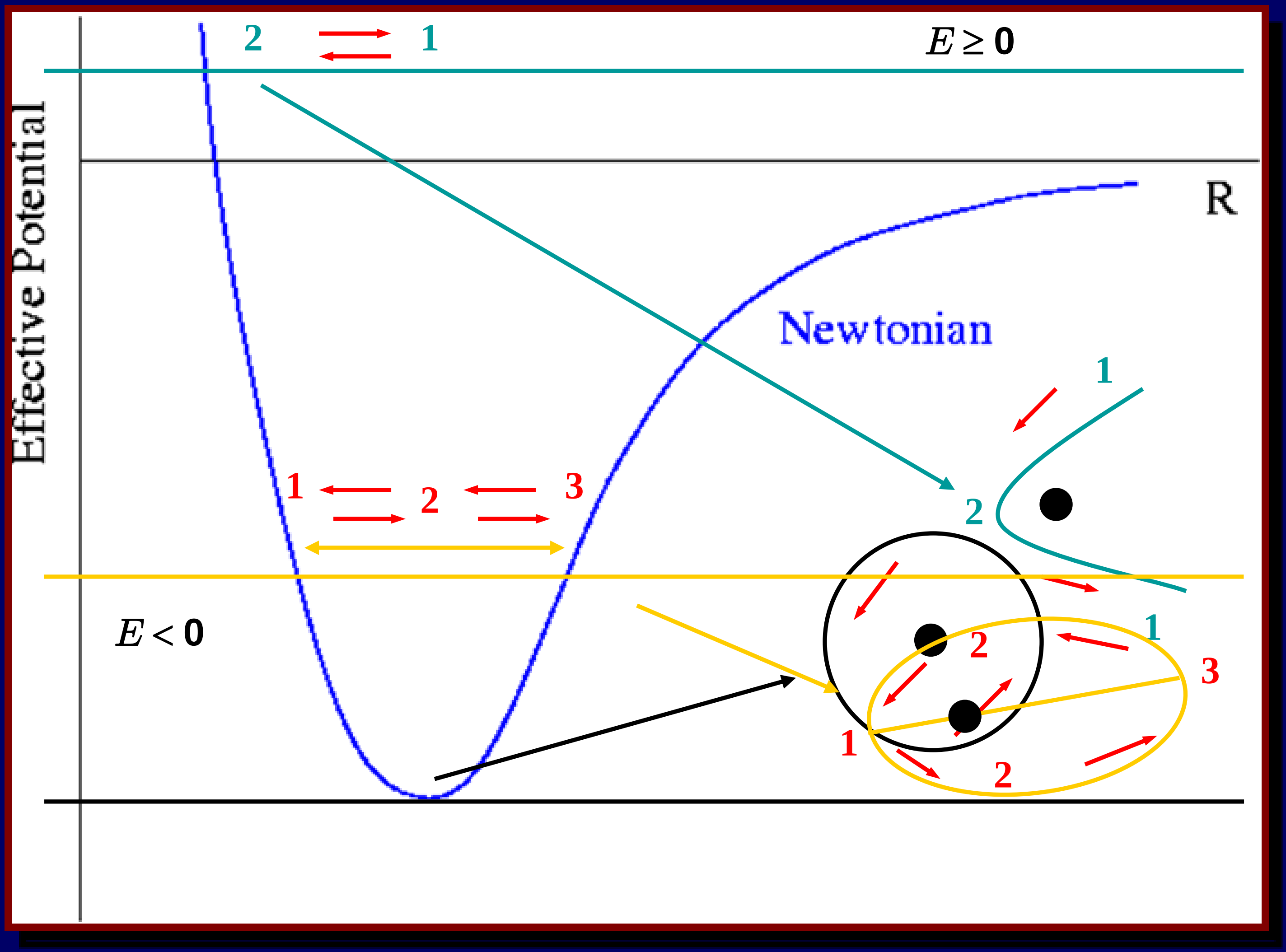
Correlated spectral and timing properties of neutron stars

Mariano Méndez

Kapteyn Astronomical Institute, University of Groningen, The Netherlands

Marginally Stable Orbit (MSO)



$$V_{\text{eff}}(R) = V(R) + \frac{\ell^2}{2mR^2}$$

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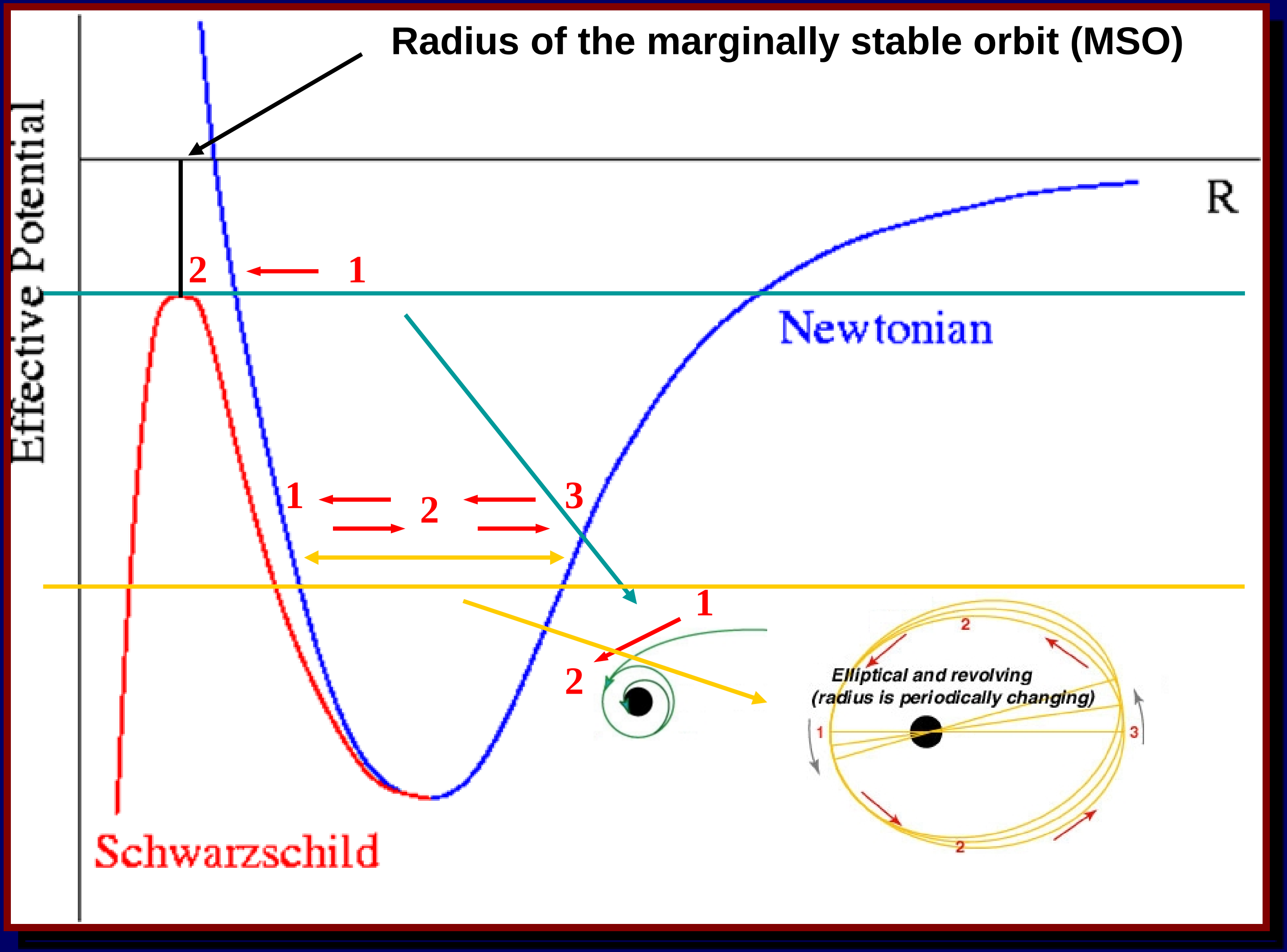
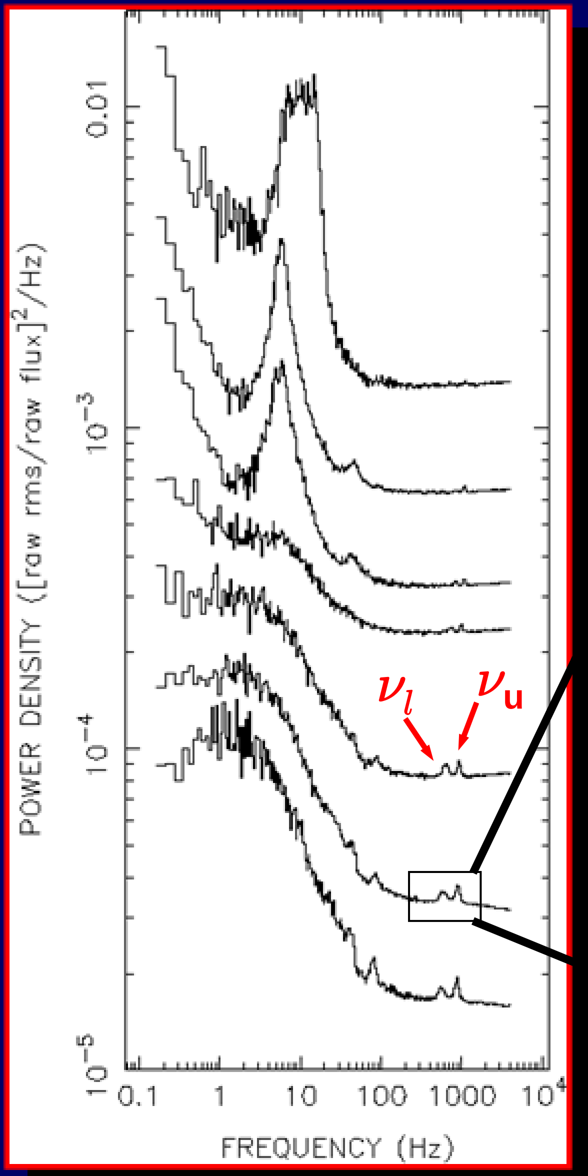
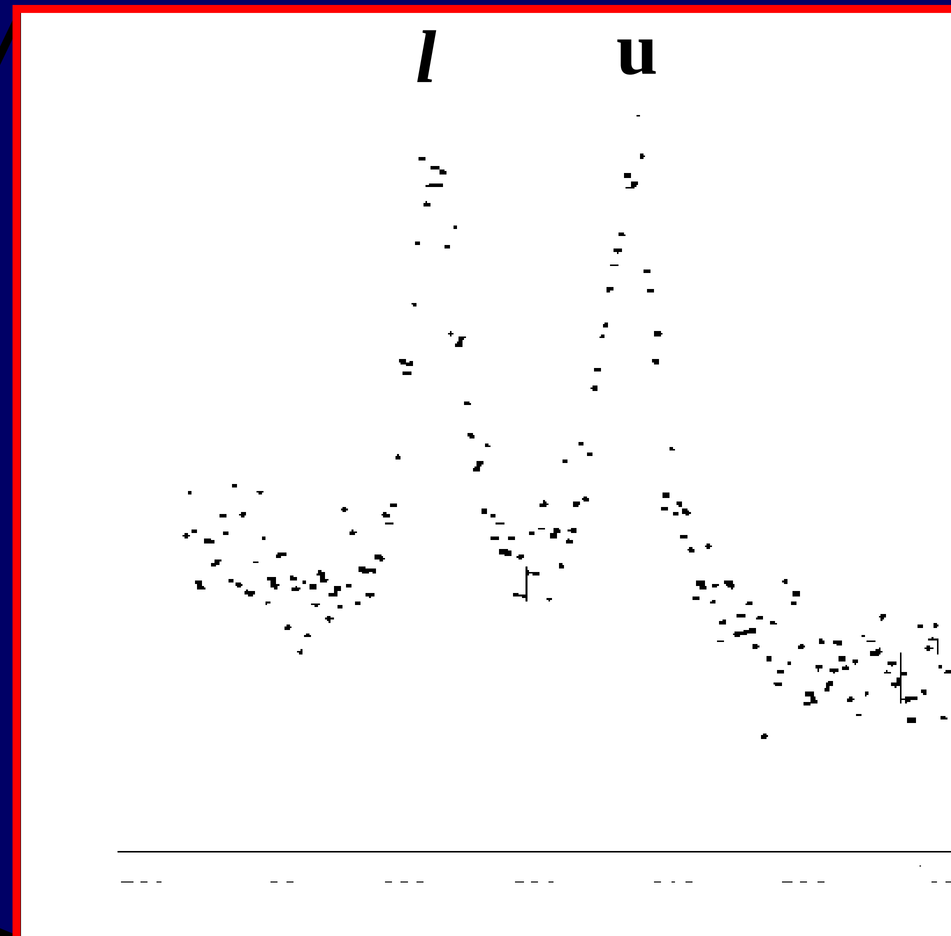


Kilohertz quasi-periodic oscillations (QPOs)

van der Klis et al. 1997



kHz QPOs

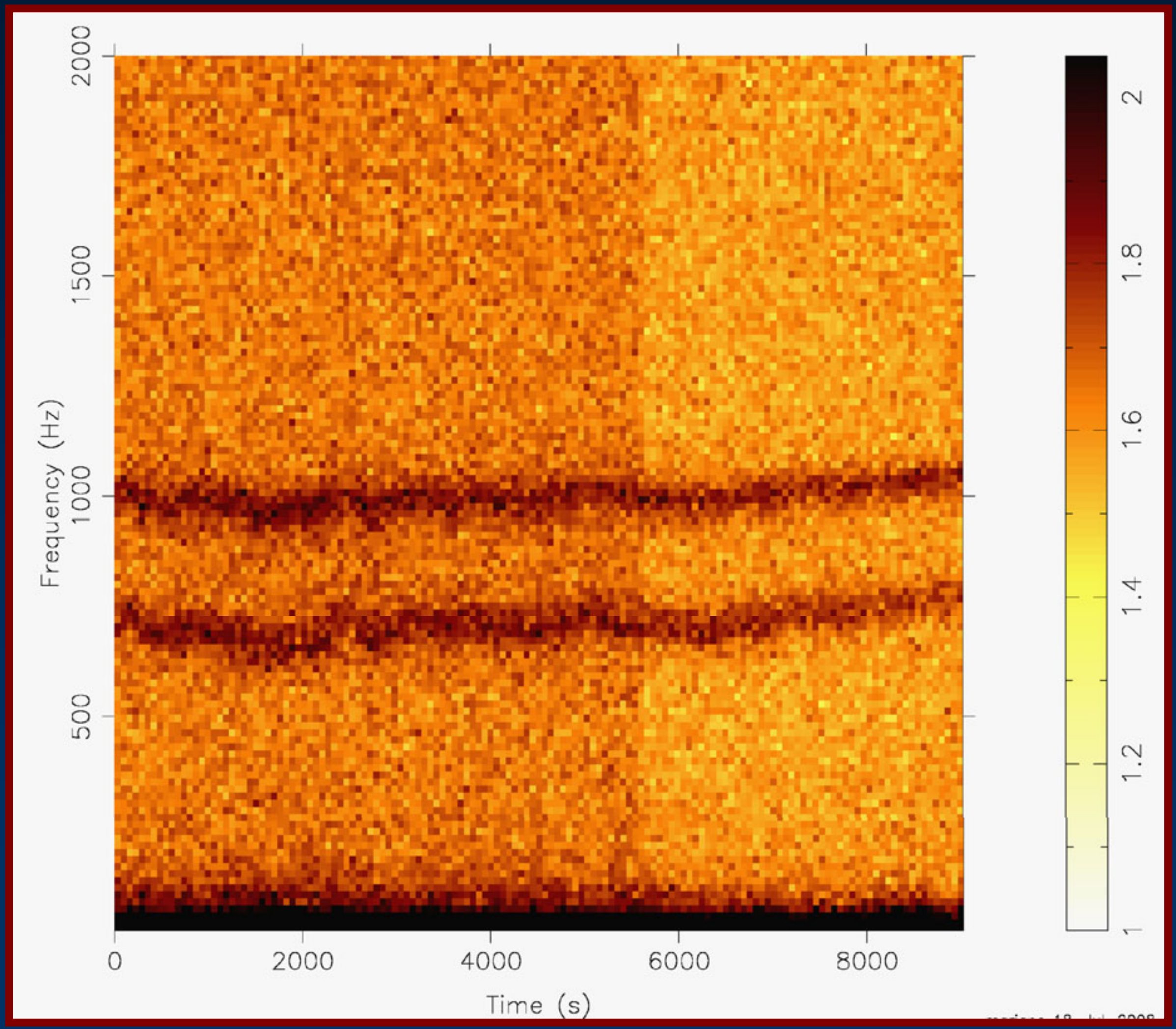


ν_{Kepler} (r=15 km) ≈ 1180 Hz for a 1.4 $M_\odot$ star

The frequencies of the two QPOs change with time.

Sco X–1

Frequency →

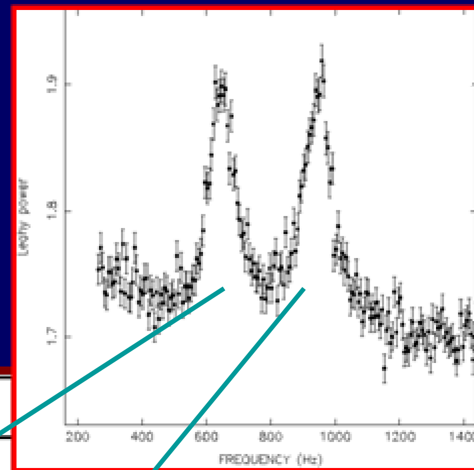


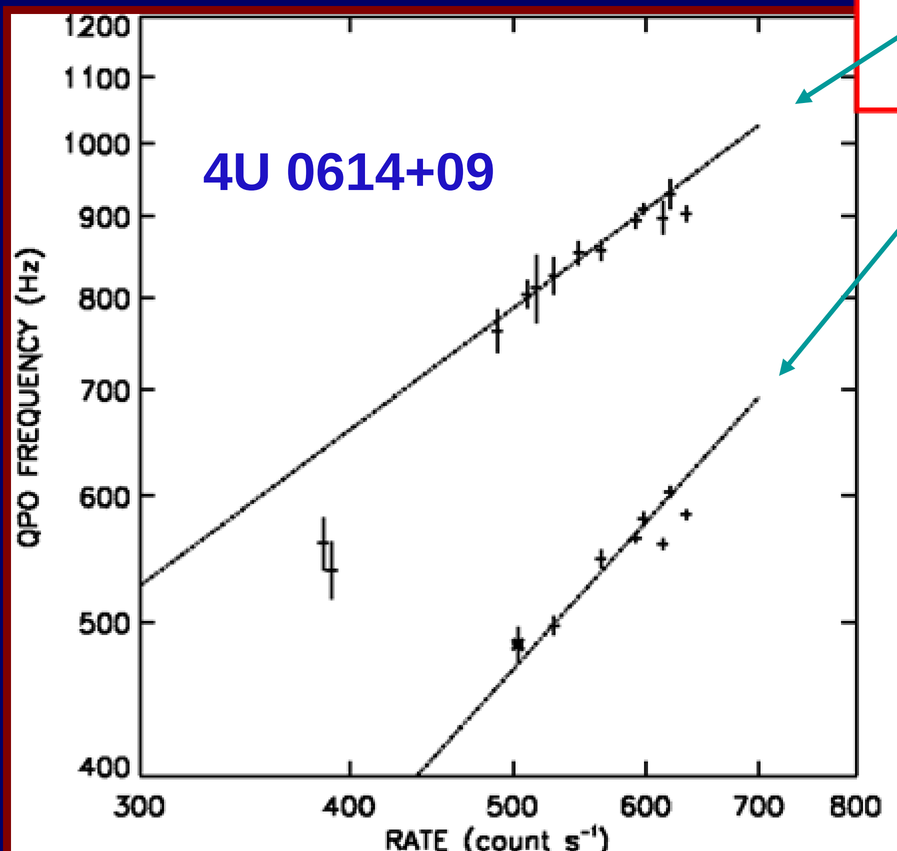
Power scale

Time →

Mendez & van der Klis 2001

Systematic frequency variations

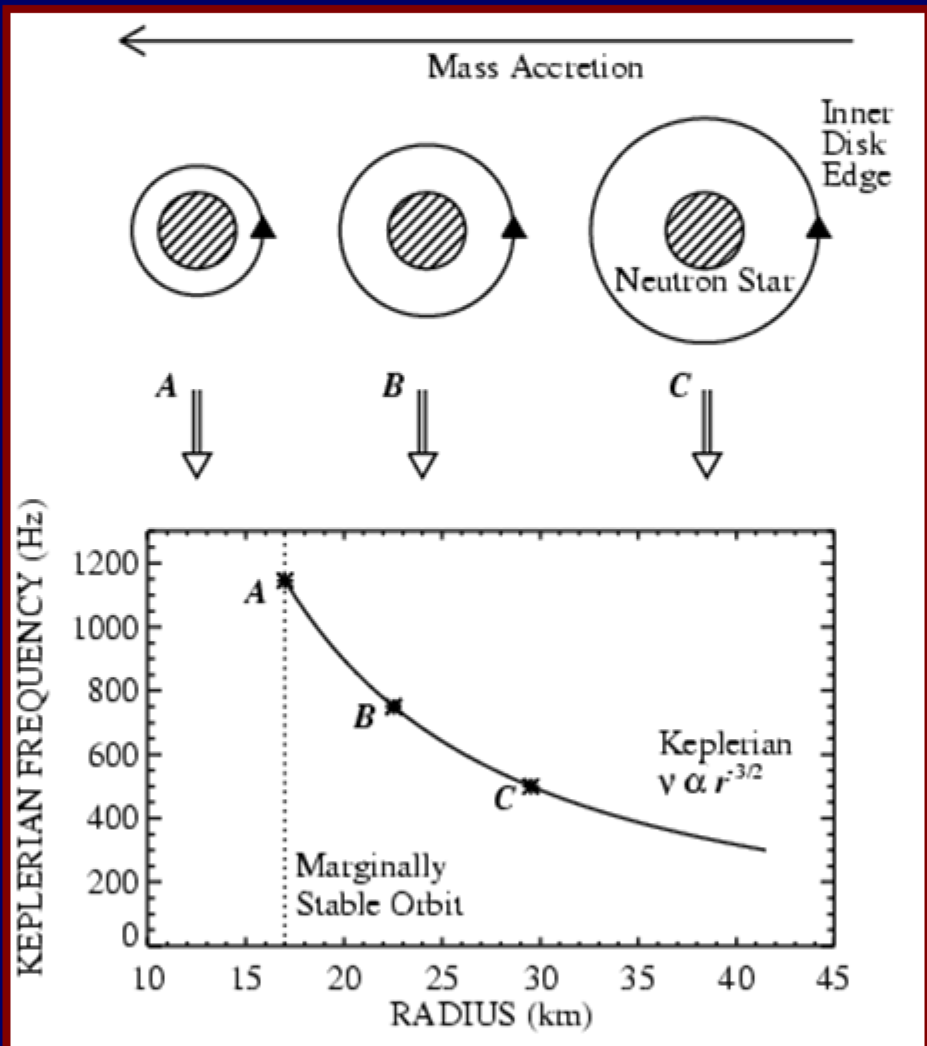




Strohmayer et al. 1996; Ford et al. 1996

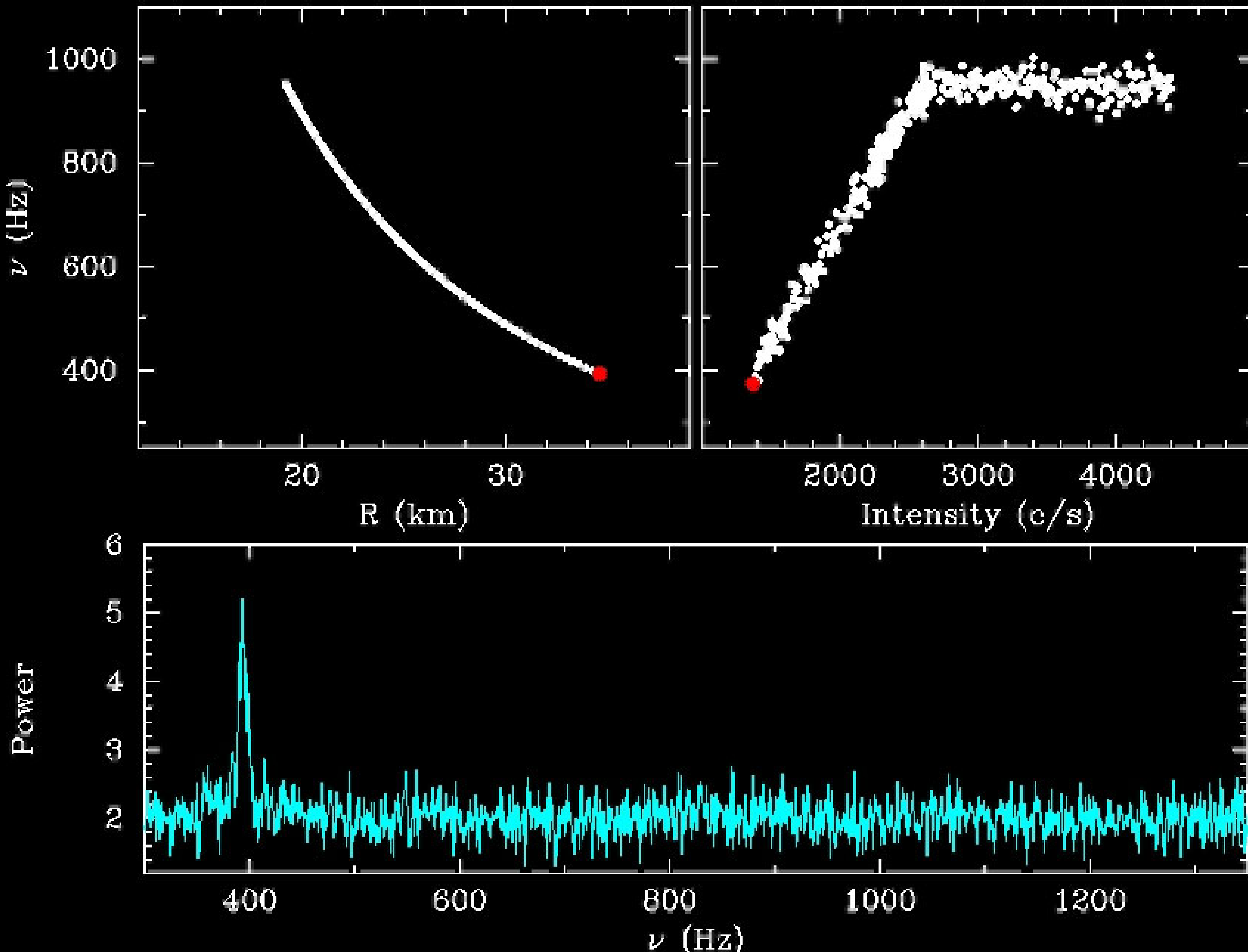
Initial observations suggested the frequencies of the QPOs, ν_l and ν_{u}, were well correlated with the intensity of the source.

Marginally Stable Orbit



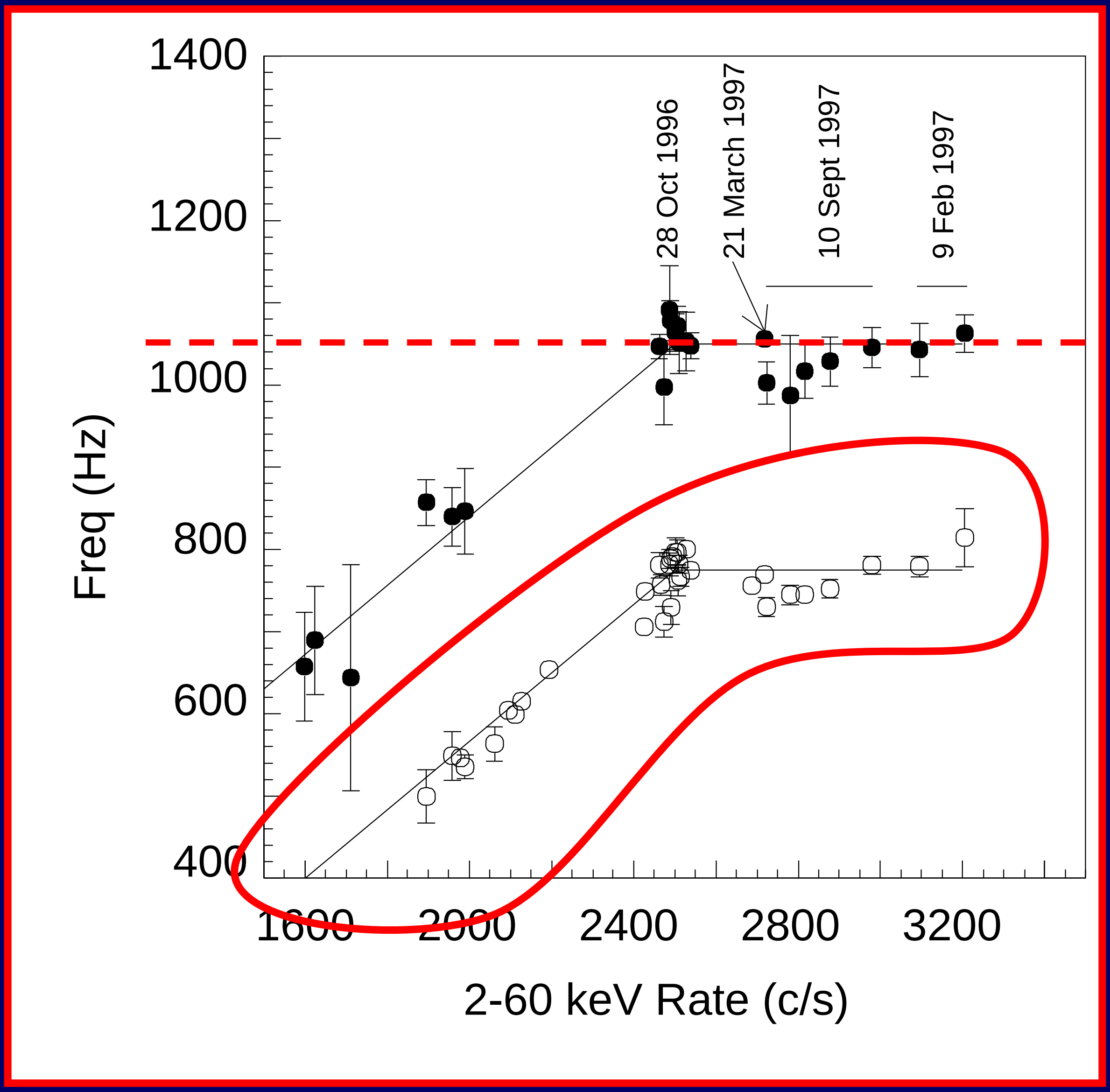
As the radius of the inner edge of the accretion disc decreases, probably driven by the rate of mass accretion through the disc, the orbital frequency at that radius increases.

But this frequency cannot be higher than the Keplerian frequency at the MSO.



ν (Hz)
1000
800
600
400
20
30
R (km)
2000
3000
4000
Intensity (c/s)
Power
6
5
4
3
2
400
600
800
1000
1200
ν (Hz)

MSO: Observational evidence?

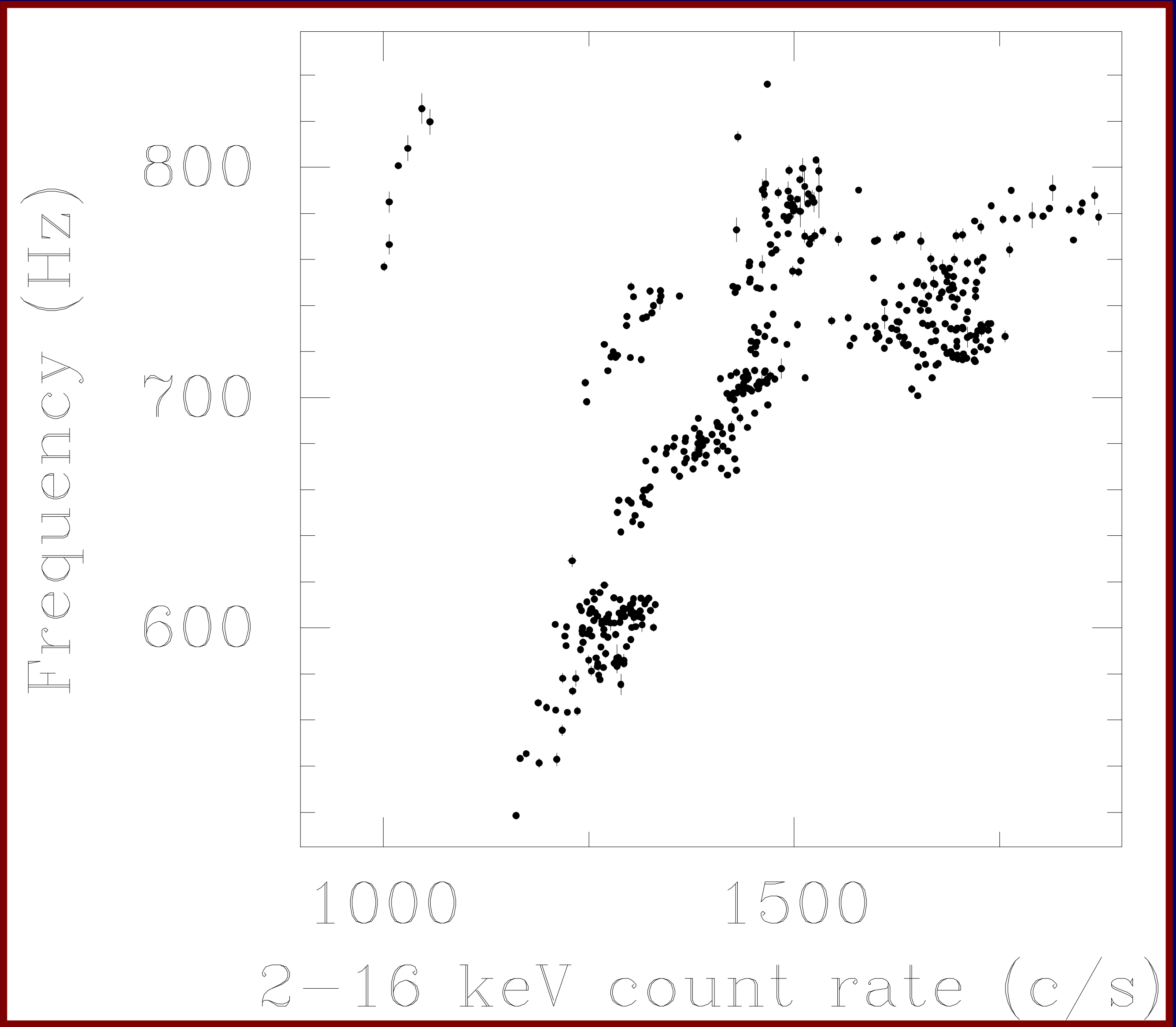


ν_{MSO}

Zhang et al. 1998

4U 1820–30

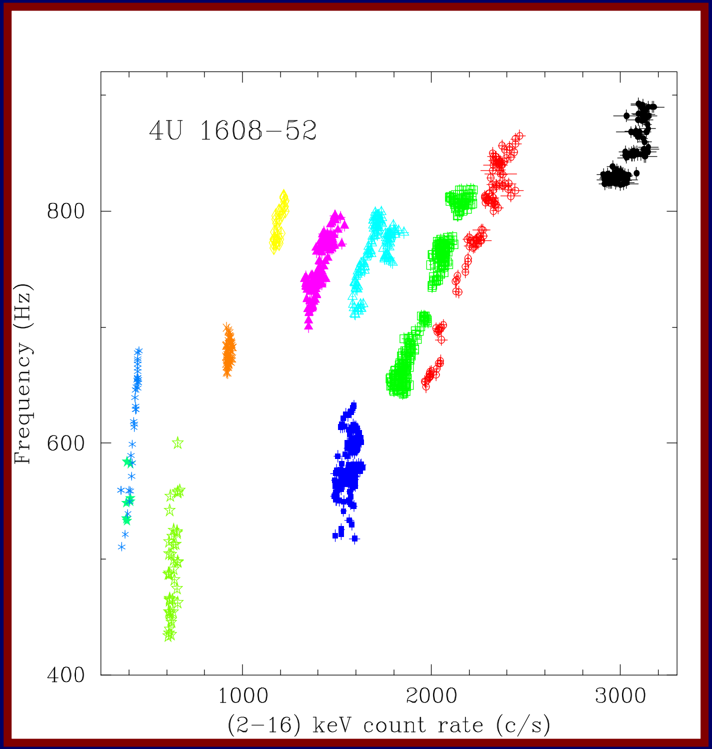
Detailed view

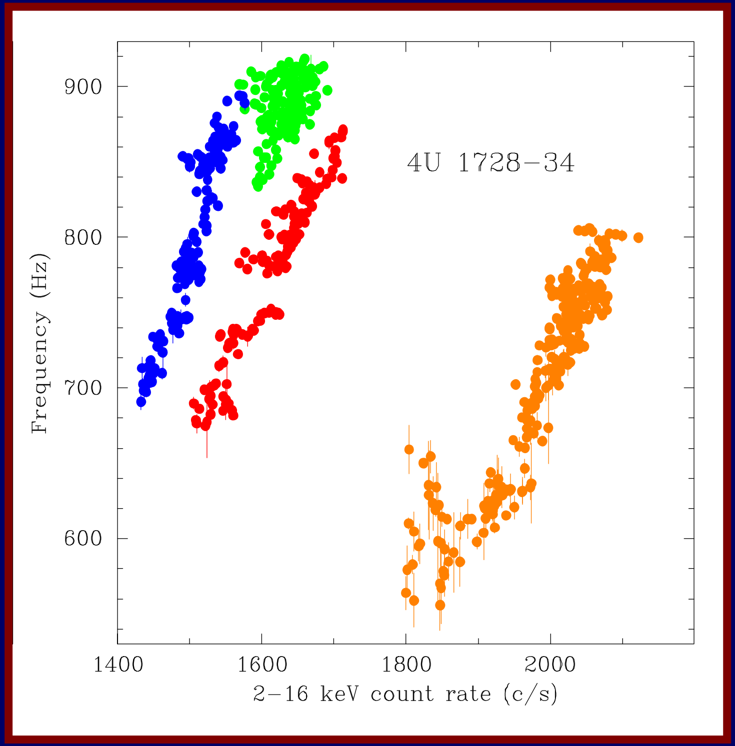


Mendez 2000

4U 1820–30

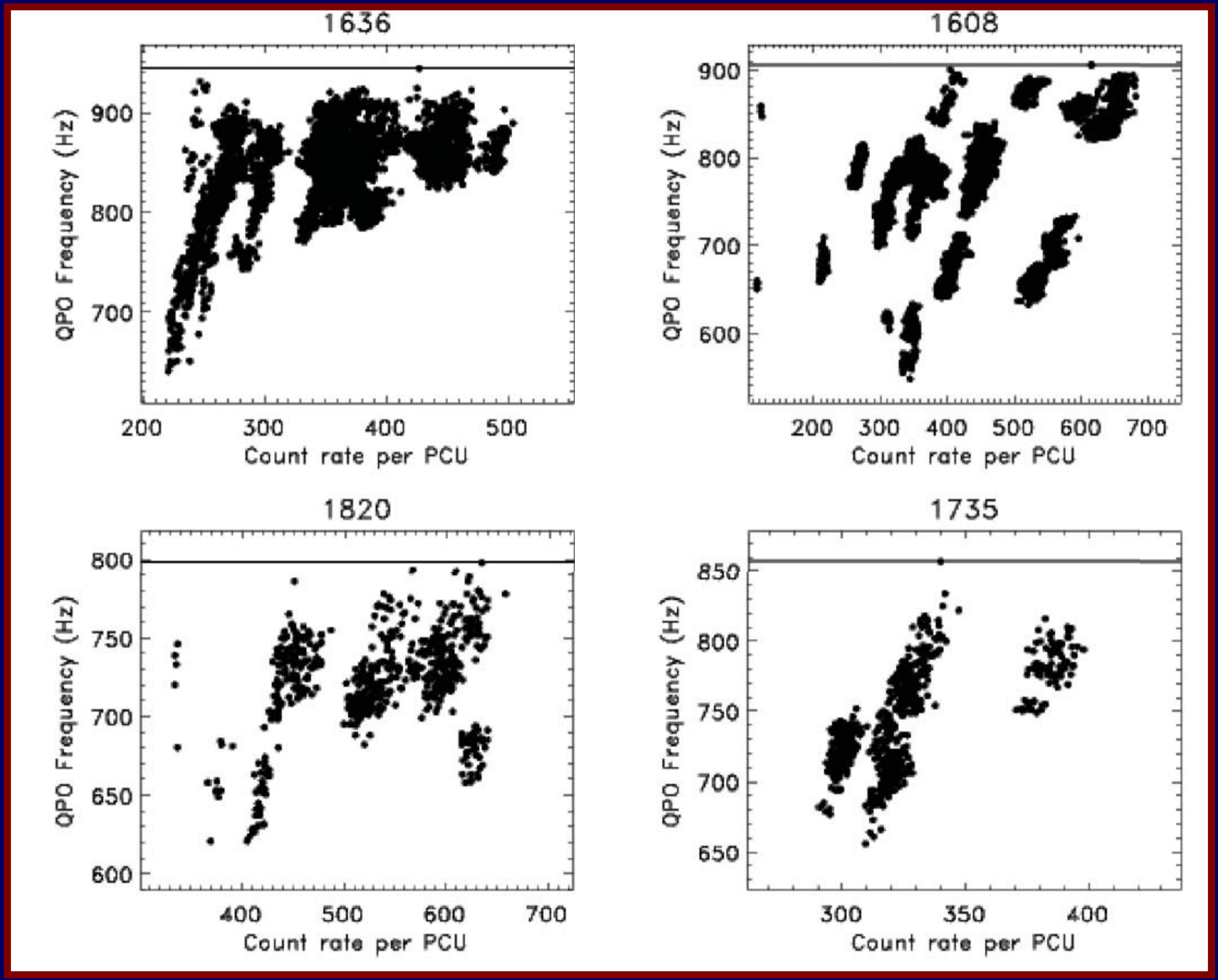
“Parallel Tracks”





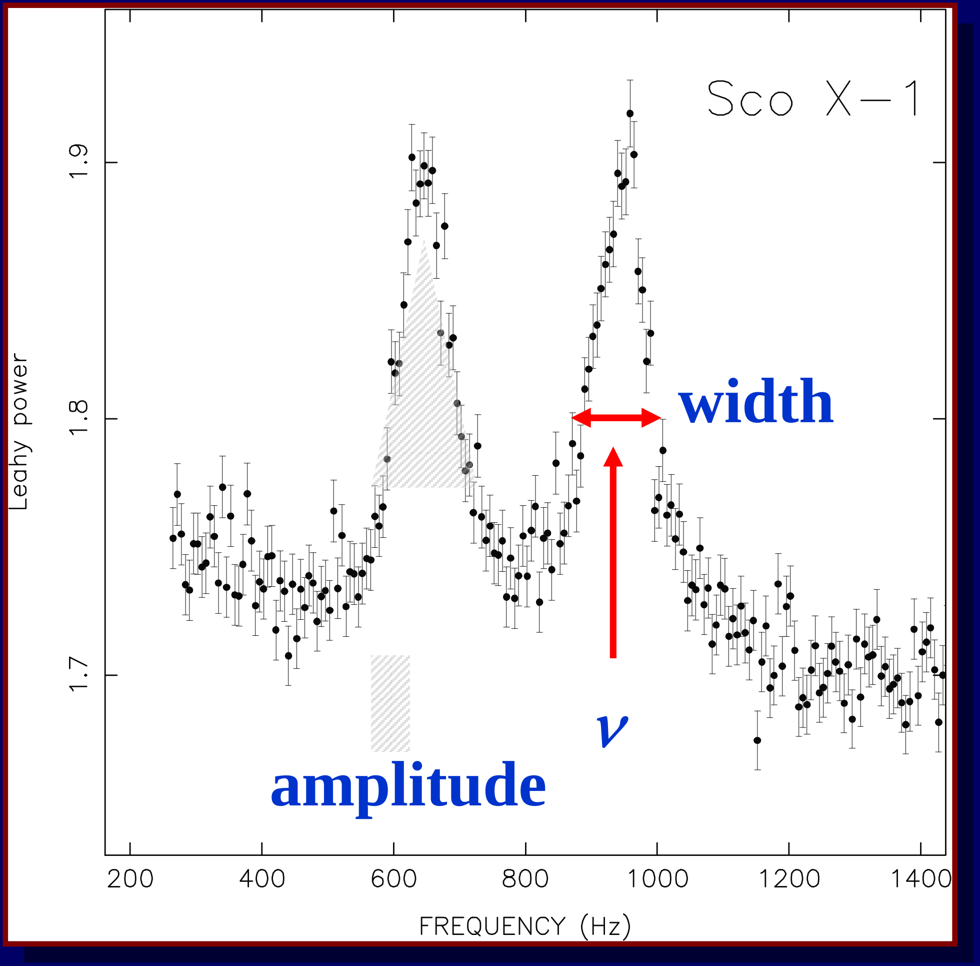
Mendez et al. 1998; Mendez & van der Klis 1999

MSO: Upper frequency bound?



Barret et al. 2005,2006

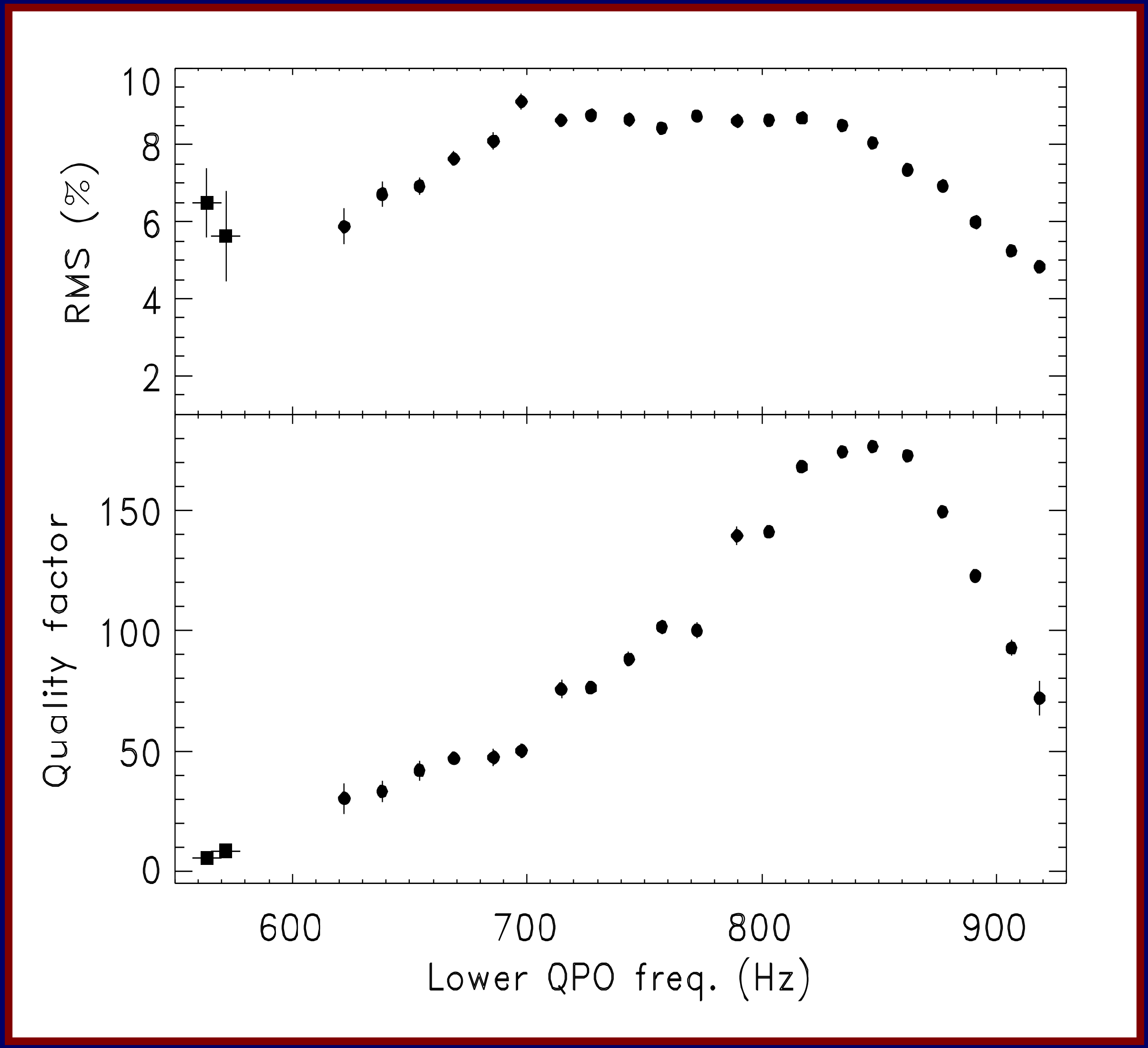
The other properties of the (kHz) QPOs



- Either width (≡ FWHM) or coherence ($Q = \nu$ / FWHM; a.k.a. Quality Factor)

- Amplitude (% rms ≡ r)

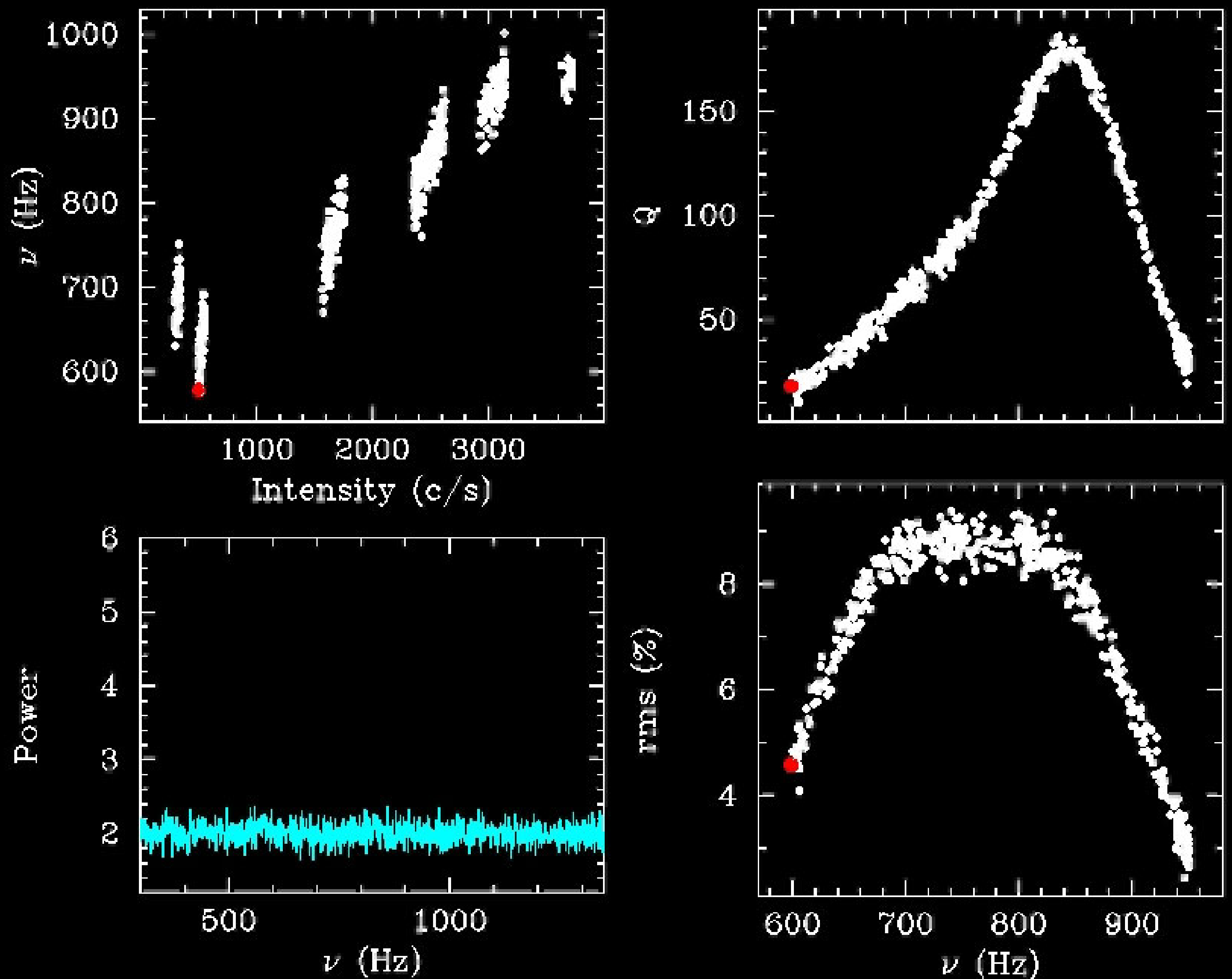
Drop of *Q* and rms at high frequencies: MSO?



4U 1636–53

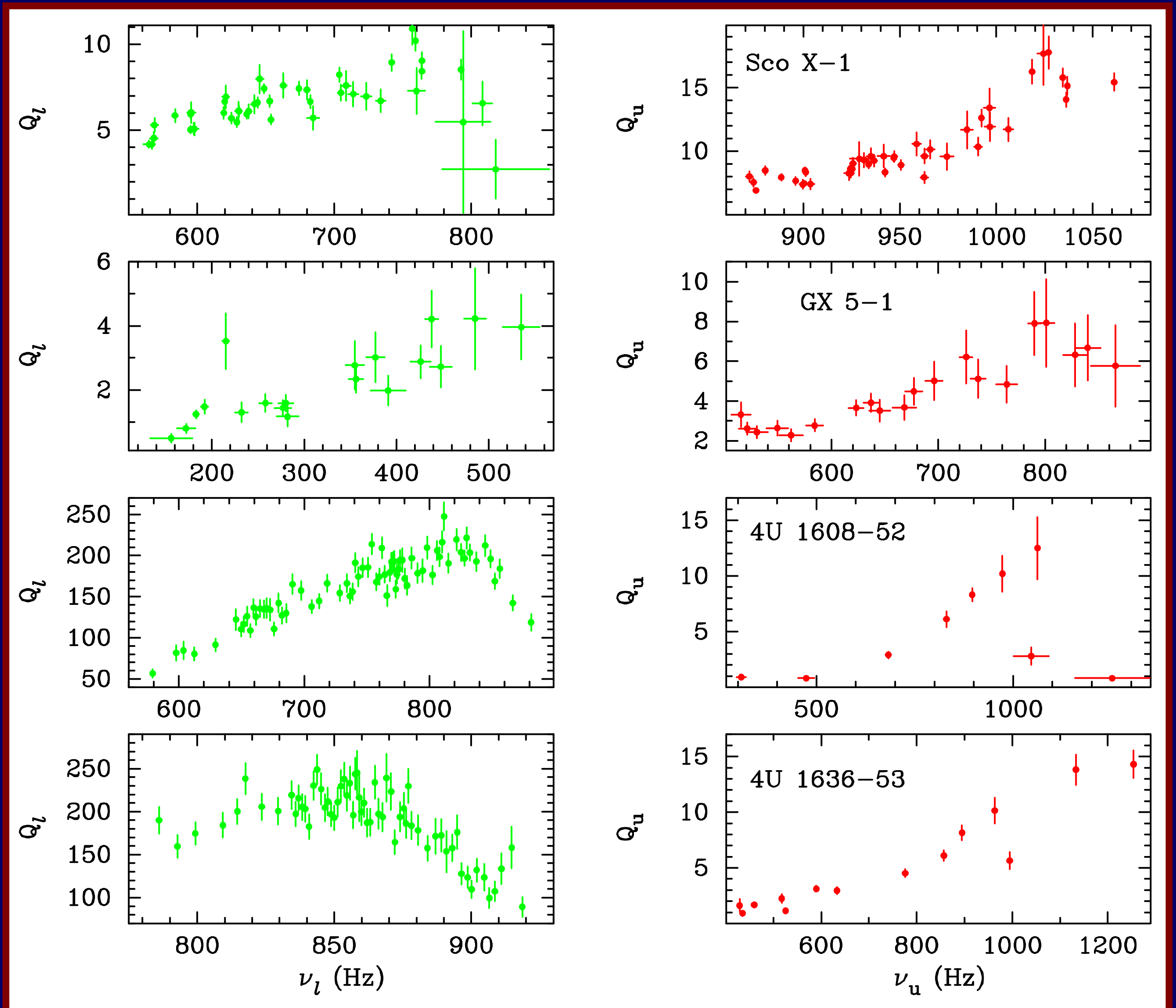
Barret et al. 2005,2006

also Di Salvo et al. 2001, 2003; Mendez et al 2001; van Straaten et al. 2002, 2003



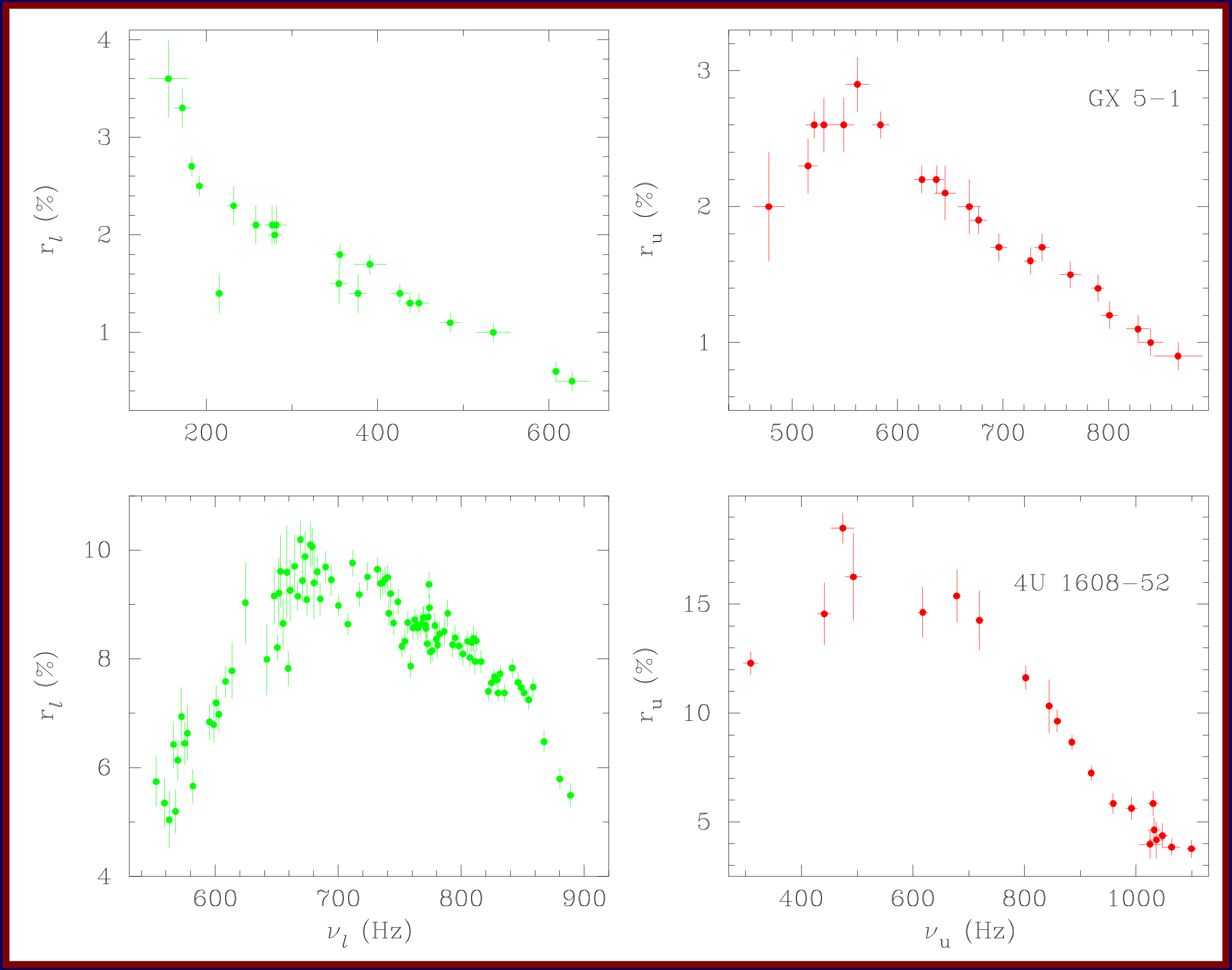
1000
900
800
700
600
ν (Hz)
1000
2000
3000
Intensity (c/s)
150
100
50
Q
6
5
4
3
2
Power
500
1000
ν (Hz)
8
6
4
rms (%)
600
700
800
900
ν (Hz)

Coherence of the kHz QPOs across sources



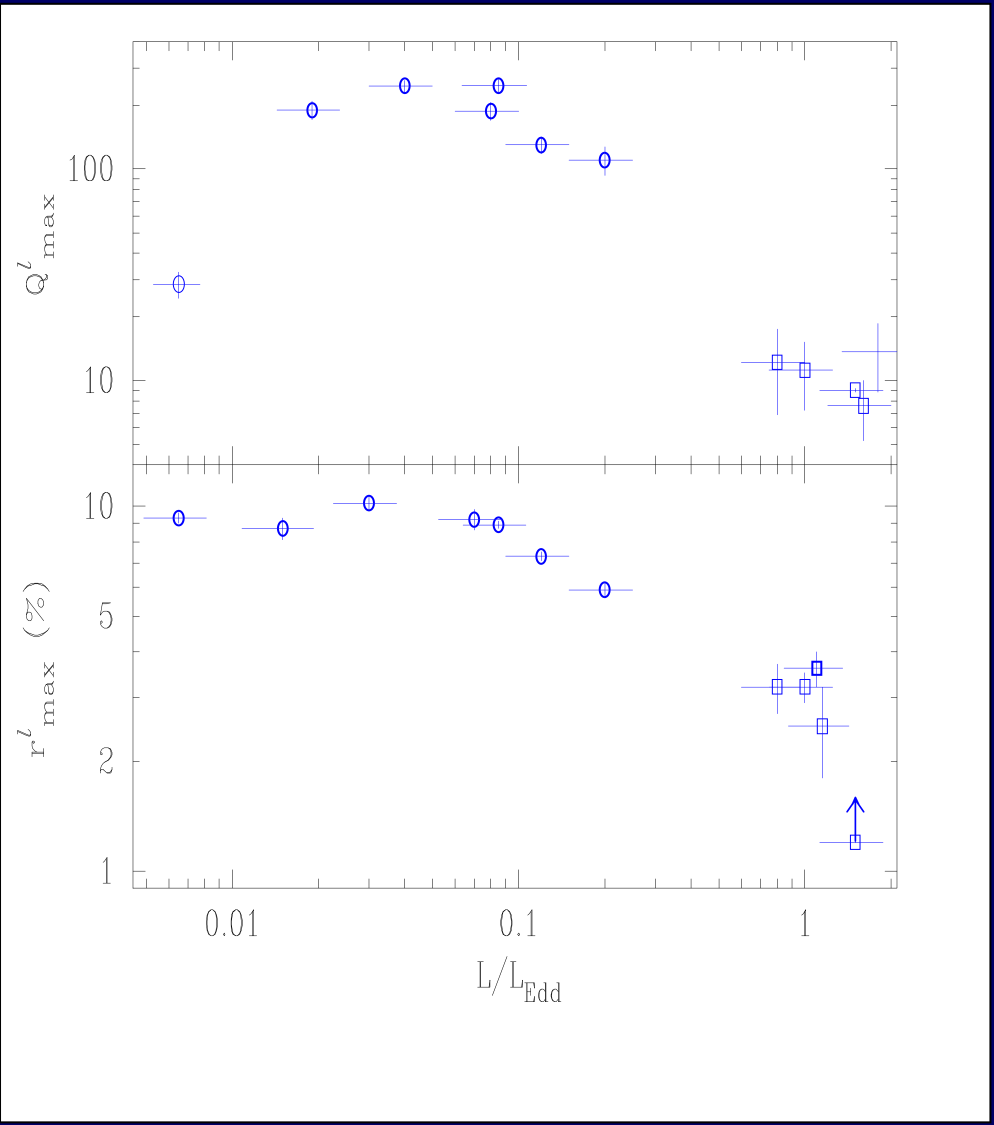
van der Klis et al. 1997; Jonker et al. 2000; Mendez et al. 2001; Di Salvo et al. 2003

Amplitude of the kHz QPOs across sources



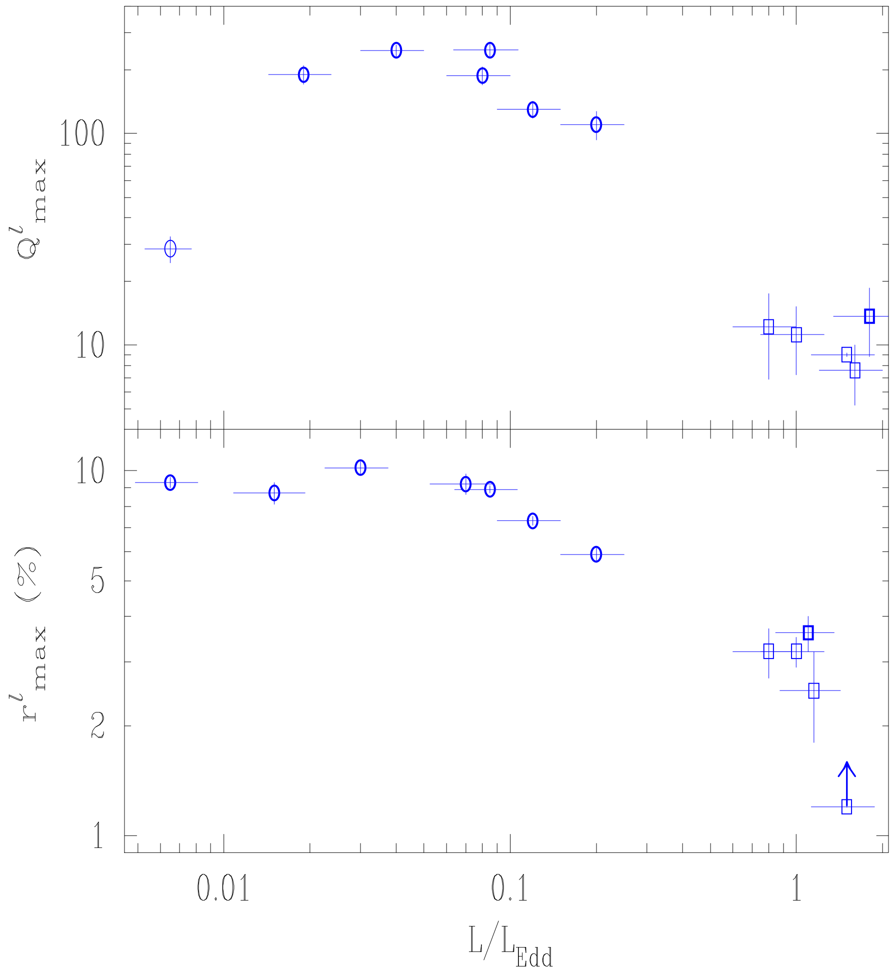
Jonker et al. 2000; Mendez et al. 2001

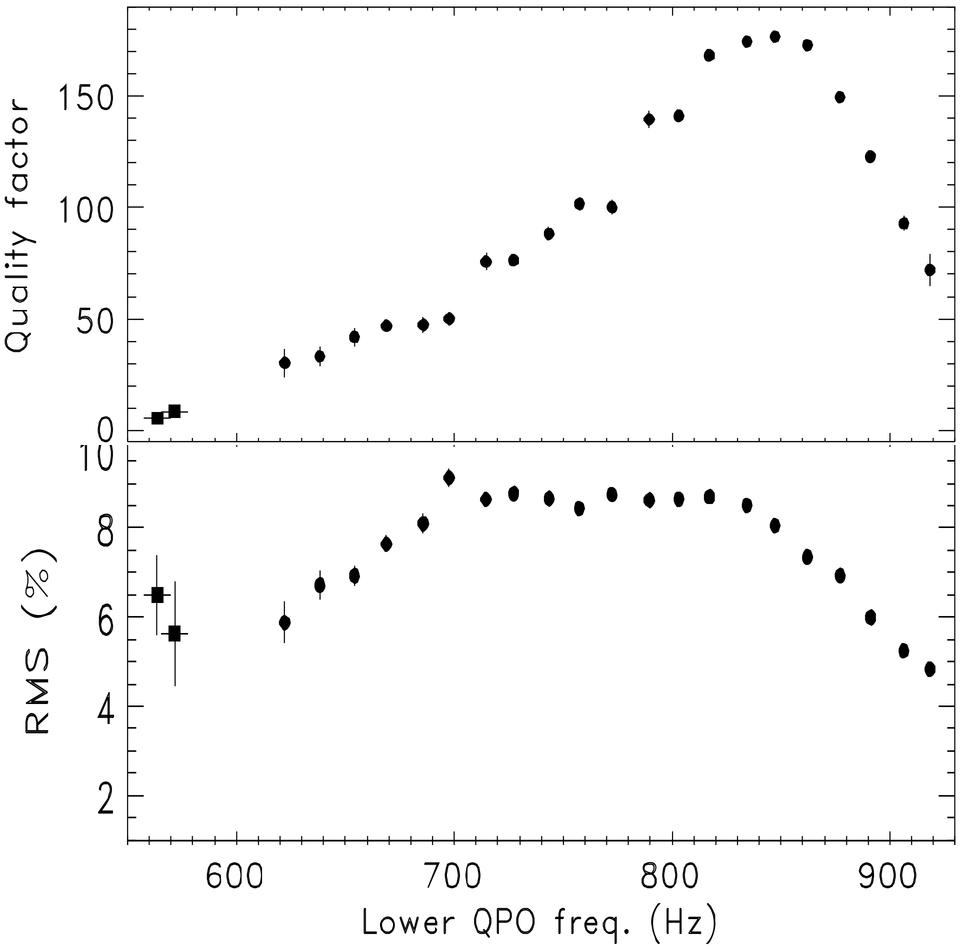
Max. *Q* and *rms* of the kHz QPOs across sources



Mendez 2006

Q and rms of the kHz QPOs across sources

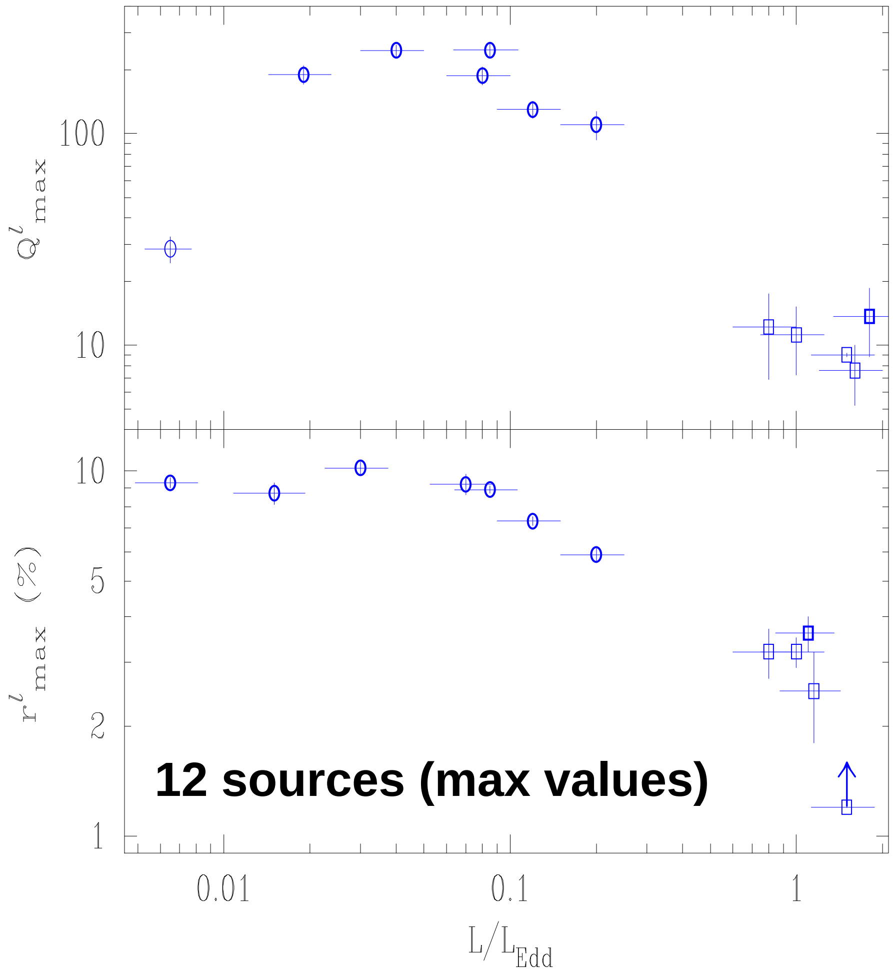


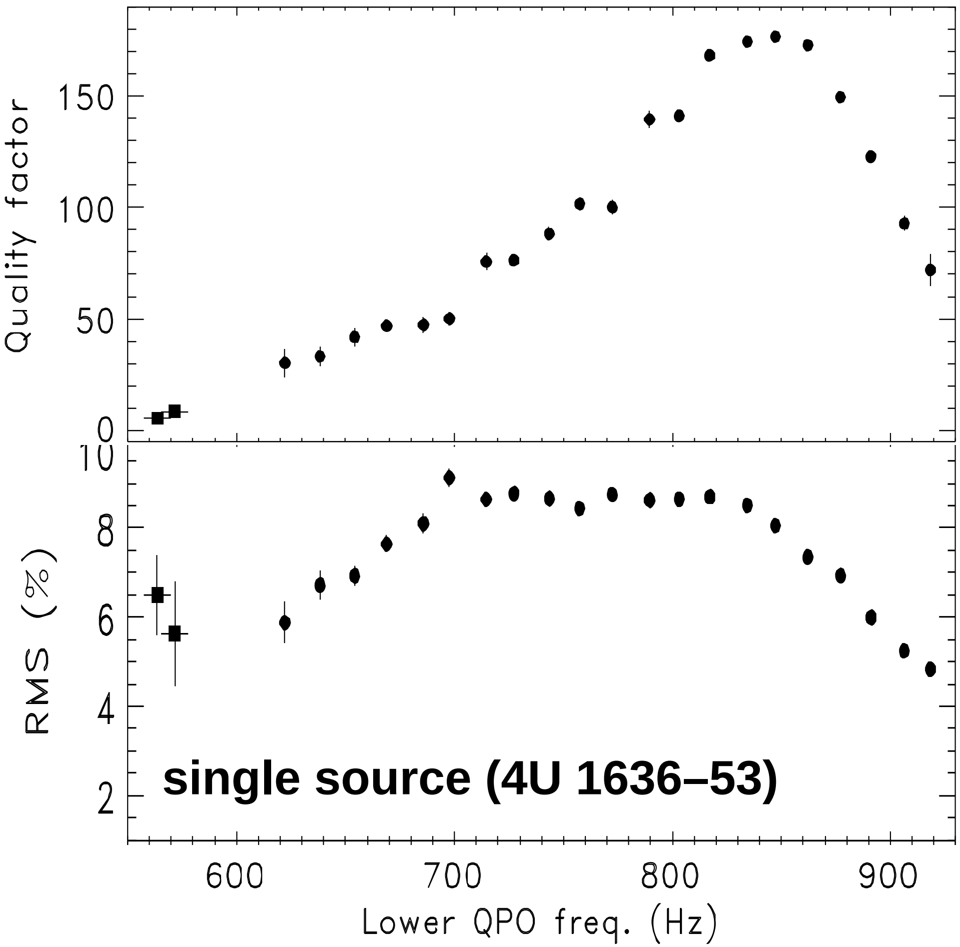


Mendez 2006

Barret et al. 2006

Q and *rms* of the kHz QPOs across sources

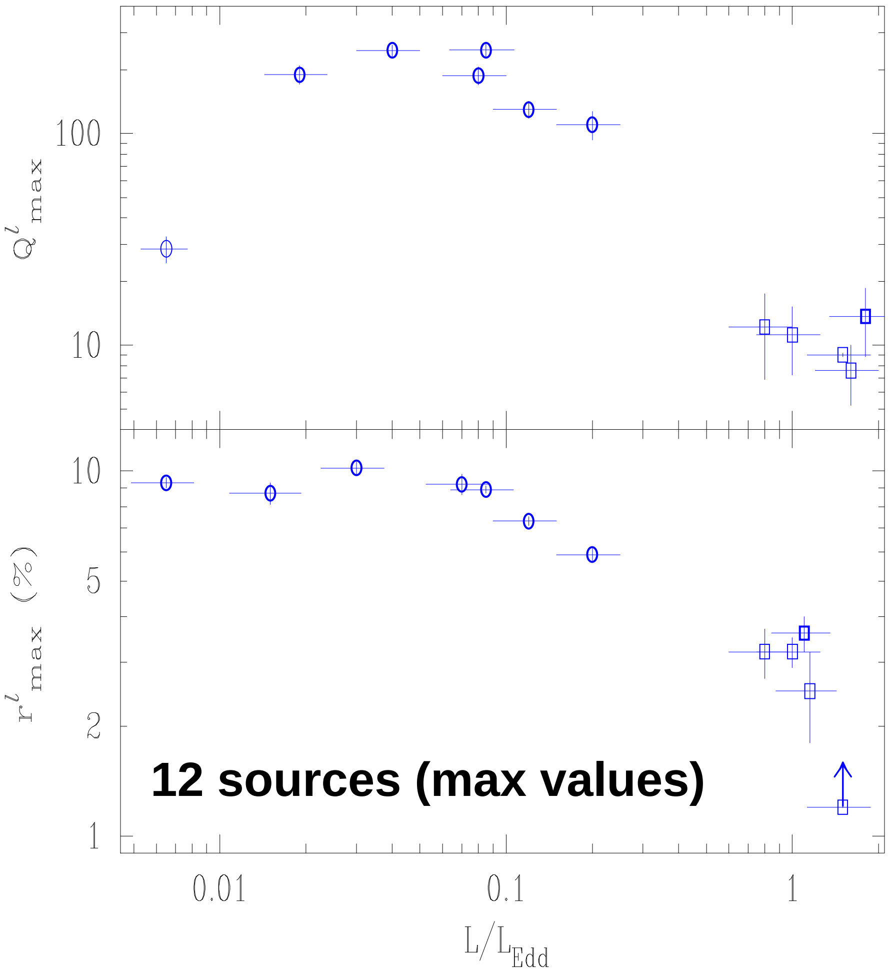


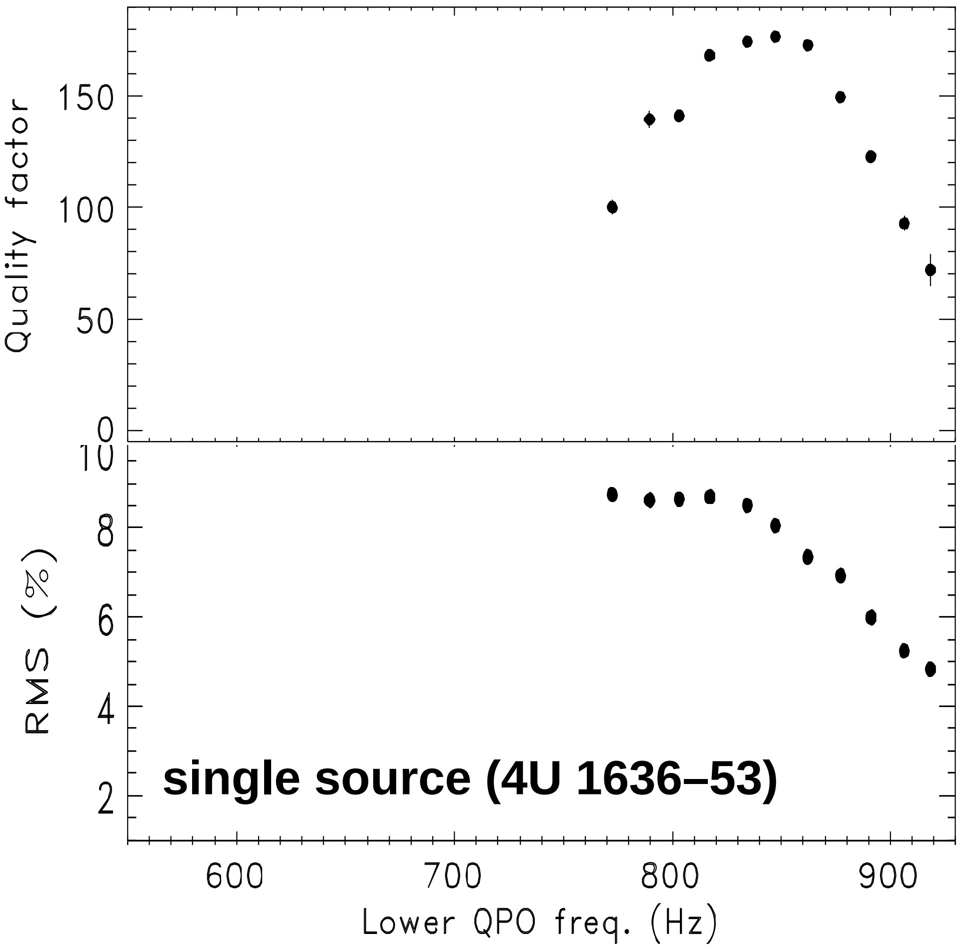


Mendez 2006

Barret et al. 2006

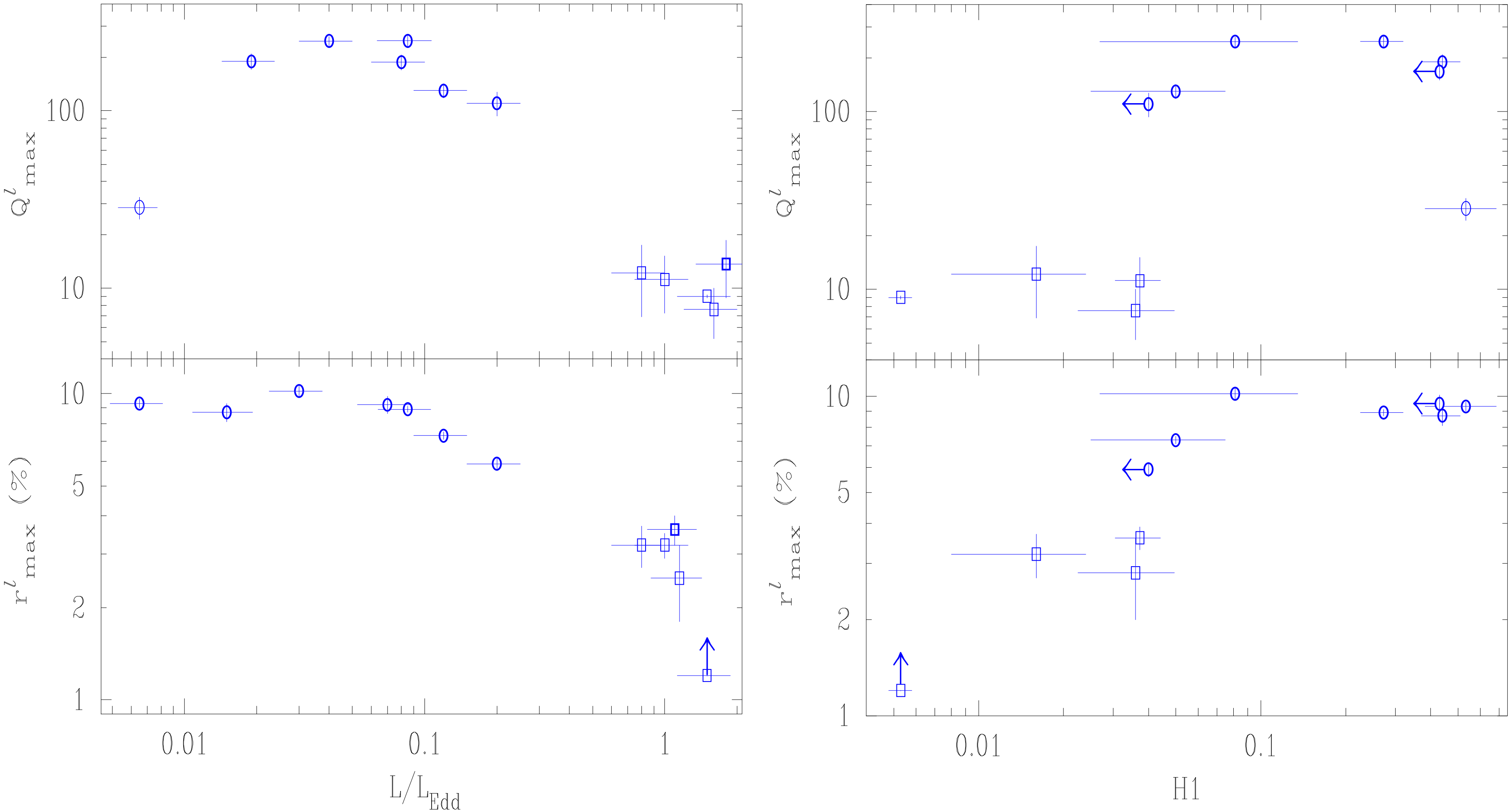
Q and *rms* of the kHz QPOs across sources





Mendez 2006 *Barret et al. 2006*

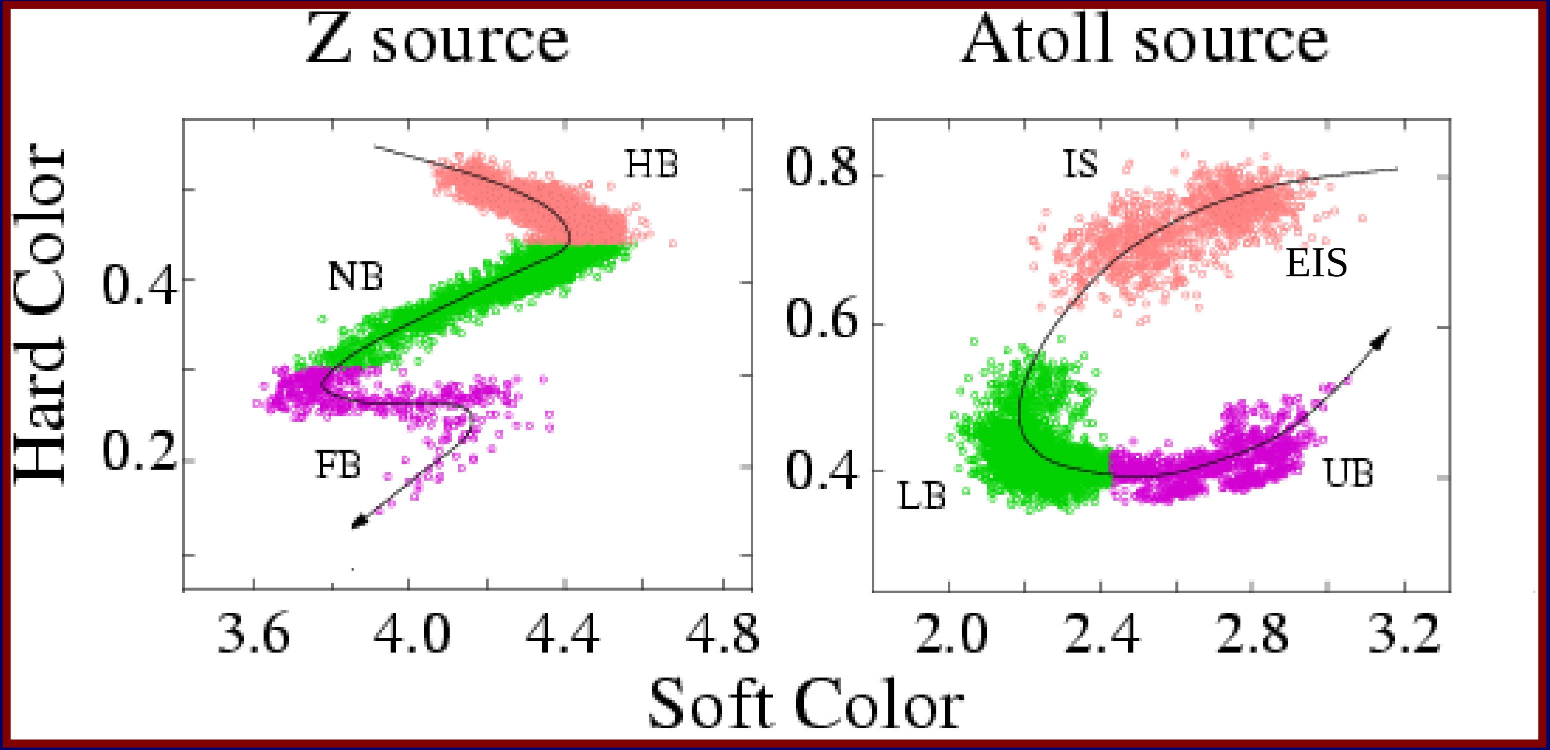
Q and *rms* of the kHz QPOs across sources



$I_{40–80\ keV} / I_{13–25\ keV}$

Mendez 2006

About Z's and Atolls



Hasinger & van der Klis 1989

Individual sources vs. the population: Similar mechanism?

Individual sources:

- QPO coherence and amplitude drop at high QPO frequencies.
  - Higher frequencies generally imply source is brighter
  - Sources become softer as they become brighter.

→ *QPO coherence and amplitude drop when the source becomes brighter and softer.*

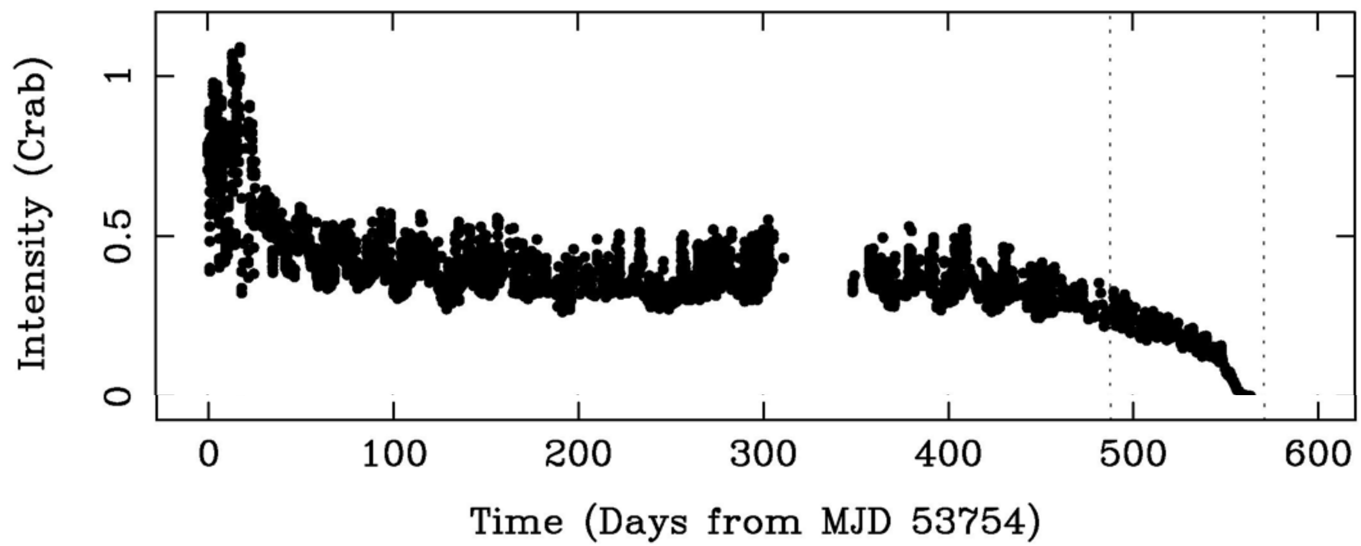
The population of sources:

- Maximum QPO coherence and amplitude drop in brighter sources.
  - Brighter sources (Z) are softer than weaker sources (Atoll).

→ *Maximum QPO coherence and amplitude drop for bright and soft sources.*

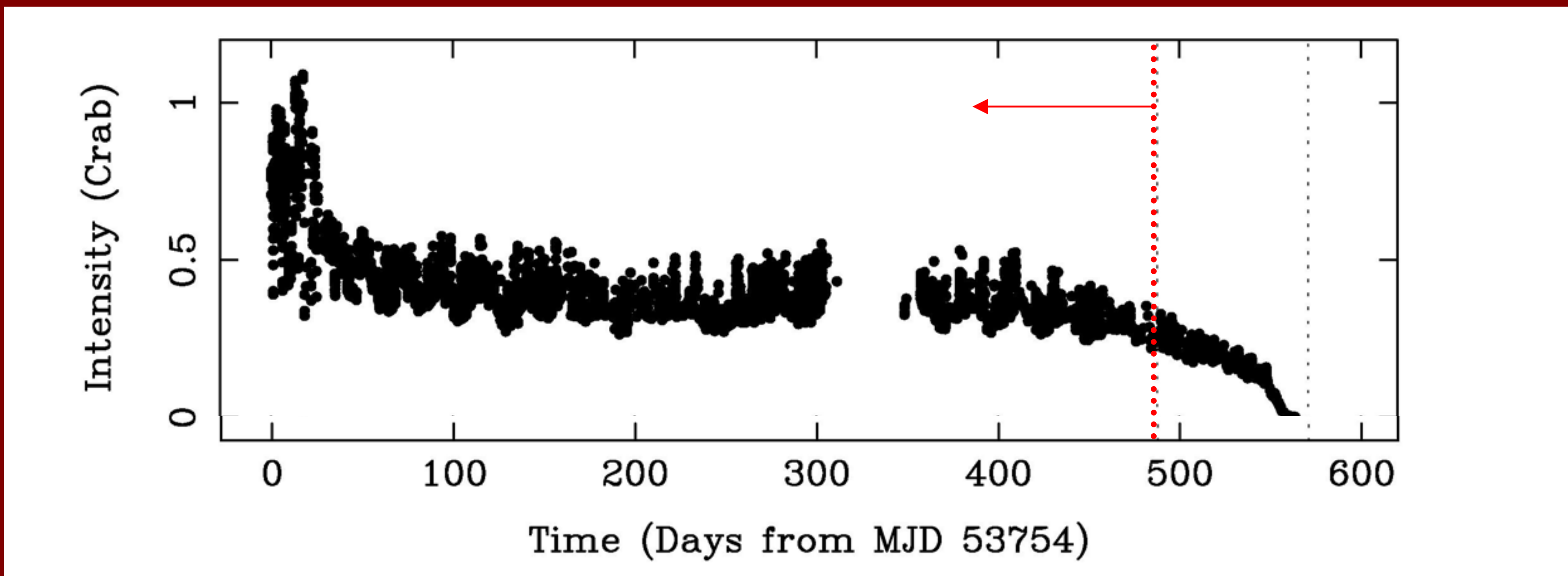
The transient XTE J1701–462:

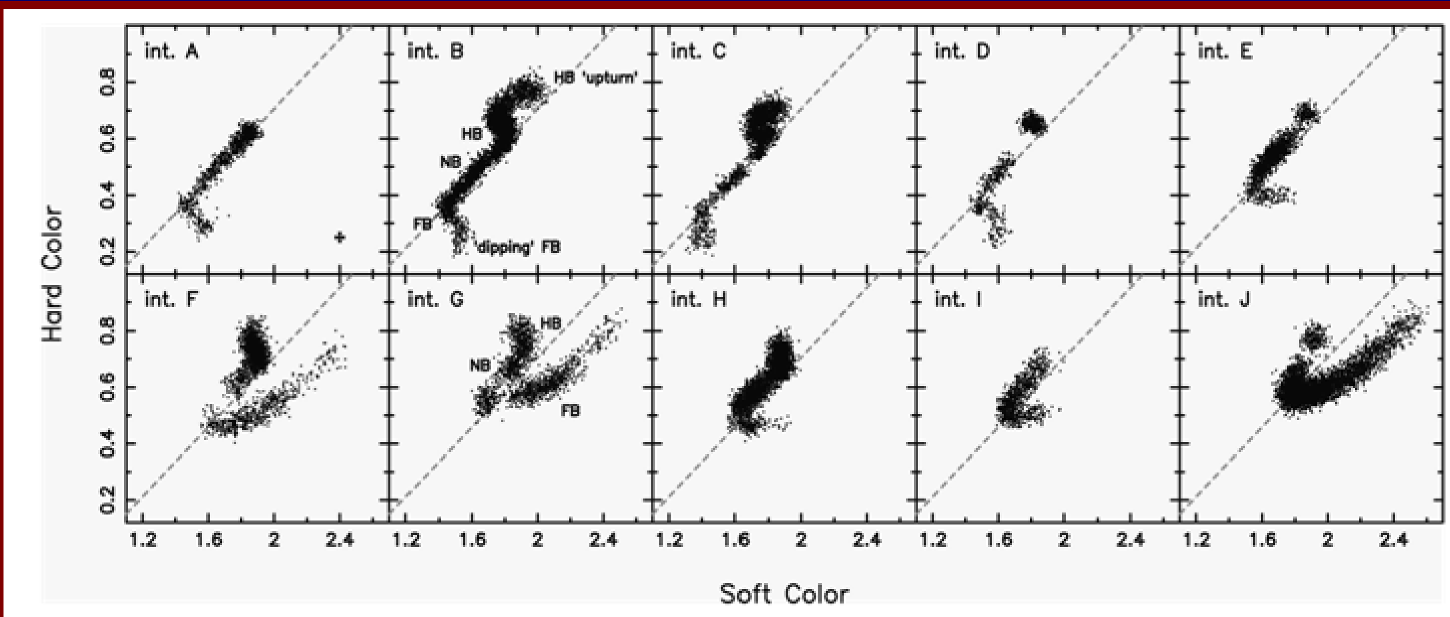
The first Z source to convert into an Atoll source



Homan et al. 2007

The transient XTE J1701–462:
The first Z source to convert into an Atoll source





Homan et al. 2007

The transient XTE J1701–462:
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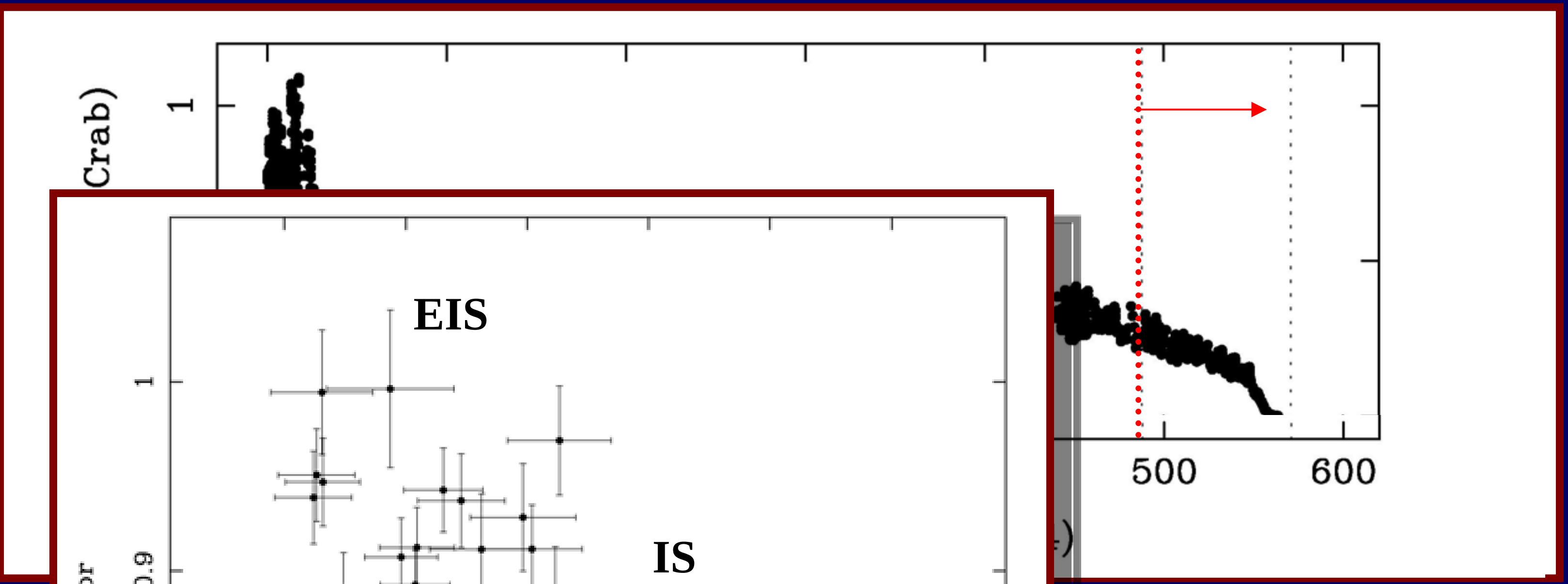
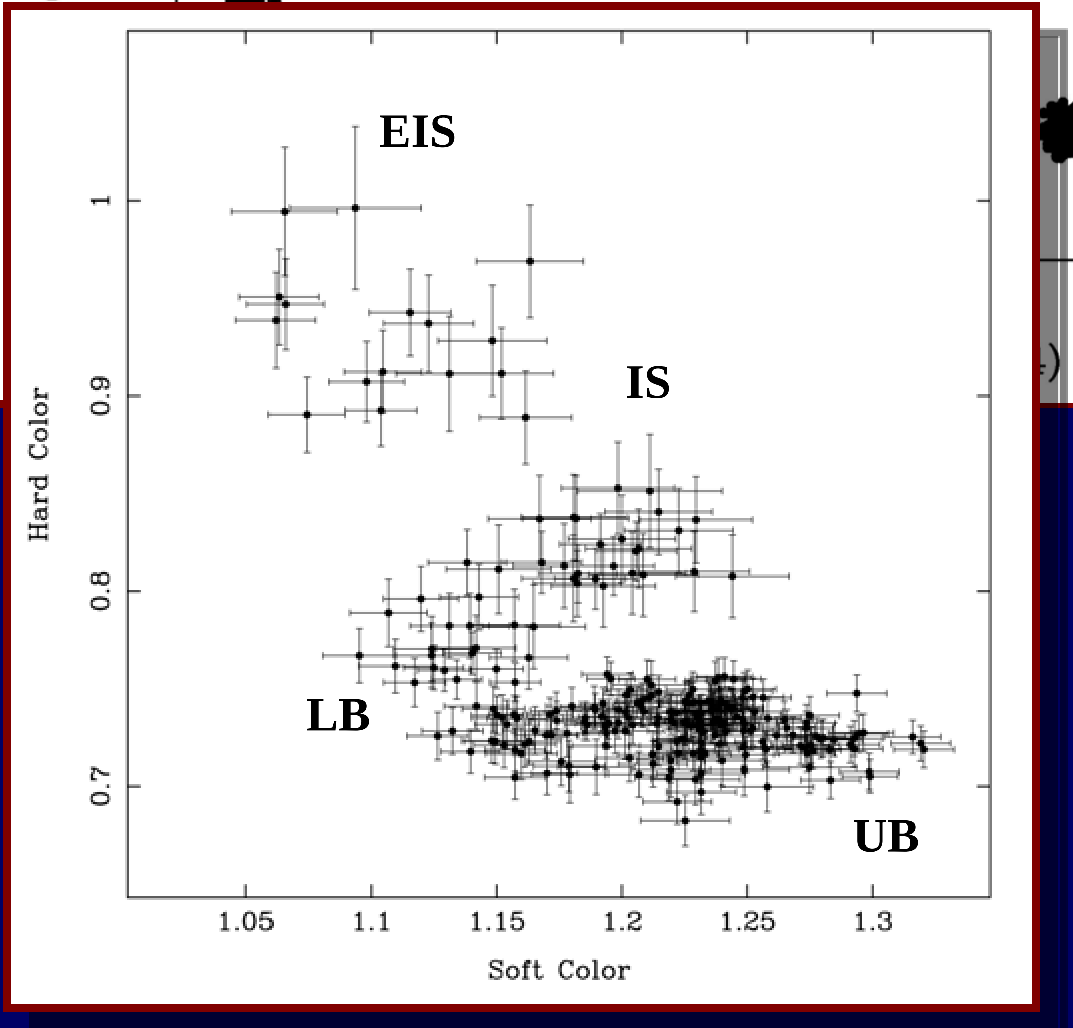
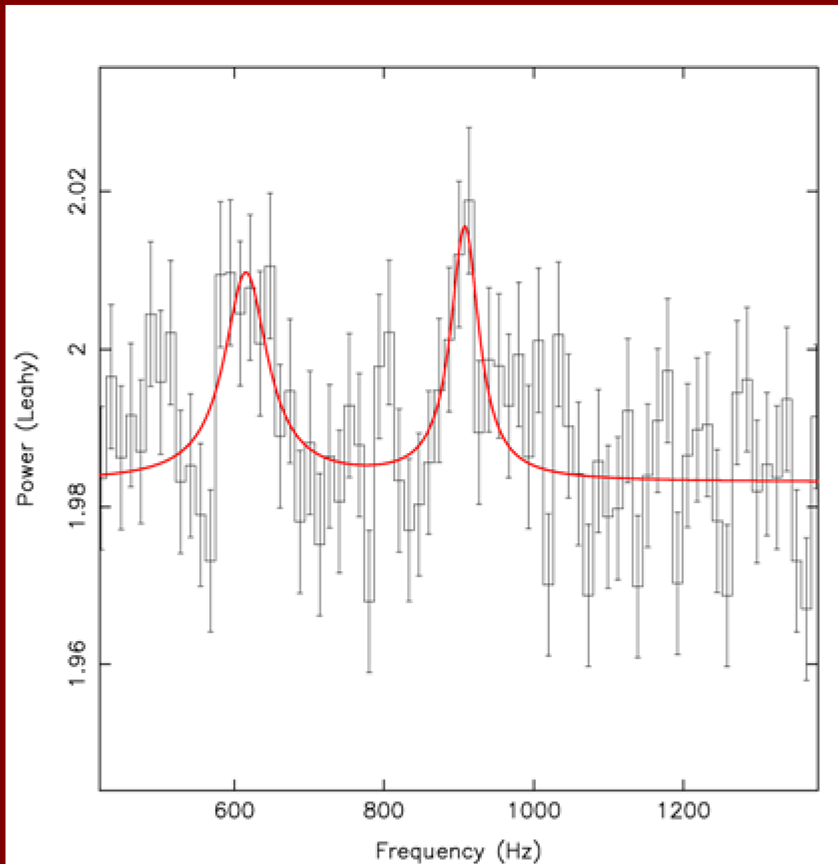


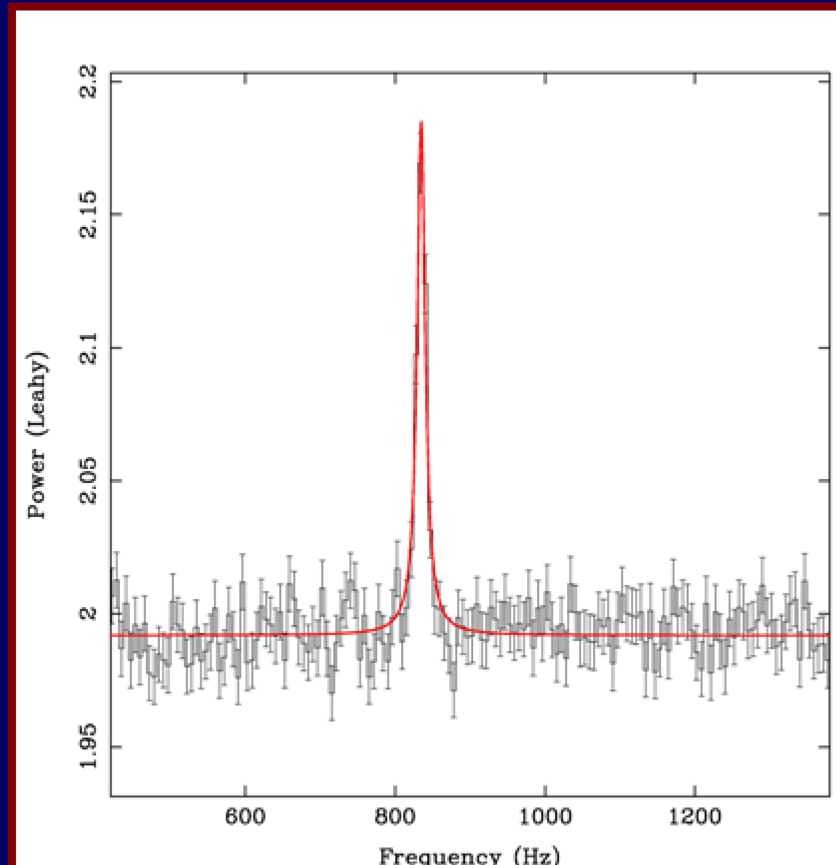


The transient XTE J1701–462:
The Z and Atoll type of kHz QPOs



ν_l ~ 600 Hz
Q_l ~ 8
R_l ~ 3%

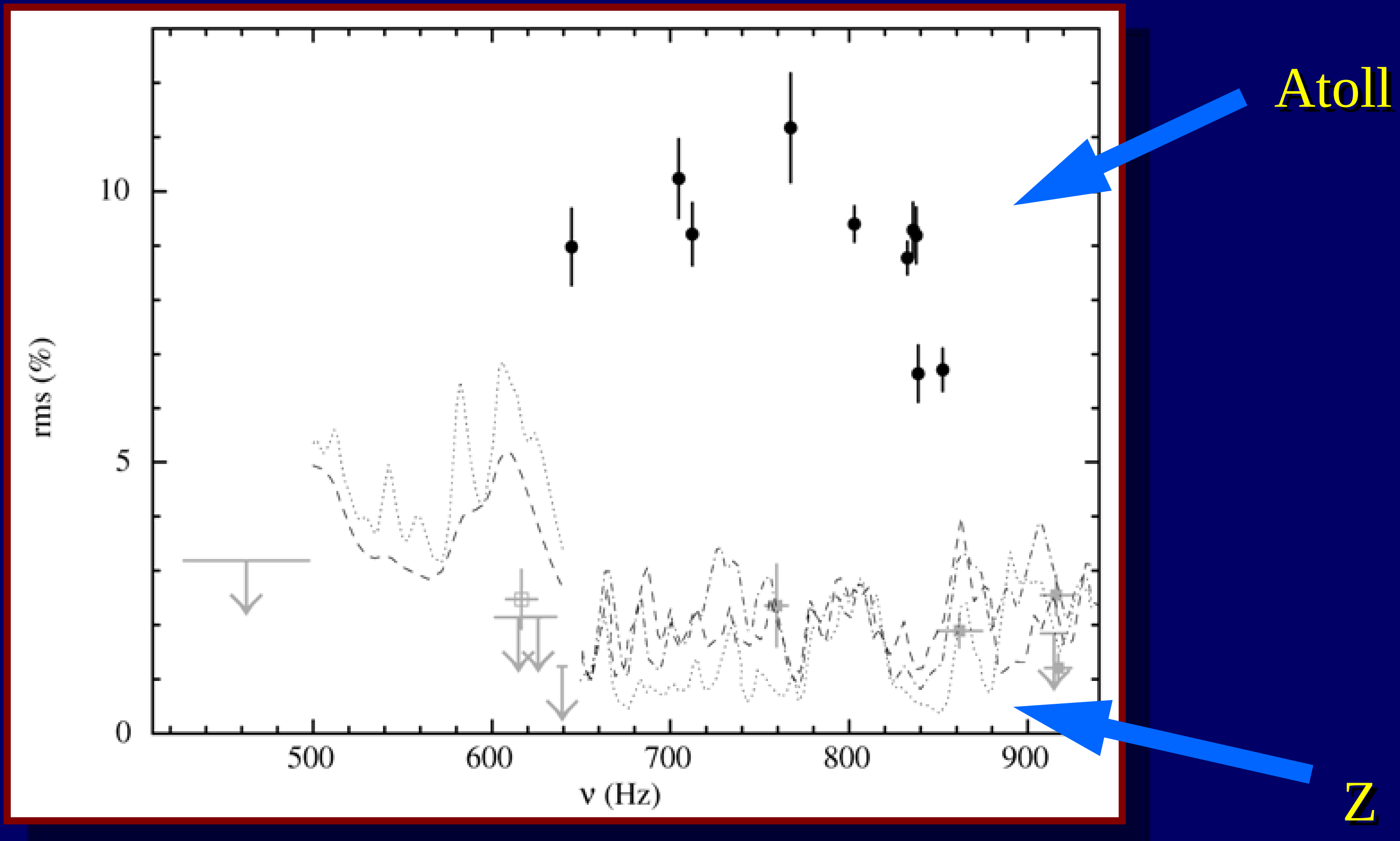
ν_u ~ 900 Hz
Q_u ~ 10
r_u ~ 3%



ν_l ~ 800 Hz
Q_l ~ 100
r_l ~ 10%

Sanna et al. 2009

The transient XTE J1701–462:
Amplitude vs. frequency

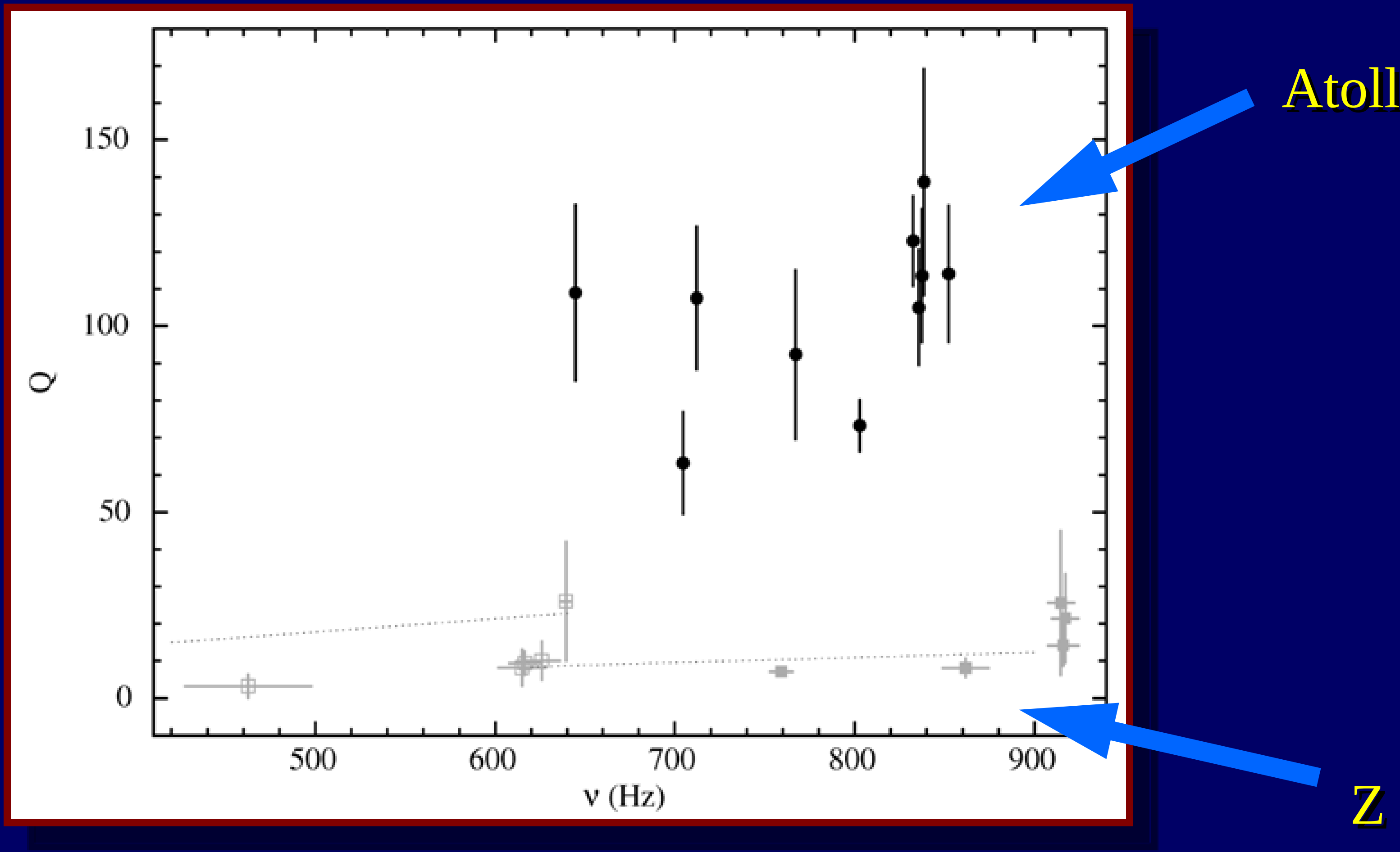


Sanna et al. 2009

Upper limit for *Q*=20,50
Atoll phase, in 256s

Upper limit for *Q*=100
Z phase, in 128s, 256s
and 512s

The transient XTE J1701–462:
Coherence vs. frequency



Sanna et al. 2009

Minimum *Q* for a 3-sigma detection of a 5% QPO in 256s, Atoll phase, 3PCUs

Minimum *Q* for a 3-sigma detection of a 5% QPO in 128s, Z phase, 4 PCUs

Oscillation vs. Modulation

- ***Oscillator:*** Probably in the disc; e.g.:

  - Orbital, radial or vertical epicyclic frequencies,
  - Resonances.

- ***Modulator:*** Probably in a Comptonizing corona or boundary layer:

  - QPO amplitudes larger than disc contribution to total flux.
  - QPO rms spectrum increases steeply with energy.
  - High amplitude at energies where disc contribution is negligible.

  – Coherence of the QPO: Either lifetime of the oscillator, or time dependent efficiency of the modulator.
  – Amplitude of the QPO: Energy-dependent efficiency of the modulator.

$$f(t) \propto A(E) \times e^{-t/\tau} \sin(2\pi\nu t)$$

Modulation mechanism

- Using a time-dependent Comptonization model, Lee & Miller (1998) find that the ability of a Comptonizing corona to modulate the oscillations decreases as the corona becomes cooler and more optically thick; this is also the regime at which the high-energy part of the emission becomes softer (e.g. Gierlinski & Done 2002).

- Gilfanov et al. (2003) find that the rms spectrum of the QPOs in 2 sources can be explained as variability in the flux of the boundary layer. They also find that the relative contribution of the boundary layer to the total flux decreases as inferred mass accretion rate increases (i.e., when sources become brighter).

Conclusions

1. Similar behavior of *Q* and *r* in individual sources and in the population of sources suggests that these QPO parameters are most likely determined by the same mechanism in both cases.

2. 4U 1701-462 converted from a *bright and soft* Z source into a *hard and weak* Atoll source; the amplitude and coherence of the kHz QPOs changed accordingly, in line with what was known for other Z and Atoll sources.

   The MSO cannot be the (only) cause of the drop of *r* and *Q* at high QPO frequencies in individual sources