Observations and interpretations of reverberation lags in BHXRBs

Barbara De Marco

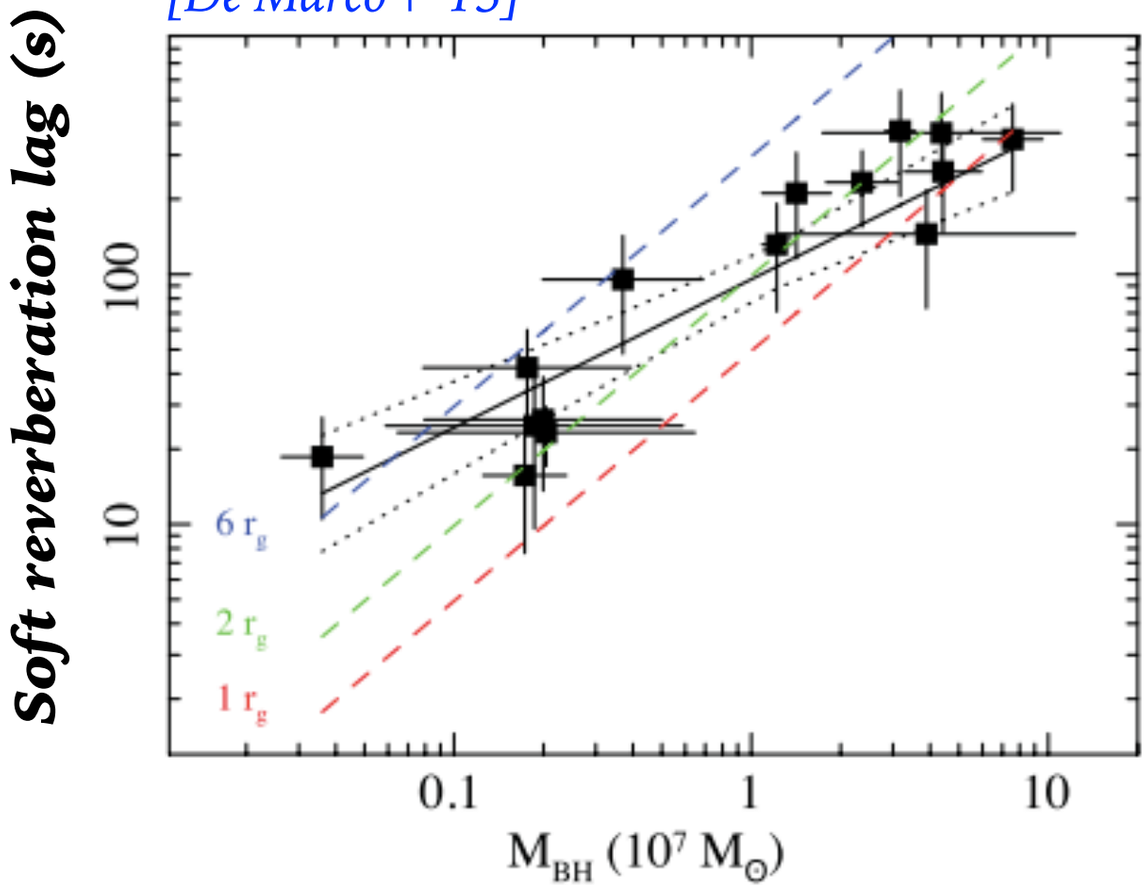
N. Copernicus Astronomical Center of the Polish Academy of Sciences

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreements No. 798726

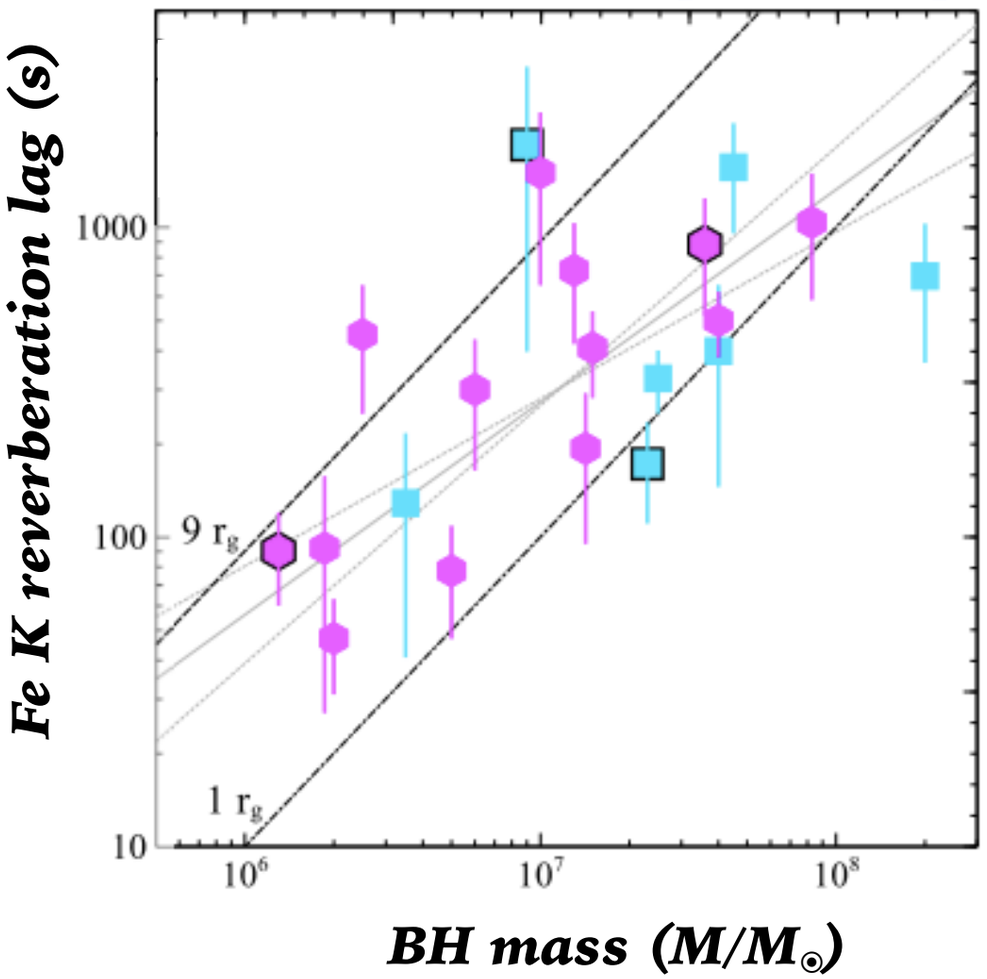
Recap of previous talk

Radio quiet AGN

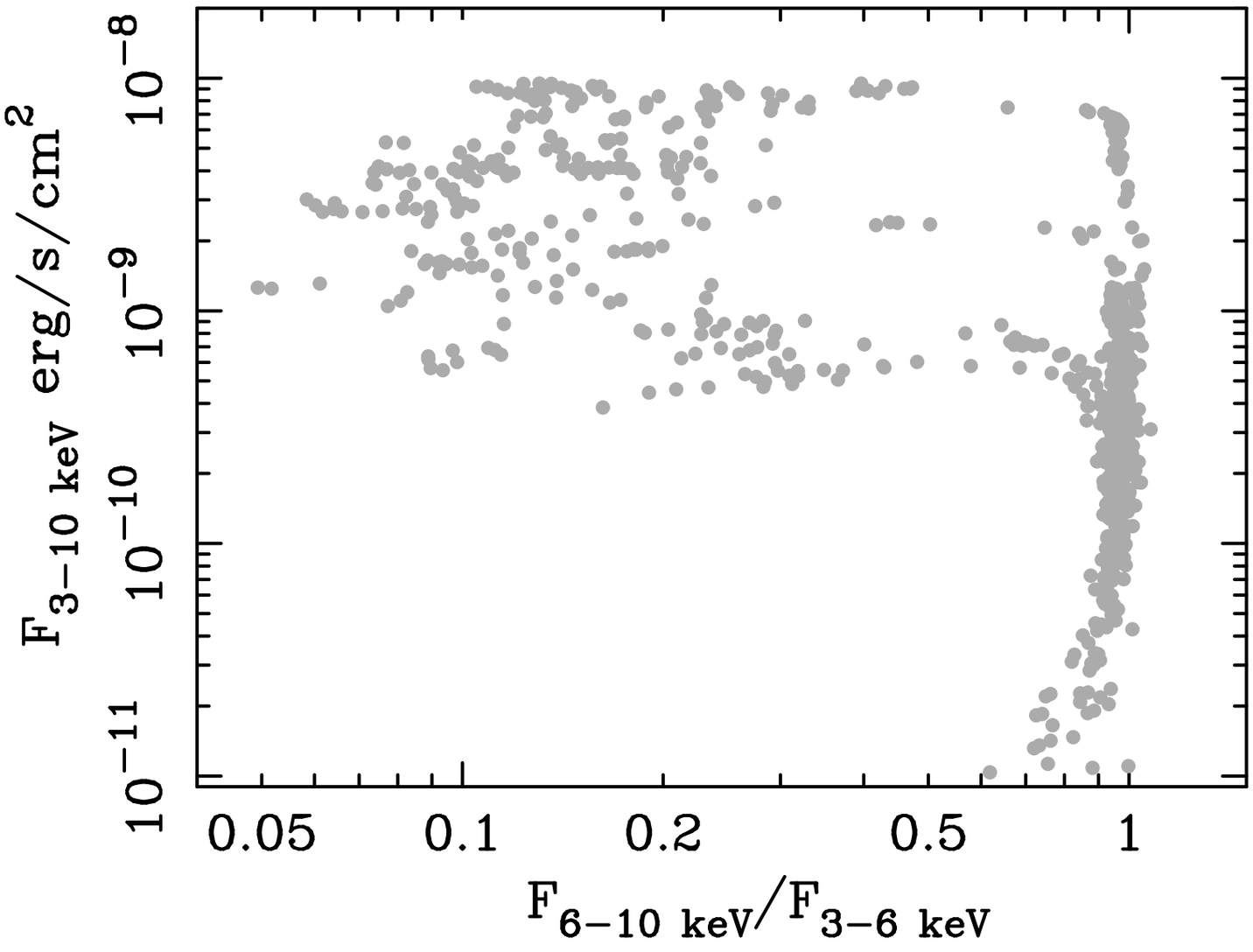
[De Marco+'13]



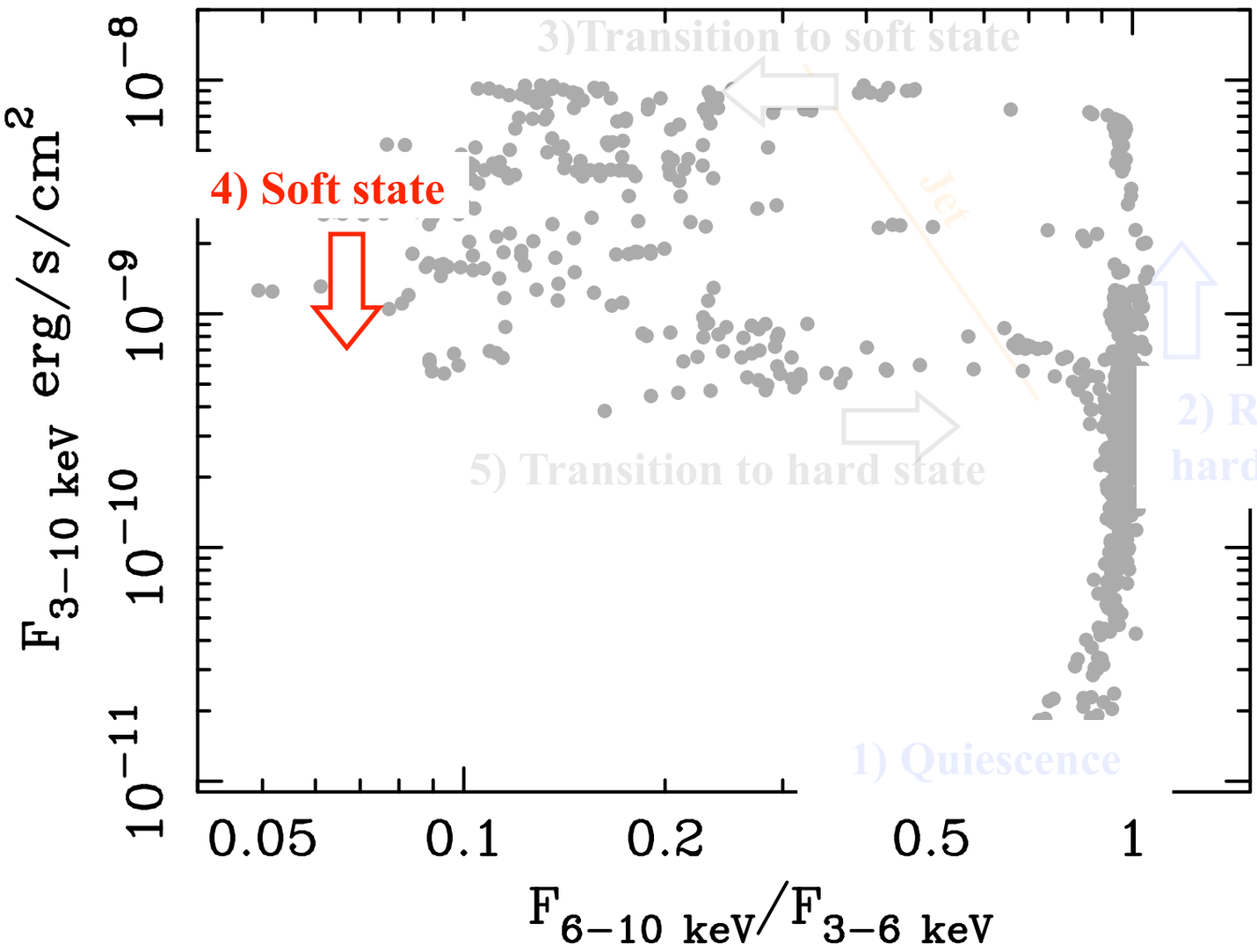
[Kara+'16]

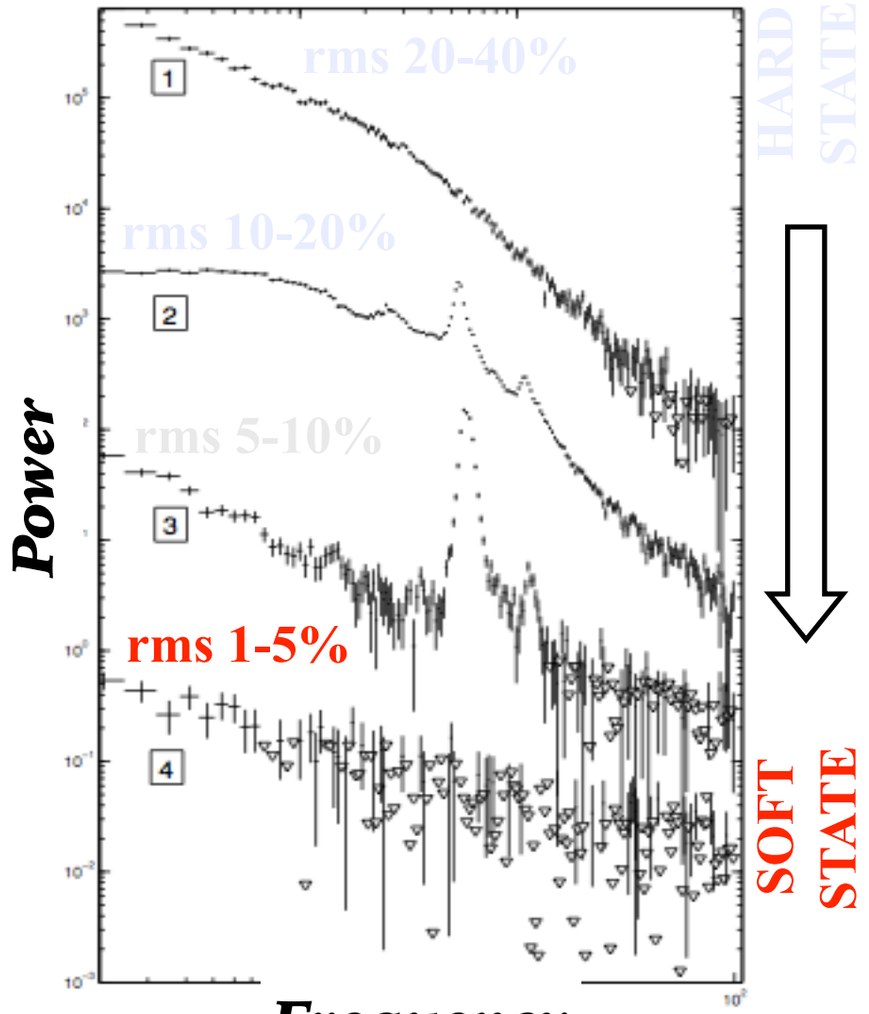


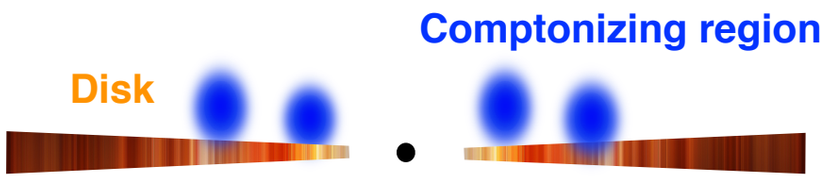
Goal: Mapping reverberation throughout accretion states in BHBs

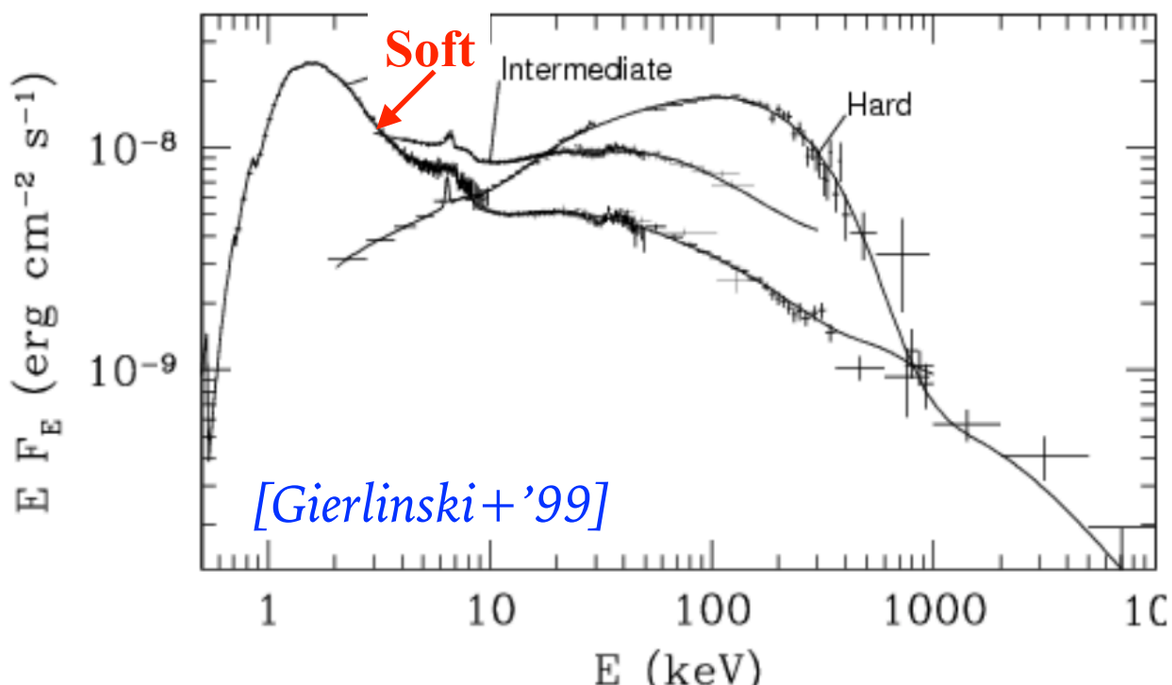


Accretion states in BHBs



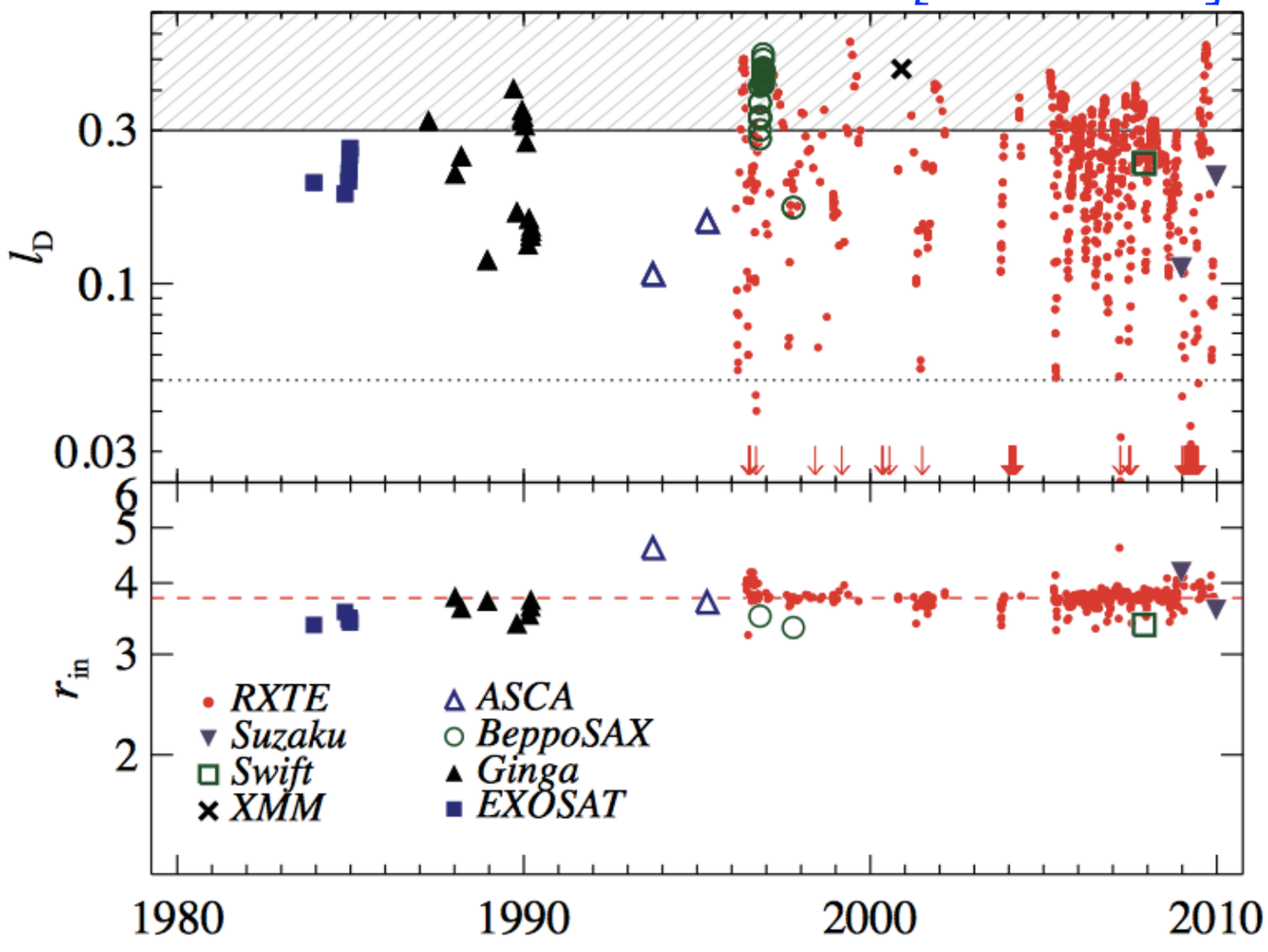




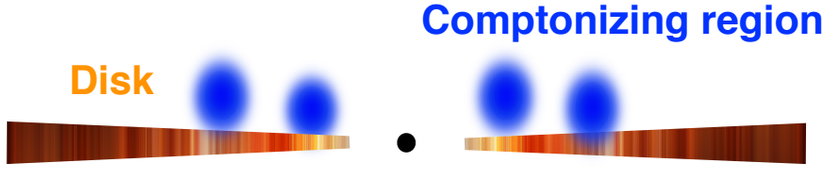


Geometry in soft state

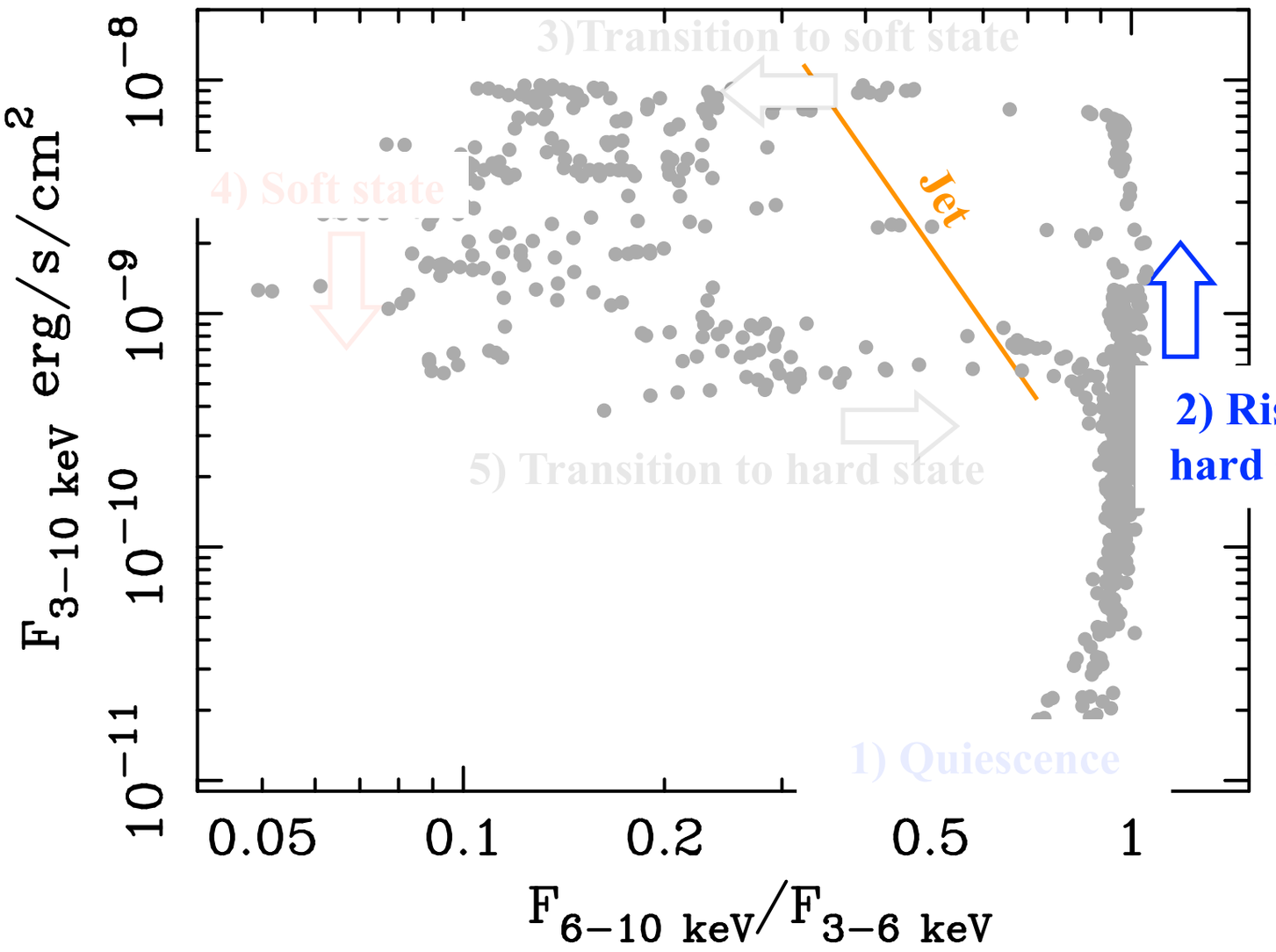
[Steiner+'10]

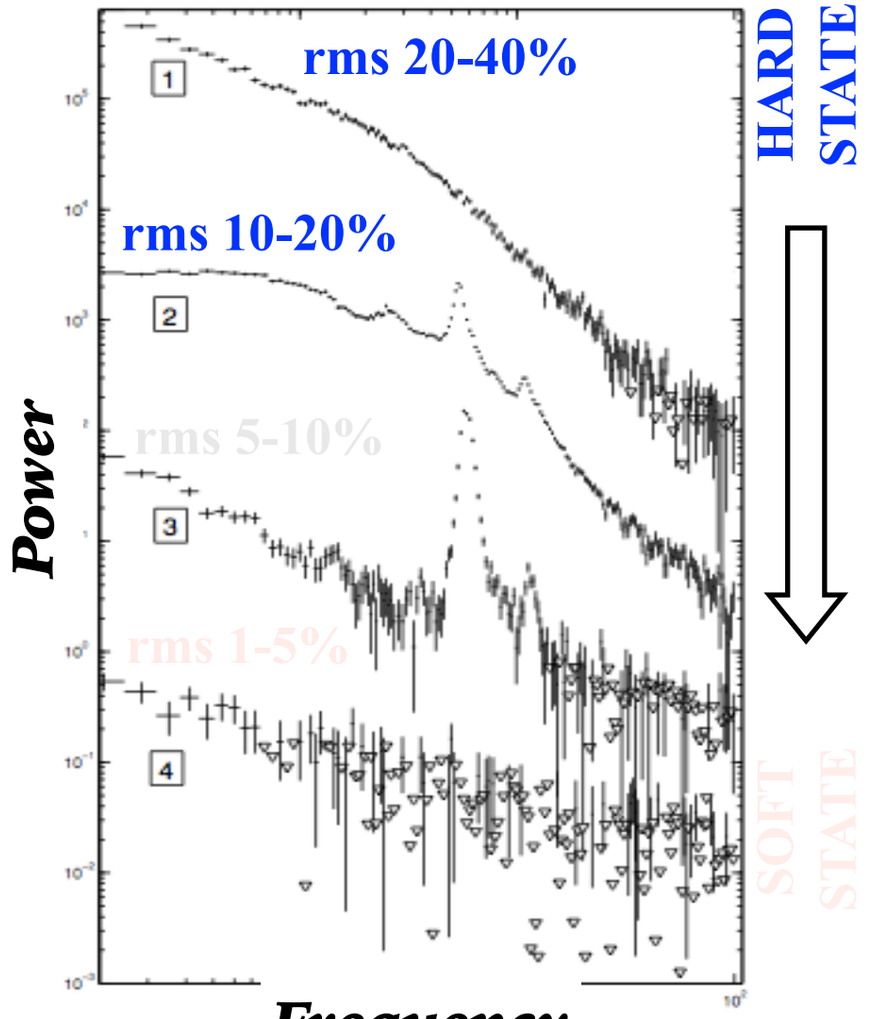


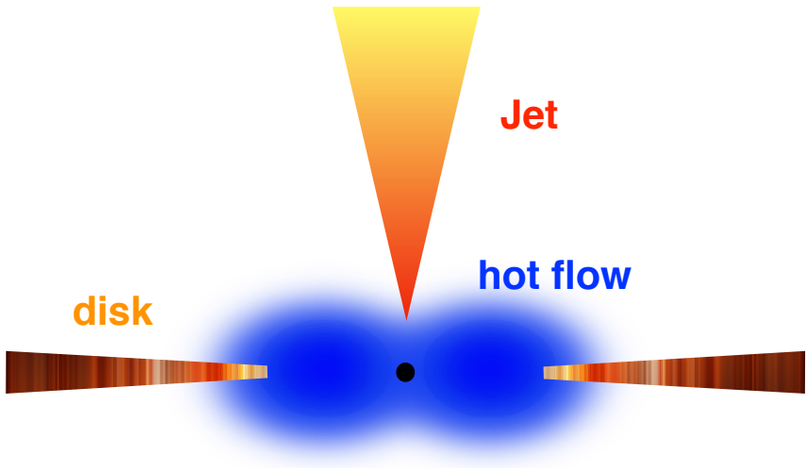
R_{in} *small and stable*

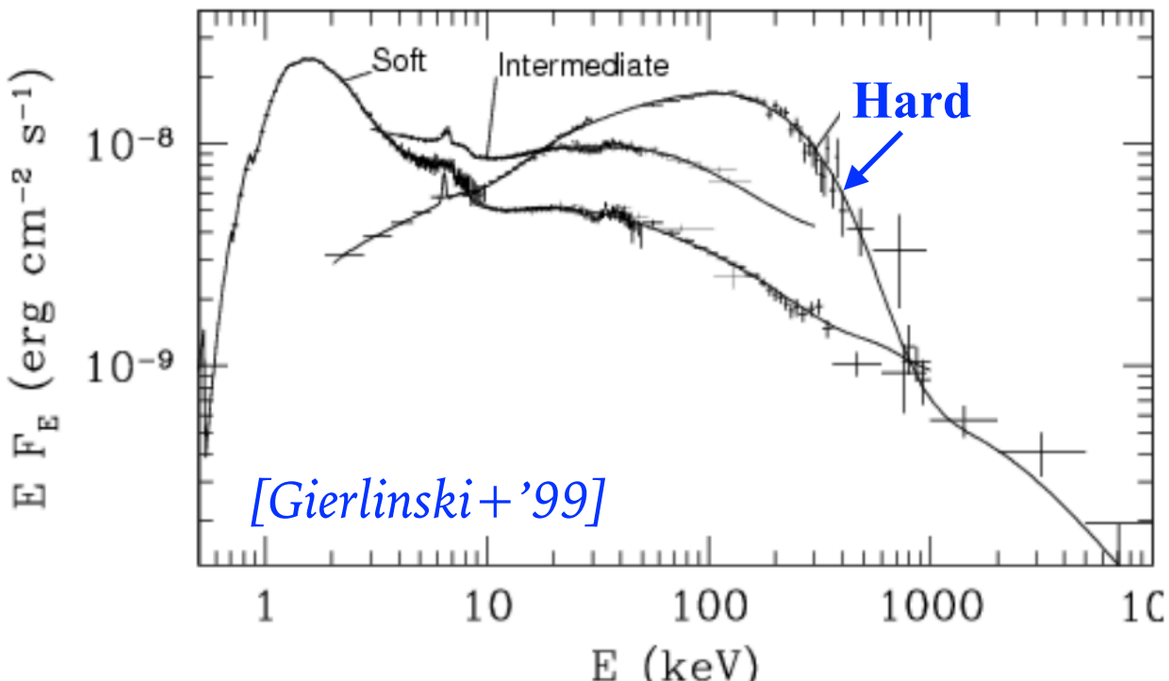


Accretion states in BHBs

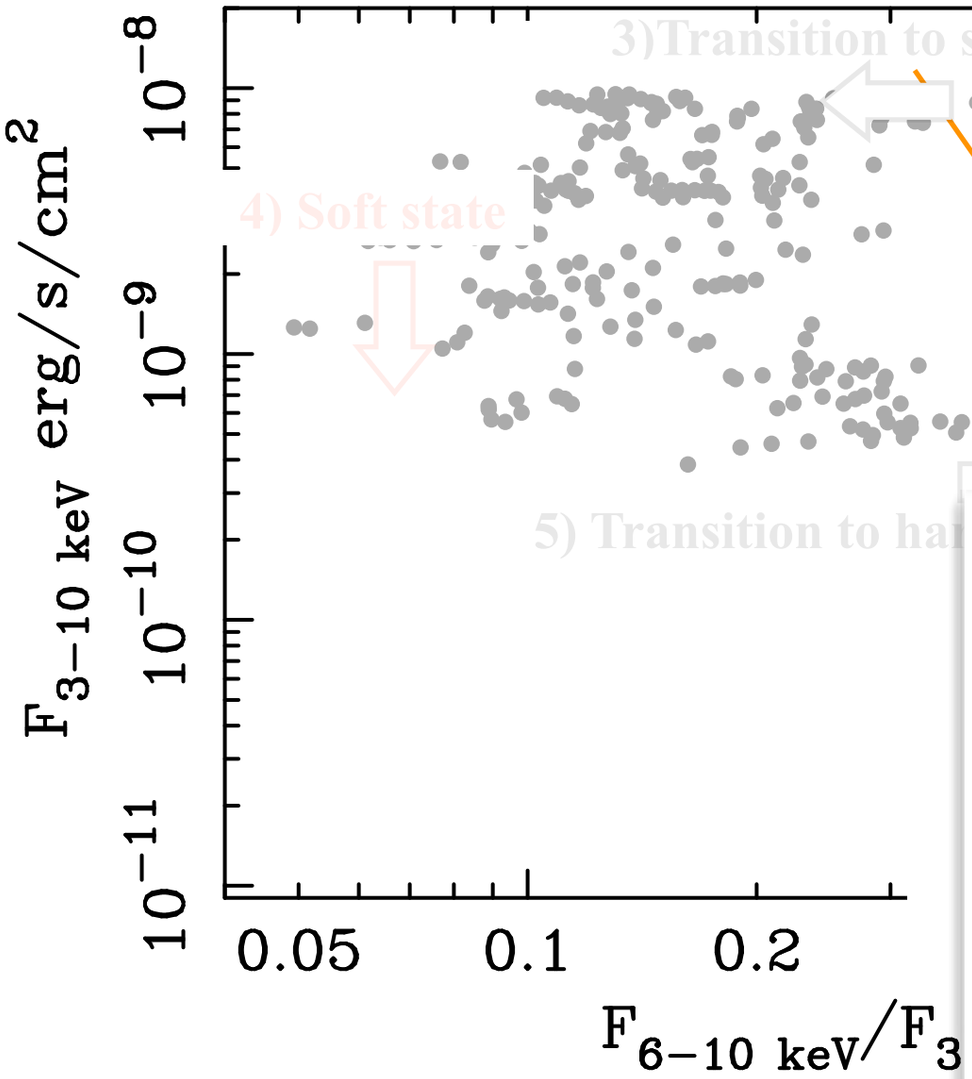


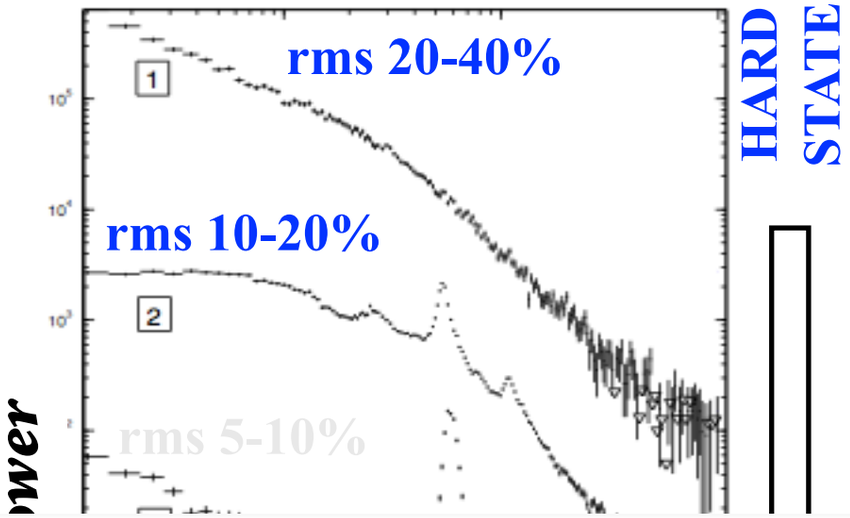






Accretion states in BHBs





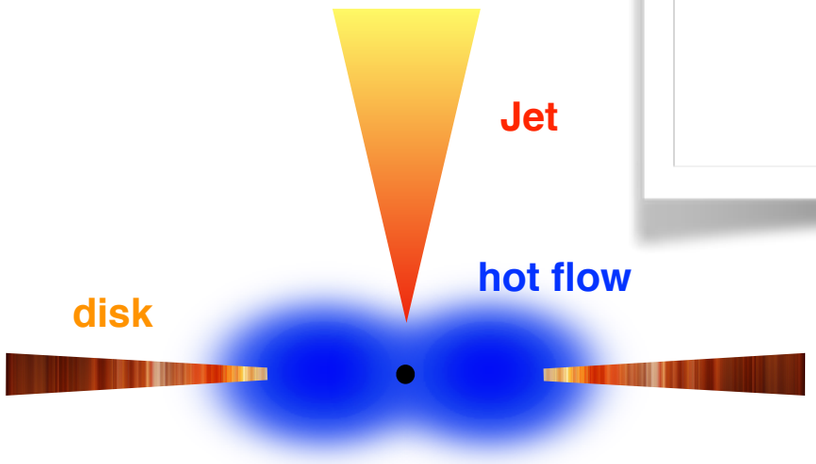
This scenario can explain:

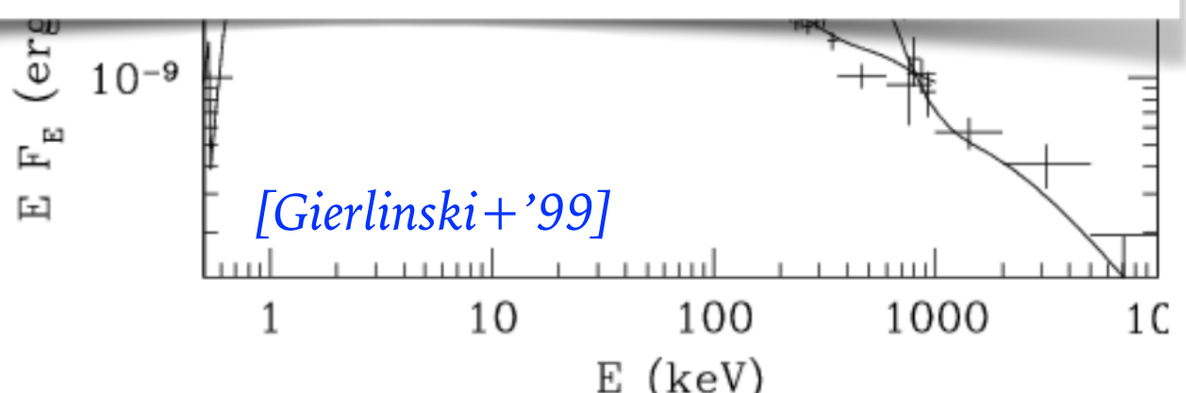
Evolution of type C QPOs

Spectral properties

Evolution of characteristic time scales

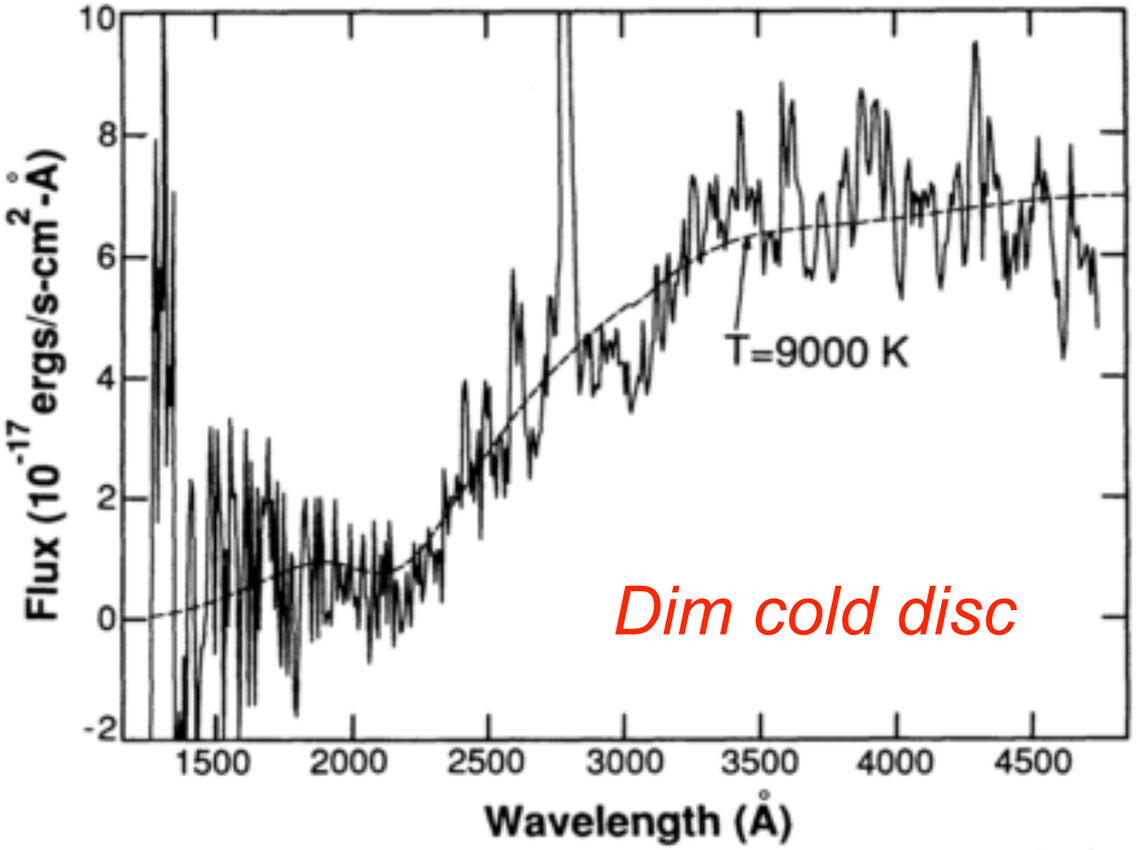
X-ray variability



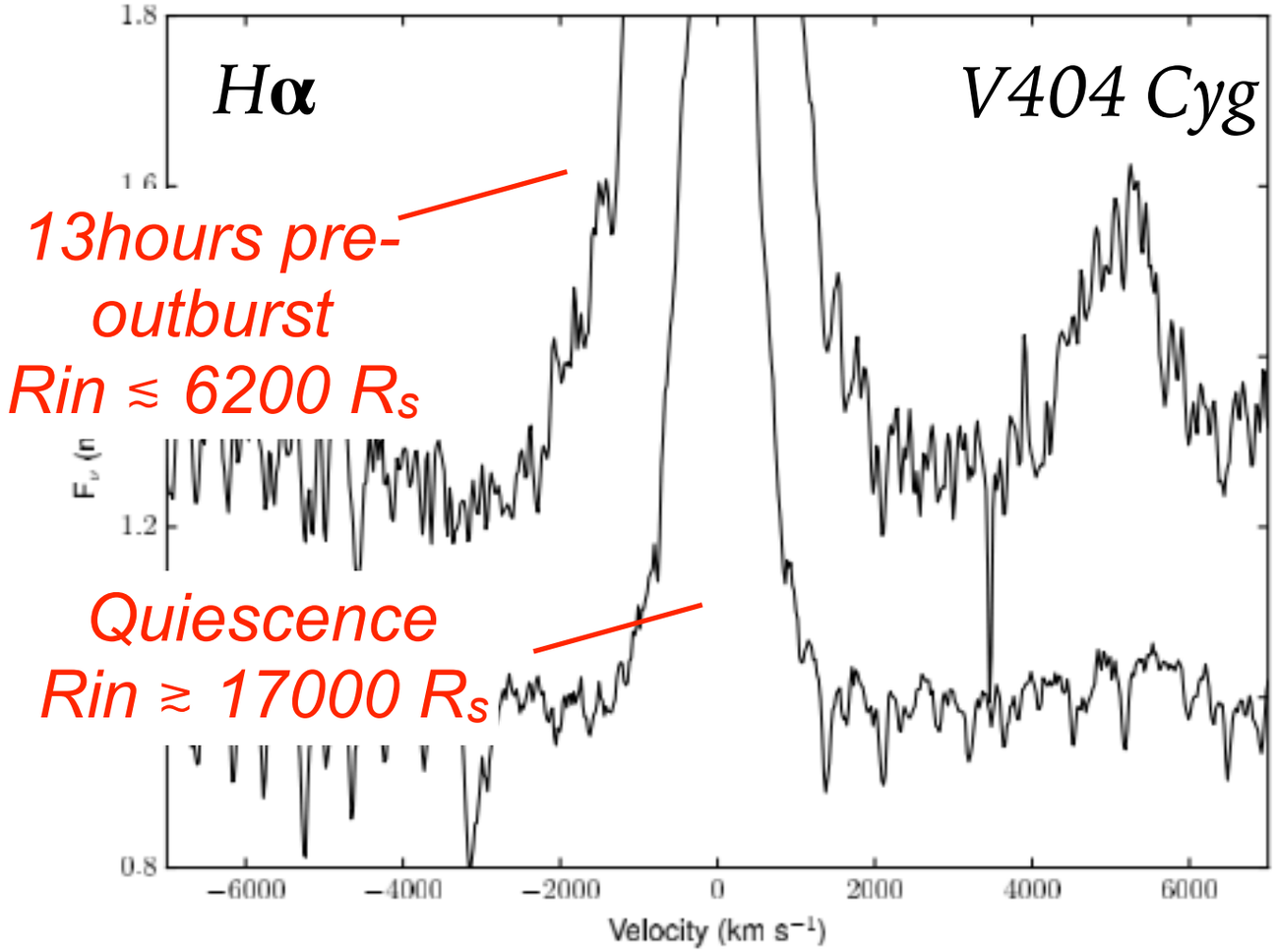


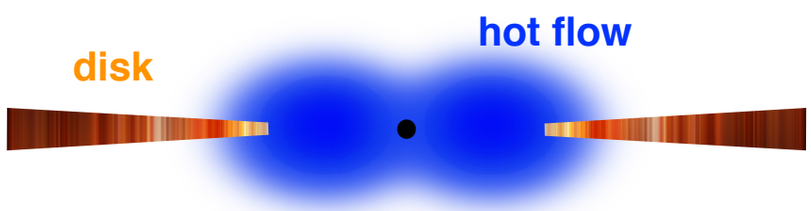
Geometry in quiescent state

[McClintock+'95]



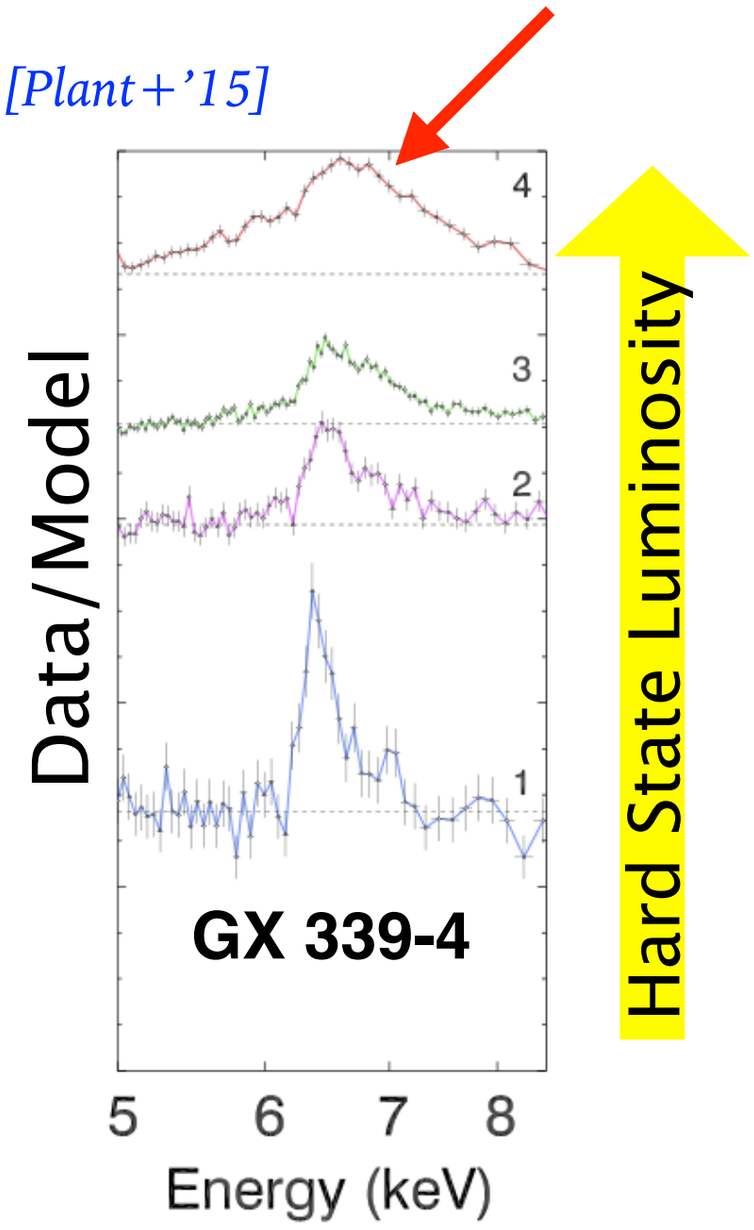
[Bernardini+'16]





The disc inner radius in the hard state

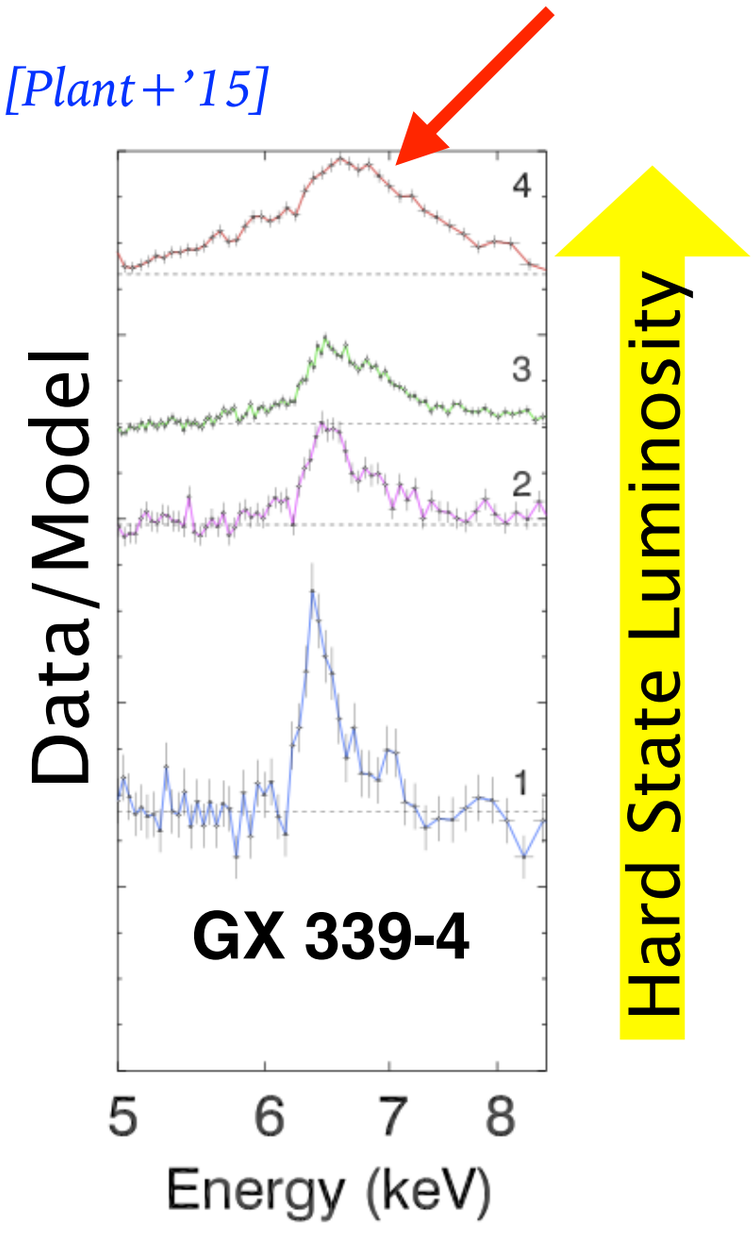
[Plant+'15]

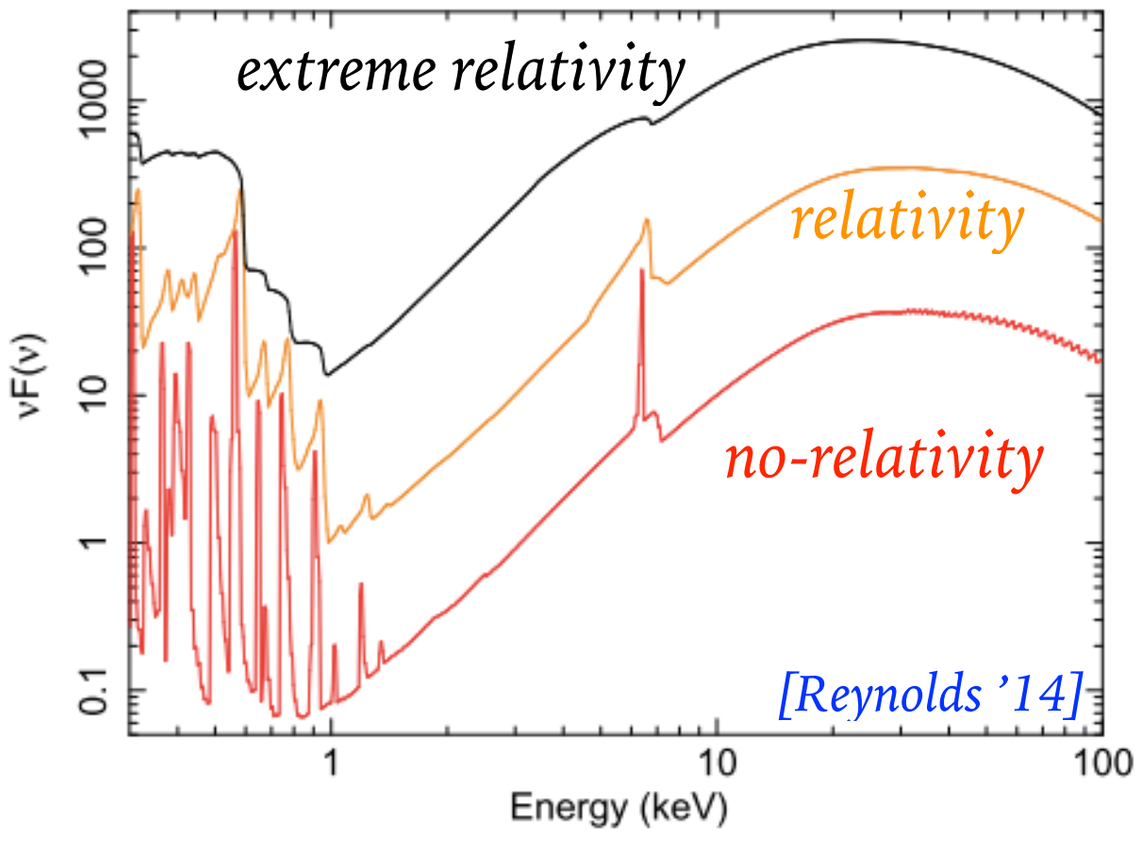


Hard State Luminosity

The disc inner radius in the hard state

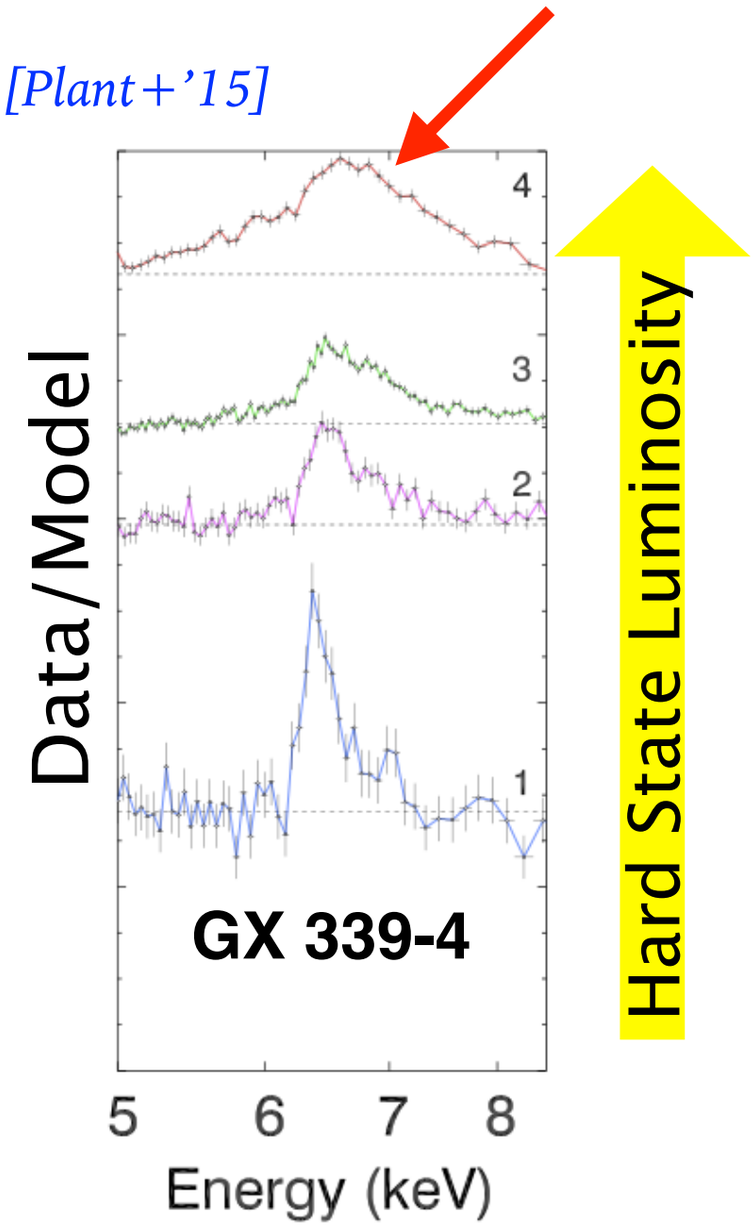
[Plant+'15]



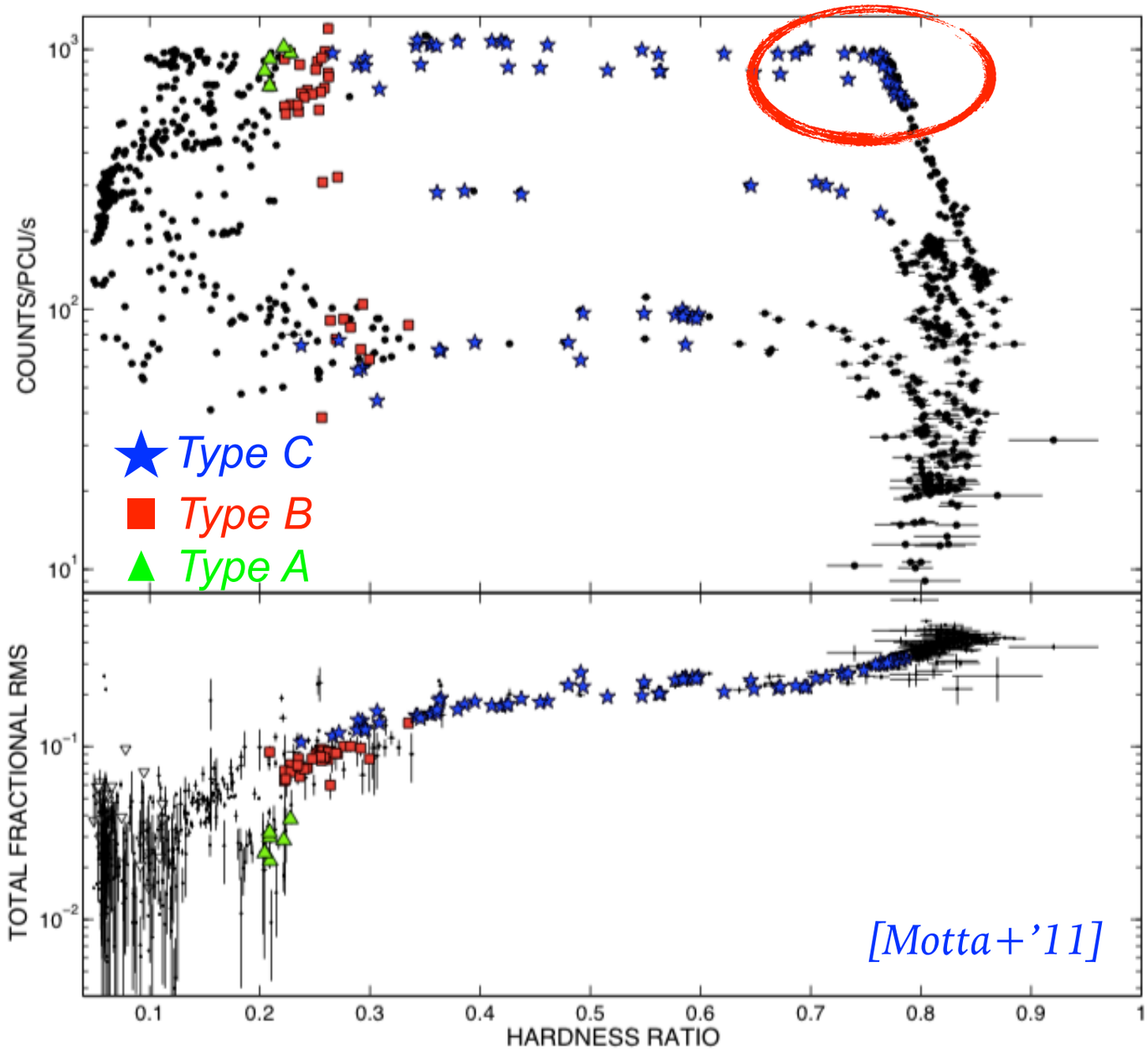


The disc inner radius in the hard state

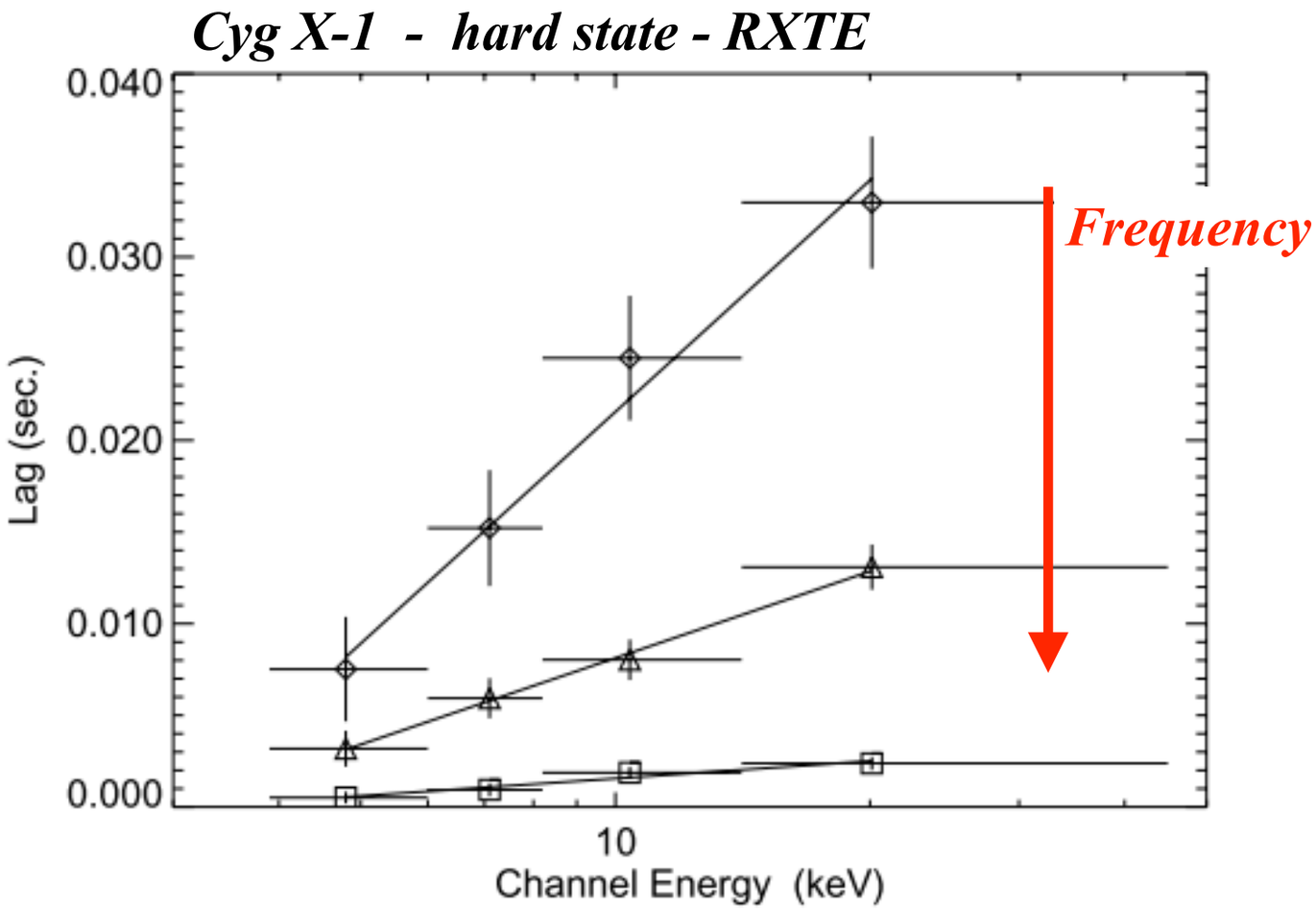
[Plant+'15]



Hard State Luminosity



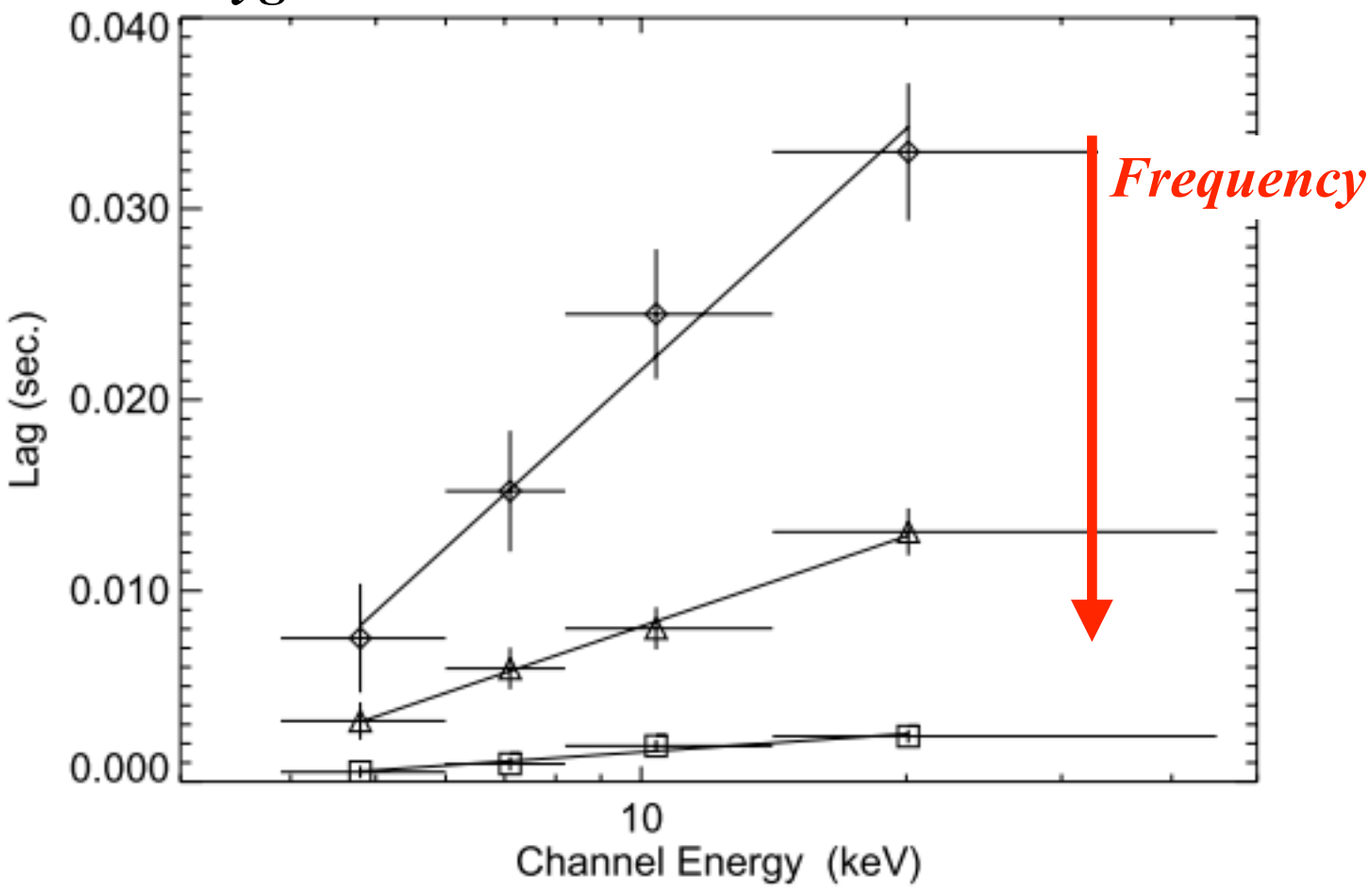
Hard lags in the primary X-ray continuum



[e.g. Miyamoto+'89; Nowak+'99; Kotov+'01; Pottschmidt+'01; Grindberg+'14; Zdziarski+'19]

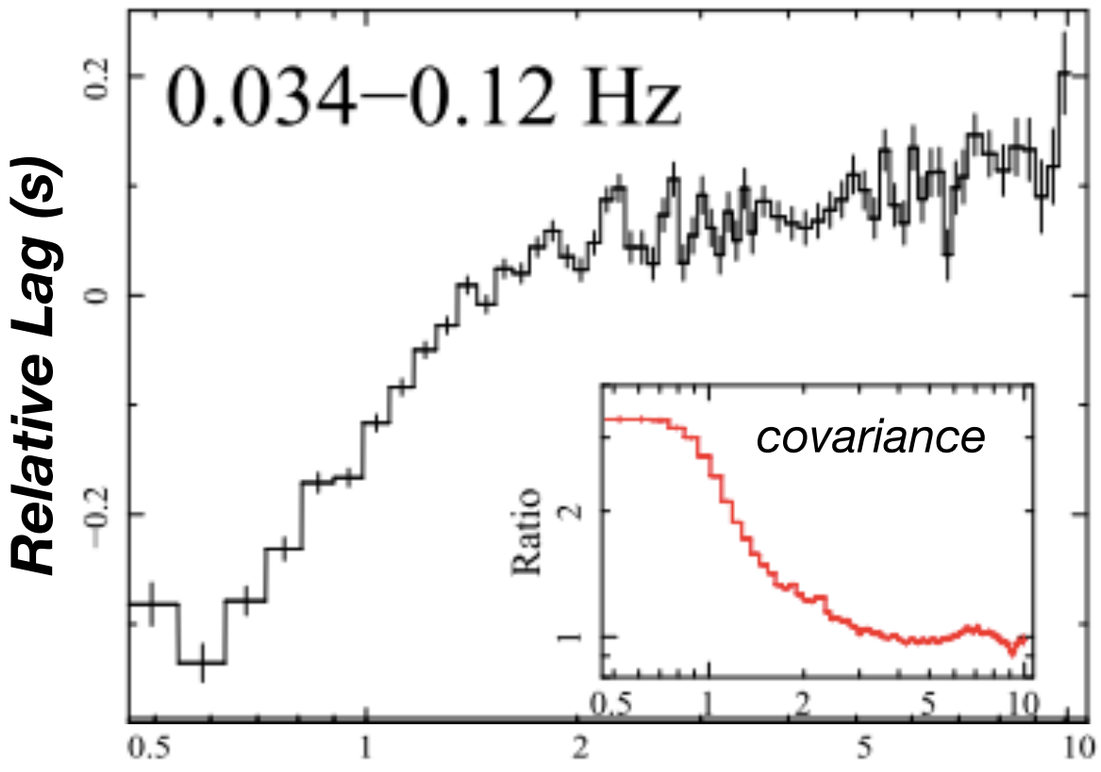
Hard lags in the primary X-ray continuum

Cyg X-1 - hard state - RXTE



[e.g. Miyamoto+'89; Nowak+'99; Kotov+'01; Pottschmidt+'01; Grindberg+'14; Zdziarski+'19]

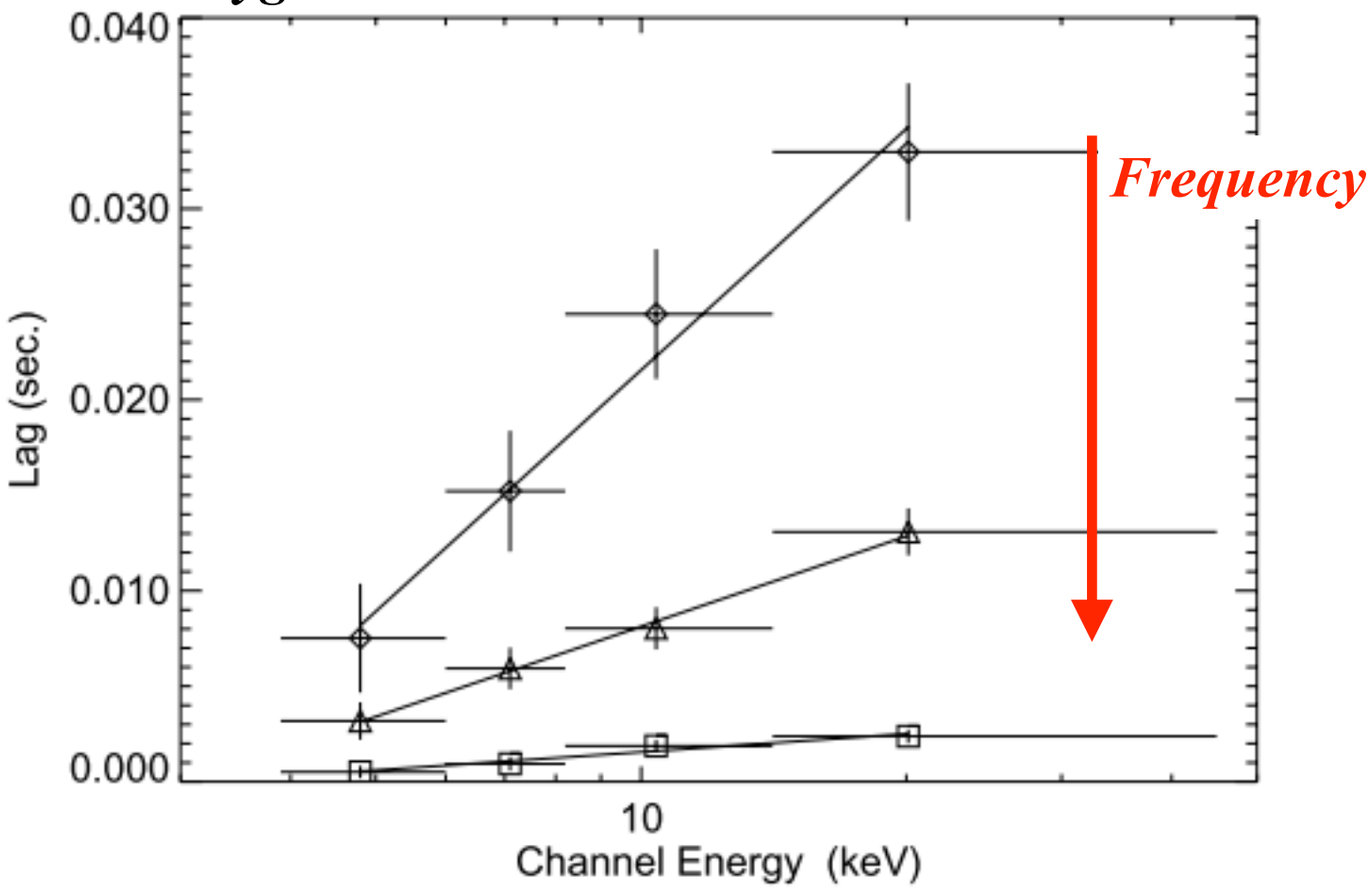
GX 339-4 - hard state - XMM Newton



[Uttley+'14; De Marco +'15b, '16, '17; Kara+'19]

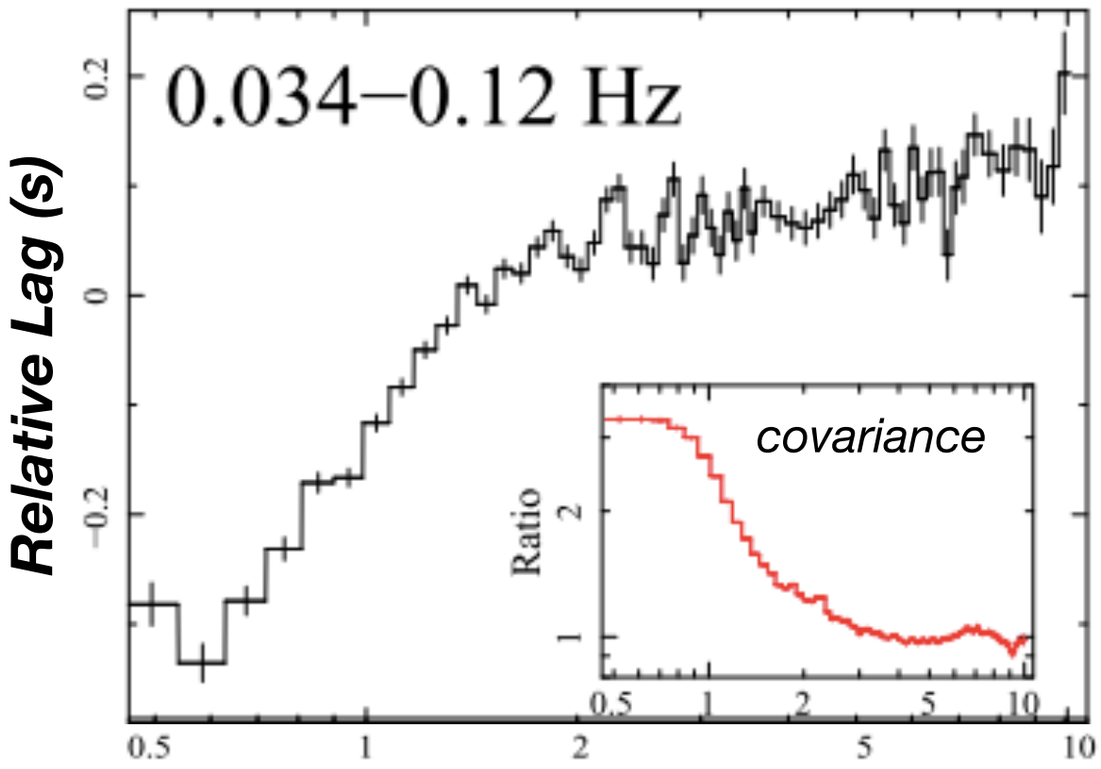
Hard lags in the primary X-ray continuum

Cyg X-1 - hard state - RXTE



[e.g. Miyamoto+'89; Nowak+'99; Kotov+'01; Pottschmidt+'01; Grindberg+'14; Zdziarski+'19]

GX 339-4 - hard state - XMM Newton

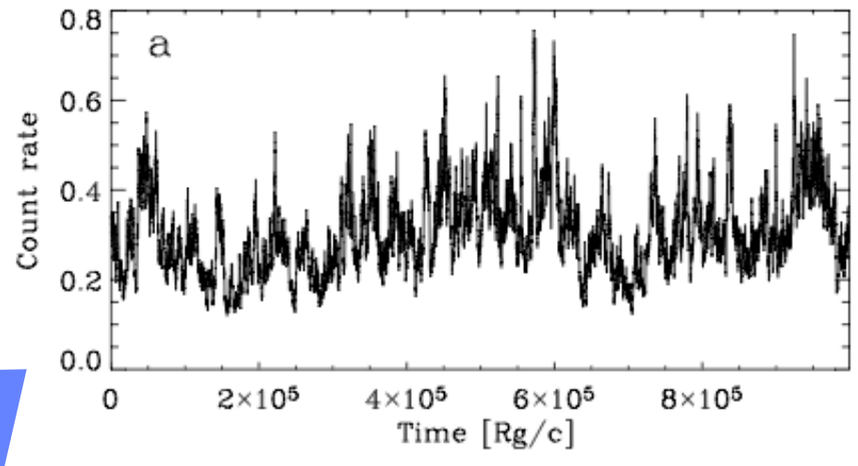


[Uttley+'14; De Marco +'15b, '16, '17; Kara+'19]

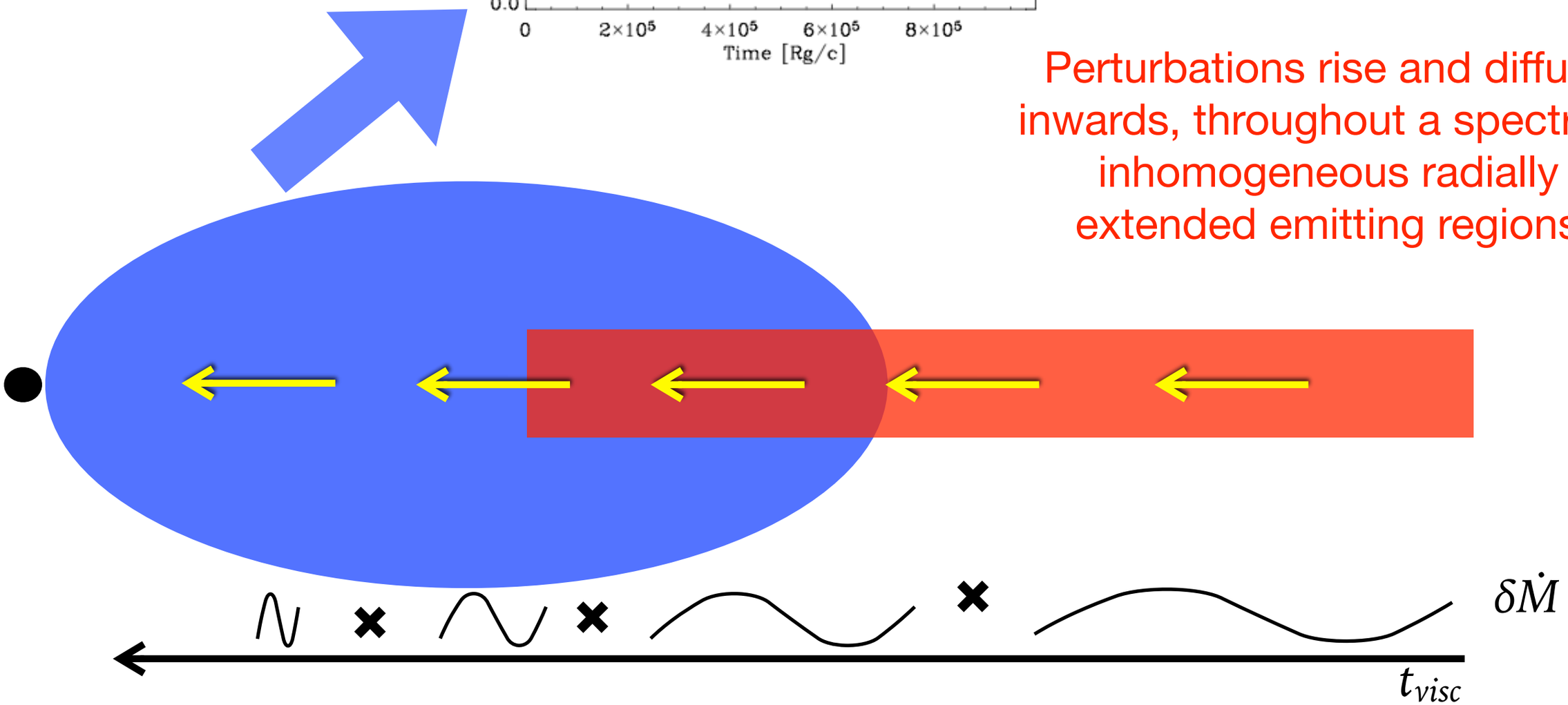
More rapid variability associated with increasingly shorter delays, disc driving power law variability on long (10-30 sec) time scales

Explaining observed spectral-timing properties

Propagating $\dot{M}$ fluctuations

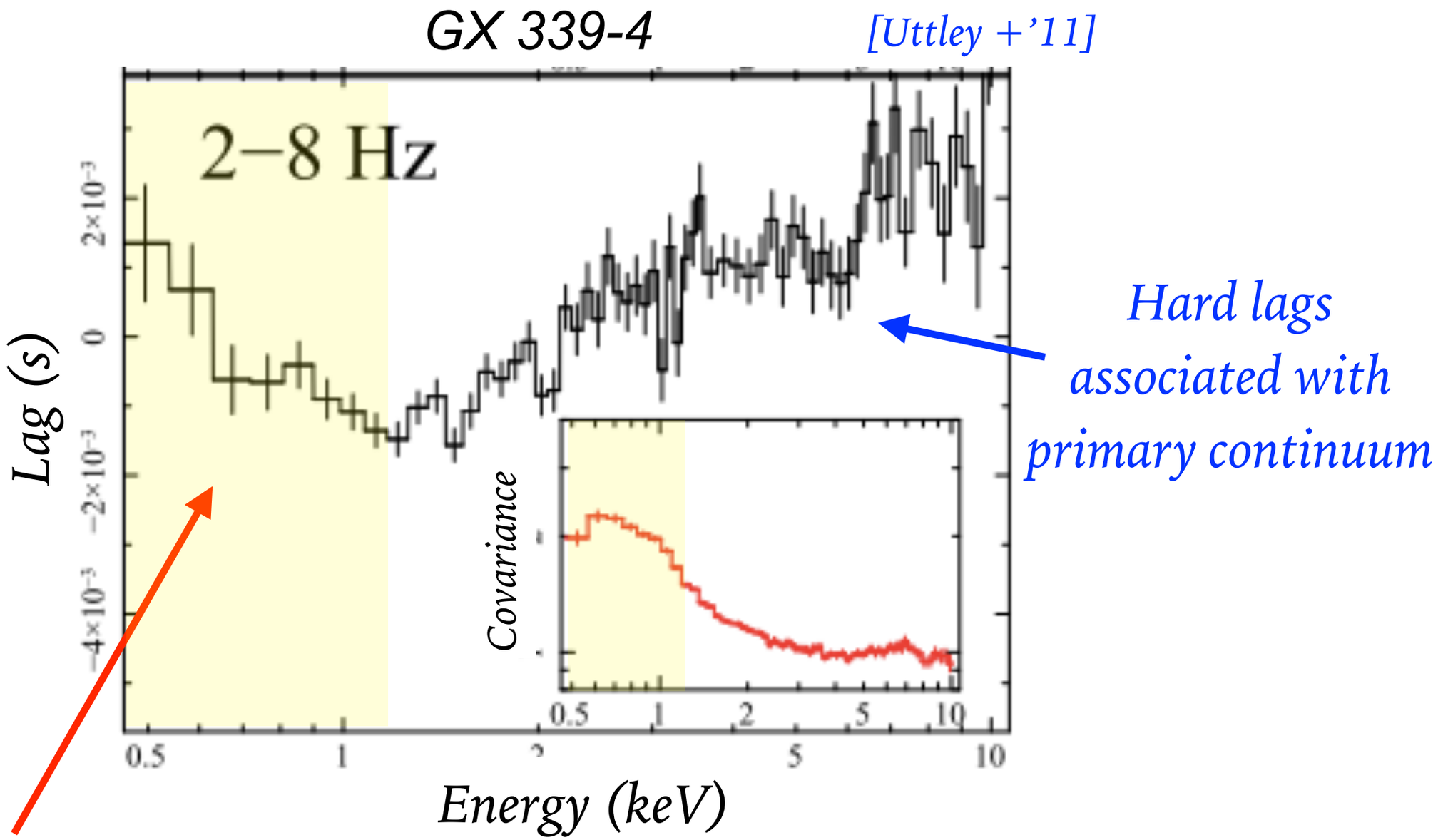


Perturbations rise and diffuse inwards, throughout a spectrally inhomogeneous radially extended emitting regions



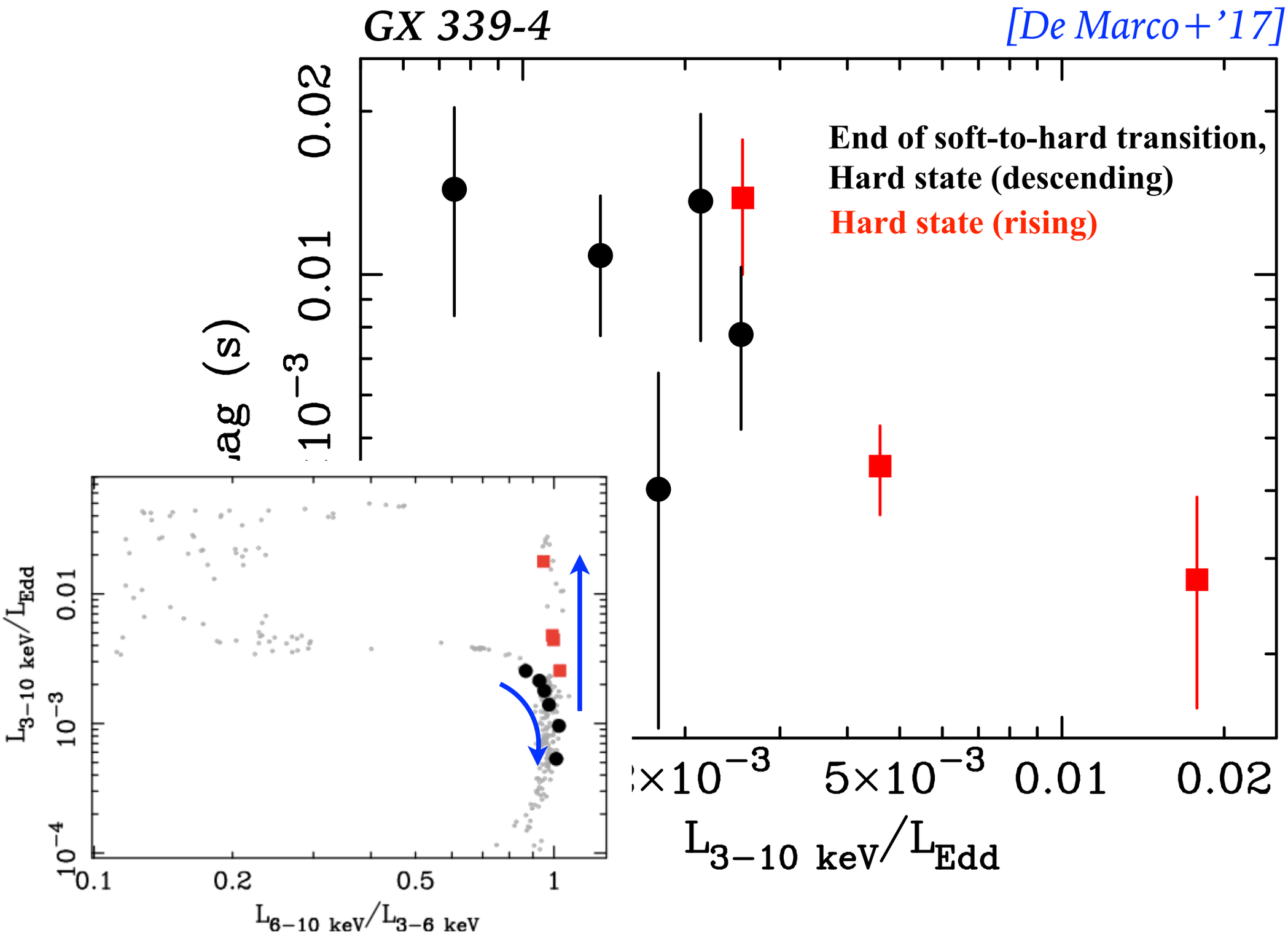
[Lyubarskii '97; Kotov +'01; Arévalo & Uttley '06; Ingram & van der Klis'13; Hogg & Reynolds '15; Mushtukov +'18; Mahmoud & Done '18; Bollimpalli +'19]

Disc reverberation in BHXRBs



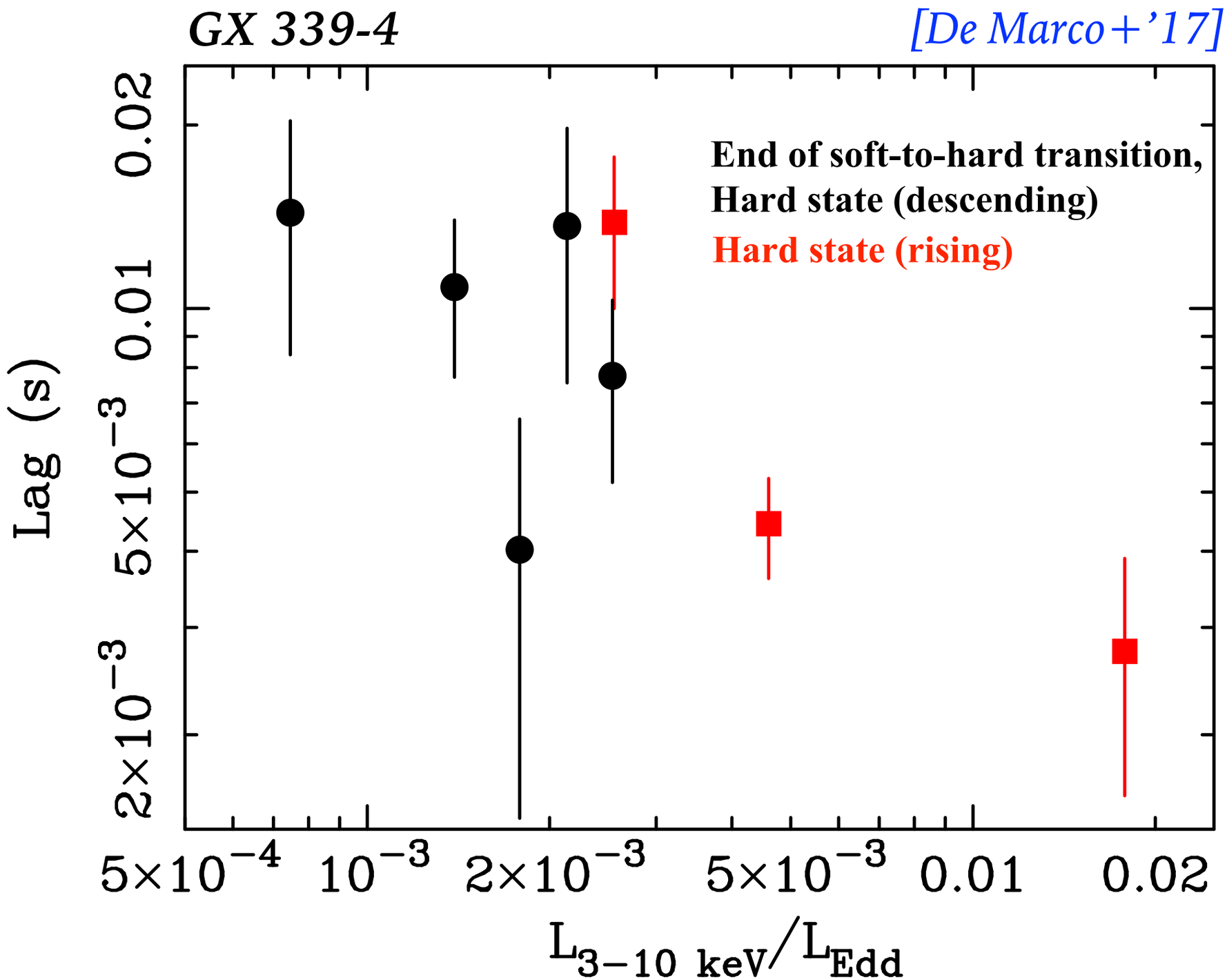
Evolution of reverberation lag

Distance mapped by the lag decreases towards luminous hard states, indicating variations of geometry



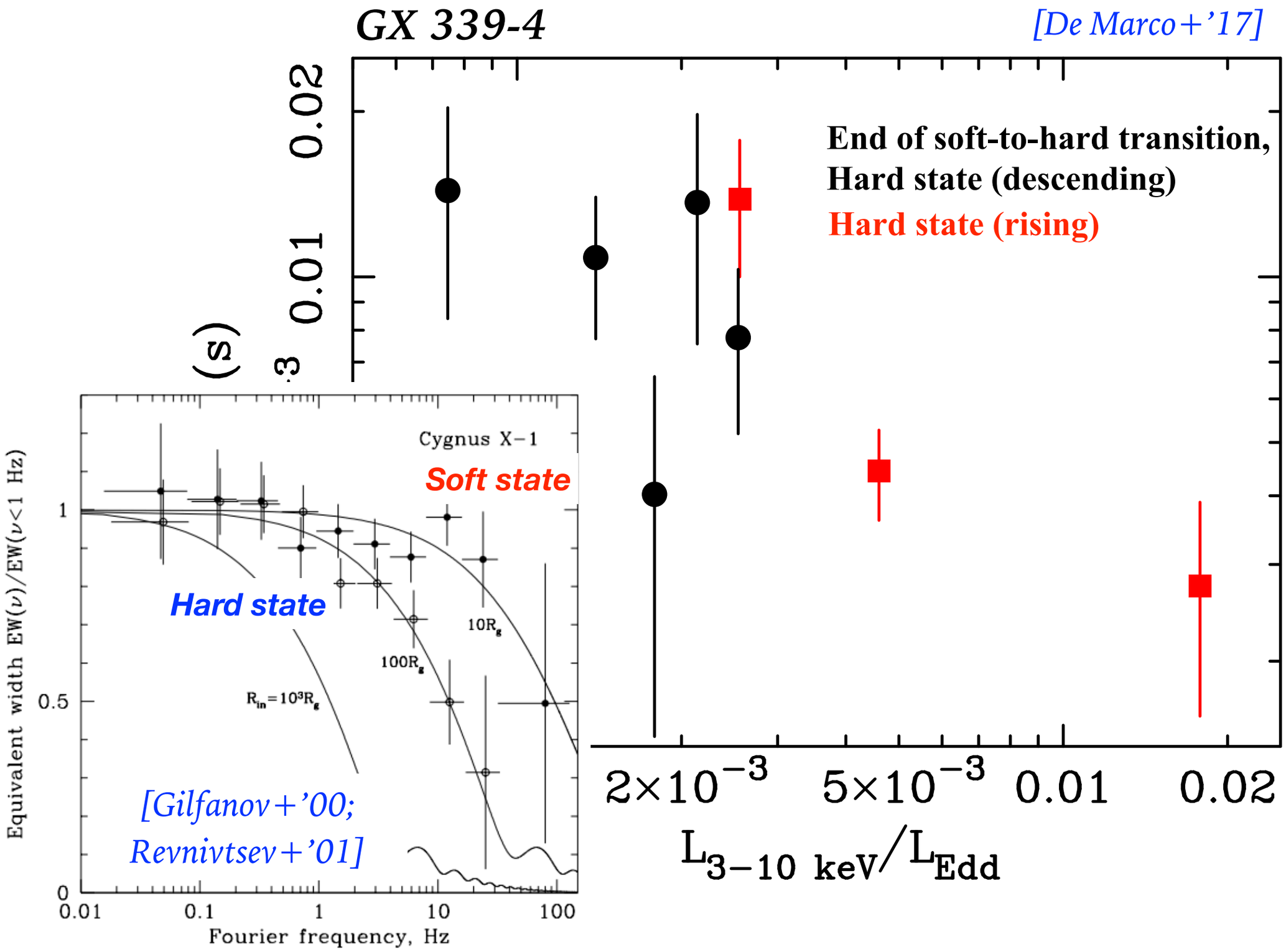
Evolution of reverberation lag

Distance mapped by the lag decreases towards luminous hard states, indicating variations of geometry



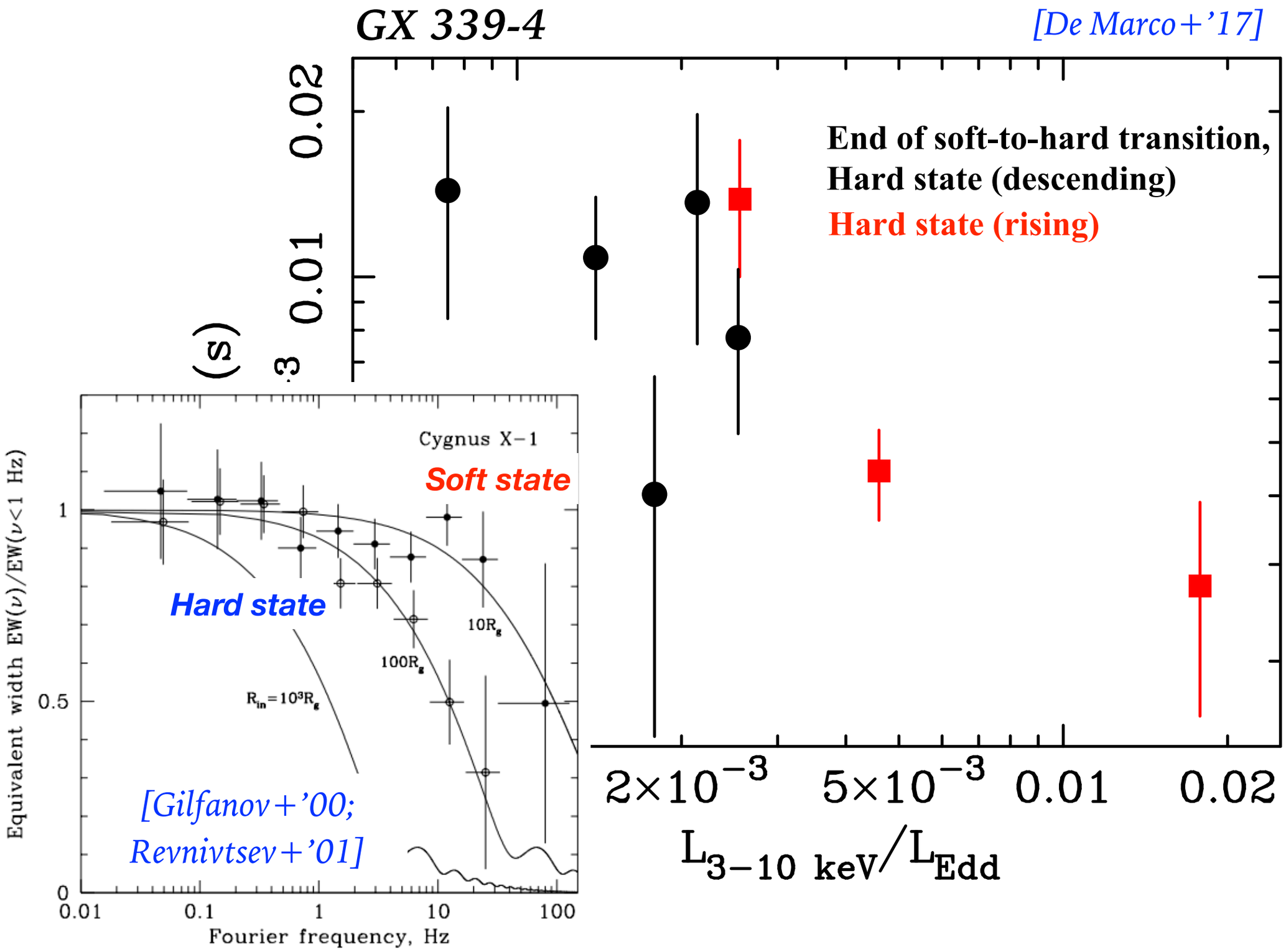
Evolution of reverberation lag

Distance mapped by the lag decreases towards luminous hard states, indicating variations of geometry



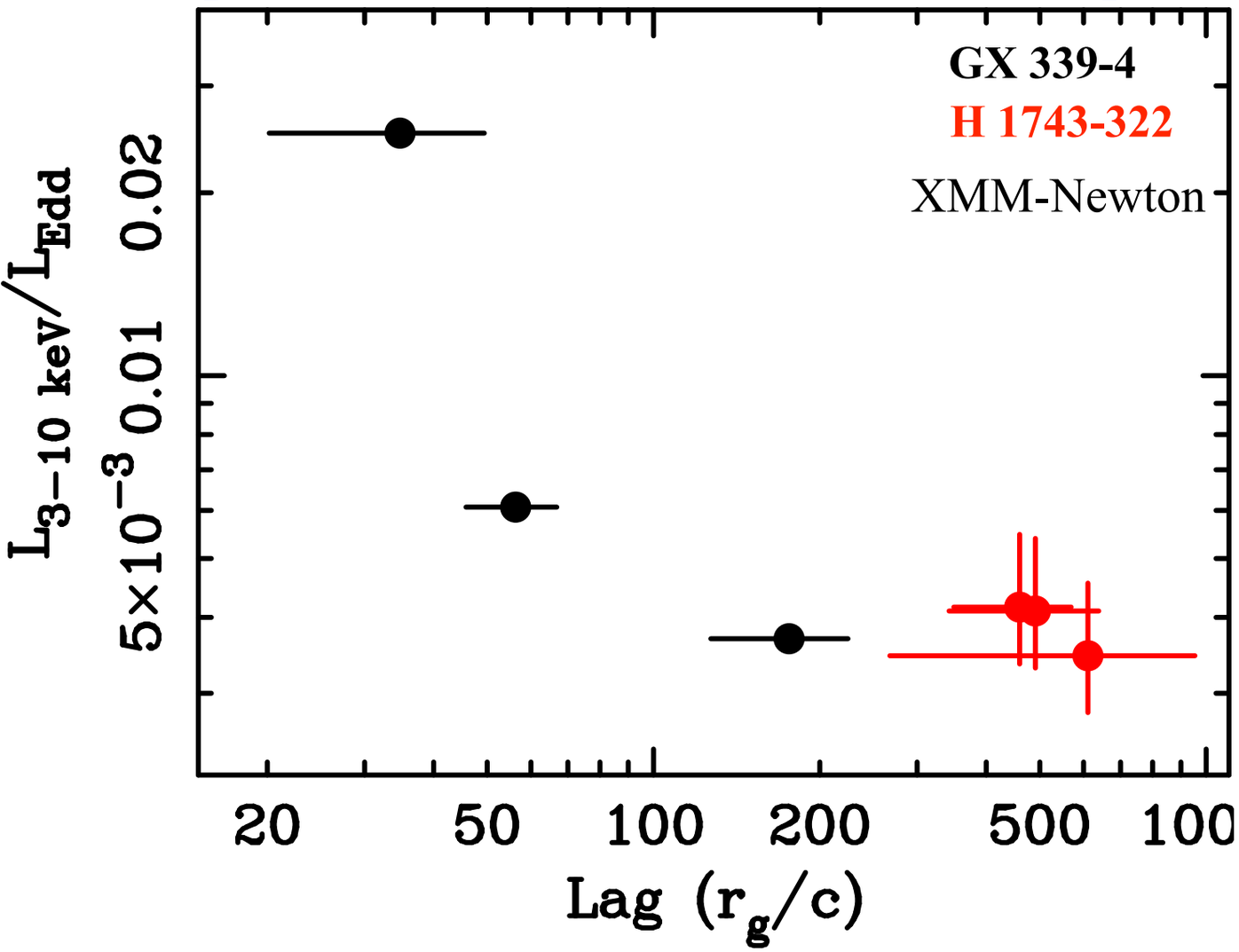
Evolution of reverberation lag

Distance mapped by the lag decreases towards luminous hard states, indicating variations of geometry

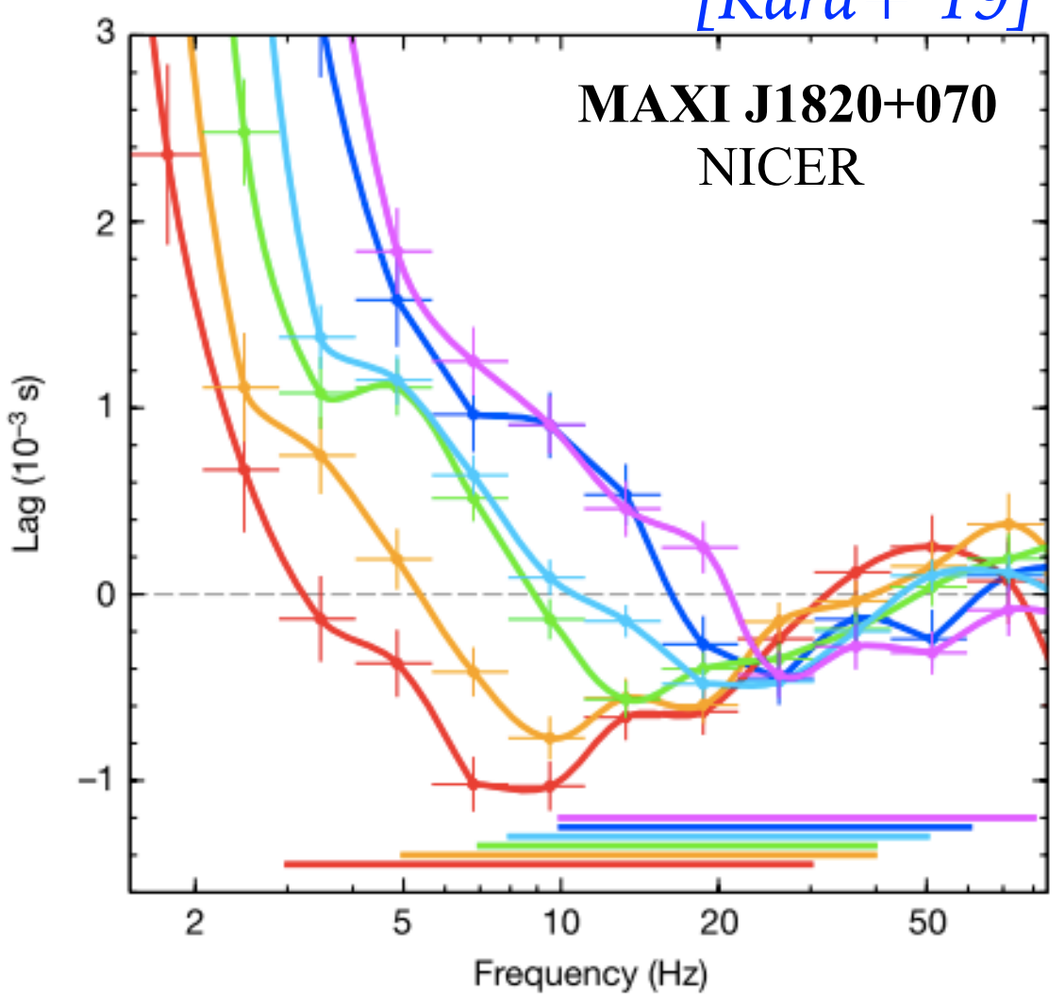


Evolution of reverberation lag

[De Marco+'15; De Marco & Ponti '16]



[Kara+'19]

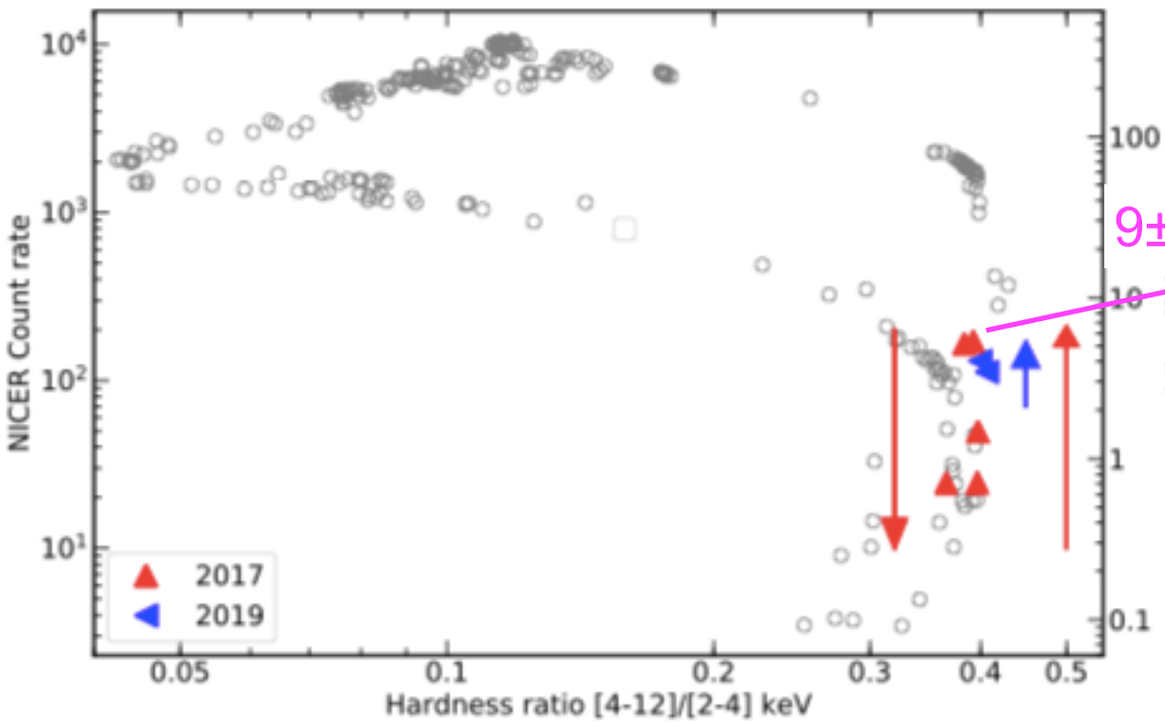


Lags evolution seen in different sources

Evolution of reverberation lag

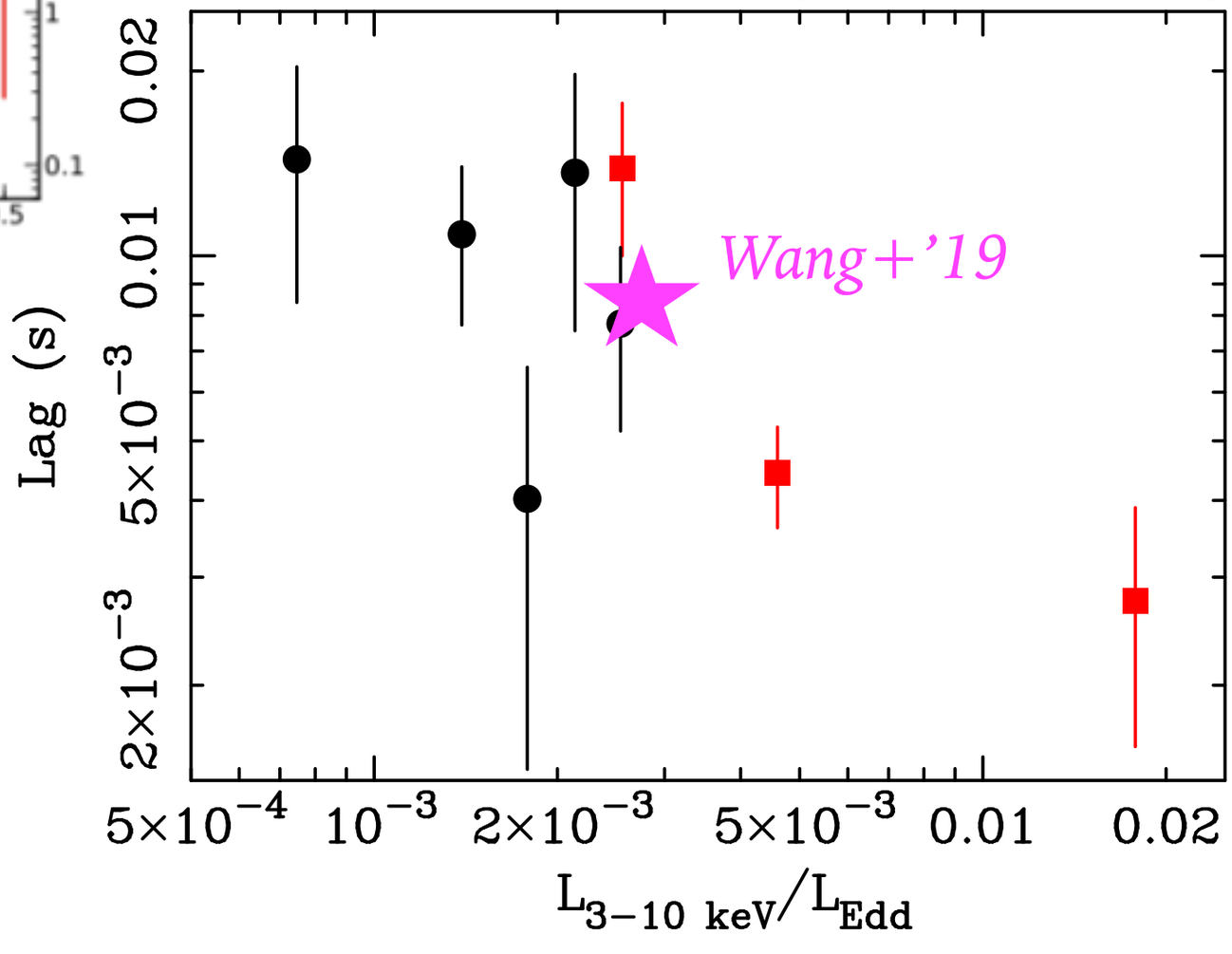
GX 339-4

[Wang+'19]



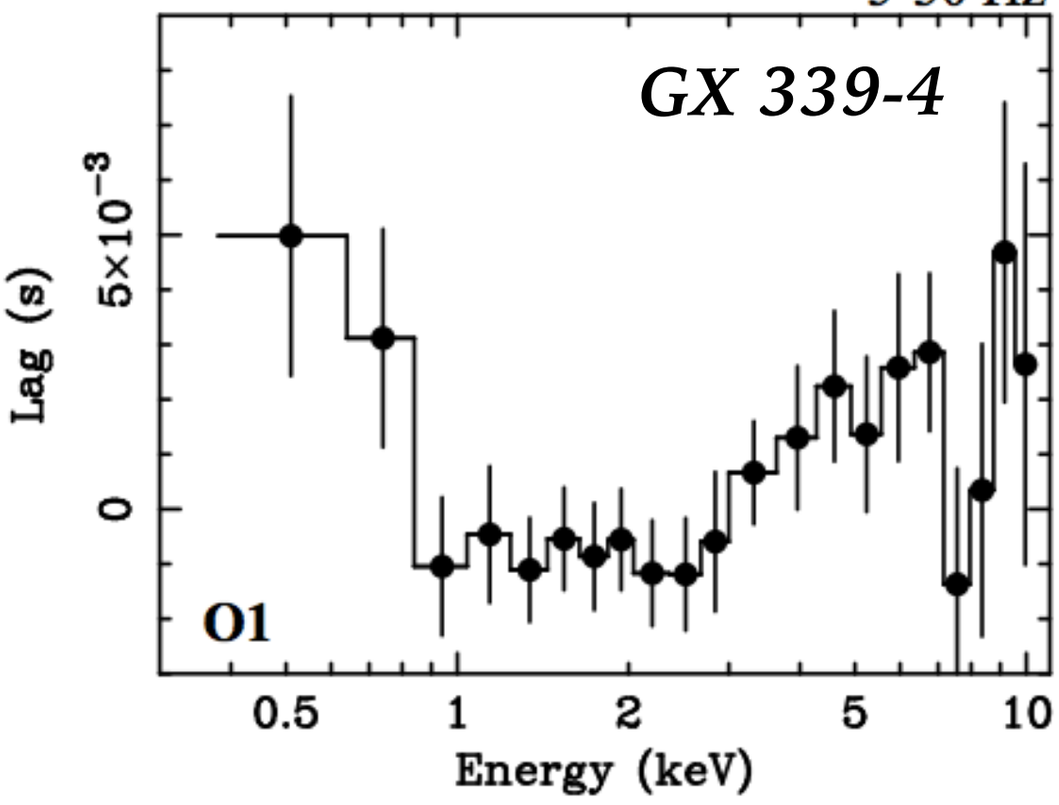
9±3 ms thermal reverberation lag

[De Marco+'17]



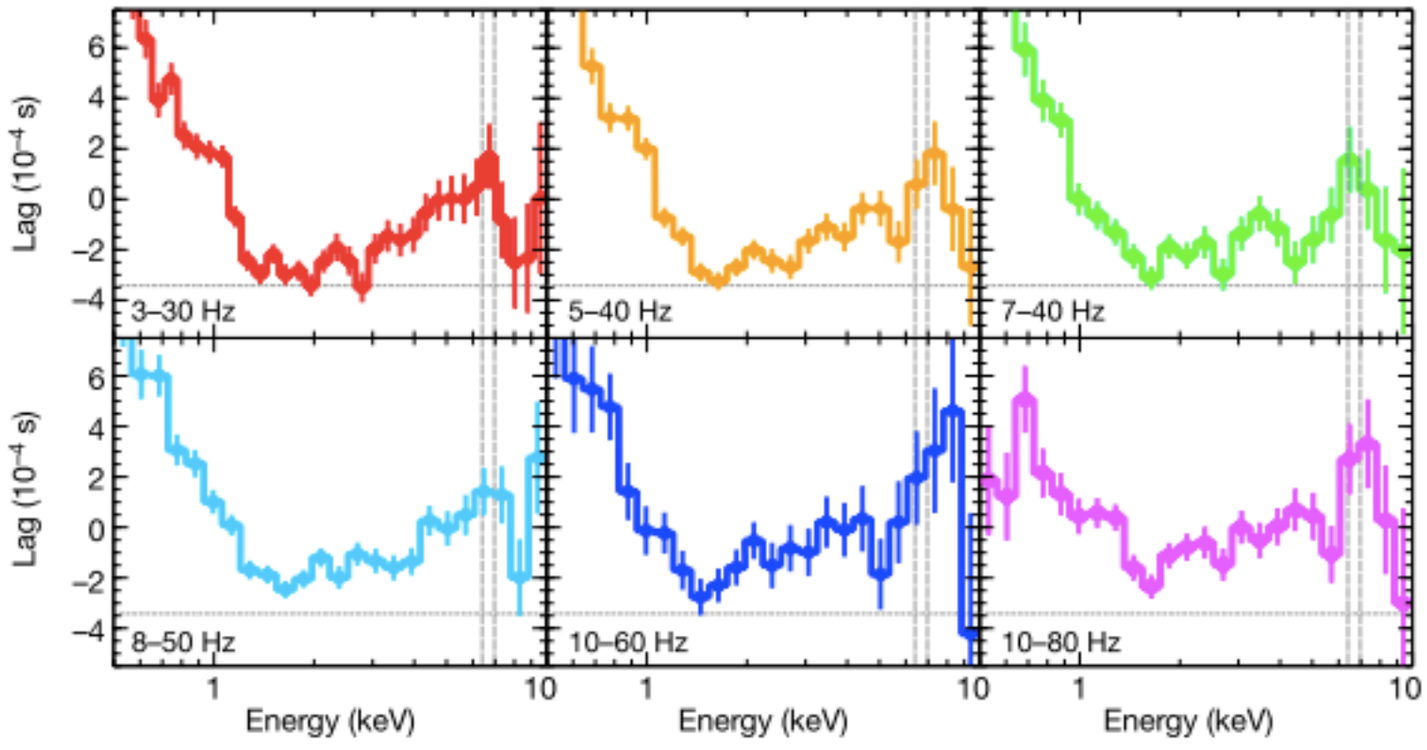
FeK reverberation

[De Marco+'17]

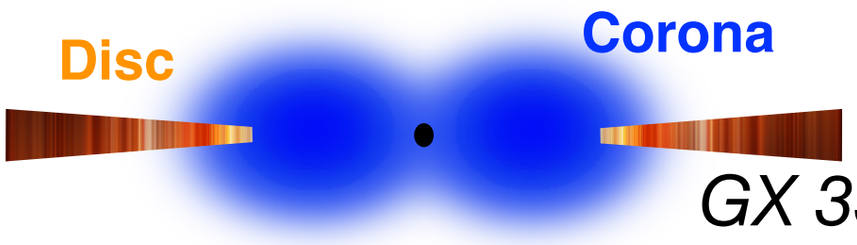


[Kara+'19]

MAXI J1820+070

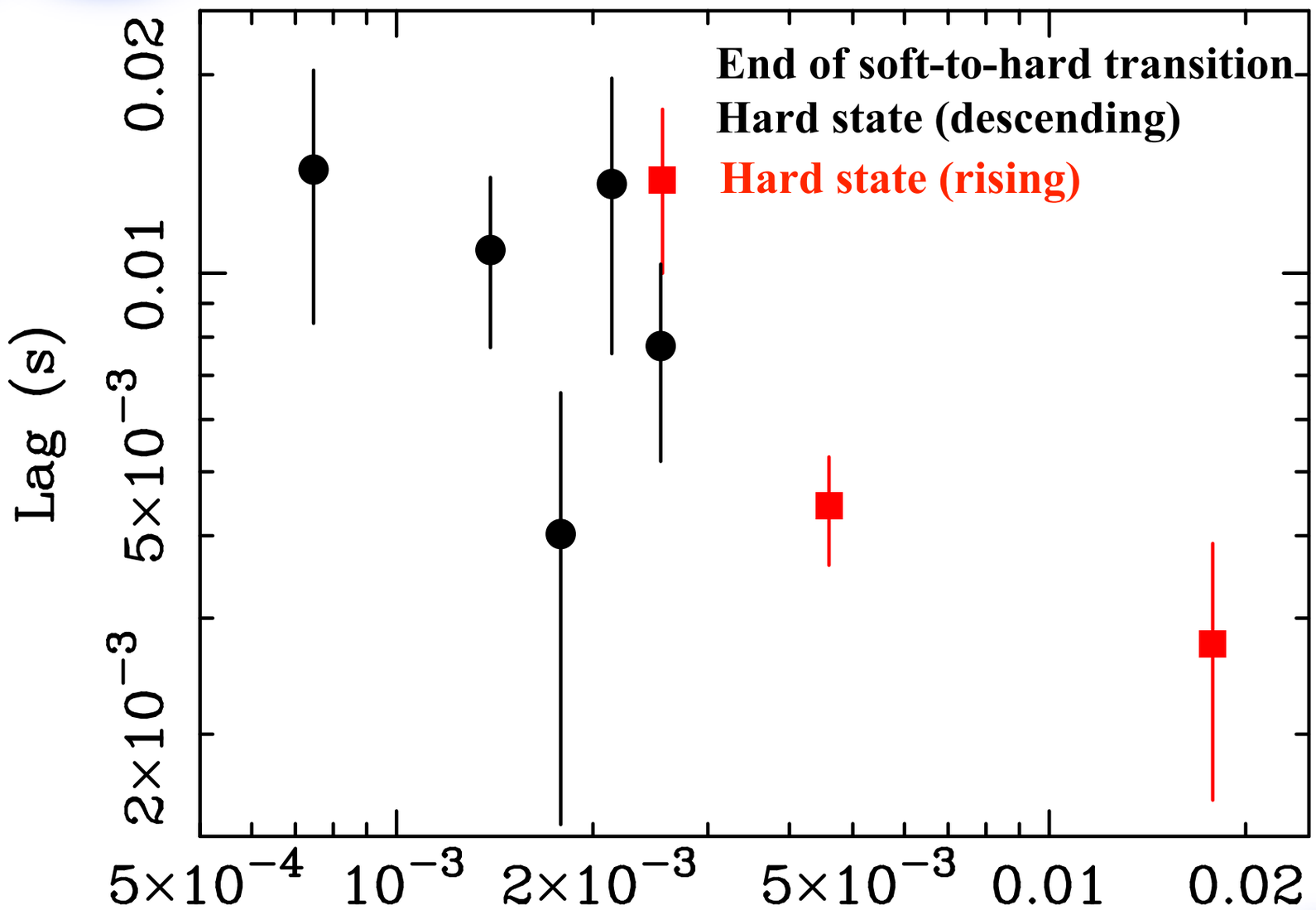


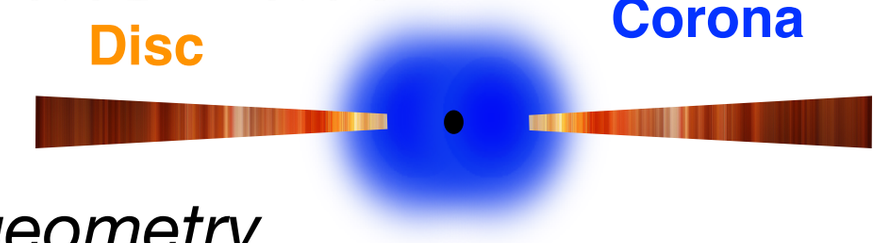
Interpretation #1



[De Marco+'17, '15, '16]

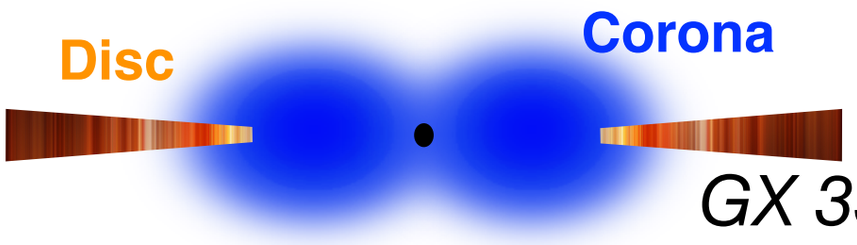
GX 339-4 - hard state - XMM Newton





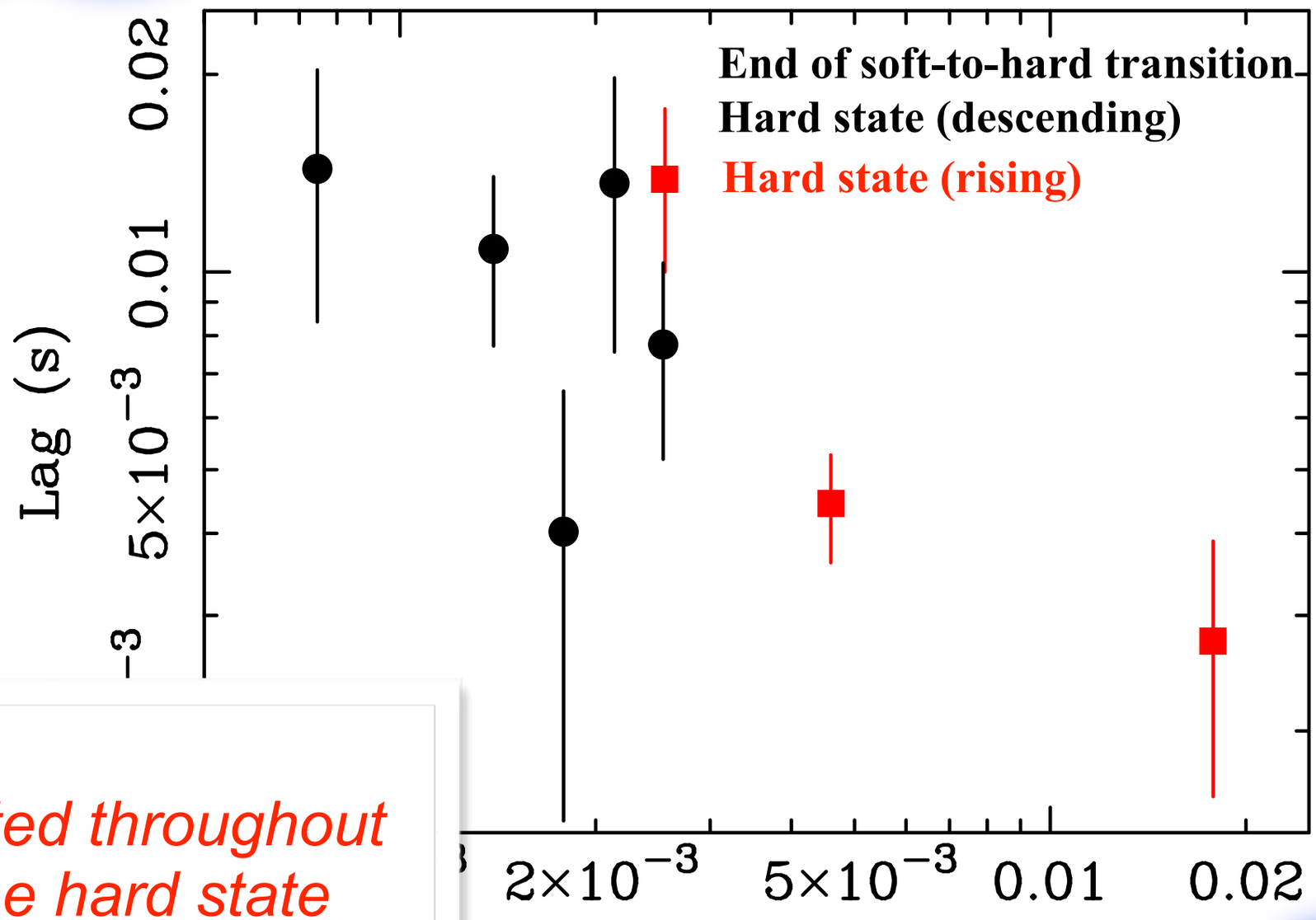
Evolution of disc-corona geometry

Interpretation #1

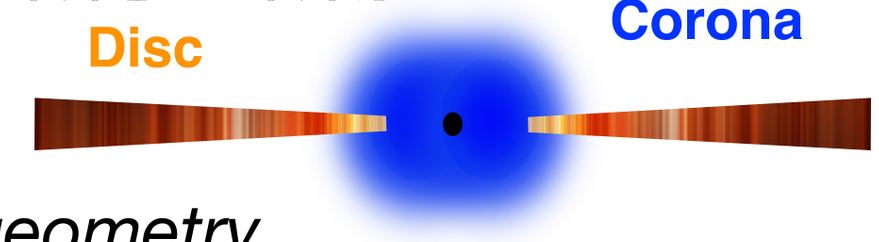


[De Marco+'17, '15, '16]

GX 339-4 - hard state - XMM Newton



Disc truncated throughout most of the hard state



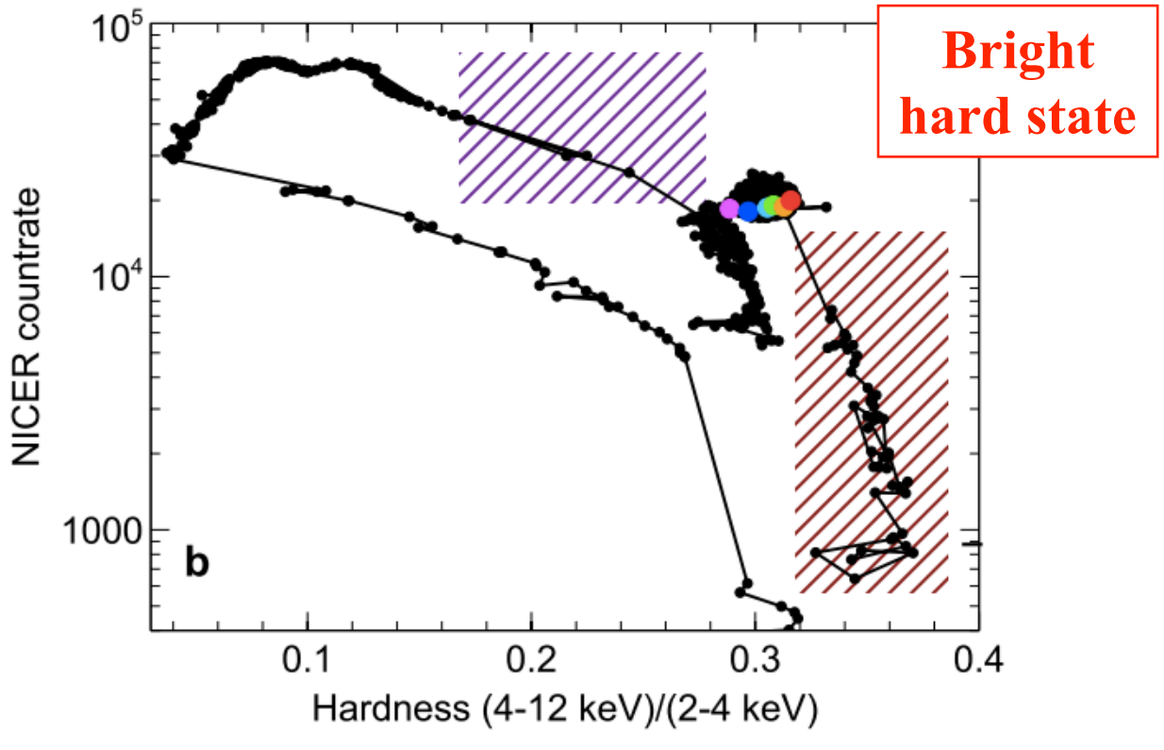
Evolution of disc-corona geometry

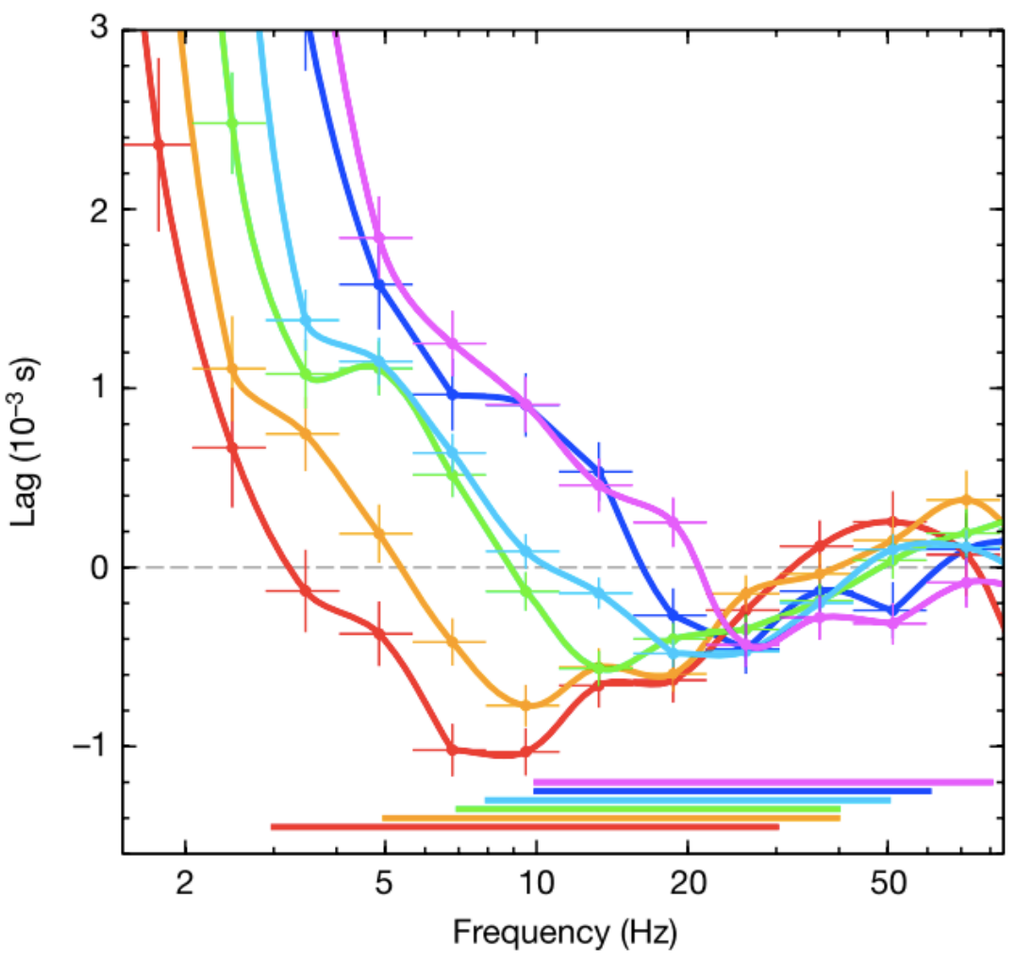
Interpretation #2

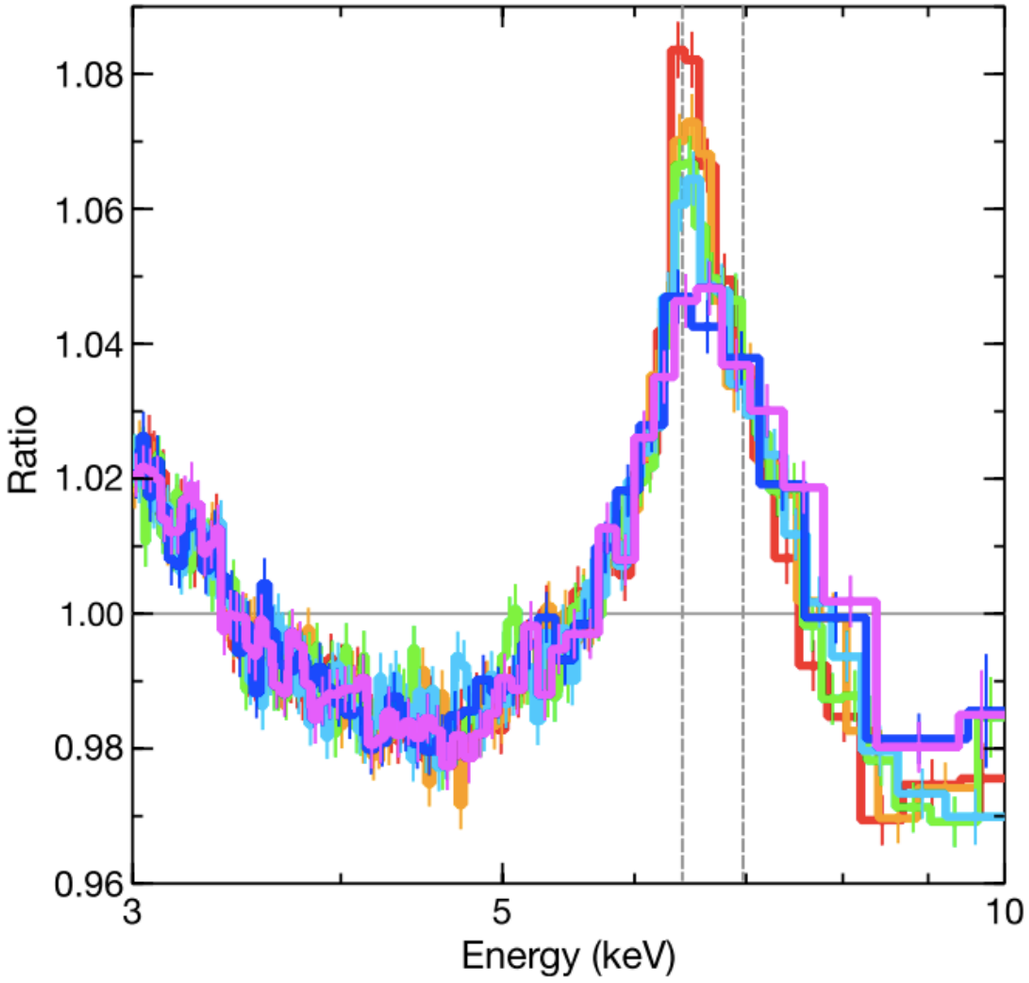
MAXI J1820+070

NICER

[Kara+'19]

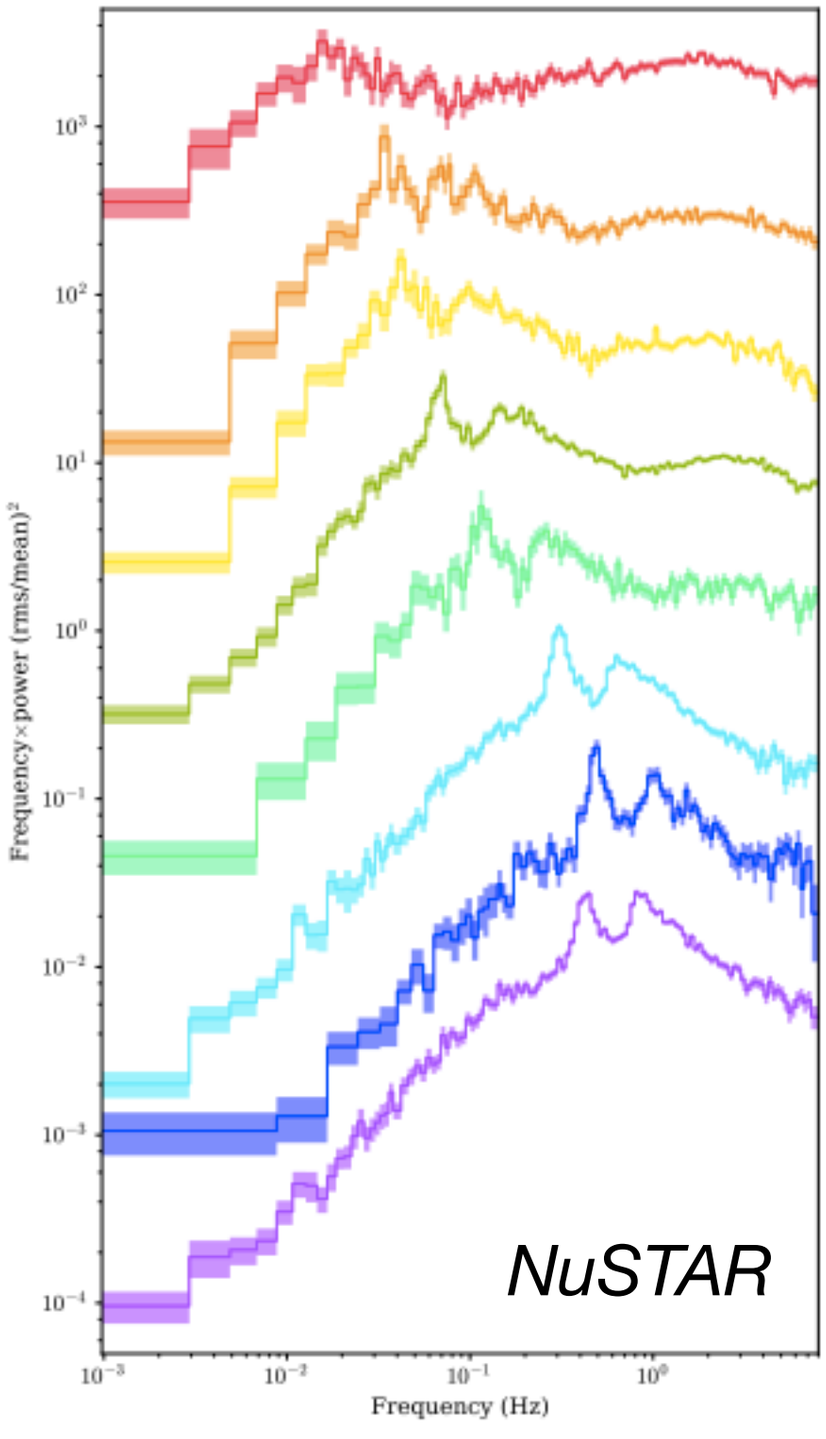




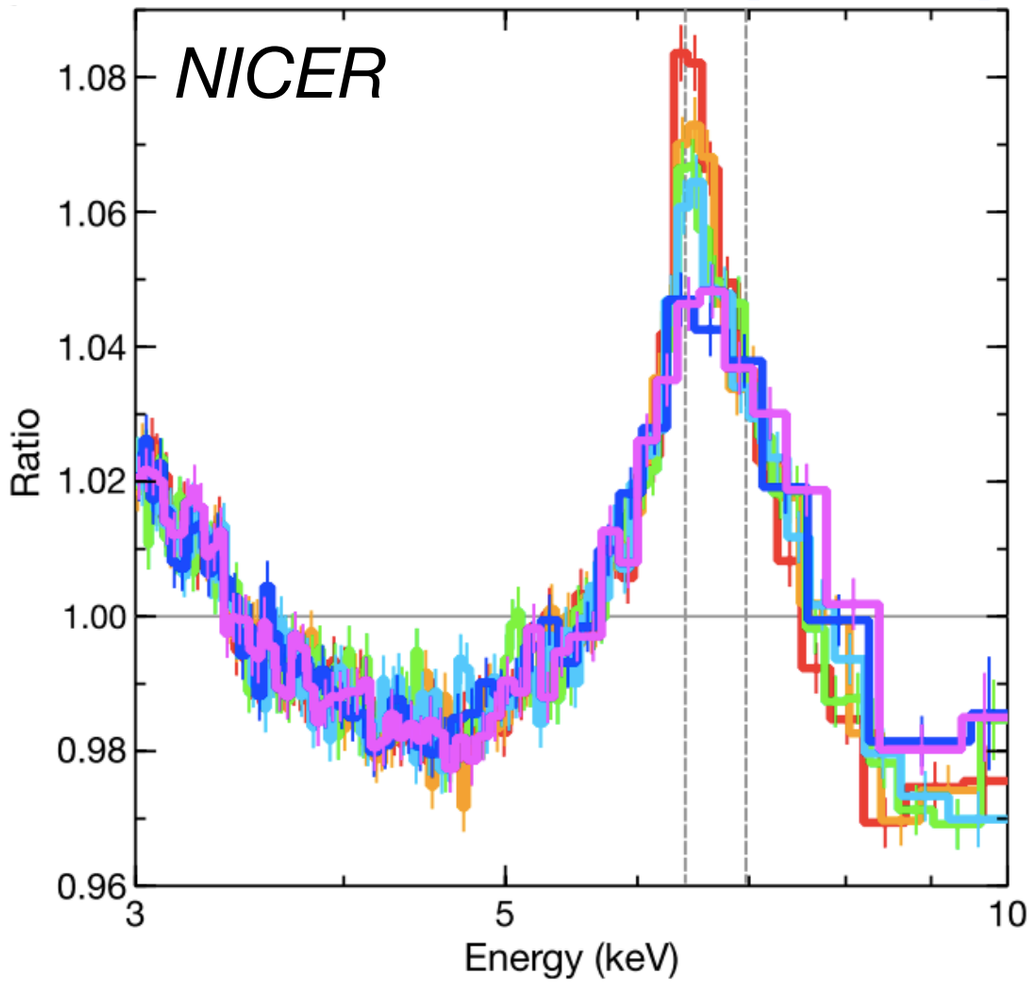


Interpretation #2

MAXI J1820+070 *[Buisson+'19]*

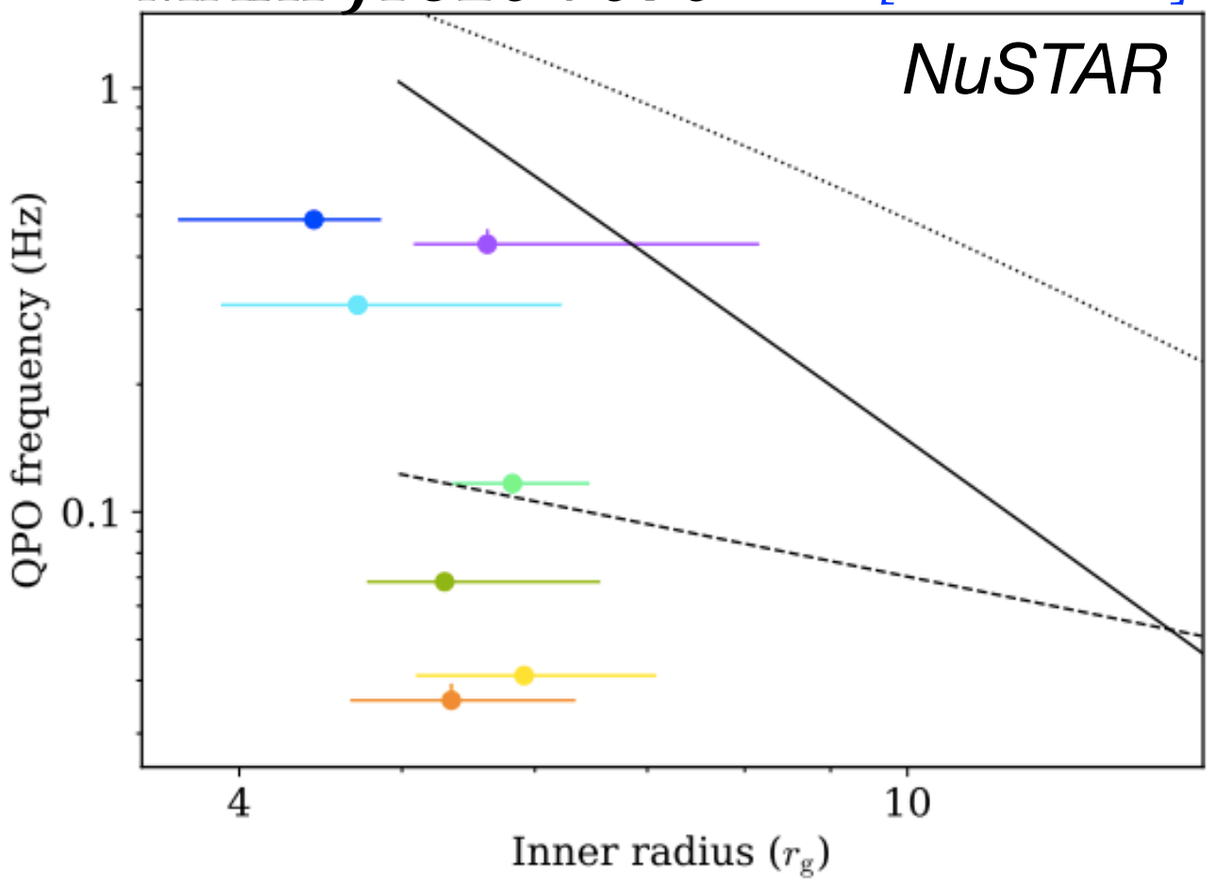


[Kara+'19]

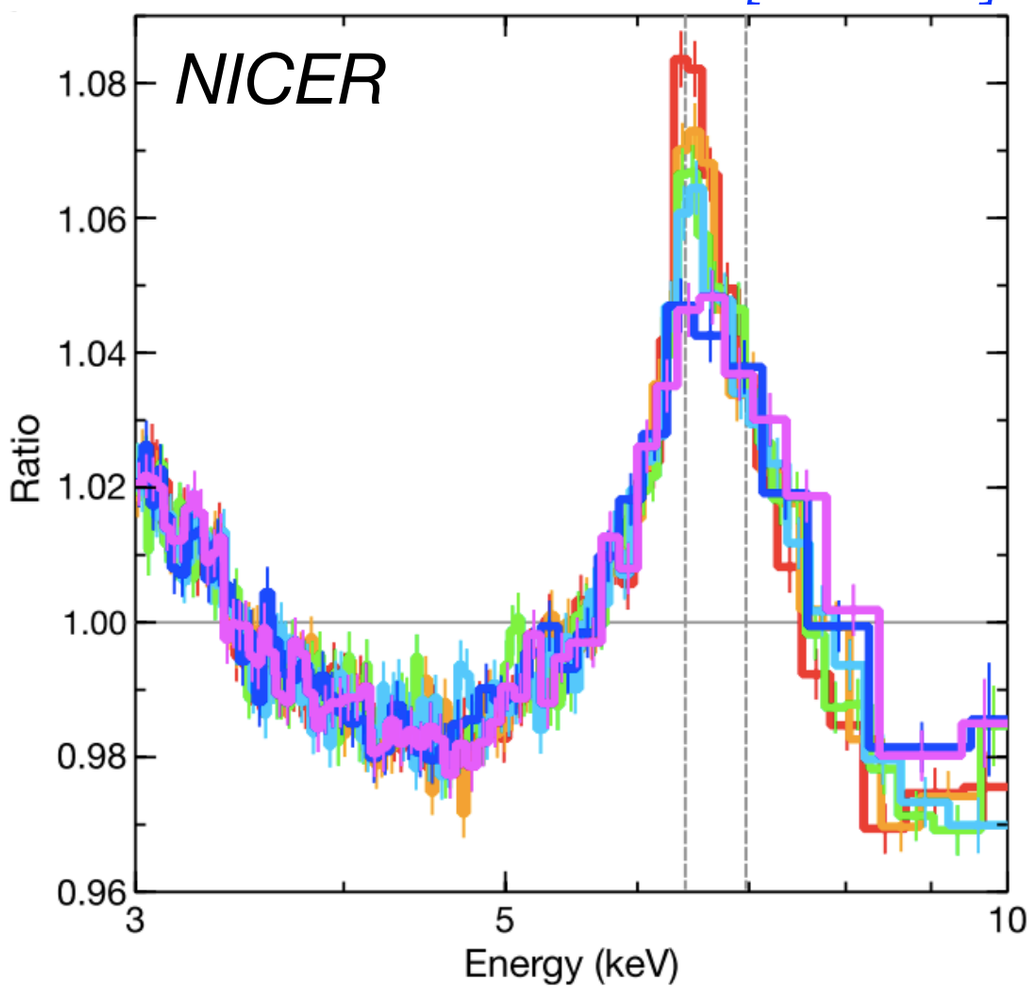


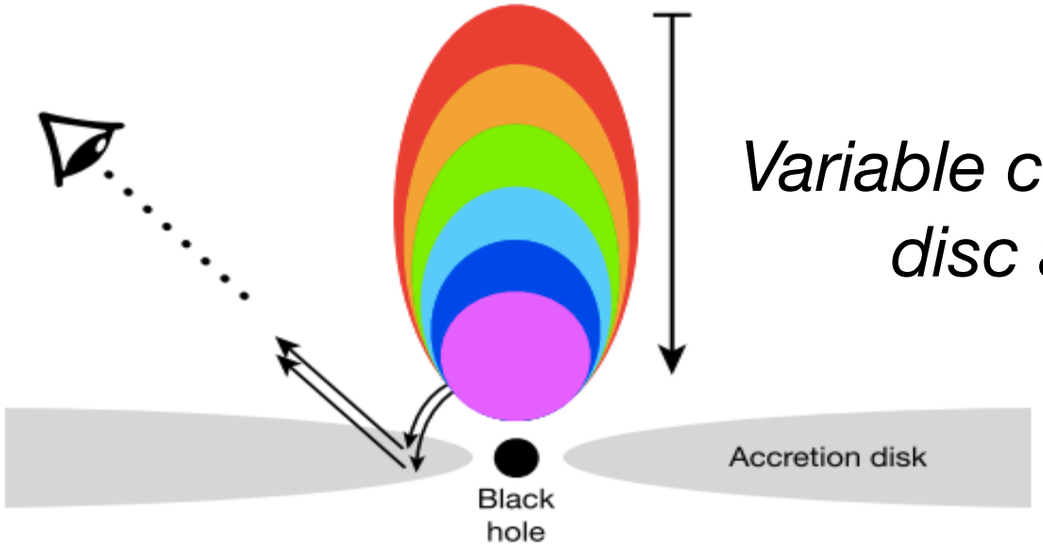
Interpretation #2

MAXI J1820+070 *[Buisson+'19]*



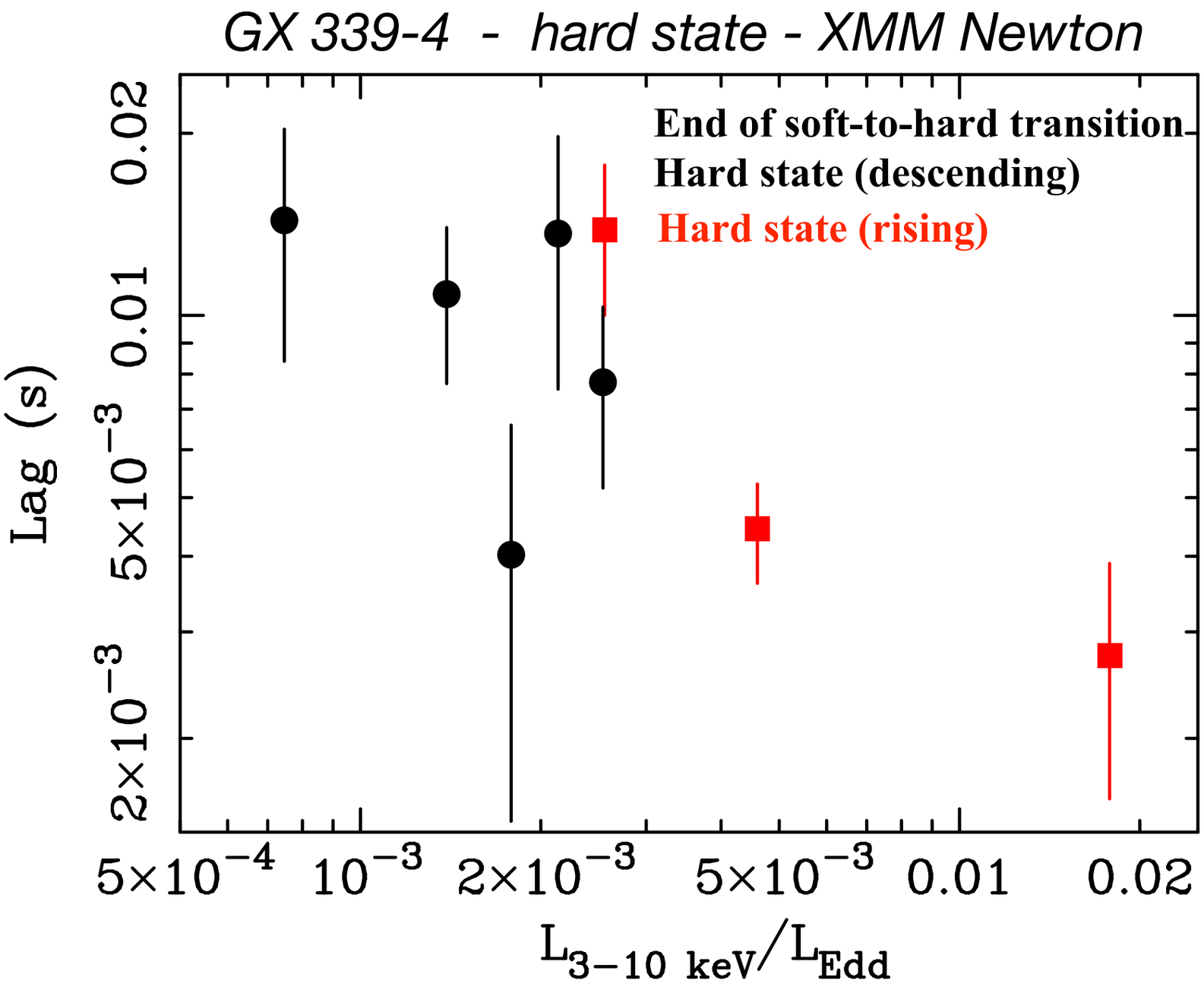
[Kara+'19]





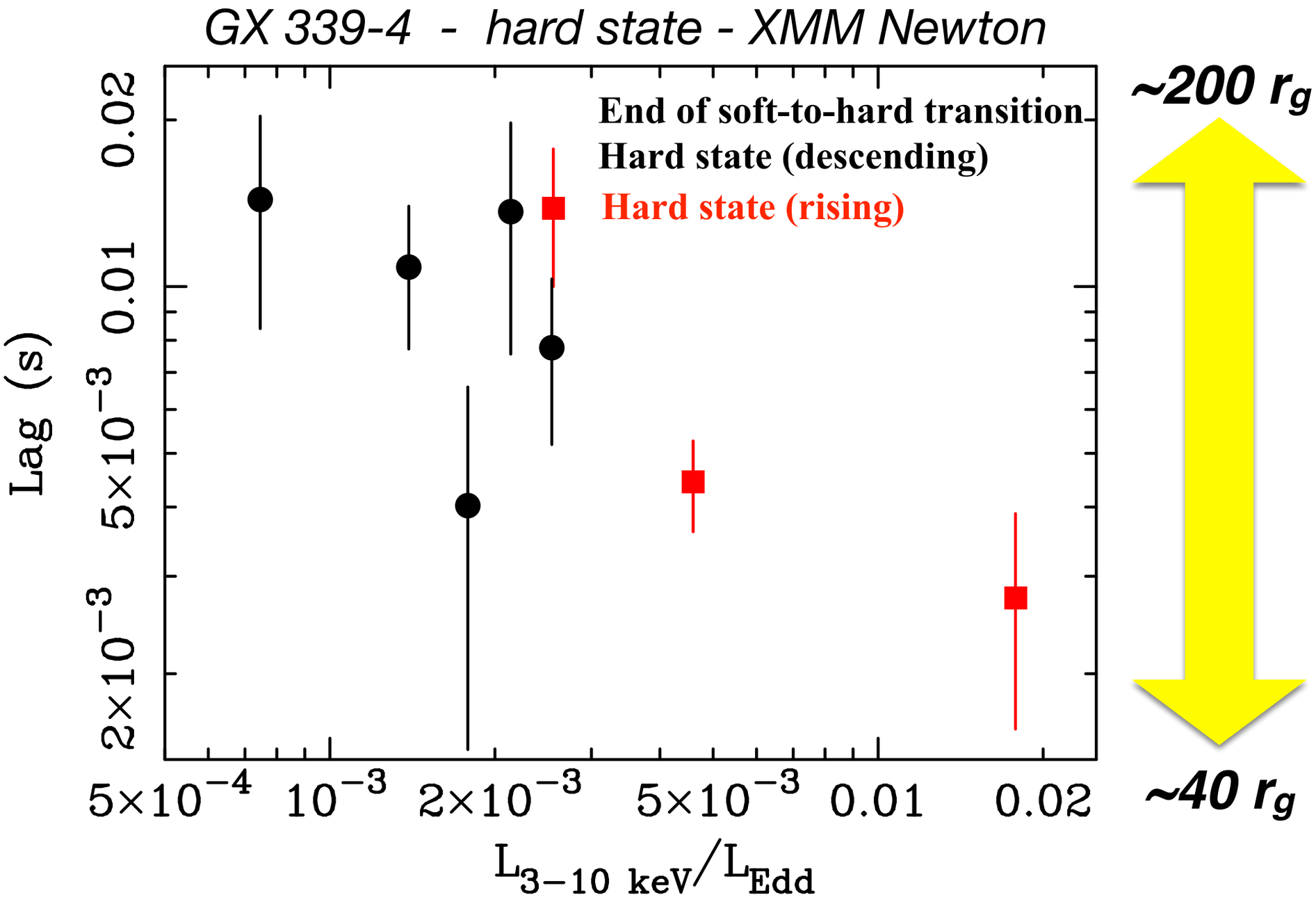
Variable coronal geometry disc at the ISCO

The amplitude of the lag



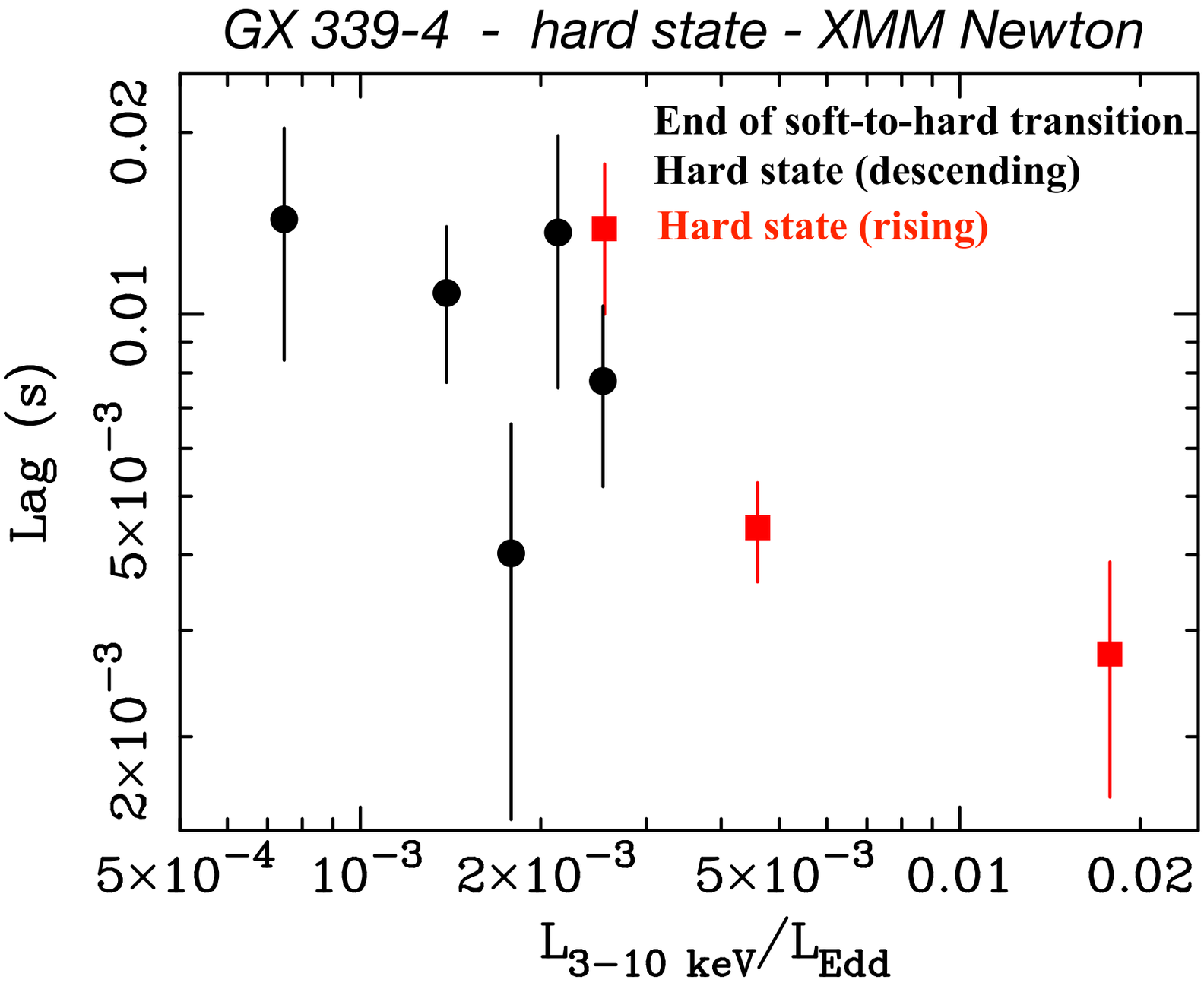
[De Marco+'17, '15, '16]

The amplitude of the lag



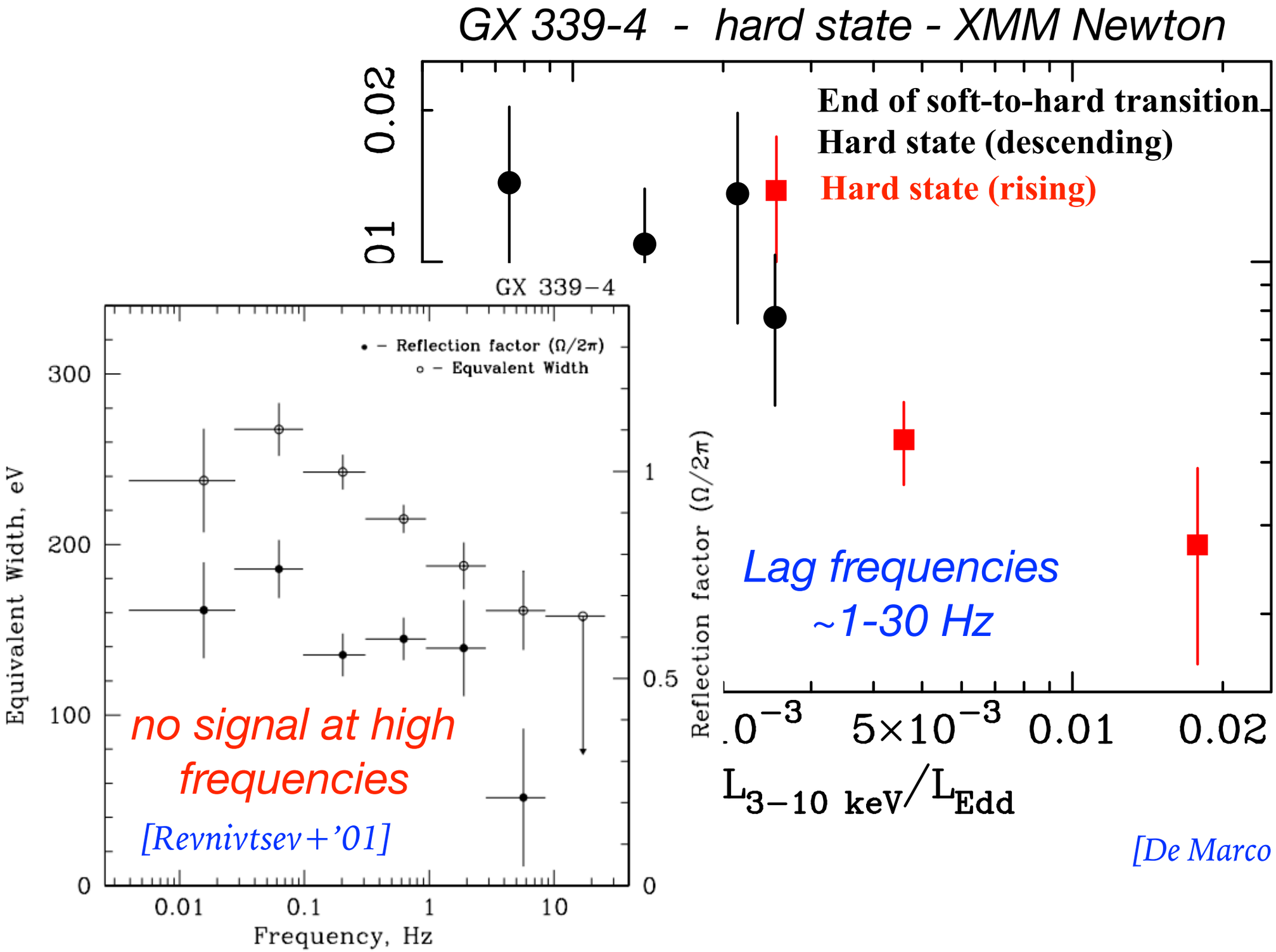
[De Marco+'17, '15, '16]

Probing the highest frequencies



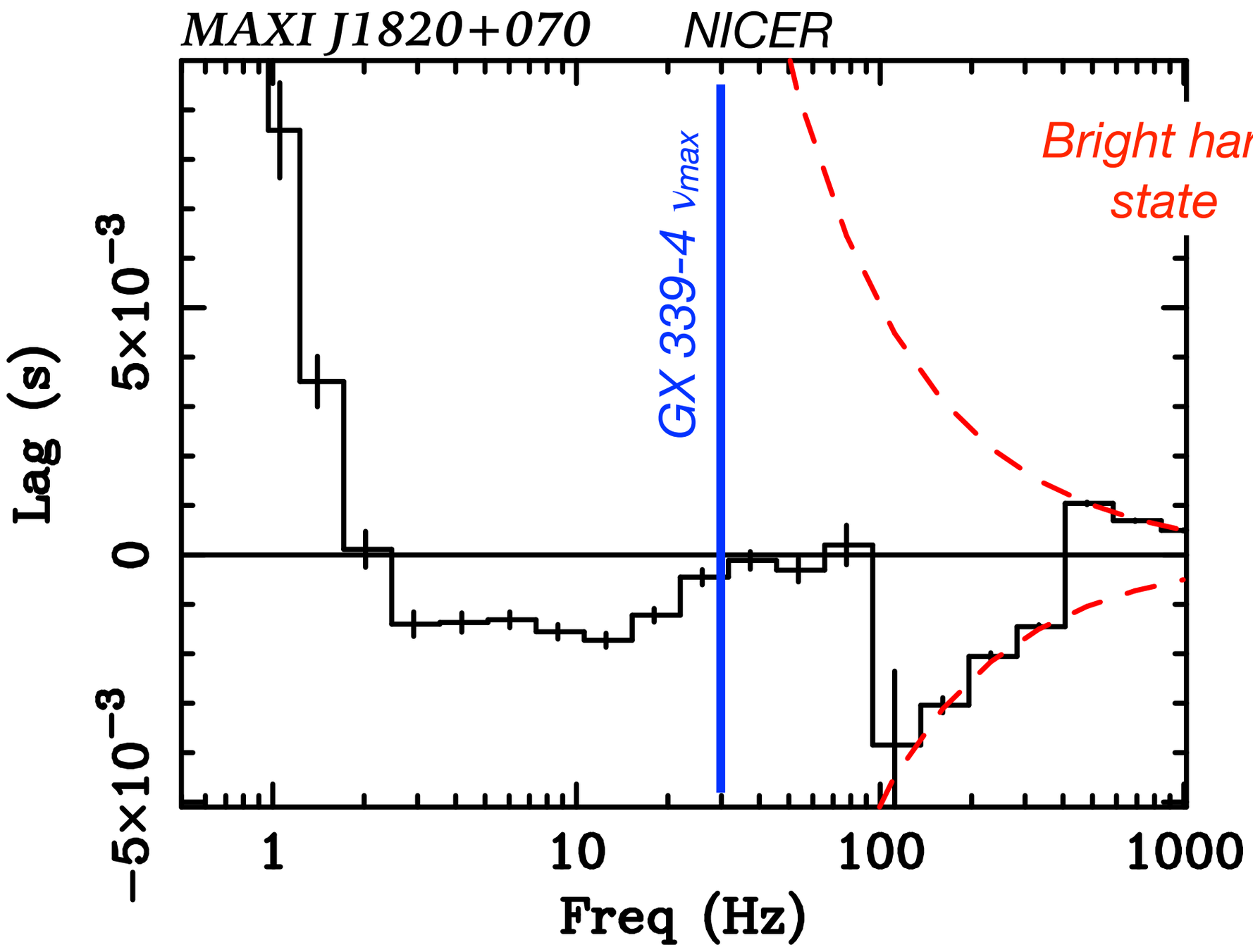
[De Marco+'17, '15, '16]

Probing the highest frequencies

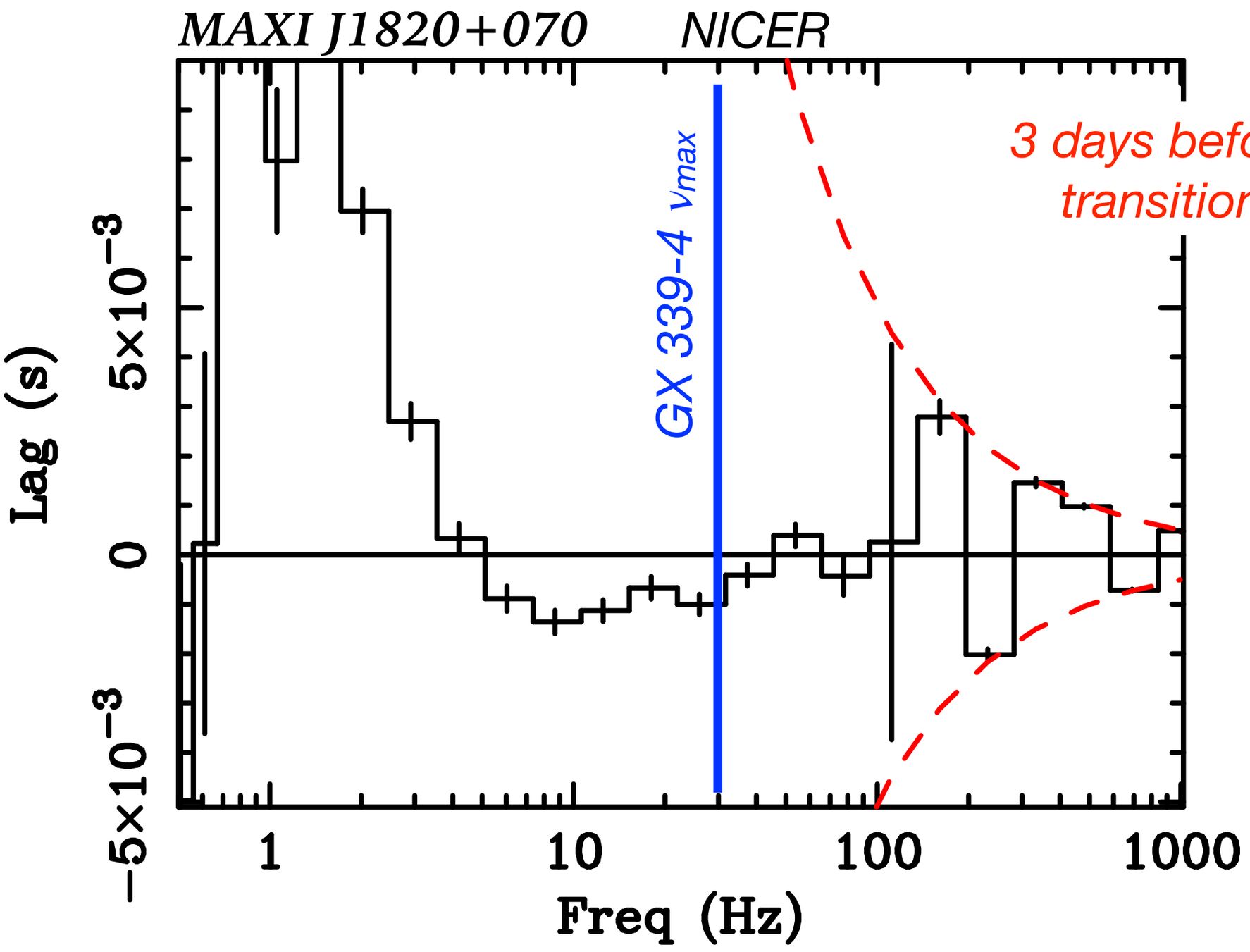


[De Marco+'17, '15, '16]

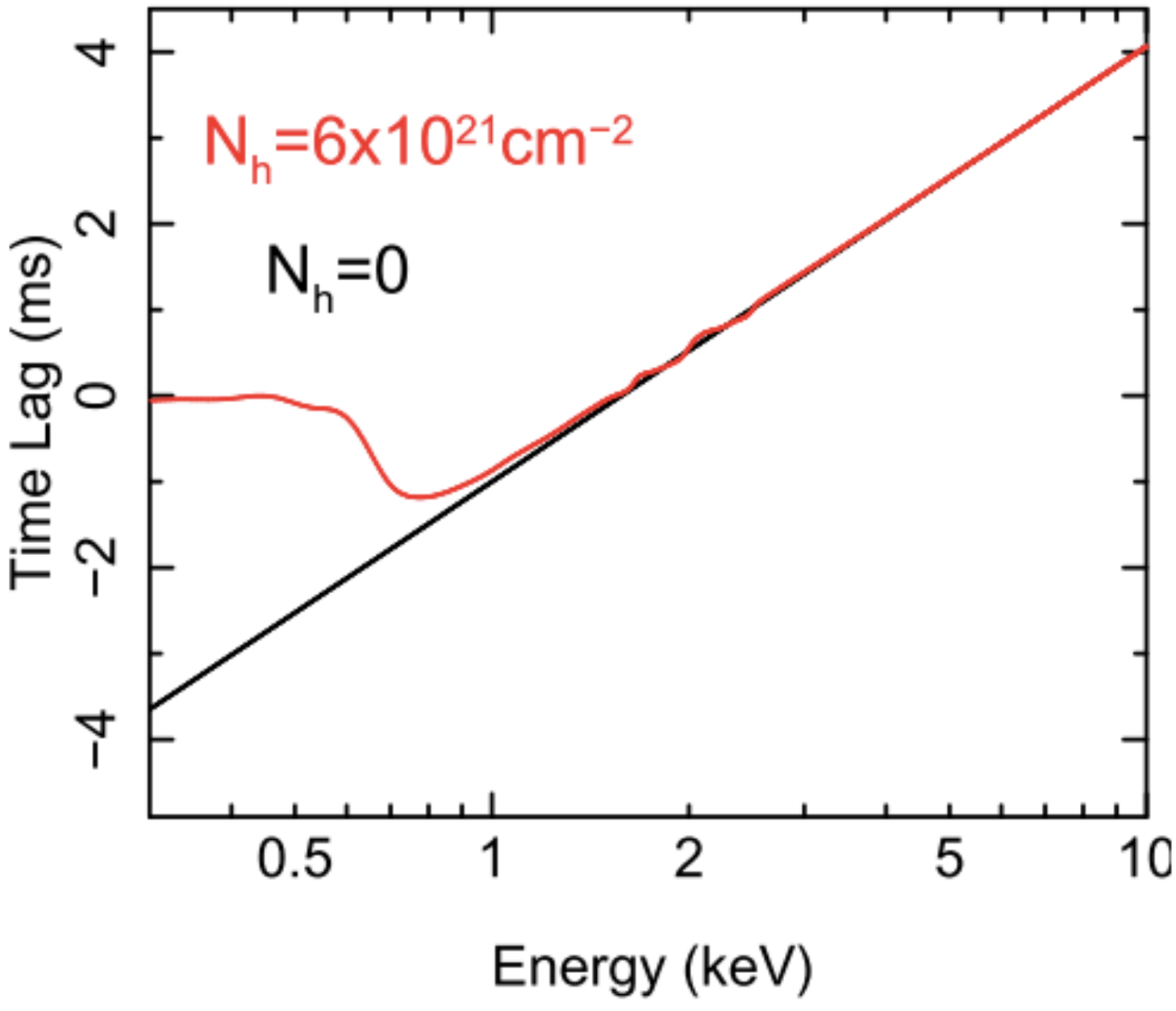
Probing the highest frequencies



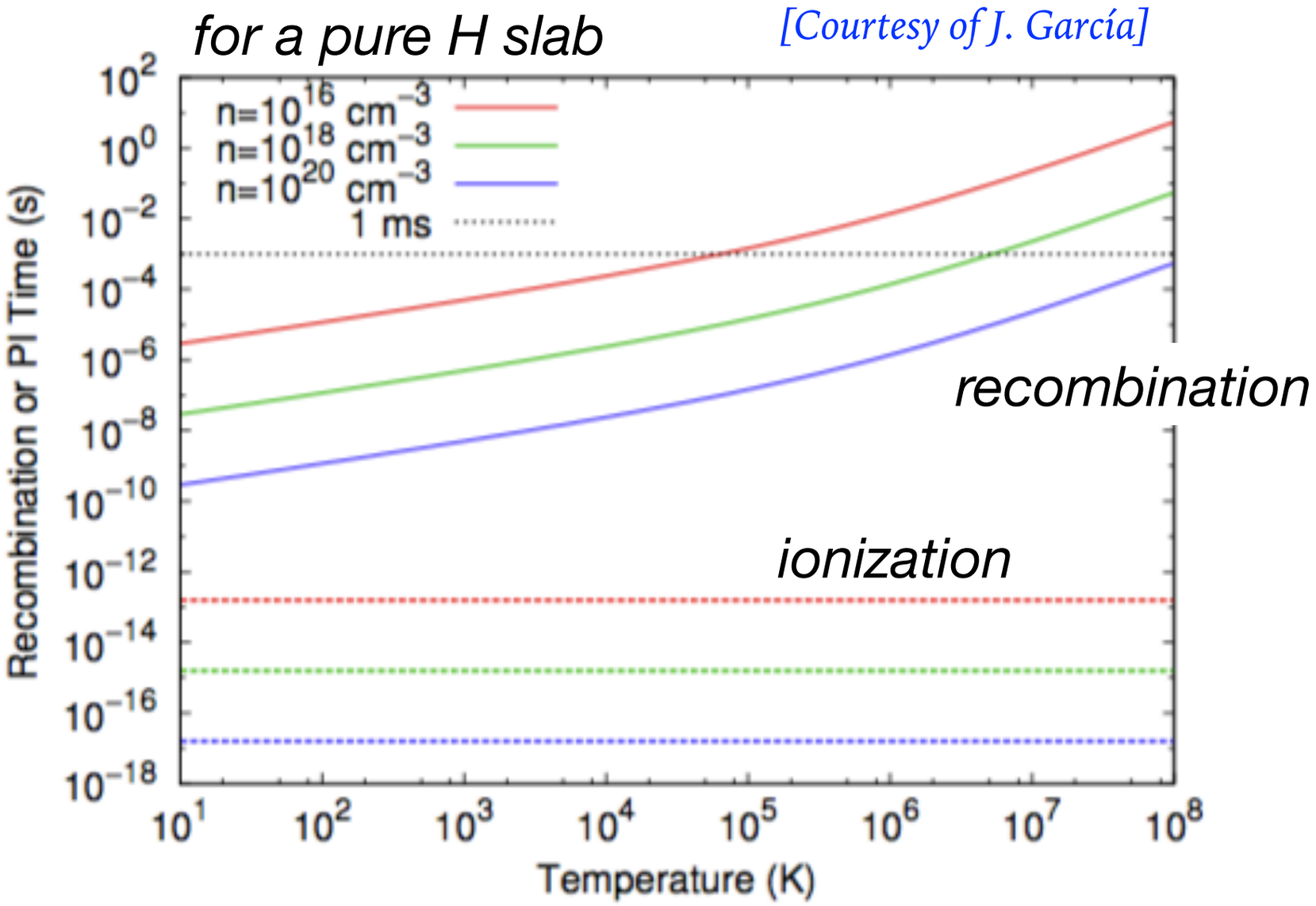
Probing the highest frequencies



Neglecting instrument response



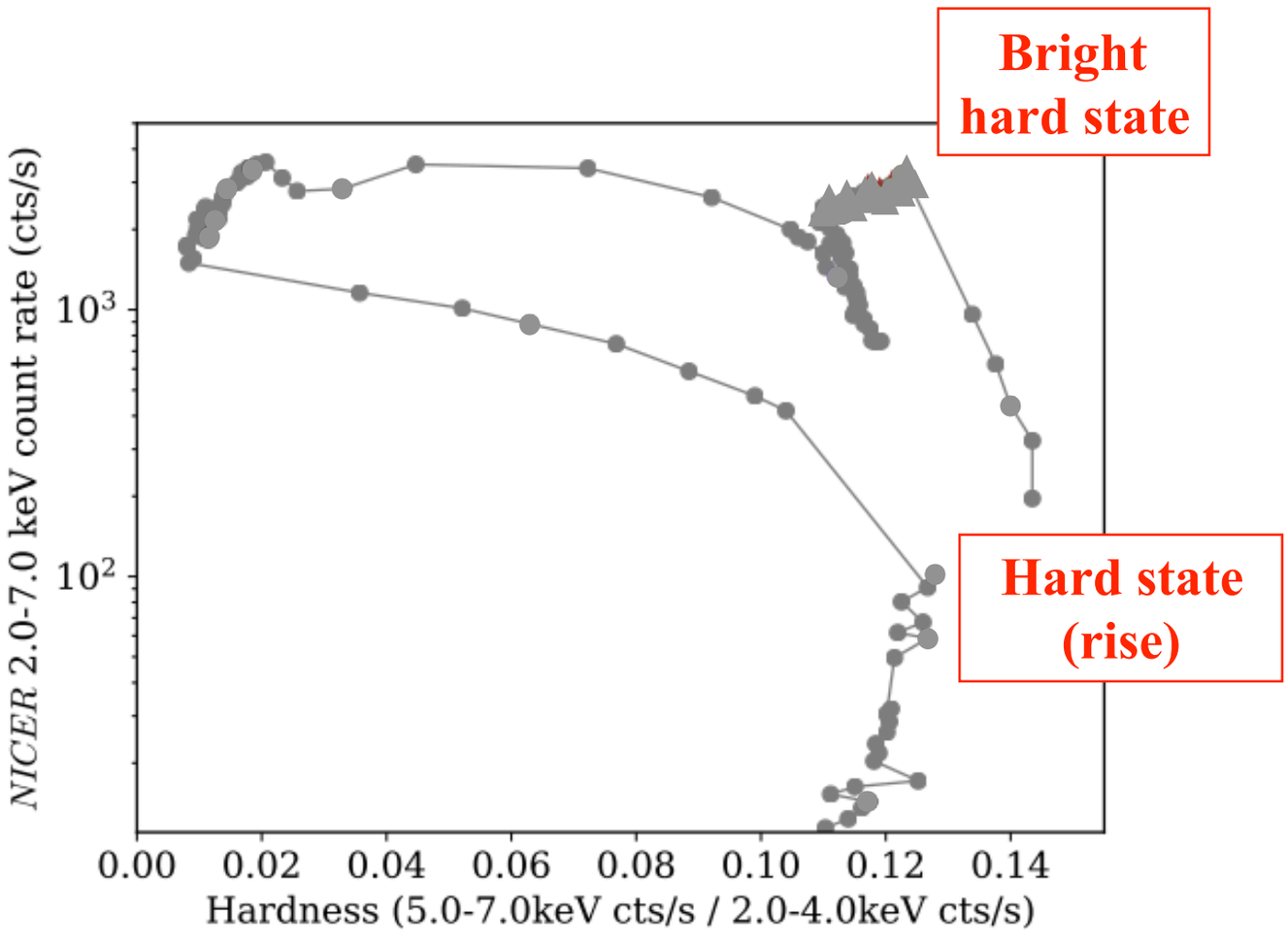
Reprocessing time scales

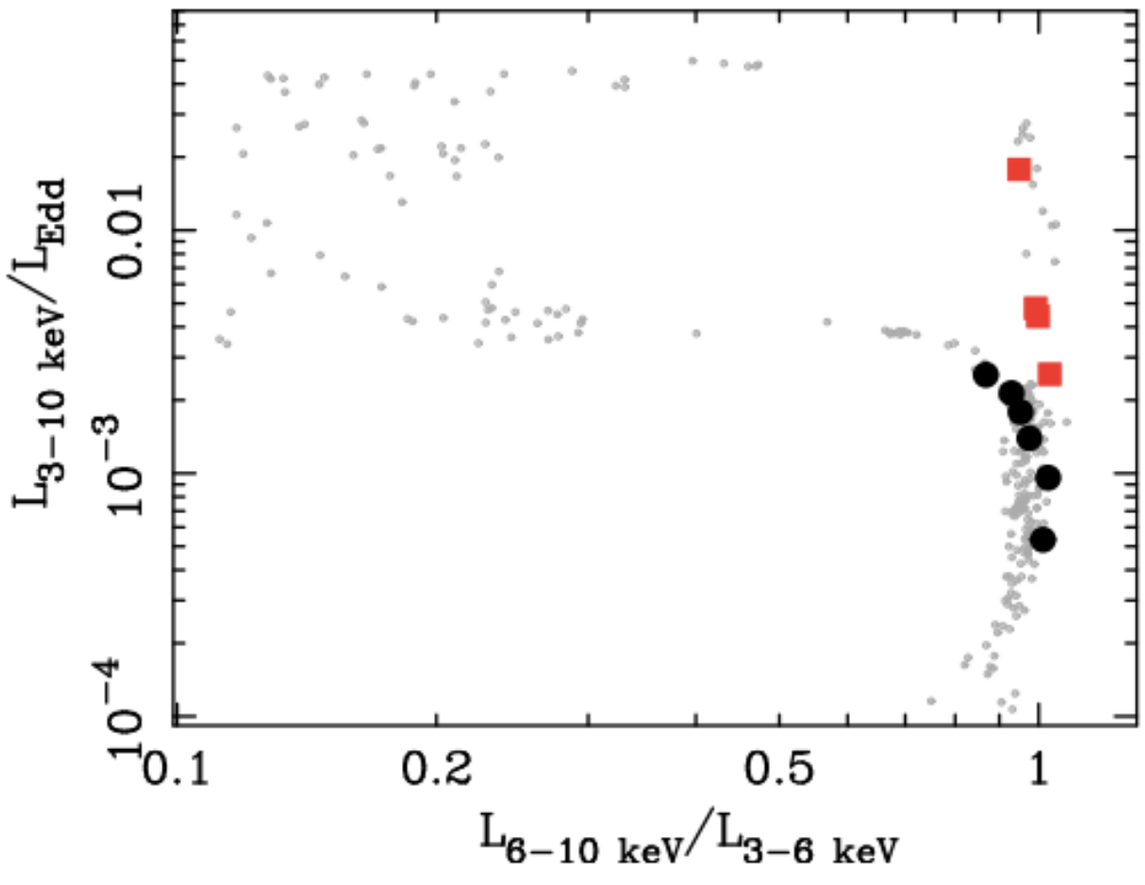


Depending on the density and temperature of the disc, recombination time scales can be of the order of ms

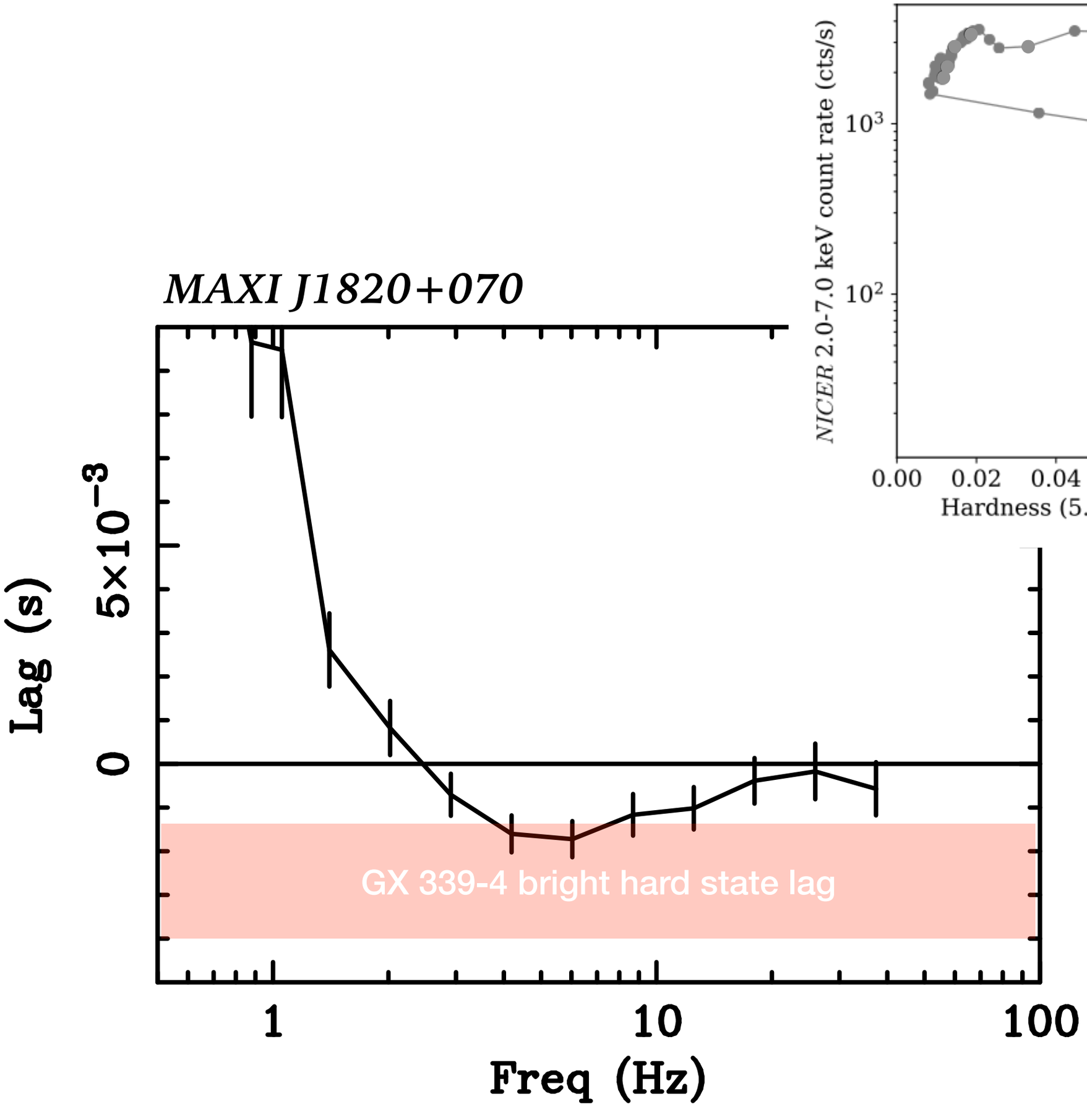
What about thermal reprocessing?

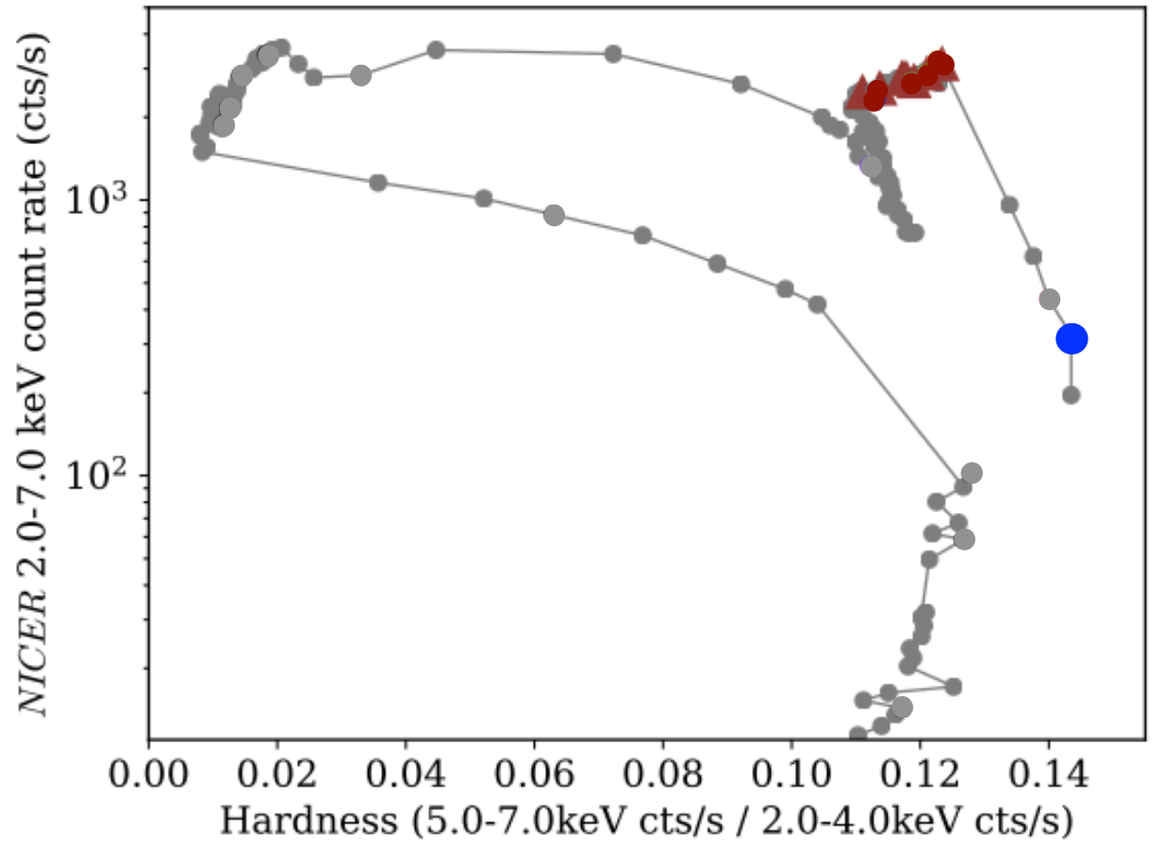
Comparison of lag amplitudes in MAXI J1820+070 and GX 339-4



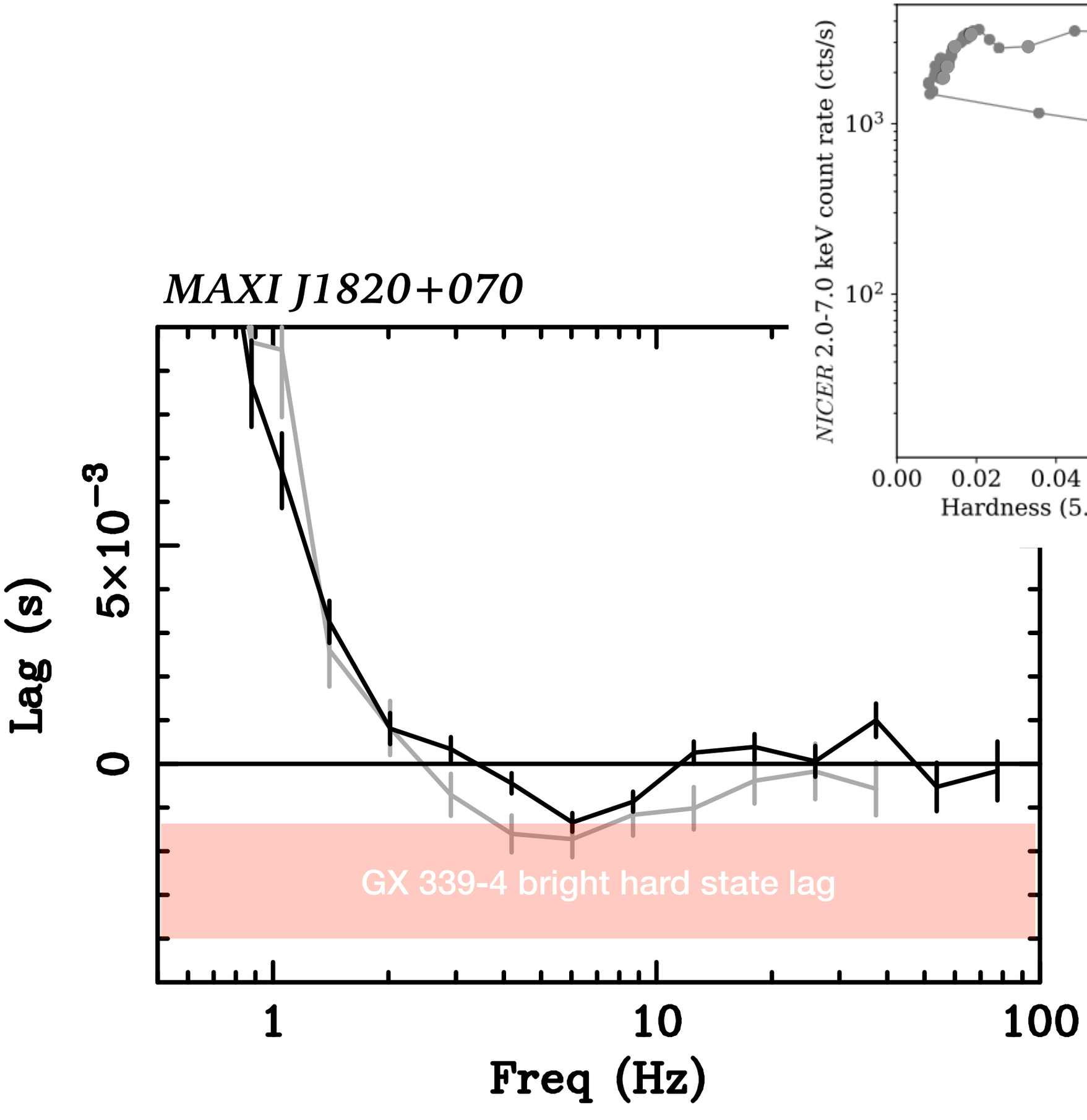


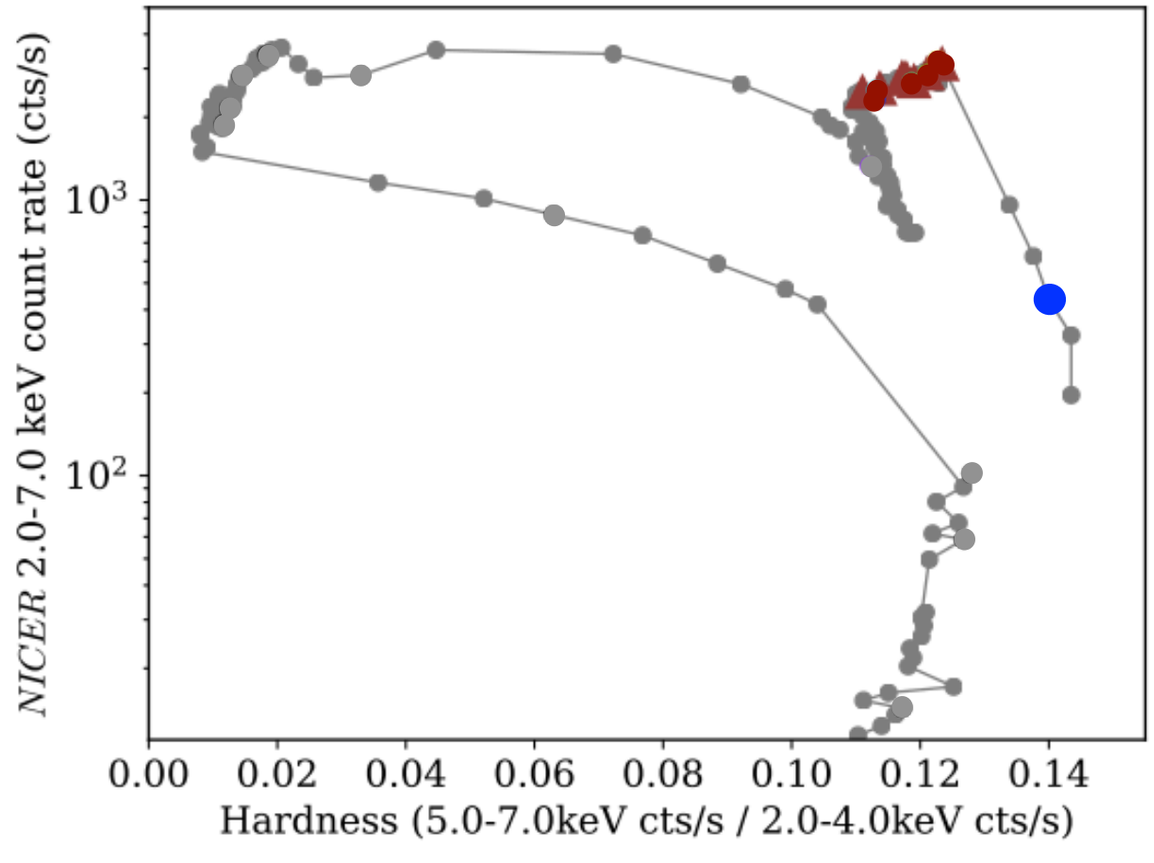
Hard state rise



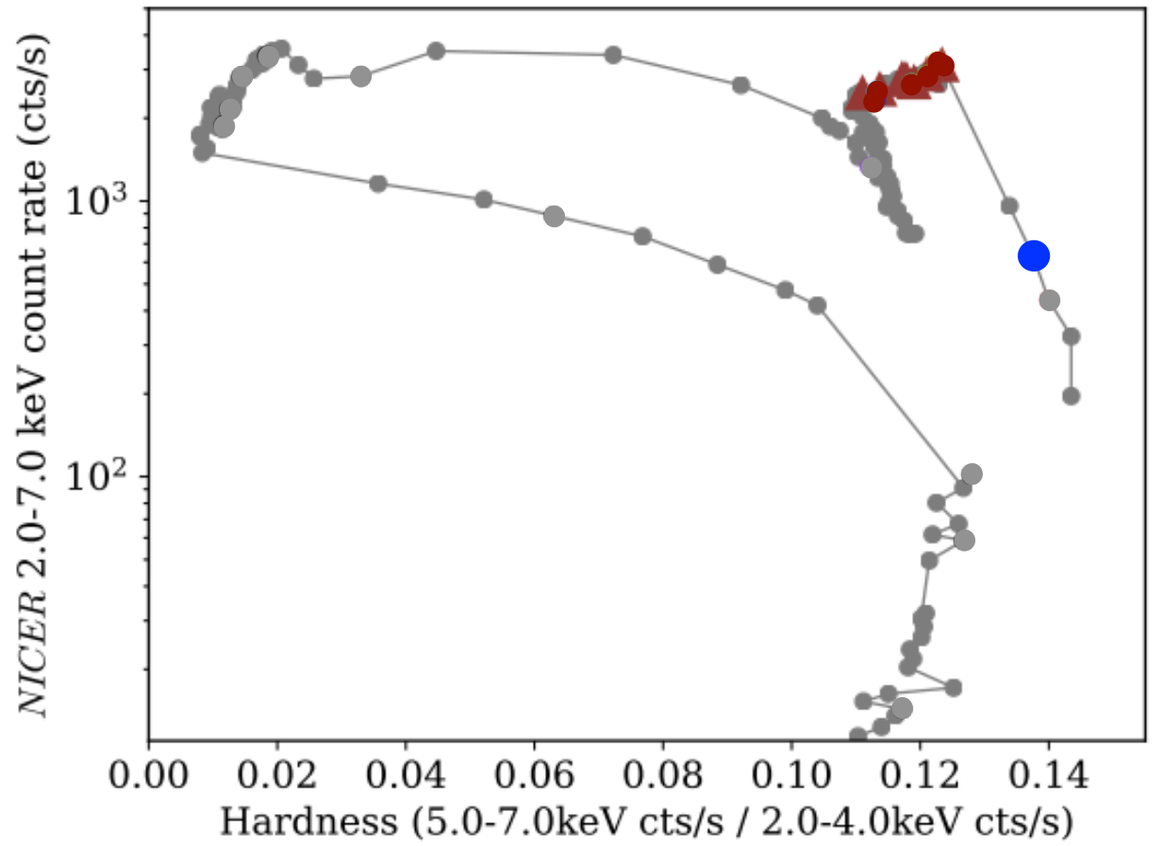


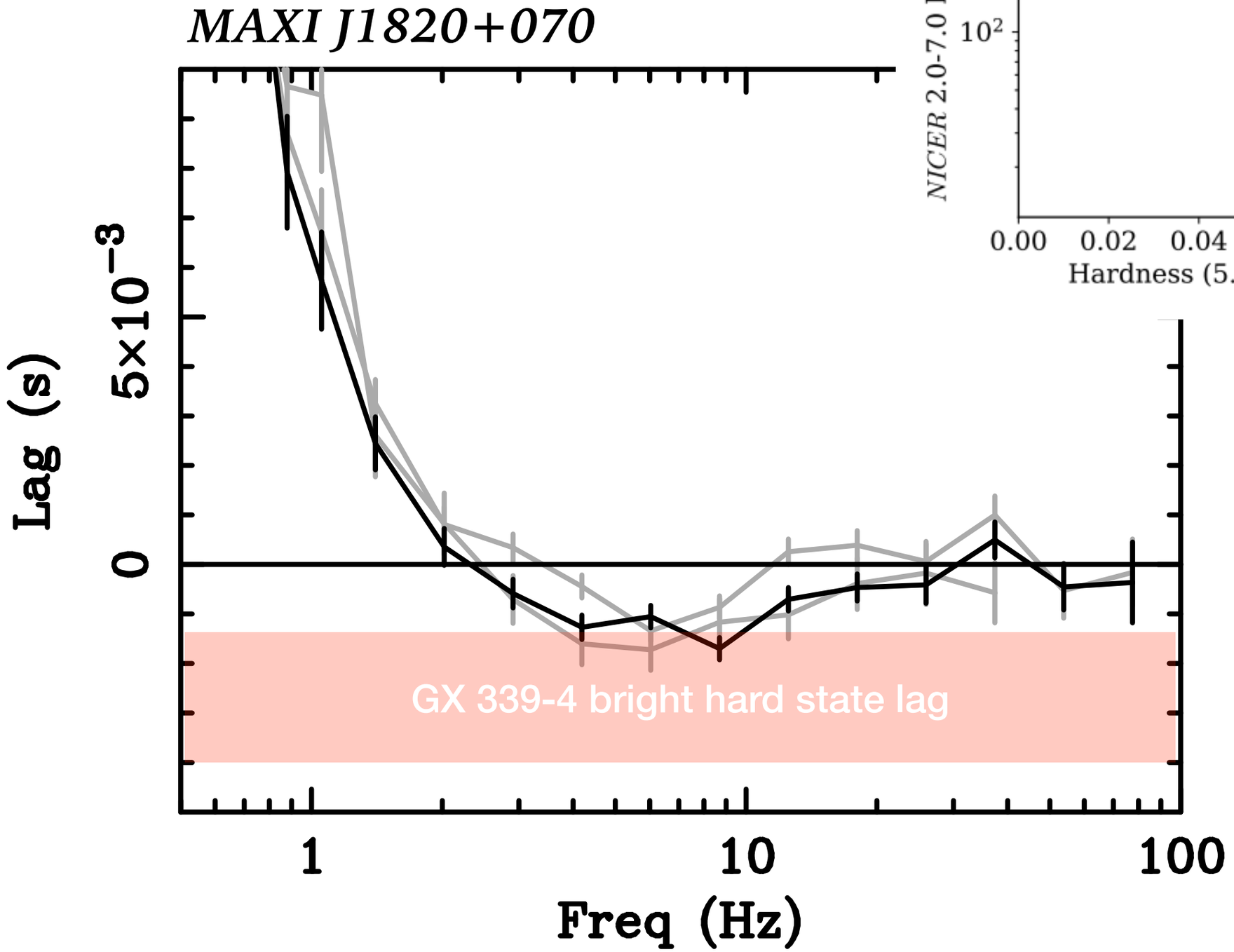
Hard state rise



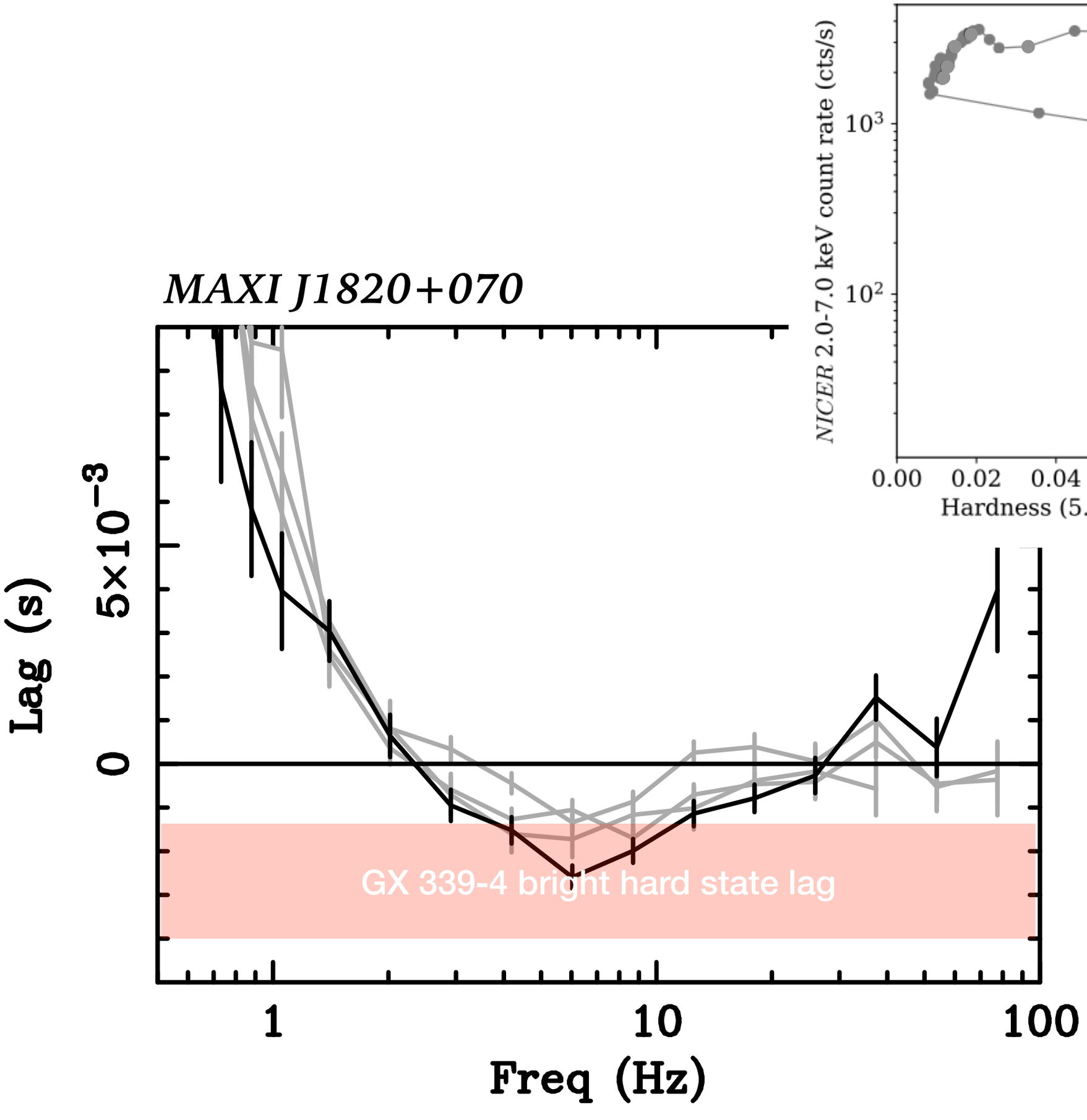


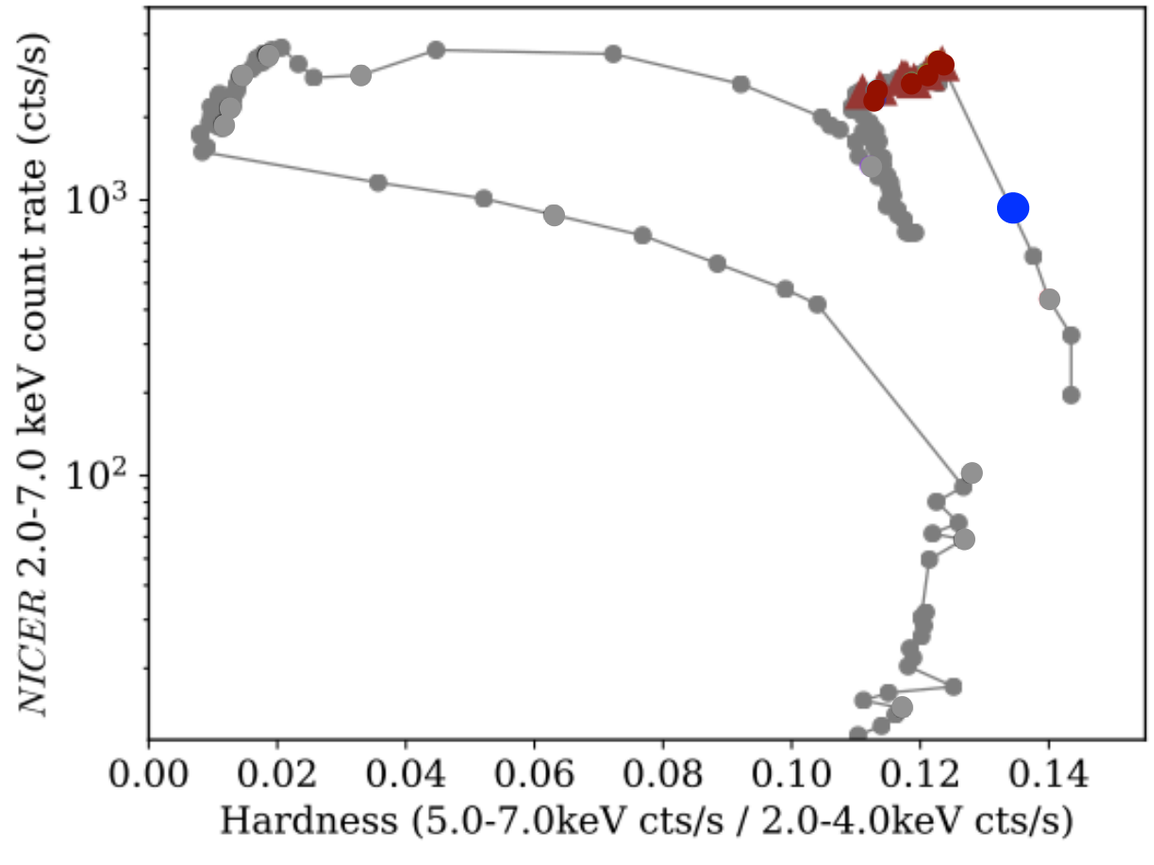
Hard state rise



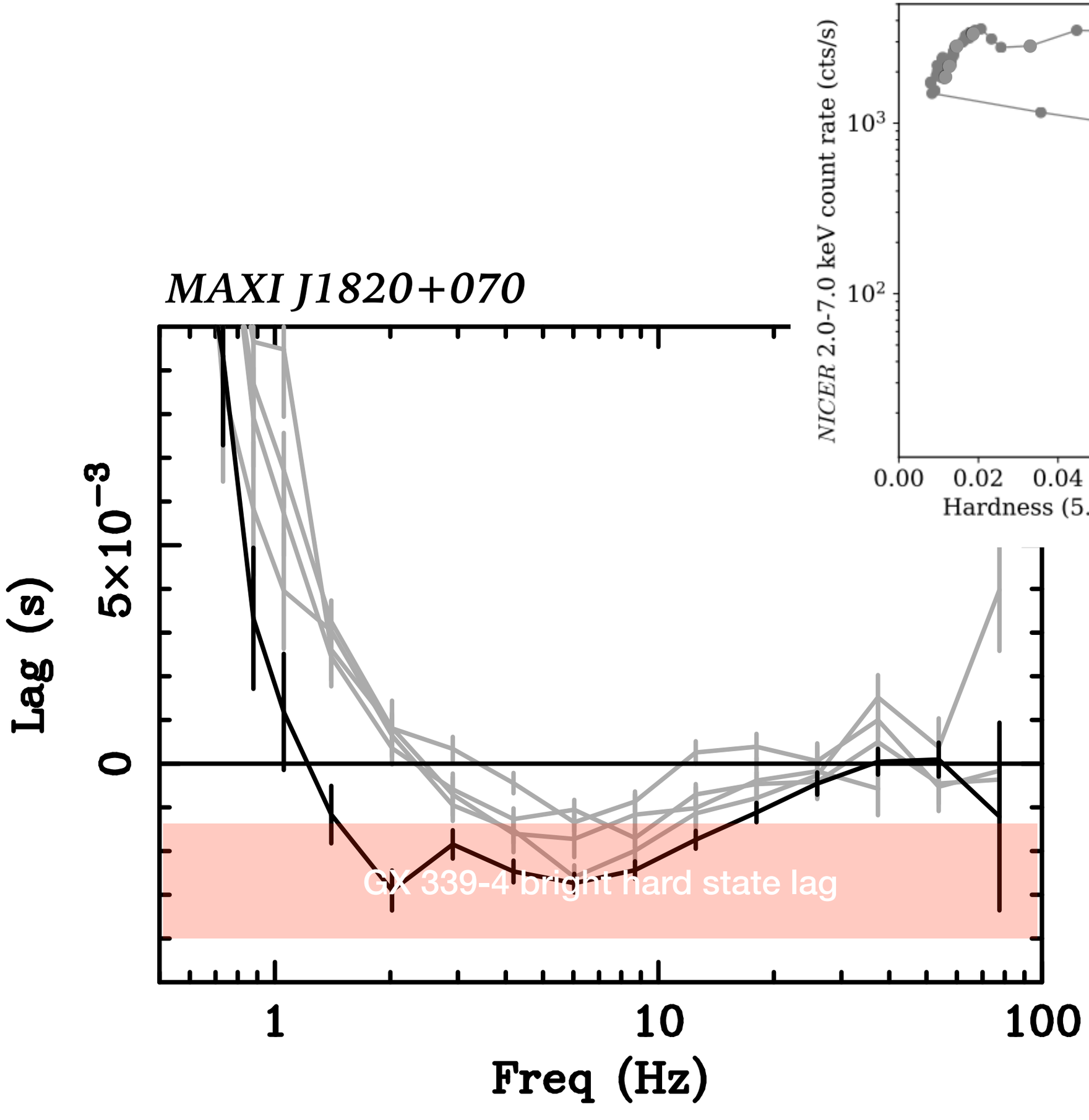


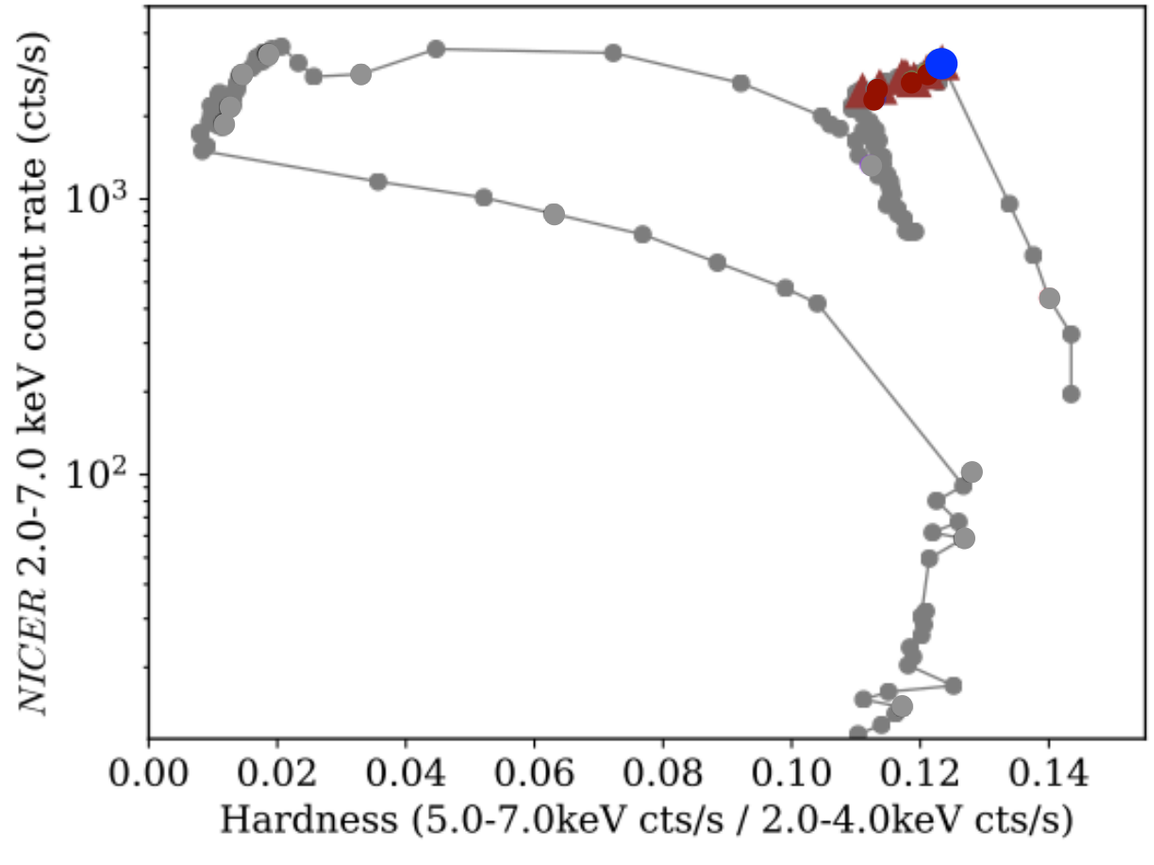
Hard state rise



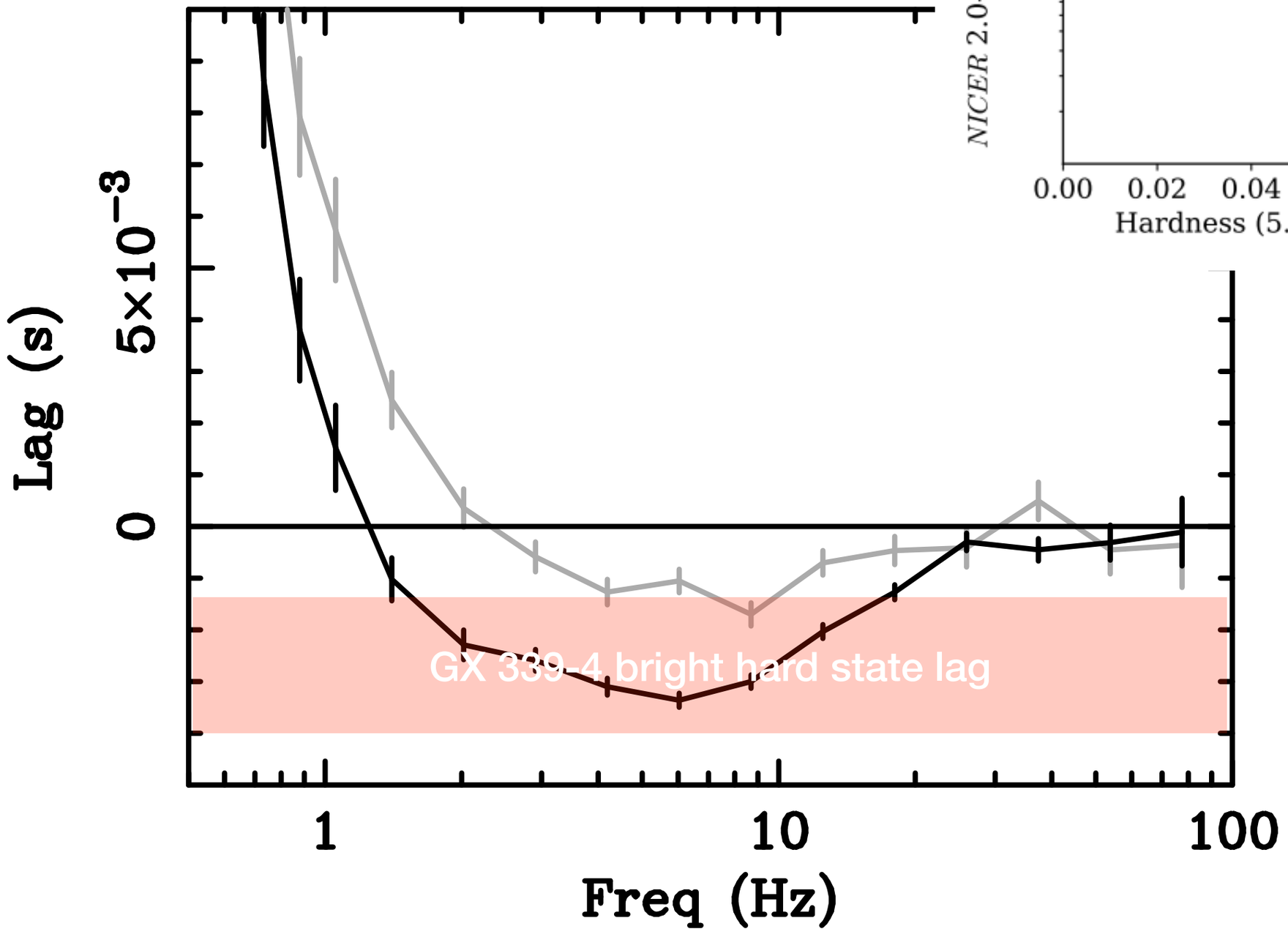


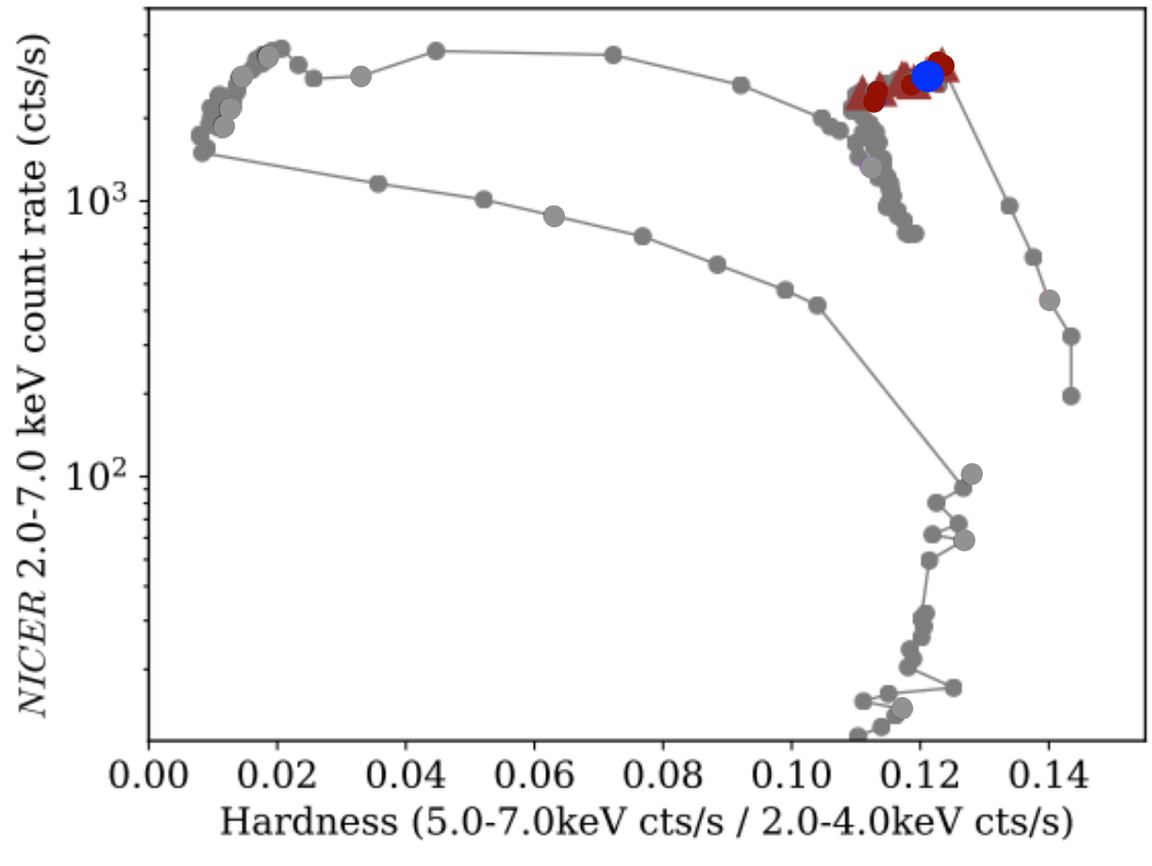
Hard state rise



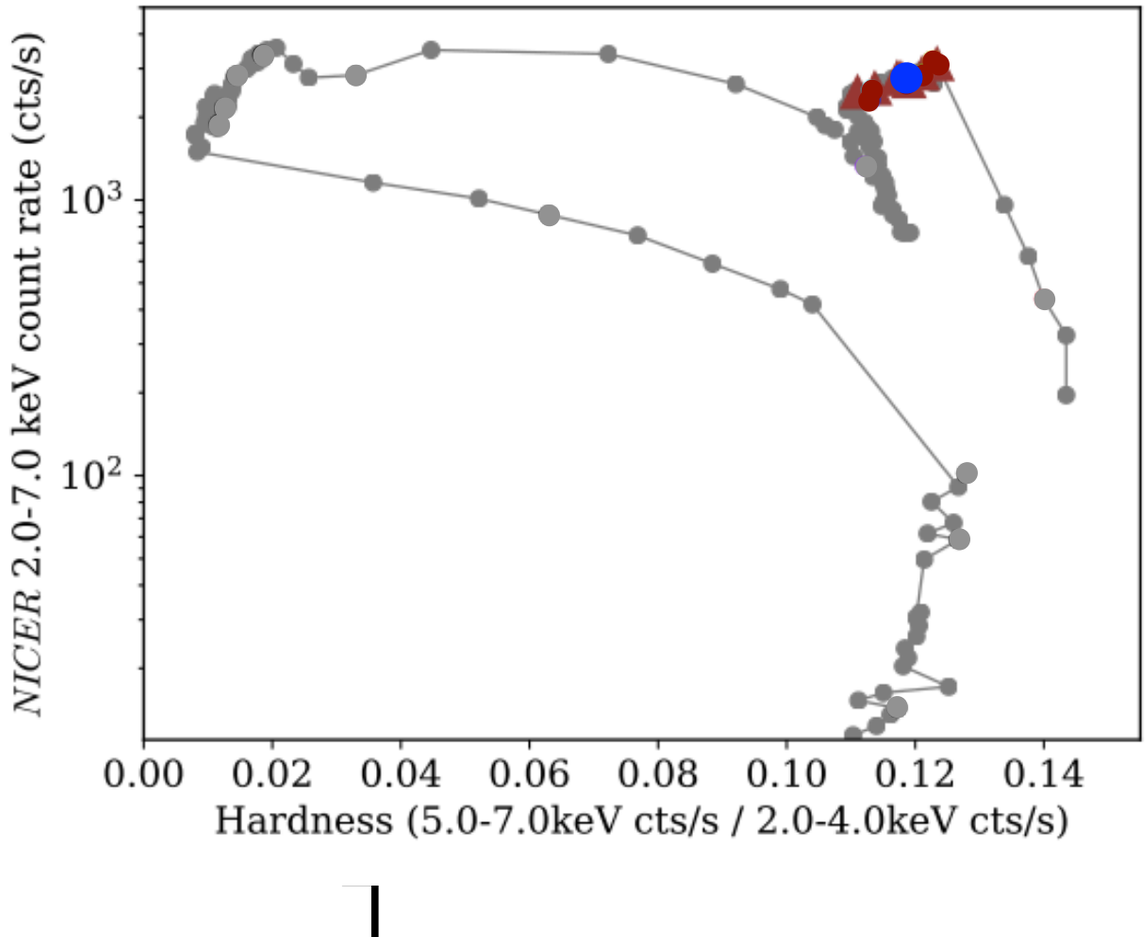


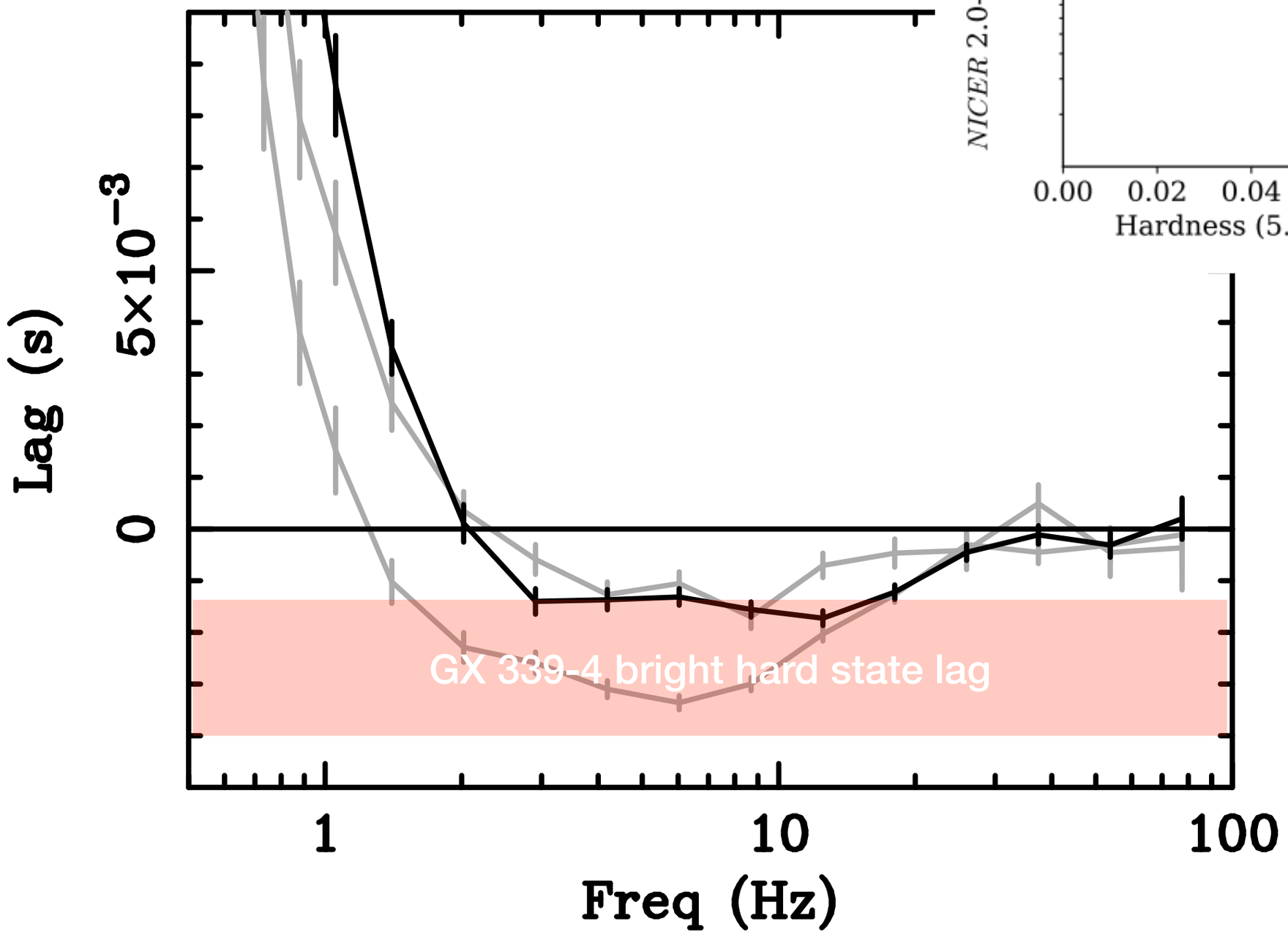
Bright hard state



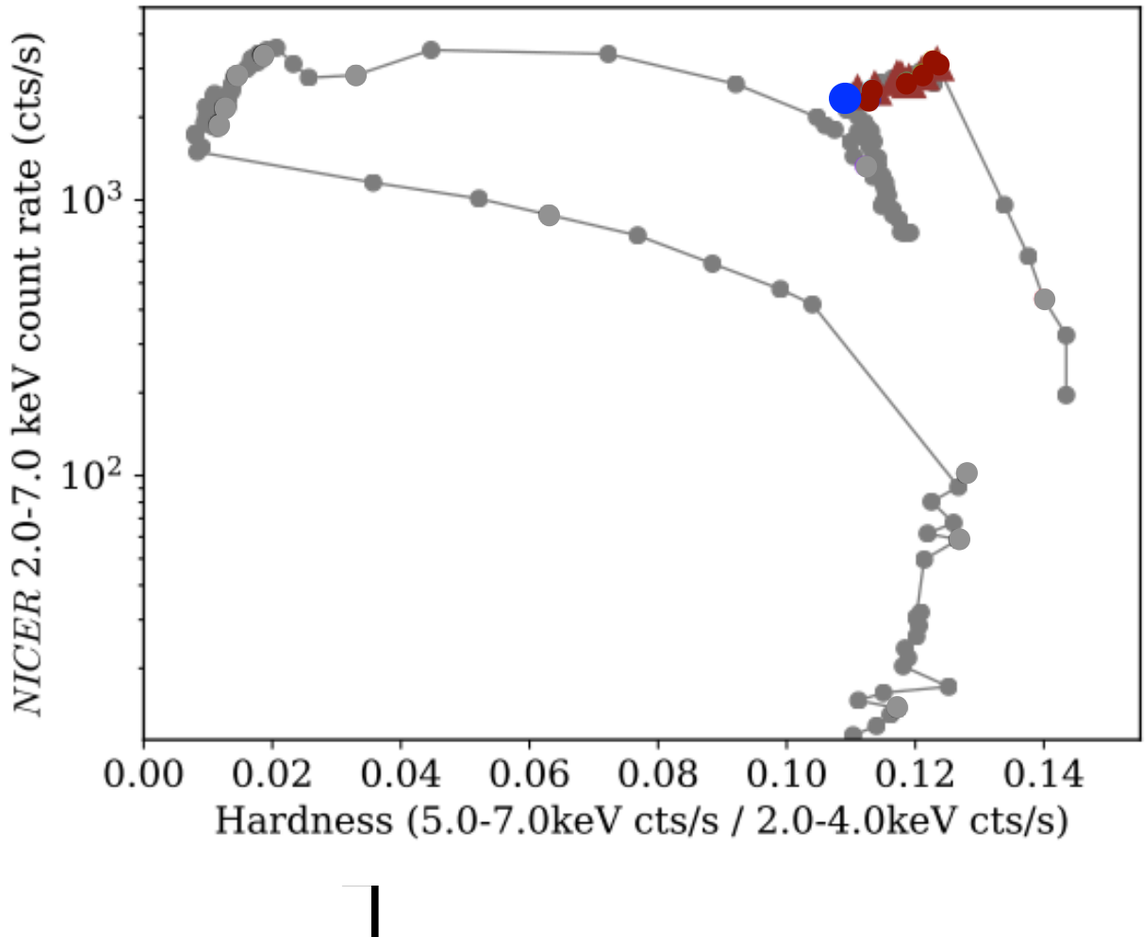


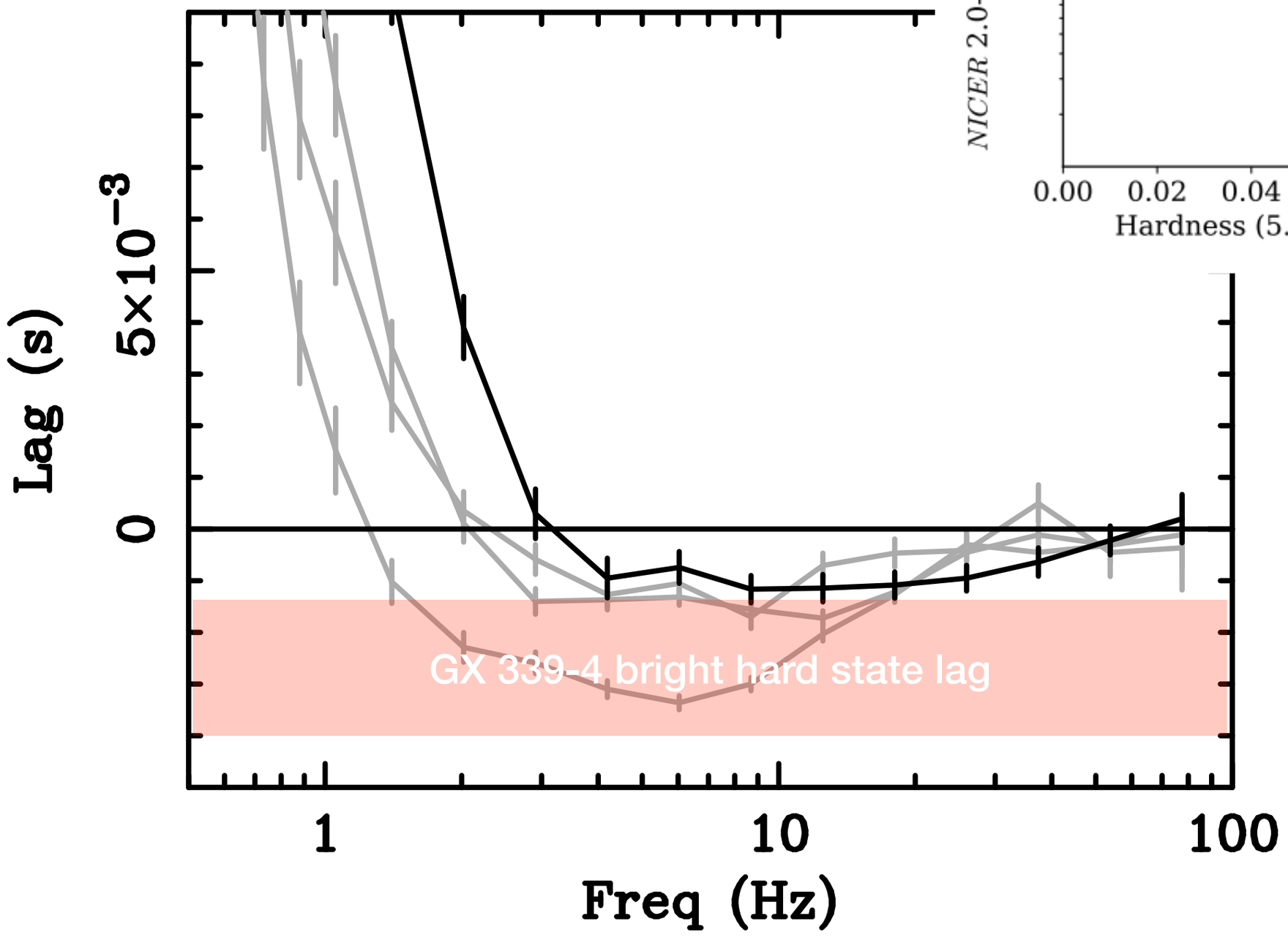
Bright hard state



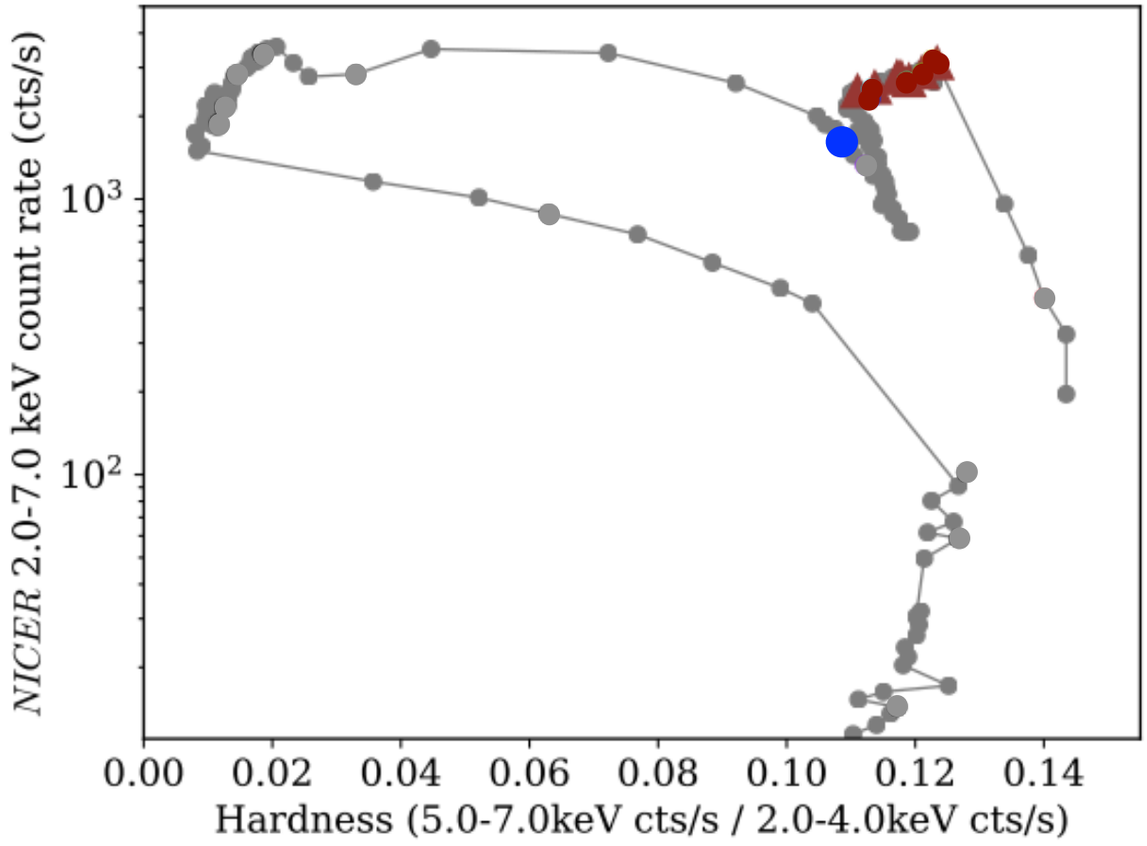


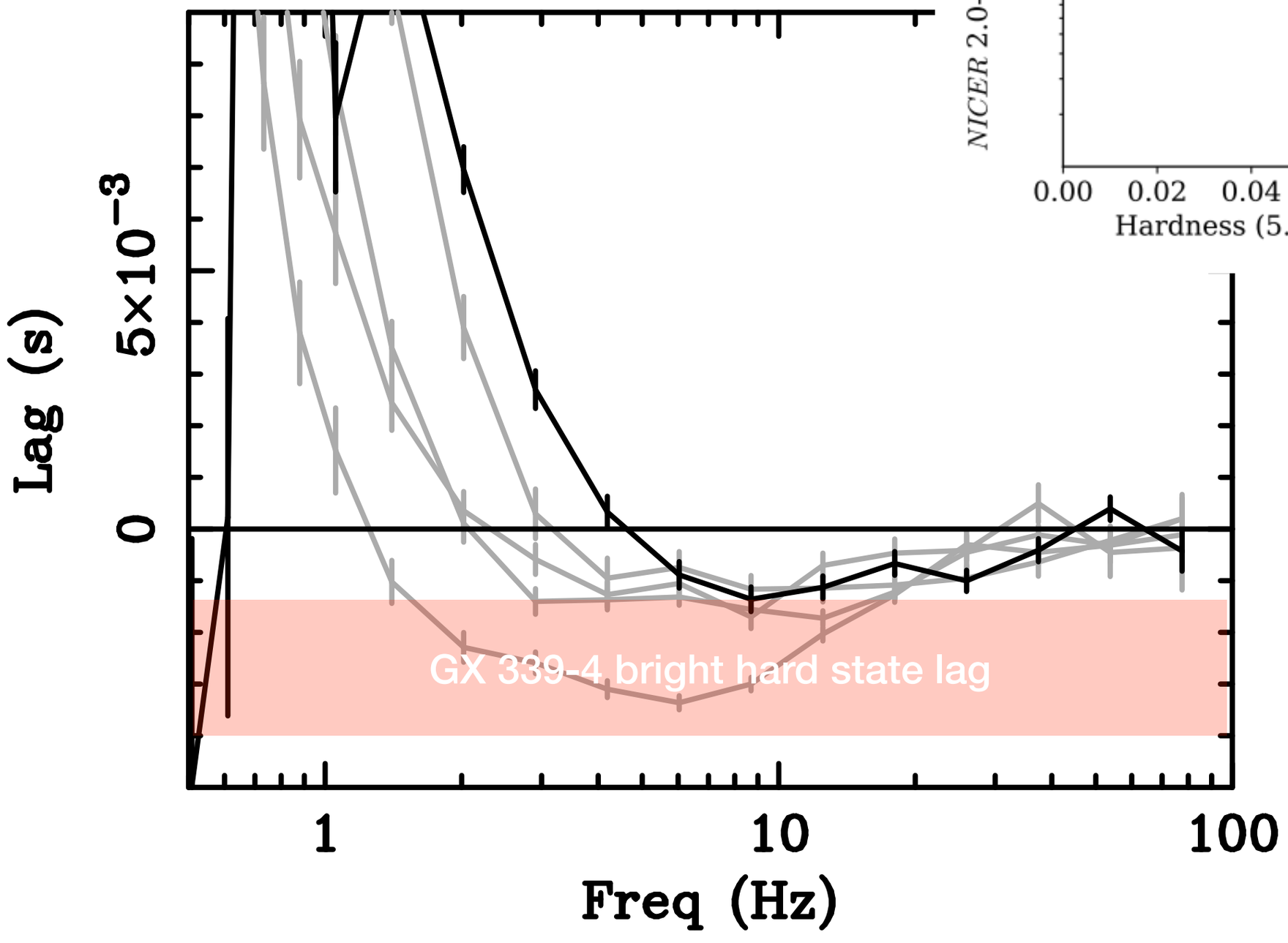
Bright hard state



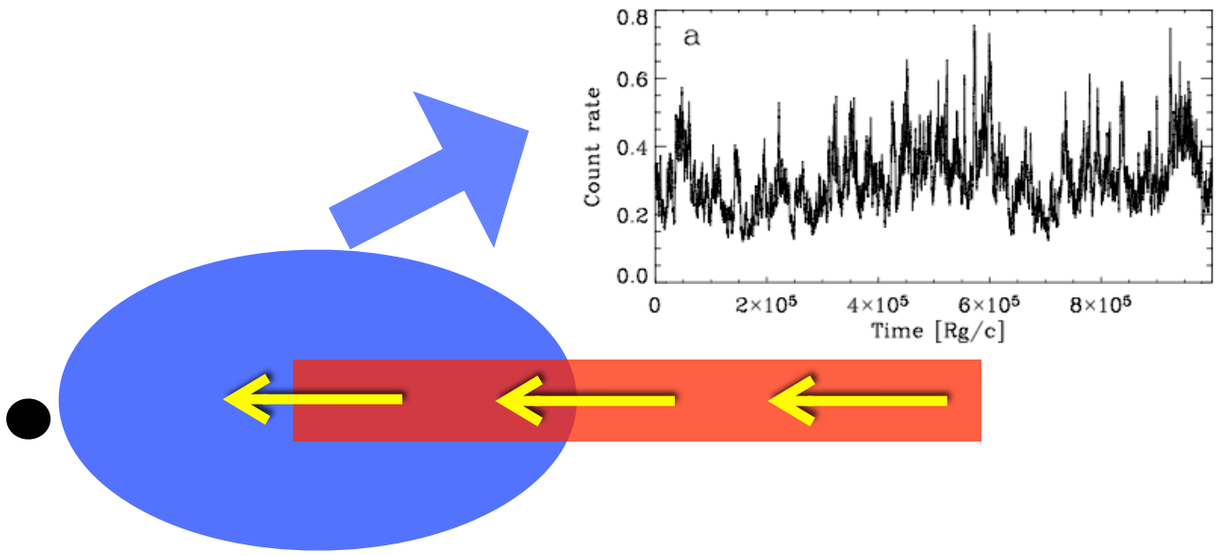


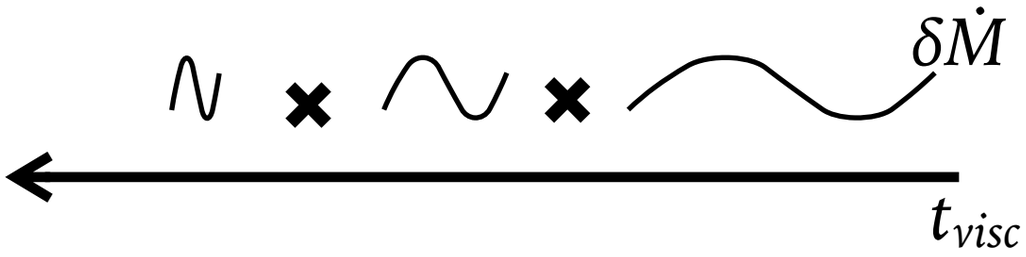
3 days before transition



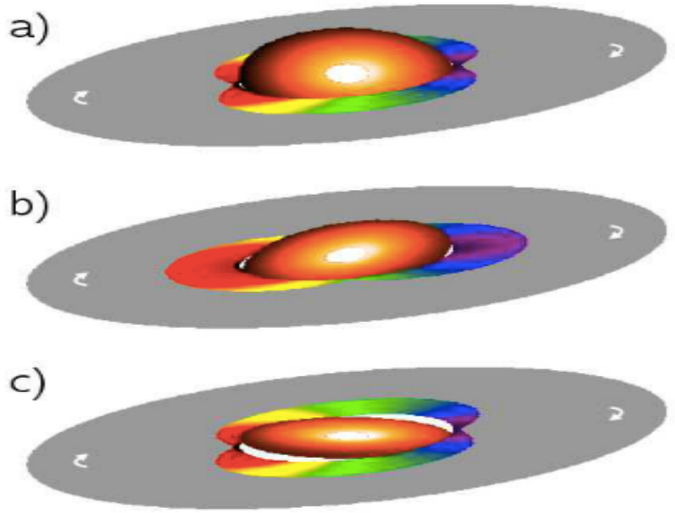


Self-consistent spectral-timing modelling

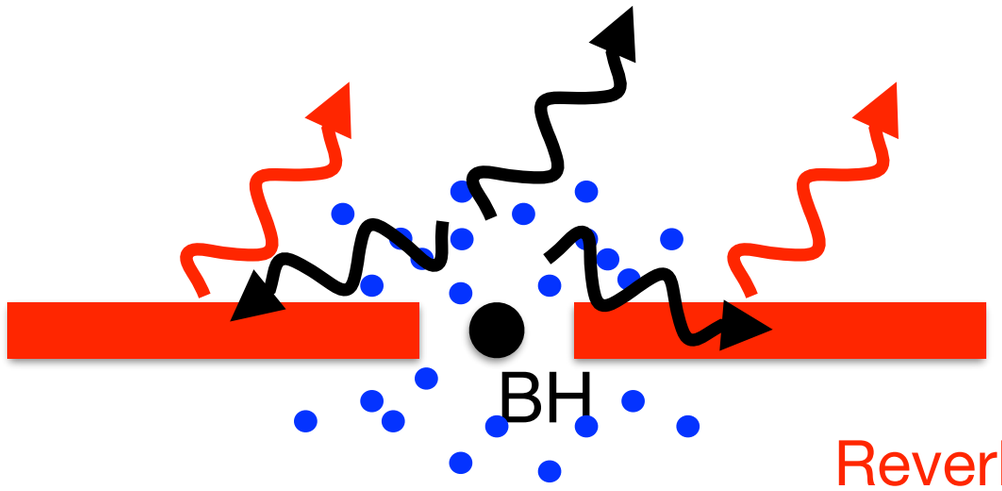




Propagating perturbations



Lense-Thirring precession



Reverberation

Spectral-timing models

Propagating $\dot{M}$ fluctuations (through the disc and the hot flow) and relativistic precession - PROPFLUC

[Ingram & Done '11,'12; Ingram & van der Klis '13; Rapisarda +'14; '16; '17a; '17b]

✓ *Propagating $\dot{M}$ fluctuations (through the inner disc and the hot flow), relativistic precession and reverberation*

[Mahmoud & Done '17,'18, Mahmoud, Done & De Marco '19]

Spectral pivoting and reverberation (plus proper treatment of instrumental response!) - RELTRANS

[Ingram + '19; Mastroserio+'18; '19; Uttley & Malzac in prep.]

Small truncation in hard state of Cyg X-1

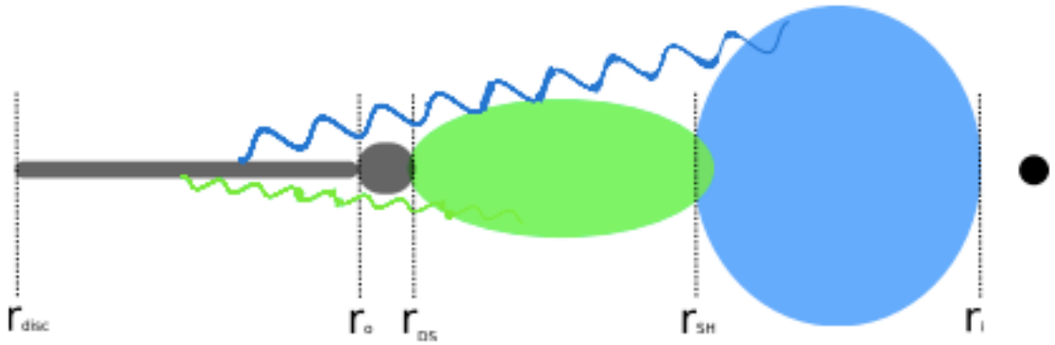
Interference between two comptonization continua (associated with different seed photons)

[Veledina '16; '18]

Spectral-timing fits

Spectrally inhomogeneous comptonizing region

[Mahmoud +'17,'18,'19]



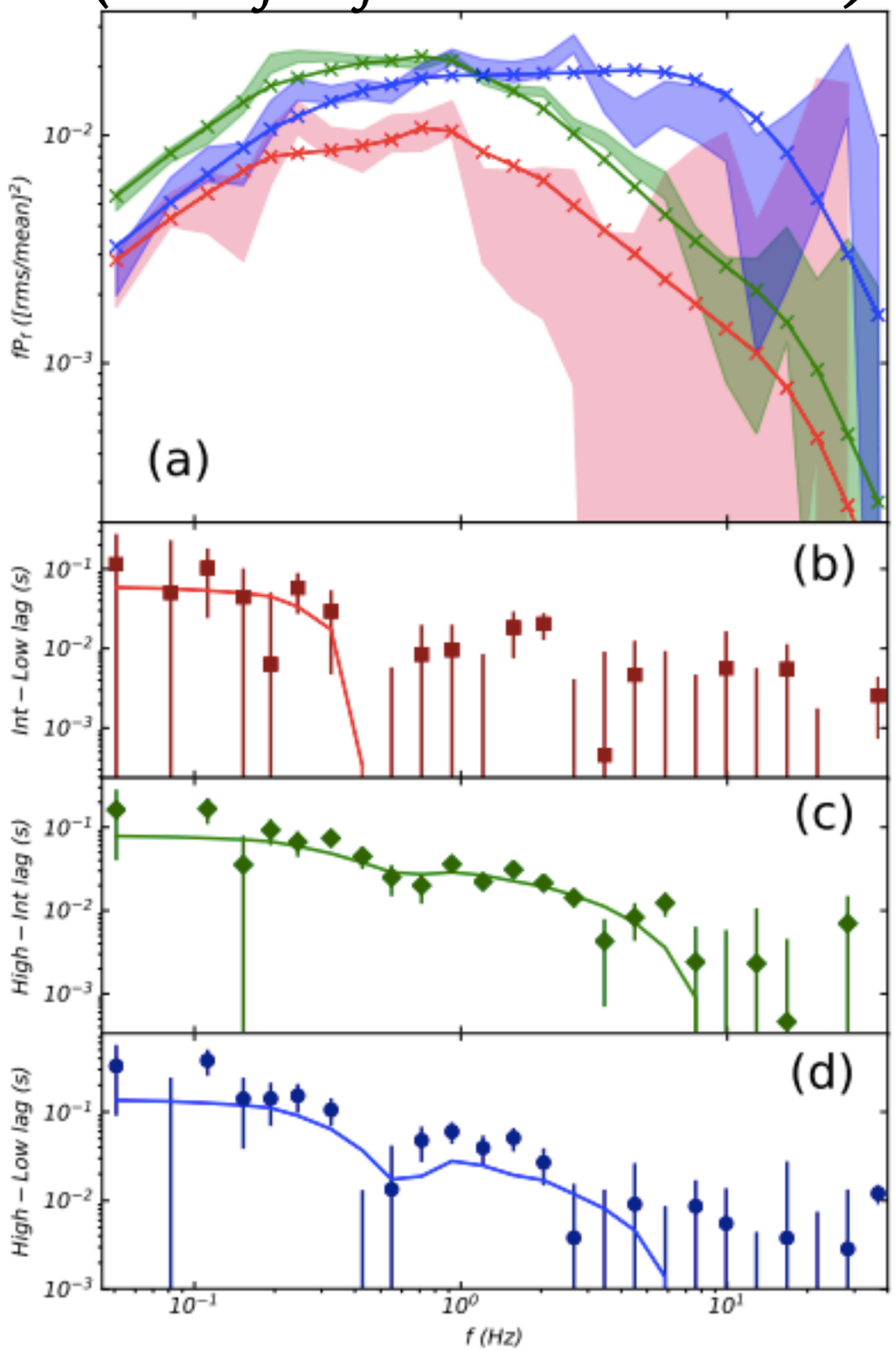
Comptonization regions

Unstable disc

Stable disc (reflecting/ reprocessing region)

GX 339-4

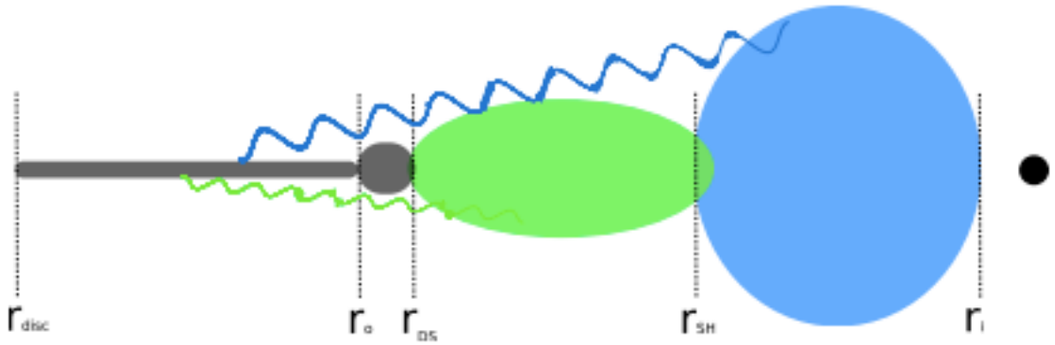
(end of soft-hard transition)



Spectral-timing fits

Spectrally inhomogeneous comptonizing region

[Mahmoud +'17,'18,'19]

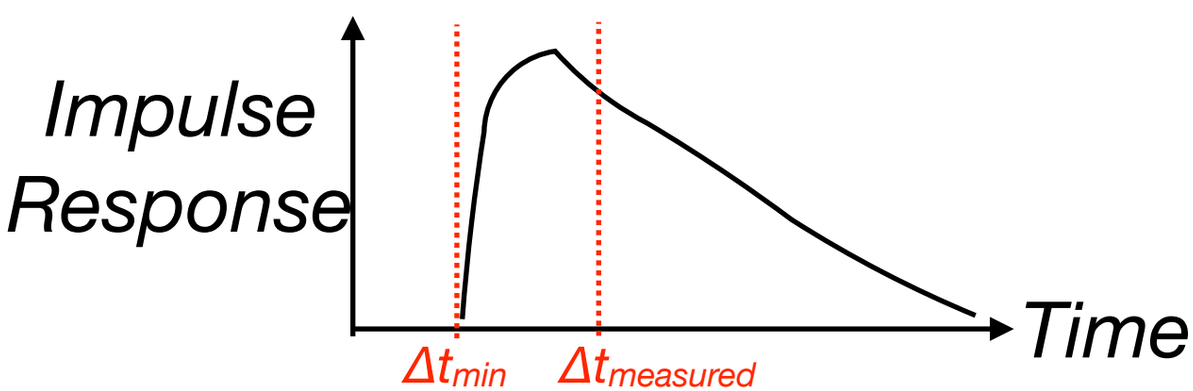


Comptonization regions

Unstable disc

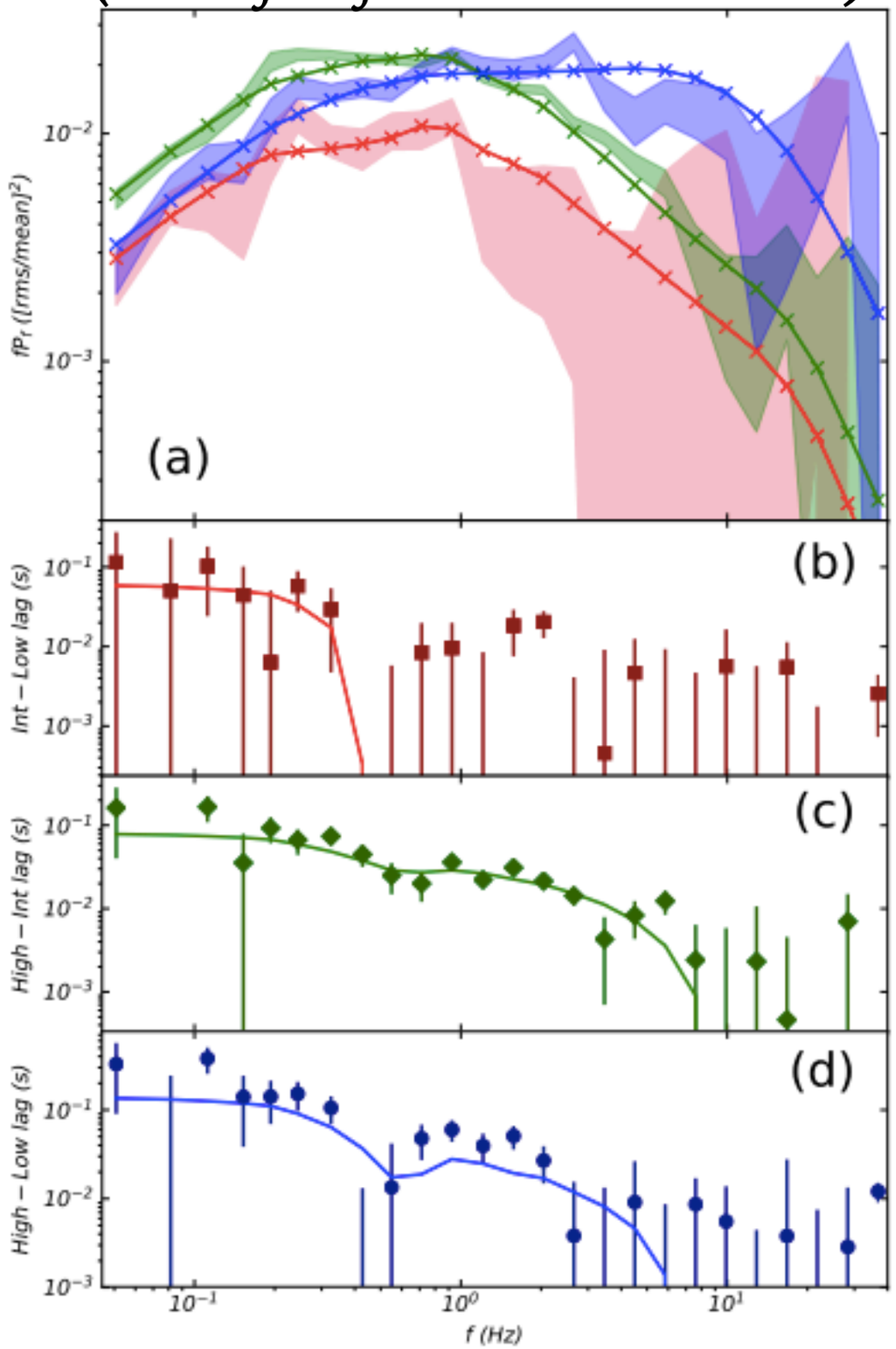
Stable disc (reflecting/ reprocessing region)

Disc truncated at ~20 r_g at the end of the transition from the soft to the hard state



GX 339-4

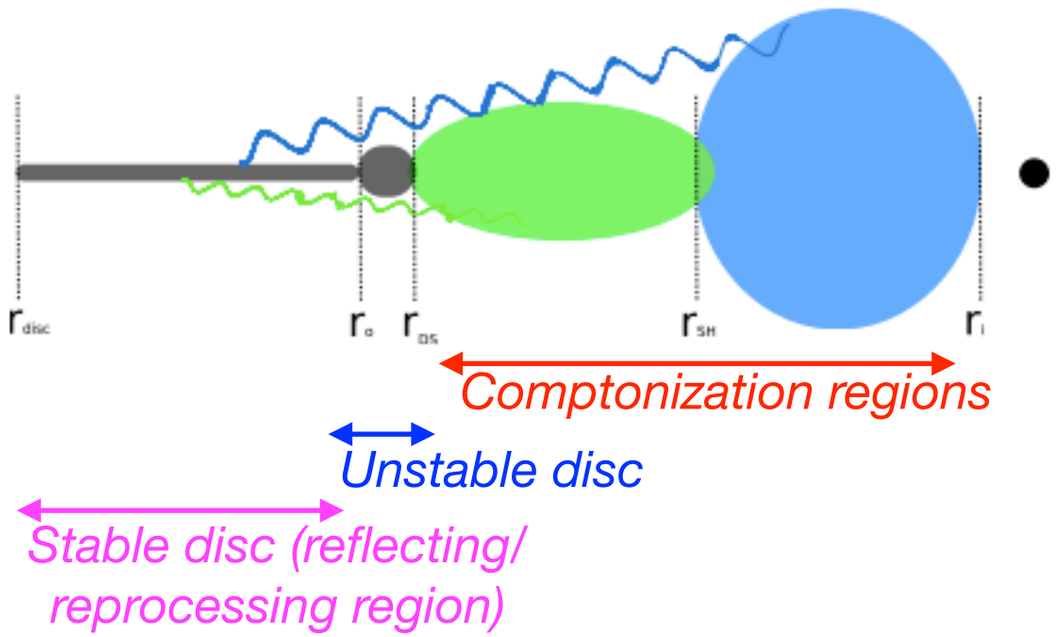
(end of soft-hard transition)



Spectral-timing fits

Spectrally inhomogeneous comptonizing region

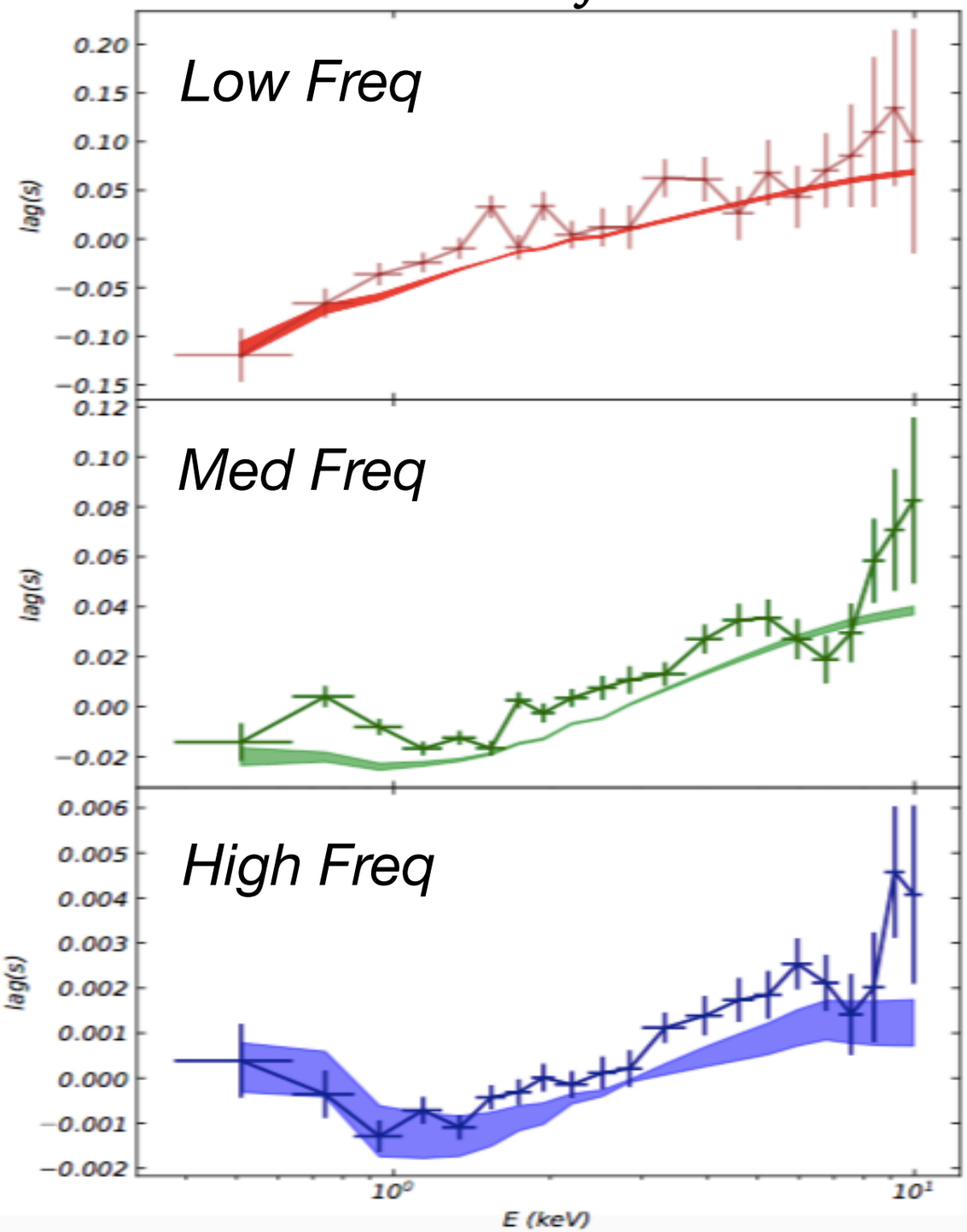
[Mahmoud +'17,'18,'19]



Disc truncated at ~20 r_g
at the end of the transition
from the soft to the hard state

GX 339-4

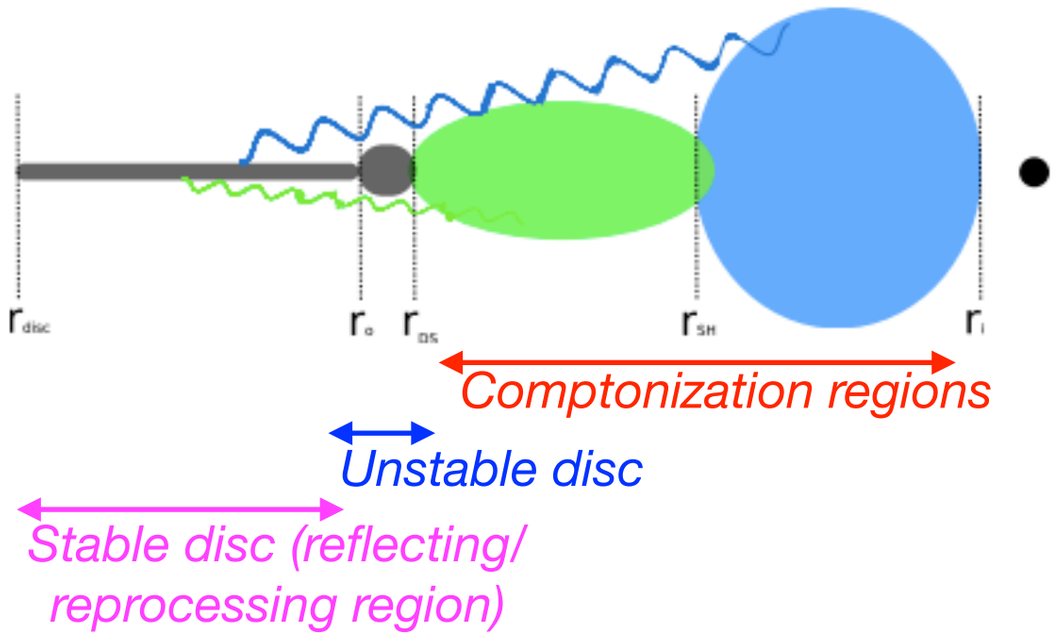
Predictions of the model



Spectral-timing fits

Spectrally inhomogeneous comptonizing region

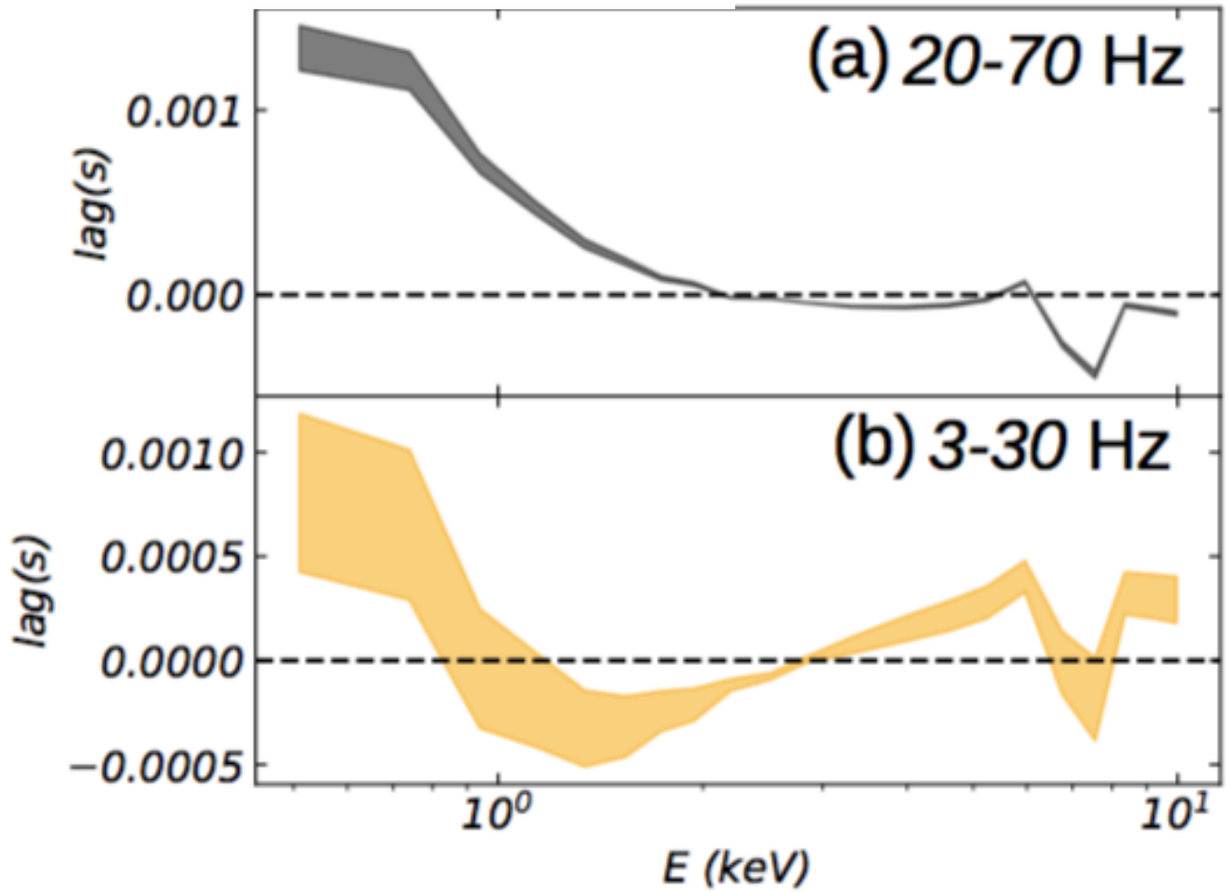
[Mahmoud +'17,'18,'19]



GX 339-4

Predictions of the model

Very High Freq



Disc truncated at ~20 r_g
at the end of the transition
from the soft to the hard state

Summary

Thermal reverberation lag evolves as a function of accretion state

In the hard state of GX 339-4 smooth evolution of lag with luminosity, in agreement with a truncation radius gradually decreasing

Hints of a FeK reverberation lag seen in GX 339-4 and MAXI J1820+070

Both in GX 339-4 and MAXI J1820+070 no reprocessing signal above a few tens of Hz

Thermal reverberation lag in the bright hard state of GX 339-4 and in MAXI J1820+070 have similar amplitude