Local Particle-in-cell Simulations Of The Magnetorotational Instability In Stratified, Sub-relativistic Accretion Disks

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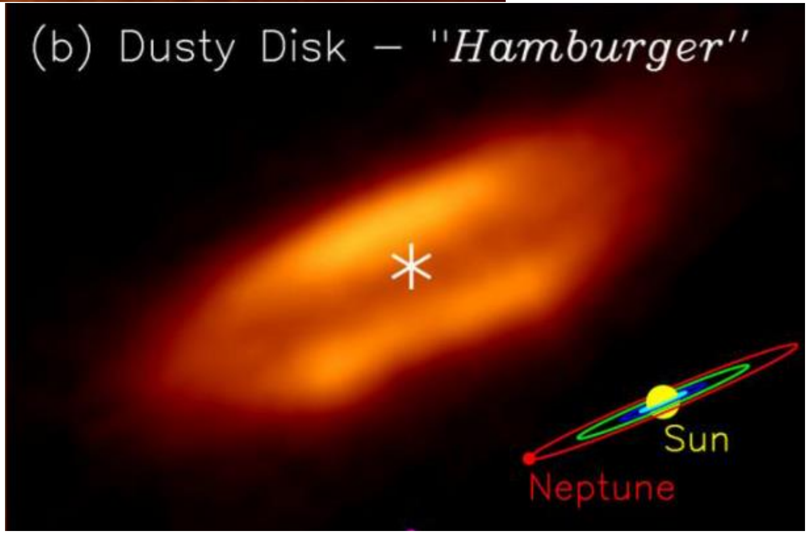
Accretion disks

Credit: NASA/JPL-Caltech/R. Hurt (IPAC)



Credit: ALMA (ESO/NAOJ/NRAO)/Lee et al.

Accretion disks are very common in astrophysics.

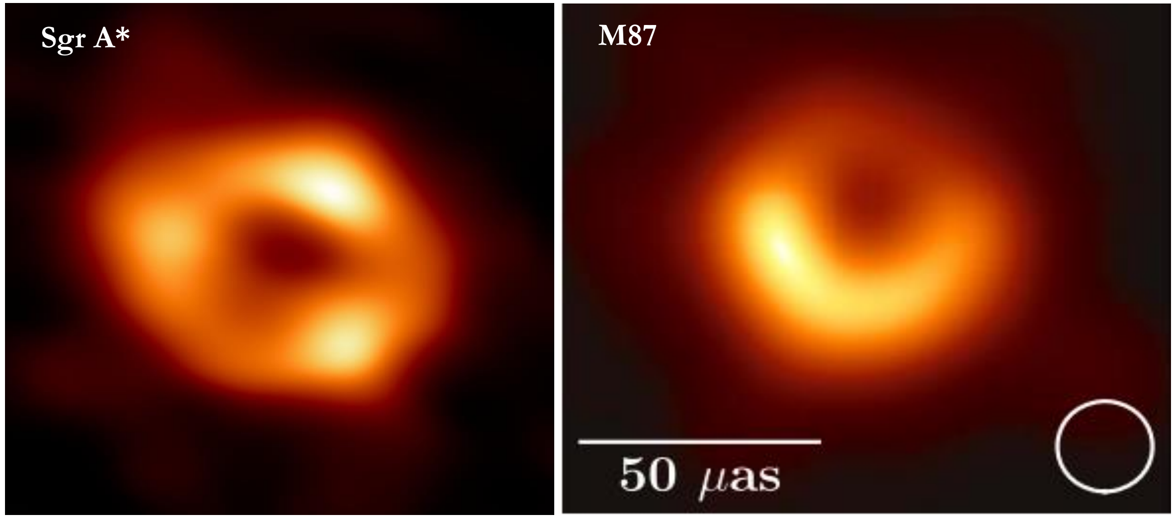
They correspond to gas rotating around a central gravitating object, which gradually falls onto it.

There are many astrophysical examples of accretion disks, which include:

- Cataclysmic variables (CVs).
- Active Galactic Nuclei (AGNs).
- Protostars.
- X-ray binaries (XTBs).

Why to study the collisionless MRI?

- For very low luminosity accretion disks, where $\dot{M} \ll \dot{M}_{Edd}$, the plasma thermalization time due to Coulomb collisions can be much larger than the accretion times of the plasma.
- Examples: Sgr A* and M87



(EHT Collaboration, 2022) (EHT Collaboration, 2019)

- Thermalization time for electrons, t_{ee}, at $r \approx 10R_s$

$$t_{ee} = \frac{\sqrt{2\pi}}{n_e \sigma_t c \, ln \, \Lambda} \left(\frac{k_B T}{m_e c^2} \right)^{3/2} \approx 10 \, [yr]$$

(Mahadevan & Quataert, 1997)

and the accretion time is

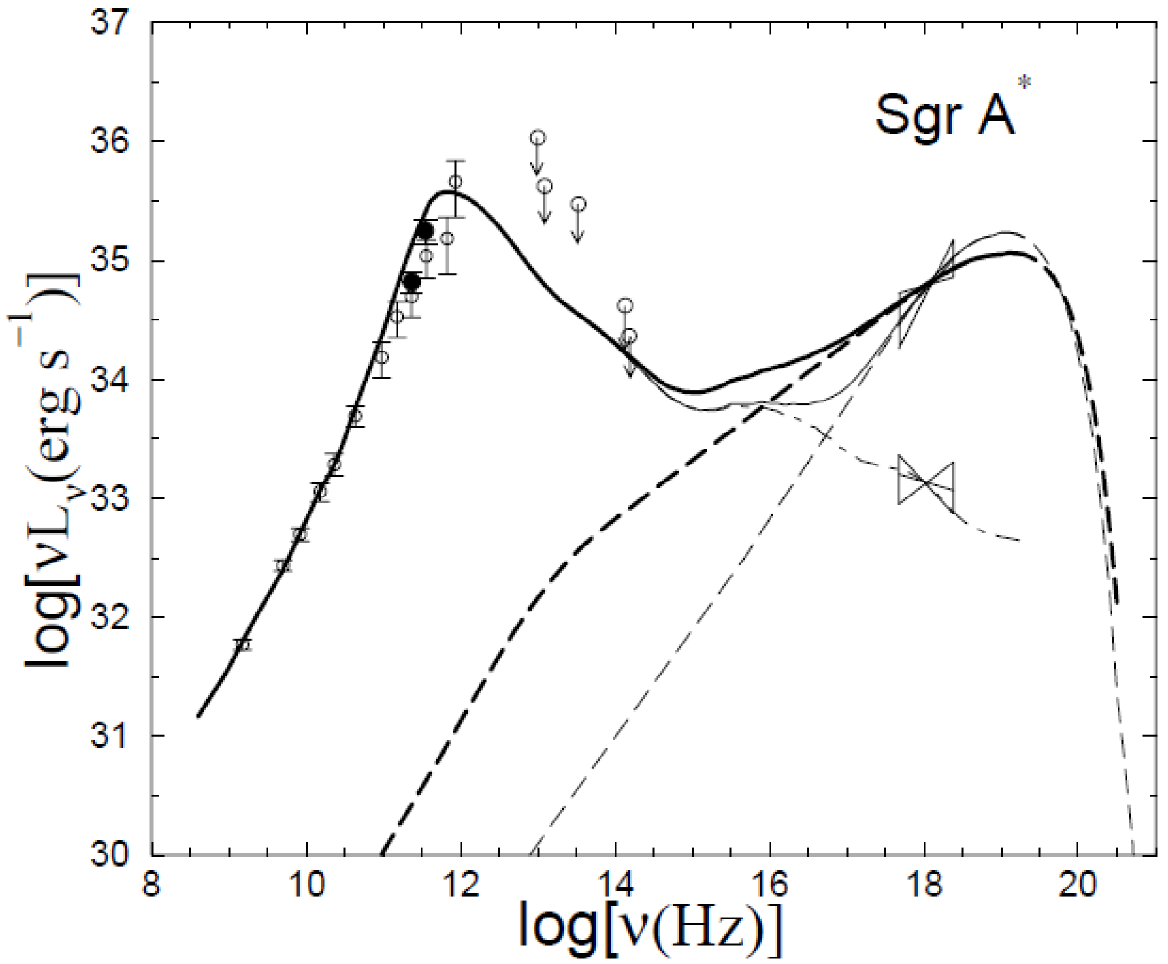
$$t_{acc} \approx 1{,}8 \times 10^{-5} \alpha^{-1} m r^{\frac{3}{2}} \, [s] \approx 1 \, [hour]$$

- This means that in the inner region of the disk around Sgr A*:

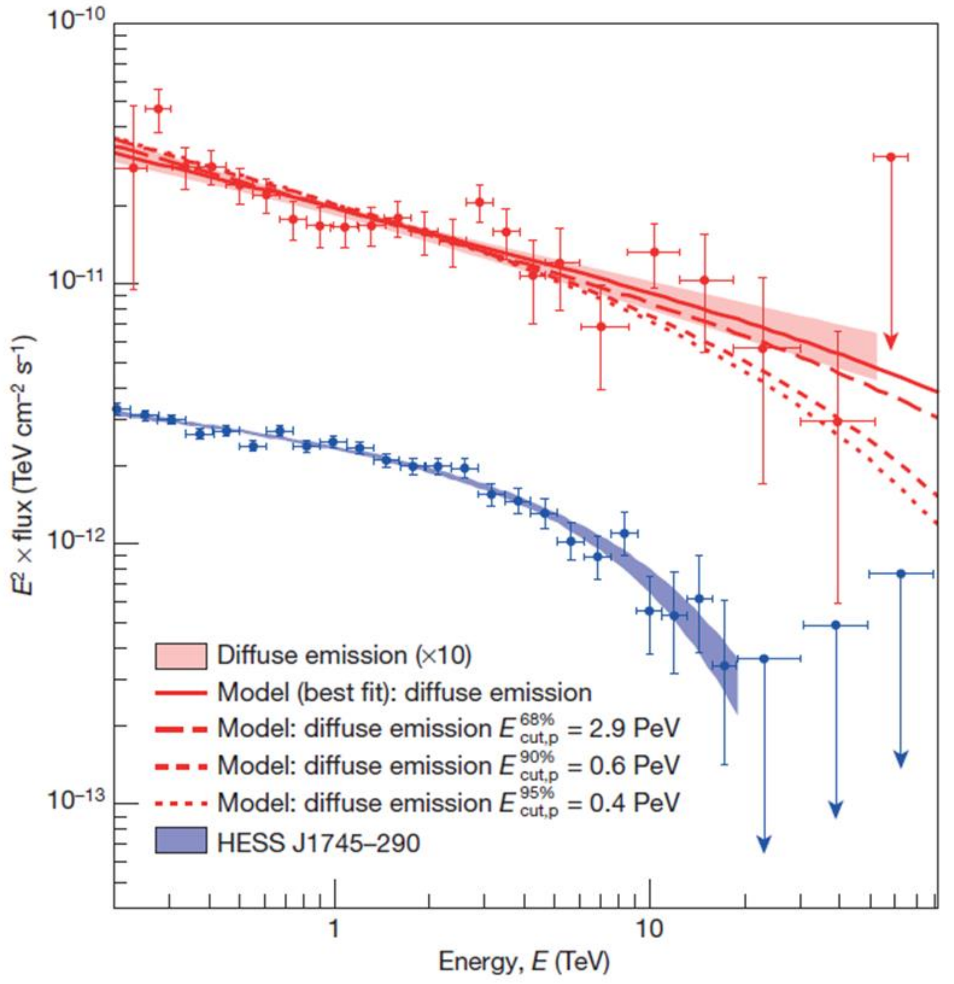
$$t_{pp} \gg t_{pe} \gg t_{ee} \gg t_{acc},$$

meaning that the accreting plasma is "collisionless"

Non-thermal emission



(Yuan et al., 2003)



(HESS Collaboration, 2016)

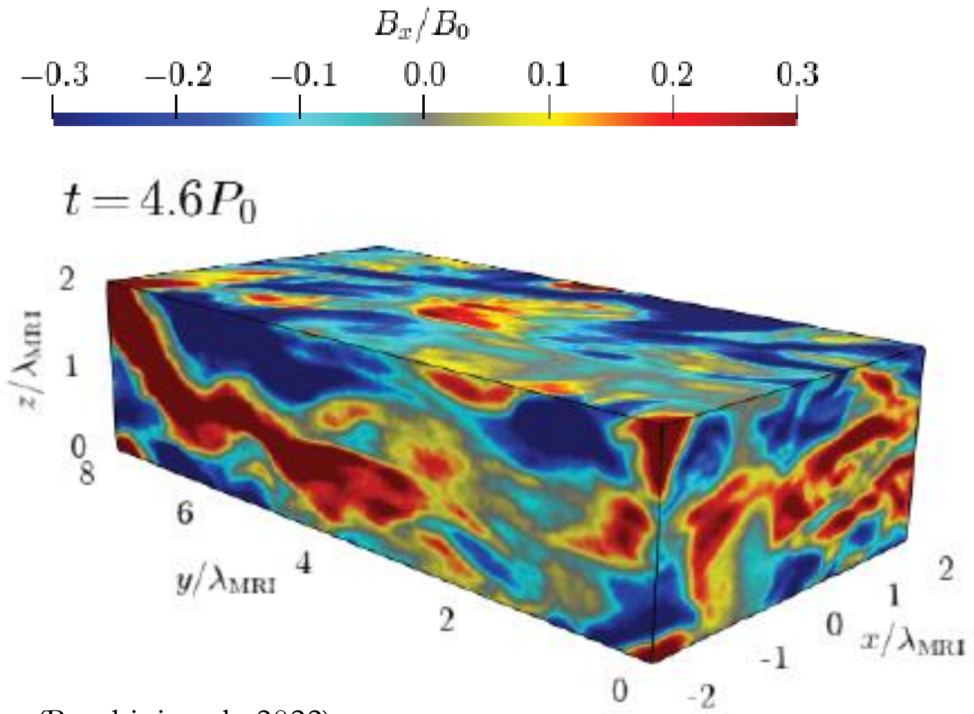
MRI: what has been done?

Local shearing box approximation.

- Previous studies consider homogeneous plasma simulations.
- Simulation box corotate with a piece of accretion disk.
- From the corotational point of view, the plasma have a shear like velocity profile.

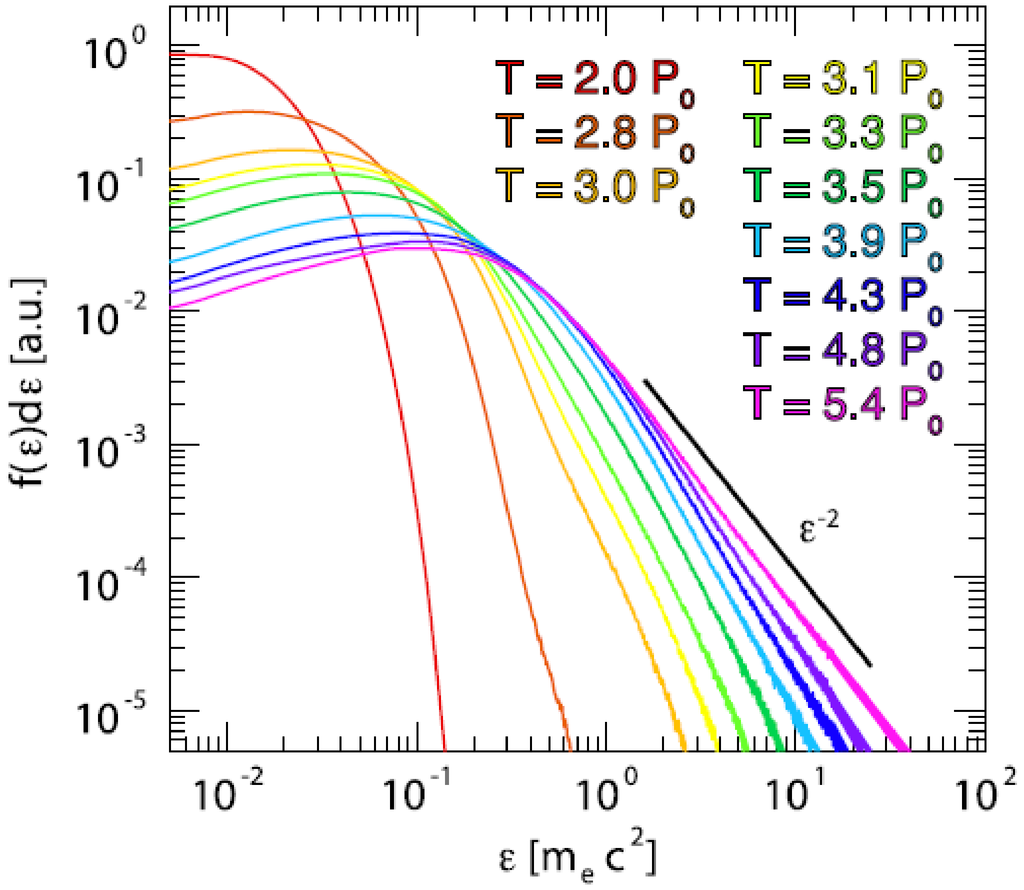
- (Riquelme et al., 2012; Hoshino, 2013, 2015; Kunz et al., 2016; Inchingolo et al., 2018, Bacchini et al., 2022)

Collisionless scenario



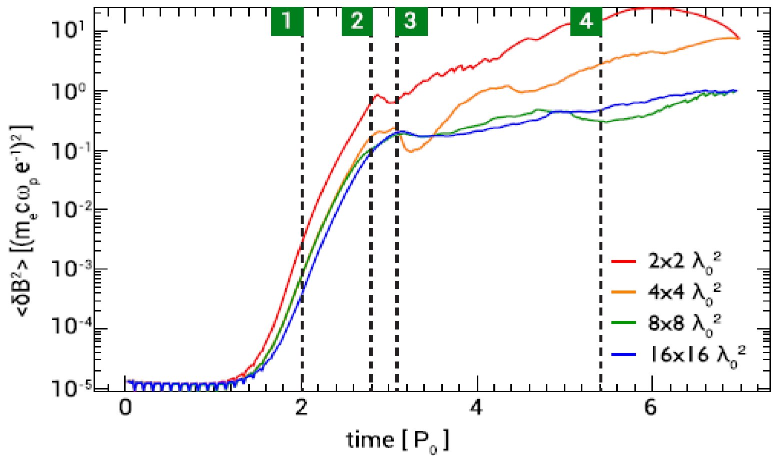
(Bacchini et al., 2022)

MRI with PIC: what has been done?



(Inchingolo et al., 2018)

- Particle acceleration consistent with previous Magnetic Reconnection studies (Werner et al., 2016.)
- However, the existence of MRI turbulence depends on box size plasma.



$$H \sim \frac{v_{th}}{\Omega_0} \sim \sqrt{\beta}\frac{v_A}{\Omega_0} \sim \sqrt{\beta}\lambda_0,$$

where $\beta \equiv \dfrac{P}{B^2/8\pi}$

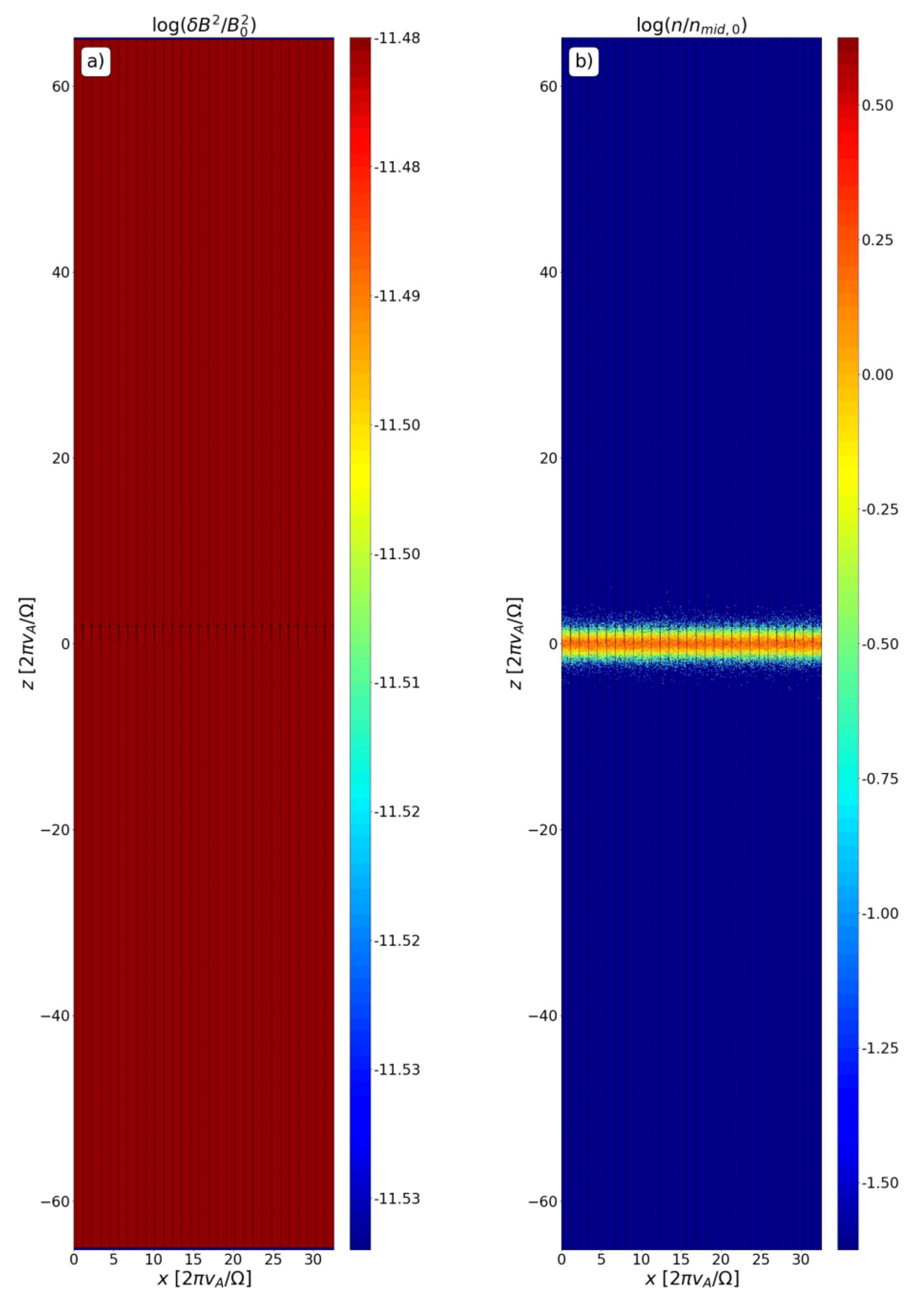
MRI with PIC: what we are doing

- **Stratification effects.**
- Sub-relativistic regime $\left(\frac{k_B T}{m_i c^2} < 1\right)$,relevant for accretion disk around black holes.
- Starting point: pair plasma simulations $(m_i = m_e)$.
  - Relevant for ion dynamic.
- Starting point: 2D simulations.
- Low cyclotron frequency to rotation frequency $\left(\frac{\omega_c}{\Omega_0} = 7 - 20\right)$.
  - Realistic expected values range $\frac{\omega_c}{\Omega_0} \approx 10^8 - 10^{12}$, for Sgr A* and M87 at $R \approx 10\ R_s$.

Current Work

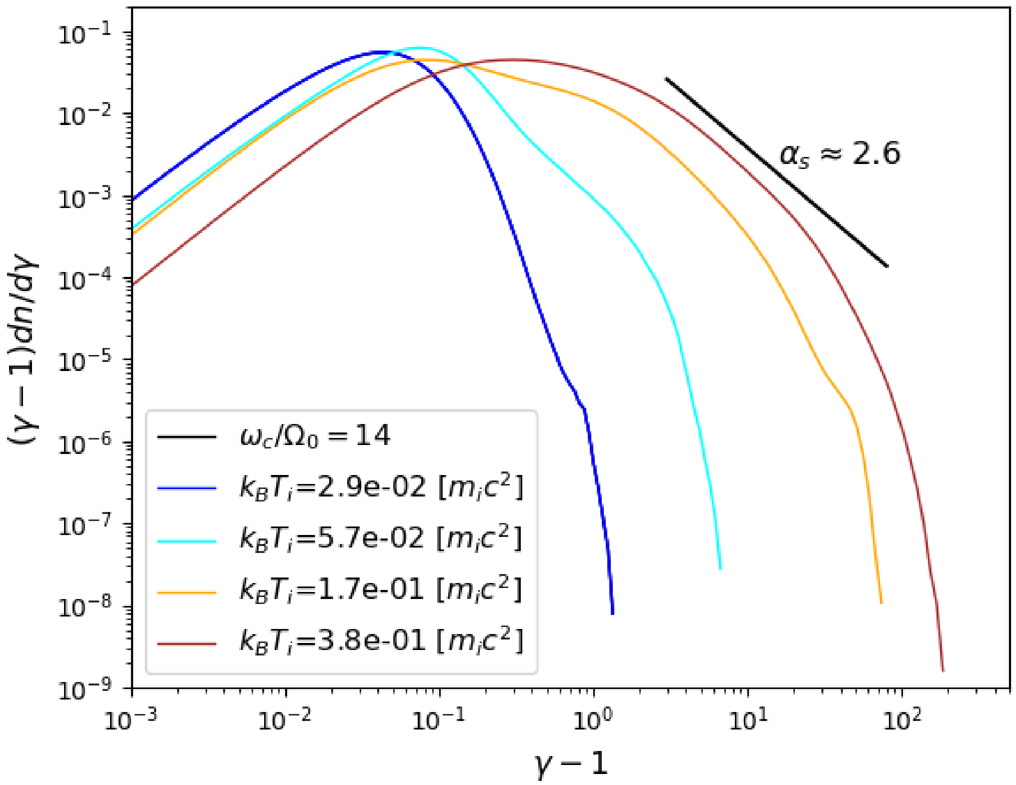
- 2D Stratified simulations.
- Open boundary conditions.
- Plasma initialized as isothermal disk in hydrodynamical equilibrium.
- Uniform vertical magnetic field.
  - The Instability starts in the disk.
  - The disk like structure is sustained during the simulation.

$$H \sim \sqrt{2k_B T / m_i \Omega_0^2}$$

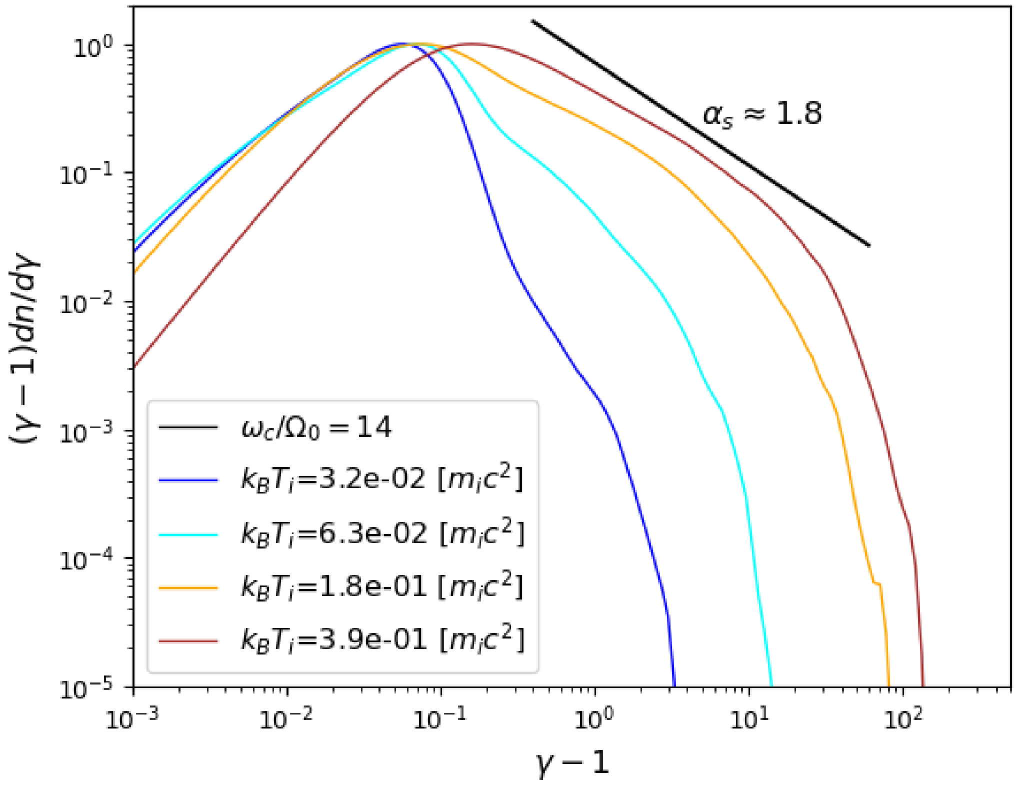


Particle acceleration

Unstratified simulations



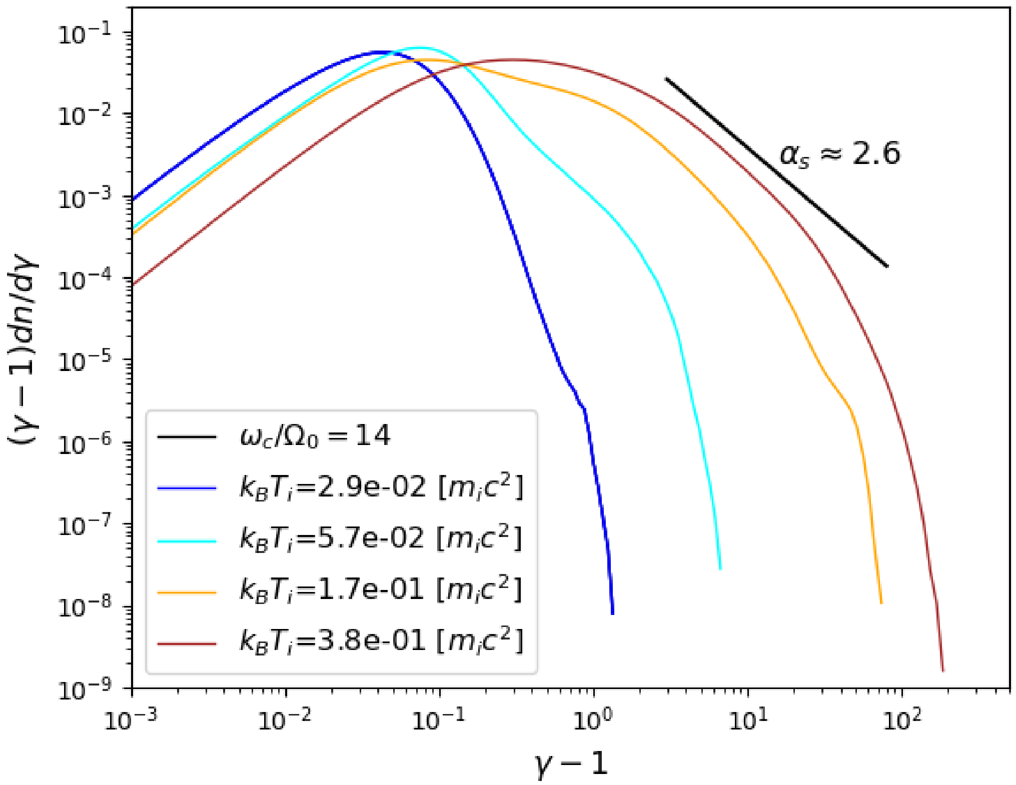
Stratified simulations



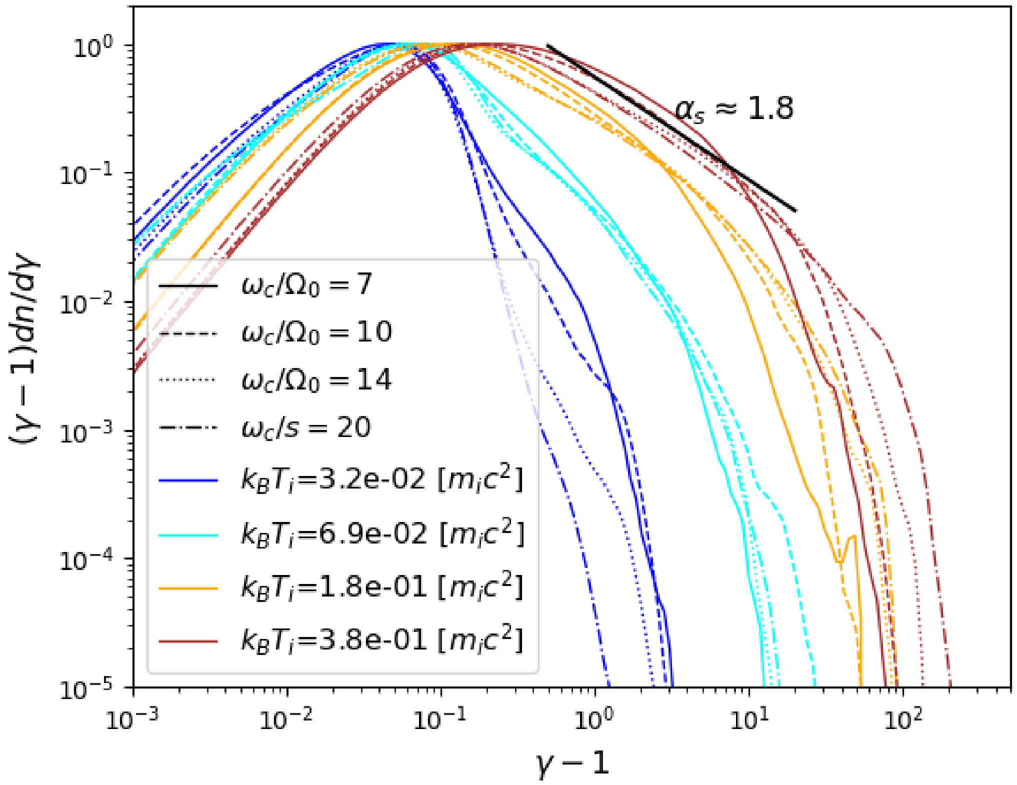
$$\frac{\omega_c}{\Omega_0} = \frac{qB_0}{m_i c \Omega_0}$$

Particle acceleration

Unstratified simulations



Stratified simulations



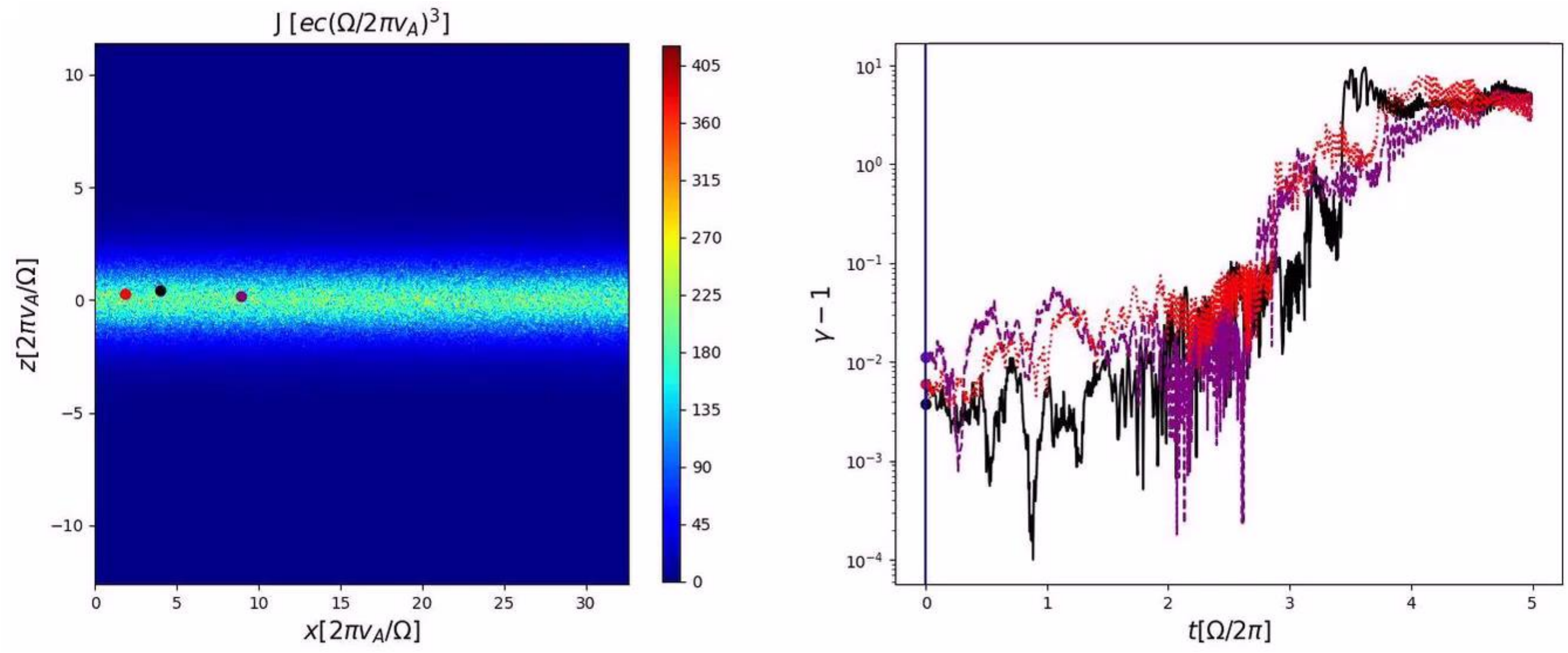
$$\gamma_{max} \propto \frac{\omega_c}{\Omega_0} \propto \frac{eBL}{mc^2}\frac{E^2}{B^2}$$

(Larrabee et al., 2003)

$$\frac{\omega_c}{\Omega_0} = \frac{qB_0}{m_i c \Omega_0}$$

L: length scale of the magnetic field.

Accelerated Particles Orbits



Conclusions

- The inclusion of stratification modifies the development of the MRI in several ways:
  - It allows the expansion of the disk as the plasma gets heated.
  - It allows magnetic flux to abandon the disk.
  - It distinguishes the disk midplane from the corona.
  - Particle acceleration is more efficient than in the unstratified situation.

Next steps

- Run a 3D simulation to explore the effect of using 2D simulation.
- Relax the $m_i/m_e = 1$ assumption by using moderate values of m_i/m_e.
- Study the effect of the initial $\beta = \frac{P}{B^2/8\pi}$.

Thanks!