# Probing the inner accretion flow with high-frequency X-ray variability

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STRONGGRAVITY
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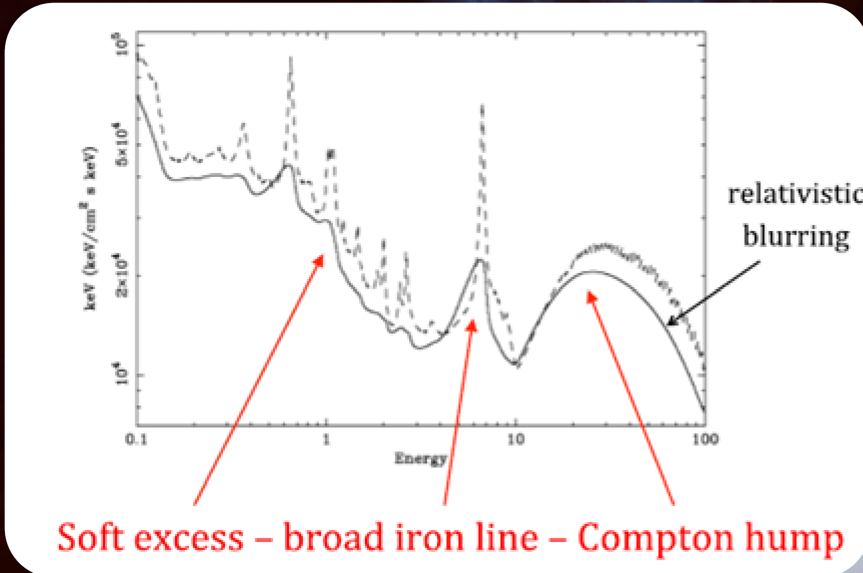
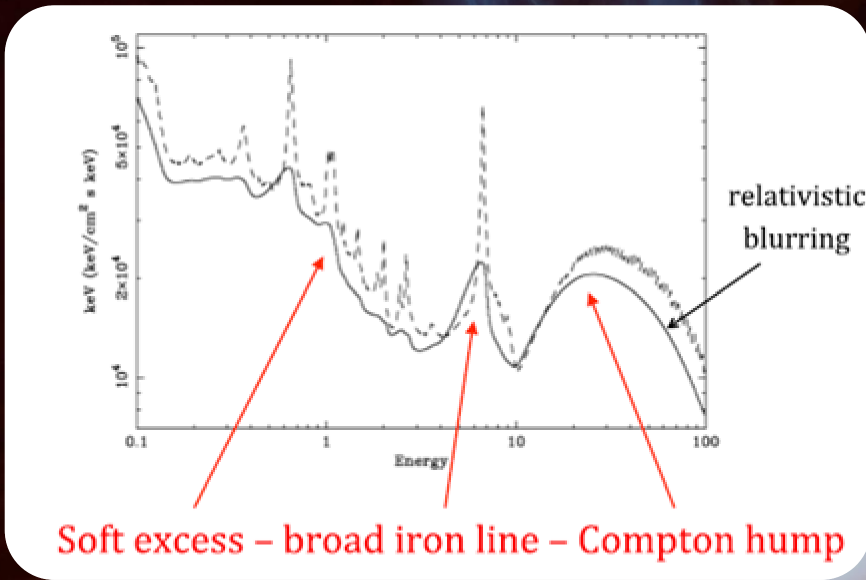
NAM
06-07-15

Cambridge X-Ray Astronomy



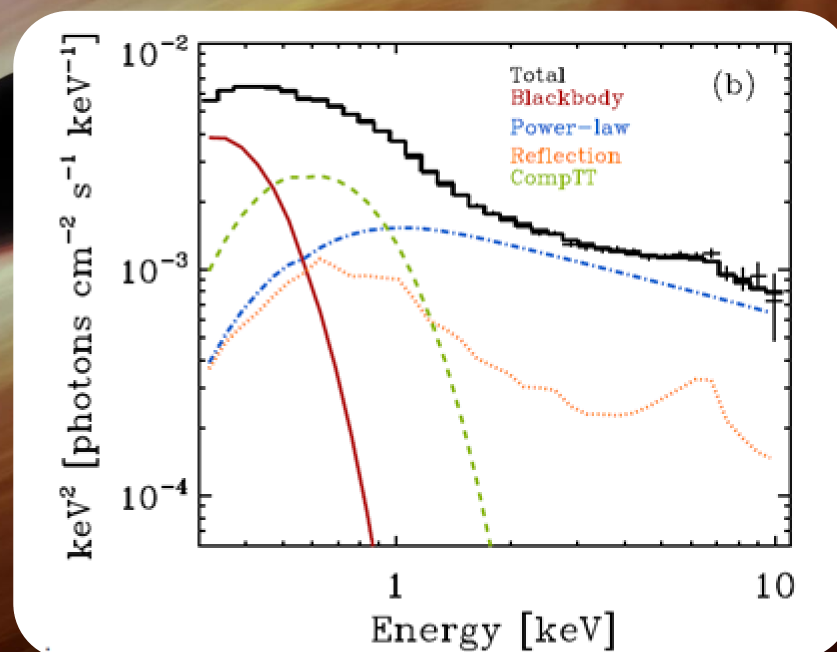

Iron Kα (6.4 keV) and blurring of reflection spectrum can be used to constrain BH spin (see e.g. Reynolds & Fabian 2000)

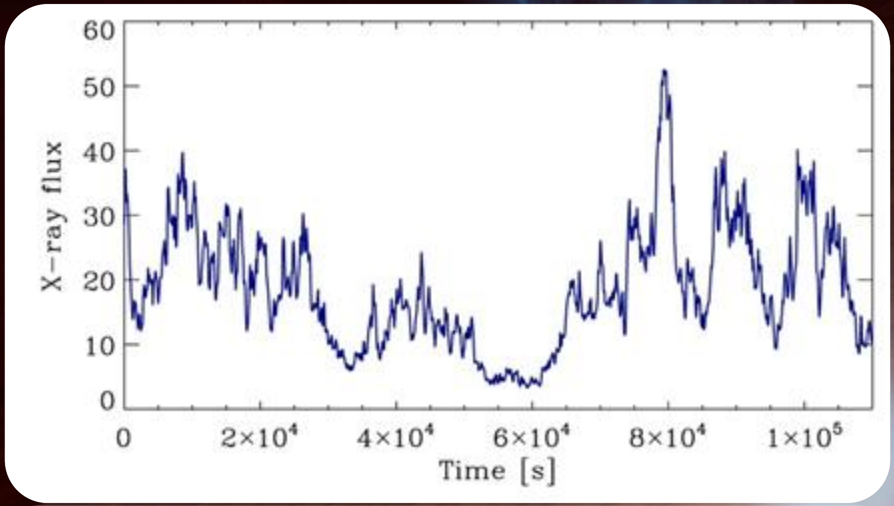



Iron Kα (6.4 keV) and blurring of reflection spectrum can be used to constrain BH spin (see e.g. Reynolds & Fabian 2000)

But, AGN spectra are messy, particularly below 1 keV

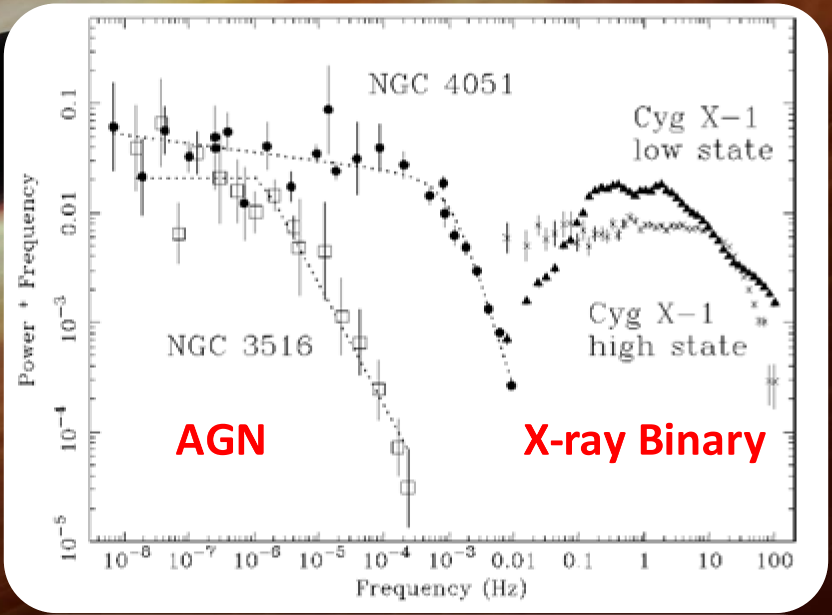
=> Want to use spectral variability to understand variable emission components





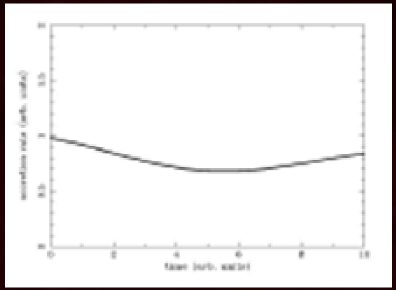

Variable in all wavebands and on all timescales. Largest, most-rapid variations seen in X-rays

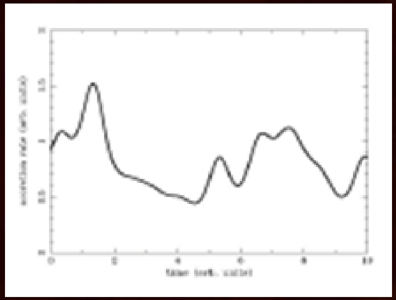
Variability amplitude as a function of temporal frequency

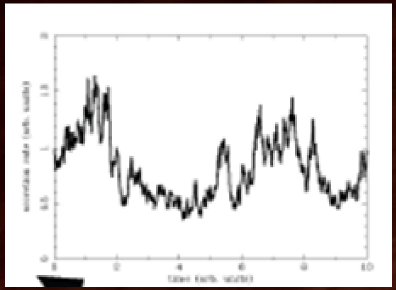


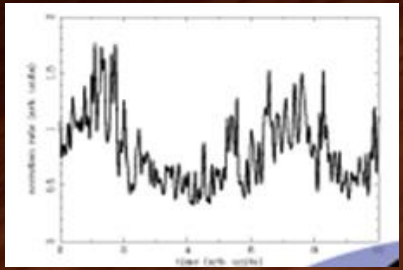
# Propagation of mass accretion rate fluctuations

Modulation of independent frequencies (e.g. Arevalo & Uttley 2006)

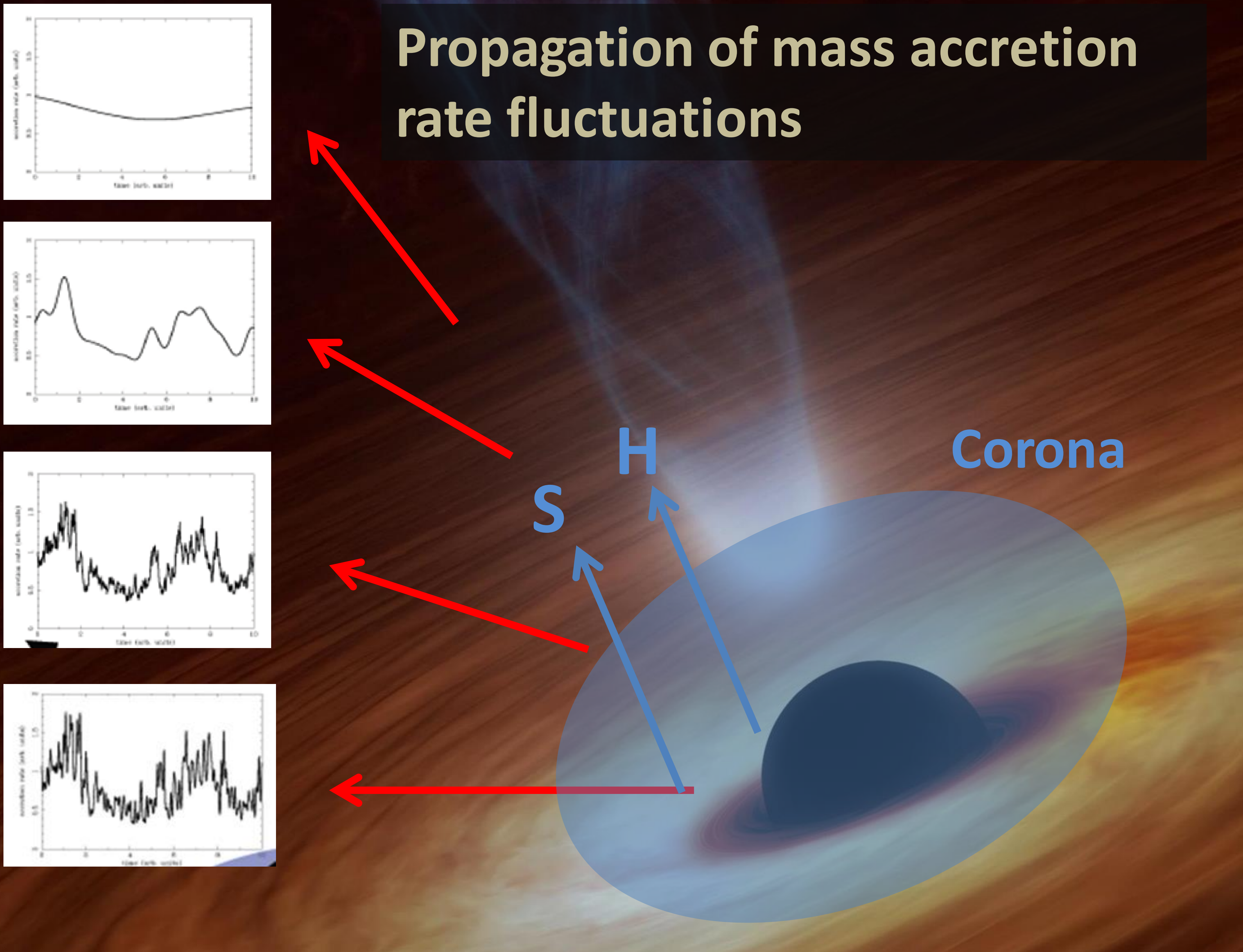




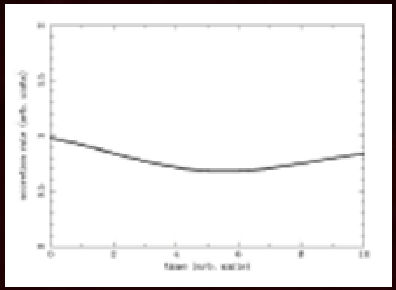


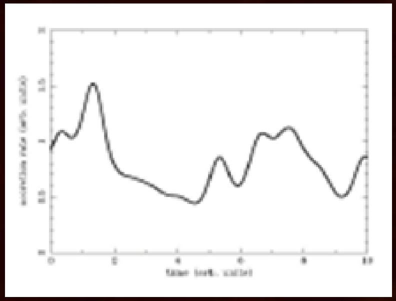


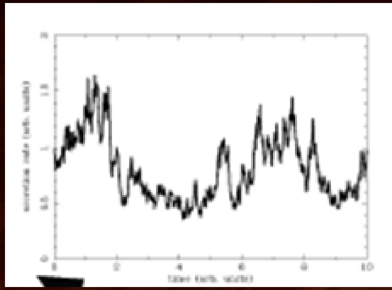
# Propagation of mass accretion rate fluctuations

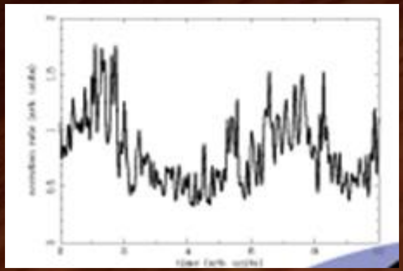


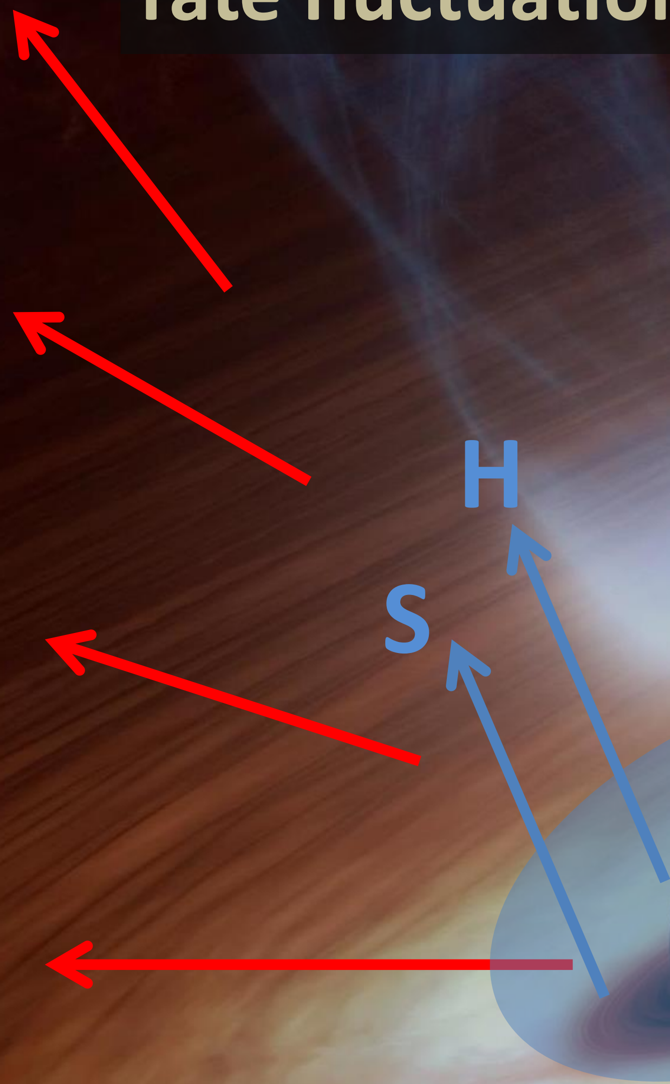
# Propagation of mass accretion rate fluctuations

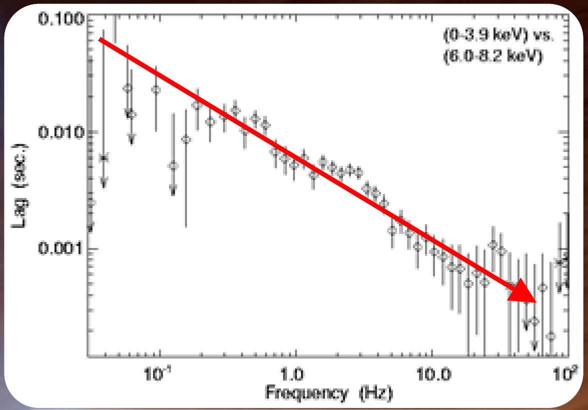




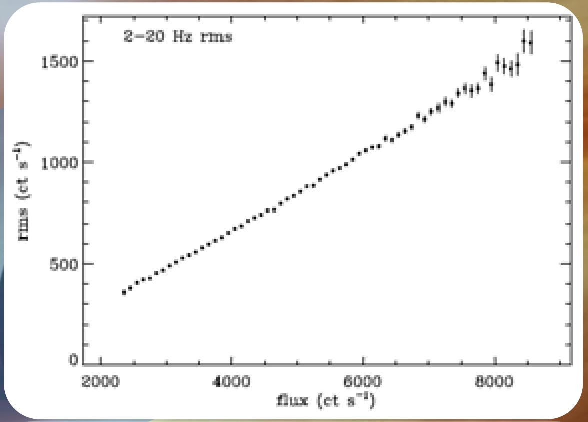






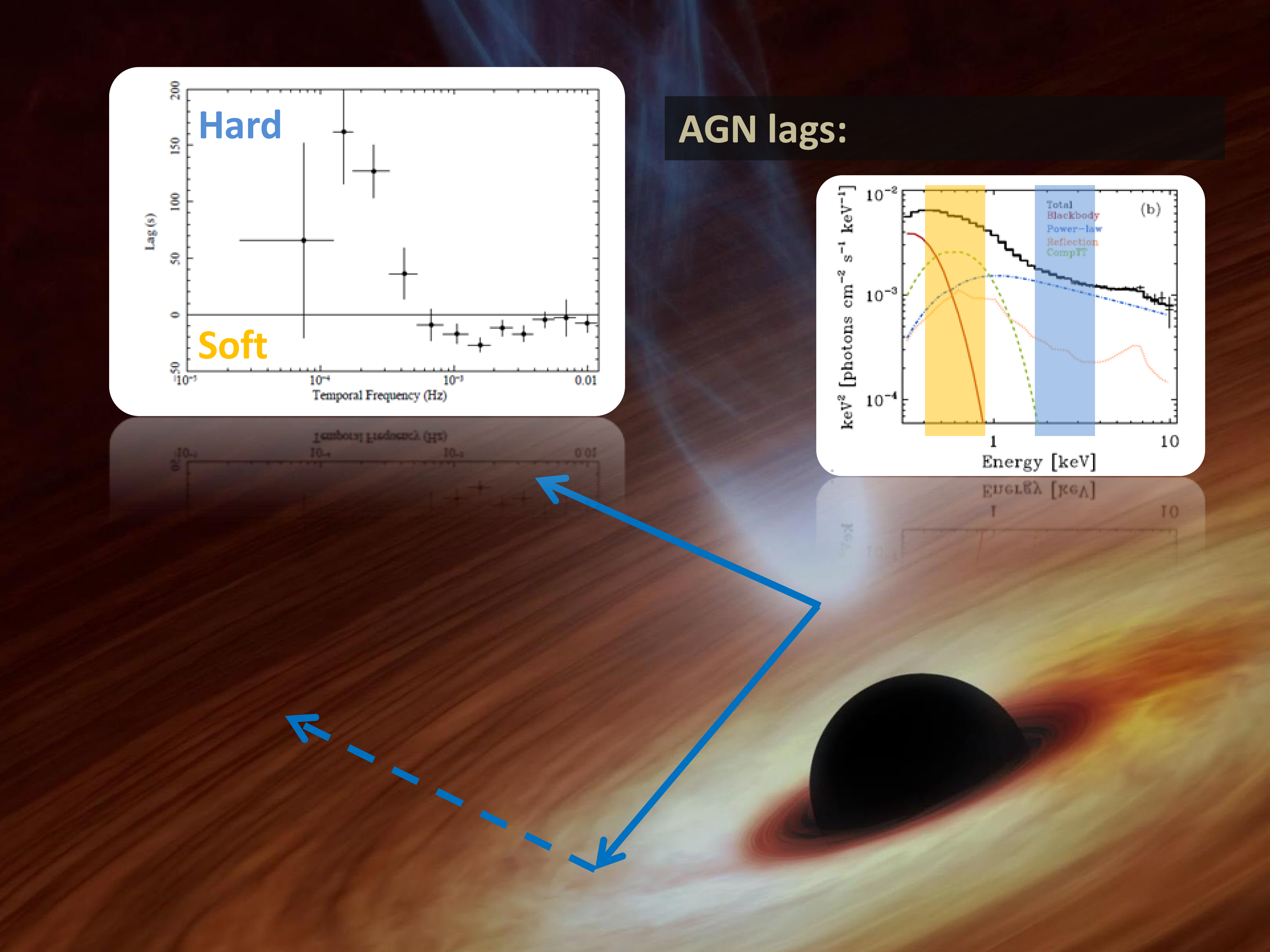




Hard band lags

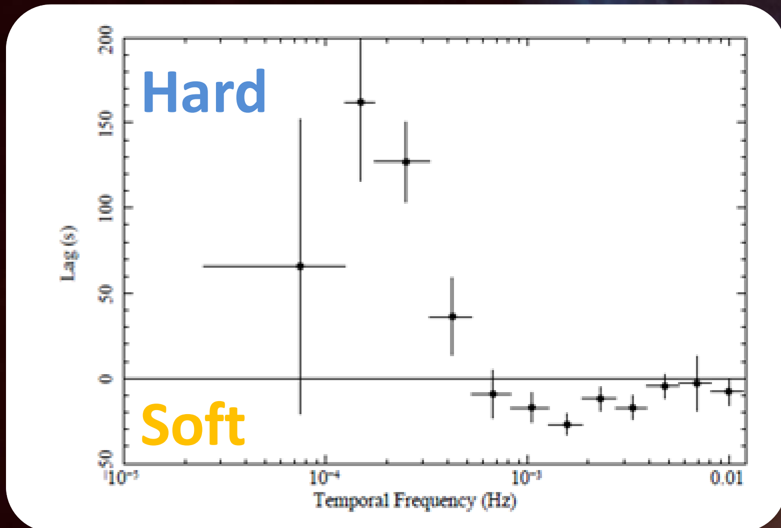



rms-flux relation

# AGN lags:



Hard
Soft
Lag (s)
Temporal Frequency (Hz)
10⁻⁵
10⁻⁴
10⁻³
0.01
200
150
100
50
0
-50
keV² [photons cm⁻² s⁻¹ keV⁻¹]
Energy [keV]
(b)
Total
Blackbody
Power−law
Reflection
CompTT
1
10

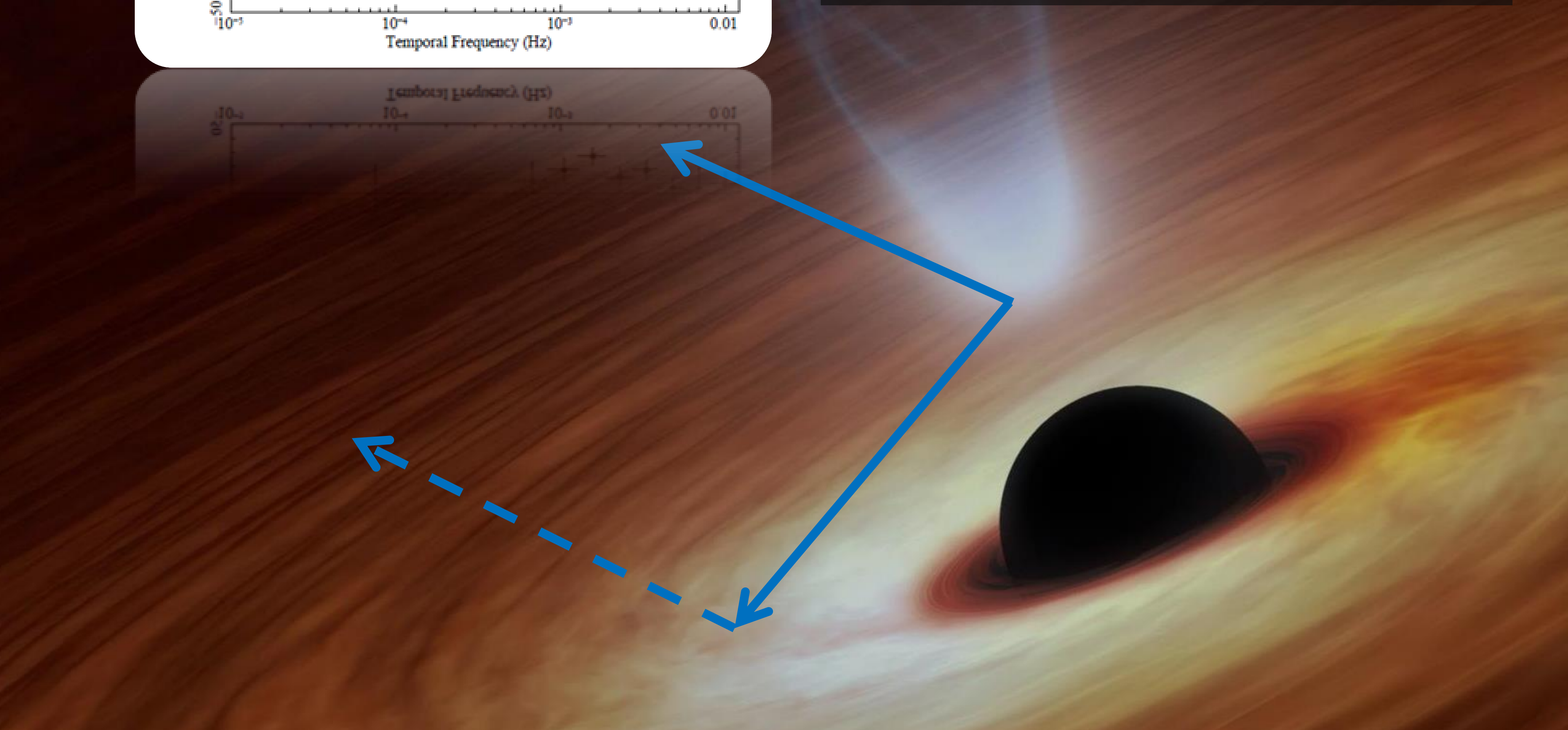


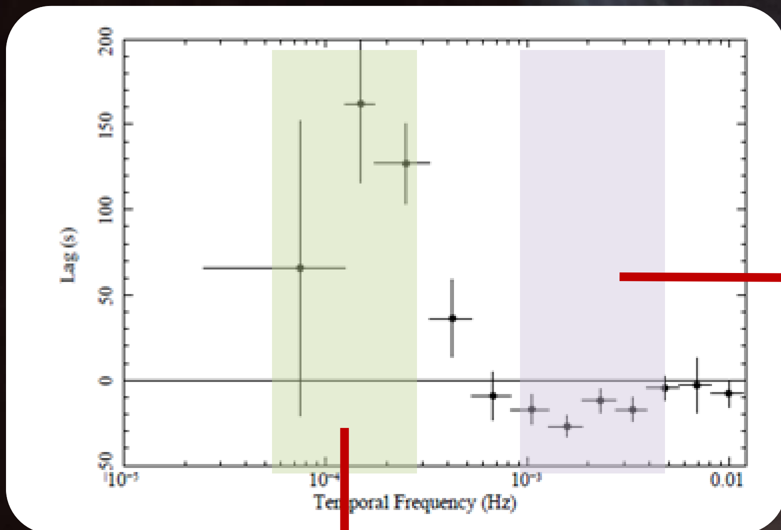

**AGN lags:**

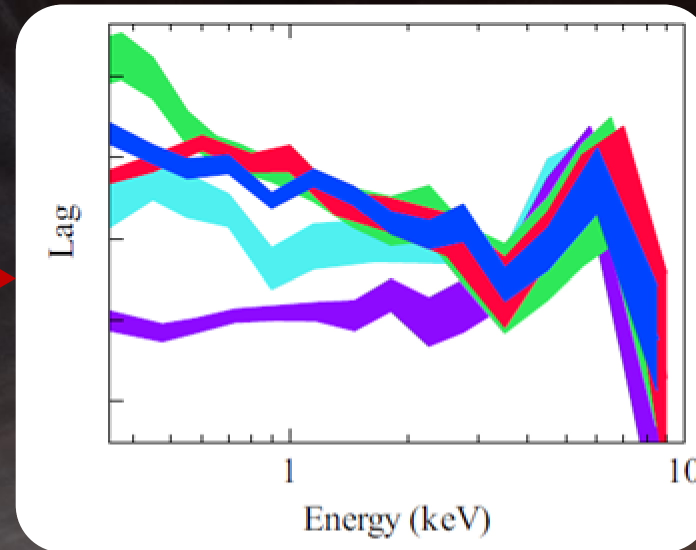
**Hard bands lag at low-f**

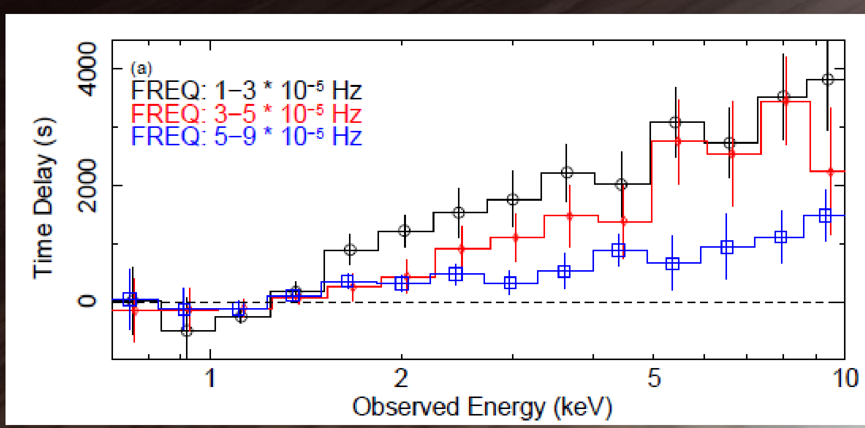
**Soft bands lag at high-f**

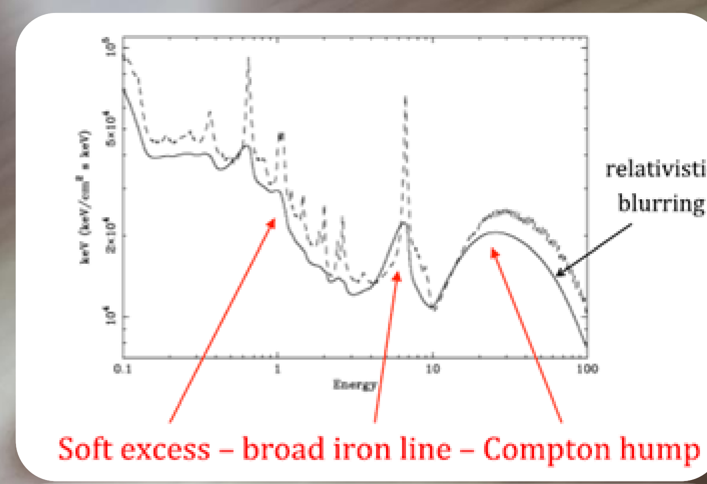
**- Interpreted as reverberation of primary continuum**




Lag (s)
200
150
100
50
0
-50
$10^{-5}$
$10^{-4}$
$10^{-3}$
0.01
Temporal Frequency (Hz)

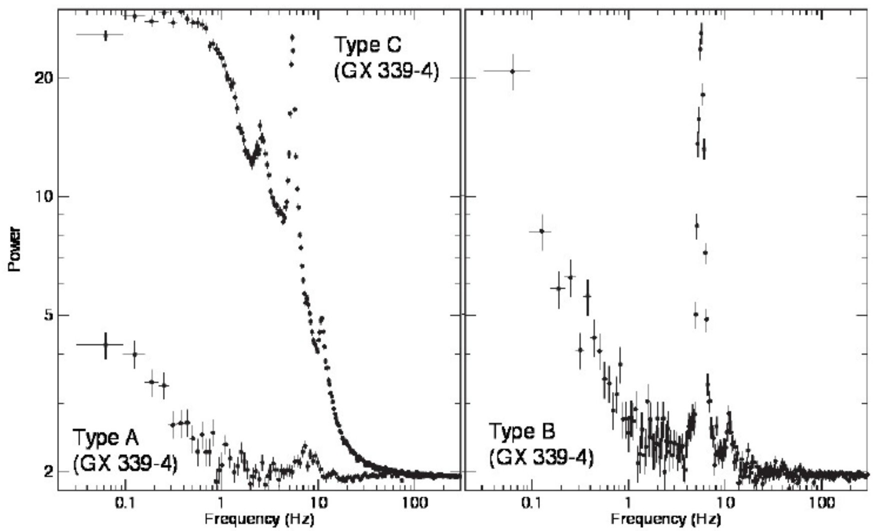

Lag
1
10
Energy (keV)


(a)
FREQ: 1–3 * $10^{-5}$ Hz
FREQ: 3–5 * $10^{-5}$ Hz
FREQ: 5–9 * $10^{-5}$ Hz
Time Delay (s)
4000
2000
0
1
2
5
10
Observed Energy (keV)


relativistic
blurring
0.1
1
10
100
Energy
Soft excess – broad iron line – Compton hump

# QPOs in BH-XRBs

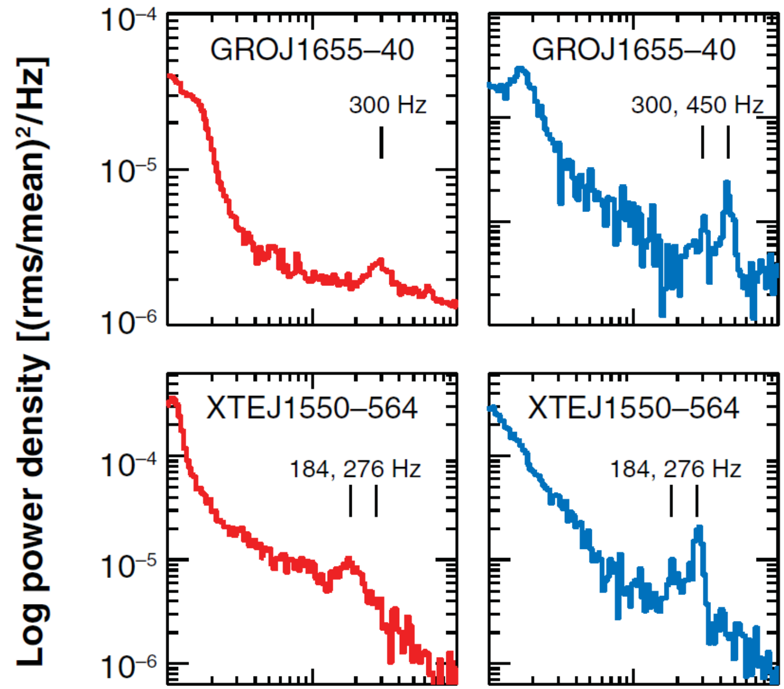
**LFQPOs < 10 Hz**




**SIMS: A + B**
**HIMS: C**
**LHS: C**
**HSS: C**

Motta + 2011
See also Belloni & Stella 2014

**HFQPOs > 30 Hz**

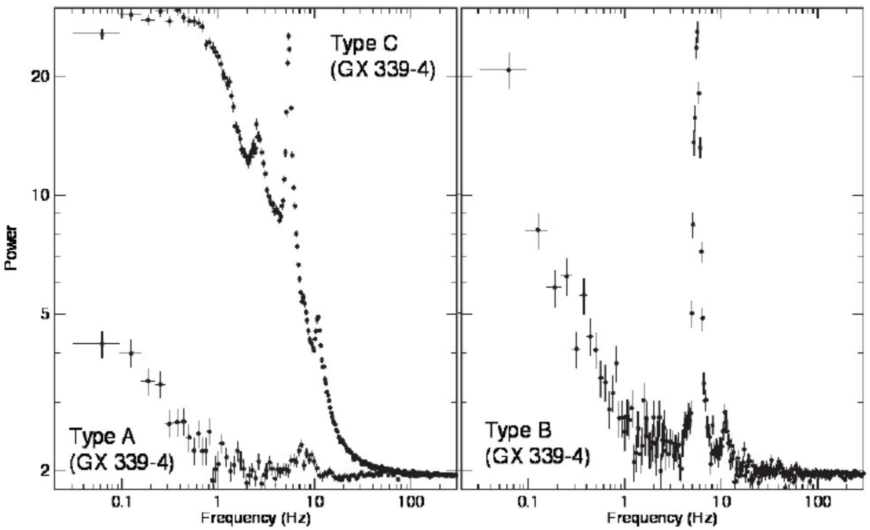



**VH/I states**

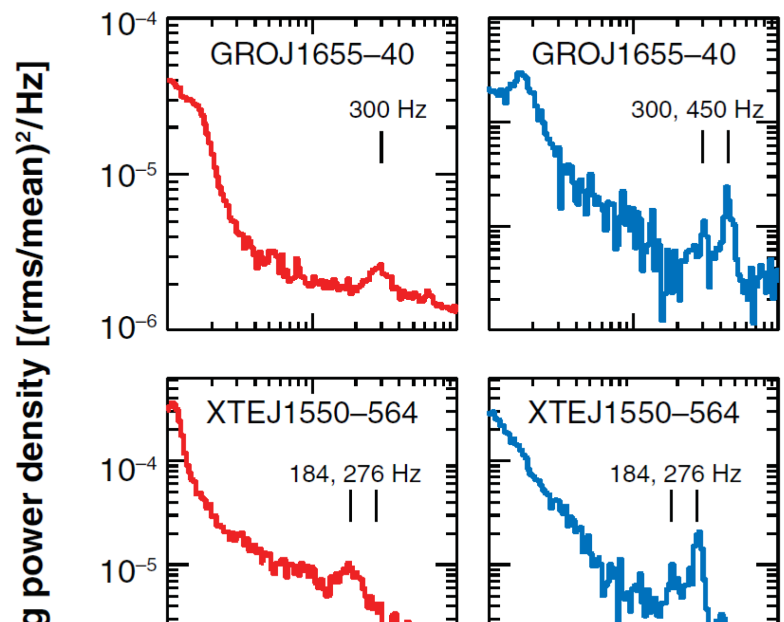
Remillard & McClintock 2006

# QPOs in BH-XRBs

## LFQPOs




## HFQPOs



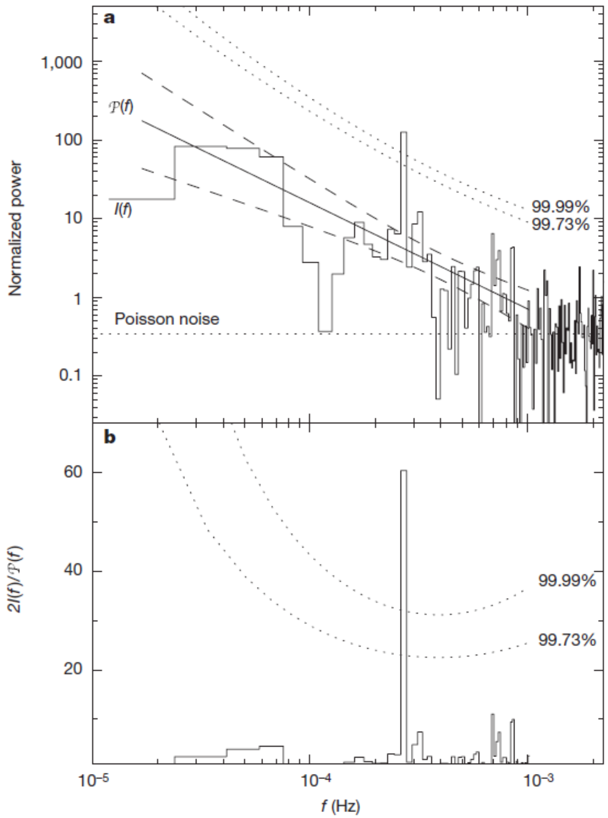

**If accretion process is scale invariant then we expect to see both HF and LF QPOs in AGN**

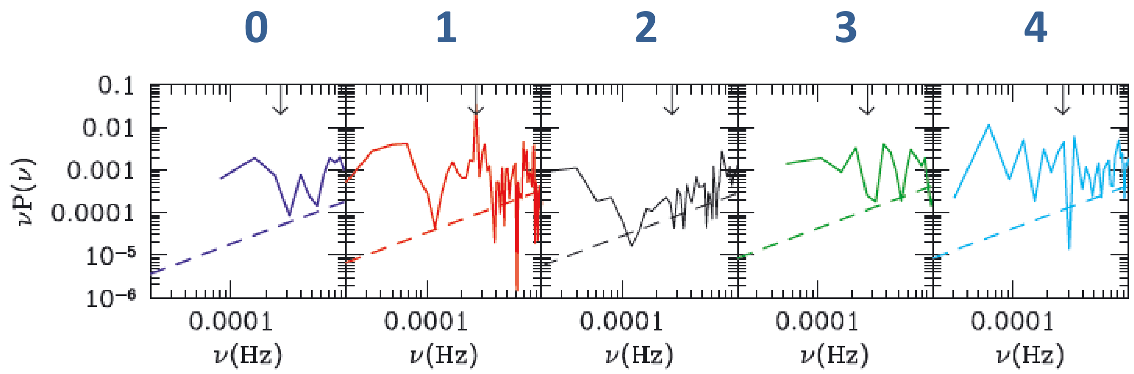
Motta + 2011
See also Belloni & Stella 2014

Remillard & McClintock 2006

# QPO in RE J1034+396 (NLS1)

**Ob 1: 90 ks**



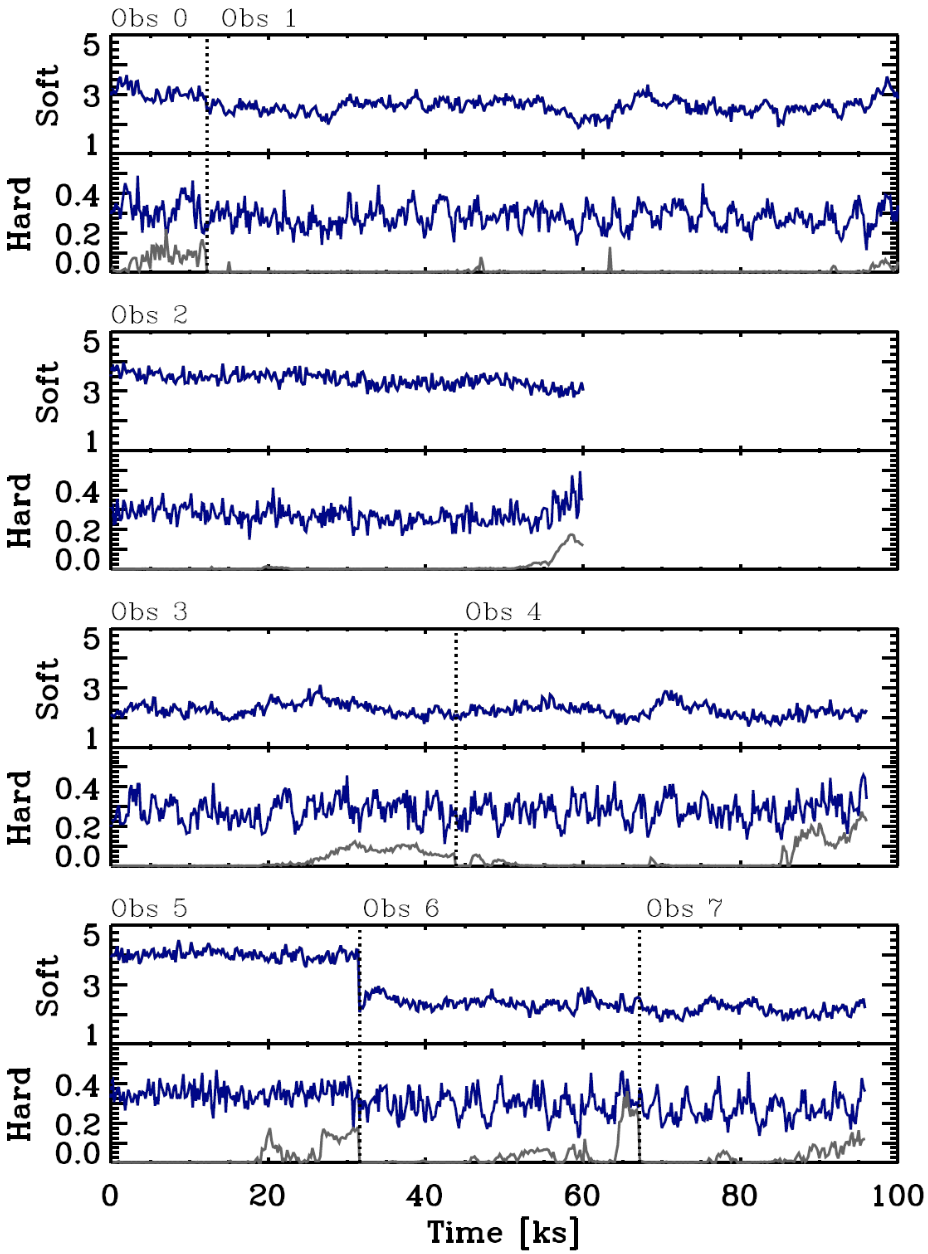




- $2.6 \times 10^{-4}$ Hz (1 hour)
- $L_{Bol} / L_{Edd}$ ~ 1-4
- HFQPO (but LFQPO not ruled out)
- Only seen in full (0.3-10 keV) in Obs 1

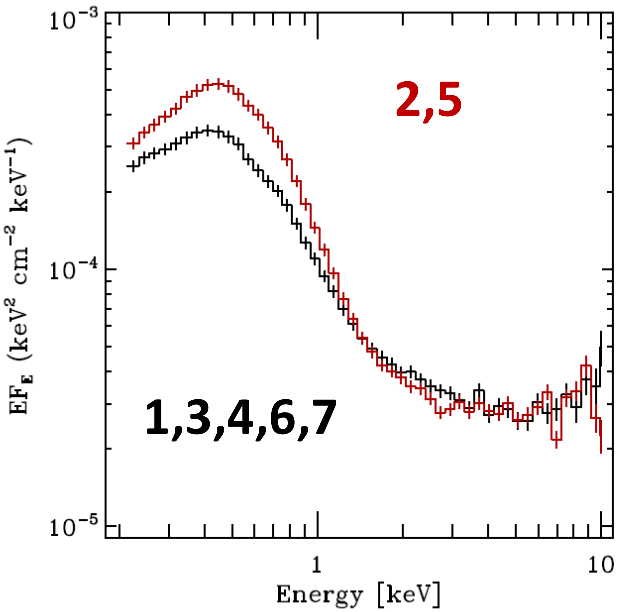
Gerlinski + 2008
See also Vaughan 2010

Middleton + 2011

# *XMM* observations (0.3-0.8 and 1-4 keV)



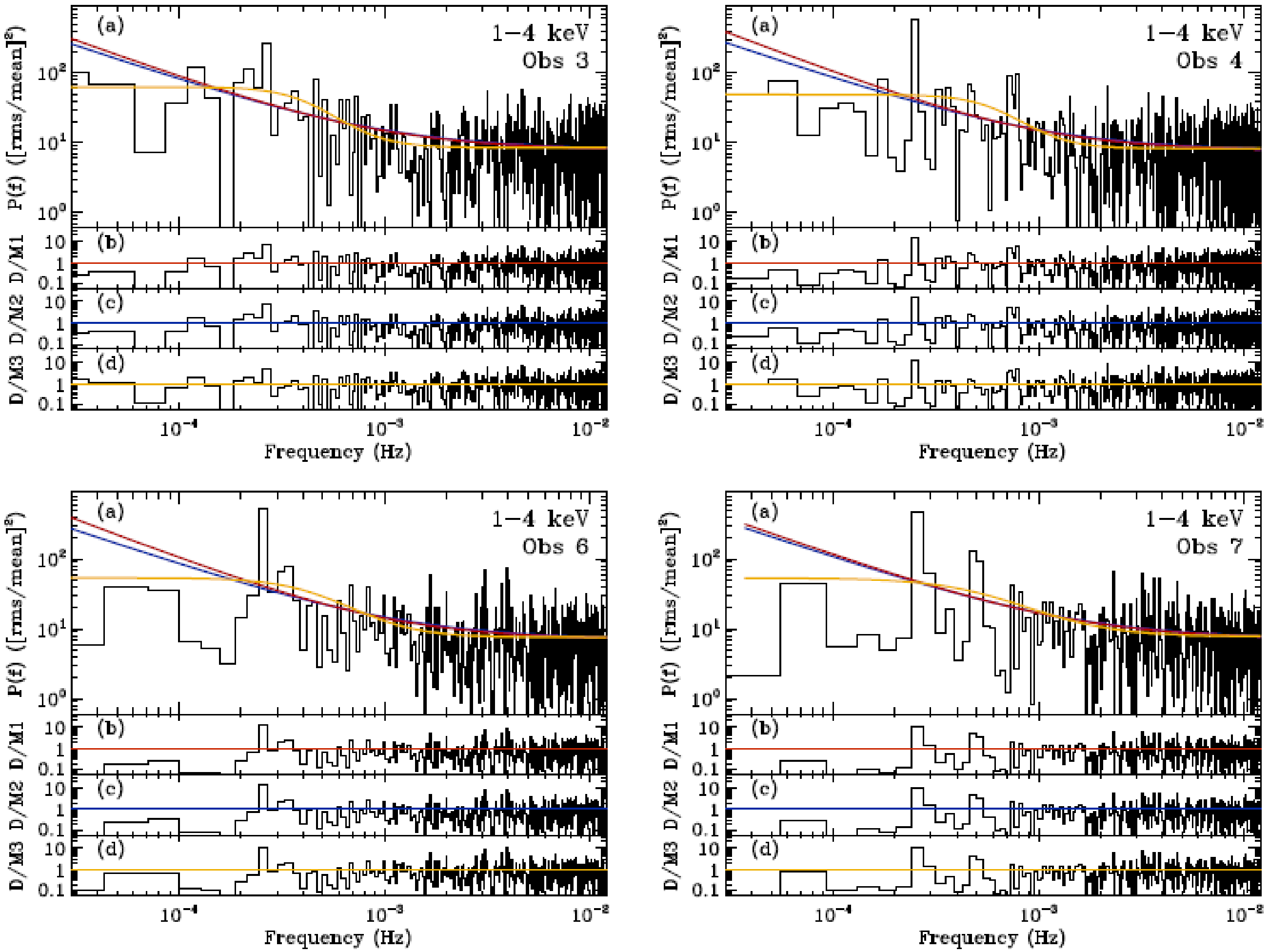

**2007**




**2011**

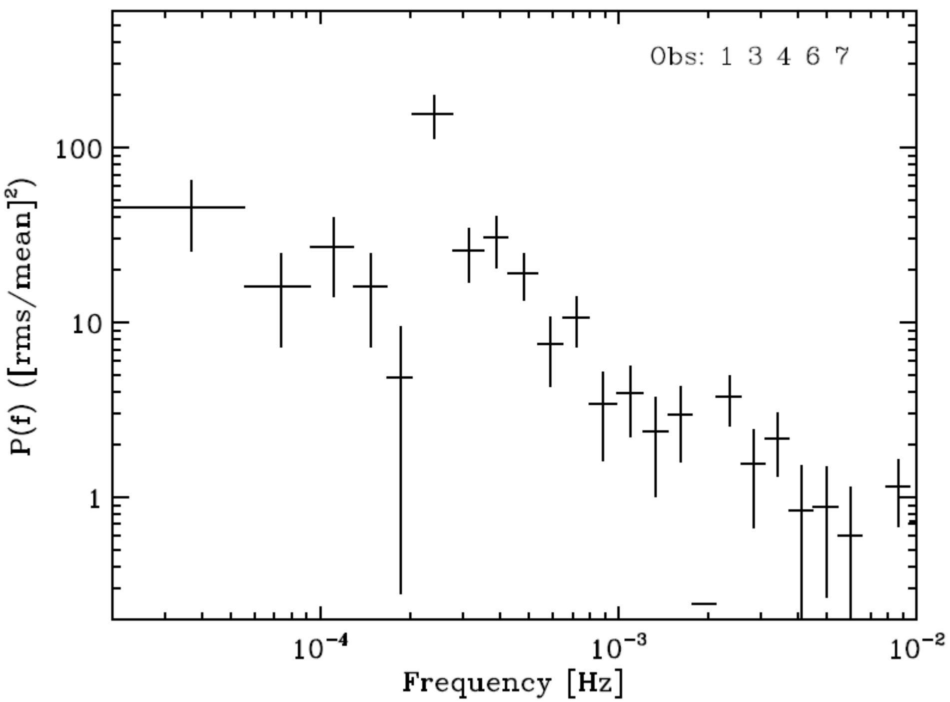
# QPO present in 1-4 keV band in the 5 low flux/ spectrally-harder observations

~6 % rms




WA, Markeviciute, Kara, Fabian, Middleton, 2014, MNRAS , 445, 16

# RE J1034+396 hard band PSD




Now 250 ks of QPO data

Accretion timescales:

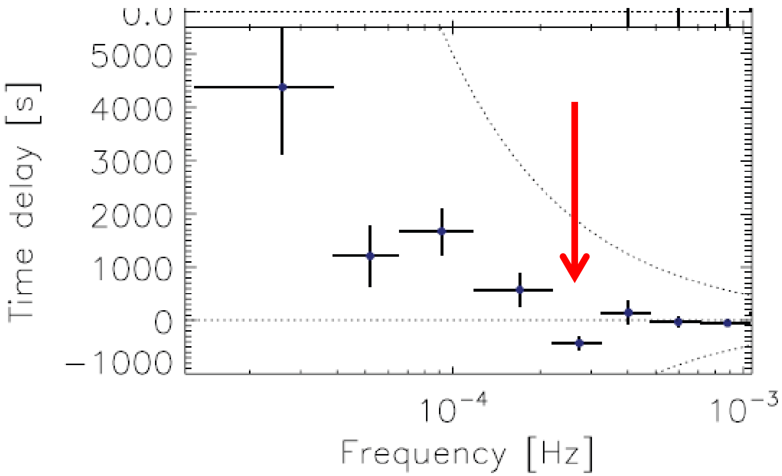
XRBs:
~ 1000 ct/s ($M_{bh}$ ~ 10)

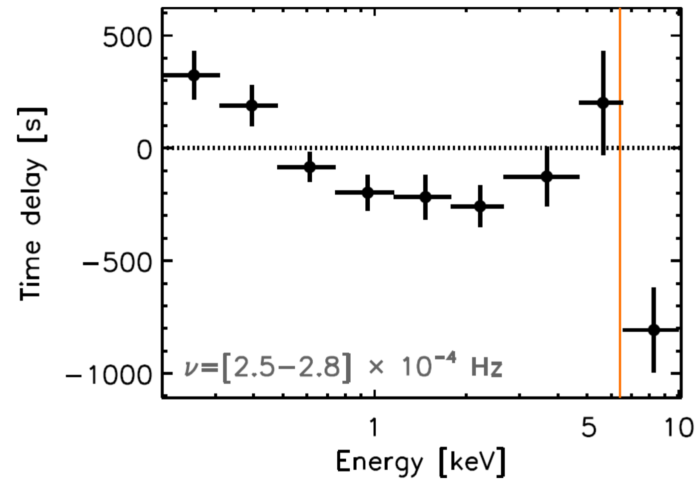
AGN:
~ 10 ct/s ($M_{bh}$ ~$10^6$)

But, characteristic timescale of variability scales with $M_{bh}$ ($10^5$)

Therefore, factor ~1000 more counts per characteristic timescale in AGN

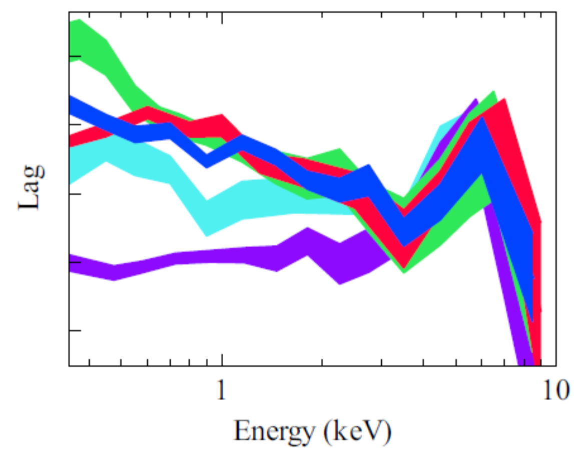
# RE J1034+396 time lags




**Soft lag at QPO**
**(see also Zoghbi + 2011)**

**Evidence for Fe K reverberation from QPO**



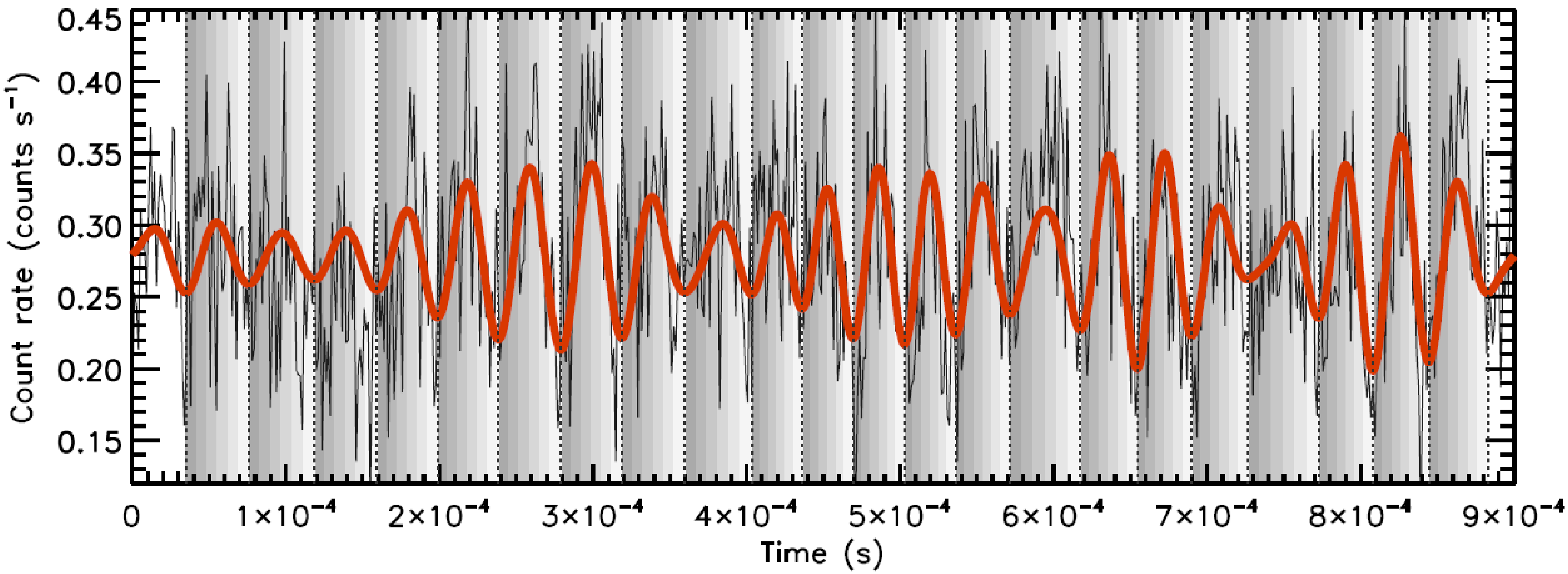

Markeviciute, WA, et al, *in prep*

Uttley et al 2014

# Phase resolving the QPO

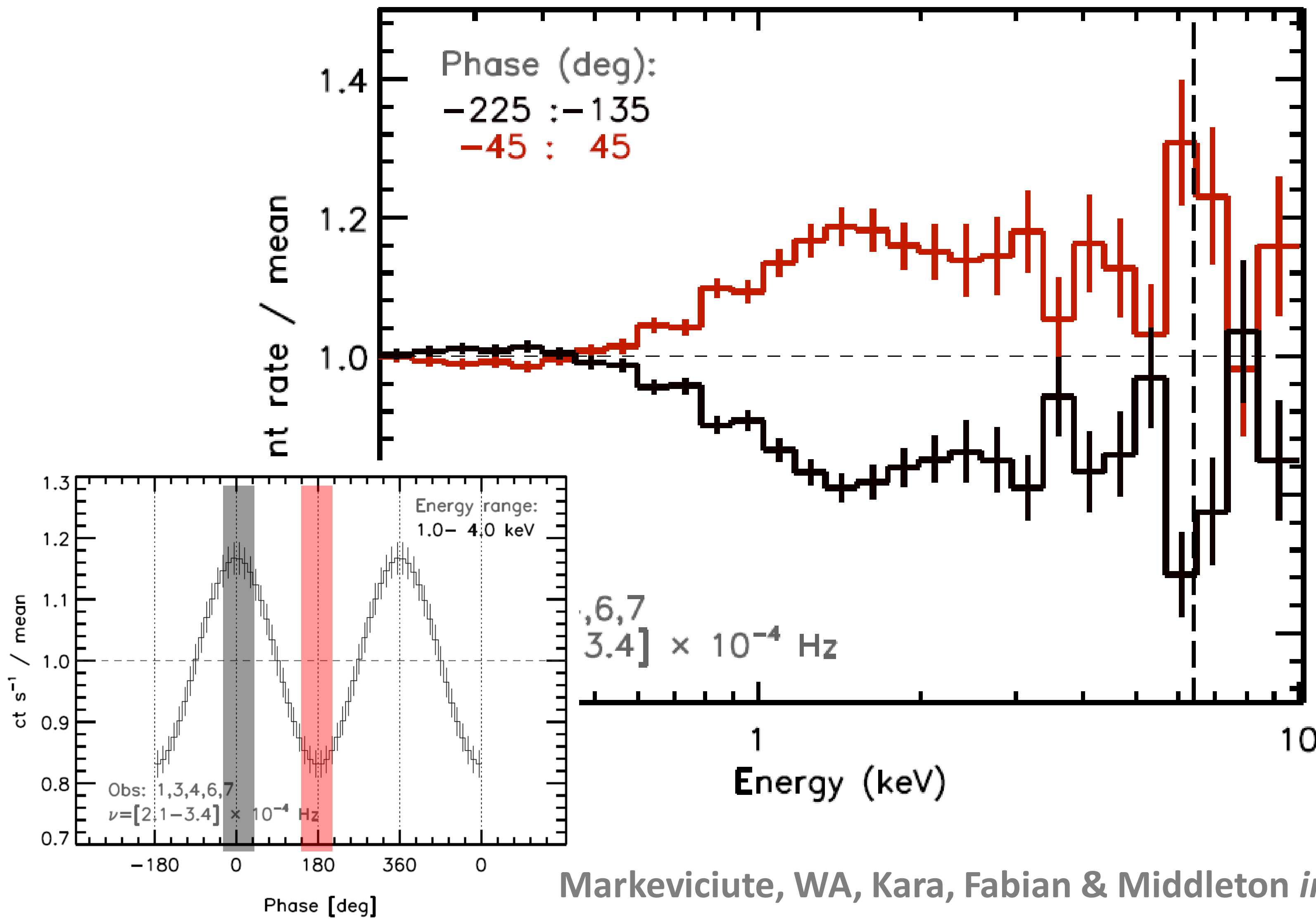
**Following Tomsick & Kaaret (2001):**

- **Filter light curve with filter width +/- 20% QPO freq.**
- **Find minima and slice into X equally space phase bins between minima. Sum over phase bins.**



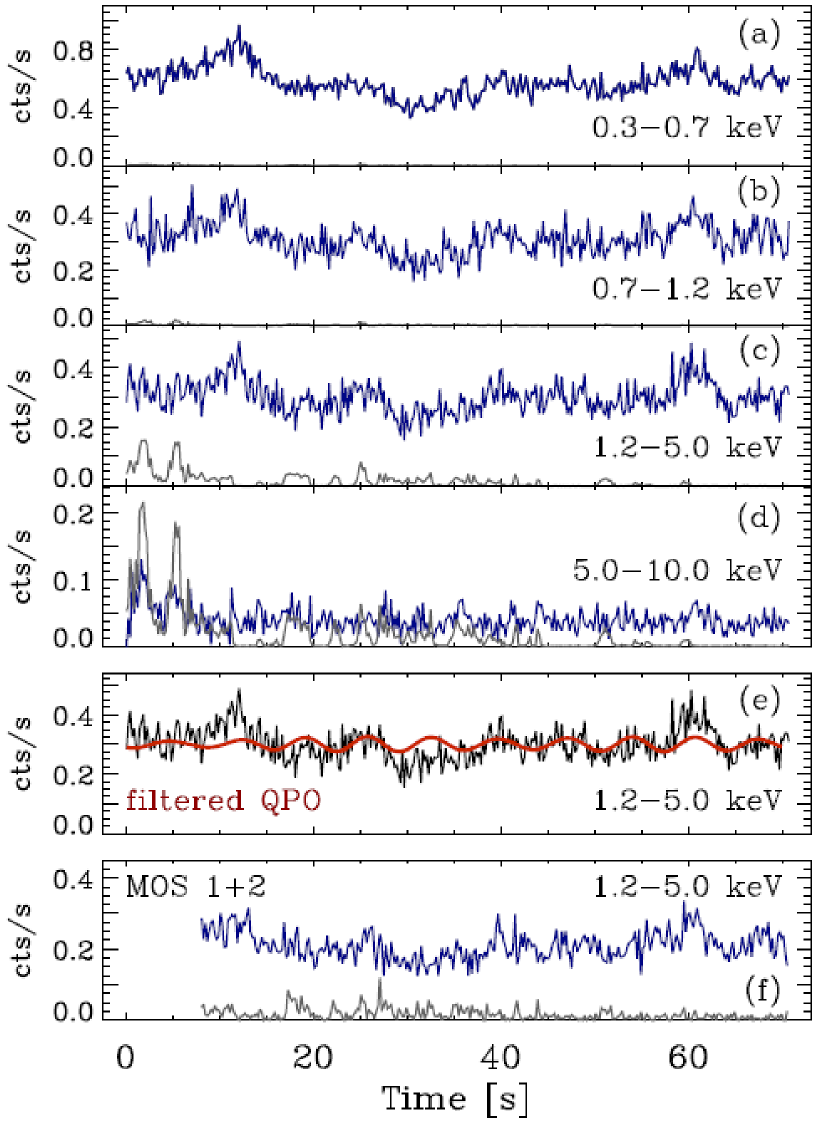

Markeviciute, WA, Kara, Fabian & Middleton, *in prep*

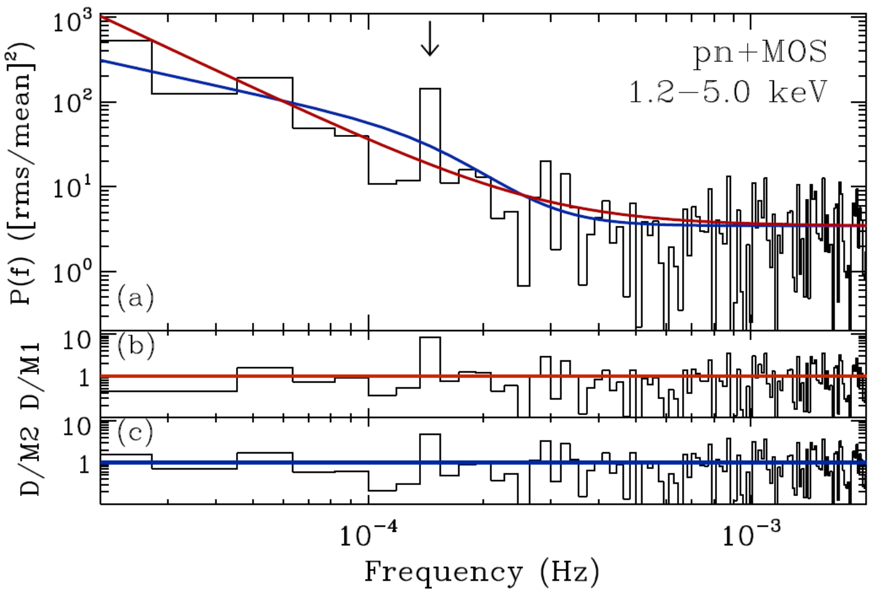
# Phase resolved spectroscopy




Markeviciute, WA, Kara, Fabian & Middleton *in prep*

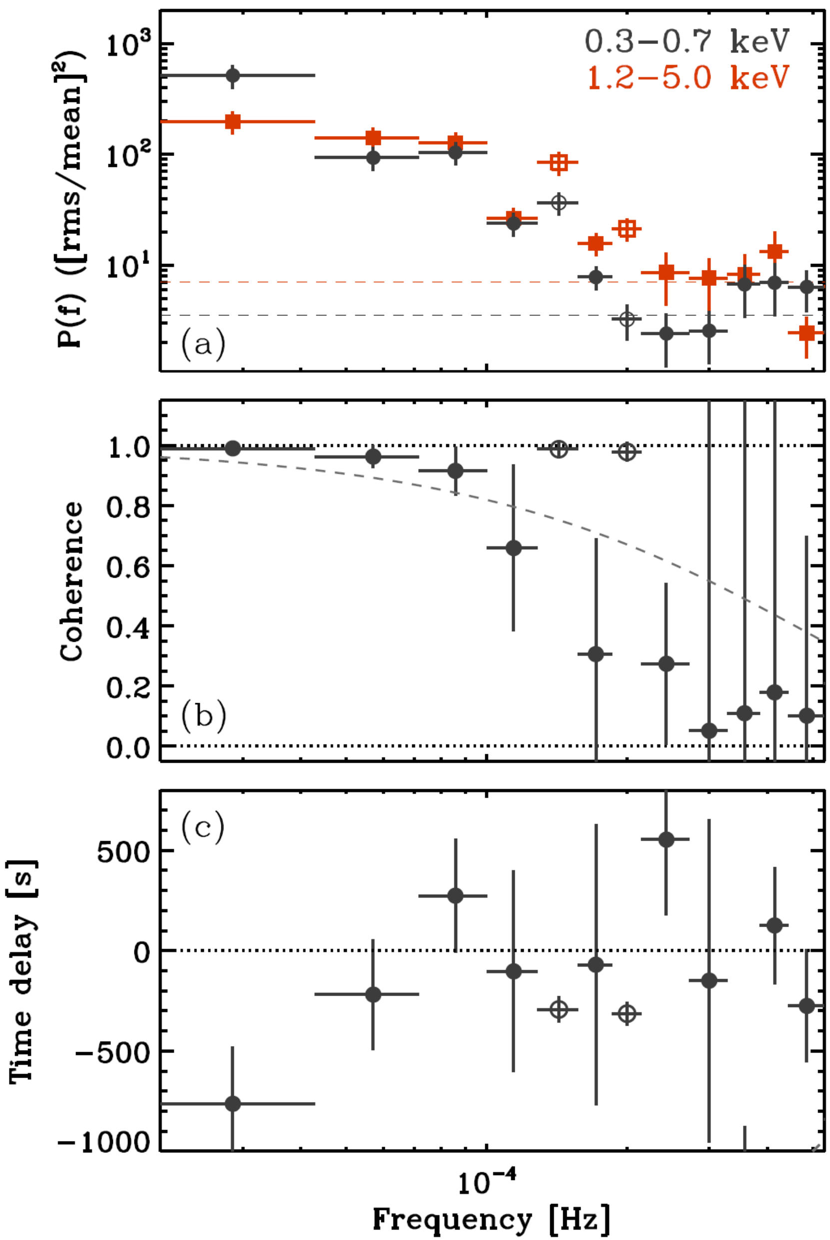
# A QPO in MS 2254.9-3712 (NLS1)



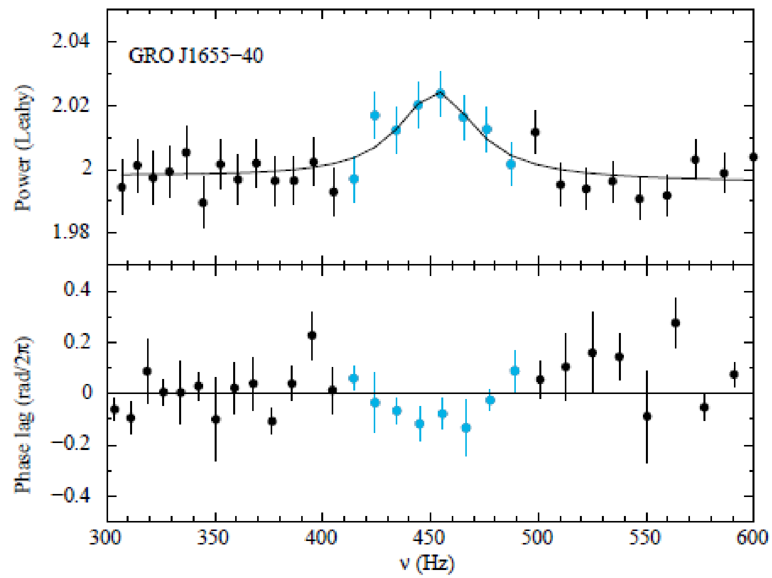

**$1.5 \times 10^{-4}$ Hz QPO detected in hard band**

Alston + 2015, MNRAS, 449, 467




# Cross-Spectral products between soft (0.3-0.7) and hard (1.2-5.0) bands

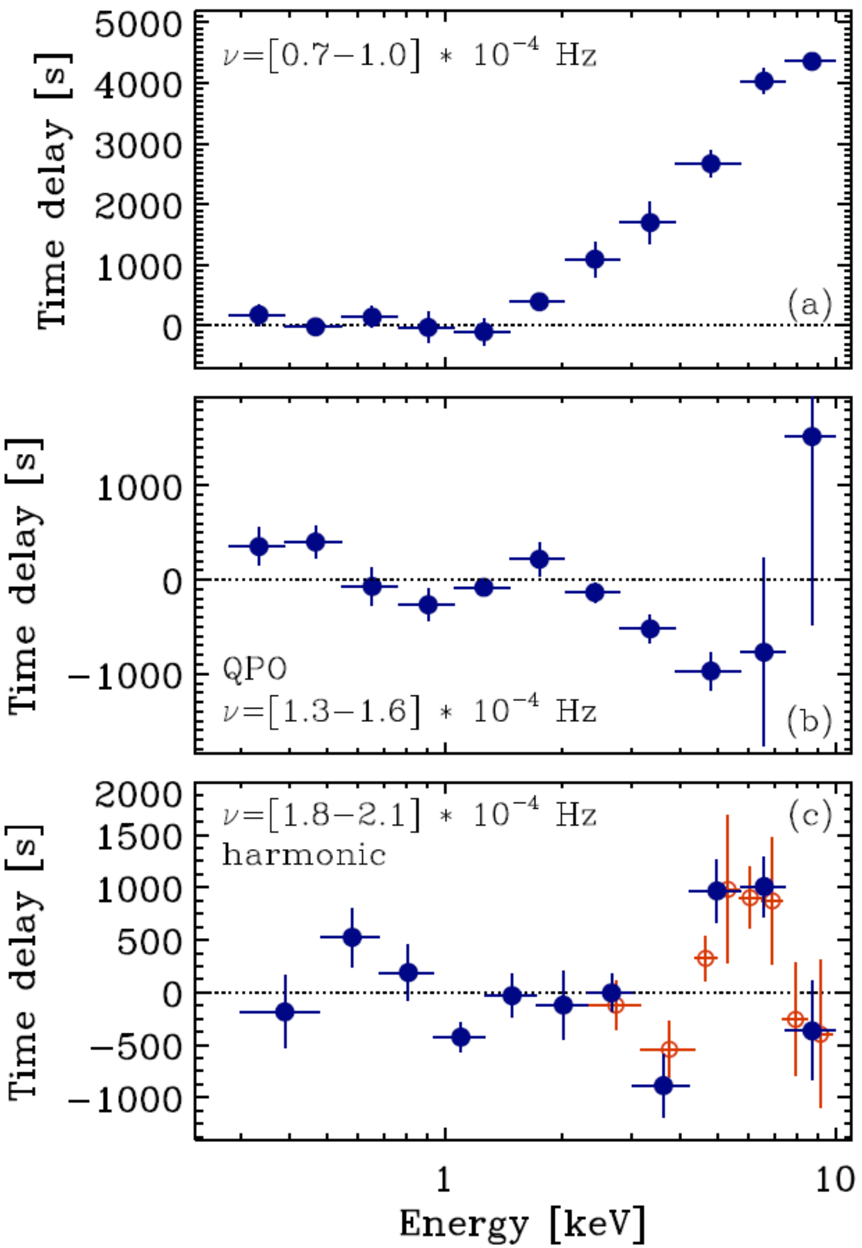
## Soft lags observed in some BHB HFQPOs




Mendez + 2013

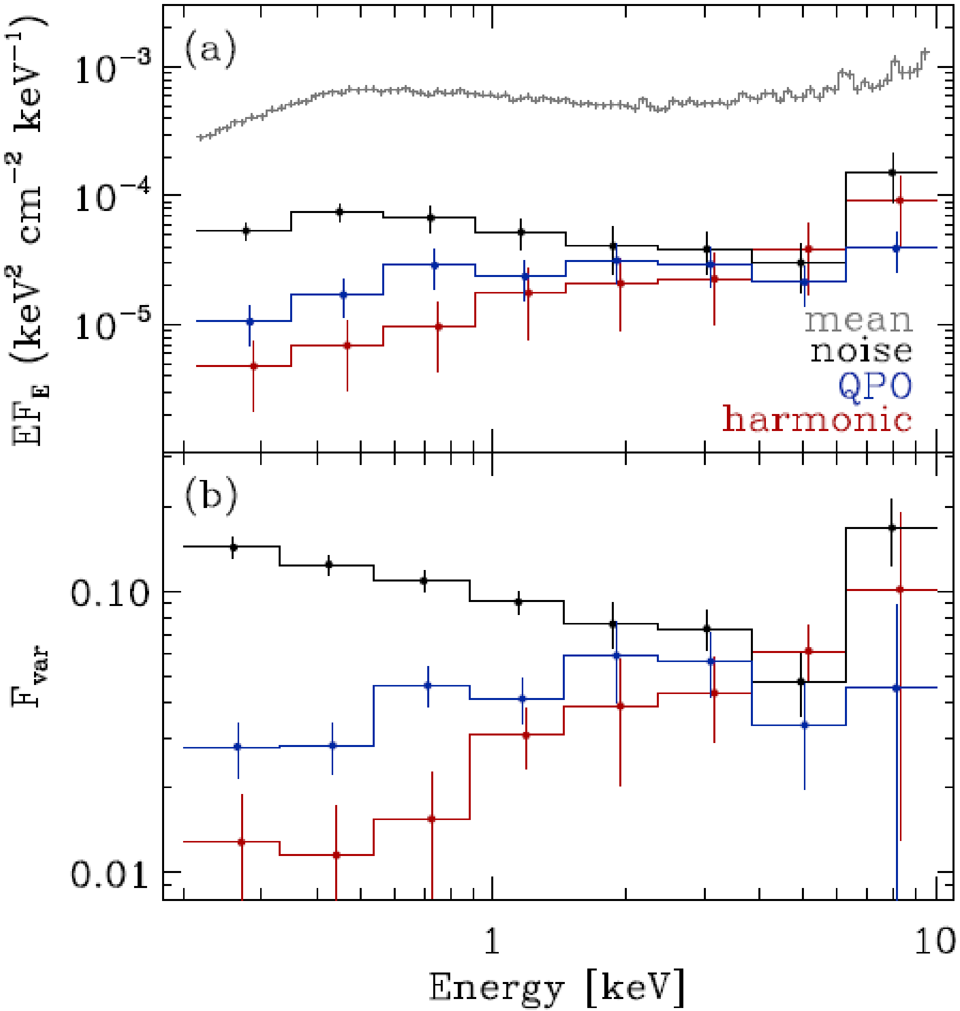
Time delays as a function of energy at a given frequency

Positive lag indicates lag of comparison band vs total energy band (minus comparison band)




Alston + 2015, MNRAS, 449, 467

# Mean and *rms*-spectra

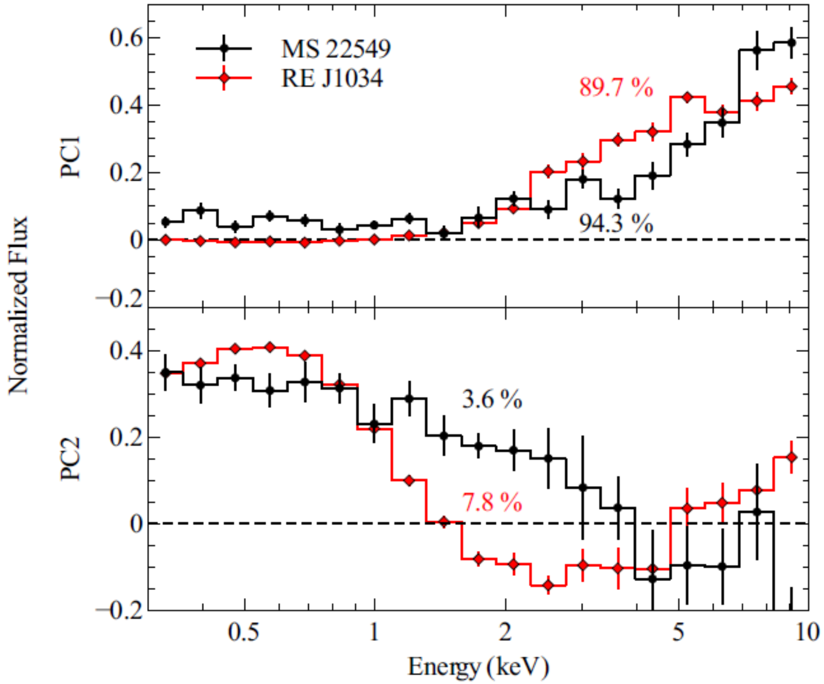



Mean spectrum well described by two absorbed PL (Γ~2.8; 1.5) plus neutral reflection

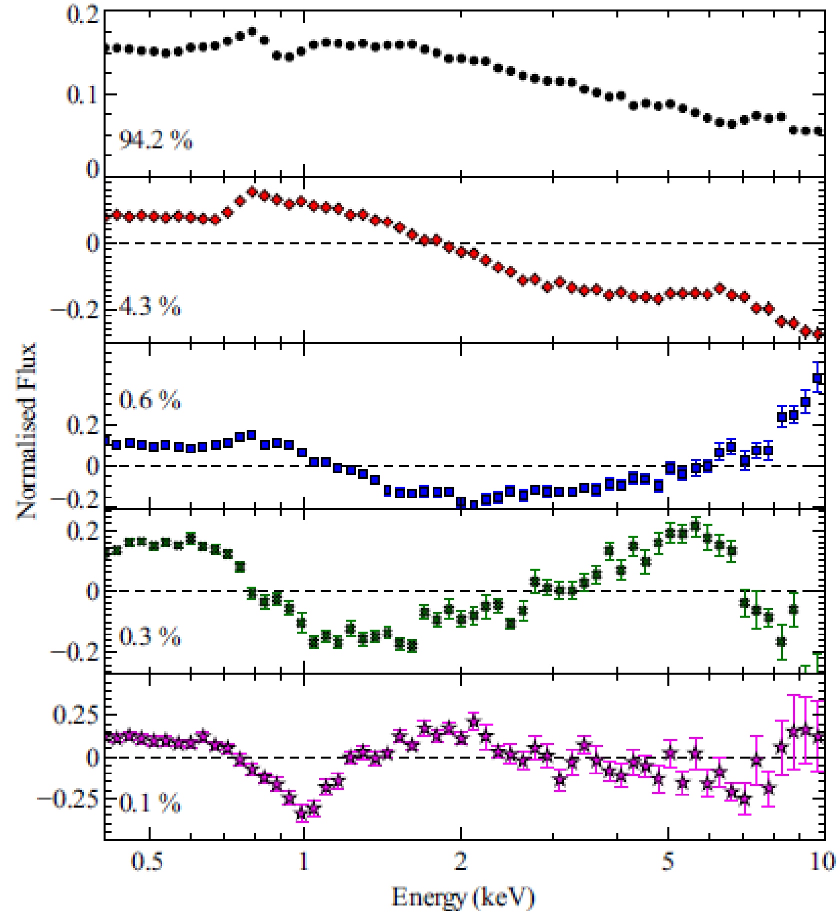
**Hard QPO spectral variability observed in BHBs and RE J1034 (e.g. Belloni 2010 review)**

Alston + 2015, MNRAS, 449, 467

# Principle components analysis (PCA)




NGC 4051

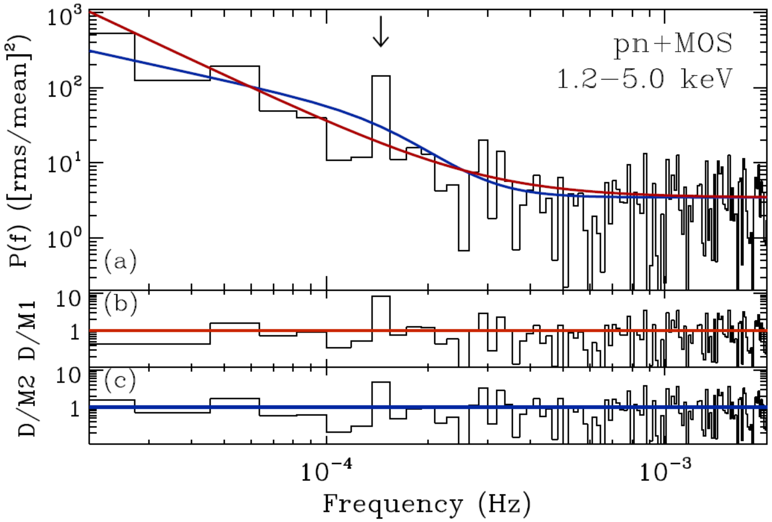


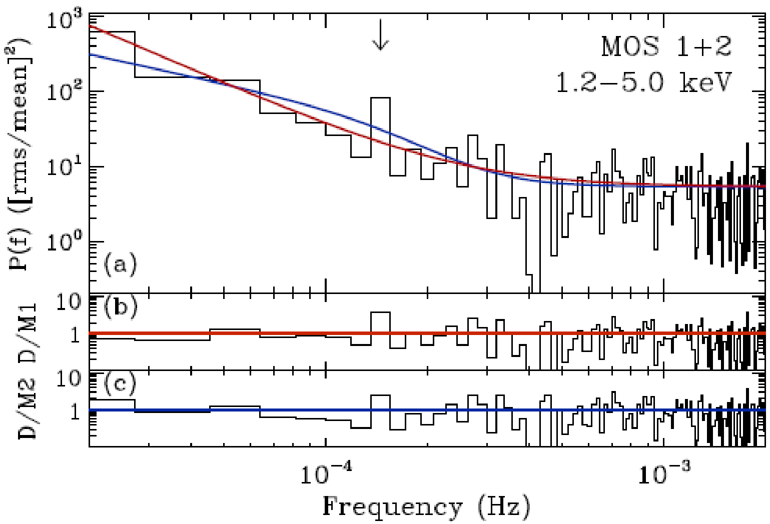

**Variability is broken down into set of variable spectral components.**

Alston + 2015, MNRAS, 449, 467

Parker + 2014

# MS 22549 QPO identification




- $M_{BH}$ ~ 0.4-1 x $10^7$ $M_{sun}$

- Broadband noise present
- High coherence in BB noise
- 3:2 harmonic (maybe)
- ~5 % rms

- Consistent with HFQPOs observed in BHBs

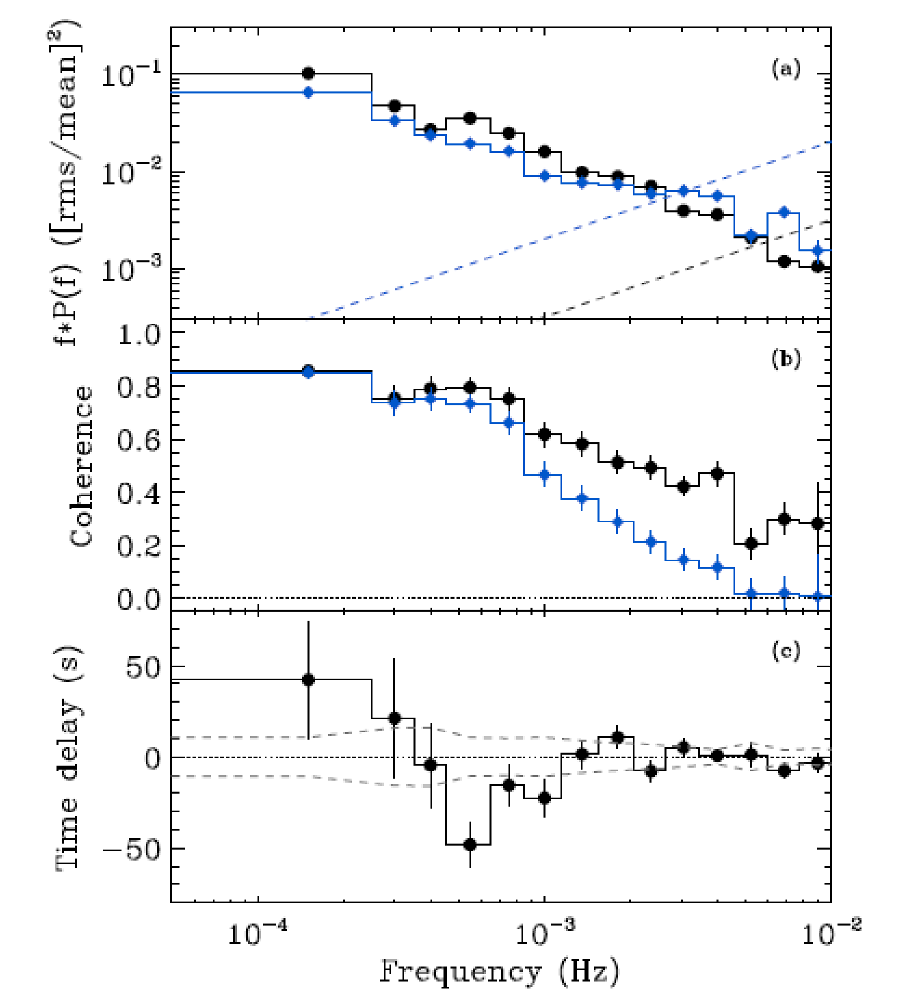
- LFQPO: $M_{BH}$ < 1 x $10^6$ $M_{sun}$

XMM-Newton campaign underway to confirm the QPO

# Summary

- Fast variability probes the inner accretion flow
- QPOs important probe of the inner accretion flow
  - More counts/timescale in AGN
- 1 hr QPO detected in 5 low-flux/spectrally harder observations of RE J1034+396
- 2 hr QPO detected in MS 2254.9-3712
  - Shows similar spectral-timing properties to RE J1034
  - Consistent with being HFQPO
- Reverberation lag seen at $f_{QPO}$
  - Constraint for QPO models
- Evidence for two independent variability processes
  - Reverberation from faster variability component

# Cross Spectrum




$$x(t), y(t) \longrightarrow X(f), Y(f)$$

$$C_{xy} = X^*(f)Y(f)$$

$$= |X||Y|e^{i(\phi_y - \phi_x)}$$

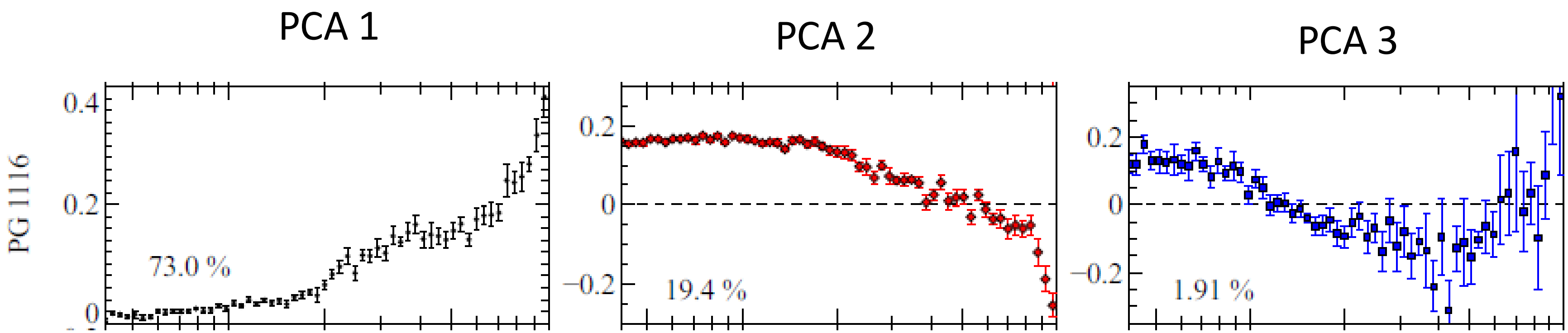
$$\gamma^2(f) = \frac{\left|\langle C_{xy}(f)\rangle\right|^2}{\langle |X(f)|^2\rangle\langle |Y(f)|^2\rangle}$$

$$\phi(f) = \arg\left(\langle C_{xy}(f)\rangle\right)$$

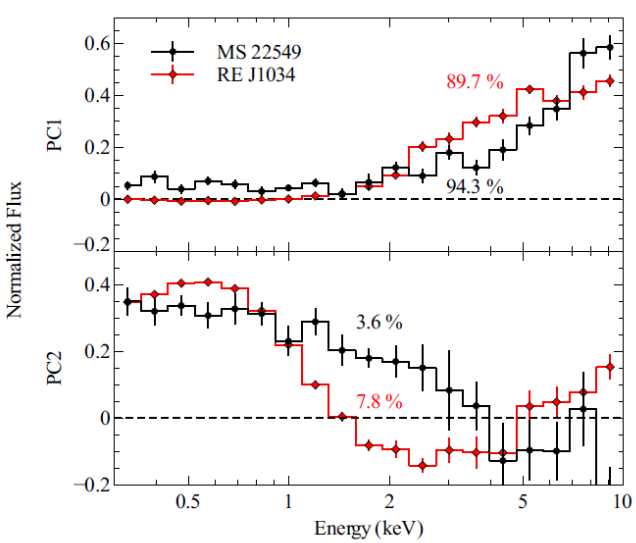
$$\tau(f) = \frac{\phi(f)}{2\pi f}$$

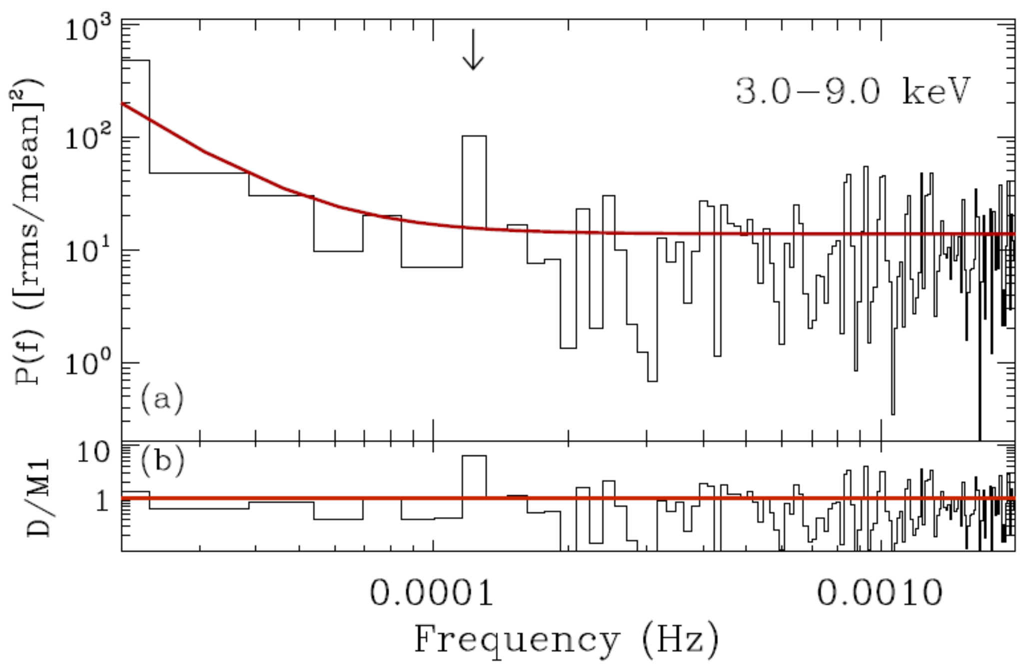
e.g. Vaughan & Nowak (1997)

# PG 1116+215: another QPO detection? (2.6 σ)

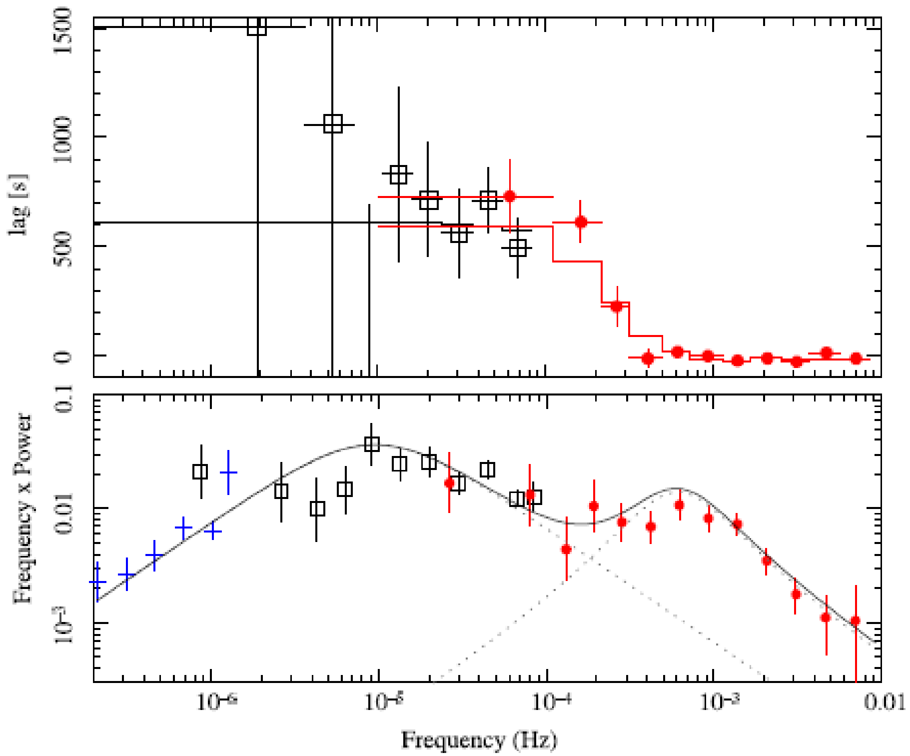



Parker et al 2015



# What about other Seyferts?




$$Lor(\nu) = N \frac{\sigma/2\pi}{[(\nu - \nu_0)^2 + (\sigma/2)^2]}$$

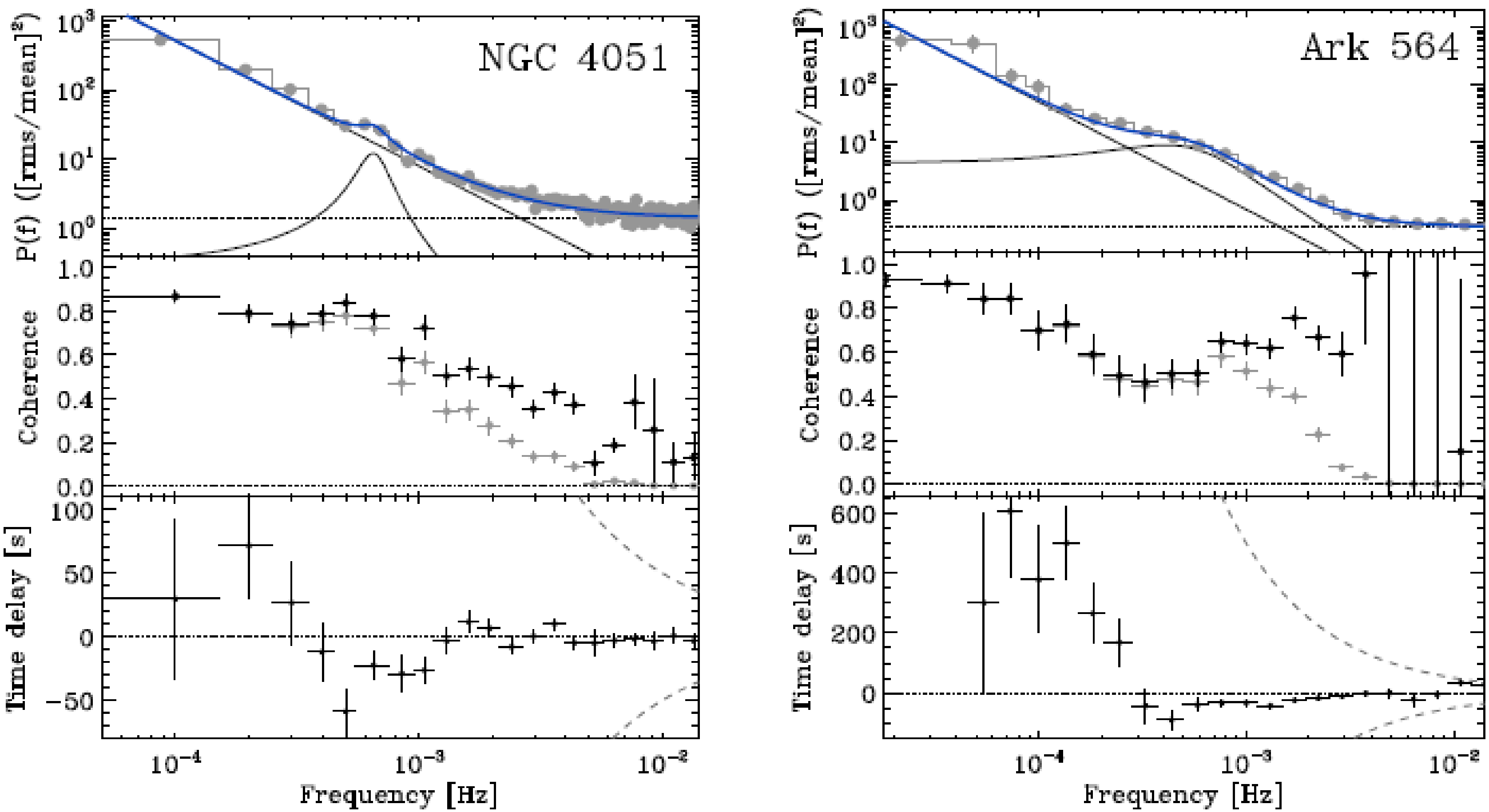
**Ark 564 (NLS1)**

**PSD modelled with two broad Lorentzians**

**Hard lags seen at low f, with switch to soft lag at high frequency Lorentzian**

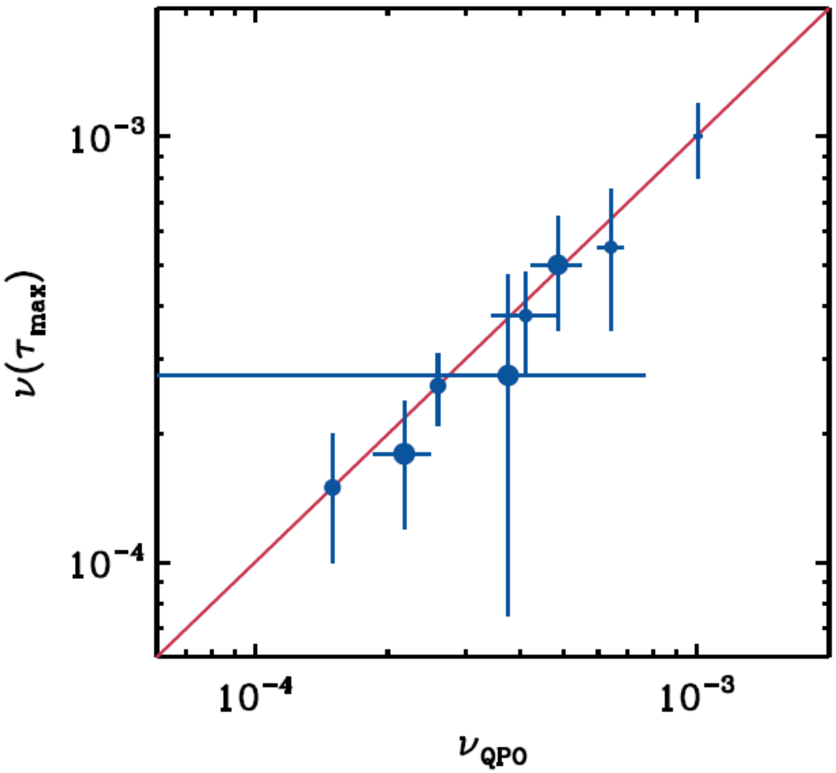
McHardy et al (2007)

# PSD modelled with PL + Lor
# See soft lag at frequency where Lor peaks
# Sample of 8 objects

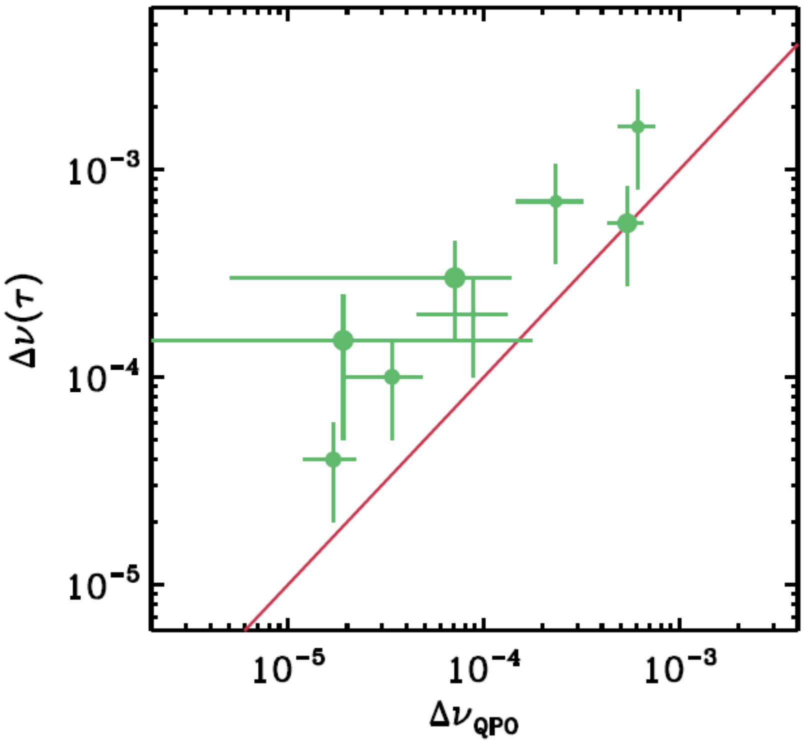


# Soft lag vs Lorentzian

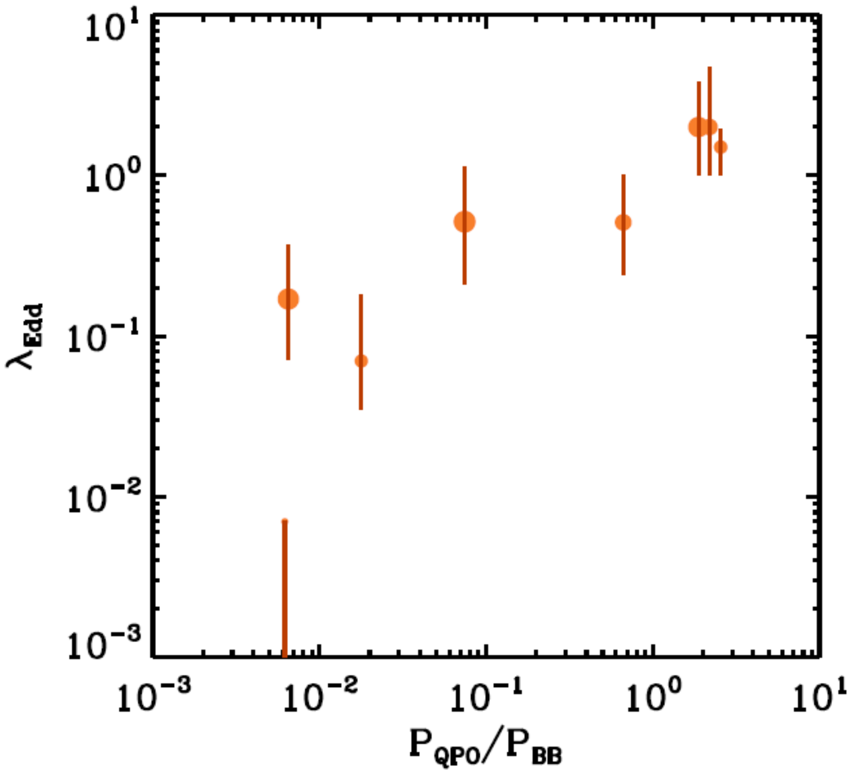
## Central frequency




## Lag width vs FWHM



# Variability power vs $\lambda_{Edd}$

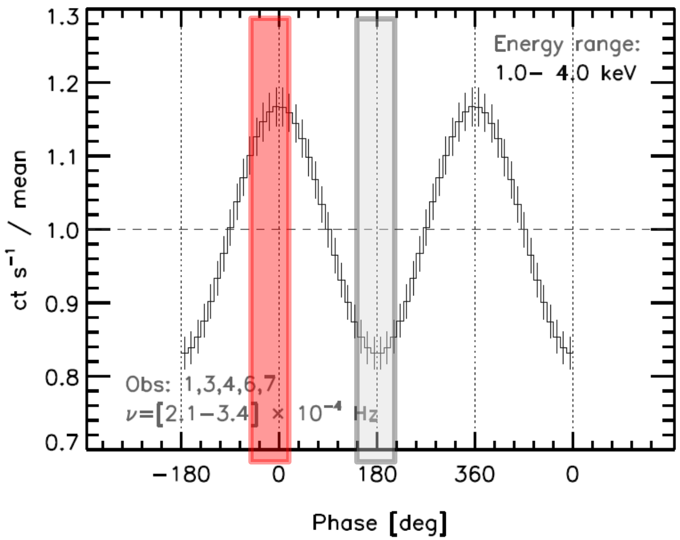


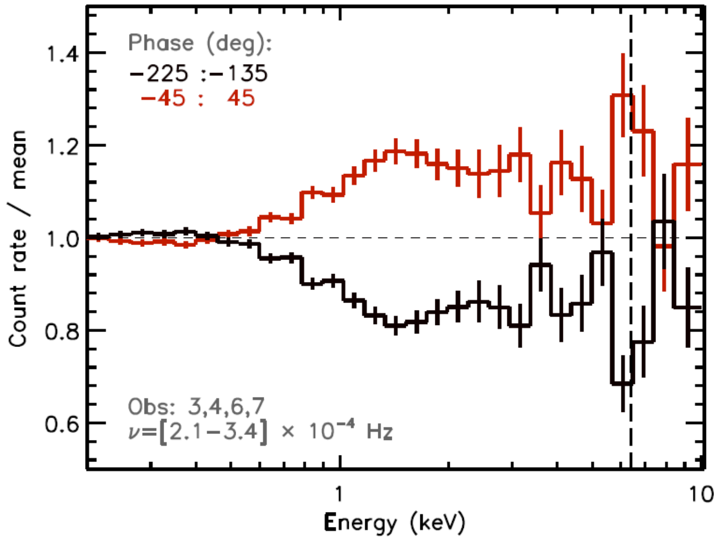

**Ratio of integrated power in Lorentzian relative to that in PL noise**

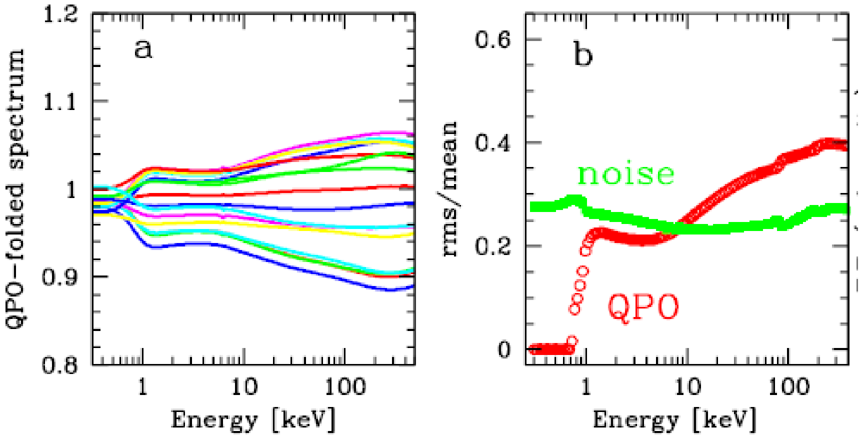
$\lambda_{Edd} = L_{Bol} / L_{Edd}$

**Variability power in Lorentzian increases with $\lambda_{Edd}$**

# Phase resolved spectroscopy




**Modulation of heating rate with no modulation of cooling rate**

Markeviciute, WA, *in prep*

Zycki & Sobolewska 2005