# *X-ray reverberation: a tool to unveil the inner regions of accreting black holes*

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*Thanks to:*

*G. Ponti; P. Uttley; M. Cappi; K. Nandra; T. Muñoz-Darias; G. Miniutti; A. Fabian; et al.*

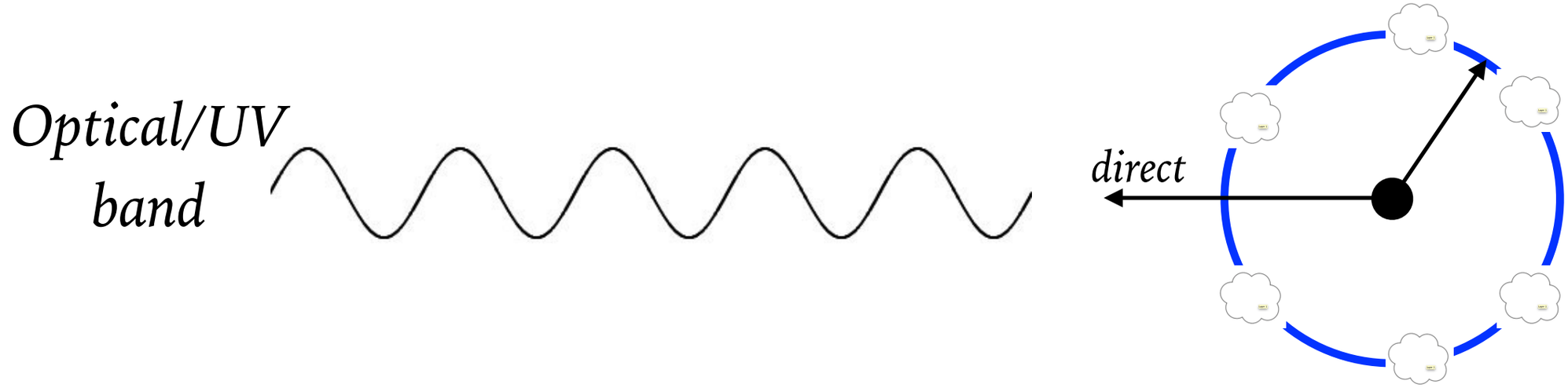
MAX-PLANCK-GESELLSCHAFT

MPE

# *Why studying X-ray reverberation?*

# *Reverberation "as we know it"*

*The intensity of the emission lines in BLR of Active Galactic Nuclei (AGN) responds to variations of the primary illuminating source*



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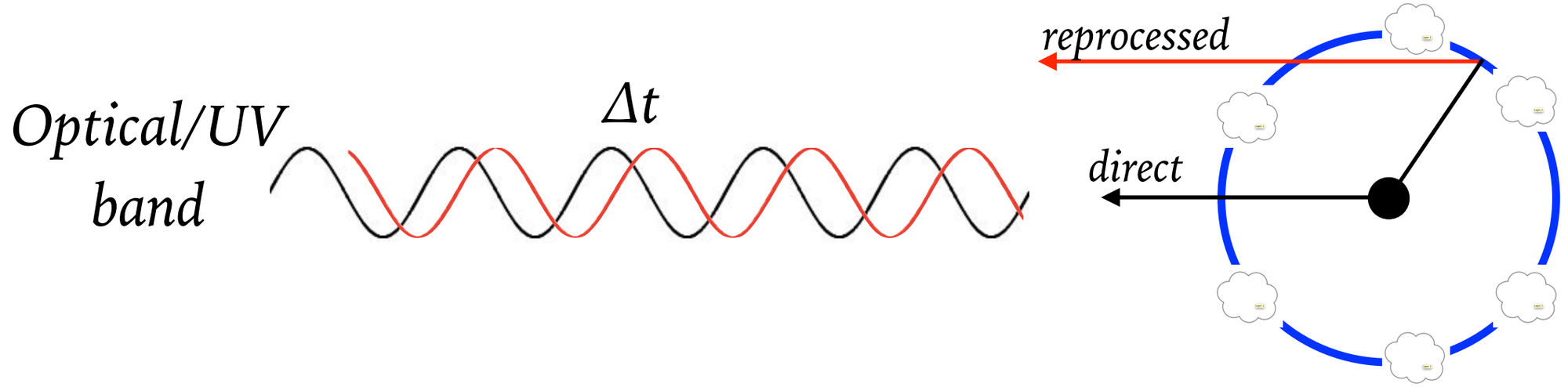


*Two effects: 1) light travel time delay*

*2) smoothing of short time-scale variability*

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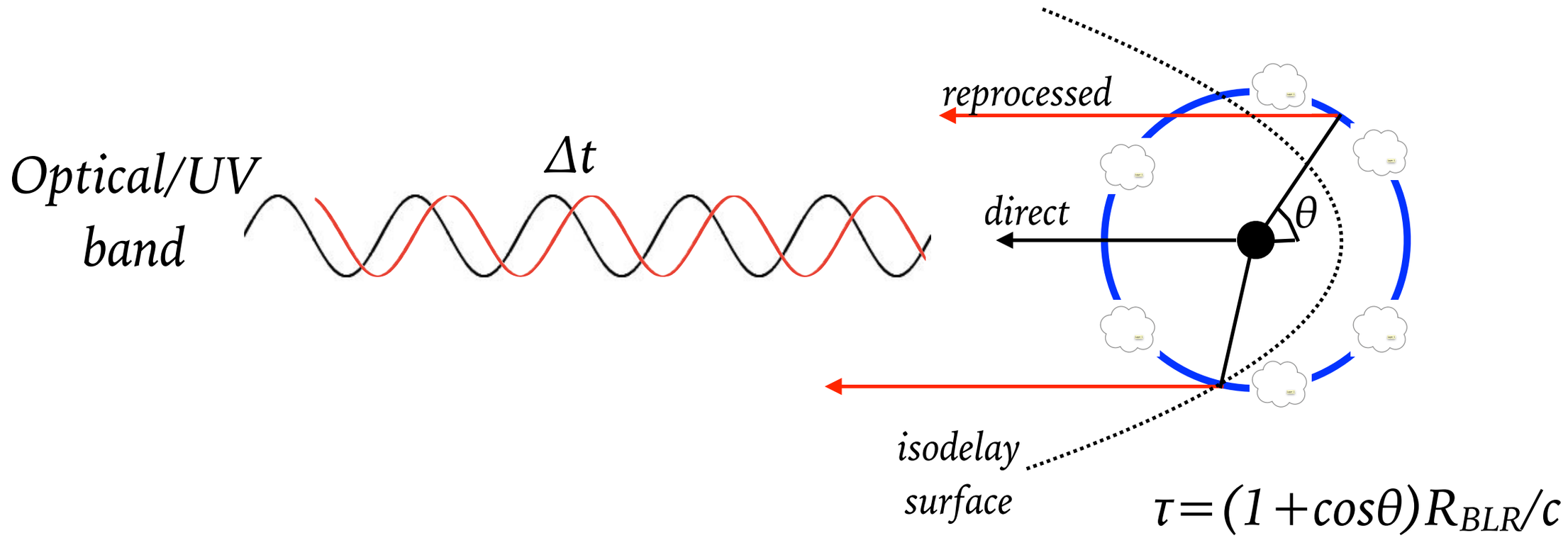


$$\tau = (1 + \cos\theta) R_{BLR}/c$$

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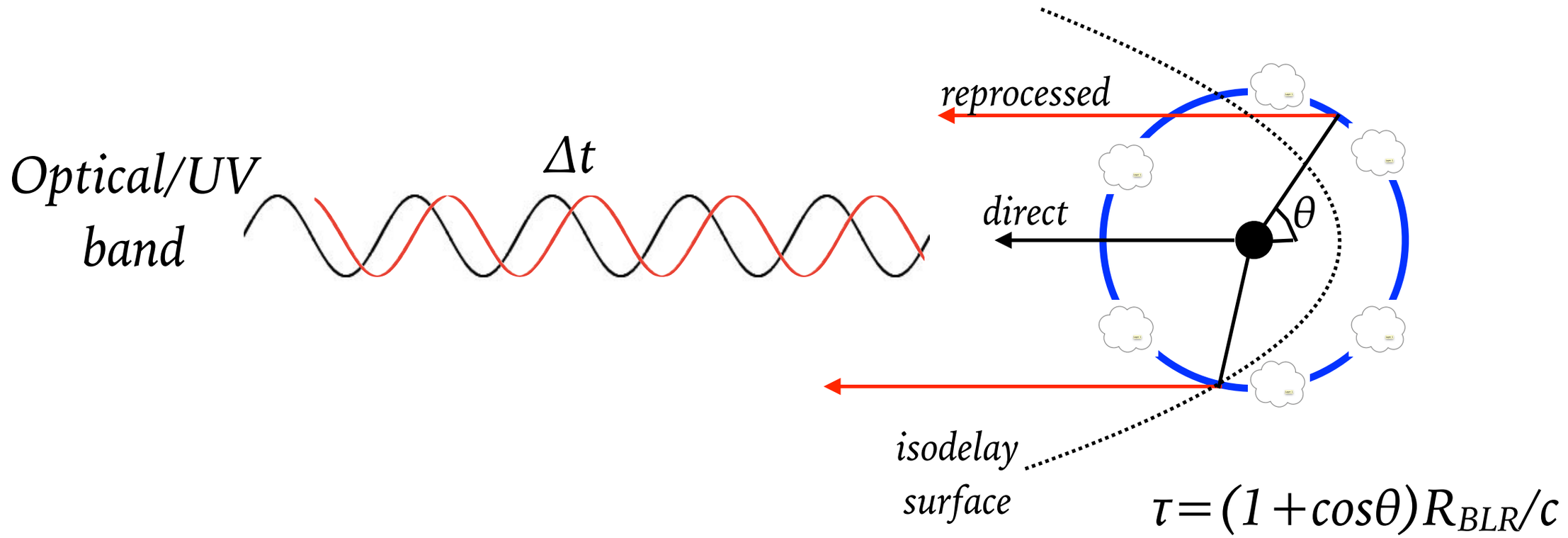


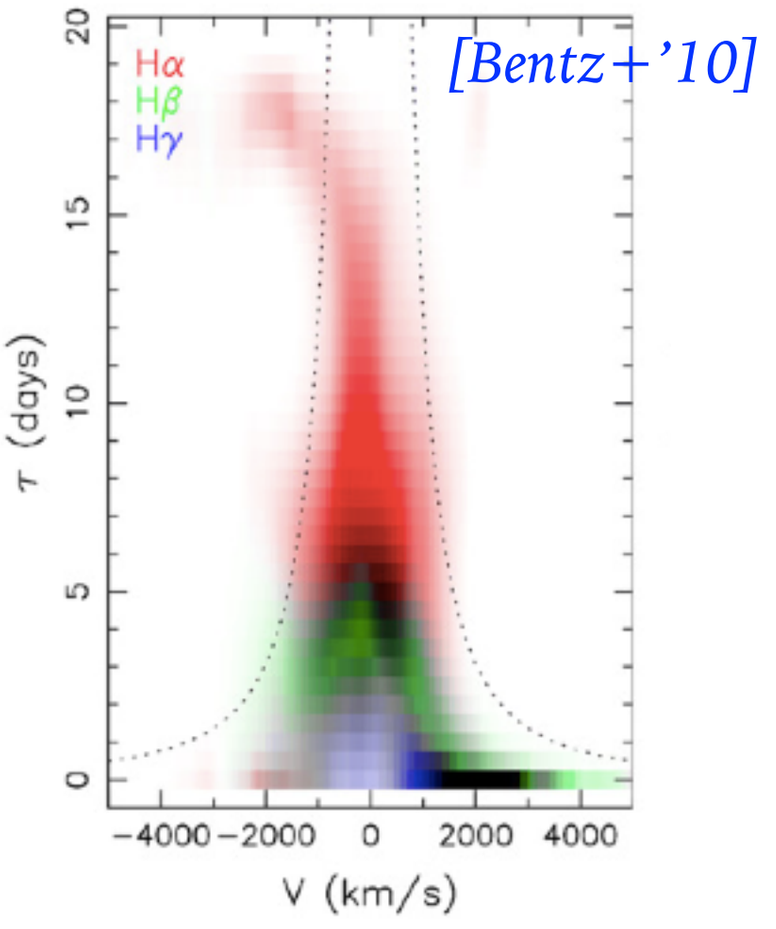

*Direct method to measure BH mass in AGN*

*(e.g. Peterson+'04)*

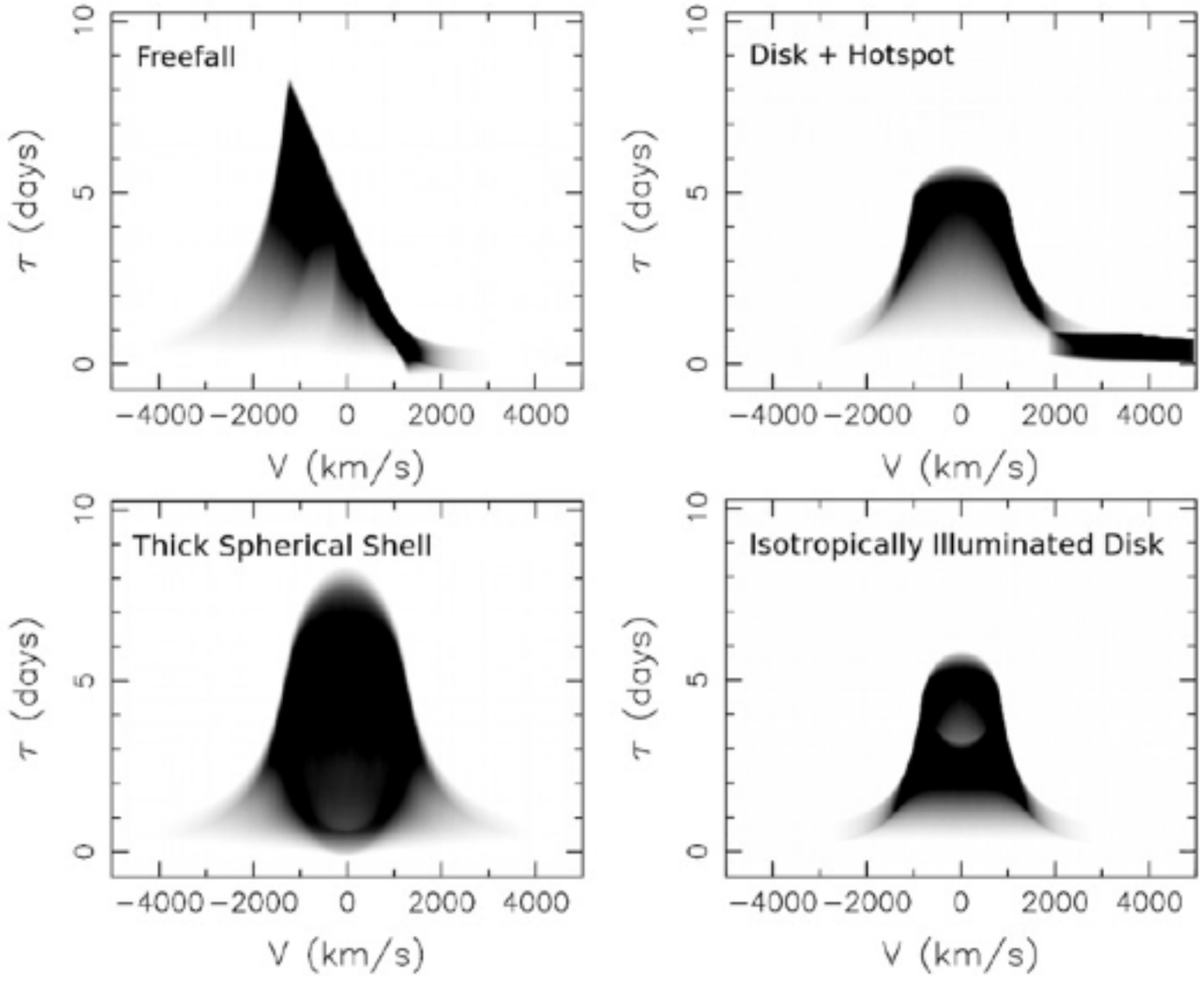
# *Reverberation "as we know it"*

*Allows to constrain the kinematics of BLR*

*(e.g. Bentz+'10, Pancoast+'12, Grier+'13)*




*[Bentz+'10]*



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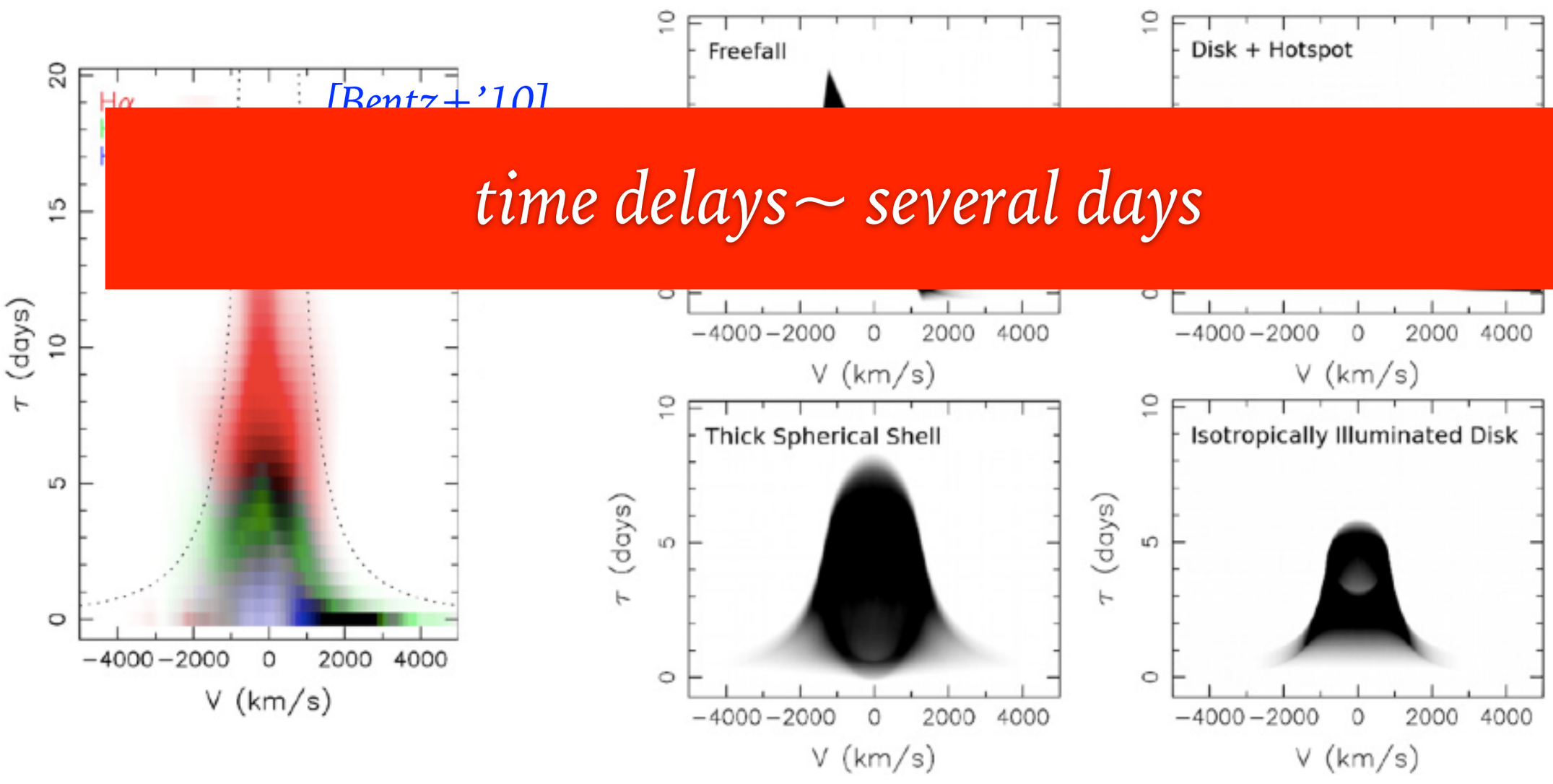
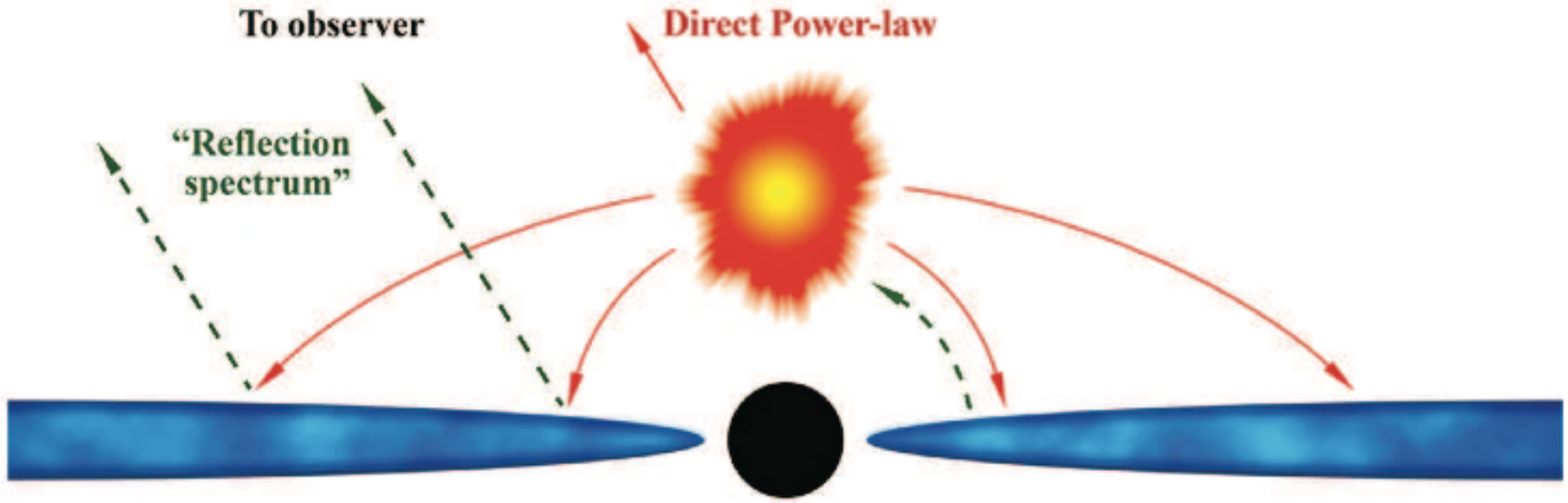



*time delays~ several days*

# *Reverberation in the X-ray band*

*Can we detect reverberation in the X-ray band and use it to understand the structure of the corona and of the inner accretion flow?*

*[recent review Uttley+'14]*



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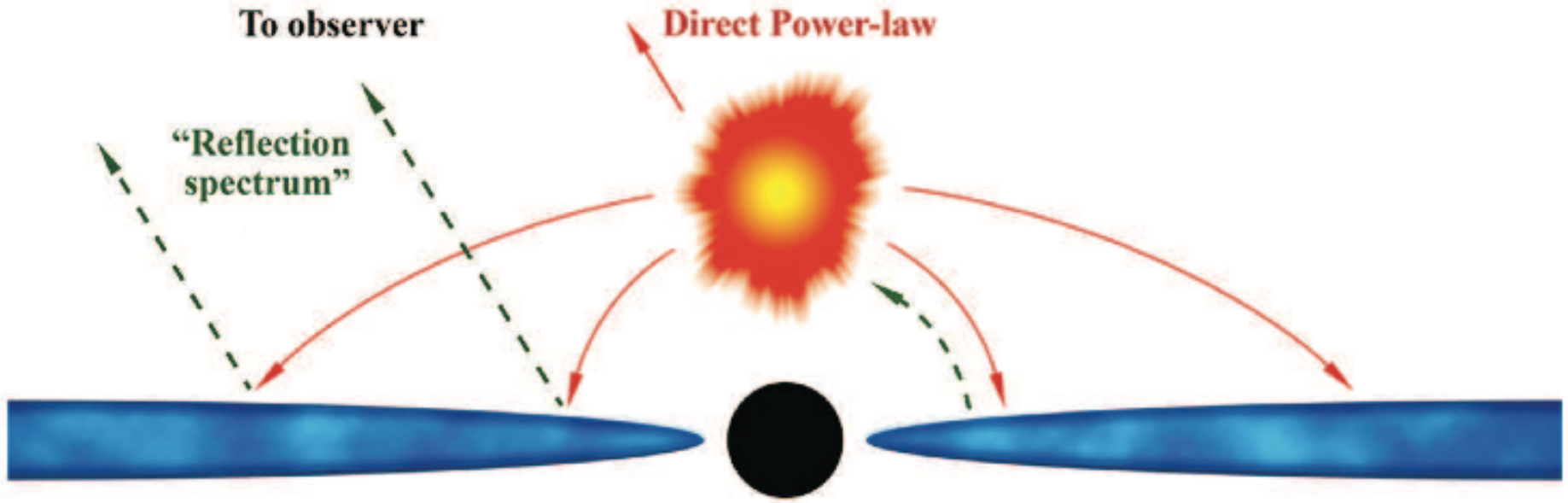
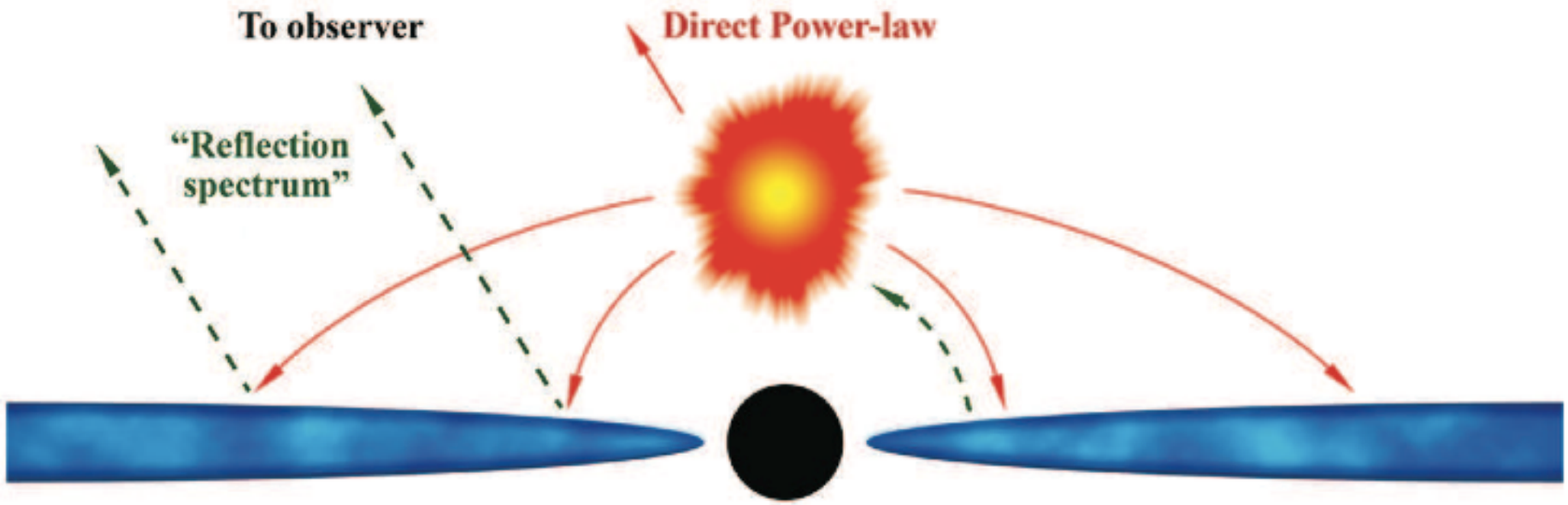
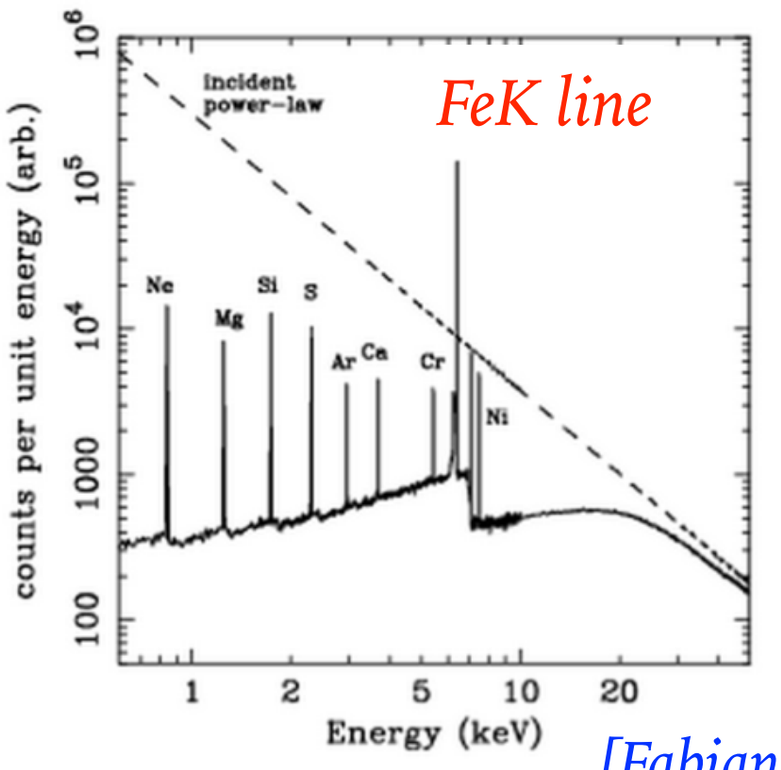



*time delays~ few hours*

# *Reverberation in the X-ray band*




*FeK line*

*[Fabian+'00]*

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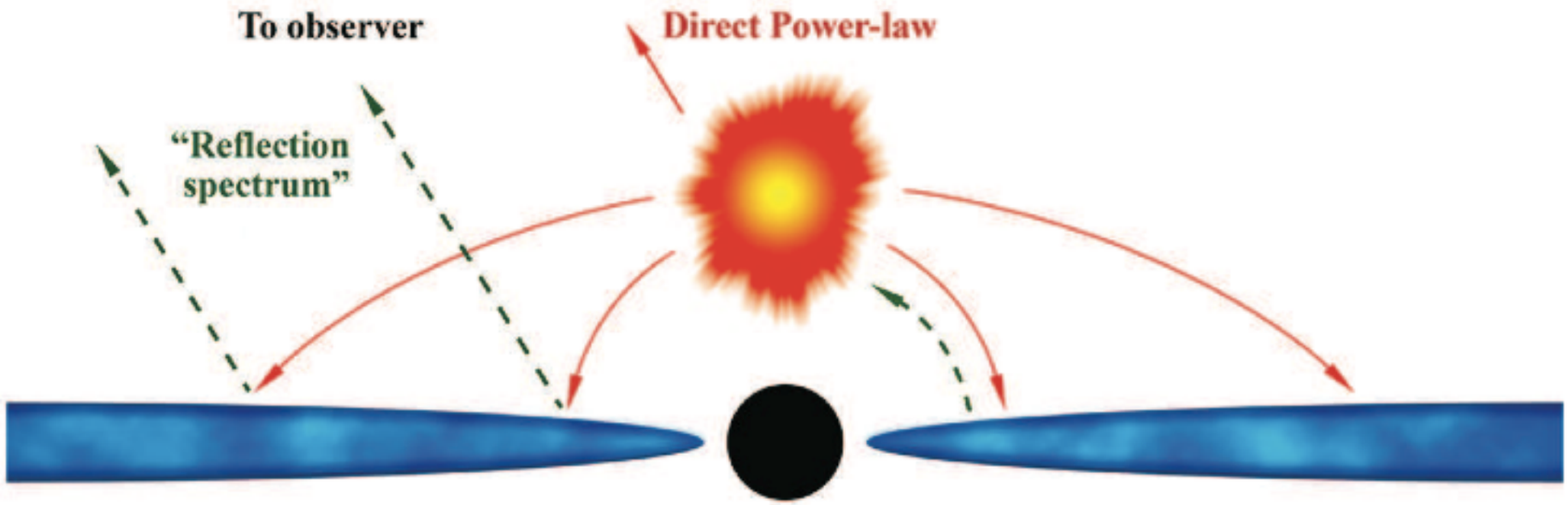
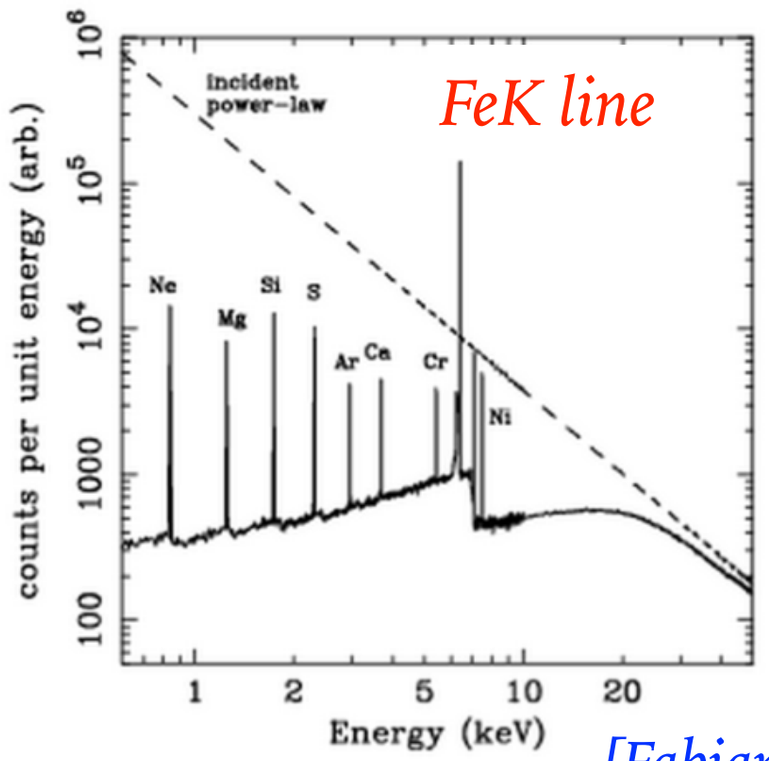
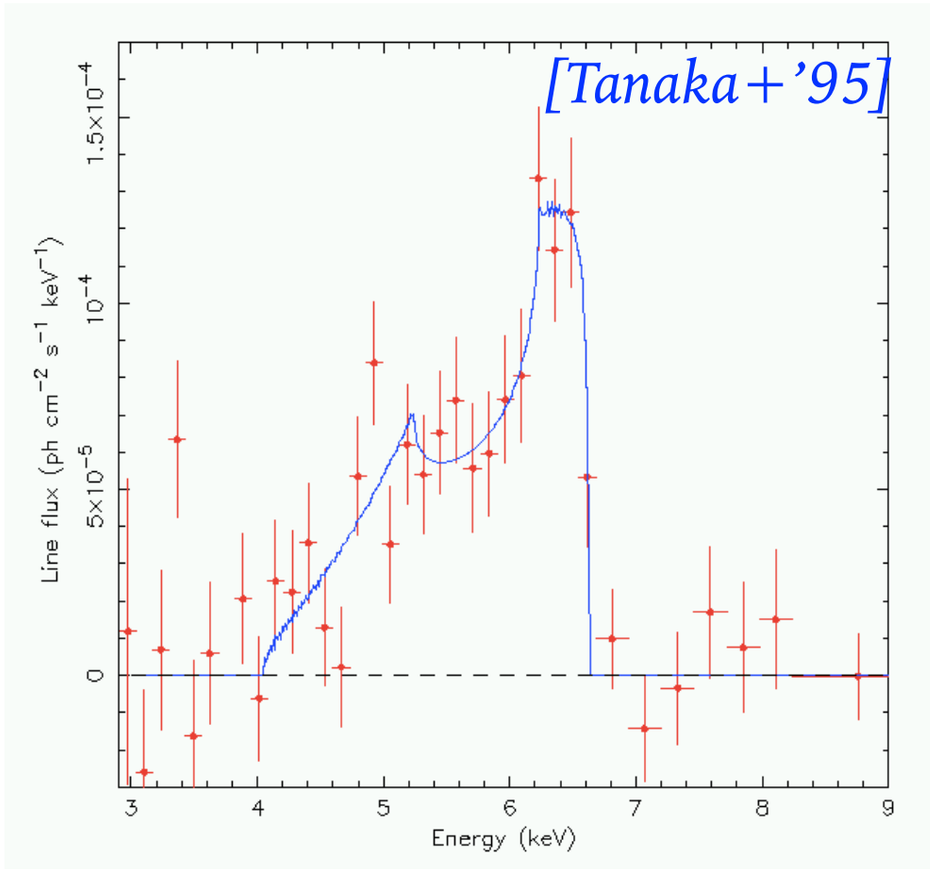



*FeK line*

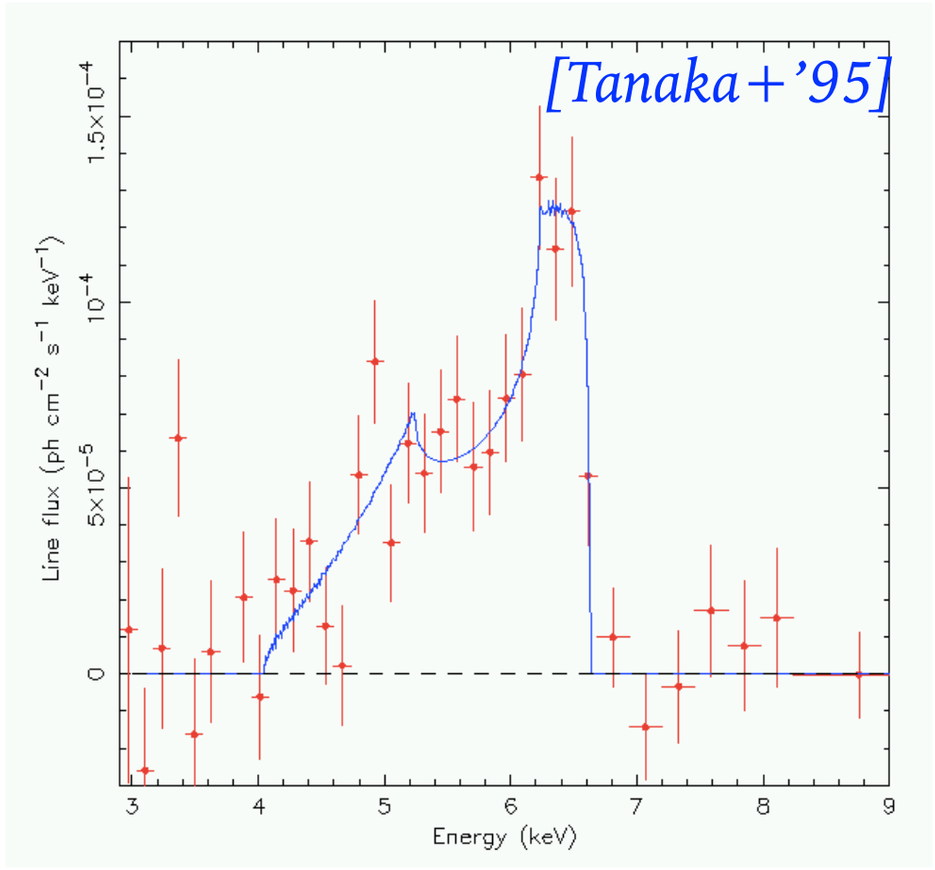
*[Fabian+'00]*

*Relativity (r<10 rg)*



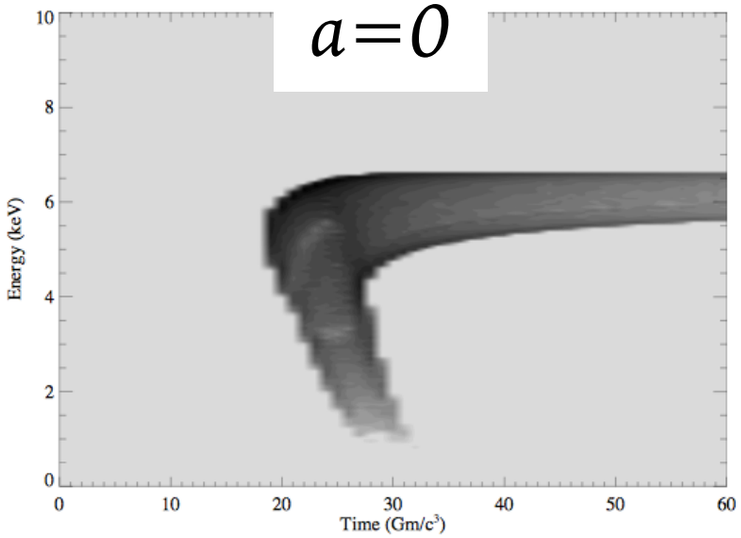
# *X-ray reverberation in AGN accretion disc:*

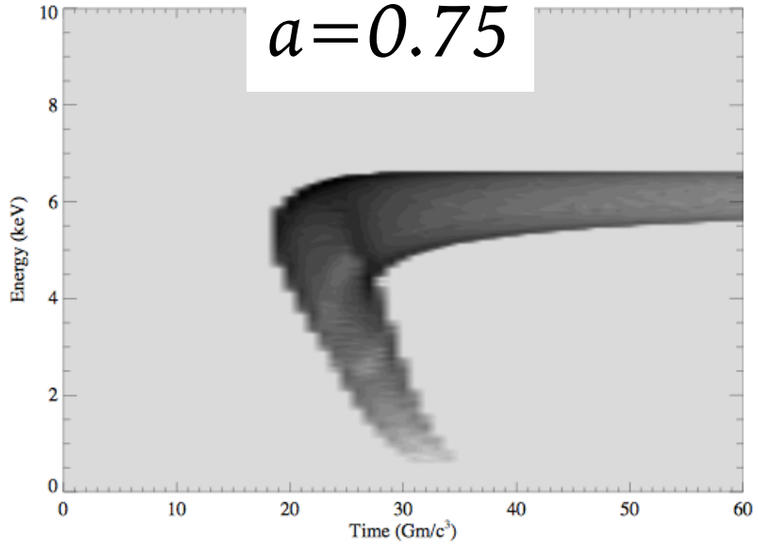
## ** Fe K line*

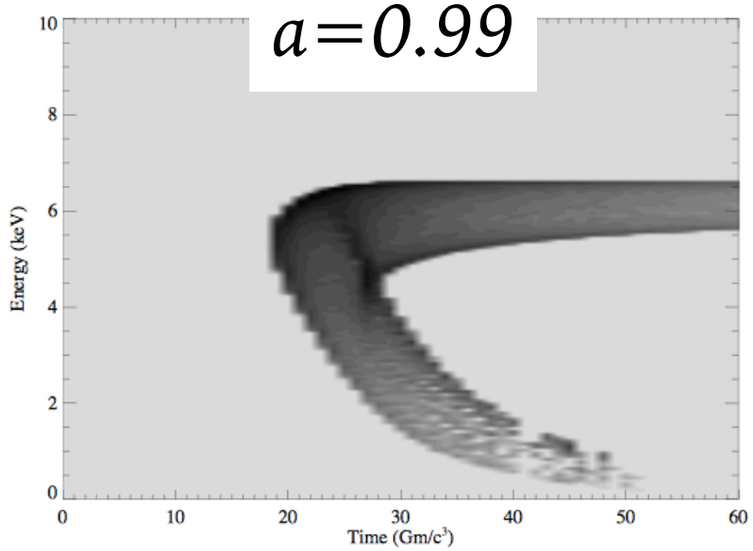


# *FeK line reverberation: predictions*

*Fabian+'89; Stella '90; Matt & Perola '92; Campana & Stella '93*




*[Reynolds+'99, Young & Reynolds '00]*

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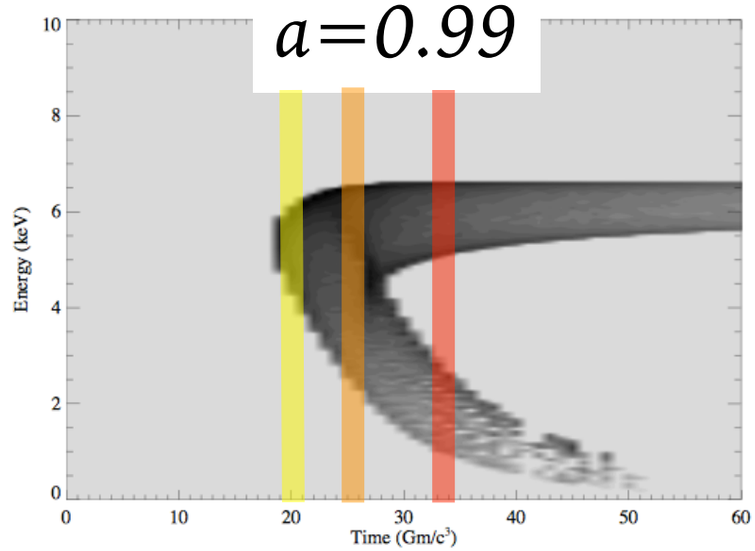


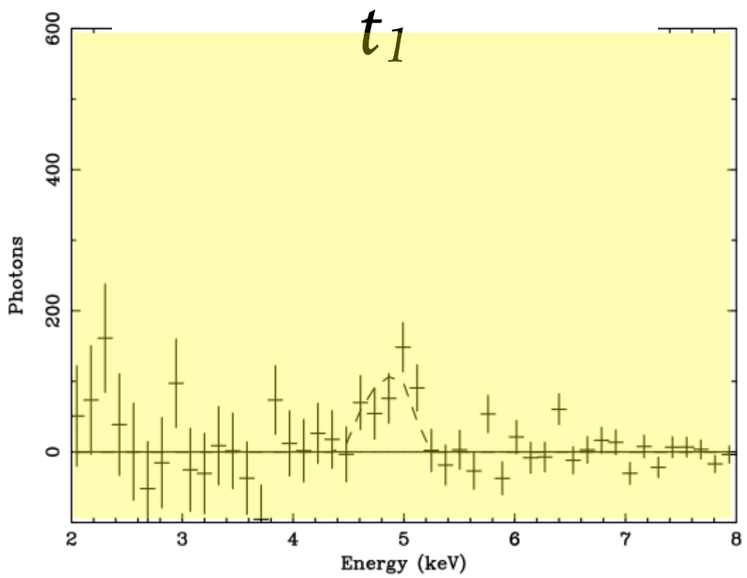


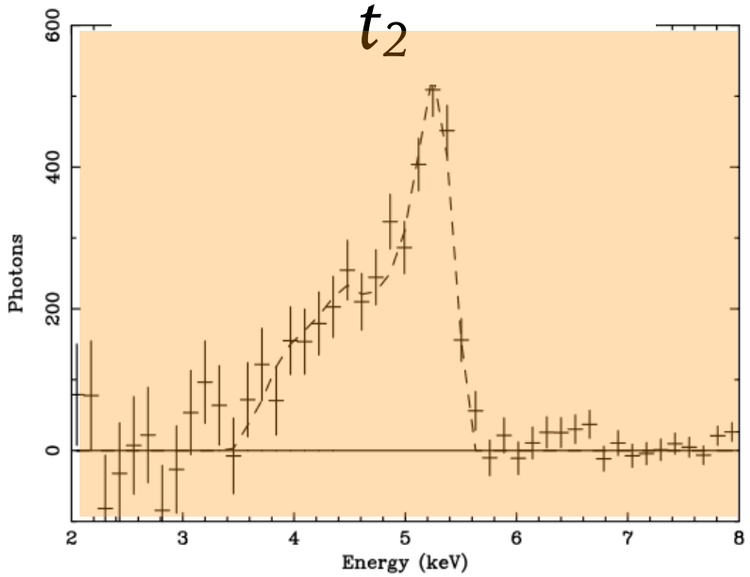


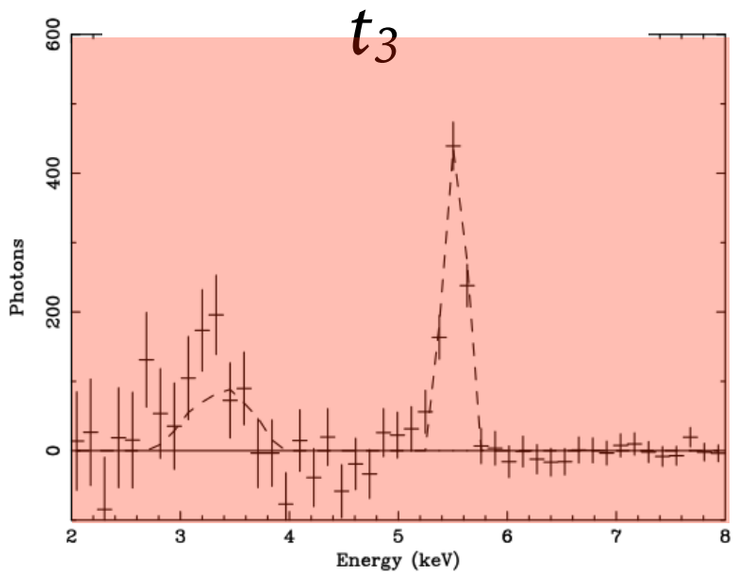


*[Reynolds+'99, Young & Reynolds '00]*

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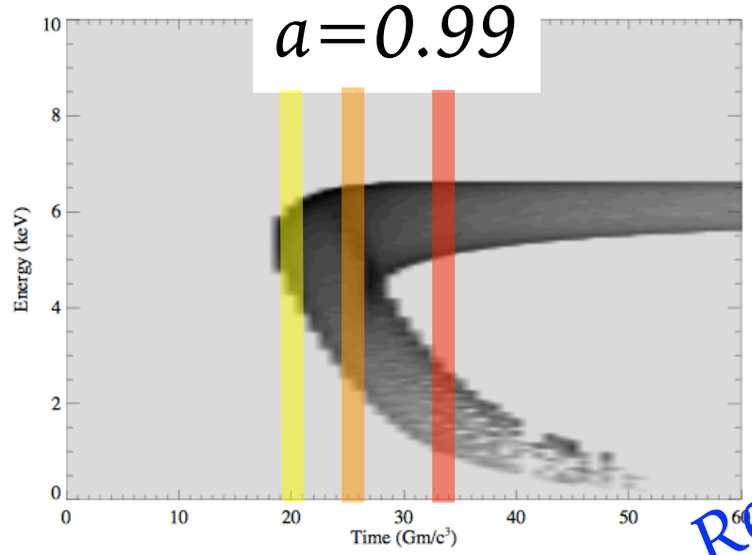
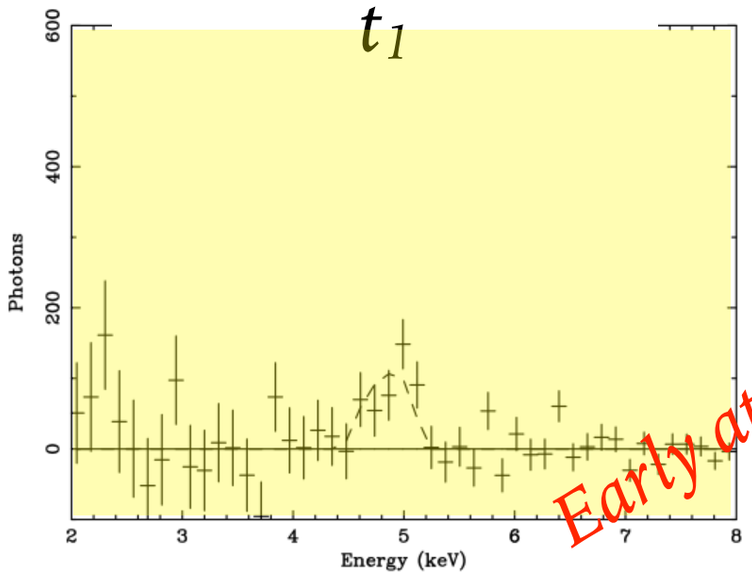
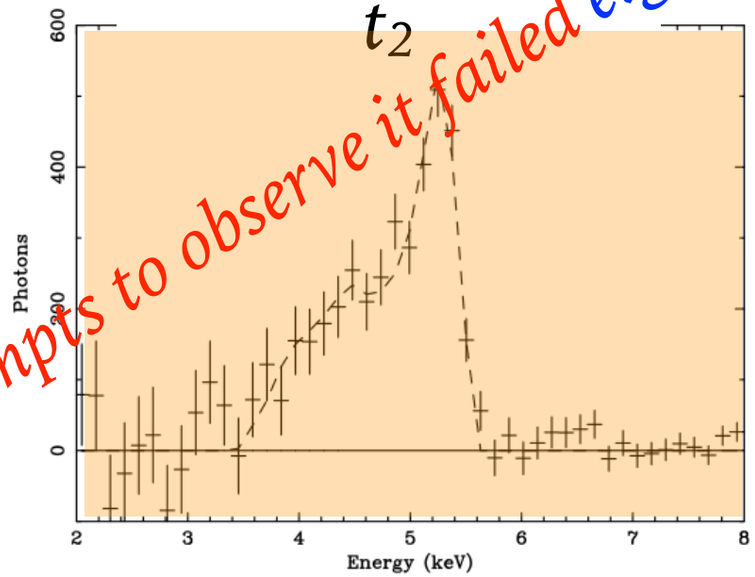
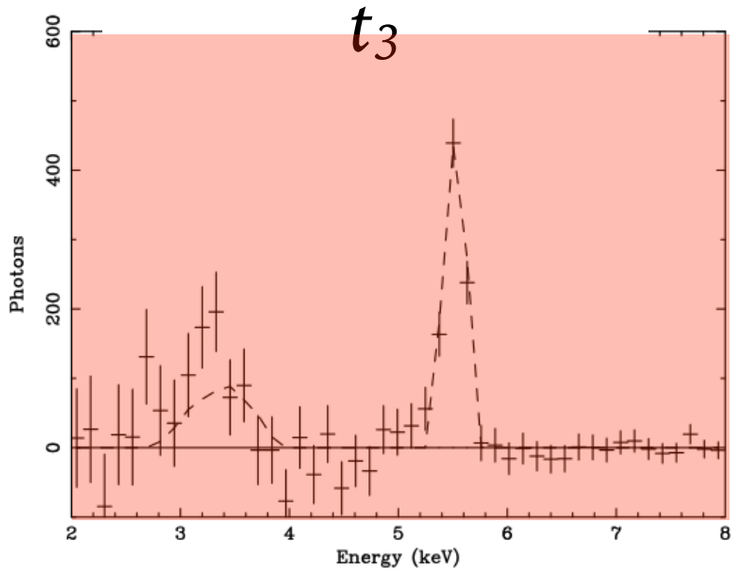


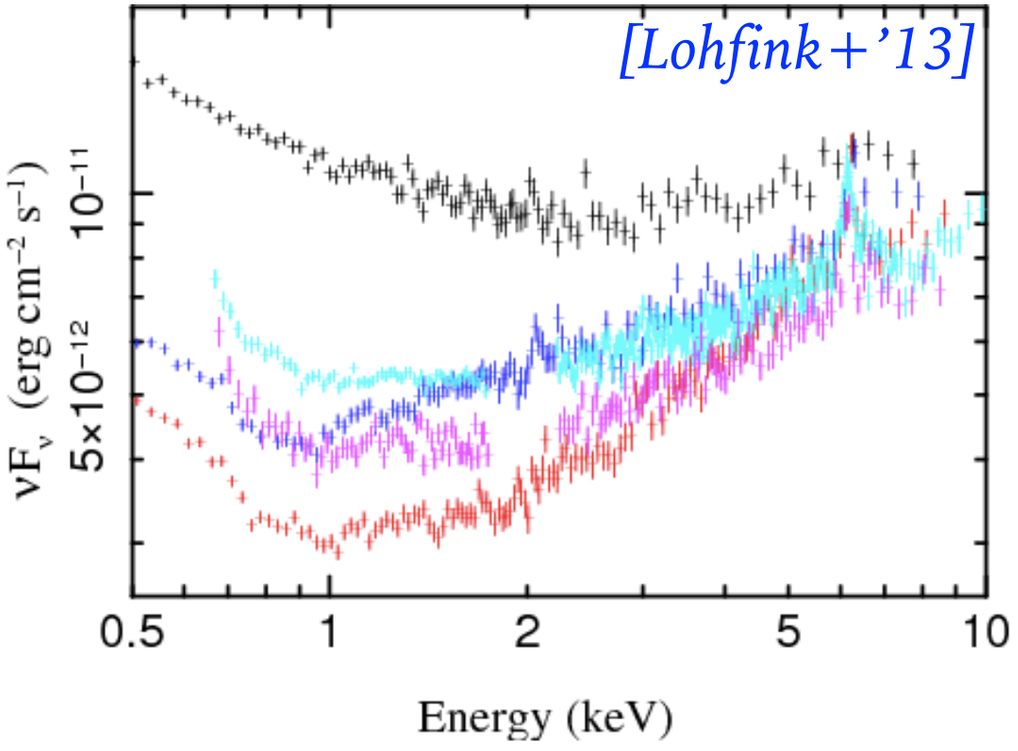

*Early attempts to observe it failed e.g. Reynolds+'00*

*[Reynolds+'99, Young & Reynolds '00]*

# *X-ray reverberation in AGN accretion disc:*

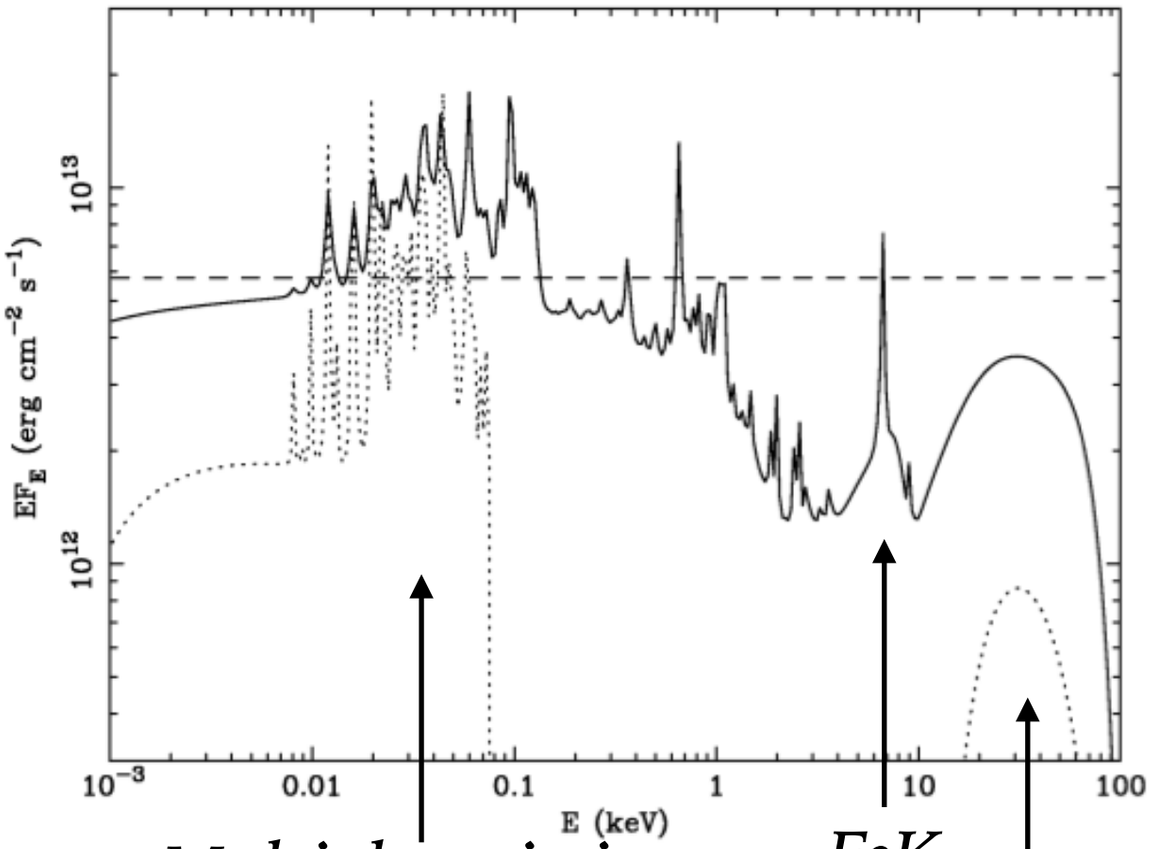
## * *Soft X-ray excess*

$E < 1\ keV$



# *Other reflection features*

*[Ross & Fabian '05]*

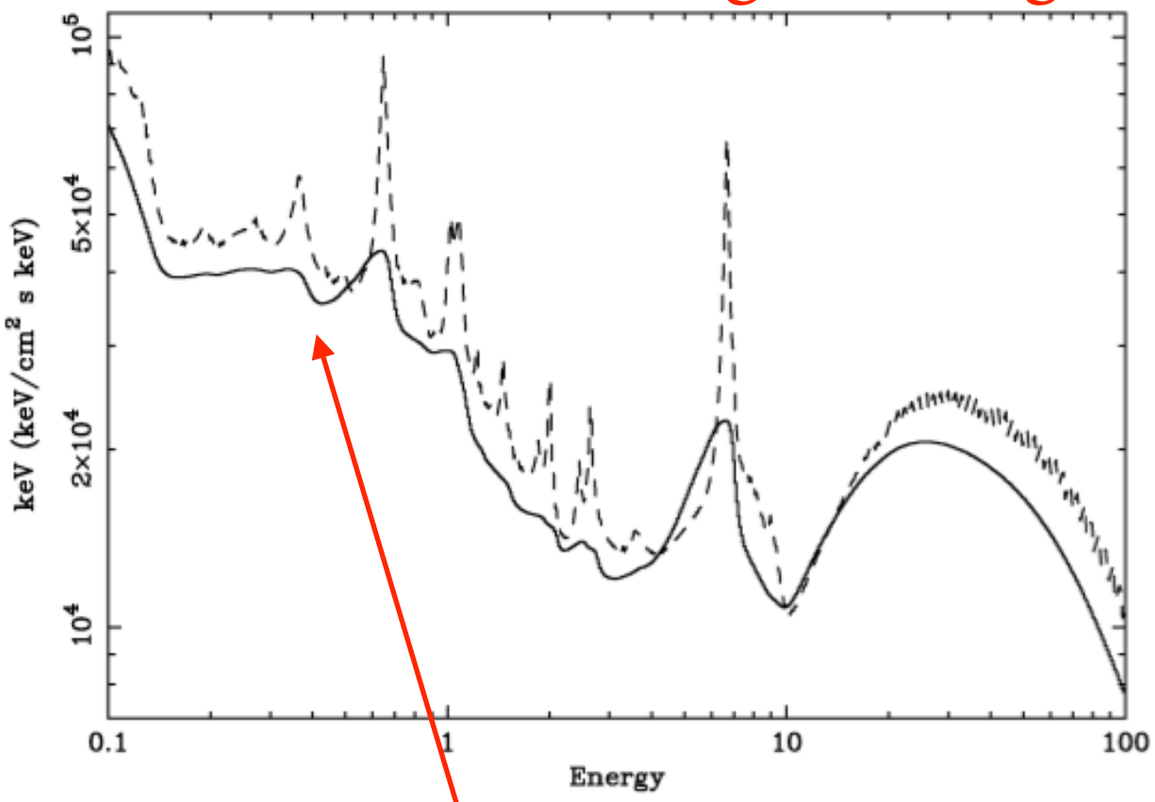



*Multiple emission lines*

*FeK*

*Compton hump*

*Relativistic blurring (r<10 rg)*



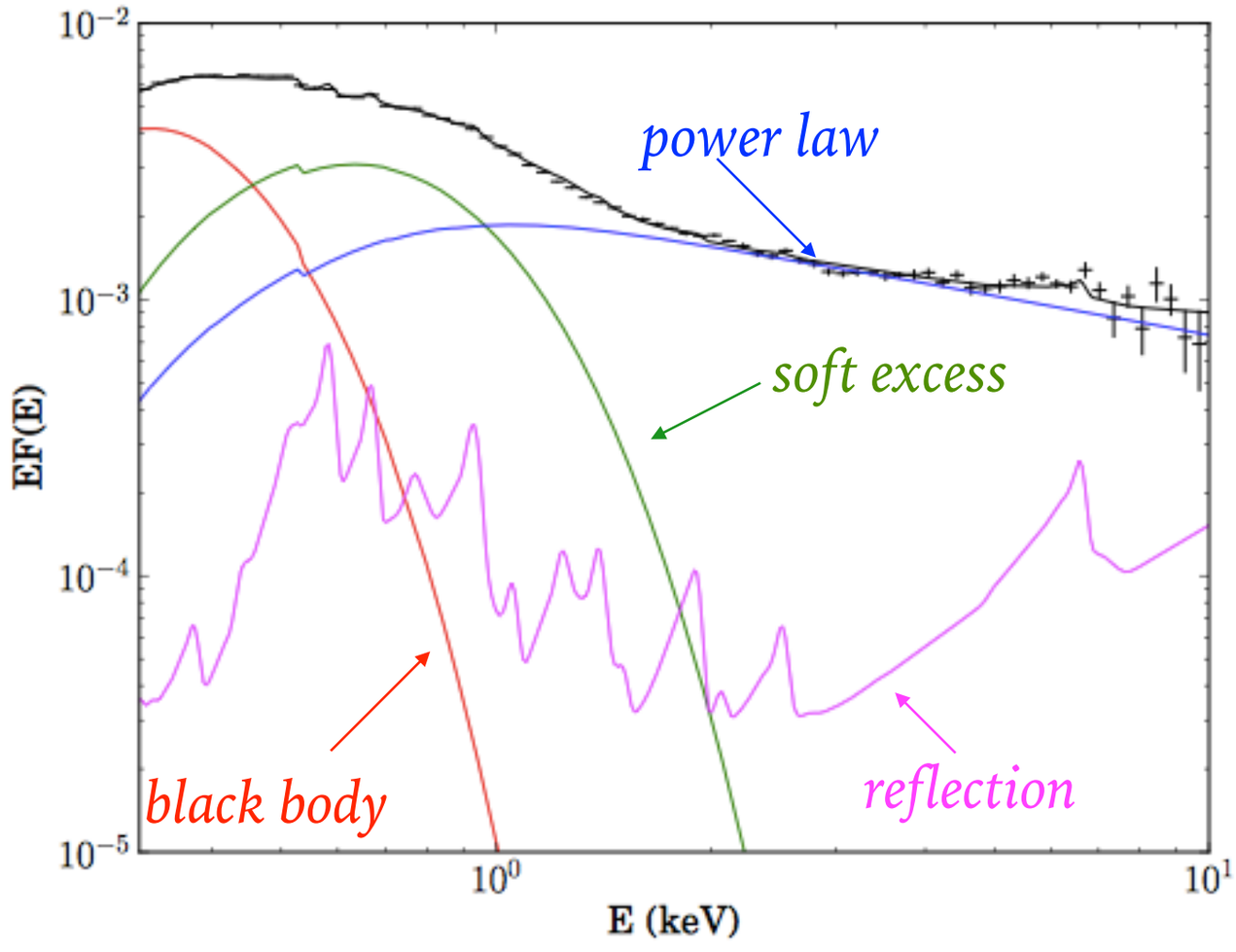

*One possible explanation for the soft excess*

*e.g. Crummy +'06*

# *Pros and Cons*

***Fe K :*** *"clean" region of the spectrum but low statistics*

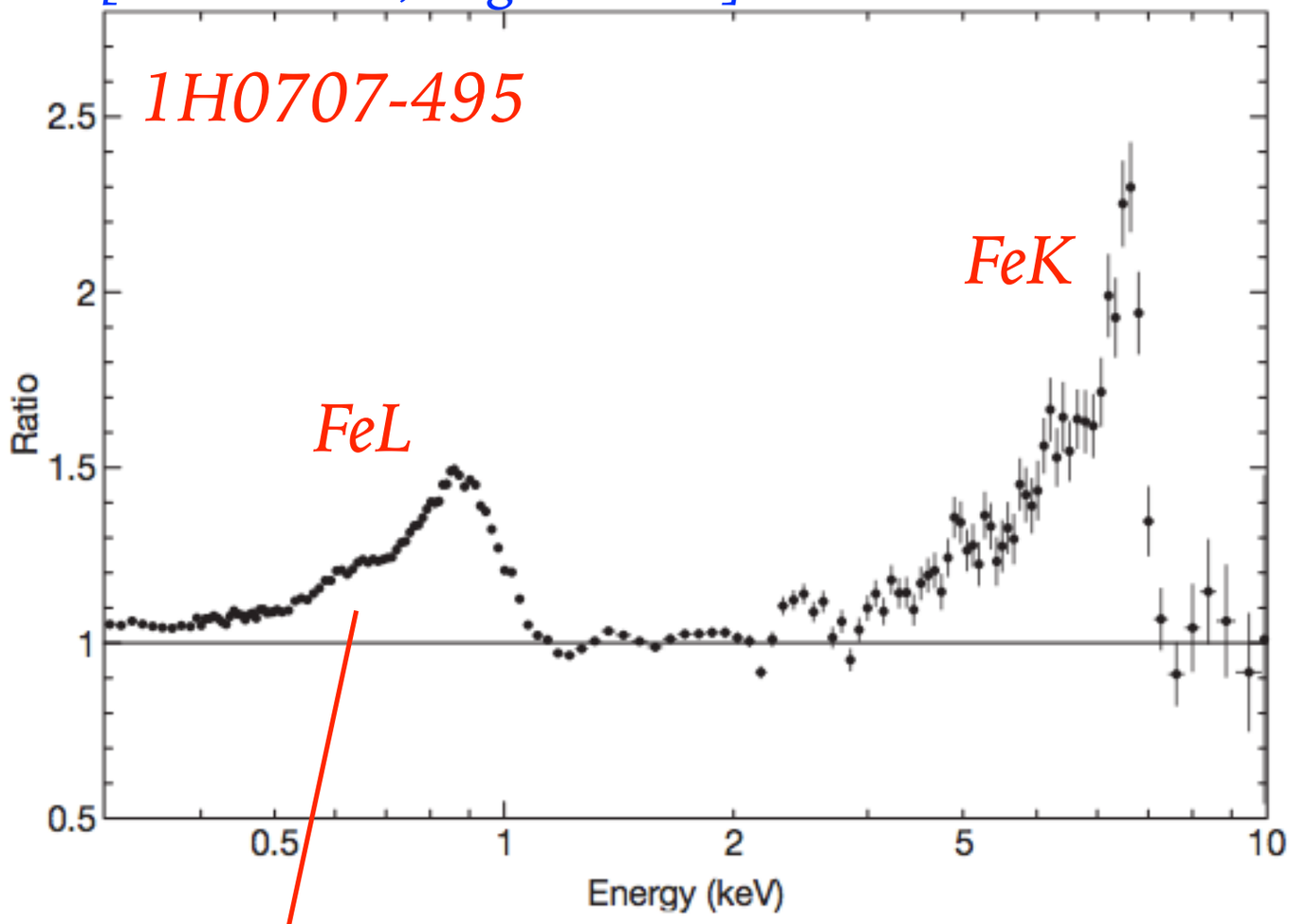
***Soft X-ray excess :*** *more statistics but "crowded" region of the spectrum and uncertain interpretation*



# *First detections of X-ray reverberation in AGN*

# *FeL and FeK*

*[Fabian+'09, Zoghbi +'10]*

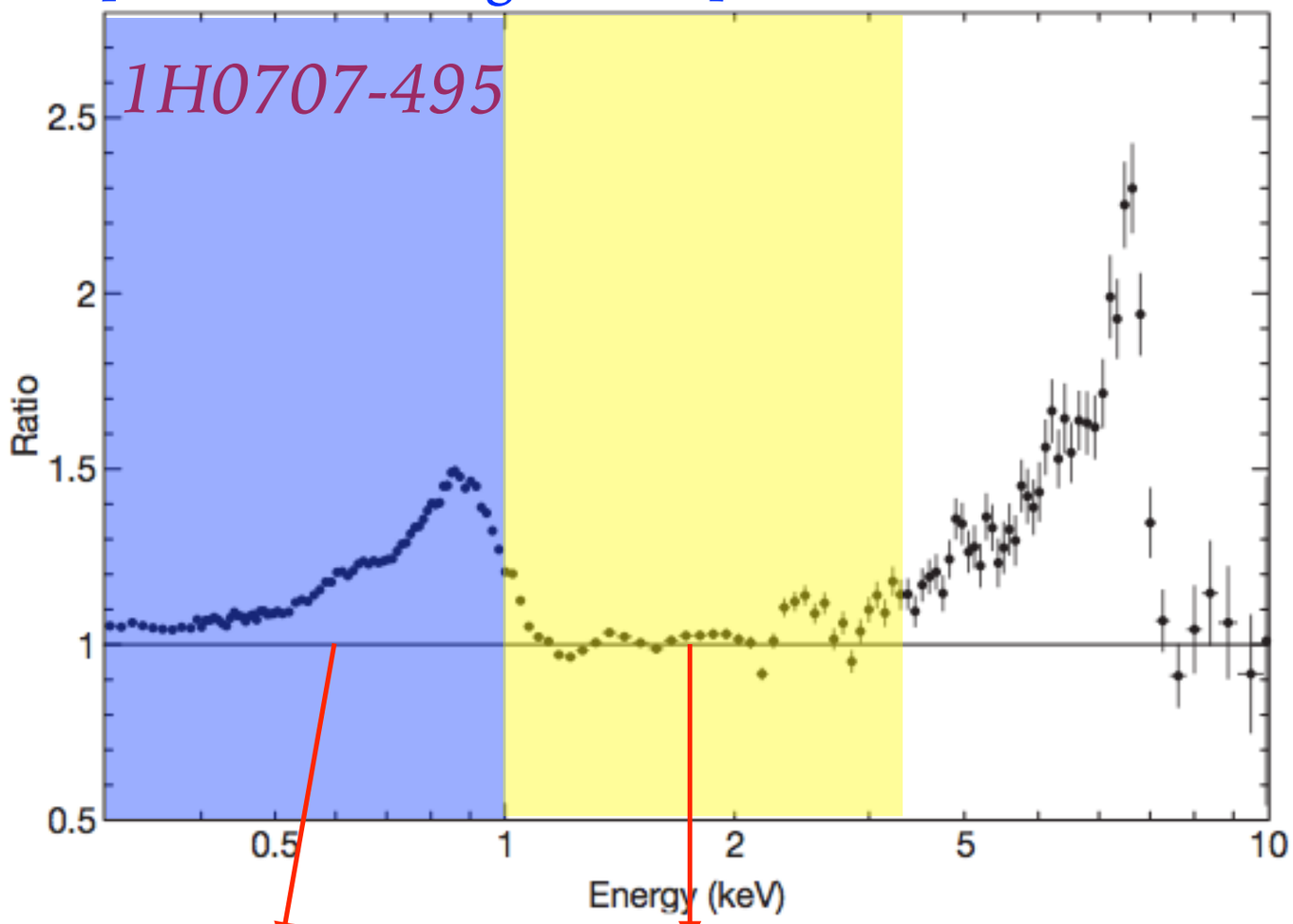



*Soft X-ray reflection feature*

*Detectable when Fe abundance is high*

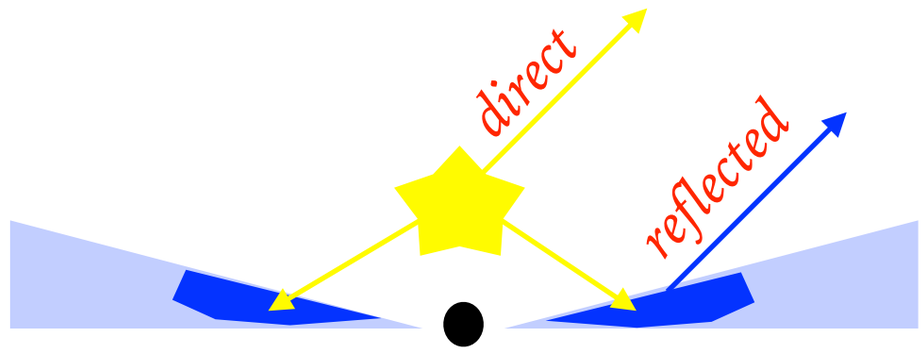
# *FeL and FeK*

*[Fabian+'09, Zoghbi+'10]*



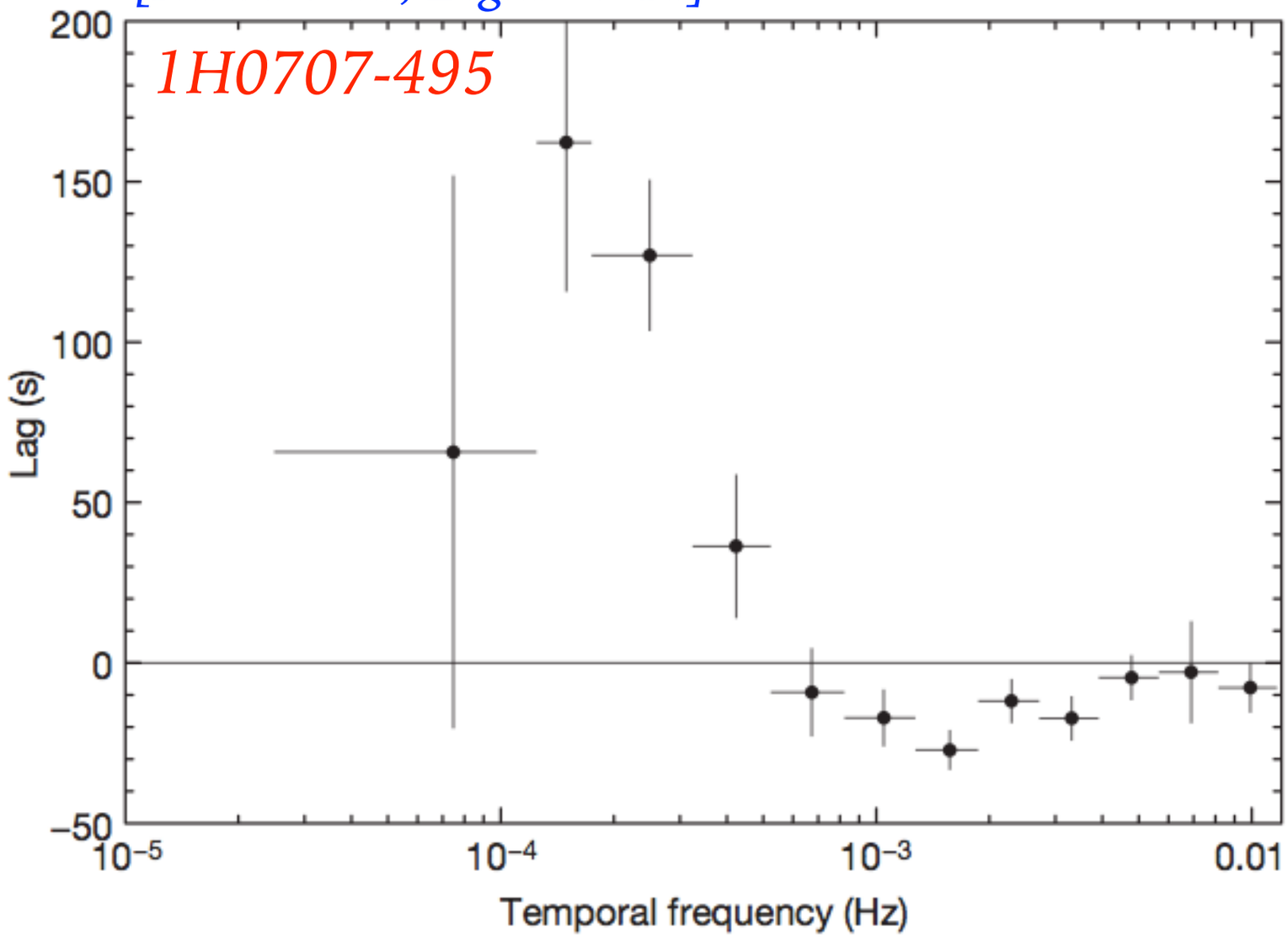

*Soft excess (FeL) dominated*

*Power law dominated*



# *Time lags in 1H0707-495*

*[Fabian+'09, Zoghbi +'10]*



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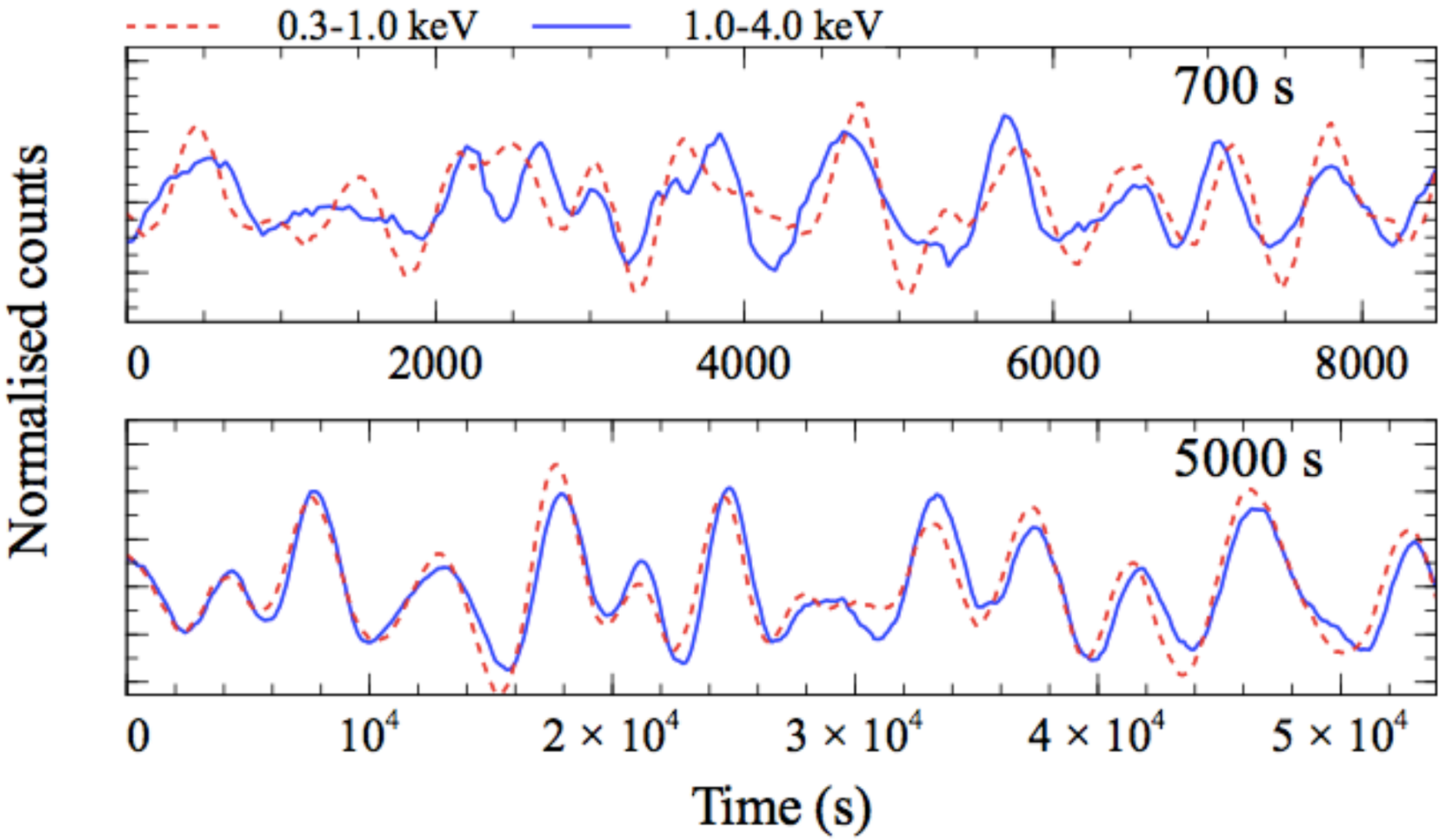

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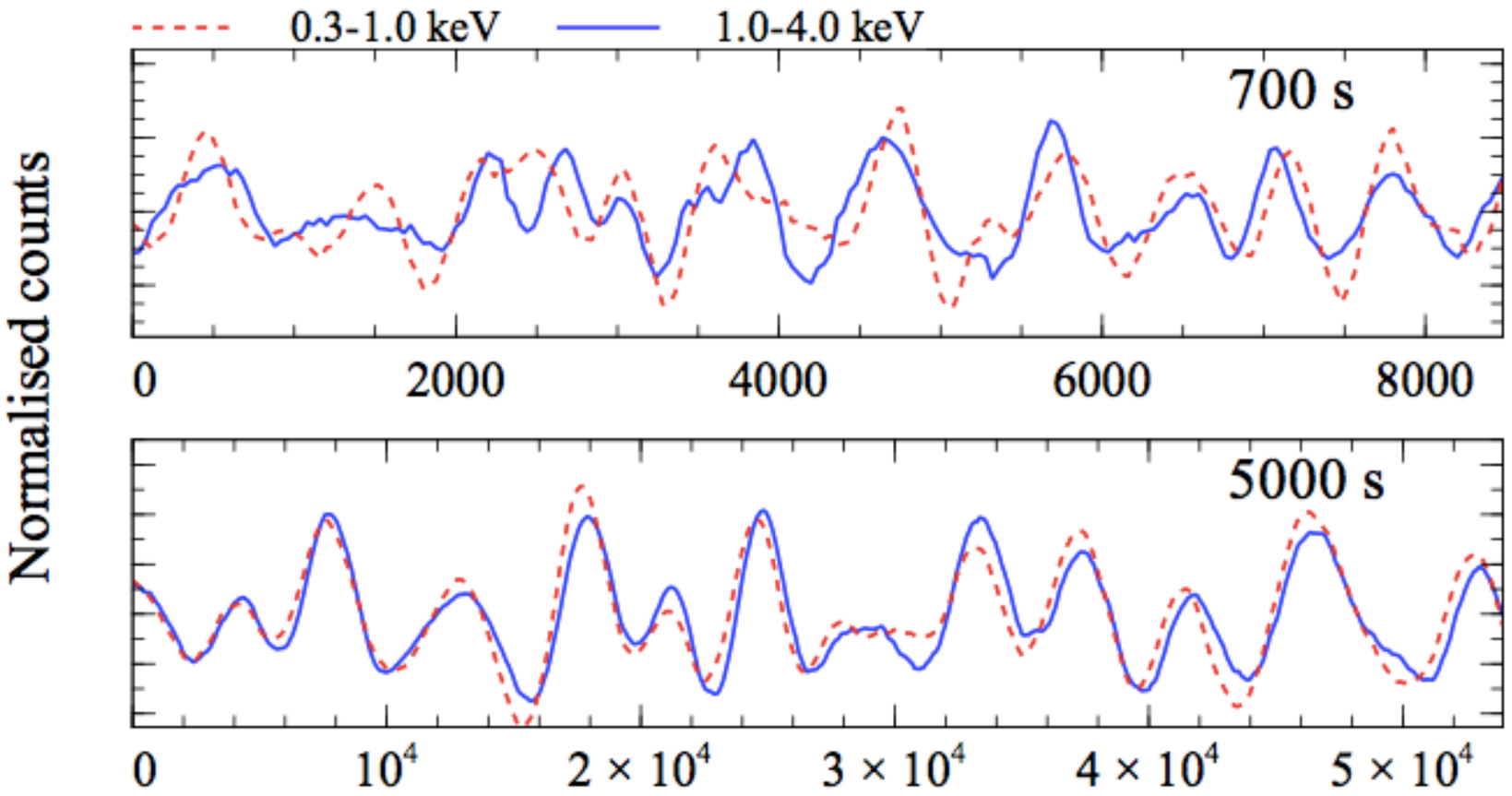
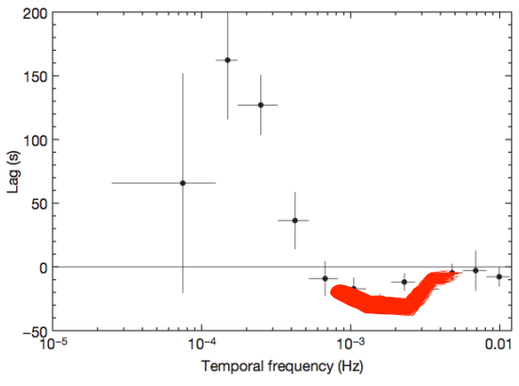
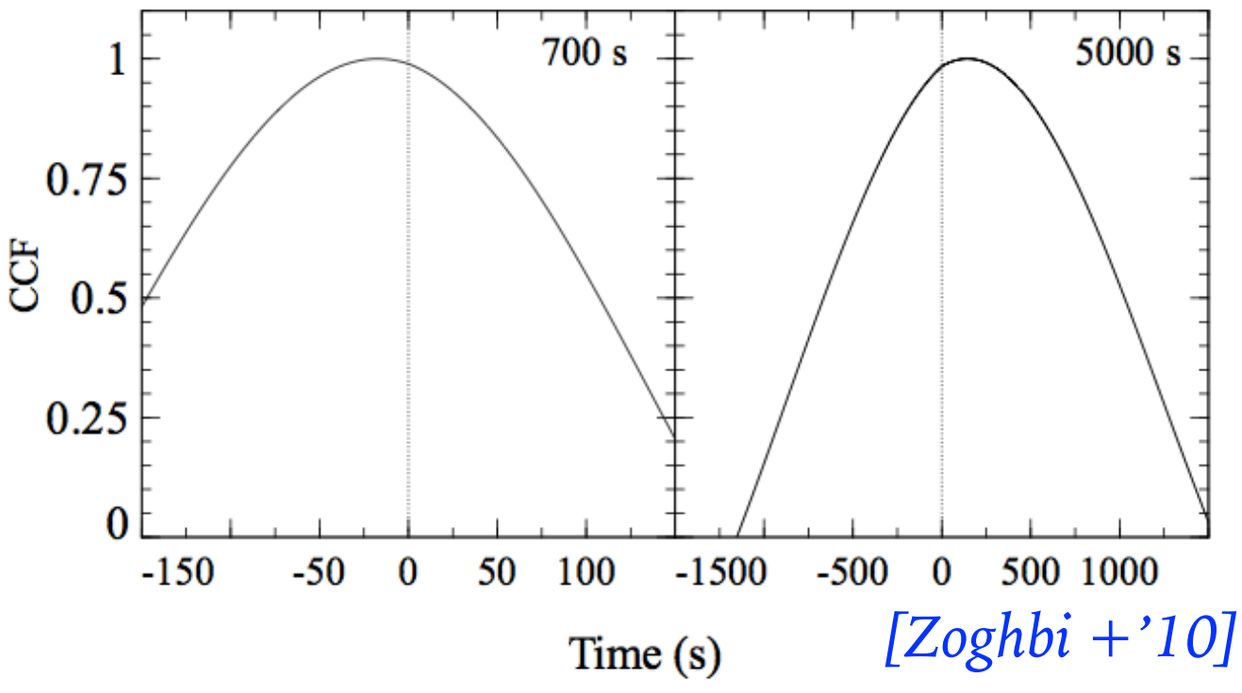
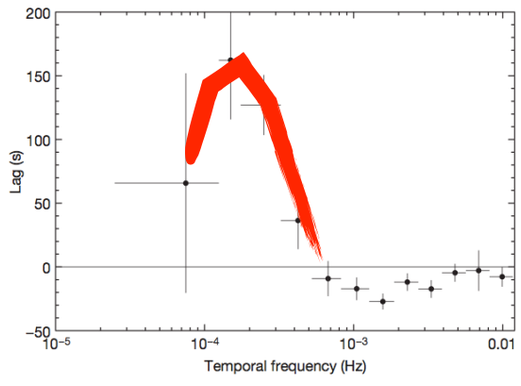



*Hard X-ray leading short time scales variations*




*[Zoghbi +'10]*

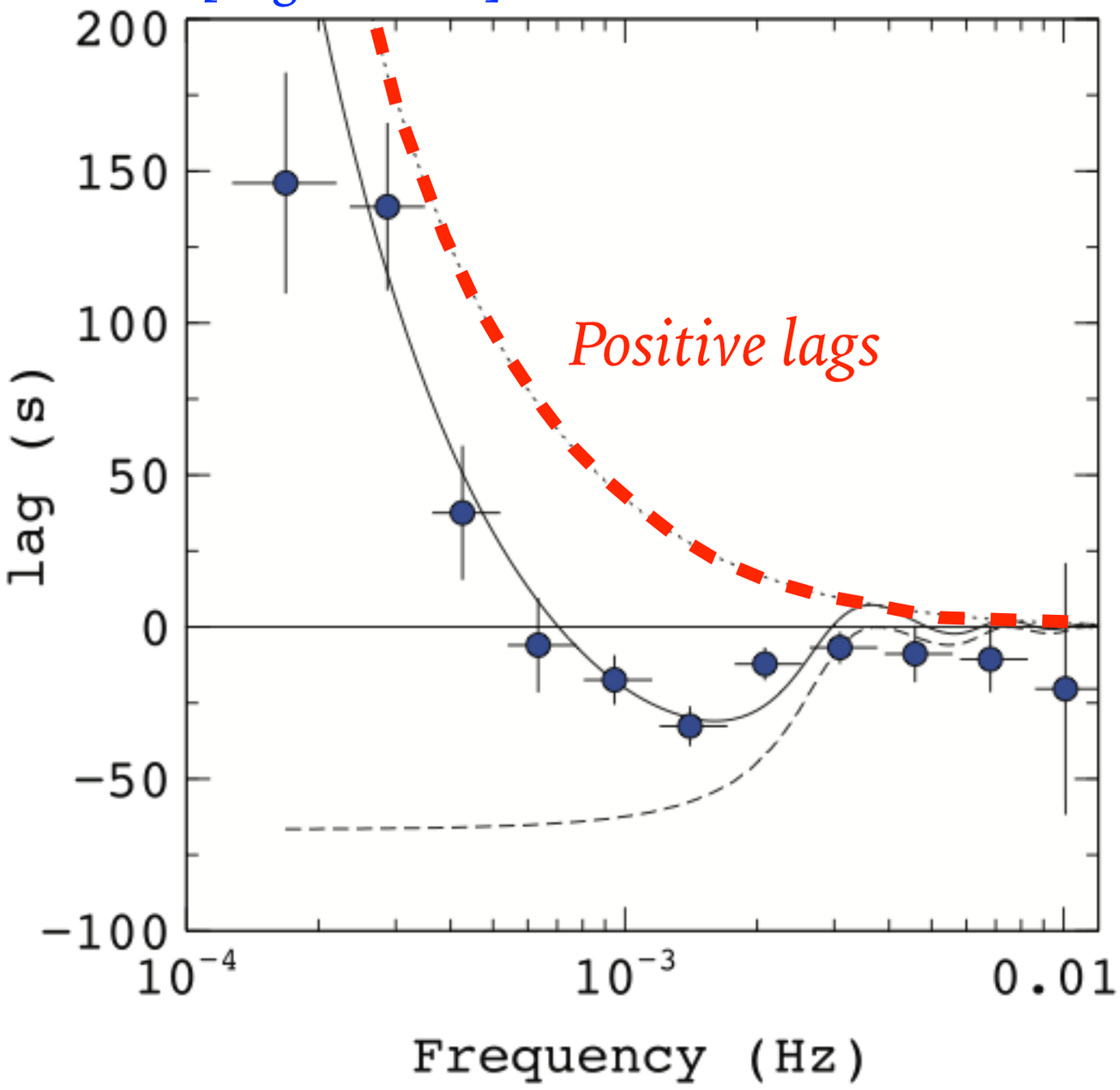



*Soft X-ray leading short time scales variations*

# *Interpretations*

# *1H0707-495: positive lags-component*

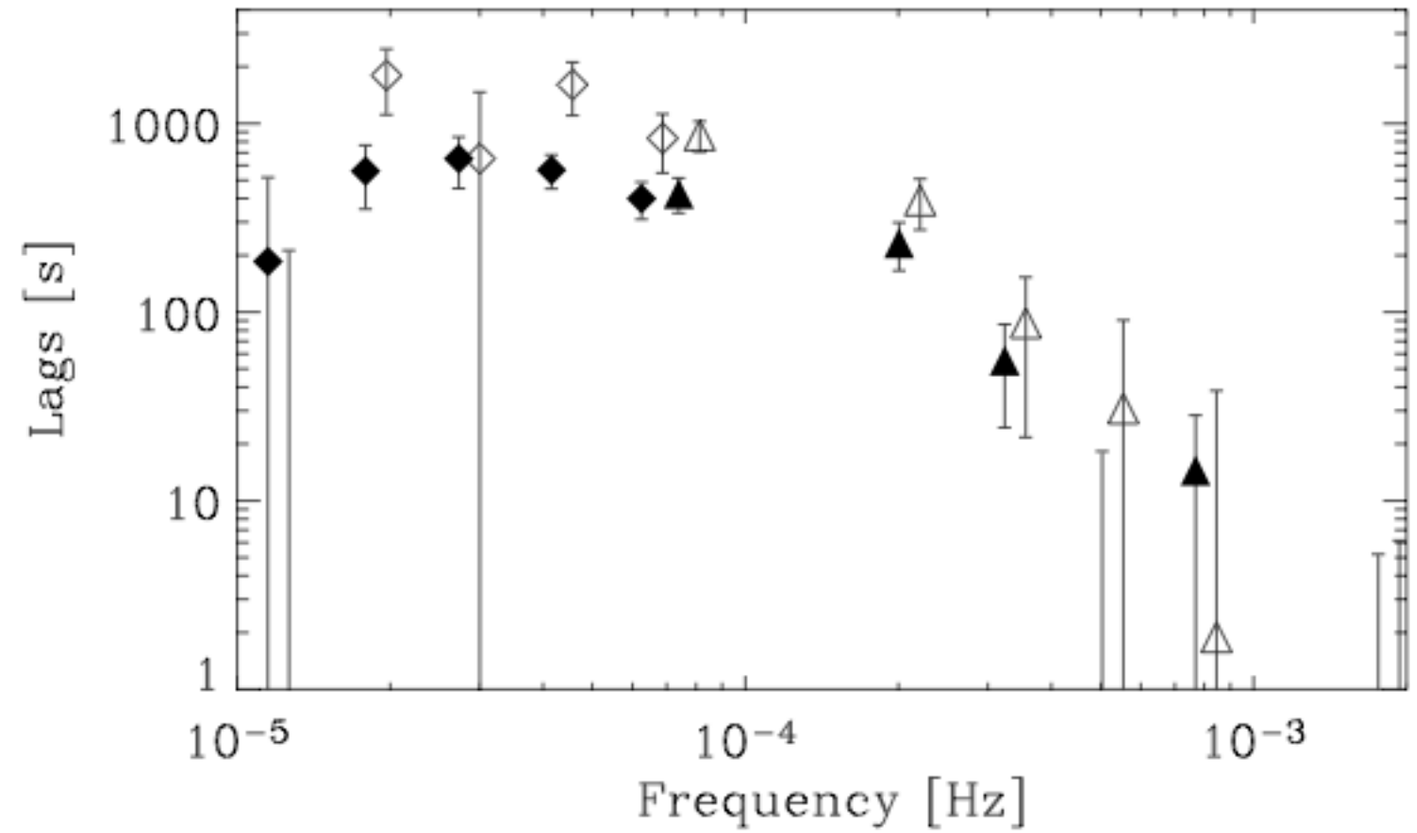
*[Zoghbi +'11]*




*Hard lag-component:*
*soft excess variations*
*lead*
*power law variations*
*by hundreds of seconds*

# *Hard X-ray lags in AGN...*

*Ark 564* *[Arévalo +'06, McHardy+'07]*




*Well known to be present in many AGN:*

*NGC 7469 [Papadakis+'01]*

*MCG-6-30-15 [Vaughan+'03]*

*NGC 4051 [McHardy+'04]*

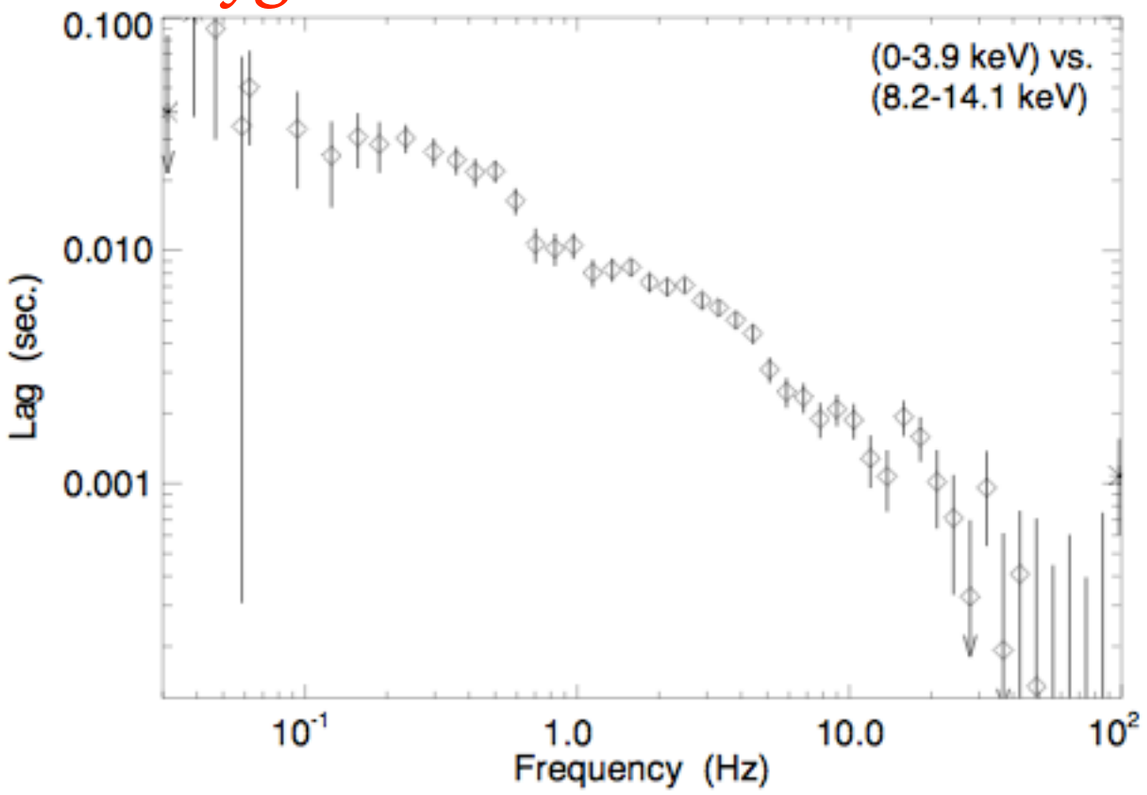
*NGC 3783 [Markowitz+'05]*

*Mrk766 [Markowitz+'07]*

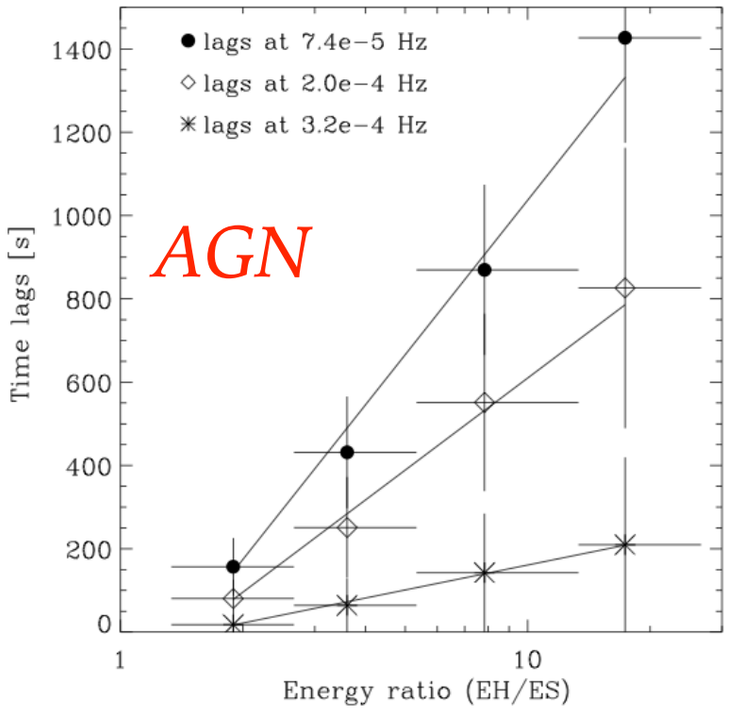
*Mrk 335 [Arévalo+'08]*

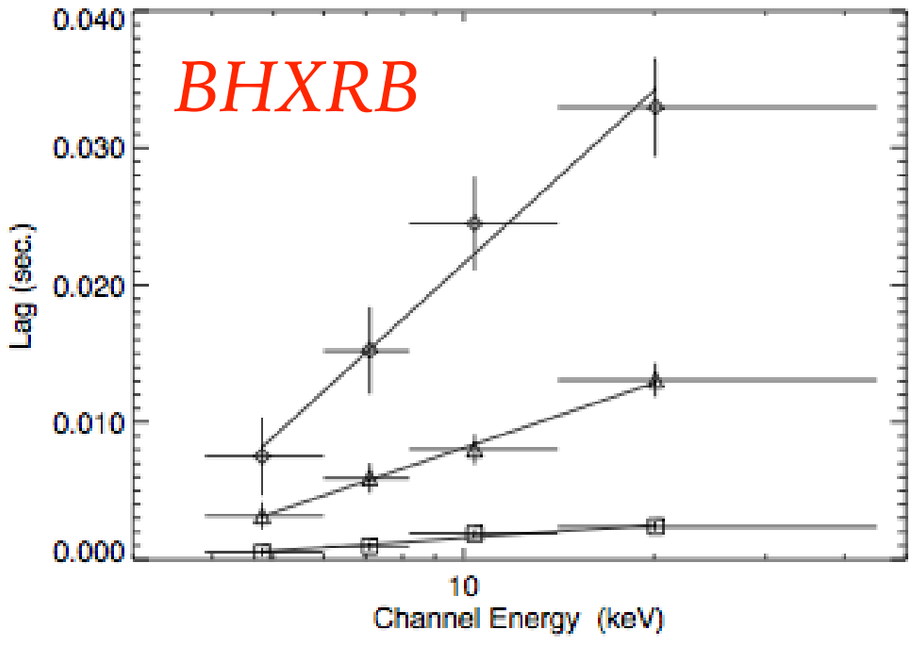
# ...and hard X-ray lags in BHXRBs

*Cyg X-1* *[Nowak+'99]*



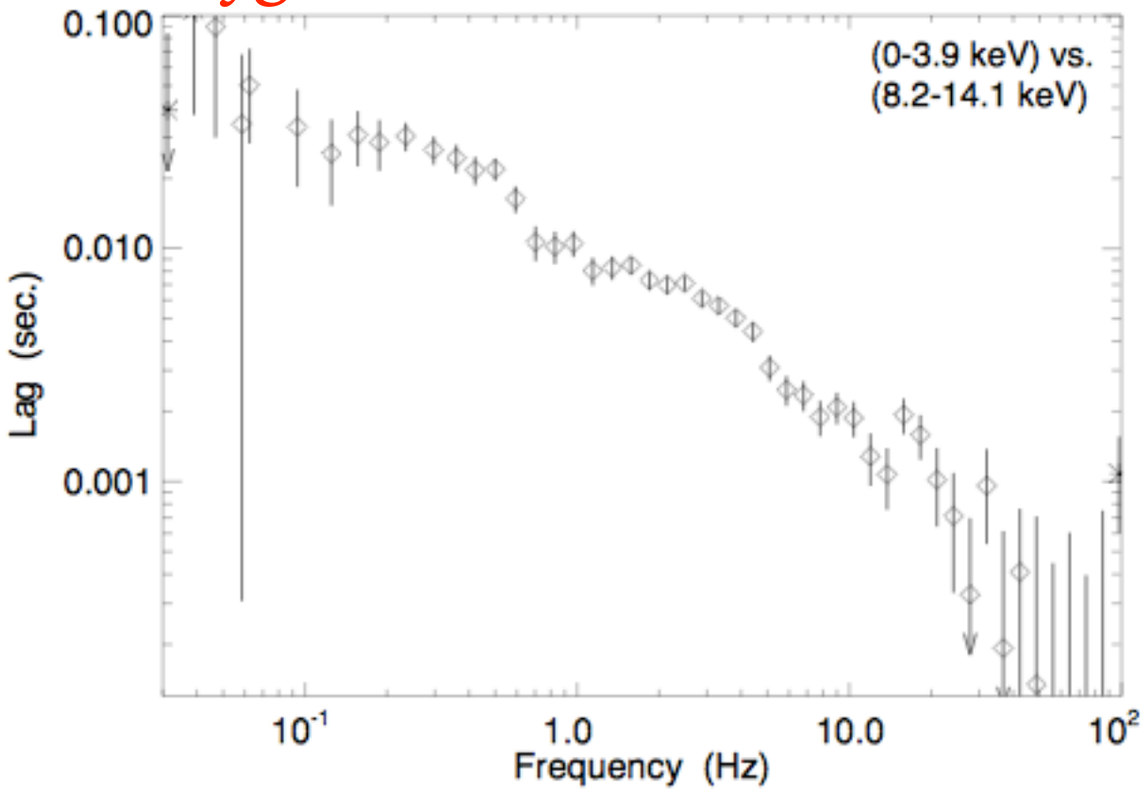

*Lag-Energy spectra*



# ...and hard X-ray lags in BHXRBs

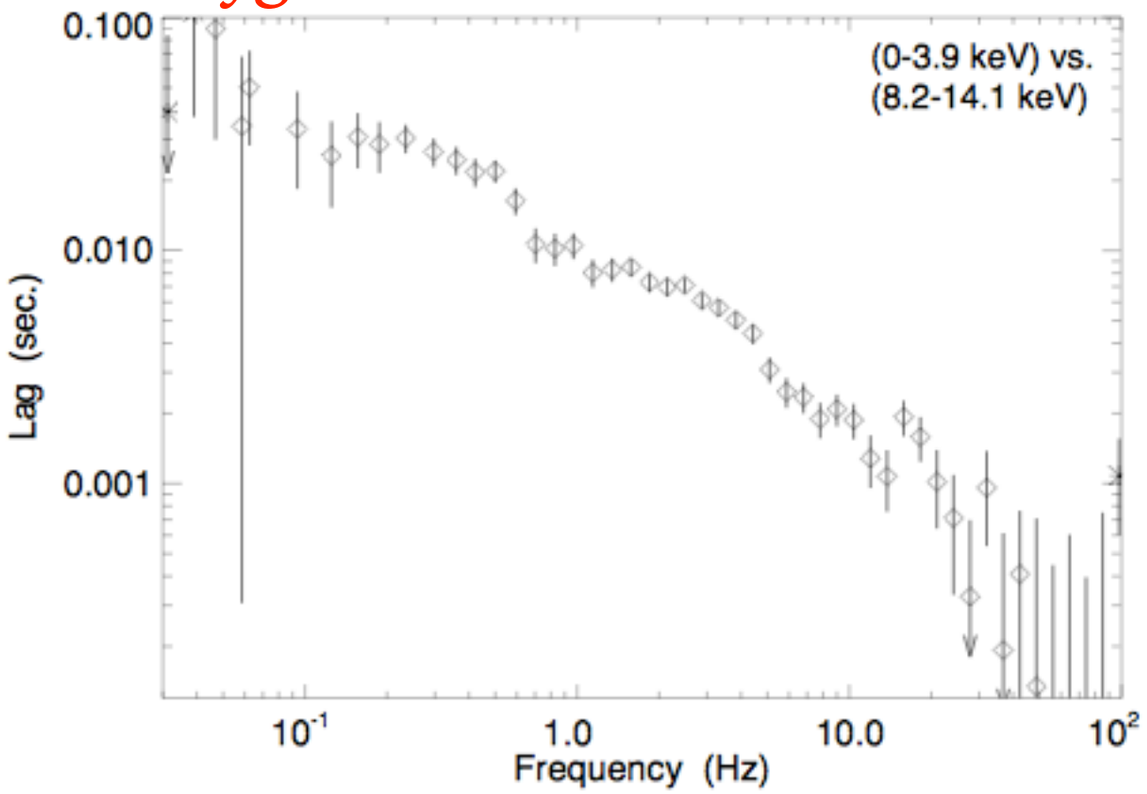
*Cyg X-1* *[Nowak+'99]*




*Striking similarity suggests common origin*

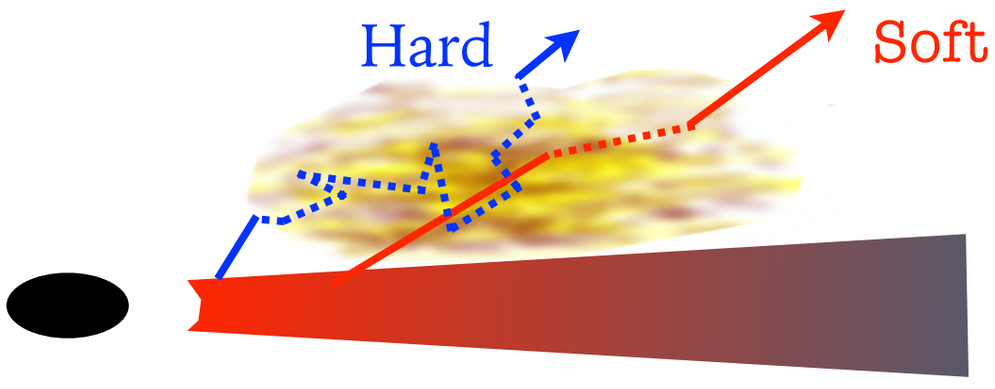
# ...and hard X-ray lags in BHXRBs

*Cyg X-1* *[Nowak+'99]*




*Striking similarity suggests common origin*

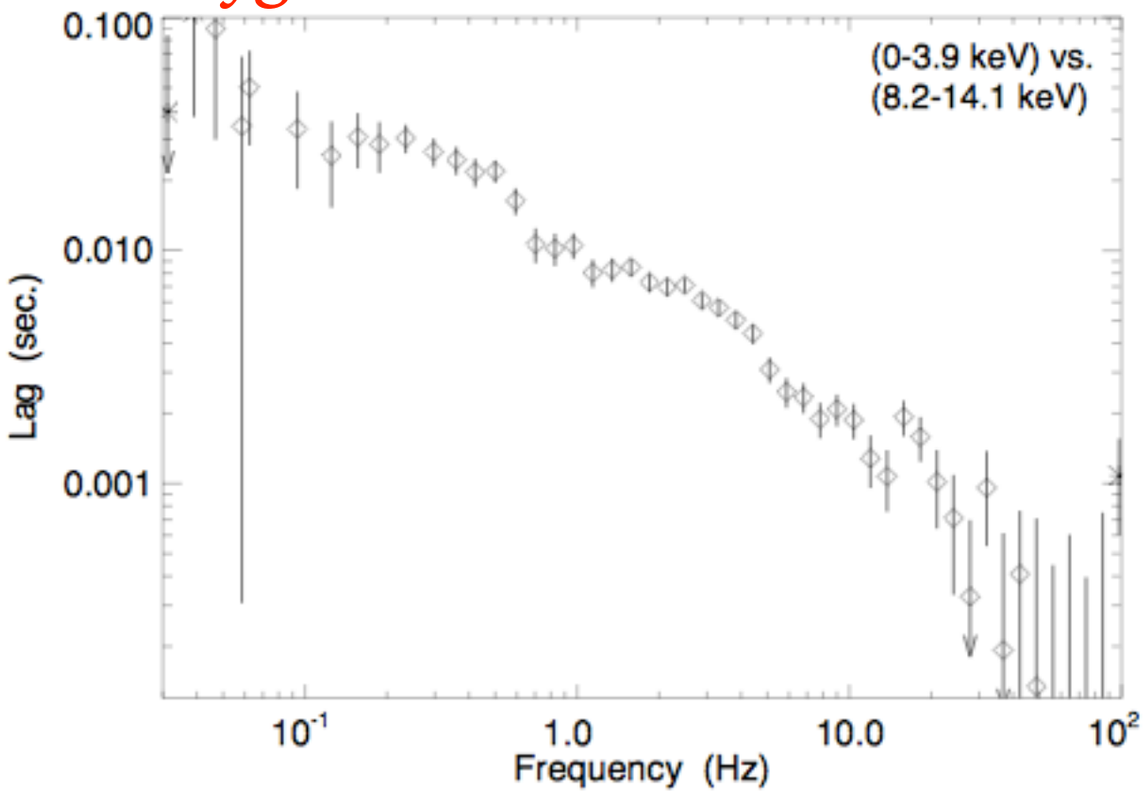
COMPTONIZATION:




*[Kazanas+'97; Nowak+'99]*

# ...and hard X-ray lags in BHXRBs

*Cyg X-1* *[Nowak+'99]*

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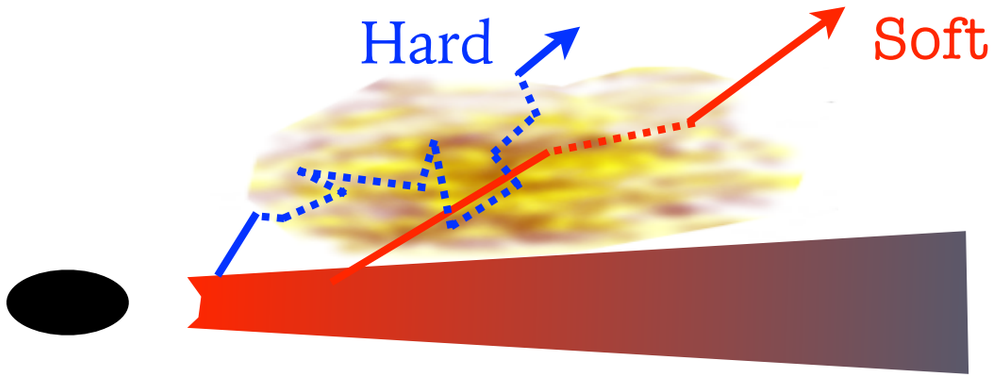
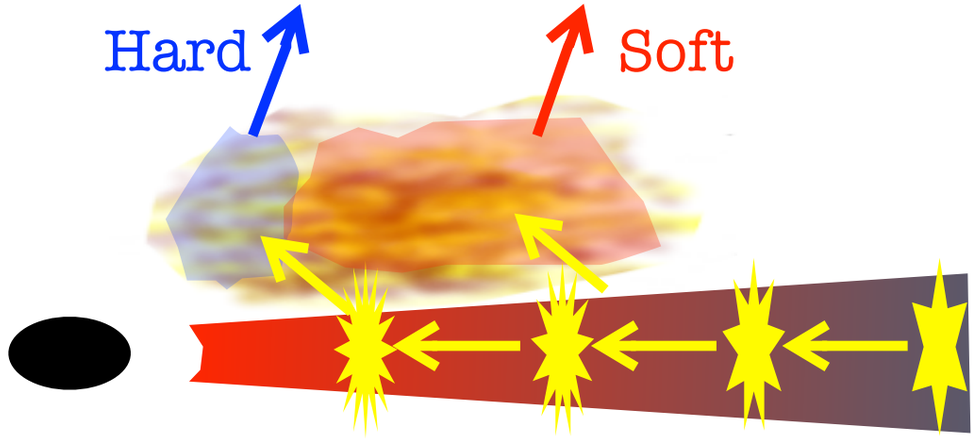



*[Kazanas+'97; Nowak+'99]*

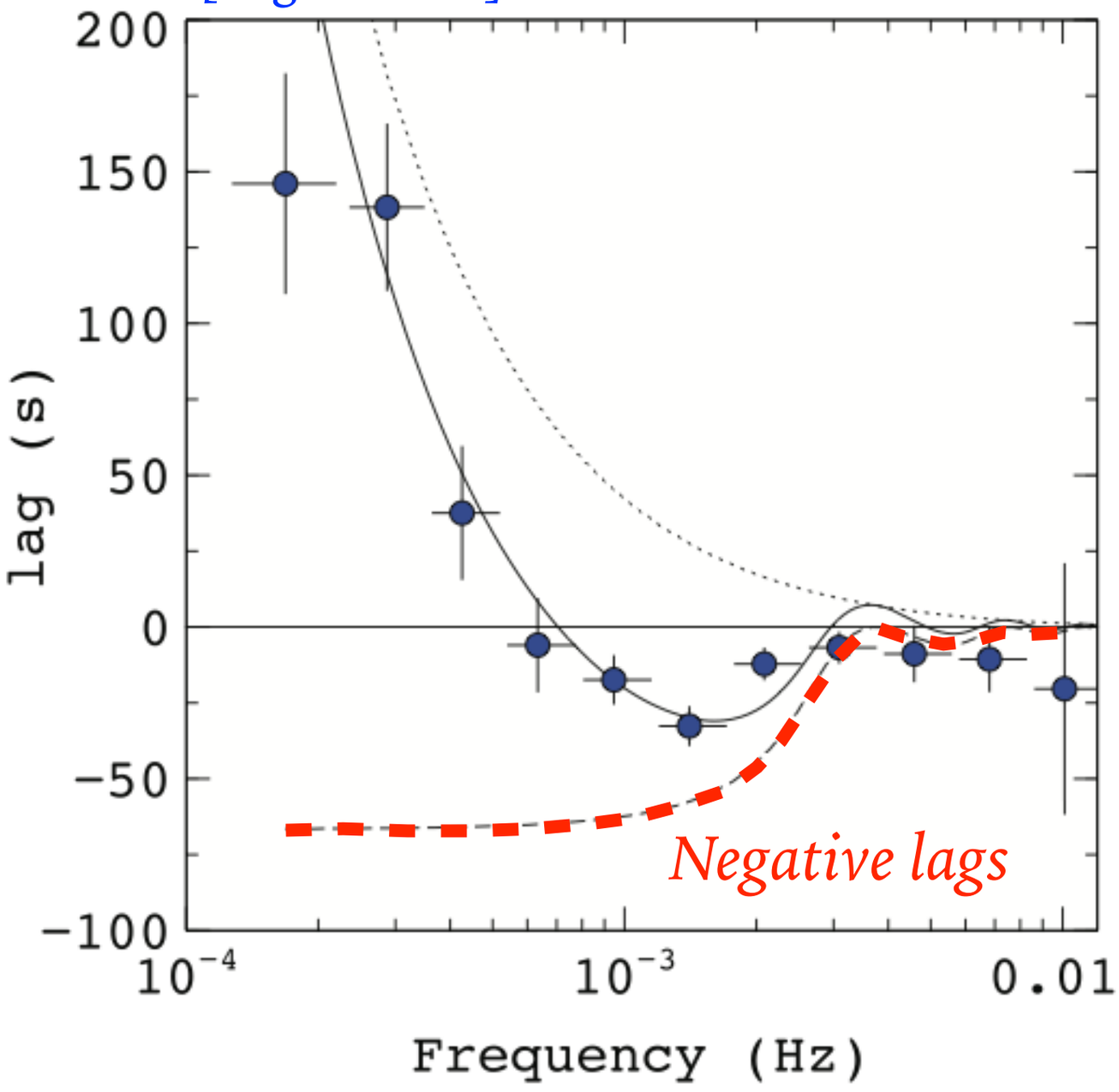
PROPAGATION OF $\dot{M}$ FLUCTUATIONS:




*[Lyubarskii '97; Kotov+'01; Arévalo & Uttley '06]*

# 1H0707-495: negative lags-component

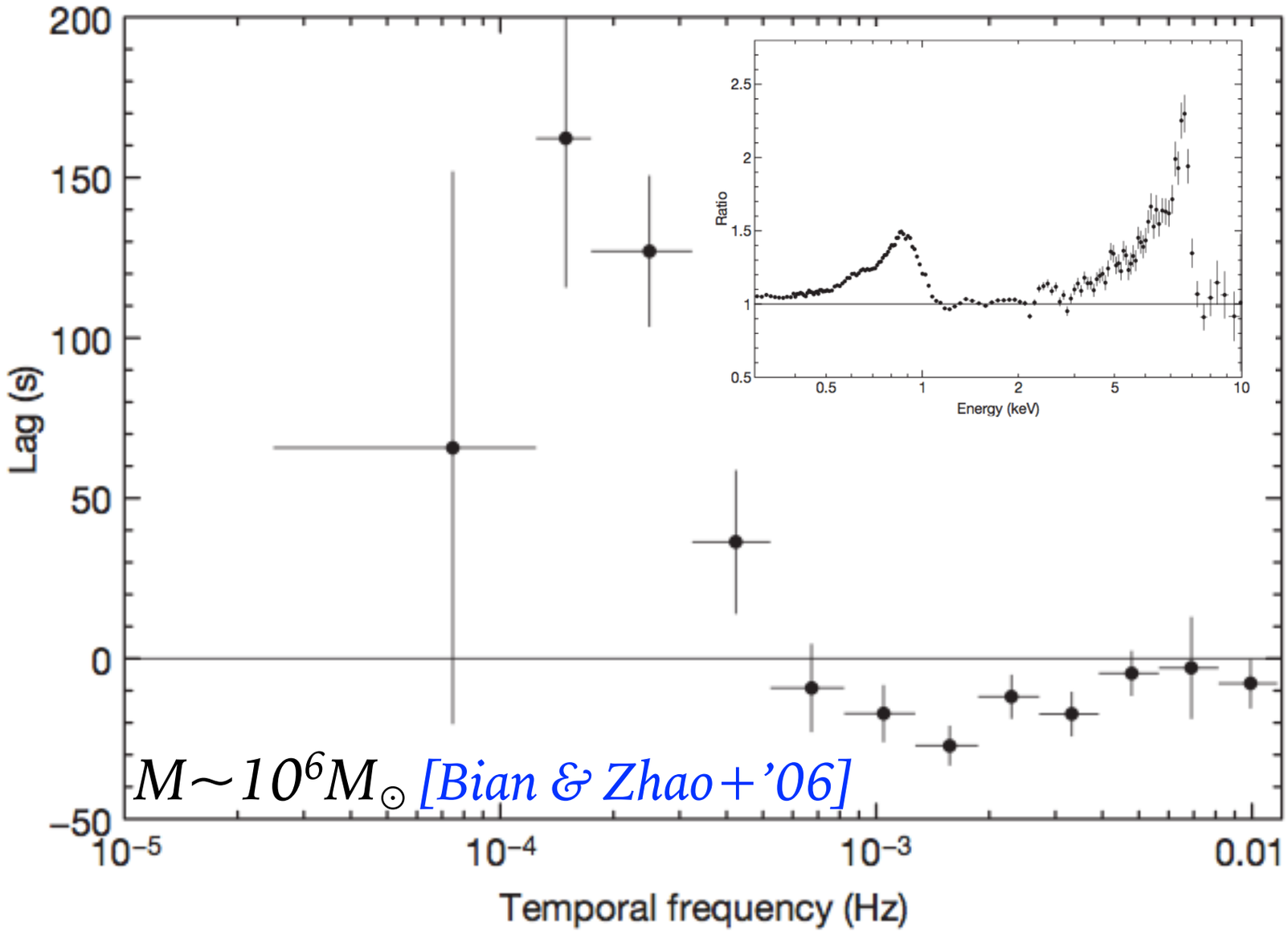
*[Zoghbi +'11]*




*Soft lag-component:*
*power law variations*
*lead*
*soft excess variations*
*by tens of seconds*

# *Soft X-ray lags in AGN*

*Never observed before neither in AGN nor in BHXRBs*
*(only one tentative detection reported in Ark 564 [McHardy+'07])*

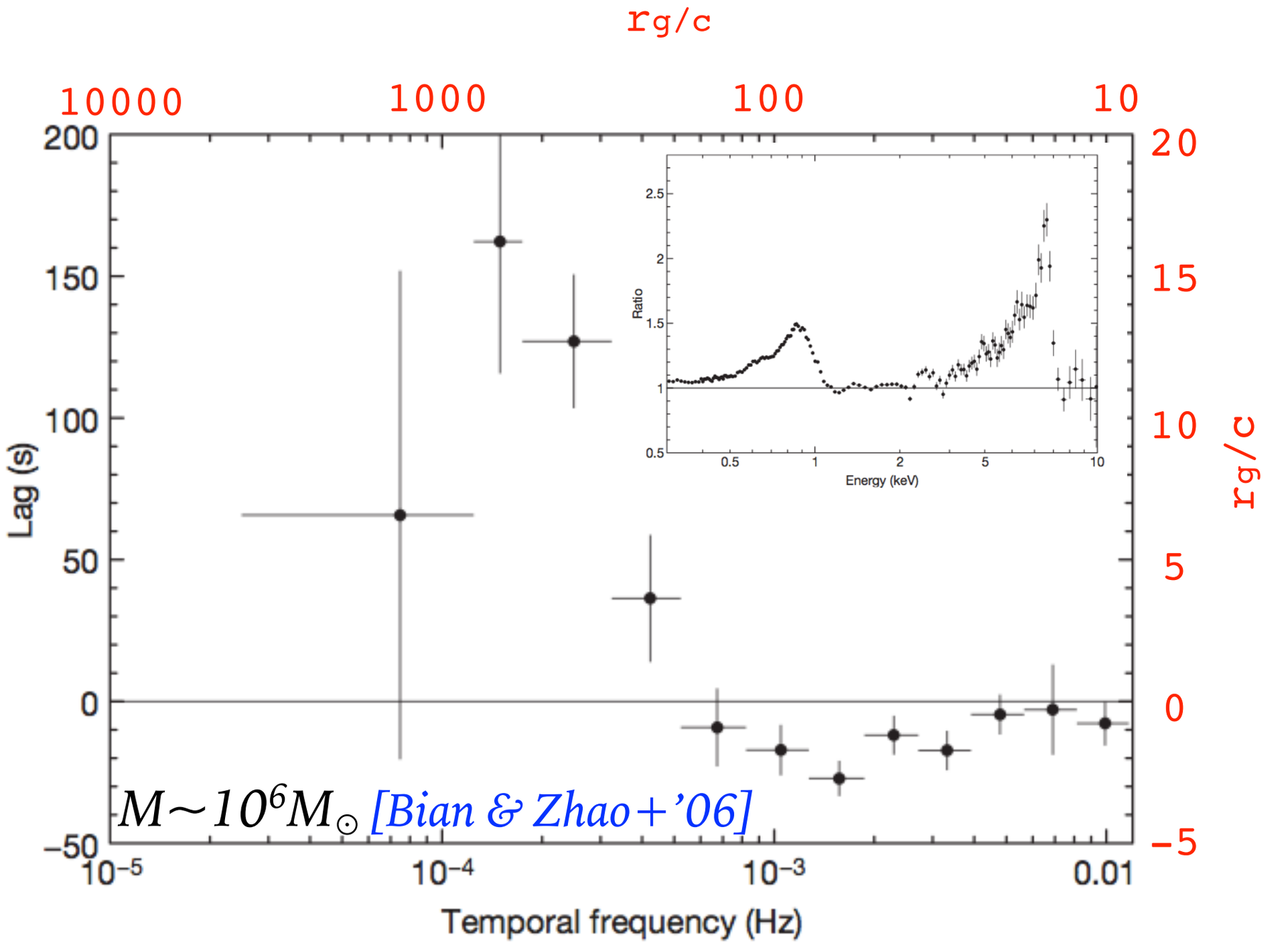



$M \sim 10^6 M_\odot$ *[Bian & Zhao+'06]*

$t = r_g/c = GM/c^3$

# *Soft X-ray lags in AGN*

*Never observed before neither in AGN nor in BHXRBs*
*(only one tentative detection reported in Ark 564 [McHardy+'07])*




$t = r_g/c = GM/c^3$

# *Soft X-ray lags in AGN*

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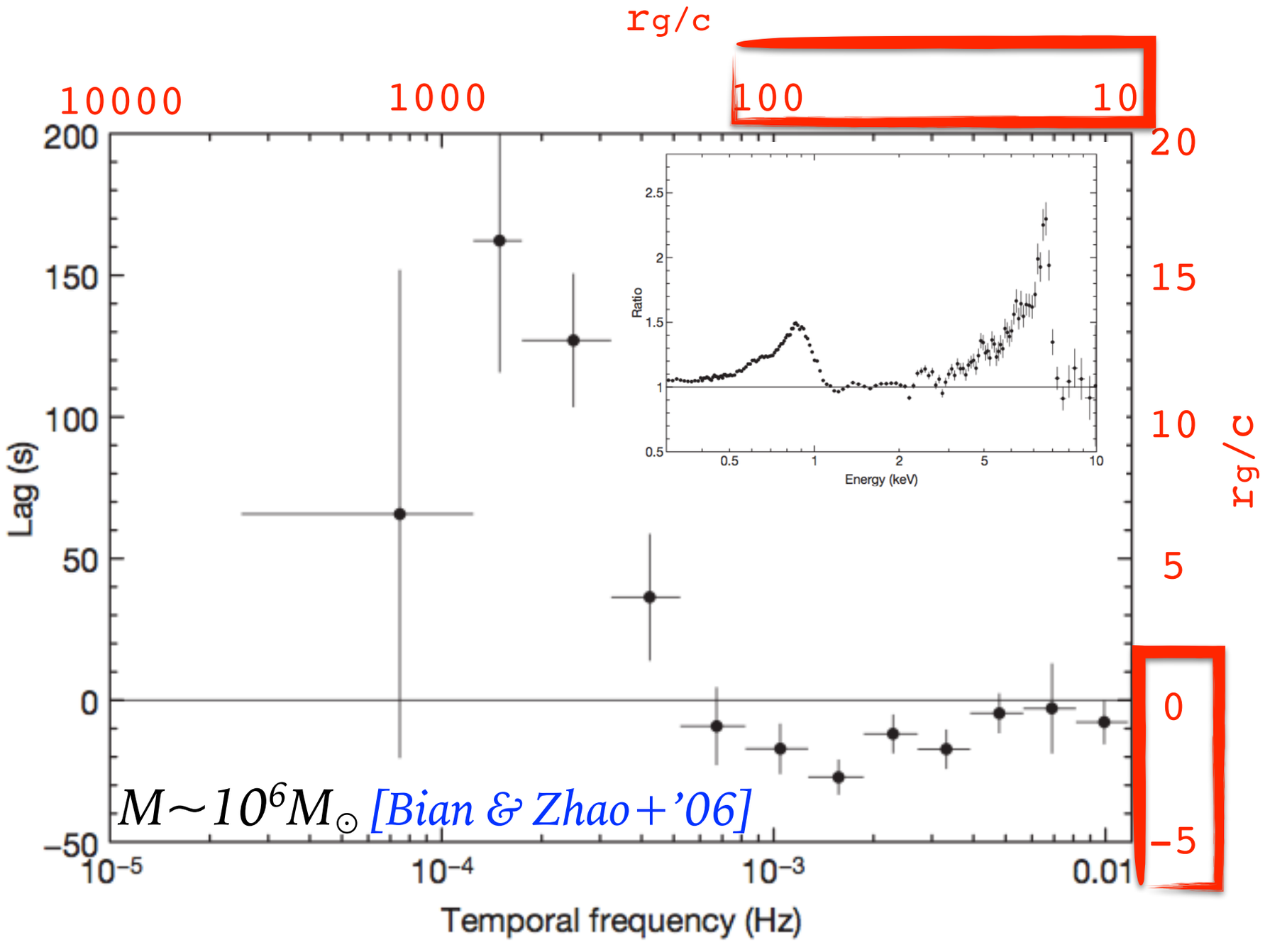


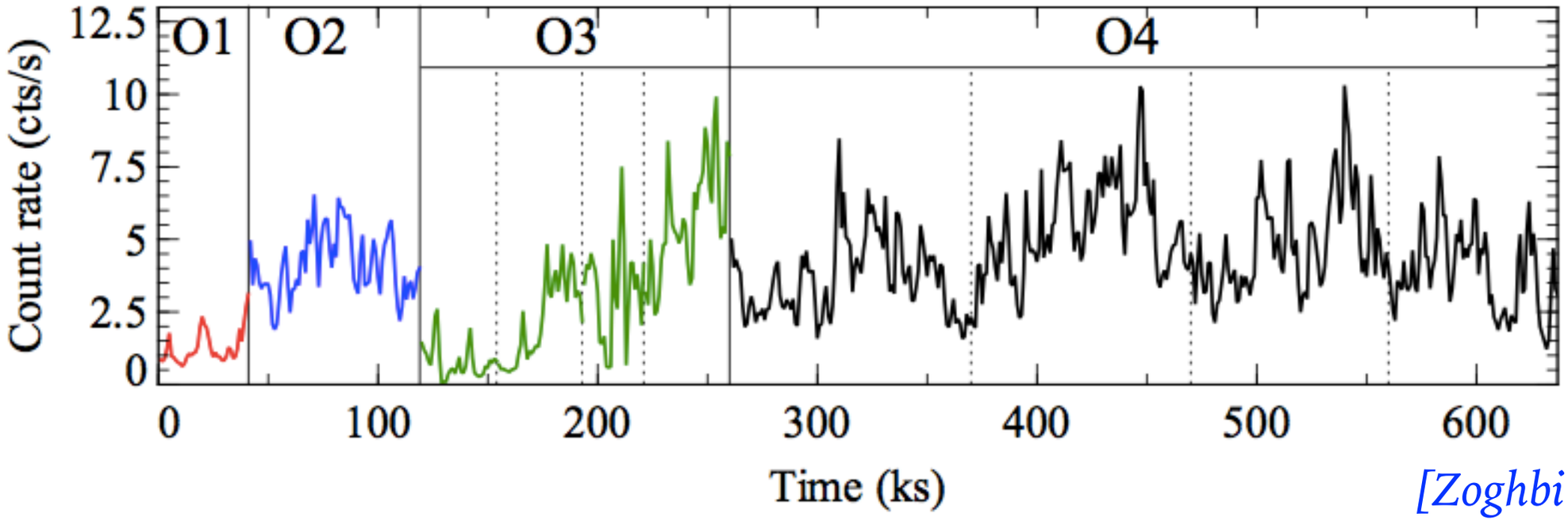

$t = r_g/c = GM/c^3$

*The time scales imply short distances and compact reprocessing regions*

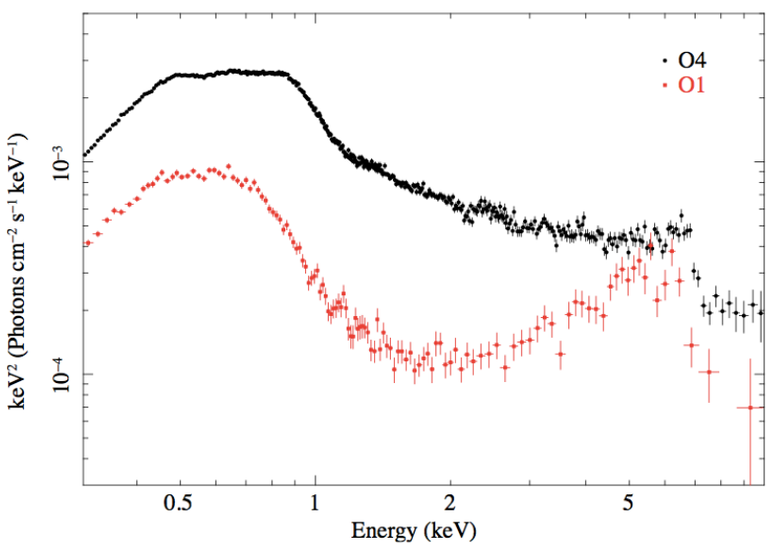
# *Can we detect reverberation lags in different AGN?*

# *Peculiarities of 1H0707-495*

*Narrow line Seyfert 1: strong variability, strong soft excess, low mass*




*[Zoghbi +'10]*

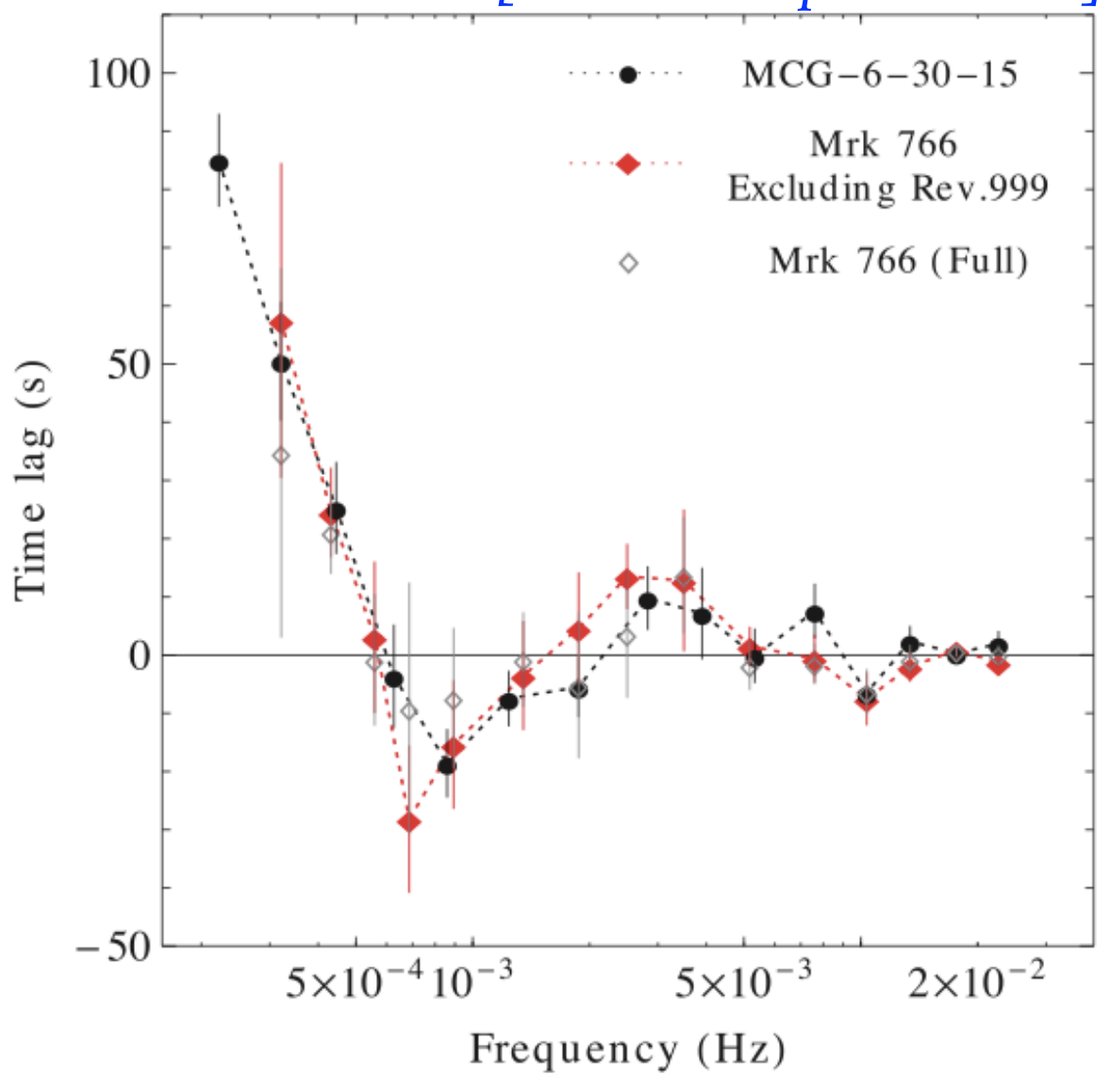



*Extreme spectral features: if modeled with reflection imply high Fe abundance and $r_{in} = 1.3\ r_g$*

*[Zoghbi +'10]*

# *Reverberation lags in NLSy1*

*[Emmanoulopoulos+'11]*

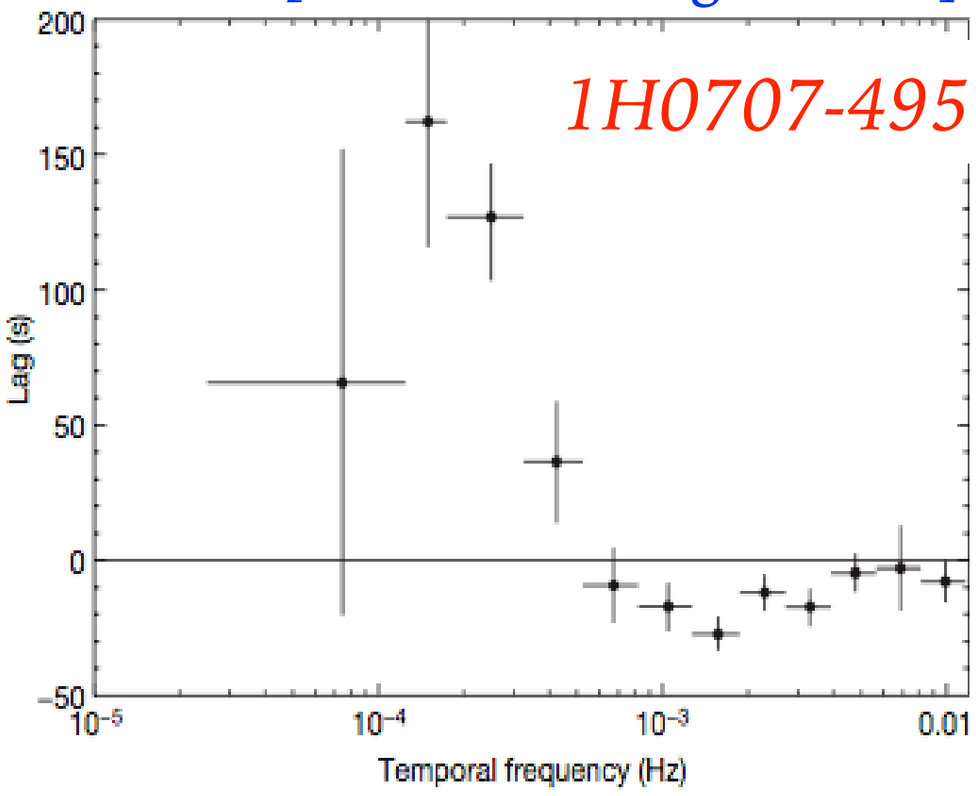



*But masses and variability properties similar to 1H0707-495*

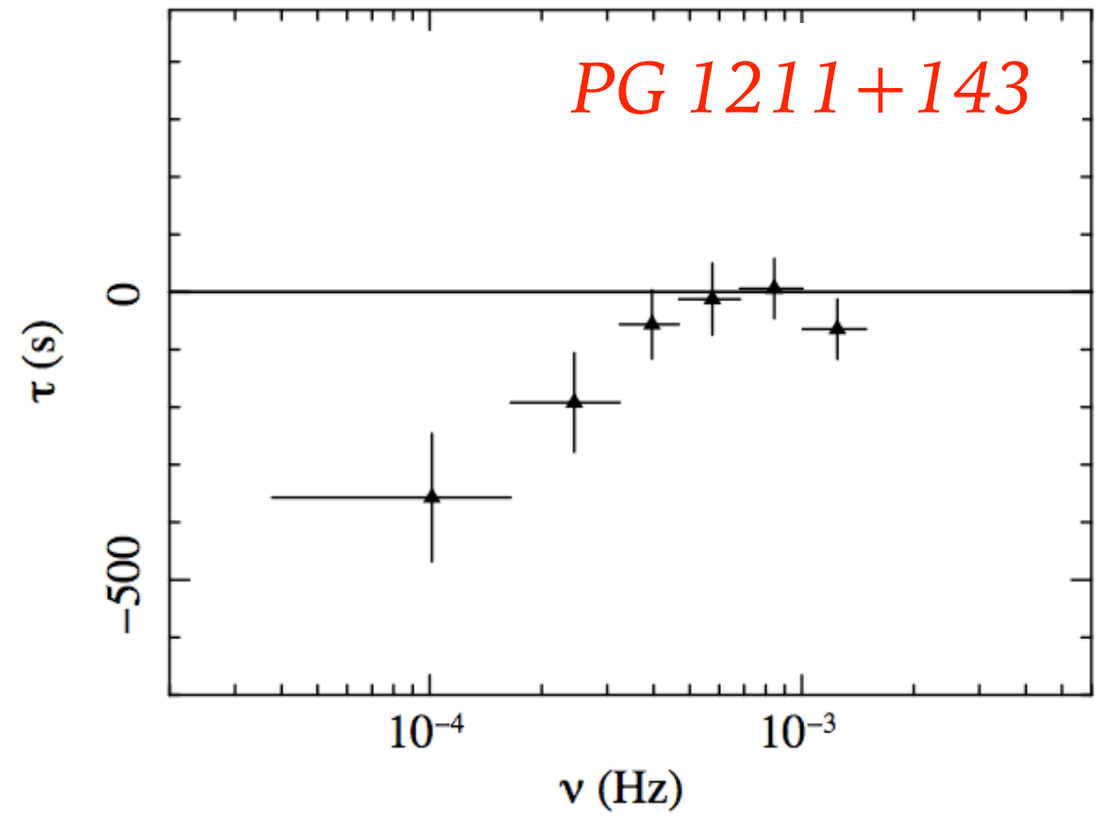
# *Higher masses*

# *The case of PG1211+143*

*[Fabian+'09, Zoghbi +'10]*



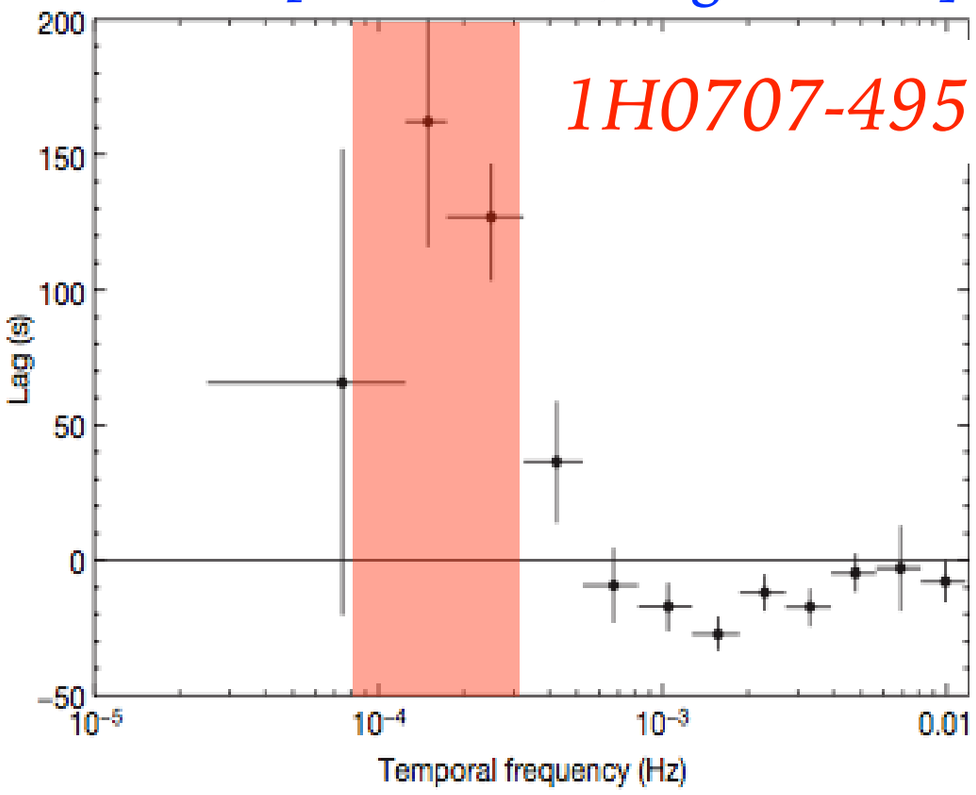

*[De Marco+'11]*



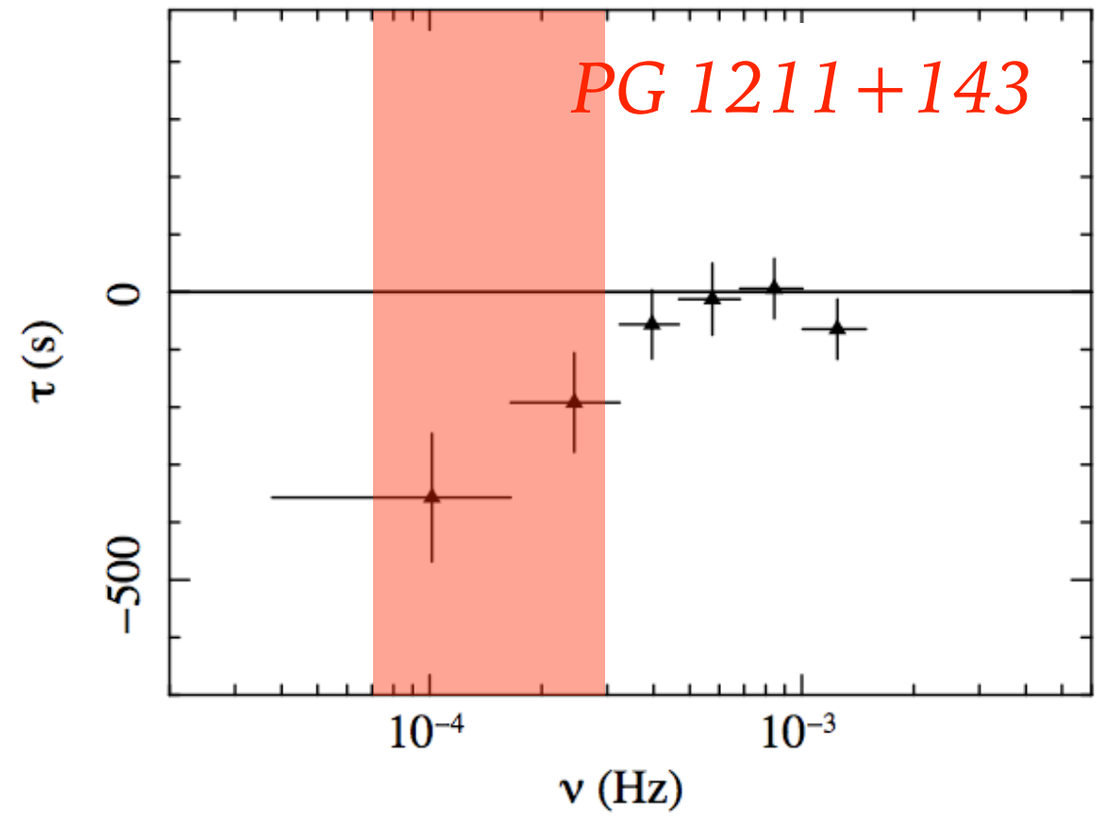

$\times 10 M_{BH}$

# *The case of PG1211+143*

*[Fabian+'09, Zoghbi +'10]*

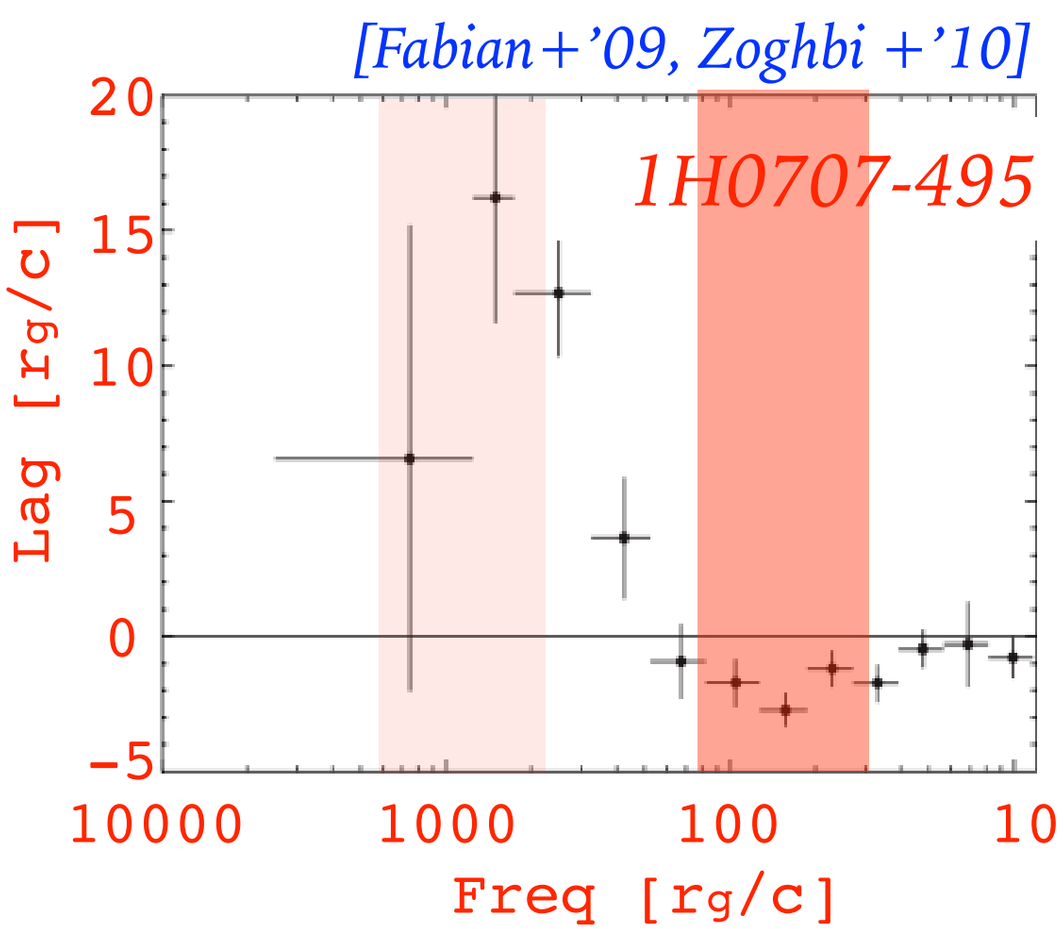


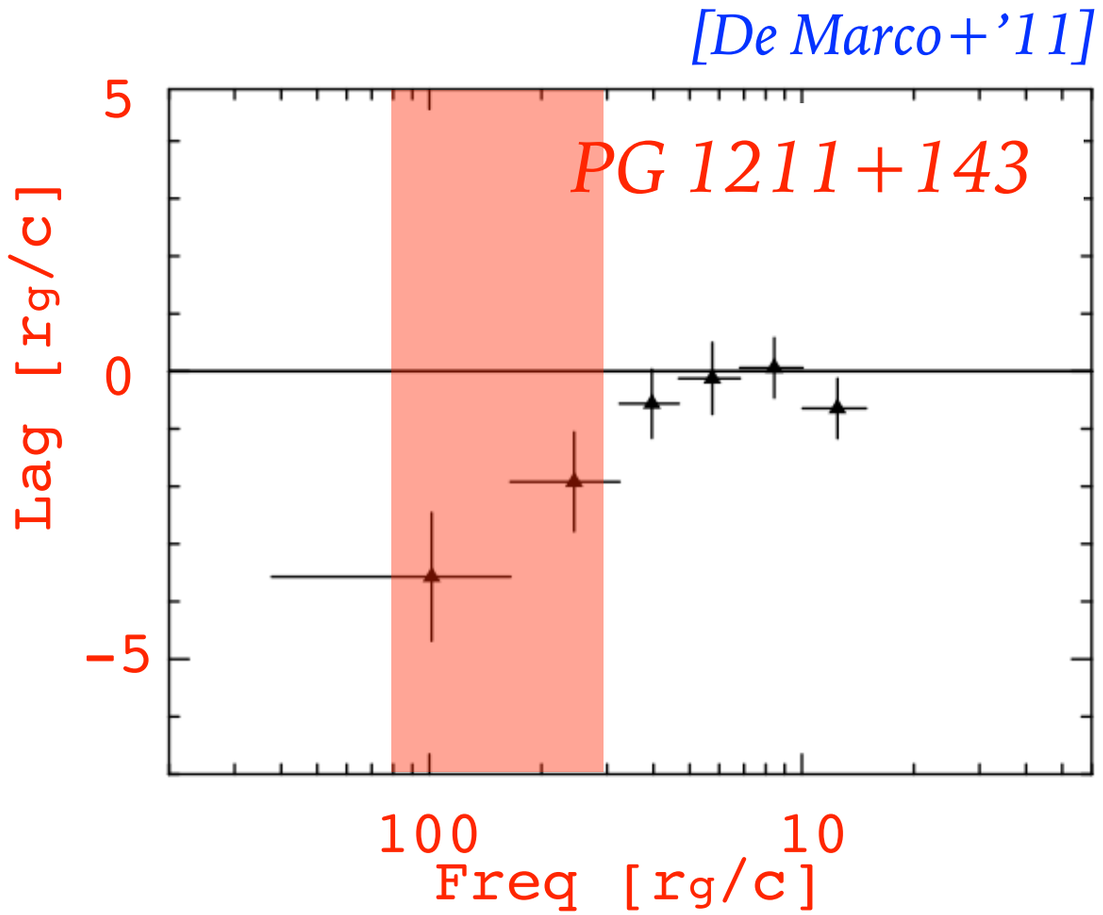

*[De Marco+'11]*




$\times 10 M_{BH}$

# The case of PG1211+143




$\times 10 M_{BH}$

*Suggests soft lags map a common distance to the same compact reprocessing region*

# *Soft lags - systematic detections*

**Radio quiet*

**X-ray unobscured AGN*

**Long XMM-Newton observations (>40 ks)*

** BH mass known*

** Soft excess vs power law-dominated energy bands*

*[De Marco+'13a]*

# *Soft lags - systematic detections*

**Radio quiet*

**X-ray unobscured AGN*

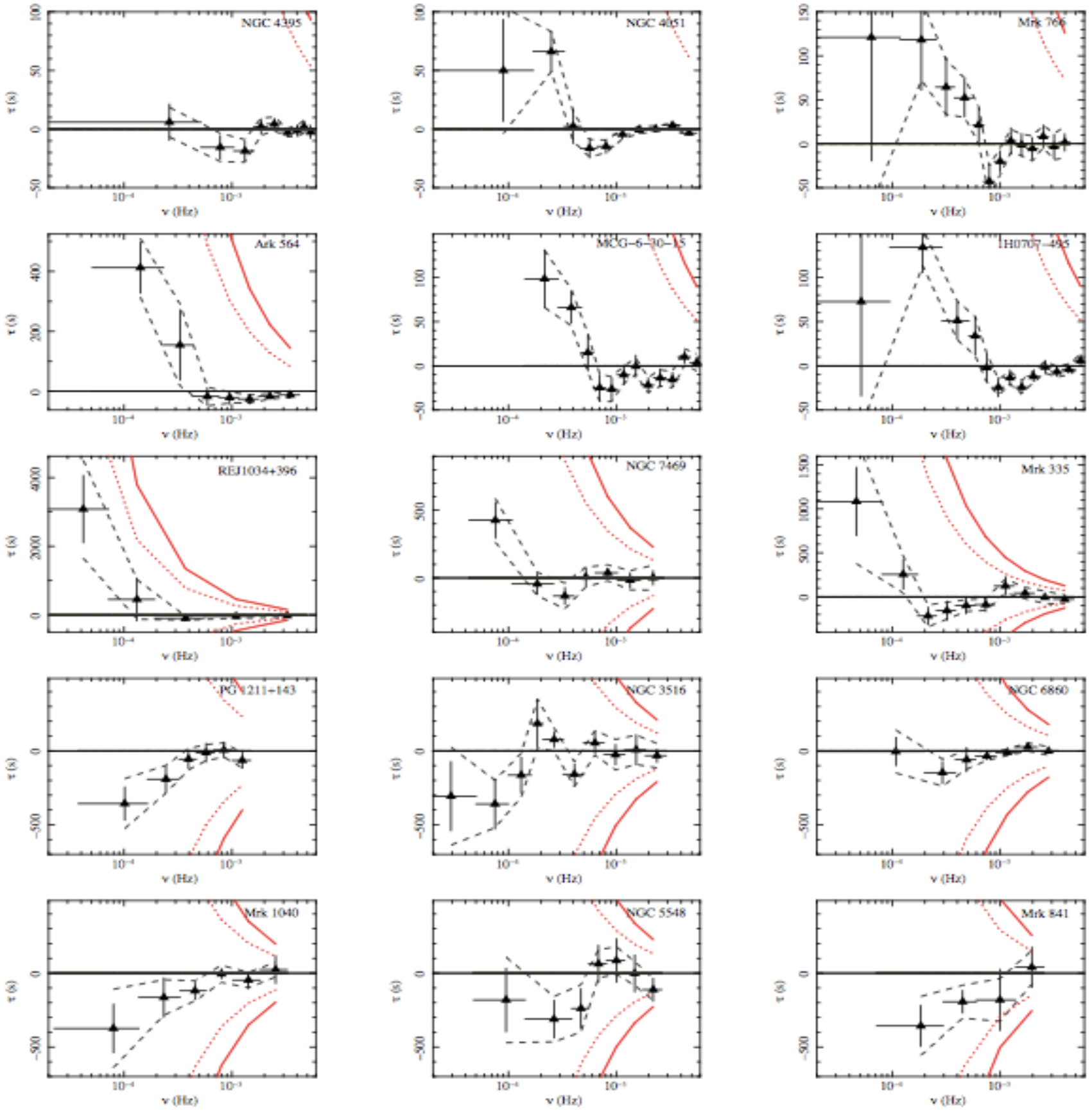
**Long XMM-Newton observations (>40 ks)*

** BH mass known*

** Soft excess vs power law-dominated energy bands*

*32 sources, 15 detections*

*[De Marco+'13a]*



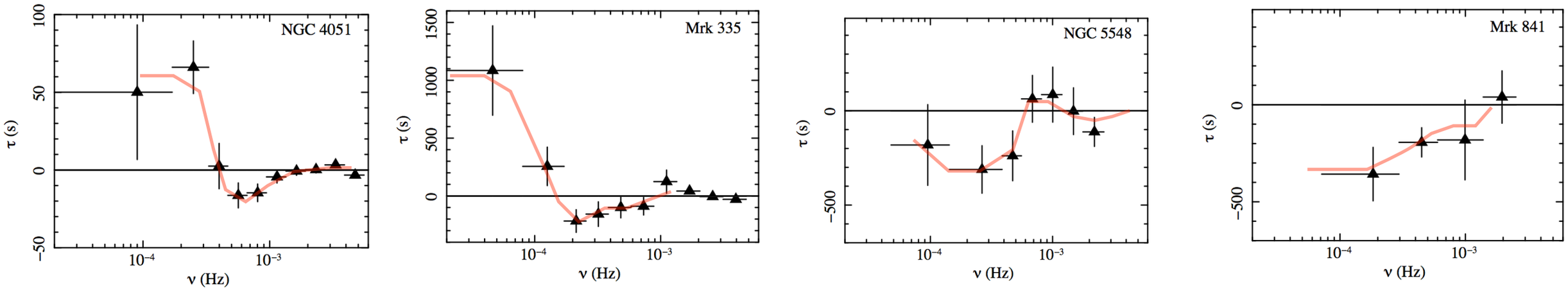
# *Soft lags - changing with mass*

*[De Marco+'13a]*

# Soft lags - changing with mass

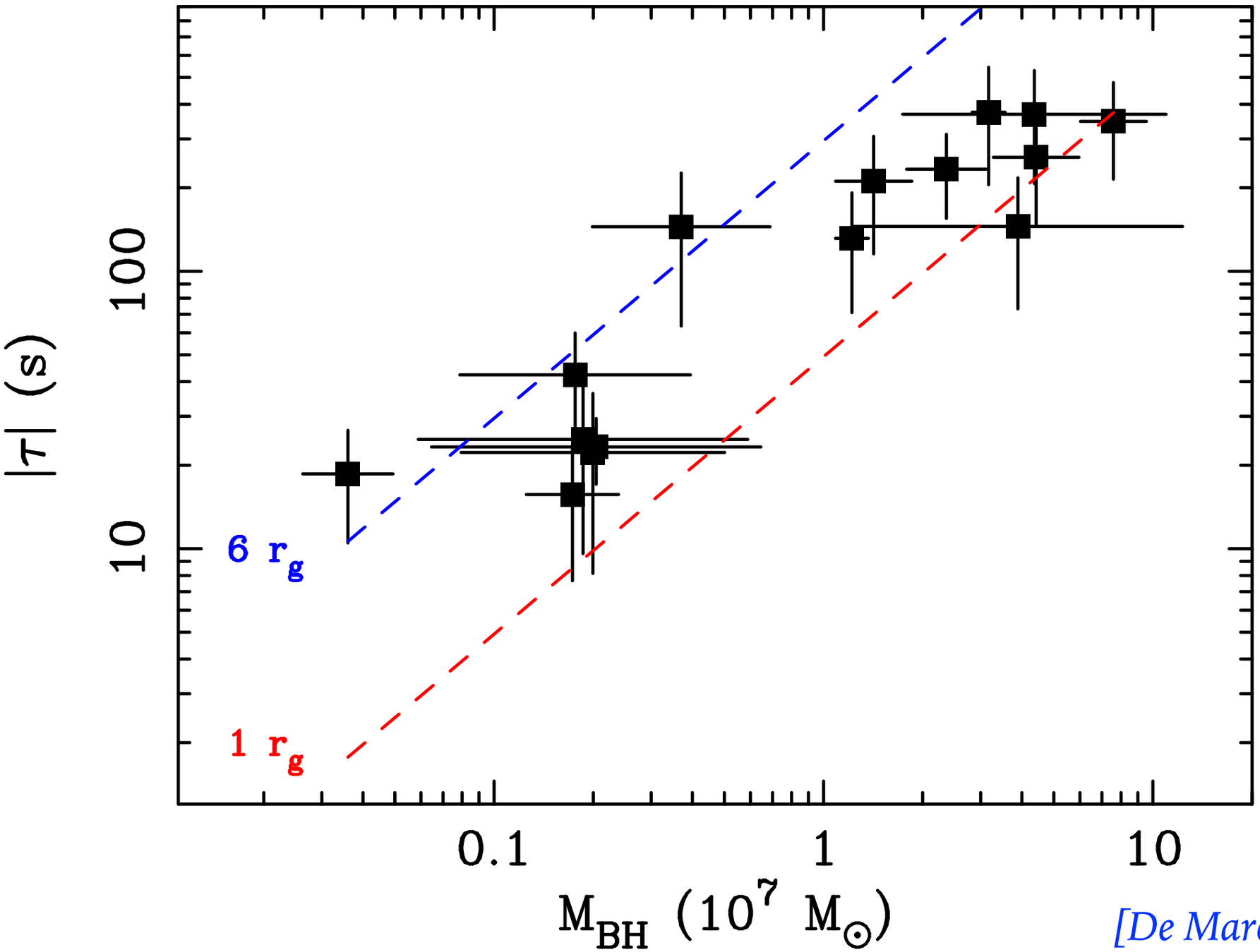
*Mass*

$10^6$ → $10^8$




*[De Marco+'13a]*

# *Soft lags - correlation with mass*

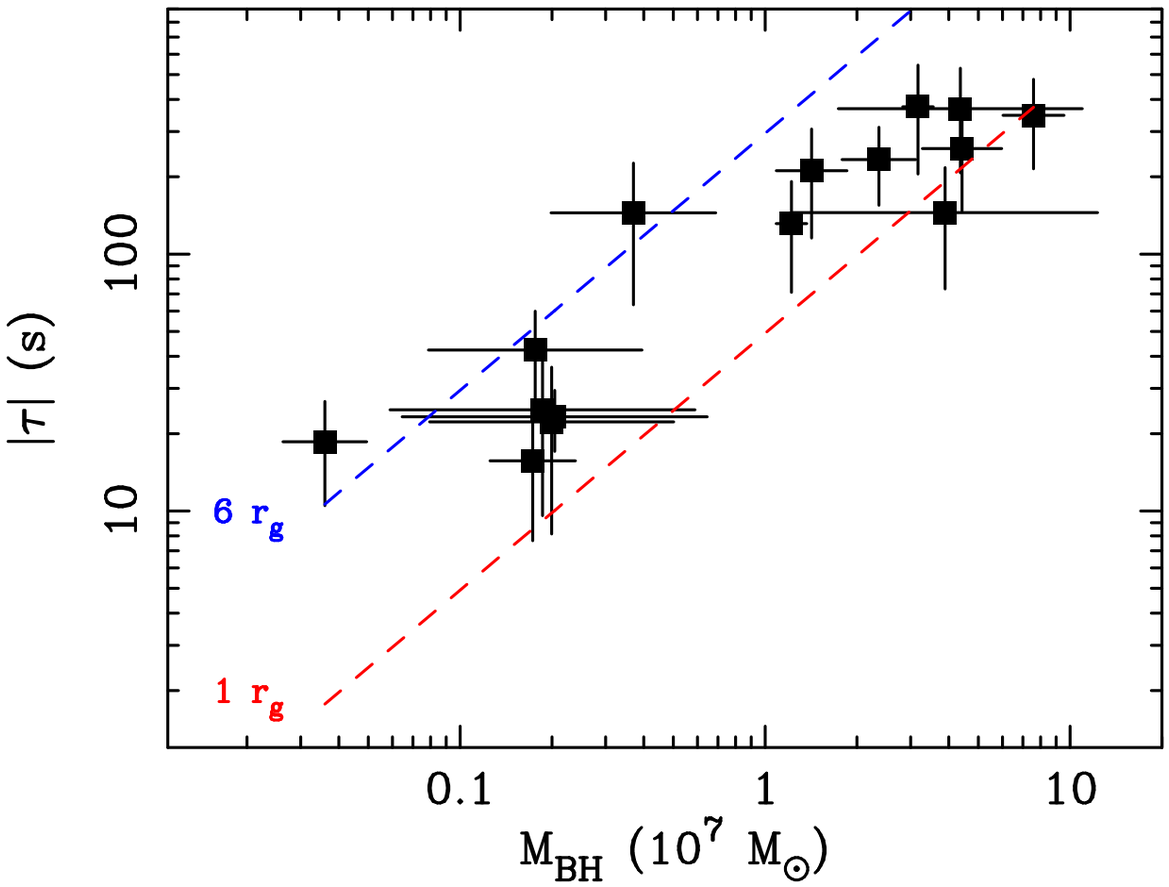



*[De Marco+'13a]*

*[…same correlation between lag-frequency and mass]*

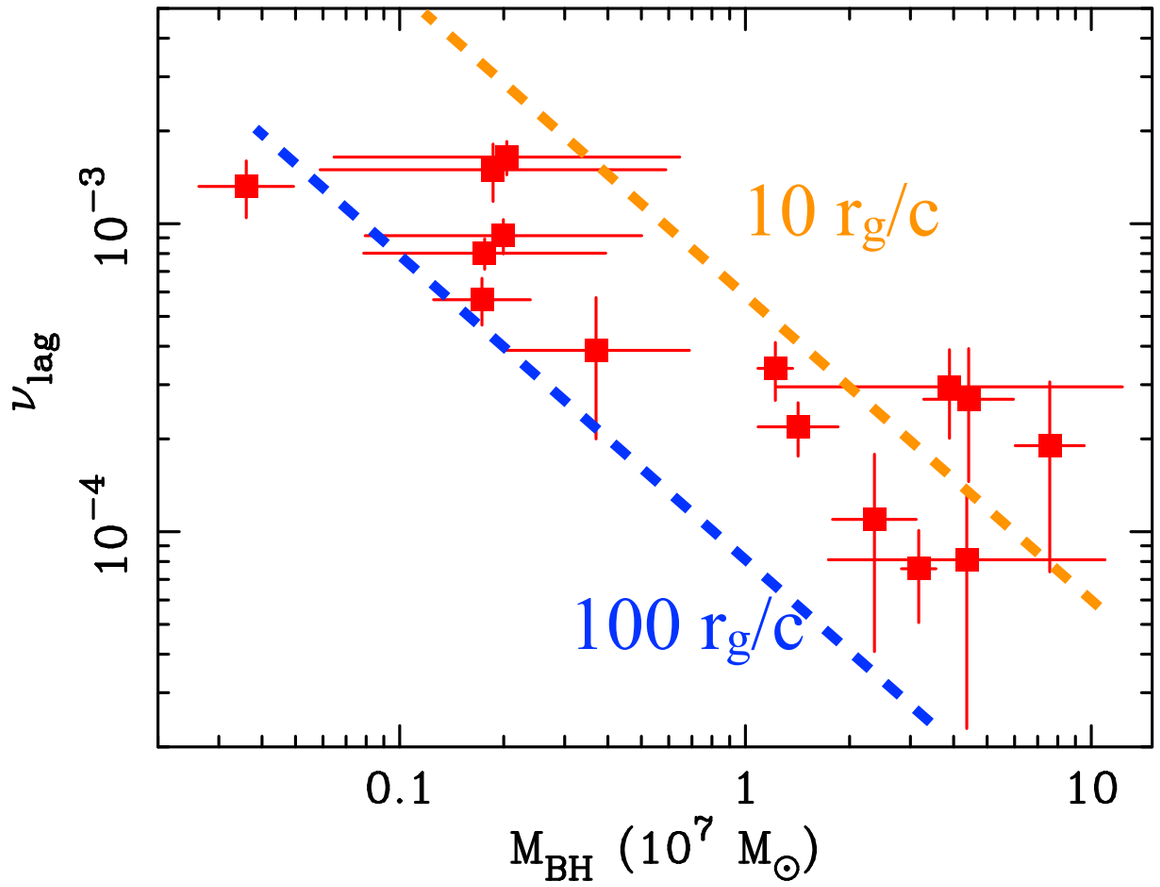
# *Soft lags - correlation with mass*

*lag-amplitude vs BH mass*




*short primary-to-reprocessing regions distance*

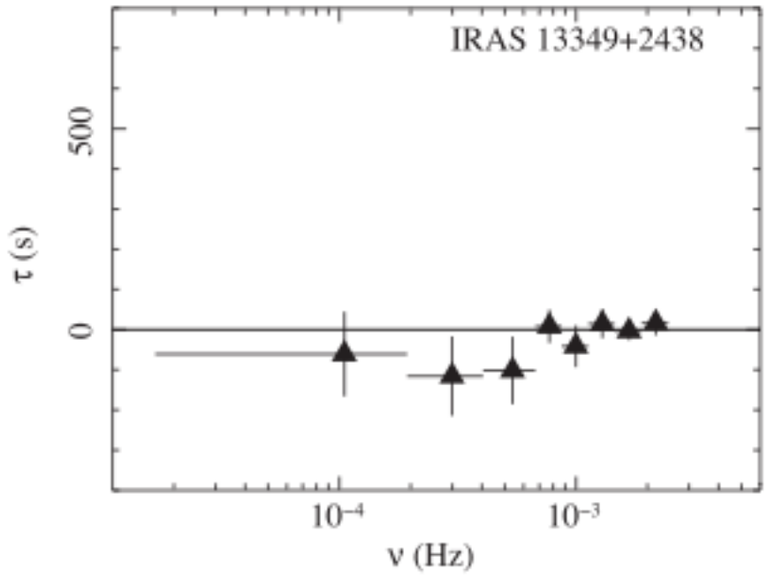
*lag-frequency vs BH mass*

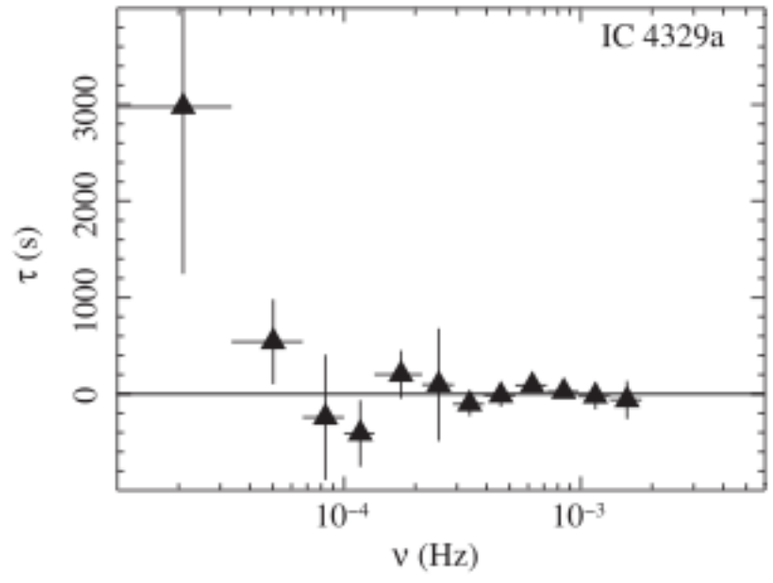



*[De Marco+'13a]*

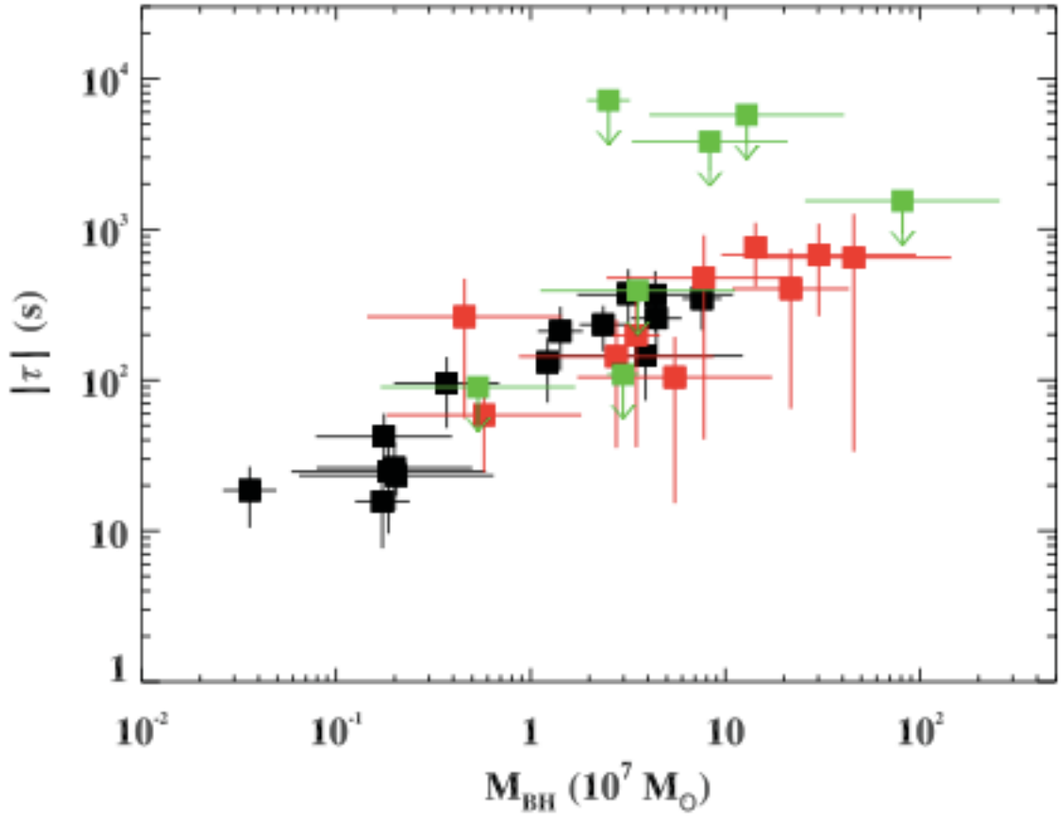
*compact reprocessing region*

# *Soft lags - common in AGN*



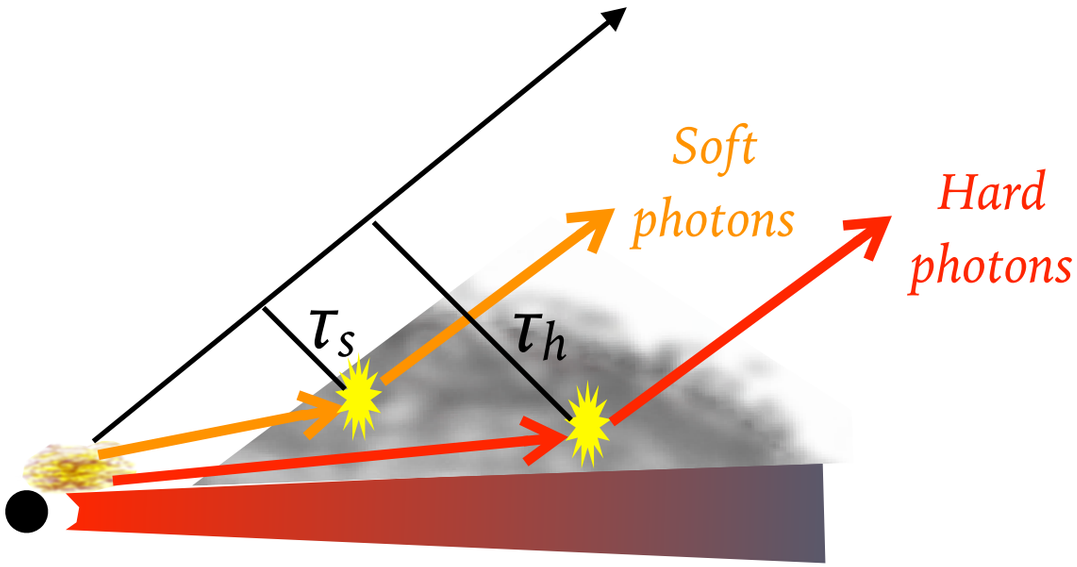

- *detections (15)*
- *low signficance detections (10)*
- *90% upper limits (7)*

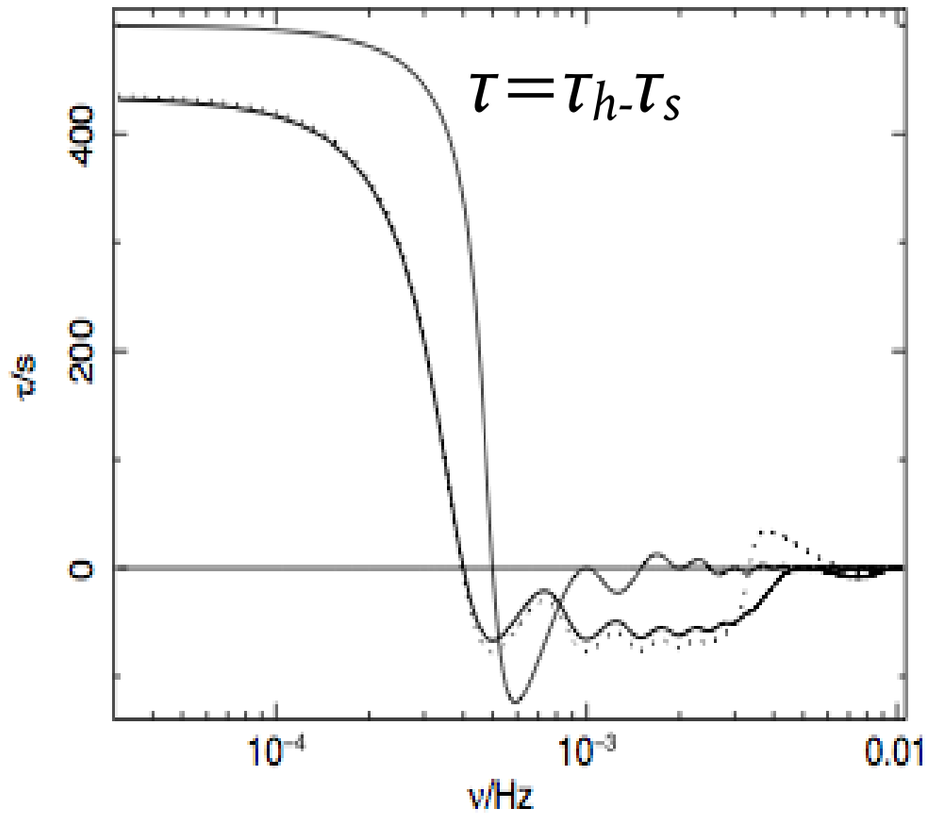



*[De Marco+'13a]*

# *Alternatives to inner disc reflection*

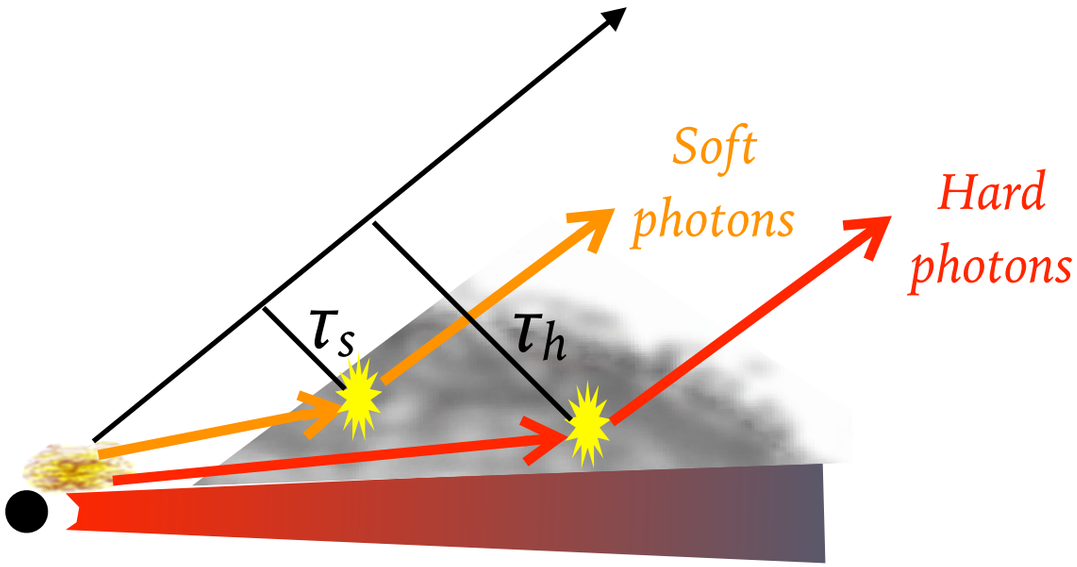
# *Distant reflector/scatterer*

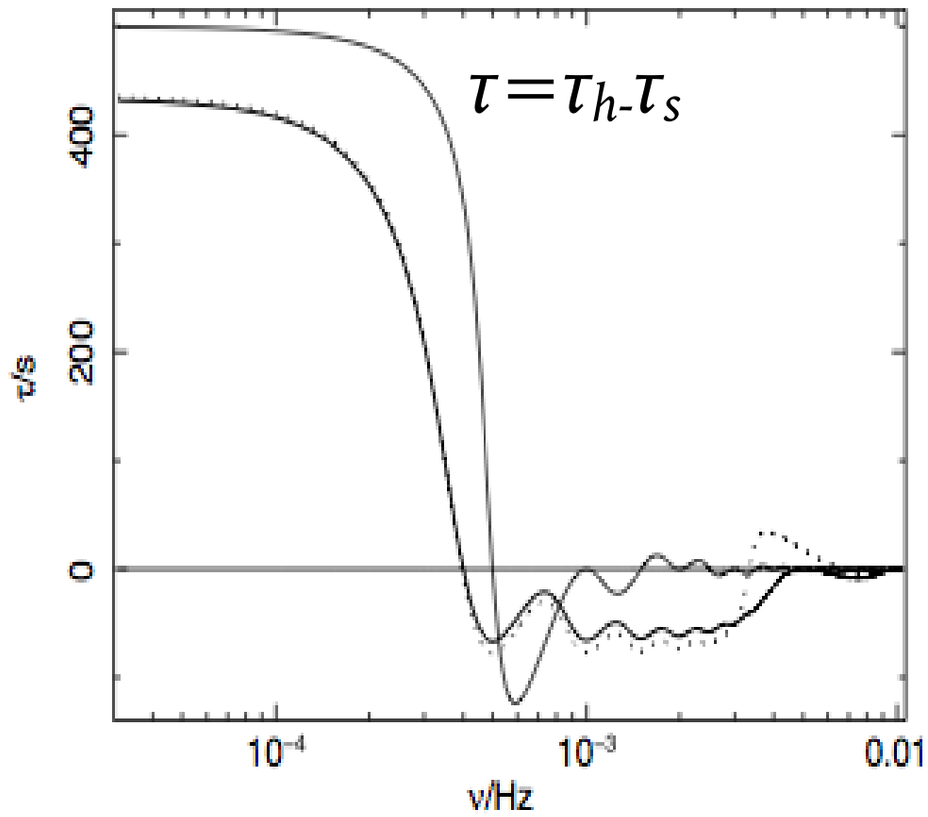


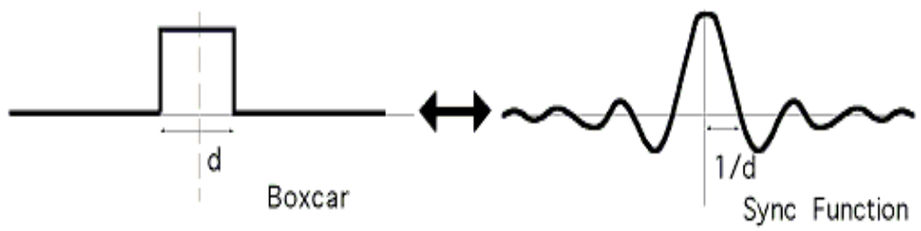




*[Miller+'10,'11]*

# *Distant reflector/scatterer*




*Time domain* *Frequency domain*

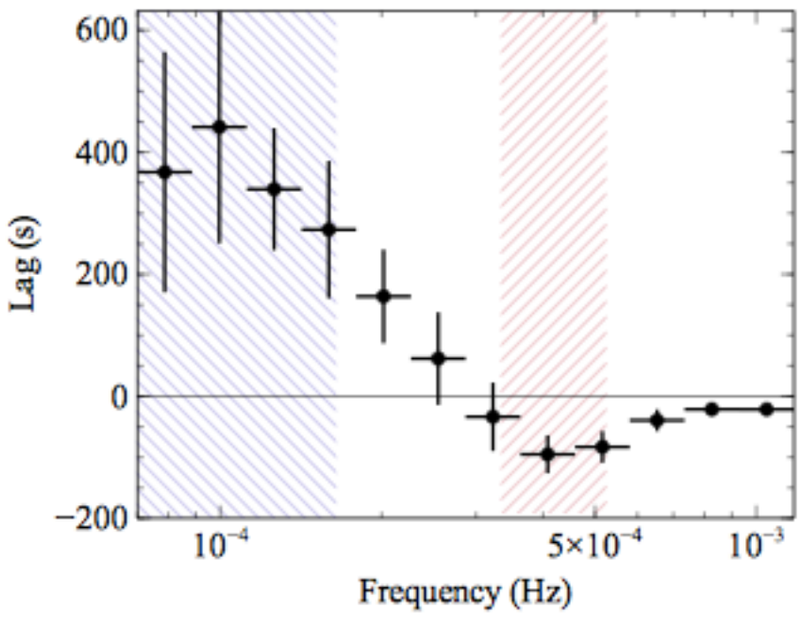
*The negative lag is an artifact:*
*e.g. sharp-edged*
*transfer function*

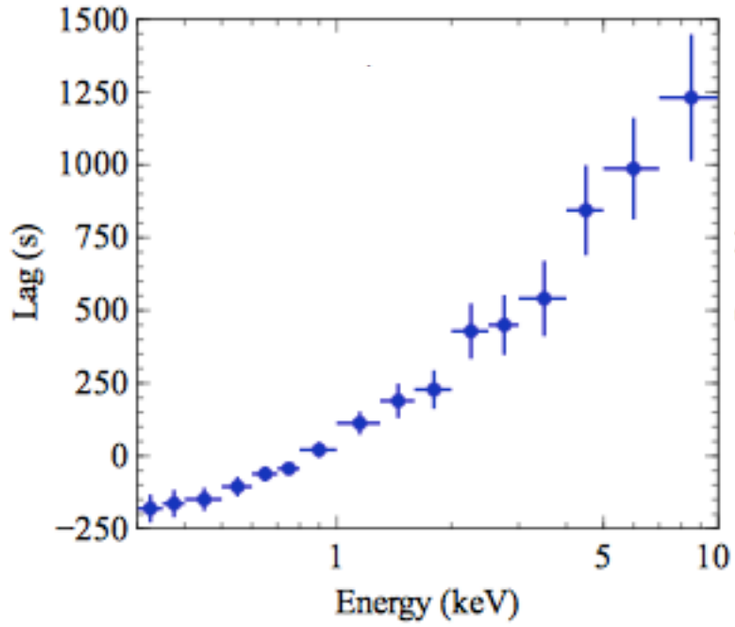
*[Miller+'10,'11]*

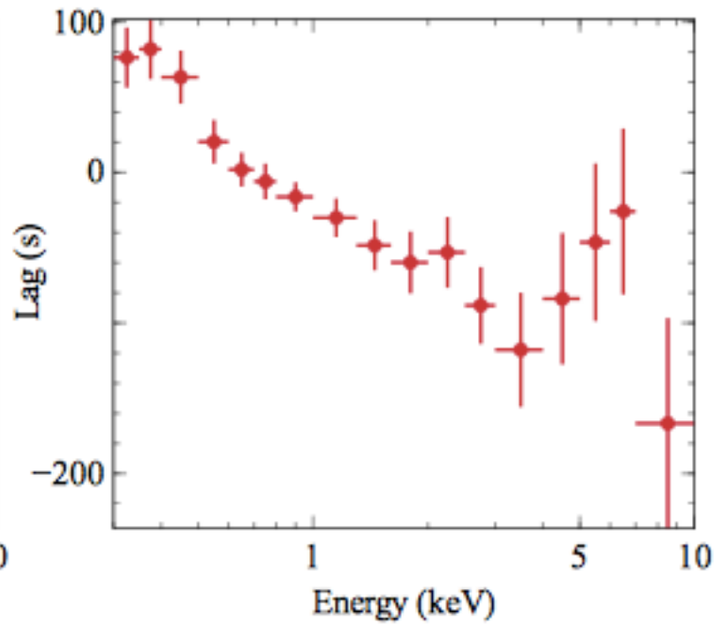
# *Distant reflector/scatterer*

*The soft lag should mirror the hard lag*

*Ark 564*



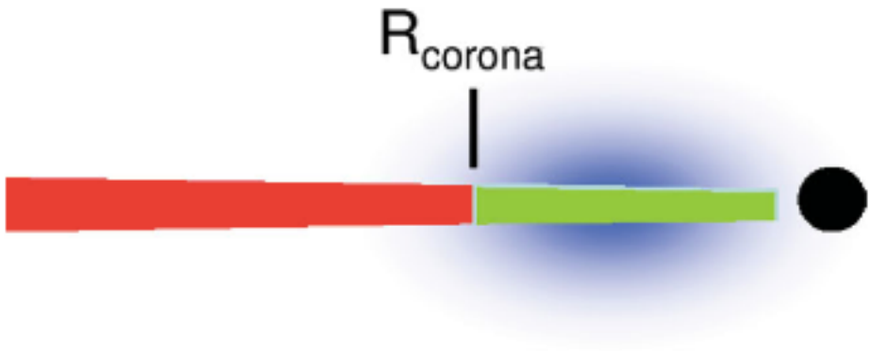



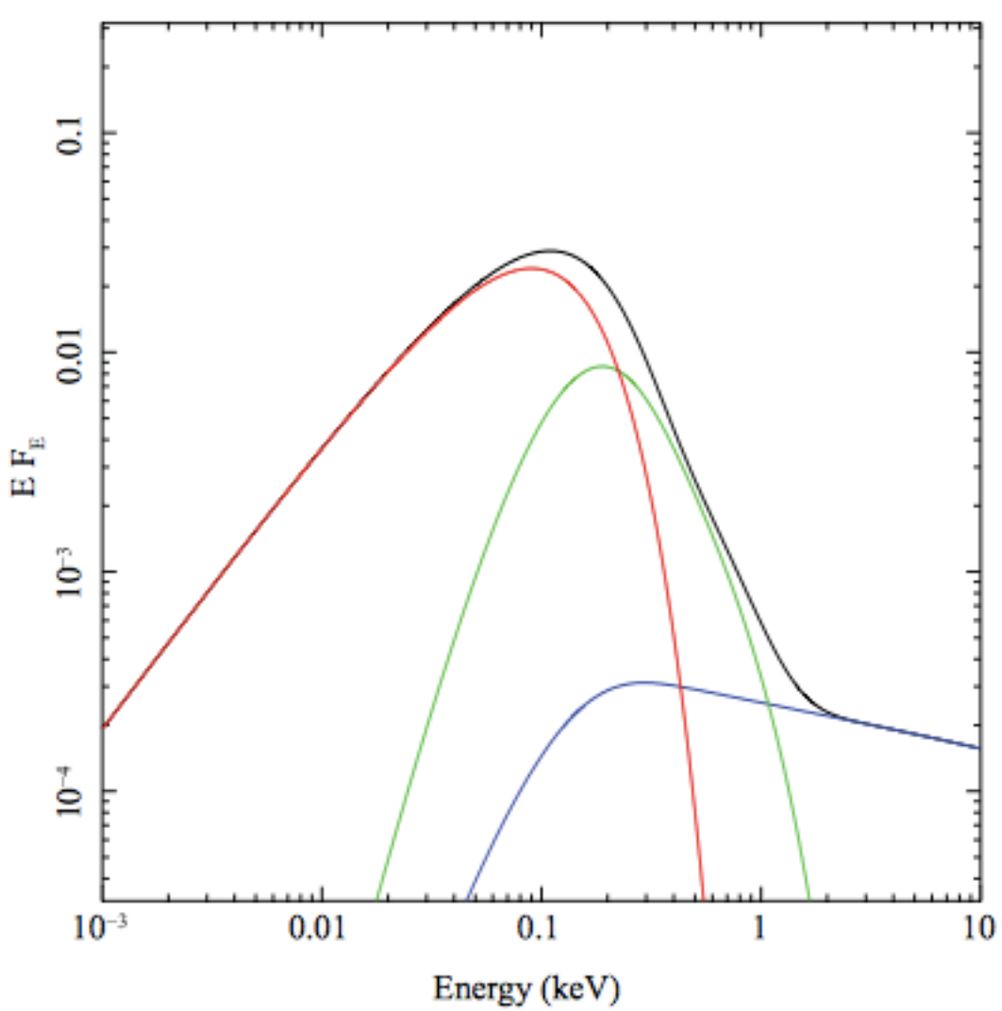

*[Kara+'13b]*

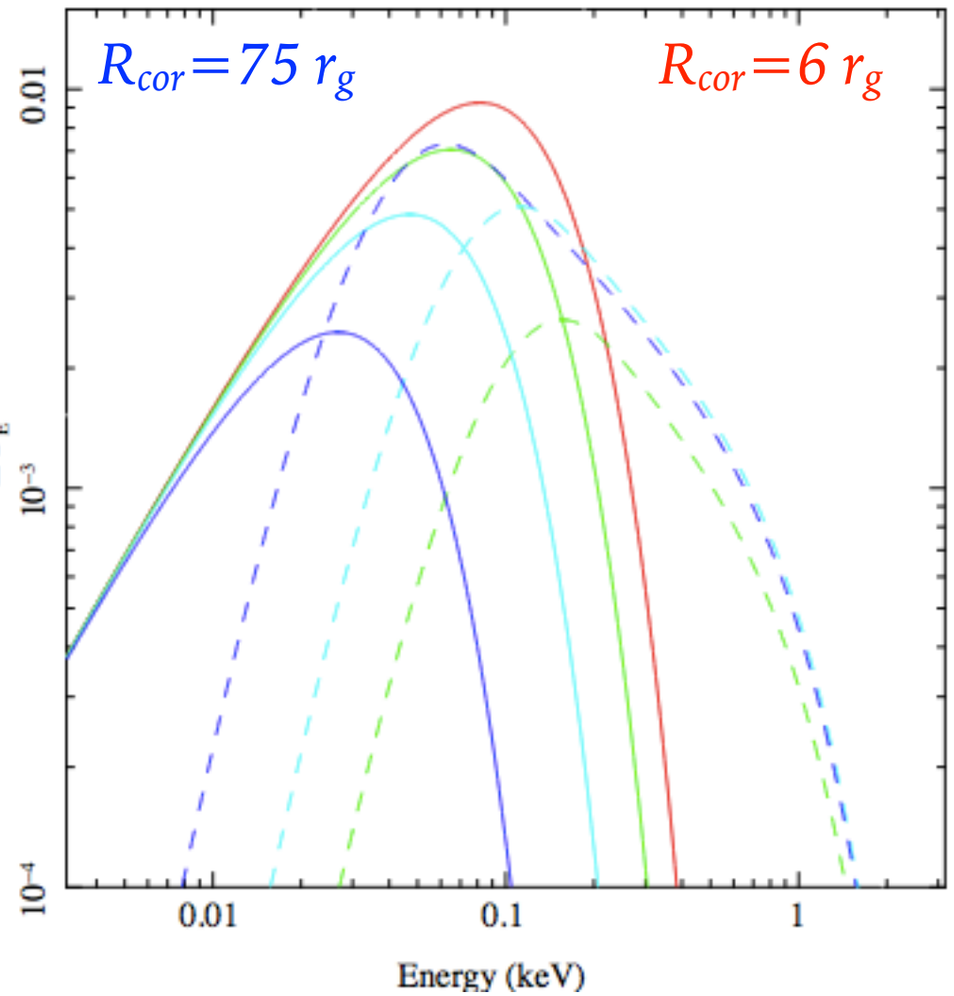
*But the lag spectra do not mirror each other*

# *Alternatives to blurred reflection*




*warm corona Comptonization*



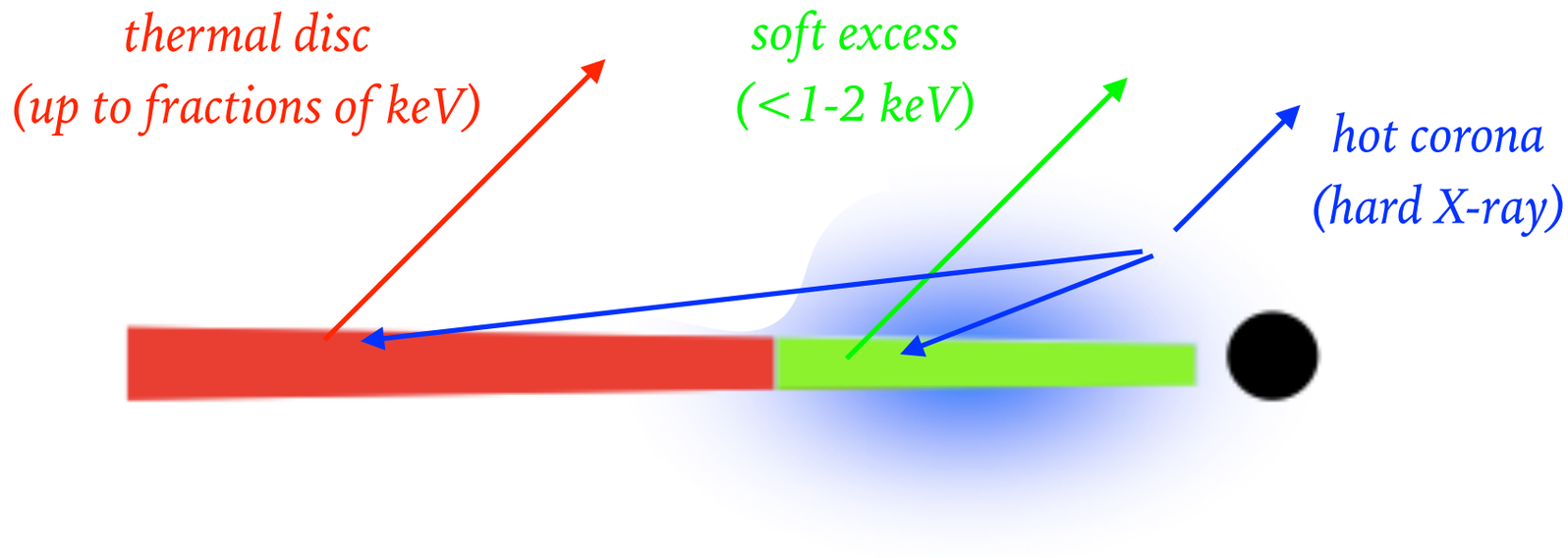




*[Done+'12, see also Petrucci +'12, Mehdipour+'15]*

# Soft lags due to thermal reprocessing

*The fraction of photons not reflected are thermalized*

*[Guilbert & Rees '89]*



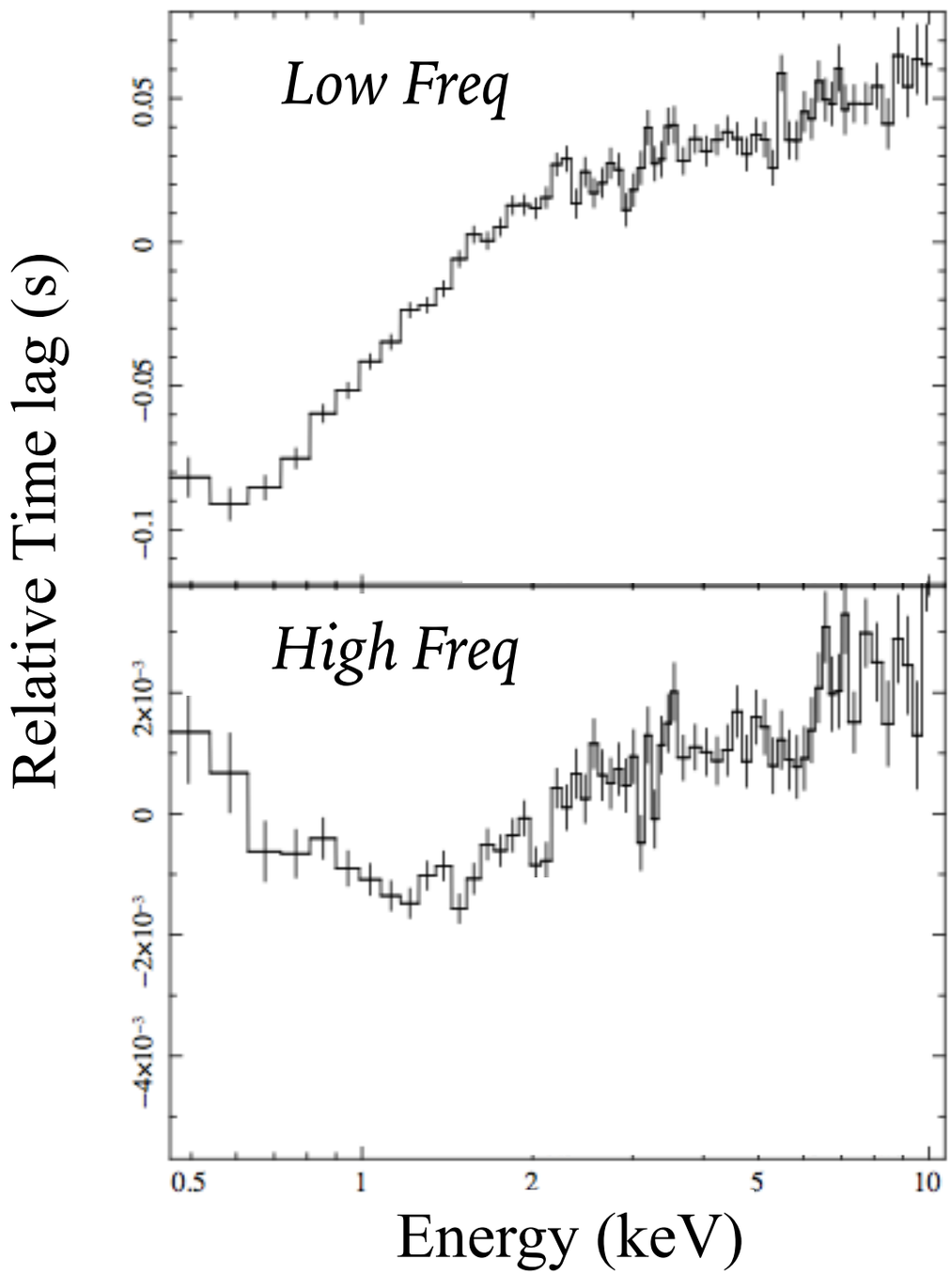

*PG 1244+026* *[Gardner & Done '14]*

*Might explain detections of soft X-ray lags in sources with low relativistic reflection and Fe abundance*

# *Lags in smaller accreting systems*

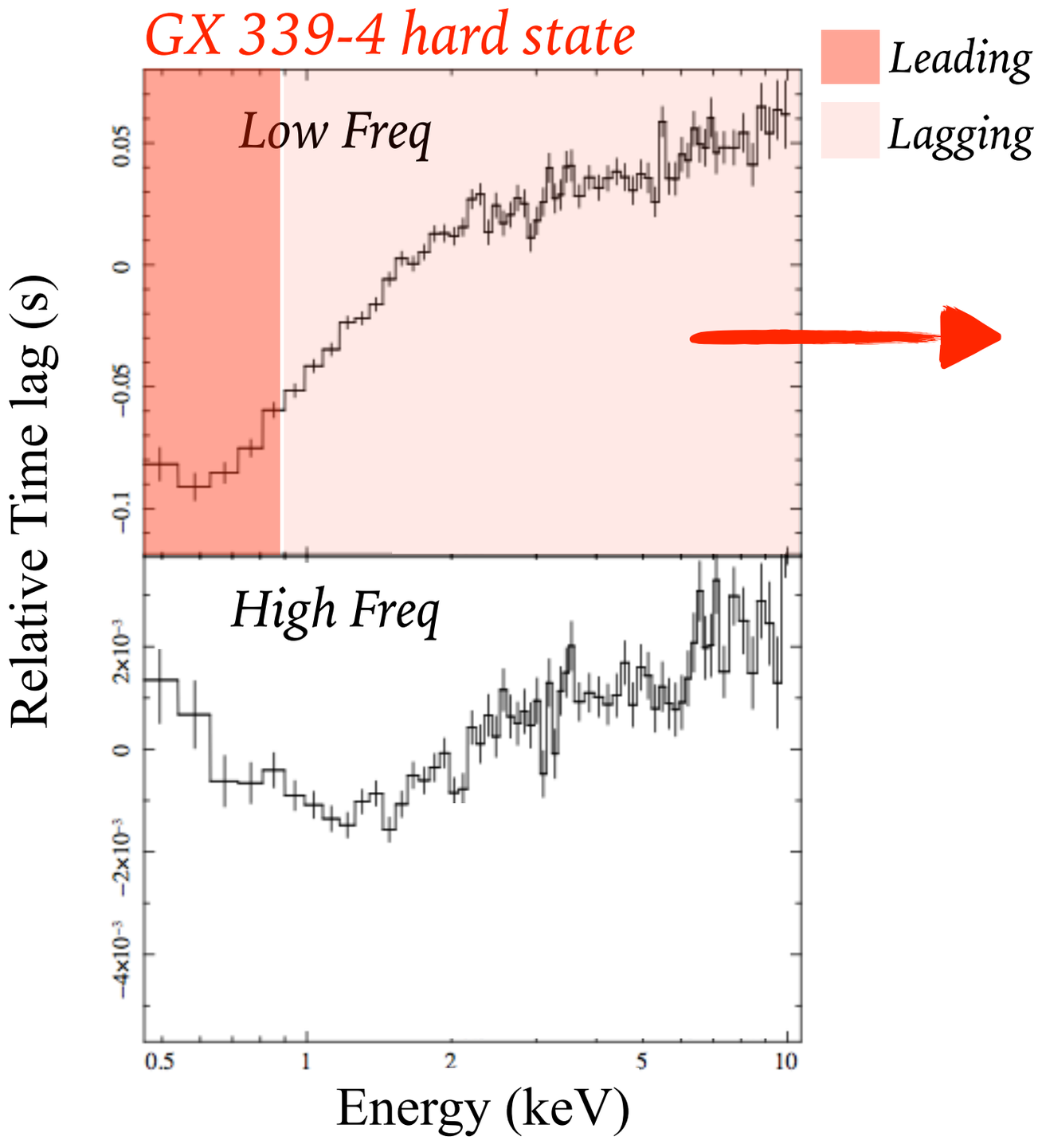
# *Thermal reprocessing in BHXRBs*

*GX 339-4 hard state*



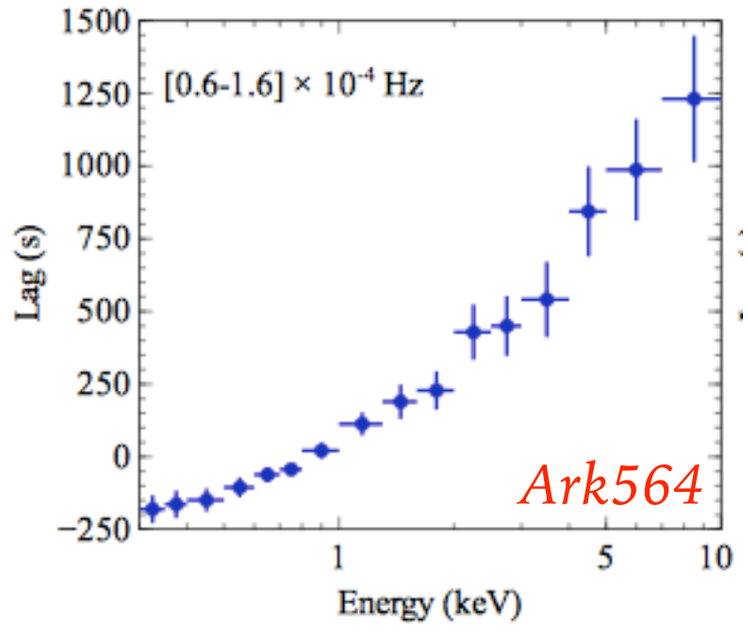

*[Uttley+'11]*

# Thermal reprocessing in BHXRBs

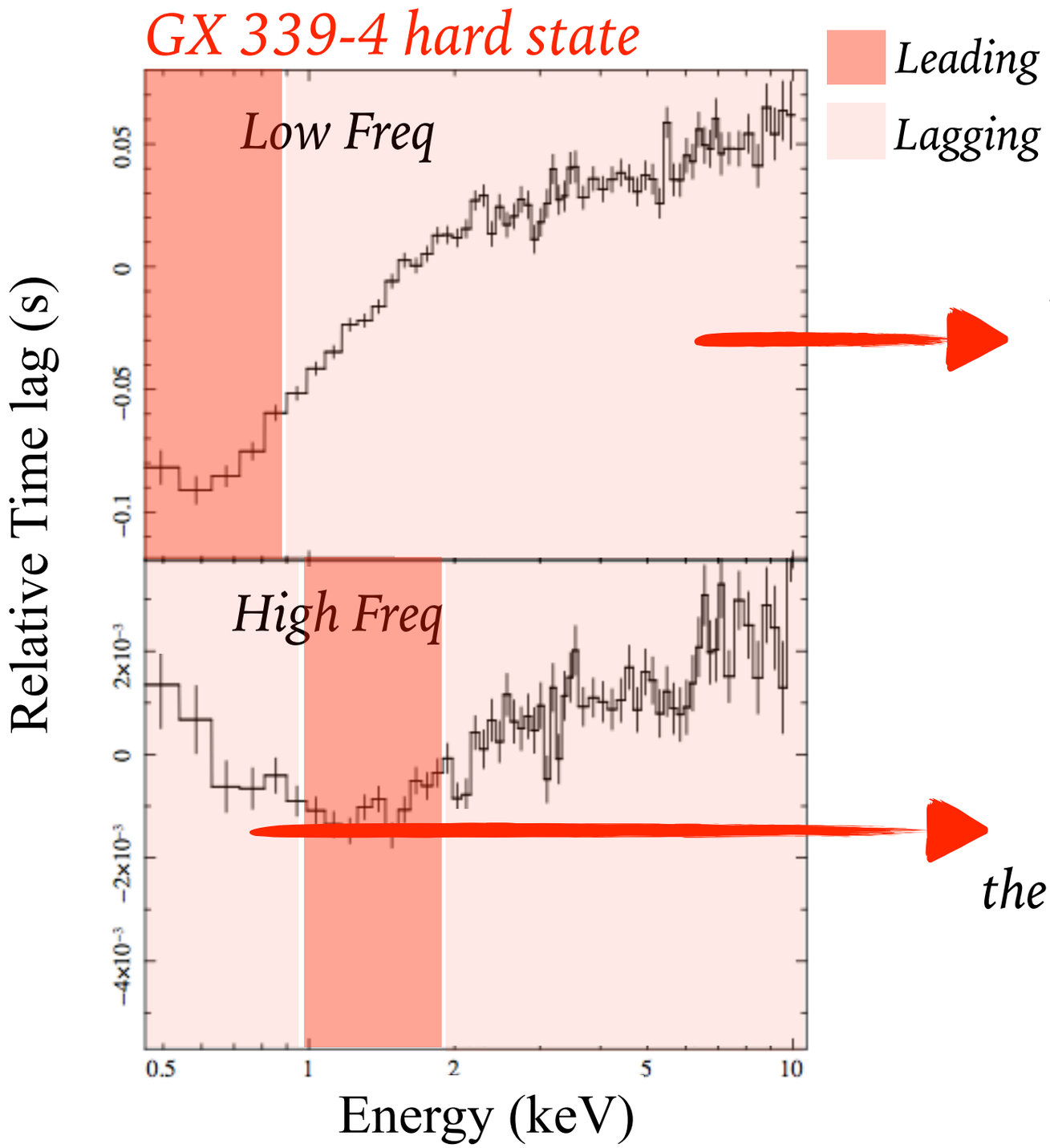



[Uttley+'11]

*Hard bands lagging the soft bands:*
*as for low-frequency lags in AGN*



# *Thermal reprocessing in BHXRBs*



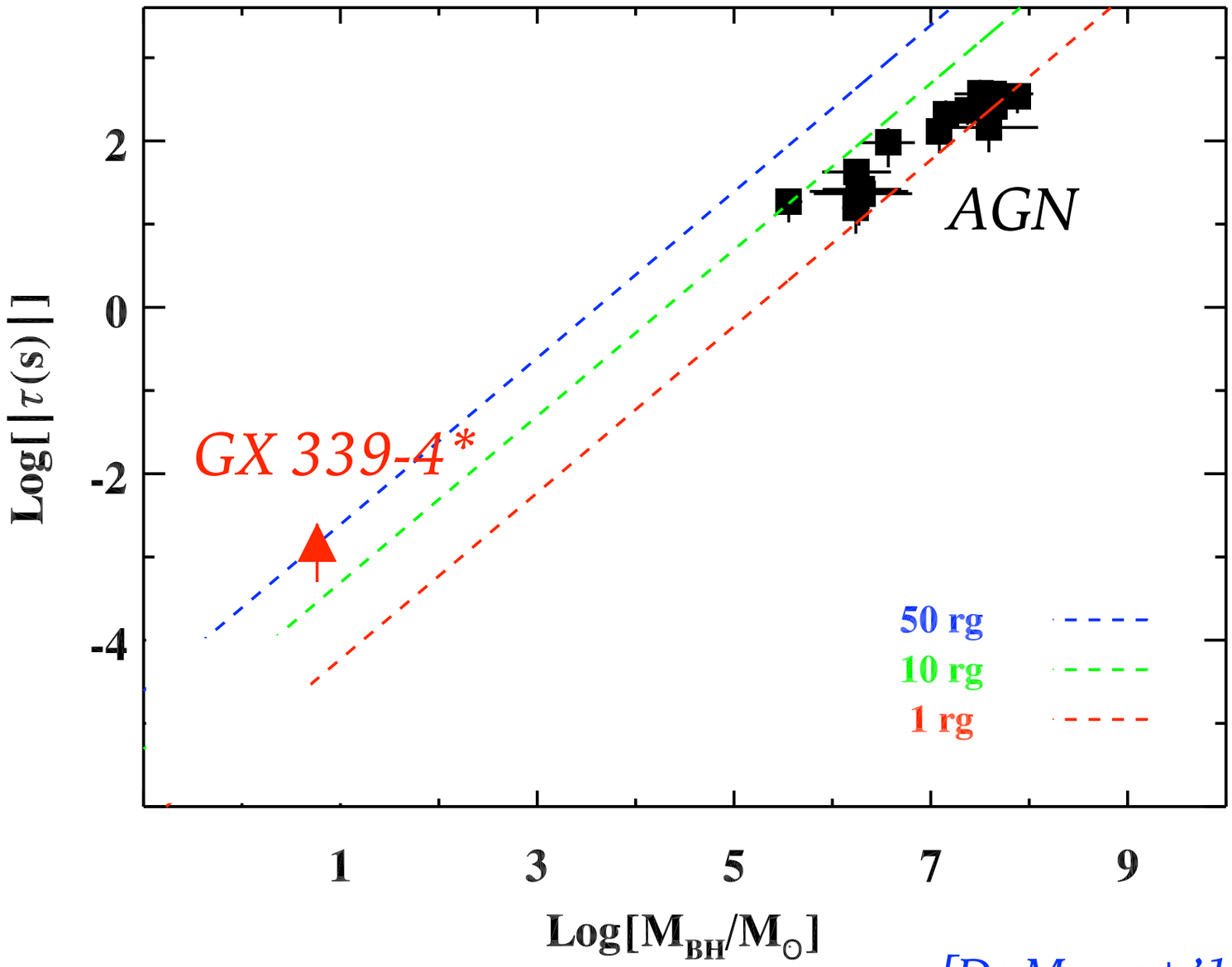

*[Uttley+'11]*

*Hard bands lagging the soft bands:*
*as for low-frequency lags in AGN*

*Soft band: inversion of the trend,*
*the 1-2 keV band leads the <1 keV band:*

*Thermal reverberation*

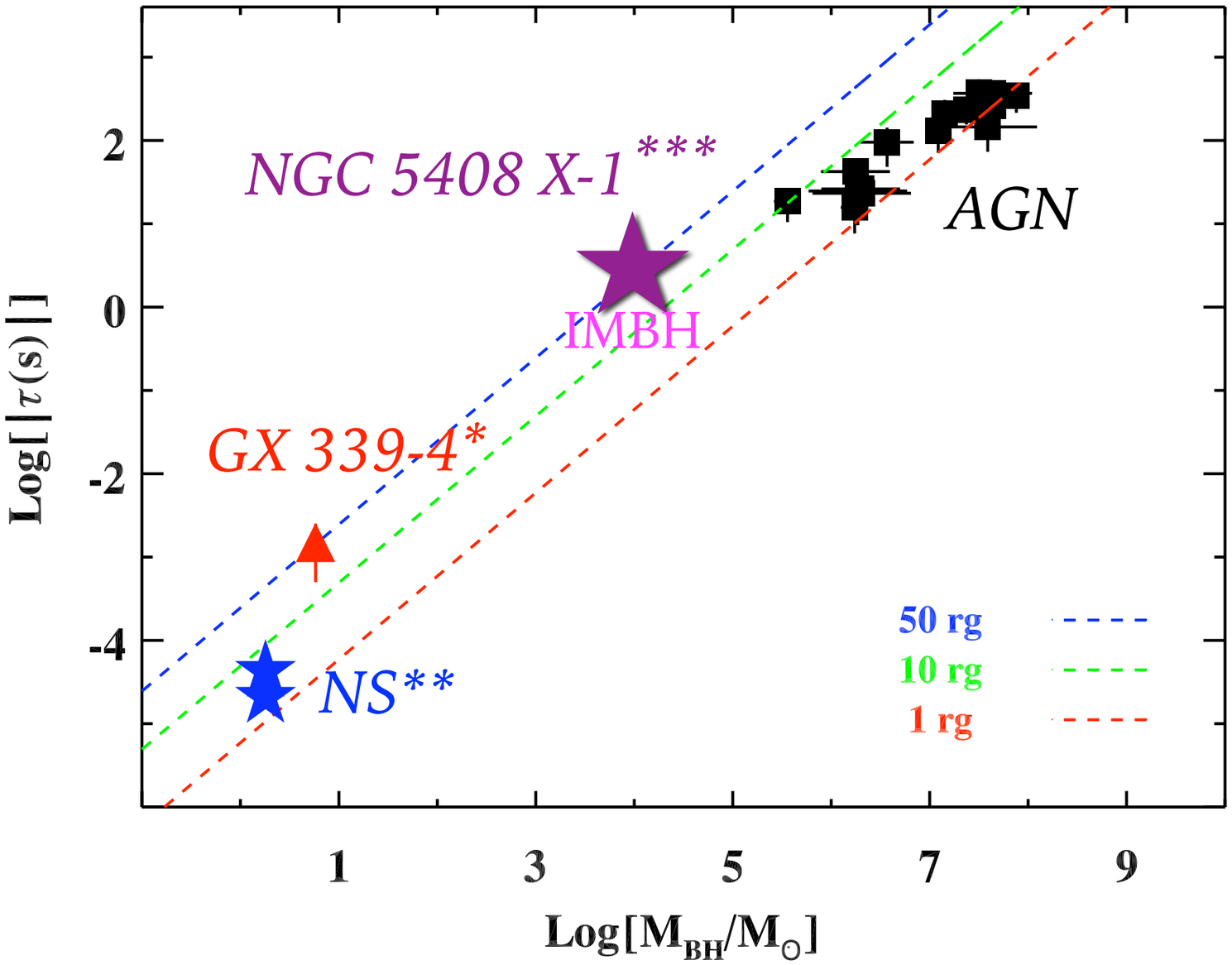
# *Soft time lags over different masses*




* *[Uttley+'11]*

*[De Marco+'13b]*

# *Soft time lags over different masses*



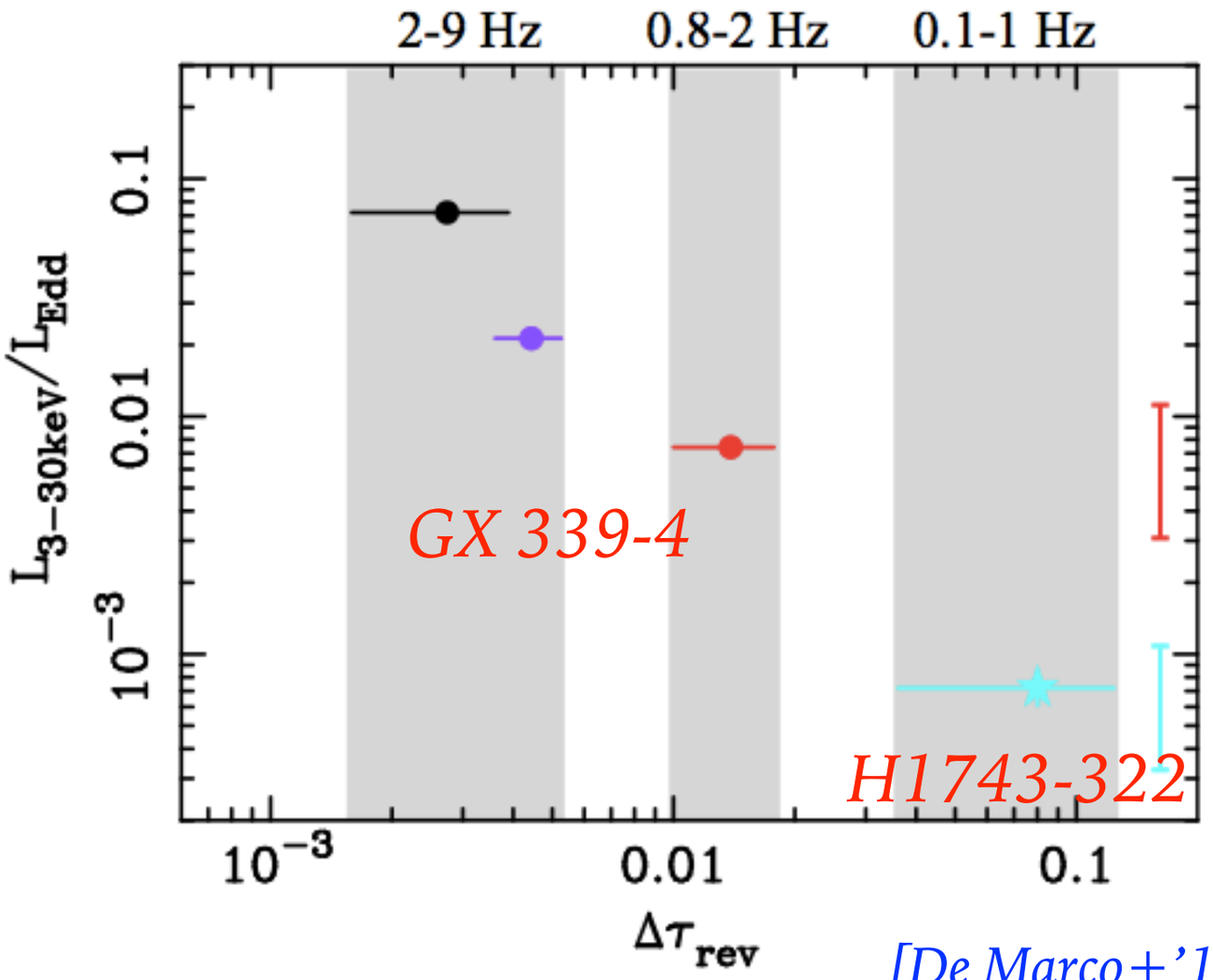

* *[Uttley+'11]*

** *[Vaughan+'98, Kaaret+'99, deAvellar+'13, Barret+'13]*

*** *[De Marco+'13b]*

*Do soft lags map the same fundamental distance in AGN, BHXRBs, ULXs and NS?*

# *Does the reverberation lag scale with L?*




[De Marco+'15]

*In hard-state BHXRBs the amplitude of the reverberation lag scales with luminosity*

*Evolving inner disc radius?*

# *Fe K lags*

*Error on the lag ∝ [(Intrinsic variability power in excess of noise fluctuations) (number of sampled variability cycles)]$^{-1/2}$*

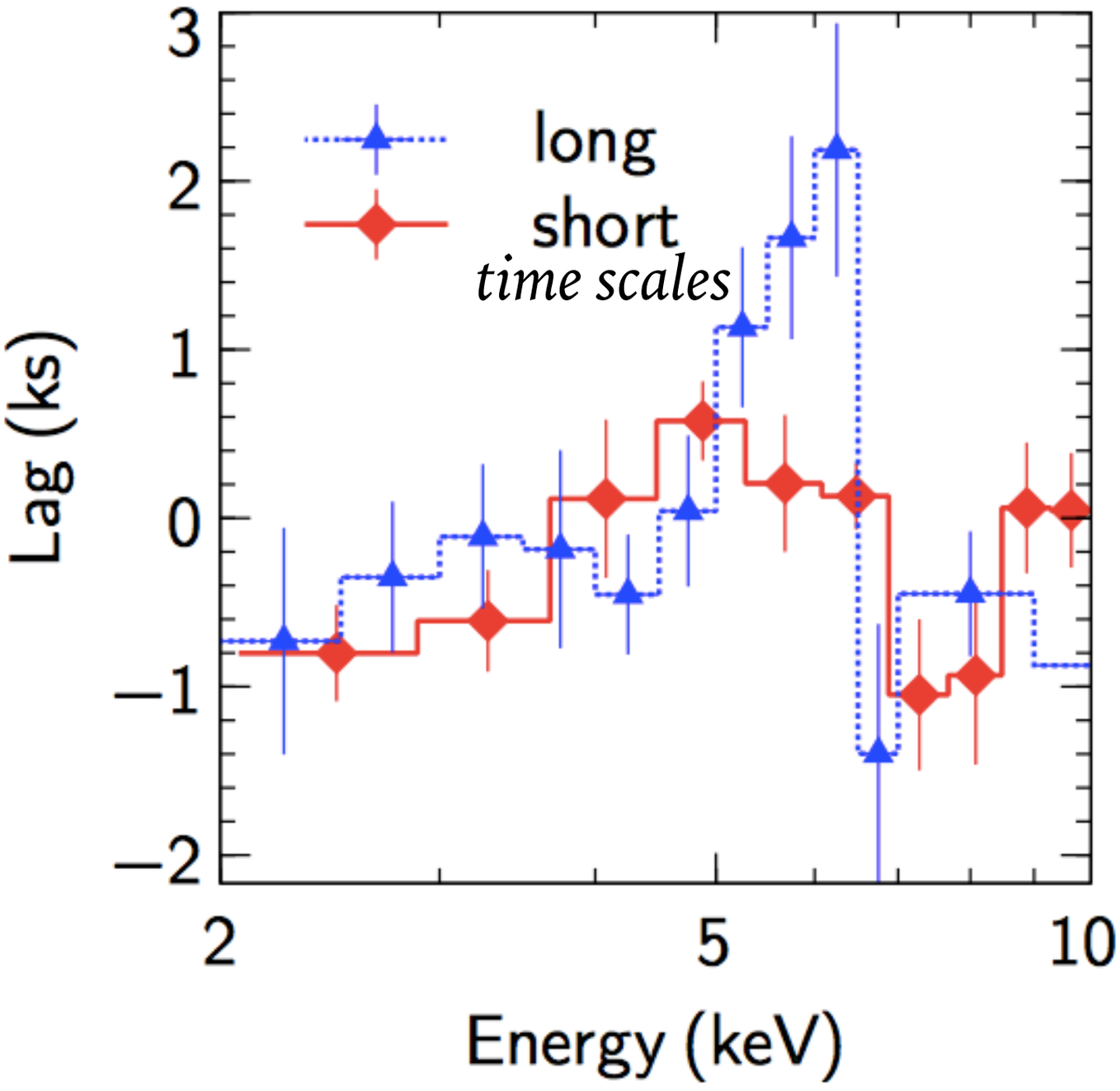
# *Fe K lags*

*Error on the lag ∝ [(Intrinsic variability power in excess of noise fluctuations) (number of sampled variability cycles)]$^{-1/2}$*

*Longer monitorings*

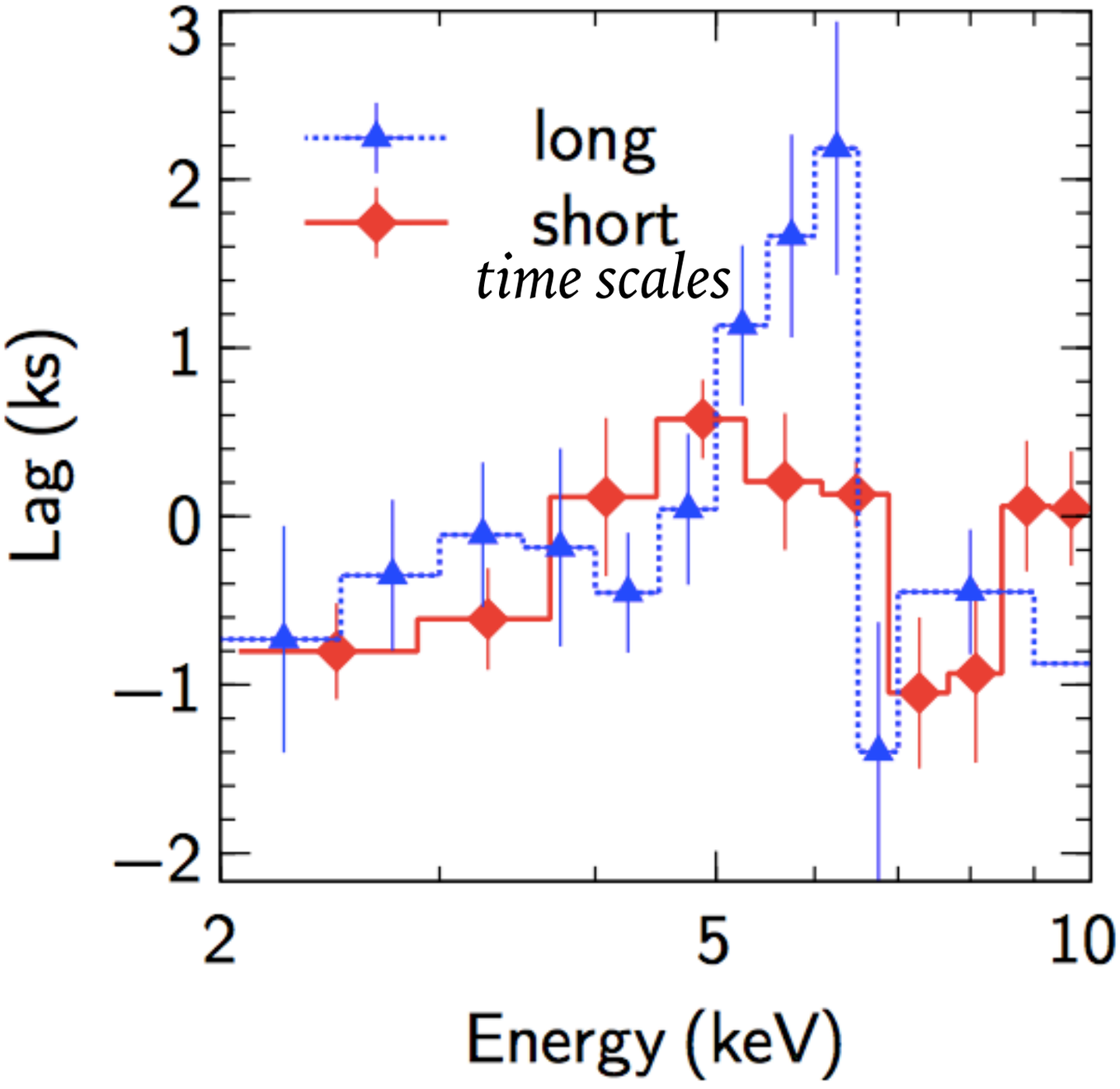
# *Fe K lags*

*First evidence: NGC 4151* *[Zoghbi+'12]*



# *Fe K lags*

*First evidence: NGC 4151* [*Zoghbi+'12*]




*Reverberation in the red tail occurs at high frequencies (short time scales) and has shorter delays*

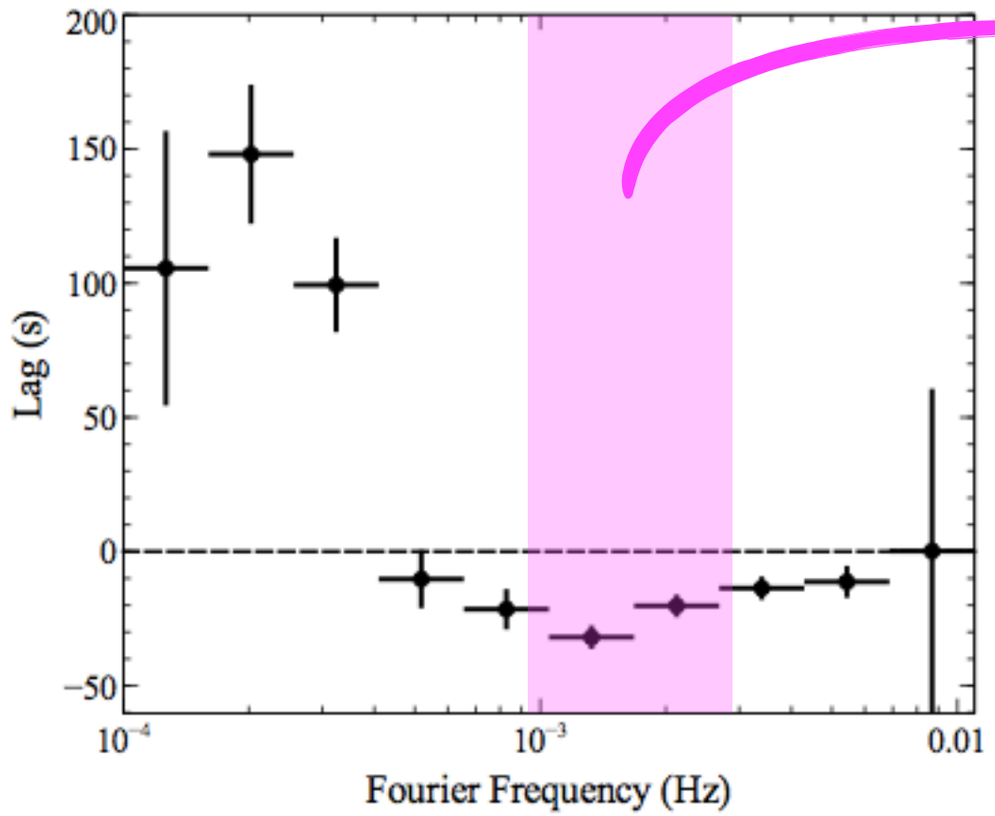
*smaller length scales*

*inner radii respond first*

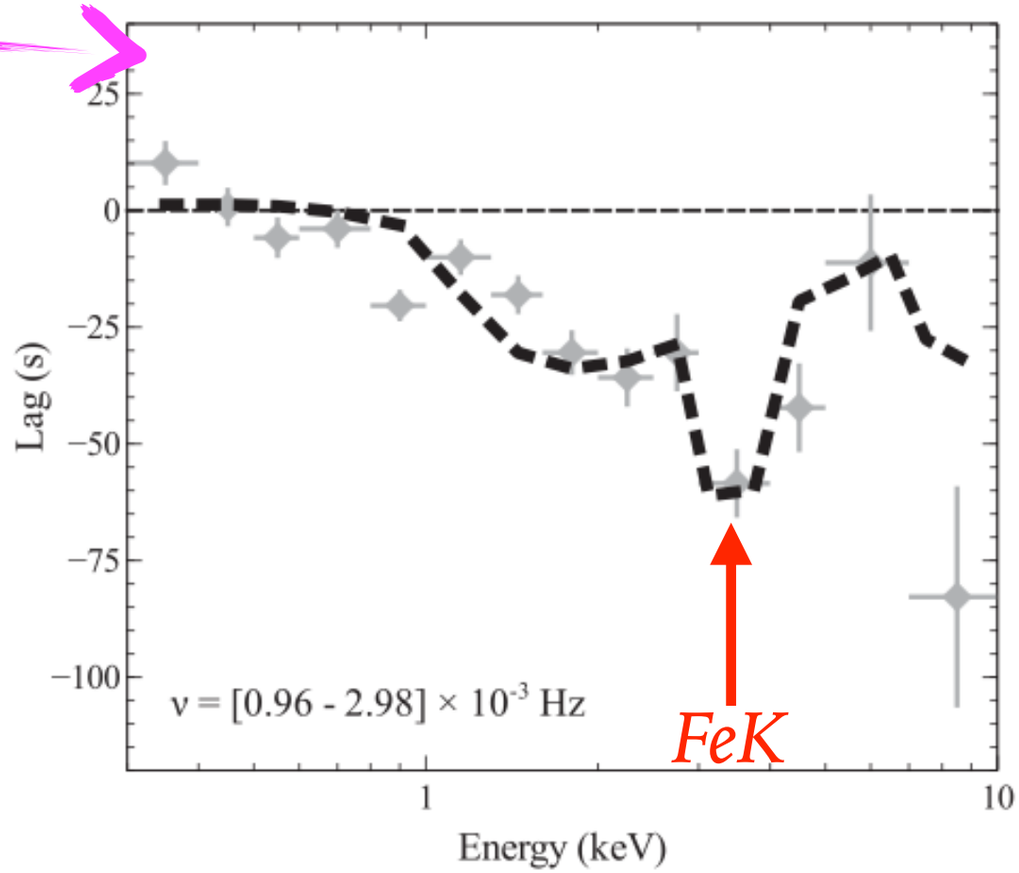
# *Fe K lags*

*1H0707-495*

*Lag vs Frequency*

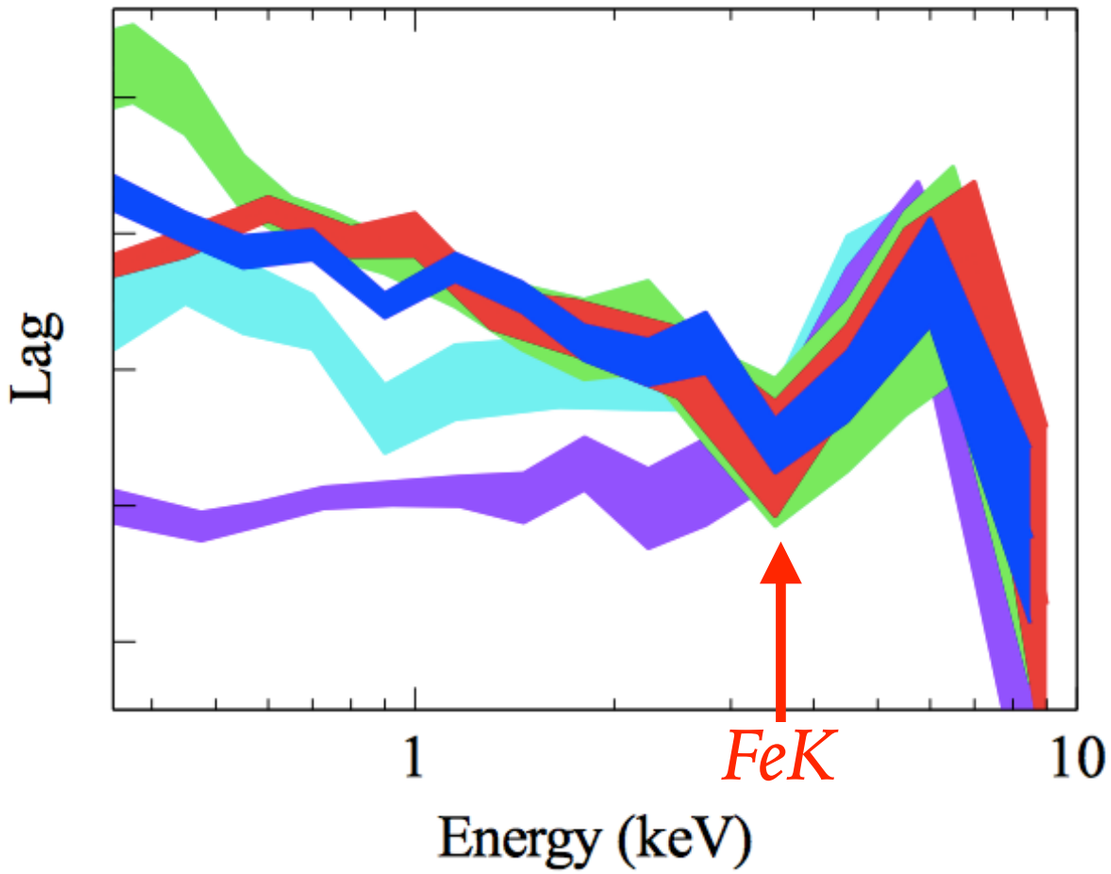


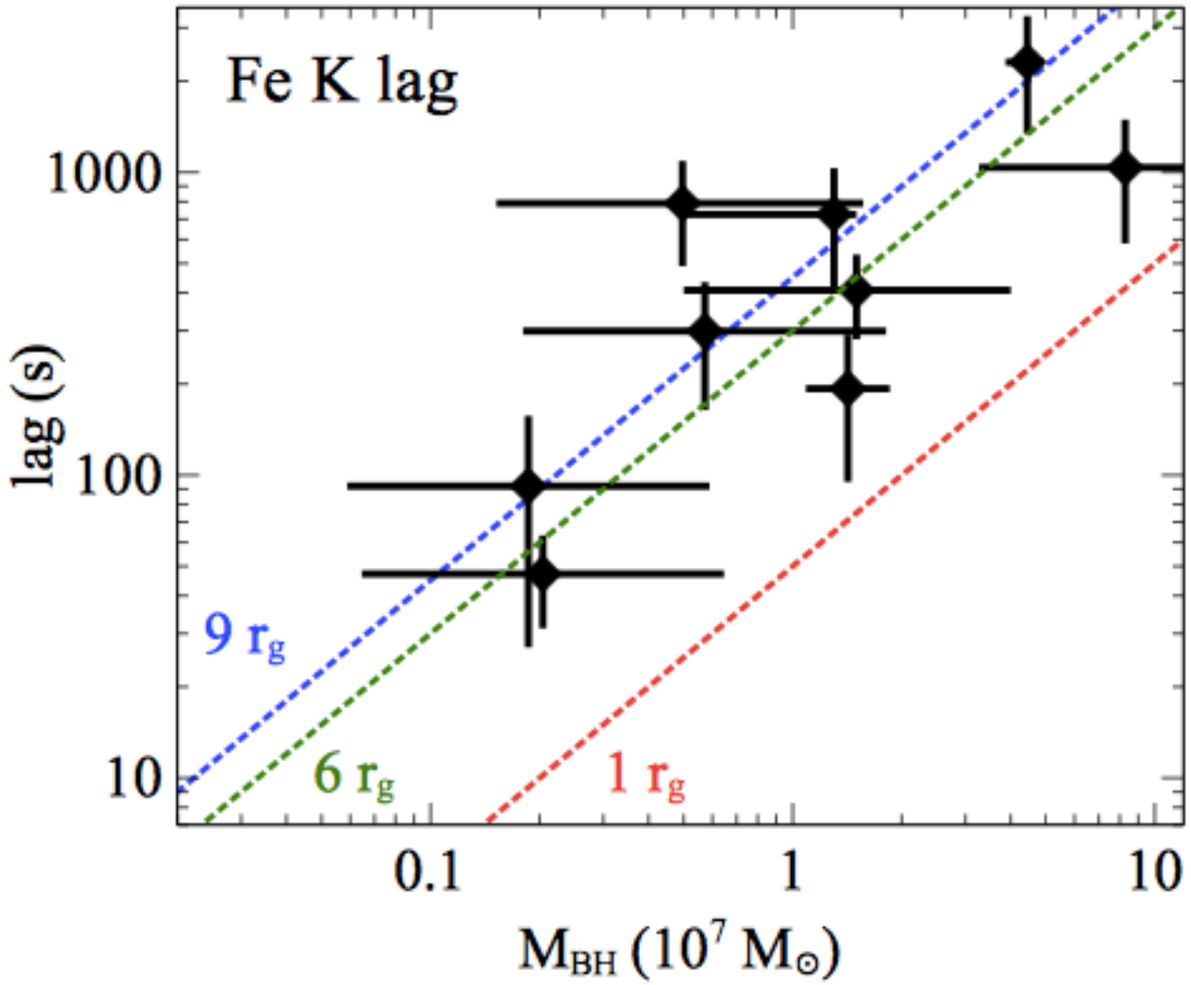

*Lag vs Energy*




*[Kara+'13a]*

# *Fe K lags*




*[Kara+'13b]*

# *Near future*

*Systematically characterize the phenomenology of high frequency X-ray lags (e.g. flux-dependence, Kara+'13; Alston+'13)*

*Characterize high frequency X-ray lags at E>10 keV (e.g. NuSTAR, Zoghbi+'14; Kara+'15)*

*Constrain the role of other components (propagation of accretion rate fluctuations, thermal reprocessing, distant reflection) in shaping the observed lags at all frequencies.*

*Modelling of the lags to constrain variability and geometry (e.g. Chiankun & Young 12; Wilkins & Fabian 13)*

*Explore the link of AGN high frequency lags with those observed in systems of different size (e.g. BHXRBs, Uttley +'11, De Marco+'15,ULXs, De Marco+'13b, NS, Barret+'13, deAvellar+'13)*

# *Near future*

*Systematically characterize the phenomenology of high frequency X-ray lags (e.g. flux-dependence, Kara+'13; Alston+'13)*

*Characterize high frequency X-ray lags at E>10 keV (e.g. NuSTAR, Zoghbi+'14; Kara+'15)*

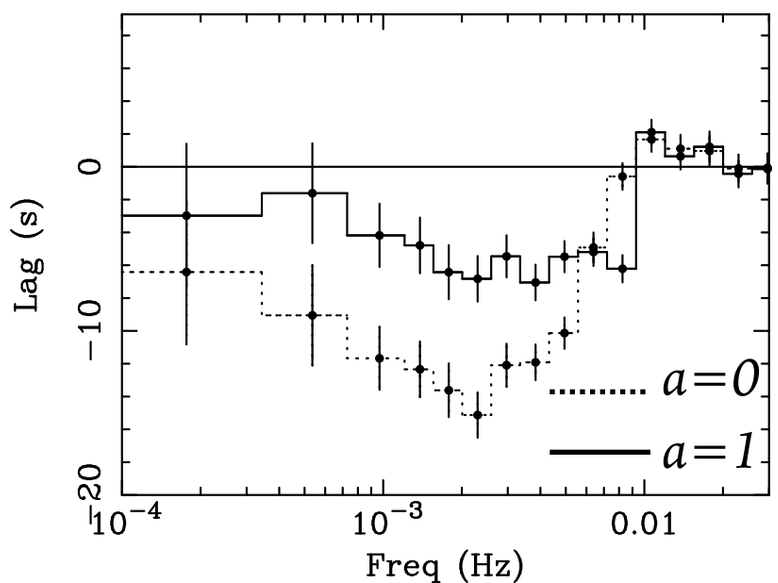
*Constrain the role of other components (propagation of accretion rate fluctuations, thermal reprocessing, distant reflection) in shaping the observed lags at all frequencies.*

*Modelling of the lags to constrain variability and geometry (e.g. Chiankun & Young 12; Wilkins & Fabian 13)*

*Explore the link of AGN high frequency lags with those observed in systems of different size (e.g. BHXRBs, Uttley +'11, De Marco+'15,ULXs, De Marco+'13b, NS, Barret+'13, deAvellar+'13)*

# *Far future*

*Athena will significantly improve the quality of X-ray lags measurements (mostly in the soft band) ➔ constrain important parameters, e.g. BH spin*



***Thanks!***