Magnetic suppression of corotational instabilities in thick accretion disks

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Accretion disks

- Accretion on compact objects is the central engine that powers up a list of astrophysical systems (AGNs, GRBs, X-Ray Binaries, etc...).
- It occurs almost always through a disk (conservation of angular momentum).
- Accretion $\Rightarrow$ transport of angular momentum outwards $\Rightarrow$ local shear stress.
- e.g. Accretion disk standard model (Shakura and Sunyaev, 1973)

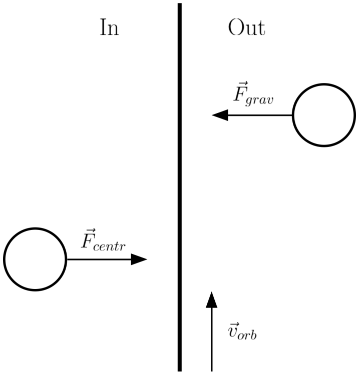
$$T_{r\phi} = \alpha_{\rm disk} P$$

Hydrodynamic disks

- Hydrodynamic disks are remarkably stable!
- Balance between gravitational pull and centrifugal forces $\Rightarrow$ epicyclic oscillations.
- Local stability criterion (Rayleigh):

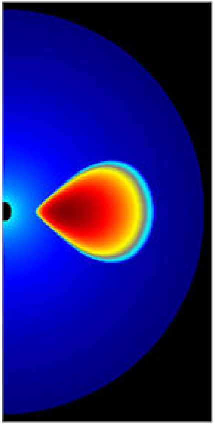
$$\frac{d(R^4\Omega^2)}{dR} > 0$$

- How is accretion triggered? What determines α?



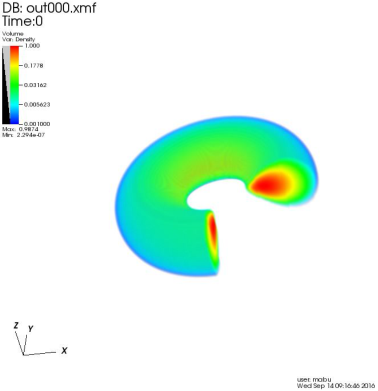
Thick disks

- Significant pressure gradients $\Rightarrow$ disk supported not just by rotation.
- Sub-Keplerian angular momentum distribution, thicker and hotter than standard-model.
- Used to model accretion flows close to the black hole event horizon.
- Locally stable, but unstable to global non-axisymmetric perturbation!



(Gammie et al., 2003)

Papaloizou-Pringle instability (PPI)



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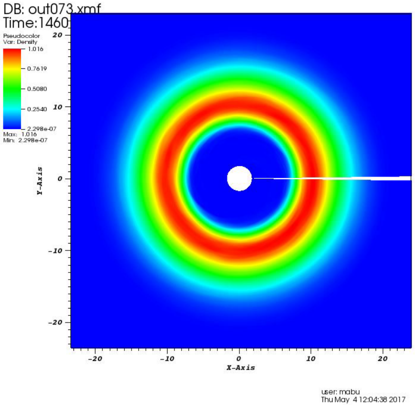
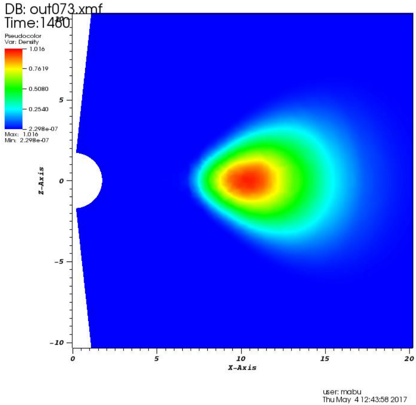
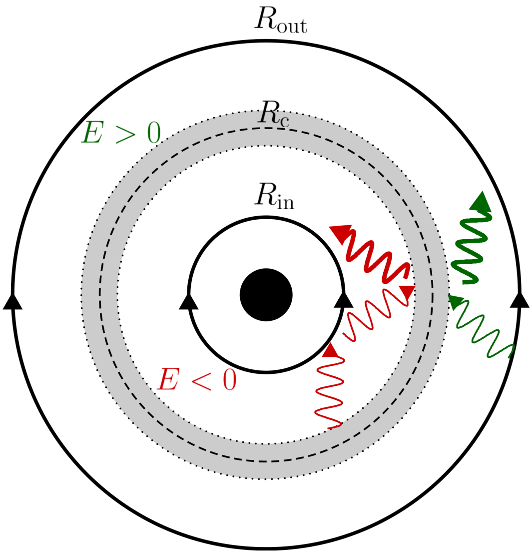




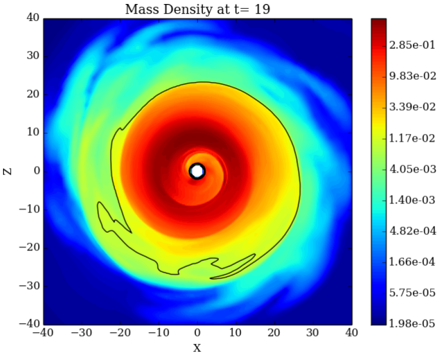
The core mechanism: corotation resonance



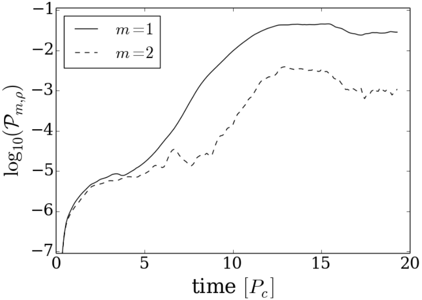
- $E < 0$: slower than the medium
- $E > 0$: faster than the medium
- $E = 0$: corotating with the medium

Papaloizou-Pringle instability (PPI)

- Constant-l tori are most susceptible to develop PPI (De Villiers and Hawley, 2002; Mewes et al., 2016).
- Redistribution of angular momentum ($q_{\rm sat} \sim \sqrt{3}$), GW emission (Kiuchi et al., 2011).
- The $m =: k_\phi R = 1$ is the fastest growing mode $\Rightarrow$ need for the whole azimuthal range $[0, 2\pi]$.



$$\mathcal{P}_{m,\rho} = \left\| \frac{1}{2\pi} \int_0^{2\pi} \rho e^{im\phi} \mathrm{d}\phi \right\|^2$$



Magnetorotational instability

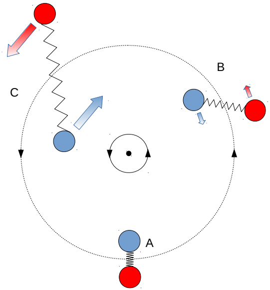
- Disks are hydrodynamically stable by the *Rayleigh stability criterion*

$$\frac{d(R^4\Omega^2)}{dR} > 0$$

- But they are MHD unstable when (Balbus and Hawley, 1998)

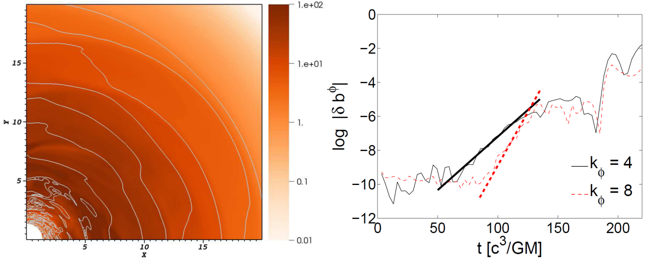
$$\frac{d(\Omega^2)}{dR} < 0$$

- Local instability
- Linear instability (normal mode analysis)
- Independent of field strength and orientation
- Grows on dynamical time scales



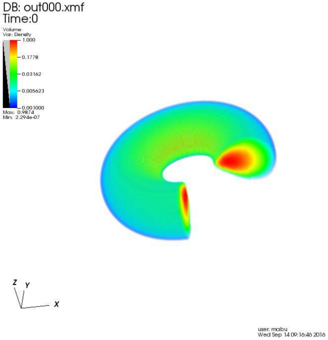
Non-axisymmetric MRI

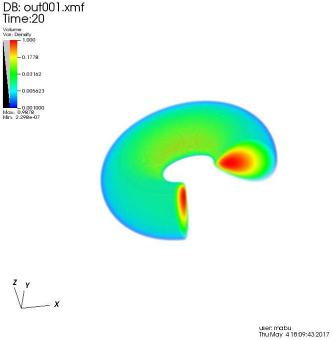
- Strong toroidal magnetic field shown to trigger MRI in global simulations (Wielgus et al., 2015):



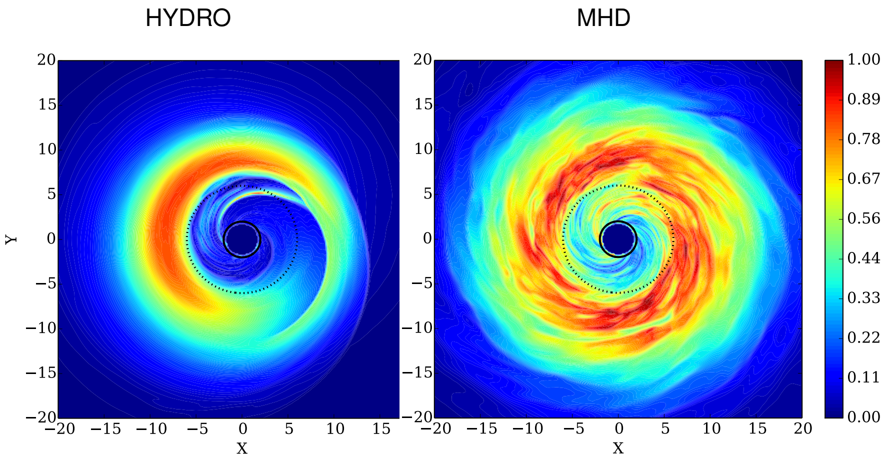
- How do PPI and MRI interact in a global simulation with $\phi \in [0, 2\pi]$?

Magnetized torus

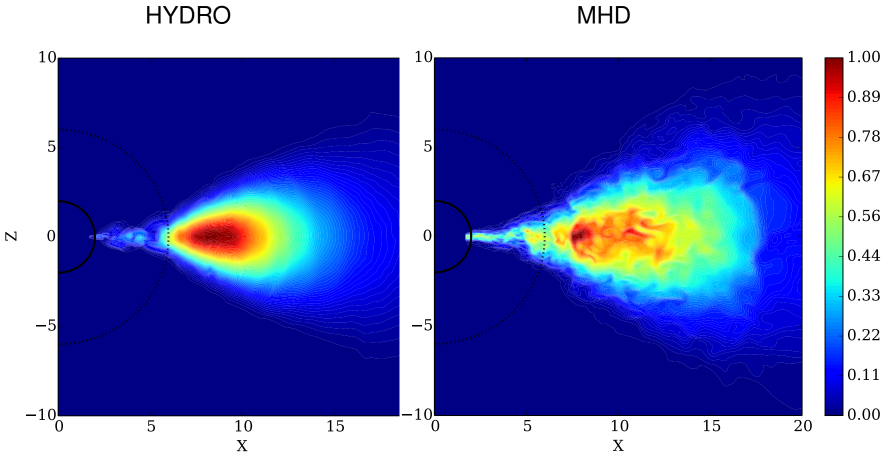




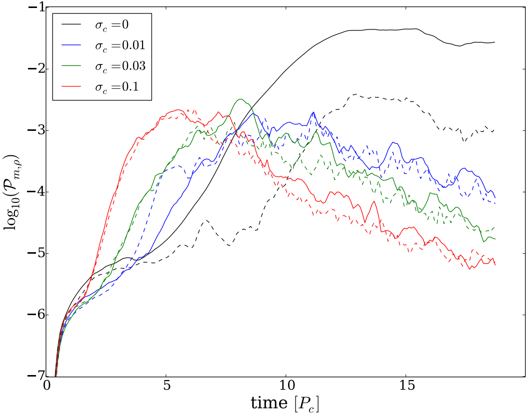
Equatorial density slices



Meridional density slices

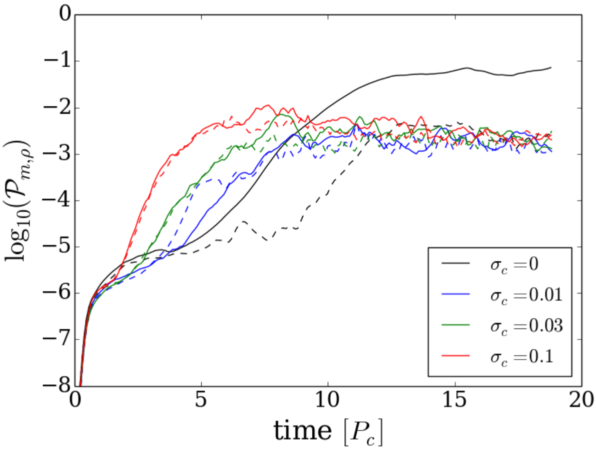


Azimuthal modes power



- Solid $\Rightarrow m = 1$
- Dashed $\Rightarrow m = 2$
- P_c: central orbital period
- σ_c: central magnetization

Azimuthal modes power



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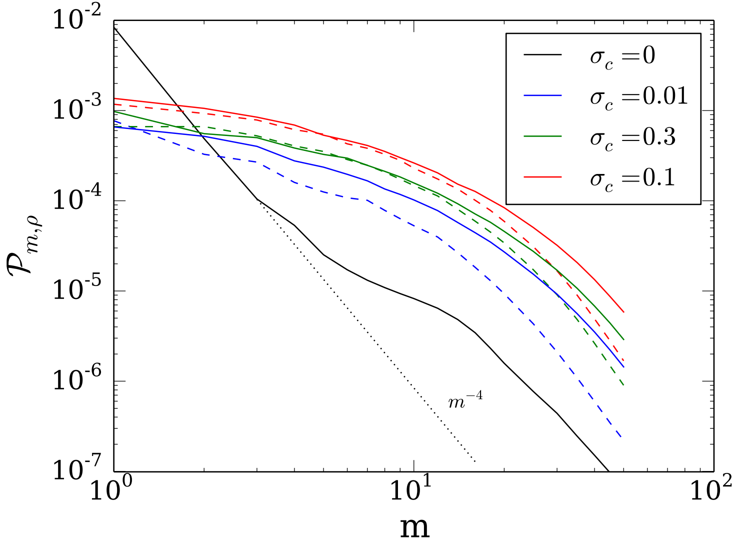
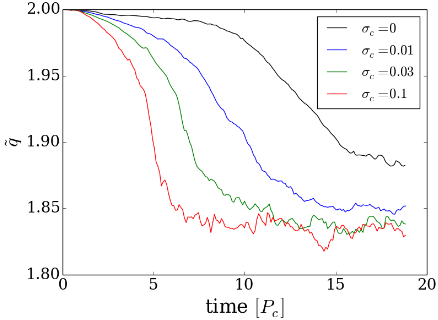
Density Spectrum



What is preventing the growth of the PPI?

Previous popular explanations in literature (Hawley, 2000):

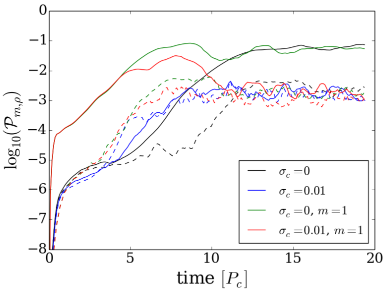
- MRI triggers early accretion in the disk $\Rightarrow$ loss of internal reflective boundary $\Rightarrow$ negative-energy waves are advected.
- MRI transports angular momentum outwards $\Rightarrow$ the disk is led to a PPI stable configuration.

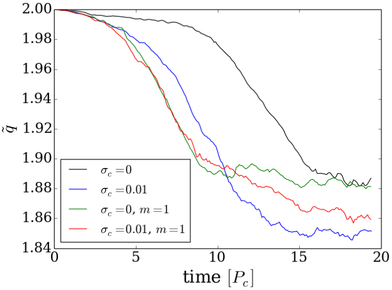


- Angular velocity: $\Omega \propto R^{-\tilde{q}}$
- $2 < \tilde{q} < \sqrt{3}$

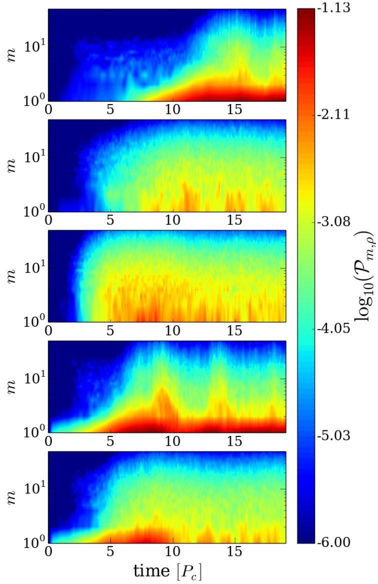
What if the PPI has an initial "upper hand"?

- Initial $m = 1$ perturbation in the orbital velocity
- Transient growth of the PPI, then the $m = 1$ mode is damped
- No clear deviation in the angular momentum profile!





Spectrograms

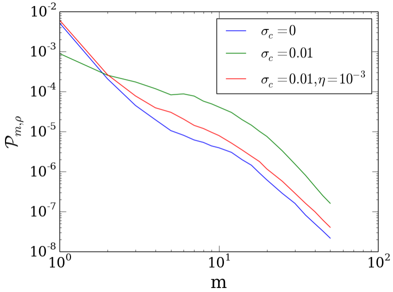


- The $m = 1$ mode couples with higher order modes excited by the MRI
- Energy is transferred to smaller scales
- The final state is independent of the initial perturbation

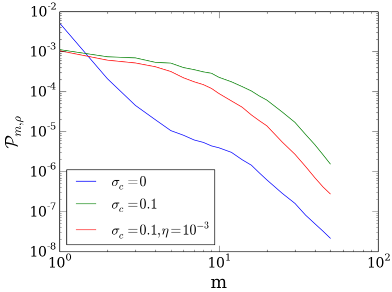

MRI
PPI

An aid for PPI: Magnetic Dissipation

- Turbulent resistivity (η) can weaken the action of MRI.
- In resistive GRMHD (Palenzuela et al., 2009), preliminary simulations show a revival of the PPI.



Low magnetization



High magnetization


PPI
MRI

Summary

PPI vs. MRI (Bugli et al., 2017)

- General suppression of the $m = 1$ mode selected by PPI.
- Possible transient growth of the PPI, followed by a damping due to the coupling with higher order modes.
- Magnetic diffusion could allow for a significant growth of the $m = 1$ mode.

Current and Future Developments

- Test more general magnetized equilibrium solutions (Gimeno-Soler and Font, 2017).
- Non-trivial prescriptions for turbulent resistivity: non-uniform, time-dependent η.
- Inclusion of the disk's self-gravity could significantly affect the suppression of PPI (Mewes et al., 2016).
- Computation of GW signatures of the interplay between PPI and MRI (Kiuchi et al., 2011).


Thank you for your attention!

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