How common are warped accretion disks?

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Sasha Tchekhovskoy, Danat Issa, Nick Kaaz & Zack Andalman (*Northwestern University*)

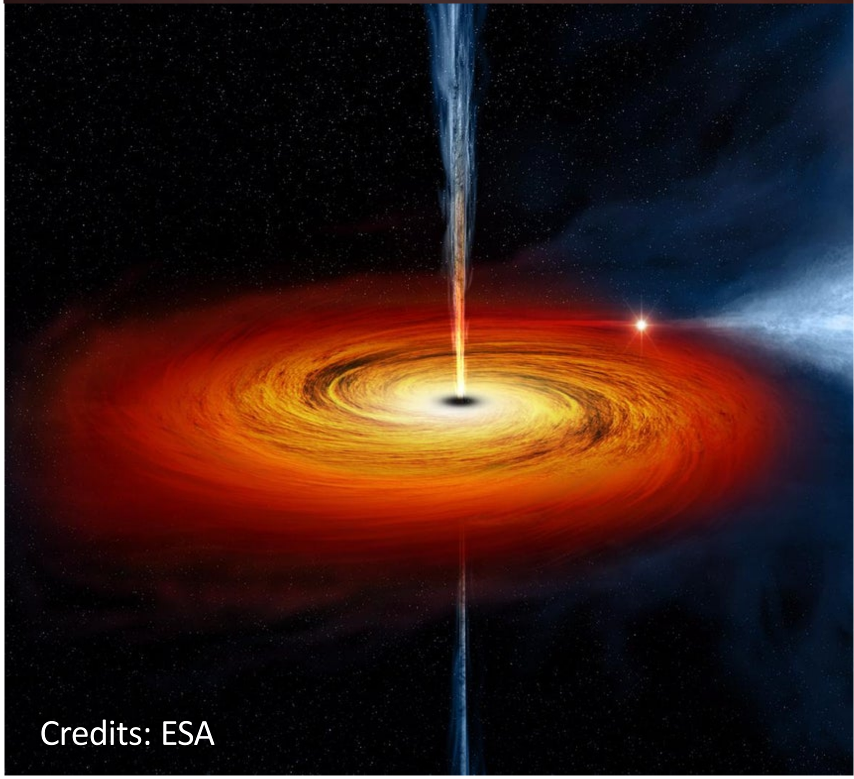
Andrew West (→*U. of Arizona*) & Henric Krawczynski (*Washington University*)

Bart Ripperda & Gibwa Musoke (*U. of Toronto*)

Supermassive Black Hole

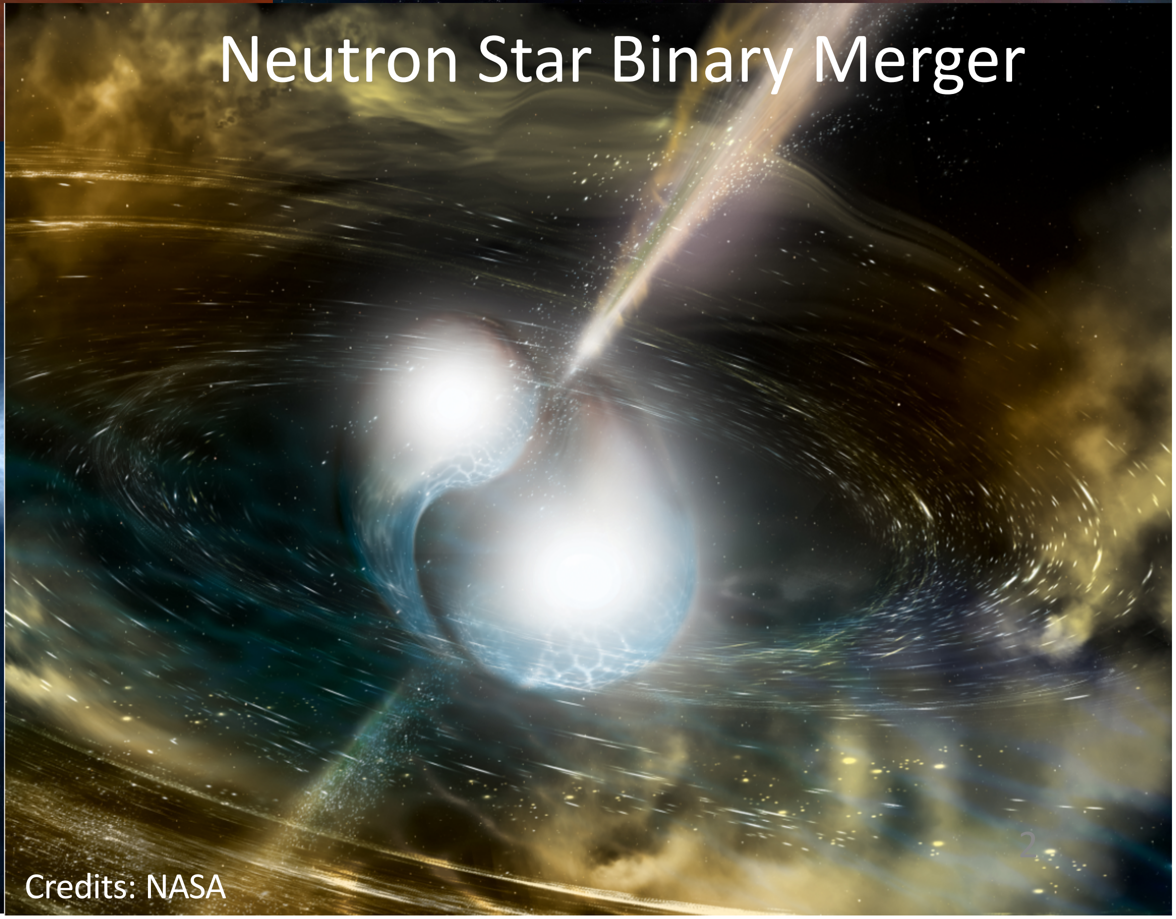
Credits: ESA

Core-collapse Supernova



Credits: ESA

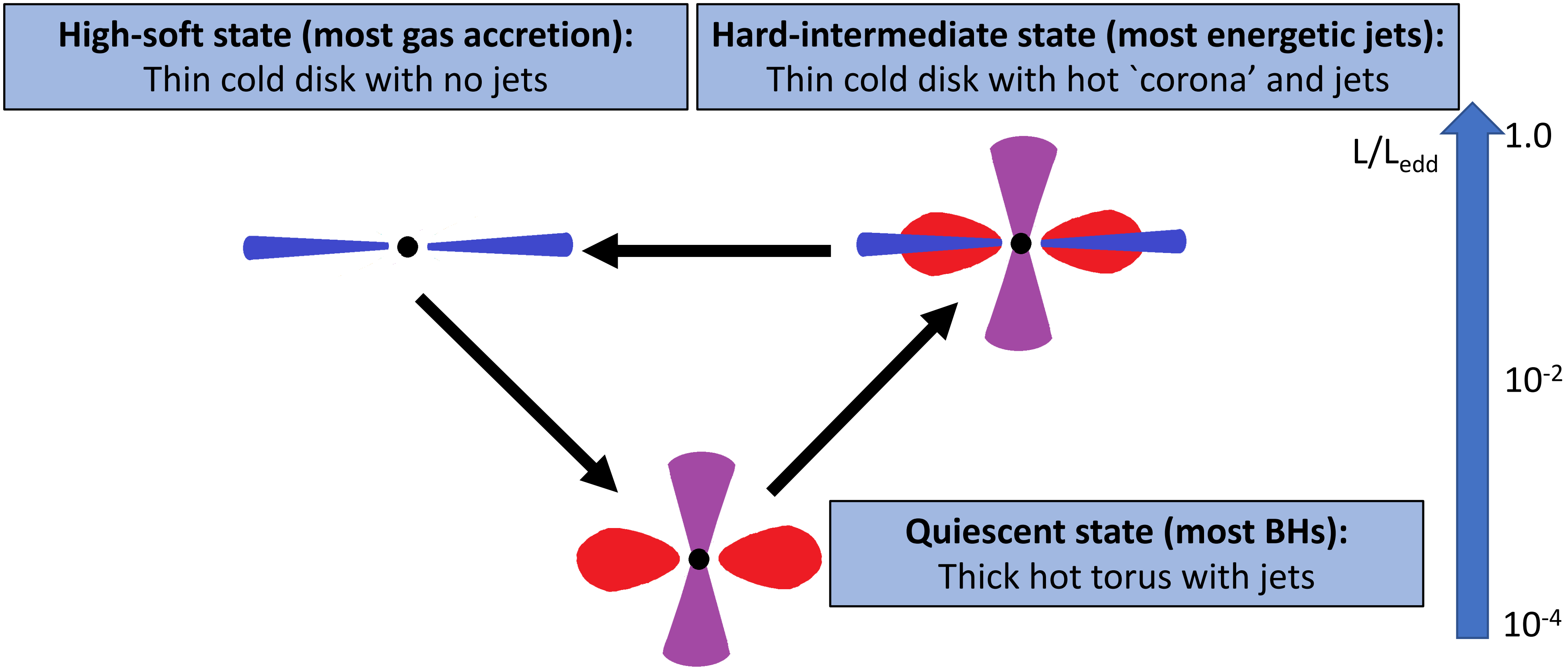
Neutron Star Binary Merger



Credits: NASA

Accretion disk states

- XRBs and AGN can be found in various (spectral) states of accretion



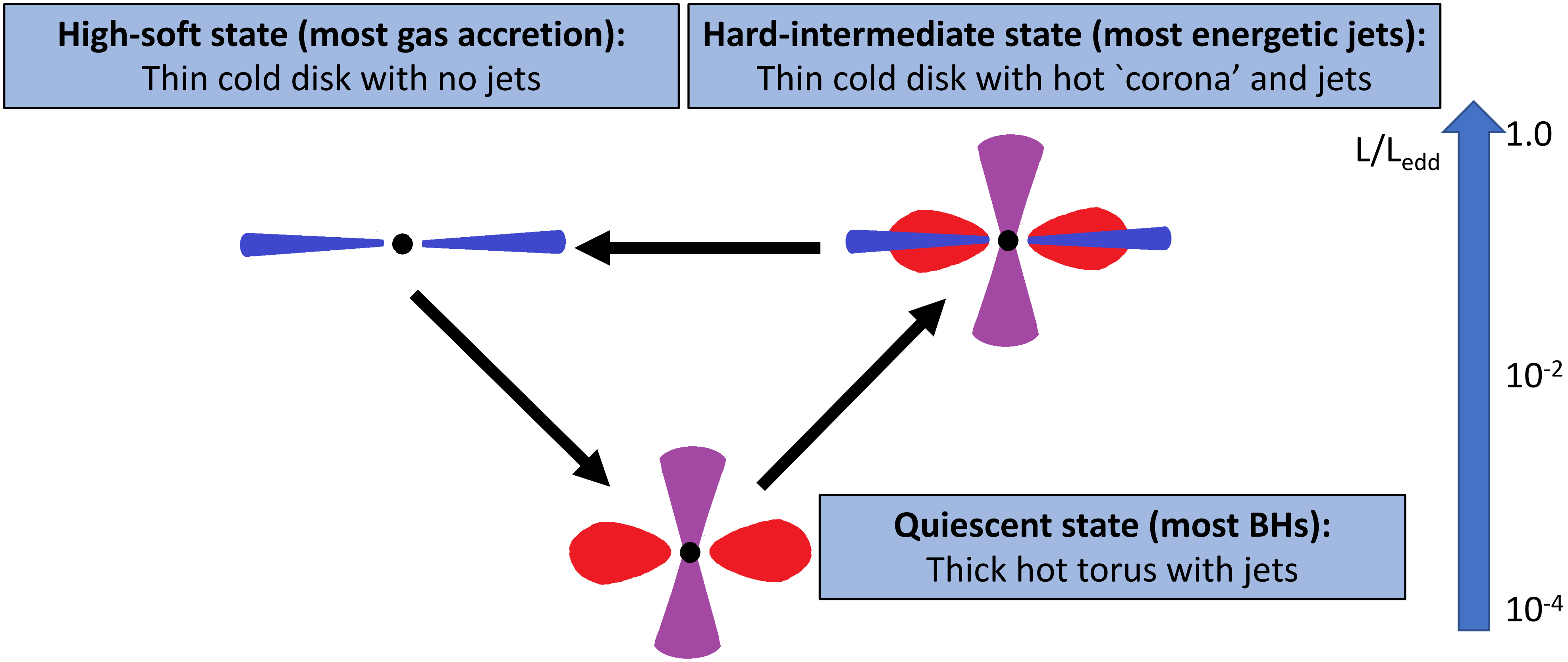
High-soft state (most gas accretion):
Thin cold disk with no jets

Hard-intermediate state (most energetic jets):
Thin cold disk with hot `corona’ and jets

Quiescent state (most BHs):
Thick hot torus with jets

Accretion disk states

- XRBs (and maybe AGN) transition through various (spectral) states of accretion



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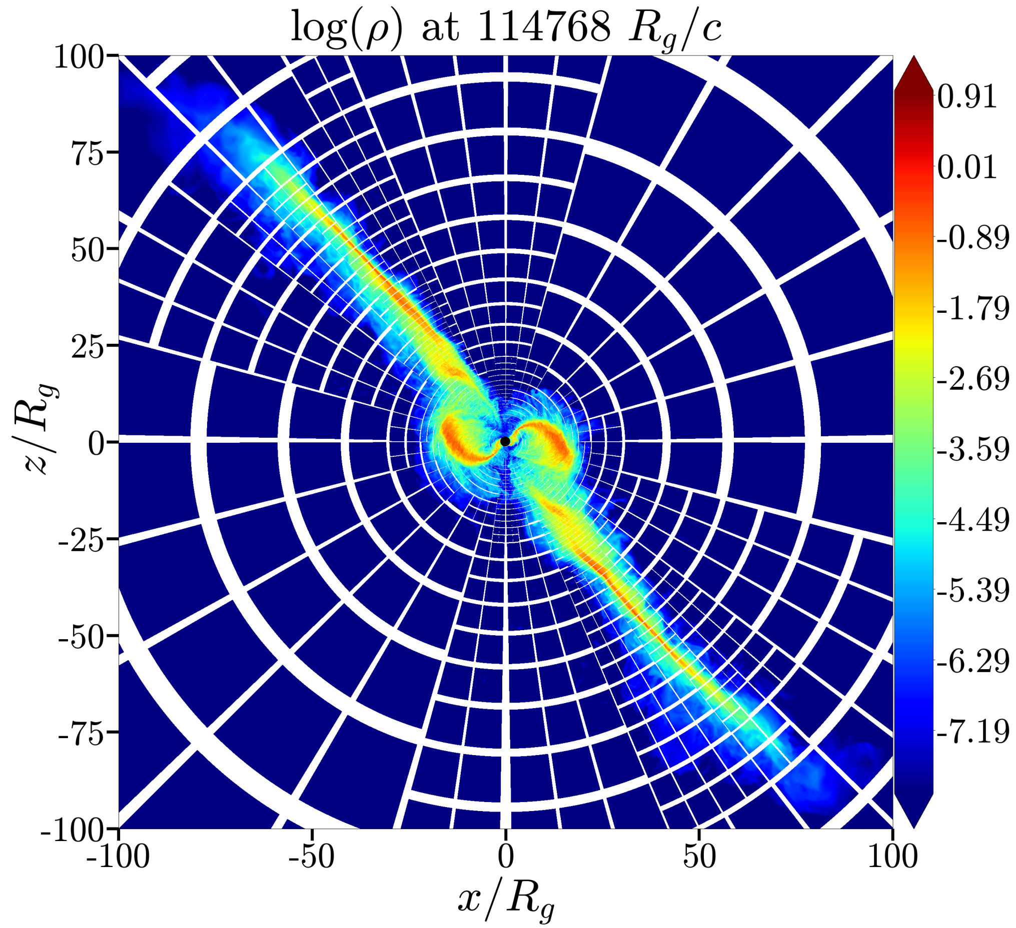
	Quiescent state	**Hard-intermediate state (HIMS)**	**High-soft state (HSS)**
Radiation	Not important	Very important	Very important
Computational cost	1	10^3-10^5	10^3-10^5
Physical understanding	Very good	Non-existent	Poor

H-AMR: Unifying accretion on GPUs

- Solves radiative 2T GRMHD equations on a grid (**Liska** et al. 2022)
  - Features (3-dimensional) static and adaptive mesh refinement (SMR/AMR) capability
  - First GPU-accelerated GRMHD code and excellent scaling up to ~16000 GPUs
- Increases computational efficiency by 5+ orders of magnitude in luminous disks (HIMS and HSS)
  - Led to discovery of fundamentally new accretion physics in HIMS and HS state (this talk)



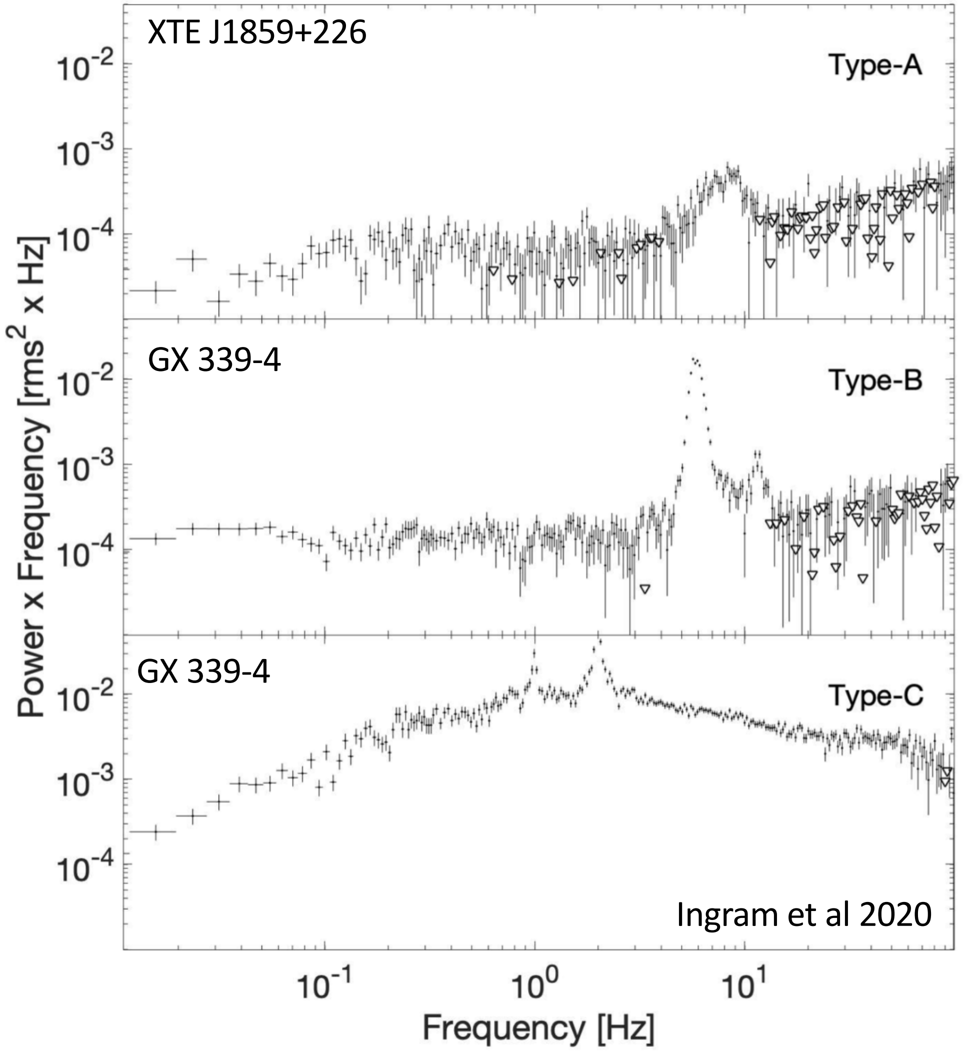
Speedup compared to 20 core CPU

	Quiescent state	HIMS and HSS
Base resolution	$304 \times 192 \times 192$	$1680 \times 576 \times 1024$
Effective resolution	$304 \times 192 \times 192$	$13440 \times 4608 \times 8192$
Block size	$76 \times 32 \times 48$	$48 \times 46 \times 64$
Grid outer radius	$150 r_g$	$10^5 r_g$
Physical duration	$10^4 r_g/c$	$1.5 \times 10^5 r_g/c$
Hardware computational cost	18 GPU hours	3.8×10^6 GPU hours
System scale	1 V100 GPU	5400 V100 GPUs
Number of cells	9.2×10^6	$12-22 \times 10^9$
Number of real zone-cycles	0.64×10^{13}	1.7×10^{17}
Number of effective zone-cycles	1.6×10^{13}	1.5×10^{18}
Effective zone-cycles/s	$\gtrsim 2.5 \times 10^8$/GPU	$\gtrsim 1.1 \times 10^8$/GPU
LAT $\times$ GPU Speedup	71	31
SMR Speedup (#*Timesteps*)	1.17	3.3
AMR Speedup (#*Cells*)	1	35
AMR Speedup (#*Timesteps*)	1	53
Total Speedup	83	1.9×10^5

Problem 1: Origin of quasi-periodic oscillations

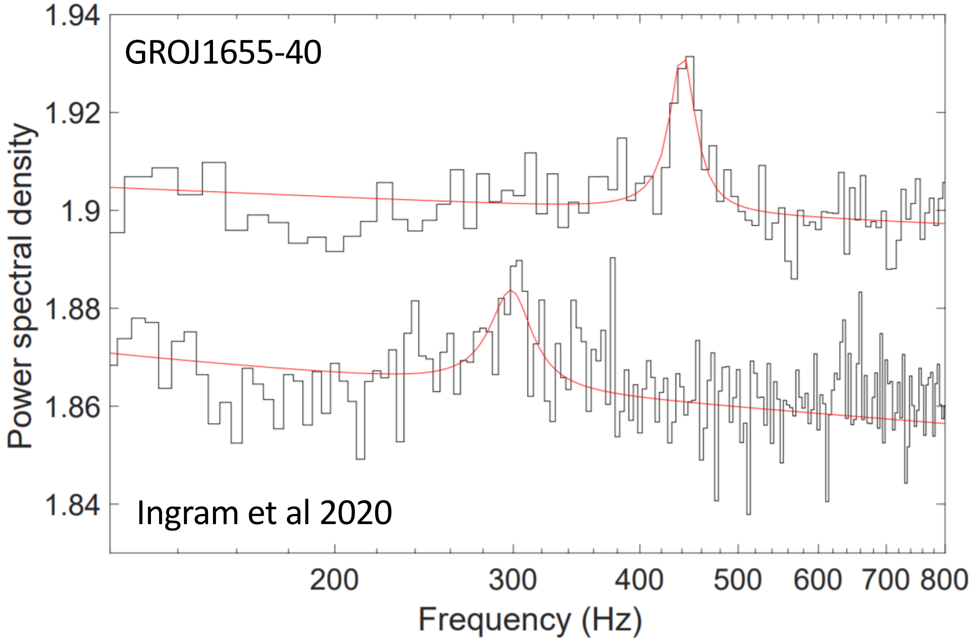
- Low and high frequency quasi-periodic oscillations (QPOs) observed in luminous XRBs and AGN
  - Bad news: Physical origin of QPOs (ubiquitous in luminous states) is unknown
  - Good news: No-one simulated a *misaligned* disk in any of the luminous states ☺

Low frequency QPOs come in different types



Ingram et al 2020

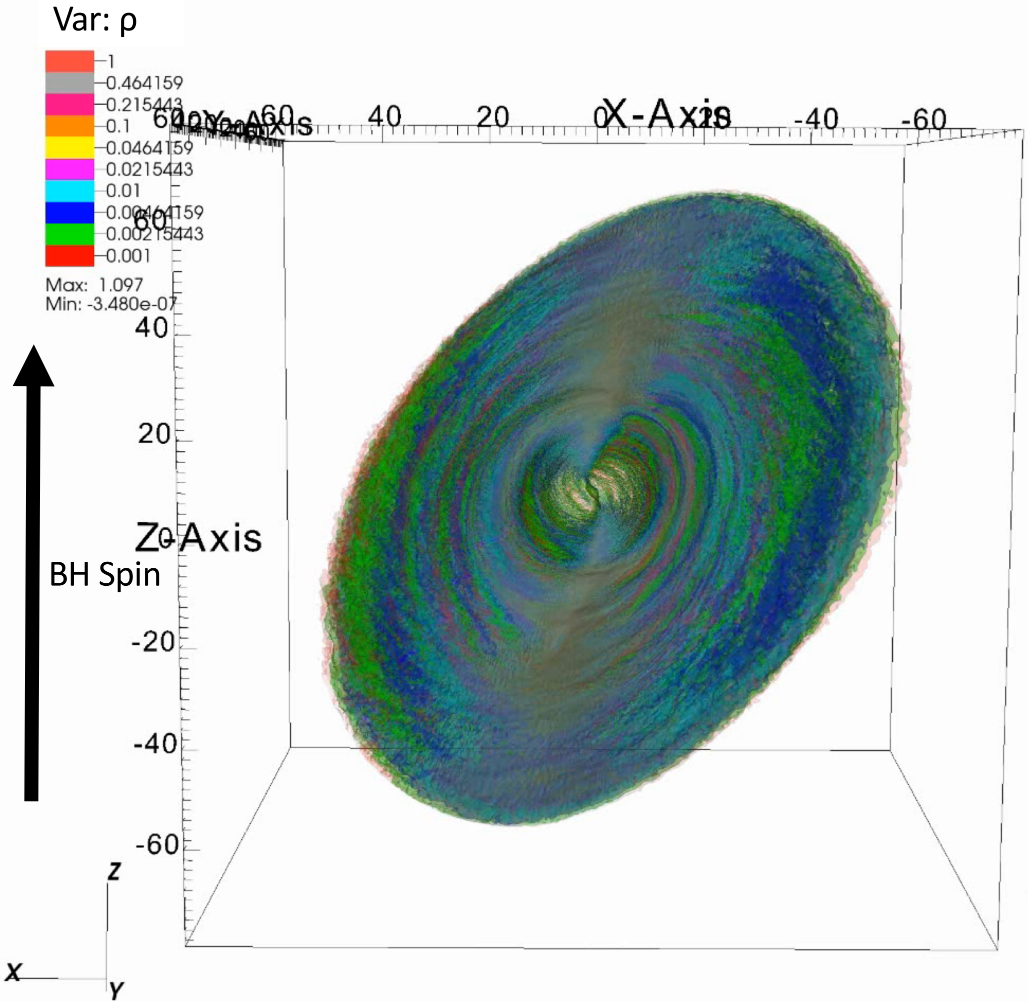
High frequency QPOs come in 3:2 pairs

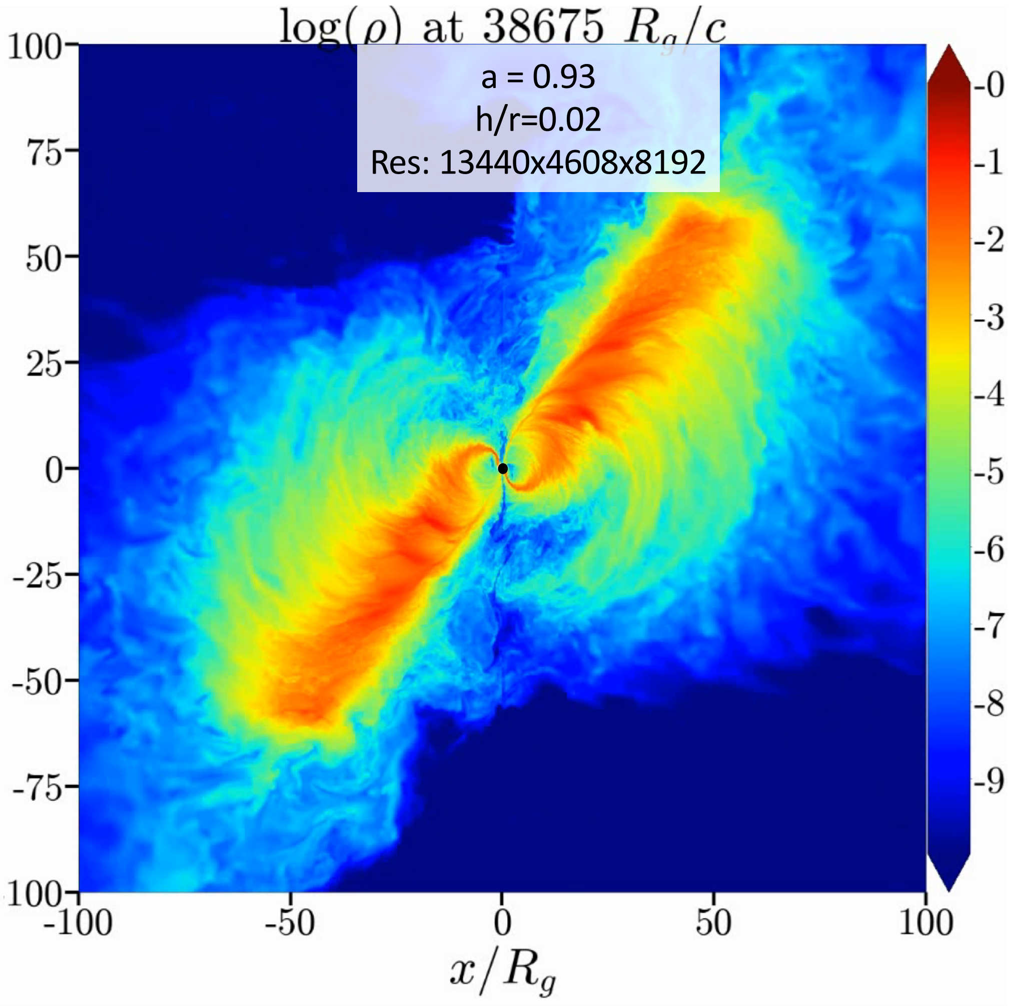


Ingram et al 2020

Misaligned thin accretion disks tear

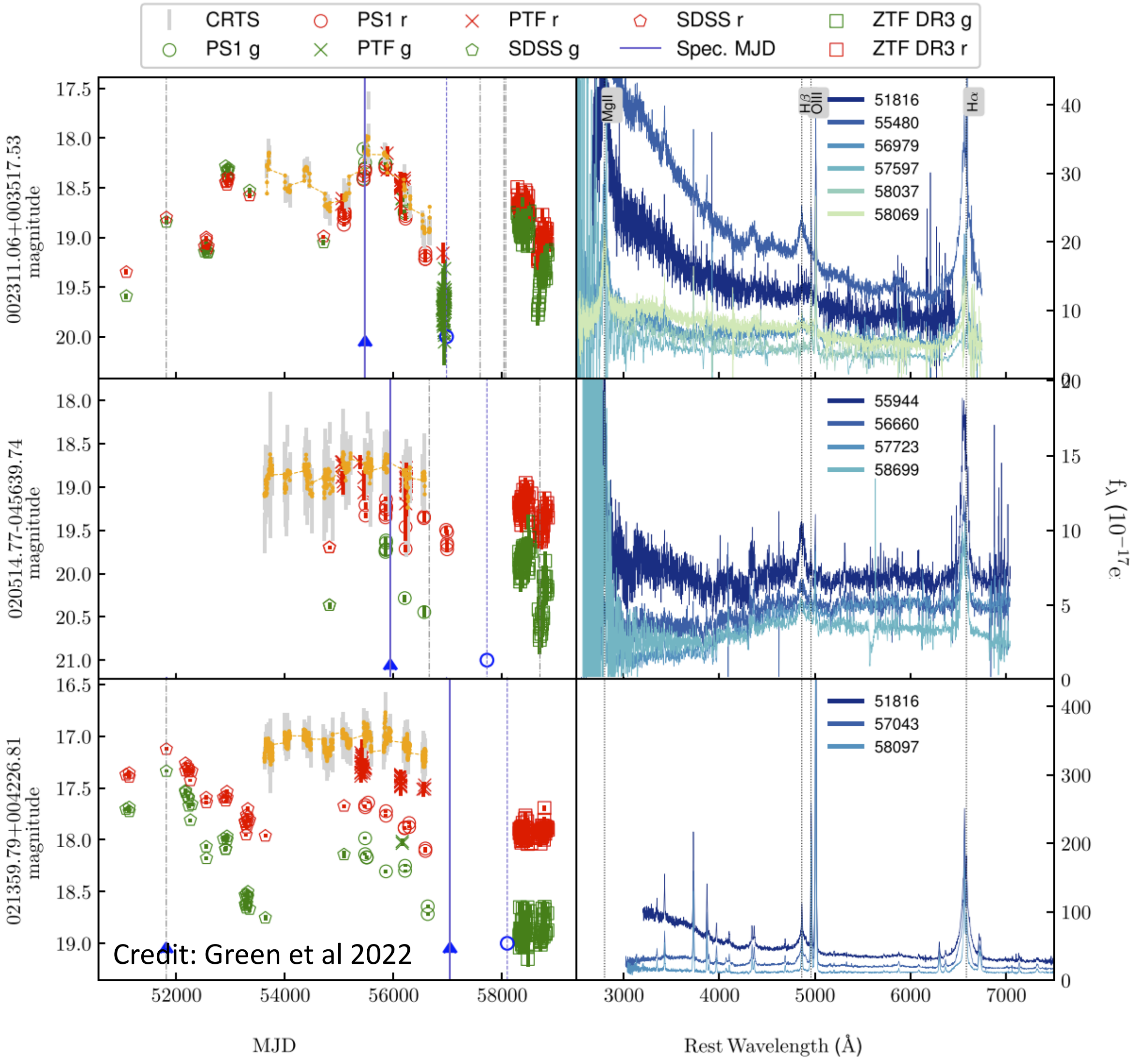
- First GRMHD simulation of a 65° tilted *thin* disk threaded by a toroidal field (**Liska** et al 2022)
  - Demonstrates that precessing disks tear of in cycles (featuring ~5 precession periods)
  - NEW result: Tearing radius (and precession frequency) depend on amount of magnetic flux!





Problem 2: Origin of rapid AGN variability

- Some `changing look’ AGN show order-of-magnitude *luminosity* and spectral swings
  - Time scale incompatible with naïve-estimate for accretion/viscous timescale
  - (Assuming that accretion is driven by magnetized turbulence ☺)

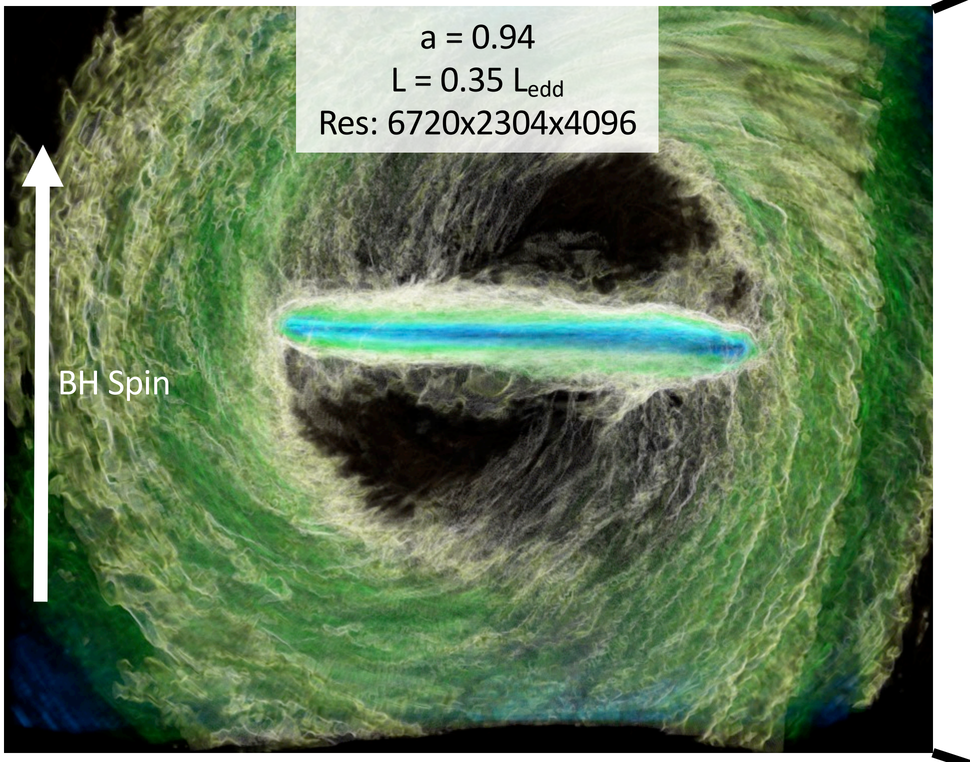


Credit: Green et al 2022

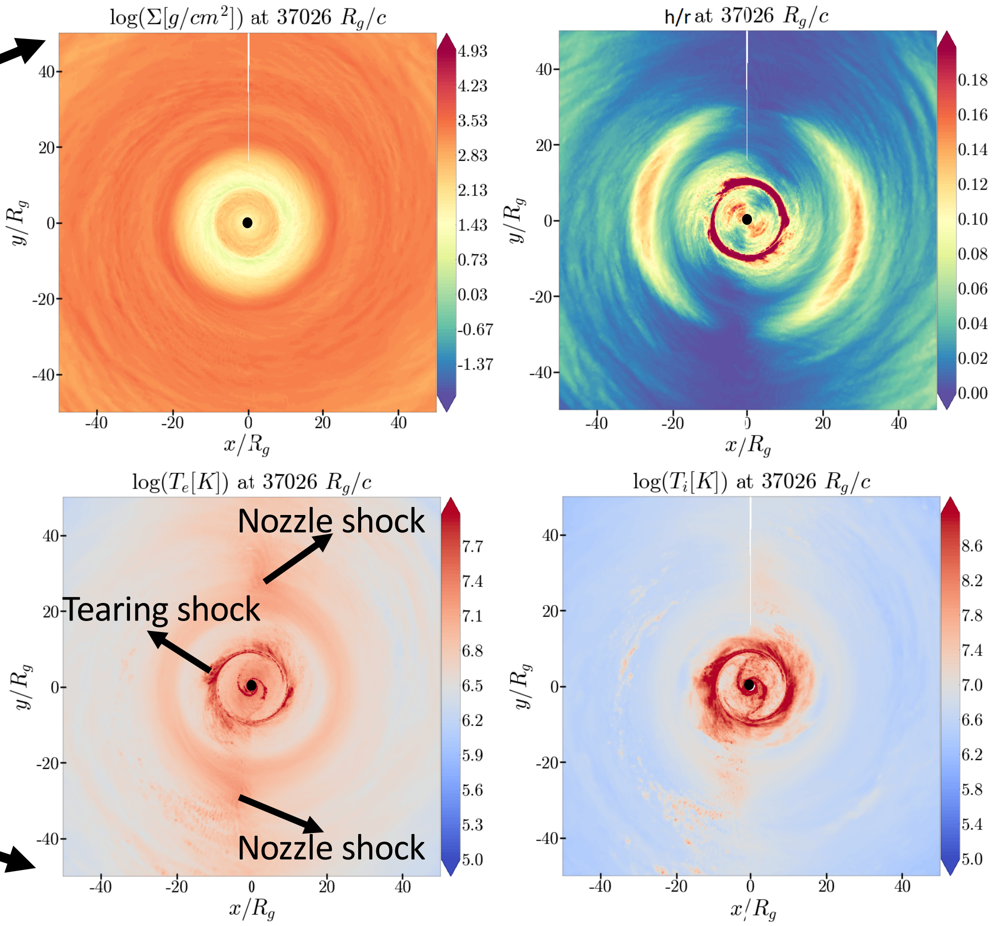
Shock formation in tilted luminous accretion disks

- First radiative 2T GRMHD simulation of a *tilted* disk radiating at L~0.35 L_{edd} (**Liska**, Kaaz et al 2022)
  - First demonstration of shock heated gas in luminous accretion disks in high-soft state
- Shocks don't only lead to a different emission pattern, but also change how disks accrete
  - See next slide

Volume rendering



Vertical projection

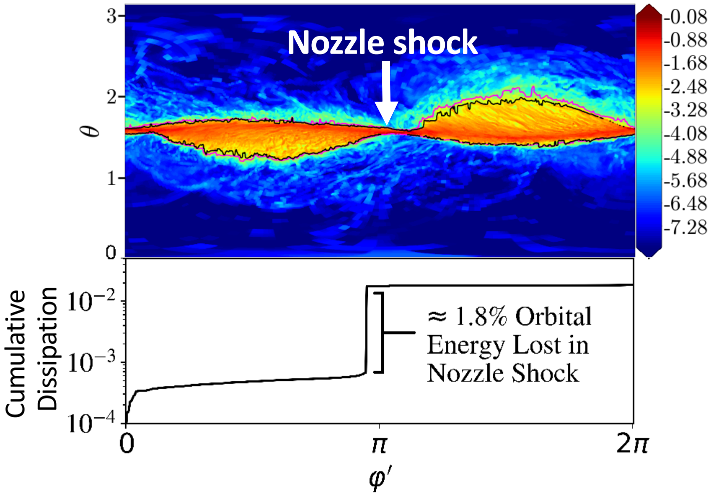


Nozzle shocks drive accretion (with Nick Kaaz)

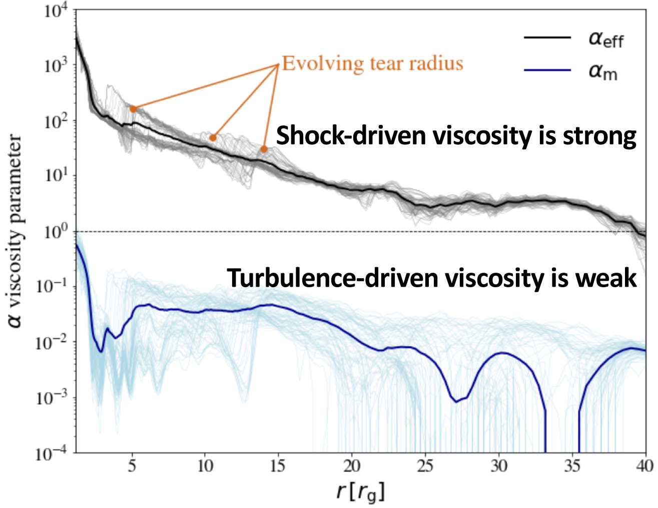
- Nozzle shock drives rapid (and variable) accretion (Kaaz, **Liska** et al 2023)
  - Challenges 30 year old paradigm of magnetized turbulence (MRI) driven accretion
  - Observed variability consistent with luminosity swings in (changing-look) AGN

Nick Kaaz
Graduate student
Northwestern U.

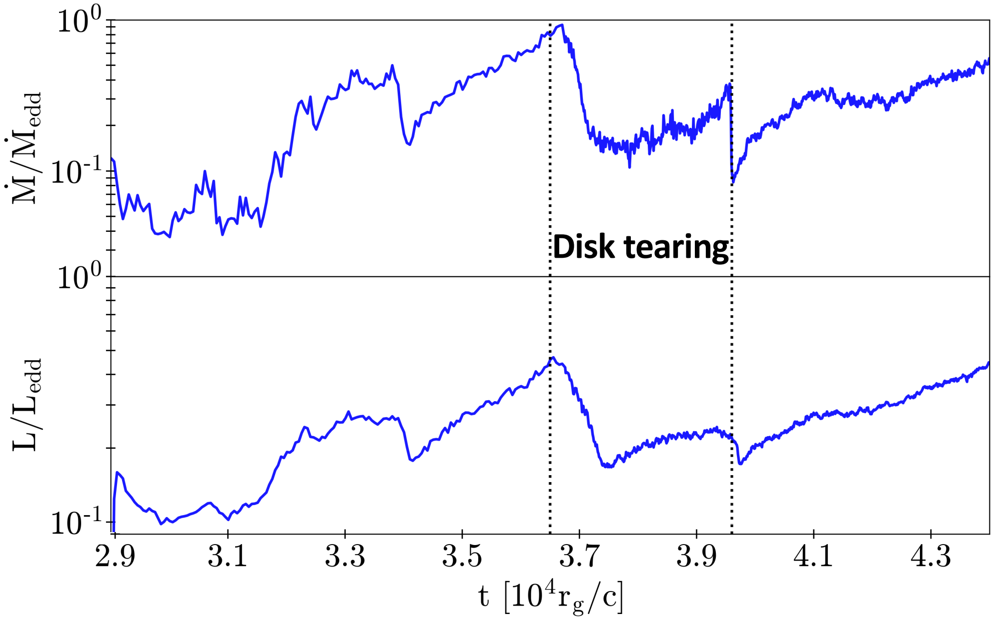
Azimuthal slice of log(ρ) at r=10 r_g



Viscosity is driven by the nozzle shock

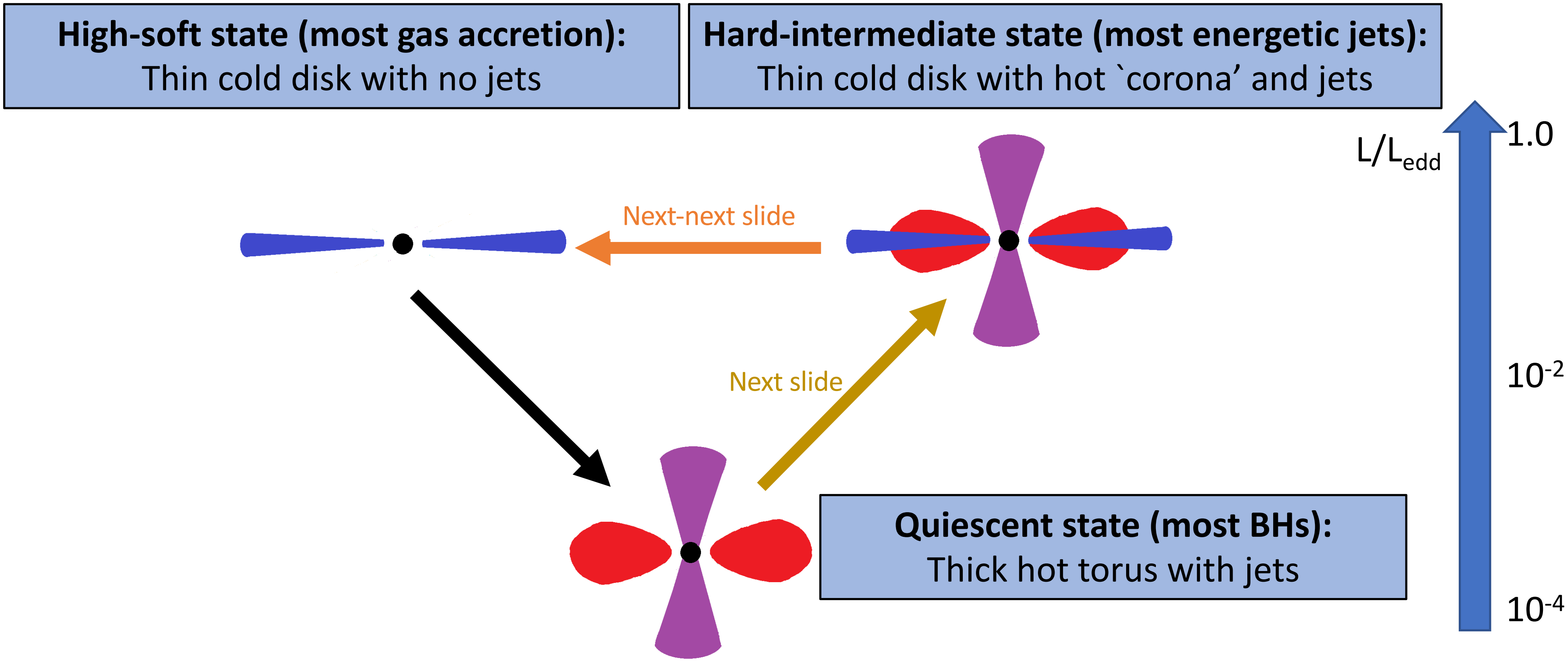


Factor ~5-30 variability in accretion rate and luminosity



Next step: Simulating *transitions* between states

- Simulated all spectral states (quiescent, HIMS, and HSS) successfully with H-AMR
  - Transitions between states still poorly understood (e.g. what drives them)



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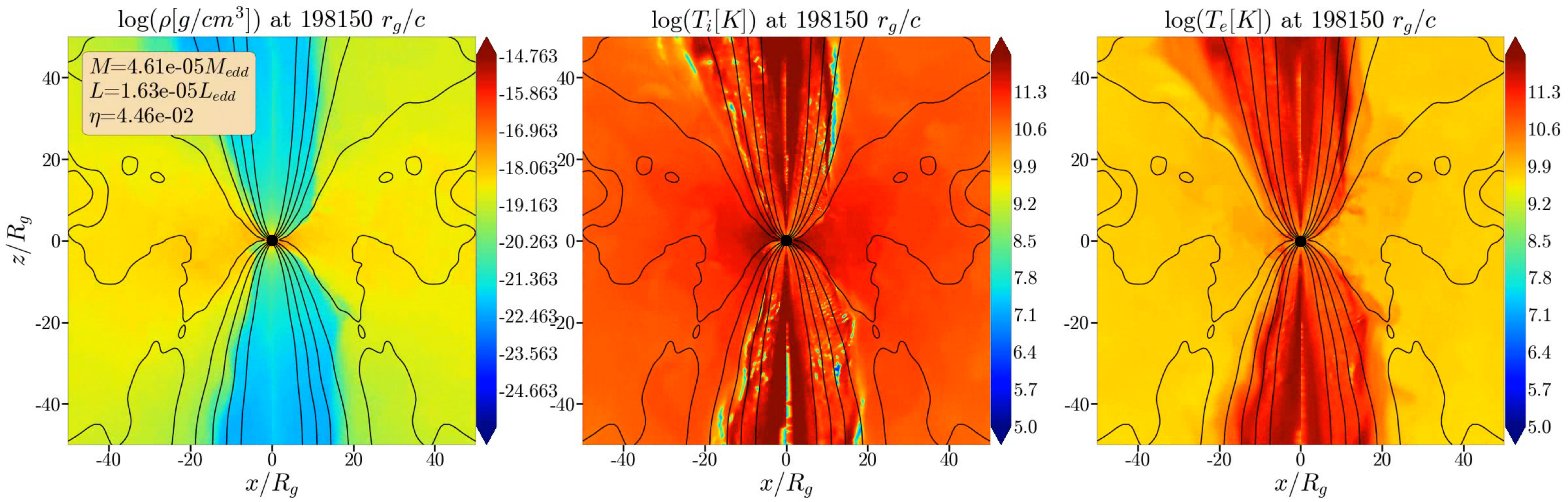
Computational cost	1	10^3-10^5	10^3-10^5
Physical understanding	Very good	Basic	Basic

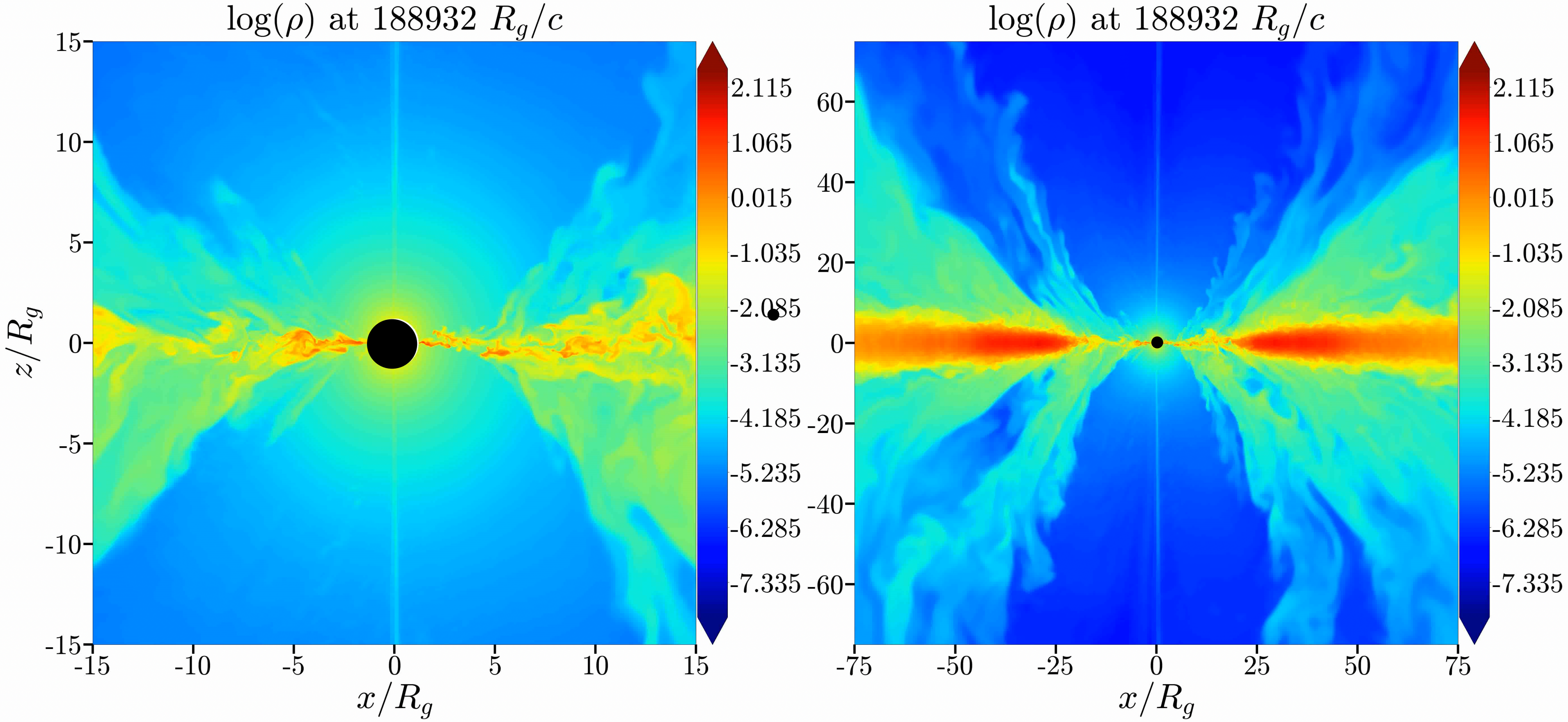
Next step: Simulating *transitions* between states

- First radiative GRMHD simulations of transition from quiescent state to HIMS
  - Demonstrates that torus collapses into a thin accretion disk (**Liska** et al 2024)
  - Structure of disk/corona depends on magnetic flux saturation



Next step: Simulating *transitions* between states

- First radiative GRMHD simulations of transition from HIMS to soft state
  - Demonstrates shrinking of truncation radius when magnetic flux is removed (**Liska** et al 2025 in prep)
  - Jet also becomes order(s) of magnitude weaker as magnetic flux declines



Summary

- Leap in understanding of black hole accretion across the luminosity spectrum
  - Disk tearing leads to disk and jet precession which might explain QPOs
  - Shocks drive accretion in luminous spectral states (challenges MRI-turbulence driven accretion)
- Future looks exciting
  - Fusion of H-AMR with GPU clusters such as FRONTIER will enable even more advanced simulations
  - Wealth of new observational data will provide powerful benchmark for numerical models