Towards reliable simulations of magnetic fields in galaxies

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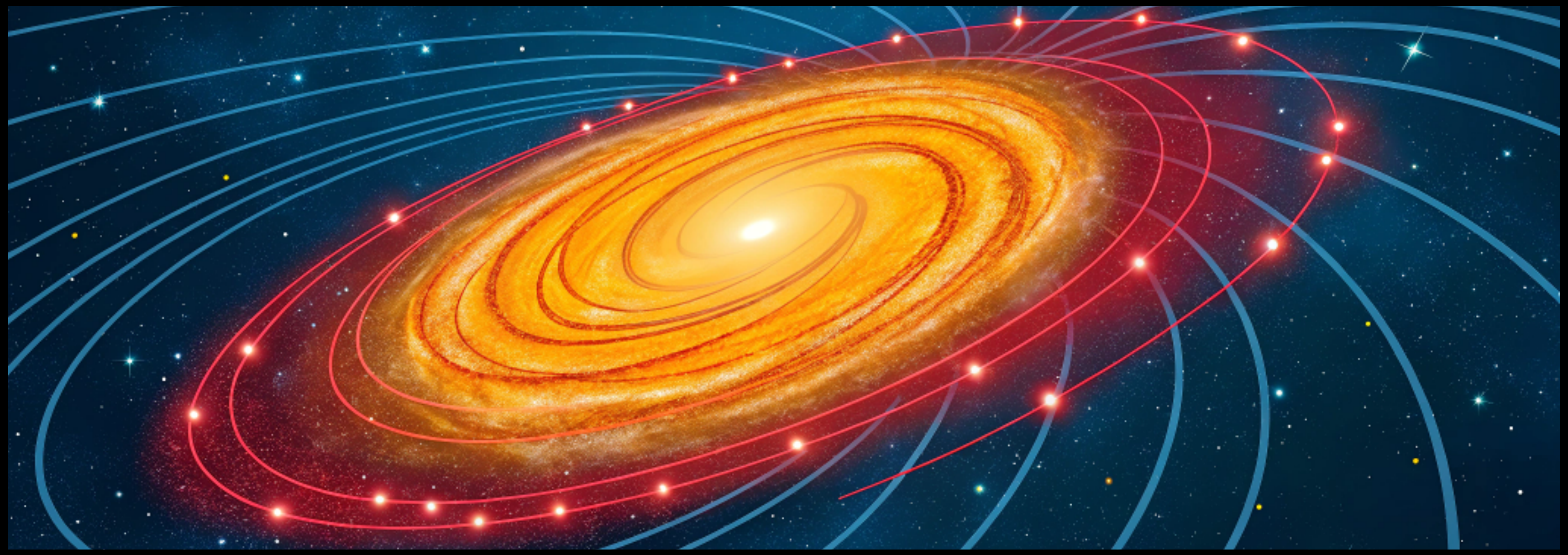
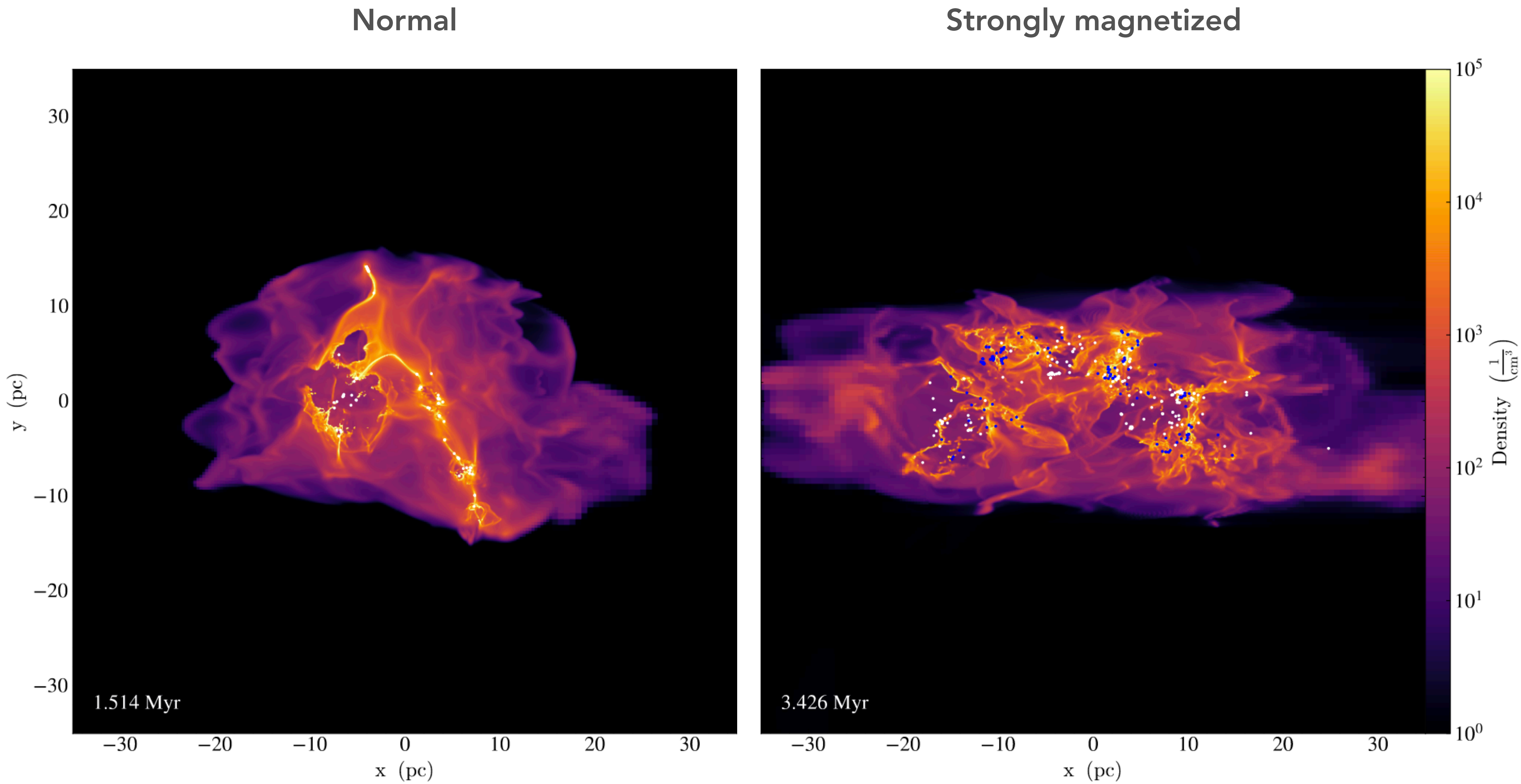


18th Potsdam ThinkShop • AIP Potsdam • 16/7/2025

NSF

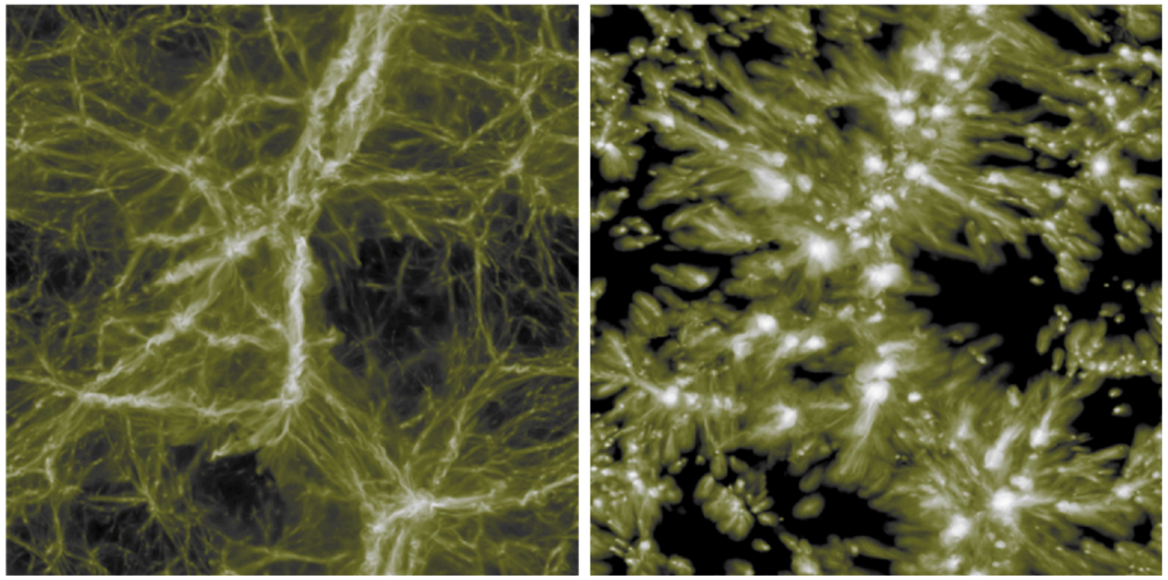
ALFRED P. SLOAN FOUNDATION

Effect on star formation?

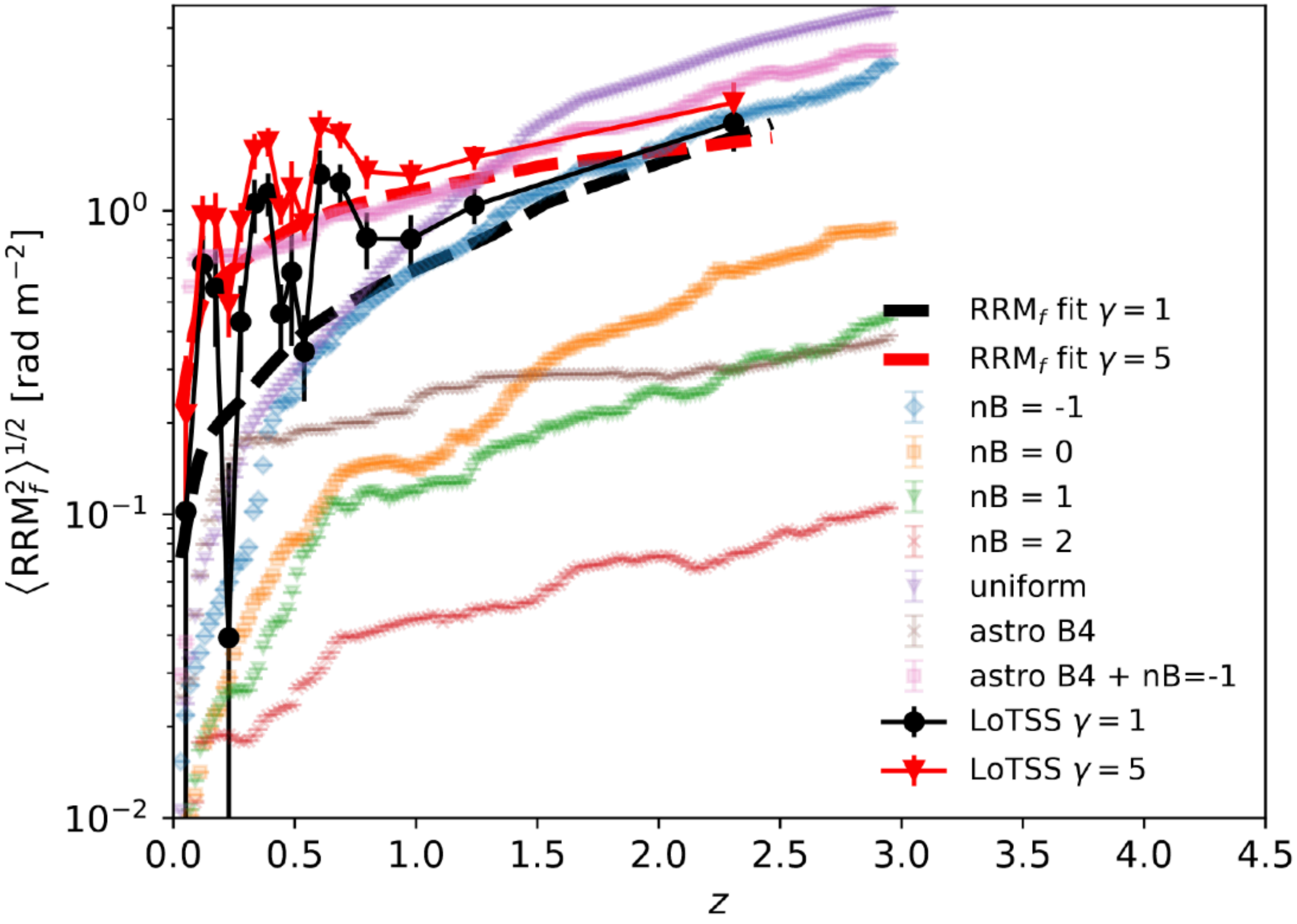


Hix, He & Ricotti 2023

What are the magnetic seeds?

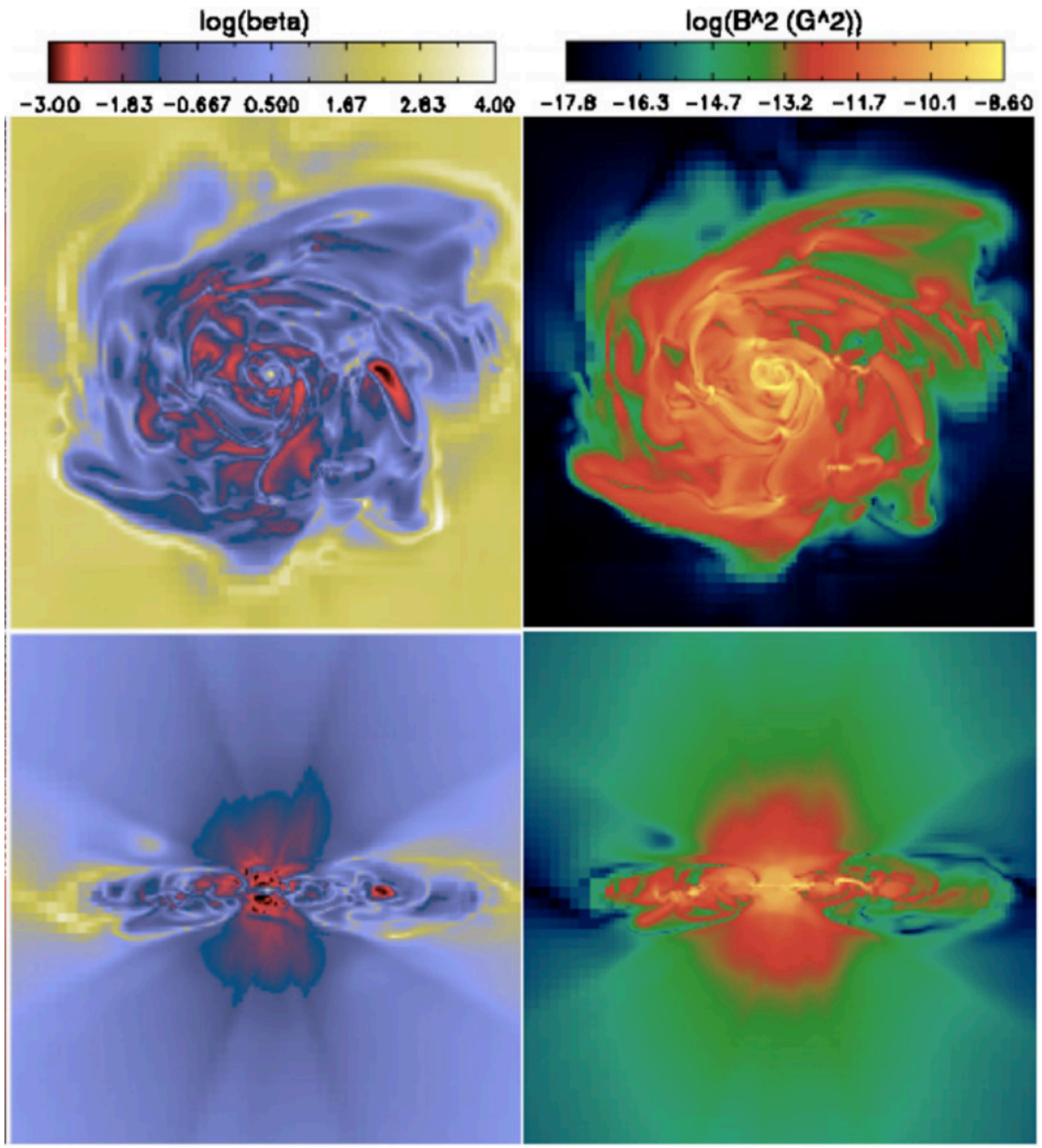


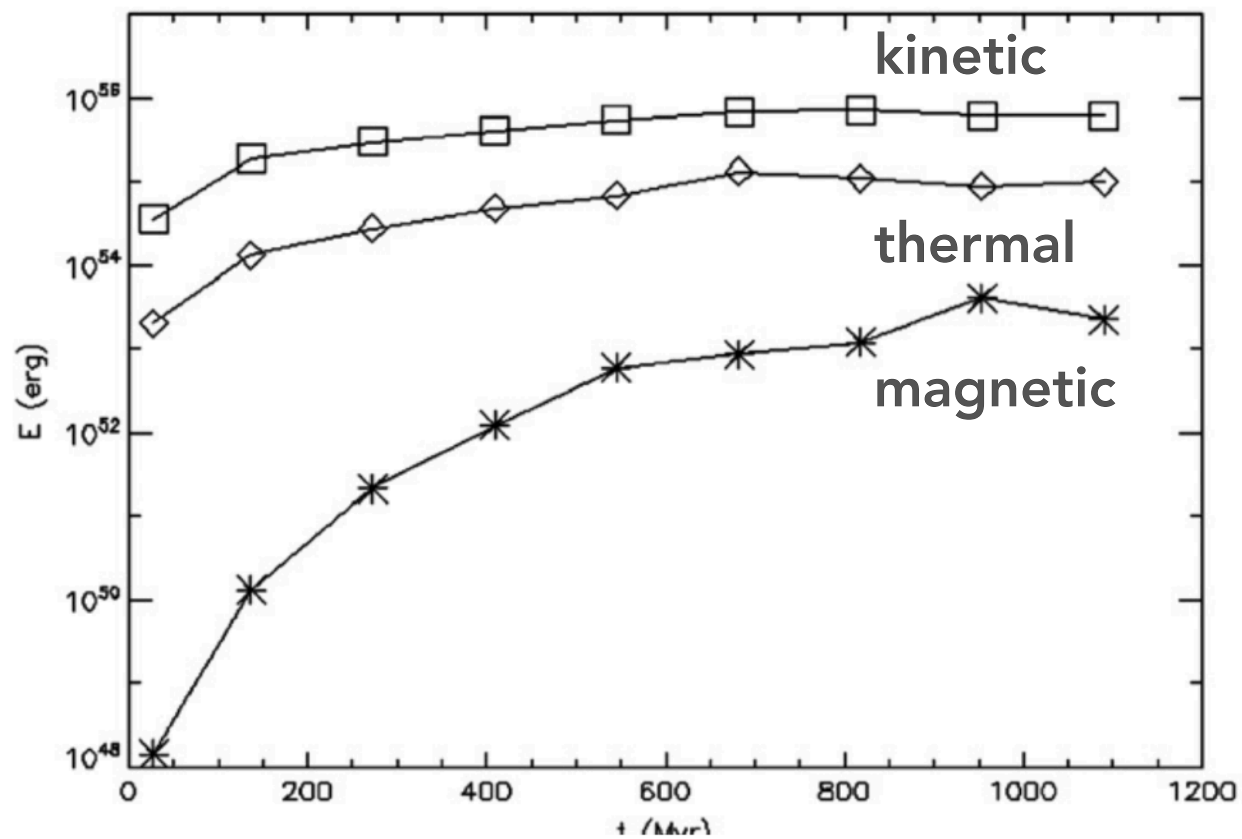
Uniform Astrophysical



Carretti & Vazza 2025 • see also Carretti et al. 2023

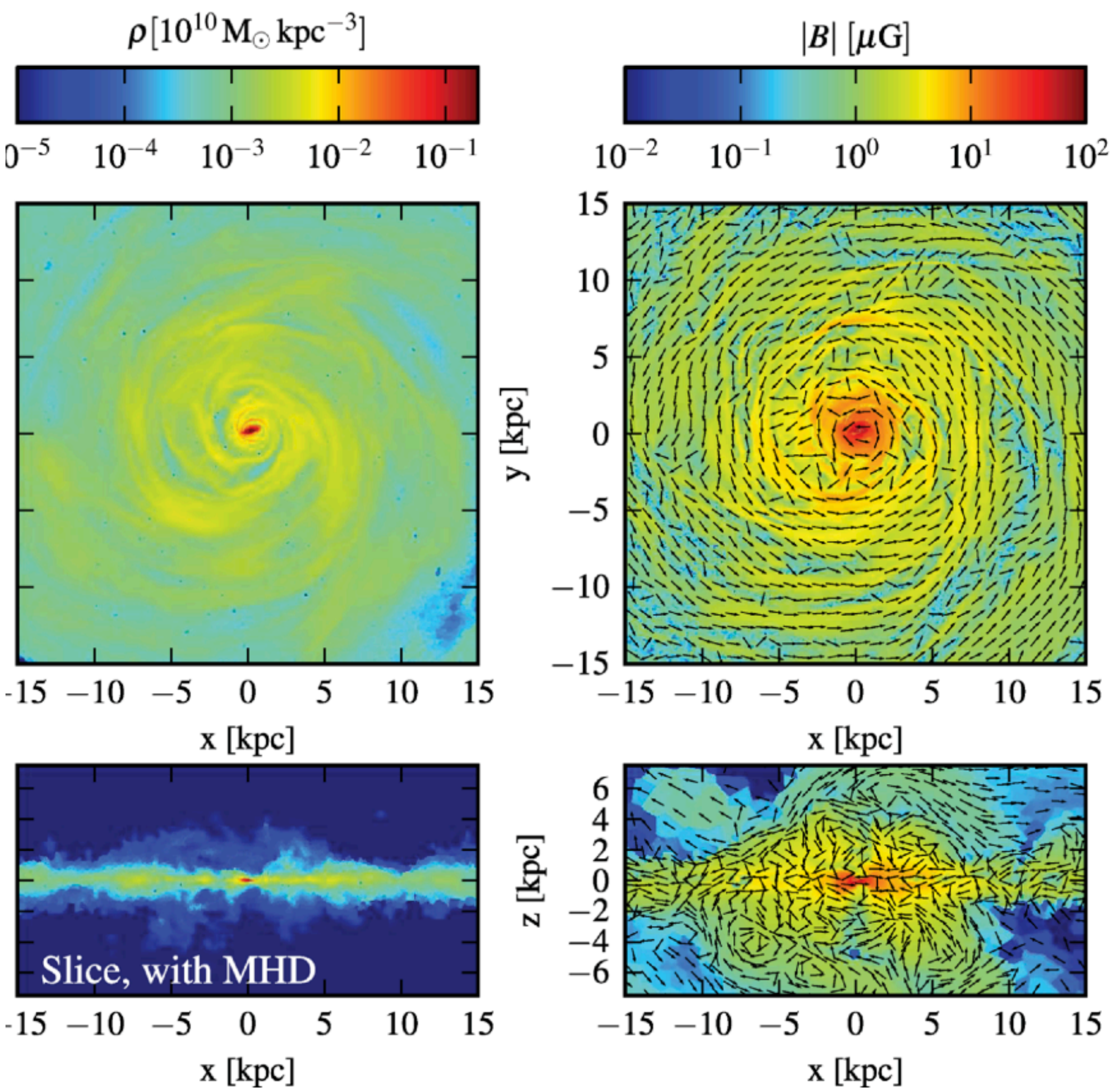
Results from the literature

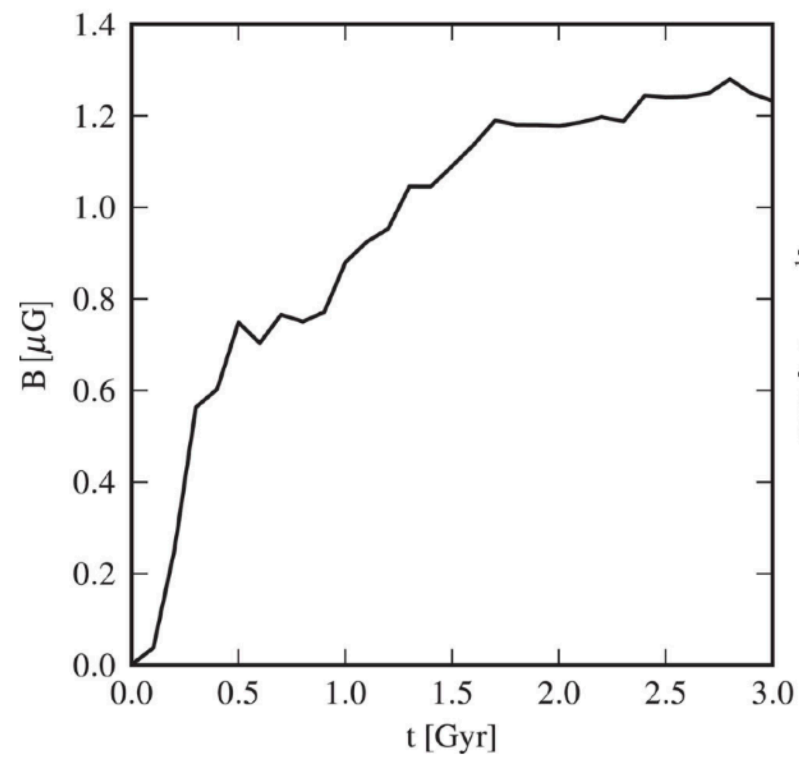


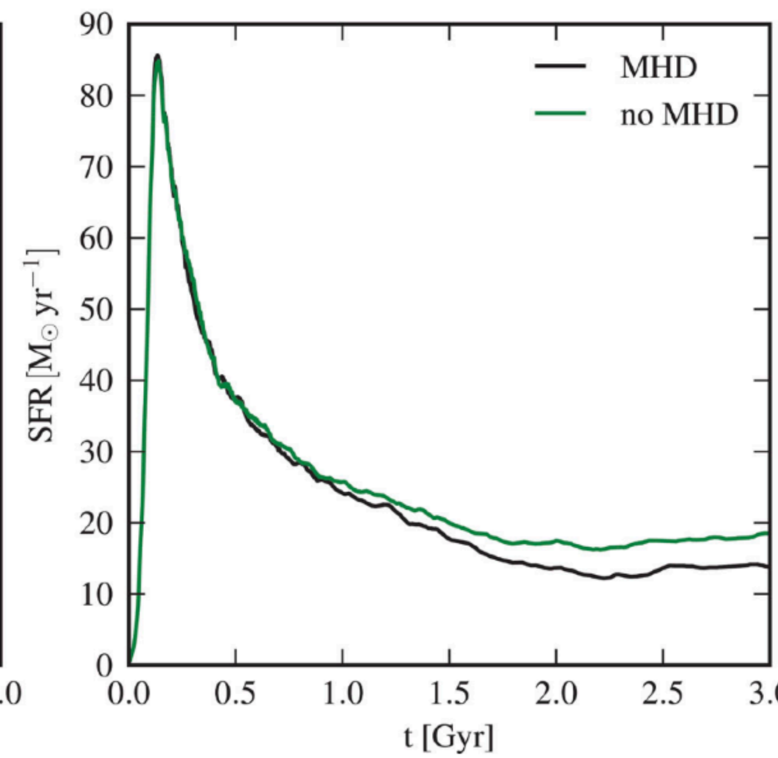


Wang & Abel 2009

Results from the literature

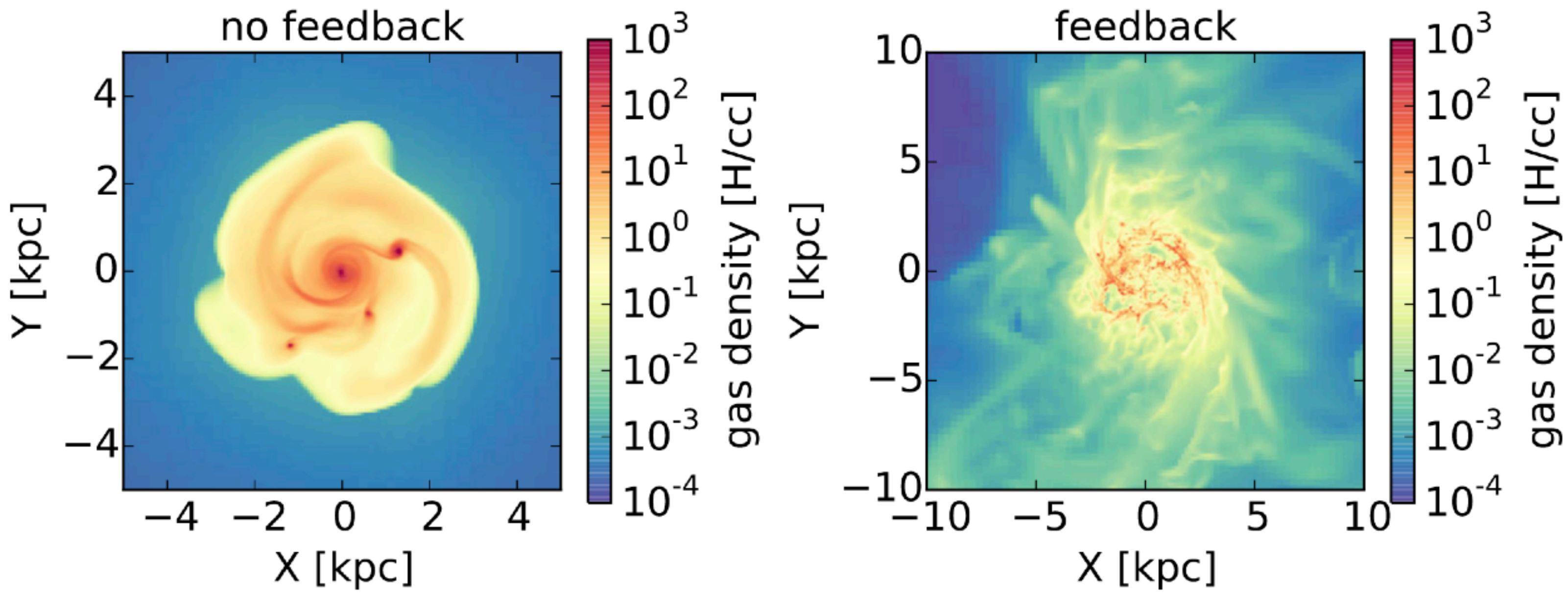


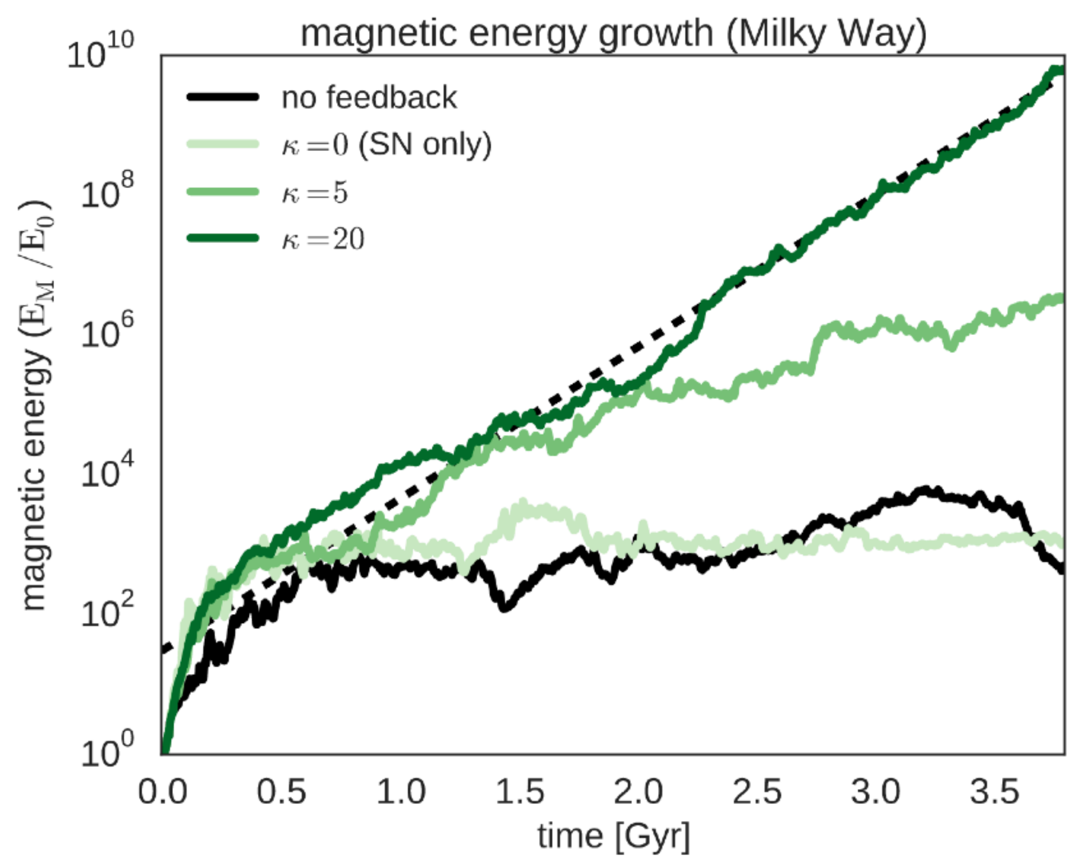




Pakmor et al. 2013, 2014, 2017, 2023 • see also Werhahn et al. 2025

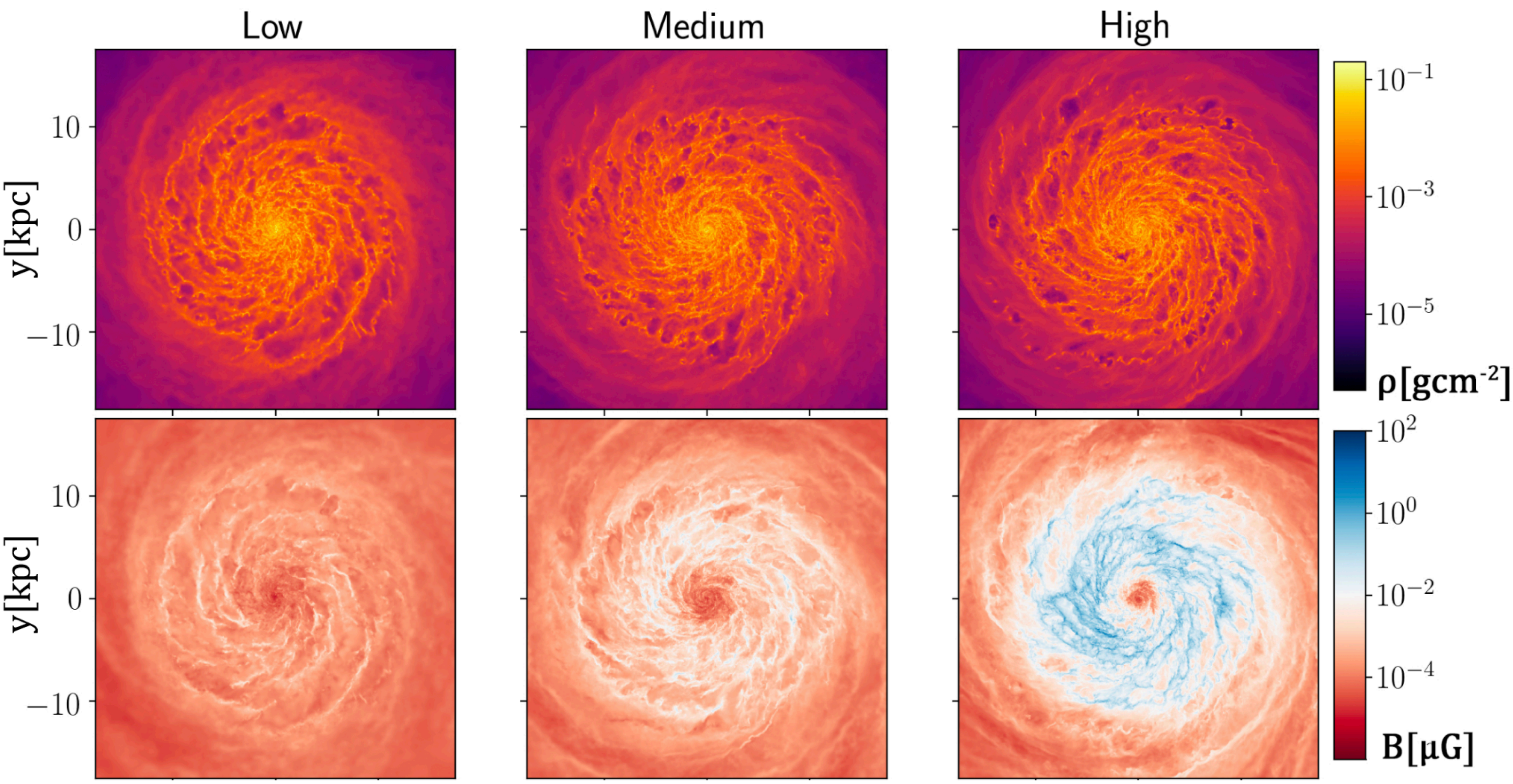
Results from the literature





Rieder & Teyssier 2016, 2017ab • Liu, Kretschmer & Teyssier 2022

Results from the literature



Wissing & Shen 2023 • see also Hopkins et al. 2019

MHD

Fluid equations in conservation-law form

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{u}) = 0$$

$$\frac{\partial (\rho \boldsymbol{u})}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{u} \otimes \boldsymbol{u} + \boldsymbol{I} P) = -\rho \boldsymbol{\nabla} \Phi$$

$$\frac{\partial E}{\partial t} + \boldsymbol{\nabla} \cdot ([E + P] \boldsymbol{u}) = \rho \frac{\partial \Phi}{\partial t} + \Gamma - \Lambda$$

Ideal MHD equations in conservation-law form

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{u}) = 0$$

$$\frac{\partial (\rho \boldsymbol{u})}{\partial t} + \boldsymbol{\nabla} \cdot \left(\rho \boldsymbol{u} \otimes \boldsymbol{u} + \boldsymbol{I} \left[P + \frac{\boldsymbol{B}^2}{2} \right] - \boldsymbol{B} \otimes \boldsymbol{B} \right) = -\rho \boldsymbol{\nabla} \Phi$$

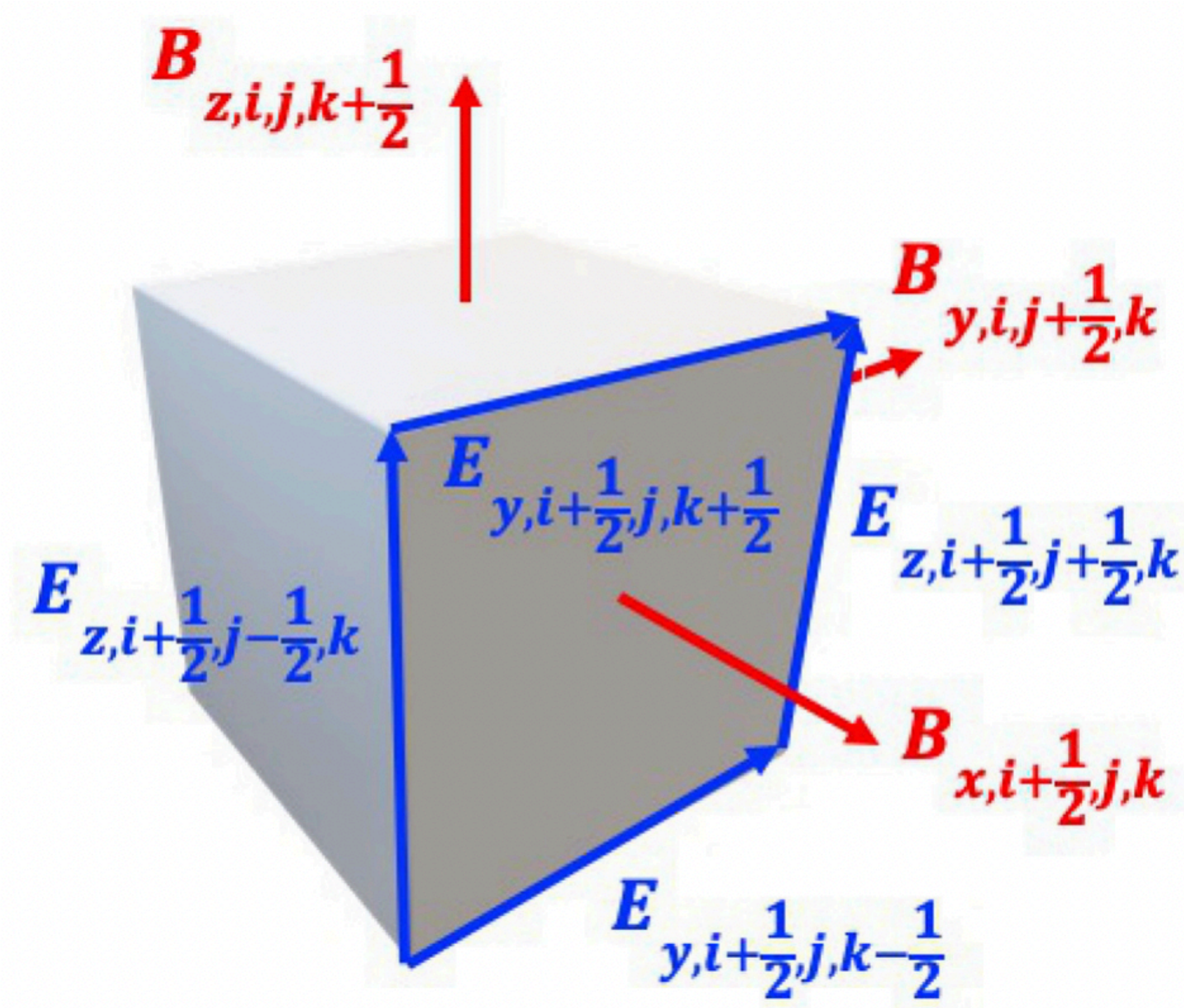
$$\frac{\partial E}{\partial t} + \boldsymbol{\nabla} \cdot \left(\left[E + P + \frac{\boldsymbol{B}^2}{2} \right] \boldsymbol{u} - \boldsymbol{u} \cdot \boldsymbol{B} \otimes \boldsymbol{B} \right) = \rho \frac{\partial \Phi}{\partial t} + \Gamma - \Lambda$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + \boldsymbol{\nabla} \cdot (\boldsymbol{u} \otimes \boldsymbol{B} - \boldsymbol{B} \otimes \boldsymbol{u}) = 0$$

and:

$$\boldsymbol{\nabla} \cdot \boldsymbol{B} = 0$$

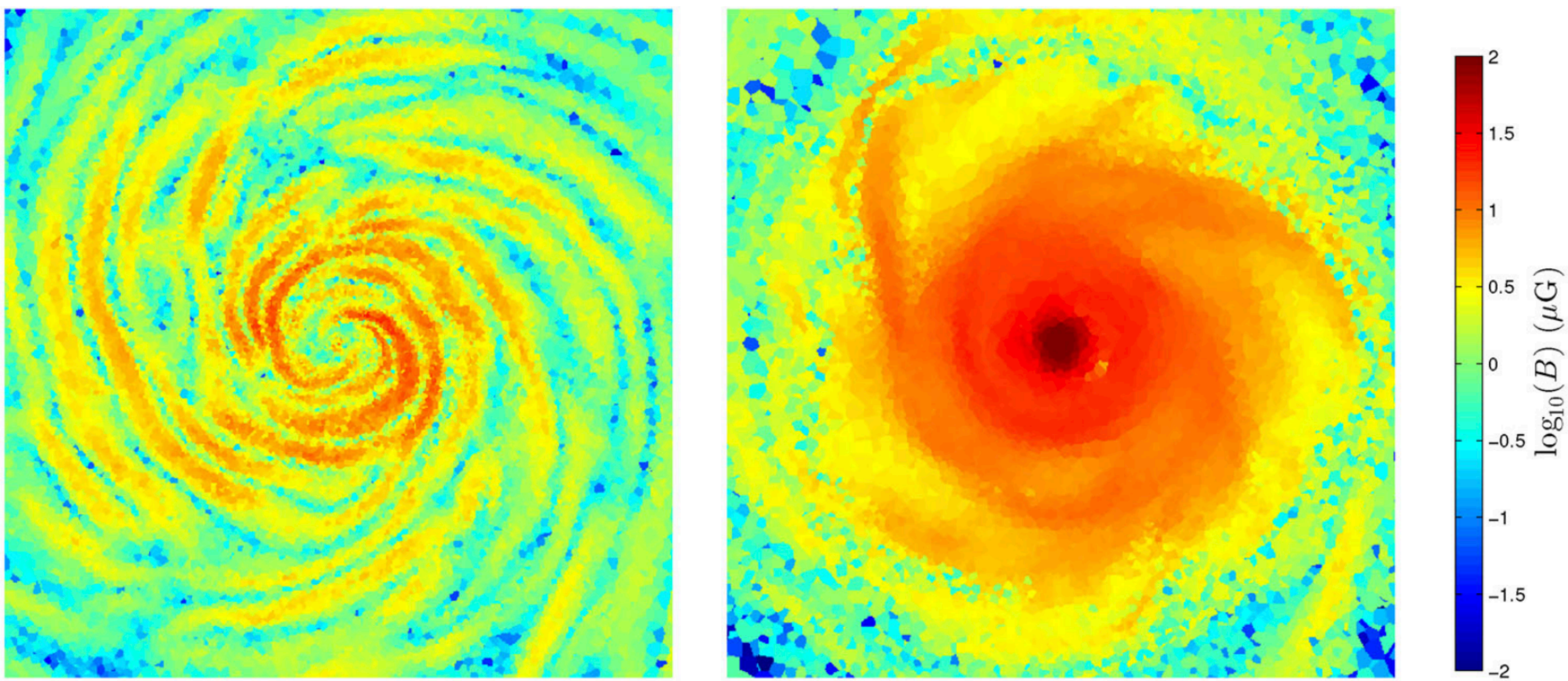
Constrained transport schemes



Evans & Hawley 1988 • Stone & Norman 1992 • Image: Teyssier & Commercon 2019

Powell schemes

Constrained transport (no div.) Powell



Powell et al. 1999 • Janhunen 2000 • Mocz et al. 2016

Dedner (GLM) schemes

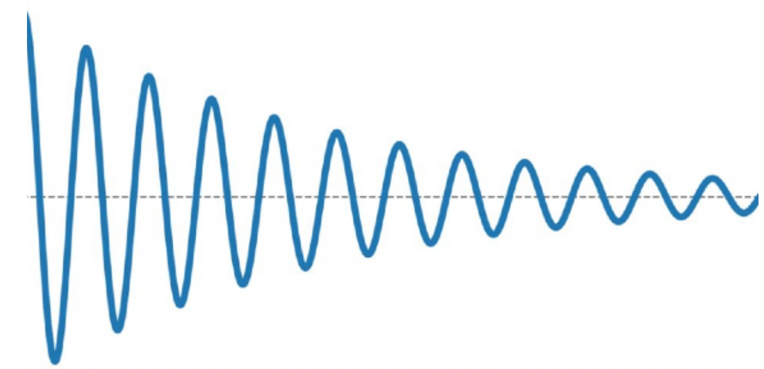
Idea:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{u} \times \boldsymbol{B})$$
$$\nabla \cdot \boldsymbol{B} = 0\,.$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{u} \times \boldsymbol{B}) - \nabla \psi$$
$$\nabla \cdot \boldsymbol{B} = -\frac{1}{c_\mathrm{h}^2}\frac{d\psi}{dt} - \frac{1}{c_\mathrm{p}^2}\psi\,,$$

Damped wave equ. for ψ :

$$\frac{\partial^2 \psi}{\partial t^2} + \frac{c_\mathrm{h}^2}{c_\mathrm{p}^2}\frac{\partial \psi}{\partial t} = c_\mathrm{h}^2 \nabla^2 \psi$$



f_{ch} = wave speed in units of CFL

Set to fraction of CFL speed:

$$c_\mathrm{h} = f_\mathrm{ch} C_\mathrm{CFL} \frac{\Delta x}{\Delta t}$$

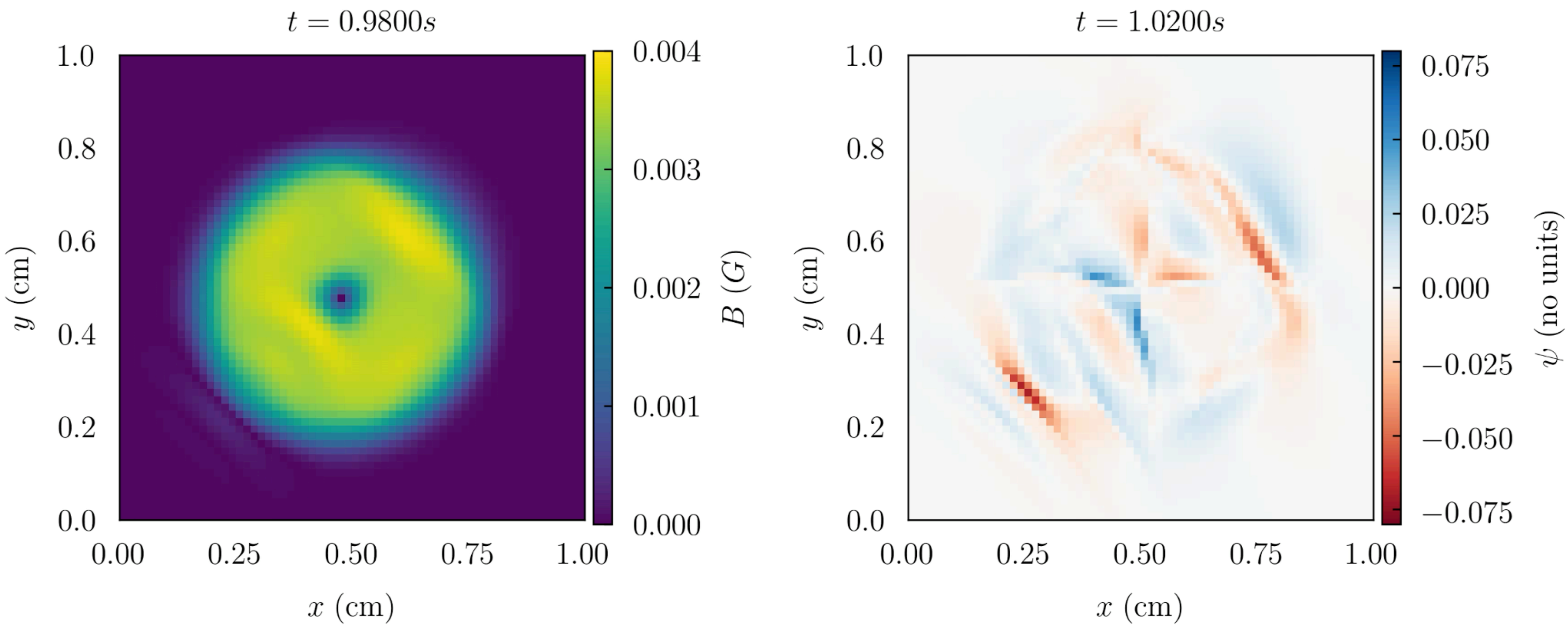
α = strength of damping

Damping:

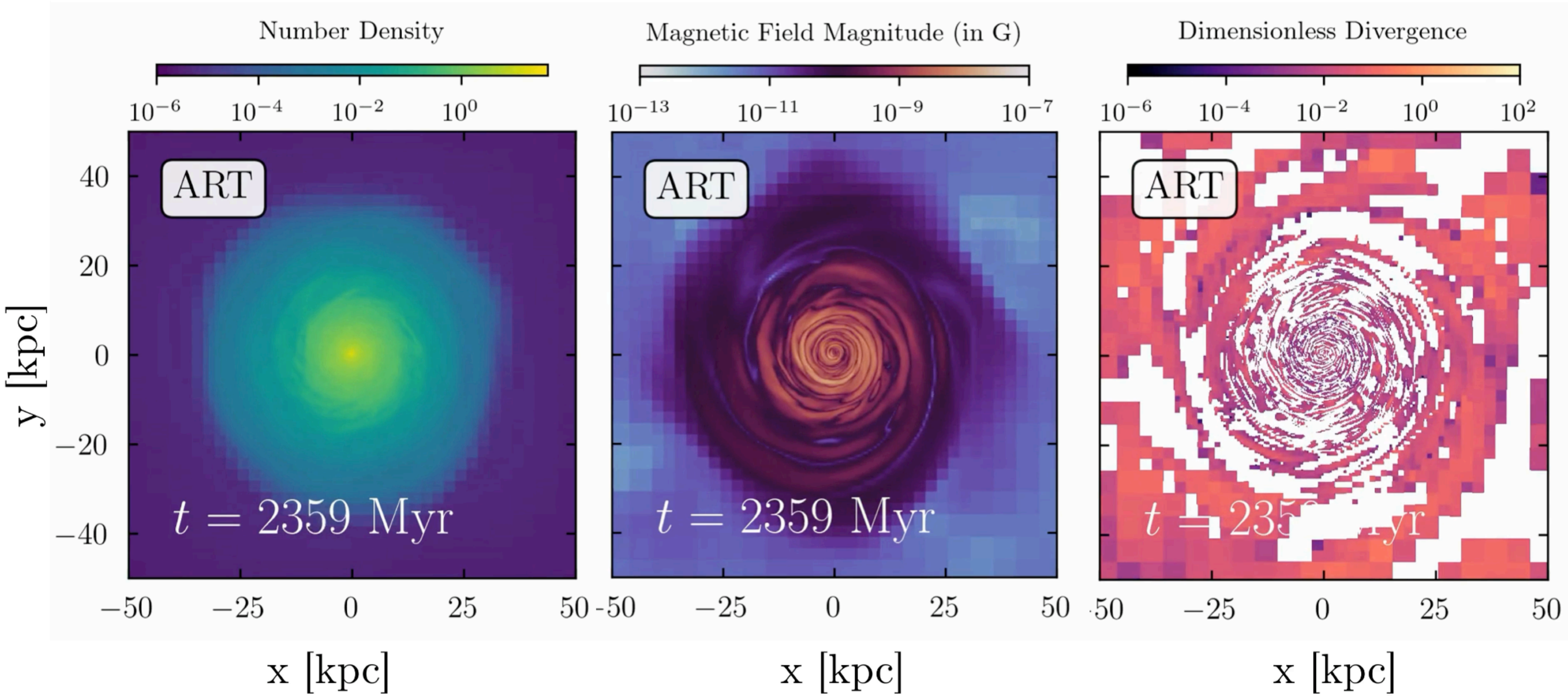
$$\psi^{n+1} = \psi^n \exp\left(-\alpha\, c_\mathrm{h} \frac{\Delta t}{\Delta x}\right) \qquad \alpha \equiv \Delta x \frac{c_\mathrm{h}}{c_\mathrm{p}^2}$$

Dedner et al. 2002 • Mignone & Tzeferacos 2010

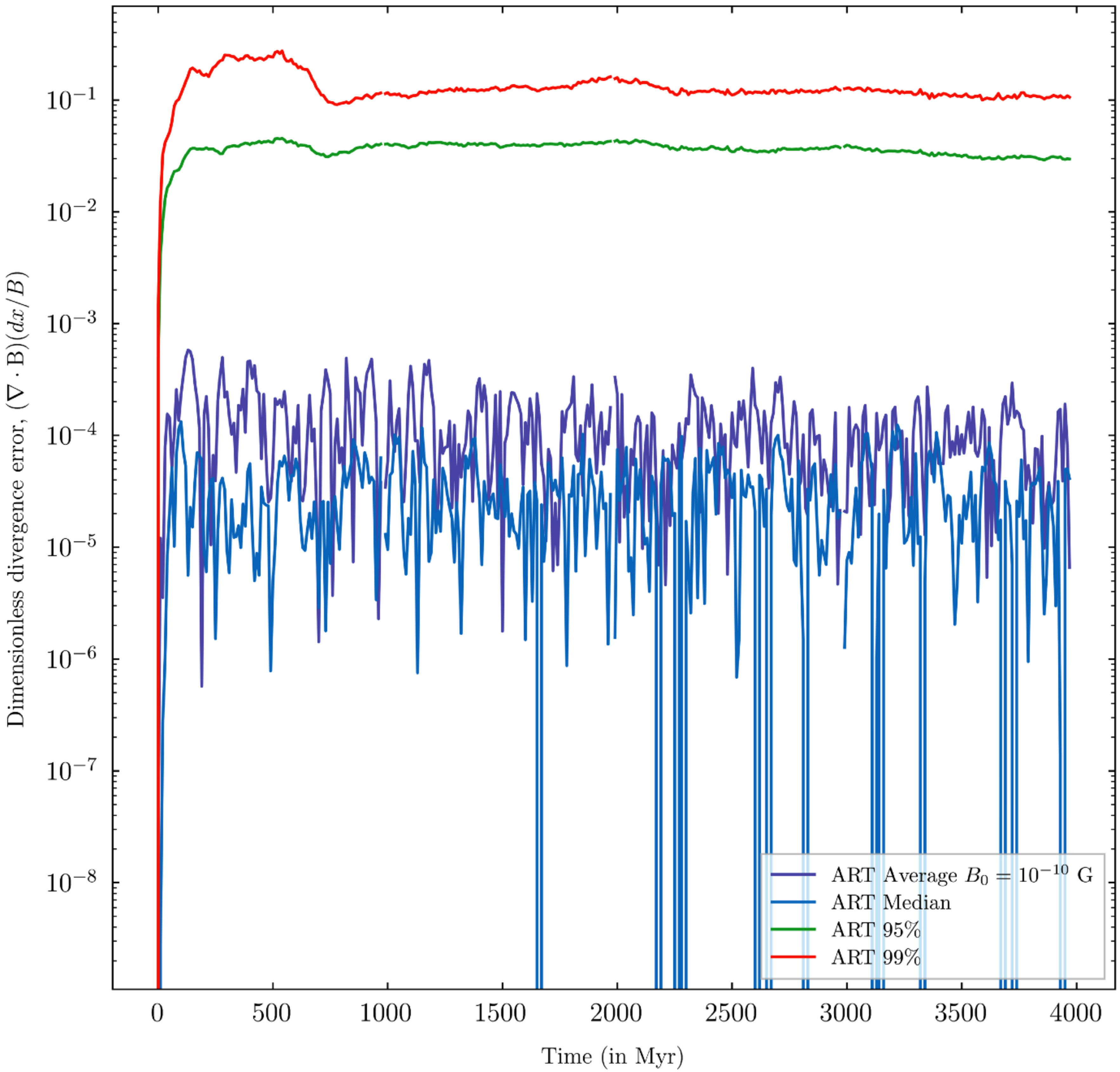
Dedner (GLM) schemes



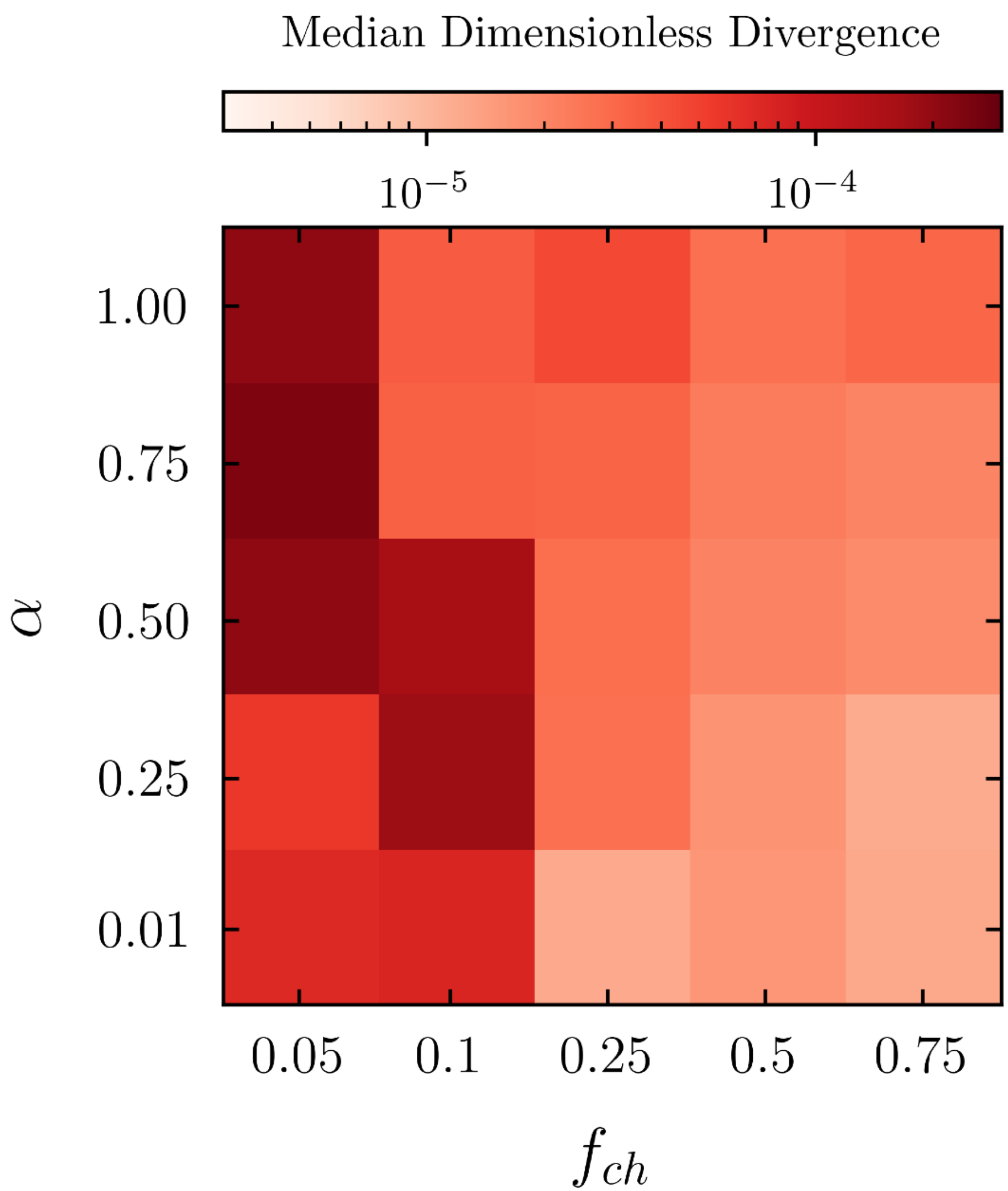
Magnetic field implementation with ART+Dedner



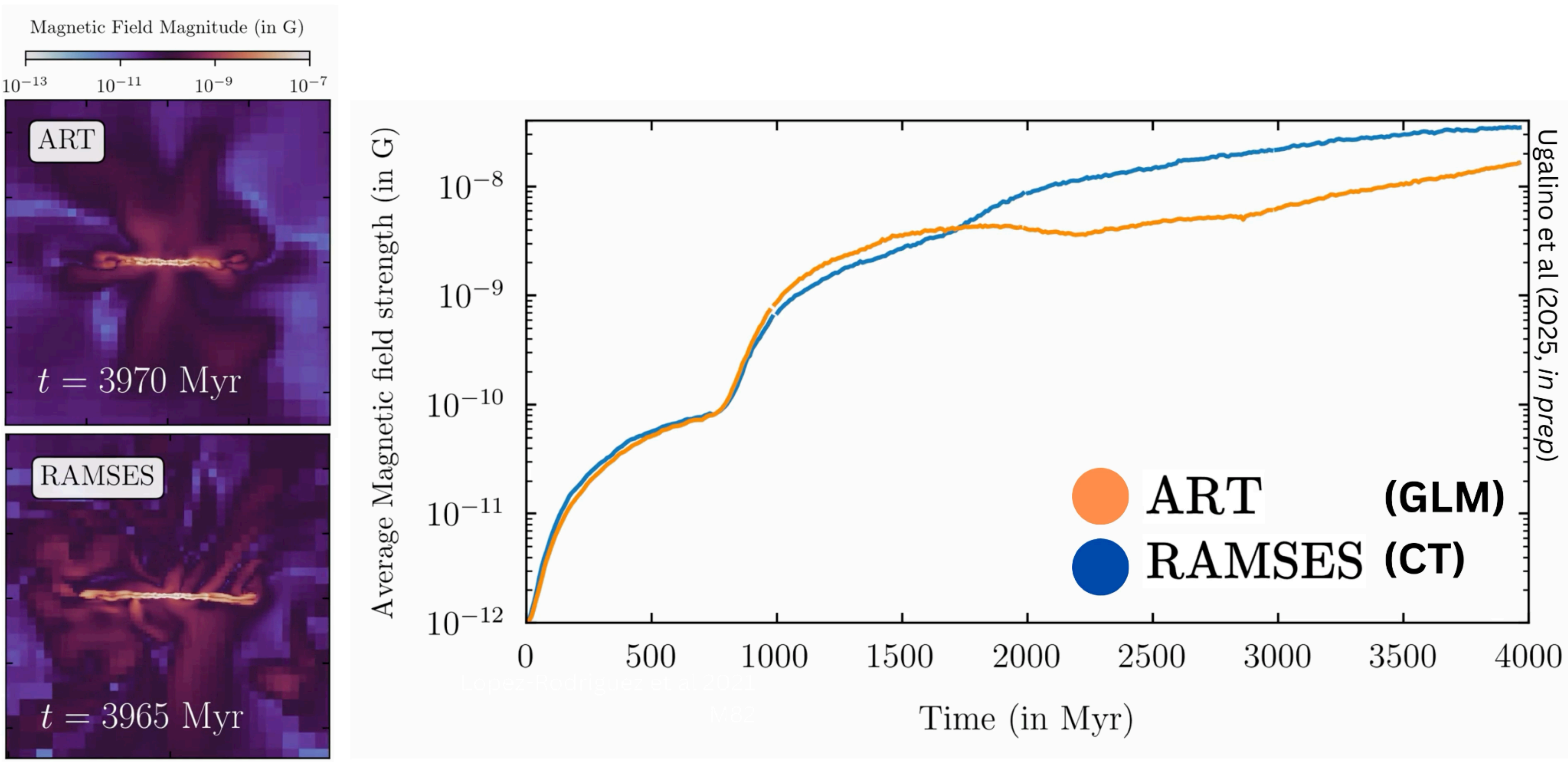
Divergence errors



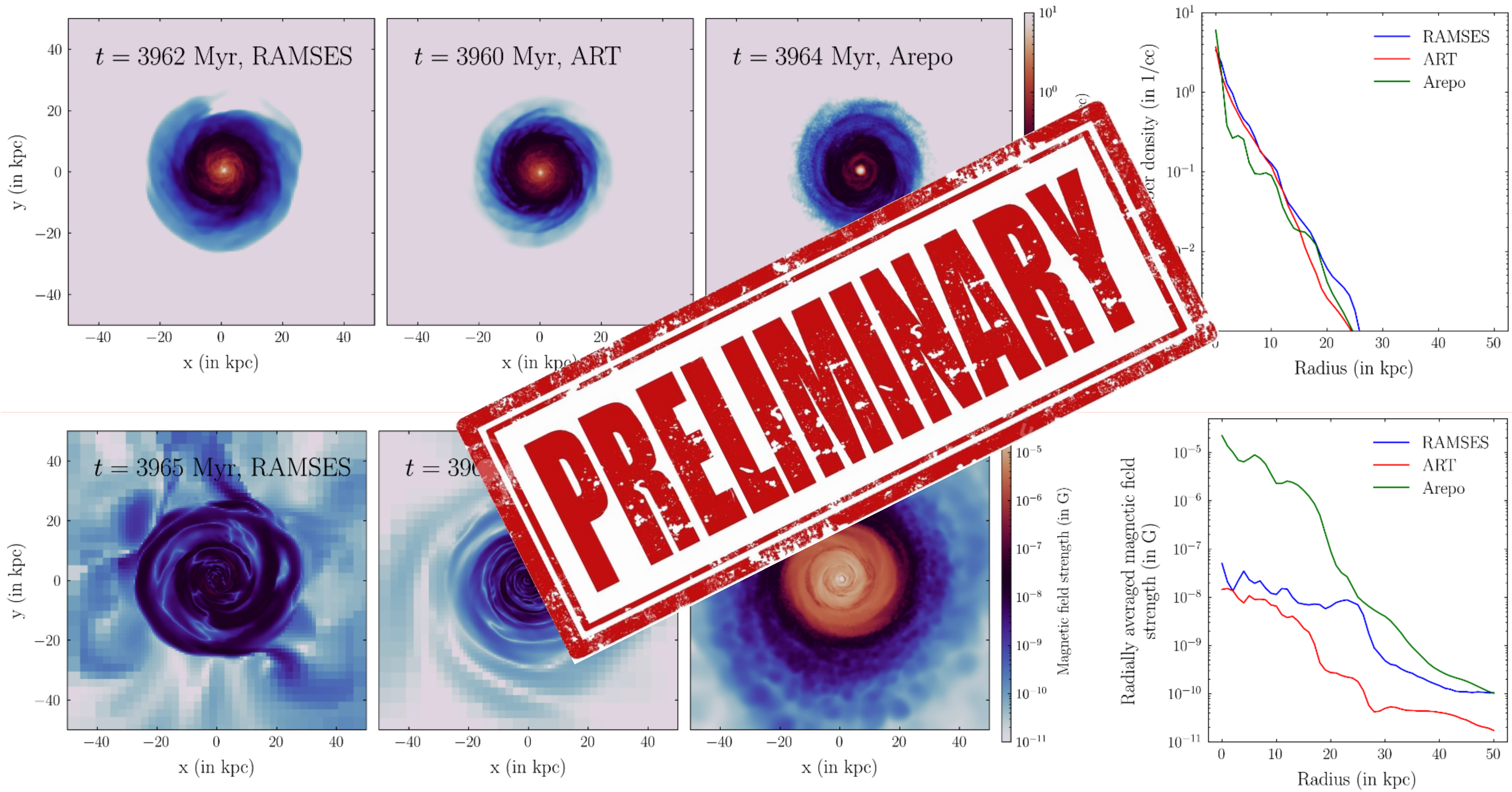
Divergence errors



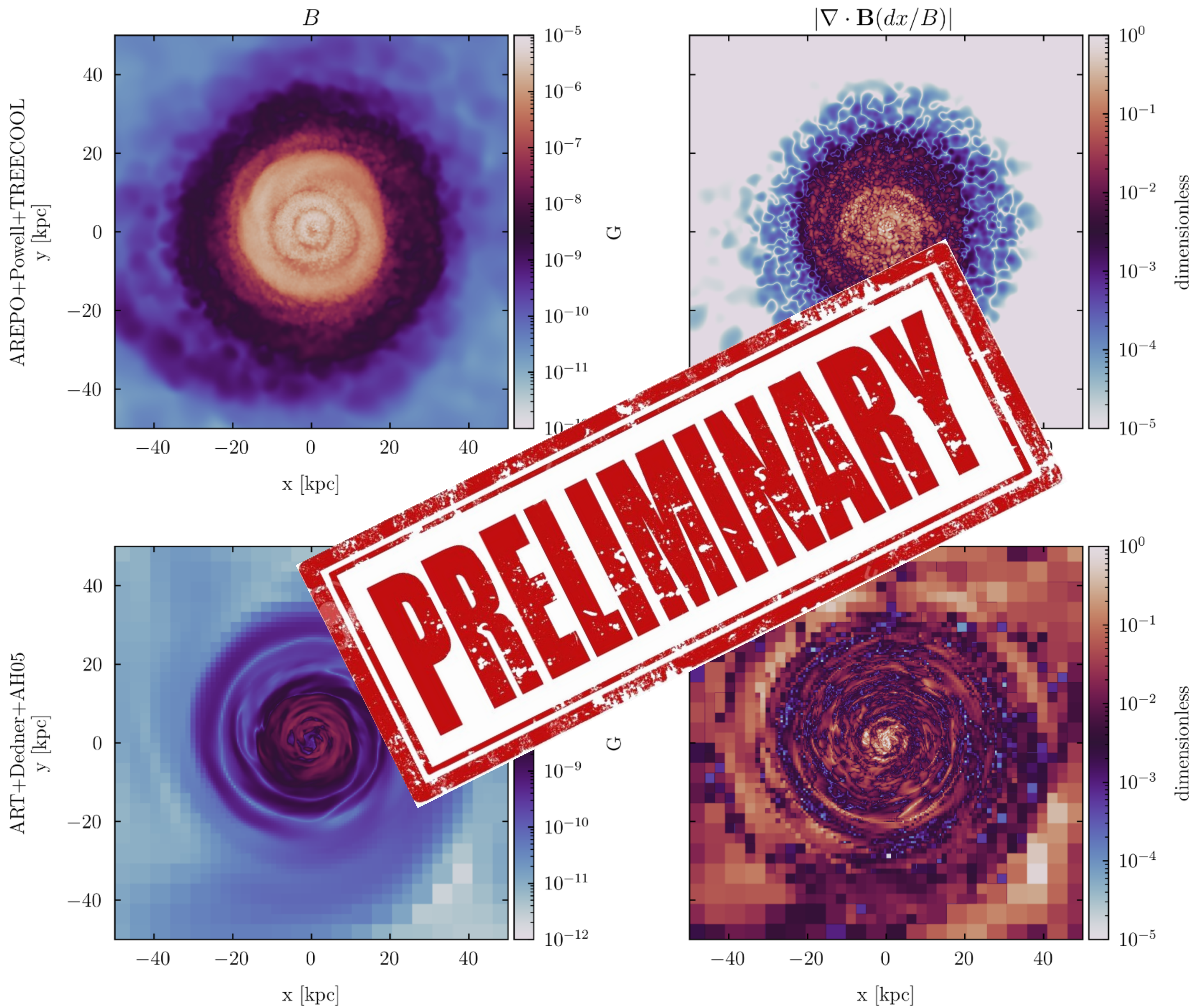
Code comparison



Code comparison: ART, Ramses, Arepo



Code comparison: Divergence in ART & Arepo



Take-aways

- Dedner-style divergence cleaning schemes are promising for galaxy simulations, as long as the **free parameters** are reasonable

- Stay tuned for a more detailed code comparison!

Ulula: ultra-lightweight 2D hydro solver

ULULA

Run simulation:

```
import ulula.setups.kelvin_helmholtz as setup_kh
import ulula.run as ulula_run

setup = setup_kh.SetupKelvinHelmholtz()
ulula_run.run(setup, tmax = 4.0, nx = 200)
```

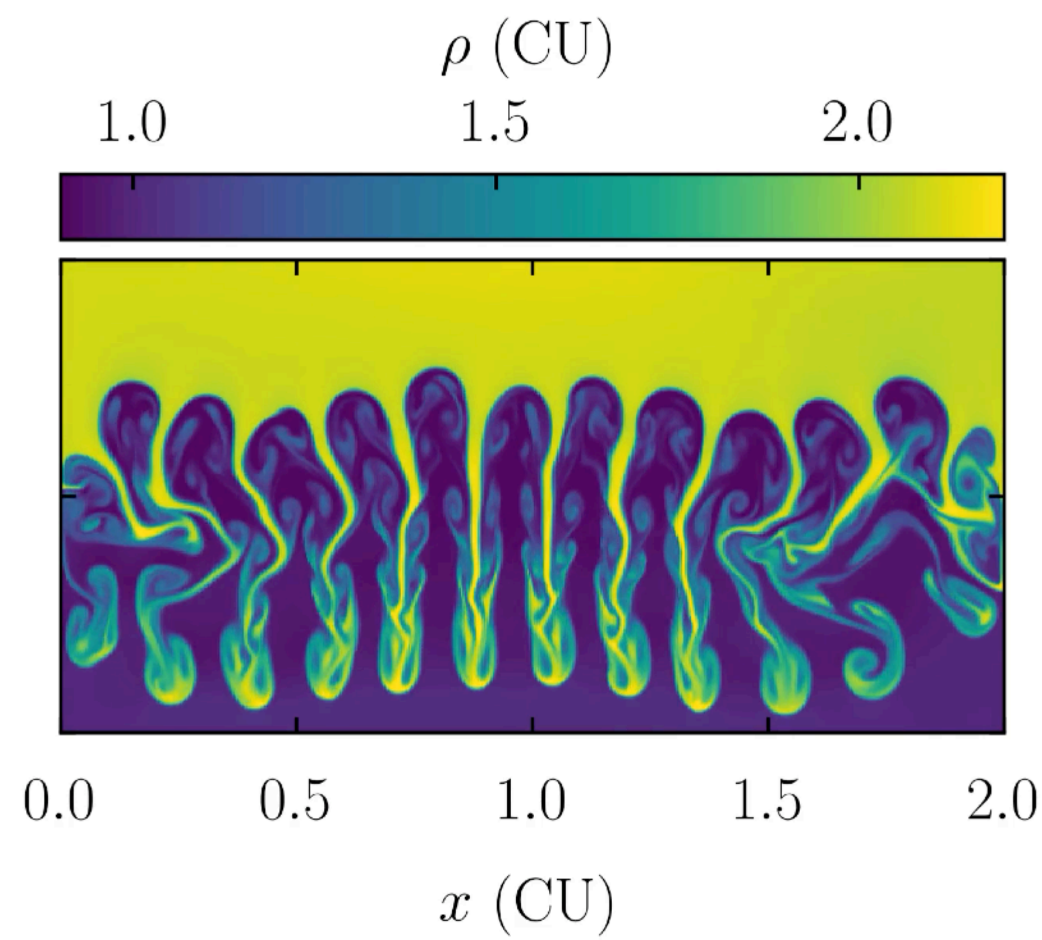
Change hydro scheme:

```
import ulula.simulation as ulula_sim

hs = ulula_sim.HydroScheme(reconstruction = 'linear', limiter = 'mc', cfl = 0.9)
ulula_run.run(setup, hydro_scheme = hs, tmax = 4.0, nx = 200)
```

Make plots or movies:

```
ulula_run.run(setup, tmax = 4.0, nx = 200, plot_time = 0.5, q_plot = ['DN', 'PR'])
ulula_run.run(setup, tmax = 4.0, nx = 200, movie = True, q_plot = ['DN'])
```



Diemer 2025 • bdiemer.bitbucket.io/ulula