Investigating magnetized outflows from rotating black holes:

Effects of aligned and misaligned spin

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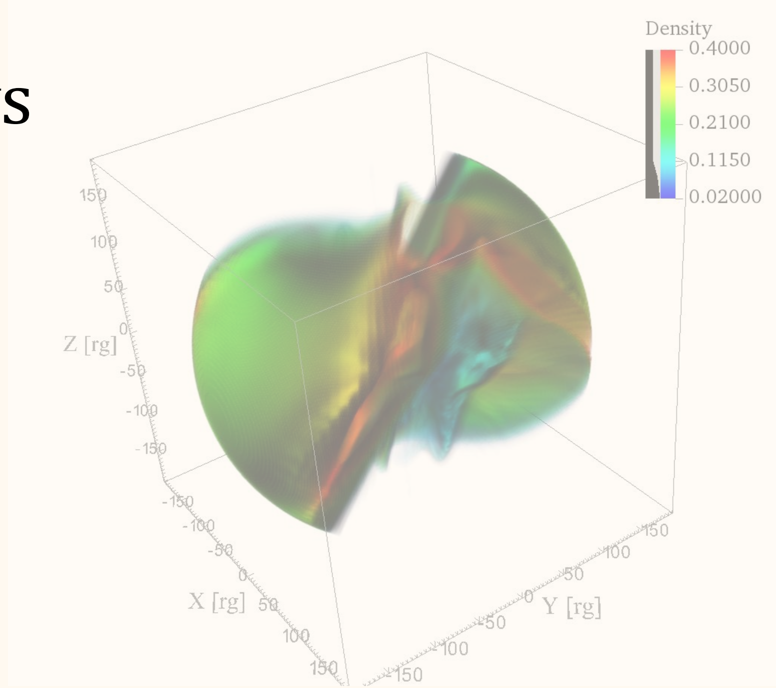
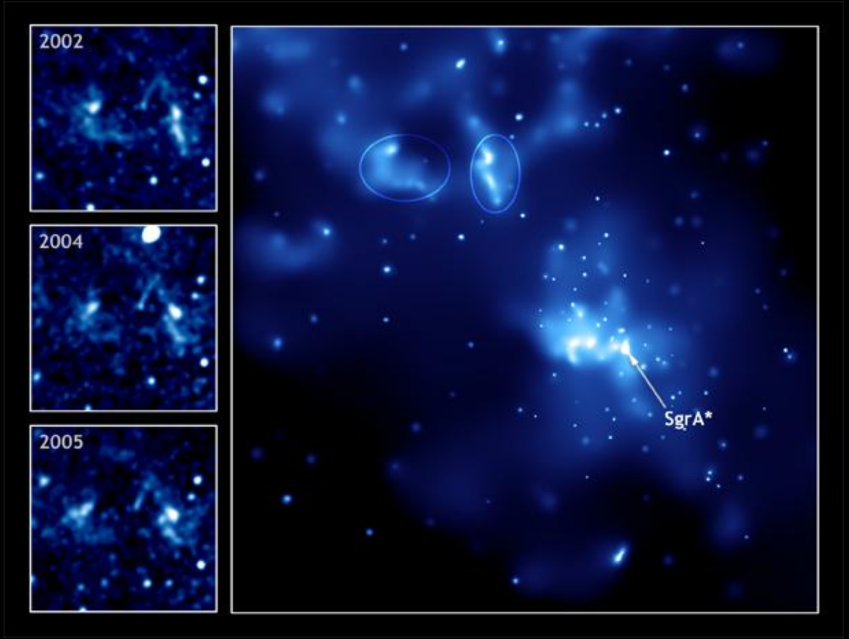


Introduction

Motivation

- Most accreting black hole sources show variable outflows at different mass scales
- Galactic nuclei, e.g. Sgr A*, show intermittent flares and outbursts in X-ray and IR
- Plasma at large scales is magnetized due to its environment (The Event Horizon Telescope Collaboration et al. 2021a, b)
- GRMHD studies show that the inner magnetospheres of thes accreting sources have a pronounced effect on these emissions (Ripperda et al. 2020, 2022)
- We investigated how the geometric structure and strength of the large-scale magnetic field near the BH horizon influence the resulting outflows



This set of Chandra images shows evidence for a light echo generated by the Milky Way's supermassive black hole. This is from an X-ray outburst which then reflected off gas clouds near Sgr A*

Credit: NASA/CXC/Caltech/M.Muno et al.

Background

- Accretion drags frozen-in magnetic flux inward; when enough flux builds up to balance the pressure of infall, the flow becomes a magnetically arrested disk (MAD) (Narayan et al. 2003; Tchekhovskoy et al. 2011)

- Rotating BH and an ordered field: electromagnetic extraction of spin energy, powering relativistic jets along polar axis (Blandford & Znajek 1977); validated in GRMHD (Tchekhovskoy et al. 2011 and others)

- A competing effect at near-extremal spin: Meissner-like expulsion of field lines from the horizon (suggested by Bičák & Janiš 1985; King et al. 1975), which could slightly affect BZ efficiency –

  Komissarov & McKinney (2007) showed that ongoing accretion counteracts this expulsion. But the full time dependent balance between these competing effects was not fully resolved by them

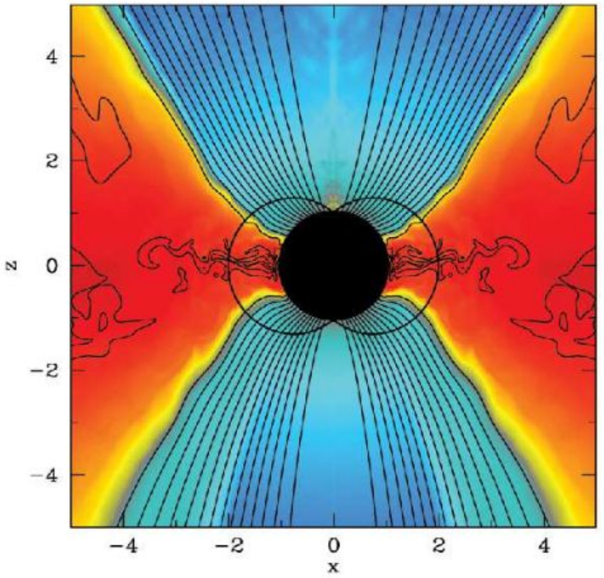


Figure 3. Quasi-steady GRMHD magnetized accretion disk solution for a black hole with $a = 0.999$ at time $t = 2000GM/c^3$. Contours show the magnetic field lines and the colour image shows logarithm of the rest-mass density. Amount of flux threading black hole is qualitatively similar to lower black hole spins for similar models. The Meissner effect is not observed.

(Komissarov & McKinney 2007)

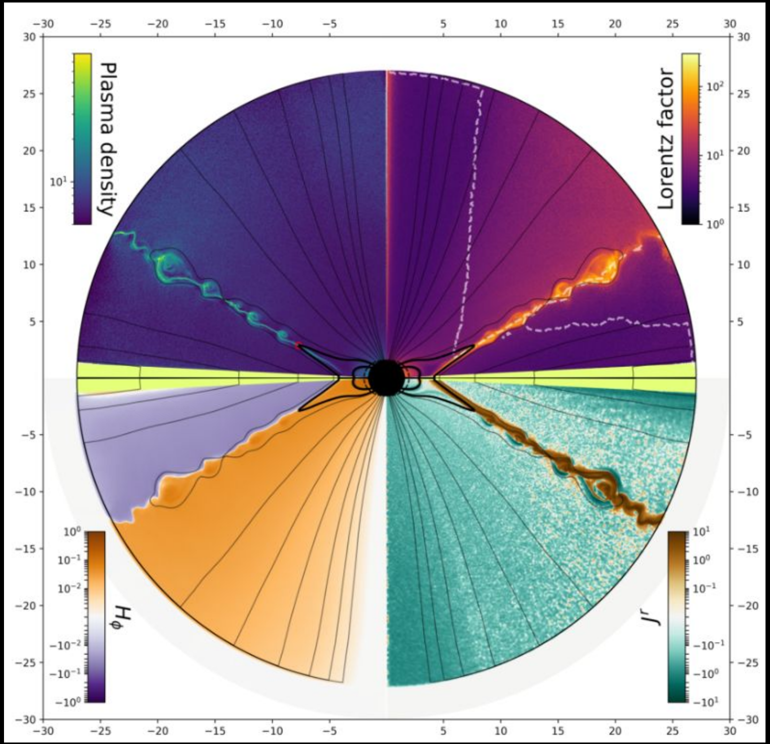
Background

- PIC simulations (Crinquand et al. 2022; El Mellah et al. 2022, 2023; Hakobyan et al. 2023) show equatorial current sheets, flux ropes and flares. But initial fields decay within a few dozen t_g, due to open boundary conditions, limiting long-term evolution

- GRMHD models (Ressler et al. 2021, 2023) studied initially tilted uniform field with zero angular momentum flow; showed jet power peaked for tilted geometry

  Kwan et al. (2023) showed Bond-type accretion needs a minimum angular momentum to sustain MAD and episodic jets

- We rather focus on equatorial outflows and how they are influenced by the inner magnetosphere



(El Mellah et al. 2022)

The plan of our work, goals

- Start from a steady state, spherically symmetric (zero angular momentum) Bondi-type inflow
- Impose a large-scale uniform field, and systematically compare aligned vs. inclined field geometries across a spin/magnetization grid,
- Track equatorial outflow rates in detail
- Quantify how the outflow rate depends on spin, magnetization, simulation dimensionality (2D vs 3D, if any), and field inclination w.r.t. the BH spin

Methods, numerical models

Numerical Setup: HARM code

HARM is a conservative and shock capturing scheme for evolving the equations of GRMHD (Gammie et al. 2003).

The code provides a solver for the continuity, energy-momentum conservation and induction equations in General Relativity:

$$\nabla_\mu(nu^\mu) = 0, \quad \nabla_\mu(T^{\mu\nu}) = 0, \quad \nabla_\mu(u^\nu b^\mu - u^\mu b^\nu) = 0.$$

The stress-energy tensor, in general, contains the fluid and electromagnetic parts: $T^{\mu\nu} = T^{\mu\nu}_{gas} + T^{\mu\nu}_{EM}$

$$T^{\mu\nu}_{gas} = \rho h u^\mu u^\nu + p g^{\mu\nu} = (\rho + u + p) u^\mu u^\nu + p g^{\mu\nu}$$

$$T^{\mu\nu}_{EM} = b^2 u^\mu u^\nu + \frac{1}{2} b^2 g^{\mu\nu} - b^\mu b^\nu; b^\mu = u^*_\nu F^{\mu\nu}$$

where n is the baryon density in fluid frame, ϱ is the rest mass density, h is the fluid specific enthalpy, p is fluid pressure, u is internal energy, u^μ is four-velocity of fluid, $F^{\mu\nu}$ is the Faraday tensor, $^*F^{\mu\nu}$ its dual, and $b^\mu = (1/2)\, \epsilon^{\mu\nu\lambda\delta} u_\nu F_{\lambda\delta}$.

In the force-free approximation, electric field in fluid frame $e_\nu = u_\mu F^{\mu\nu} = 0$.

Numerical Setup: grid setup, units

- Domain: outer boundary R_{out} at 10^4 or 10^5 r_g; inner boundary R_{in} at 0.98 r_g
- Resolution:

  2D runs at 600×512 (r,θ);

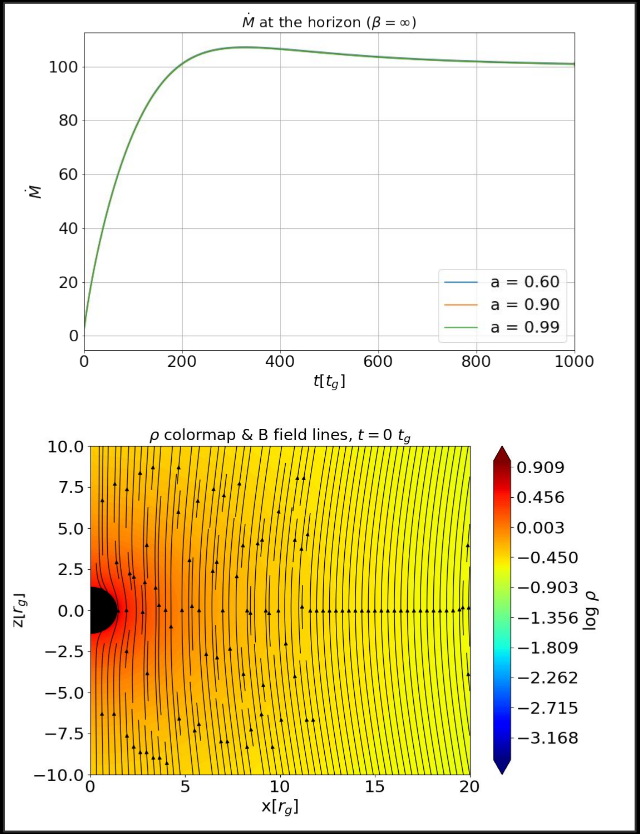
  3D runs at 288×256×128 (r,θ,φ)
- Ideal-gas equation of state with adiabatic index γ = 4/3
- The code uses geometric units, $G=c=M_{BH}=1$; so the BH mass scales the simulation results: $r_g = GM/c^2$; $t_g = GM/c^3$

adopted a black hole mass of $M = 6.2 \times 10^9\ M_\odot$ considering M87*.

Physical quantity	Geometric units	cgs units
Length	$r_g = GM/c^2$	9.159×10^{14} cm
Time	$t_g = GM/c^3$	3.055×10^4 s

Numerical Setup: initial conditions

- Bondi inflow, Kerr BH at center
- The computational domain initially filled with a low uniform density and spherical inflow boundary conditions - then evolved to reach a steady state Bondi-type solution
- At this stage, the magnetic field is introduced with the prescribed geometry and strength and the system is evolved further
- The plasma β (= P_{gas}/P_{mag}), tracked at either the maximum or minimum value within the domain, sets the field strength
- This two stage method: establishing a steady state inflow and introducing the field then, isolates the effect of the field on an already settled flow



Numerical Setup: Aligned field (Wald solution)

- Field vertically aligned with the BH spin axis, given by the Wald (1974) vector potential

$$A_\phi = B\left[\frac{1}{2}(r^2 + a^2) - a^2 r \Sigma^{-1}(1 + \cos^2\theta)\right]\sin^2\theta$$

where $\Sigma = r^2 + a^2\cos^2\theta$ and B is a constant

- We ran the simulation for the following: spin values a = 0, 0.60, 0.90, 0.99. Magnetization, β_{max} = 0.1, 0.5, 1.0 (strongly magnetized to near-equipartition),

  2D runs for all cases, 12 models, 3D runs for 2 cases to check axisymmetric effects and validate 2D results

Model (†)	β_{max}	a	Final $\dot{M}_{in,H}$ (code units)	$\langle\phi_{BH}\rangle_t$	$\langle\dot{M}_{out,10r_g}\rangle_t$ (code units)
b1.a0.2D	1.0	0	4.91	43.08	3.00×10^{-5}
b1.a60.2D	1.0	0.60	0.49	41.95	3.07×10^{-5}
b1.a90.2D	1.0	0.90	0.62	35.06	4.82×10^{-5}
b1.a99.2D	1.0	0.99	1.54	28.72	8.11×10^{-5}

Numerical Setup: Inclined field (Bicak & Janis 1985)

- Magnetic field inclined with respect the BH spin axis. Prescribed according to the vacuum solution by Bičák & Janiš (1985).

  B_r, B_θ, B_ϕ components depend on two constants B_0 and B_1, setting the field strengths along the Z (polar) and X (equatorial) directions.

- The inclination angle was set to 45°. Run in 3D, two representative models.

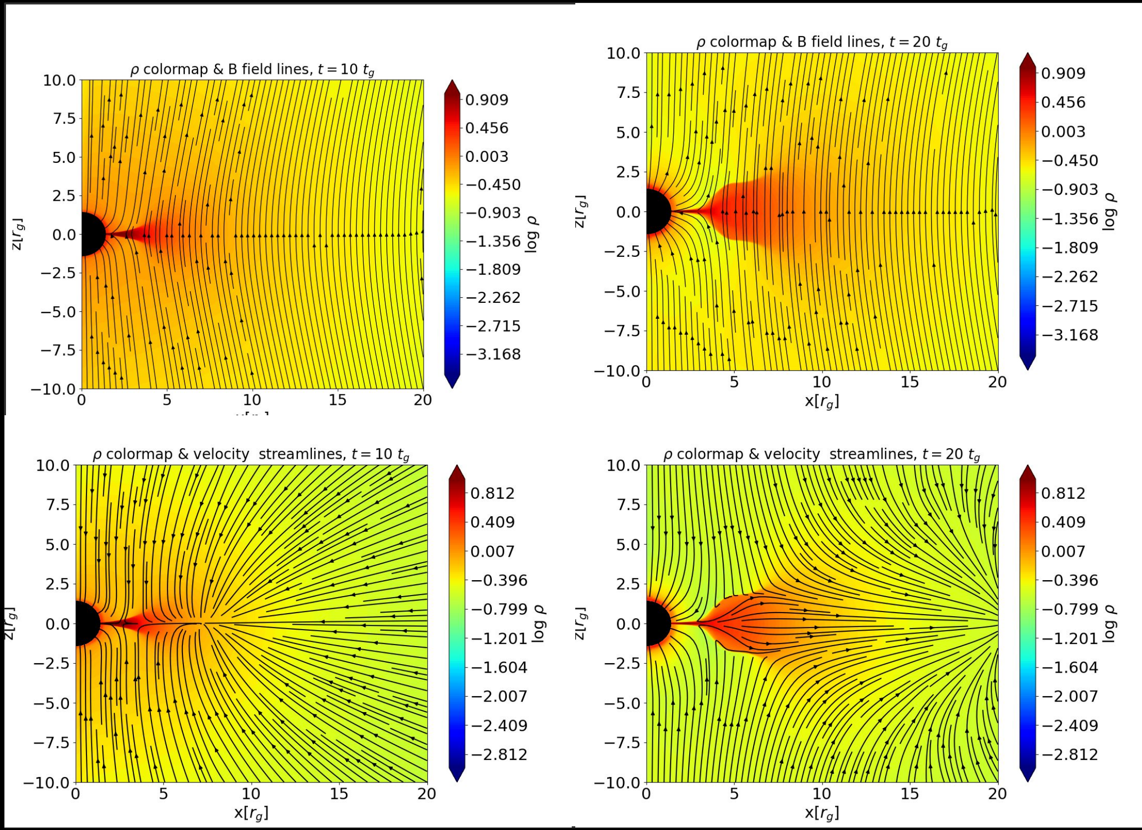
  β_{min} = 0.0003 at 10^4 r_g, chosen intentionally not to abruptly disrupt the steady state flow, but still strong enough to influence it.

Model	Angle of inclination	$\beta_{\rm min}$	a	Final $\dot{M}_{\rm in,H}$	$\langle \phi_{\rm BH} \rangle_t$	$\langle \dot{M}_{{\rm out},10r_g} \rangle_t$ (code units)
incl45.bmin0003.a90	45°	0.0003	0.90	1.53	36.09	2.18×10^{-4}
incl45.bmin0003.a99	45°	0.0003	0.99	2.68	29.12	3.21×10^{-5}

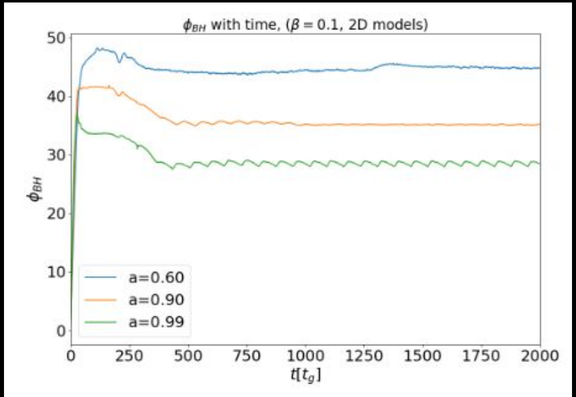
Results, further prospects

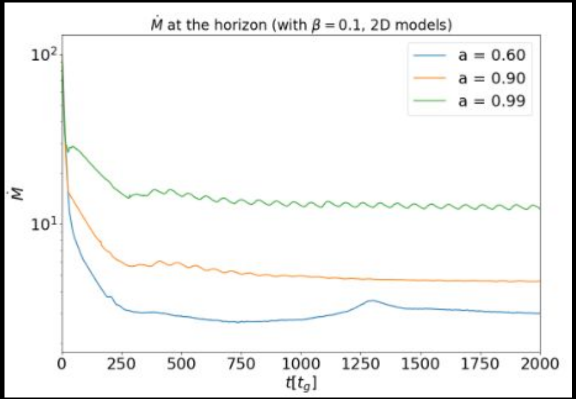
Results: Aligned field models

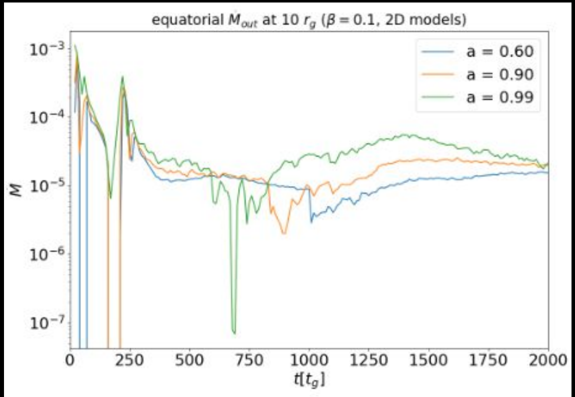
- As the accretion proceeds, the plasma drags the field lines inward, bending them in the equatorial region, and the Meissner-like expulsion disappears immediately due the flow
- The idealized initial field evolves to a turbulent, reconnecting structure near the horizon ($r \lesssim 10\ r_g$), with more organized field lines in the polar funnel
- An equatorial outflow develops in every aligned field model tested; a robust, geometry independent result
- A persistent reconnection layer develops in the equatorial region which feeds a transient outflow



Results: Aligned field models

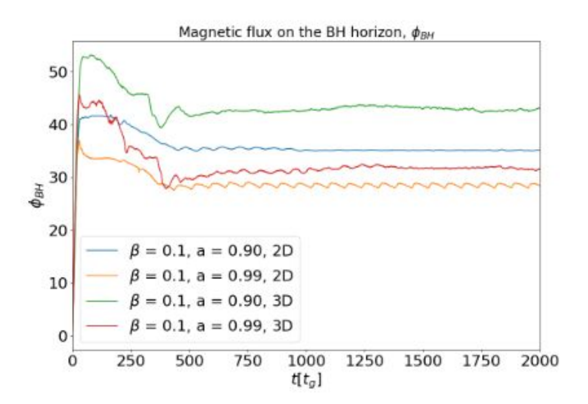


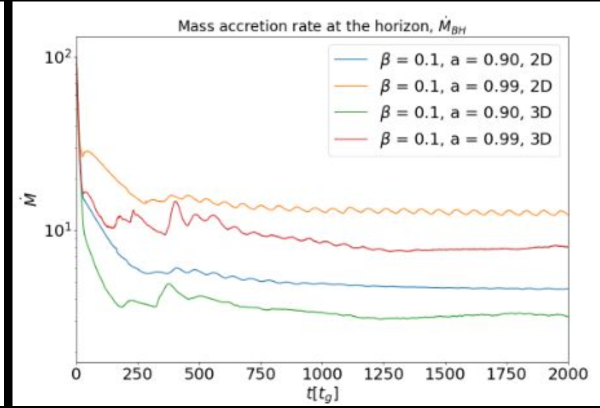


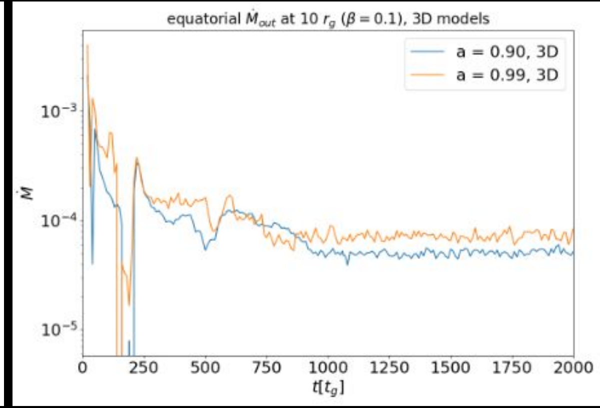


- Outflow rate increases systematically with spin, across all magnetizations
- Outflow rates show no clear dependence on field strength, i.e. spin, not the magnetic field is the controlling parameter
- Quasi-periodic fluctuations occur in in both the accretion rate and the horizon flux – plausibly caused by the repeated reconnection-driven field line expulsion

Results: Aligned field, 2D vs. 3D



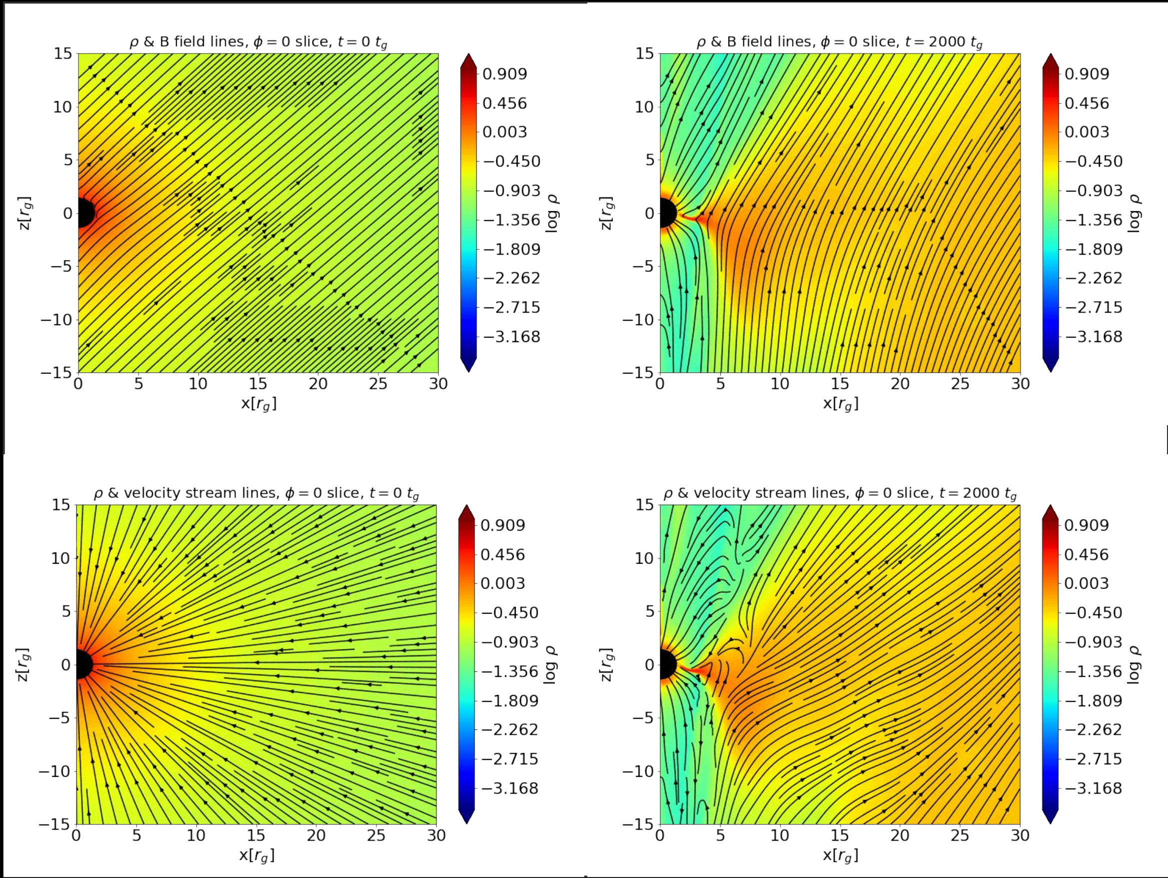




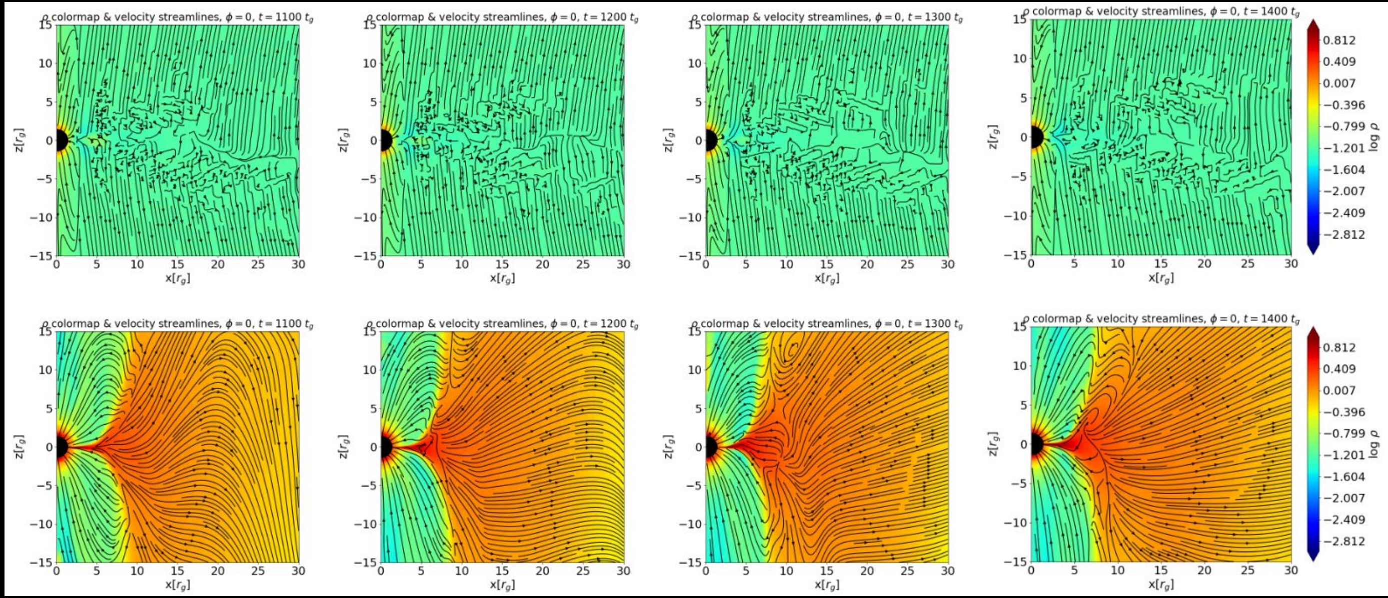
- 3D models show slightly lower magnetic flux but systematically higher mass outflow rates than their 2D counterparts
- Additional dimensionality allows outflows along more directions and support more efficient equatorial reconnection. So 2D models tend to underestimate the outflow rates.
- The fluctuations in accretion rate and magnetic flux are smoother in 3D than in 2D

Results: Inclined field – evolution, funnel formation

- As accretion proceeds, the field is dragged in and reconnects in the equatorial region, similar to the aligned case
- The inclined filed progressively realigns with the black hole spin axis with time
- A low-density funnel region forms allow the BH spin axis, rather than along the direction of the initial inclination of the field. But, a dense outflow persists along the original field inclination at larger radii.



Results: Inclined field vs. Aligned field



- The velocity structures differ substantially: Aligned field models develop strongly turbulent equatorial velocity patterns. Inclined field models results in more streamlined, ordered outflows roughly influenced by the initial inclination at larger distances

- Near the BH horizon, spin dictates the flow geometry in both the cases. At larger distances, the initial field inclination have an effect

Summary

- A uniform initial field is rapidly dragged into the BH by the accreting plasma, even at very high magnetization ($\beta \ll 1$) and near-extremal spin ($a=0.99$)
- In the initially aligned field models, an equatorial current sheet develops always, driving enhanced turbulence and sustained outflow that diverts part of the accreted material
- Outflow rates depend on black hole spin, but show no clear dependence on magnetic field strength
- In initially inclined field configurations, a low-density funnel develops along the spin axis, and a dense outflow persists at larger radii roughly along the initial field inclination
- BH spin always governs the flow geometry near the horizon and the field inclination or geometry matters only at larger distances

Further connections, prospects

- The outflow/density variability on scales of ~ 10 r_g is broadly consistent with rapid flare timescales seen in Sgr A* from GRAVITY (GRAVITY Collaboration 2018; Witzel et al. 2021). But we cannot directly confirm the orbital/circular plasmoid motion inferred from GRAVITY astrometry.

- Kinetic simulations (e.g. Crinquand et al. 2021) capture more microphysics, but suffer from field decay, after a few tg, due to open boundaries; GRMHD sustains reconnections – two approaches are complementary

- Natural next step: combined kinetic + fluid simulations (cf. Makwana, Keppens & Lapenta 2017) to capture both large-scale dynamics and small-scale reconnection physics self-consistently

- Other open directions: introduce initial angular momentum to compare with the the MAD threshold found by Kwan et al. (2023); probe other inclination angles, longer/higher resolution runs for the inclined field models

Thank you for your attention!

More details:
James, Janiuk & Karas, A&A, 687, A185 (2024)

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