Multi-scale approach of magnetic amplification and particle acceleration near astrophysical shocks

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Outline of the talk

- ➡ Non-resonant streaming instabilities near relativistic MHD shocks (test particle limit).
- ➡ Particles in [RMHD] Cells framework
- ➡ AMR PI[MHD]C code test cases:
  - ✦ CR filamentation instability in the precusors of shocks
  - ✦ Magnetic field amplification and particle acceleration near non-relativistic astrophysical shocks .

Particle acceleration and magnetic turbulence near astrophysical shocks

• Observations exhibit non thermal high energy emissions near astrophysical shocks (e.g. Cassam-Chenaï et al. 2004).

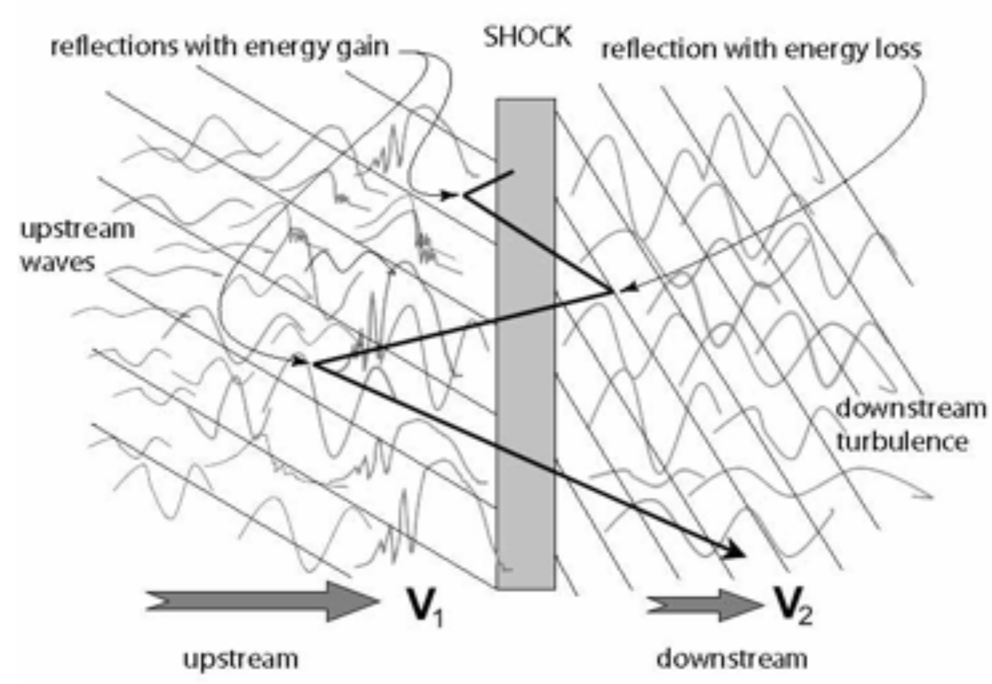
•Thin bright X-ray rims are observed at the location of the forward shock (e.g. Bamba et al 2006).

•X-ray rim structure in agreement with a localized magnetic field amplification ($\sim 10^2\ B_{ISM}$, e.g. Parizot et al 2006)

•Similar magnetic amplification is likely to occur in GRB (external relativistic shocks, e.g. Li & Waxman 2006).

•Fermi acceleration is likely to take place near the shock front.

SNR Tycho



Non-resonant streaming instability near ultra-relativistic MHD shocks

- RMHD shock setup
- RMHD simulations of magnetosonic wave amplification in the precursor of RMHD shocks

Streaming instability near relativistic shocks

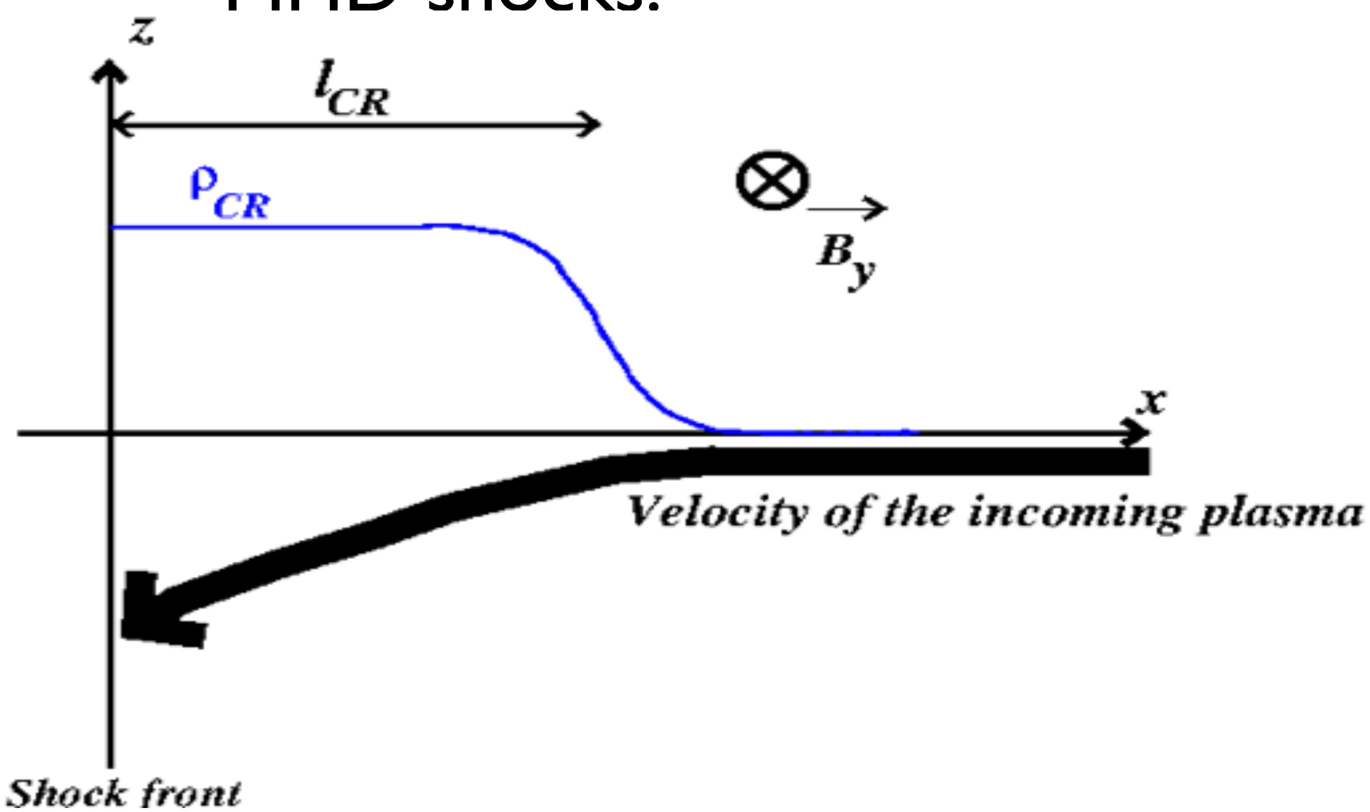
- When a significant supra-thermal particles production is achieved, a fast instability regime is reached on MHD scales (e.g. Bell'04'05, Pelletier+06, Amato & Blasi'09…).
- In the case of relativistic MHD shocks, growth rate of the instability is (Pelletier et al.'09, Casse et al.'13)

$$\tau_x(x) = \xi_{CR}\left(\frac{k_x}{l_{CR}}\frac{\beta_z(x)}{\beta_z^{SH}}\frac{\Gamma_{SH}-1}{\Gamma_{SH}+1}\right)^{\frac{1}{2}}$$

- At kinetic wavelength a very efficient electromagnetic current-driven instability is at work (Lemoine et al.'14).
- The challenge for MHD codes is to be able to accurately describe the amplification of short wavelength MHD waves in the shock precursor.
- MPI-AMRVAC (Keppens et al. 2012) is a finite volume RMHD code able to compute the propagation of such waves.

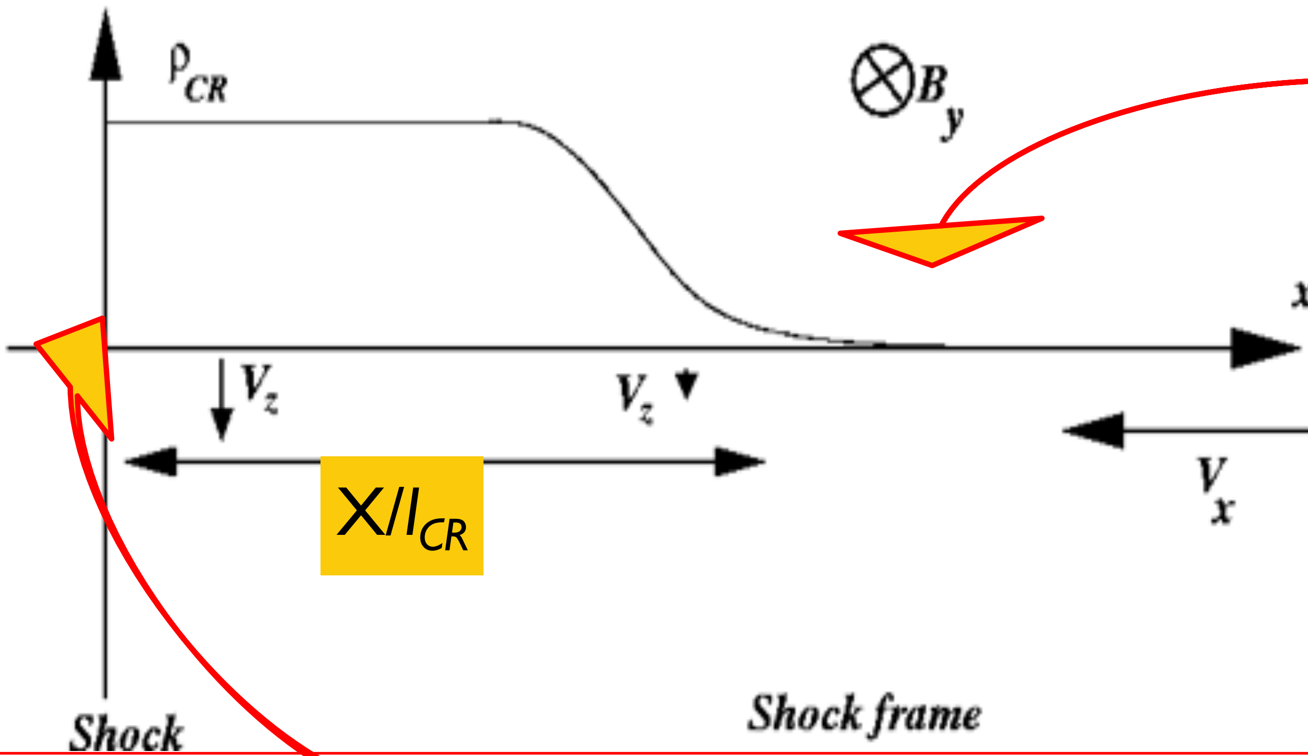
RMHD shock structure

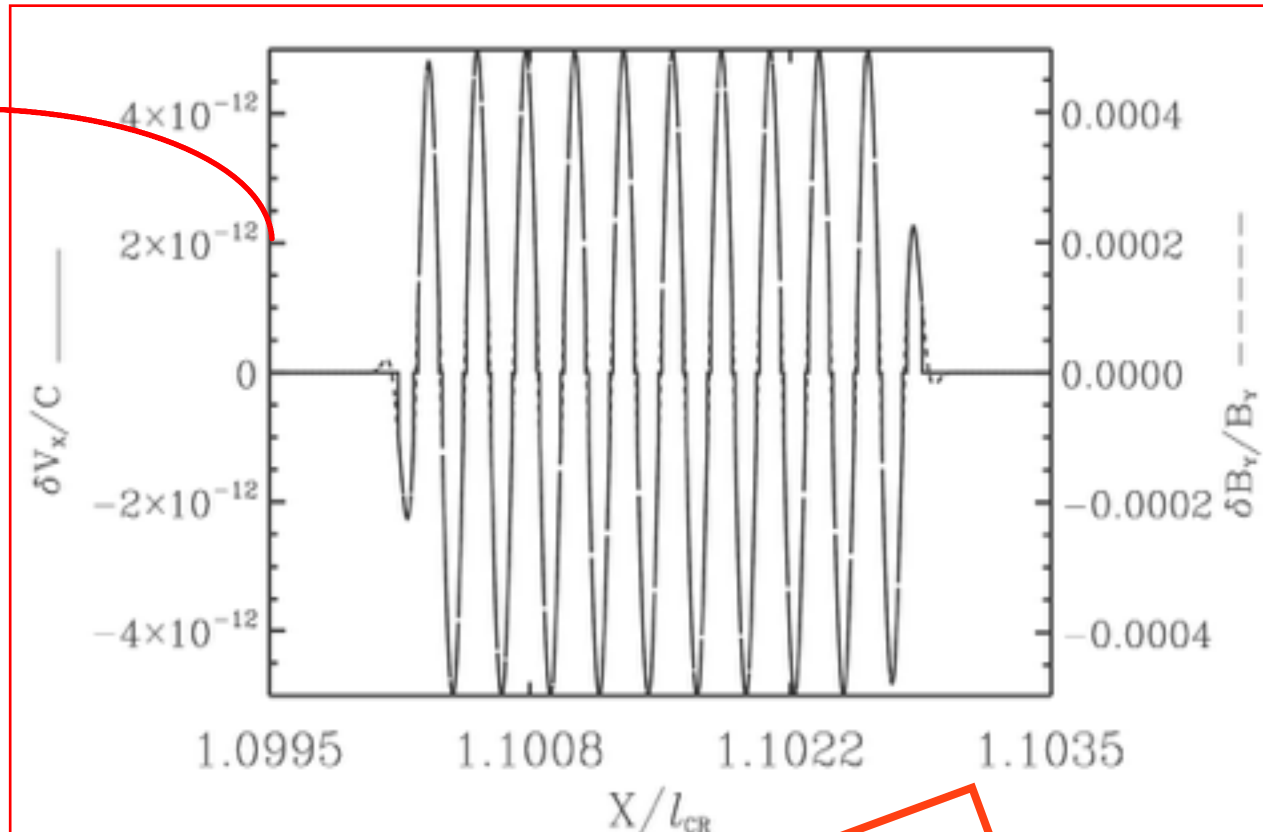
- Relativistic shocks are likely to exhibit near perpendicular magnetic field.
- The equilibrium of the upstream medium is modified by the electric charge carried by the thermal plasma.
- Non-resonant streaming instability is believed to efficiently amplified short wavelength magnetic perturbations near relativistic MHD shocks.



$$\left|\frac{v_z}{v_x}\right|^{SH} \approx \xi_{CR} = \frac{e_{CR}}{\Gamma_{SH}(\Gamma_{SH}-1)\rho_u c^2} < 1$$

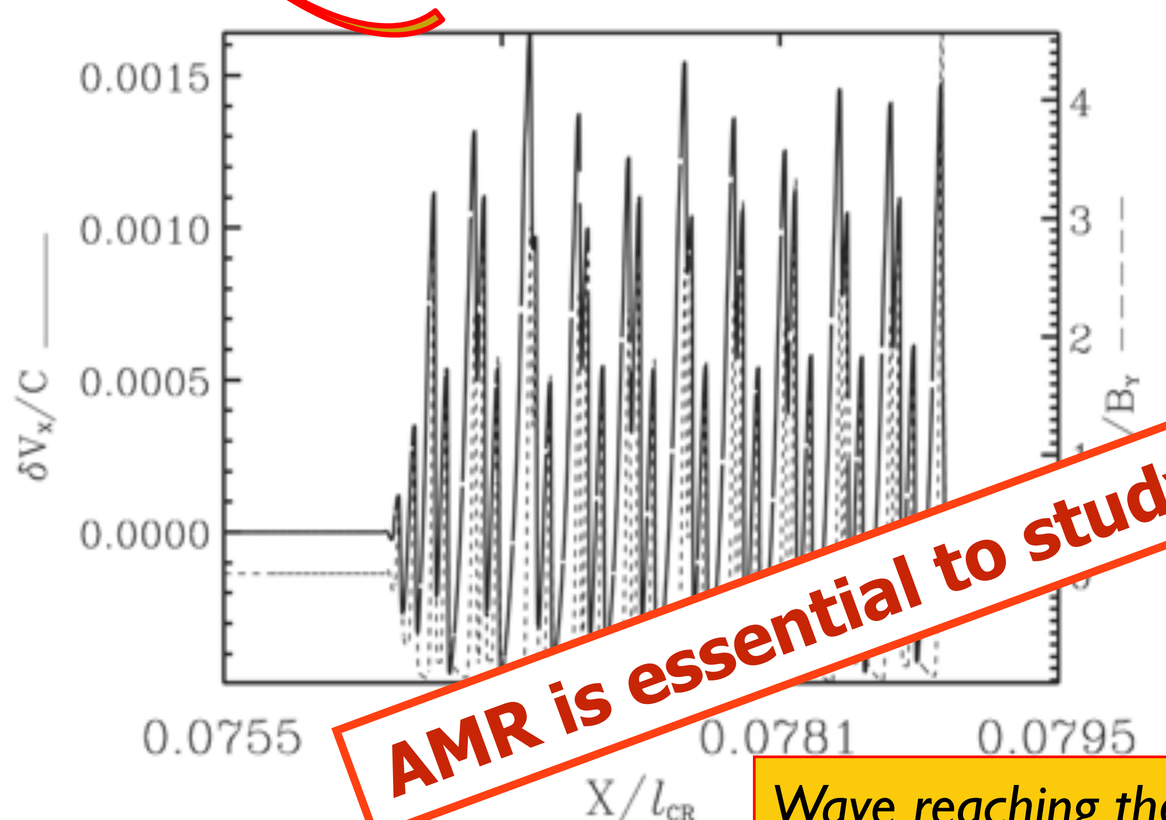
Are Relativistic MHD codes able to capture CD instability ?





RMHD … precursor

Casse et al. (2013)



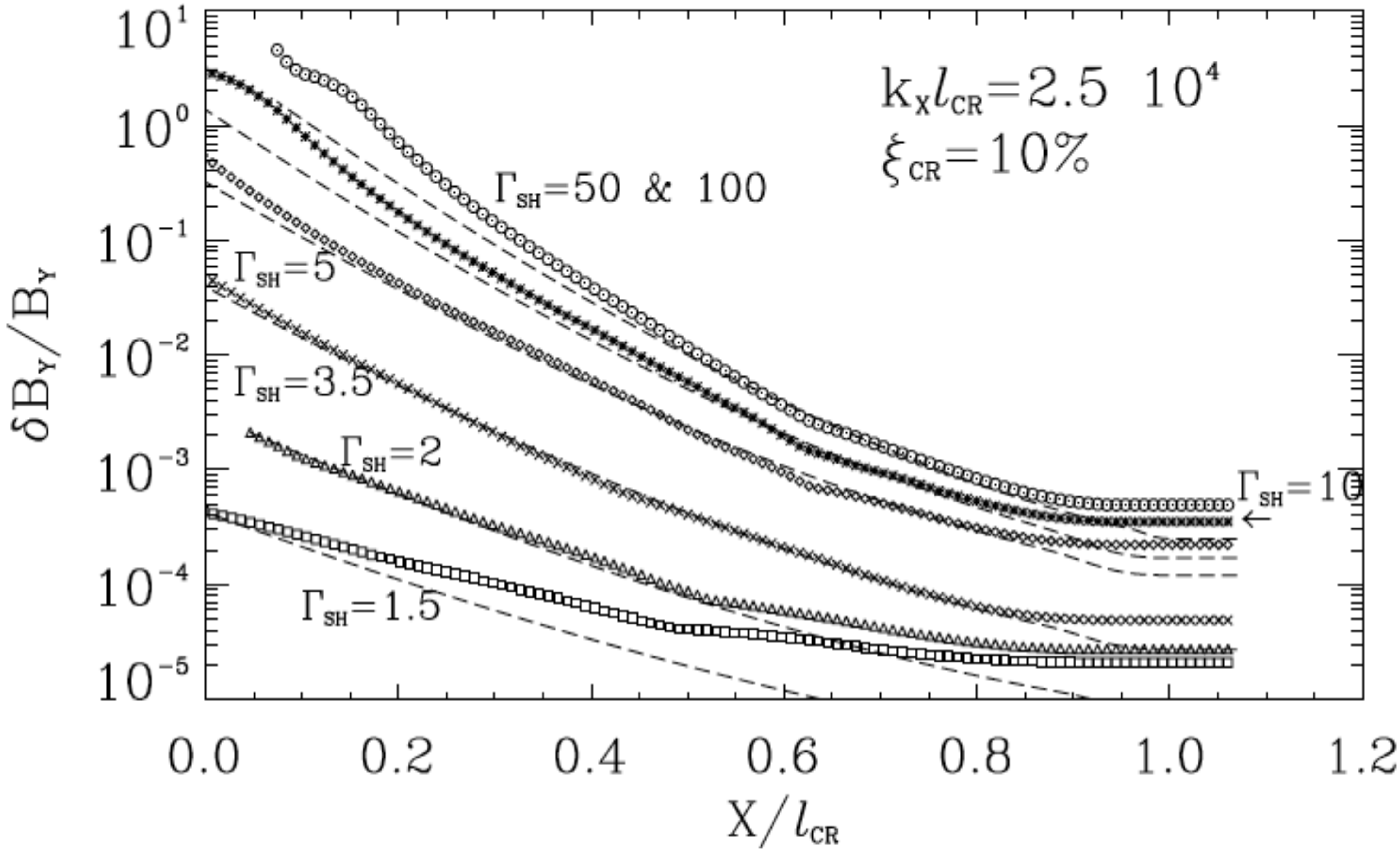
Wave reaching the front shock

AMR is essential to study CD instabilities near RMHD shocks

- … of cosmic rays destabilized MHD …ves in precursor of ultra relativistic shocks.
- Relativistic ***Adapatative Mesh Refinement*** MHD simulations describes the magnetic perturbation growth.

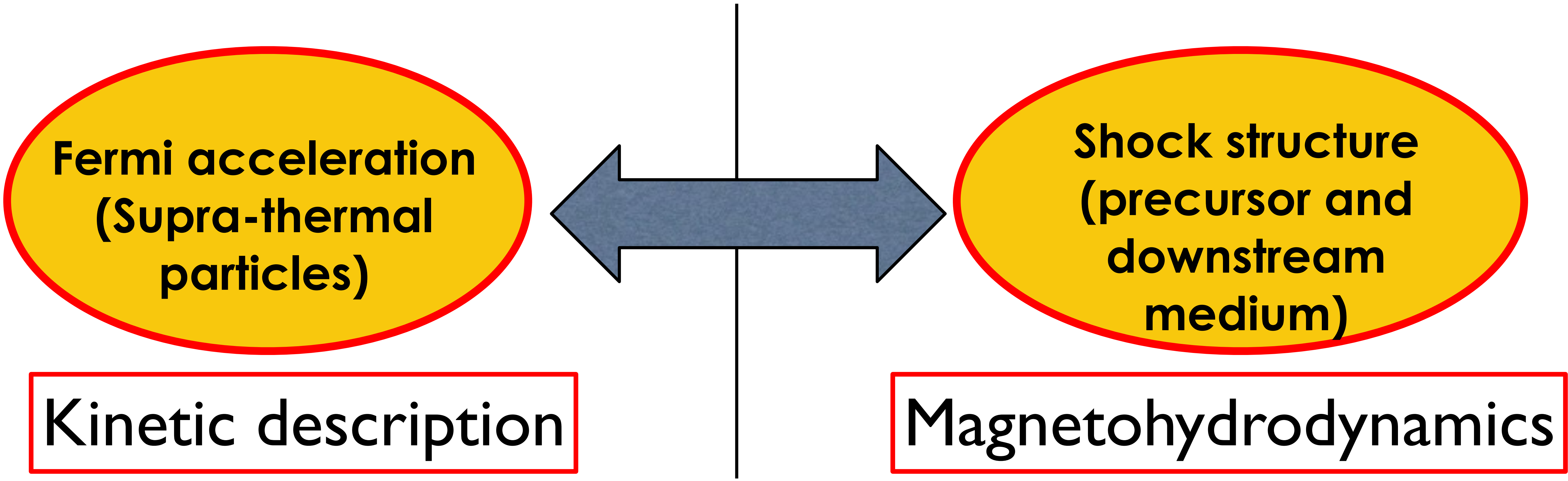
Non-resonant streaming instability near relativistic shocks

Casse et al. (2013)



We need to include the backreaction from CR

Multi-scale description of particle acceleration



- In the past decade, Particle In Cells (PIC) codes have been able to address the DSA mechanism.
- Computational costs prevent the description of the full acceleration region (computational timescale of PIC simulations <<< macroscopic shock timecale).
- Multiscale simulations may be an option to partially alleviate the computational memory and time issue ?

Particle In MHD Cells

- Principles
- Adaptative Mesh Refinement & PI[MHD]C

PI[MHD]C principles

- ➡ Several studies have already used such approach to model current driven instability (e.g. Lucek & Bell'00, Reville & Bell'13, Bai et al.'15)
- ➡ We need to take into account the self-consistent backreaction of the thermal plasma upon cosmic rays:
  - Suprathermal particles described using some PIC techniques
  - Thermal plasma and large scale B described by (R)MHD
- ➡ Supra-thermal particles dynamics is limited to the MHD scales (no microscopic instabilities can be treated).
- ➡ Initiating the supra-thermal particles relies on PIC simulations input as no self-consistent injection can be achieved in PI[MHD]C.
- ➡ Coupling PIC and MHD simulations requires modifications dealing with the electromagnetic field treatment.

PI[MHD]C framework

➡ Both codes time-advance the electromagnetic field but in a different way

- PIC simulations solve the Maxwell equations.
- MHD relies on the Ohm's law to express the electric field as a function of other quantities.

➡ Ohm's law with cosmic rays (cf Bai et al.'15)

$$n_e q_e(\vec{\mathbf{E}}+\vec{\mathbf{U}}_e\times\vec{\mathbf{B}}) = \vec{\nabla}P_e \;\Rightarrow\; \vec{\mathbf{E}} = -\vec{\mathbf{U}}\times\vec{\mathbf{B}} - \cancel{\frac{\vec{\mathbf{J}}_{TOT}\times\vec{\mathbf{B}}}{n_e q_e}} + \frac{n_{CR}}{n_e}(\vec{\mathbf{U}}-\vec{\mathbf{U}}_{CR})\times\vec{\mathbf{B}} + \cancel{\frac{\vec{\nabla}P_e}{n_e q_e}}$$

$$n_e q_e + n_i q_i + n_{CR} q_i = 0$$

$$\vec{\mathbf{J}}_{TOT} = \vec{\mathbf{J}}_{PL} + \vec{\mathbf{J}}_{CR} = n_e q_e \vec{\mathbf{U}}_e + n_i q_i \vec{\mathbf{U}}_i + n_{CR} q_i \vec{\mathbf{U}}_{CR}$$

➡ One can safely neglect thermal electron pressure gradient because of usual MHD ordering provided that the magnetic field is not much smaller than equipartition.

➡ The classical Hall term is significant on scales smaller than **c/ω_{pi}** ..

$$\vec{\mathbf{E}} = -\left(\left(1-\frac{n_{CR}}{n_e}\right)\vec{\mathbf{U}} + \frac{n_{CR}}{n_e}\vec{\mathbf{U}}_{CR}\right)\times\vec{\mathbf{B}}$$

PI[MHD]C framework

➡ In classical MHD, the momentum equation is modified because of the presence of CR (neglecting Hall term) as well as induction and energy equations

$$\frac{\partial \rho \vec{\mathbf{U}}}{\partial t} + \vec{\nabla}.\left(\rho \vec{\mathbf{U}}\vec{\mathbf{U}} - \frac{\vec{\mathbf{B}}\vec{\mathbf{B}}}{\mu_o} + P\vec{\mathbf{I}}\right) = \left(1 - \frac{\rho_{CR}}{|\rho_e|}\right)\left\{\rho_{CR}\vec{\mathbf{U}} \times \vec{\mathbf{B}} - \vec{\mathbf{J}}_{CR} \times \vec{\mathbf{B}}\right\}$$

➡ In RMHD, the displacement current changes the definition of some conserved quantities such as relativistic MHD momentum (tricky switch from primitive to conservative quantities)

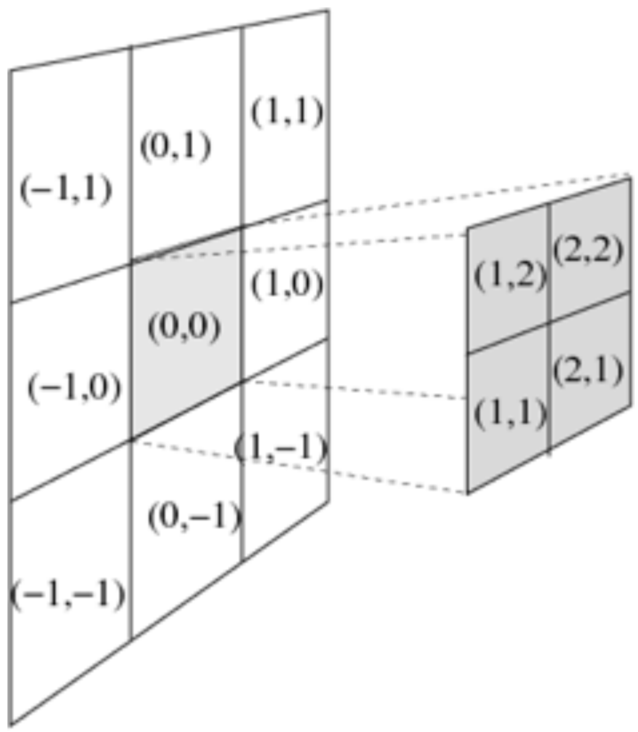
$$\frac{\partial}{\partial t}\left\{\gamma^2 \rho h \vec{\mathbf{U}} + \vec{\mathbf{E}} \times \vec{\mathbf{B}}\right\} + \vec{\nabla}.\left\{[\gamma^2 \rho h]\vec{\mathbf{U}}\vec{\mathbf{U}} - \vec{\mathbf{B}}\vec{\mathbf{B}} - \vec{\mathbf{E}}\vec{\mathbf{E}} + \left(P + \frac{B^2 + E^2}{2}\right)\vec{\mathbf{I}}\right\} = \rho_{CR}(1 - \Theta)(\vec{\mathbf{U}} - \vec{\mathbf{U}}_{CR}) \times \vec{\mathbf{B}}$$

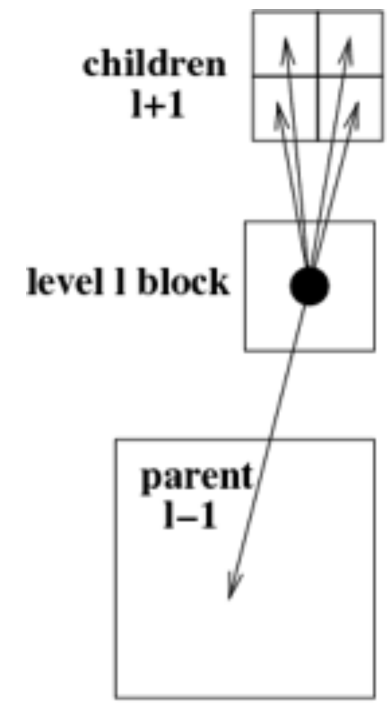
➡ The PIC motion equation related to the particles is also modified according to the new Ohm's law

$$\frac{d\gamma \vec{v}_k}{dt} = -\frac{q_k}{m_k}\left(\left\{1 - \frac{n_{cr}}{n_g}\right\}\vec{U} + \frac{n_{cr}}{n_g}\vec{U}_{cr} - \vec{v}_k\right) \times \vec{B}$$

HPC and PI[MHD]C code

➡ PI[MHD]C version of MPI-AMRVAC is based an MPI finite volume code using an adaptative mesh refinement grid organized as an quad(oct)-tree in 2D(3D).





➡ Flux at cell interface is computed using various slope limiter ("upwind" scheme) and various type of solvers can be considered (TVD-MUSCL, Lax-Friedrichs, HLLC, HLLE, Roe, etc…).

➡ AMR also influences the way suprathermal particles charge and current are translated to the MHD code as (electrical charge conservation).

AMR & PI[MHD]C code

➡ The structure of the grid is controlled by an Adaptative Mesh Refinement (AMR) algorithm that locally enforces resolution where needed.

➡ Refinement/coarsening is triggered by user's defined criterion: e.g. Lohner's criterion

$$Tol_1 \leq \sum_i g_i \frac{\Delta w_i^2}{w_i^2 + \varepsilon} \rightarrow \text{refine}$$

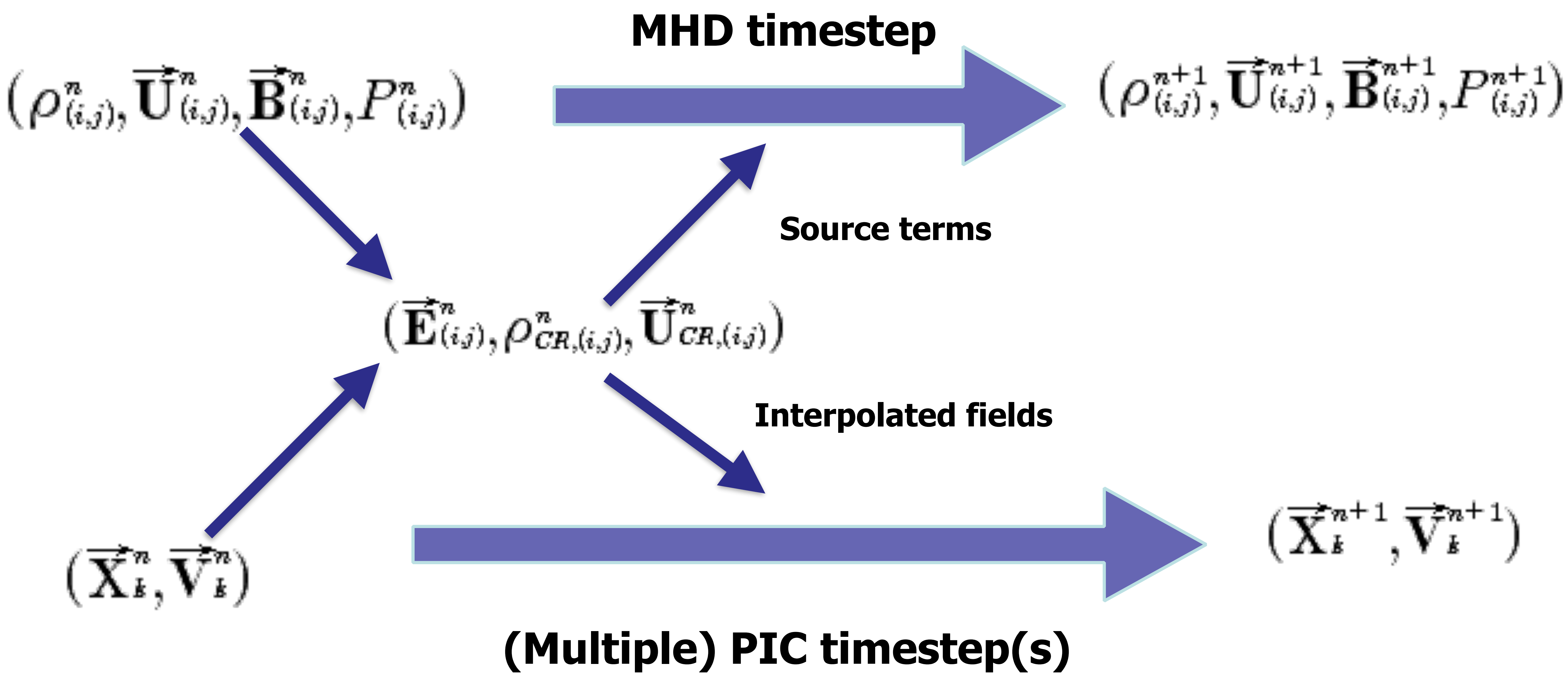
$$Tol_2 \geq \sum_i g_i \frac{\Delta w_i^2}{w_i^2 + \varepsilon} \rightarrow \text{coarsen with } Tol_1 > Tol_2$$

➡ PIC quantities also have to be considered in the refinement criterion

- ✓ High CR density should be described with high resolution
- ✓ Refinement/coarsening helps to keep the computing MPI effciency of the code.

➡ Grids are dynamically dispatched using MPI with a Morton load balance algorithm (weak scaling remains good with particles !)

Basics of Particle in MHD Cells simulations



Two applications of AMR PI[MHD]C

- CR filamentation in shock precursors
- Magnetic field amplification & particle acceleration near non-relativistic shocks

Testing CR filamentation

➡ Reville & Bell'12 has presented 2D PIC/MHD computations of the filamentation instability induced by CR in shock precursors.

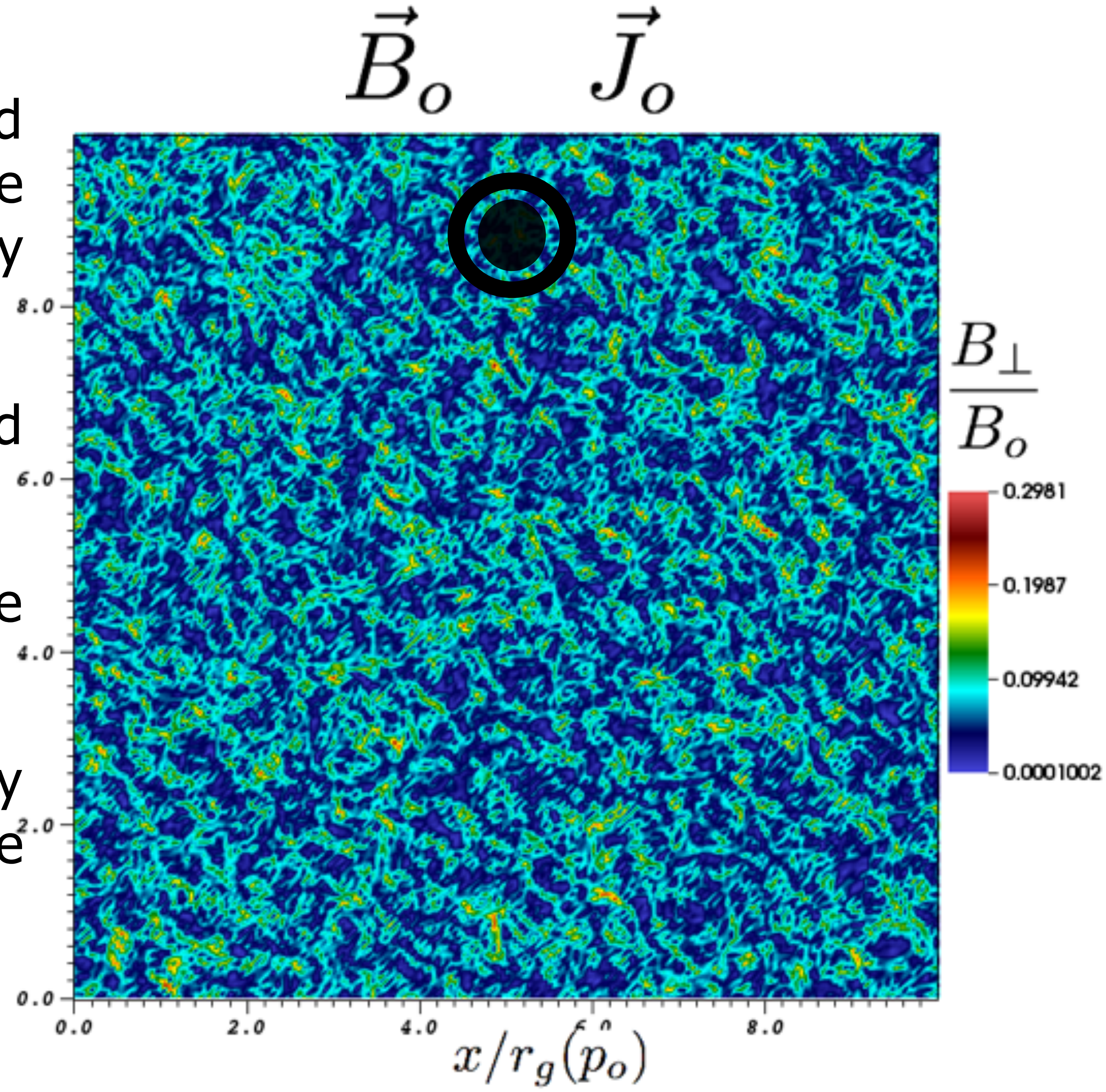
➡ Perpendicular turbulent B field (Kolmogorov spectrum).

➡ Uniform CR current along the mean B field.

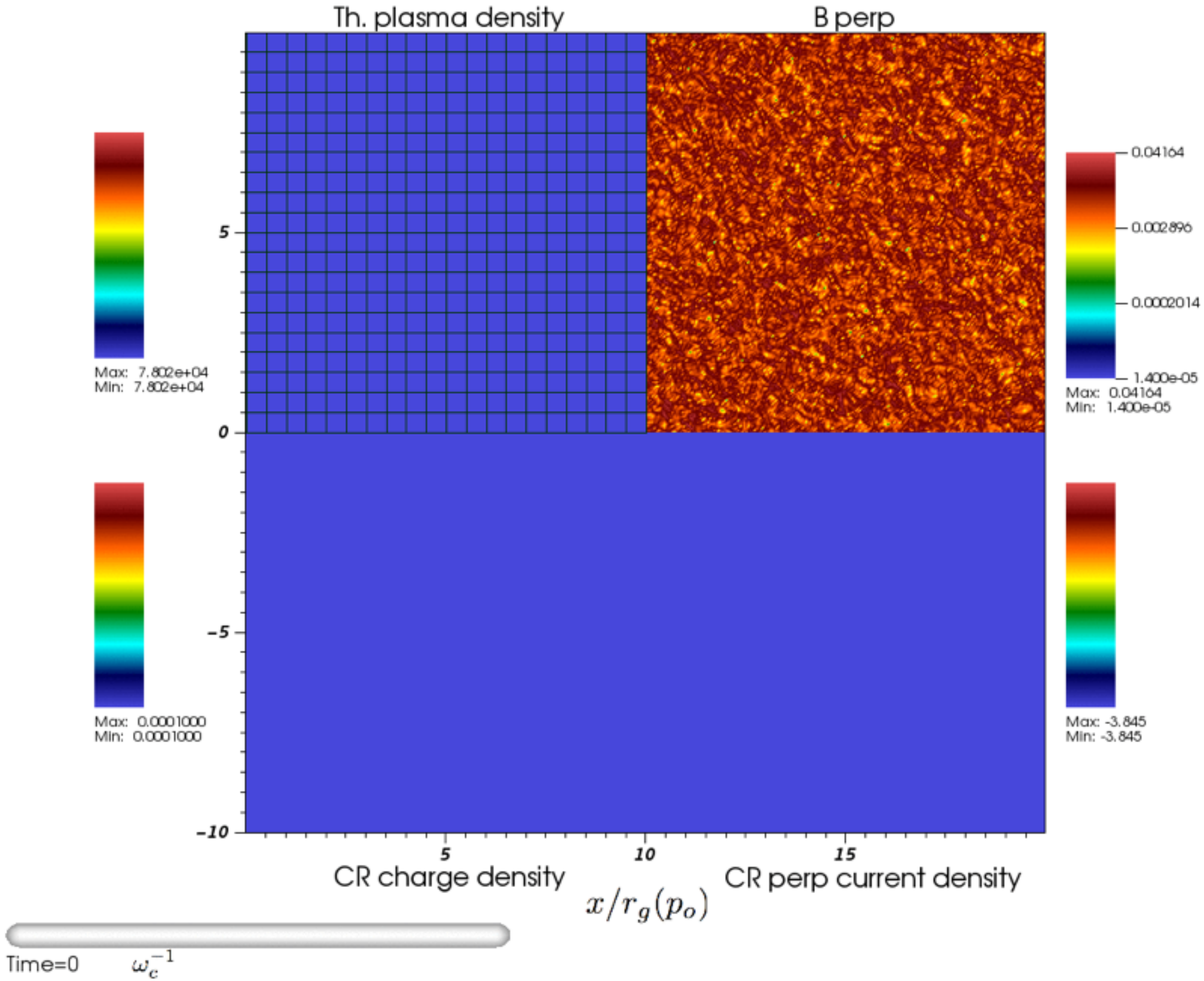
➡AMR triggered by gas density gradient and high CR charge density.

$$\frac{U_{cr}}{\rho_g v_{sh}^2} \sim 7\% \qquad \frac{v_{sh}}{c} = 0.1$$

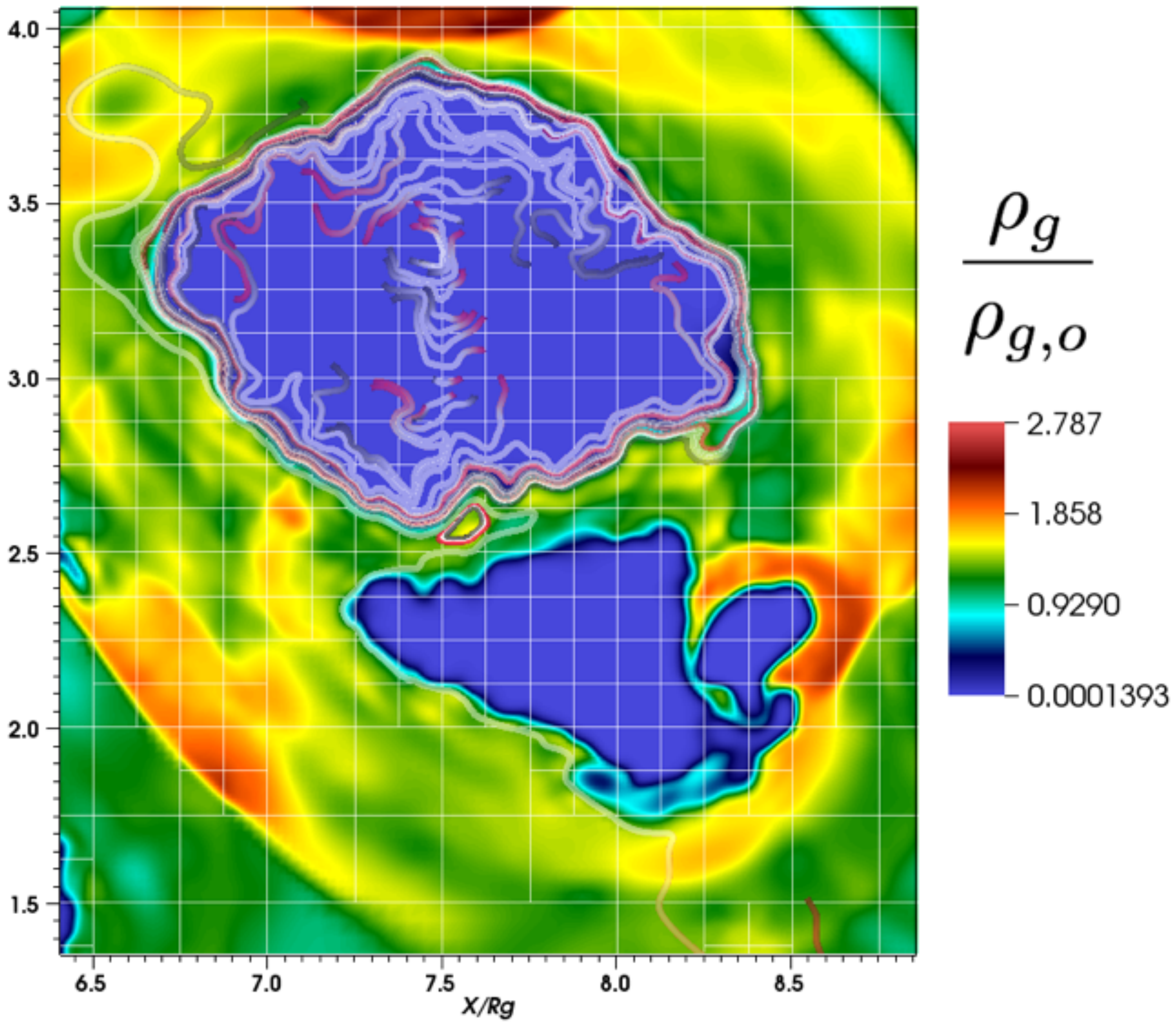
$$\frac{\rho_{cr}}{\rho_g} = 10^{-4} \qquad \frac{v_A}{c} = 5 \times 10^{-4}$$



Testing CR filamentation



Close-up of a filament



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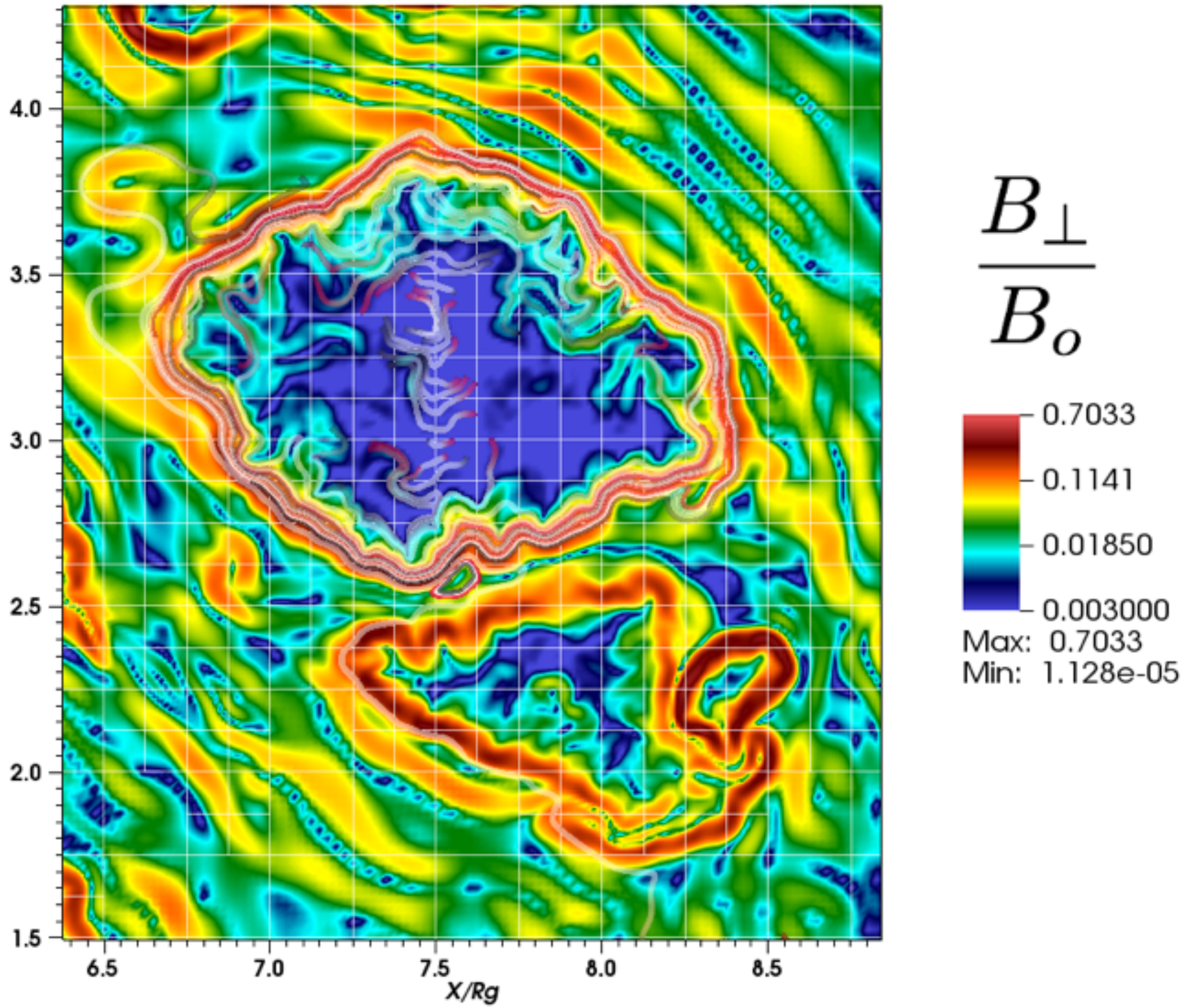

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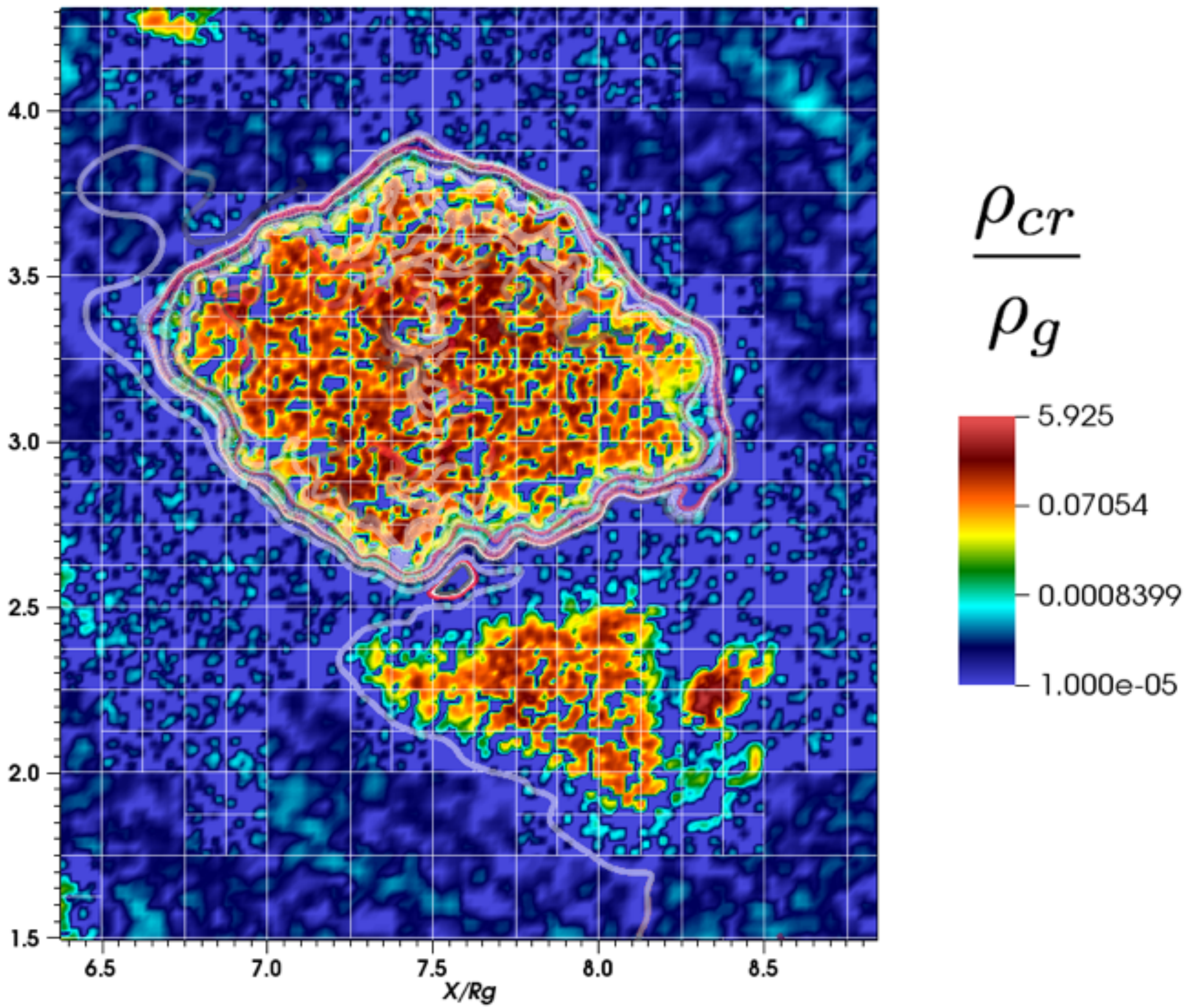

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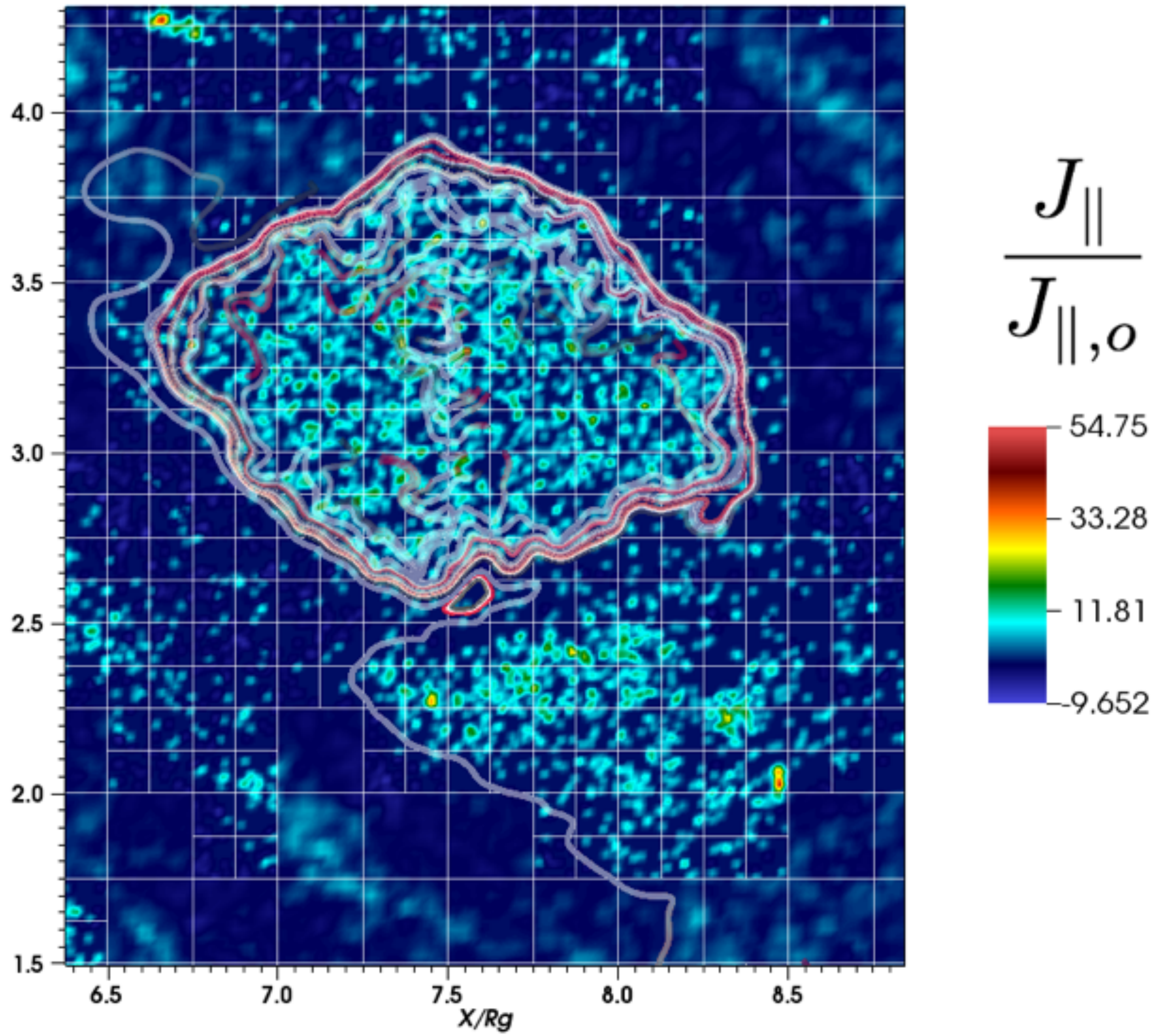
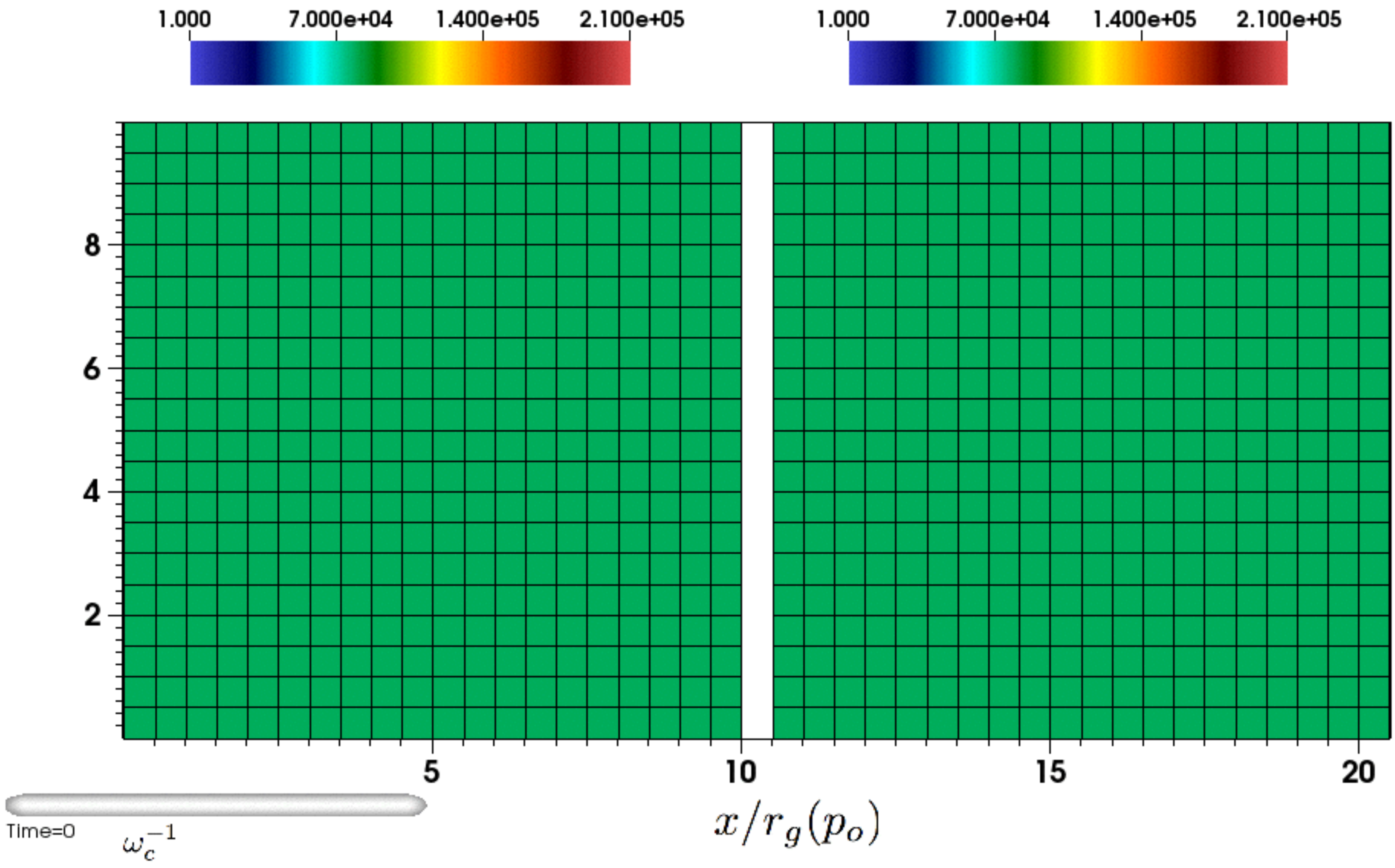


Effect of AMR upon PI[MHD]C simulations



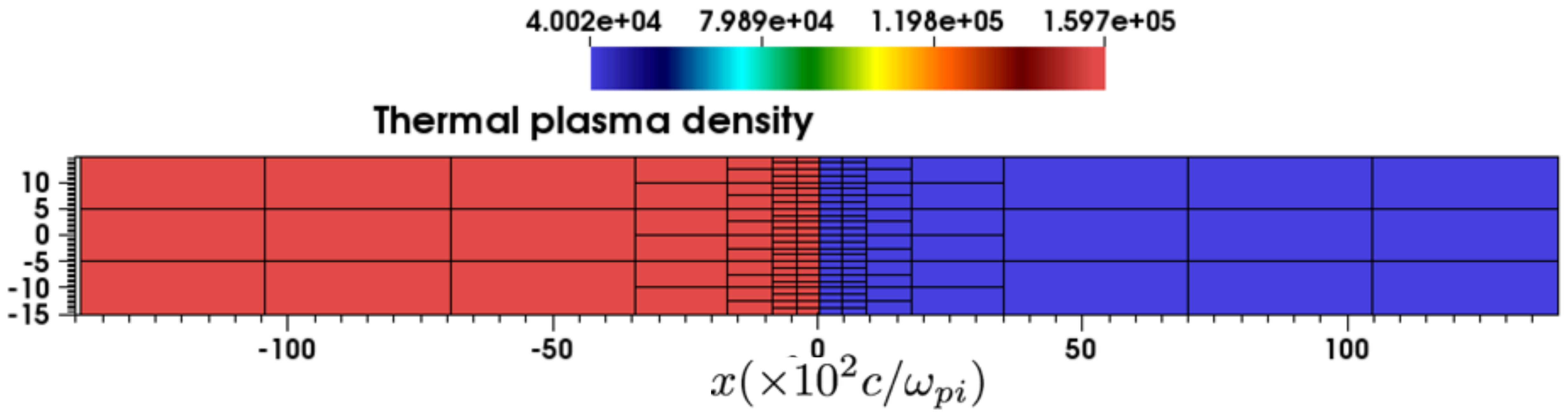
CR filamentation near shocks

➡ Non-relativistic super-Alfvénic shock with parallel magnetic field in the shock rest frame (same physical conditions than in Bai et al.'15).

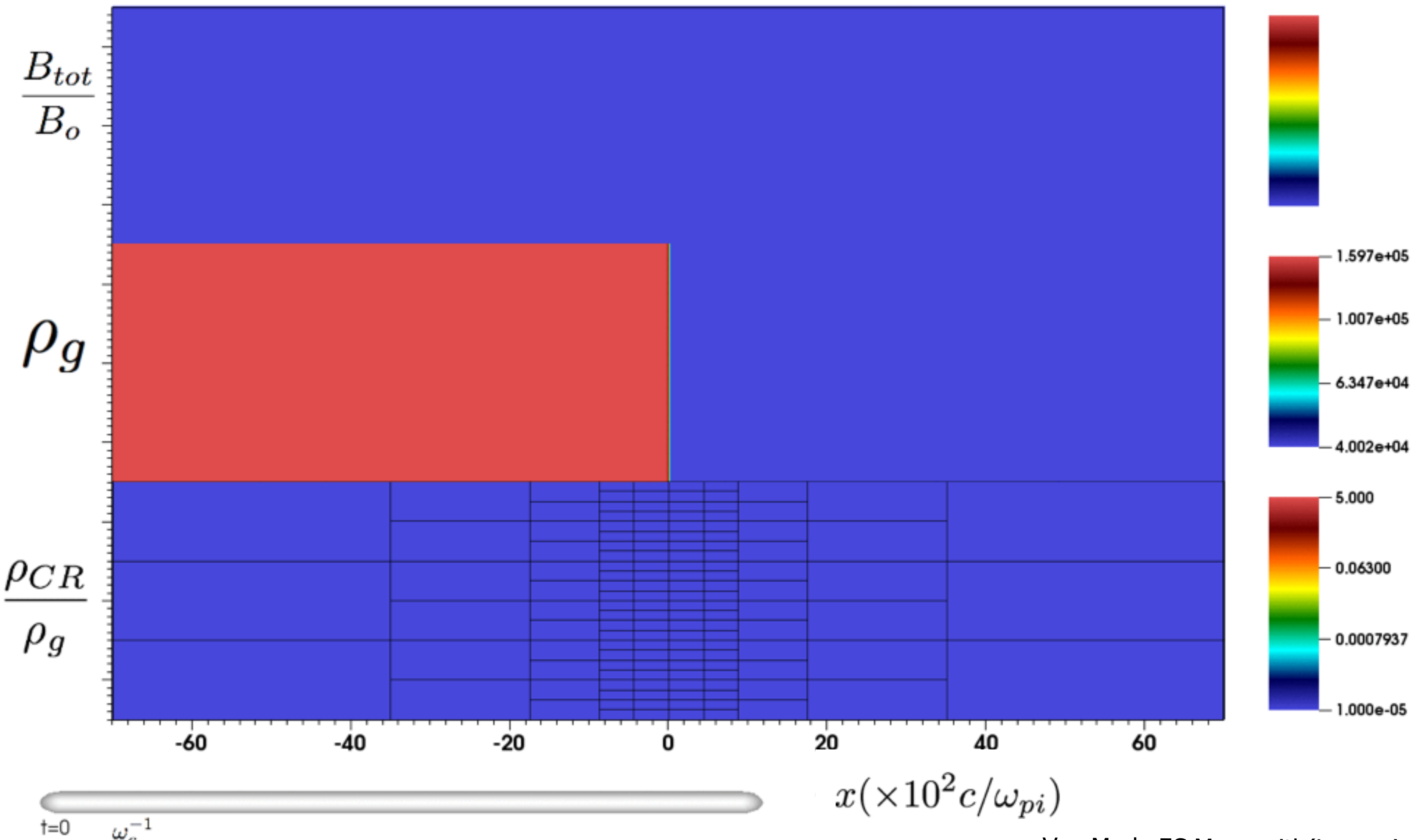
➡ Continuous injection of mono-energetic particles near the shock front with random velocity orientation ($V_{inj} \sim 3V_{SH}$).

➡ AMR is triggered using 5 refinement levels with a base resolution of 320x30 cells ➜ effective resolution 5120x 480 cells (run performed on local workstation with 20 CPUs in 1 day)

➡ Simulation box size is 28,000 x 3,000 in c/ω_{pi} units.



CR filamentation near shocks



Van Marle,FC,Marcowith(in prep)

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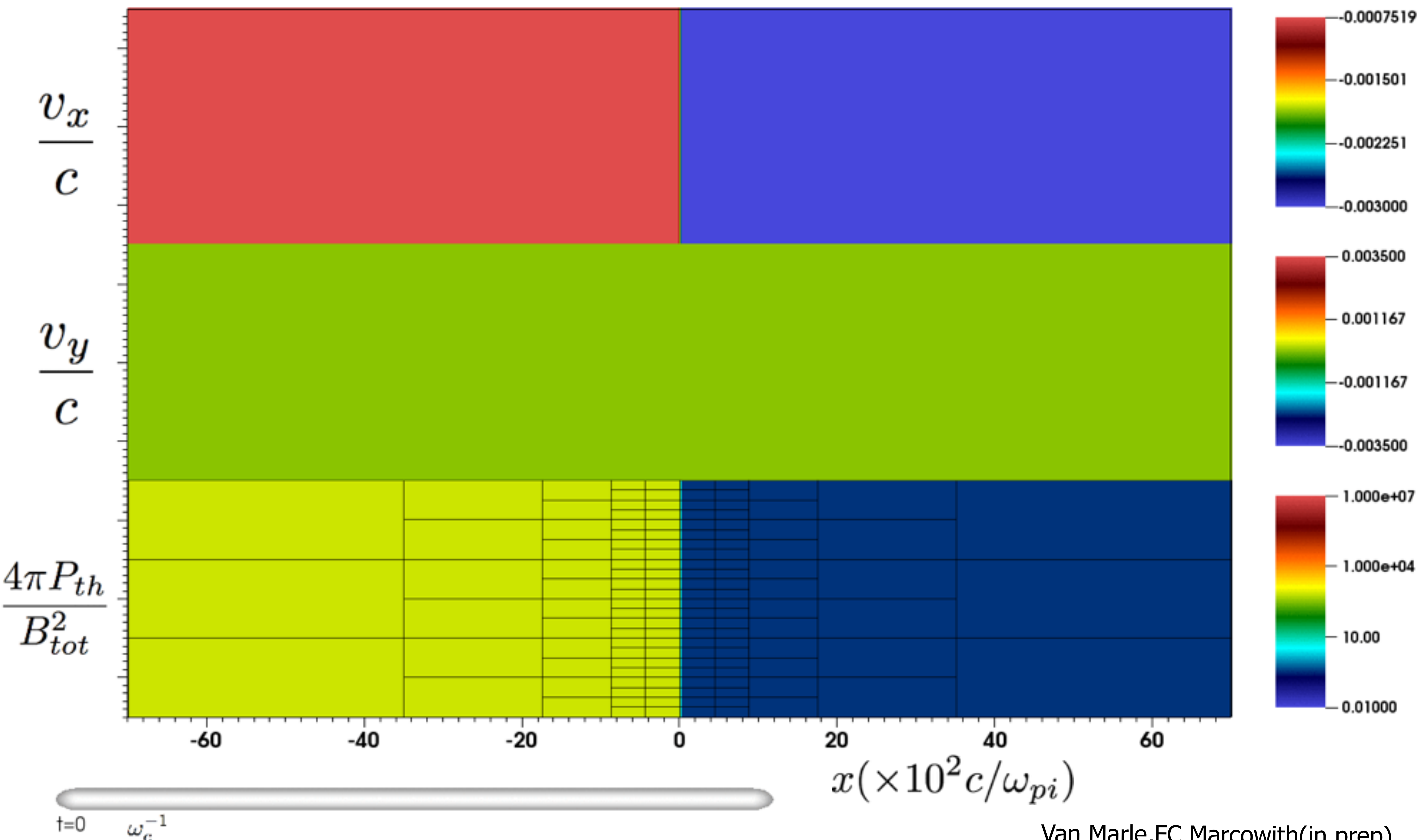

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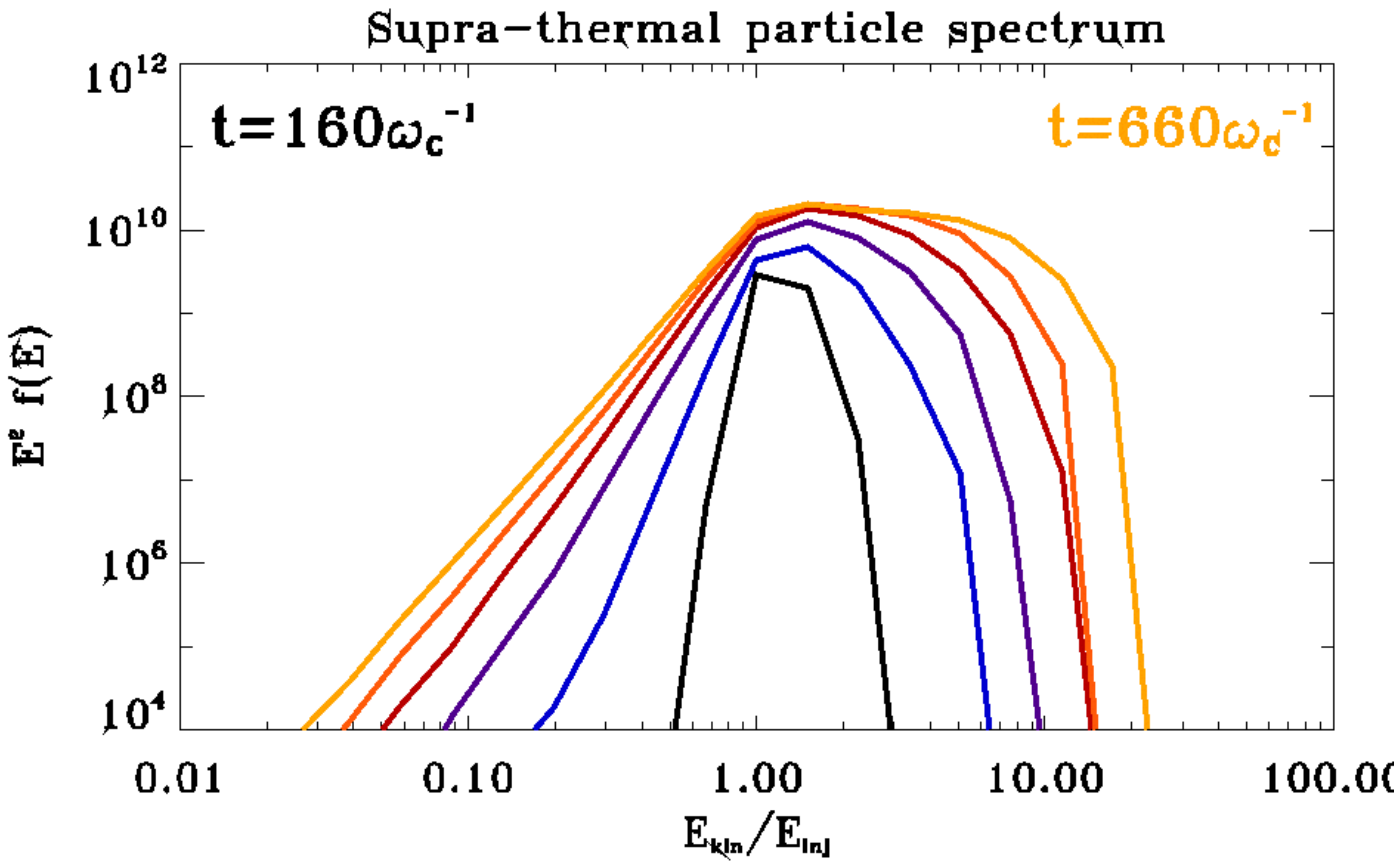

Outlook

- ➡ Applications presented here were mostly test cases showing the benefit we can get from PI[MHD]C simulations with AMR.

- ➡ AMR PI[MHD]C simulations show promising computing performances (will it be enough to describe the whole shocks structure ?).

- ➡ The implementation of PI[RMHD]C will enable us to explore the whole velocity regime of astrophysical shocks.

- ➡ Large-scale computations should help us to reach a wider CR dynamical range.