initiation of magnetic flux eruptions at accreting black holes

a high-energy phenomenon at the base of relativistic outflows

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BH magnetic flux saturation

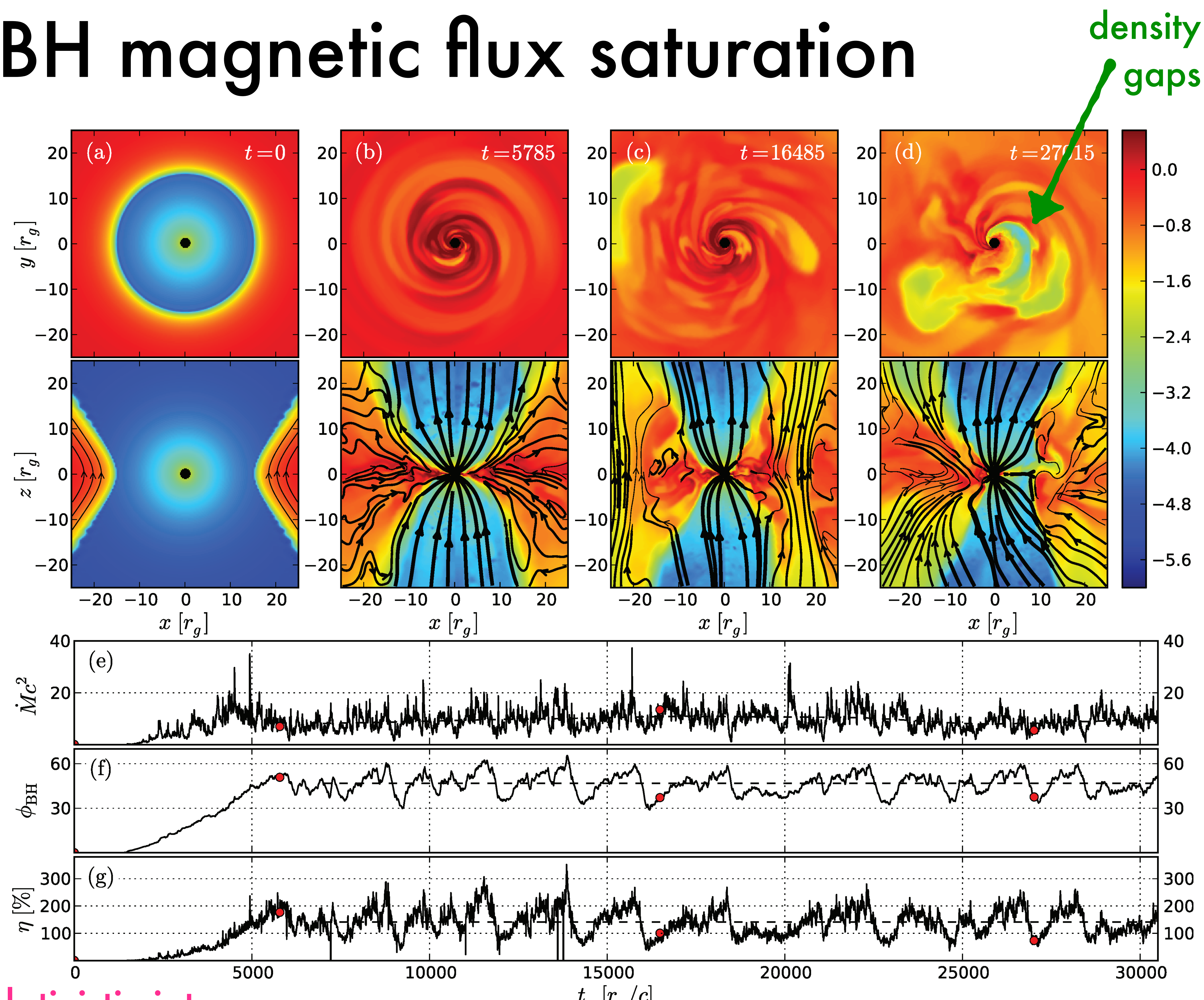
GRMHD

MAD?

BH flux:
- slow increase
- fast decrease (eruptions)

$\Phi_{BH}/\dot{M}^{1/2}$

$P_{jet}/\dot{M}c^2 > 1$



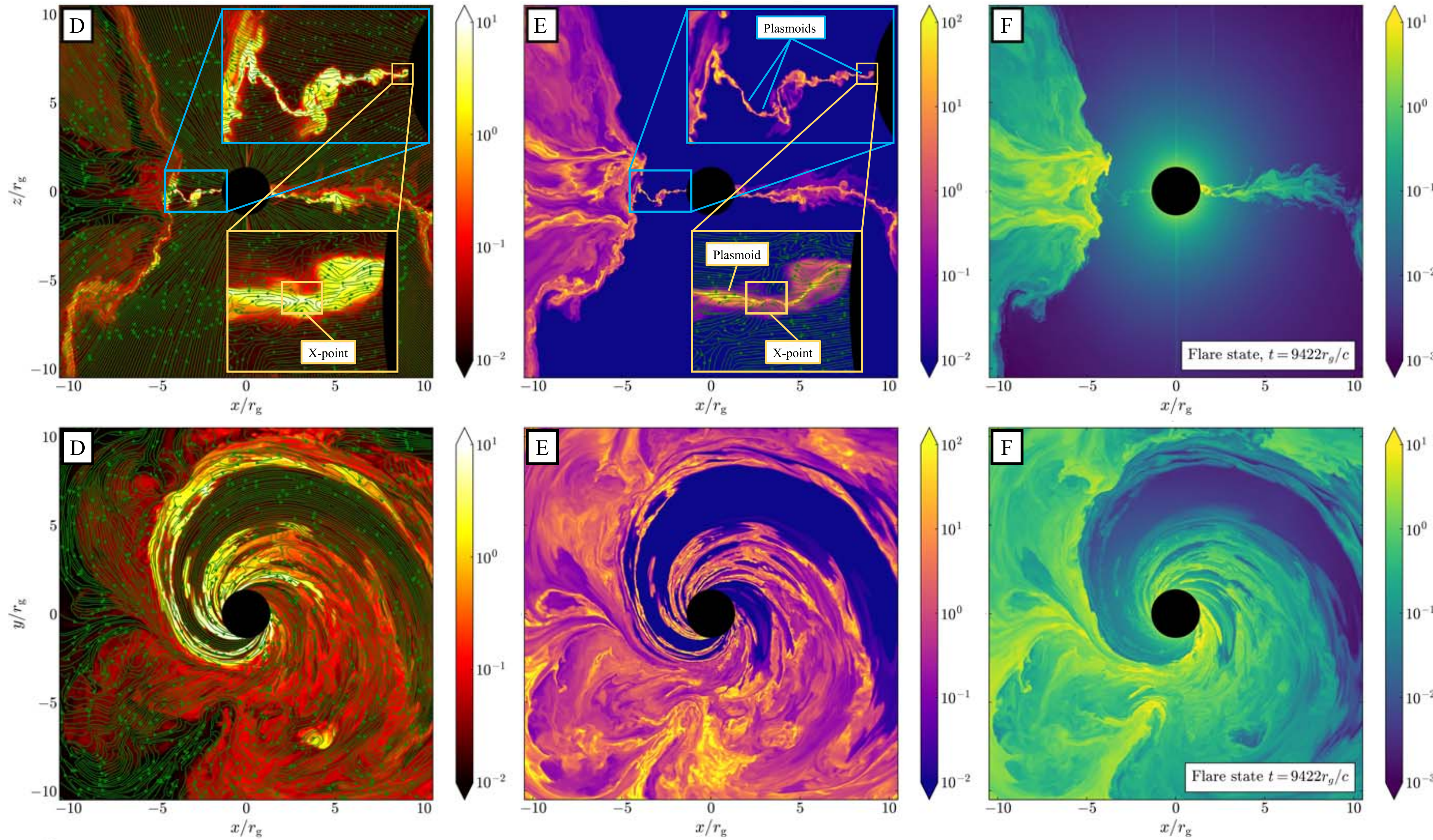
most powerful relativistic jets:

$P_j \propto a^2 \Phi_{BH}^2$ - Blandford & Znajek (1977)

Tchekhovskoy, Narayan & McKinney (2011)

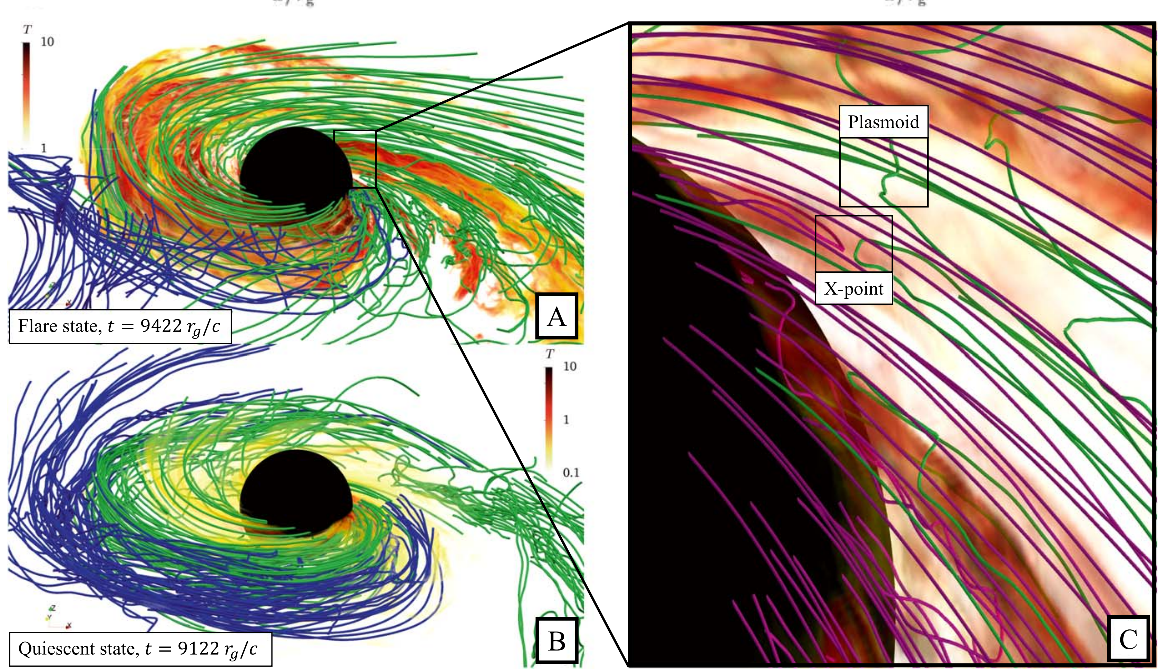
BH magnetic flux eruptions

relativistic temperature



density gap

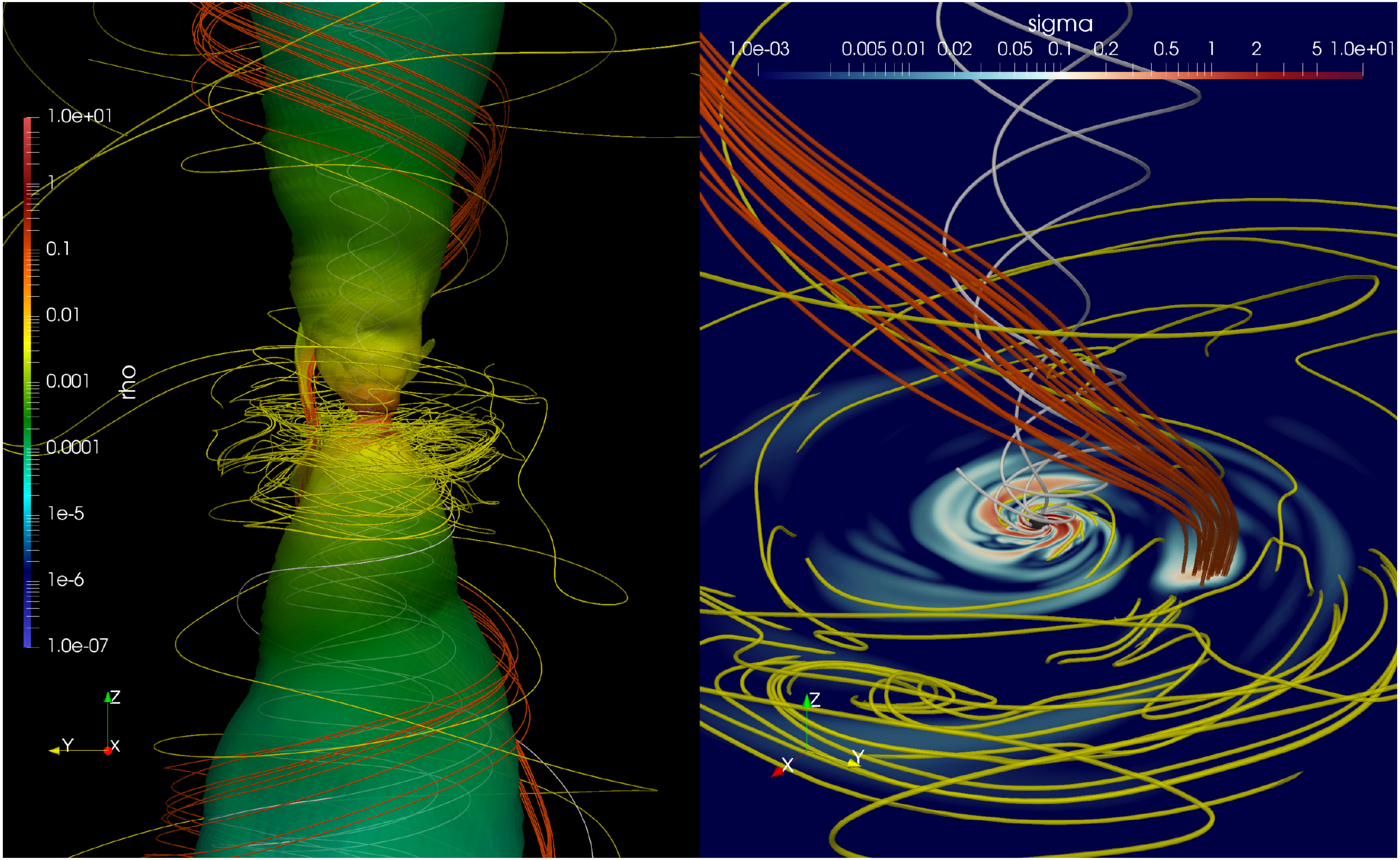
magnetic reconnection with plasmoids



Ripperda, Liska, Chatterjee, Musoke, Philippov, Markoff, Tchekhovskoy, & Younsi (2022)

effective resolution 5376 x 2304 x 2304 (H-AMR, GPU)

orbiting hotspots (Sgr A*)



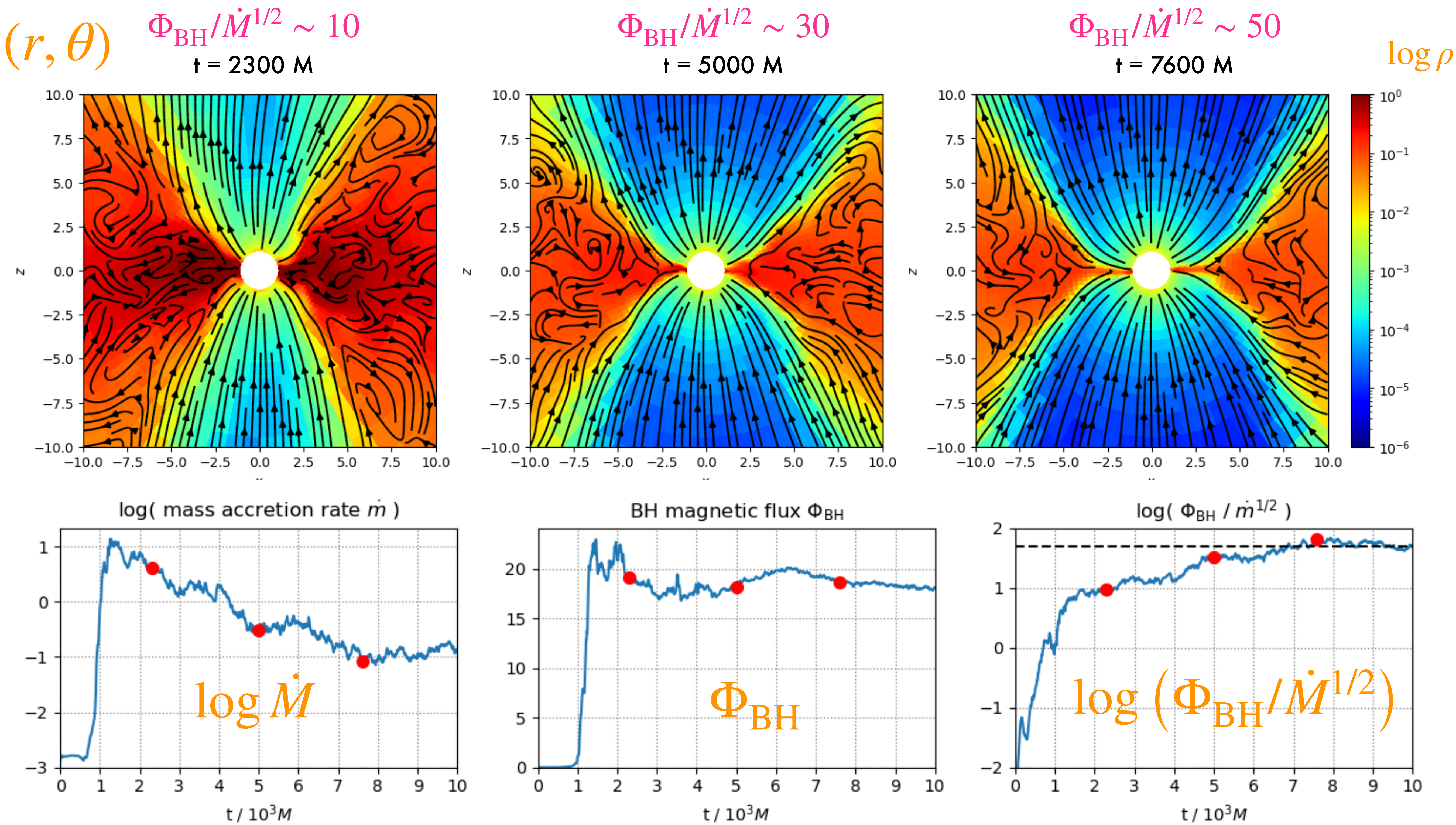
Porth, Mizuno, Younsi & Fromm (2021)

see also Dexter, Tchekhovskoy, Jiménez-Rosales, et al. (2020)

low-resolution demonstration of magnetic flux saturation

Kerr metric (a=0.9); Kerr-Schild coordinates ($N_r = 72, N_\theta = N_\phi = 64$)

prograde MF76 torus; $\gamma = 13/9$; Athena++ (HLLE, PPM, vL2)

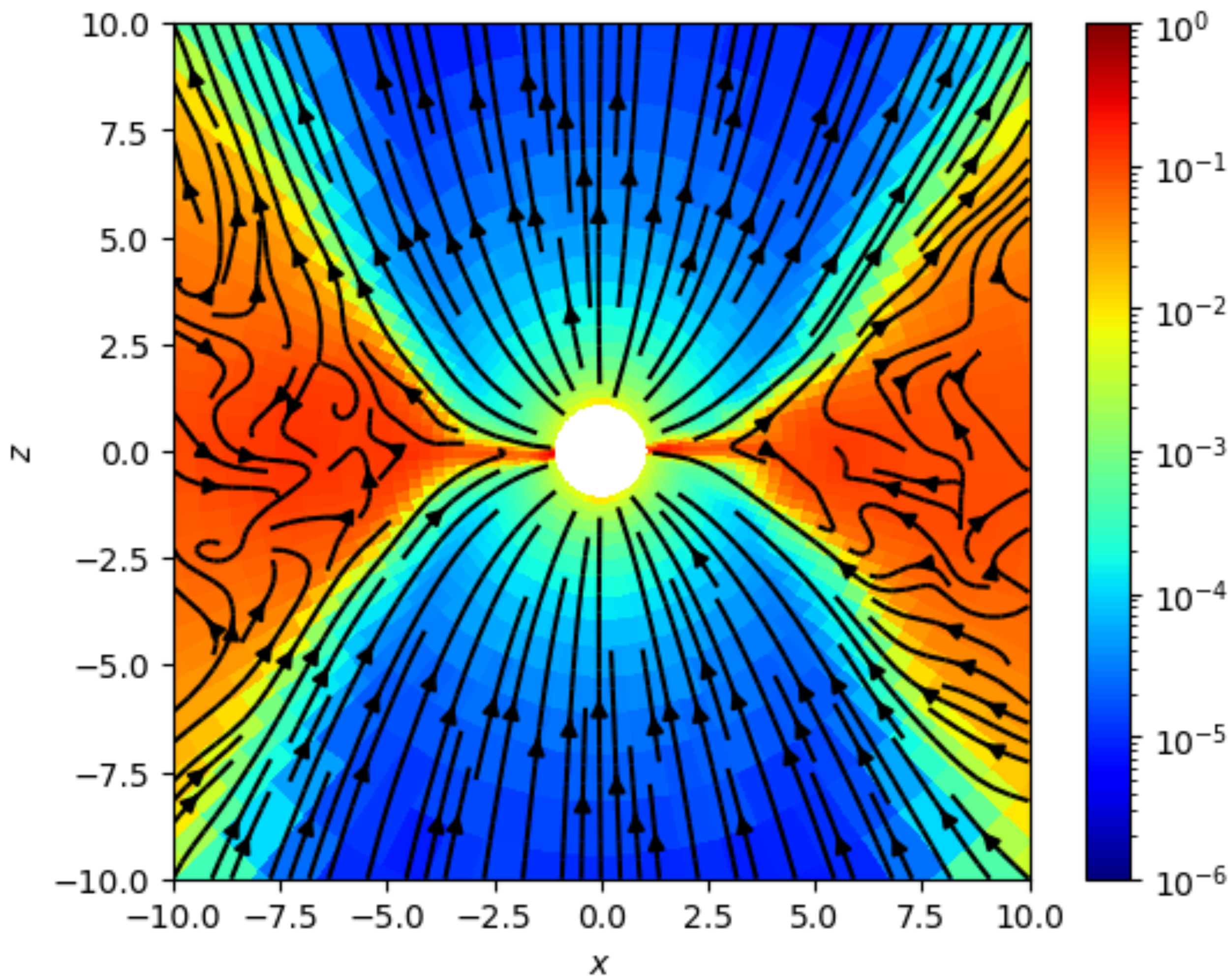


bulging magnetospheres constrict (choke) the accretion flow into a thin disk

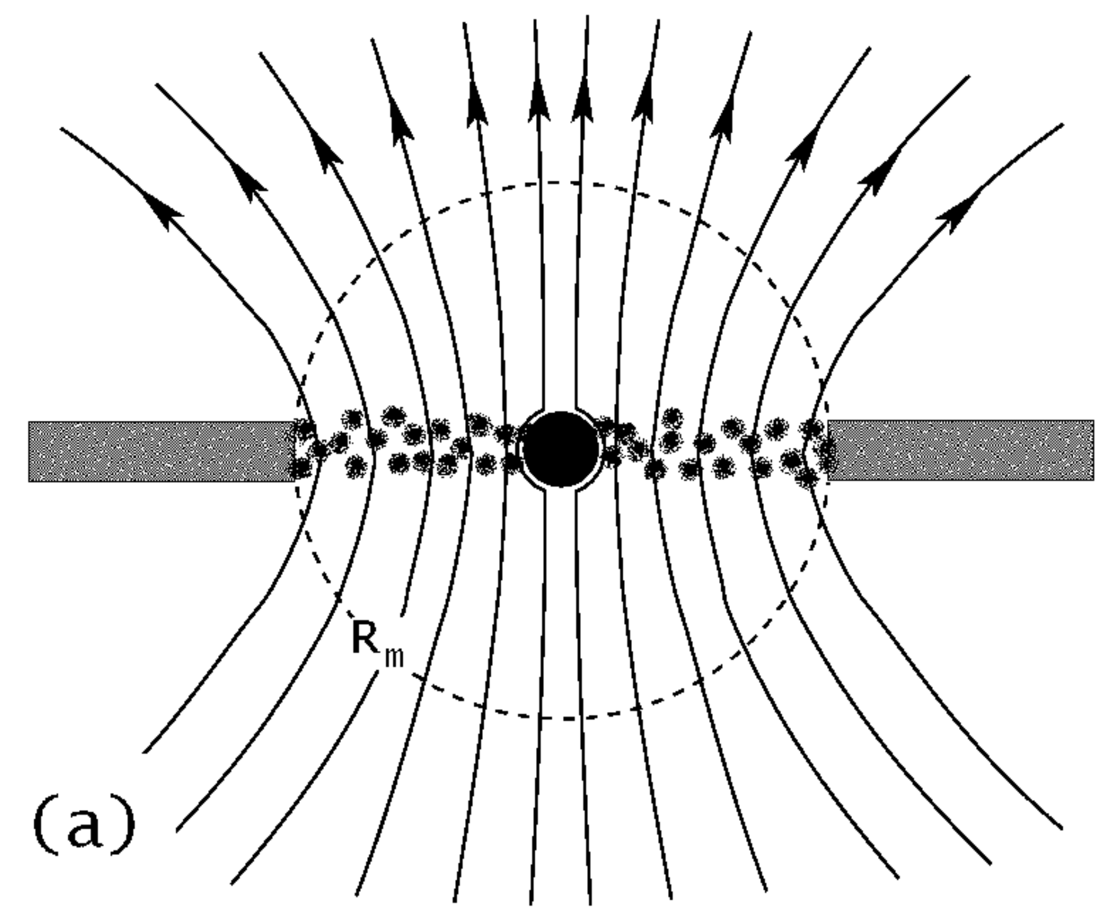
no opportunity to set up a magnetic barrier

accretion flow at magnetically saturated BH

- weak B^θ (Begelman, Scepi & Dexter 2022) - no magnetic barrier, no interchange
- strong B^r - split monopole pinned on the horizon (Meissner effect overwhelmed; Komissarov & McKinney 2007)
- no magnetic connection between accretion flow and magnetospheres (?)
- smooth, stable, sub-Keplerian, supported by laminar torque of magnetized wind (Scepi, Begelman & Dexter 2023; see also Manikantan et al. 2023)



„hourglass” (Punsly et al. 2009)
Magnetically Choked Accretion Flow (MCAF)
McKinney, Tchekhovskoy & Blandford (2012)



Magnetically Arrested Disk (MAD)
Narayan, Igumenshchev & Abramowicz (2003)

(r, ϕ)

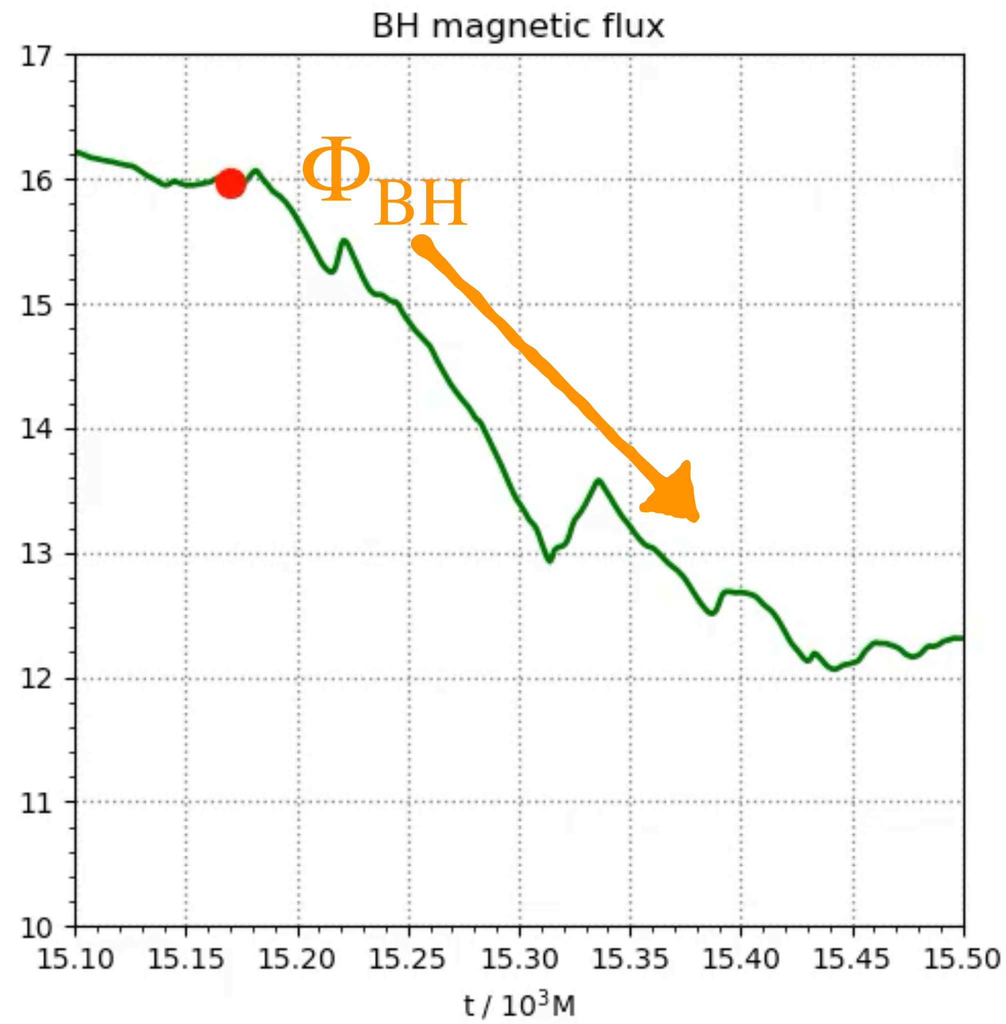
$\Delta t = M$

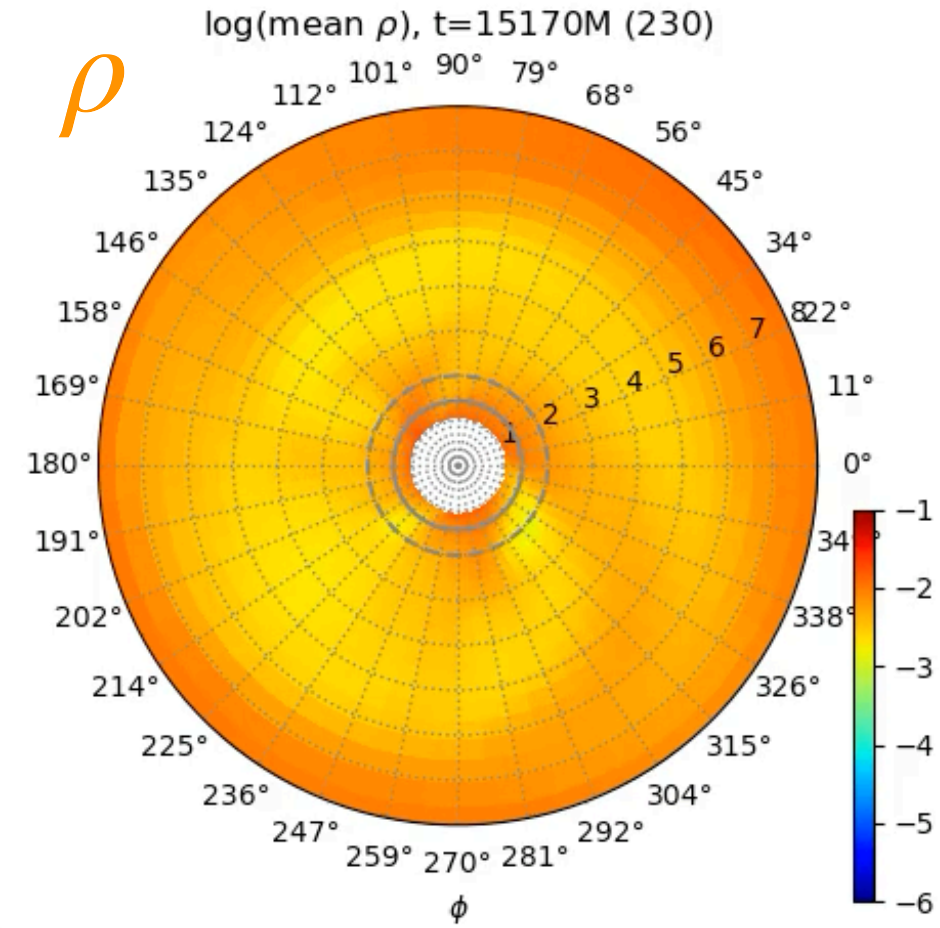
magnetic flux eruption:

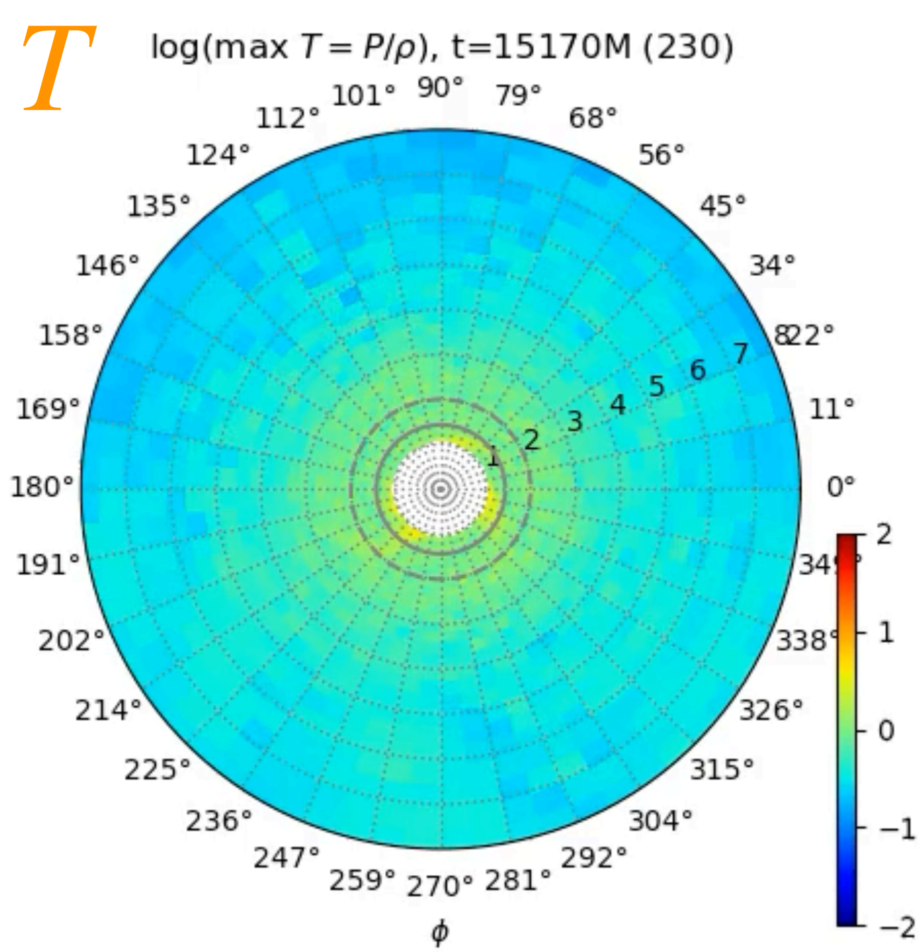
- density gaps
- relativistic temperature
- radial outflows

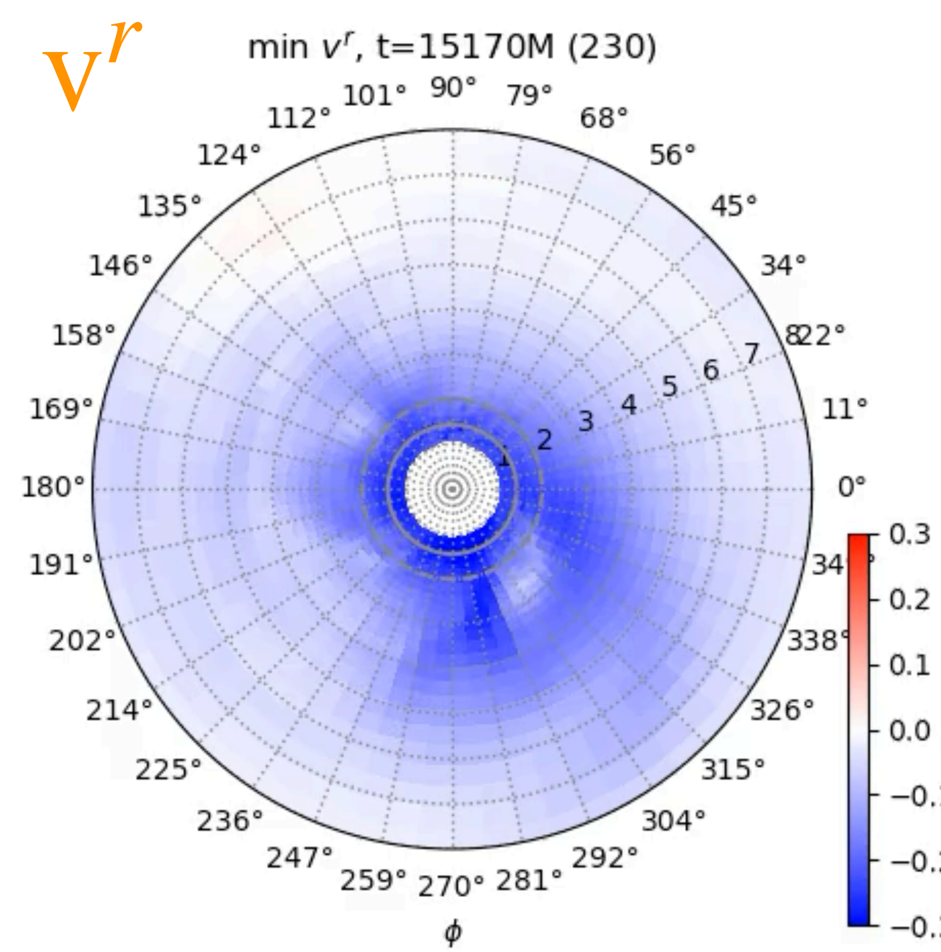
parameter statistics over $\pi/4 < \theta < 3\pi/4$:

- mean ρ
- max T
- min v^r

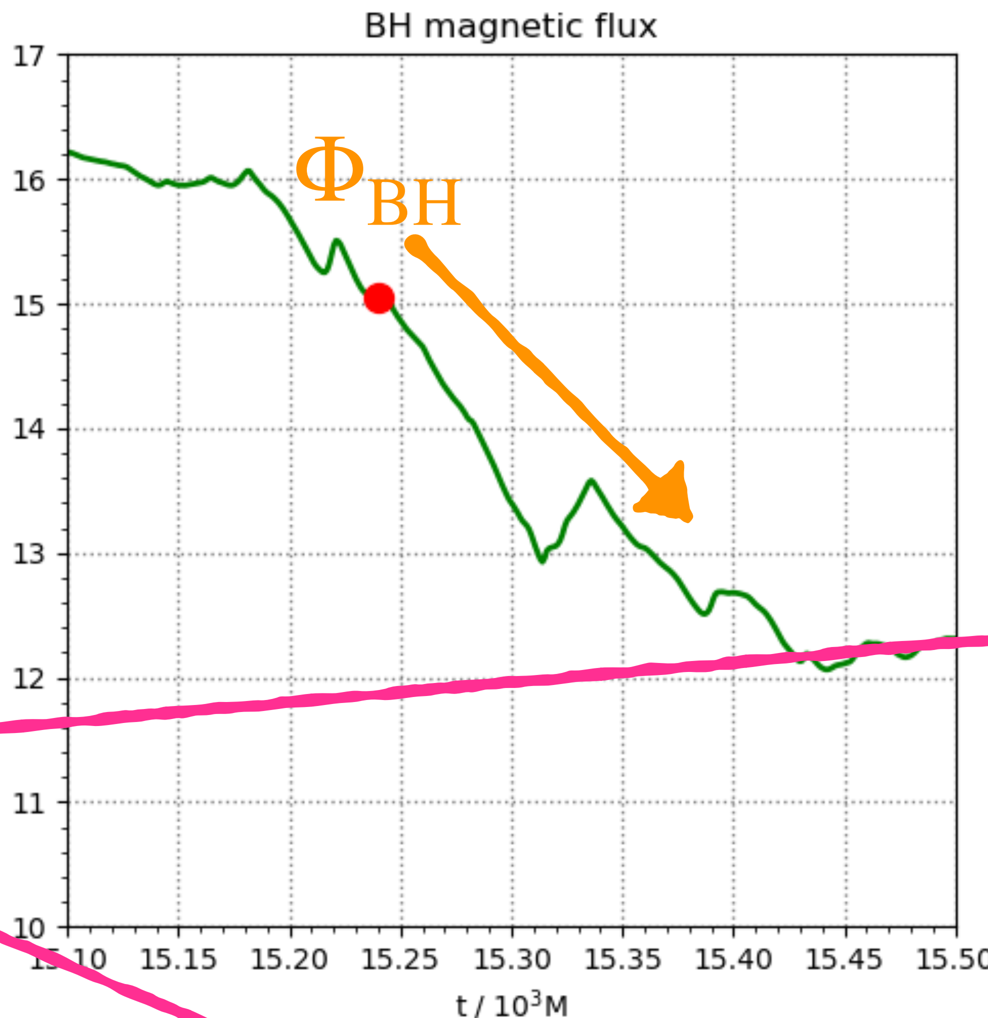


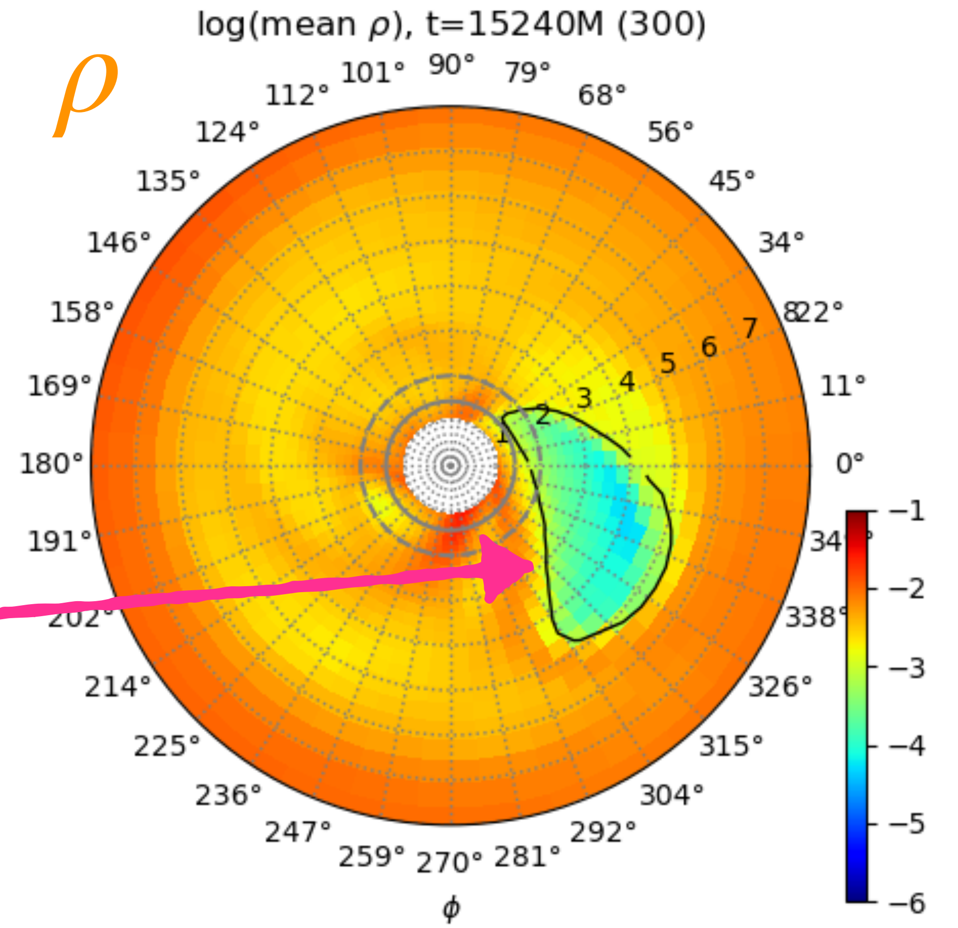






(r, ϕ)



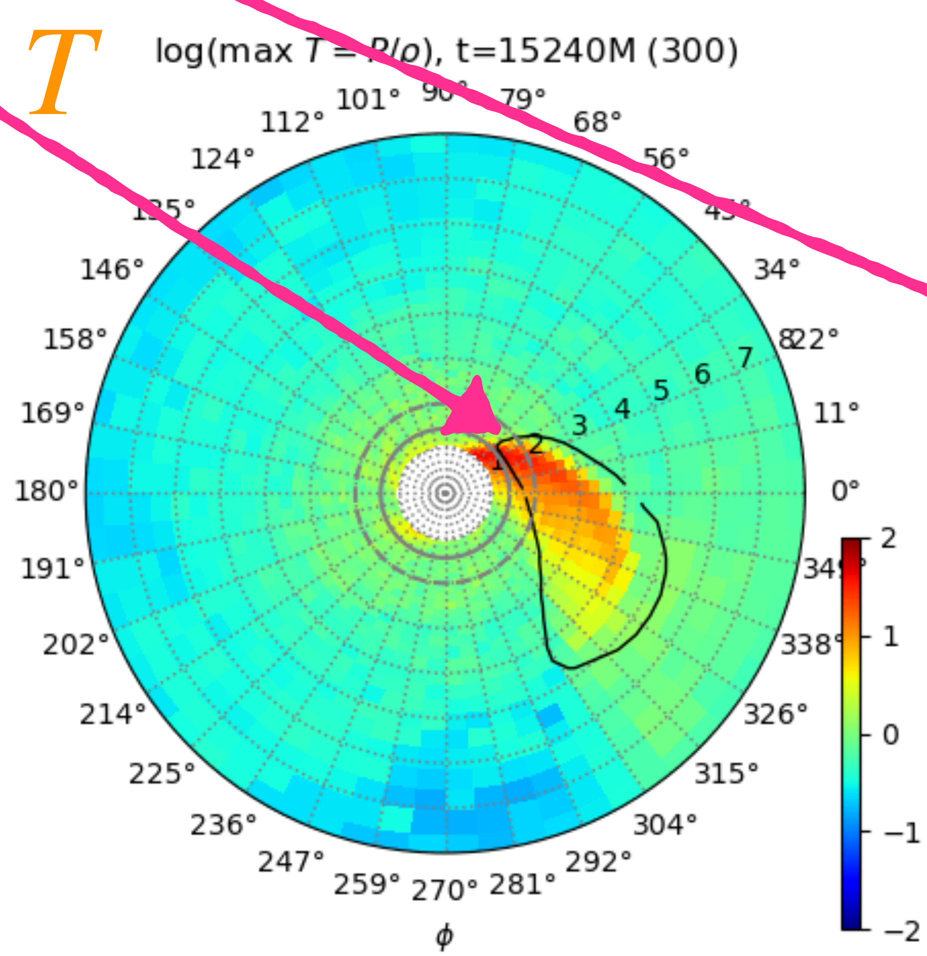


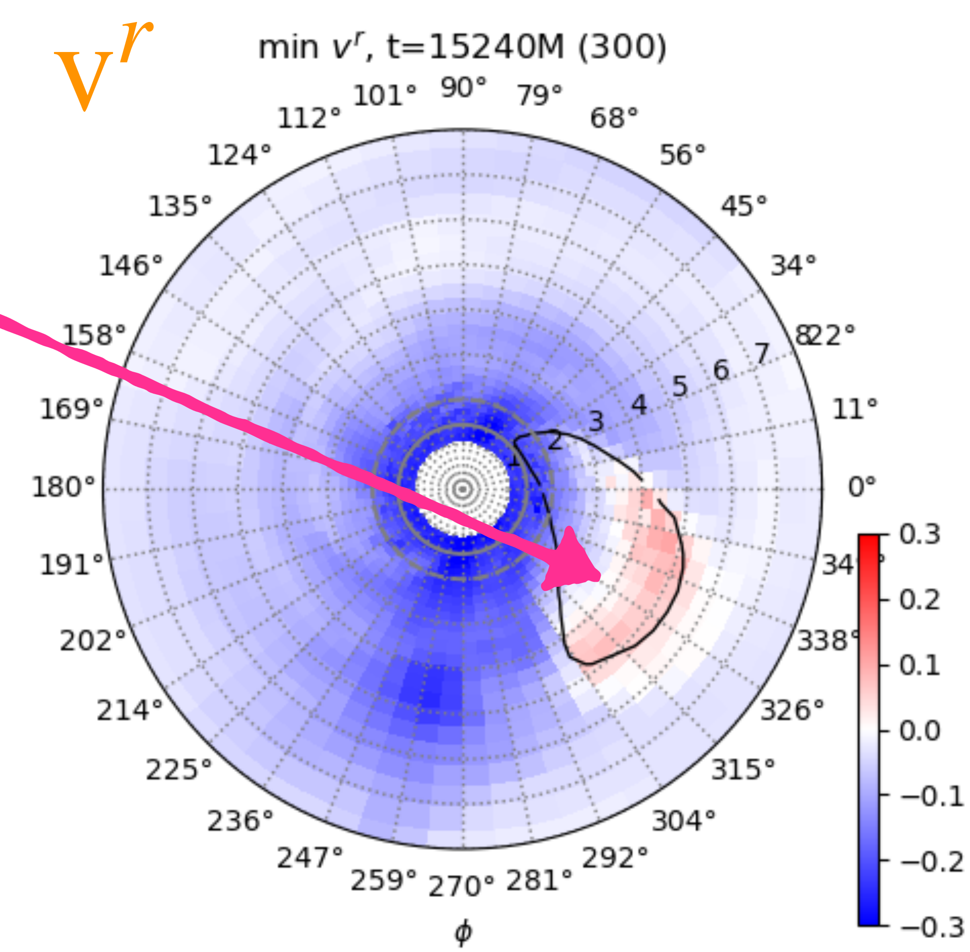
magnetic flux eruption:

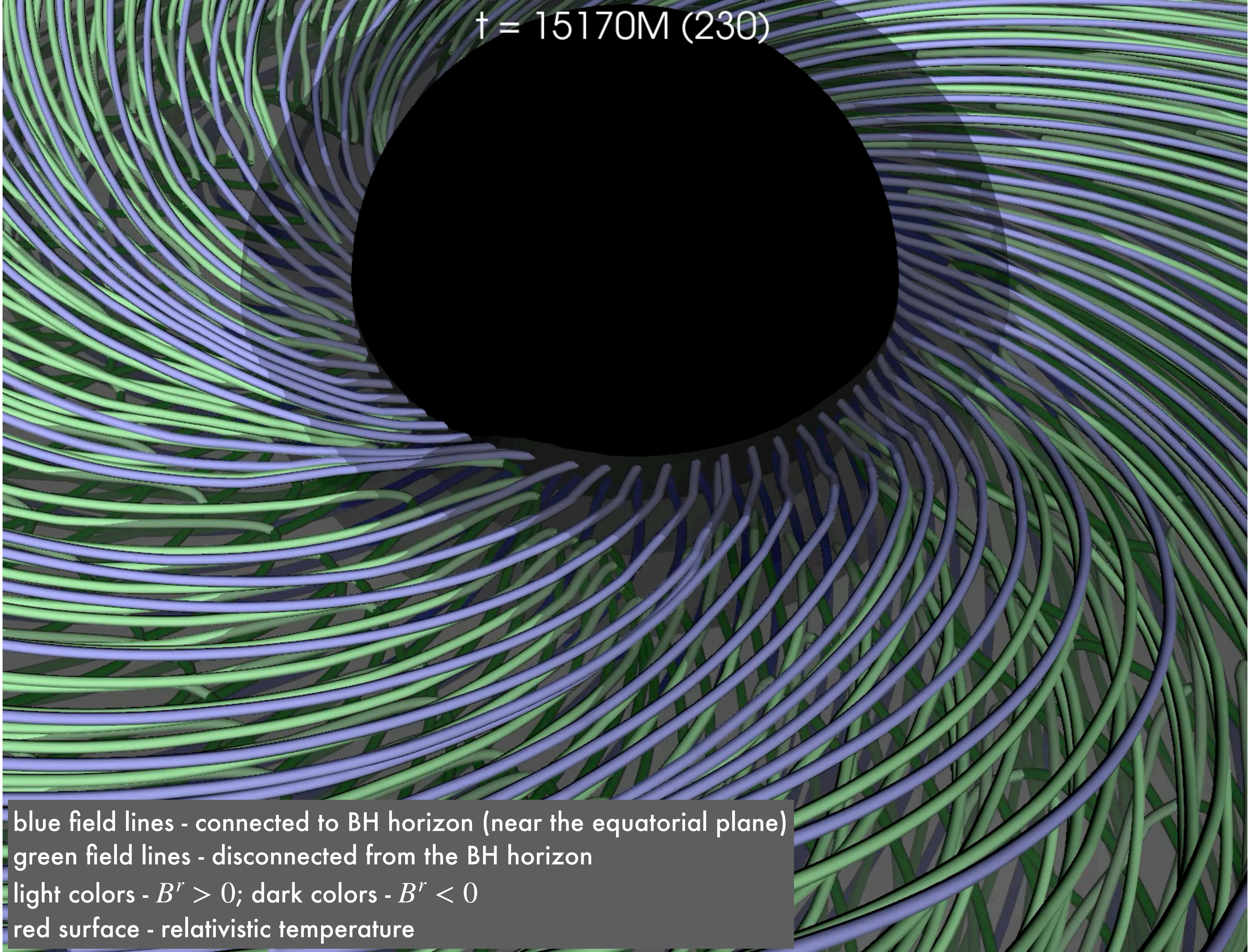
- density gap
- radial outflow
- relativistic temperature

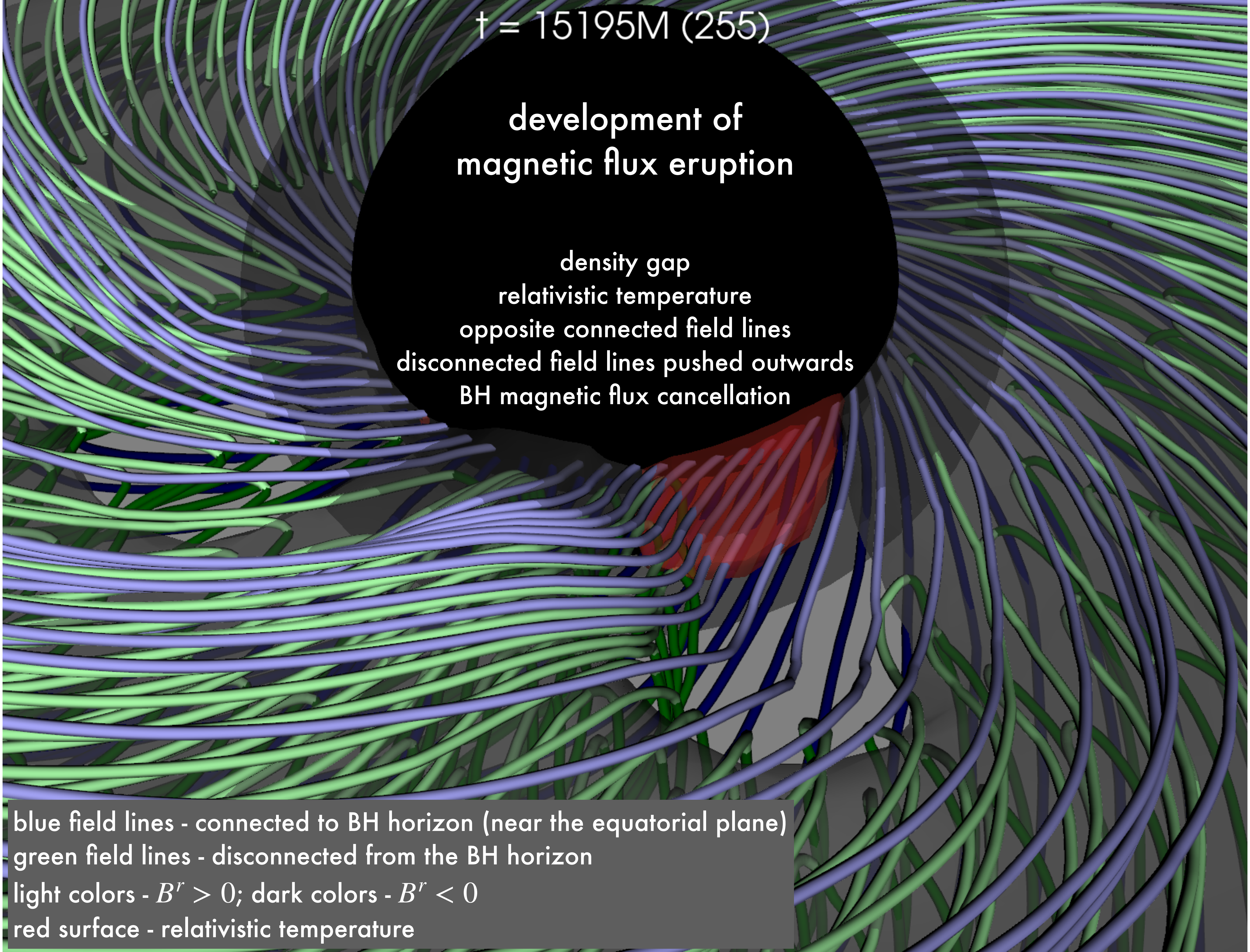
parameter statistics over $\pi/4 < \theta < 3\pi/4$:

- mean ρ
- max T
- min v^r






t = 15170M (230)
blue field lines - connected to BH horizon (near the equatorial plane)
green field lines - disconnected from the BH horizon
light colors - $B^r > 0$; dark colors - $B^r < 0$
red surface - relativistic temperature

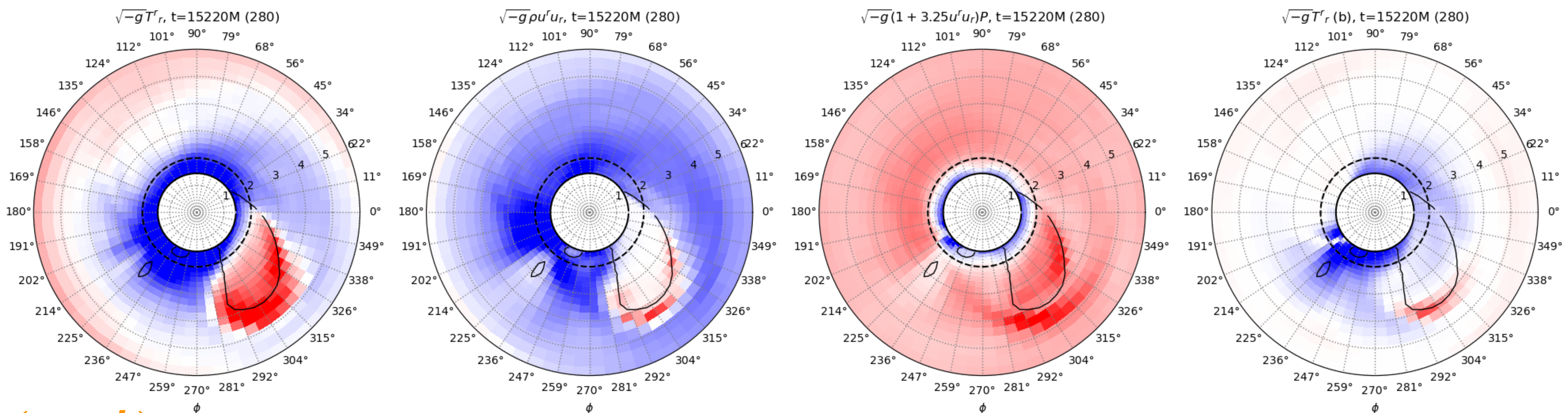

t = 15195M (255)
development of
magnetic flux eruption
density gap
relativistic temperature
opposite connected field lines
disconnected field lines pushed outwards
BH magnetic flux cancellation
blue field lines - connected to BH horizon (near the equatorial plane)
green field lines - disconnected from the BH horizon
light colors - $B^r > 0$; dark colors - $B^r < 0$
red surface - relativistic temperature

What drives the radial outflow?

conservation of radial momentum $\partial_\mu \left(\sqrt{-g} T^\mu{}_r \right) = \sqrt{-g} \Gamma^\sigma{}_{\rho r} T^\rho{}_\sigma$

radial stress tensor $T^r{}_r = \rho u^r u_r + (3.25 u^r u_r + 1) P + (b^2 u^r u_r + b^2/2 - b^r b_r)$

total | matter inertia | matter enthalpy | magnetic



(r, ϕ)

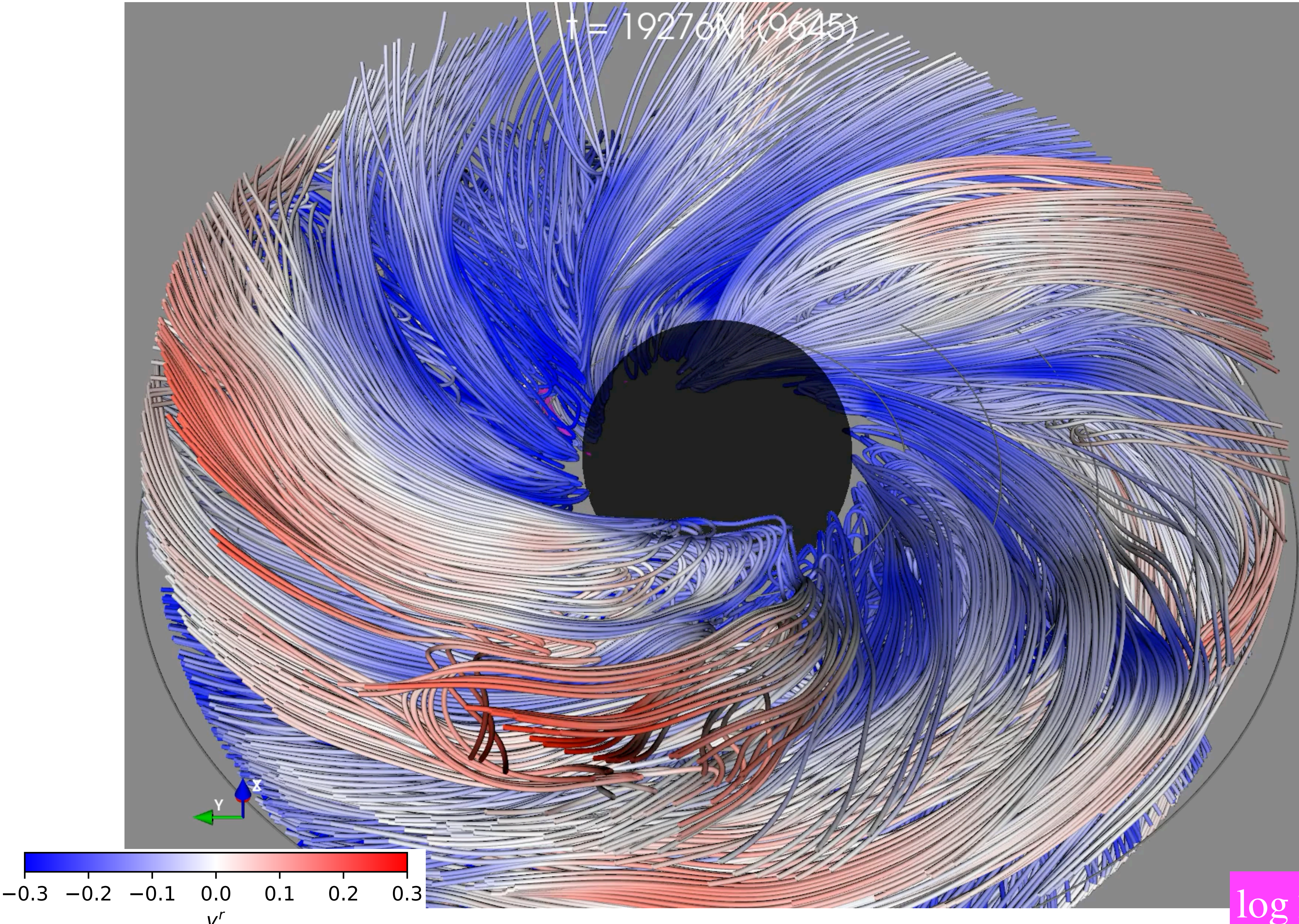
- magnetic energy converted by reconnection to internal energy of matter
- unbalanced matter enthalpy drives the radial outflow
- magnetic forces subdominant

Kerr metric (a=0.9); MKS coordinates ($N_r = 288, N_\theta = N_\phi = 256$)

Janiuk & James (2022)

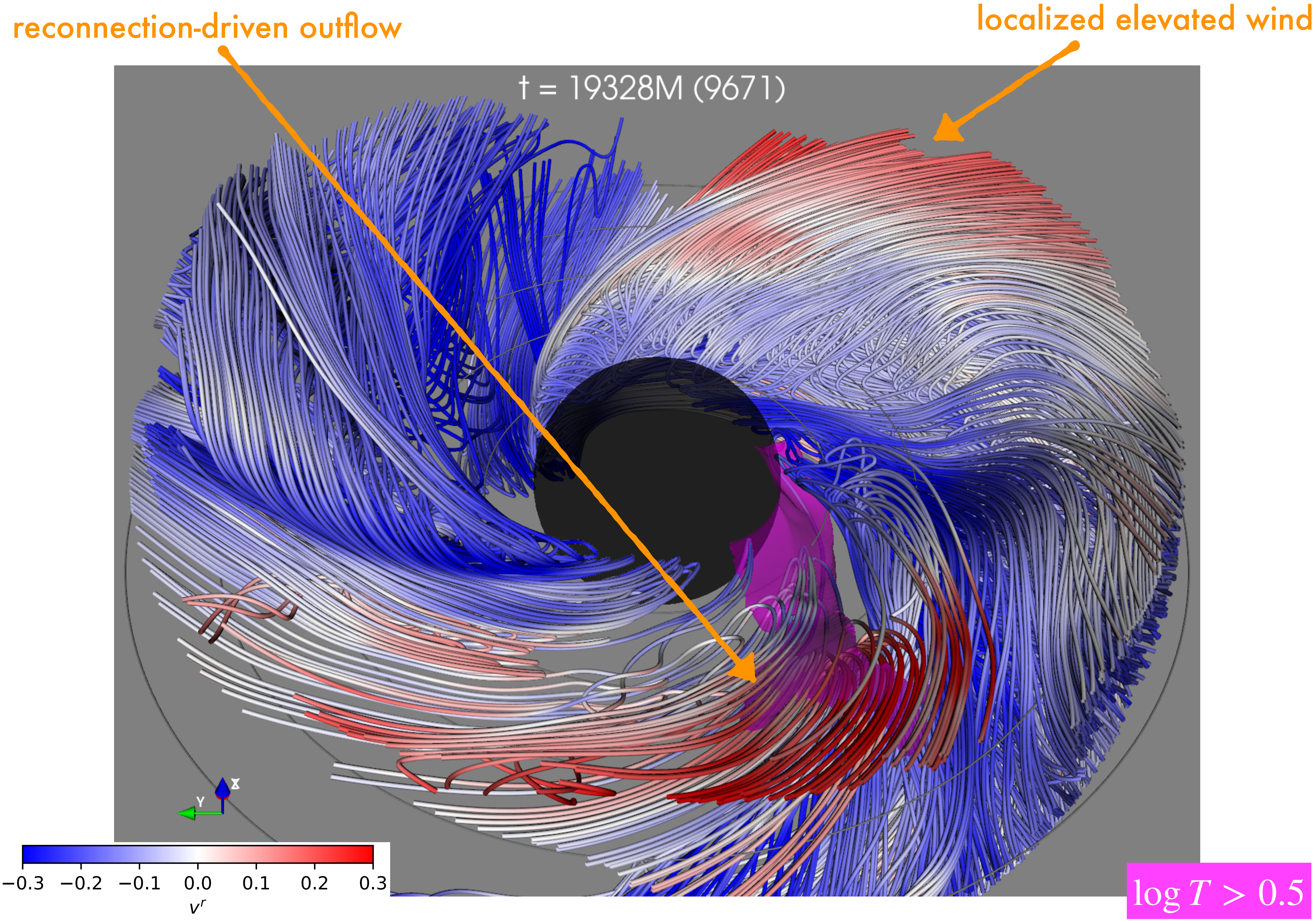
prograde MF76 torus; $\gamma = 4/3$; HARM-COOL (HLL)

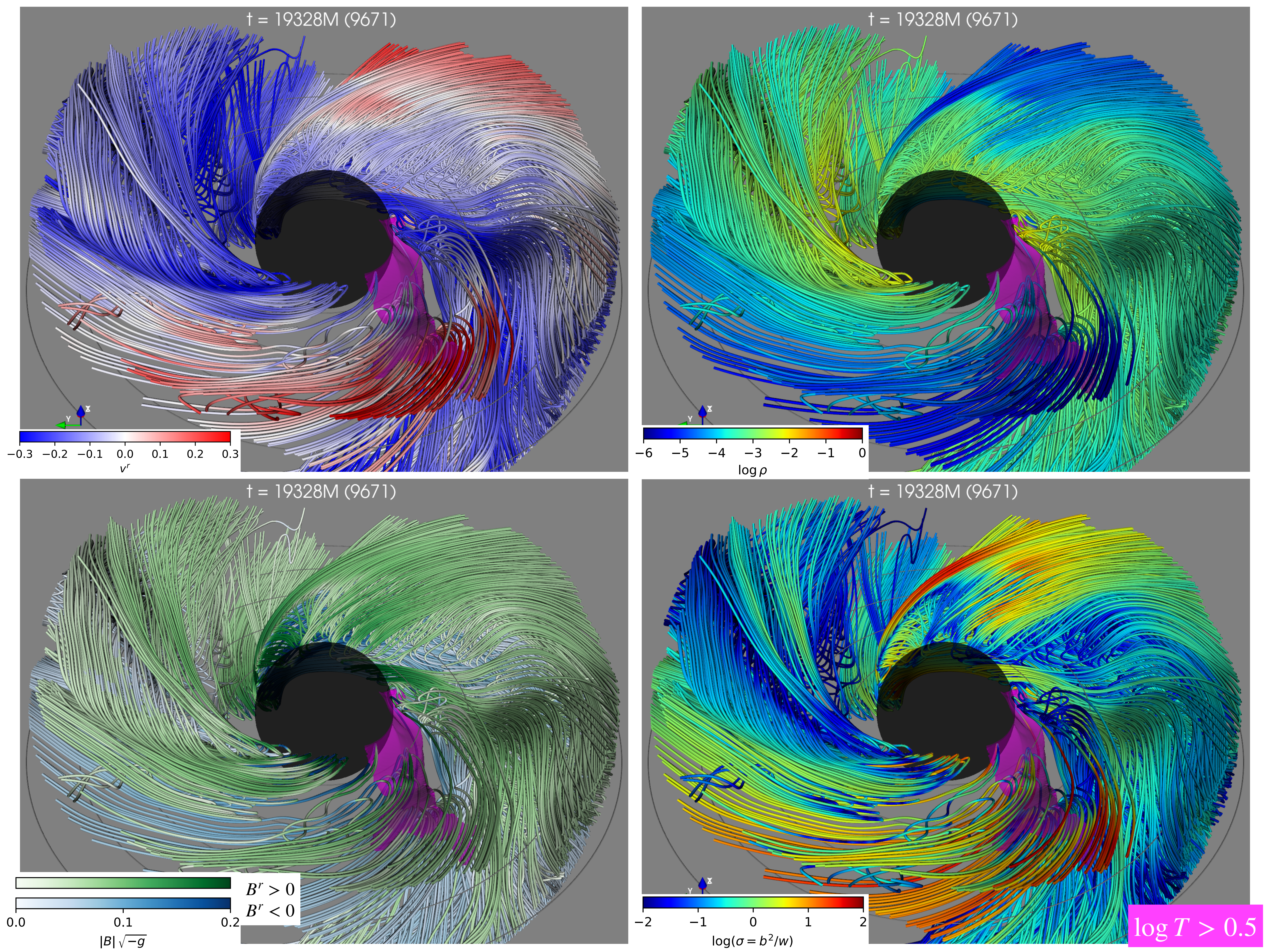
detached magnetic field lines (complete sample for $r_H < r_{min} < 4M$; $r_0 = 6M$)



$\log T > 0.5$

detached field line region: strong azimuthal modulation



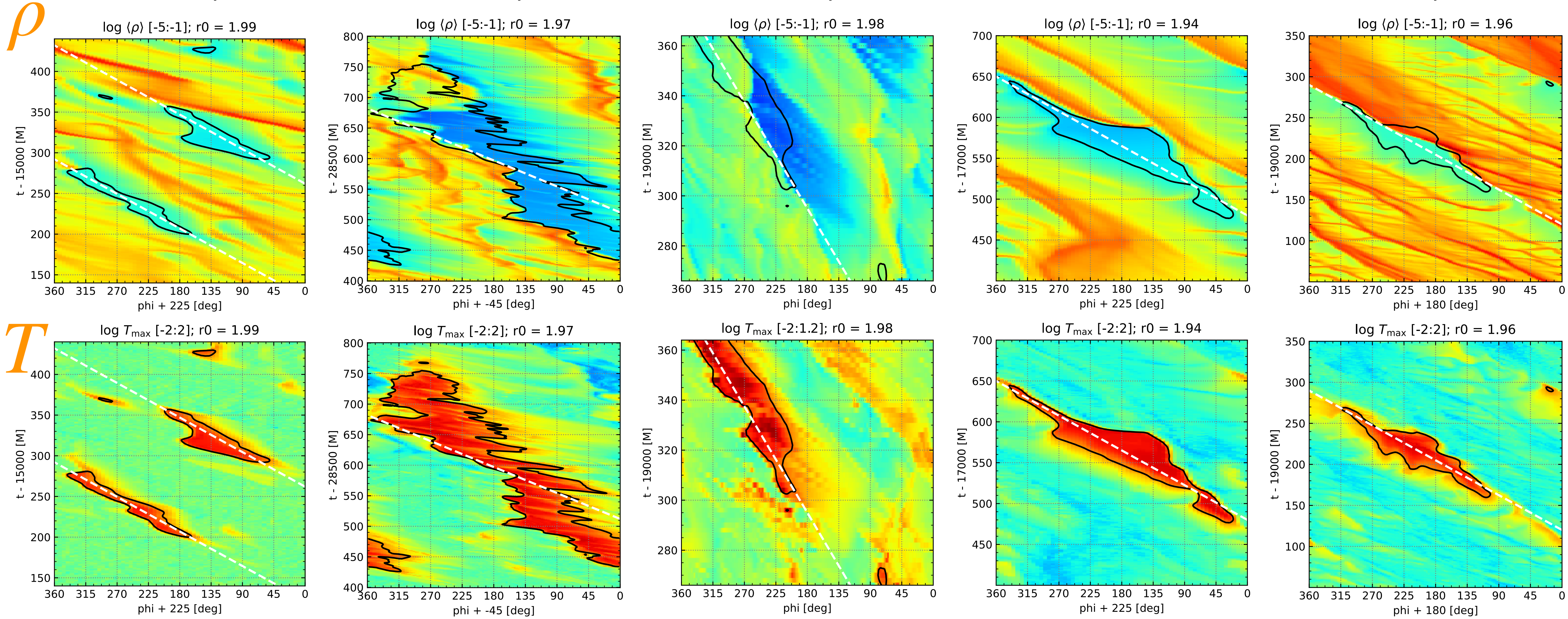


t = 19328M (9671)
−0.3 −0.2 −0.1 0.0 0.1 0.2 0.3
v^r
t = 19328M (9671)
−6 −5 −4 −3 −2 −1 0
$\log\rho$
t = 19328M (9671)
$B^r > 0$
$B^r < 0$
0.0 0.1 0.2
$|B|\sqrt{-g}$
t = 19328M (9671)
−2 −1 0 1 2
$\log(\sigma = b^2/w)$
$\log T > 0.5$

systematic rotation of the reconnection region

(PRELIMINARY)

a=0.9, N_ϕ=64 | a=0.9, N_ϕ=128 | a=0.9, N_ϕ=256 | a=0, N_ϕ=64 | a=0, N_ϕ=128



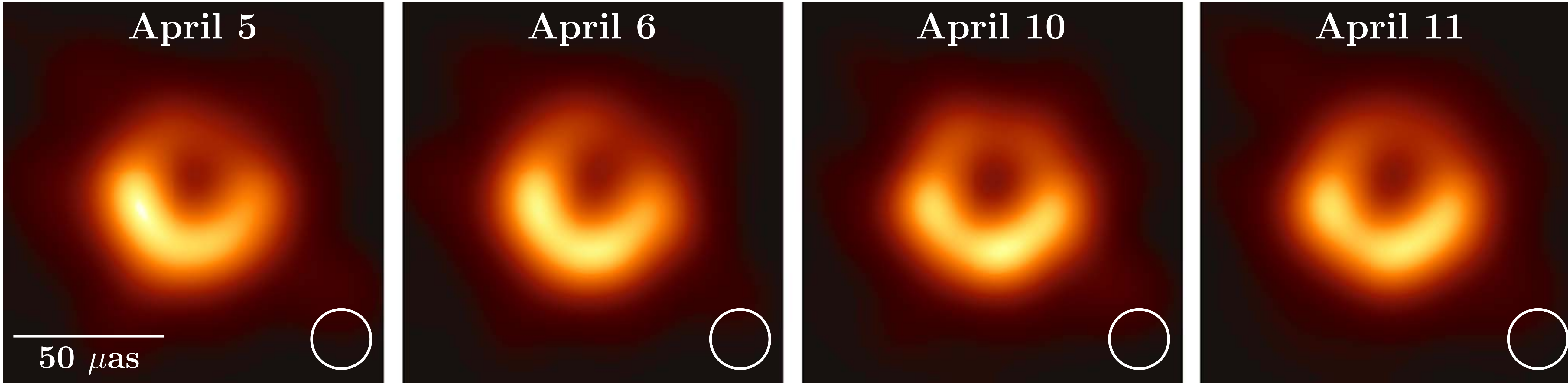
φ

t

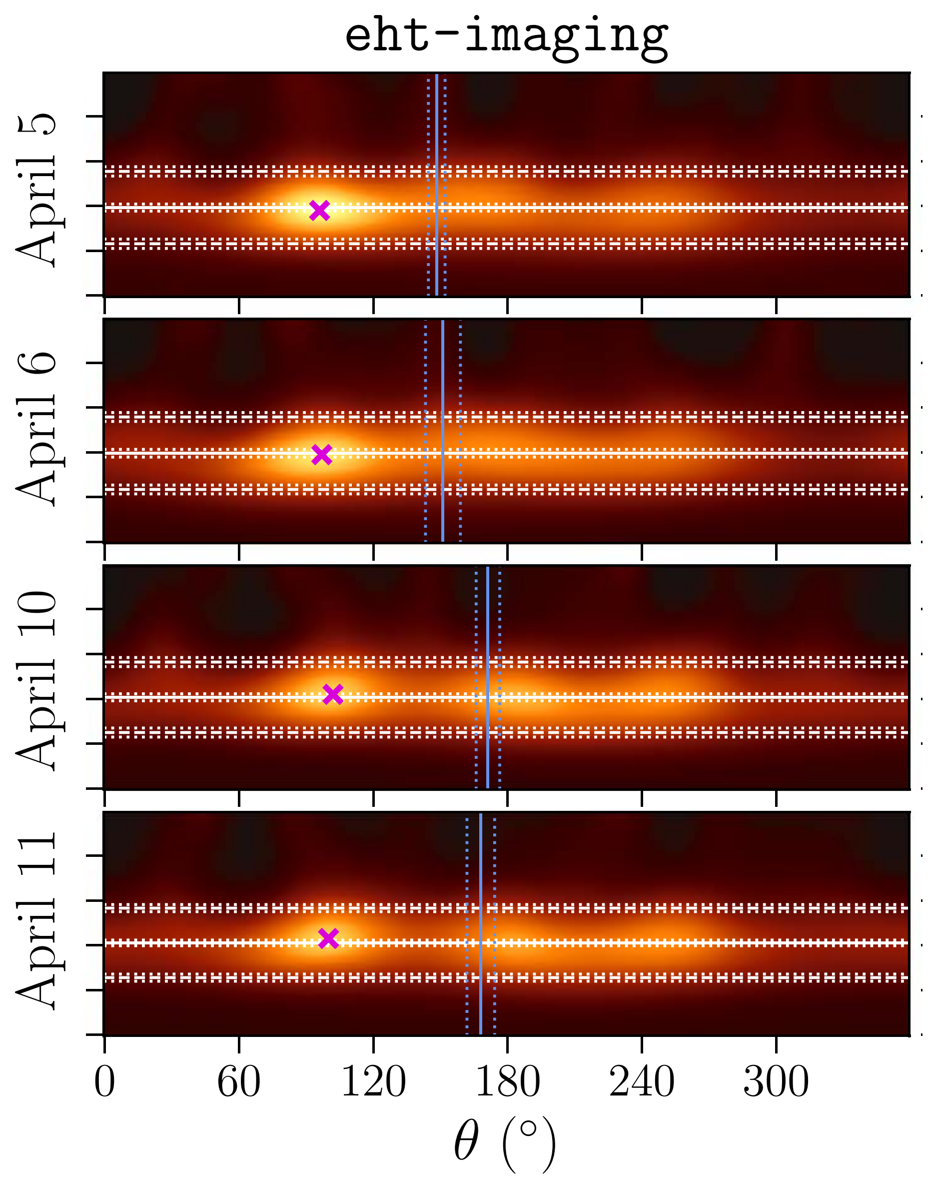
period ~170M (not a fit) at r=2M

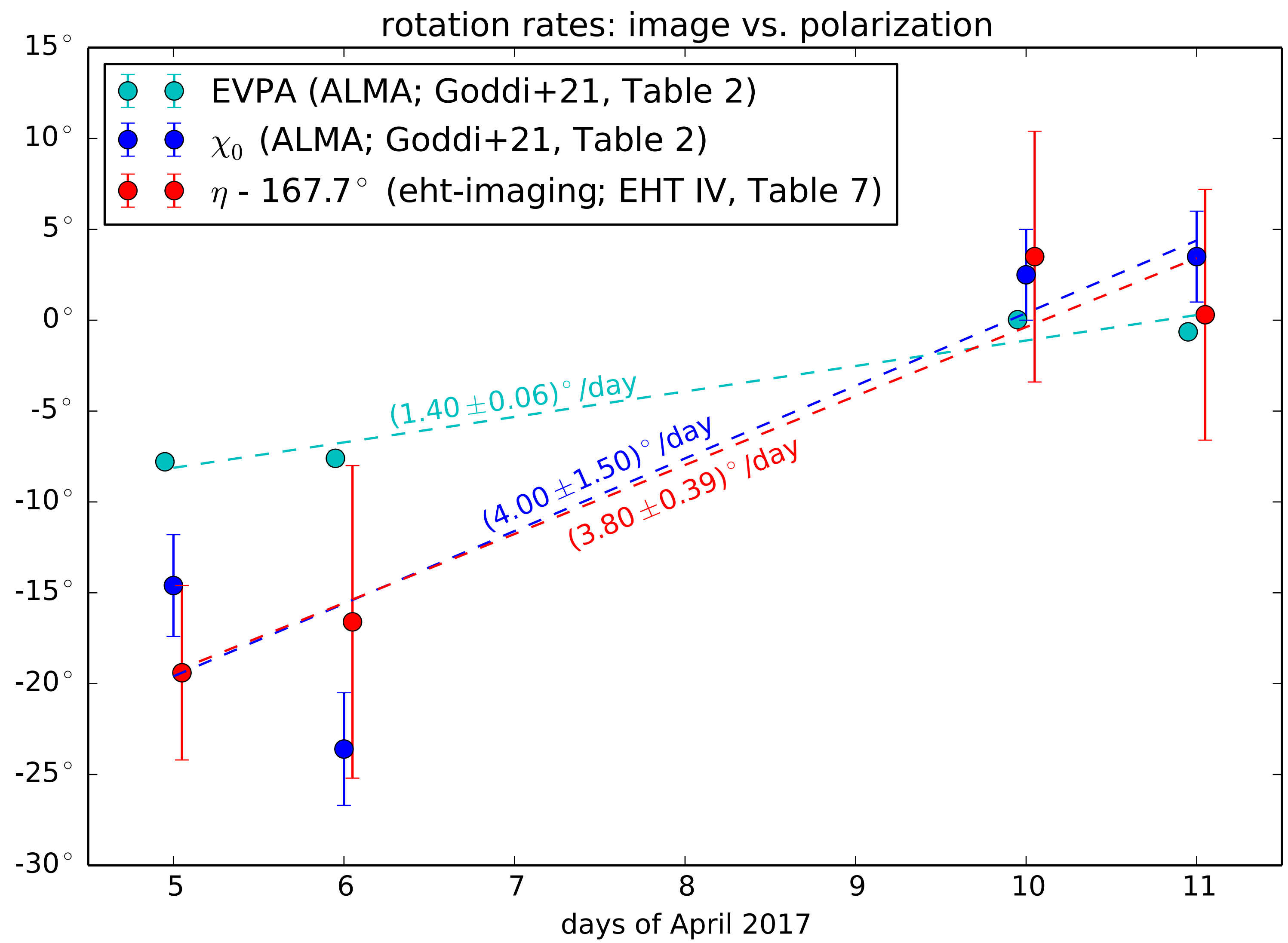
quasi-stationary pattern

apparently independent of BH spin



EHT M87 paper IV (2019)





$3.9°/\text{day}$ **for M87 means** $P \simeq 2.7 P_{\rm ISCO} \simeq 250\, R_{\rm g}/c$

(KN 2021, arXiv:2111.07735)

conclusions

- Magnetic flux accumulated on accreting black holes (BH) in GRMHD simulations is subject to a saturation mechanism (Tchekhovskoy+11) based on flux eruptions involving large-scale reconnection (Ripperda+22).

- In a magnetically saturated state, magnetic flux through the equatorial plane is relatively small (Begelman+22). Accretion flow is not arrested (MAD), but choked geometrically into a thin disk (MCAF; McKinney+12).

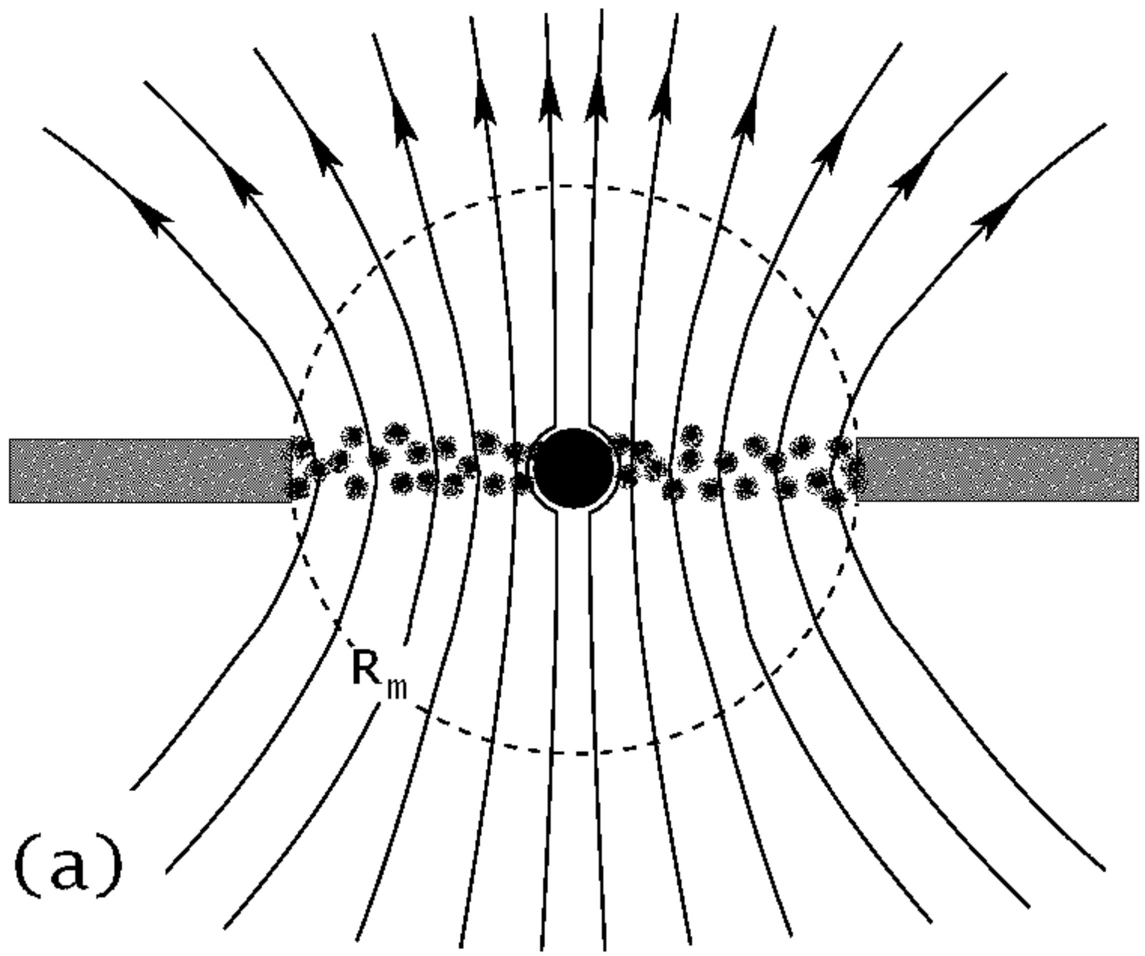
- The region magnetically disconnected from the BH has a strong azimuthal structure including localized elevated winds. Winds are important in removing angular momentum to maintain a stable plunging sub-Keplerian accretion (Scepi+23).

- Instead of interchange instability, magnetic reconnection (in ideal MHD always due to numerical diffusion) heats low-density gas to relativistic temperatures and drives radial outflows (minijets).

- Once the innermost disk becomes critically thin, any perturbation may form a density gap, activating reconnection and triggering a flux eruption.

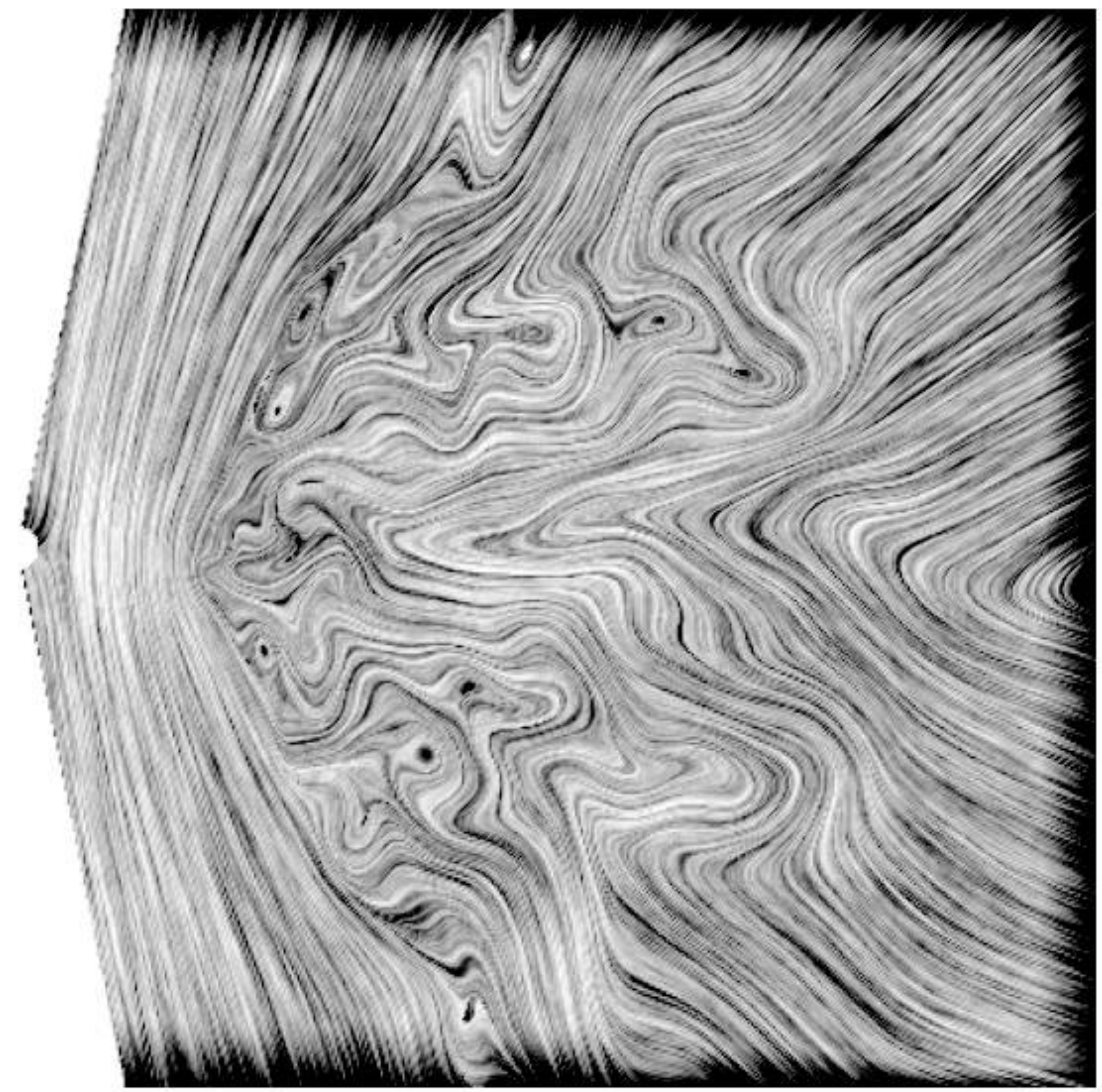
- Magnetic flux eruptions form quasi-stationary patterns systematically rotating around the BH with period $\sim 200\,R_{\rm g}/c$, apparently independent of BH spin.

magnetically arrested disk (MAD)



Narayan, Igumenshchev & Abramowicz (2003)

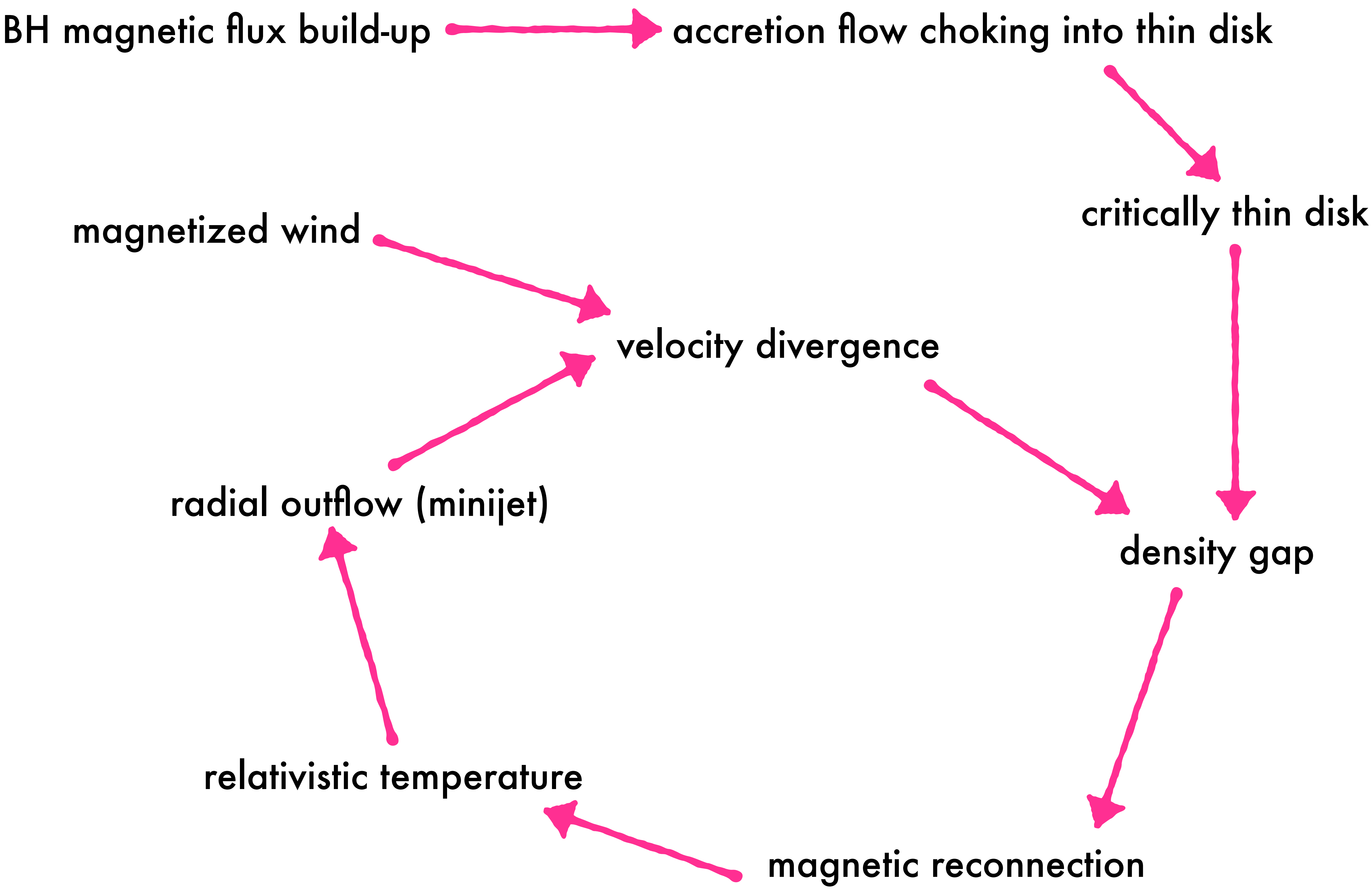
magnetic barrier at radius $R_{\rm m}$
accretion within by interchange instability
(magnetic Rayleigh-Taylor)
BH Meissner effect
(expulsion of poloidal field from the BH horizon)
Geroch-Bekenstein engine
(high-efficiency mass-to-energy conversion)



Igumenshchev (2008)

3D pseudo-Newtonian MHD
magnetic barrier set up during initial 2D stage
(axisymmetry)

initiation of magnetic flux eruption



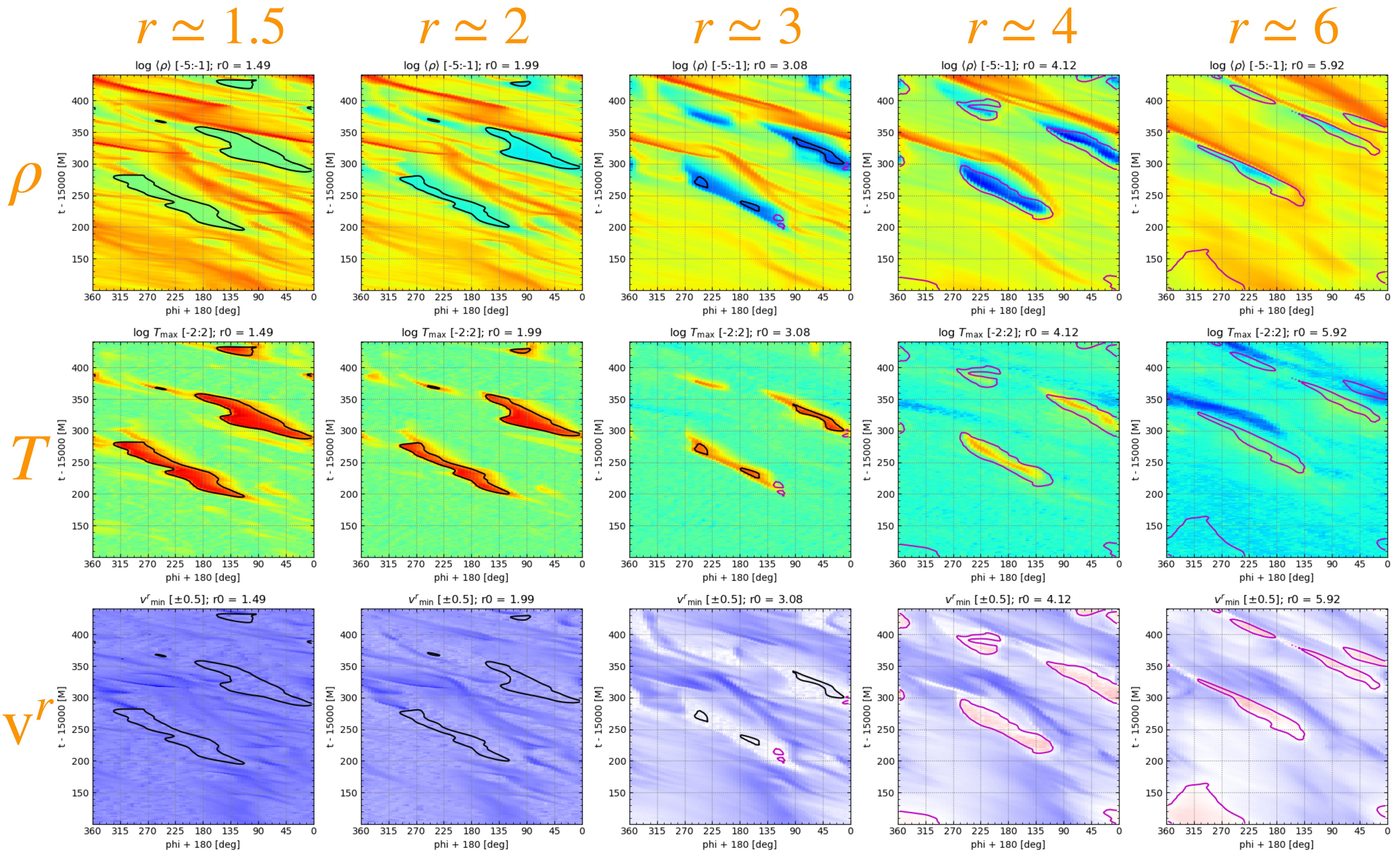
(ϕ, t)

magnetic flux eruptions

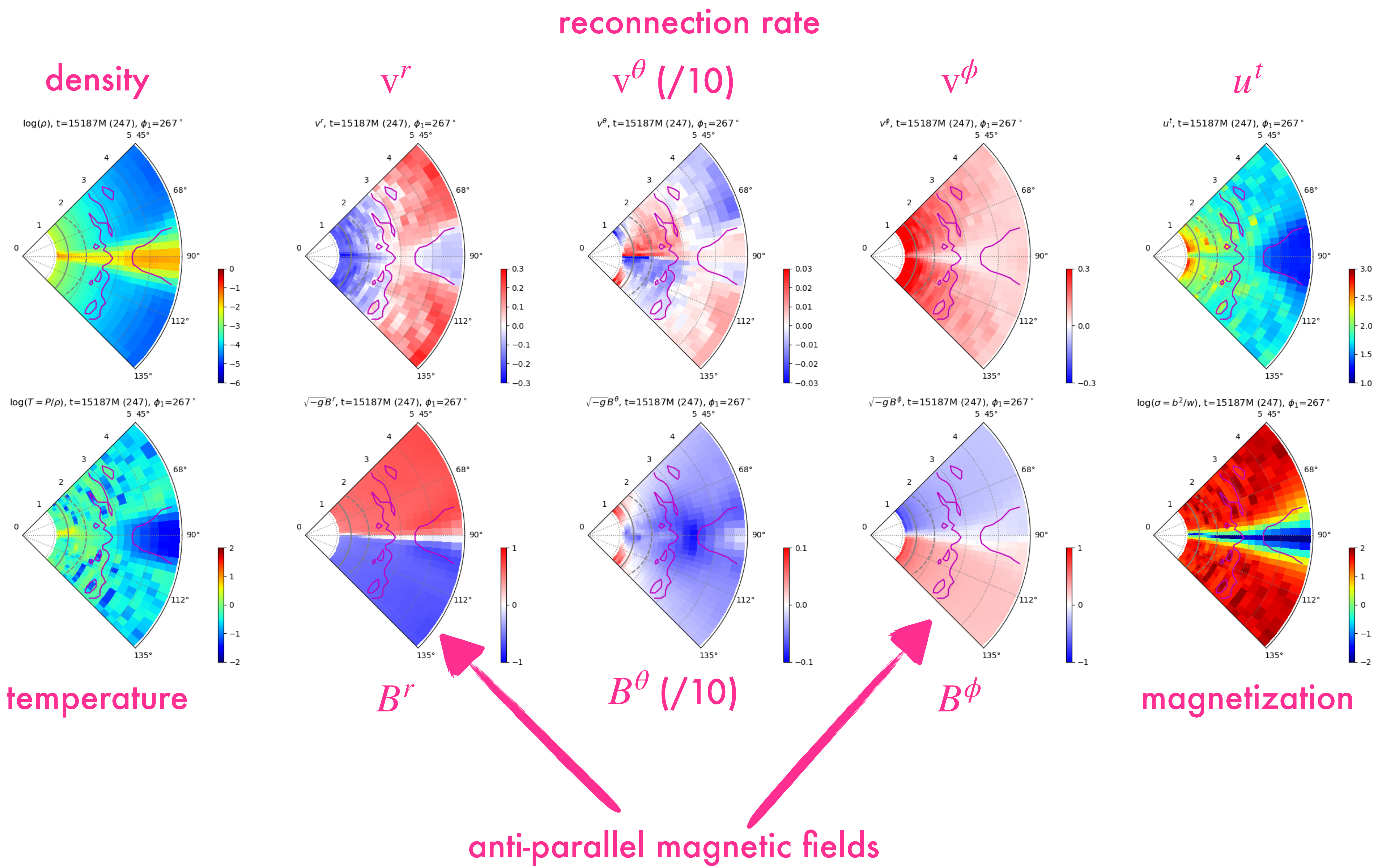
systematic rotation

half-way around the BH

active reconnection along the leading edge

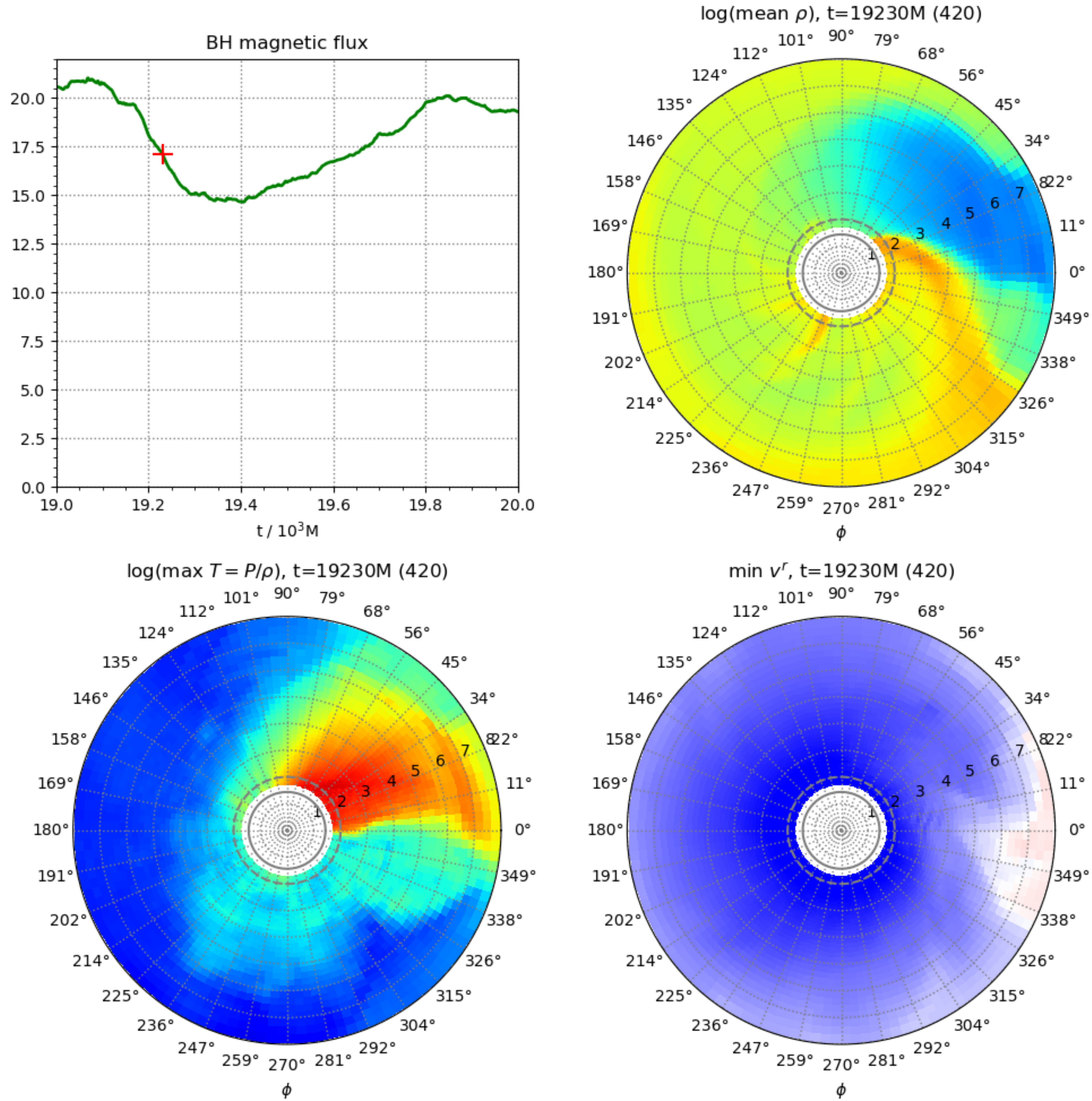


(r, θ)

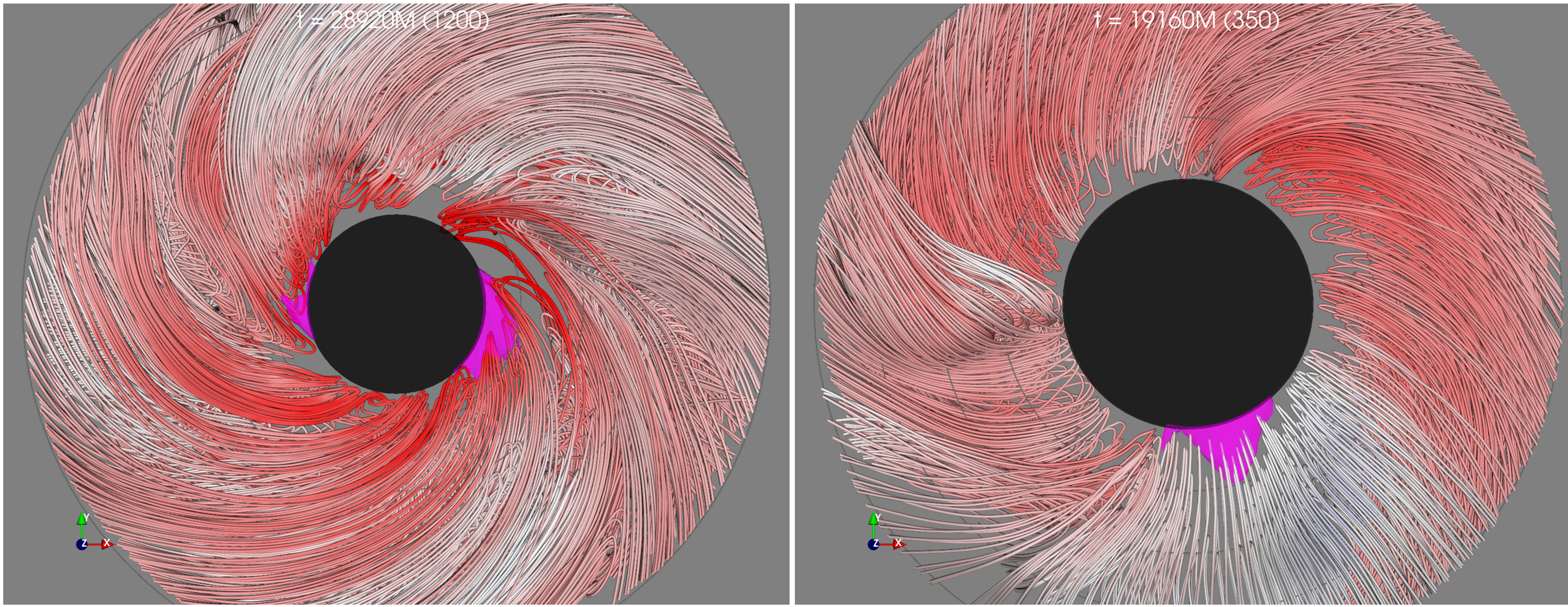


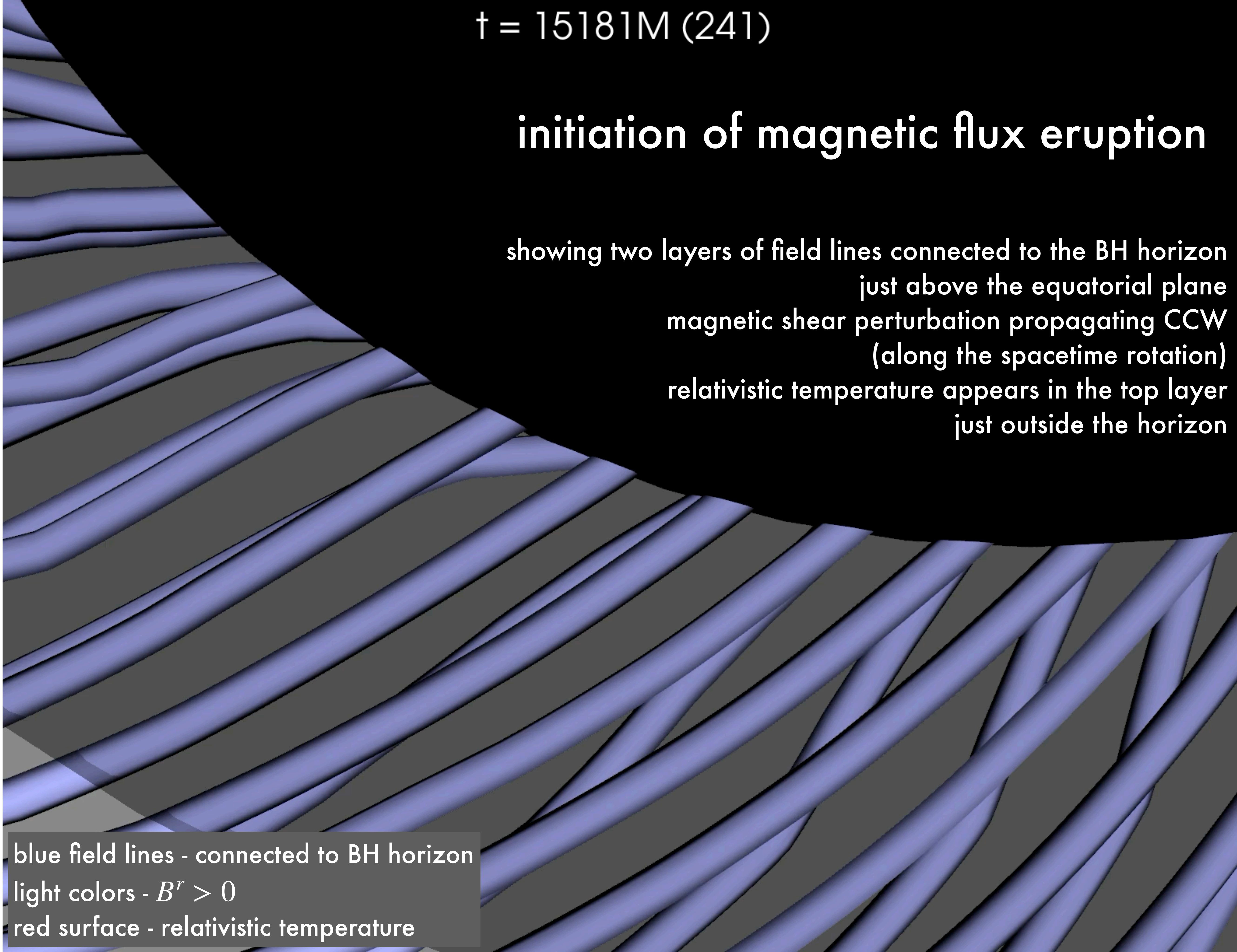
reconnection rate
density
v^r
v^θ (/10)
v^ϕ
u^t
log(ρ), t=15187M (247), ϕ1=267°
v^r, t=15187M (247), ϕ1=267°
v^θ, t=15187M (247), ϕ1=267°
v^ϕ, t=15187M (247), ϕ1=267°
u^t, t=15187M (247), ϕ1=267°
log(T = P/ρ), t=15187M (247), ϕ1=267°
√−g B^r, t=15187M (247), ϕ1=267°
√−g B^θ, t=15187M (247), ϕ1=267°
√−g B^ϕ, t=15187M (247), ϕ1=267°
log(σ = b²/w), t=15187M (247), ϕ1=267°
temperature
B^r
B^θ (/10)
B^ϕ
magnetization
anti-parallel magnetic fields

$a = 0$; $N_\phi = 128$


BH magnetic flux
t / 10³M
log(mean ρ), t=19230M (420)
log(max T = P/ρ), t=19230M (420)
min v^r, t=19230M (420)
ϕ

$a = 0.9; N_\phi = 128$ $a = 0; N_\phi = 128$




t = 15181M (241)
initiation of magnetic flux eruption
showing two layers of field lines connected to the BH horizon
just above the equatorial plane
magnetic shear perturbation propagating CCW
(along the spacetime rotation)
relativistic temperature appears in the top layer
just outside the horizon
blue field lines - connected to BH horizon
light colors - $B^r > 0$
red surface - relativistic temperature