Constraining NS EOS with QPOs

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Thanks for useful discussions with
Michiel van der Klis, Fred Lamb, Mariano Mendez, Tomaso Belloni, Phil Uttley, Holger Stiele, …

Outline

1. X-ray Variability in NS LMXBs - the Treasure for eXTP

Many of the approaches on NS EOS rely on detections X-ray pulse profiles, type I bursts and magnetar giant flares. But eXTP will provide us with much more timing data of QPOs in NS LMXBs

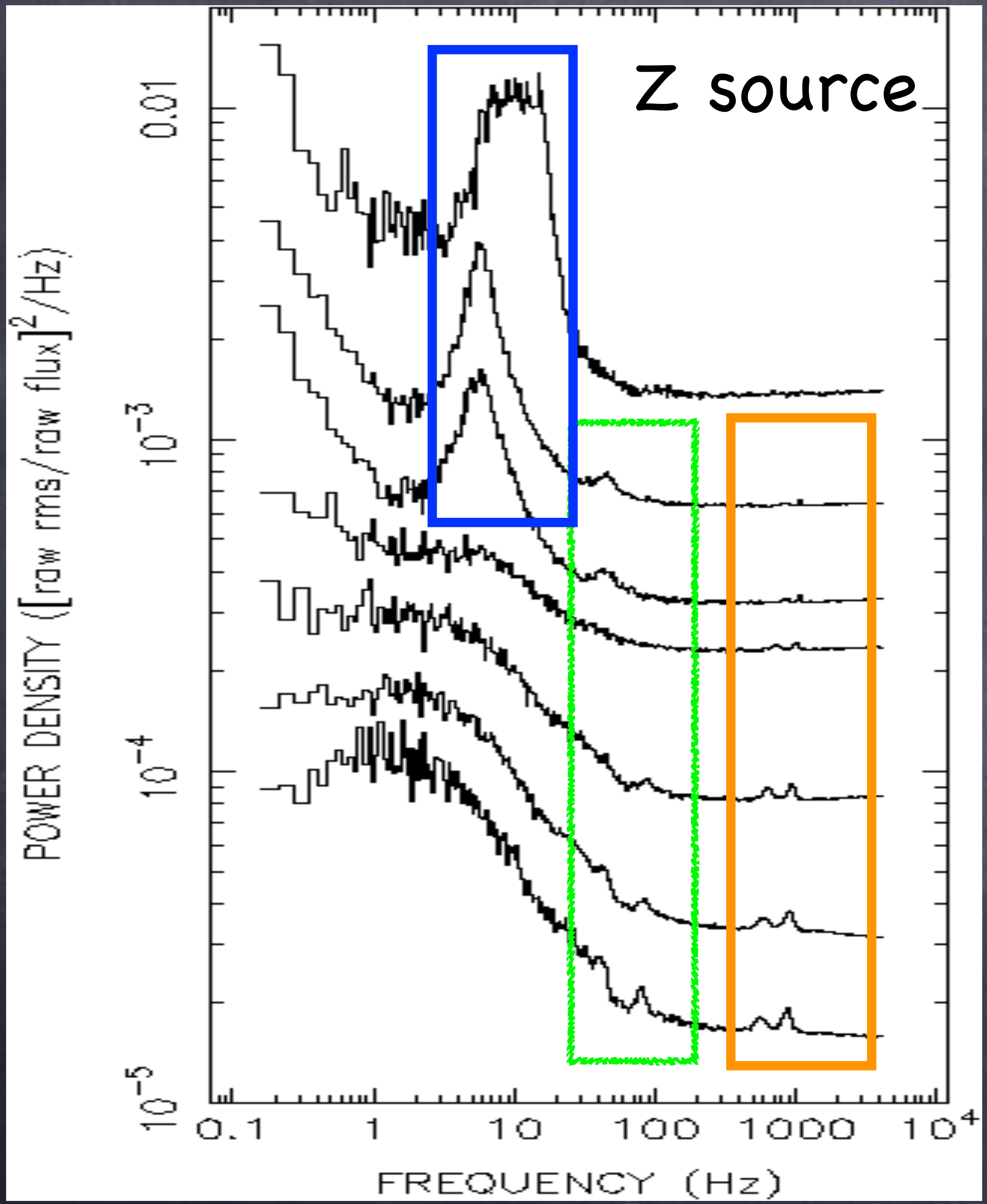
2. kHz QPOs in NS LMXBs and NS EOS

3. mHz QPOs in NS LMXBs and NS EOS

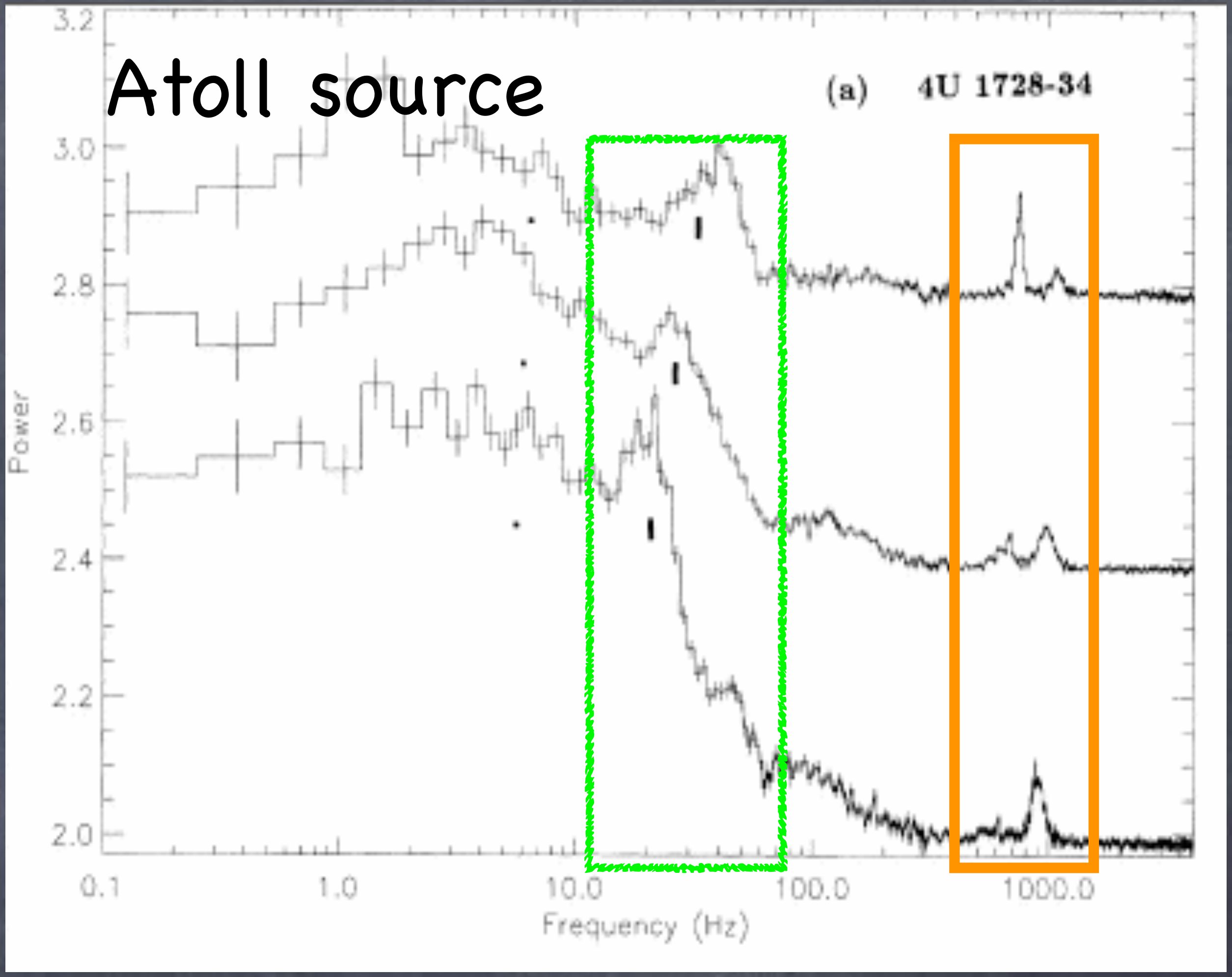
- old ideas and new approaches

Aperiodic X-ray Variability in NS LMXBs

Brings information of the accretion flow and compact objects



Sco X-1 from HB (bottom) to NB (top)
van der KLis 1997



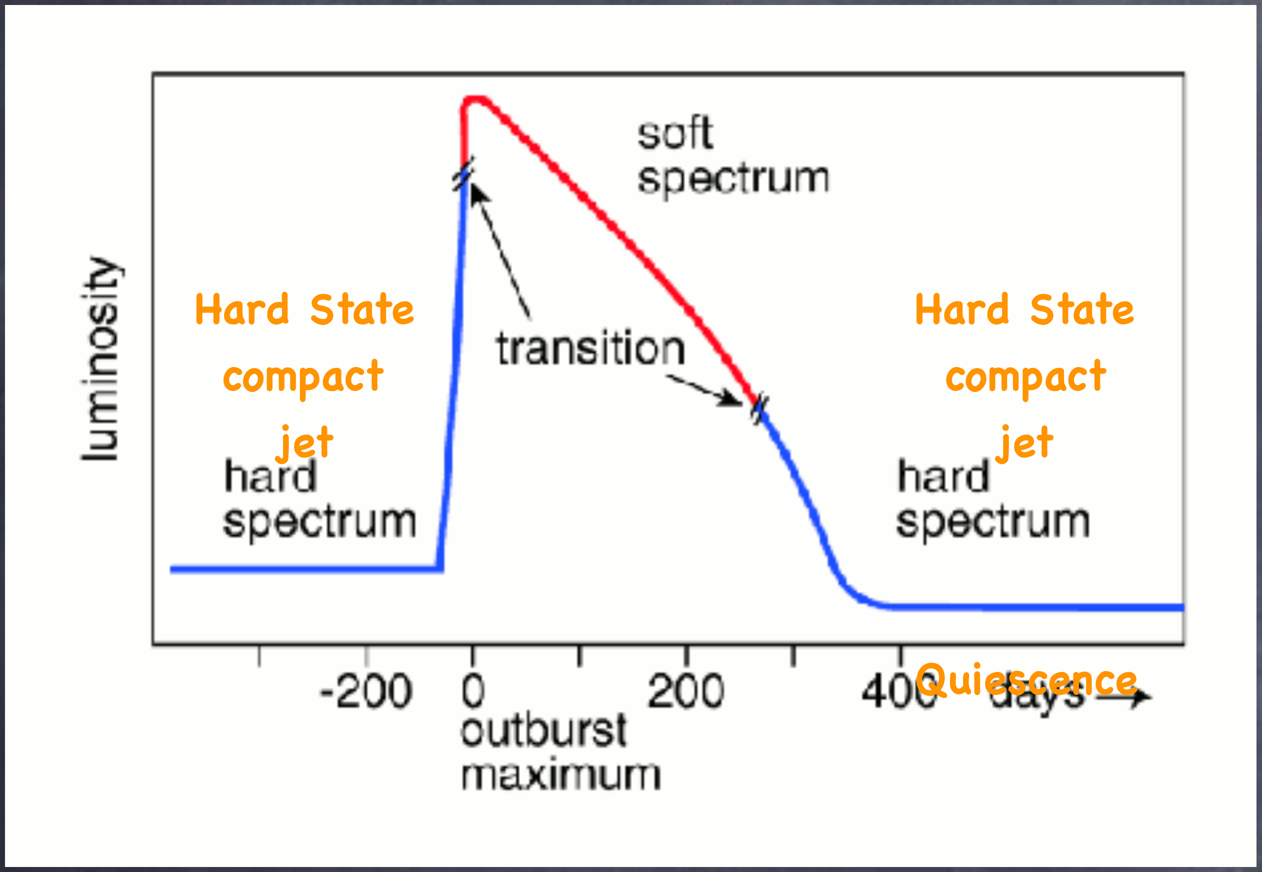
4U 1728-34: Stella & Vietri 1997

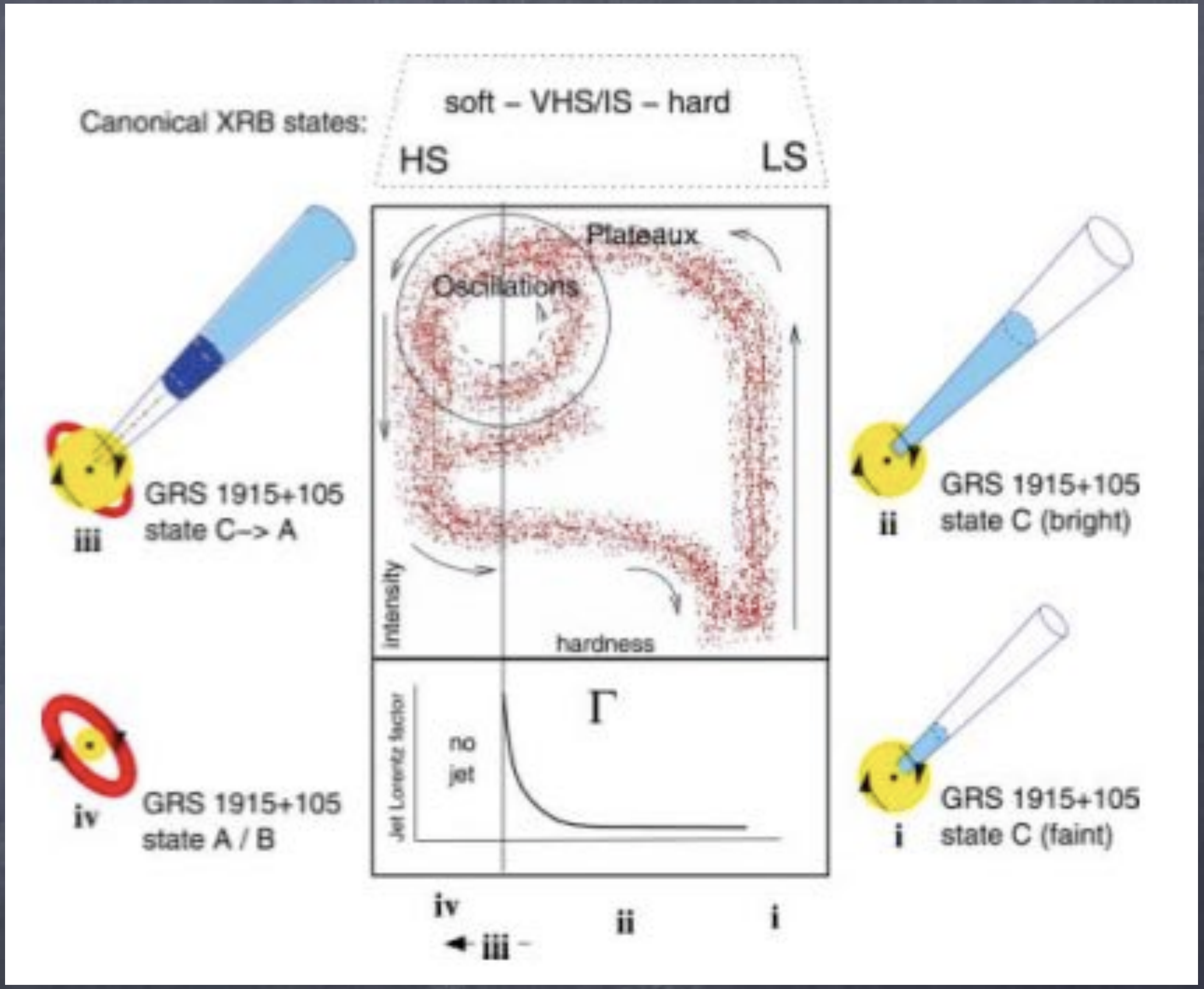
Simultaneous, correlated timing features over a wide frequency range

Kilohertz QPOs, LF QPOs, NBOs

Soft X-ray Transients and States

Fender 2006





Variability is rich in NS LMXBs especially in the relatively hard state

Atoll sources: island or lower banana state as seen in the X-ray color color diagram

Z sources: normal branch, horizontal branch, and flaring branch

Kilohertz QPOs as the Probe of NS EOS

Innermost Stable Circular Orbit (ISCO) -- constrain NS mass & radius

$$R_{ISCO} = \frac{6GM}{c^2} \sim 12.5\ (\frac{M}{1.4\ M_\odot})\ \text{km}$$

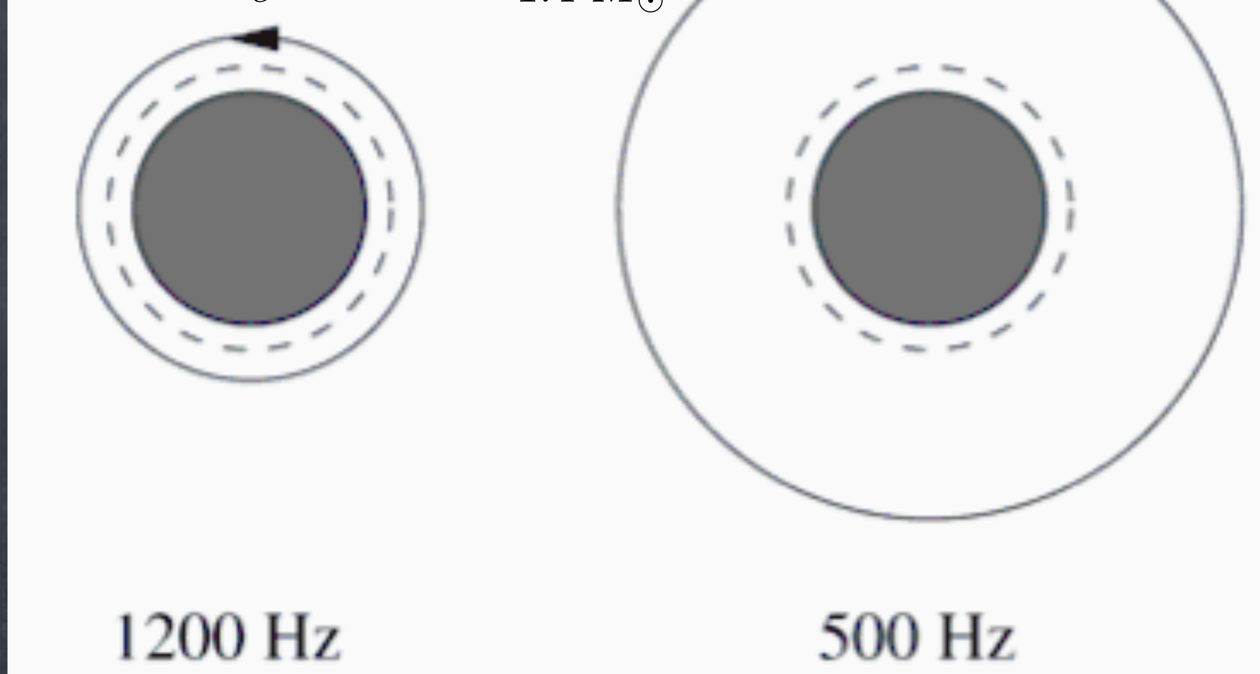
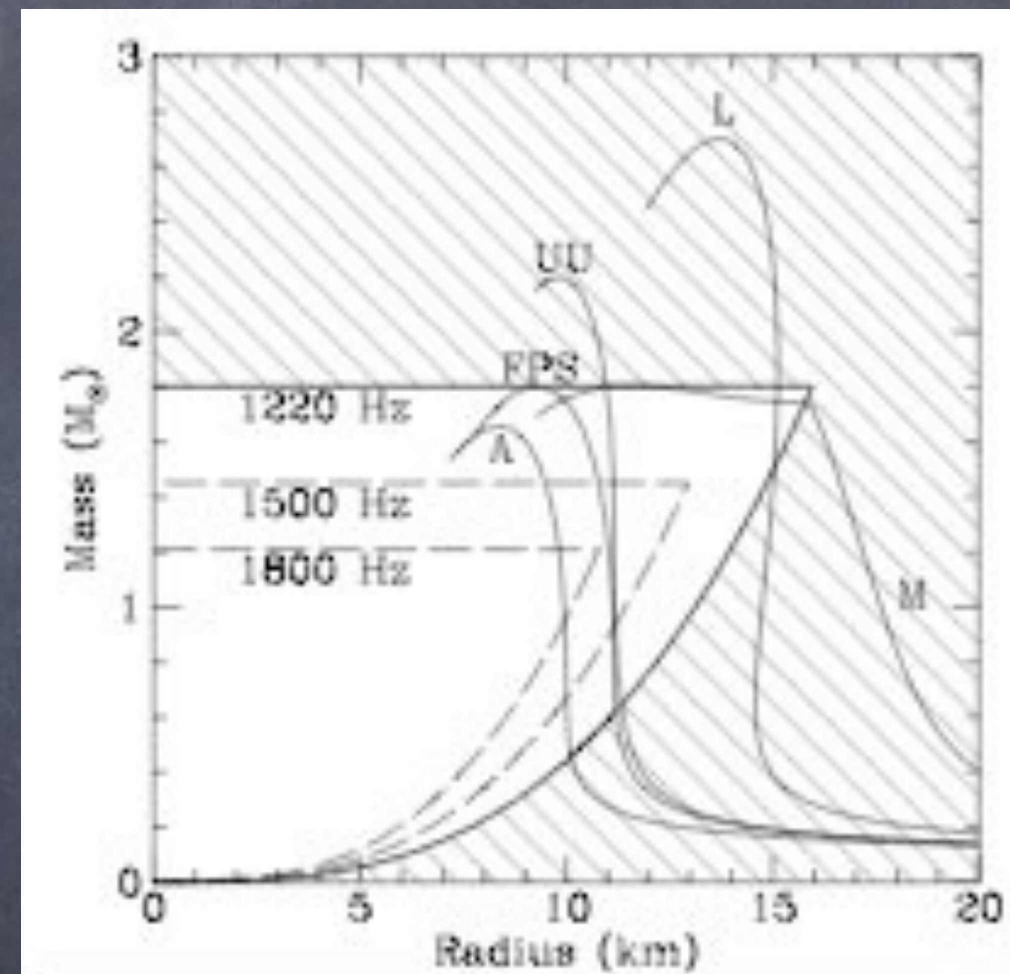


Figure 6 A 10-km radius, 1.4 $M_\odot$ neutron star with the corresponding innermost circular stable orbit (ISCO; *dashed circles*) and orbits (*drawn circles*) corresponding to orbital frequencies of 1200 and 500 Hz, drawn to scale.



from Miller et al. 1998

No stable orbital motion is expected below the ISCO radius!

Assume kHz QPOs - an indicator of the orbital motion in the accretion disk

The maximum frequencies of the kHz QPOs

Kilohertz QPOs and the Probe of NS EOS

eXTP should focus on the disappearance of kHz QPOs

- At their maximums:

  do we have a persistent or an instantaneous ceiling in frequency ?

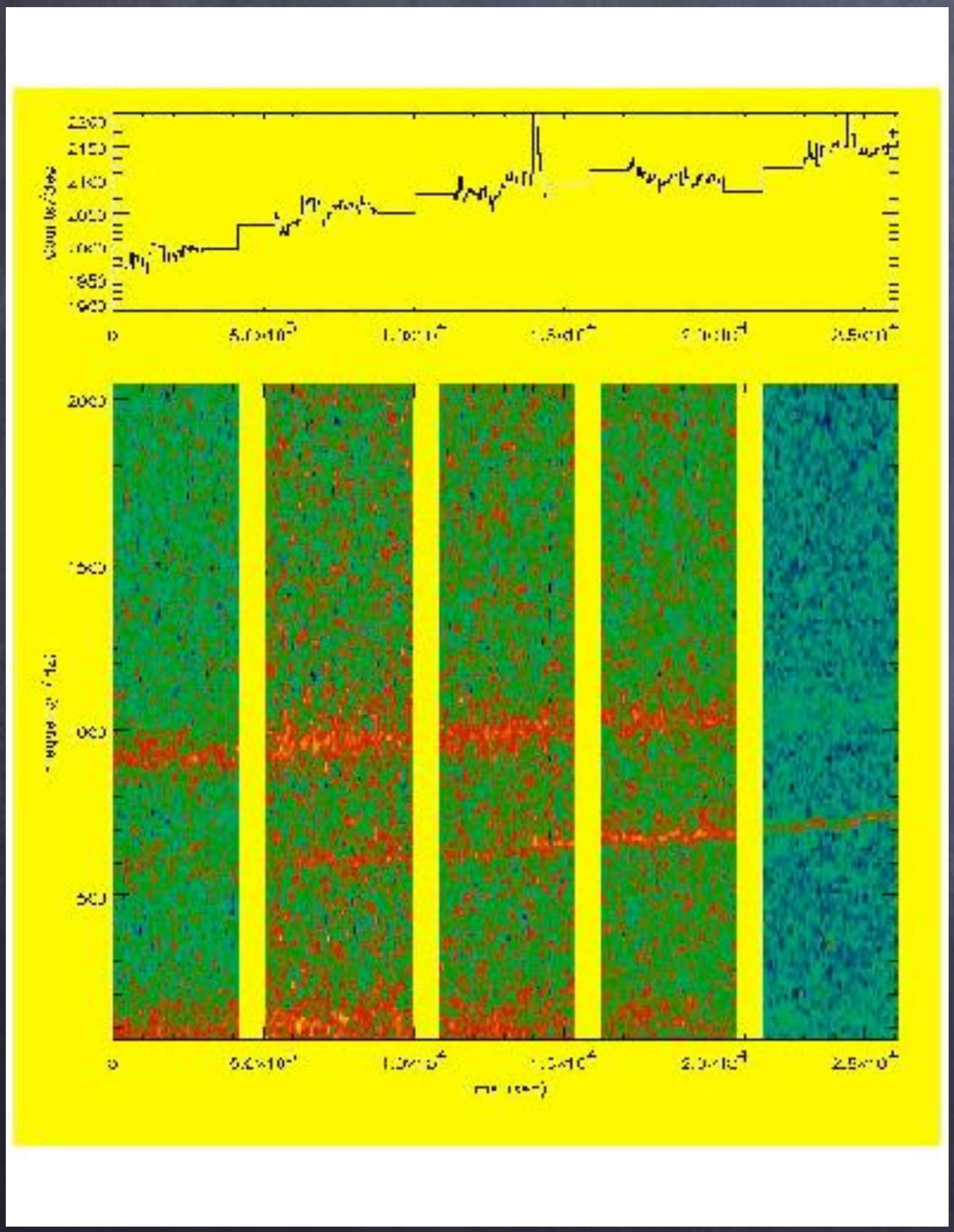
- Towards softer energies than the RXTE:

  any NS surface or boundary component ?

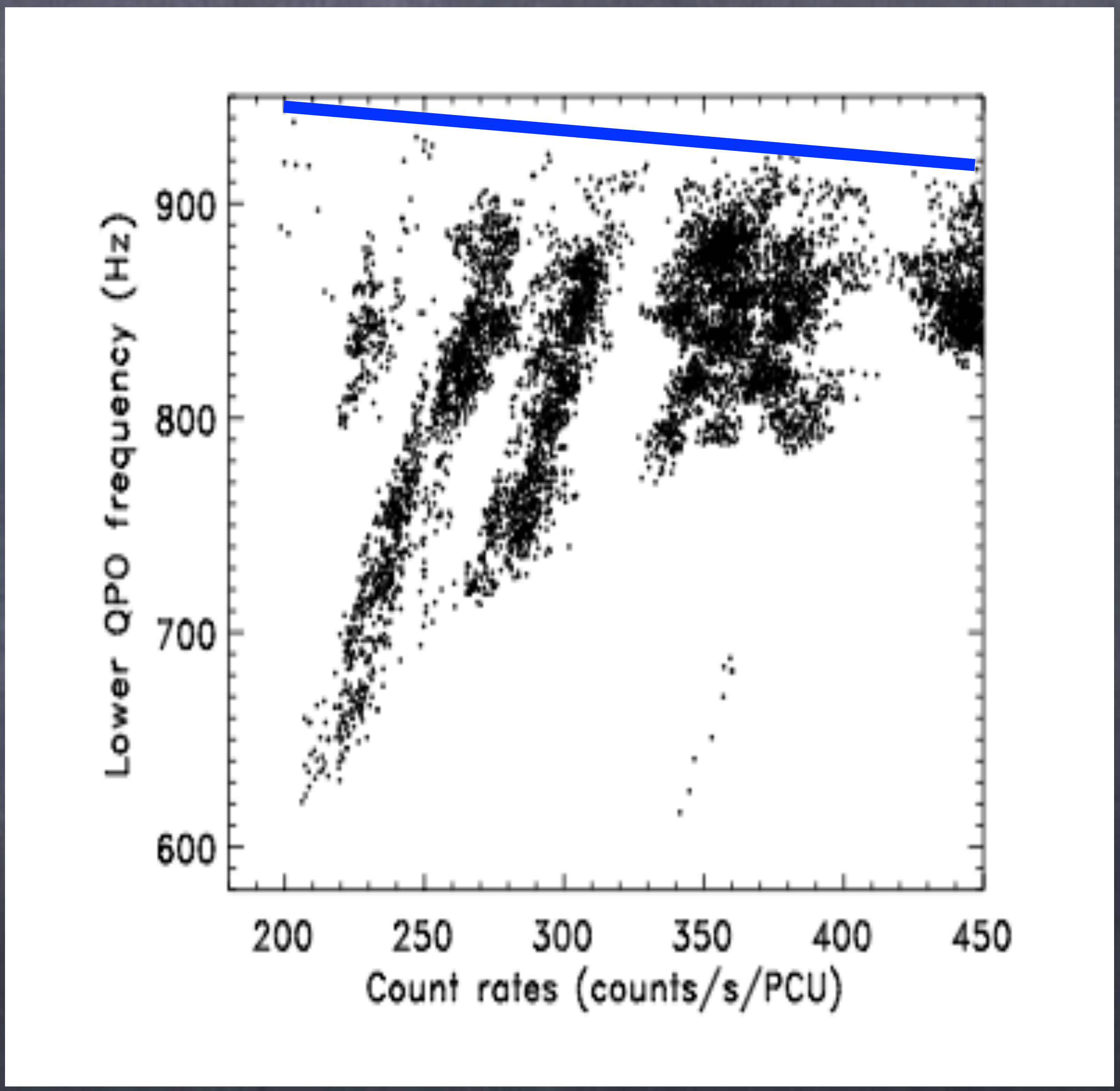
eXTP is a mission which allows us to study how the kHz QPOs appear and disappear

kHz QPOs at their maximum frequencies

kHz QPOs in NS LMXBs



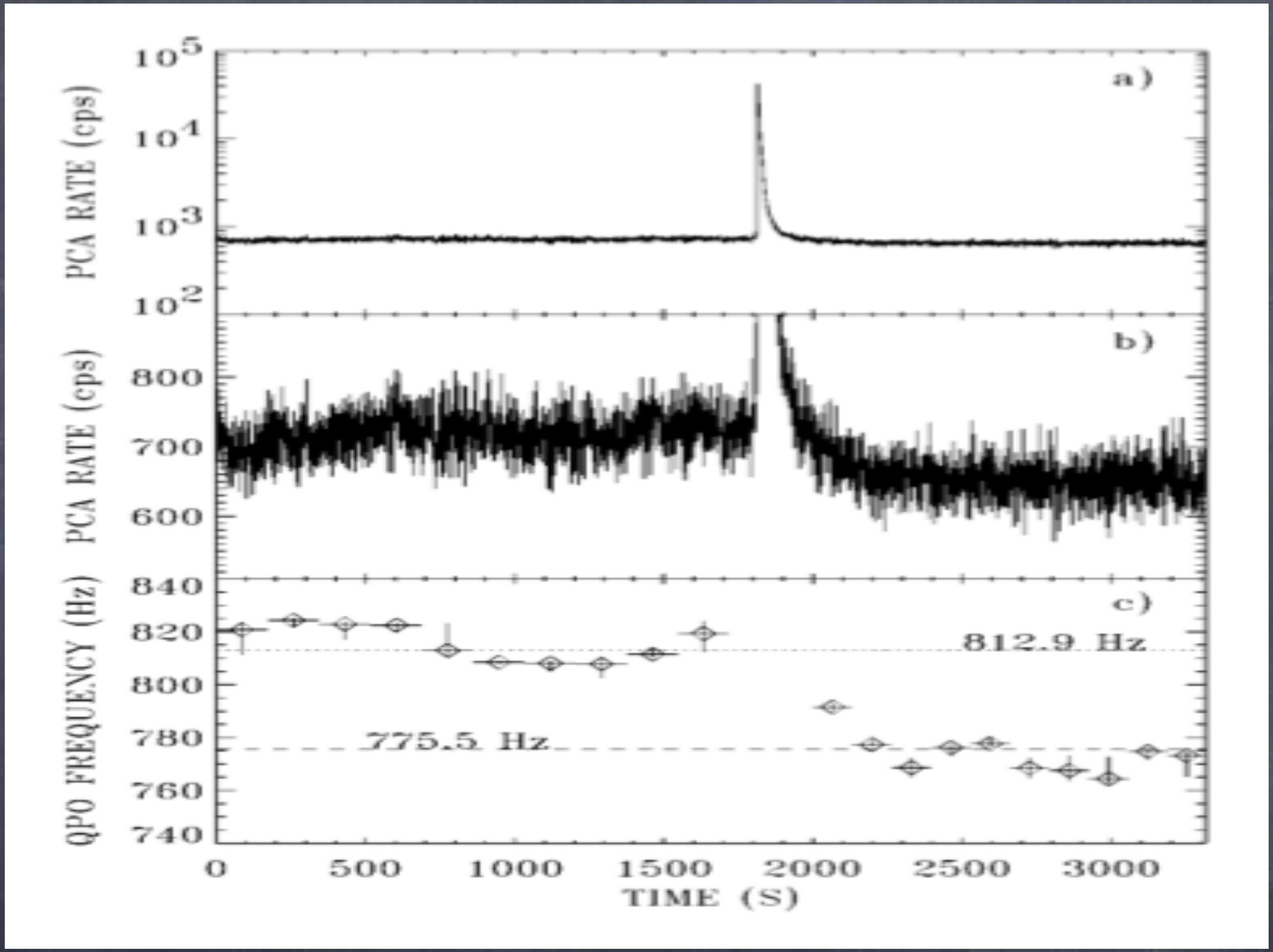
Maximum kHz QPO Frequency



Barret et al. 2005

How kHz QPO disappears near maximum

kHz QPOs in NS LMXBs: Evidence of Radiation Force Effects



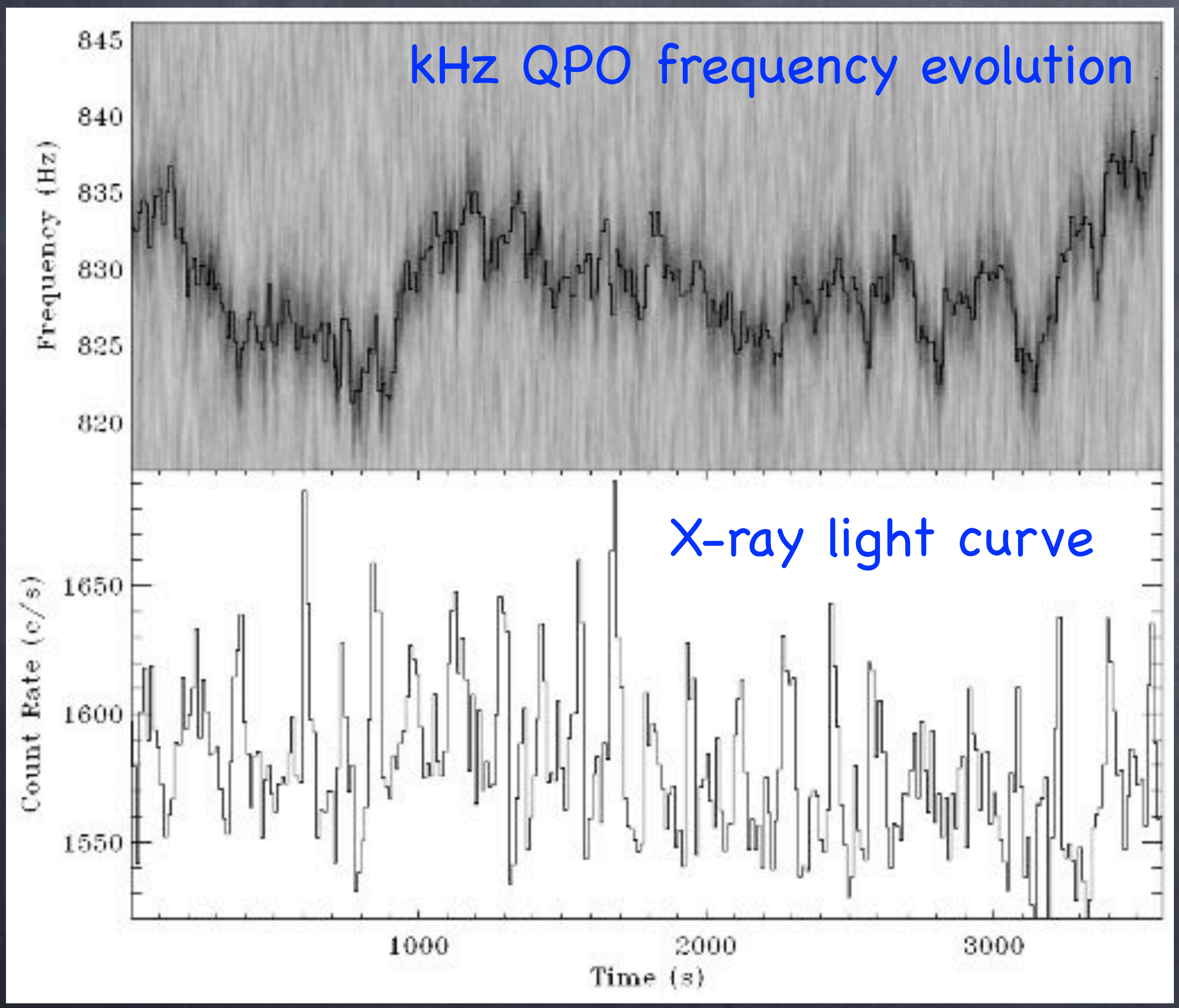
Aquila X-1: the drop of the kHz QPO frequency after type I burst

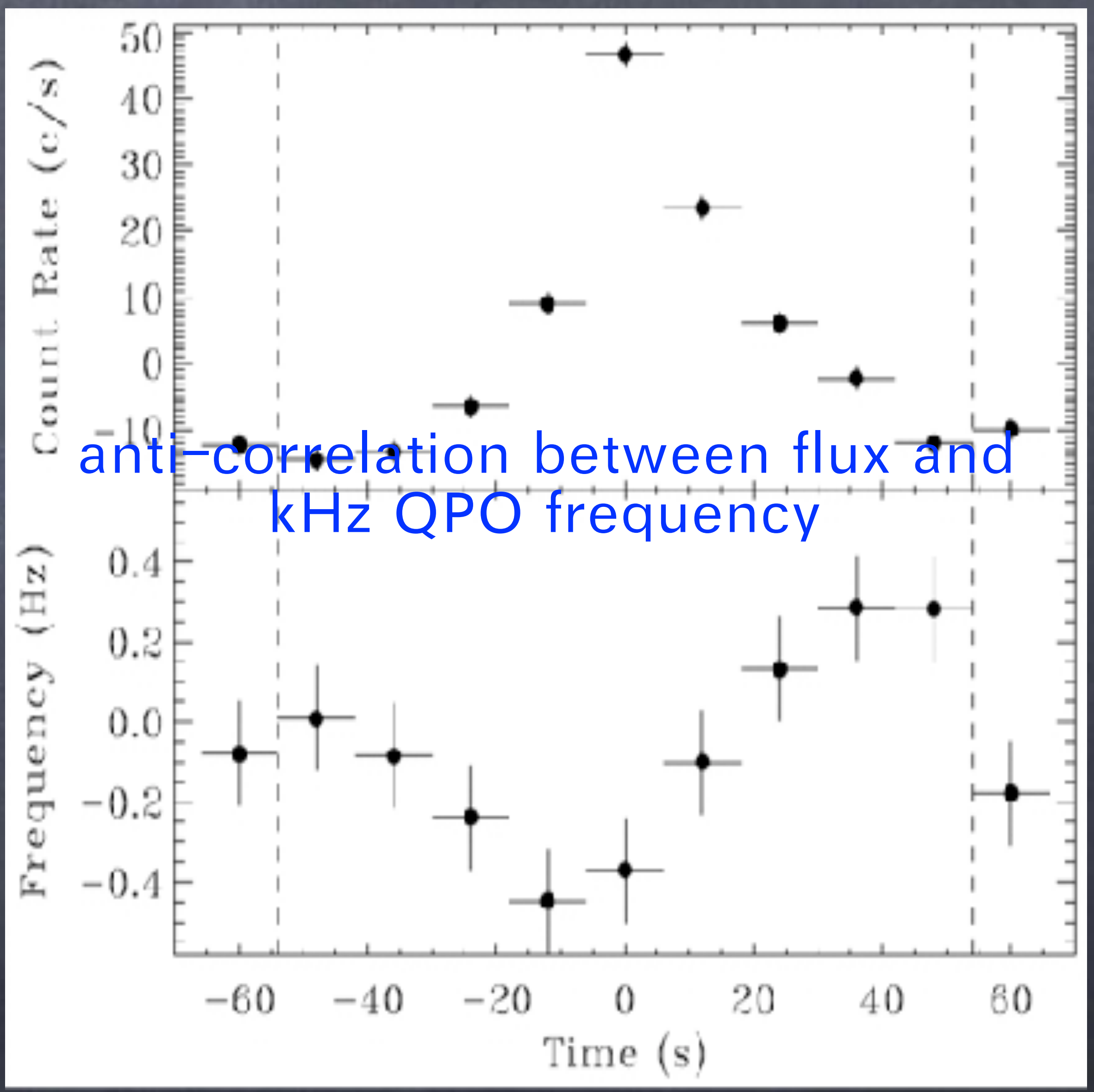
Yu et al. 1999

Coupling between the mHz QPO and the kHz QPO

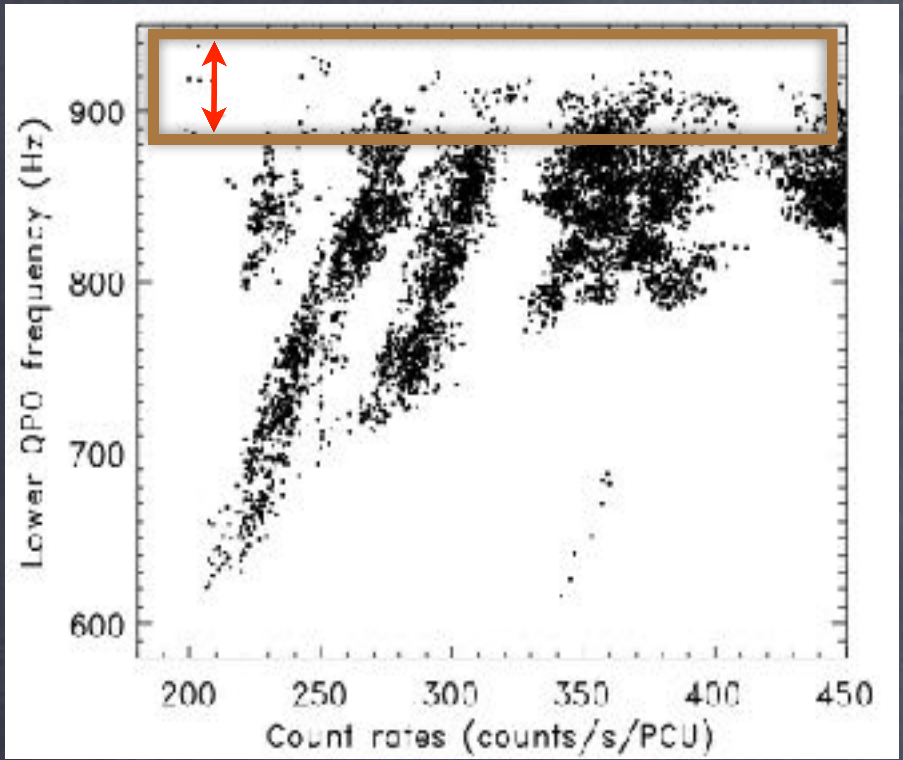
providing evidence that the mHz QPO emission originate from inside the inner disk

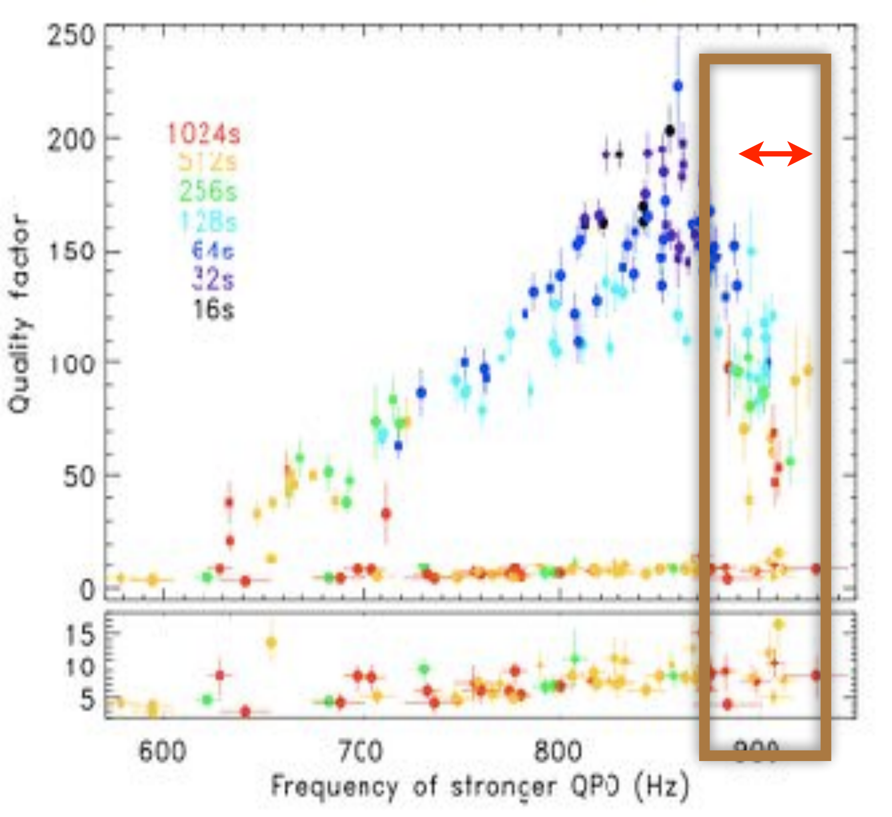
Yu and van der Klis 2002, ApJL





Maximum kHz QPO frequency vs. flux in a single source





Barret et al. 2005, 4U 1636-53

Interpretation of the Q Drop as Radiation Force Effect

Orbital Frequency

$$\nu_K = \frac{1}{2\pi}\sqrt{\frac{GM}{r^3}} \approx 1184\ \mathrm{Hz}\ (\frac{r}{15\ \mathrm{km}})^{-3/2}\ m_{1.4}^{1/2}$$

balance between gravity & radiation force -radial direction

$$\frac{\sigma_0}{4\pi r^2 c}\frac{L_E}{} - \frac{\sigma_0}{4\pi r^2 c}\frac{L}{} = m_p r(2\pi\nu_K(L))^2$$

Modified Orbital Frequency

$$\nu_K(L) = \sqrt{1-\alpha}\ \nu_K(0)$$

Orbital frequency change in response to a flux change at an rms amplitude of A

$$\delta\nu_K(L) \approx 6\ \mathrm{Hz}\ \frac{\gamma}{(1-\gamma)}(\frac{A}{1\%})(\frac{r}{15\ \mathrm{km}})^{-3/2}\ m_{1.4}^{1/2}$$

The relation between A and maximum Q under radiation

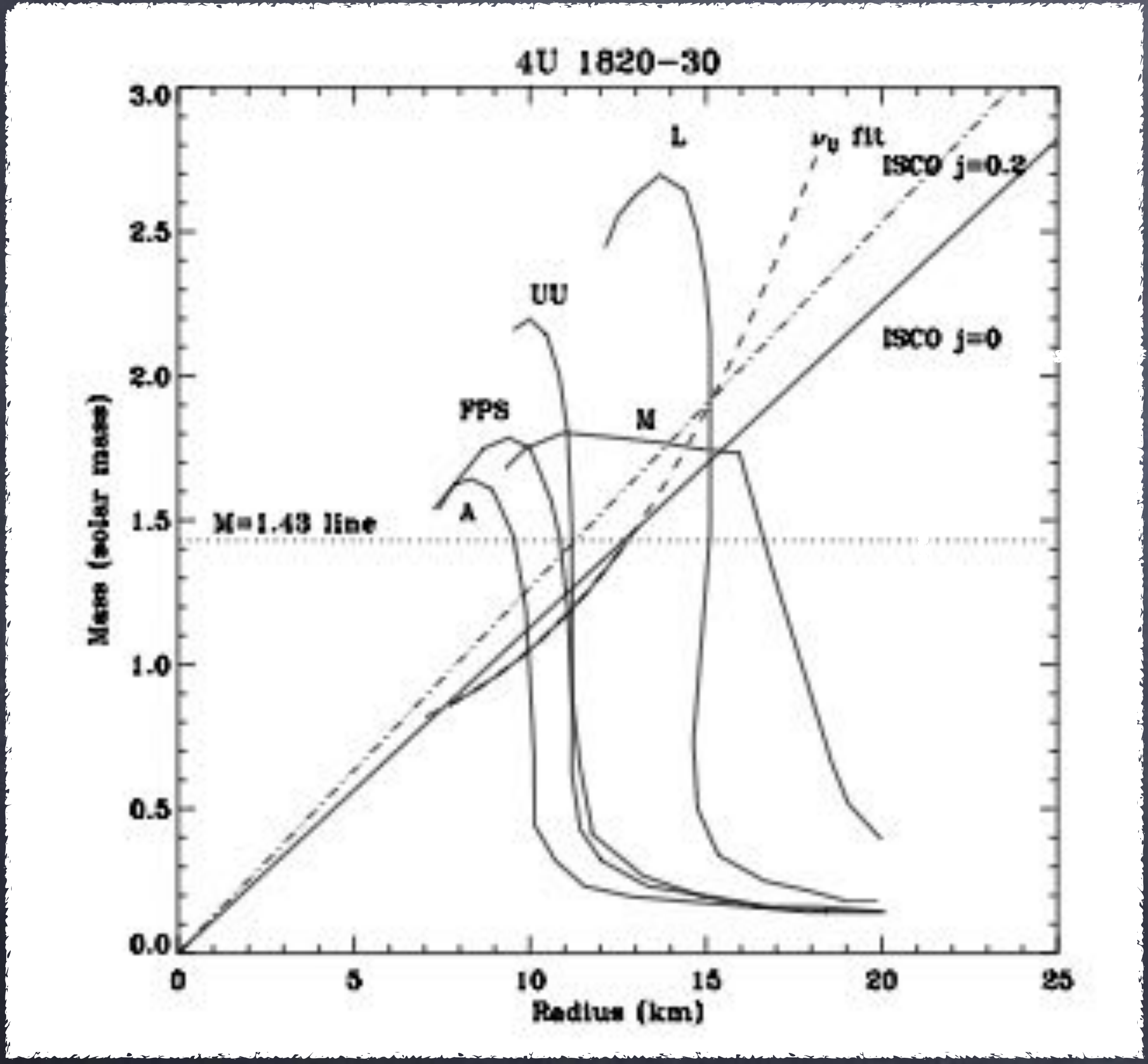
$$Q_R \approx 200\frac{1-k\beta\gamma}{k\beta\gamma}(\frac{A}{1\%})^{-1}$$

Getting closer to the NS surface, the orbital motion in the accretion flow will be strongly modulated by the radiation force from the X-ray emitting neutron star.

Application of the model can put constraints on neutron star EOS by measuring maximum frequency vs. flux (Yu 2008)

Kilohertz QPOs as the Probe of NS EOS

Application of the model can put constraints on neutron star EOS by measuring maximum frequency vs. flux relation in 4U 1820-30 (Yu 2008)



Assumptions: the upper kHz QPO frequency corresponds to the orbital frequency in the accretion flow

the RXTE data gives the results:

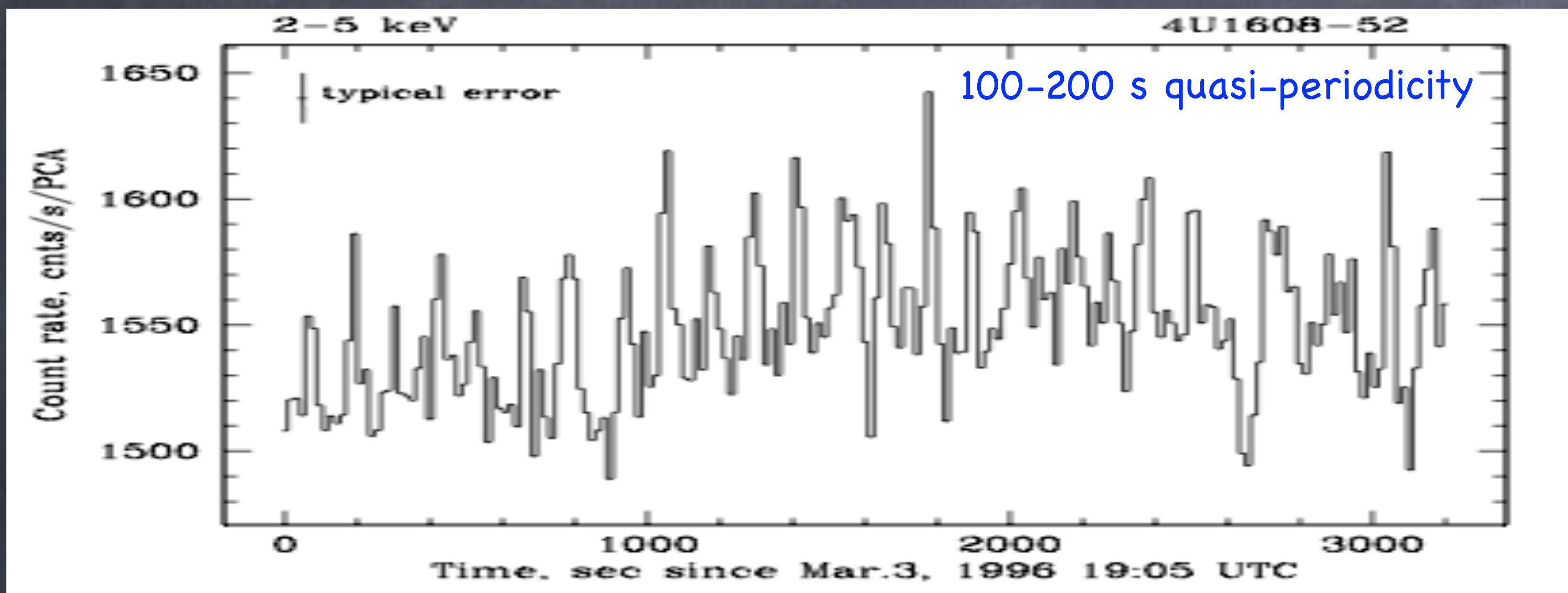
for j = 0.0:
M ~ 1.43 solar masses and R~12 km

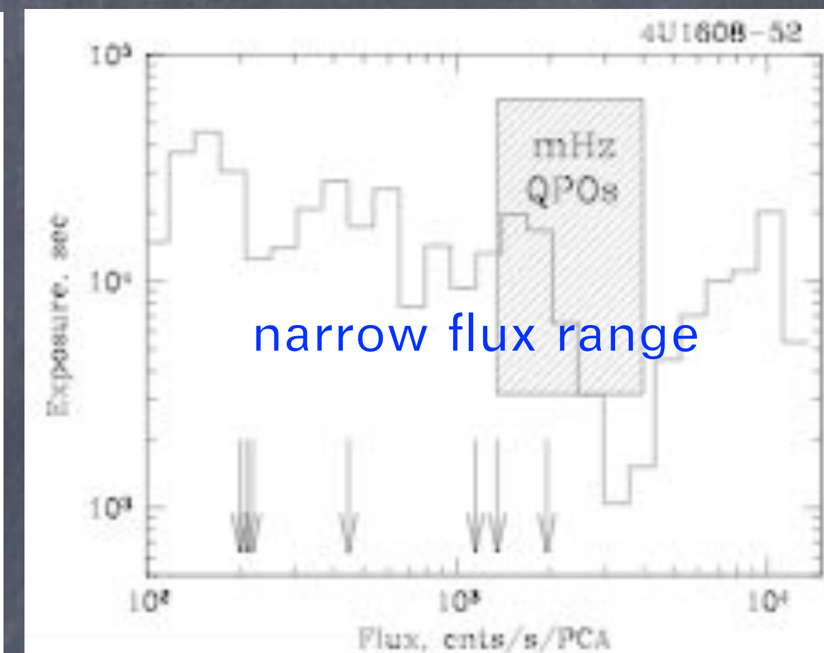
for J = 0.2:
M ~ 2.0 solar masses and R ~ 15 km

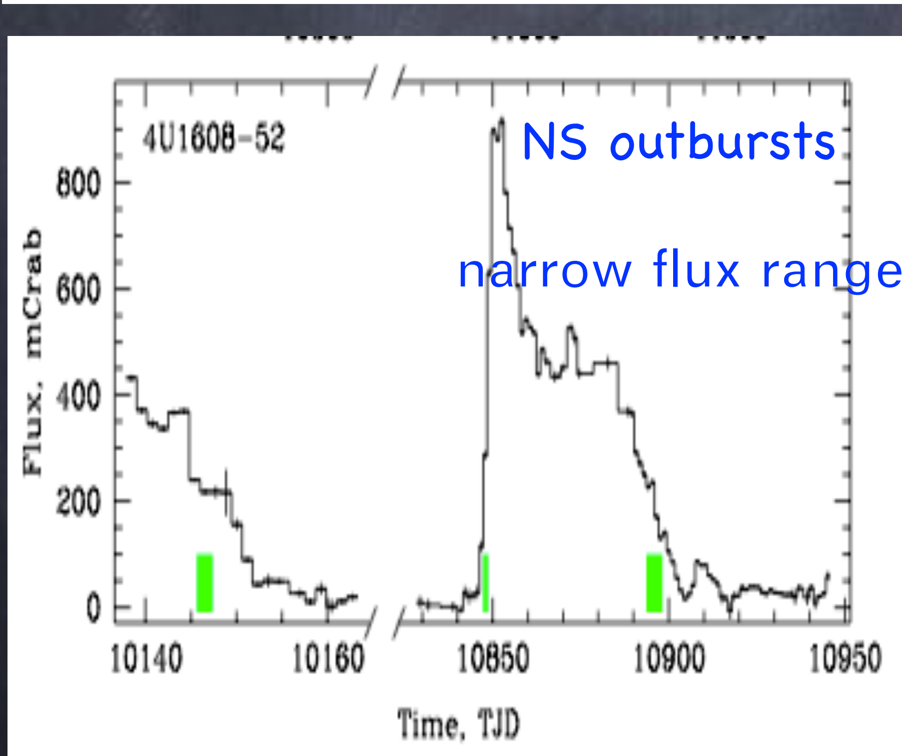
- need GRMHD with radiation simulation to determine radiation force effects from the radiating NS on the orbital motions in the accretion flow, I.e., the parameter for the effective gravity under outgoing radiation force

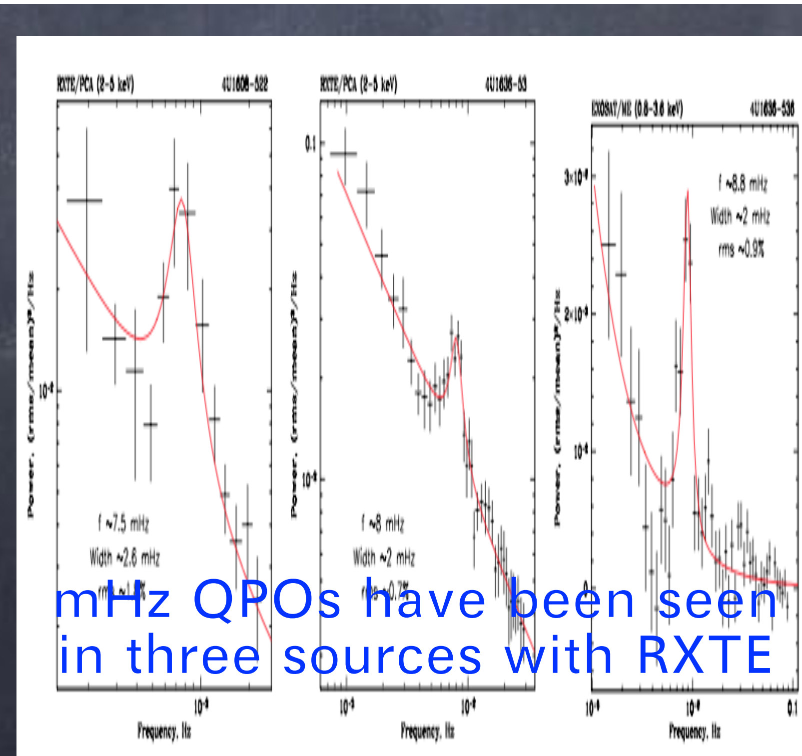
Milliherz QPOs in NS LMXBs and NS EOS

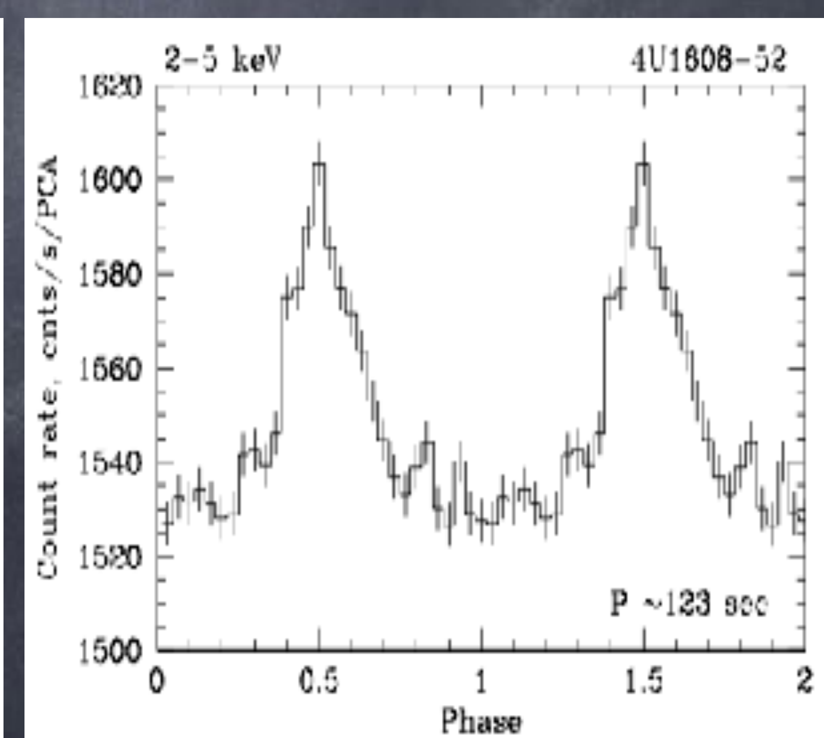
Revnivtsev et al. 2001







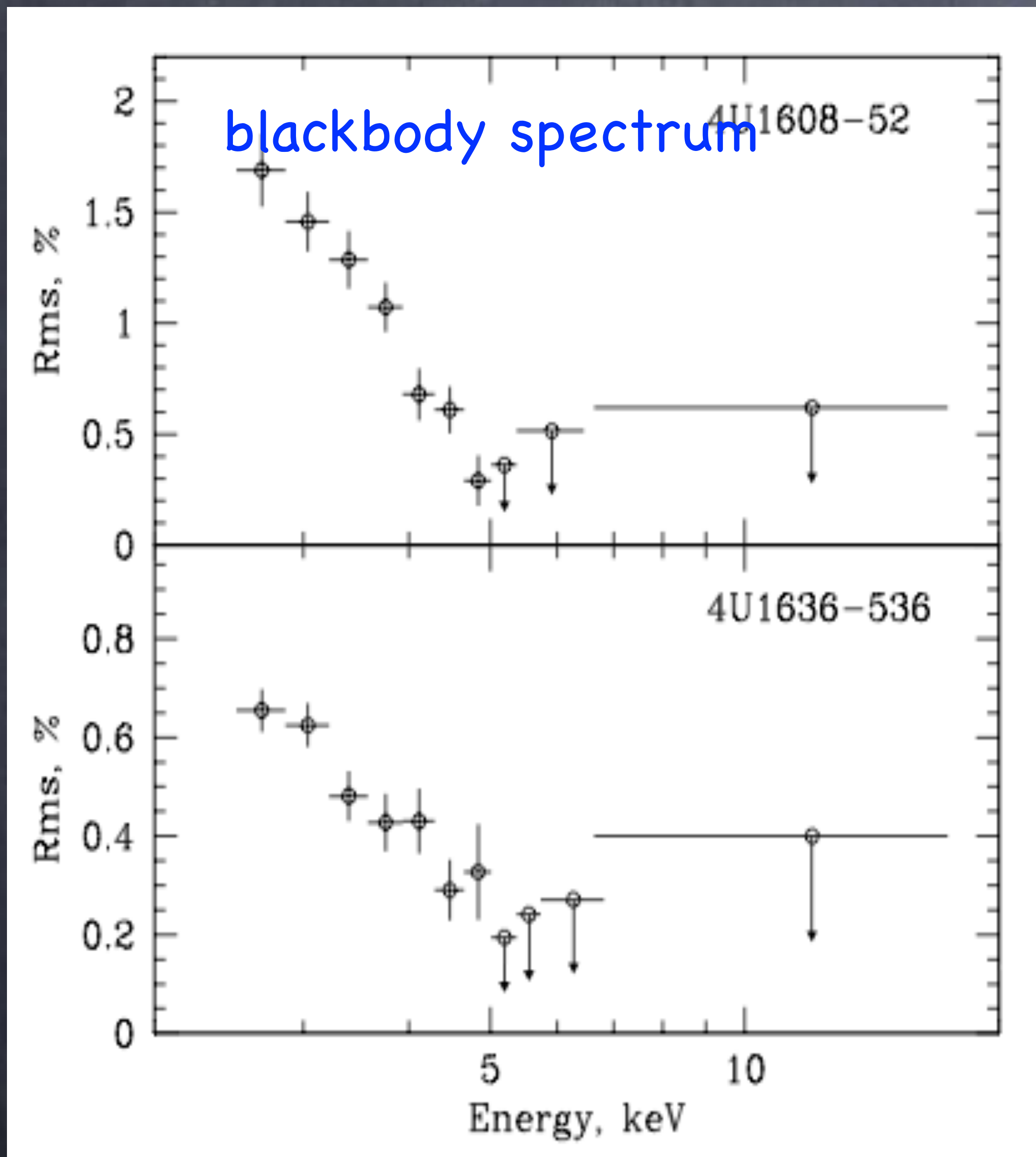


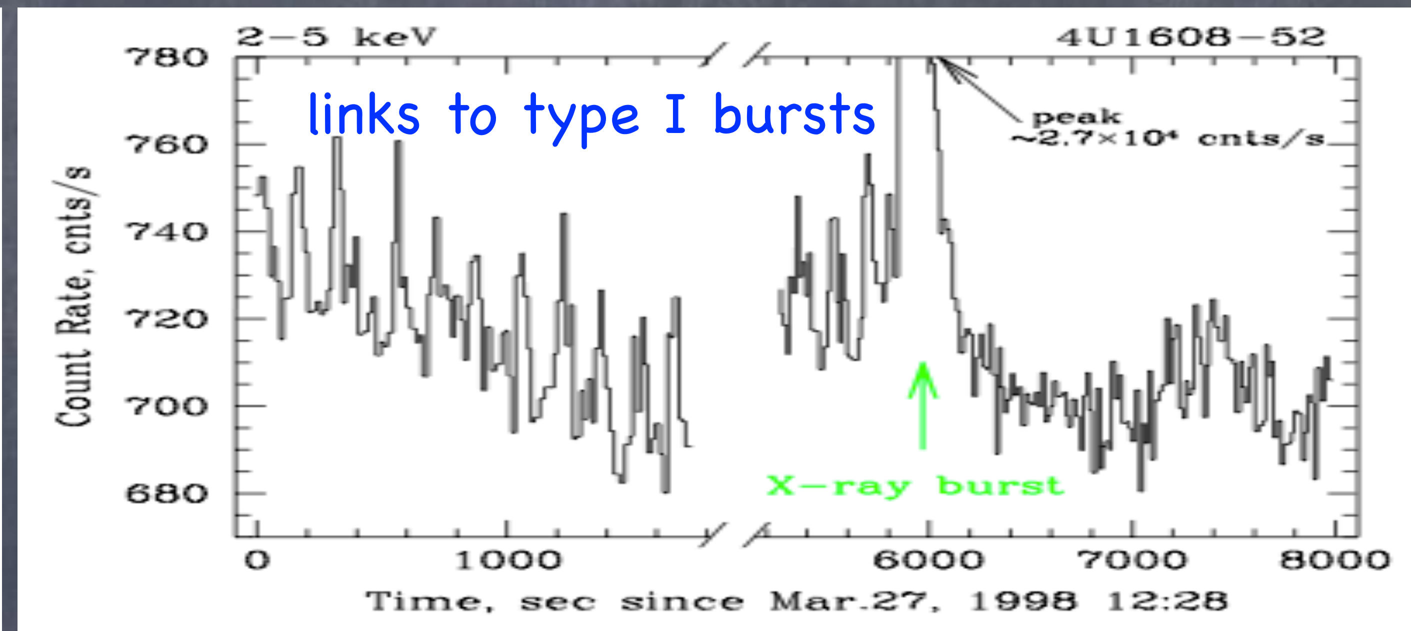


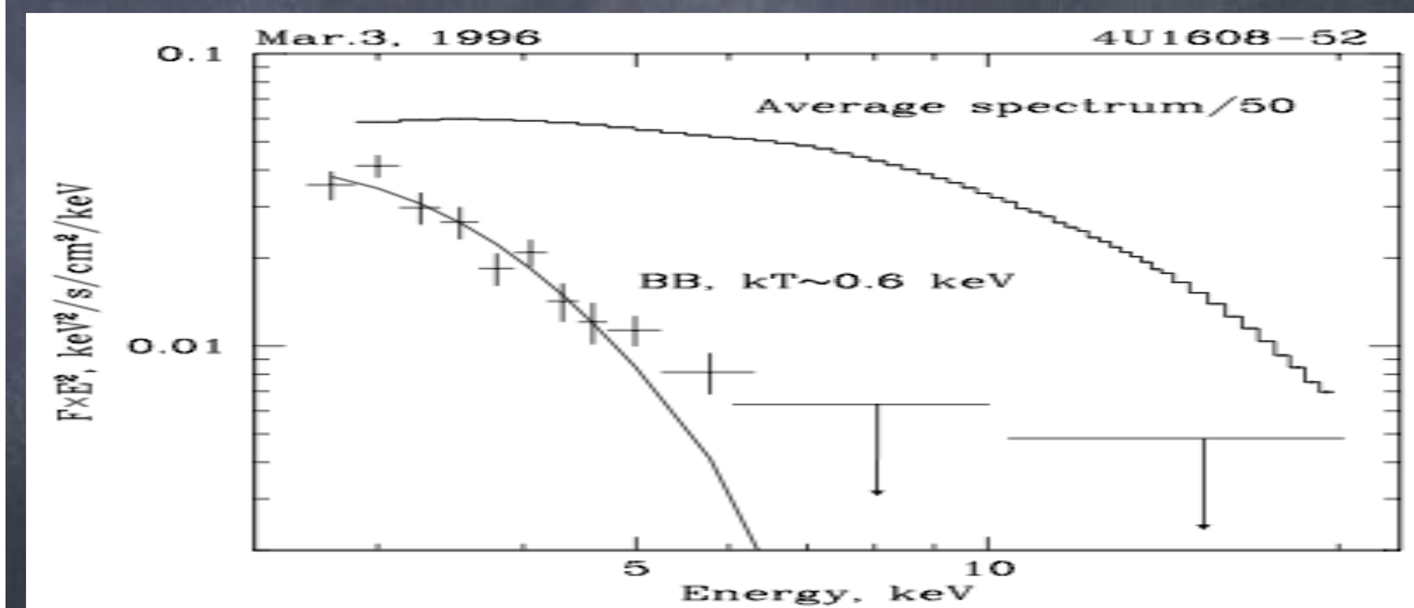
Blackbody nature of the mHz QPO emission

link to the thermonuclear burning on accreting NSs

Revnivtsev et al. 2001: 4U 1608-52, 4U 1636-53, and possibly in All X-1



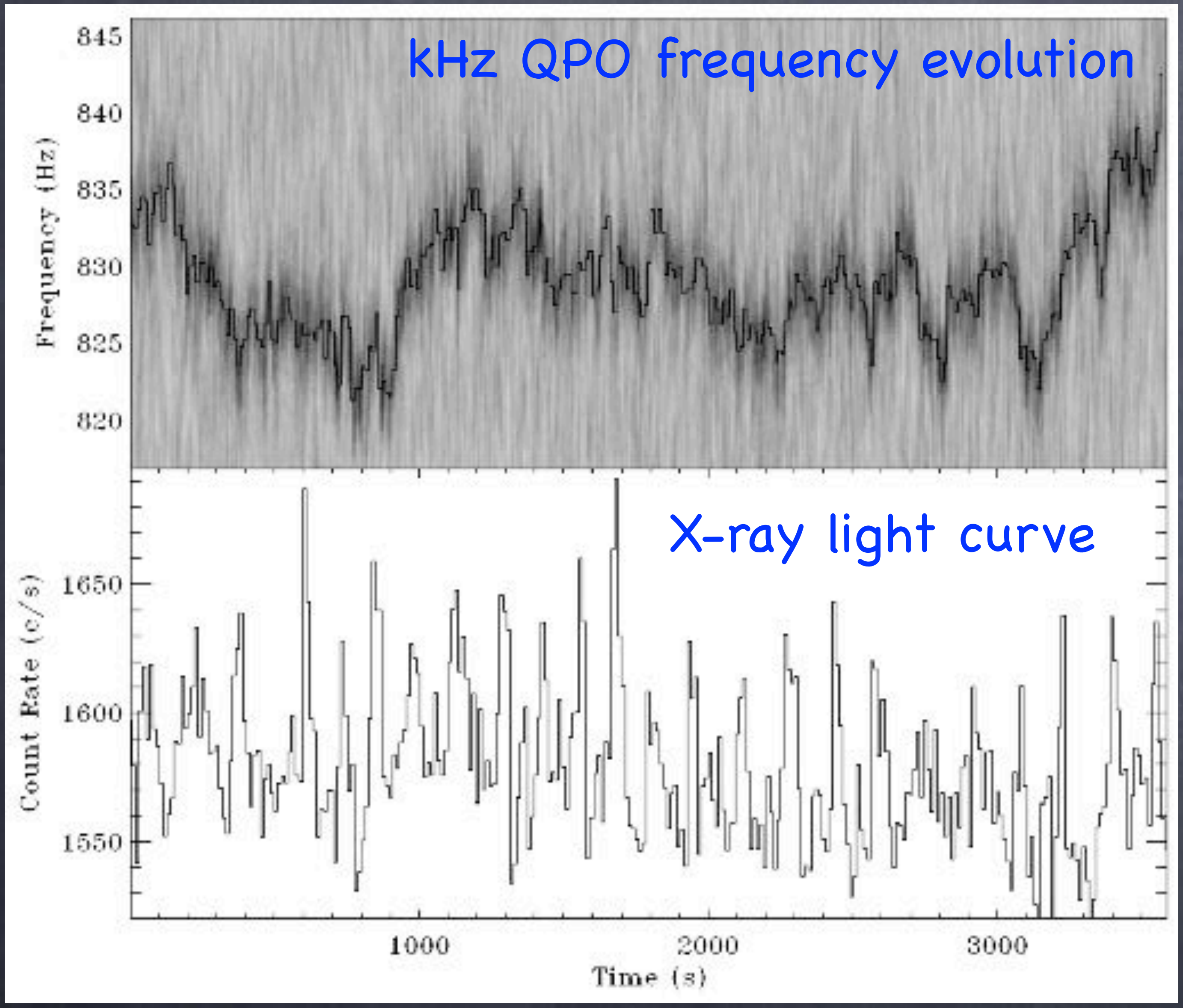


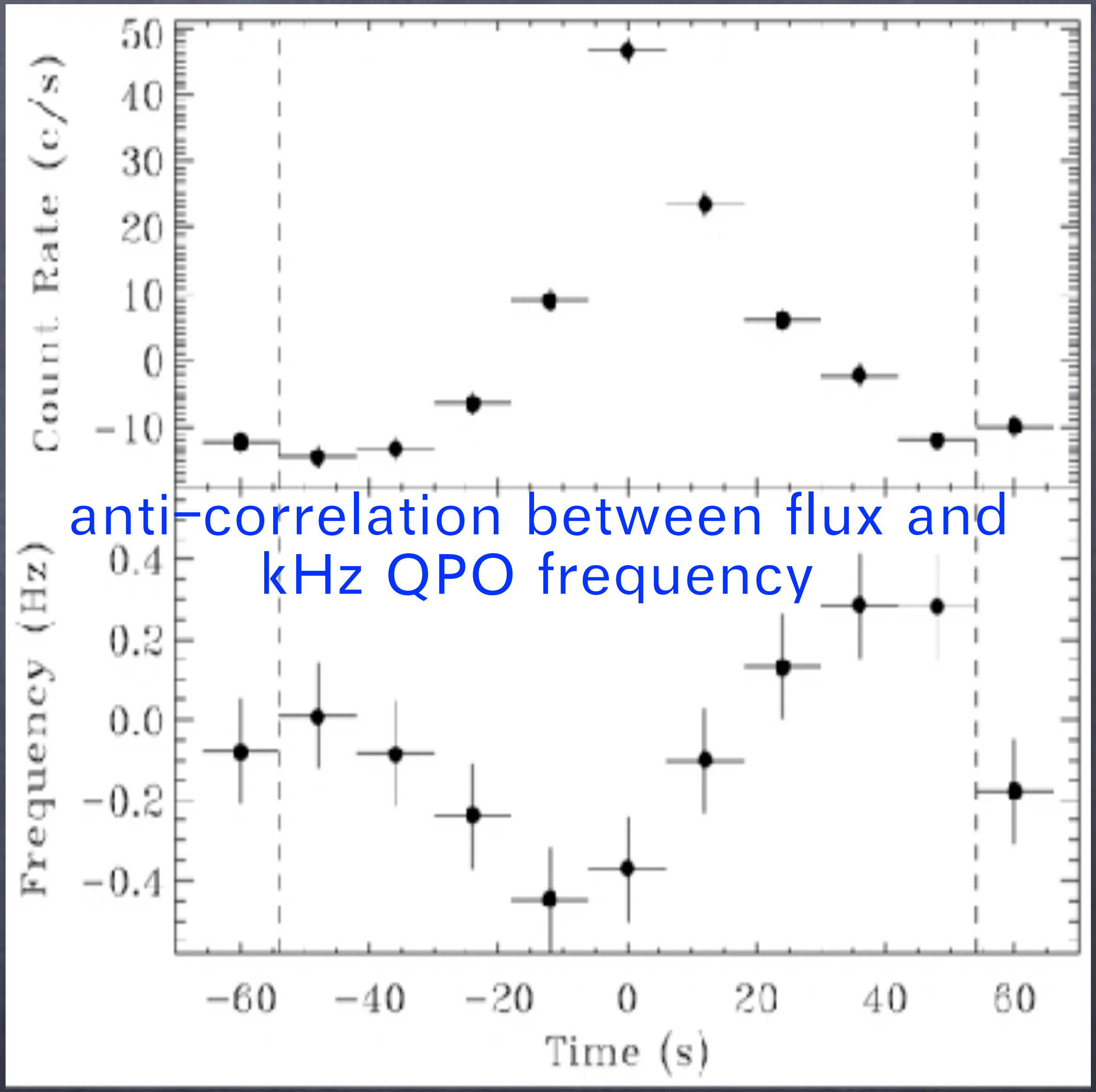


Coupling between the mHz QPO and the kHz QPO

providing evidence that the mHz QPO emission originate from inside the inner disk

Yu and van der Klis 2002, ApJL



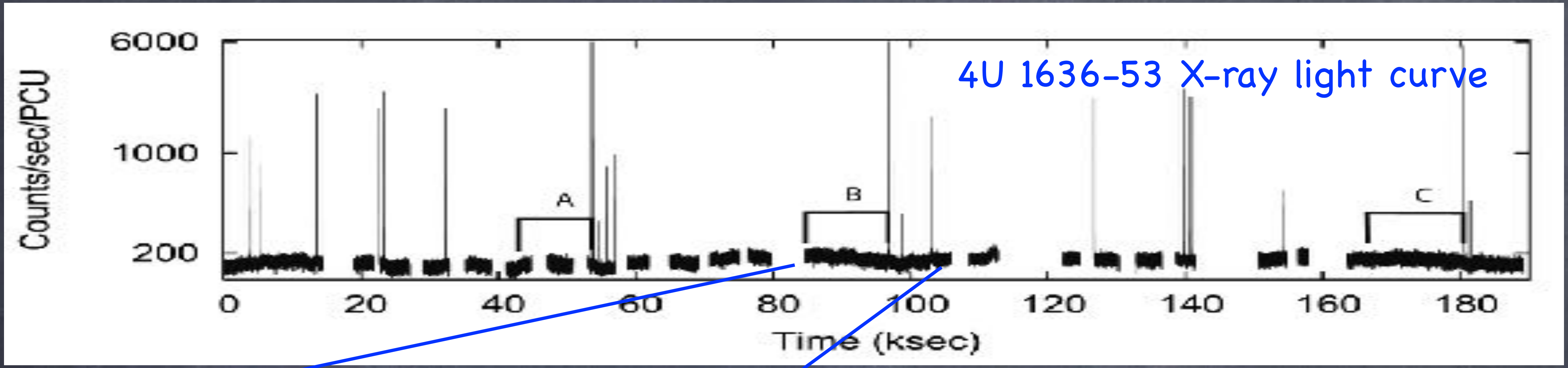


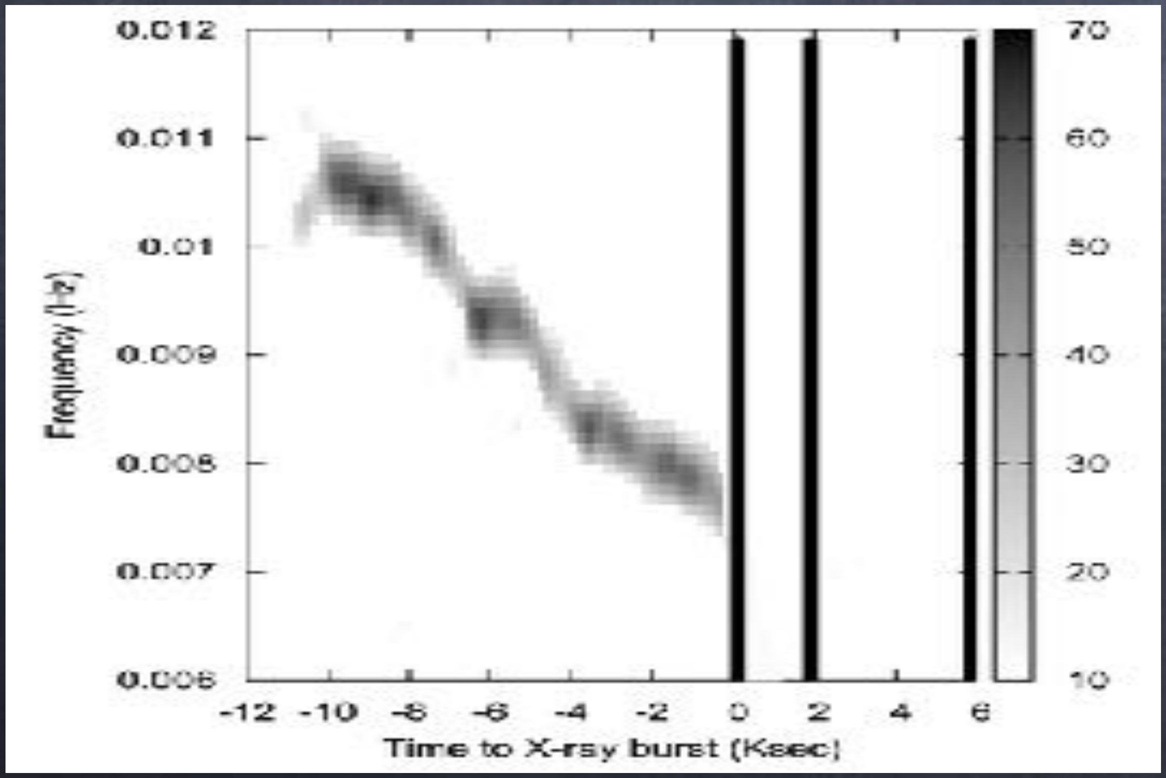
Evidence that the mHz QPO flux comes from inside the inner most edge

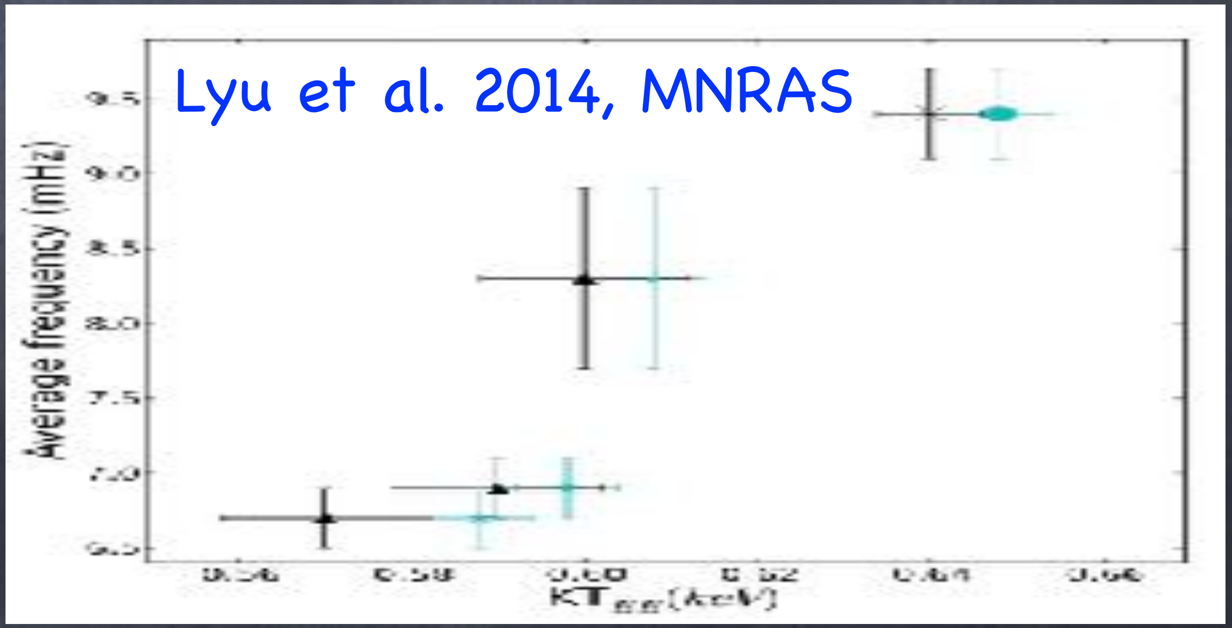
mHz QPO and type I bursts

Evidence for mHz QPO as marginally thermonuclear burning on NS surface

Altamirano et al. 2008, ApJL





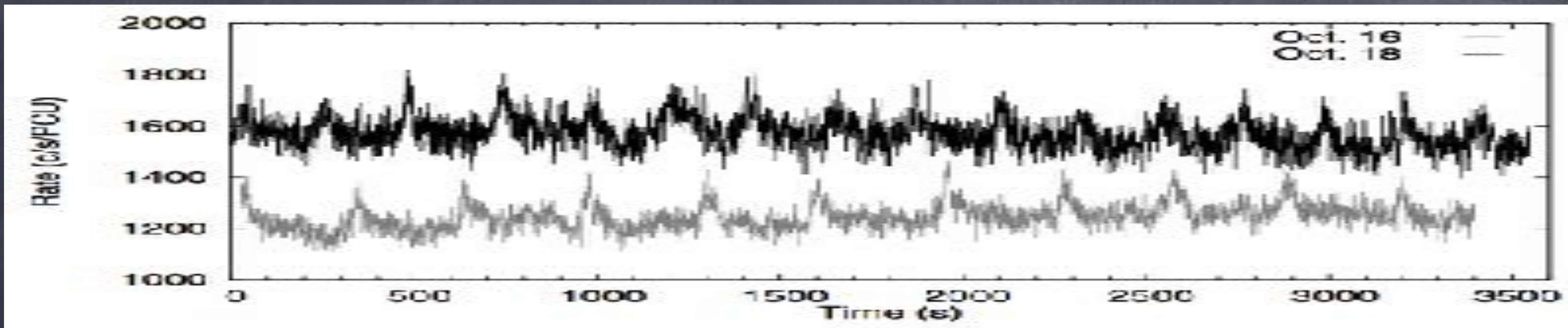


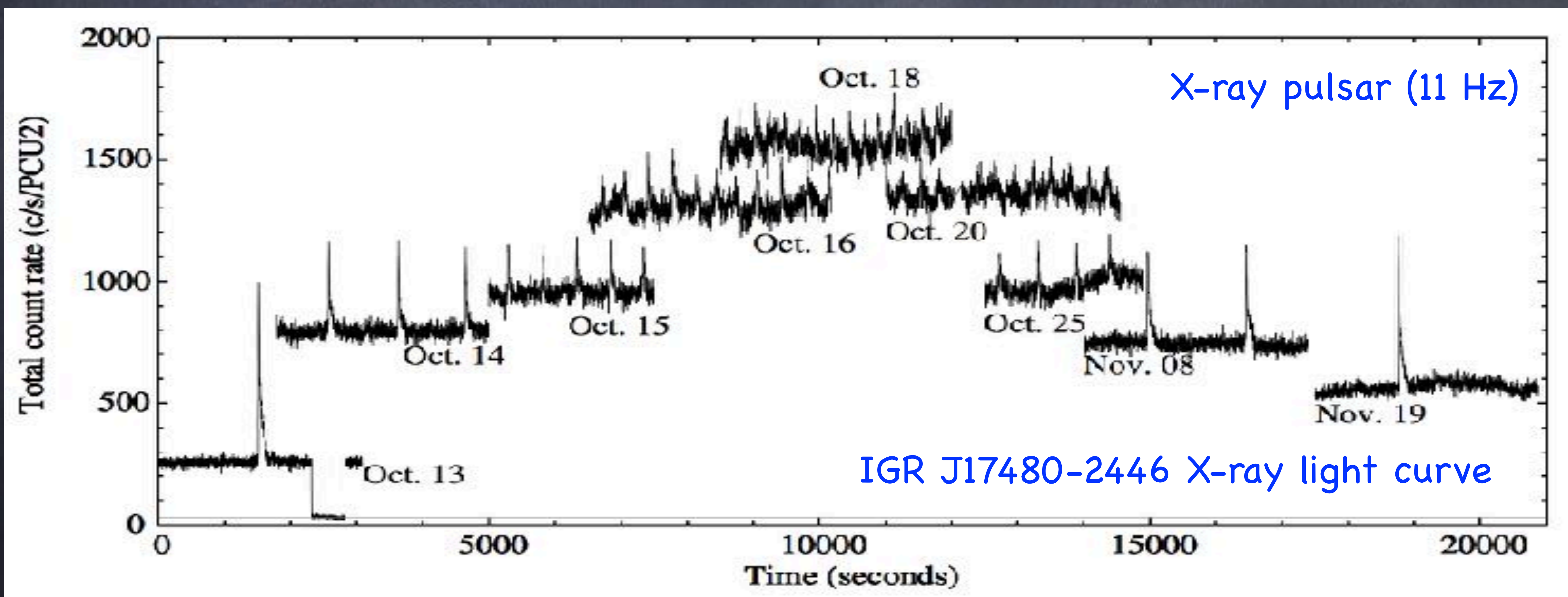
mHz QPO frequency correlates with NS temperature

mHz QPO and Outburst Flux Evolution

Evidence for marginally thermonuclear burning on NS surface

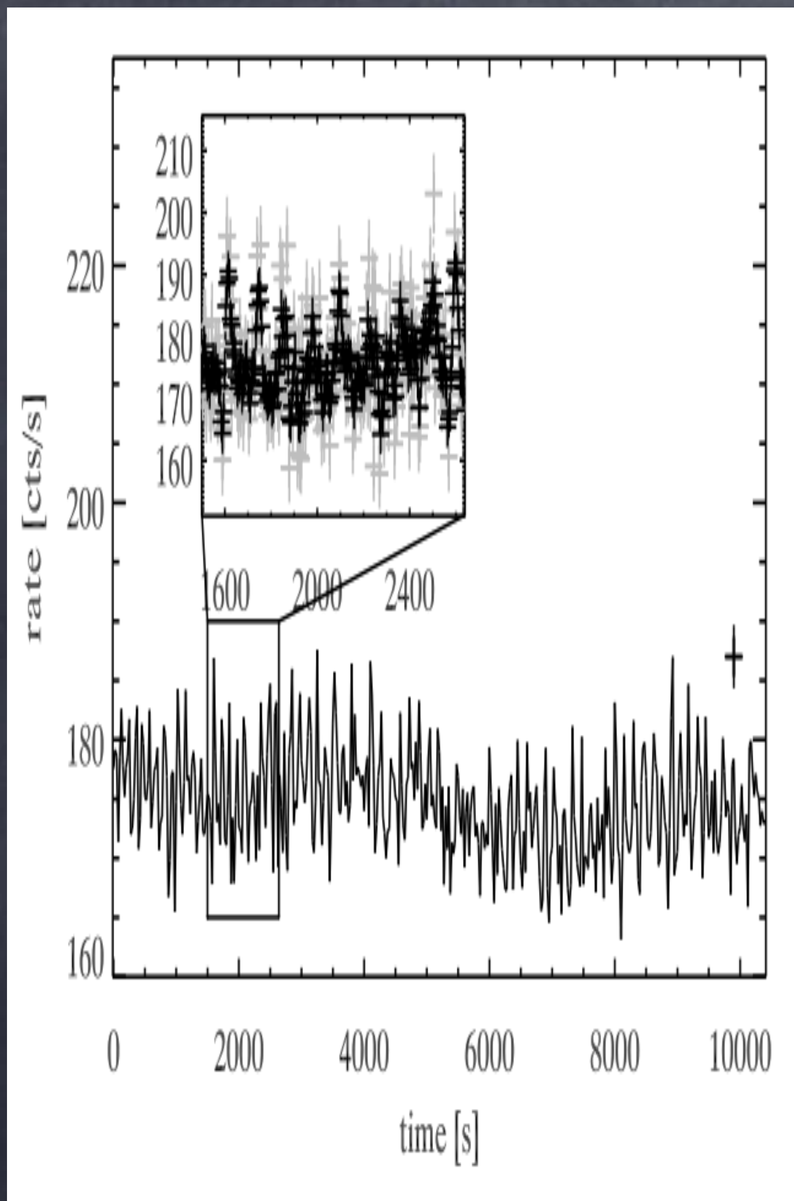
Linares et al. 2012, ApJ

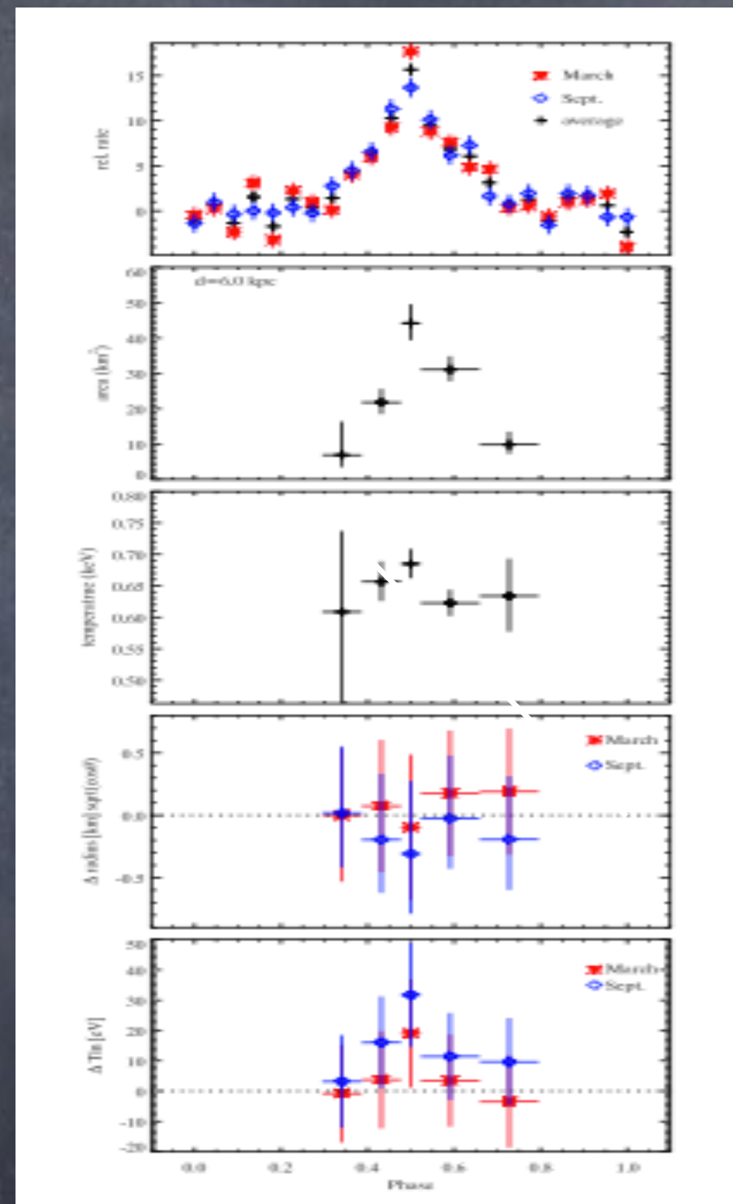




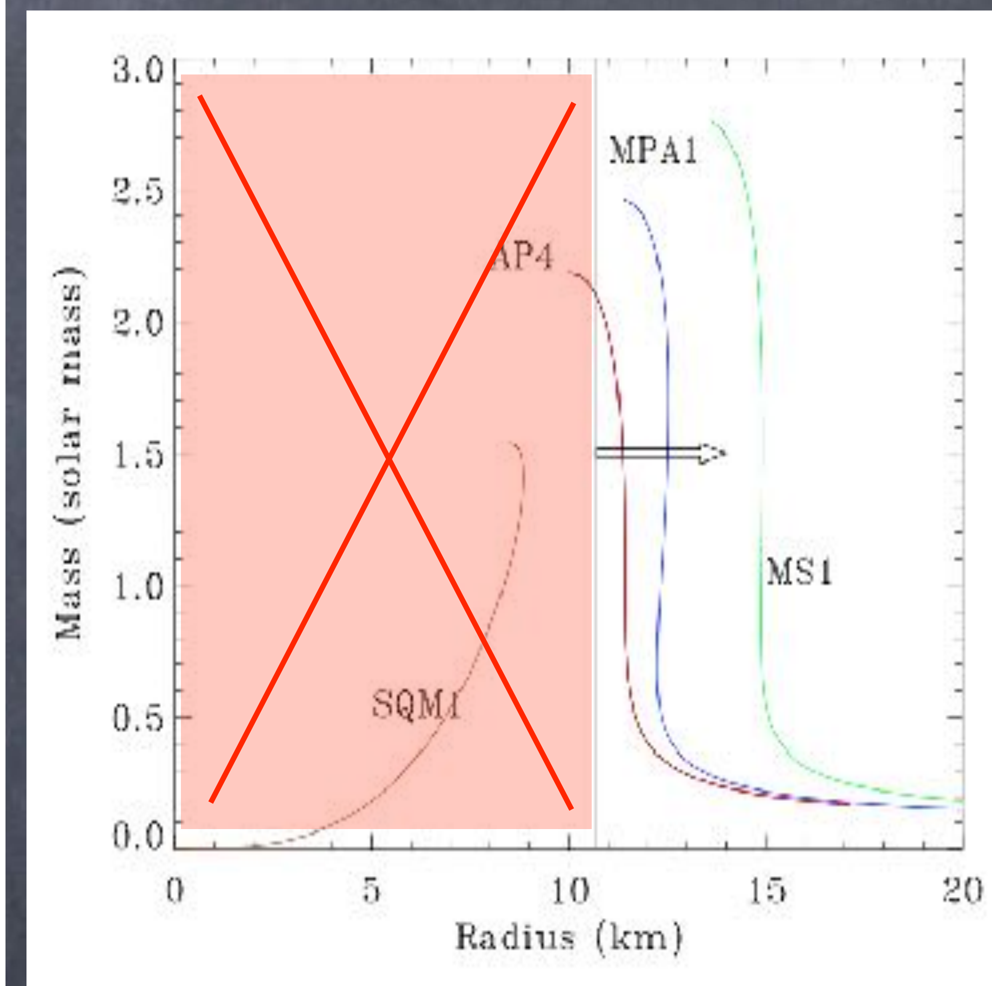
Measure mHz QPO emission area to constrain NS radius

Average results from XMM observations on 4U 1636-53 (also Stiele's talk)





Stiele, Yu & Kong 2016, ApJ



XMM-Newton is not able to resolve individual mHz QPO pulse, but eXTP will do.

- mHz QPO maximum amplitude gives the maximum emission area
- Inclination matters

Strategy for eXTP on mHz QPOs

The key points:

- eXTP will resolve individual mHz QPO pulses for NS LMXBs in the Galactic Bulge
- The maximum pulsed mHz QPO emission matters: push NS radius to larger radii

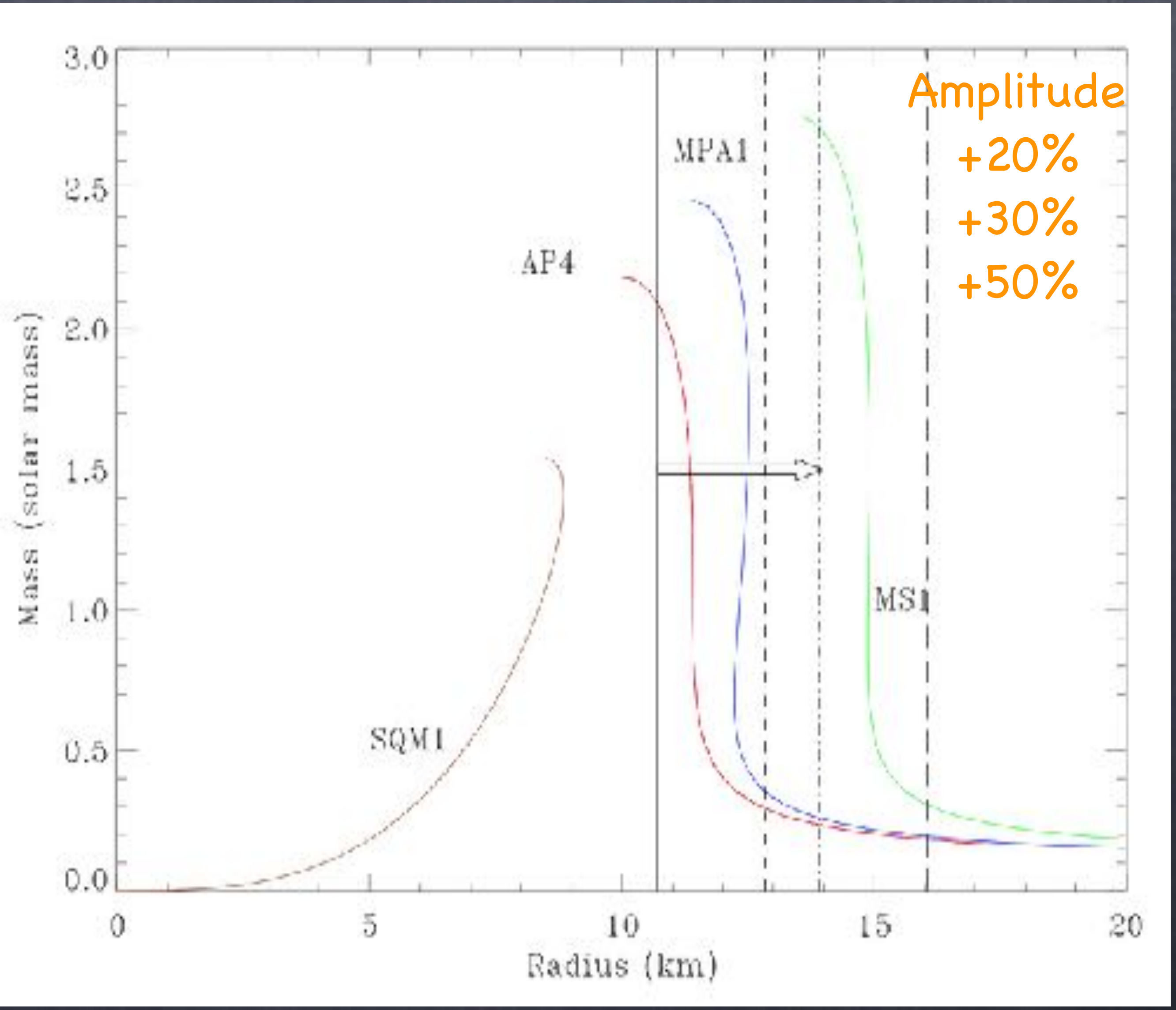
The Strategy:

- We need ToO observations, targeted at specific range of source flux
- Accumulate mHz observations for each individual NS LMXBs:

   1. Search for the mHz QPO pulses with the largest amplitude in each individual NS LMXBs

   2. Determine the upper boundary of the mHz QPO amplitude statistically

   3. Comparison among sources



Summary

Observations of QPOs in NS LMXBs provide much rich data sets than the data sets intended for the use to probe NS EOS in the methods presented in previous talks.

eXTP observations of kHz QPOs and mHz QPOs in NS LMXBs can put independent constraints on NS EOS, likely as good as other methods for the eXTP science.

The use of mHz QPOs to constrain NS EOS has an advantage over the use of PRE bursts, since mHz QPOs can only introduce small perturbation to the accretion flow and the NS environment.