3D GRMHD Simulations of Tilted Disks: Magnetically Driven Retrograde Precession

Transient Phenomena and Physical Processes
Around Supermassive Black Holes

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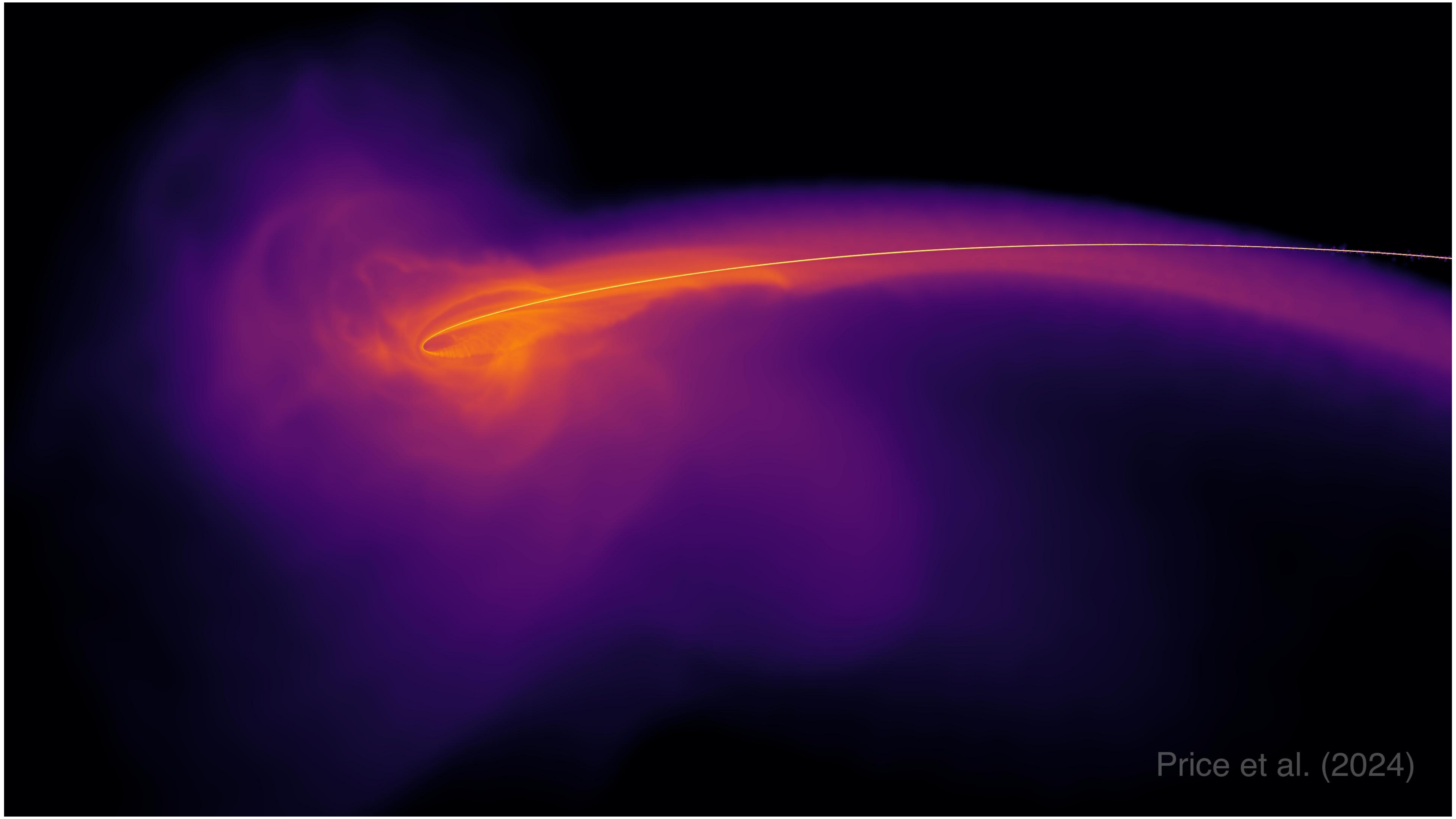
Outline

1. Introduction and observational evidences
2. Simulation result
3. Toy model
4. Magneto-spin alignment and misalignment torque
5. Conclusions

Disk formation history and orientation

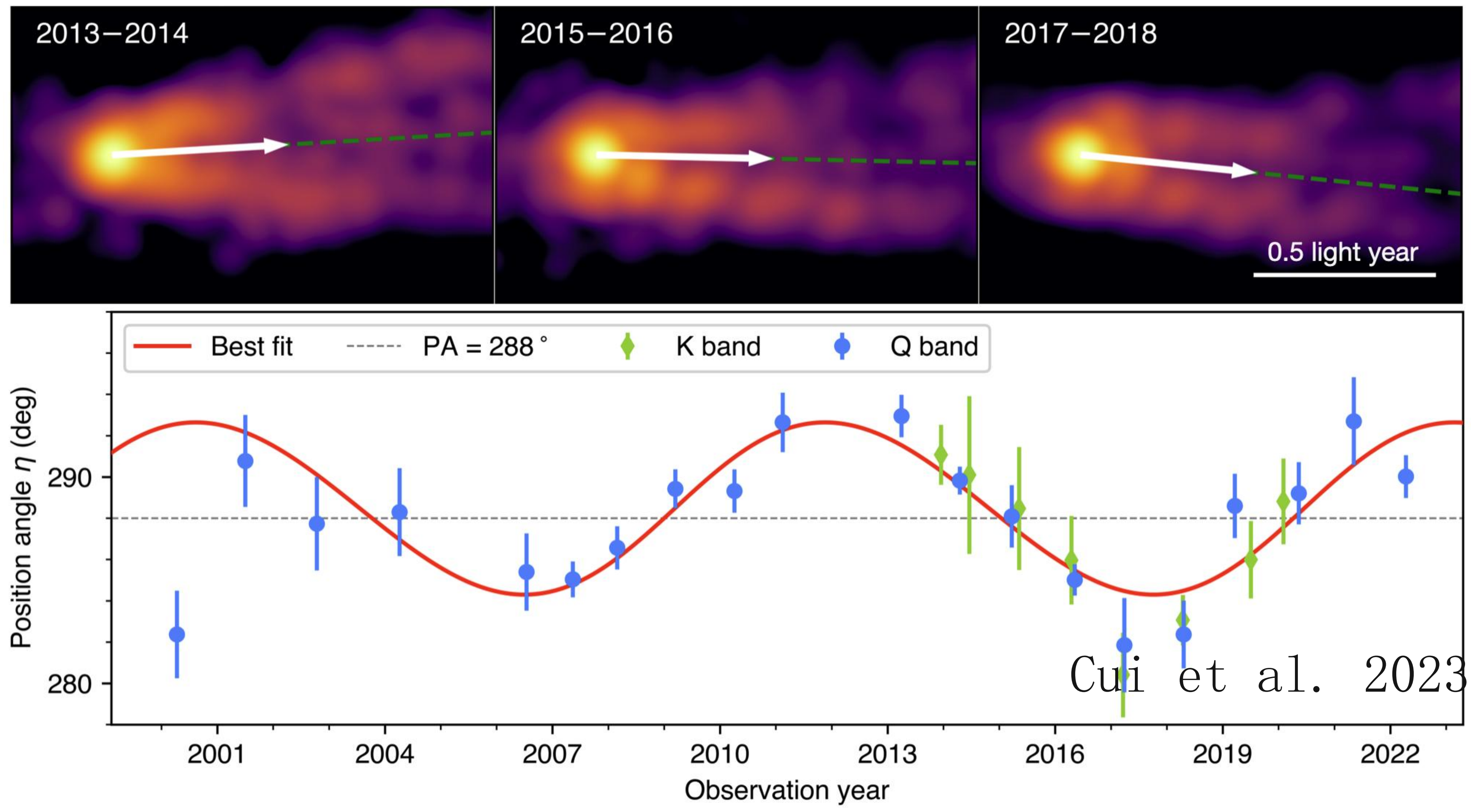


Observation evidences of jet precession

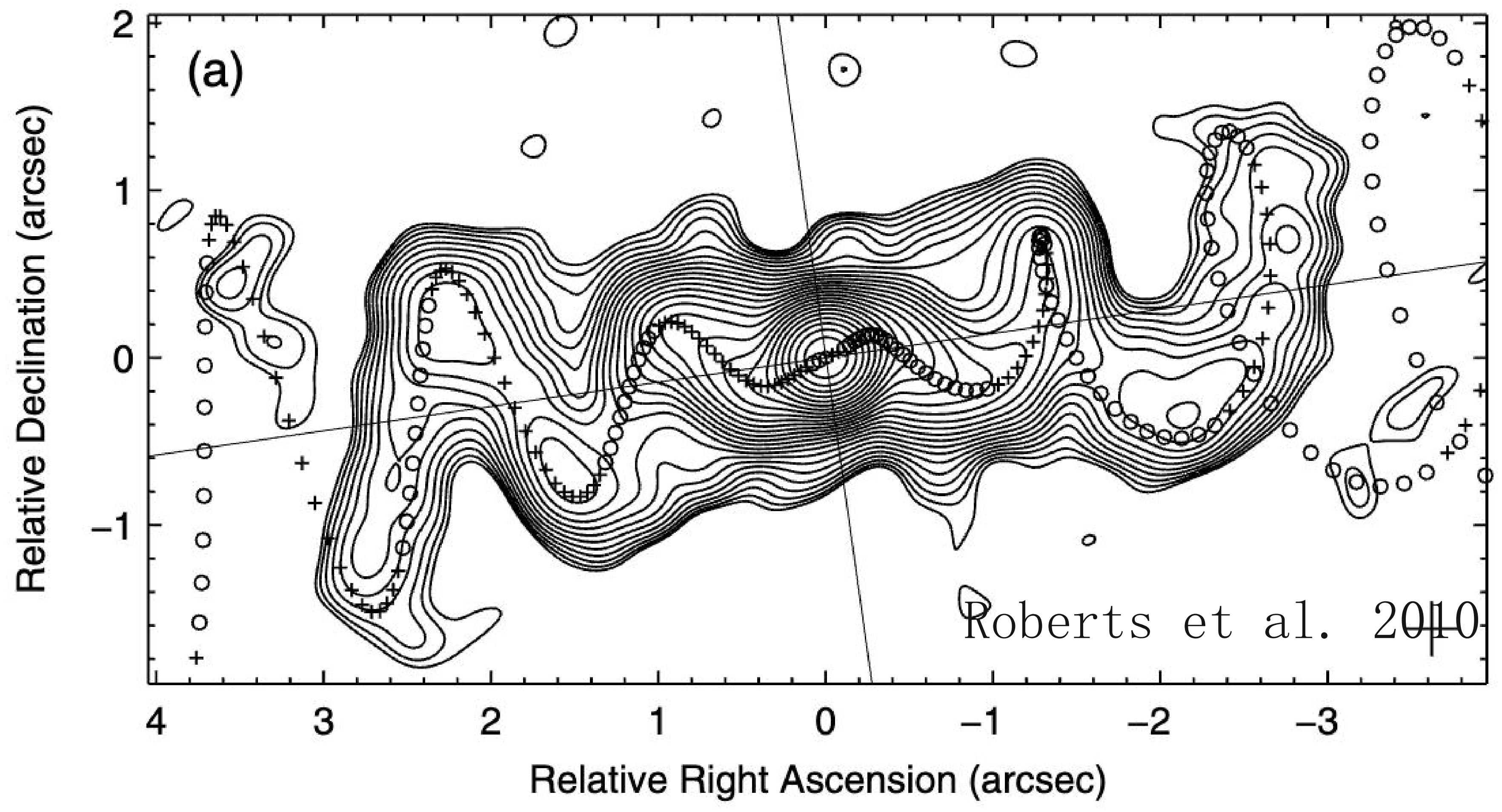
- **Tilted disks and precessing jets** are common features in various astrophysical systems, including X-ray binaries, AGN, and supermassive black hole environments.

- Jets in these systems can undergo precession due to mechanisms such as:
  1. **Lense-Thirring precession** caused by the spin of the central black hole.
  2. **Magnetic torques** in misaligned accretion disks.

SMBH: M 87



X-ray binary: SS 433



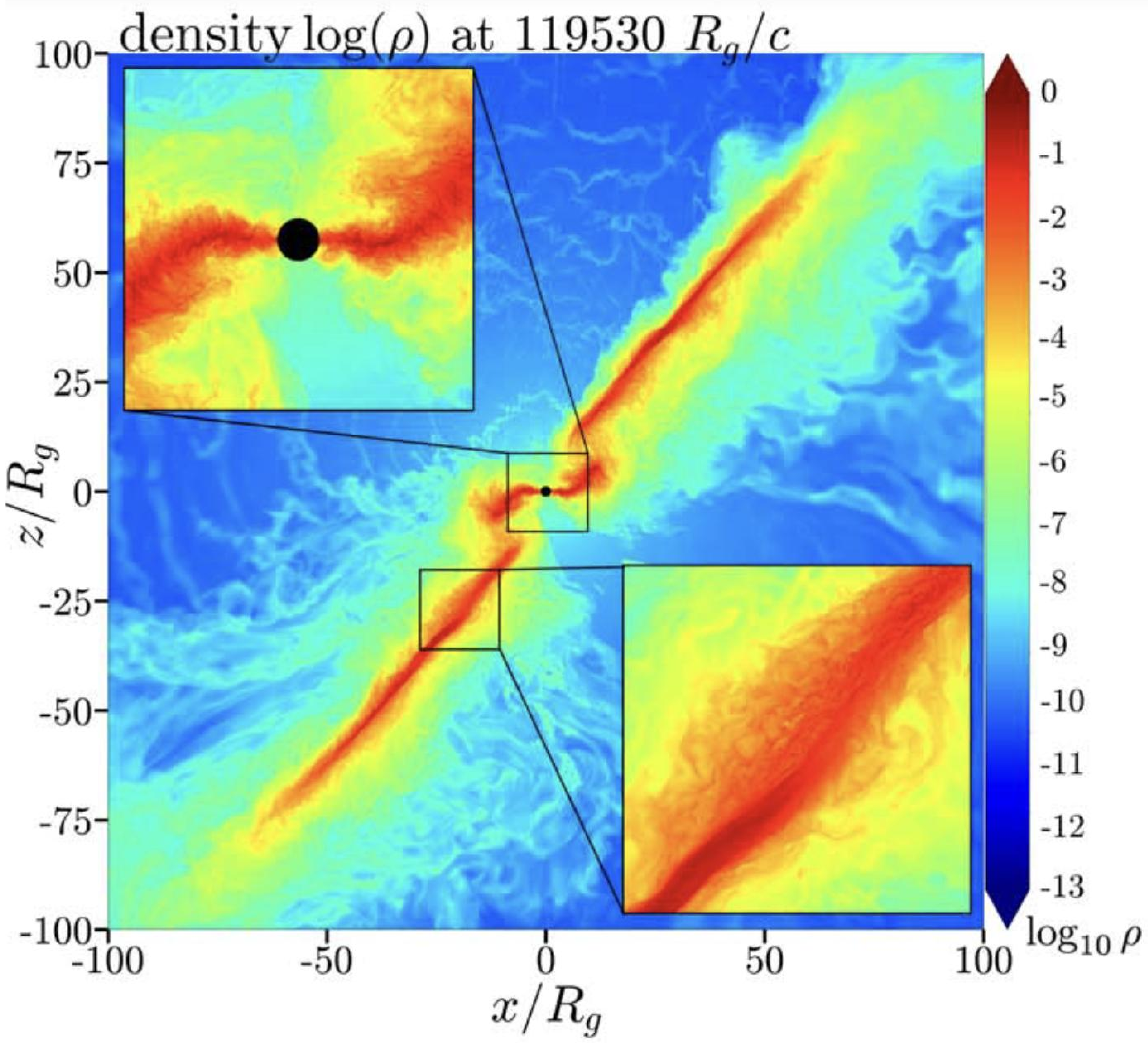
Lense-Thirring effect

The LT effect refers to the frame-dragging phenomenon caused by a rotating black hole. It drives the precession of orbiting matter as spacetime itself is dragged by the black hole's rotation.

In a tilted accretion disk, the LT torque per unit area is

$$\tau_{LT} \sim \sin\beta\, \Omega_{LT}\, L$$

where LT angular frequency $\Omega_{LT} = 2j/r^3$, j and L are the angular momentum of the BH and the disk, β is the tilt angle of the disk (McKinney et al. 2013).



Liska et al. 2019

Lense-Thirring precession in GR(M)HD simulations

Magnetically driven retrograde precession

Order of magnitude analysis: a toy model

The original of magnetic torque (Lai 2003)

Suppose a tilted accretion disk in a vertical magnetic field, in the tilted coordinate the vertical magnetic field

$$\boldsymbol{B_z} = B_z \cos\beta \hat{l} + B_z \sin\beta \sin\phi \, \hat{r}$$

where $\hat{r}$ is the radial direction in the tilted disk, β is the tilted angle

Assuming a toroidal surface current K_ϕ in the disk, it gives the magnetic force $\boldsymbol{F_{mag}} = - K_\phi B_z \sin\beta \sin\phi \hat{l}$. Then the average torque per area in the disk is

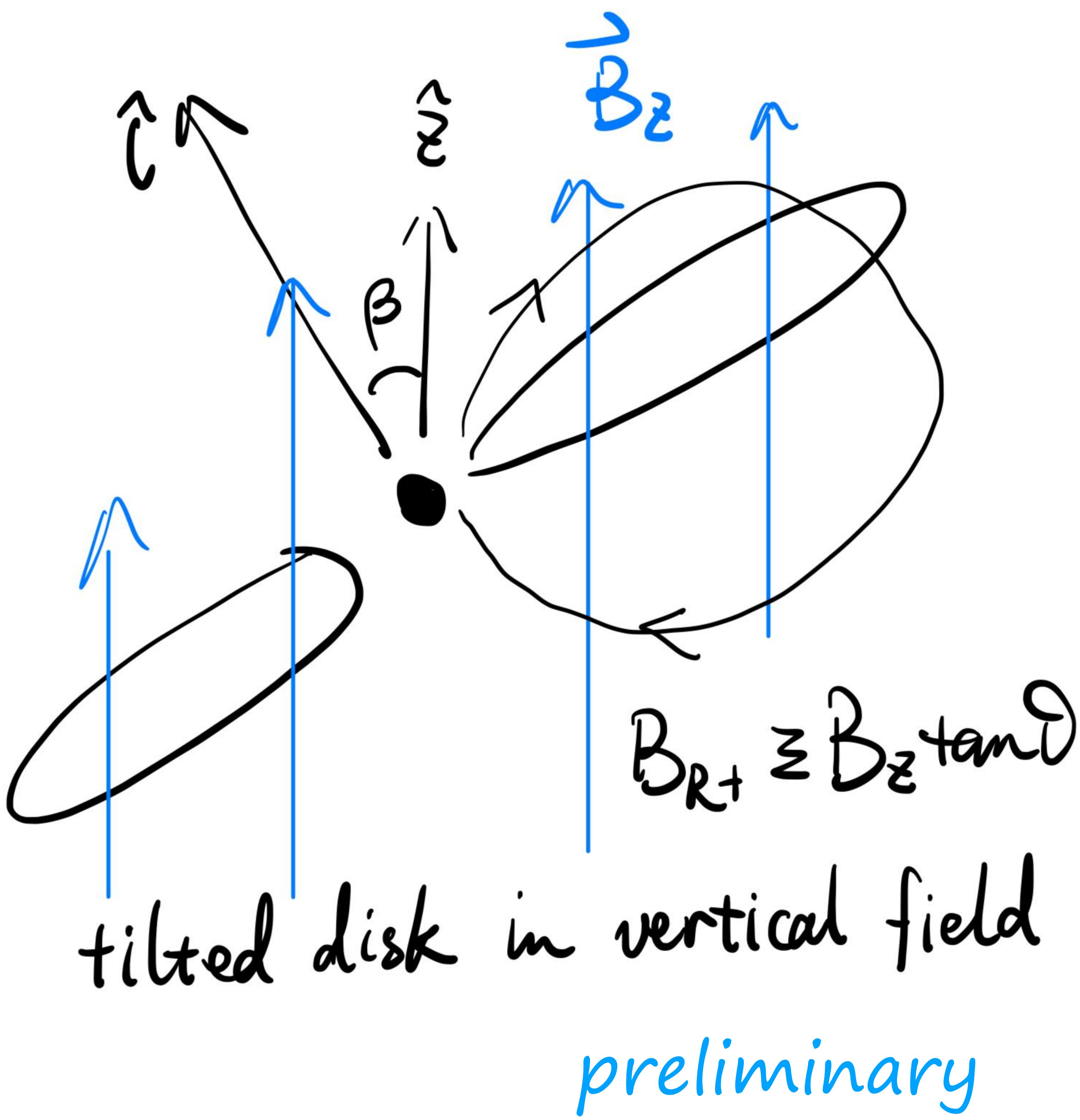
$$< \boldsymbol{T_{mag}} > \; = - r K_\phi B_z \hat{z} \times \hat{l}$$

In the milldly tilted disk, the surface current

$$K_\phi \sim \tan\theta B_z c / 2\pi$$

After some calculation, we give the expression of magnetic torque:

$$T_{mag} \sim r_d^3 B_z^2 \tan\theta / 2$$



Order of magnitude analysis: a toy model

Comparison with Lense-Thirring torque

The LT torque can be written as

$$T_{LT} \sim a\left(\frac{M}{r_d}\right)^2\left(\frac{c}{r_d}\right)4\pi r_d^2 \Sigma {r_d}^2 \Omega_d,$$

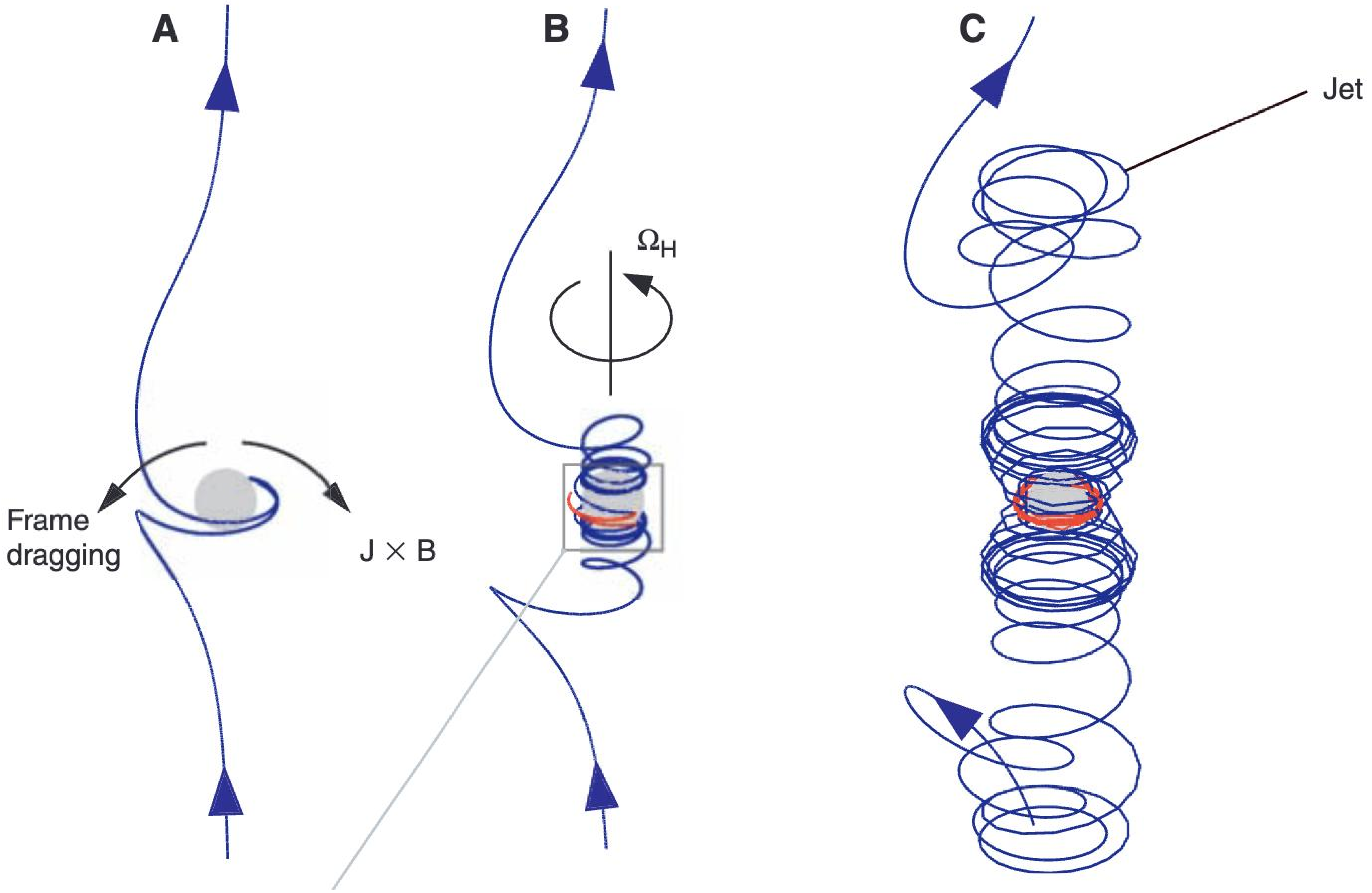
Where Σ and Ω_d are the surface density and angular velocity of the disk, a and M are the BH dimensionless spin and mass.

Since $\Sigma c \Omega_d = \rho H c \Omega_d = \rho c c_s$, the ratio between LT and magnetic torques is given by

$$\frac{T_{mag}}{T_{LT}} \sim \frac{B_z^2 \tan\theta / 8\pi}{a\left(\frac{M}{r_d}\right)^2 (\rho c c_s)}.$$

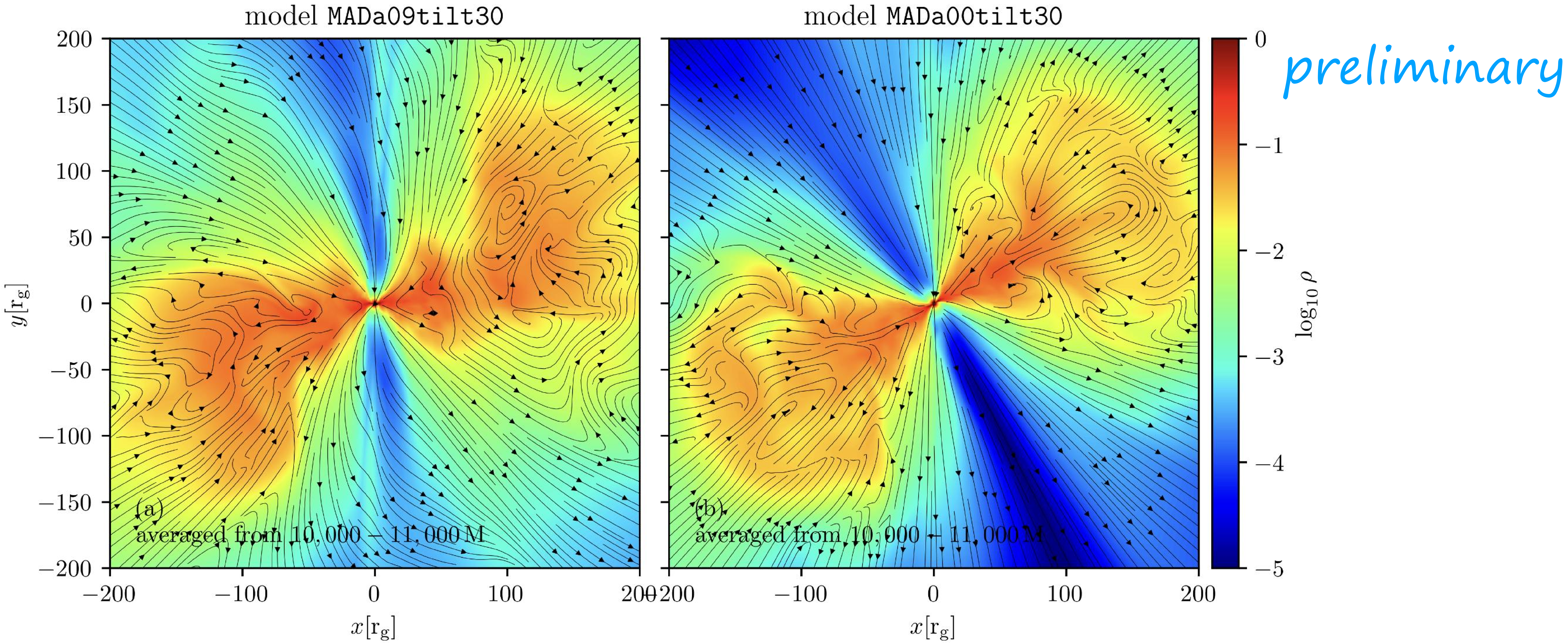
From the expression, we conclude that as long as $\sigma_z = B_z^2/\rho$ is large enough, magnetic torque will exceed LT torque.

Where does the vertical magnetic field come from?



Narayan & Eliot 2005

Magnetic alignment caused by black hole rotation



- The black hole's rotation significantly strengthens the **toroidal magnetic field**, driving magneto-spin alignment (alignment torque, McKinney et al. 2013).
- As the black hole rotates, the magnetic field aligns with the spin axis, generating a strong **vertical magnetic component** (precession torque).

Magneto-spin alignment and misalignment torque

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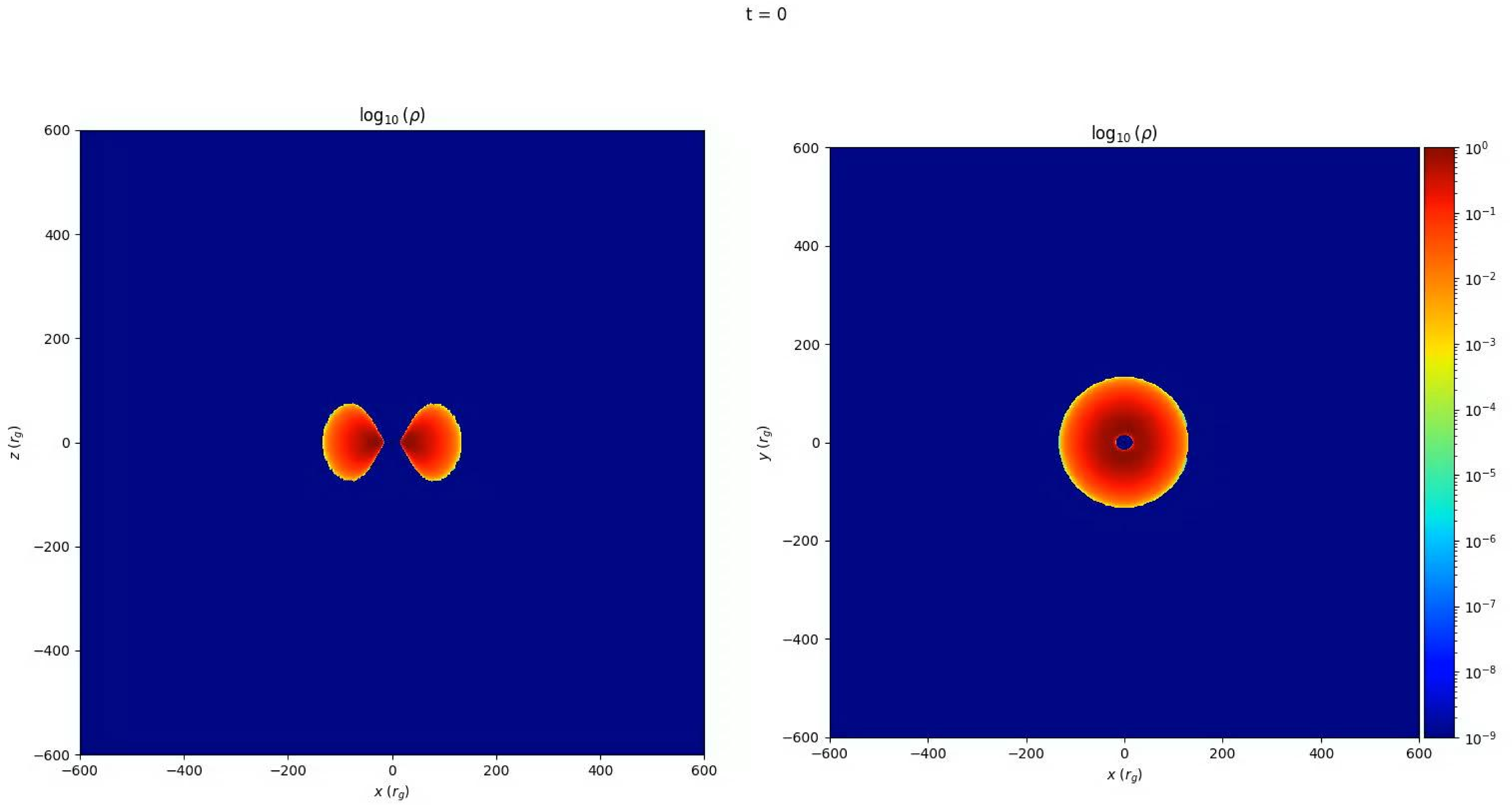

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Conclusion

- Current observations of M87* reveal a high jet precession rate, which is difficult to achieve through the Lense-Thirring effect with a standard-size torus.
- The magnetic field, acting in opposition to the Lense-Thirring effect, can efficiently induce retrograde precession in the torus.
- The main source of magnetic torque is the vertical magnetic field, generated by the alignment of the BH spin with the magnetic field configuration.
- In counter-rotating black holes, magneto-spin alignment acts as a misalignment torque, increases tilt angle.

Thanks for your listening!