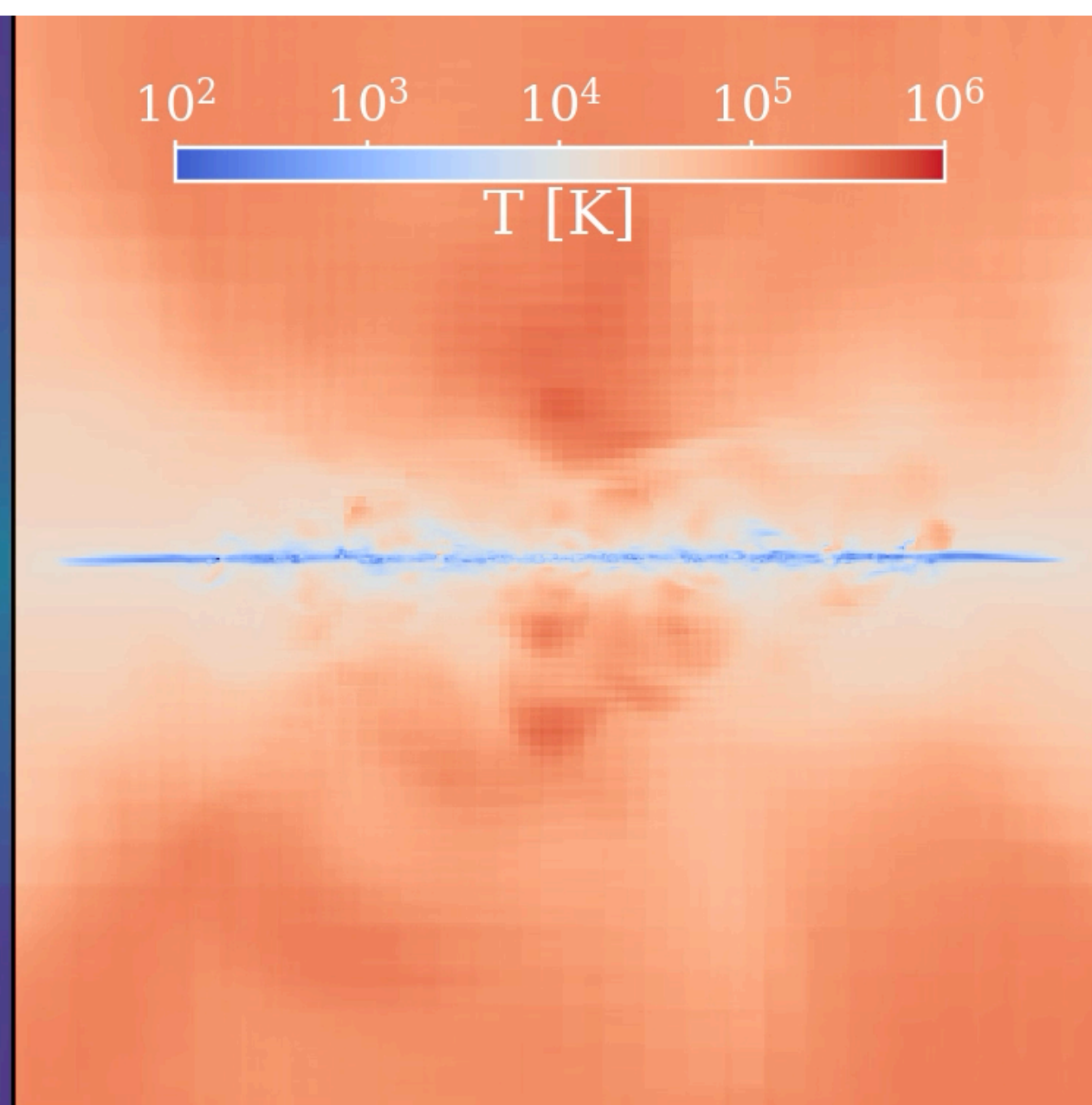
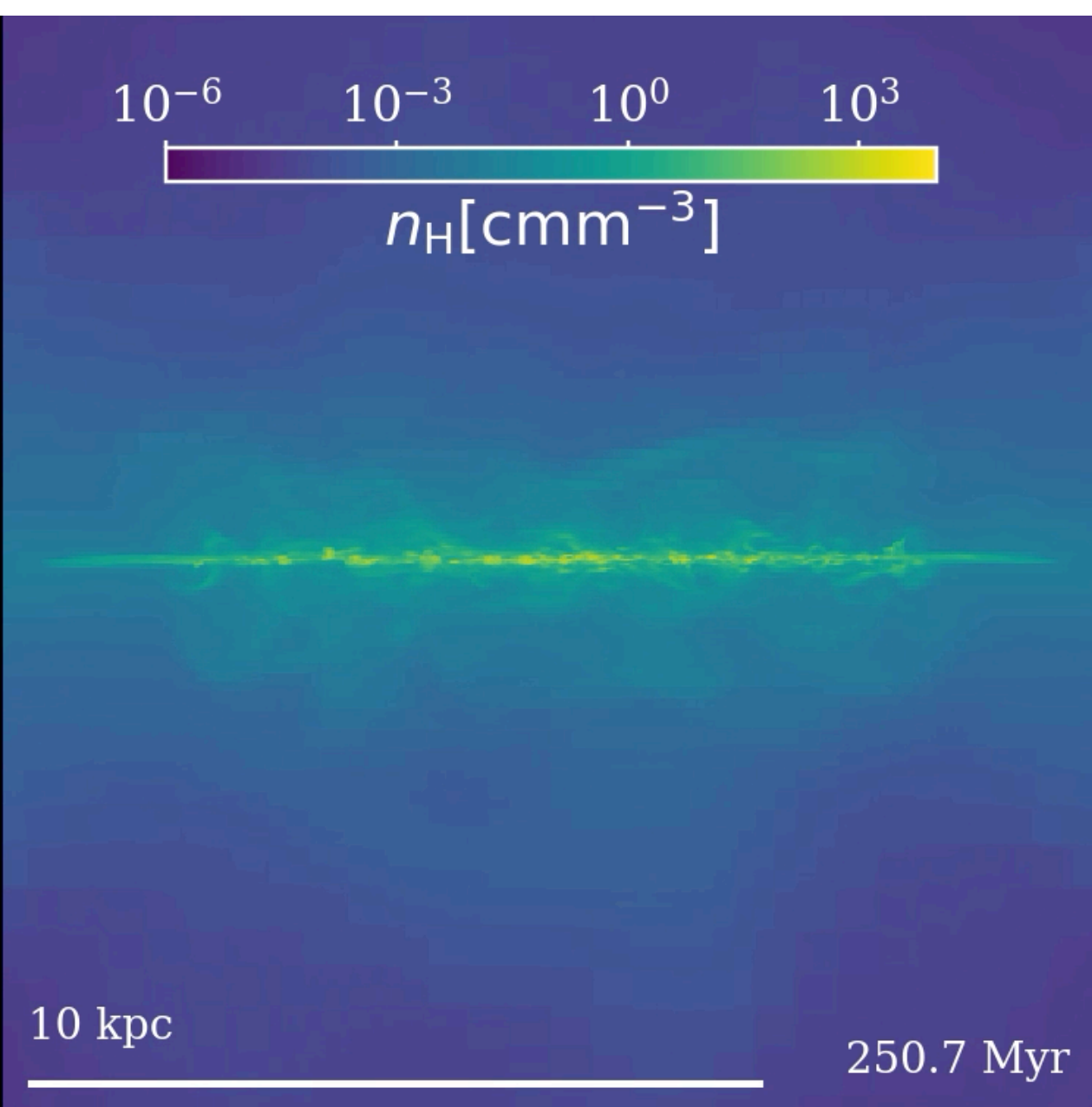
Isolated “G9” galaxy disk, described in Farcy et al. (2022)

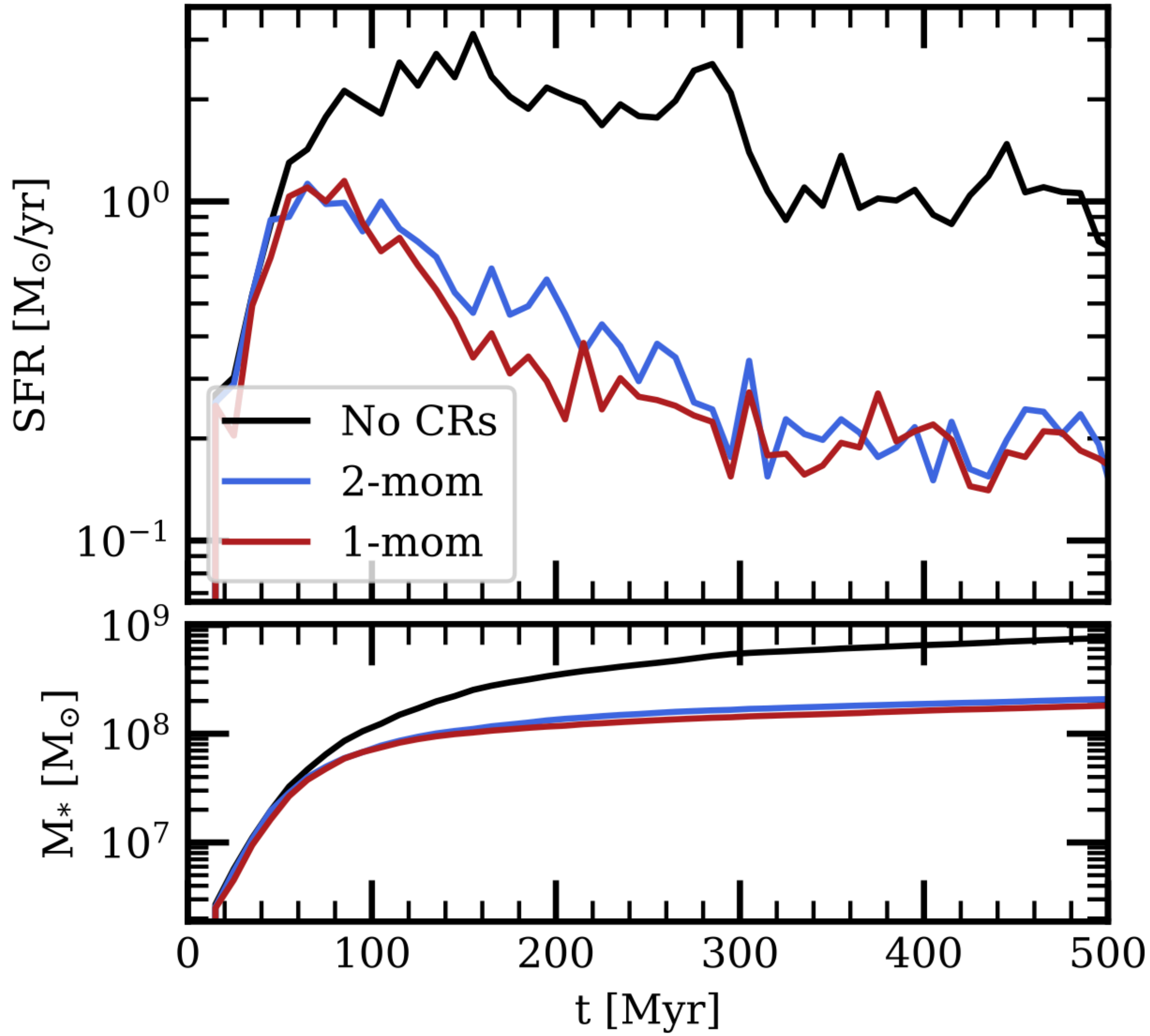
- $M^* = 10^9 M_\odot$ galaxy with 18 pc resolution
- $\kappa = 3 \times 10^{28} \text{ cm}^2/\text{s}$
- Compared with 1mom and 2mom in RAMSES



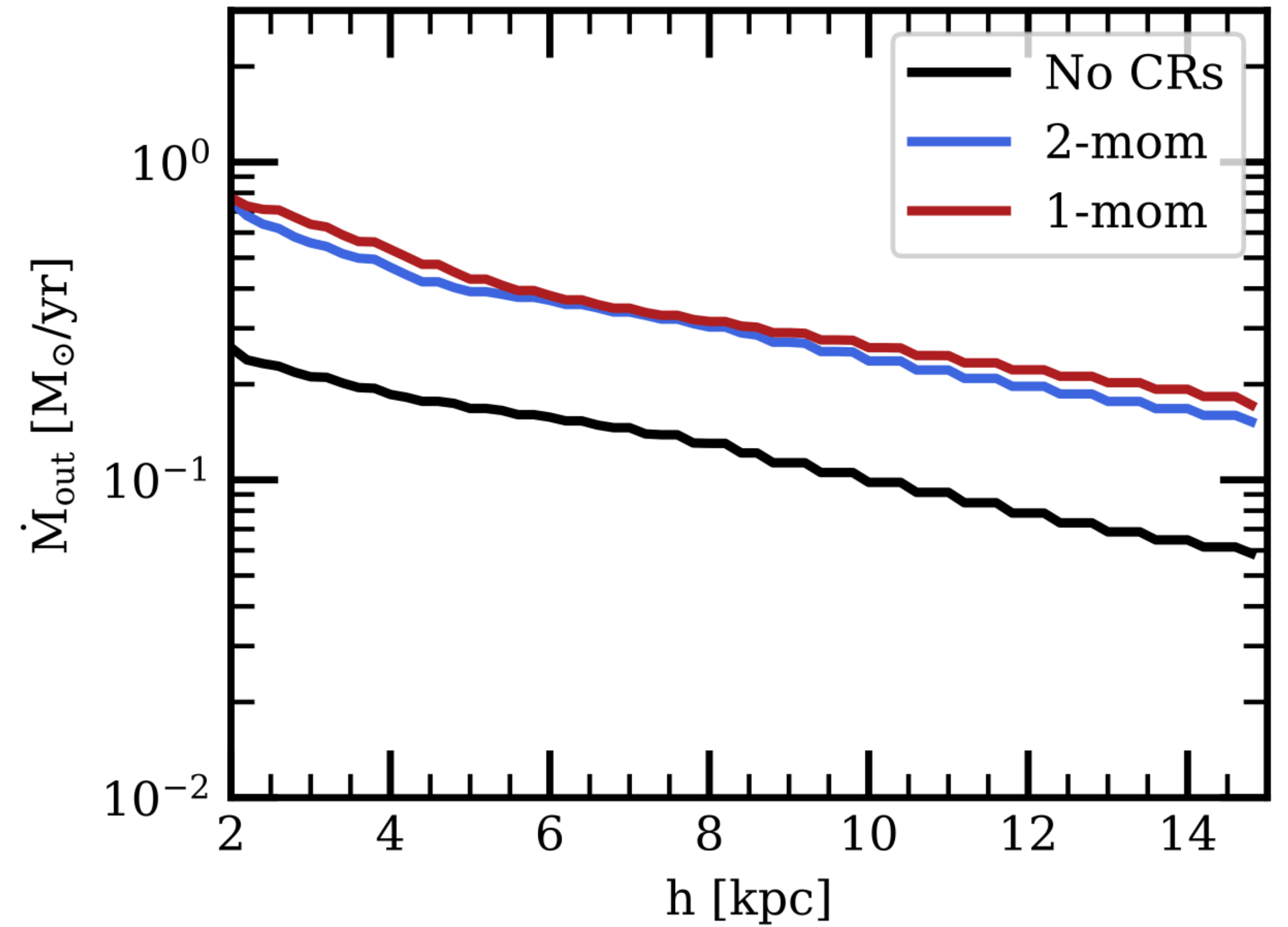
Without CRs

With 2Mom CRs





Galaxy SFRs and outflows with and without CRs



Cost

Time-step lengths

- In isolated galaxy disk runs, time-steps tend to be about 5-10 times smaller than in 1-mom version
- This can to a large extent be mitigated by decoupling CRs from under-dense gas with $\rho < 10^4 \rho_{\min}$ \rightarrow similar time-step lengths
- With a sufficiently small speed-of-light factor, the runtime for the isolated galaxy with the 2-mom method approaches that of the 2-moment method.
- **But streaming and multi-group are for free**, which is not the case for 1-moment

2-moment cosmic rays status

- The paper is submitted and on arXiv — working on the 20-page report
- 1 science paper out (Sampson+25 on CR-plasma coupling) and more to come
- Nai-Chieh Lin is putting it into the public version of RAMSES — **stay tuned!**
 - and then Mini-RAMSES
- The implementation is memory-heavy, with 4 variables per CR group!
 - We are working on a **fluid frame** approach using NENER, with two variables per group
- **Nimatou Diallo** has added **multi-group** cosmic rays and is studying their effects on galactic scales (**next talk by Yohan Dubois**)