PPI vs. MRI in accretion tori: the winner is. . .

Matteo Bugli[1]

Jérôme Guilet[1], Ewald Müller[1], Pedro Montero[1], Luca Del Zanna[2,3], Niccolò Bucciantini[3]

[1]Max Planck Institut für Astrophysik, Garching bei München
[2]Università degli Studi di Firenze, Dipartimento di Fisica e Astronomia
[3]INAF, Osservatorio Astrofisico di Arcetri, Firenze

CoCoNuT Meeting 2016
València, 14th December 2016

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)

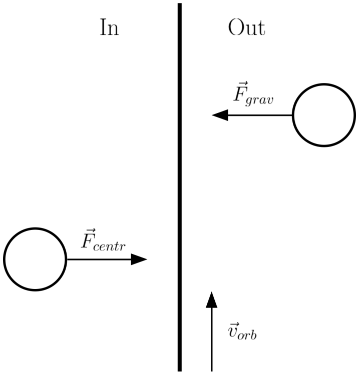
$$T_{r\phi} = \alpha_{\rm disk} P$$

Hydrodynamic disks

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

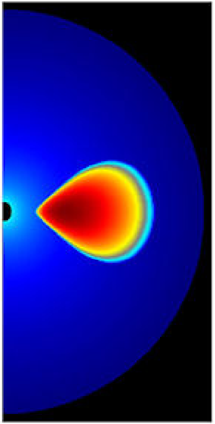
$$\frac{d(R^4\Omega^2)}{dR} > 0$$

- How is accretion triggered? What determines α?



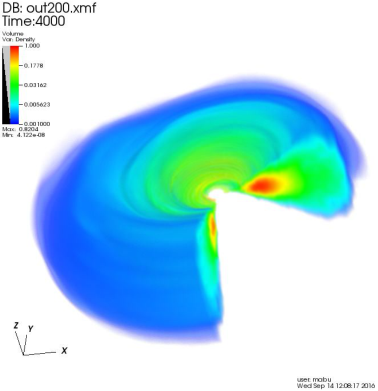
Thick disks

- 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!

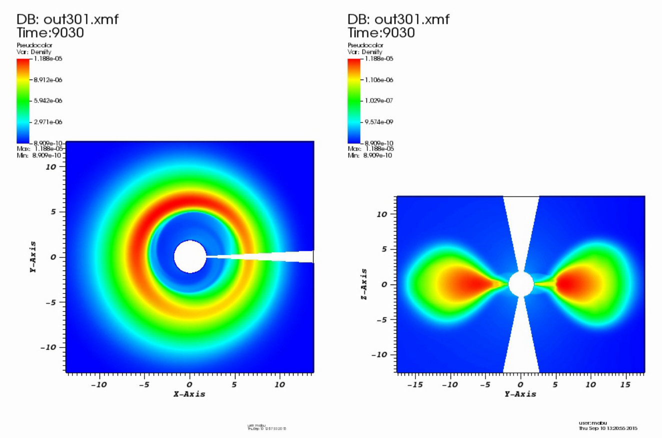


(Gammie et al., 2003)

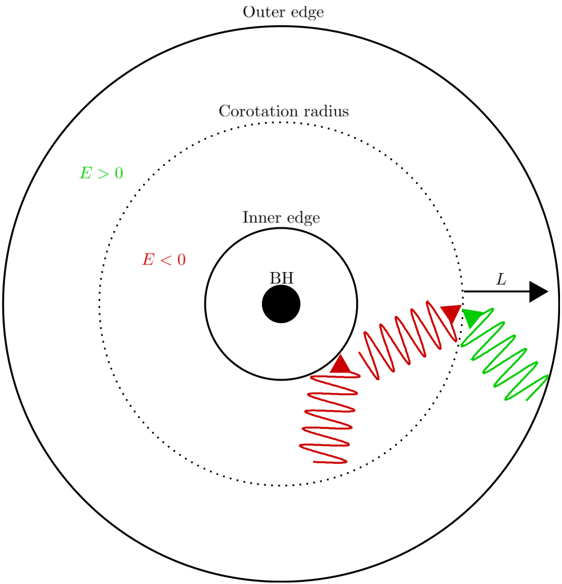
Papaloizou-Pringle instability



Papaloizou-Pringle instability

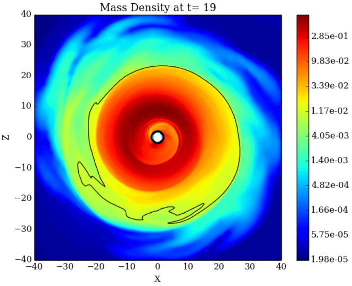


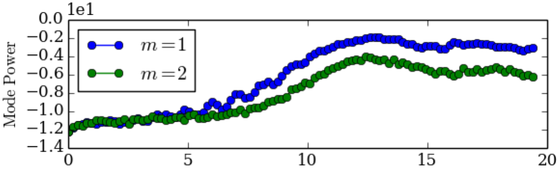
Papaloizou-Pringle instability



Papaloizou-Pringle instability

- Constant-l tori are most susceptible to develop Papaloizou-Pringle instability (PPI) (De Villiers and Hawley, 2002; Mewes et al., 2015).
- 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 $[0, 2\pi]$.





Magnetorotational instability

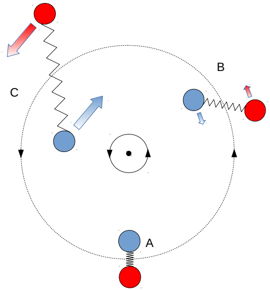
- Disks are hydrodynamically stable by the *Rayleigh stability criterion*

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

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

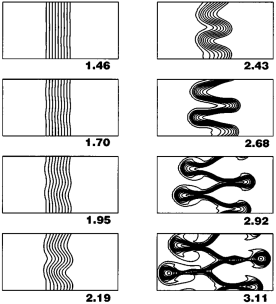
$$\frac{d(\Omega^2)}{dR} < 0$$

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



Channel modes

- Axisymmetric net vertical field ⇒ Channel modes, solution to both linear and non-linear MRI (Balbus and Hawley, 1998):

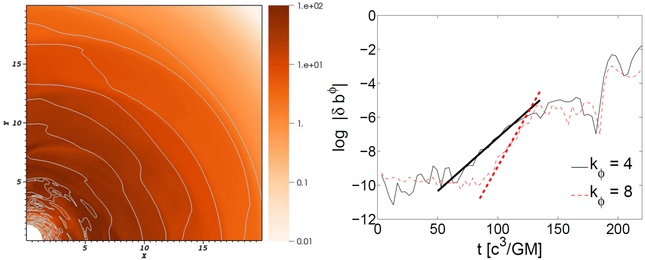


- Observed in both 2D and 3D simulations.
- Fast amplification of magnetic field (dynamo action):

$$\omega_{\rm max} = \frac{3}{4}\Omega \qquad (\boldsymbol{k} \cdot \boldsymbol{u_A})_{\rm max} = \frac{\sqrt{15}}{4}\Omega$$

Non-axissymmetric MRI

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

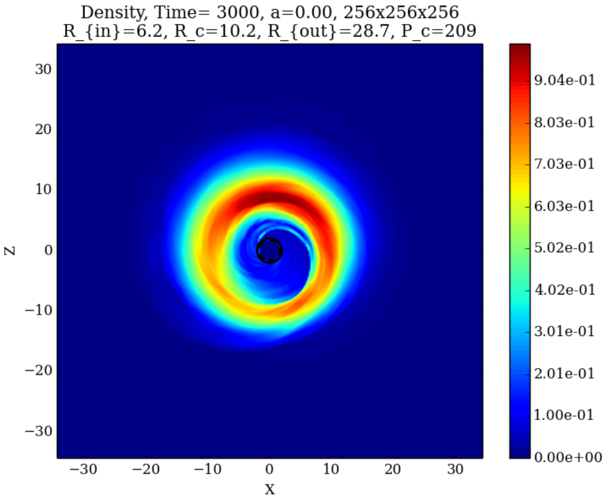


- How do PPI and MRI interact in a global simulation?

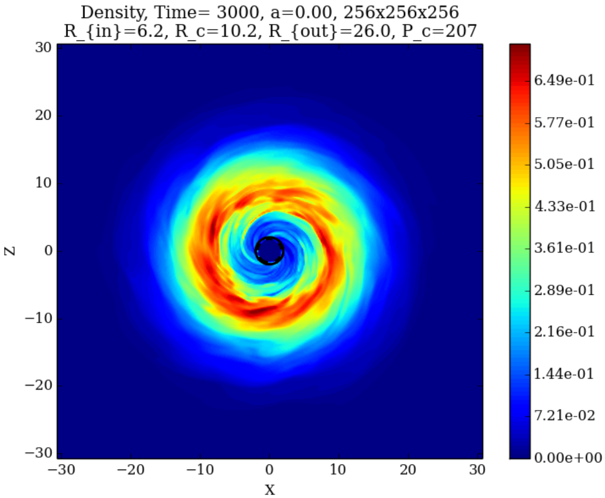
ECHO (Eulerian Conservative High Order) (Del Zanna et al., 2007)

- General relativistic MHD (covariant formulation)
- Finite differences
- Time integration $\Rightarrow$ ImEx Runge-Kutta (up to 3^{rd} order)
- Riemann solver $\Rightarrow$ LLF, HLL, HLLC
- Reconstruction $\Rightarrow$ TVD, CENO, WENO, PPM, MPE
- $\nabla \cdot \boldsymbol{B} = 0 \Rightarrow$ Constrained Transport
- Ideal, resistive, mean-field dynamo closure

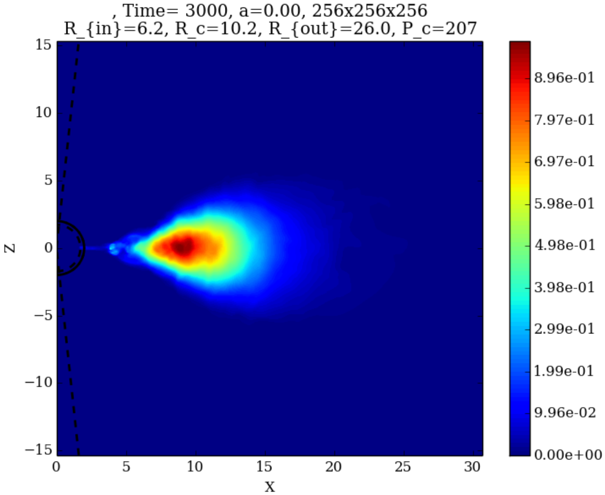
Non-axisymmetric global modes



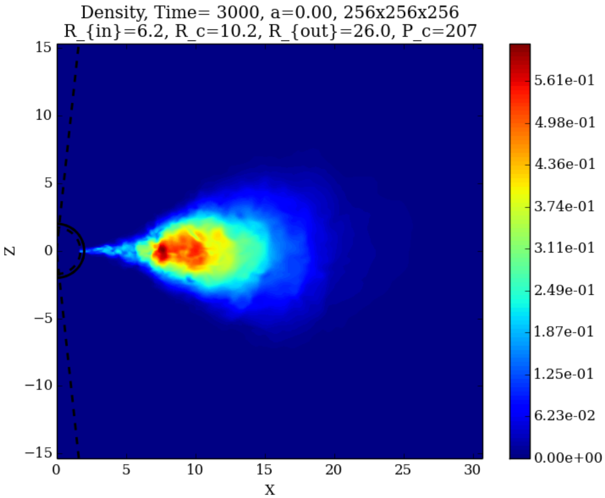
Non-axisymmetric global modes



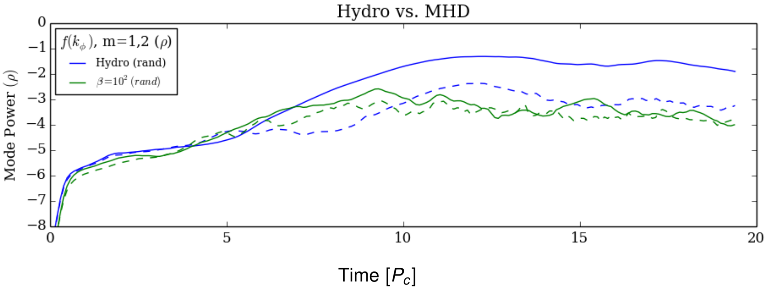
Non-axisymmetric global modes



Non-axisymmetric global modes

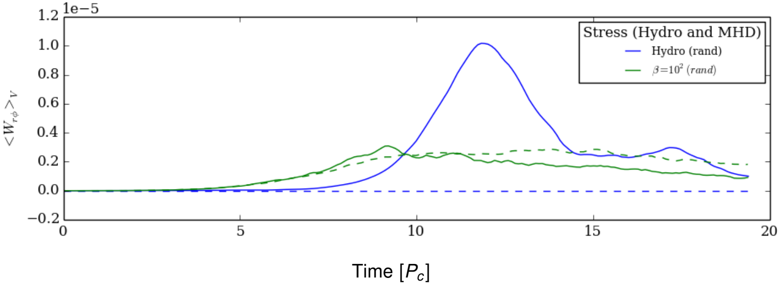


Azimuthal modes power



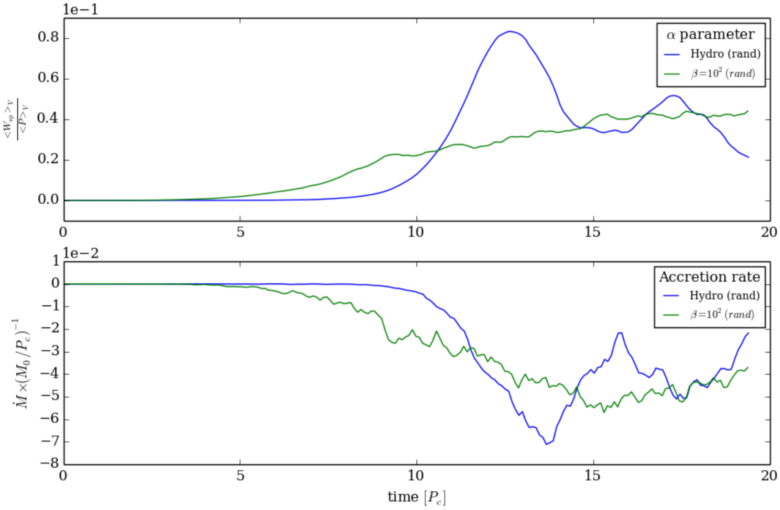
- Solid $\Rightarrow m = 1$
- Dashed $\Rightarrow m = 2$

Azimuthal modes power

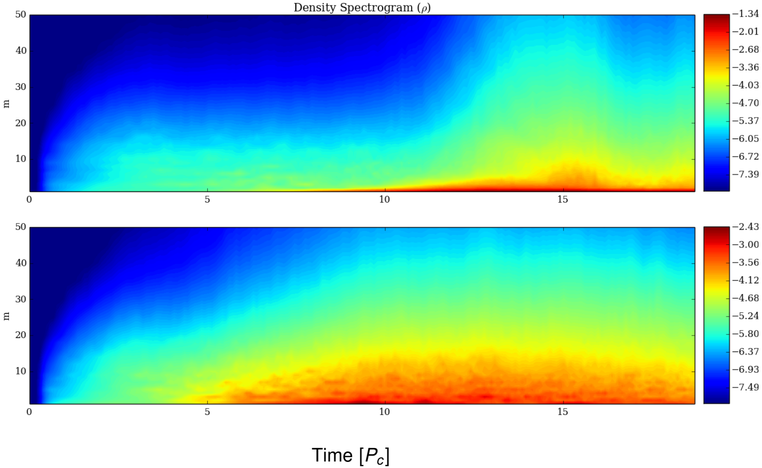


- Solid $\Rightarrow$ Reynolds stress
- Dashed $\Rightarrow$ Maxwell stress

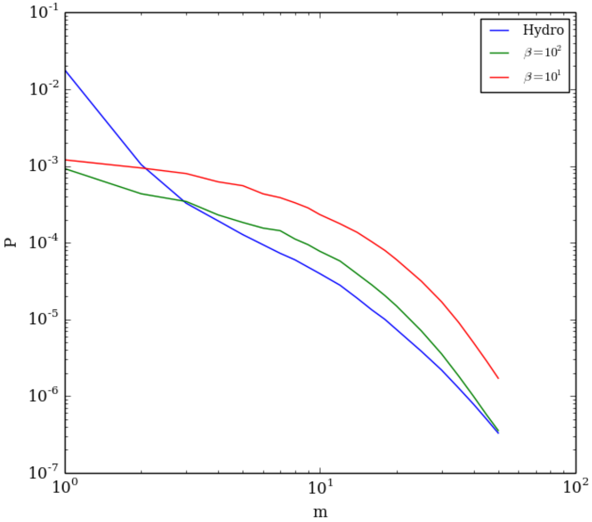
Turbulence and accretion



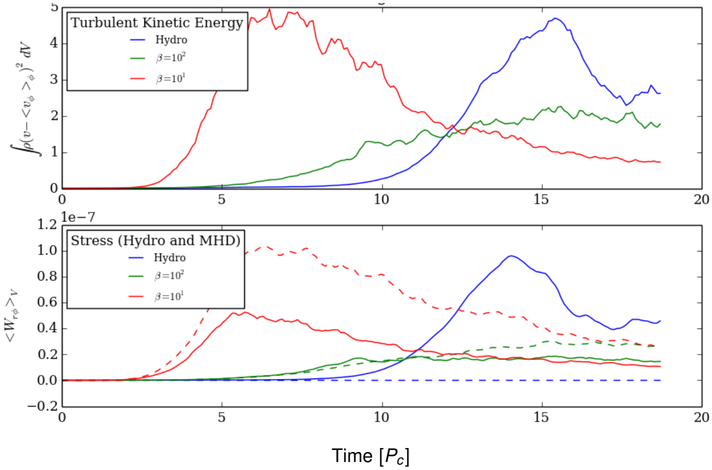
Spectrograms



Density Spectrum

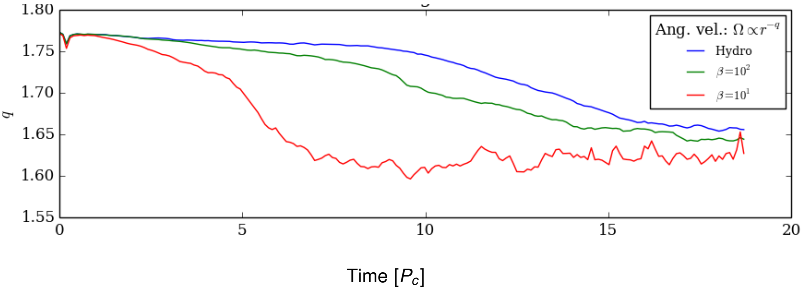


High Magnetization



What is damping the PPI?

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



Is PPI doomed?

- The torus width can play a role: slender tori show faster PPI growth.
- Turbulent resistivity (magnetic dissipation) can weaken the MRI.

Resistive GRMHD (Palenzuela et al., 2009)

$$e^{\mu} = \eta j^{\mu}$$

$$\Gamma[\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} - (\boldsymbol{E} \cdot \boldsymbol{v})\boldsymbol{v}] = \eta(\boldsymbol{J} - q\boldsymbol{v})$$


MRI
PPI

Summary

PPI vs. MRI

- Suppression of the large-scale modes selected by PPI.
- The sooner accretion is triggered, the smaller the power excess at low *m*.
- Early accretion and angular momentum redistribution *conspire* against PPI.

Current and Future Developments

- Explore the disk-parameter space: disk size, BH spin, wide/slender tori.
- Turbulent Resistivity: beyond ideal-MHD the MRI can be quenched $\Rightarrow$ could PPI take its revenge?
- GW signatures of the interplay between PPI and MRI.

References I

Balbus, S. A. and Hawley, J. F. (1998). Instability, turbulence, and enhanced transport in accretion disks. *Reviews of Modern Physics*, 70:1–53.

De Villiers, J.-P. and Hawley, J. F. (2002). Three-dimensional Hydrodynamic Simulations of Accretion Tori in Kerr Spacetimes. *ApJ*, 577:866–879.

Del Zanna, L., Zanotti, O., Bucciantini, N., and Londrillo, P. (2007). ECHO: a Eulerian conservative high-order scheme for general relativistic magnetohydrodynamics and magnetodynamics. *A&A* , 473:11–30.

Gammie, C. F., McKinney, J. C., and Tóth, G. (2003). HARM: A Numerical Scheme for General Relativistic Magnetohydrodynamics. *ApJ*, 589:444–457.

Kiuchi, K., Shibata, M., Montero, P. J., and Font, J. A. (2011). Gravitational Waves from the Papaloizou-Pringle Instability in Black-Hole-Torus Systems. *Physical Review Letters*, 106(25):251102.

References II

Mewes, V., Montero, P. J., Stergioulas, N., Galeazzi, F., and Font, J. A. (2015). General Relativistic Simulations of Accretion Disks Around Tilted Kerr Black Holes. *Astrophysics and Space Science Proceedings*, 40:121.

Palenzuela, C., Lehner, L., Reula, O., and Rezzolla, L. (2009). Beyond ideal MHD: towards a more realistic modelling of relativistic astrophysical plasmas. *MNRAS*, 394:1727–1740.

Shakura, N. I. and Sunyaev, R. A. (1973). Black holes in binary systems. Observational appearance. *A&A* , 24:337–355.

Wielgus, M., Fragile, P. C., Wang, Z., and Wilson, J. (2015). Local stability of strongly magnetized black hole tori. *MNRAS*, 447:3593–3601.