The accretion flow in black hole X-ray binaries through the “lens” of X-ray spectral-timing

Barbara De Marco

Universitat Politècnica de Catalunya

“Out to the stars” by T. Belloni
[Museu Blau, Barcelona]

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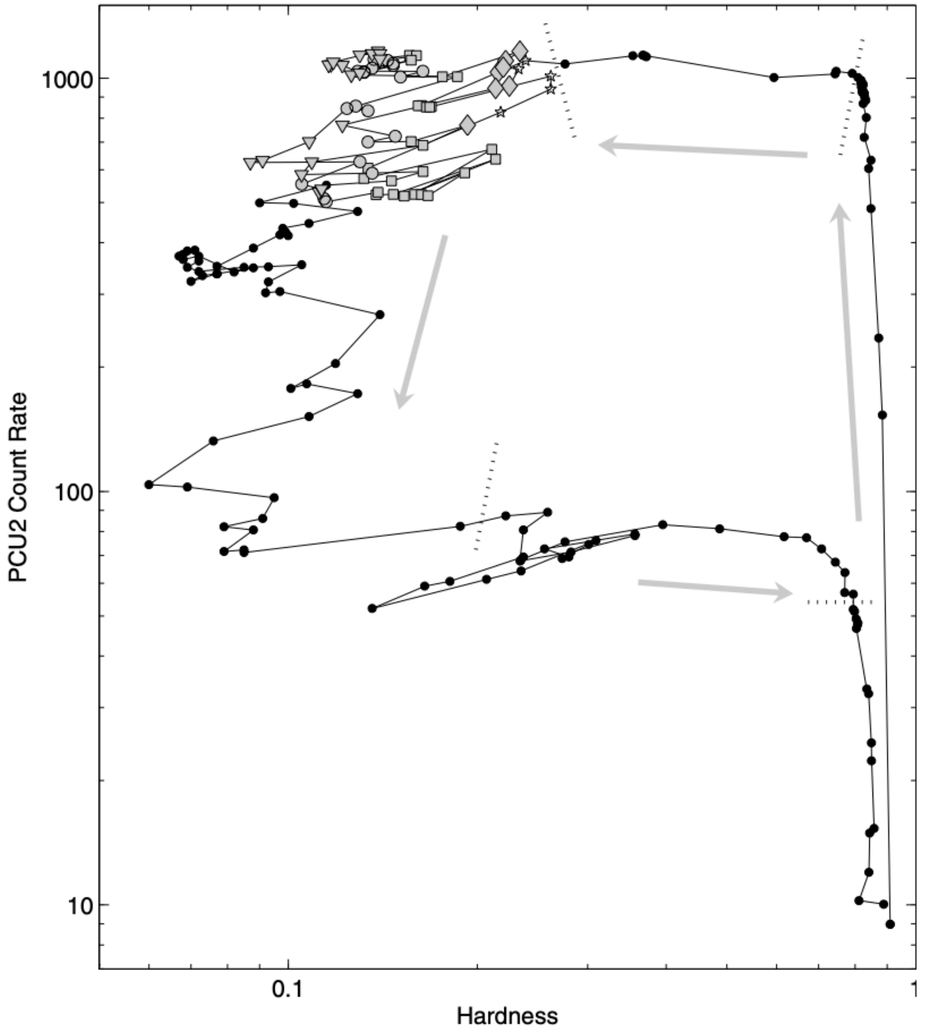
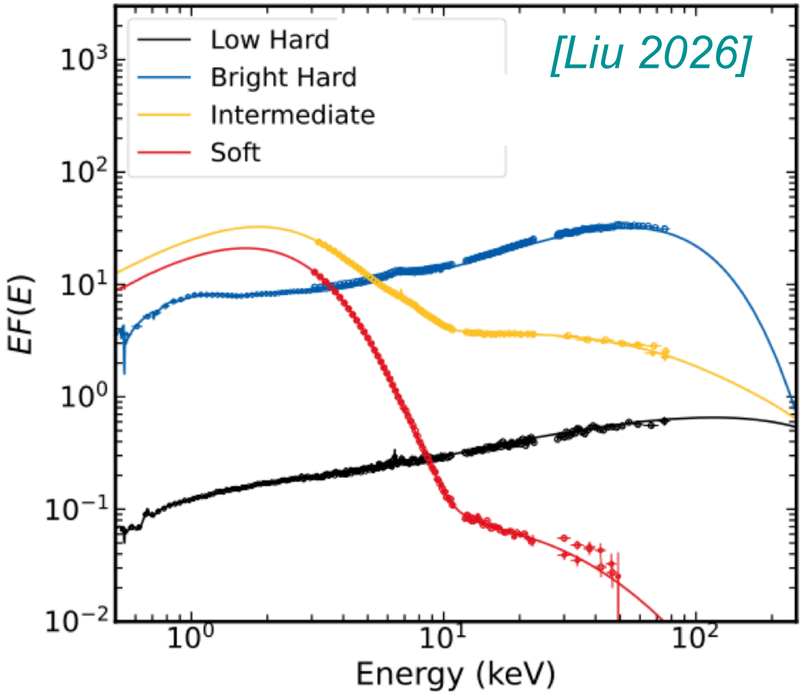
The canonical map

A common language to describe accretion states

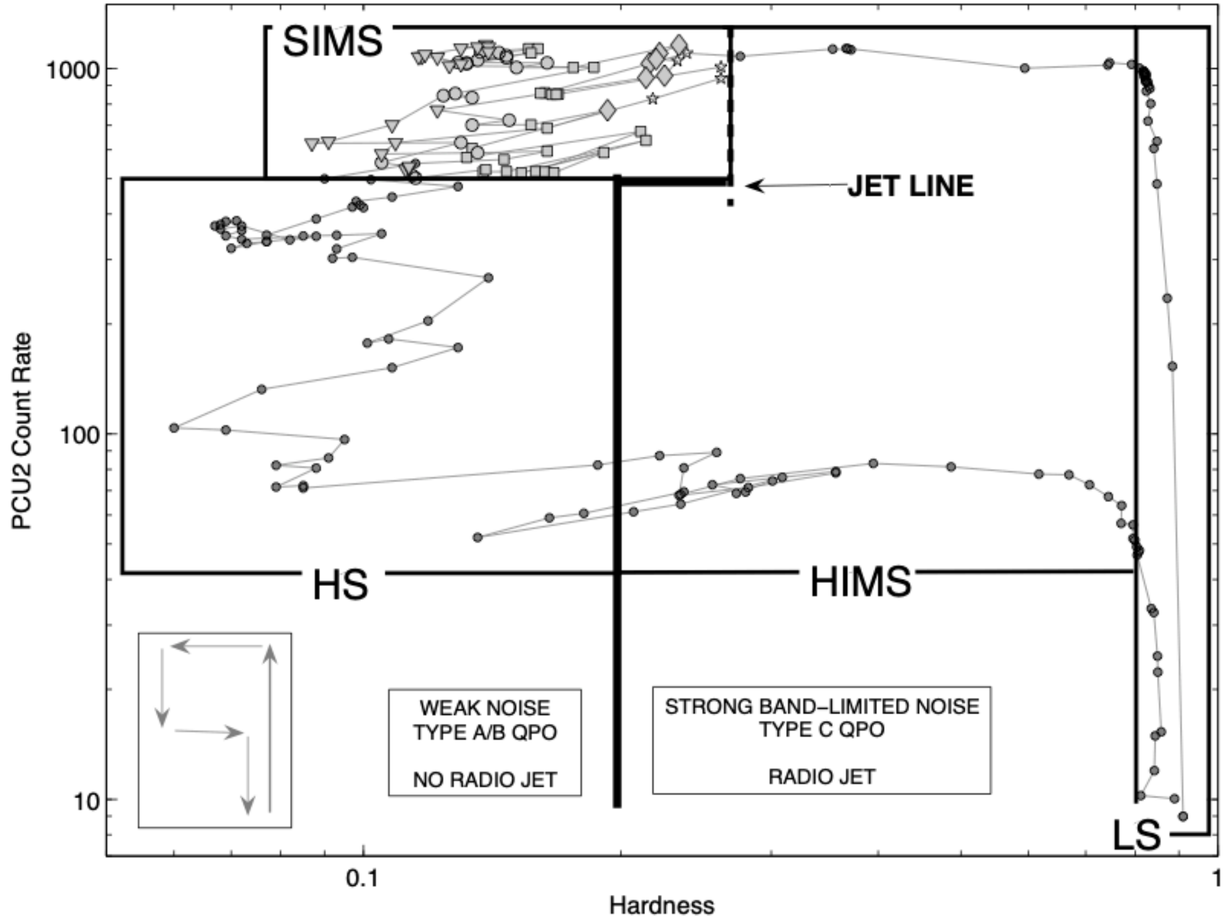


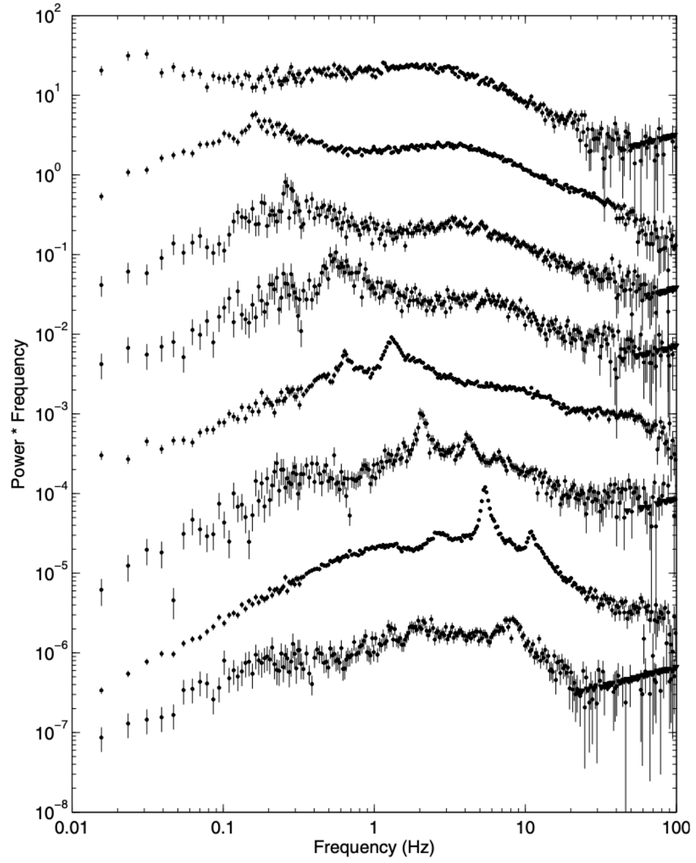


[Belloni et al. 2005; Homan & Belloni 2005; Remillard & McClintock 2006]

Fast X-ray variability

"It is now clear that fast timing variations are a key ingredient which needs to be considered in order to have a complete view of the states and state transitions" [Belloni et al. 2005]



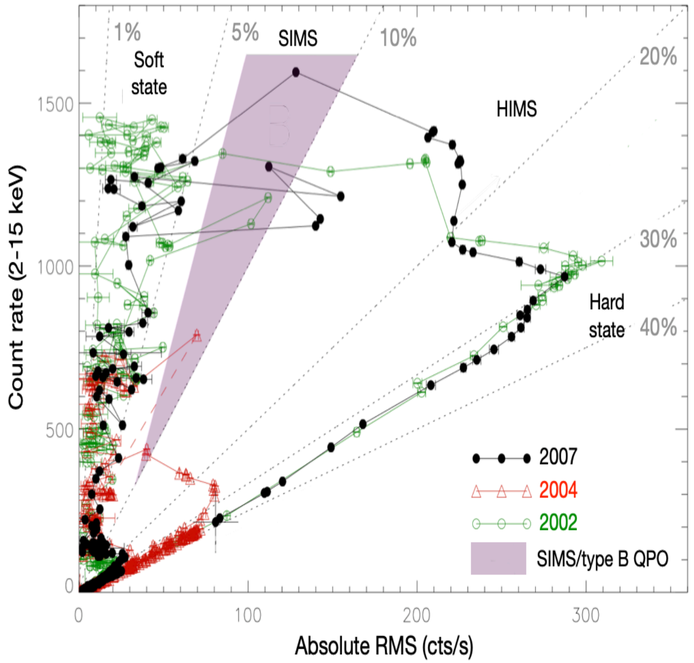


Hard state

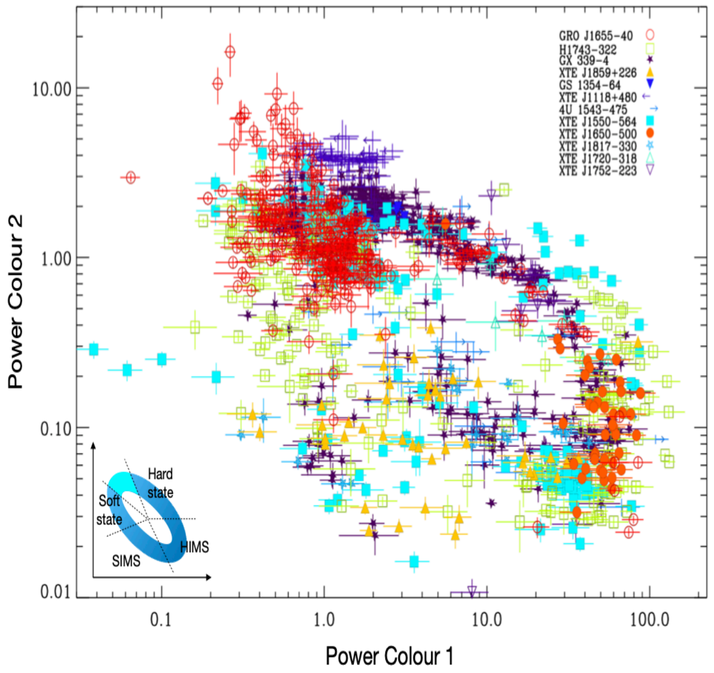
Soft state

[Belloni & Hasinger 1990; Belloni et al. 2002; Belloni et al. 2005]

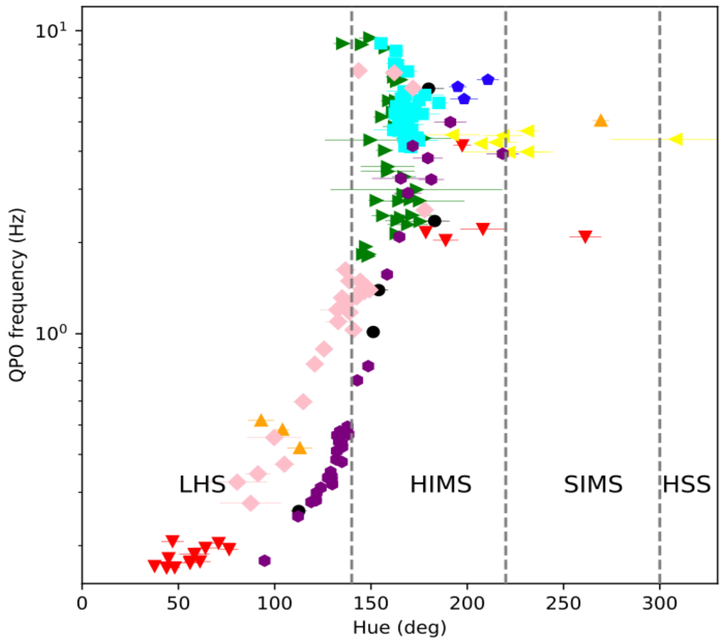
Fast X-ray variability maps



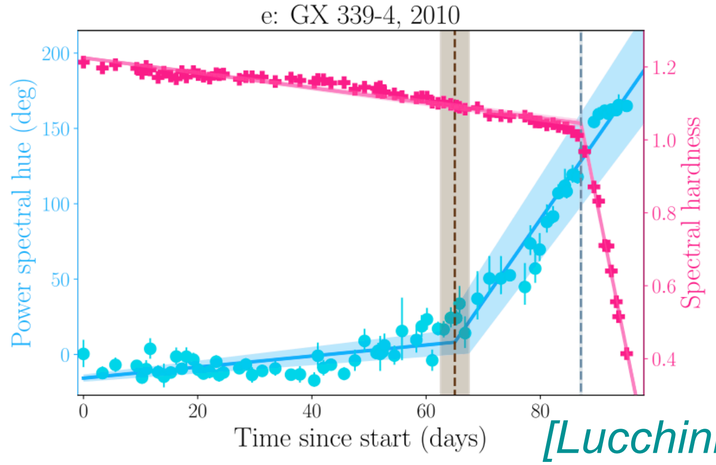
[Muñoz-Darias et al. 2011; Heil et al. 2012]



[Heil et al. 2015]



[Zhang et al. 2026]

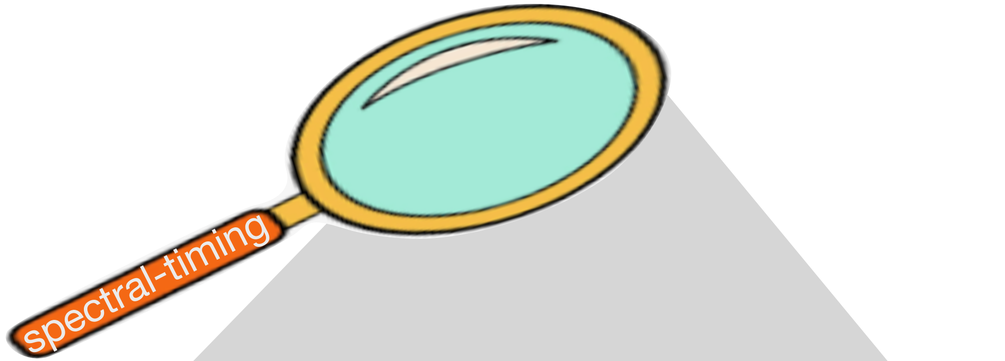


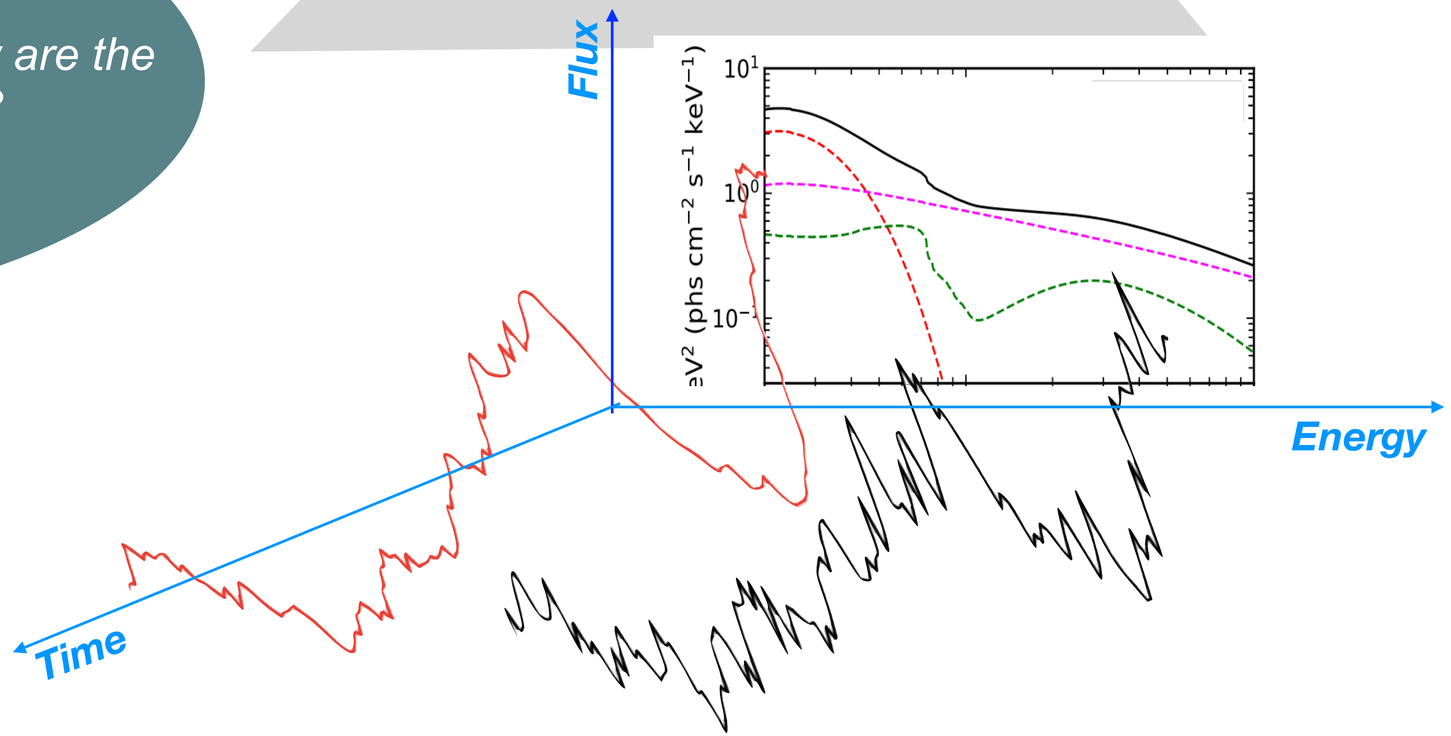
[Lucchini et al. 2023]

Rms, power colours, QPOs, hue evolution…identify states and state transitions

From state classification to physical diagnosis

Where does this variability come from and how are the different spectral components coupled?





[see E. Lai and F. Garcia talks]

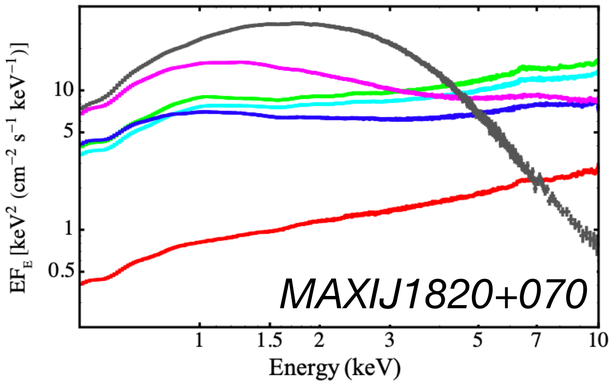
Three fundamental questions:

Where does the X-ray variability come from?

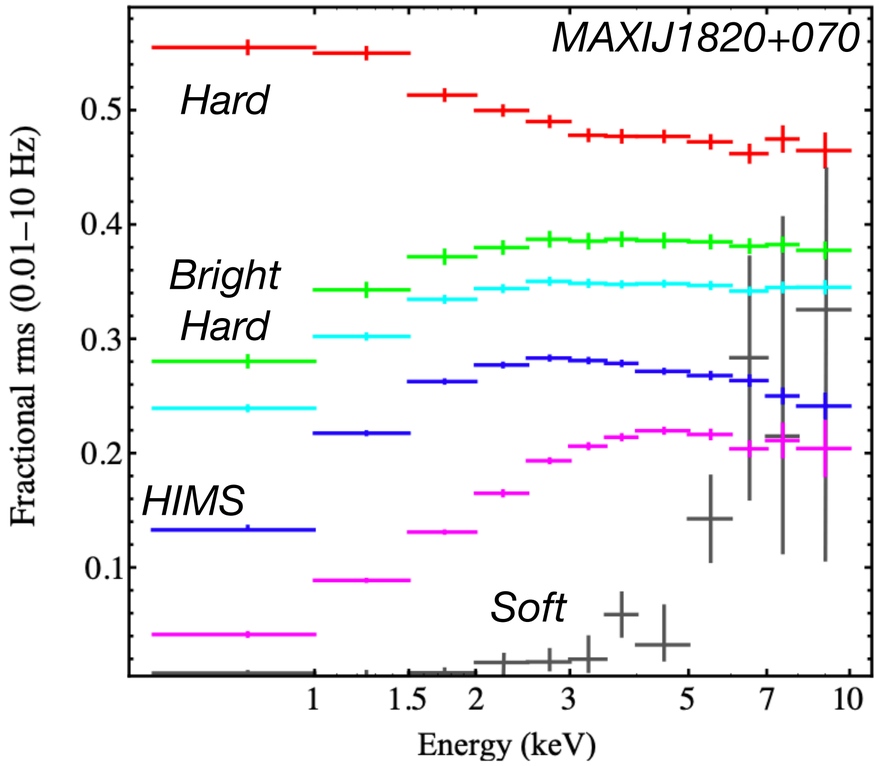
What is the geometry of the inner accretion flow?

What happens at the hard-to-soft state transition?

Where does the X-ray variability come from?

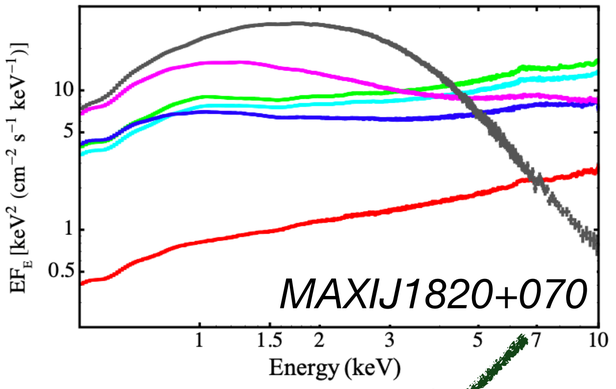


Stable disc plus variable corona?



[Axelsson & Veledina 2021; Churazov et al. 2001; Gierlinski & Zdziarski 2005]

Where does the X-ray variability come from?



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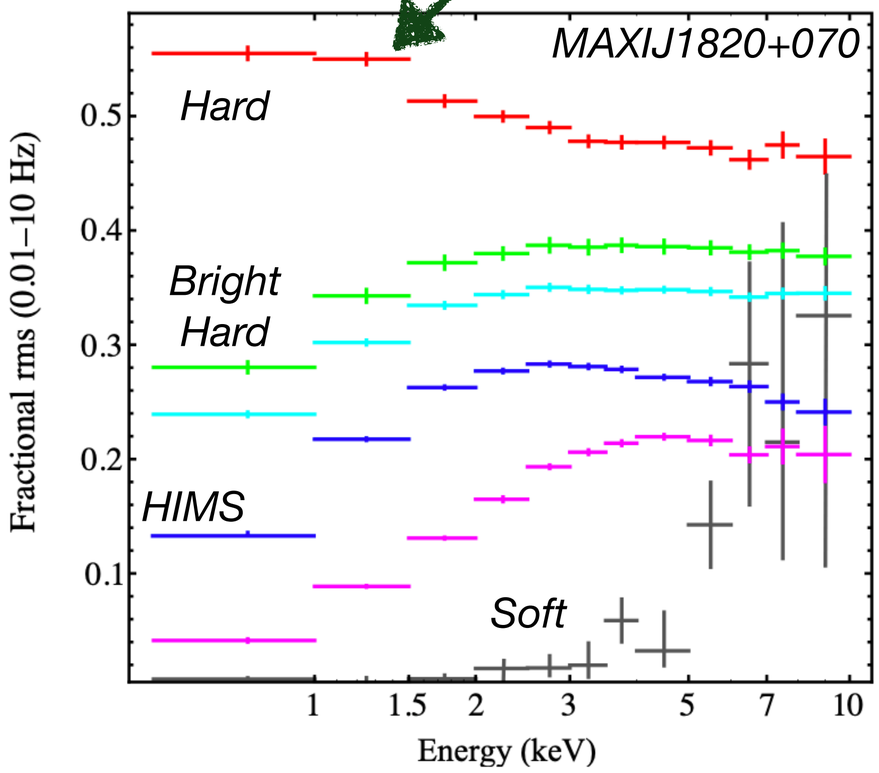
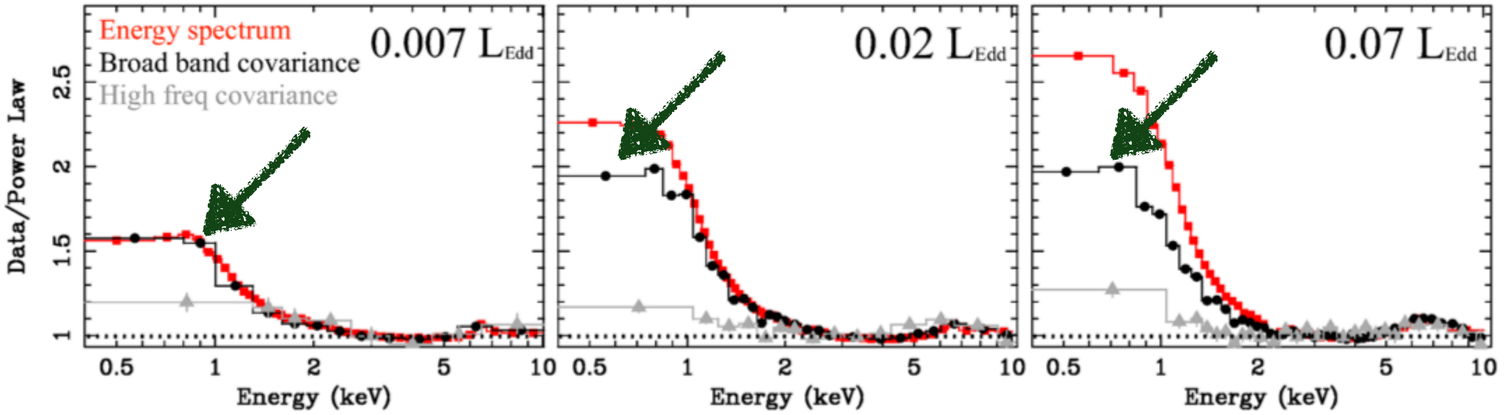


GX 339-4 (Hard state)



[De Marco et al. 2015a; Wilkinson & Uttley 2009; De Marco, Motta, Belloni 2022]

[Axelsson & Veledina 2021; Churazov et al. 2001; Gierlinski & Zdziarski 2005]

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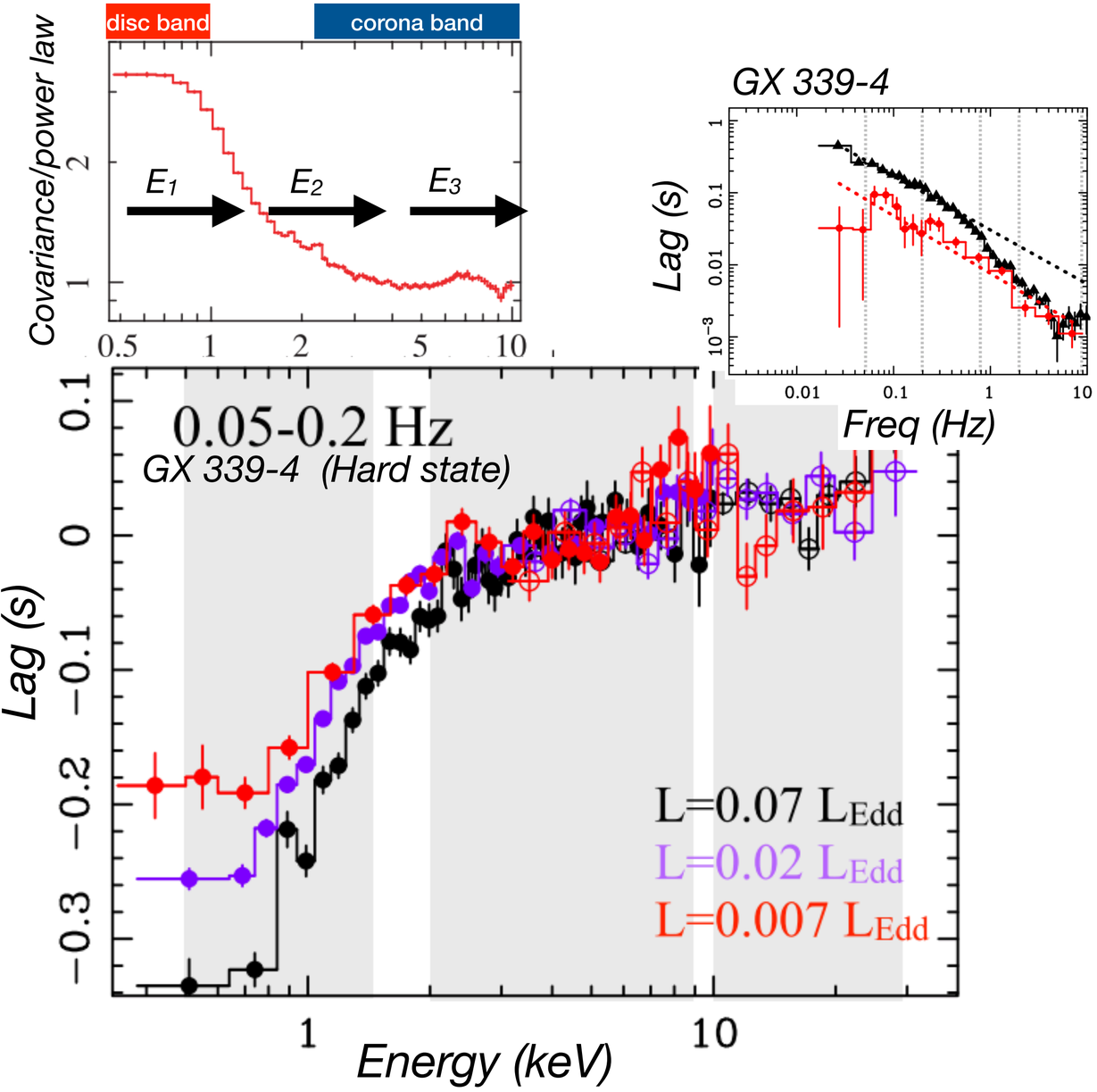

[De Marco et al. 2015b]

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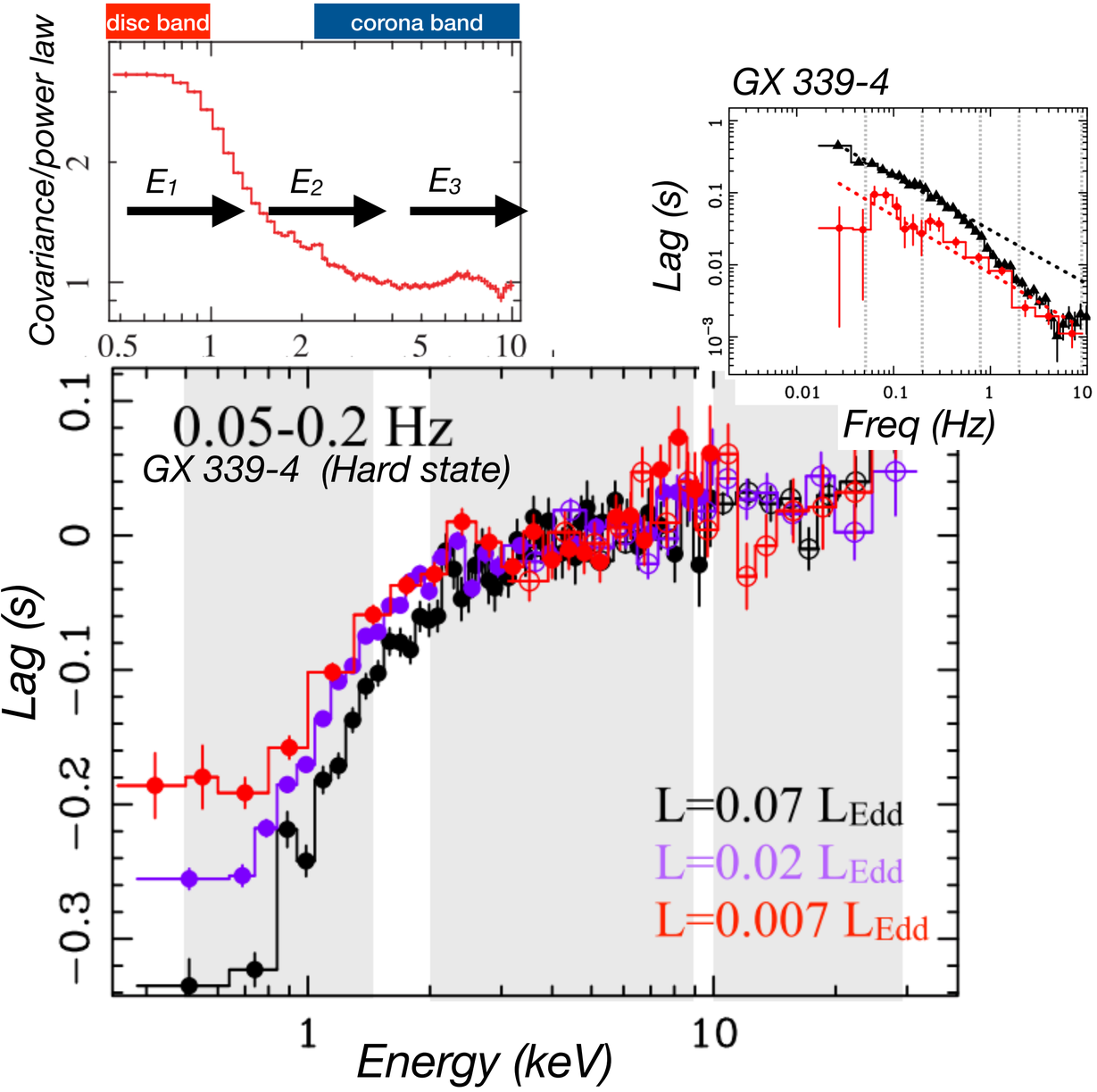
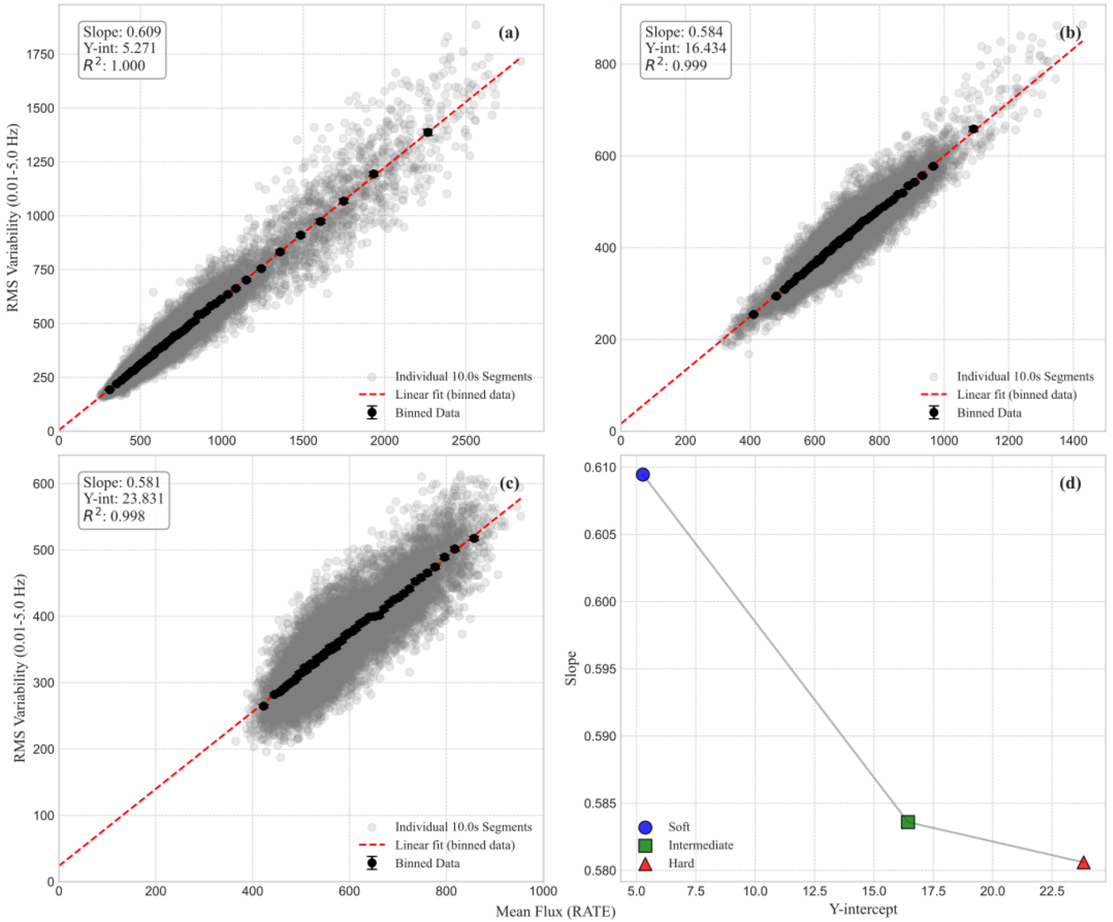


[De Marco et al. 2015b]

Cyg X1 (12 yrs NuSTAR data)



[Duraphe et al. 2026; Uttley et al. 2005; Heil et al. 2012; but see Scargle 2022]

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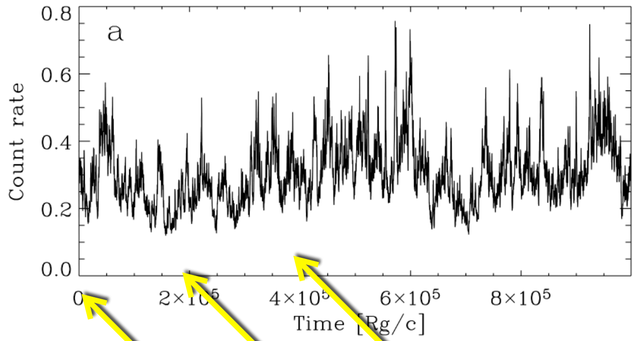
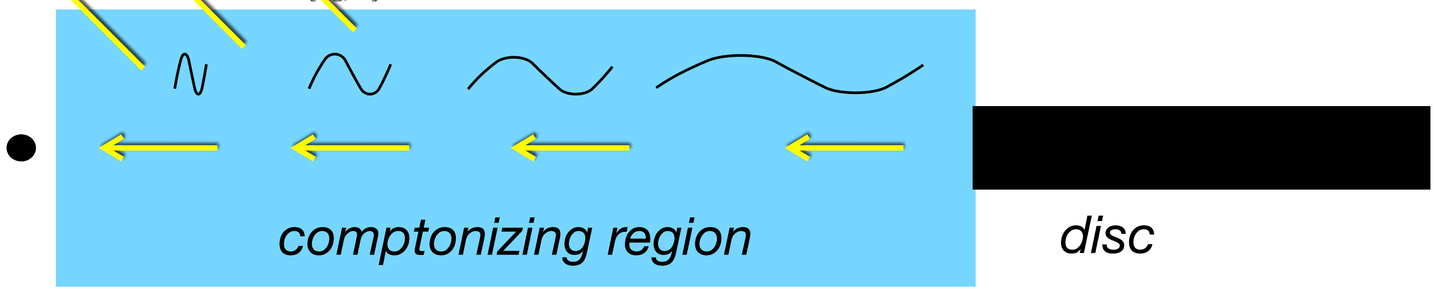


Propagating mass accretion rate fluctuations



[Lyubarskii 1997; Kotov et al. 2001; Hogg & Reynolds 2016; Mushtukov et al. 2018; Bollimpalli et al. 2020; Turner & Reynolds 2021; Mummery 2023…]

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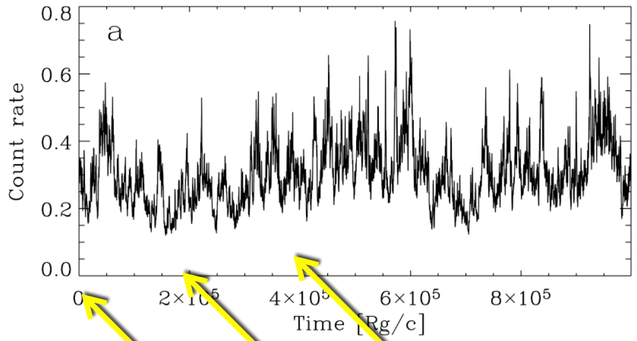

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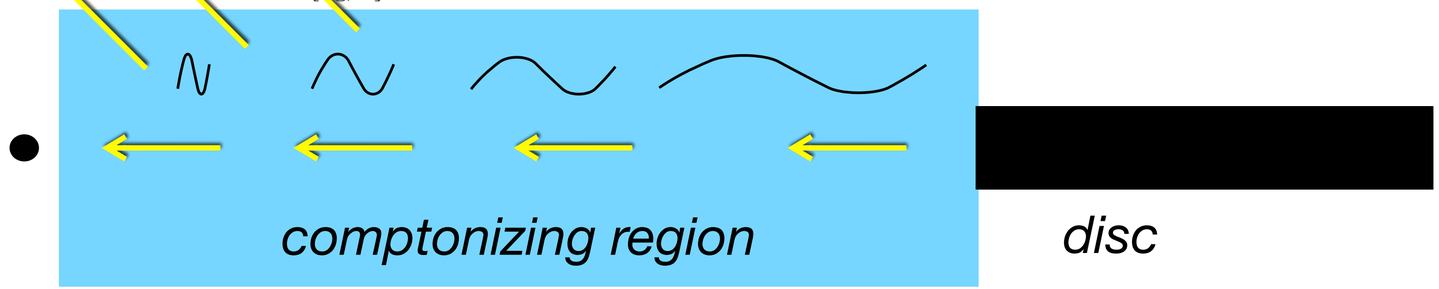
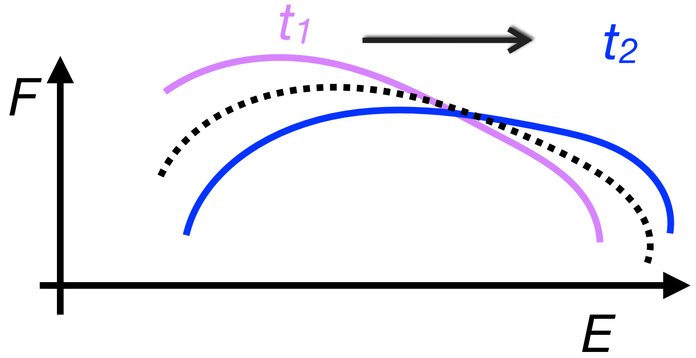
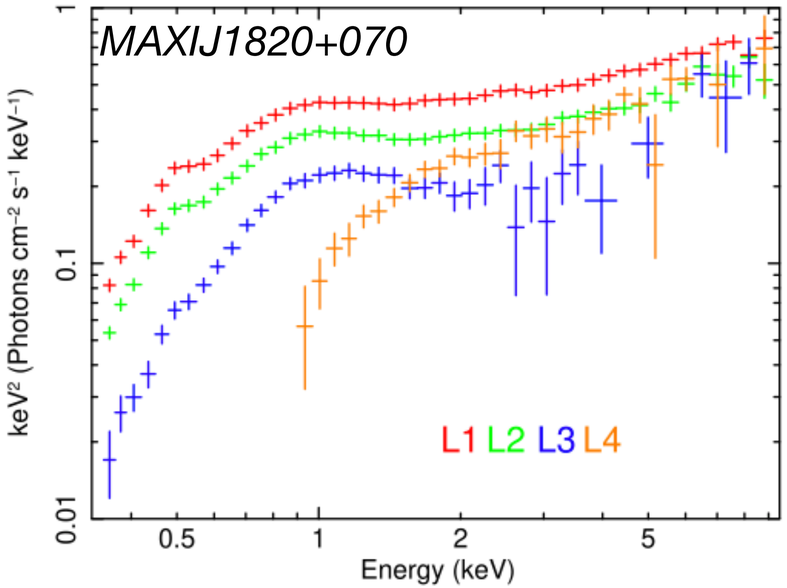


Harder

Softer





[Dziełak, De Marco, Zdziarski 2021]

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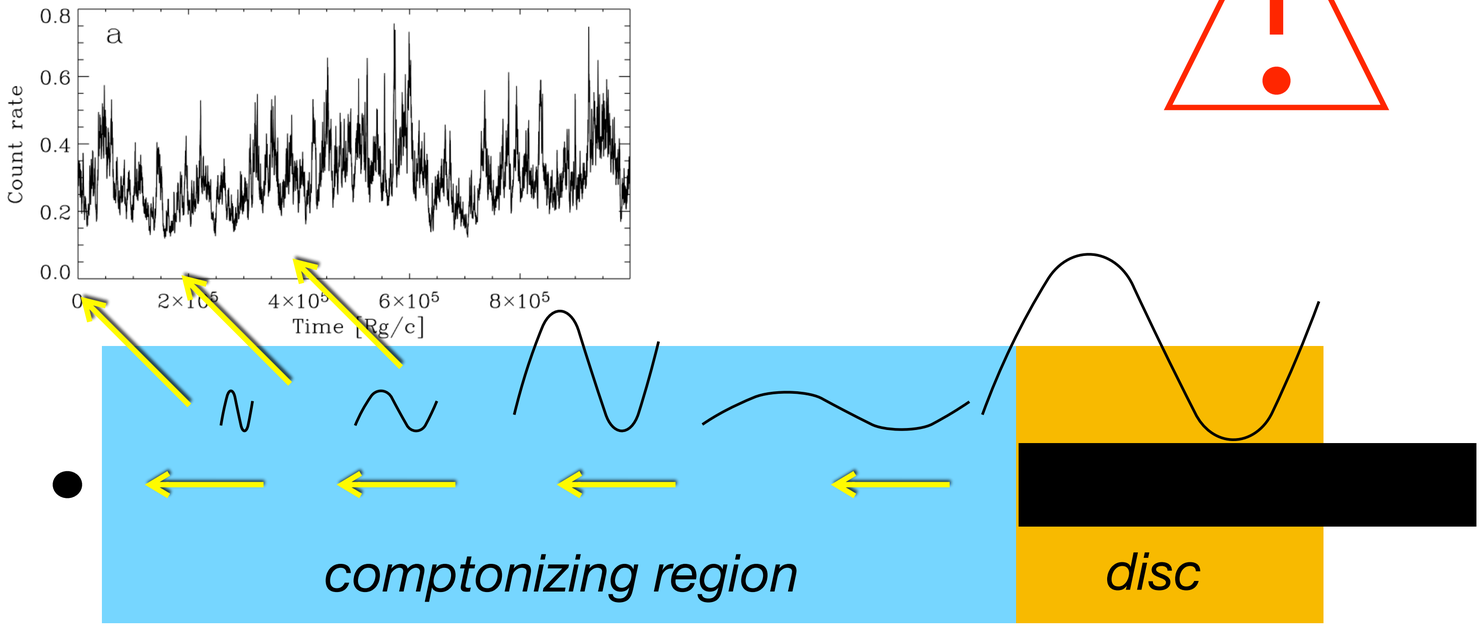
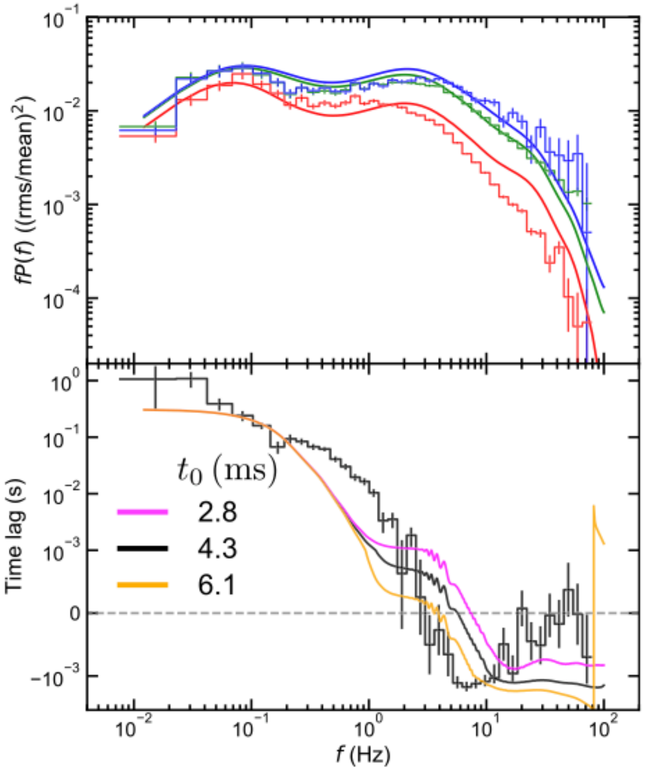


I. Region of turbulent disc emission

II. Enhanced variability/emissivity at certain radii

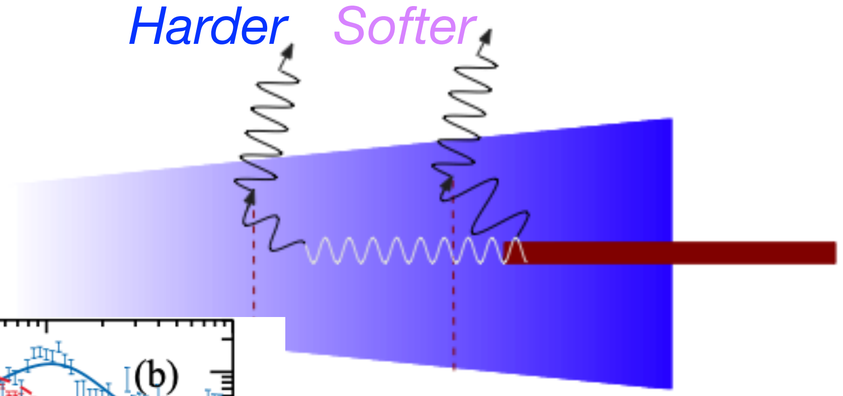
MAXIJ1820+070



[Kawamura et al. 2022; see also Rapisarda et al. 2016, Mahmoud & Done 2018]

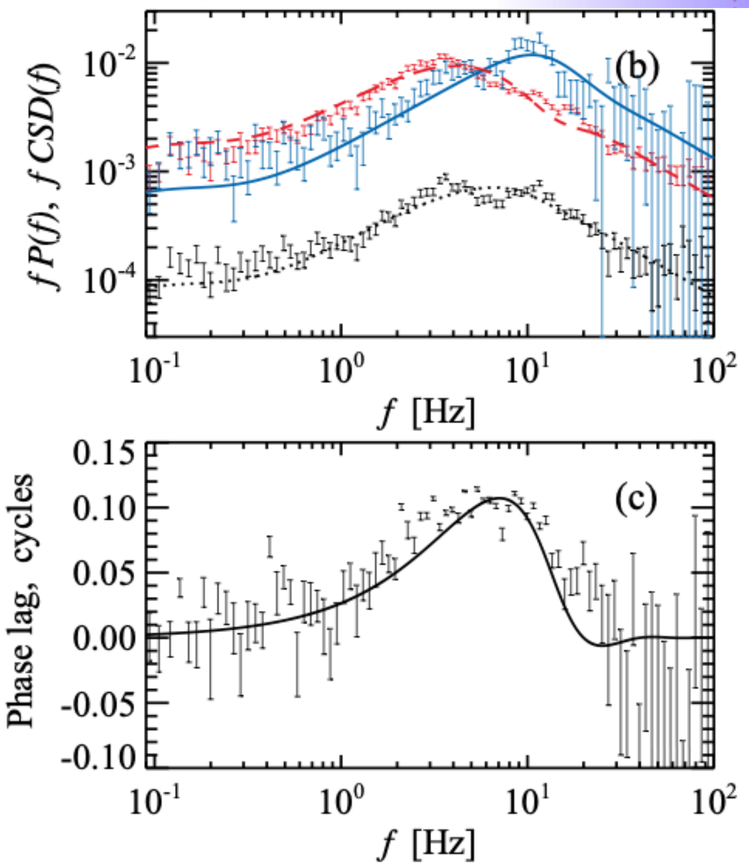
Where does the X-ray variability come from?

III. Interference of continuum variability



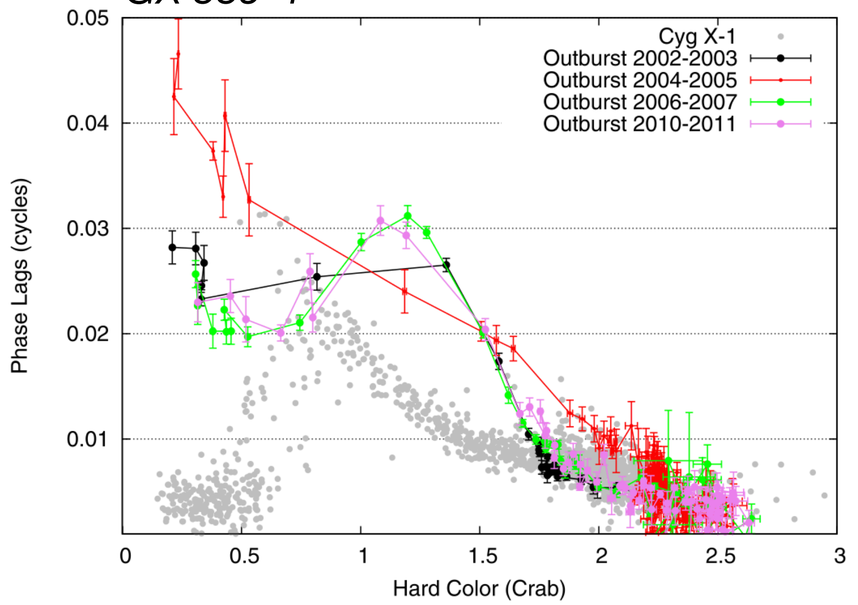
[Veledina 2016; 2018]

Cyg X1



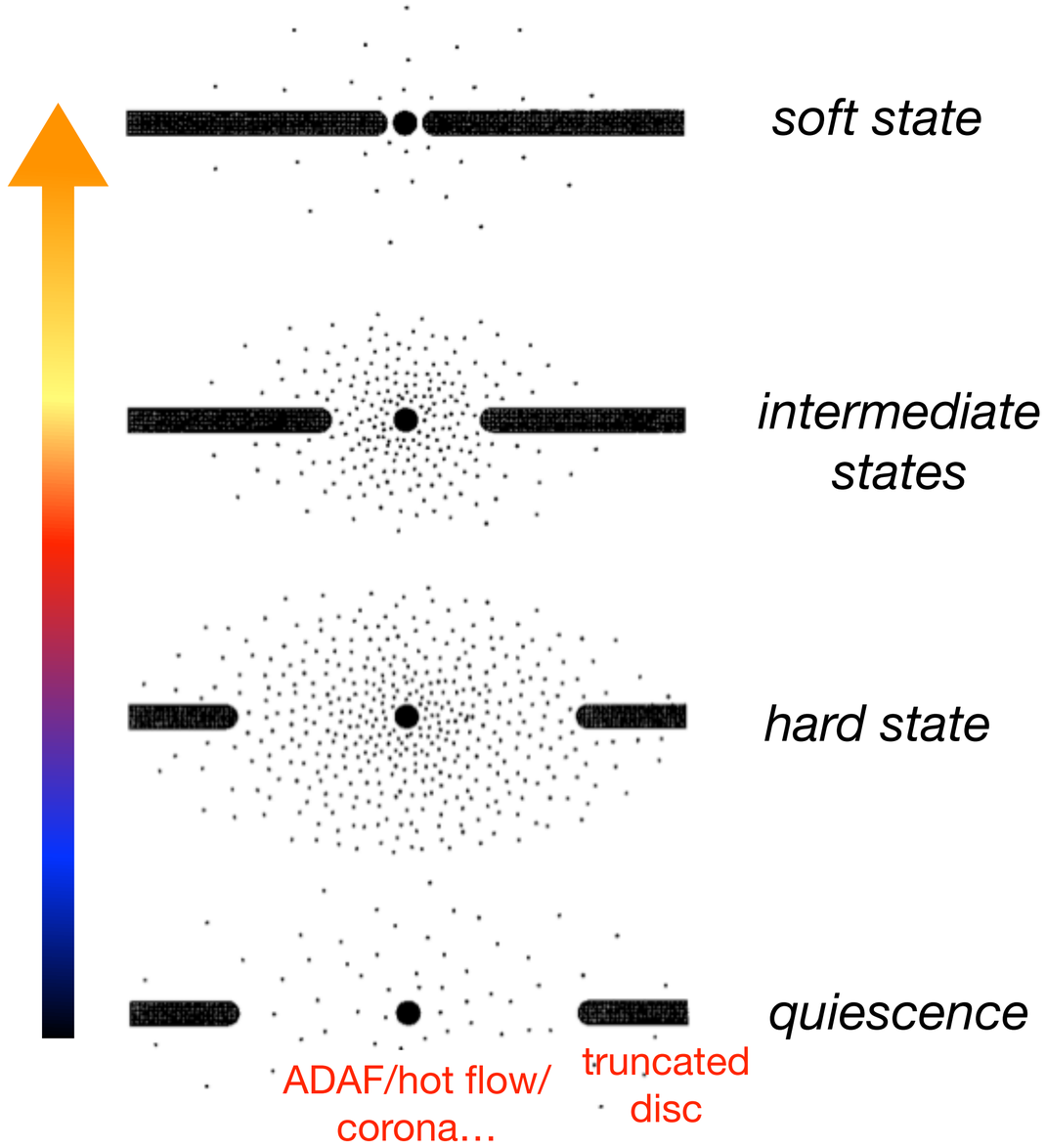
IV. Comptonization

GX 339-4



[Altamirano & Mendez 2015; Grinberg et al. 2014; Reig et al. 2018]

What is the geometry of the inner accretion flow?



[e.g. Esin+'97; Poutanen +'97; Meyer+'00; Narayan & Yi '94; Narayan & McClintock '08]

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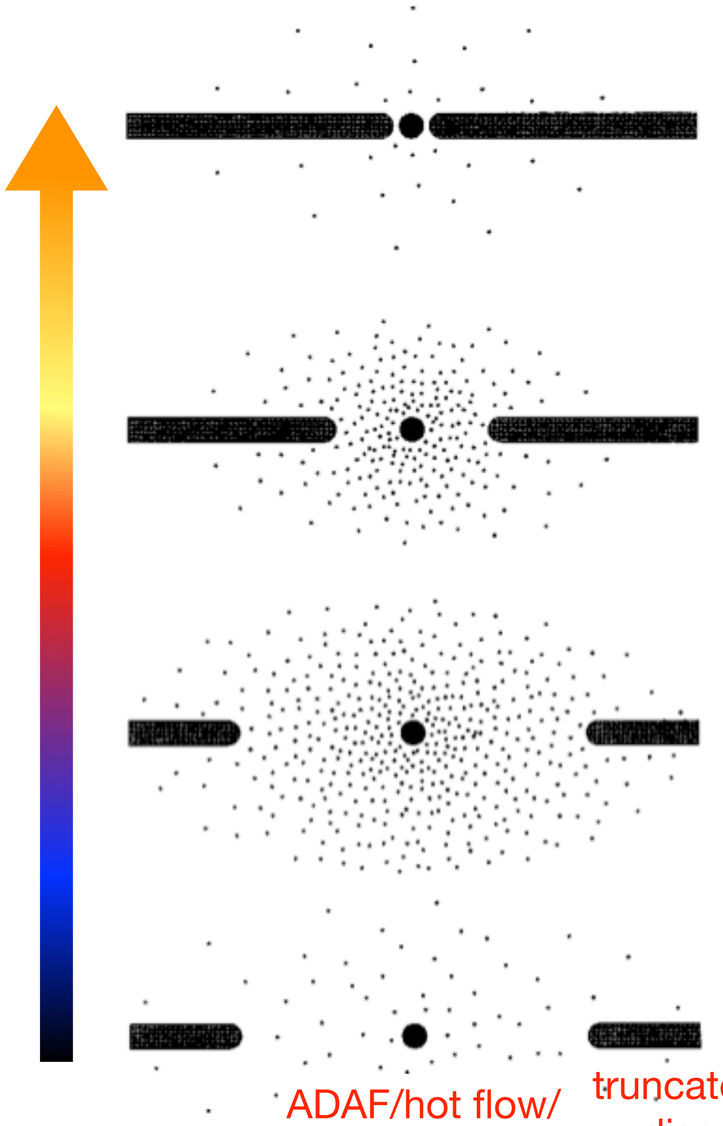


soft state

intermediate states

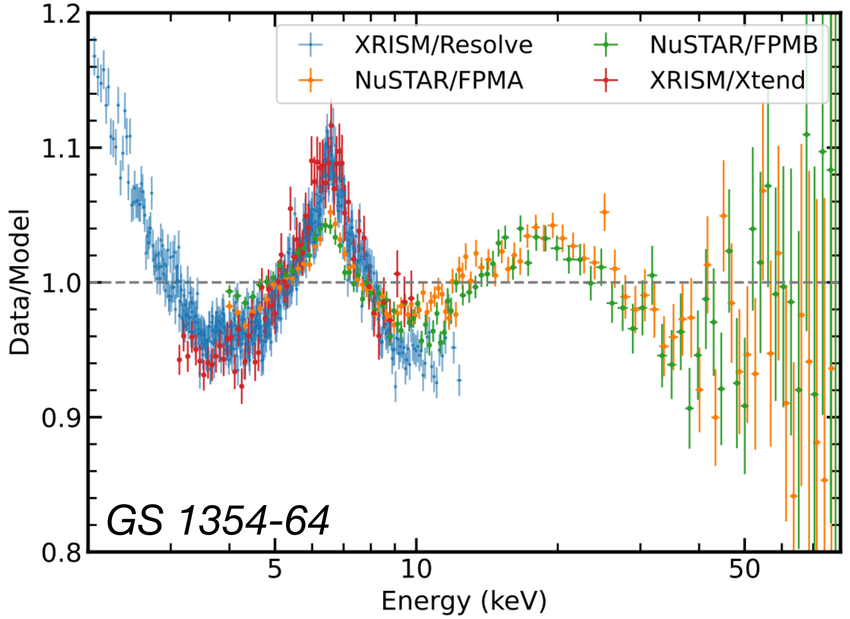
hard state

quiescence

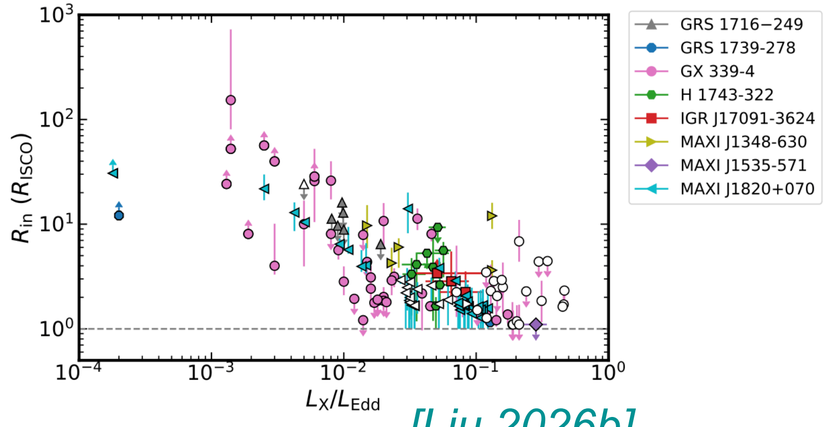
ADAF/hot flow/ corona…

truncated disc

[e.g. Esin+'97; Poutanen +'97; Meyer+'00; Narayan & Yi '94; Narayan & McClintock '08]



[Liu et al. 2026a; Garcia et al. 2015; 2018]



[Liu 2026b]

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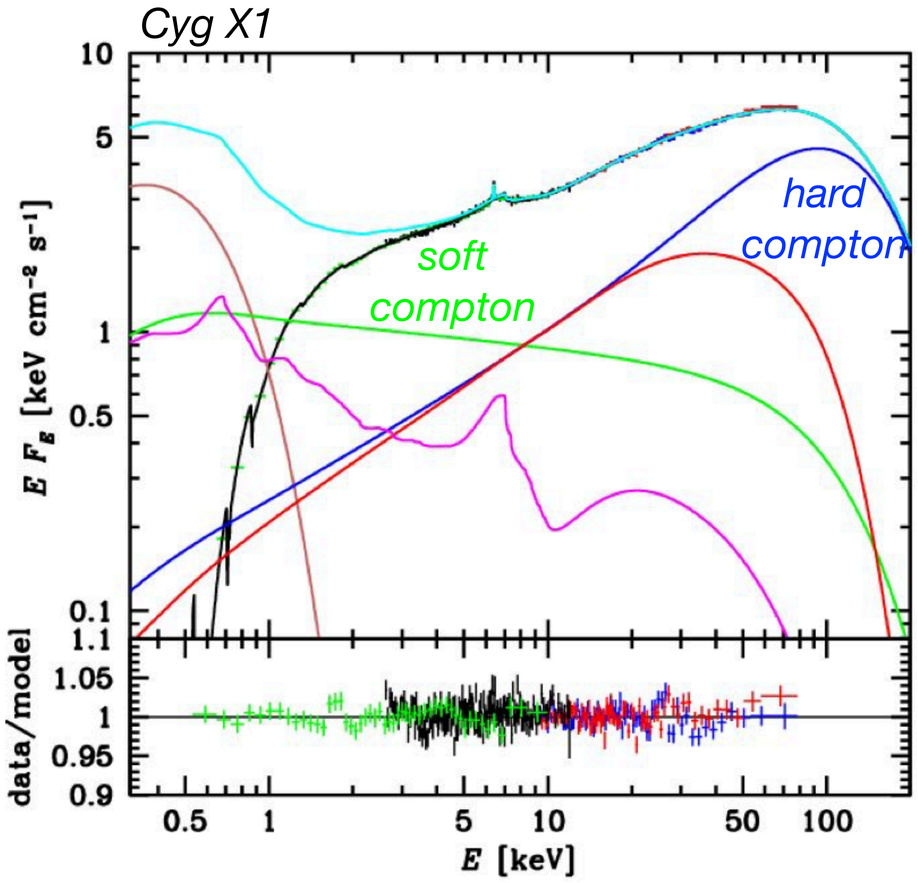
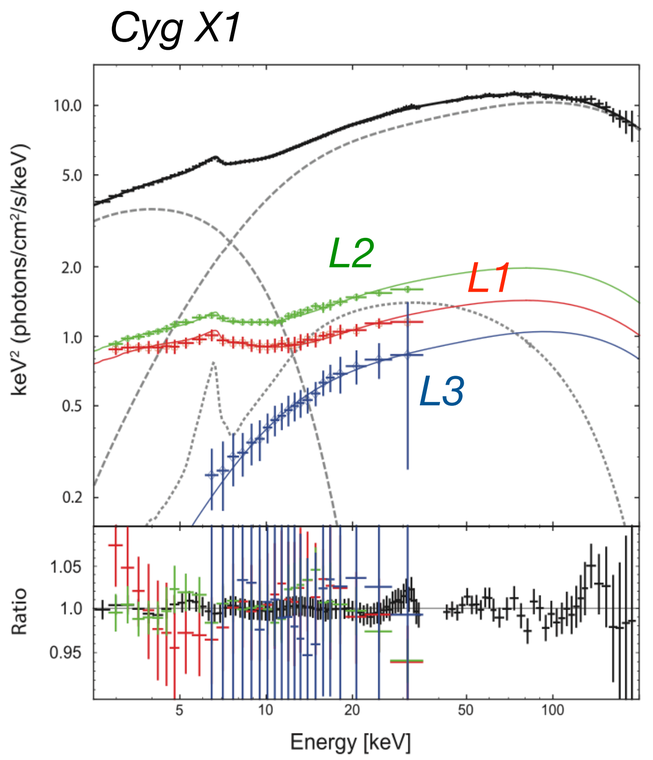
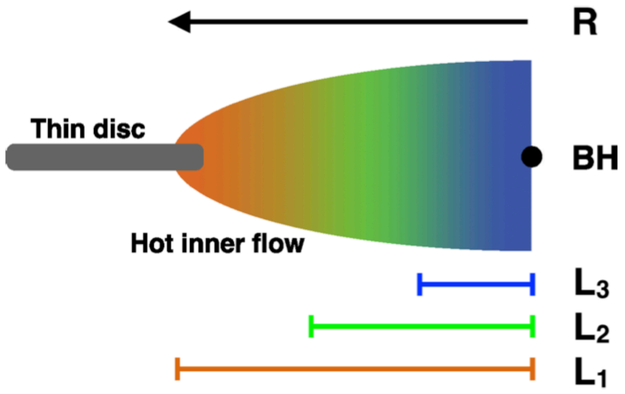


[Zdziarski et al. 2026]

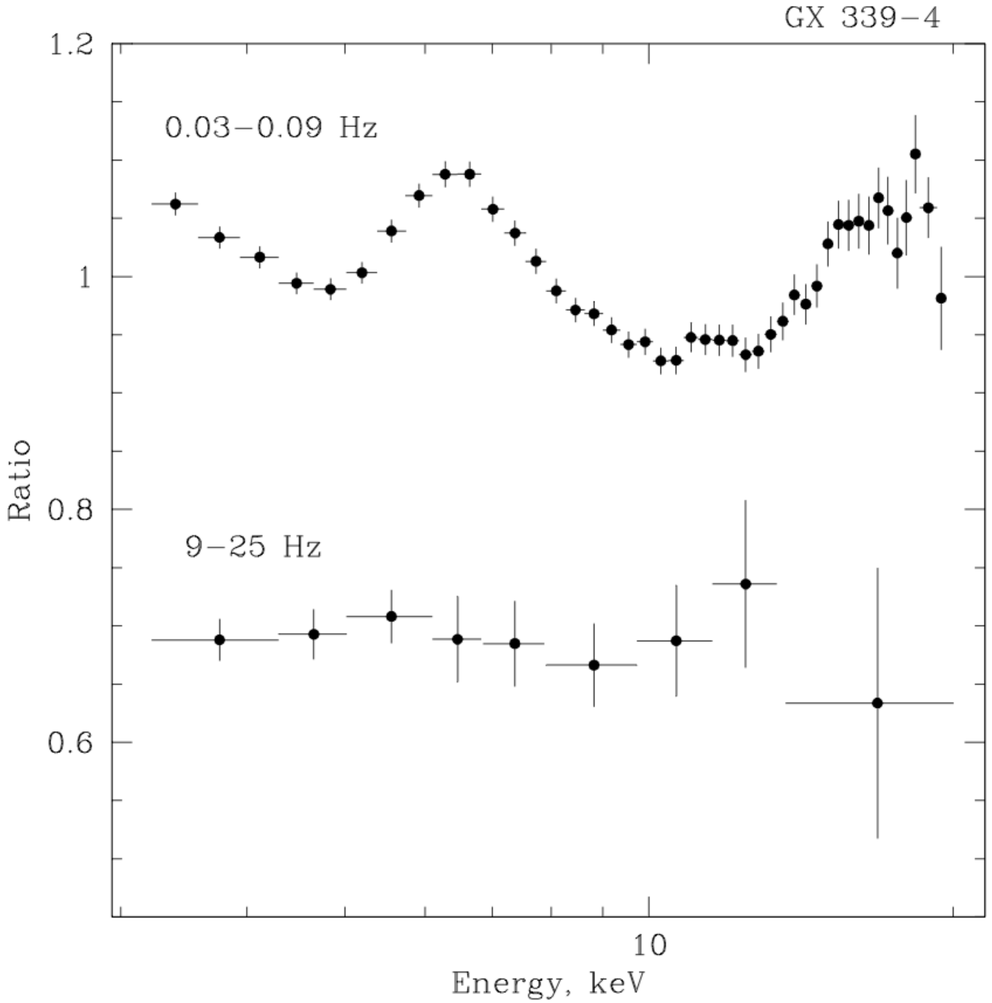


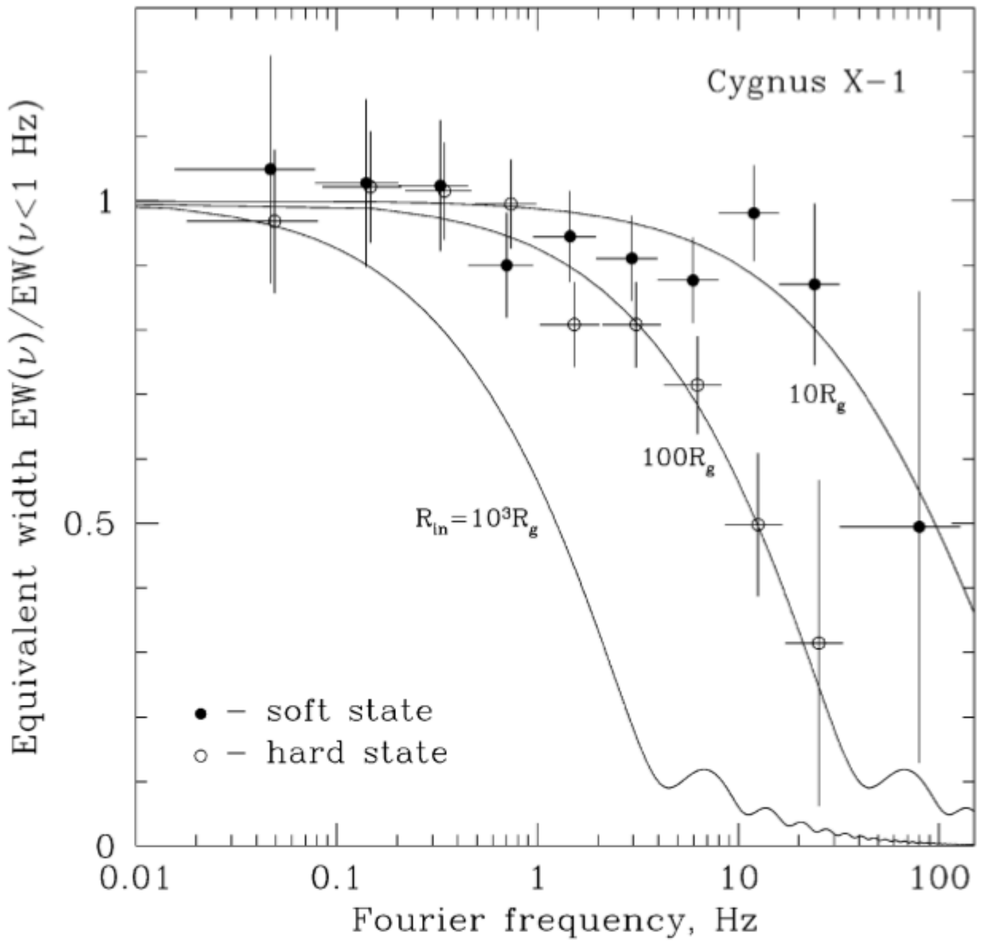


[Axelsson & Done 2018;
Dziełak, De Marco, Zdziarski 2021]

A structured comptonizing flow?

What is the geometry of the inner accretion flow?





[Gilfanov et al. 2000; Revnivtsev et al. 1999; 2001; Axelsson & Veledina 2021]

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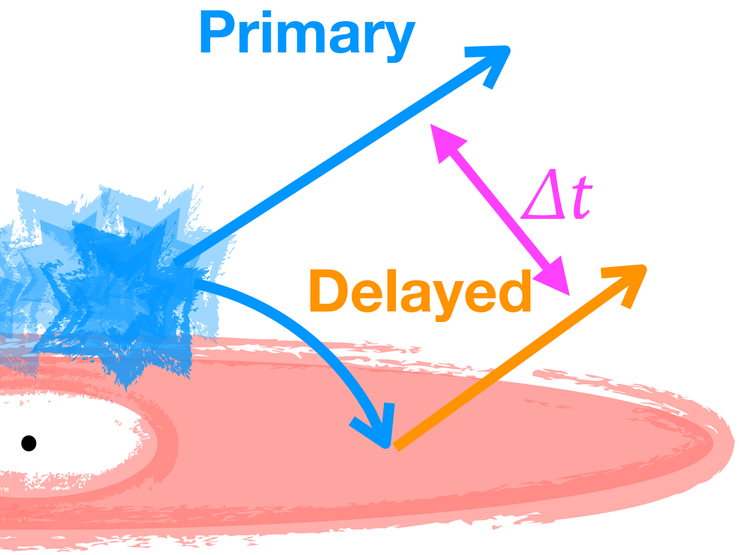
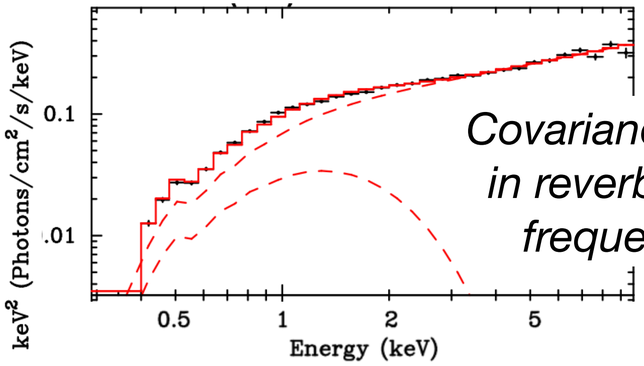
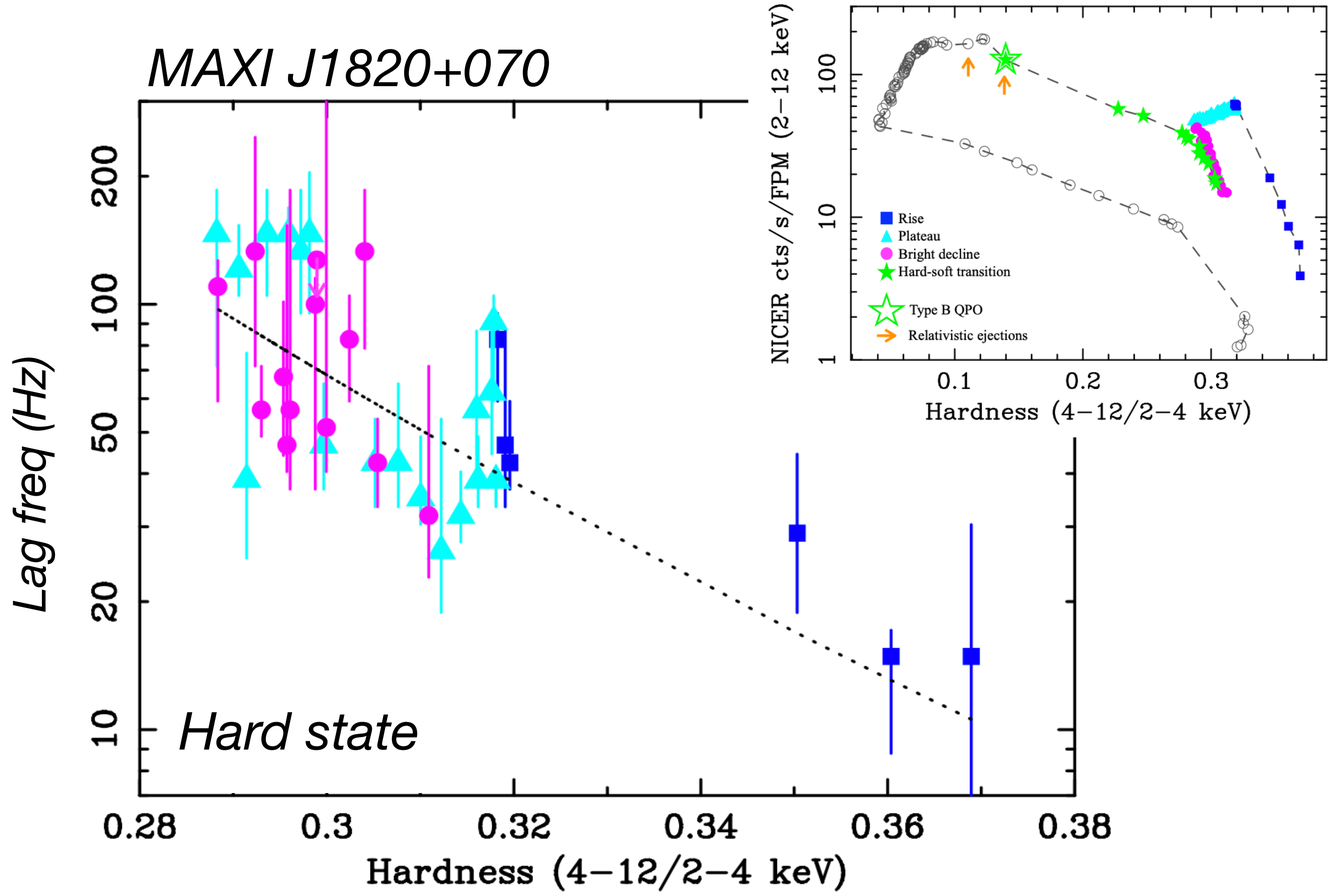




Covariance spectrum in reverberation lag frequency band

lag shorter



source softens

[De Marco et al. 2015, 2017, 2021; Kara et al. 2019; Wang et al. 2022]

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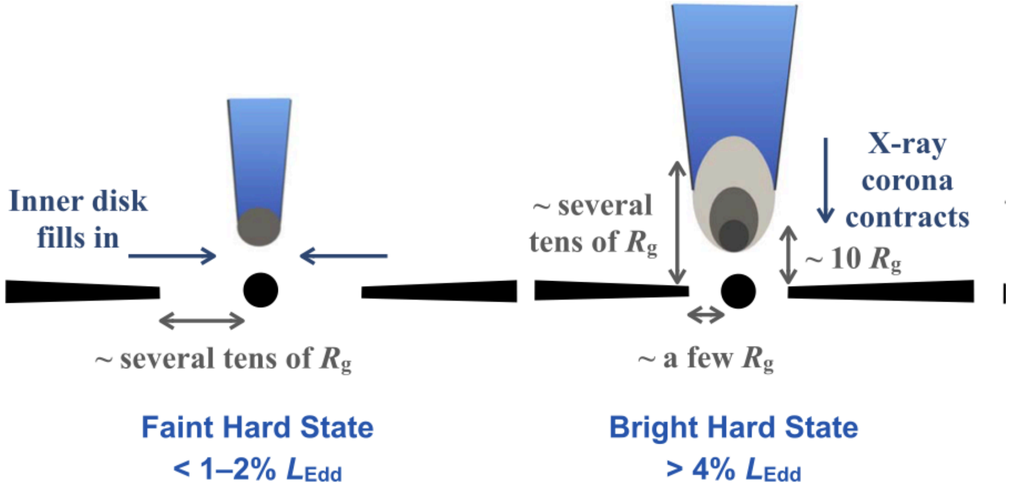
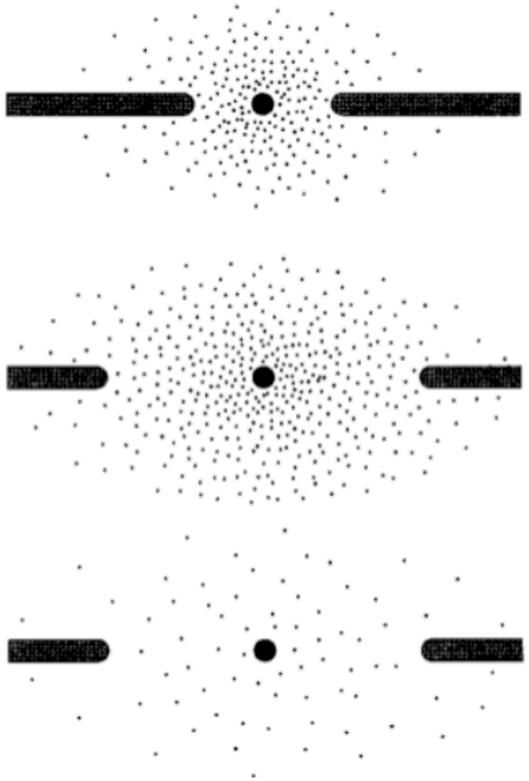


VS.

?



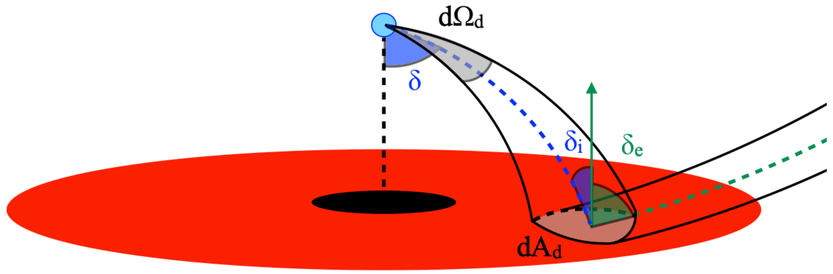
Bright Hard state

Hard state

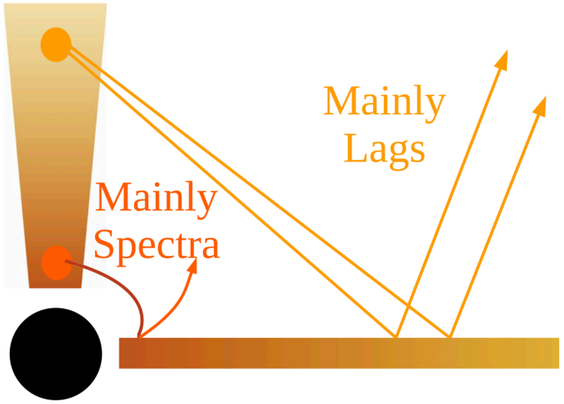
[De Marco et al. 2015, 2017, 2021; Kara et al. 2019; Wang et al. 2022]

What is the geometry of the inner accretion flow?

e.g. RELTRANS model



[Ingram et al. 2019; Mastroserio et al. 2018; 2019; 2021]



[Lucchini et al. 2023]

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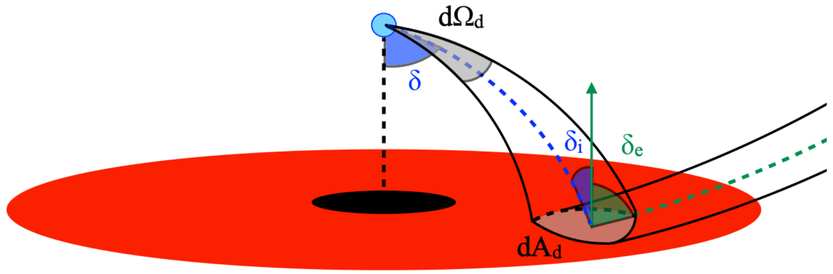

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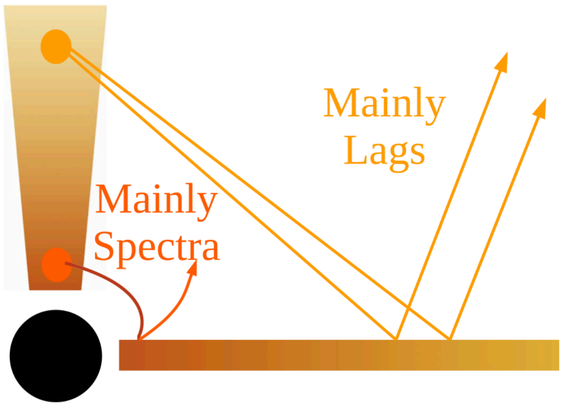

[Lucchini et al. 2023]

[Krawczynski et al. 2022]

Consistent with propagating fluctuations models and truncated discs

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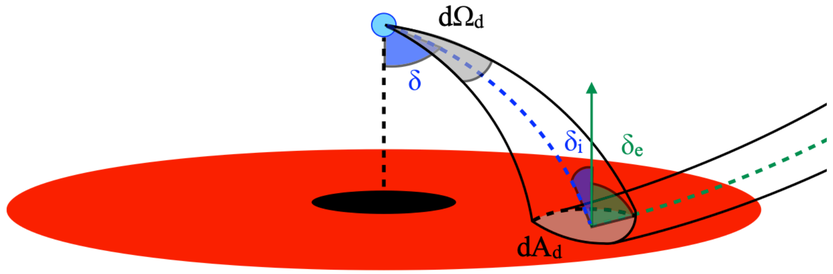
e.g. RELTRANS model



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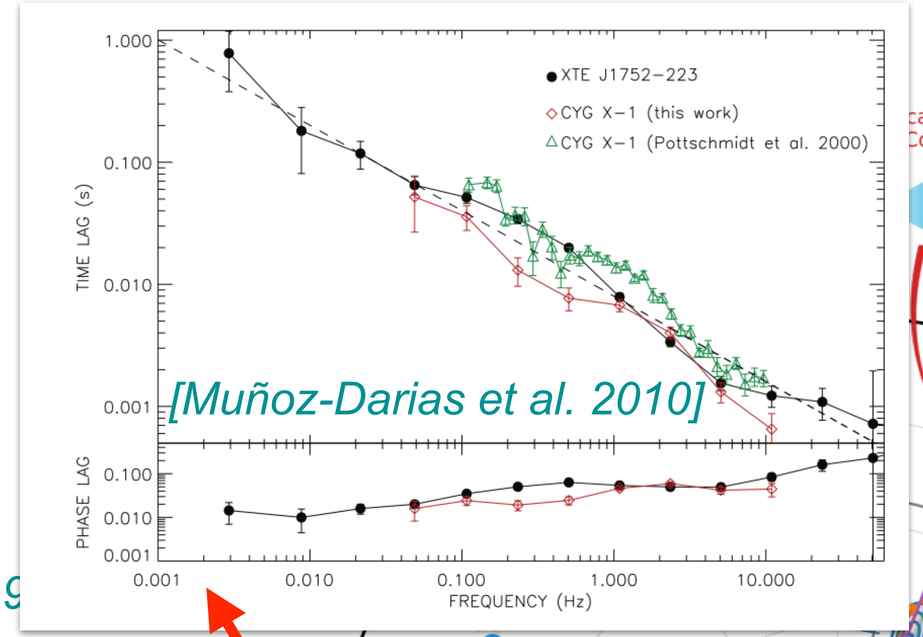
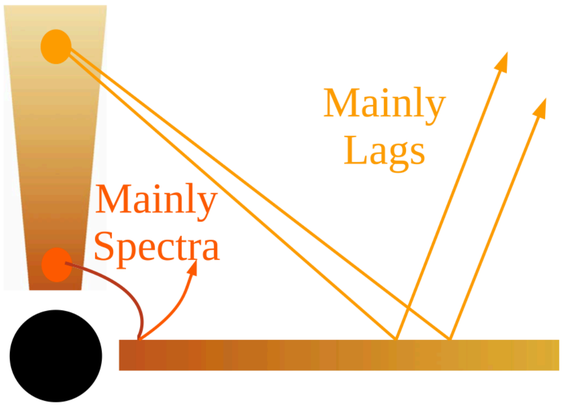


[Muñoz-Darias et al. 2010]



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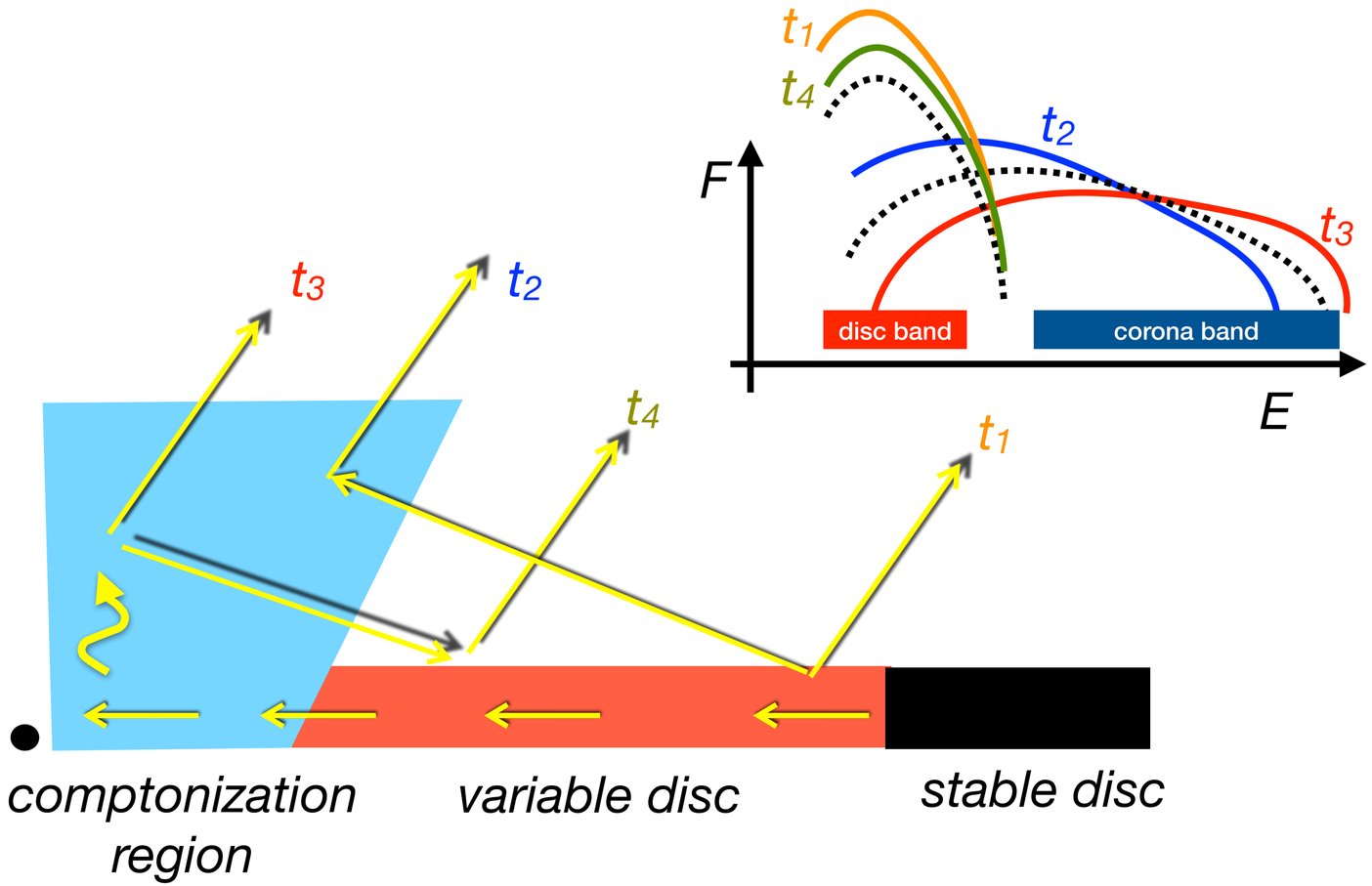
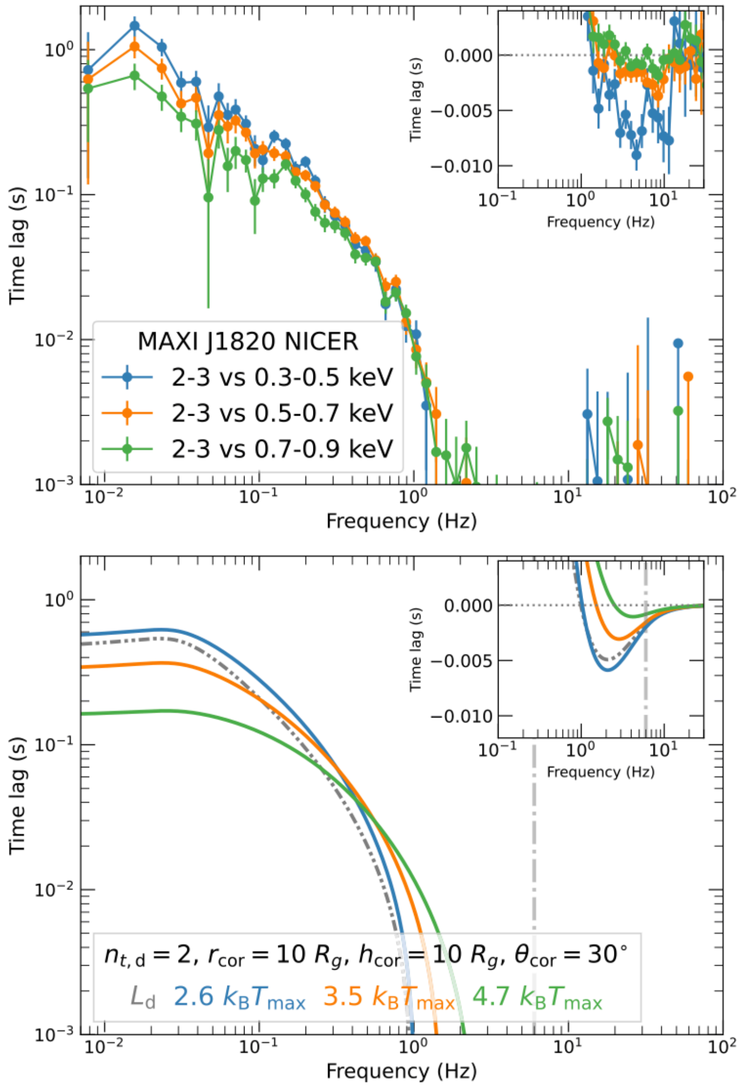
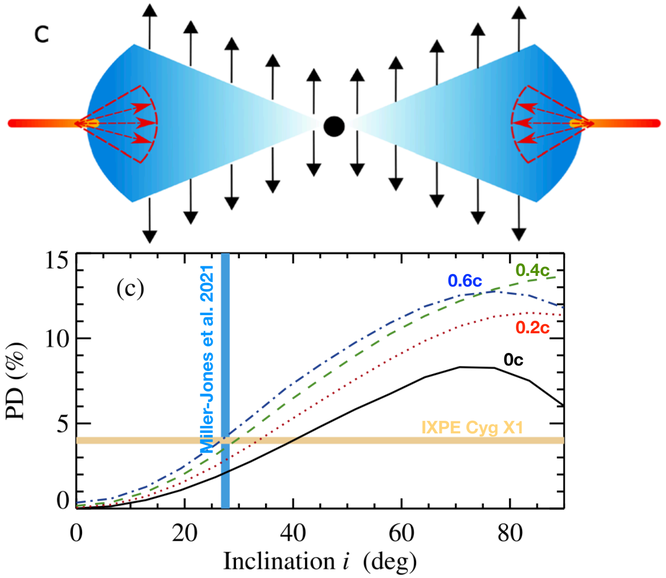


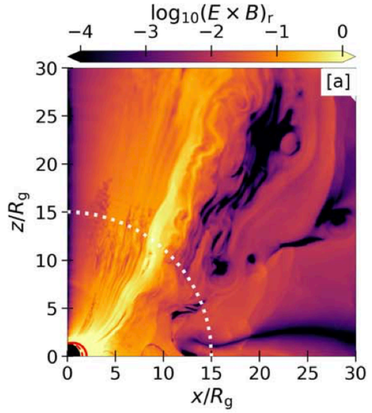


[Uttley & Malzac 2025;
see also Kotov et al. 2001; Körding & Falcke 2004; Mastroserio et al. 2018]

What is the geometry of the inner accretion flow?

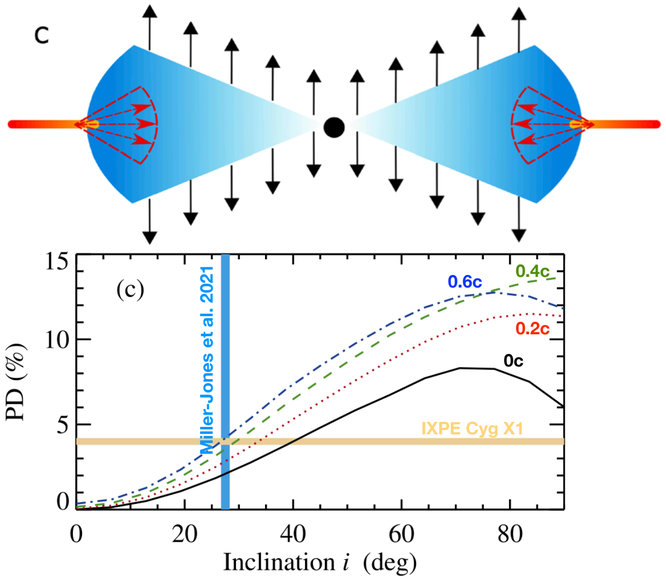


[Poutanen et al. 2023]

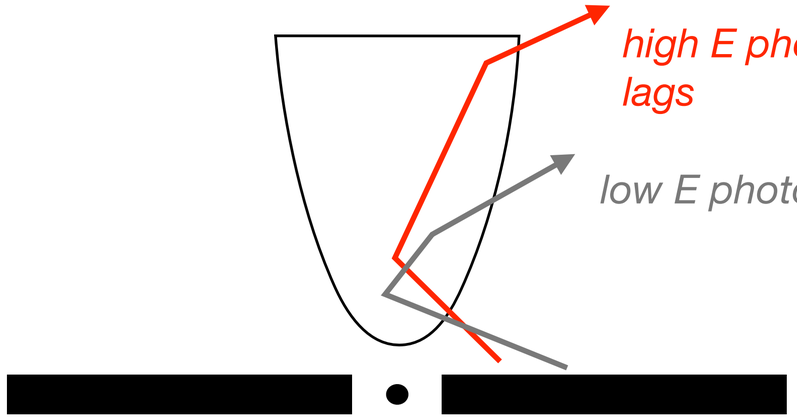


[Sridhar et al. 2025]

What is the geometry of the inner accretion flow?

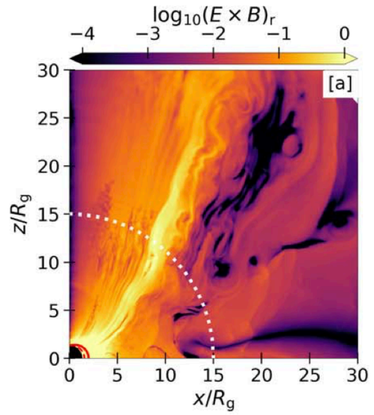


[Poutanen et al. 2023]

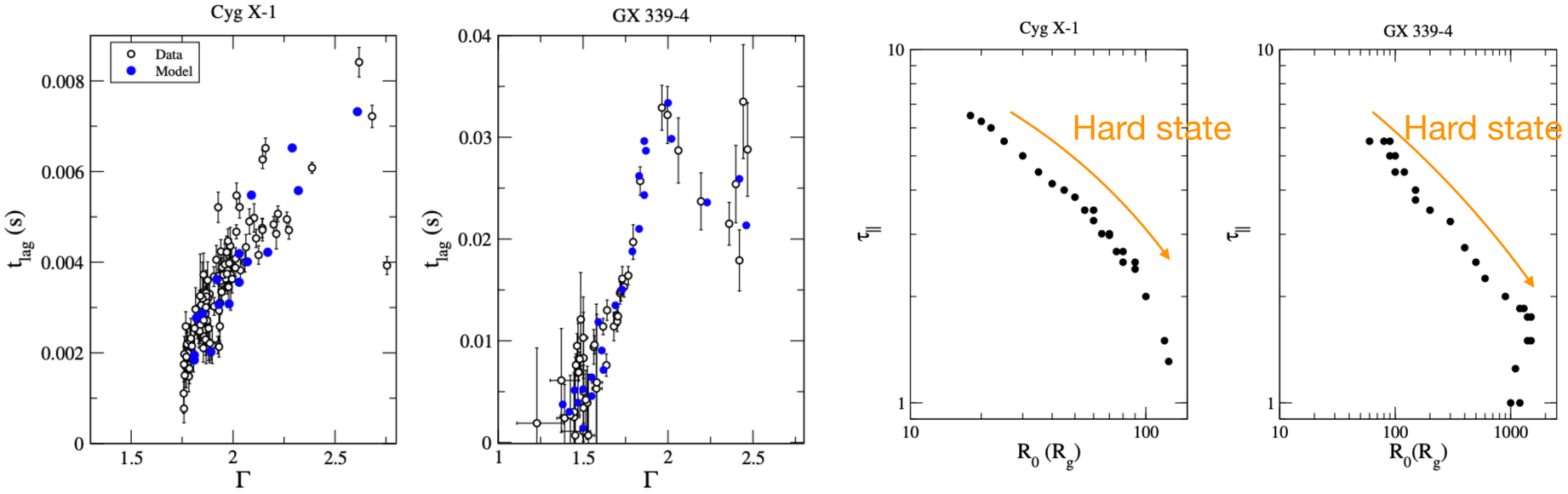


high E photons, more scatters, longer lags

low E photons, less scatters, shorter lags

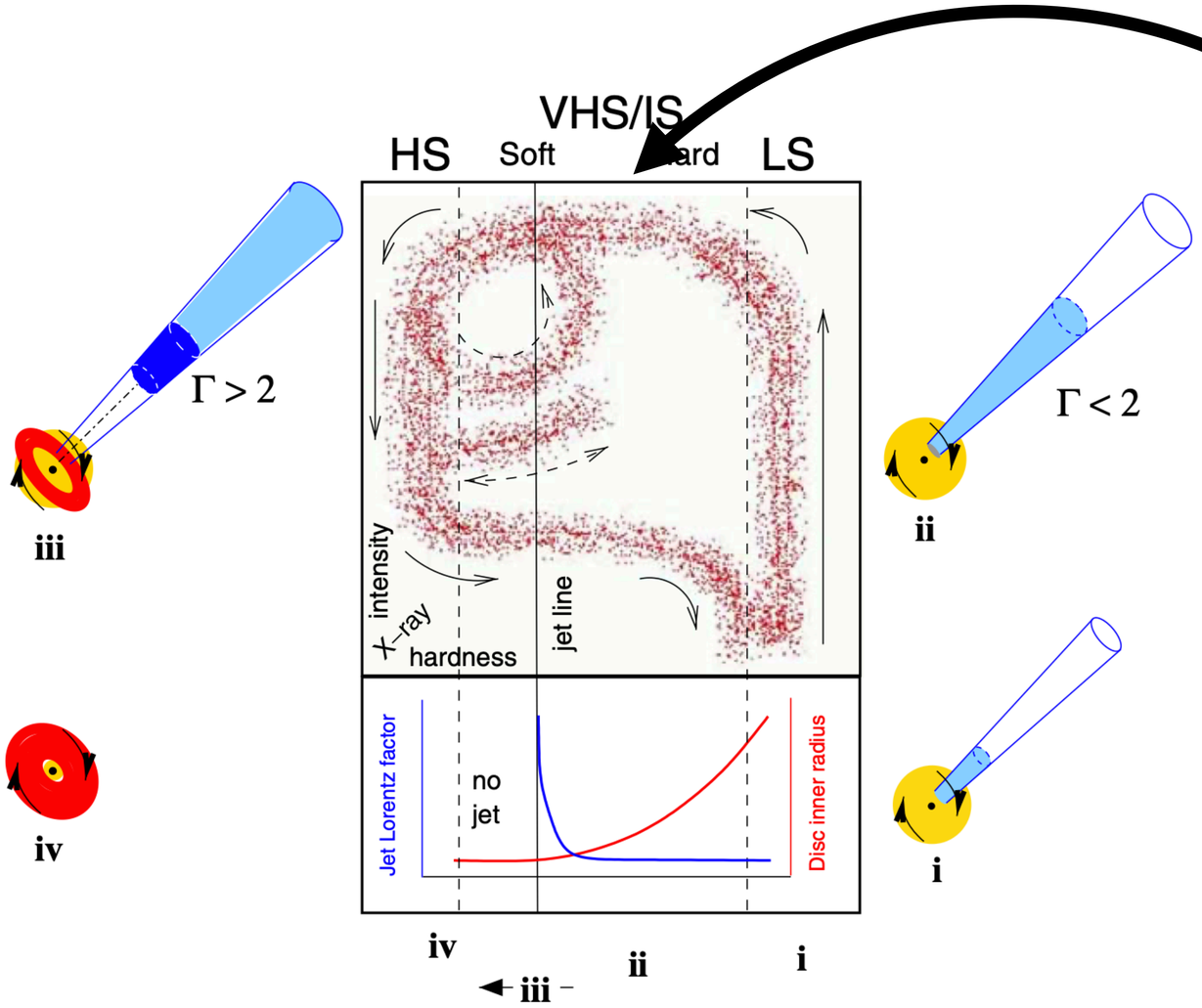


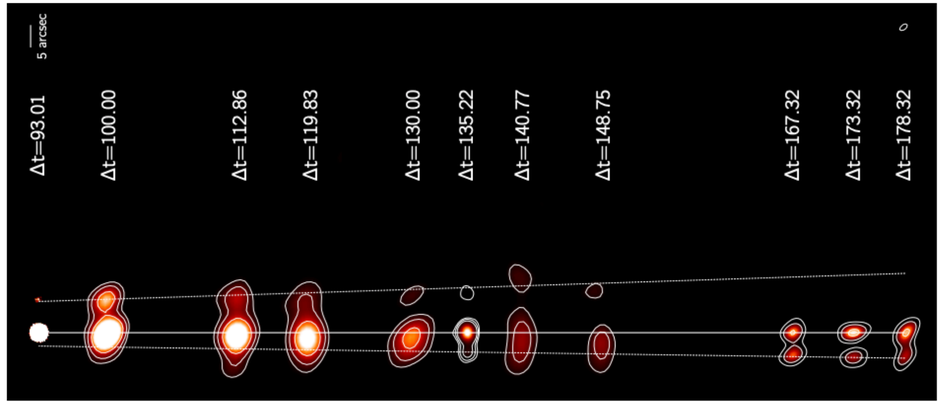
[Sridhar et al. 2025]



[Kylafis et al. 2008; Reig et al. 2018, 2019; Kylafis et al. 2024; see next talk]

What happens at the hard-to-soft state transition?

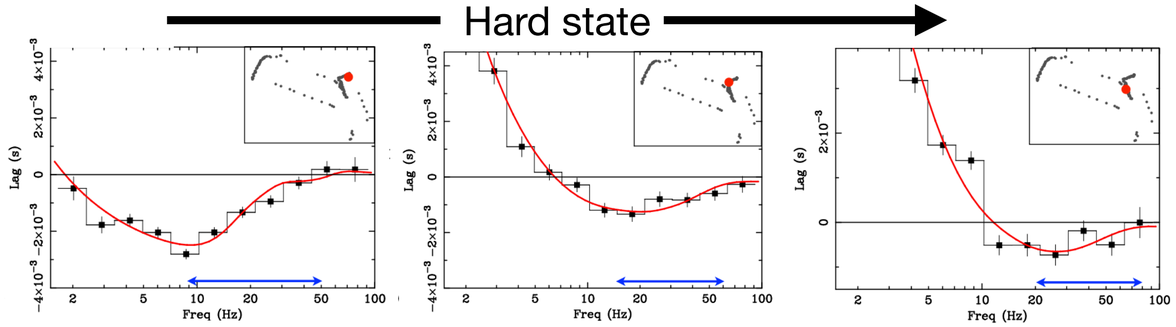




[Bright et al. 2020; Wood et al. 2021; Carotenuto et al. 2024]

[Fender & Belloni 2004; Fender, Gallo, Belloni 2004; Corbel et al. 2004]

What happens at the hard-to-soft state transition?

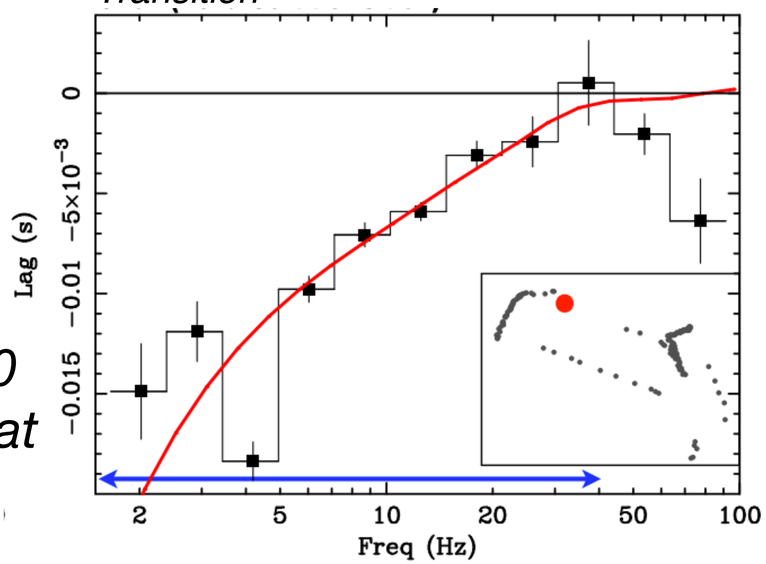


MAXI J1820+070

[De Marco et al. 2021; Wang et al. 2021]

A factor of ~10 longer soft lag at the transition

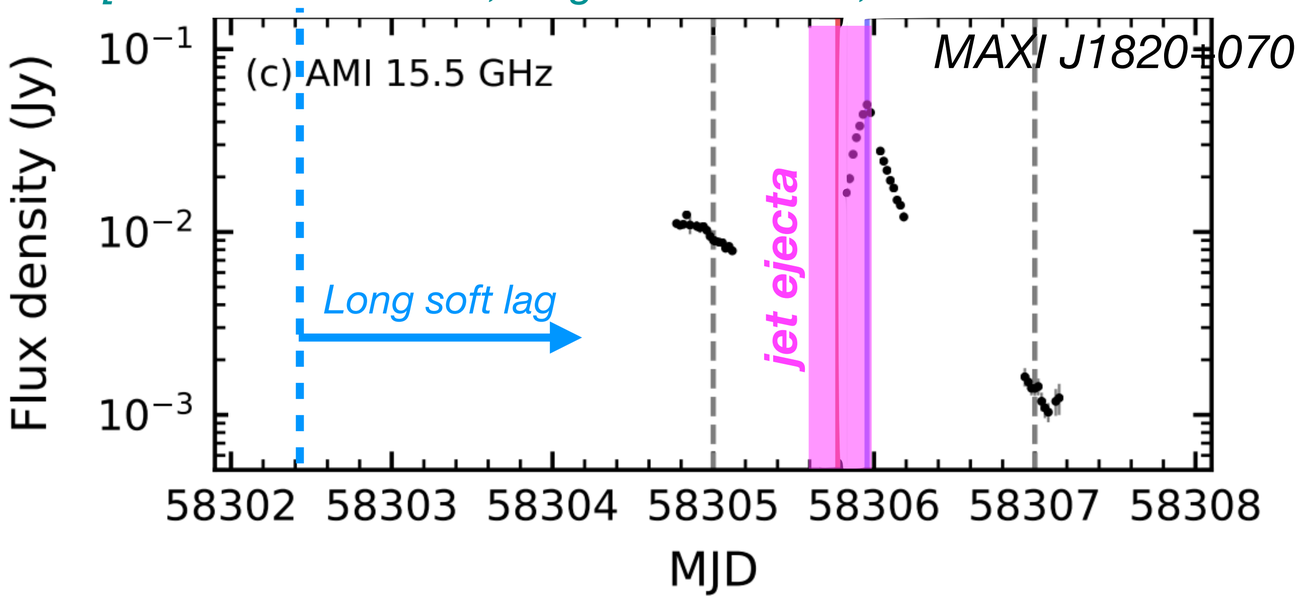
Transition

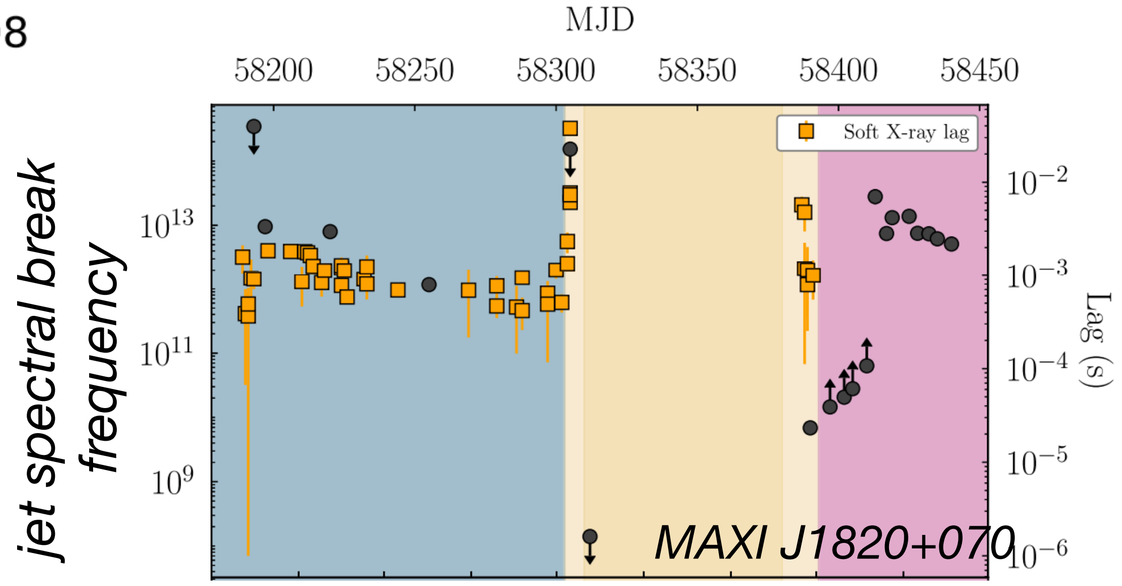


Corona more vertically extended at transition? Corona ejected?
Dissipation of hard X-rays occurring in shocked region along the jet?

What happens at the hard-to-soft state transition?

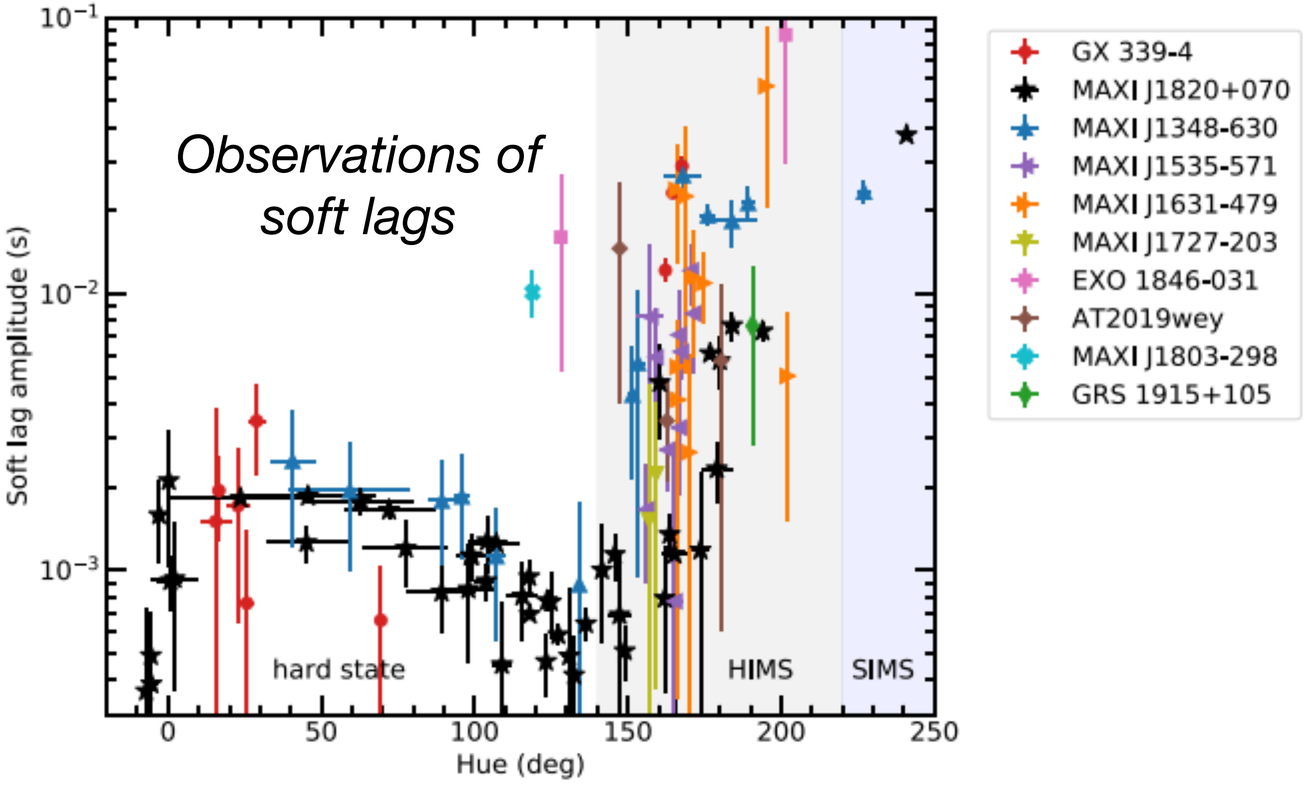
[Homan et al. 2021; Bright et al. 2020; Carotenuto et al. 2024]



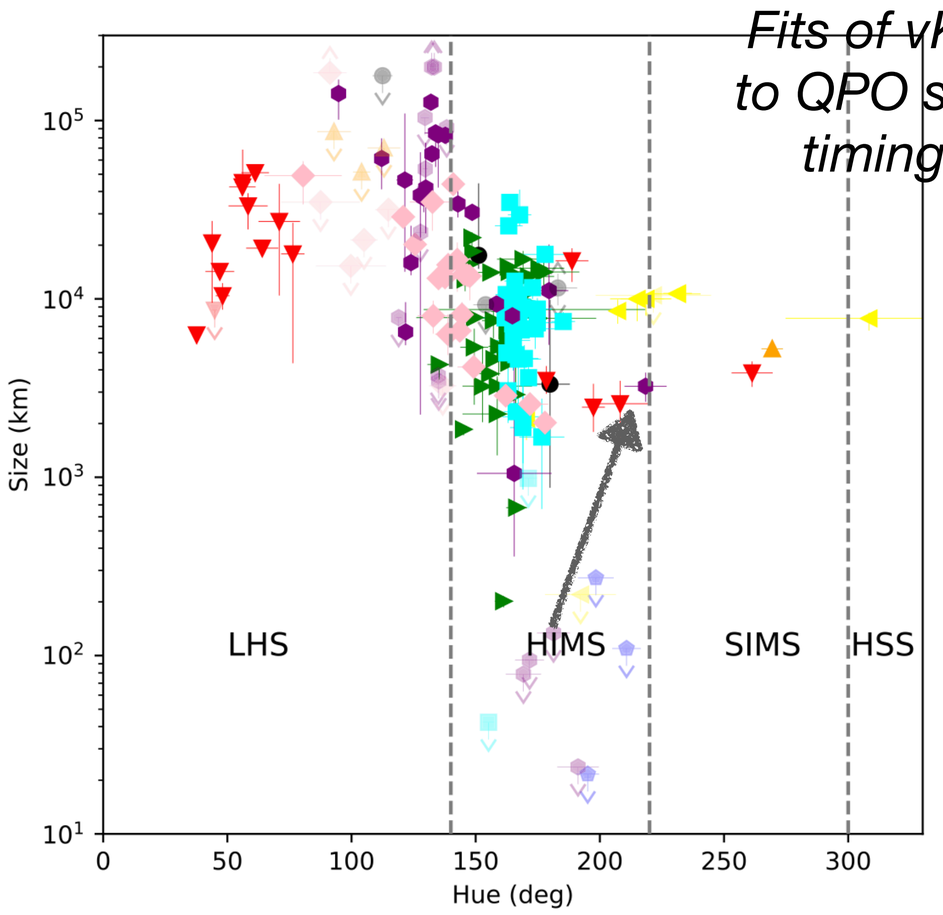


[Echiburú-Trujillo et al. 2024]

What happens at the hard-to-soft state transition?

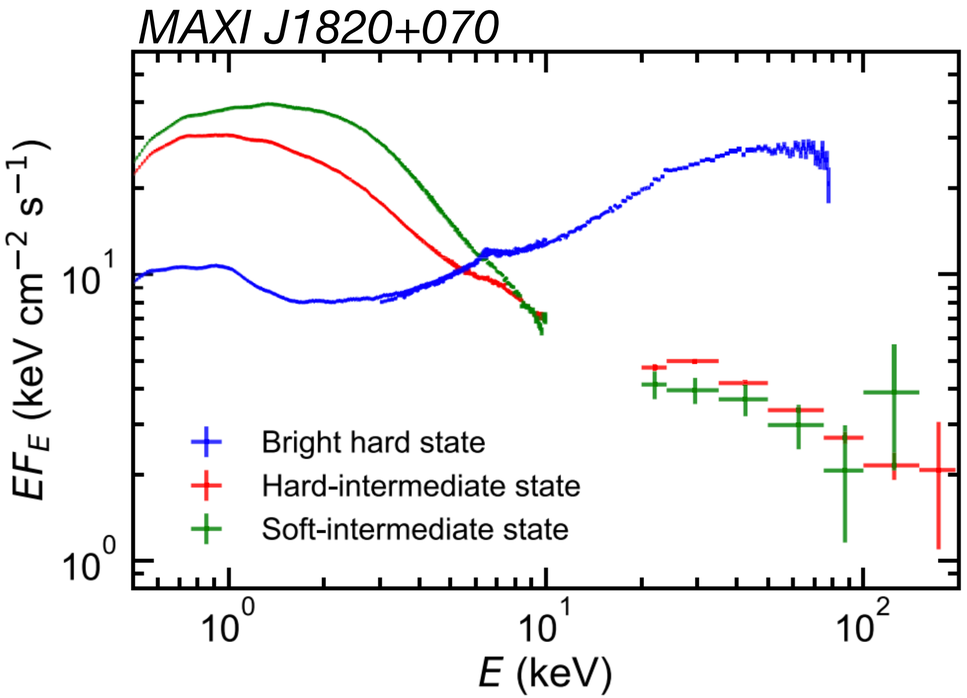


[Wang et al. 2022]

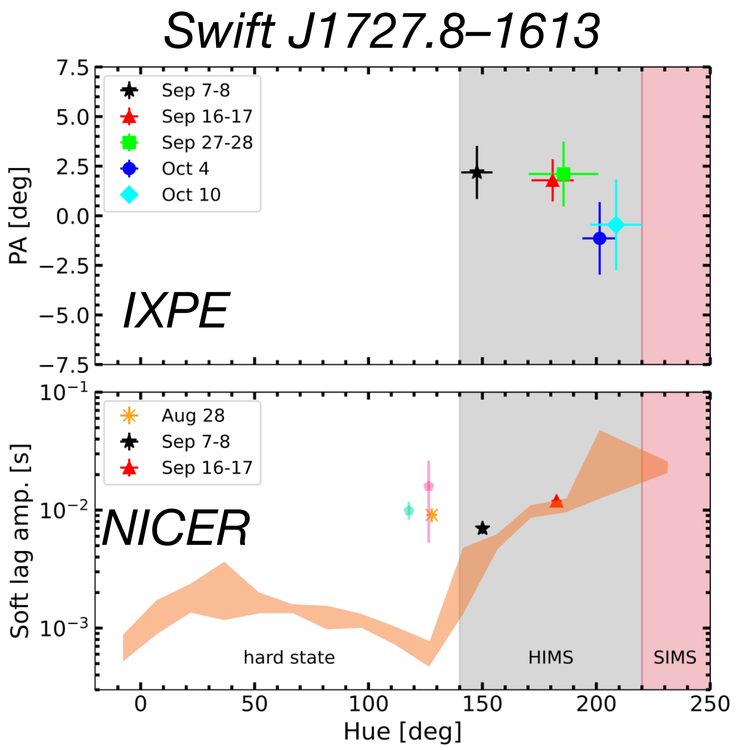


[Zhang et al. 2026; García et al. 2021; Mendez et al. 2022; Peirano et al. 2023; Alabarta et al. 2025]

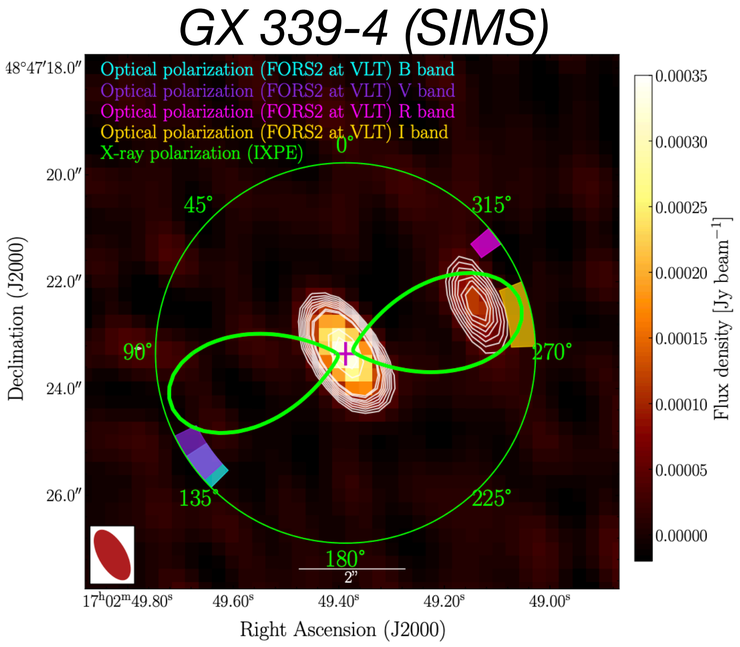
What happens at the hard-to-soft state transition?



[Kawamura et al. 2023]



[Ingram et al. 2024; Yu et al. 2026]



[Mastroserio, De Marco et al. 2024]

Conclusions

We started with three questions:

- Where does the X-ray variability come from?

Probably propagating mass accretion rate fluctuations, but model still incomplete

- What is the geometry of the inner accretion flow?

Spectral-timing results consistent with radially stratified, extended coronae and truncated disc, but polarimetry needed to break degeneracies

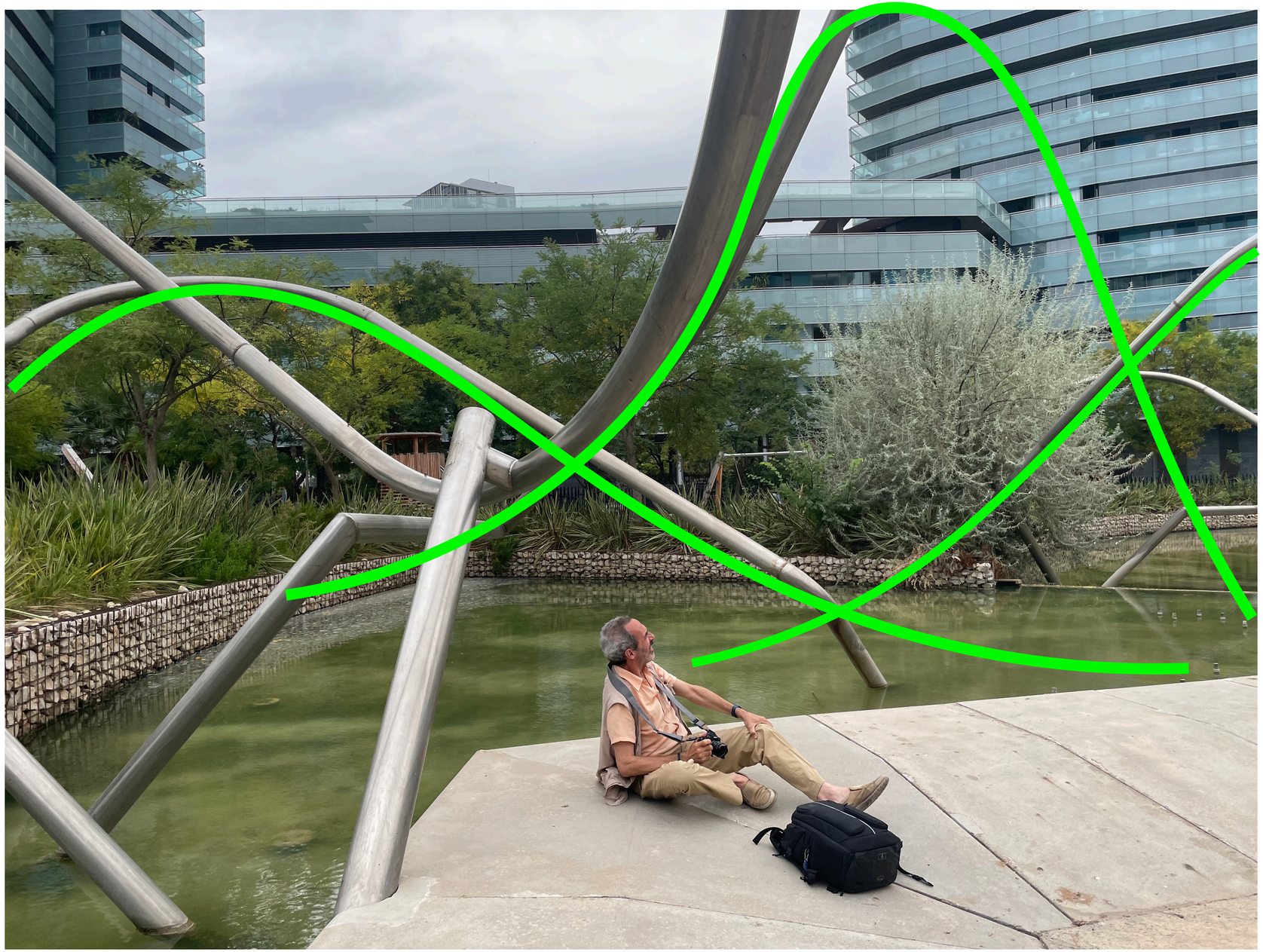
- What happens at the hard-to-soft state transition?

Lags support expanding/ejected coronae, but spectral and polarimetric results disfavour this interpretation

Conclusions

7 September 2021 Barcelona

Conclusions



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