The presence of backflow in the simulated MHD disks

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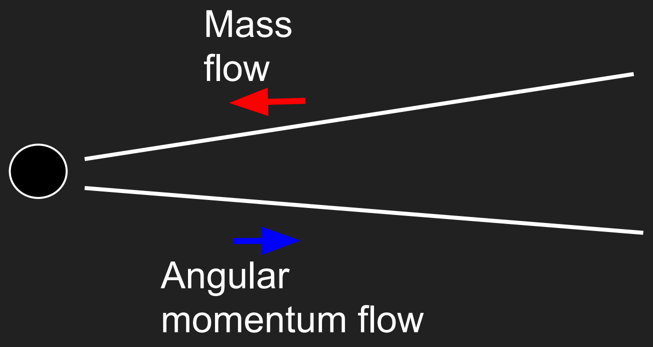
WHY ACCRETION DISKS ARE IMPORTANT

- When matter accretes into a massive object it usually takes the form of a disk.
- Accretion disks are made of rapidly rotating gas which slowly spirals into the central gravitating object.

- Most astronomical objects, such as galaxies, stars and planets, are formed by accretion process.



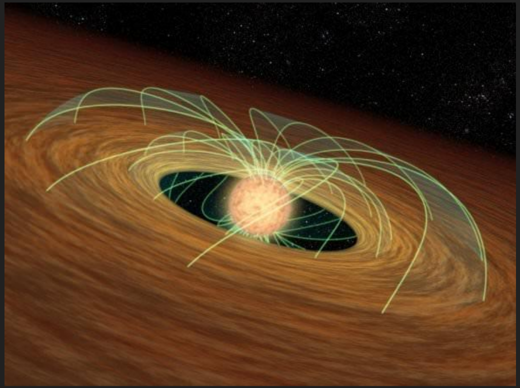
- High angular momentum of the gas is transported outwards by stresses (related to turbulence, viscosity and magnetic field)

- Loss of angular momentum allows matter to slowly move inwards and fall into the central gravitating object.

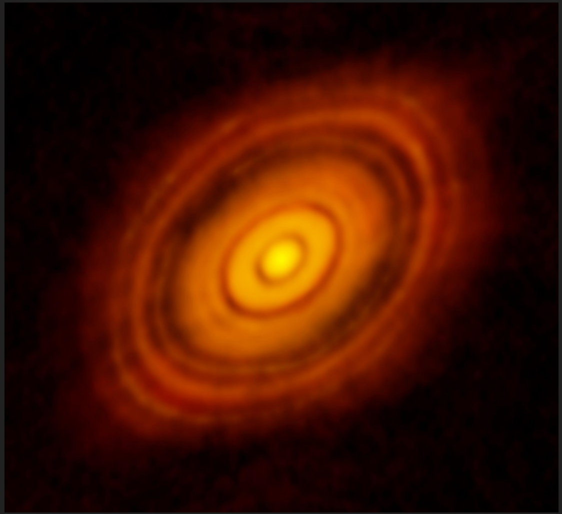
MAGNETIZED STELLAR TYPE OBJECTS

- Magnetized stellar type objects are stars with with magnetic field. (eg : T Tauri protostars, white dwarfs,neutron stars)

- They are often surrounded by accretion disk.



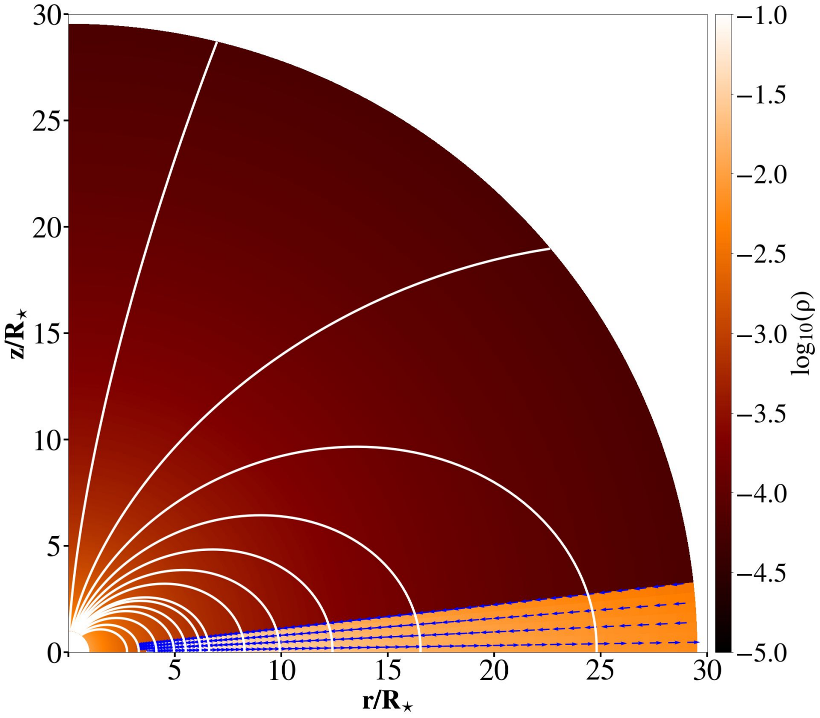
Magnetized star with accretion disk



ALMA image of the HL Tau protoplanetary disk
Marel et. al , 2018

MHD SIMULATIONS

- We perform two dimensional, axisymmetric, non ideal magneto-hydrodynamic simulations of thin accretion disk using the Pluto code.
- A logarithmically stretched grid in the radial direction in the spherical coordinates has been used. The resolution is $R \times \theta = [217 \times 200]$ grid cells for 30 stellar radii.
- For initial conditions we use alpha Keplerian accretion disk of Kluzniak & Kita (2000) and a stellar dipolar magnetic field.



MHD EQUATIONS

$$\frac{\partial \rho}{\partial t} + \nabla . (\rho \vec{v}) = 0$$

Continuity equation

$$\frac{\partial (\rho \vec{v})}{\partial t} + \nabla . \left[\rho \vec{v}\vec{v} + (P + \frac{B^2}{8\pi})\tilde{I} - \frac{\vec{B}\vec{B}}{8\pi} - \tilde{\tau} \right] = \rho g$$

Momentum conservation

$$\frac{\partial E}{\partial t} + \nabla . \left[(E + P + \frac{B^2}{8\pi})\vec{v} - \frac{(\vec{v}.\vec{B})\vec{B}}{4\pi} \right] + \nabla . \left[\eta_m \vec{J} \times \vec{B}/4\pi - \vec{v}.\tilde{\tau} \right] = (\rho g).\vec{v} - \Lambda$$

Energy conservation

$$\frac{\partial \vec{B}}{\partial t} + \nabla \times (\vec{B} \times \vec{v} + \eta_m \vec{J}) = 0$$

Induction equation

Viscous stress tensor

Magnetic resistivity

PARAMETER STUDY

We perform a parameter study by changing the magnetic field strength, resistivity and alpha viscosity for slowly rotating stars.

α_v ➡ Viscosity Parameter ➡ Intensity of viscous torque allowing the disk to accrete

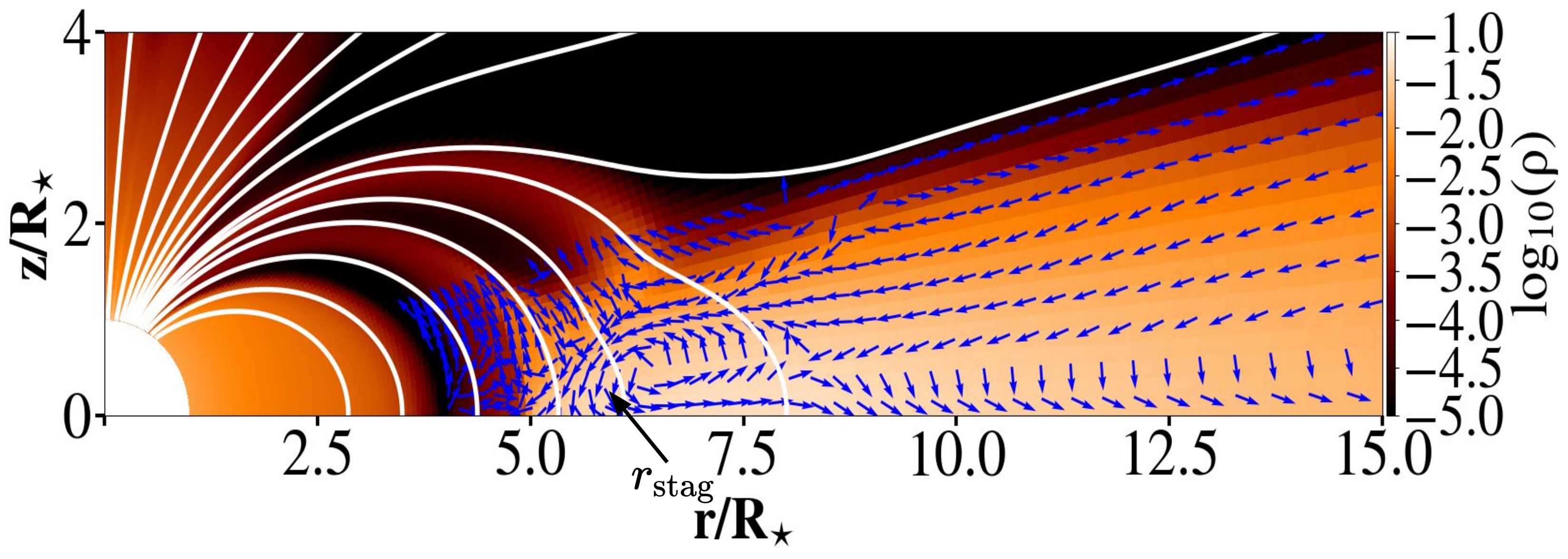
$[\,0, 1\,]$

α_m ➡ Resistivity Parameter ➡ Strength of the coupling of stellar magnetic field with the disk material

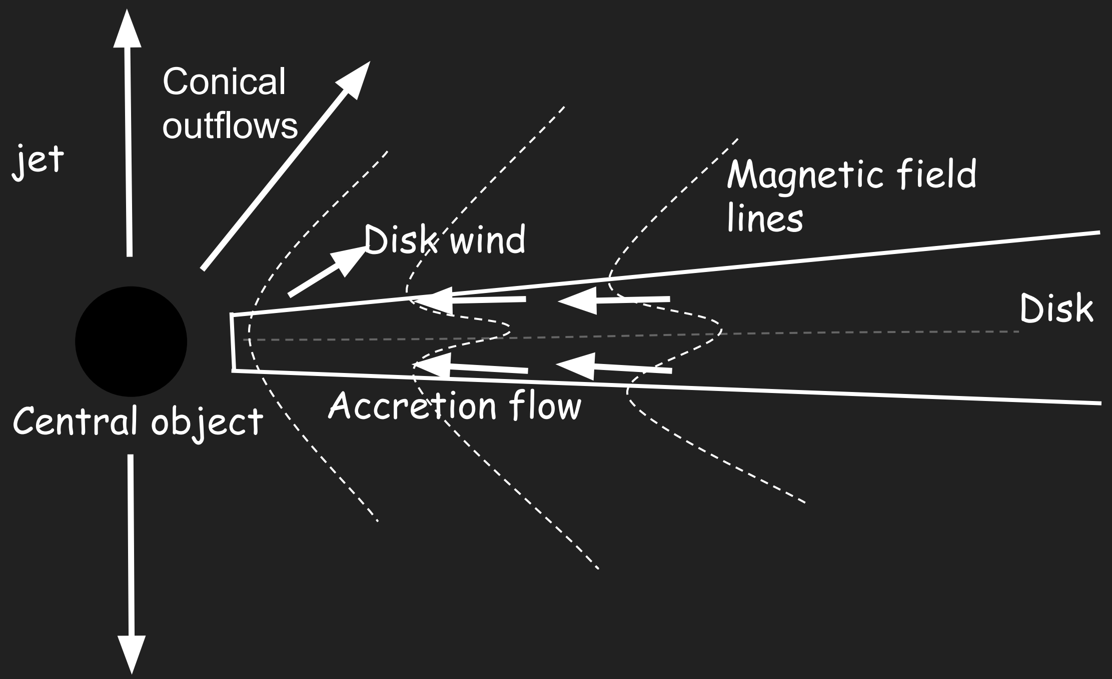
$[\,0, 1\,]$

MHD SIMULATIONS

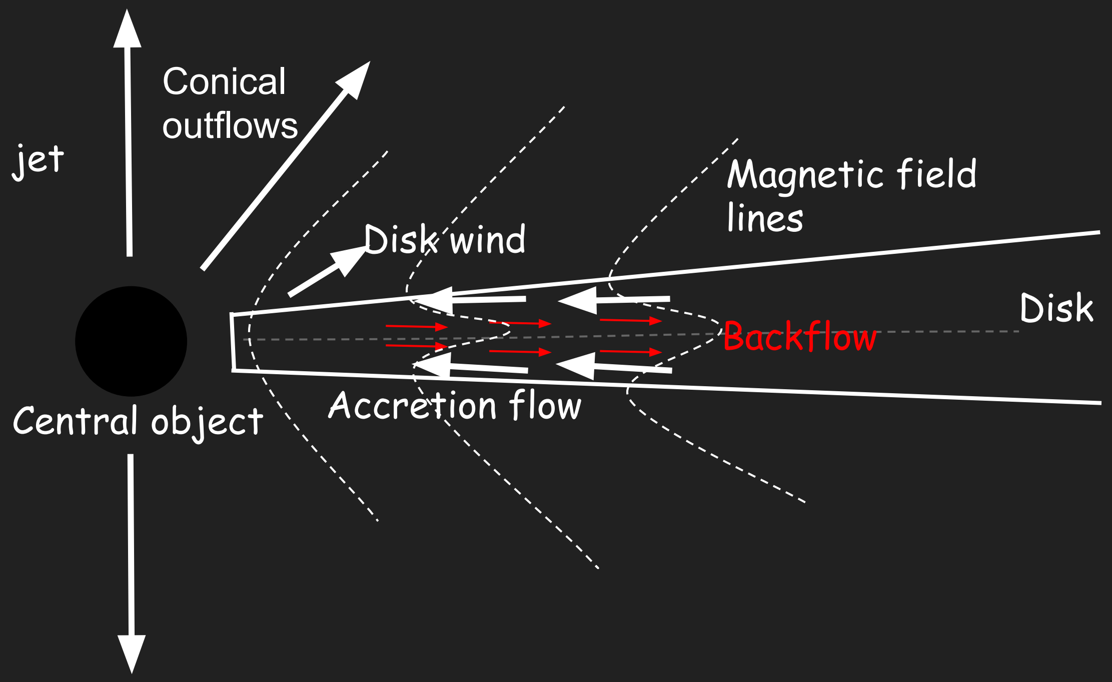
$$\alpha_m = 1, \alpha_v = 0.4, B_\star = 1000G, \Omega_\star/\tilde{\Omega} = 0.1$$



FLOWS IN STAR-DISK SYSTEM

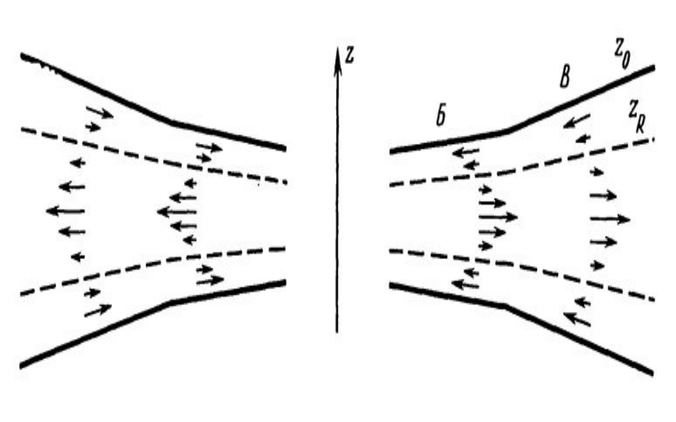


FLOWS IN STAR-DISK SYSTEM



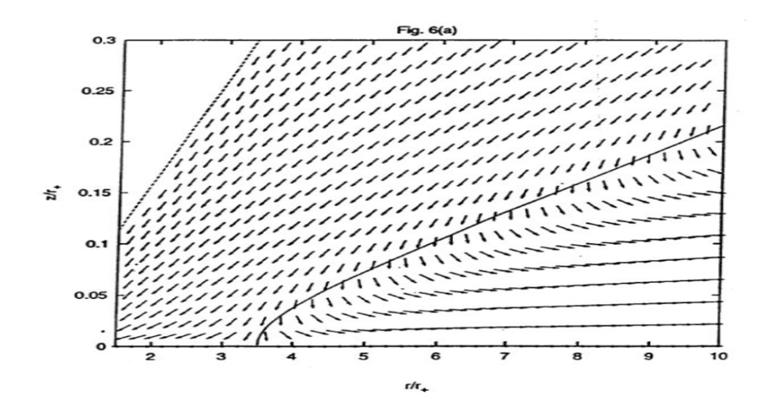
Backflow - Flow of matter, along the midplane of accretion disk, away from accreting object.

BACKFLOW IN THE DISK



Urpin(1984)

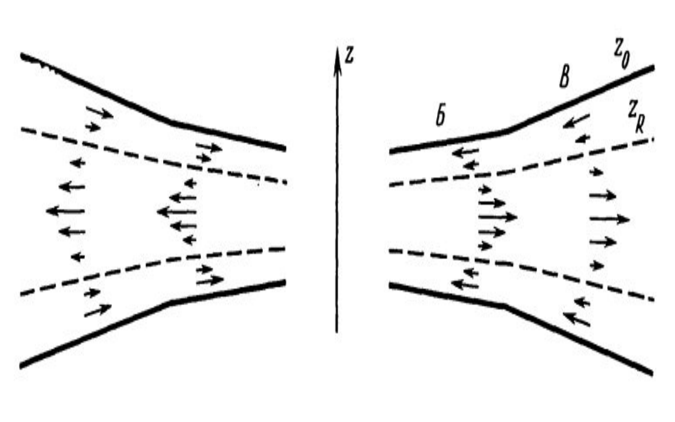
Outflow along the disk midplane for all alpha disks (local calculation)



Kita (1995), Kluźniak & Kita (2000)

Backflow along the disk midplane for alpha viscosity less than a critical value (global calculation)

BACKFLOW IN THE DISK



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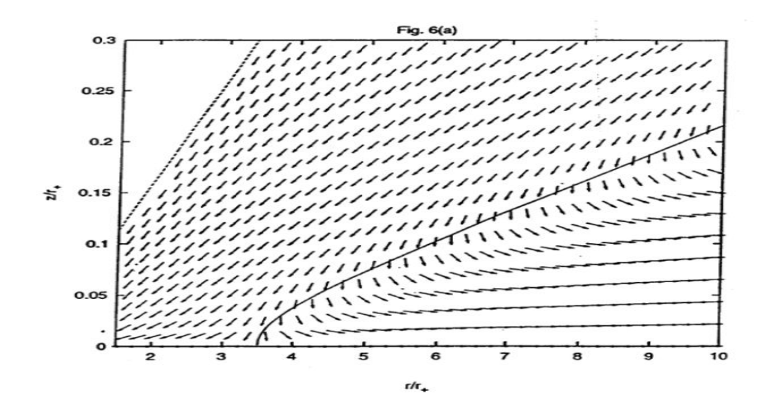


Kita (1995), Kluźniak & Kita (2000)

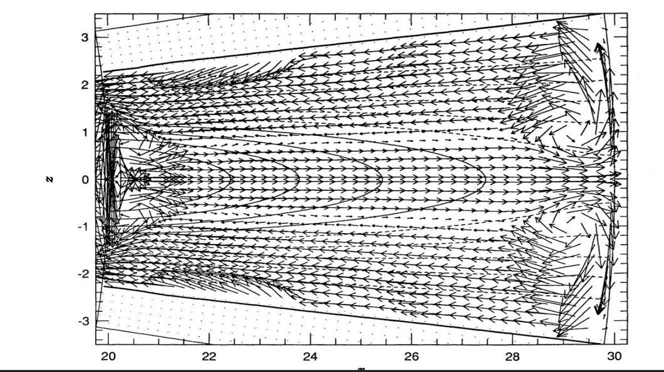
Backflow along the disk midplane for alpha viscosity less than a critical value (global calculation)

A for more details). A not so well known bias of the alpha prescription in 2D flows is that, below a critical value found to be $\alpha_{\rm crit} \sim 0.685$, there is a backflow on the disk midplane (Urpin 1984). This is certainly unphysical and arises only from the functional form of the stress tensor used to mimic turbulence. In order to circumvent this bias, we used $\alpha_{\rm v} = 0.9^2$.

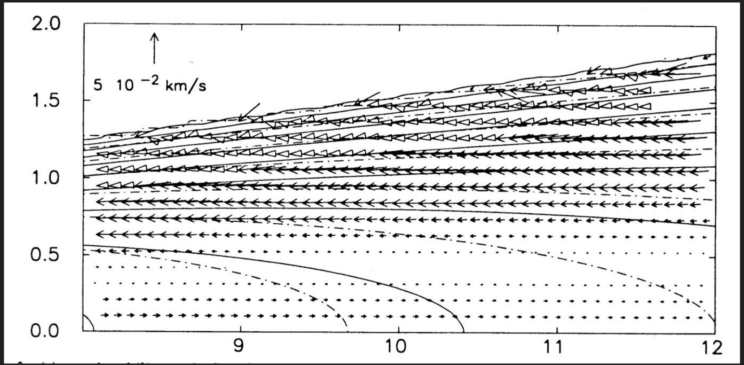
Murphy, Ferreira and Claudio Zanni (2010)

sible to neglect it when deriving the disk equilibrium Eq. (5). We neglected the $\mathcal{T}_{\theta\phi}$ component of the viscous stress tensor in order to avoid the backflow along the disk midplane, most likely unphysical, usually associated with the three-dimensional models of α accretion disks (see e.g., Regev & Gitelman 2002). Consistently, we set $\mathcal{T}_{\theta\phi} = 0$ also during the time-dependent calculations.

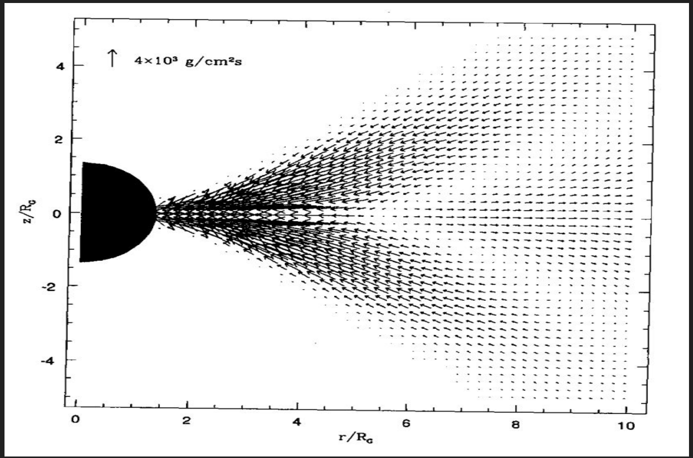
Pantolmos, Zanni and Bouvier (2020)



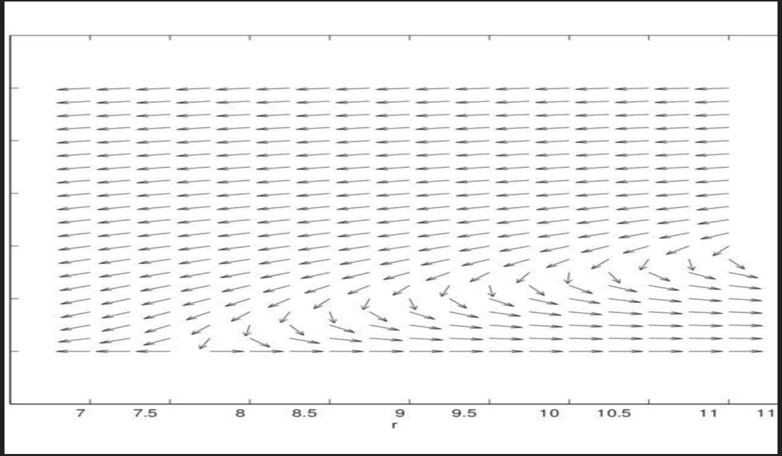
Kley & Lin (1992)



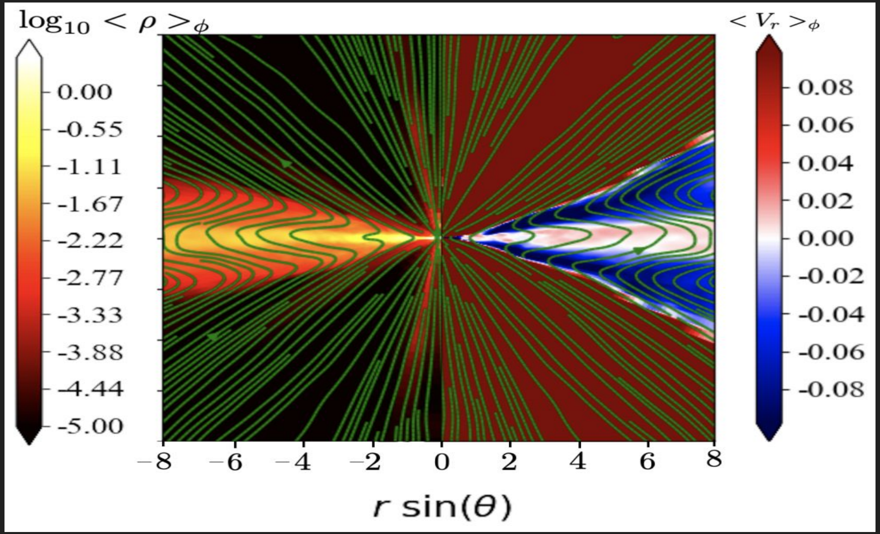
Rozyczka, Bodenheimer & Bell 1994

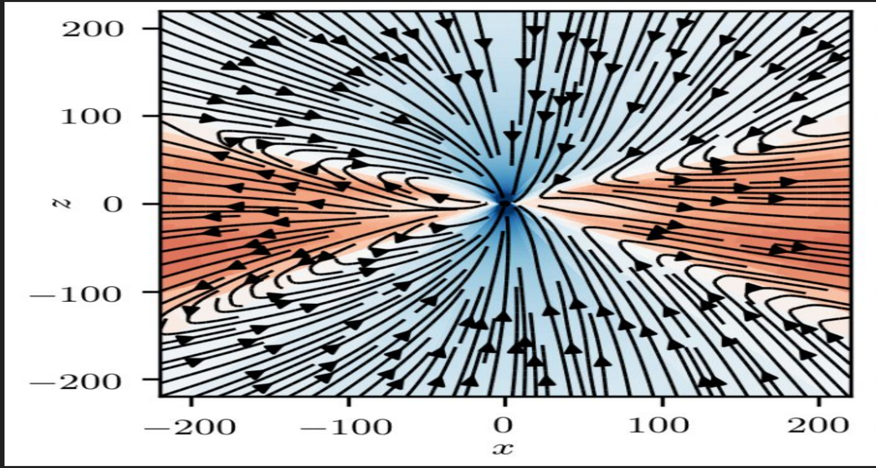


Igumenshchev, Chen and Abramowicz 1995)



, Regev & Gitelman (2002)





Disk midplane outflow in MRI

Mishra et al. (2020)

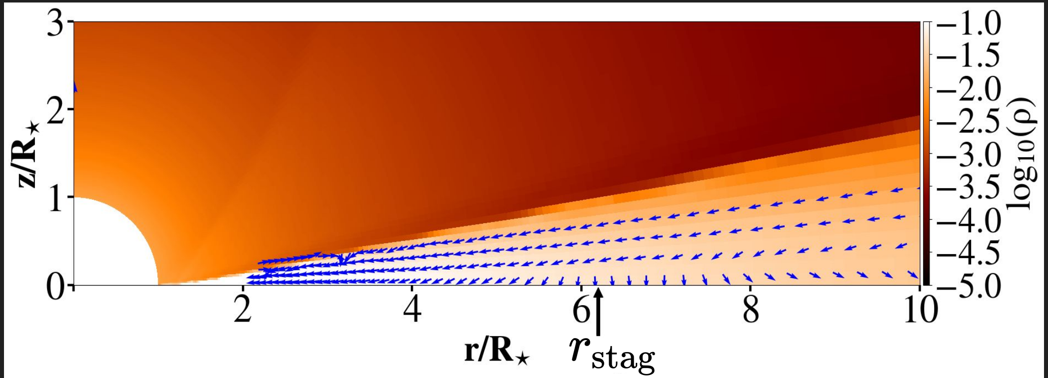
Outflow in the disk in GRMHD simulation of RIAFs

White et al. (2020)

Backflow in HD case

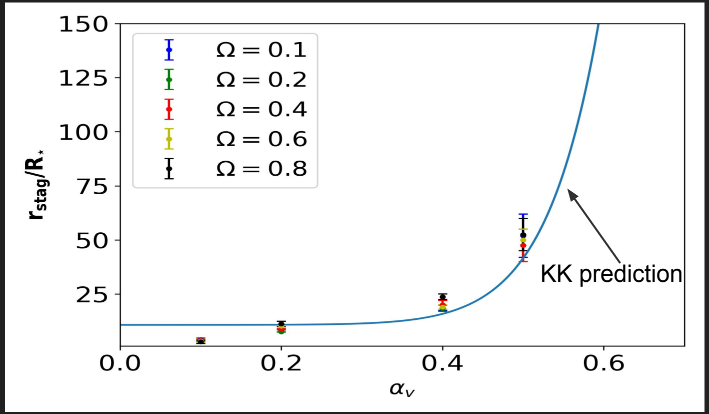
- Full three dimensional analytical solution for a polytropic viscous thin accretion disk was given by Kluzniak & Kita 2000 .
- It showed the presence of backflow in the mid-plane of the disk for values of the α less than some critical value (0.685). The disk is found to accrete only at higher latitudes, towards its surface.
- The distance in the disk where the backflow started, stagnation radius, is found to be a function of viscosity parameter.
- This has been confirmed through hydrodynamical simulation.

Backflow in the hydro disk



Mishra et al. (2020), PTA proc.
arXiv:2006.01851v2

Stagnation Radius vs α_v

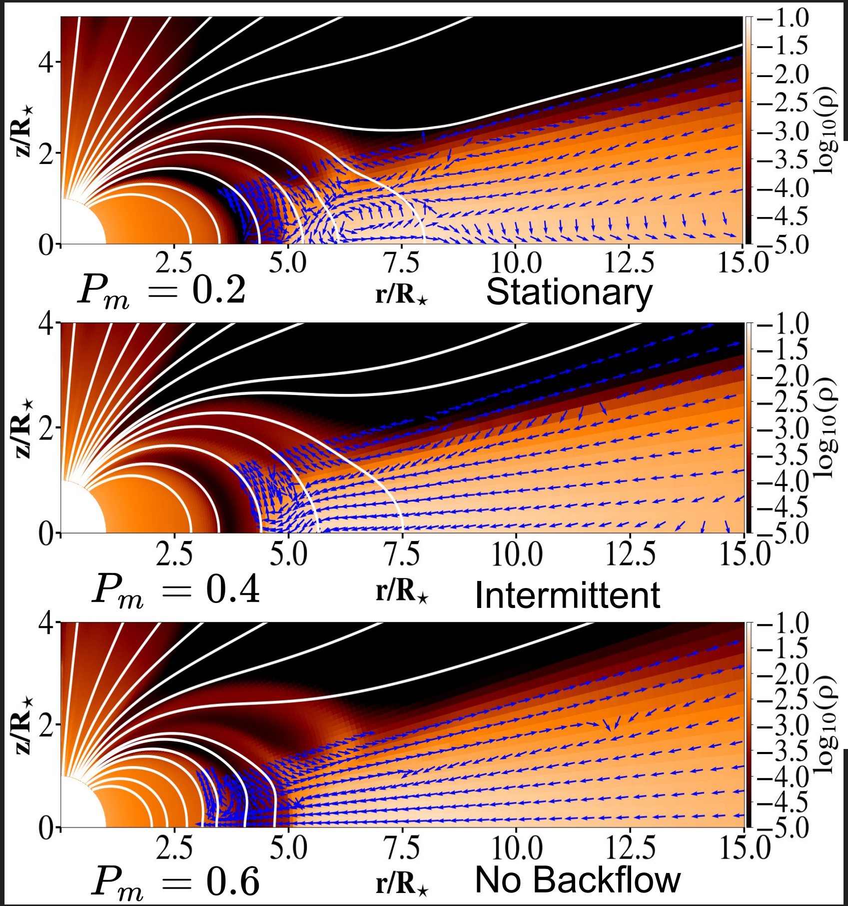


Dependence on Prandtl number

$$P_m = \frac{\nu_v}{\nu_m} = \frac{2}{3}\frac{\alpha_v}{\alpha_m}$$

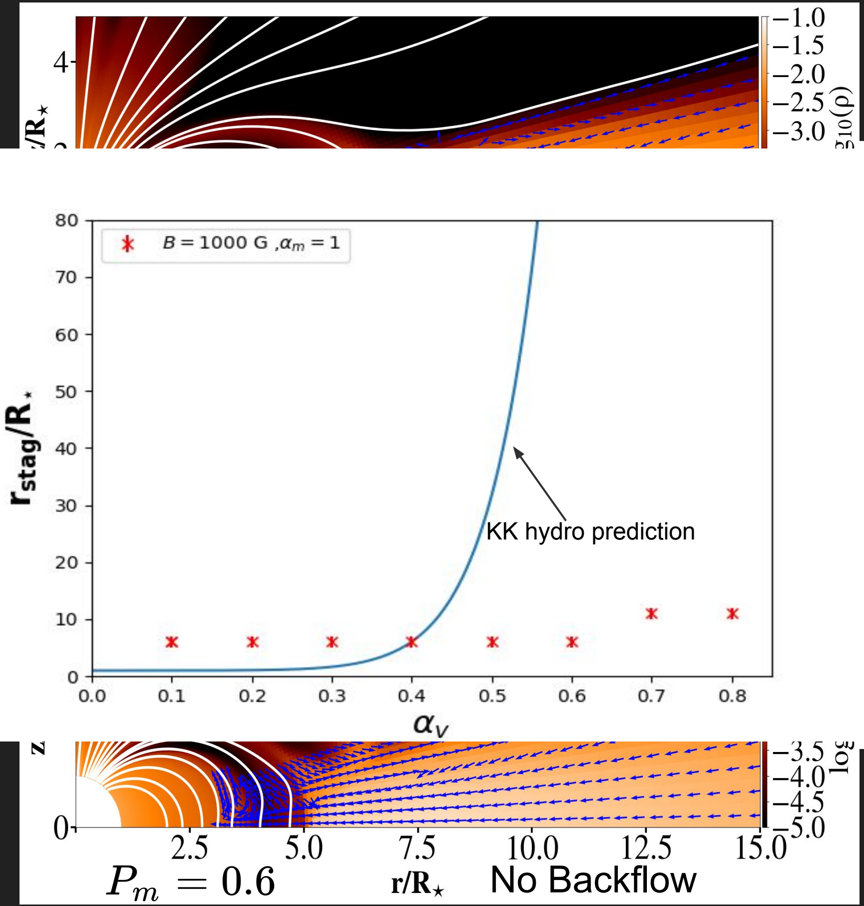
P_m	Magnetic Prandtl number
ν_v	Kinematic viscosity
ν_m	Magnetic diffusivity
α_v	Viscosity parameter
α_m	Resistivity parameter

Dependence on Prandtl number



α_v	α_m	$P_m = \frac{2}{3}\frac{\alpha_v}{\alpha_m}$	$B_\star$(G)	$\Omega_\star/\tilde{\Omega}$	Backflow	R_{stag}	Type
0.1	0.1	0.60	1000	0.1	No	–	–
0.4	0.1	2.60	1000	0.1	No	–	–
1.0	0.1	6.60	1000	0.1	No	–	–
0.1	0.4	0.16	1000	0.1	No	–	–
0.4	0.4	0.60	1000	0.1	No	–	–
1.0	0.4	1.60	1000	0.1	No	–	–
0.1	1.0	0.06	1000	0.1	Yes	6 ± 1	steady
0.2	1.0	0.13	1000	0.1	Yes	7.5 ± 1.5	steady
0.3	1.0	0.20	1000	0.1	Yes	6 ± 1	steady
0.4	1.0	0.26	1000	0.1	Yes	6 ± 2	steady
0.5	1.0	0.30	1000	0.1	Yes	6 ± 1	steady
0.6	1.0	0.40	1000	0.1	Yes	6 ± 1	steady
0.7	1.0	0.46	1000	0.1	Yes	8 ± 0.5	intermittent
0.8	1.0	0.53	1000	0.1	Yes	8 ± 0.5	intermittent
1.0	1.0	0.60	1000	0.1	No	–	–

Dependence on Prandtl number



α_v	α_m	$P_m = \frac{2}{3}\frac{\alpha_v}{\alpha_m}$	$B_\star$(G)	$\Omega_\star/\tilde{\Omega}$	Backflow	R_{stag}	Type
0.1	0.1	0.60	1000	0.1	No	–	–
0.4	0.1	2.60	1000	0.1	No	–	–
1.0	0.1	6.60	1000	0.1	No	–	–
0.1	0.4	0.16	1000	0.1	No	–	–
0.4	0.4	0.60	1000	0.1	No	–	–
1.0	0.4	1.60	1000	0.1	No	–	–
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0.6	1 0	0.40	1000	0.1	Yes	6 ± 1	steady
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1.0	1.0	0.60	1000	0.1	No	–	–

SUMMARY

- We find backflow in the simulated MHD disk for a part of parameter space.
- In presence of strong magnetic field and high resistivity we get backflow up to high values of viscous parameter (even much higher that critical α_v in hydro).
- We have backflow only for $P_m < 0.6$.
- As we approach critical P_m we have intermittent backflow in the disk.
- We do not find the same relationship of stagnation radius and viscosity parameter like the ones obtained in hydro cases.