Title: GRMHD simulations of accretion disks: QPOs, truncated disks and QPOs from truncated disks

Speakers: Gibwa Musoke

Collection/Series: Magnetic Fields Around Compact Objects Workshop

Subject: Strong Gravity

Date: March 28, 2025 - 11:30 AM

URL: https://pirsa.org/25030122

Abstract:

Black hole X-ray binaries (BHXRBs) and Active Galactic Nuclei (AGN) transition through a series of accretion states in a well-defined order. The accretion states, each associated with different luminosities, spectral and variability characteristics, quasi periodic oscillations (QPOs) and outflow properties, are thought to be triggered by physical changes in the accretion disk around the central black hole.The mechanisms behind state transitions, the geometry of transitional disks and the physical mechanisms driving the emission characteristics we observe remain highly debated.

General relativistic magneto-hydrodynamic simulations (GRMHD) are increasingly providing crucial insights into the accretion process, the launch of outflows and the physical processes driving state transitions in BHXRBs and AGN. Using GRMHD simulations conducted with the H-AMR code I: 1) Discuss how high and low-frequency QPOs can be produced by a highly tilted, geometrically thin accretion disk. 2) Present the first GRMHD simulation showing the self-consistent formation of a truncated accretion disk– a proposed disk model for the hard intermediate accretion state, in which the accretion flow is thick and hot close to the black hole, while the outer regions of the flow are thin and cool. 3) Describe how QPOs can be generated at the truncation radius (the radius at which the disk transitions from thick to thin) in a truncated accretion disk.

Event Horizon Telescope

GRMHD simulations of accretion disks: QPOs, truncated disks and QPOs from truncated disks

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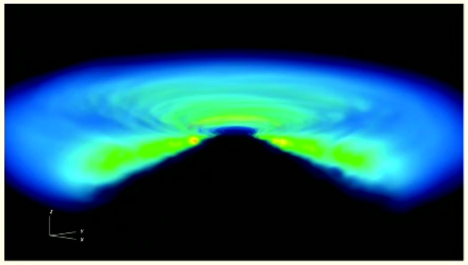
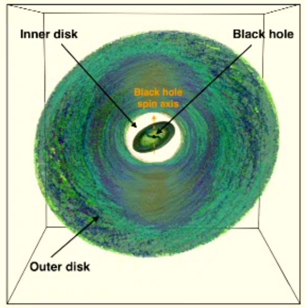
1. University of Amsterdam, **2.** Georgia Tech, **3.** Canadian Institute for Theoretical Astrophysics, **4.** University of Maryland, **5.** Northwestern University

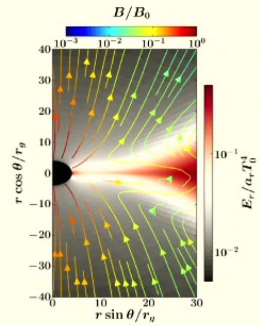
The rich phenomenology of accretion disk simulations



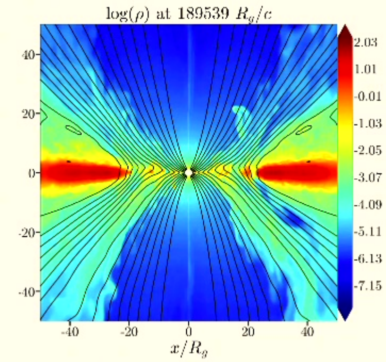
Thin disks
e.g. Teixeira, Fragile, Zhuravlev+, 2014



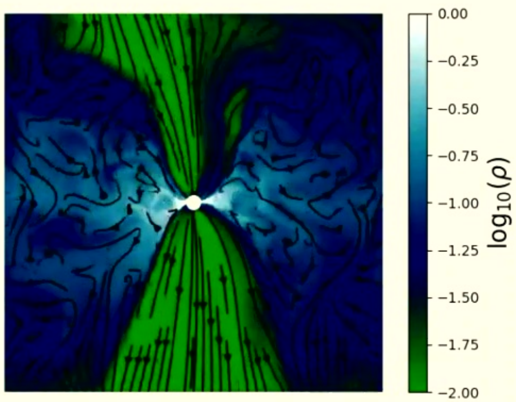
Tilted disks
e.g. Musoke, Liska, Porth+2023



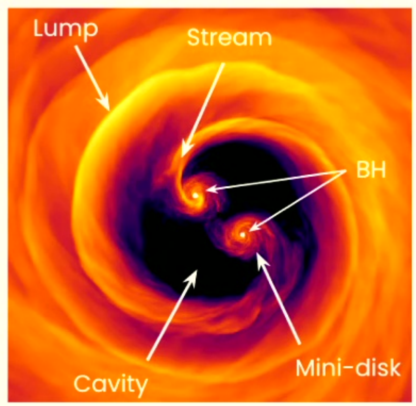
Magnetically elevated disks
e.g. Jiang, Blaes, Stone+, 2019



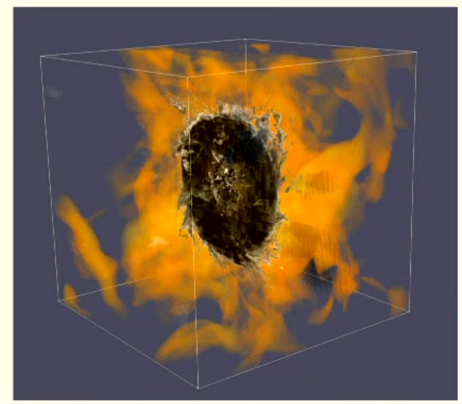
Truncated disks
e.g. Musoke, Porth, Liska+ (in prep), Bollimpalli+ 2024



Wind-fed disks
e.g. Ressler et al, 2020

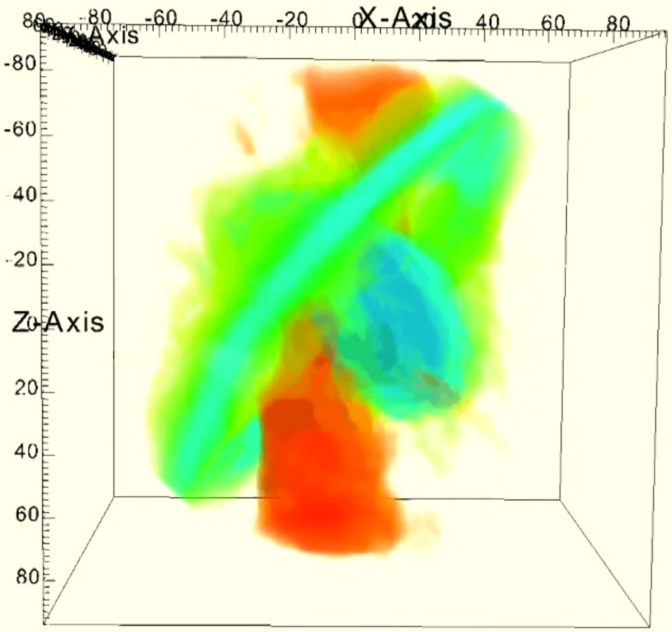


Accretion onto SMBH binaries
e.g. Gutiérrez, Combi, Ryan 2024, Gutiérrez, Combi, Noble+2022,Combi+ 2023

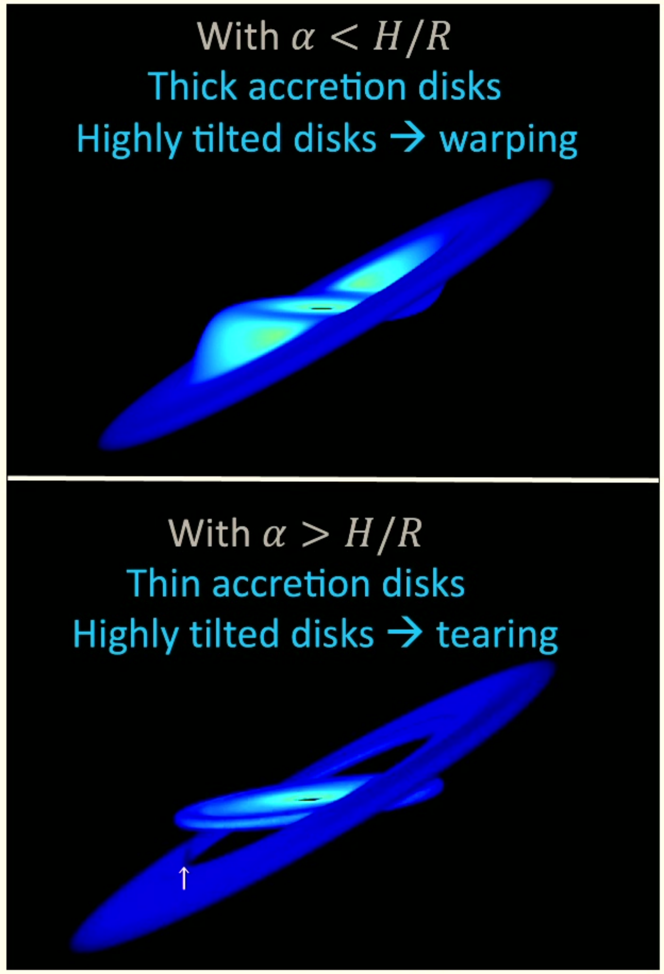


Multi-phase gas accretion
e.g. Solanki et al., 2020

The rich phenomenology of accretion disk simulations



Movie credit: M. Liska

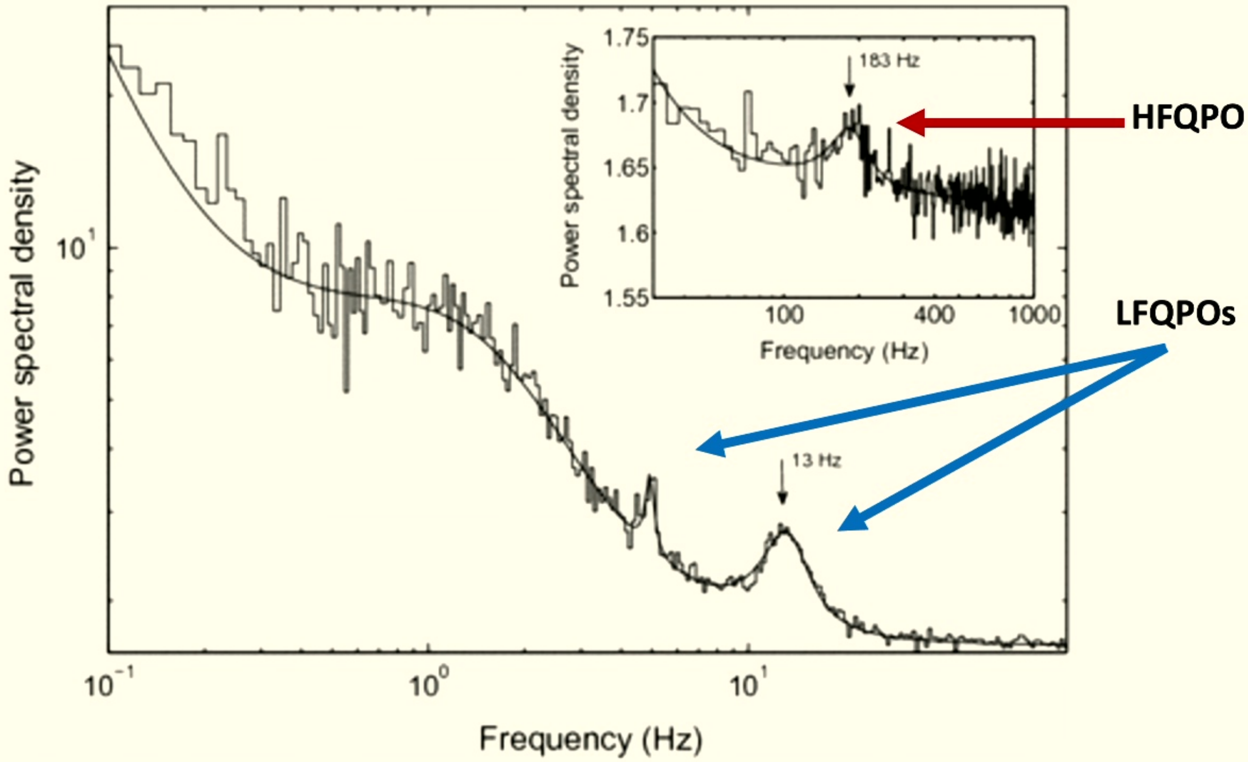


Lodato & Price 2010

Tilted disks may be associated with:

- Disk jet interactions
- Flares
- Warped/disturbed jets
- Accretion quenching
- Disk and jet precession
- Changing-look AGN
- **Quasi-periodic oscillations**

Quasi-periodic oscillations (QPOs) in BHXRBs



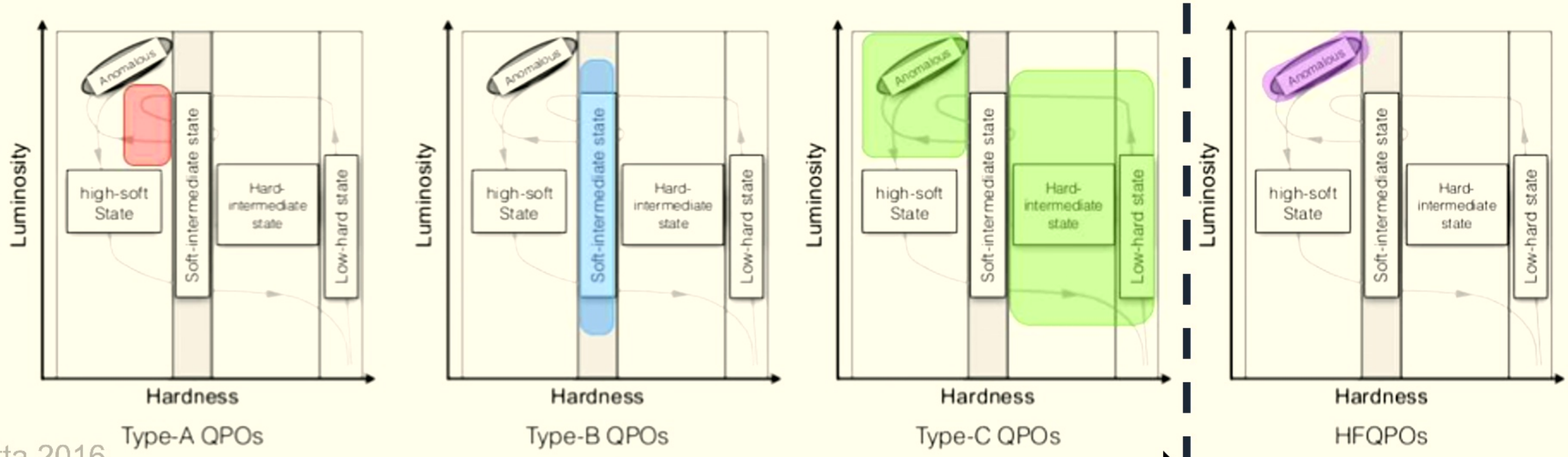
- LFQPOs: 0.1 - 30 Hz
- HFQPOs: > 30 Hz

Power density spectrum showing QPOs in XTE J1550-564 (Motta et al. 2018).

QPOs and spectral states in BHXRBs

LFQPOs

HFQPOs



lotta 2016

Origin:
Disk instabilities?

Origin:
Precession of jet base

Origin:
Disk precession
Instabilities (e.g. Accretion-ejection, Tagger & Pellat 1999, Varnière + 2002)

Origin:
Disk precession
Resonance
+ several more models…

(HF)QPO models

Can be broadly divided into two classes:

Intrinsic models

Changing mass accretion rate

e.g. Tagger & Pellat 1999

Shocks

e.g. Chakrabarti et al .2005, Tagger & Pellat 1999, Okuda et al. 2008

Resonance modes

e.g. Abramowicz & Kluzniak 2001, Kluzniak & Abramowicz 2002, Remillard et al. 2006, Kato2004, Kato 2008 Belloni & Stella2014

Discoseismic oscillations

e.g. Okazaki, Kato & Fukue 1987, Nowak & Wagoner 1991, Kato 2001, Dewberry et al. 2020.

Geometric models

Relativistic precession model

e.g. Stella & Vietri 1998, Stella, Vietri & Morsink 1999; Motta et al. 2014. Ingram & Motta 2014. Fragile+ 2007.

Bardeen-Petterson alignment

e.g. Fragile et al 2001

Tilted disks

e.g. Fragile 2001, Fragile & Anninos 2005, Lodato & Price 2010, Nixon et al. 2012, Raj & Nixon 2021. Liska+2019, Musoke+2023, Bollimpalli+2024

Tilted disks and QPOs

Code:

H-AMR (Liska+ 2019)

Numerical setup:

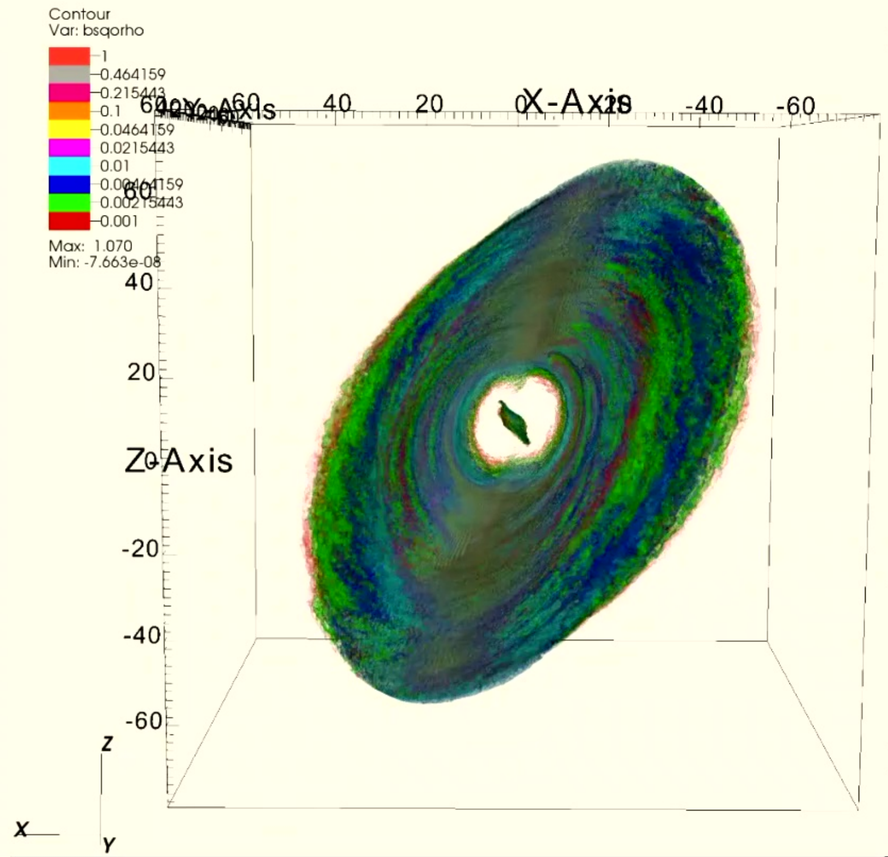
- 3D GRMHD
- Thin accretion flow (h/r = 0.02)
- BH spin a = 0.94
- Tilt = 65°
- B field: Toroidal (β = 10)
- Evolution time: 140,000 r_g/c

Grid:

- Effective resolution: 13440 x 4608 x 8096 cells
- AMR + LAT

Cluster:

OCLF Summit (70 million core hours)

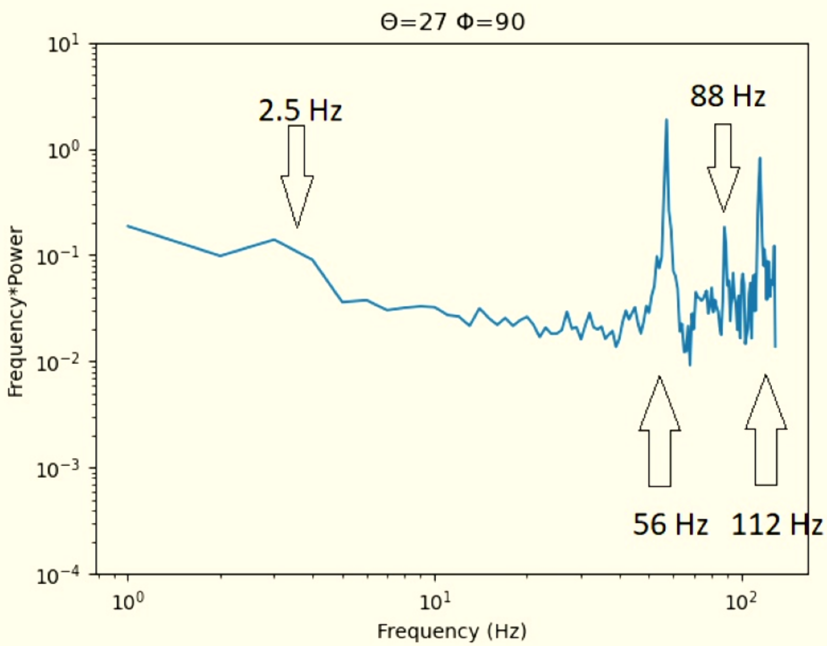


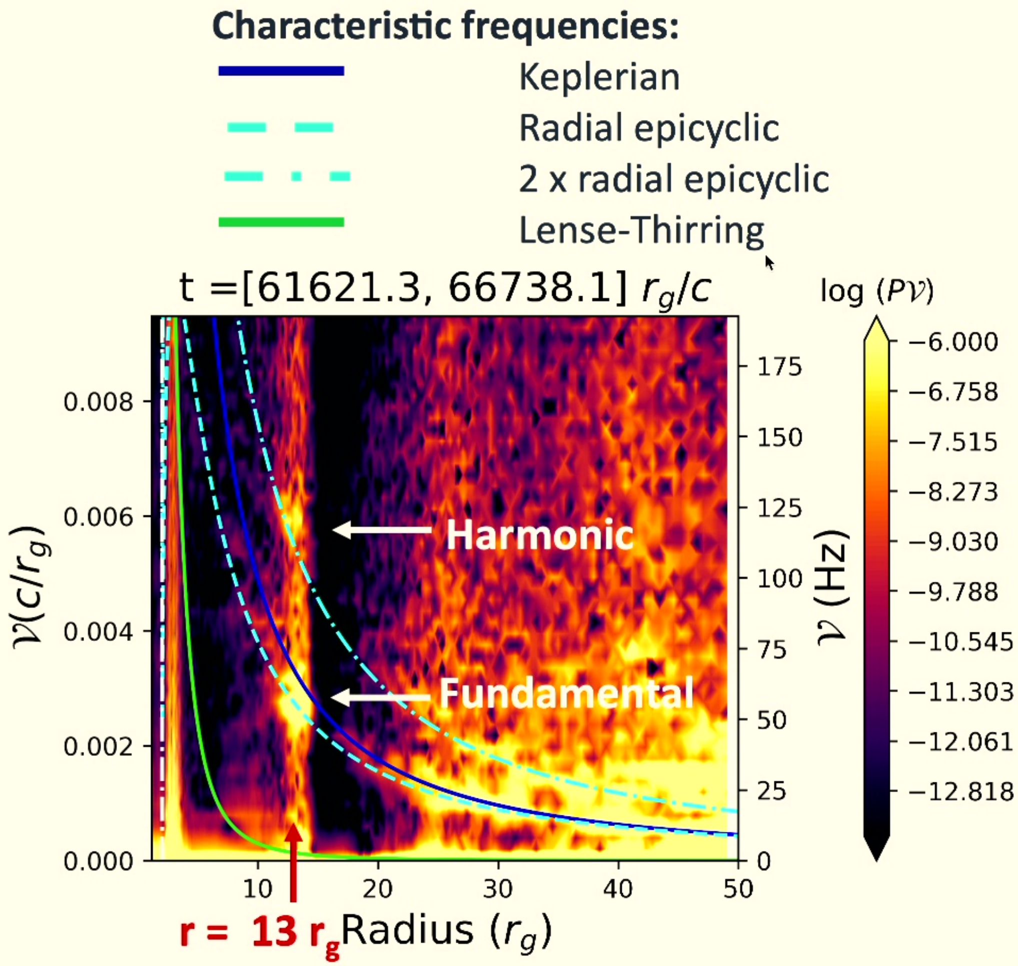
Liska, Chatterjee, Tchekhovskoy+, 2019

Musoke, Liska, Porth+, 2023

West, Liska, Musoke+, in prep

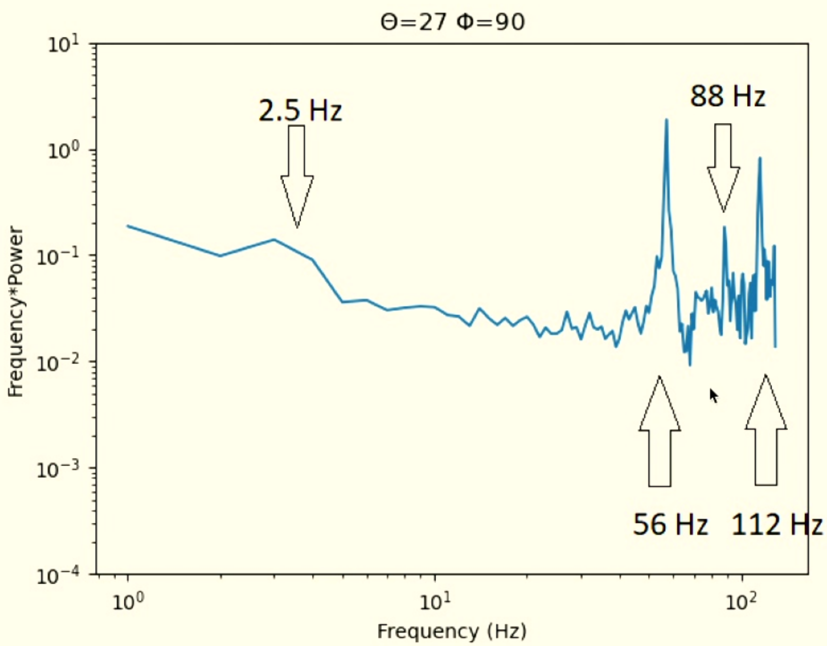
Tilted disks and QPOs





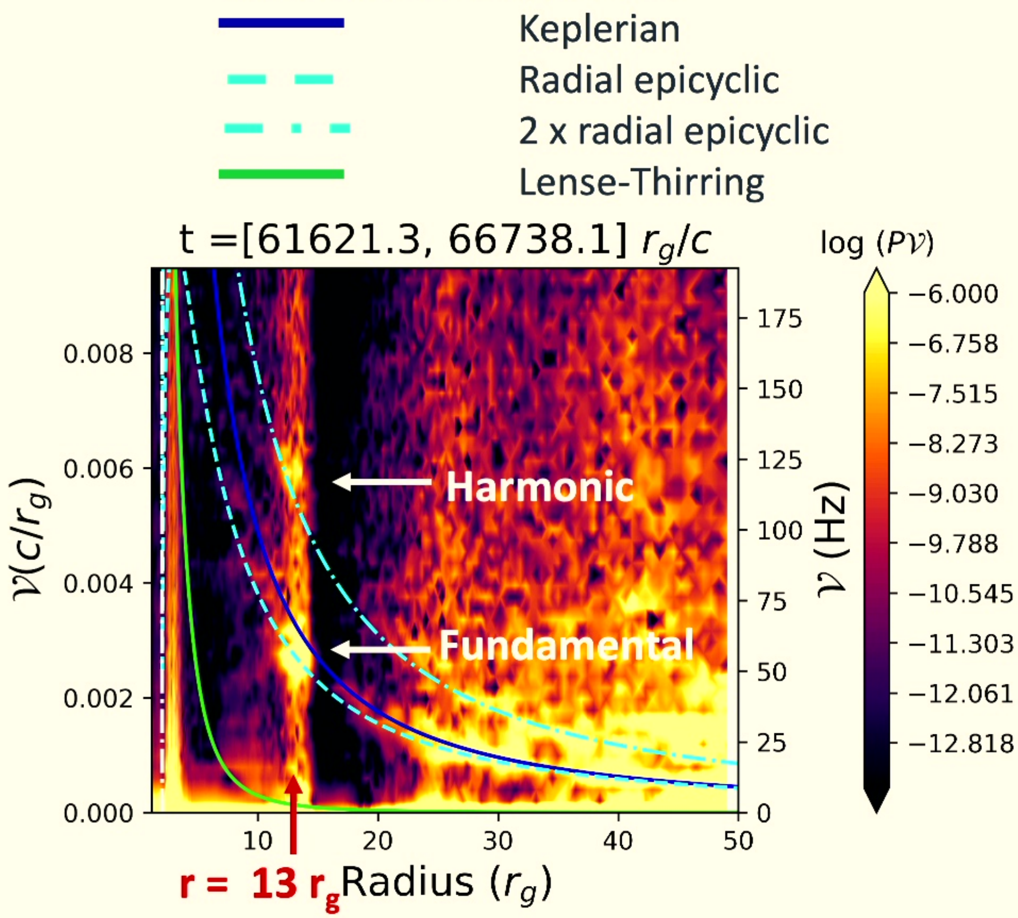
Musoke, Liska, Porth+ 2023

Tilted disks and QPOs



West, Liska, Musoke+, Nature (in prep.)

Characteristic frequencies:

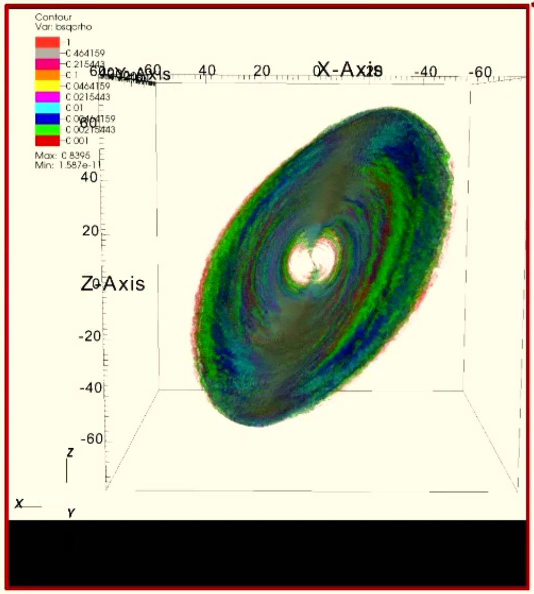


Musoke, Liska, Porth+ 2023

Frist detection of HFQPOs in a 3D turbulence resolving GRMHD simulation of BH accretion.

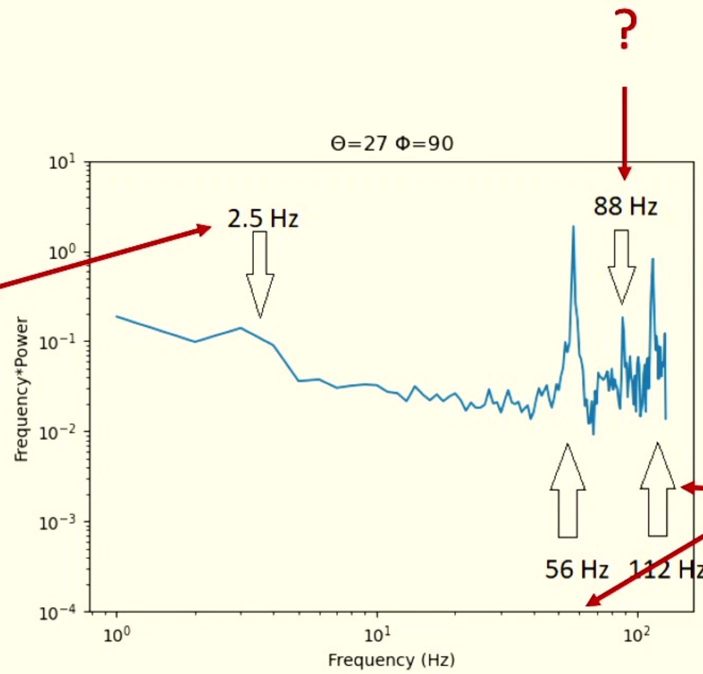
How are the QPOs produced?

Disk precession



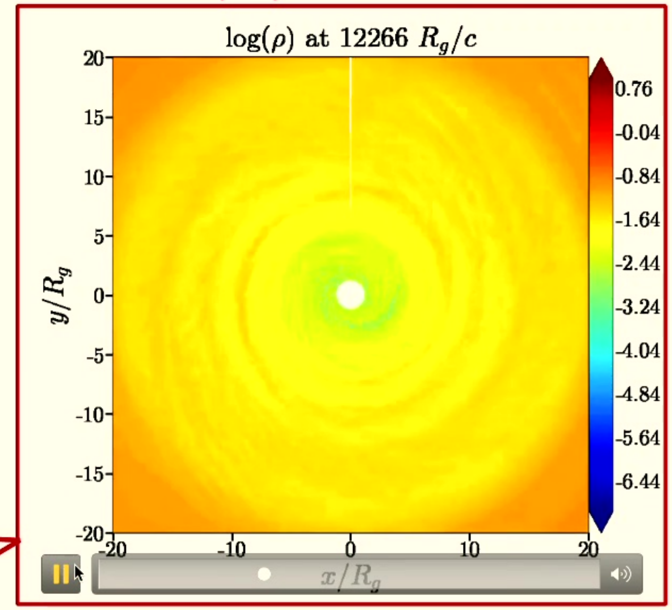
Liska+ inc. Musoke 2019

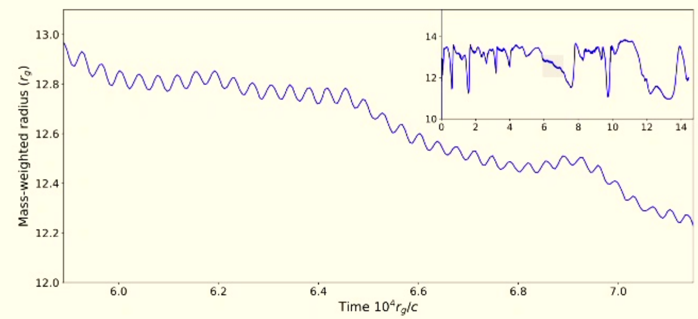
Musoke, Liska, Porth+, 2023



West, Liska, Musoke+, Nature (in prep.)

Radial epicyclic oscillations



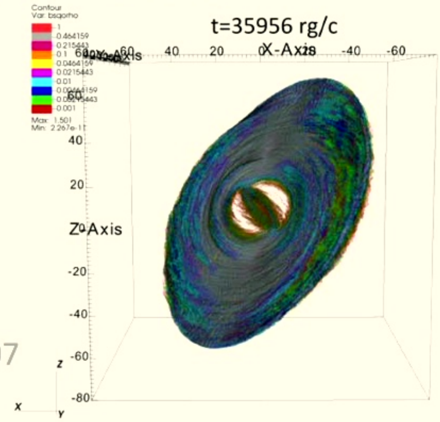


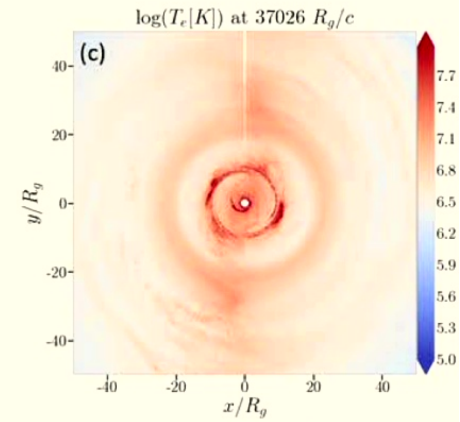
Musoke, Liska, Porth+ 2023

QPOs from tilted, warped and truncated disks

GRMHD and radiative GRMHD simulations support the theories that QPOs can be produced by:

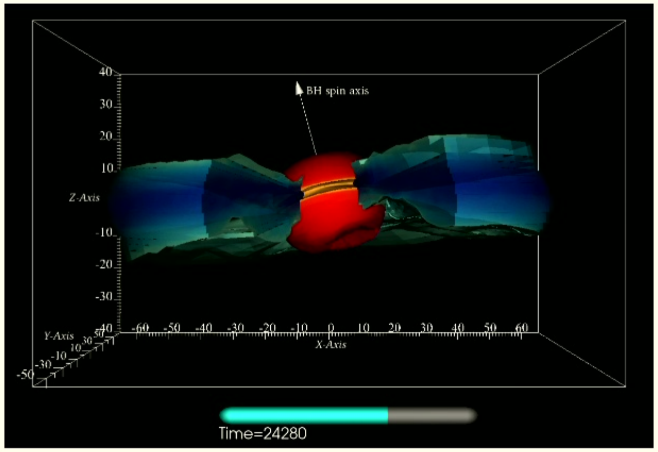
- Disk precession of hot inner flow → LFQPOs
  e.g. Stella & Vietri 1998, Motta+ 2014. Ingram & Motta 2014. Fragile+ 2007
- Radial epicyclic oscillations → HFQPOs
  (Thin tilted disks e.g. Musoke+ 2023, Liska,Kaaz+ 2024)
- Vertical epicyclic oscillations → HFQPOs
  (Truncated disks, e.g. Bollimpalli+ 2024)
- Trapped modes → HFQPOs
  (e.g. Dewberry+ 2020, Latter & Ogilvie 2018)



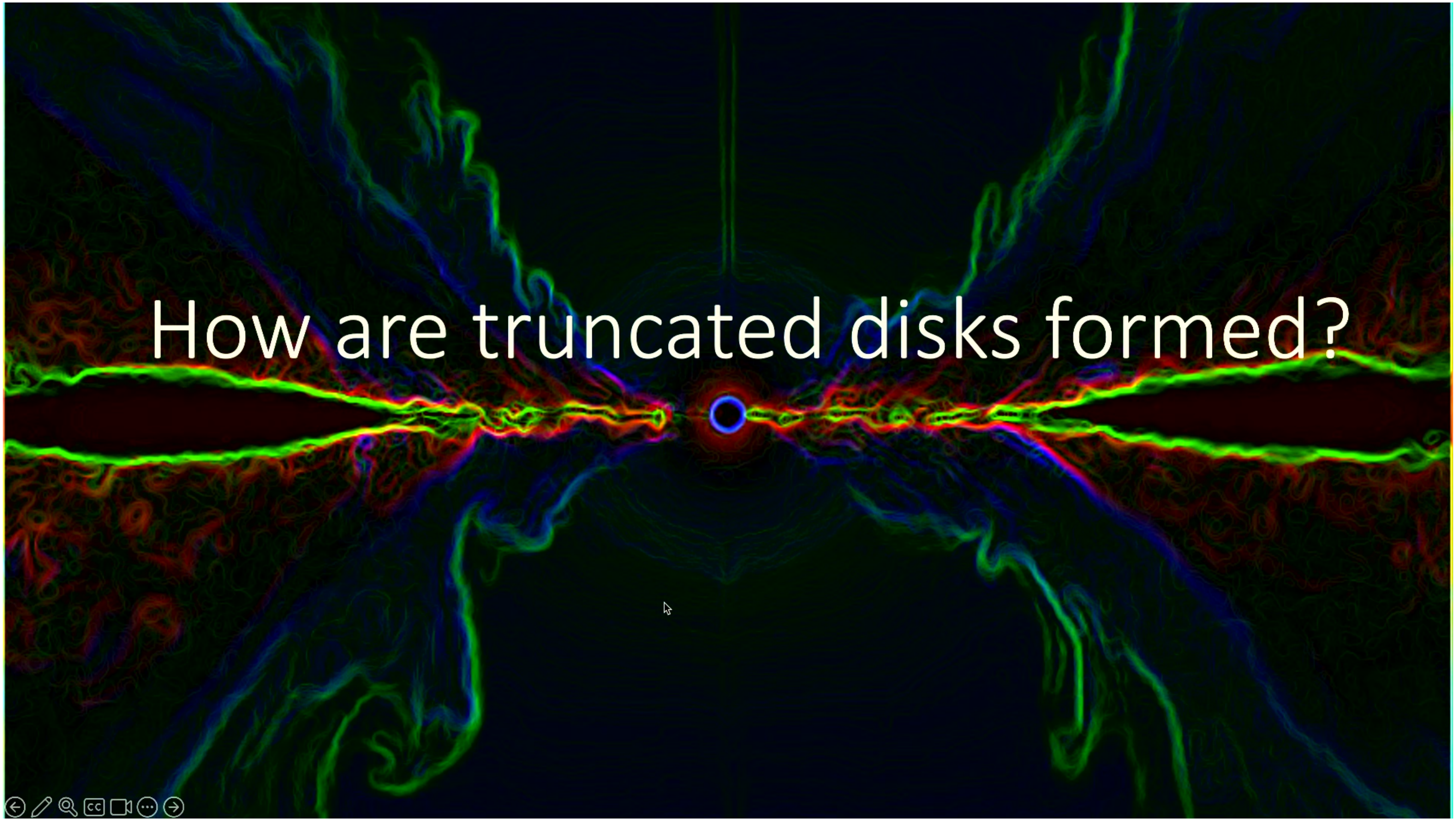


Liska, Kaaz+ (inc Musoke) 2024

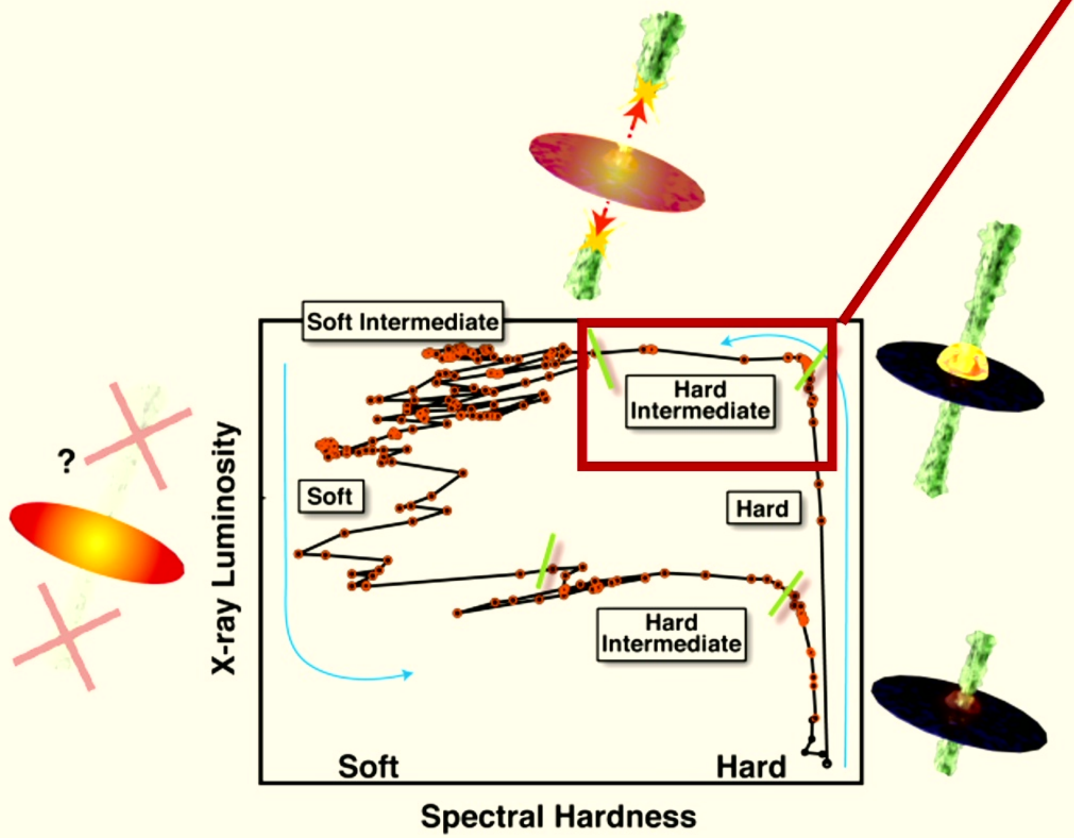
GRMHD and radiative GRMHD simulations are increasingly implying a connection between tilted disks and QPOs



Credit: D. Bollimpalli. GRMHD


How are truncated disks formed?

Truncated accretion disks



Belloni et al. 2010

geometrically thin, cool component

+

geometrically thick hot component
(the corona)

(e.g. see Remillard & McClintock 2006, Esin et al. 1997; Ferreira et al. 2006; Done et al. 2007; Marcel et al. 2018; Begelman & Armitage 2014)

Which mechanisms can generate a disk-corona stucture?
(e.g. Esin et al. 1997; Ferreira et al. 2006; Begelman & Armitage 2014)

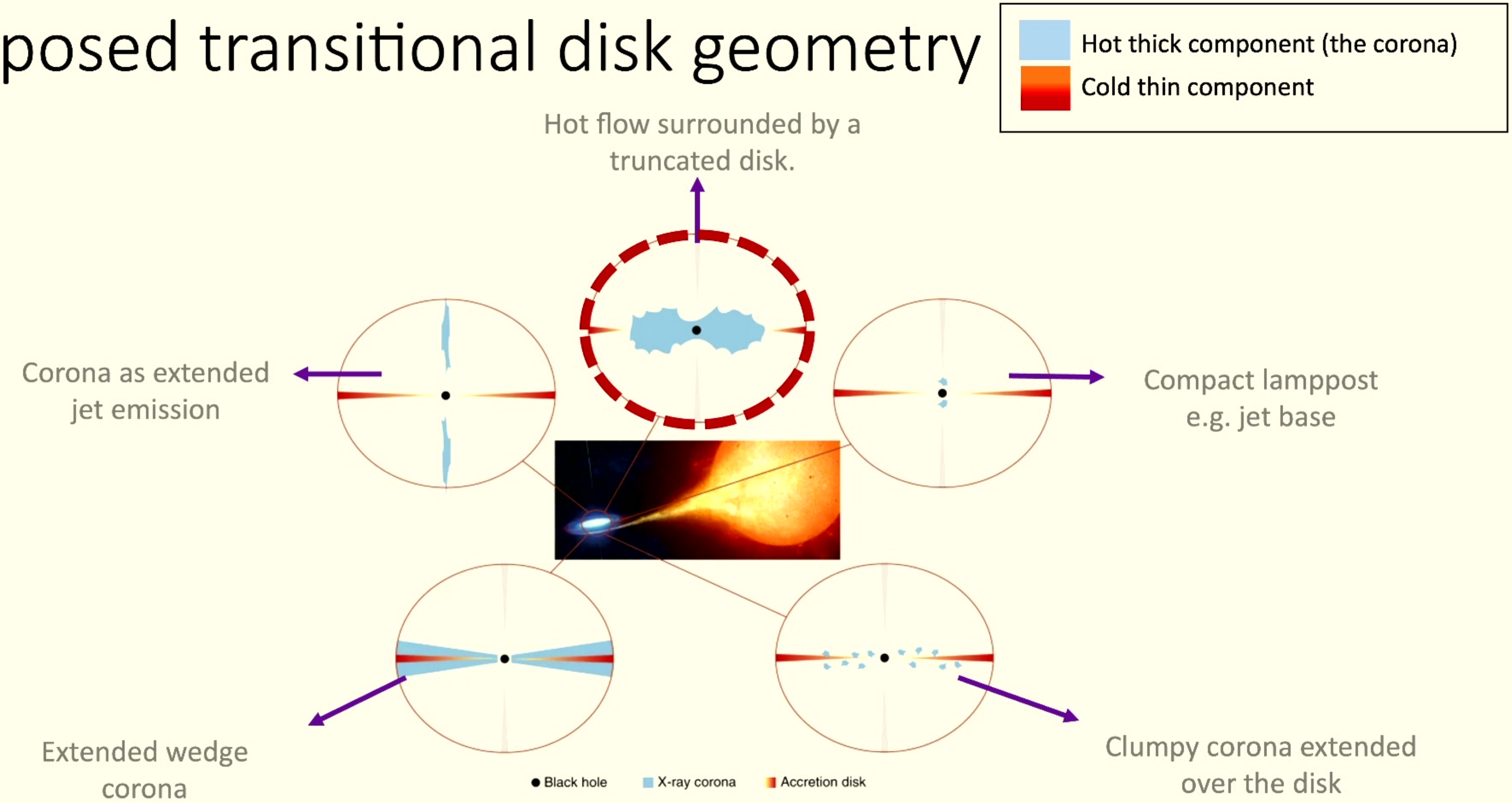
How is the corona formed?

How do truncated disks evolve and what sets the truncation radius?

Angular momentum and mgnetic flux transport in truncated disks?

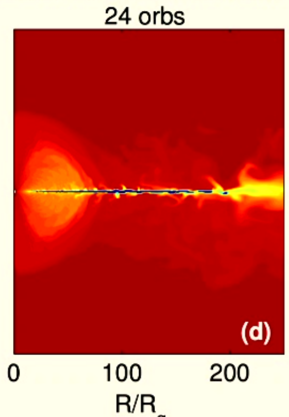
How does accretion proceed?

Proposed transitional disk geometry



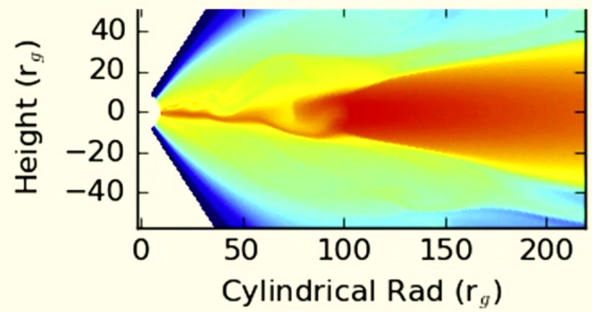
Recent simulations of transitional disks

Radiative HD simulations



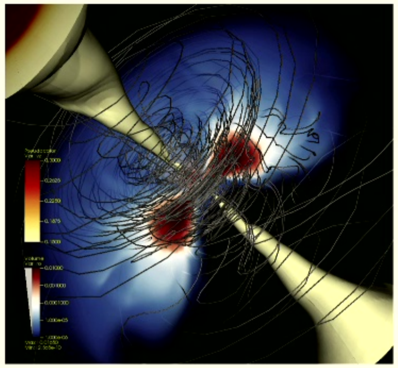
Das & Sharma 2013 (see also Wu+ 2016)

Viscous HD simulations



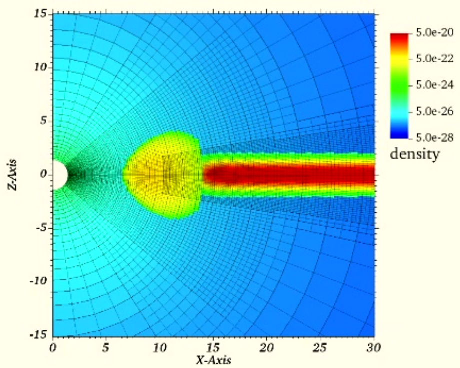
Hogg J. D., Reynolds C. S., 2017

GRRMHD simulations



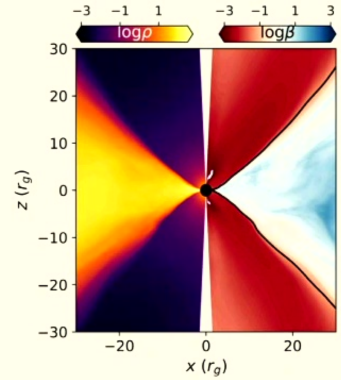
Takahashi + 2016

Truncated, Tilted Discs as a Possible Source of Quasi-Periodic Oscillations?



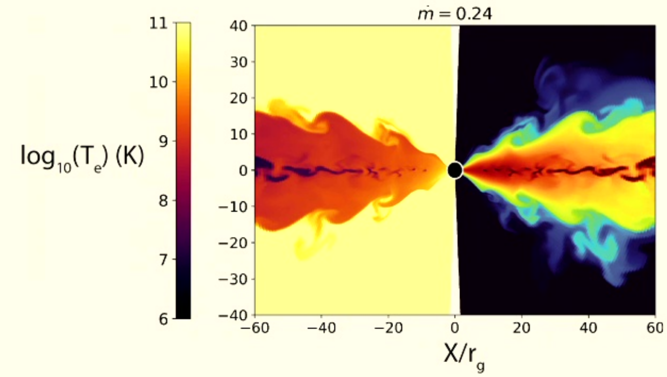
D. Bollimpalli C. Fragile,W. Dewberry, W. Kluźniak 2024
D. A. Bollimpalli, P. C. Fragile, W. Kluźniak 2022

GRRMHD Simulations of the collapse of a hot accretion flow



J. Dexter, N. Scepi, M. Begelman 2021
See also: Mishra+2016

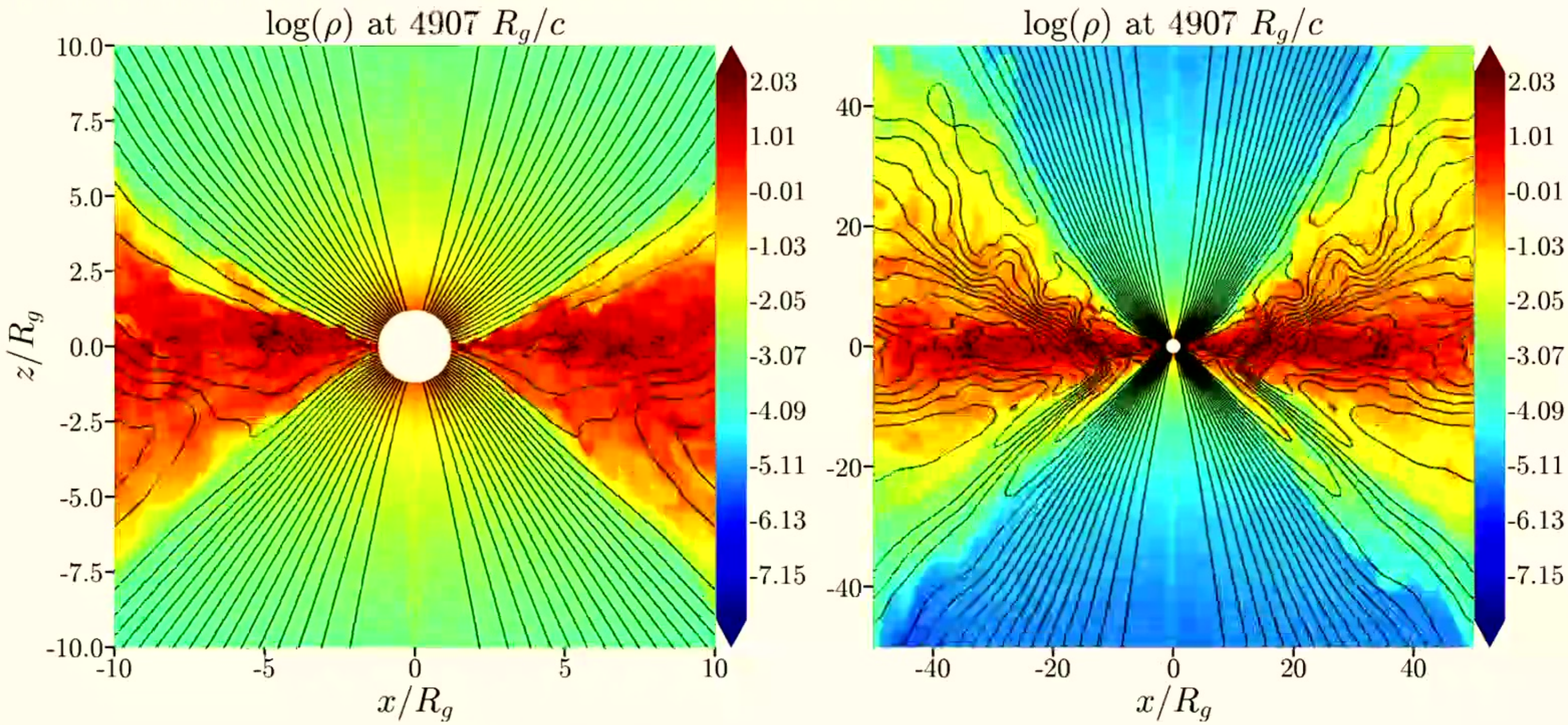
Viscous HD simulations of the corona and truncated disk



Nemmen, Vemado, Almeida+ 2023

Evolution: Thin to truncated disk structure

As disk collapses → Magnetic field threading BH leaks out → A magnetically truncated disk is formed!

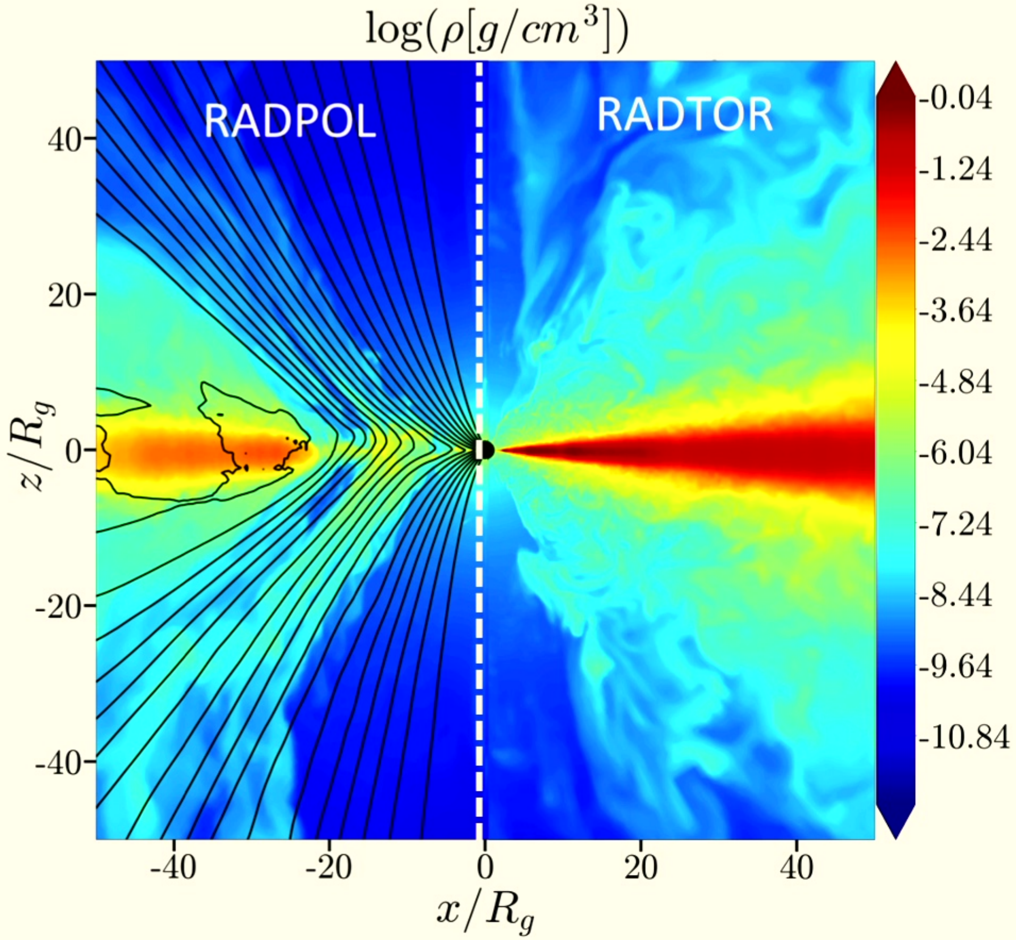


Musoke, Porth, Liska+ (in preparation)

Musoke, Ripperda, Philippov+ (in preparation)

Type of B field matters for truncation: Poloidal vs Toroidal B fields

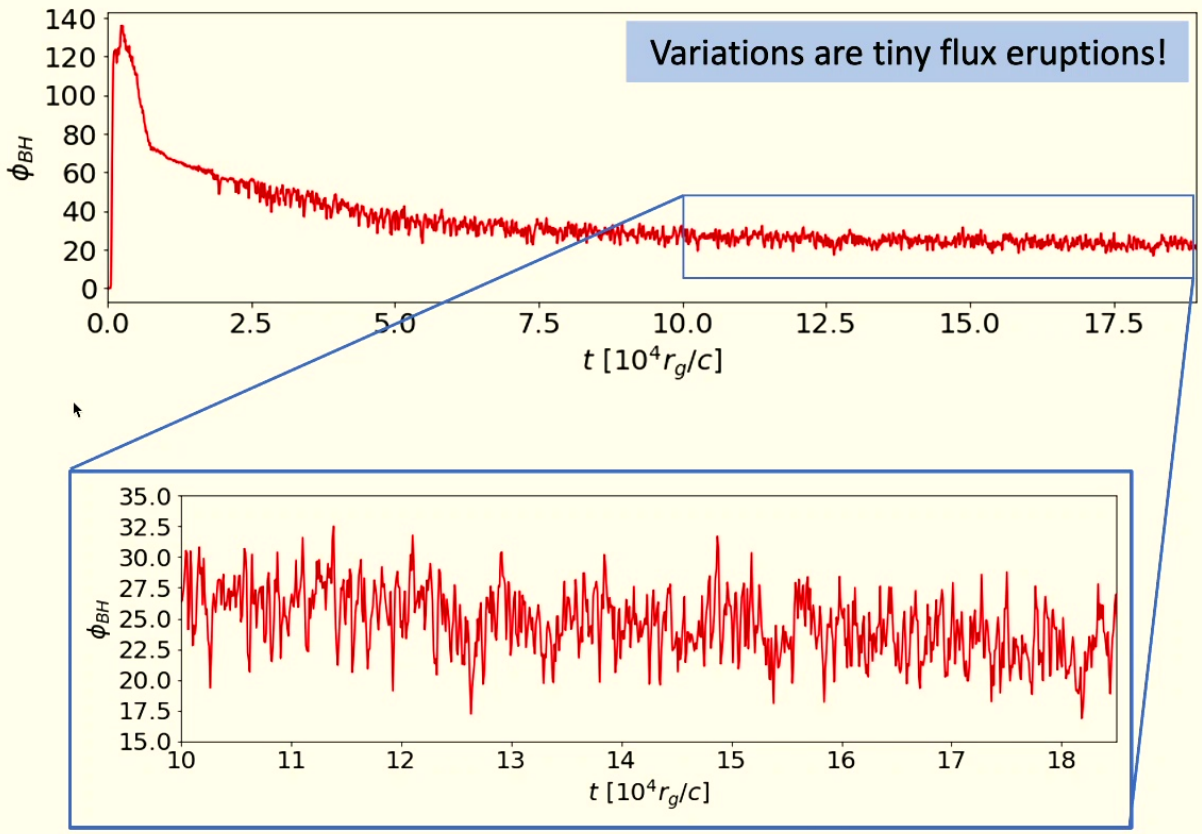
Poloidal B field
Large-scale poloidal B flux generated
Disk is truncated
Inner disk is MAD

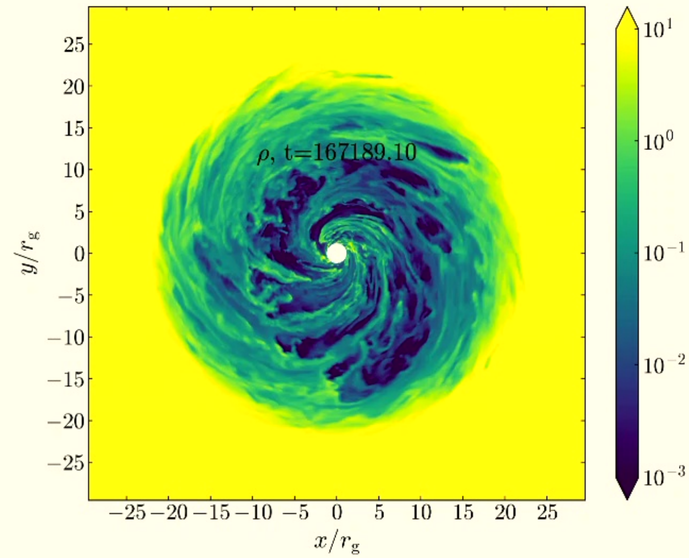


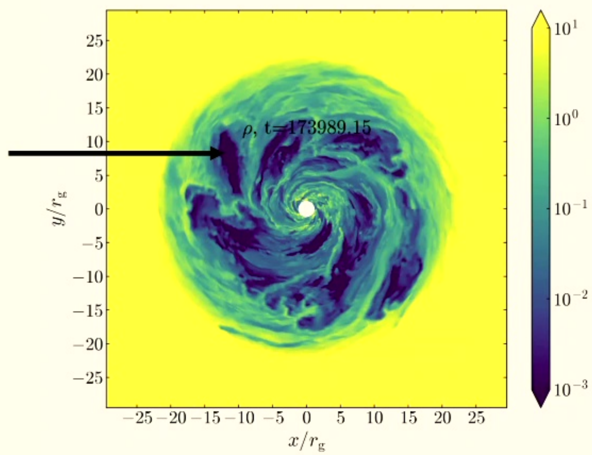
Liska, Musoke, Tchekhovskoy, Porth, Beloborodov 2022, ApJ

Toroidal B field
No large-scale poloidal B flux generated
Thin disk to ISCO
No disk truncation

Evolution of magnetic flux

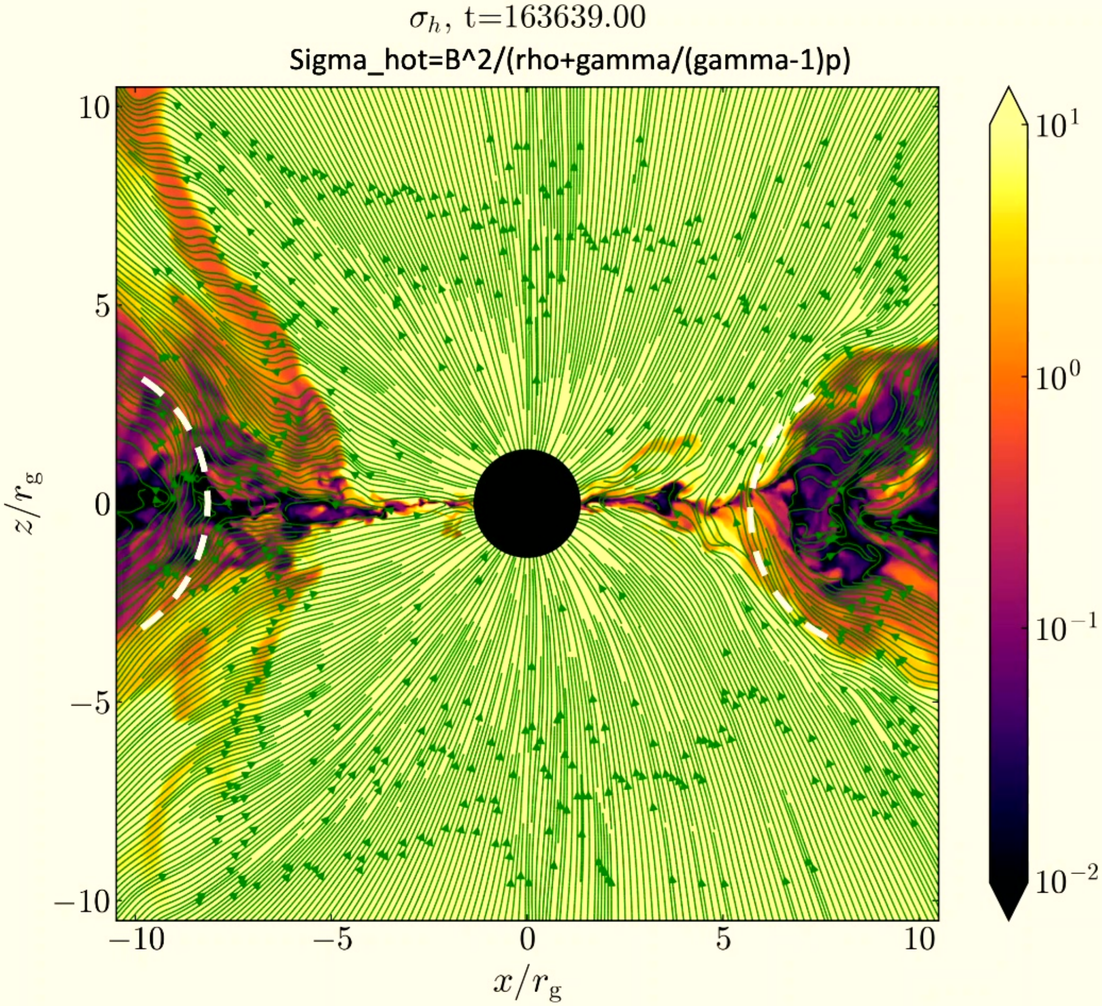






Musoke, Porth, Liska+ (in preparation)
Musoke, Ripperda, Philippov+ (in preparation)

How does magnetic truncation actually work?



Musoke, Ripperda, Philippov+ (in preparation)

Easy to onset reconnection

↓

Persistent magnetosphere

↓

Many flux eruptions

↓

Compressed B field region is formed by the compression of flux tubes

↓

Flux tubes bend around the thin disk in a 'C'- shape.

↓

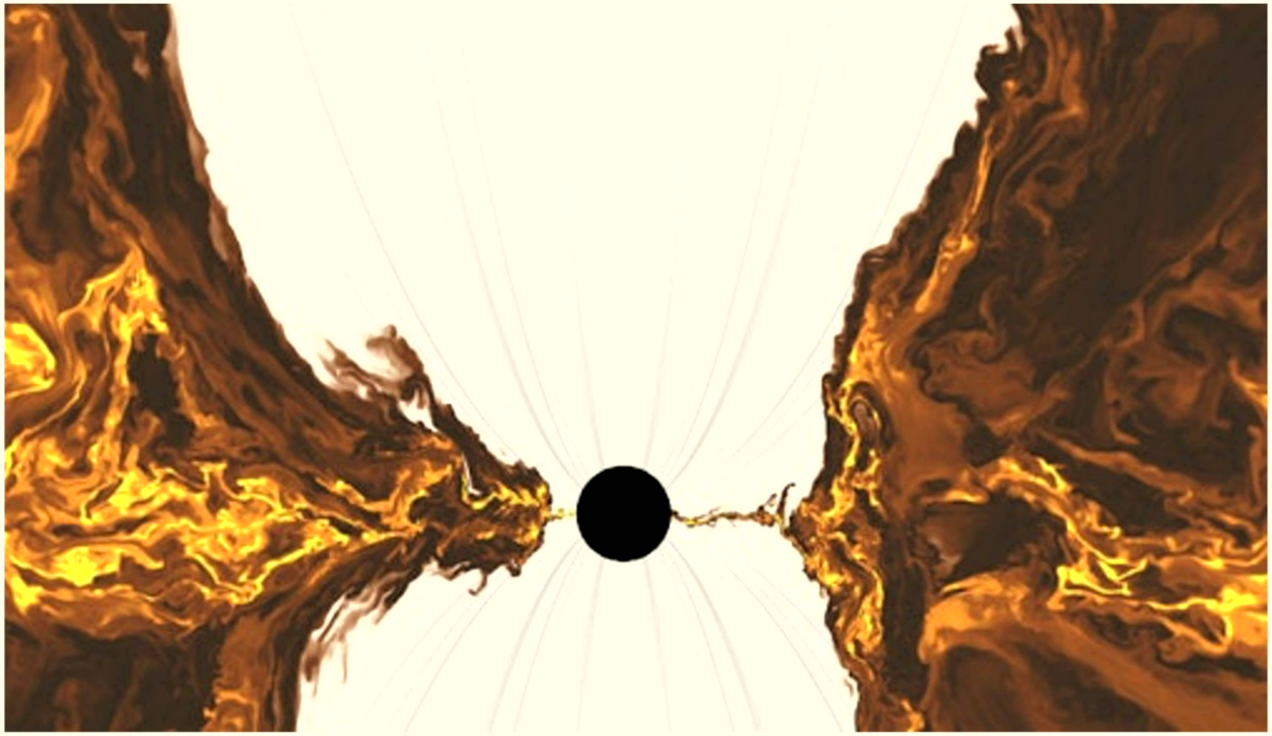
Flux tubes act as a barrier

↓

Material from thin disk can punch through compressed flux tubes via RTI

Truncation mechanism differs from most truncated models presented (e.g. Esin et al. 1997; Ferreira et al. 2006; Begelman & Armitage 2014)

Does a thick disk truncate?



Ripperda, Liska ,Chatterjee, Musoke+(2021)

Thick MAD disk case:

Very large flux eruptions

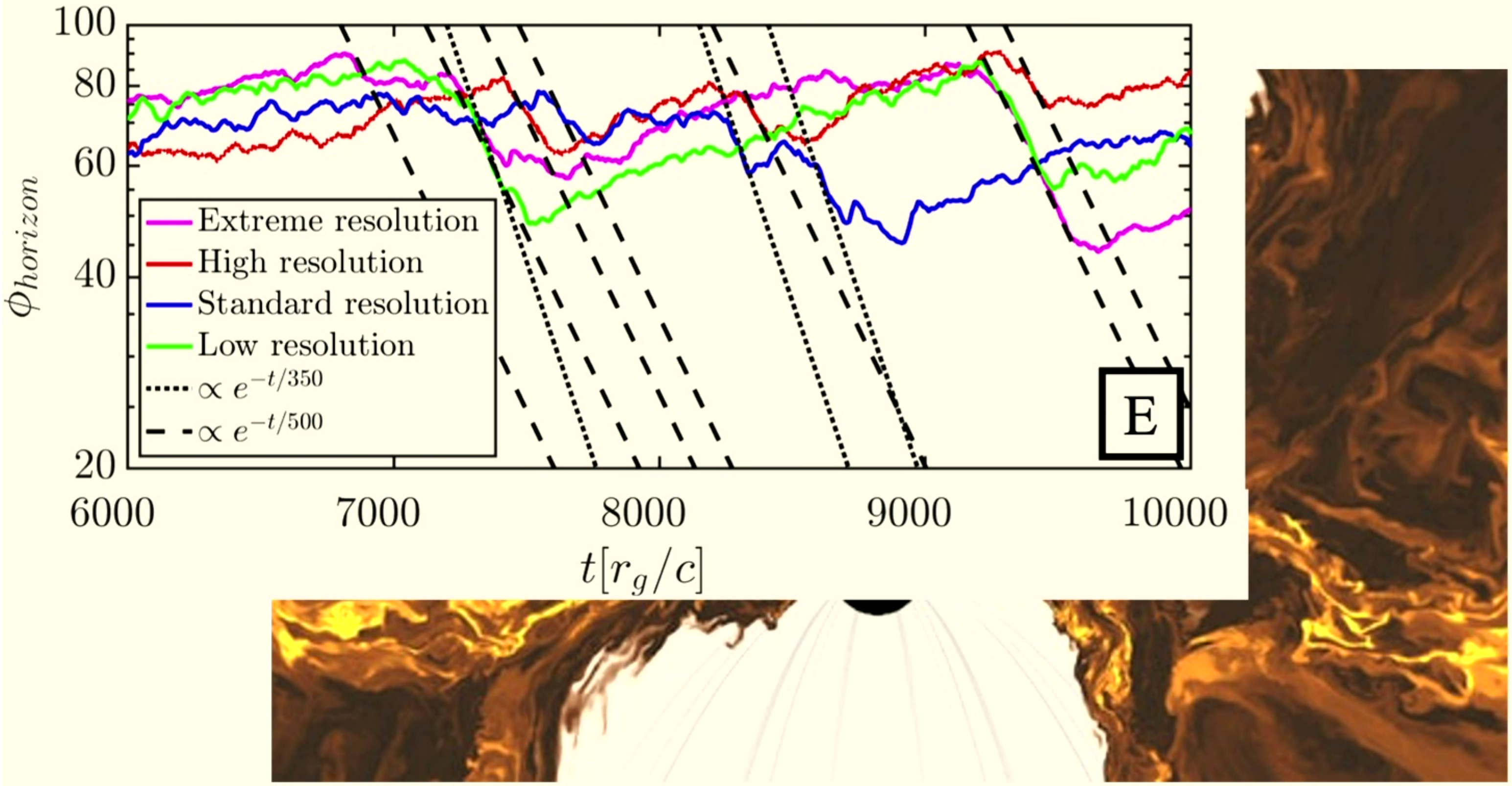
↓

Transient, non-axisymmetric current sheet within few inner r_g

↓

No persistent disk truncation

Does a thick disk truncate?



Ripperda, Liska ,Chatterjee, Musoke+(2021)

Thick MAD disk case:

Very large flux eruptions

↓

Transient, non-axisymmetric current sheet within few inner r_g

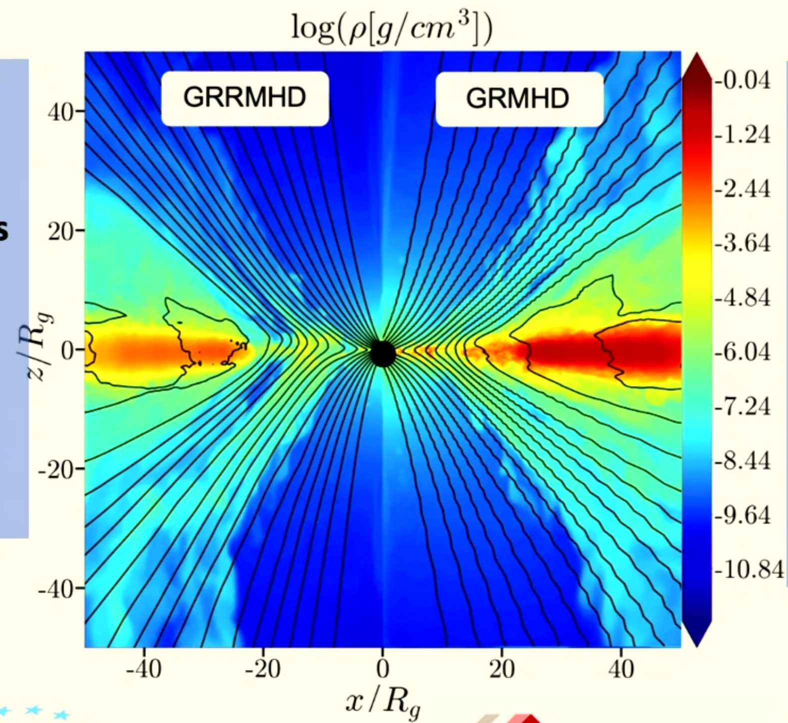
↓

No persistent disk truncation

Radiative GRMHD + 2T simulation

Radiative GRMHD simulation with 2T thermodynamics:
Liska, Musoke, Porth, Tchekhovskoy, Beloborodov, 2022 ApJ

Simulation specs:
Code: H-AMR
Cluster: JUWELS-Booster
Radiative GRMHD + 2T Thermodynamics
2T prescription: Rowan+ 2017
a = 0.94
B-field: Poloidal
Run time: +14,000 rg/c
Max resolution: 4080x1720x1152 cells
Radiation treatment: M1



Simulation specs:
Code: H-AMR
Cluster: Pizdaint
GRMHD (artificial cooling, (Noble et al. 2009**)**
H/R = 0.03
a = 0.94
B-field: Poloidal
Run time: 190,000 rg/c
Max resolution:3456x1720x1280 cells

Simulation scaled to a $10\ M_{sun}$ BH

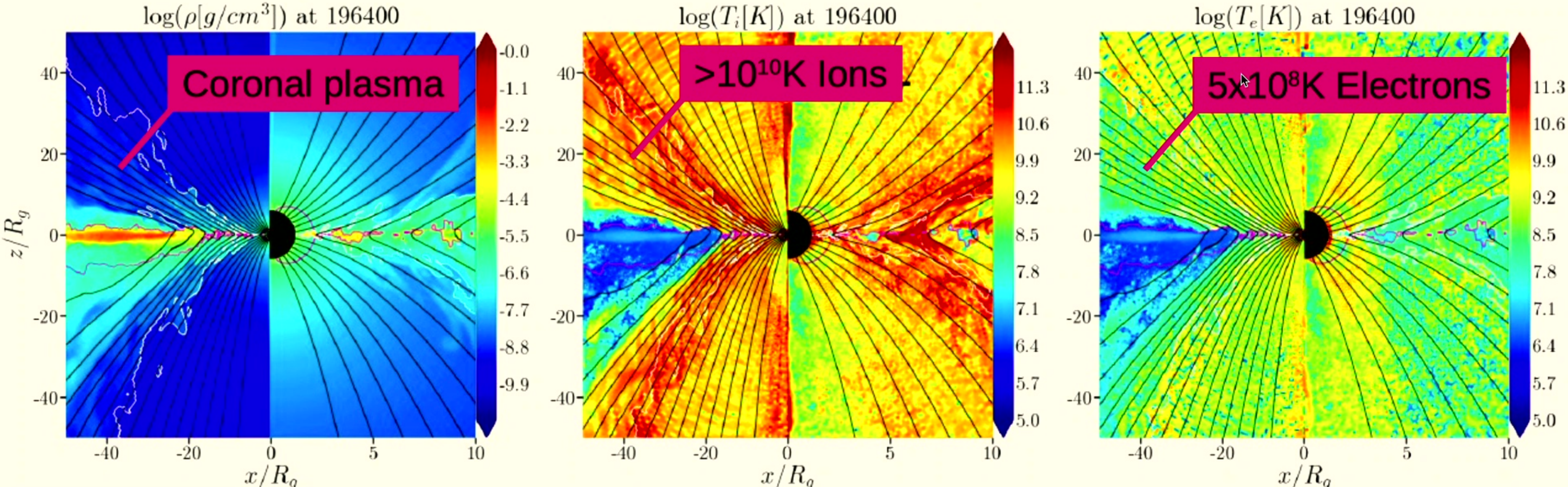
$$\dot{M}/\dot{M}_{\rm Edd} \simeq 0.35$$

PRACE JUWELS Booster CSCS PizDaint

For GRRMHD see also: Dexter, Nicolas Scepi, Begelman 2021, Liska, Musoke, Porth+ 2022, Drappeau,+2022, Abarca,+ 2018, Sądowski+ 2016, Ohsuga+2009, Ohsuga & Mineshige 2011, Sądowski+,2013, Sądowski+ 2014, McKinney+ 2014 Fragile, Olejar & Anninos 2014, McKinney+2014

Radiative GRMHD + 2T simulation

Density | Ion Temperature | Electron Temperature



- Disk threaded by large scale poloidal flux promotes 2T regions and truncation
- Develop low density, thick hot corona with $T_i > T_e$.
- Corona best described by radiative analogue of a MAD
- Corona flow has patches of cool gas floating through it.

Liska, Musoke, Tchekhovskoy, Porth, Beloborodov 2022, ApJ
Musoke, Ripperda, Philippov+ (in preparation)

Summary and Conclusions

Magnetically truncated accretion disks are a promising model for luminous radio quasars and hard-state XRBs.

- Truncation radius is determined by location of region dominated by poloidal B flux
- Constant flux eruptions and generation of flux tubes promote truncation.
- Cool patches of gas at corona midplane may explain broad iron line emission.

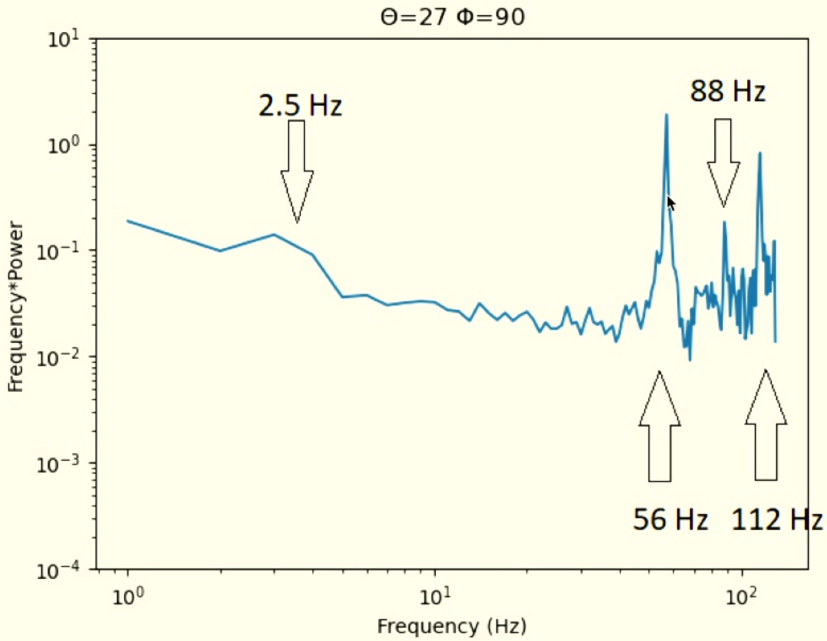
Connection between QPO production and tilted disks is being increasingly implied in GRMHD and radiative GRMHD simulations

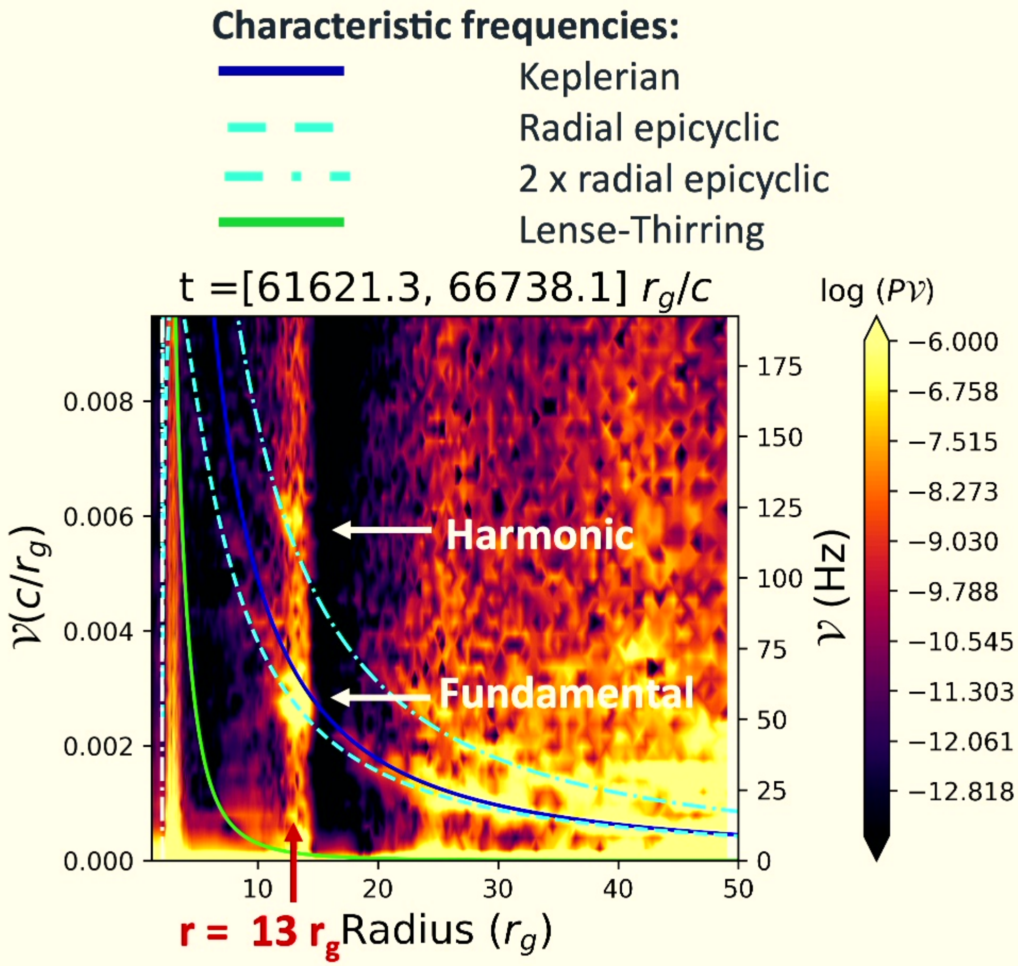
- Disk precession of hot inner flow → LFQPOs
- Radial epicyclic oscillations → HFQPOs
- Vertical epicyclic oscillations → HFQPOs
- Can simulations reproduce specific observed properties and variability of Type A,B and C QPOs?

GRMHD and radiative GRMHD simulations are allowing us to probe the physics of the corona- next steps:

- Longer duration simulations, incorporating more physics, improved sub-grid modelling, different accretion regimes/initialisation conditions/large-scale feeding?

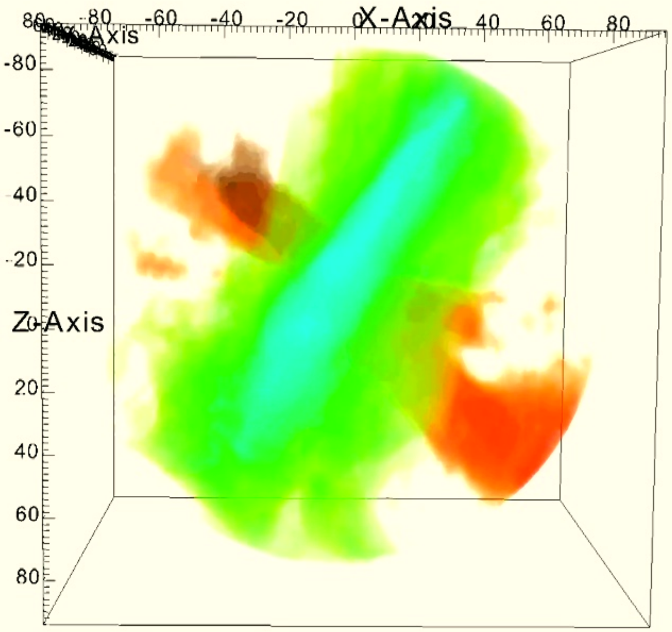
Tilted disks and QPOs



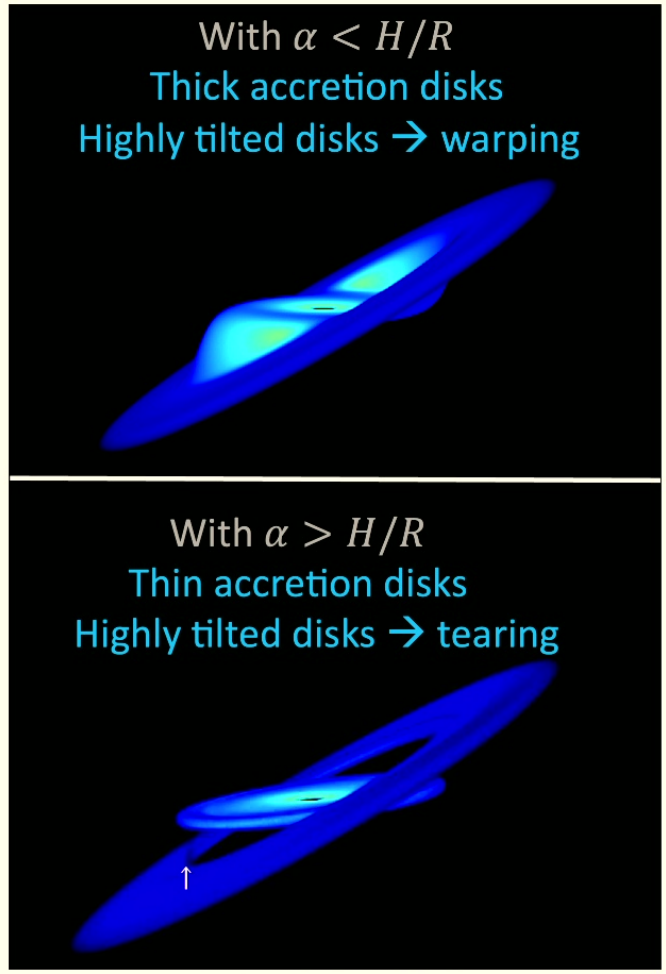


Musoke, Liska, Porth+ 2023

The rich phenomenology of accretion disk simulations



Movie credit: M. Liska



Lodato & Price 2010

Tilted disks may be associated with:

- Disk jet interactions
- Flares
- Warped/disturbed jets
- Accretion quenching
- Disk and jet precession
- Changing-look AGN
- **Quasi-periodic oscillations**