Title: Hot, Retrograde Tilted MADs: Misaligned, Precessing, and Shaped by Electromagnetic Torques

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Subject: Strong Gravity

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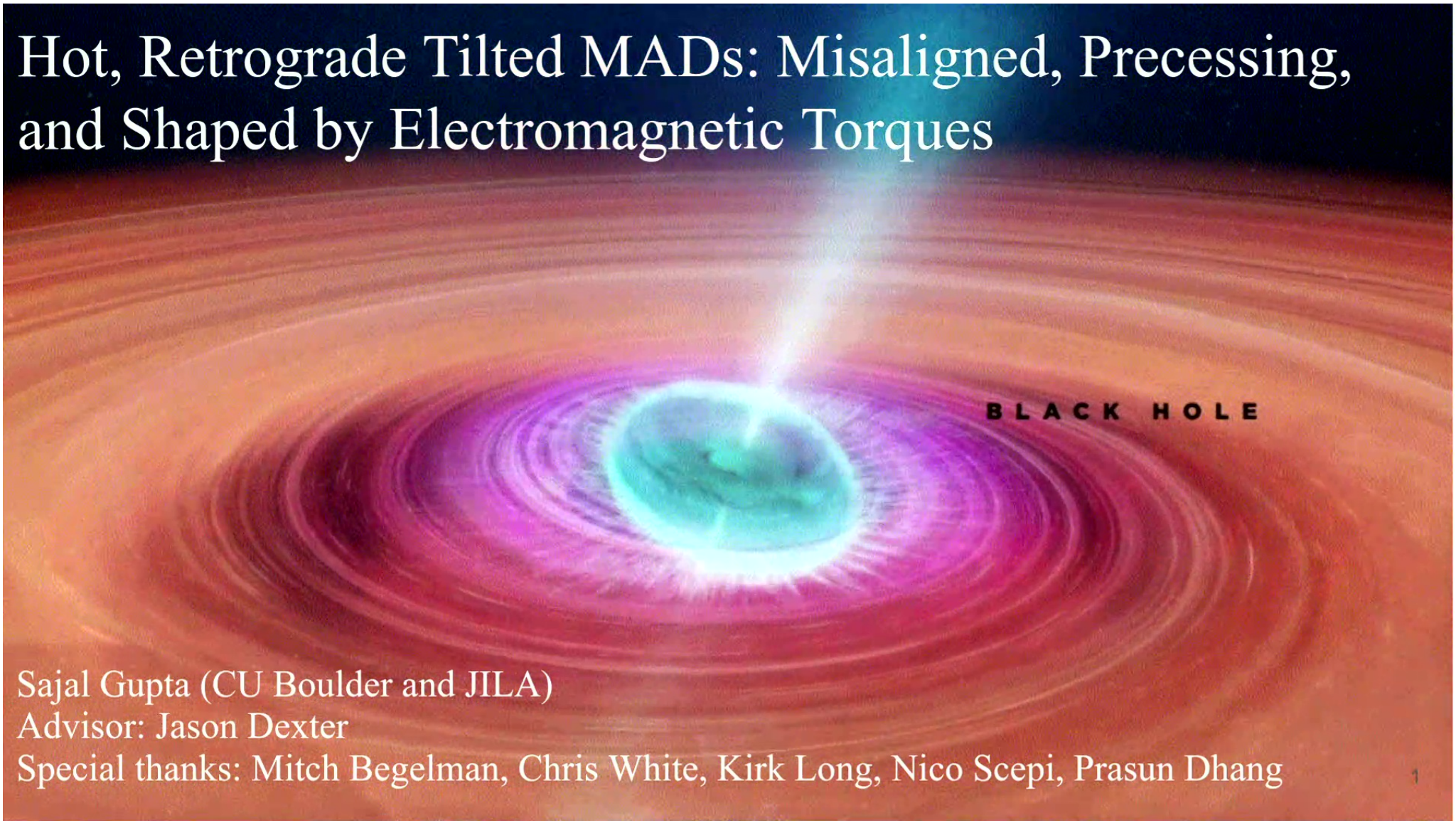
Abstract:

Tilted magnetically arrested disks (MADs) around black holes—where strong magnetic fields regulate accretion and jets—exhibit striking alignment behavior dictated by black hole spin direction. Using 3D general-relativistic magnetohydrodynamic (GRMHD) simulations of tilted MADs, we find that prograde disks align via a two-stage process: an initial rapid alignment phase, ending at the flux saturation timescale, followed by a slower, spin-independent phase. In contrast, retrograde MADs remain persistently misaligned, with their inner disks precessing four times faster than weakly magnetized systems—a potential explanation for high-frequency quasi-periodic oscillations (QPOs). By analyzing magnetic and hydrodynamic torques within ideal GRMHD, we show that alignment in prograde disks is dominated by electromagnetic stresses from the magnetosphere. However, the same magnetic forces— which always act to align the disk with the black hole spin—are significantly weaker in retrograde disks, allowing opposing hydrodynamic torques to dominate. These results suggest that jets alone may not be sufficient to align MAD disks, instead highlighting the magnetosphere’s crucial role in mediating spin-disk coupling.

Hot, Retrograde Tilted MADs: Misaligned, Precessing, and Shaped by Electromagnetic Torques



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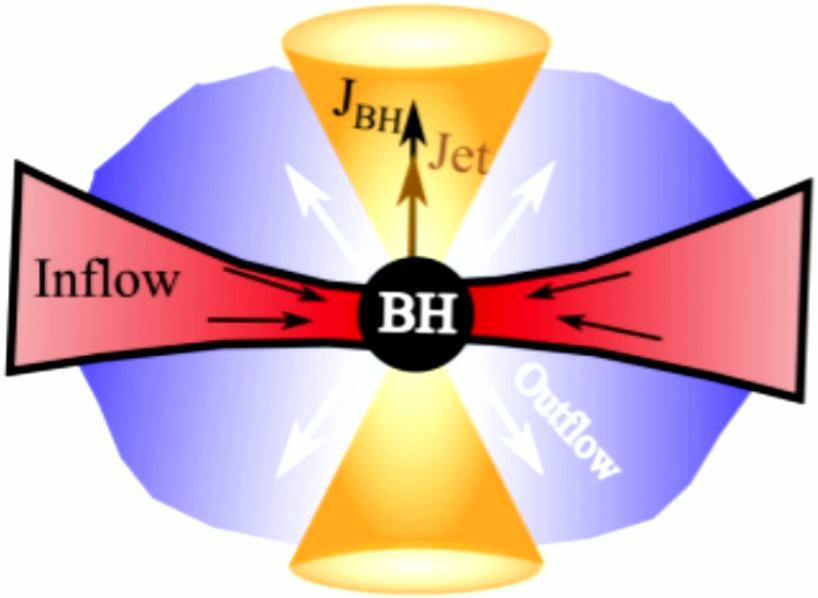
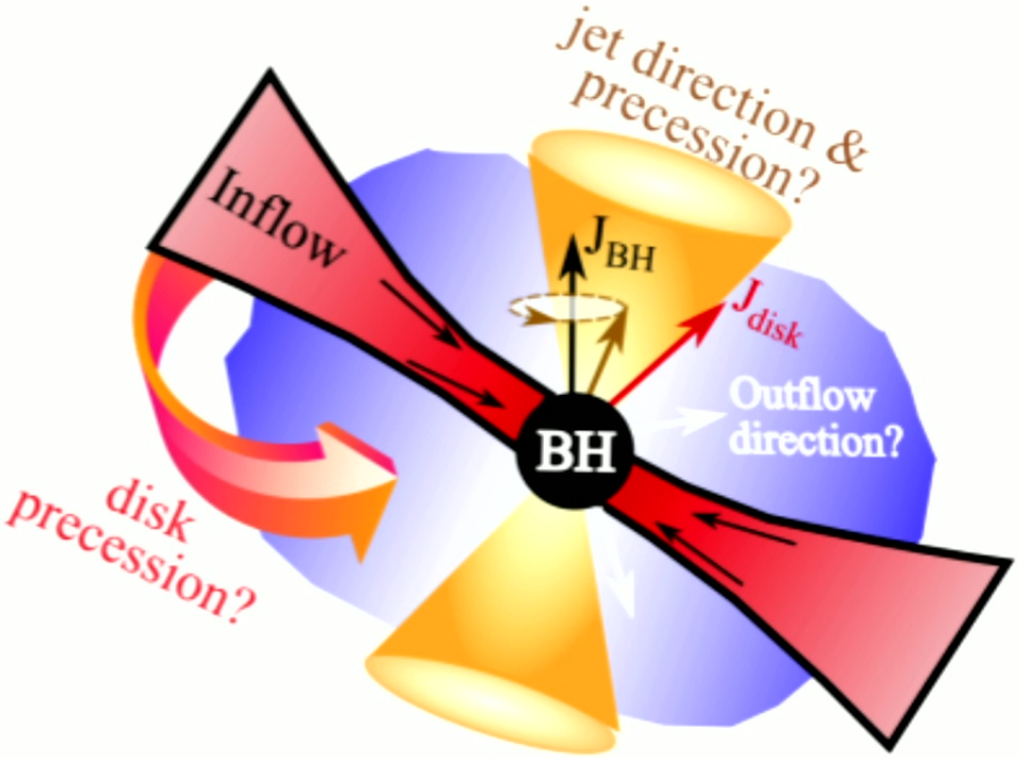
Advisor: Jason Dexter
Special thanks: Mitch Begelman, Chris White, Kirk Long, Nico Scepi, Prasun Dhang

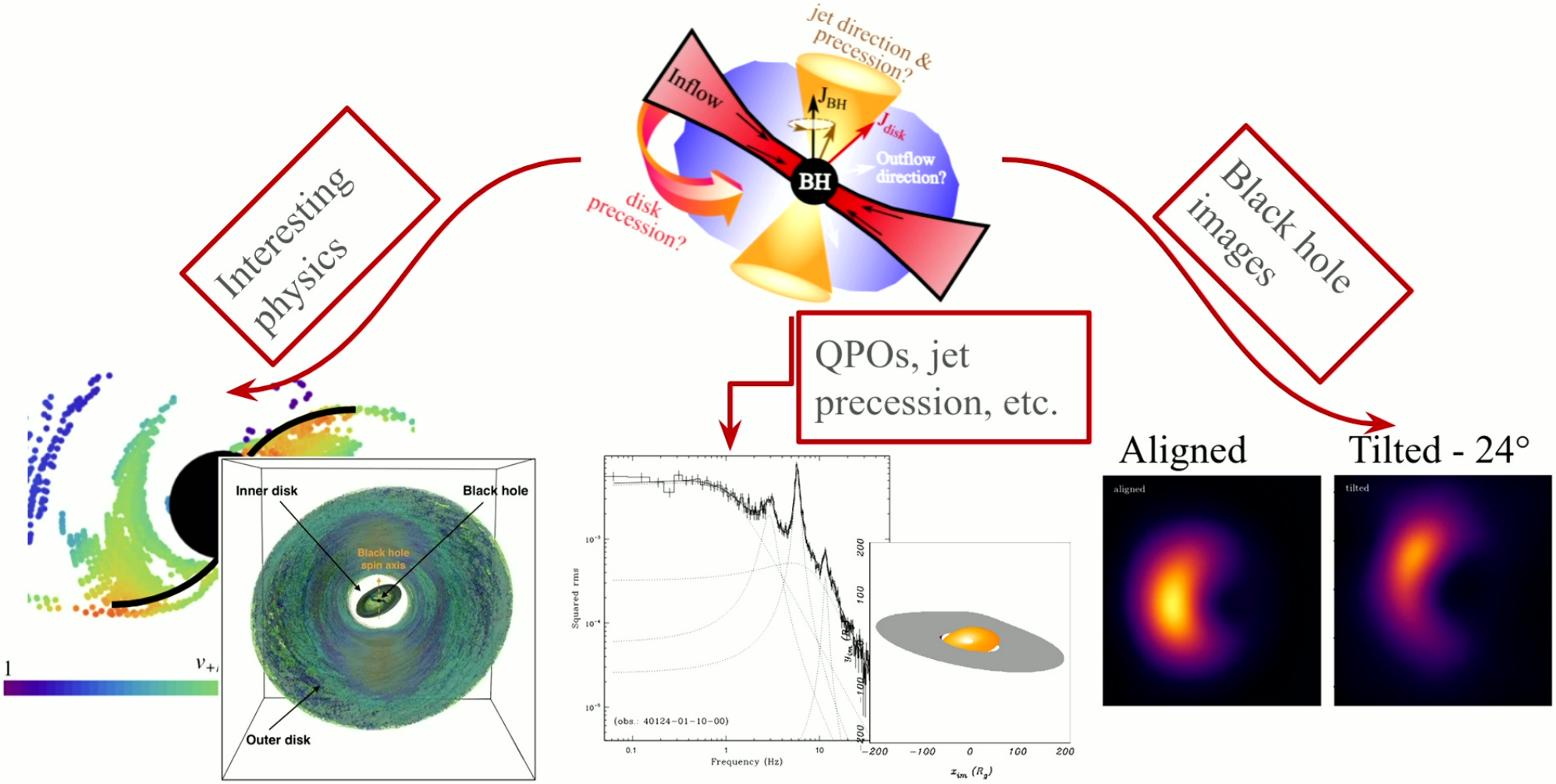
What is a tilted accretion disk?

Aligned accretion disk



Tilted accretion disk

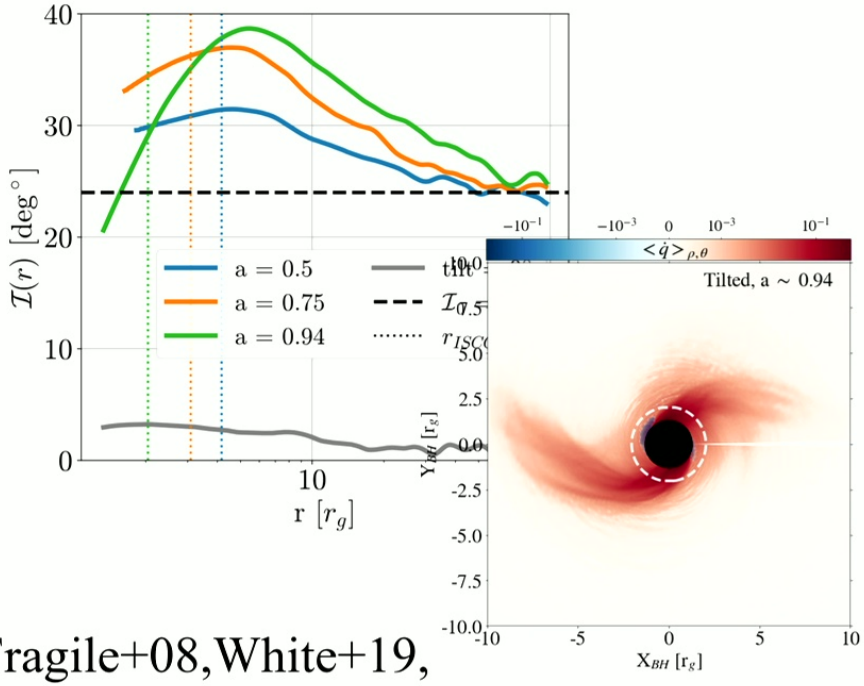




Casella+04,Fragile+07,+08,Ingram+09,19,Nixon+12,Generozov+13,Liska+19,White+19,+20,Chatterjee+20,Kaaz+23,Musoke+24, and many, many other researchers, which I couldn't name [3]

Hot, tilted accretion: Fields dictating disk evolution

Weakly magnetized
flows



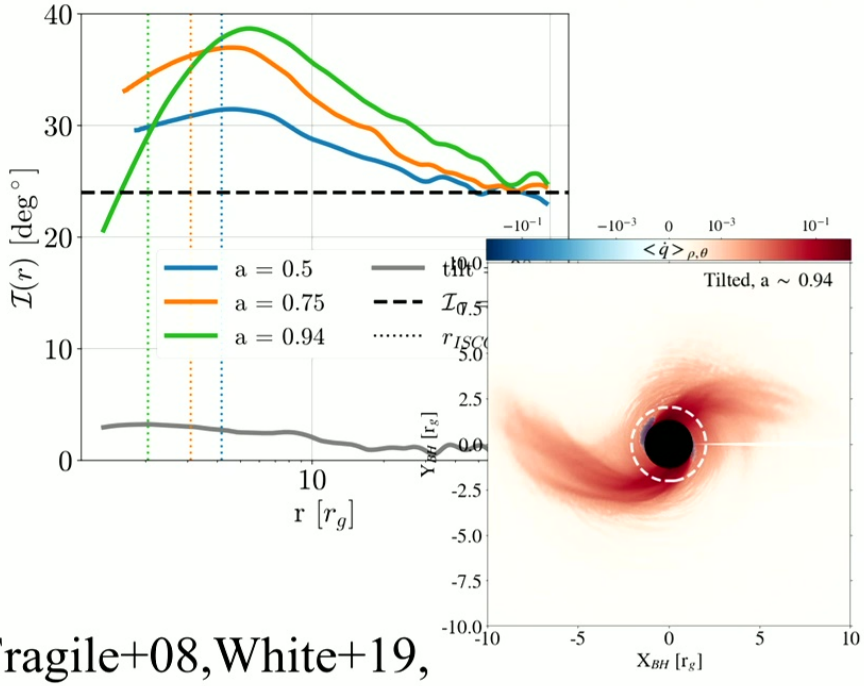
Fragile+08,White+19,
Chatterjee+20,Gupta+24

Hot, tilted accretion: Fields dictating disk evolution

Weakly magnetized flows

Increase magnetic field strength

Magnetically Arrested Disks (MAD)



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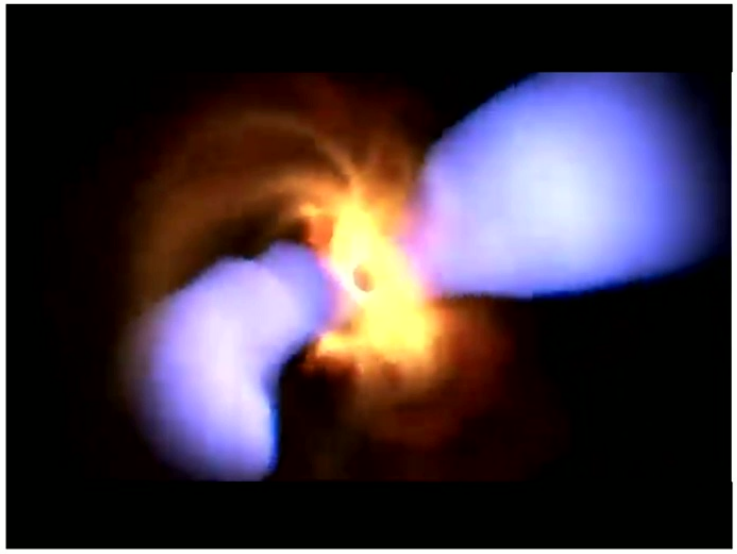


Mckinney+12

GRMHD simulations: Tilted MAD parametric Study

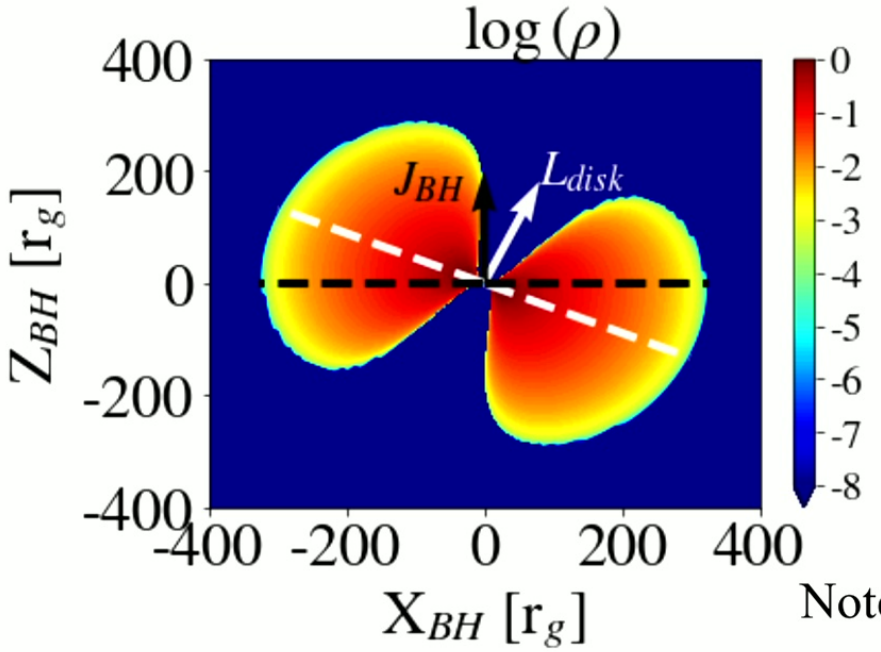
We solve:

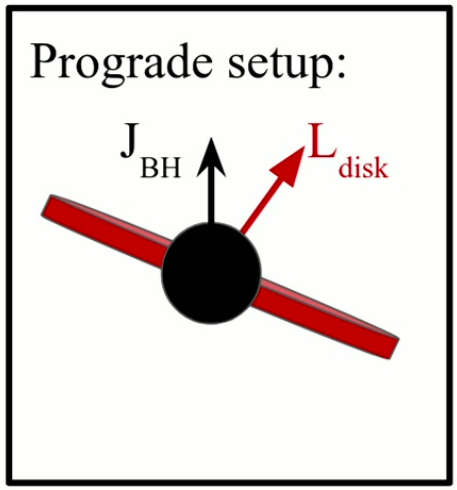
- Continuity eq.: $\nabla_\mu(\rho u^\mu) = 0$
- Energy-momentum conservation: $\nabla_\mu(T^\mu_\nu) = 0$
- Source free Maxwell eqs: $\nabla_\nu\left(*F^{\mu\nu}\right) = 0$

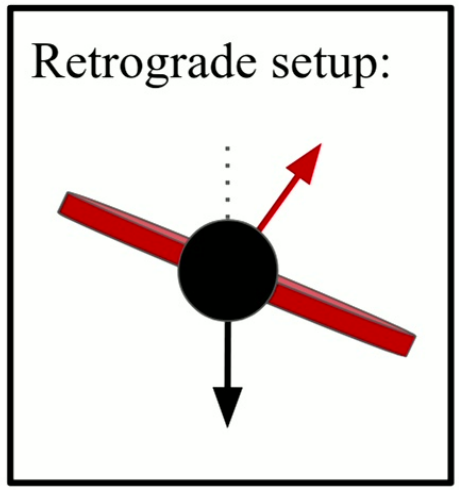
Parameters:

Black hole spin: $-0.1 \leq a \leq 0.9375$

Tilt: 16° and/or 30° wrt +Z axis



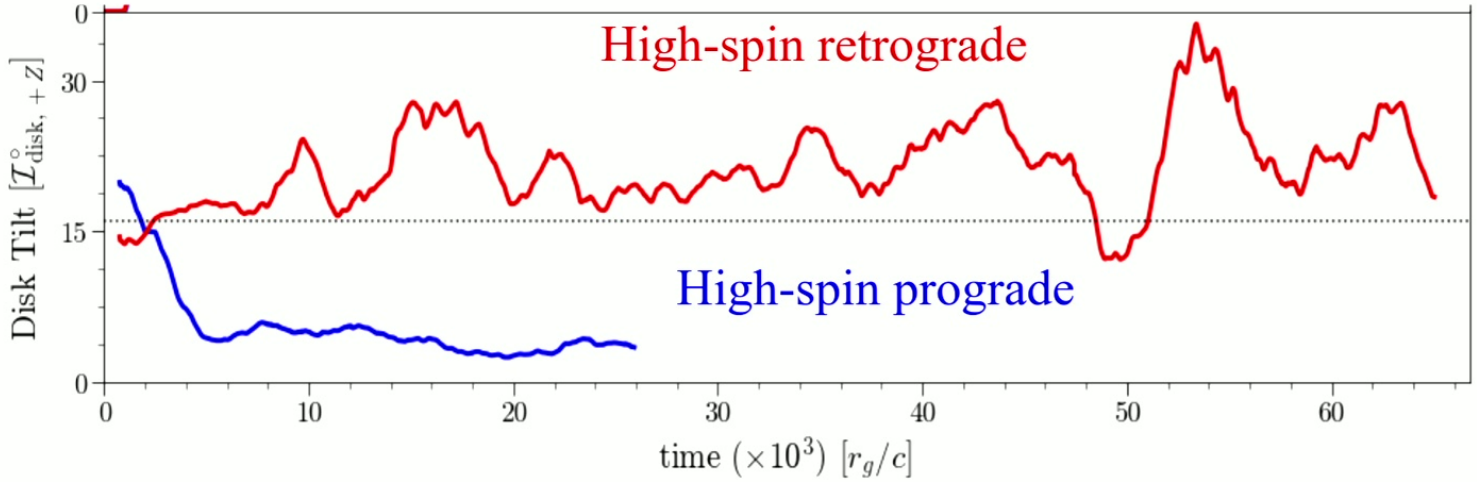


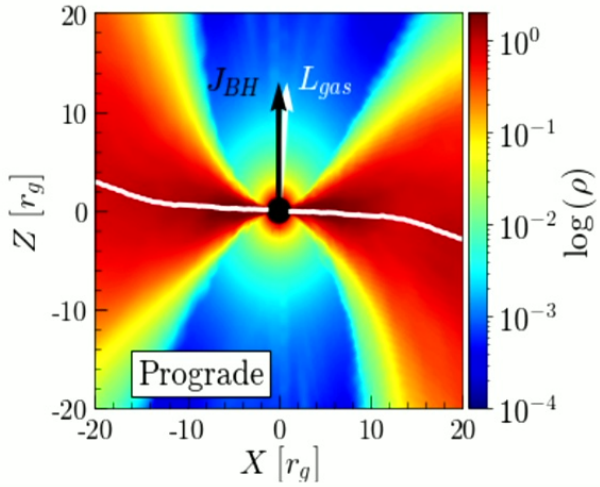


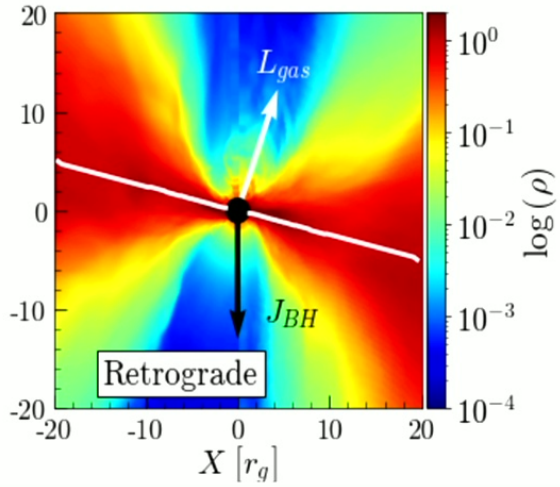
Note: gravitational radius $r_g = GM/c^2 \sim 1.5\ (M/M_{Sun})$ km

Tilted prograde MADs align, retrograde don't!

For radius = [horizon,20] r_g







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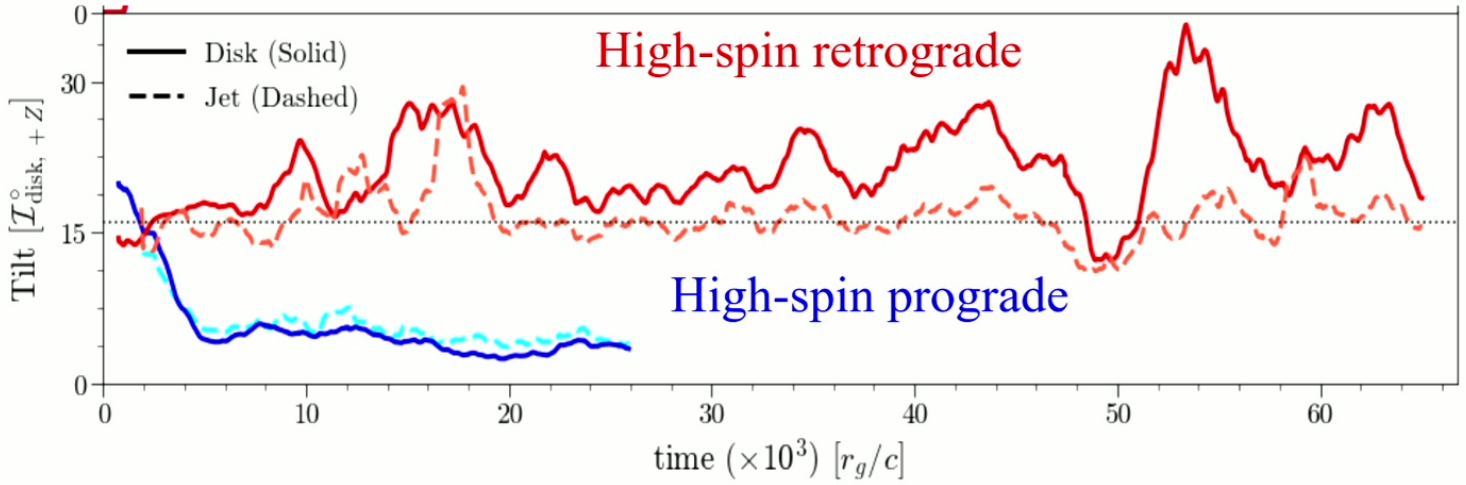
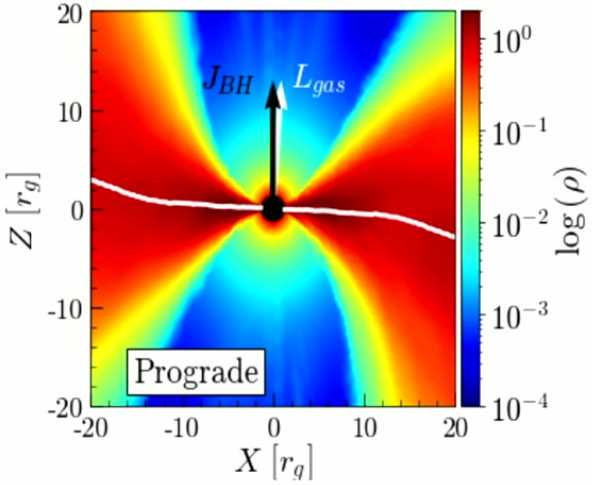
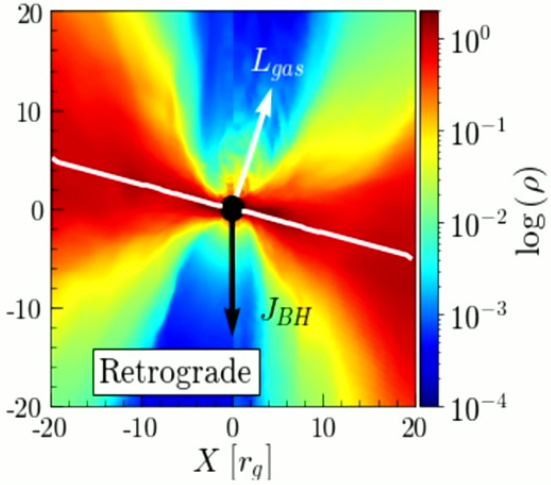
Jets emit along rotation axis of the disk

Disk (Solid)
Jet (Dashed)

For radius = [horizon,20] r_g







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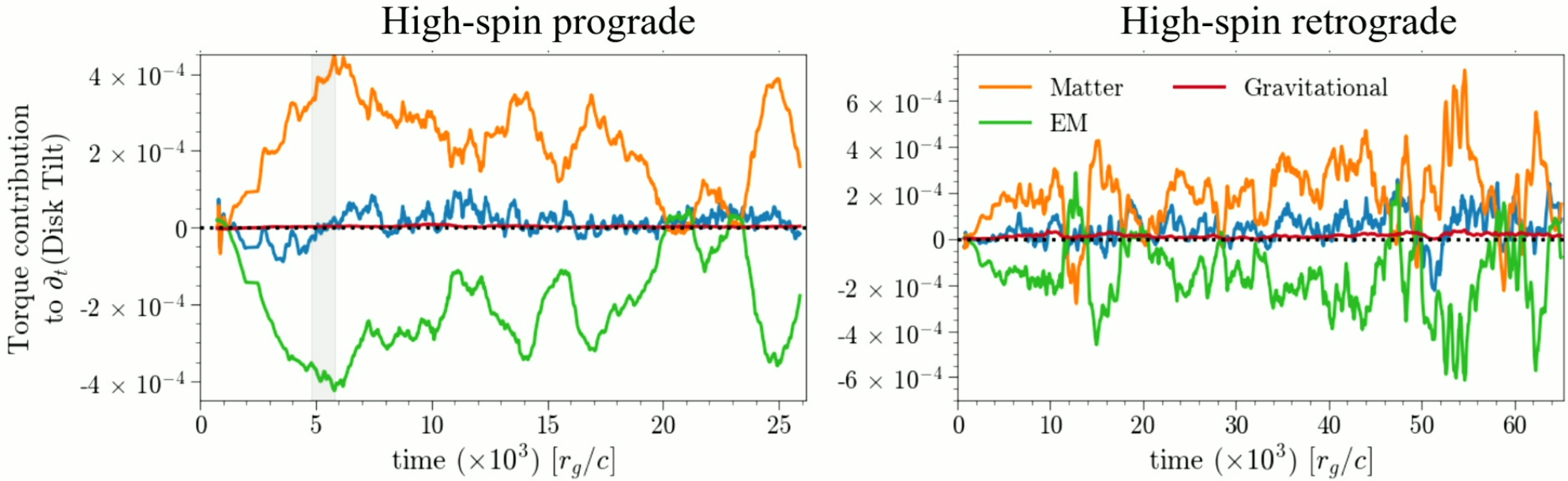
Torques: EM aligns but hydrodynamic balances retrograde

Time evolution of tilt rate from spin axis: − (Tilt decrease), + (Tilt increase)



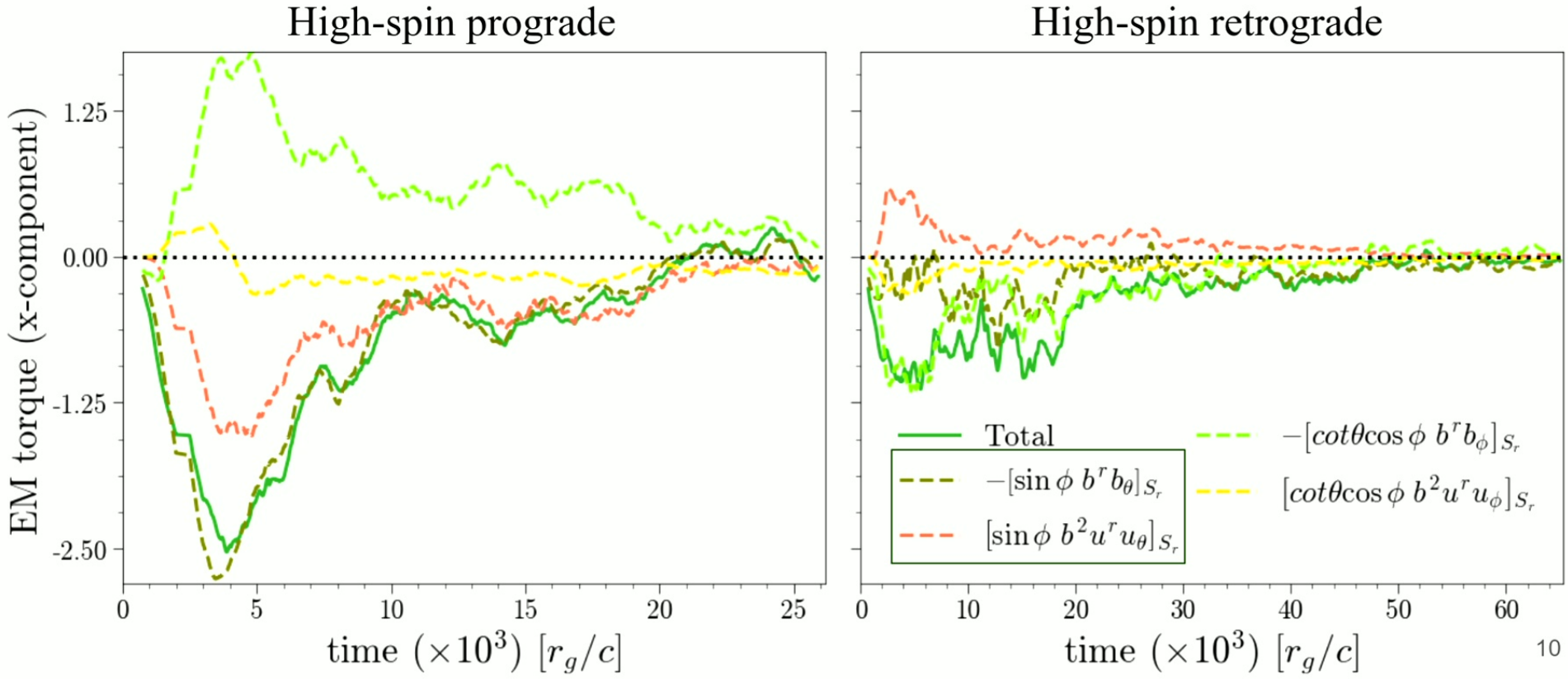
— Gravitational torques are negligible

— EM torques drives alignment: push prograde/retrograde towards spin axis

— Matter/hydrodynamic torque opposes EM forces: resist retrograde alignment

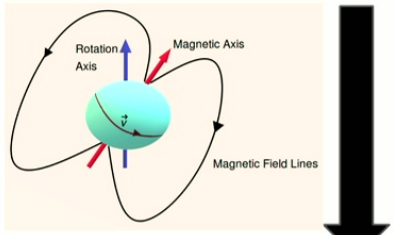
EM torque analysis: Radial-polar mag. tens. dominates

Time evolution of the EM torque's x-comp., plotted to identify alignment-driving processes



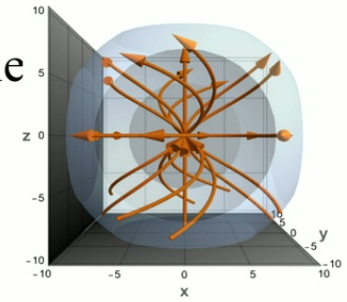
Heuristic model to understand nature of the EM torque

Assumed a rotating, split-monopole magnetic field initially aligned to +Z (or spin) axis

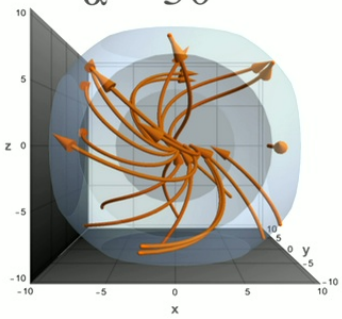


Rotated field by angle α about +Y: such that field is tilted by α wrt spin axis

$\alpha = 0°$



$\alpha = 30°$



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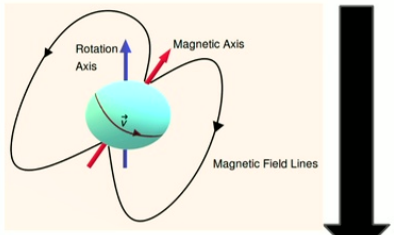

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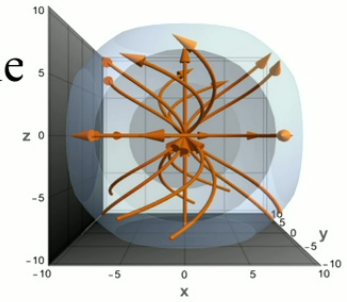

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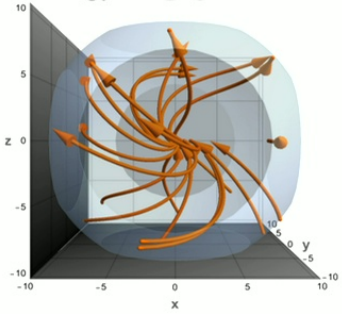
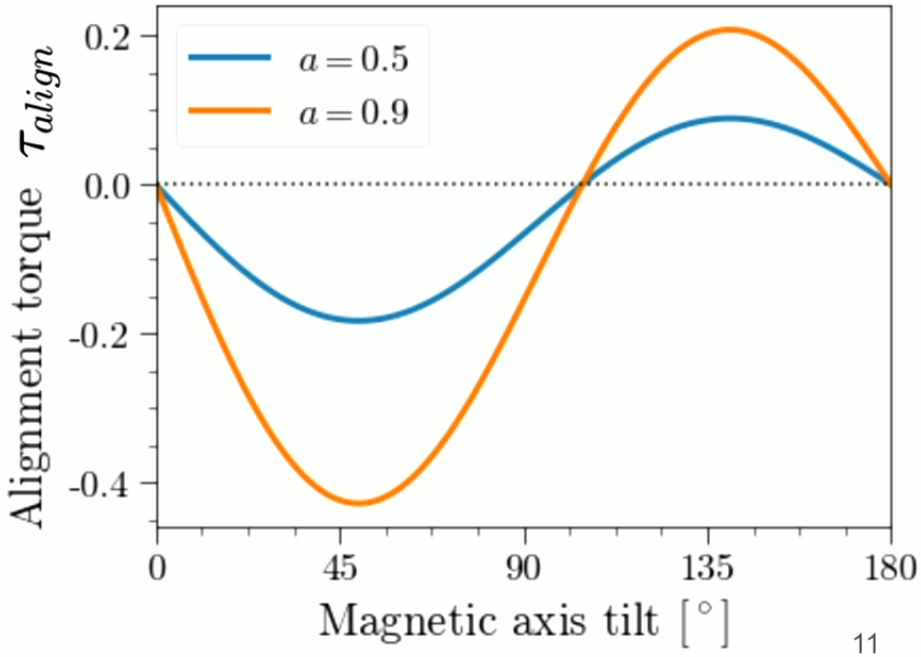


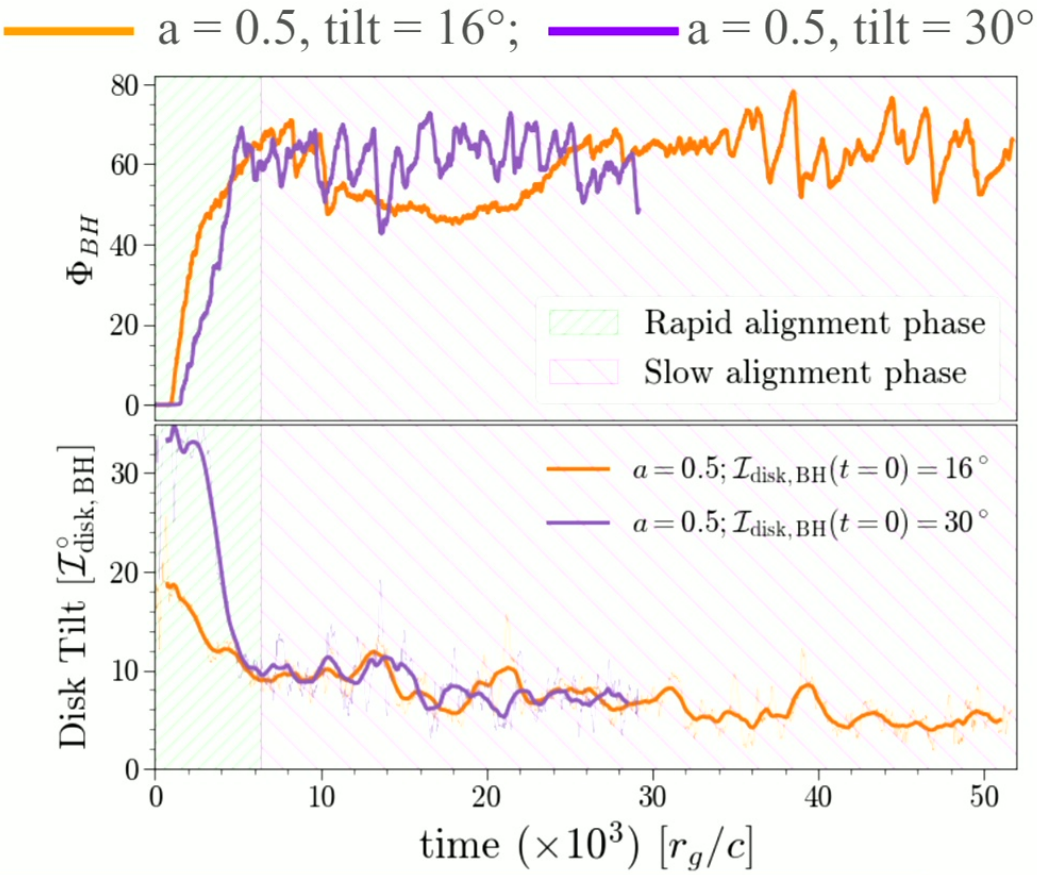
$$\tau_{align} \propto -\Phi^2_{\text{model}} \Omega_F (1 + 4\cos\alpha)\sin\alpha$$

Prograde/Retrograde → magnetic axis align toward +Z (or spin) axis,



Prograde disk align in two stages: Rapid and slow stages

- Prograde MADs align with spin through a two-stage process
- Initial rapid phase operates on the magnetic flux saturation timescale
- Followed by slower alignment phase, observed to be spin-independent

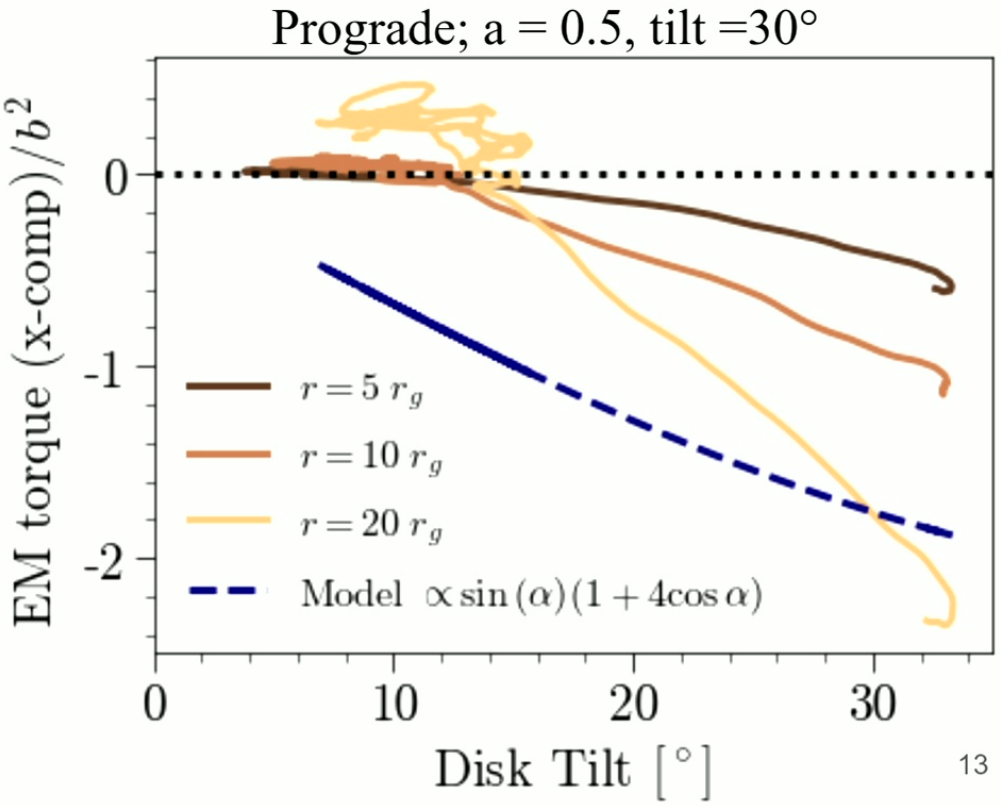


Is governing mechanism same, or different for rapid and slow phase alignment?

Possible explanation for progrades two-stage alignment

Plotting normalized x-comp of EM torque vs disk tilt: to identify if torque weakens as tilt decreases

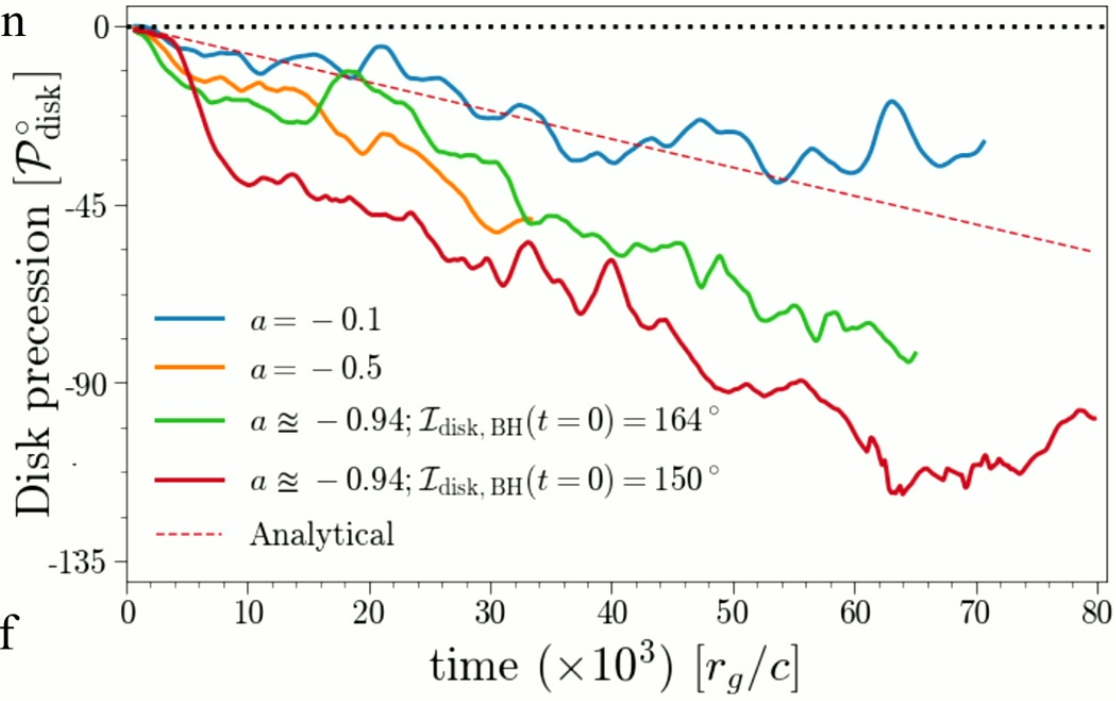
- Assuming same alignment process in both phases
- EM torque ↑ as field strength ↑ and tilt ↑ (at least in small-angle approx)
- EM torque may got weakened as the disk partially aligns!



Tilted MADs can precess (Solid body precession)

- Retrogrades show solid body precession
- Precession timescale:
  a = -0.1 ~ 5 (M/M_{Sun}) s
  ~ 1000 yrs for M87

  a = -0.9375 ~ 1.5 (M/M_{Sun}) s
  ~ 300 yrs for M87
- Timescale about 2-5 times shorter than the Lense-Thirring precession period of test-particle at disk's mean angular momentum radius



Analytical from Fragile+08 (eq. 43)

Summary

Performed ideal 3D GRMHD simulations with spins: -0.1 to ~0.94 and tilts of 16° and/or 30°

- Prograde align in two different Stages, whereas retrograde don't!
- Jet emits along disk ang. mom
- EM torques pushes disk along spin axis, overpowering hydrodynamic torque in prograde flows but balanced by it in retrograde cases

$$\tau_{align} \propto -\Phi^2_{\rm model}\Omega_F(1+4\cos\alpha)\sin\alpha$$

- Retrograde MADs precess as a solid-body