Title: The Impact of Plasma Angular Momentum on Magnetically Arrested Flows and Relativistic Jets in Hot Accretion Flows Around Black Holes

Speakers: Leon Chan

Collection/Series: Magnetic Fields Around Compact Objects Workshop

Subject: Strong Gravity

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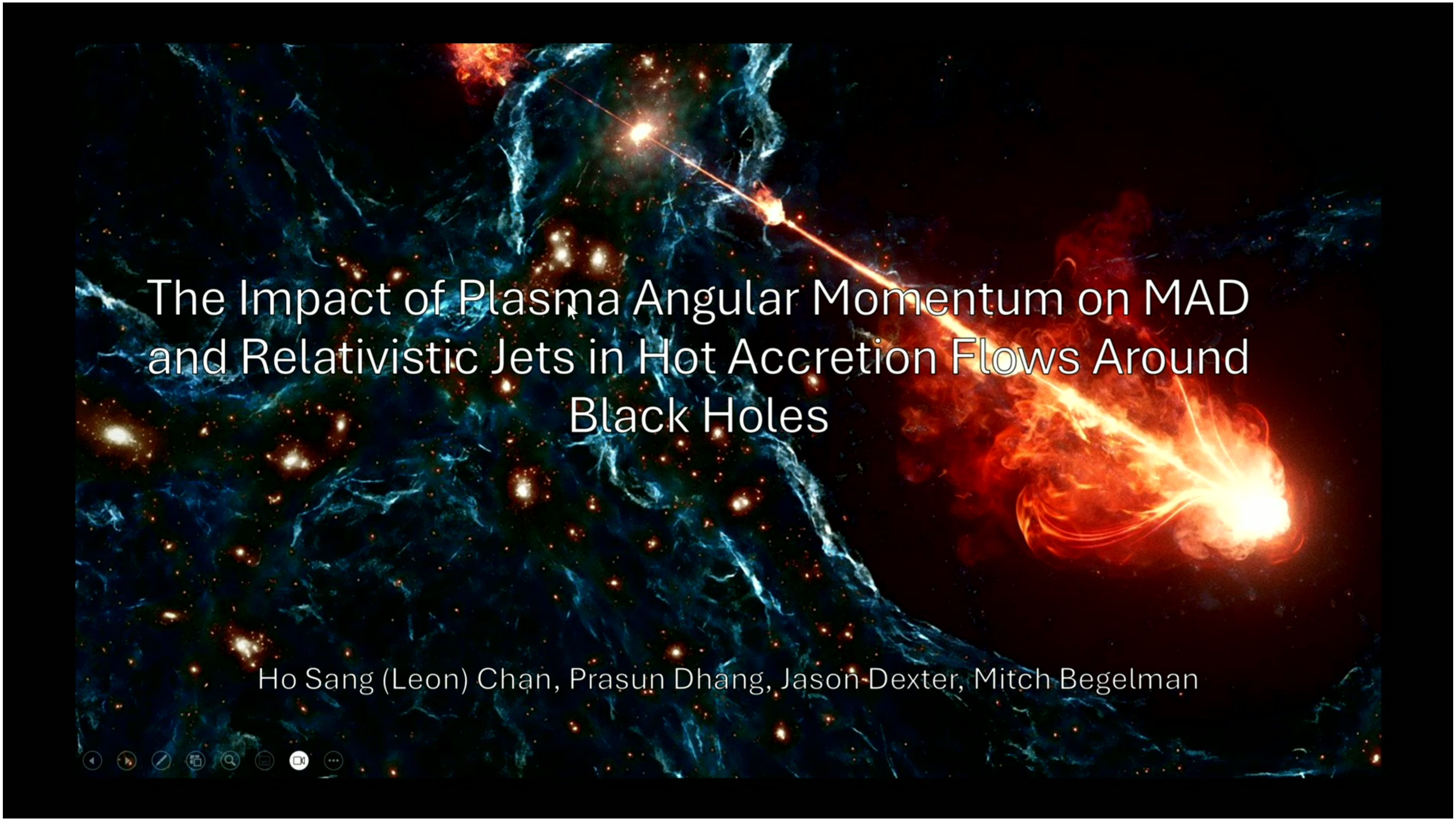
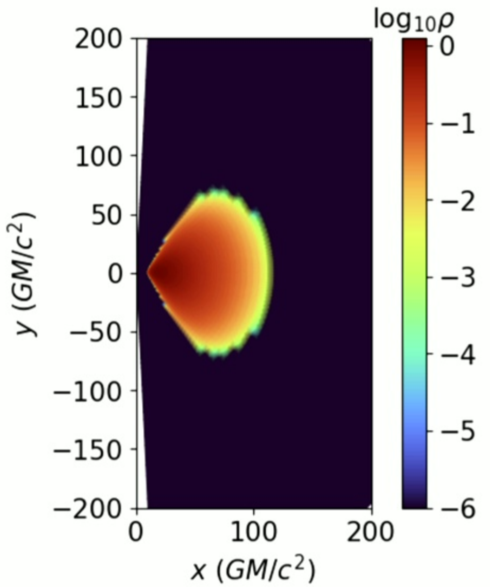
Abstract:

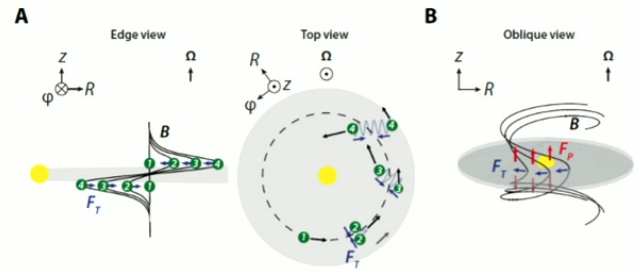
In certain scenarios, the accreted angular momentum of plasma onto a black hole could be low; however, how the accretion dynamics depends on the angular momentum content of the plasma is still not fully understood. We present three-dimensional, general relativistic magnetohydrodynamic simulations of low angular momentum accretion flows around rapidly spinning black holes (with spin $a = +0.9$). The initial condition is a Fishbone-Moncrief (FM) torus threaded by a large amount of poloidal magnetic flux, where the angular velocity is a fraction f of the standard value. For $f = 0$, the accretion flow becomes magnetically arrested and launches relativistic jets but only for a very short duration. After that, free-falling plasma breaks through the magnetic barrier, loading the jet with mass and destroying the jet-disk structure. Meanwhile, magnetic flux is lost via giant, asymmetrical magnetic bubbles that float away from the black hole. The accretion then exits the magnetically arrested state. For $f = 0.1$, the dimensionless magnetic flux threading the black hole oscillates quasi-periodically. The jet-disk structure shows concurrent revival and destruction while the gas efficiency at the event horizon changes accordingly. For $f \geq 0.3$, we find that the dynamical behavior of the system starts to approach that of a standard accreting FM torus. Our results thus suggest that the accreted angular momentum is an important parameter that governs the maintenance of a magnetically arrested flow and launching of relativistic jets around black holes.

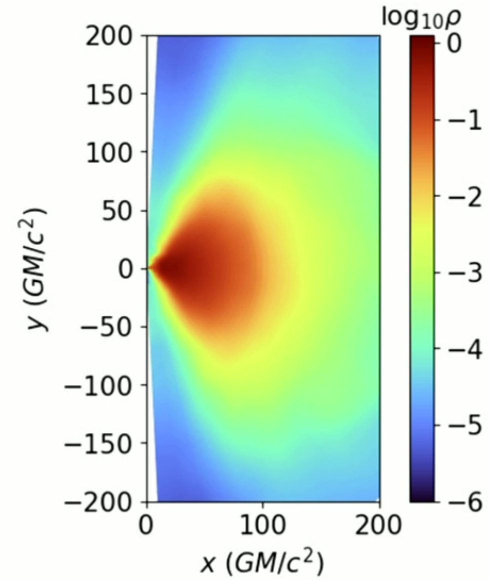

The Impact of Plasma Angular Momentum on MAD and Relativistic Jets in Hot Accretion Flows Around Black Holes
Ho Sang (Leon) Chan, Prasun Dhang, Jason Dexter, Mitch Begelman

“Standard” Accretion Simulation

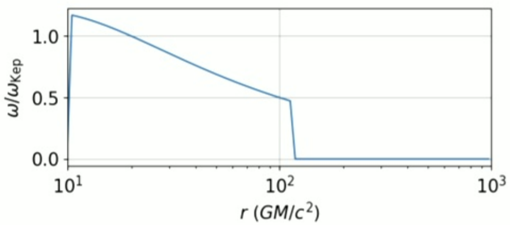


https://www.ias.tsinghua.edu.cn/

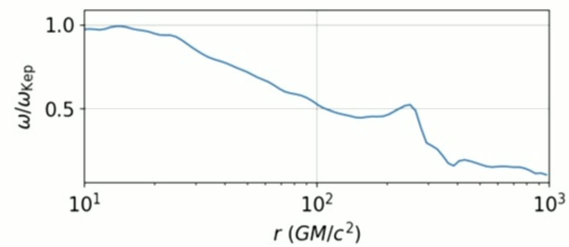




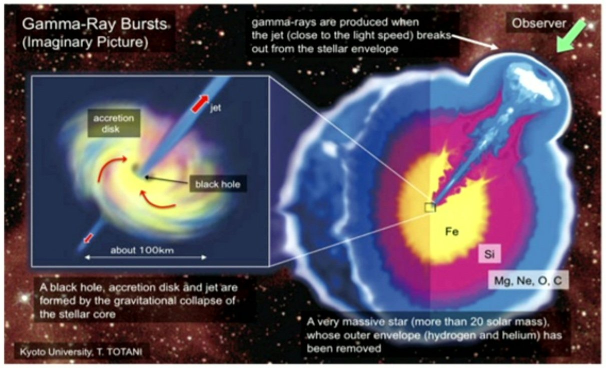
MRI



Angular Momentum Transport



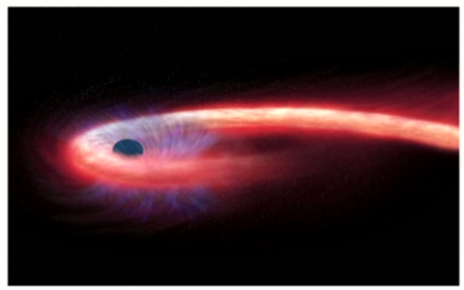
Low/Zero Angular Momentum Accretion



https://www.nao.ac.jp/

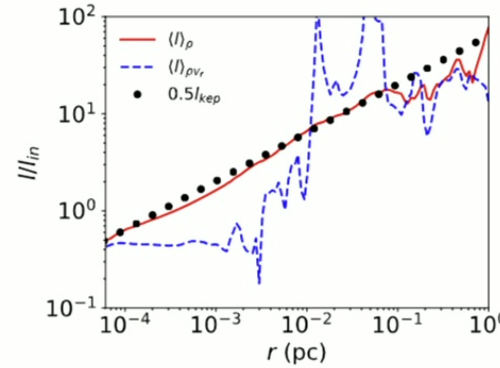
Collapsar (?)

TDEs (?)

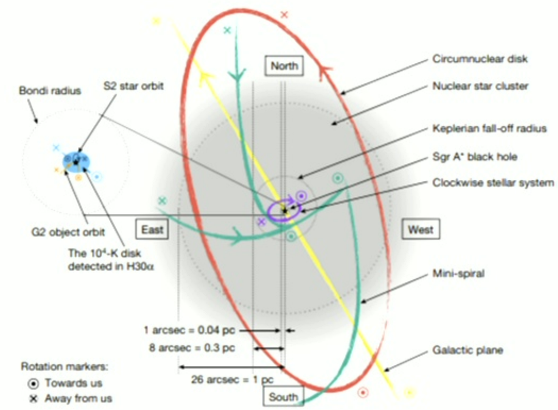


https://www.transients.science/

Ressler et al. 2018



Wind-fed (?)



Murchikova et al. 2019

The accreted angular momentum of plasma onto a black hole could be low in some cases

Plasma Angular Momentum and Jets?

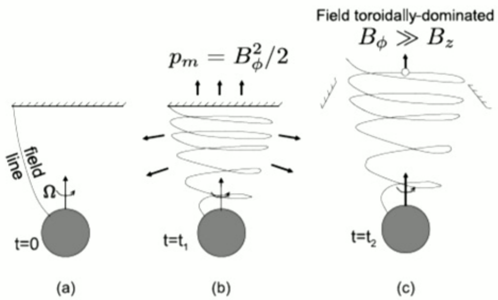
Dynamically important magnetic fields near the event horizon of Sgr A*★

GRAVITY Collaboration: A. Jiménez-Rosales[1,★★], J. Dexter[14,1], F. Widmann[1], M. Bauböck[1], R. Abuter[8], A. Amorim[6,13], J. P. Berger[5], H. Bonnet[8], W. Brandner[3], Y. Clénet[2], P. T. de Zeeuw[11,1], A. Eckart[4,10], F. Eisenhauer[1] N. M. Förster Schreiber[1], P. Garcia[7,13], F. Gao[1], E. Gendron[2], R. Genzel[1,12], S. Gillessen[1], M. Habibi[1], X. Haubois[9], G. Heißel[2], T. Henning[3], S. Hippler[3], M. Horrobin[4], L. Jochum[9], L. Jocou[5], A. Kaufer[9], P. Kervella[2], S. Lacour[2], V. Lapeyrère[2], J.-B. Le Bouquin[5], P. Léna[2], M. Nowak[2], T. Ott[1], T. Paumard[2], K. Perraut[5], G. Perrin[2], O. Pfuhl[8,1], G. Rodríguez-Coira[2], J. Shangguan[1], S. Scheithauer[3], J. Stadler[1], O. Straub[1], C. Straubmeier[4], E. Sturm[1], L. J. Tacconi[1], F. Vincent[2], S. von Fellenberg[1], I. Waisberg[15,1], E. Wieprecht[1], E. Wiezorrek[16,1], J. Woillez[8], S. Yazici[1,4], and G. Zins[9]

https://www.seramarkoff.com/

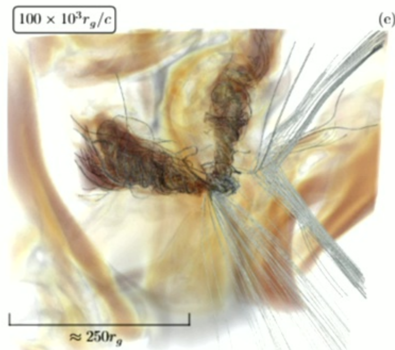
First Sagittarius A* Event Horizon Telescope Results. VIII. Physical Interpretation of the Polarized Ring

In a companion paper, we present the first spatially resolved polarized image of Sagittarius A* on event horizon scales, captured using the Event Horizon Telescope, a global very long baseline interferometric array operating at a wavelength of 1.3 mm. Here we interpret this image using both simple analytic models and numerical general relativistic magnetohydrodynamic (GRMHD) simulations. The large spatially resolved linear polarization fraction (24%–28%, peaking at ~40%) is the most stringent constraint on parameter space, disfavoring models that are too Faraday depolarized. Similar to our studies of M87*, polarimetric constraints reinforce a preference for GRMHD models with dynamically important magnetic fields. Although the spiral morphology of the polarization pattern is known to constrain the spin and inclination angle, the time-variable rotation measure (RM) of Sgr A* (equivalent to ≈46° ± 12° rotation at 228 GHz) limits its present utility as a constraint. If we attribute the RM to internal Faraday rotation, then the motion of accreting material is inferred to be counterclockwise, contrary to inferences based on historical polarized flares, and no model satisfies all polarimetric and total intensity constraints. On the other hand, if we attribute the mean RM to an external Faraday screen, then the motion of accreting material is inferred to be clockwise, and one model passes all applied total intensity and polarimetric constraints: a model with strong magnetic fields, a spin parameter of 0.94, and an inclination of 150°. We discuss how future 345 GHz and dynamical imaging will mitigate our present uncertainties and provide additional constraints on the black hole and its accretion flow.

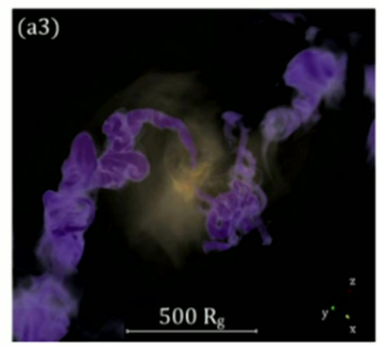


BZ-Process

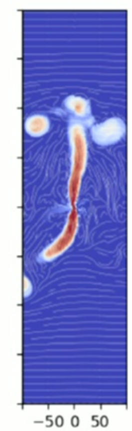
Galishnikova et al. 2025



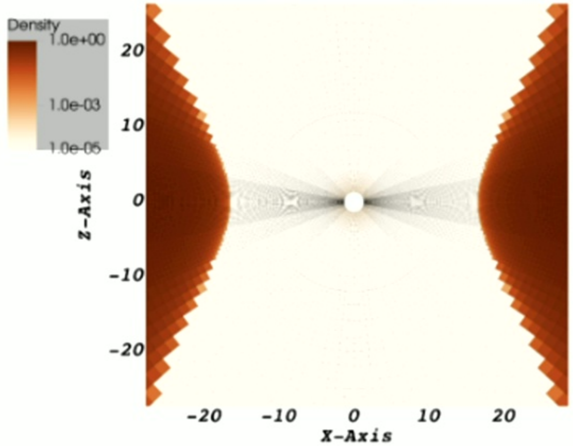
Lalakos et al. 2024

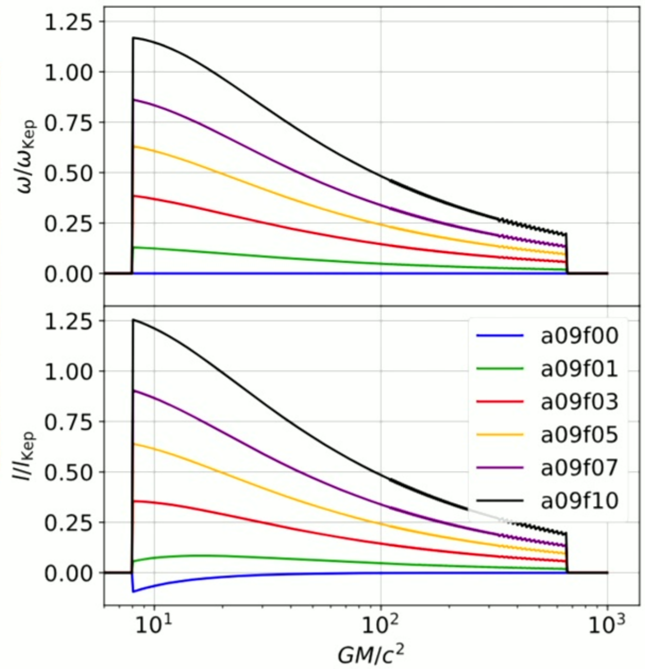


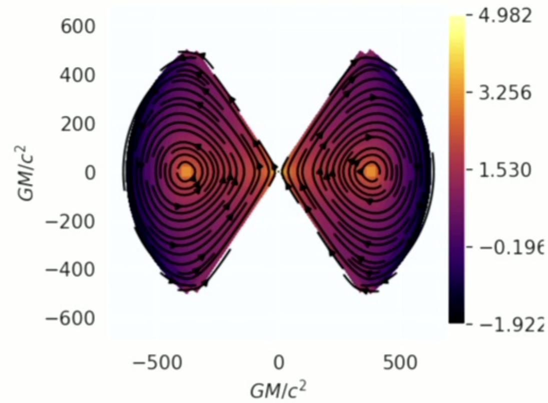
Ressler et al. 2021



Our Setup

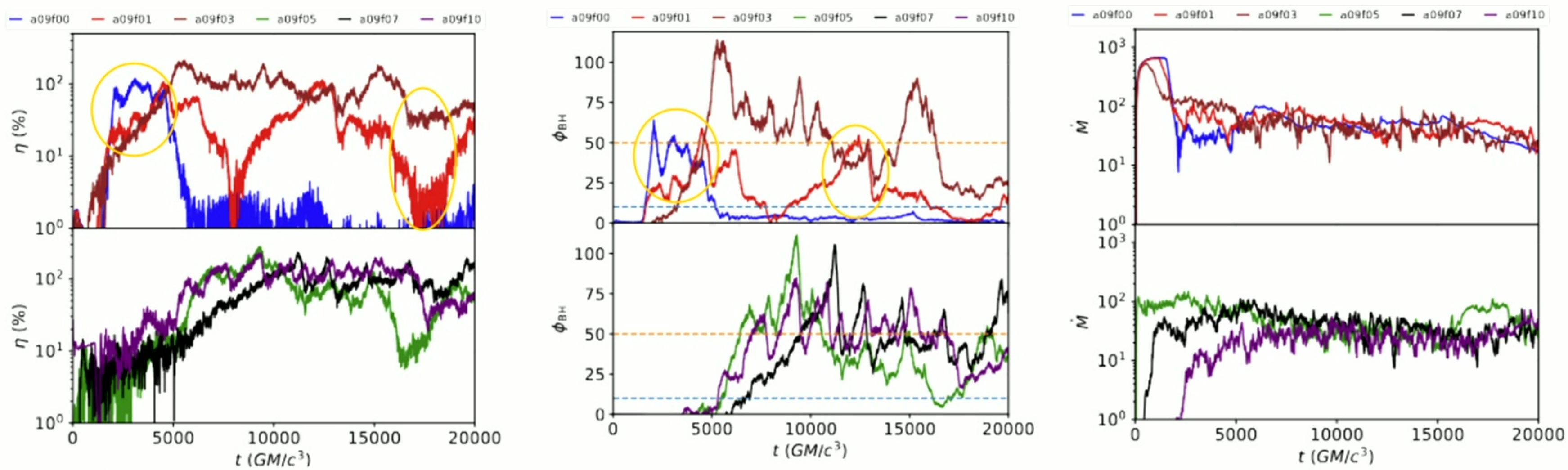






- Torus with varying angular velocity fraction f
- Threaded with a large amount of poloidal flux

Timeseries Diagnostic



$$\dot{M} = -\int_0^{2\pi}\int_0^{\pi} \rho u^r \sqrt{-g}\, d\theta d\phi,$$

$$\Phi_{\rm BH} = \sqrt{4\pi}\int_0^{2\pi}\int_0^{\pi} |B^r|\sqrt{-g}\, d\theta d\phi,$$

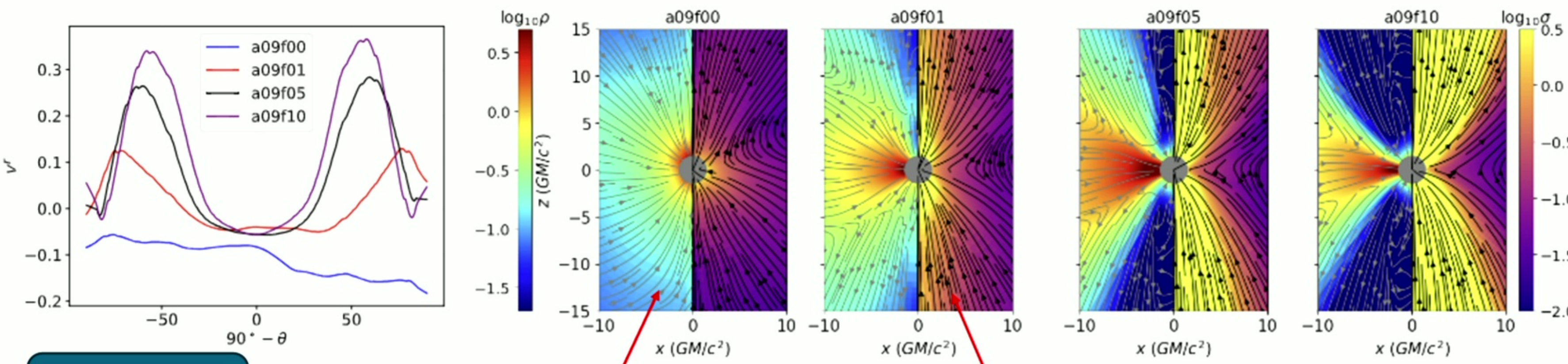
$$\dot{E} = \int_0^{2\pi}\int_0^{\pi} T^r_t \sqrt{-g}\, d\theta d\phi;$$

$$\boxed{\begin{aligned}\phi_{\rm BH} &= \Phi_{\rm BH}/(2\sqrt{\langle \dot{M}\rangle}),\\ \eta &= (\dot{M}-\dot{E})/\langle \dot{M}\rangle\end{aligned}}$$

- Model a09f00 – MAD and Jet for a short period only
- Model a09f01 – MAD and Jet quasi-periodically
- $\dot{M}$ doesn't vary as much as η and $\phi_{\rm BH}$
- Increasing f $\rightarrow$ approach "standard" MAD disc

Snapshot Analysis

$\sigma = b^2/\rho$



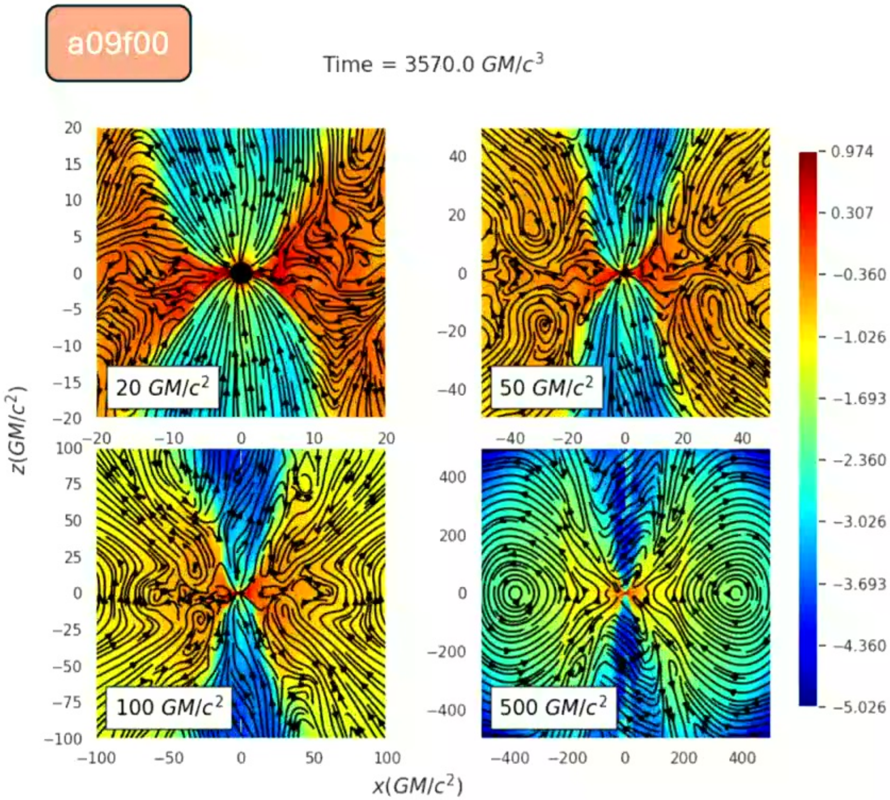
Measured at $10r_g$

Velocity

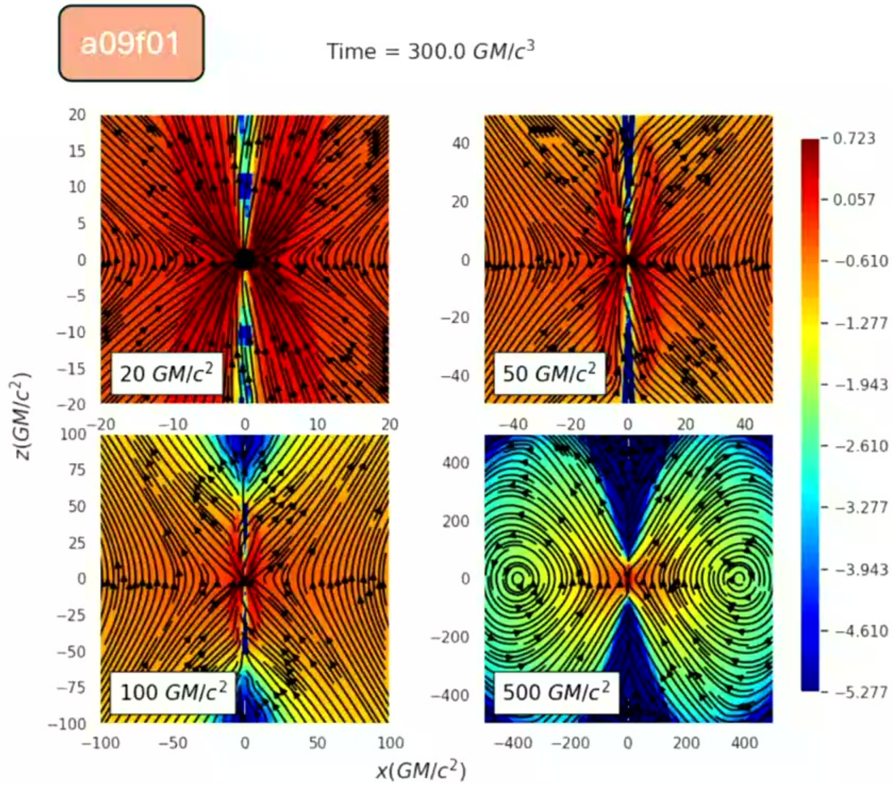
Magnetic Field

- $\phi - t$ averaged snapshot
- Model a09f00 – weak/no bipolar outflow, near symmetric inflow
- Model a09f01 – weak bipolar outflow, small opening angle
- Increasing f → approach "standard" MAD disc

Animation

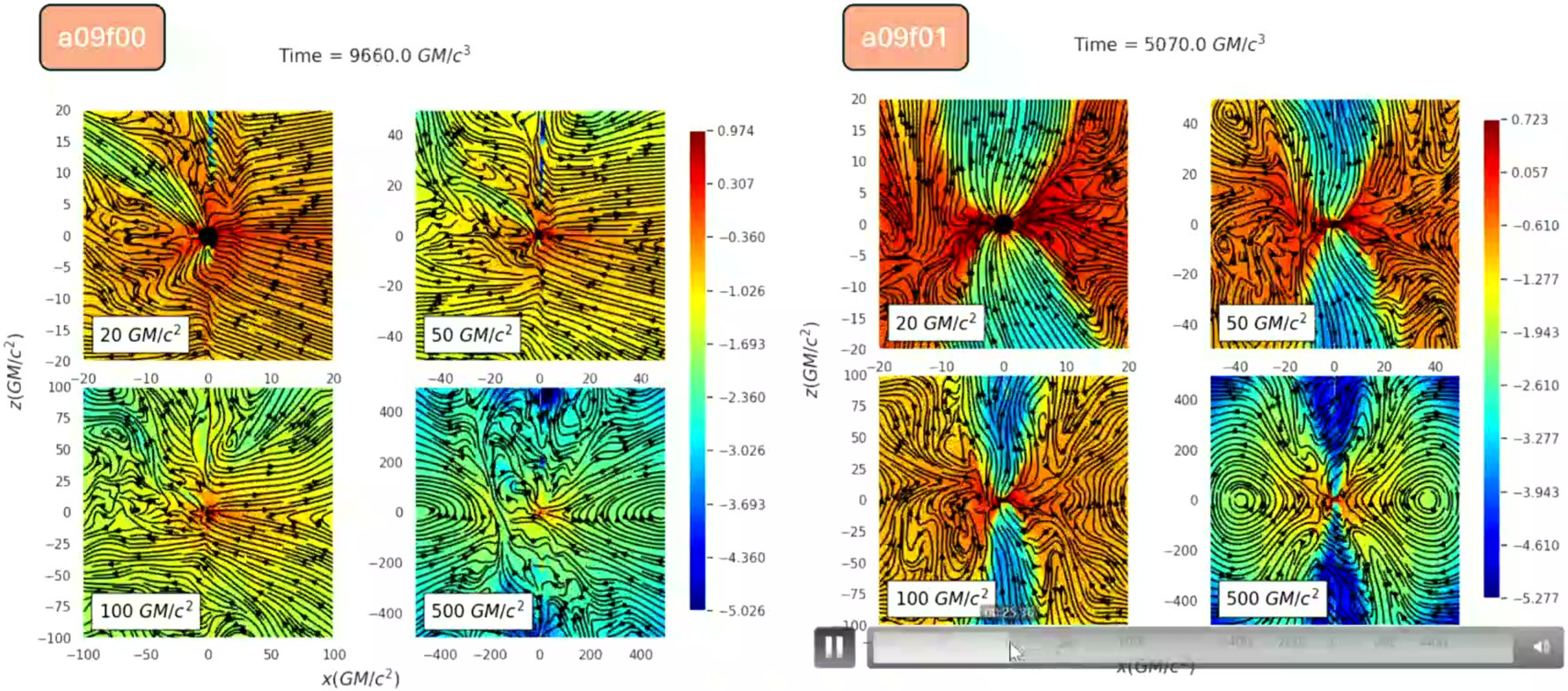


a09f00
Time = 3570.0 GM/c³
20 GM/c²
50 GM/c²
100 GM/c²
500 GM/c²
z(GM/c²)
x(GM/c²)
0.974
0.307
−0.360
−1.026
−1.693
−2.360
−3.026
−3.693
−4.360
−5.026



a09f01
Time = 300.0 GM/c³
20 GM/c²
50 GM/c²
100 GM/c²
500 GM/c²
z(GM/c²)
x(GM/c²)
0.723
0.057
−0.610
−1.277
−1.943
−2.610
−3.277
−3.943
−4.610
−5.277

Animation



a09f00
Time = 9660.0 GM/c^3
20 GM/c^2
50 GM/c^2
100 GM/c^2
500 GM/c^2
$z(GM/c^2)$
$x(GM/c^2)$
0.974
0.307
−0.360
−1.026
−1.693
−2.360
−3.026
−3.693
−4.360
−5.026
a09f01
Time = 5070.0 GM/c^3
0.723
0.057
−0.610
−1.277
−1.943
−2.610
−3.277
−3.943
−4.610
−5.277

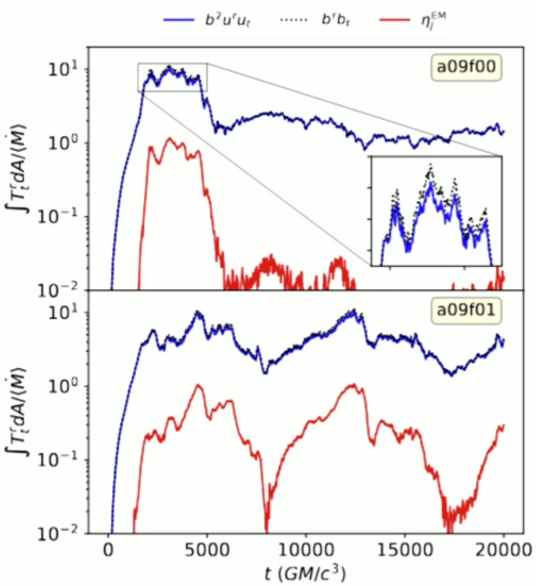
Electromagnetic Energy Extraction

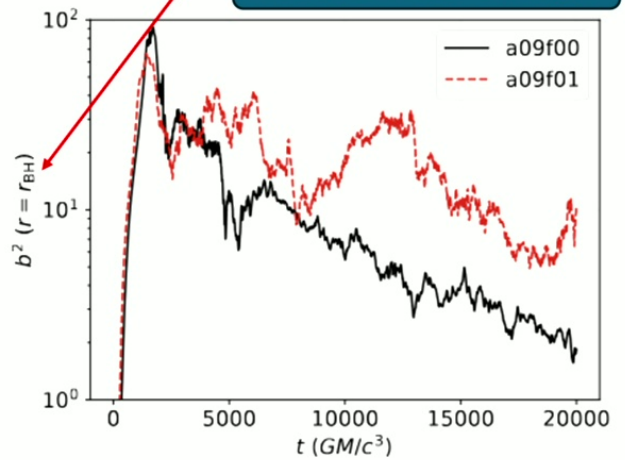
Flux Cancellations

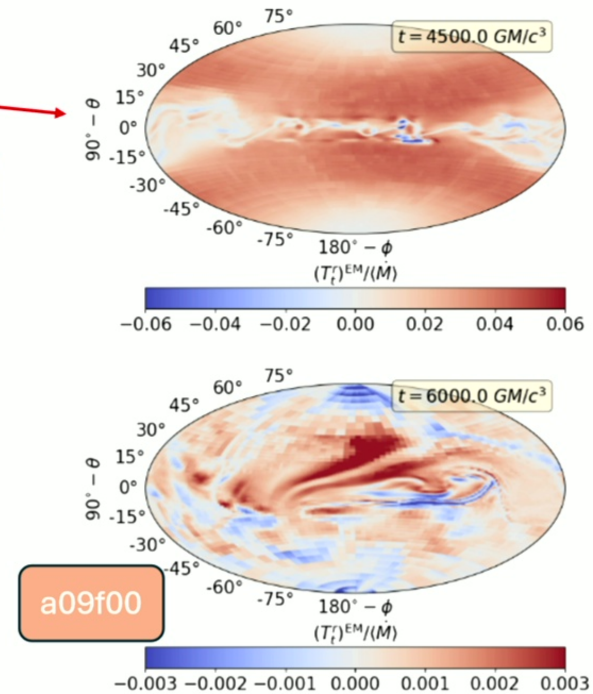
$$\eta_j^{\rm EM} = -\frac{1}{\langle \dot{M} \rangle} \int (T_t^r)^{\rm EM} \sqrt{-g} d\theta d\phi,$$

$$(T_t^r)^{\rm EM} = b^2 u^r u_t - b^r b_t$$

Reduced Field Strength

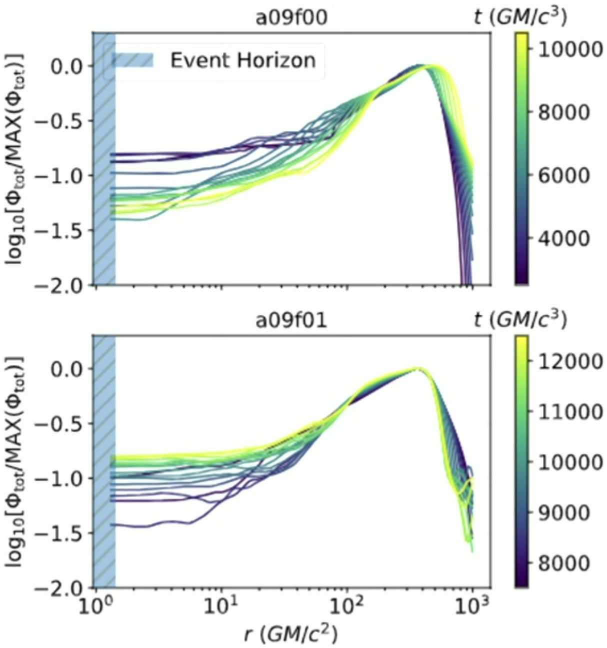






The Lack of Large-scale, Strong, Poloidal Field weaken bipolar outflows

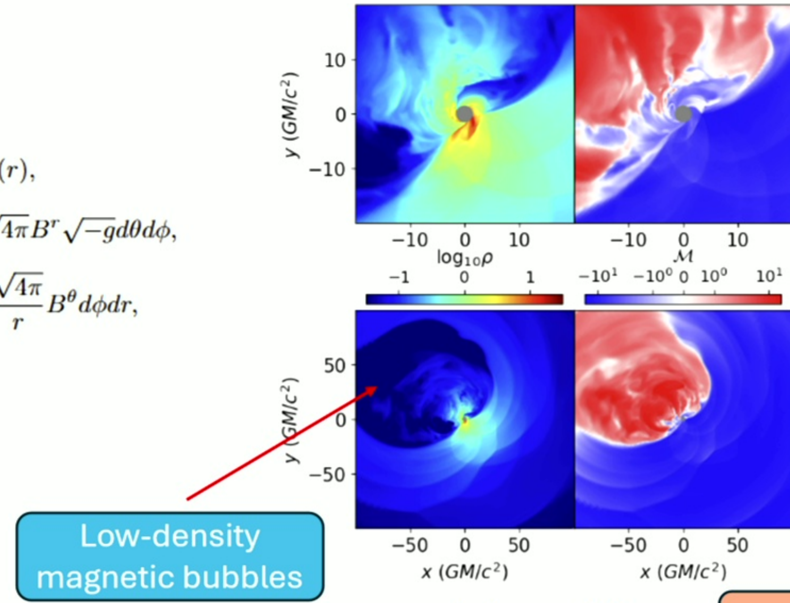
Magnetic Flux Transport



$$\Phi_{\rm tot}(r) = \Phi_{\rm NH} + \Phi_{\rm mid}(r),$$

$$\Phi_{\rm NH} = \int_0^{2\pi}\int_0^{\pi/2} \sqrt{4\pi} B^r \sqrt{-g}\, d\theta d\phi,$$

$$\Phi_{\rm mid}(r) = \int_{r_{\rm BH}}^{r}\int_0^{2\pi} -\frac{\sqrt{4\pi}}{r} B^\theta d\phi dr,$$

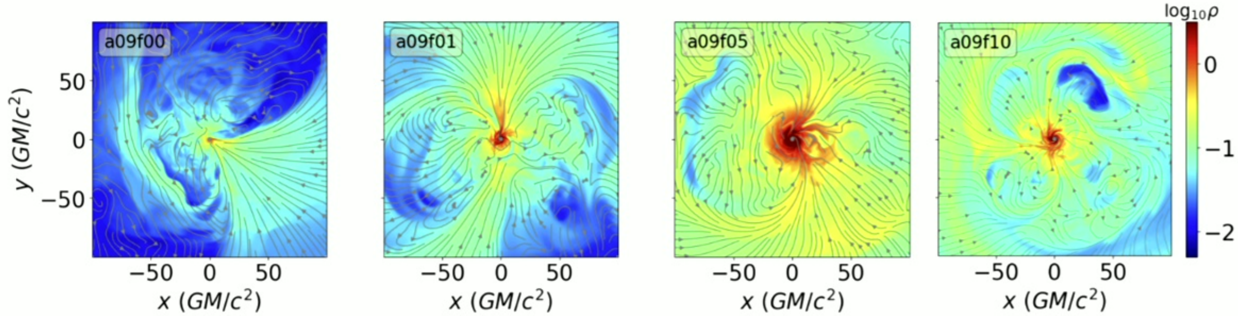


$$\mathcal{M} = v^r / c_s$$

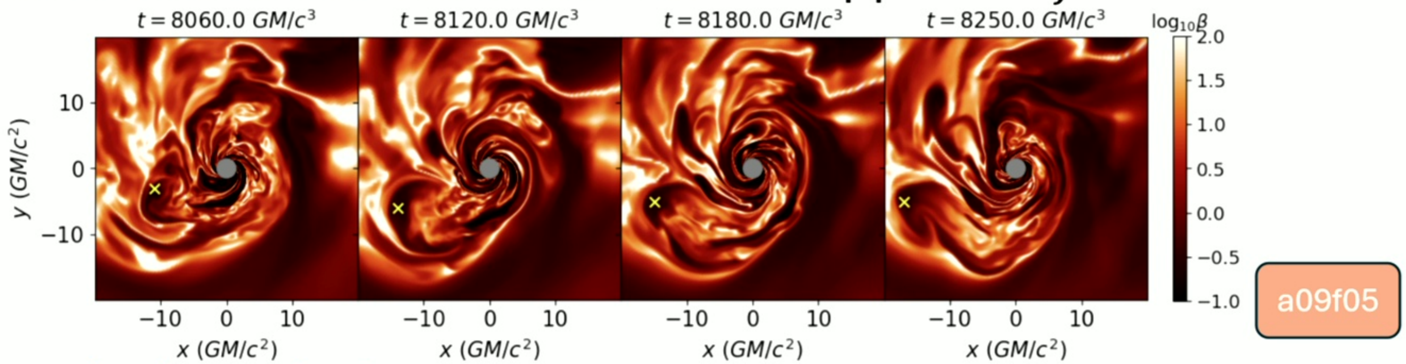
a09f00

- Jet dying/revival state associated to the transport of poloidal magnetic flux
- Model a09f00 – huge amount of flux ejected via high-speed bubbles
- Model a09f01 – flux transport inward-outward quasi periodically

The Role of Shear



- Asymmetric inflow-outflow structure – disappear as f increases



- Shear can be important
  - Stretches bubbles azimuthally
  - Mixes weakly and strongly magnetized gas

Conclusion

- Accreted angular momentum is an important parameter of MAD and jets
- Our study with torus setup – consistent with previous simulations (Bondi)
- Jet/MAD dying/revival – related to magnetic flux transport
- Small f - no large-scale poloidal field – inefficient BH energy extraction
- Larger f – shear tear the magnetic bubbles, stir them with the main accretion follow, and recycle back to the BH

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