COSMIC MAGNETIC FIELDS

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Accretion

ACCRETION AS THE ANGULAR MOMENTUM PROBLEM

For a given angular momentum the orbit of least energy is circular, so we must expect gas to form a flat disk held out from the centre by circular motion. Such a differentially rotating system will evolve due to "friction" just as described earlier for a dying quasar. Nothing happens in the absence of friction so the energy is liberated via the friction. In the cosmic situation molecular viscosity is negligible and it is most probable that magnetic transport of angular momentum dominates over turbulent transport just as it does in Alfvén's theory of the primaeval solar nebula.

Lynden-Bell (1969)

The magnetic field, which must exist in the matter flowing into the disk, and turbulent motions of the matter enable angular momentum to be transferred outward. The efficiency of the mechanism of angular momentum transport is characterized by parameter

$$\alpha = \frac{v_t}{v_s} + \frac{H^2}{4\pi\varrho v_s^2}$$

Shakura & Sunyaev (1973)

MAGNETOROTATIONAL INSTABILITY (MRI)

- Accretion disk with weak vertical magnetic field.
- Unstable axisymmetric modes redistributing angular momentum.
- Discovered by **Velikhov (1959)** in the context of Couette flow experiments.
- see the presentation of Balbus & Hawley (1991)

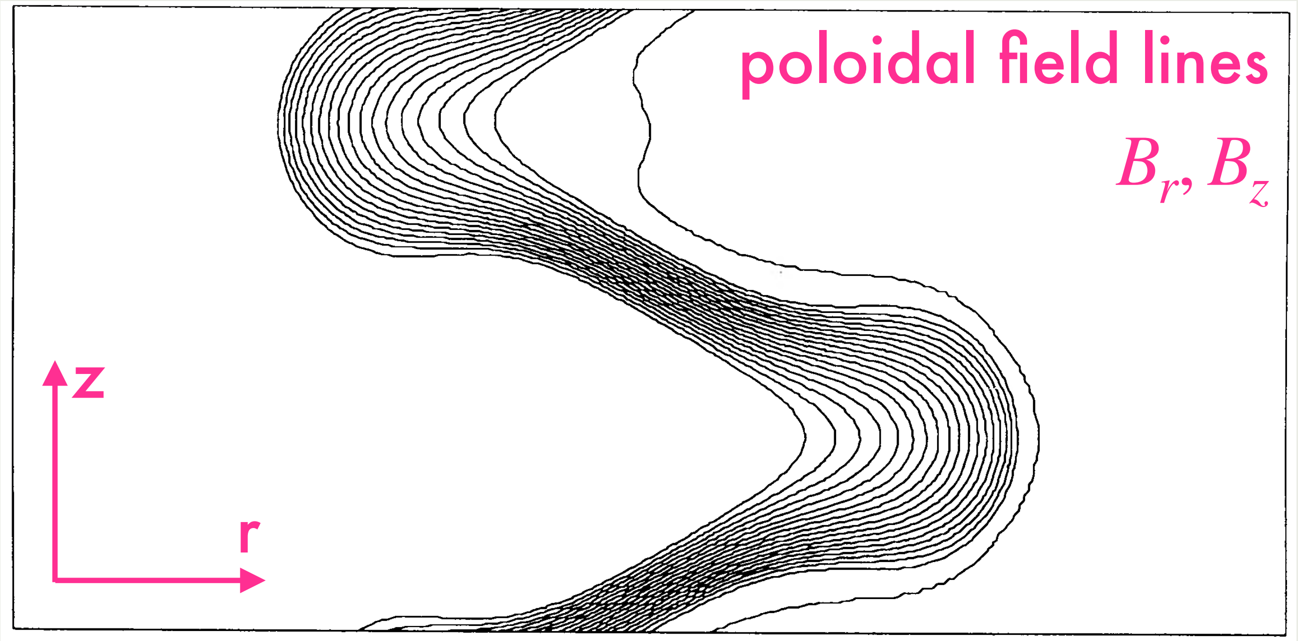


FIG. 3b

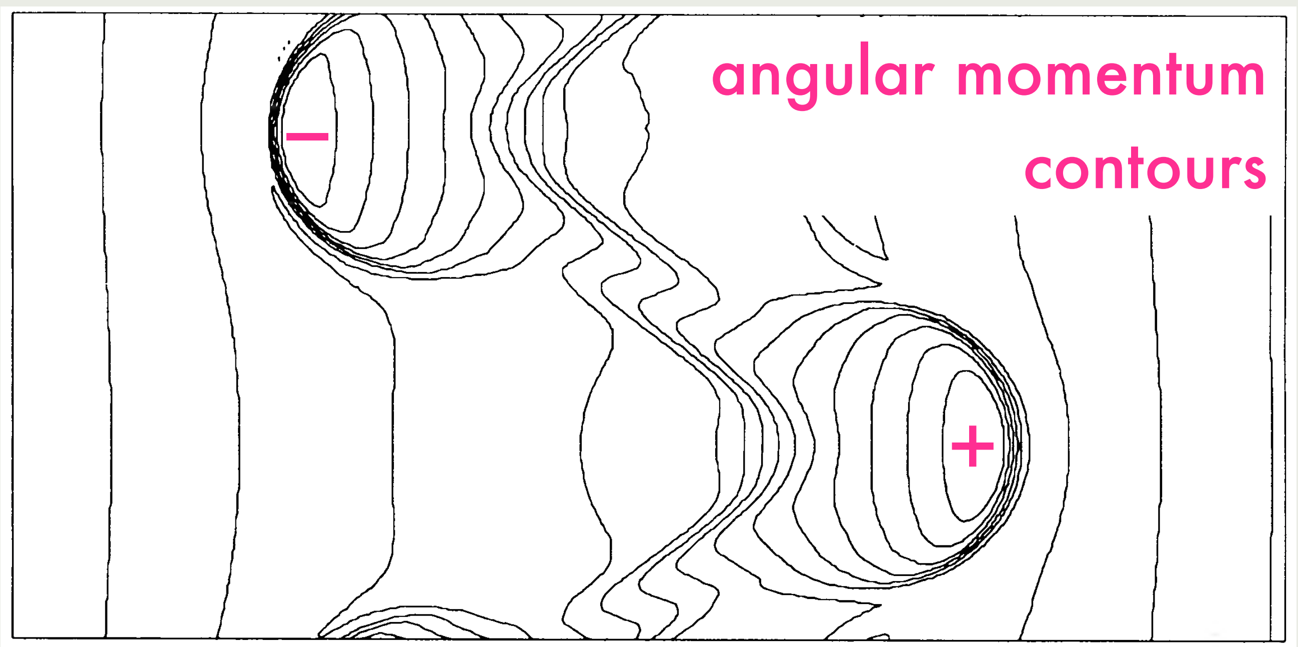


FIG. 3d

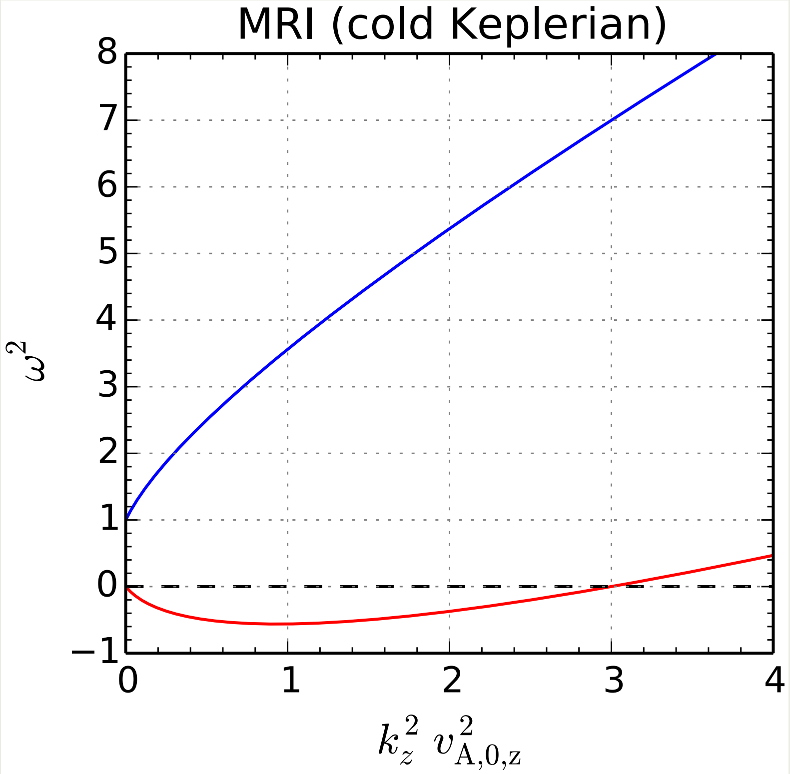
Hawley & Balbus (1991)

MAGNETOROTATIONAL INSTABILITY (MRI)

- Dispersion relation ($\partial_z X_0 = 0$, $P_0 = 0$, $k_r = 0$, $|k_z| \ll 1/r$):
  $\tilde{\omega}^4 - \Omega^2_{\mathrm{ec},0}\tilde{\omega}^2 - 4\Omega_0^2 k_z^2 \mathrm{v}^2_{\mathrm{A,0,z}} = 0,$
  where $\tilde{\omega}^2 \equiv \omega^2 - k_z^2 \mathrm{v}^2_{\mathrm{A,0,z}}$,
  $\mathrm{v}_{\mathrm{A,0,z}} = B_{0,z}/\sqrt{4\pi\rho_0}$ is the vertical Alfvén speed,
  $\Omega_0 = \mathrm{v}_{0,\phi}/r$ is the orbital frequency,
  $\Omega^2_{\mathrm{ec},0} \equiv 2\Omega_0(2\Omega_0 + r\partial_r\Omega_0)$ is the squared epicyclic frequency.

- For $B_{0,z} = 0$, the disk is stable if $\Omega^2_{\mathrm{ec},0} > 0$. Keplerian disk with $\Omega_0 \propto r^{-3/2}$ has $\Omega^2_{\mathrm{ec},0} = \Omega_0^2$, is thus stable.

- Unstable solution for weak vertical field.
  For Keplerian disk: $k_z^2 \mathrm{v}^2_{\mathrm{A,0,z}} < 3$;
  fastest growth $\omega^2 = -(9/16)\Omega_0^2$ for $k_z^2 \mathrm{v}^2_{\mathrm{A,0,z}} = 15/16$.



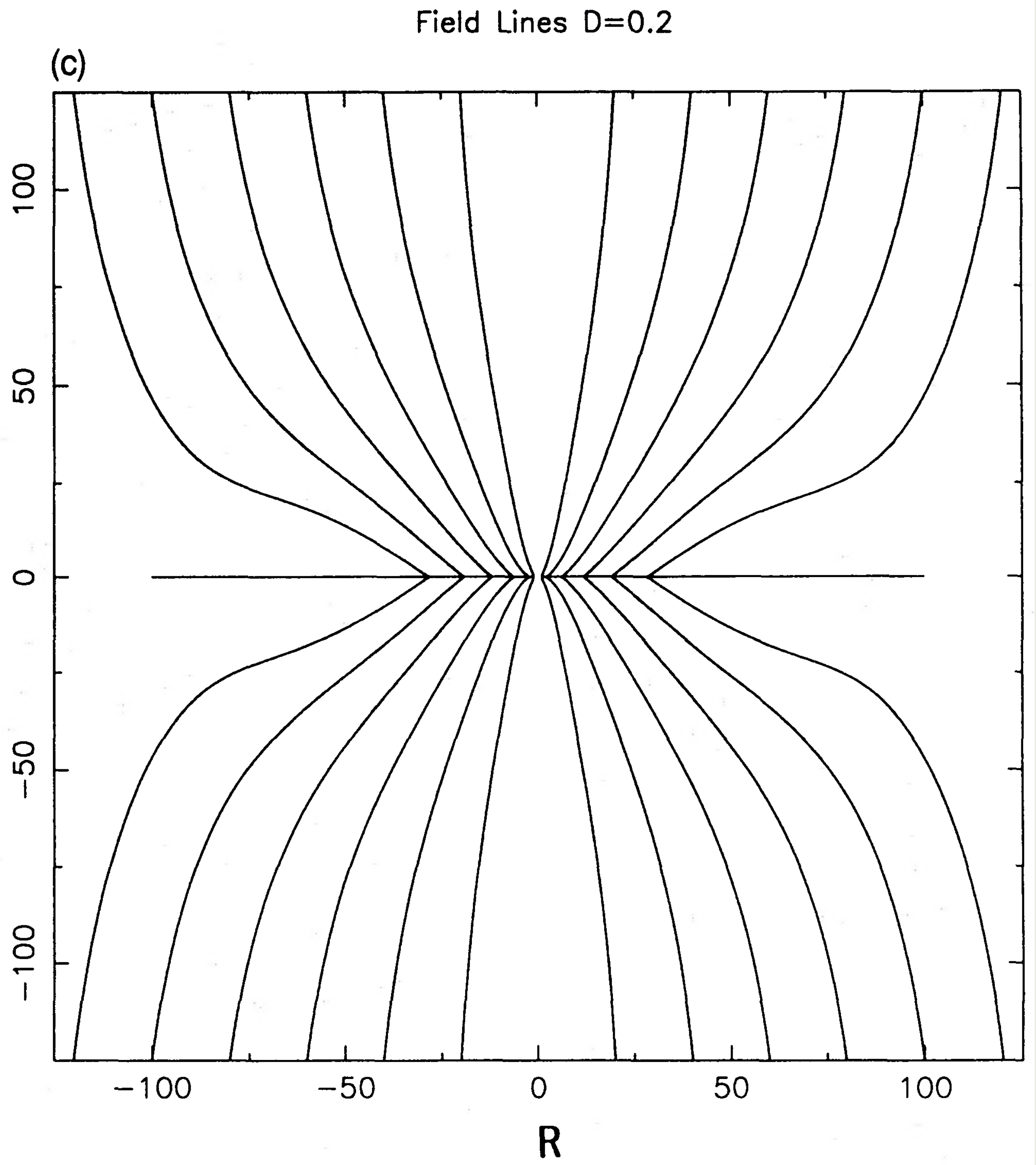
ADVECTION OF POLOIDAL MAGNETIC FIELDS

- Poloidal magnetic field can be dragged inwards by accretion disk for $\mathscr{D} = \left(\frac{R}{H}\right)\left(\frac{\eta}{\nu}\right) \lesssim 1$,

  P_{m}^{-1}

  where H is the disk half-thickness at radius R,
  η is magnetic diffusivity,
  ν is kinematic viscosity.

- Field line inclination angle:
  $\tan\theta \simeq 1.5/\mathscr{D}$.



Lubow, Papaloizou & Pringle (1994)

CORONAL FIELD TRANSPORT

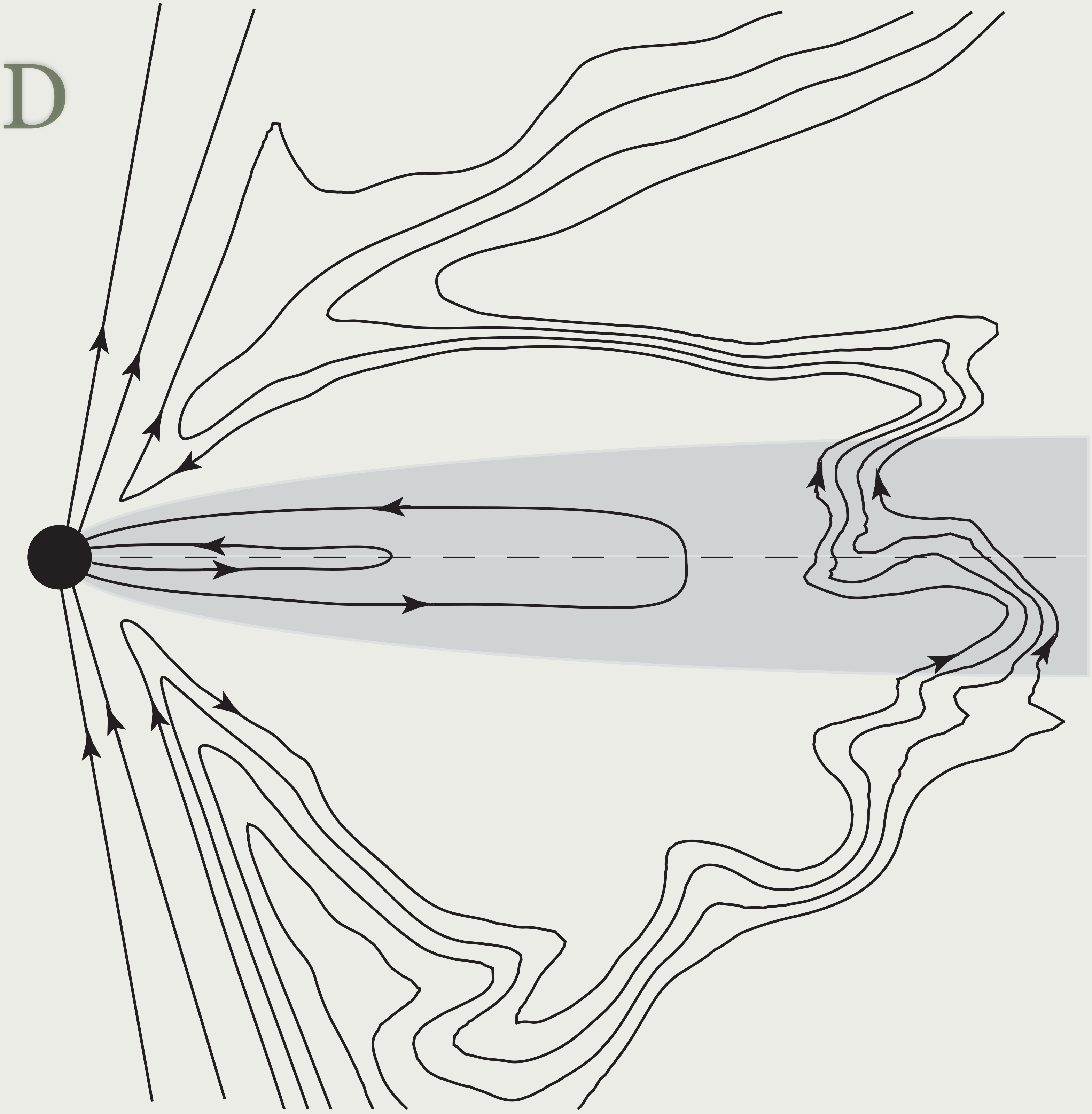
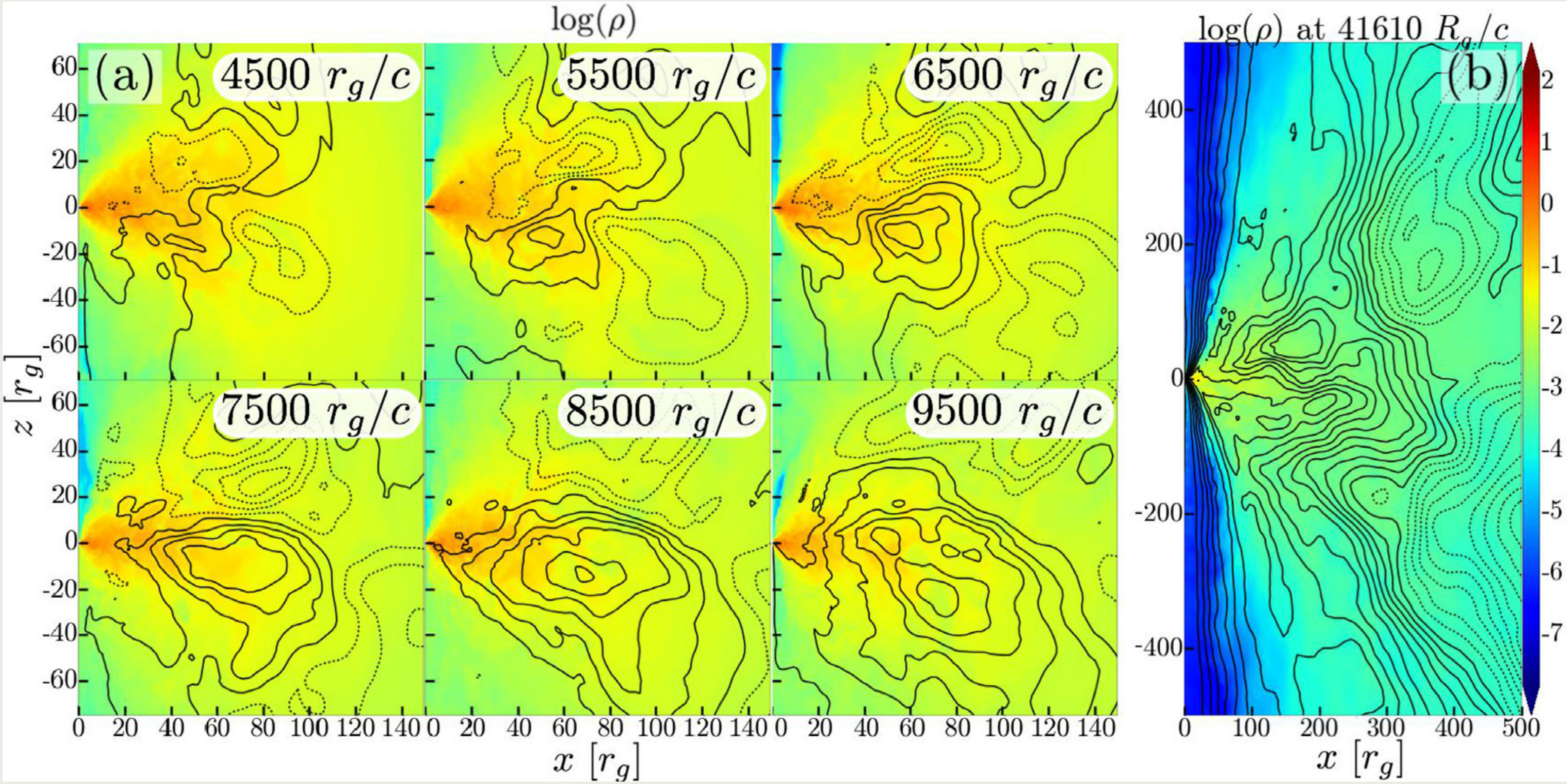


Figure 10. Schematic of the field line structure in the coronal mechanism. Field lines within the corona are carried in toward the black hole, forming a hairpin-like structure. When the hairpin connects to the horizon, flux is added to the funnel field and opposite-signed flux is added to the disk (shaded region). Reconnection across the equator (dashed line) allows this field to form loops that accrete. Accretion of those field loops results in an increase of the net horizon flux.

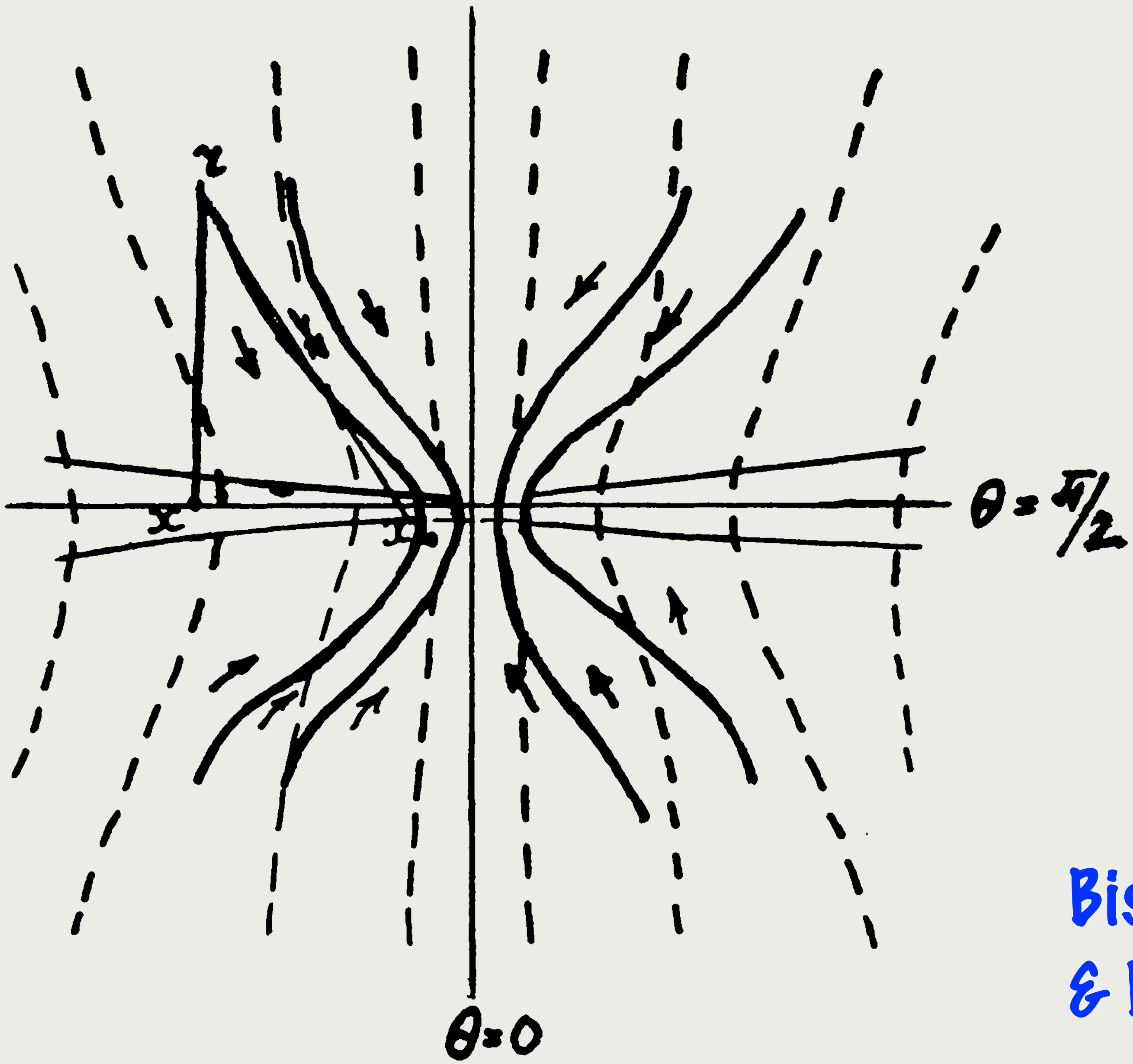
Beckwith, Hawley & Krolik (2009)

POLOIDAL FIELD DYNAMO IN ACCRETION FLOWS



Liska, Tchekhovskoy & Quataert (2020)

ACCRETION WITH POLOIDAL MAGNETIC FIELD

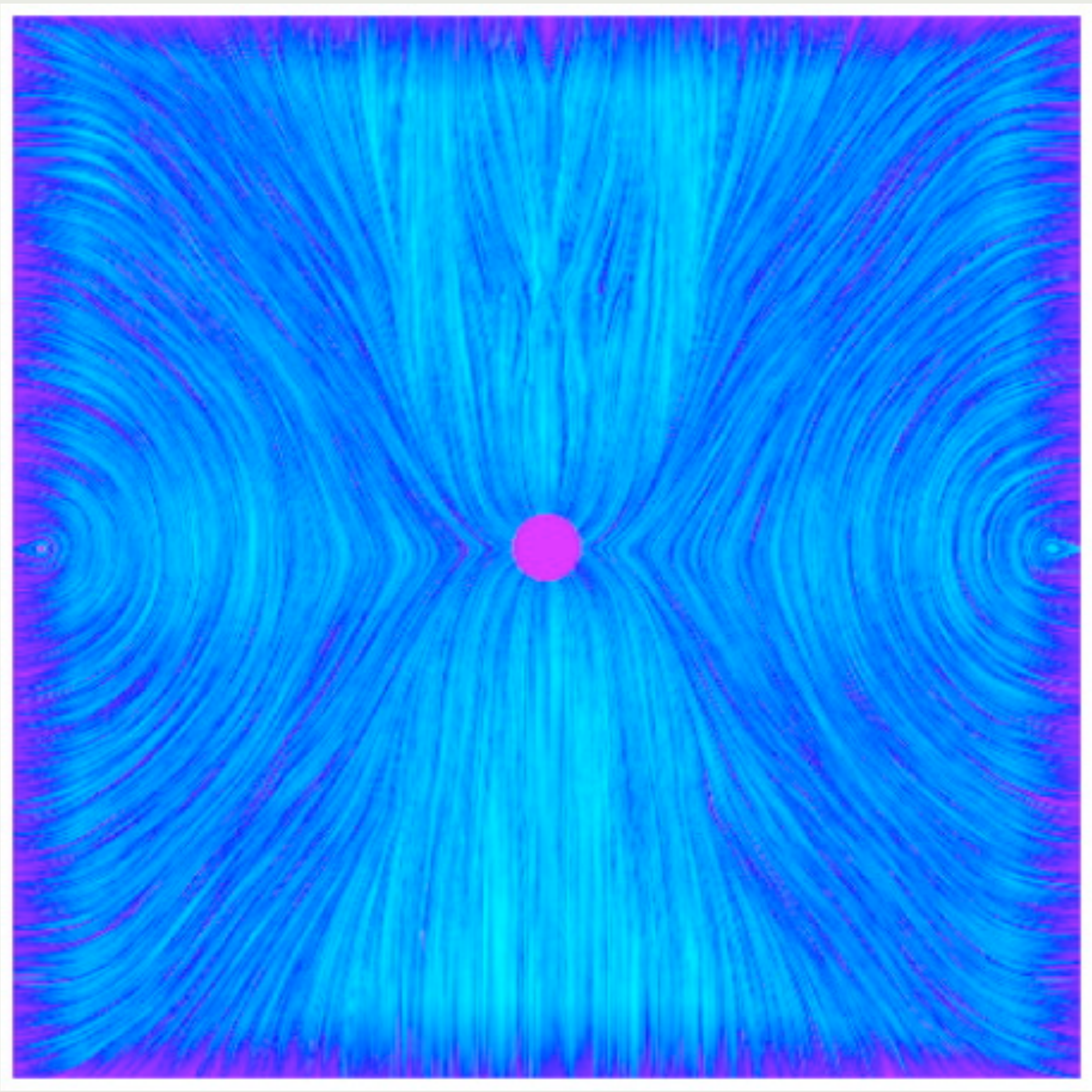


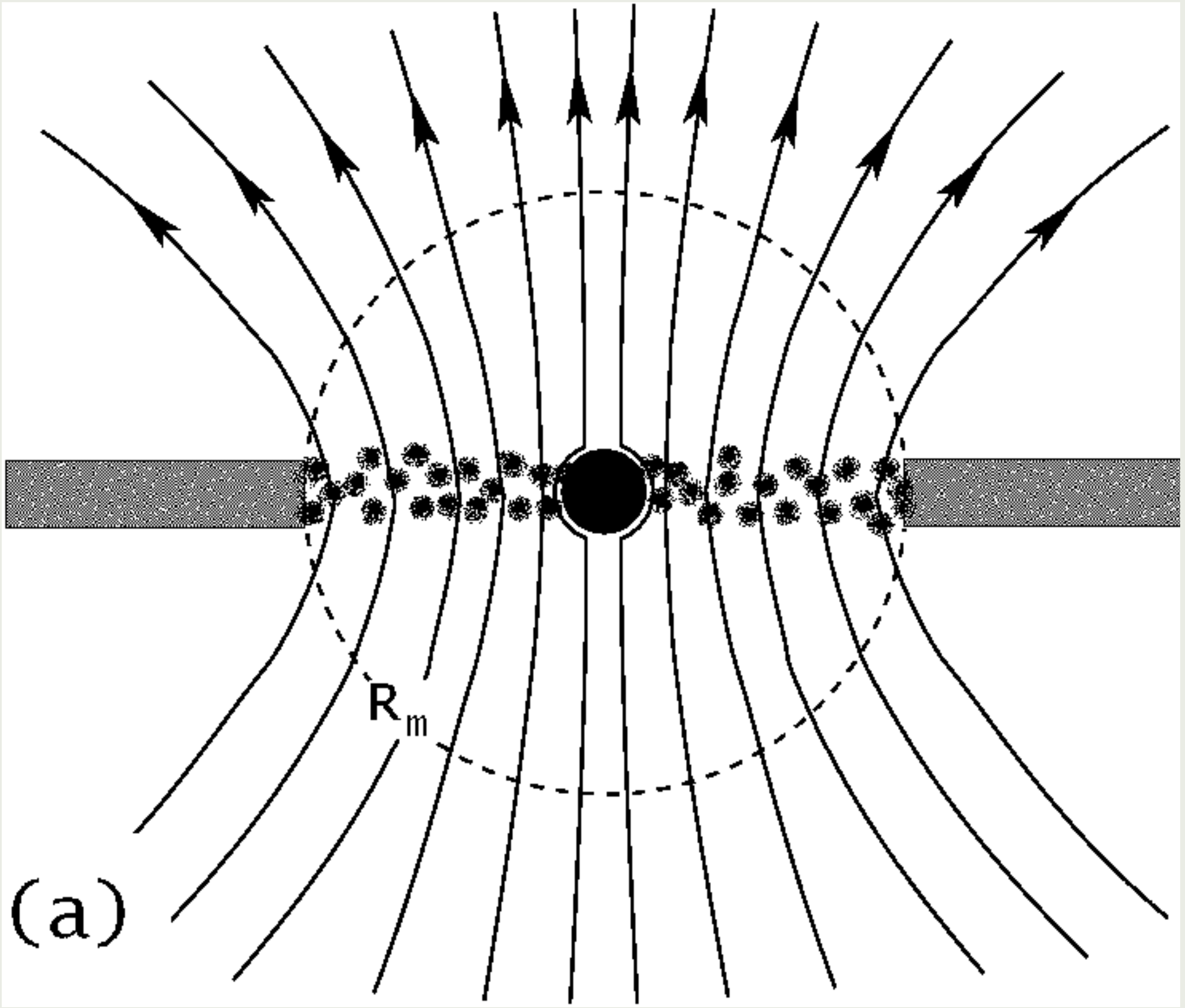
Bisnovatyi-Kogan & Ruzmaikin (1976)

Fig. 2. A schematic picture of force lines of the external magnetic field where the disturbances due to the currents in the disc are taken into account. The non-perturbed external magnetic field is shown by broken lines, the field disturbed by the disc is shown by solid lines. The influence domain is determined by the radius $r(x_0)$, $x(x_0)$ where the disturbances of the field due to the disc become negligible. The arrows indicate the direction of the flux velocity with regard to disturbances.

MAGNETICALLY ARRESTED DISK (MAD)

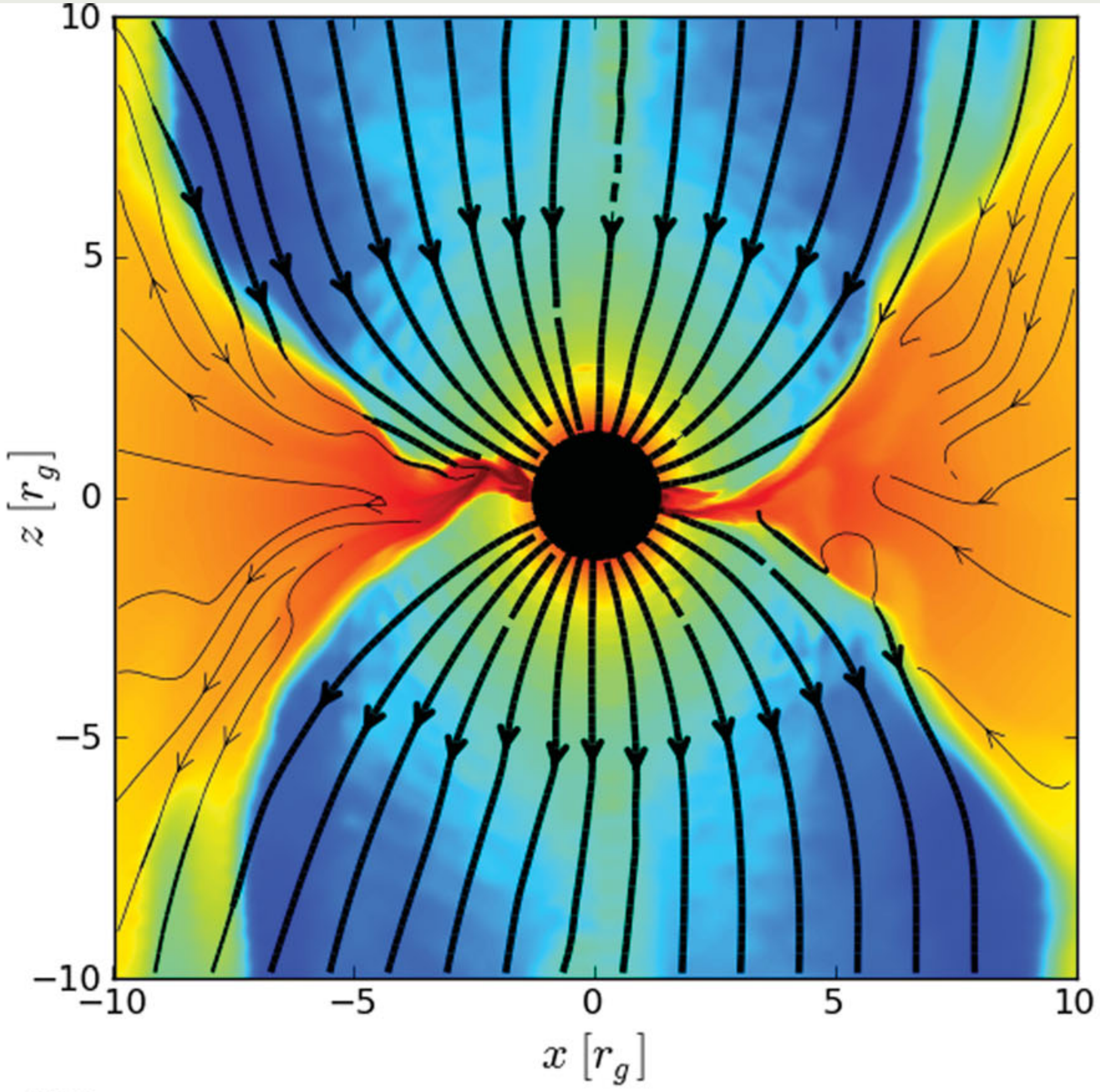
Igumenshchev, Narayan & Abramowicz (2003)





Narayan, Igumenshchev & Abramowicz (2003)

MAGNETICALLY CHOKED ACCRETION FLOW (MCAF)



bulent accretion flow. The flow that develops in our simulations is conceptually similar to the 'magnetically arrested disc' (MAD) flow (Narayan et al. 2003). While the standard weakly magnetized MRI-driven MHD turbulent flow has gas and magnetic pressures in force balance near the BH, the MAD state develops as magnetic flux accumulates and magnetic forces balance the inflow's ram or gravitational forces. The originally conceived MAD flow has a sharp magnetospheric boundary layer with a large density contrast at some radius, as confirmed by low-resolution 3D MHD simulations (e.g. fig. 13 in Igumenshchev et al. 2003; also seen in our 2D axisymmetric simulations). In these pioneering studies, accretion occurs primarily via diffusive reconnection events.

Our high-resolution fully 3D simulations show that efficient non-axisymmetric magnetic RT instabilities prevent the formation of the MAD's sharp magnetospheric barrier. Any additional magnetic flux that tries to accrete on to the BH is redistributed out in the disc by these instabilities. Also, we found that the magnetosphere geometrically compresses the dense inflow. We call this fully non-linear MAD flow a 'magnetically choked accretion flow' (MCAF), referring to the magnetic flux compressing the dense inflow leading to enhancement of the magnetization over much of the horizon.

Such a magnetic choke is analogous to chokes in man-made engines, within which it enriches the fuel mixture by partially shutting off the air intake.

McKinney, Tchekhovskoy & Blandford (2012)

MAD/MCAF

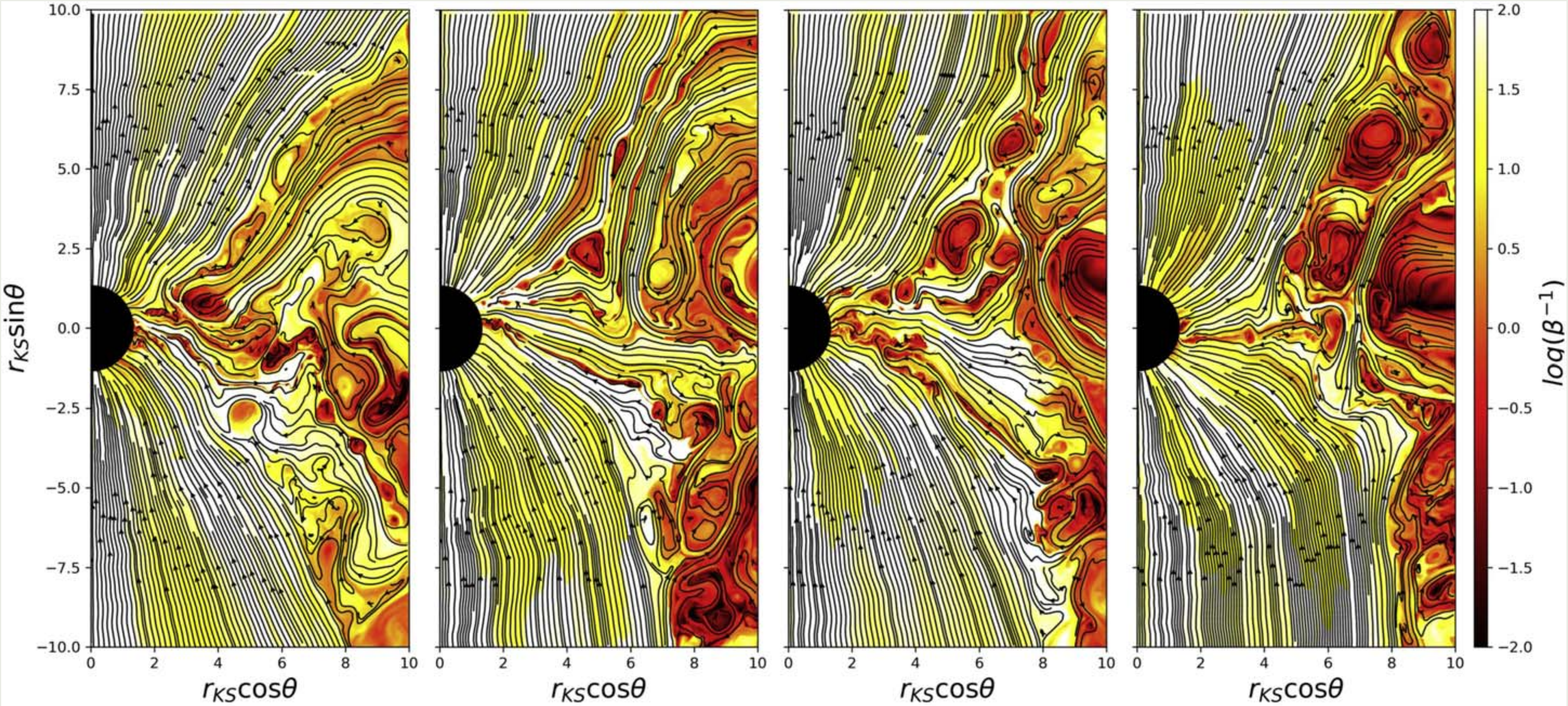


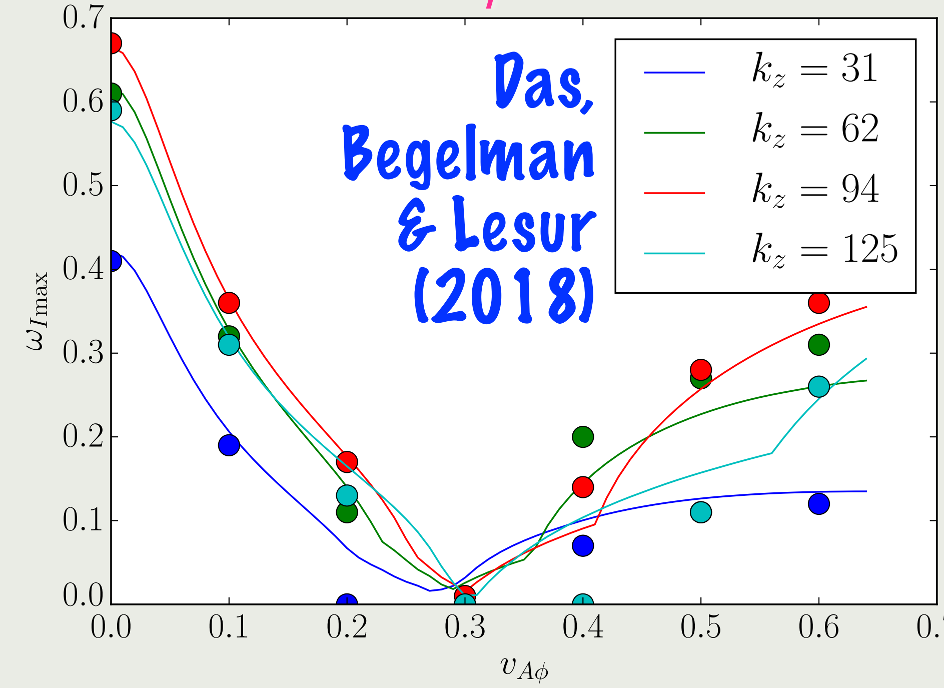
Figure 10. $\beta^{-1} = b^2/(2p)$ at four typical times $t = [2941, 2971, 2988, 3009]r_g/c$ (from left to right) during the quasi-steady-state phase of accretion in the MAD configuration. Magnetic field lines are plotted on top as solid black lines. In the top half, one can detect the accretion of a magnetic flux tube (left panel) at $x \approx 3r_g$, $y \approx 1r_g$ that opens up and becomes tearing unstable (second panel) after it connects to the black hole and produces copious plasmoids coalescing into large-scale structures (third and fourth panels) at $x \approx 5r_g$, $y \approx 2.5r_g$, with a typical size of about one Schwarzschild radius.

Ripperda, Bacchini & Philippov (2020)

STRONG TOROIDAL FIELDS

- Standard accretion disk models suffer from instabilities (thermal, viscous, fragmentation - self-gravity).
- A central layer of strong toroidal field should stabilize the disk (Begelman & Pringle 2007), confirmed by GRMHD simulations.
- Increasing B_ϕ initially suppresses the MRI, then new modes appear.

effect of B_ϕ on the MRI



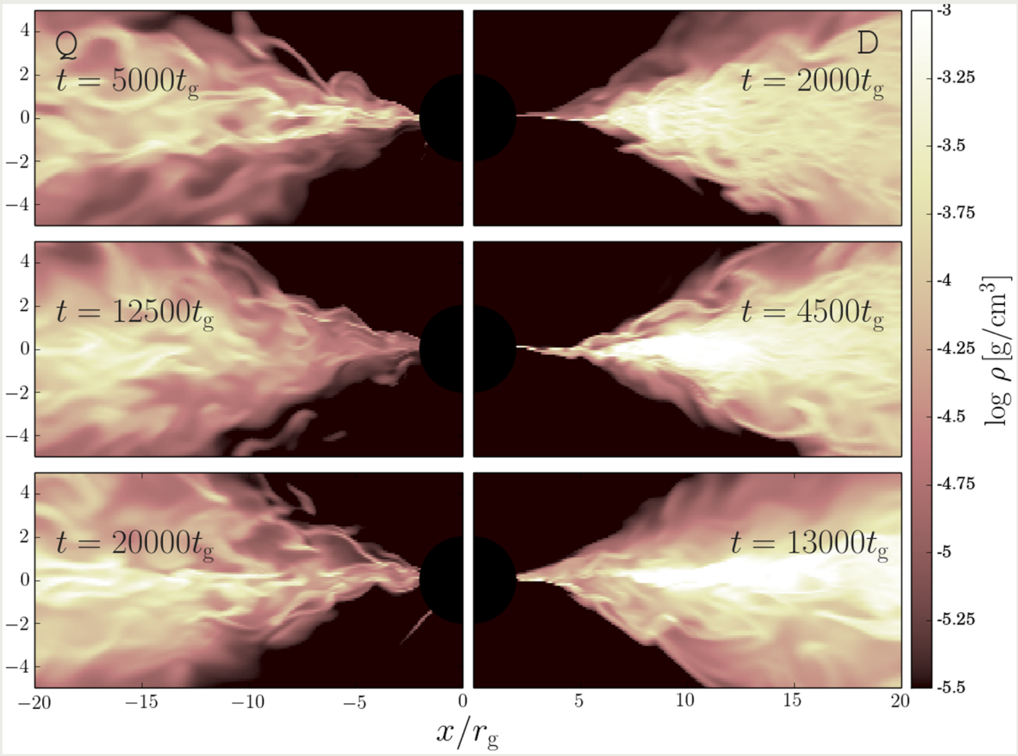


Figure 7. Time evolution of the strongly (model Q, left-hand panels) and weakly (model D, right-hand panels) magnetized discs. Only the magnetically supported disc retains the equilibrium state. The weakly magnetized one cools down, collapses towards the equatorial plane, and leads to under-resolving the MRI.

Sądowski (2016)

SUMMARY

- Accretion flows require a mechanism of redistributing angular momentum (viscosity).
- Magnetic fields have long been considered to provide such a mechanism. The most important mechanism has been identified in the magnetorotational instability (MRI).
- Strong toroidal magnetic fields can stabilize accretion disks (thermal, viscous, self-gravity modes), but also induce additional MRI modes, can be sustained against buoyancy by shear-driven Ω dynamo.
- Poloidal magnetic fields must be advected onto central object to produce jets. Inwards advection is possible in thick accretion flows and via coronae, generation from toroidal fields through an α dynamo has also been demonstrated.