Simulating Bondi-Like Accretion Flows Around Black Holes

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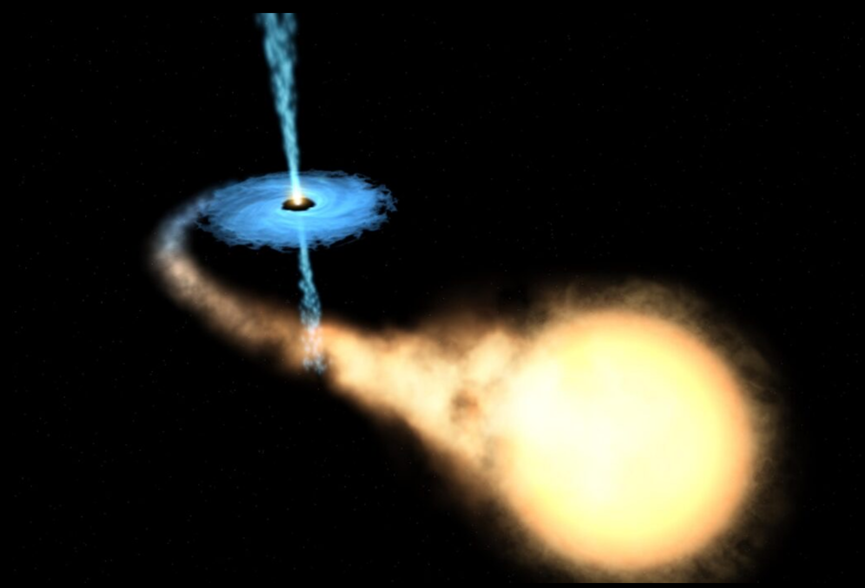
Astrophysical Black Holes: A Rapidly Moving Field
24 June 2023

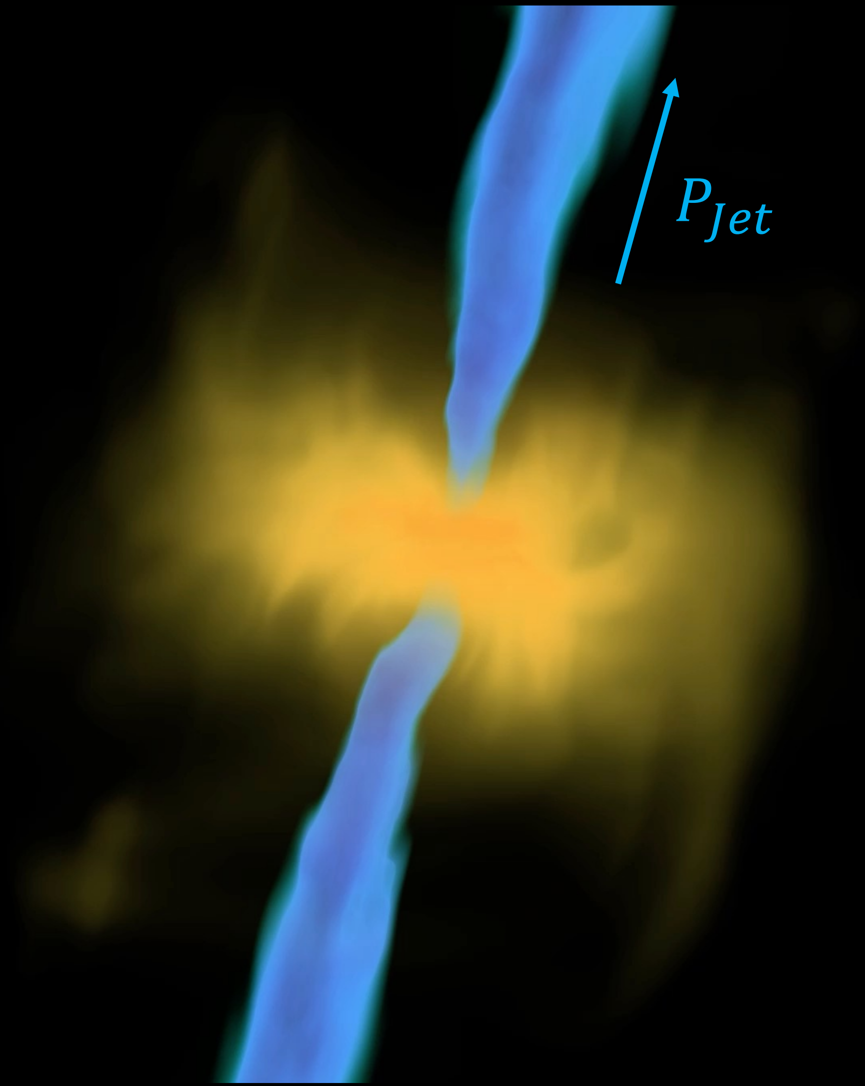
Black Holes and Accretion Disks



Credit: ESA/NASA/Felix Mirabel

- Gas accreting onto black hole carries angular momentum and forms a disk
- Disk viscous process allows the gas accrete and powers luminous emission
- Sometimes a relativistic jet is produced!

Relativistic Jets launched from Black Holes



Blandford-Znajek Mechamism (1977)

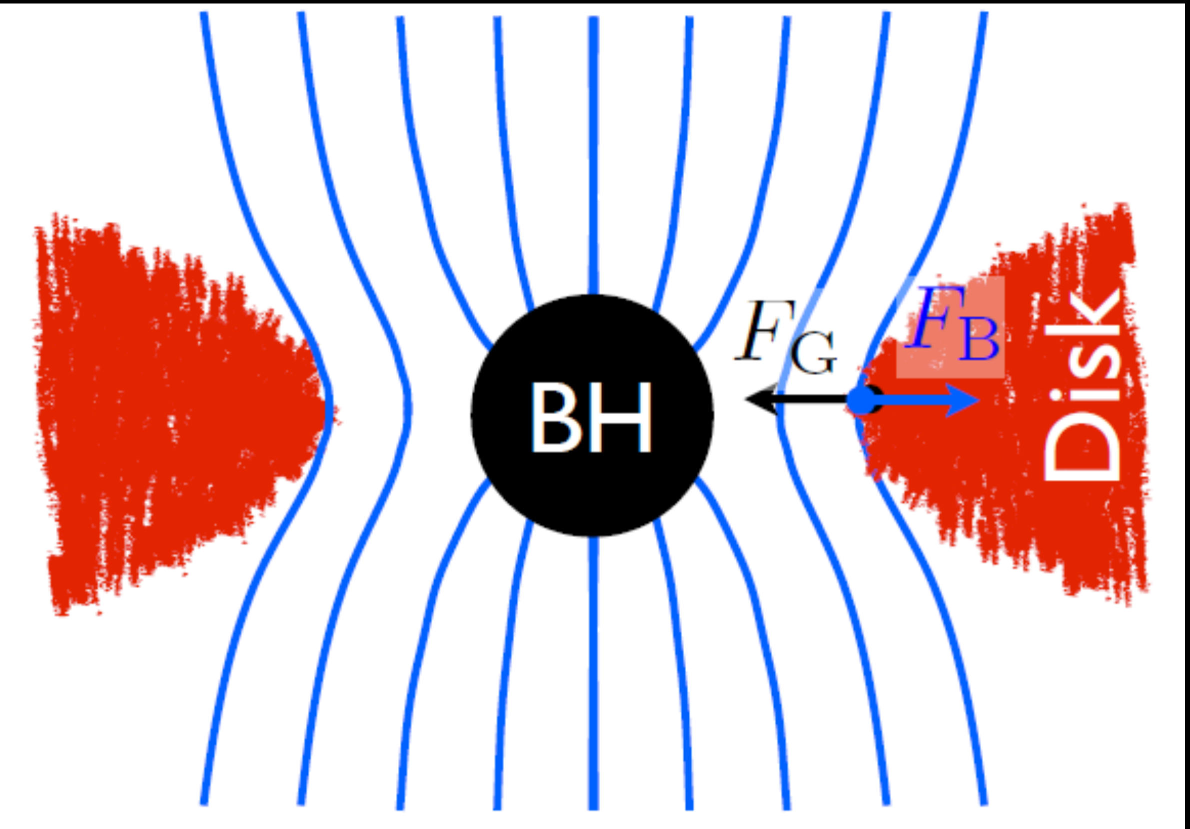
$$P_{jet} \propto \phi^2 a^2$$

Jet Power

Magnetic flux

Black hole spin

Magnetically Arrested Disk



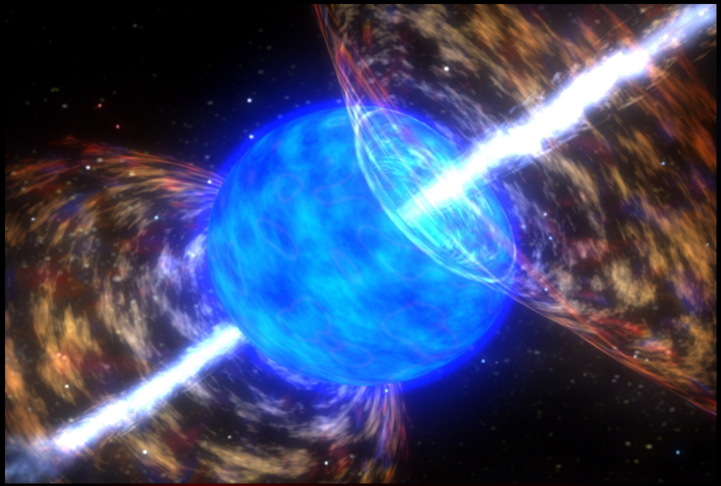
Tchekhovskoy+ 2011; McKinney+ 2012

- Magnetically Arrested Disk (*MAD*) is formed when the inflow carries strong, ordered magnetic flux near the BH
- Dimensionless magnetic flux at horizon (MAD parameter)

$$\phi_H = \frac{\Phi_H}{\sqrt{\dot{M}_H}} \gtrsim 40$$

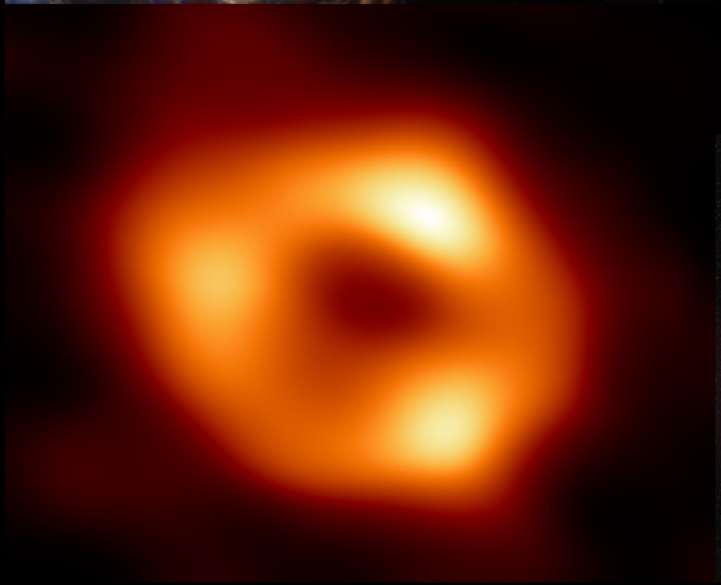
- A powerful jet can be launched
- Disk carries large angular momentum

What if the accretion flow carries low angular momentum?

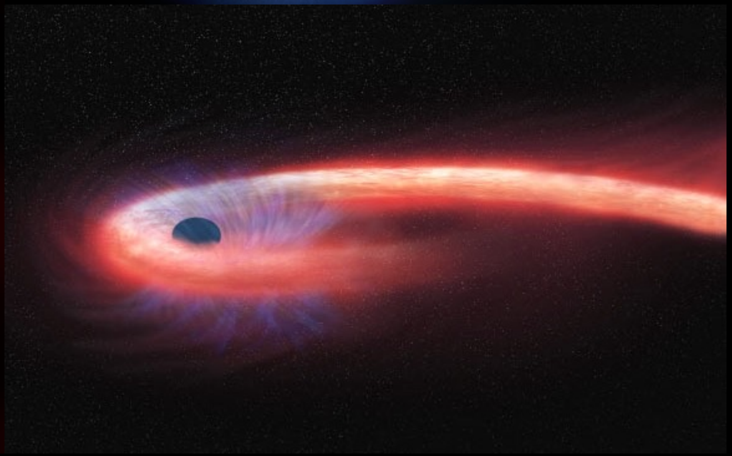


Long Gamma Ray Bursts
(Credit: NASA / SkyWorks Digital)

BH High-mass
X-ray Binary
(Credit: ESA)



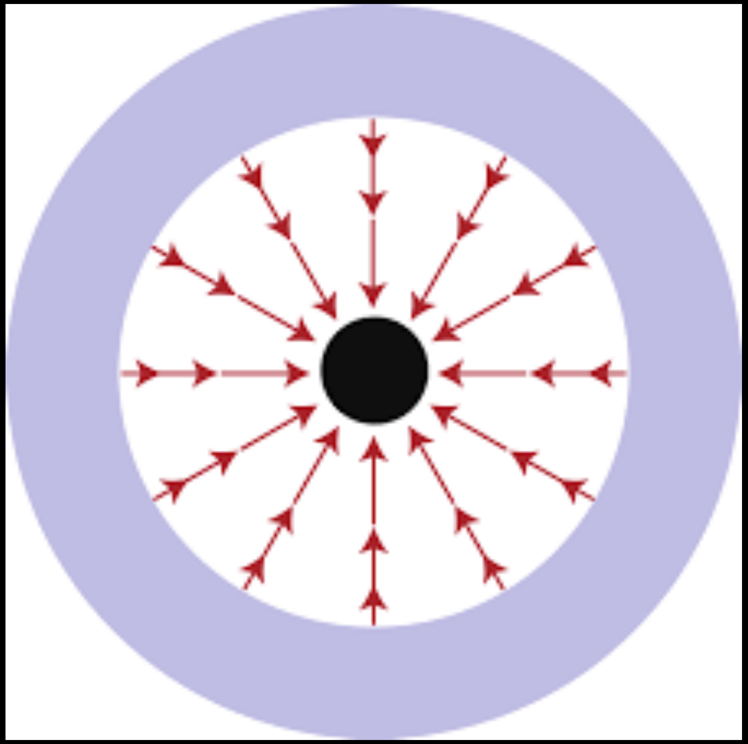
Sgr A*
(Credit: EHT)



Tidal
Disruption
Events
(Credit: NASA/ CXC
/ M. Weiss)

Bondi & Bondi-like Accretion

- Zero angular momentum: Bondi model
- A thick torus structure can form when gas has low angular momentum (e.g. Proga & Begelman 2003; Lee & Ramirez 2006; Sukova 2015)



Bondi 1952

Bondi & Bondi-like Accretion

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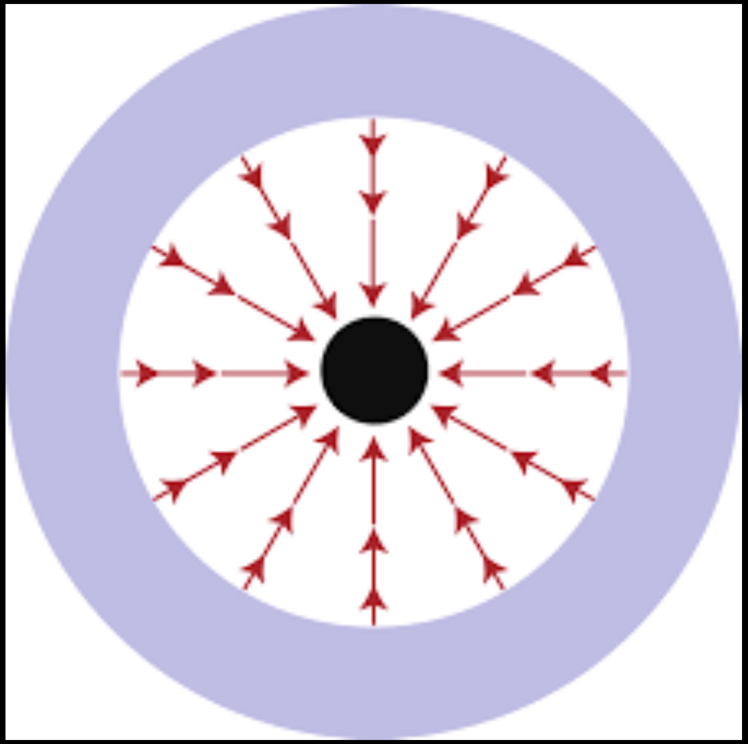
The effect of magnetic field, GR & BH spin?



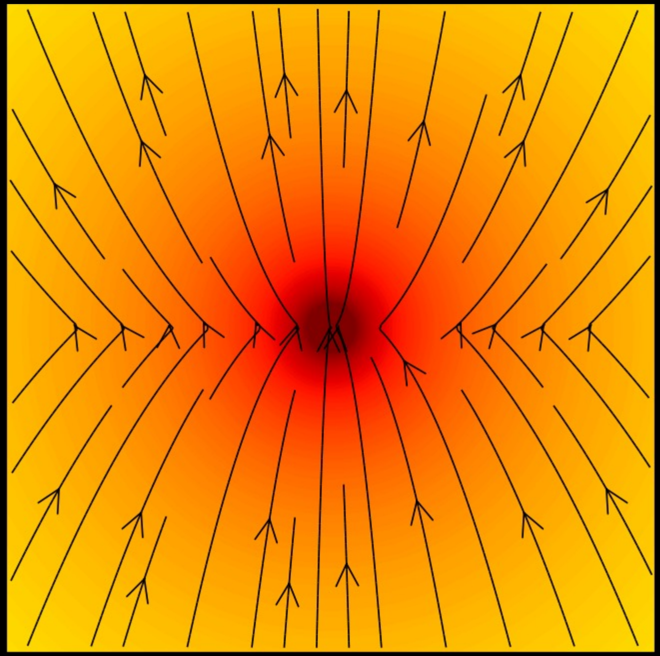
Bondi 1952

Simulation Code: HARM

- 3D general relativistic magnetohydrodynamics (GRMHD) code HARM (Gammie+ 2003, Noble+ 2006, McKinney+ 2012)

Continuity equation
$$\nabla_\mu (n u^\mu) = 0$$
Conservation of Energy-Momentum
$$T^\mu_\nu = T^{MA}{}^\mu_\nu + T^{EM}{}^\mu_\nu$$ $$\nabla_\mu T^\mu_\nu = 0$$
Conservation of Magnetic flux
$$\partial_t\left(\sqrt{-g}B^i\right) = -\partial\left[\sqrt{-g}\left(b^j u^i - b^i u^j\right)\right]$$

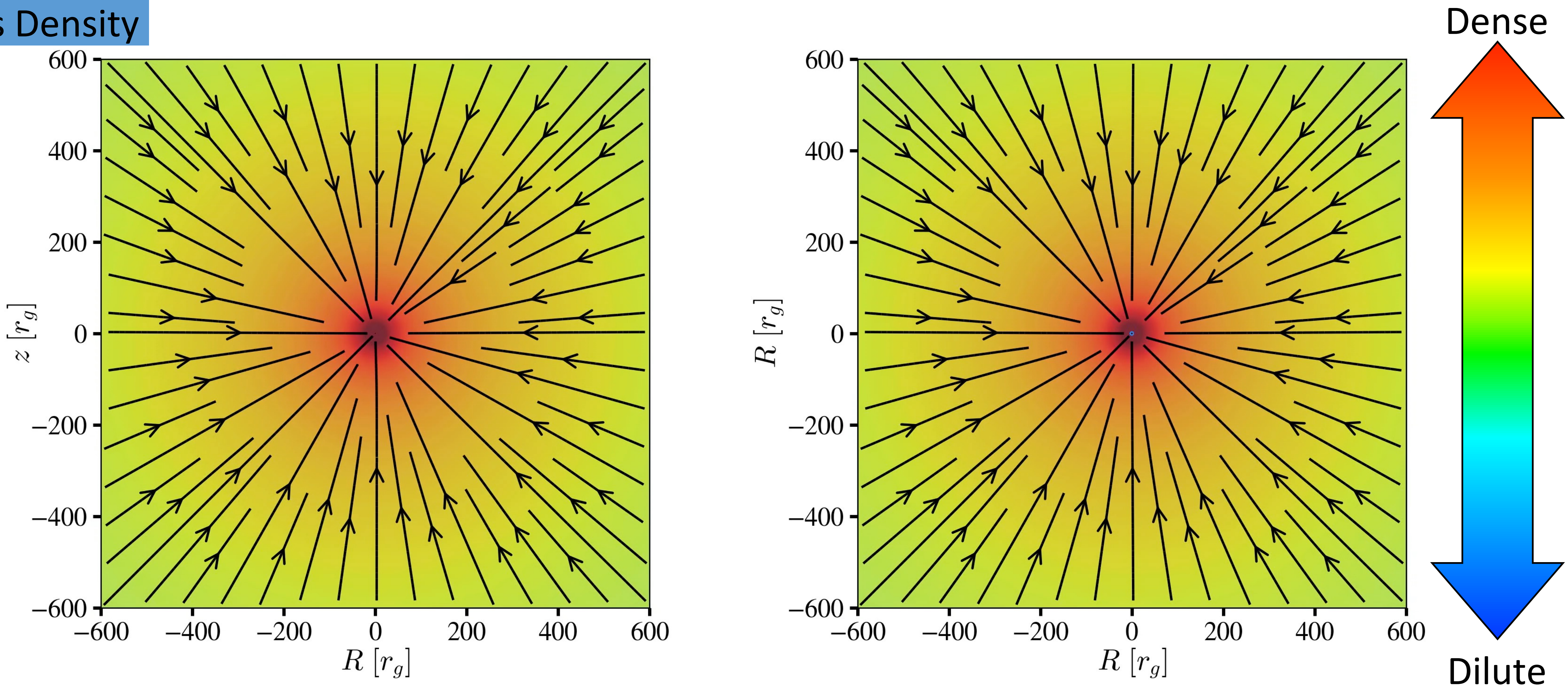
GRMHD Simulations Setup



- Three simulations with zero or very small specific angular momentum
- Black hole spin: 0.9
- Spherically symmetric gas density
- Circularization radius $R_c = 0, 10, 50\ r_g$ (BH gravitational radius)
- Poloidal magnetic field in the gas
- Simulation box: $10^5 r_g$

$R_c = 0\ r_g$

Gas Density

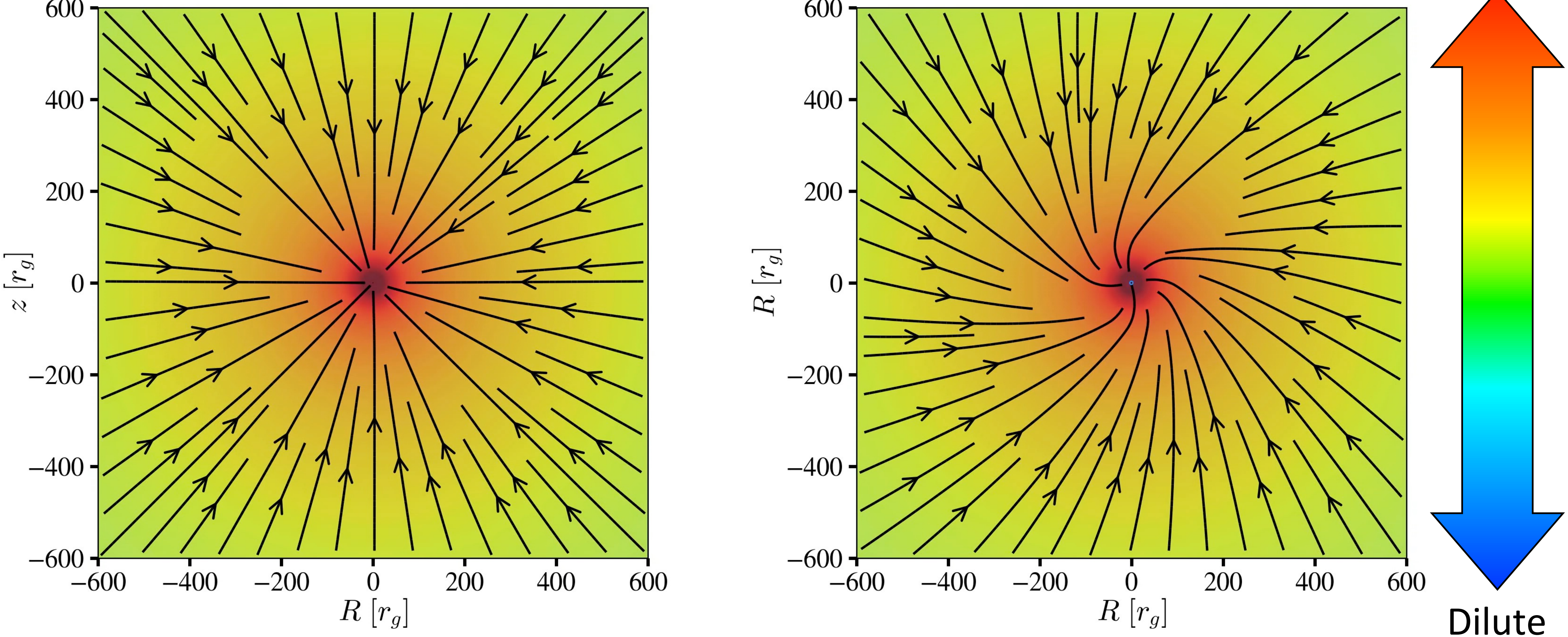


Edge-on view

Face-on view

$R_c = 50\ r_g$

Gas Density

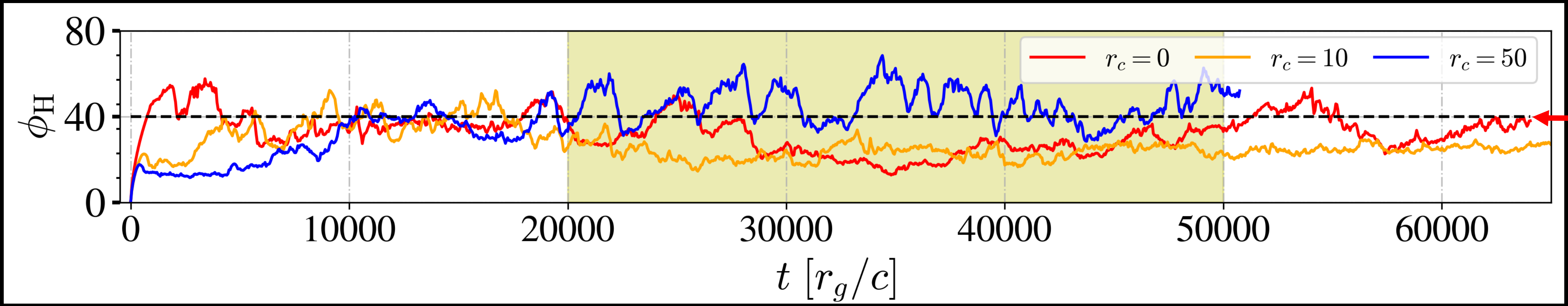


Edge-on view

Face-on view

MAD Formation

MAD condition

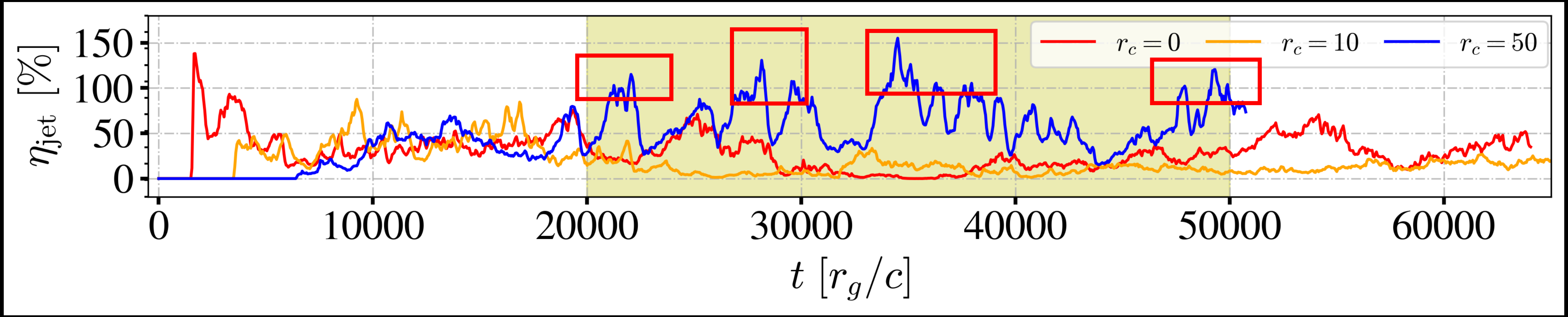


Kwan et al. 2023

R_c	ϕ_H
0	27.4
10	23.4
50	45.6

- $R_c = 0{,}10r_g$: form MAD initially but later fail to maintain MAD
- $R_c = 50\ r_g$: build up slowly but maintain MAD

Jet Power



Kwan et al. 2023

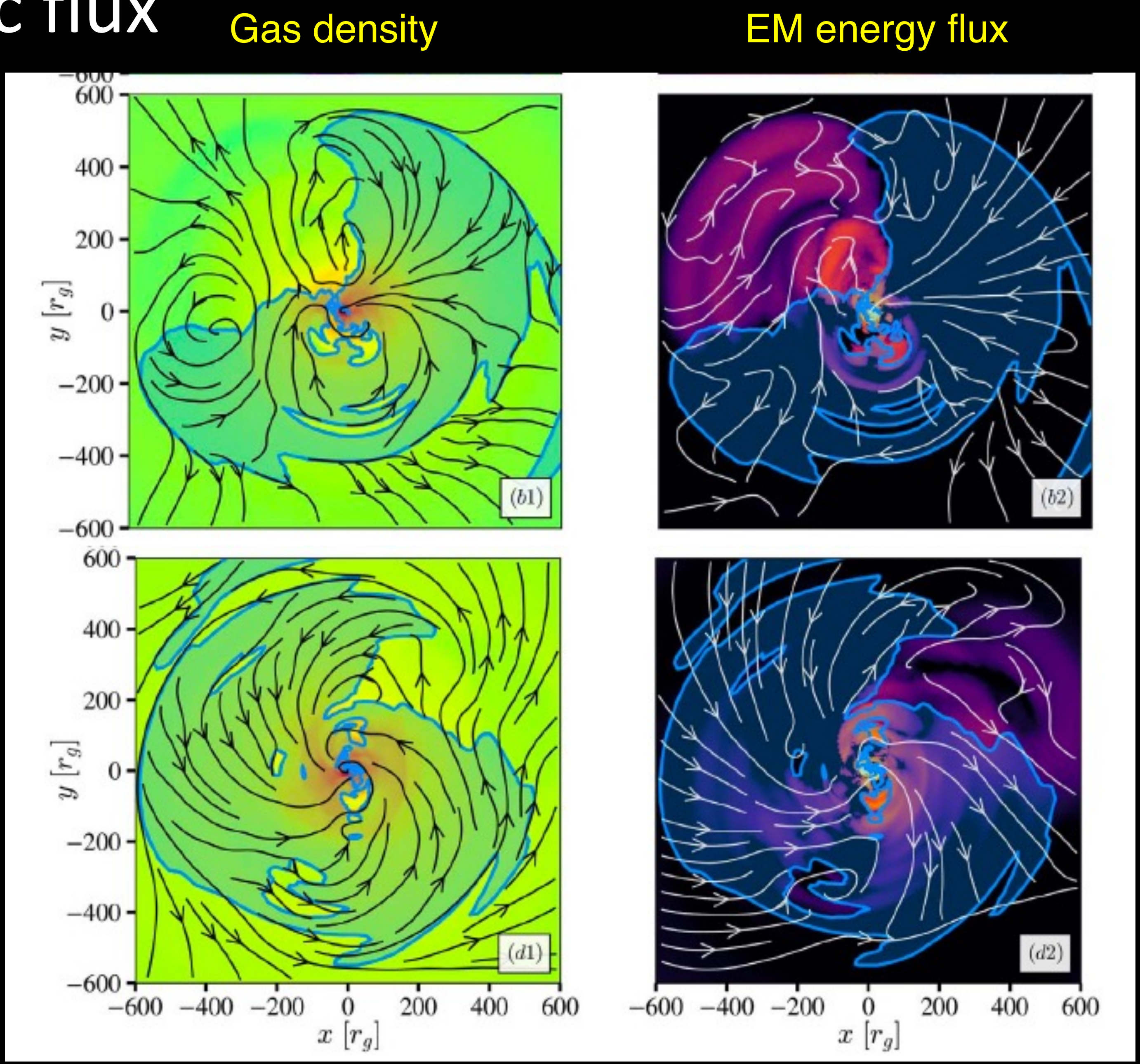
R_c	ϕ_H	$\eta_{jet}(\%)$
0	27.4	18.6
10	23.4	10.1
50	45.6	$\boxed{61.4}$

- $R_c = 50\ r_g$: powerful jets with high jet efficiency
- $R_c = 0{,}10 r_g$: weaker jets with jet efficiency$\sim 10\%$

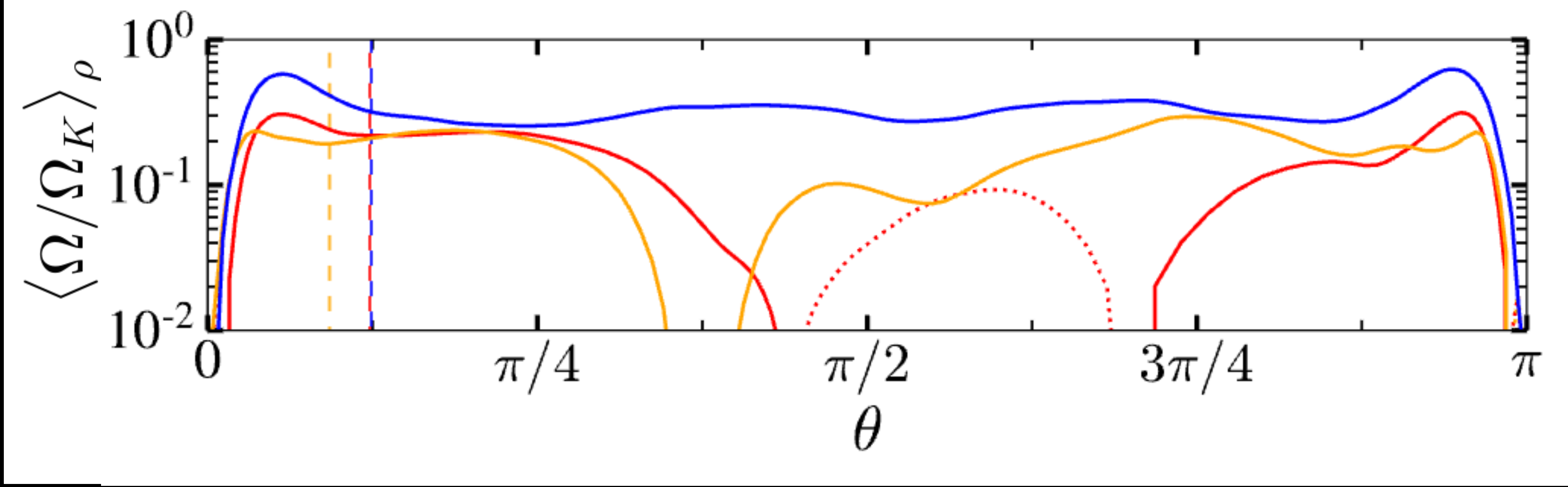
Dissipation of magnetic flux

$R_c = 0$

$R_c = 50r_g$



Is a “disk” produced?

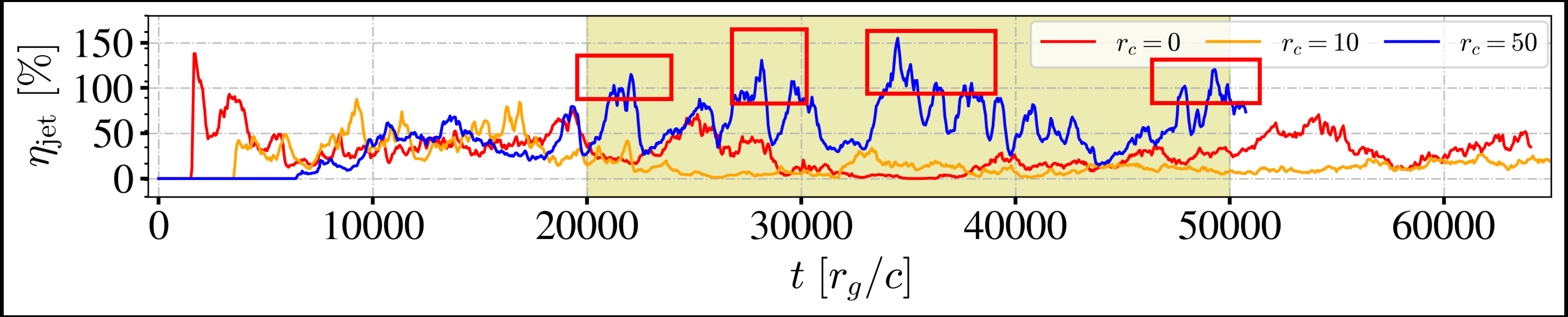


$R_c = 0{,}10 r_g$:

- Gas rotating in different directions at different latitude
- Outflow in some ϕ-directions even along mid-plane

Kwan et al. 2023

Jet Power



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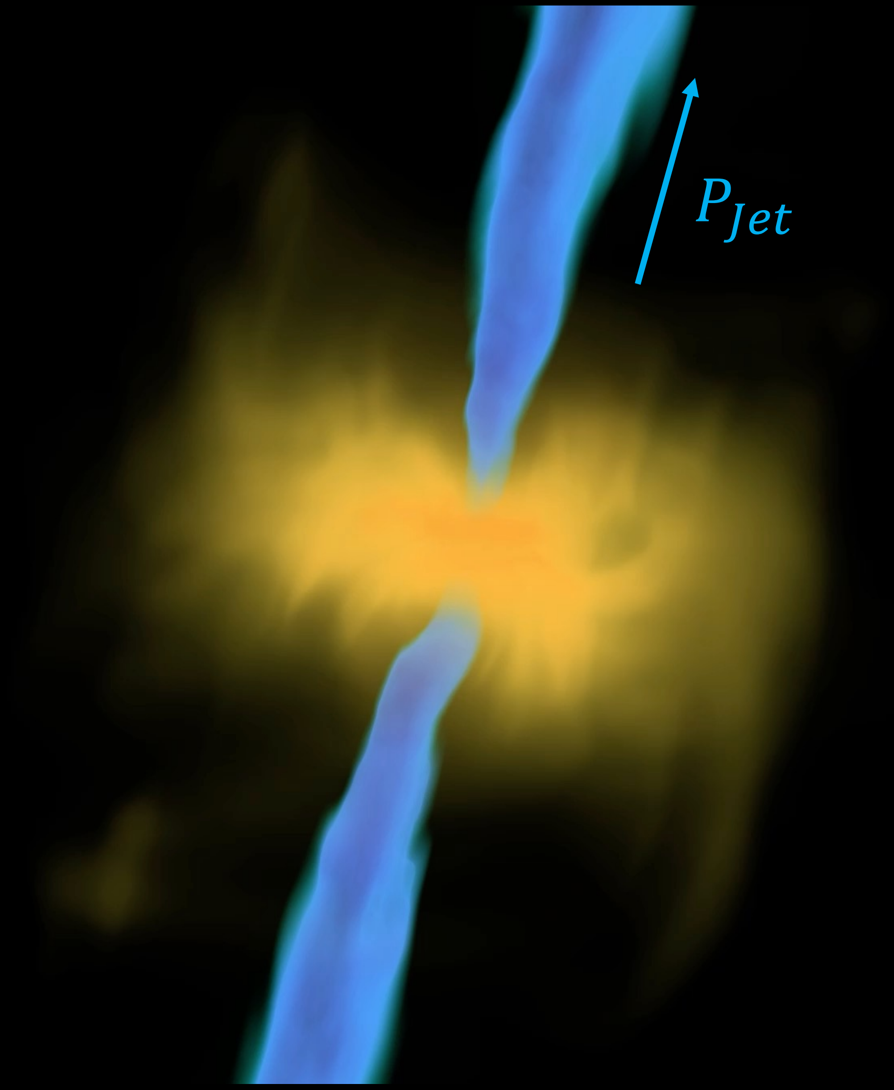
Relativistic Jets launched from Black Holes



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Jet Power

Magnetic flux

Black hole spin

Key messages

- A disk is not needed to produce a jet
- Zero gas angular momentum accretion flow around a spinning black hole can still launch a jet through BZ process
- A small specific angular momentum threshold is needed for the accreting gas to sustain MAD and launch very powerful jets
- The interplay between gas angular momentum and magnetic flux is important!

Kwan, T. M., Dai, L., Tchekhovskoy, A, 2023, ApJL, 946, L42