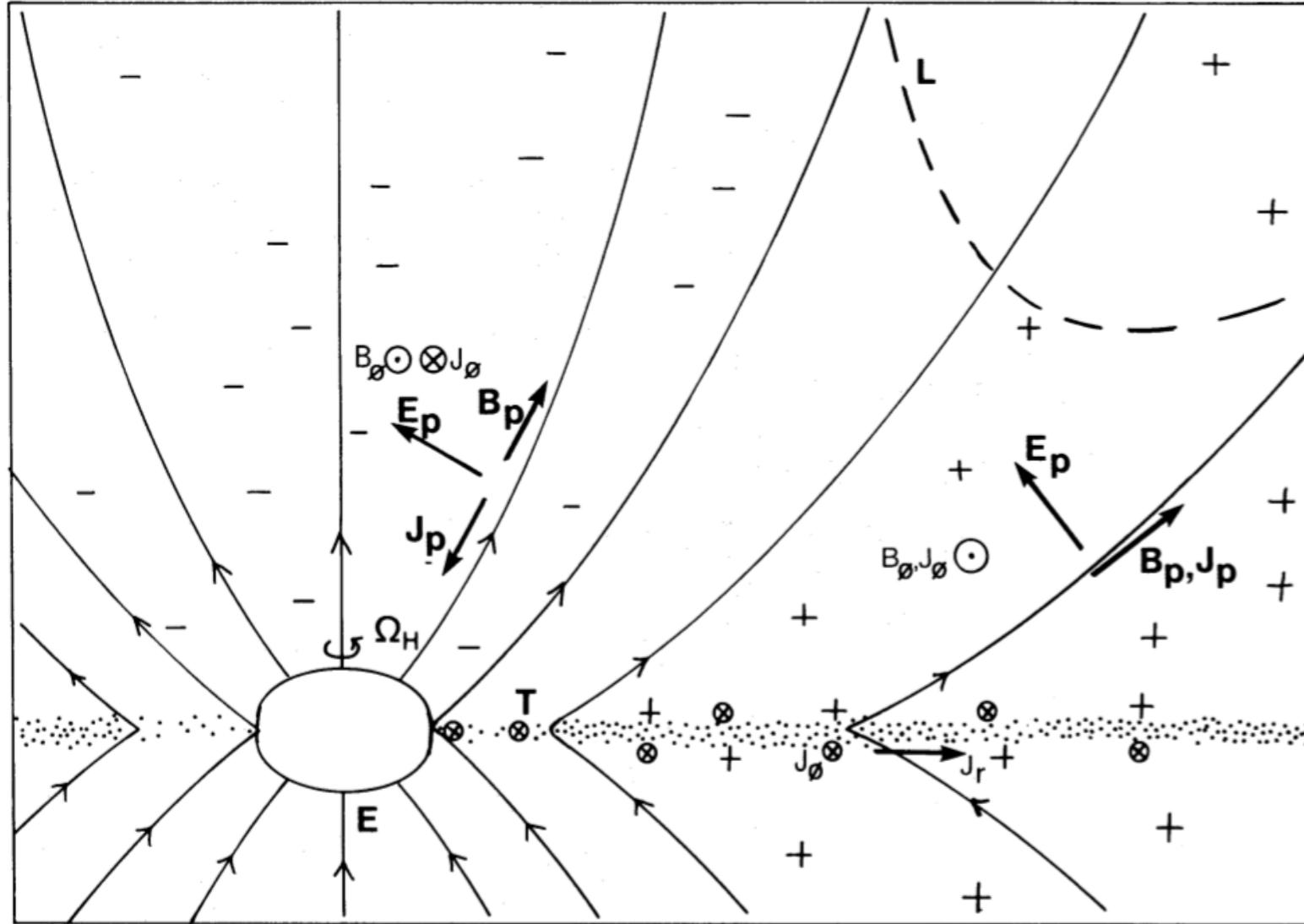


Black Hole Jets from MRI-Generated Magnetic Fields

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Lawrence Berkeley National Laboratory
with
Dimitrios Giannios
Andrei Beloborodov



Black hole-powered jets



Blandford & Znajek 77

Jet power

$$L_j \simeq \Upsilon \frac{\Phi^2 a^2}{r_H^2} c$$

$$\Phi = \frac{1}{2} \int_{\theta_\phi} |B^r| dS_r \simeq 2\pi r_H^2 B_\perp$$

$$\Upsilon \simeq 10^{-3}$$

e.g. Tchekhovskoy,
Narayan, McKinney 10

Need enough flux Φ through the horizon to produce observed L_j

Concerns:

1. does the system have enough flux?
2. if so, can it be brought onto the black hole?

1. Flux supply

Flux needed ($a \sim 1$): $\Phi \simeq 27.5 \sqrt{L_j \text{ erg/s}} \frac{M_{\text{BH}}}{M_{\odot}}$

Flux available: $\Phi_{\text{star}} \sim 10^{25} \frac{B}{10^3 \text{ G}} \left(\frac{r_{\text{star}}}{10^{11} \text{ cm}} \right)^2 \text{ G cm}^2$

1. Long GRB: $L_j \sim 10^{50.5} \text{ erg/s} \rightarrow \Phi \sim 10^{27} \frac{M_{\text{BH}}}{3 M_{\odot}} \text{ G cm}^2$

2. Stellar TDE: $L_j \sim 10^{46} \text{ erg/s} \rightarrow \Phi \sim 10^{30} \frac{M_{\text{BH}}}{10^6 M_{\odot}} \text{ G cm}^2$
(SW 1644+57)

2. Flux transport

Thin disks can't efficiently advect flux inward...

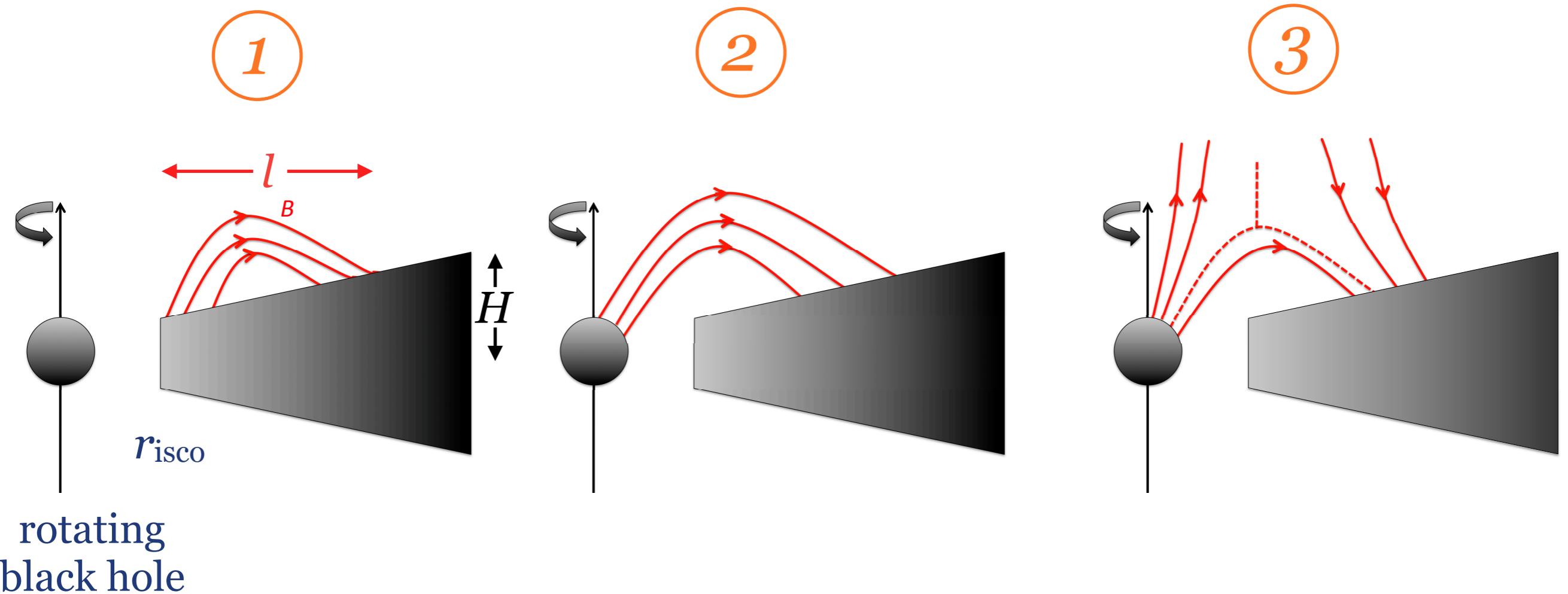
Lubow+ 94; Reyes-Ruiz & Stepinski 96; Heyvaerts+ 96; ...

... and, e.g., AGN disks expected to be thin at large radii:

$L_{\text{disc}} \sim 0.1 L_{\text{edd}}$ for FSRQs

Sun & Malkan 89
Ghisellini+ 10

Jets from small-scale fields



1. Field loops created by MRI in disk, on scale $l \sim 2 H$
Rise into corona via Parker instability (Galeev+ 79)
2. Inner foot-points are accreted
3. Loop opens toward infinity, forming jet
Swallowed/ejected when second foot-points are accreted

Black hole-disk coupling

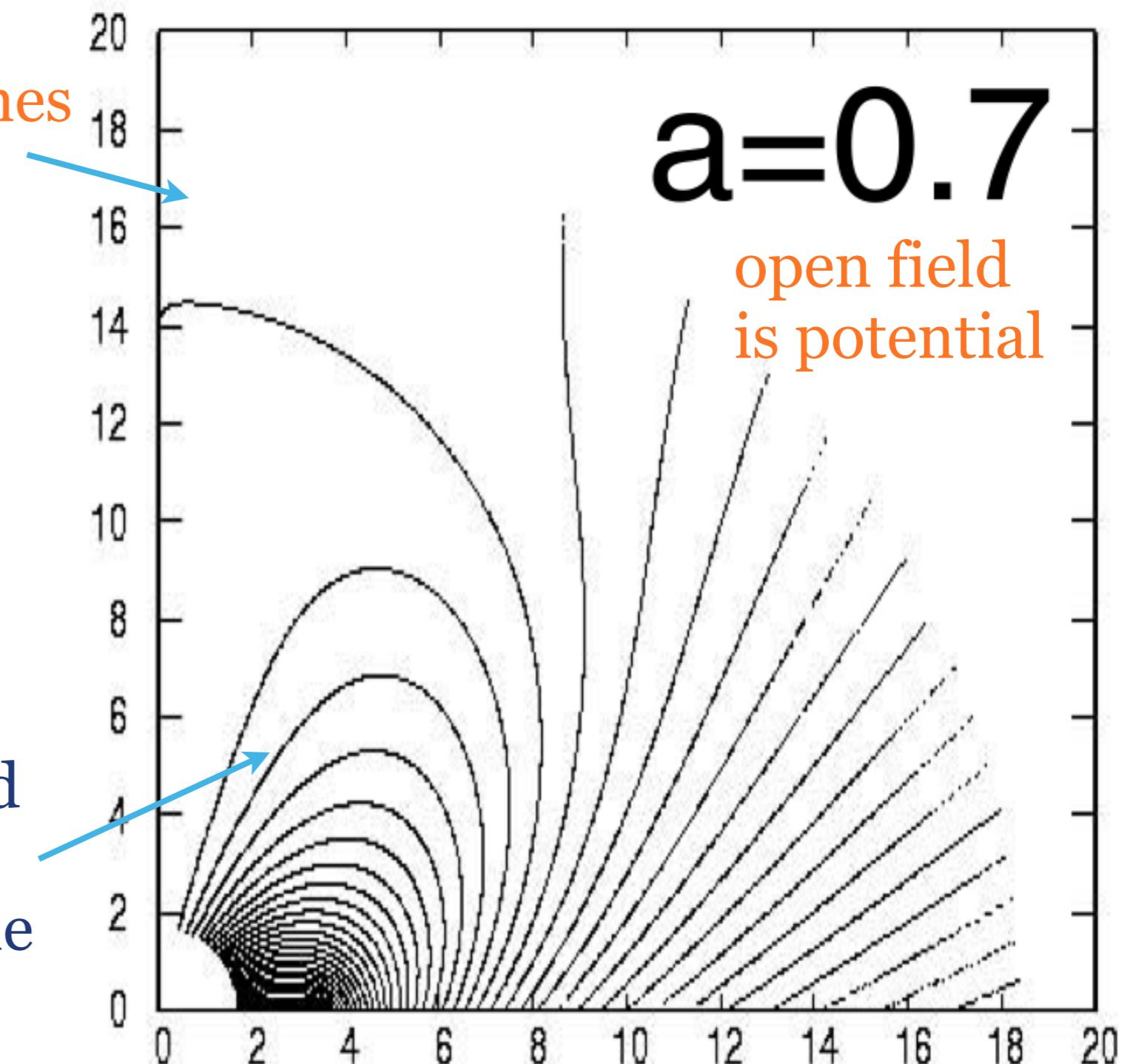
Steady-state solution of
Grad-Shafranov eqn.

region of closed field
lines connecting the
inner disk to the hole

no field lines
to infinity

$a=0.7$

open field
is potential

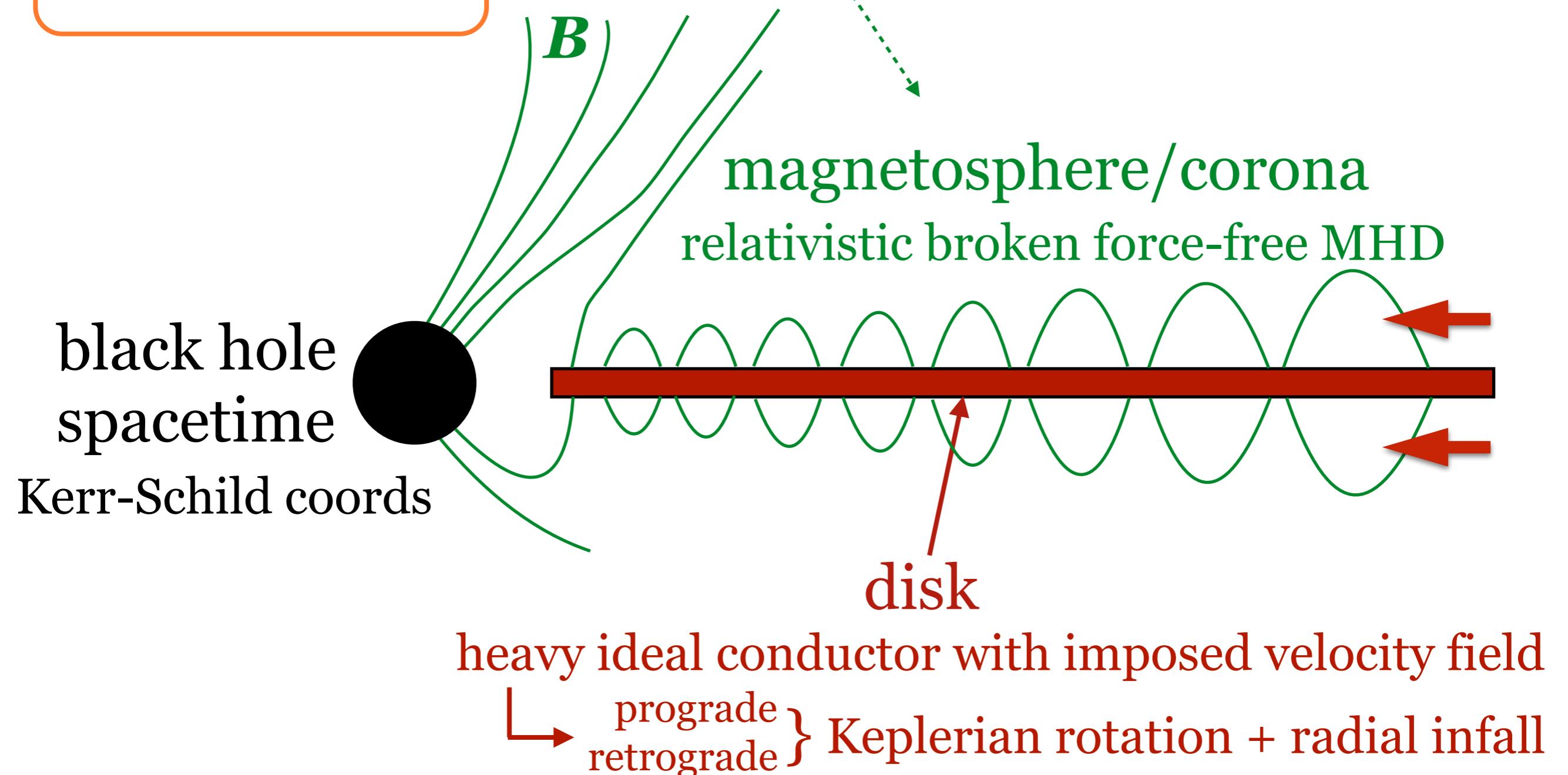


Uzdensky 05

Simulations

“broken”: force-free MHD + causal resistive corrections

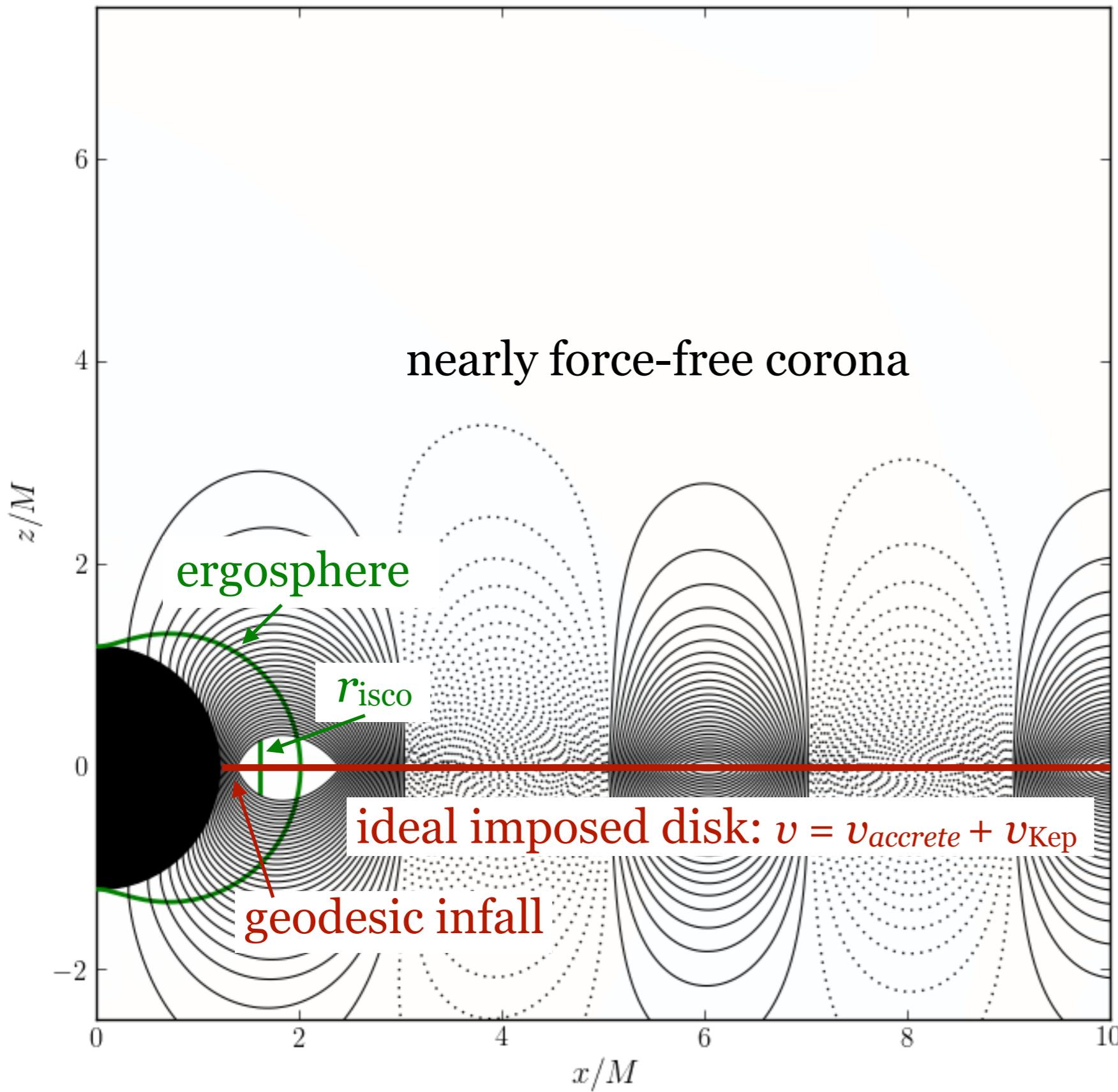
Parfrey 2016, in prep



Use pseudospectral GR force-free simulation code **PHAEDRA**

Parfrey, Beloborodov, Hui 2012

$t = 0 M$



Prograde disc

loop width = $2 r_g$

loop direction

clockwise

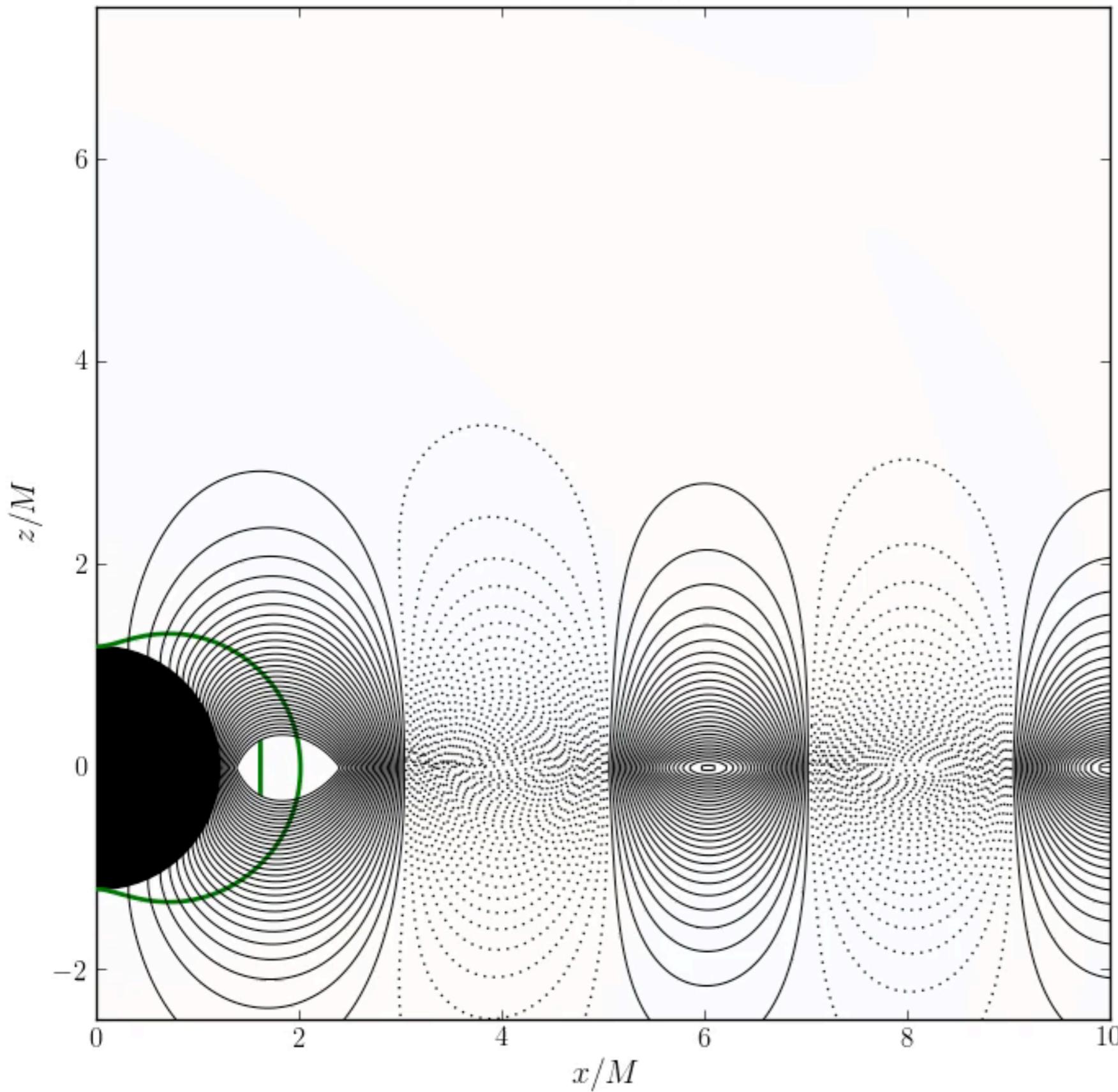
anti-clockwise

Colour: H_φ positive
negative

$v_{\text{accrte}} = c/200$

$a/M = 0.98$

$t = 0 M$



Prograde disc

loop width = $2 r_g$

loop direction

clockwise

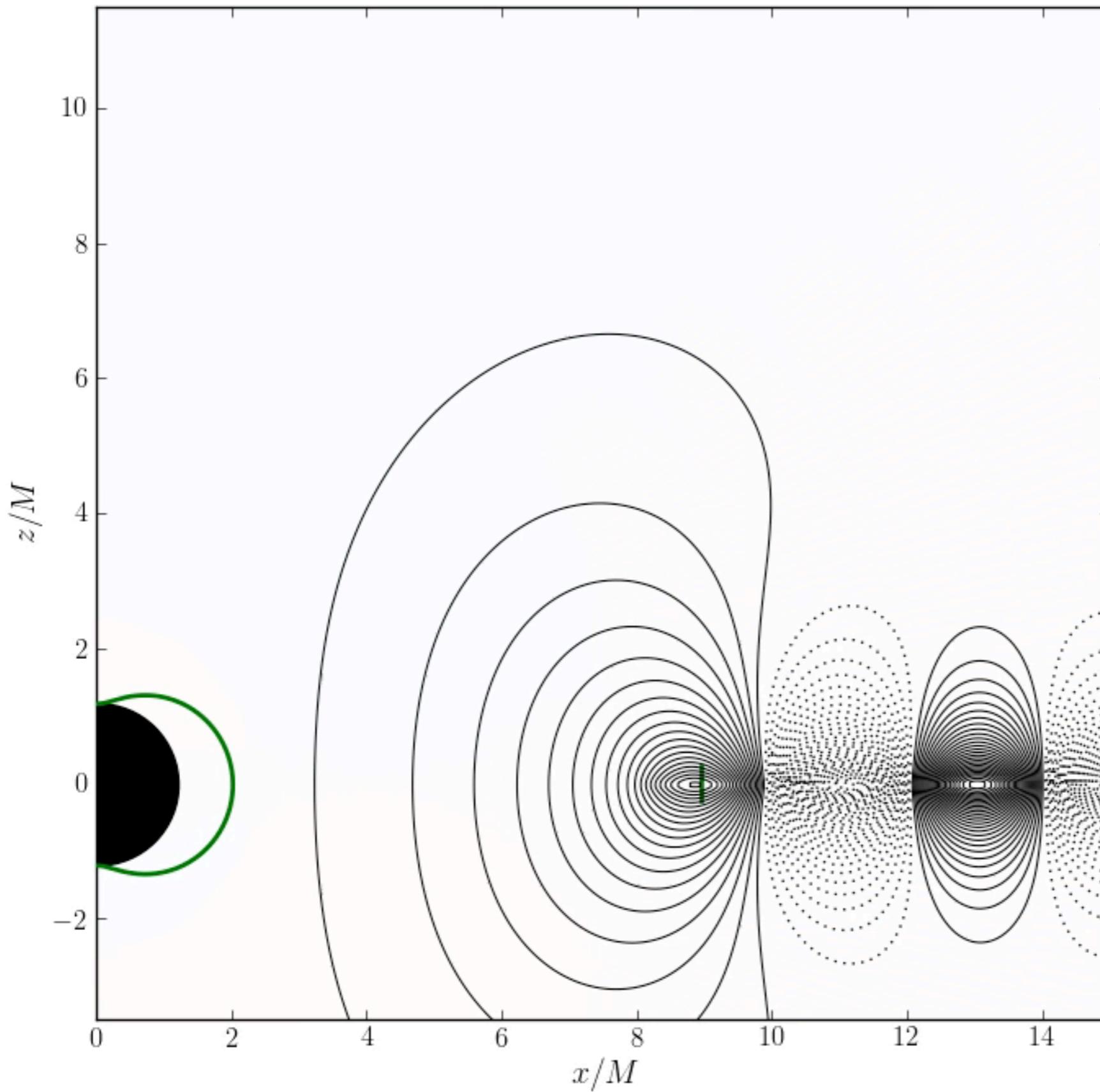
anti-clockwise

Colour: H_φ positive
negative

$v_{\text{accrete}} = c/200$

$a/M = 0.98$

$t = 0 M$



Retrograde disc

loop width = $2 r_g$

loop direction

clockwise

anti-clockwise

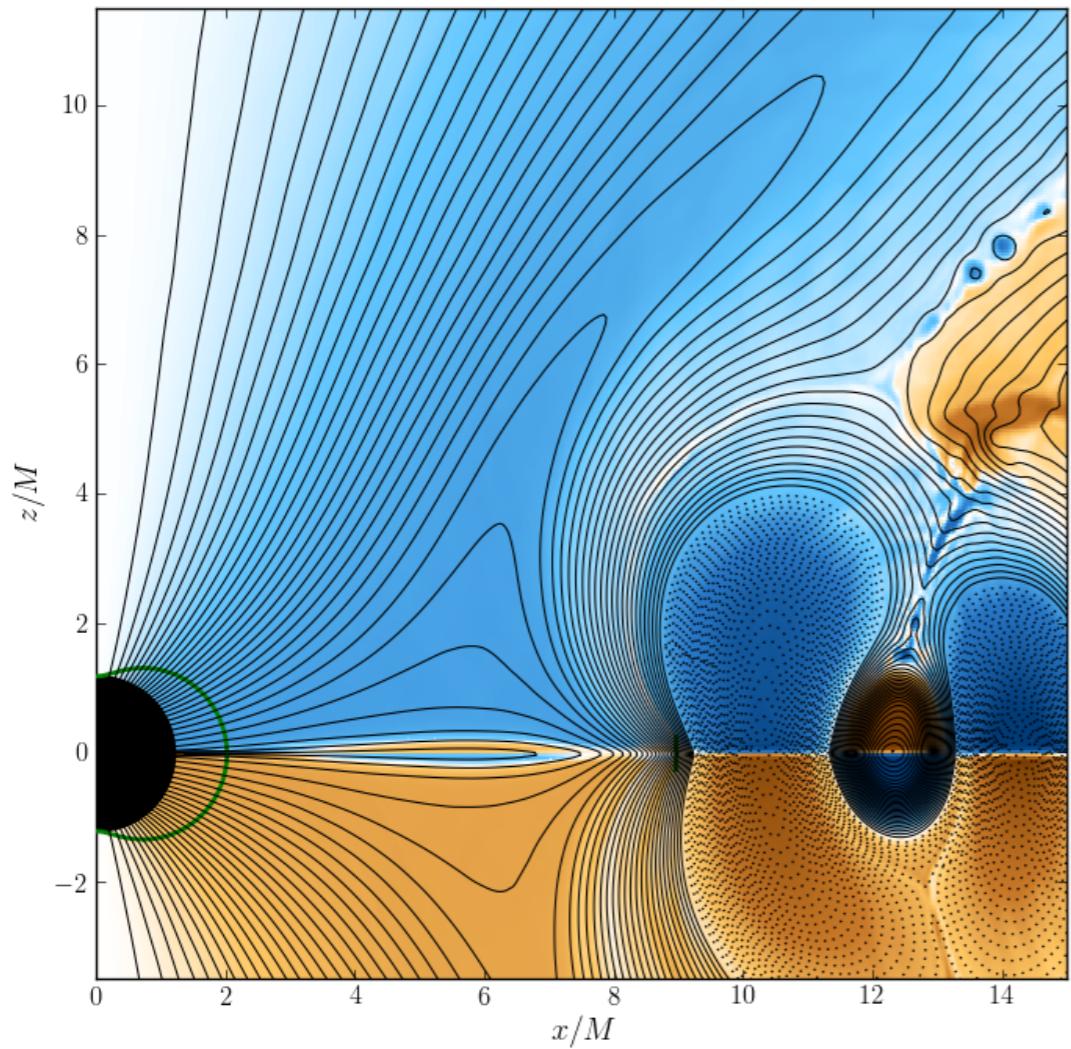
Colour: H_φ positive
negative

$v_{\text{accrete}} = c/200$

$a/M = 0.98$

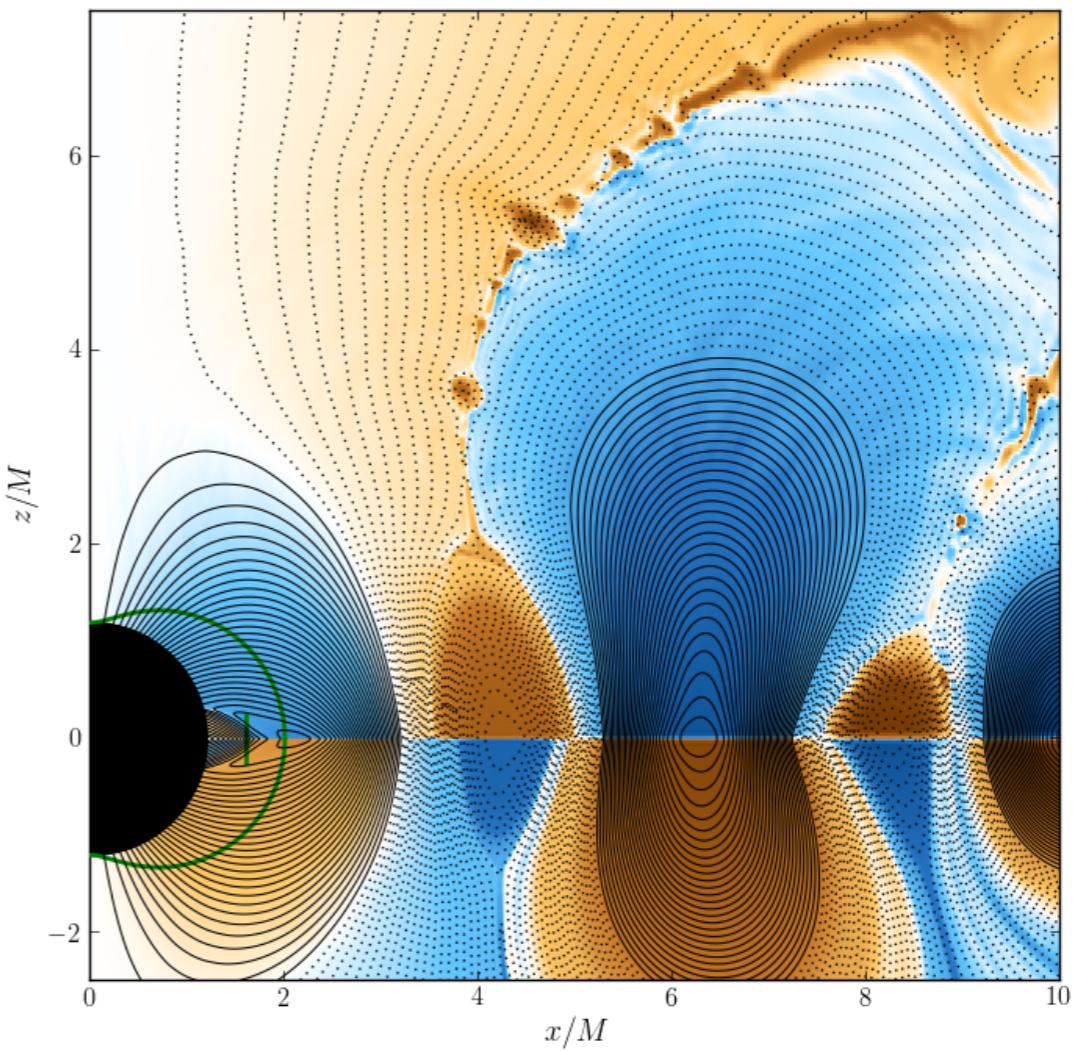
Prograde disk with larger loops – $l > l_{\text{crit}}$

Jet active

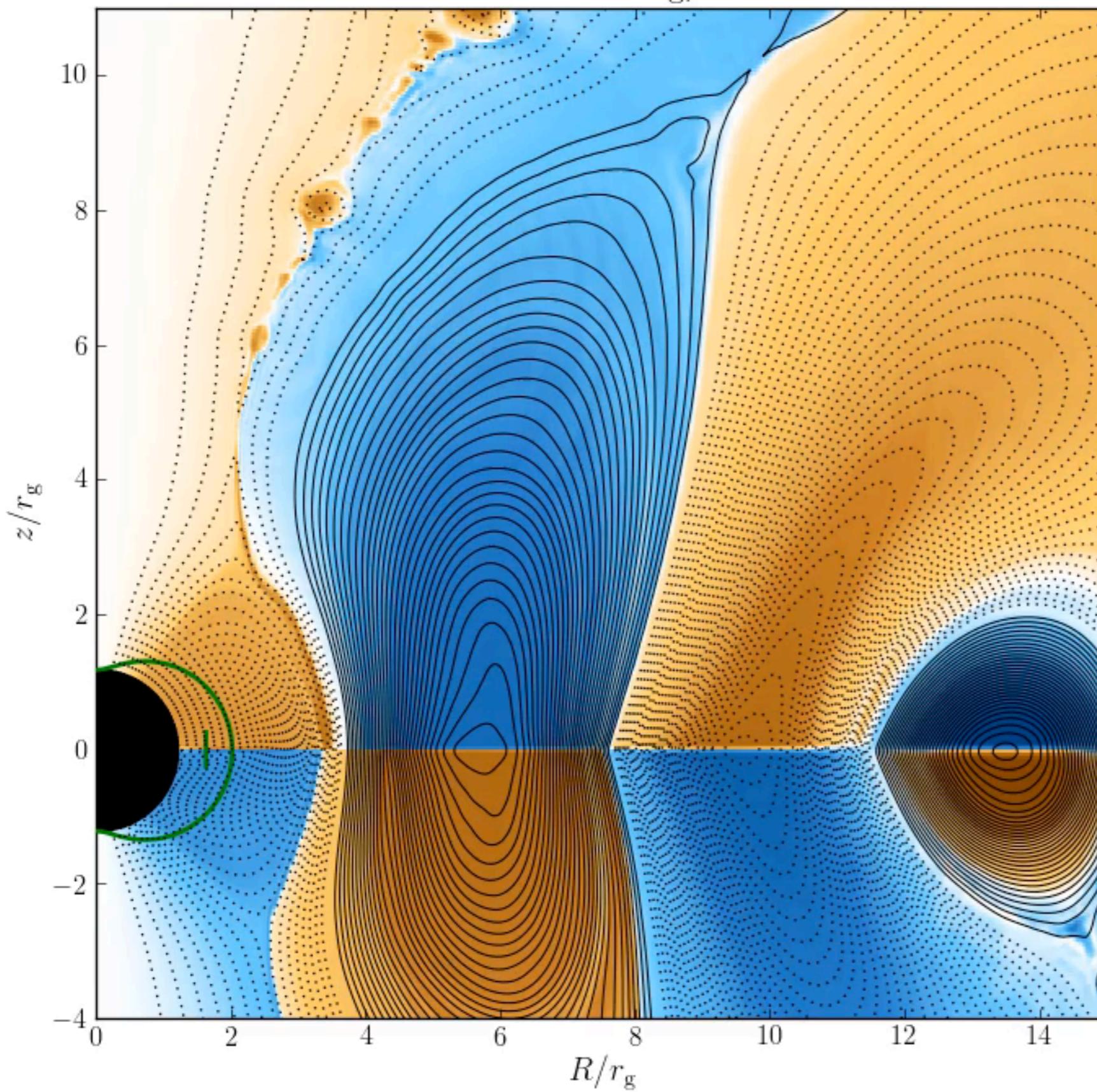


$l_{\text{crit}} \approx 3.2 r_g$ for $a/M = 0.98$

Jet quenched



$$t = 1470 r_g/c$$



Prograde disc

$$\text{loop width} = 4 r_g$$

loop direction

clockwise

anti-clockwise

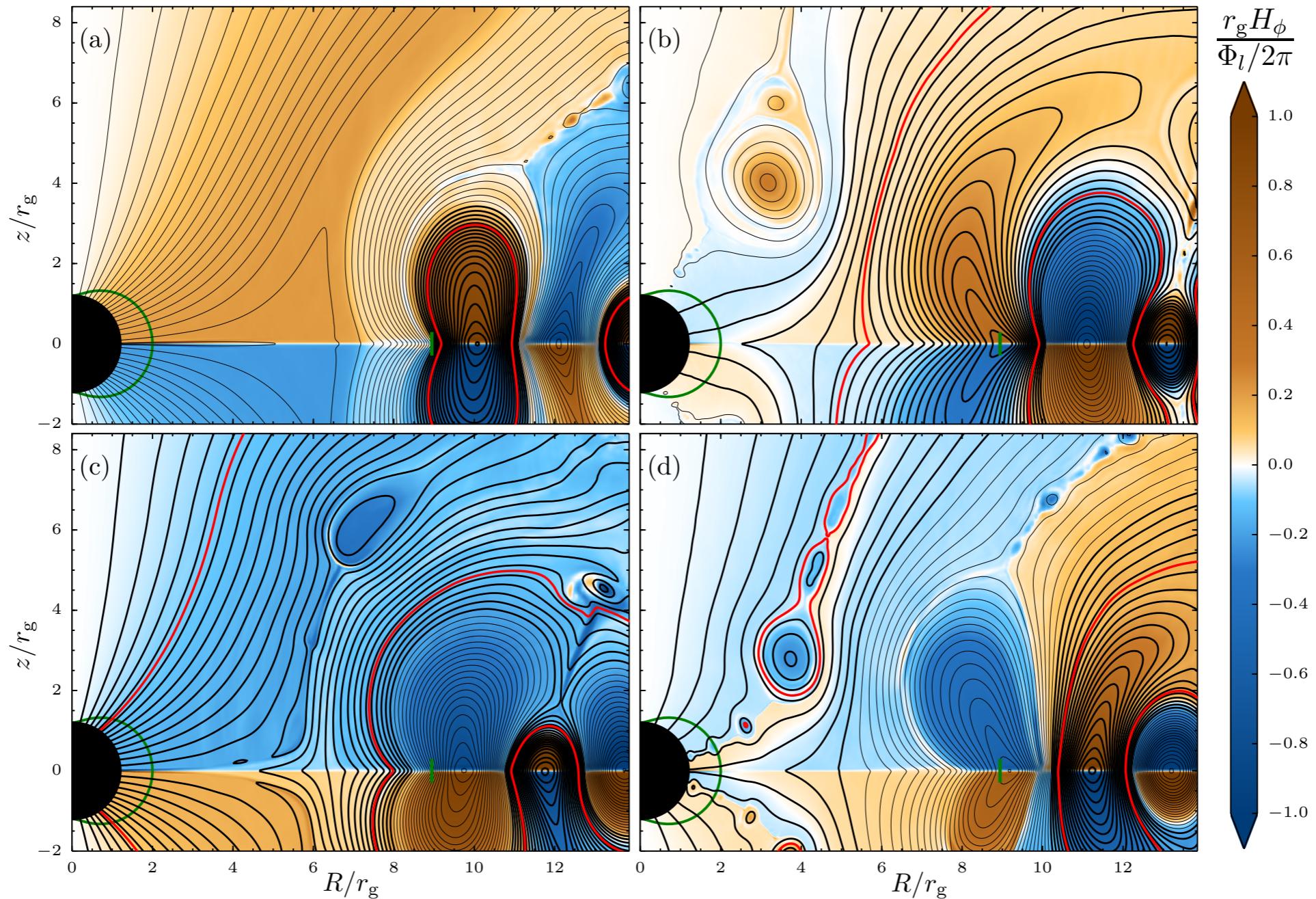
Colour: H_φ positive
negative

$$v_{\text{accrete}} = c/100$$

$$a/M = 0.98$$

Reconnection-heated X-ray corona?

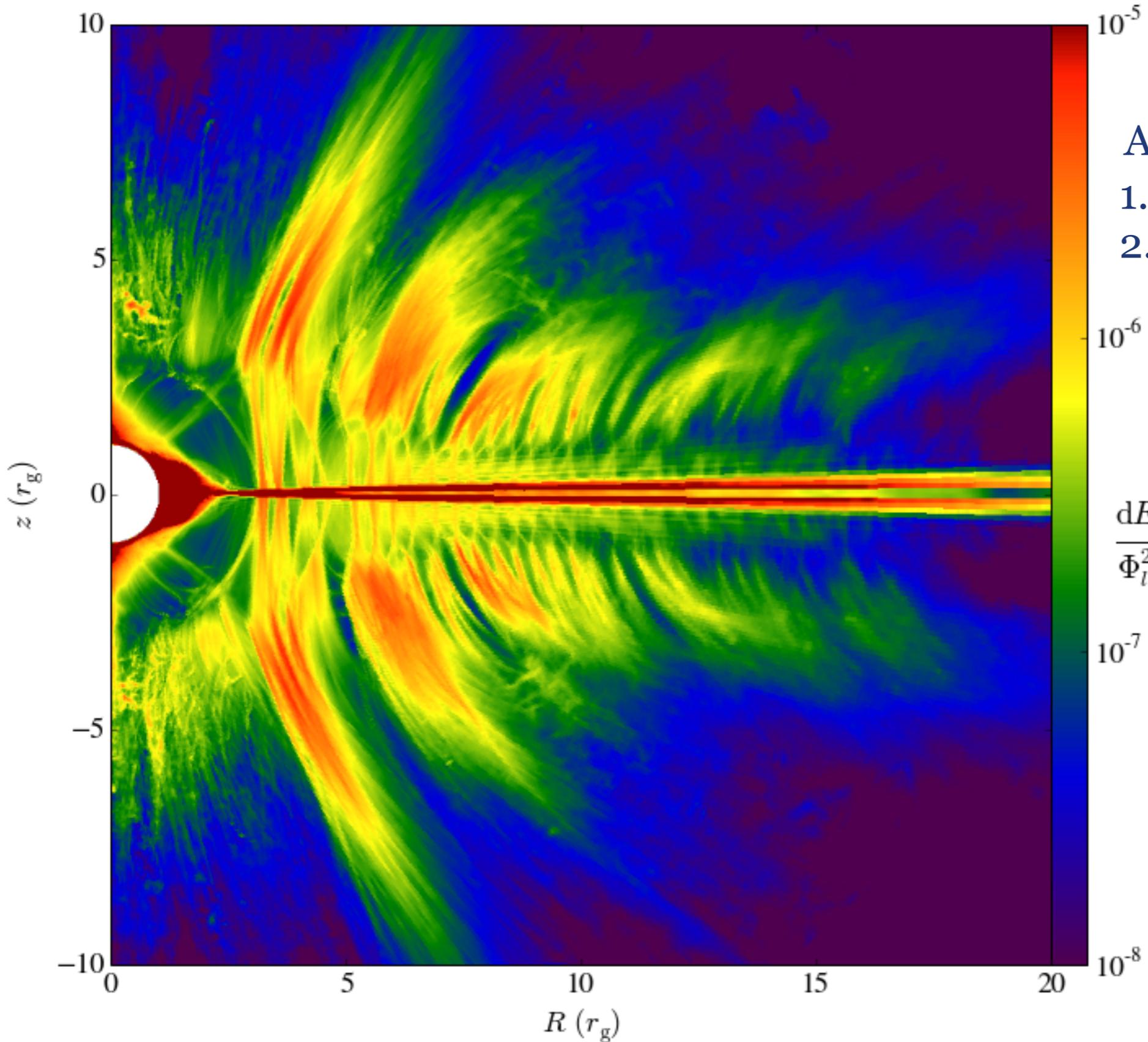
Parfrey, Giannios, Beloborodov (2015)



Reconnection dissipation concentrated at small radii
quasar microlensing limits size of emitting region to $\sim 10 r_g$

Morgan+ 08; Chartas+ 09; Chen+ 12

Dissipation map – prograde



Average dissip. rate from:
1. $\mathbf{E} \cdot \mathbf{J}$ heating
2. current-sheet capturing

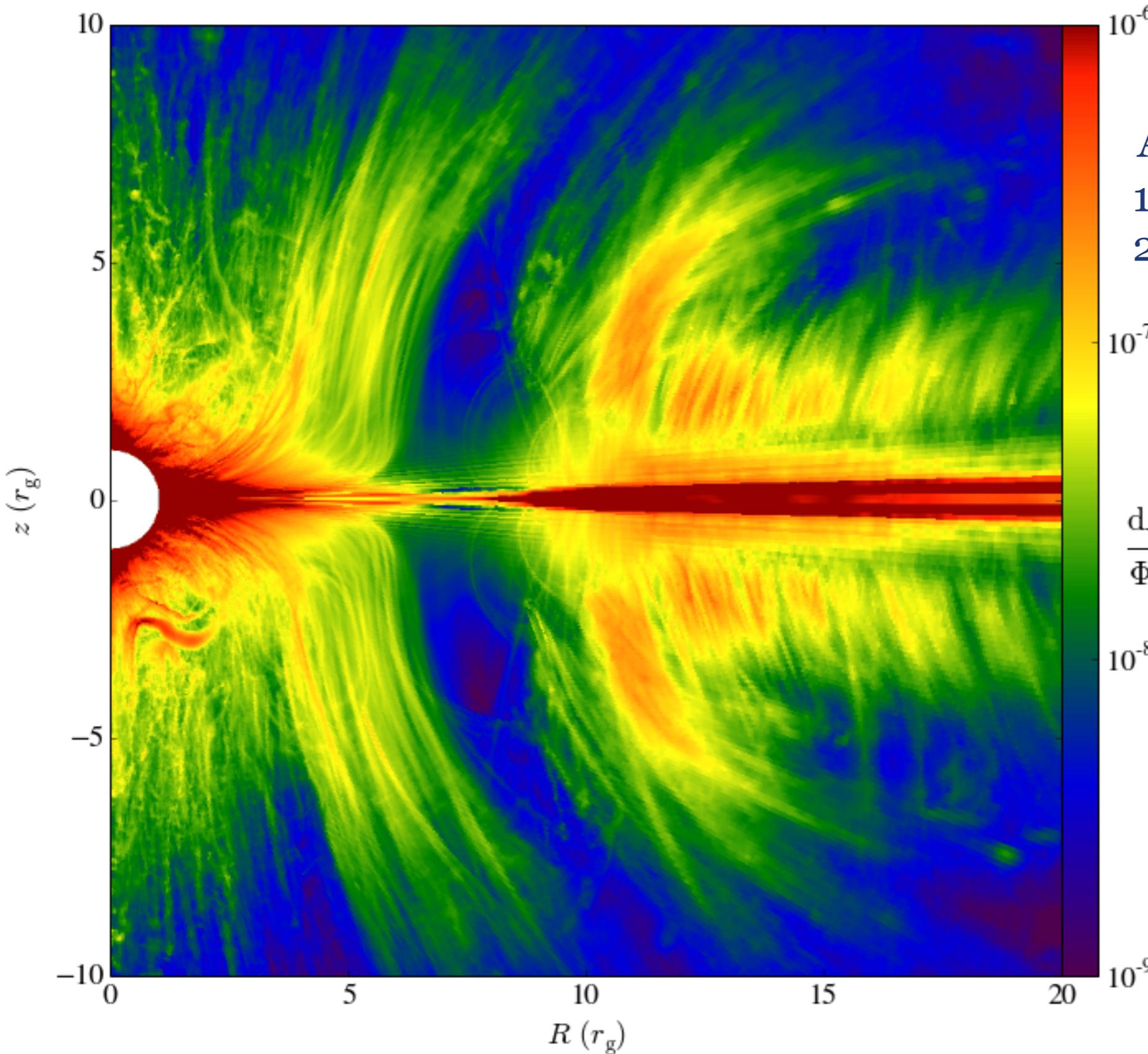
$$\frac{dE_{\infty}}{dt} / \Phi_l^2 c/r_g^5$$

10^{-7}

$$E_{\infty} = -\alpha T_0^0$$

energy-at-infinity
(redshifted energy)

Dissipation map – retrograde



Average dissip. rate from:
1. $E \cdot J$ heating
2. current-sheet capturing

$$\frac{dE_\infty}{dt} / \Phi_l^2 c/r_g^5$$

10^{-8}

10^{-6}

10^{-7}

10^{-9}

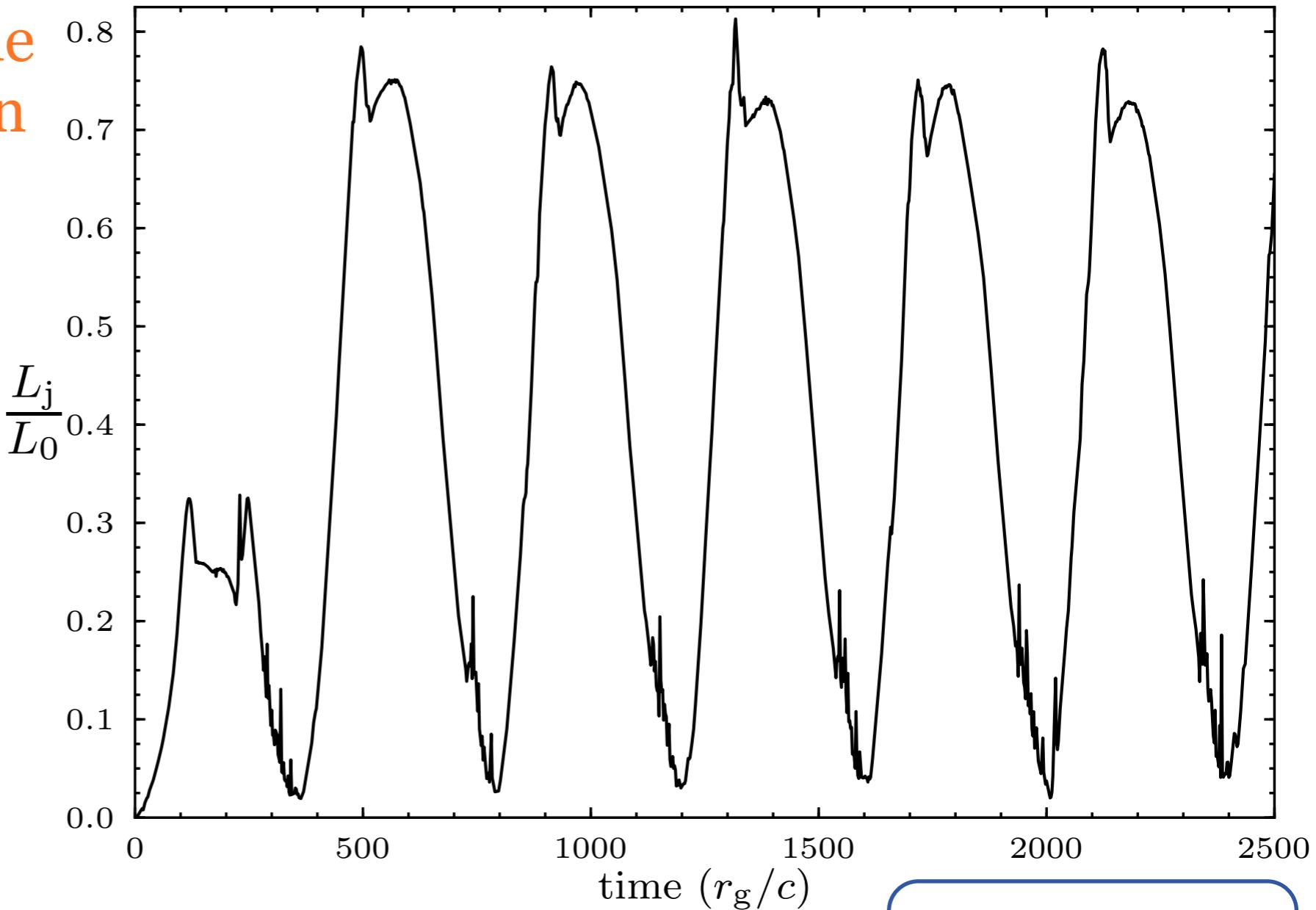
$$E_\infty = -\alpha T_0^0$$

energy-at-infinity
(redshifted energy)

Measured jet power

Parfrey, Giannios, Beloborodov (2015)

Retrograde simulation
outgoing power through horizon
 $L_j \equiv L_{\text{out}}$



highest power expected given loop flux Φ_l

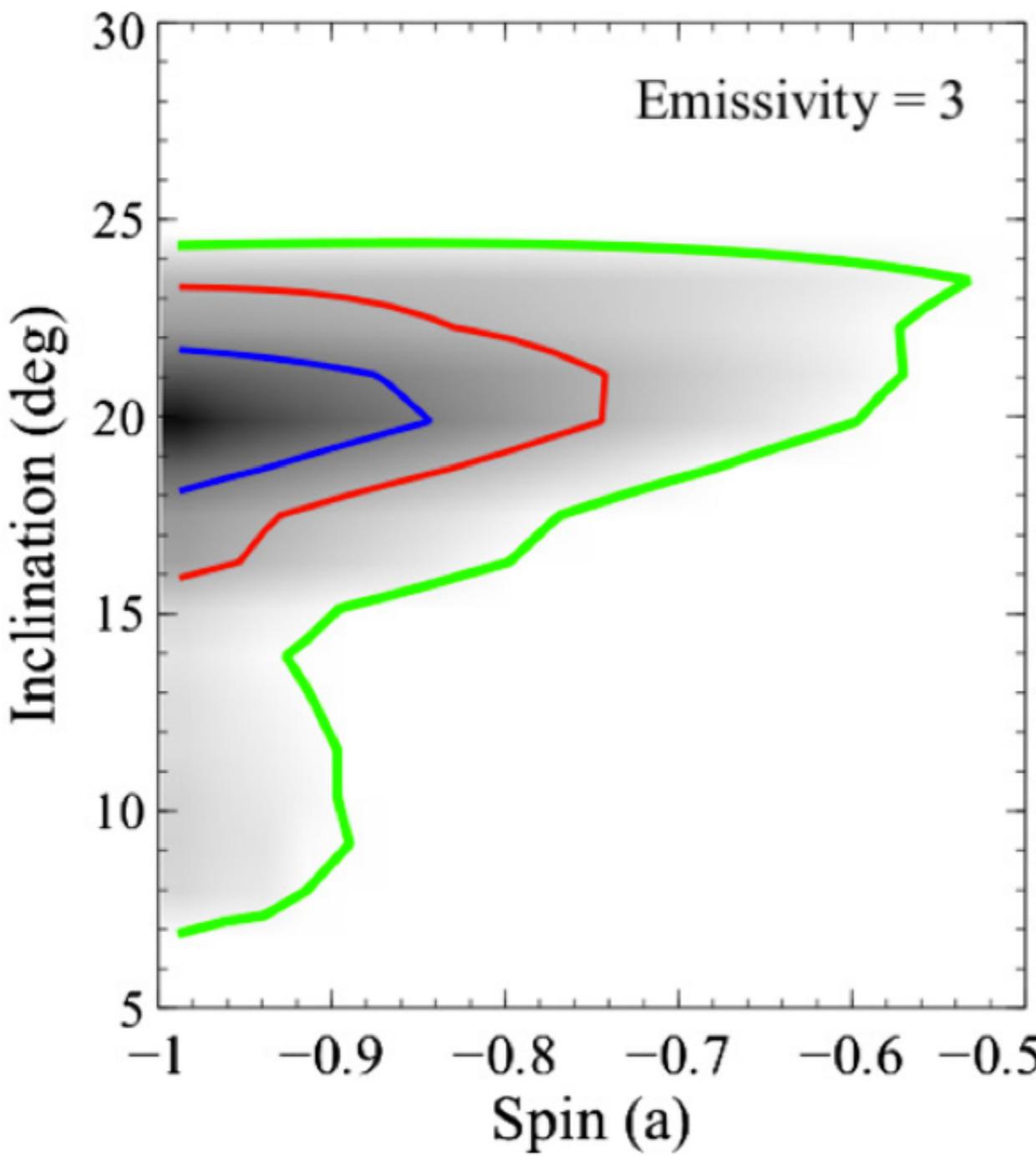
$$L_0 \equiv \Upsilon \frac{\Phi_l^2 a^2}{r_H^2} c$$

$$\approx 0.16 \frac{H}{r} \left(\frac{r_{\text{isco}}}{r_g} \right)^{3/2} \left(\frac{B_p}{B} \right)^2 \dot{M} c^2 \quad \xleftarrow{\text{using } l = 2H}$$

$$\langle L_j \rangle = 0.43 L_0$$

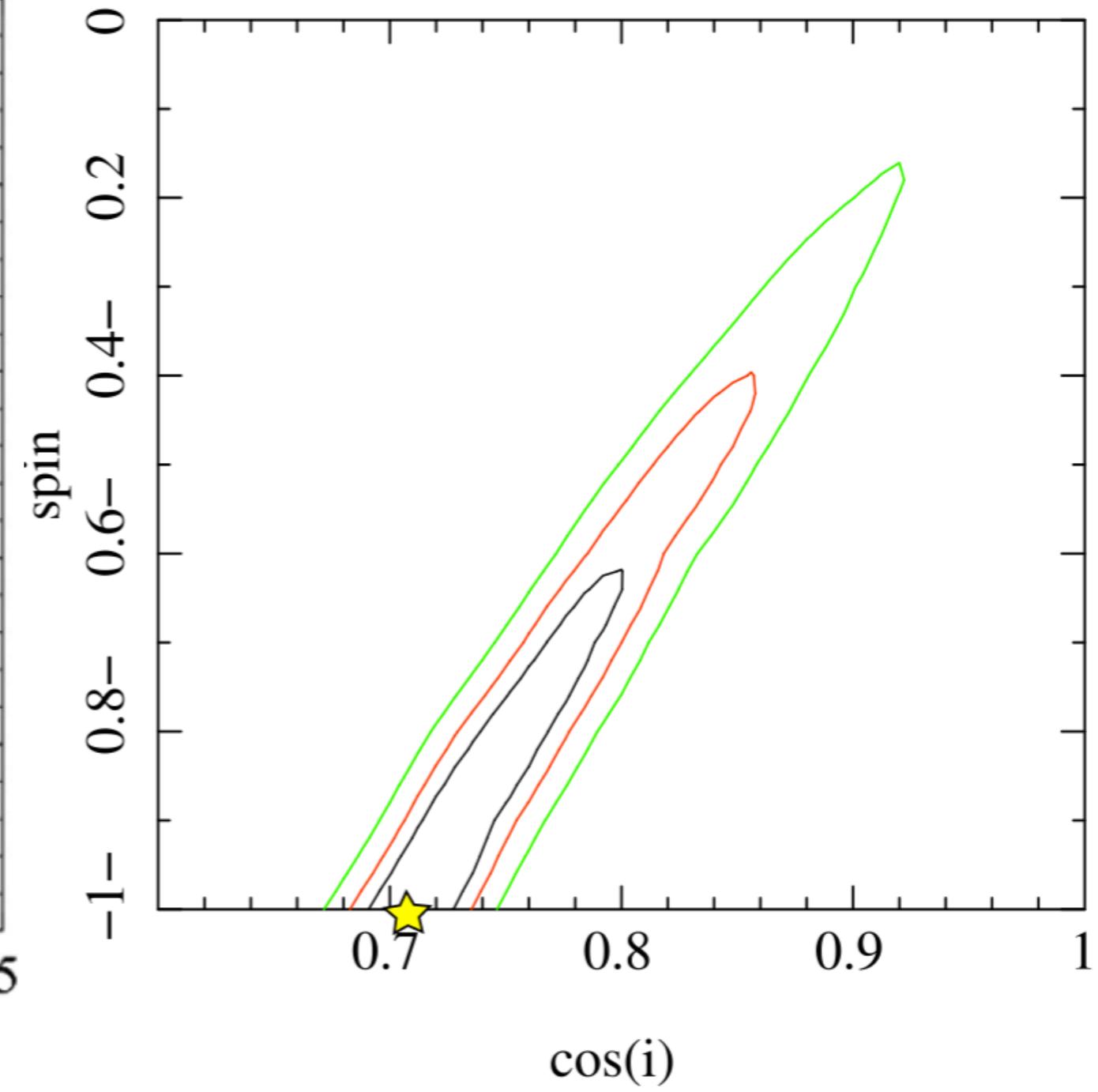
Retrograde microquasars

Swift J1910.2-0546



Reis+ 13

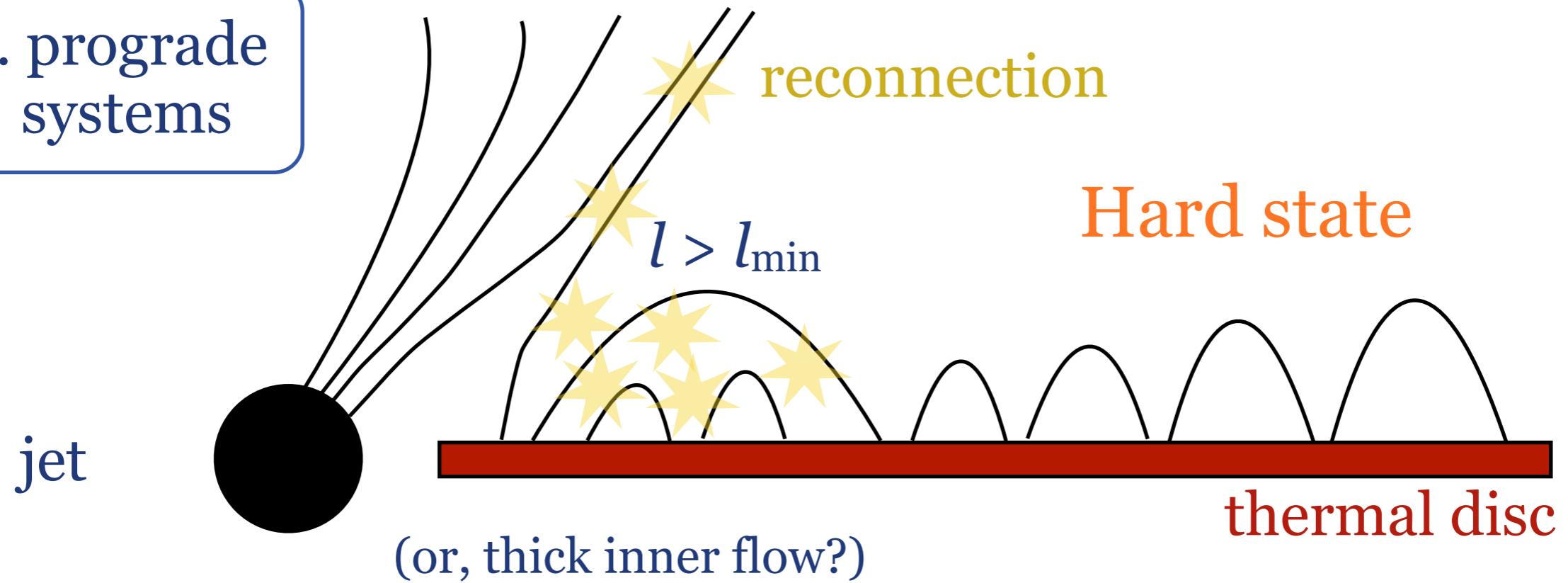
XMMU J004243.6 + 412519
(M31 microquasar)



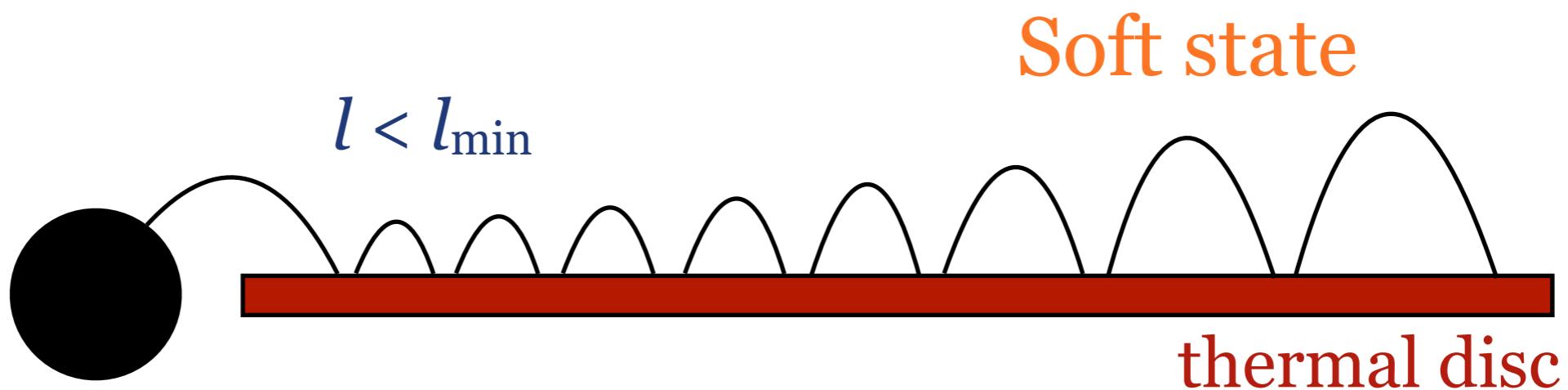
Middleton, Miller-Jones, Fender 14

Jet quenching in BH-XRB soft states?

e.g. prograde systems

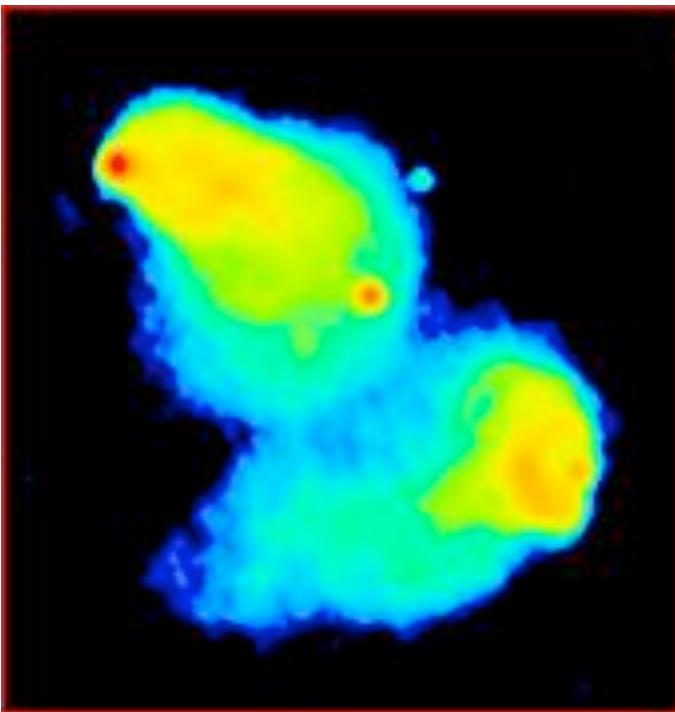


hole-disk
coupling



Radio Galaxies

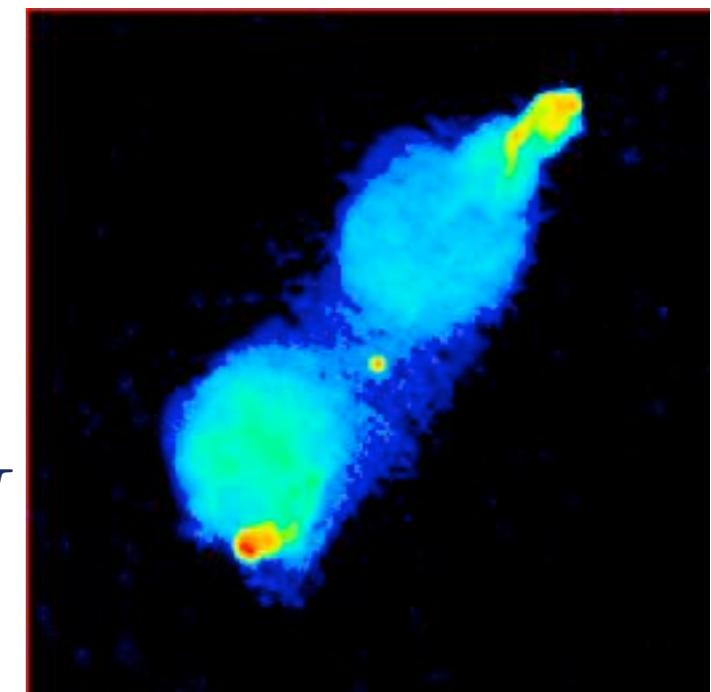
Leahy & Perley 91



3C 382

$$r_{\text{in}} \approx 10 M$$

Sambruna+ 11



3C 390.3

$$r_{\text{in}} \gtrsim 20 M$$

Sambruna+ 09

Retrograde accretion?

Coronal inverse cascade?

Thick inner disk?

Seyferts

$$a/M > 0.8$$

MCG 6-30-15

Miniutti+ 07

NGC 3783

Brenneman+ 11

NGC 1365

Risaliti+ 13

Leahy & Perley 95

Summary

- Prograde disk: minimal poloidal loop scale
 - $l < l_{\text{crit}}$: differential rotation-powered plasmoid wind
 - $l > l_{\text{crit}}$: black hole-powered jet
- Retrograde disk: black hole-powered jet even for small loops
- Jets highly variable on timescales $\sim 10\text{--}10^3 r_g/c$
- Unavoidable reconnection may power the corona
 - naturally places major dissipation region at small radii