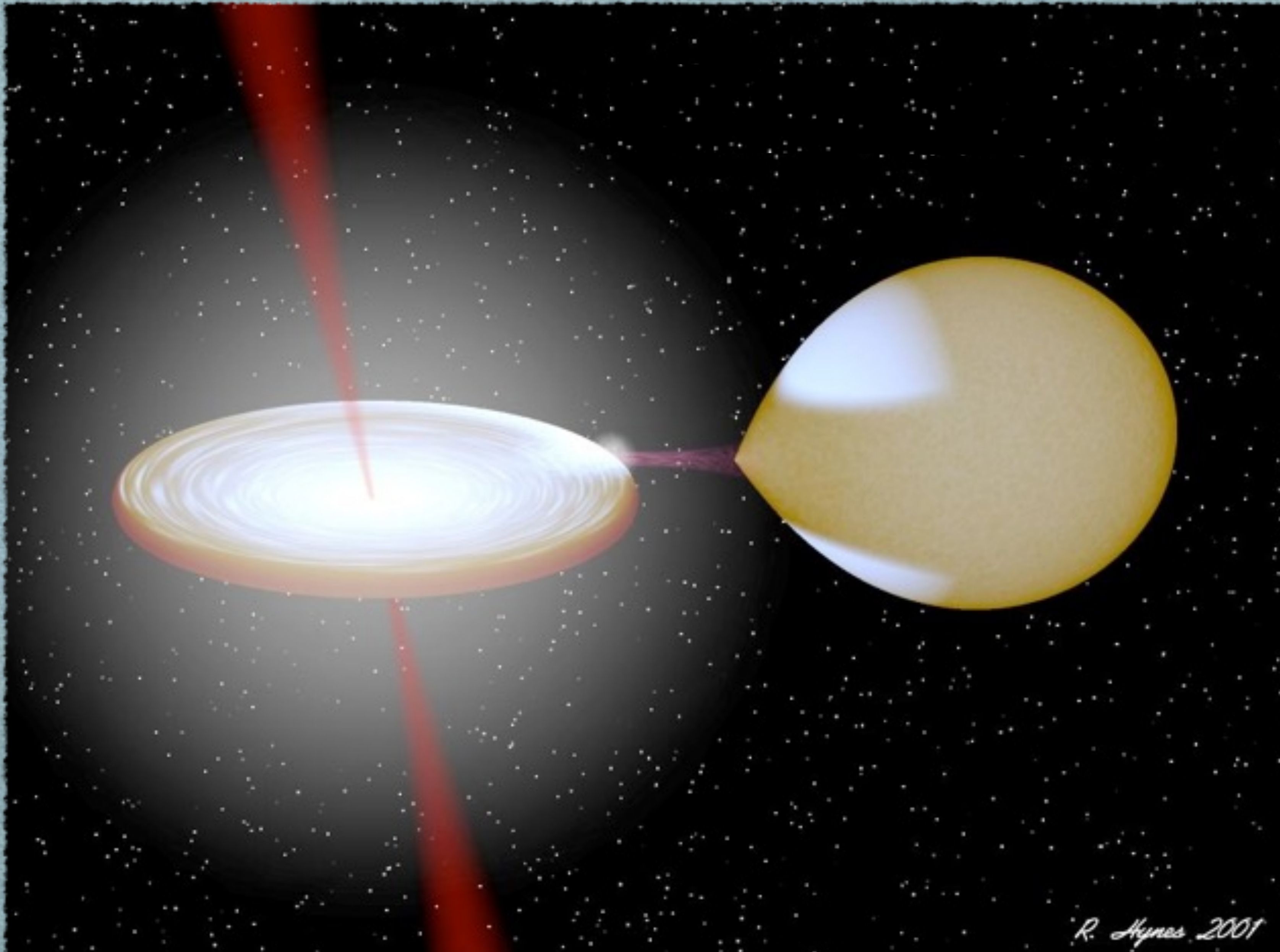
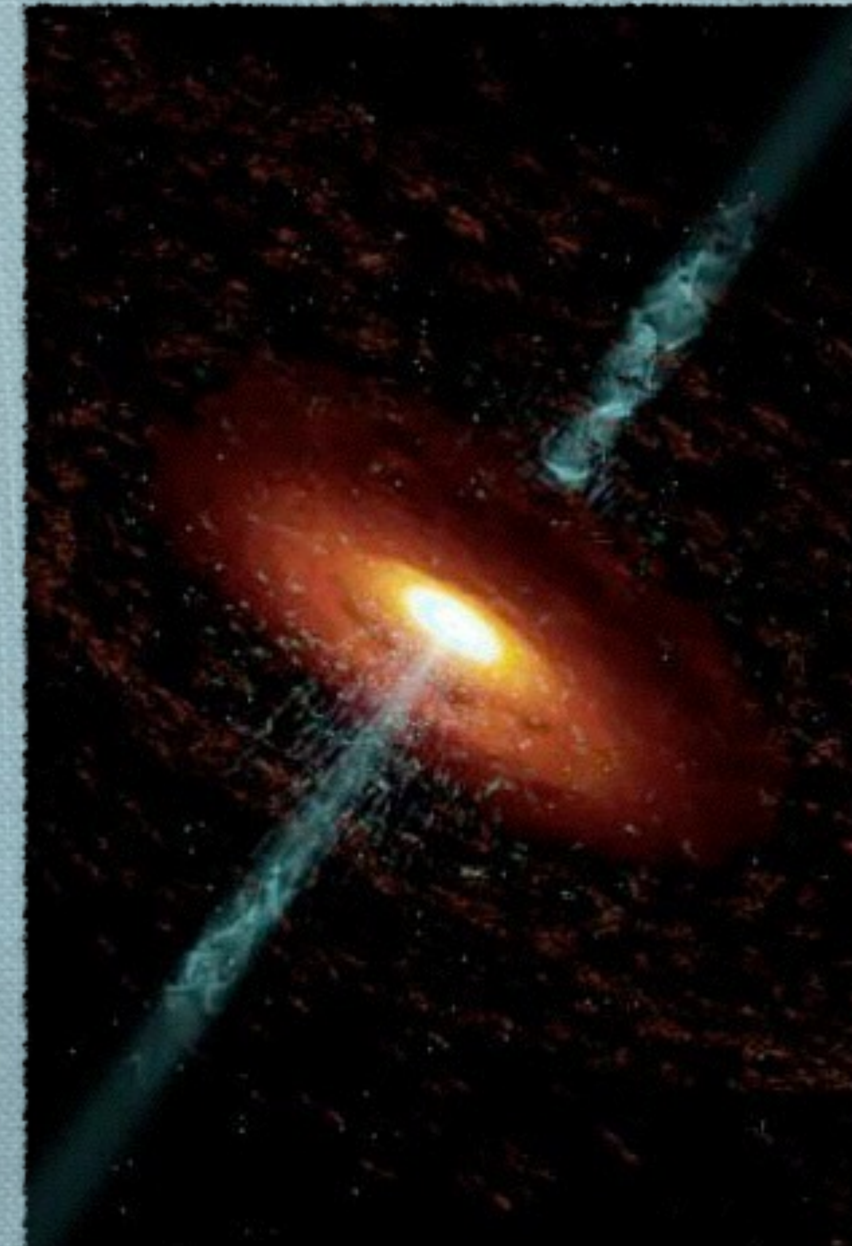




Black-hole binaries

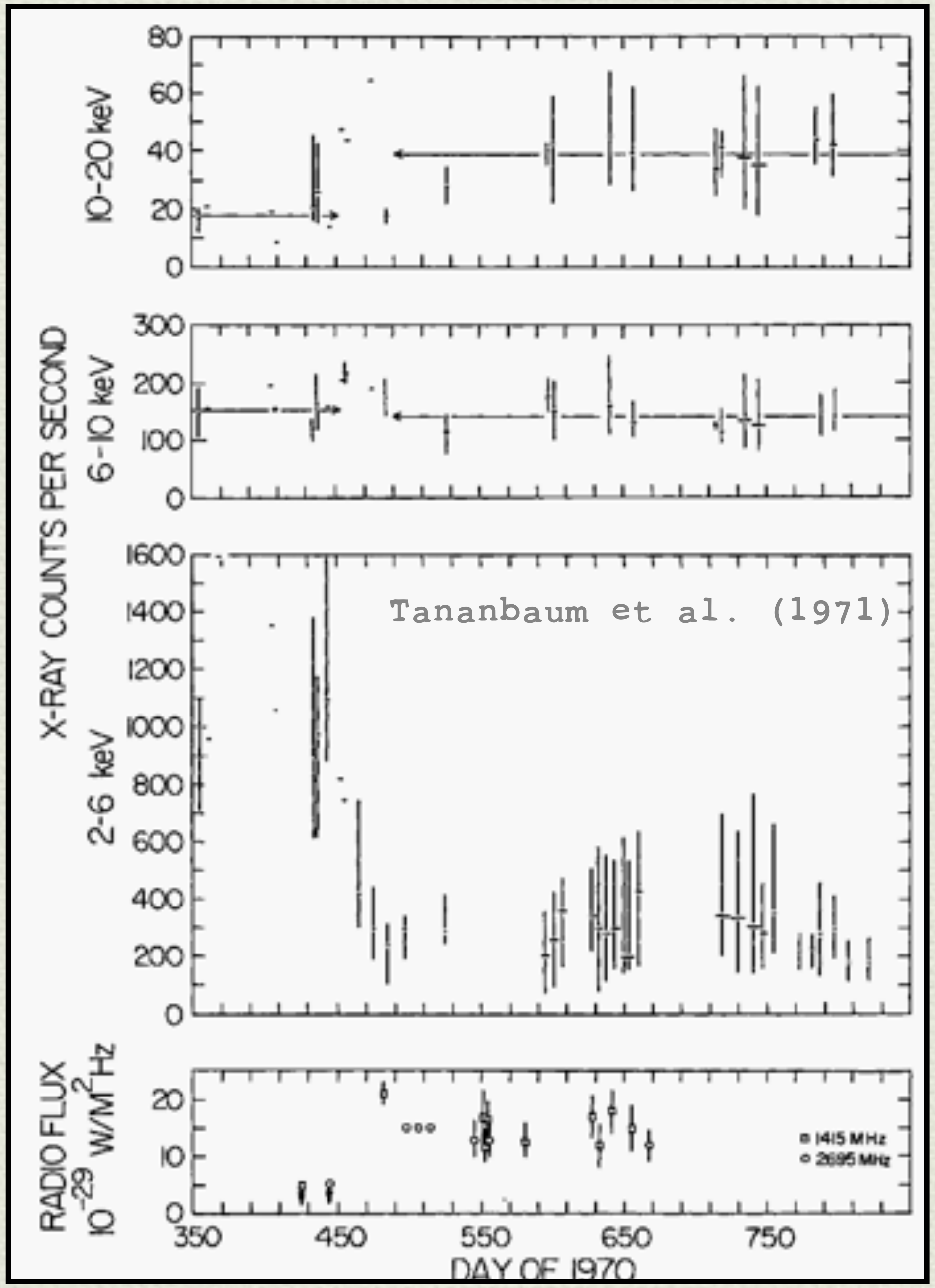
Tomaso M. Belloni
(INAF - Osservatorio Astronomico di Brera)
(Visiting Professor, Univ. of Southampton)

OUTLINE

- Lecture I: Accretion onto compact objects, X-ray binaries, black hole candidates, X-ray pulsars
- Lecture II: High-energy emission and spectra
- **Lecture III: Time variability on all scales**
- Lecture IV: Radio emission, jets, accretion/ejection
- Lecture V: BH parameters & GR, AGN connection
- Lecture VI: Neutron-Star binaries + ULX + more

BH states: the beginning

- We need something to work with.
- Some properties appear discontinuous
- Time evolution is crucial
- Only now we can see the most important things



The curious case of Cyg X-1

- Everyone finds a period

THE ASTROPHYSICAL JOURNAL, 172:L13–L16, 1972 February 15

DYNAMIC SPECTRUM ANALYSIS OF CYGNUS X-1

M. ODA, M. WADA,* M. MATSUOKA, S. MIYAMOTO,
N. MURANAKA, AND Y. OGAWARA
Institute of Space and Aeronautical Science, University of Tokyo, Tokyo
Received 1971 December 16

ABSTRACT

The oscillatory structure of the counting-rate data trains of Cyg X-1 obtained by the AS&E and the M.I.T. group was studied. Instead of applying the Cooley-Tukey fast Fourier-transform algorithm to the entire data, we obtained the dynamic spectrum by fitting the wave with time sections of the data trains. Also, the Hissagram, which is a quantitative exhibition of the sonagram, was produced for the same train. It was concluded that the oscillation lasts typically for several seconds and its frequency drifts within a few seconds repeatedly.

THE ASTROPHYSICAL JOURNAL, 174:L35–L41, 1972 May 15

SHOT-NOISE CHARACTER OF CYGNUS X-1 PULSATIONS*

N. JAMES TERRELL, JR.
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1972 February 22

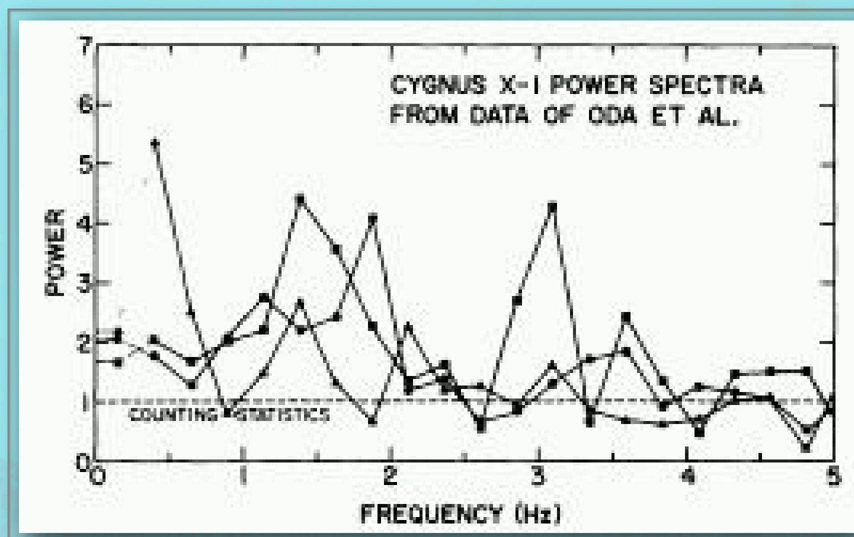
ABSTRACT

The pulsating X-ray source Cyg X-1 has been reported as having various conflicting or changing periodicities, or as being nonperiodic. The reported data have been reanalyzed in an effort to clarify this situation, and are found to be indistinguishable from shot noise due to short overlapping outbursts of X-ray emission, with no true periodicity. Computer-generated shot-noise data have the same appearance and lead to similar power spectra. The observational data are consistent with random pulses which have an effective pulse length of 0.3 ± 0.1 s and occur at varying rates of the order of several hundred per second. The pulse length indicates a maximum source size of ∼0.8 light-seconds. It is suggested that some other fluctuating X-ray sources, such as Sco X-1 and Cir X-1, may also have such a shot-noise character.

DATA ON X-RAY PULSARS

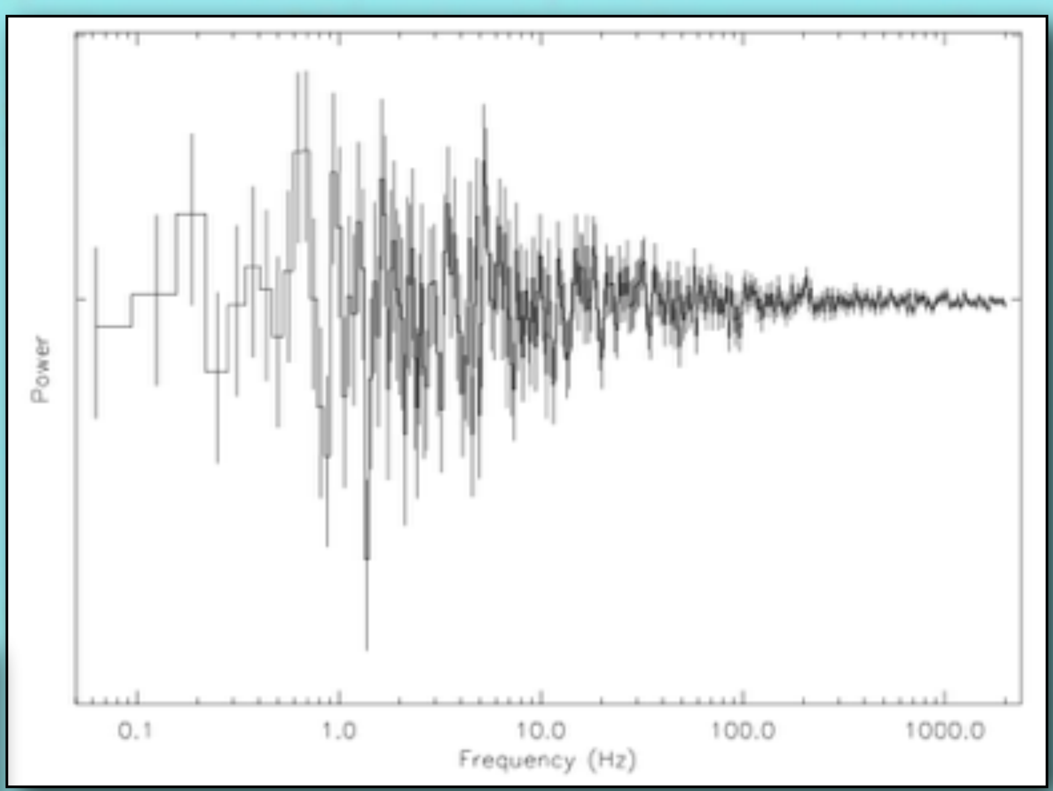
PARAMETER	STAR: NP 0532*	Cygnus X-1†	Centaurus X-3
Period τ (seconds)......	0.033	0.073 or 0.292 1.1 or 1.3 Possibly >5	4.87

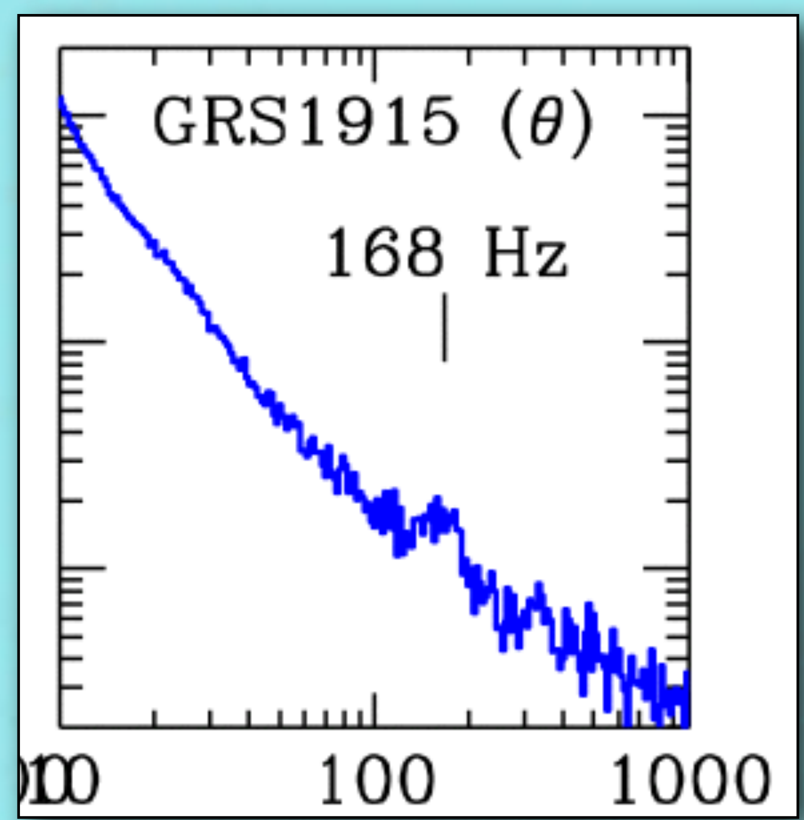
- Someone has an idea.. noise



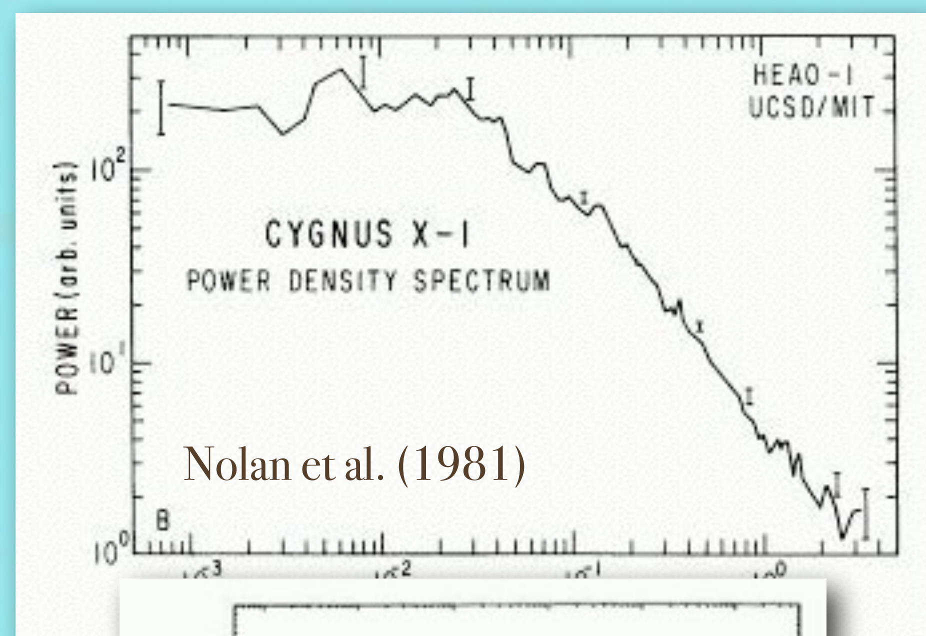
Learn from history

- Be careful with periods
- (Real) Number of trials
- Presence of noise
- Errors

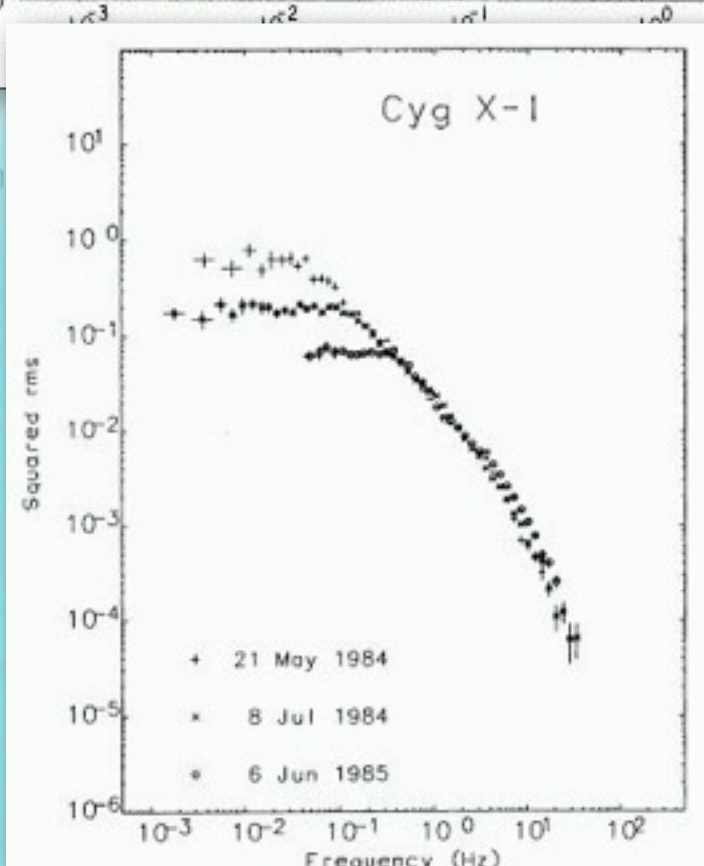




Things got a lot better

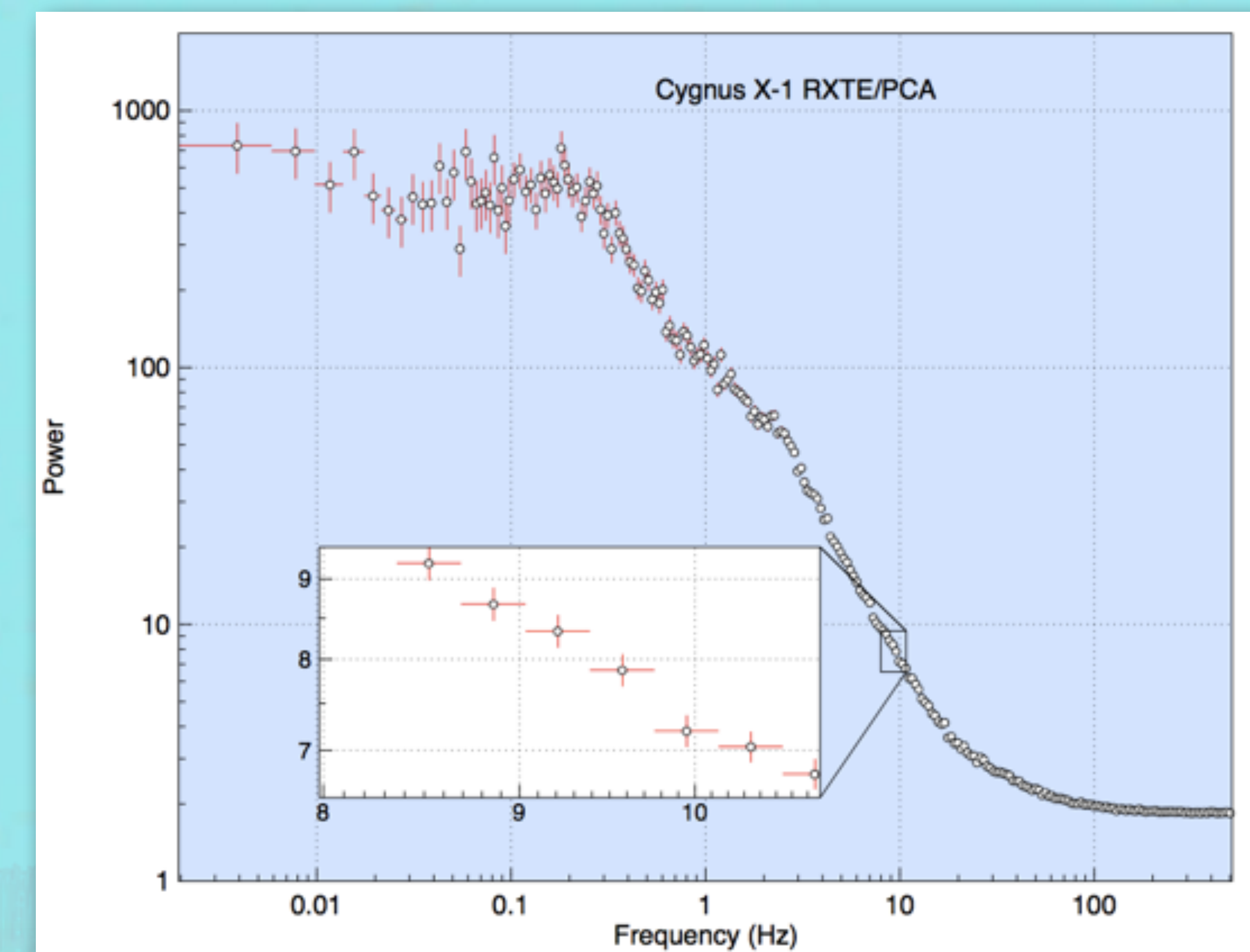


Nolan et al. (1981)



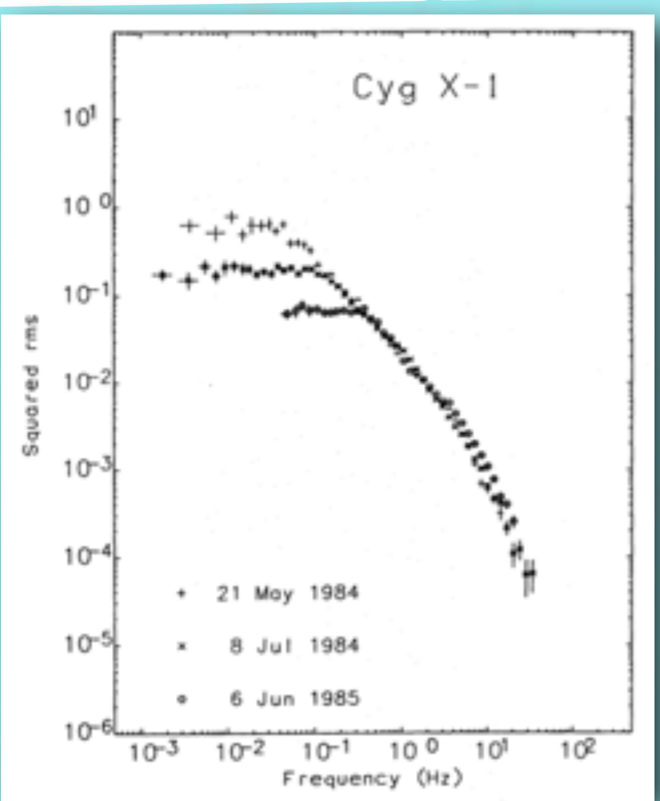
Belloni & Hasinger (1990)

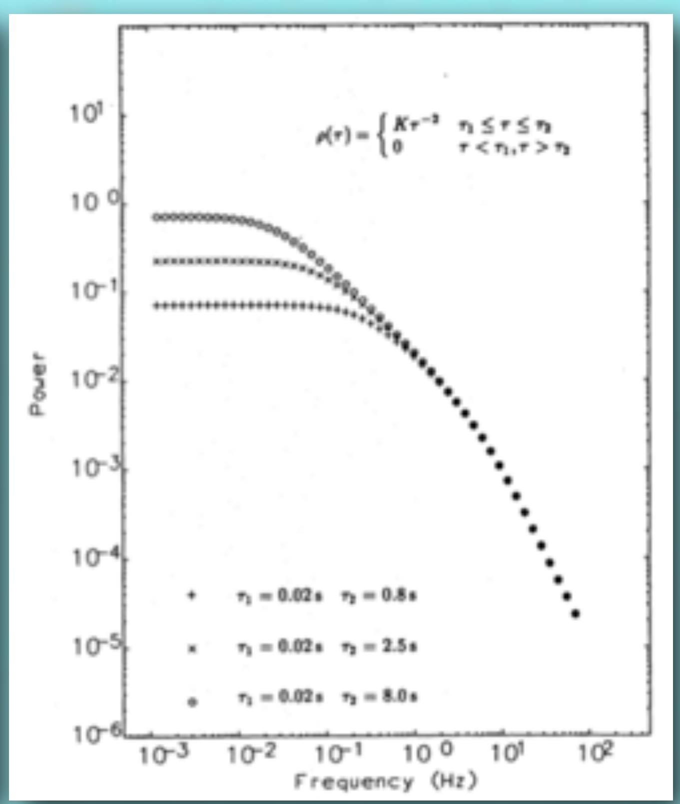
RXTE: Observation in 1996



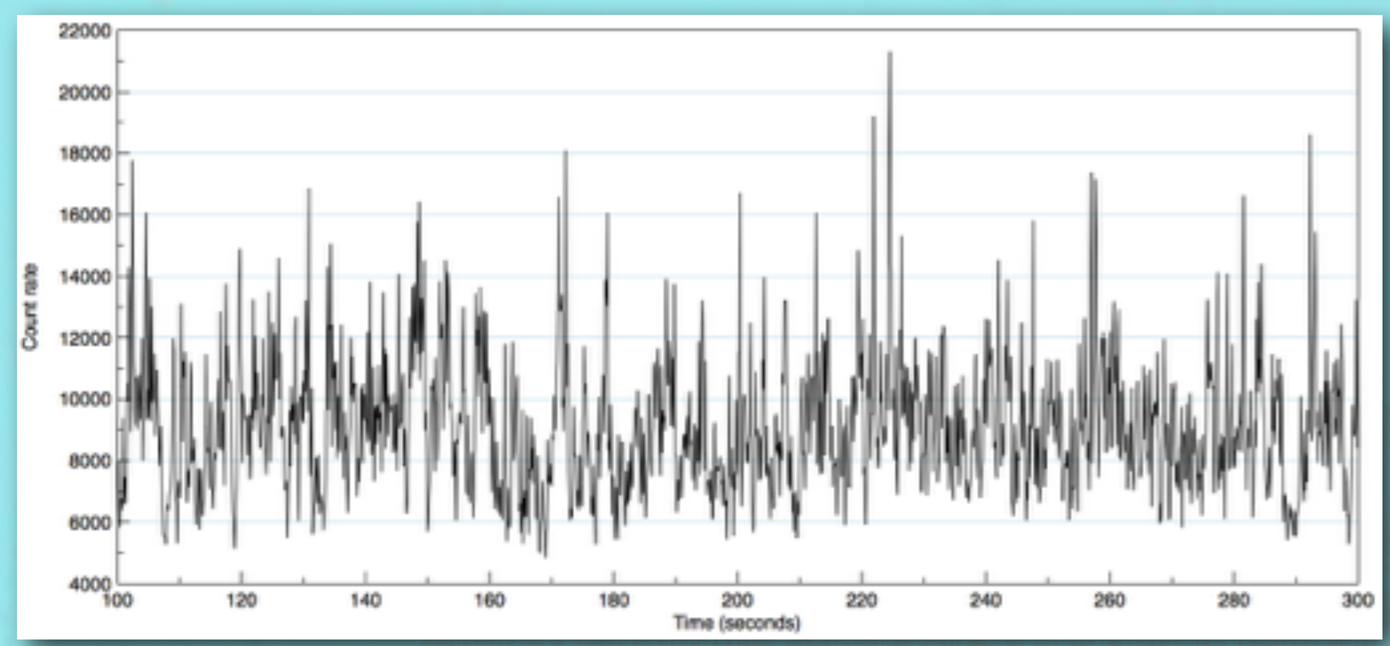
Flat-top noise

- Broken power laws
- Shot noise does not work
- Multiple shot noise does
- Spectra are already too good



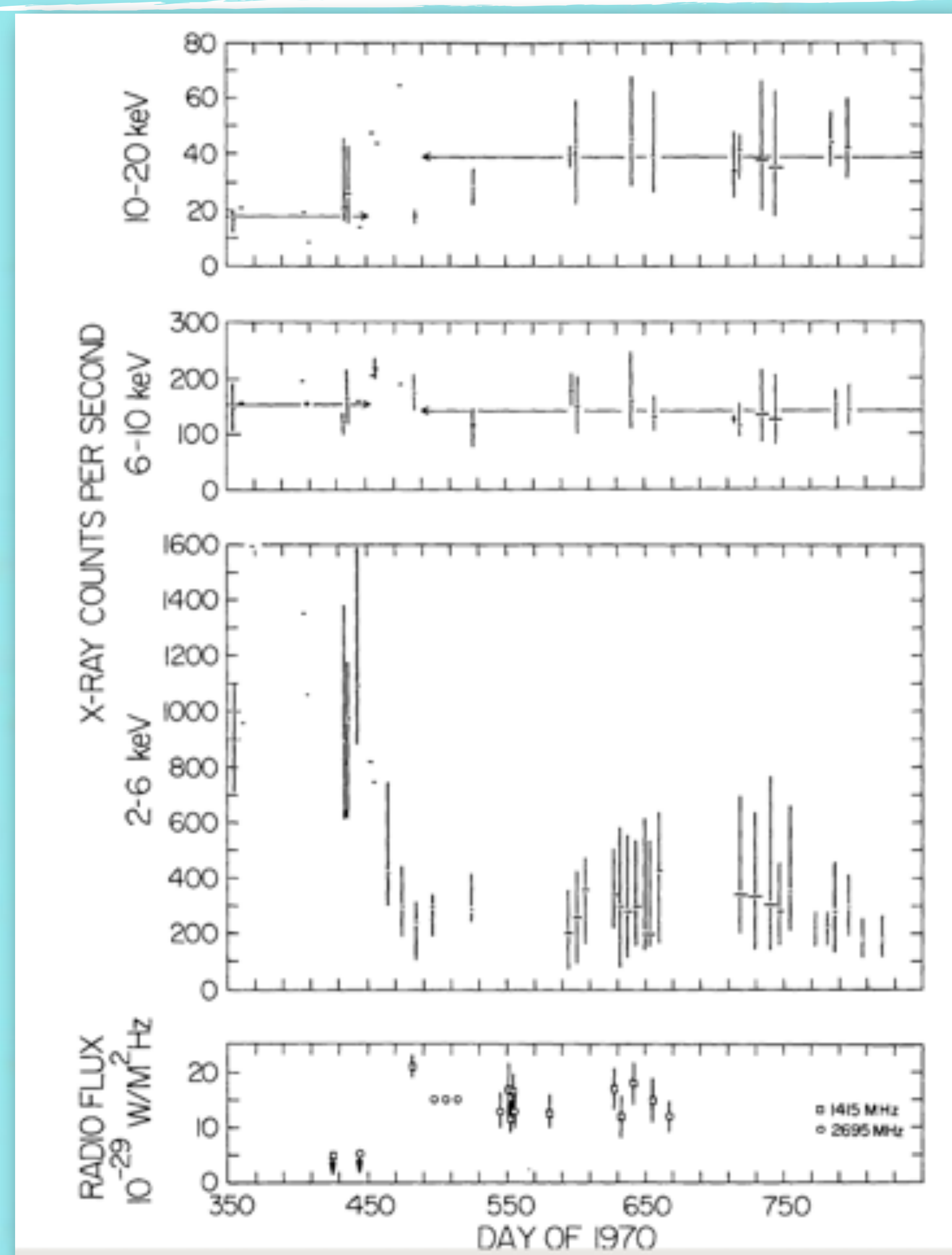


Belloni & Hasinger (1990)



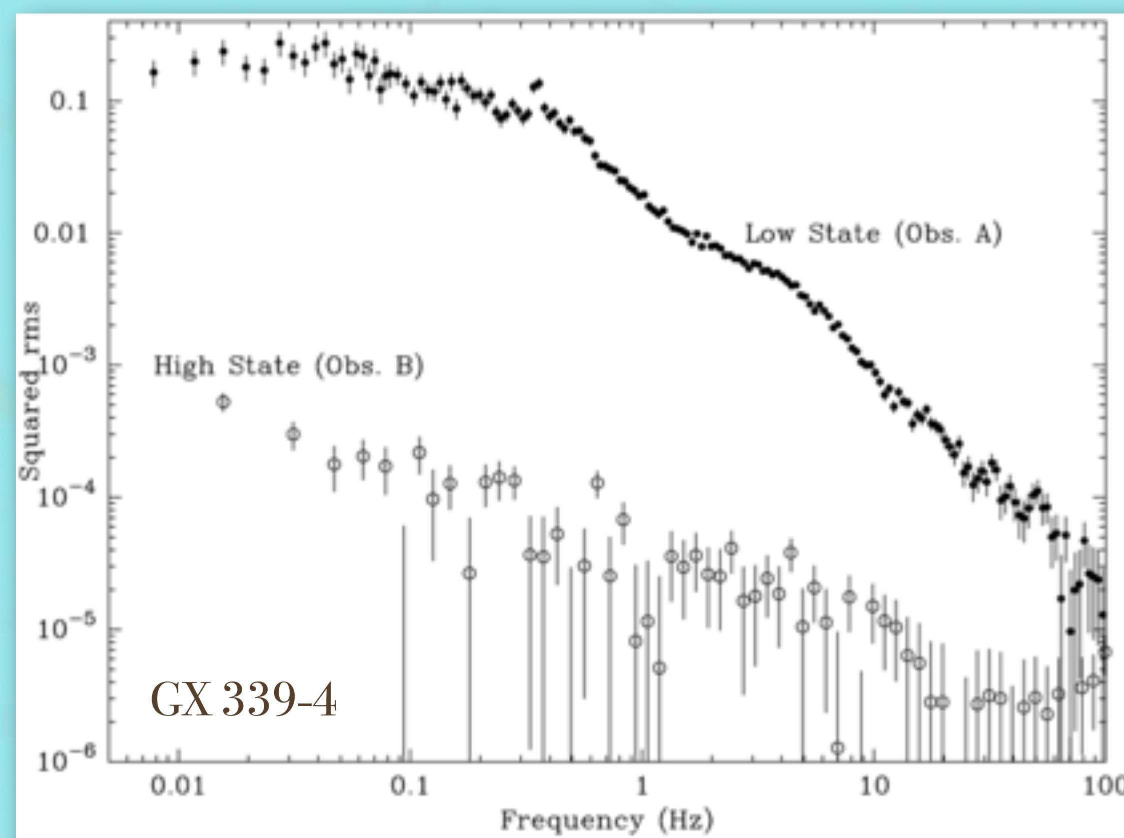
Shots?

Soft state



Tananbaum et al. (1991)

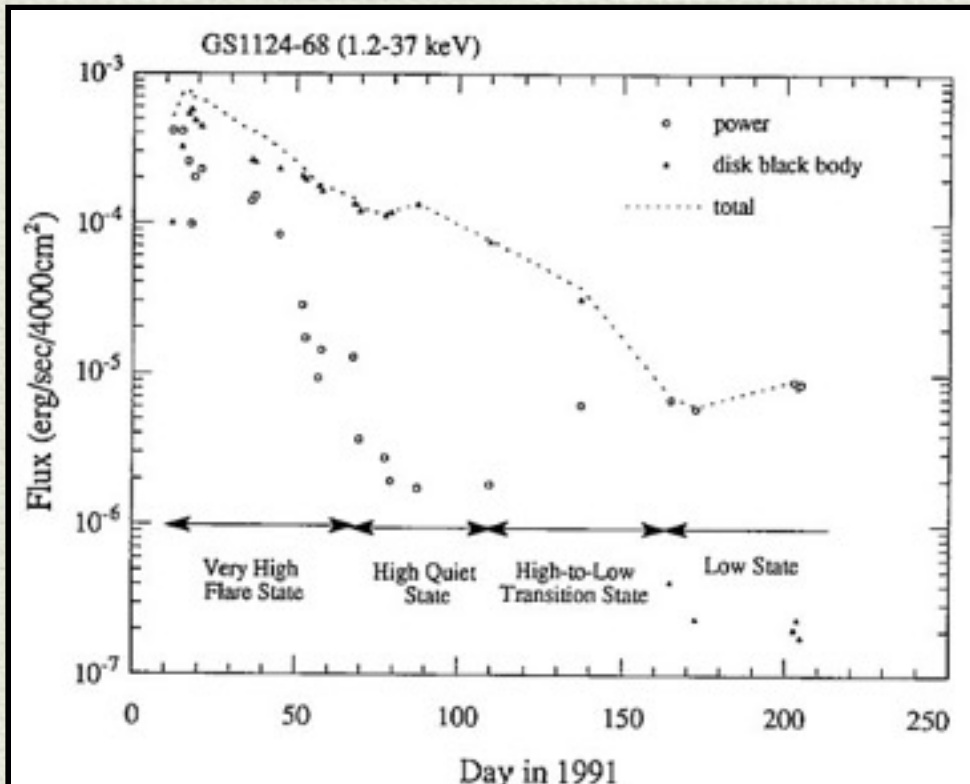
- Different energy spectrum
- Different origin?



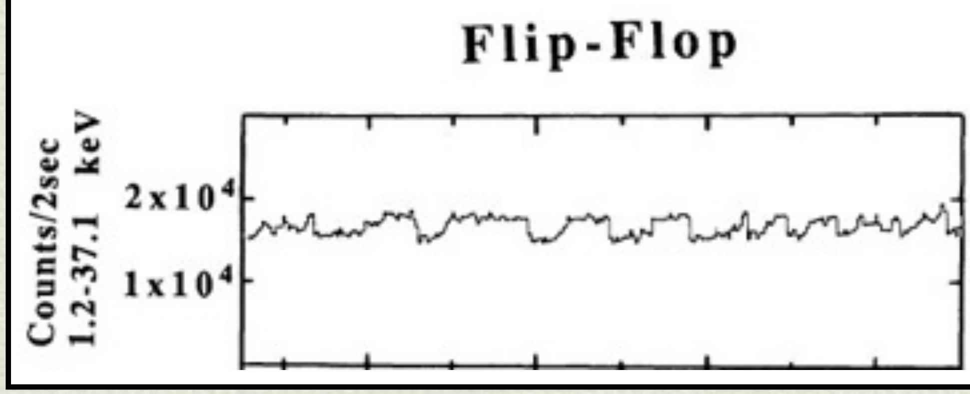
Belloni et al. (1999)

State transitions

- Before RXTE, they simply were not available
- We had isolated observations of a few objects
- Some fast ones were seen, but not considered too much



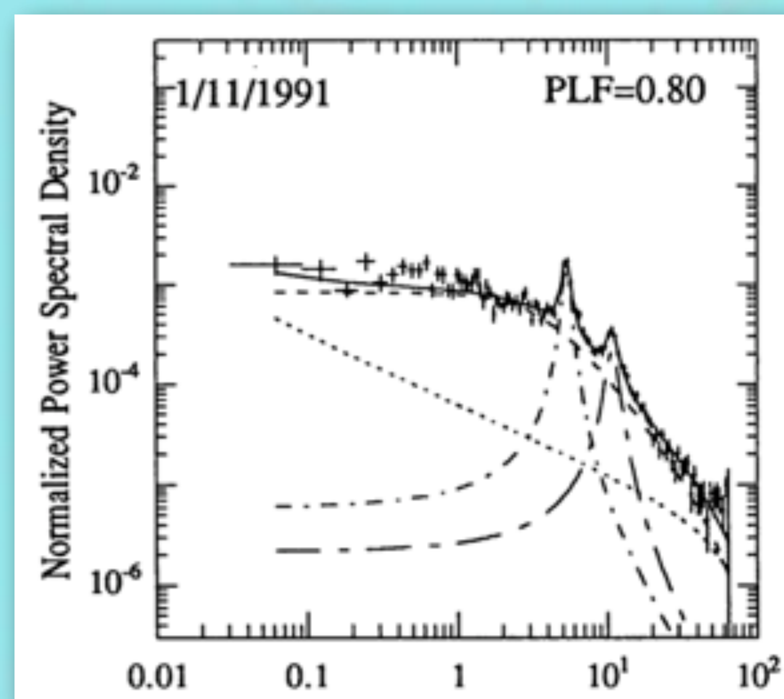
Ebisawa et al. (1994)

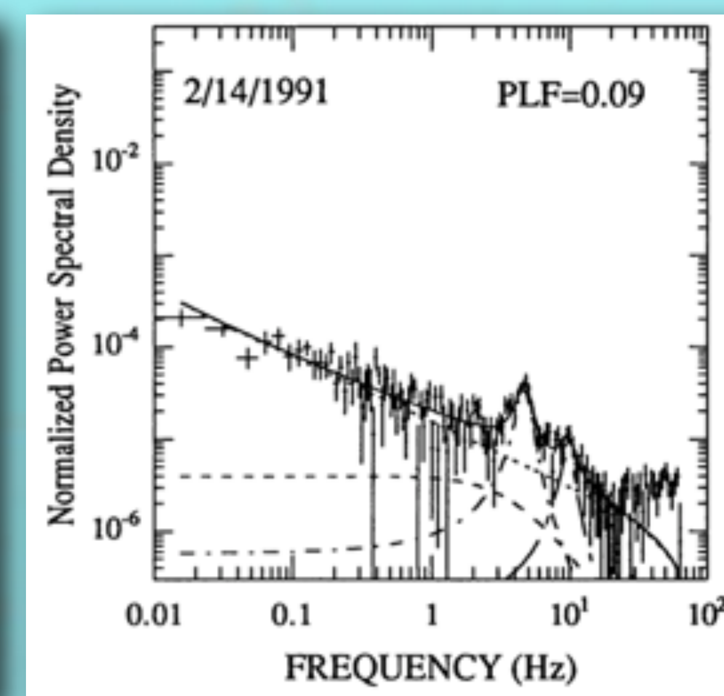


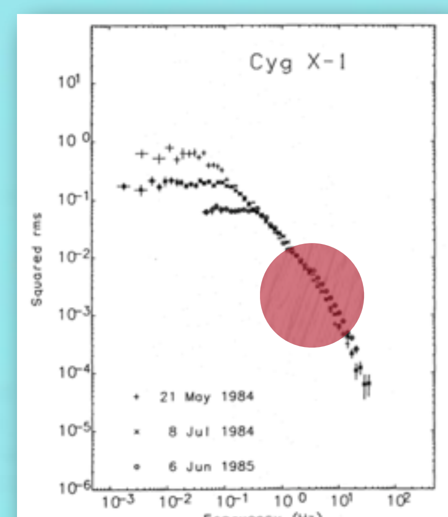
Only broad-band noise?

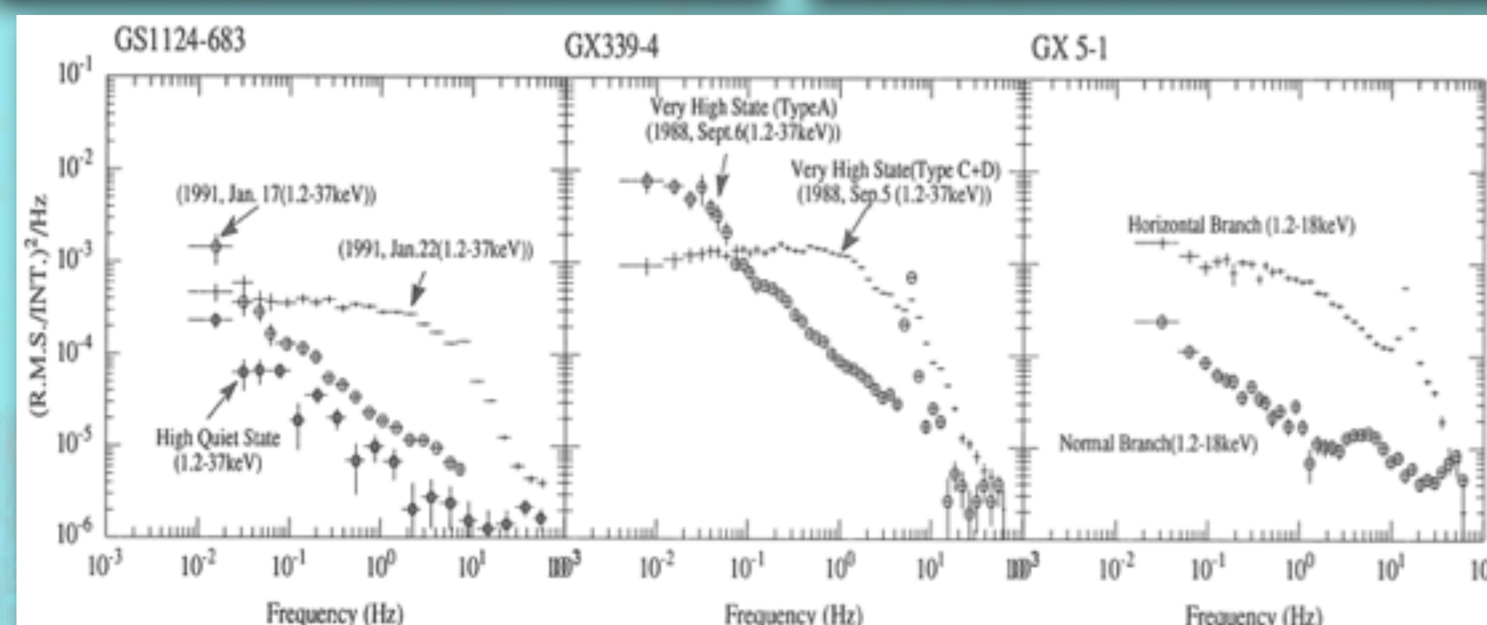
- QPOs!
- A new state: VHS
- Intermediate spectrum
- Two flavors of timing

Miyamoto et al. (1994)





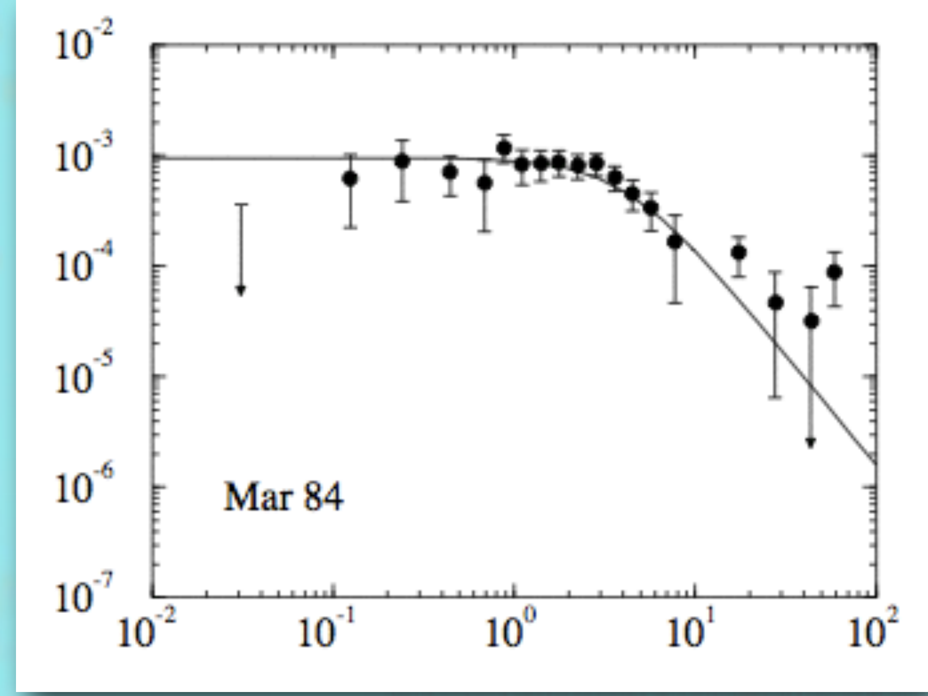




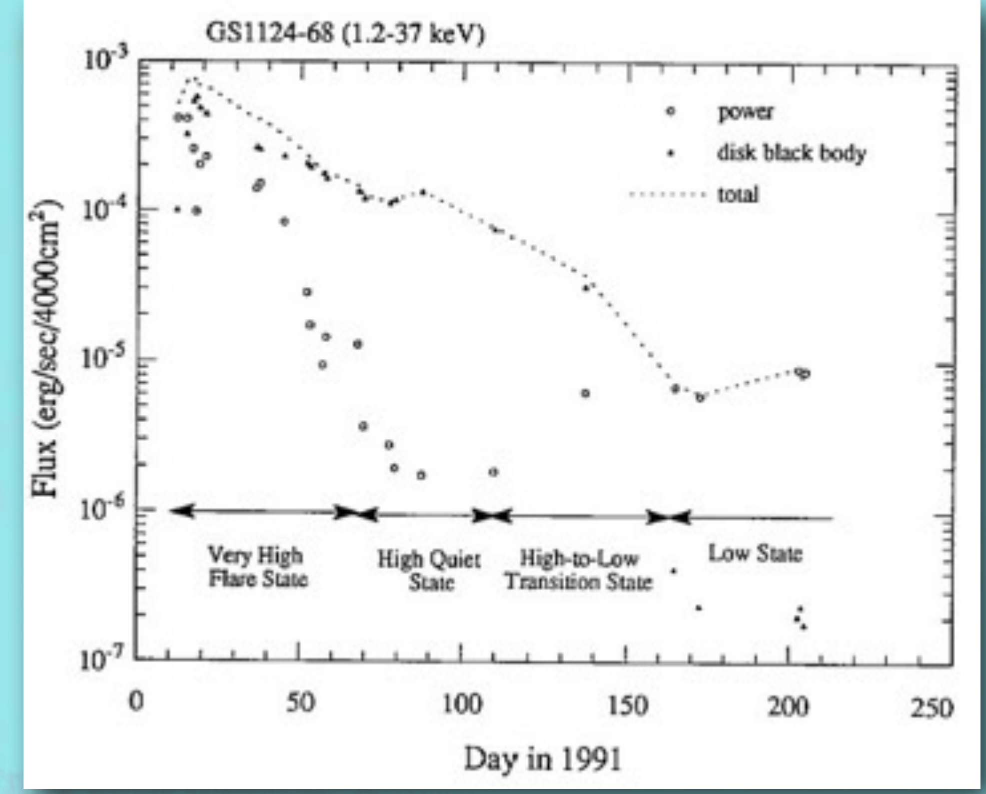
Miyamoto et al. (1993)

Intermediate/Very High

- At high flux: VHS
- At lower flux: Intermediate



Méndez & van der Klis (1997)
[Belloni et al. 1997]



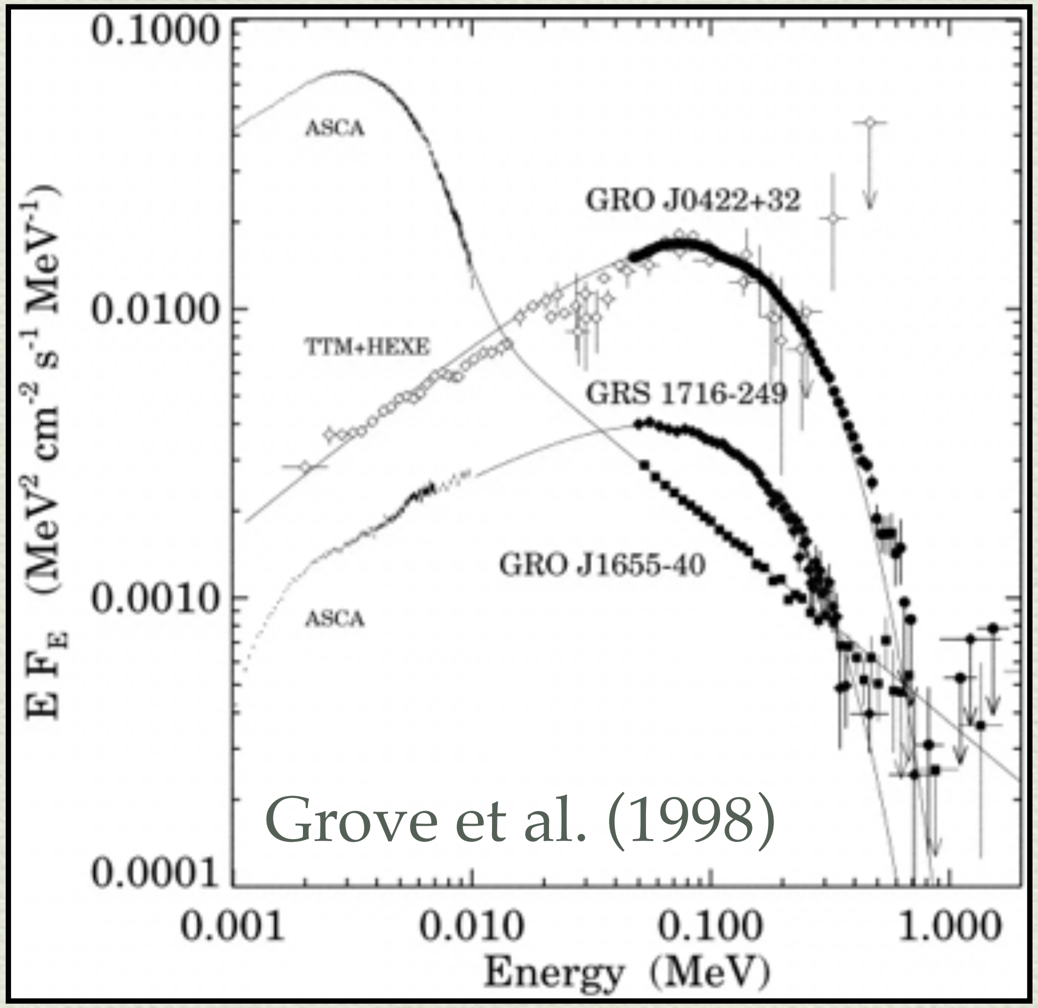
Ebisawa et al. (1994)

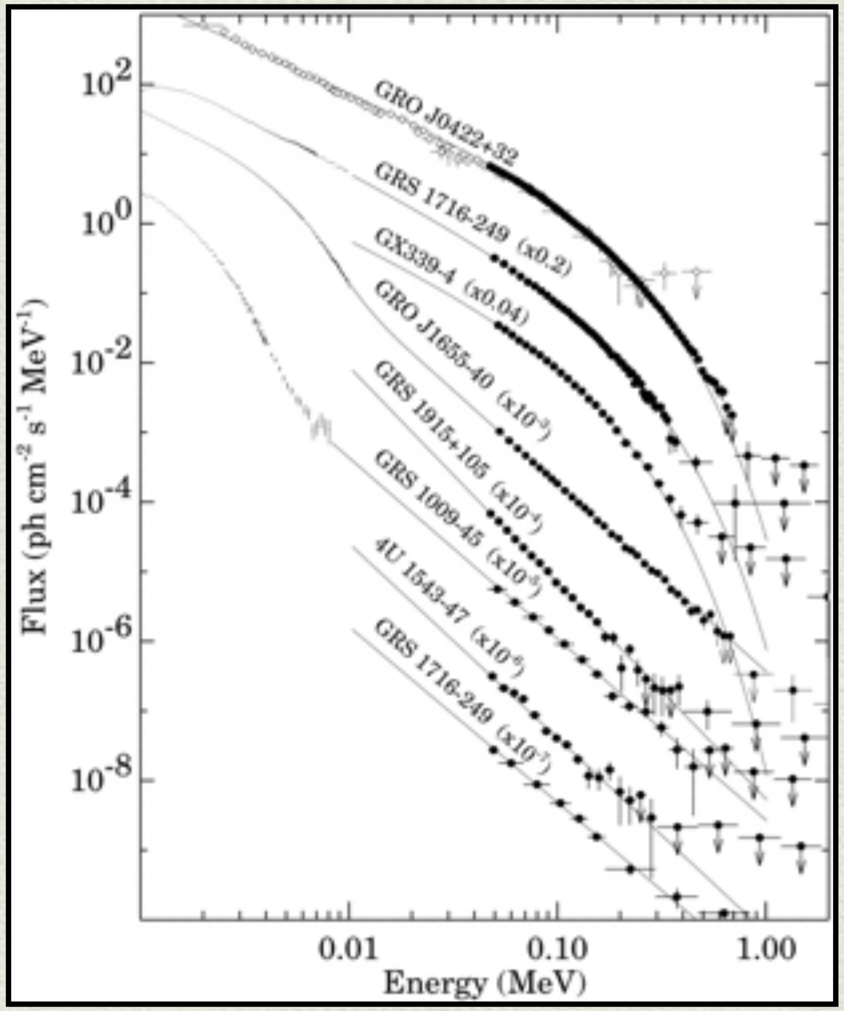
The canonical states

Ginga

- Low state: strong flat-top noise, dominant PL in energy spectrum
- High state: weak power-law noise, dominant DBB in spectrum
- Very-High state: very-high flux, different PDS, presence of QPO, fast switches (“flip-flops”)
- Intermediate state: same as VHS, but at lower luminosity

Hard & soft states



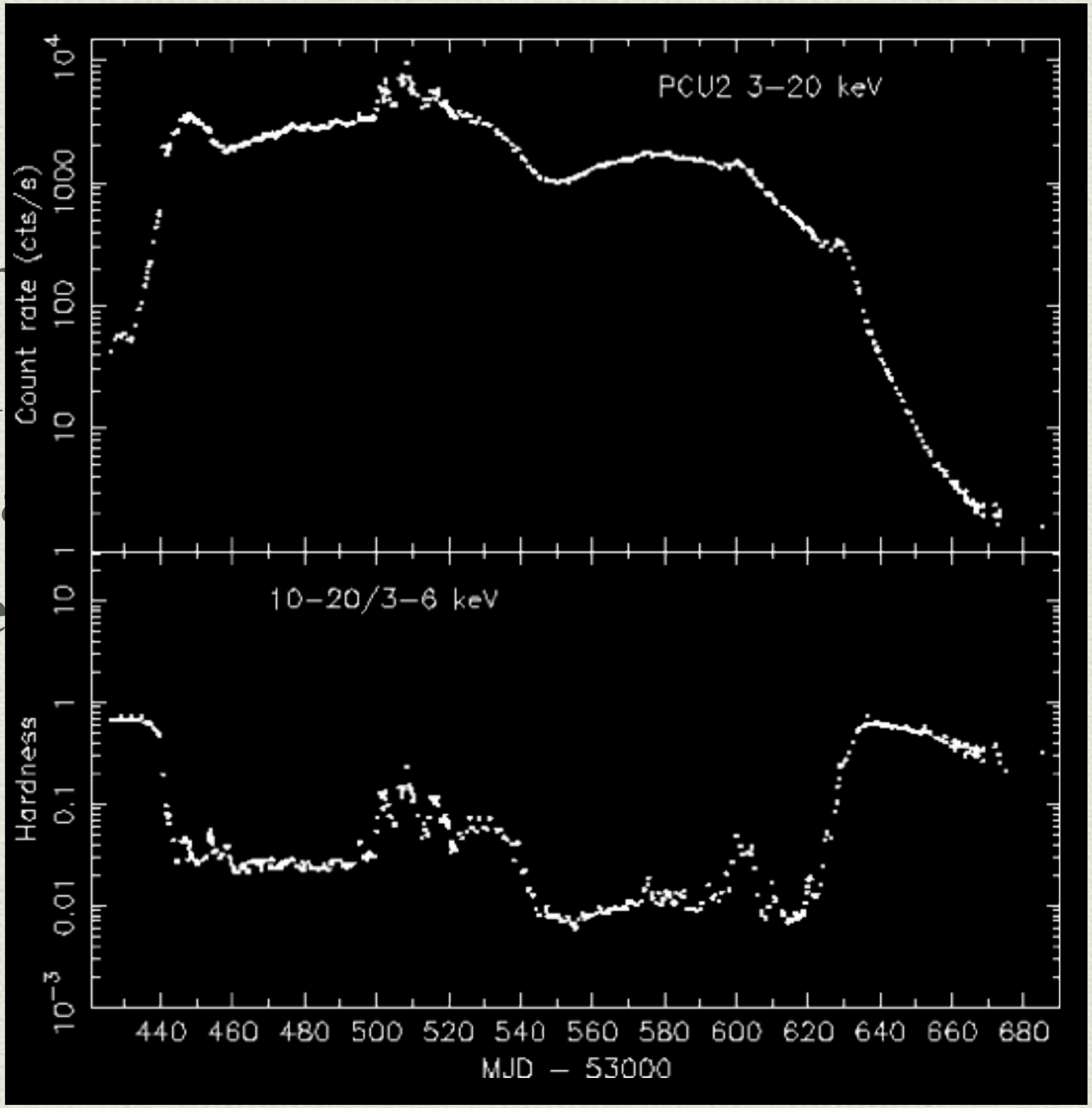


- We have seen these
- What states were actually sampled?

Enter RossiXTE (1995-2012)

- All-Sky m
- Great tim
- Large are
- High-Ene

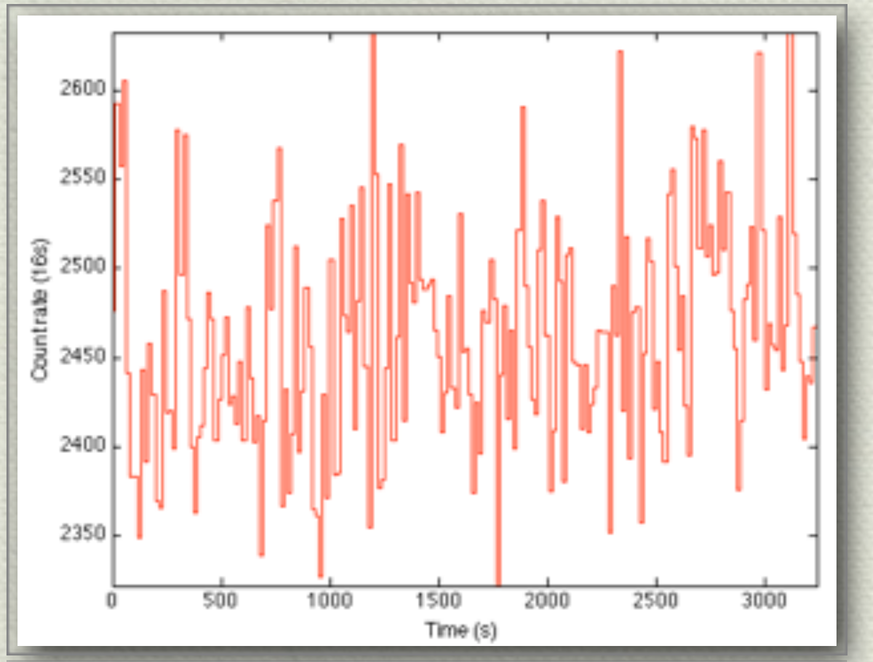
- Good for

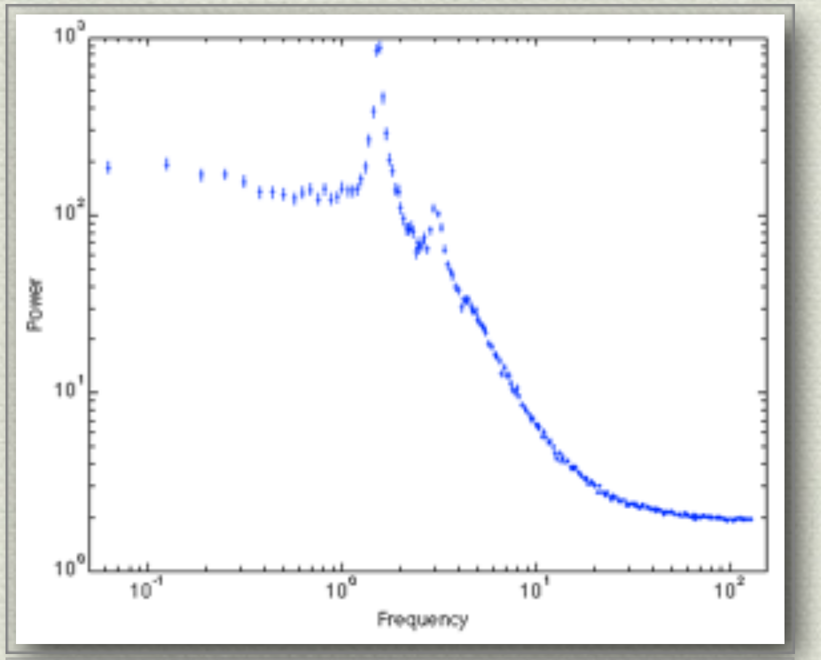


Timing analysis

- Main tool: Power Spectrum

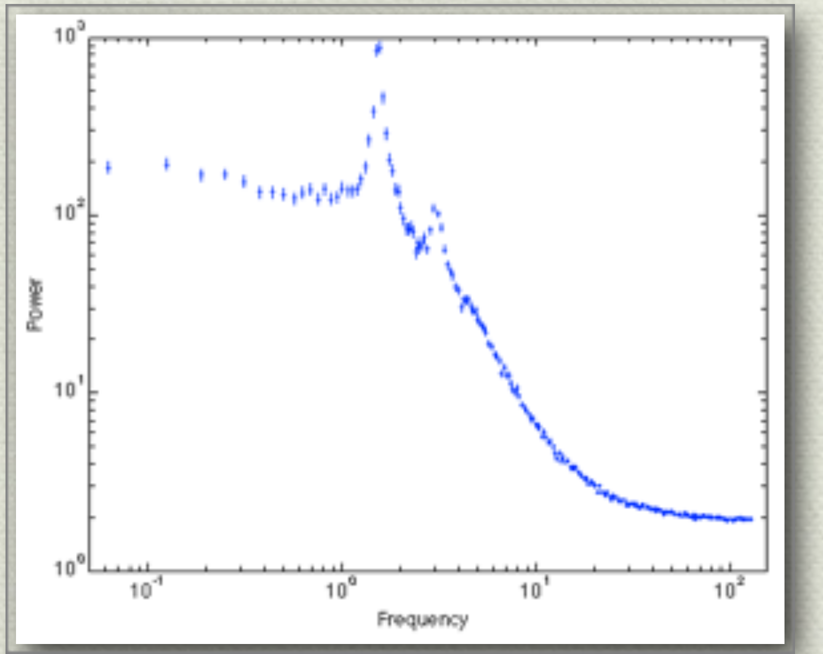
$$P = \frac{2}{N_{phot}} |a|^2$$

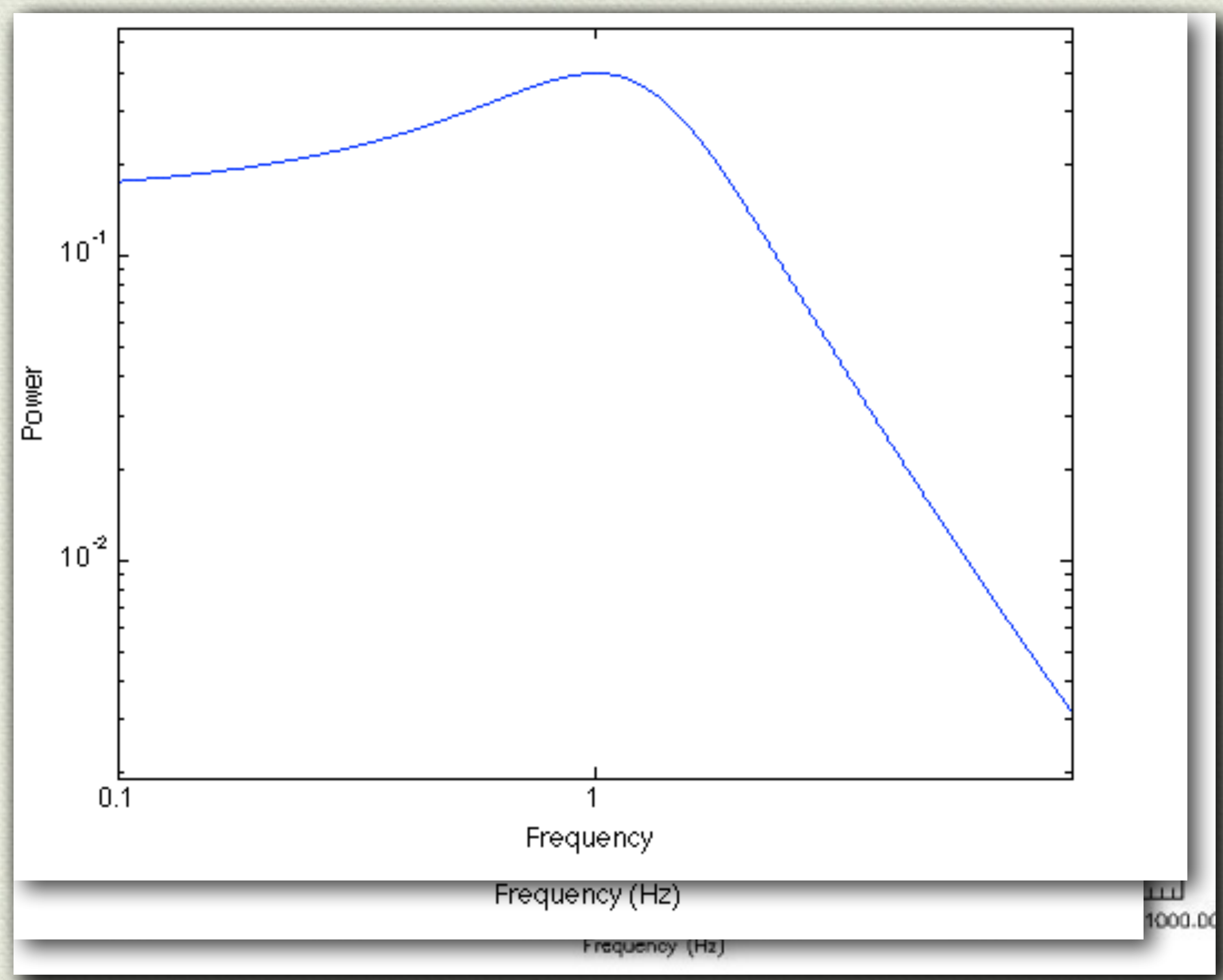




Timing analysis

- Coherent peaks
- Noise components
- QPOs
- Peaked noise

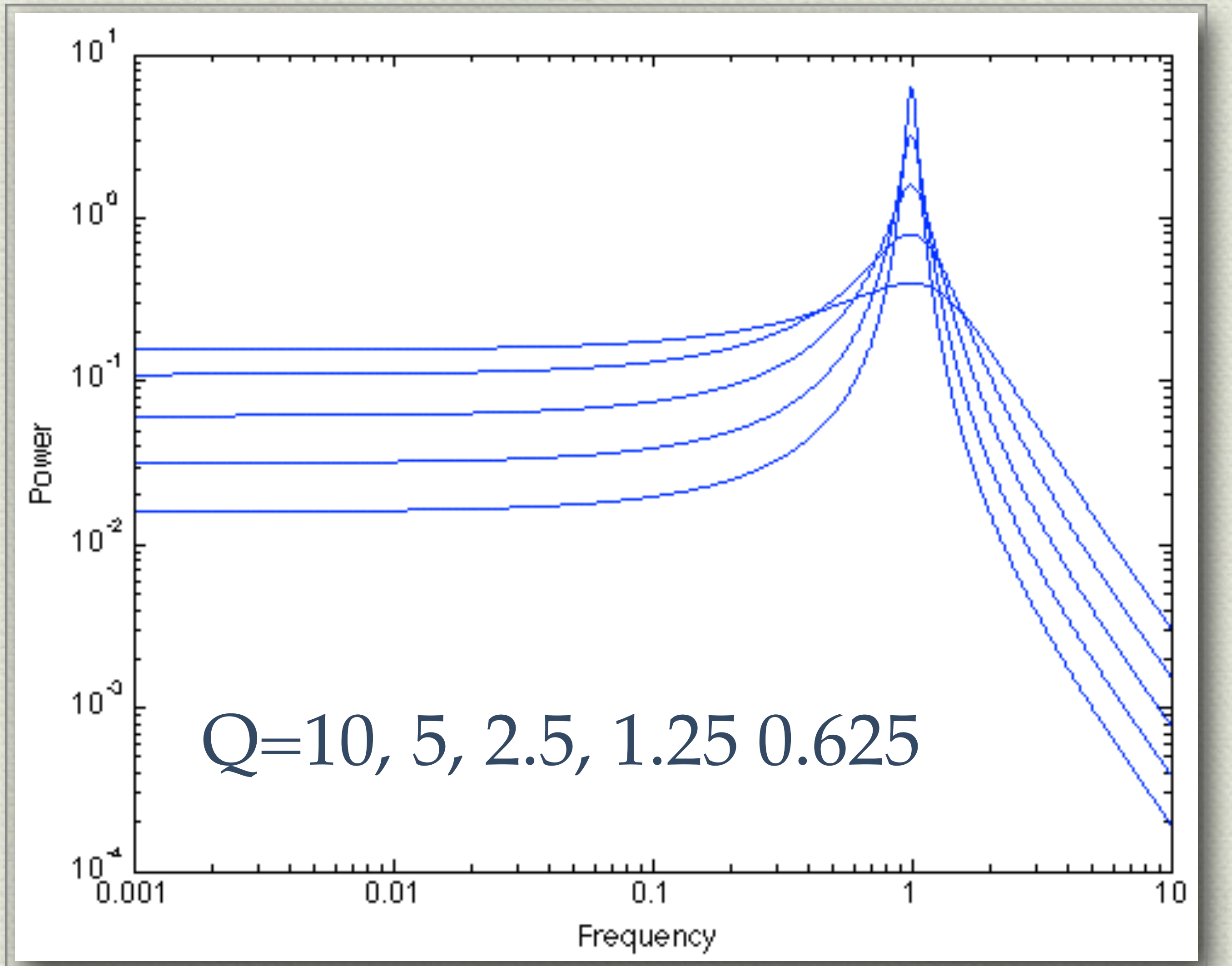




Timing quantities

- Centroid frequency
- Width (FWHM)
- Q = quality factor

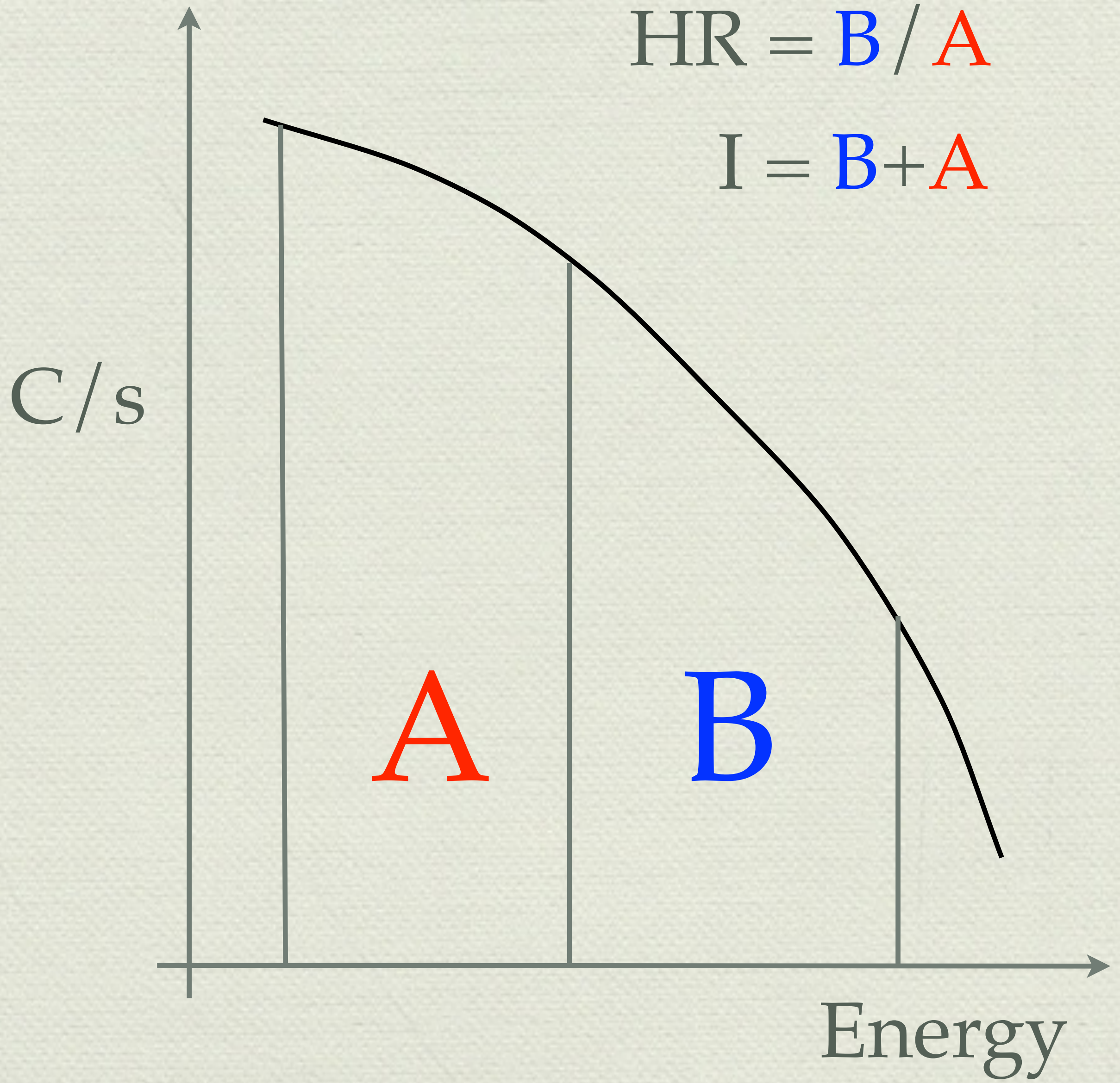
- Fractional rms
- Integrated % rms



Color analysis

- X-ray colors
- Hardness Ratio (HR)

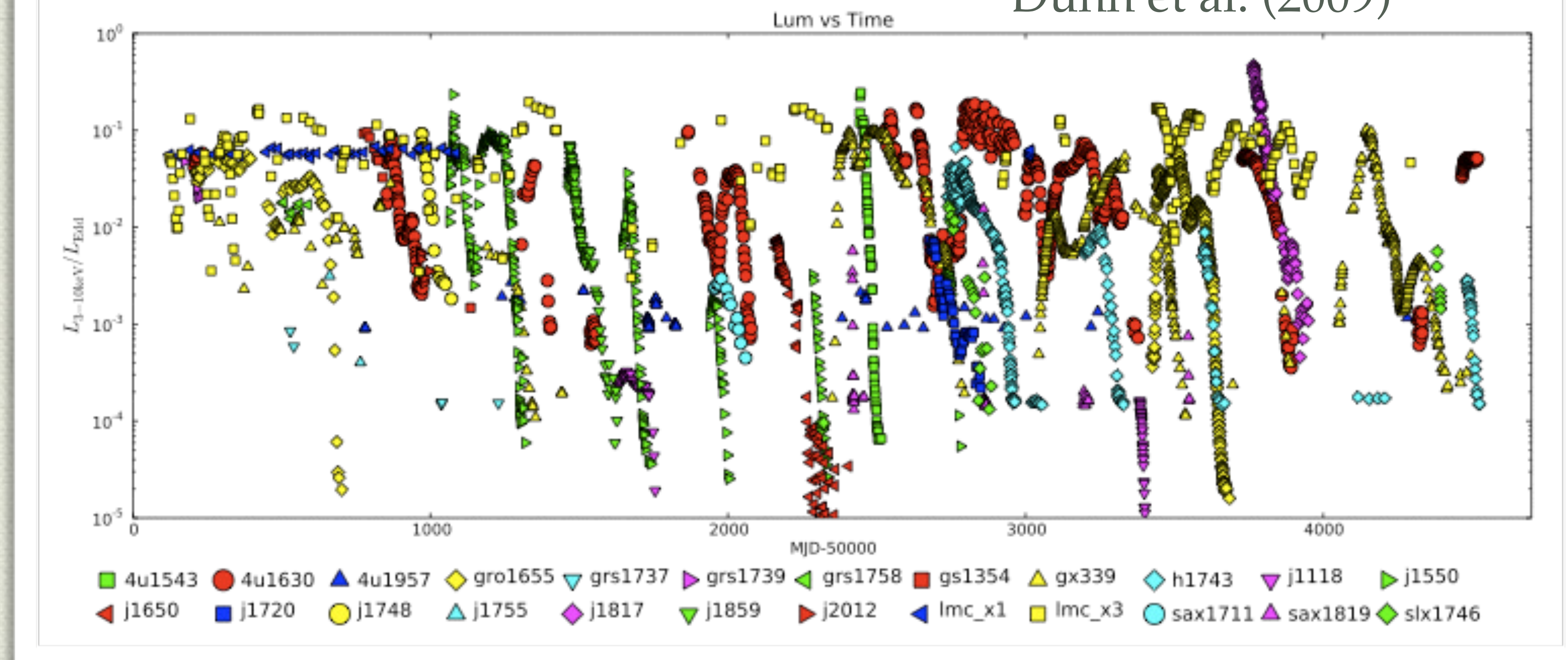
- General spectral behavior



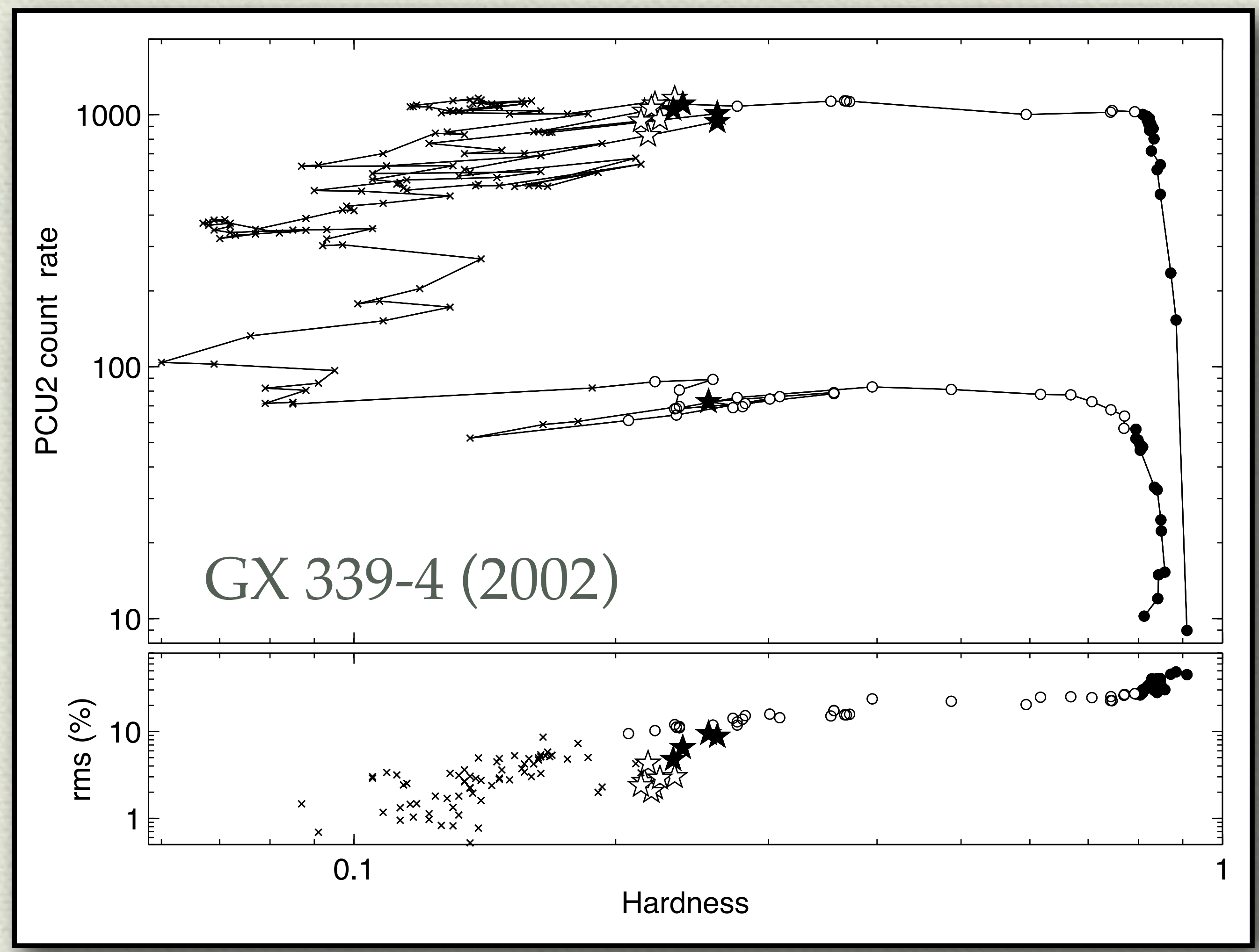
Transients

- Very different time evolutions
- Large spectral variations (remember hard and soft)
- Correlated variability properties

Dunn et al. (2009)



The basic diagrams

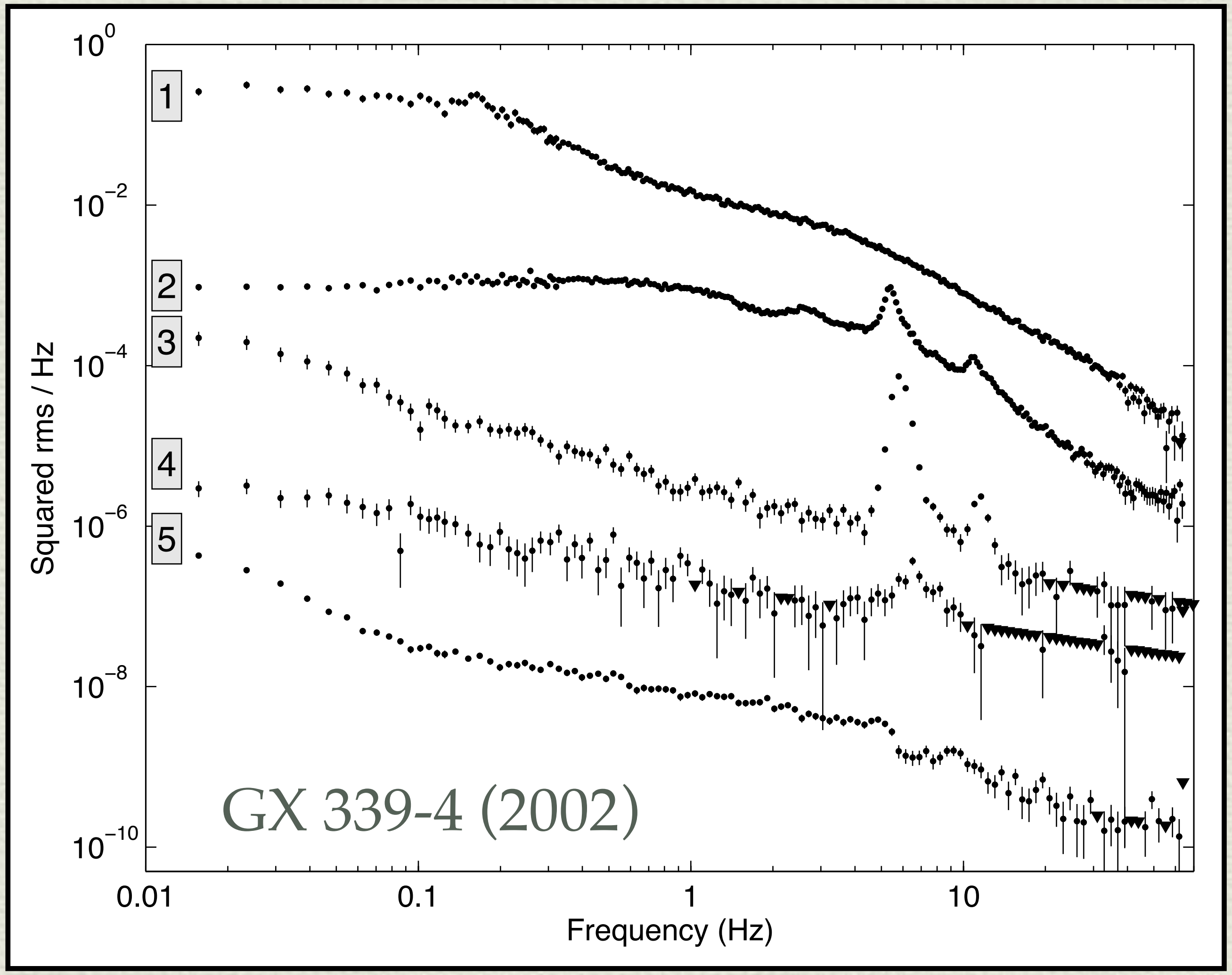


HID

HRD

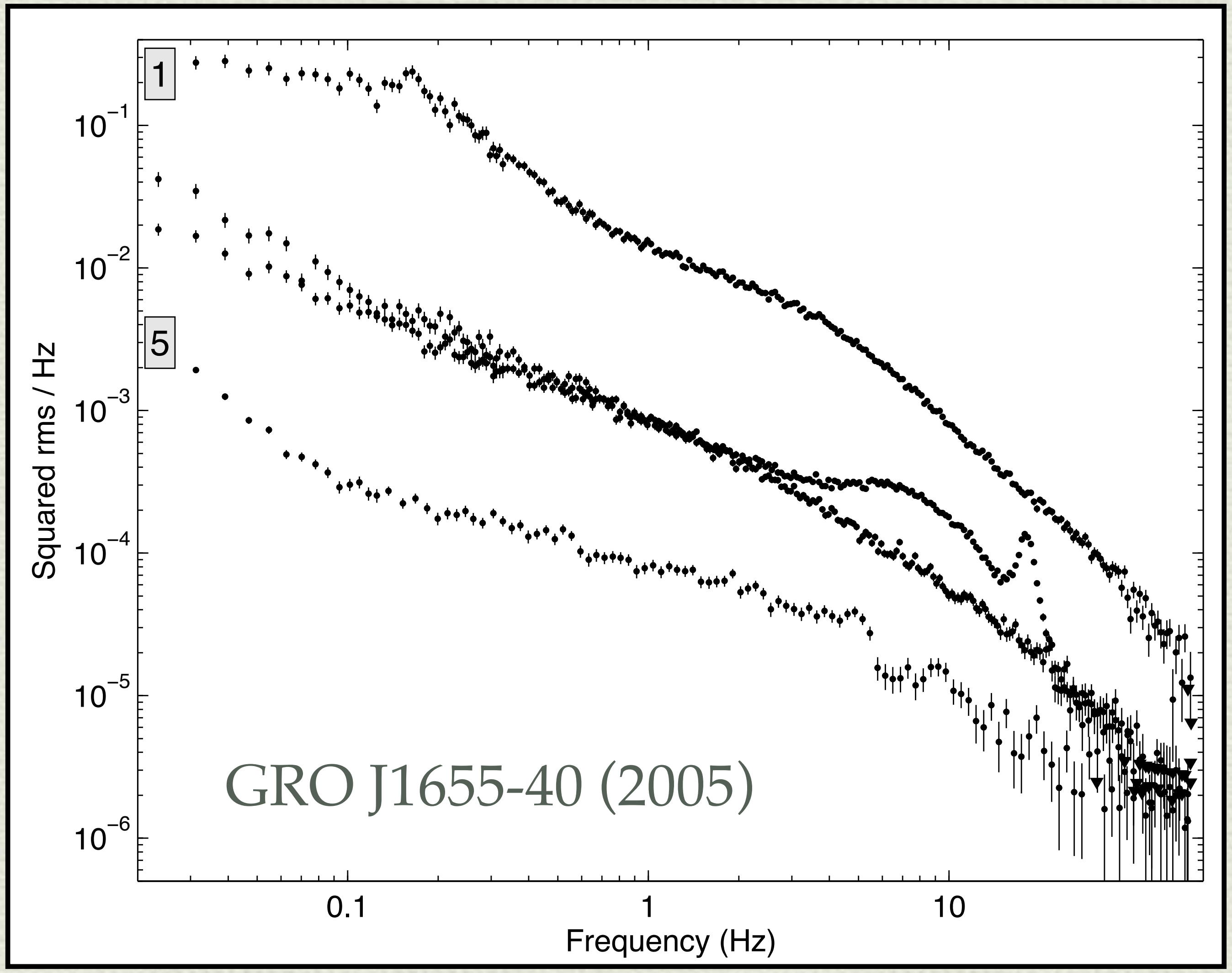
- HID: Hardness-Intensity Diagram
- HRD: Hardness-rms Diagram

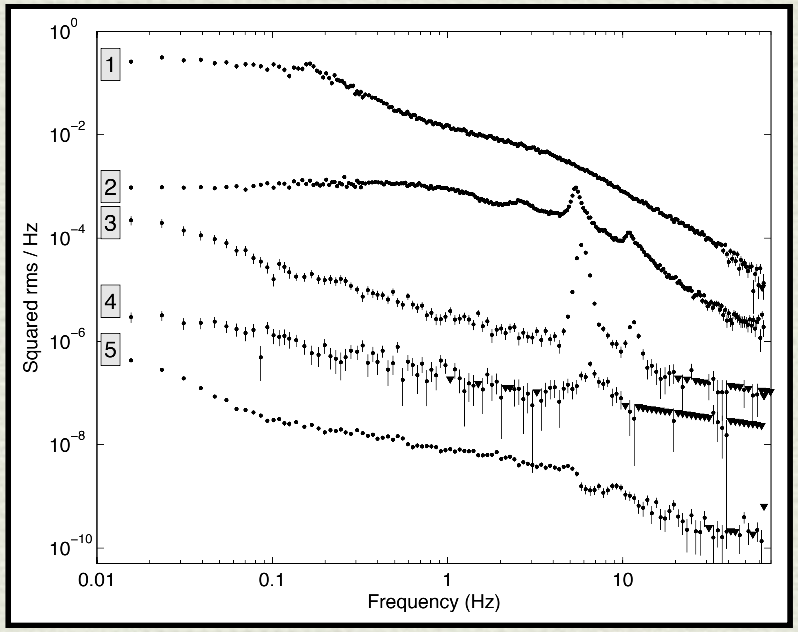
The fast variability (I)



- A few classes of Power Density Spectra
- Plus an additional odd class

The fast variability (II)





- A couple more classes

The fast variability (III)

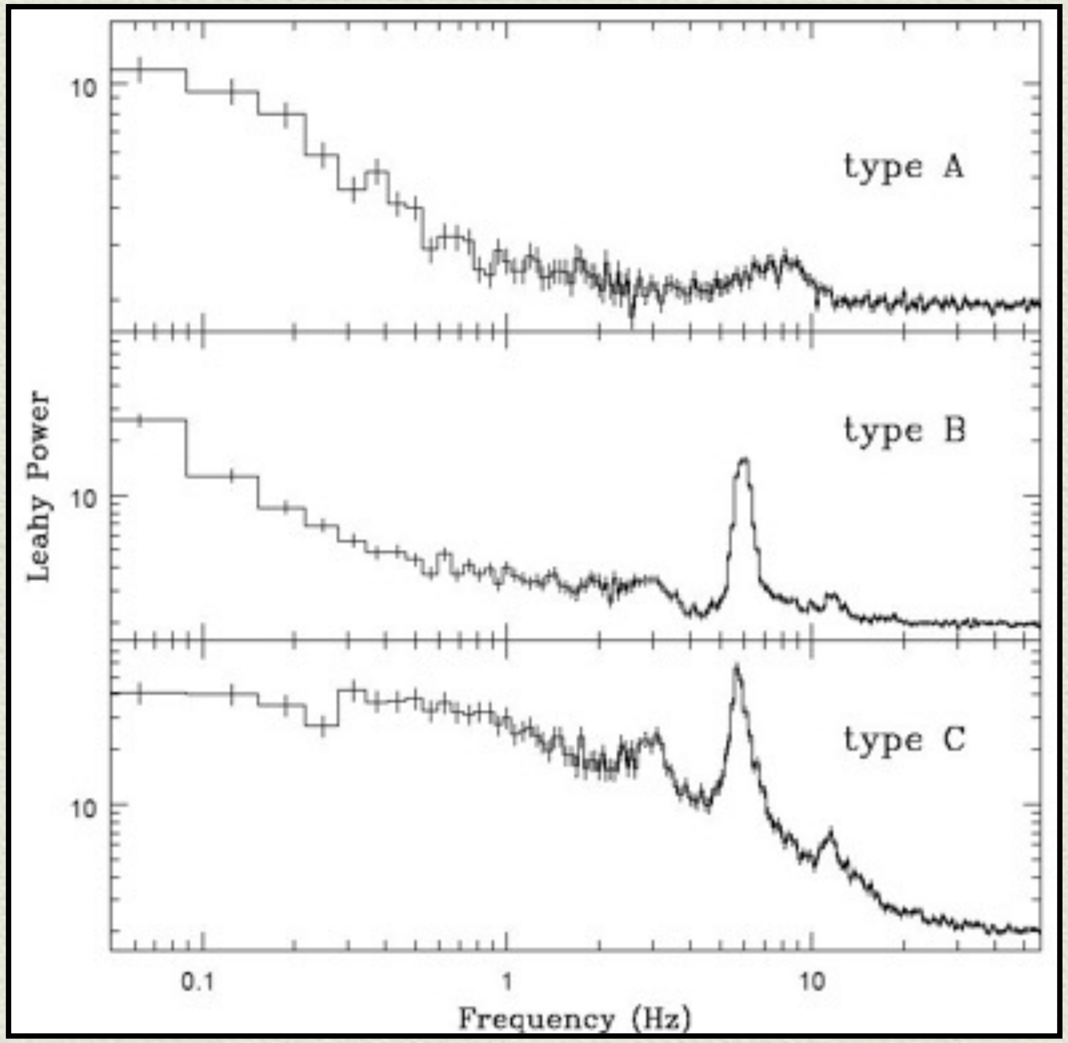


TABLE 1
SUMMARY OF TYPE-A, -B AND -C LFQPOs PROPERTIES

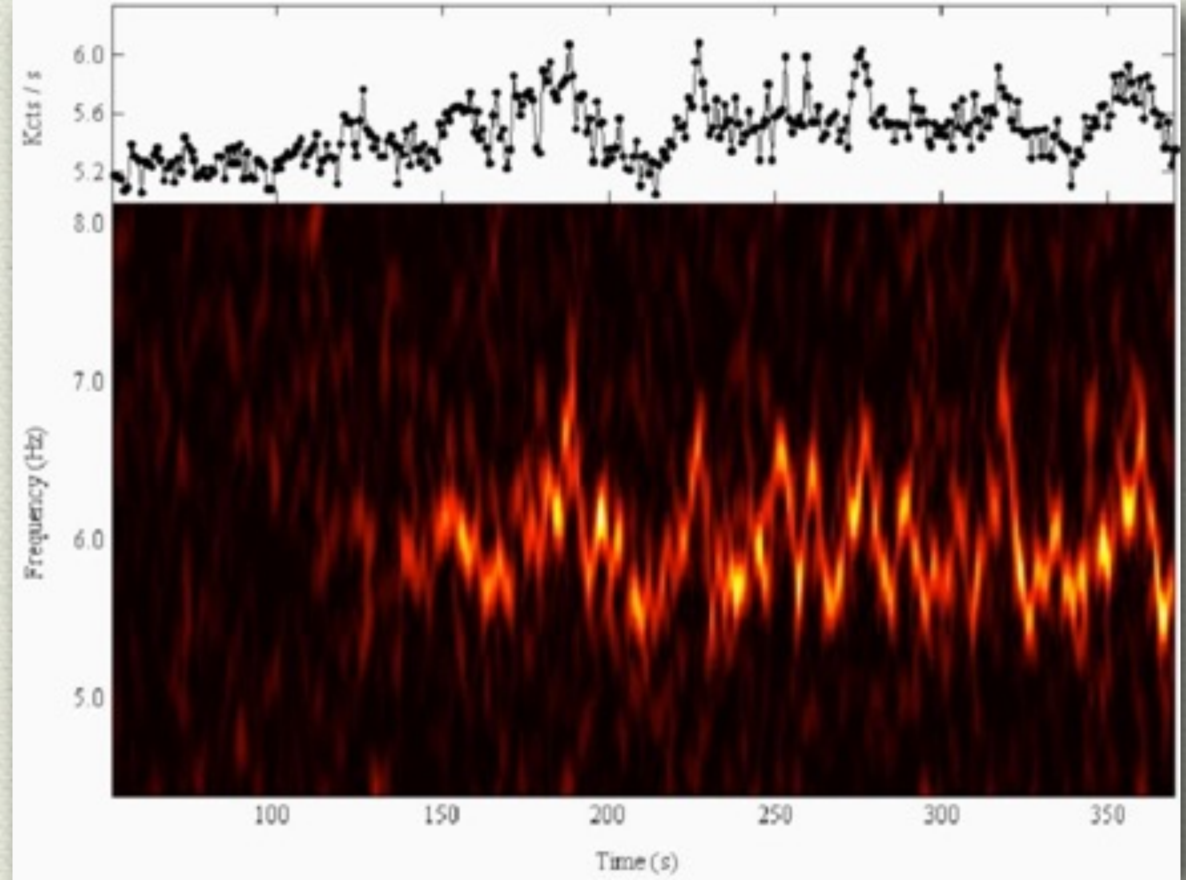
Property	Type C	Type B	Type A
Frequency (Hz)	~0.1-15	~5-6	~8
Q (ν/FWHM)	~7-12	$\gtrsim$6	$\lesssim$3
Amplitude (%rms)	3-16	~2-4	$\lesssim$3
Noise	strong flat−top	weak red	weak red
Phase lag @ν_{QPO}	soft/hard	hard	soft
Phase lag @$2\nu_{QPO}$	hard	soft	...
Phase lag @$\nu_{QPO}/2$	soft	soft	...

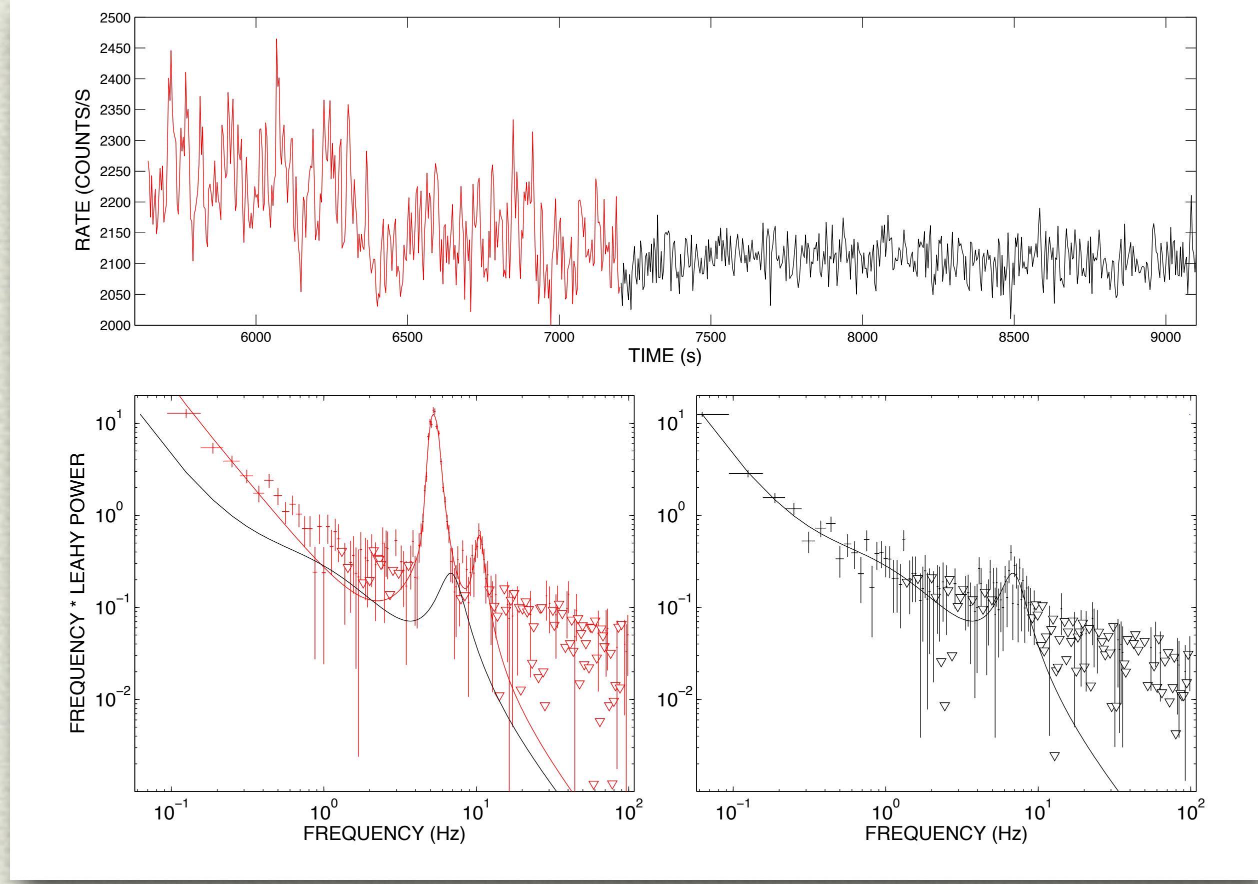
Casella et al. (2005)

- Three types of QPO

The fast transitions

GX 339-4



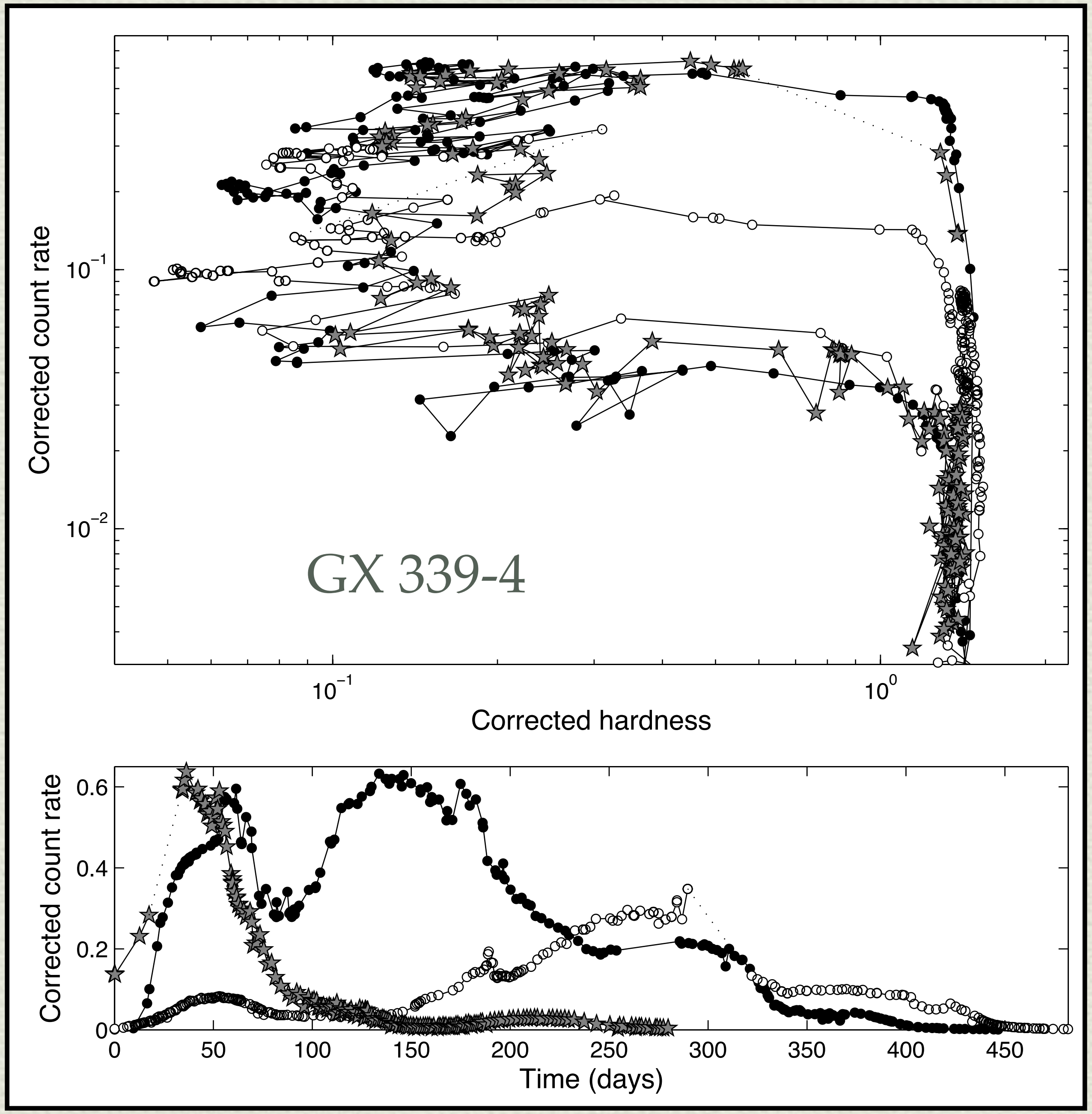


Nespoli et al. (2003)

Motta et al. (2011)

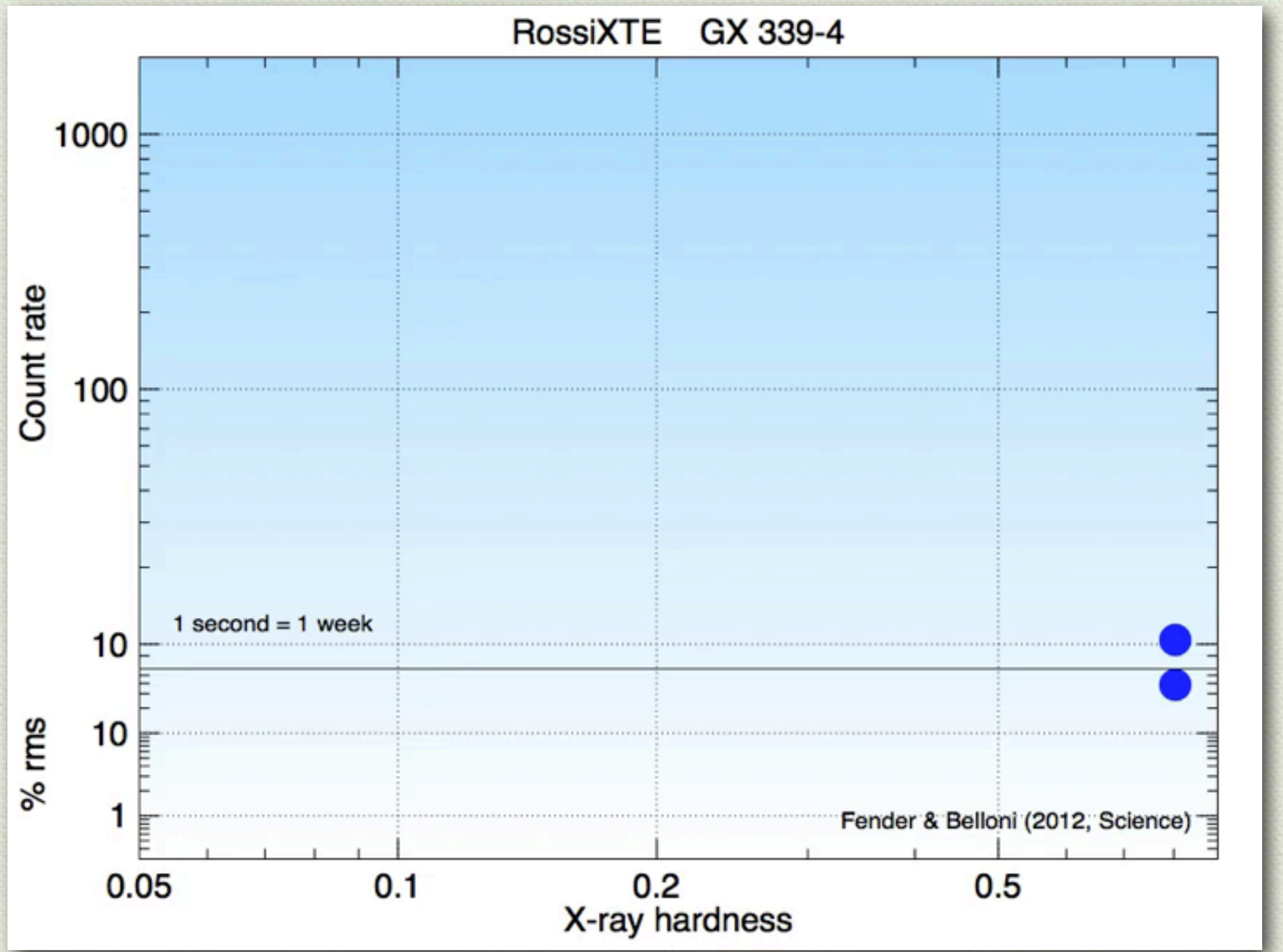
The time evolution

- Three outbursts of GX 339-4
- Different in time evolution
- Similar in HID/HRD



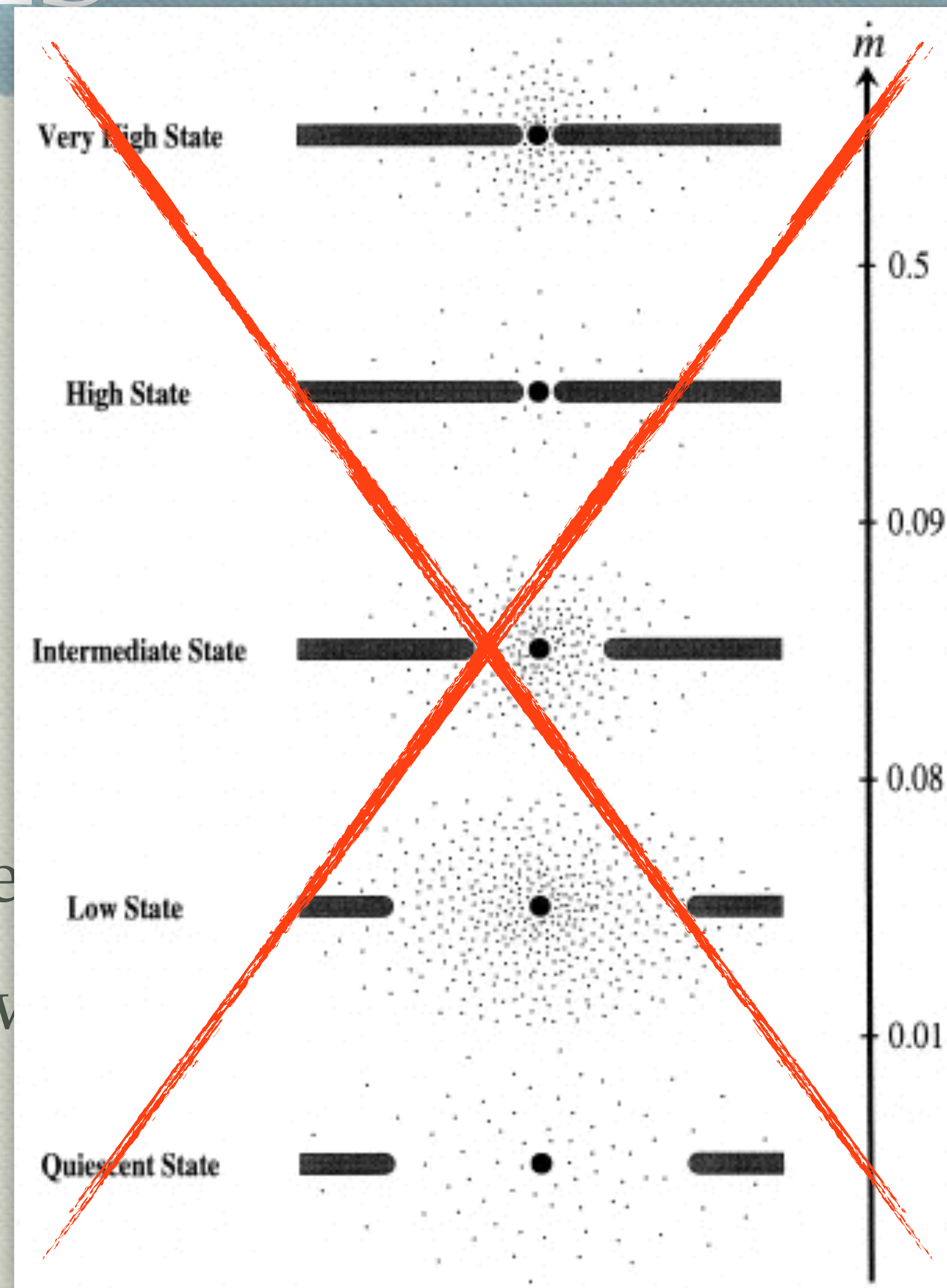
The movie

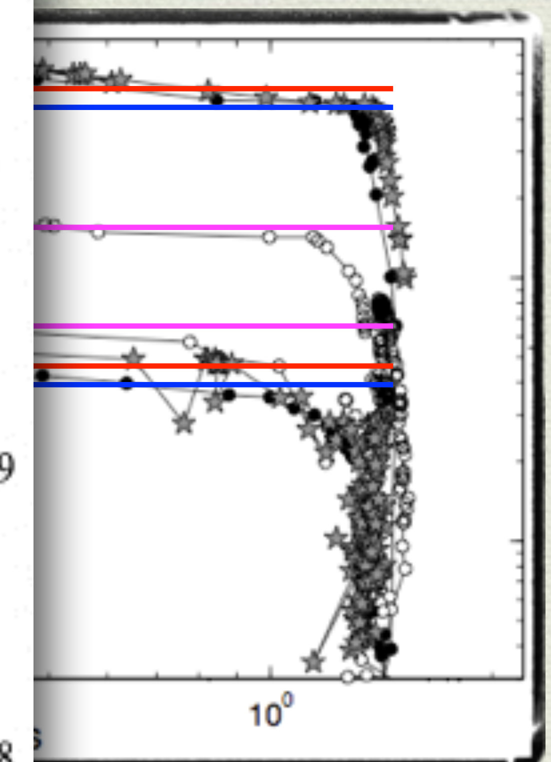
Fender & Belloni (20012)



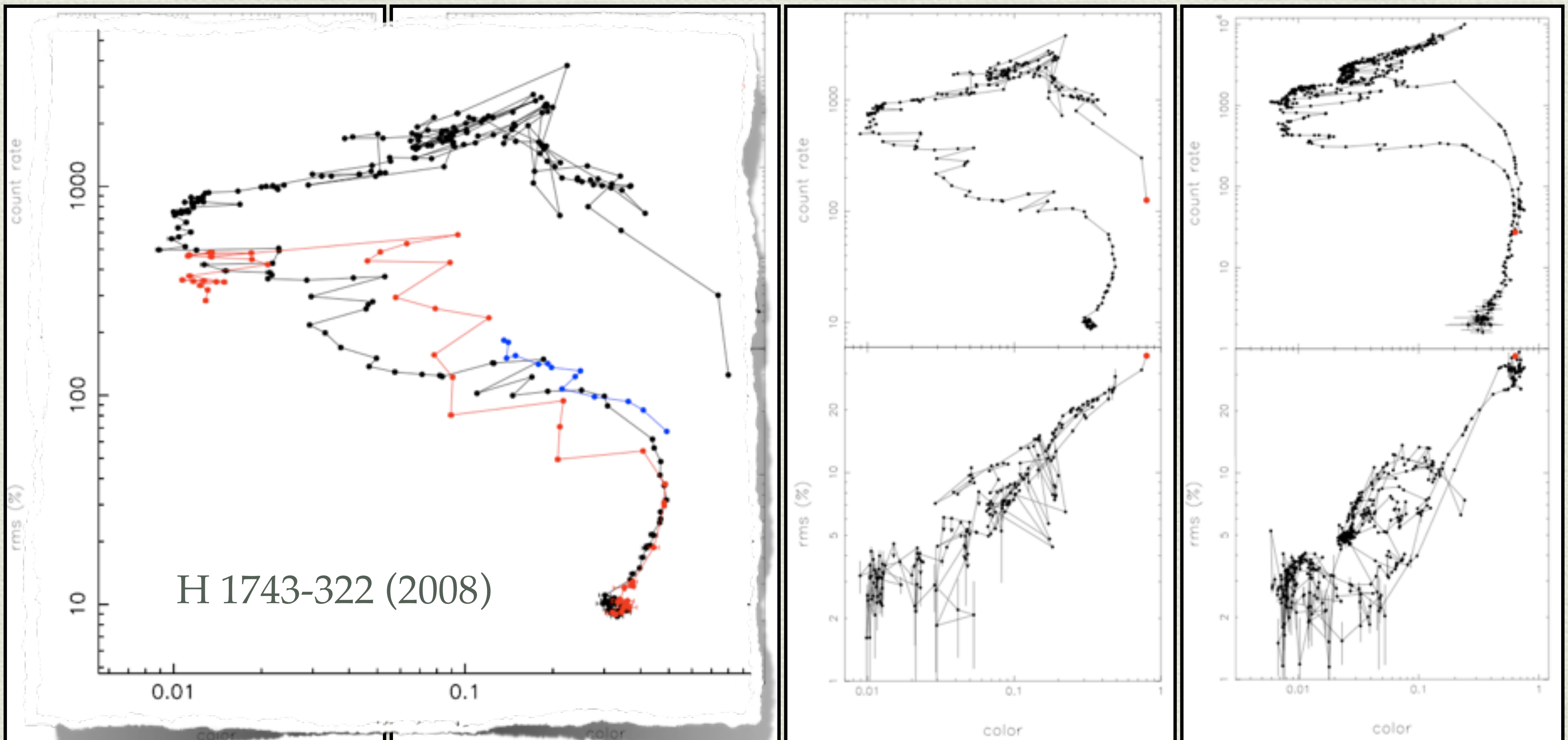
Hysteresis

- Not in HRD
- "Return effect"
- What is the reason?
- Second parameter ne
- Possible correlation v



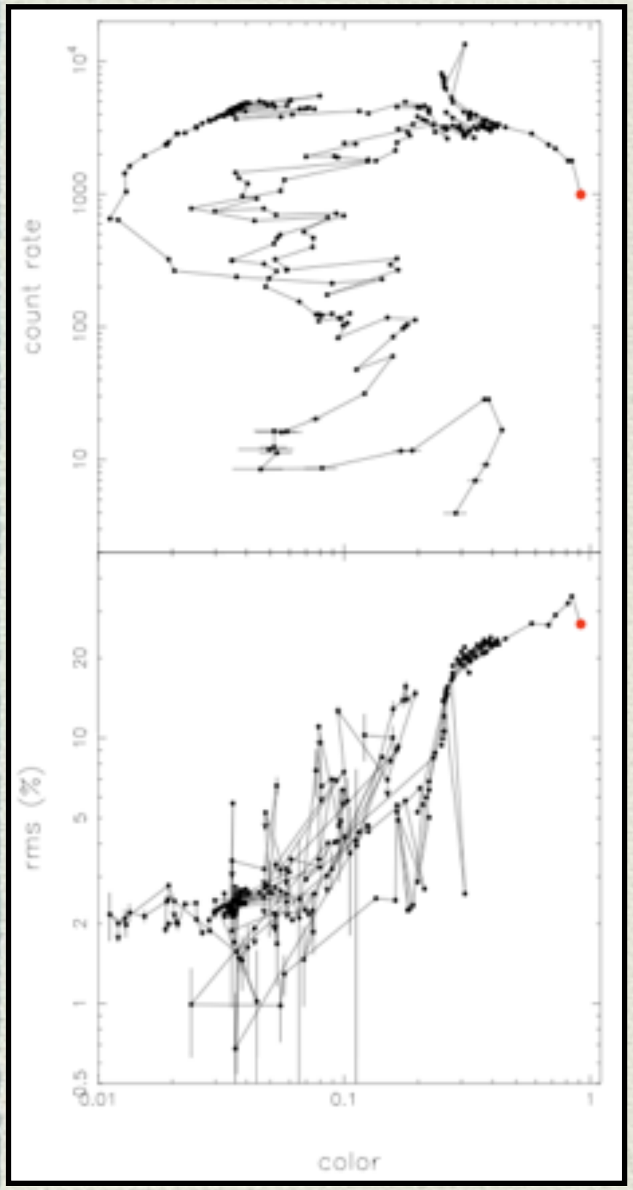


Other sources (I)

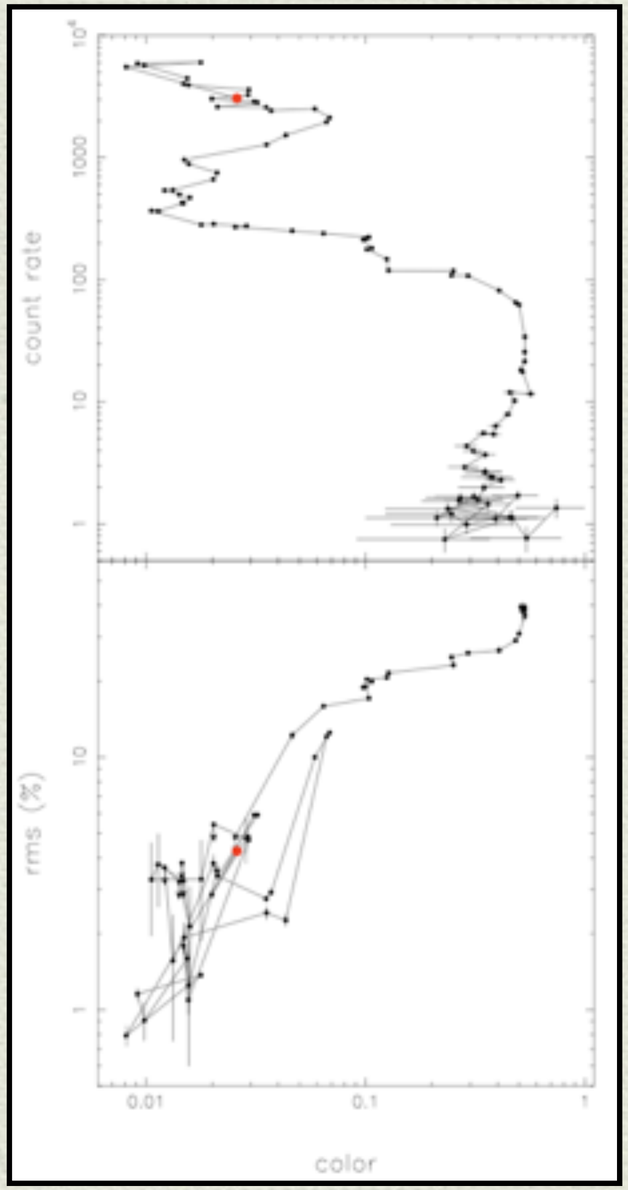


XTE J1655-500 XTE J1859+226 H 1743-322 GRO J1655-40

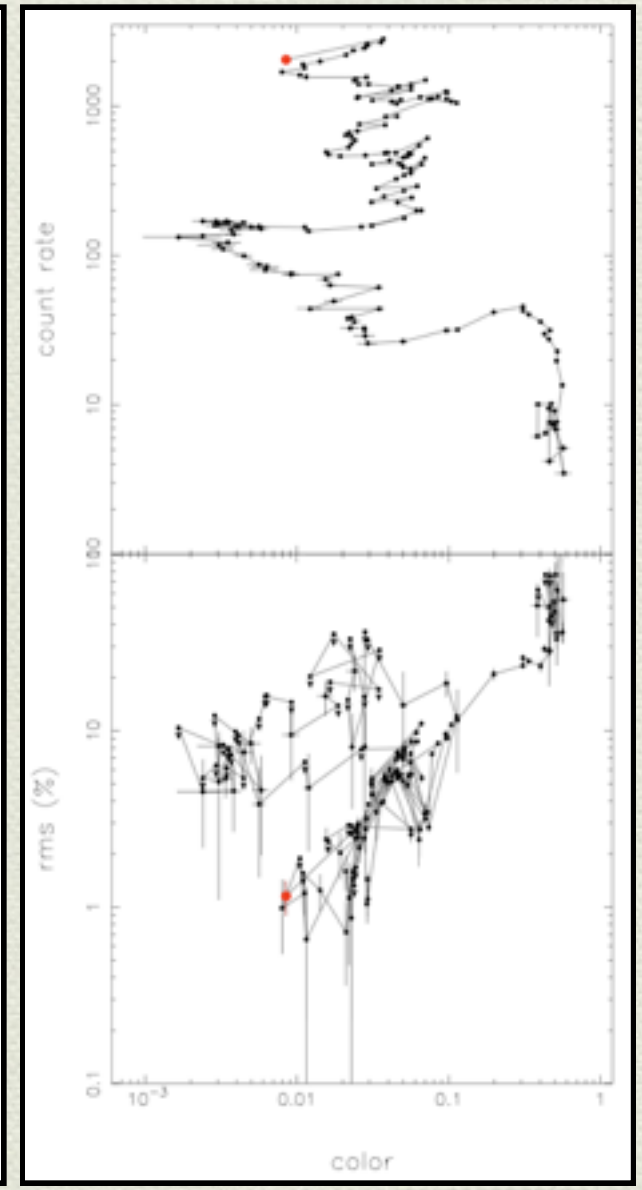
Other sources (II)



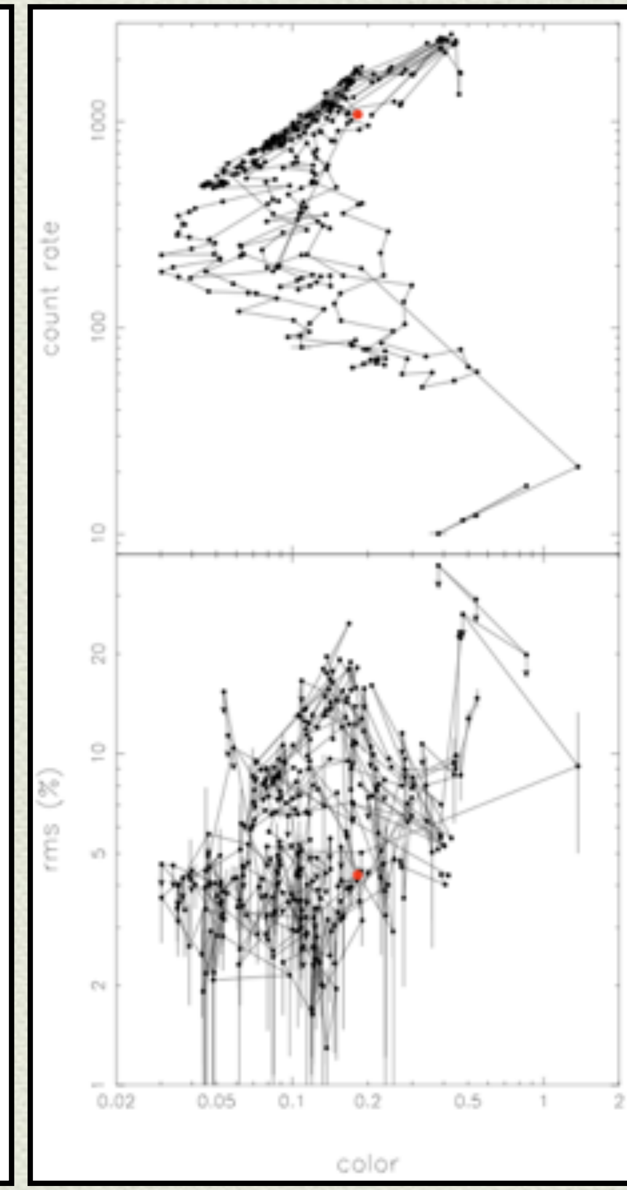
XTE J1550-564



4U 1543-475

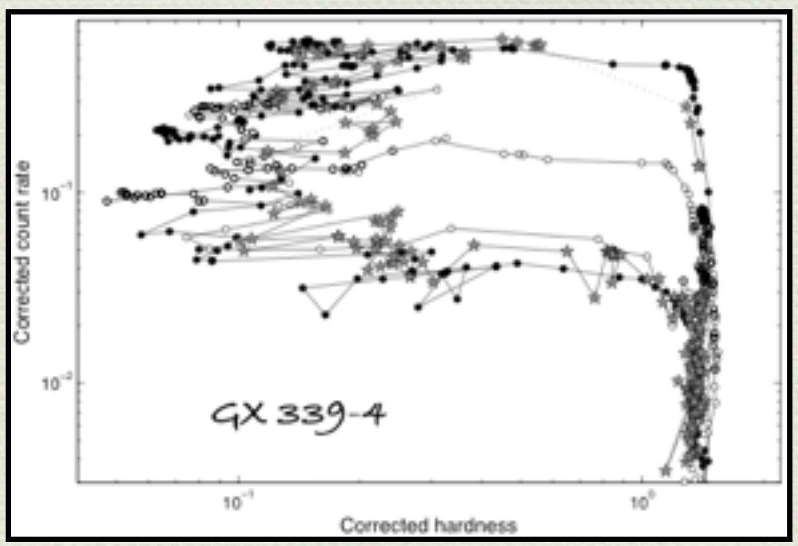


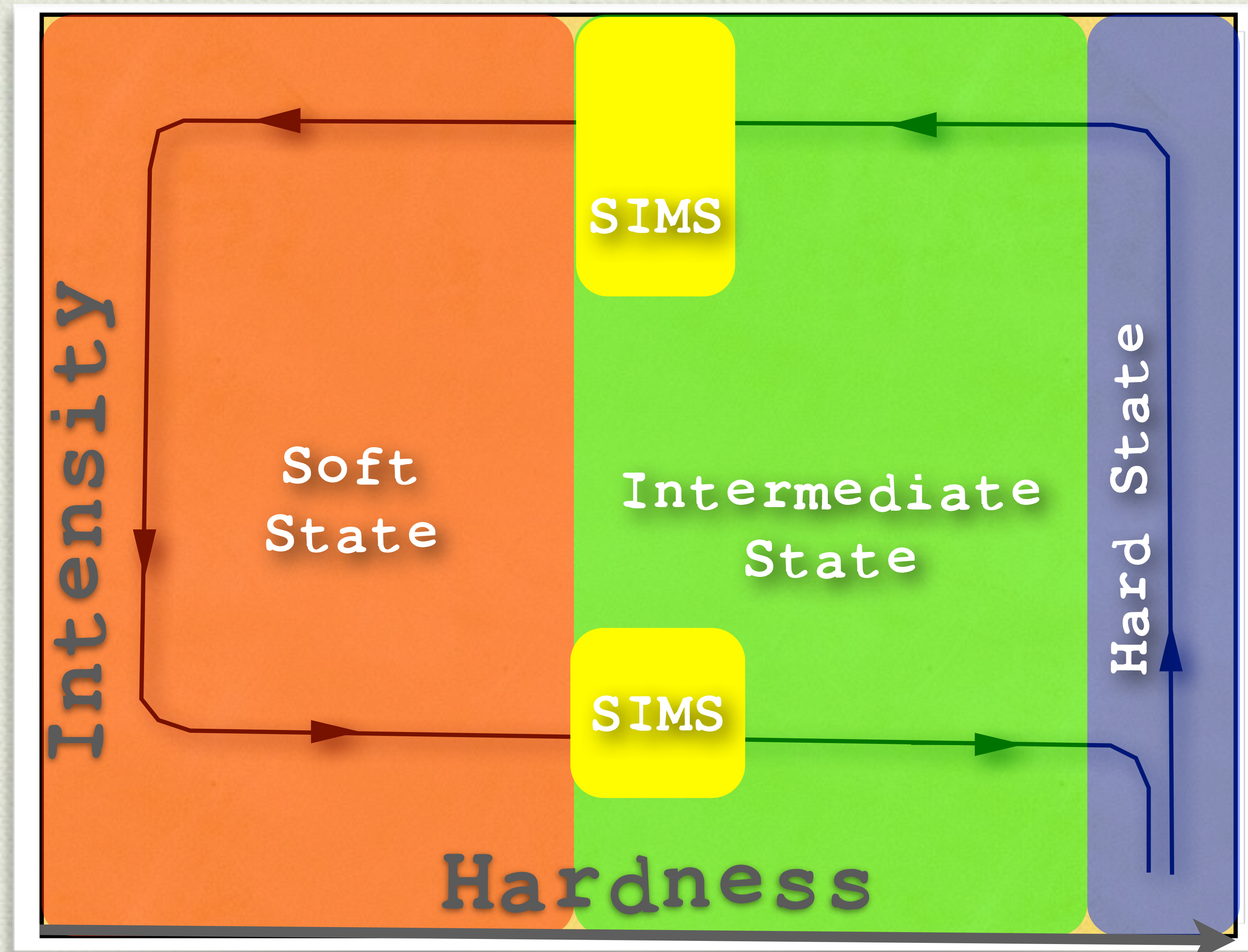
XTE J1817-330



4U 1630-47

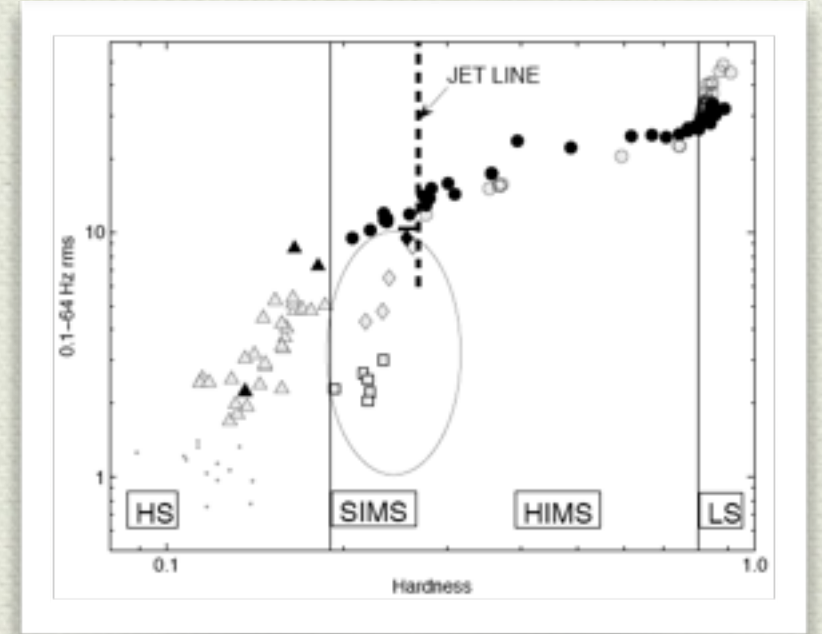
A new paradigm



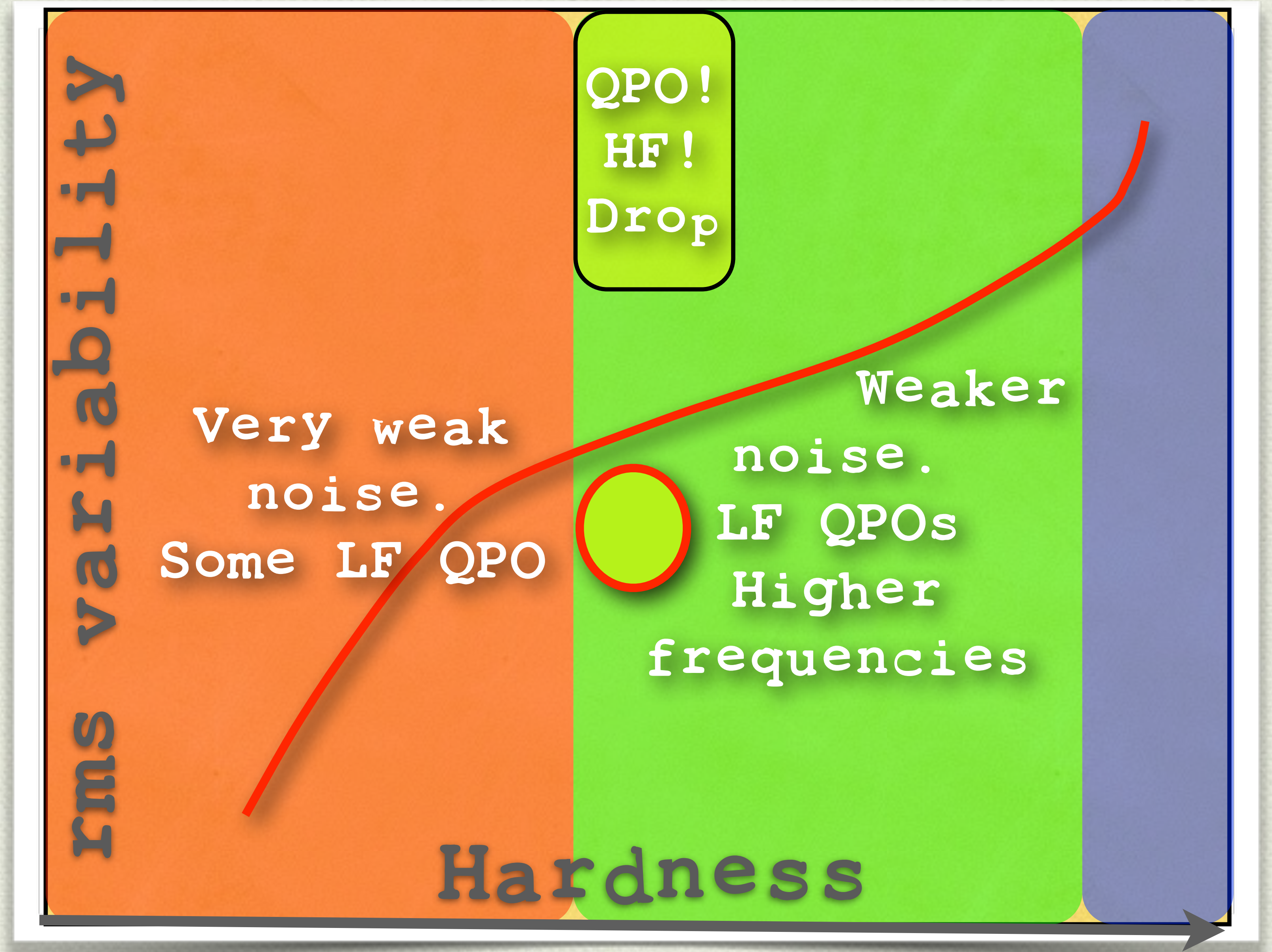


Belloni (2010)

The fast variability

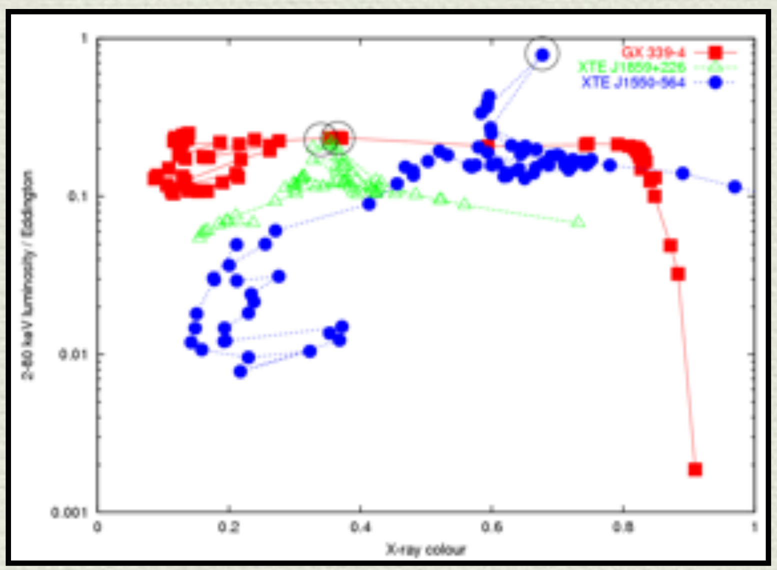


Belloni et al.(2005)

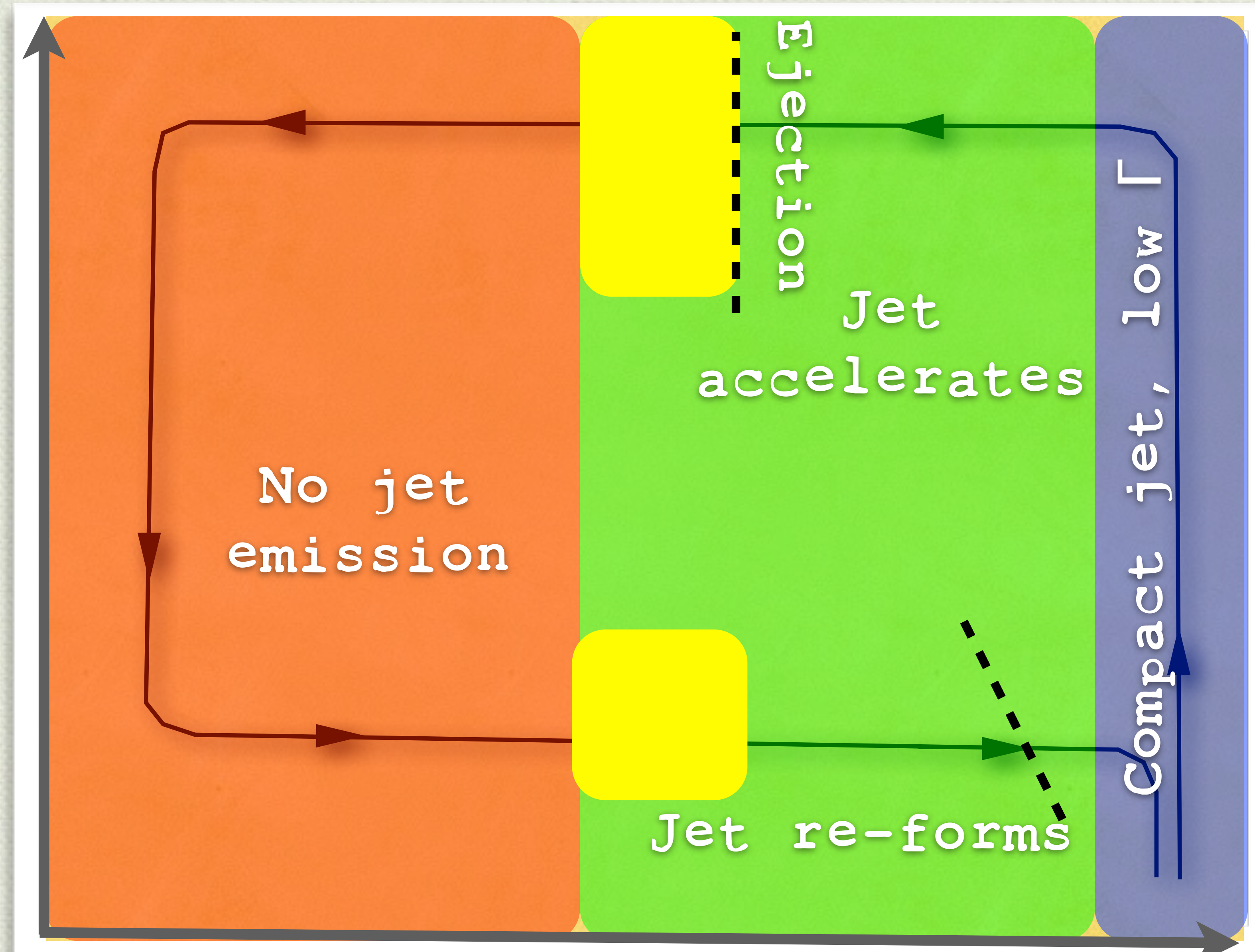


Belloni (2010)

The jet connection



Fender, Belloni & Gallo(2004)



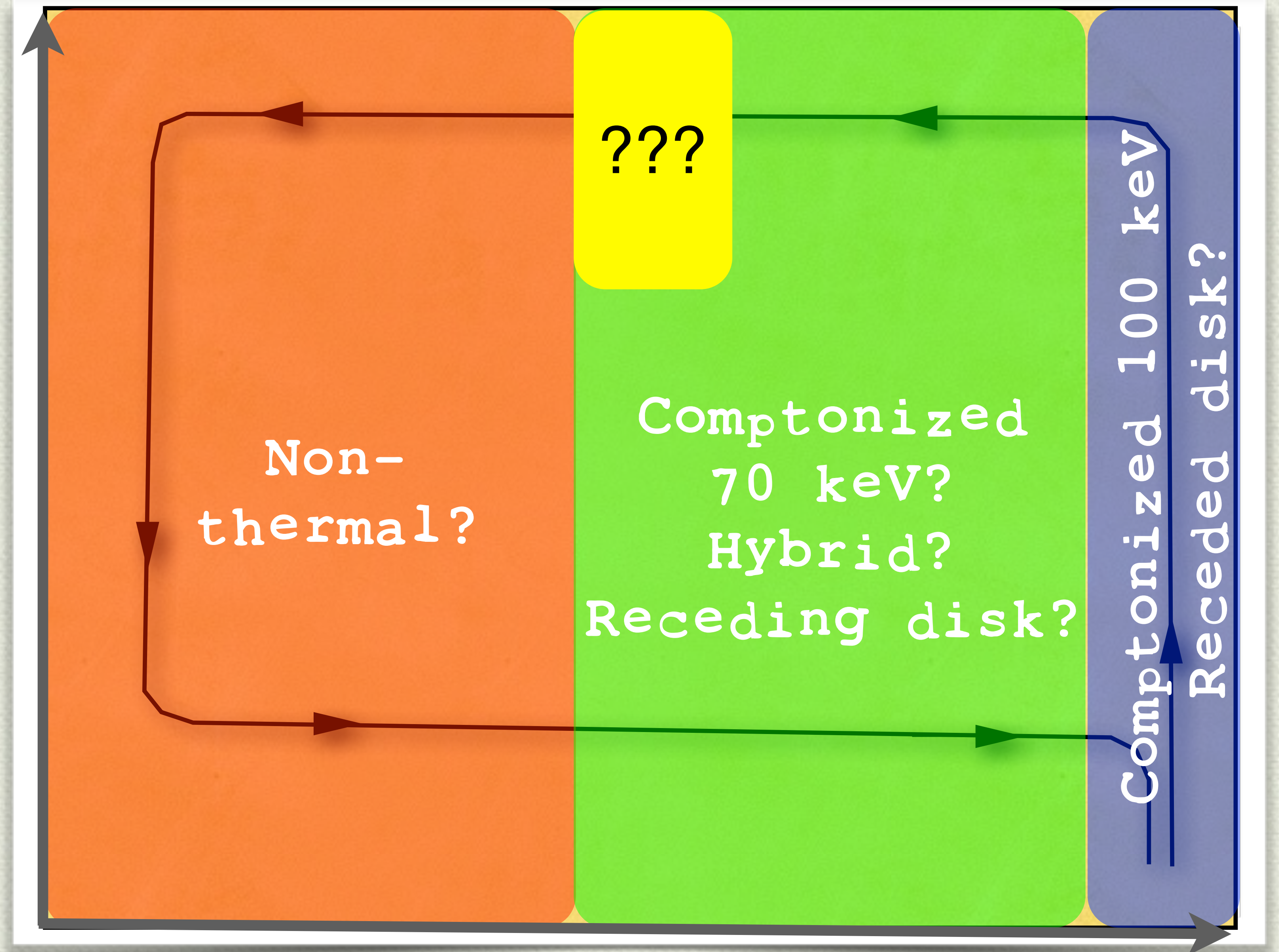
Homan & Belloni (2009)

(High-)Energy

	Orbit 1	Orbit 2
PL Index	2.44 ± 0.02	2.44 ± 0.10
E_c (keV)	190^{+10}_{-90}	110^{+70}_{-40}
T_{in} (keV)	0.89 ± 0.01	0.92 ± 0.01
E_{line} (keV)	6.86 ± 0.11	6.7 ± 0.2
F_{Tot}[a]	$(2.06 \pm 0.06) \times 10^{-8}$	$(2.25 \pm 0.17) \times 10^{-8}$
F_{disk}[a]	$(1.30 \pm 0.04) \times 10^{-8}$	$(1.18 \pm 0.02) \times 10^{-8}$
F_{pow}[a]	$(7.71 \pm 0.35) \times 10^{-9}$	$(1.02 \pm 0.03) \times 10^{-8}$
L_{tot} (erg s^{-1})	$(3.73 \pm 1.86) \times 10^{37}$	$(4.07 \pm 2.05) \times 10^{37}$

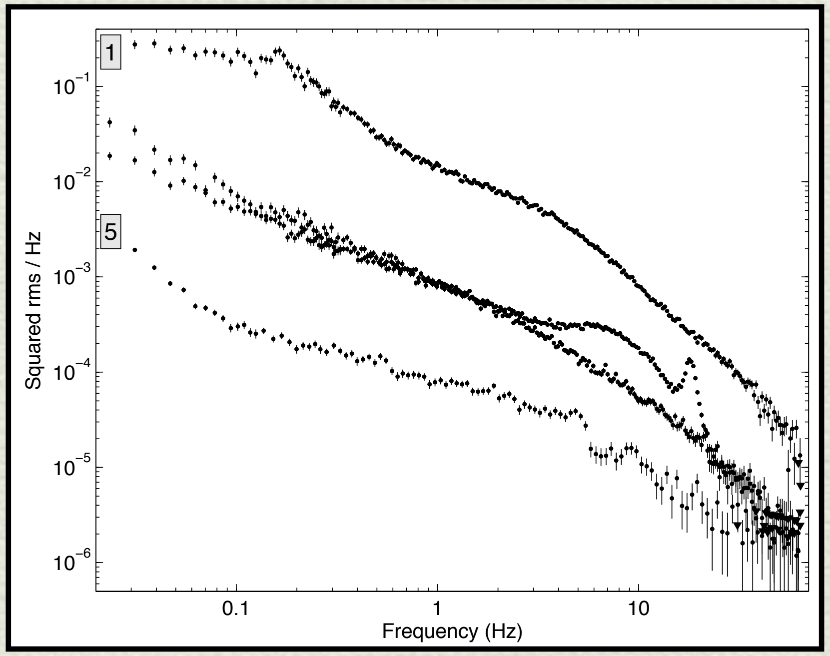
[a] Unabsorbed 2–100 keV flux (erg cm^{-2} s^{-1}).

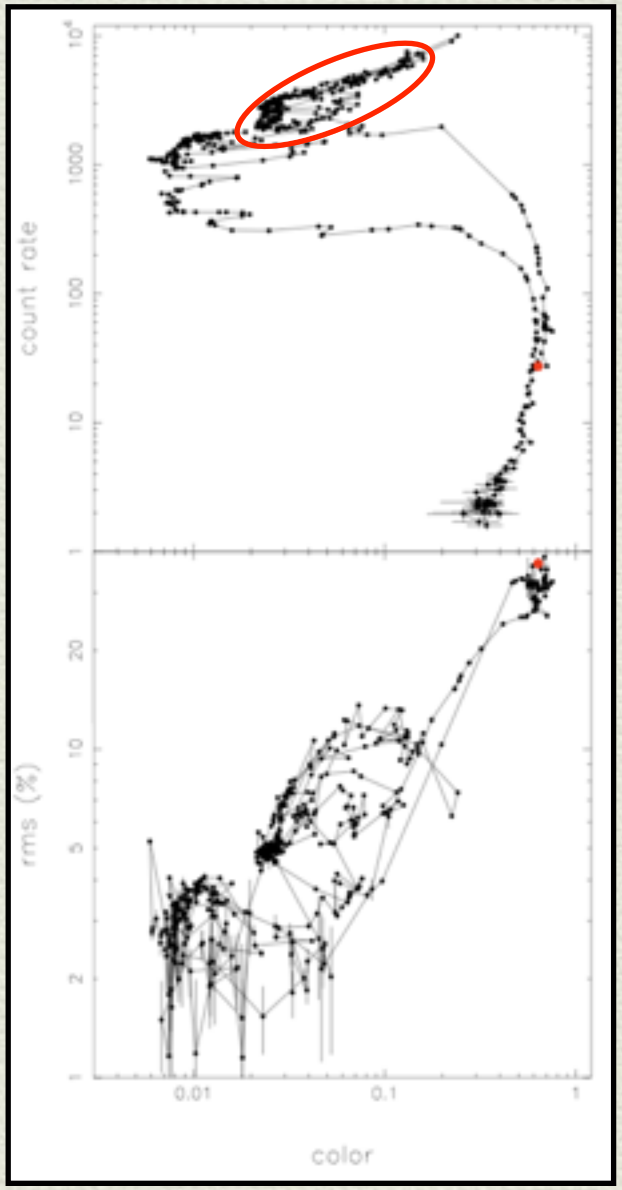
Nespoli et al. (2003)



Homan & Belloni (2009)

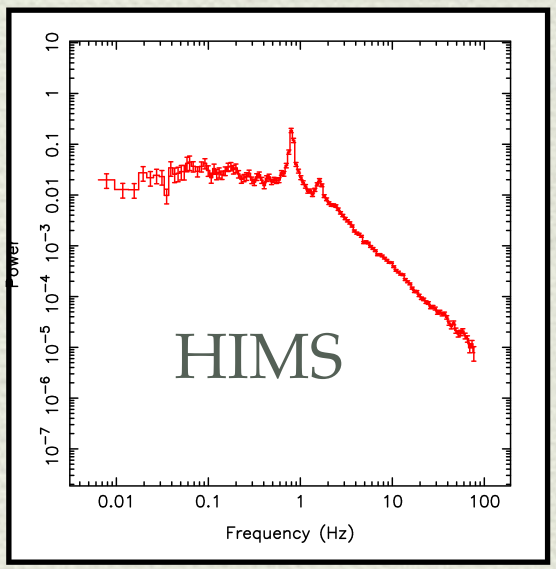
Complications...

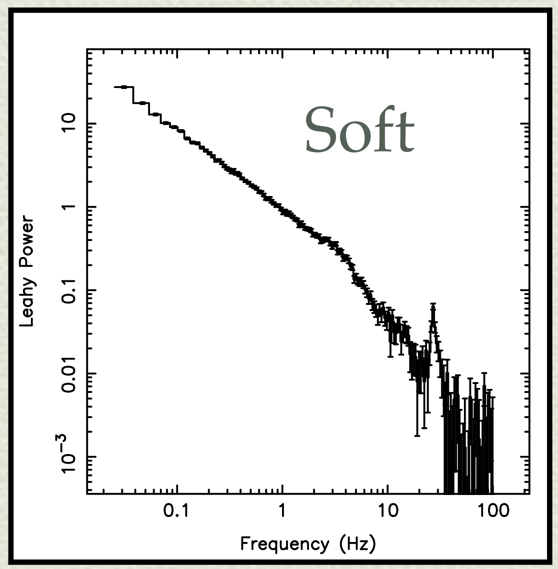


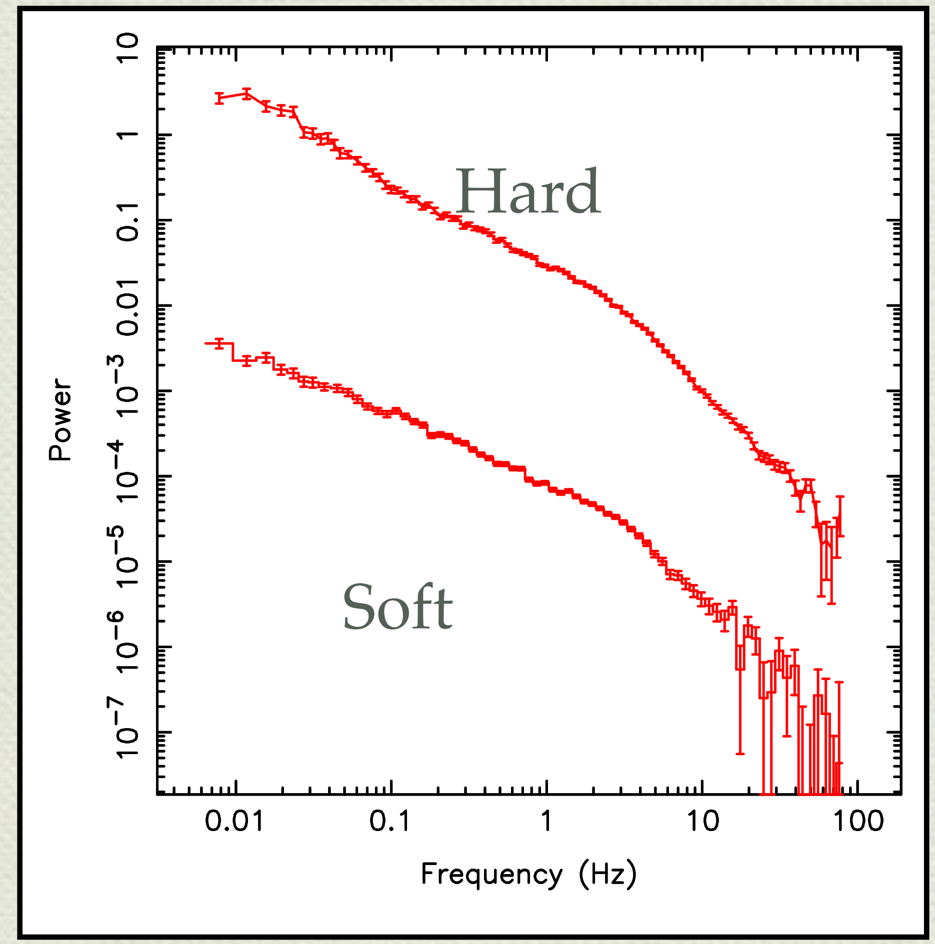


- Additional PDS
- A different state?
- Anomalous - ultraluminous

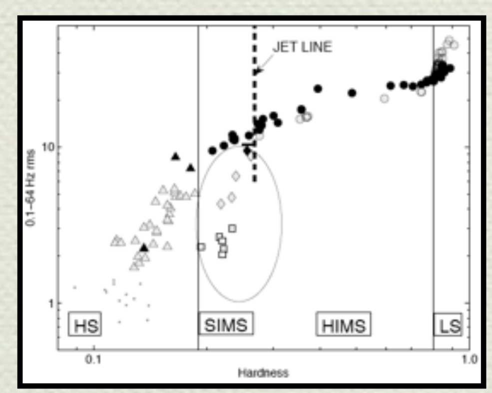
Complications...







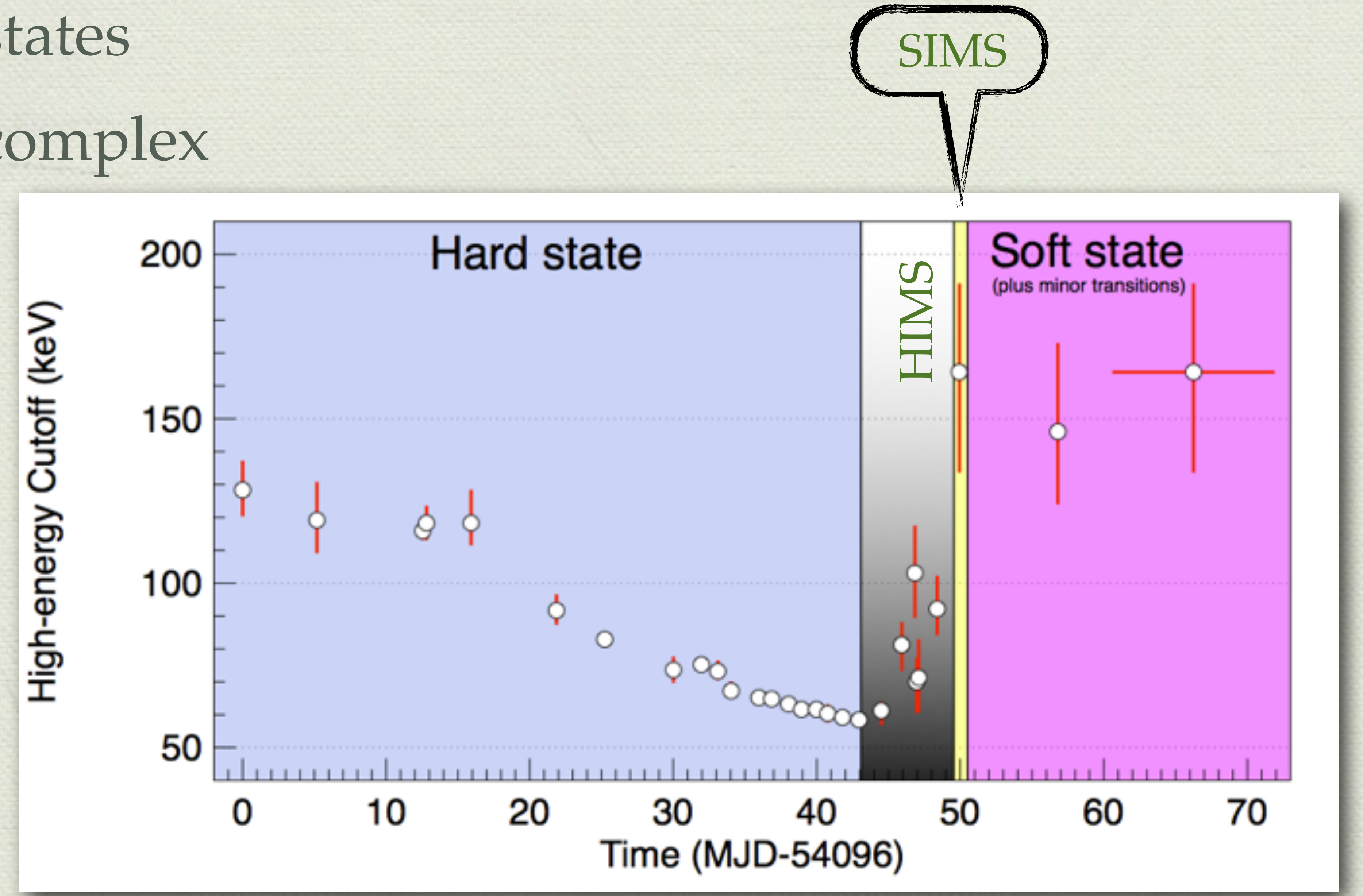
- Hard & soft...
- ... are connected!



The transition

Motta, Belloni & Homan (2009)

- Now full states
- Still very complex

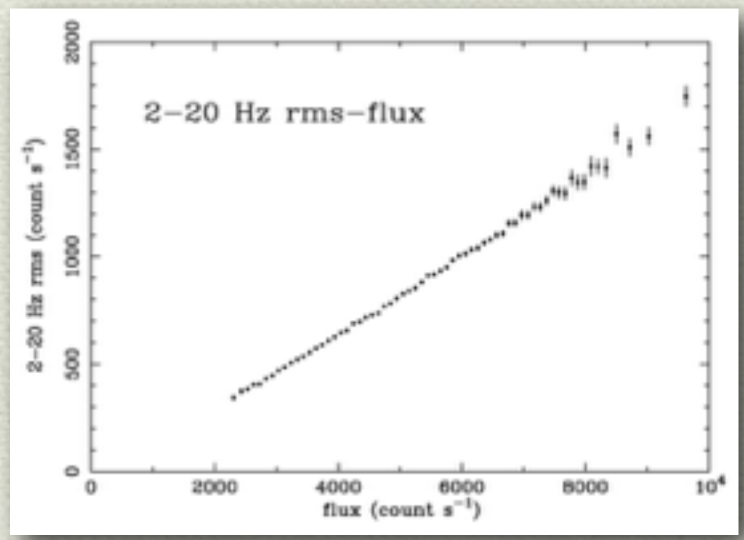


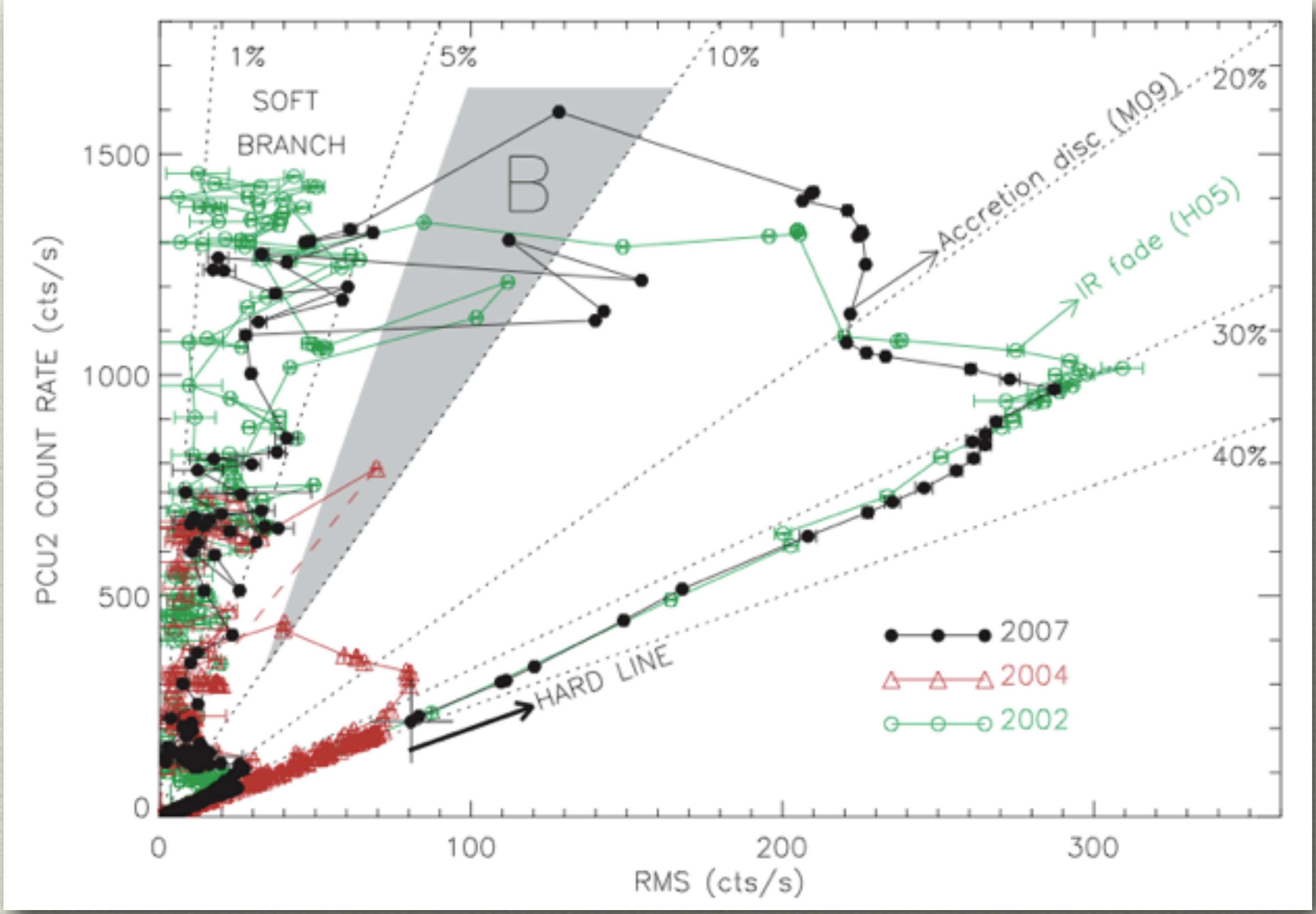
rms-intensity diagram

- rms-flux

Gleissner et al. (2004)

Uttley, McHardy & Vaughan (2005)

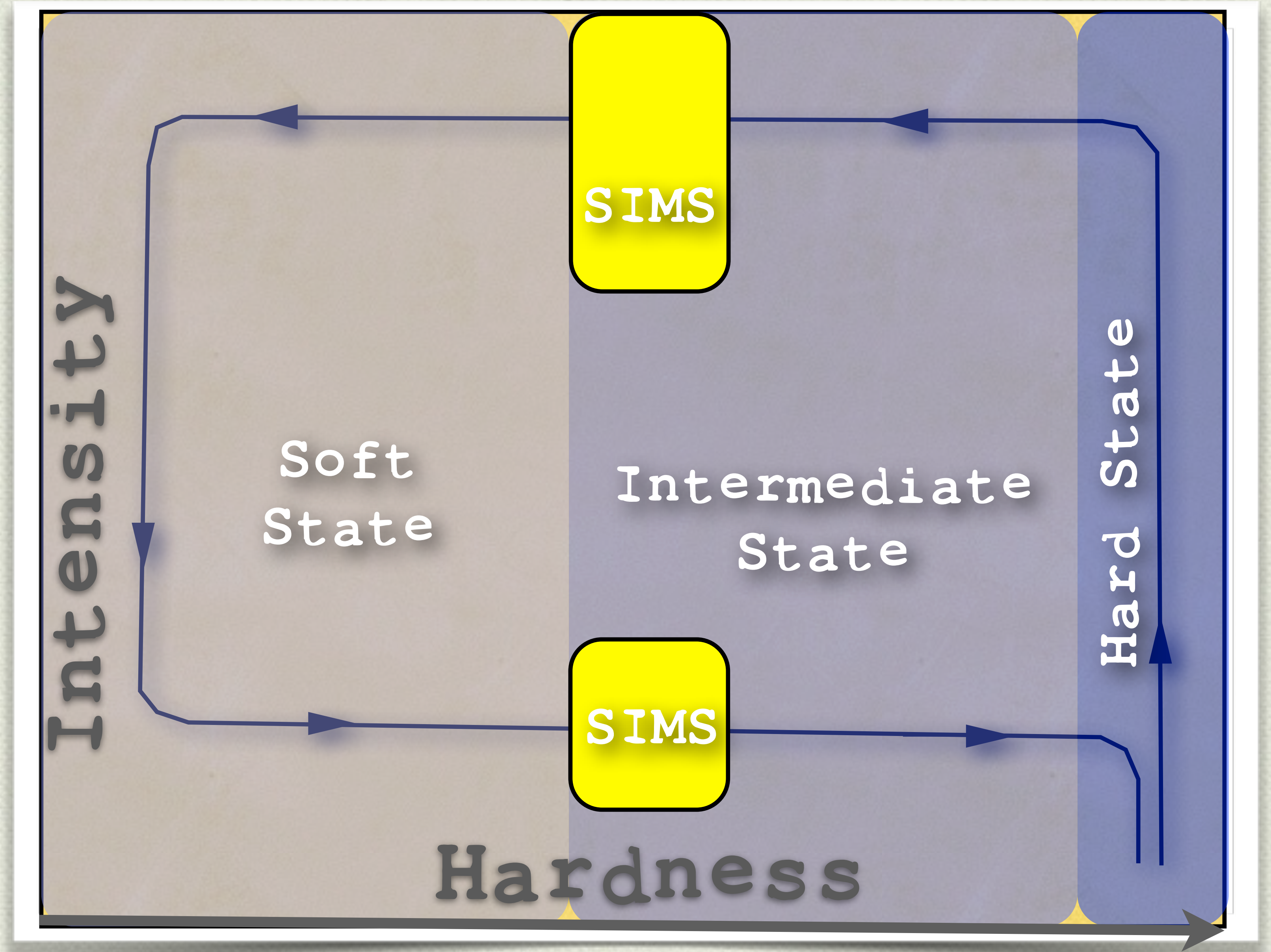




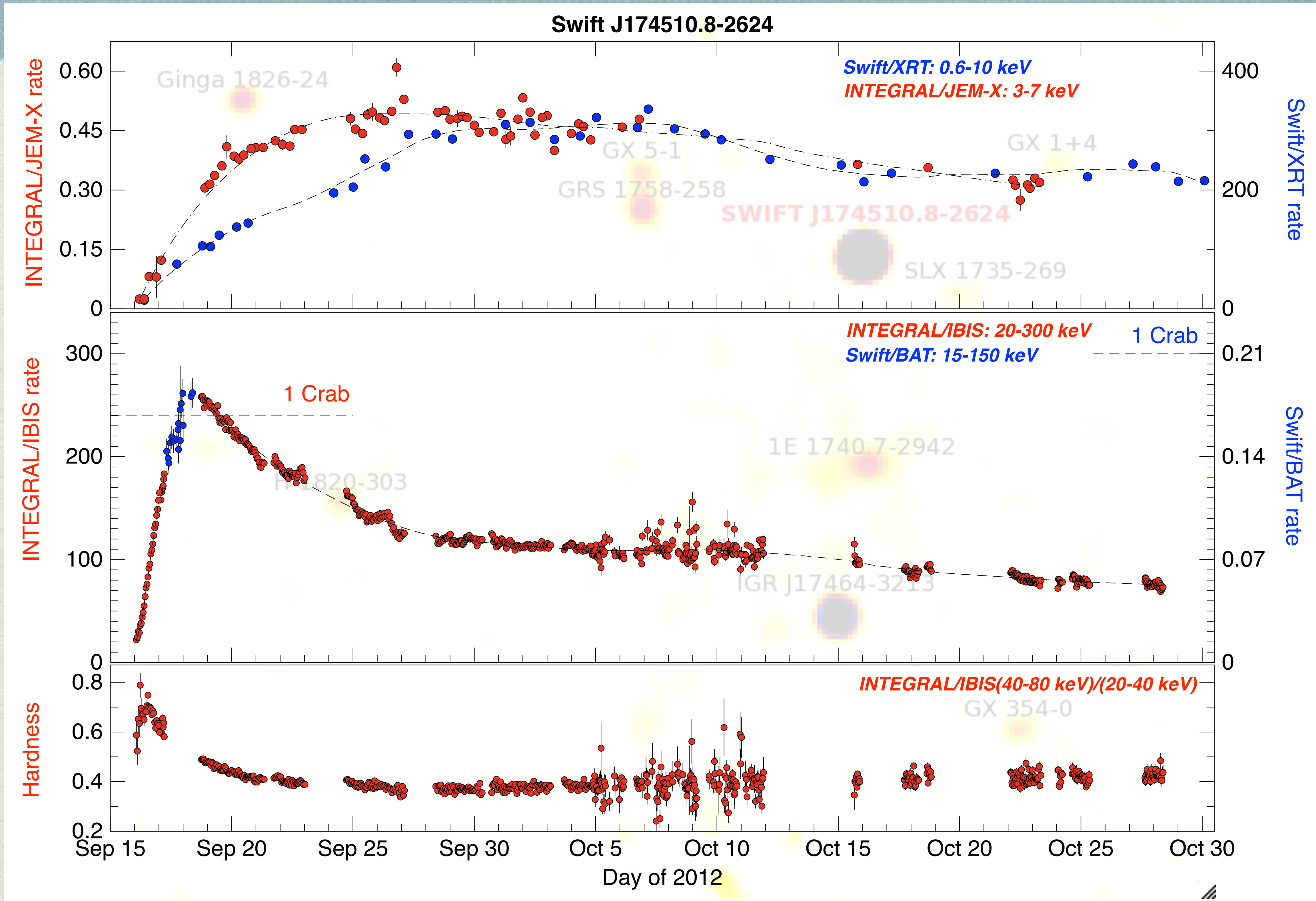
Muñoz-Darias et al. (2010)

Only two states??

- All happens there!
- Continum of properties
- But: high-energy spectra?

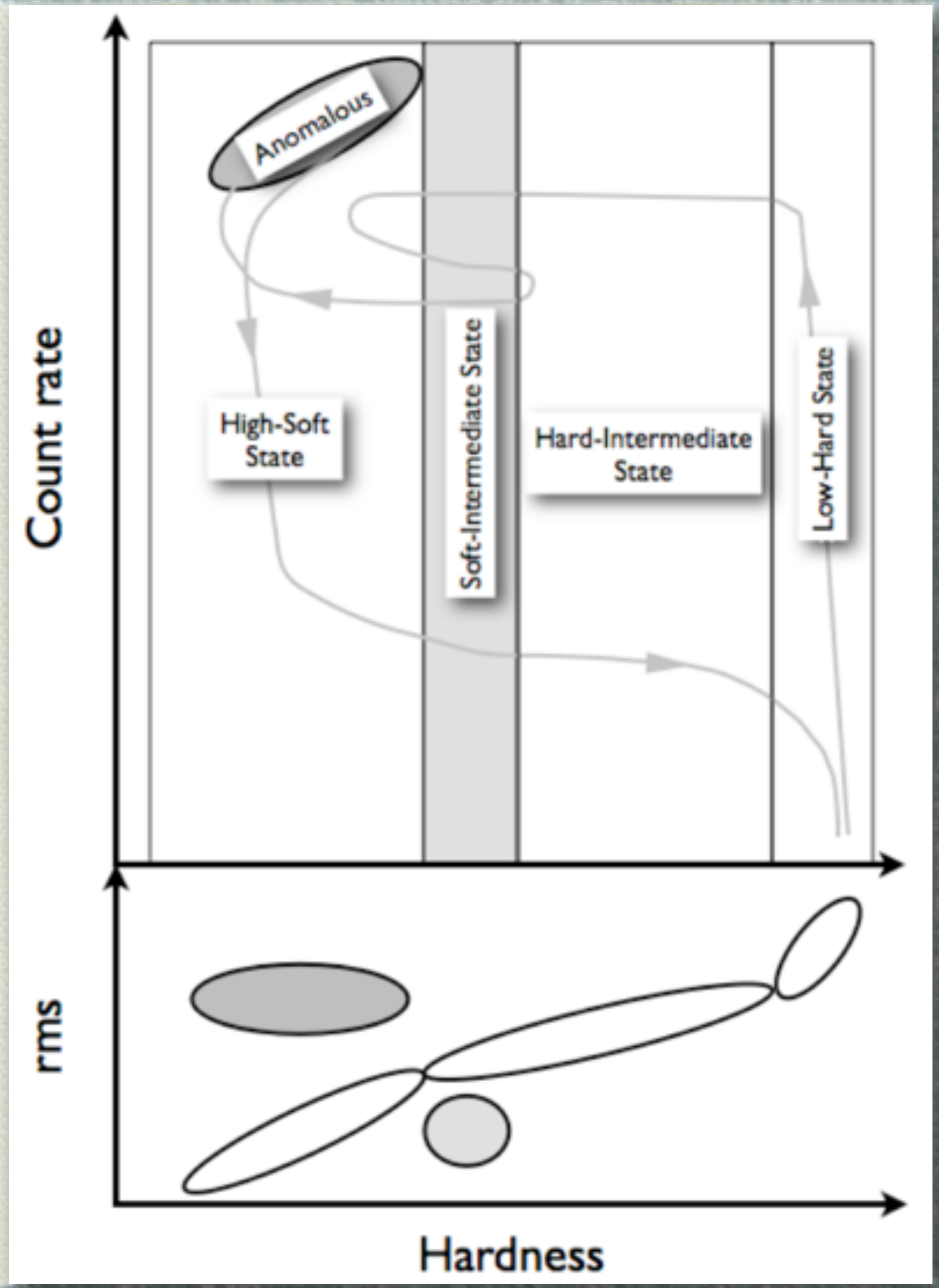


Without RXTE



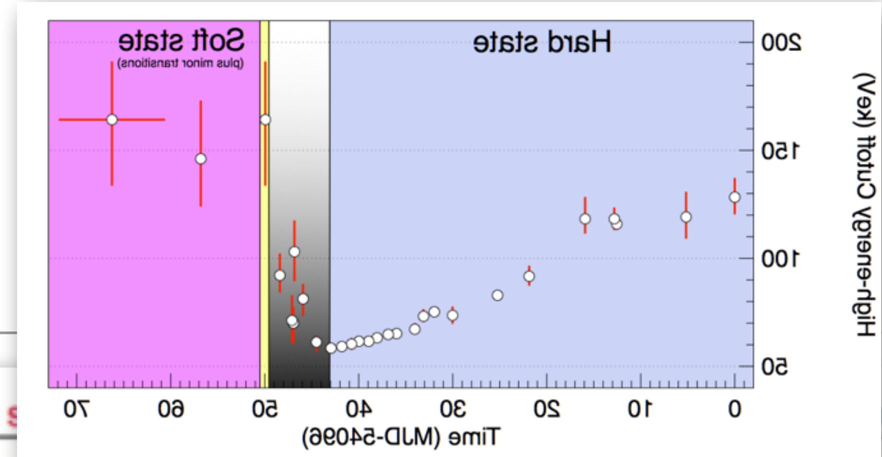
Summarizing

- States are defined by spectral (hardness) an timing parameters
- Time evolution
- Transitions are crucial
- Jet connection (later)

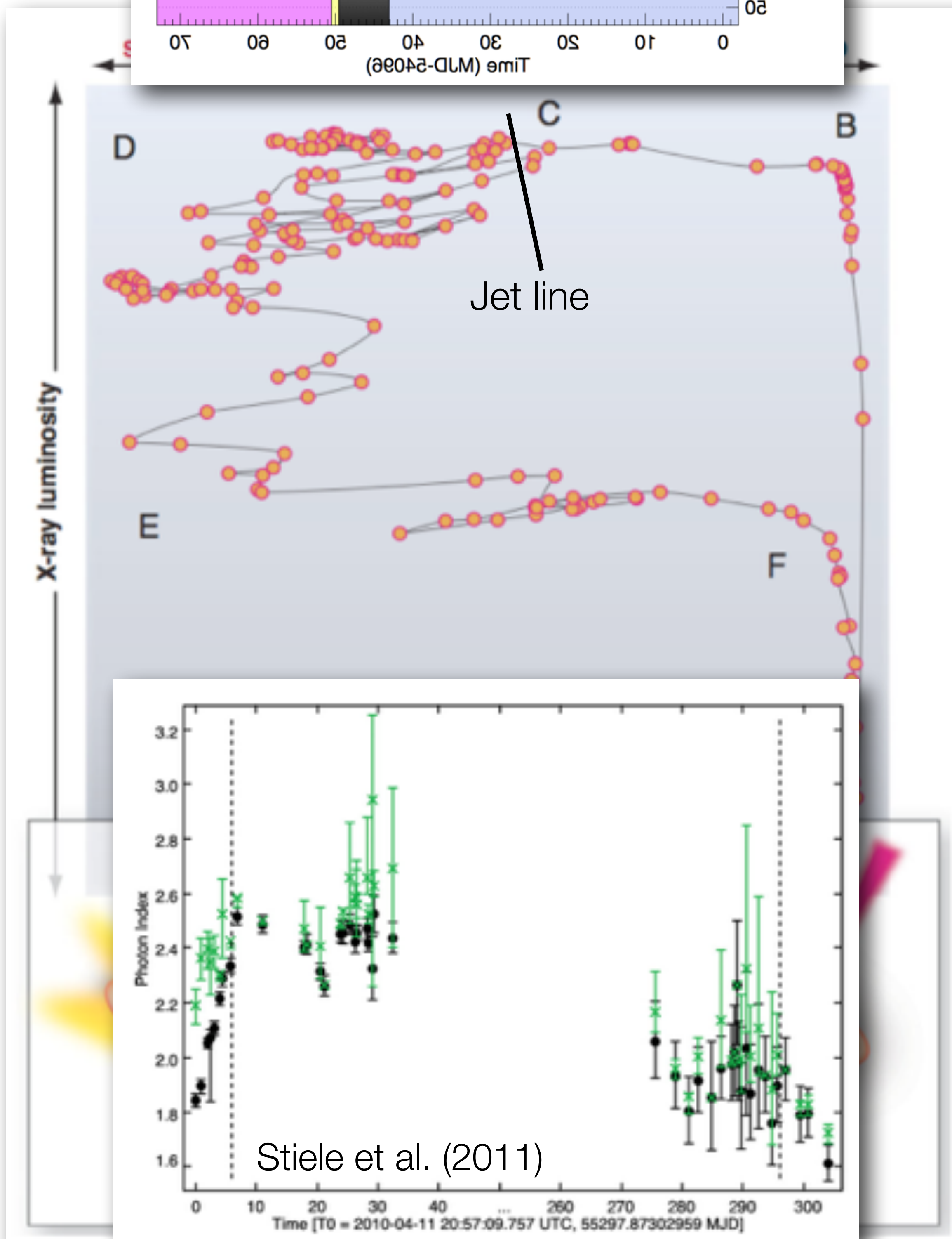


Belloni (2010)

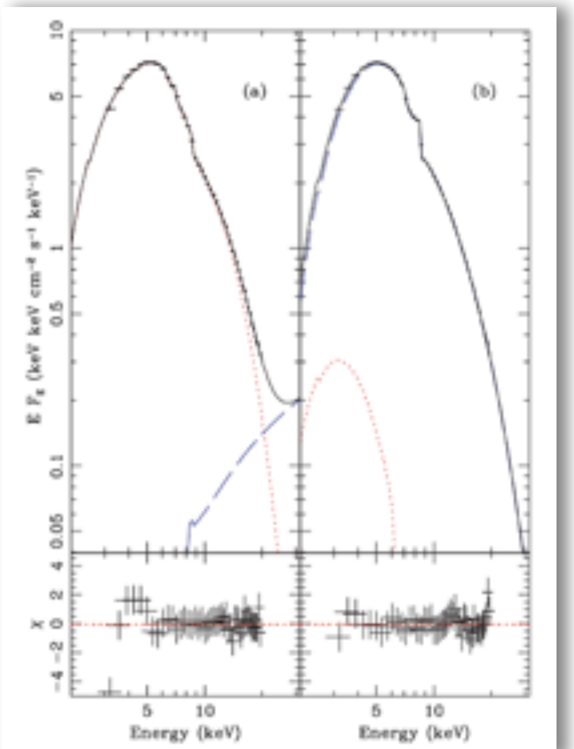
SPECTRA



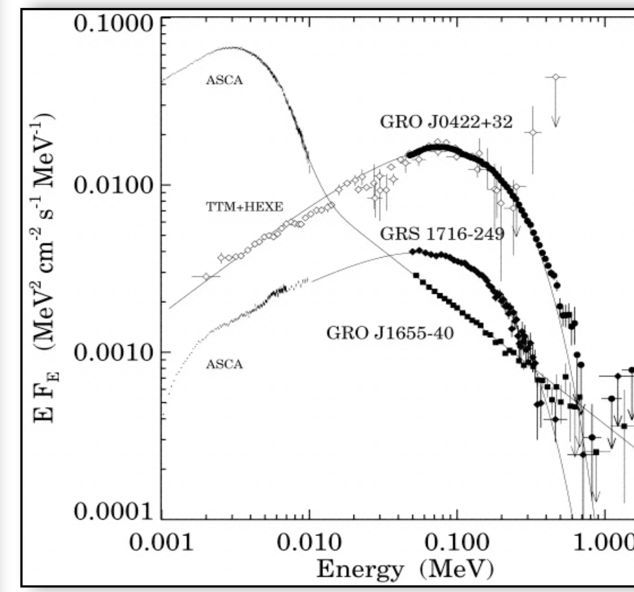
Motta, TMB, Homan (2009)



Stiele et al. (2011)

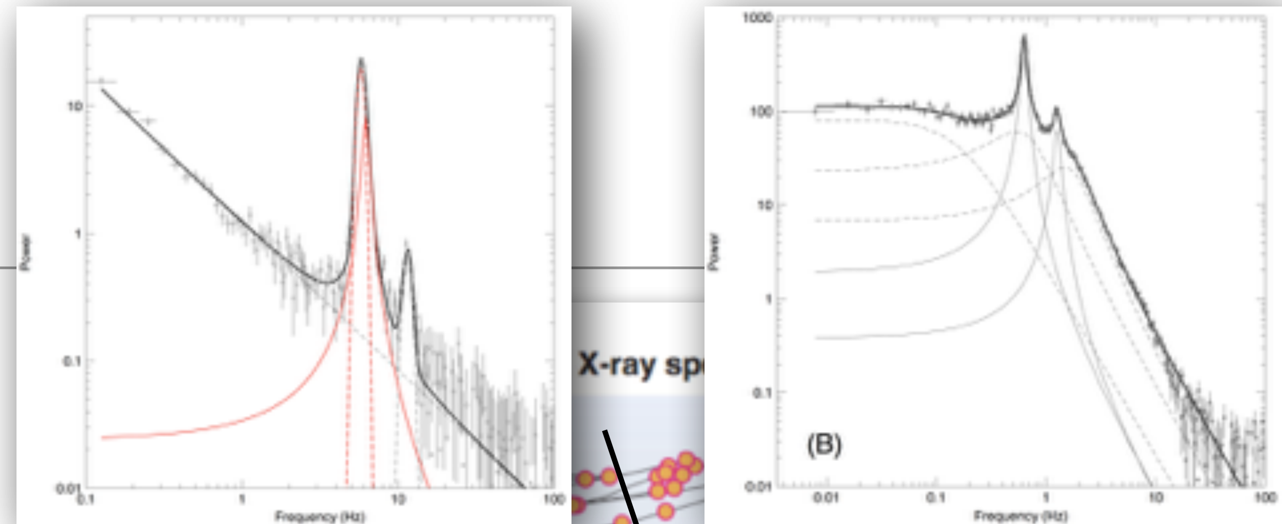


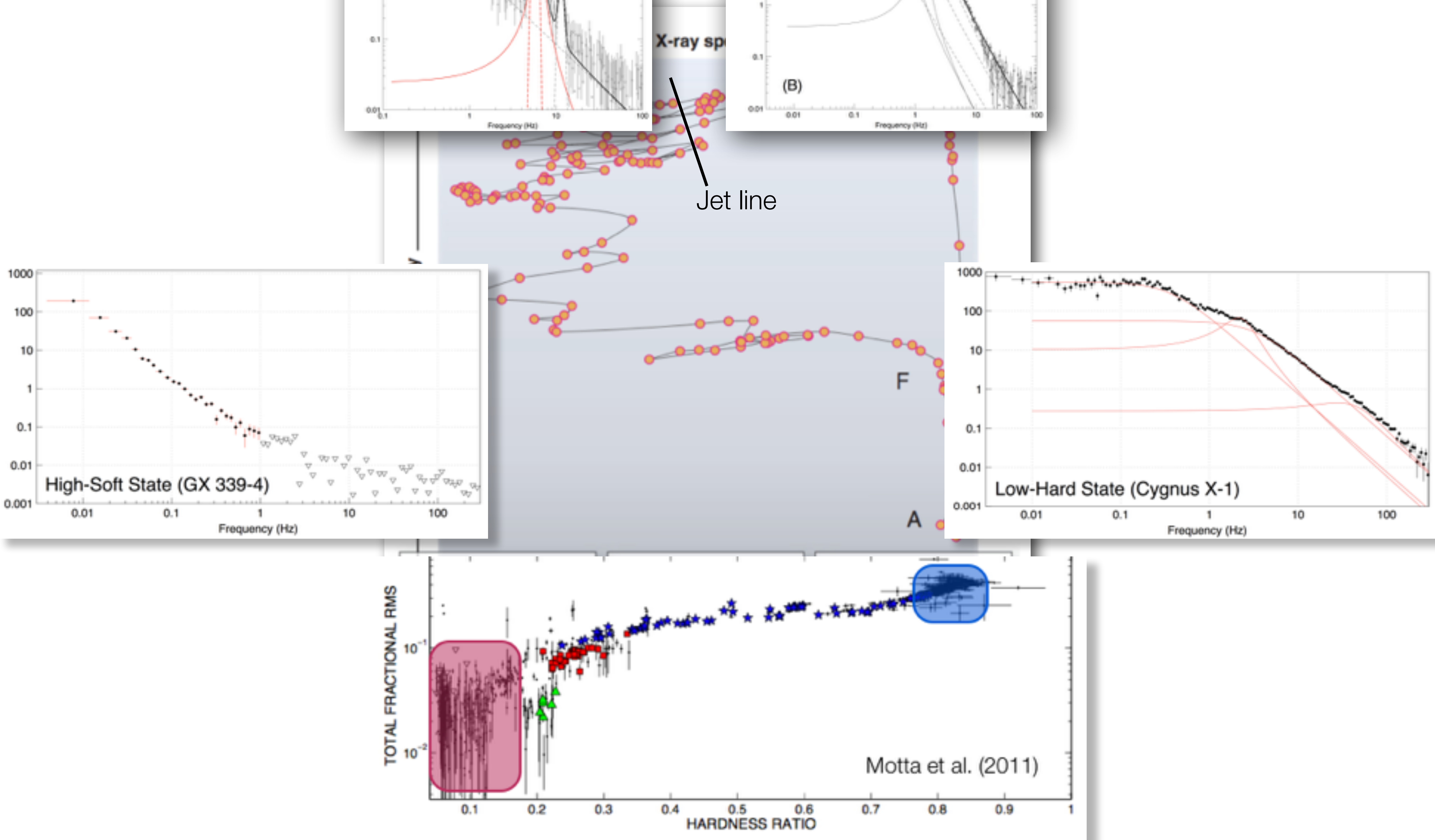
Middleton et al. (2006)



Grove et al. (1998)

TIMING


(B)
Frequency (Hz)
Power


Jet line
F
A
High-Soft State (GX 339-4)
Frequency (Hz)
Low-Hard State (Cygnus X-1)
Frequency (Hz)
TOTAL FRACTIONAL RMS
HARDNESS RATIO
Motta et al. (2011)

Alternative views

- Classification is not unique
- Nor can be right or wrong

	H	SPL	TD	INT
LHS	17	-	-	2
HIMS	4	3	-	7
SIMS	-	3	-	1
HSS	-	2	19	25

Motta, Belloni & Homan (2009)

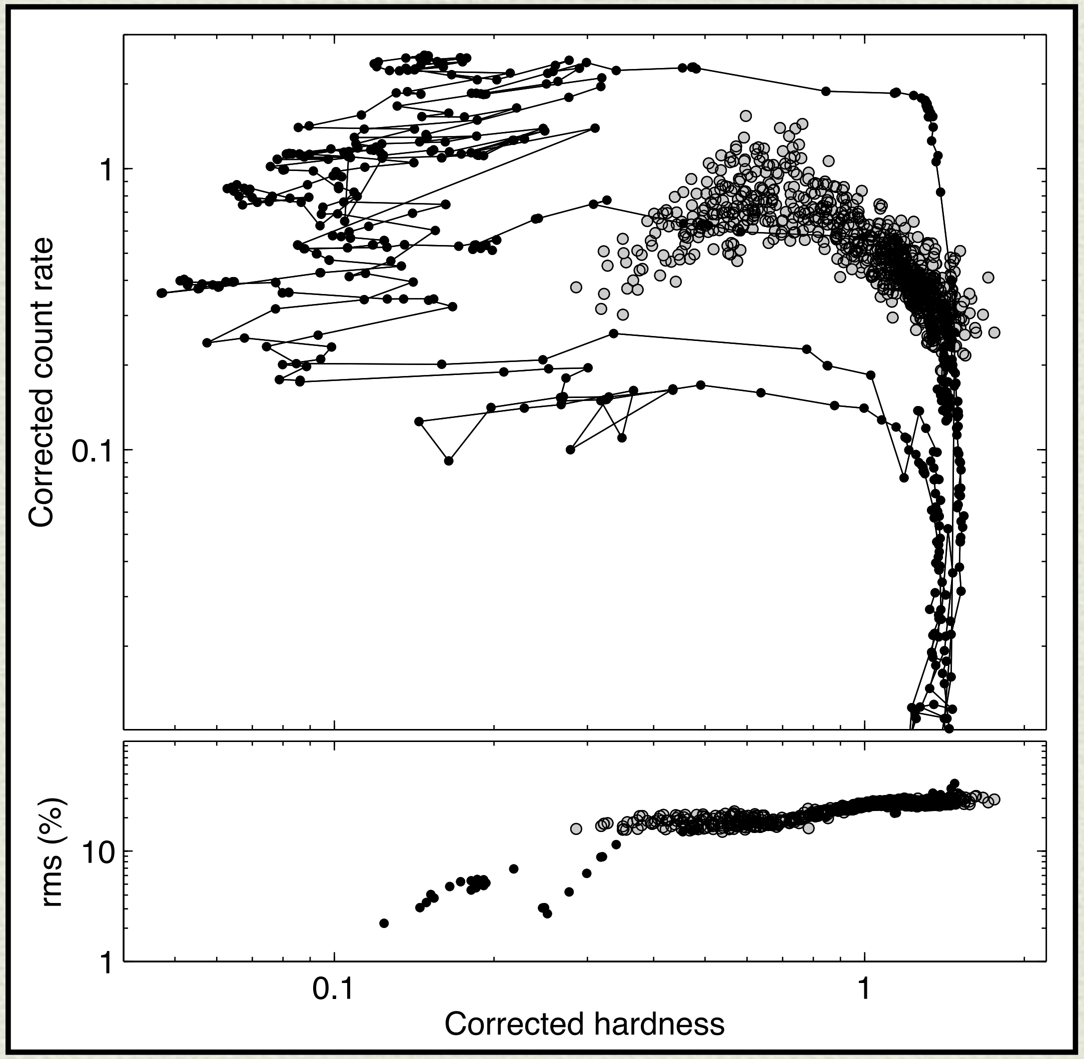
New State Name (Old State Name)	Definition of X-ray State[a]
Thermal (High/Soft)	Disk fraction[b] $> 75\%$ QPOs absent or very weak: $a^c < 0.005$ Weak power continuum: $r^d < 0.075^e$
Hard (Low/Hard)	Disk fraction[b] $< 20\%$ (i.e., Power-law fraction[b] $> 80\%$ $1.4^f < \Gamma < 2.1$ Strong power continuum: $r^d > 0.1$
Steep Power Law (SPL) (Very high)	Presence of power-law component with $\Gamma > 2.4$ Power continuum: $r^d < 0.15$ Either disk fraction[b] $< 80\%$ and 0.1-30 Hz QPOs present with $a^c > 0.01$ or disk fraction[b] $< 50\%$ with no QPOs present.

[a] 2–20 keV band.
[b] Fraction of the total 2–20 keV unabsorbed flux.
[c] QPO amplitude (rms).
[d] Total rms power integrated over 0.1–10 Hz.
[e] Formerly $r < 0.06$ in McClintock & Remillard 2006.
[f] Formerly $1.5 < \Gamma$ in McClintock & Remillard 2006.

Remillard & McClintock (2006)
McClintock et al. (2009)

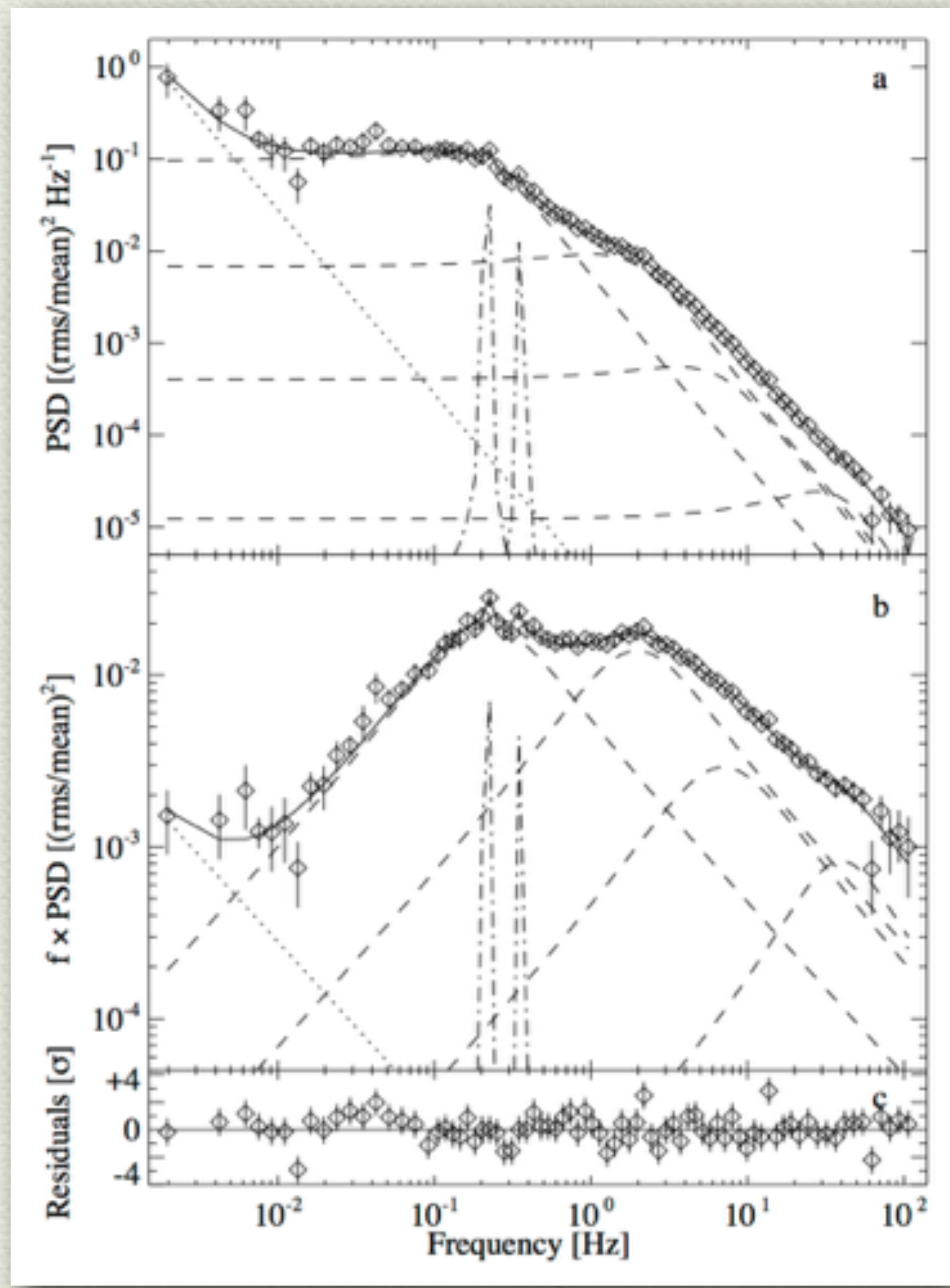
Other sources: Cyg X-1

- No hysteresis
- It just makes it to the jet line
- Radio ejections
- PDS shapes?



Other sources: Cyg X-1

Pottschmidt et al. (2003)



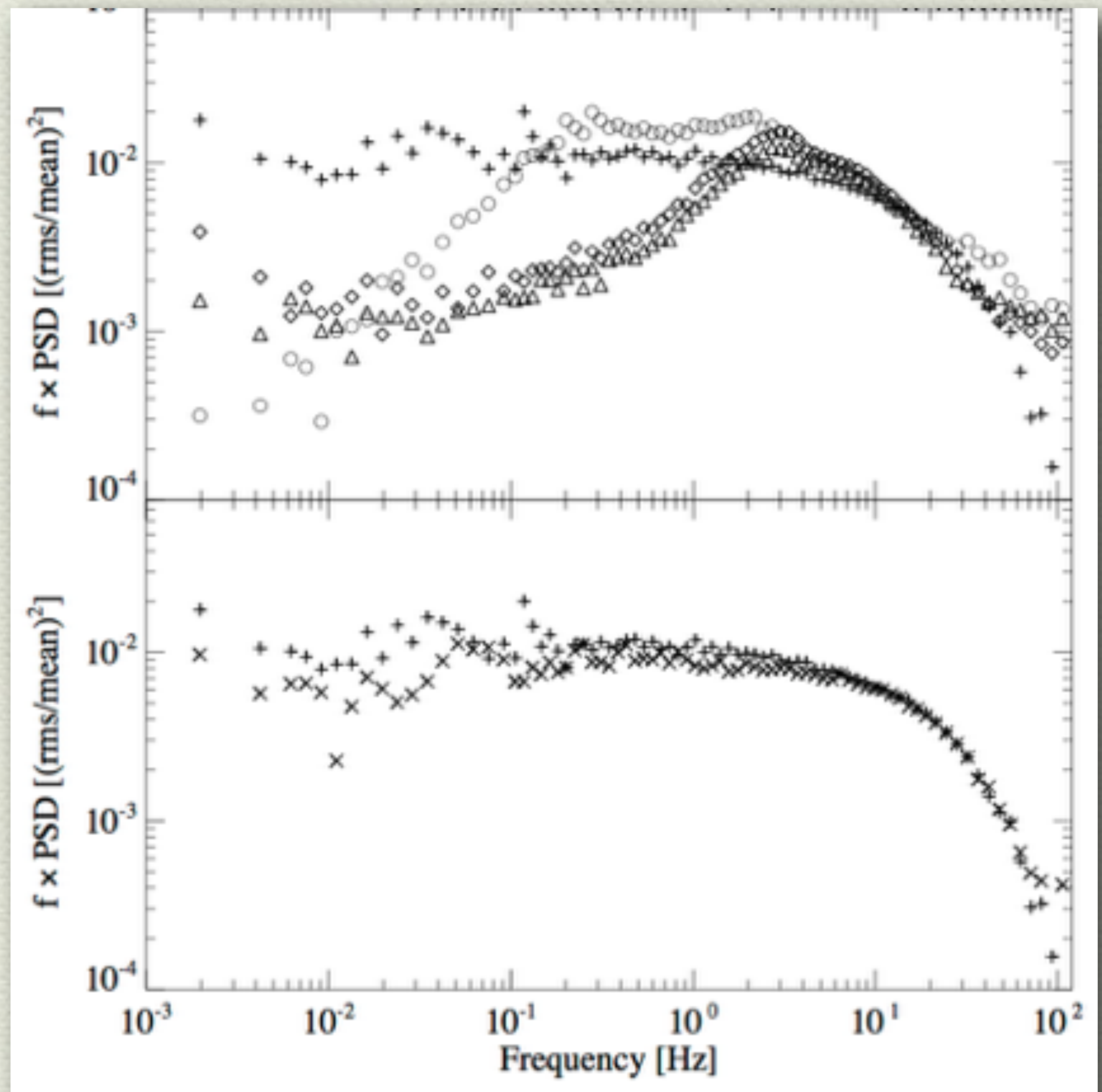
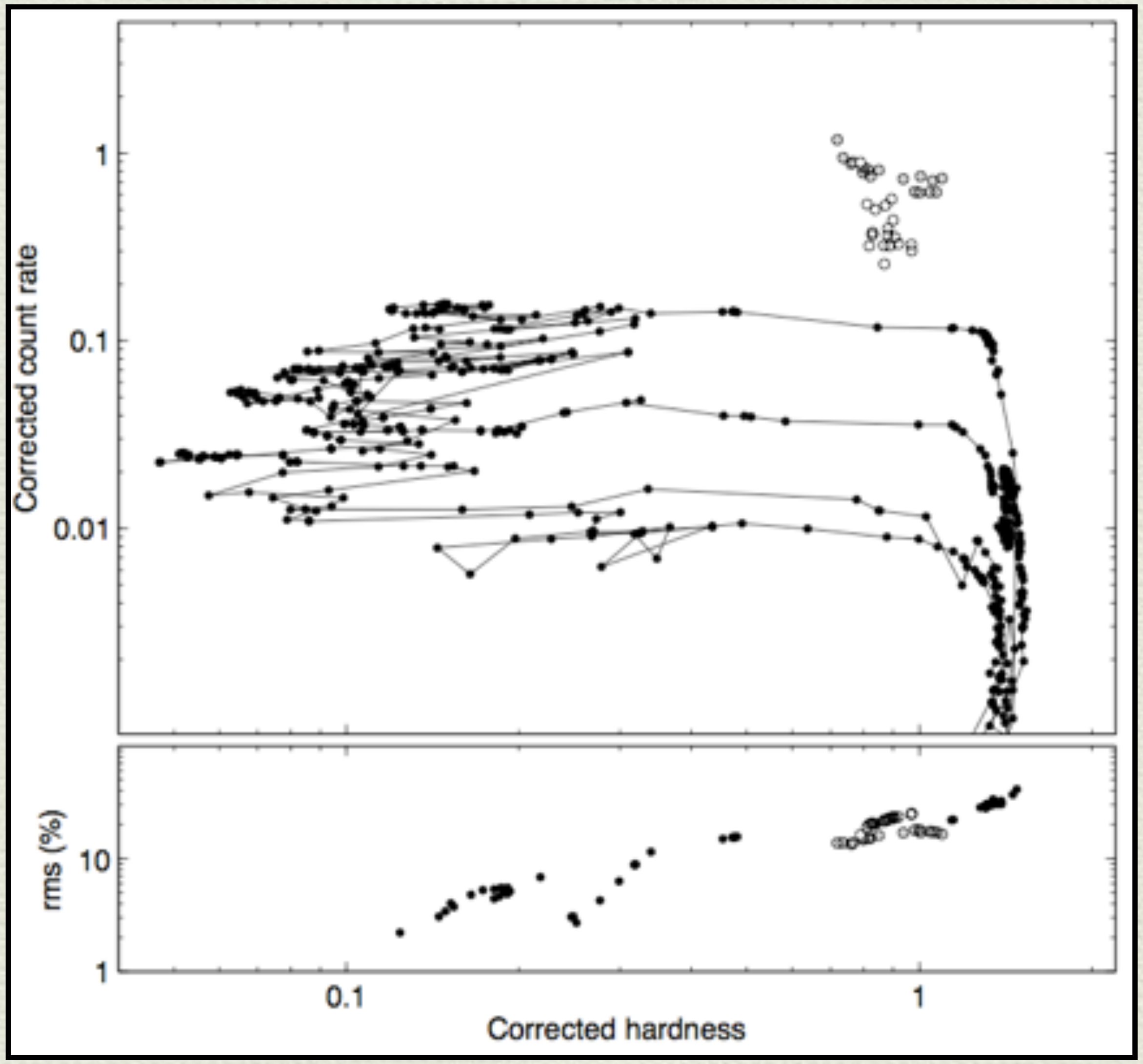
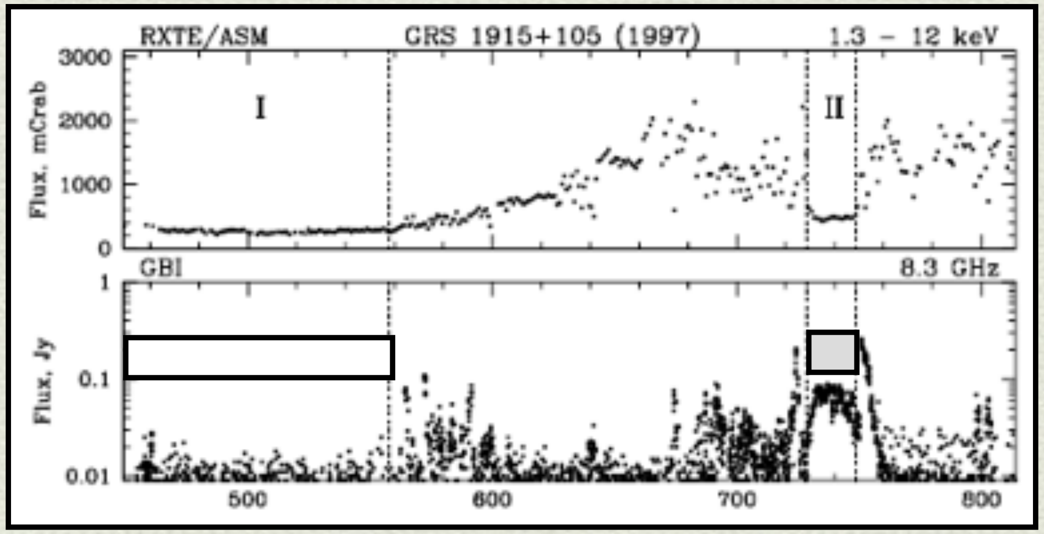


Fig. 14. Time lags and PSD for the soft state of 2001 Oct. compared with other typical soft state, hard state, and failed state transition data.

Other: GRS 1915+105

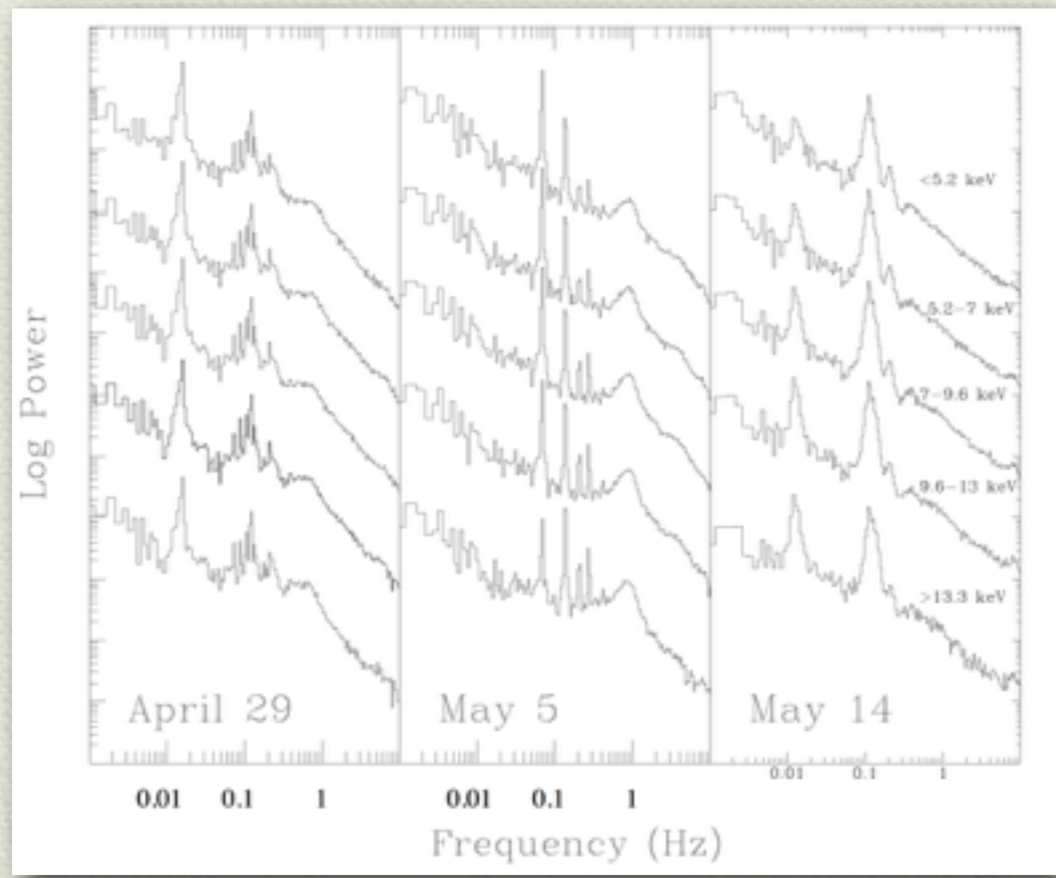
- Plateau Obs.
- Hardest and not crazy
- HIMS PDS



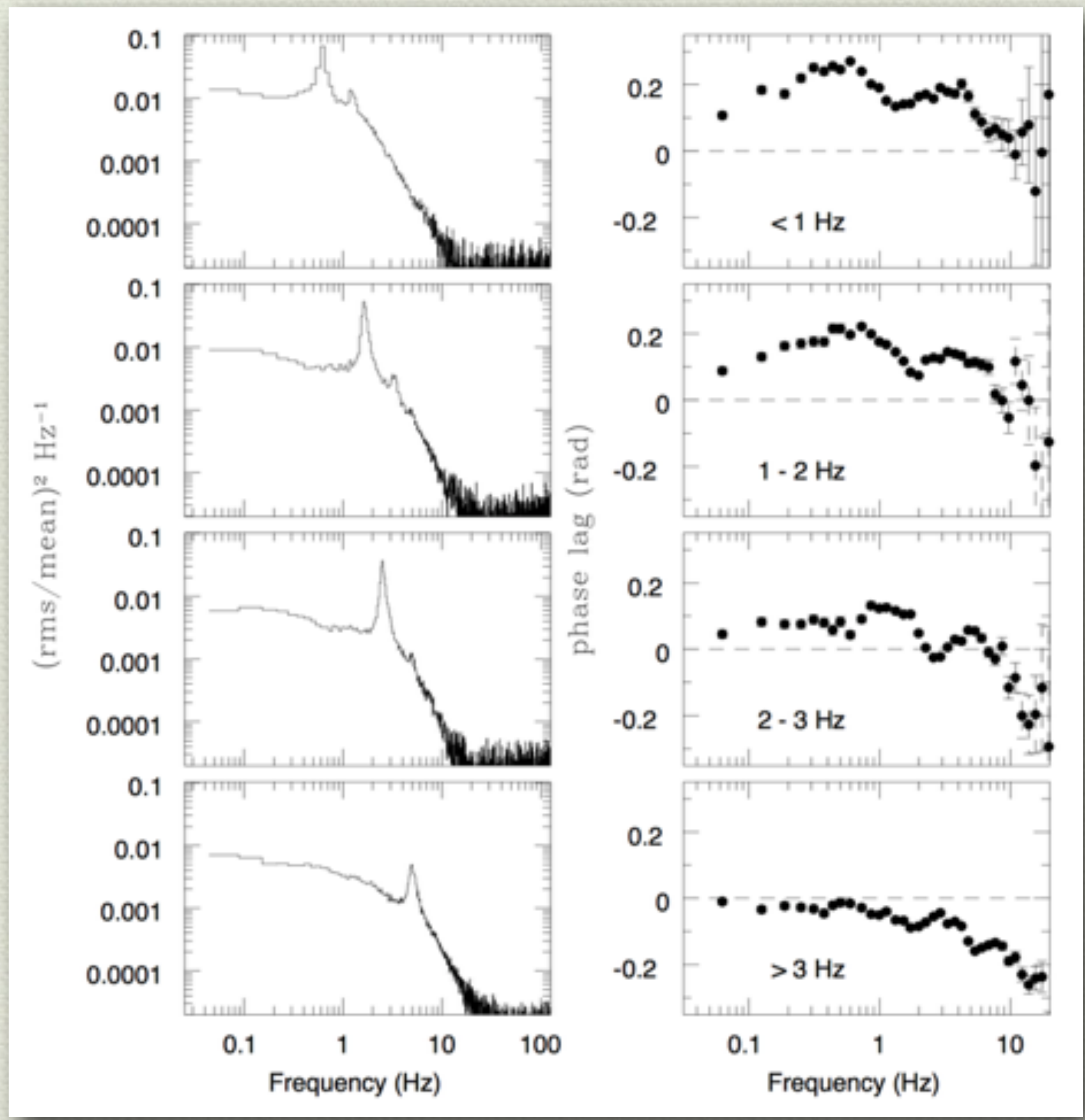


Other: GRS 1915+105

Morgan et al. (1997)

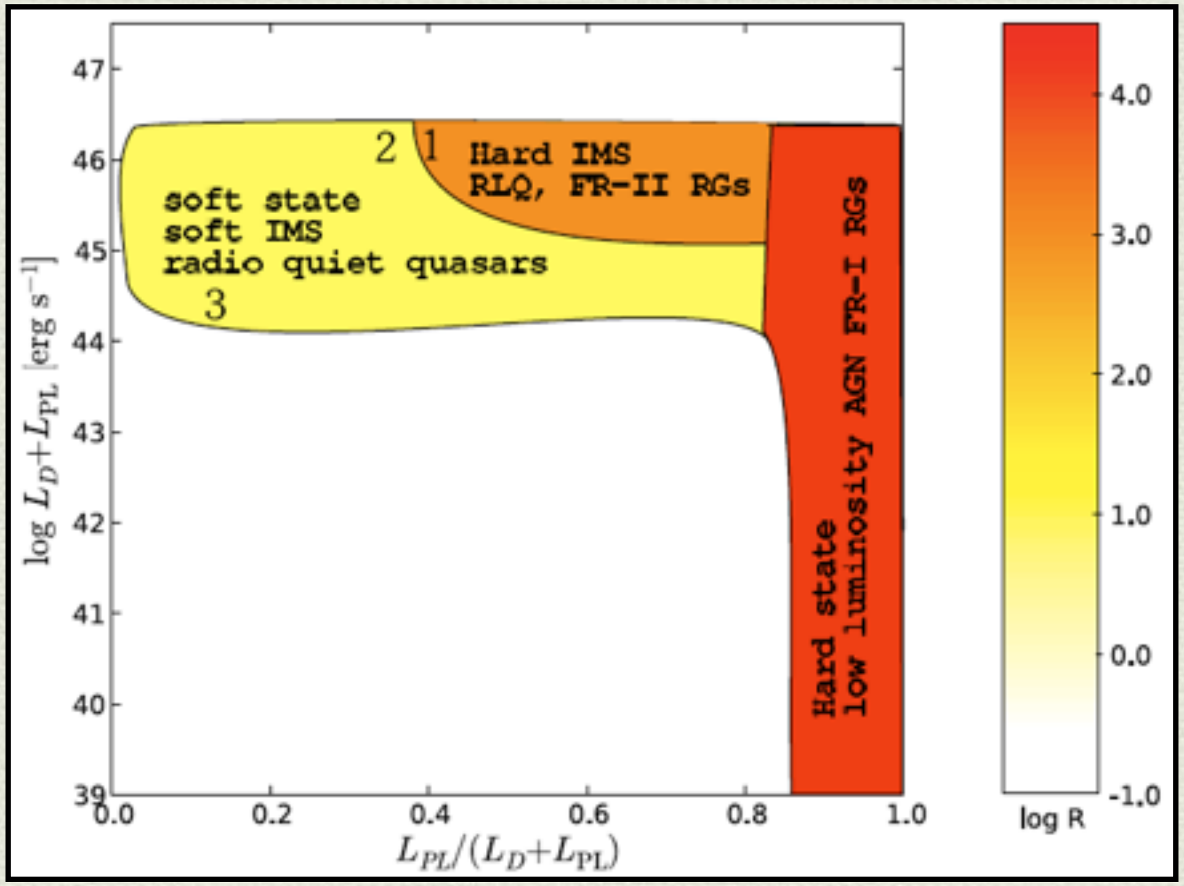


Reig et al. (2000)



Other sources: AGN

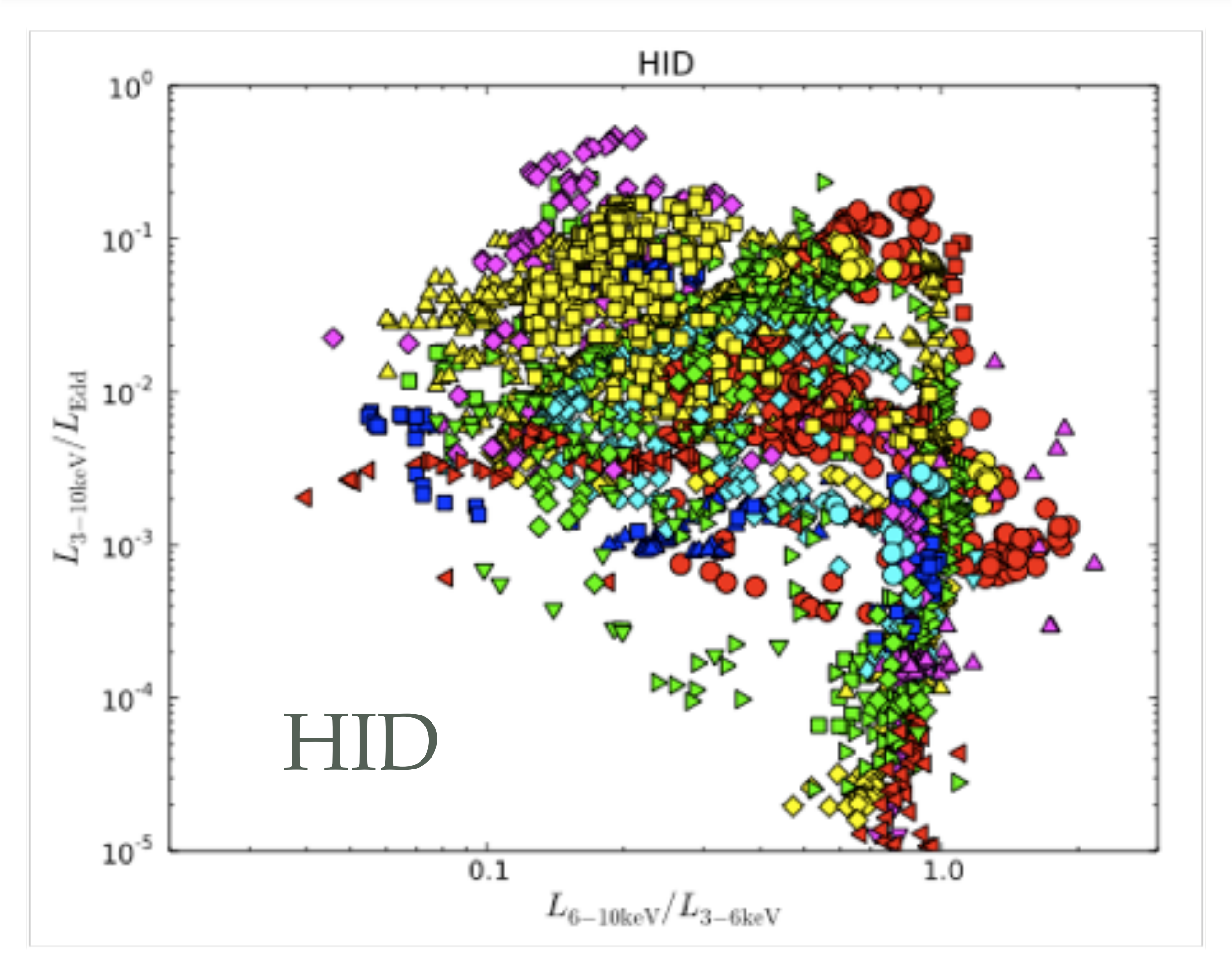
- Disk Fraction Luminosity Diagram (DFLD)
- Similar behavior?
- Different time scales

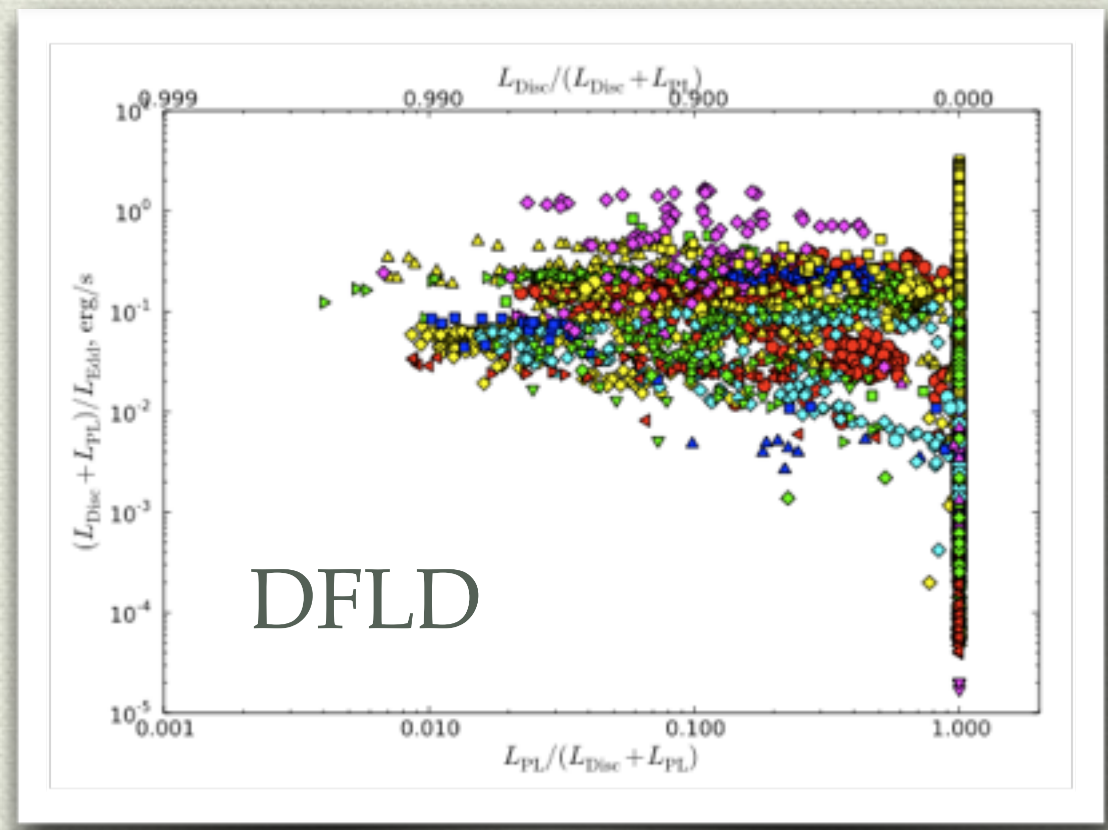


Körding et al. (2006)

The book of binaries

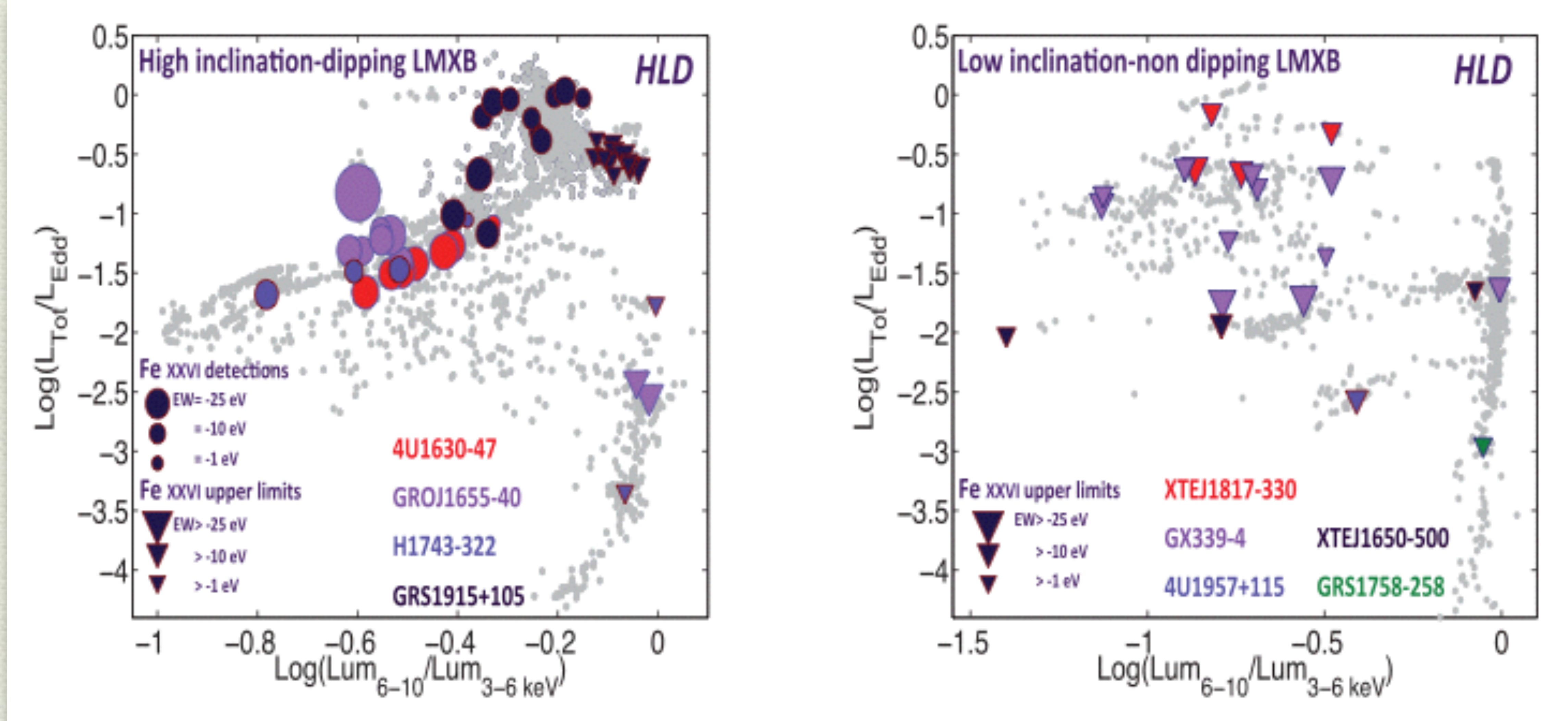
- HID of all systems
- L/L_{Edd}
- Low L: hard only
- Transitions at all Ls





Dunn et al. (2009)

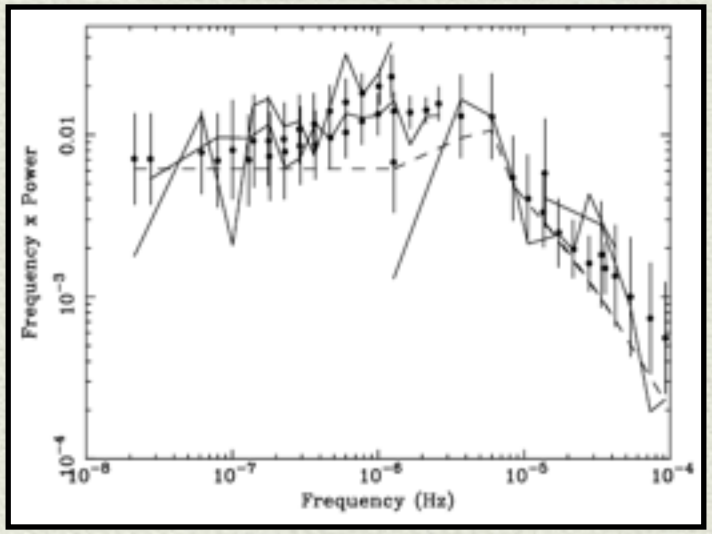
Inclination effects



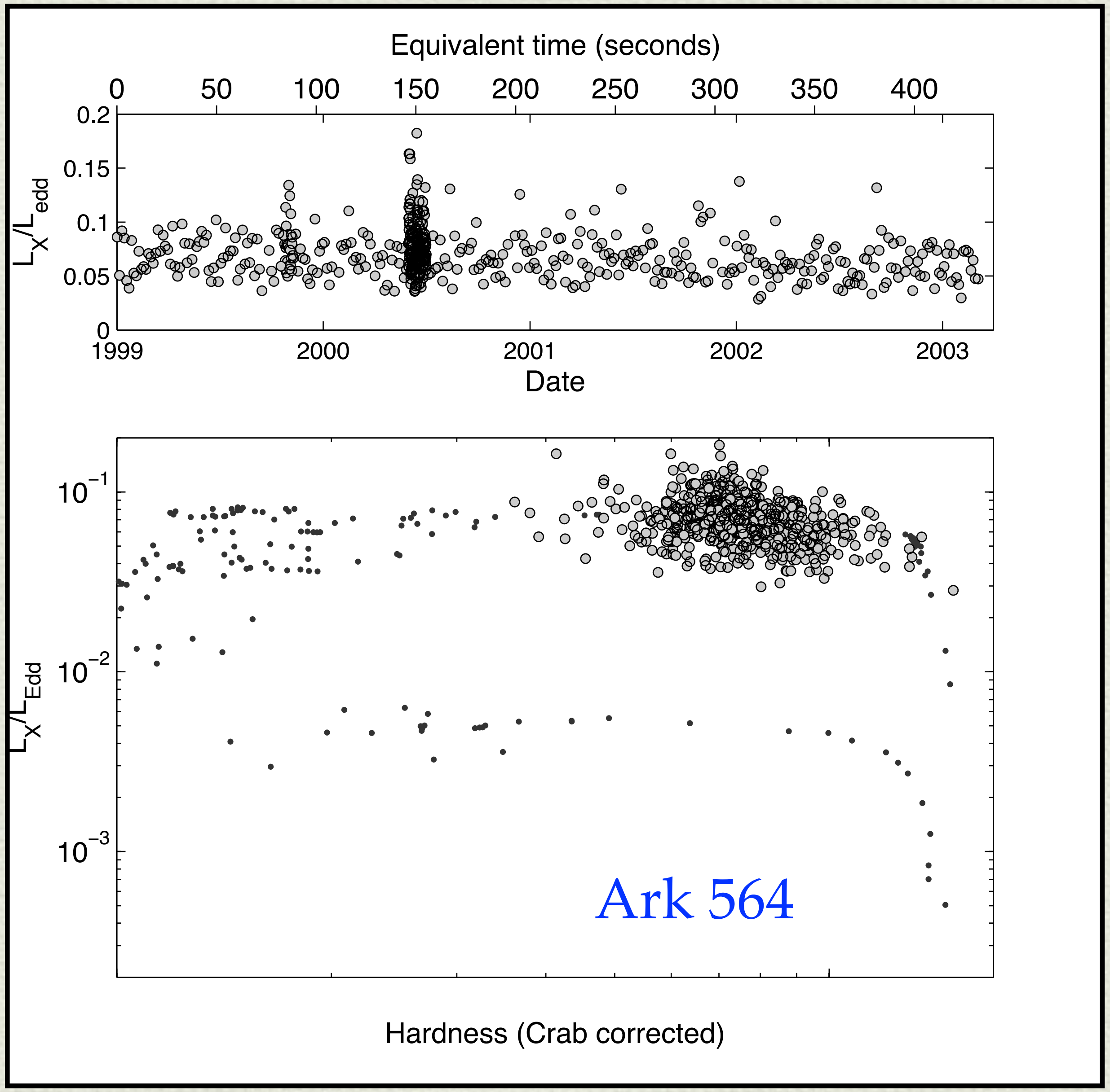
Ponti et al. (2012)
Muñoz-Darias et al. (in prep.)

Other sources: AGN

- Same analysis
- No soft disk
- Different time scales



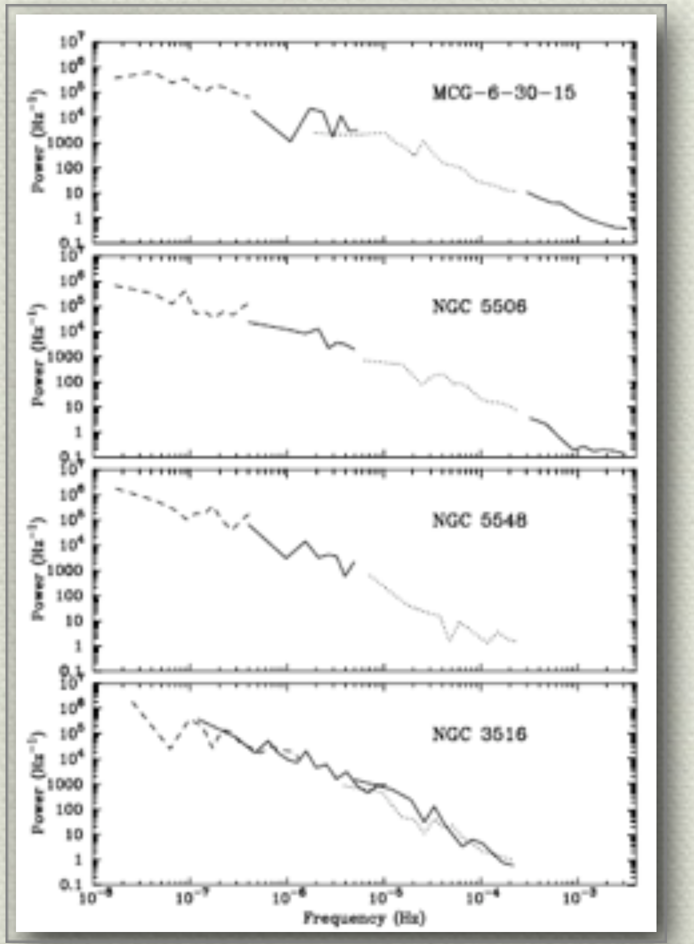
Summons et al. (2007)

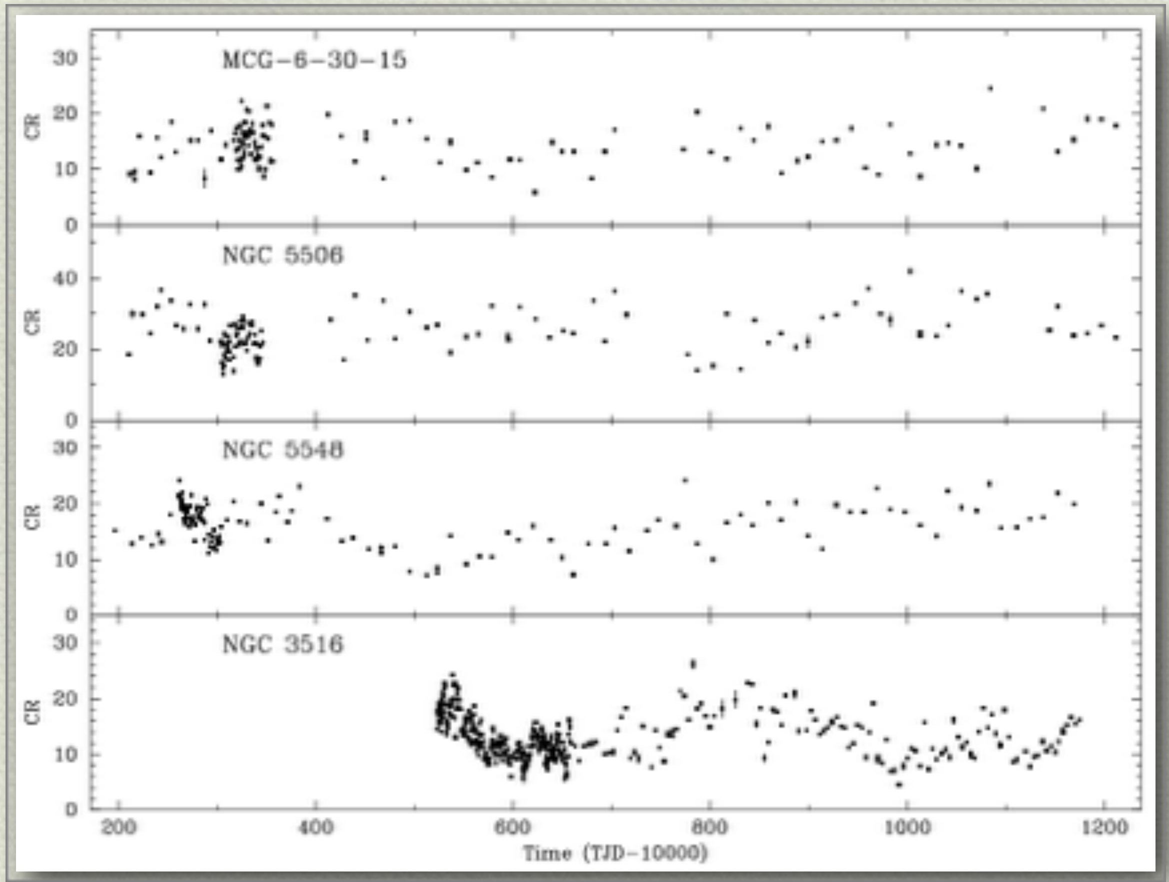


Belloni et al. (2008)

Long-term periods

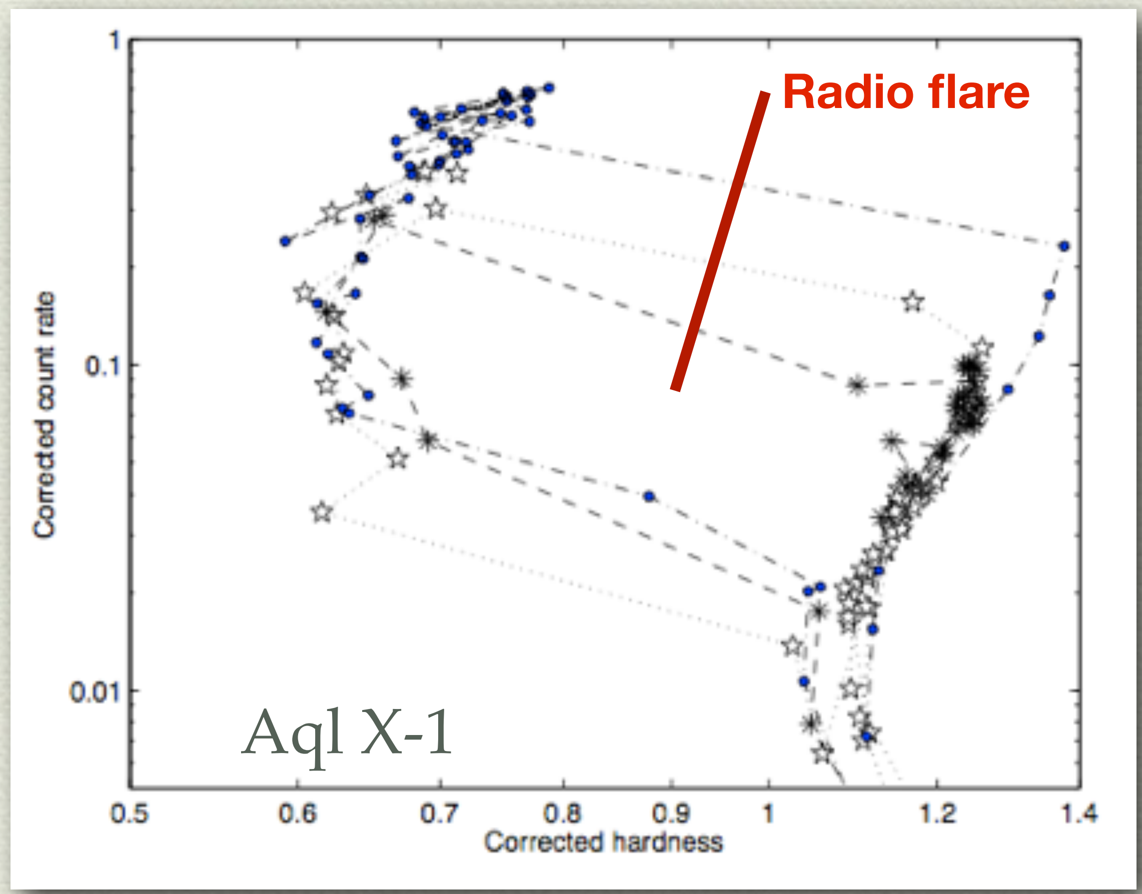
- Difficult techniques
- Important for AGN studies
- Analysis then timing



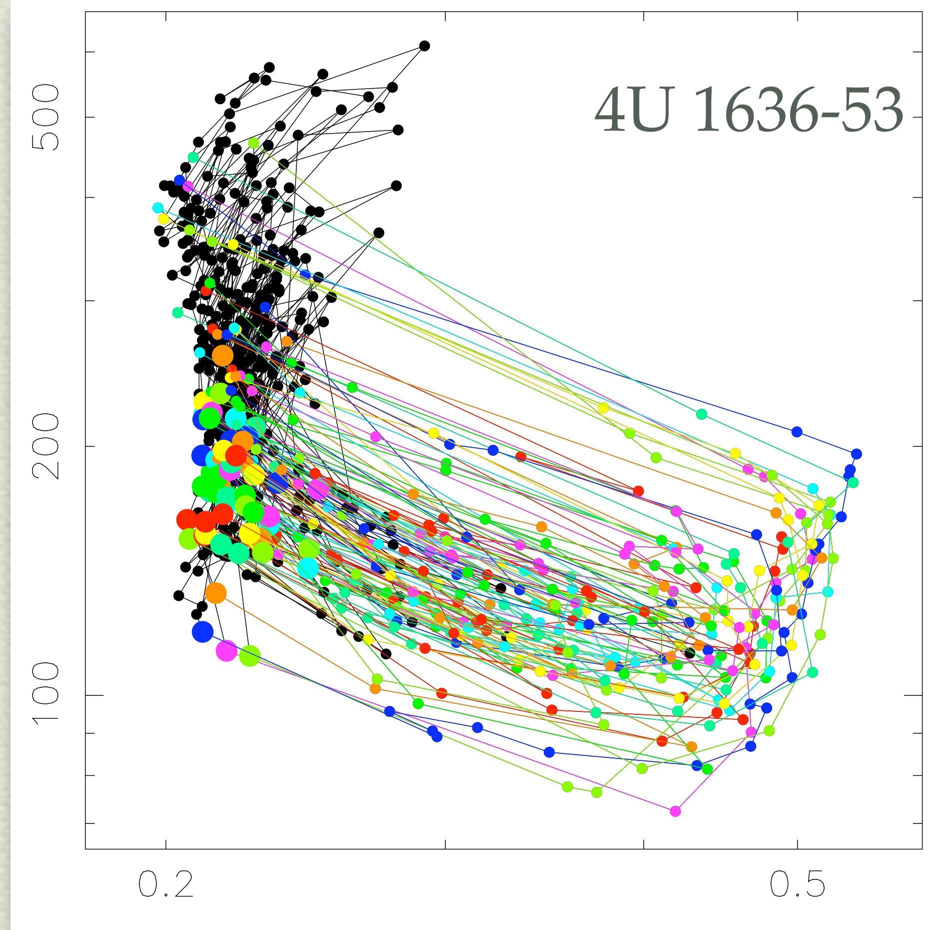


Others: Neutron Stars

- Same evolution for transients and persistent?

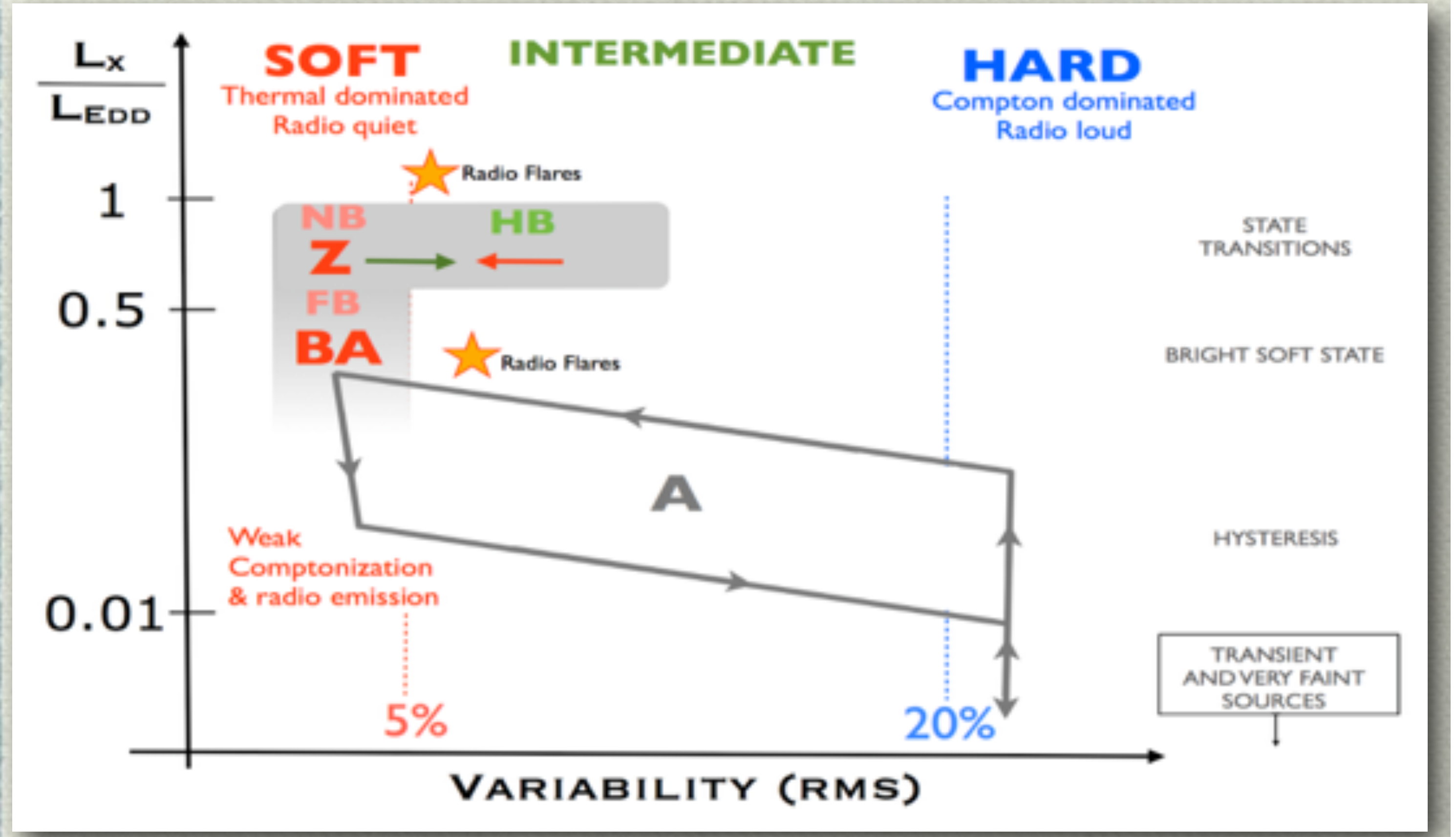


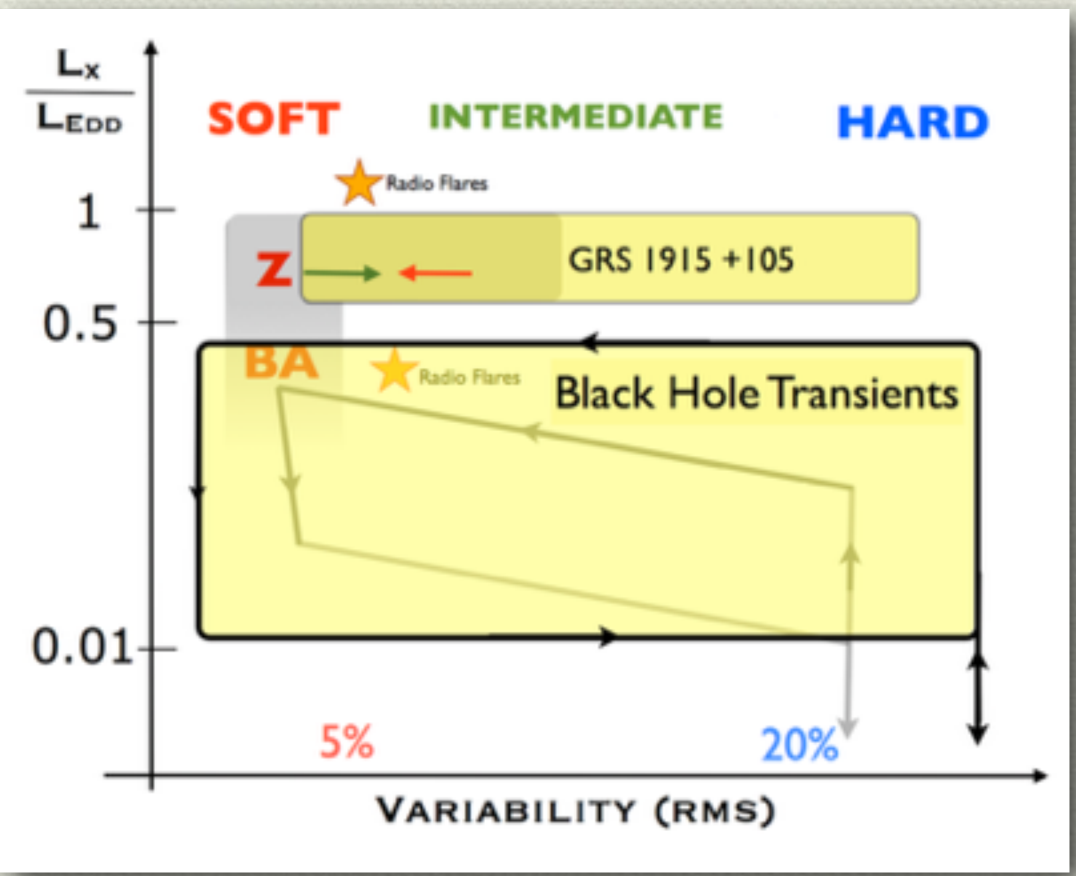
Belloni (2010)



Homan et al. (2011)

Others: Neutron Stars

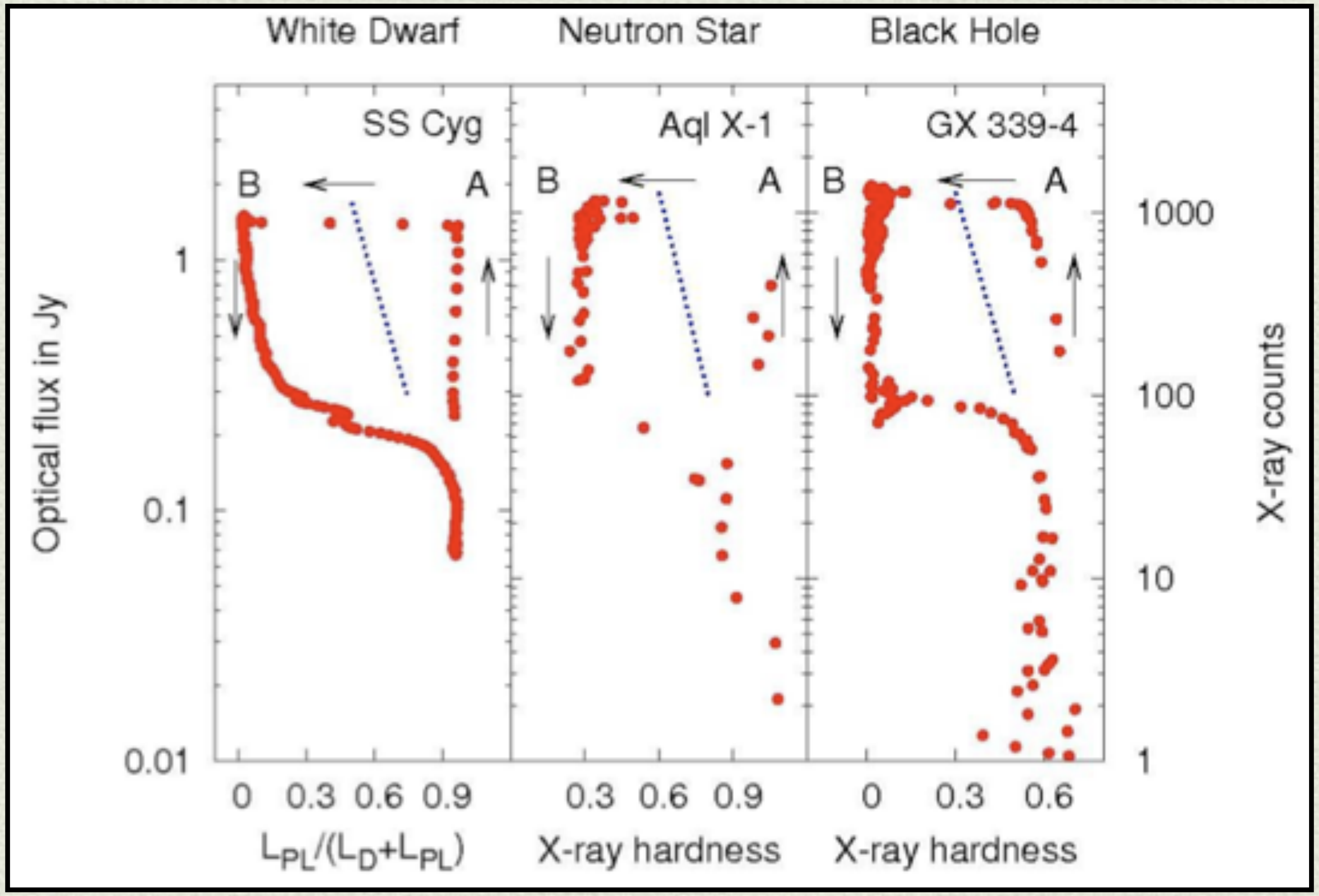




Muñoz-Darias et al. (2014)

Others: Dwarf Novae?

- SS Cyg
- A radio flare
- Comparison

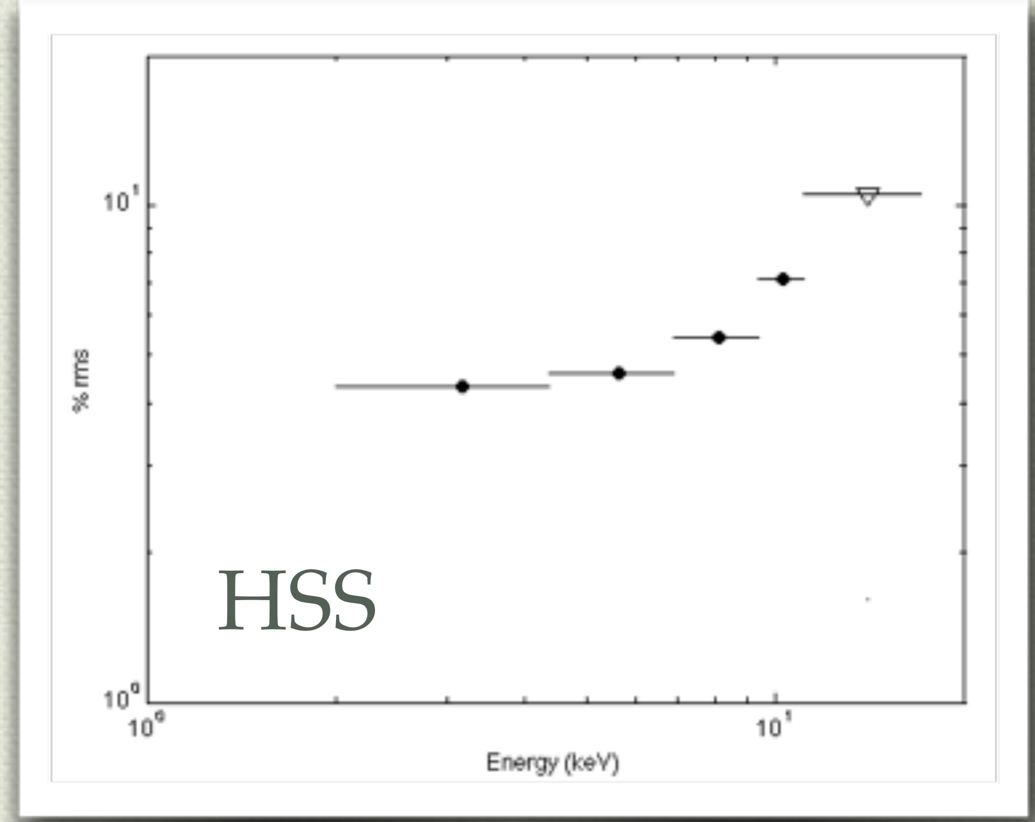


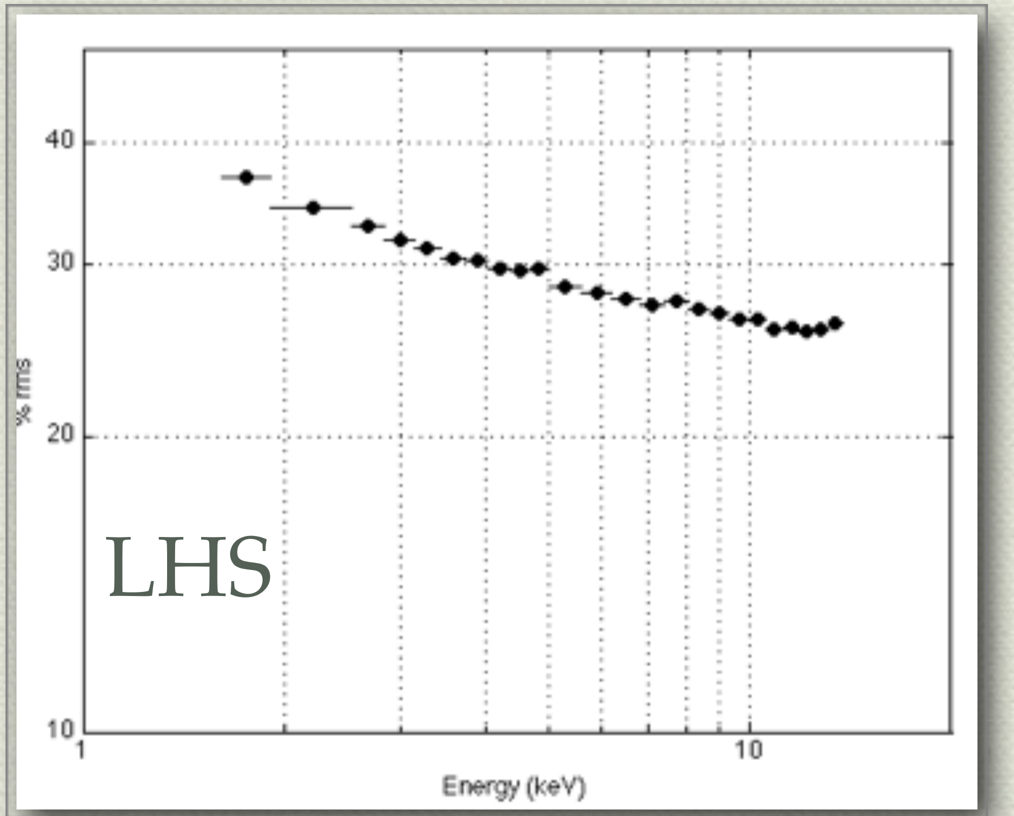
WHAT DOES IT MEAN?

Körding et al. (2008)

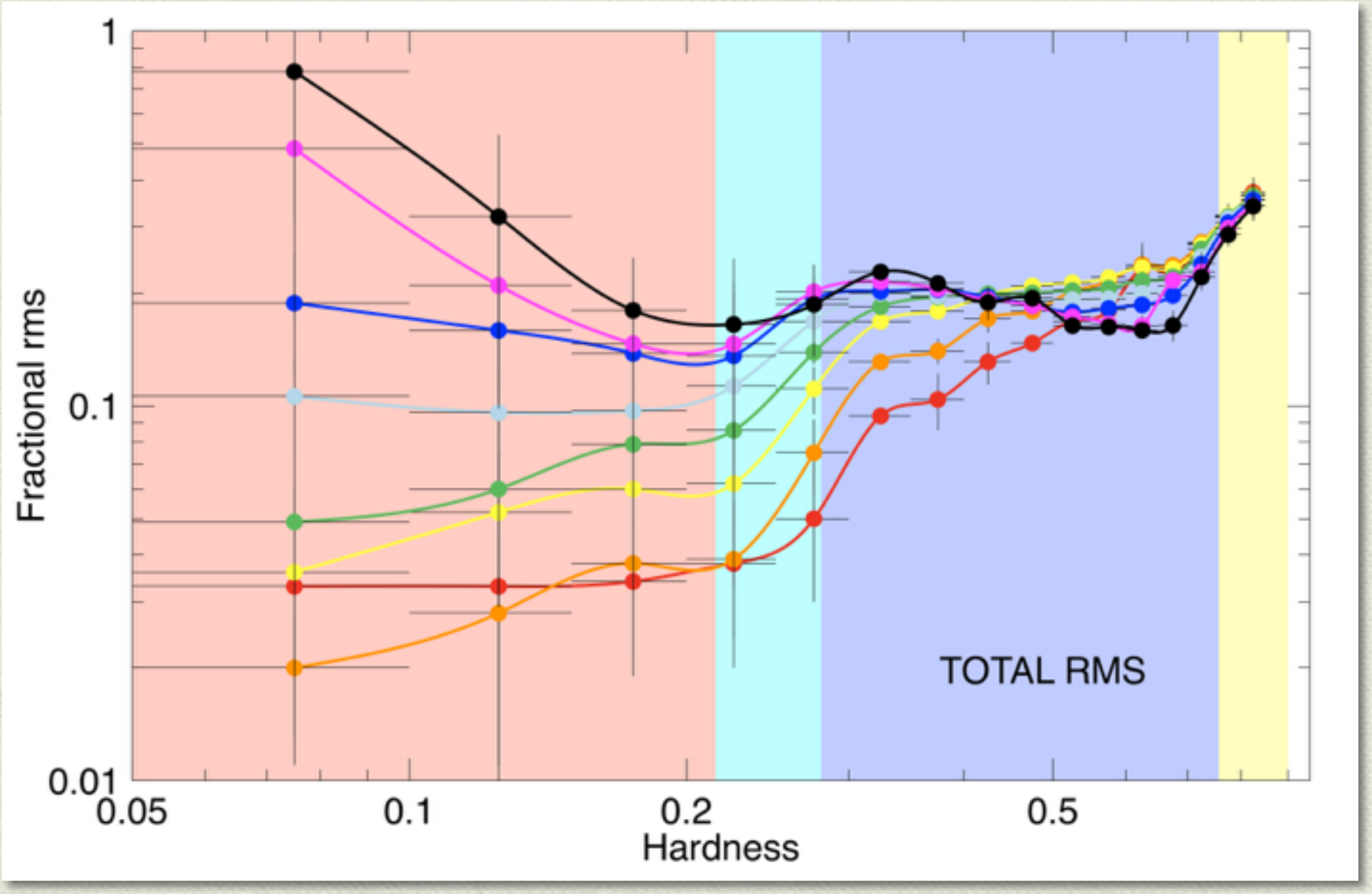
Some more timing

- Low/Hard State: (lots of) variability (Comptonization?)
- High/Soft State: little variability (S&S)
- Energy dependence?

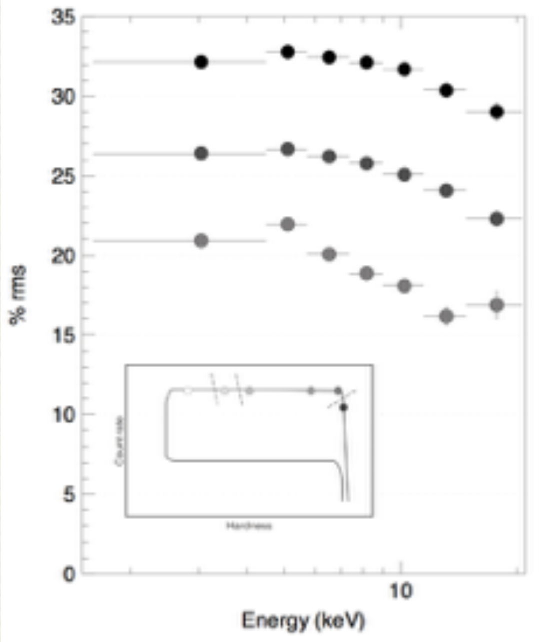


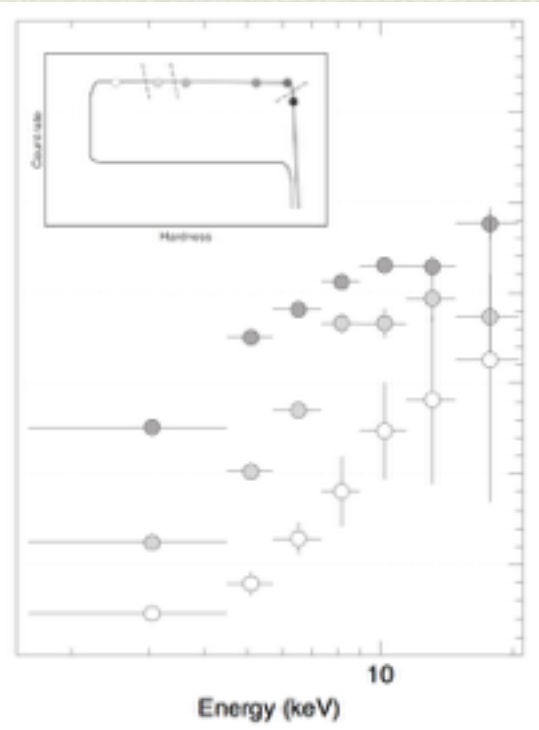


Again transitions



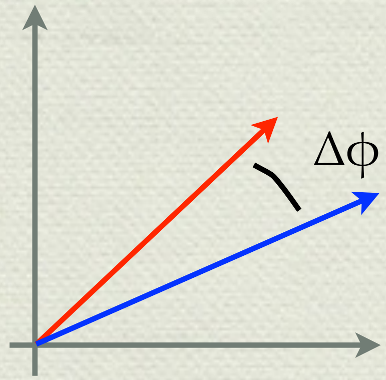
TMB et al. (2011; in prep.)



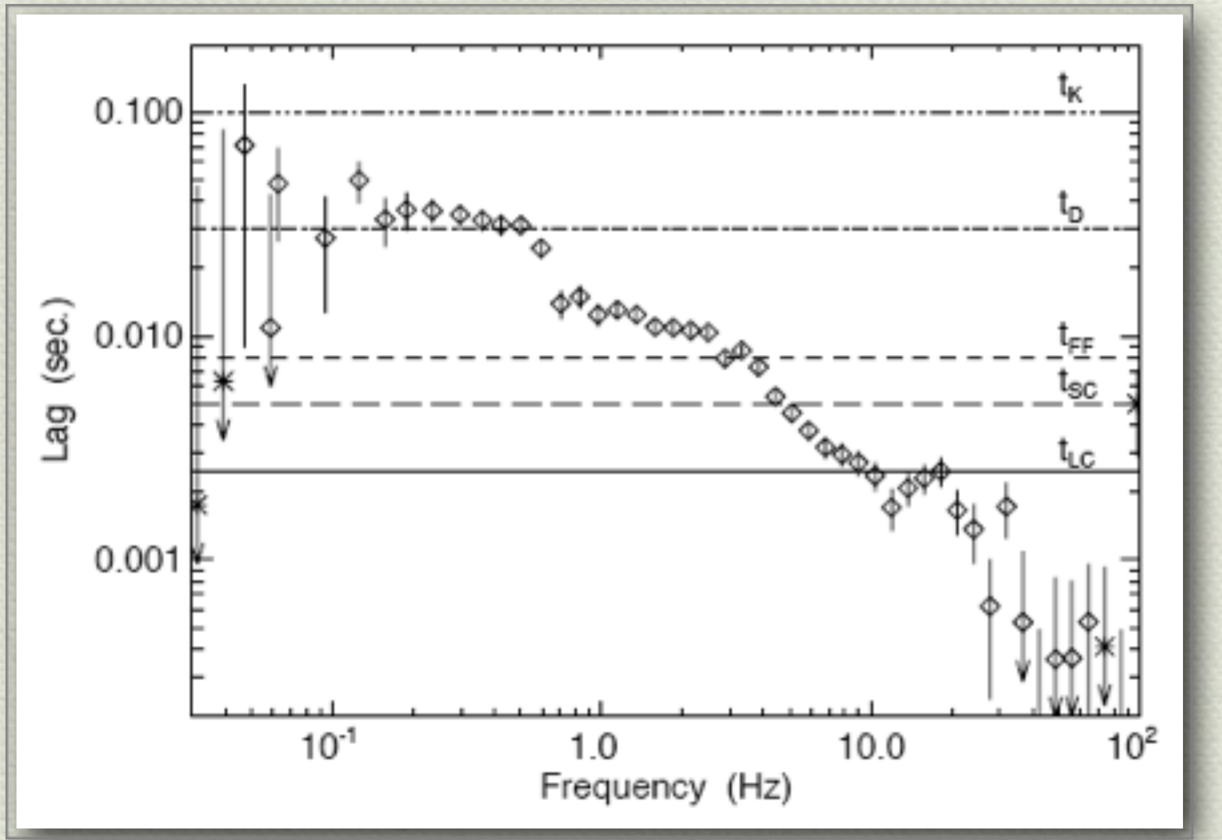


Time / phase lags

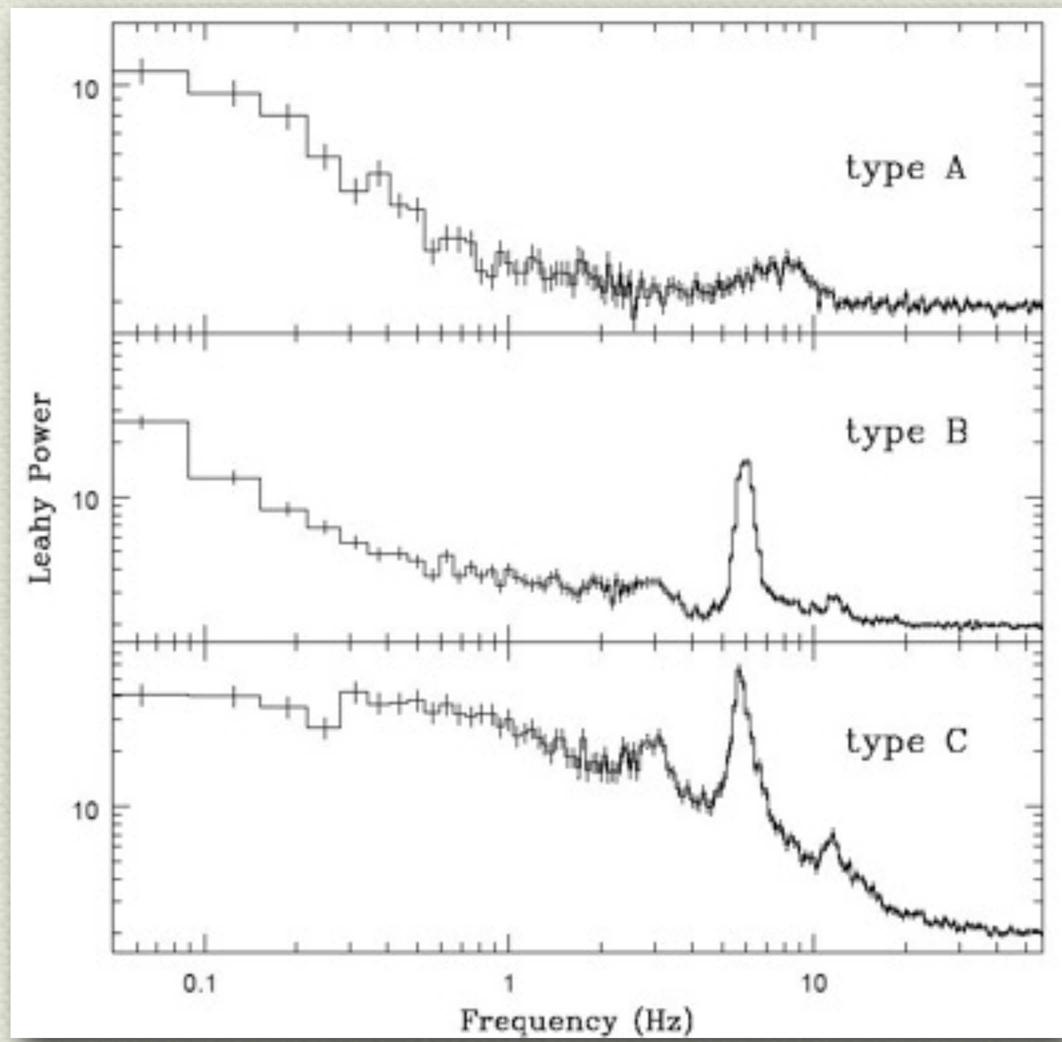
- Cross-spectrum $C_{f,g}(\nu) = F_f^*(\nu) \times F_g(\nu)$
- Phases of sinusoidal components
- Phase difference



- Hard delay
- Comptonization?
- Size issue



Low-frequency QPOs



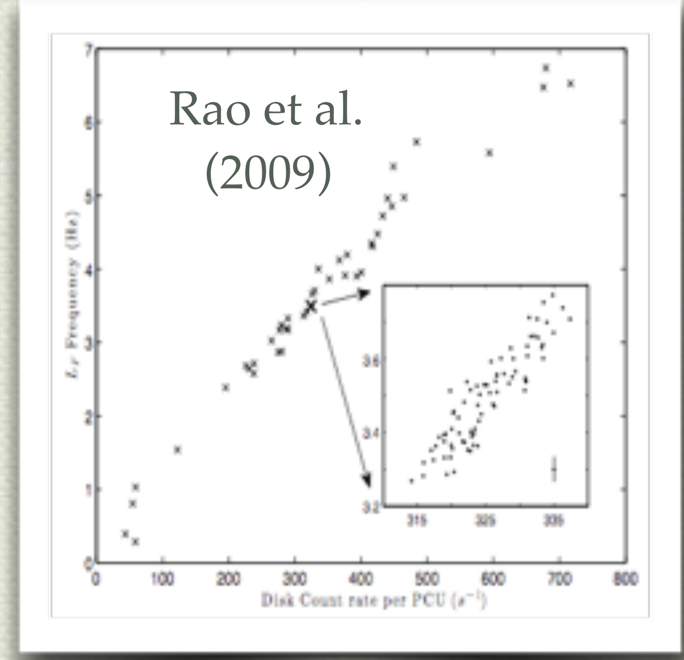
Casella et al. (2005)

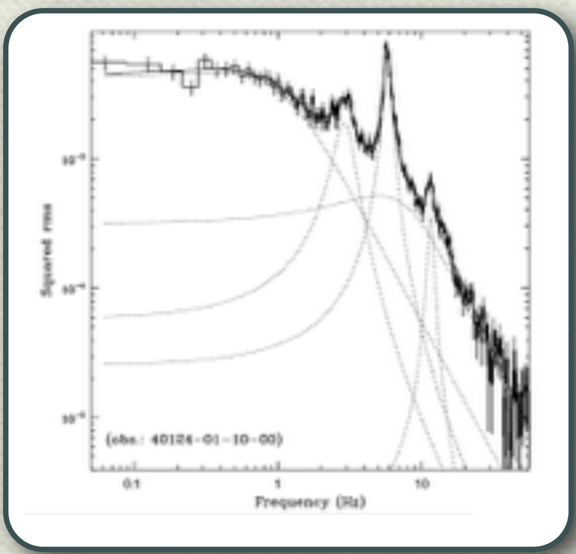
TABLE 1
SUMMARY OF TYPE-A, -B AND -C LFQPOS PROPERTIES

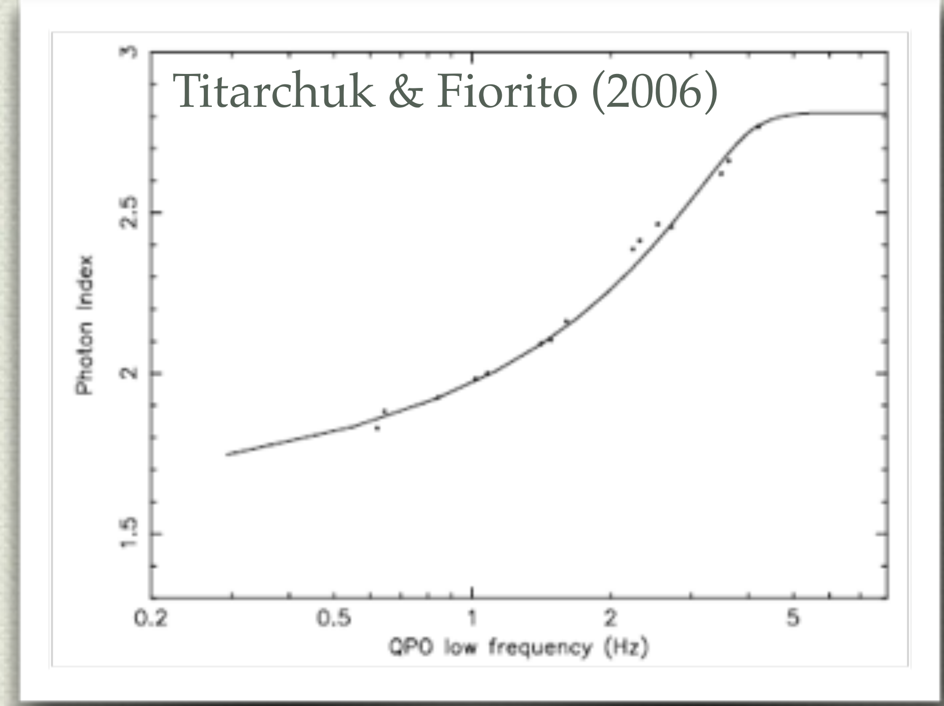
Property	Type C	Type B	Type A
Frequency (Hz)	~0.1-15	~5-6	~8
Q (ν/FWHM)	~7-12	$\gtrsim$6	$\lesssim$3
Amplitude (%rms)	3-16	~2-4	$\lesssim$3
Noise	strong flat–top	weak red	weak red
Phase lag @ν_{QPO}	soft/hard	hard	soft
Phase lag @$2\nu_{QPO}$	hard	soft	...
Phase lag @$\nu_{QPO}/2$	soft	soft	...

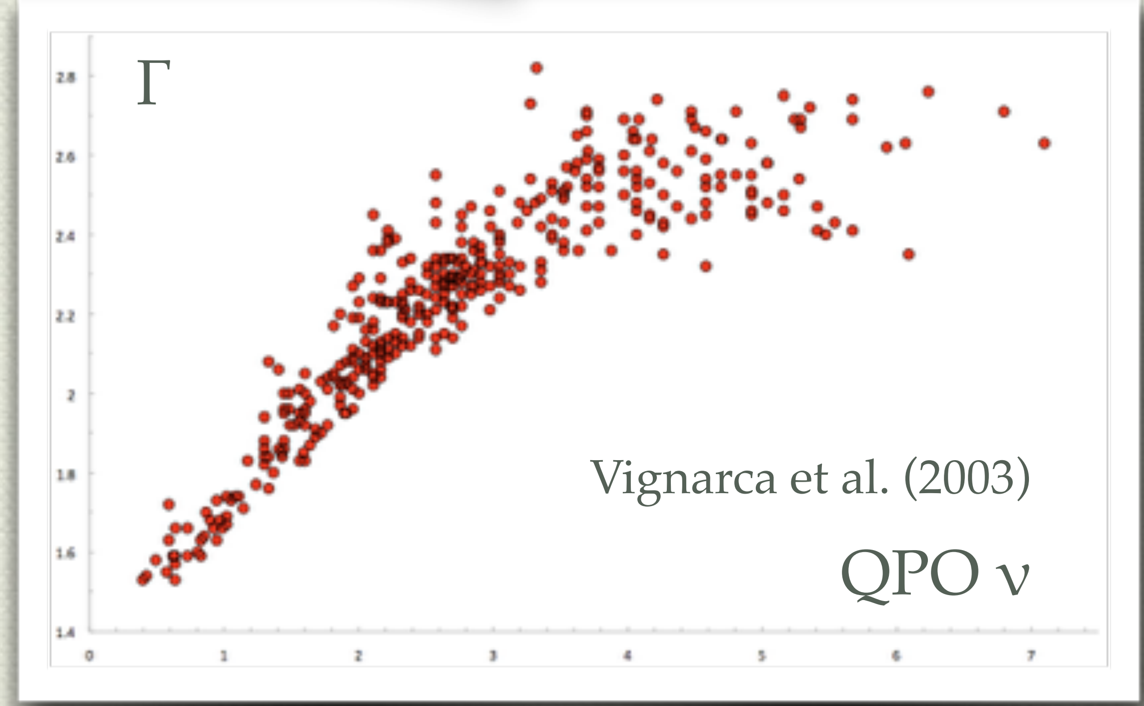
Low-frequency QPOs

- Very clear oscillations
- Type-C: large range in ν
- Correlation with spectra
- .. and disk luminosity



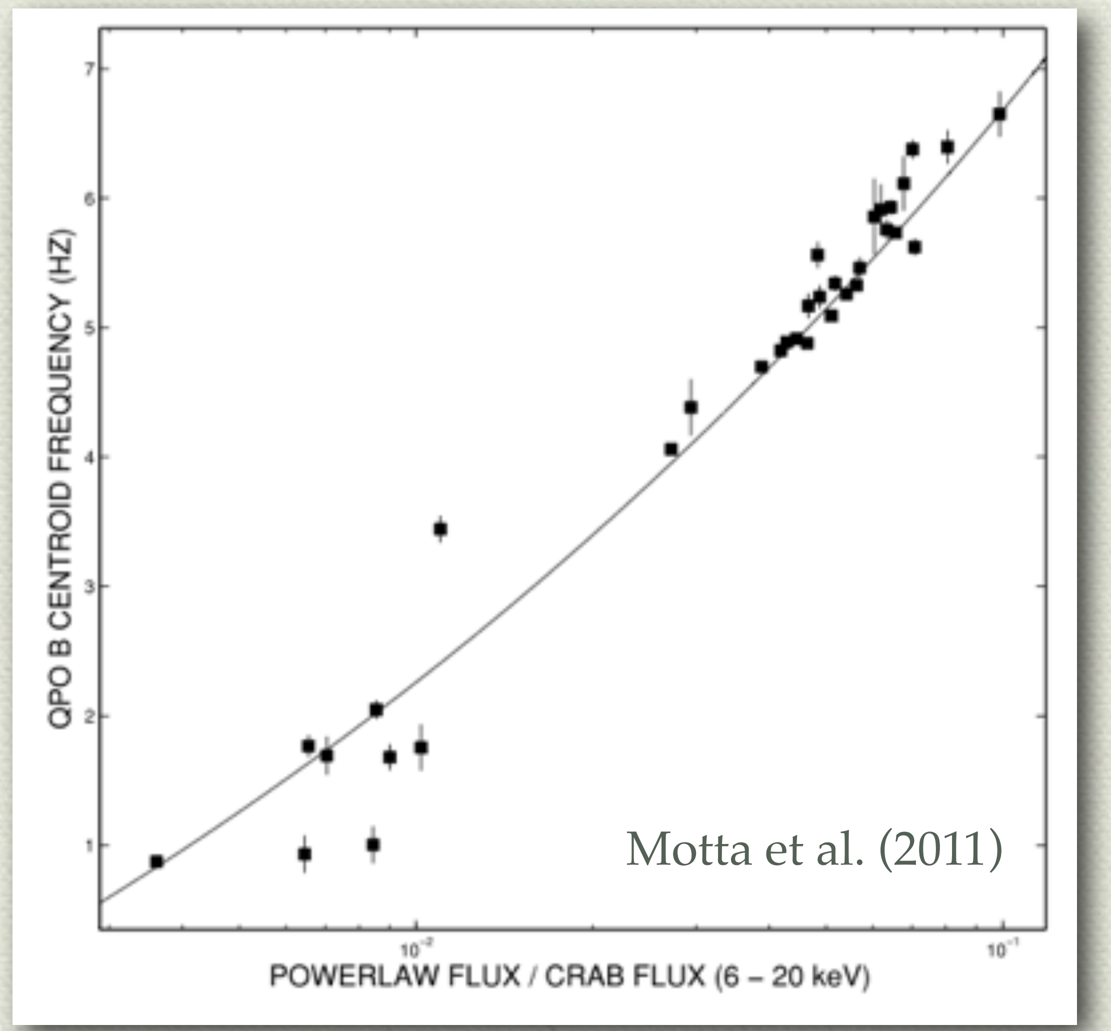


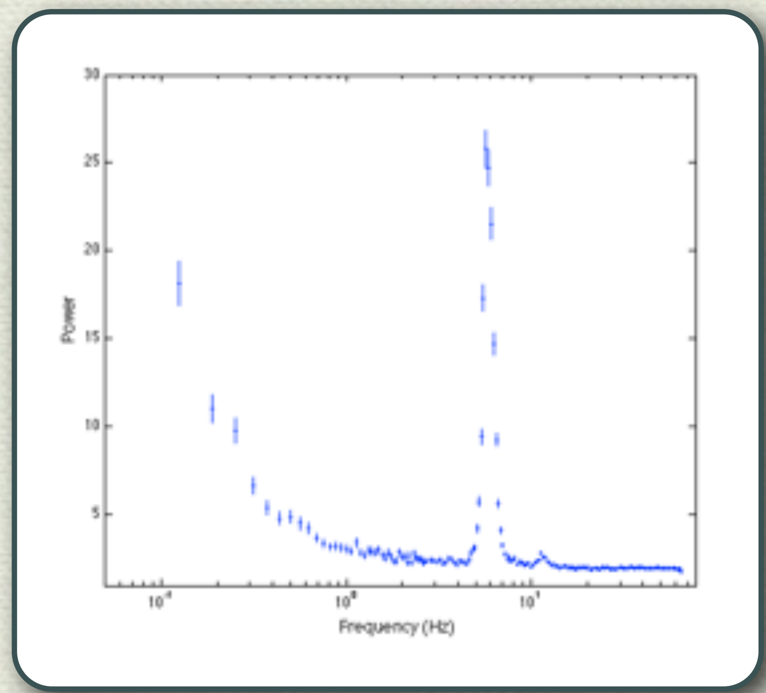




Low-frequency QPOs

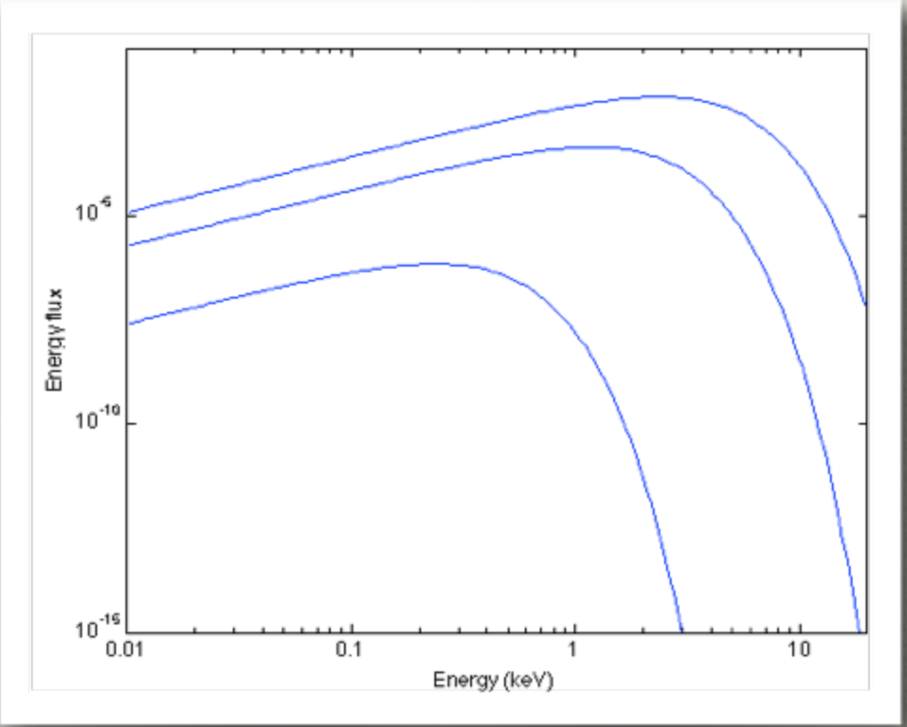
- Type-AB: small range in ν
- Correlation with PL luminosity

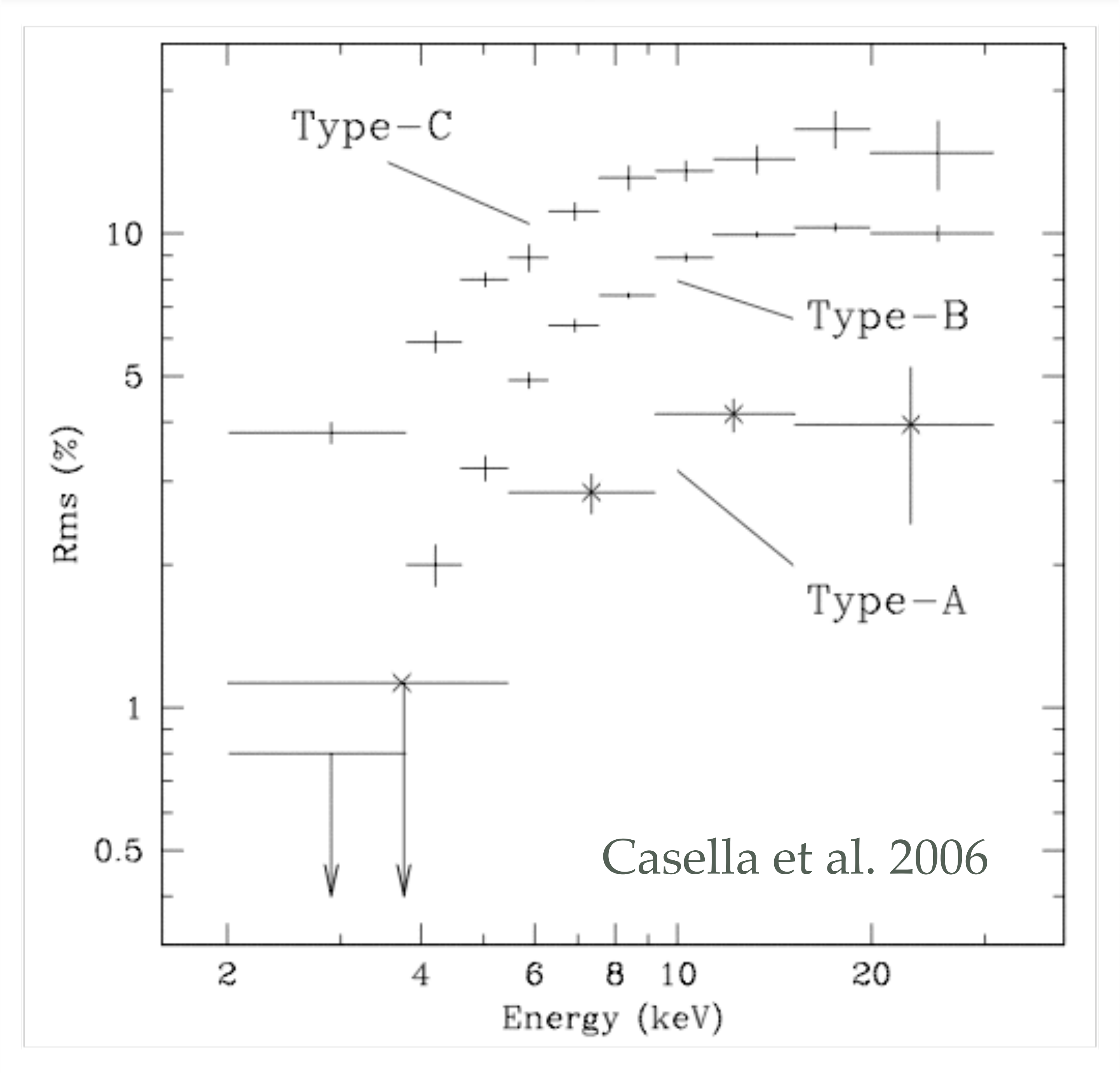




Energy dependence

- Hard, hard, hard
- No Disk!



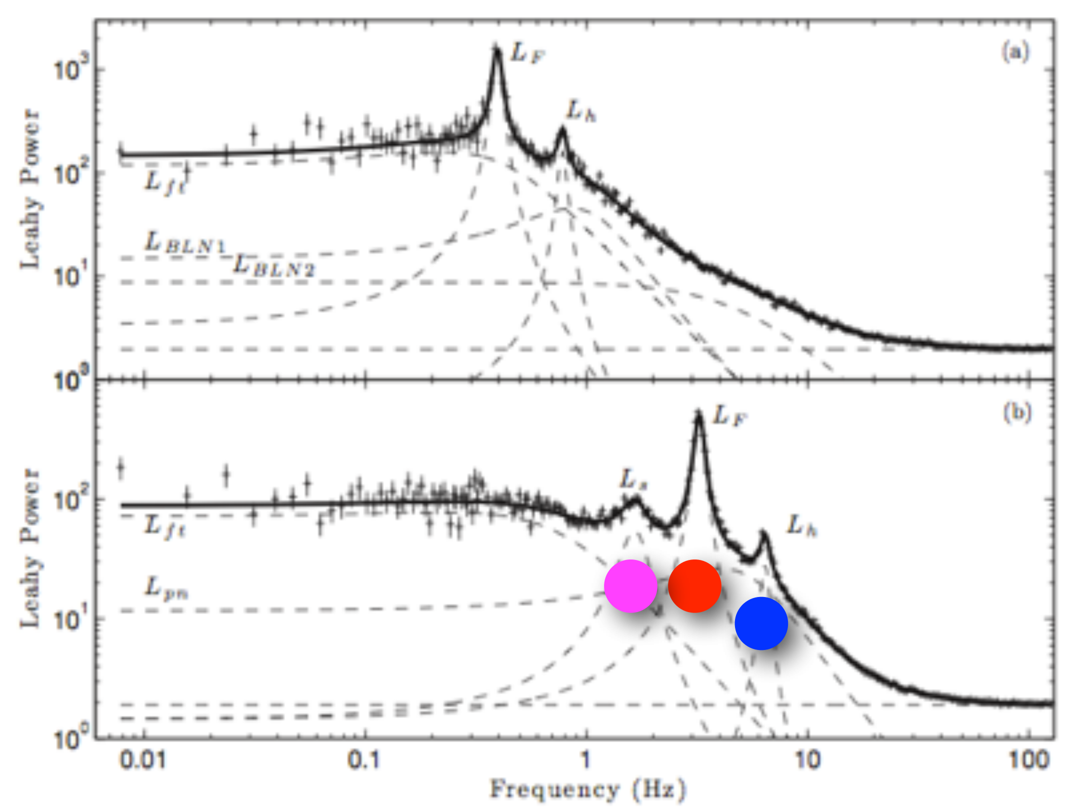


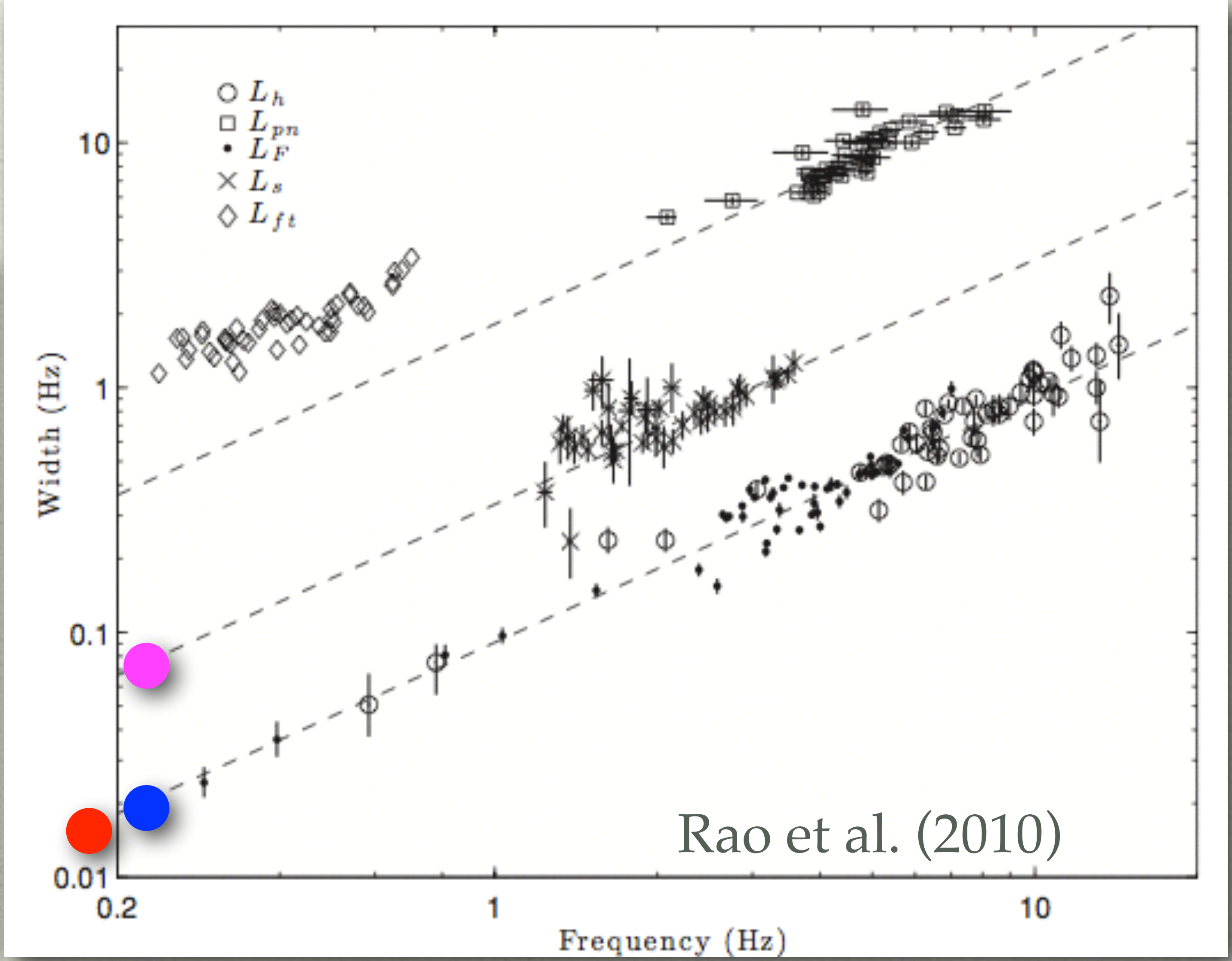
Casella et al. 2006

Which modulation?

- AM / FM
- No phase modulation
- Difference if harmonics

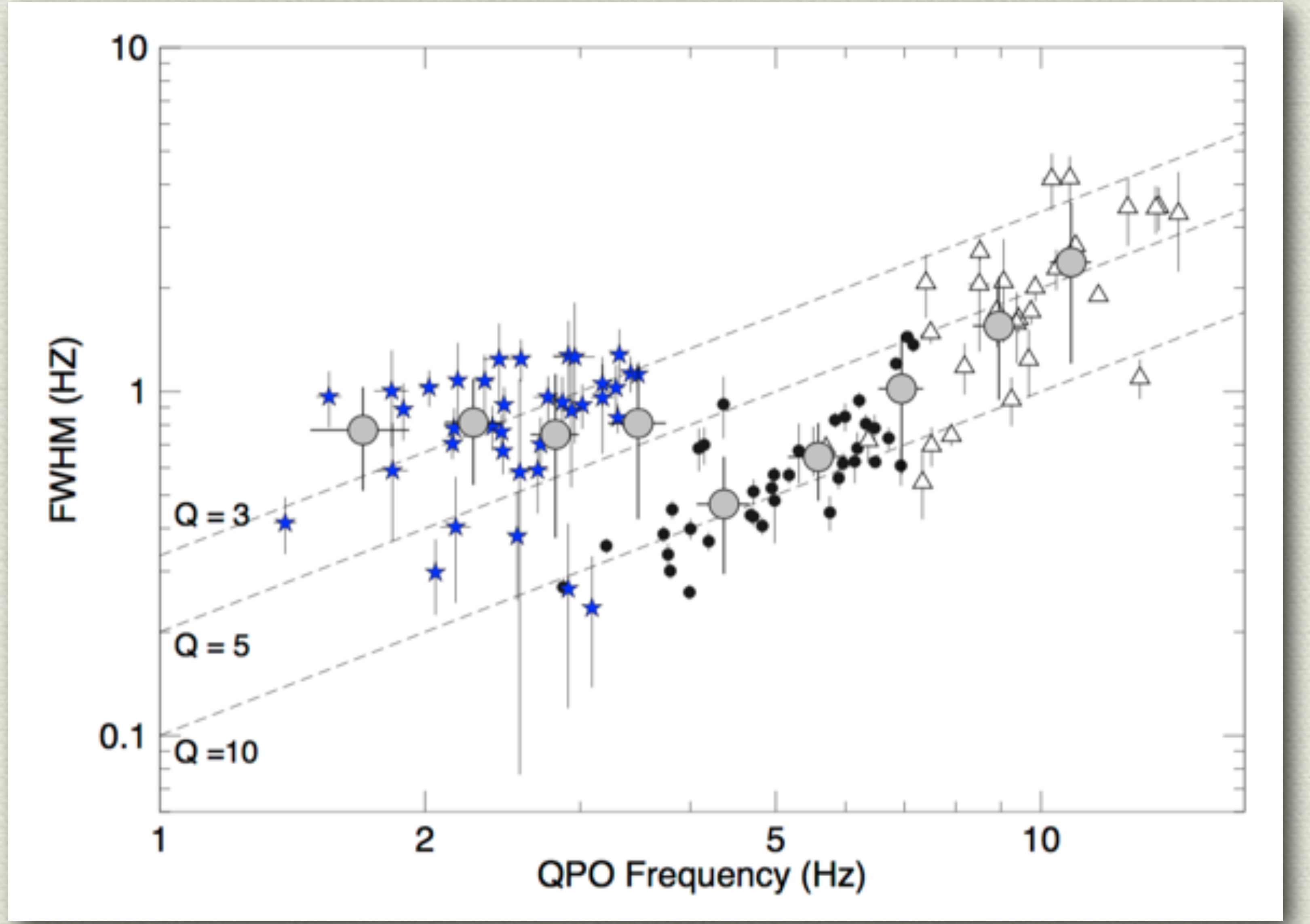
$$F(t) = A \sin(\omega t + \phi)$$

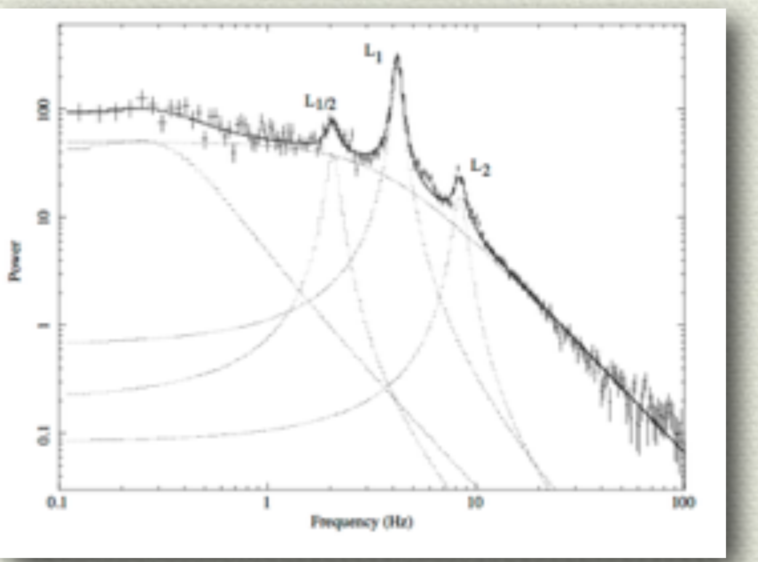




Rao et al. (2010)

Which modulation?

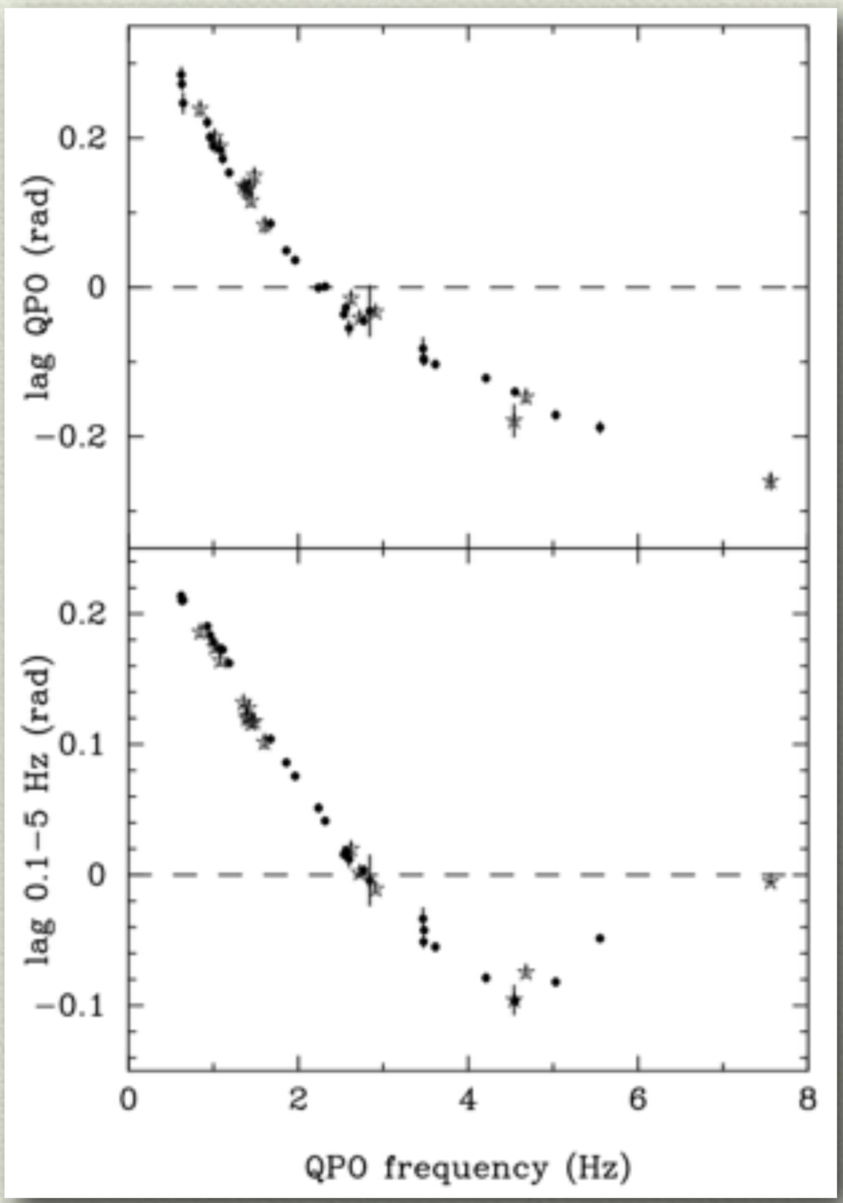


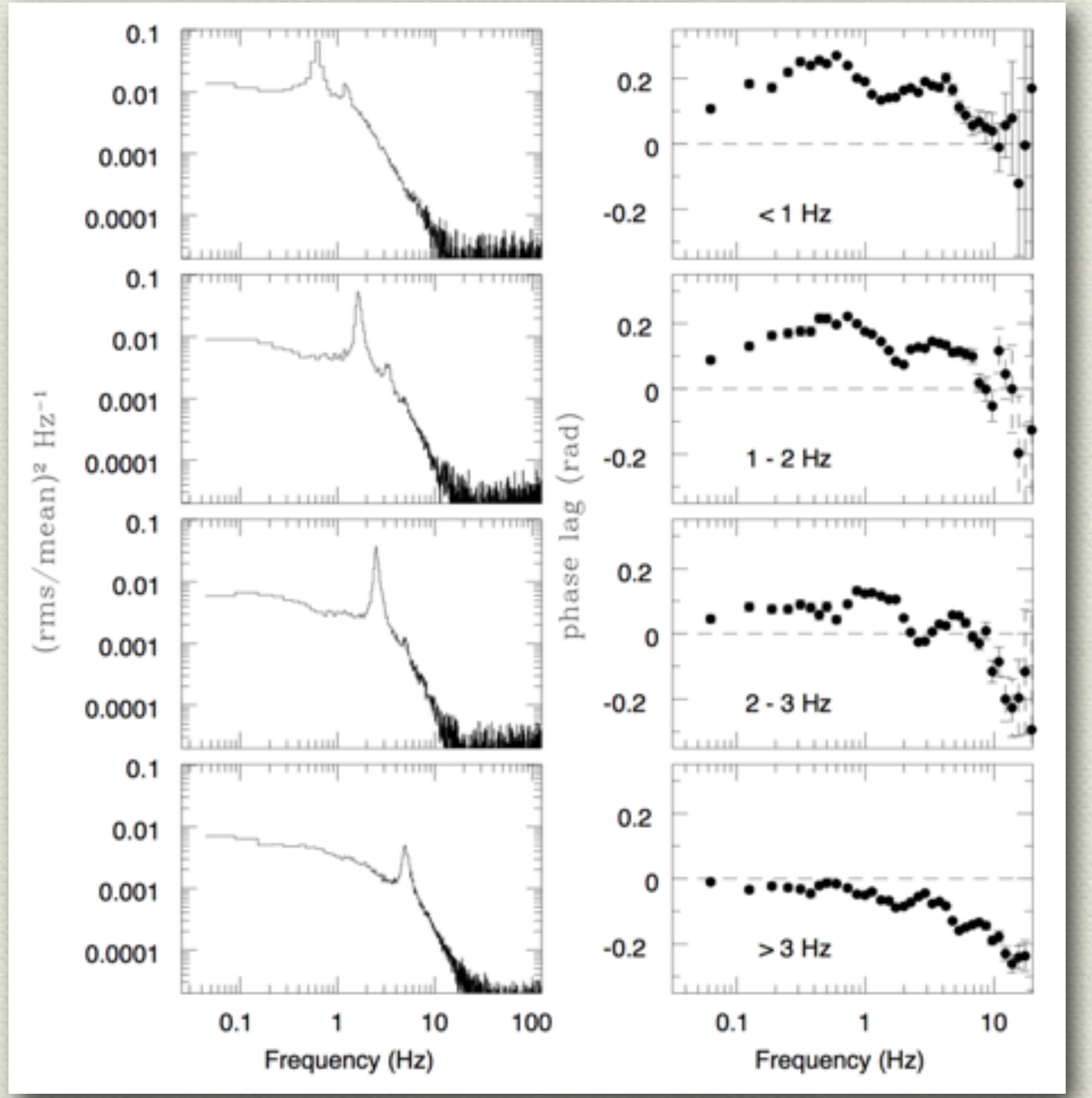


Pawar et al. (2015)

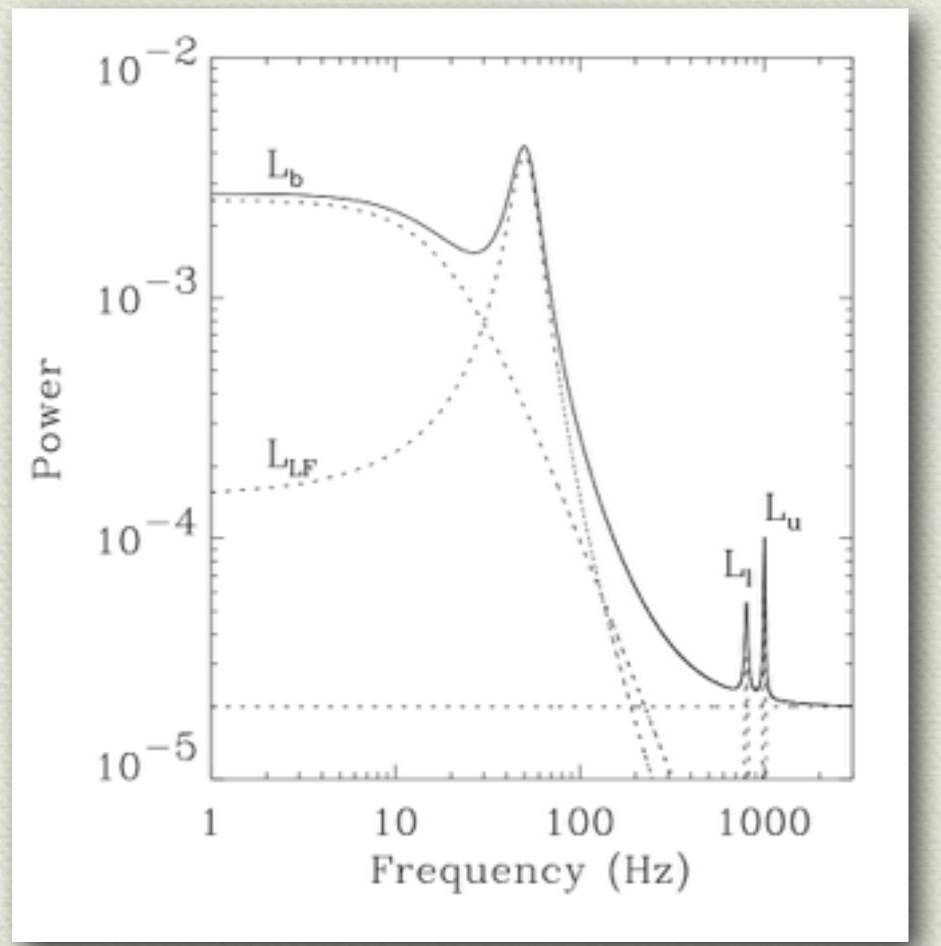
Complex lags

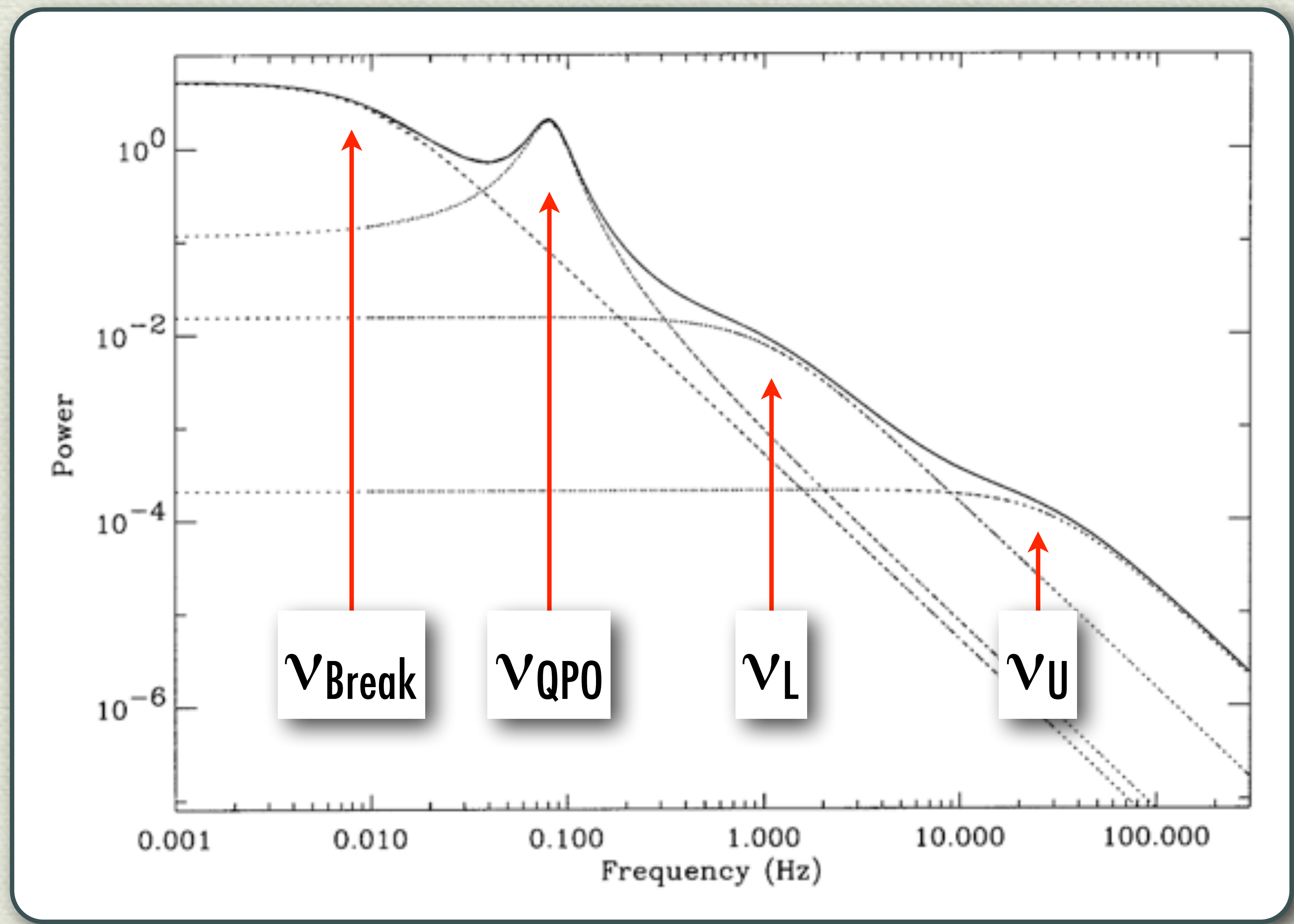
Reig et al. (2000)





PDS decomposition



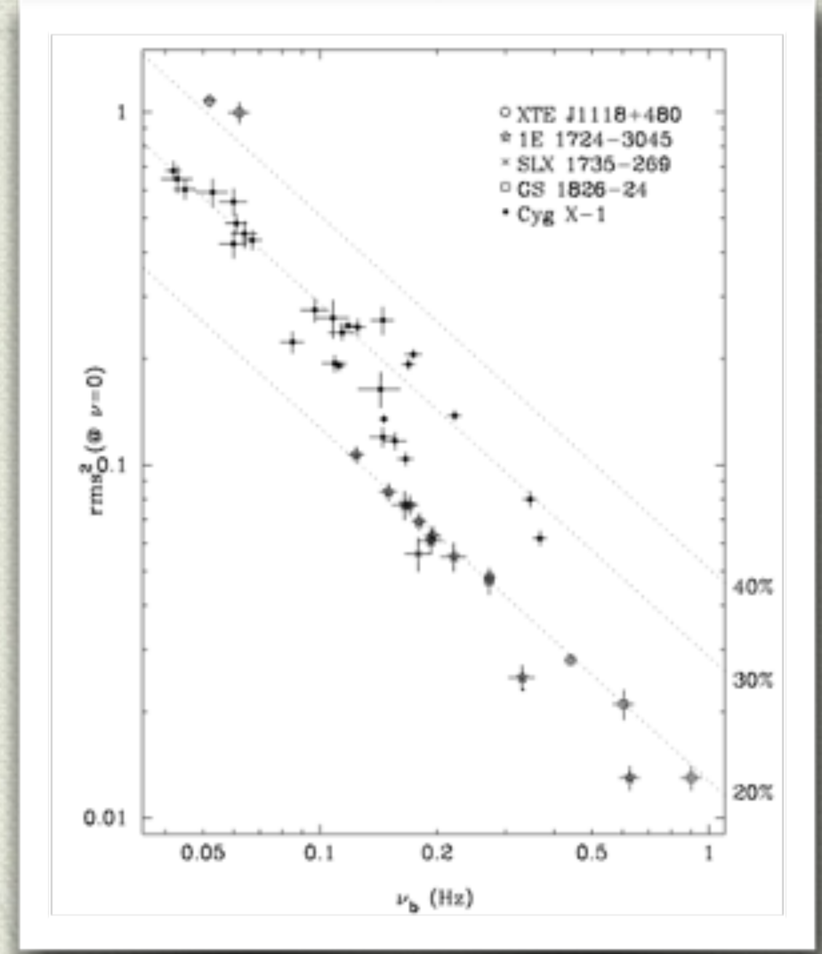


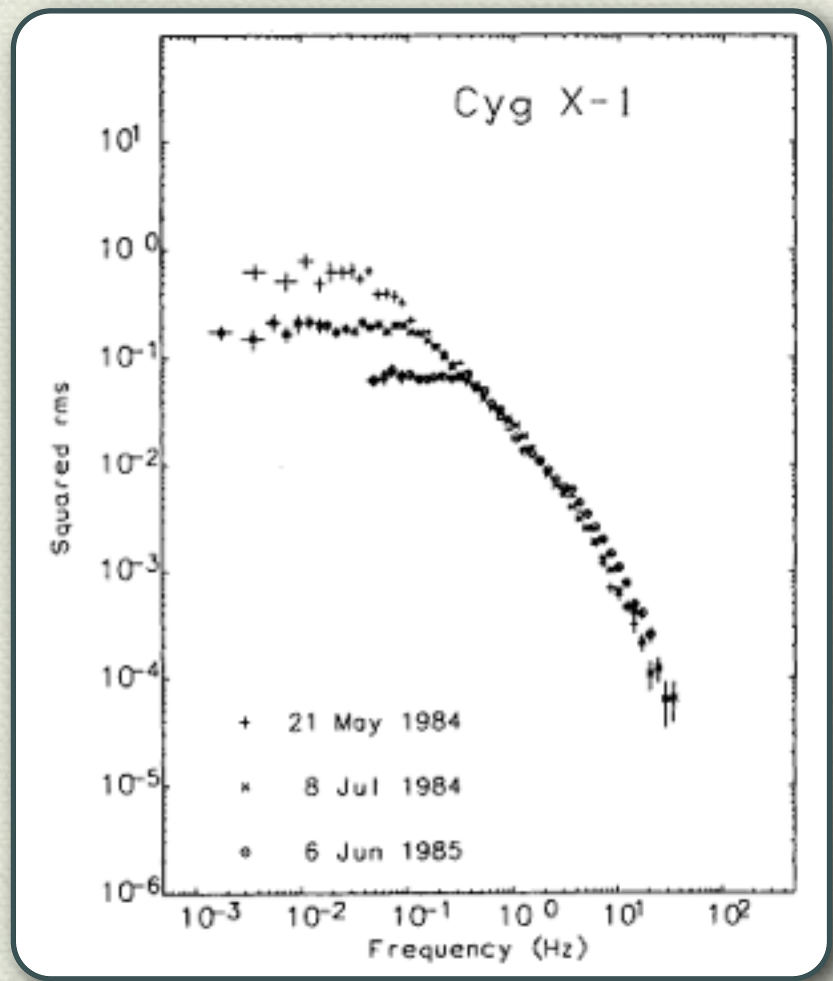
Belloni, Psaltis & van der Klis (2002)

Frequency correlations

- Correlation 1: Belloni-Hasinger

Belloni & Hasinger (1990)

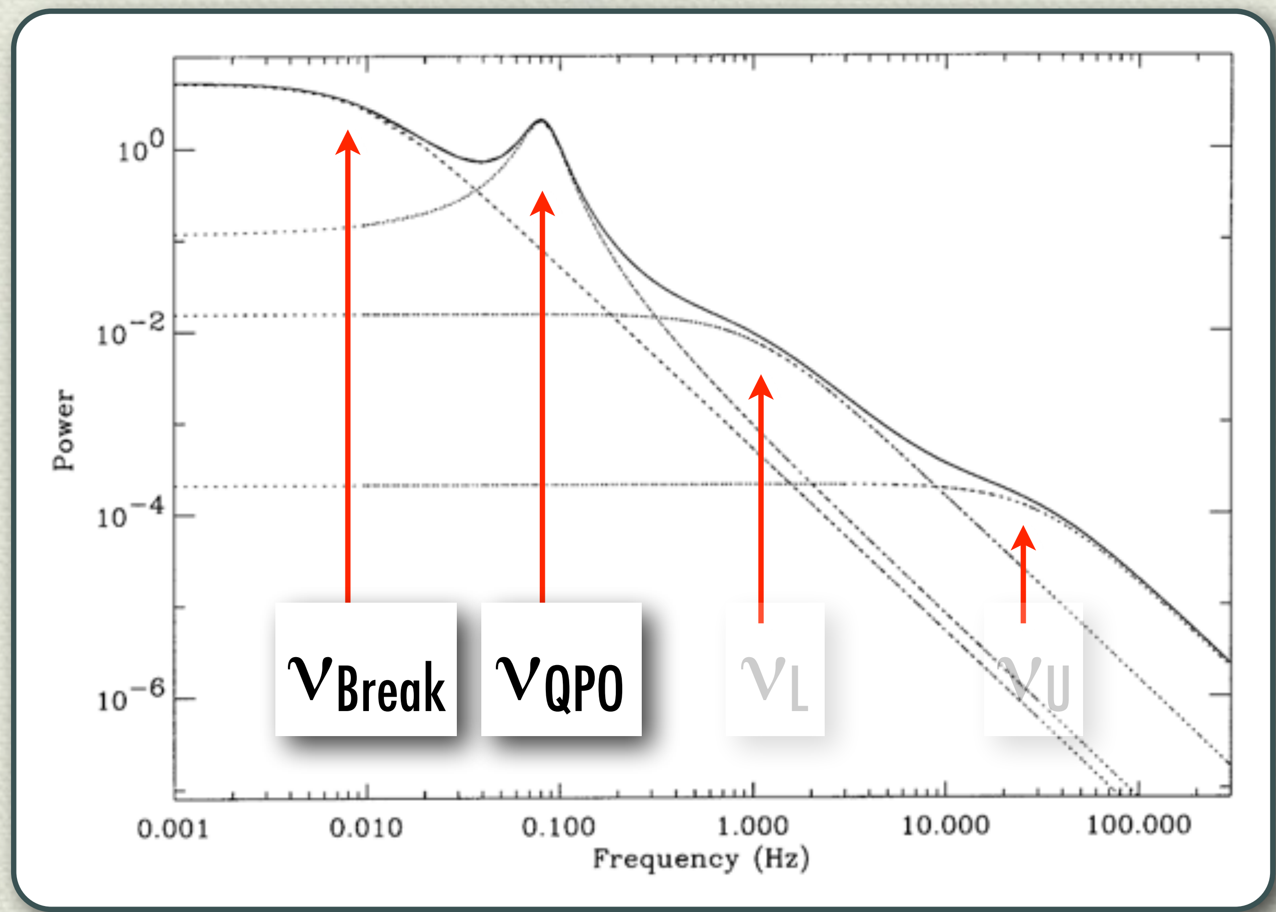


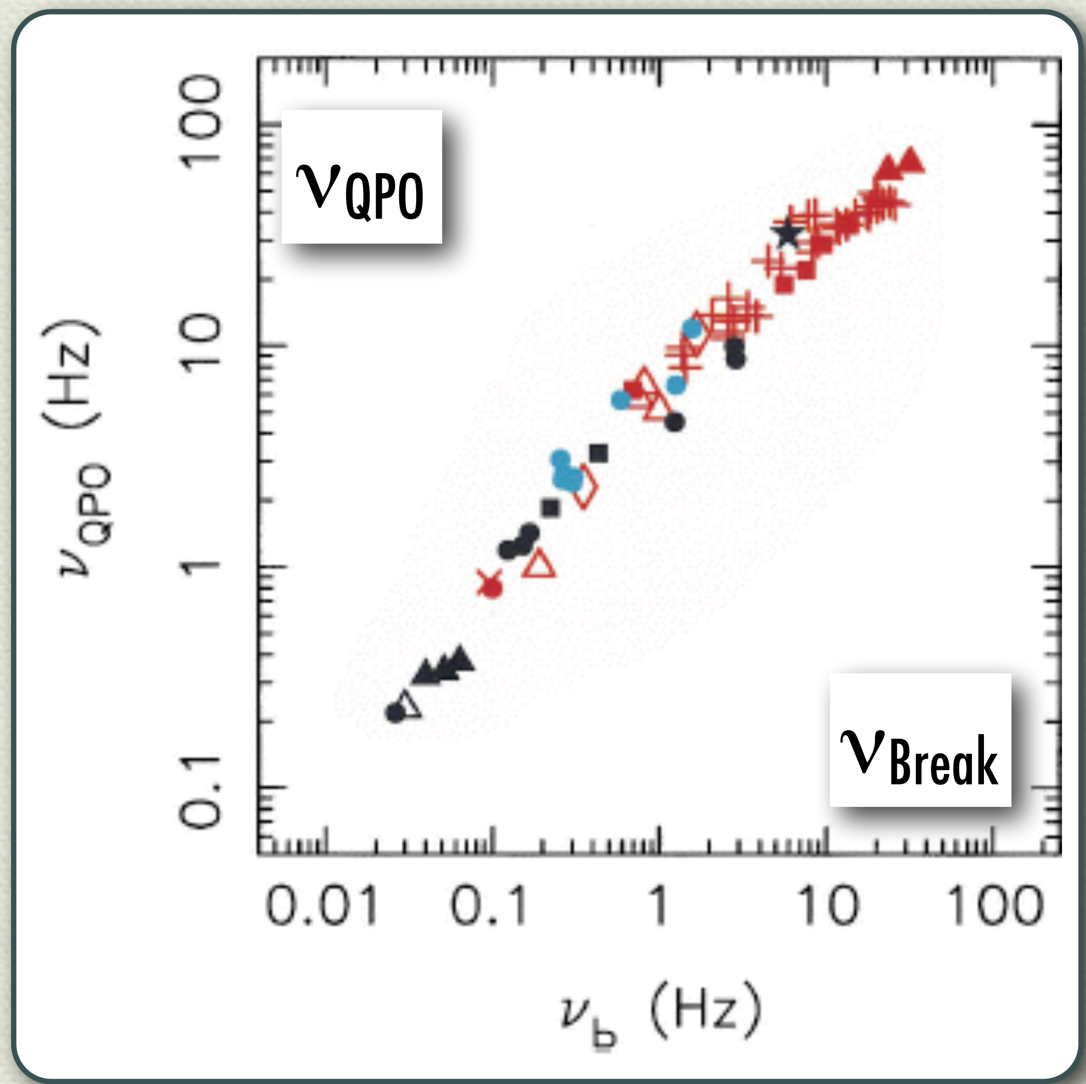


Frequency correlations

- Correlation 2: Wijands & van der Klis

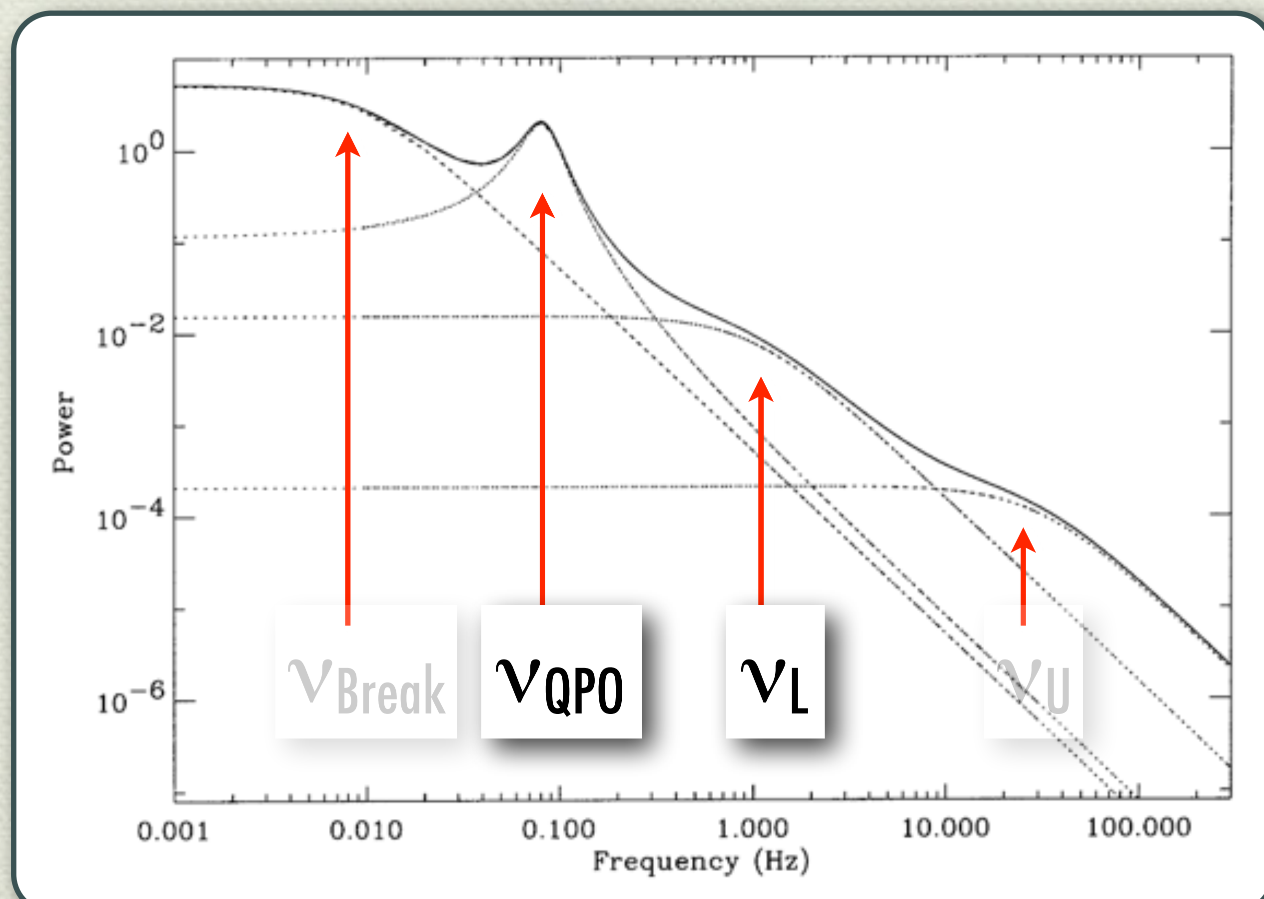
Wijnands & van der Klis (1999)



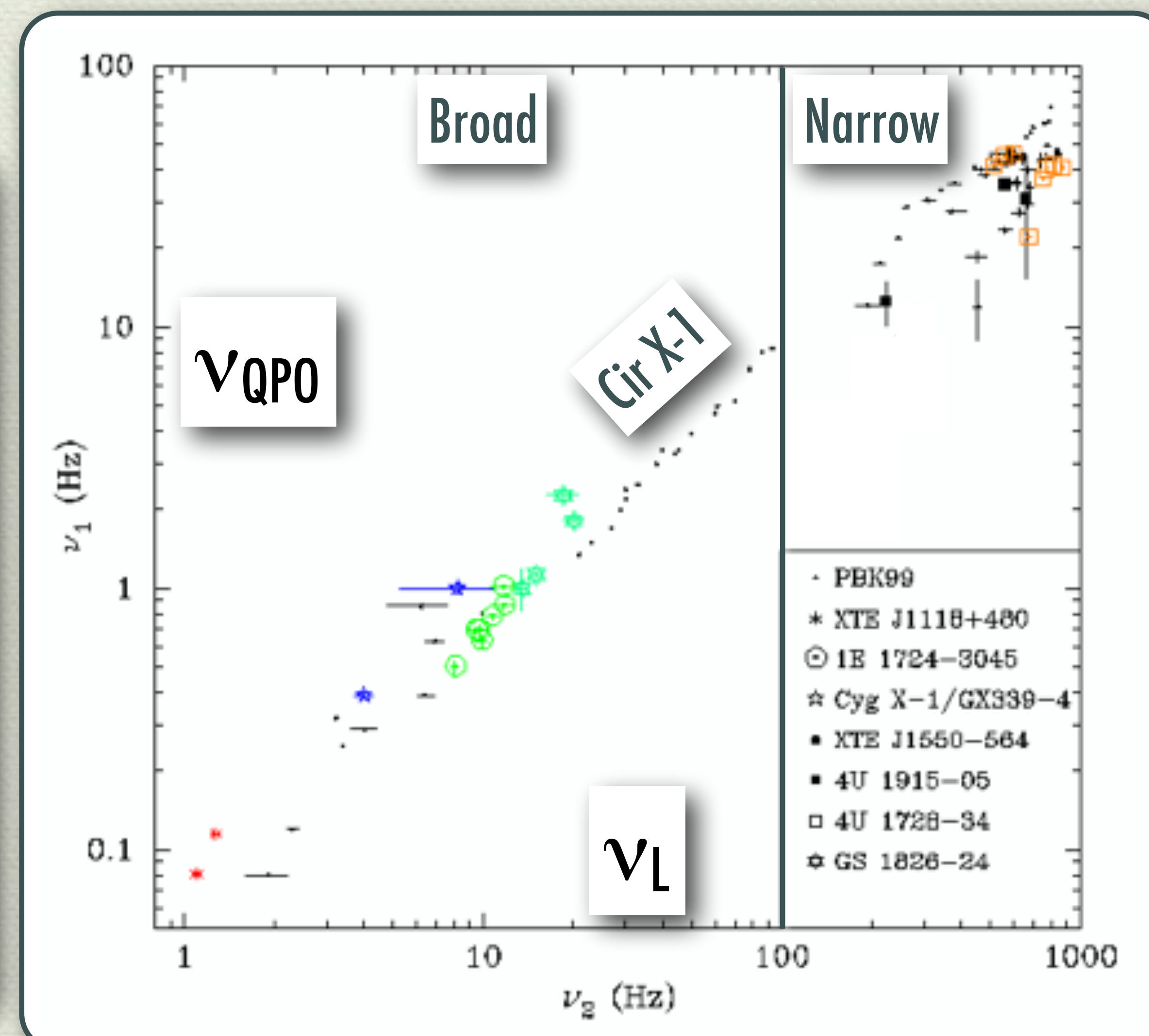


Frequency correlations

- Correlation 3: Psaltis, Belloni & van der Klis

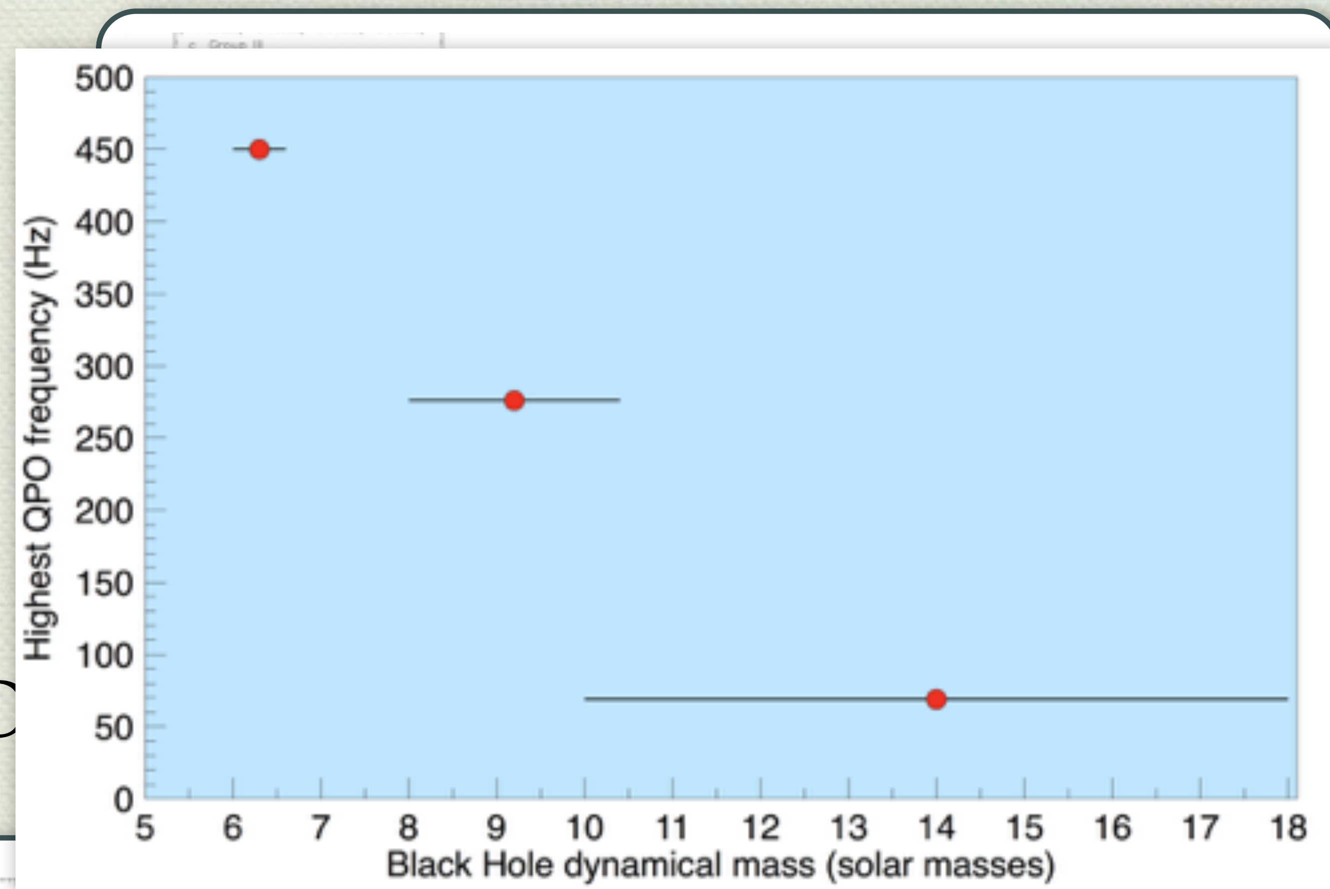


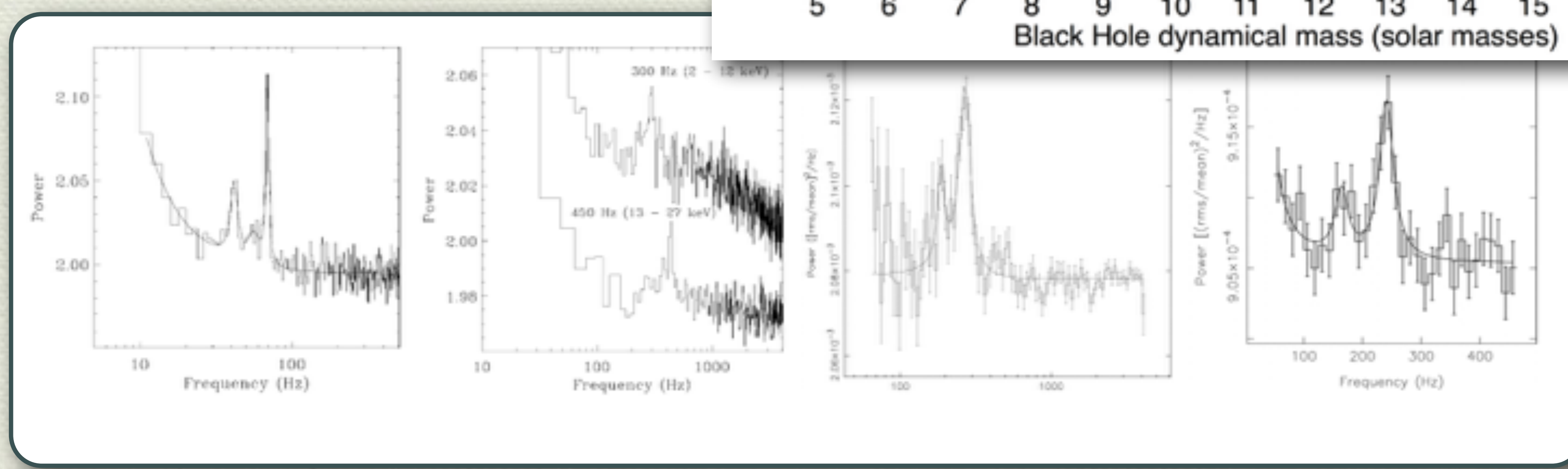
Psaltis, Belloni & van der Klis (1999)



High-frequency QPOs

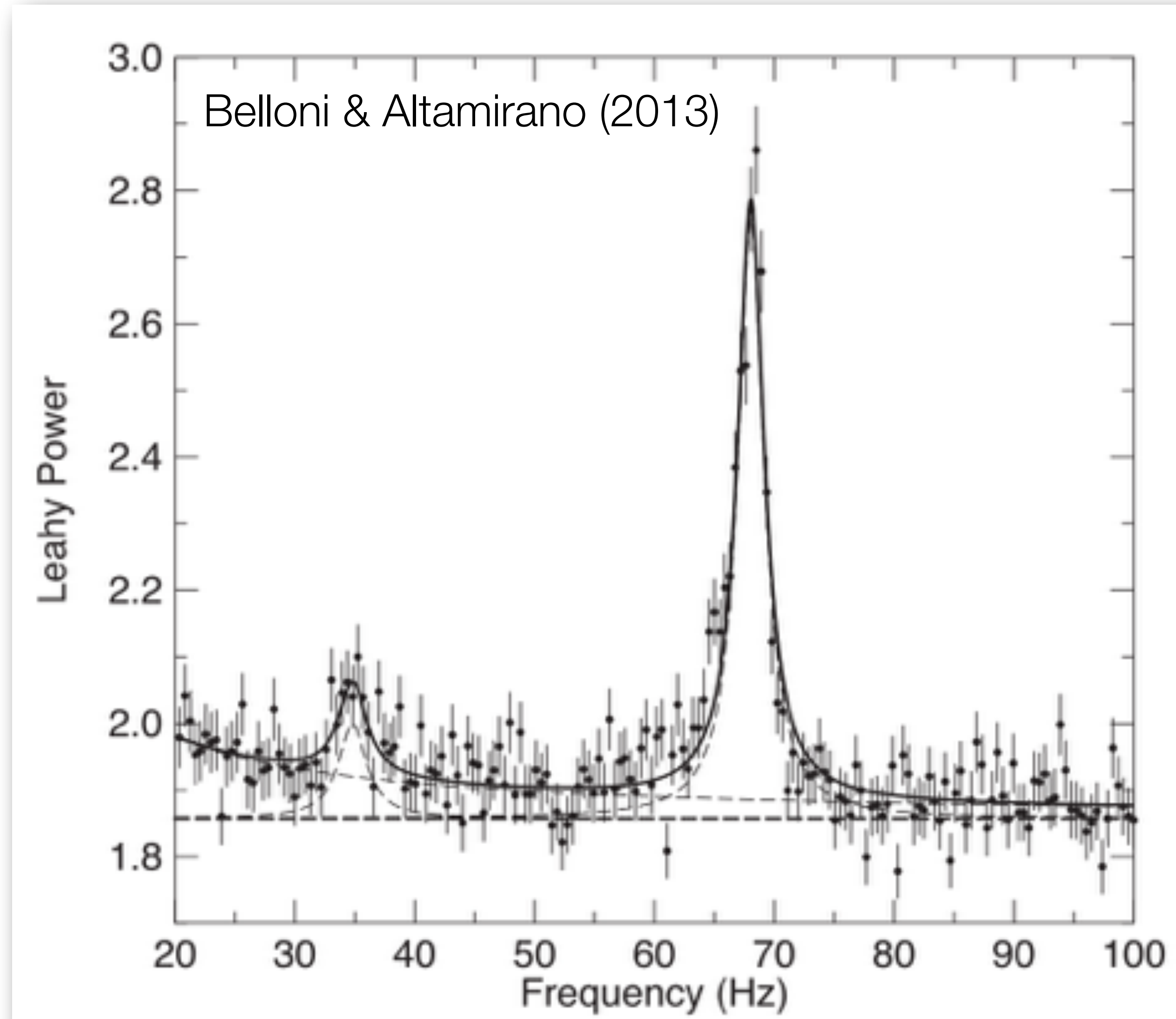
- Frequencies 30-450 Hz
- Weak and rare
- Fixed frequencies
- Some (4/7) come in pairs
- Different from NS kHz QPO





HFQPO

- In BH
  - Very few weak cases
  - 30-450 Hz
  - Even fewer pairs
  - Frequencies change little
  - Usually not with LFQPO
  - One object has many around 80 Hz



High-Frequency QPOs

- Complete reanalysis of the full RXTE archive

Belloni, Sanna & Méndez (2012)

- 12 Ms of data
- 11 detections from two sources only

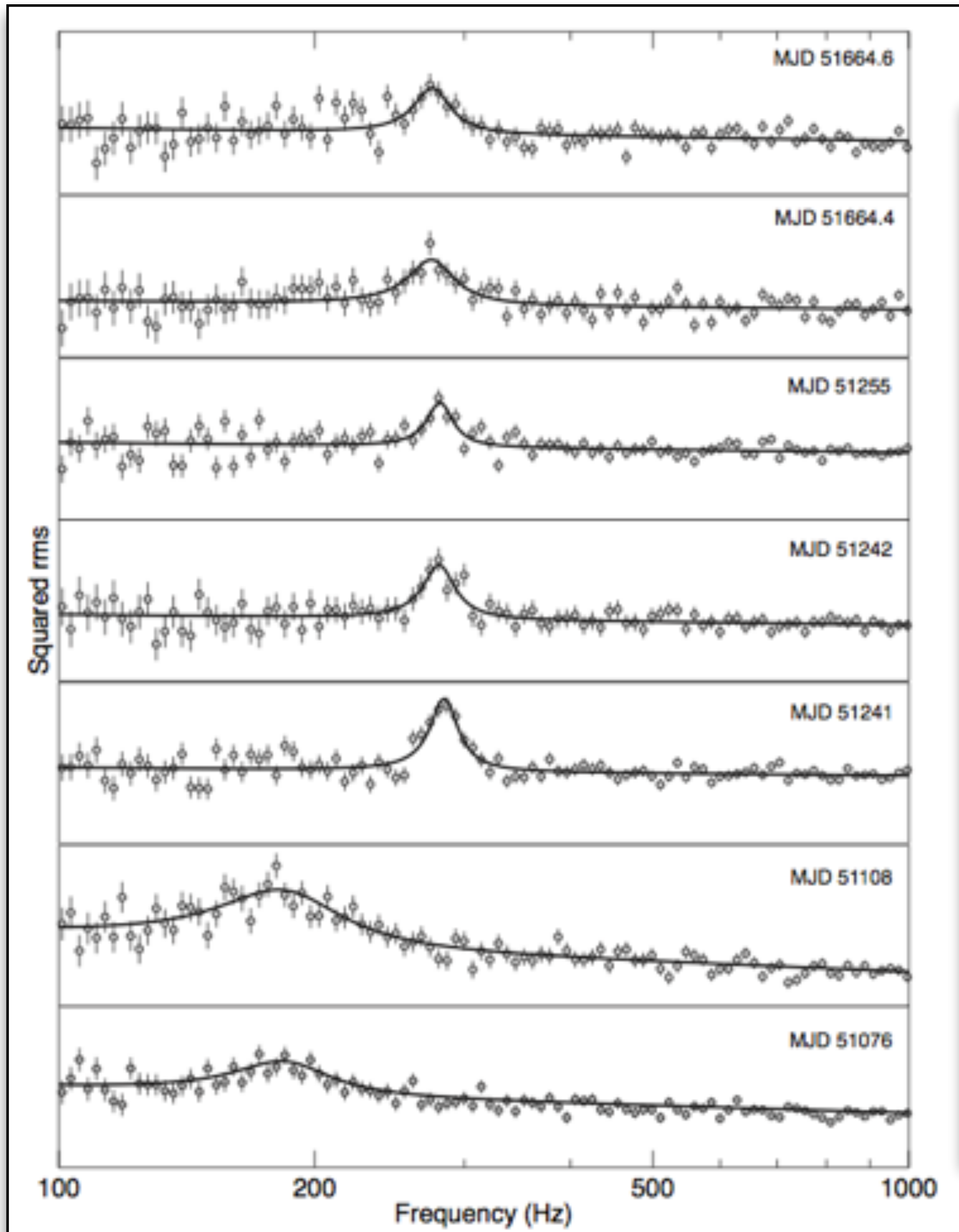
- 5.2 Ms of data on GRS 1915+105

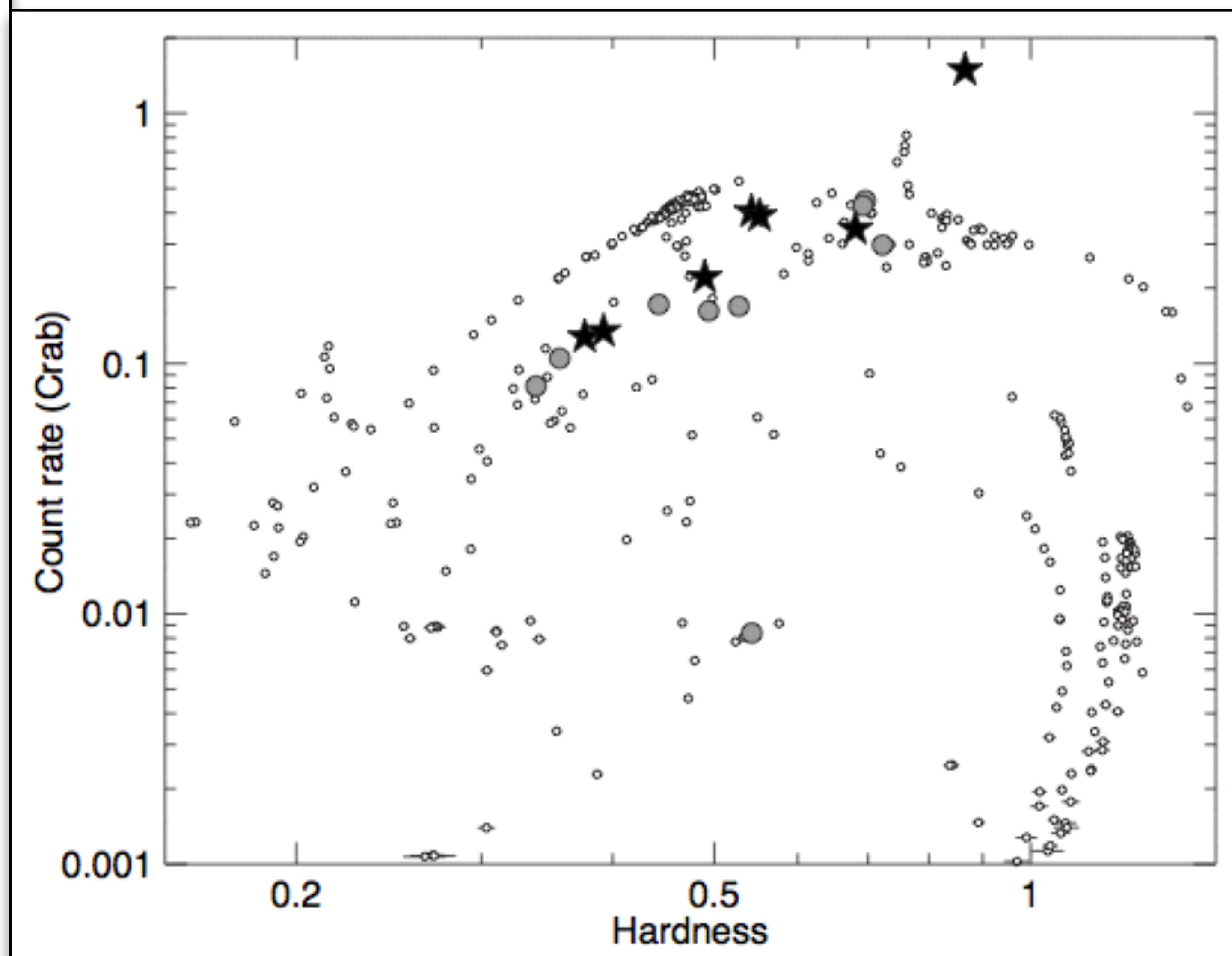
Belloni & Altamirano (2012)

- 46 detections

XTE J1550+564

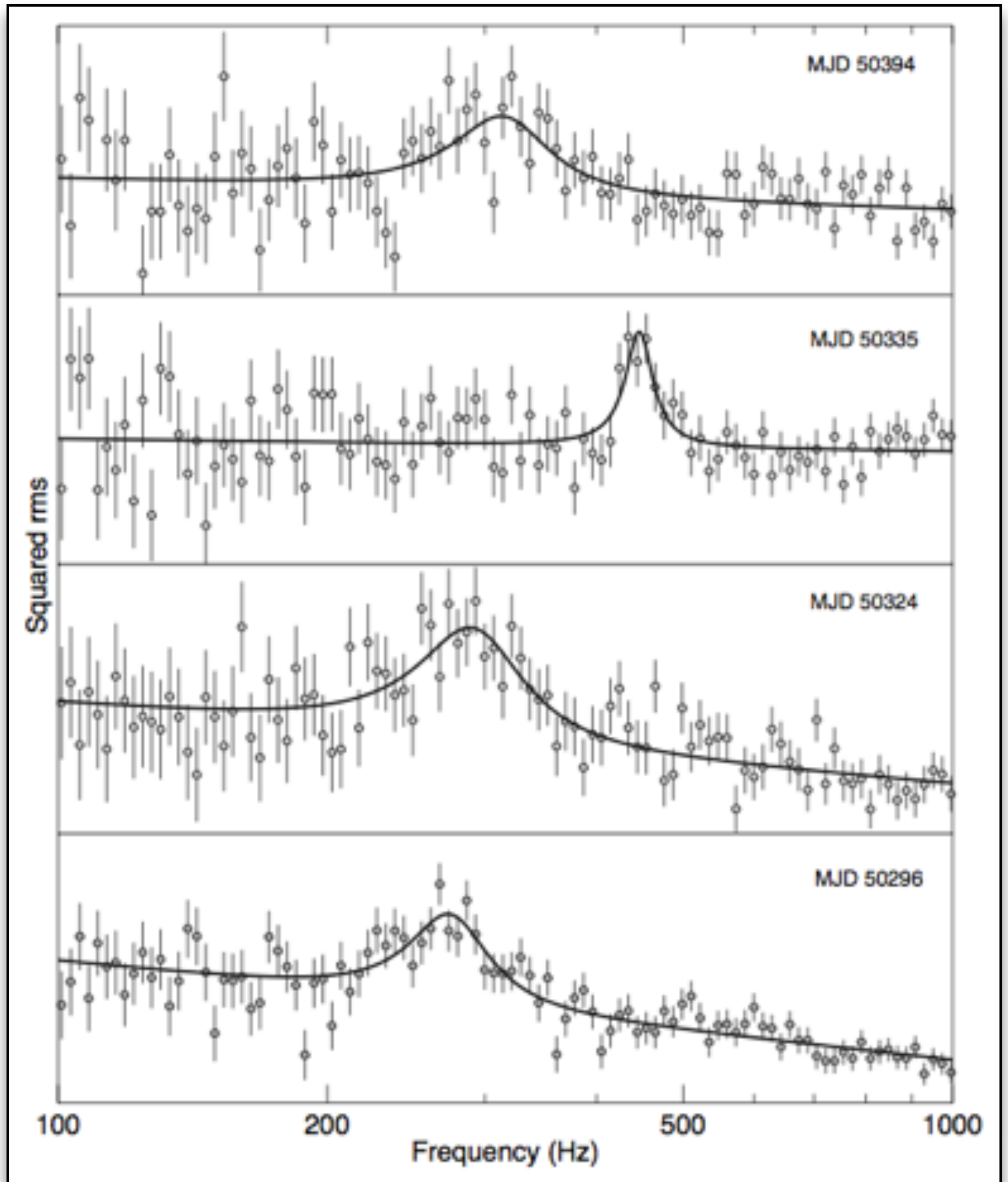
Belloni, Sanna & Méndez (2012)

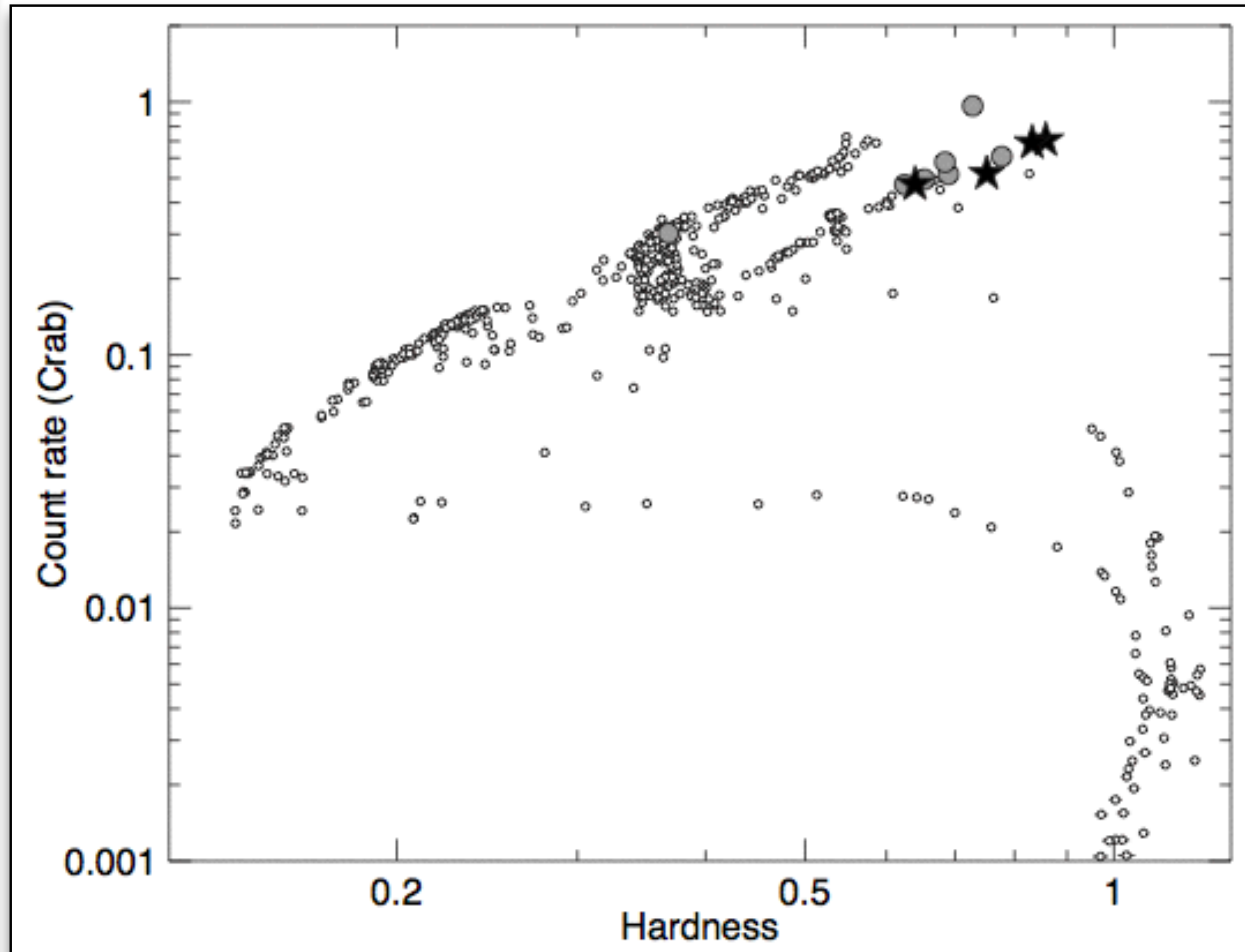




GRO J1655-40

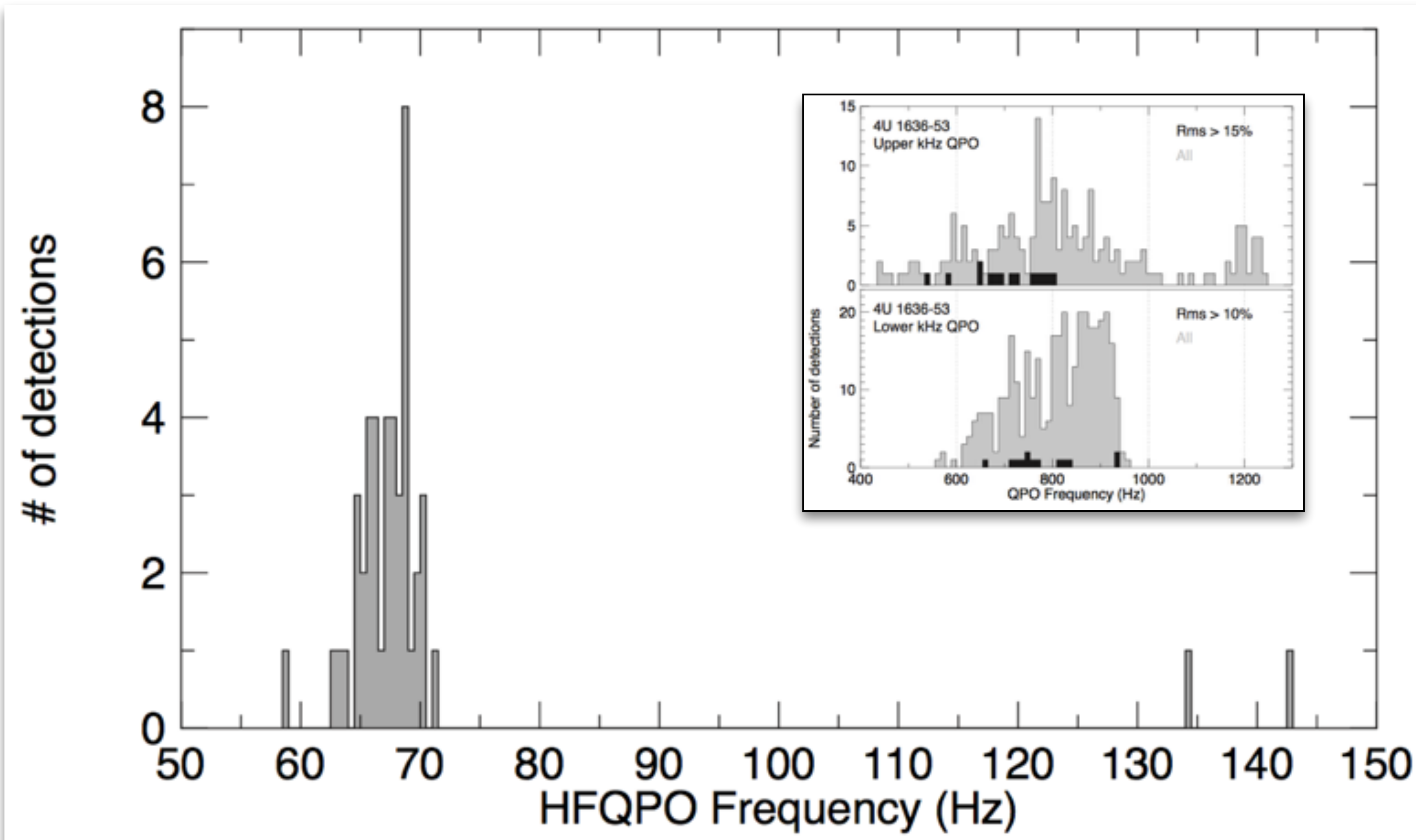
Belloni, Sanna & Méndez (2012)





GRS 1915+105

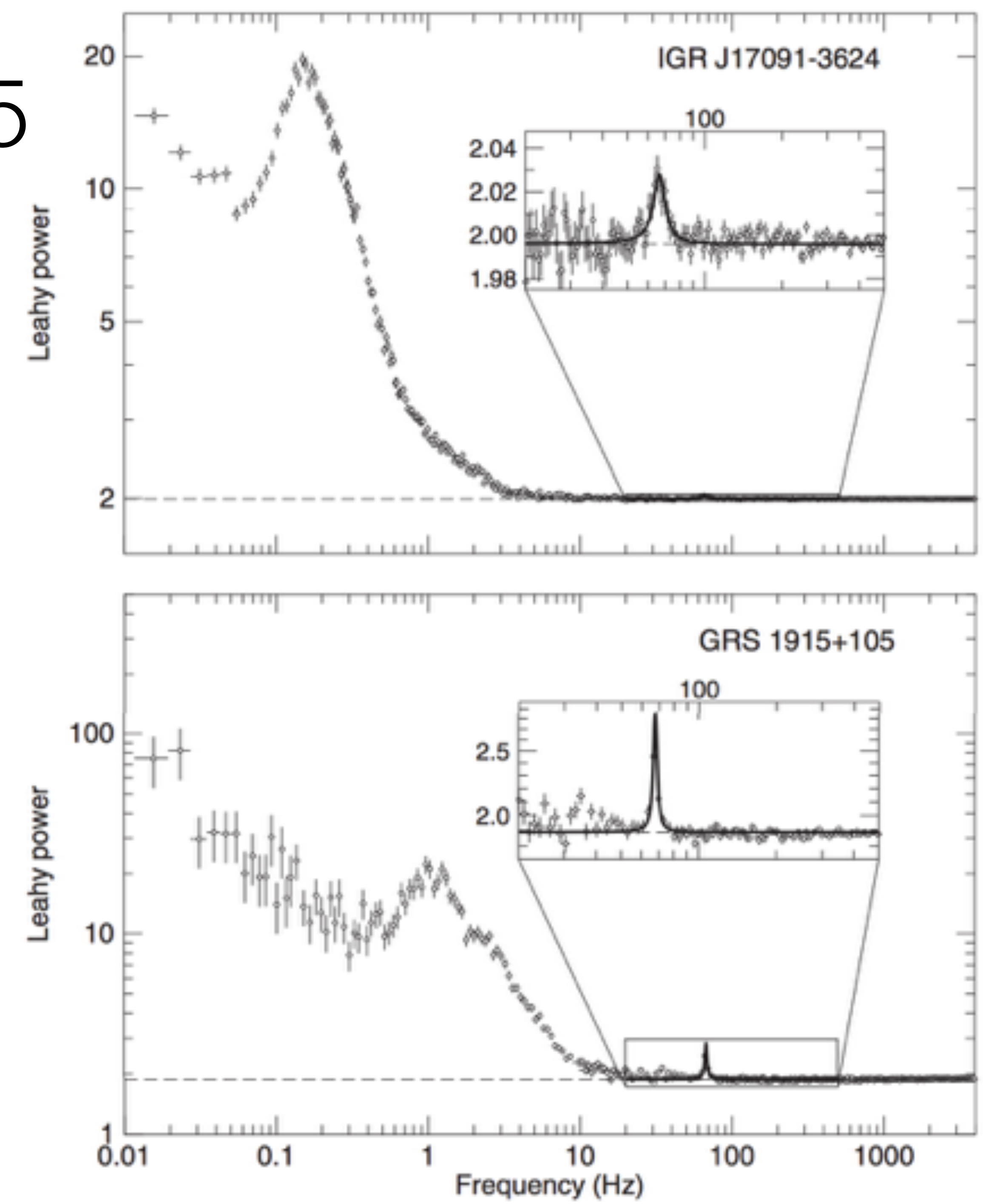
Belloni & Altamirano (2012)



IGR J17091-3624

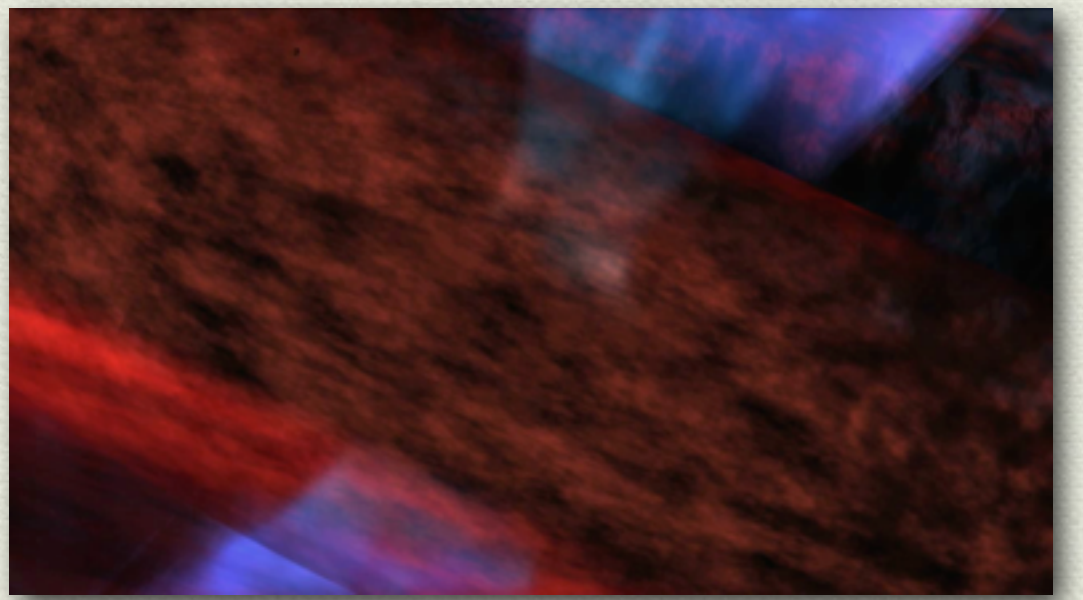
Altamirano & Belloni (2011)

- ☐ Same as GRS 1915+105
- ☐ Lower L_X
- ☐ Lower mass?
- ☐ Exactly 67 Hz



I have a question..

- "What does it all mean?"
- Not minor disturbances
- Frequencies and processes
- General Relativity
- Direct measurements



- The key to physics
- Dirty systems (no pulsar)
- Fifth lecture