Flux ropes in SANE disks

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Outline

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- Full 3D GRMHD numerical simulation setup.
- Results in SANE simulations
- Formation of magnetic islands and flux ropes
- Reconnection layers
- Summary

Introduction-episodic jets

- In the accreting systems, large scale jets are usually steady, while episodic jets are sometimes related to flares, which are observed on the smaller scale. One example is Sgr A*, the massive BH in the Galactic centre, where we observe radio, infrared and X-ray flares several times a day. Conclusion was that delays in peaks in the light curves at different wavebands and their fast rise and slow decay in the brightness and polarisation are related to the ejection and expansion of plasmoids from the accretion flow.
- Knots in the jets are also observed, e.g. in 3C 120 and M87, and could be related to episodic emission.
- There are models, like e.g. Blandford & Znajek (1977) and Blandford & Payne (1982) for continuous jets, but we still do not have a viable model for episodic jets.
- In Yuan et al. (2009), such a model was proposed, in analogy with Coronal Mass Ejections (CMEs) in the Sun, with the closed magnetic field lines emerging from the main body of the accretion flow, expelled to the corona region: The footpoints of the magnetic loops are positioned in the turbulent accretion flow, and their twisting results in magnetic reconnection, forming the flux ropes. Because of the ongoing reconnection below such a flux rope, the magnetic tension force weakens, and the initial equilibrium between the magnetic tension and the magnetic pressure is not maintained, the flux ropes will be accelerated outwards, forming the episodic jet. The flares, observed from such jets, are from the emission originating from the electrons accelerated by the reconnection.

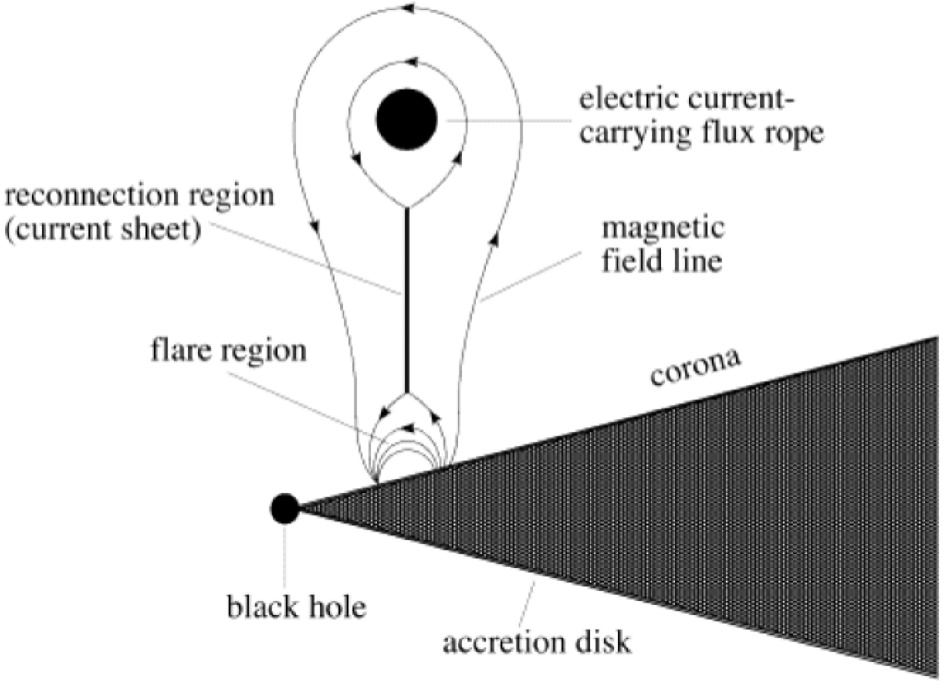
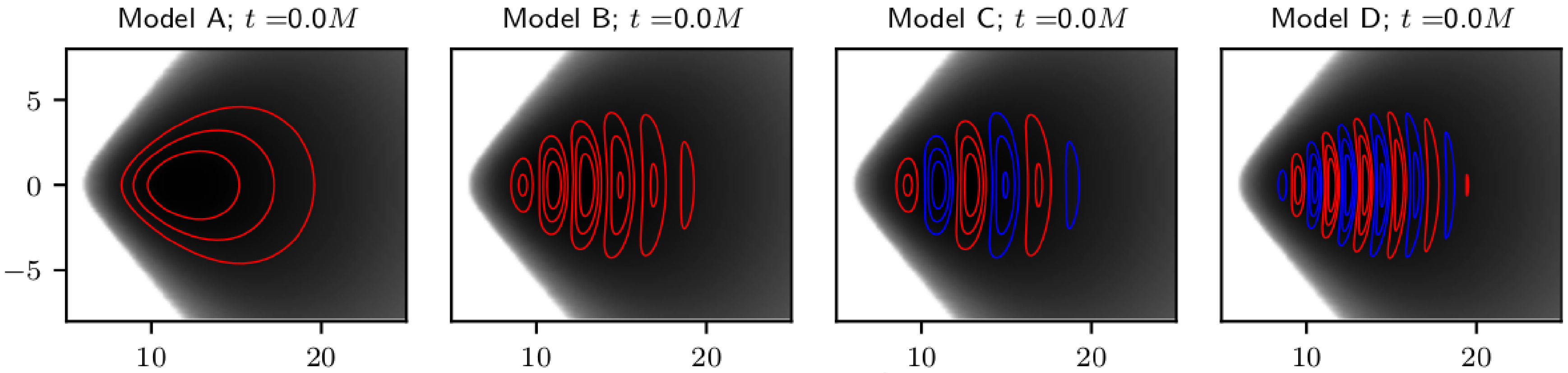


Fig. 1b from Yuan et al. (2009).

- In Shende et al. (2019) another model, in analogy with Toroidal Instability from tokamak research, was proposed-also used to model the CMEs.

Introduction-MAD and SANE simulations in 2D

- Nathanail et al. (2020) presented results of 2D ideal GRMHD simulations with the Black Hole Accretion Code (BHAC, Porth et al. 2017), with Adaptive Mesh Refinement (AMR) of both Magnetically Arrested and Standard and Normal Evolution (MAD and SANE) discs, with the different initial magnetic field configurations, in resolutions Rxϑ equal to 2048x1024, 4096x2048 and, for Model D, 6144x3072 grid cells (resolution is important because of numerical dissipation). They obtain results with formation of copious plasmoids and describe formation and moviement of plasmoids.



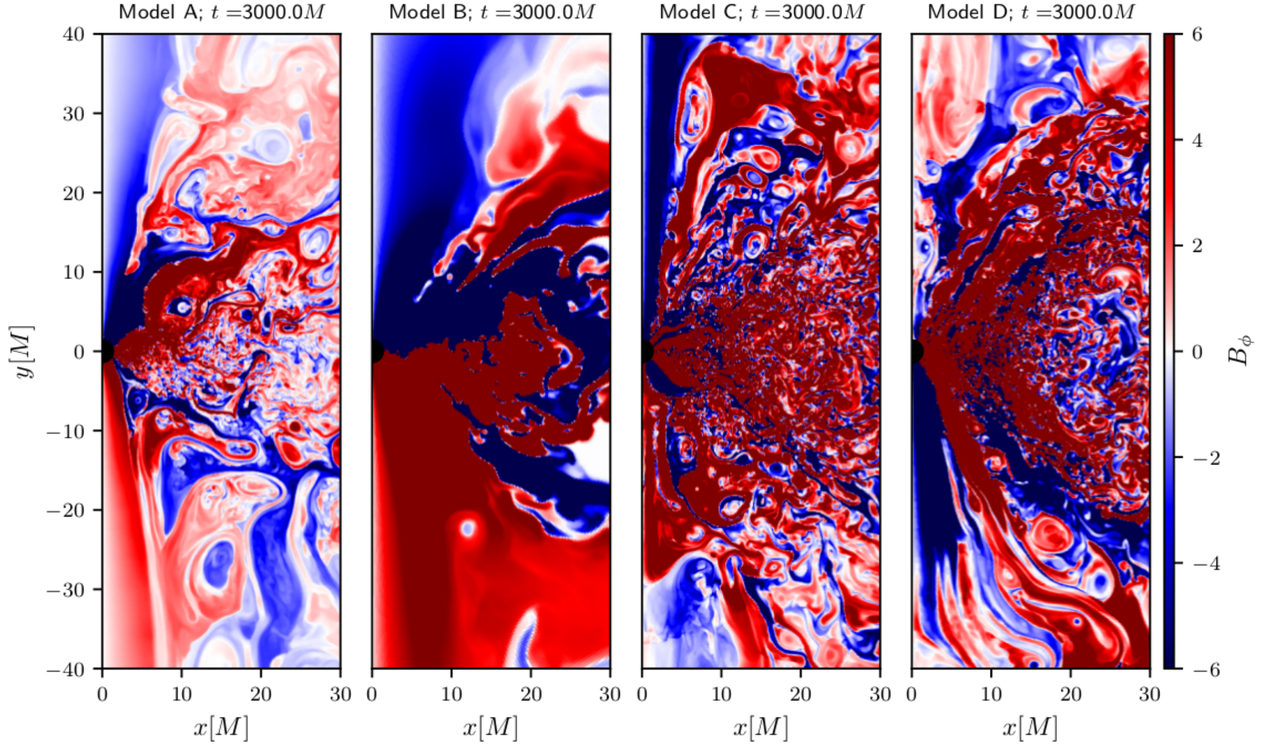
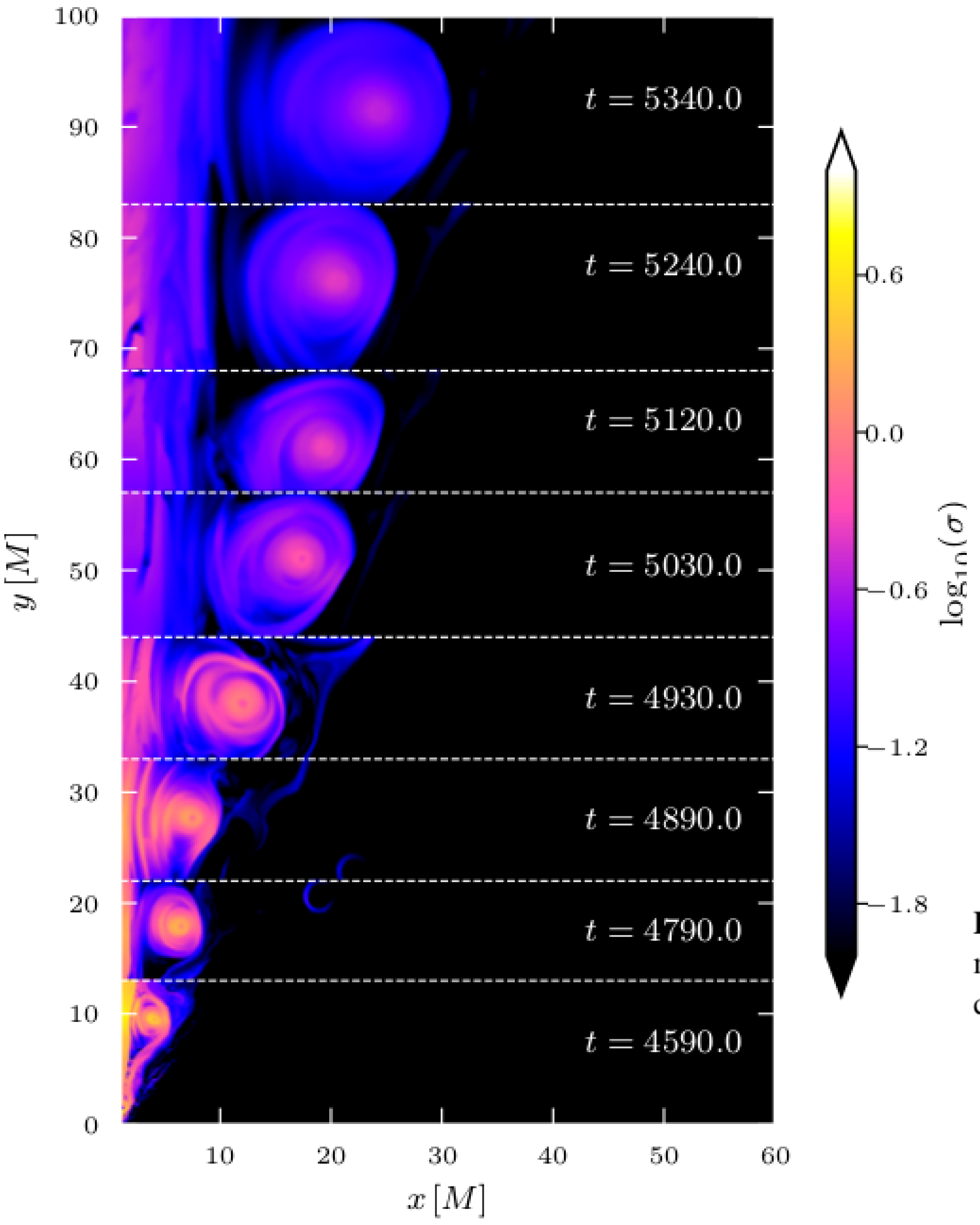


Figure 6. The B_ϕ component of the magnetic field for the four models at time $t = 3000\ M$. The red and blue regions denote regions where the magnetic field has different polarity. The resolutions are: base resolution for `Model B`, 4× base resolution for `Models A`, `C` and `D`.

Introduction-MAD and SANE simulations in 2D

- Plasmoids move outwards, in 3D rendering they would spiral out of the system (Nathanail et al. 2020):



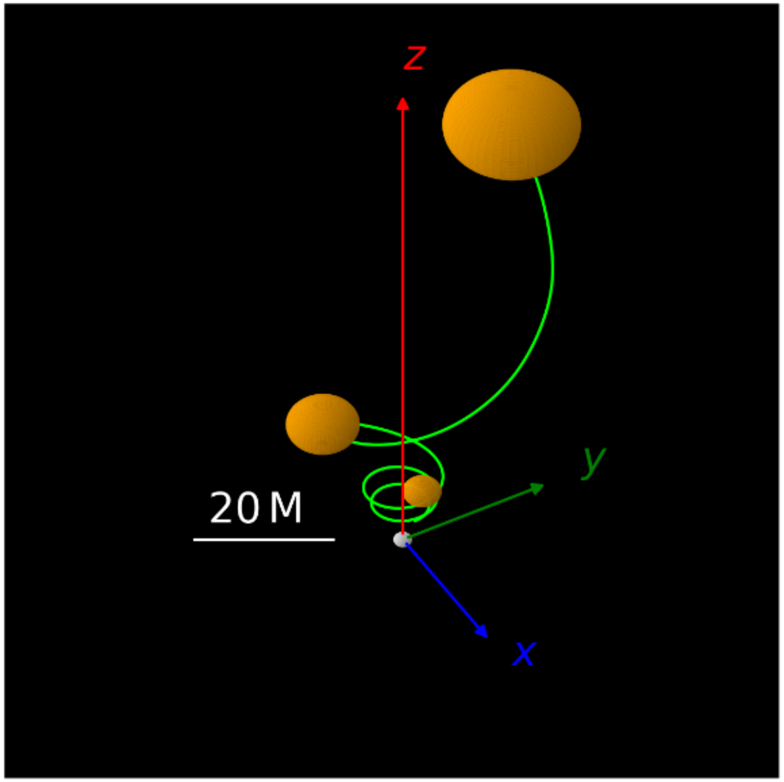
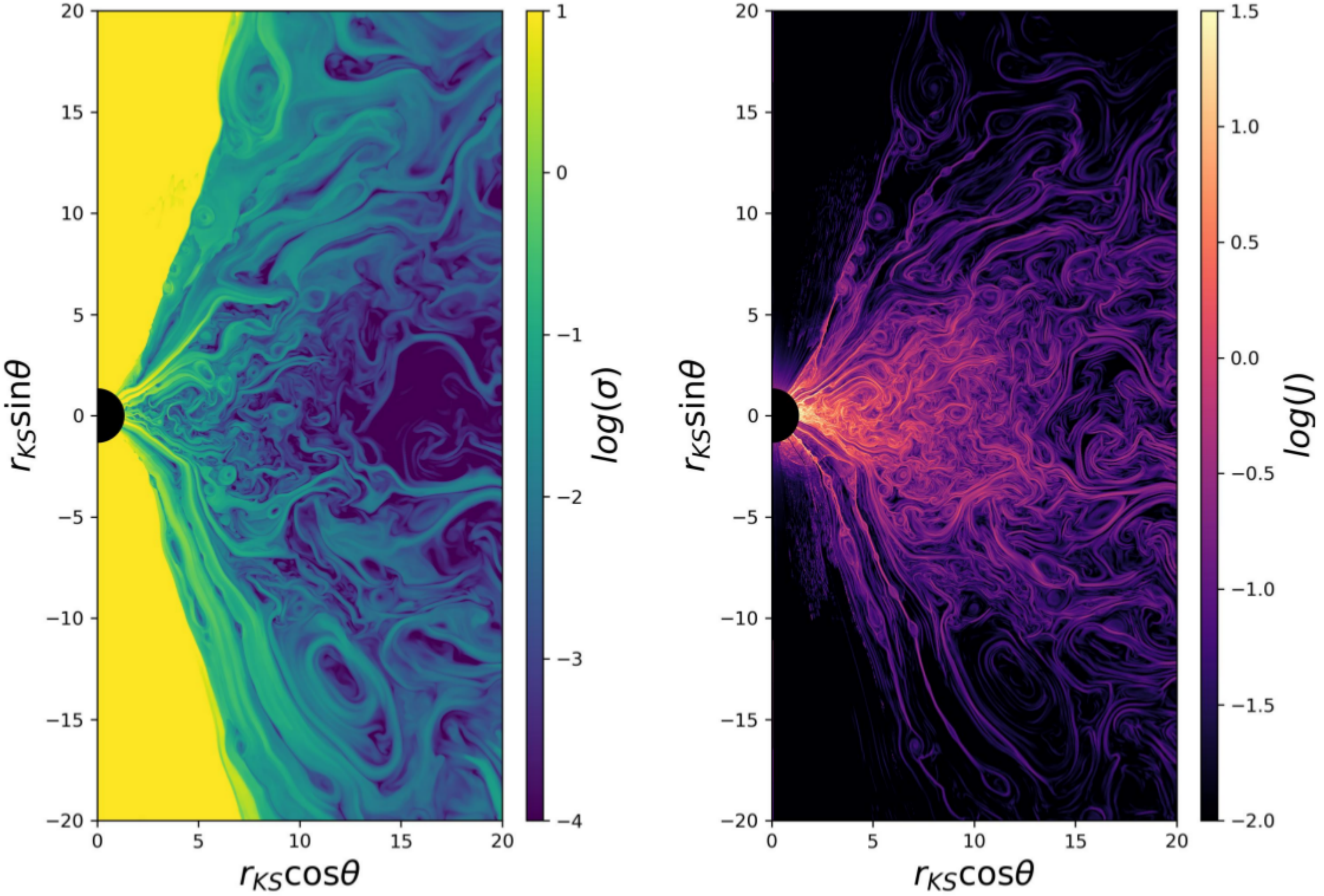


Figure 10. 3D reconstruction of the trajectory of the outward moving plasmoid shown in Fig. 9 after integrating in time the velocity of its core, including the azimuthal component.

Introduction-MAD and SANE simulations in 2D

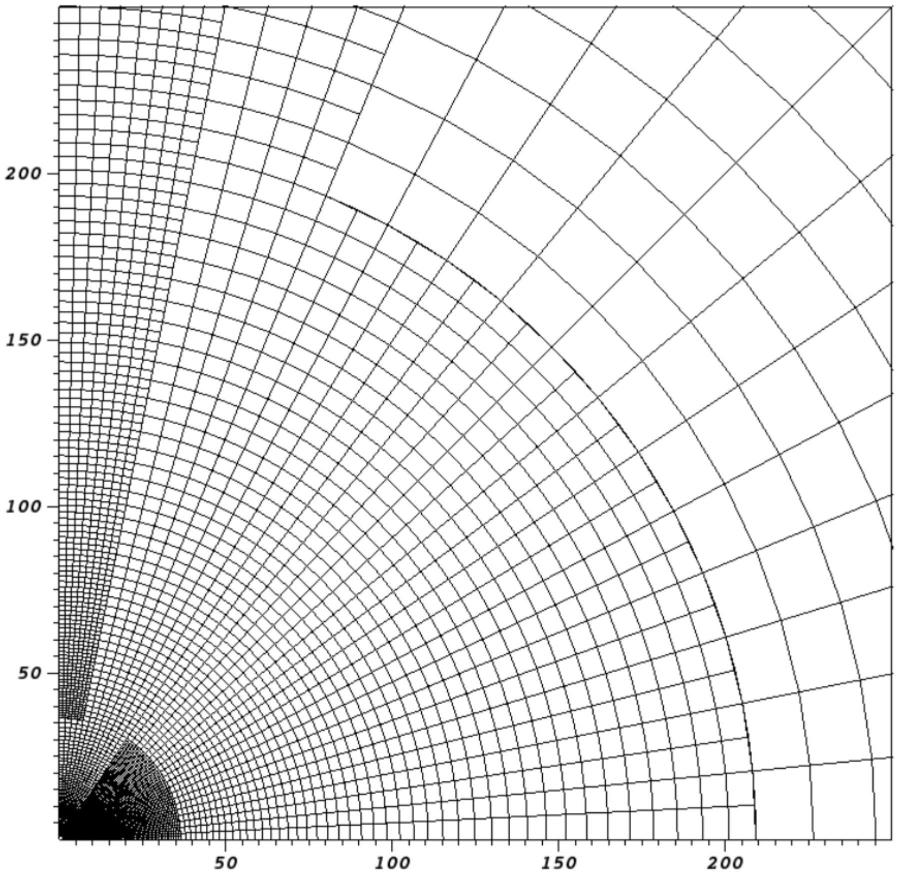
- In Ripperda et al. (2020) presented are similar, but resistive 2D GRMHD simulations with the same code, BHAC. In their simulations there is no difference in results between the ideal and weakly resistive simulations-with enough resolution reaching up to 6144x3072 grid cells, and showing that in half of this resolution results converge all the same. Conclusion is that ideal MHD results, with only the numerical resistivity dissipating the magnetic field, are capturing the physics in such simulations.

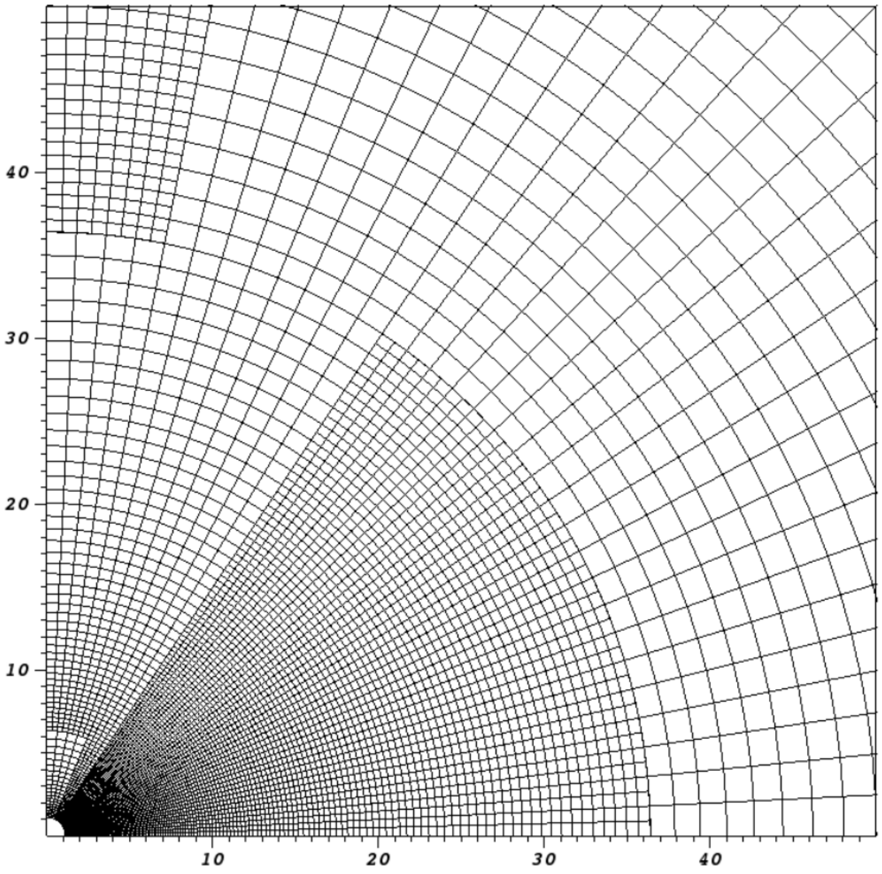


- Snapshot in quasi-steady-state phase of accretion at $t = 1540\ r_g/c$ in SANE case. Magnetization $\sigma=B^2/\rho$ shows that current sheets along the jet's sheath are in the relativistic regime $\sigma \gg 1$, whereas in the disk they are in the trans-relativistic regime $\sigma \leq 1$. The thin tearing-unstable reconnection layers are indicated by a strong current density in the right panel.

Numerical simulations setup

- In the Prof. Feng Yuan's group in SHAO, Hai Yang performed numerical simulations using the GRMHD code Athena++ (White et al. 2016) in full 3D, solving the ideal MHD equations in the Kerr metrics, in Kerr-Schild (horizon penetrating) coordinates (t, R, θ, φ).
- Resolution is Rxϑxφ=[704x256x128] grid cells in spherical coordinates, in a physical domain reaching to 2500 gravitational radii; we use different refinements in this grid.
- The staggered mesh Constrained Transport method is applied to maintain the divergence-free magnetic field.
- Static mesh refinement is used for the grid, to obtain largest resolution where it is most needed.





Initial conditions

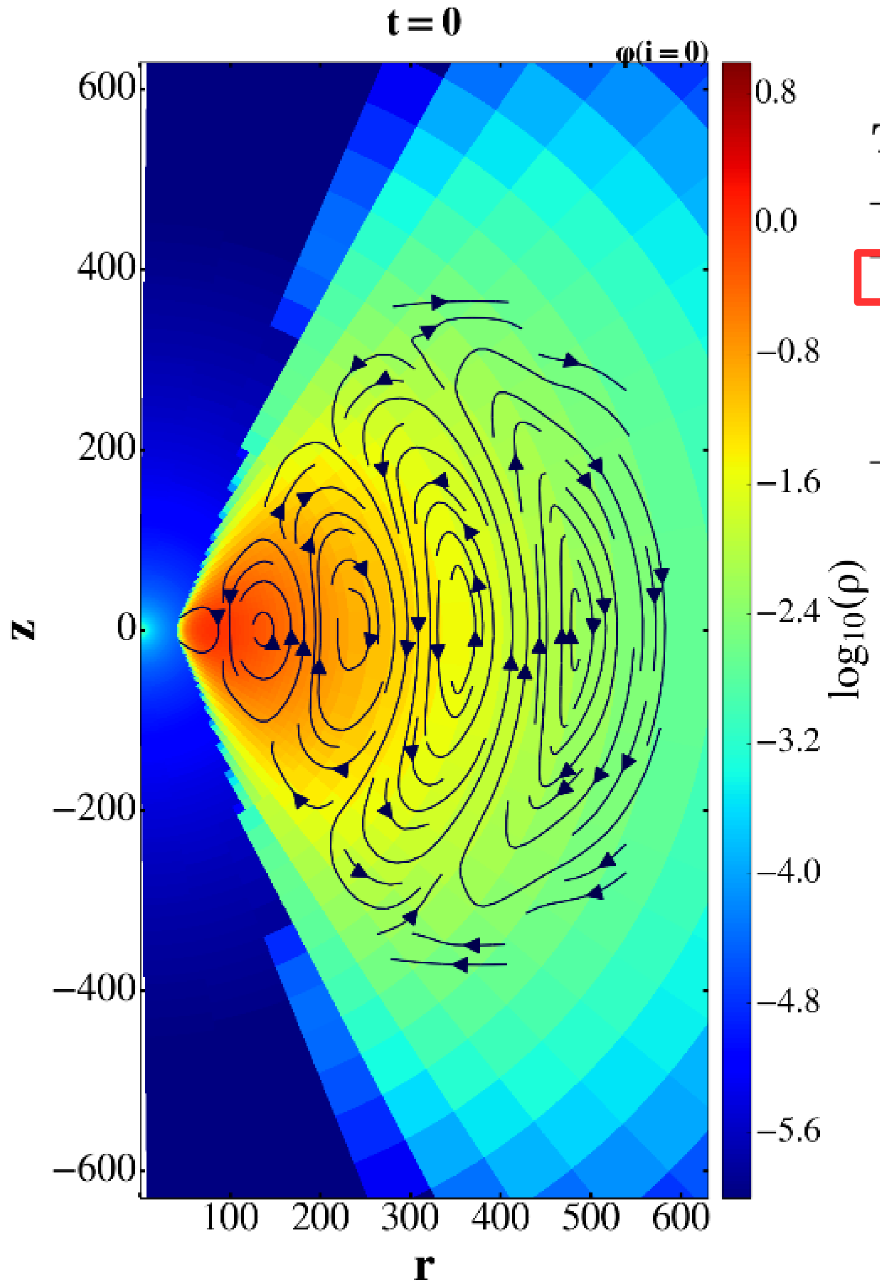


Fig. 1. Density in a logarithmic colour grading and a poloidal magnetic field contained inside the torus around a black hole in our SANE setup. Loops of poloidal magnetic field are shown with solid lines, with arrows showing the clockwise and counter-clockwise direction of the initial loops of magnetic field.

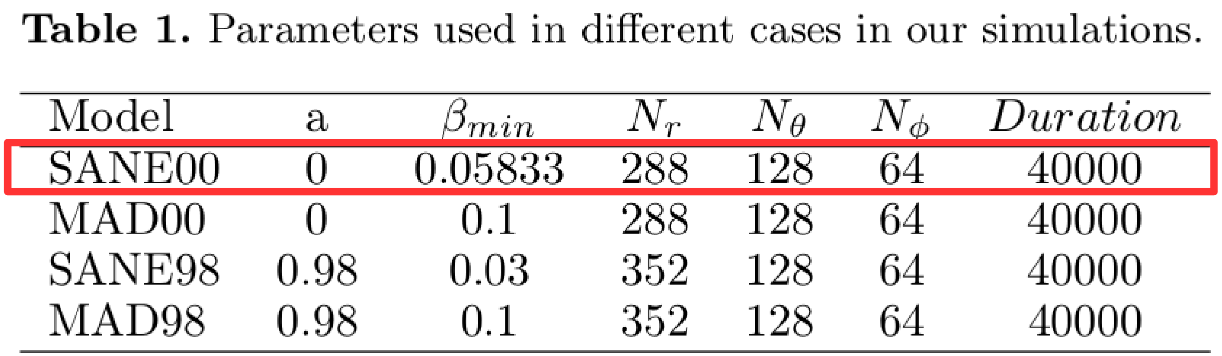
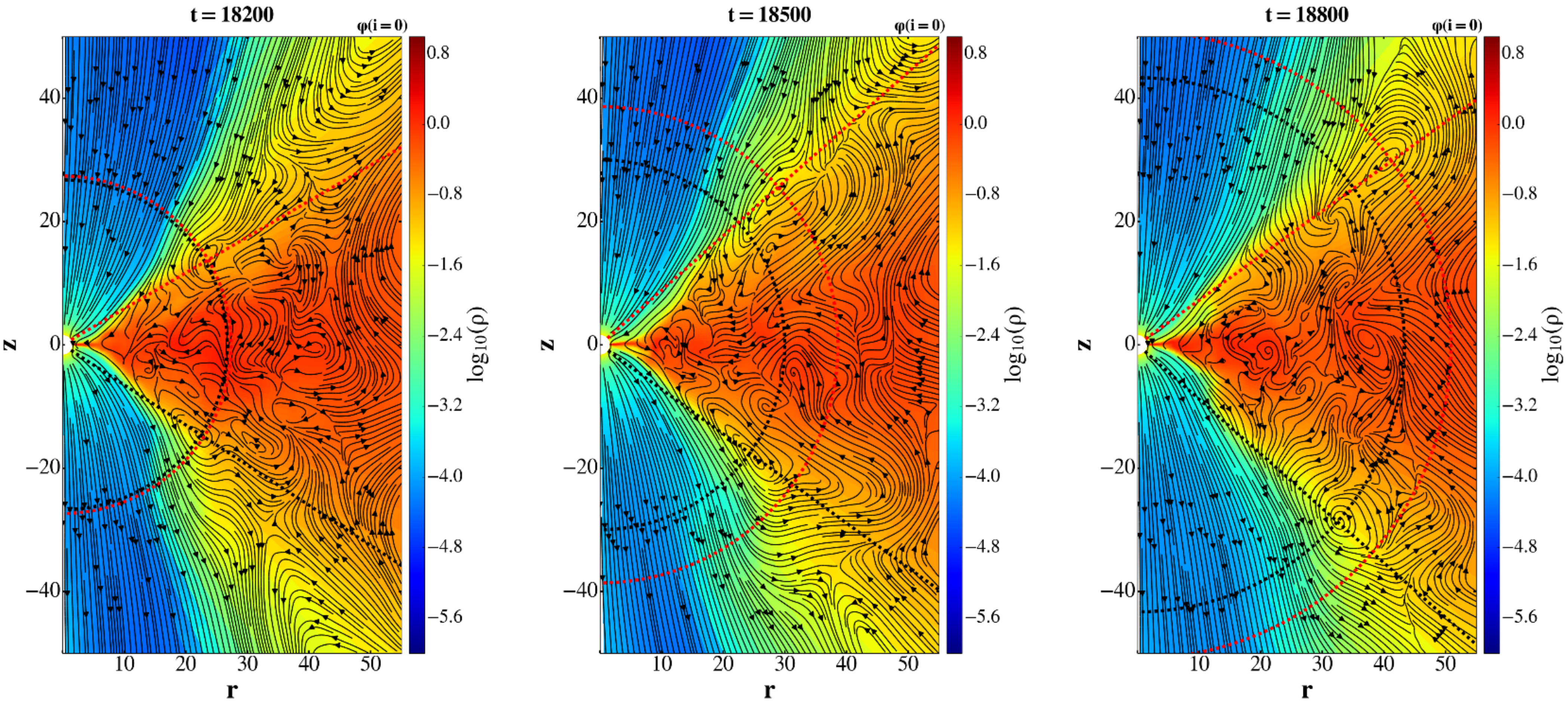


Table 1. Parameters used in different cases in our simulations.

Model	a	β_{min}	N_r	N_θ	N_ϕ	$Duration$
SANE00	0	0.05833	288	128	64	40000
MAD00	0	0.1	288	128	64	40000
SANE98	0.98	0.03	352	128	64	40000
MAD98	0.98	0.1	352	128	64	40000

Results in the SANE case in 3D



- Slices at $\varphi(i = 0)$ azimuthal plane at times T=18200 to T=18800, showing density in logarithmic colour grading, overplot with poloidal magnetic field lines, computed as streamlines of poloidal magnetic field. Arrows mark the direction of the poloidal magnetic field. The dashed black and red lines are spherical coordinate lines passing through the centers of the two flux ropes. We describe the motion of the flux ropes by following the positions of their centers, which are visible as magnetic islands in the Rxϑ poloidal plane, and analyze the velocity components, forces and other physical quantities along the dashed lines.

Motion of magnetic islands

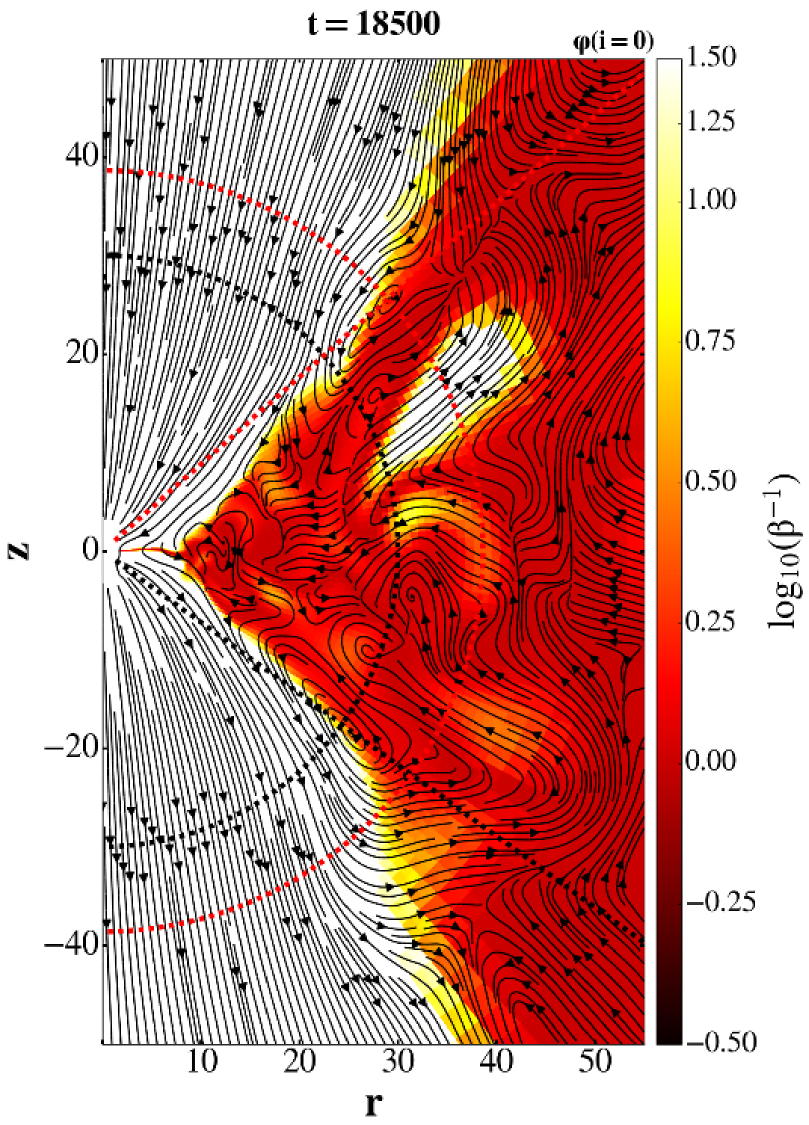


Fig. 5. Plasma β at T=18500 in our simulation shown in logarithmic color grading. Both flux ropes are positioned at the disk surface near the locations where plasma β approaches unity.

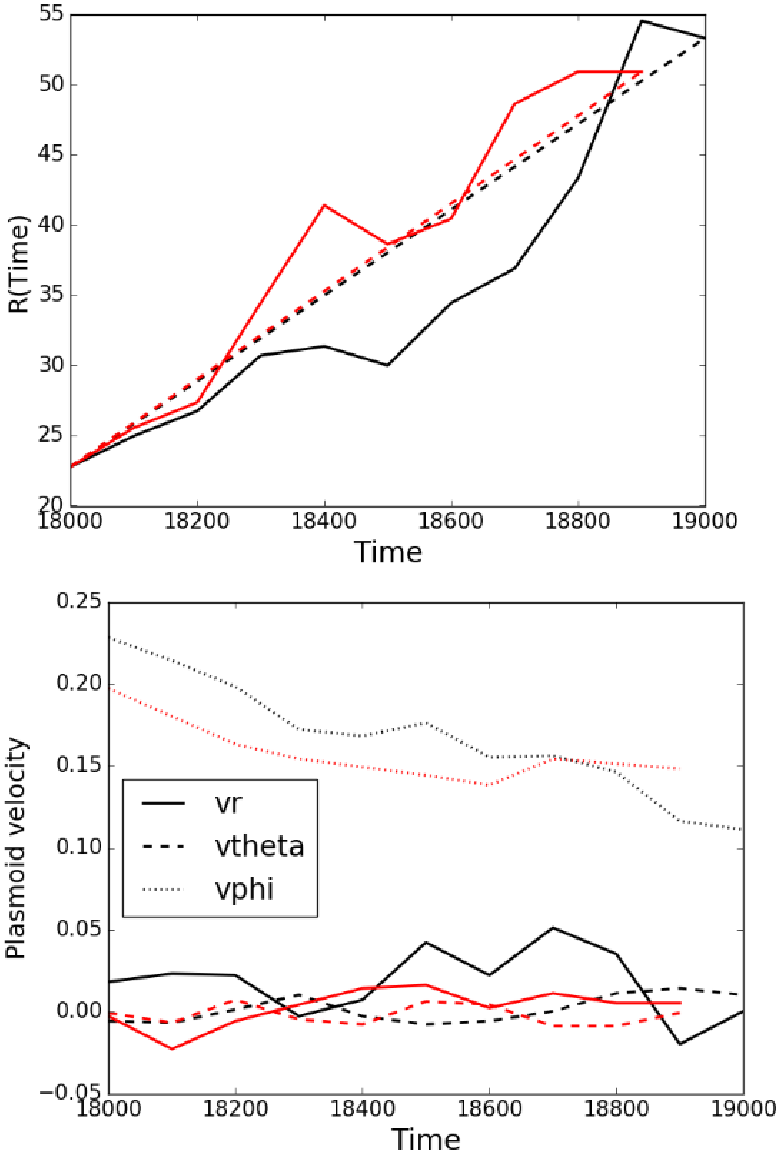
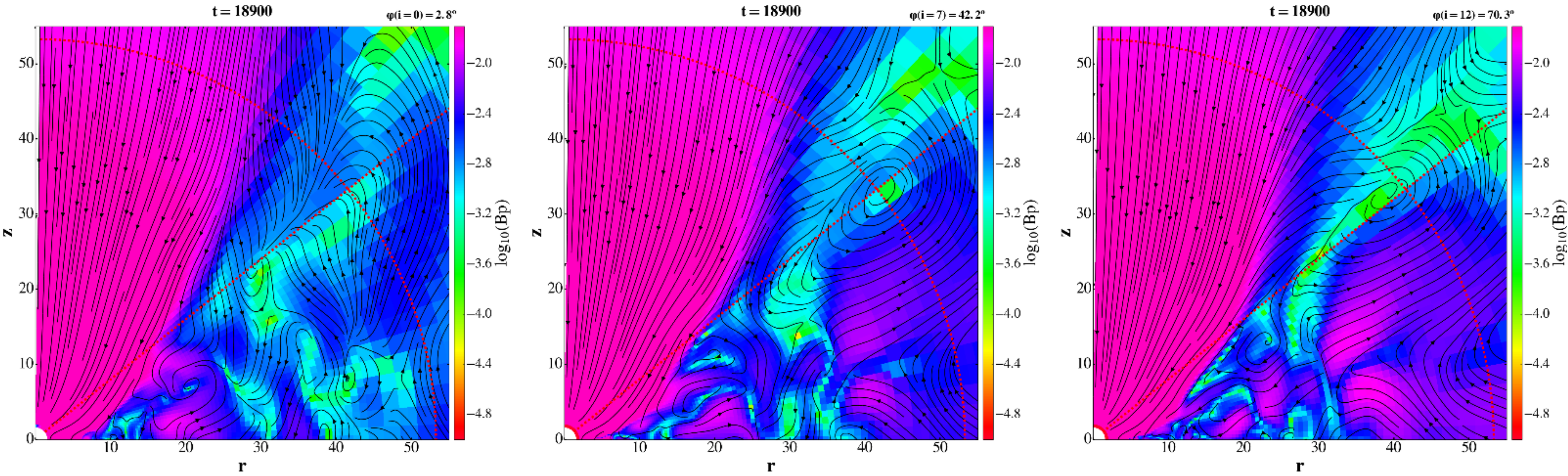


Fig. 7. *Top panel*: Time dependence of the two flux ropes distance above (red) and below (black) the equatorial plane of the accretion flow shown in Fig. 3. The dashed lines are simple "fits" to guide our eyes. *Bottom panel*: Time dependence of velocity components in the two followed flux ropes. For both flux ropes, the average radial velocity is roughly 0.03 c.

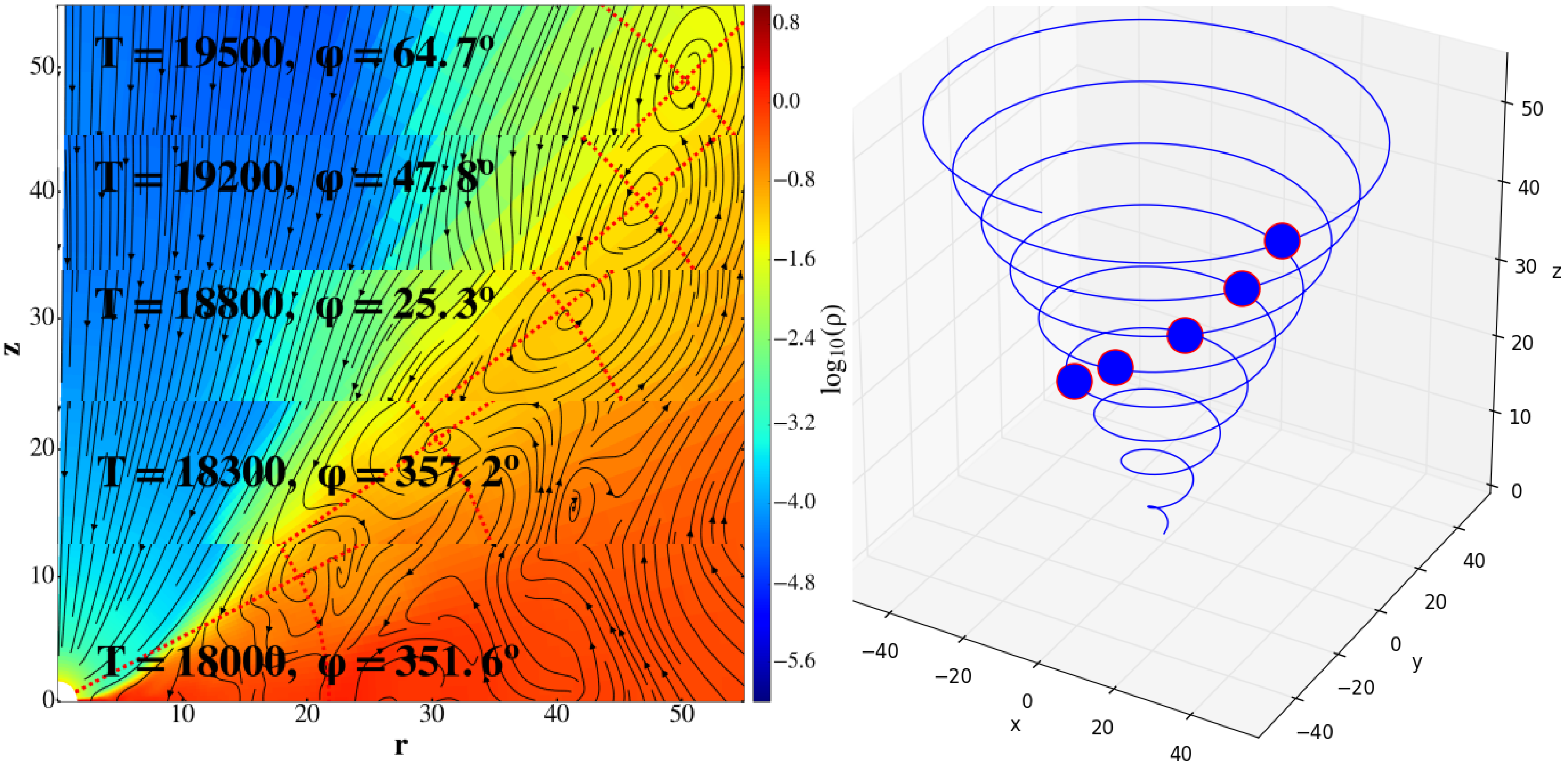
$\beta = P_{gas}/P_{mag}$

Emerging of the magnetic flux rope from the disk surface



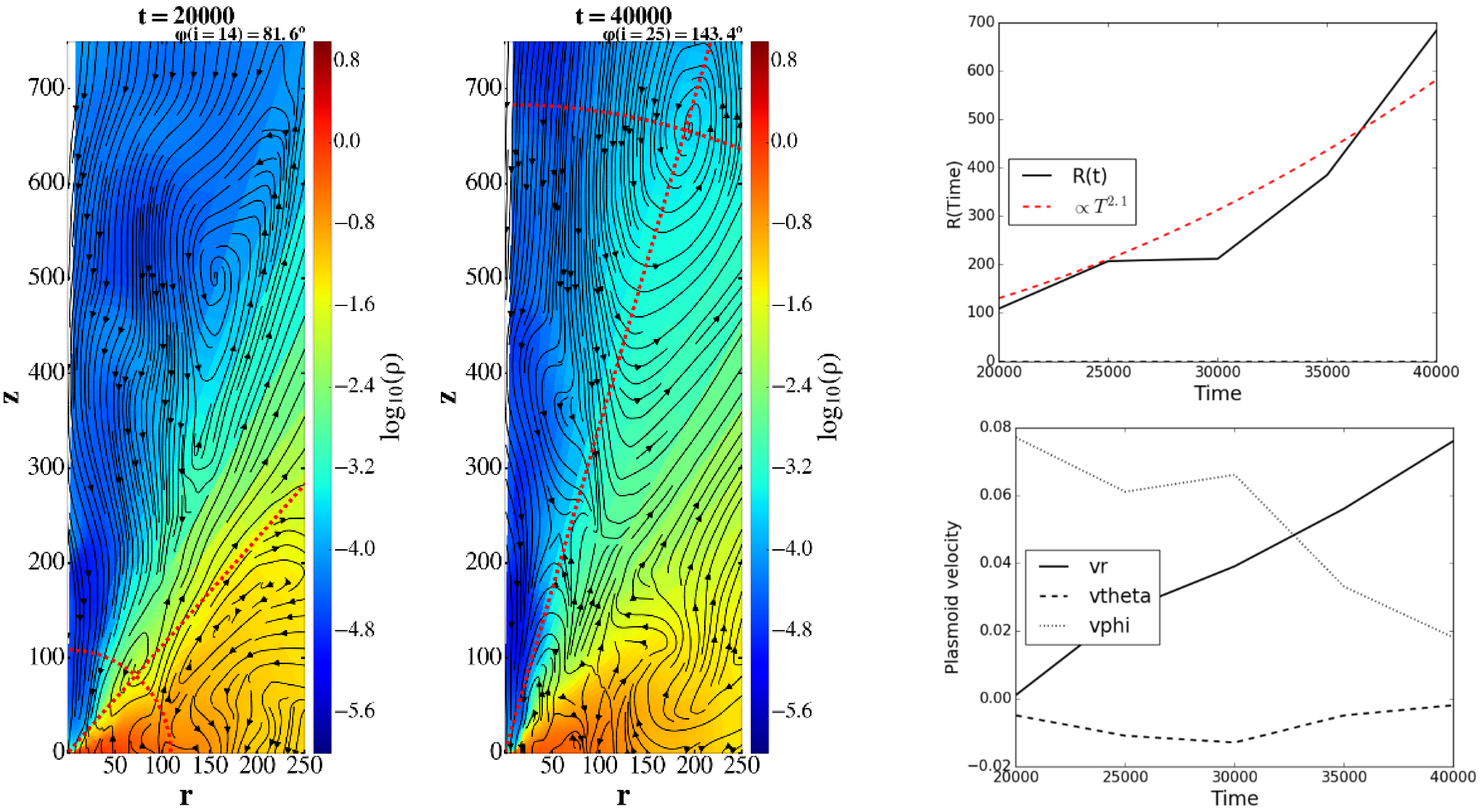
- Magnetic field lines and strength of the poloidal magnetic field Bp (in logarithmic color grading) at the same instant of time T=18900, but varying the position in the azimuthal direction φ=3º−70º . In the φ = 3º plane the flux rope is not present, because of the rotation it moved to another planes, at different φ. The flux rope and reconnection layers are positioned around the local minima of the poloidal magnetic field strength. This is an example of a magnetic flux rope emerging from the disk surface and rotating with it.

Spiraling-out of the flux ropes



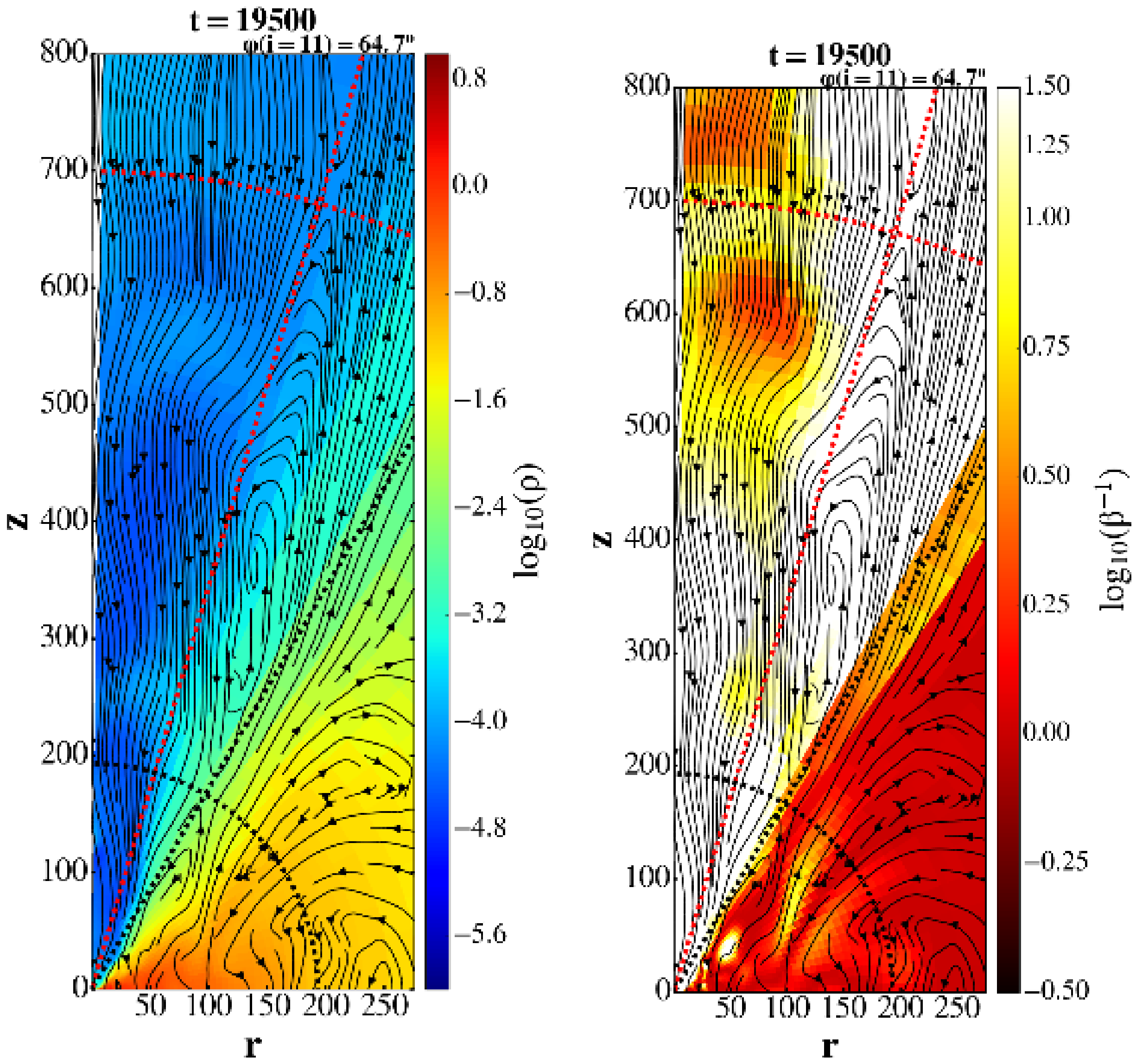
- Slices at different times crossing the middle of the flux rope in our simulation (left panel). The distance from the origin is increasing in time. The angle φ of the colatitudinal plane in which the middle of the flux rope is positioned, is also increasing with time and given in the figure. The flux rope is spiraling away from the black hole, as shown in the 3D schematic plot (right panel) depicting the trajectory of its center.

Ejection of the flux ropes



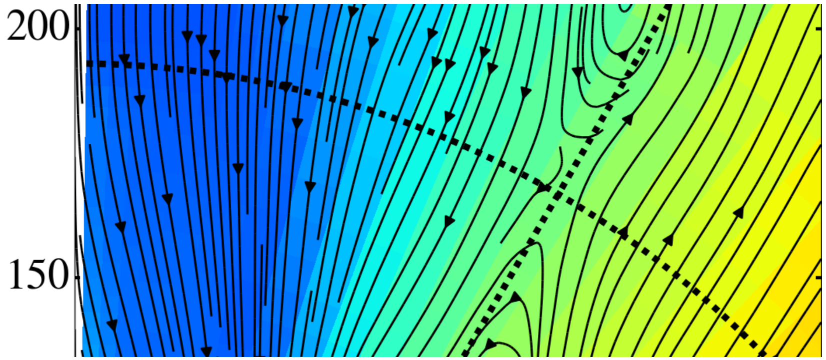
- Slices at different azimuthal planes at times T=20000 and T=40000, during the ejection of the flux rope in the corona. We describe the motion of the flux ropes by following the positions of their centers, and analyze the velocity components along the dashed lines.

Reconnection layers



- Reconnection layers are clearly visible in the snapshot at T=19500 in our simulation along the disk boundary, where the flux rope emerges. In the left panel are shown the poloidal magnetic field lines with density in logarithmic colour grading as a background, and in the right panel the background is plasma β. With red and black dotted lines are shown the coordinate lines, along which we compute the physical quantities.

Reconection



- A zoom into one of the reconnection layers, with dotted lines along which we compute the physical quantities. Results in both such layers are qualitatively similar, and reconnection layers are connected.

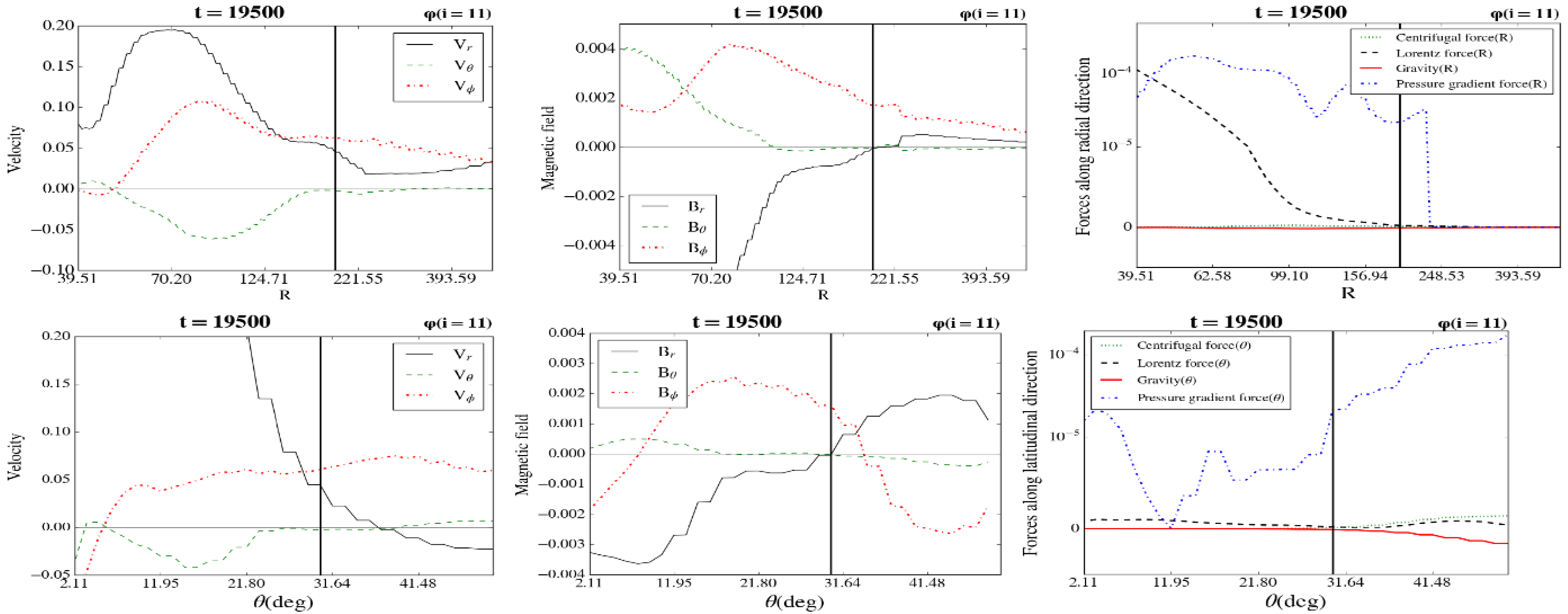
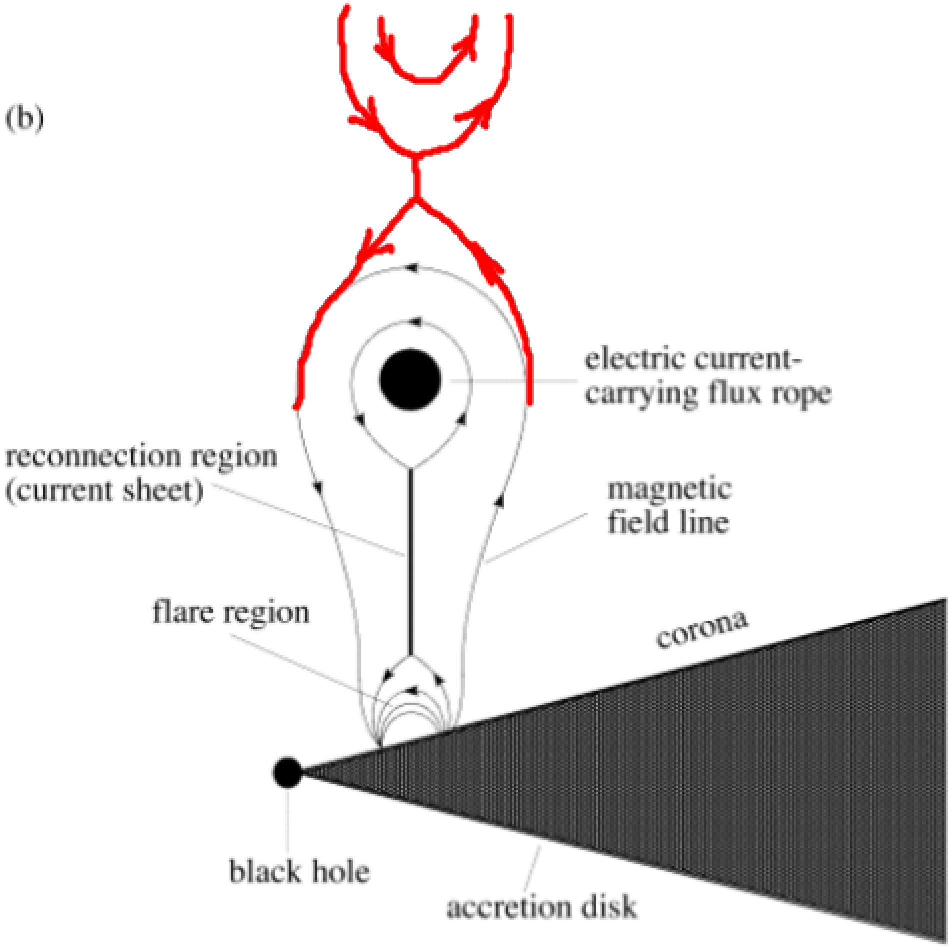


Fig. 11. Velocity, magnetic field and force components across the reconnection layer at T=19500 in our SANE00 simulation, along the coordinate lines in R and θ directions from the bottom panel in Fig. 10. In each panel a vertical solid line marks the position of the reconnection layer.

Additional reconection layer



- In addition to the reconnection layer below the magnetic flux rope, there is another reconnection layer, above the magnetic flux rope in our simulations. It helps in opening of the magnetic field lines.

Summary

- I presented our recent work on formation of magnetic flux ropes in 3D GRMHD numerical simulations with the code Athena++.
- Magnetic structures which show as magnetic islands in 2D simulations, can develop into the magnetic flux ropes in 3D.
- Flux ropes rotate and loop around the central object.
- Because of reconnection, flux ropes are pushed out of the disk surface, and are launched into the corona. Additional reconnection layer can form, helping the launch of the rope. This would cause episodic flaring from the vicinity of the disk around a black hole.

Thank you!