How do black holes ~~shine~~ accrete and eject?

Bart Ripperda
Canadian Institute for Theoretical Astrophysics
University of Toronto
Flatiron Institute

Work done by and in collaboration with Sasha Philippov, Sean Ressler, Matthew Liska, Koushik Chatterjee, Alisa Galishnikova, Vladimir Zhdankin, Gibwa Musoke

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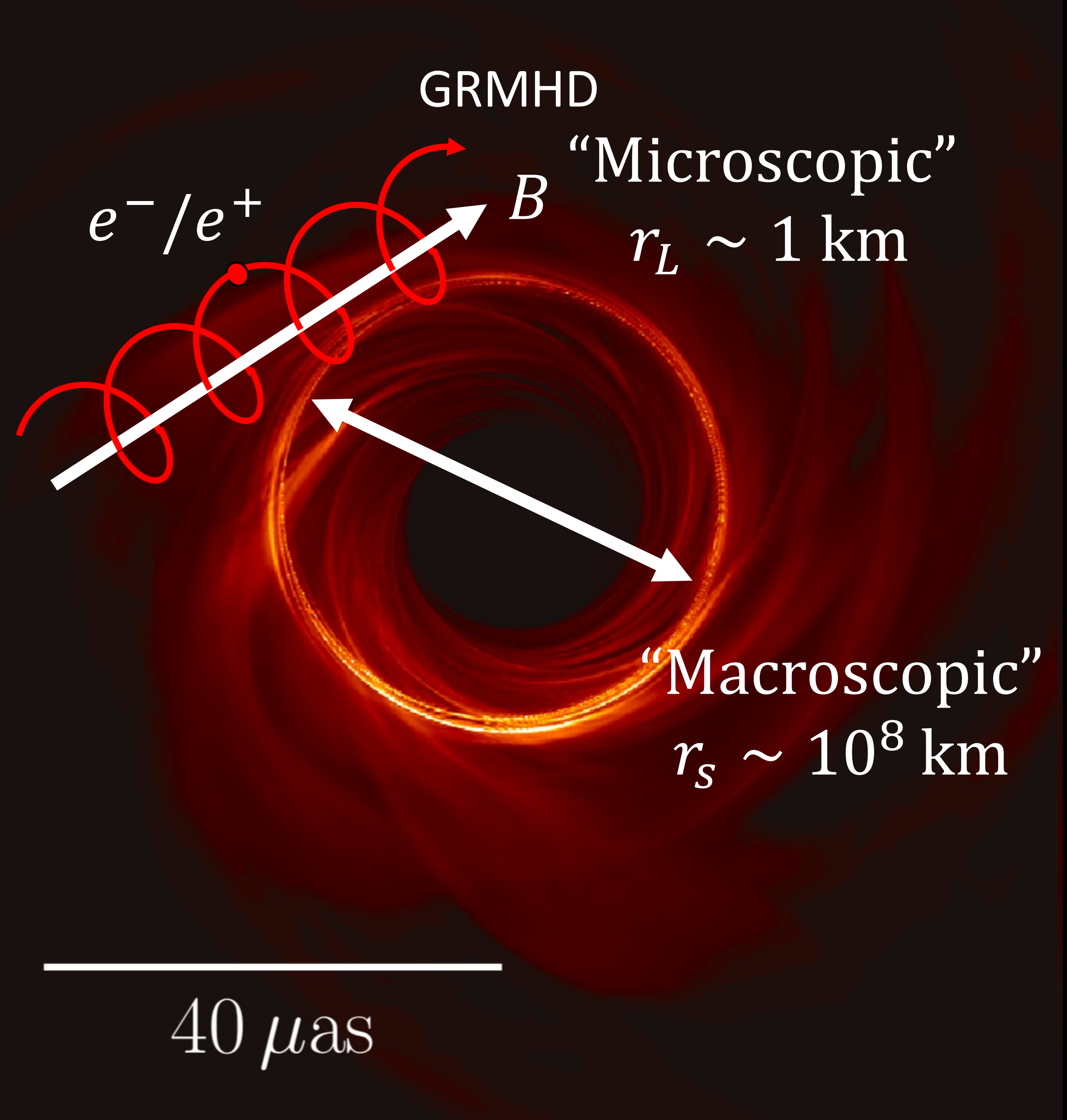


Plasma properties for M87

Credit: NASA Hubble

→ Jet power: magnetic field at horizon $\sim 100\ G$

→ Mean free path $> 10^8 r_s$ (Schwarzschild radii)
  → Collisionless plasma
    → Non-thermal effects important

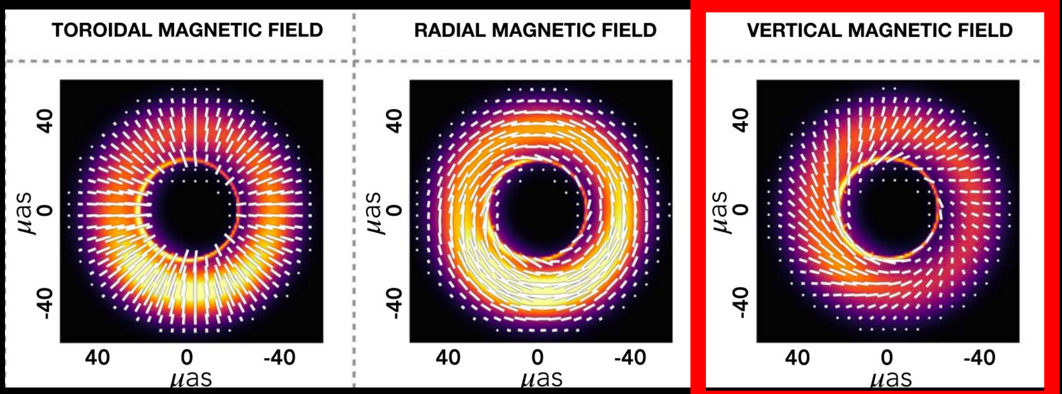
→ GRMHD treats plasma as collisional thermal fluid
  → electron temperature unknown

→ Main uncertainty in interpreting radiation and where it comes from by which mechanism!

→ GRMHD can help with where and how

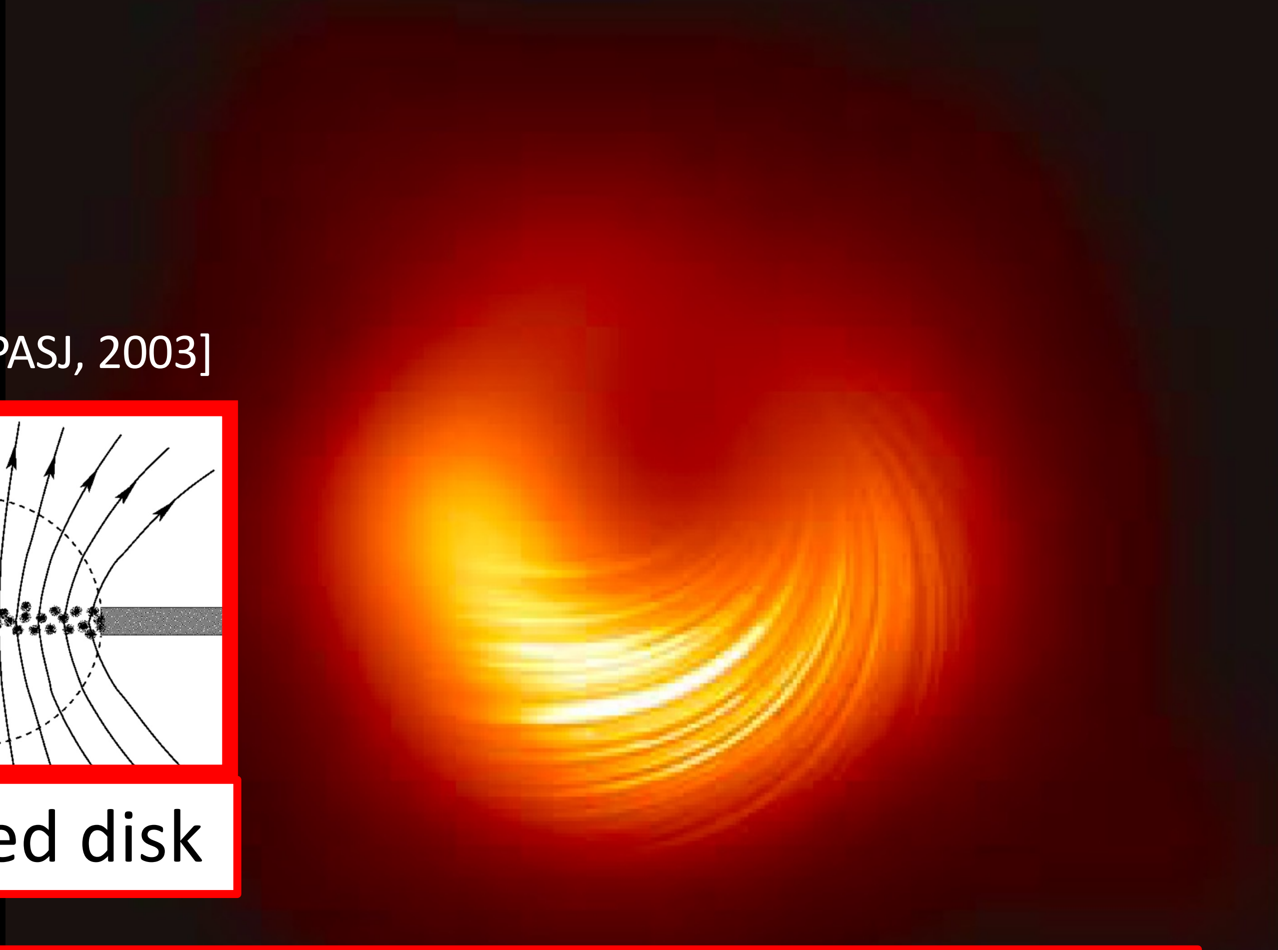
[EHT collaboration (**incl. Ripperda**), ApJL, 2019]

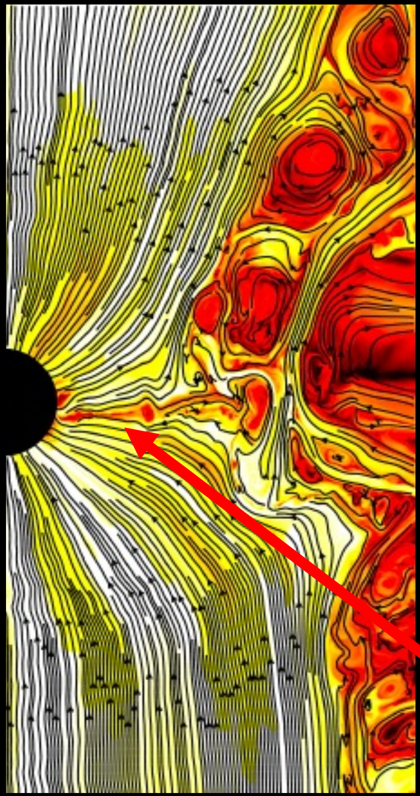
GRMHD and Polarization images tell us M87*'s magnetic field structure



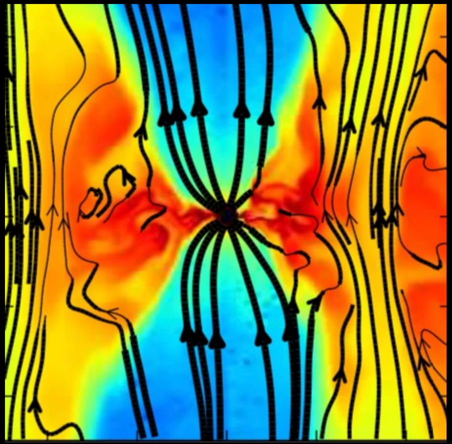
[EHT (incl. **Ripperda**), ApJL, 2021]

"Weak and turbulent" or "<u>strong and coherent</u>"?

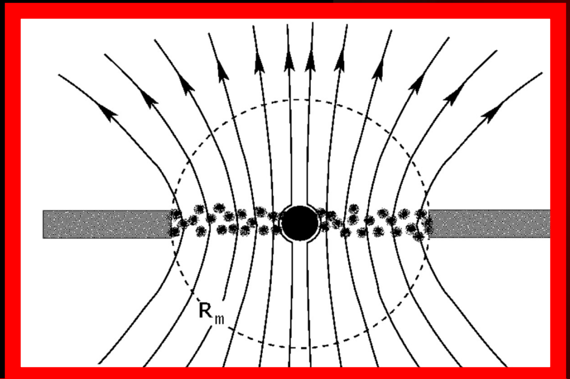




[Tchekhovskoy et al, MNRASL, 2011]



[Narayan et al, PASJ, 2003]



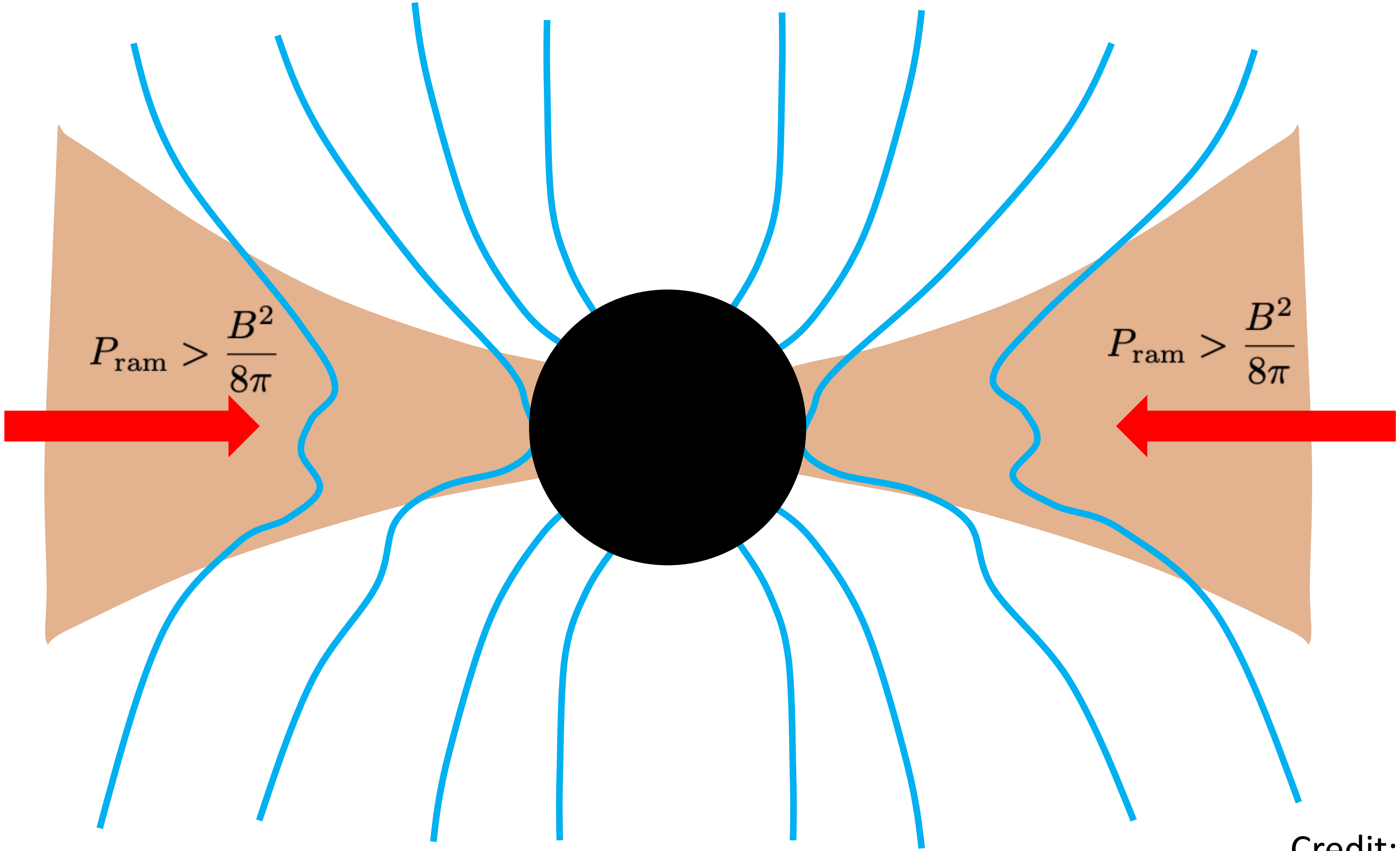
Magnetically arrested disk

Extreme resolution 2D resistive GRMHD: reconnection!

[**Ripperda** et al, ApJ, 2020]

How does reconnection occur close to the black hole horizon?

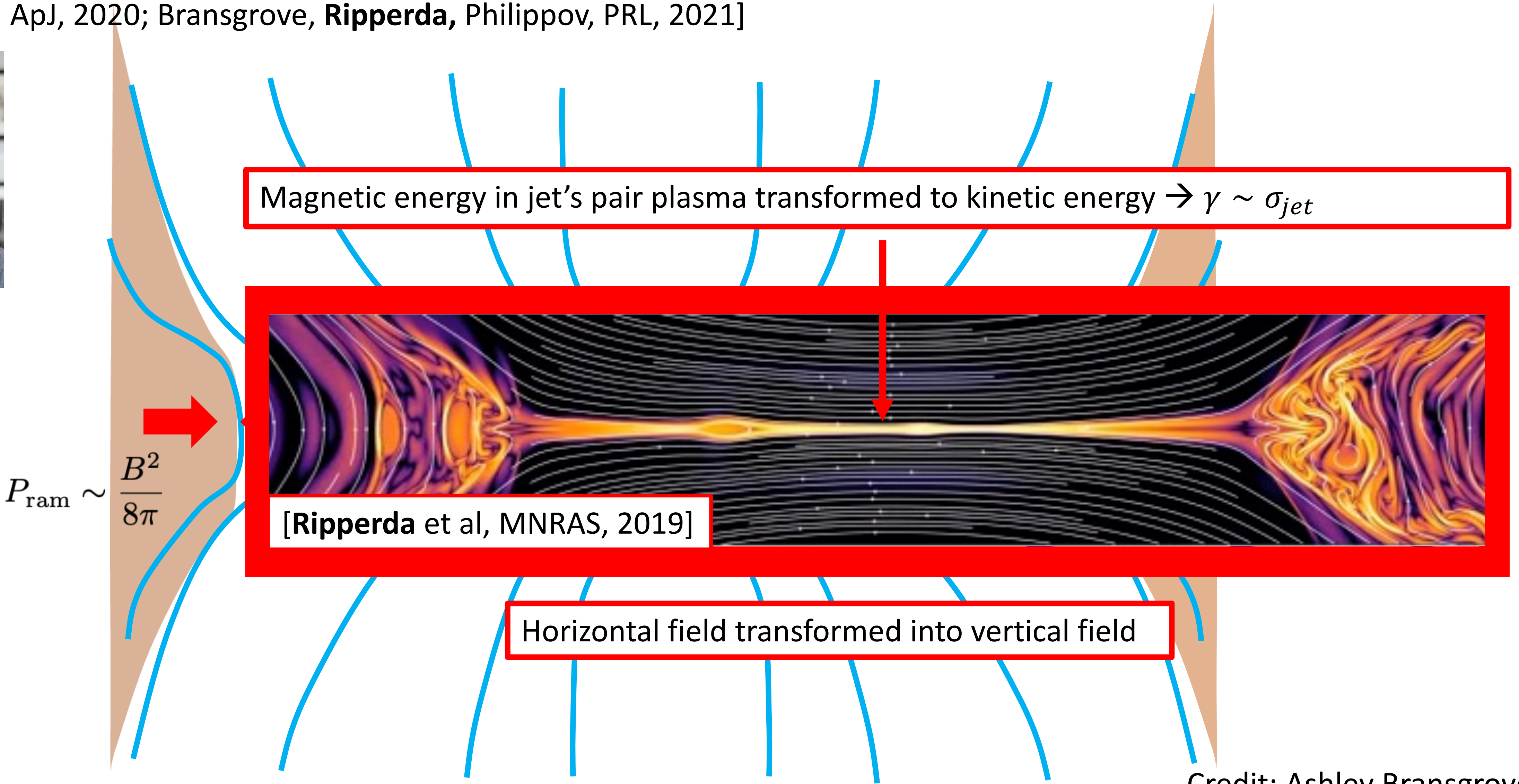
Idea: Accretion cycle of magnetically arrested state starts with infalling cold weakly magnetized gas



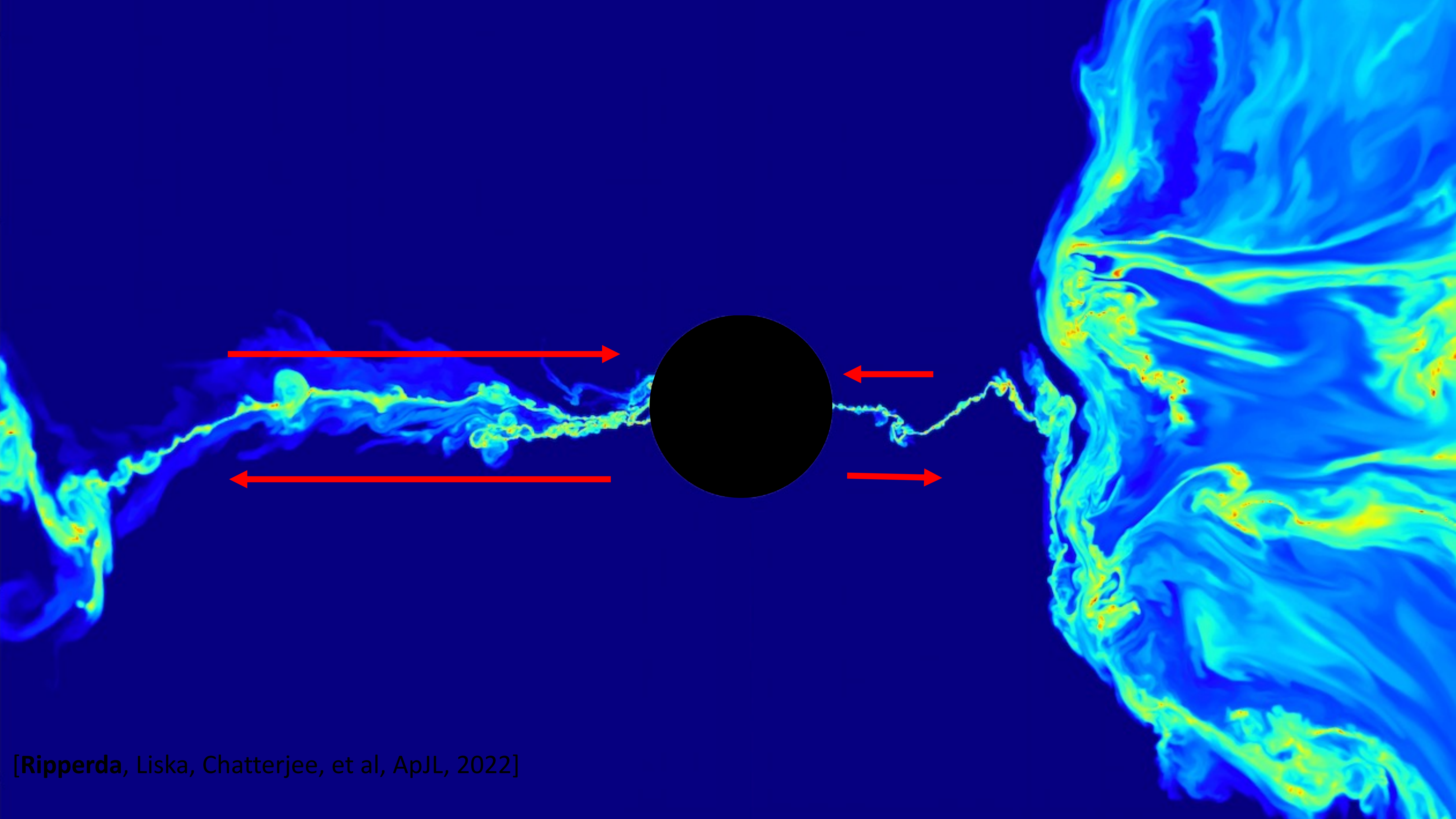
Credit: Ashley Bransgrove

How does reconnection occur close to the black hole horizon?

Idea: Episodically flux builds up to maximum $p_{gas} \sim B^2/8\pi$, then magnetic reconnection expels magnetic field to power flare [**Ripperda** et al, ApJ, 2020; Bransgrove, **Ripperda,** Philippov, PRL, 2021]



Credit: Ashley Bransgrove

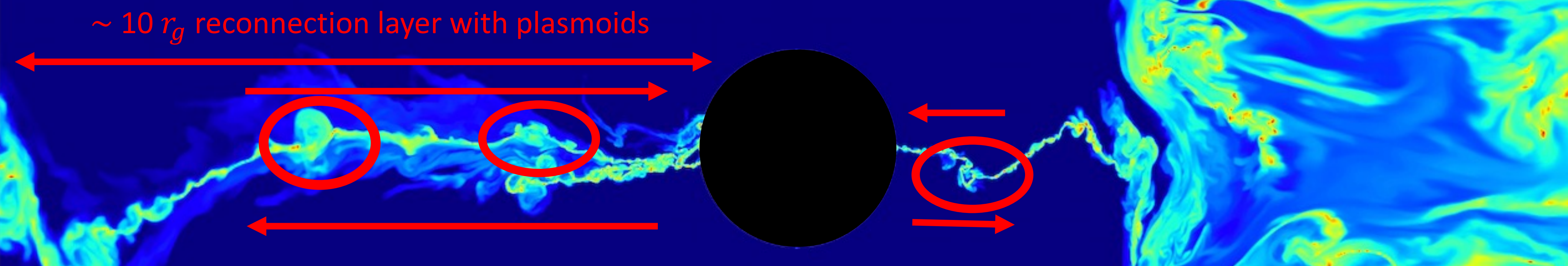


[**Ripperda**, Liska, Chatterjee, et al, ApJL, 2022]

Largest 3D GRMHD simulation ever zooms into Event Horizon

Take-away from 3D GRMHD:

- Transient non-axisymmetric macroscopic reconnection layer and ejected disk in accretion duty cycles
- Jet’s reconnected magnetic energy can power a very high energy flare
- Reconnection is essential in accretion duty cycle to redistribute magnetic flux!

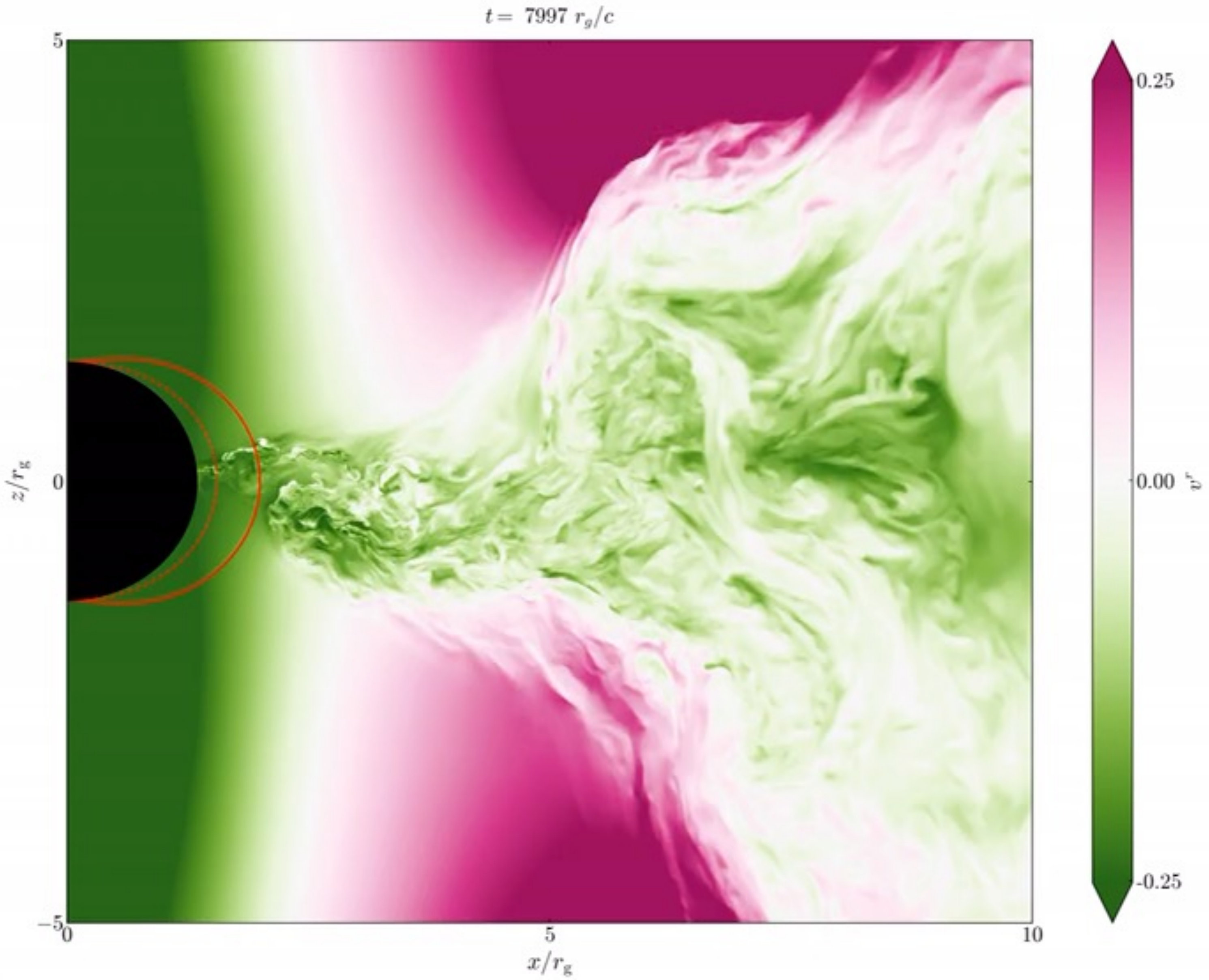


- Resolving fast reconnection requires $\geq 5000\times2500\times2500$ cells
- $> 10\times10\times10$ larger than our EHT simulations → 2.1×10^6 GPU hours on 6000 GPU’s
- Only possible with GPU-accelerated H-AMR code! [Liska et al, arXiv:1912.10192]

Details depend on collisionless kinetic plasma dynamics:

- particle acceleration, radiation, pair creation, kinetic instabilities

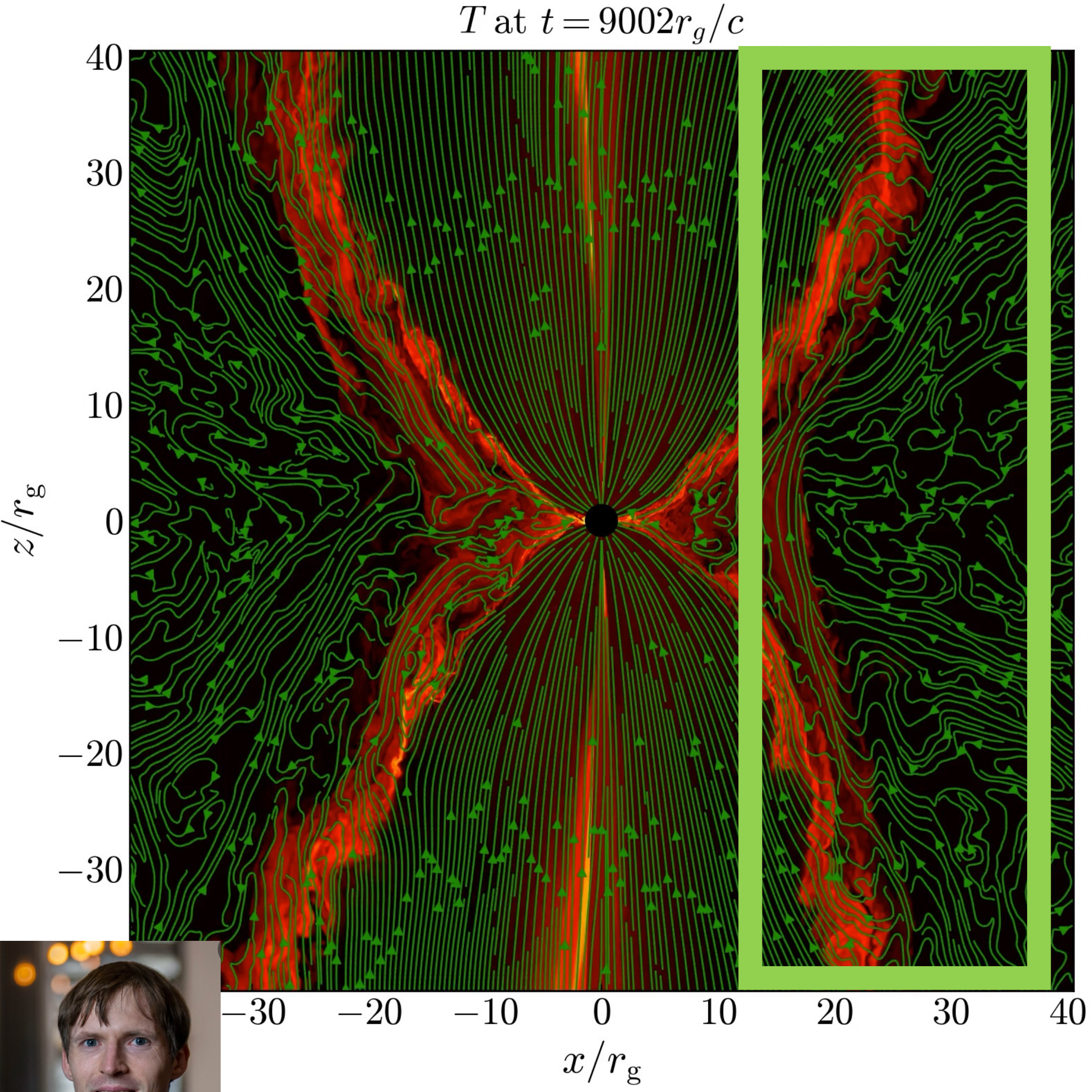
[**Ripperda,** Liska, Chatterjee, et al, ApJL, 2022]

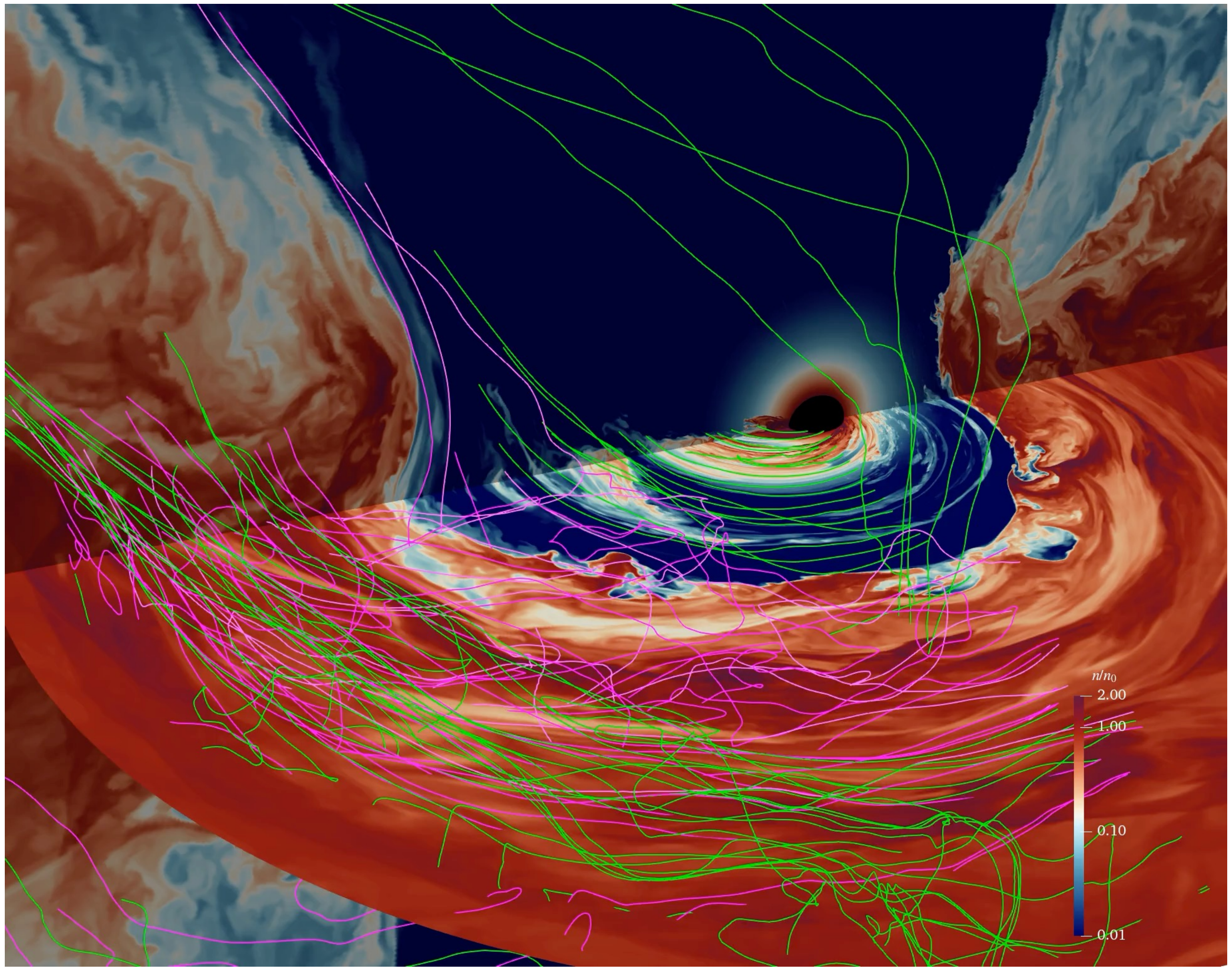


During the turbulent accretion phase there is inflow at the equator but mildly relativistic outflow in the form of a wind between the inner disk and the jet

During flux eruptions there is a large outflow/ejection!

Exhaust from reconnection drives accretion?



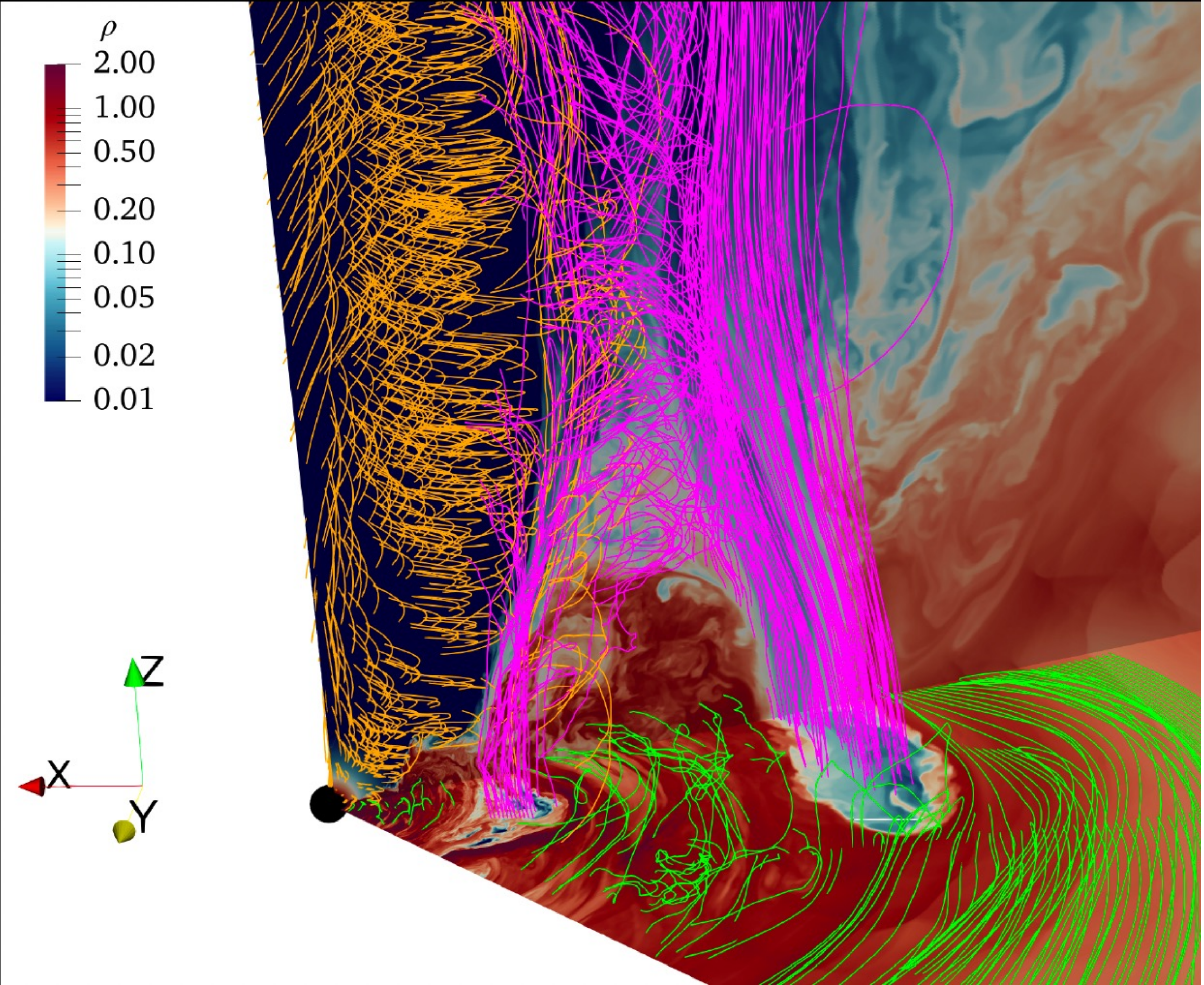


[Zhdankin, **Ripperda**, Philippov PRR (2023)]

Reconnection expels flux tube with vertical field confining pair plasma

→ Rayleigh-Taylor instability on hot spot boundary drives mixing of

- → Vertical magnetic field
- → Pair plasma into electron-ion disk



Reconnection expels flux tubes with vertical field at every duty cycle

They interact and stir the accretion flow

Can the eruptions be major drivers of turbulence?

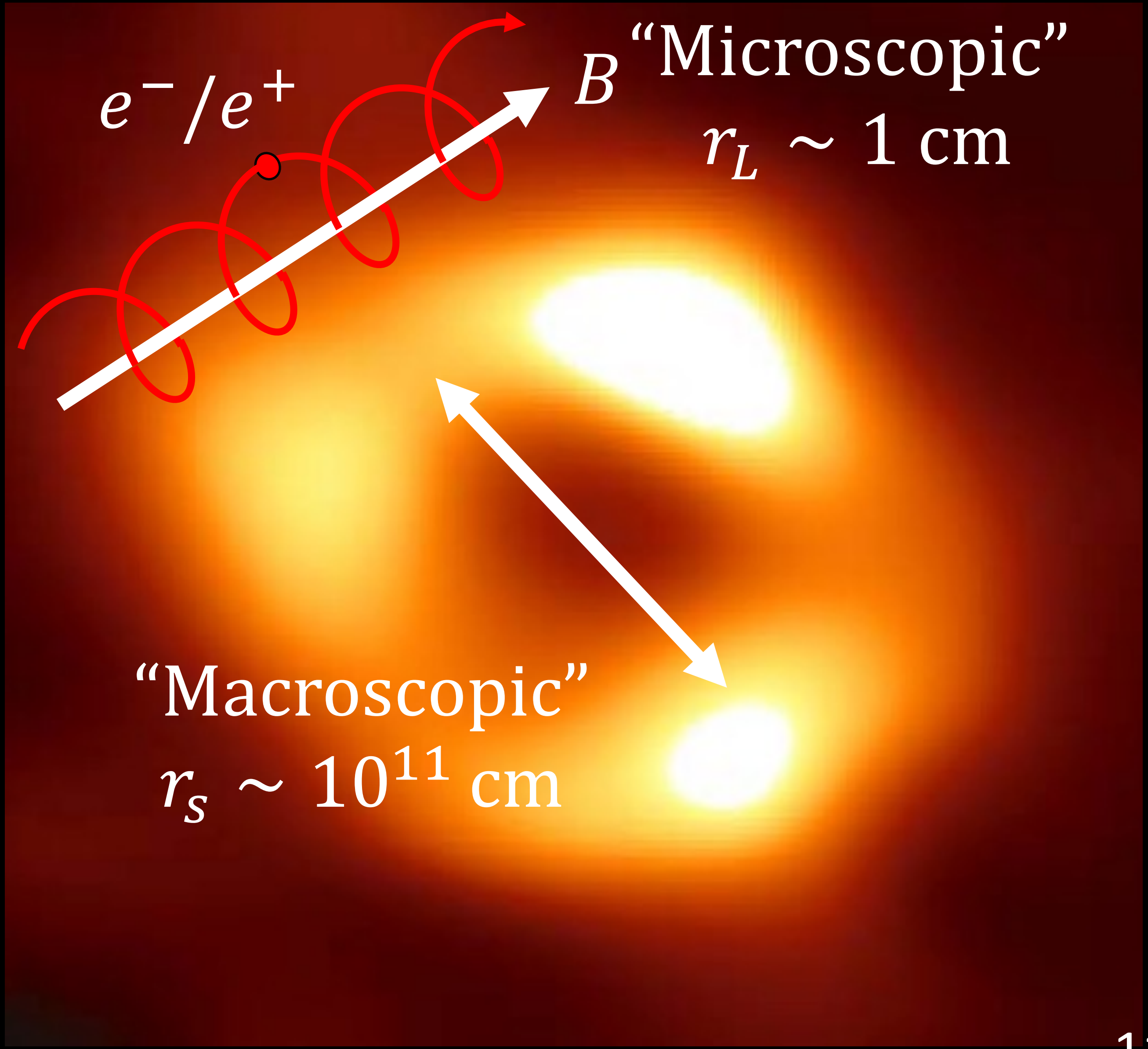
Can they make up the corona?

Similar picture for zero-angular momentum flows (MRI plays no role in driving turbulence in inner region?).

Plasma properties for Sgr A*

[EHT (incl. Ripperda), ApJL, 2022]

Sgr A* April 2017



→ No clear observed jet

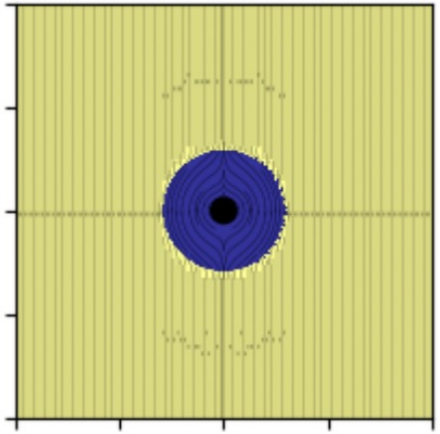
→ Collisionless, magnetized ($\lambda_{mfp} \gg r_s$, $r_L \ll r_s$)

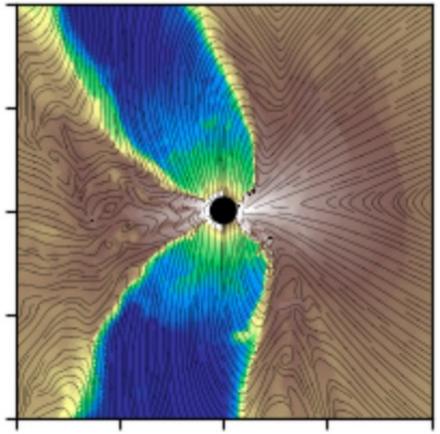
→ $\mathrm{B_{horizon}} \sim 100G$ ($29G$ at few r_s (Schwarzschild radii))

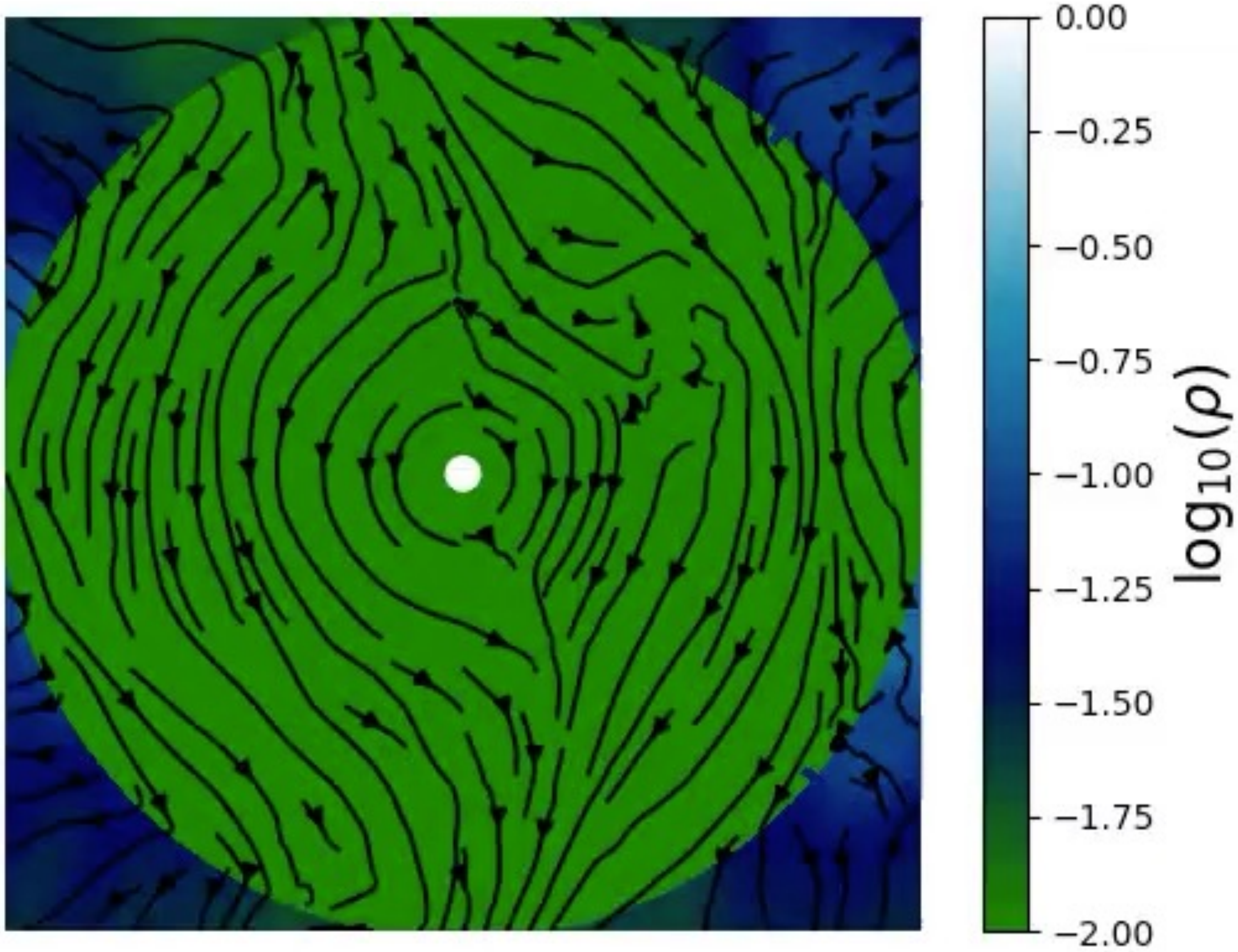
What is the magnetic structure of the accretion flow of Sgr A*?

Starting from unmagnetized wind-fed accretion, a magnetically arrested low-angular-momentum near-spherical accretion forms

- Transiently looks like a magnetically arrested disk [Ressler et al, MNRAS, 2021]
- Jet destroyed by kink instability → is that why Sgr A* shows no jet?
- MAD supported by Sgr A* observations [EHT (incl. Ripperda, ApJL, 2022)]

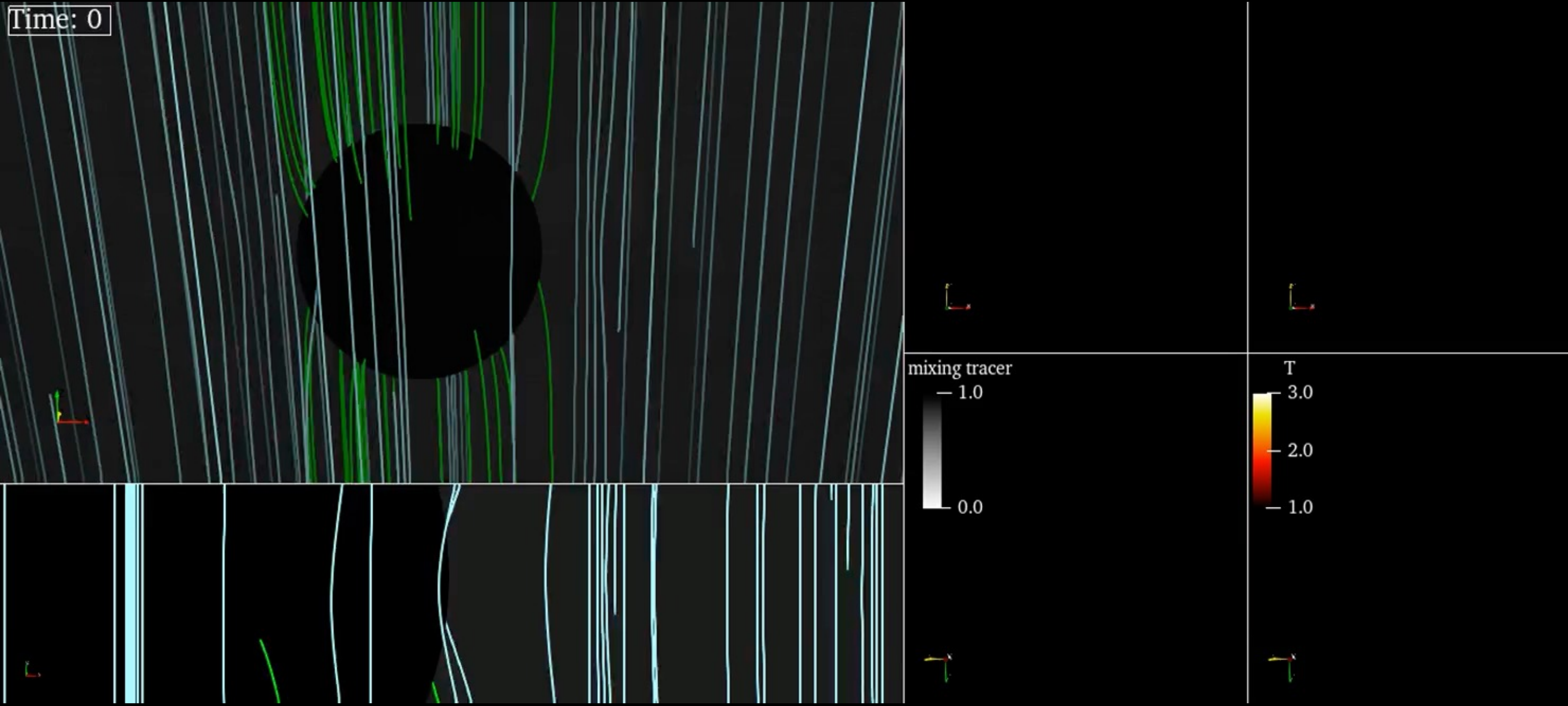






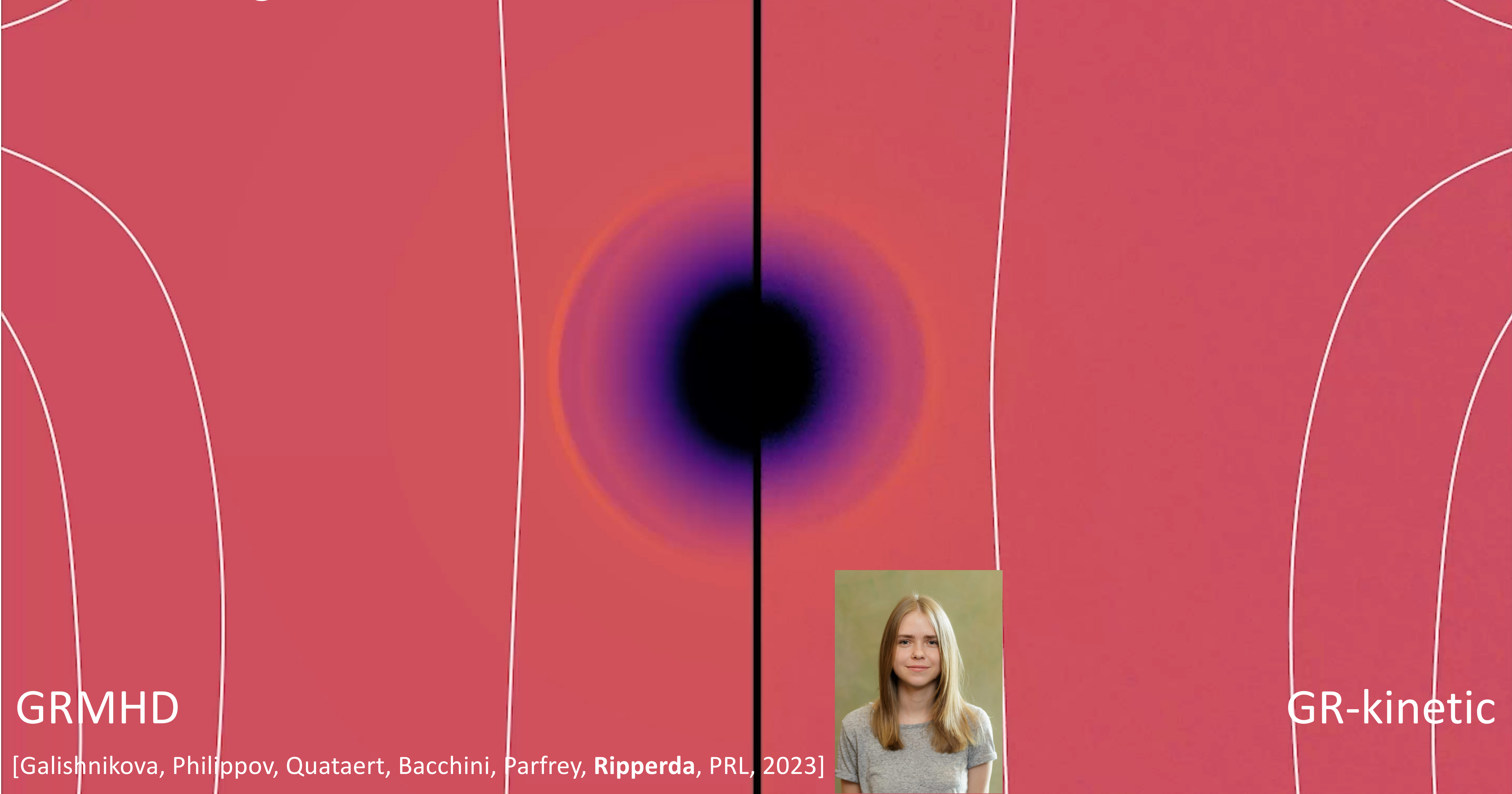
[Ressler et al, ApJL, 2020]

Can ejected flux tubes drive angular momentum in spherical accretion?



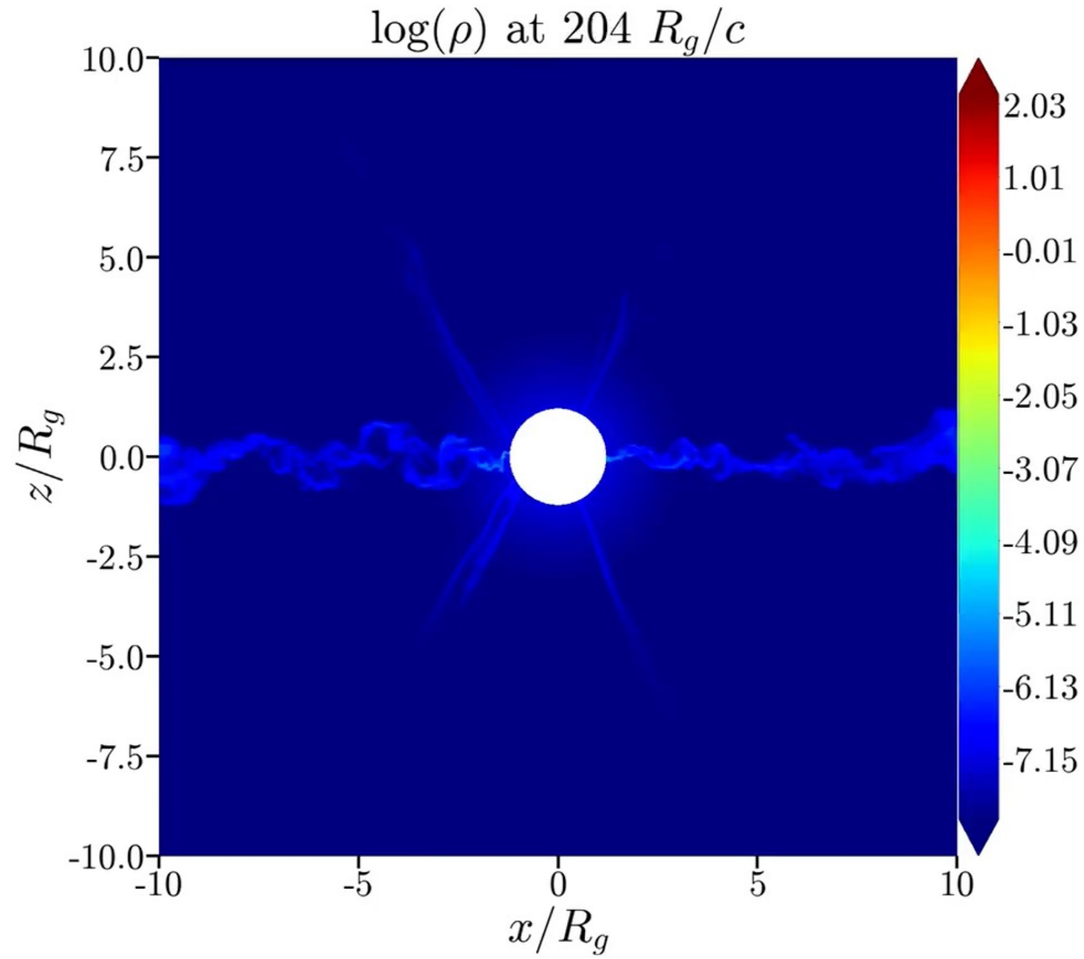
[**Ripperda,** Philippov et al, in prep.]

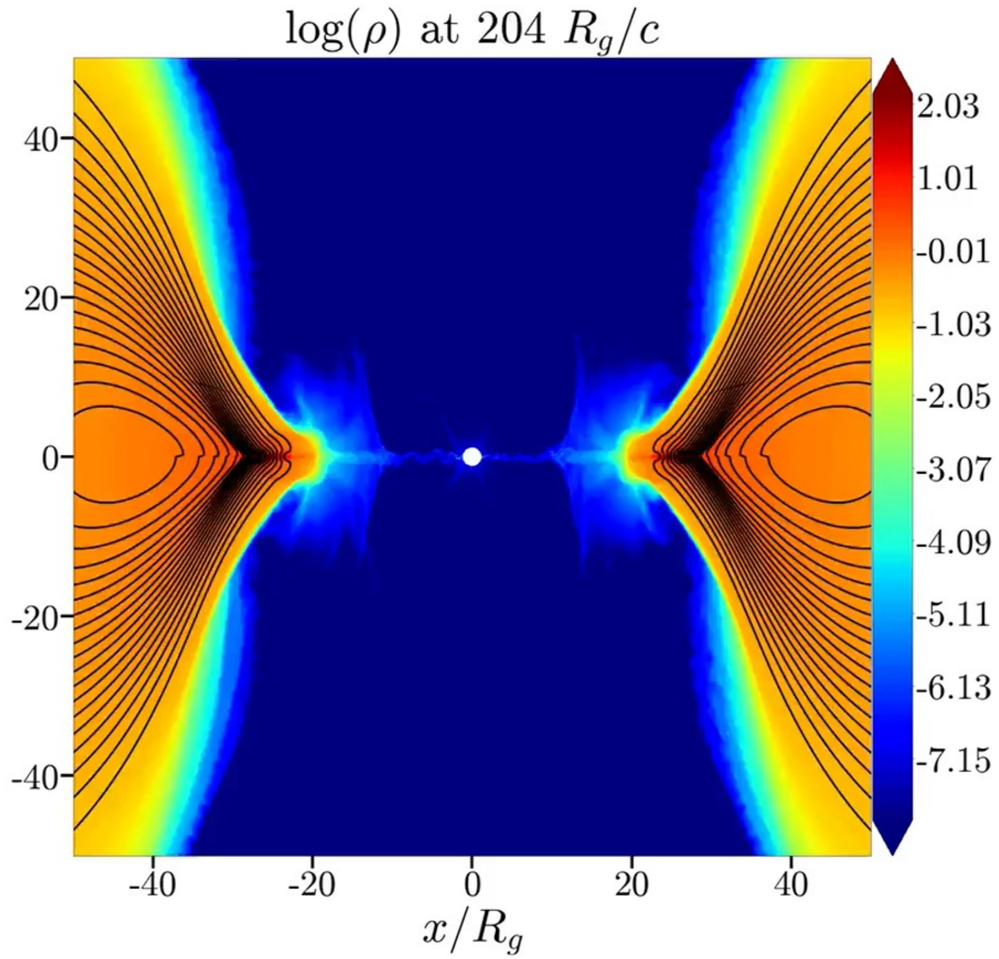
The first general relativistic kinetic simulation of black hole accretion

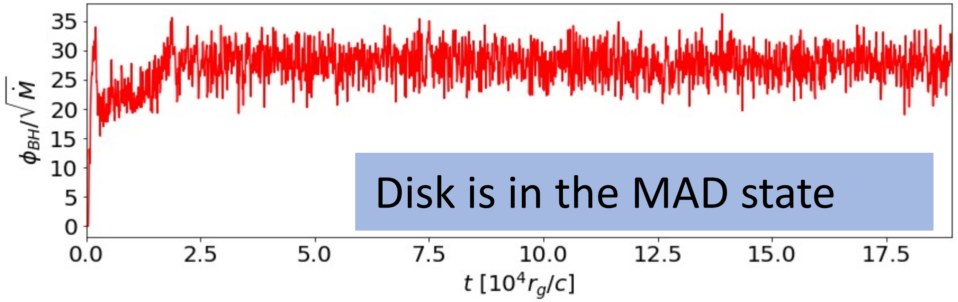


[Galishnikova, Philippov, Quataert, Bacchini, Parfrey, **Ripperda**, PRL, 2023]

Can luminous AGN also become MAD?



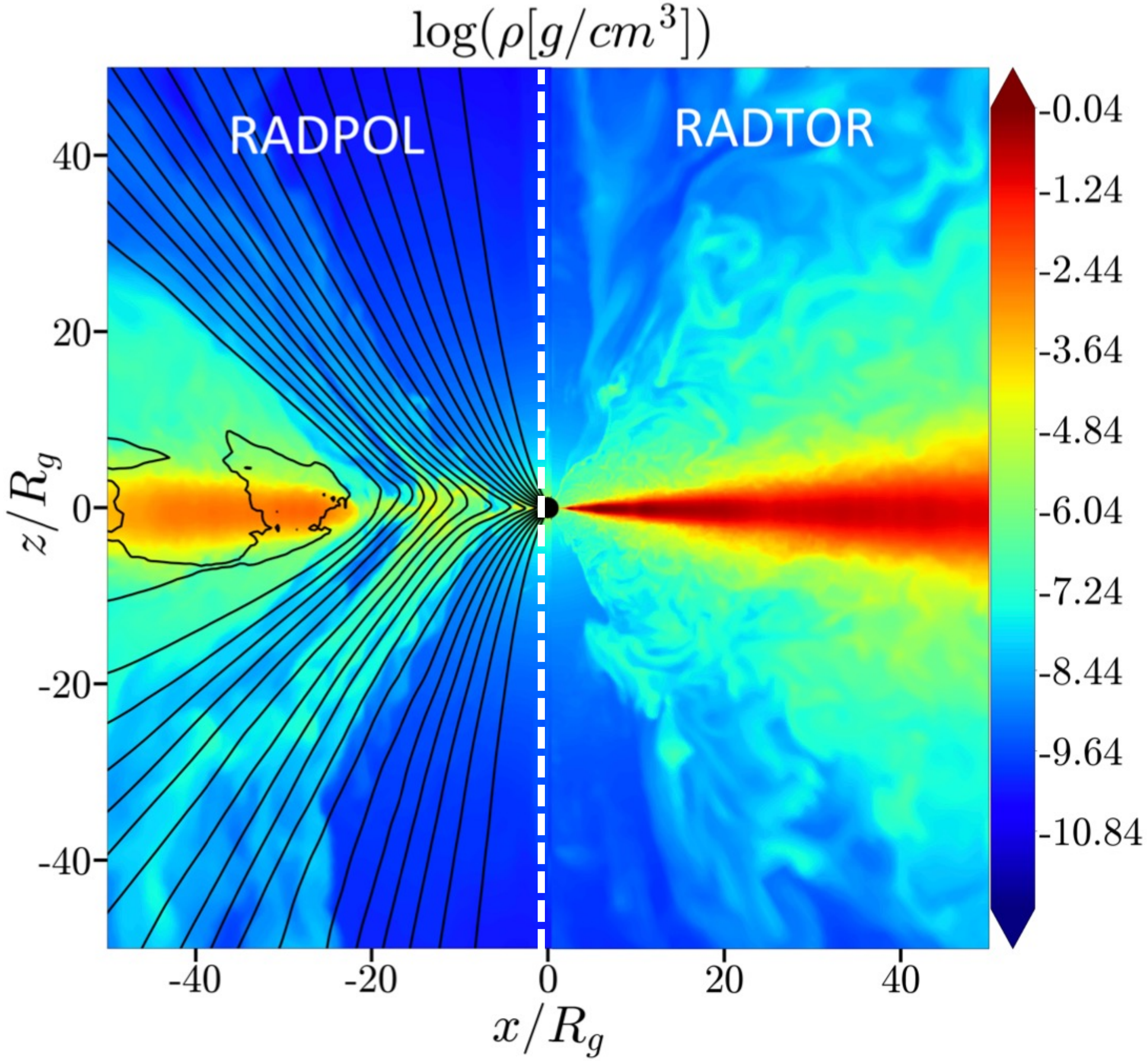




[Liska, Musoke, et al, ApJL (2022); Musoke et al, in prep.]

Poloidal versus toroidal fields

Poloidal B field
Large-scale poloidal B flux generated Inner disk is MAD



Toroidal B field
No large-scale poloidal B flux generated Thin disk to ISCO

[Liska, Musoke, et al, ApJL (2022); Musoke et al, in prep.]