Title: Forming truncated accretion disks

Speakers: Gibwa Musoke

Collection/Series: Strong Gravity

Subject: Strong Gravity

Date: November 21, 2024 - 1:00 PM

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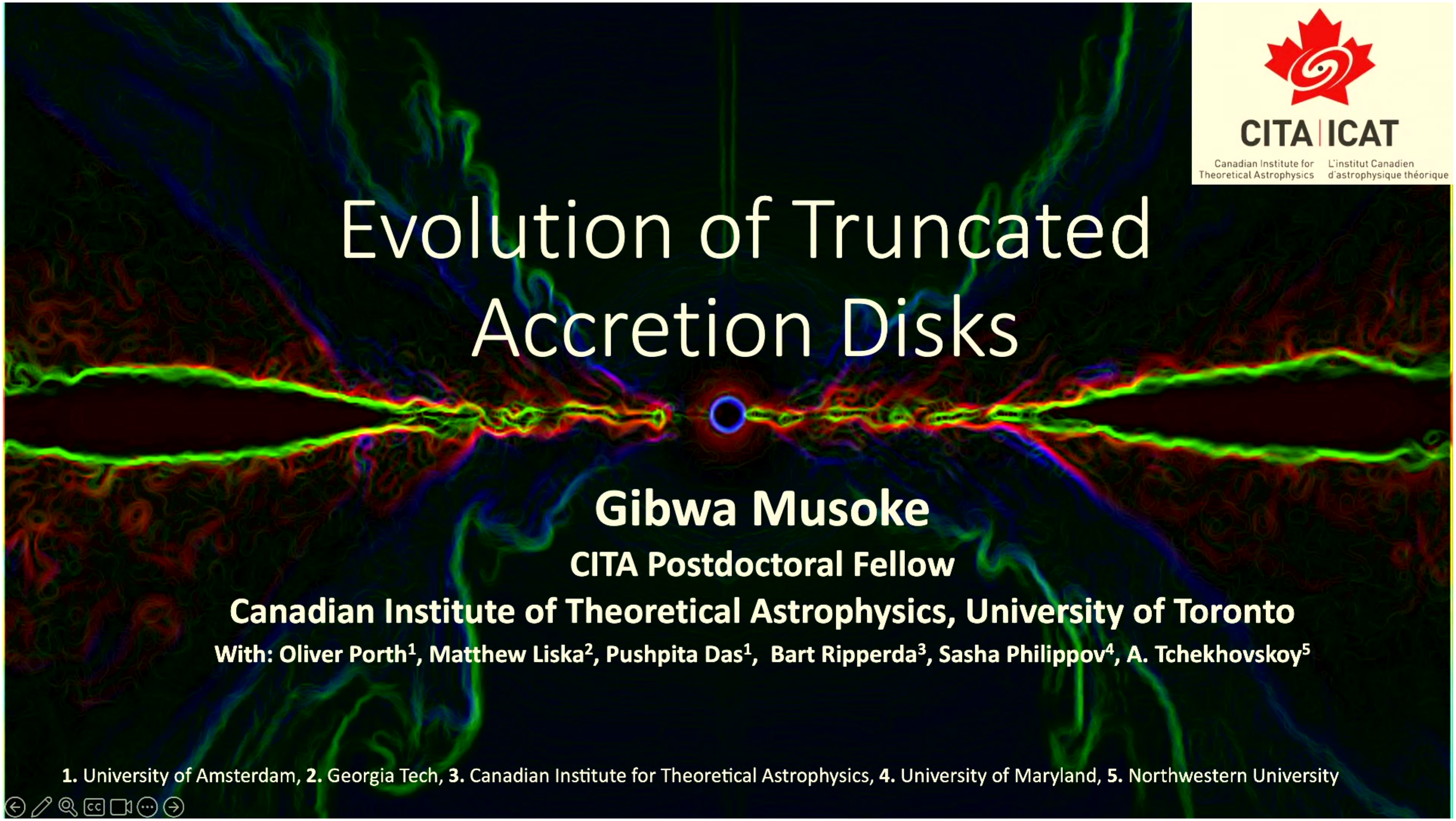
Abstract:

Black hole X-ray binaries and Active Galactic Nuclei transition through a series of accretion states in a well-defined order. During a state transition, the accretion flow changes from a hot geometrically thick accretion flow, emitting a power-law–like hard spectrum to a geometrically thin, cool accretion flow, producing black-body–like soft spectrum. The hard intermediate accretion state present in the midst of a state transition is thought to be associated with the presence of both a hot geometrically thick component, termed the corona, and a cool, geometrically thin component of the accretion flow. The details concerning the geometry of the disk in the hard intermediate state are not agreed upon and numerous models have been proposed: In the “truncated disk” model, the accretion flow is geometrically thick and hot close to the black hole, while the outer regions of the flow are geometrically thin and cool. There are many open questions concerning the nature of truncated accretion disks: Which mechanisms generate the truncated disk structure? What sets the radius at which the disk truncates? How is the corona formed and what is its geometry? In this talk I present the first high-resolution 3D General Relativistic Magneto-Hydrodynamic (GRMHD) simulation and radiative GRMHD simulation modelling the self-consistent formation of a truncated accretion disk around a black hole.



Evolution of Truncated Accretion Disks

Gibwa Musoke

CITA Postdoctoral Fellow

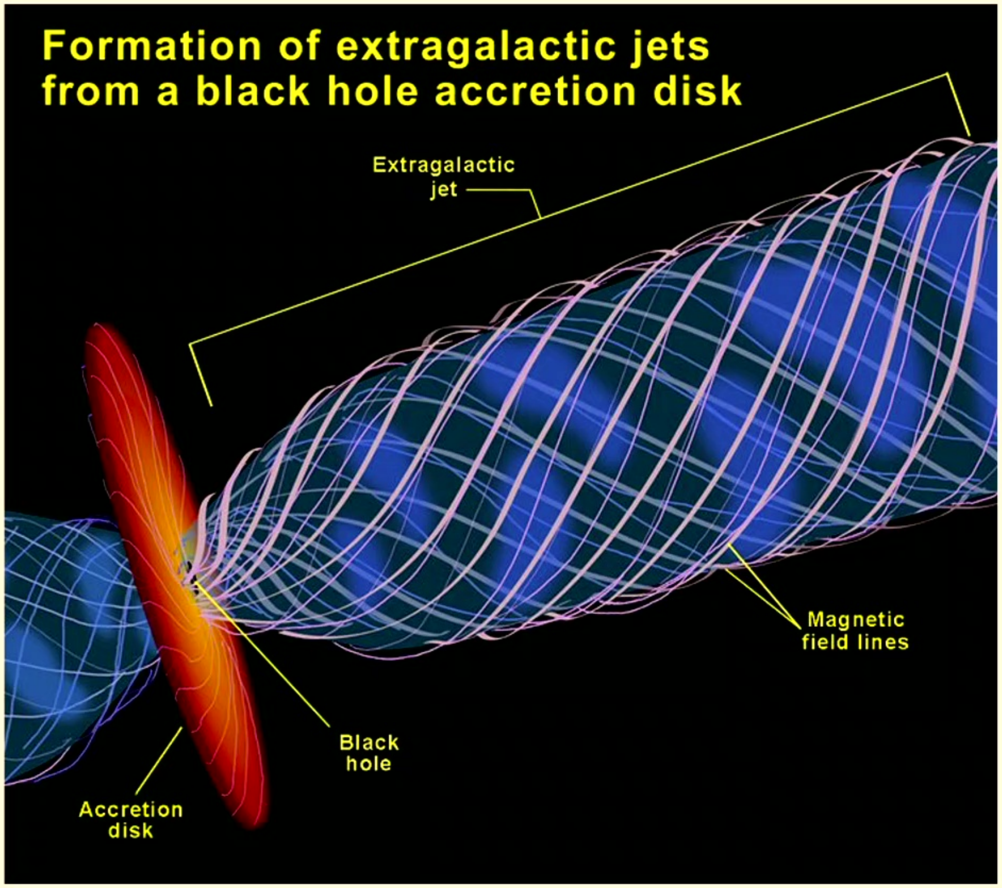
Canadian Institute of Theoretical Astrophysics, University of Toronto

With: Oliver Porth[1], Matthew Liska[2], Pushpita Das[1], Bart Ripperda[3], Sasha Philippov[4], A. Tchekhovskoy[5]

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

Black holes and their outflows

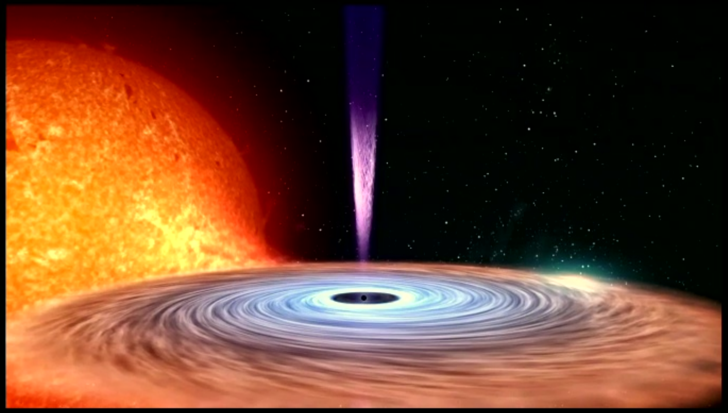
Simulation of an accreting black hole. Credit: Hotaka Shiokawa.



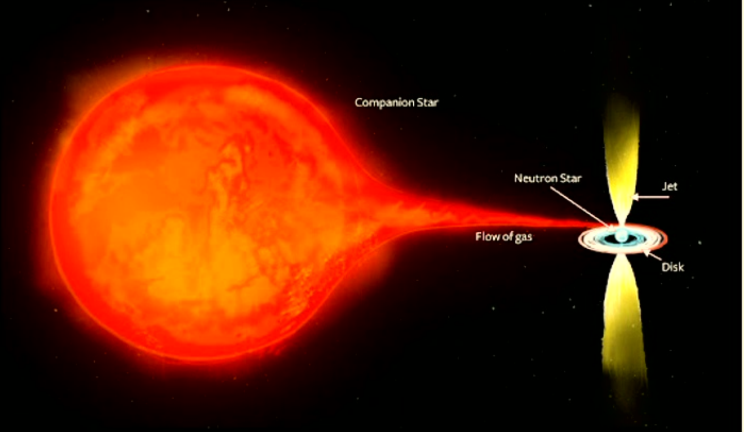
Credit: NASA/ESA/Ann Feild

Jets are also found in other astrophysical systems

Active galactic nuclei
(AGN)



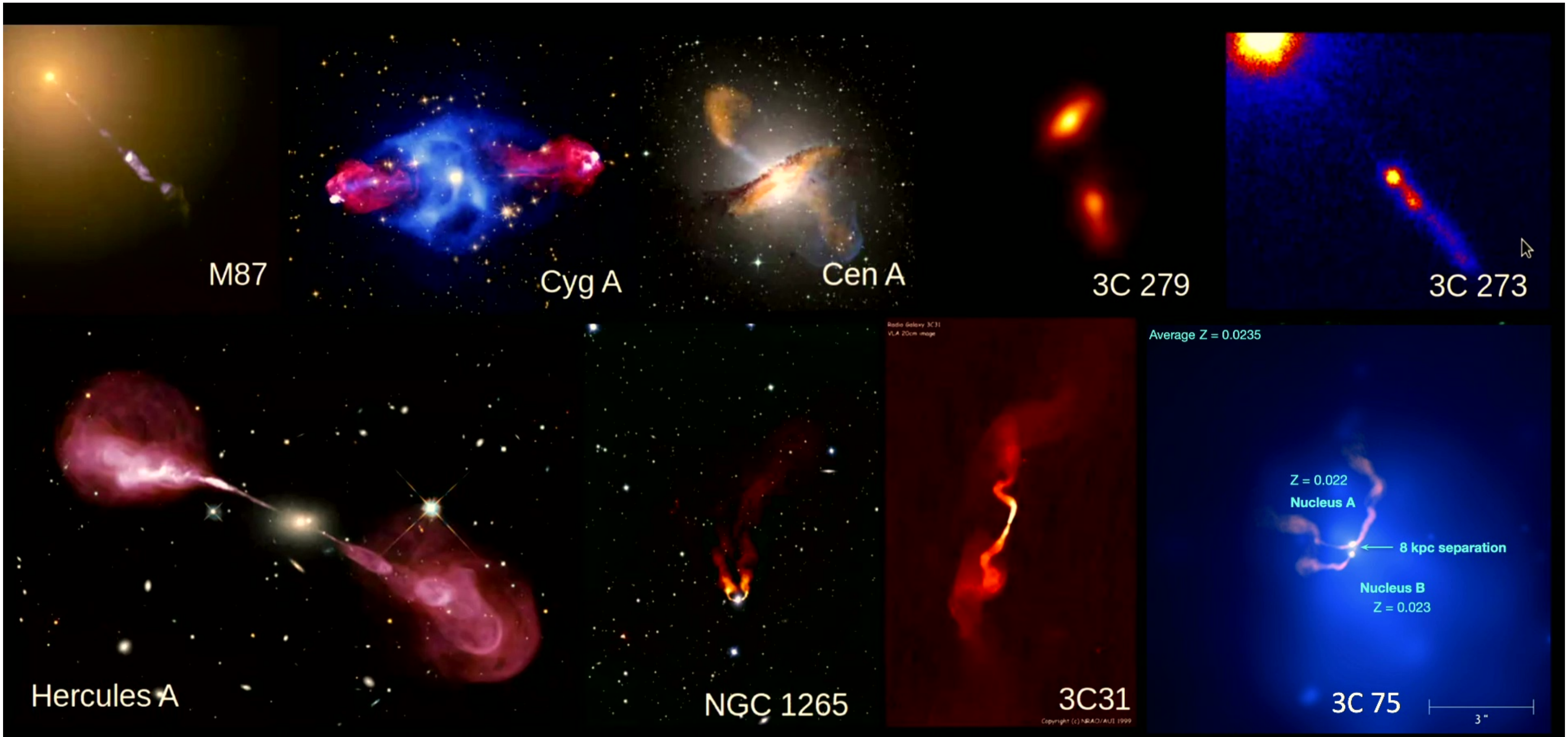
Black hole X-ray binaries
(BHXRBs)



Neutron star X-ray binaries
(NSXRBs)

Image/movie credit:

1. Aurore Simonnet, Sonoma State University
2. Gabriel Perez Diaz; IAC
3. ICRAR

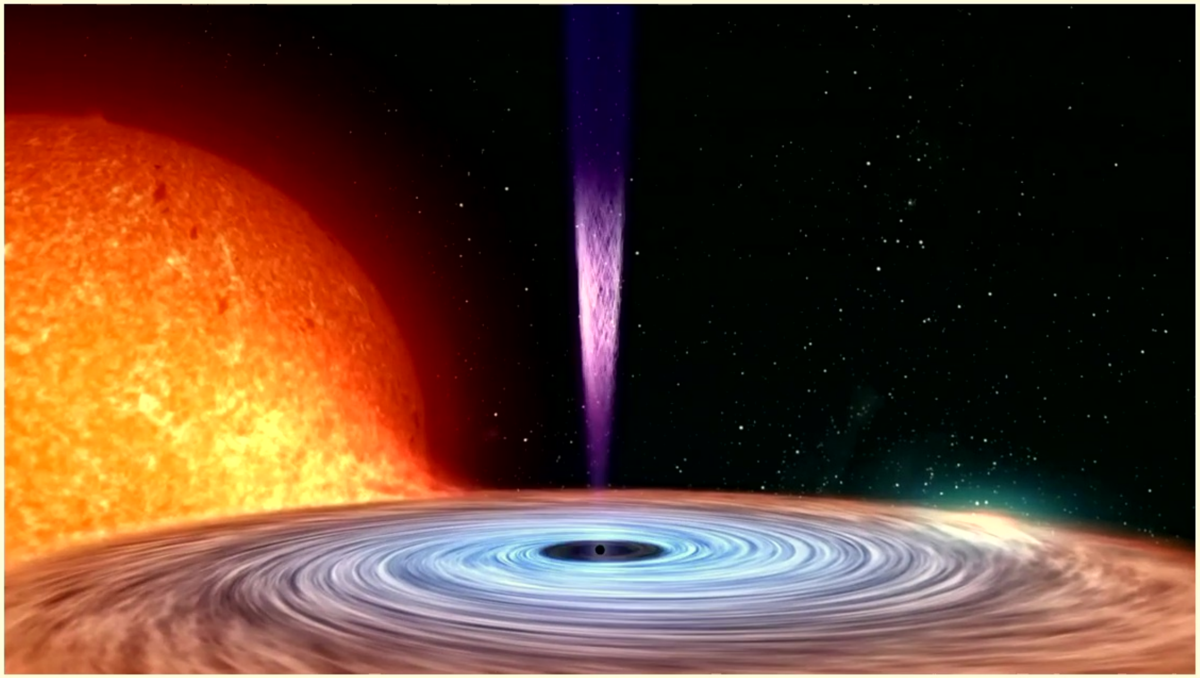


Credits: (M87: HST), (Cyg A: Chandra/HST/VLA (Cyg A), (Cen A: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)), (NGC 1265: M. Gendron-Marsolais et al.; S. Dagnello, NRAO/AUI/NSF; Sloan Digital Sky Survey),(3C279, EHT),(3C293, Chandra),(Hercules A, HST/VLA),(NGC1265,M. Gendron-Marsolais et al.; S. Dagnello, NRAO/AUI/NSF; SDSS), (3C31, VLA), (3C296, AUI, NRAO) (3C 75): X-ray: NASA/CXC/D. Hudson, T.Reiprich et al. (AlfA); Radio: NRAO/VLA/ NRL- f.

(For simulations of interacting jets see Musoke+ 2020, Molnar,.., Musoke+ 2017)

Image adapted from M. Moscibrodzk

Open questions



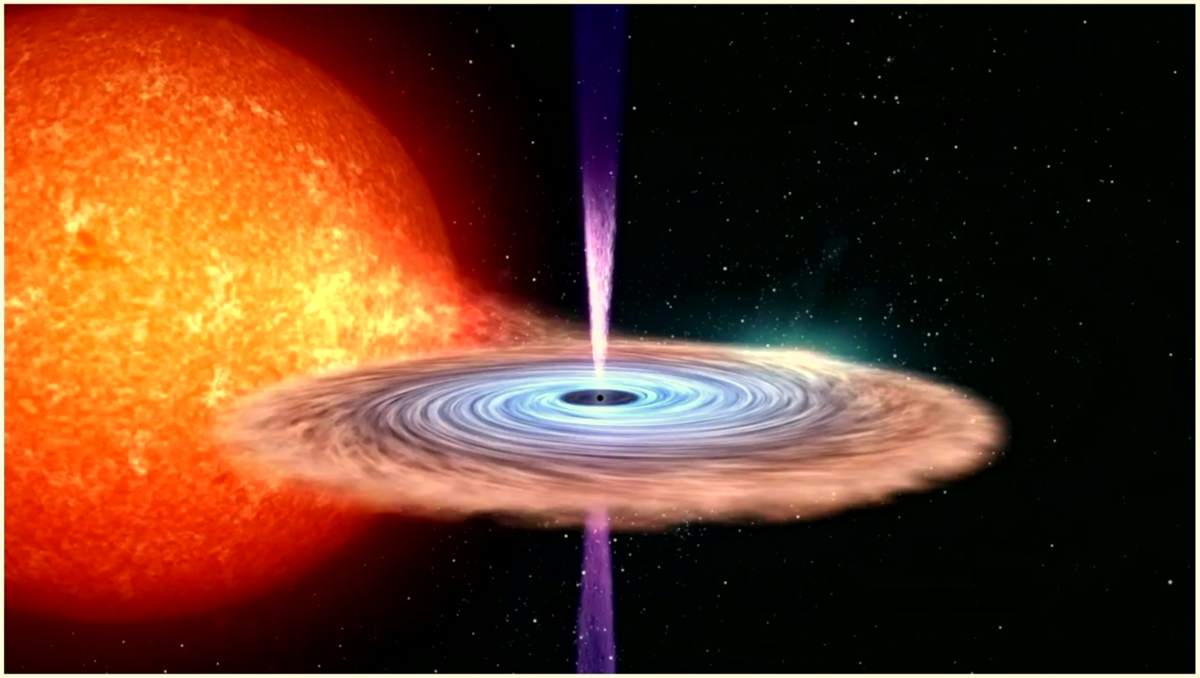
Animation Credit: Gabriel Perez Diaz; IAC:

What are the properties (e.g. dynamics, density, temperature, geometry) of the accretion flow?

How do the properties of the accretion flow evolve?

How are these properties connected to the emission that we observe?

Open questions



Animation Credit: Gabriel Perez Diaz; IAC:

What are the properties (e.g. dynamics, density, temperature, geometry) of the accretion flow?

How do the properties of the accretion flow evolve?

How are these properties connected to the emission that we observe?

How are jets launched, accelerated and collimated?

How do jet properties relate to the conditions of the accretion flow?

Which process are responsible for triggering state transitions?

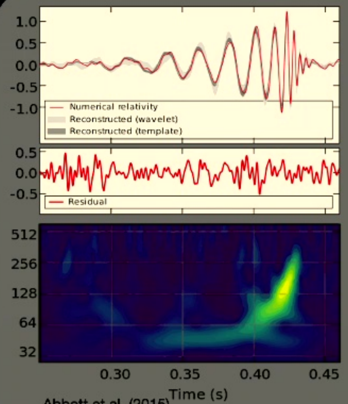
Simulating accretion disks

Accretion disk methods:

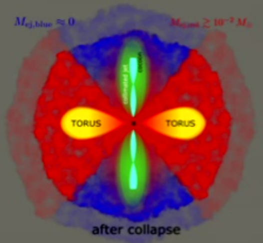
- **SPH**
- **MHD**
- **GRMHD**

Simulation of an accreting black hole. Magnetic field lines are shown by the white lines. Credit: Hotaka Shiokawa.

GW counterparts

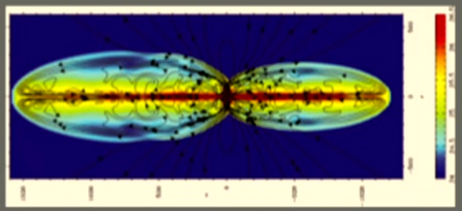


Abbott et al. (2015)



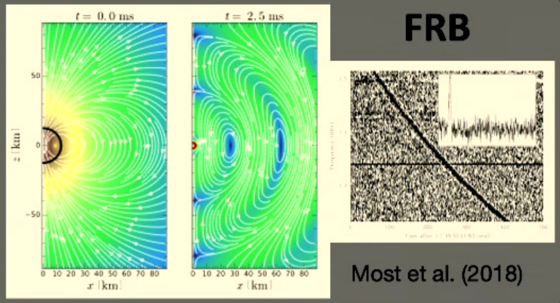
e.g. Gill et al. (2019)

Long GRB: collapsars



Komissarov & Barkov (2009)

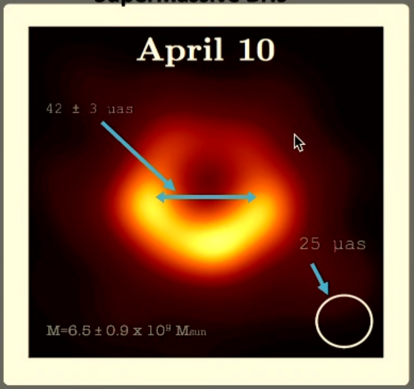
FRB



Most et al. (2018)

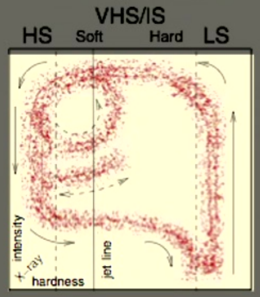
> *"general relativistic source modeling is in high demand"*

Supermassive BHs



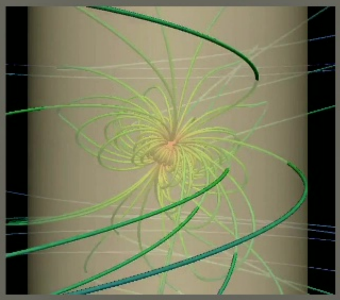
EHT (2019)

BH X-ray binaries

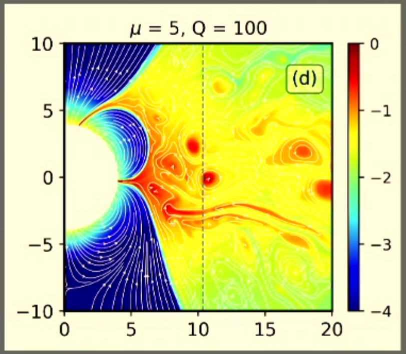


Fender et al. (2004)

Pulsar Magnetospheres



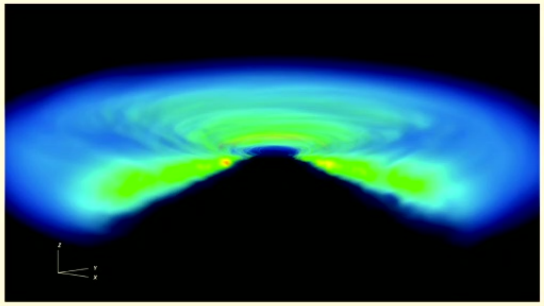
Accreting millisecond pulars



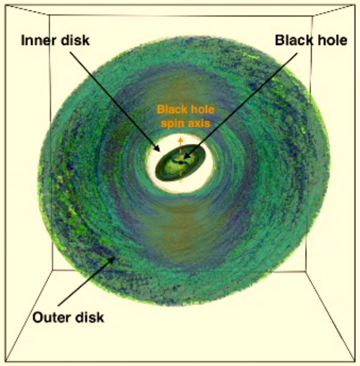
Das et al. 2022

Slide courtesy of O. Porth

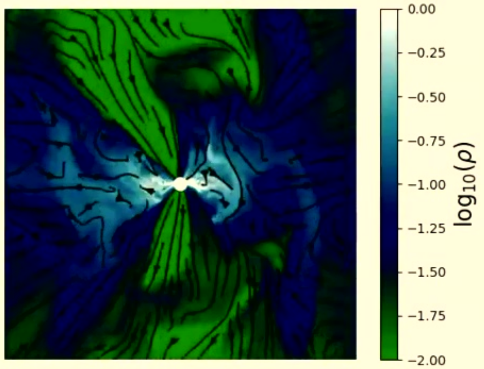
The rich phenomenology of accretion disks



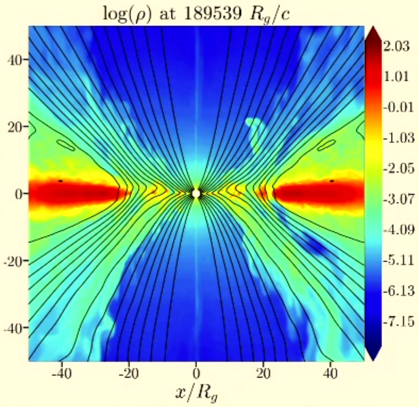
Thin disks e.g. Teixeira, Fragile, Zhuravlev+, 2014



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

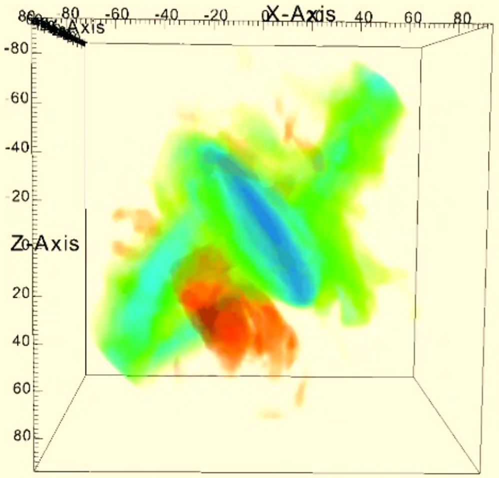


Wind-fed disks e.g. Ressler et al, ApJL, 2020

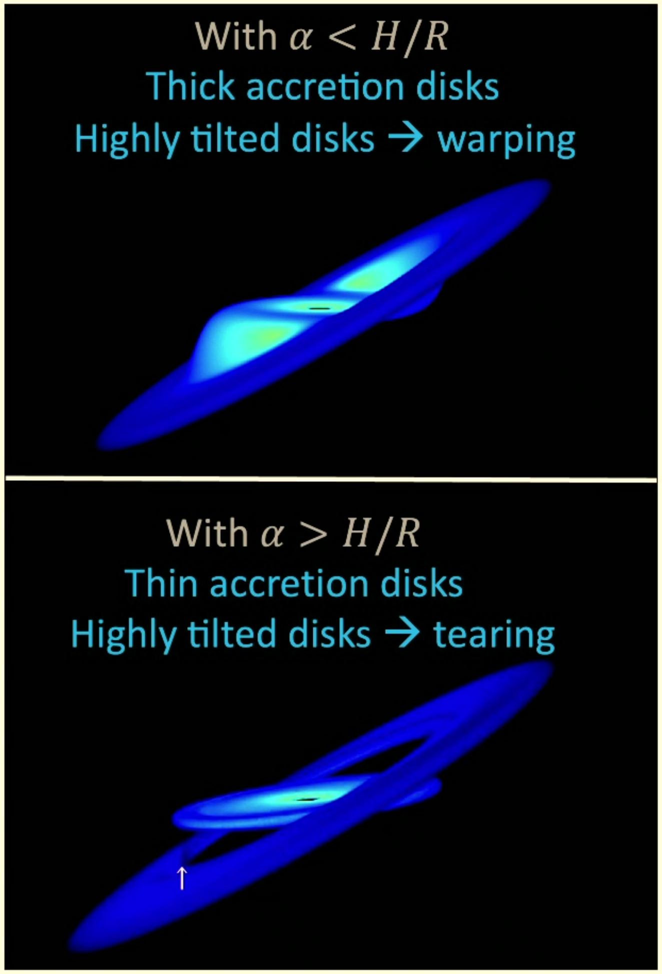


Truncated disks e.g. Musoke, Porth, Liska+ (in preparation)

The rich phenomenology of accretion disks



Movie credit: M. Liska



With $\alpha < H/R$

Thick accretion disks

Highly tilted disks → warping

With $\alpha > H/R$

Thin accretion disks

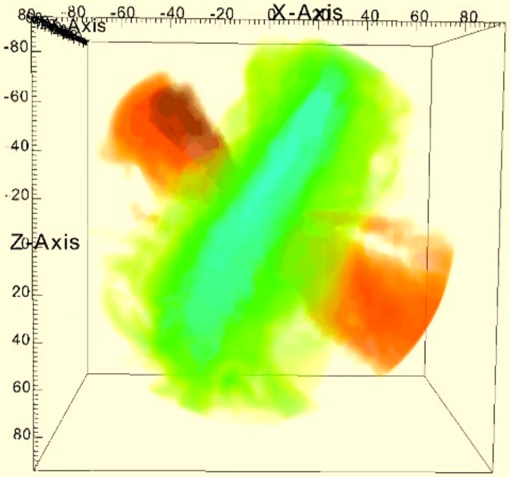
Highly tilted disks → tearing

Lodato & Price 2010

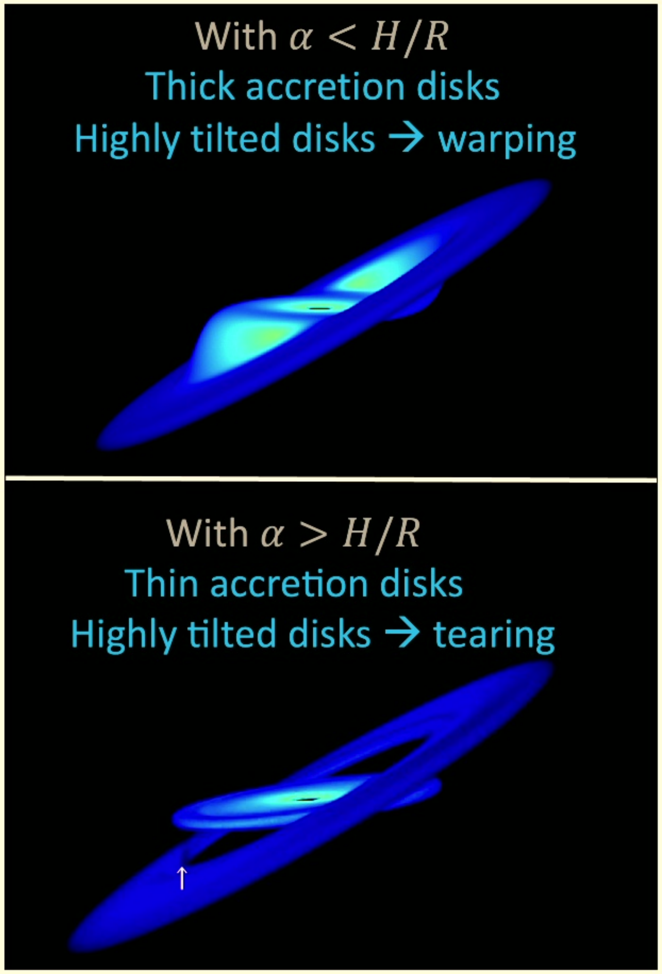
(e.g. Papaloizou & Pringle 1983, Lodato & Price 2010, Nelson & Papaloizou 1999, 2000)
See also: Kaaz, Liska,.., Musoke+ 2023)

(e.g. Lodato & Price 2010, Nixon & King 2018, Nixon et al. 2012, Dogan 2018, Raj & Nixon 2021, Musoke et al. 2022)

The rich phenomenology of accretion disks



Movie credit: M. Liska



With $\alpha < H/R$

Thick accretion disks

Highly tilted disks → warping

With $\alpha > H/R$

Thin accretion disks

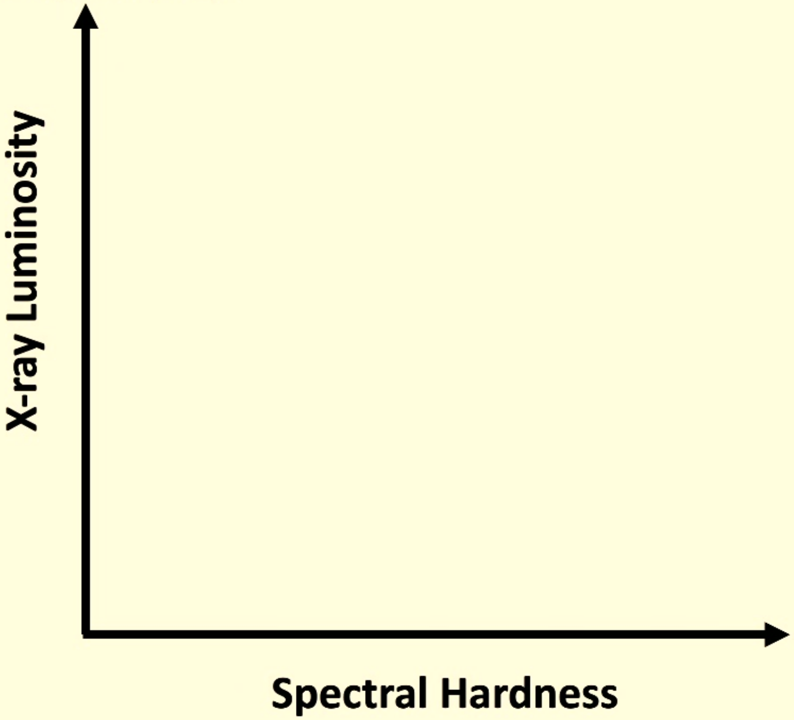
Highly tilted disks → tearing

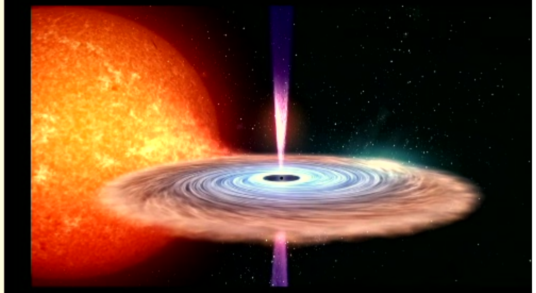
Lodato & Price 2010

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

Spectral state transitions

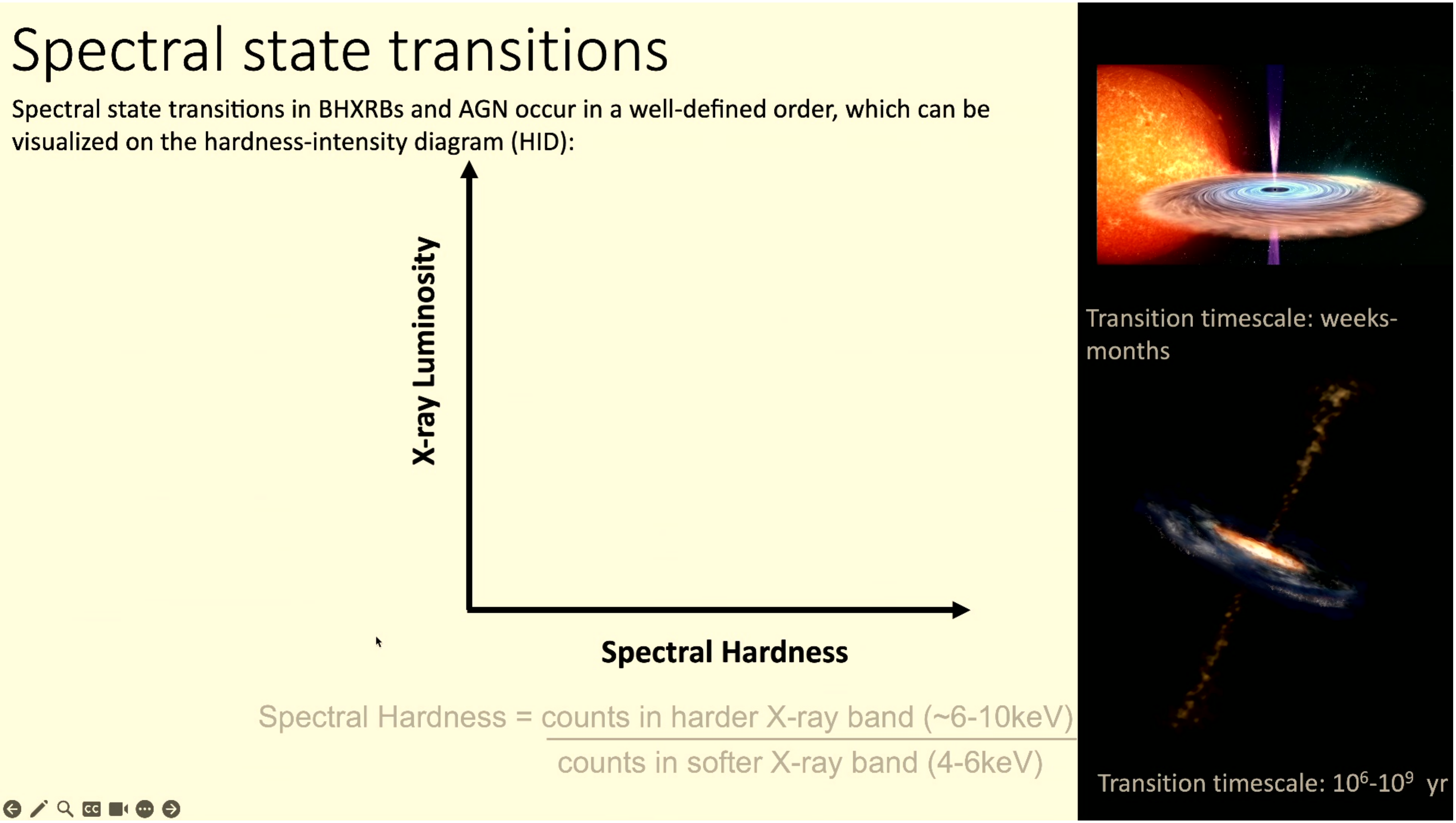
Spectral state transitions in BHXRBs and AGN occur in a well-defined order, which can be visualized on the hardness-intensity diagram (HID):





Transition timescale: weeks-months

Transition timescale: 10^6-10^9 yr



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$$\text{Spectral Hardness} = \frac{\text{counts in harder X-ray band (}\sim\text{6-10keV)}}{\text{counts in softer X-ray band (4-6keV)}}$$

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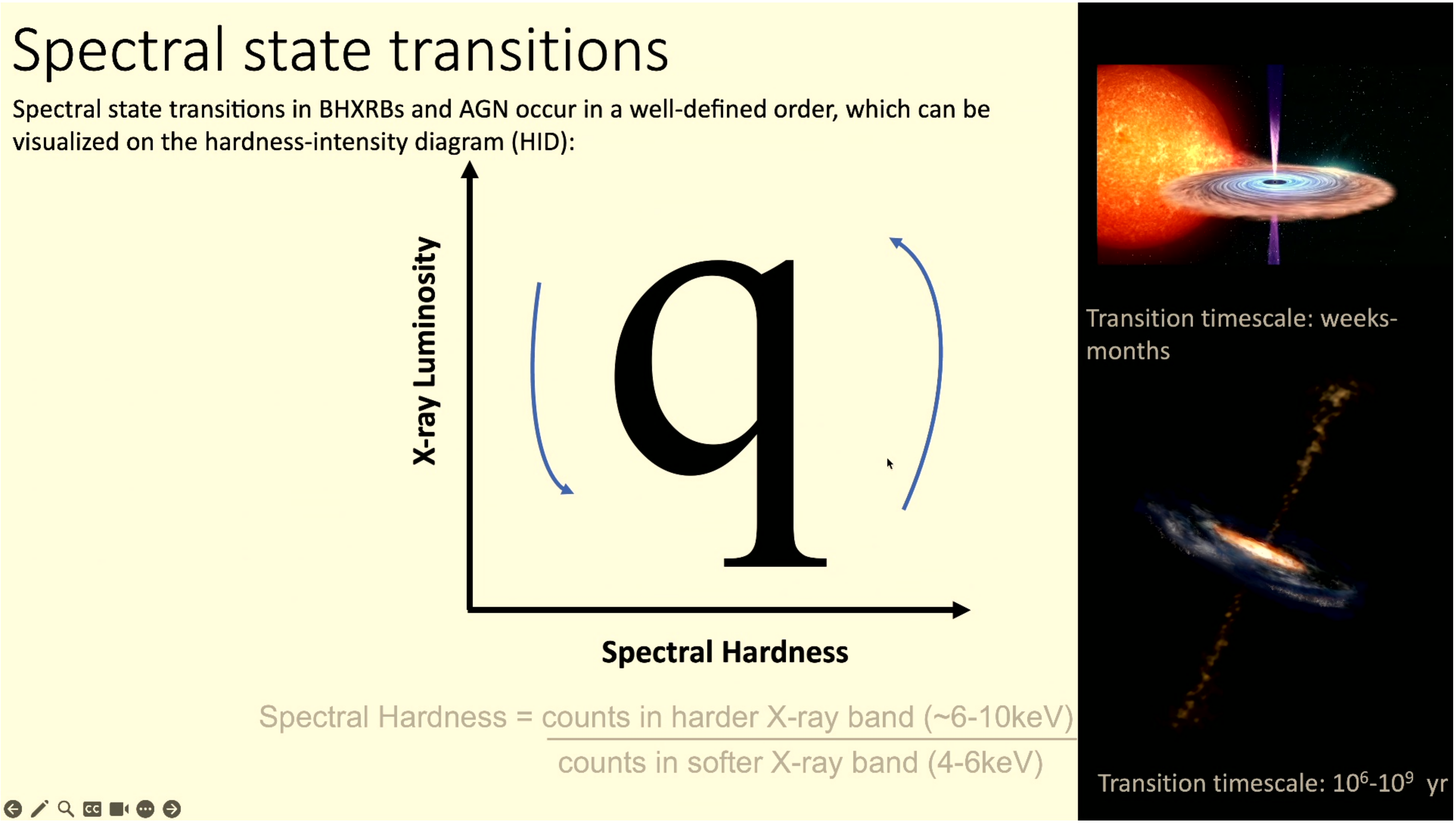


Spectral state transitions

Spectral state transitions in BHXRBs and AGN occur in a well-defined order, which can be visualized on the hardness-intensity diagram (HID):

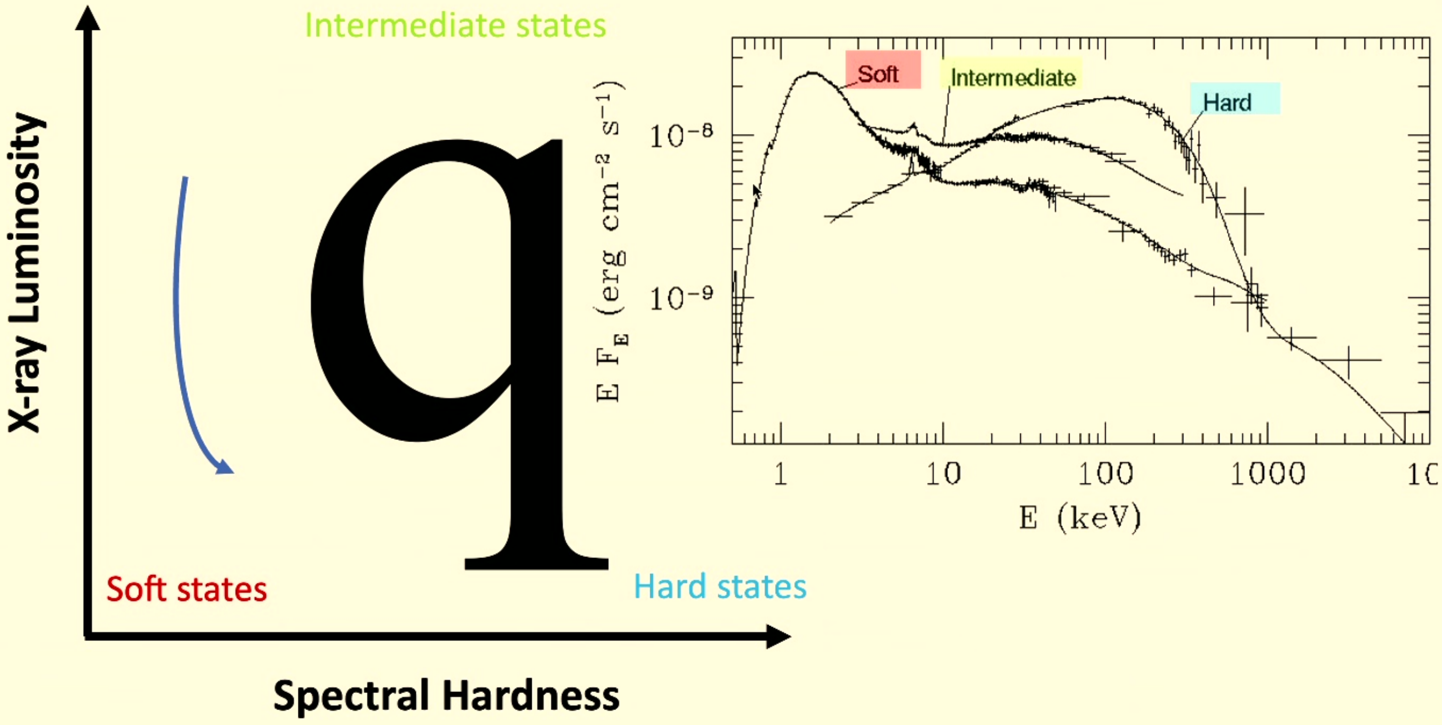
Spectral Hardness = counts in harder X-ray band (~6-10keV) / counts in softer X-ray band (4-6keV)

Transition timescale: weeks-months

Transition timescale: 10^6-10^9 yr

Spectral state transitions

The three spectral states of Cyg X-1
(Merloni 2022, see also Zdziarski 2000 for a review)



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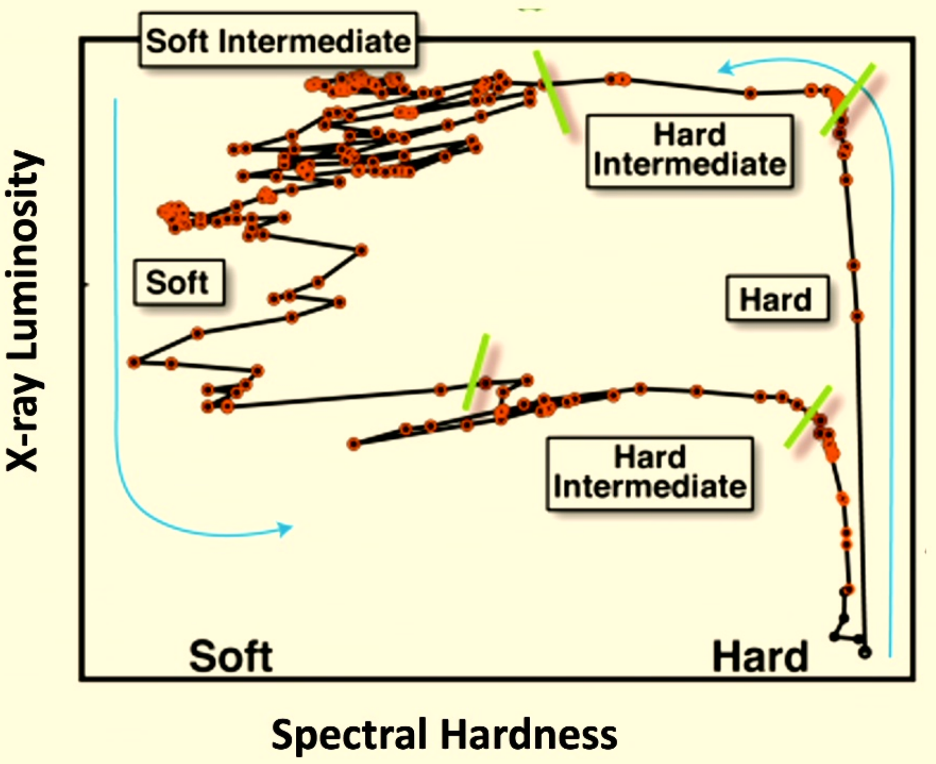
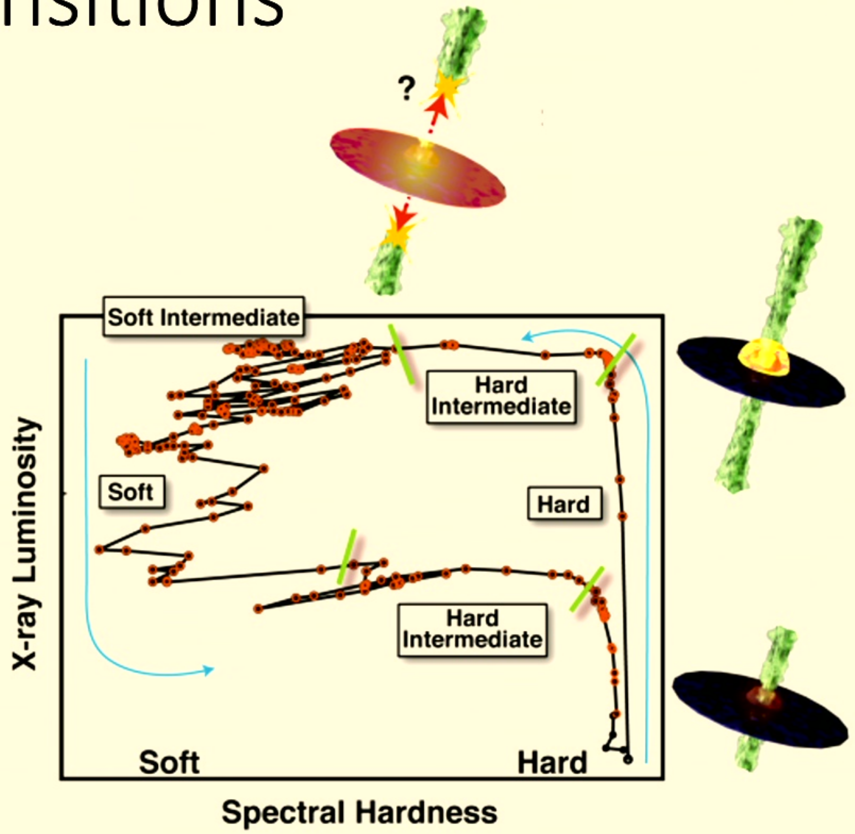
Spectral state transitions



Spectral Hardness = counts in harder X-ray band (~6-10keV) / counts in softer X-ray band (4-6keV)

Spectral state transitions



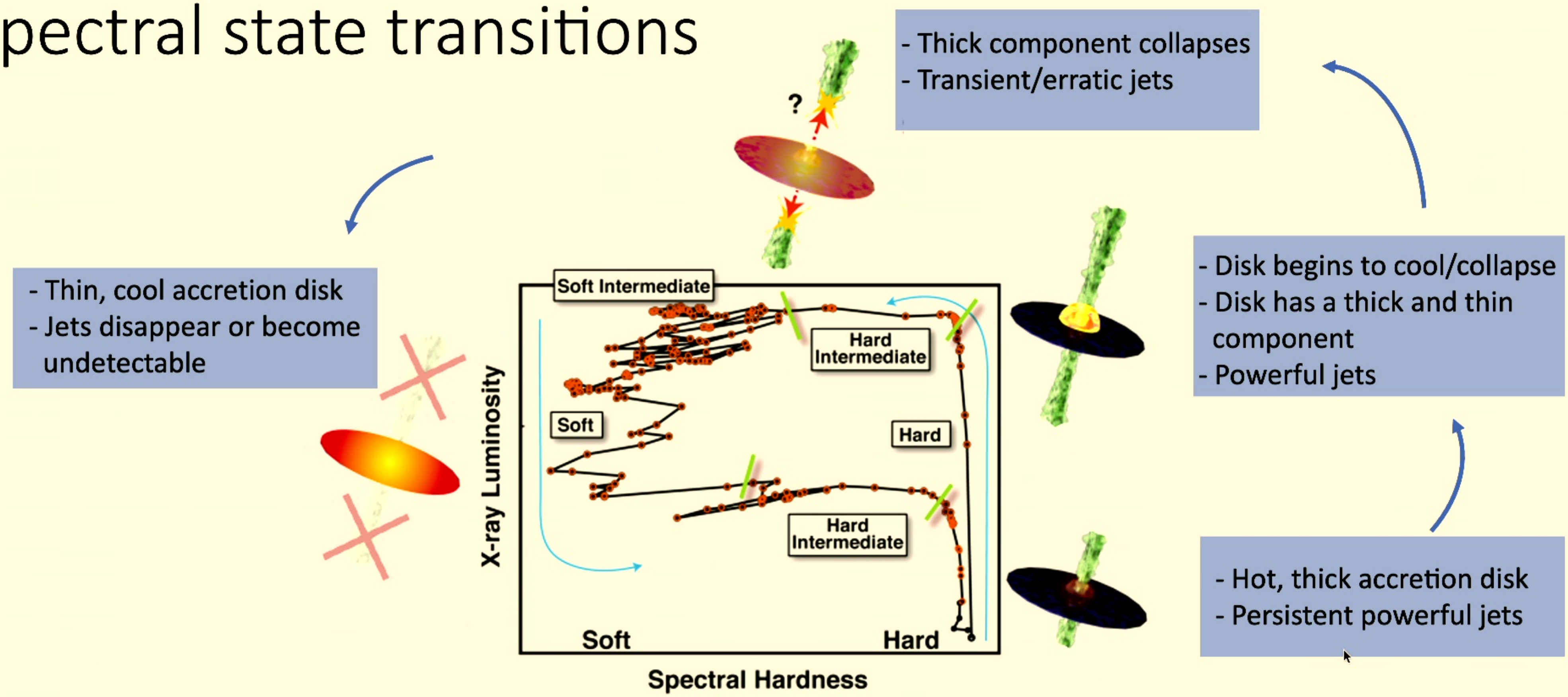
- Disk begins to cool/collapse
- Disk has a thick and thin component
- Powerful jets

- Hot, thick accretion disk
- Persistent powerful jets

Schematic of the hardness intensity diagram (Belloni et al. 2010)

State transitions in XRBs may be driven by changes in mass accretion rate and possibly the magnetic field topology (e.g. Begelman et al 2014)

Spectral state transitions



- Thick component collapses
- Transient/erratic jets

- Thin, cool accretion disk
- Jets disappear or become undetectable

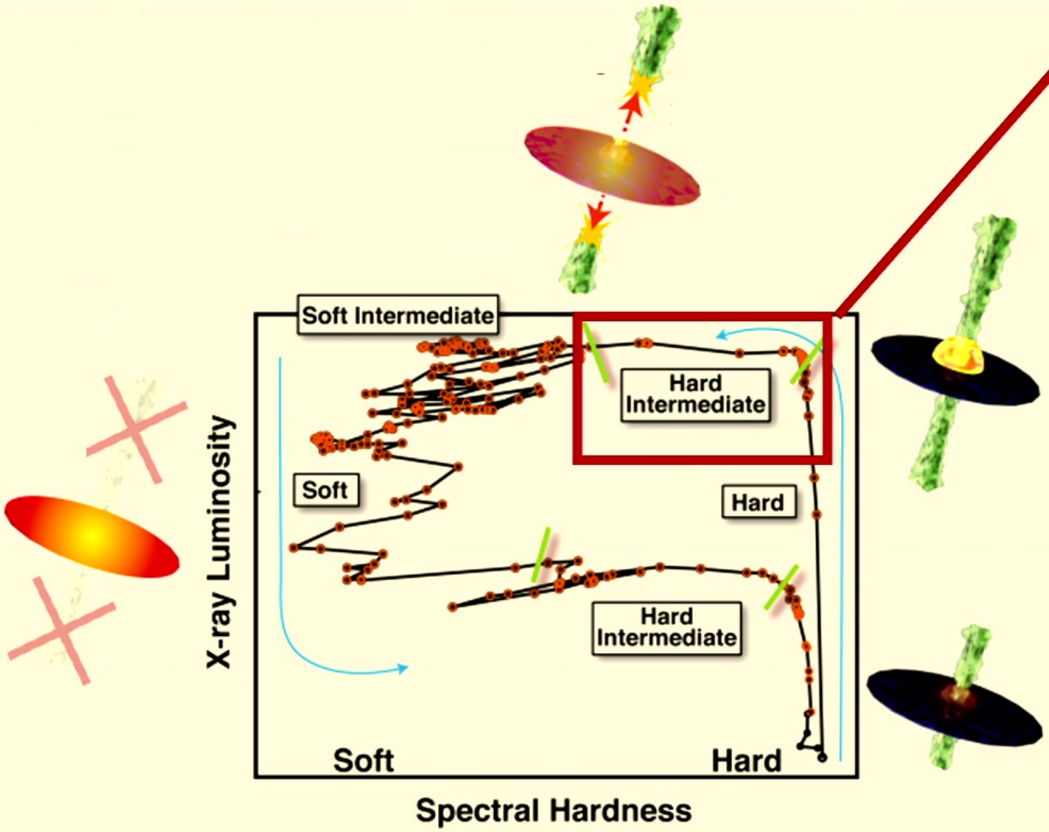
- Disk begins to cool/collapse
- Disk has a thick and thin component
- Powerful jets

- Hot, thick accretion disk
- Persistent powerful jets

Schematic of the hardness intensity diagram (Belloni et al. 2010)

State transitions in XRBs may be driven by changes in mass accretion rate and possibly the magnetic field topology (e.g. Begelman et al 2014)

Transitional accretion disks



Belloni et al. 2010

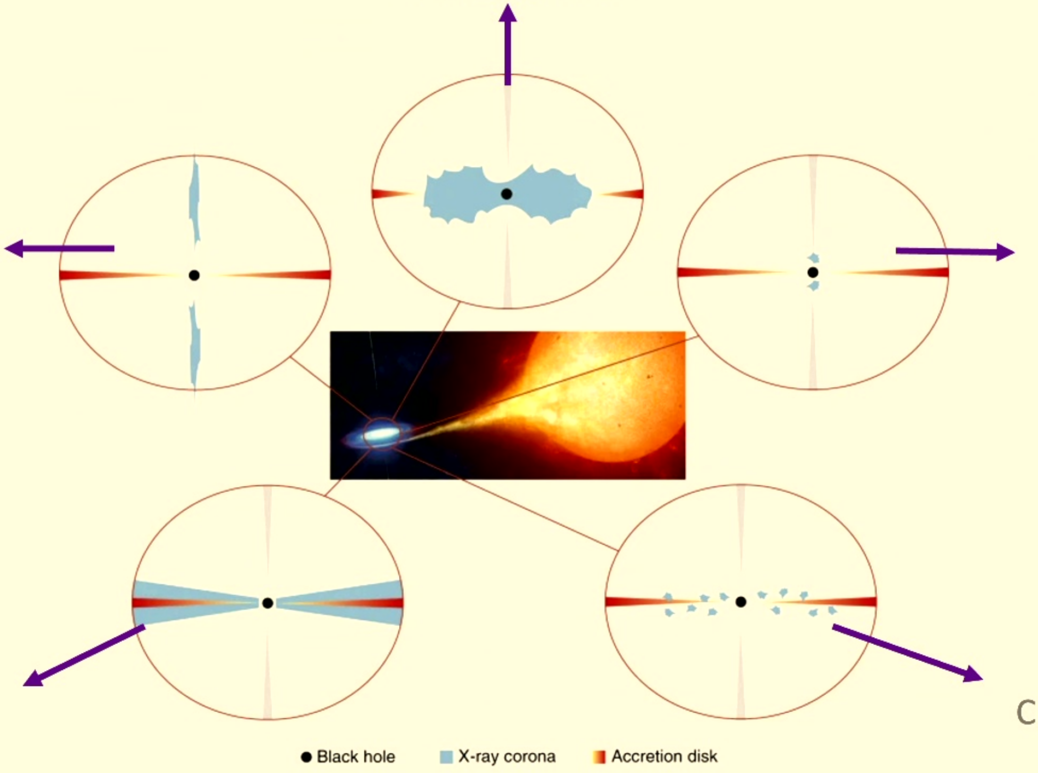
geometrically thin, cool component

+

geometrically thick hot component
(the corona)

Proposed transitional disk geometry

🟦 Hot thick component (the corona)
🟥 Cold thin component



Hot flow surrounded by a truncated disk.

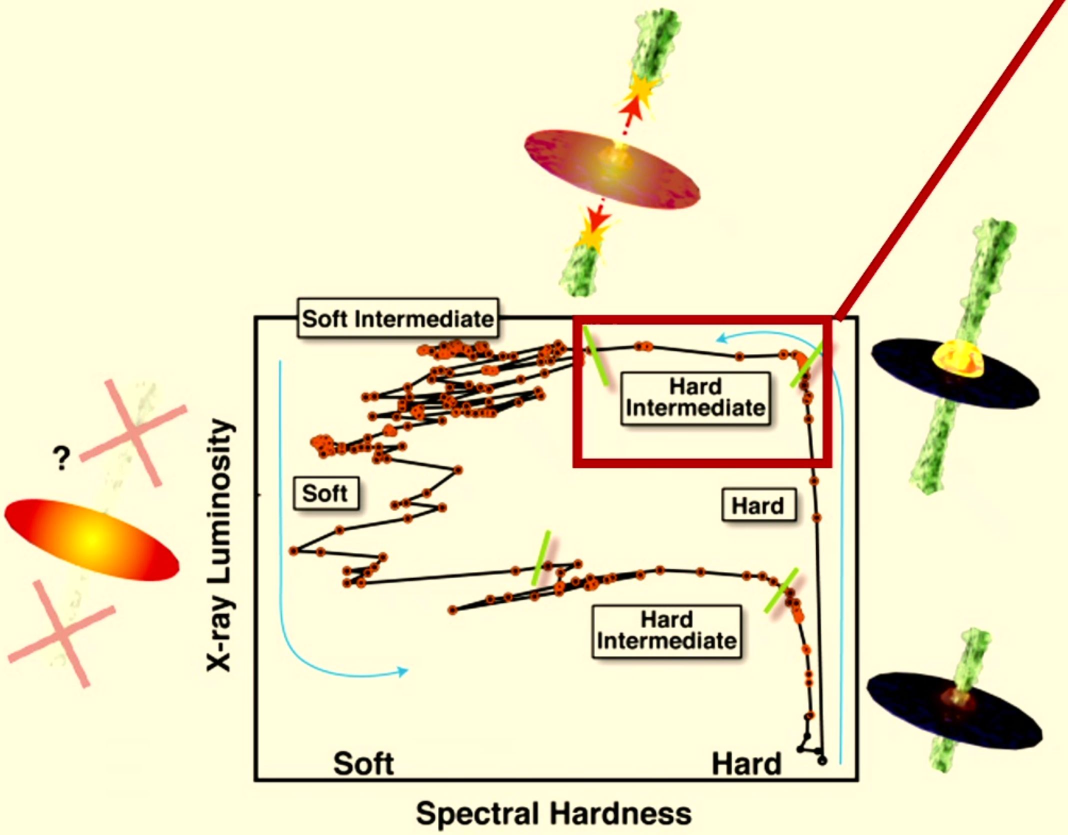
Corona as extended jet emission

Compact lamppost e.g. jet base

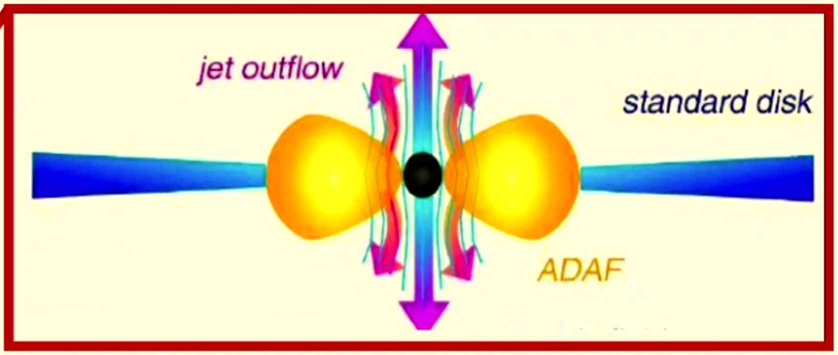
Extended wedge corona

Clumpy corona extended over the disk

Truncated accretion disks



Belloni et al. 2010



(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?

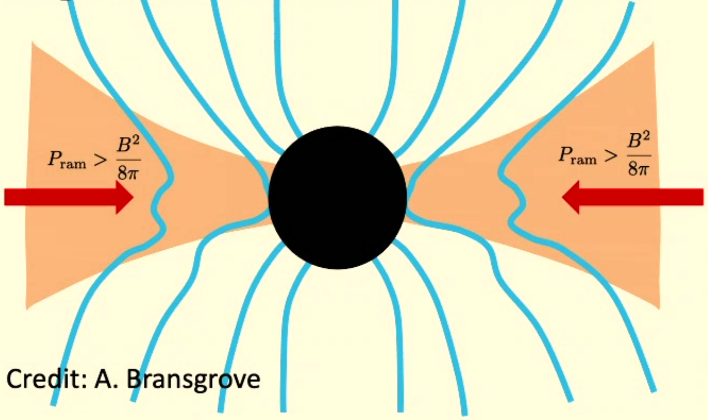
How does accretion proceed?

Advancements in global GRMHD simulation codes

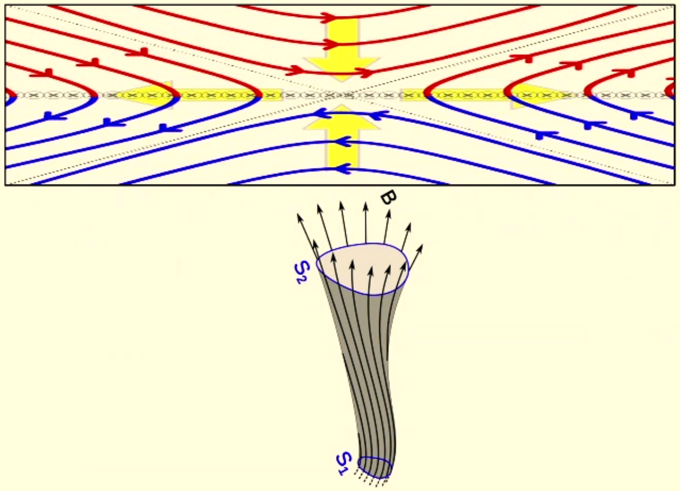
Code speed:

- Computational hardware
- AMR
- LAT
- GPU-acceleration

Magnetic reconnection in accretion flows



Credit: A. Bransgrove

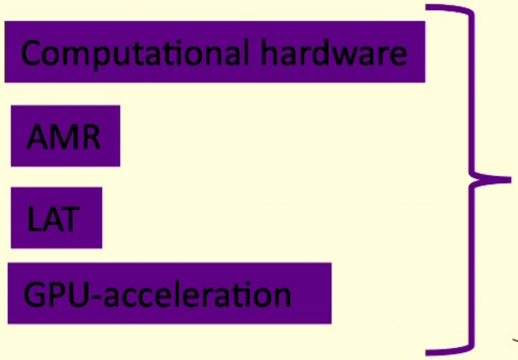


Magnetic reconnection movie and flux tube schematic- credit Wikipedia

Reconnection and turbulence may play an important role in the properties of the emission observed in different spectral states.

Advancements in global GRMHD simulation codes

Code speed:



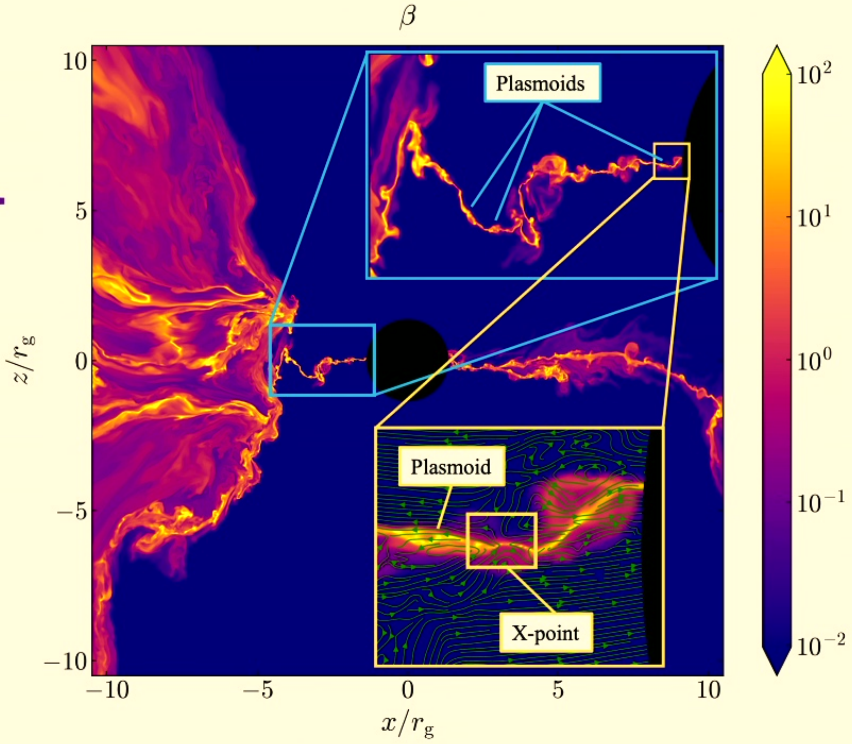
Computational hardware

AMR

LAT

GPU-acceleration

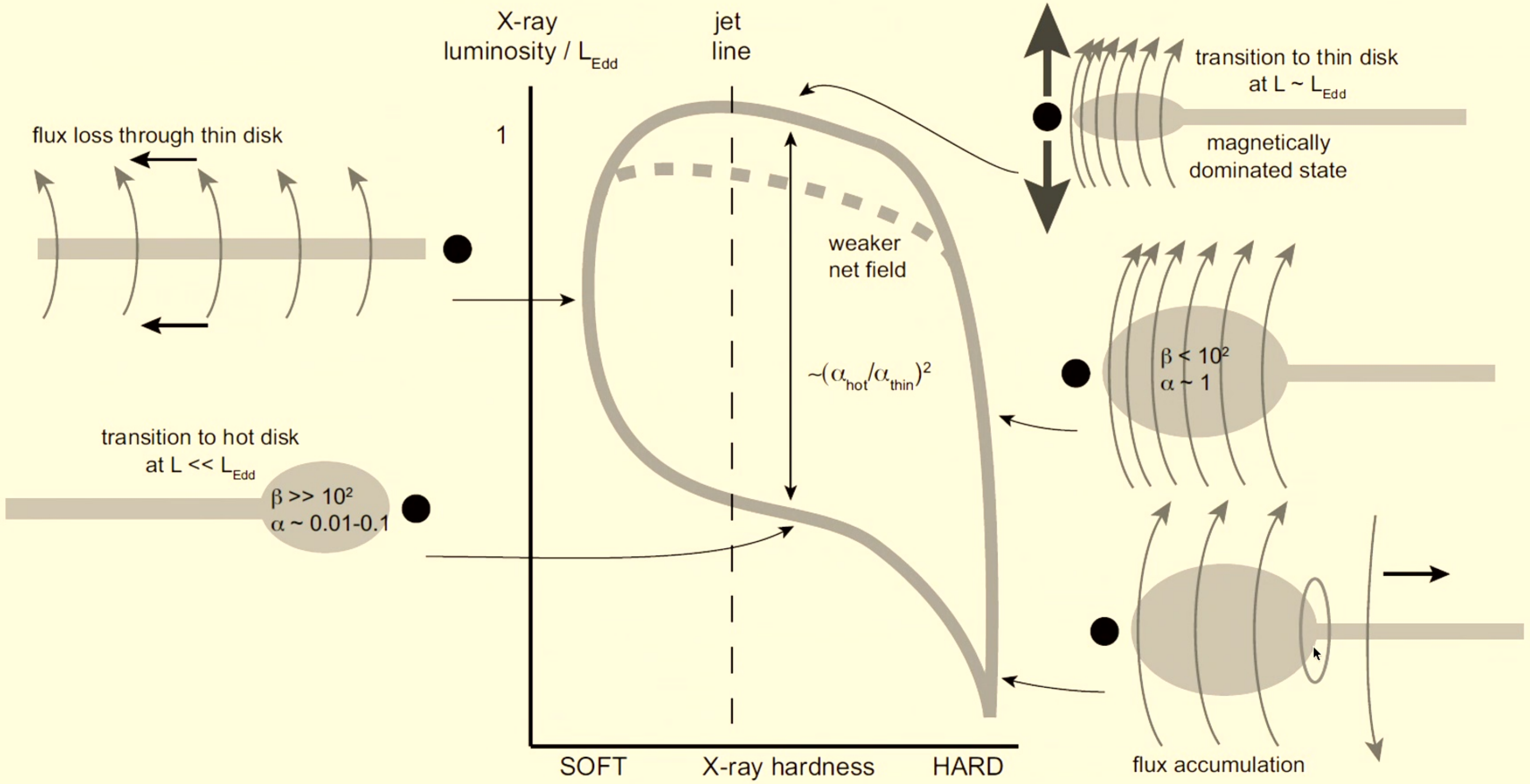
Extreme spatial resolution in a 3D MAD GRMHD simulation



Ripperda, Liska ,Chatterjee, Musoke+(2021)

- Can now achieve very high effective resolutions: 5376 × 2304 × 2304 cells (e.g. H-AMR, Liska+ 2019)
- Can capture plasmoid driven reconnection in GRMHD 3D MADs. (see also Dihingia et al. 2021 for 2D)

Temporal ‘resolution’



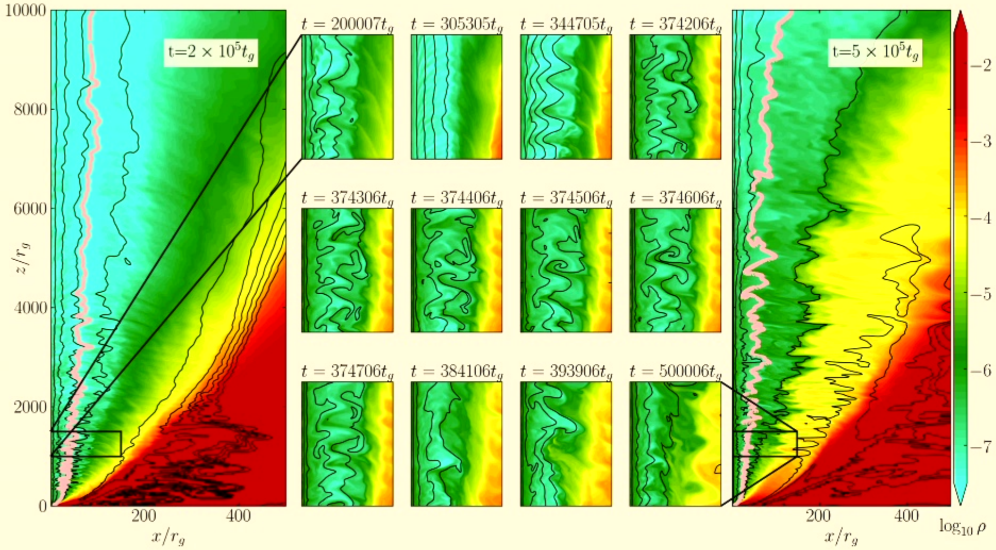
Advancements in global GRMHD simulation codes

Enhanced code speed:

- Computational hardware
- AMR
- LAT
- GPU-acceleration

Enhancements in dynamical evolution:

- Length-scales
- Time-scales



Parsec-scale GRMHD simulation of jet launched by accreting BH. Chatterjee +2019

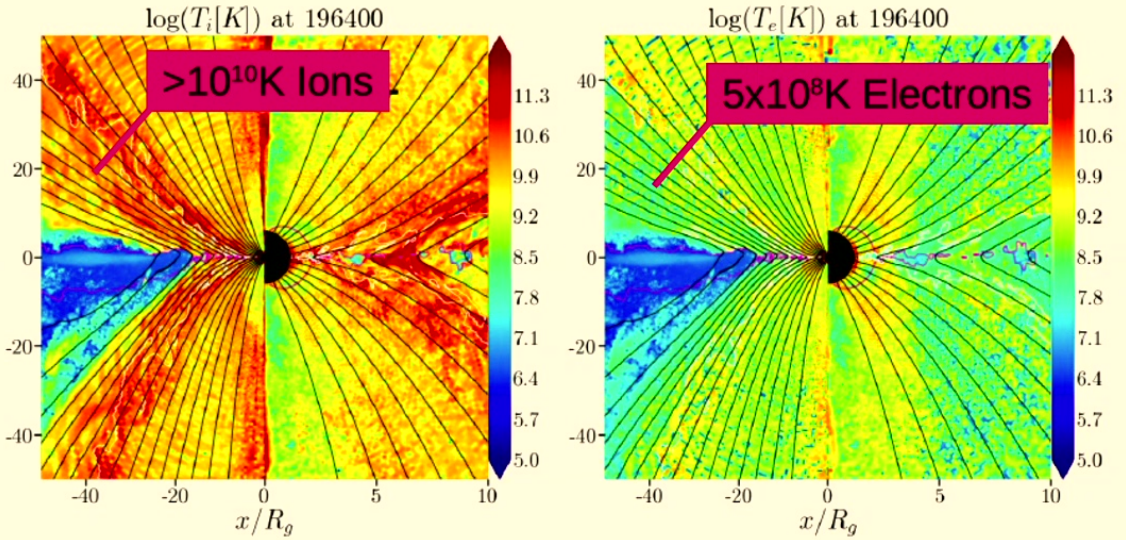
Advancements in global GRMHD simulation codes

Enhanced code speed:

- Computational hardware
- AMR
- LAT
- GPU-acceleration

Two-Temperature thermodynamics

Important for modelling optically thin flows



$>10^{10}$K Ions

5×10^{8}K Electrons

Liska, Musoke, Tchekhovskoy, Porth, Beloborodov 2022

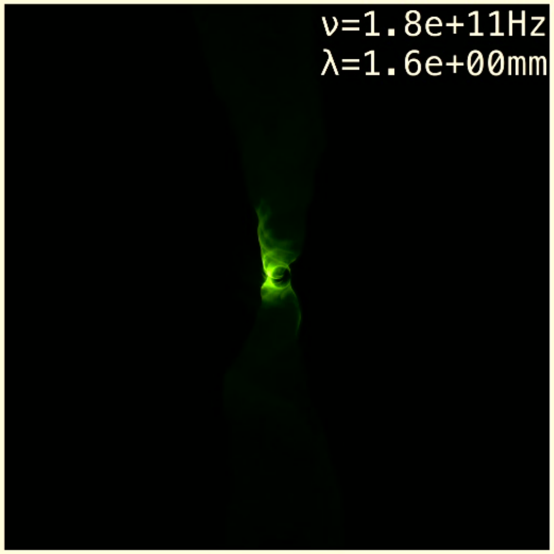
Advancements in global GRMHD simulation codes

Enhanced code speed:

- Computational hardware
- AMR
- LAT
- GPU-acceleration

Two-Temperature thermodynamics

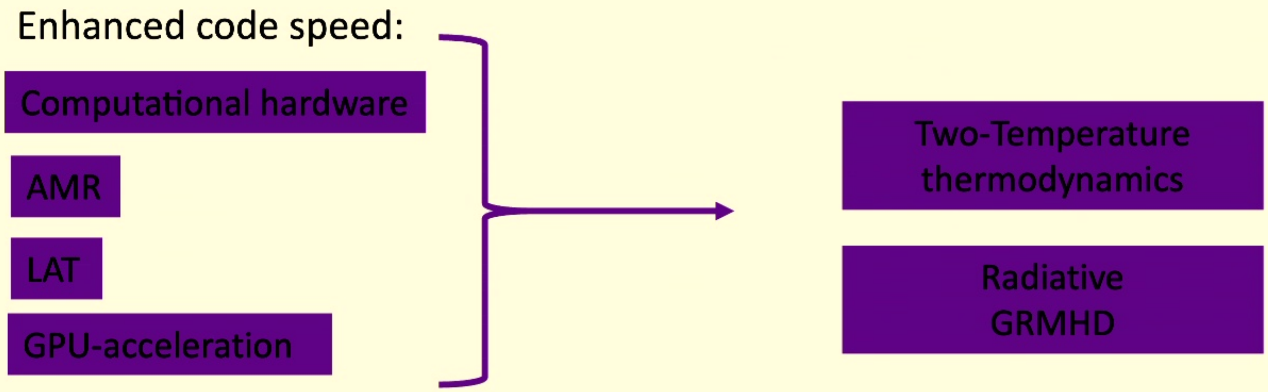
But what about radiation?



Multi frequency emission GRRT mapping of GRMHD simulation: CK Chan, EHTC

e.g. Moscibrodzka, Yfantis, 2023, Mościbrodzka, Falcke, Shiokawa, Gammie 2014, Davelaar Haiman 2022, Chan, Psaltis, Özel+, 2015, Dexter, Eric Agol, Fragile 2009, Mizuno, Younsi, Fromm, 2018, Gelles, Prather, Palumbo 2021, Yoon, Chatterjee, Markoff+, 2020, Chatterjee, Markoff, Neilsen, Younsi+, 2021

Advancements in global GRMHD simulation codes



Enhanced code speed:

Computational hardware

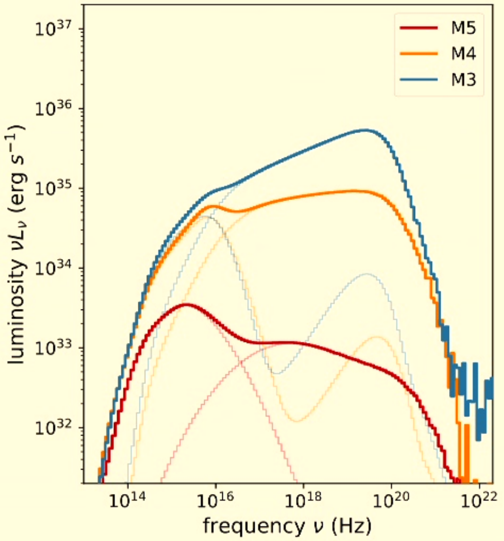
AMR

LAT

GPU-acceleration

Two-Temperature thermodynamics

Radiative GRMHD



Spectra from radiative GRMHD simulation.
Dexter, Scepi, Begelman 2021

e.g. 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

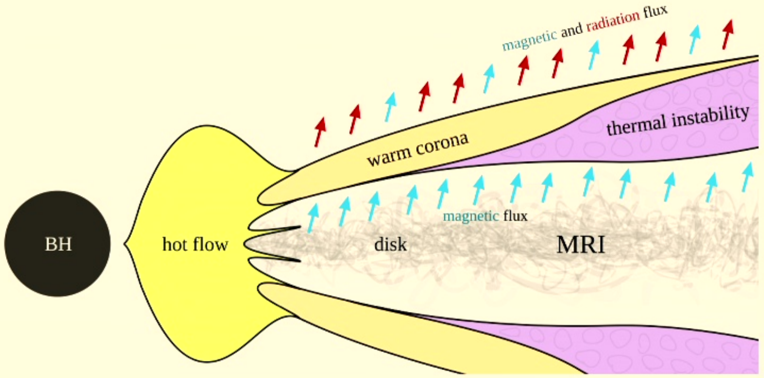
Advancements in global GRMHD simulation codes

Enhanced code speed:

- Computational hardware
- AMR
- LAT
- GPU-acceleration
- Two-Temperature thermodynamics
- Radiative GRMHD

Implications for:

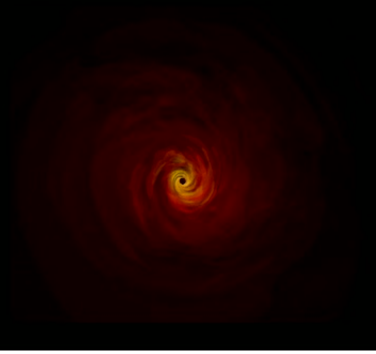
- Formation and evolution of the corona
- Coronal heating
- Understanding mechanisms behind observable MWL emission phenomena
- Disk winds and their formation mechanisms
- State transitions
- Linking simulations to observational data



Gronkiewicz+ 2019

H-AMR: The world's fastest GRMHD code

- Multi-GPU 3D GRMHD H-AMR ("hammer", Liska et al. 2020):
  - Solves radiative 2T G(R)RMHD, includes advanced Riemann solvers
  - Optimizations (e.g. AVX vectorization) make it intrinsically (one of) the fastest codes **x6**
  - GPUs speed up H-AMR by another factor of 5 vs 20-core CPUs of the same generation **x5**
- Includes advanced features:
  - Adaptive mesh refinement (AMR) focuses the resolution where it is needed **x10**
  - A local adaptive timestep speeds up H-AMR **x3-5** to 3x10^8 cycles/s/GPU
  - Unique grid increases the timestep by a factor of **x10-20**
  - Scalable up to the #1 supercomputer Summit with 28800 GPUs (tested up to 6000 GPUs)

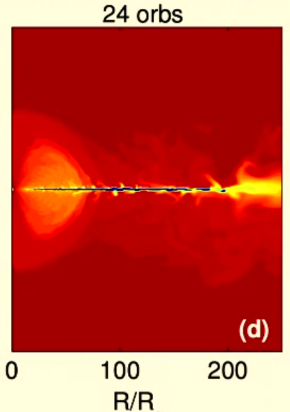


For accretion disk simulations:
x 100 speedup compared to conventional AMR code
x 10 000 speedup compared to unigrid

slide courtesy of M. Liska

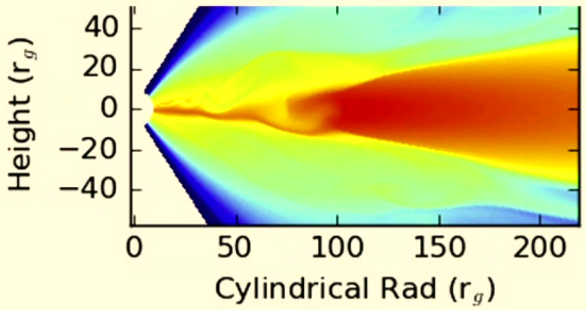
Recent works

Radiative HD simulations



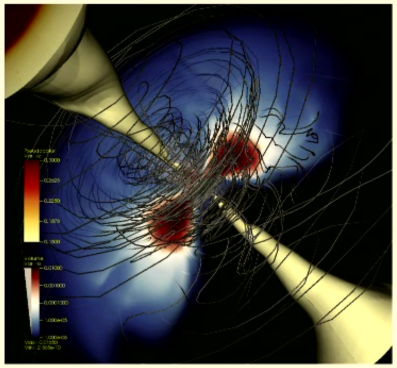
Das & Sharma 2013 (see also Wu+ 2016)

Viscous HD simulations



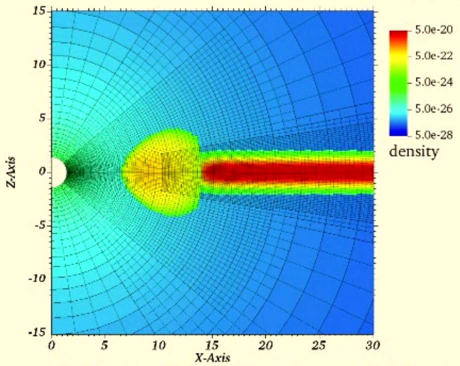
Hogg J. D., Reynolds C. S., 2017

GRRMHD simulations



Takahashi + 2016

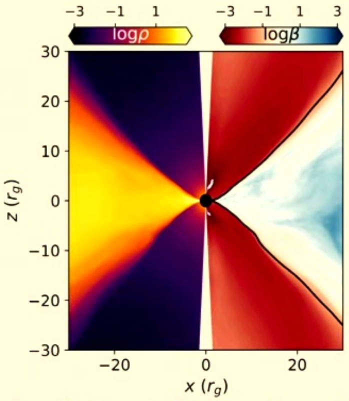
Truncated, Tilted Discs as a Possible Source of Quasi-Periodic Oscillations?



D. Bollimpalli C. Fragile,W. Dewberry, W. Kluźniak 2023

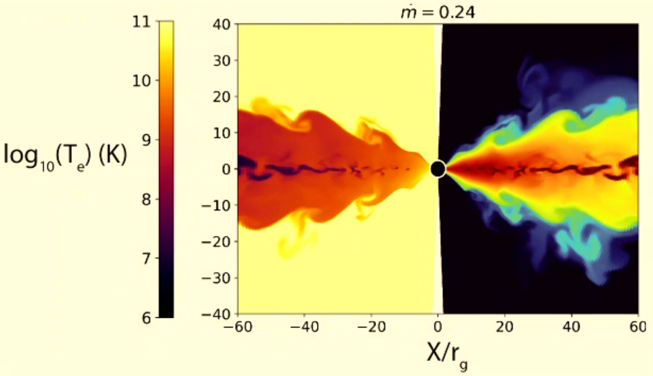
D. A. Bollimpalli, P. C. Fragile, W. Kluźniak 2022

GRRMHD Simulations of the collapse of a hot accretion flow



J. Dexter, N. Scepi, M. Begelman 2021

Viscous HD simulations of the corona and truncated disk



Nemmen, Vemado, Almeida+ 2023

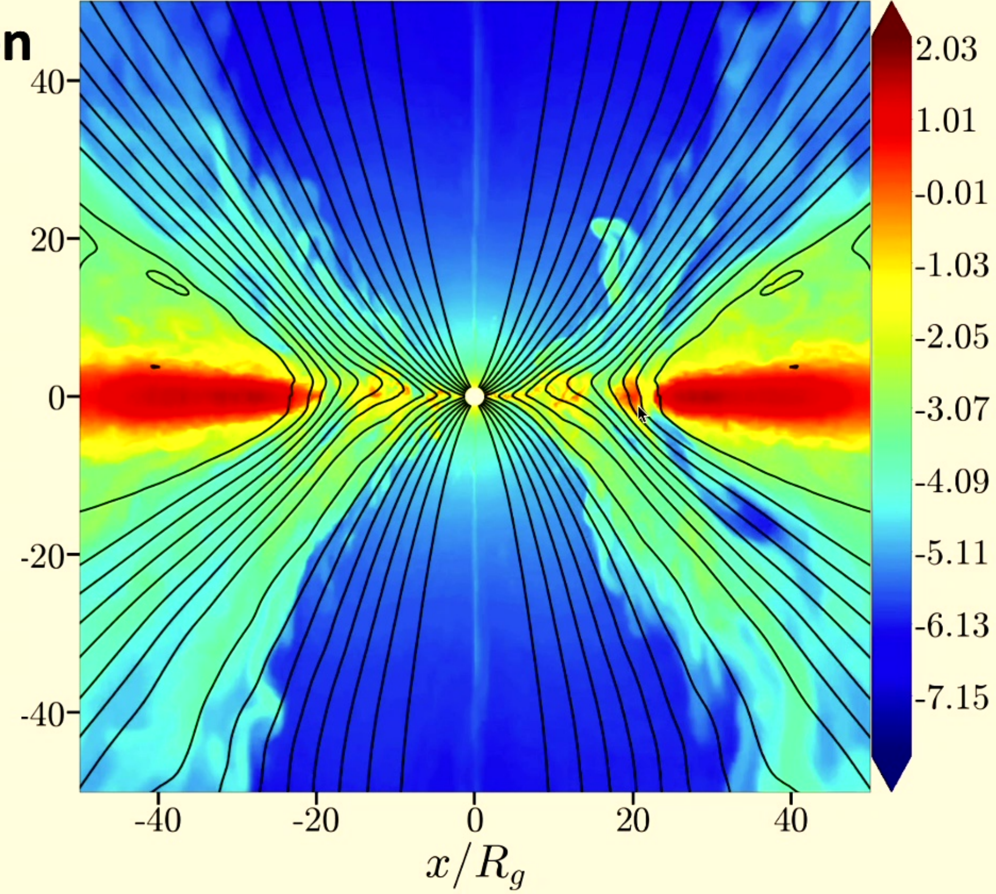
Simulating the long-term evolution of a thin accretion disk

Longest ever simulation of a thin accretion disk

Simulation specs:
Code: H-AMR (Liska+ 2019)
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

CSCS
PizDaint

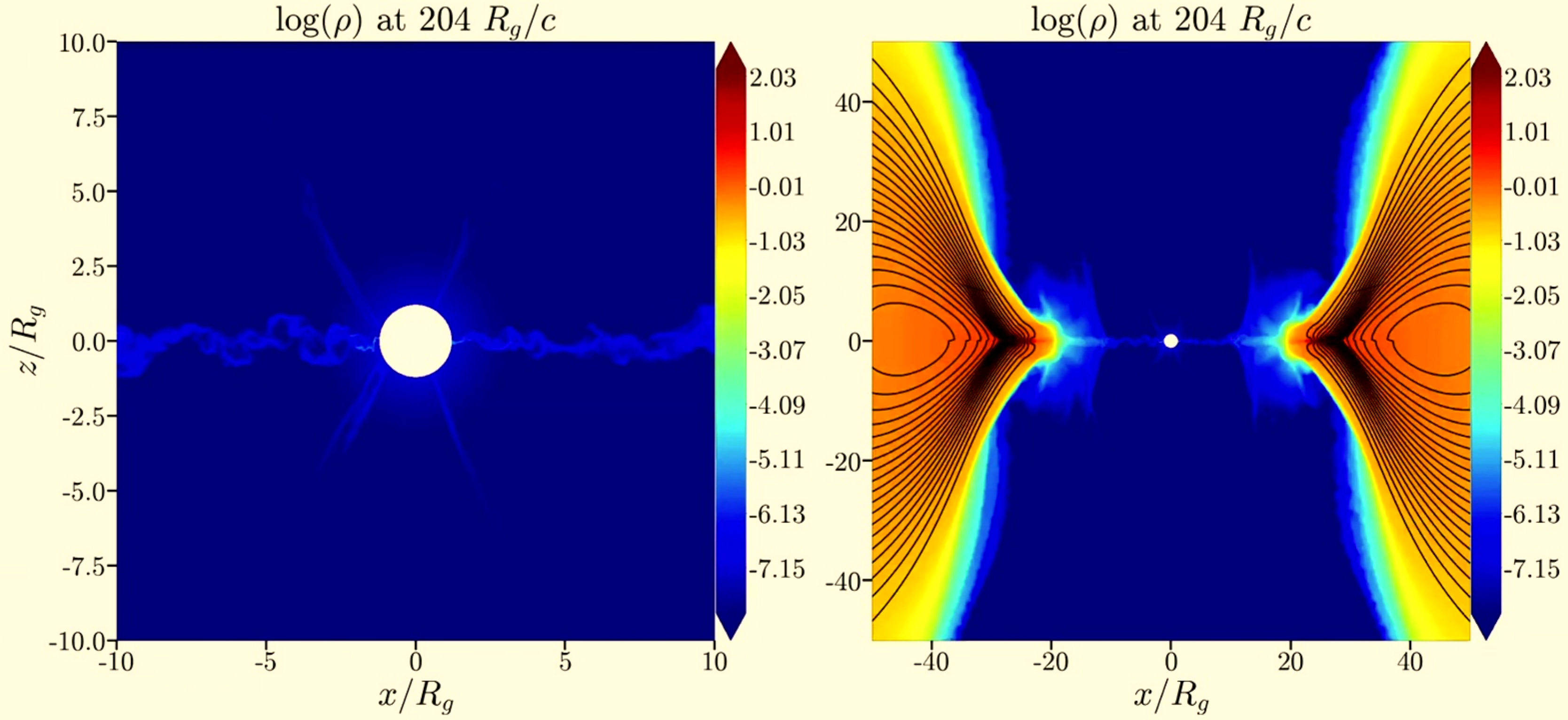
log(ρ) at 189539 R_g/c



Musoke, Porth, Liska+ (in preparation)

Evolution: Thin to truncated disk structure

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



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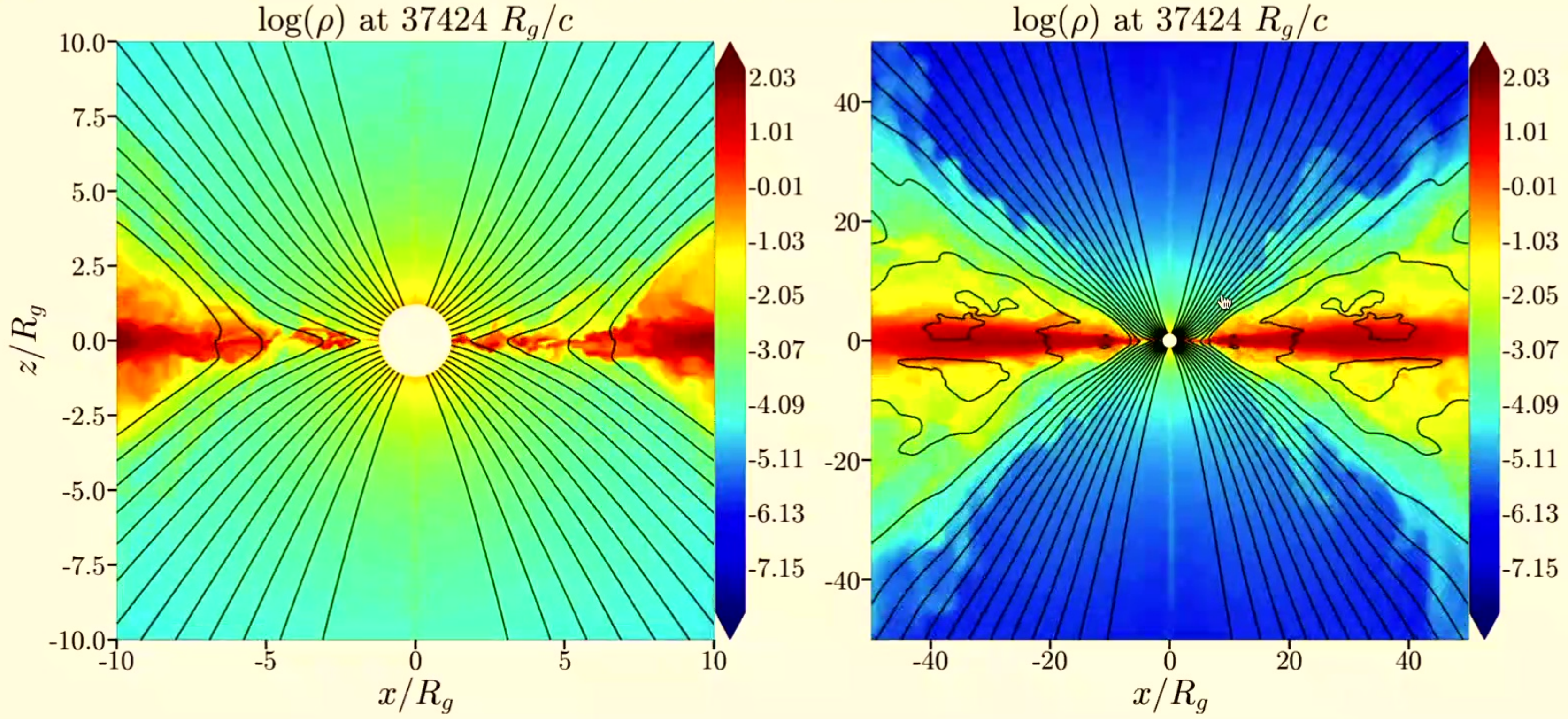


Musoke, Porth, Liska+ (in preparation)

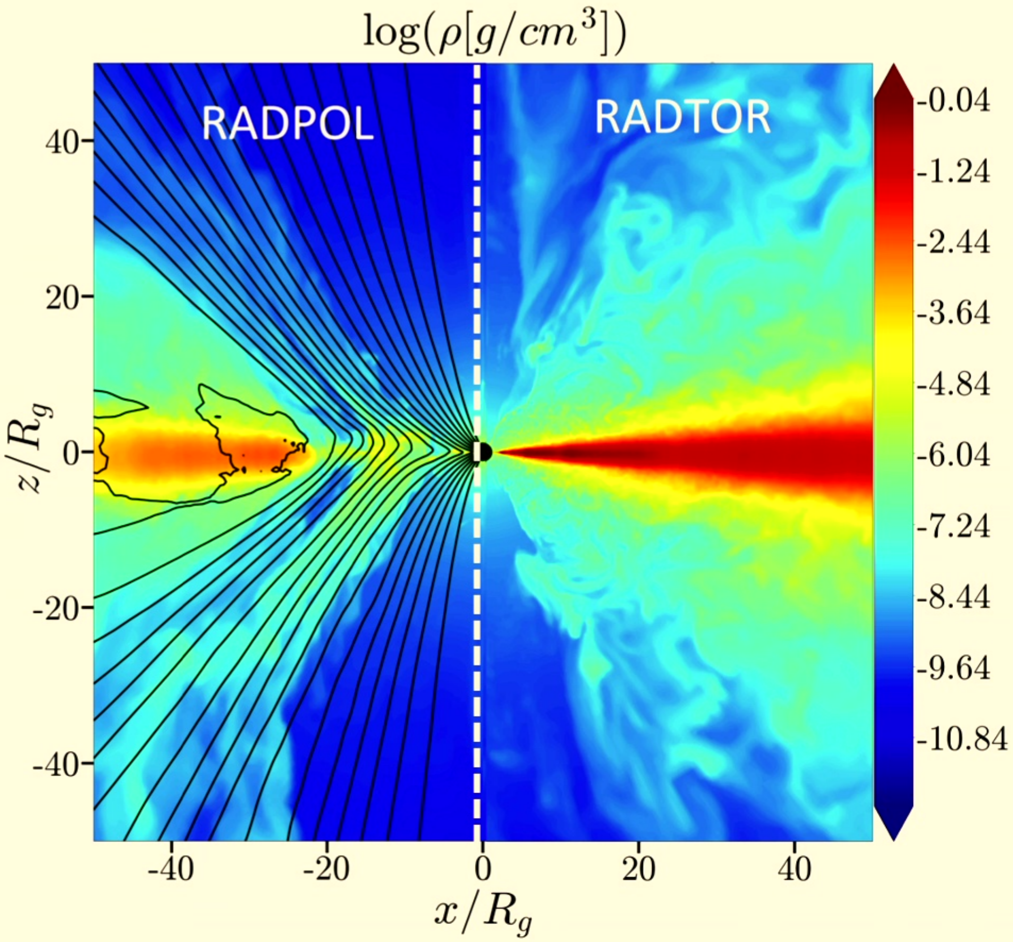
Type of B field matters for truncation: Poloidal vs Toroidal B fields

Poloidal B field

Large-scale poloidal B flux generated

Disk is truncated

Inner disk is MAD



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

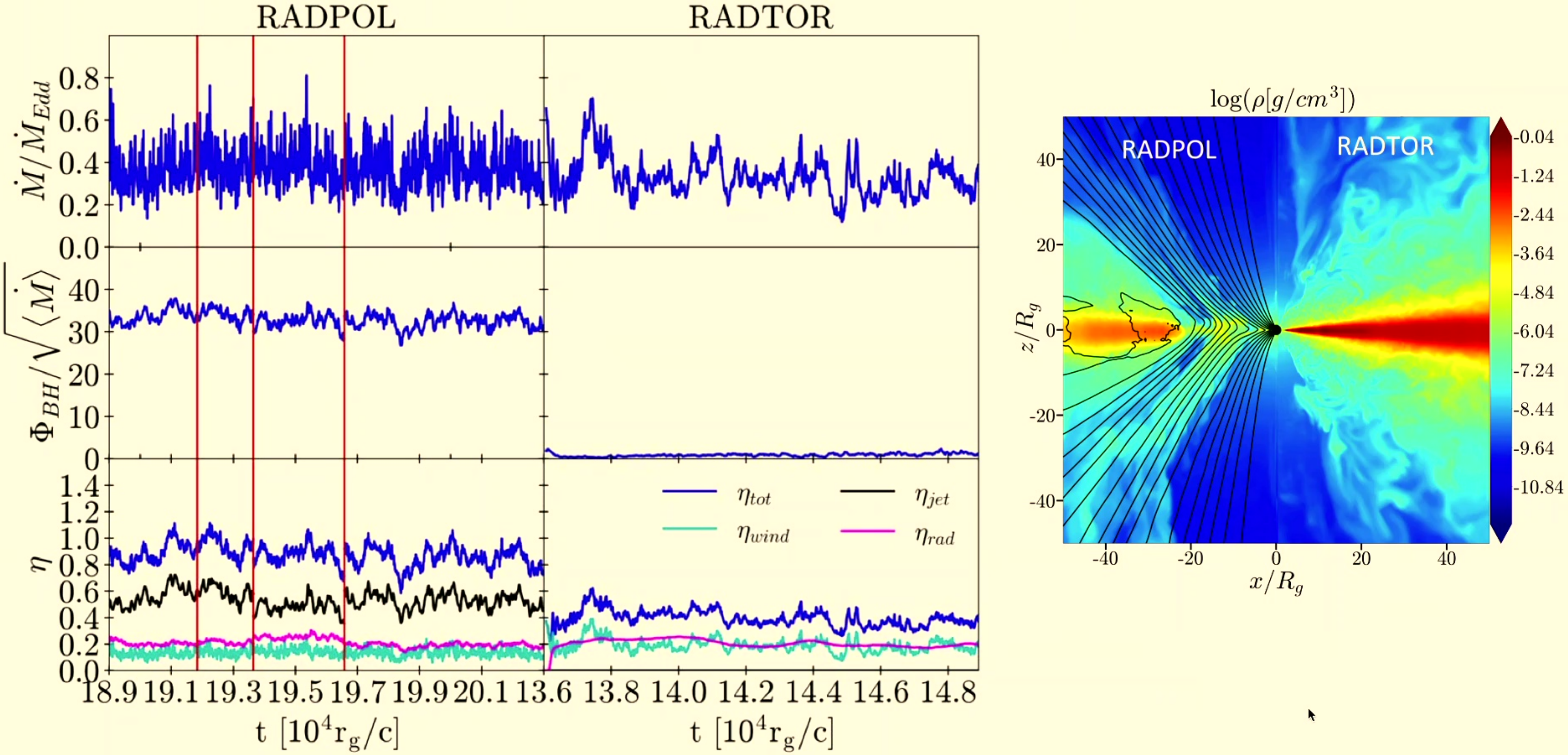
Toroidal B field

No large-scale poloidal B flux generated

Thin disk to ISCO

No disk truncation

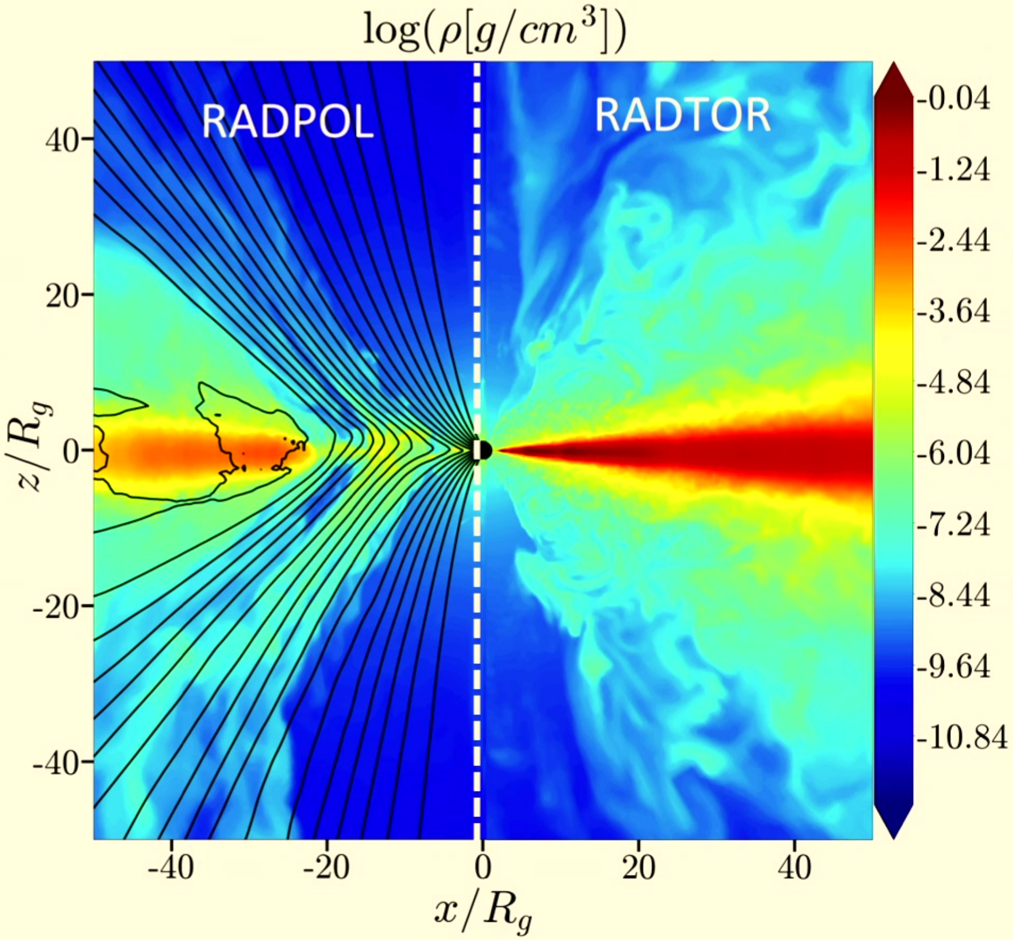
Type of B field matters for truncation: Poloidal vs Toroidal B fields



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

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

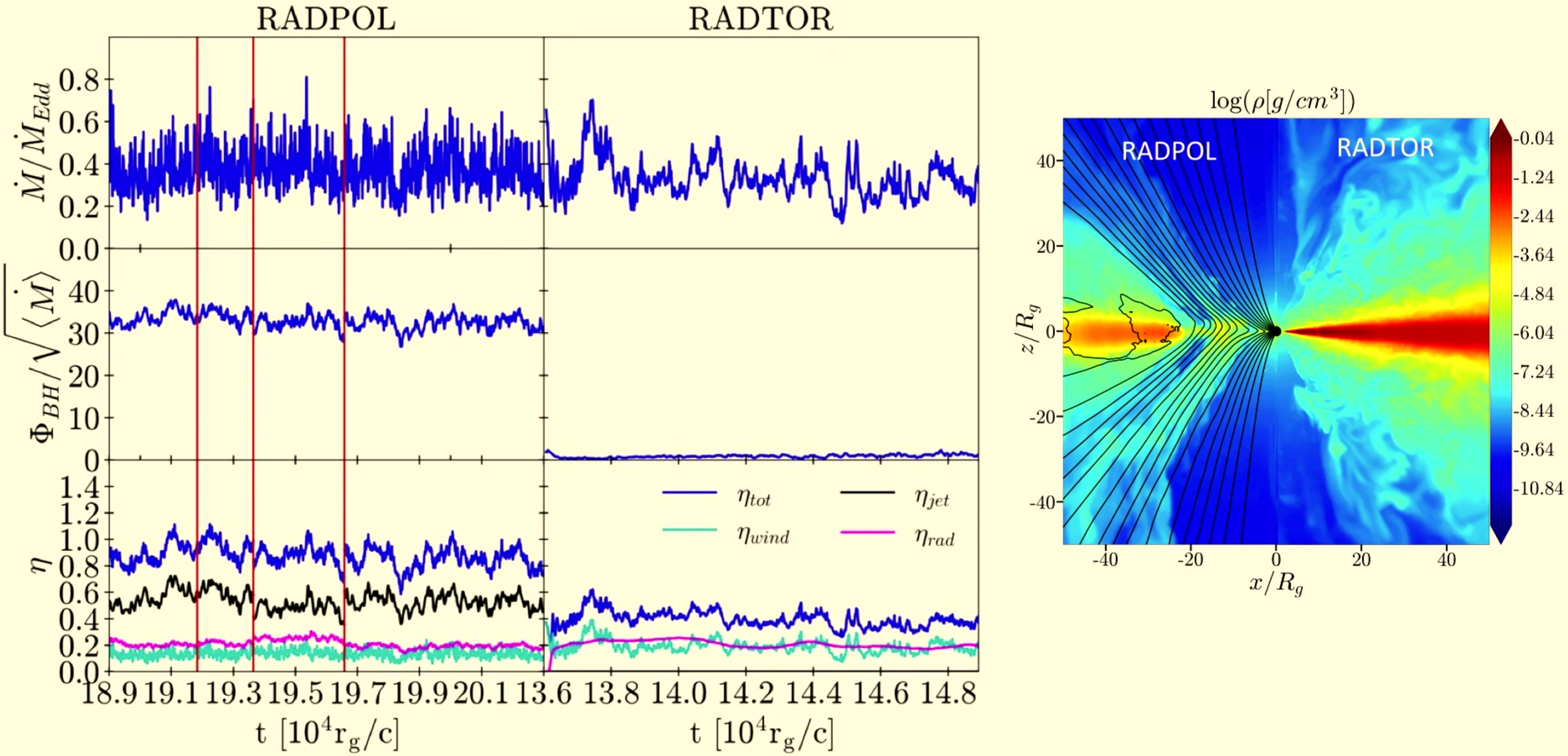
Poloidal B field
Large-scale poloidal B flux generated Disk is truncated Inner disk is MAD



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

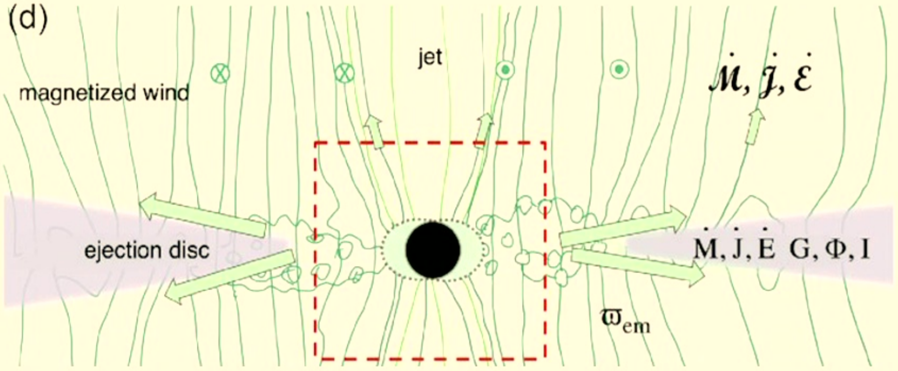
Toroidal B field
No large-scale poloidal B flux generated Thin disk to ISCO No disk truncation

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

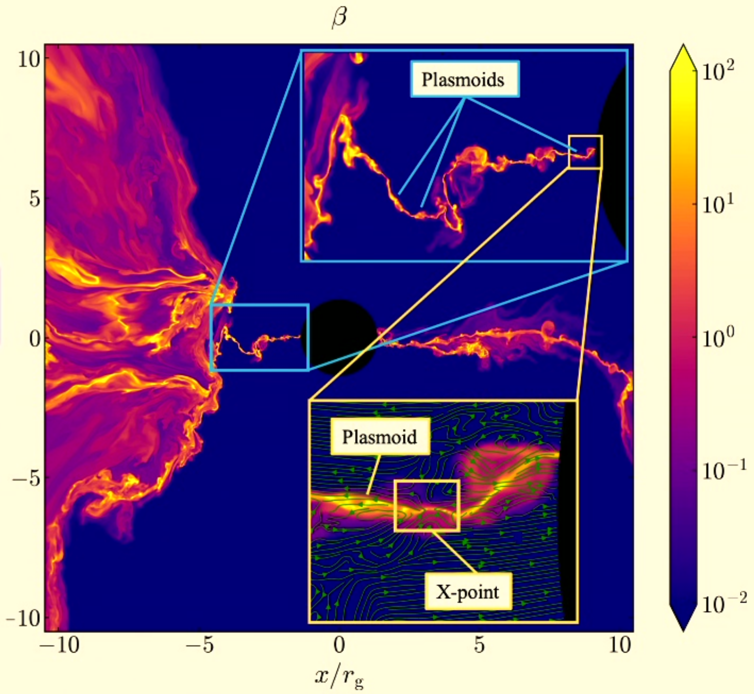


Liska, Musoke, Tchekhovskoy, Porth, Beloborodov 2022, ApJ

Disk structure and properties



Blandford & Globus 2022



Ripperda, Liska ,Chatterjee, Musoke+(2021)

Thick MAD disk case:

Flux eruptions short duration compared to accretion timescales

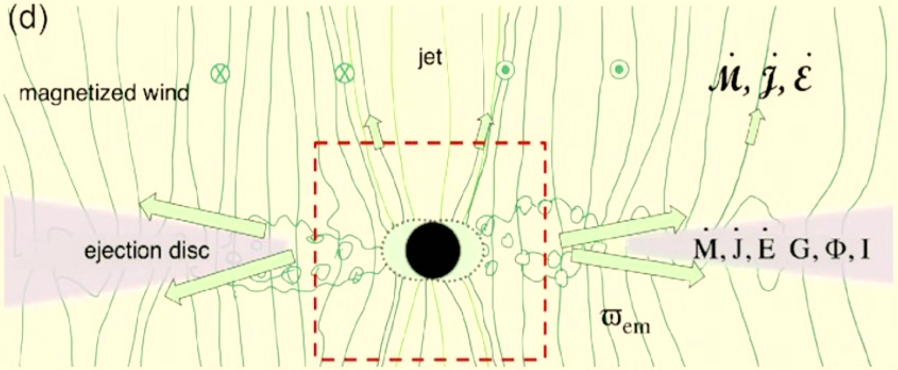
↓

Transient, non-axisymmetric magnetosphere

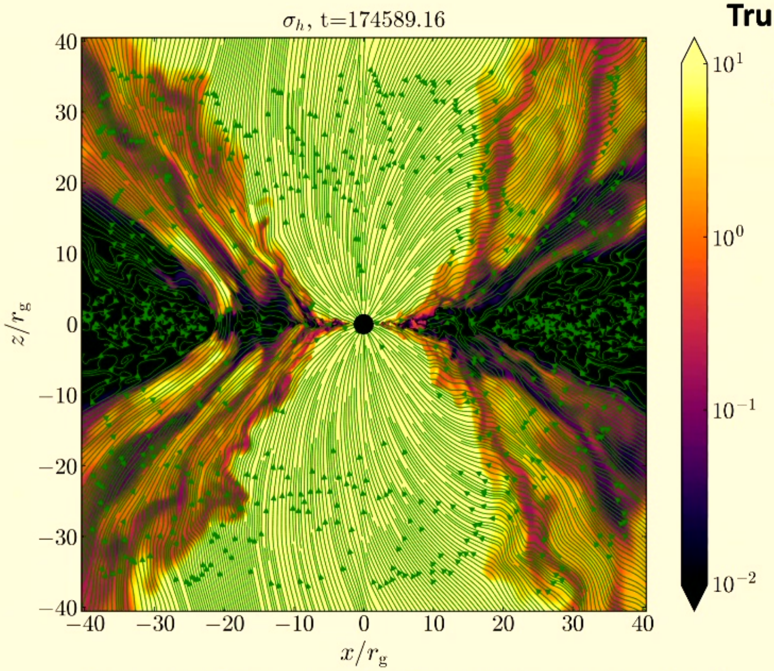
↓

Transient current sheet within few inner r_g

Disk structure and properties



Blandford & Globus 2022



Musoke, Ripperda, Philippov+ (in preparation)

Truncated MAD disk case:

Low density within truncation radius

↓

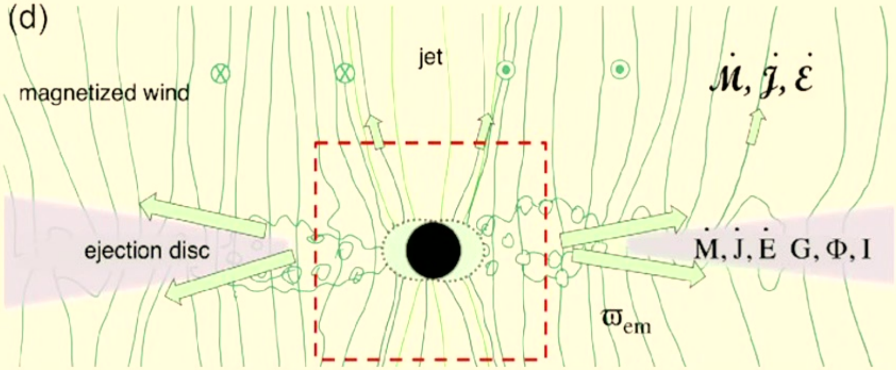
Easy to onset reconnection in the coronal current sheet

↓

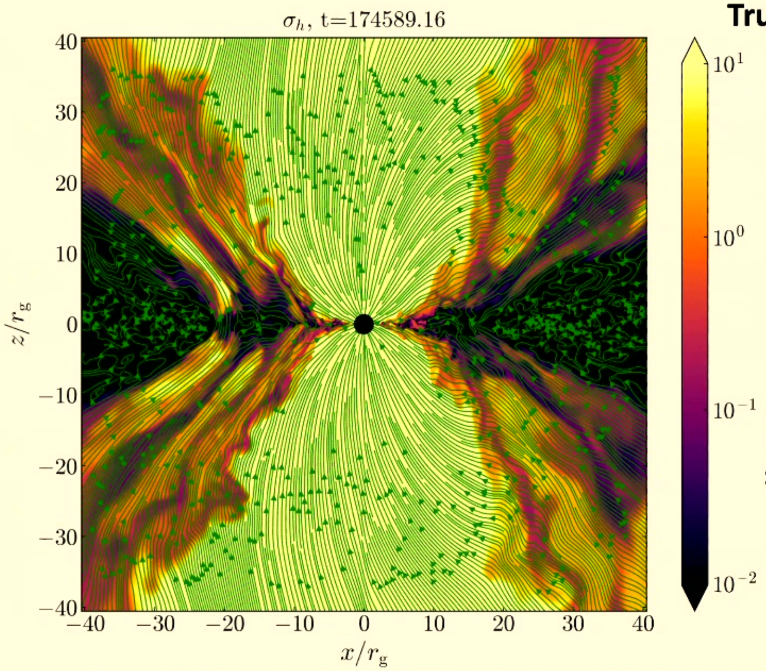
Many reconnection driven flux eruptions

Magnetisation Sigma_hot=B^2/(rho+gamma/(gamma-1)p)

Disk structure and properties



Blandford & Globus 2022



Musoke, Ripperda, Philippov+ (in preparation)

Truncated MAD disk case:

Flux eruptions occur continuously

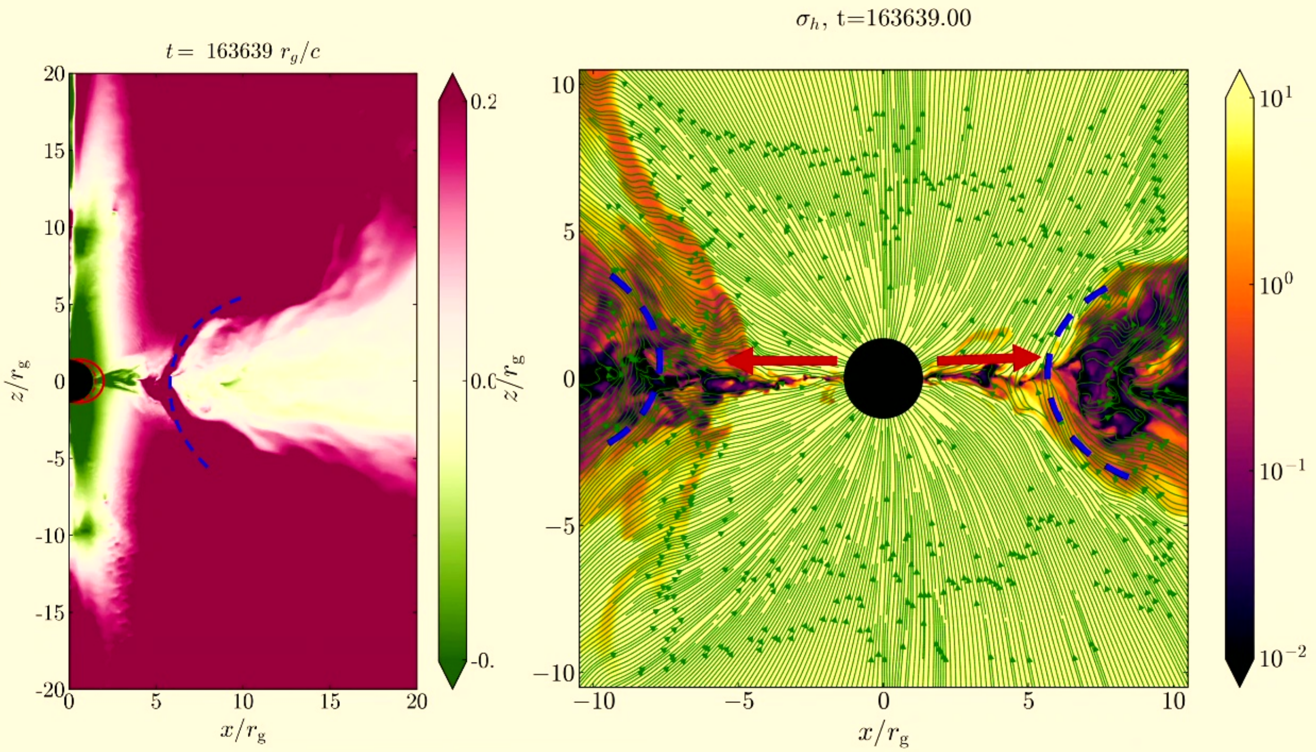
↓

Thin disk continuously 'blown away'

↓

Persistent thin current sheet, extending out to 10s of r_g

How does magnetic truncation actually work?



Musoke, Ripperda, Philippov+ (in preparation)

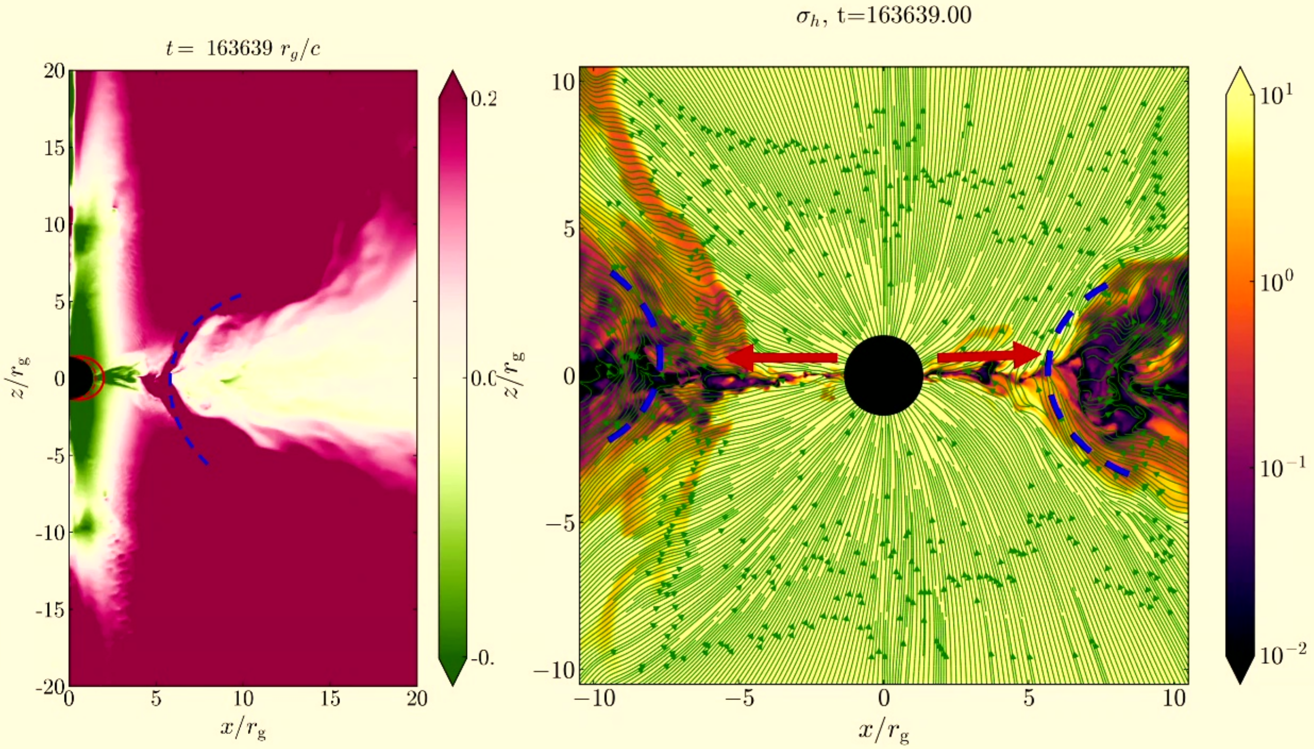
A compressed B field region is formed by the compression of multiple flux tubes

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

Flux tube acts as a barrier, stifling accretion in inner disk region

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

How does magnetic truncation actually work?



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

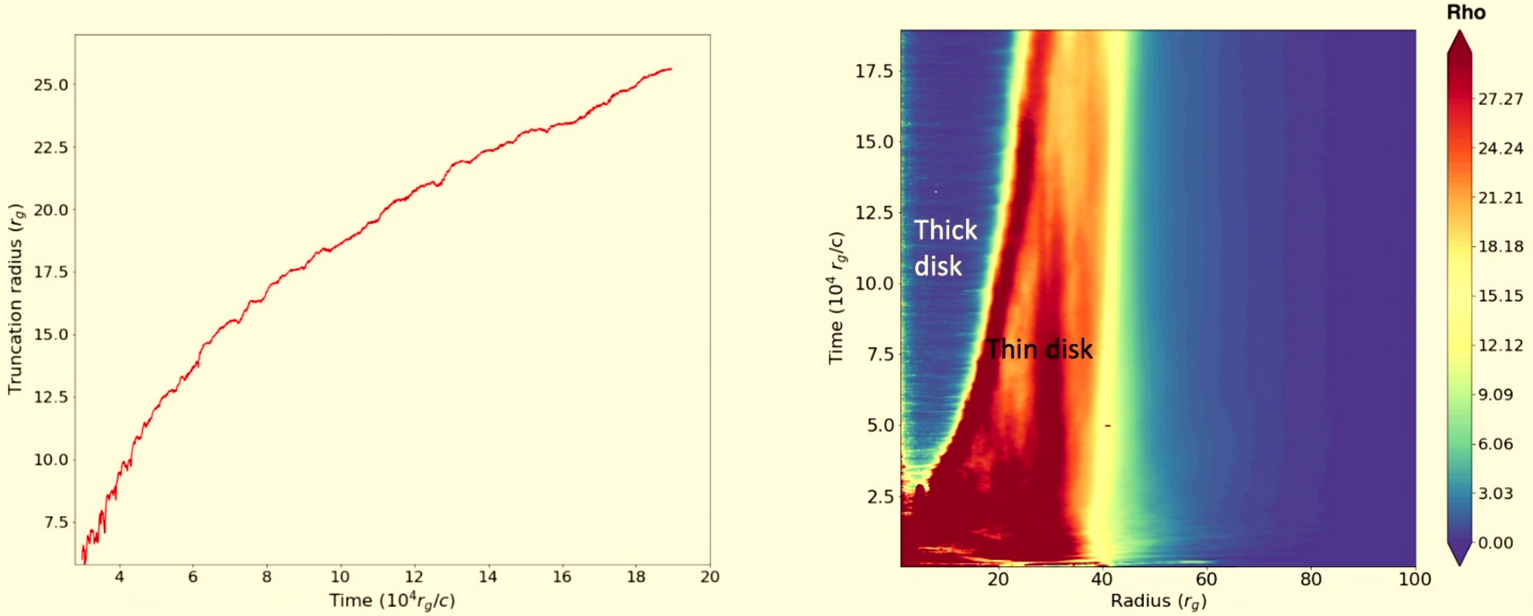
Flux tube acts as a barrier, stifling accretion in inner disk region

Material from the thin disk can punch through the 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)

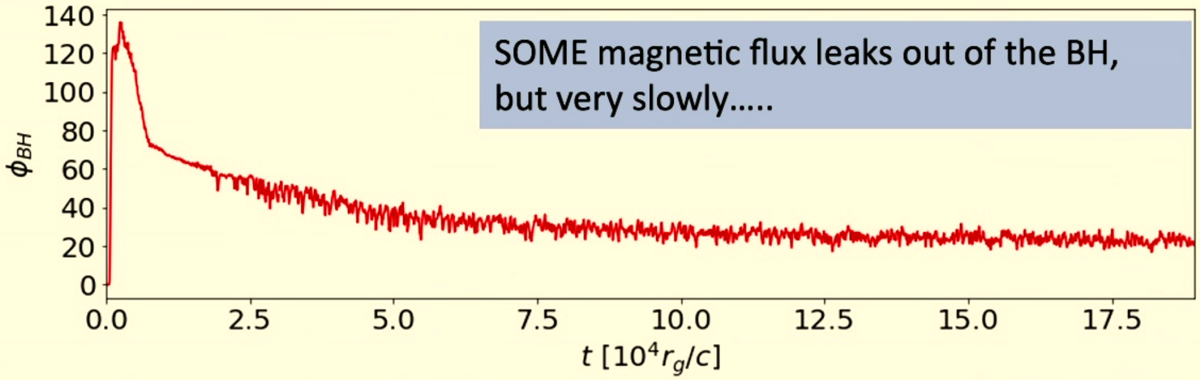
How does the truncation radius evolve?

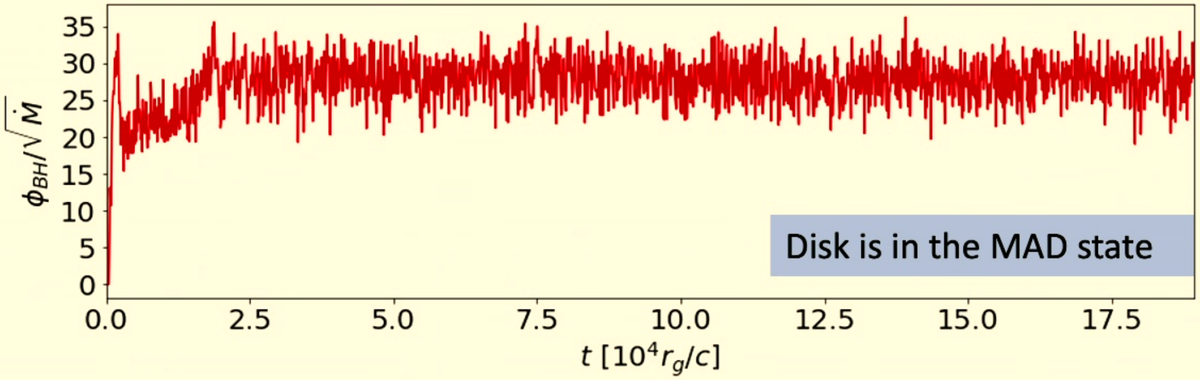
Disk truncation radius moves out with increasing evolution time!?

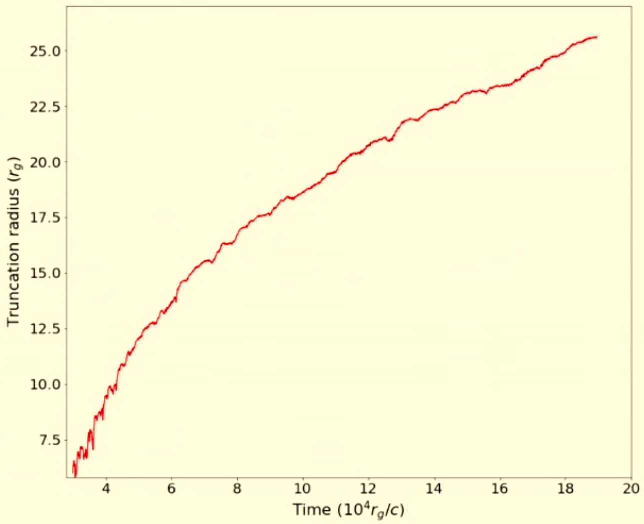


Musoke, Porth, Liska+ (in preparation)

Evolution of magnetic flux


SOME magnetic flux leaks out of the BH, but very slowly.....

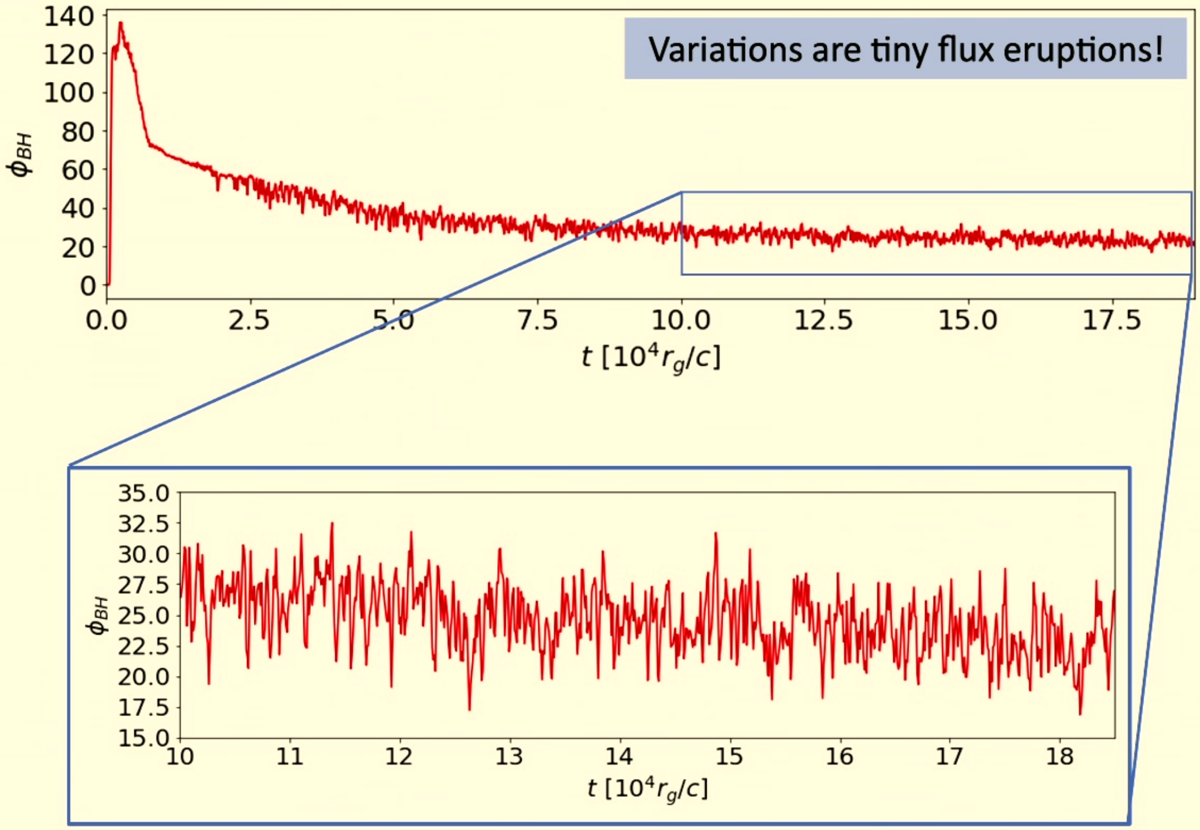

Disk is in the MAD state



Musoke, Porth, Liska+ (in preparation)

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

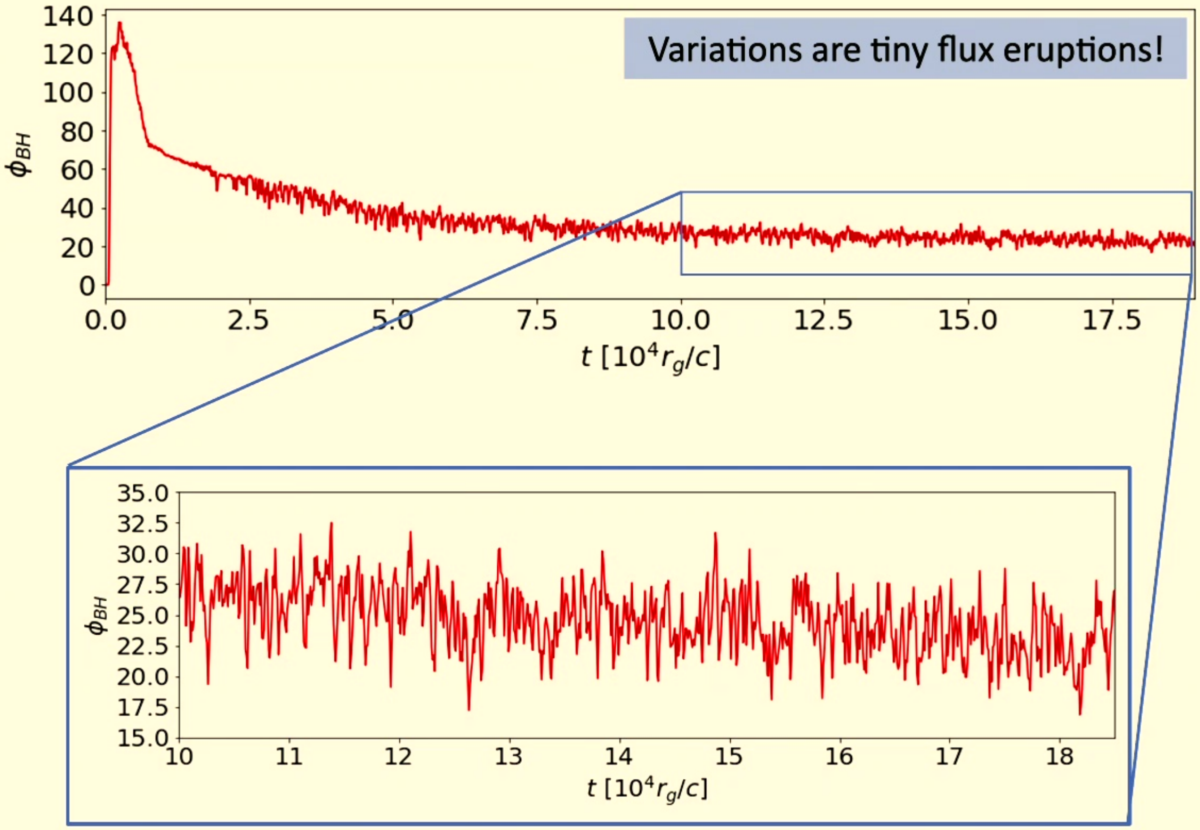
Evolution of magnetic flux



Variations are tiny flux eruptions!

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

Evolution of magnetic flux



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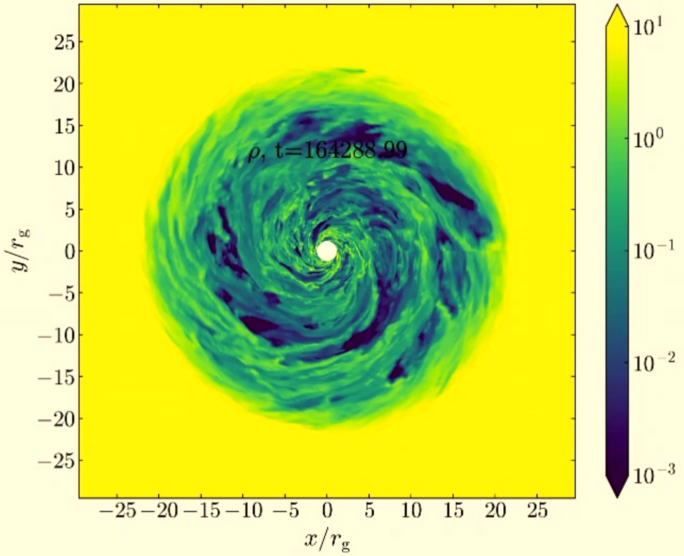
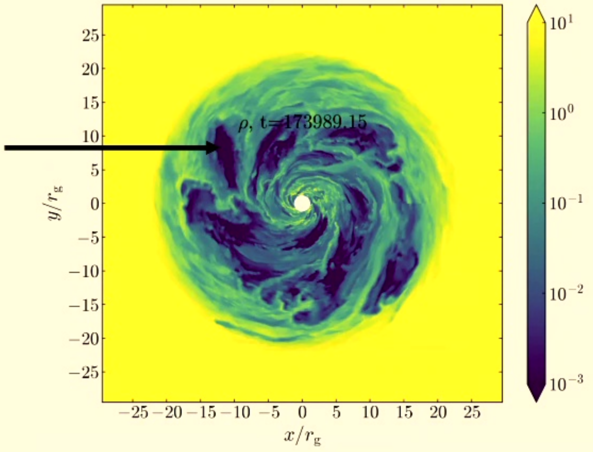
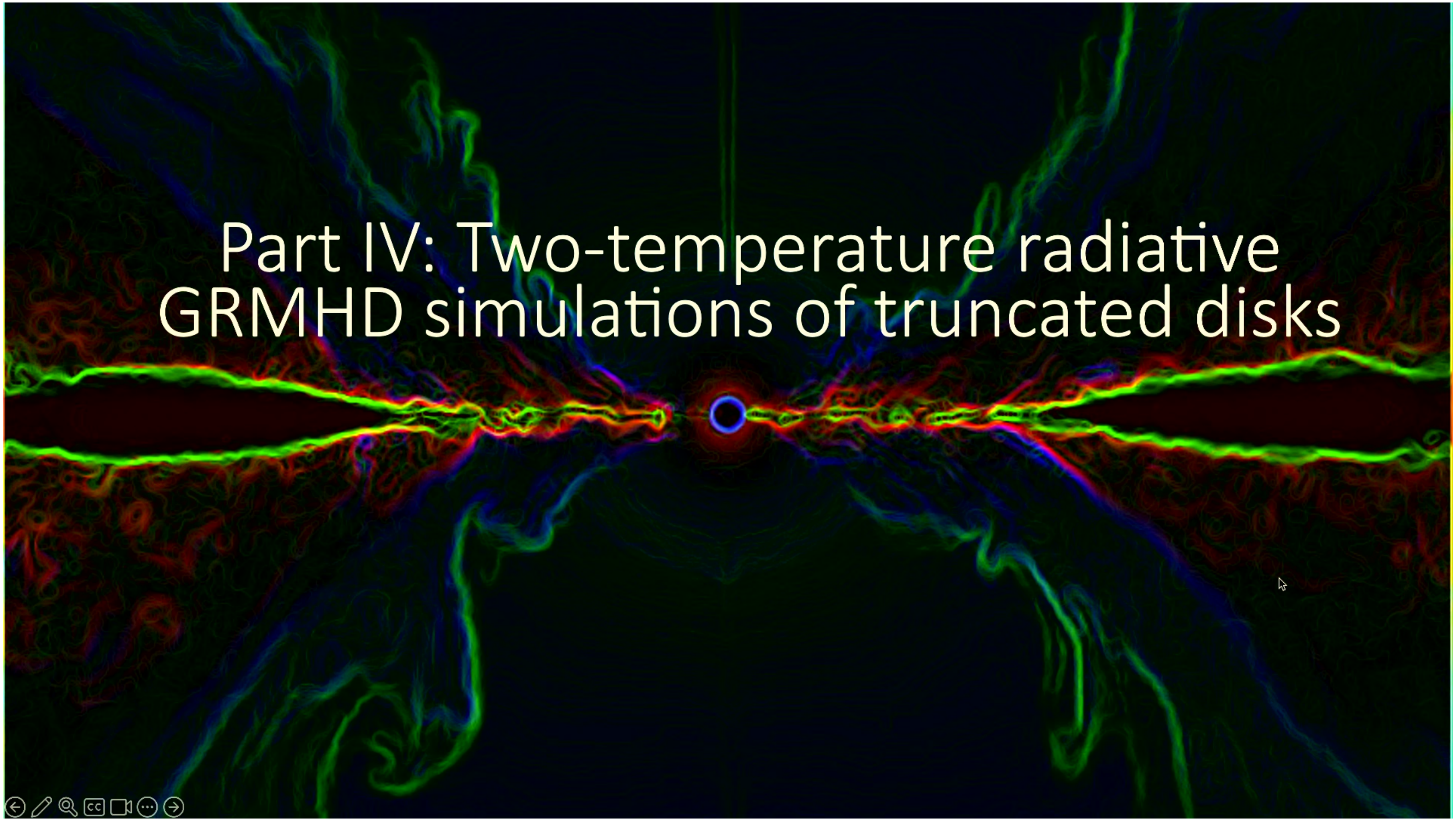




Musoke, Porth, Liska+ (in preparation)
Musoke, Ripperda, Philippov+ (in preparation)



Part IV: Two-temperature radiative GRMHD simulations of truncated disks

Radiative GRMHD + 2T truncated disk simulation

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

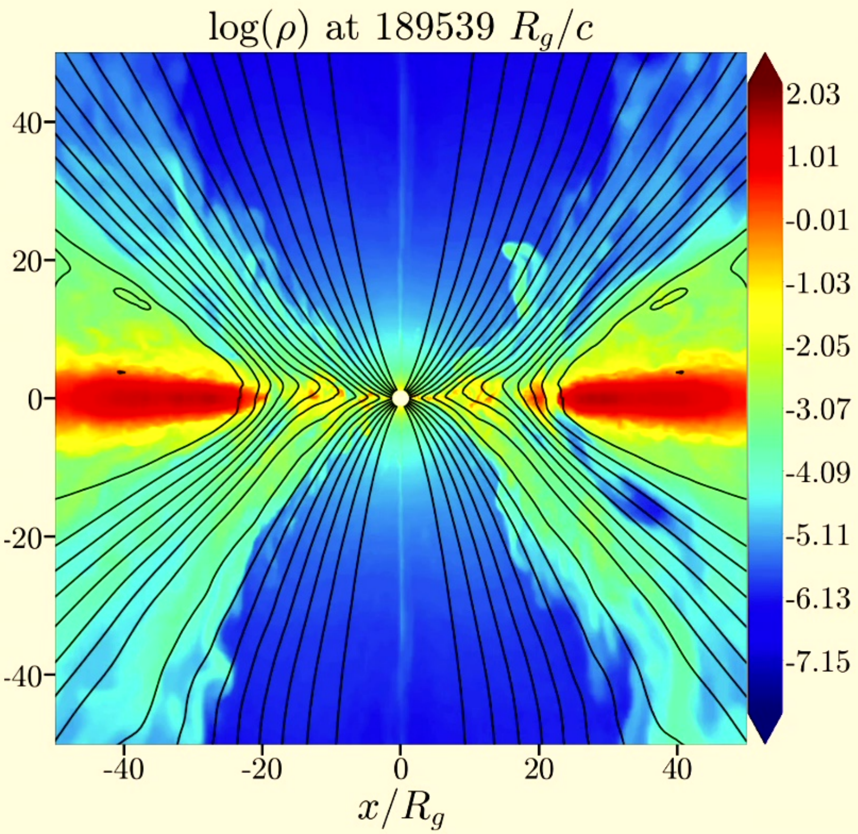
How is the corona formed (self-consistently)?

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

Angular momentum and mgnetic flux transport in truncated disks?

3D Radiative + 2T GRMHD simulations

log(ρ) at 189539 R_g/c

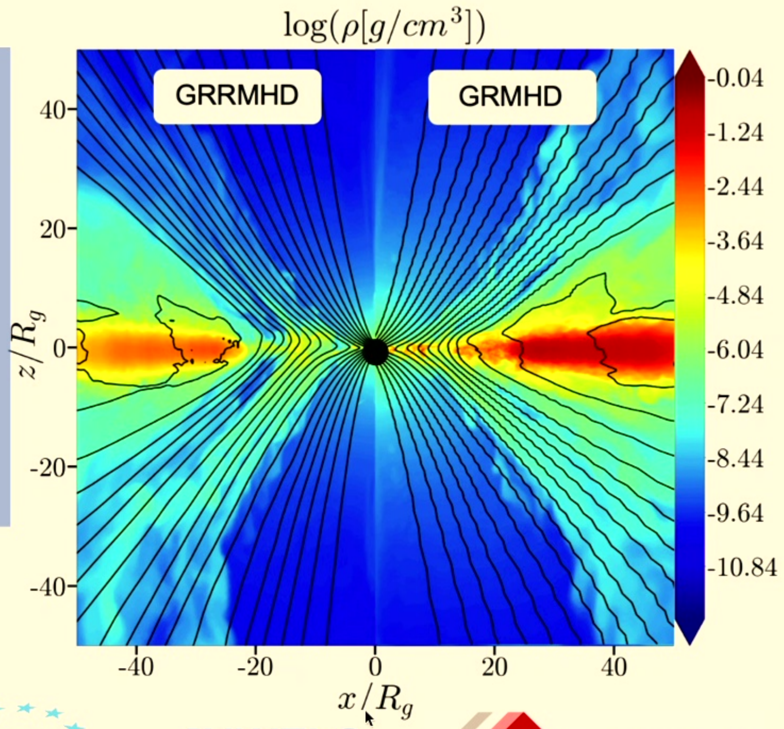


Musoke, Porth, Liska (in preparation)

Radiative GRMHD + 2T simulation

Radiative GRMHD simulation with 2T thermodynamics:
Liska, Musoke, Porth, Tchekhovskoy, Beloborodov, 2022 ApJ, https://arxiv.org/abs/2201.03526,

Simulation specs:
Code: H-AMR
Cluster: JUWELS-Booster
Radiative GRMHD + 2T Thermodynamics
H/R = 0.03
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

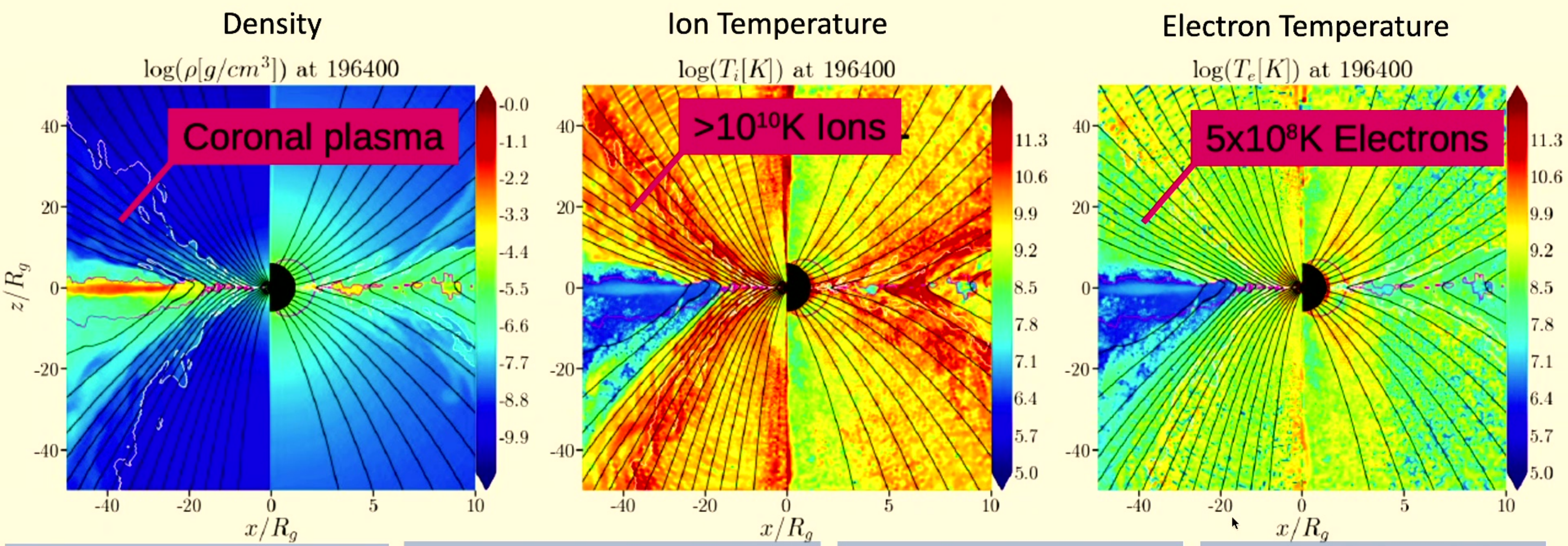
$$\dot{M}/\dot{M}_{\rm Edd} \simeq 0.35$$

PRACE

JUWELS Booster

CSCS PizDaint

Radiative GRMHD + 2T simulation: Disk evolution



Density

Ion Temperature

Electron Temperature

Coronal plasma

$>10^{10}$K Ions

5×10^{8}K Electrons

Disk threaded by large scale poloidal flux promotes 2T regions and truncation

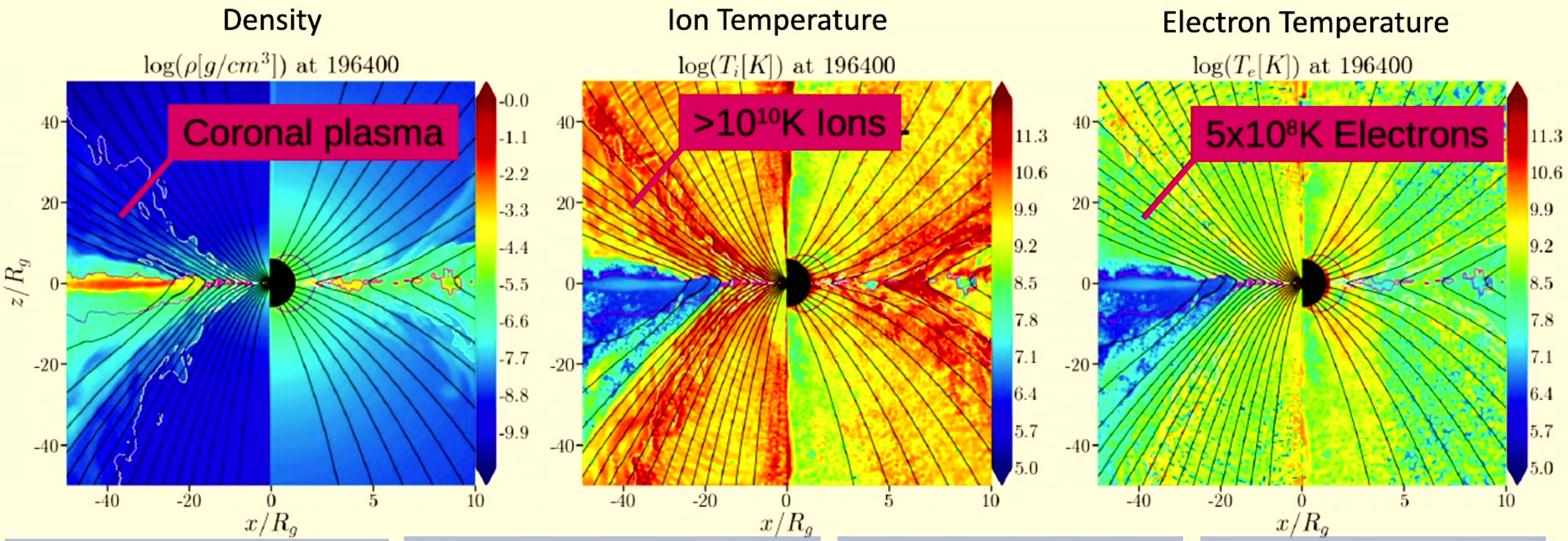
Develop low density, thick hot corona with $T_i > T_e$.

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)

Radiative GRMHD + 2T simulation: Disk evolution



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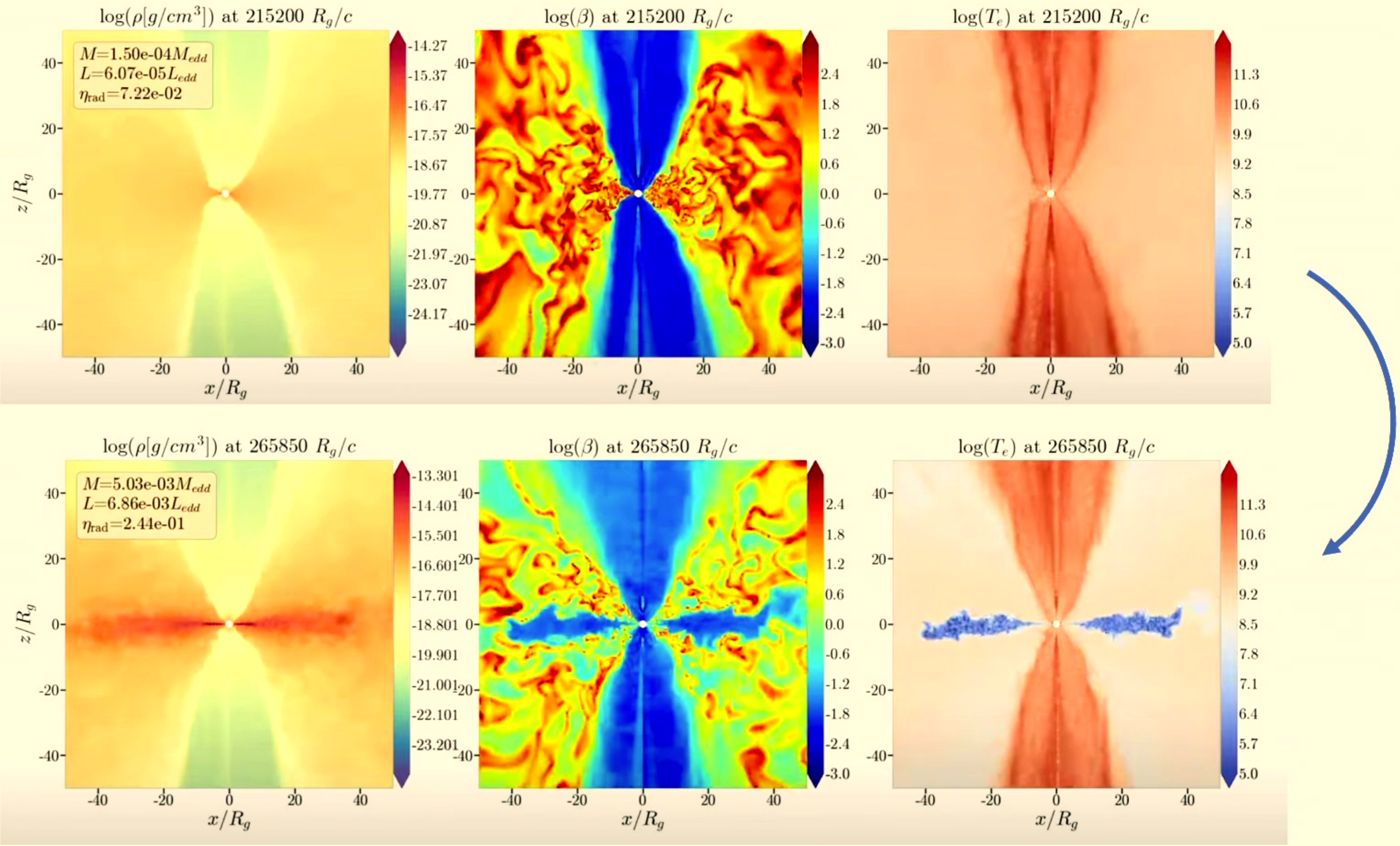
Liska, Musoke, Tchekhovskoy, Porth, Beloborodov 2022, ApJ
Musoke, Ripperda, Philippov+ (in preparation)

May explain broad iron line emission observed in the hard spectral states of XRBs and AGN.

‘State transitions’- Low to high, SANE AGN

Artificially shorten transition timescale by rescaling the accretion rate as a function of time for both SANE and MAD disks



Spectral signatures in state transitions are tied closely to level of magnetic flux saturation:

SANE → Sandwich

MAD → Truncated?

Liska, Kaaz, Chatterjee, Emami, Musoke, submitted, 2024

Summary and Conclusions

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

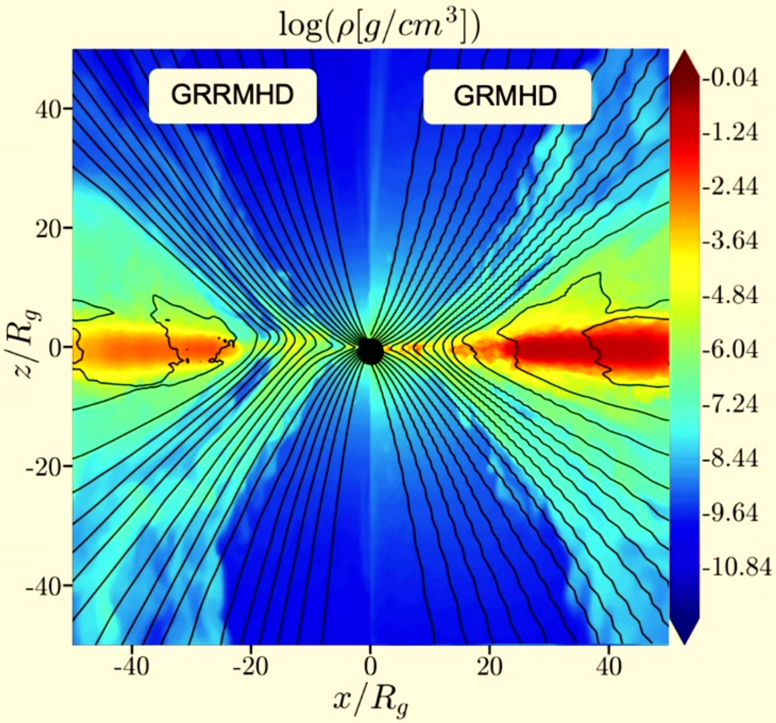
- Truncation radius is determined by location of region dominated by poloidal B flux
- Constant flux eruptions and generation of flux tubes promote truncation.
- Expelled flux tubes bend into a c-shape, truncating the disk

Large-scale magnetic stress governs AM transport within truncation radius

- → Blandford Payne wind

Cool patches of gas at corona midplane may explain broad iron line emission.

Next generation GPU-accelerated radiative GRMHD simulations are allowing us to probe the physics of the corona.



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

Musoke, Porth, Liska+ (in preparation)

Musoke, Ripperda, Philippov+ (in preparation)