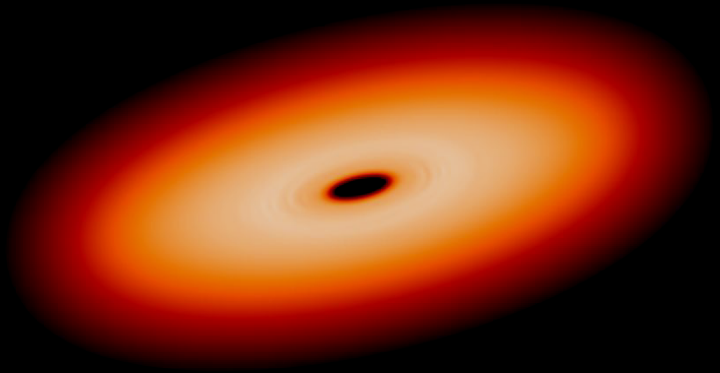
Magnetohydrodynamic Simulations of Accretion Discs



Jacksen Narvaez
M.Sc. Student @ MUN
jjnarvaezcor@mun.ca

Supervisor: Dr. Terrence Tricco

2nd European Phantom users workshop

Simulation, Modeling and Synthetic Data Lab

MEMORIAL UNIVERSITY

Magnetized Accretion Discs

Accretion $\rightarrow$ mechanism for angular momentum transport.

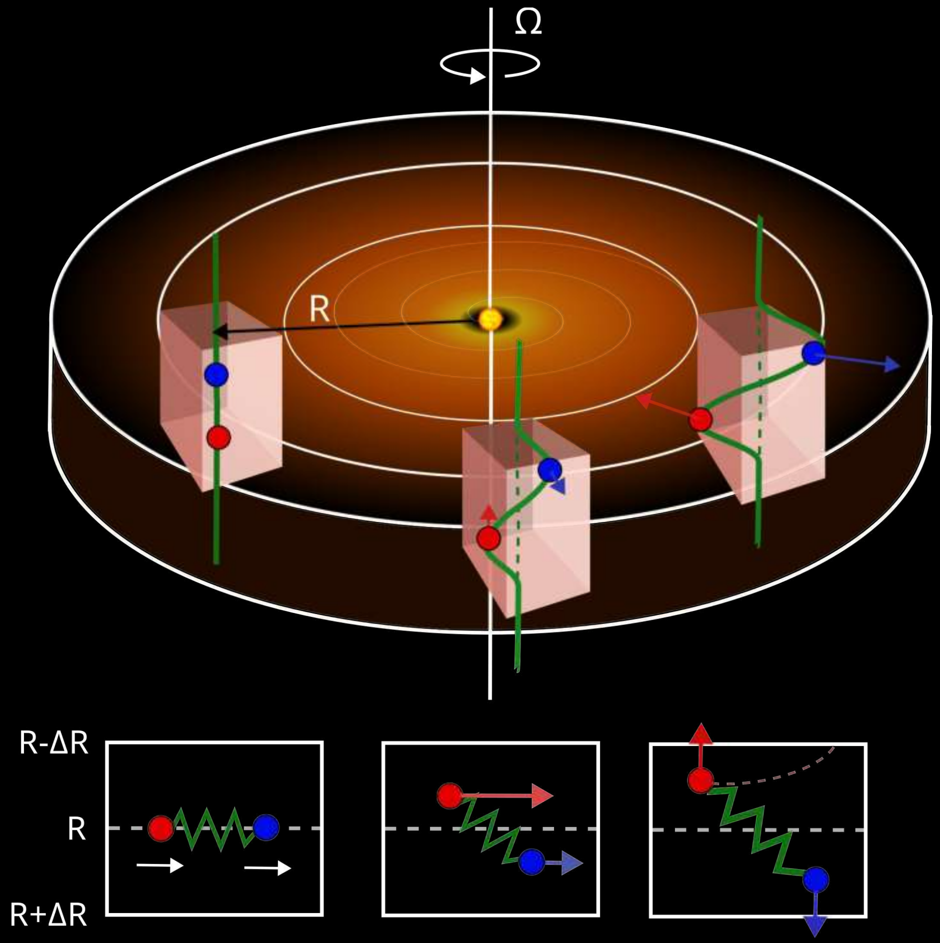
Shakura-Sunyaev (1973)

$$\nu = \alpha c_s H \quad \rightarrow \text{Turbulence.}$$

$\downarrow$

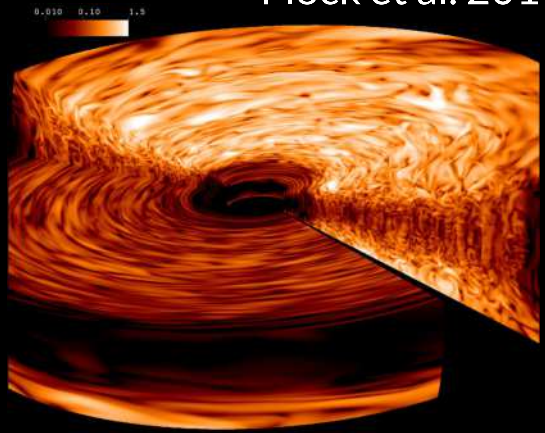
$$\boxed{\text{Magnetorotational instability (MRI)}} \qquad \frac{d\Omega^2}{dr} < 0$$

Balbus & Hawley 1991



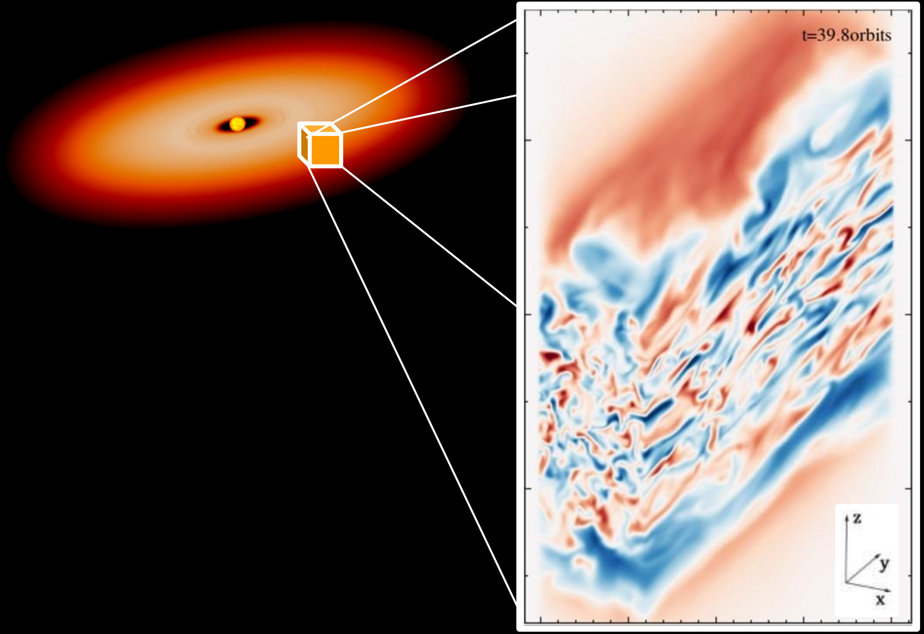
Global Disc Simulations

Flock et al. 2011



Grid codes

PLUTO: Flock et al. 2010, 2011, 2012, 2013; Mignone et al. 2012; Parkin & Bicknell 2013; Parkin 2014a,b. **ATHENA++:** Sorathia et al. 2012; Ju et al. 2016, 2017; Pjanka & Stone 2020; Rodman & Reynolds 2024. **GLOBAL & NIRVANA:** Fromang & Nelson 2006



Adapted from Wissing *et al.* 2022

Meshless codes

GIZMO: Deng et al. 2020

SPH [Shearing box approximation]

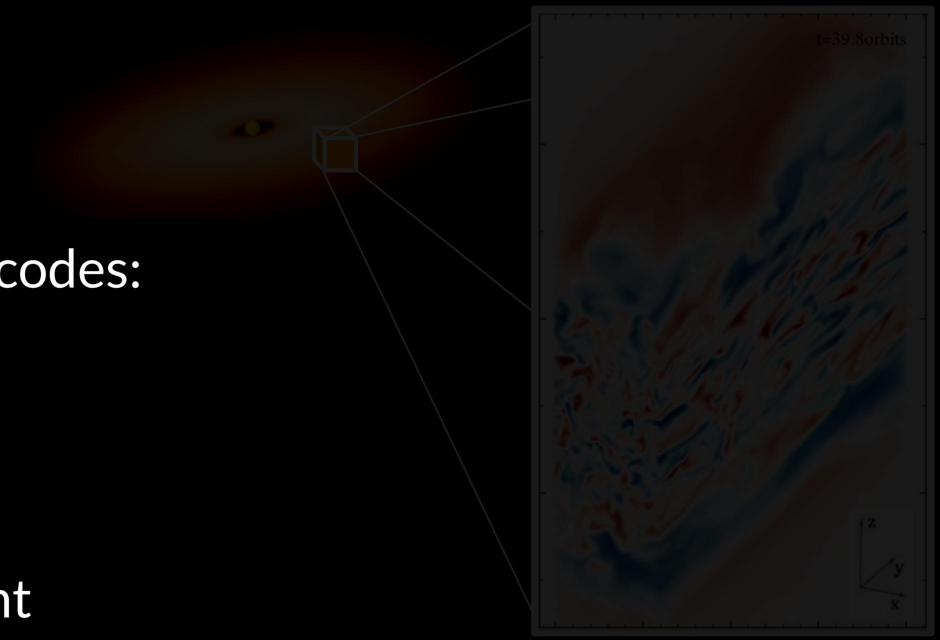
Hopkins & Raives 2015; Tricco 2015; Deng et al. 2019; Wissing et al. 2022

Global Disc Simulations

Flock et al. 2011

Main challenges for meshless codes:

- ➢ Resolution
- ➢ Dissipation
- ➢ Divergence-free constraint



Grid codes
PLUTO: Flock et al. 2010, 2011, 2012, 2013;

Meshless codes
GIZMO: Deng et al. 2020

Adapted from Wissing *et al.* (2021)

Aim: Study the suitability of the SPMHD algorithm for reproducing MRI in global disc simulations.

Model Setup

3D ideal MHD simulations.

Initial Conditions:

$M_d = 0.05\ M_\odot$

$H/R_{in} = 0.05$ (Thin disc)

Hydrostatic equilibrium

Toroidal magnetic fields: β_0=25

EOS: Locally Isothermal

$$\Sigma(R) = \Sigma_0 \left(1 - \sqrt{\frac{R_{in}}{R}}\right) \left(\frac{R}{R_{ref}}\right)^{-p}$$

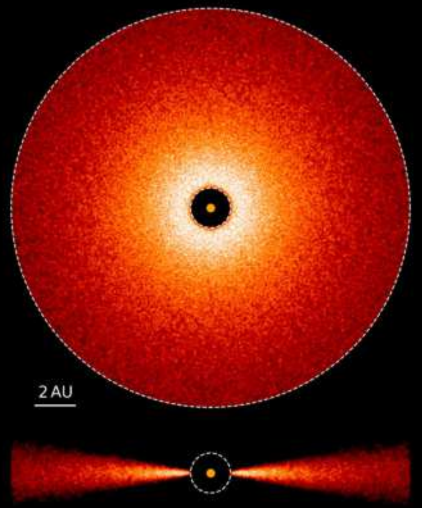
$$v_\phi{}^2 = v_k{}^2 - c_s^2 \left(\frac{3}{2} + p + q\right) \left(1 + \frac{1}{\beta_0}\right)$$

$$B_\phi = \sqrt{\frac{2P_g}{\beta_0}}, \quad B_R = B_z = 0$$

$$c_s = c_{s0} r^{-q}$$

PHANTOM [SPH]

Domain. R: 1-10, z: ±3H, φ: 2π



Resolution:

$$N_p \geq 10^6$$

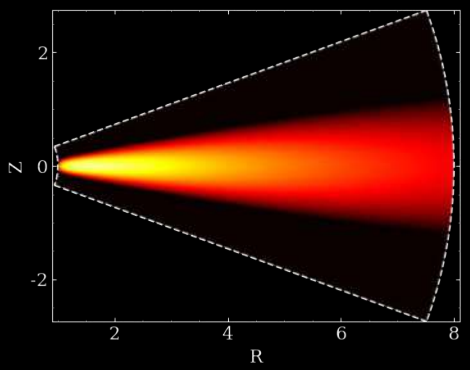
Source:

https://phantomsph.github.io/

https://github.com/ttricco/sarracen/

PLUTO [Godunov scheme]

Domain. r: 1-8, θ: π/2 ± 0.3, φ: π/2



Resolution:

$$\begin{aligned} N_r &= 800 \ (log) \\ N_\theta &= 280 \\ N_\phi &= 560 \end{aligned}$$

Δr : rΔθ : rΔφ

1 : 1.04 : 0.93

Source:

https://plutocode.ph.unito.it/

https://github.com/GiMattia/PyPLUTO

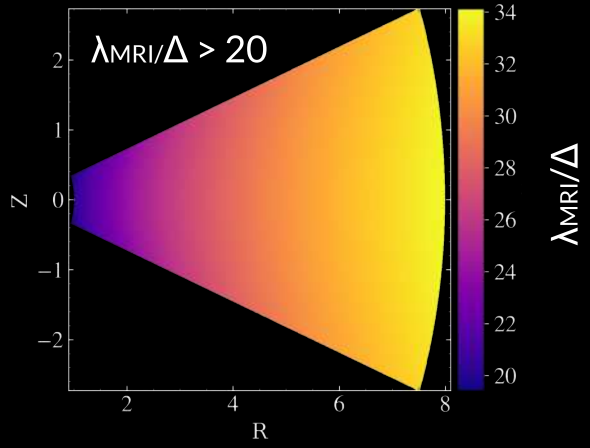
Capturing MRI

Fastest growing mode

$$\boxed{\lambda_{MRI} = 2\pi\sqrt{\frac{16}{15}}\frac{v_A}{\Omega}}$$

Grid codes: λMRI/Δ > 5

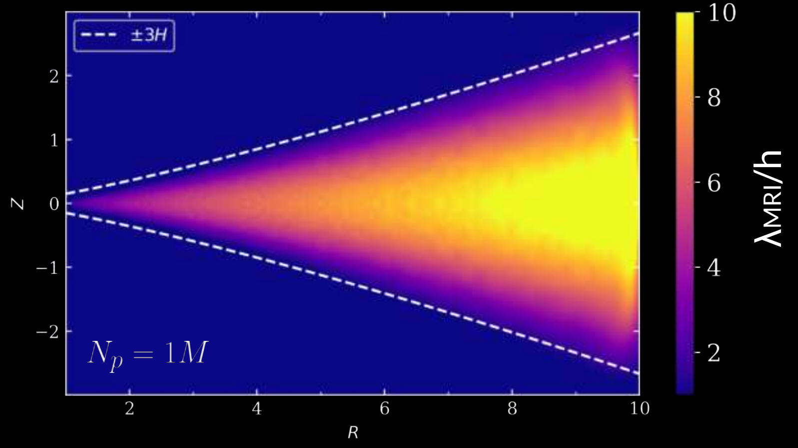
e.g. Hawley et al. 1995; Miller & Stone 2000



SPH [Shearing box approximation]

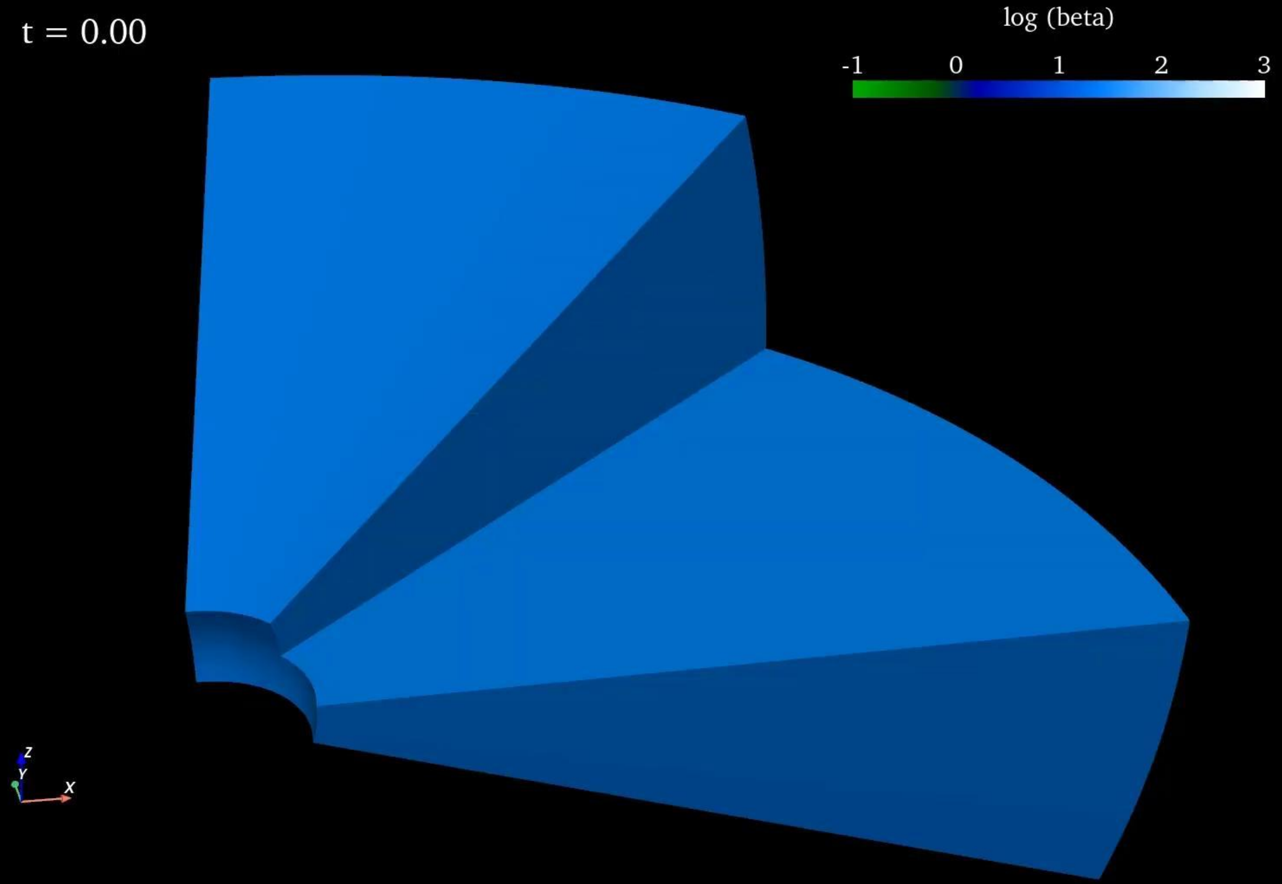
Q = λMRI/*h* → Quality factor

Wissing et al. (2022) used Q > 40 for stratified net flux simulations.



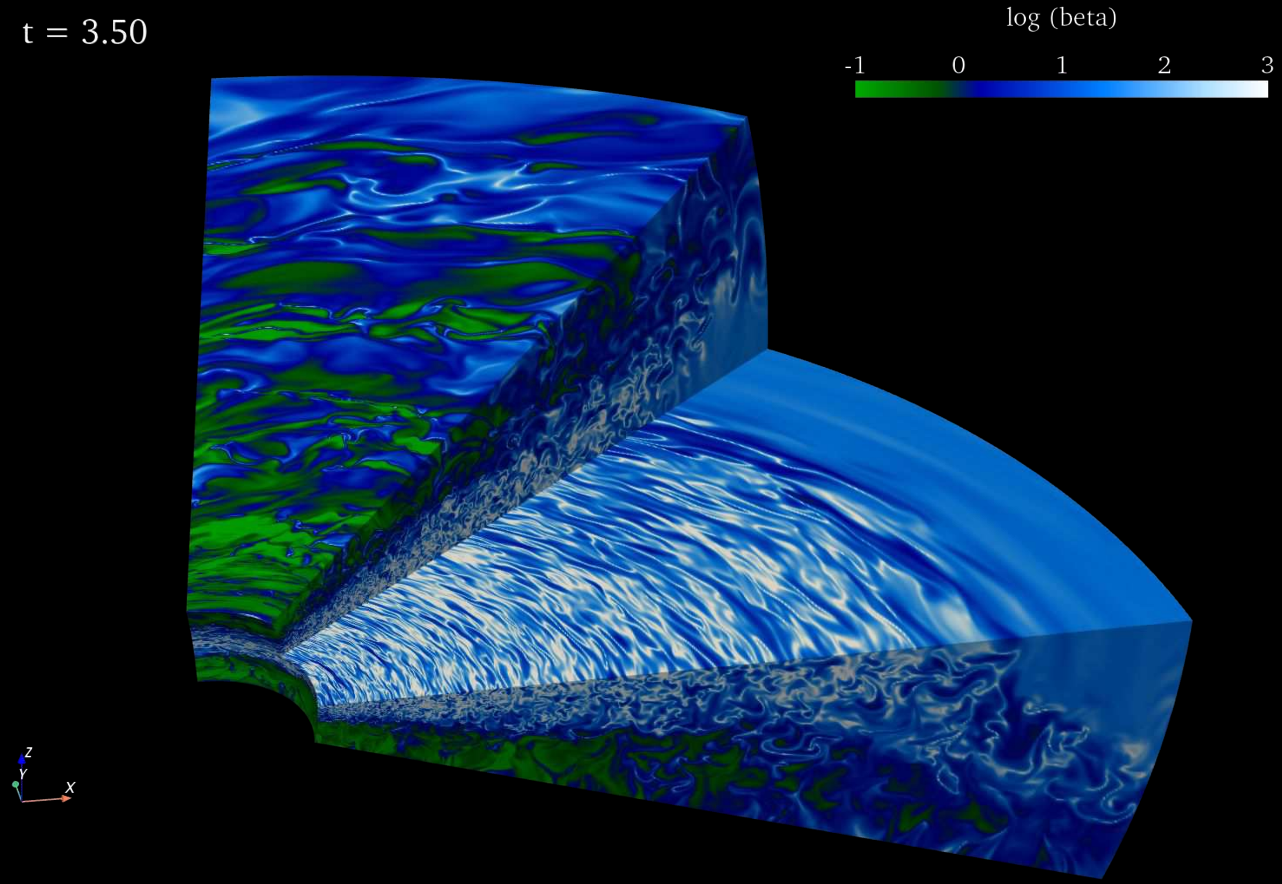
PLUTO: Early disc evolution

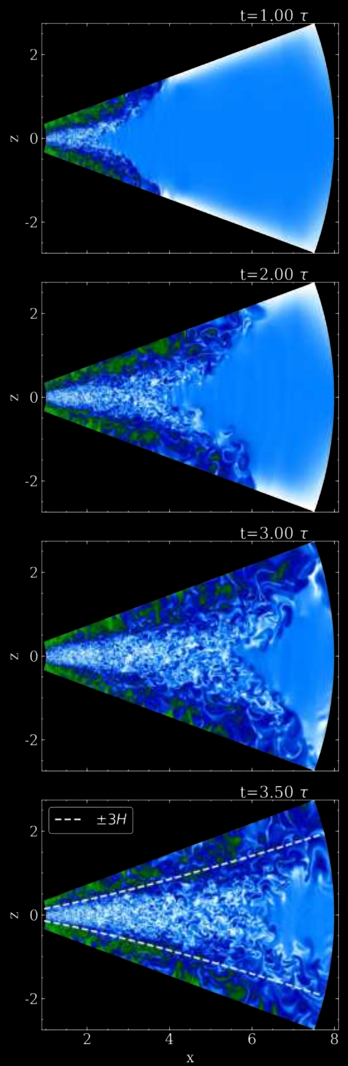
$$\beta = \frac{P_{gas}}{P_{mag}}$$



PLUTO: Early disc evolution

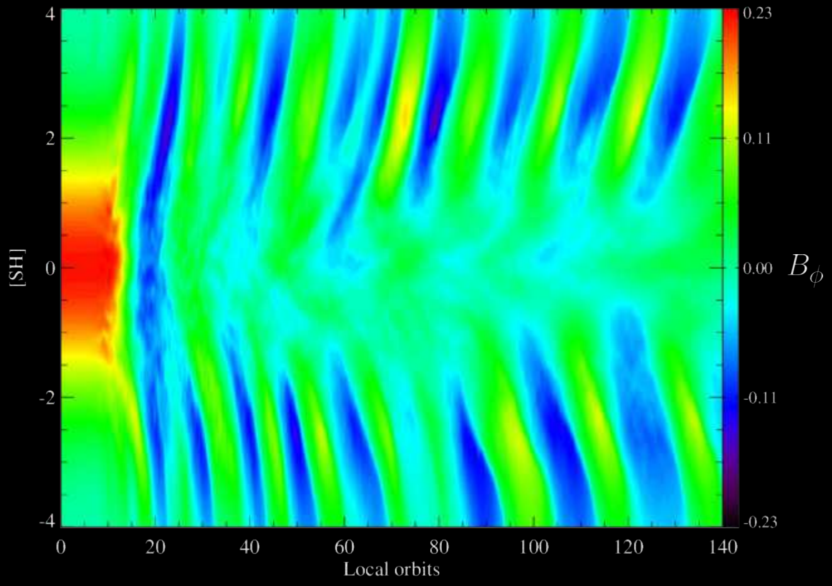
$$\beta = \frac{P_{gas}}{P_{mag}}$$



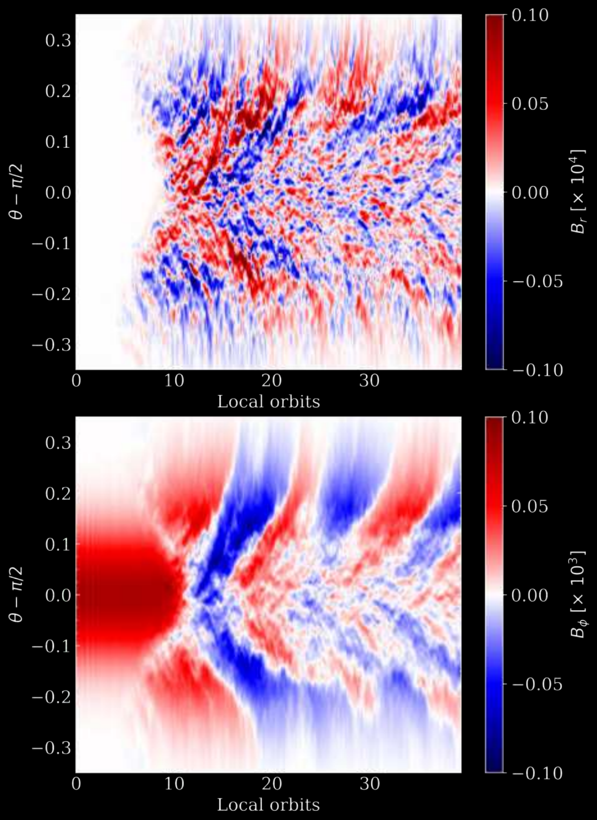


PLUTO: The butterfly diagram

Flock et al. 2011



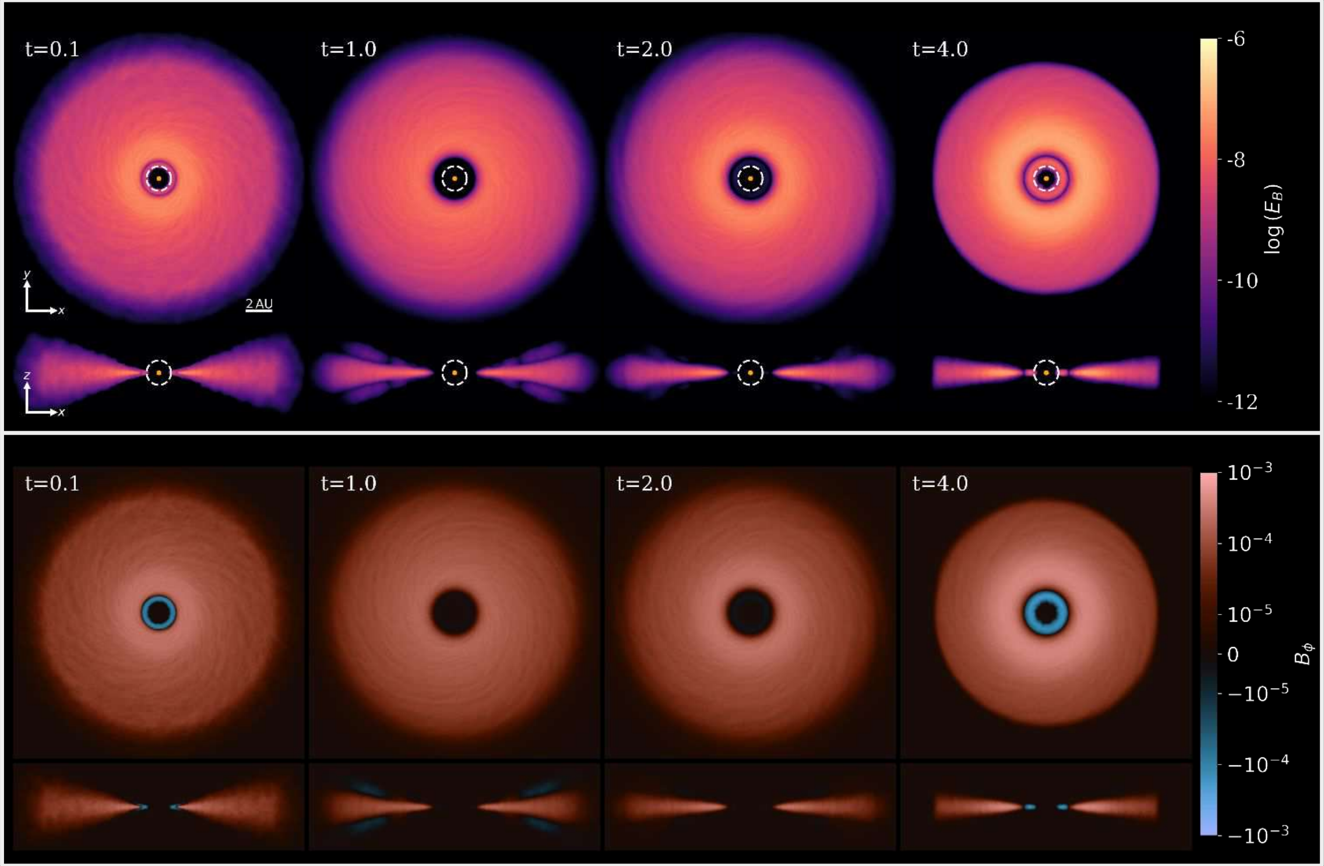
* At R=2



Np = 1M

PHANTOM

Growth of strong toroidal fields.



Reported also by

Dobbs et al. 2016,
Deng et al. 2019,
Wissing et al. 2022

PHANTOM

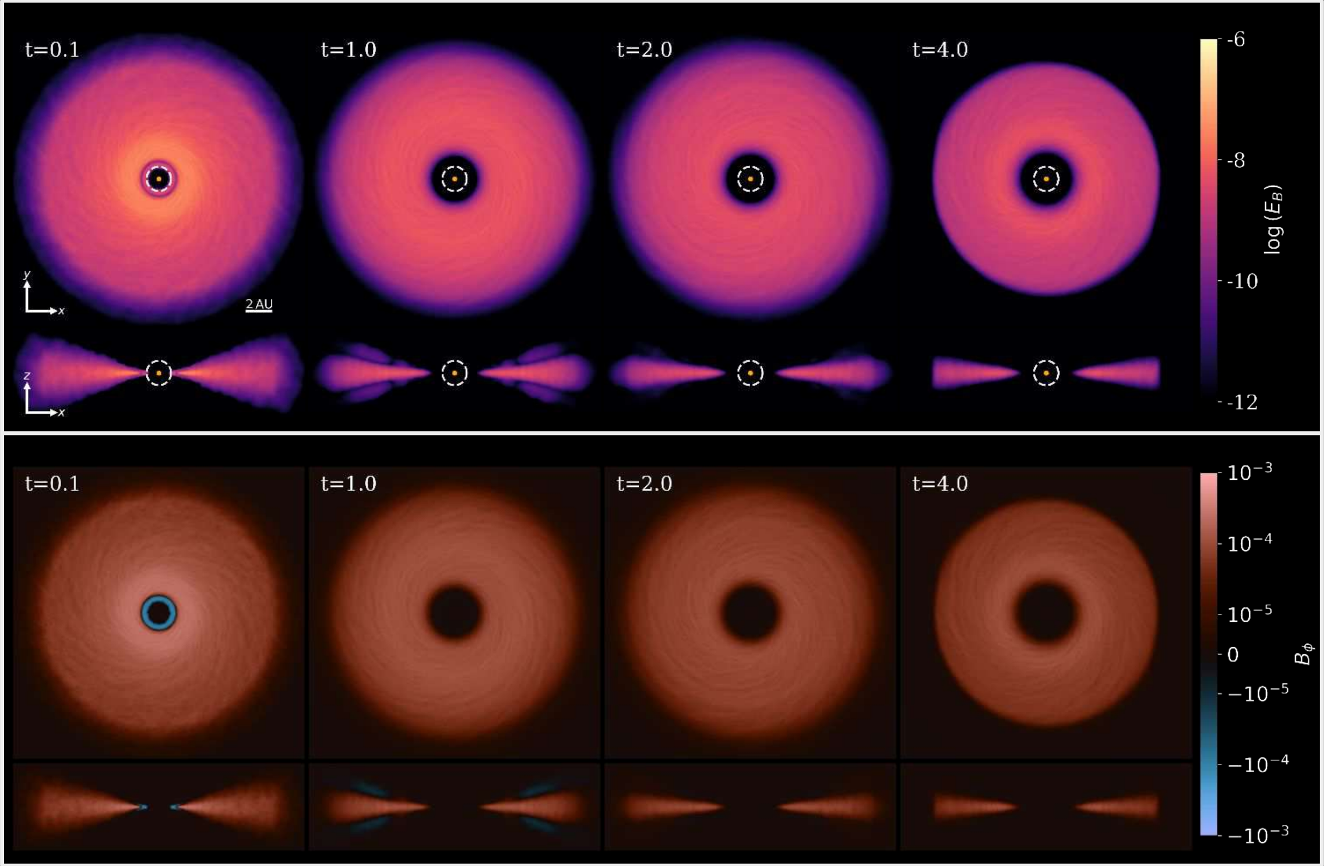
Divergence cleaning
Tricco et al. (2016)

Overcleaning

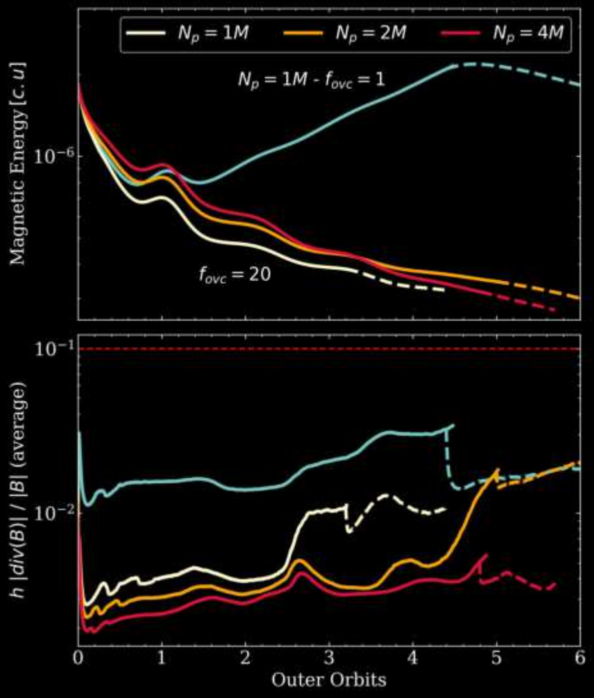
Increase the cleaning wave speed

$$C_h \longrightarrow f_{ovc} C_h$$

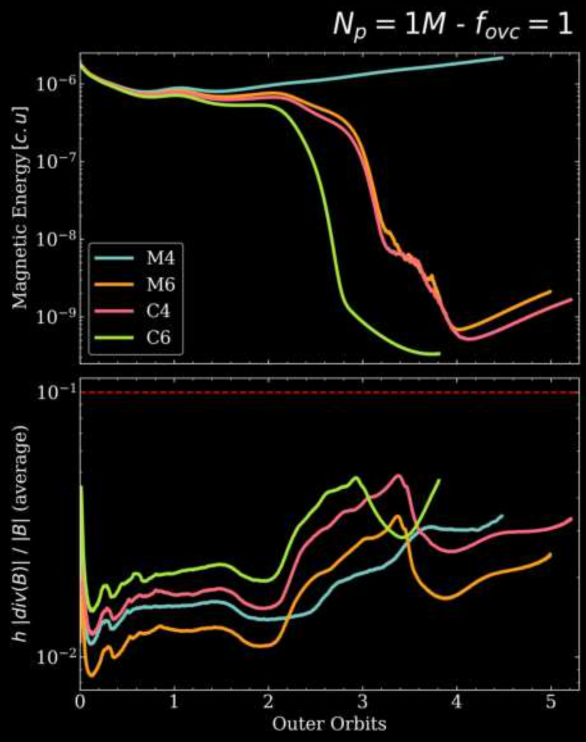
$f_{ovc} = 20$



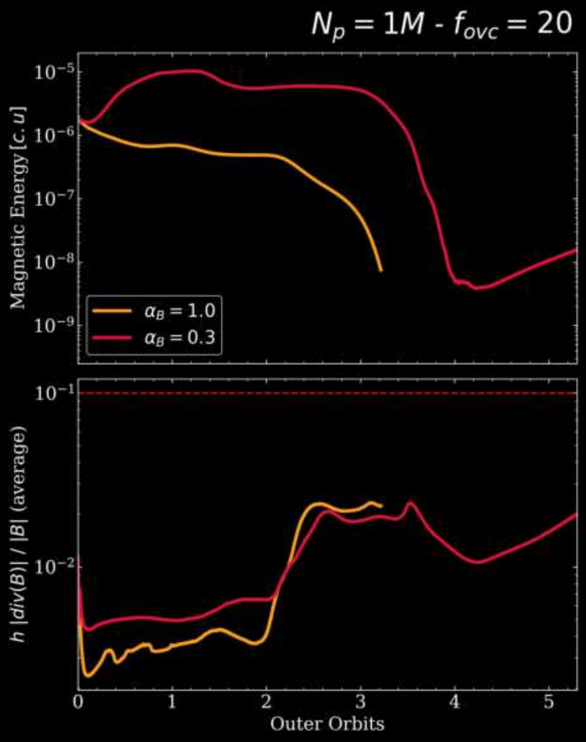
Resolution



Kernel



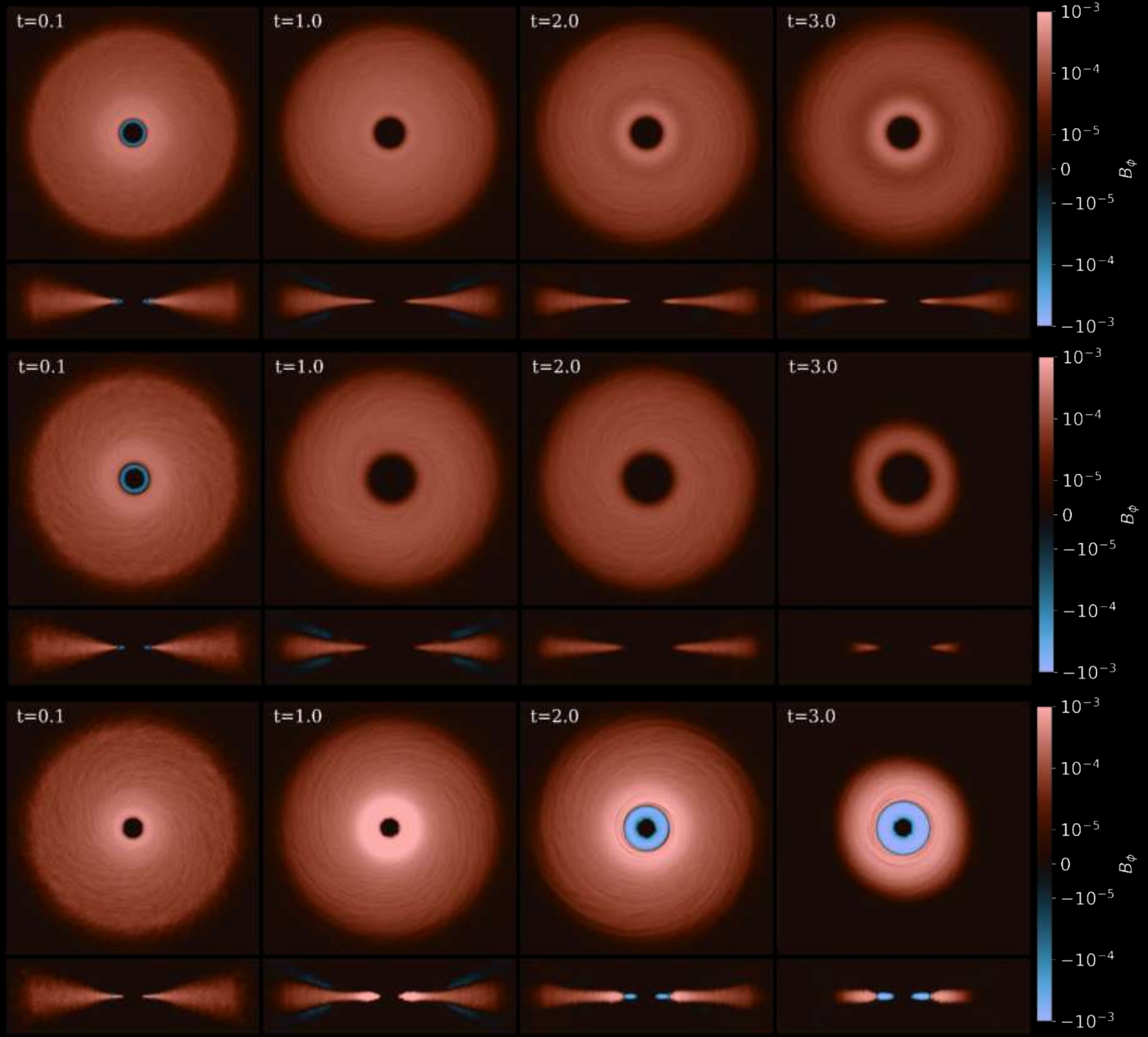
Artificial resistivity



M4 Kernel
N_p = 4M

M6 Kernel
N_p = 1M

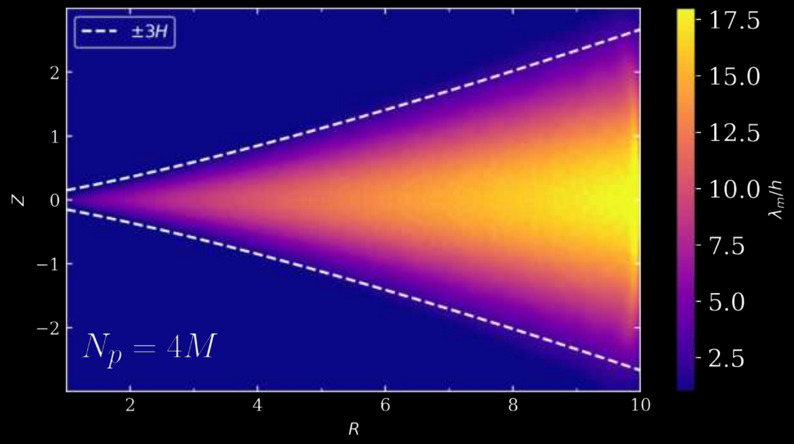
M6 Kernel
N_p = 1M
α_B = 0.3



Summary

- In SPH, MRI has not been activated yet
- Critical challenges for Global Disc MHD Simulations:
  - Dissipation
  - Divergence cleaning

- Future Work:
  - Study energy loss due to artificial resistivity, divergence cleaning, …
  - Improve resolution: Include adaptive particle refinement (APR)



Thanks!

Jacksen Narvaez
jjnarvaezcor@mun.ca