A close up look at accreting BHs: the innermost regions as seen by Athena

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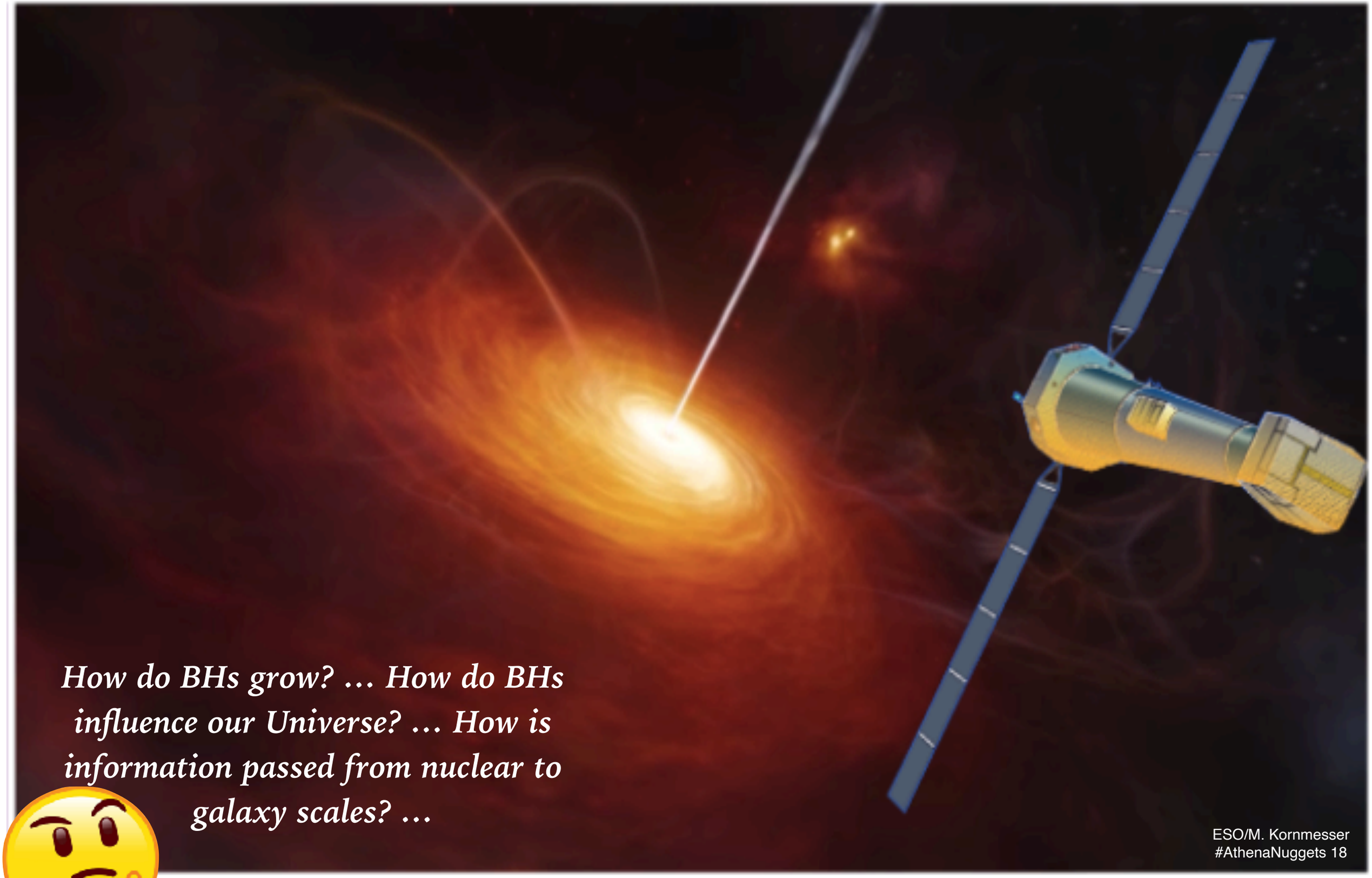
Why looking so close?



How do BHs grow? … How do BHs influence our Universe? … How is information passed from nuclear to galaxy scales? …

[e.g. King & Pounds '03; Berti & Volonteri '08; Kormendi & Ho '13; Wagner+13]

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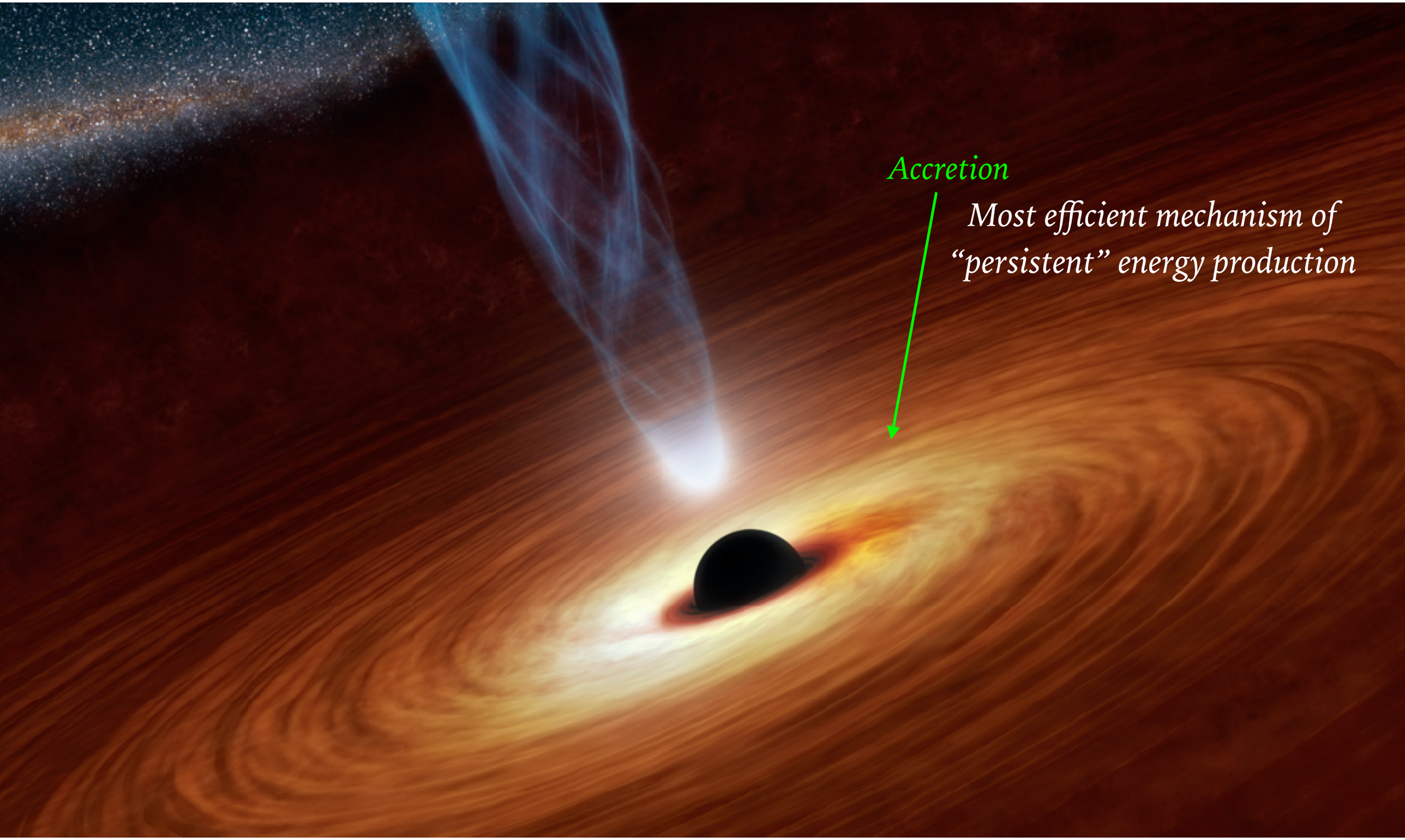

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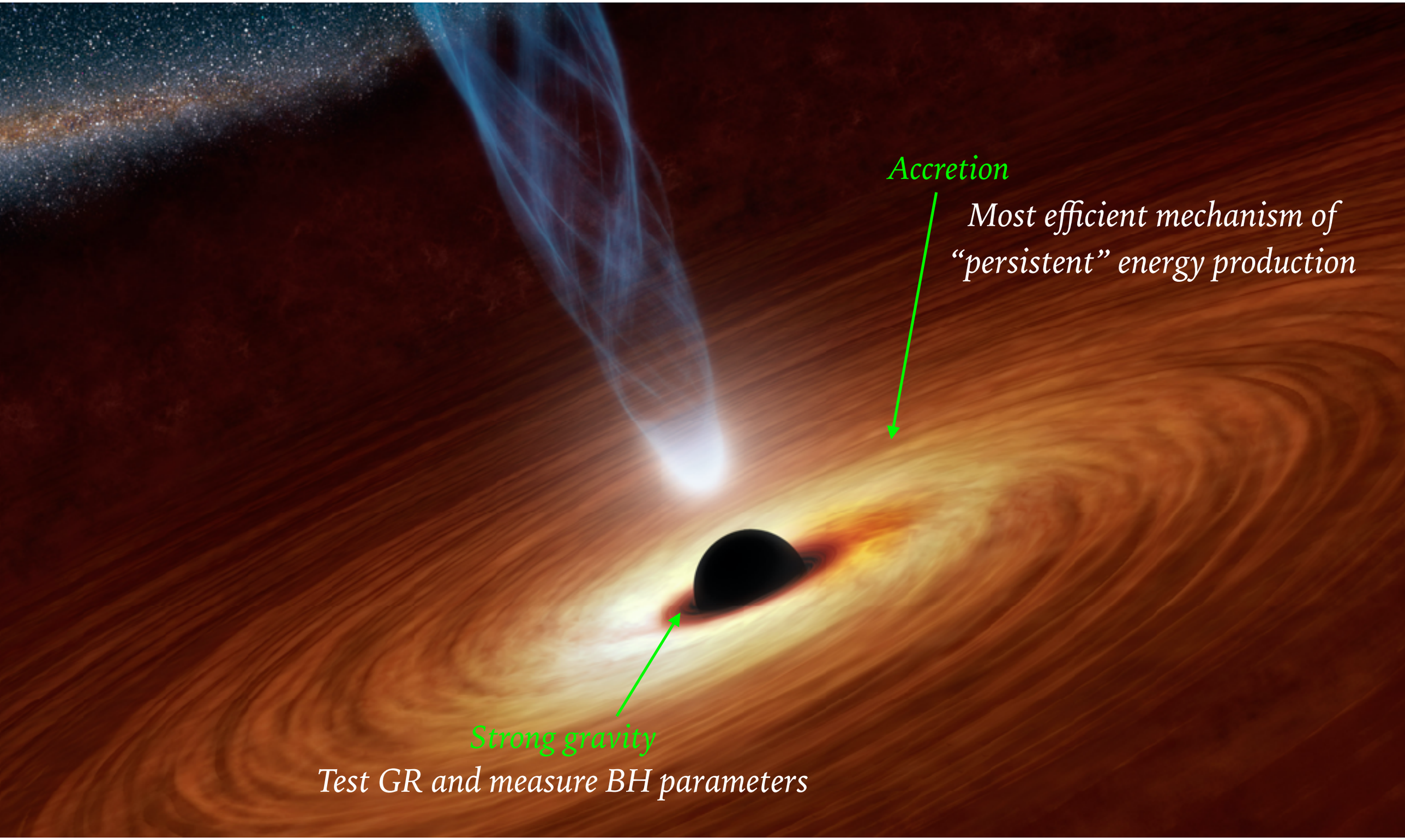

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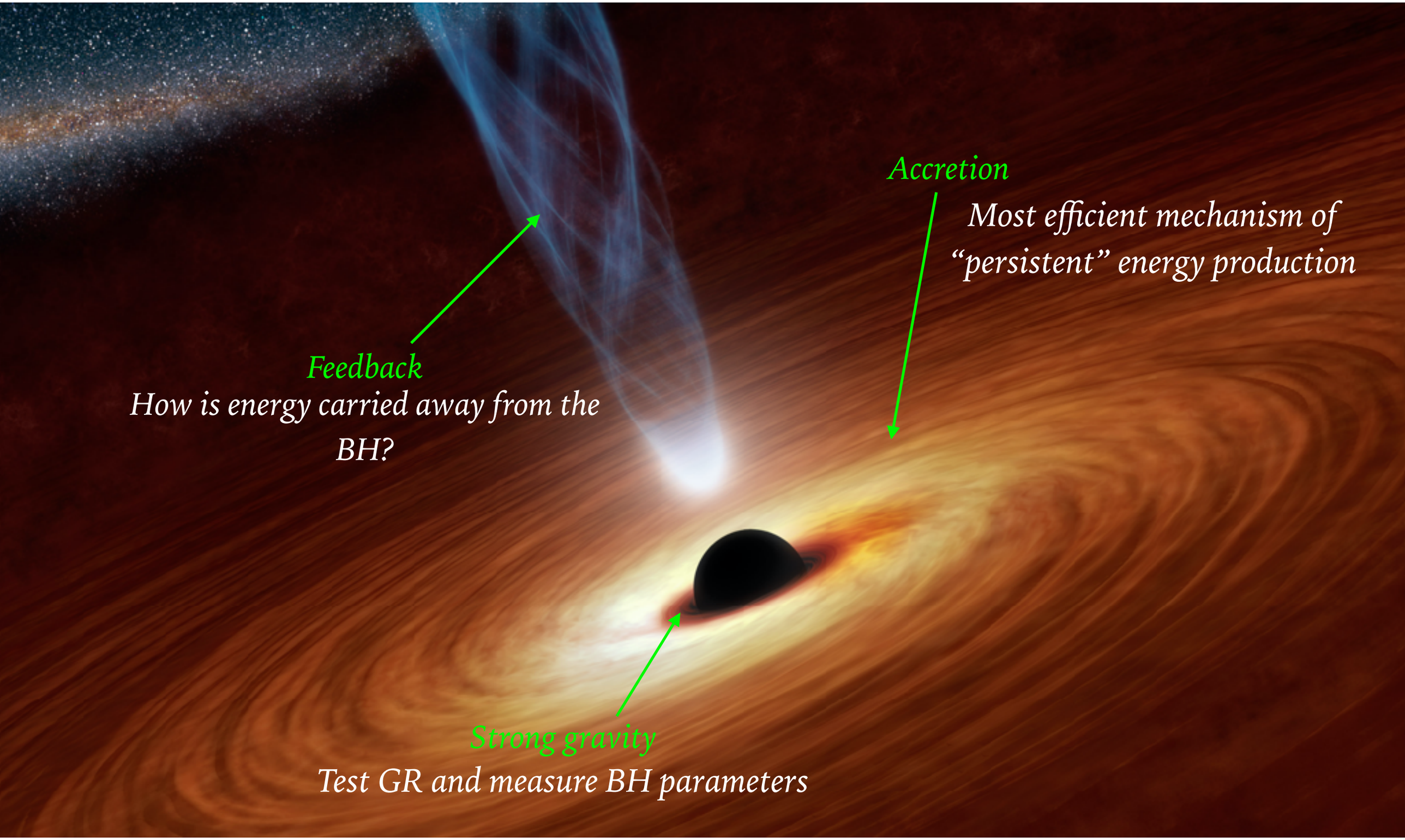

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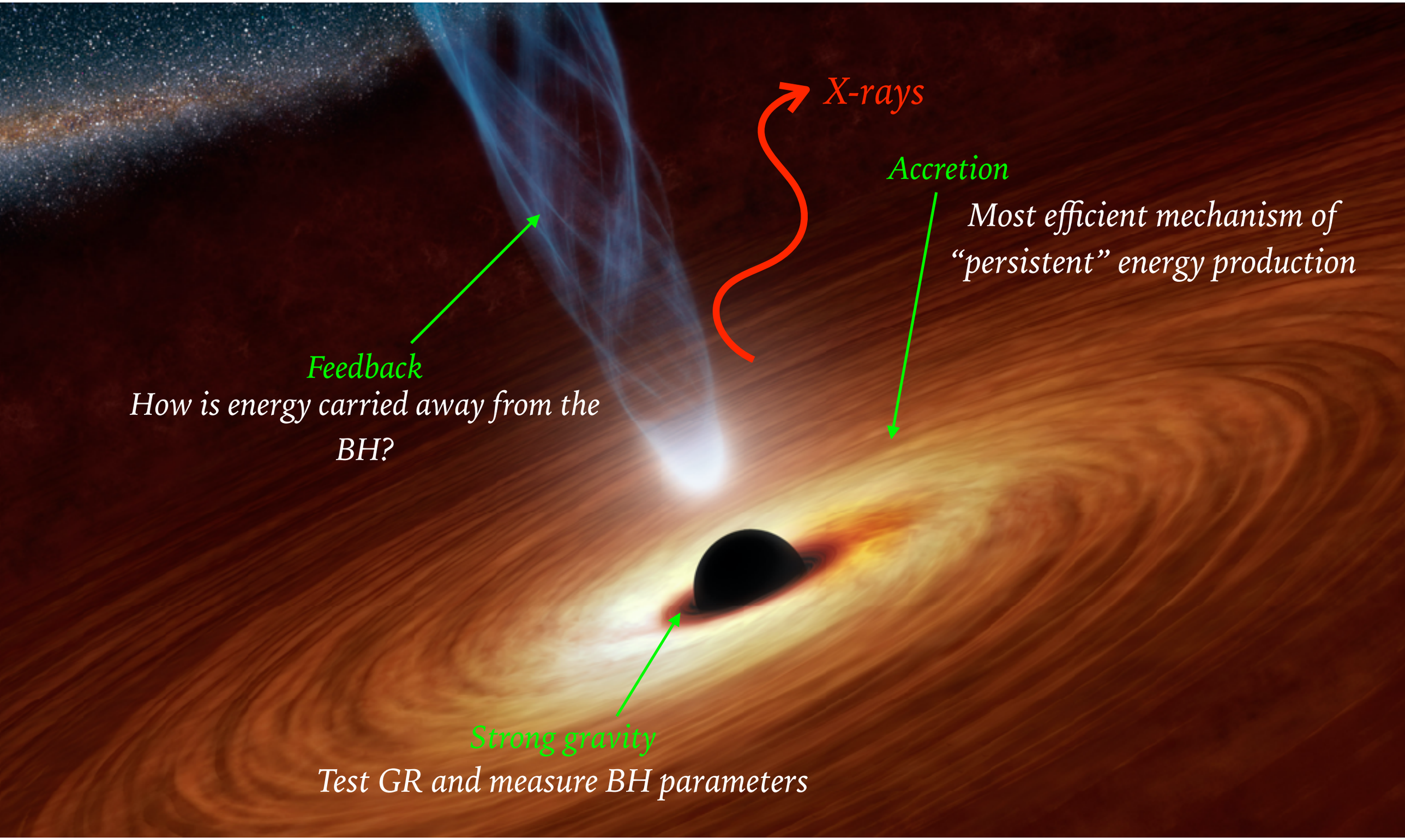

Plan of the talk

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What is the nature/geometry/location of the X-ray source?

Can inform us about the powering mechanism

Does the disc always extend down to the ISCO/ under which physical conditions is it truncated?

Relevant for spin measurements, jet formation, etc.

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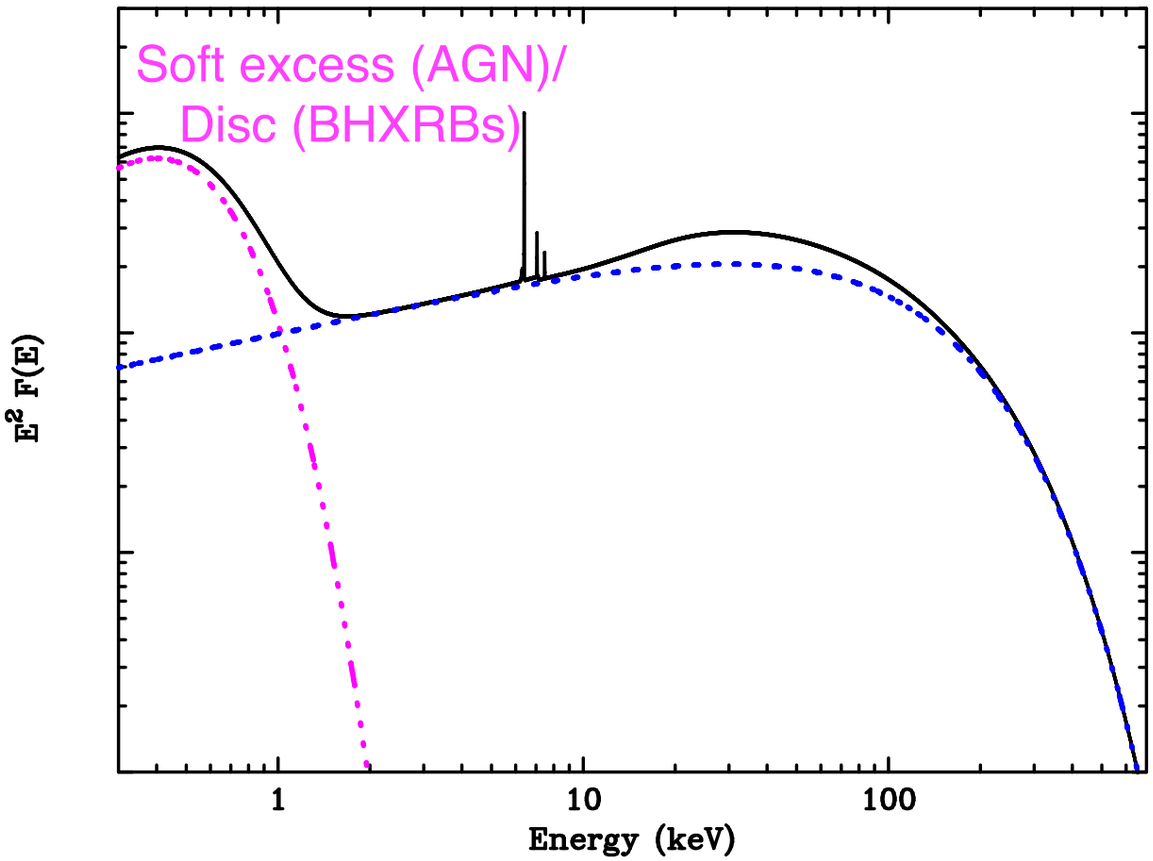
Combining spectral and timing information

Recent results

How Athena will boost this field

The hard X-ray source

A hot "corona" near the BH



[e.g. Shapiro+'76; Lightman+'81; Haardt & Maraschi '91;'93; Zdziarski+'94; Titarchuk '94; Merloni & Fabian '01]

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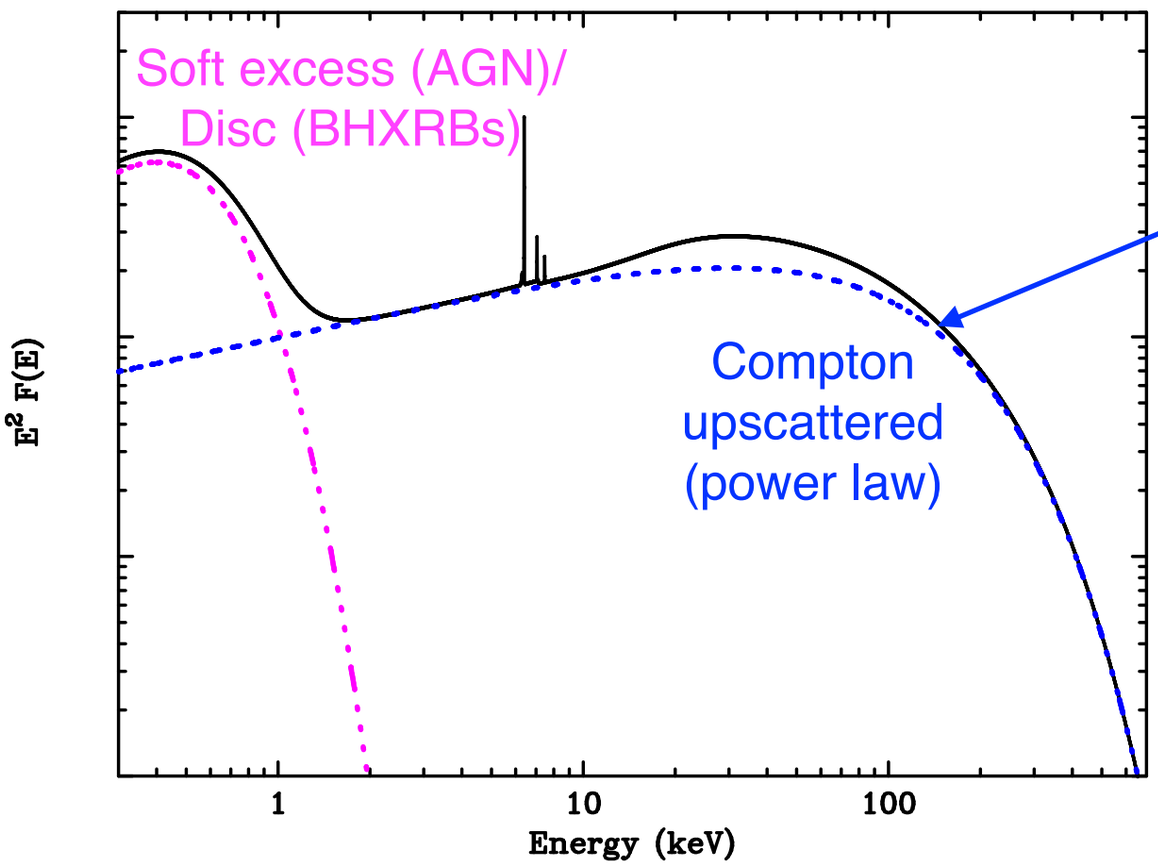
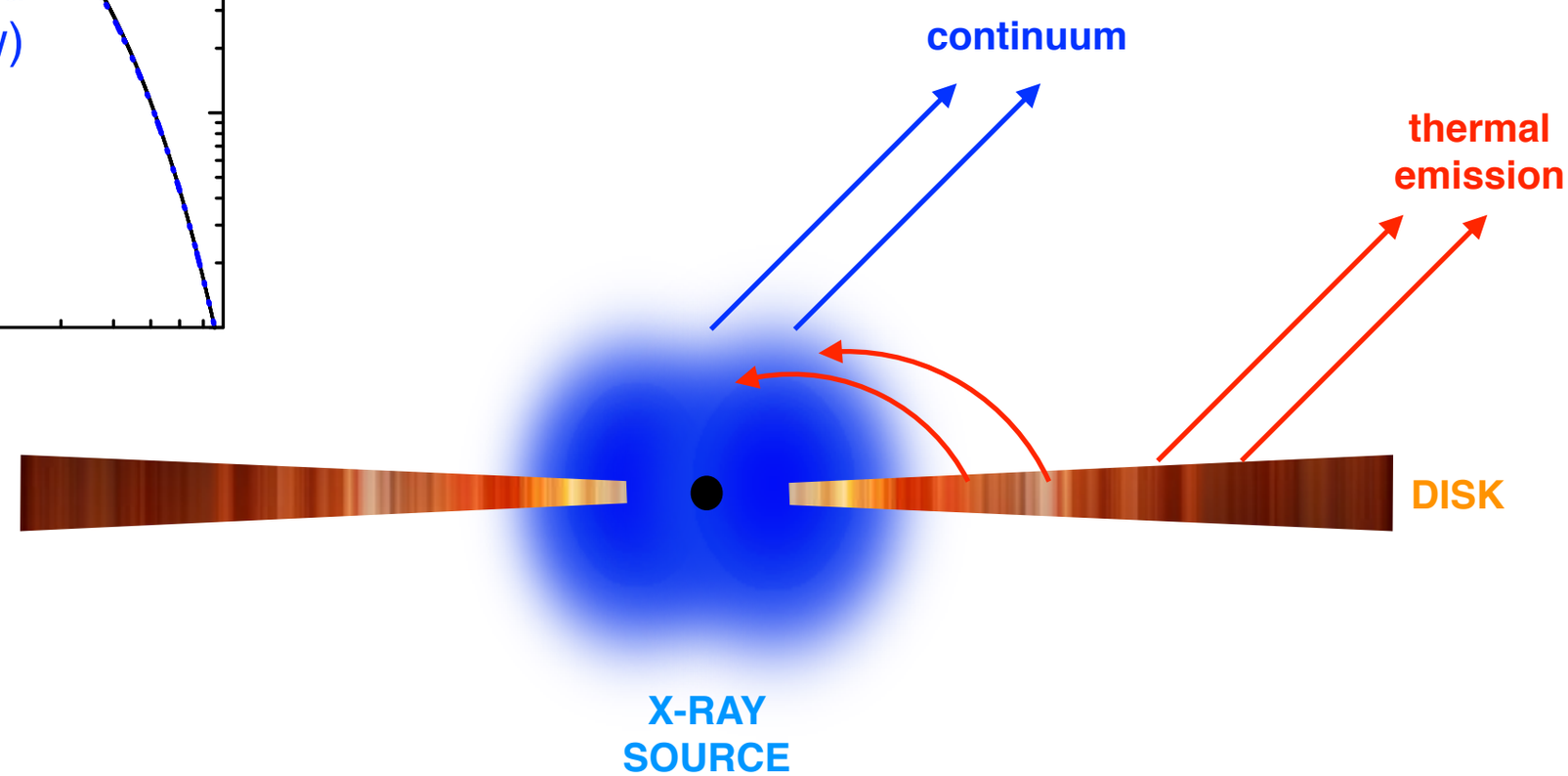


~10%-50% of the bolometric power in AGN *[e.g. Vasudevan & Fabian '07]*

Dominant X-ray component in hard state of BHXRBs *[e.g. McClintock & Remillard '04; Dunn+'10]*



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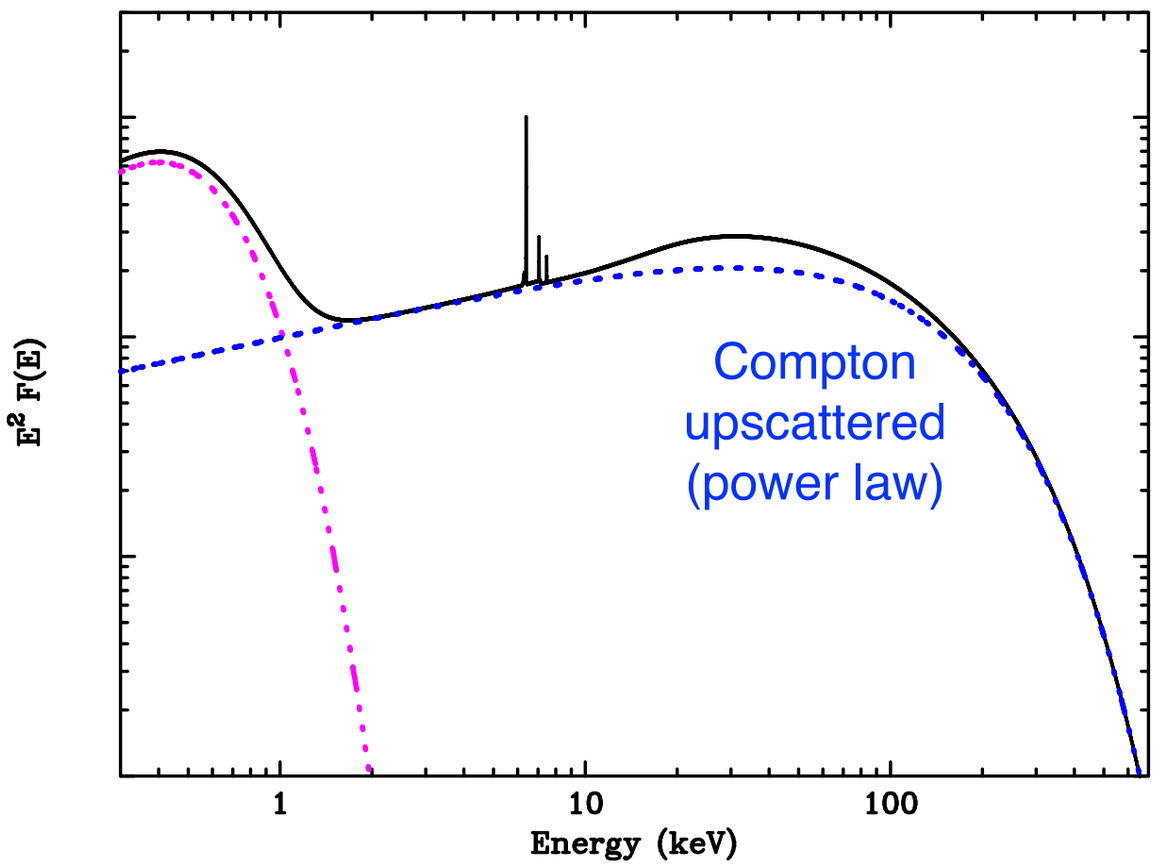

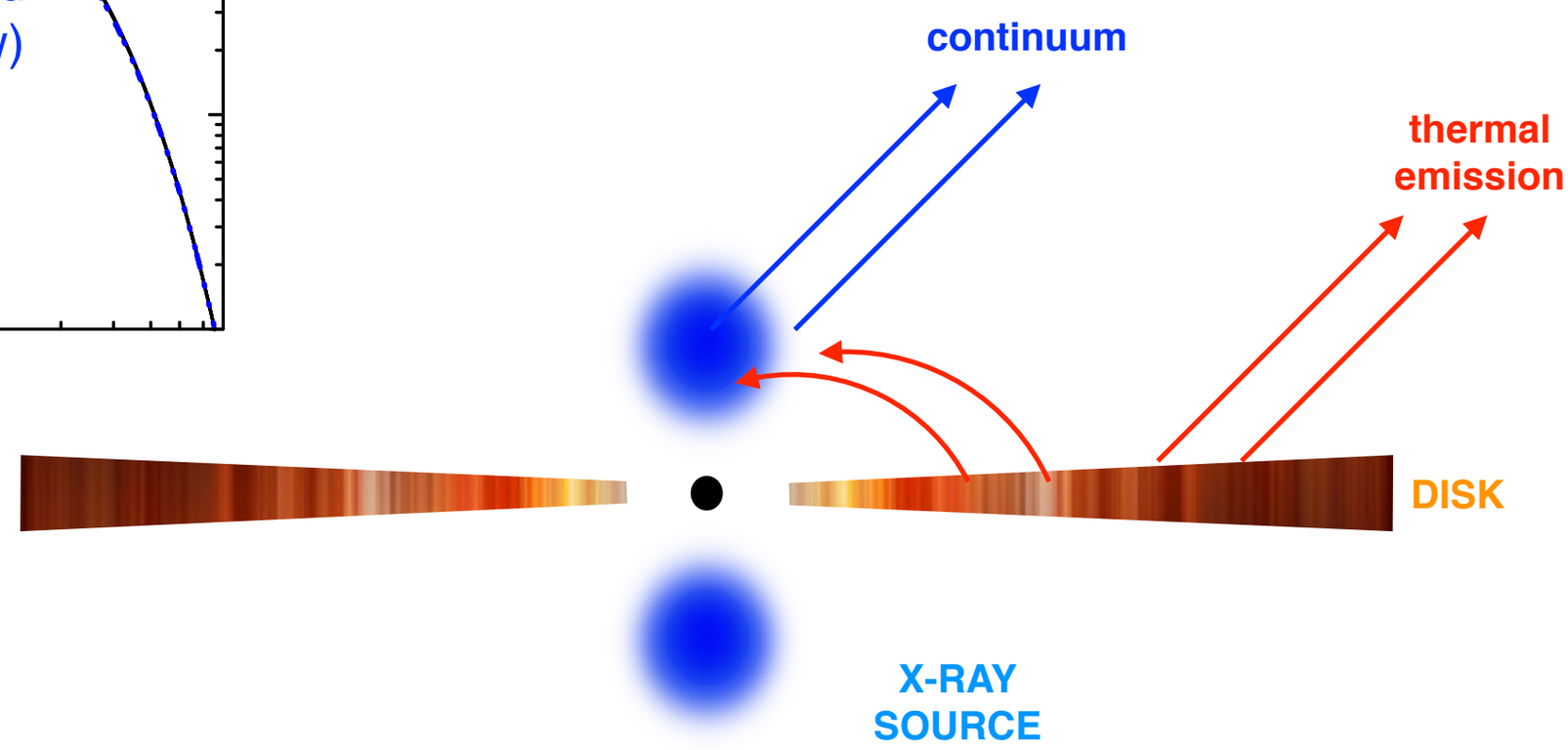

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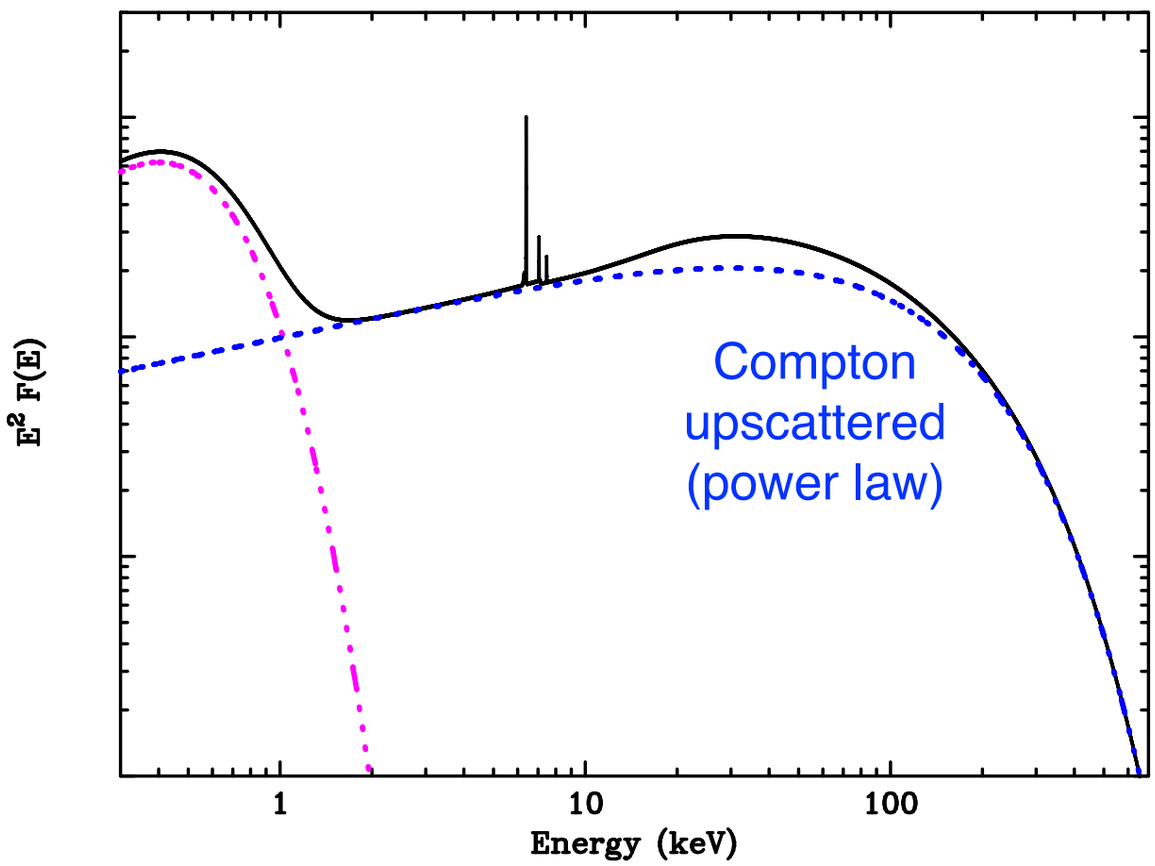

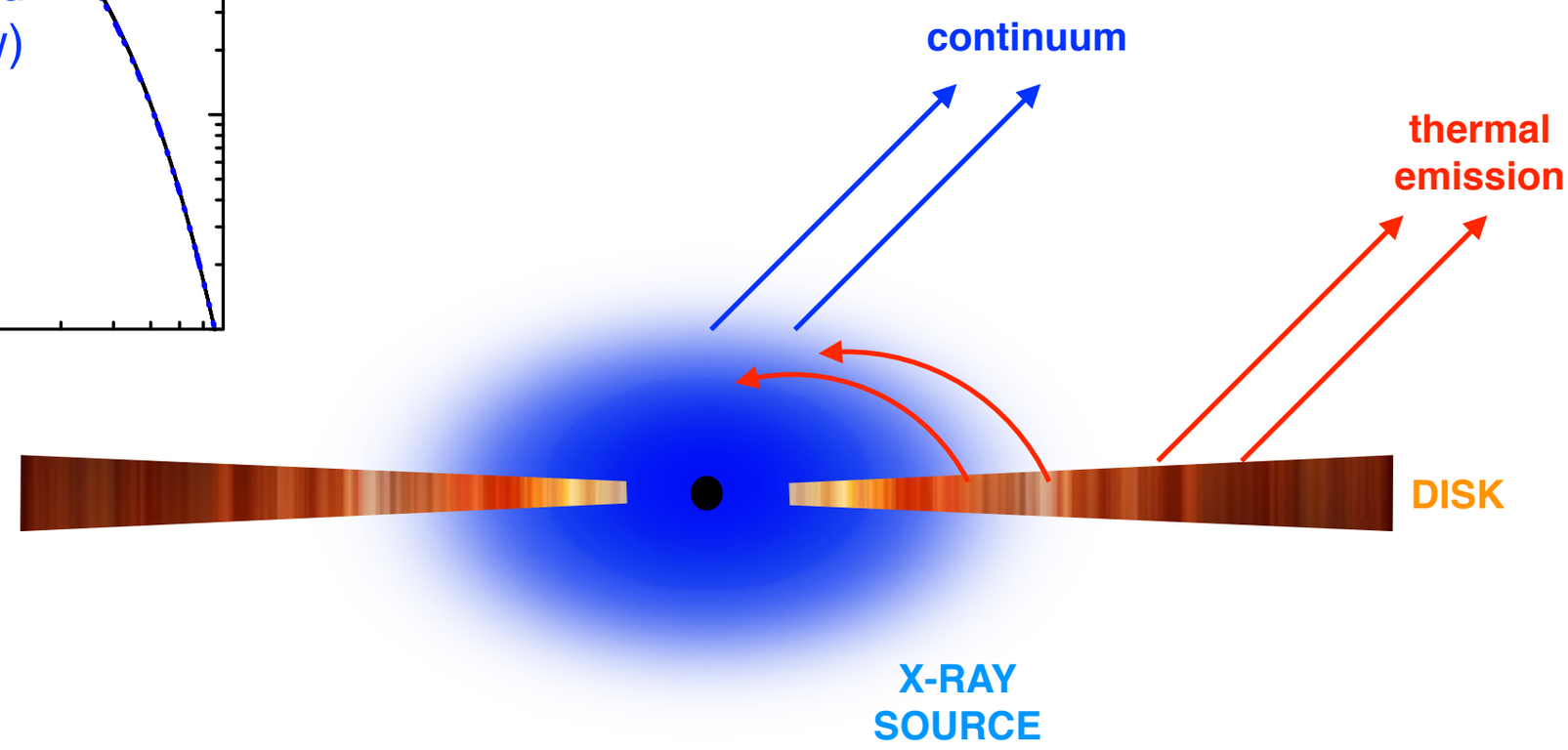

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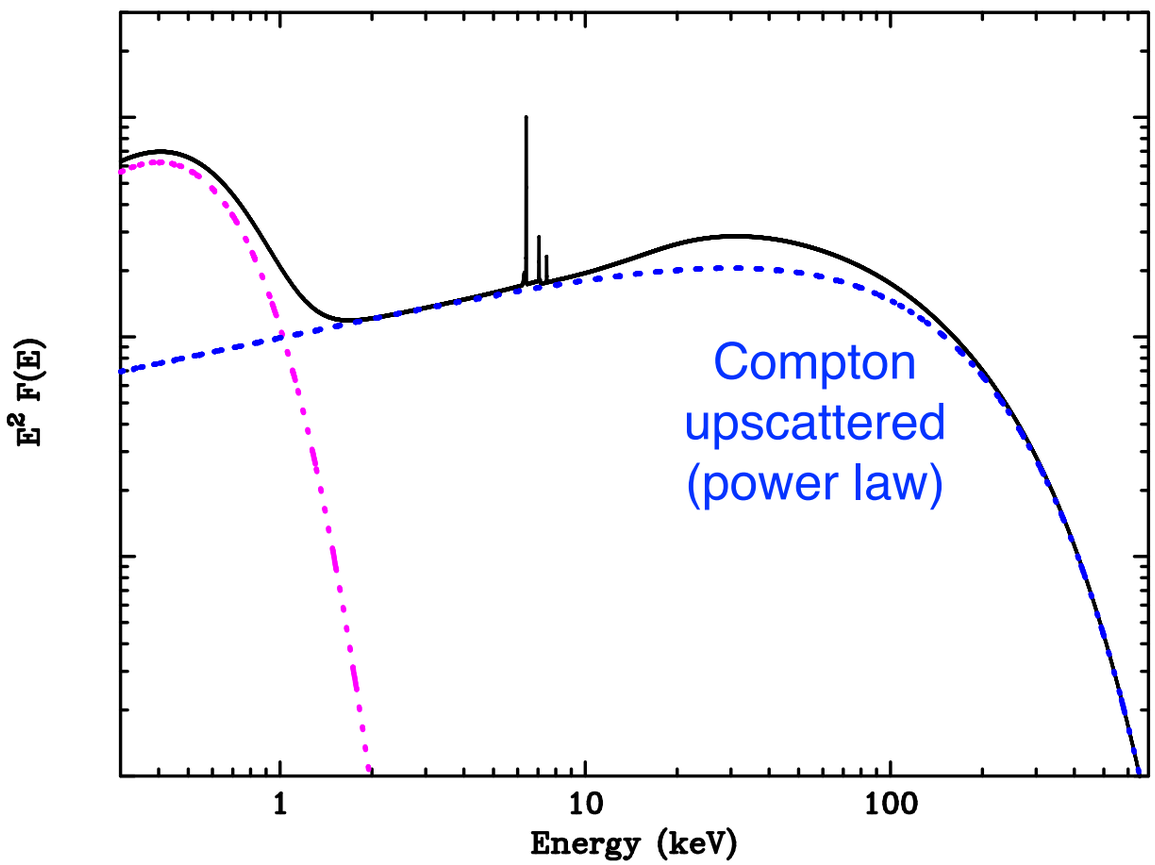

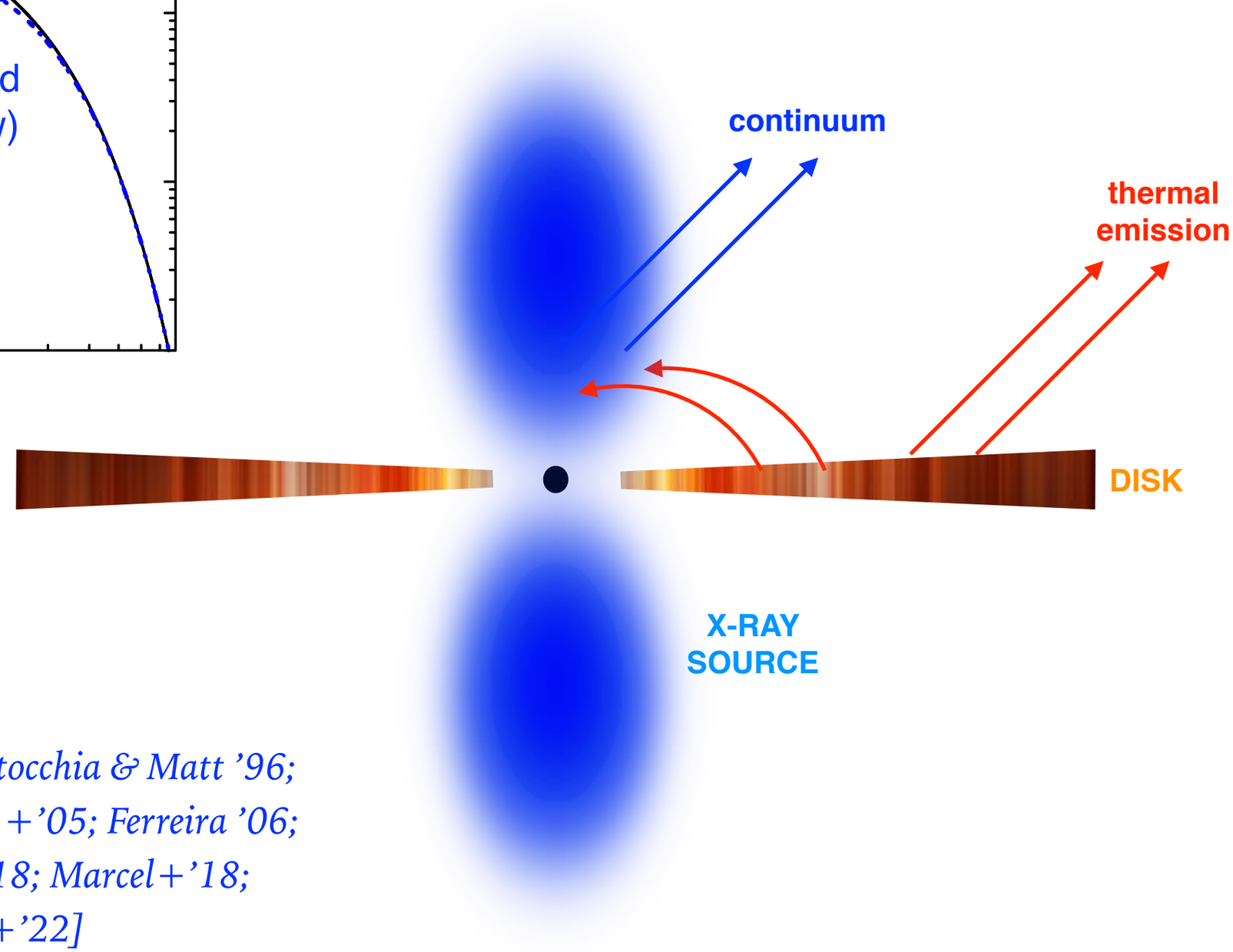

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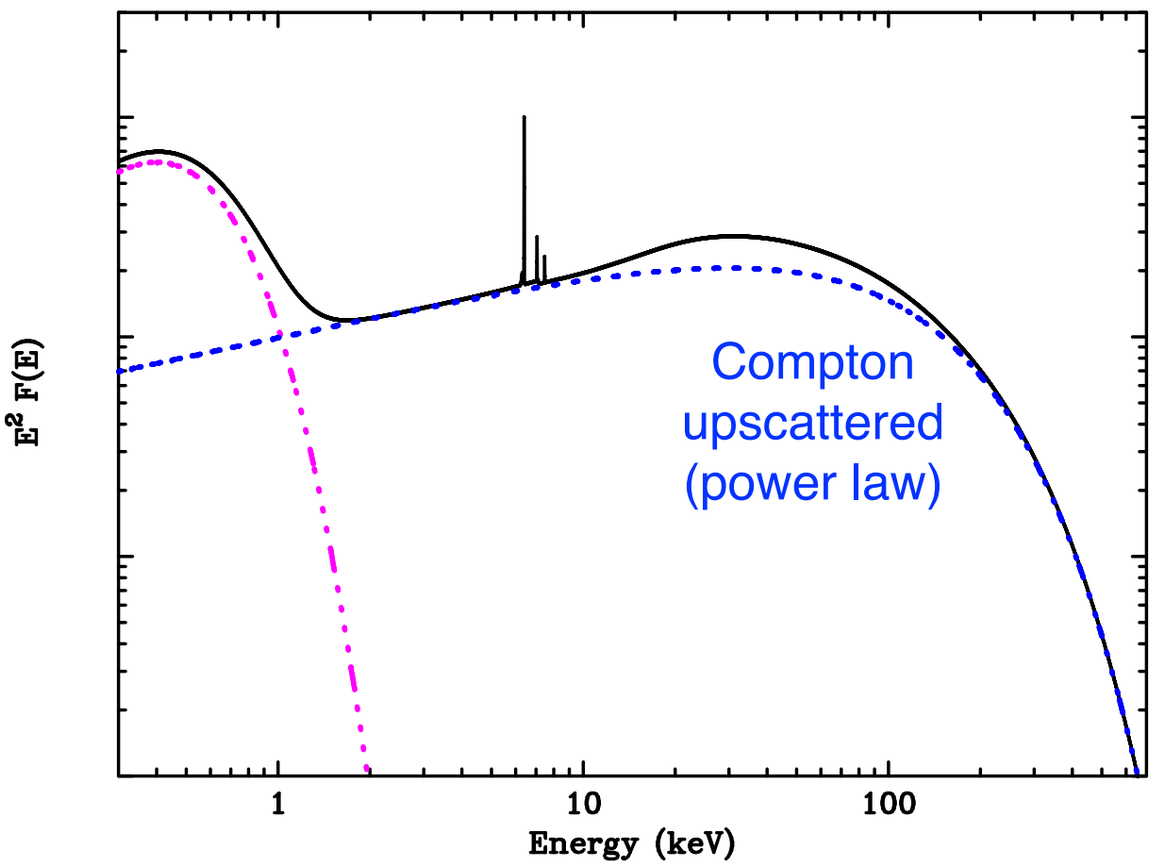

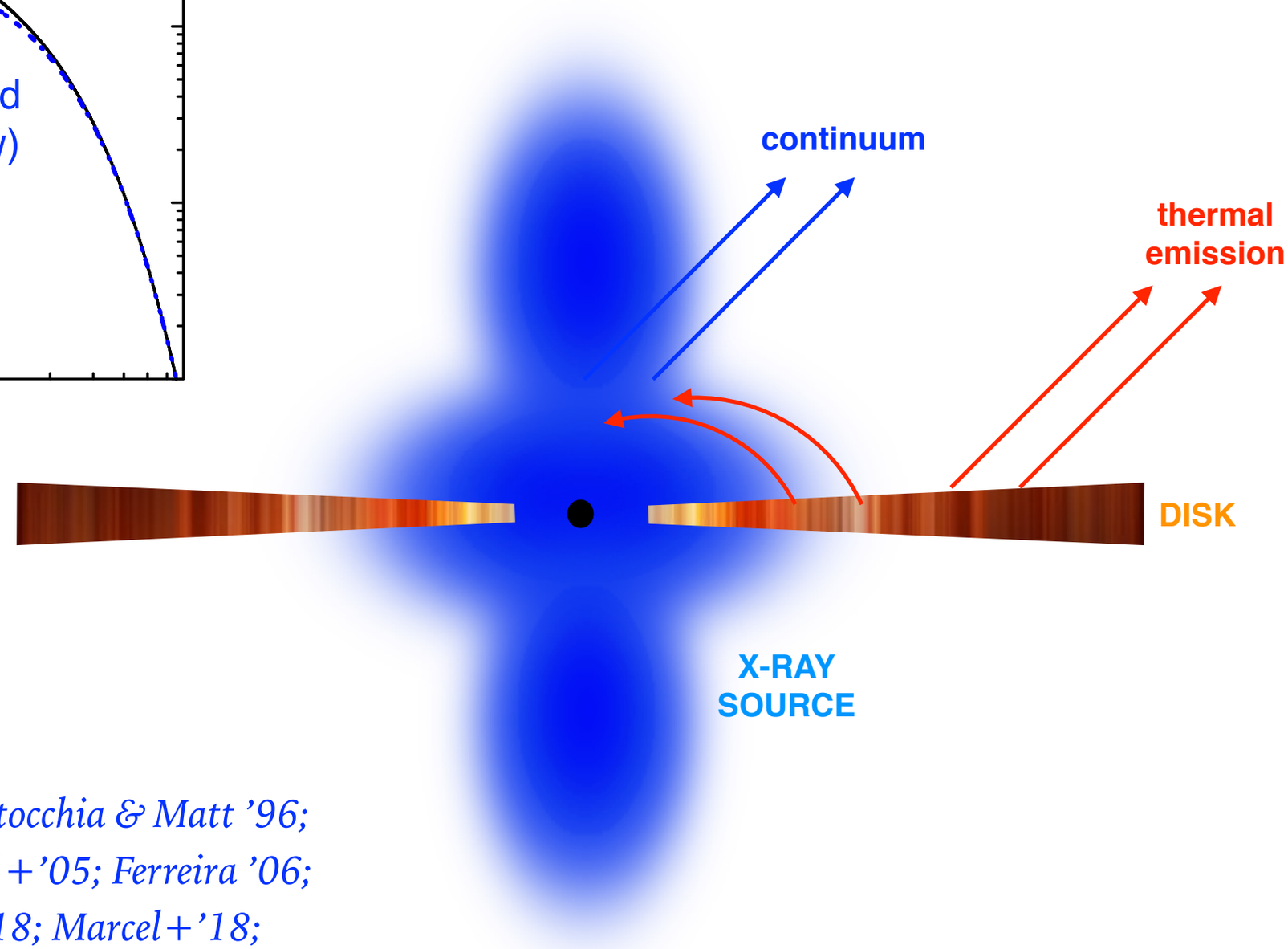

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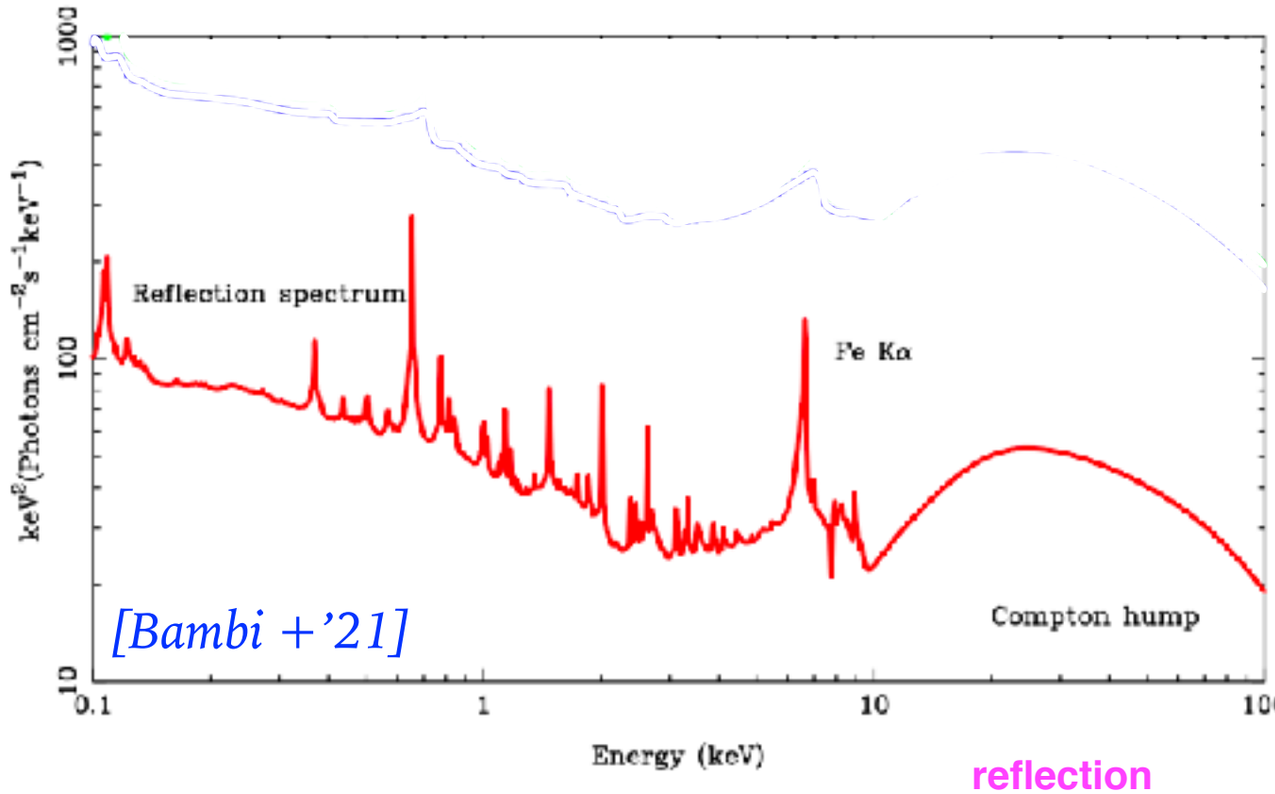
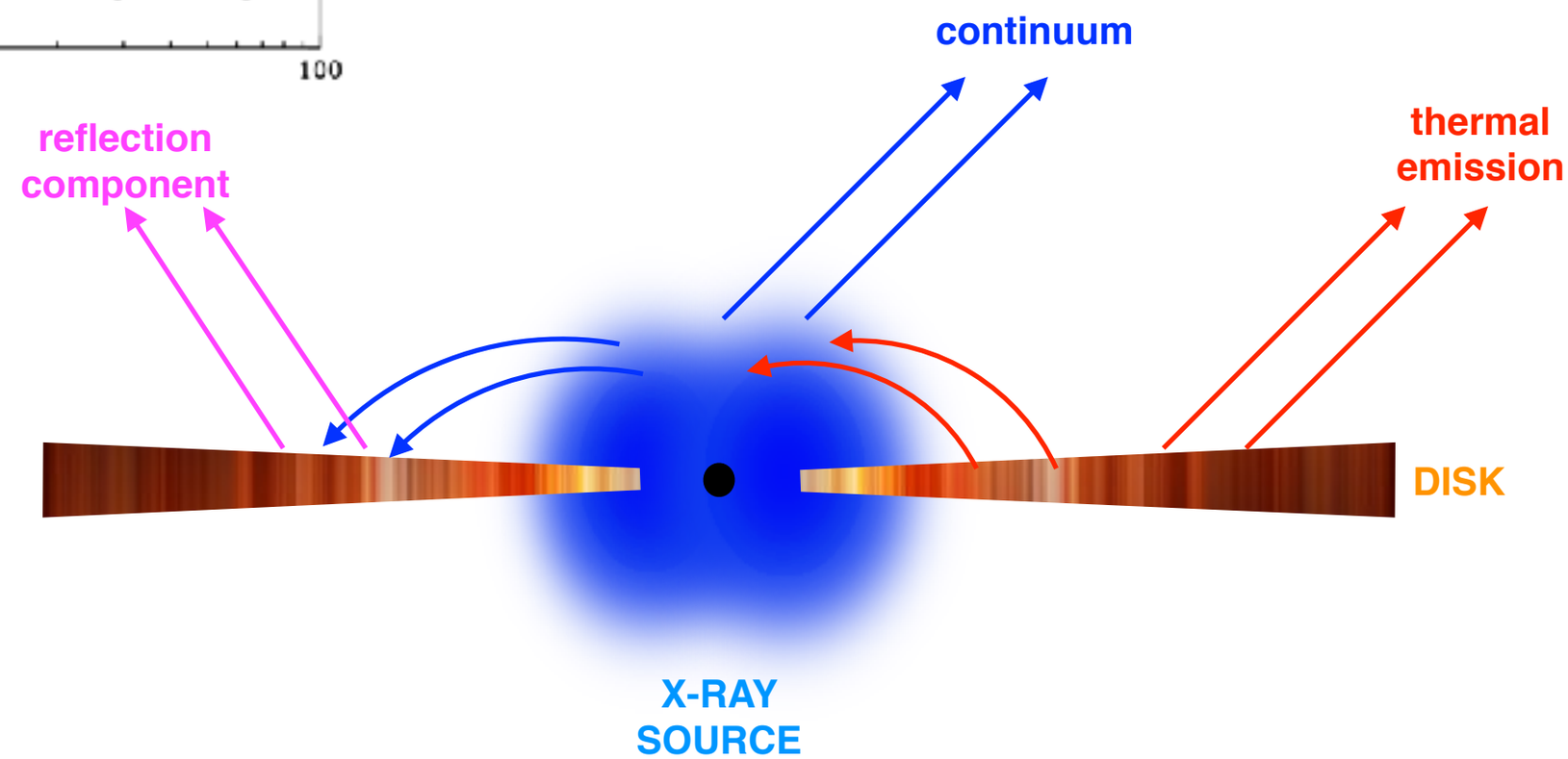
A powerful tool to study the corona and the disc





[e.g. Guilbert & Rees '88; George & Fabian '91; Ross & Fabian+'05; García & Kallman '10]

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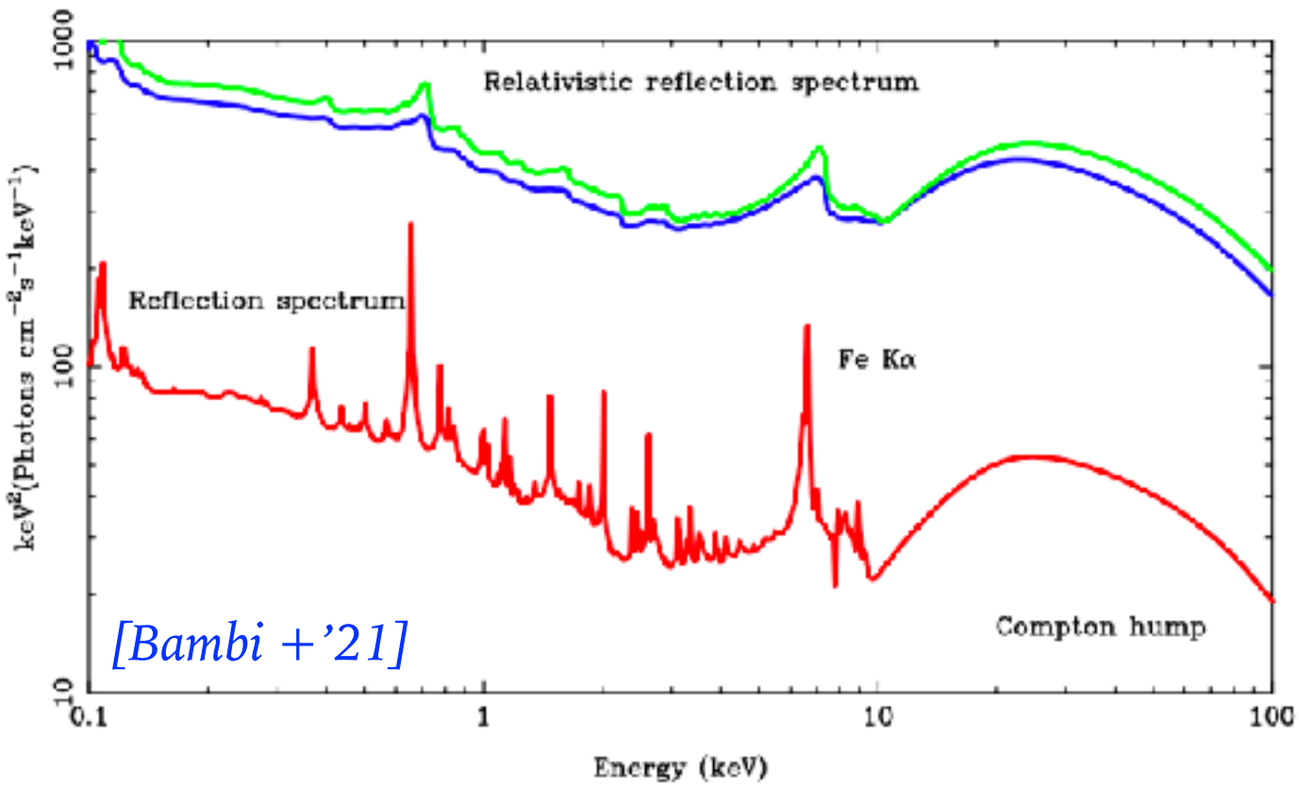

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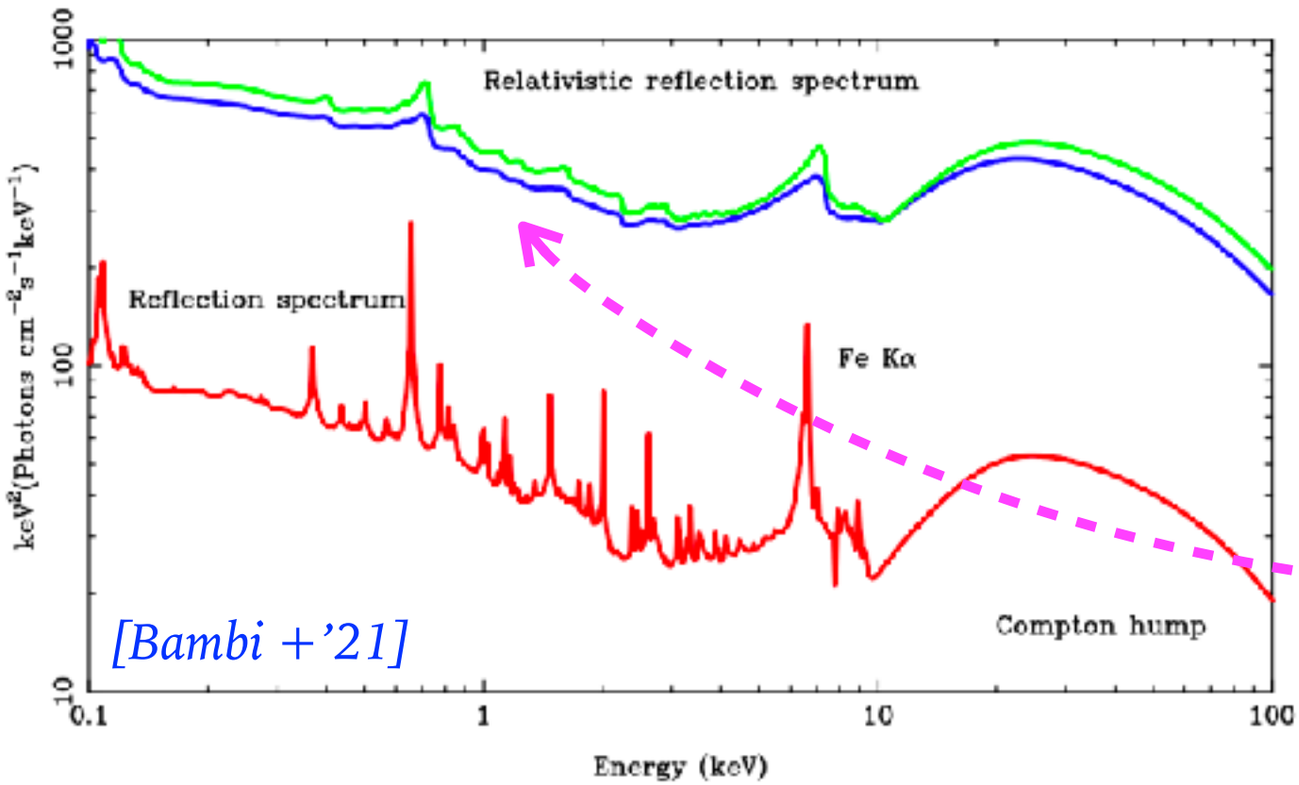

Smooth soft continuum
(can fit AGN soft excess)
[e.g. Crummy+'06]

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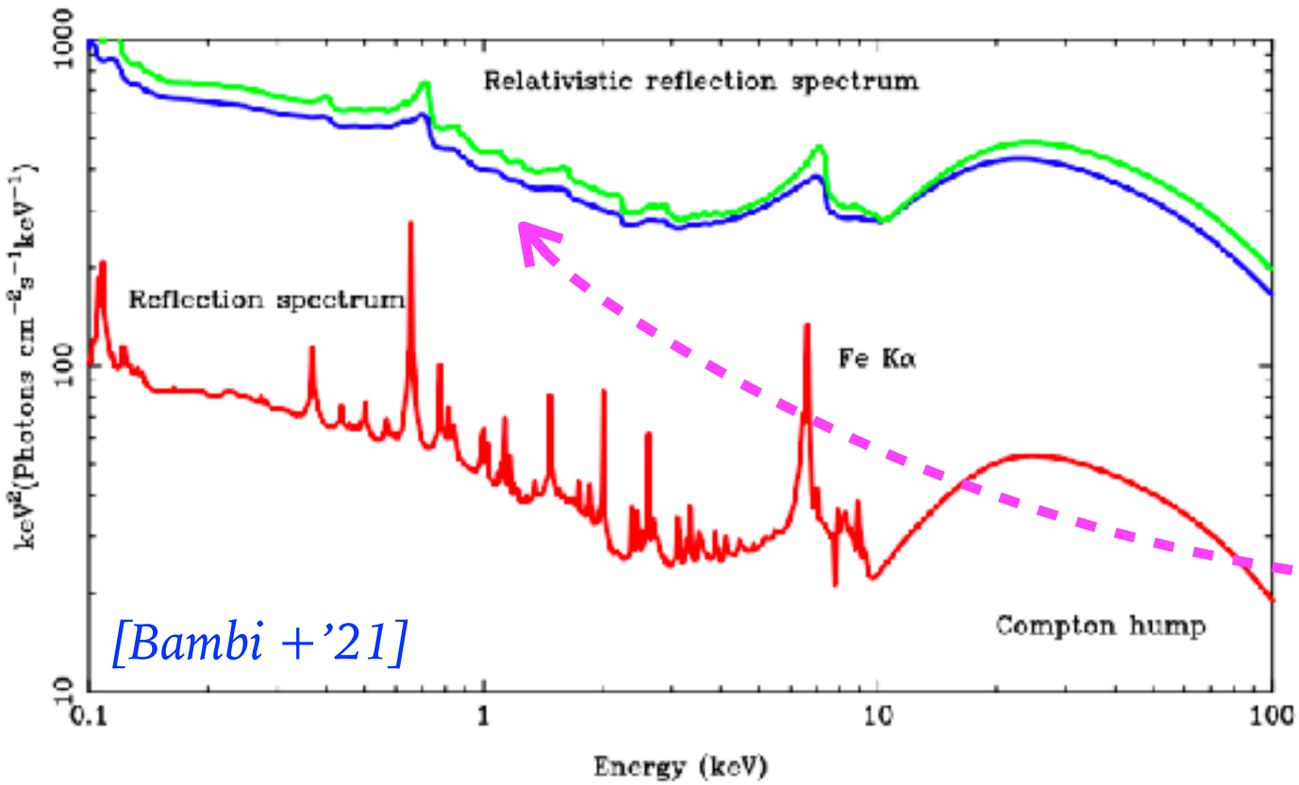

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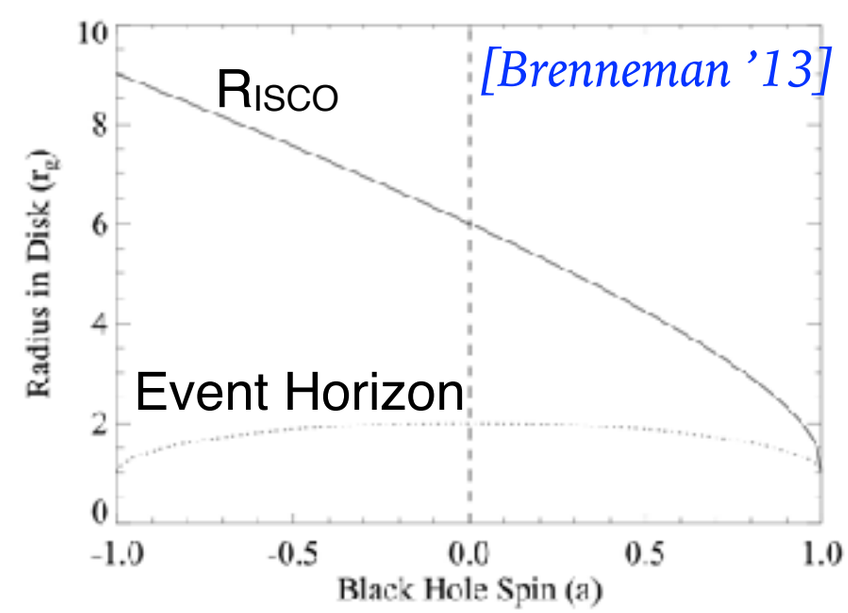

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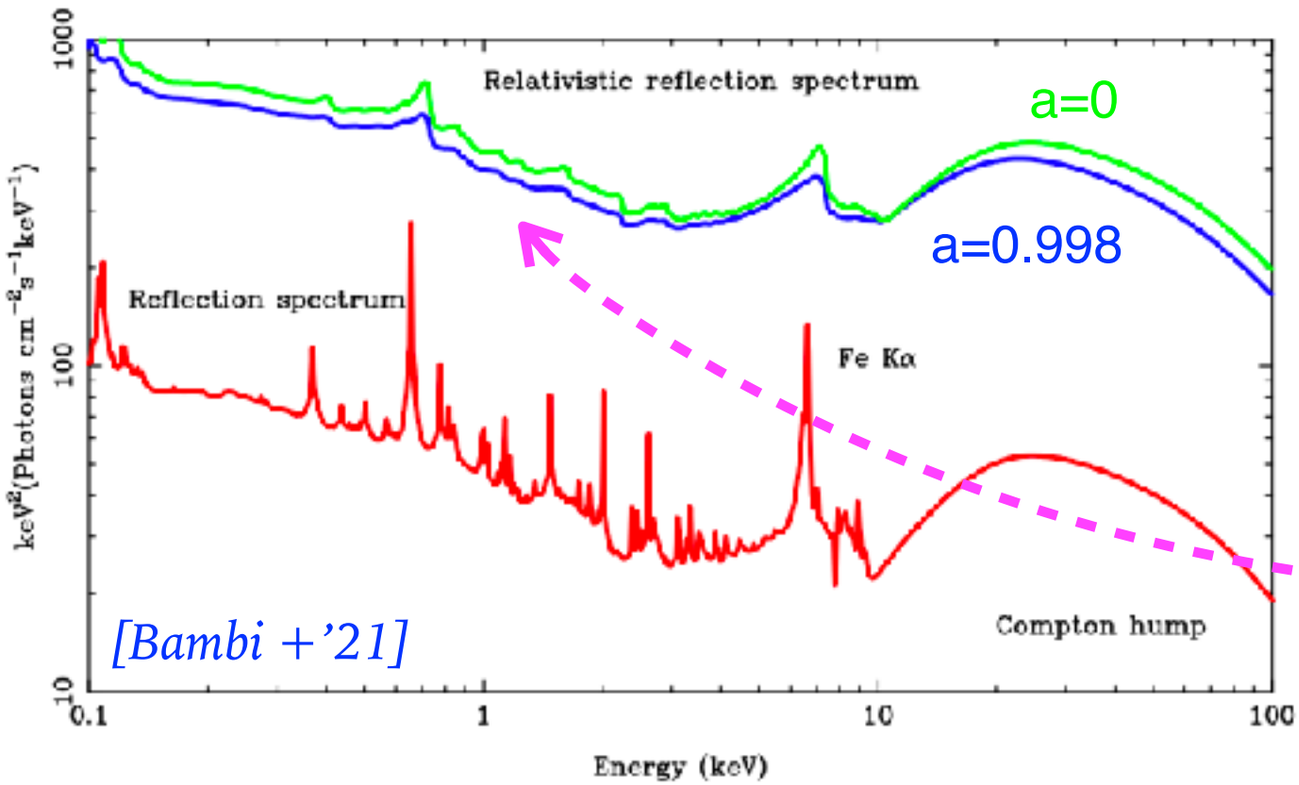

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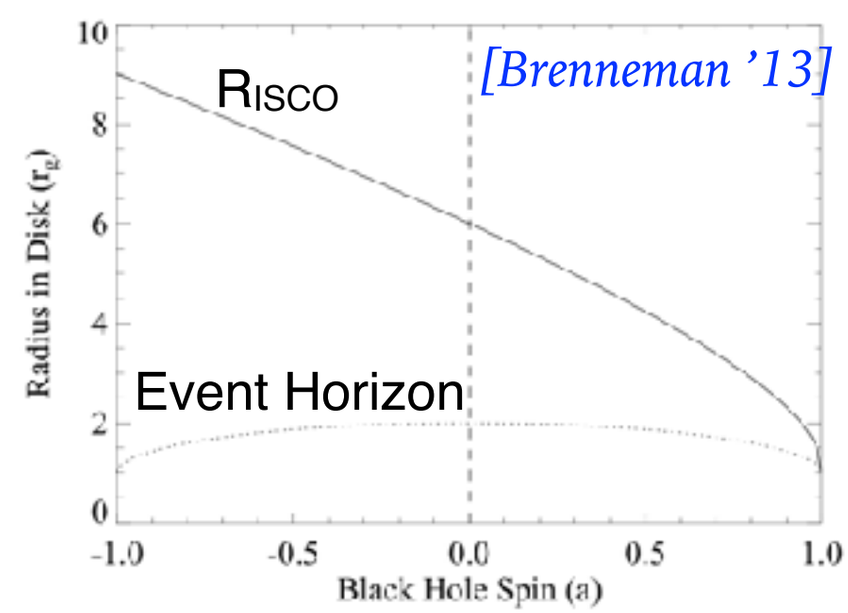

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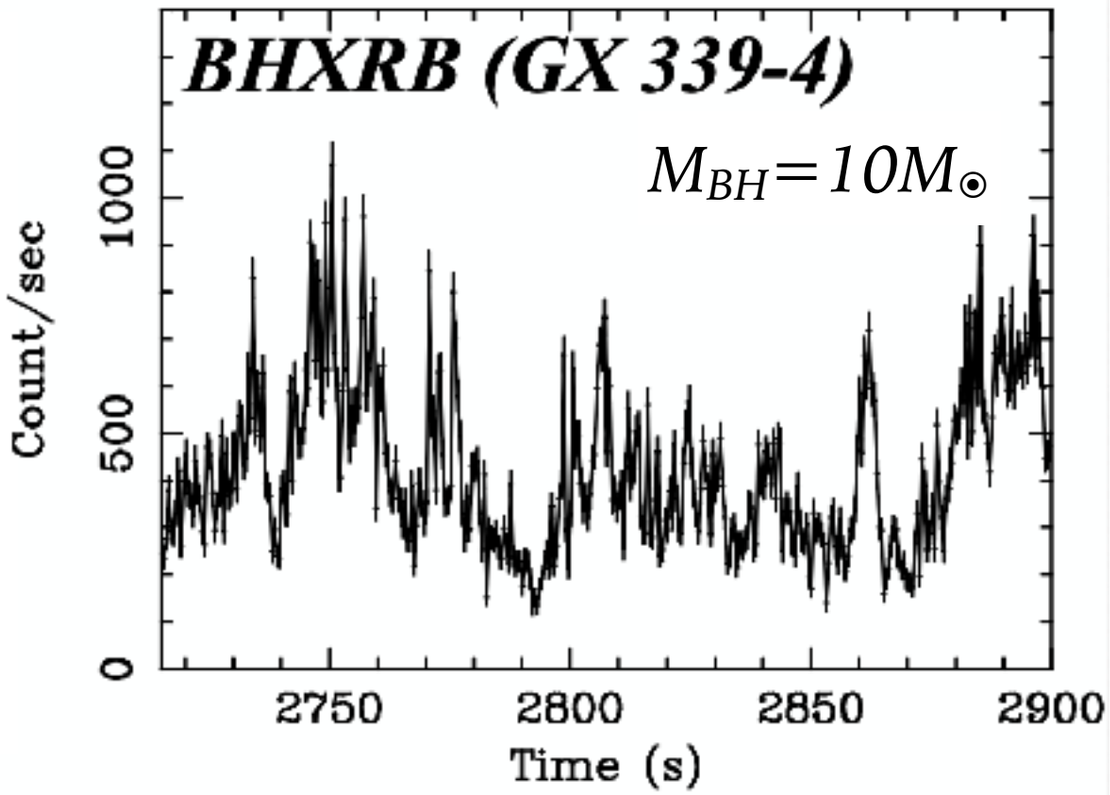
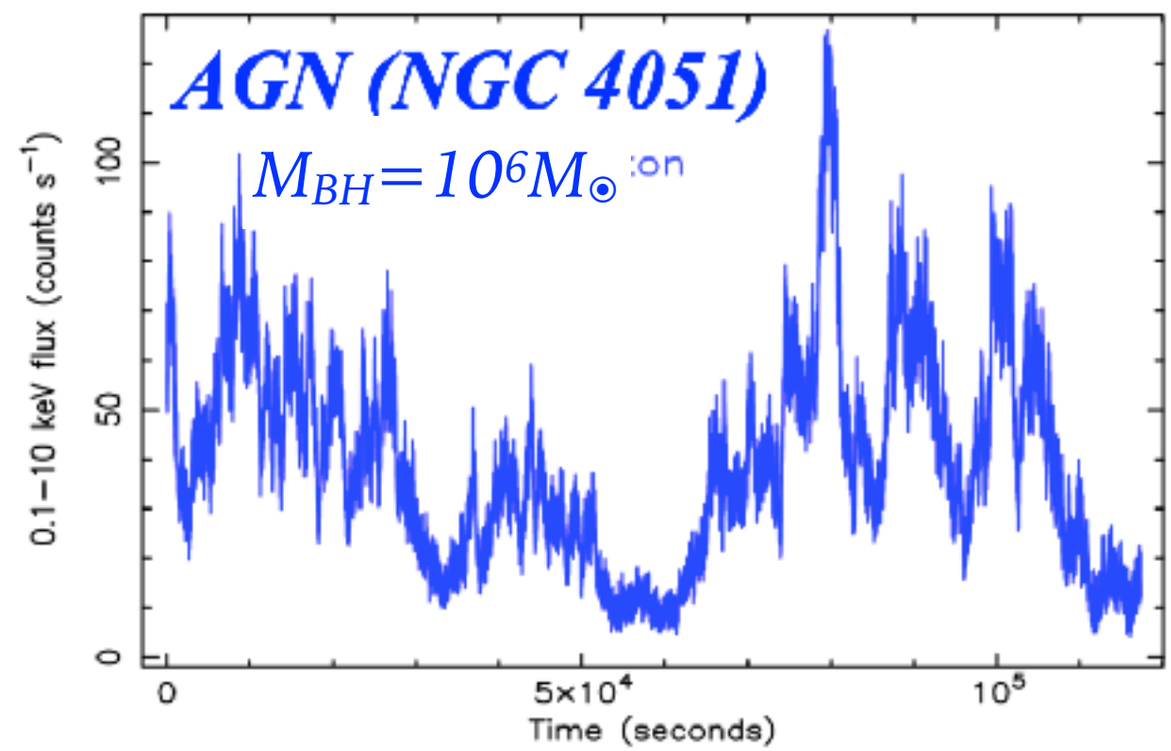
X-ray variability

A dynamic view of BH-accretion

Variability time scales scale inversely with the BH mass

[e.g. McHardy +'04; McHardy+'06; Koerding+'07]





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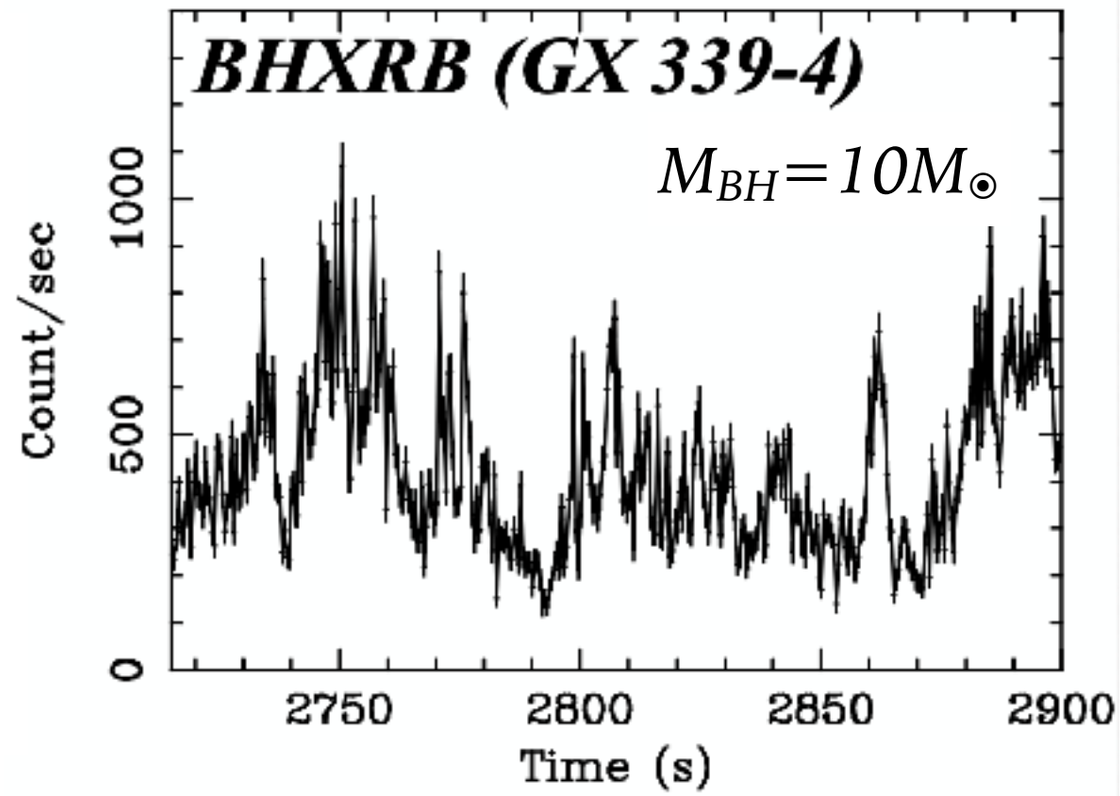
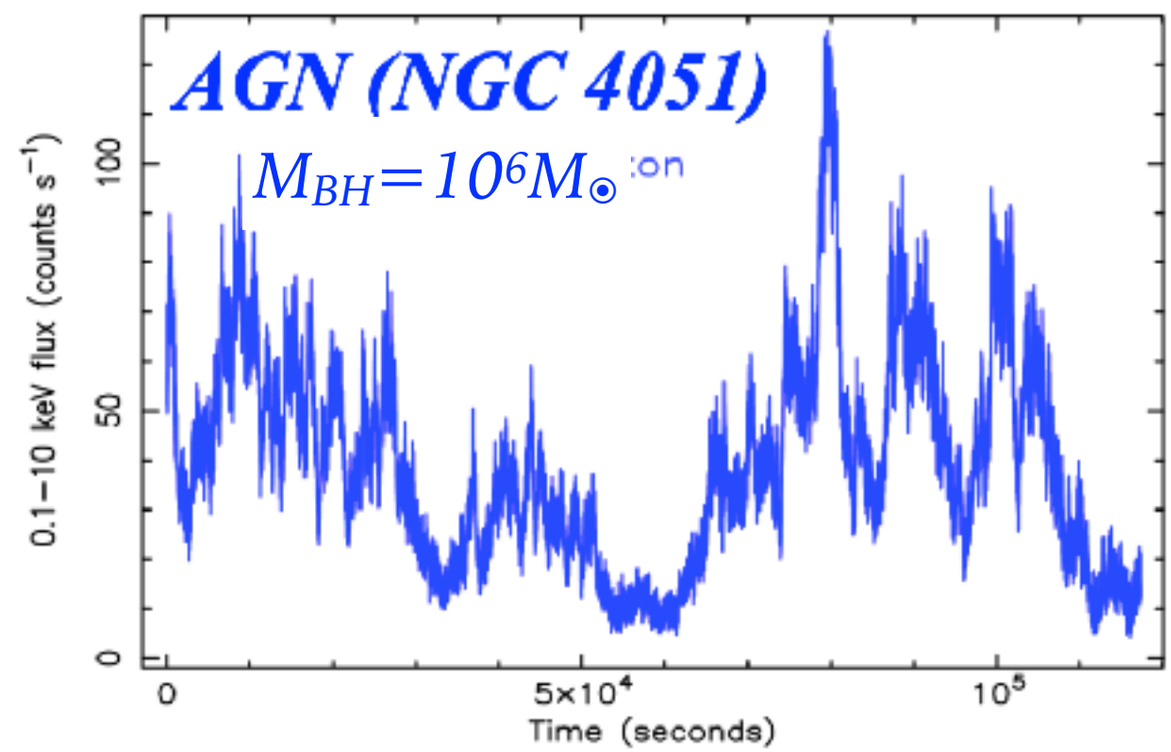




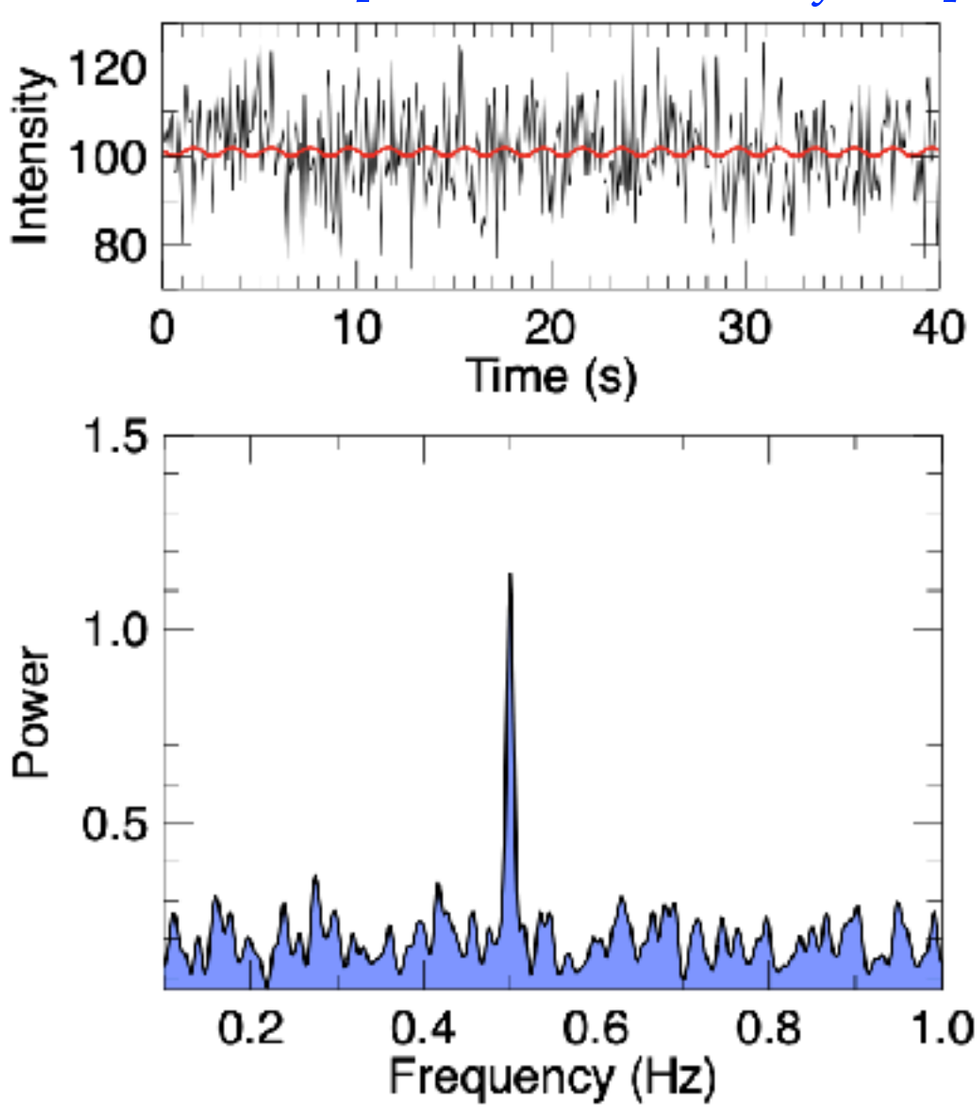
Time scales also depend on the extension/ distance of the region where variability originates

[e.g. Miniutti & Fabian '04; Uttley +'05; McHardy+'99; Krongold+'05]

X-ray spectral-timing

A powerful tool to single out variability components

[Belloni & Bhattacharya '22]



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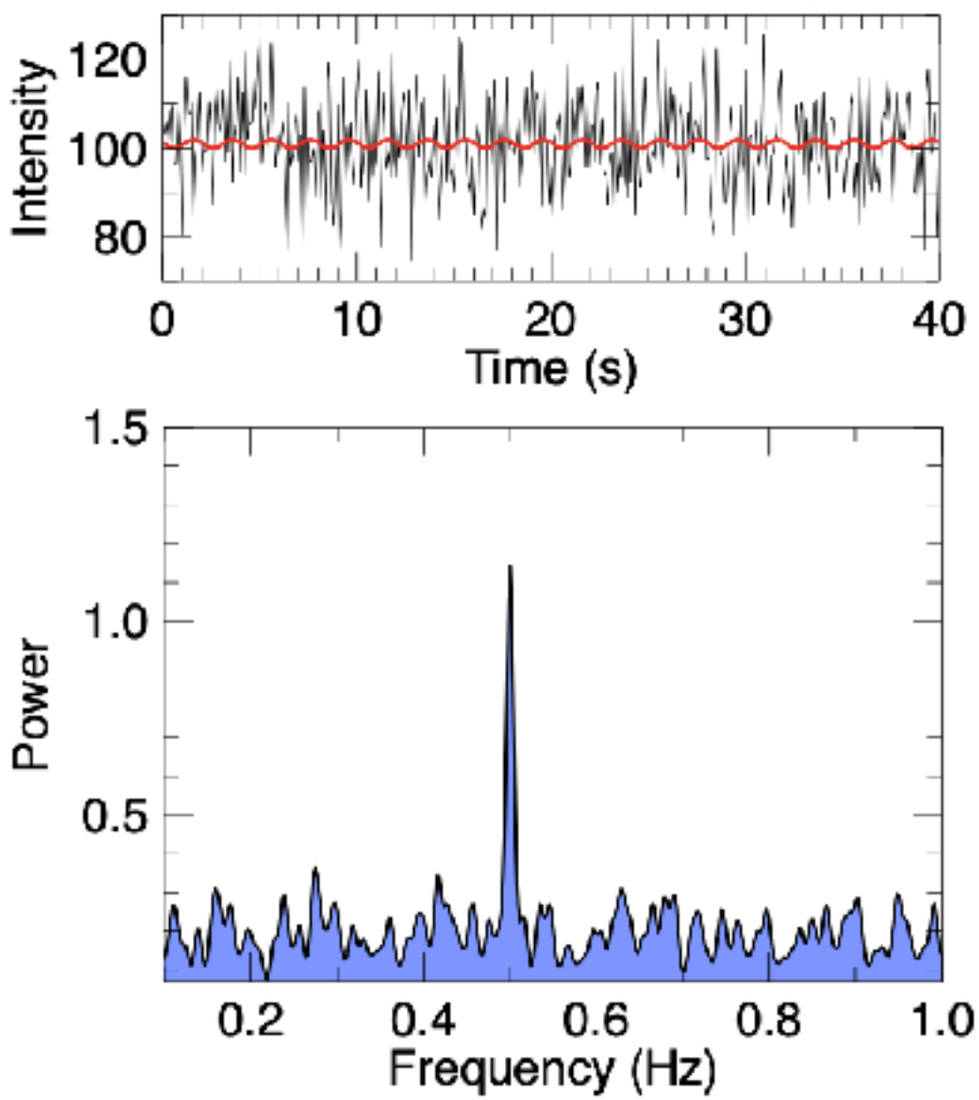

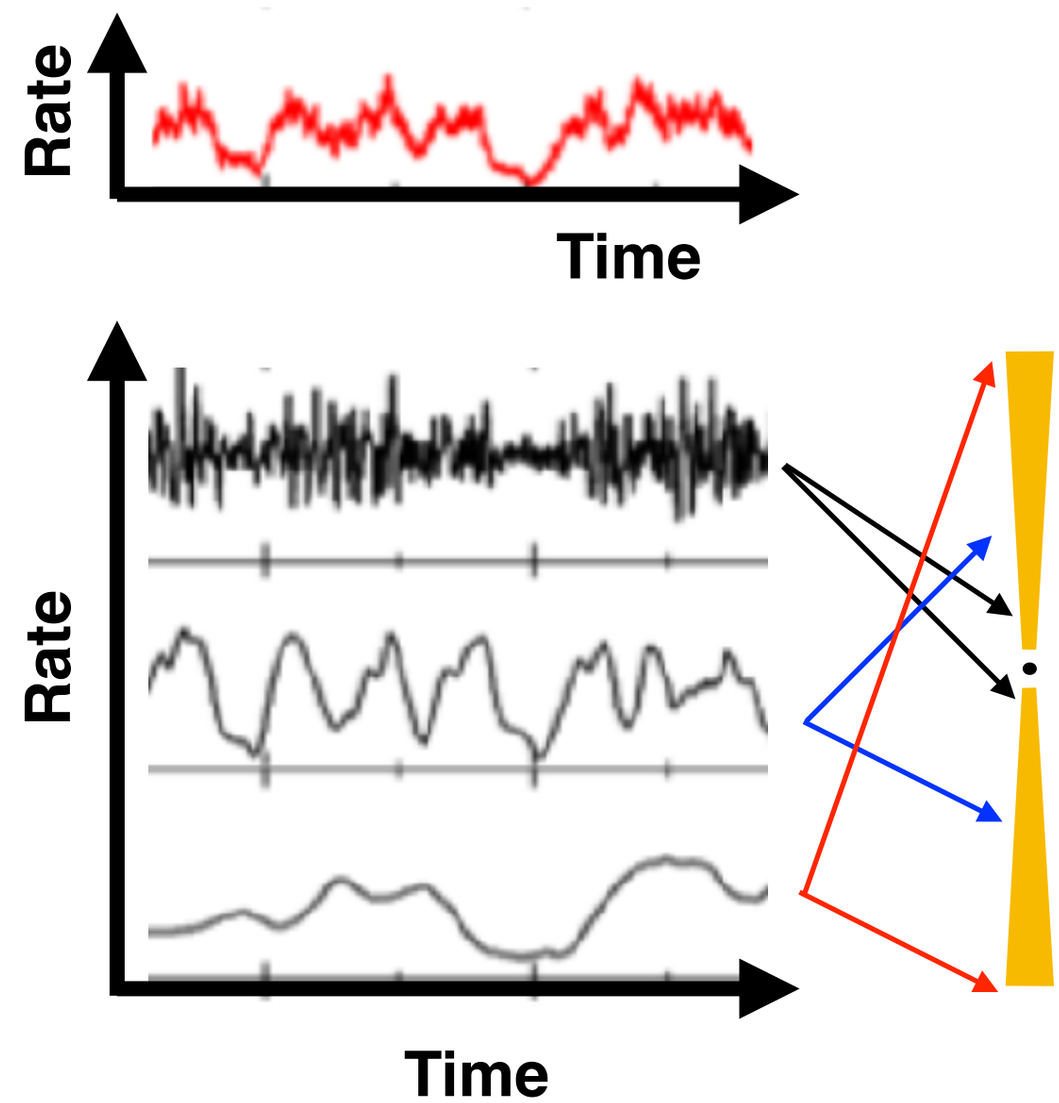

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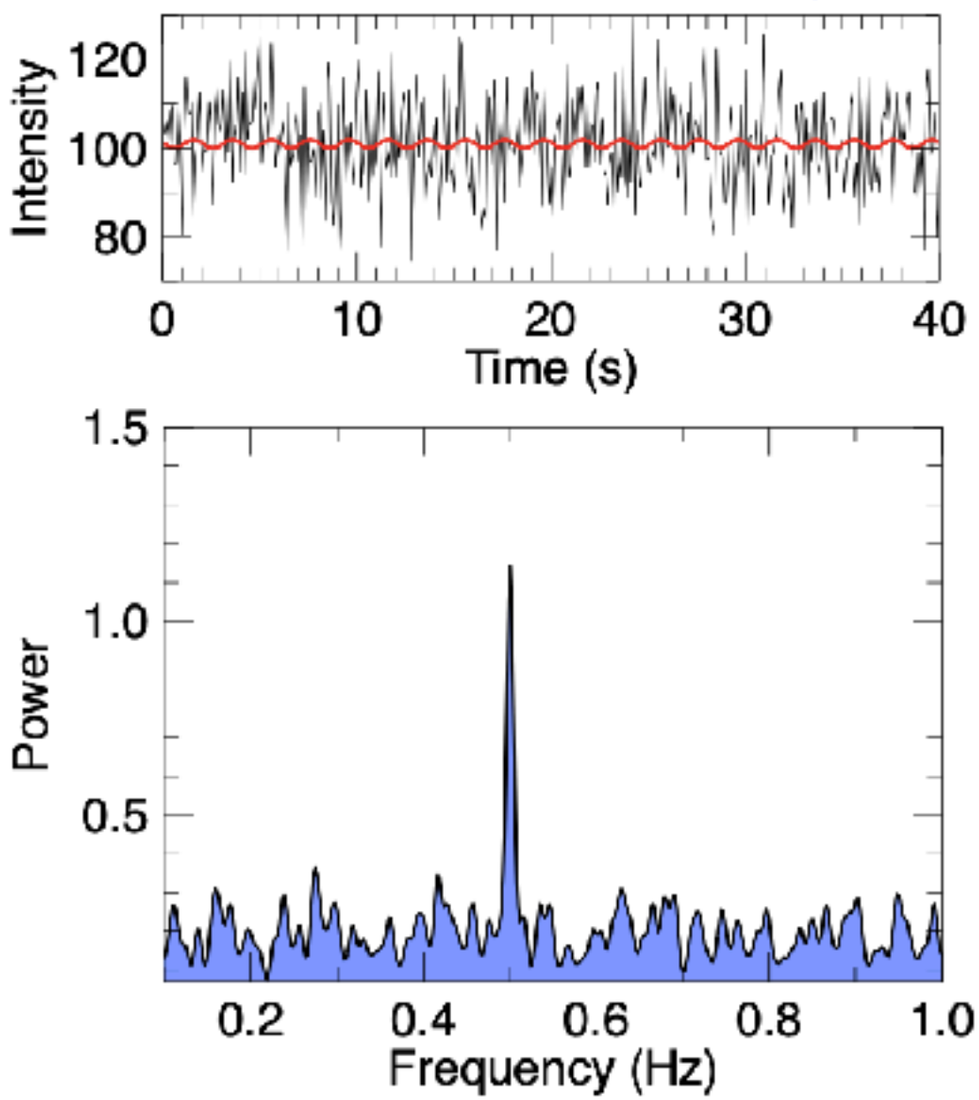
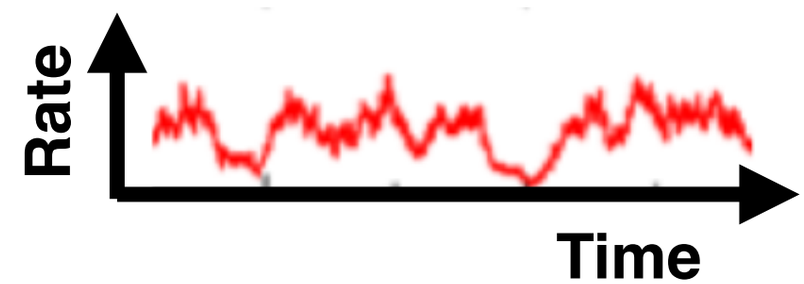
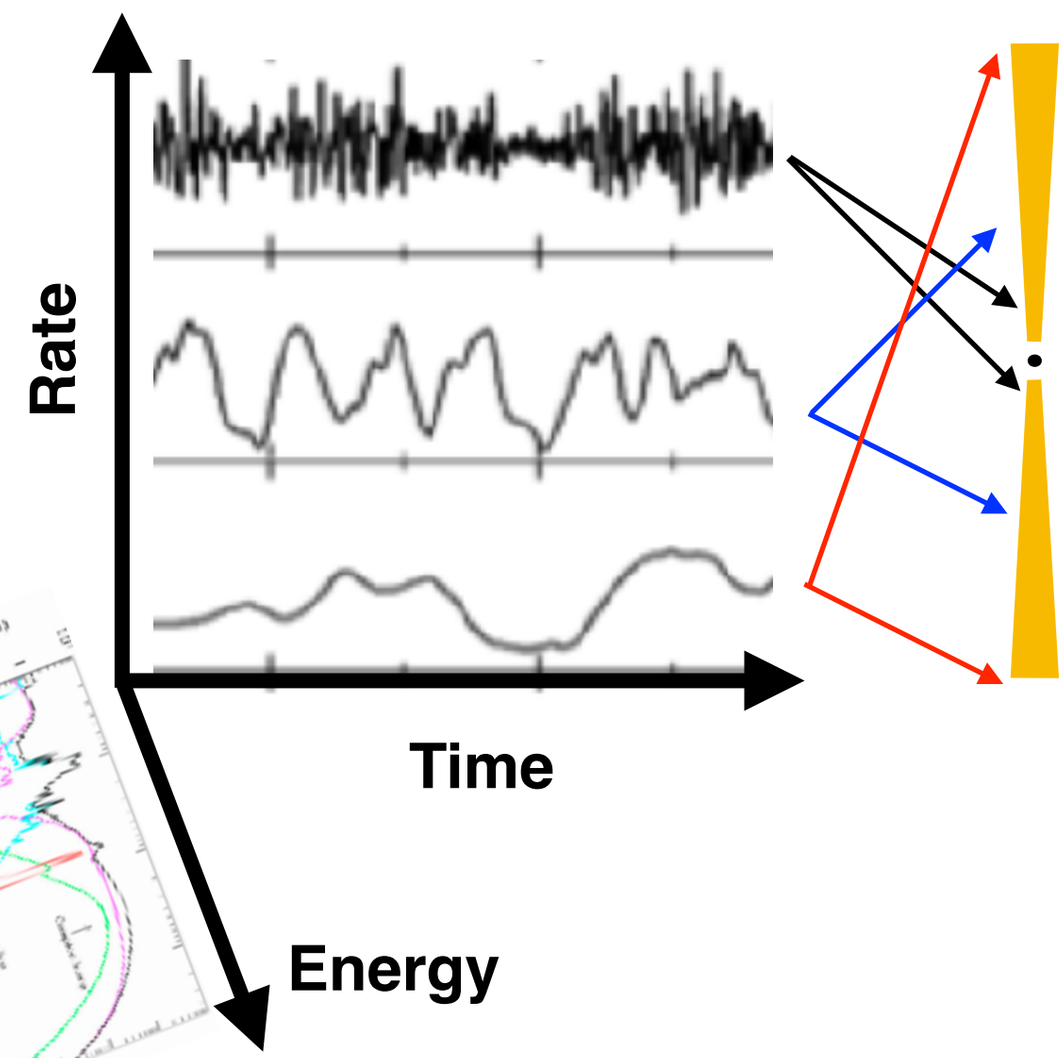
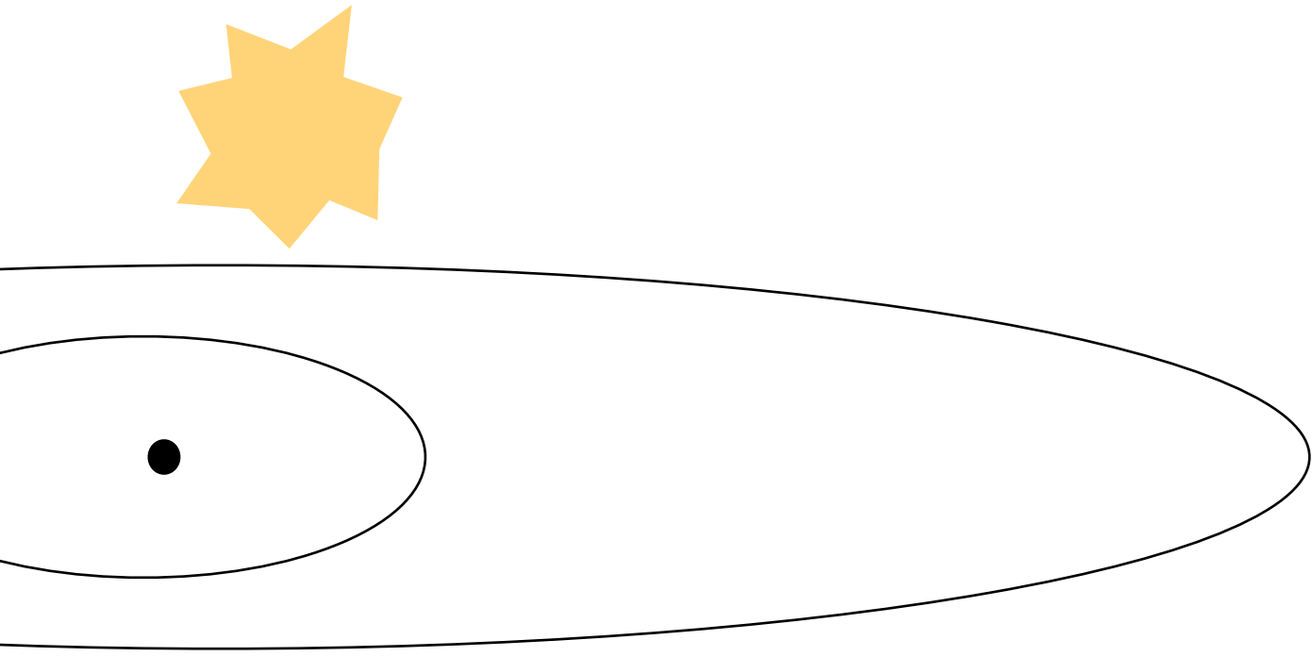






X-ray reverberation

Response of the irradiated disc



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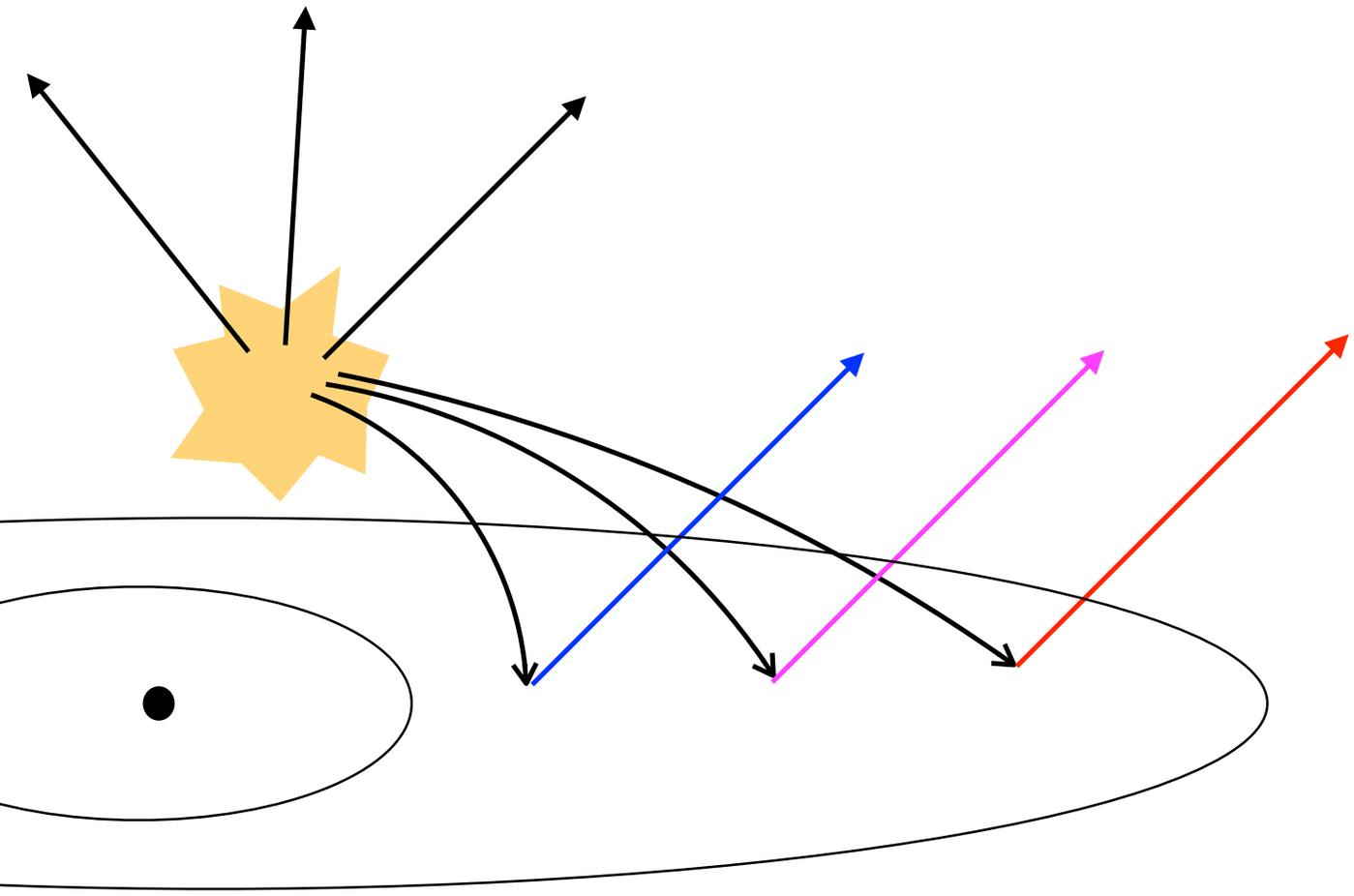

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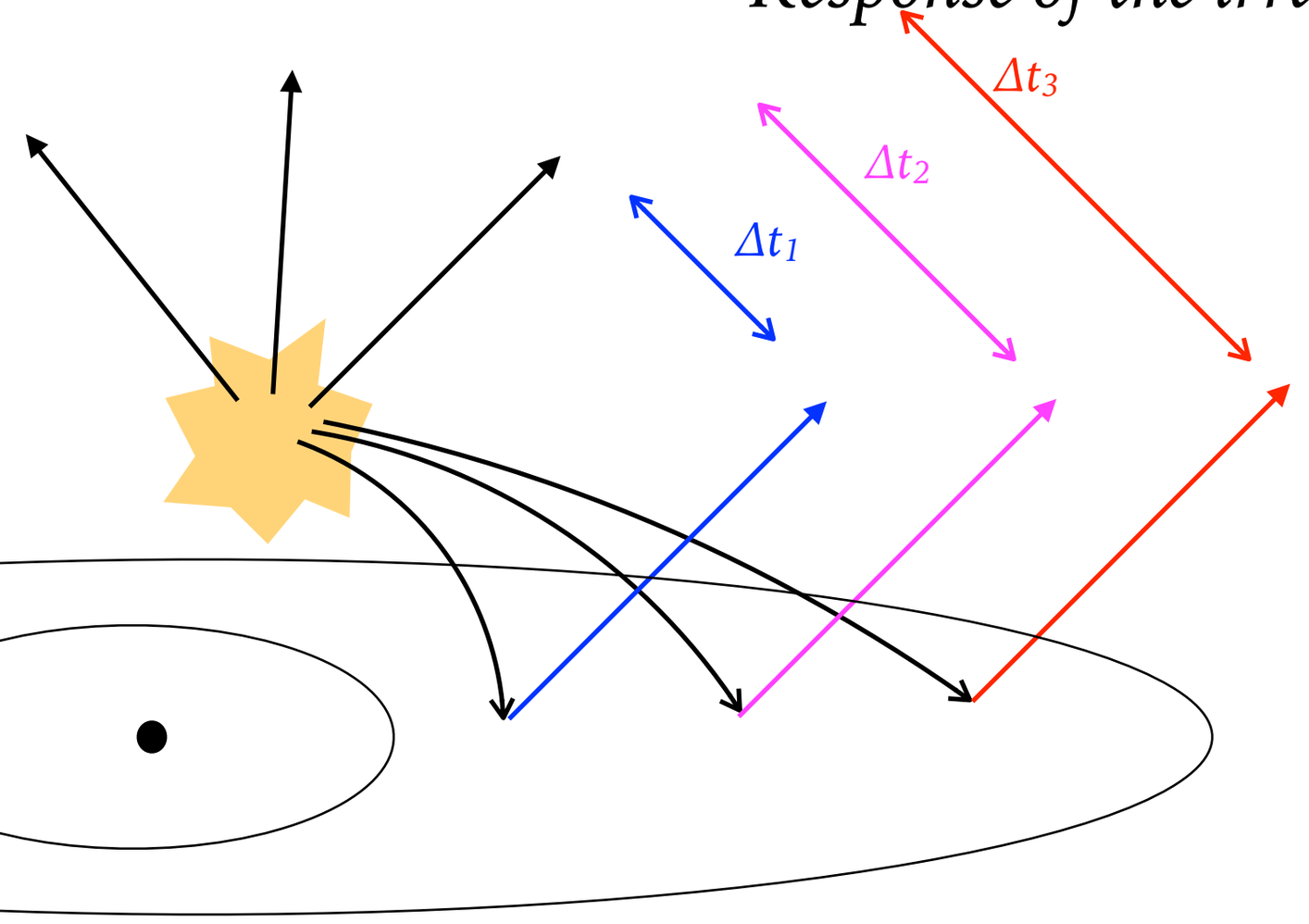

Physical separation between emitting and reprocessing regions should produce delays

[e.g. Fabian +'89; Stella '90; Reynolds+'99; Fabian+'00; Young & Reynolds '00]

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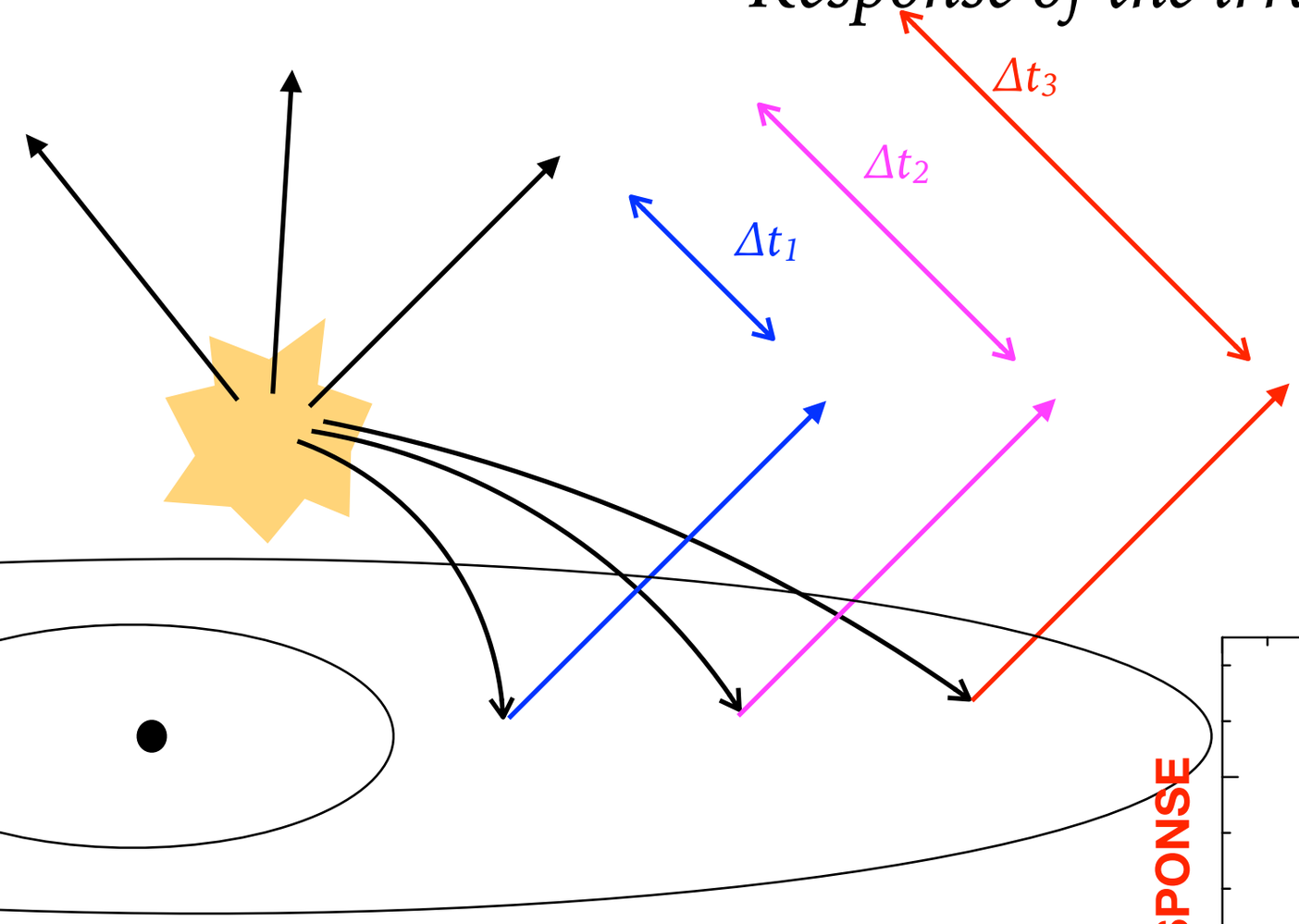

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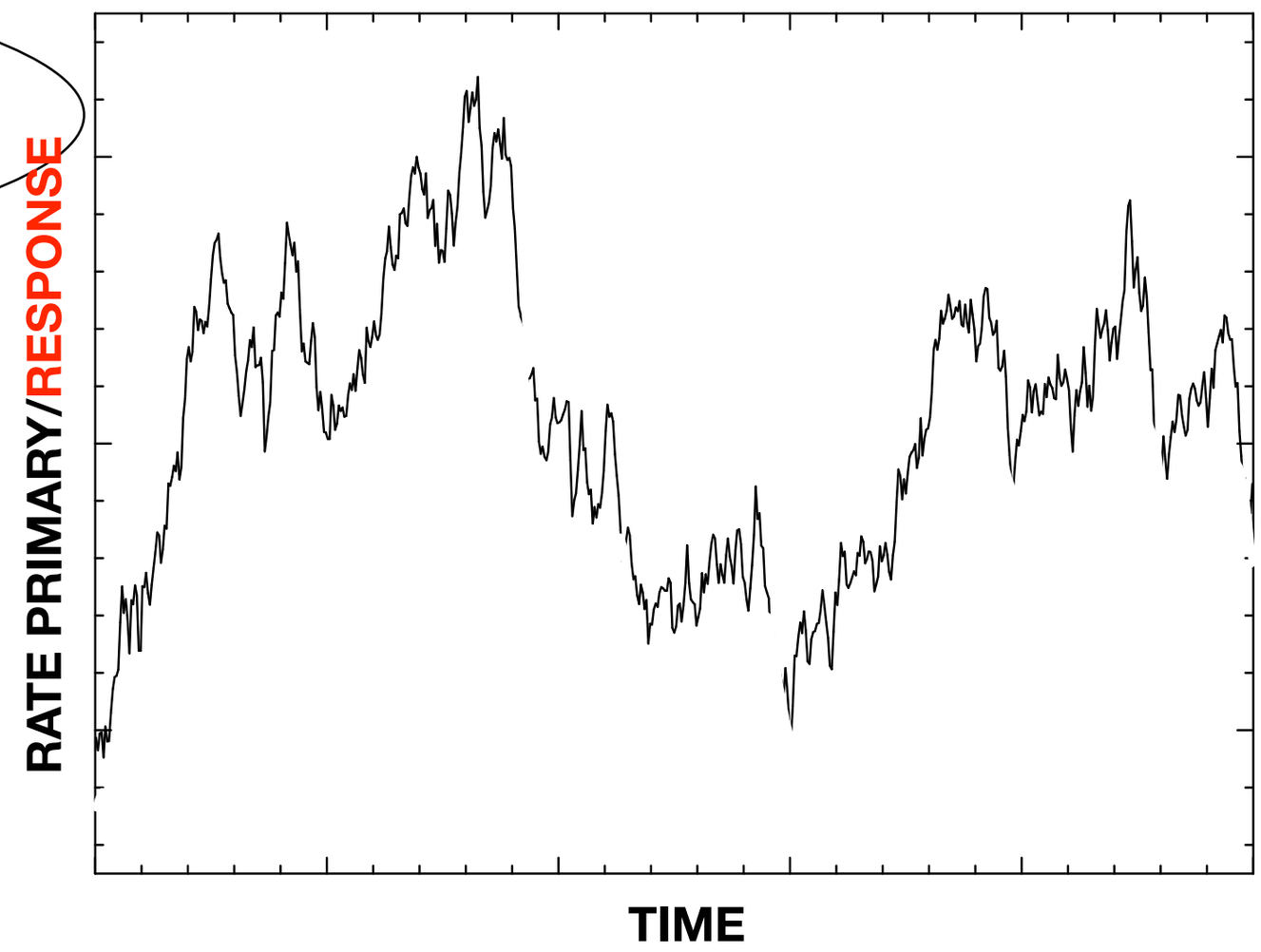

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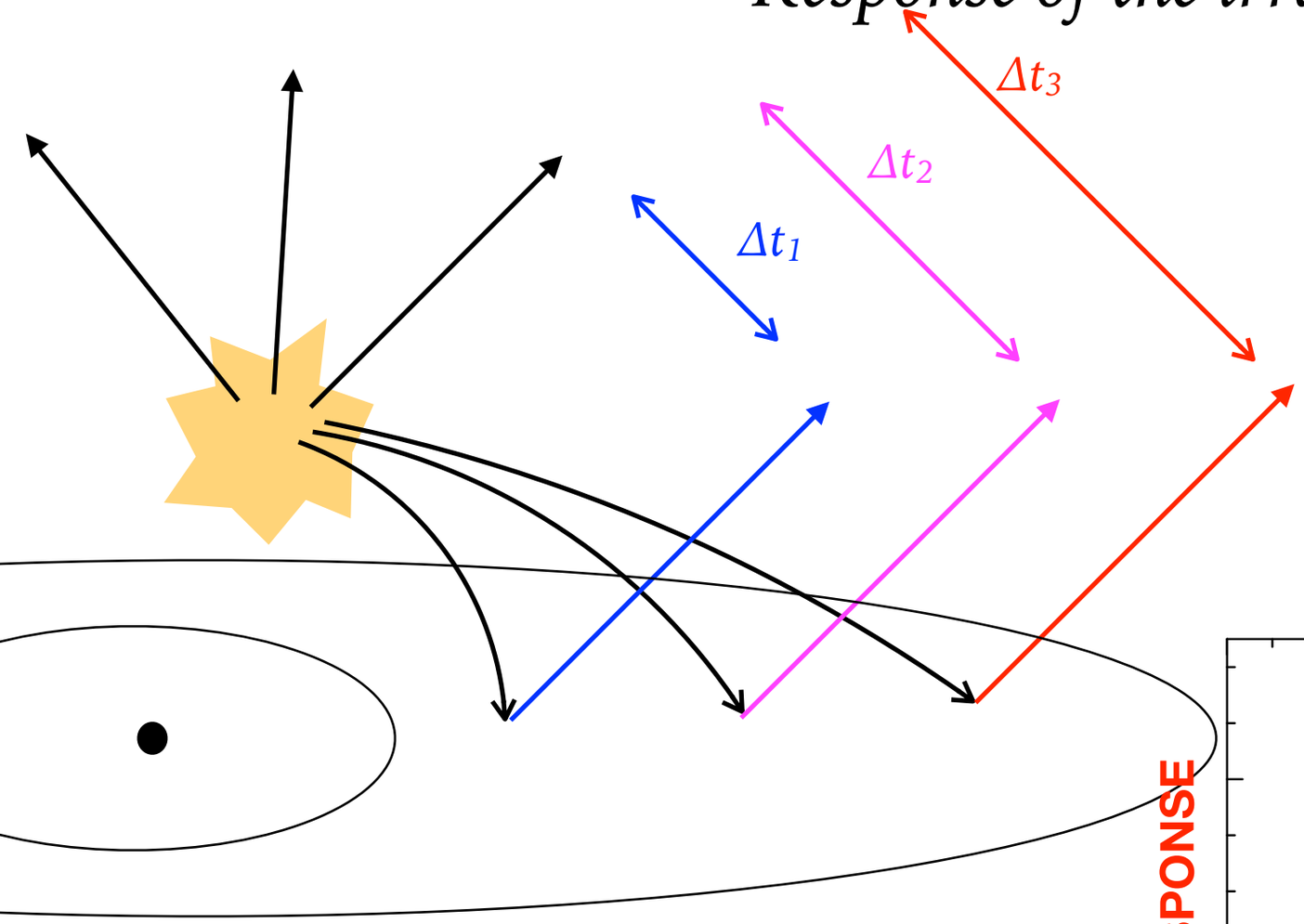

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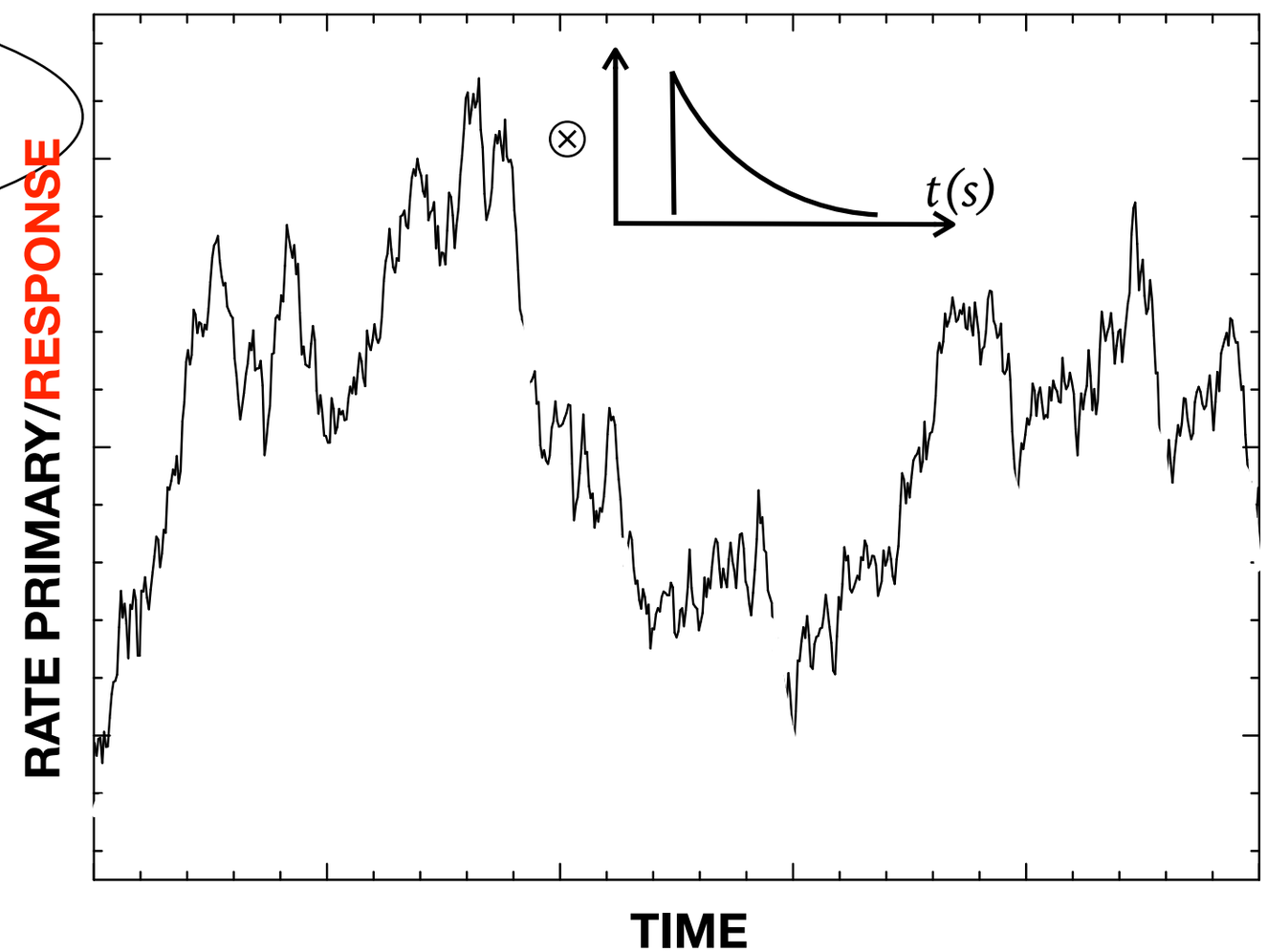

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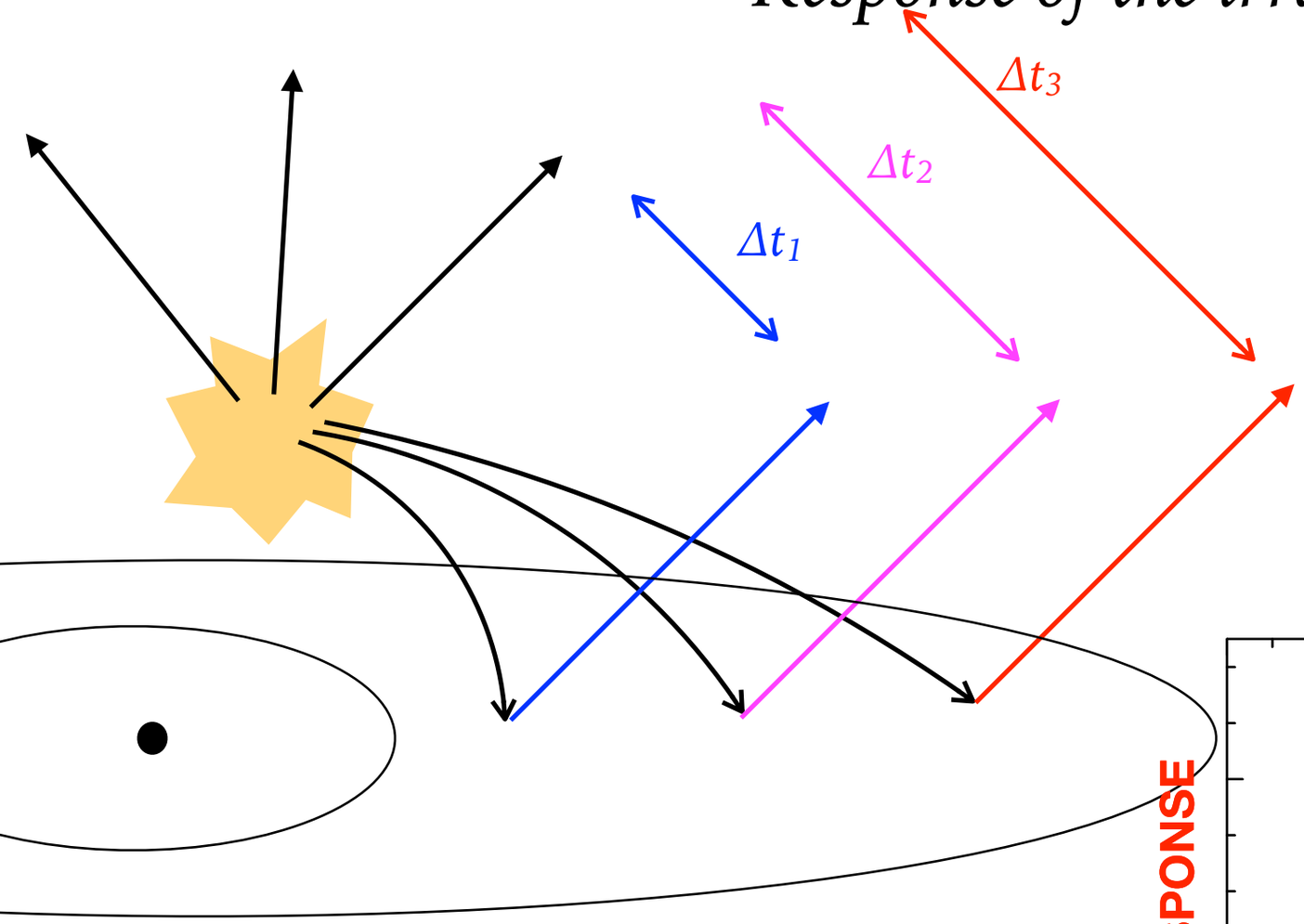

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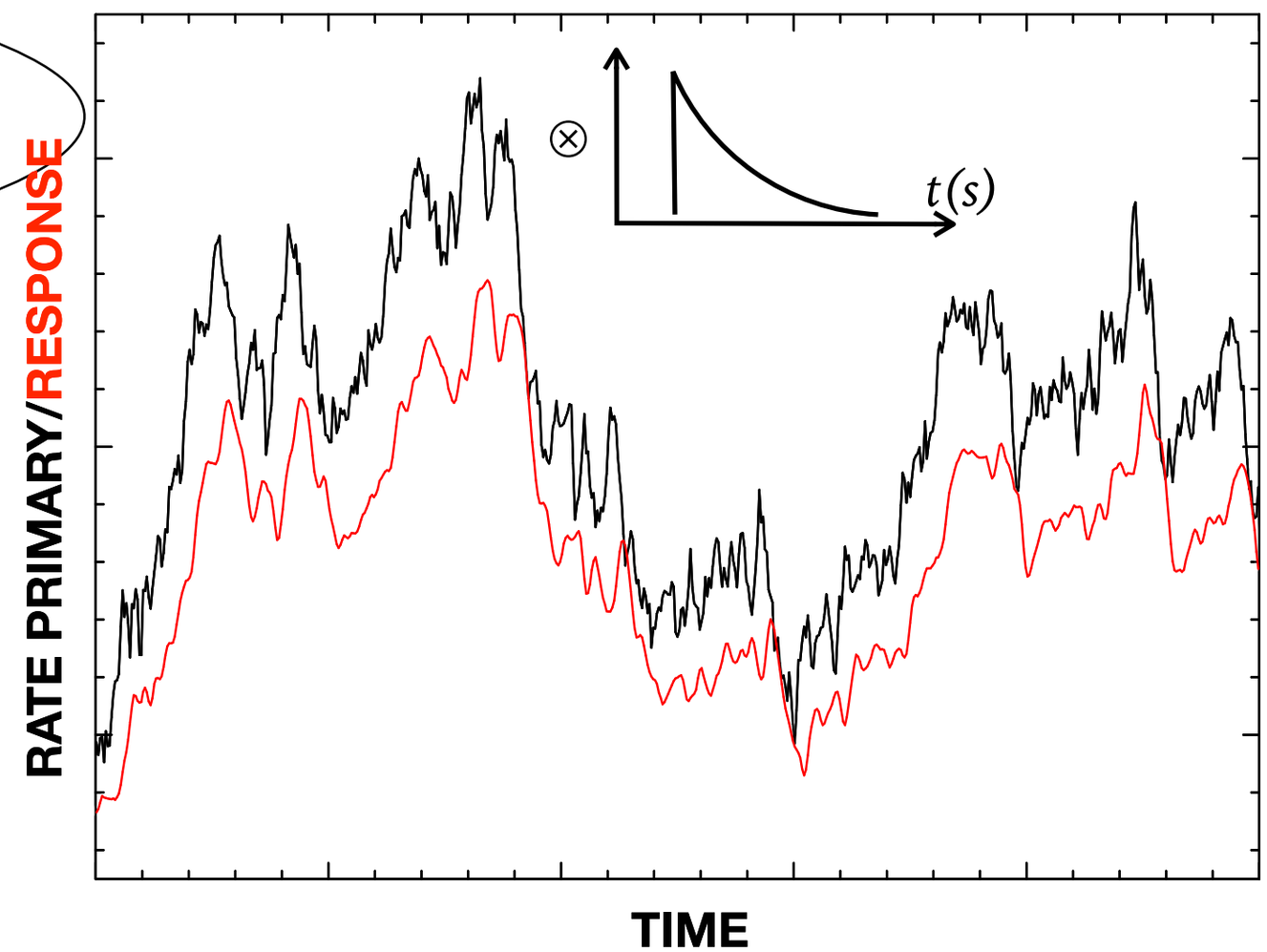

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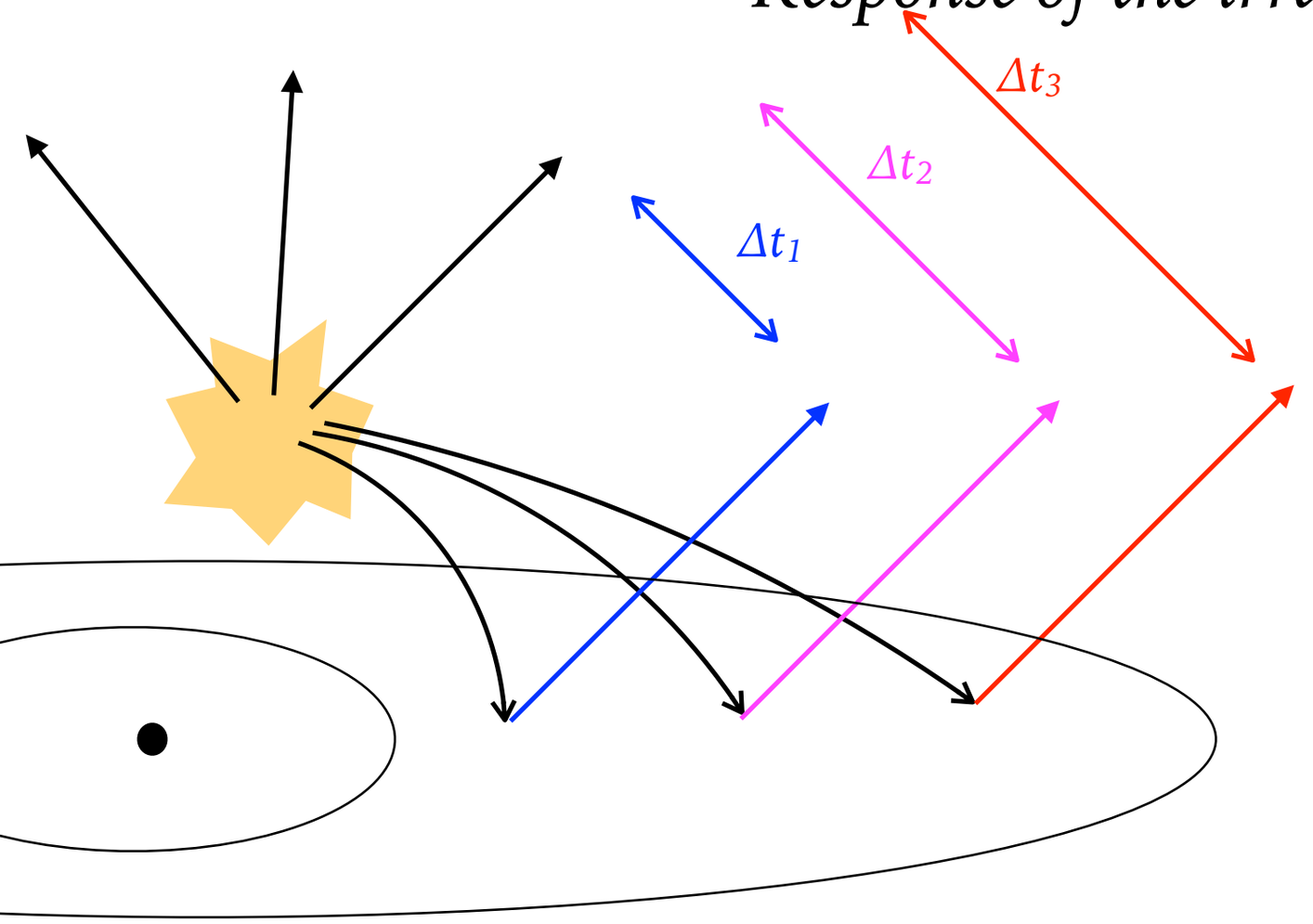

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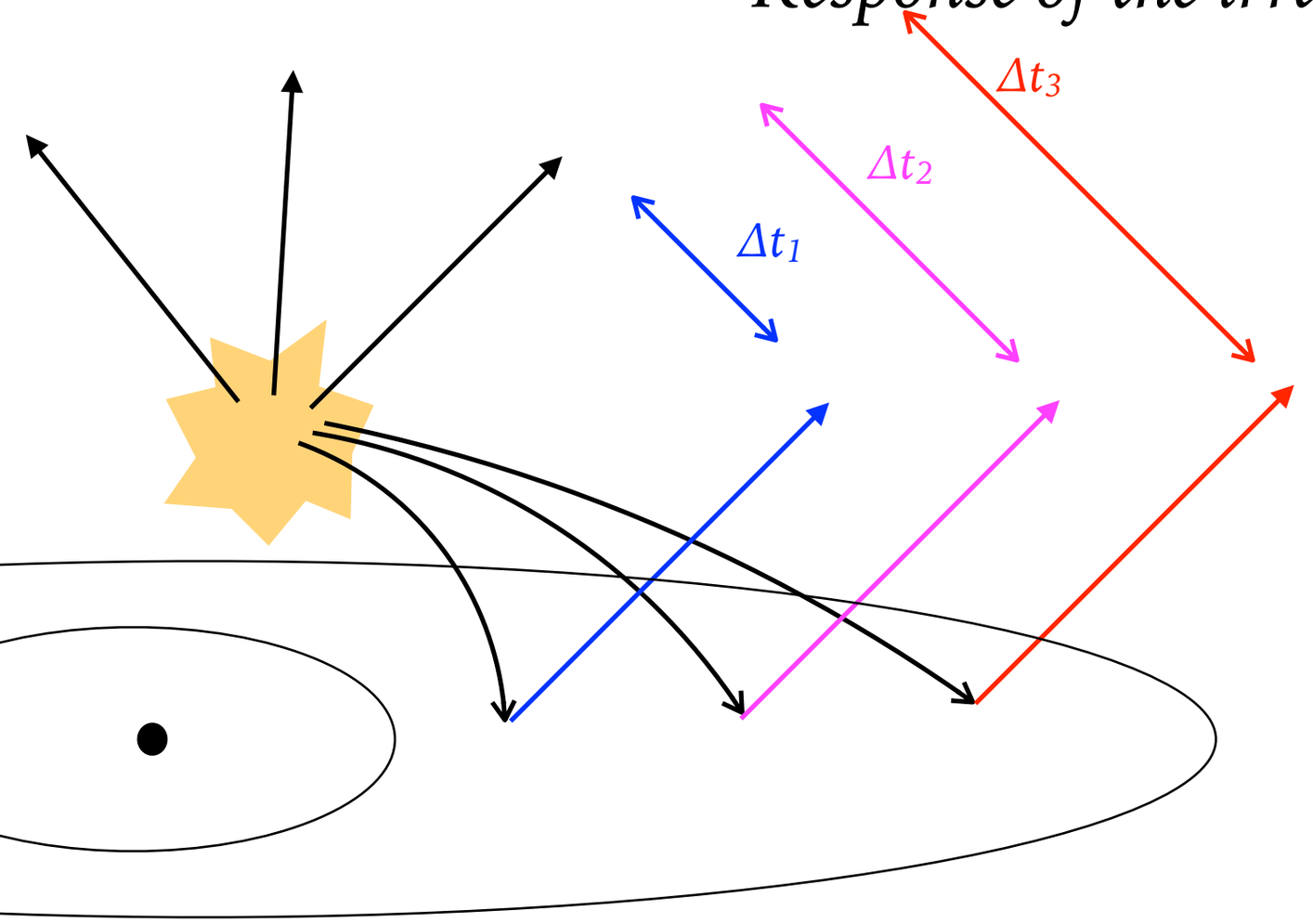

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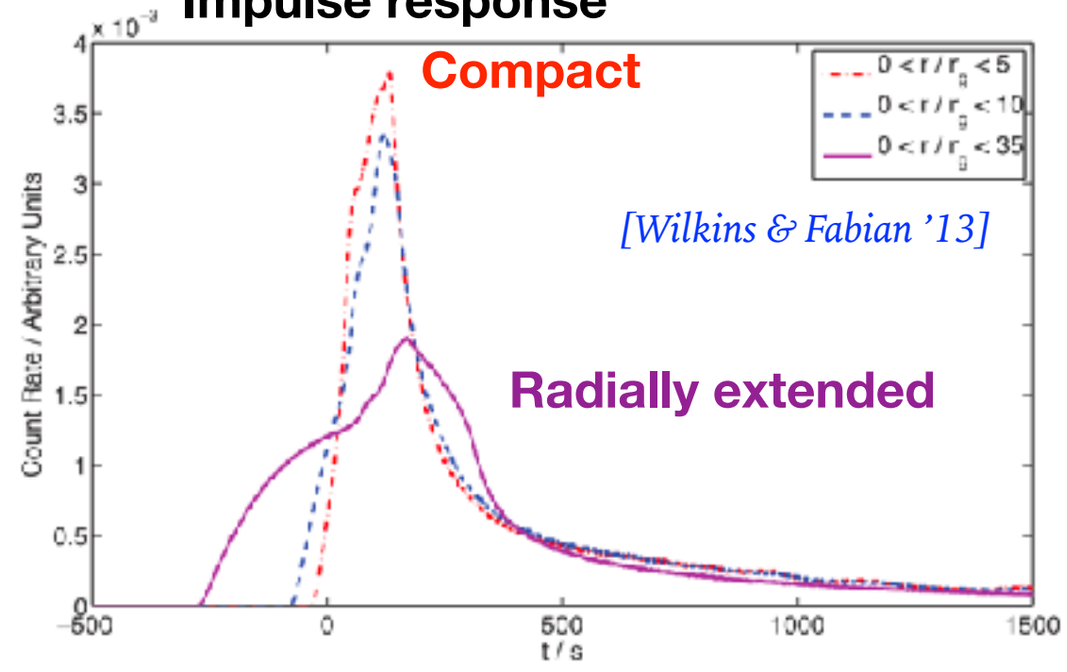
Impulse response



[Wilkins & Fabian '13]

Results obtained from the X-ray spectral-timing study of AGN and BHXRBs

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accreting WD

[e.g. Scaringi+'13]

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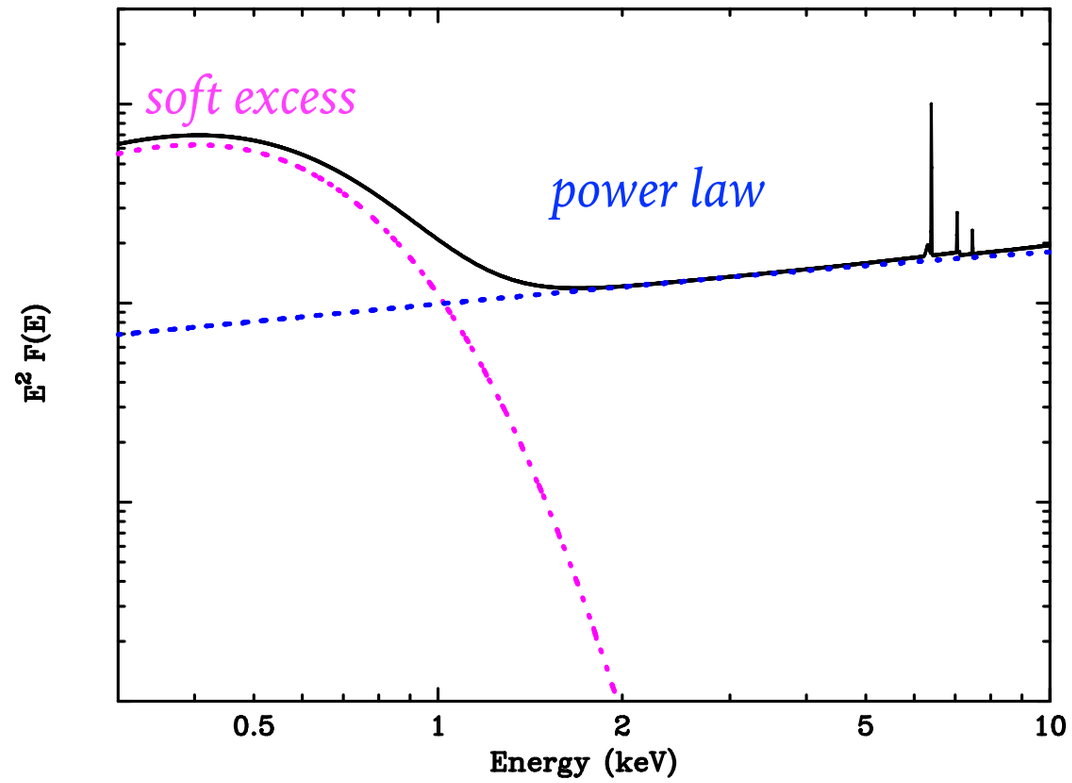
Detection of X-ray reverberation in AGN

Revealing a causal relation between the soft excess and the hard power law



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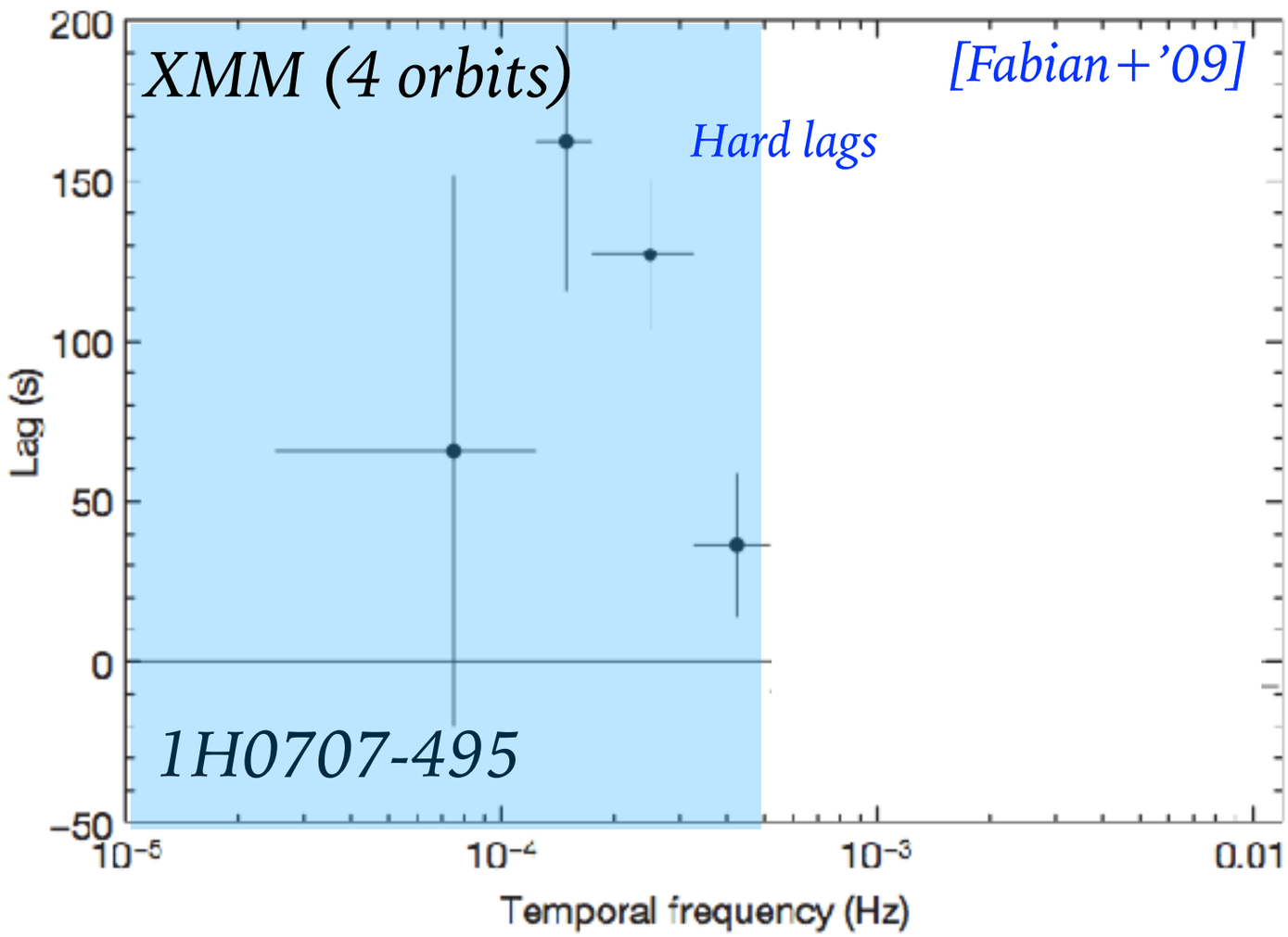

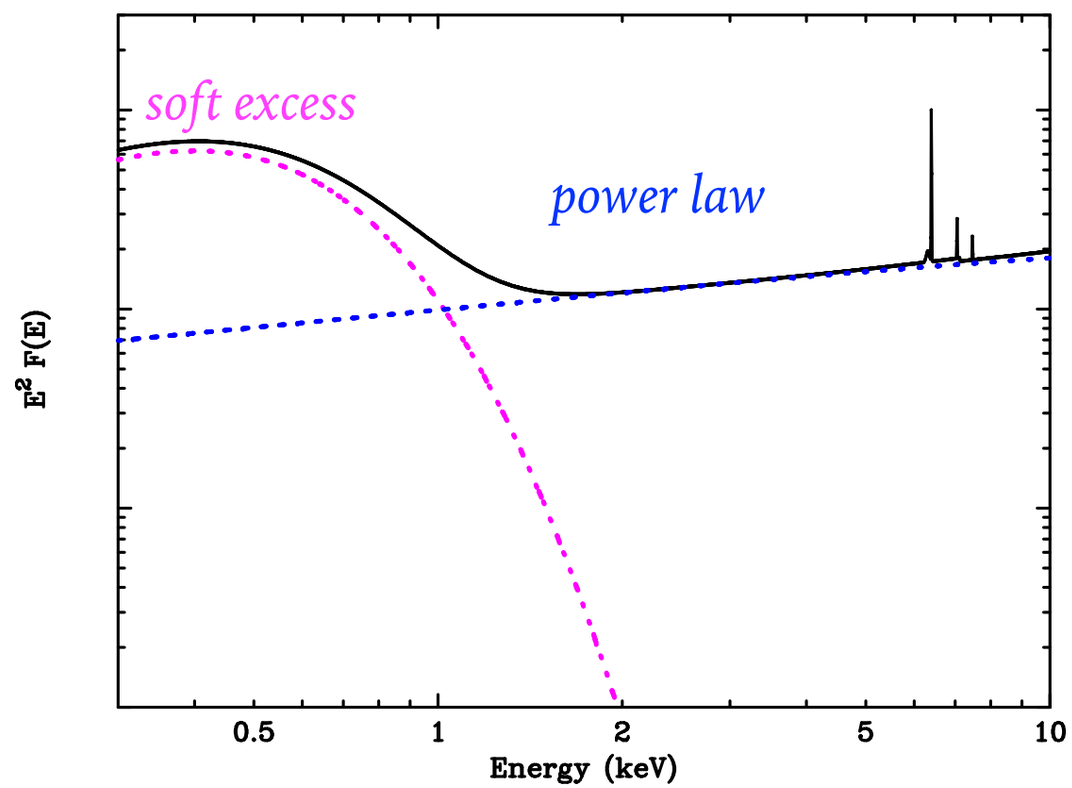

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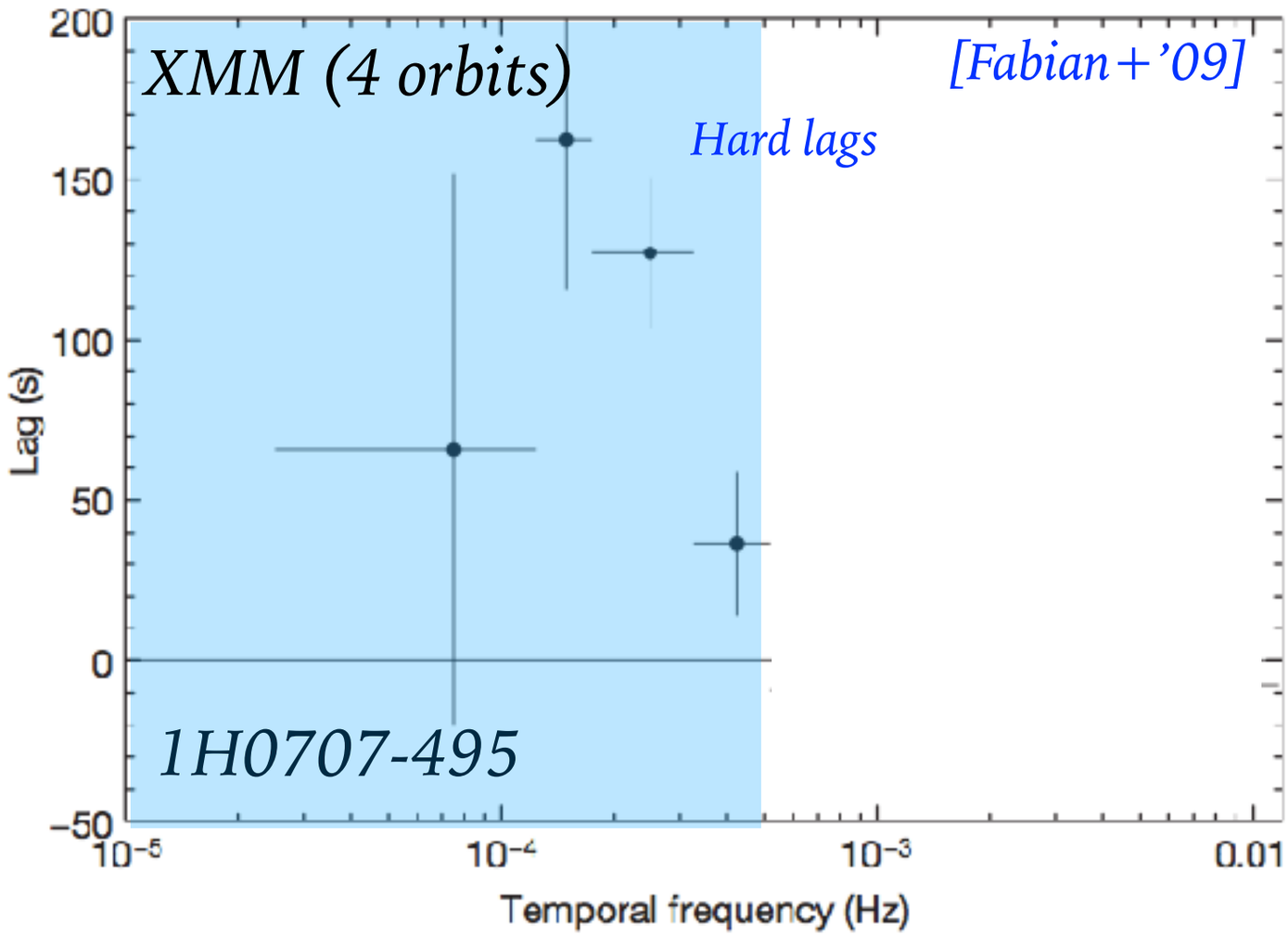

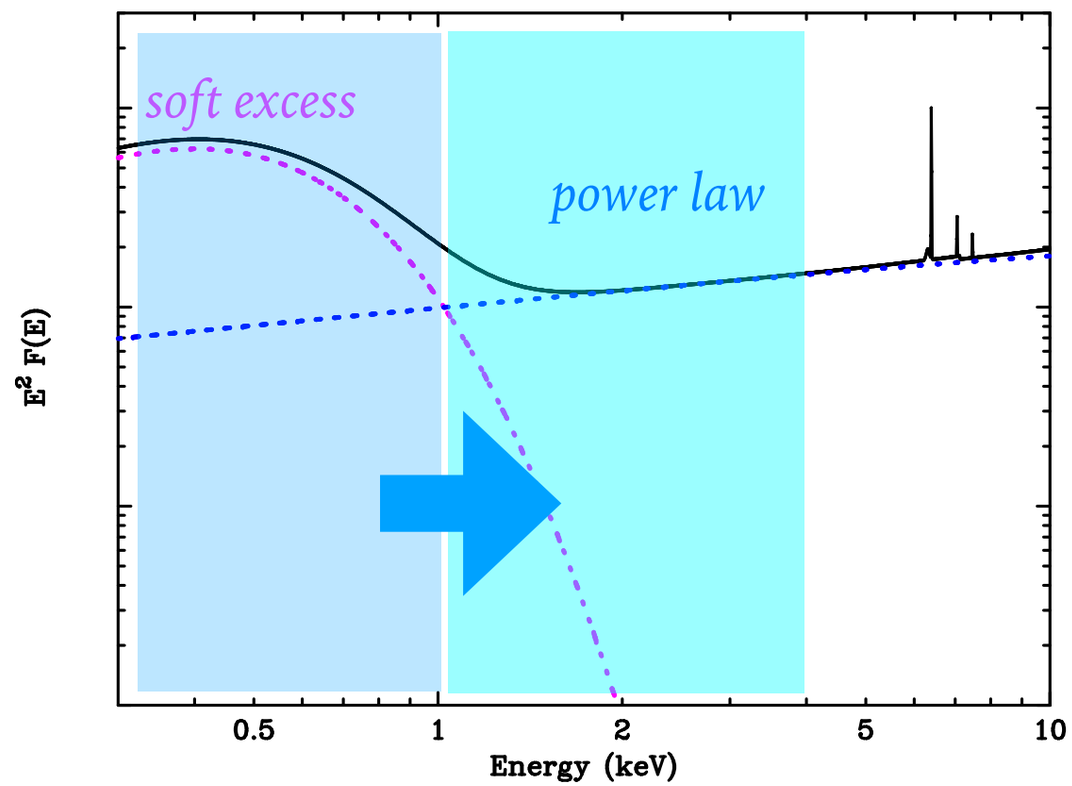

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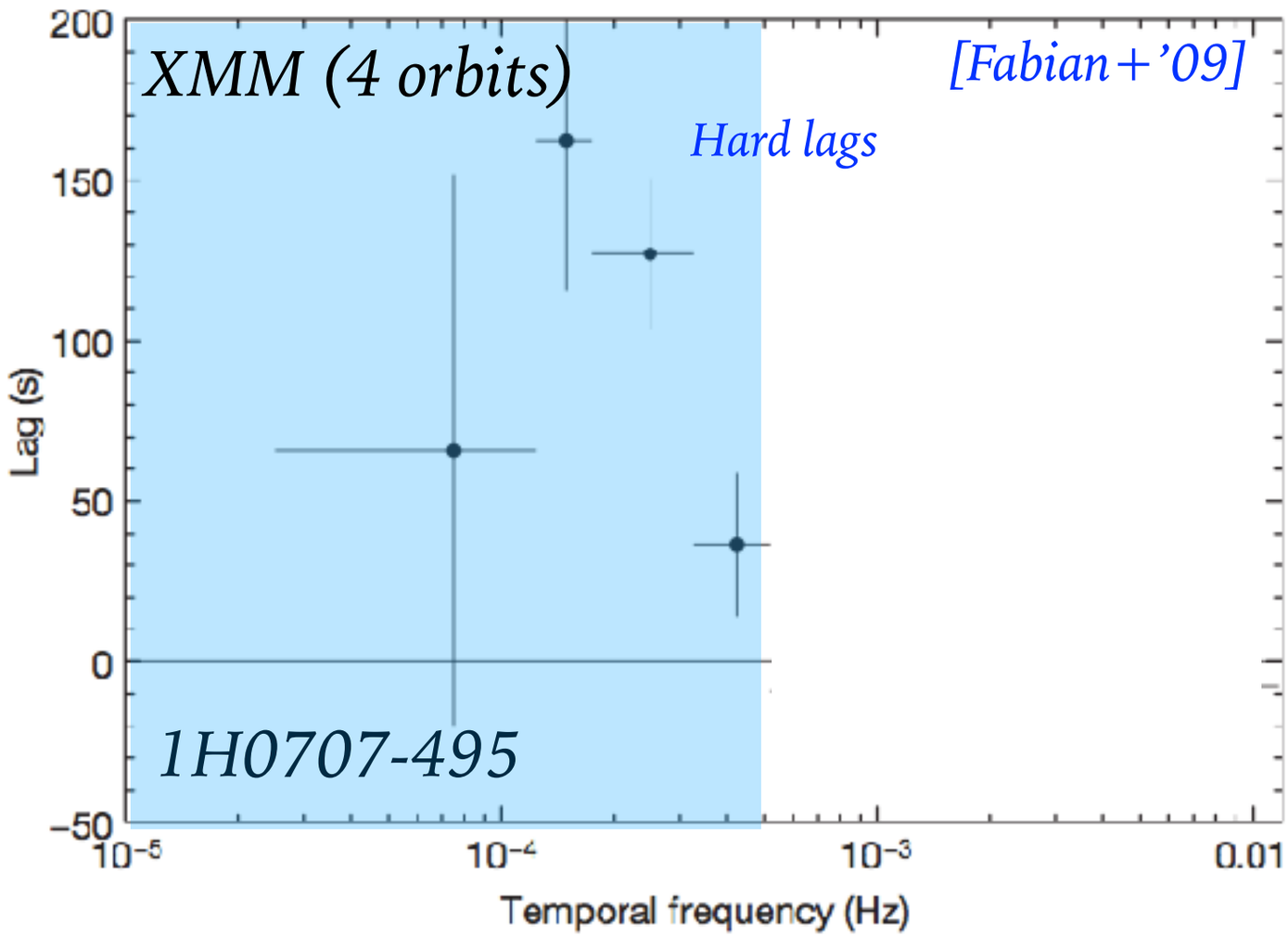

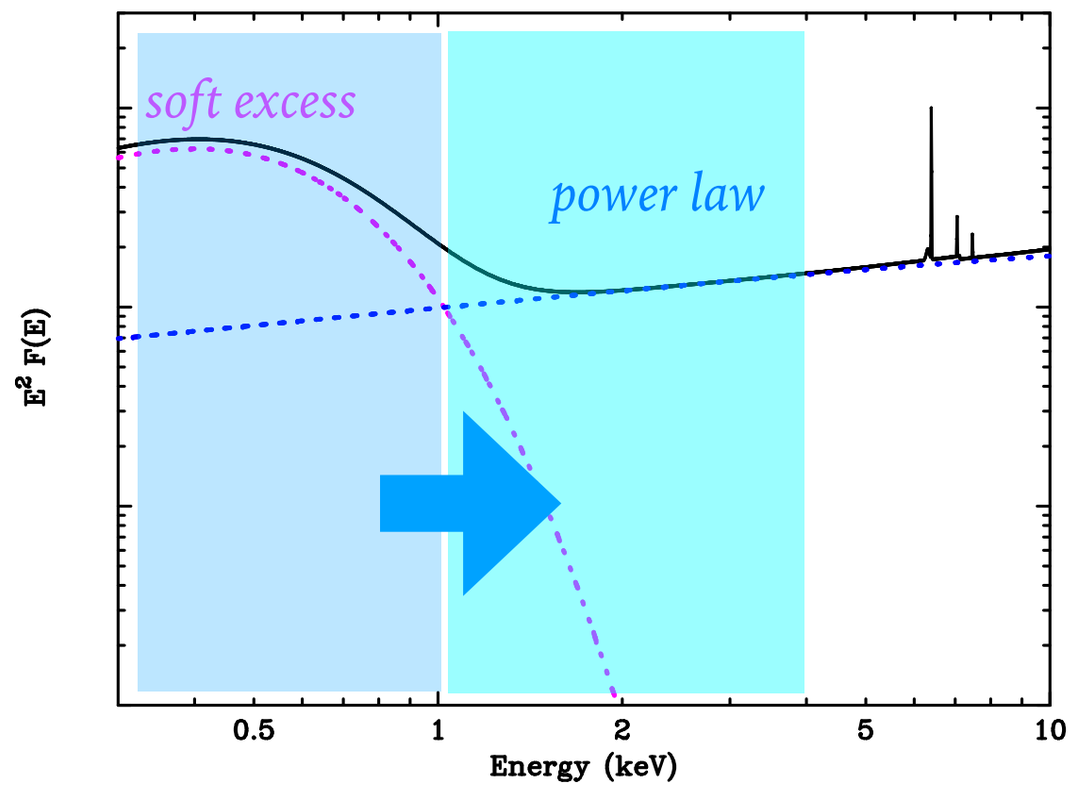

Hard lags in BHXRBs

e.g. Miyamoto+'88; Kazanas+'97; Nowak+'99; Kotov+'01; Arévalo & Uttley '06; Cassatella+'12; Veledina '18

Hard lags in AGN

e.g. Papadakis+'01; Vaughan+'03; McHardy+'04; Markowitz+'07; Arévalo+'08

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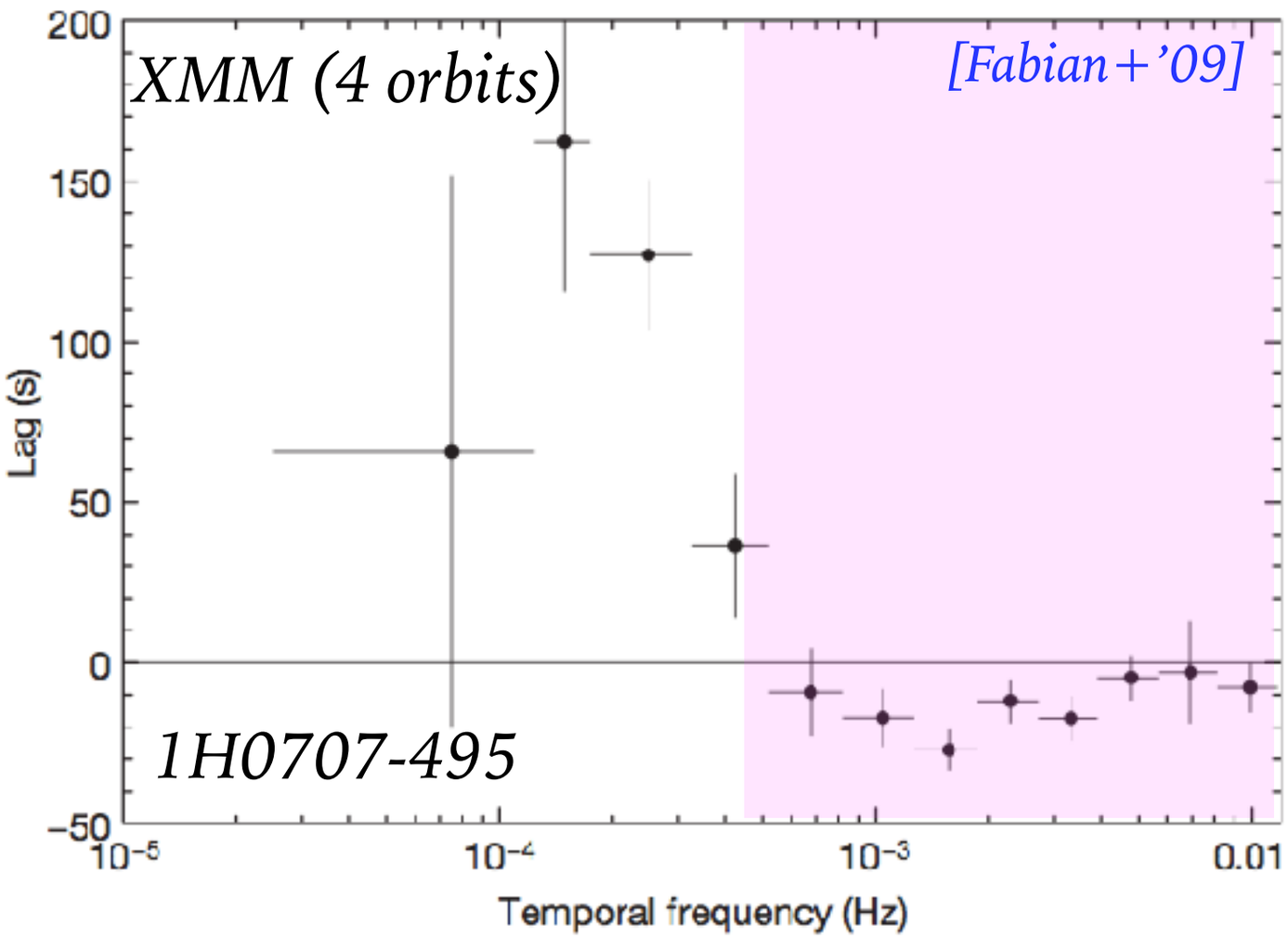

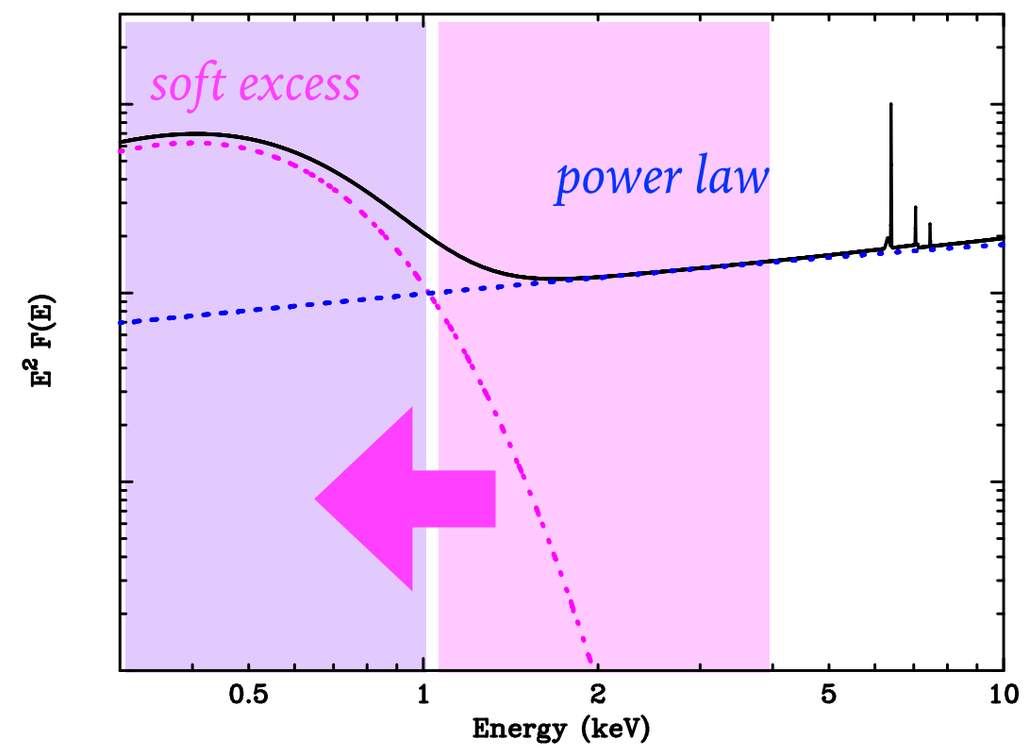

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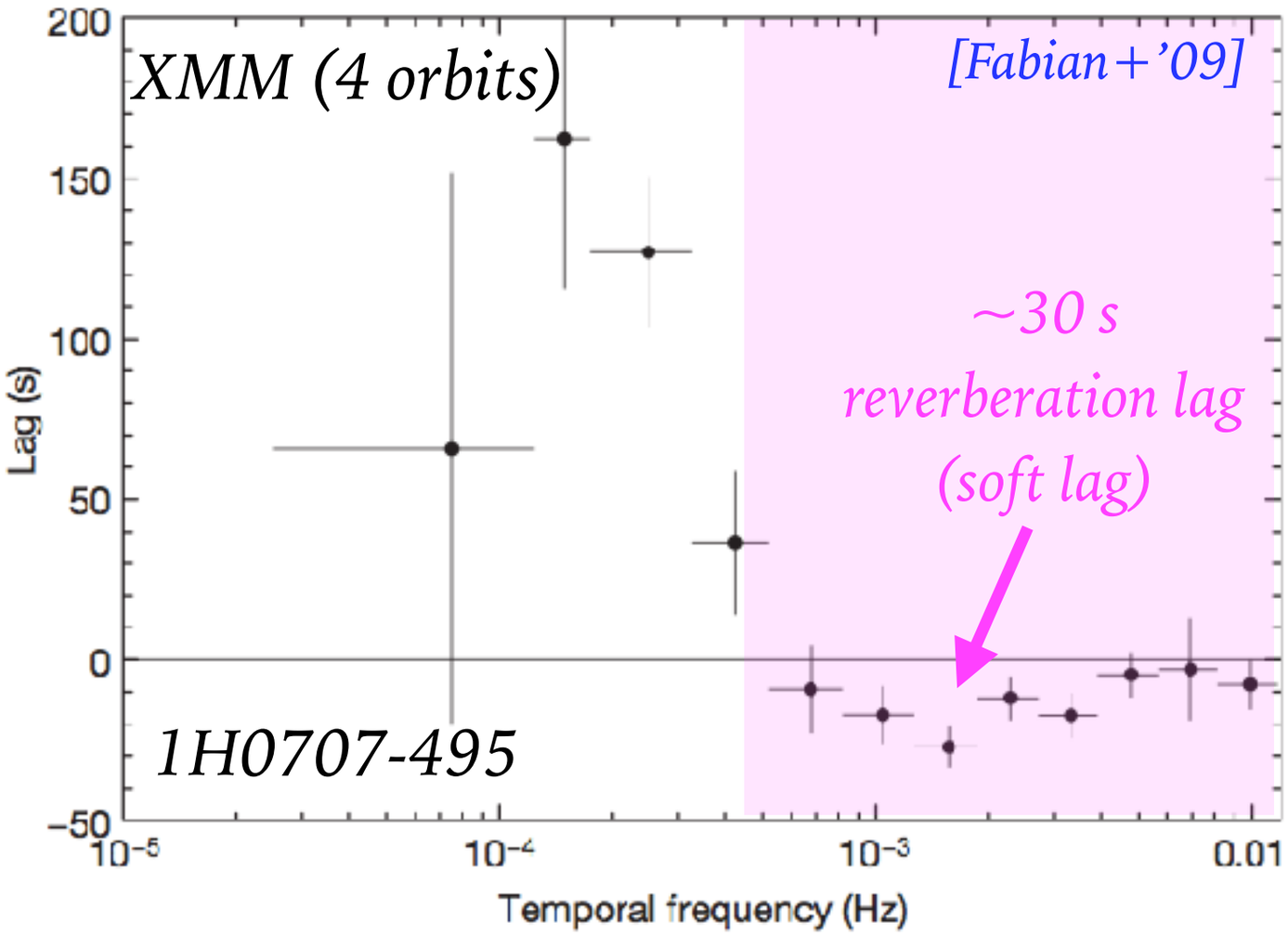

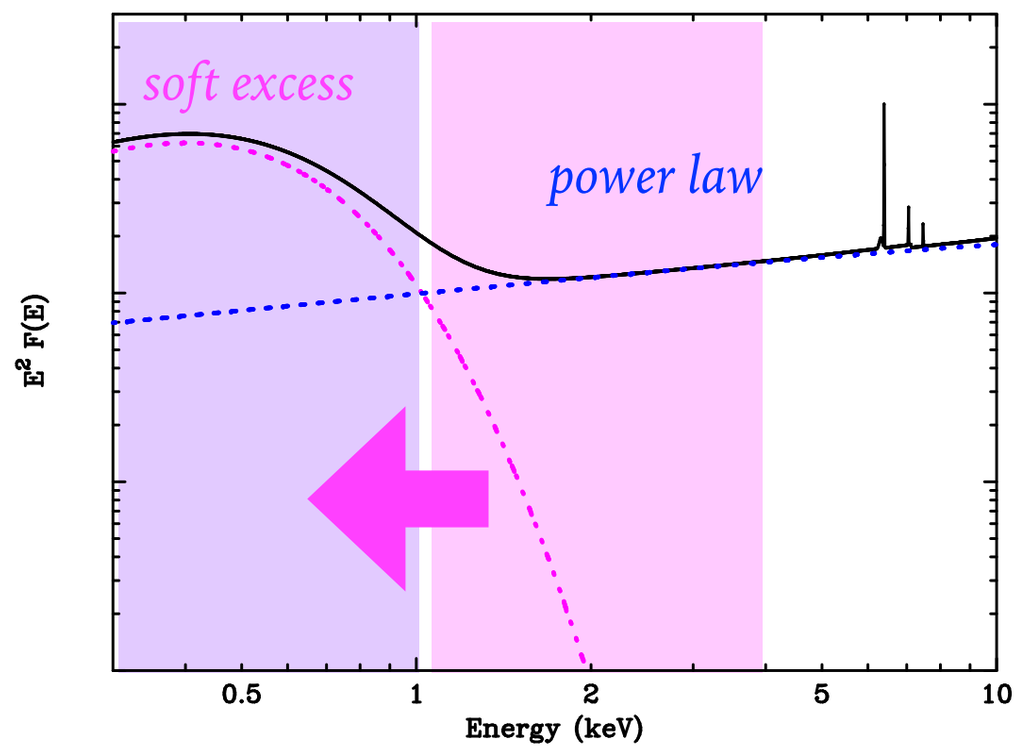

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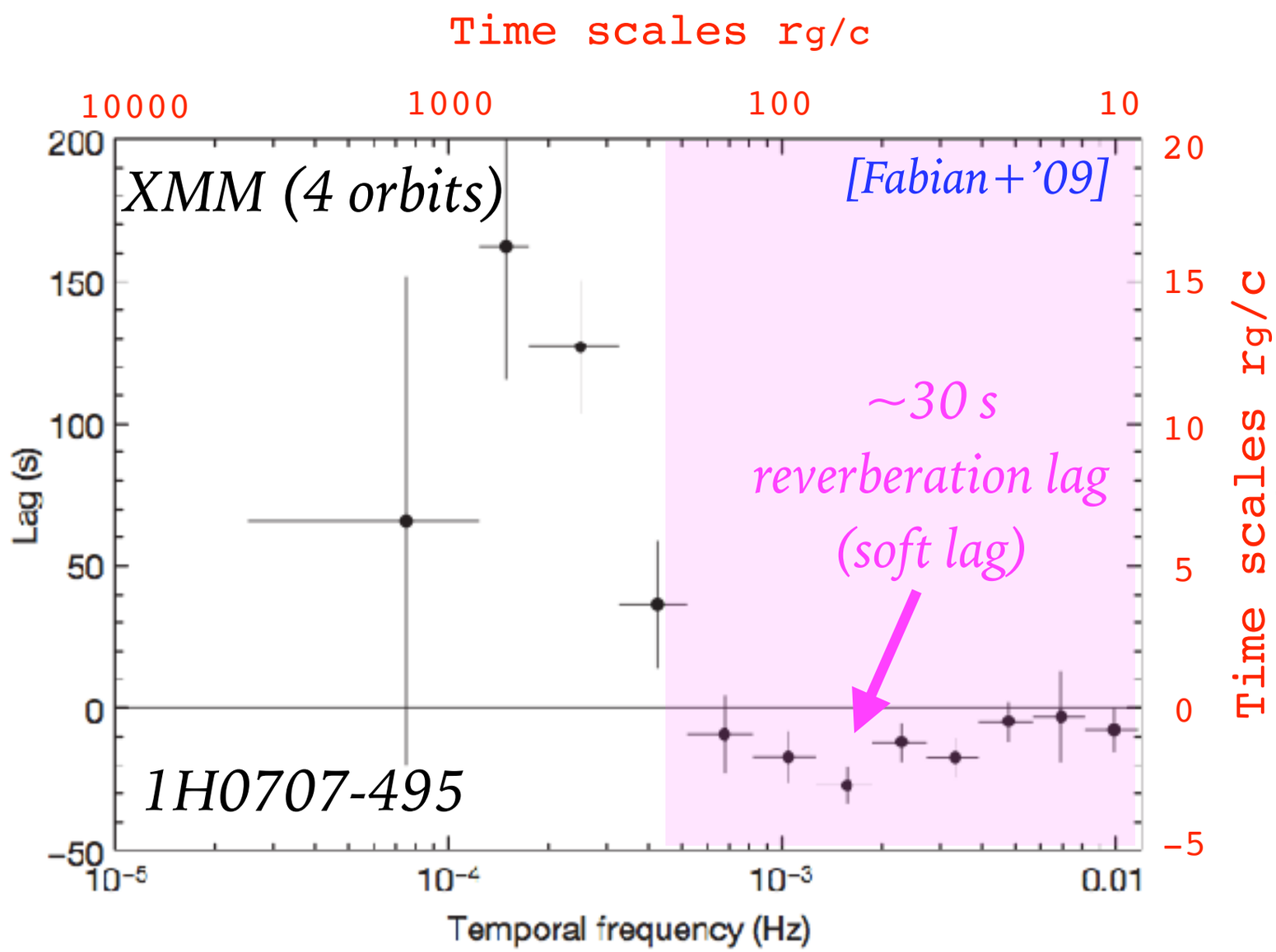

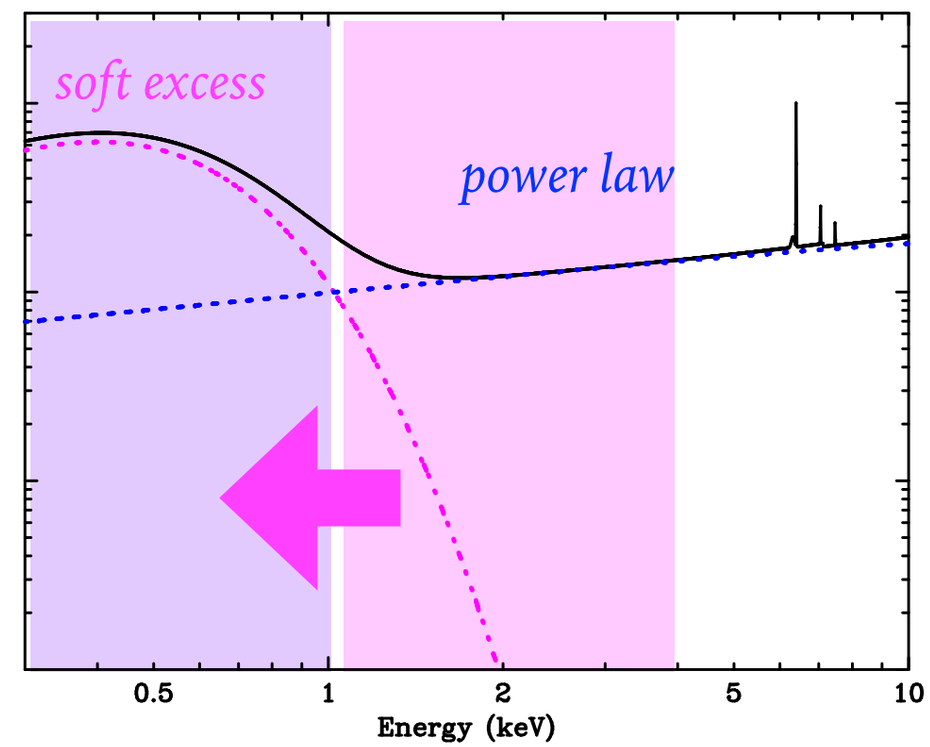

Compact corona, short disc-corona distance ➜ disc at ISCO

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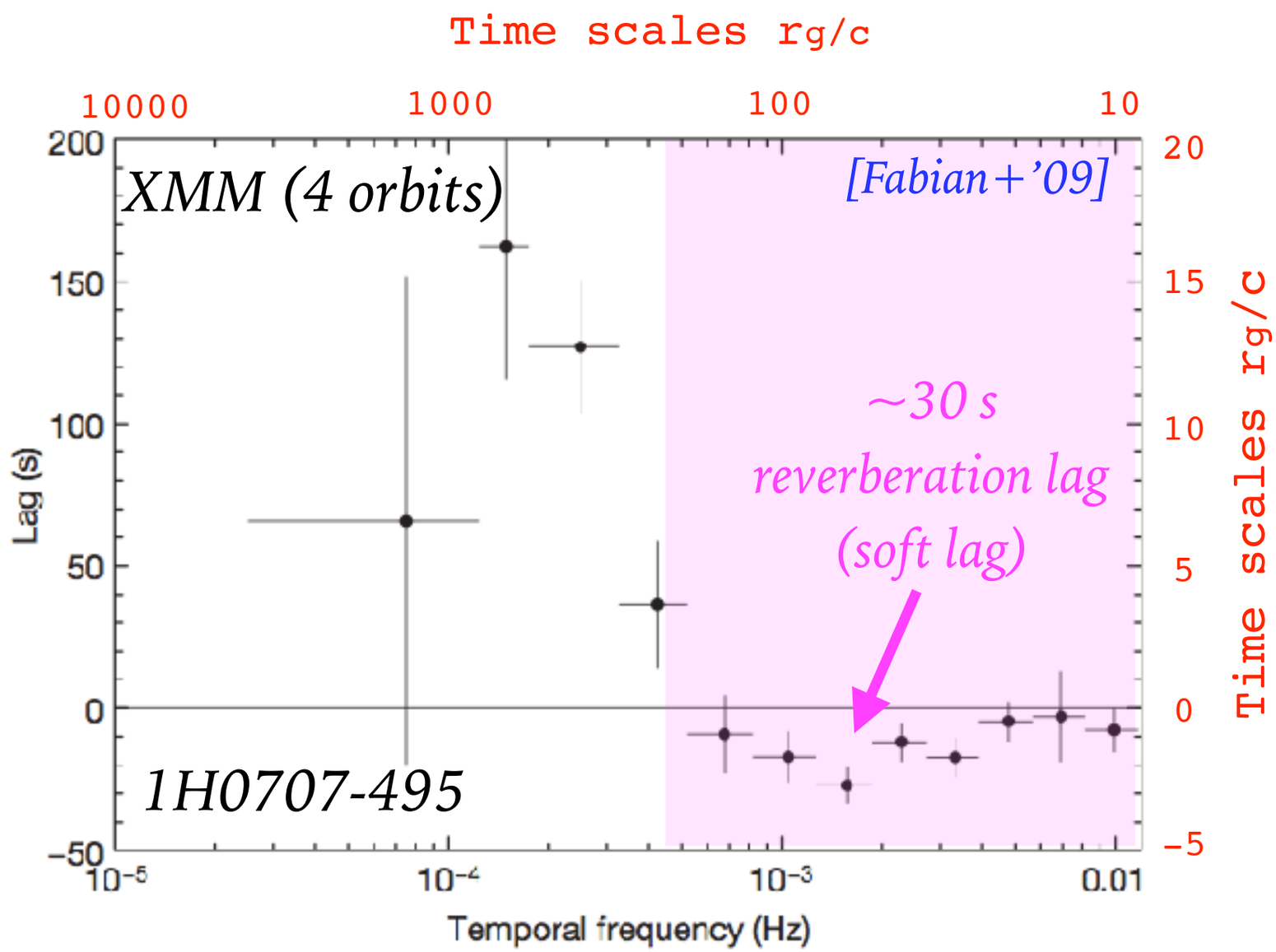
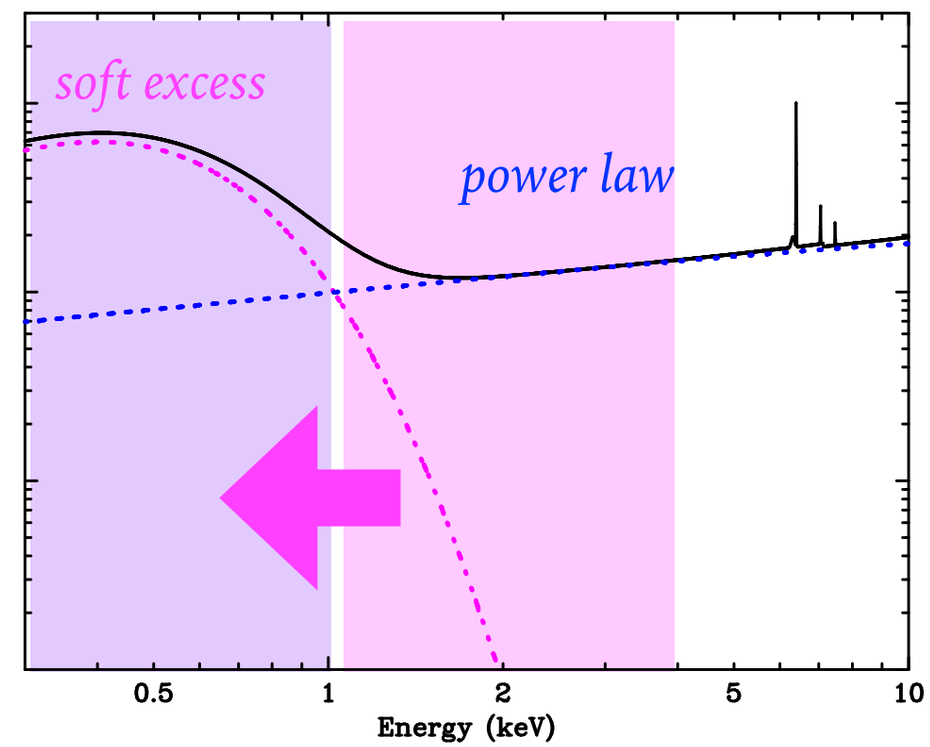


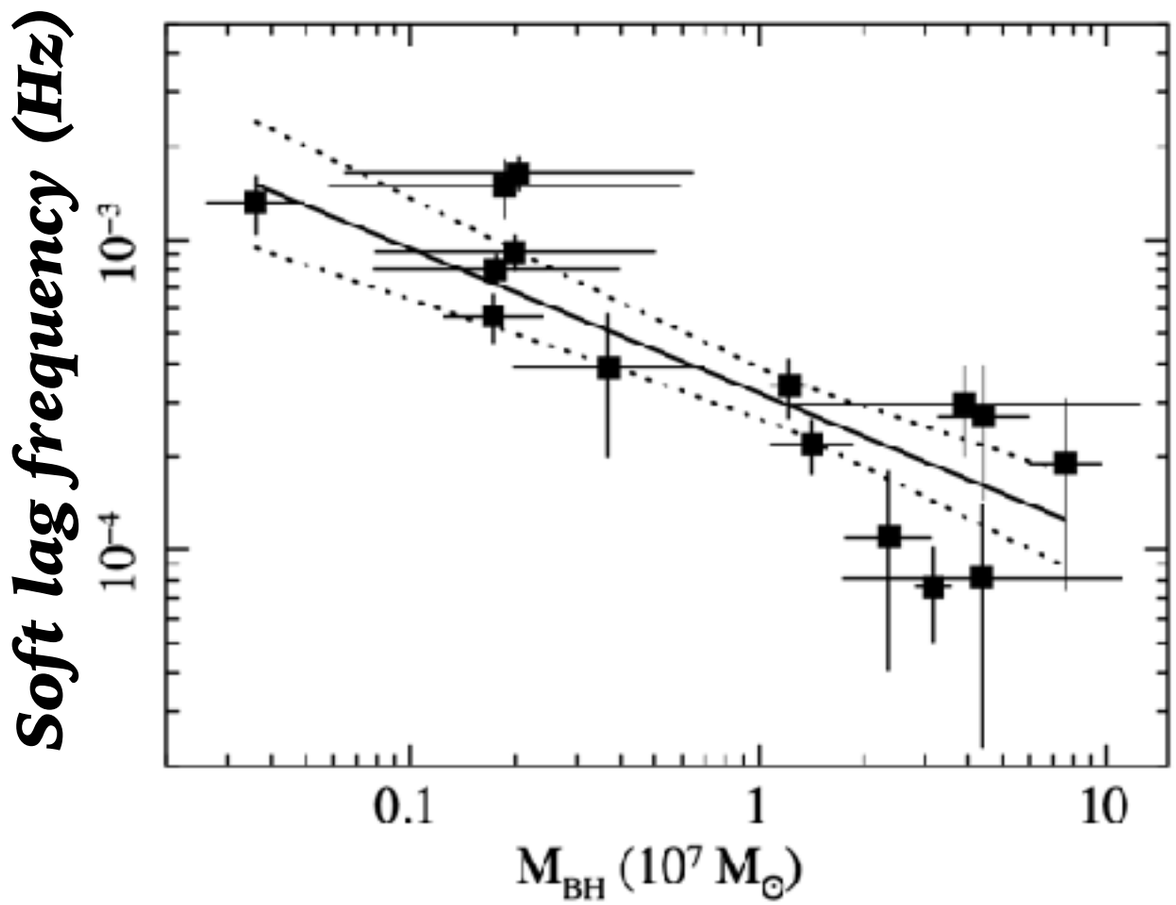


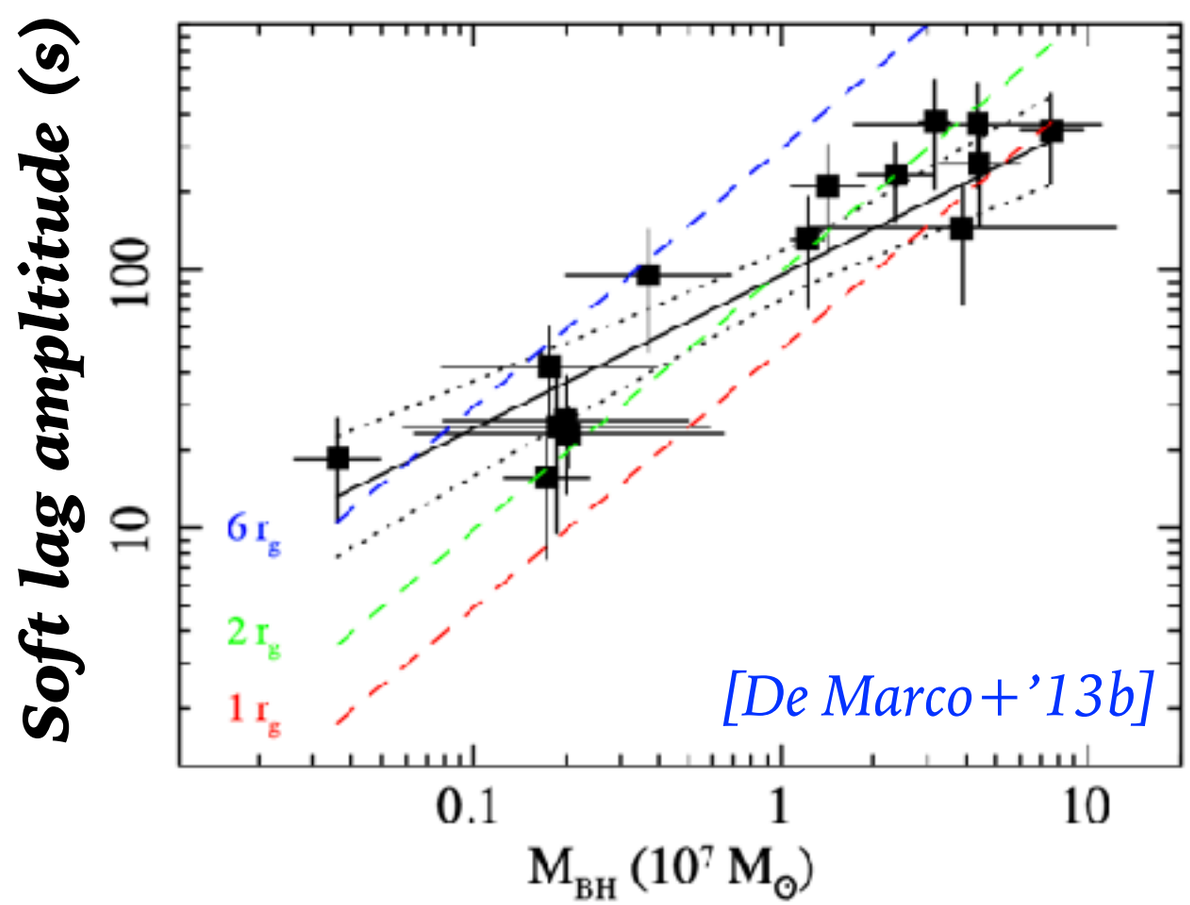
Compact corona, short disc-corona distance ➜ disc at ISCO

[e.g. McHardy+'07; Zoghbi+'10; De Marco+'11; Tripathi +'11; Emmanoulopoulos+'11; Zoghbi & Fabian '11; Cackett+'13; Epitropakis & Papadakis+'16; De Marco+'19']

The reverberation lag correlates with BH mass

Revealed from a systematic study of soft X-ray lags with XMM





(sample extracted from CAIXAvar; Ponti+'12)

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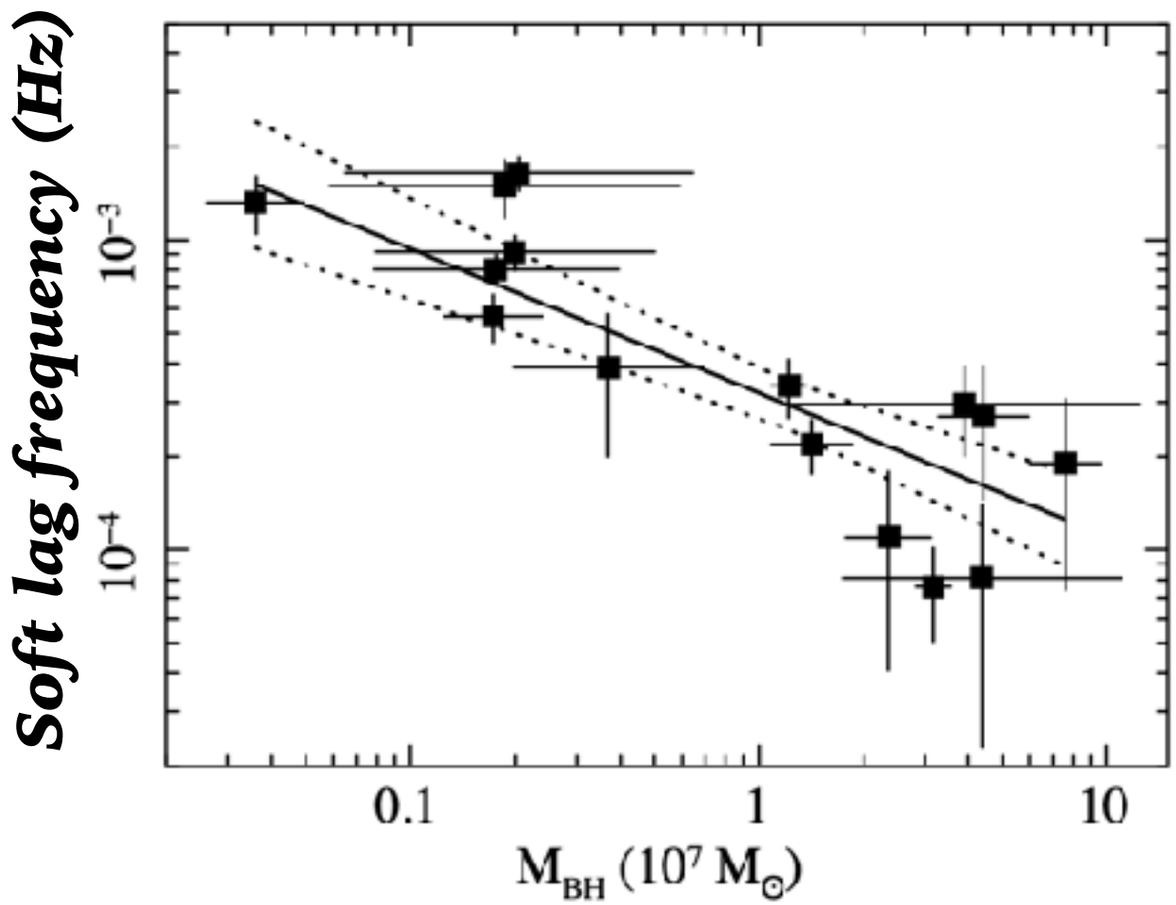

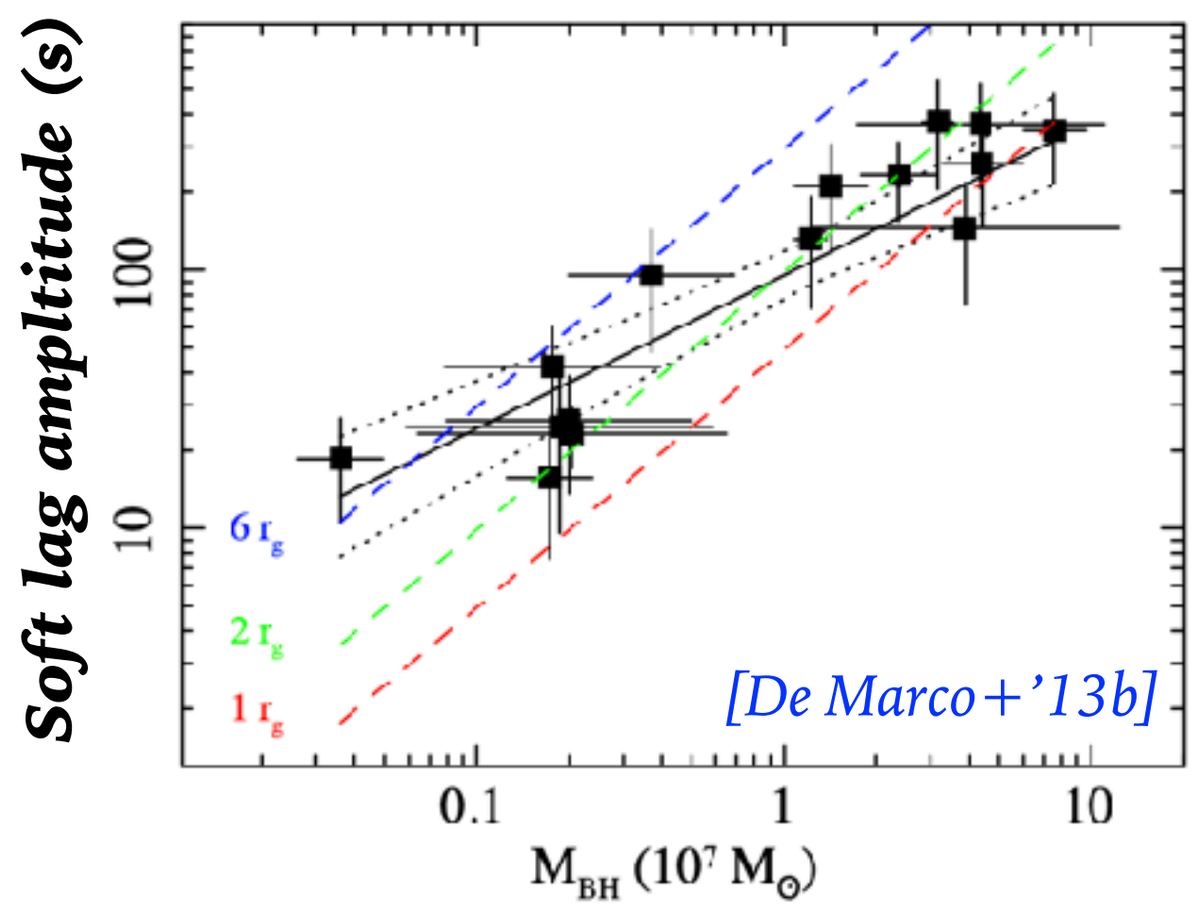

(sample extracted from CAIXAvar; Ponti+'12)

Same inner flow geometry in (bright radio quiet) AGN

Compact corona, disc extending down to the ISCO

The reverberation lag correlates with BH mass

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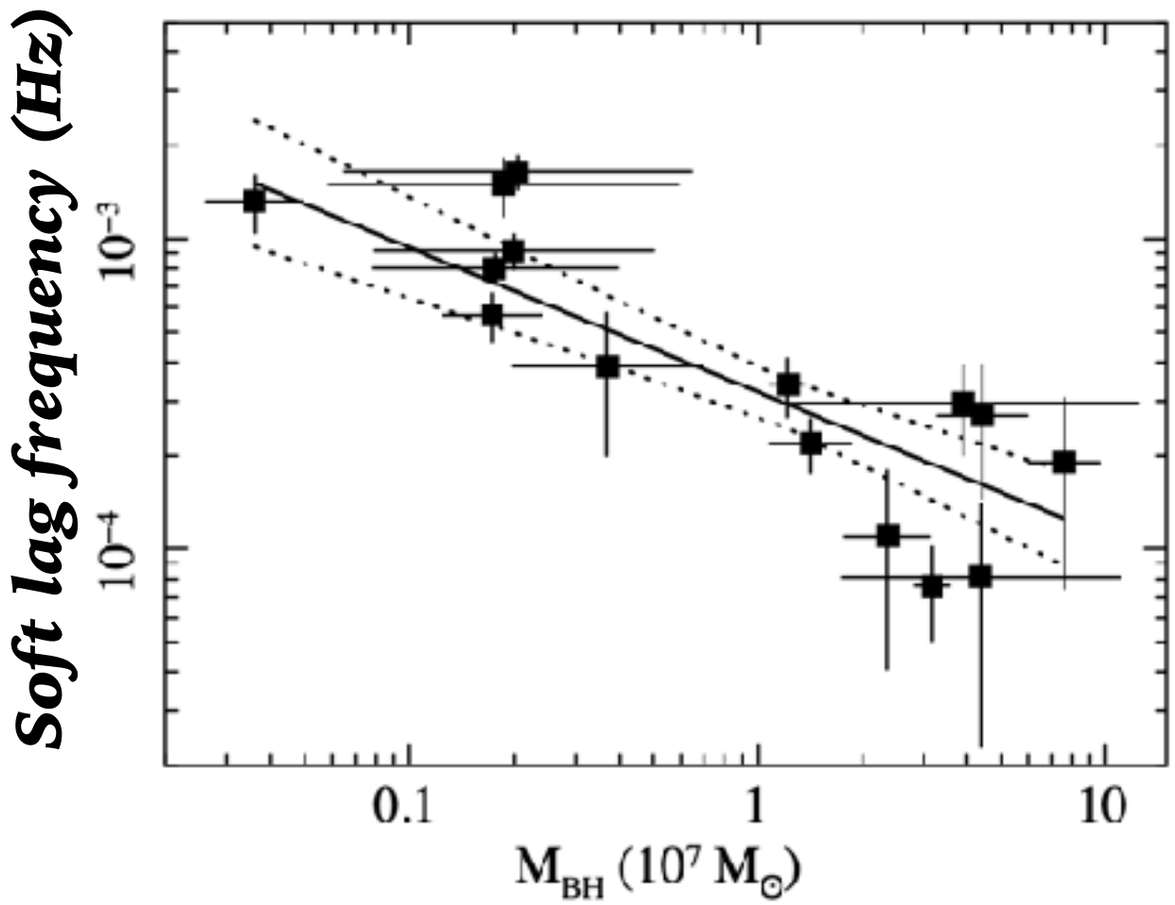

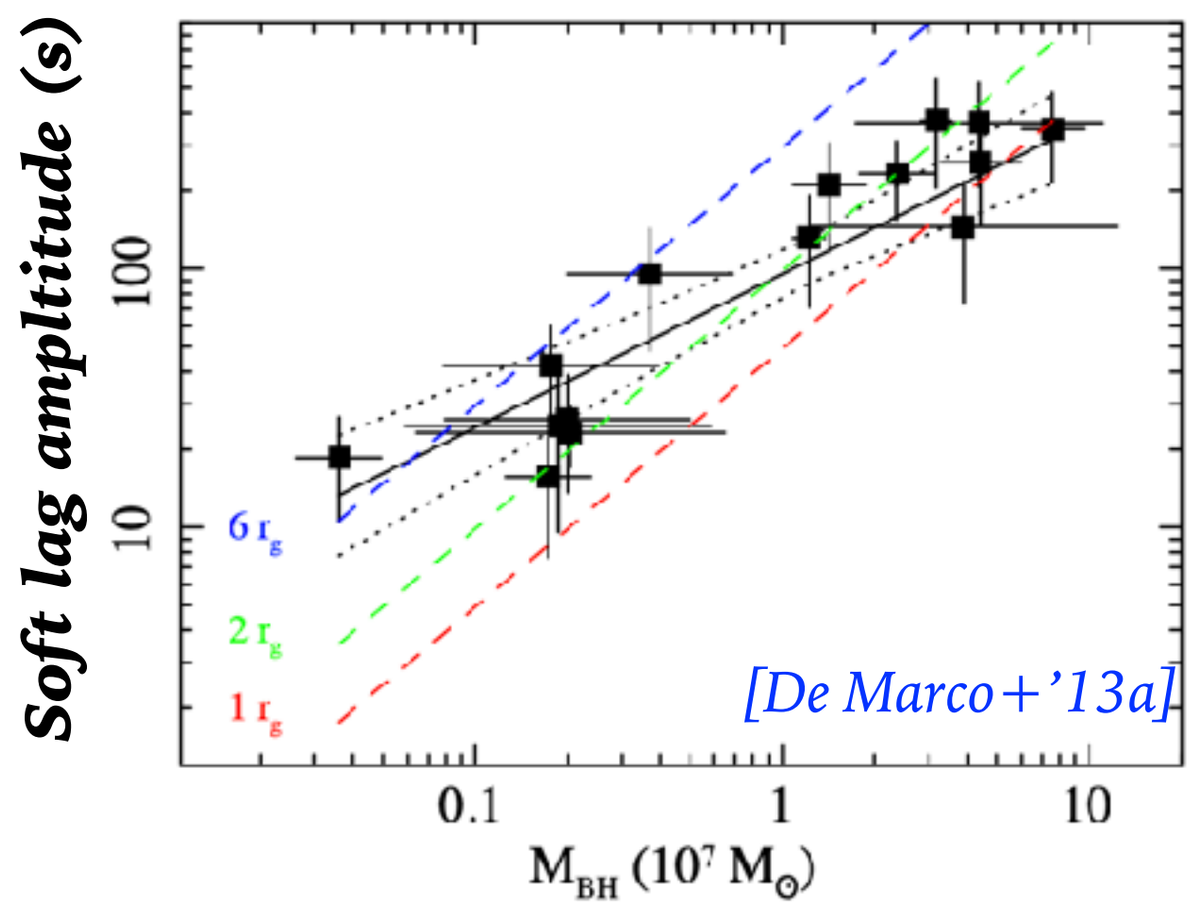

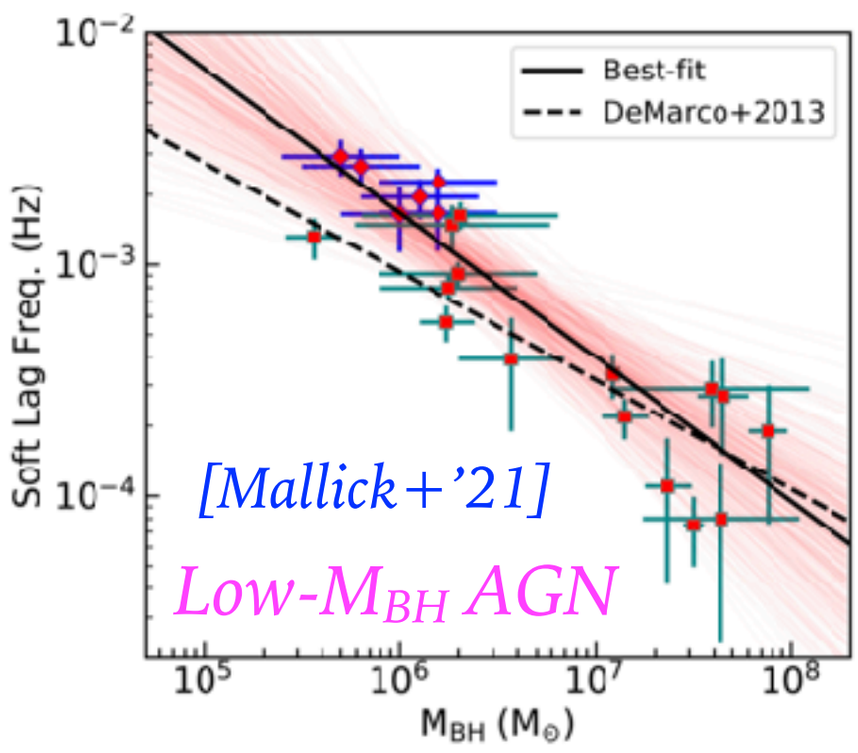

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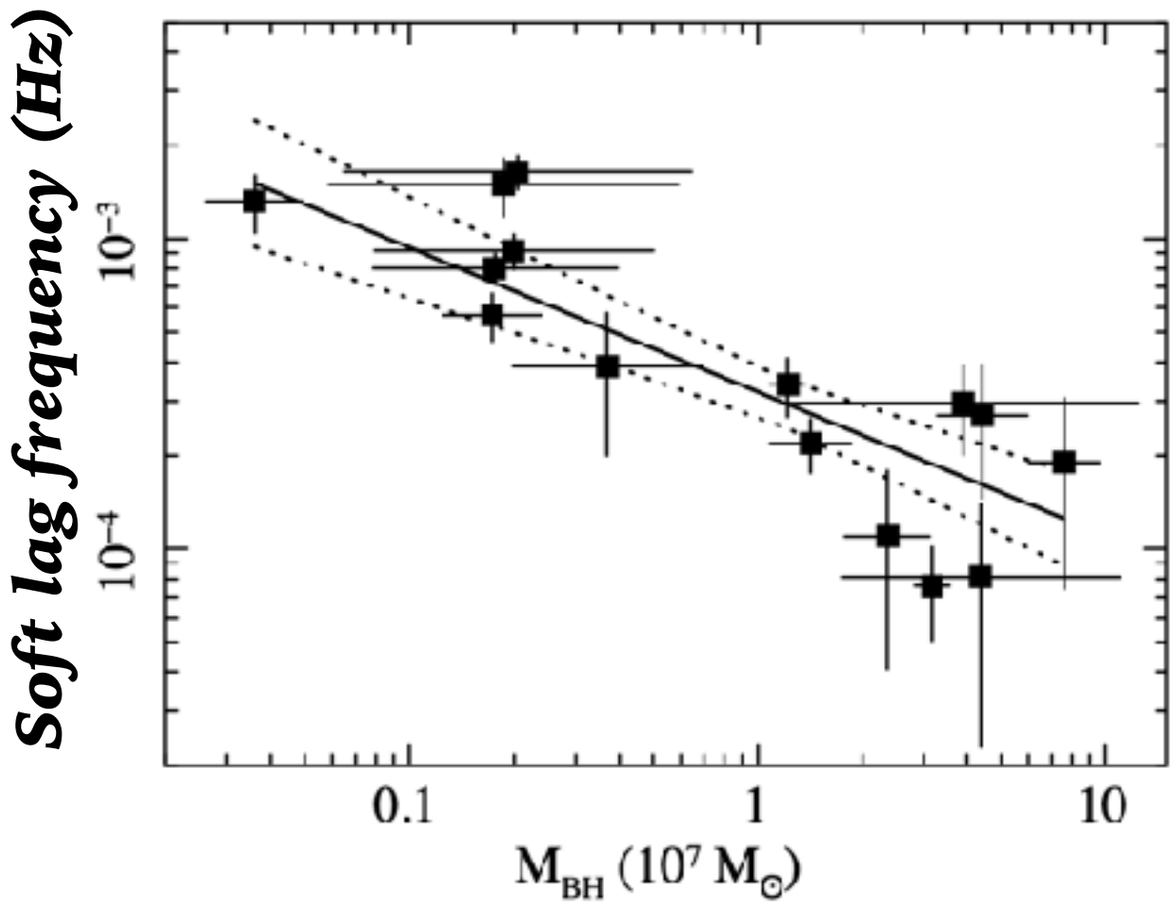
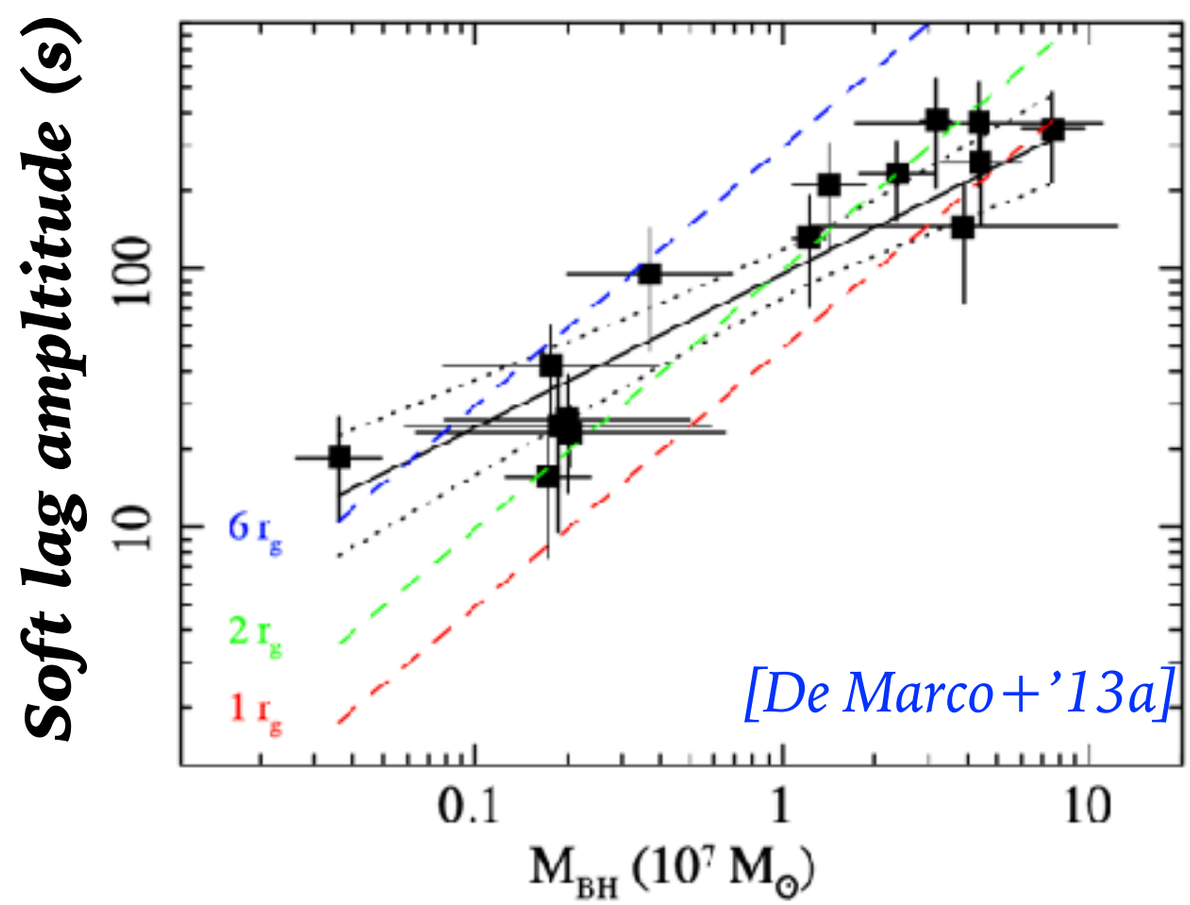
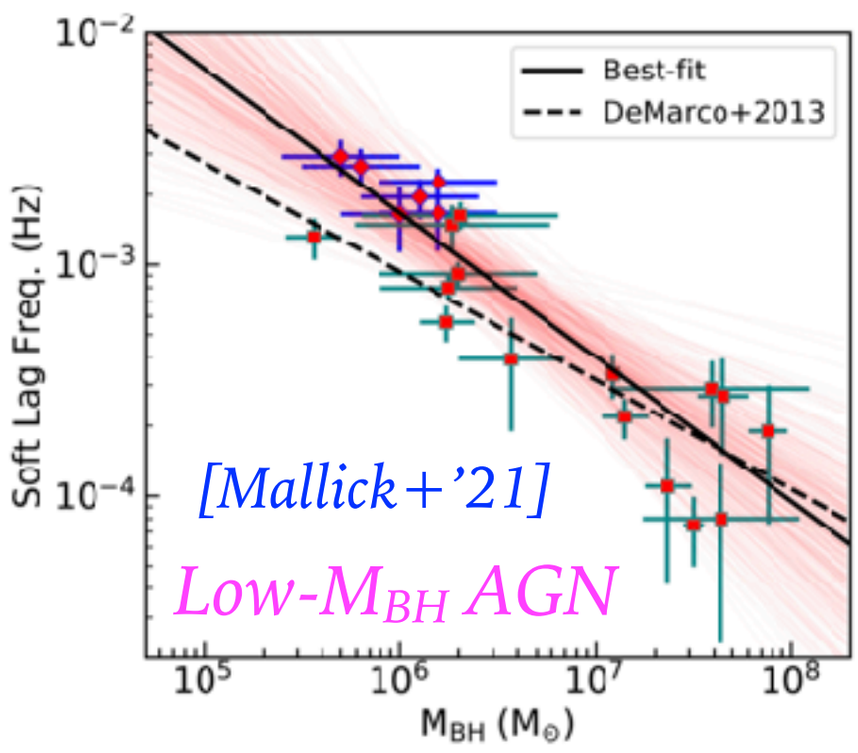


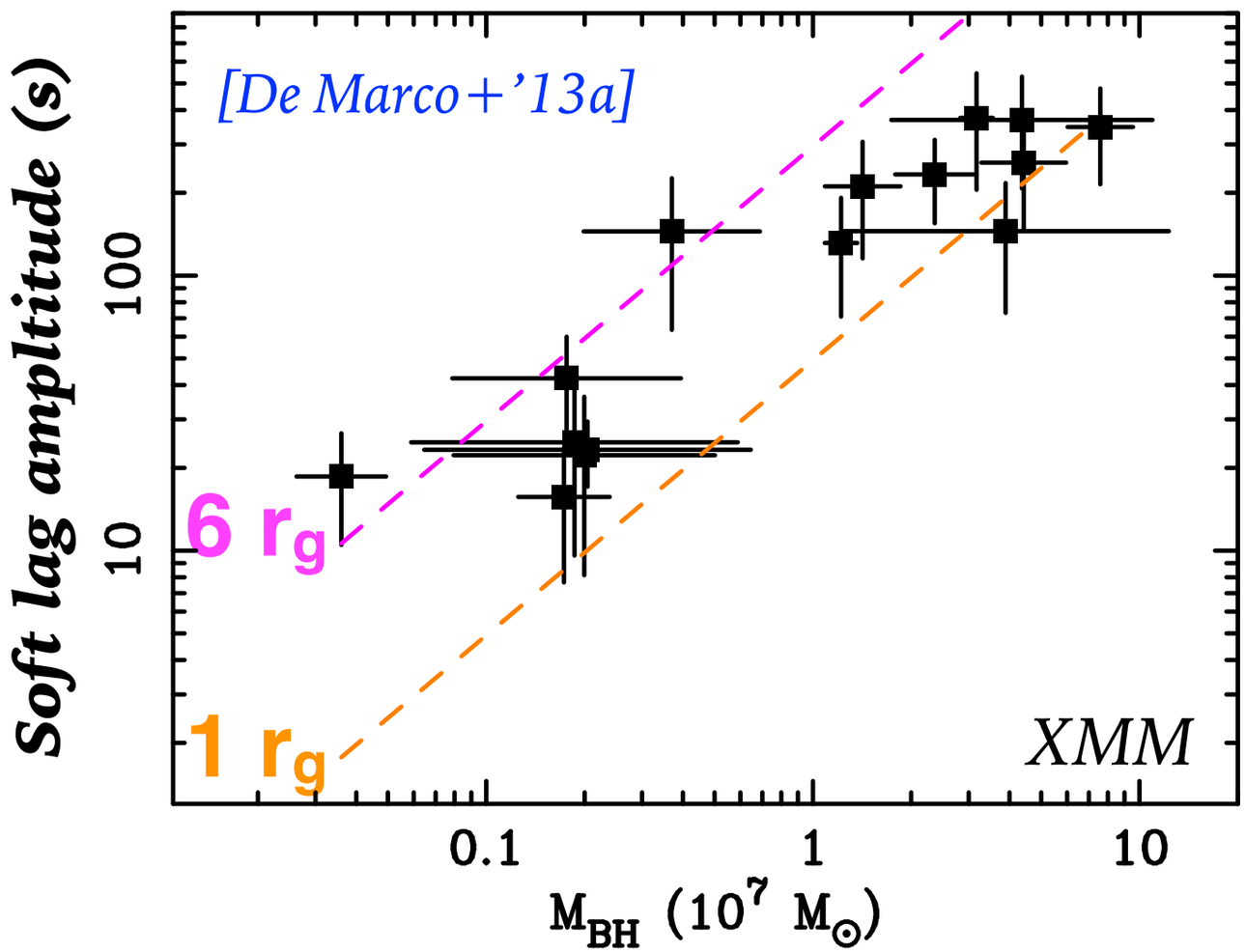


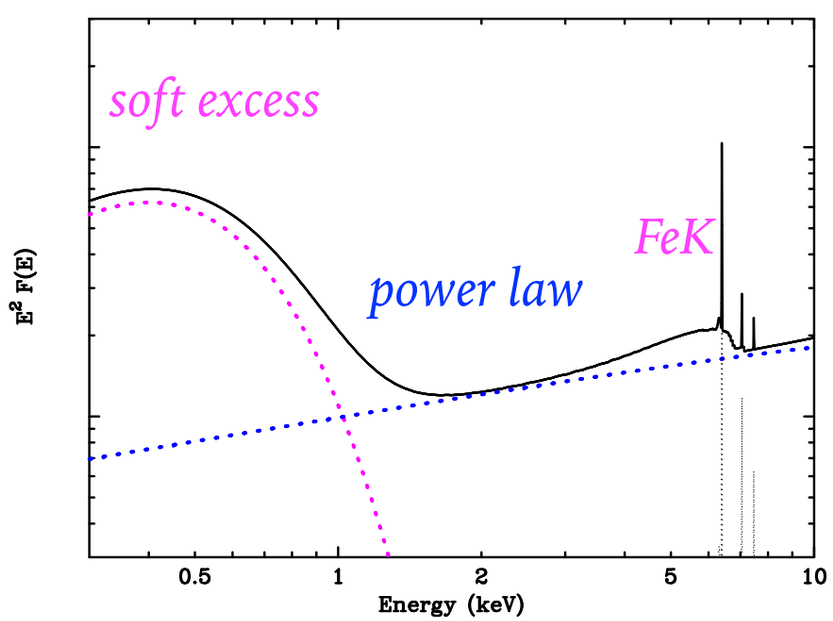


Same mechanism and geometry over broad range of BH masses

Discovery of FeK lags in AGN

Same correlation with BH mass





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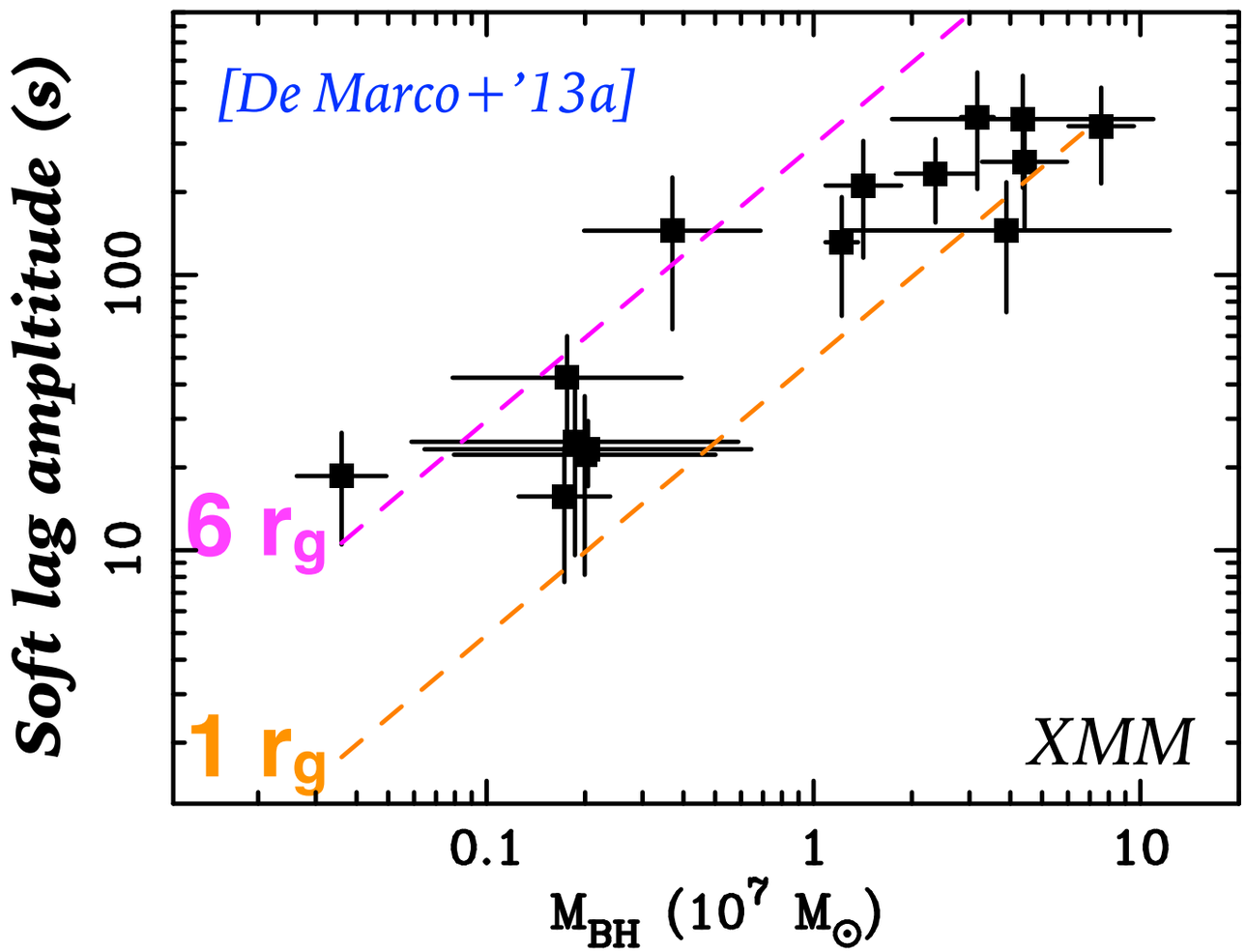
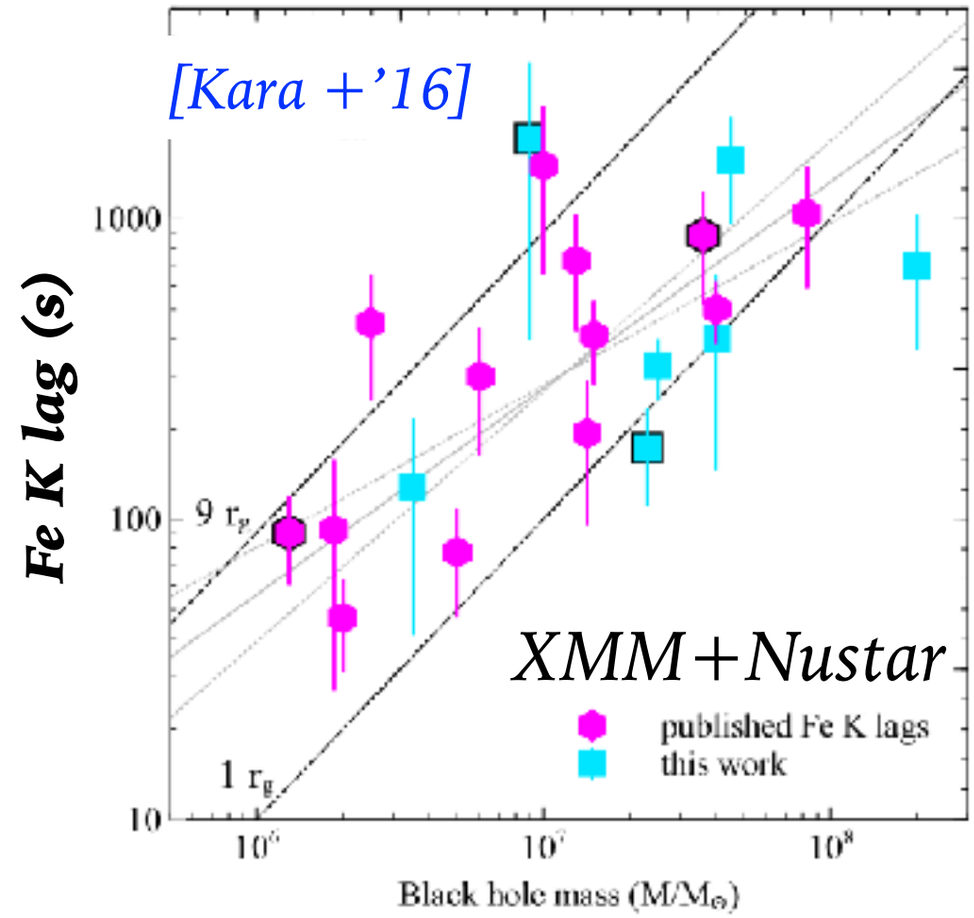
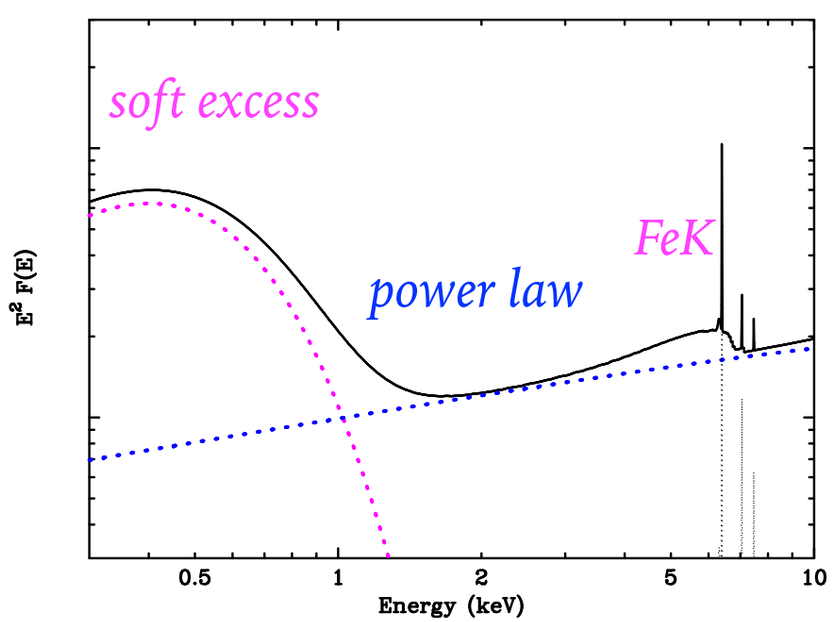




[see also Zoghbi+'12, '13, ';14; Kara +'13a,b,c; '15;]



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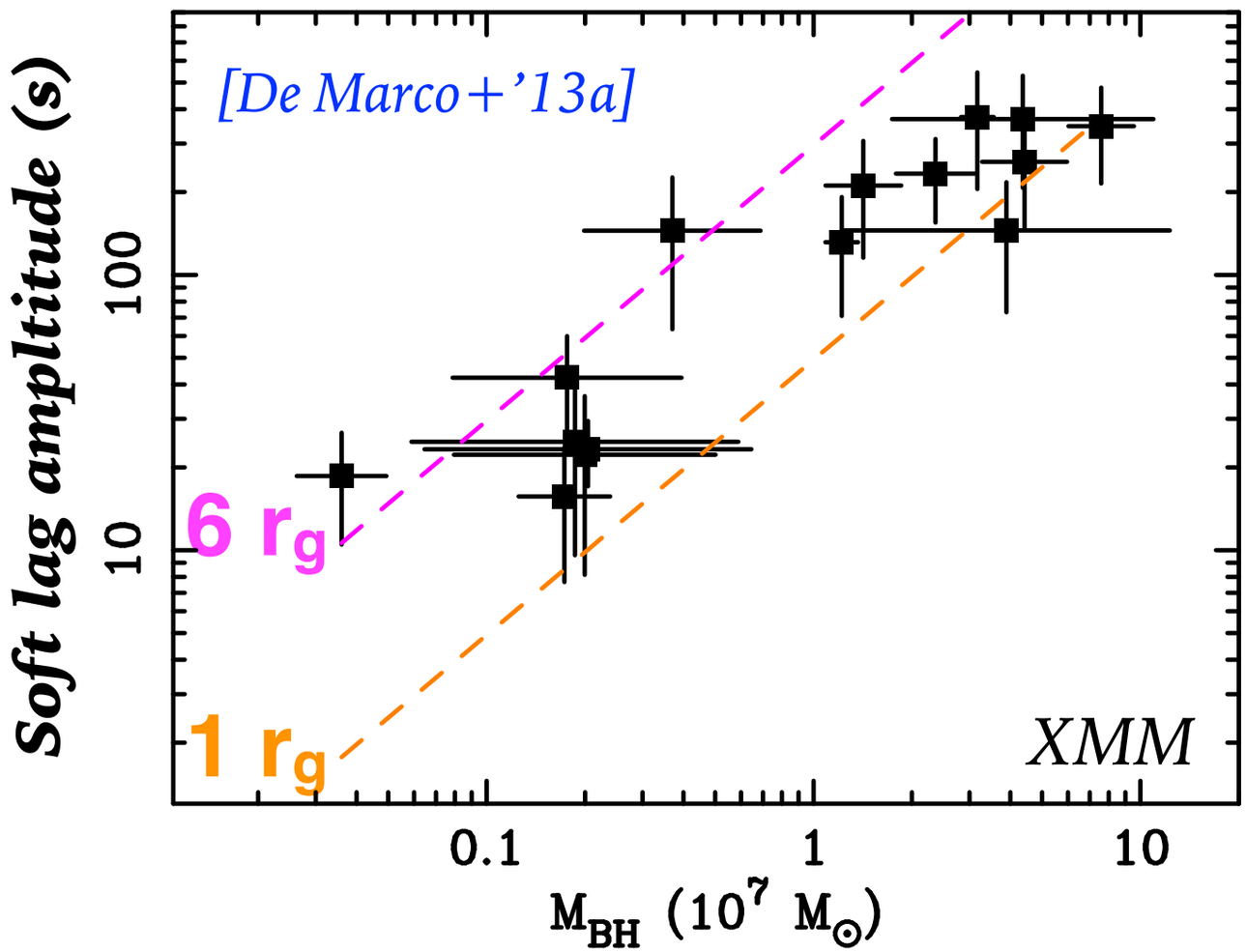

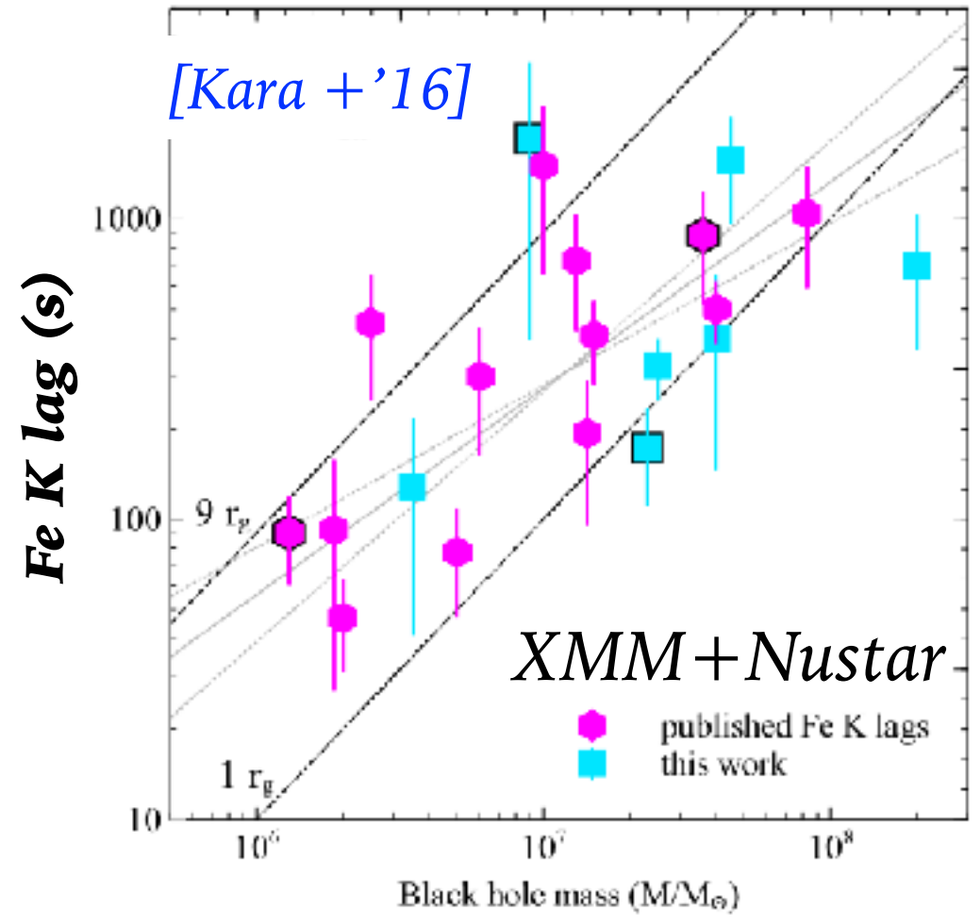

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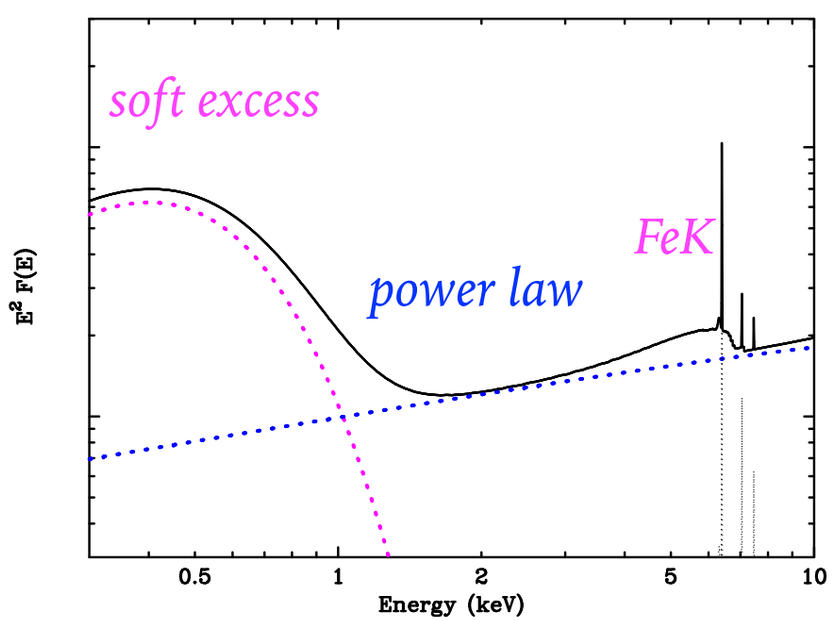
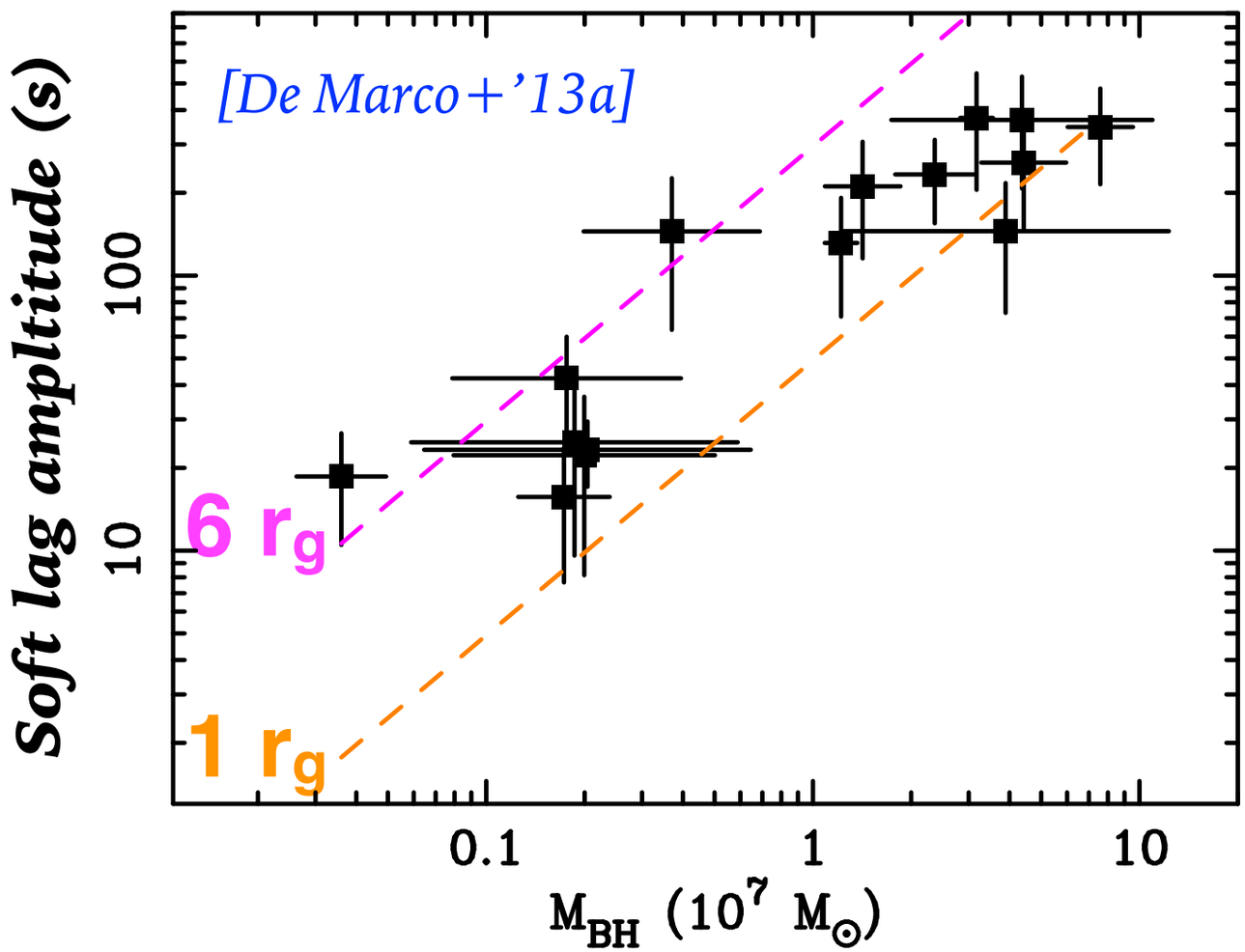
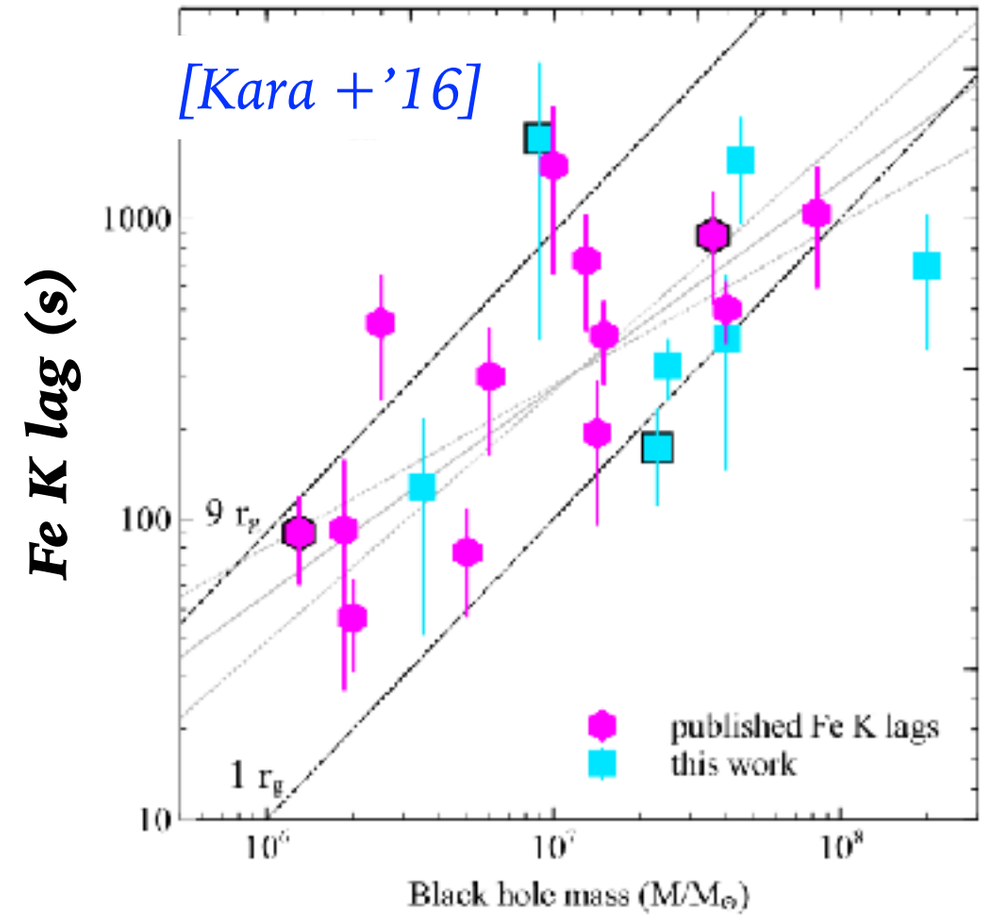


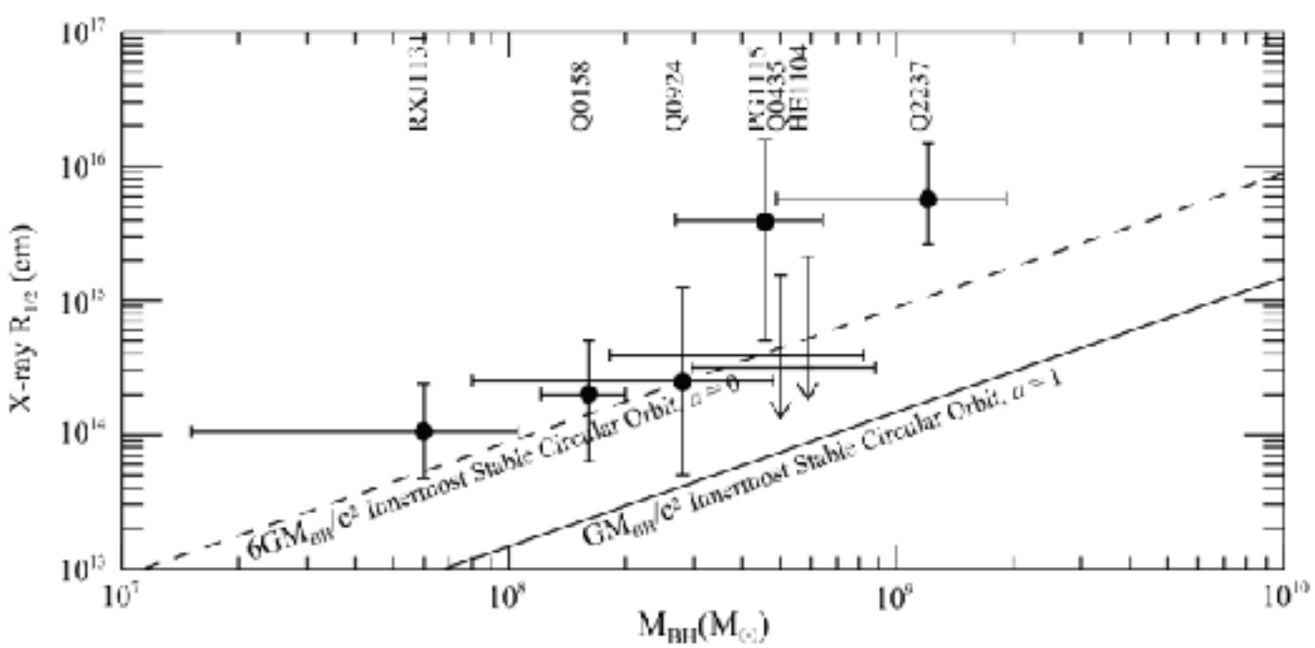
Both the soft excess and the FeK both arise from a region close to the BH

A compact X-ray source

Comparison with microlensing results







Sizes inferred from microlensing and reverberation are consistent

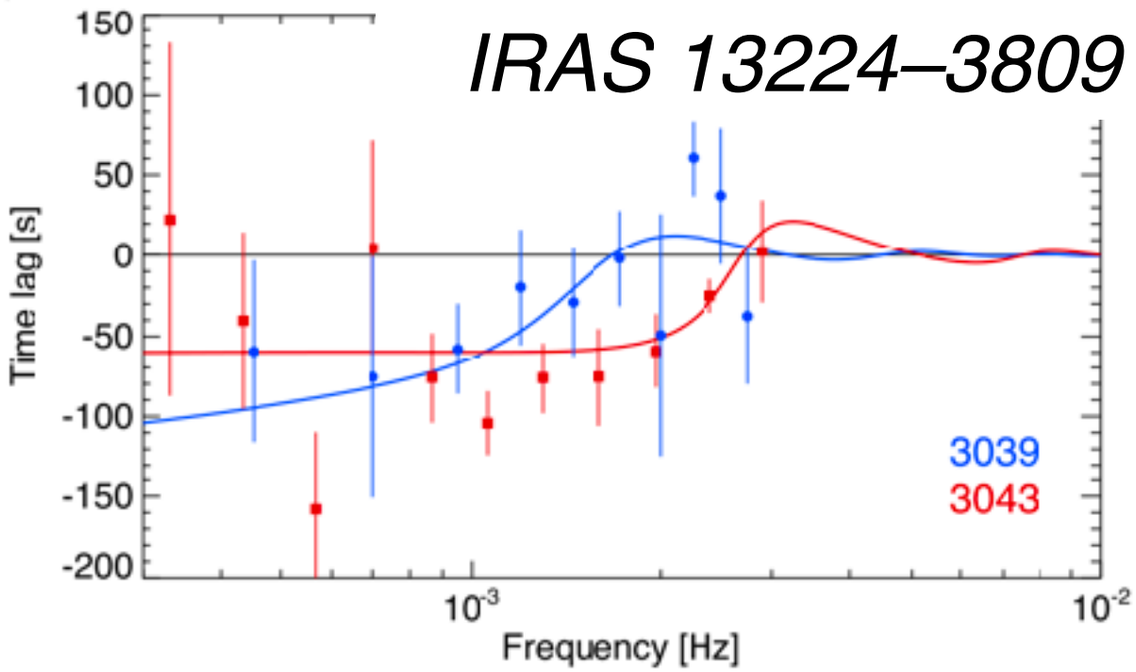
[e.g. MacLeod+'15; Blackburne+'14; '15; Mosquera+'13; Morgan+'08, '12; Dai+'10; Chartas+'09;'16]

Insights into a dynamic corona

Reverberation tracking quick changes of coronal geometry

XMM (16 orbits)

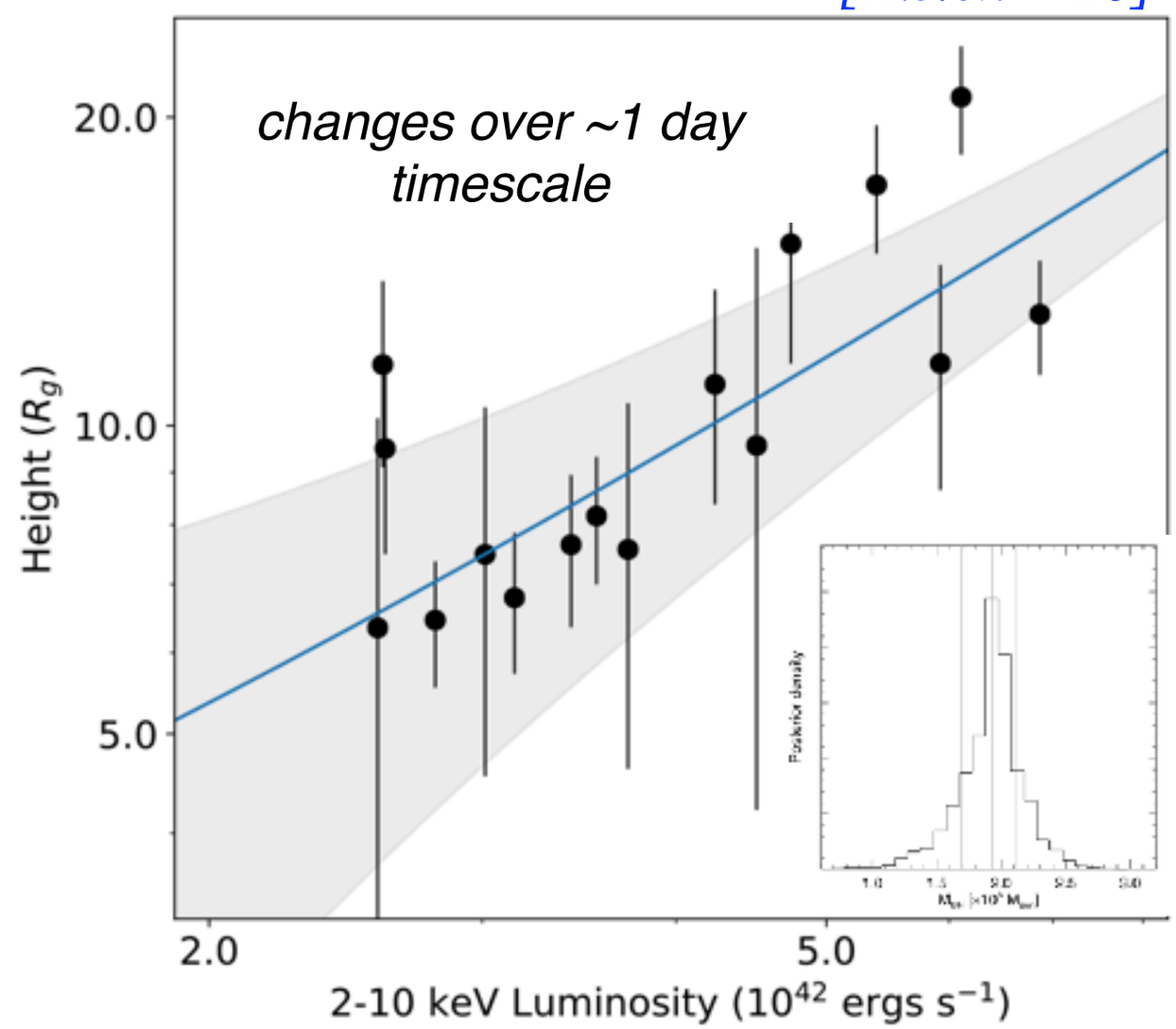
IRAS 13224–3809



KYNreverb package

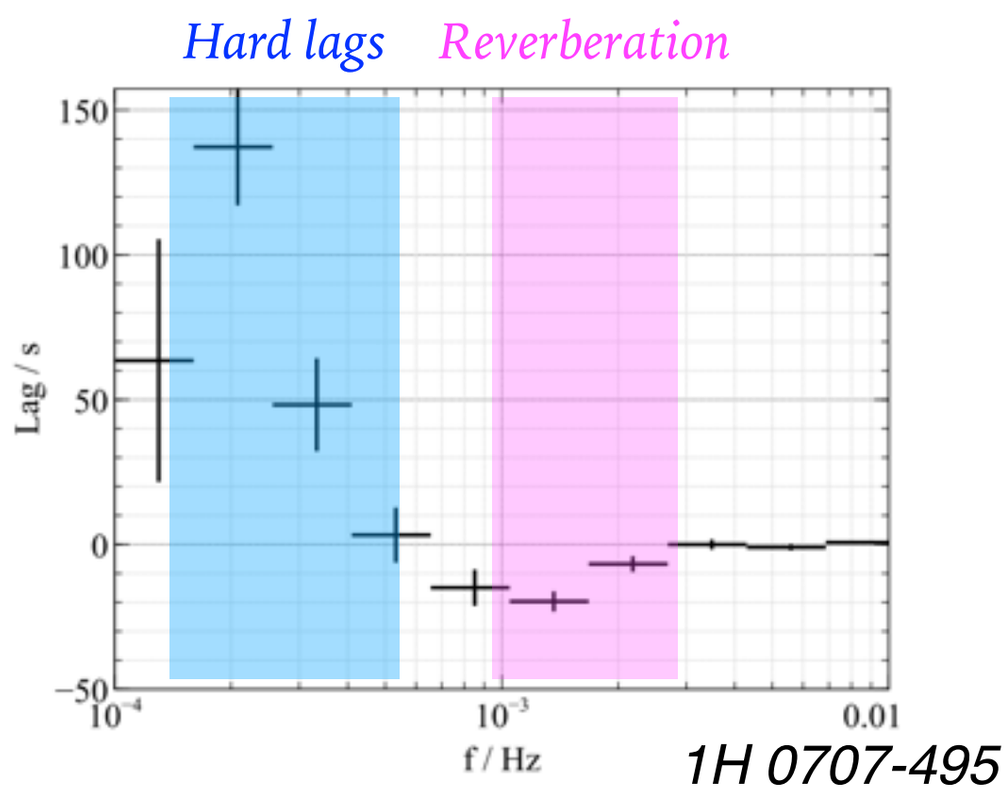
[M. Dovčiak; see also Caballero-García+'18]

[Alston+'20]



Insights into a structured corona

X-ray lags reveal a composite region



[e.g. Kotov+'01; Arévalo & Uttley+'06; Ingram & van der Klis+'13; Wilkins+'13; '16]

Insights into a structured corona

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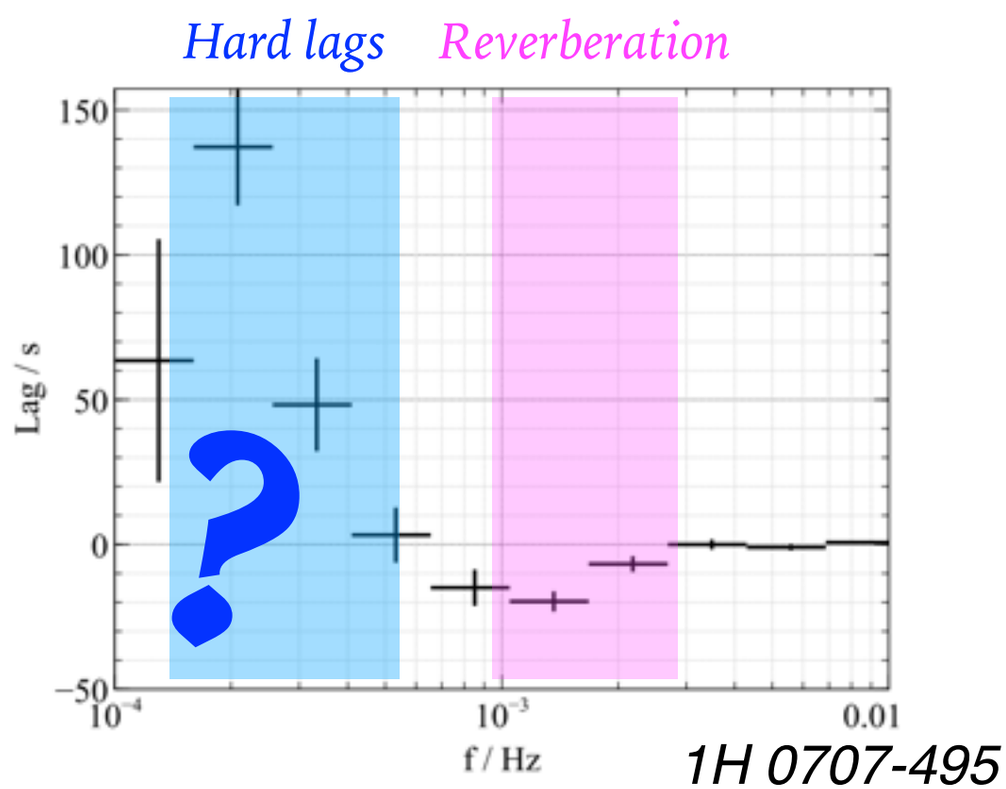

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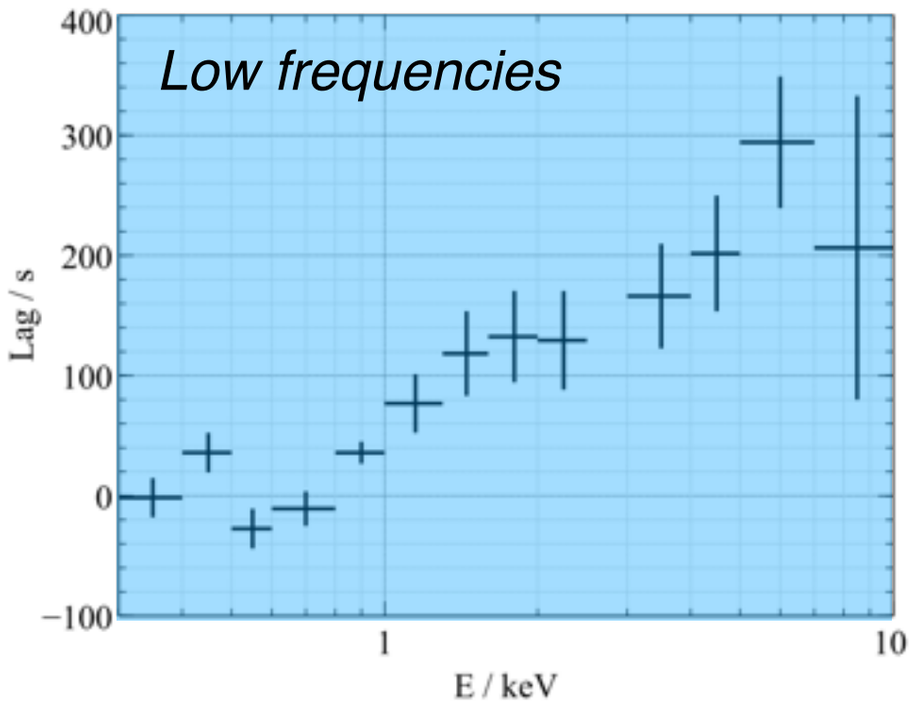

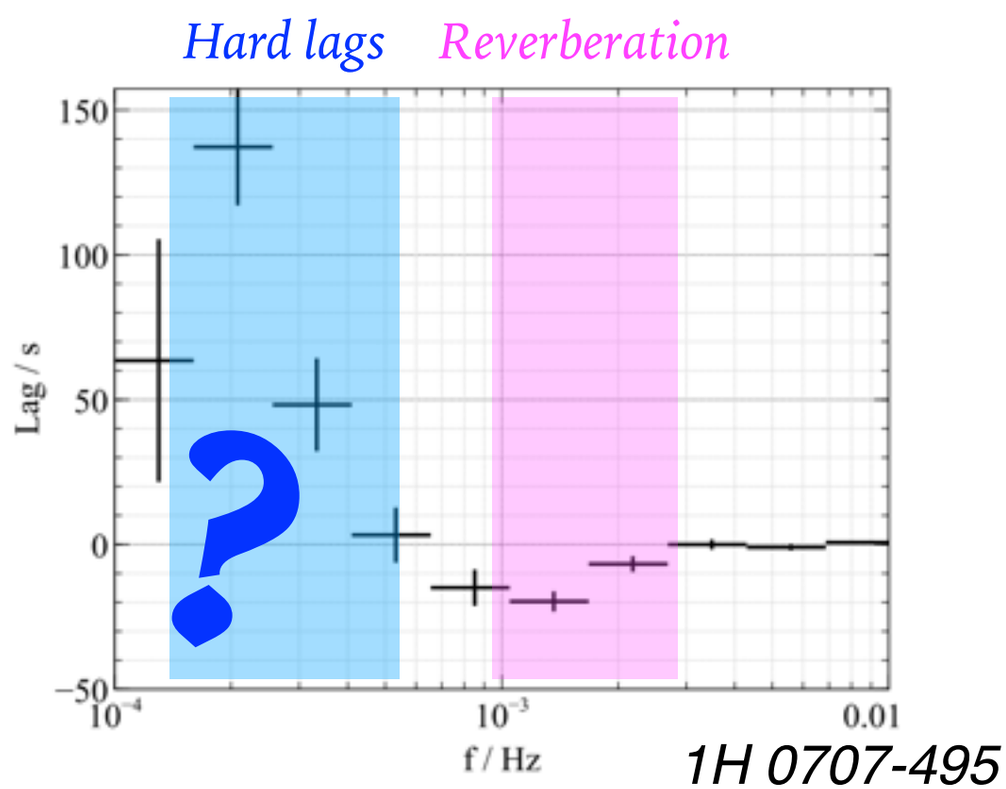

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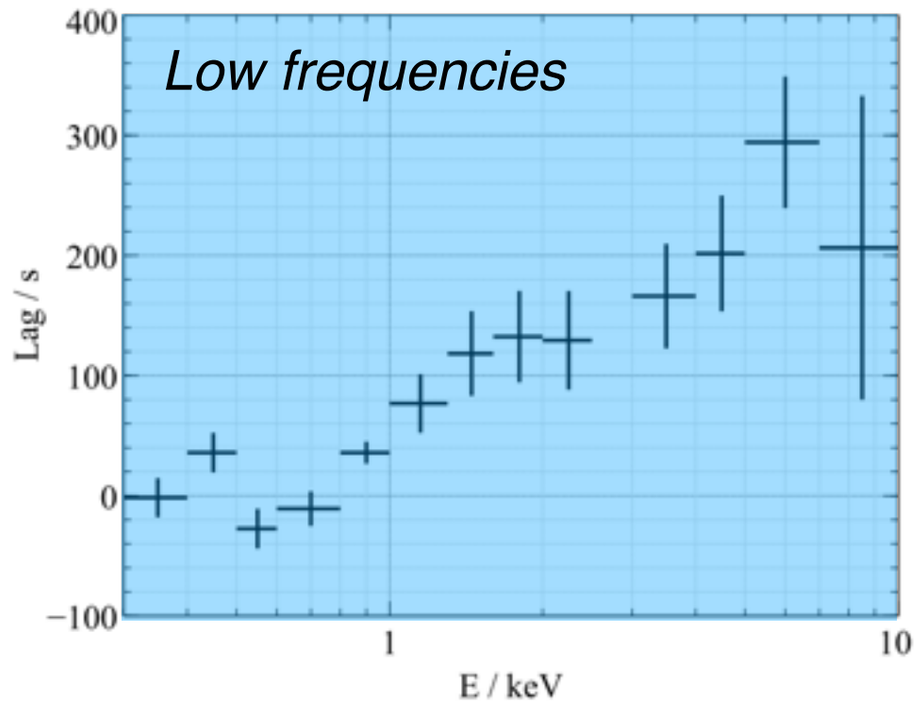

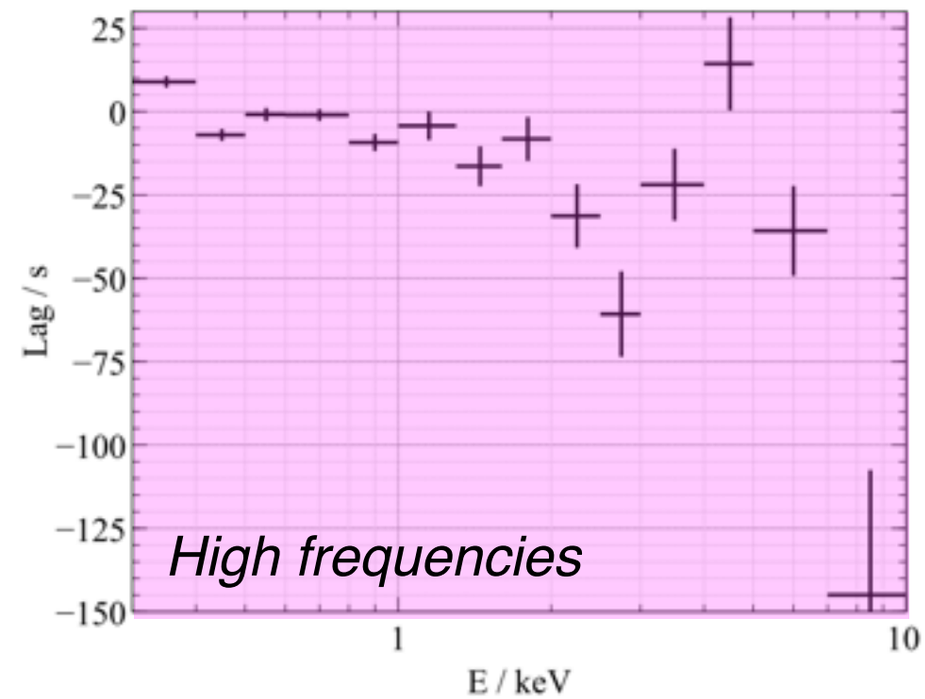

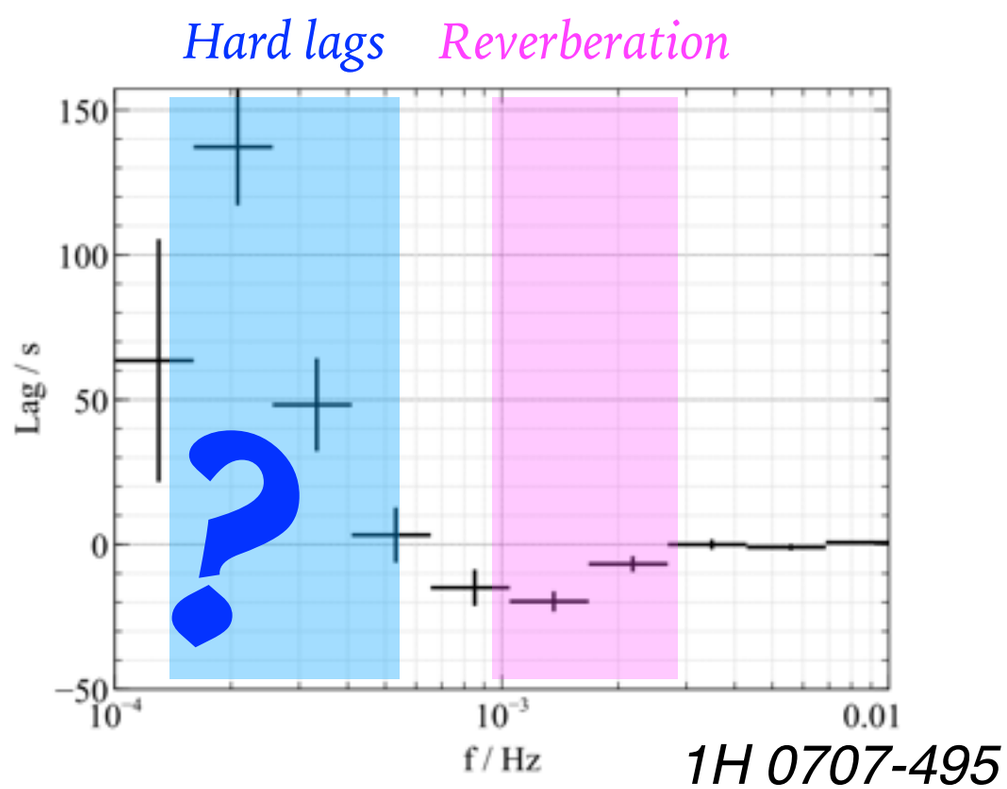

1H 0707-495

[e.g. Kotov+'01; Arévalo & Uttley+'06; Ingram & van der Klis+'13; Wilkins+'13; '16]

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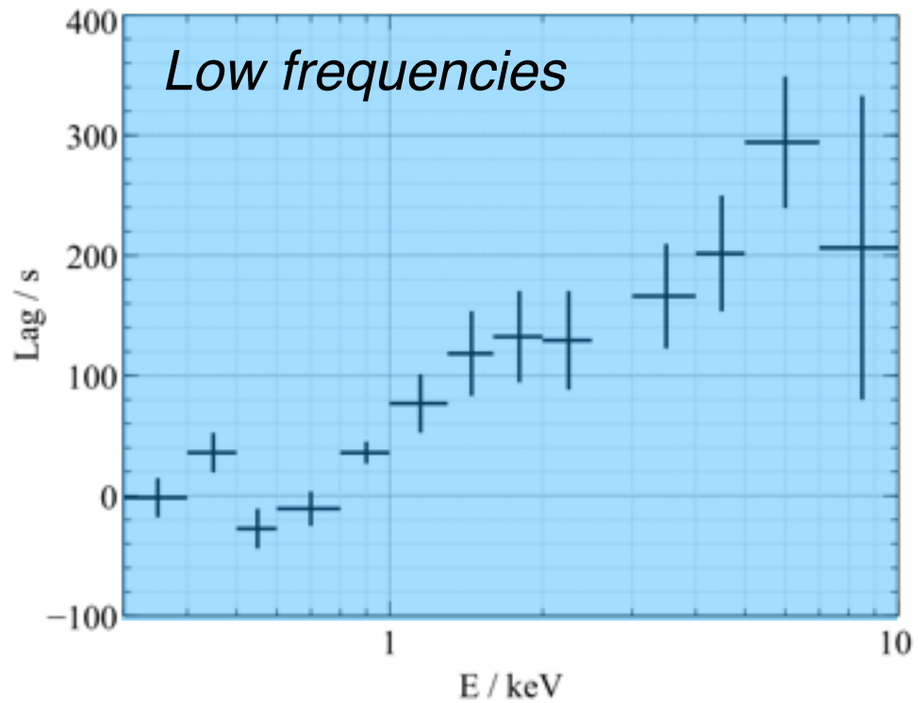

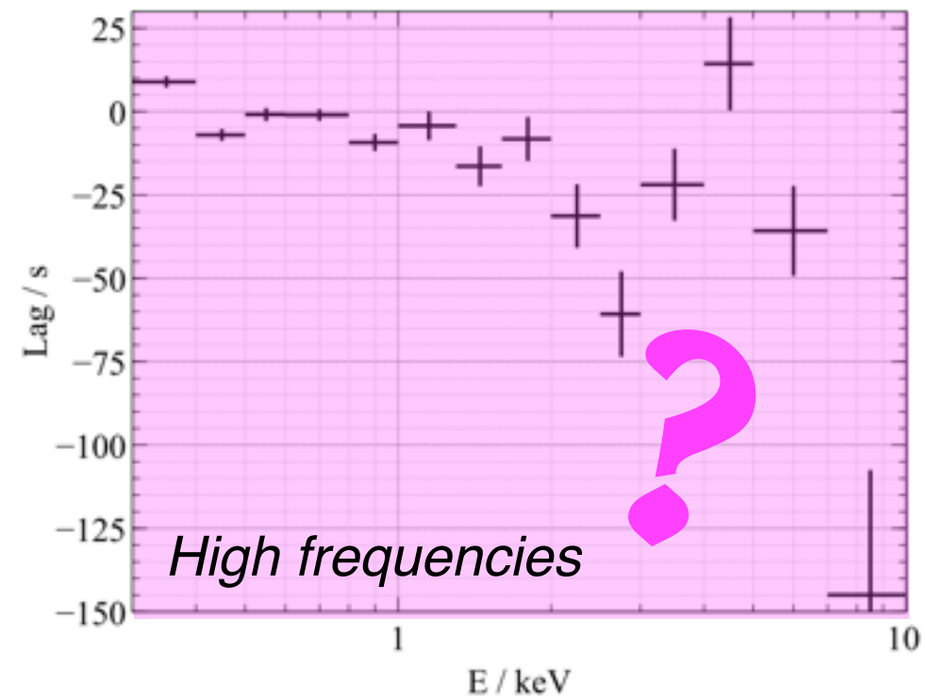

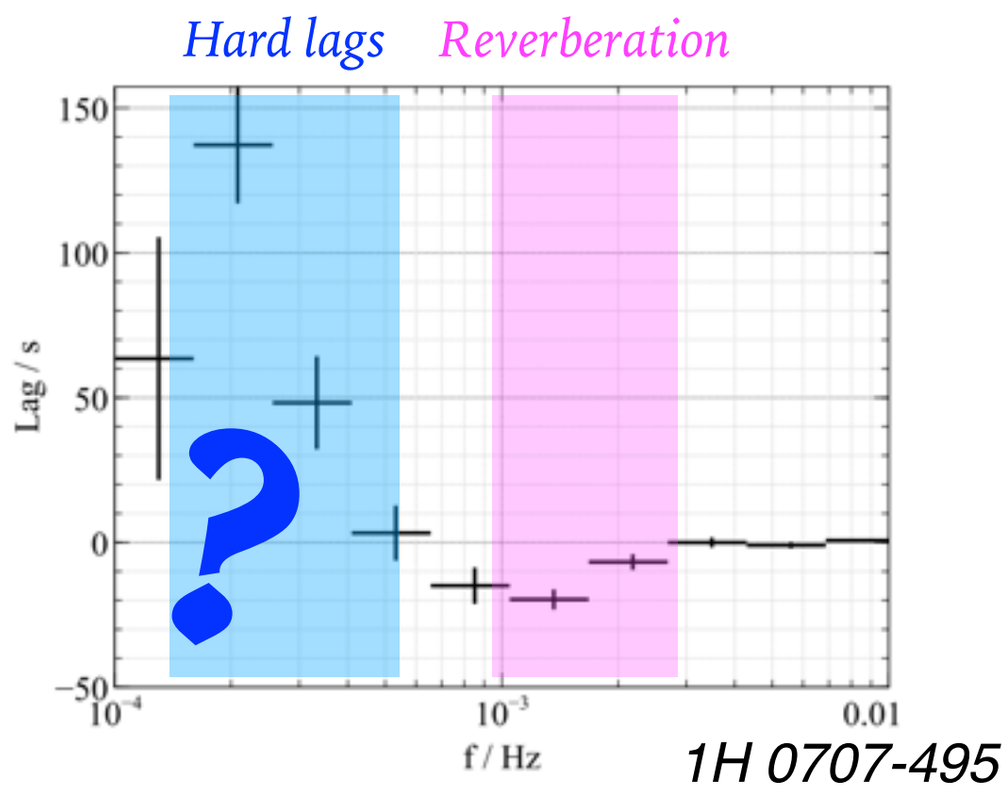

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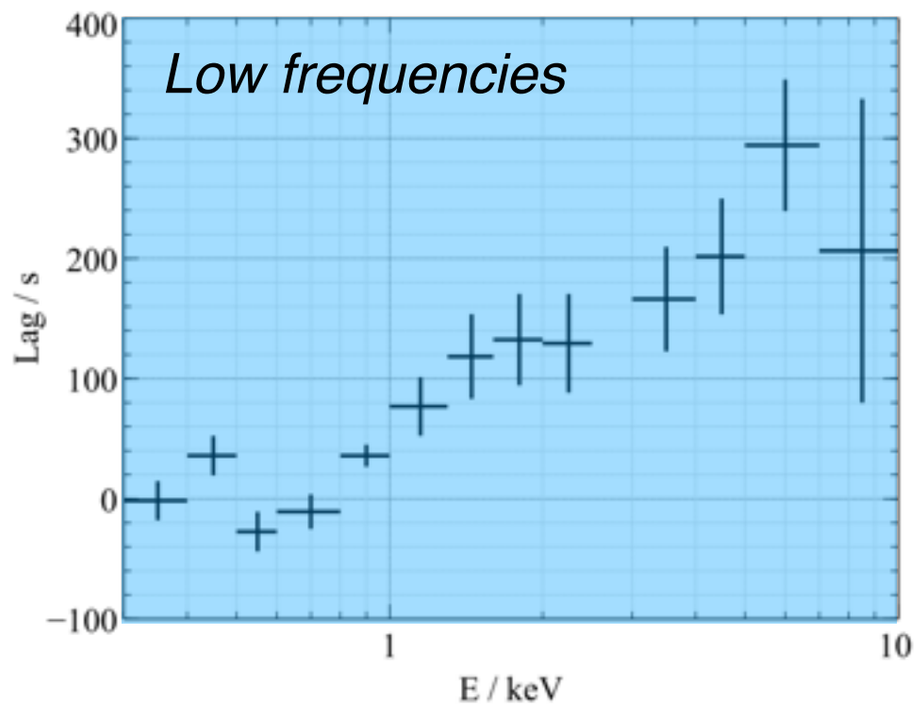
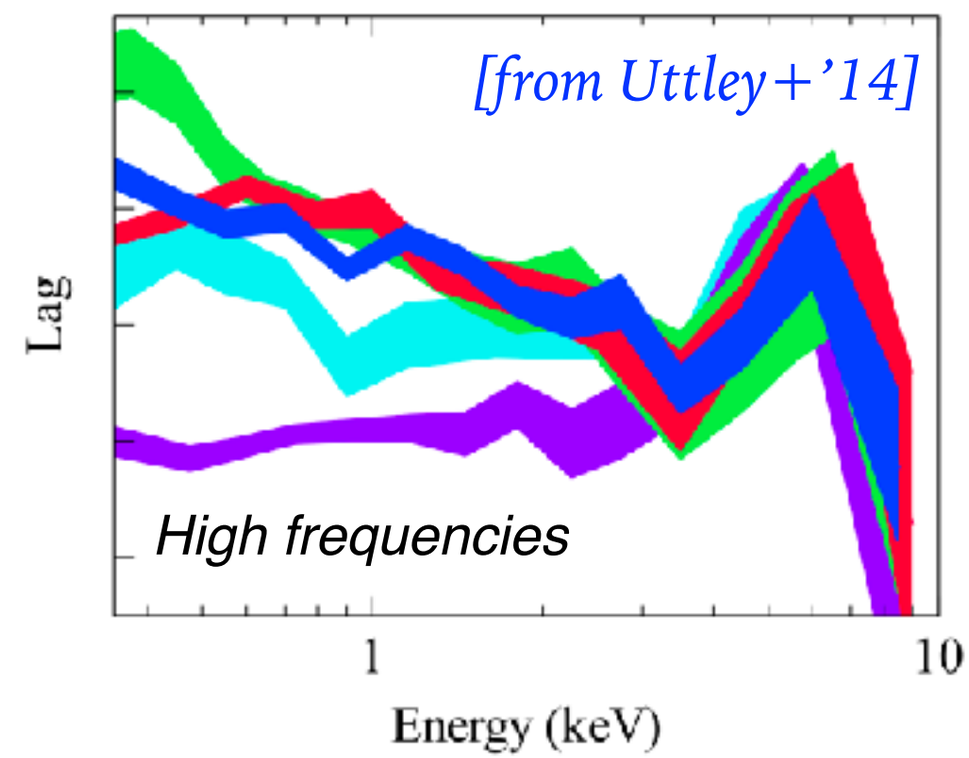
Insights into the structured corona

X-ray lags reveal a composite region





[Wilkins+'13; '16; '22; see also Chainakun+'15; '17]

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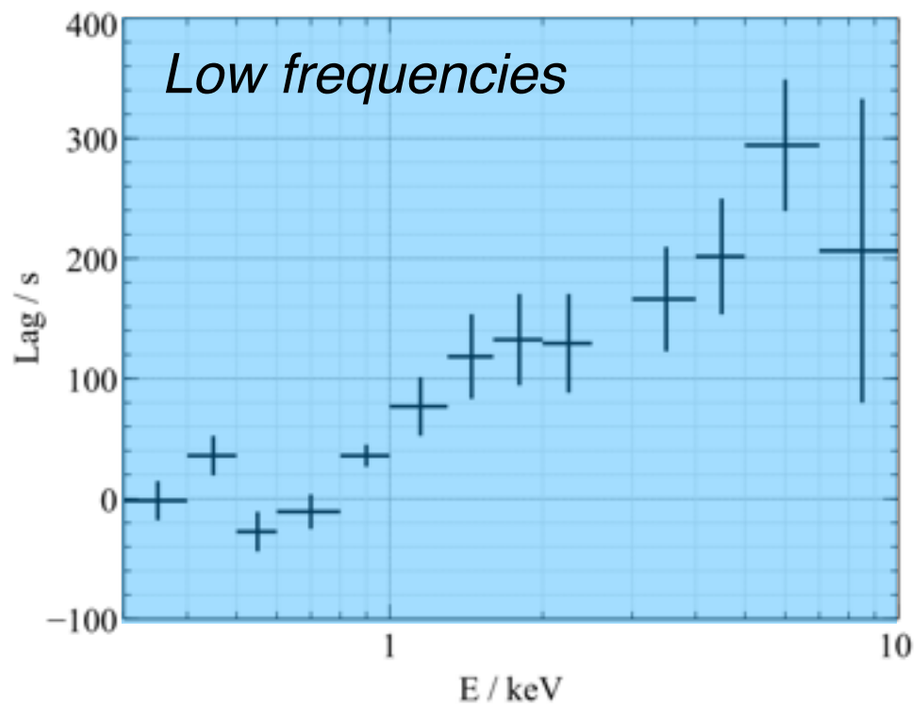
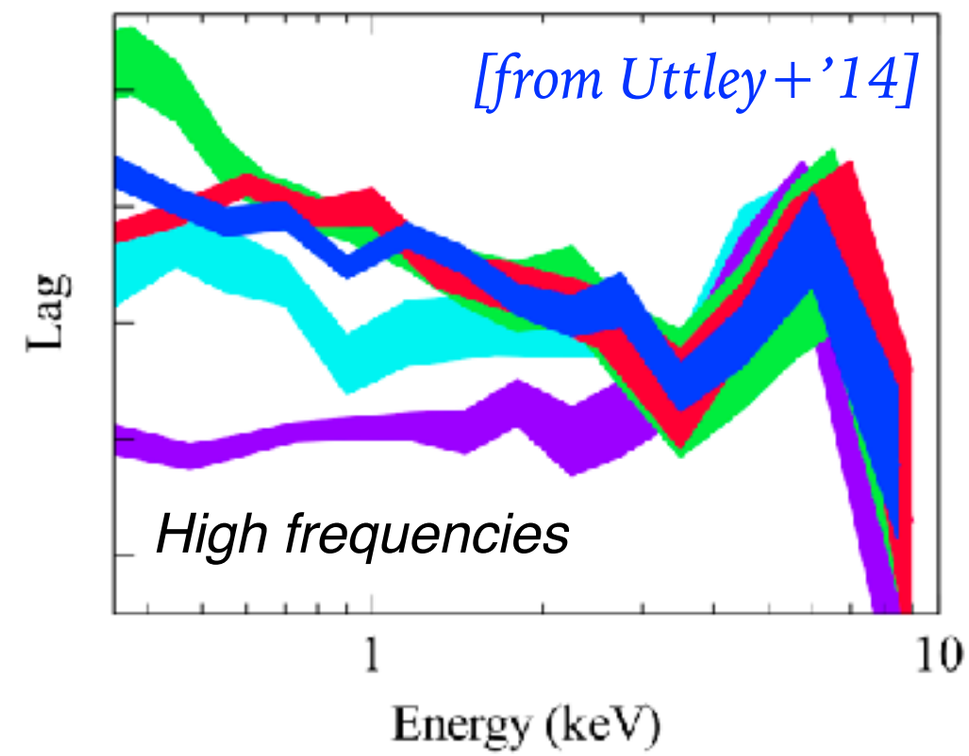
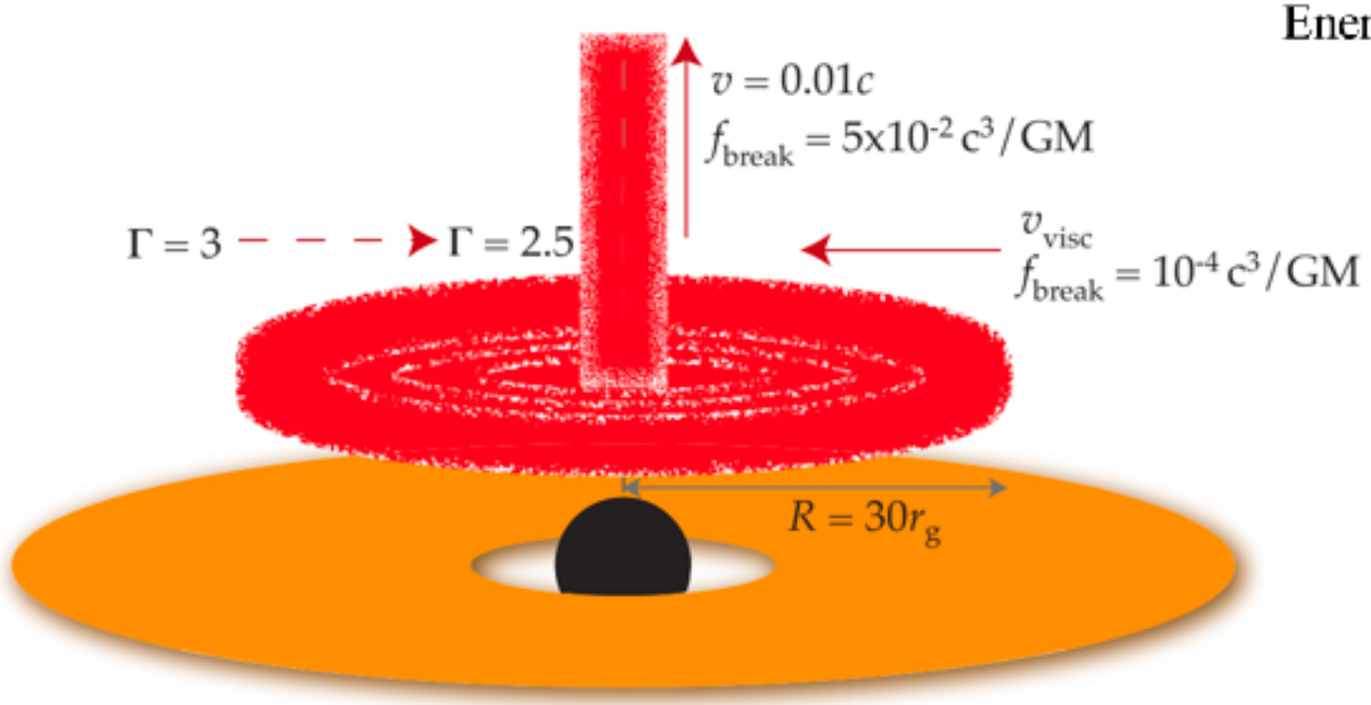


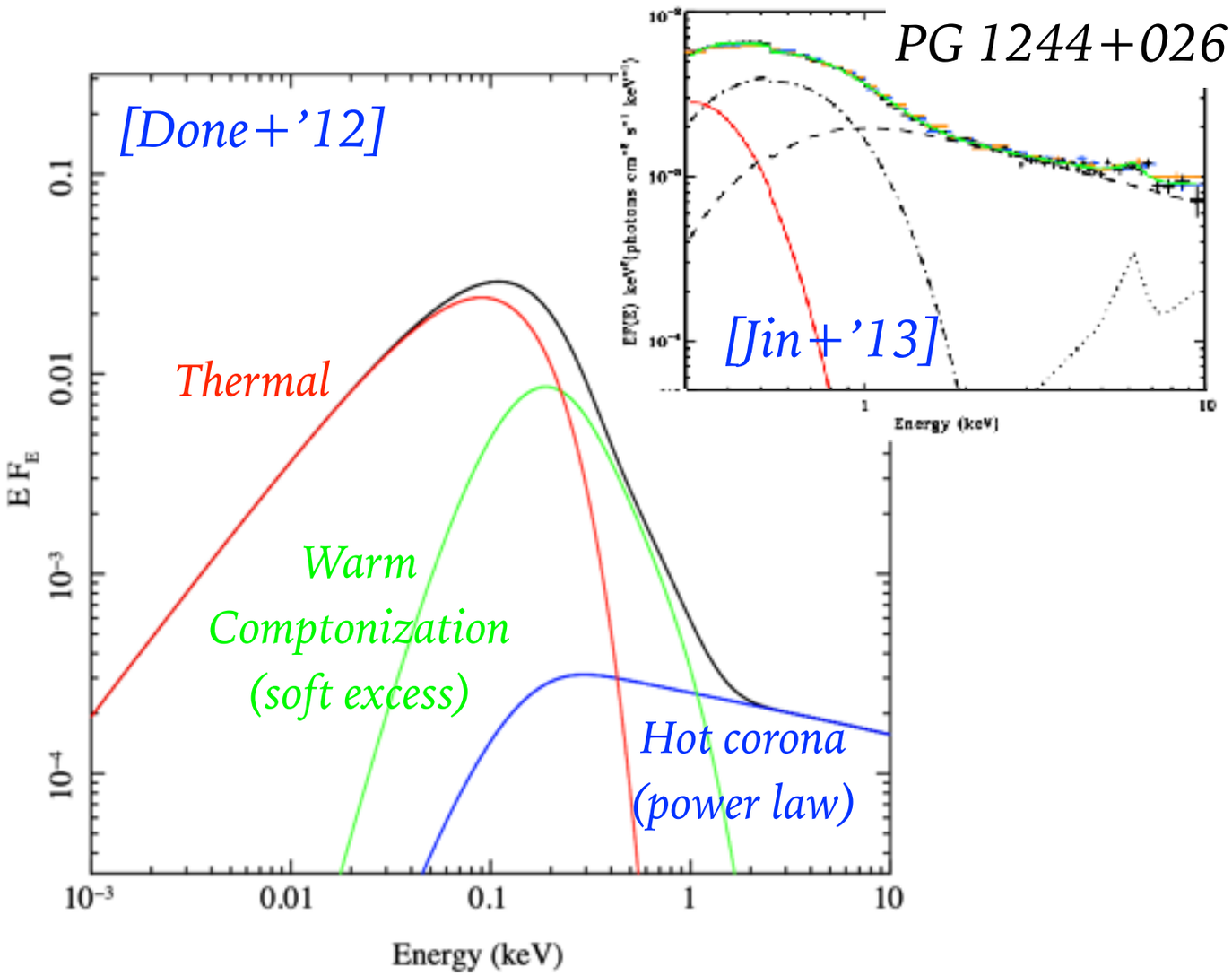


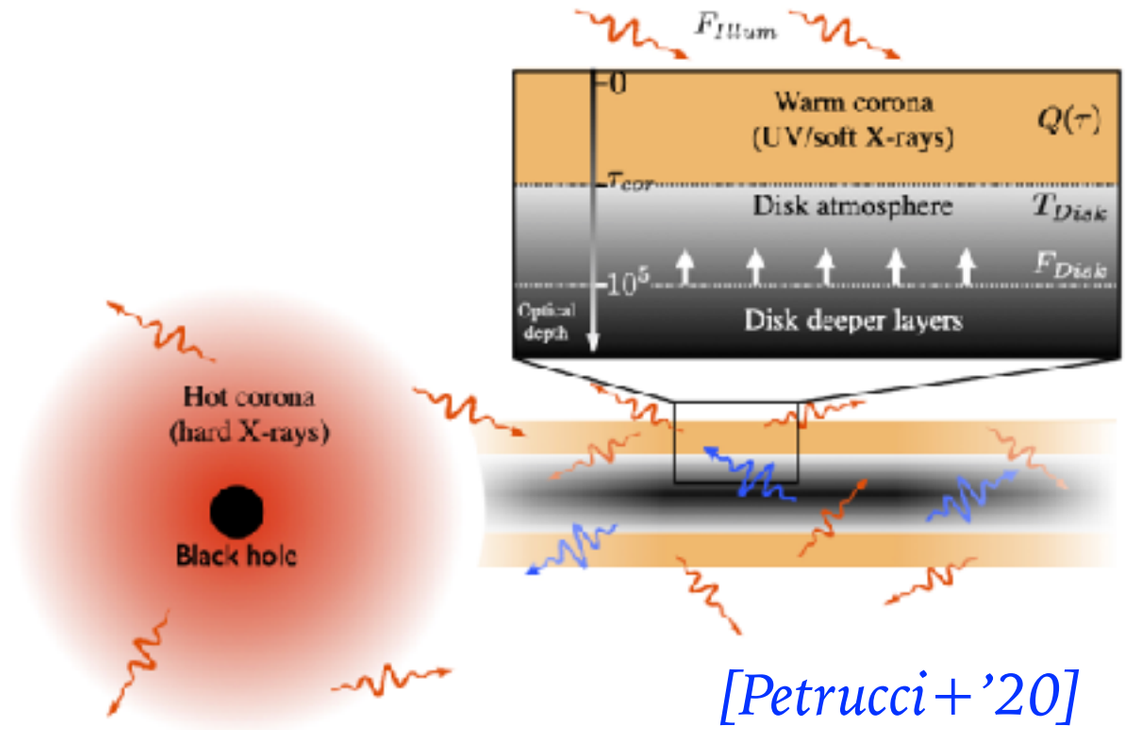


[Wilkins+'13; '16; '22; see also Chainakun+'15; '17]

Insights into the structured corona

A warm corona contributing to the soft excess?





[Petrucci+'20]

[see also Petrucci+'13; '18; Różańska+'15; García+'19; Gronkiewicz & Różańska'20; Ballantyne'20; Xiang+'22]

Insights into the structured corona

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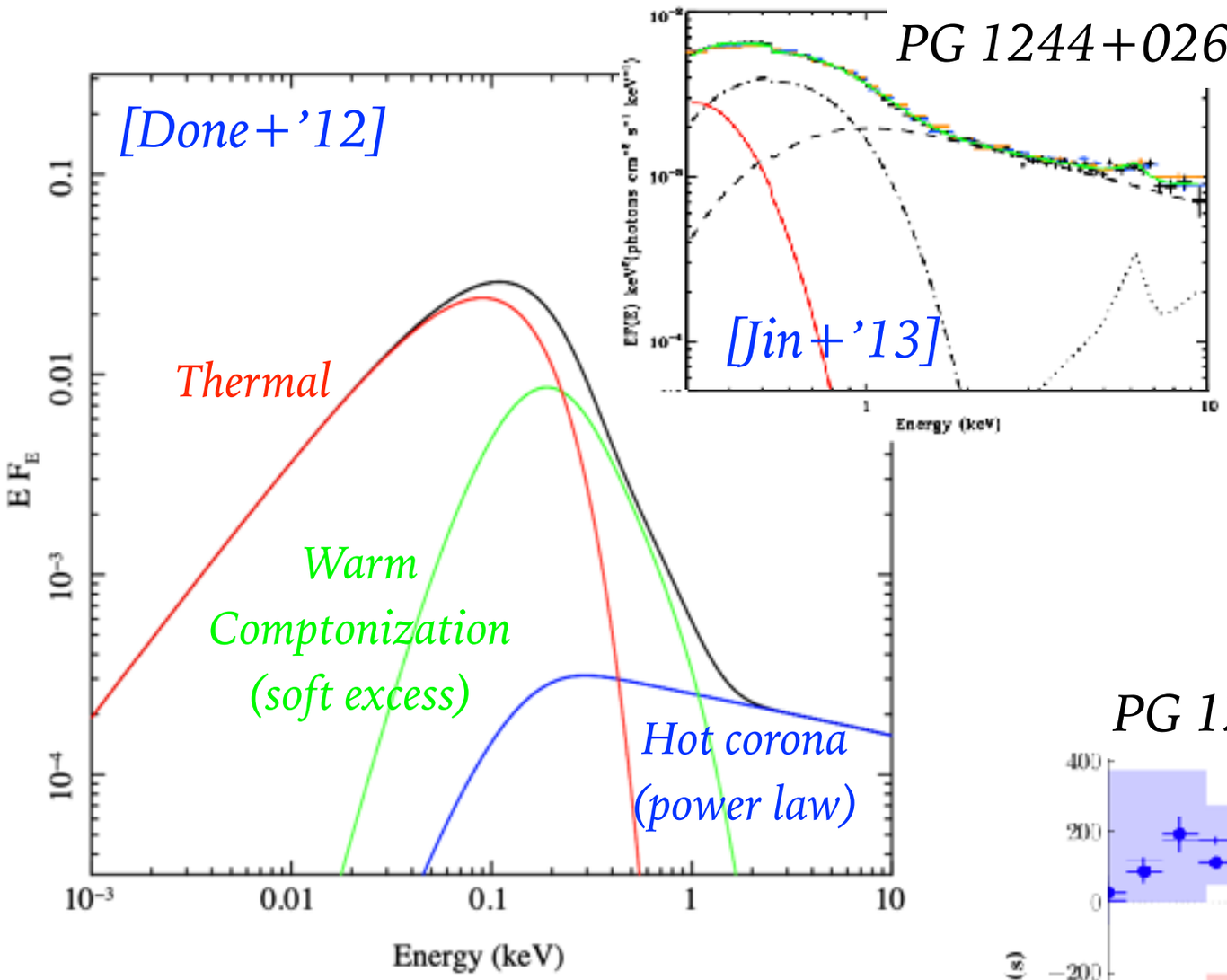
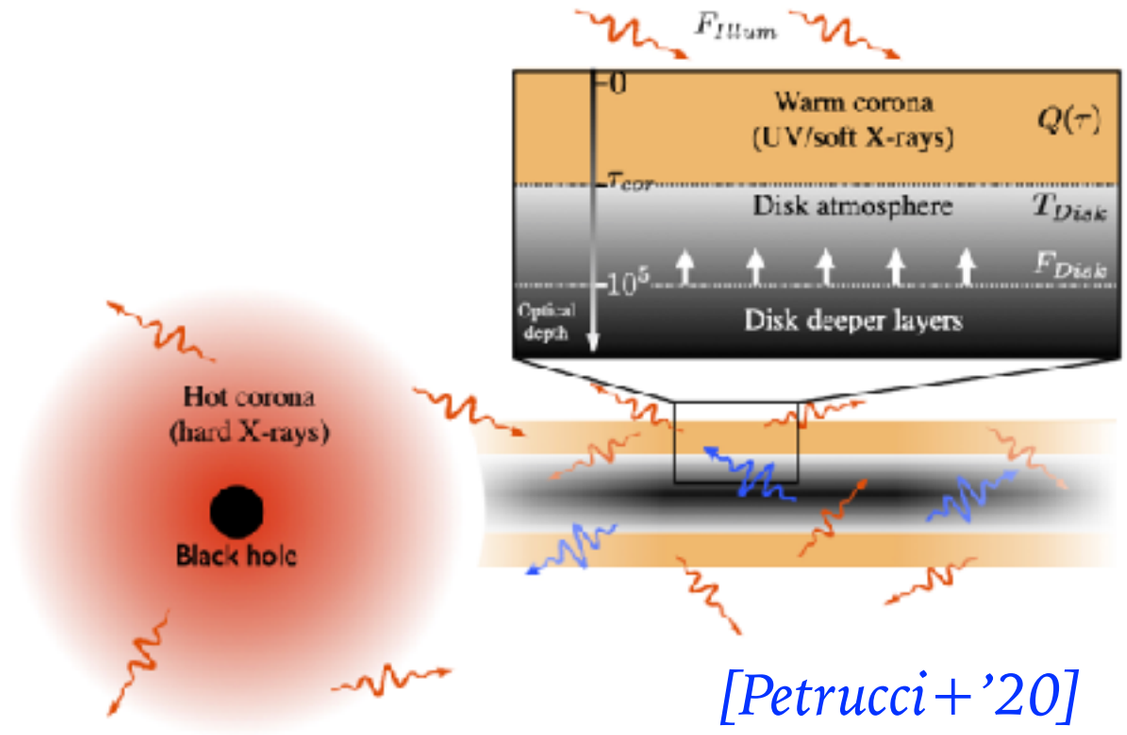
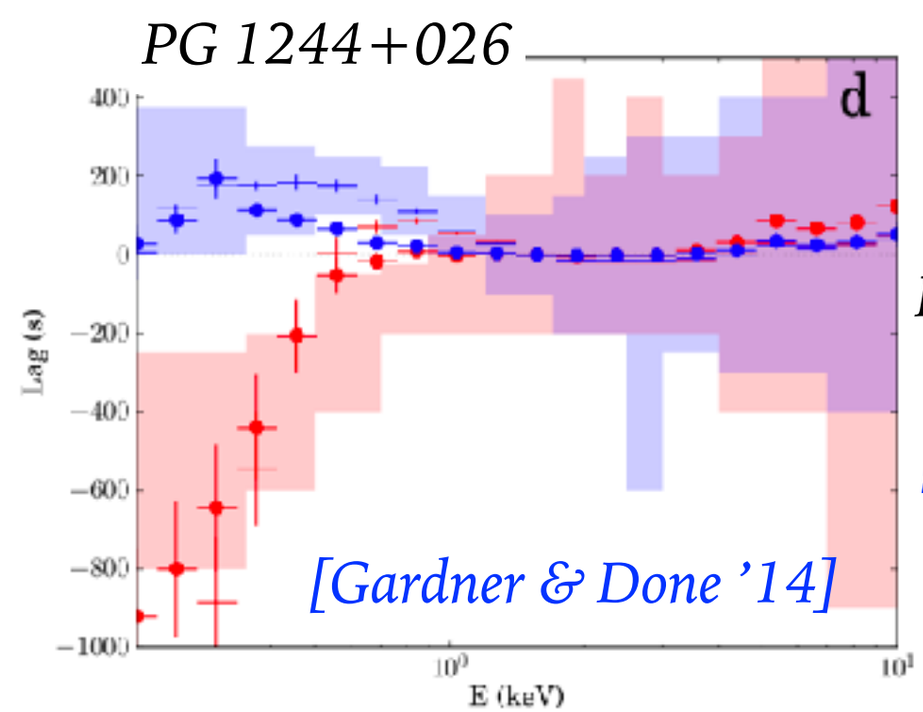






Is thermalization time scale relevant?

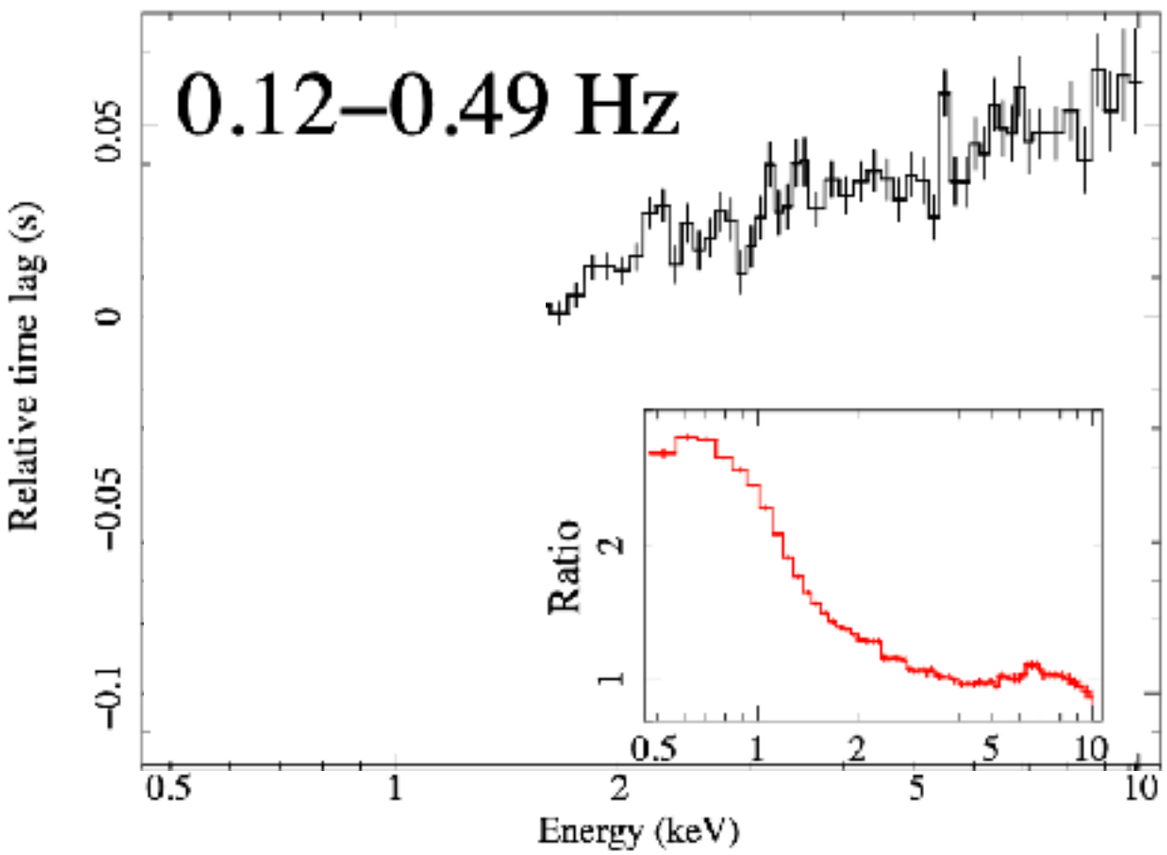
[see also Salvesen'22]

[see also Petrucci+'13; '18; Różańska+'15; García+'19; Gronkiewicz & Różańska'20; Ballantyne'20; Xiang+'22]

First detection of X-ray reverberation in BHXRBs

The thermal response of the irradiated disc

GX 339-4 (Hard state, XMM)



[Uttley +'11]

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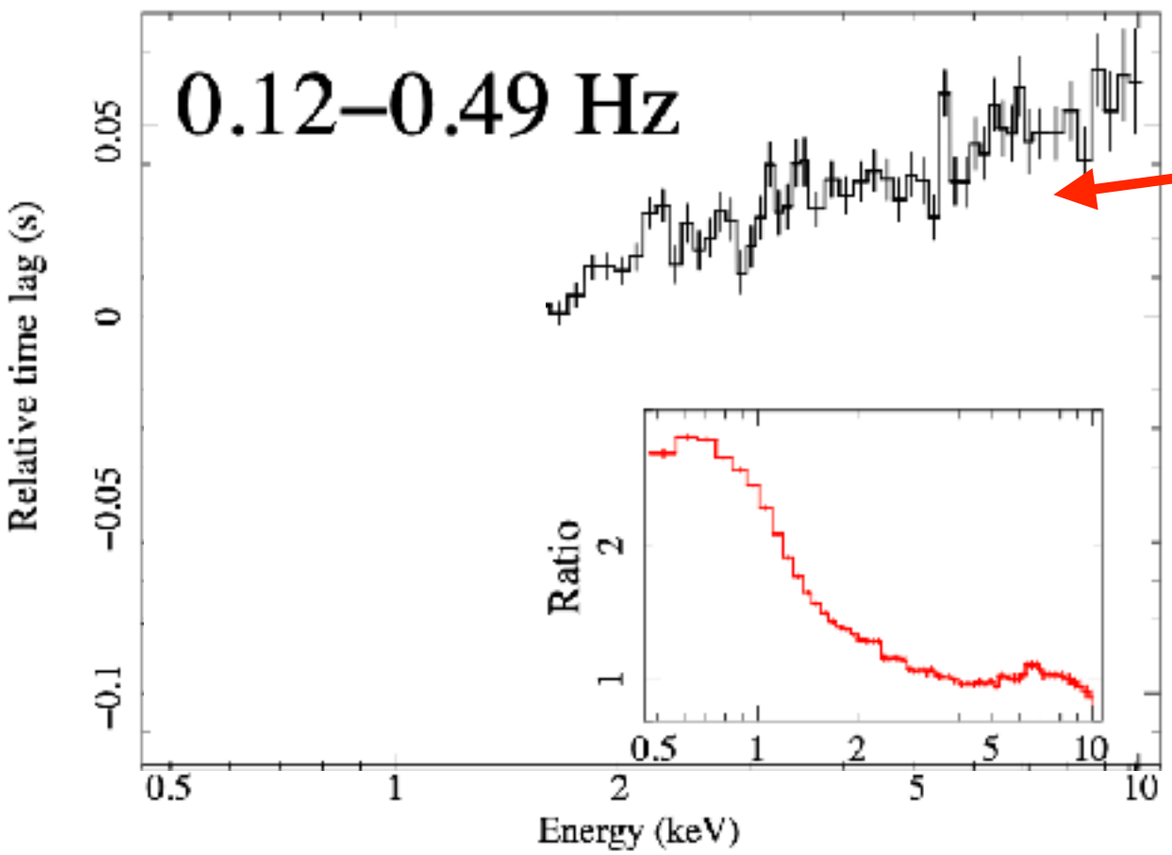

Propagation of ṁ fluctuations

[e.g. Kotov+'01; Arévalo & Uttley 2006]

[Uttley +'11]

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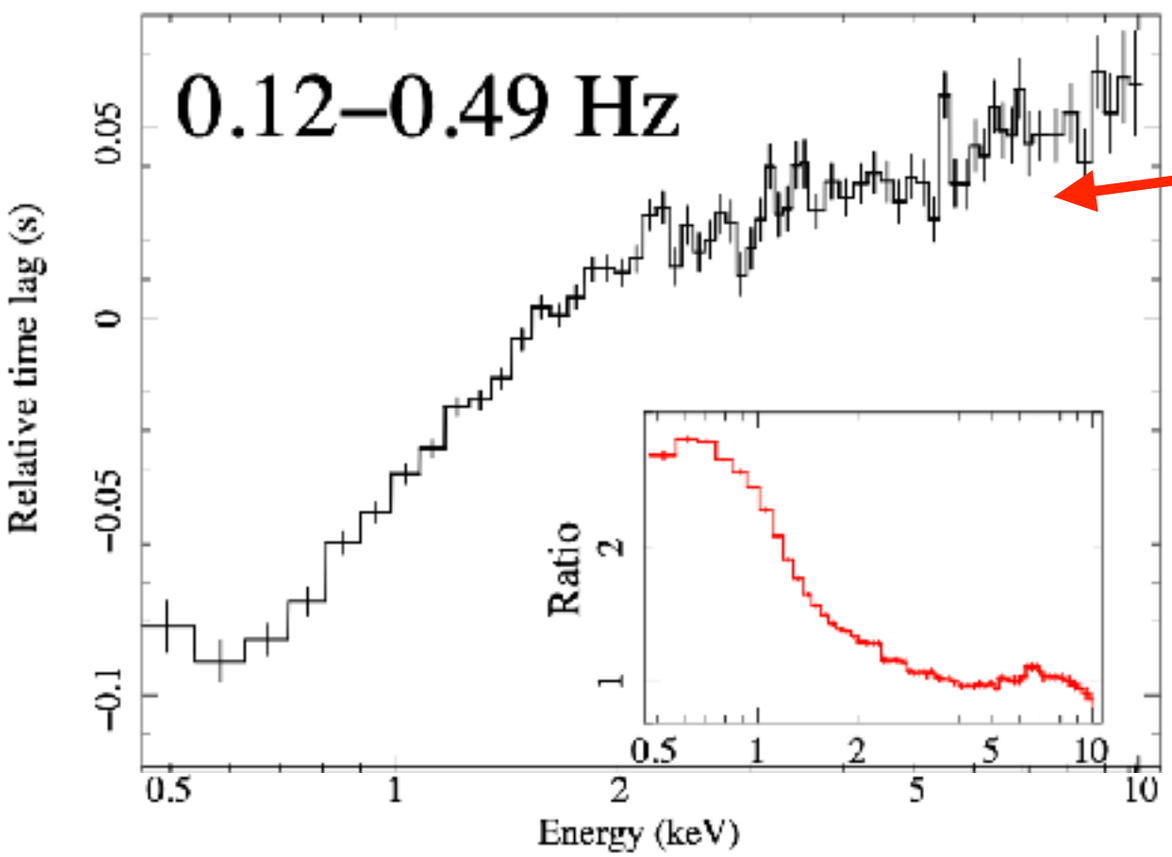

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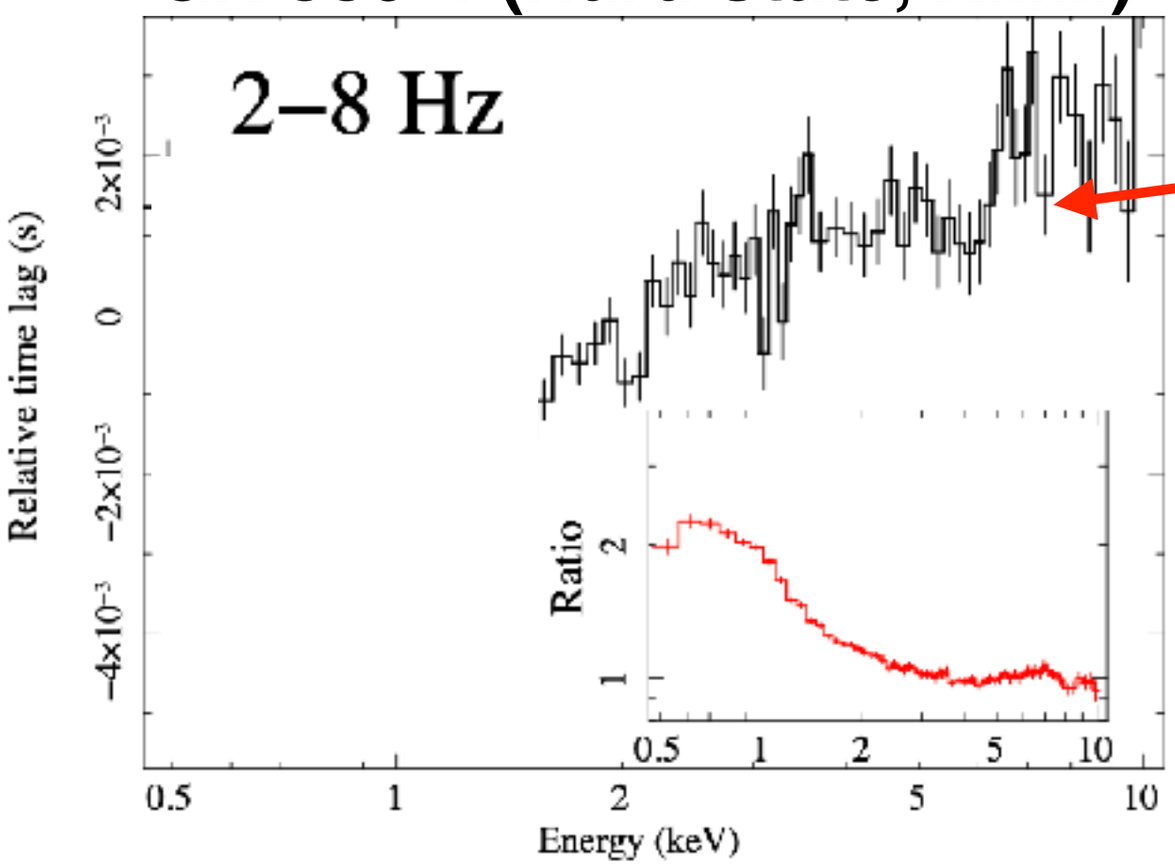

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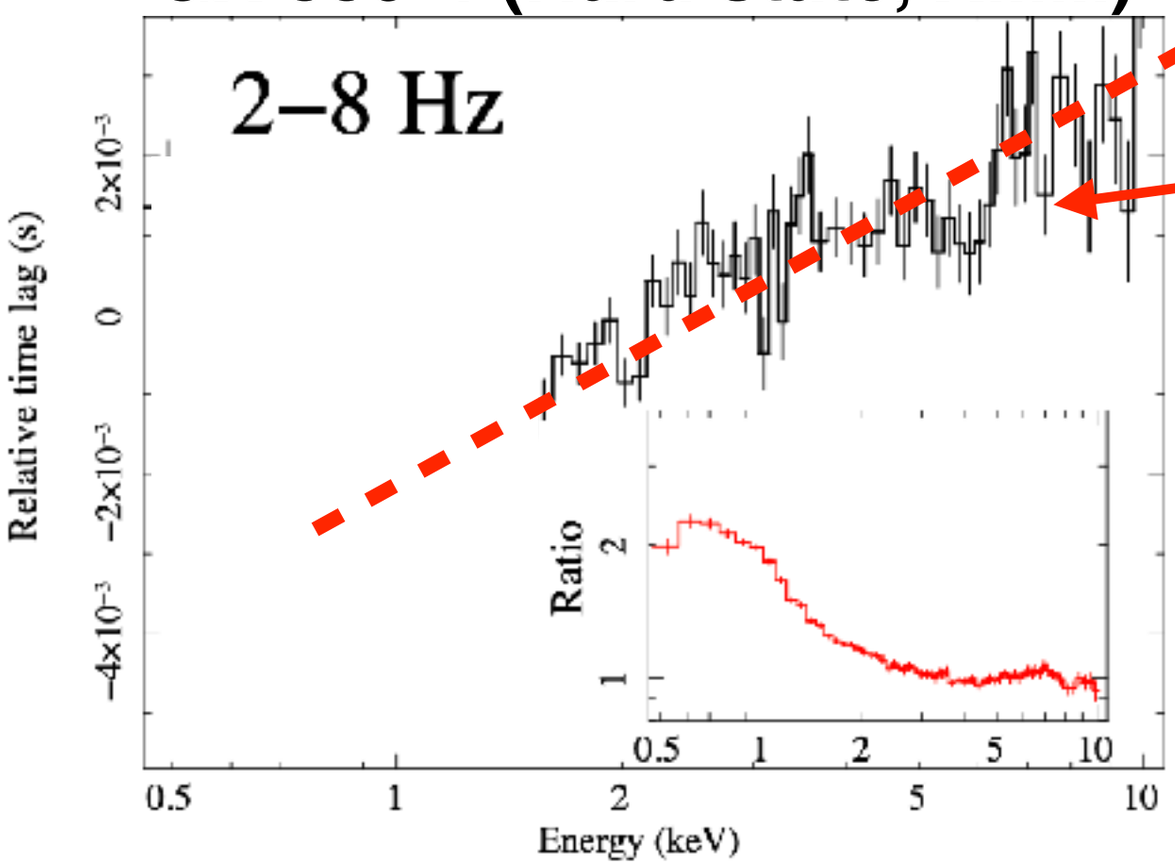

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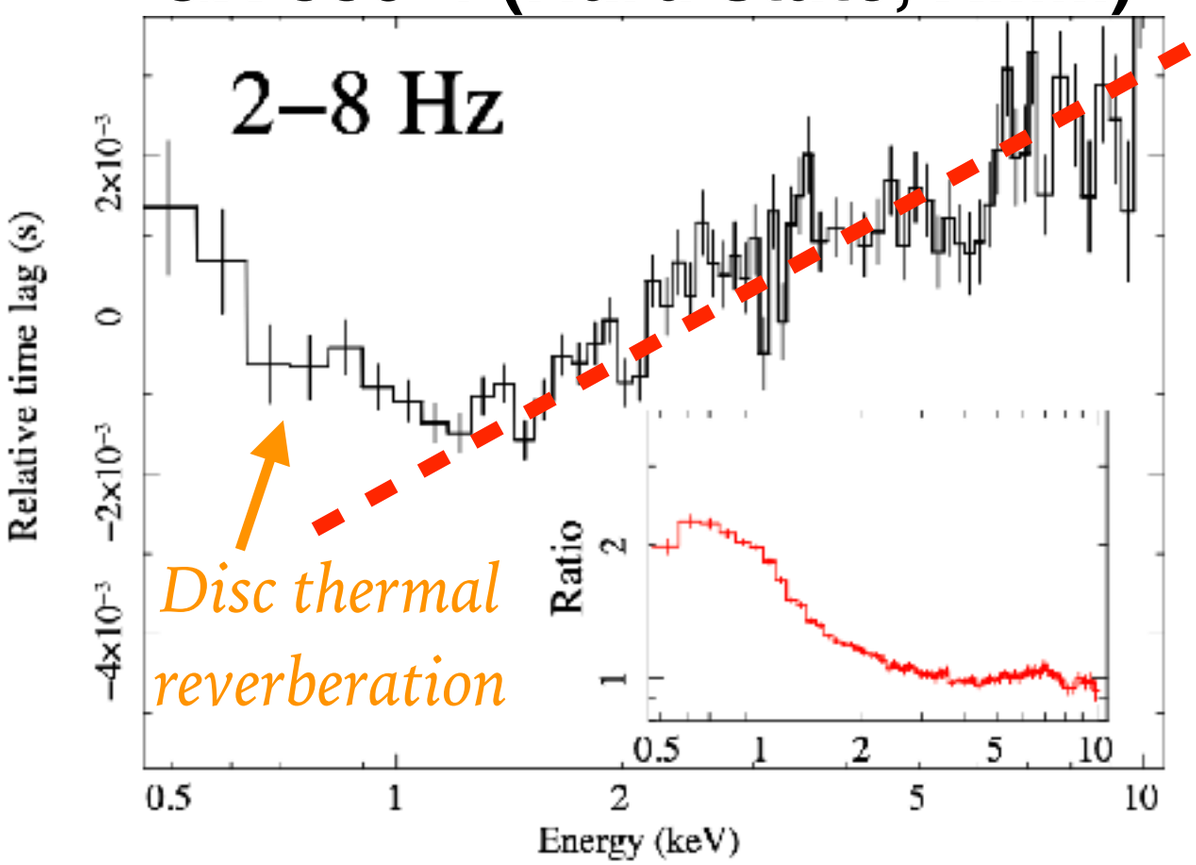

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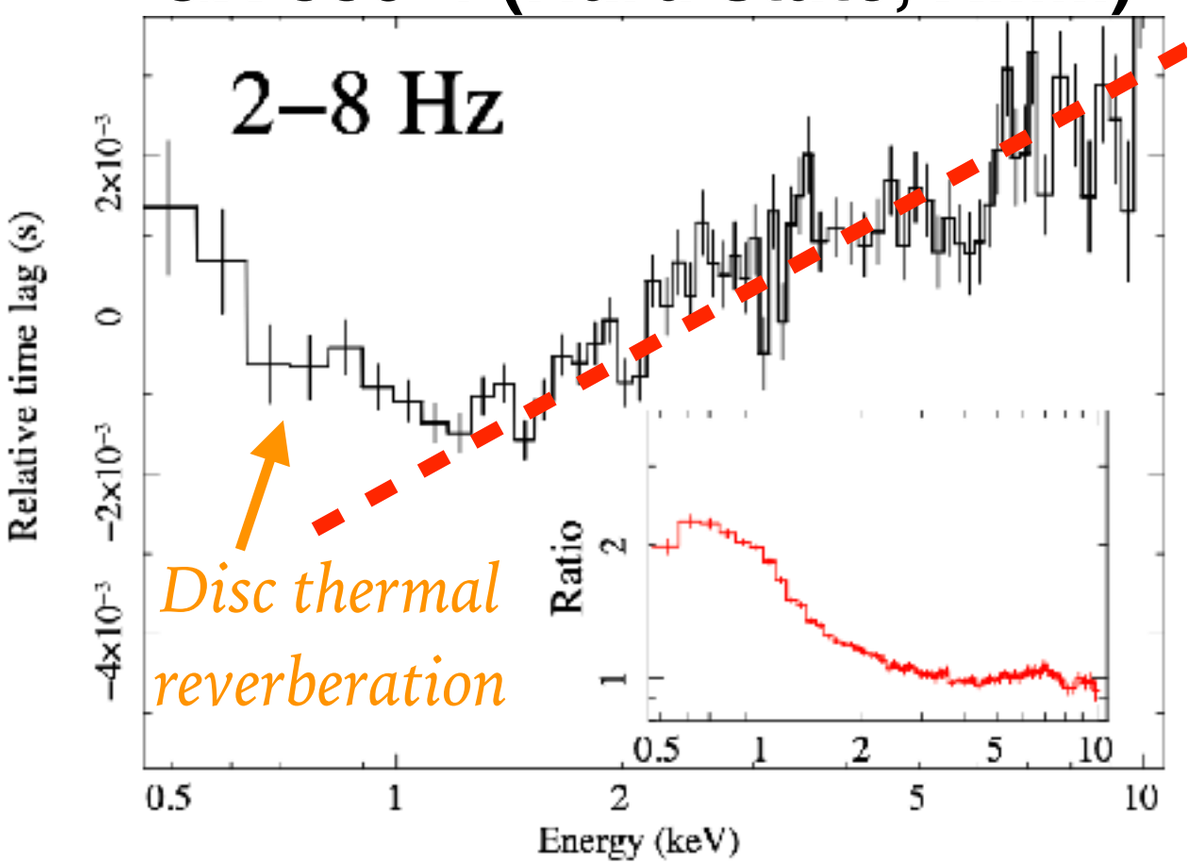
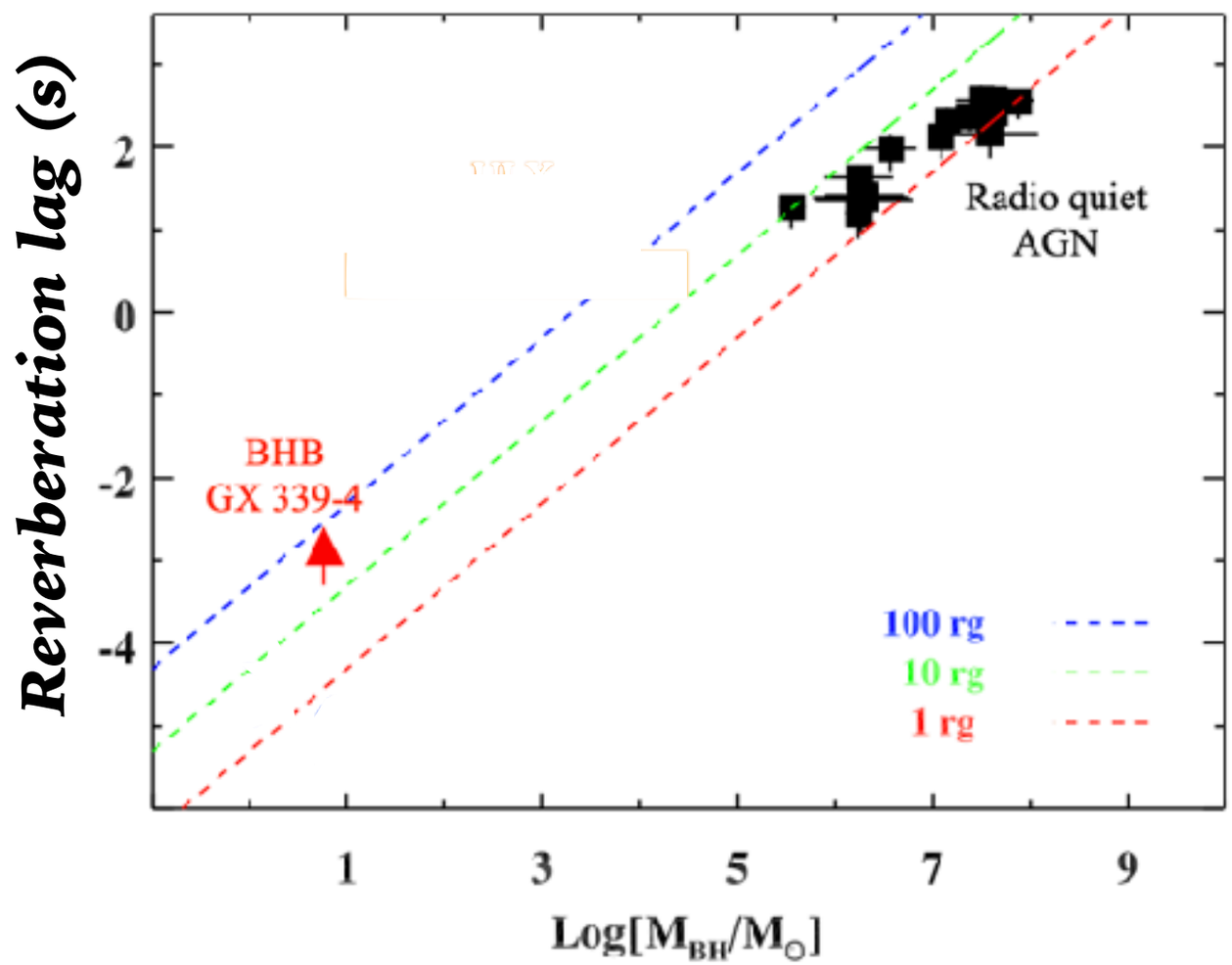


[Uttley +'11]

[De Marco+'13a; '13b]



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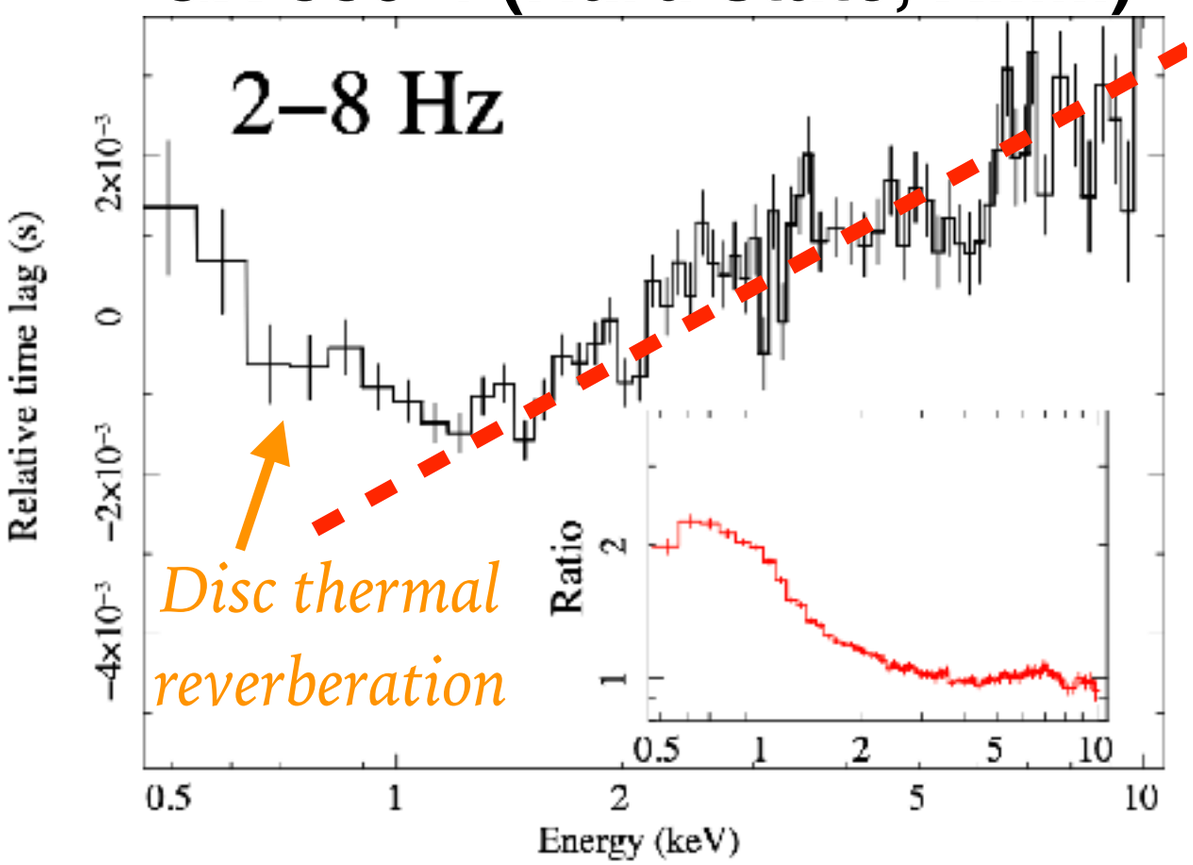

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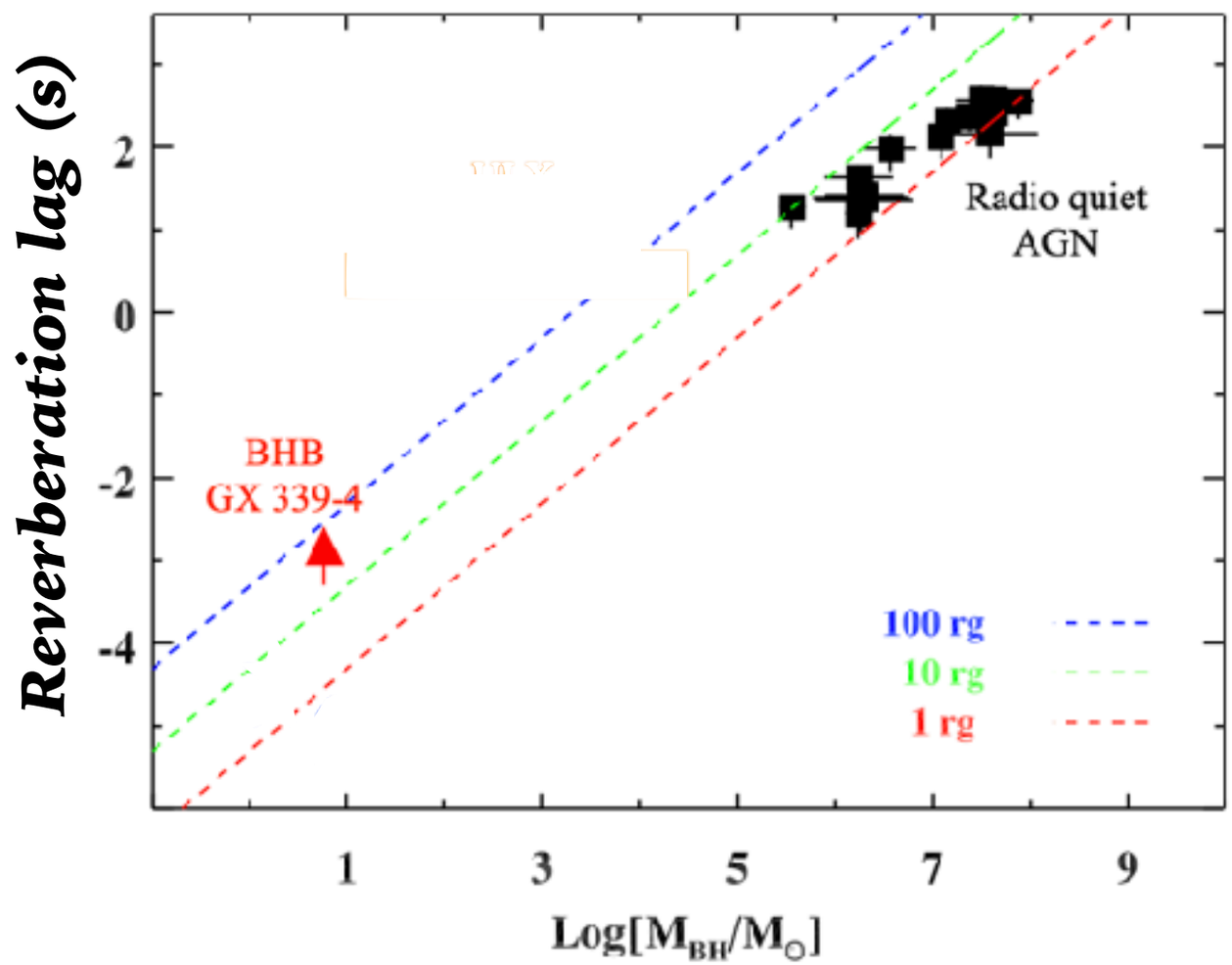
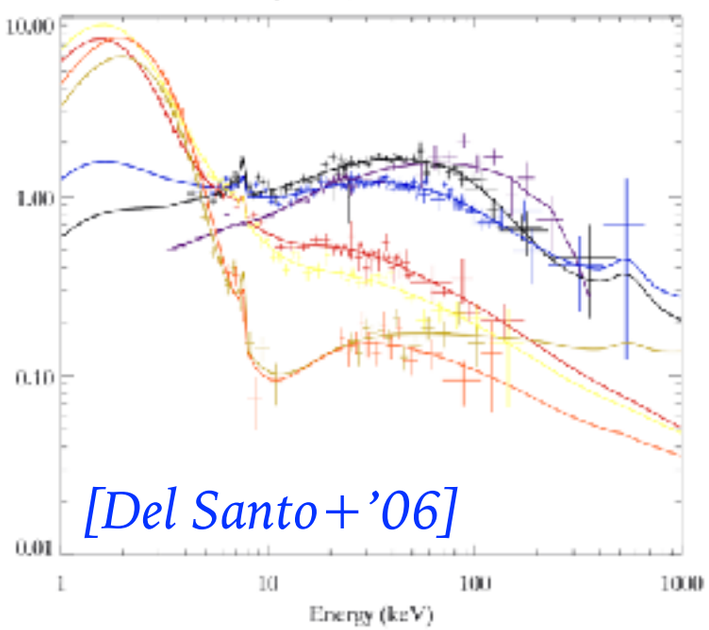


Lag a factor of ~10 longer than expected for a disc at ISCO and a compact corona

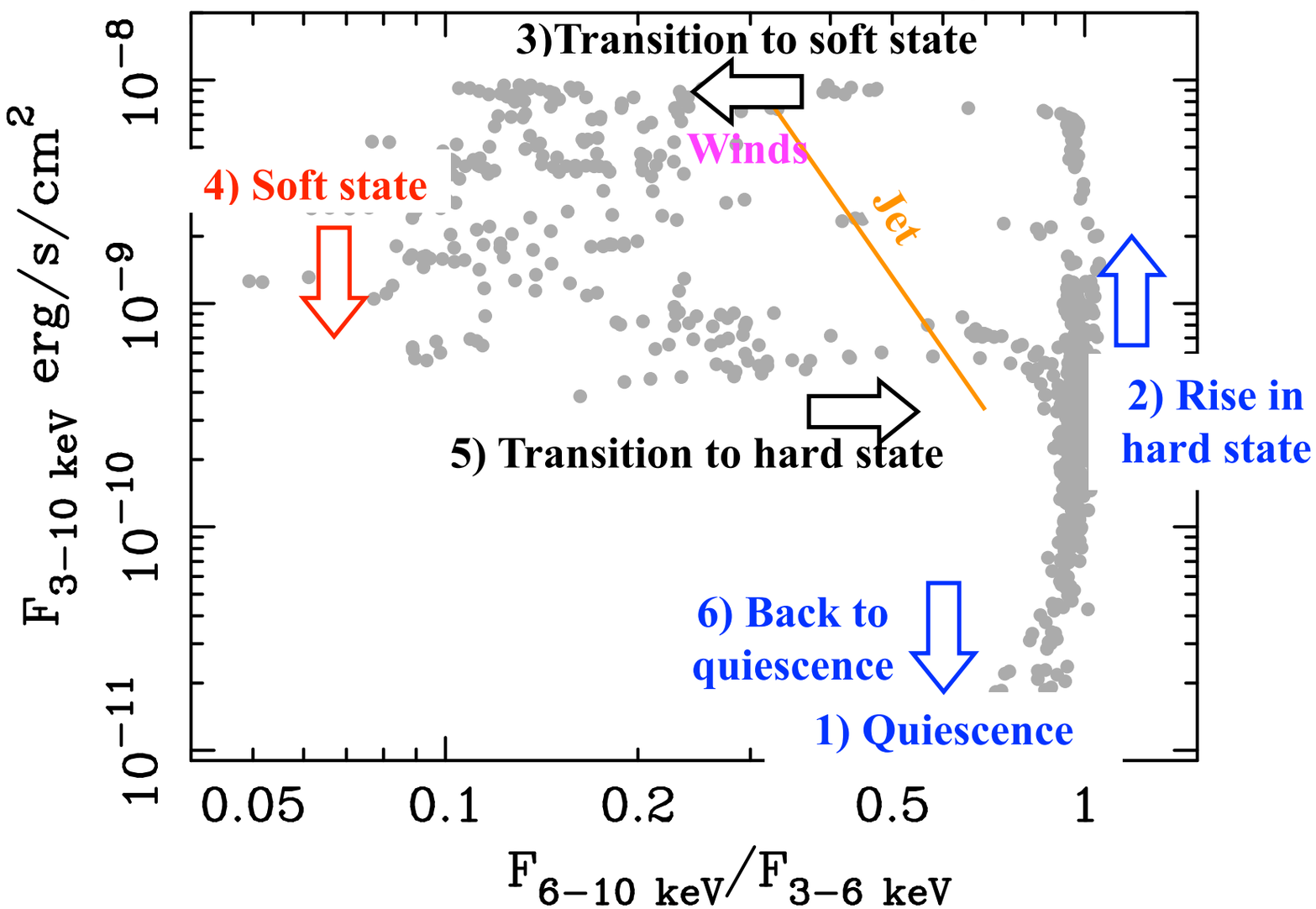
Accretion states in BHXRBs

Complex spectral evolution during outbursts

X-ray spectrum



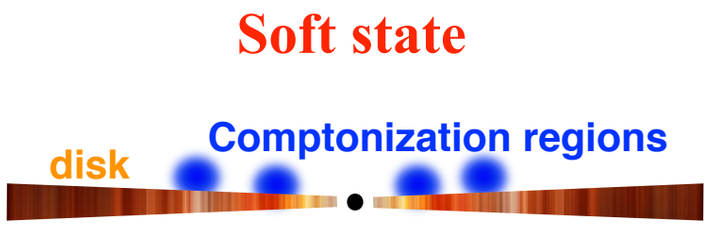
GX 339-4: Hardness-intensity diagram

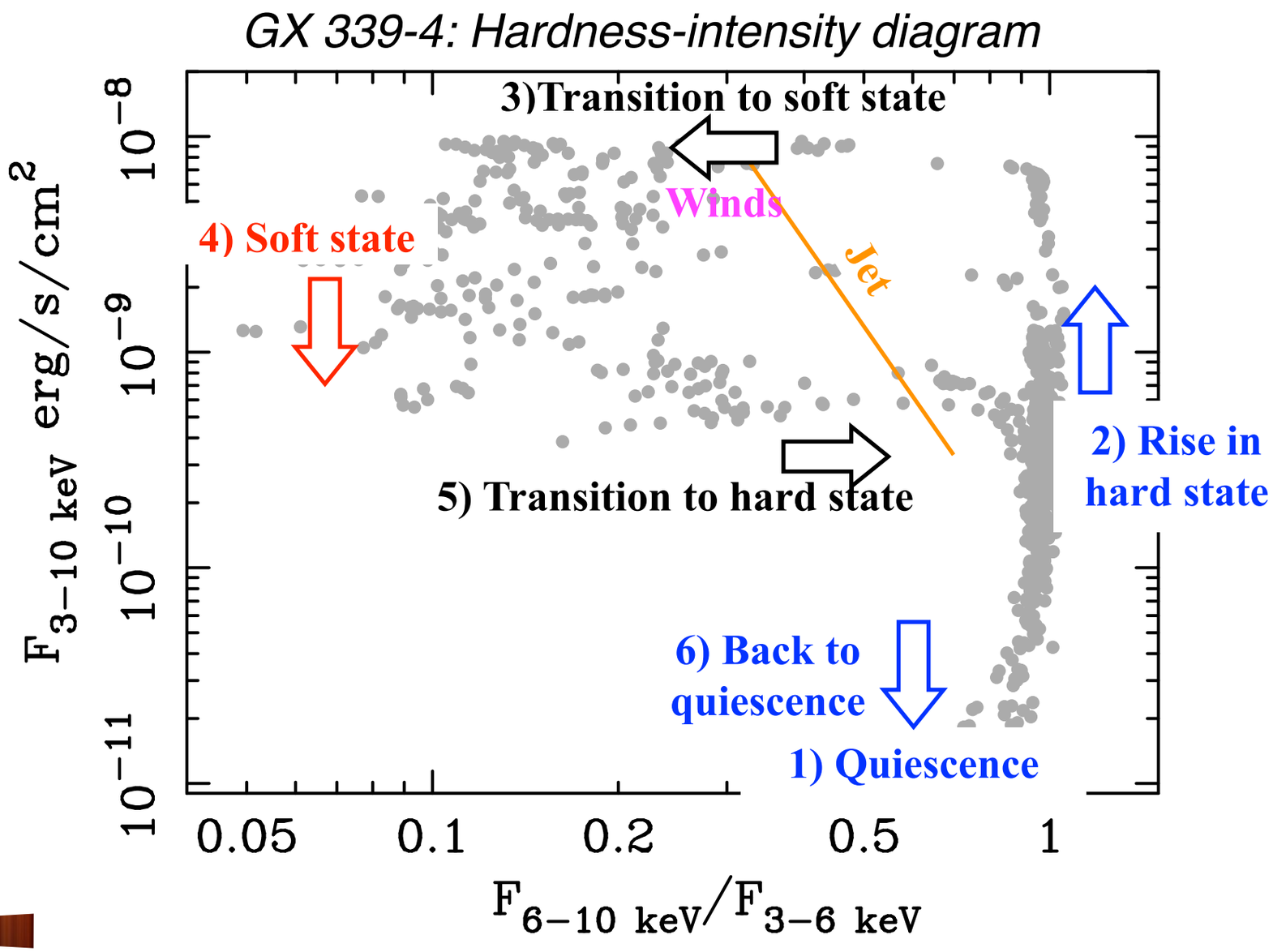


[e.g. Mirabel & Rodriguez '99; Fender +'04; Homan & Belloni '05; Remillard & McClintock '06; Fender & Belloni '12]

Accretion states in BHXRBs

Evolving geometry of the innermost accretion flow





[e.g. McClintock+'95; Esin +'97, '01; Gierlinski & Done 04; Tomsick +'09; Steiner+'10; Bernardini +'16]

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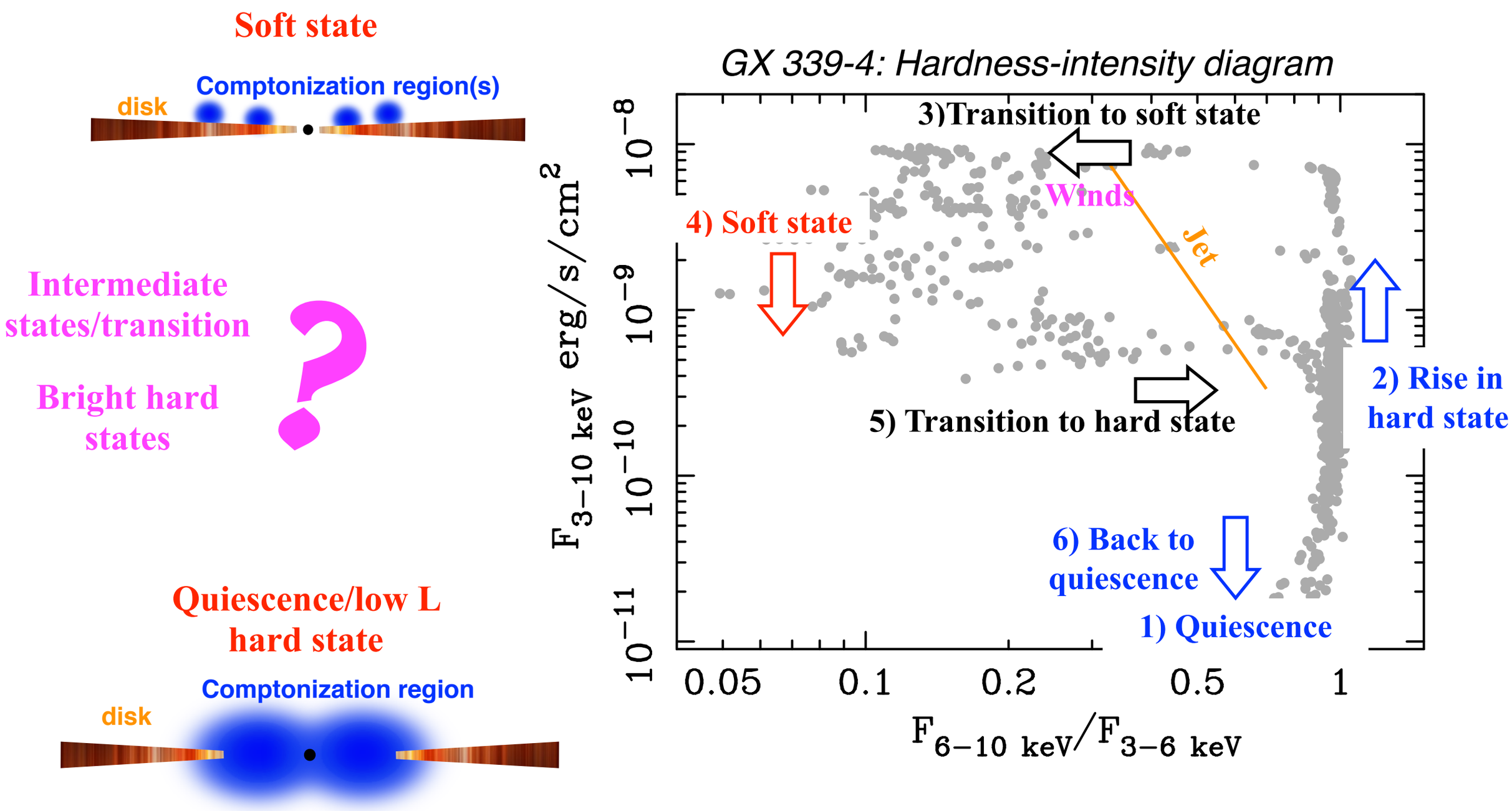

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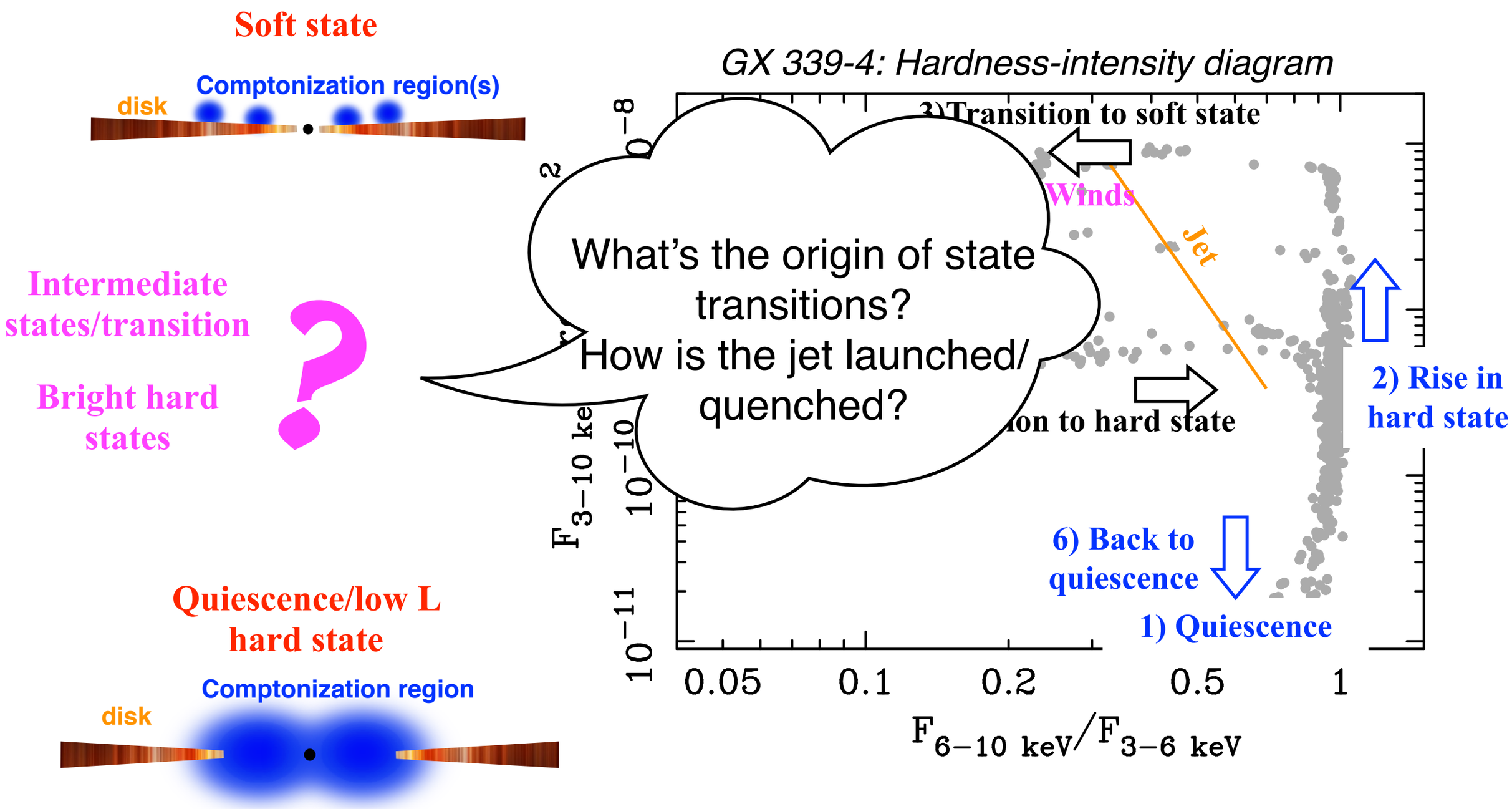

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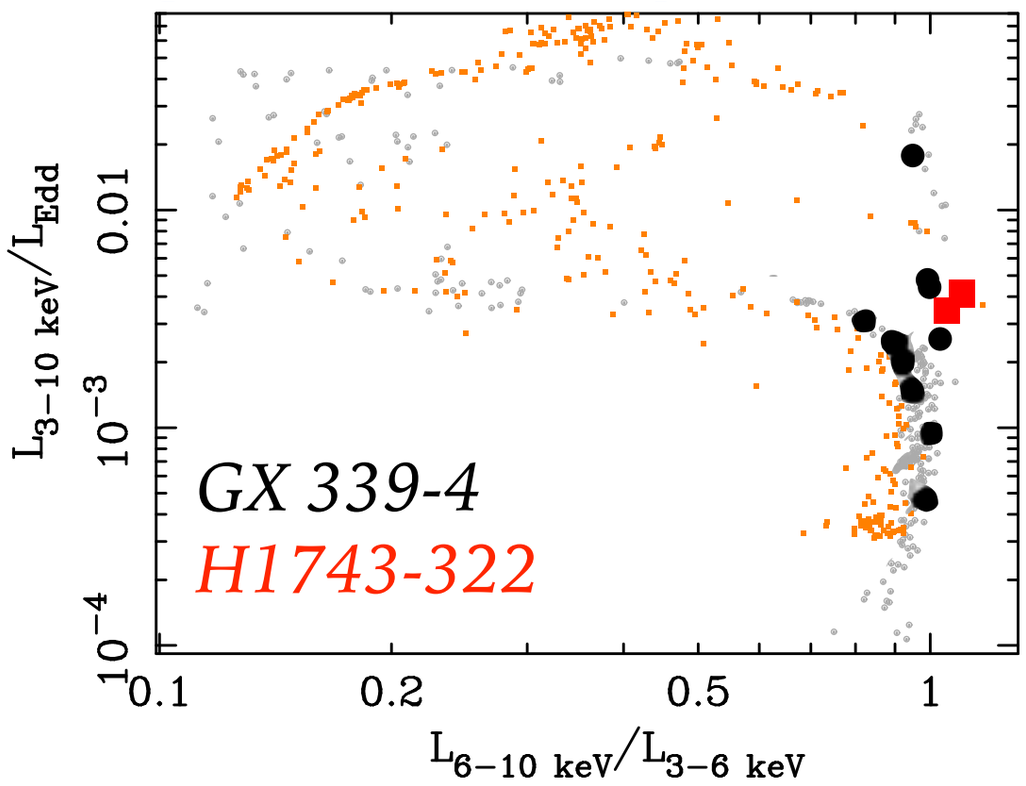
Lags shorter at higher luminosities in hard state

A systematic search with XMM

[De Marco & Ponti '16]



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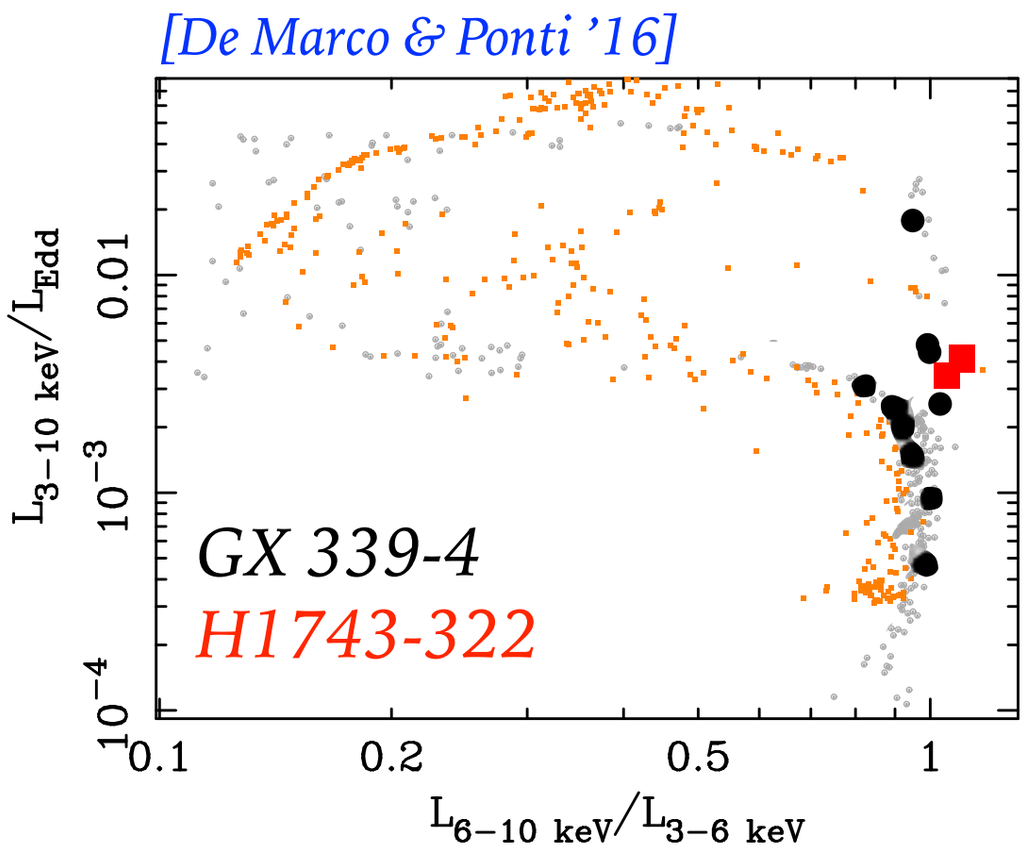

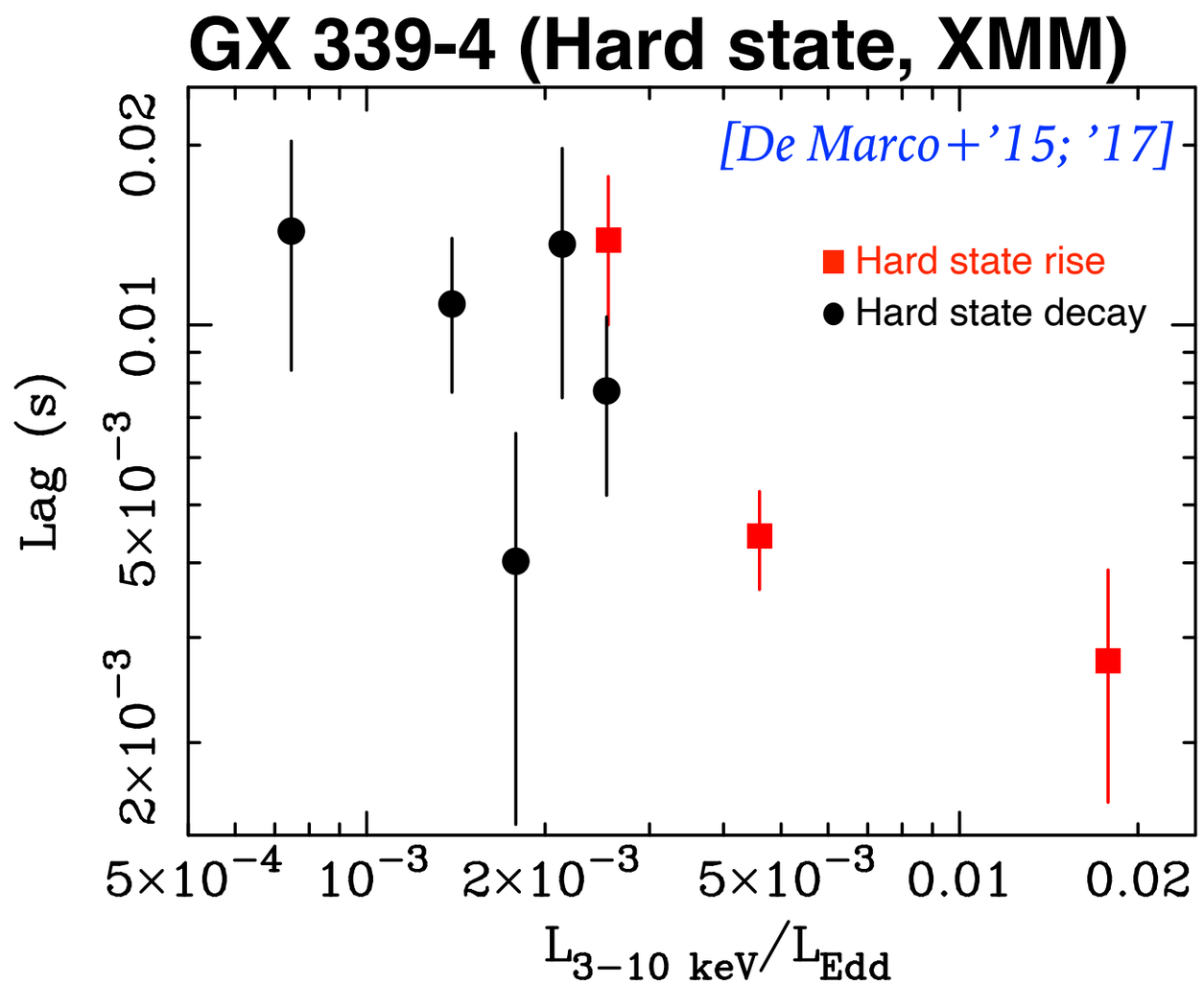

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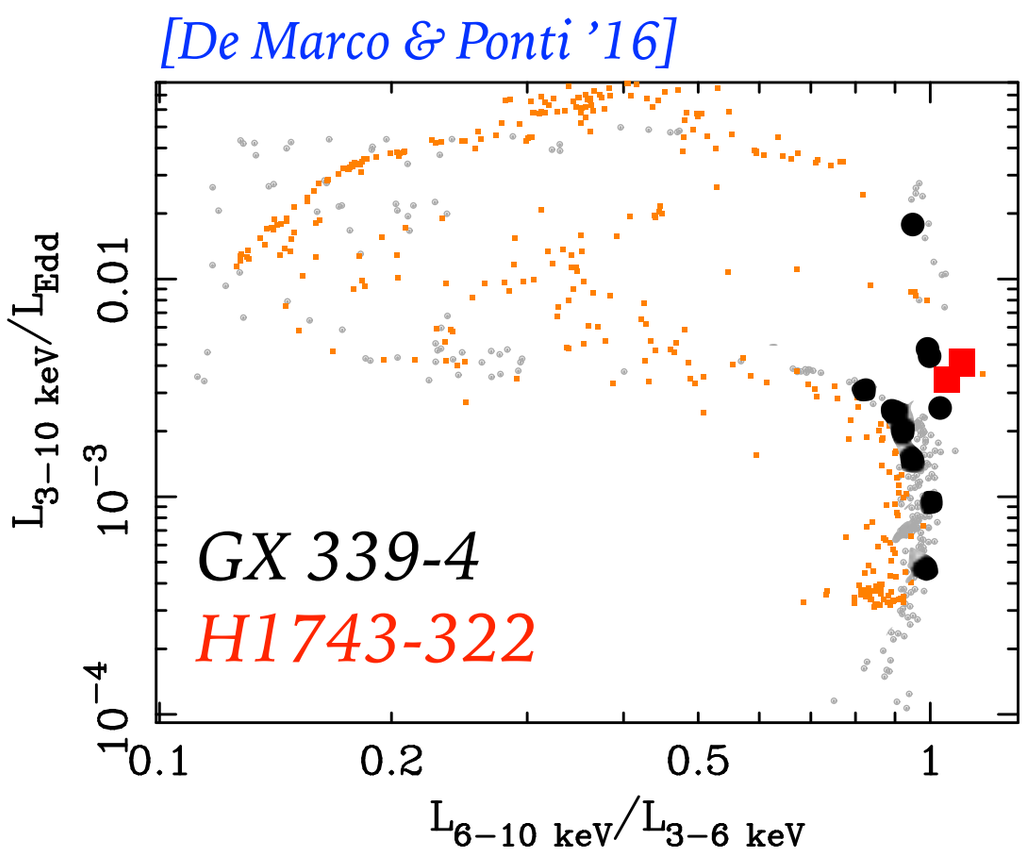
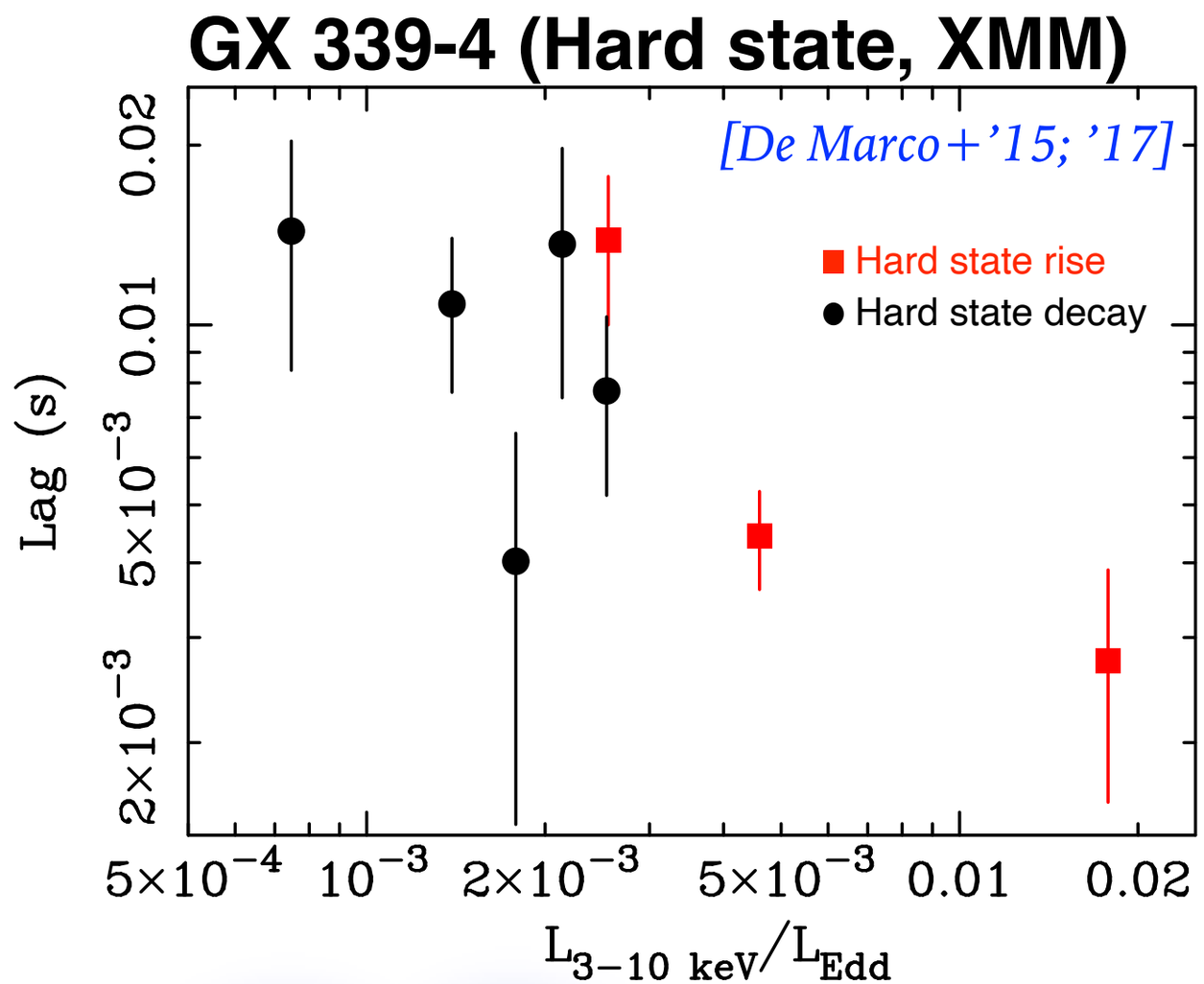
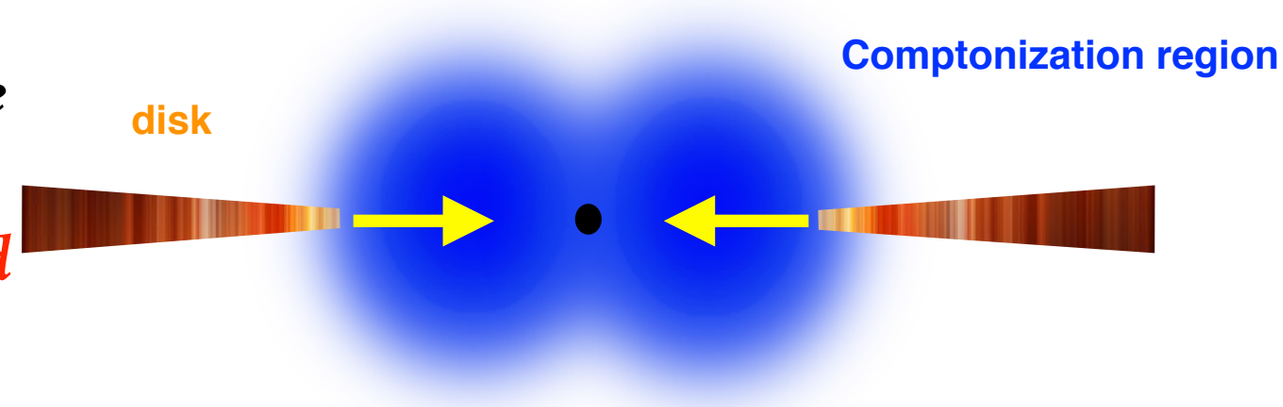




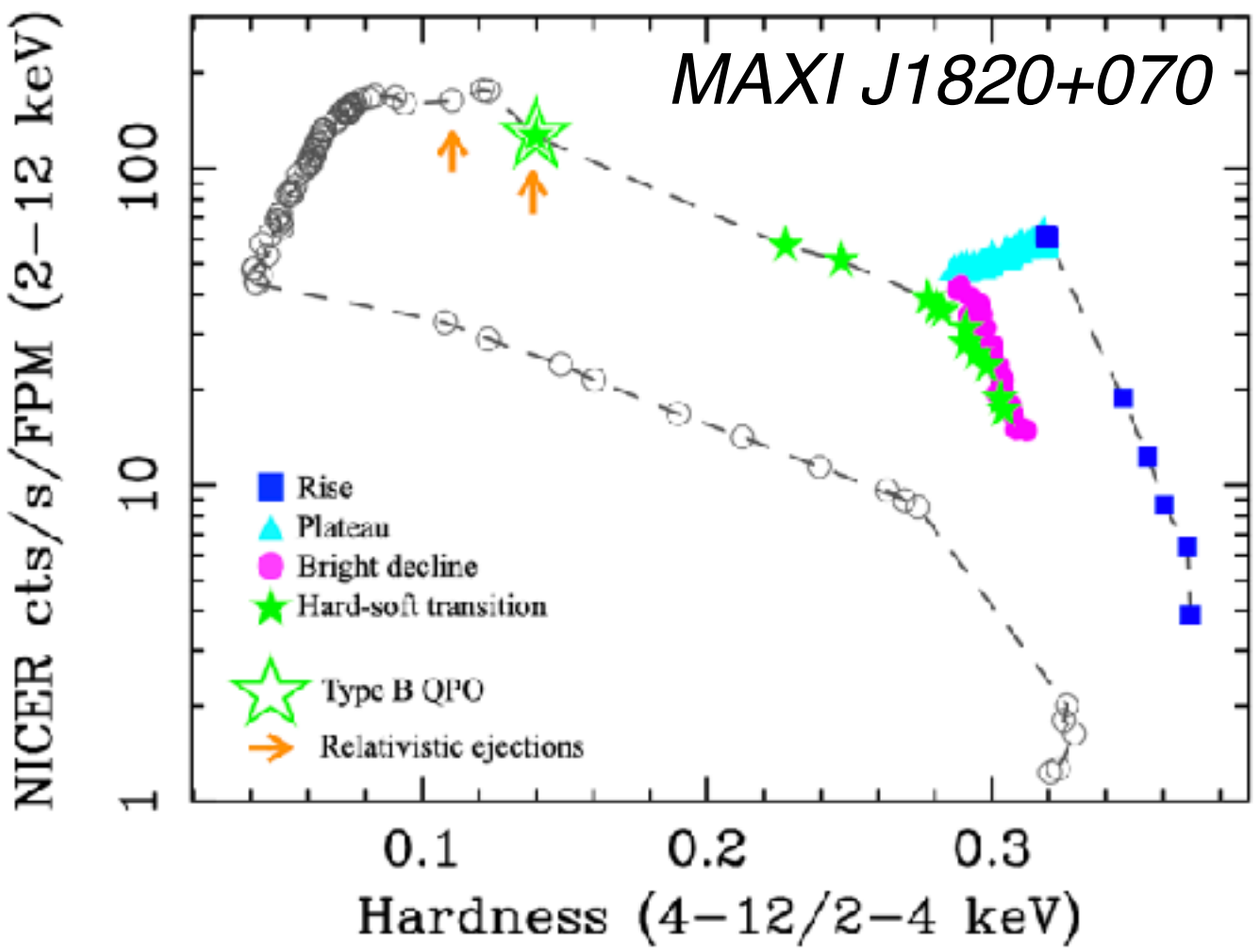
Steady change of the geometry of the inner flow in the hard state

(shorter light paths between disc and X-ray source at high L)



Reverberation lags with NICER

The case of MAXI J1820+070



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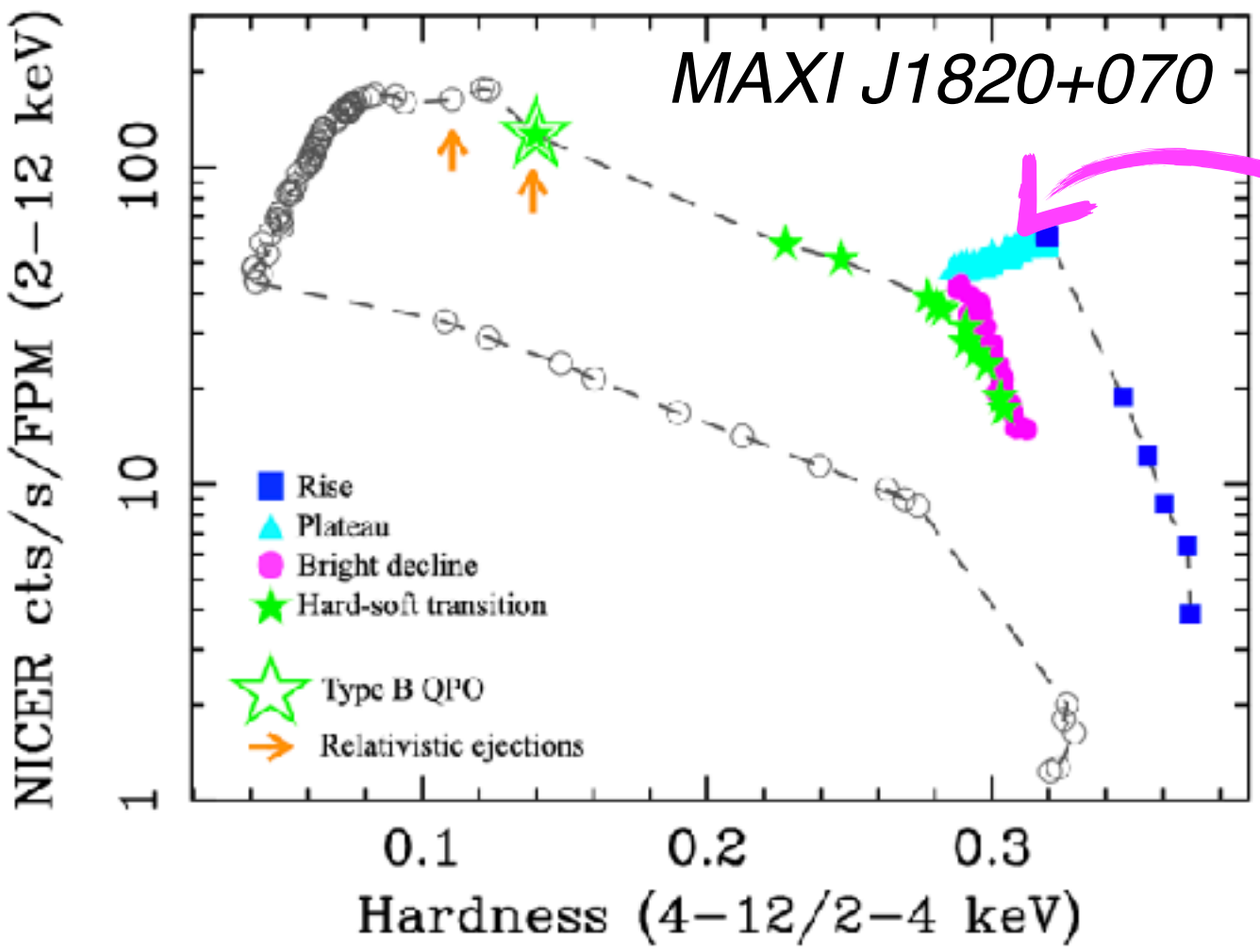
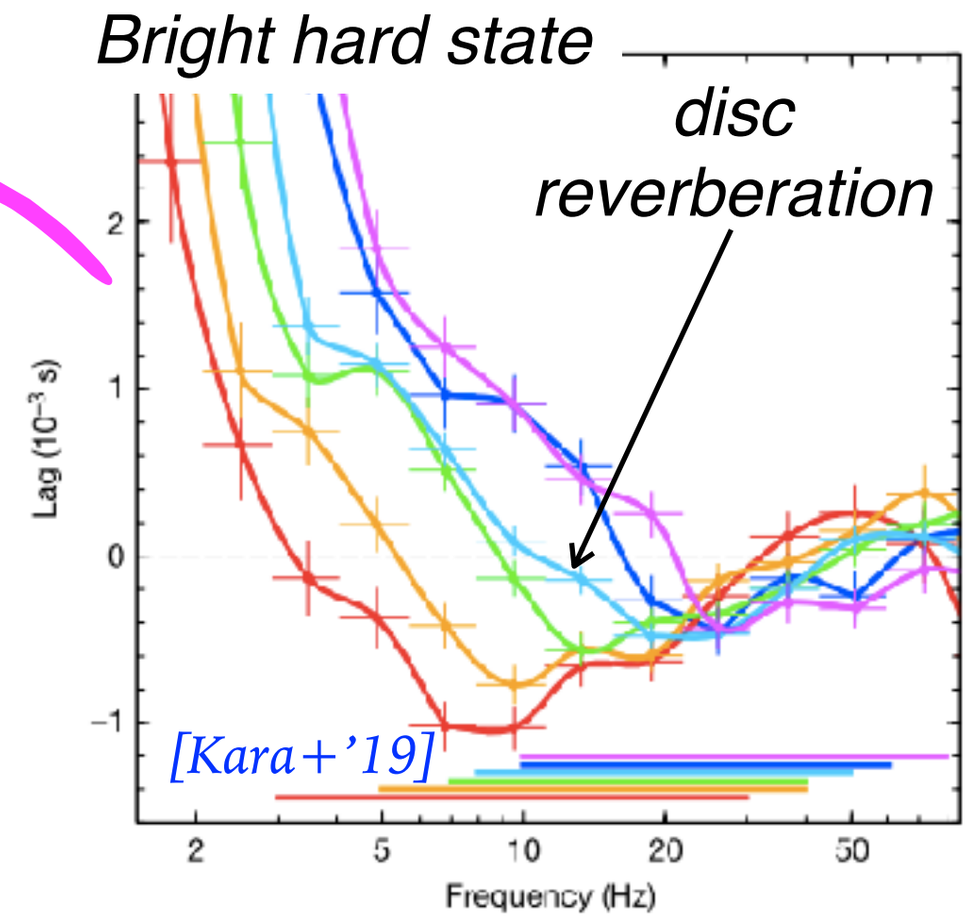
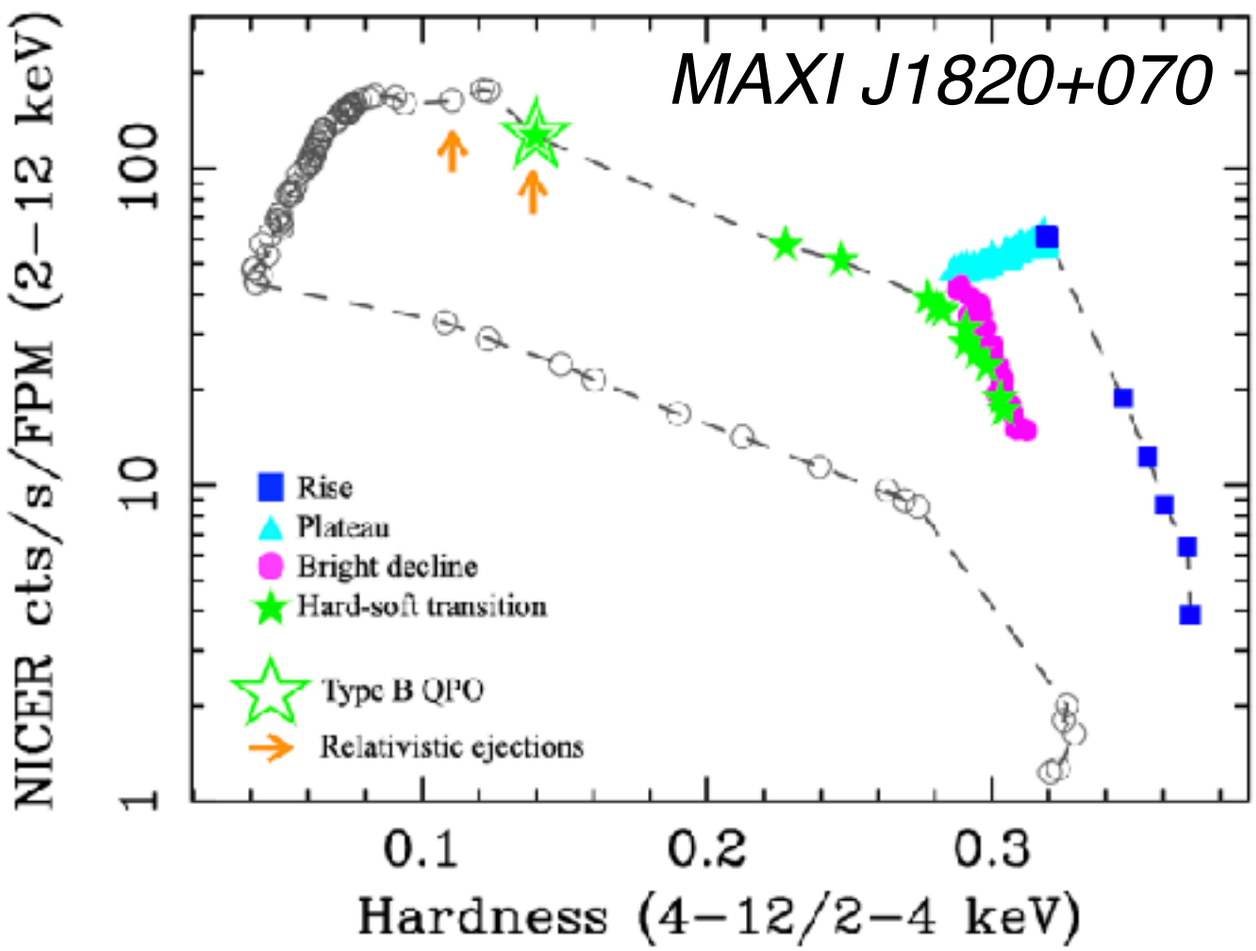
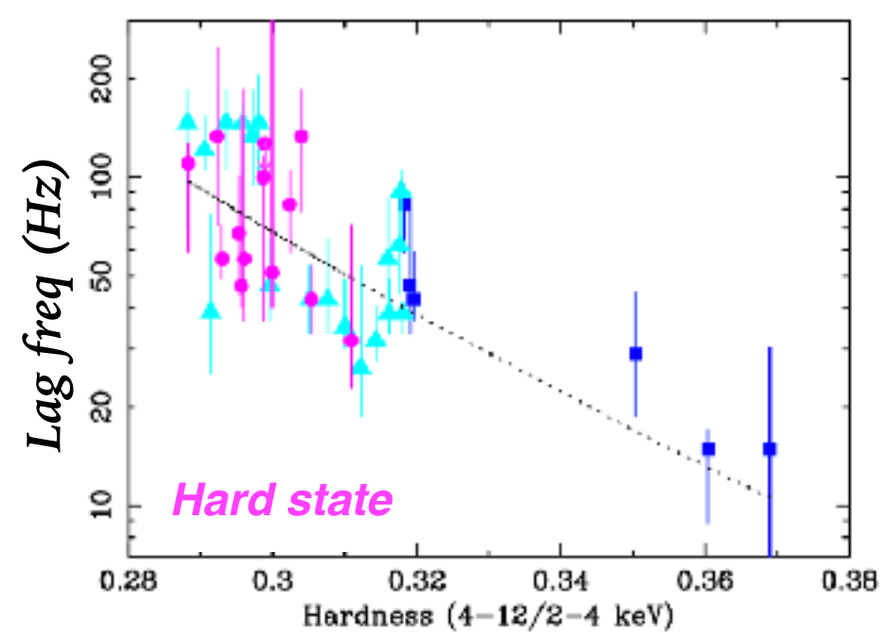




Evolution of reverberation lags during outburst

First long monitoring of X-ray reverberation





Shorter lags

Longer lags

[De Marco+'21]

Evolution of reverberation lags during outburst

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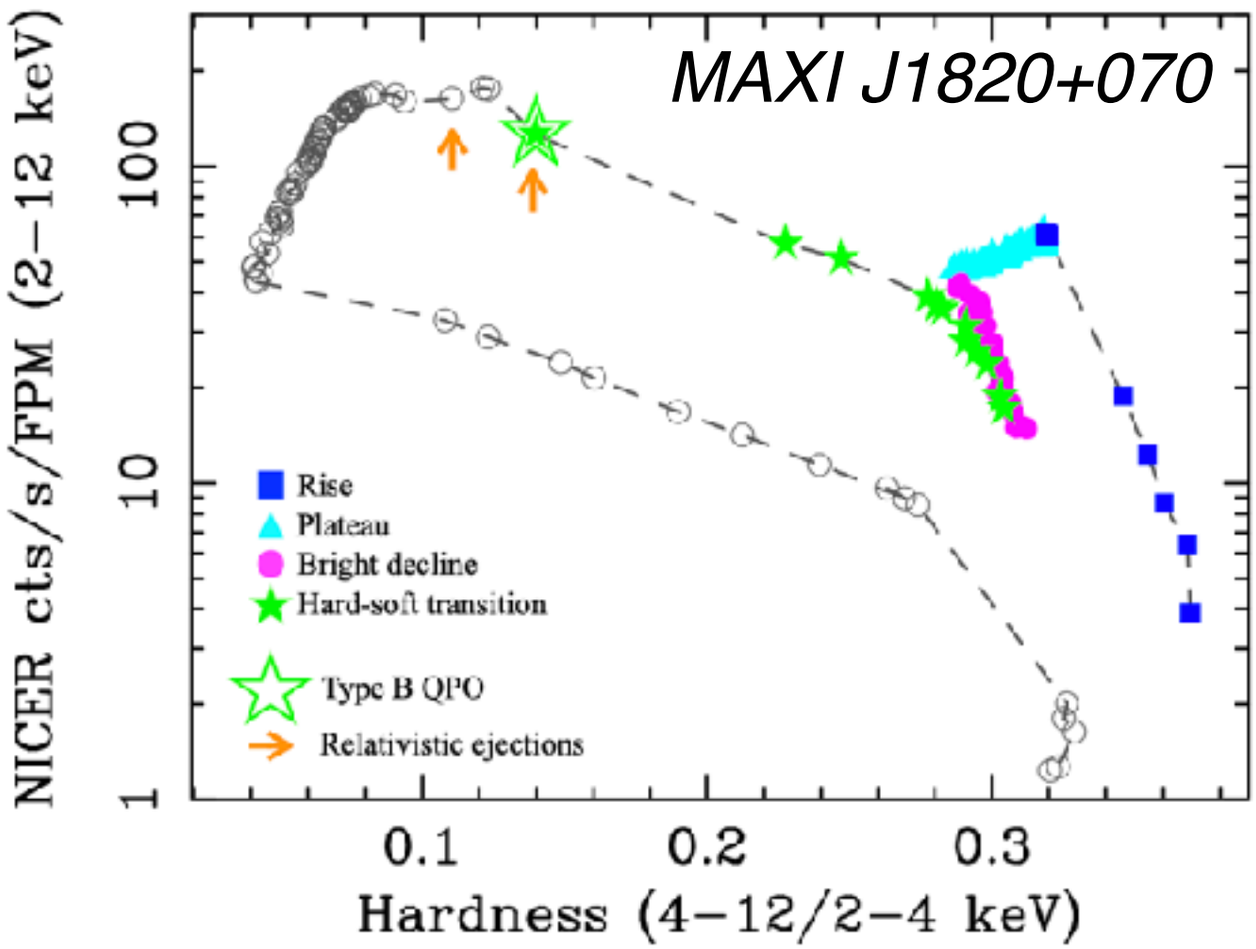
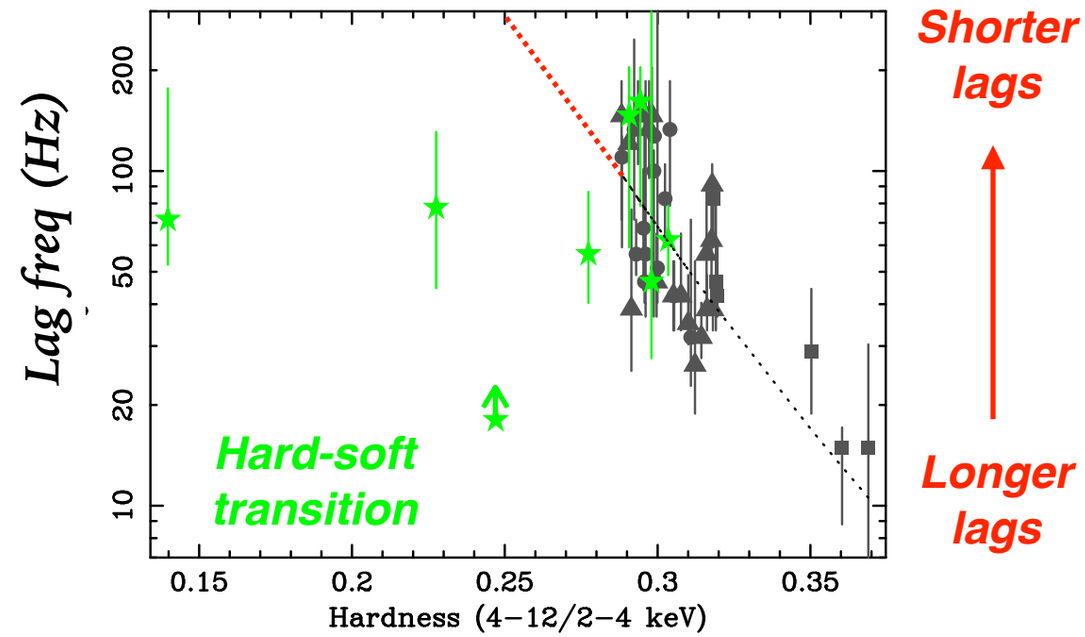
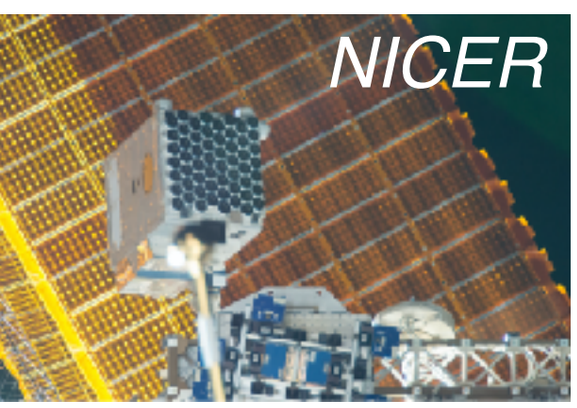
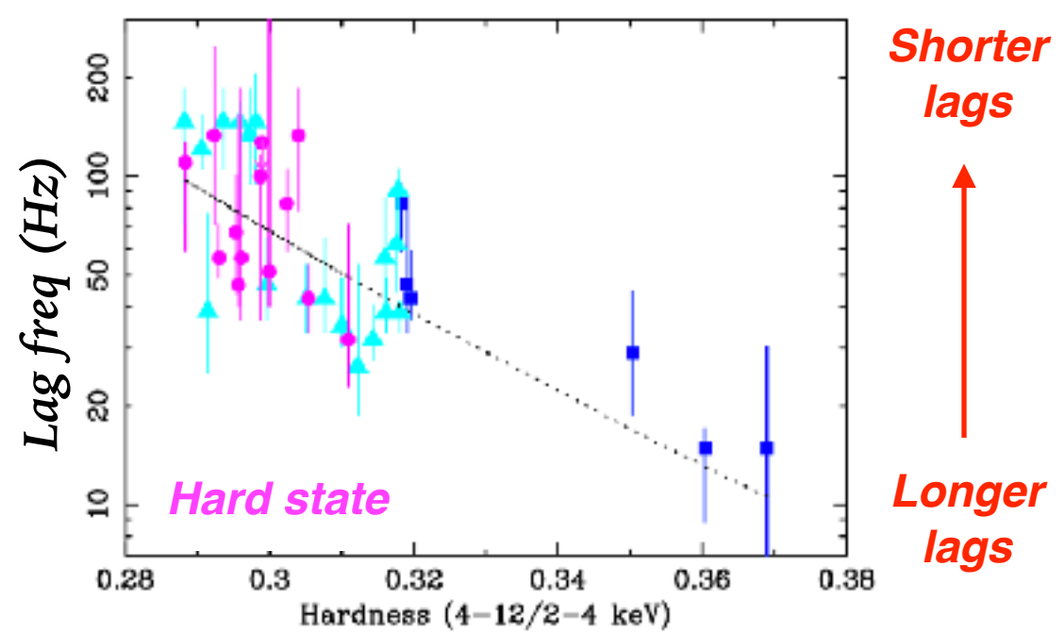






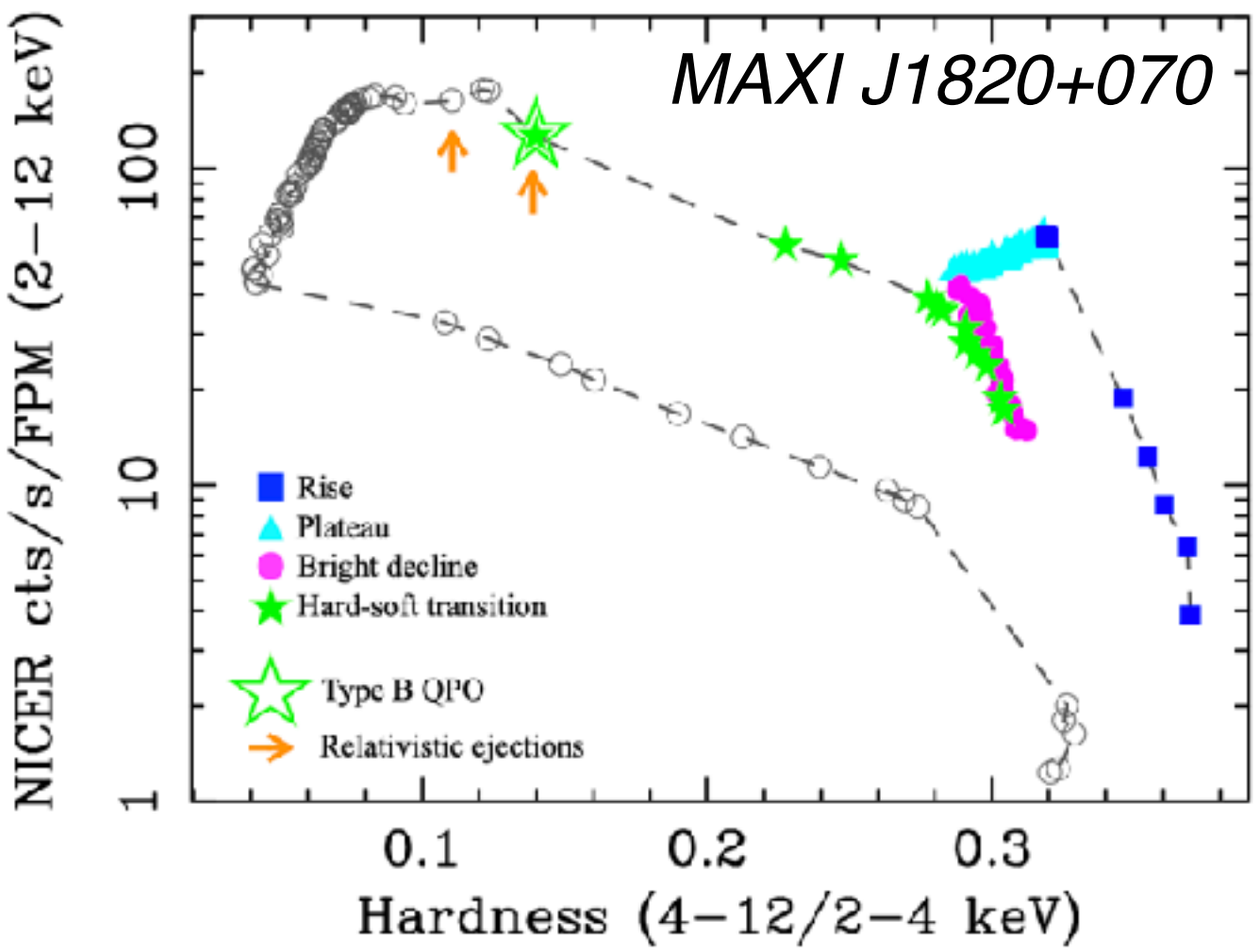


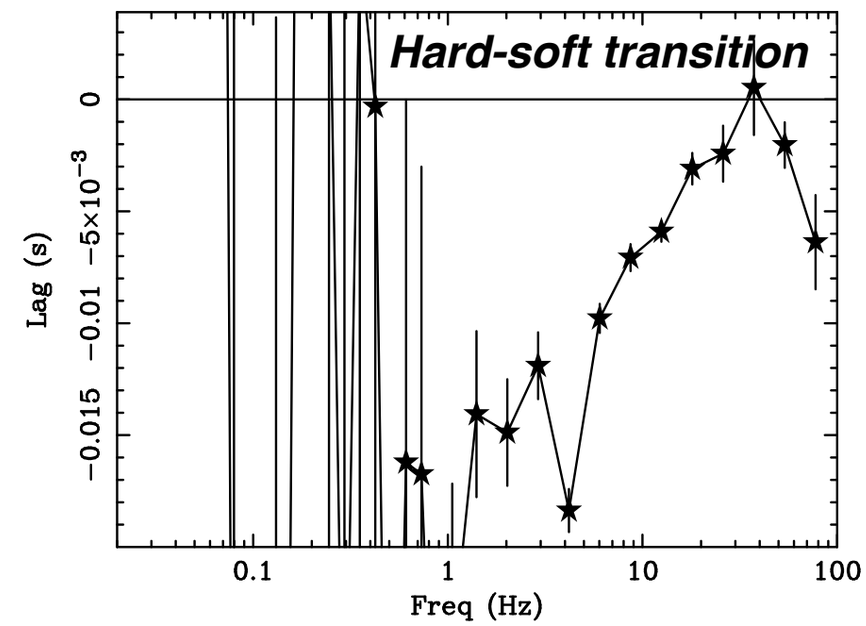
[De Marco+'21]

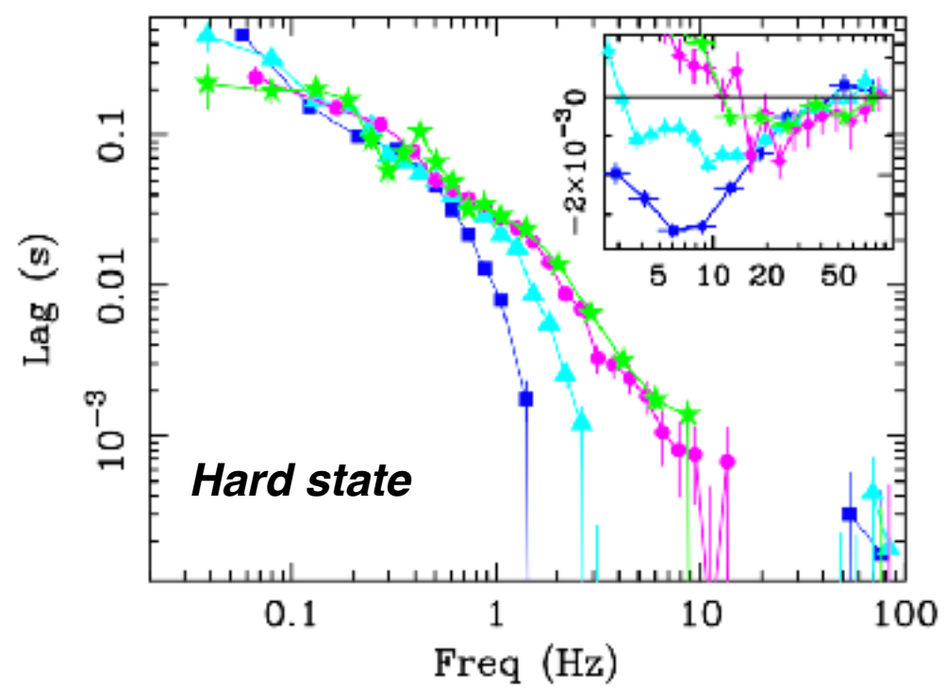
Evolution of reverberation lags during outburst

A long lag at transition

[De Marco+'21]







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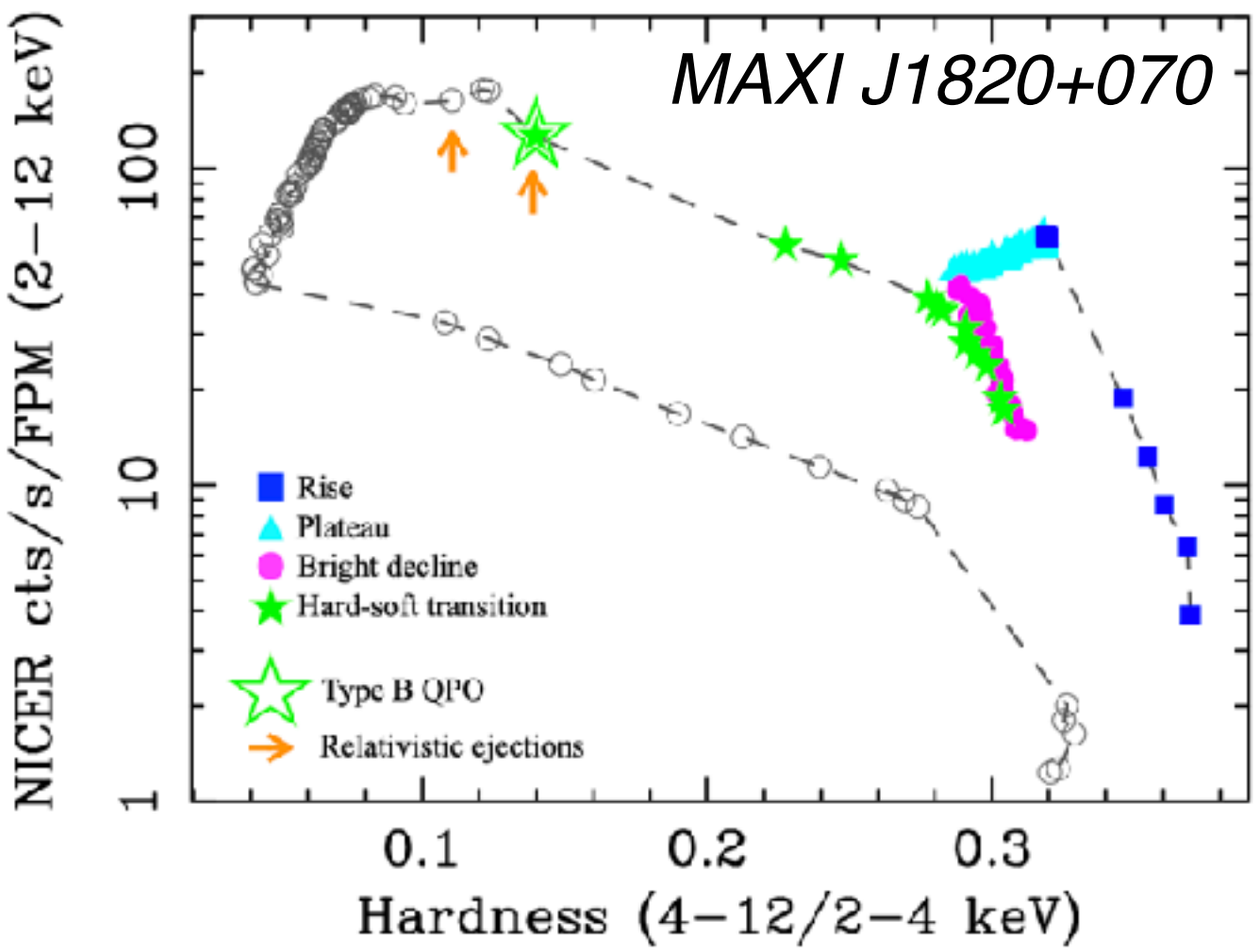

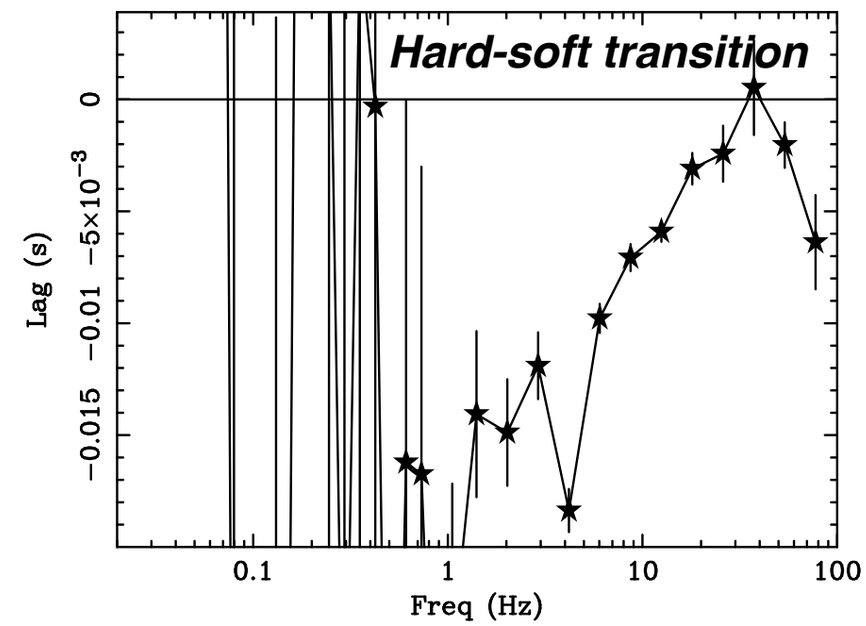

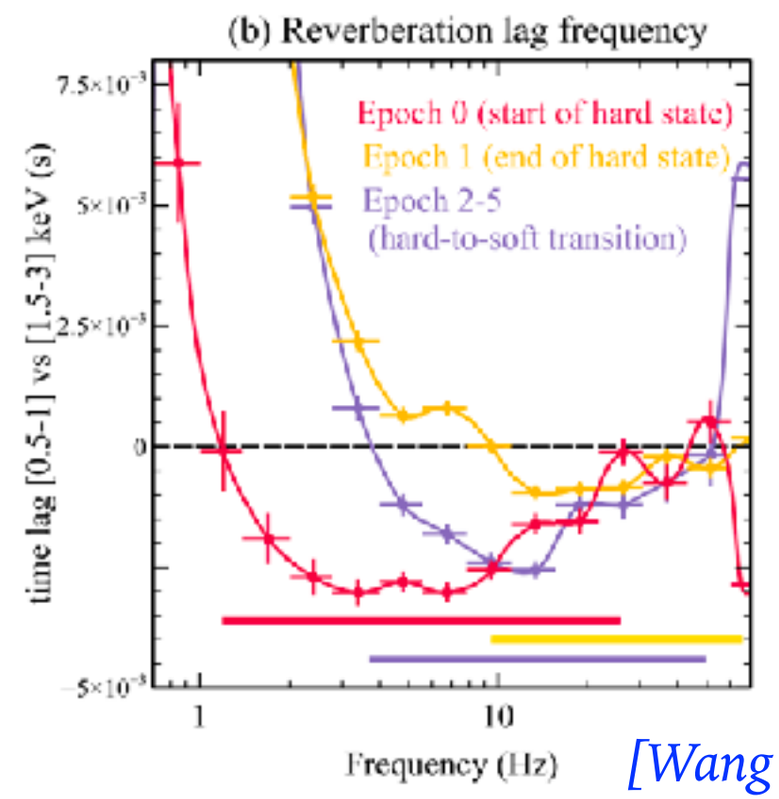

[Wang+'21]

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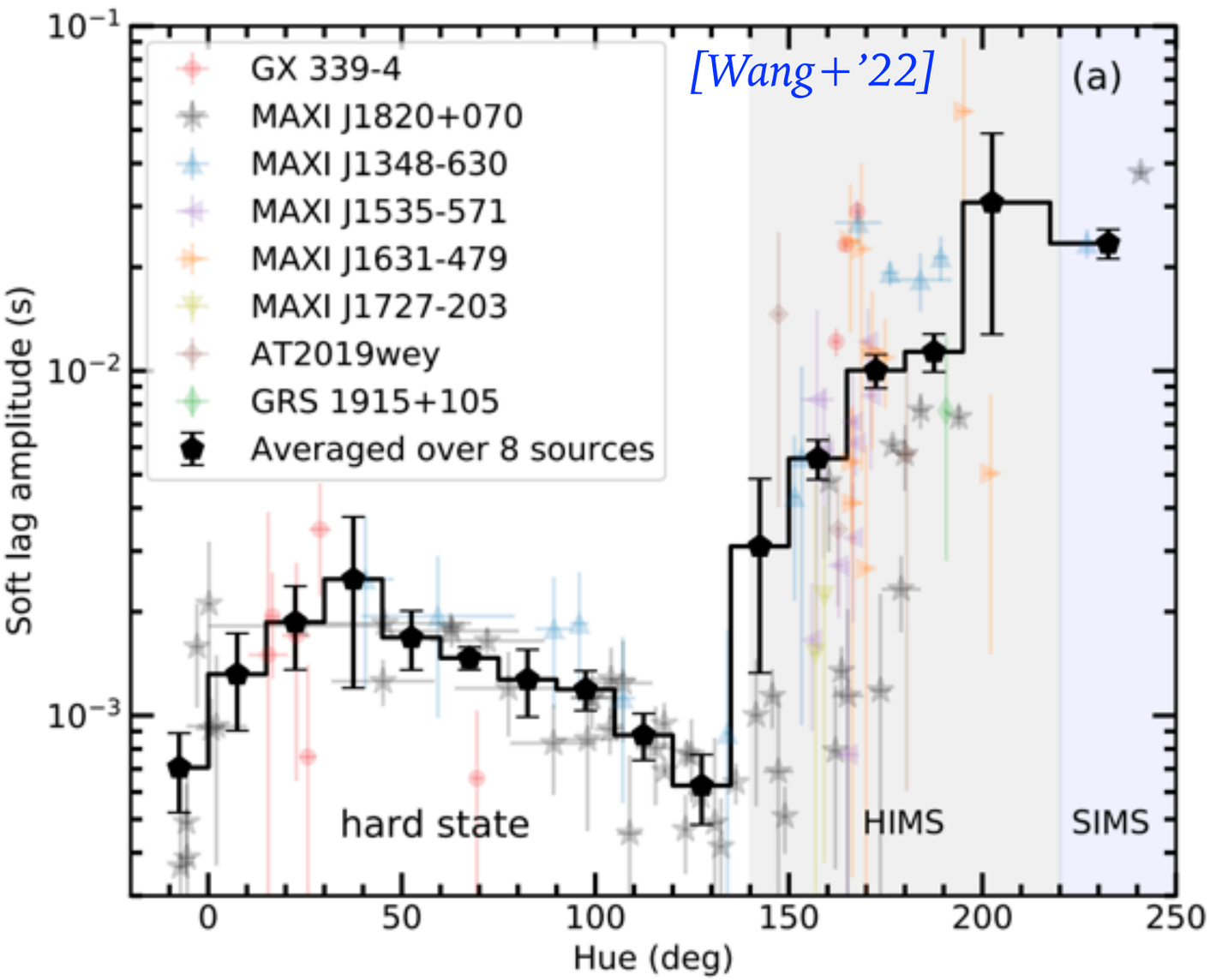
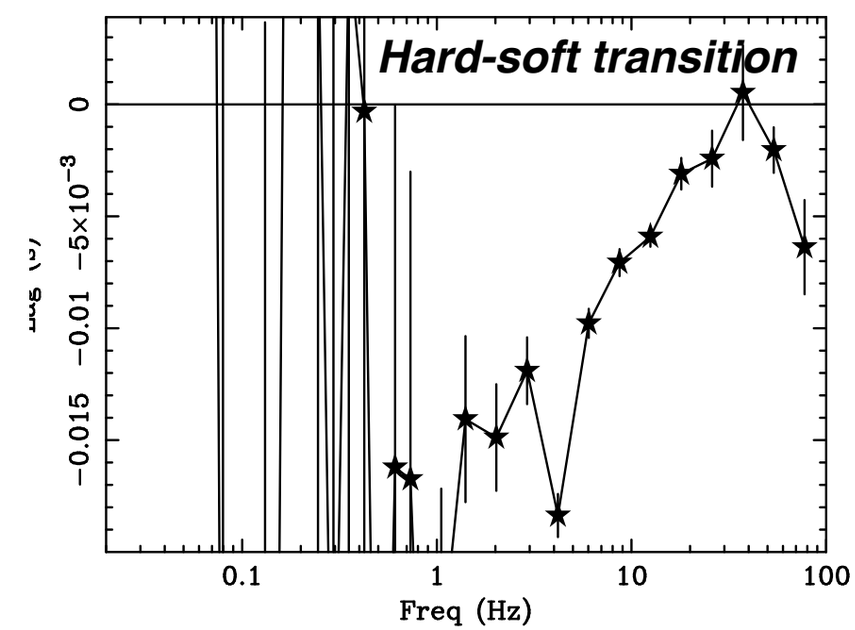
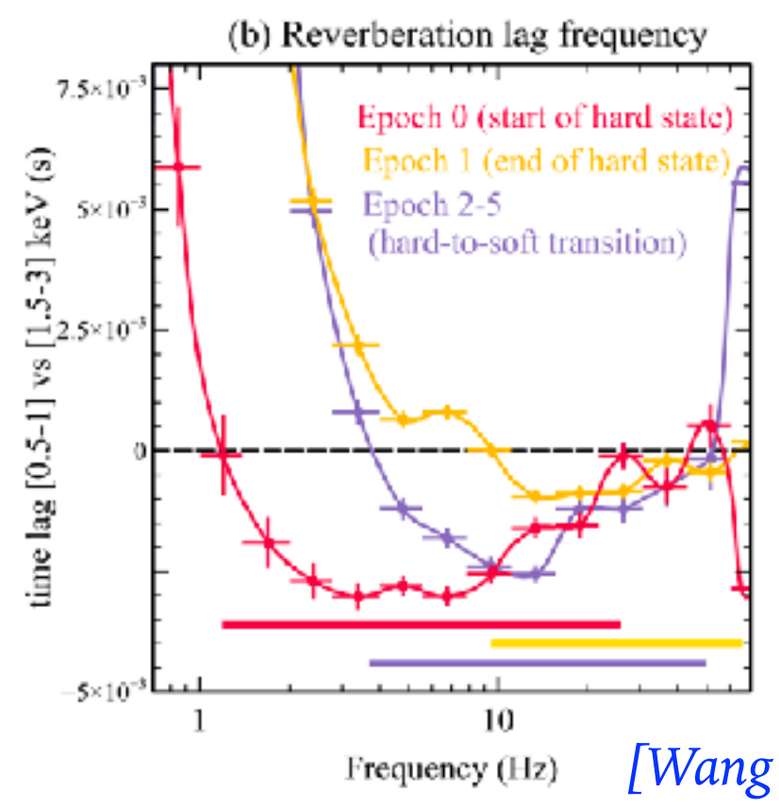


[De Marco+'21]

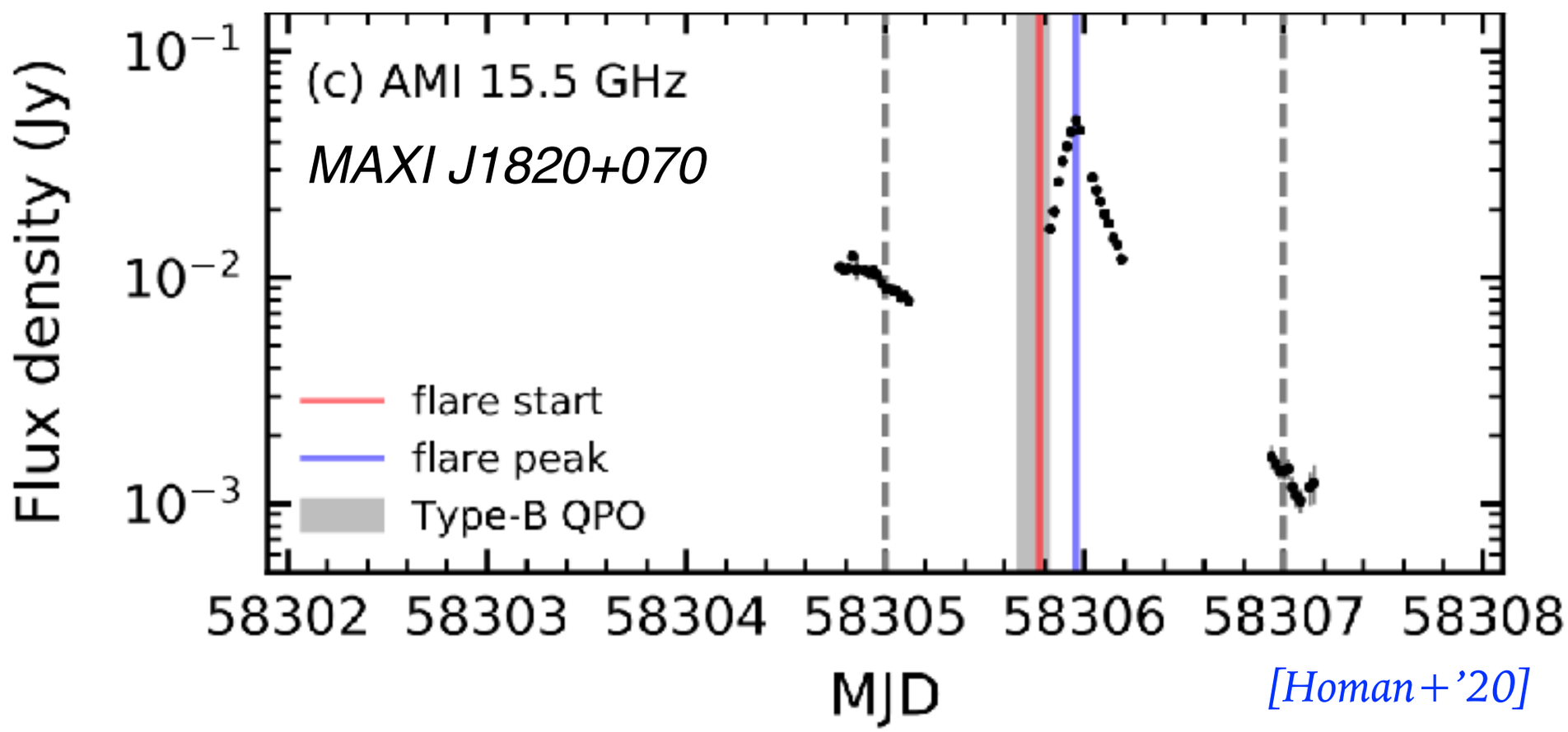




[Wang+'21]

Corona-jet connection at transition

A long reverberation lag before jet ejections

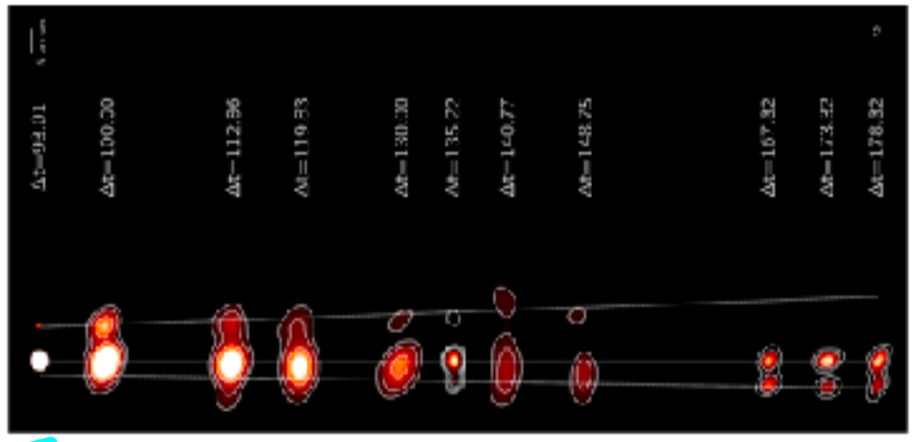


[Homan+'20]

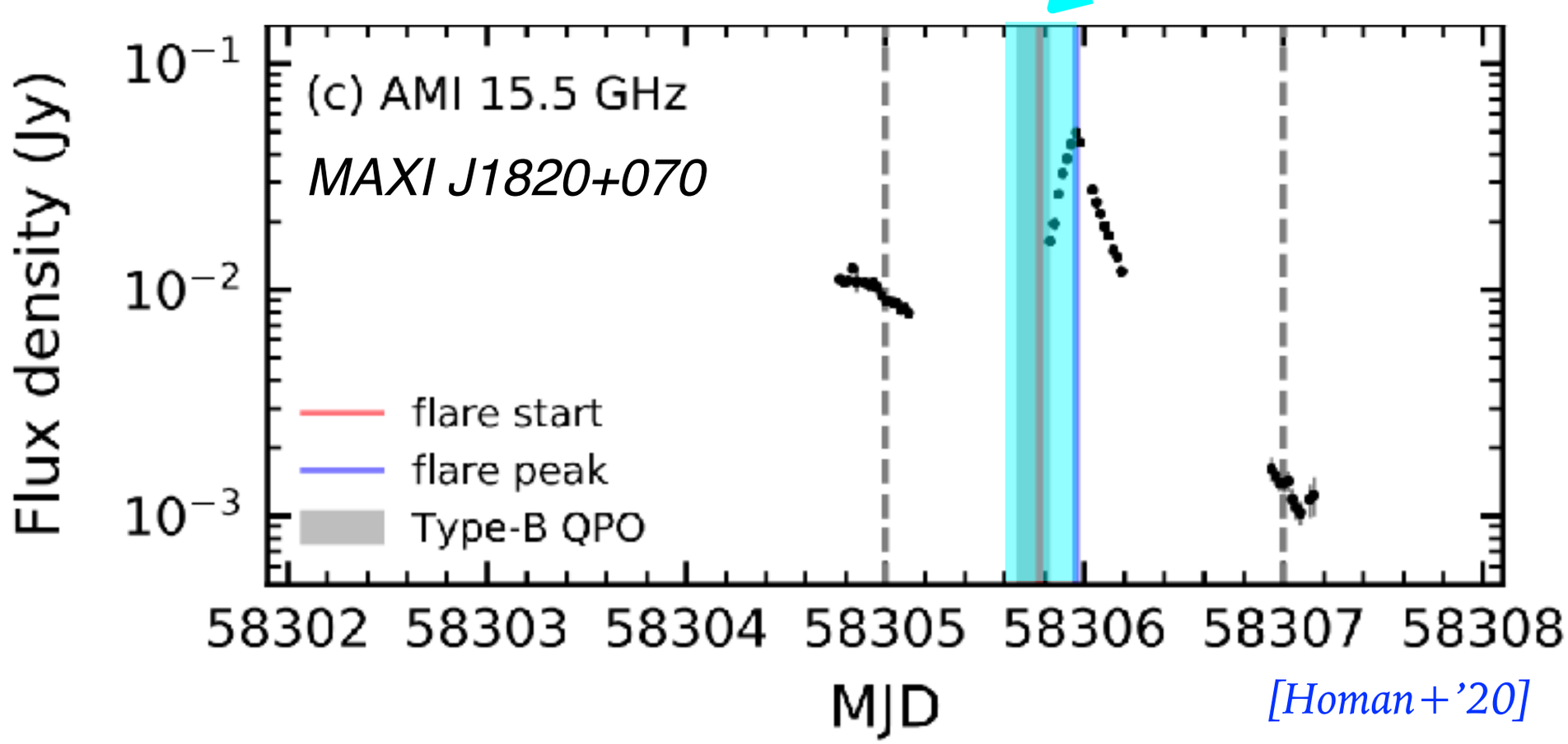
Corona-jet connection at transition

A long reverberation lag before jet ejections

Ejection of discrete jet knots



[Bright+'20; Espinasse+'20; Wood+'21]

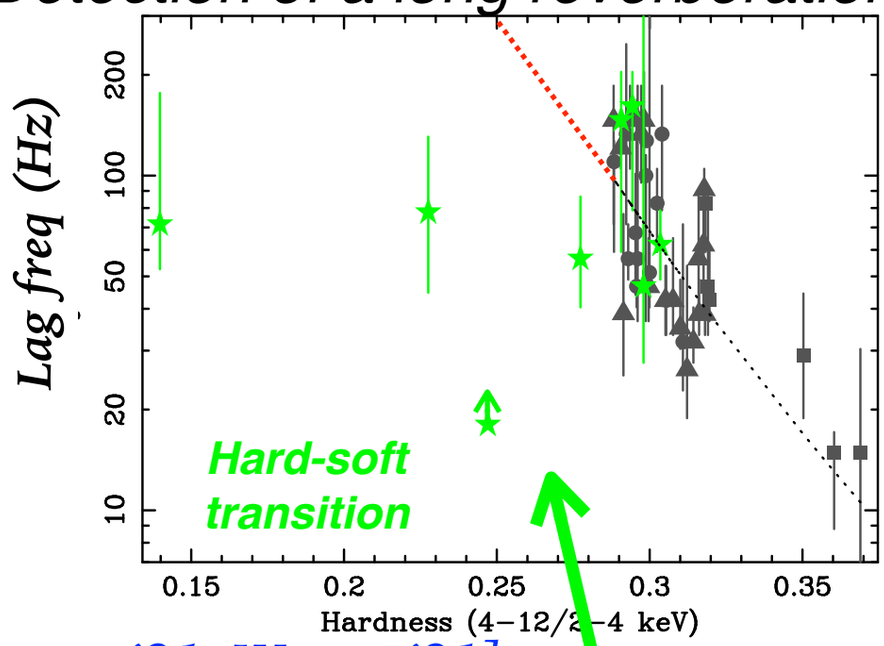


[Homan+'20]

Corona-jet connection at transition

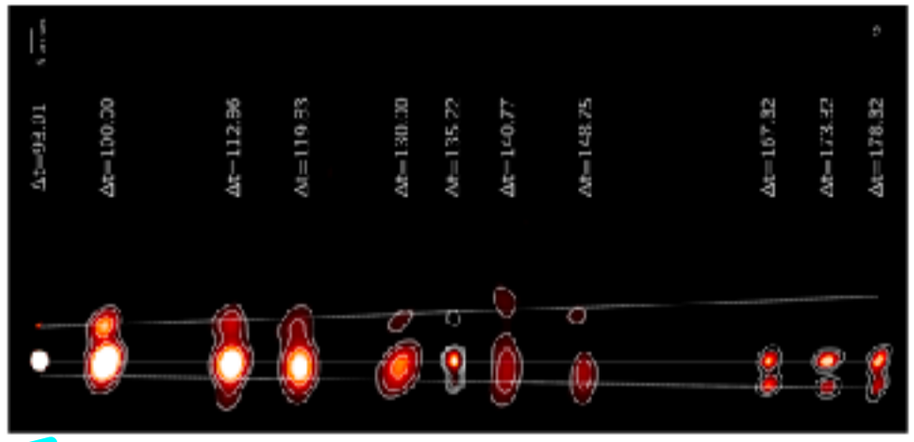
A long reverberation lag before jet ejections

Detection of a long reverberation lag

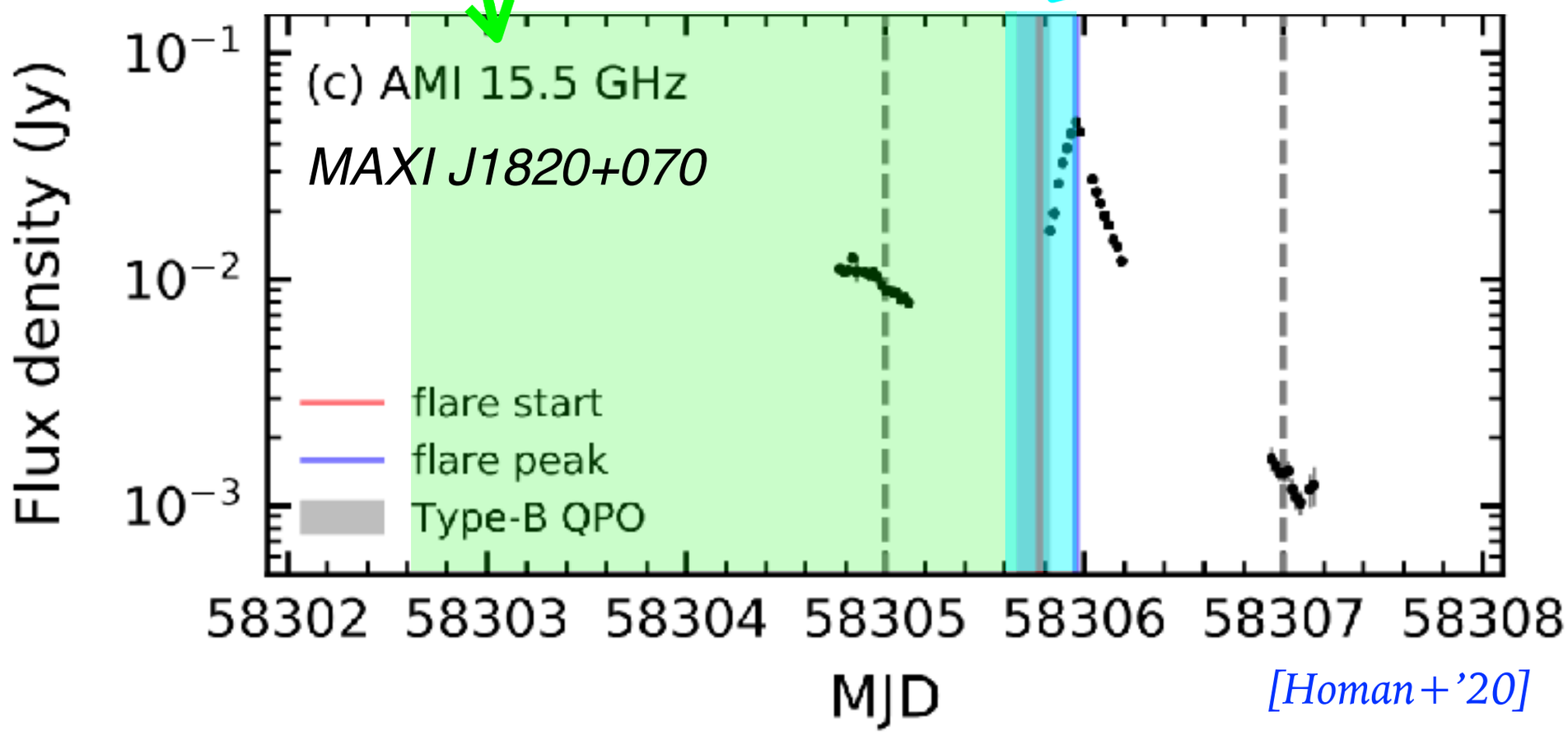


[De Marco+'21; Wang+'21]

Ejection of discrete jet knots



[Bright+'20; Espinasse+'20; Wood+'21]



[Homan+'20]

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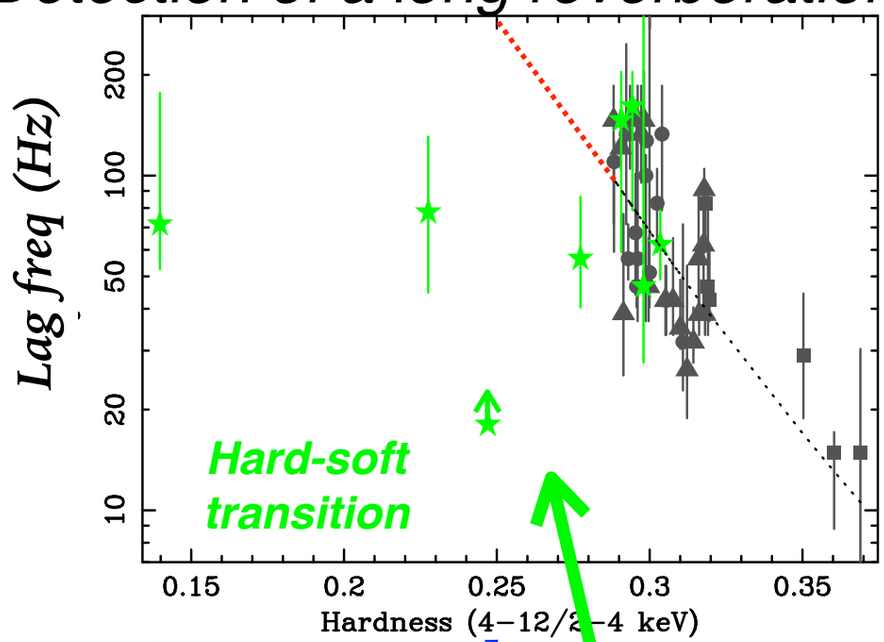

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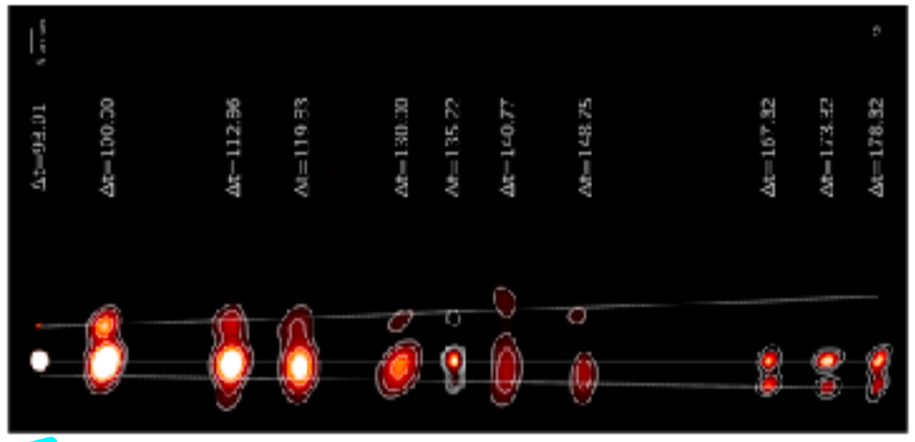

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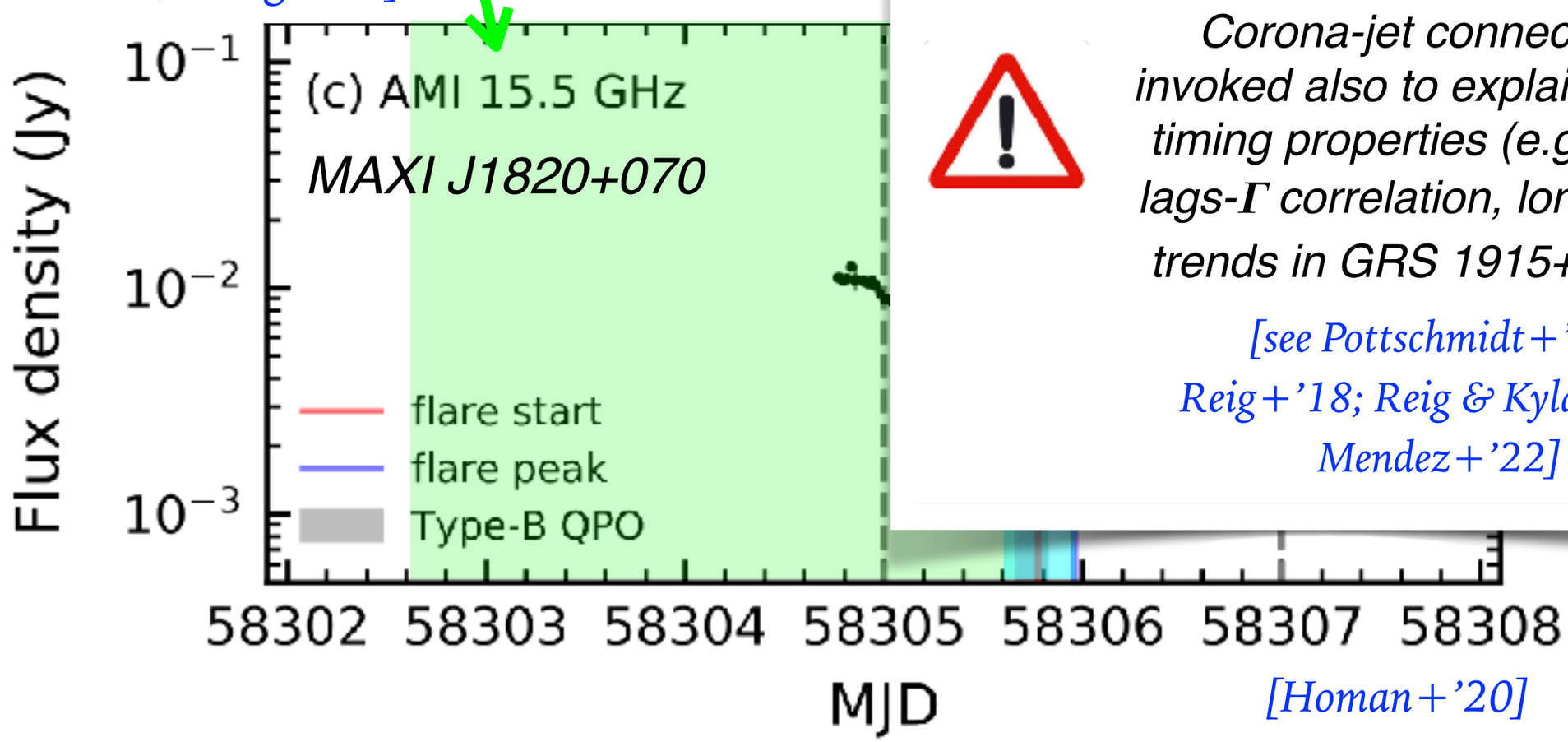


[Homan+'20]

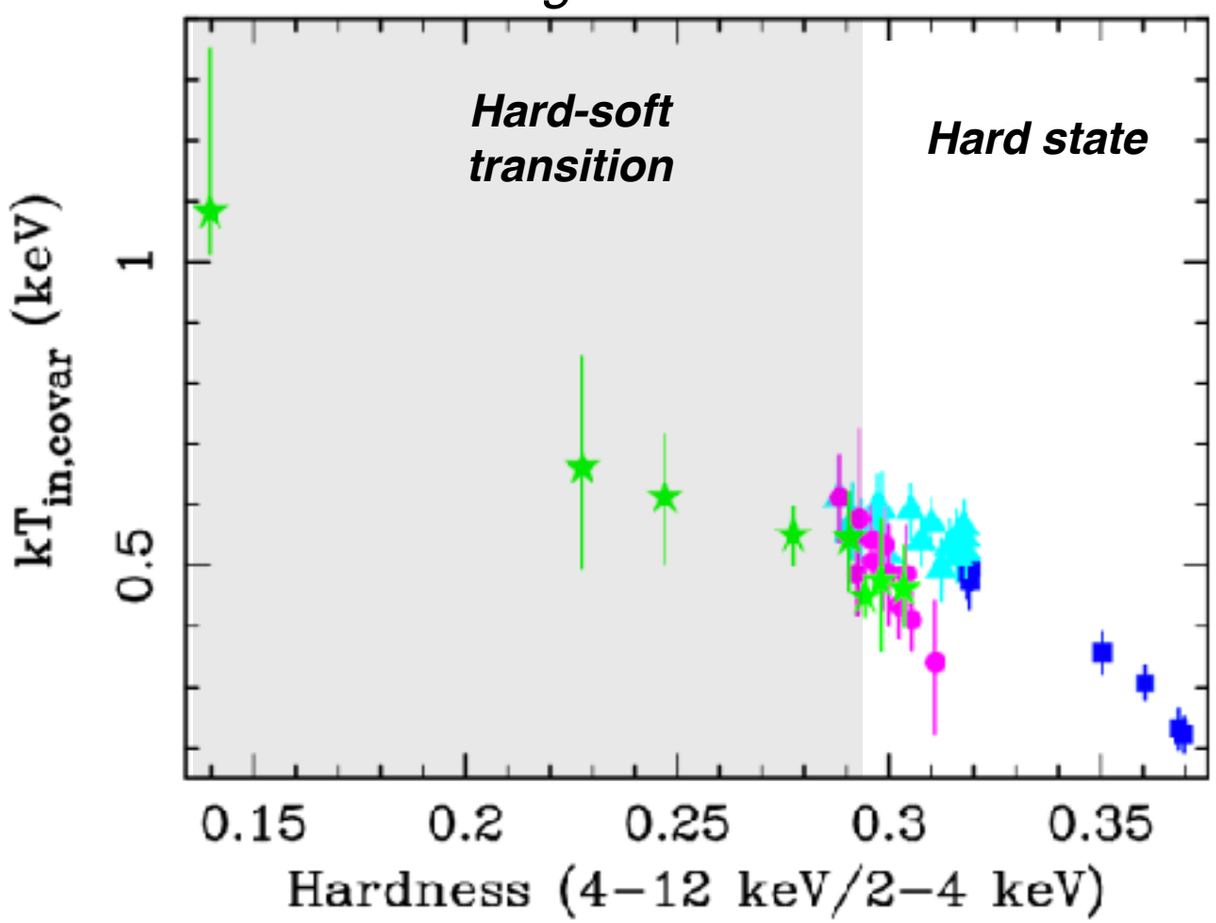
Corona-jet connection invoked also to explain other timing properties (e.g. hard lags-Γ correlation, long term trends in GRS 1915+105..)

[see Pottschmidt+'00; Reig+'18; Reig & Kylafis '19; Mendez+'22]

Evolution of the inner radius of the accretion disc

Data consistent with disc at ISCO at transition

Temperature of the "reverberating" region of the disc



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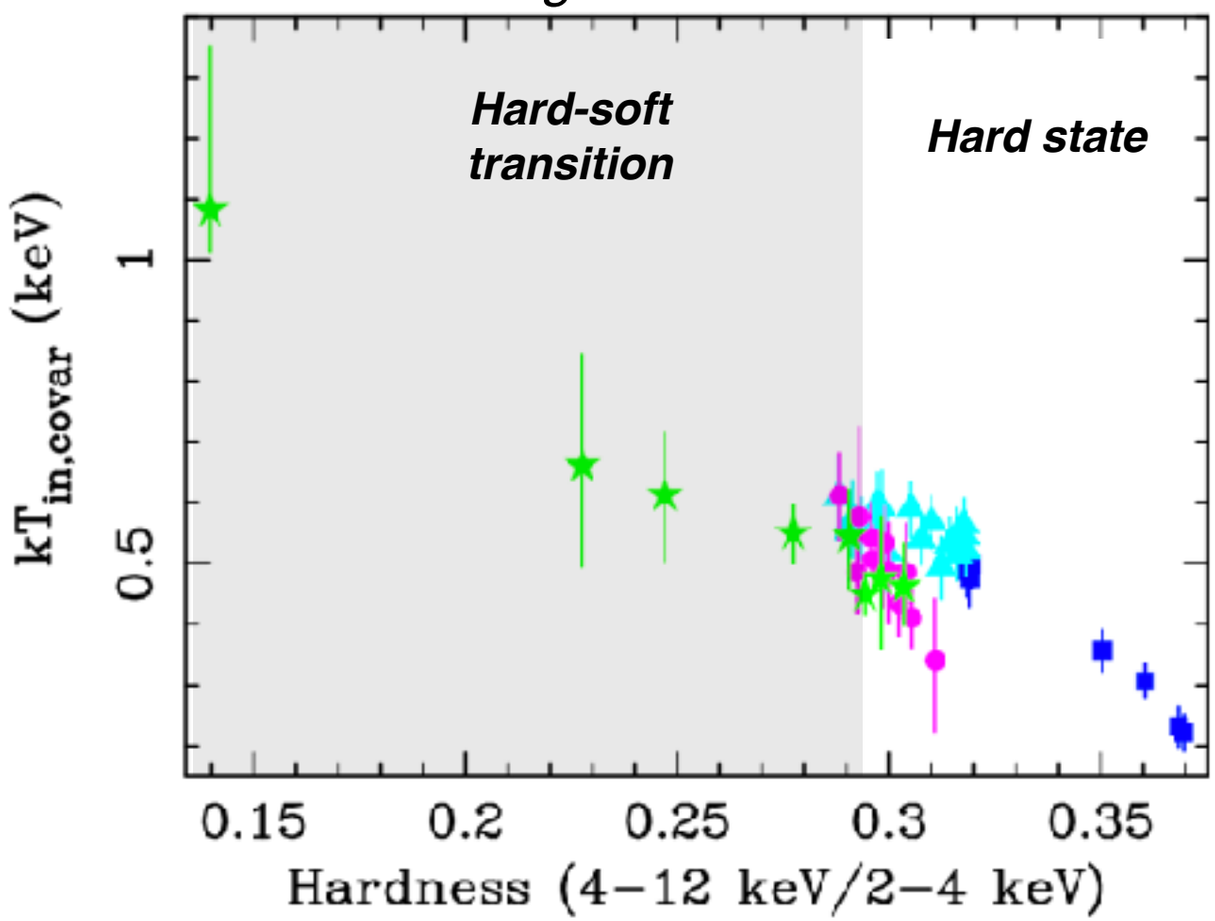
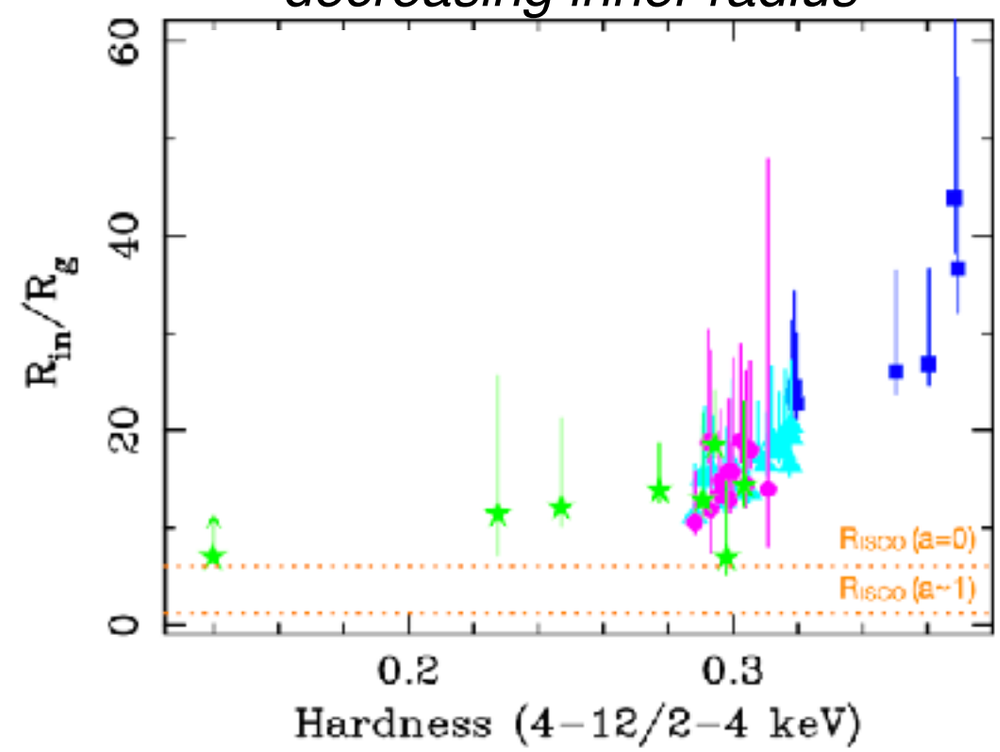


[De Marco+'21; Zdziarski & De Marco '20]

Consistent with a steadily decreasing inner radius



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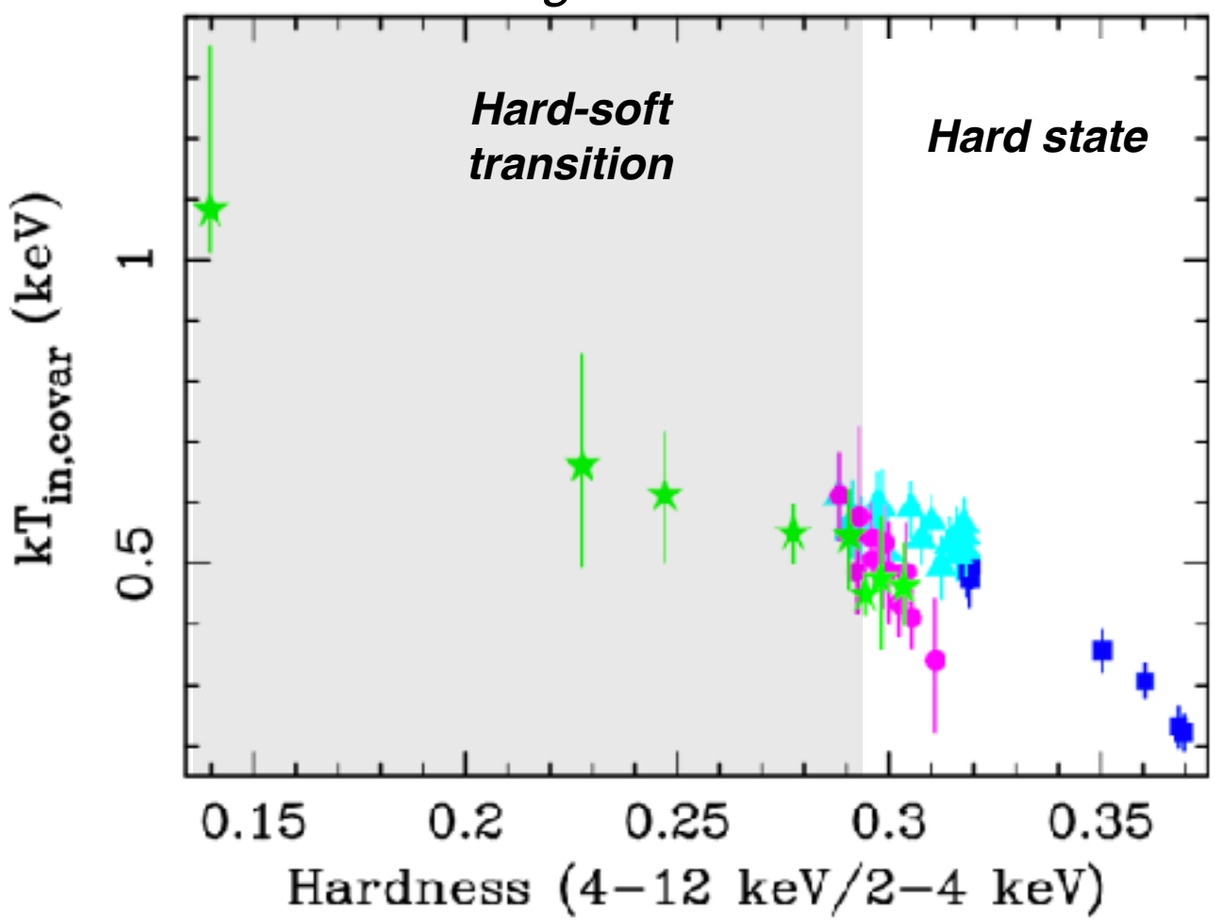

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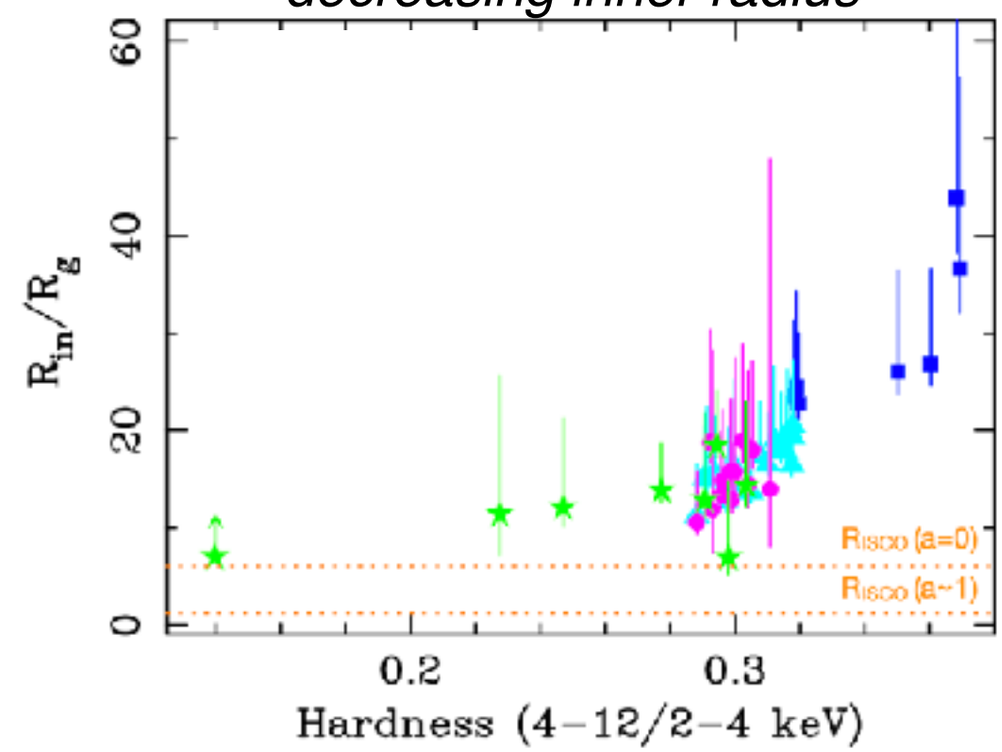
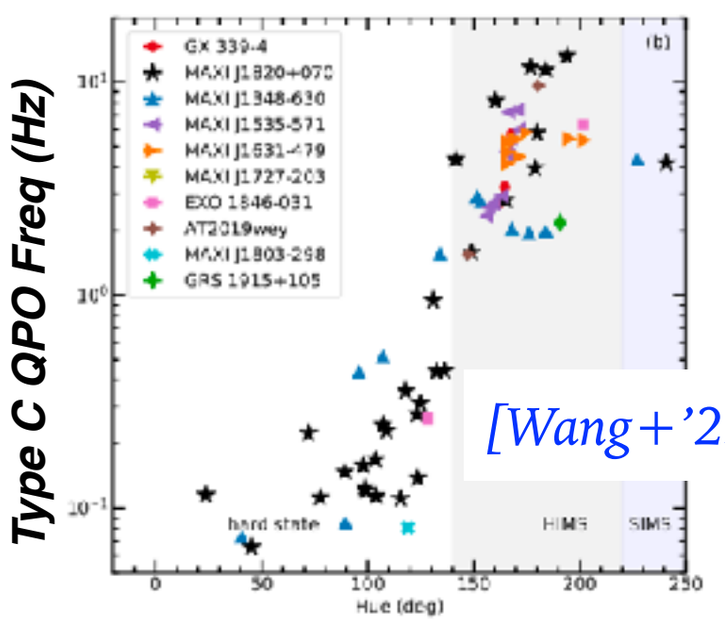




[Wang+'22]

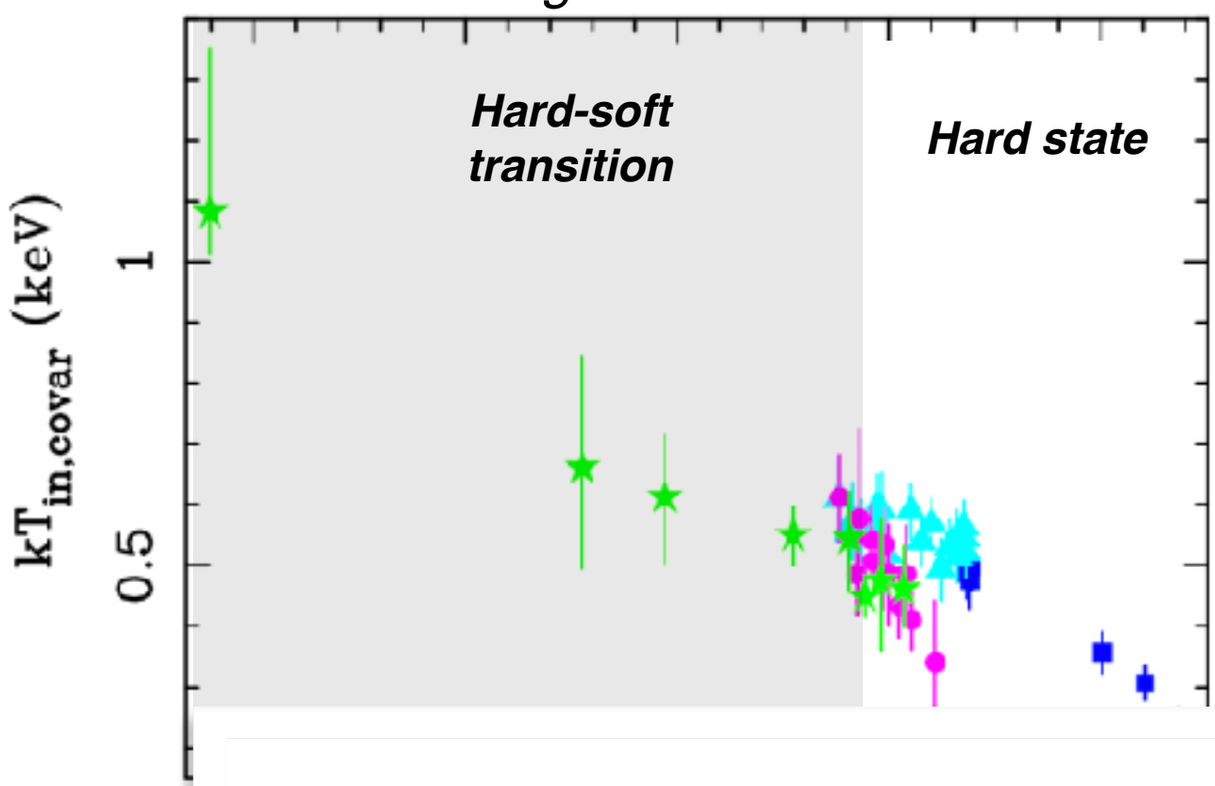
Also explained by a progressively less truncated disc

[e.g. Ingram+'09, Motta+'15]

Evolution of the inner radius of the accretion disc

Data consistent with disc at ISCO at transition

Temperature of the "reverberating" region of the disc



[De Marco+'21; Zdziarski & De Marco '20]

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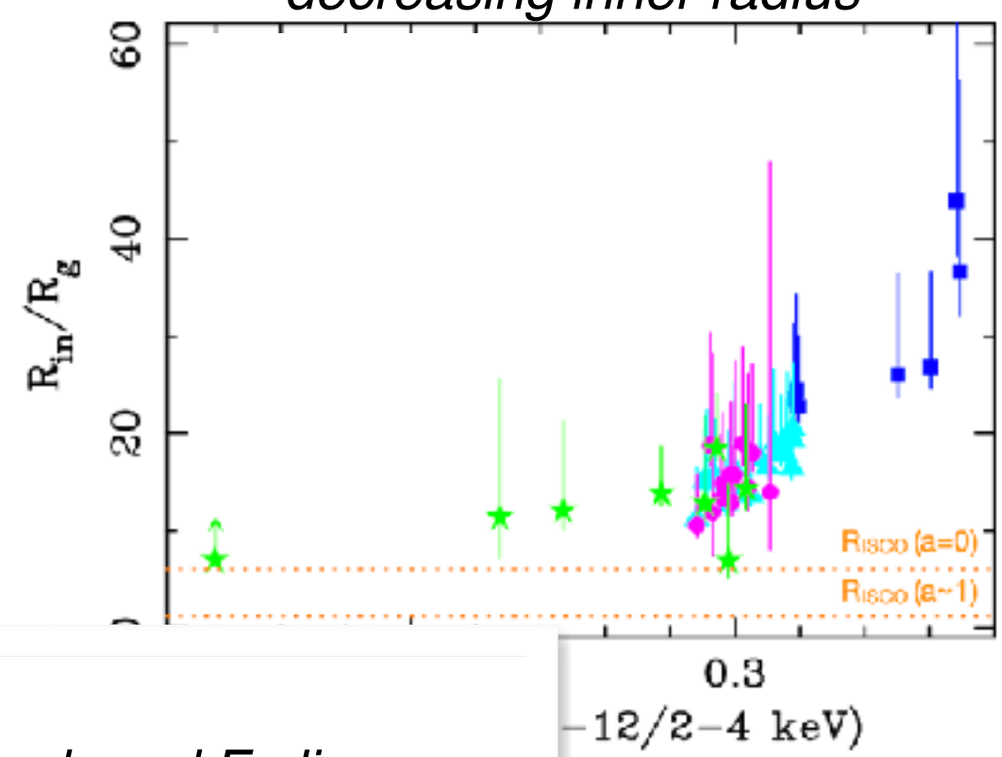


Based on the evolution of the broad Fe line a vertically contracting corona has been proposed

[see Kara+'19; Buisson+'19; Wang+'21;'22; You+'21]

But IXPE results suggest X-ray source extended on the plane of the disc in hard state

[Krawczynski+'22]

ogressively
disc

am+'09, Motta+'15]

Development of spectral-timing models

To get constraints on physical parameters (e.g. R_{in}, coronal geometry…)

e.g. KYNREFREV, PROPFLUC, RELTRANS…

Account for GR, properties of the disc…so far a few different coronal geometries explored

Self-consistently account for hard X-ray lags

Simultaneously fit time-averaged spectra and spectral-timing products (e.g. lags, power spectra, rms-spectra…) to break degeneracies

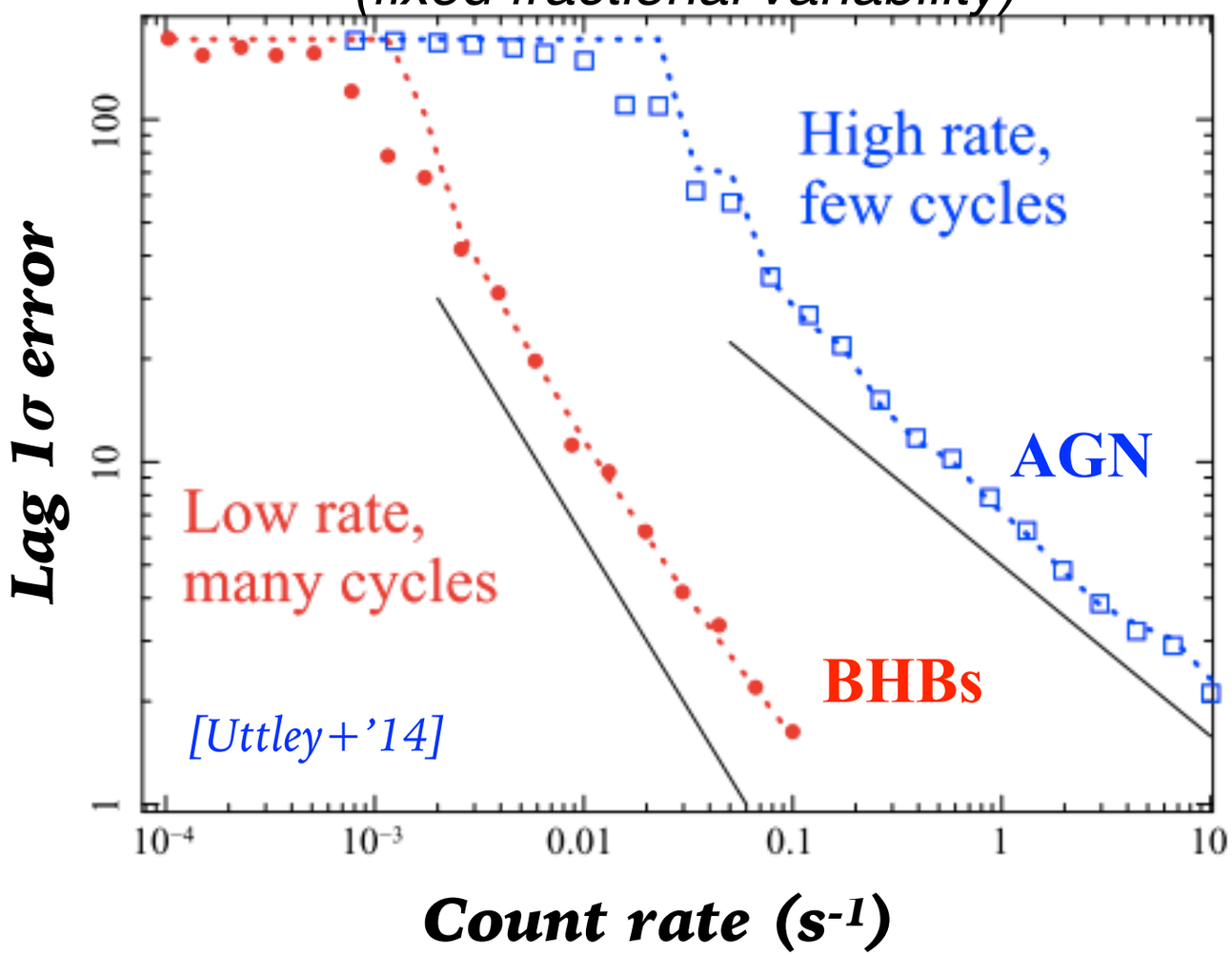
[e.g. Wilkins+'13; '16; Emmanoulopoulos+'14; Cackett+'14; Chainakun+'15; '17; Rapisarda+'16; '17; Veledina'18; Ingram+'19; Mastroserio+'18; '21; Caballero-Garcia+'18; Mahmoud+'18; '19; Taylor+'18; Karpouzas+'20; Kawamura+'22a, '22b; Uttley & Malzac in prep.]

X-ray reverberation with Athena

Time lags and X-ray reverberation with Athena

Sensitivity of lag measurements

Effects of counting noise on lag sensitivity
(fixed fractional variability)



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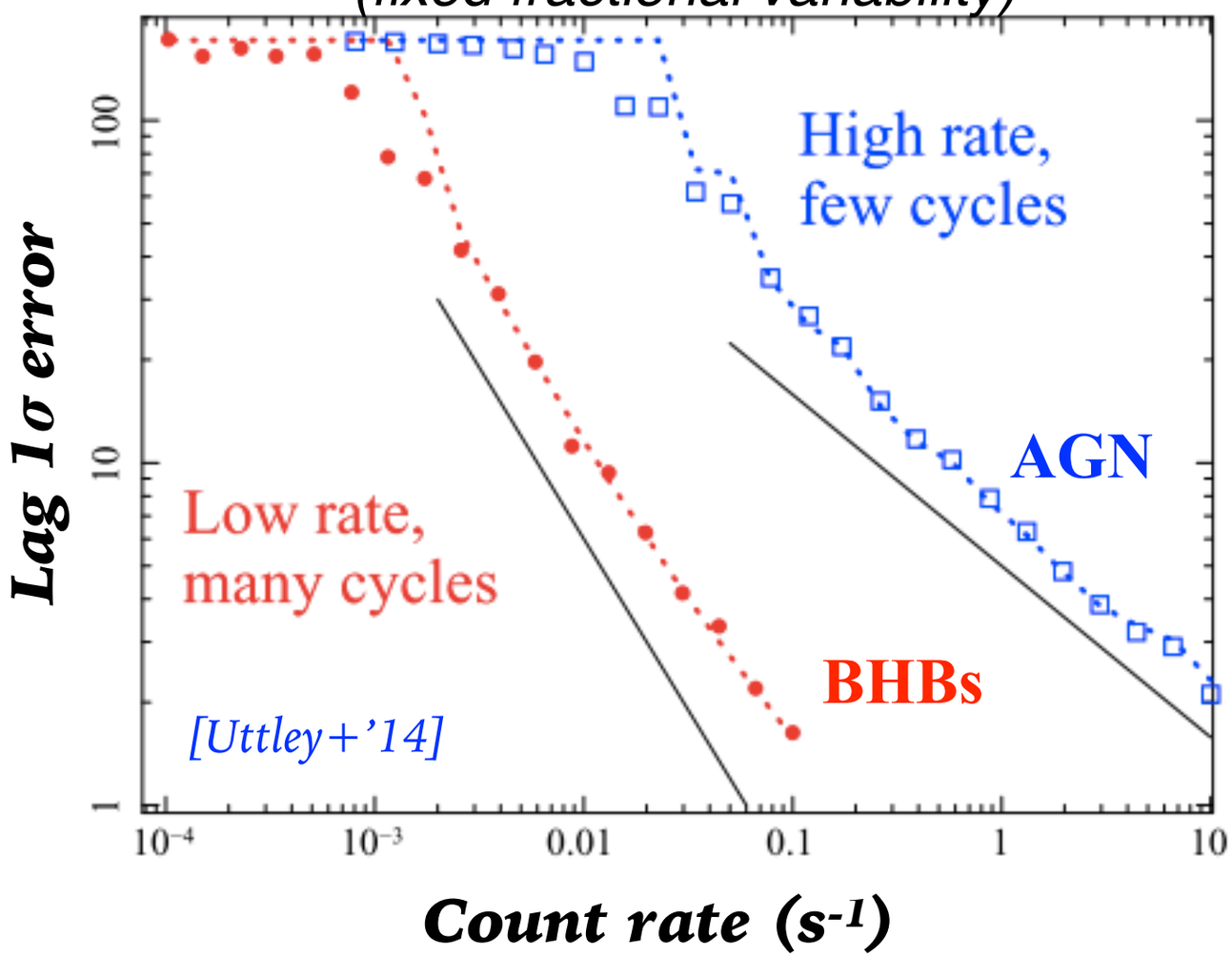

$\sigma_\tau \sim Exposure^{-1/2}$

$\sigma_\tau \sim (rate)^{-1/2}$ *AGN (many photons per variability cycle)*

$\sigma_\tau \sim (rate)^{-1}$ *BHXRBs (few photons per variability cycle)*

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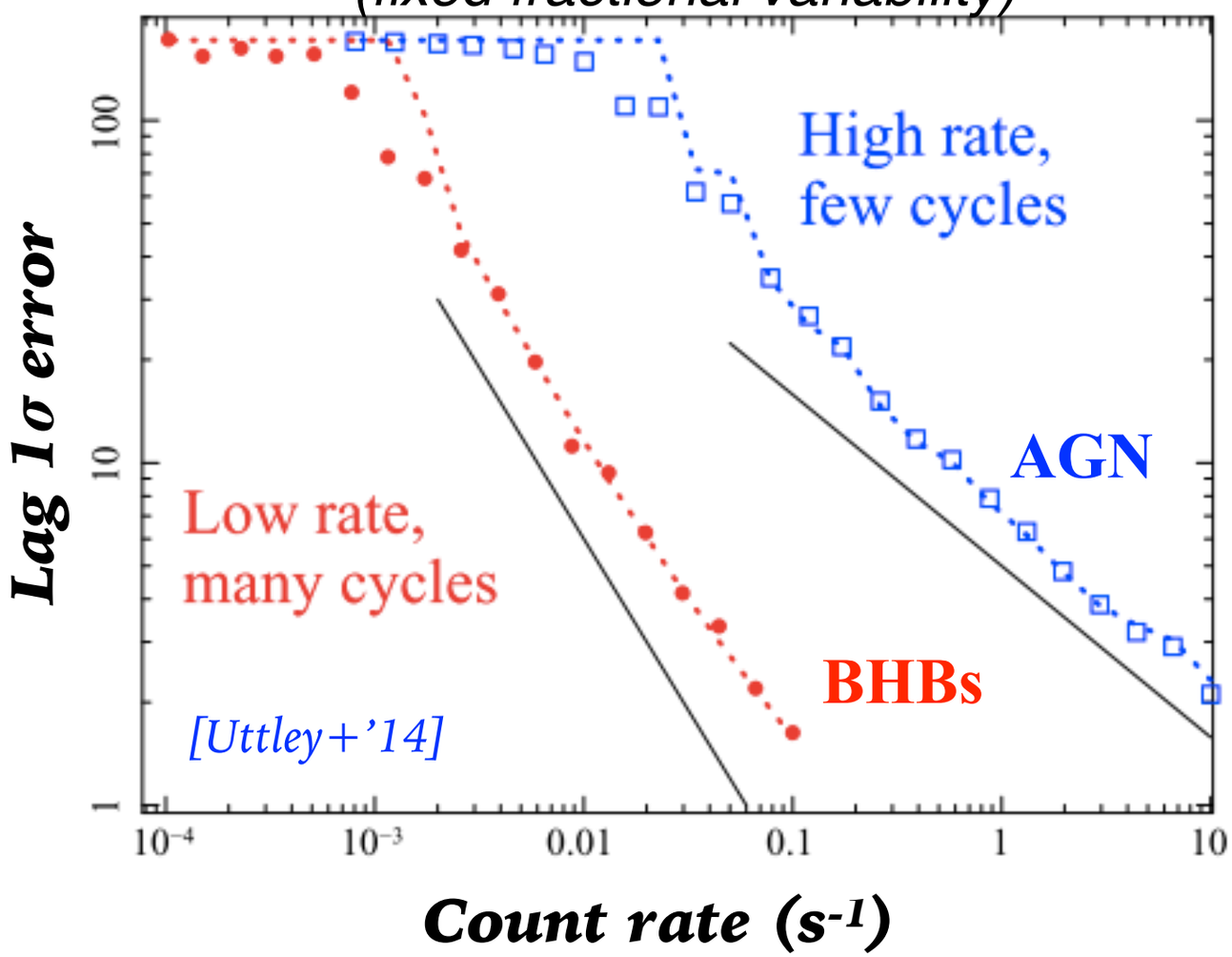

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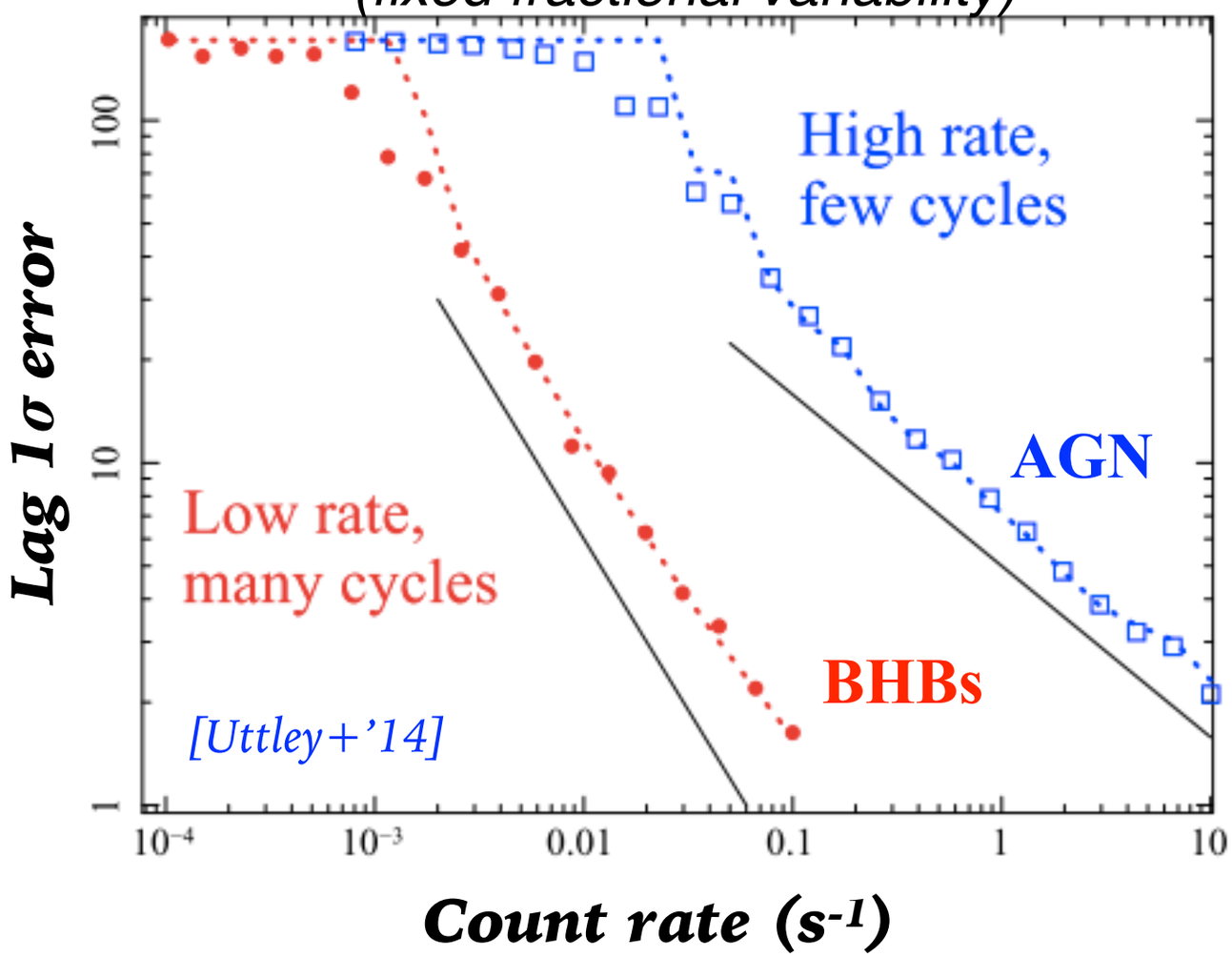
Large area detectors needed to fully exploit this technique

Time lags and X-ray reverberation with Athena

Sensitivity of lag measurements

Effects of counting noise on lag sensitivity (fixed fractional variability)



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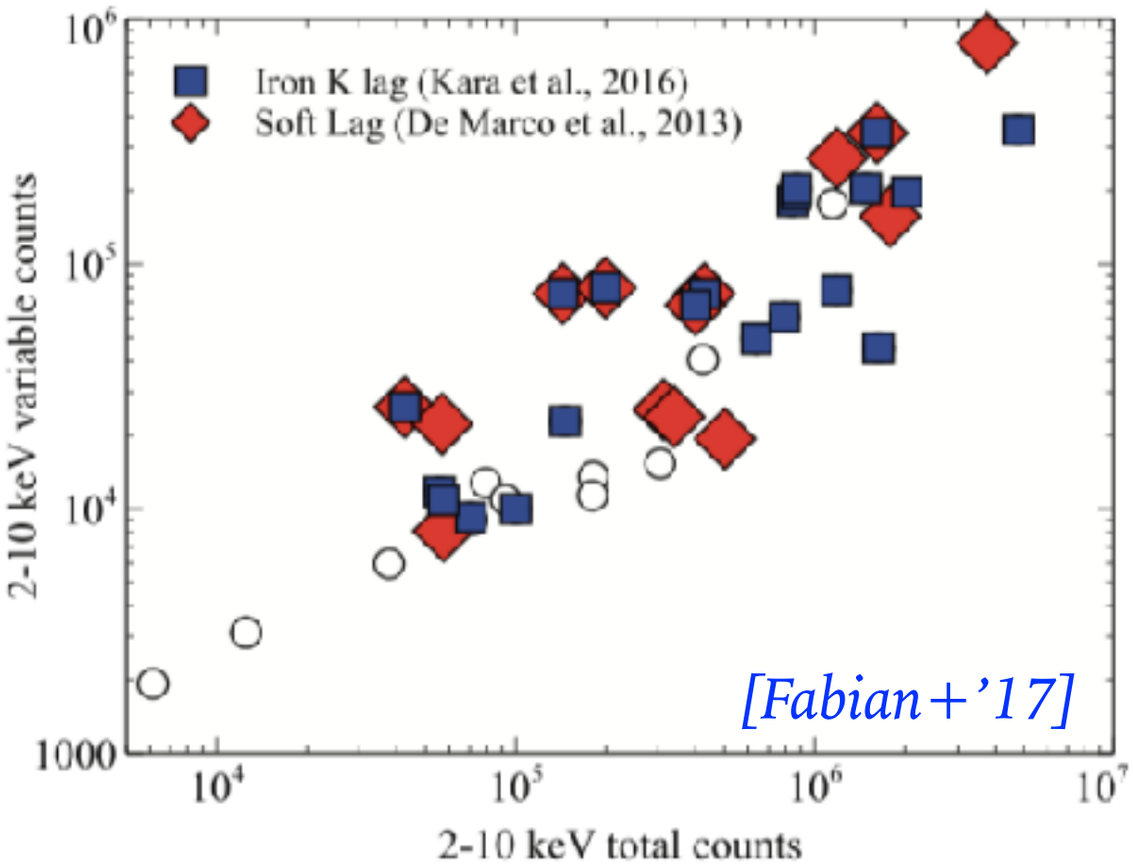
Large area detectors needed to fully exploit this technique

Caveat: BHXRBs can get VERY bright… (need to manage pile up!)

Time lags and X-ray reverberation with Athena

Increasing the number of detections

Variable counts=
total counts × fractional var > 7e3



+ long exposures (>40 ks)
to be sensitive to a broad range of
BH masses

Time lags and X-ray reverberation with Athena

Increasing the number of detections

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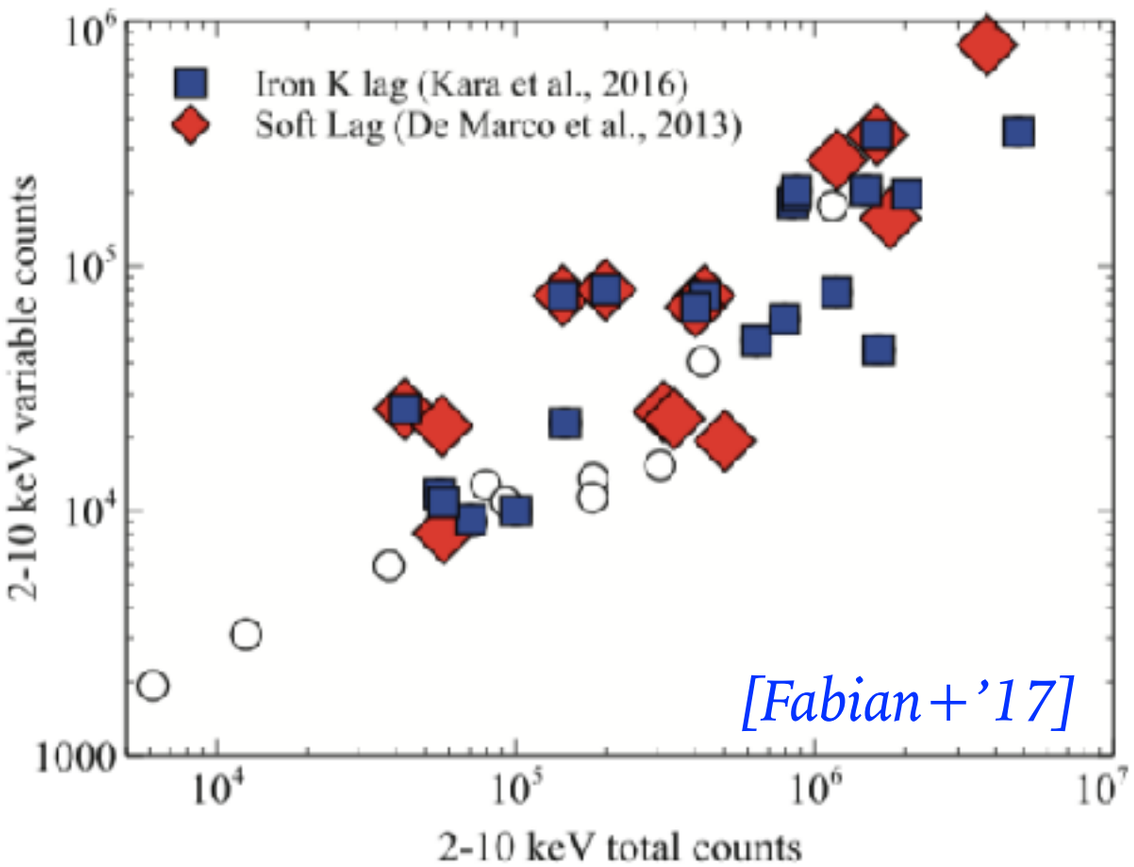
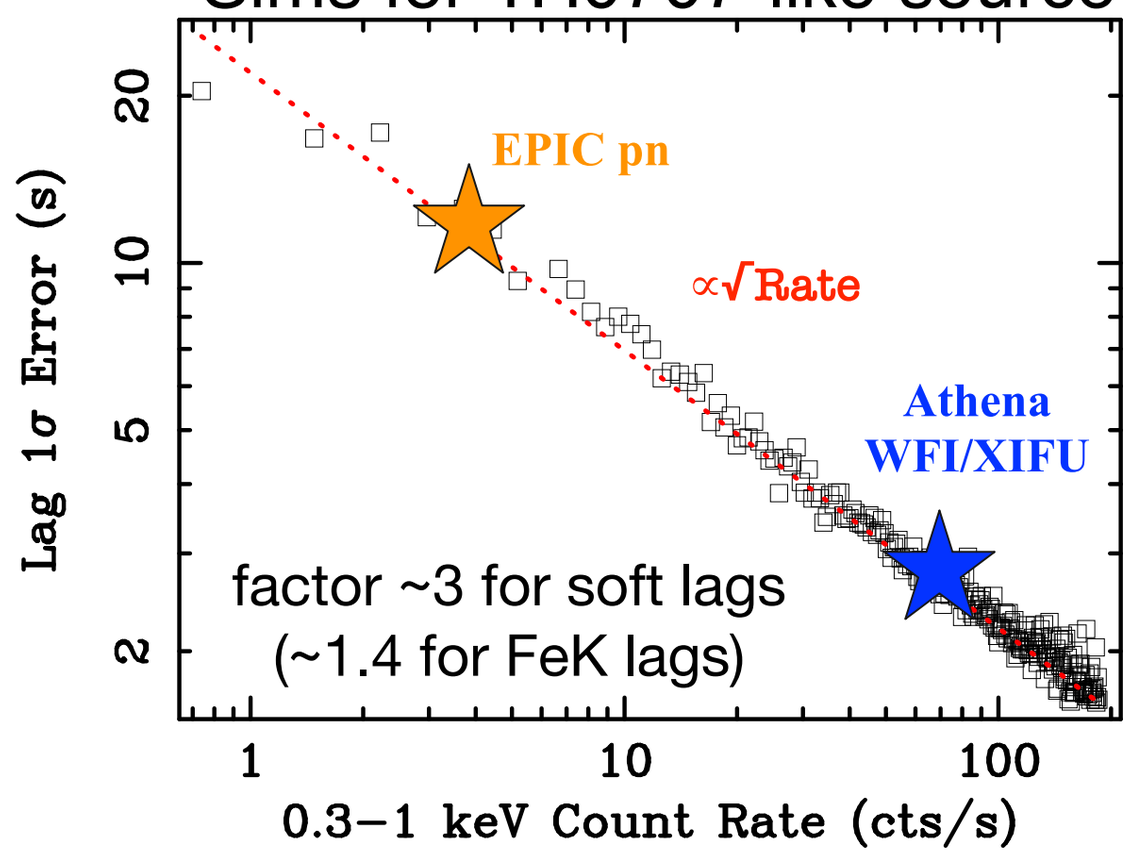


Sims for 1H0707-like source

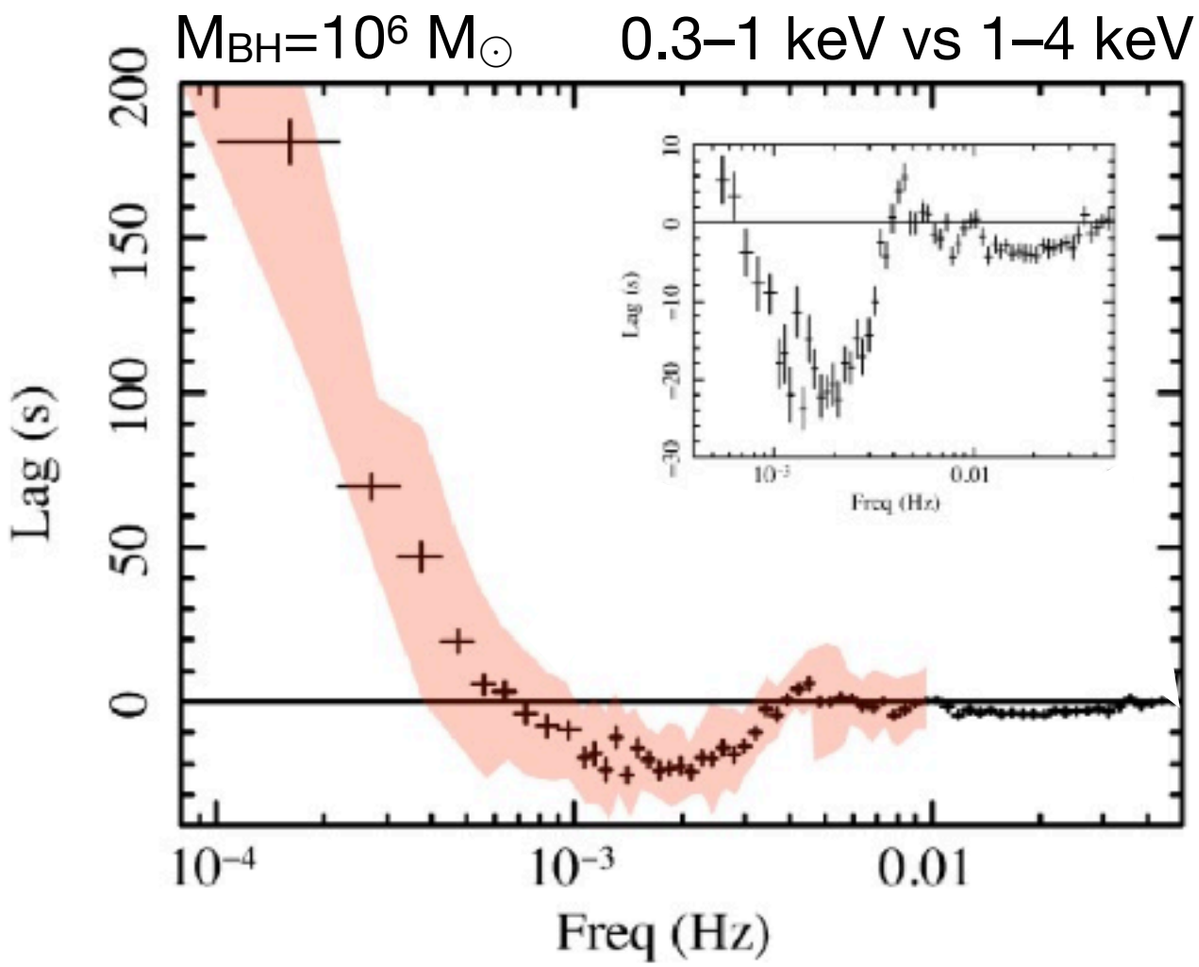


+ long exposures (>40 ks)
to be sensitive to a broad range of
BH masses

about 3x more detections (study rev in different AGN classes and BHXRB states)

Time lags and X-ray reverberation with Athena

Constraining the transfer function



XMM pn data (500 ks)

\+ Athena WFI sims (500 ks)

[see Dovčiak+'13]

Time lags and X-ray reverberation with Athena

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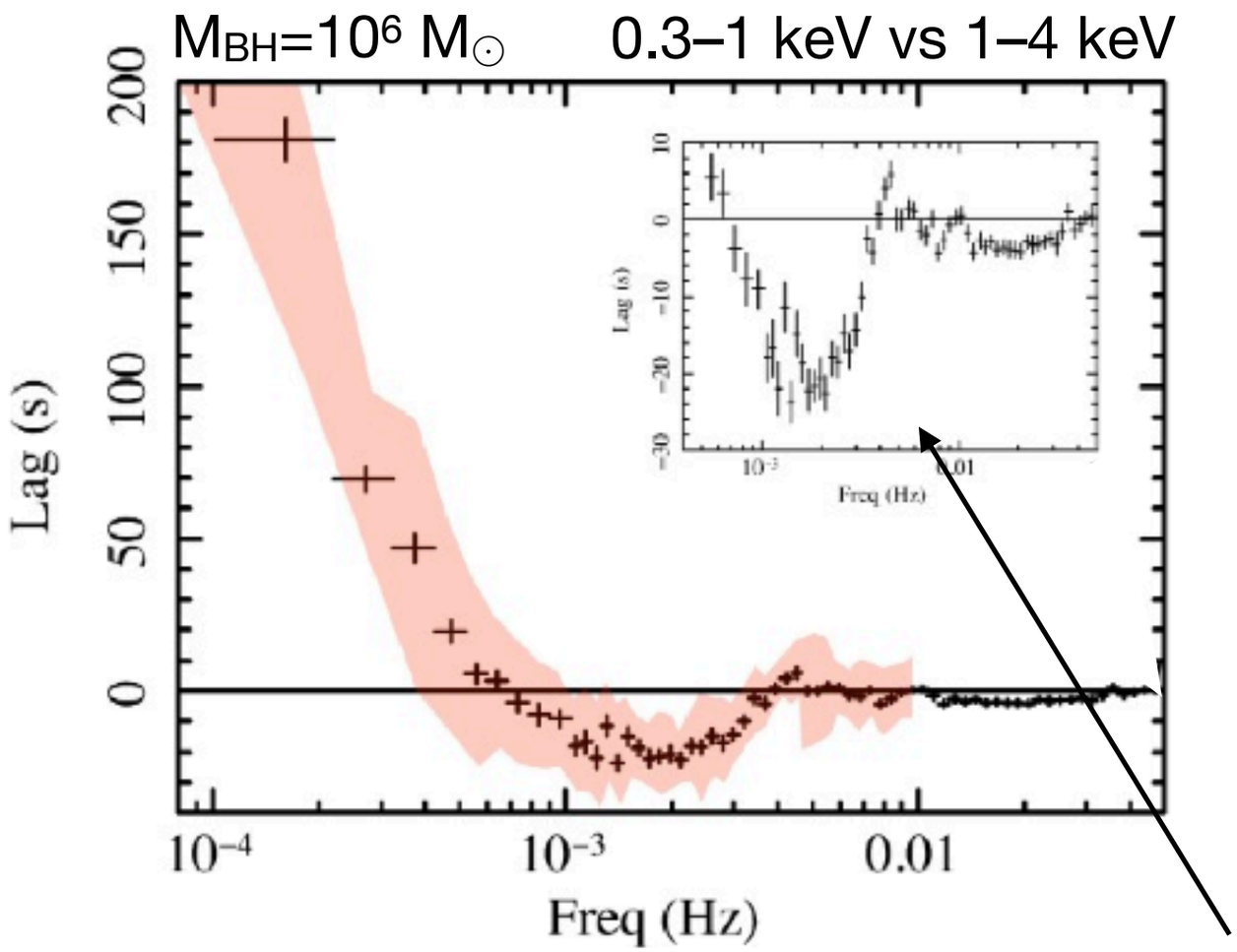

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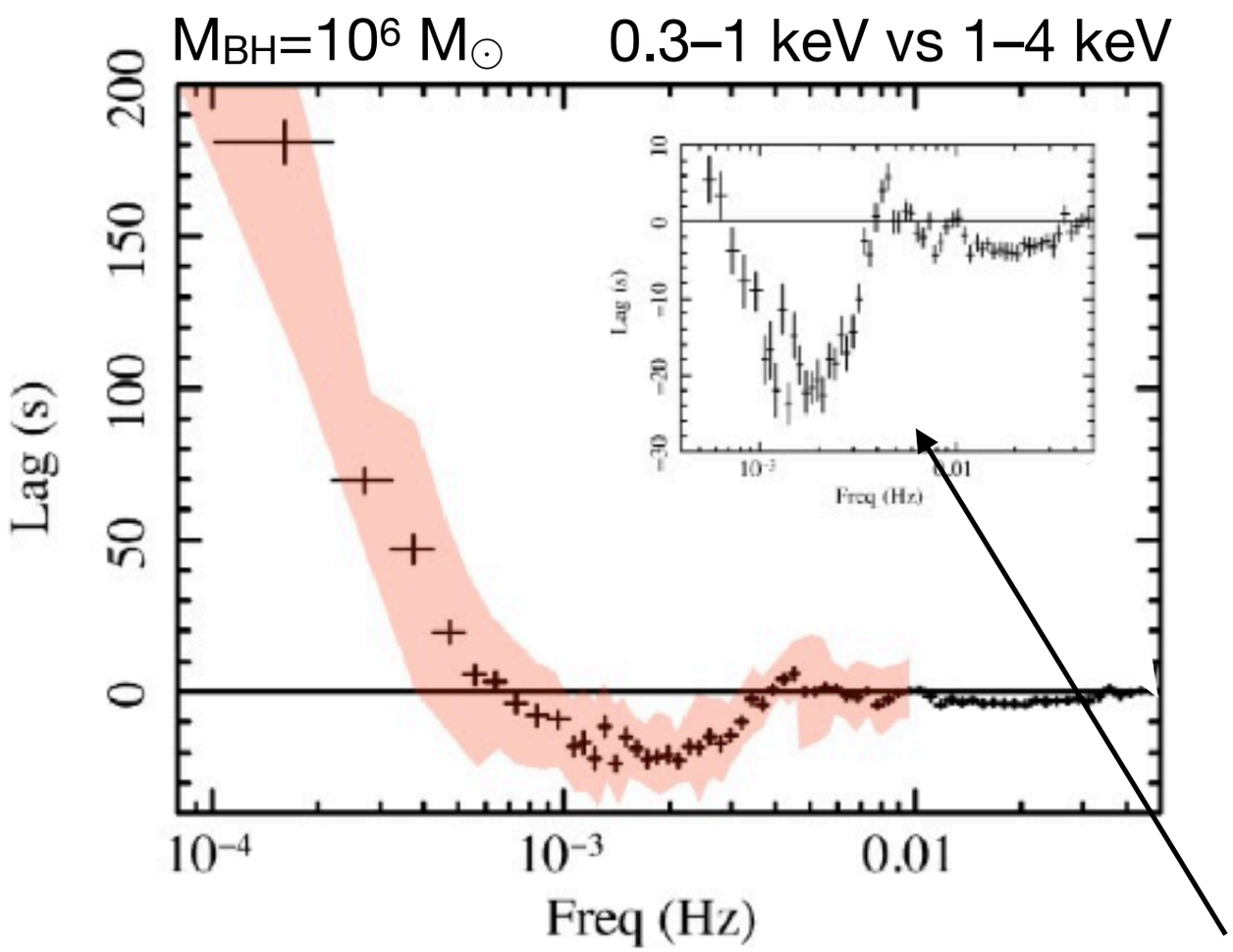
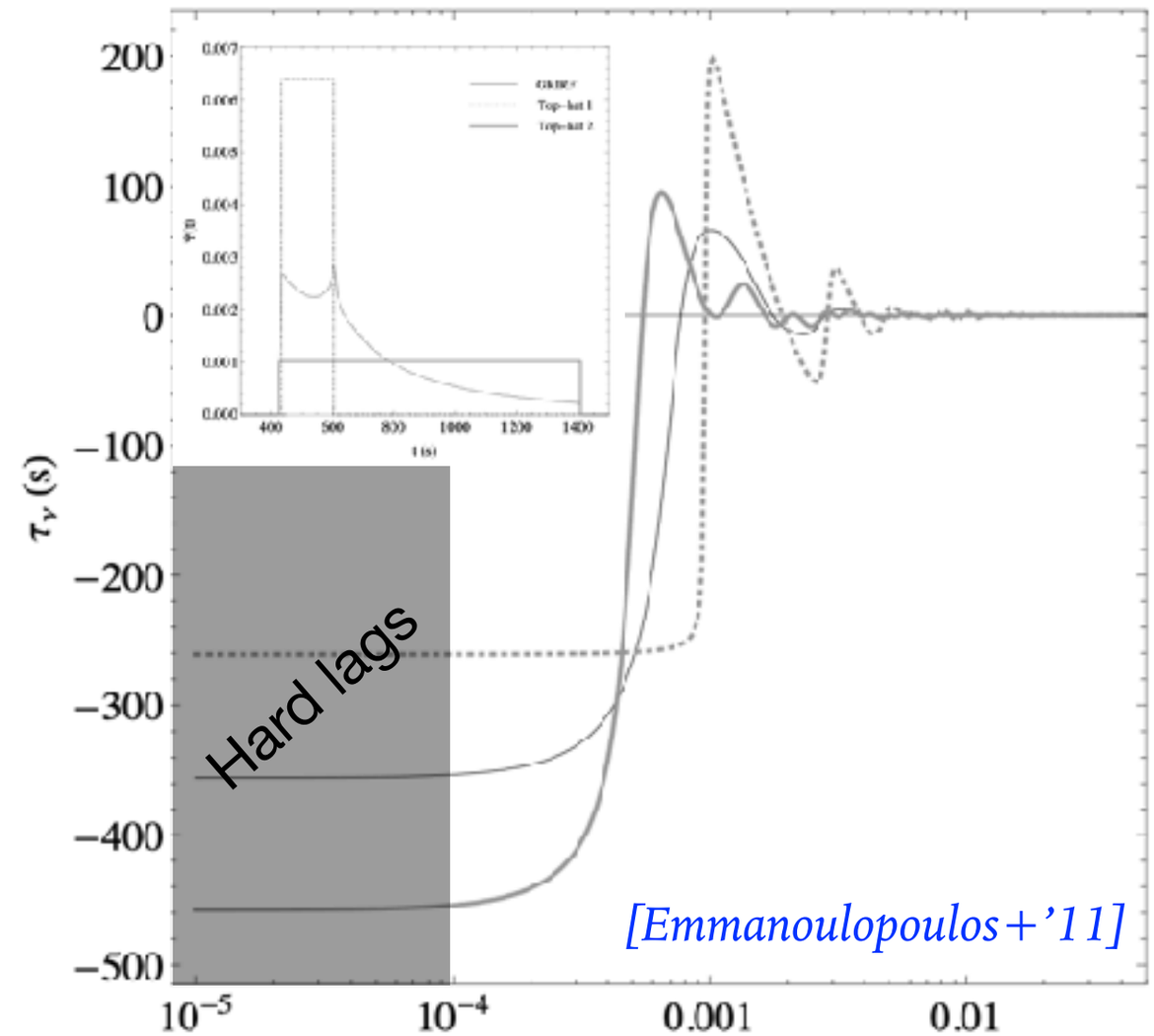
[see Dovčiak+'13]

Sensitive to high frequencies
(mapping delays of $1r_g/c$)
and to structured transfer functions

Time lags and X-ray reverberation with Athena

Constraining the transfer function





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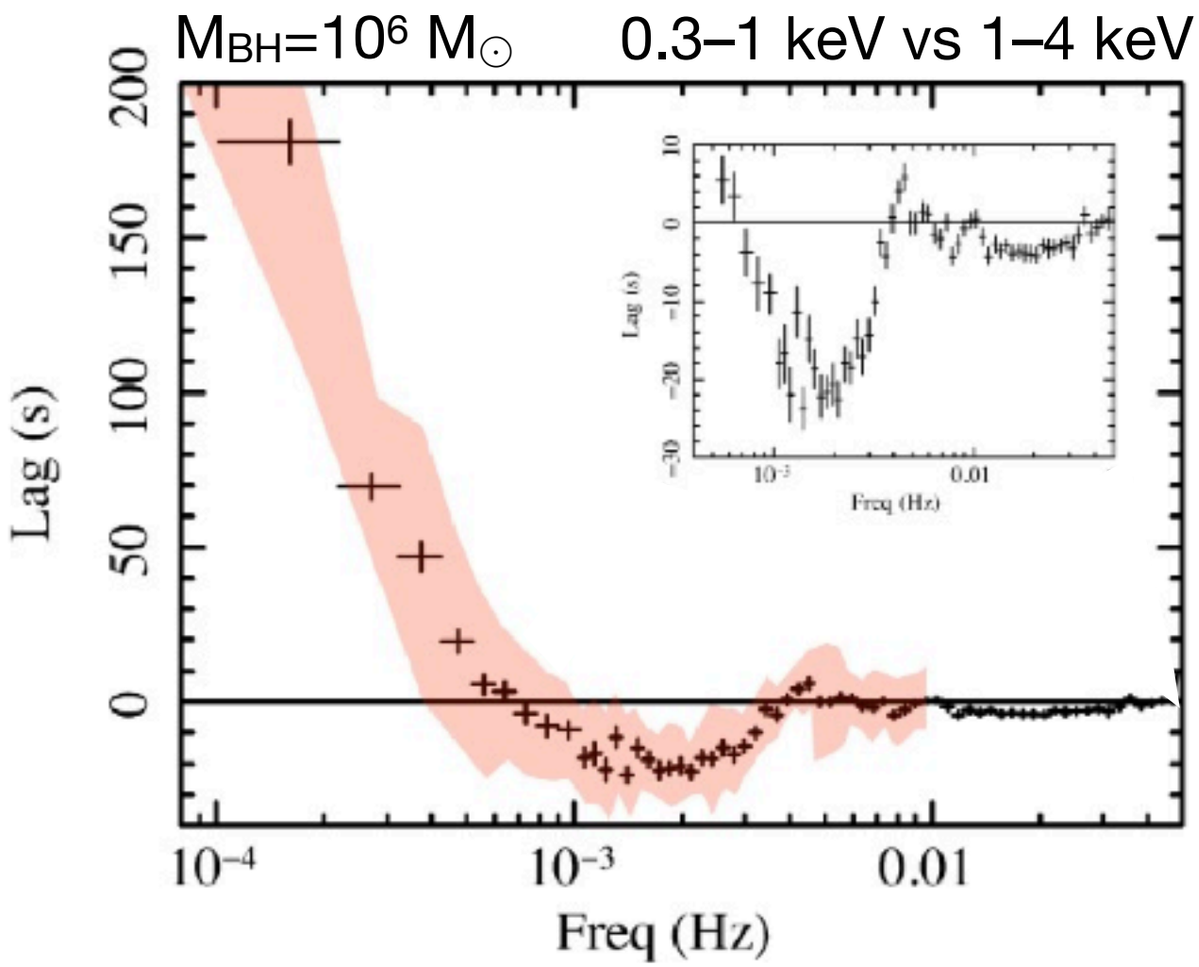

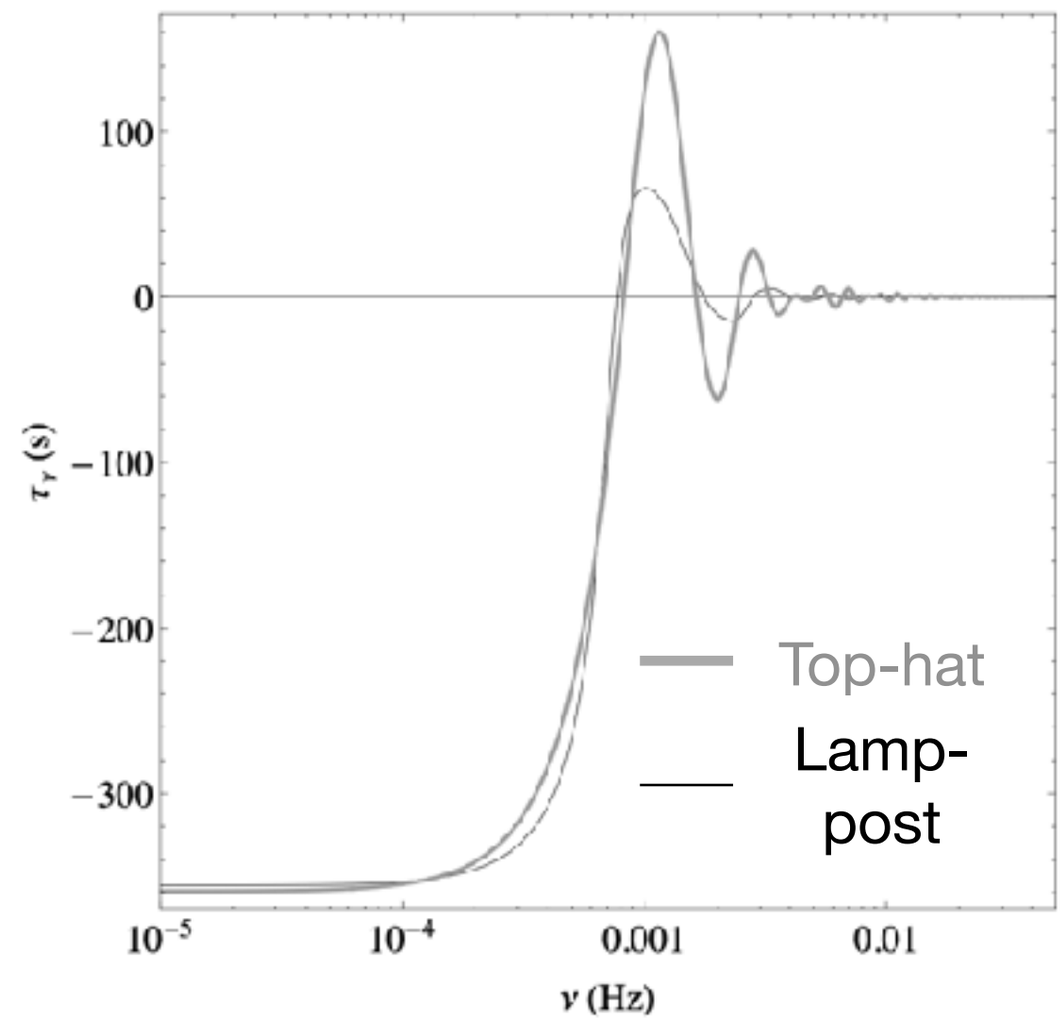

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[see Dovčiak+'13]

Time lags and X-ray reverberation with Athena

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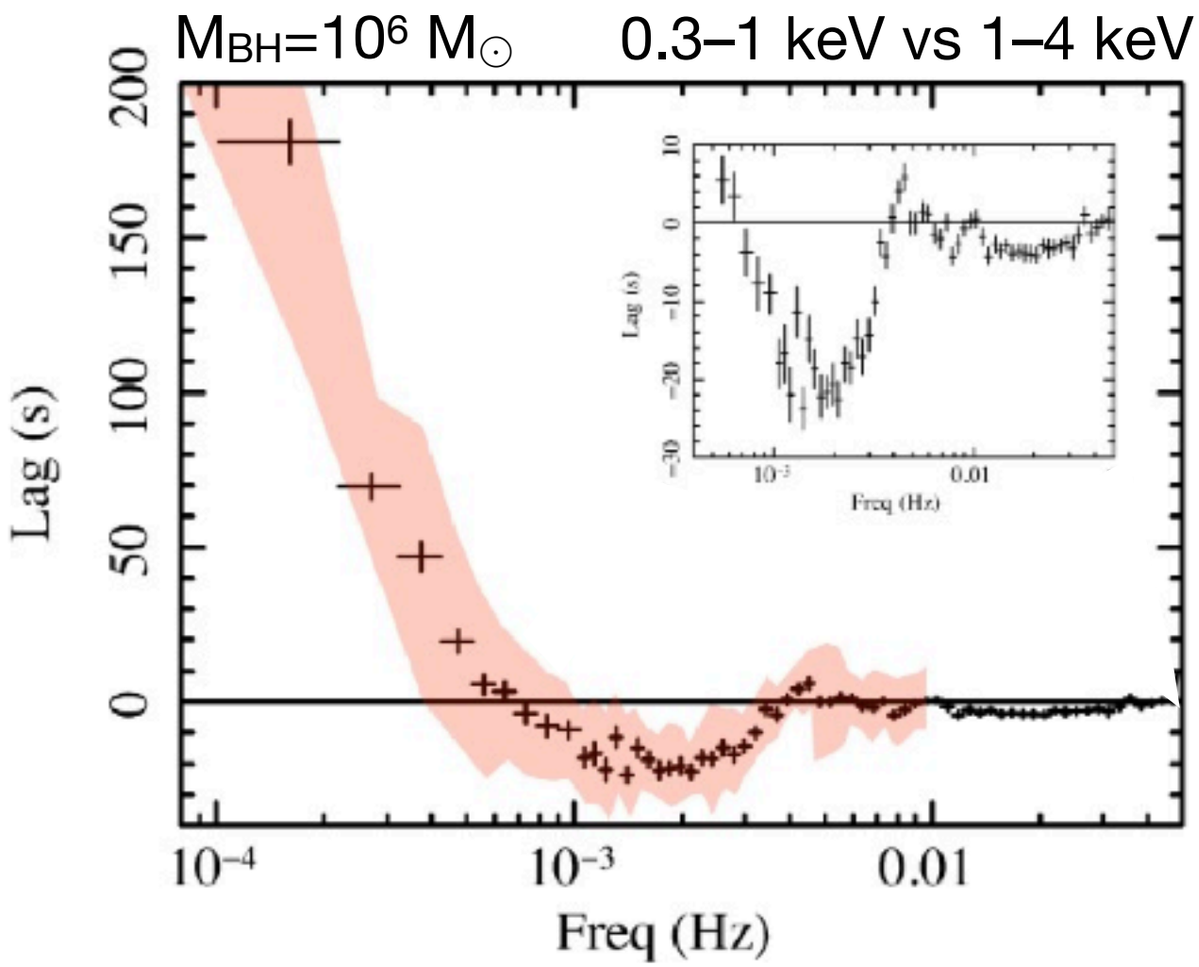
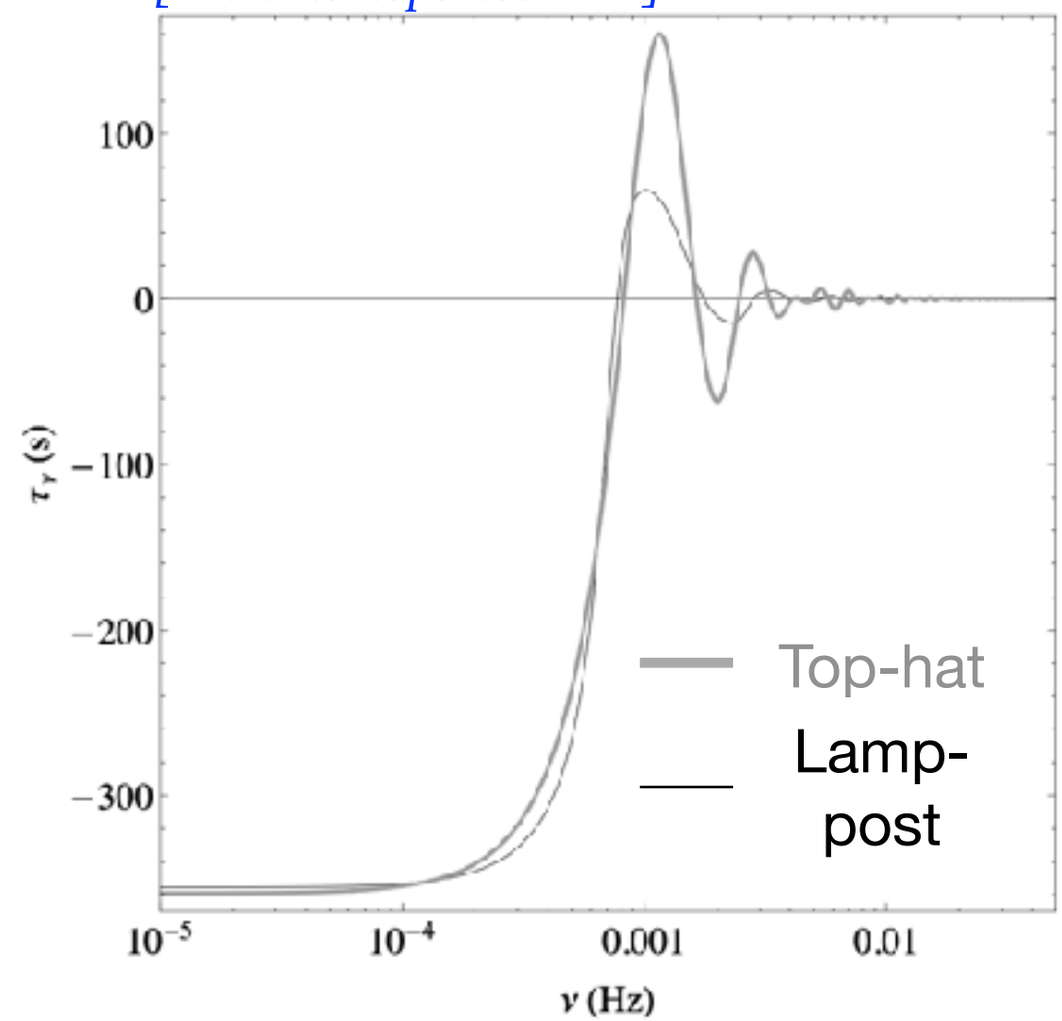


XMM pn data (500 ks)

\+ Athena WFI sims (500 ks)

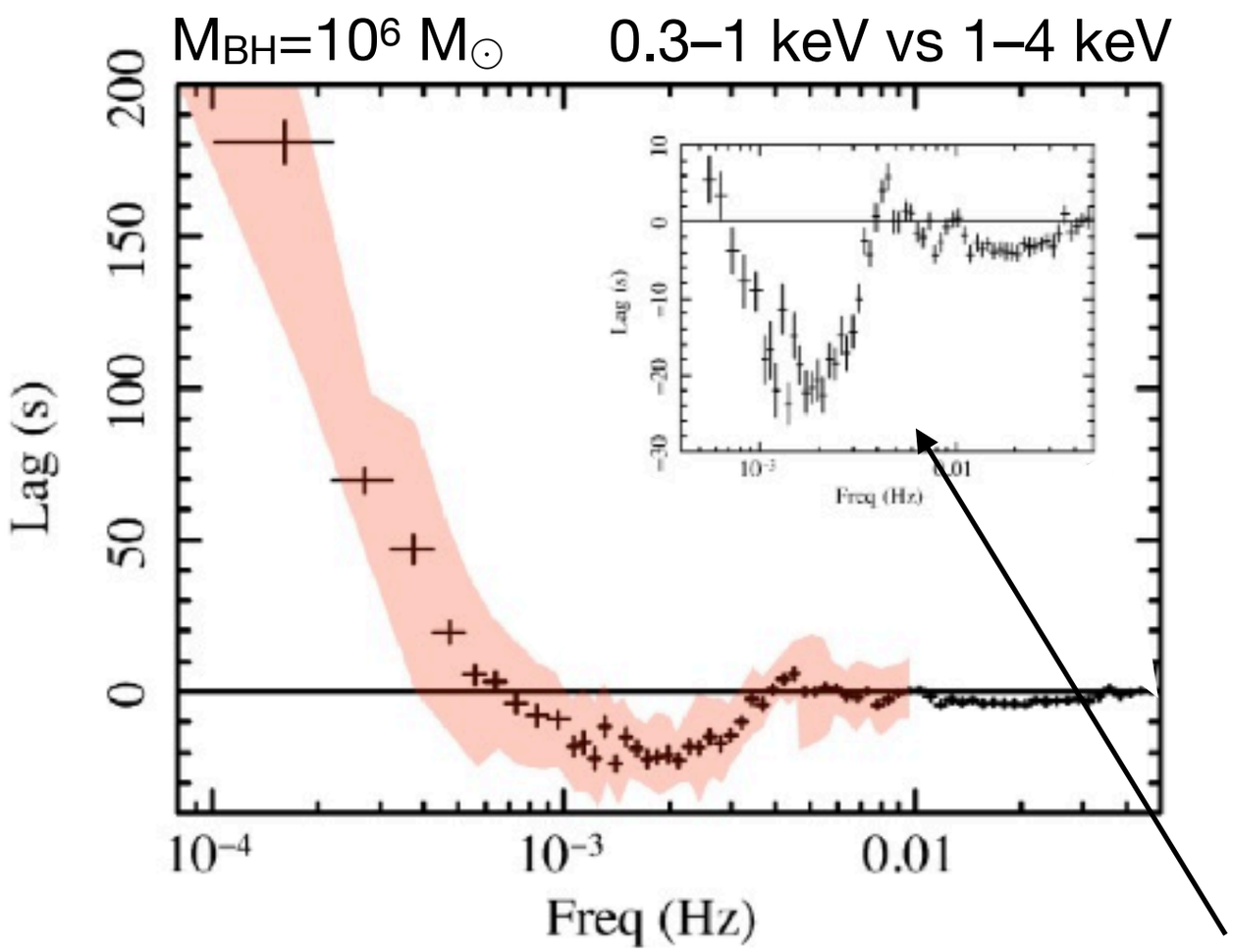
[see Dovčiak+'13]

[Emmanoulopoulos+'11]

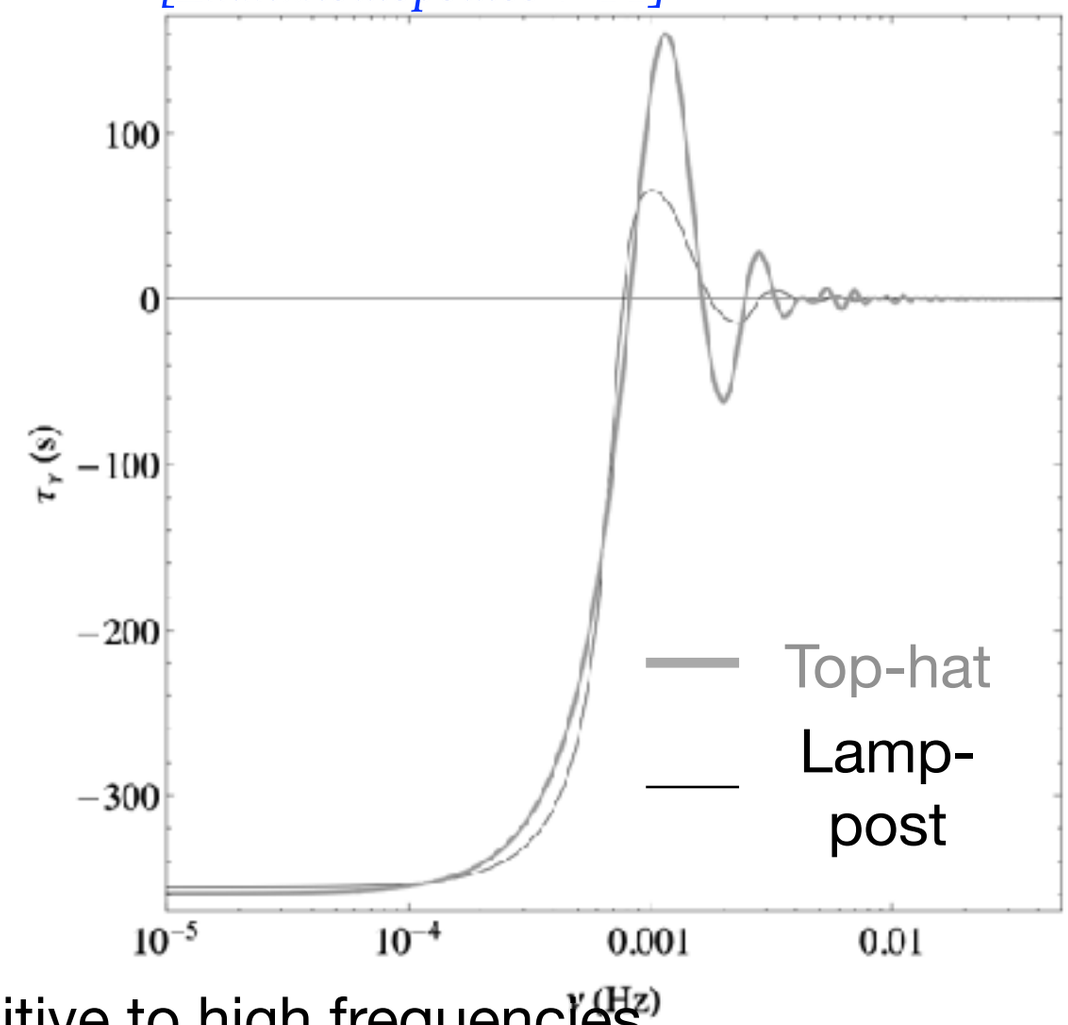


Time lags and X-ray reverberation with Athena

Constraining the transfer function



[Emmanoulopoulos+'11]



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[see Dovčiak+'13]

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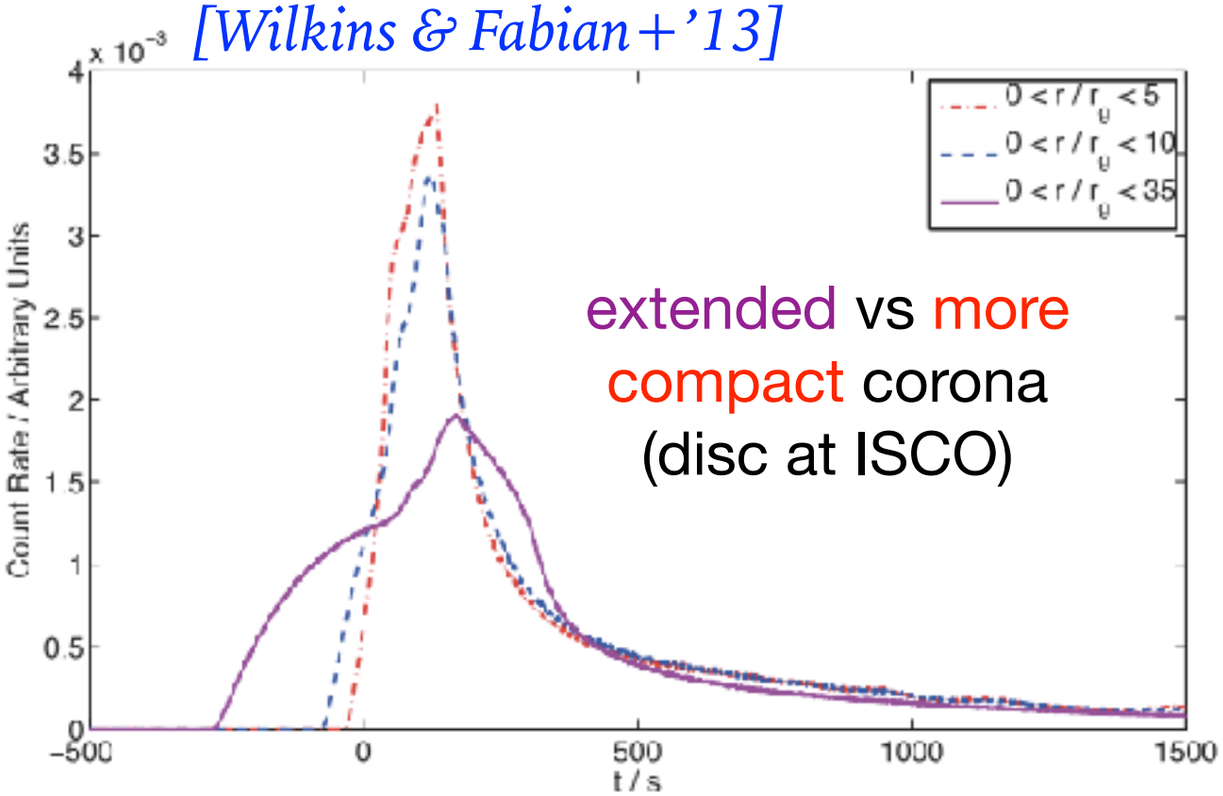
Time lags and X-ray reverberation with Athena

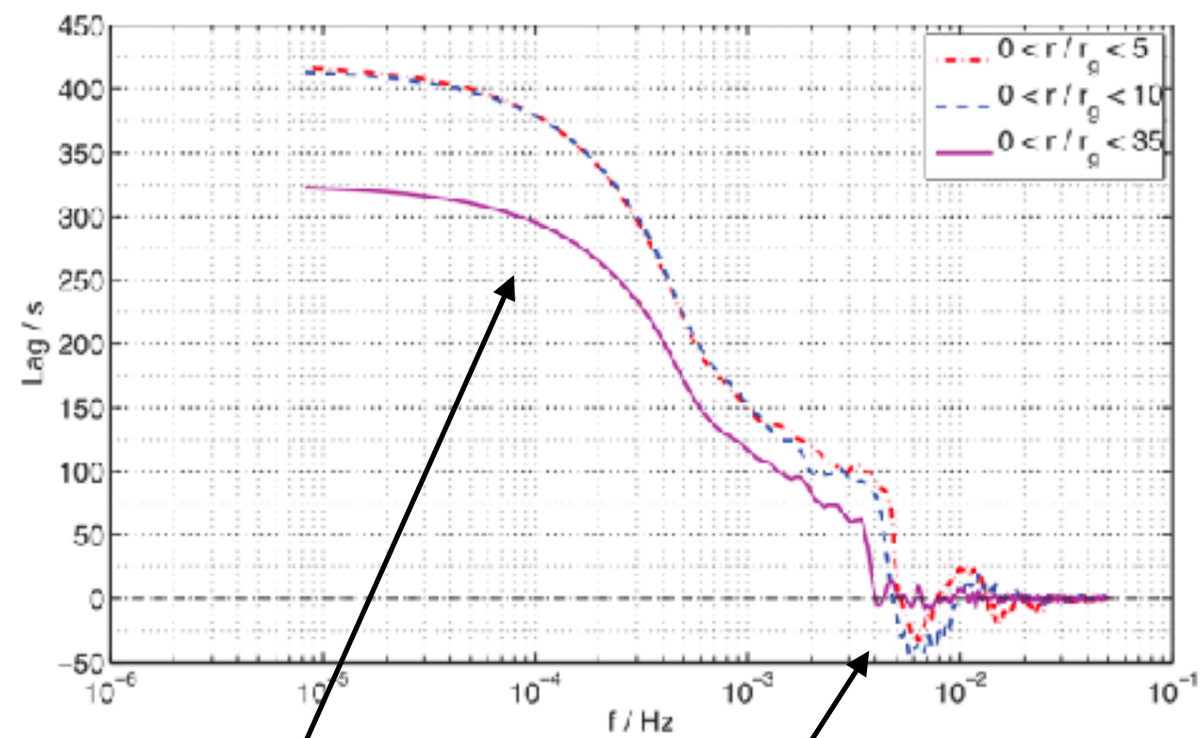
Constraining coronal geometry: compact vs extended

[Wilkins & Fabian+'13]



extended vs more compact corona (disc at ISCO)

Importance of good S/N at high-frequencies



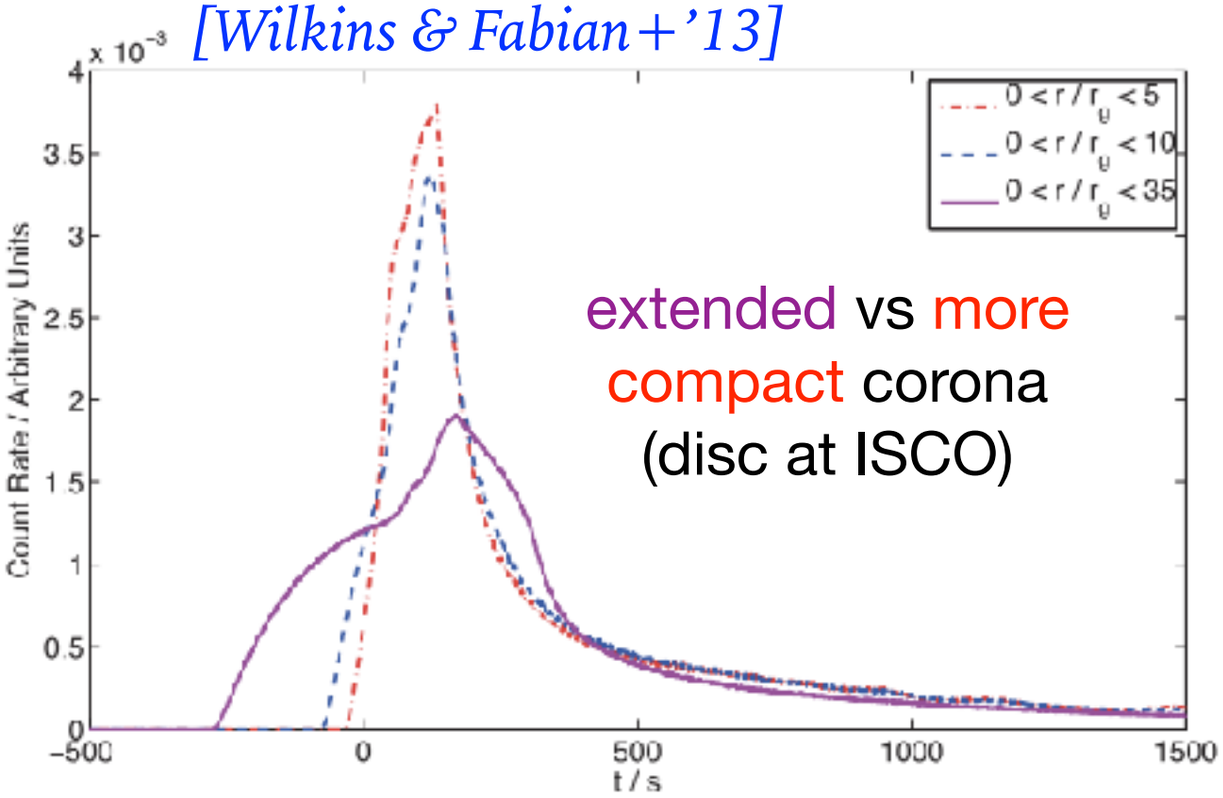
Similar shape at low/intermediate frequencies

Different structures at high frequencies

Time lags and X-ray reverberation with Athena

Constraining coronal geometry: compact vs extended

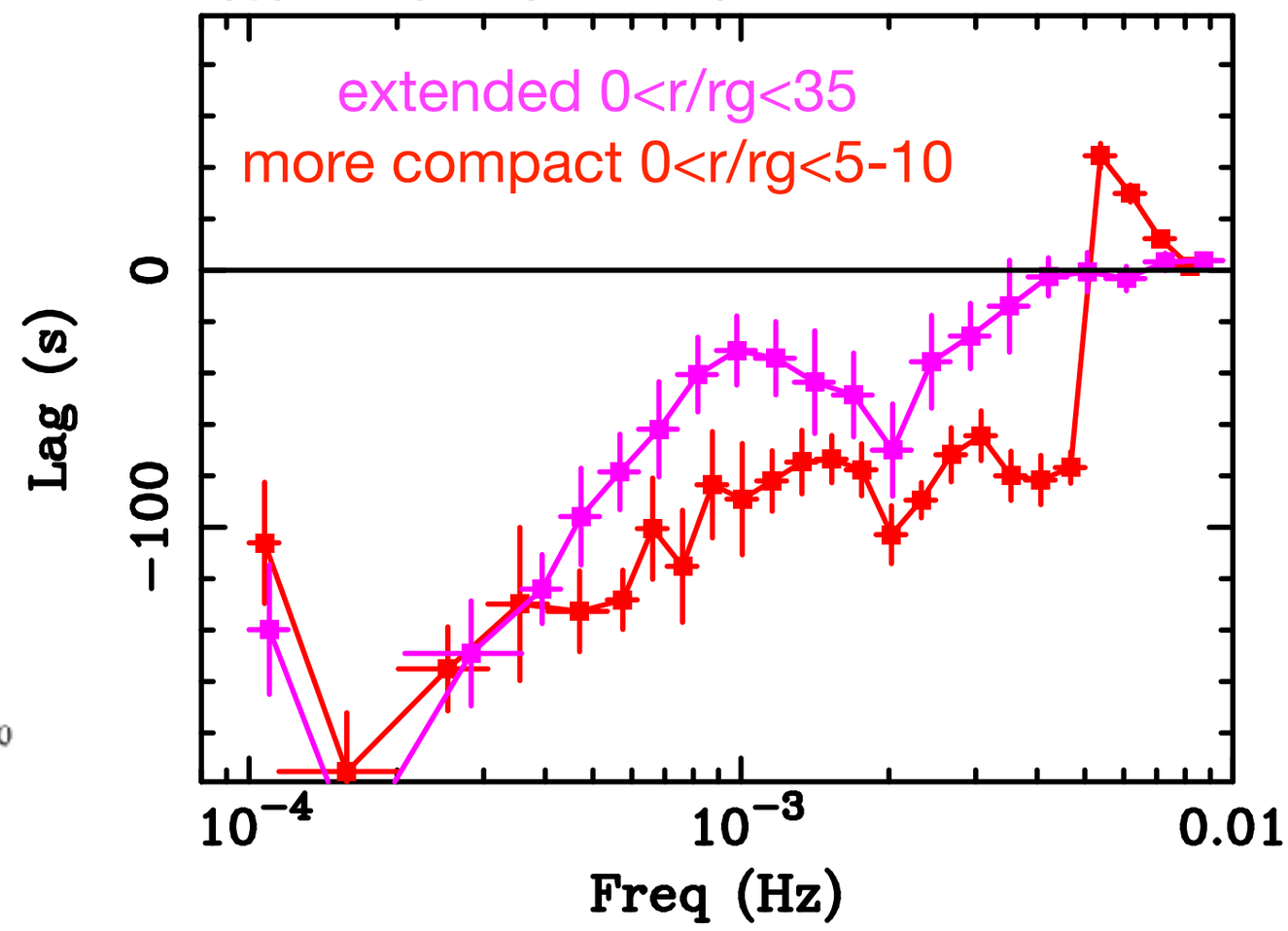
[Wilkins & Fabian+'13]



Athena

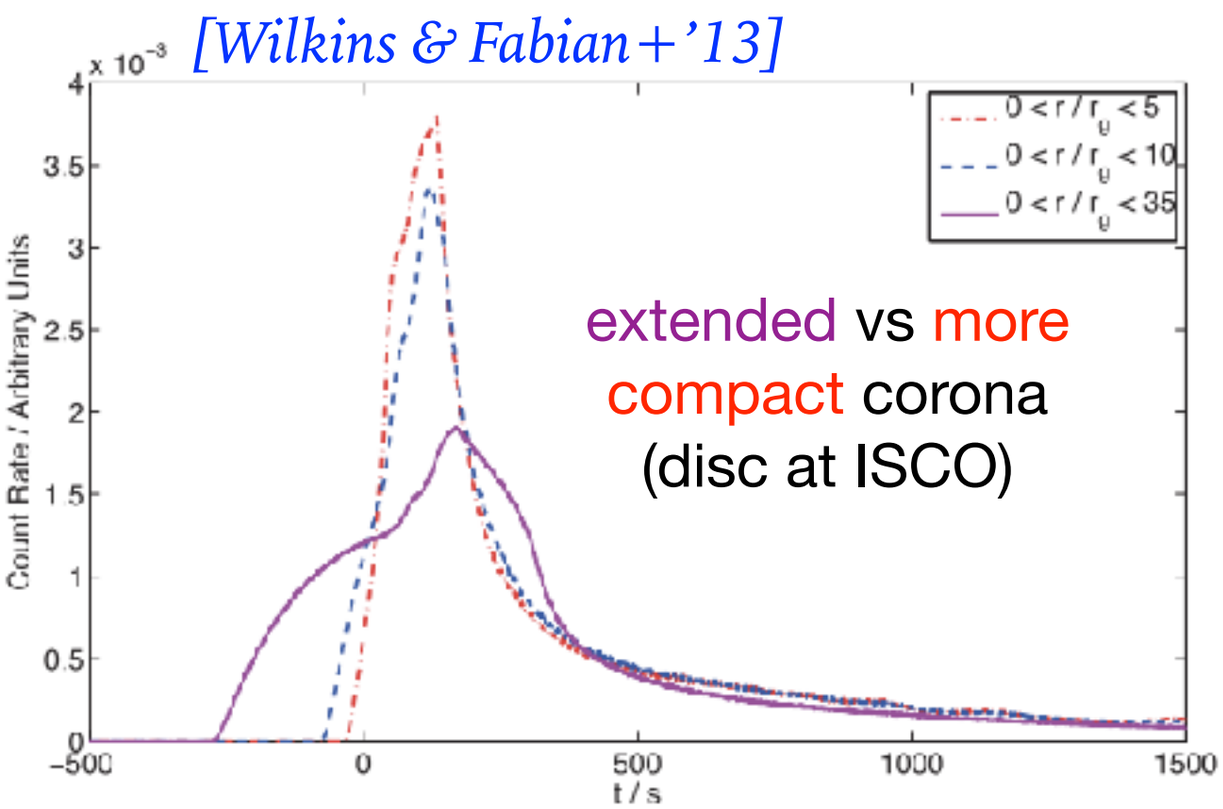
100 ks - $M_{BH}=10^6\ M_\odot$

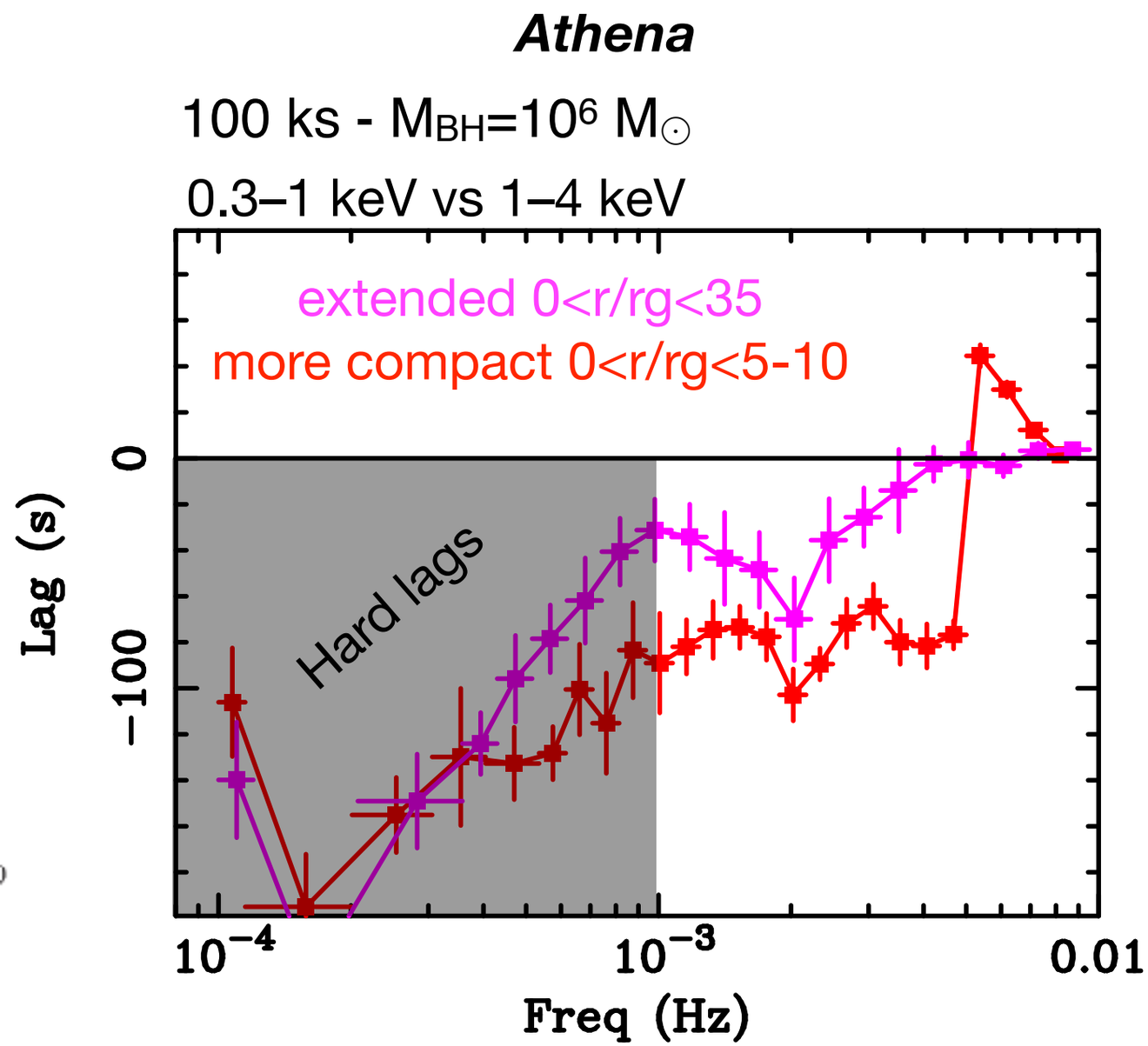
0.3–1 keV vs 1–4 keV



Time lags and X-ray reverberation with Athena

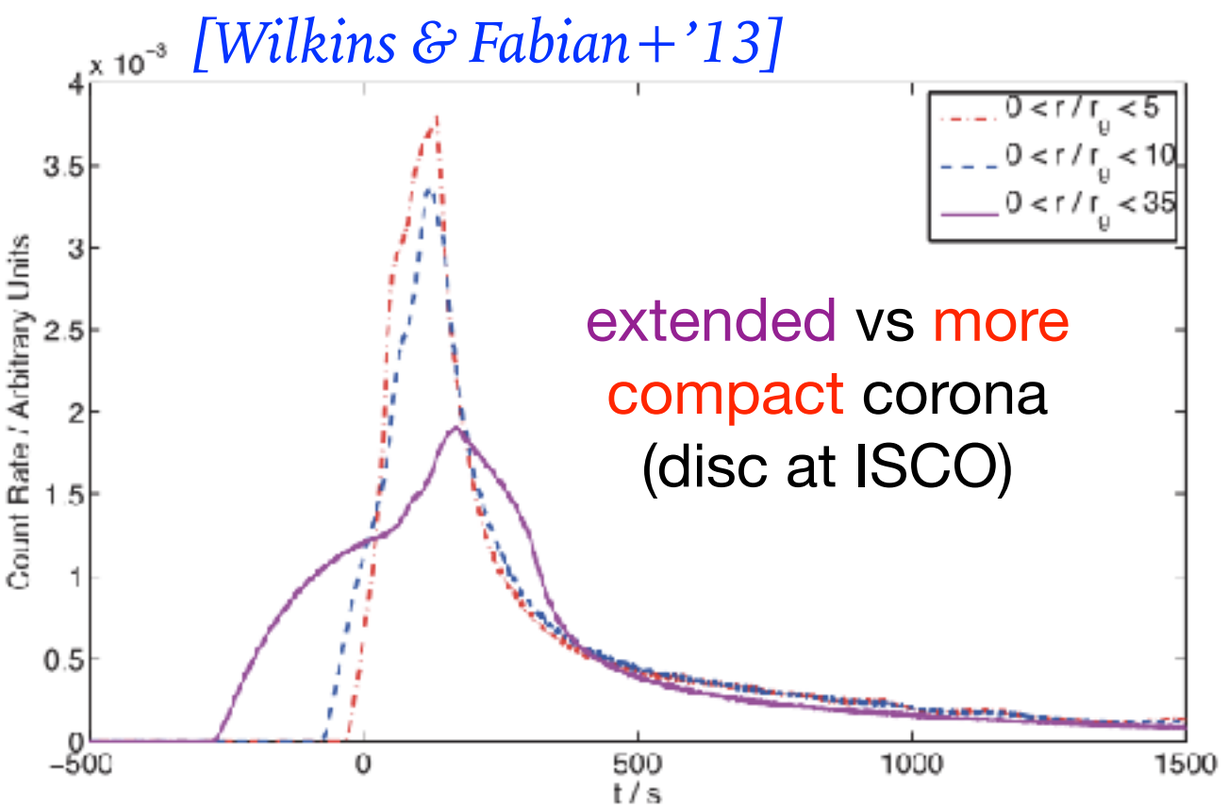
Constraining coronal geometry: compact vs extended

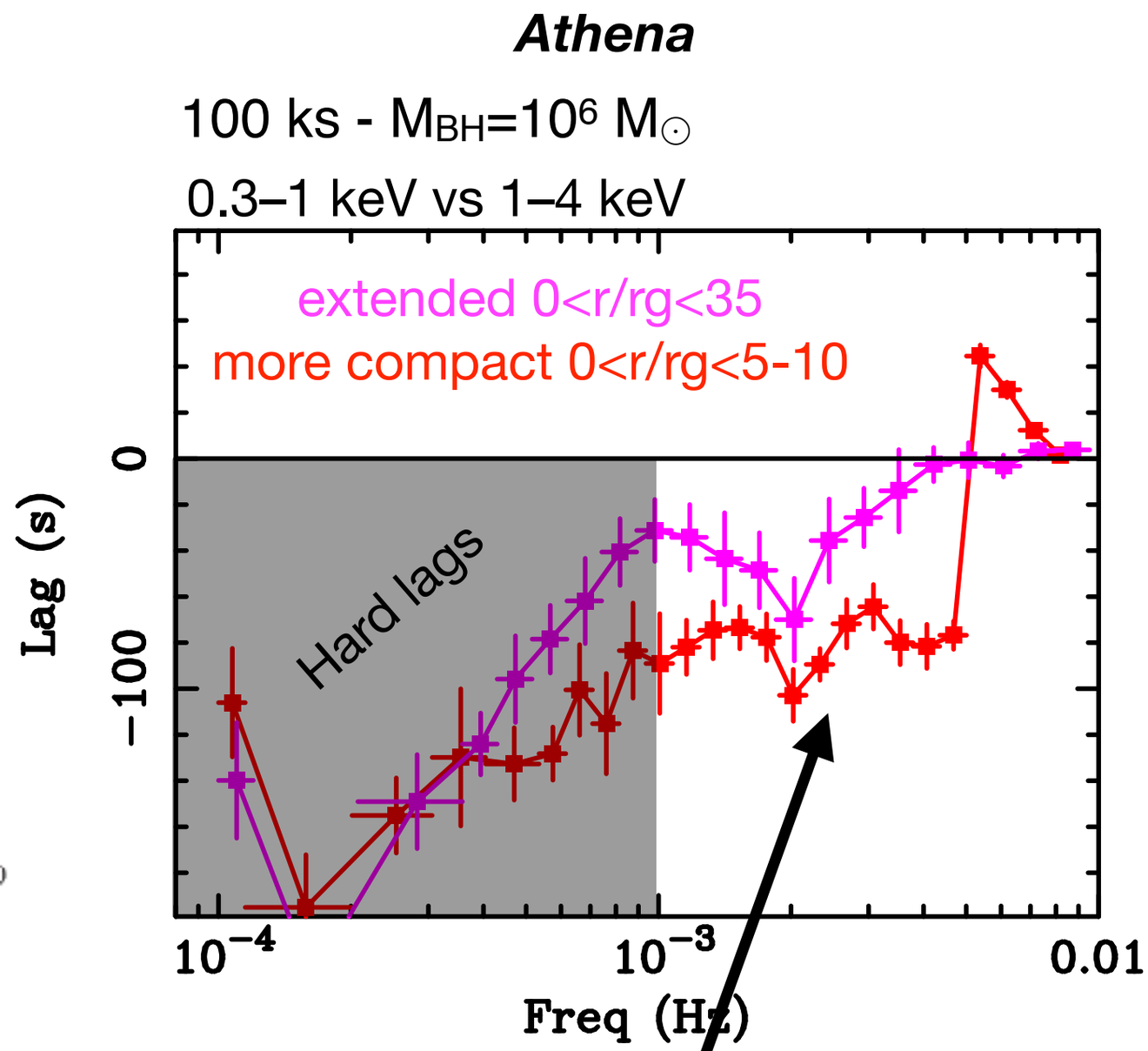




Time lags and X-ray reverberation with Athena

Constraining coronal geometry: compact vs extended



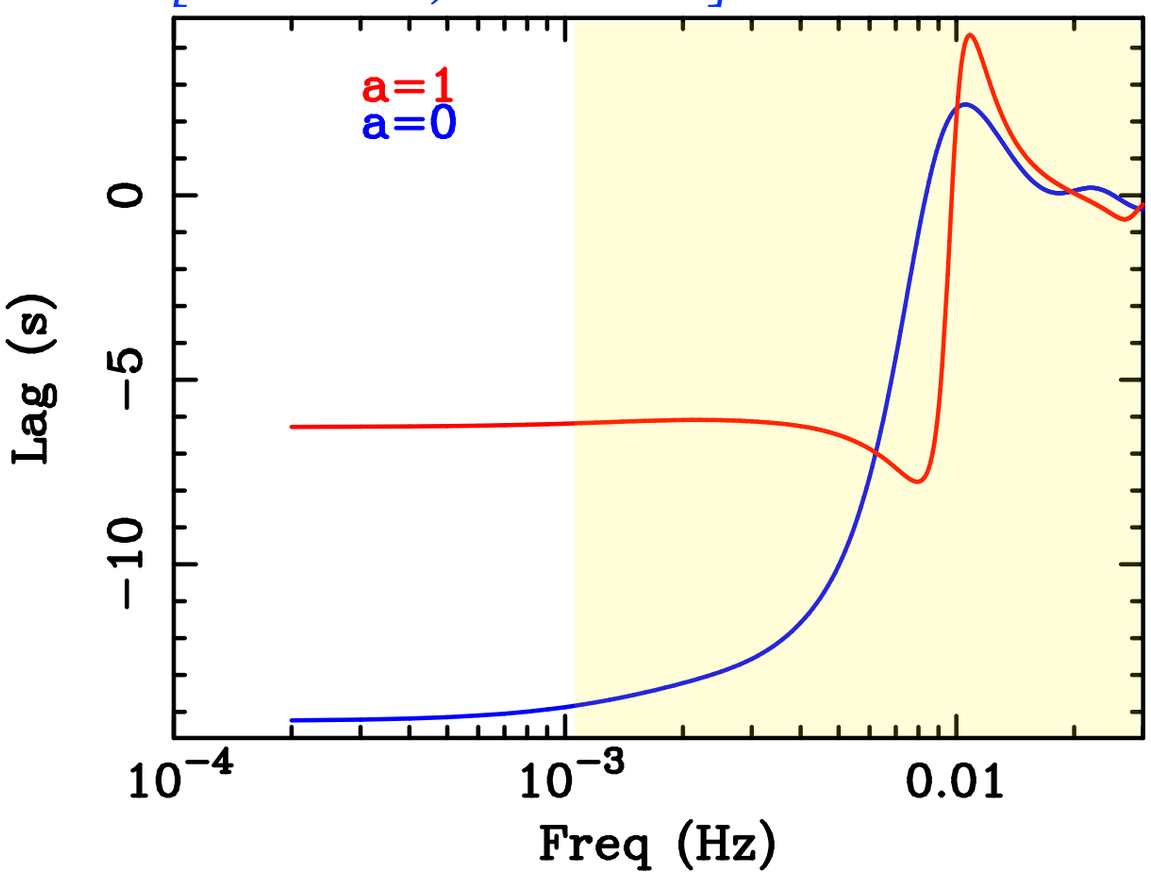


significant differences in the shape of the response at high frequencies

Time lags and X-ray reverberation with Athena

Constraining the BH spin

[KYNreverb, M. Dovčiak]

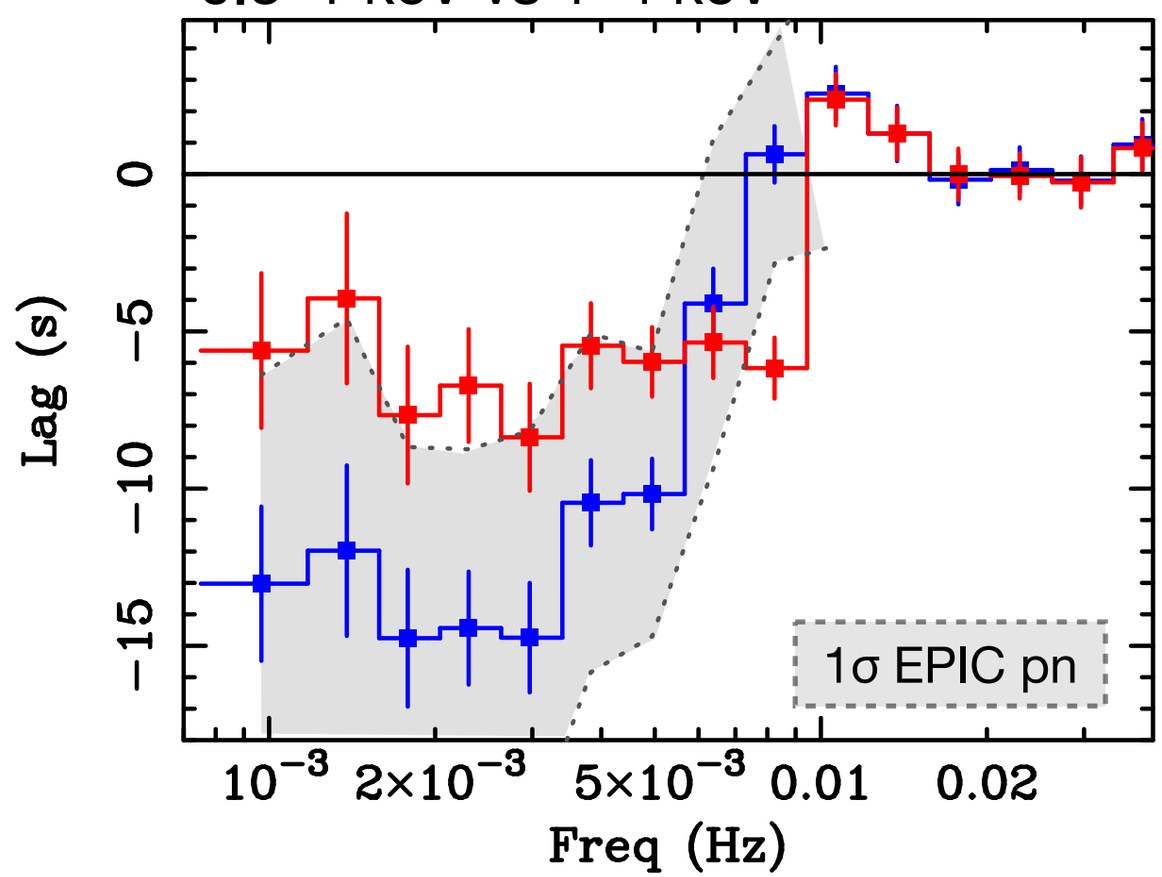


lamp post geometry ($h \sim 2r_g$)

Athena

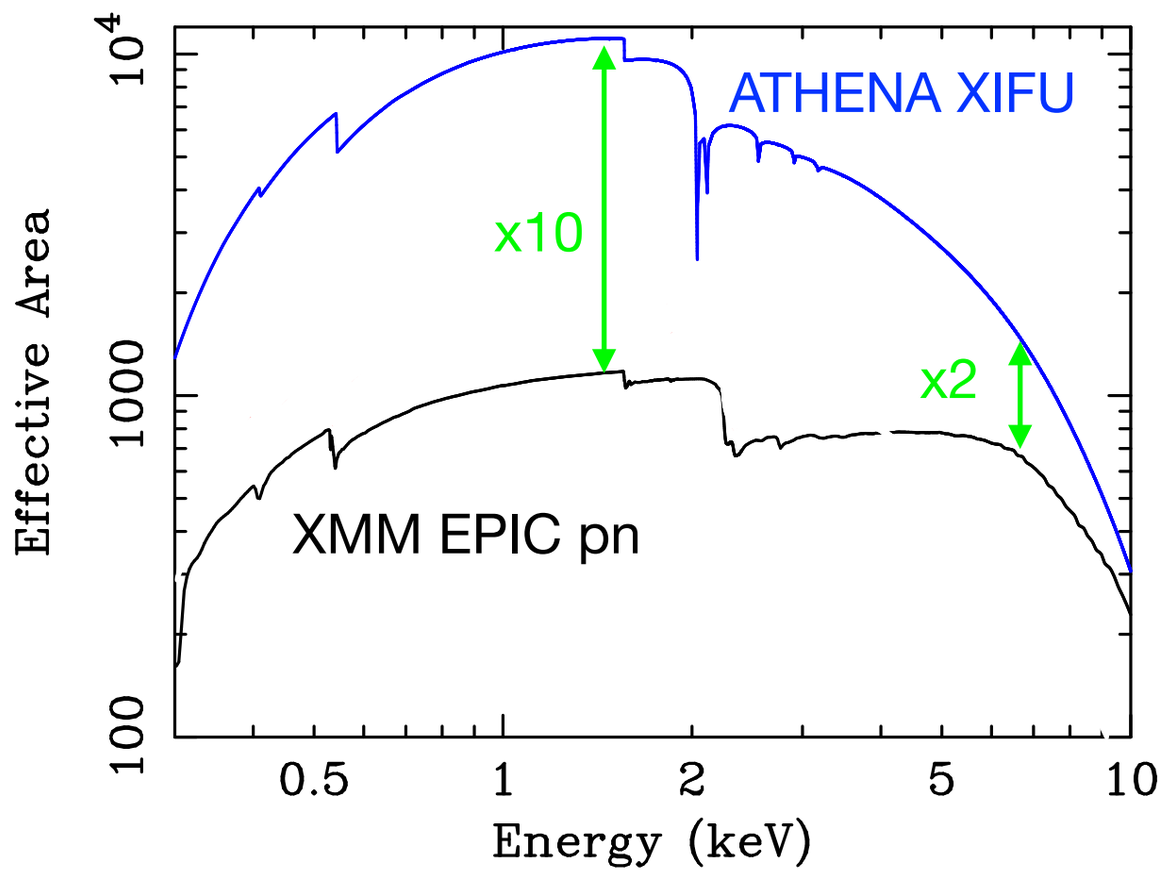
400 ks - $M_{BH}=10^6\ M_\odot$

0.3–1 keV vs 1–4 keV



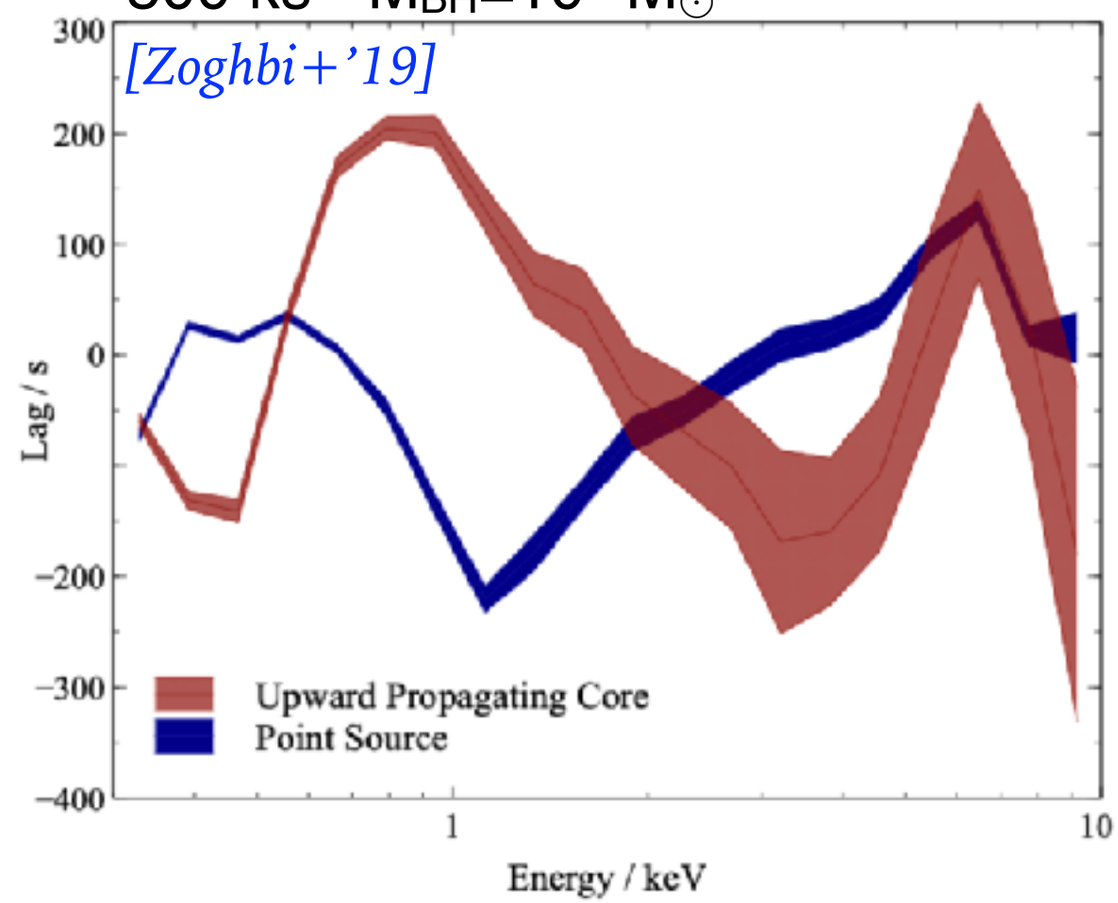
Time lags and X-ray reverberation with Athena

Fe K reverberation and propagating fluctuations



Athena

500 ks - $M_{BH}=10^7\ M_\odot$



Testing the expectations of lag models over a broad range of energy+ unprecedented spectral resolution!

Conclusions

X-ray reverberation is an independent, powerful method to study the inner accretion flow and constrain the geometry of the disc and the X-ray source

XMM-Newton and NICER allowed us to make important step forwards in our understanding of X-ray reverberation signals

Better data allow us to go beyond the simple measurements of X-ray reverberation, by enabling more detailed modelling and complex studies of the dynamics of the BH-systems

Athena will provide high S/N spectral timing data, combined with unprecedented spectral resolution, broad band coverage and good timing capabilities.
This will allow for great improvements in this field

Conclusions

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Let's build Athena!

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Thanks!