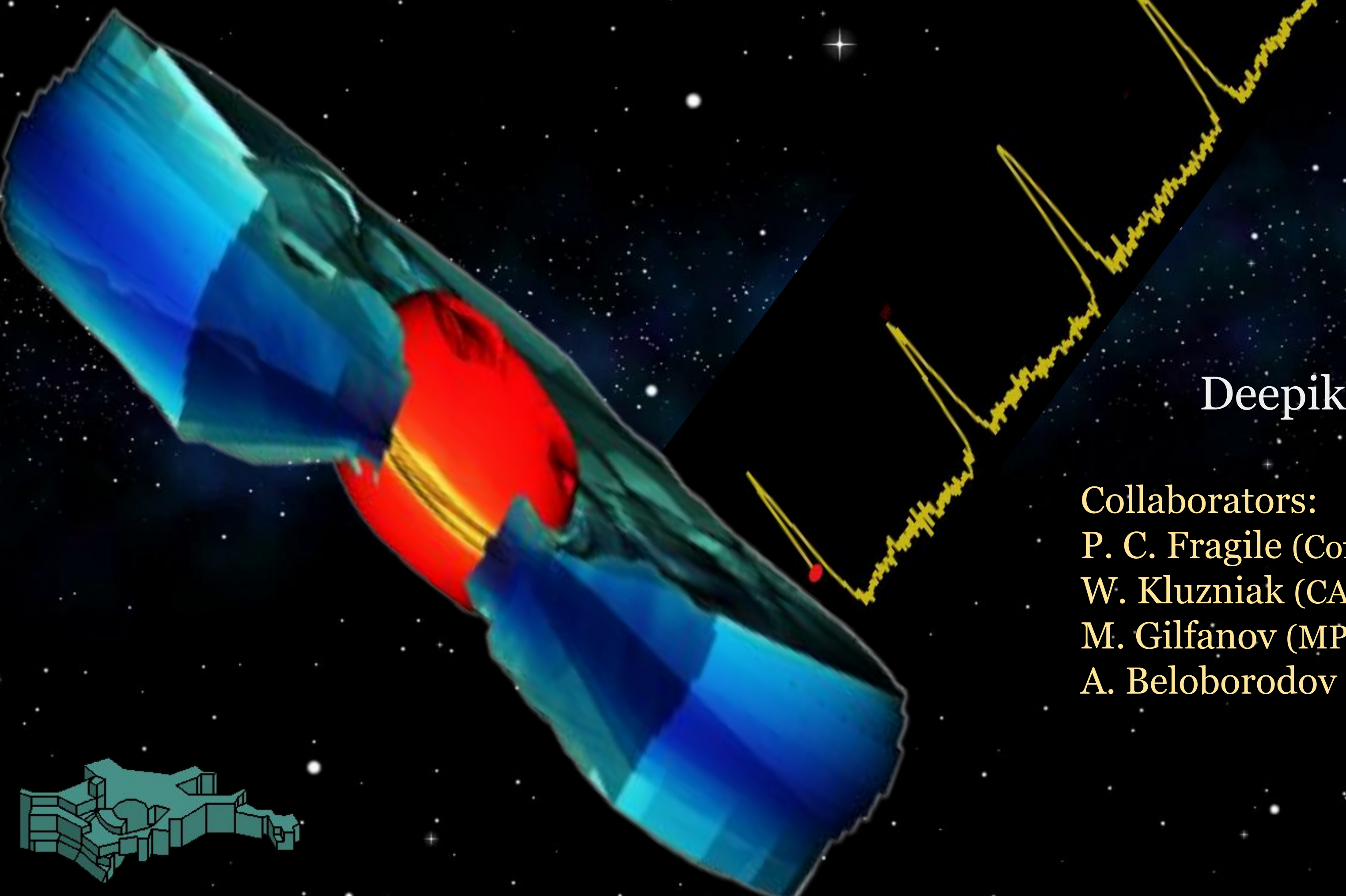
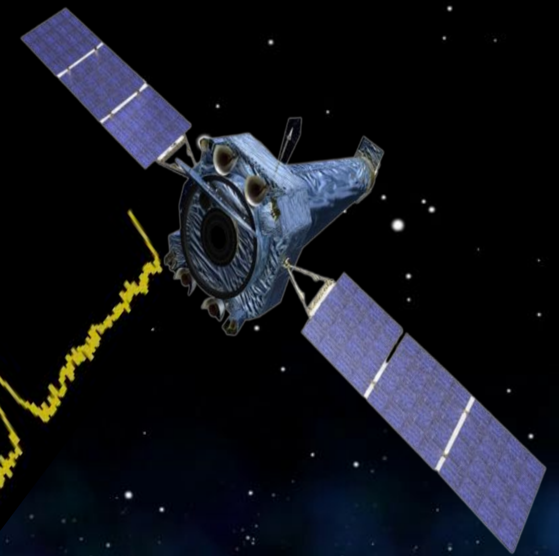
Variability in discs around black holes : Broadband variability & QPOs





Deepika Bollimpalli

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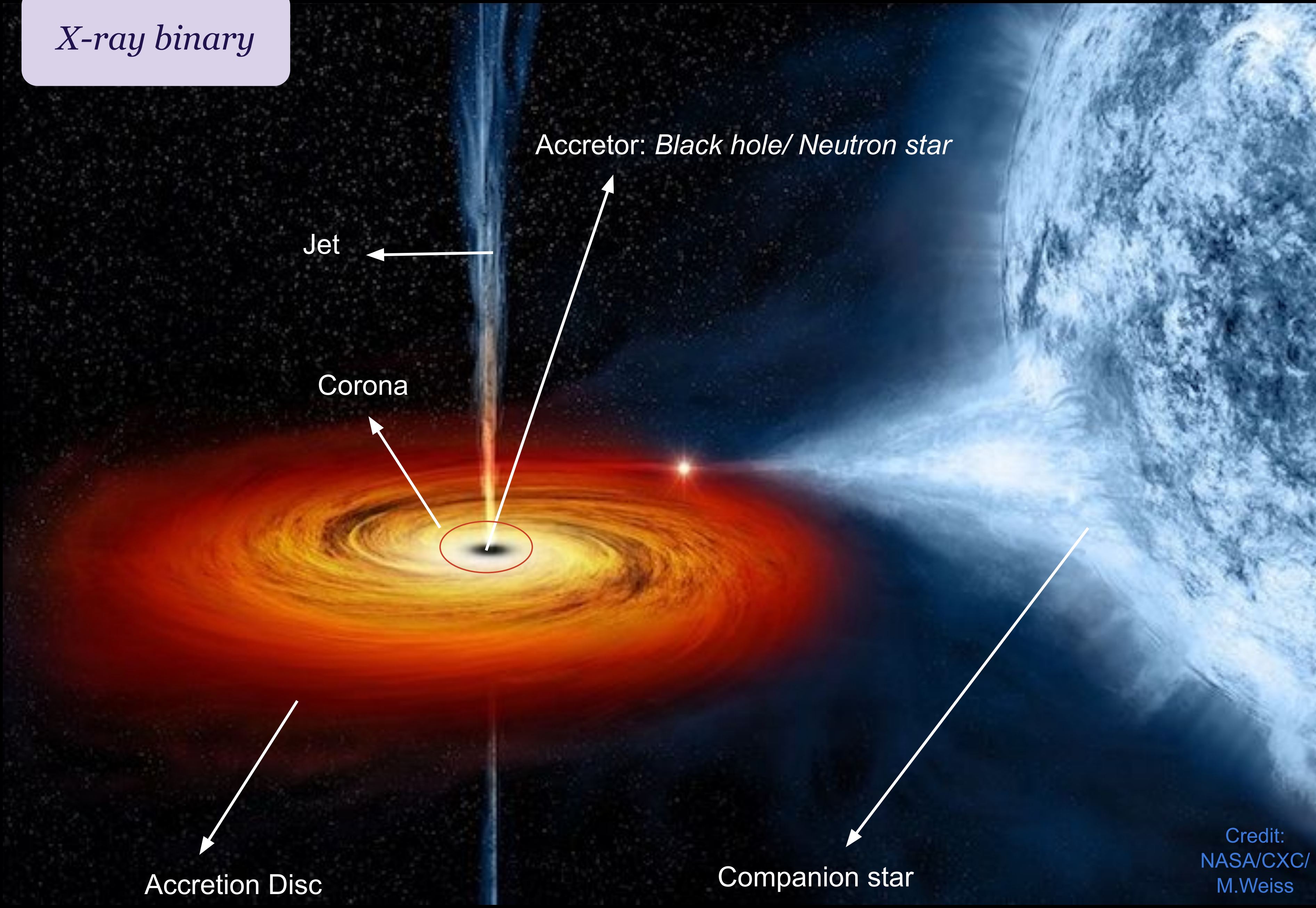
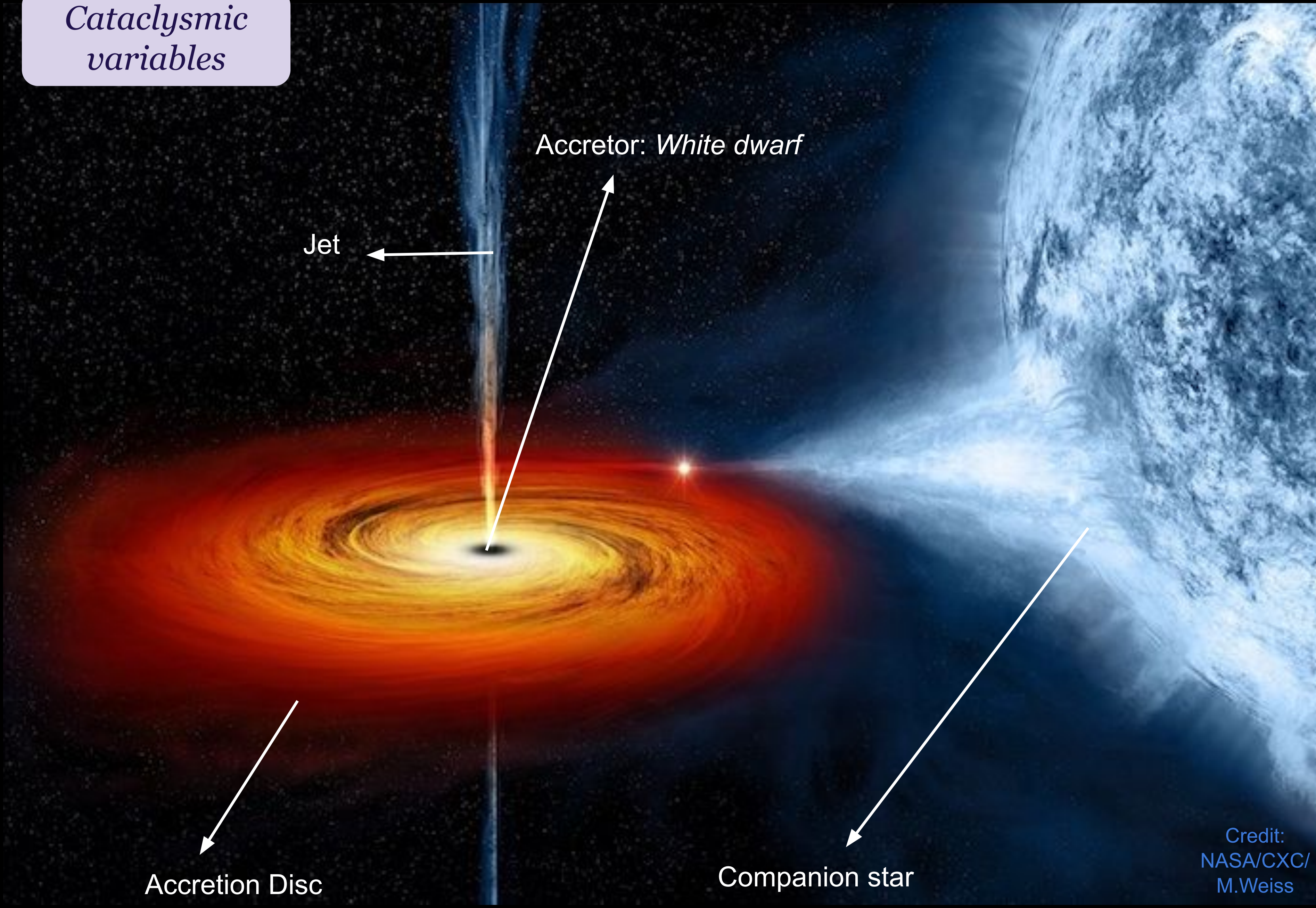
Max Planck Institute for Astrophysics, Garching

May 17, 2022
Growing Black Holes: Accretion and Mergers, Kathmandu

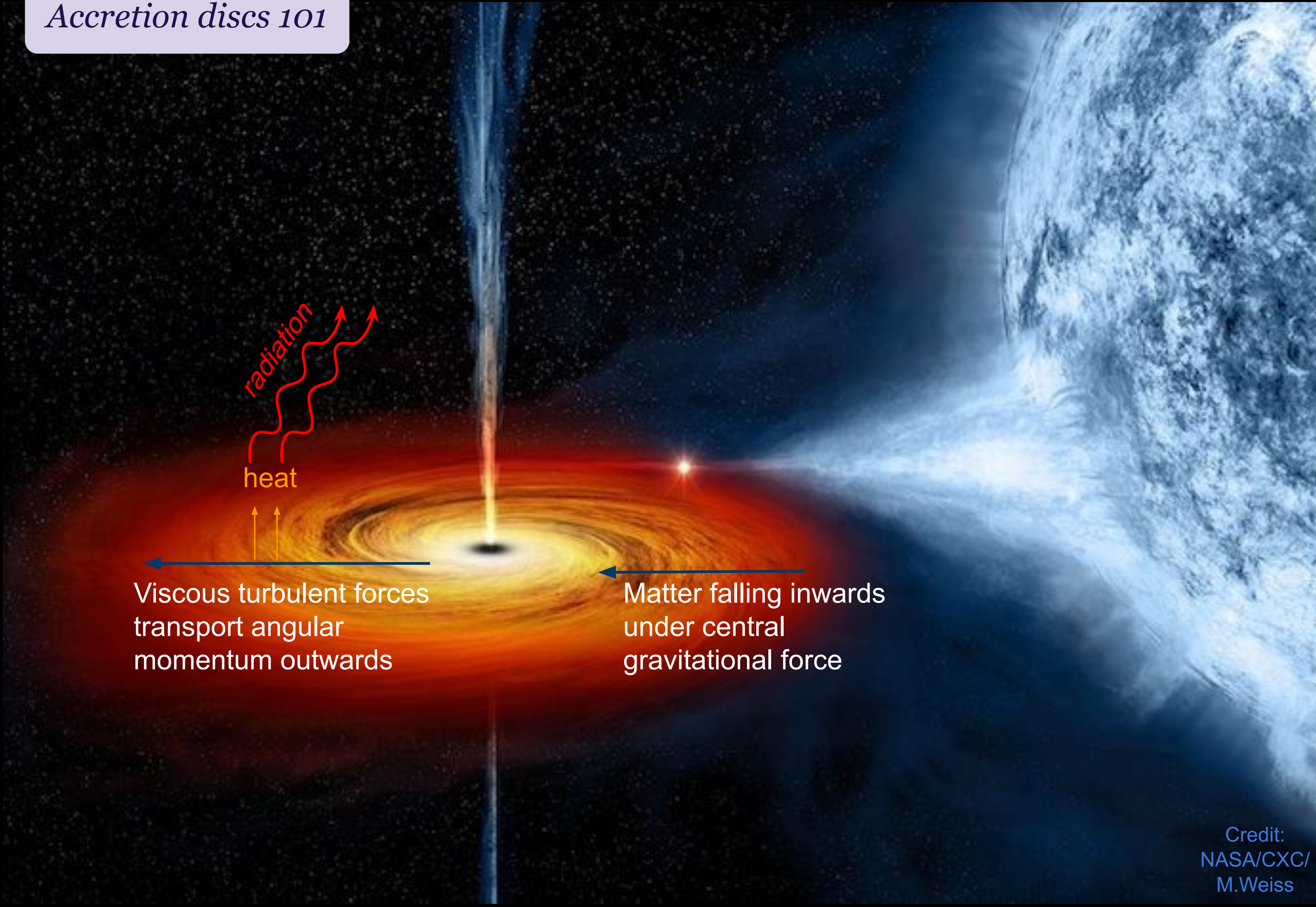
X-ray binary


Accretor: *Black hole/ Neutron star*
Jet
Corona
Accretion Disc
Companion star
Credit: NASA/CXC/ M.Weiss

Cataclysmic variables



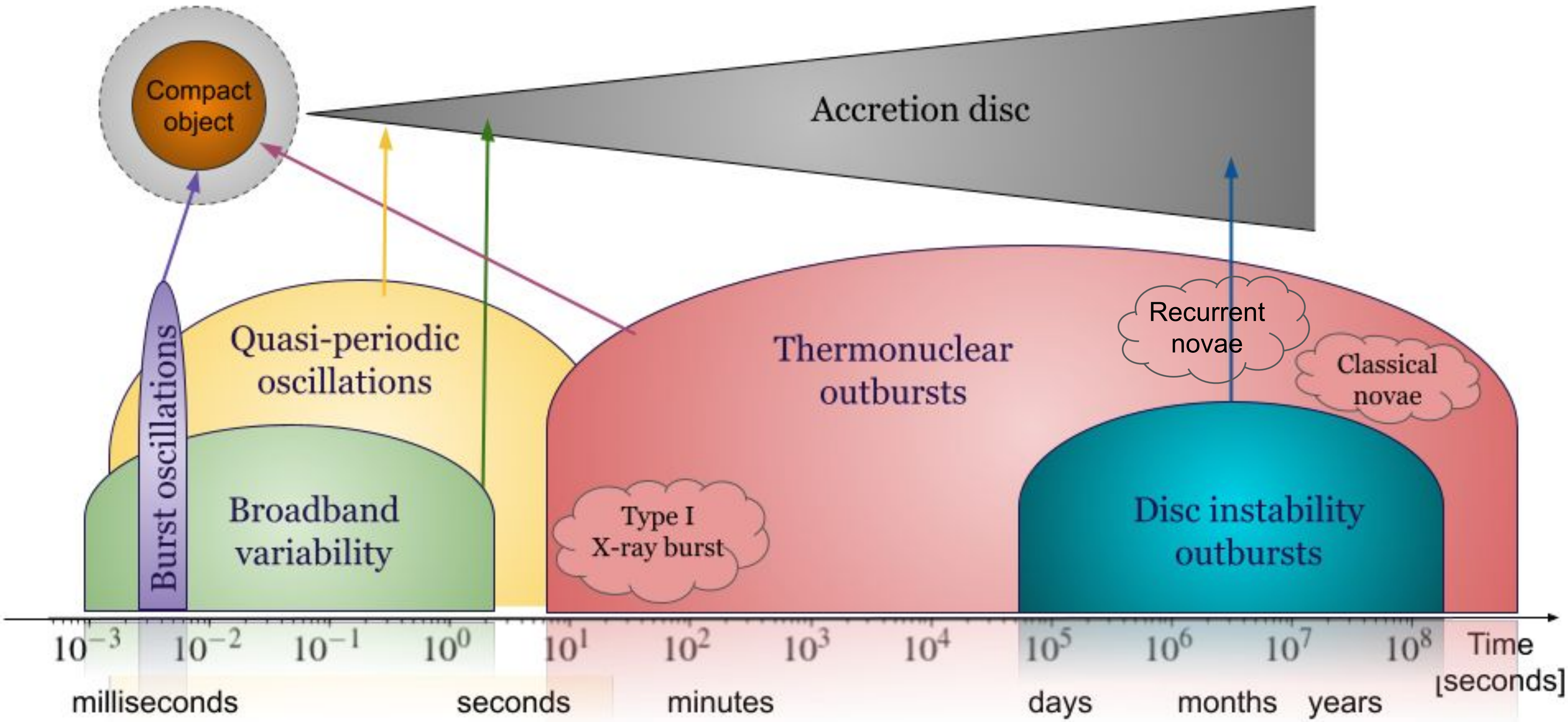
Accretion discs 101



Credit: NASA/CXC/ M.Weiss

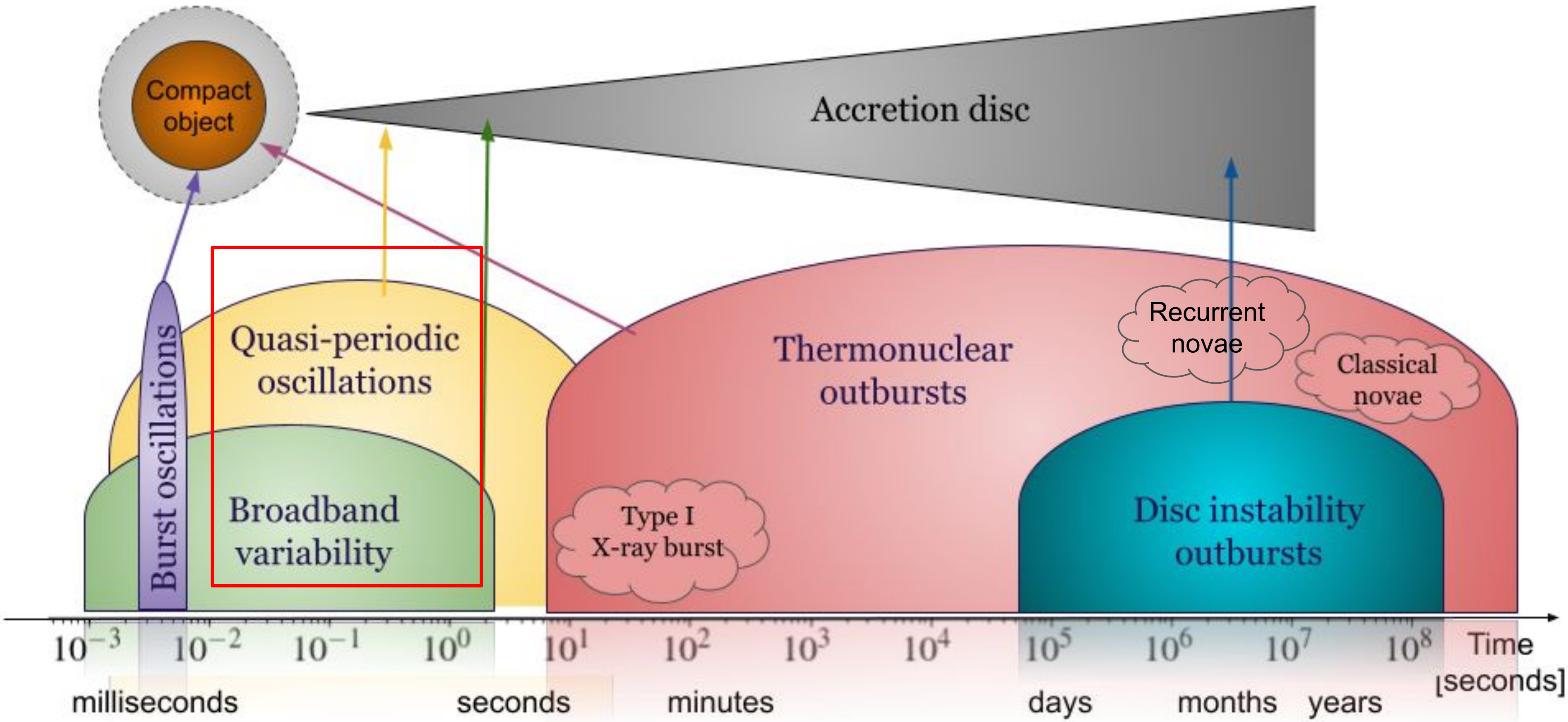
Important variability phenomena - instabilities, oscillations

❗ Magnetic fields of the compact object are not considered

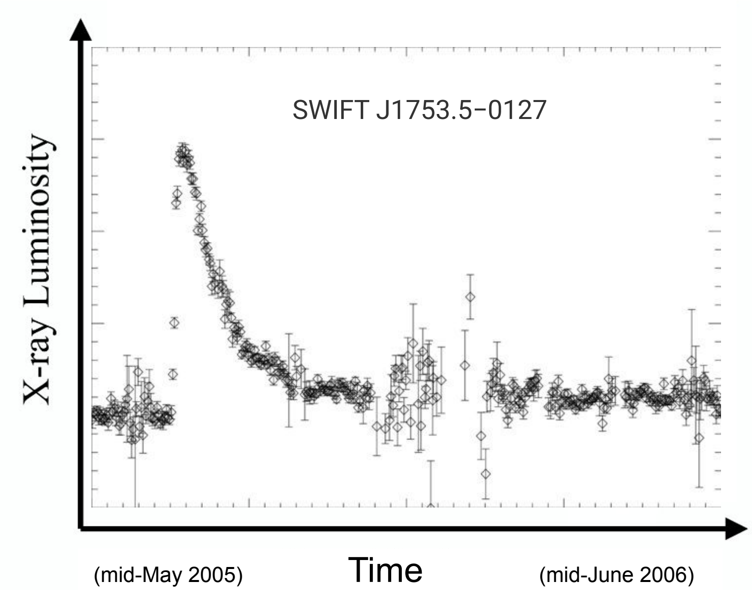


Important variability phenomena - instabilities, oscillations

! Magnetic fields of the compact object are not considered



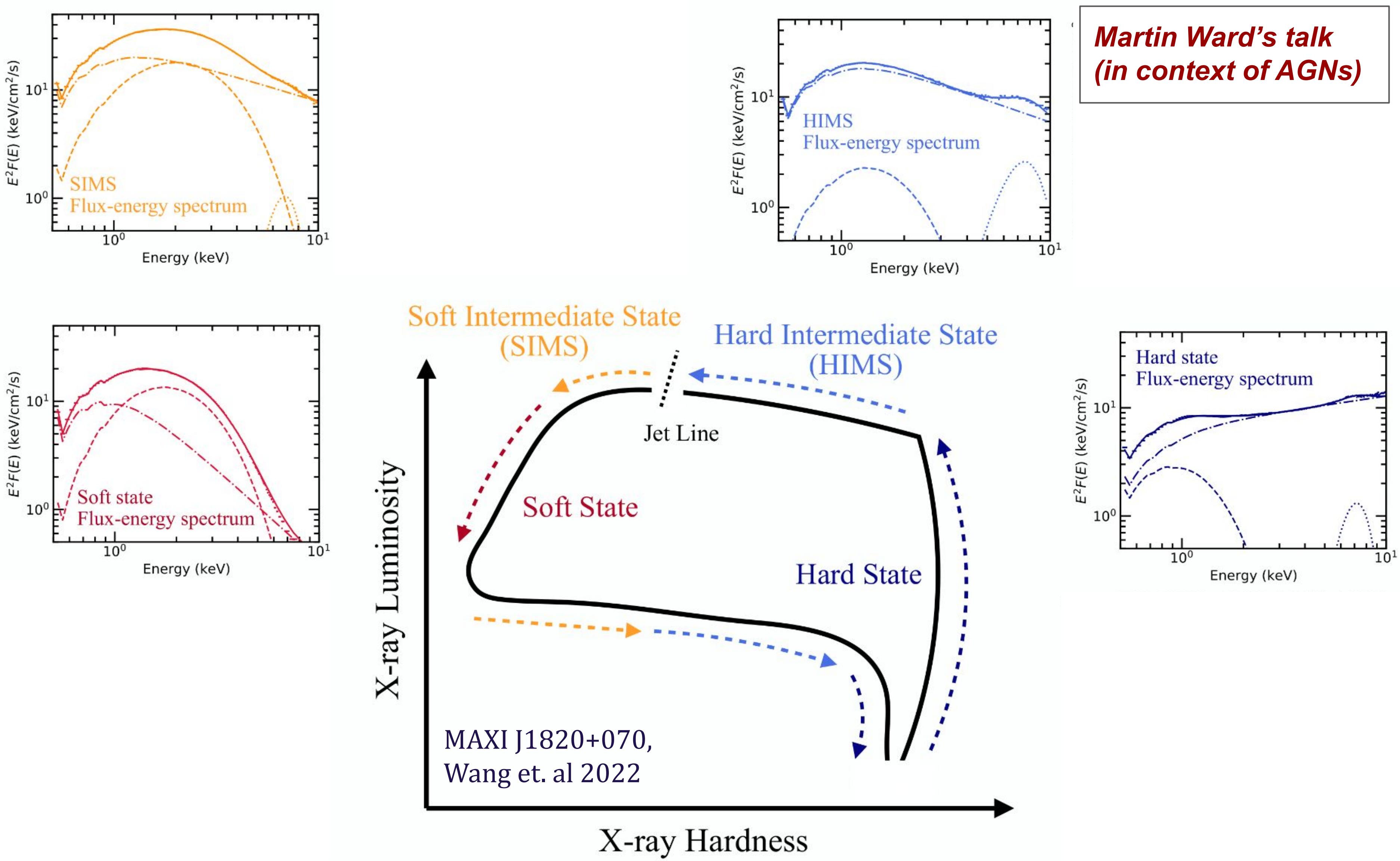
These systems are quite variable



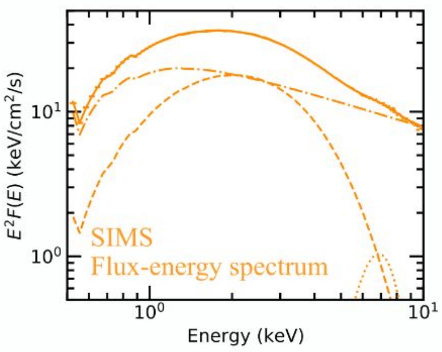
Cadolle Bel, M. et. al 2007

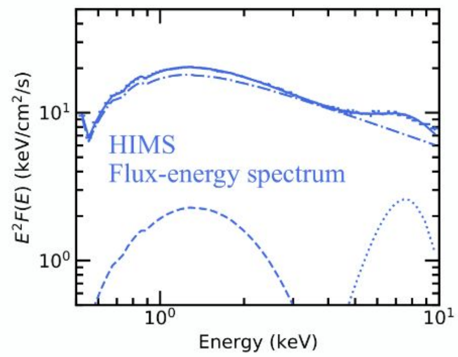
Spectral variability in X-ray binaries

Martin Ward's talk (in context of AGNs)



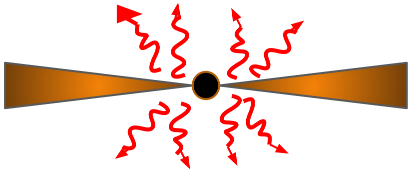
Spectral variability in X-ray binaries



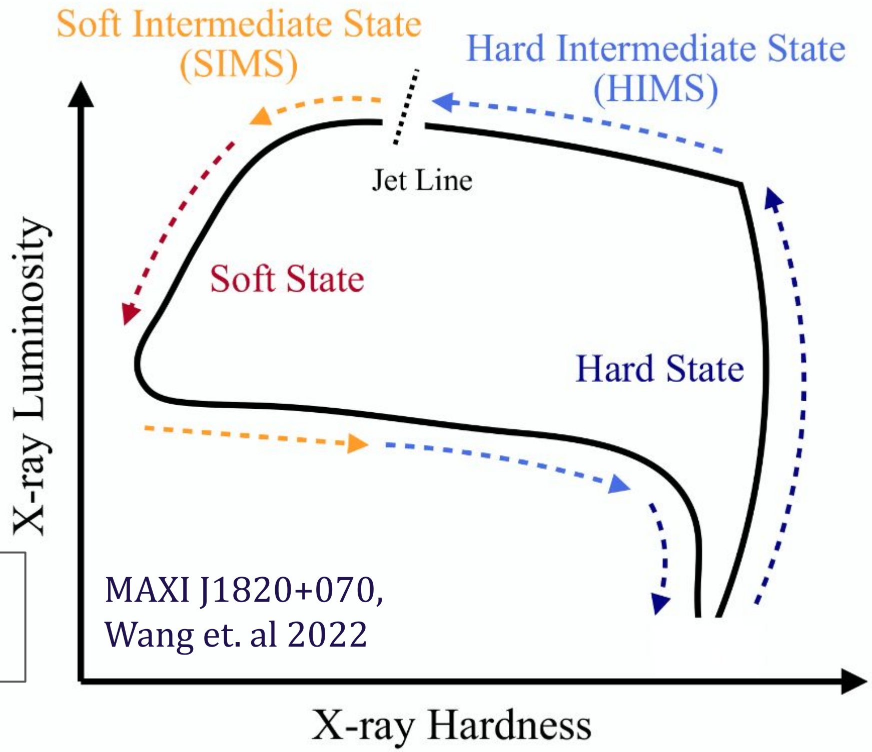


Andrzej Niedźwiecki's talk

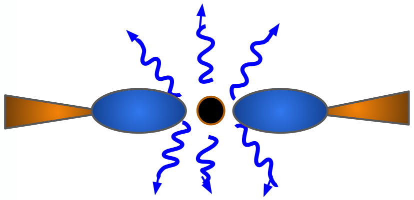
Soft state



Soft photons



Hard state

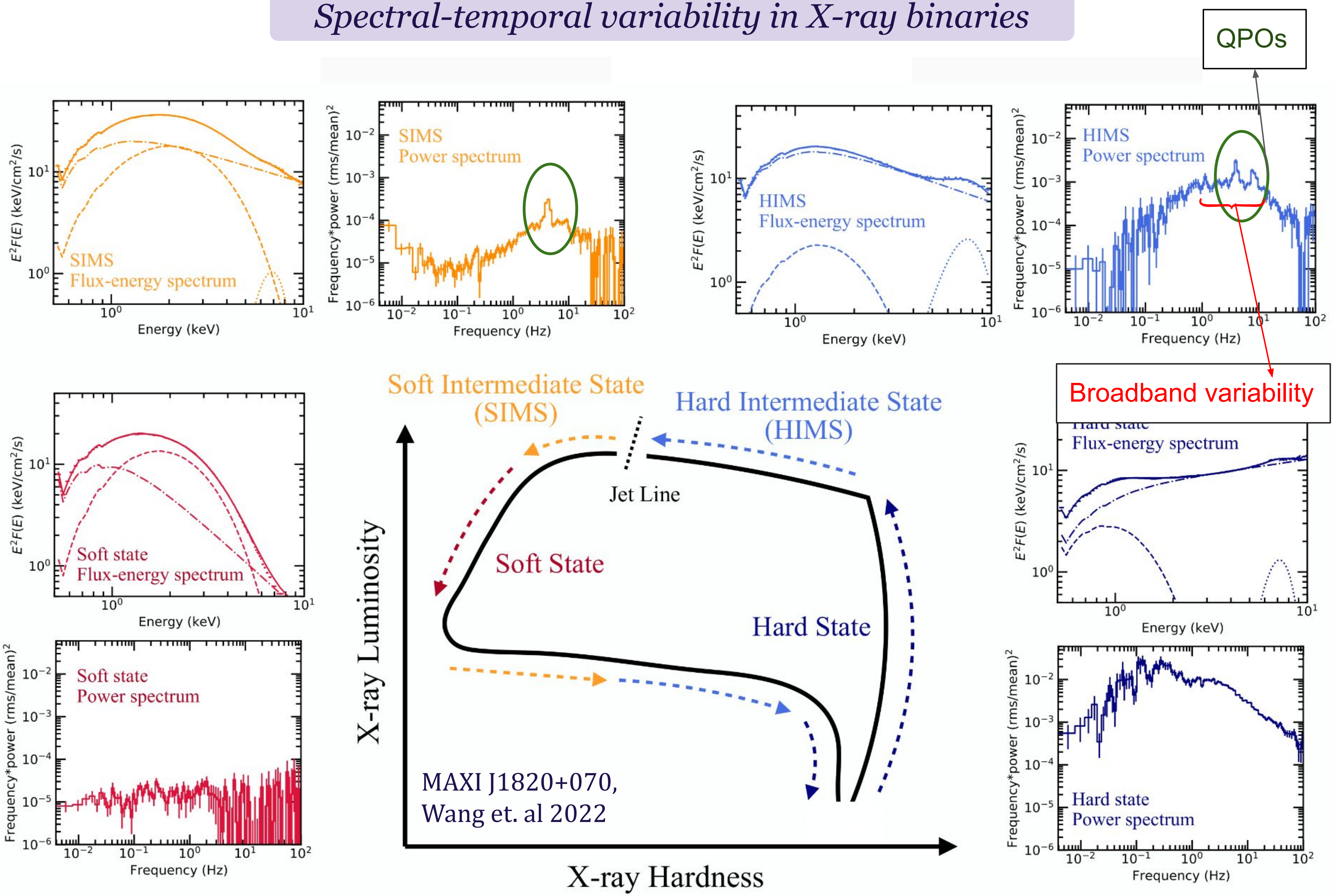


Hard photons

State of corona is debatable

Sneha Prakash Mudambi's talk

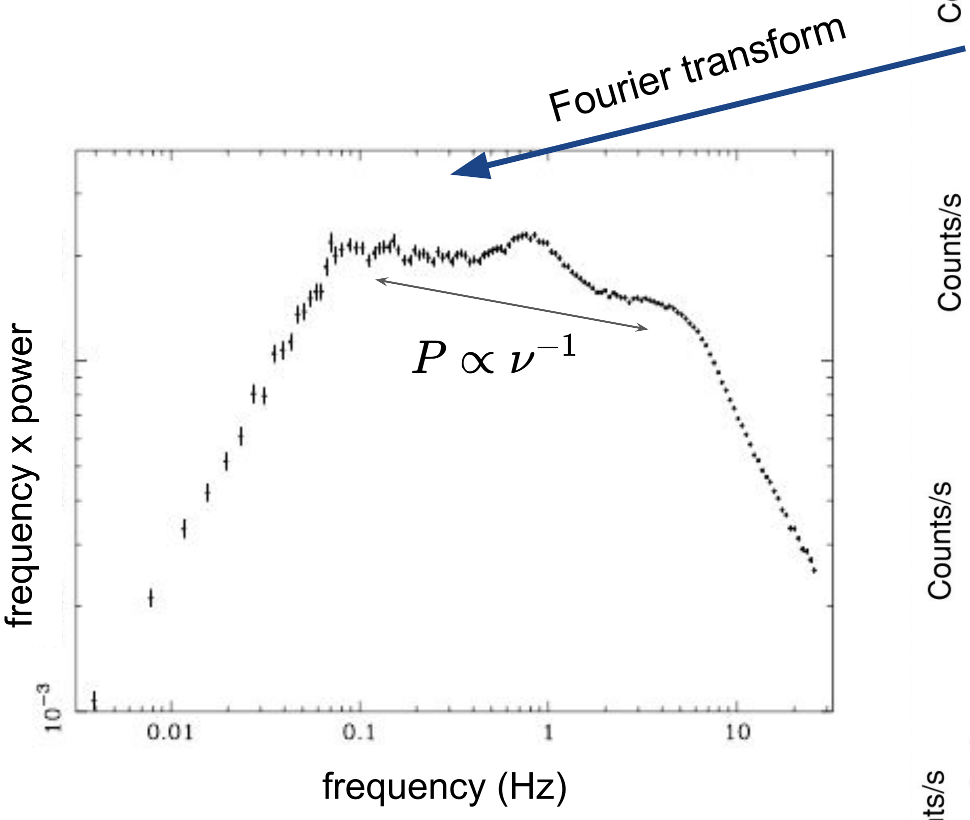
Spectral-temporal variability in X-ray binaries

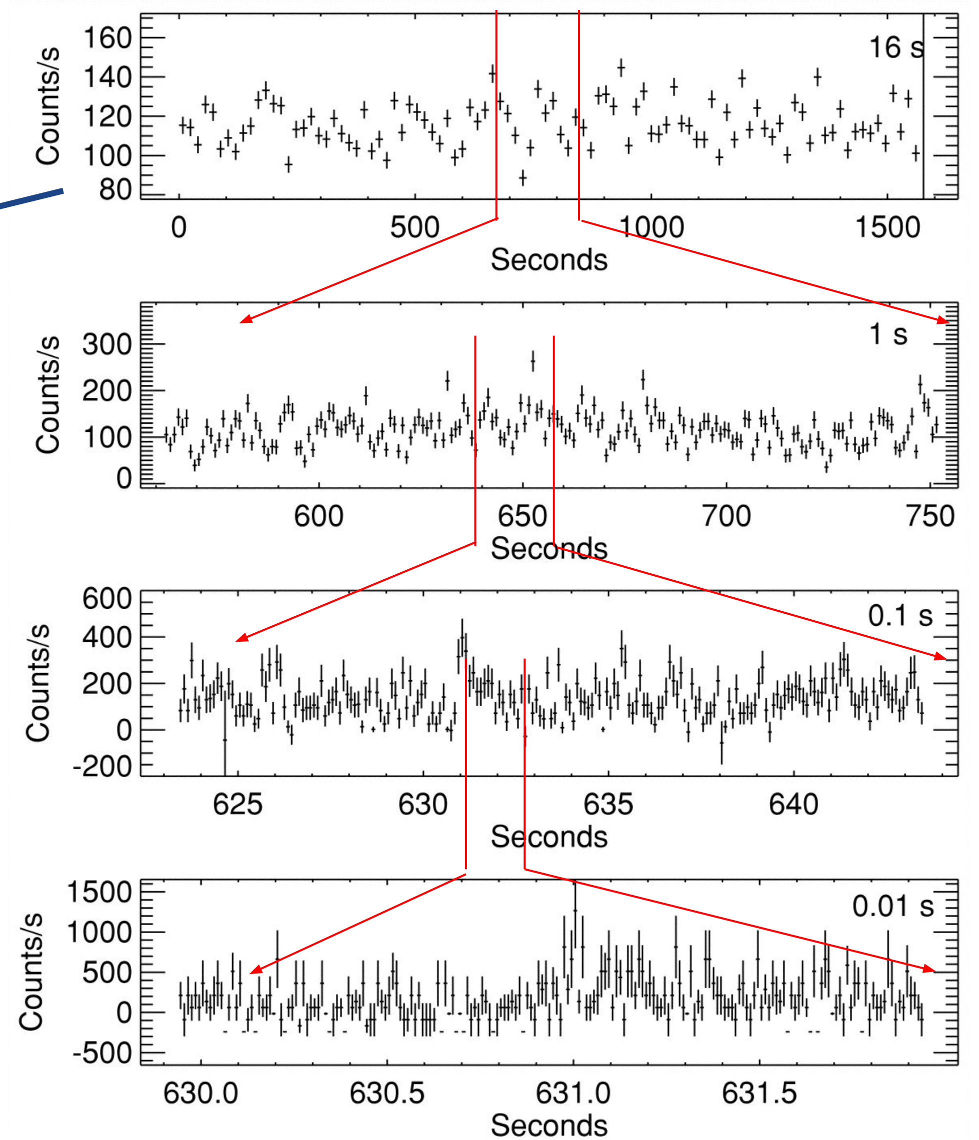


Broadband variability

GRS 1758−258 (Lin et. al 2000)

➢ *Variability on broad timescales* - a few seconds to milliseconds.

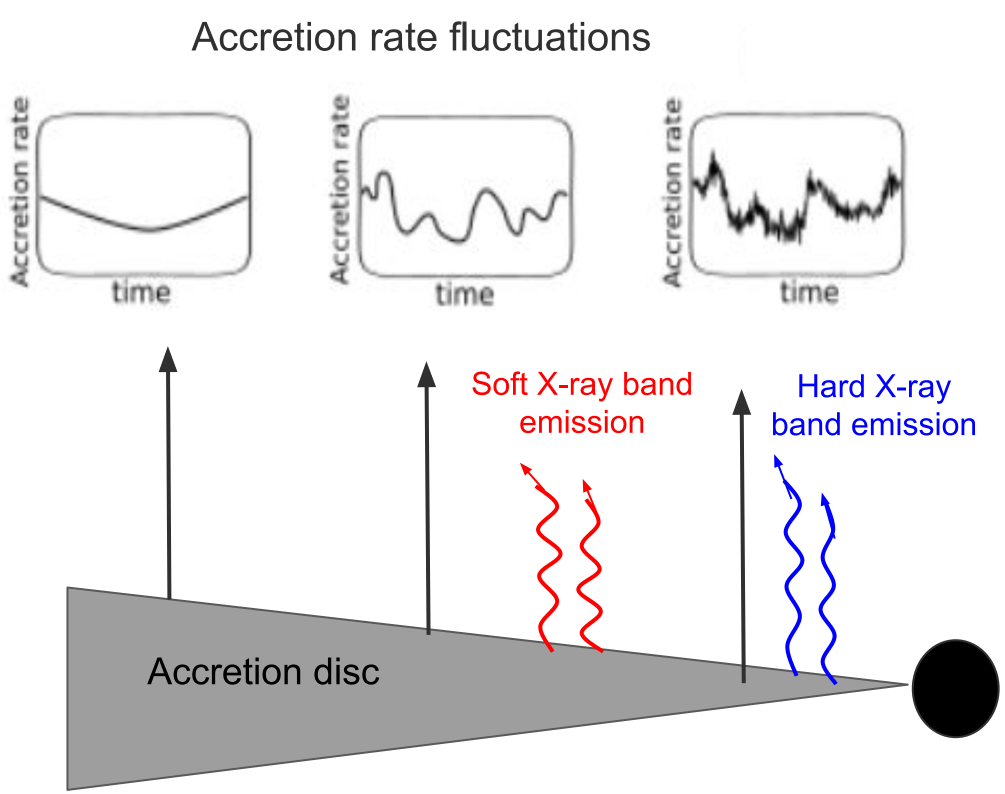




➢ *Characteristic features:* Strong coherence, frequency-dependent time lags, log-normal distribution, linear rms-flux relation.

What causes the broadband variability?

Propagating fluctuations



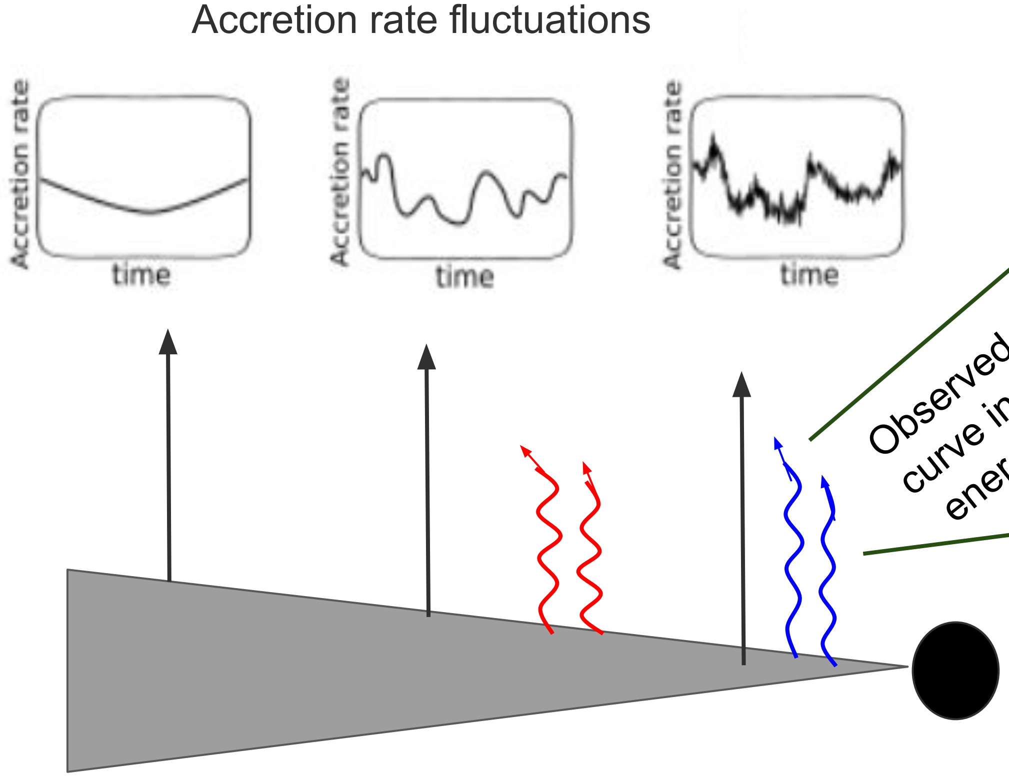
Simple picture: homogeneous disc/corona

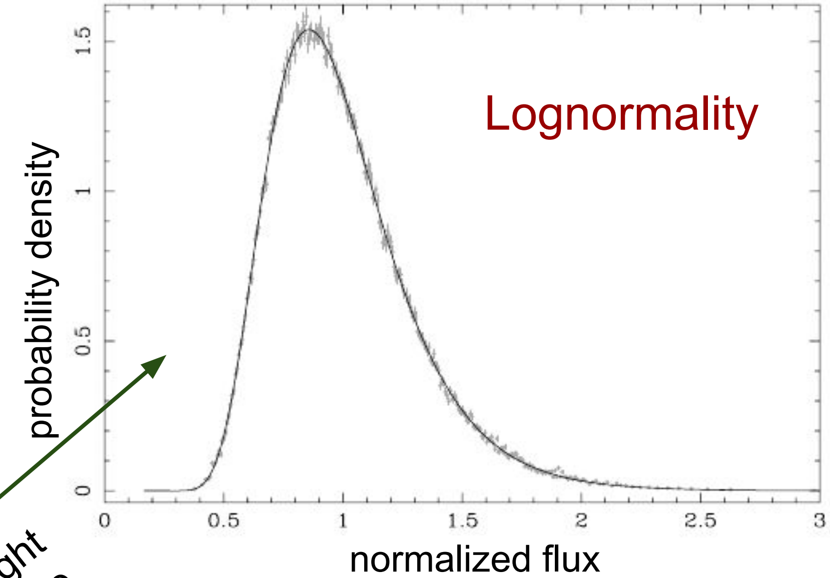
Viscous fluctuations rising on **local viscous time scales** at different radii drive fluctuations in accretion rate, which propagate inwards and couple together to produce the multiplicative behaviour in the accretion rate; thus the observed flux.

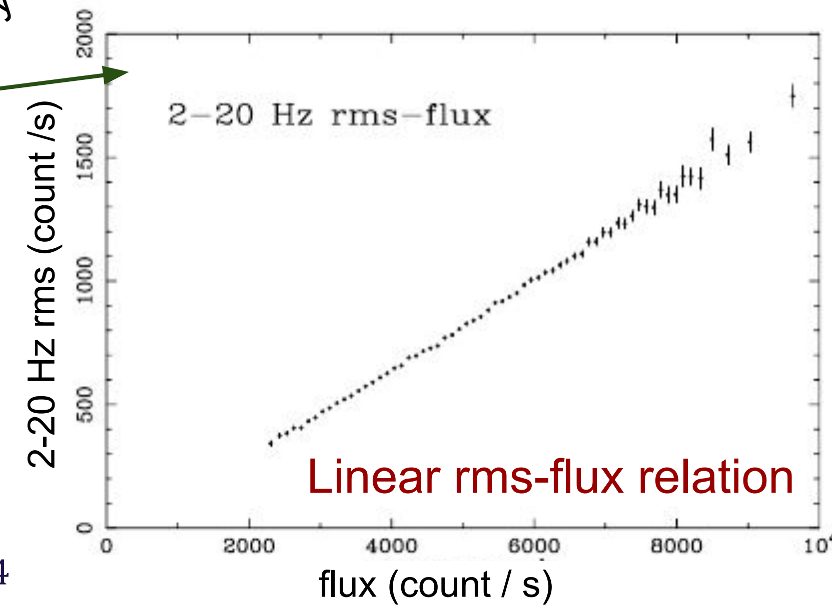
Lynden-Bell & Pringle 1974, Lyubarskii 1997, Kotov et. al 2001, Done 2007

Viscous timescale longer at larger radii

Propagating fluctuations

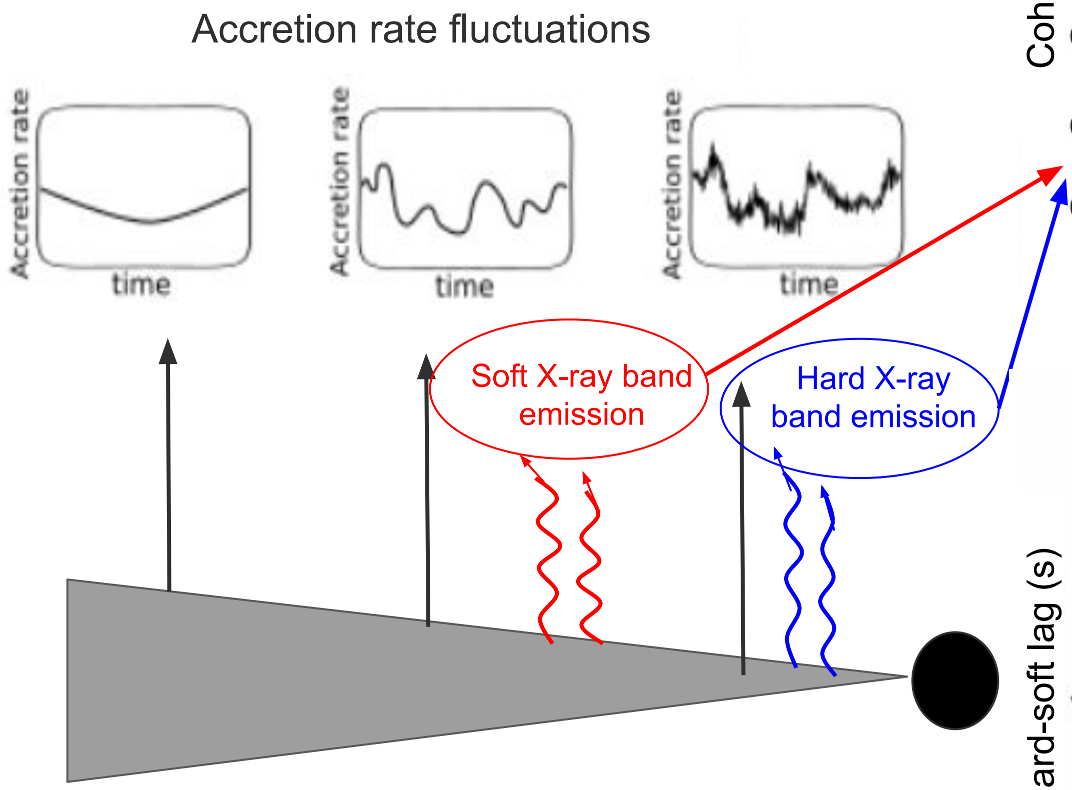


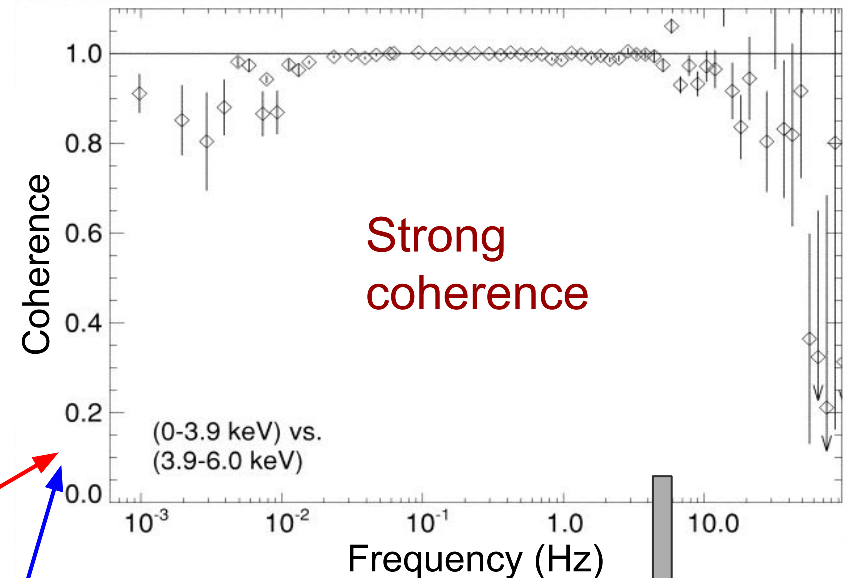


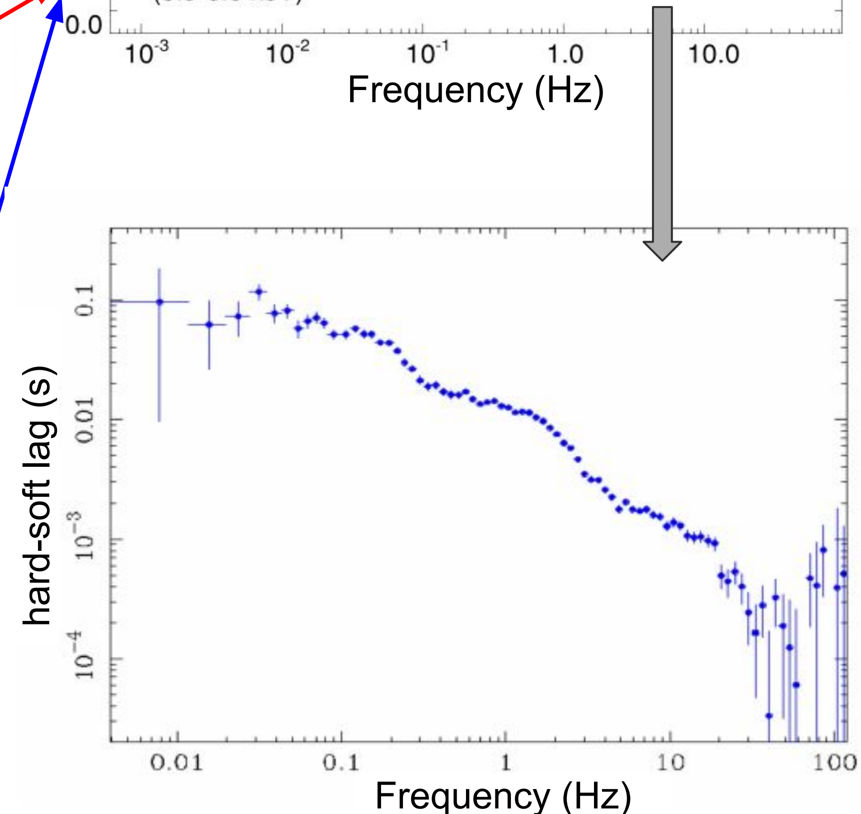


Uttley et. al 2005, 2014

Propagating fluctuations



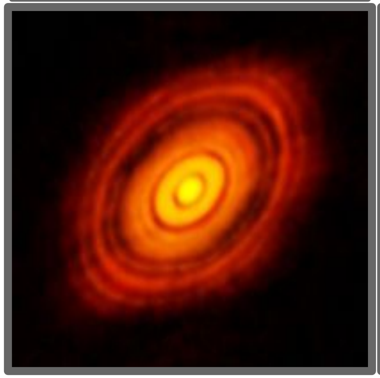
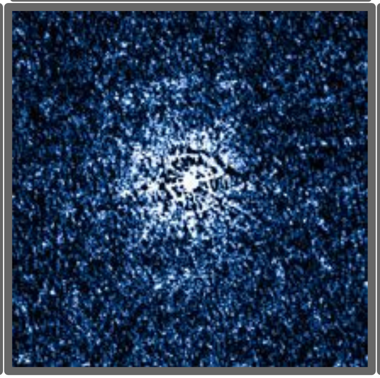
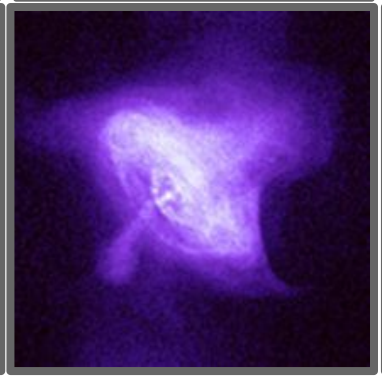
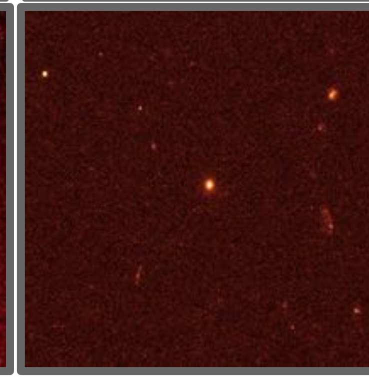




Nowak et. al 1999; Uttley et. al 2014

Quick note

Gopal Bhatta's talk

proto-star systems	white dwarfs (WD) in cataclysmic binaries	black hole (BH) or neutron star (NS) binaries	AGN	gamma ray burst (GRB) sources
				
Scaringi et al 2015b	Scaringi 2013, Van de Sande 2015	Wijnands & Van der Klis 1999	Gaskell 2004	H.E.S.S. Collaboration, Rieger F. M., 2019

These variability features are observed in other accreting systems as well

- *variability must be related to accretion discs*

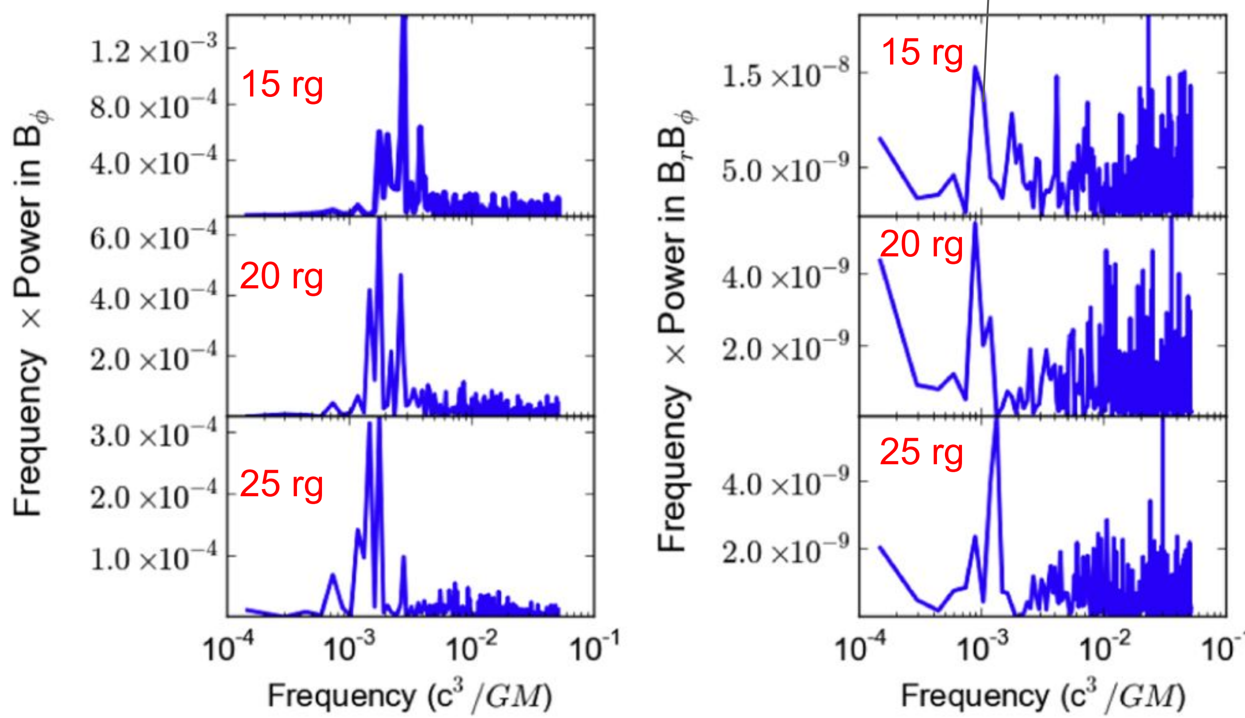
What drives these fluctuations?

Turbulent viscosity

↑

Magnetorotational instability

10 times smaller than the local orbital frequency



MHD simulations of **geometrically thin discs** (Hogg & Reynolds 2016)

Dynamo cycle → Fluctuations in magnetic stresses → Fluctuations in accretion rate

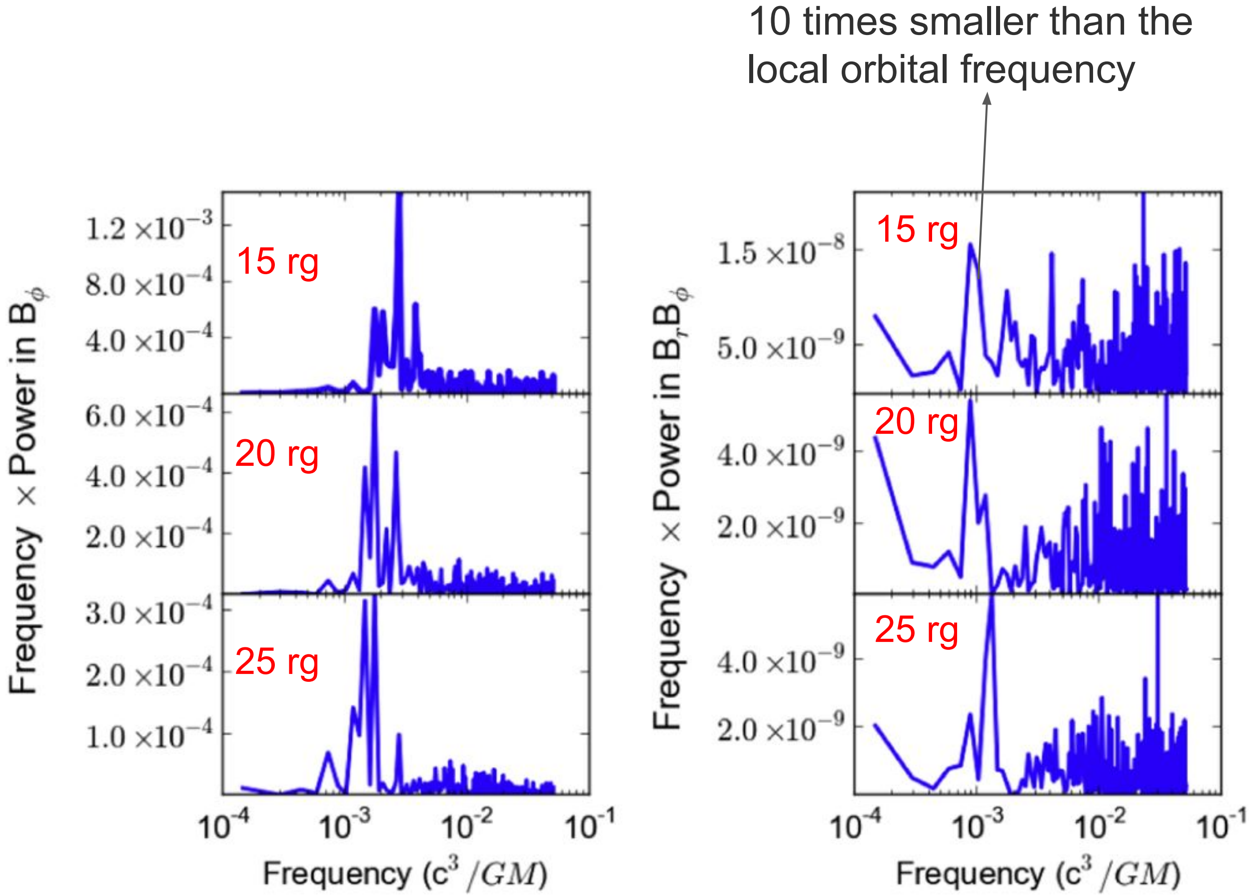
What drives these fluctuations?

Turbulent viscosity

↑

Magnetorotational instability

High frequency variability require geometrically thick, optically thin accretion flows
(Churazov et al. 2001; Arévalo & Uttley 2006; Ingram & Done 2011; Mahmoud & Done 2018a)



MHD simulations of **geometrically thin discs** (Hogg & Reynolds 2016)

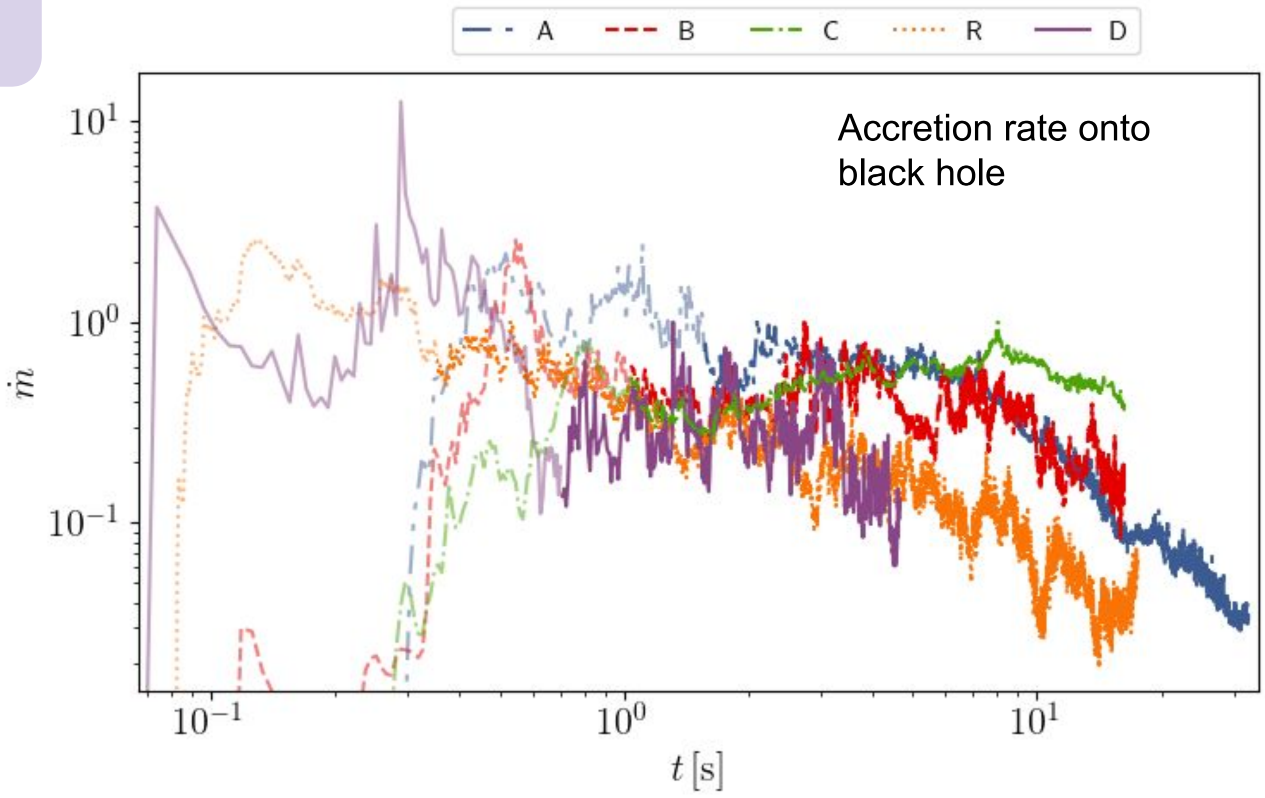
Unordered → Dynamo cycle → Fluctuations in magnetic stresses → Fluctuations in accretion rate

(Hogg & Reynolds 2018)

Mass accretion rate as proxy for luminosity

- Non-radiative GRMHD simulations

- How well does the mass accretion rate from the numerical simulations reproduce the observed variability features in black hole binaries?



Bollimpalli et. al 2020

Simulations **A**, **B**, and **C** using ***Athena++*** (White et. al 2020)

Simulation **R** using ***HARM*** (Narayan et. al 2012)

Simulation **D** using ***Cosmos++*** (**Bollimpalli** et. al 2020)

Strong evidence : Radial coherence

Fourier transform

$$\dot{m}(r_1, t) \longrightarrow H(f)$$

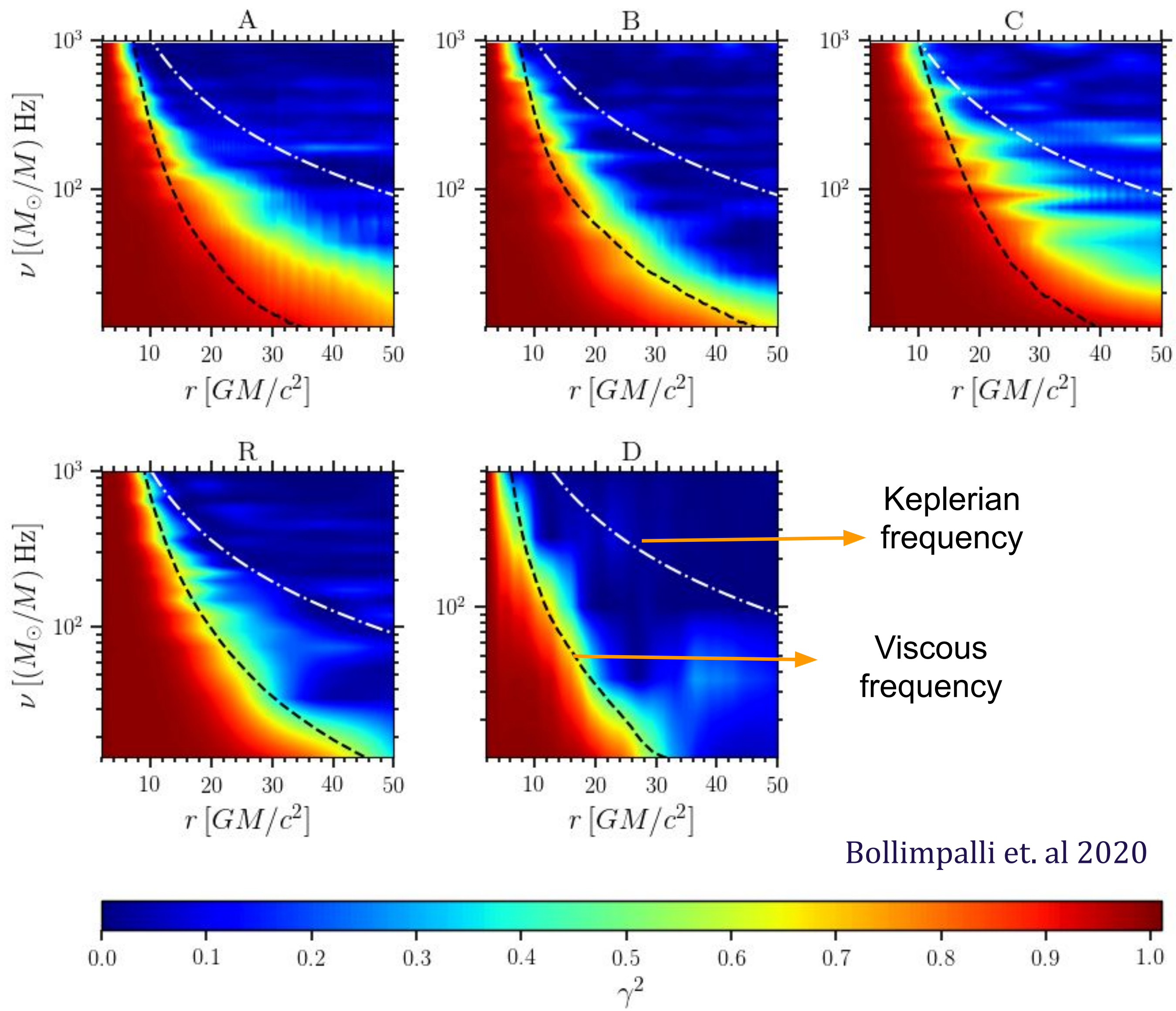
$$\dot{m}(r_2, t) \longrightarrow S(f)$$

$$\gamma^2 = \frac{\langle |H^*(f) S(f)|^2 \rangle}{\langle |H(f)|^2 \rangle \langle |S(f)|^2 \rangle}$$

1, if $\dot{m}(r_1, t)$ and $\dot{m}(r_2, t)$ are ***linearly related***.

Here, we take

$r_1 = 2r_g, r_2 > r_1$



Bollimpalli et. al 2020

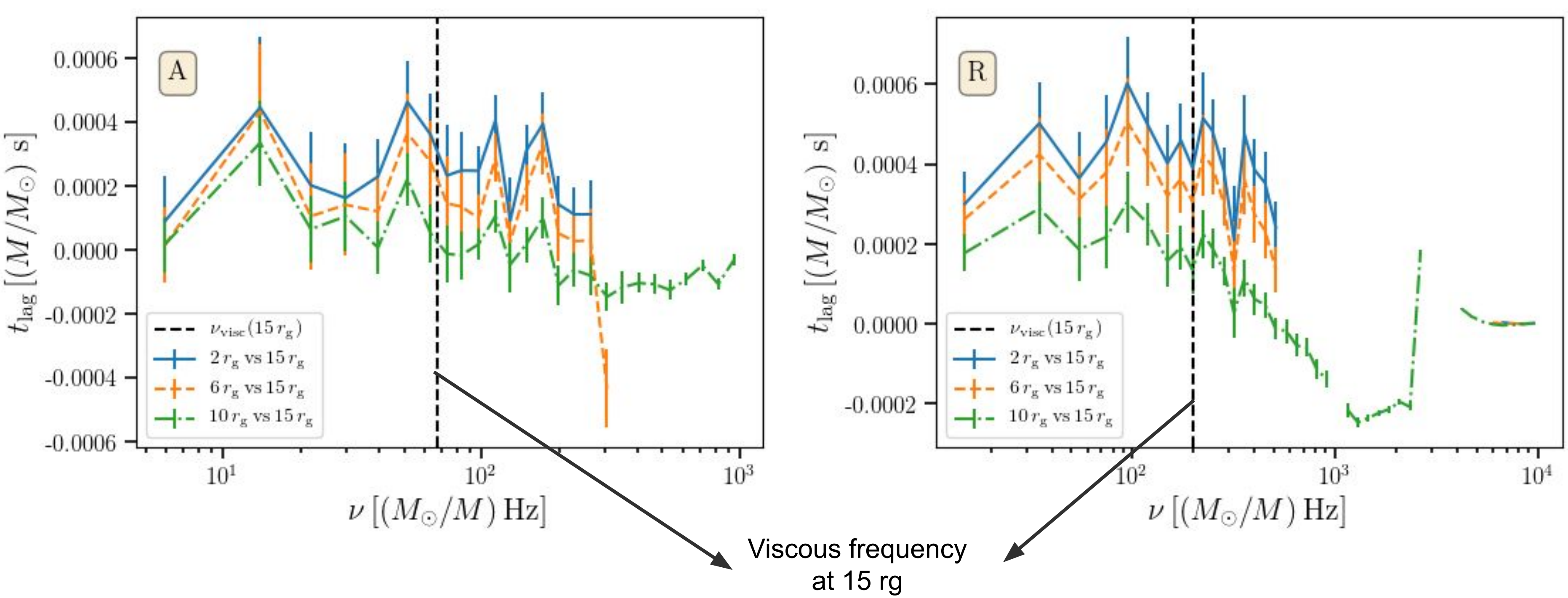
Remarkable coherence below the viscous frequency - *propagating fluctuations*

Time lags in fluctuations

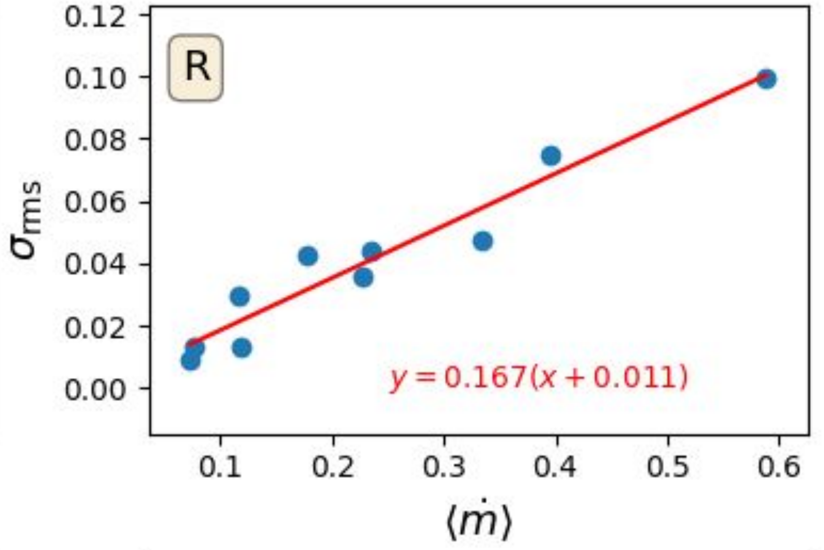
- ➢ Positive lags - why frequency independent?
  fluctuations are propagating inward

- ➢ Variability at smaller radii lags variability at larger radii
  - *Propagating timescales are independent of the Fourier frequencies.*
  - Maybe dissipative process are responsible?

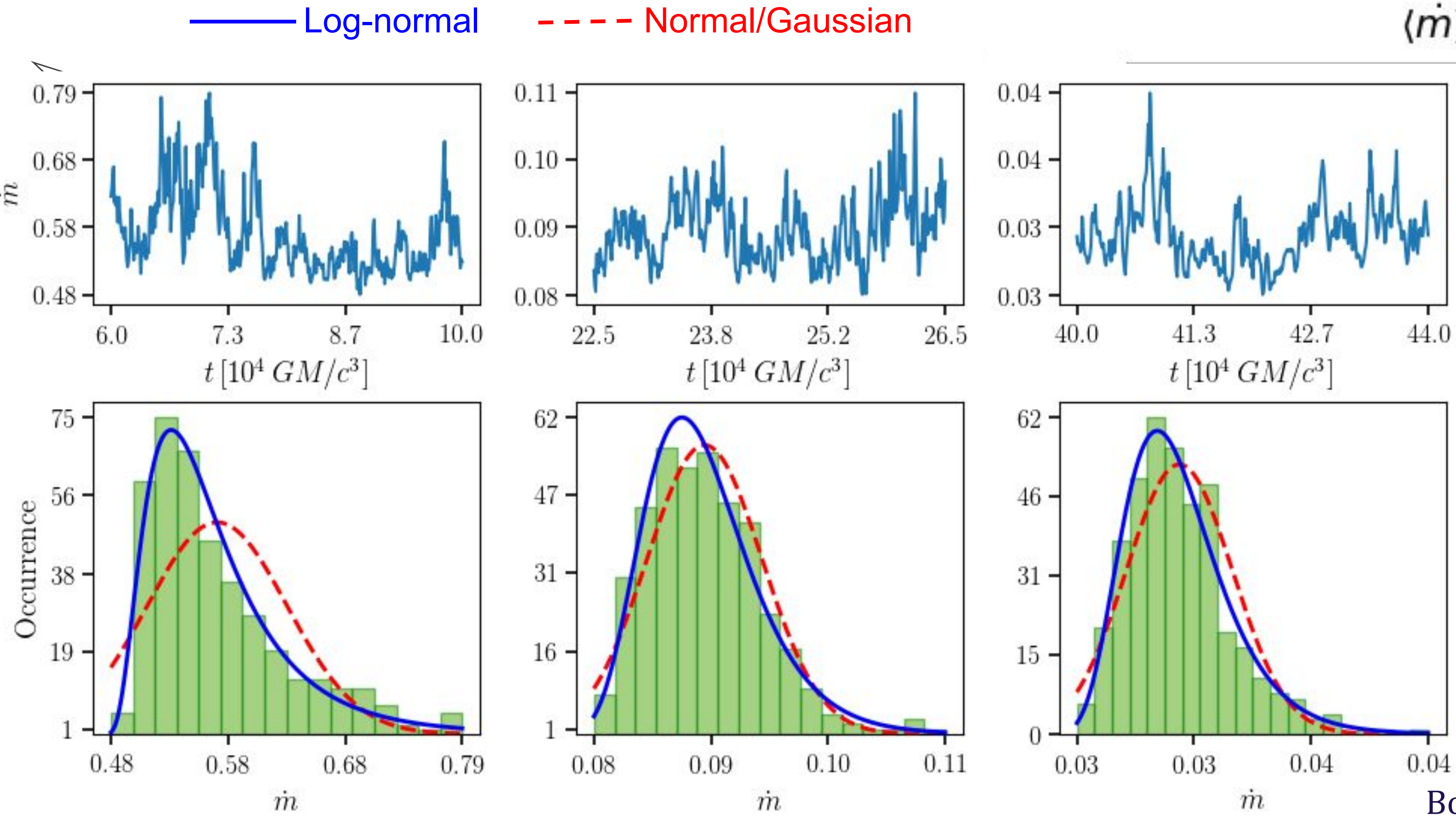
Bollimpalli et. al 2020



Distribution of mass accretion rate



- Log-normal distribution - underlying variability process is *multiplicative* in nature.
- RMS-mean relation - All simulations exhibit *linear* relation - the higher the accretion rate, larger the variability.

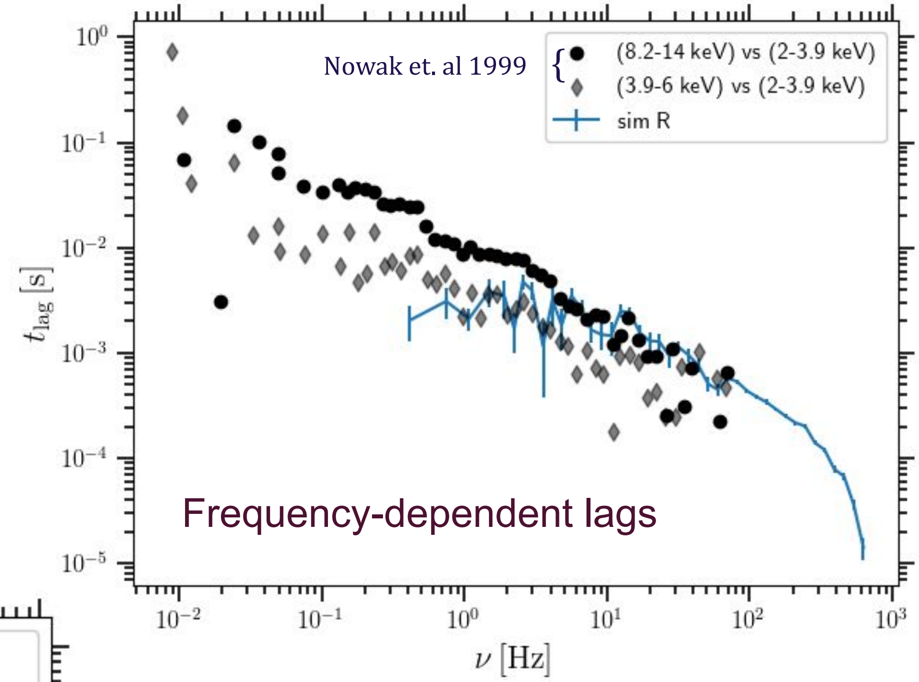


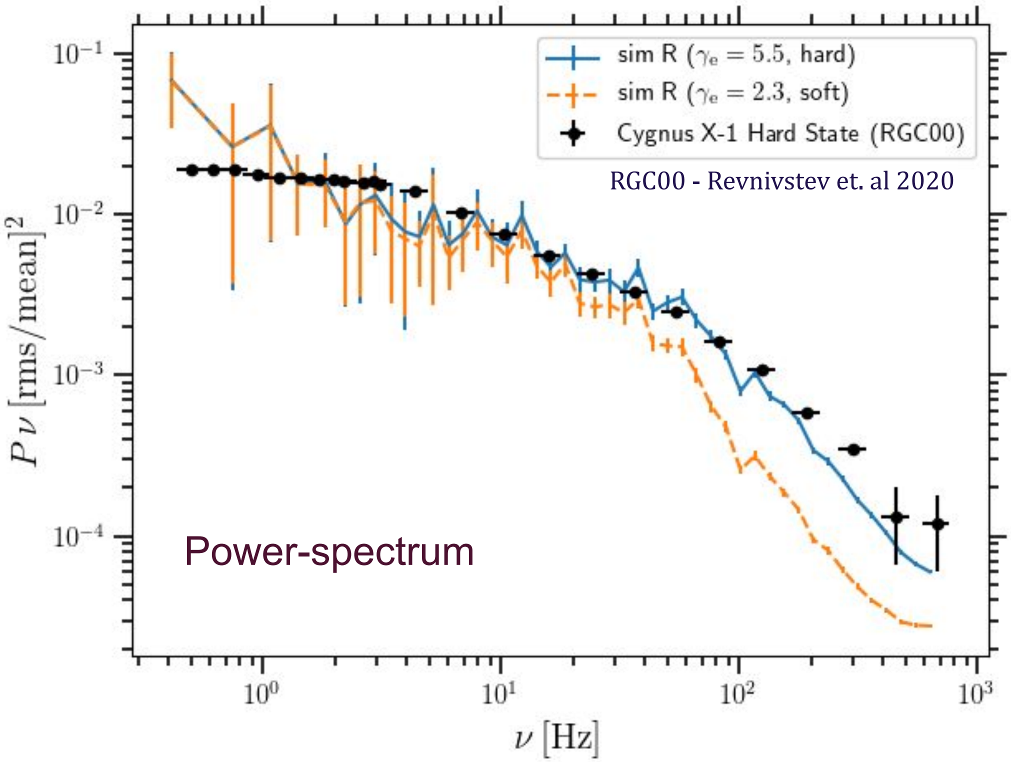
Bollimpalli et. al 2020

Comparison with observations

- Synthetic light curves generated from the simulations using an emissivity profile - $\epsilon \propto r^{2-\gamma}$

$$f(t) = \sum_{r=2r_g}^{25r_g} \epsilon(r)\, \dot{m}(r,t)$$

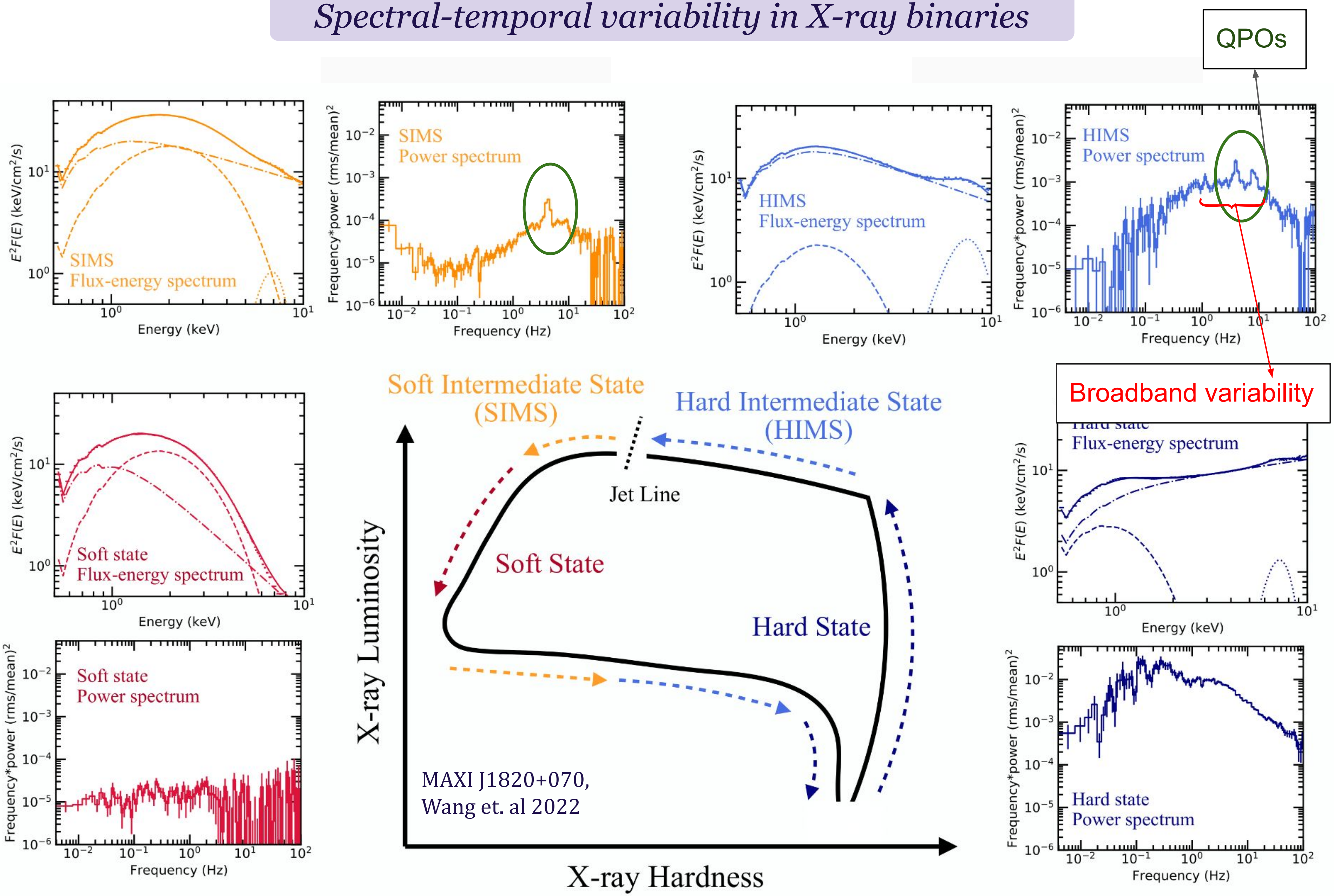




Bollimpalli et. al 2020

Simulations agree well with the observations of the low/hard state of *Cygnus X-1*.

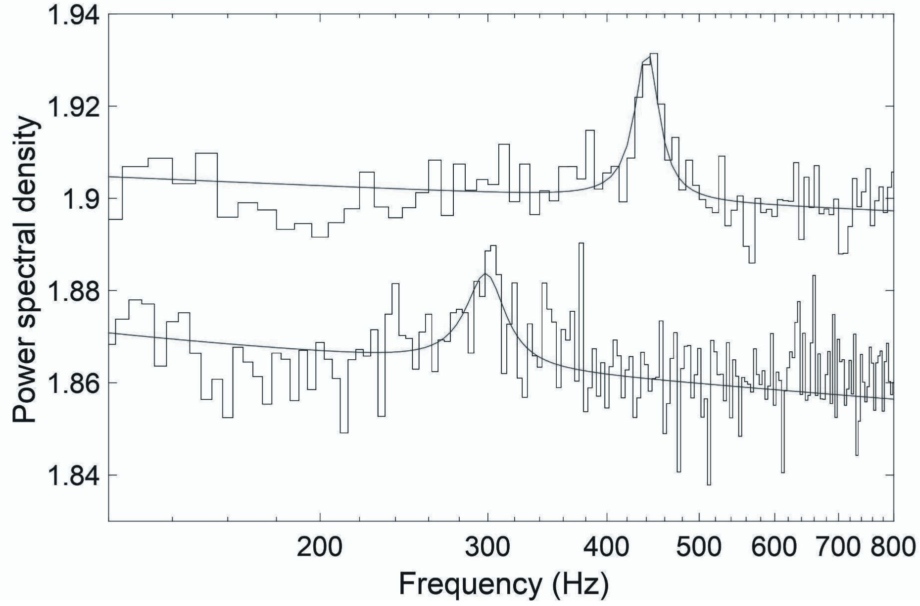
Spectral-temporal variability in X-ray binaries



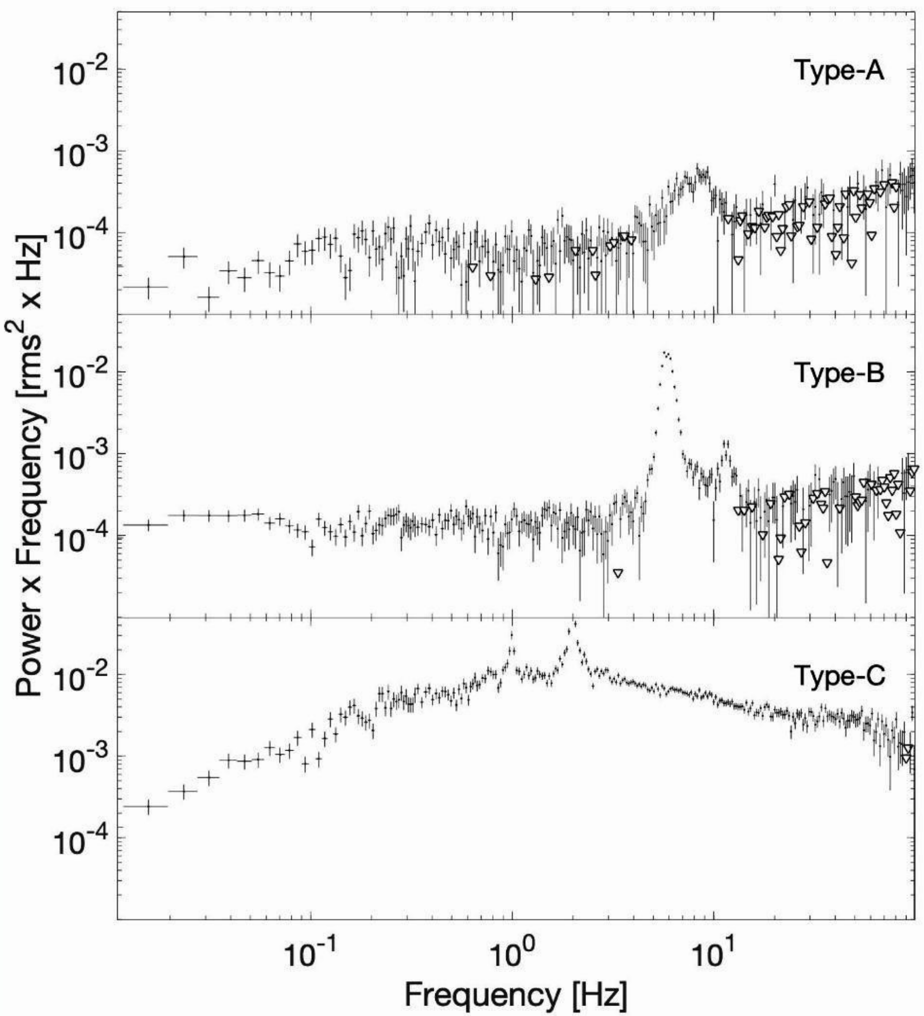
Quasi-periodic oscillations (QPOs)

- Rapid variability; Frequency modulates.
- Low-frequency QPOs (mHz to < ~ 30 Hz)
- High-frequency QPOs (> ~ 60 Hz)
- Probes for strong gravity, accretion disc geometry e.t.c.

High-frequency QPOs



Low-frequency QPOs

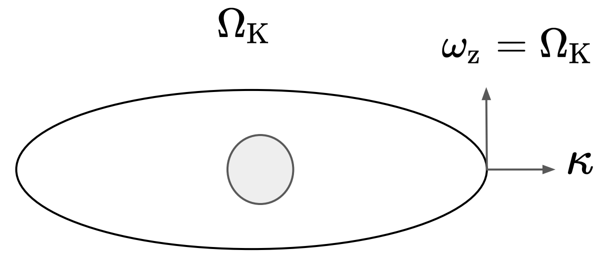


See reviews by van der Klis 2006, Remillard & McClintock 2006, Ingram & Motta 2020

High frequency QPOs in black hole binaries

HF QPOs - detected only in a handful of sources.

non spinning BH



Potential models:

1. Oscillations in discs (discosesmic modes)

p-modes are commonly observed in the simulations (Reynolds & Miller 2009, Mishra et. al 2018, Bollimpalli et. al 2020)

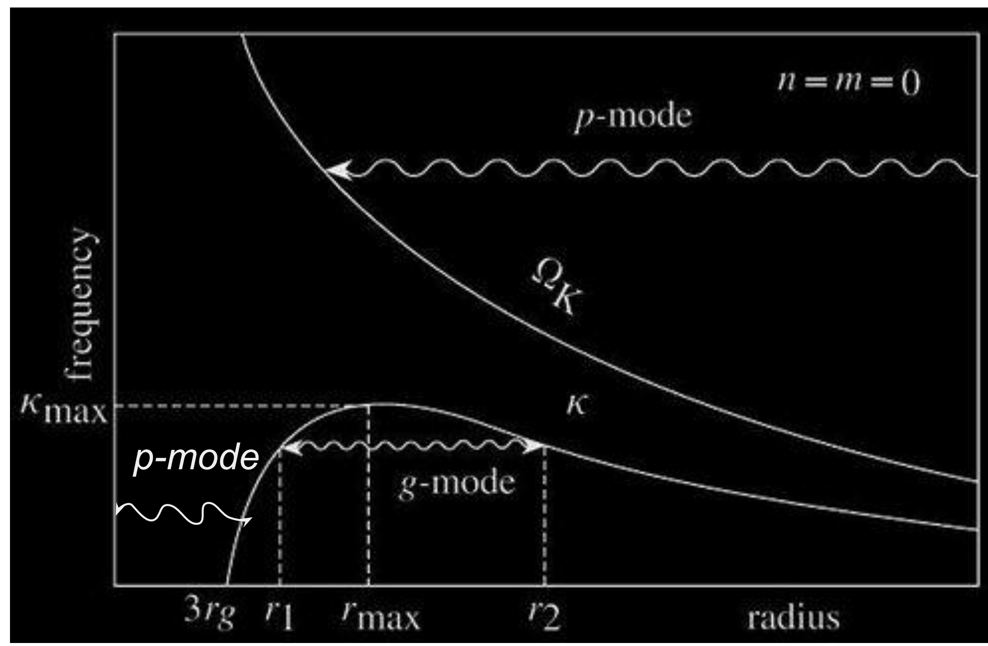
g-modes are damped by MHD turbulence (Reynolds & Miller 2009)

Eccentricity (>0.03) in warped discs can excite inertial g-modes (Dewberry et. al 2020a, 2020b)

2. Parametric resonance model (Abramowicz & Kluźniak 2001,2003; Abramowicz et. al 2002, 2003)

Resonance between modes at particular radius

Hard to reproduce in the simulations.

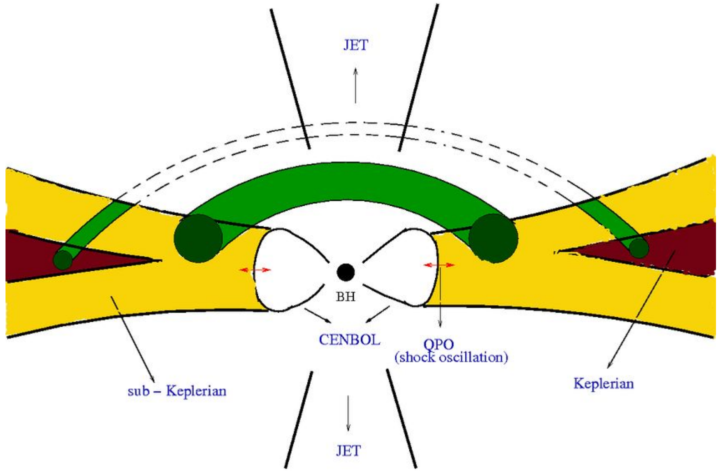


Propagation diagram for axisymmetric modes. (Kato et. al 1998)

Continuation…

3. Oscillating shocks

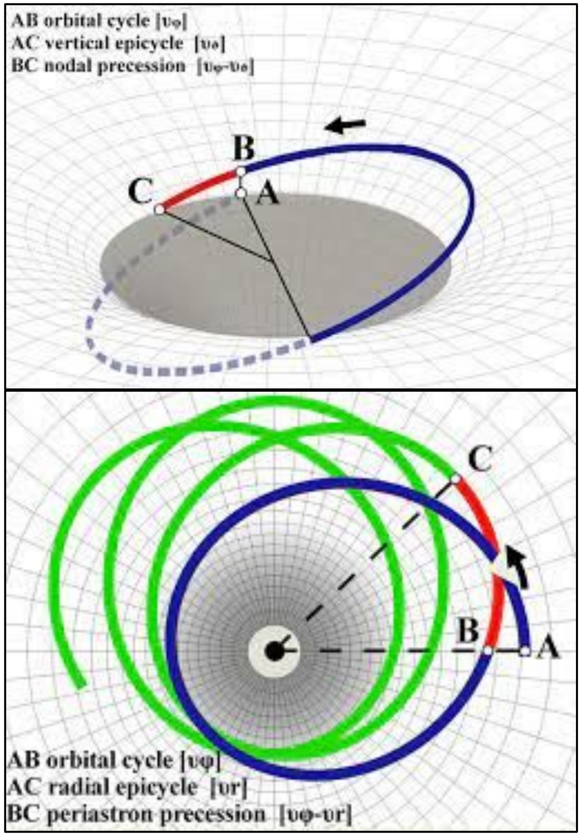
(Chakrabarti & Titarchuk 1995)



(Radhika et. al 2013)

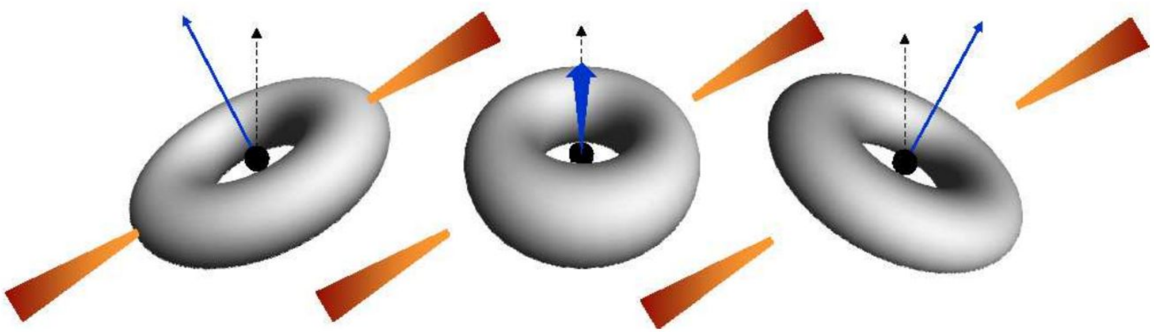
4. Relativistic precession model

Upper HF QPO - Orbital frequency; Lower HF QPO - periastron precession frequency; Low-frequency QPO - nodal precession frequency (Stella & Vietri 1998; Stella et. al 1999)



3:2 HF QPOs - breathing and vertical epicyclic frequencies of globally oscillating hot, thick flow (Fragile et. al 2016)

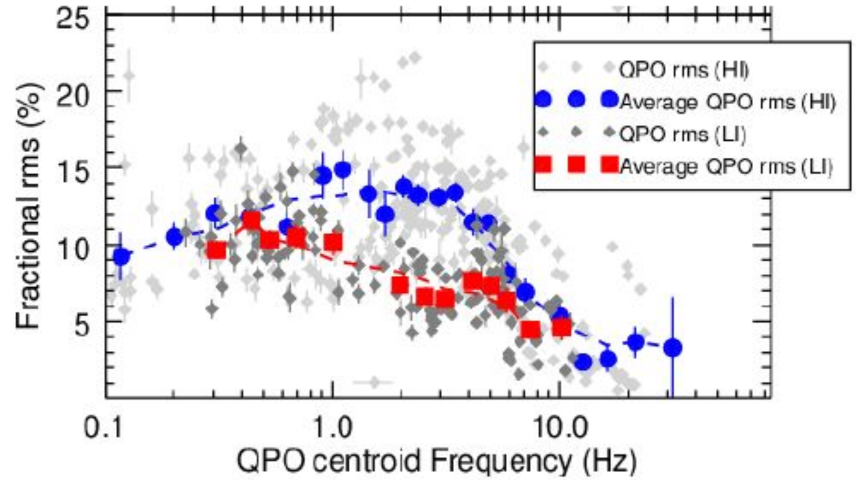
Low-frequency Type-C QPO - Precessing hot flow in a truncated disc geometry (Ingram et. al 2009; Ingram & Done 2011)



Courtesy: Sara E. Motta

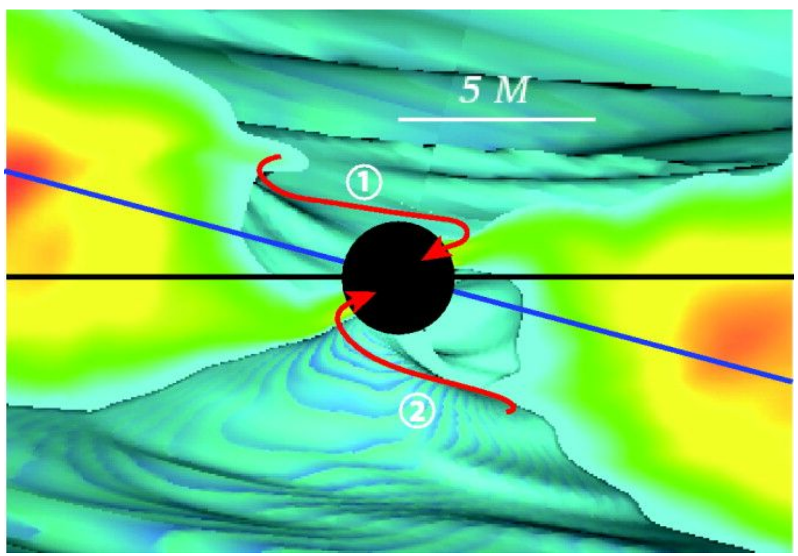
Type - C Low frequency QPO

- ➢ Centroid frequency is tightly correlated with the spectral state (a few mHz in the hard state to ~10 Hz in the intermediate states).
- ➢ Strong inclination dependence of the QPO amplitude and phase lag suggests that it is likely a geometrical effect.

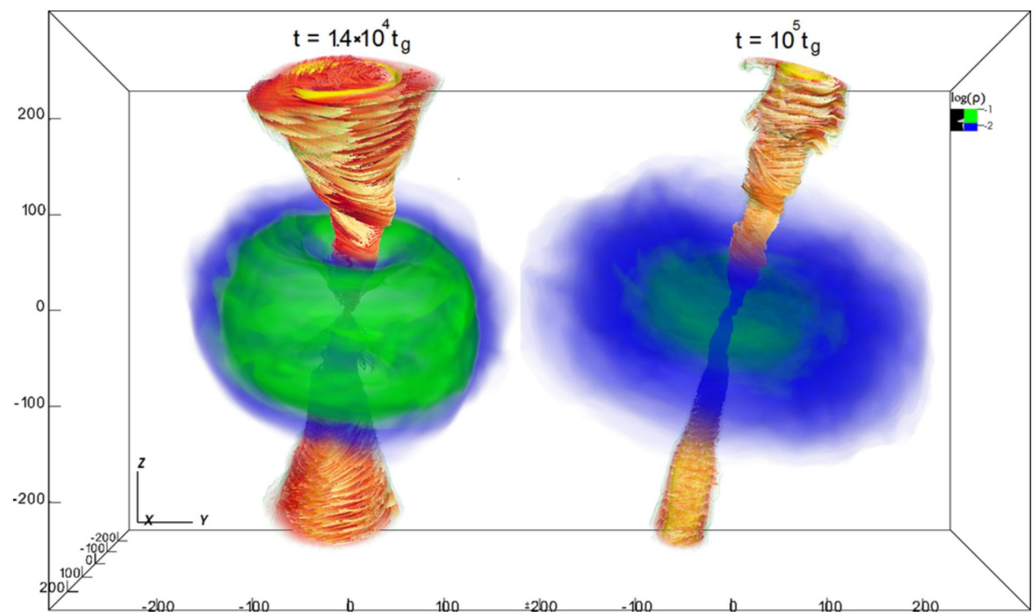


Ingram & Motta 2020

- ➢ Other models: accretion-ejection instability ; pressure or accretion rate modes
  - all require a moving inner radius.



Fragile et. al 2007



Liska et. al 2018

Type - C Low frequency QPO

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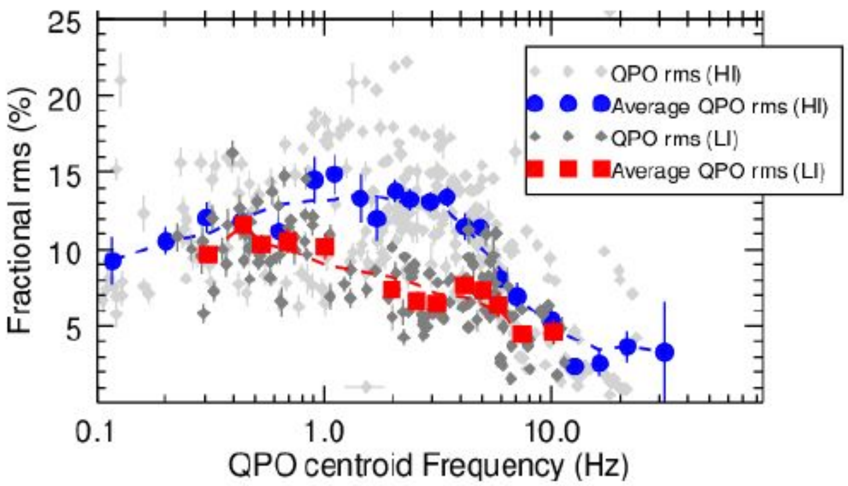
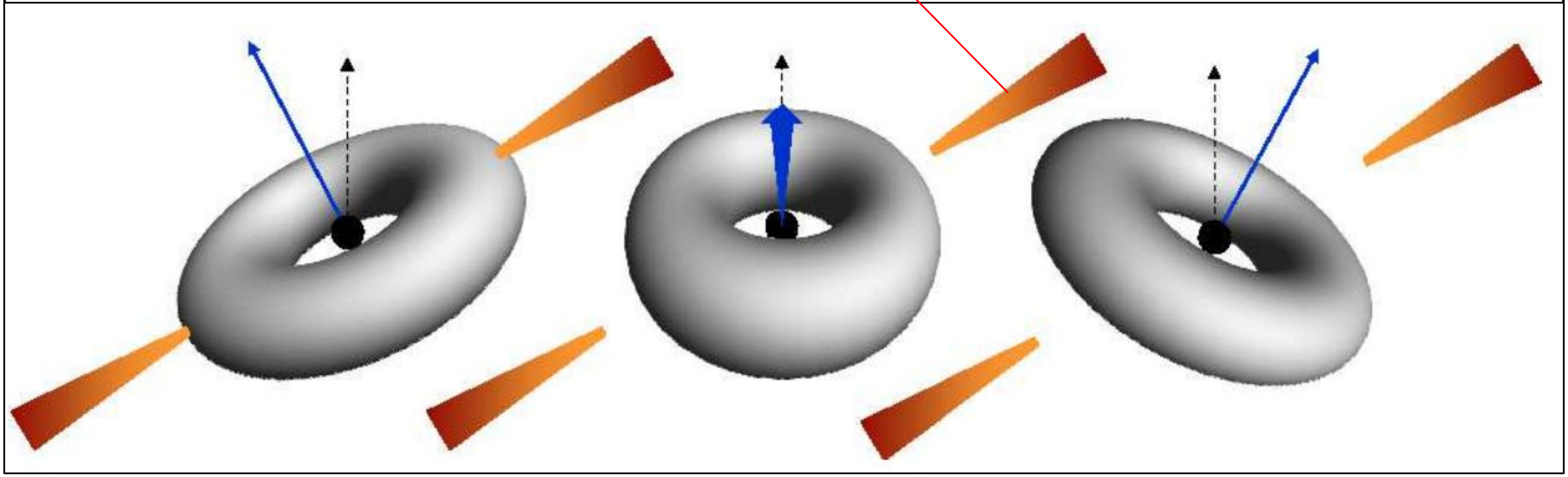
- Strong inclination dependence of the QPO amplitude and phase lag suggests that it is likely a geometrical effect.



Ingram & Motta 2020

- Other models: accretion-ejection instability ; pressure or accretion rate modes
  - all require a moving inner radius.

What happens when the outer thin disc present?

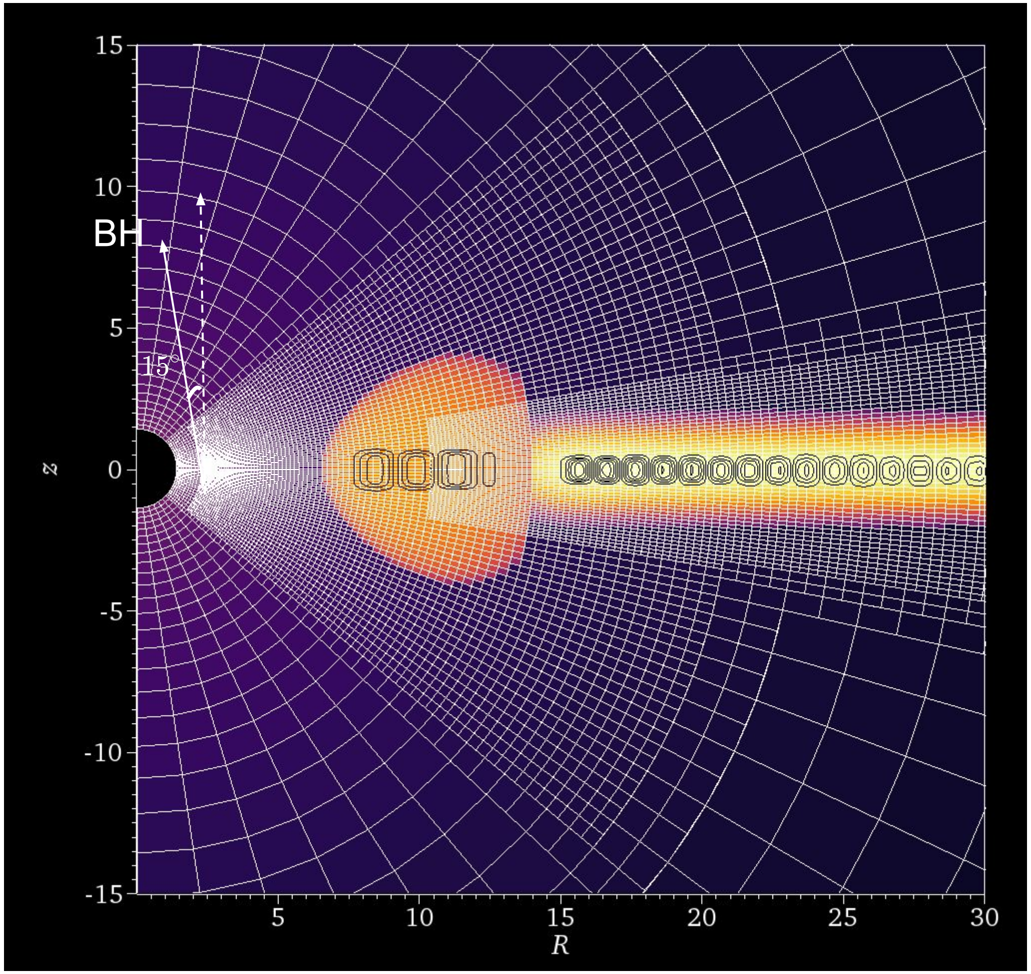


GRMHD simulations of Tilted & Truncated accretion disc

- Using GRMHD code *Cosmos*++
  (Anninos et al. 2005; Fragile et al. 2012, 2014)

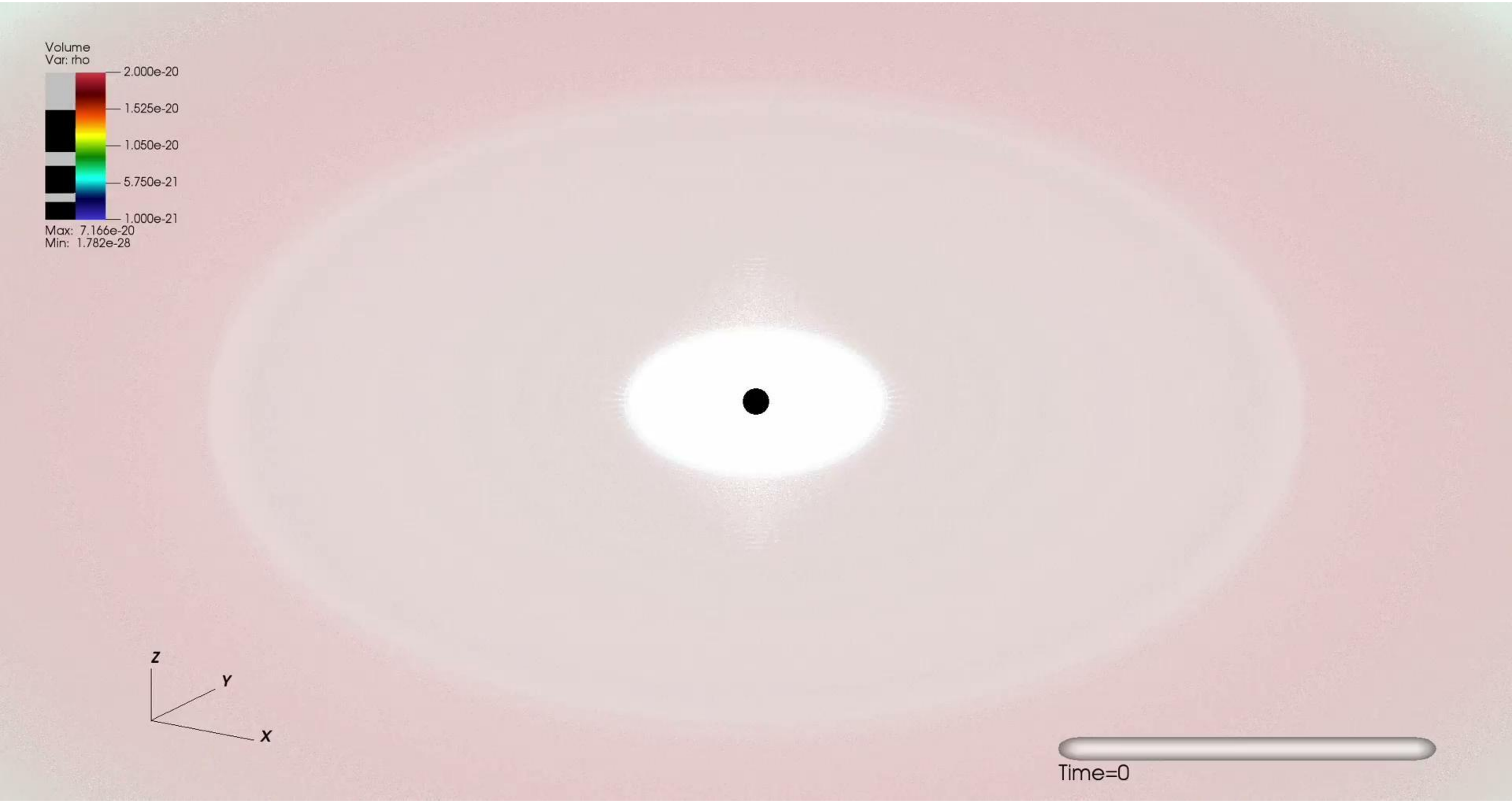
- Initial setup

  - Torus surrounded by a thin slab at 15 gravitational radii
  - Artificial cooling implemented to maintain the slab structure with *H/r = 0.05*
  - Spinning black hole (*a = 0.9*) at a tilt of 15 degrees with respect to the disc.



Bollimpalli et. al (in preparation)

GRMHD simulations of Tilted & Truncated accretion disc



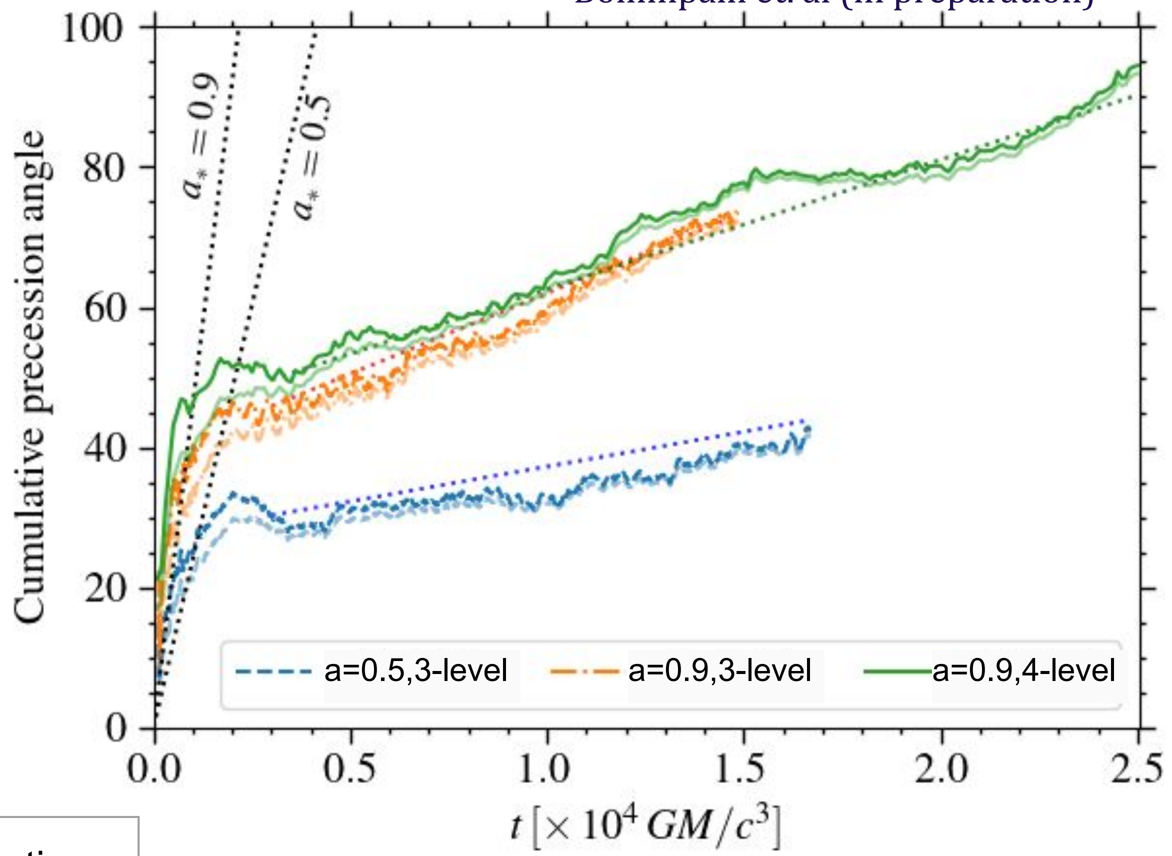
What is the effect of the outer disc?

- Expected precession rate

(Fragile et. al 2007; Ingram et. al 2009)

$$\Omega_{\text{prec}} = \frac{\int_{R_{in}}^{R_{out}} \Omega_{\text{LT}}(R)\, L(R)\, R\, dR}{\int_{R_{in}}^{R_{out}} L(R)\, R\, dR}$$

Bollimpalli et. al (in preparation)

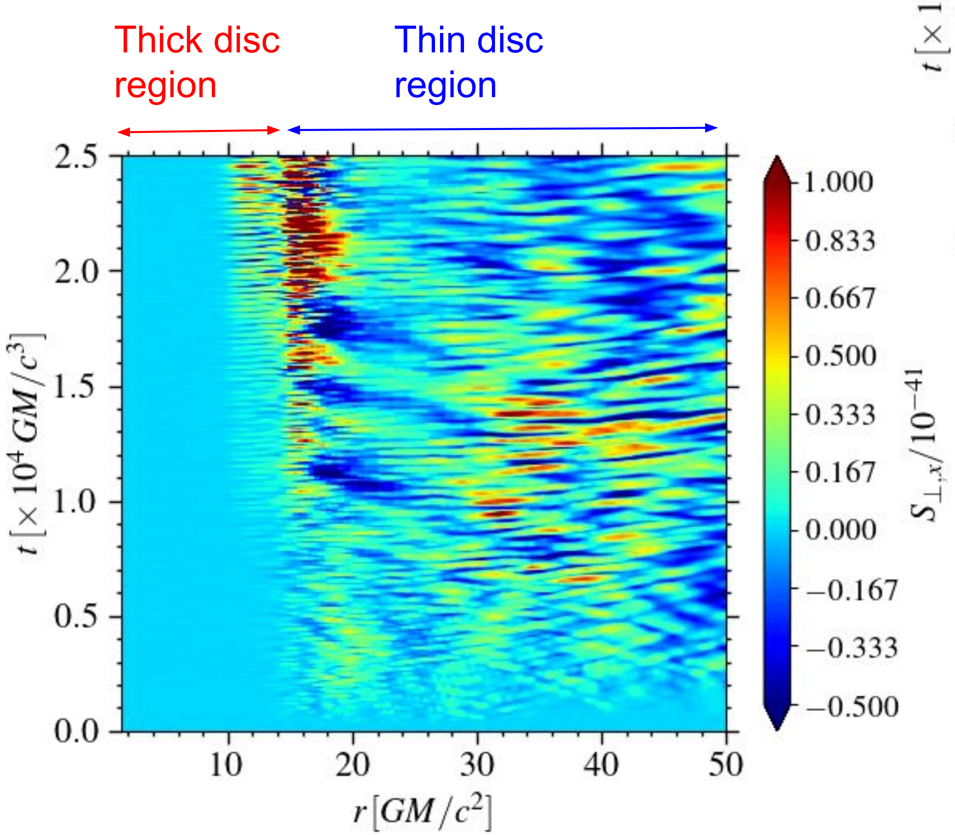


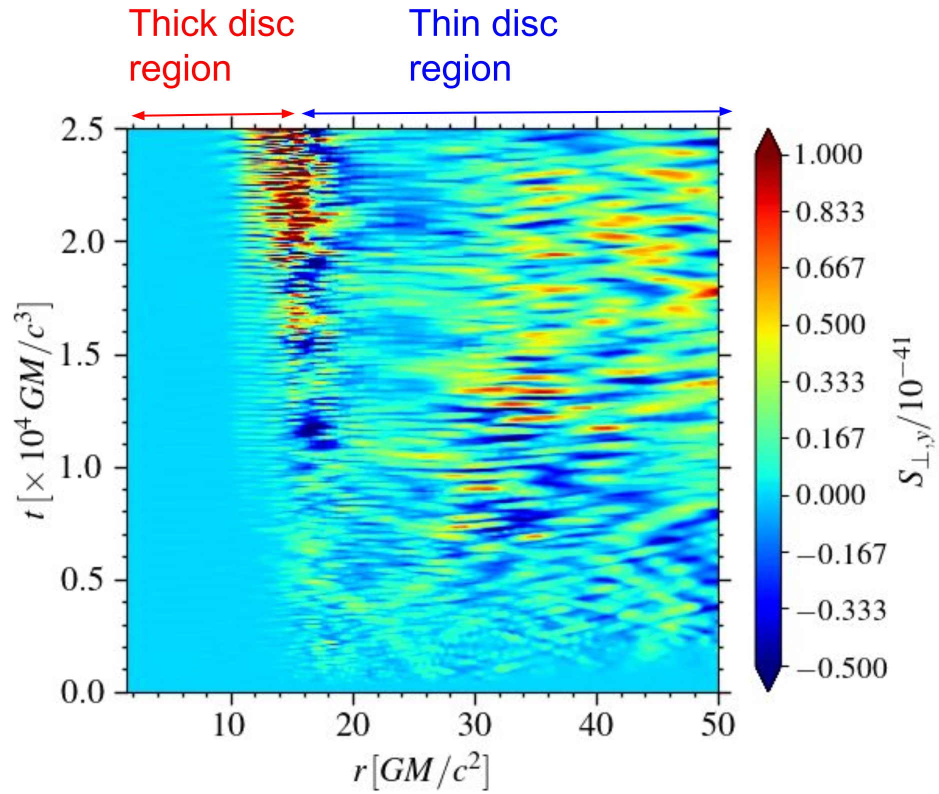
	Spin	Isolated torus (in Hz)	Simulation (in Hz)
3-level	0.5	8.5	0.3
3-level	0.9	16.3	0.85
	0.9	16.7	0.74

Relative decrease in the precession rate is roughly 95 percent.

How is the outer thin disc affecting the precession rate?

Well, if the applied Lense-Thirring torque is used to transport the angular momentum outwards (Sorathia et. al 2013)





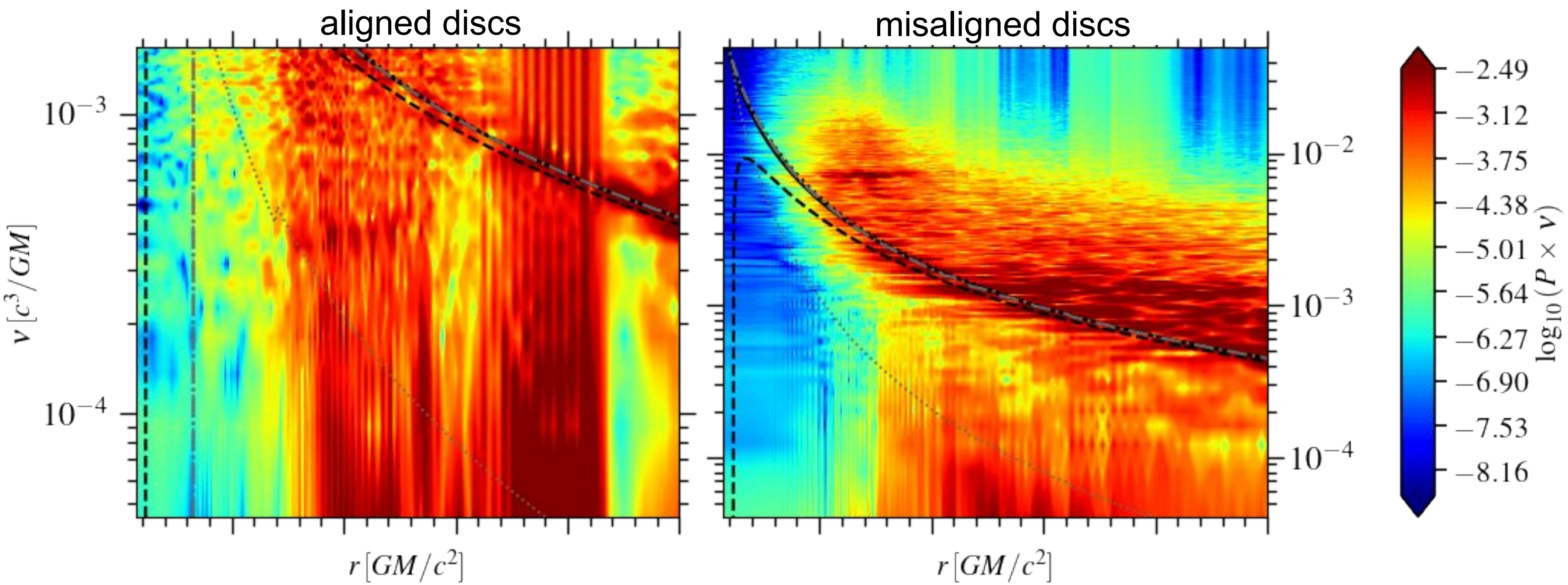
Increased angular momentum flux computed in the precessing plane.

Bollimpalli et. al (in preparation)

Variability in misaligned accretion discs

- The accretion rate in the torus region is orders of magnitude lower when compared to the outer thin disc - *variability along the radial epicyclic frequency/ Keplerian frequency.*

Power density spectra of accretion rate



Variability in misaligned accretion discs

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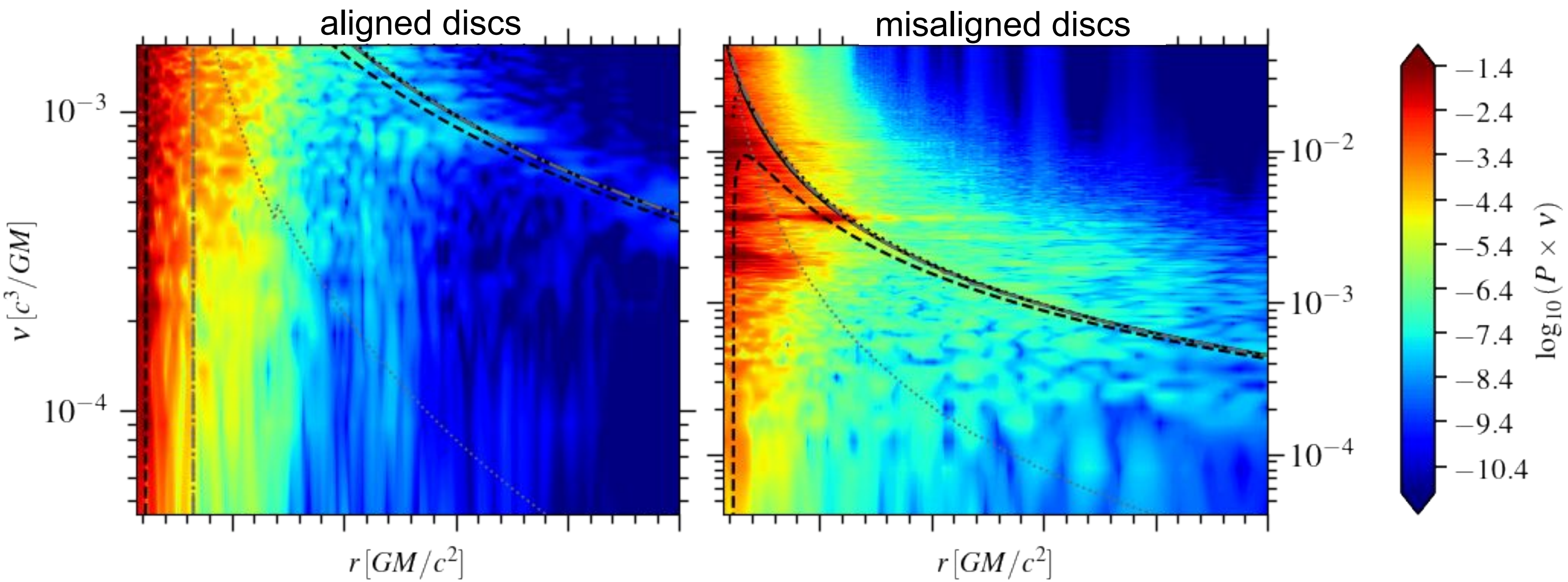
- QPO-like features noted in misaligned discs; disc undergoing vertical oscillations. 40 Hz for a 10 solar mass BH.

Power density spectra of vertical velocity



Variability in misaligned accretion discs

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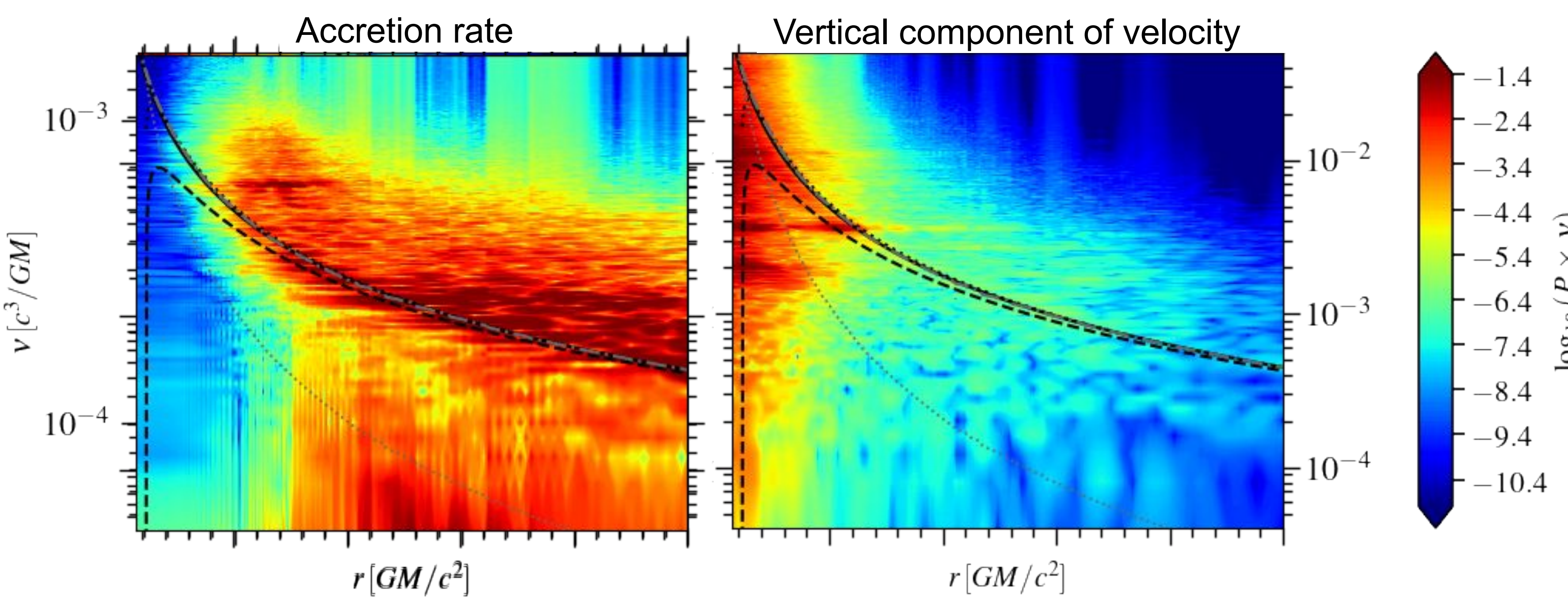
Are these trapped modes? Inertial or acoustic?

Are these oscillations related to the variability in accretion rate?

Power density spectra



Summary

email :
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- Mass accretion rate from non-radiative GRMHD simulations do show the evidence for *propagating fluctuations* theory.
    - Absorption mechanisms can also cause some variability; Radiative simulations
    - Disc-jet connection?
    - Understanding the frequency breaks in the power spectrum

- Simulations suggest that presence of outer thin disc reduces the expected precession rate by nearly 95 percent.
    - Could solve the problem of requirement of larger precessing, corona in systems like GRS 1915+105, MAXI J1535-571.
    - Does the outer thin disc break into rings? (Nixon et. al 2012, Liska et. al 2019)

Theory
Simulations

Super-computing power

Advanced numerical techniques

Current & Future missions

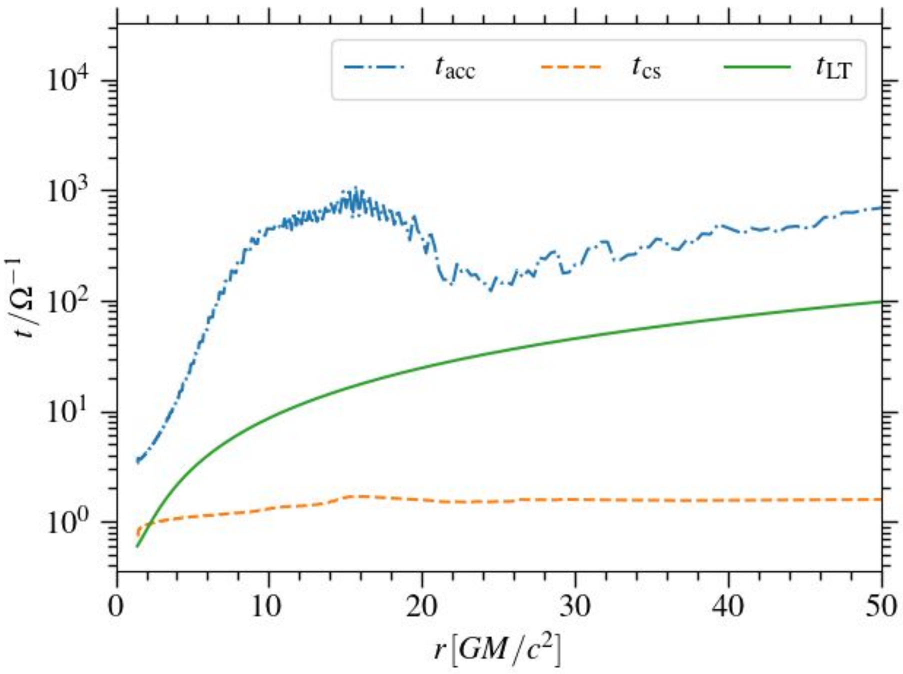
eXTP, HMXT

Andrea Santangelo's talk

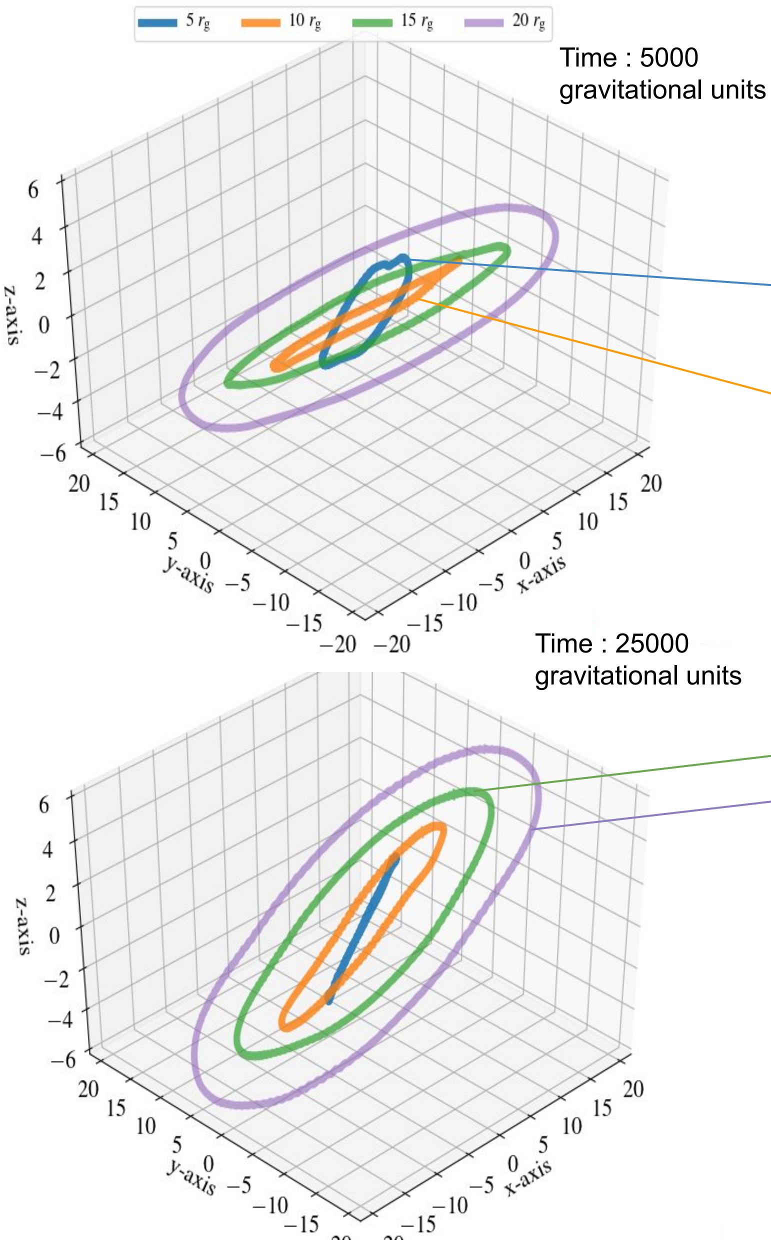
NICER, IXPE, Astrosat

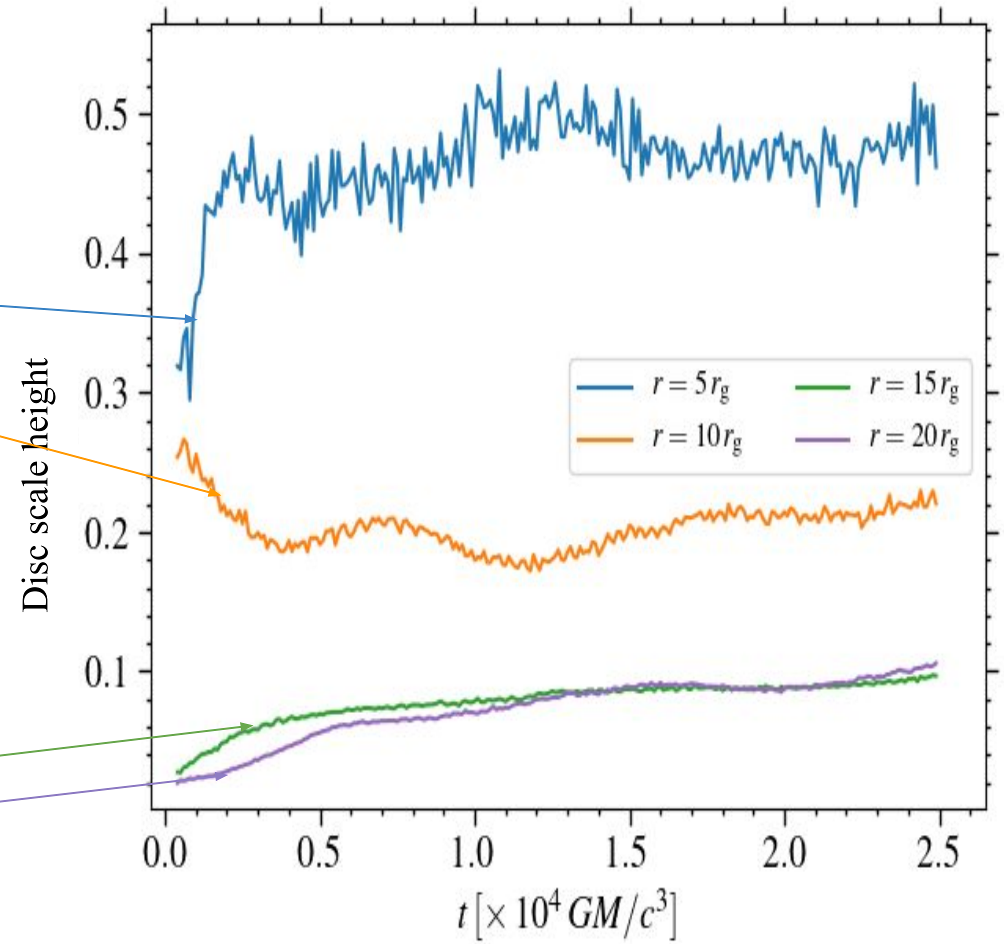
ATHENA,

Backup slides:



Does the flow really have truncated disc geometry?



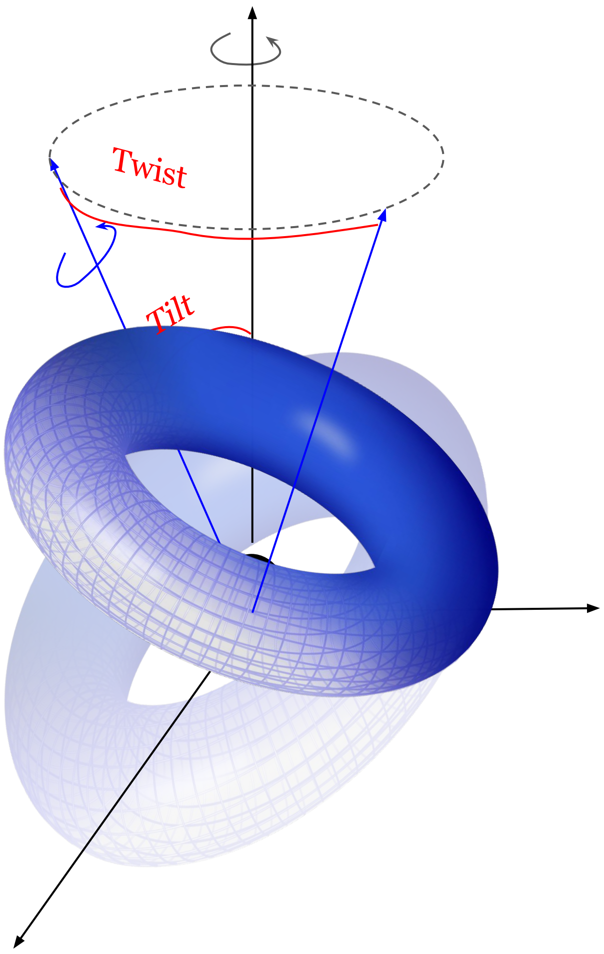


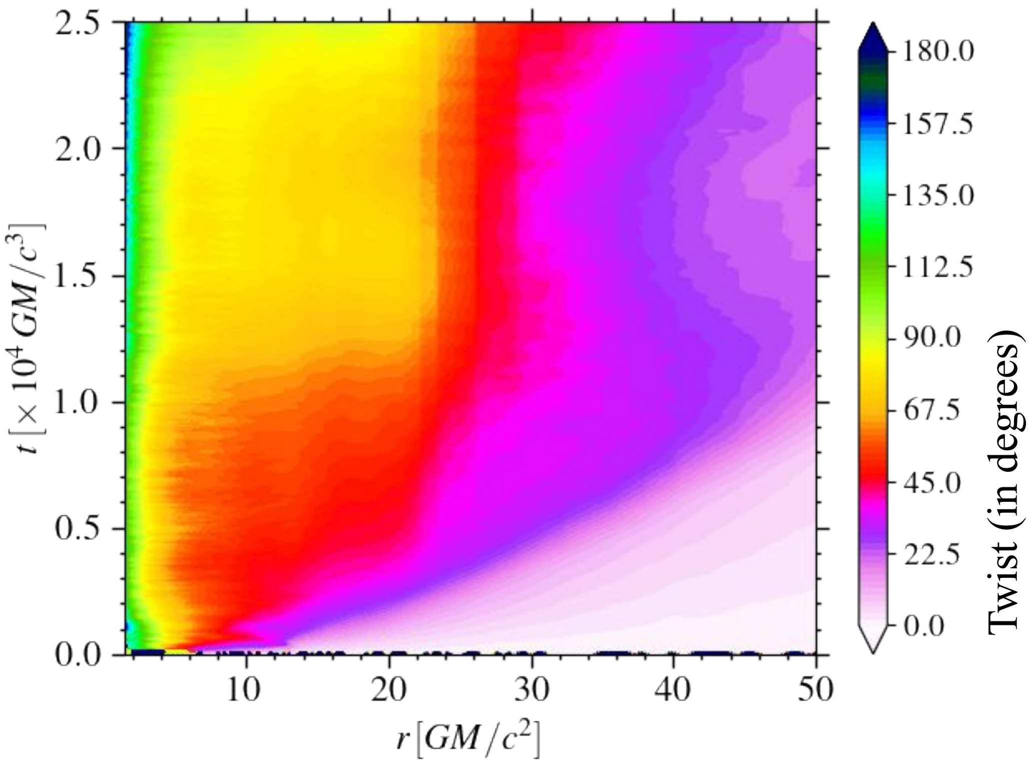
- ➢ The two-component structure is maintained

Bollimpalli et. al (in preparation)

Measuring precession :Twist angle

- Solid body precession in the torus region.
- The outer disc also undergoes precession, but at comparatively small rates.

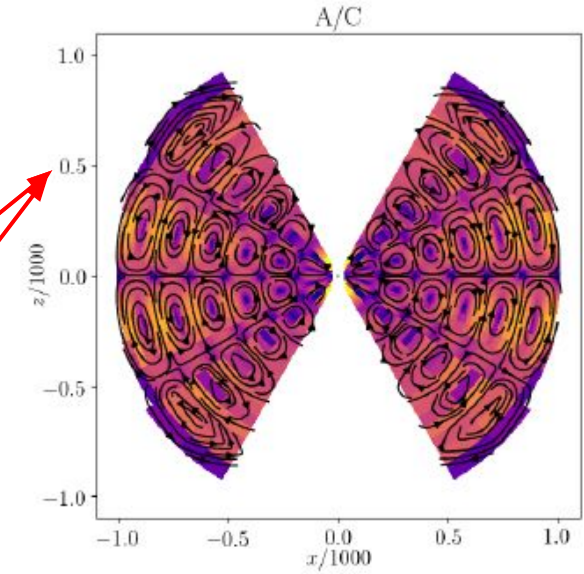


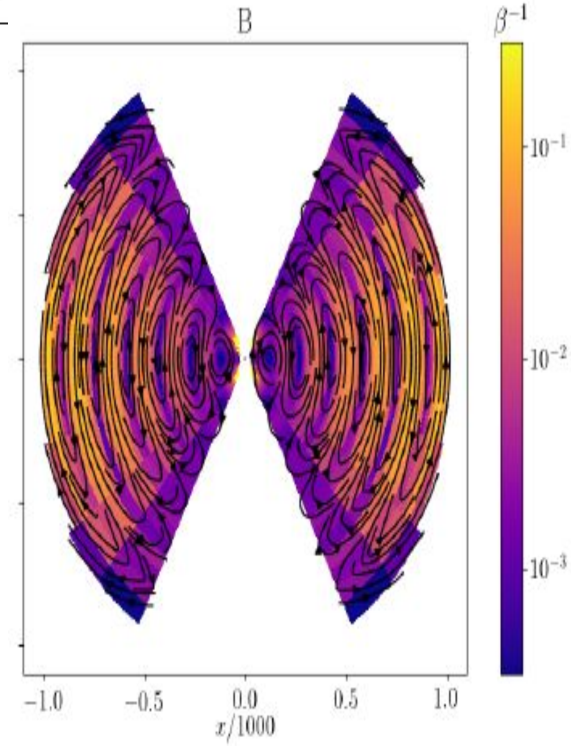


Bollimpalli et. al (in preparation)

Numerical simulations

	Simulation	run length (GM/c^3)	$r_{\max}$ (GM/c^2)	B field
Athena++ (White et. al 2020)	Sim A	440,000	52	$N_r = 6, N_\theta = 4$
	Sim B	220,000	52	$N_r = 6, N_\theta = 1$
	Sim C	220,000	52	$N_r = 6, N_\theta = 4$
	Sim R	200,000	20	$N_r = 8, N_\theta = 1$
HARM (Narayan et. al 2012)	Sim D	50,700	40	$N_r = 1, N_\theta = 1$
Cosmos++ (Bollimpalli et. al 2020)				





- ➢ The initial setups are different for all these simulations
- ➢ The resulting radiatively inefficient accretion flows are also different, particularly simulations A & C which have polar inflows and equatorial outflows.