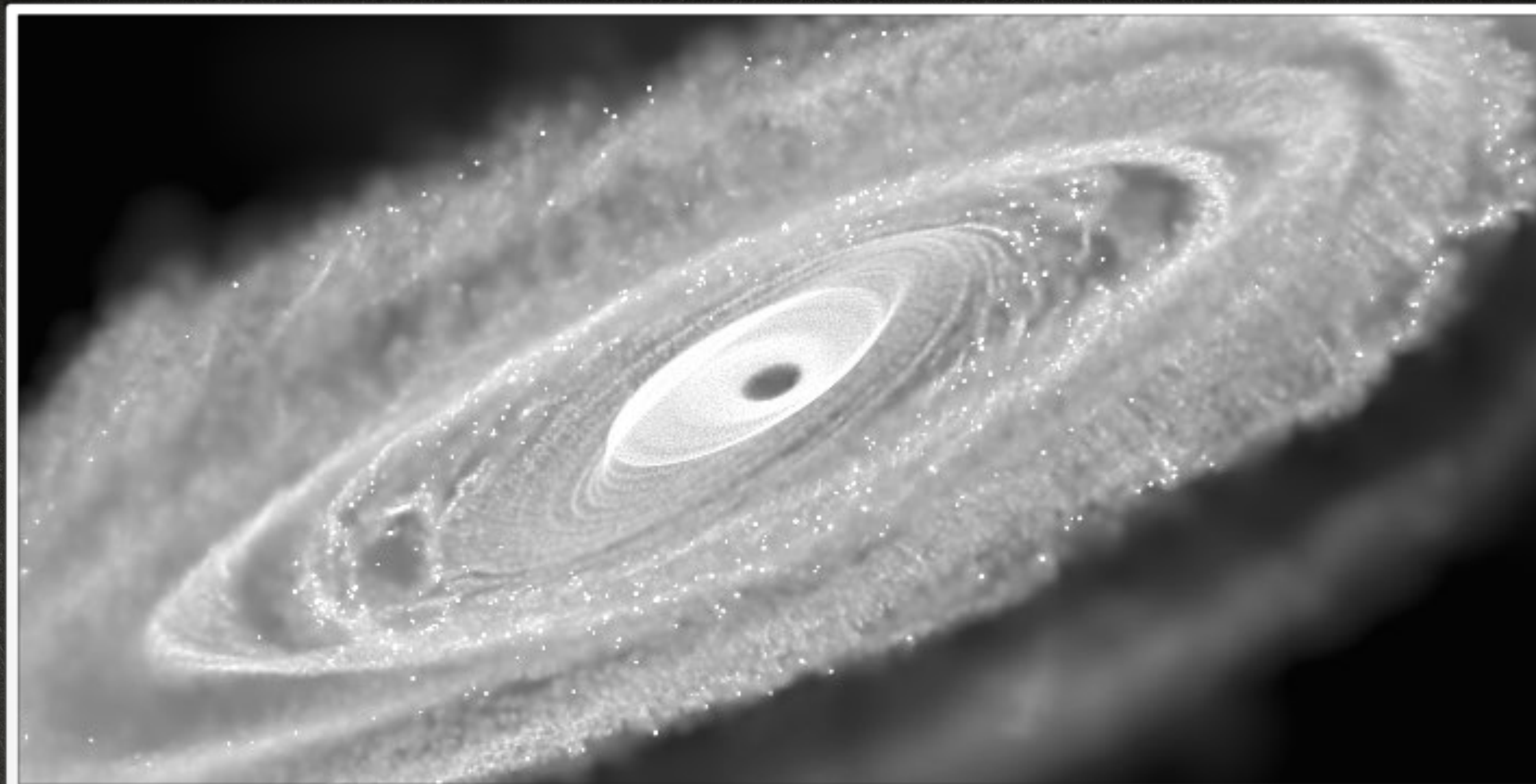
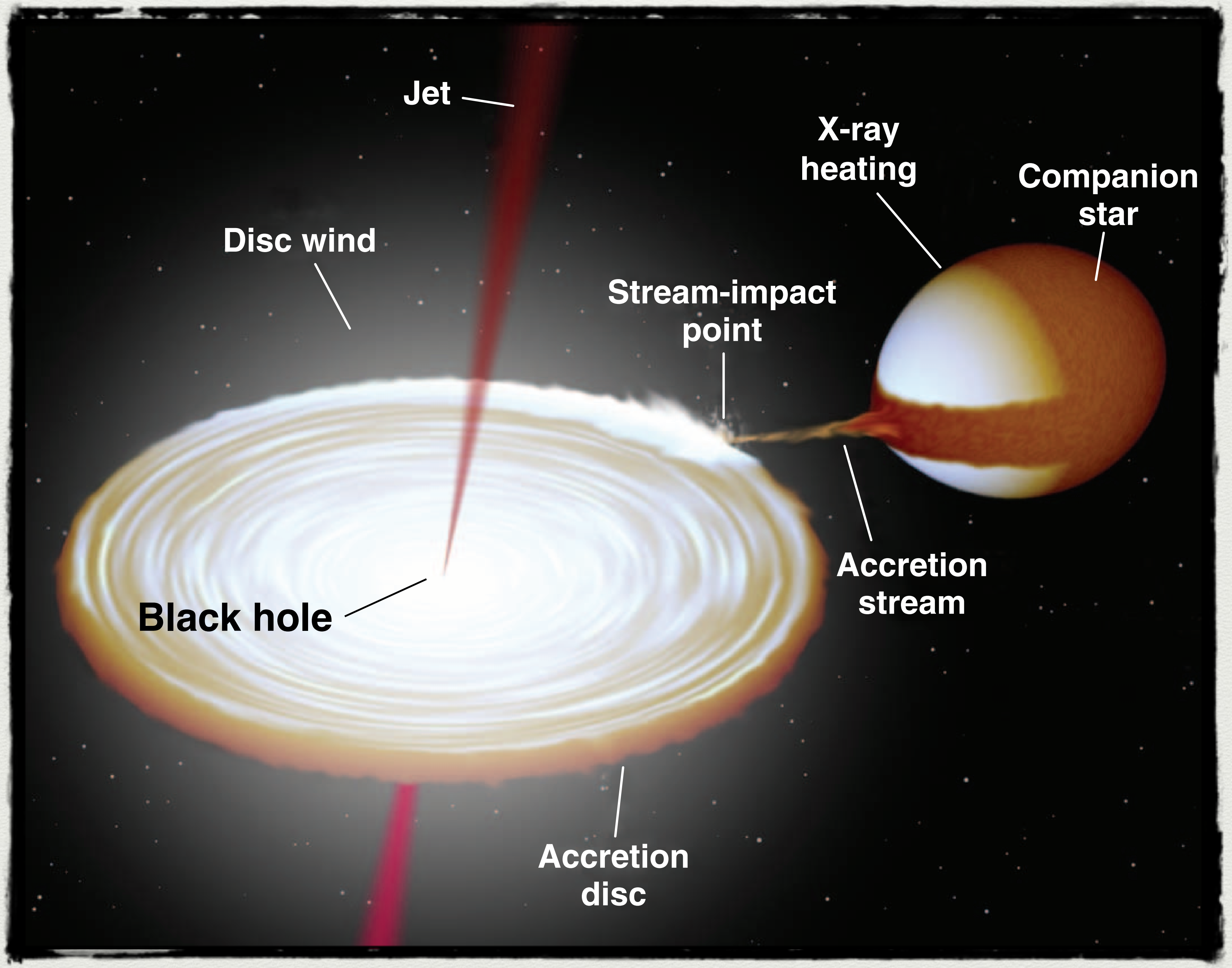


QUASI PERIODIC OSCILLATIONS IN BLACK HOLE BINARIES

Sara E. Motta

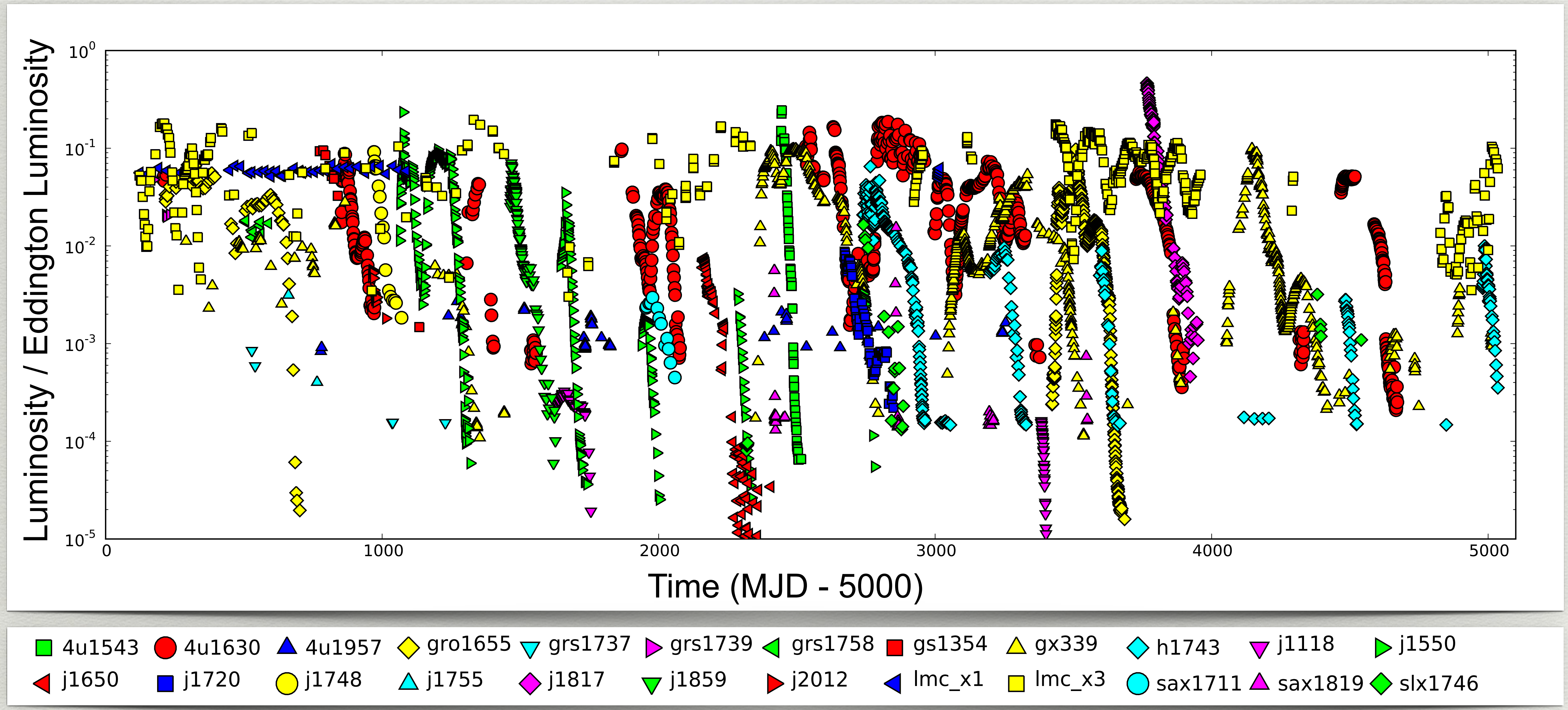
2016 July, 21st

X-ray binaries



Fender & Belloni 2012

X-ray binaries: they vary!



14 years

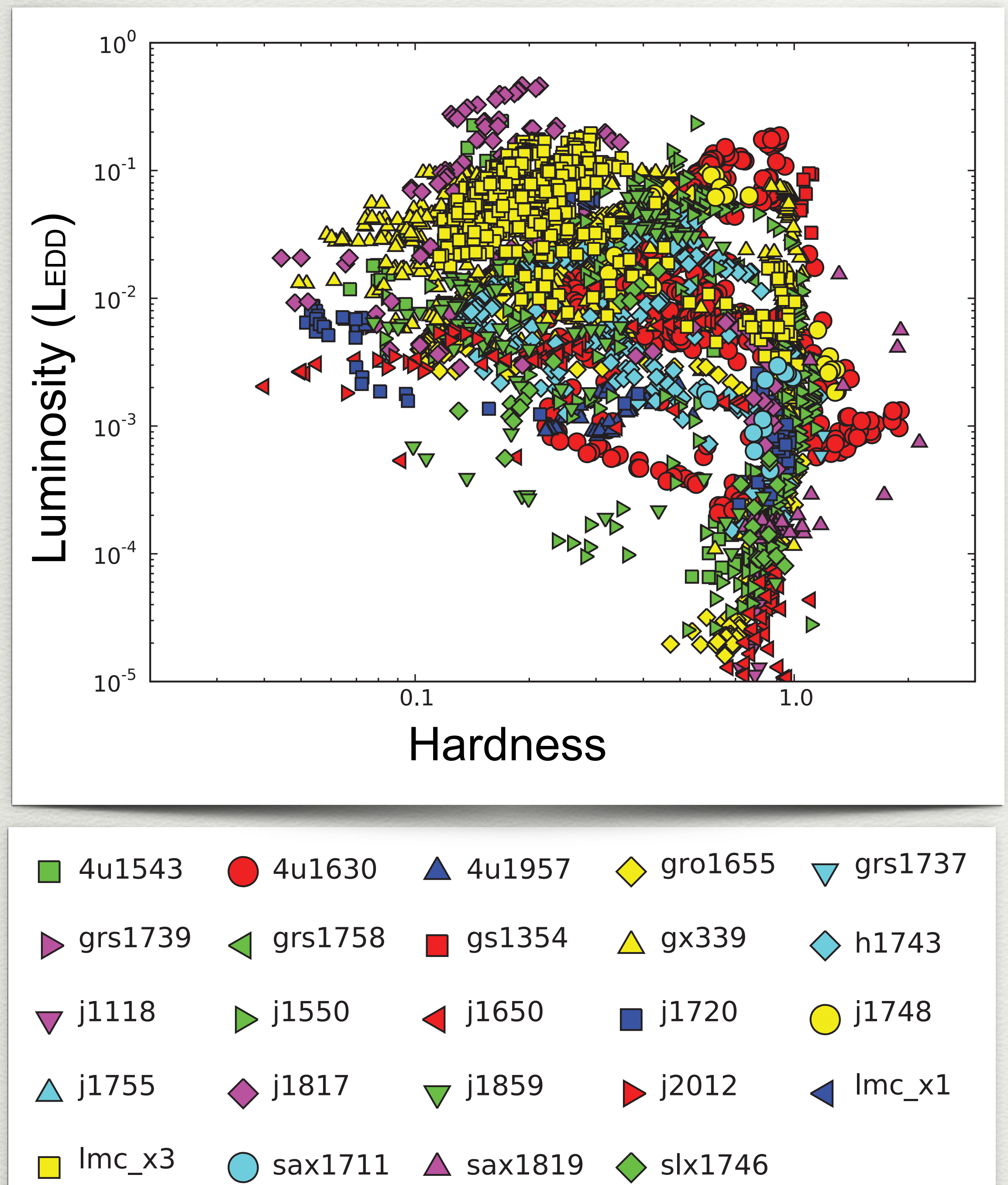
24 BH transients in the RXTE era

Dunn et al. 2010

X-ray binaries: they vary!

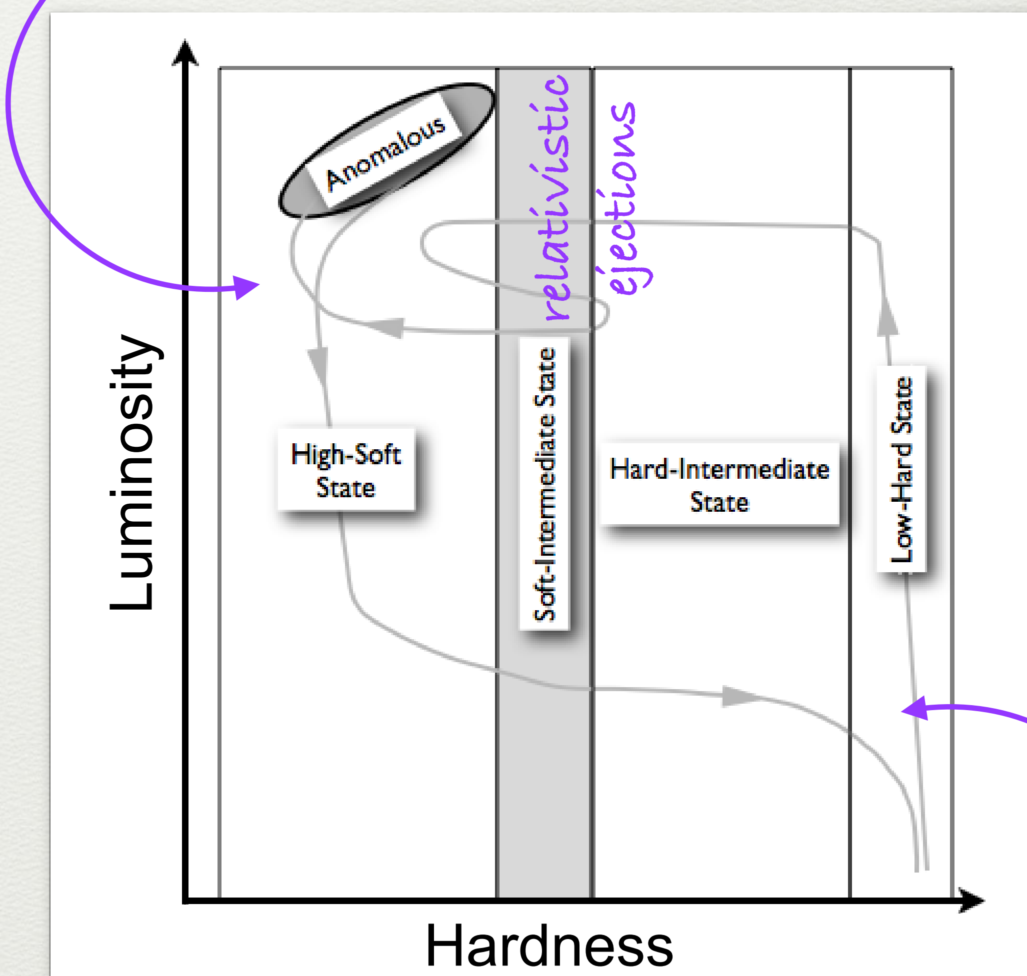
Hardness Intensity diagram

Dunn et al. 2010



SOFT STATES

Disk emission dominates
Low variability
No Jet



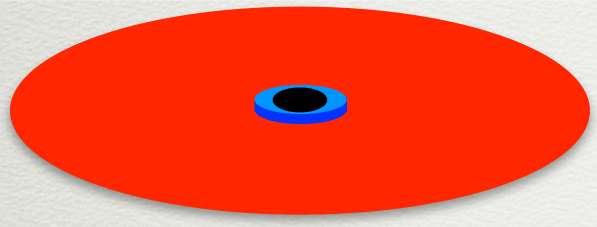
relativistic ejections

Homan et al. 2001

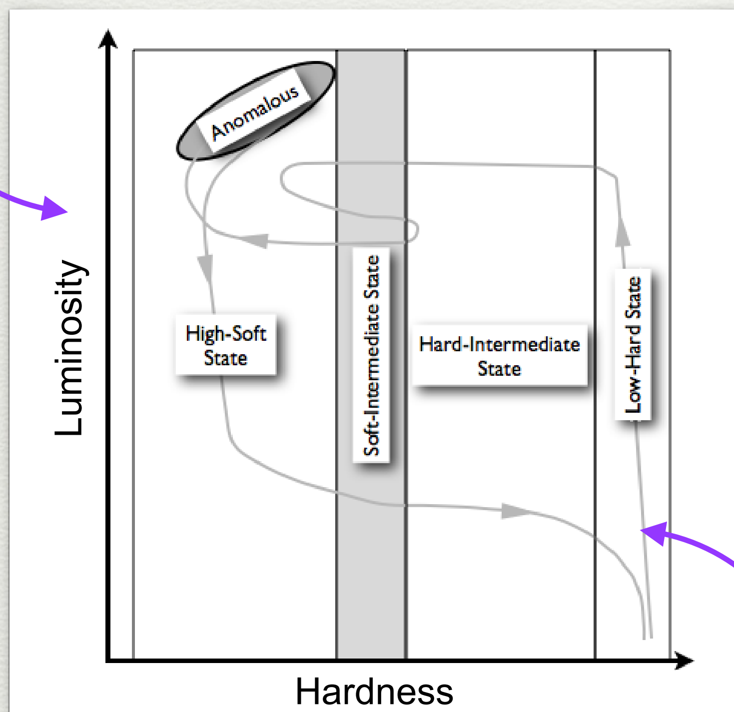
Hard emission dominates
High variability
Steady radio jet

HARD STATES

X-ray binaries: they vary!

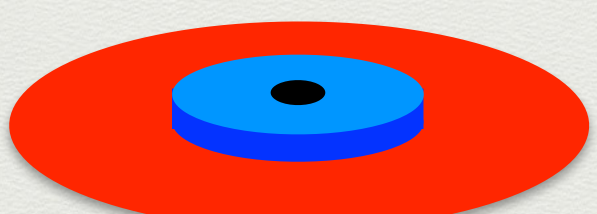


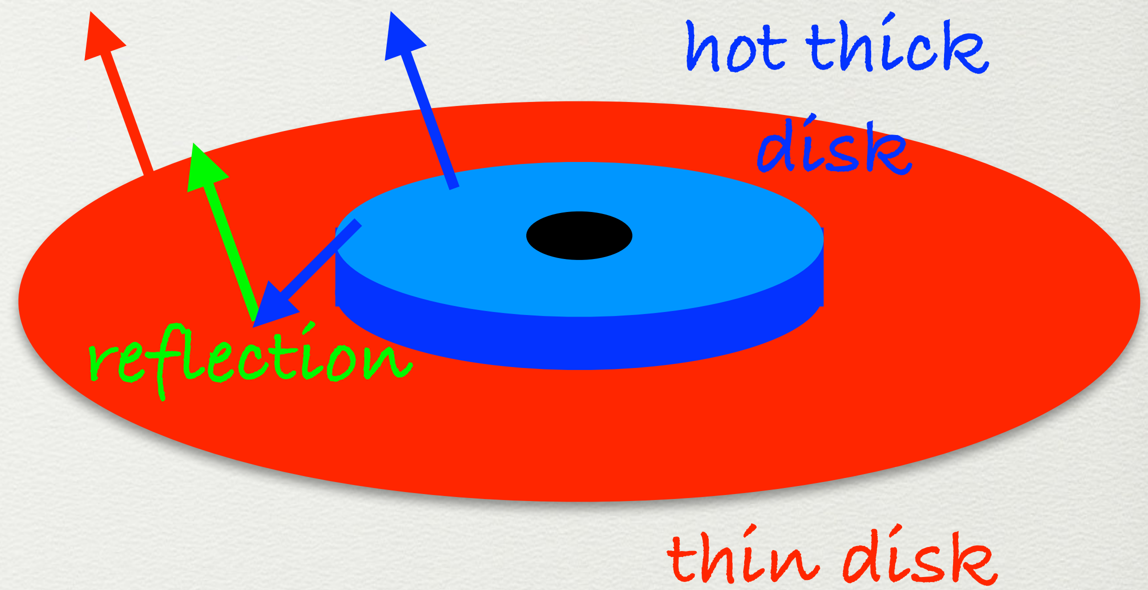
small
truncation radius

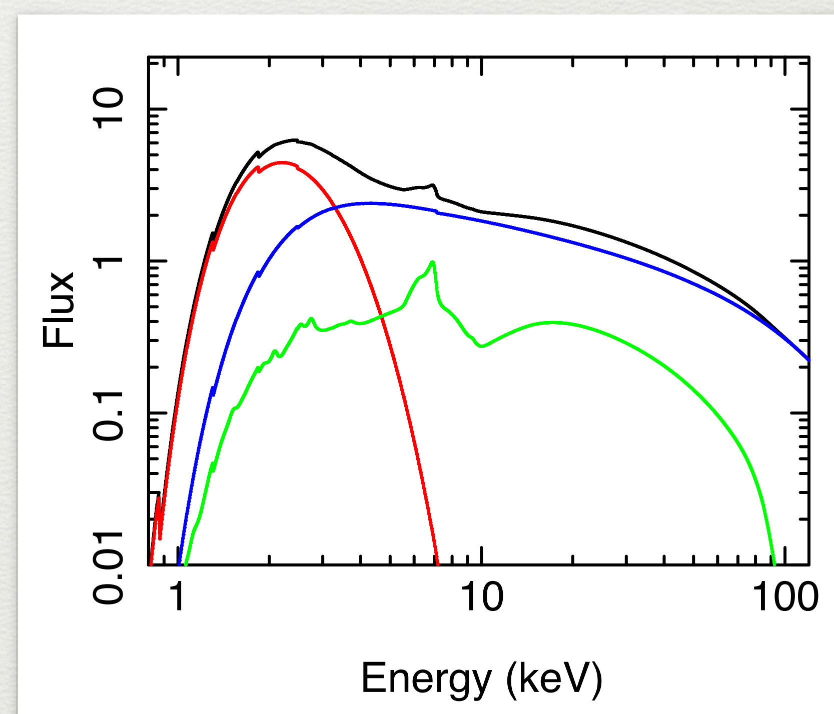


Homan et al. 2001

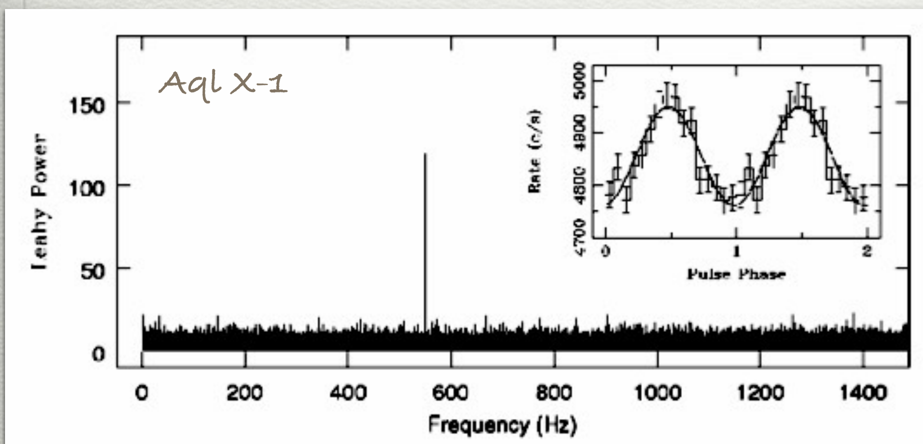
large
truncation radius





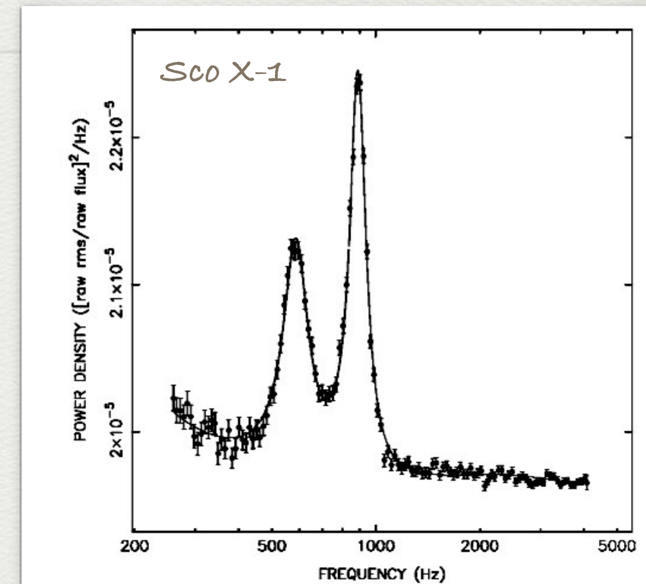


…on several timescales

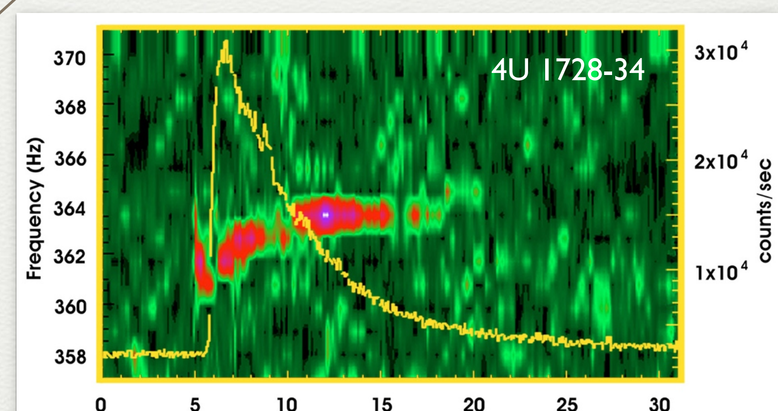


Pulses from accreting X-ray pulsars

kHz QPOs



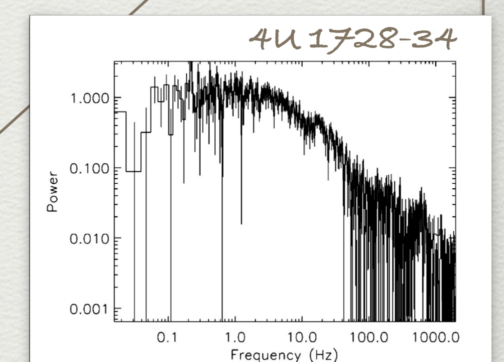
Burst Oscillations



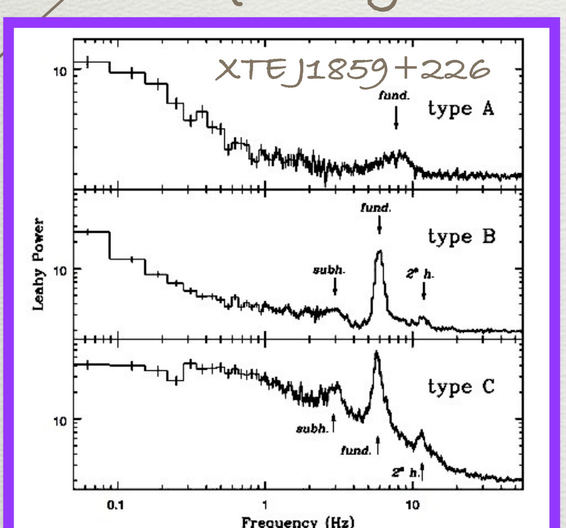
Periodic variability

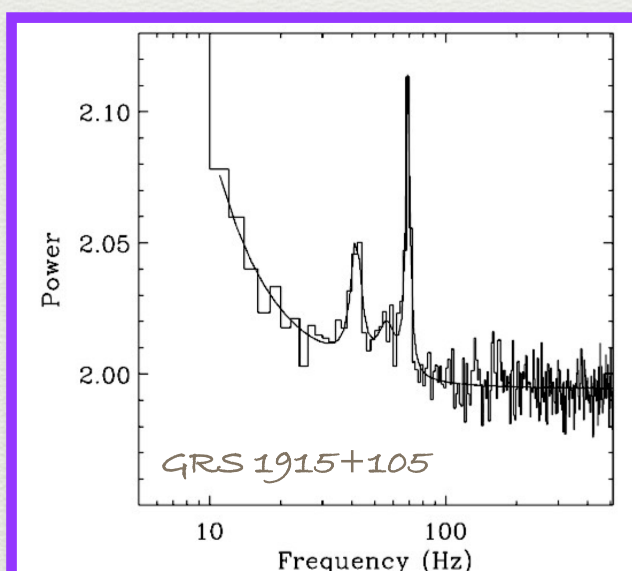
Quasi periodic variability

Aperiodic variability



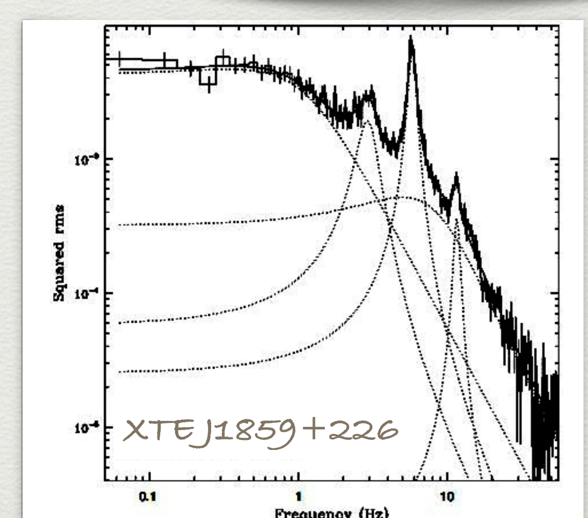
Low Frequency QPOs





High Frequency QPOs

Broad band Noise

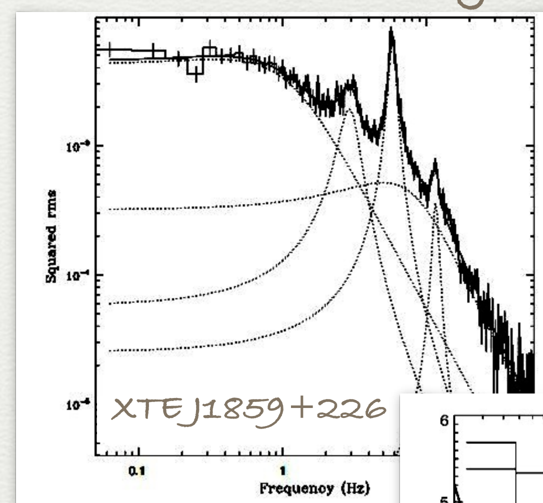


What is a QPO?
Quasi-Periodic Oscillation

- Quasi periodic signal in the flux
  (CVs, BHs, NSs, ULXs, even AGN)
- Becomes apparent in a power density spectrum
- They come in different flavours
- Associated to noise

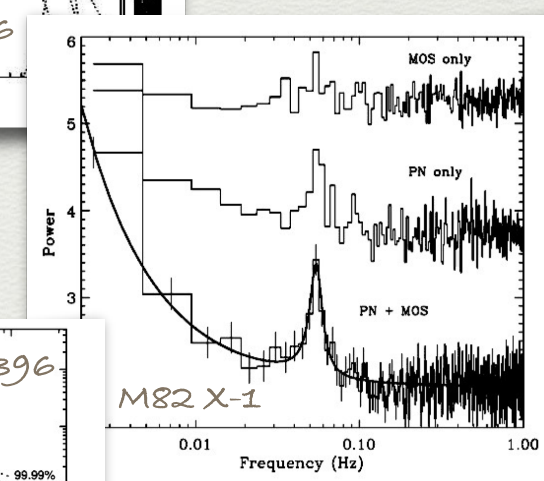
Black Hole binary

Casella et al. 2004



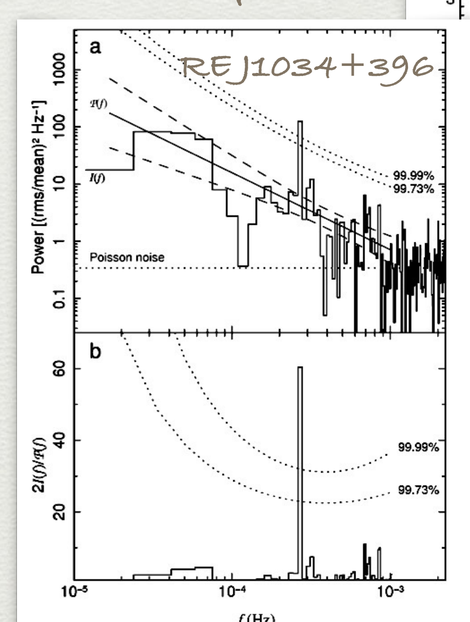
ULX

Strohmayer et al. 2003



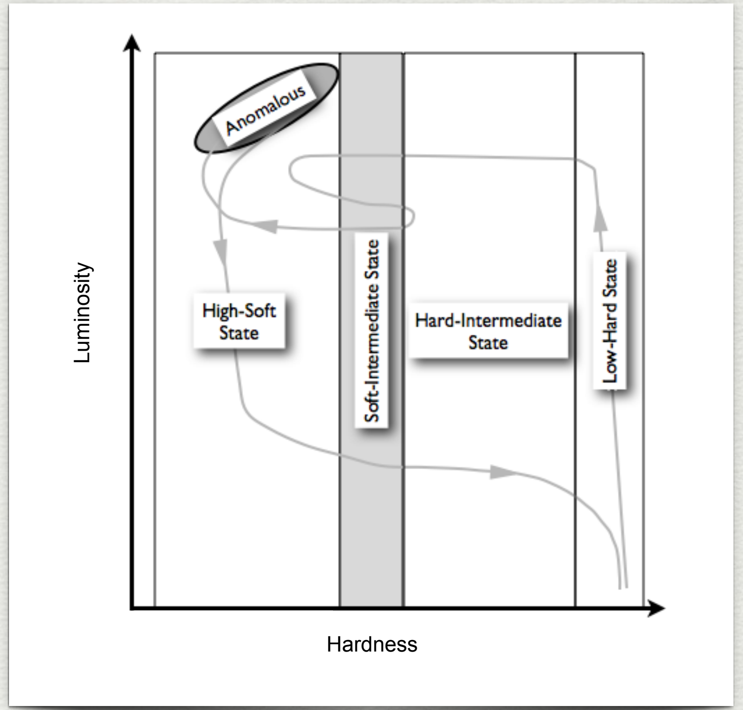
AGN

Gierliński et al. 2008



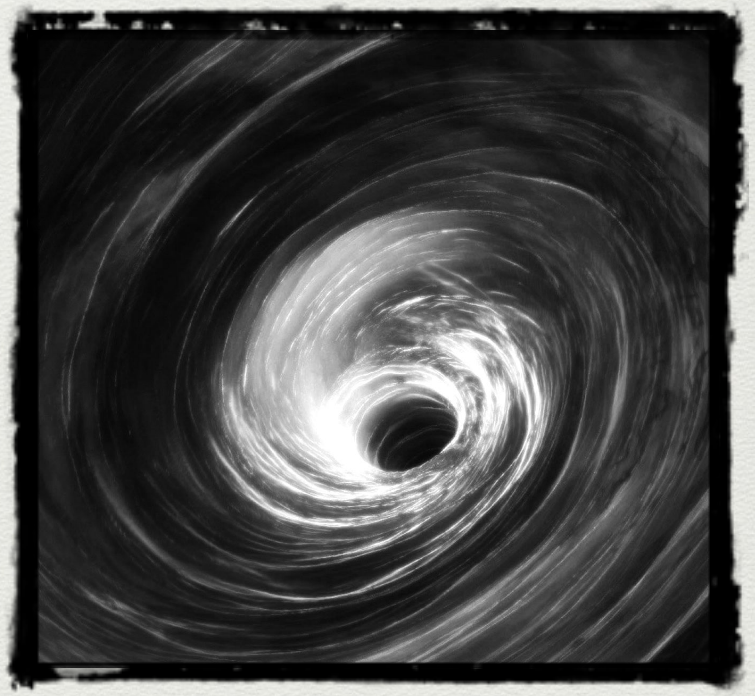
Why should we care?

- They are useful!
  Common and easy to study, they help identifying source states



- Produced close to the central compact object

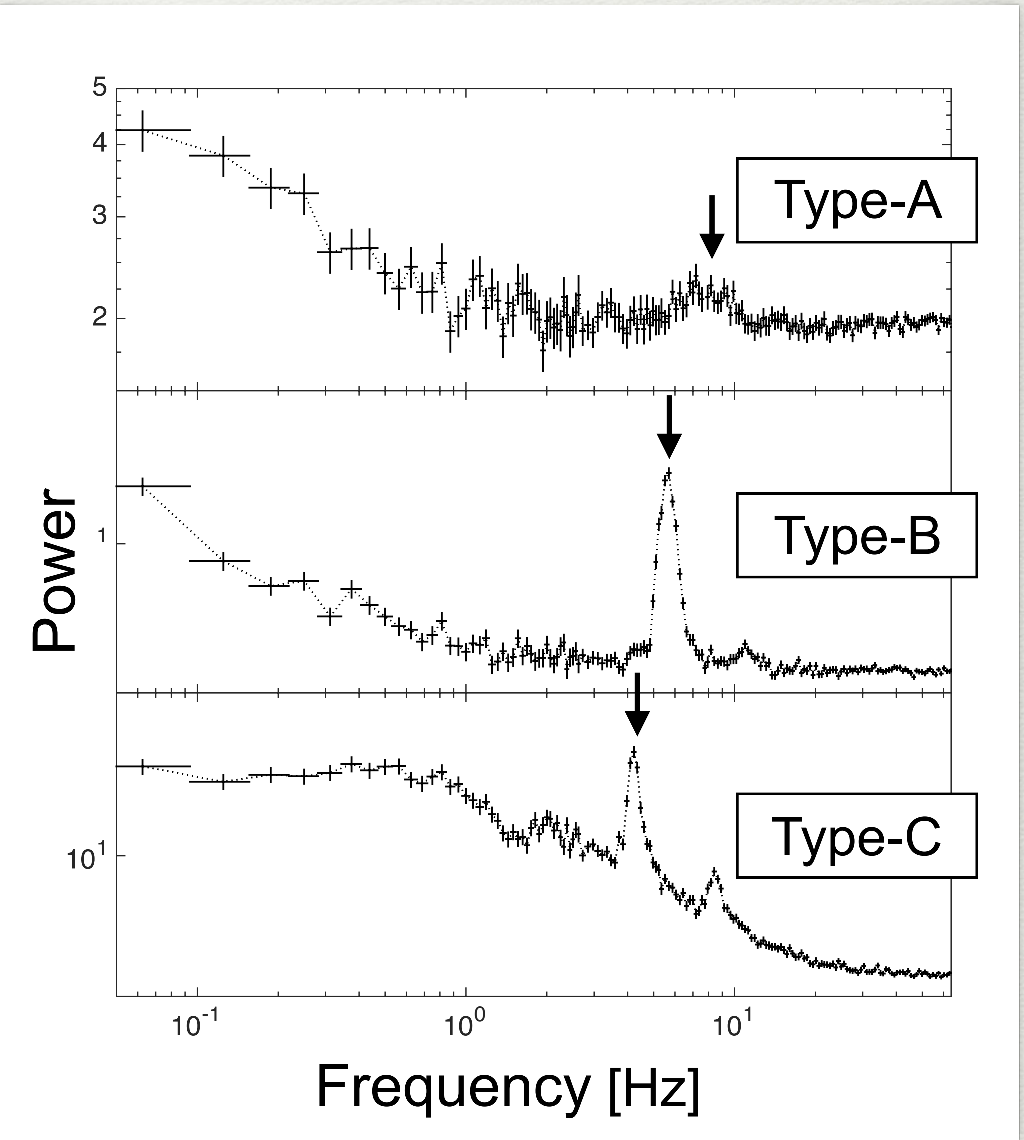
- Geometry constraints and strong gravity tests.



Low frequency QPOs in Black Hole binaries

- Discovered in the 80s in NS (EXOSAT, GX 5-1) and BHs (Ariel 6, GX 339-4)
- First "types" from Ginga data
- Very common
- Seen in NSs as well (HBOs, NBOs, FBOs…)

0.1 - 30 Hz



Motta et al. 2011

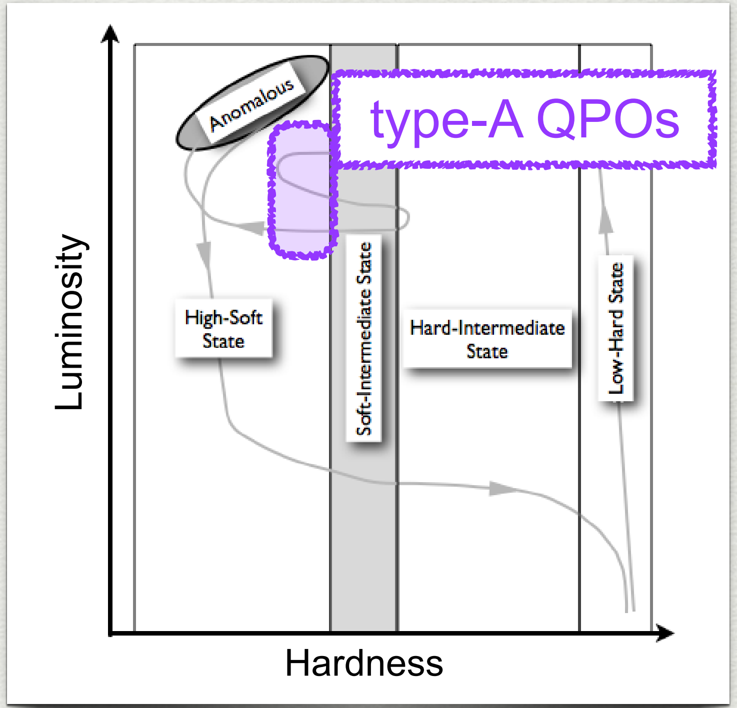
	A	B	C
ν	$\sim$6 Hz	$\sim$6 Hz	0.1-30 Hz
Q	1-3	$\geqslant 6 (\geqslant 2)$	$\geqslant 6 (\geqslant 2)$
rms	$\sim 1-5\%$	$\sim 1-10\%$	$\sim 1-25\%$
noise	weak red	weak red	strong flat-top

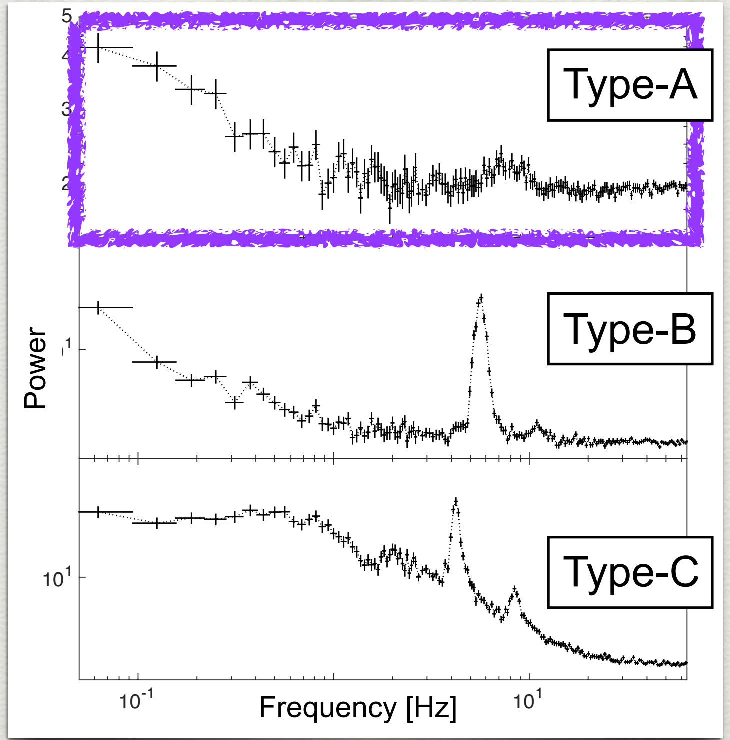
Motta et al. 2015

see e.g. Van der Klis et al. 1985 and Motch et al. (1983), Miyamoto et al. 1991, Wijnands et al. 1999; Homan et al. 2001; Remillard et al. 2002; Casella et al. 2005, …

Type-A QPOs

- Very few detections (~10 in the RXTE archive)
- Observed in soft states, close to type-B QPOs
- broad and faint
- Origin: Disk instabilities? Possibly related to type-B QPOs.

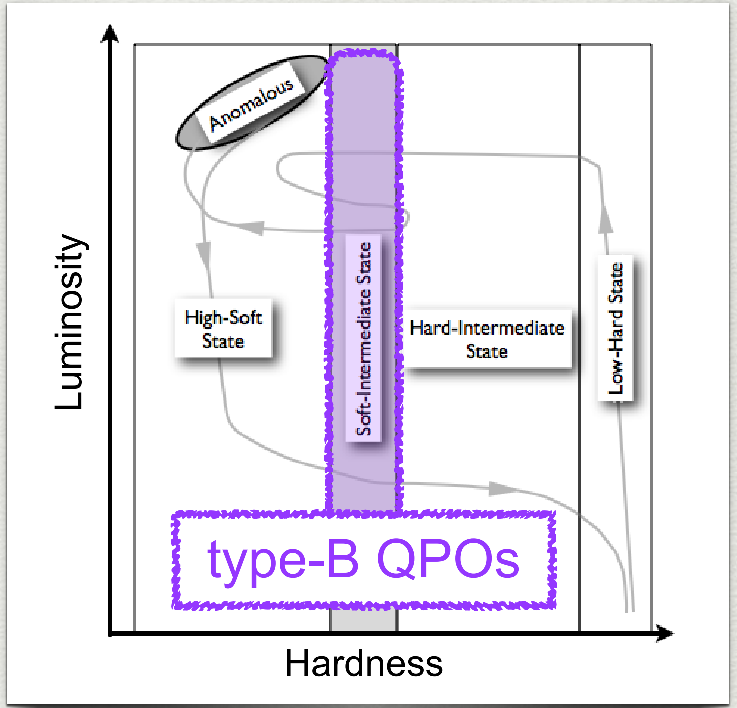


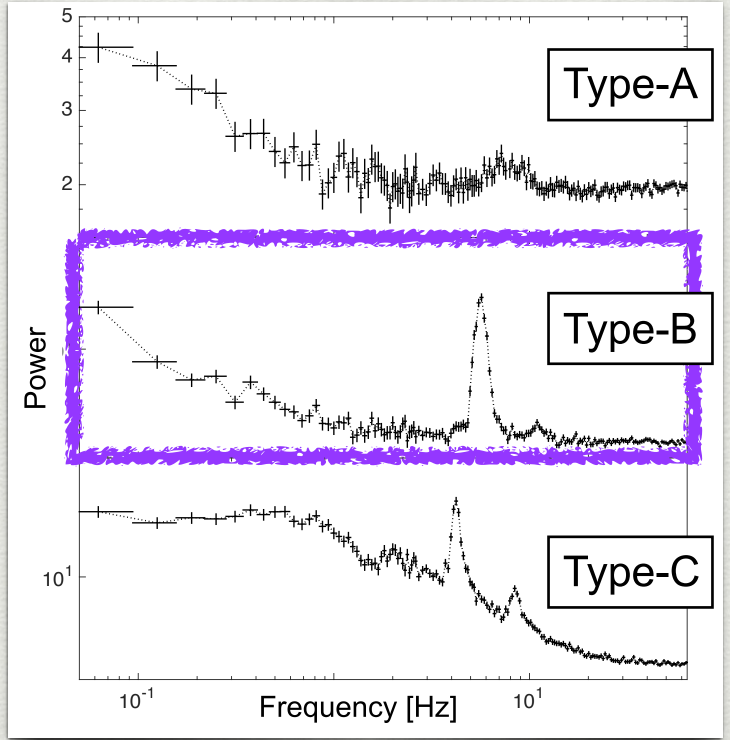


~ 7Hz

Type-B QPOs

- Fairly common QPO
- Observed in intermediate states
- Strong peak(s) and weak red noise
- Origin: probably associated to jets. Disk instabilities? (e.g. Varnière et al. 2002,2012)

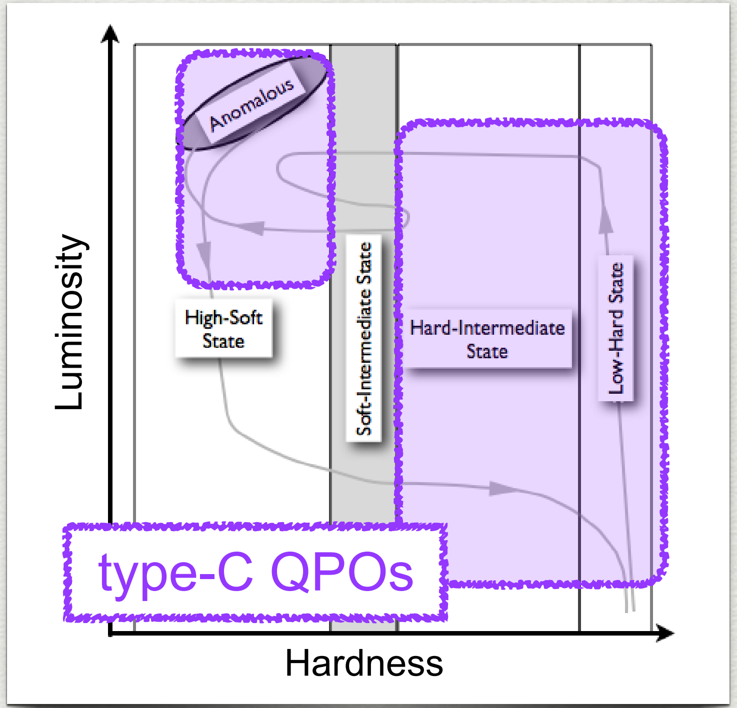


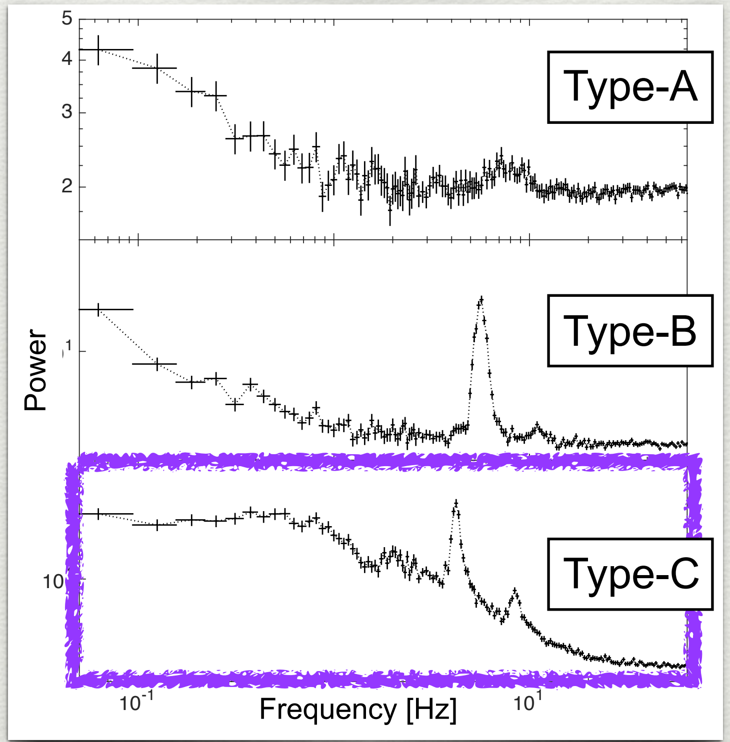


~ 5-7Hz

Type-C QPOs

- The most common QPO of all, they vary a lot in frequency
- Observed in hard and soft states
- Strong peak(s) and strong flat-top noise
- Origin: instabilities or geometrical effects (i.e. precession)





0.1-30Hz

Type-C QPOs

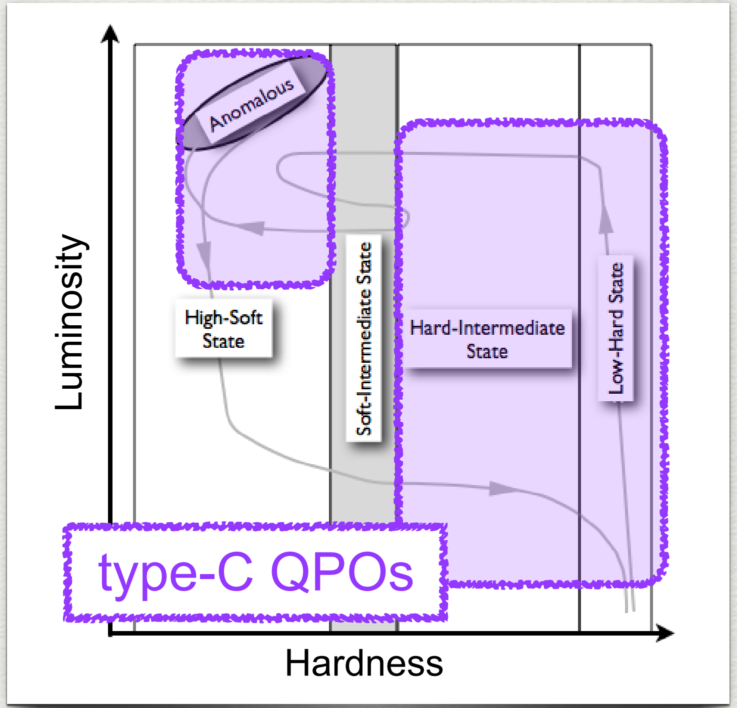
Instabilities

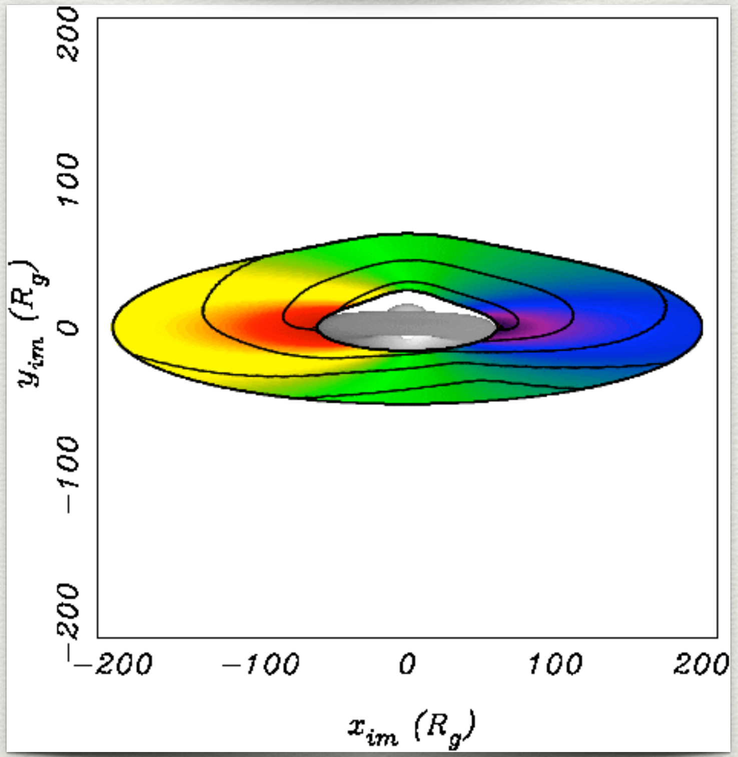
- Oscillations of boundary layers/ coronae
  (e.g. Titarchuk & Fiorito 2004 and Cabanac et al. 2010)

- Accretion-ejection instability
  (Tagger & Pellat 1999 and Varnière et al. 2002,2012)

Geometrical effects

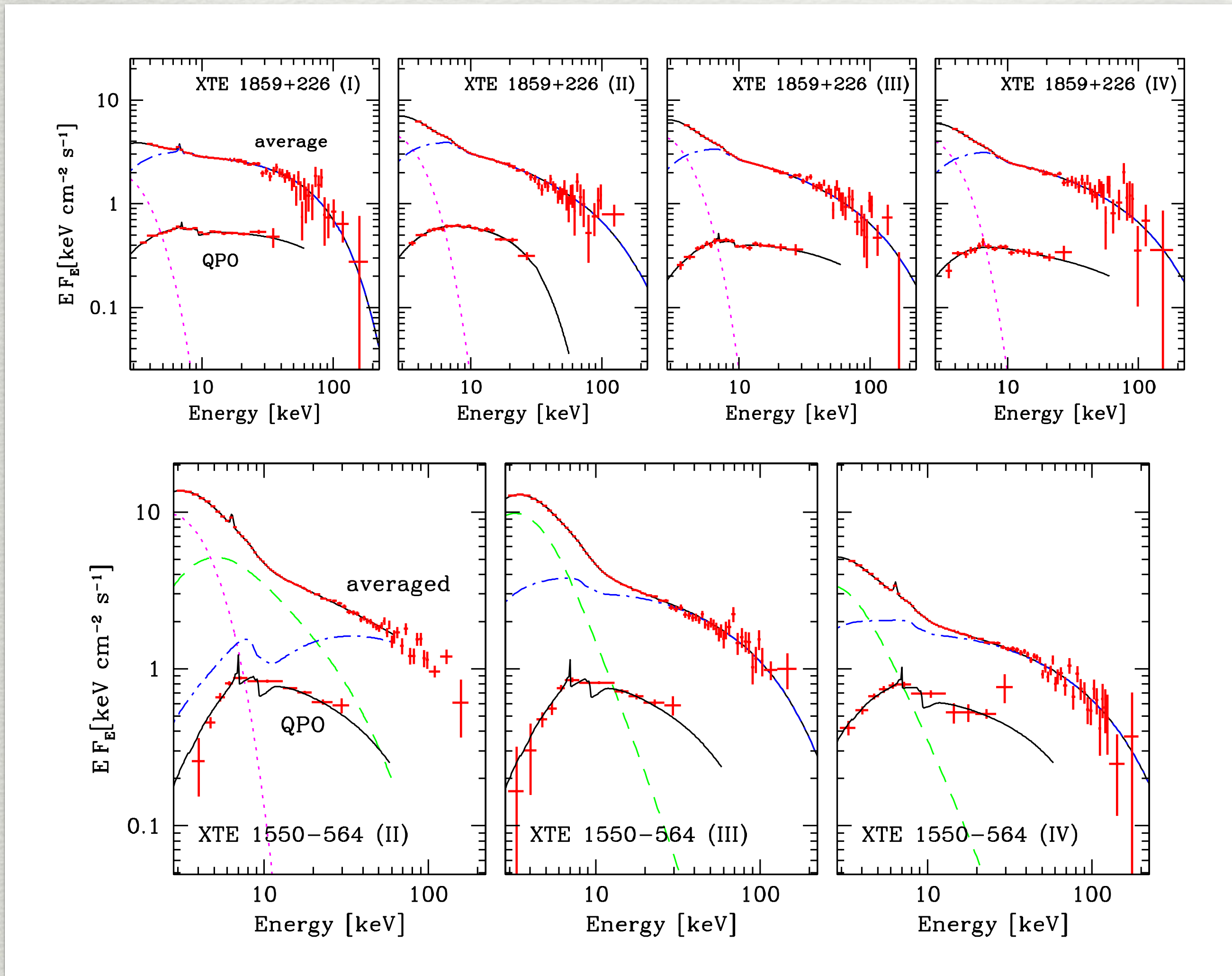
- Relativistic precession
  (Stella & Vietri 1998, Schnittman et al. 2006, **Ingram et al. 2009…16**)



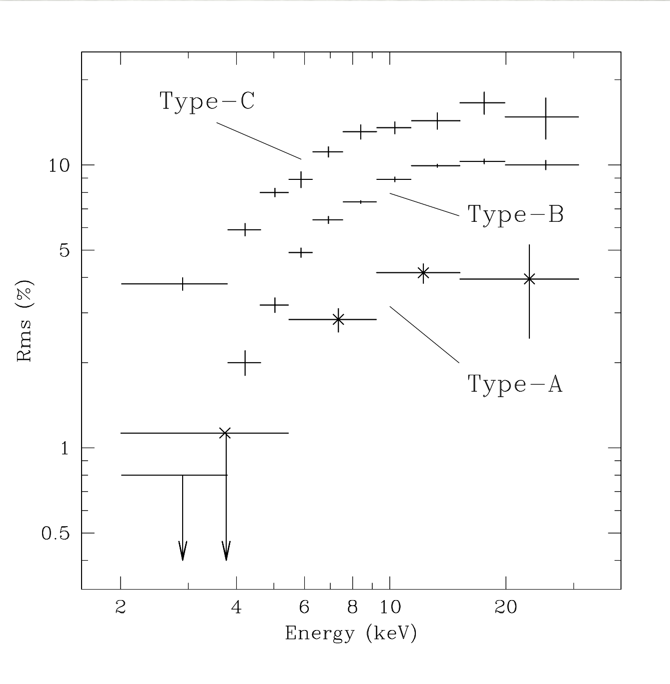


Courtesy of Adam Ingram

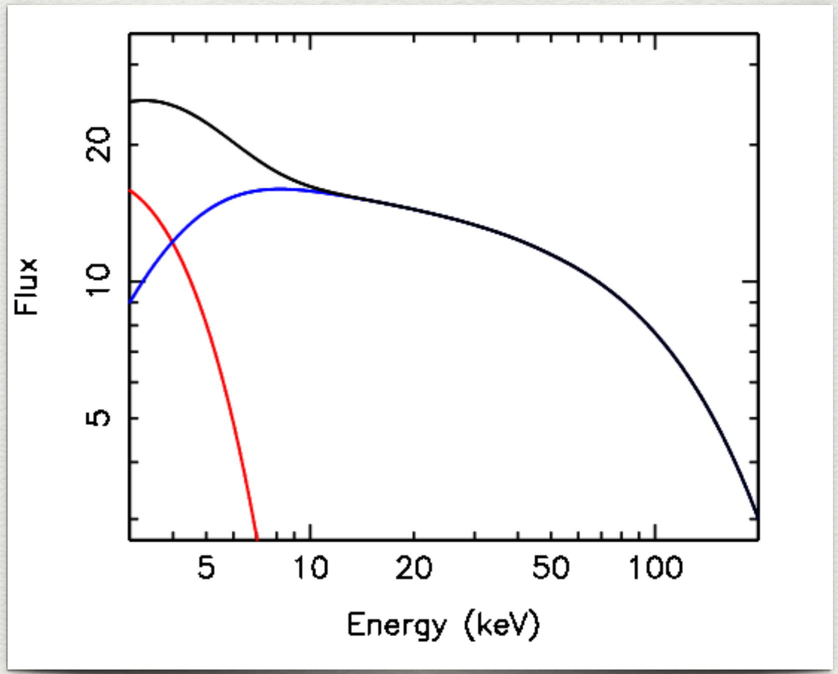
QPO spectrum: it is hard!



Sobolewska & Zycki 2005



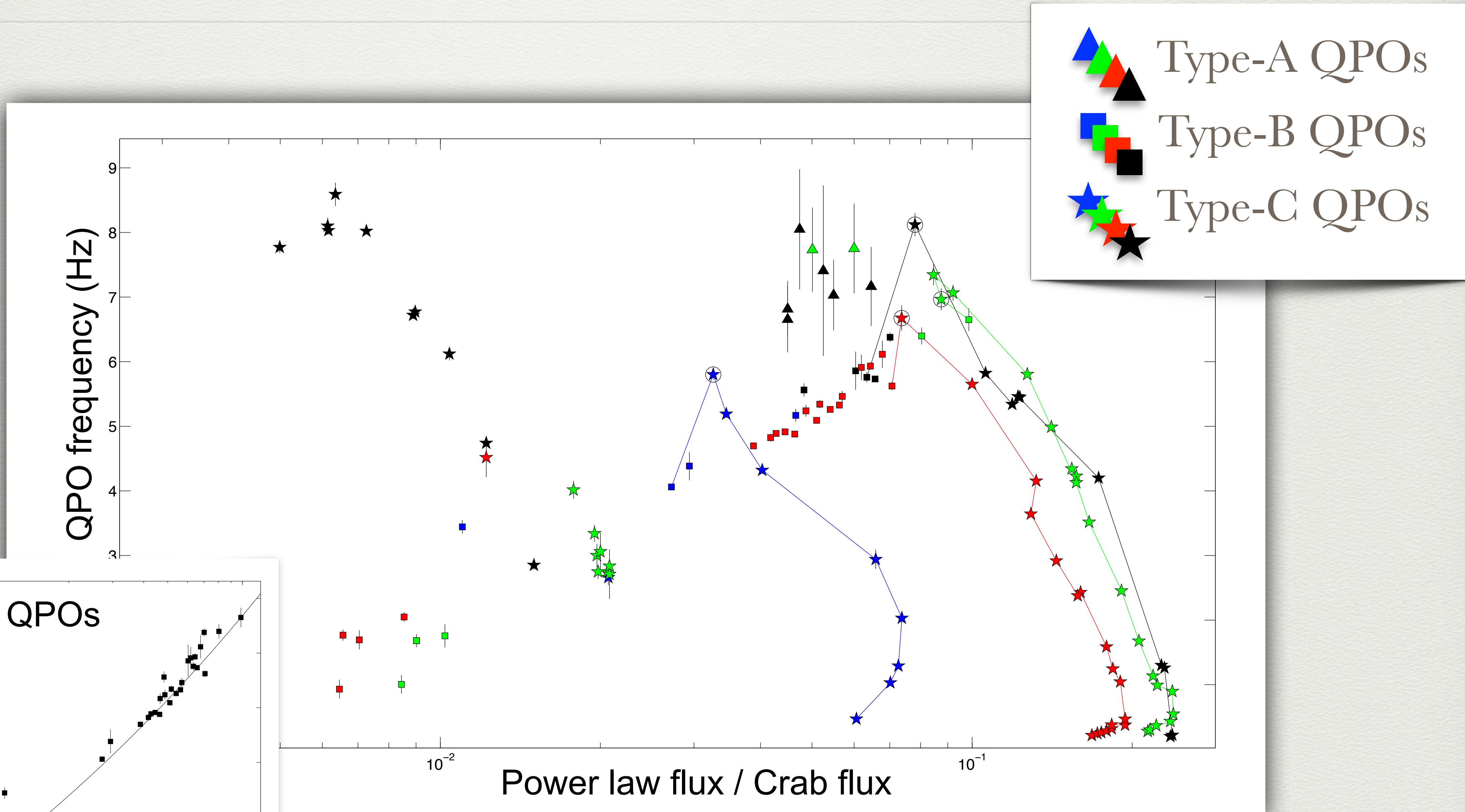
Casella et al. 2004

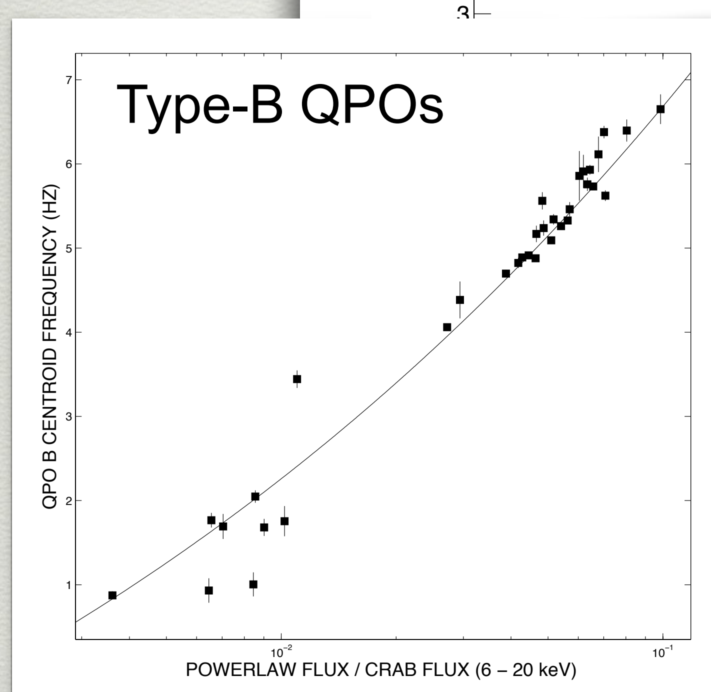


Courtesy of Adam Ingram

Flux vs Frequency: different dependencies

Motta et al. 2011b



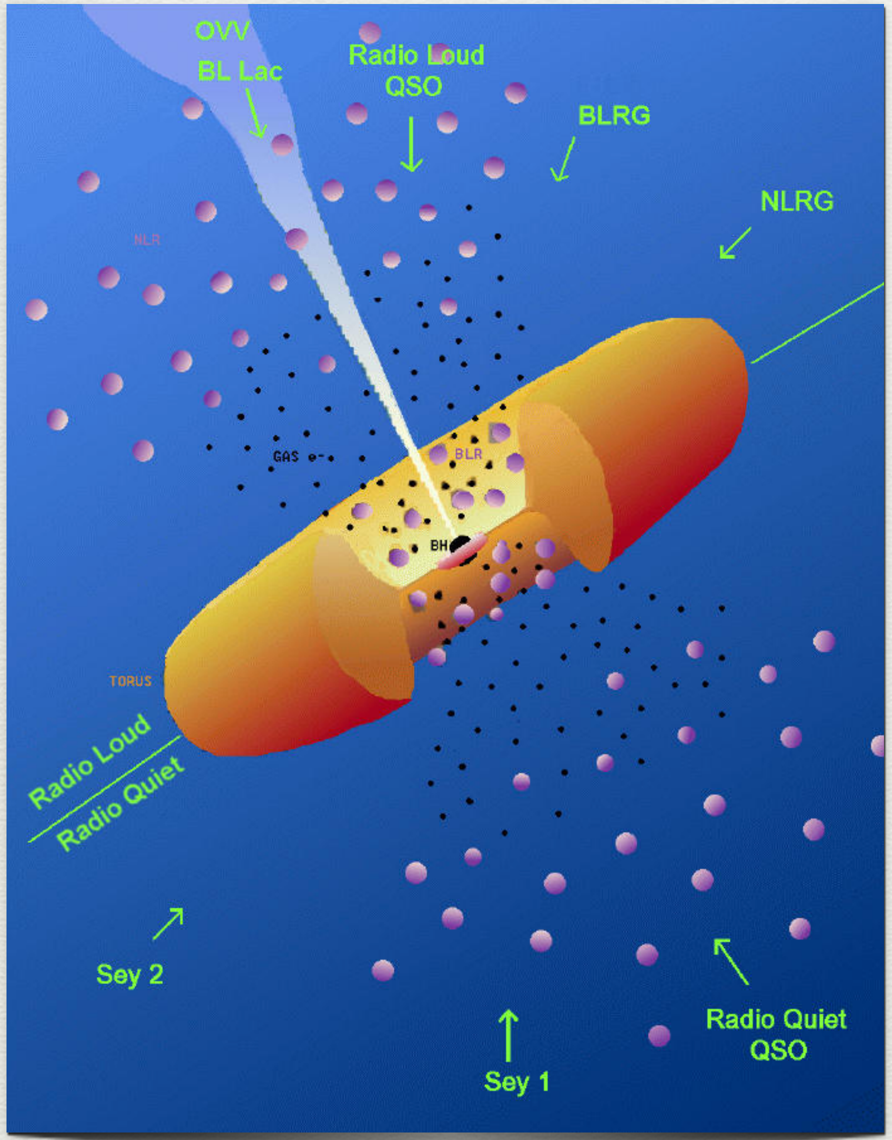


GX 339-4

Inclination effects

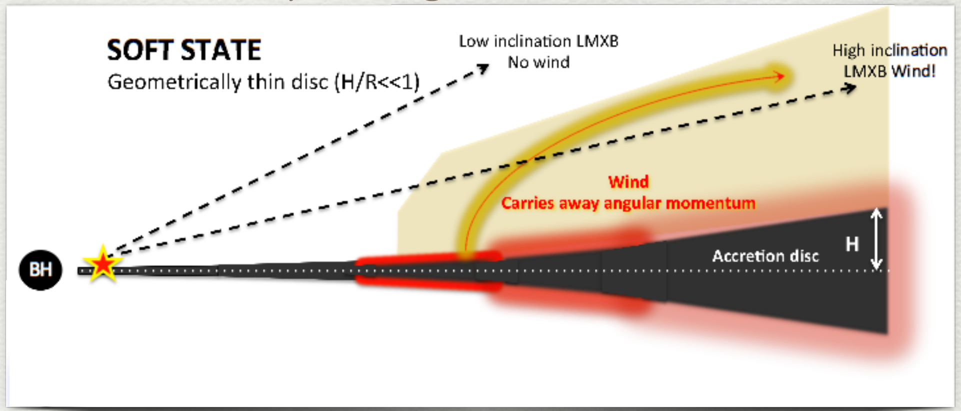
Supermassive black holes in AGN

"different" objects at different inclinations



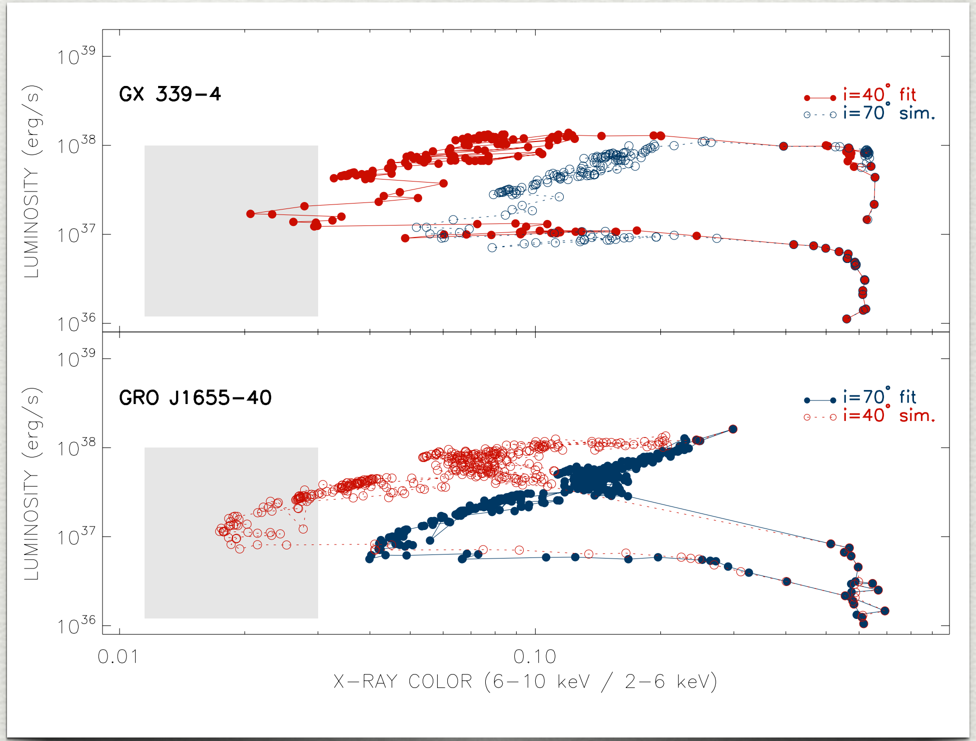
Stellar mass Black holes in binaries

winds only in high-inclination sources



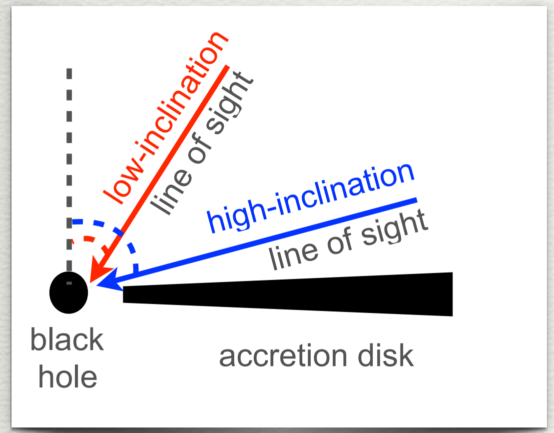
Ponti et al. 2012

hotter disks in high-inclination sources

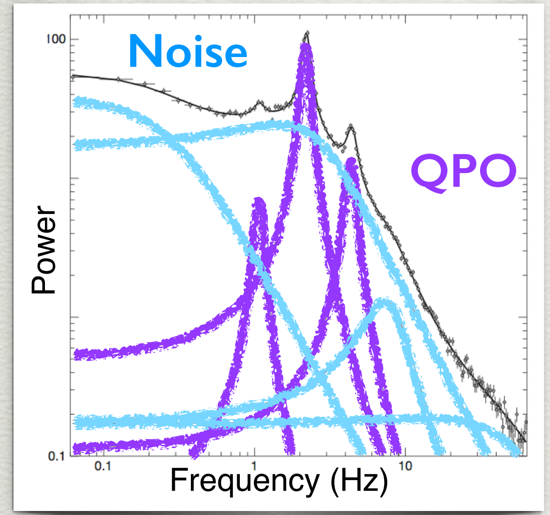


Moñuz-Darias et al. 2013

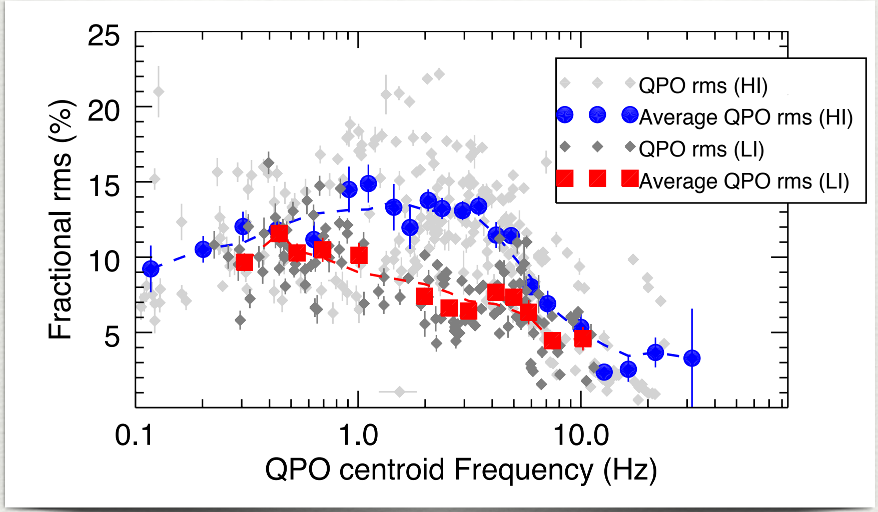
QPOs (and noise) amplitude depend on inclination



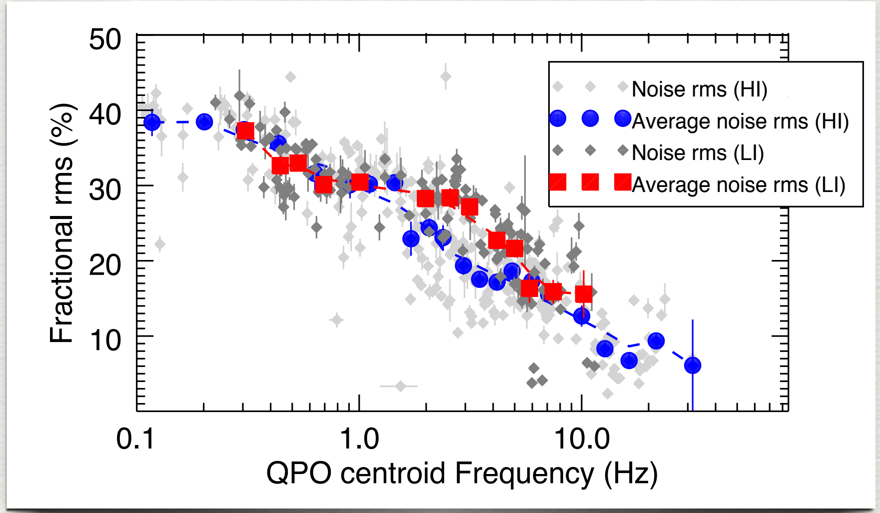
Motta et al. 2015



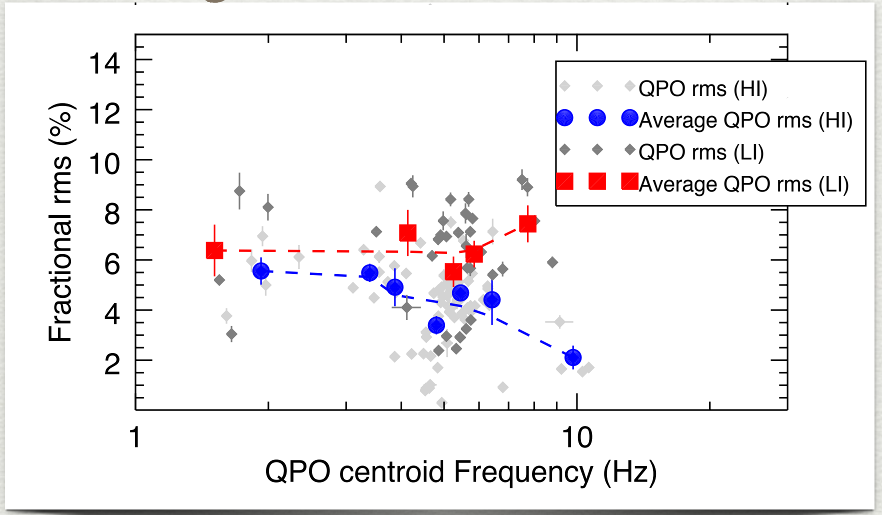
Type-C QPOs stronger at high inclination



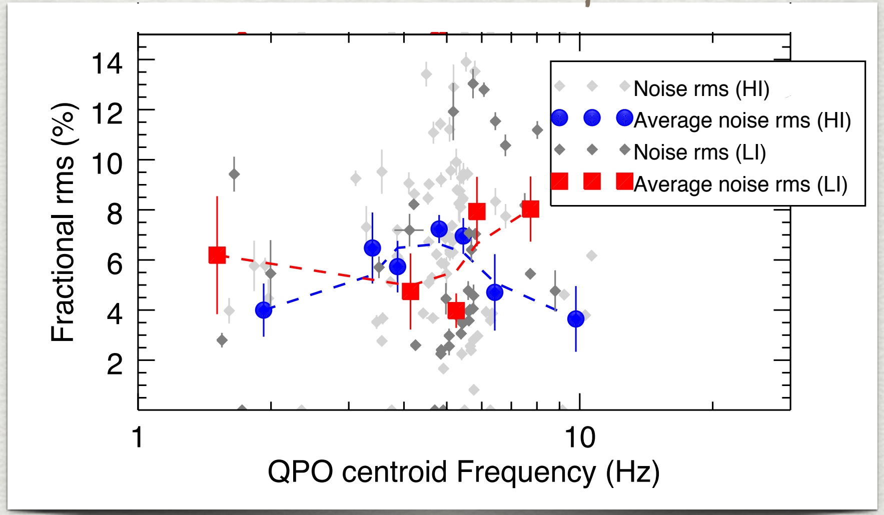
Type-C noise stronger at low inclination



Type-B QPOs stronger at low inclination

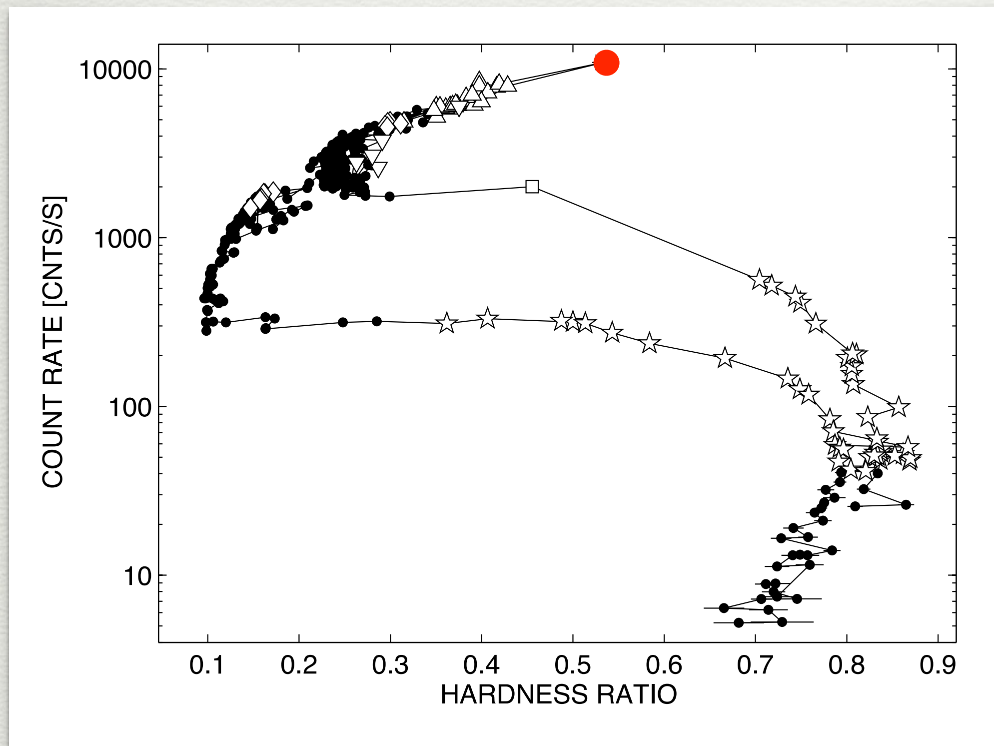


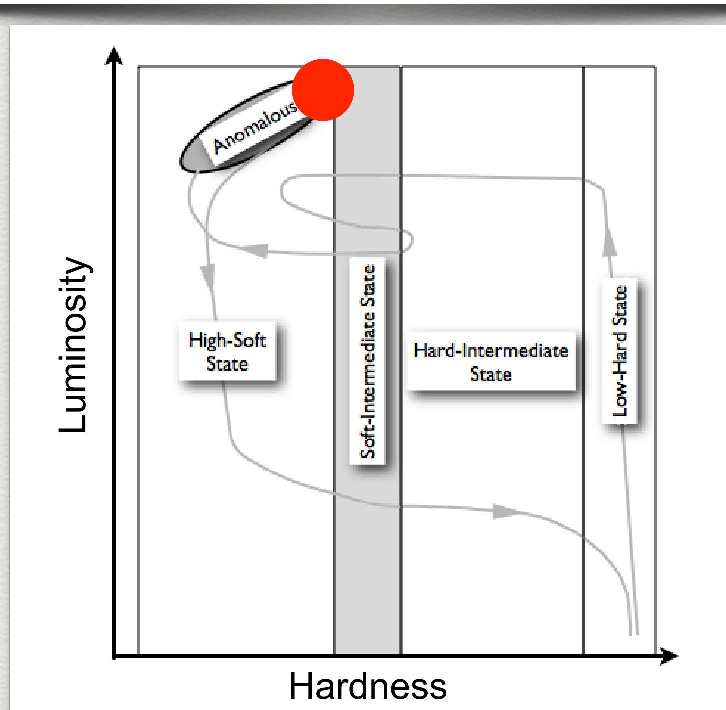
Type-B noise inclination independent



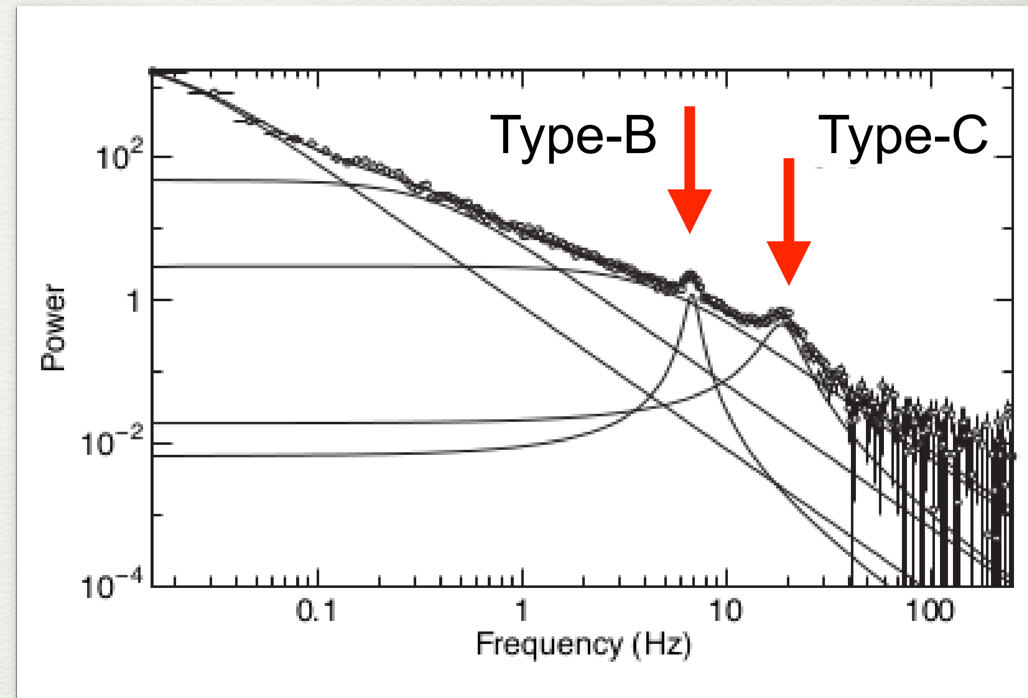
Simultaneous Type-B and -C QPOs

Motta et al. 2015





GRO J1655-40



This happens also for:

XTE J1550-564 (Motta et al 2014b)

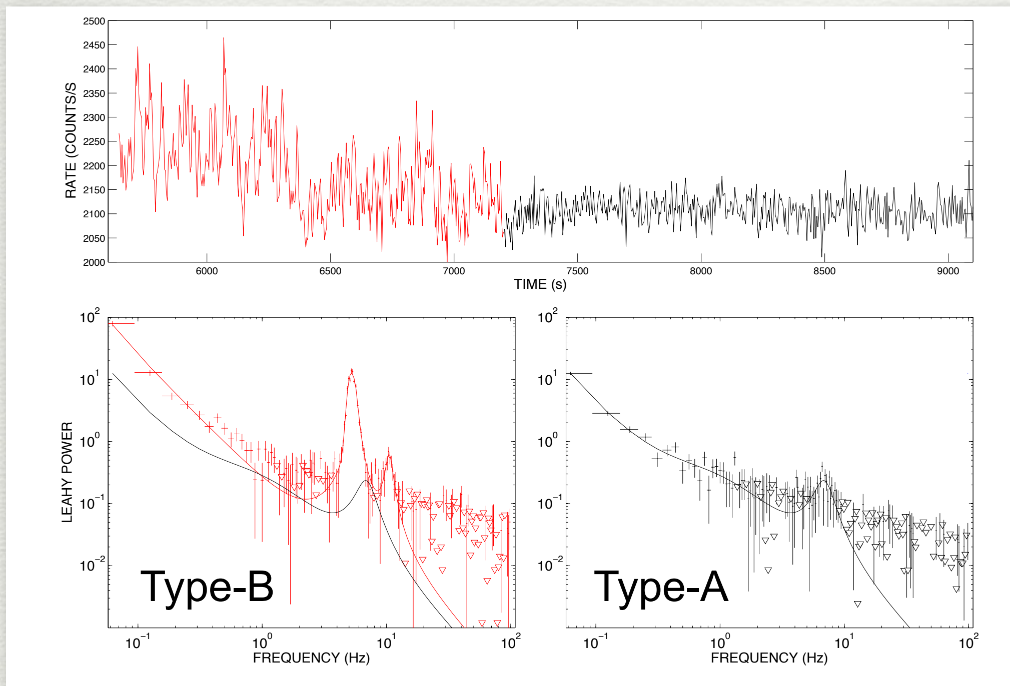
4U1630-472 (Motta et al 2015)

H1743-322 (Motta et al 2015)

Always in or very close to the Ultra Luminous state

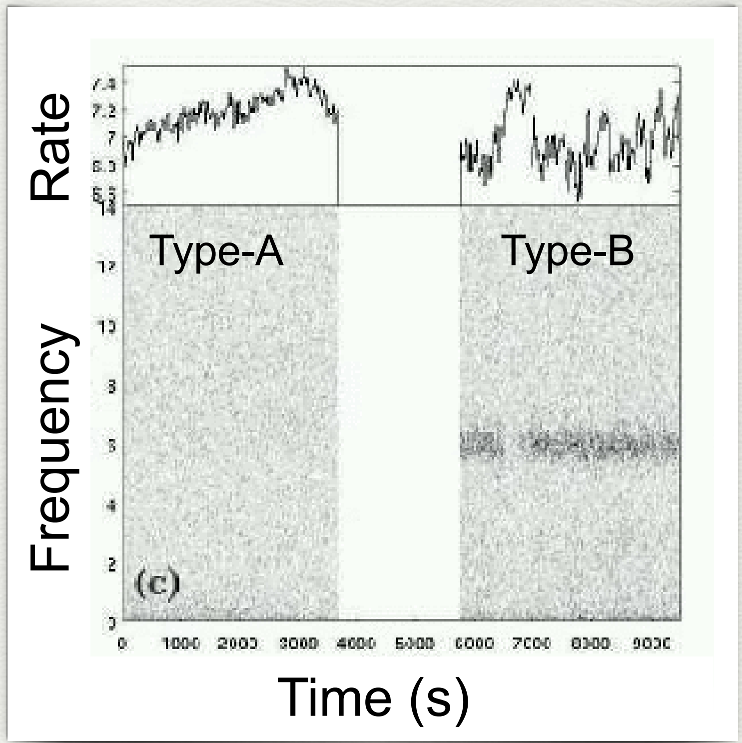
Type-A and Type-B

GX 339-4



Motta et al. 2011b

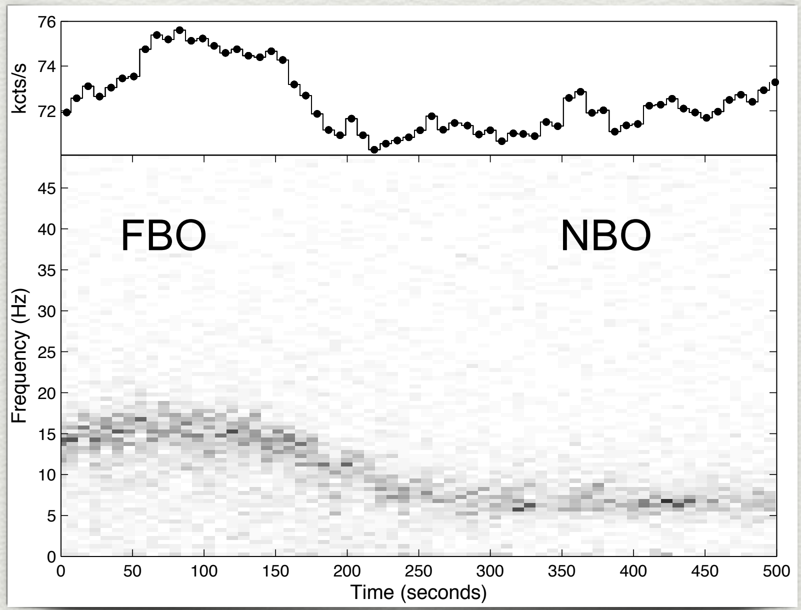
XTE J1859+226



Casella et al. 2004

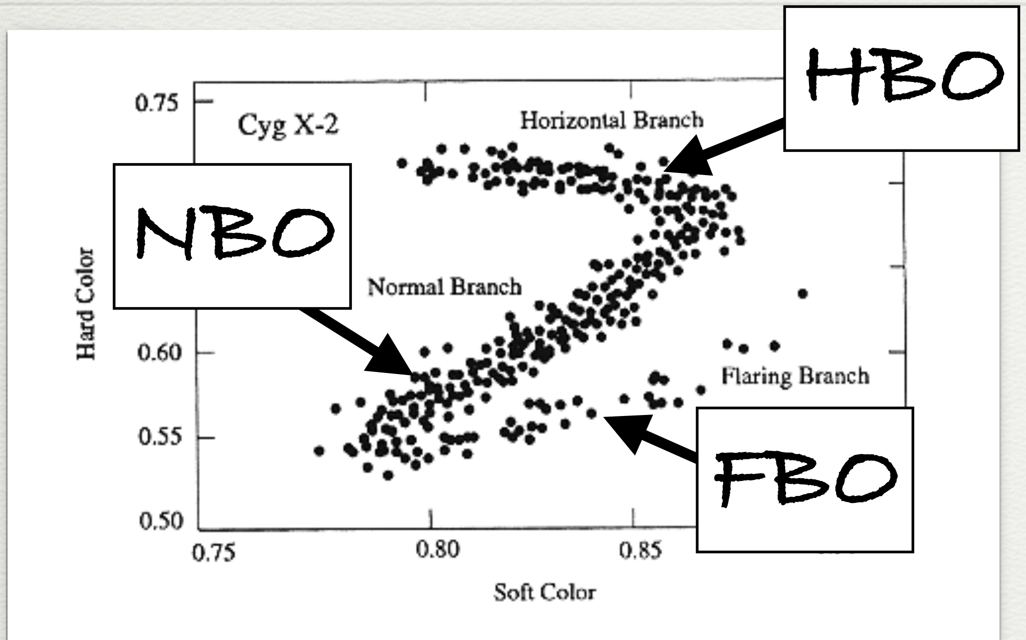
The case of Z-sources

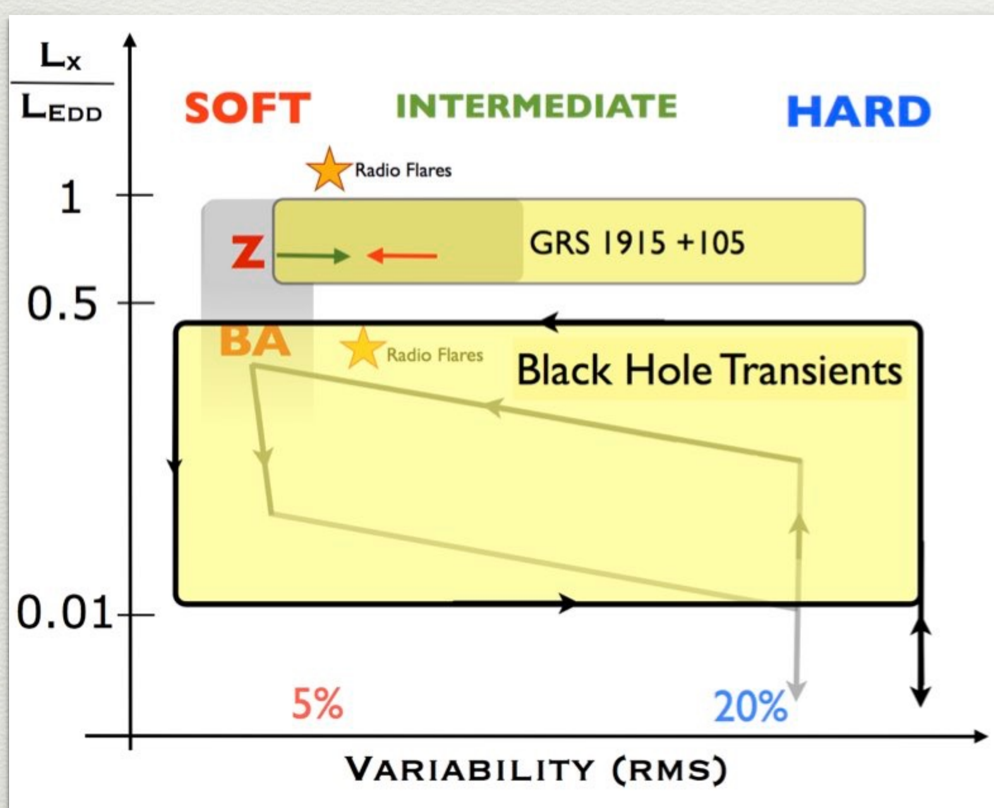
Sco X-1



Casella et al. 2006

Comparison with NS might help





Munoz-Darias et al. 2014

QPOs in BH and NS binaries are the same?

- type-C = HBOs
- type-B = NBOs
- type-A =(?) FBOs

Proposed by Casella et al. 2005, based on a few sources

BH and NS binaries can be described in the same way through variability

Take home message n.1

- All low frequency QPOs have an **hard spectrum**
- They **behave differently** w.r.t. flux
- They **depend on inclination**: Type-C stronger edge on, Type-B stronger face on
- **Type-C** are most likely related to the inner hot flow and come from **geometrical effects (precession)**
- **Type-B** are probably related to the **jet-launching mechanism**
- **no clue on type-A QPOs**, more data needed (or a clever use of BH data, and possibly NS data)

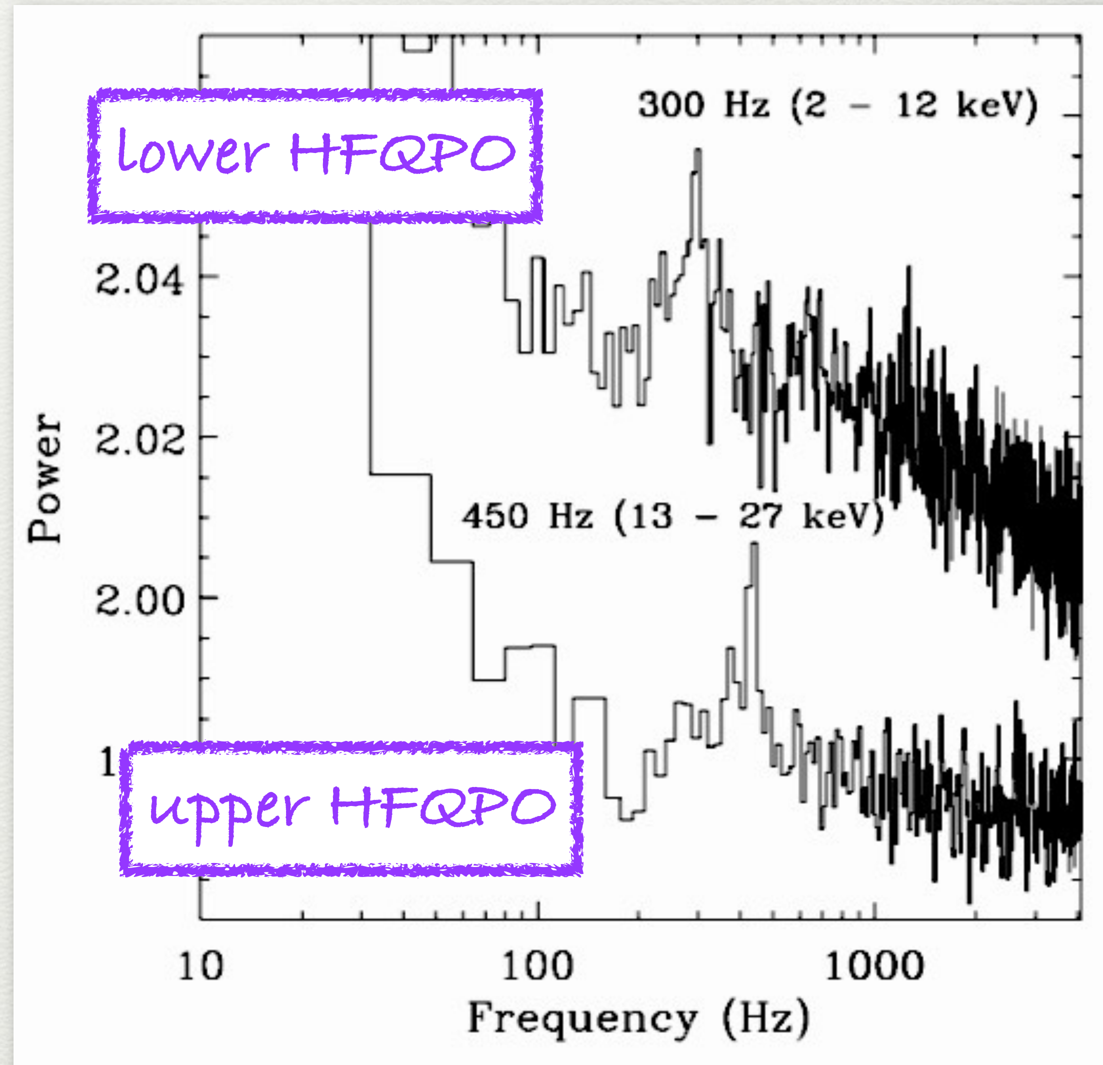
High frequencies QPOs in Black Holes

- Discovered with RXTE in the 90s in GRS1915+105
- Quite rare, and difficult to detect, especially in pairs
- Exist in neutron stars as well (as kHz QPOs)

HFQPO sources

XTE J1550-564	GX 339-4
GRO J1655-40	XTE J1752-223
XTE J1859+226	4U 1630-47
H 1743-322	IGR J17091-3624
	GRS J1915+105

100 - 500 Hz



Strohmayer et al. 2001, Motta et al. 2014a

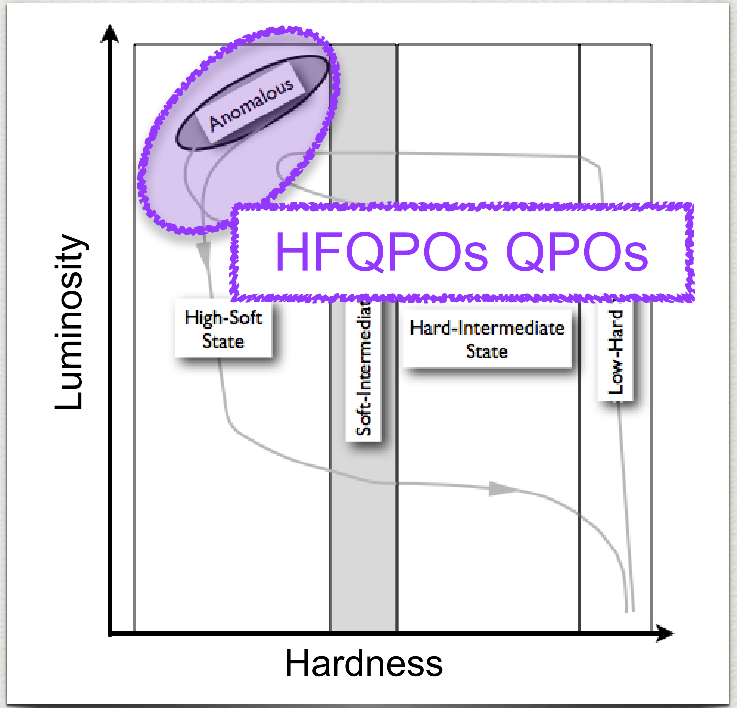
See e.g. Morgan et al. 1997, Remillard et al. 1999, Strohmayer et al 2001, Belloni et al. 2012 , Altamirano et al. 2012

High frequencies QPOs
in Black Holes

- **11 significant detections from 2 sources** in the RXTE archive (or 42 detections from 7 sources)

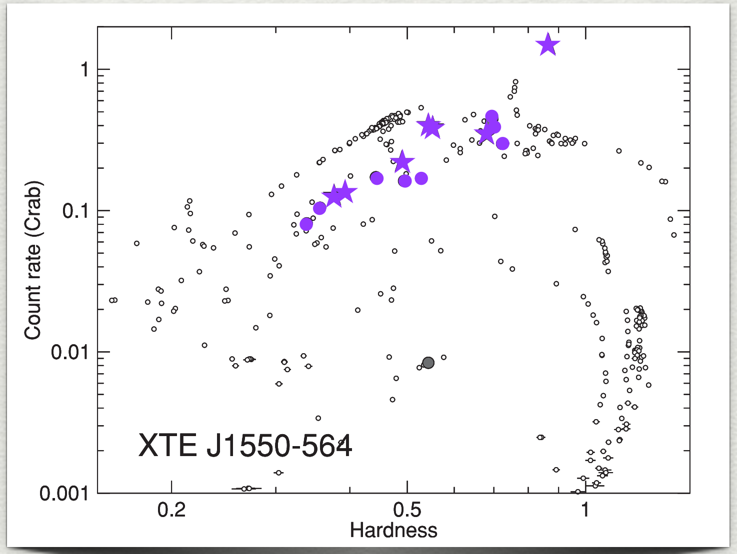
See Belloni, Sanna, Méndez 2012

in 10000+ observations



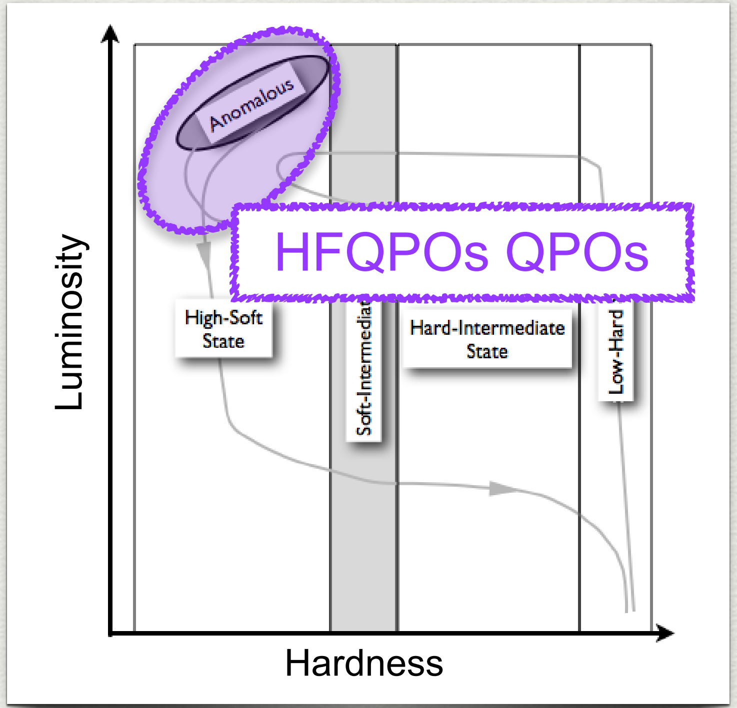
- Observed only at high luminosity

- Frequencies close to Keplerian values



Belloni et al. 2012

High frequencies QPOs in Black Holes

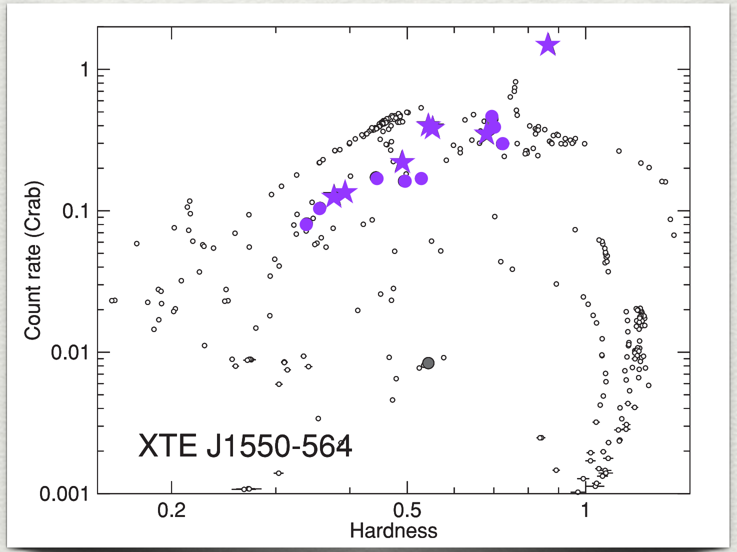


- Two main mechanism: **relativistic motions** and **resonances** models

- Several models, but only seldom tested

E.g.
Relativistic precession model (Stella & Vietri 1999);
modified relativistic precession model (Bursa 2006);

Non-linear resonance model (Aliev & Gal'tsov 1981);
keplerian non-linear resonance model (Abramowicz & Kluzniak 2004), warped-disk model (Kato 2004)

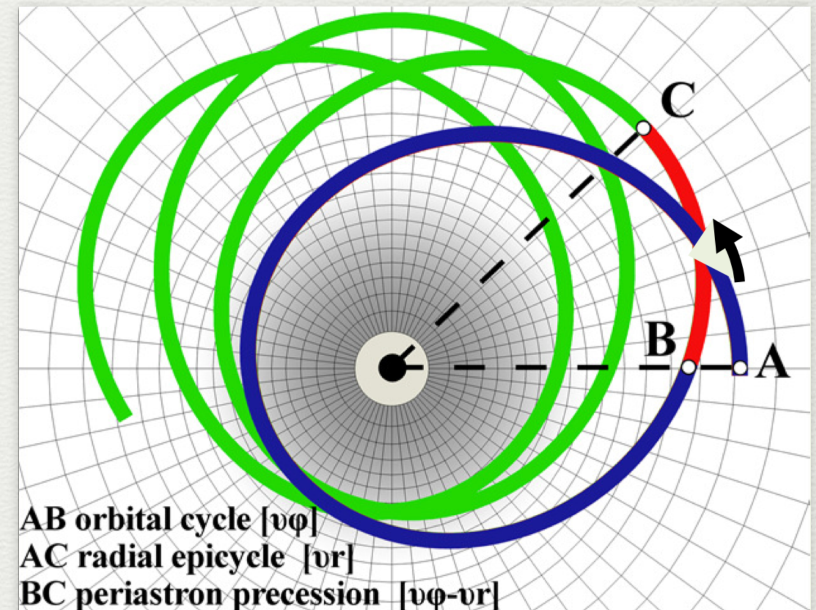


Belloni et al. 2012

Models can be tested: the Relativistic Precession Model

Stella & Vietri 1998, Stella et al. 1999

- The RPM associates three frequencies - **orbital, periastron precession and nodal precession** - to three QPOs.



upper HFQPO

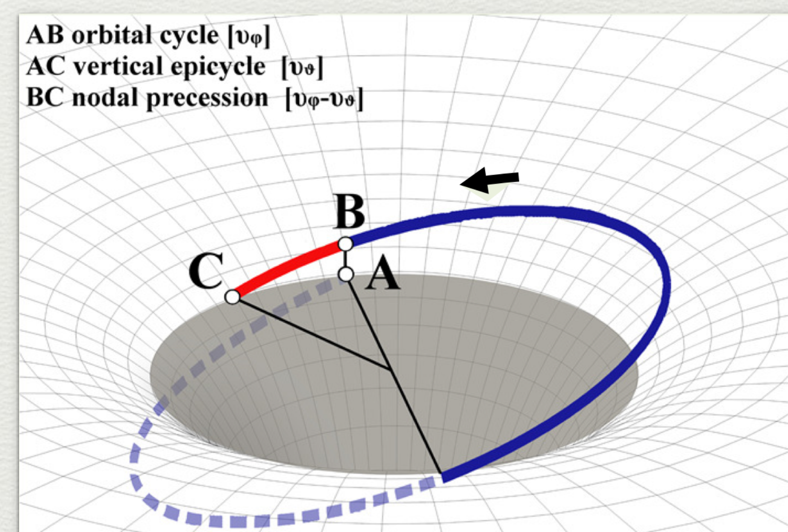
$$\nu_\phi = \pm\frac{1}{2\pi}\left(\frac{M}{r^3}\right)^{1/2}\frac{1}{1\pm a\left(\frac{M}{r}\right)^{3/2}}$$

lower HFQPO

$$\nu_{per} = v_\phi\left(1-\left(1-\frac{6M}{r}-3a^2\left(\frac{M}{r}\right)^2\pm 8a\left(\frac{M}{r}\right)^{3/2}\right)^{1/2}\right)$$

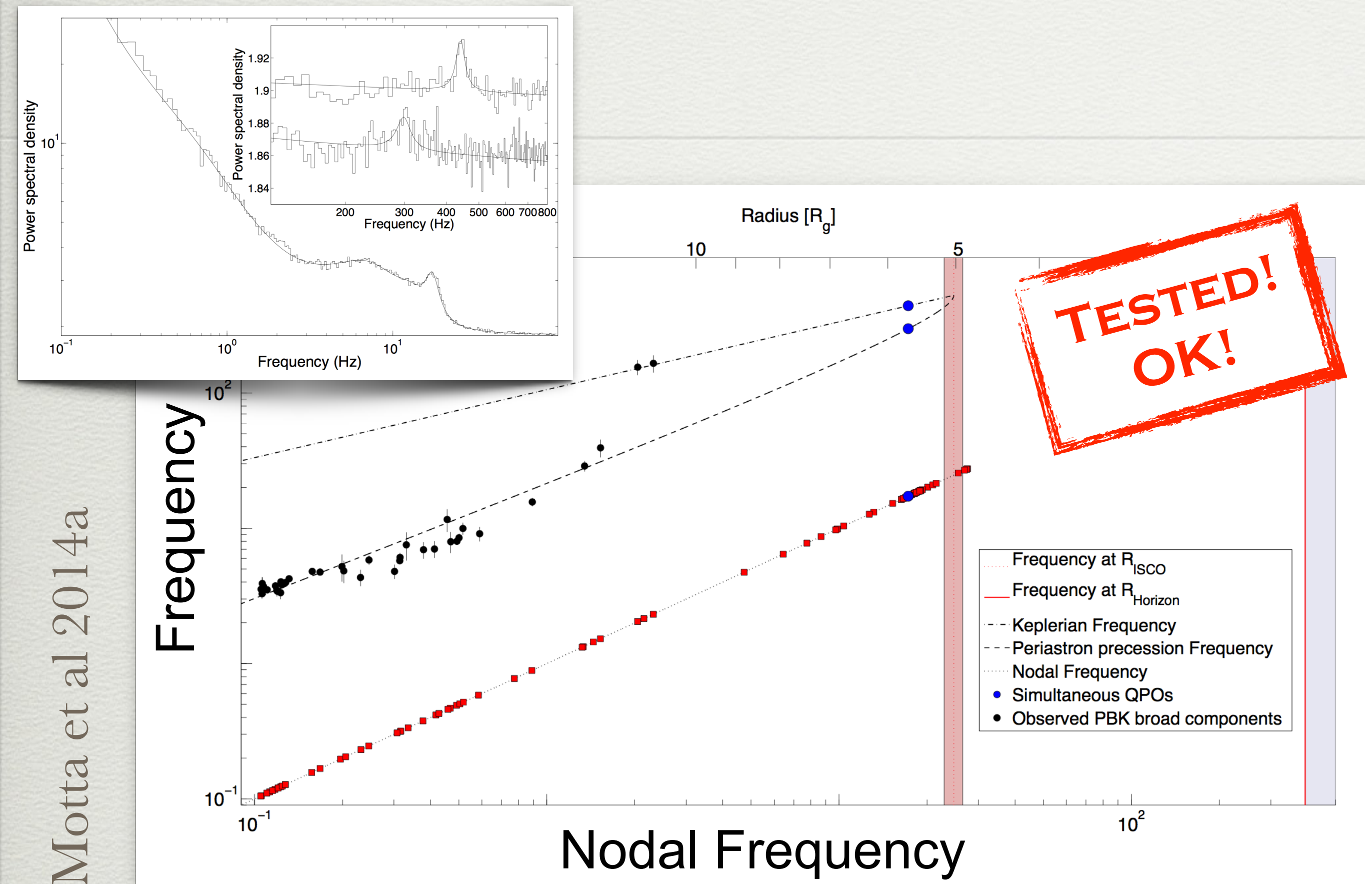
type-C QPO

$$\nu_{nod} = v_\phi\left(1-\left(1+3a^2\left(\frac{M}{r}\right)^2\mp 4a\left(\frac{M}{r}\right)^{3/2}\right)^{1/2}\right)$$

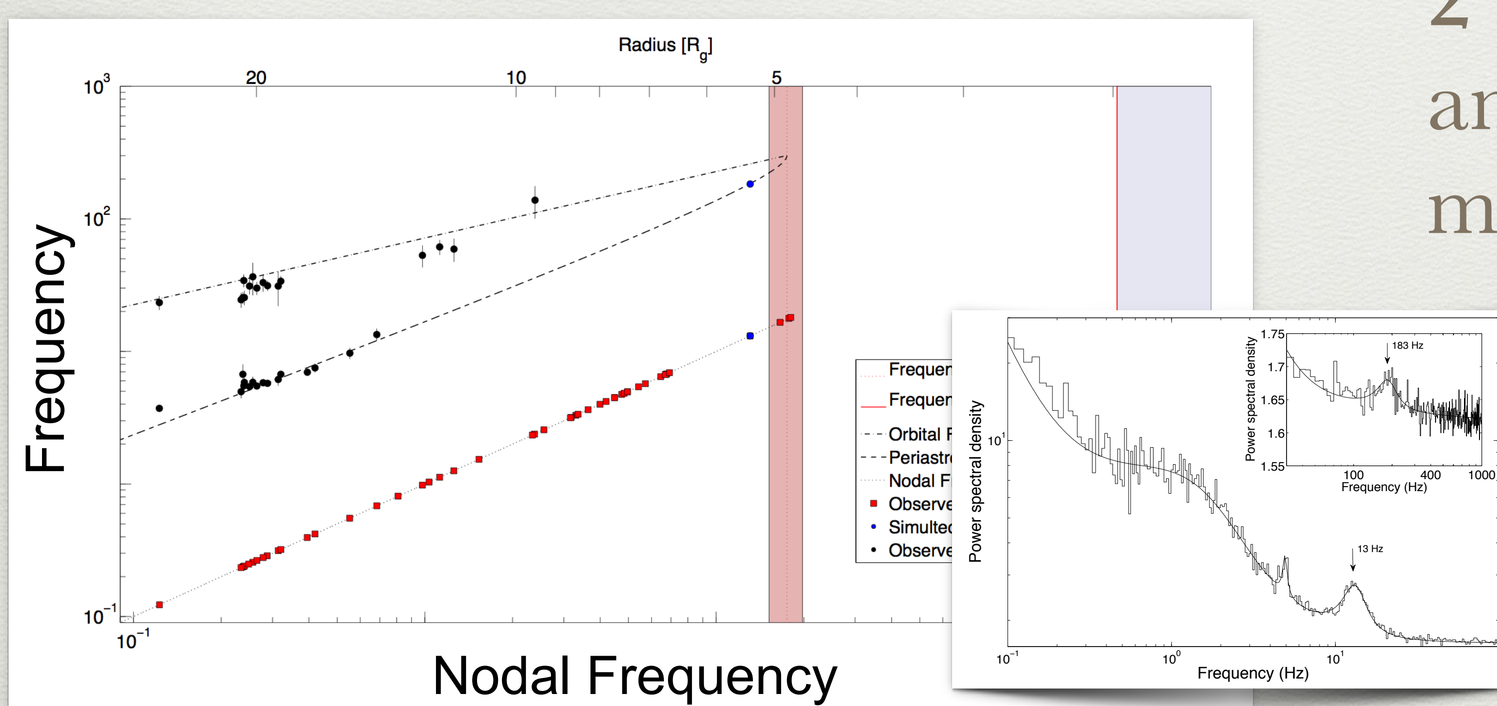


Motta et al. 2014a,b; Ingram & Motta 2014

RPM Field testing



Motta et al 2014a



Motta et al 2014b

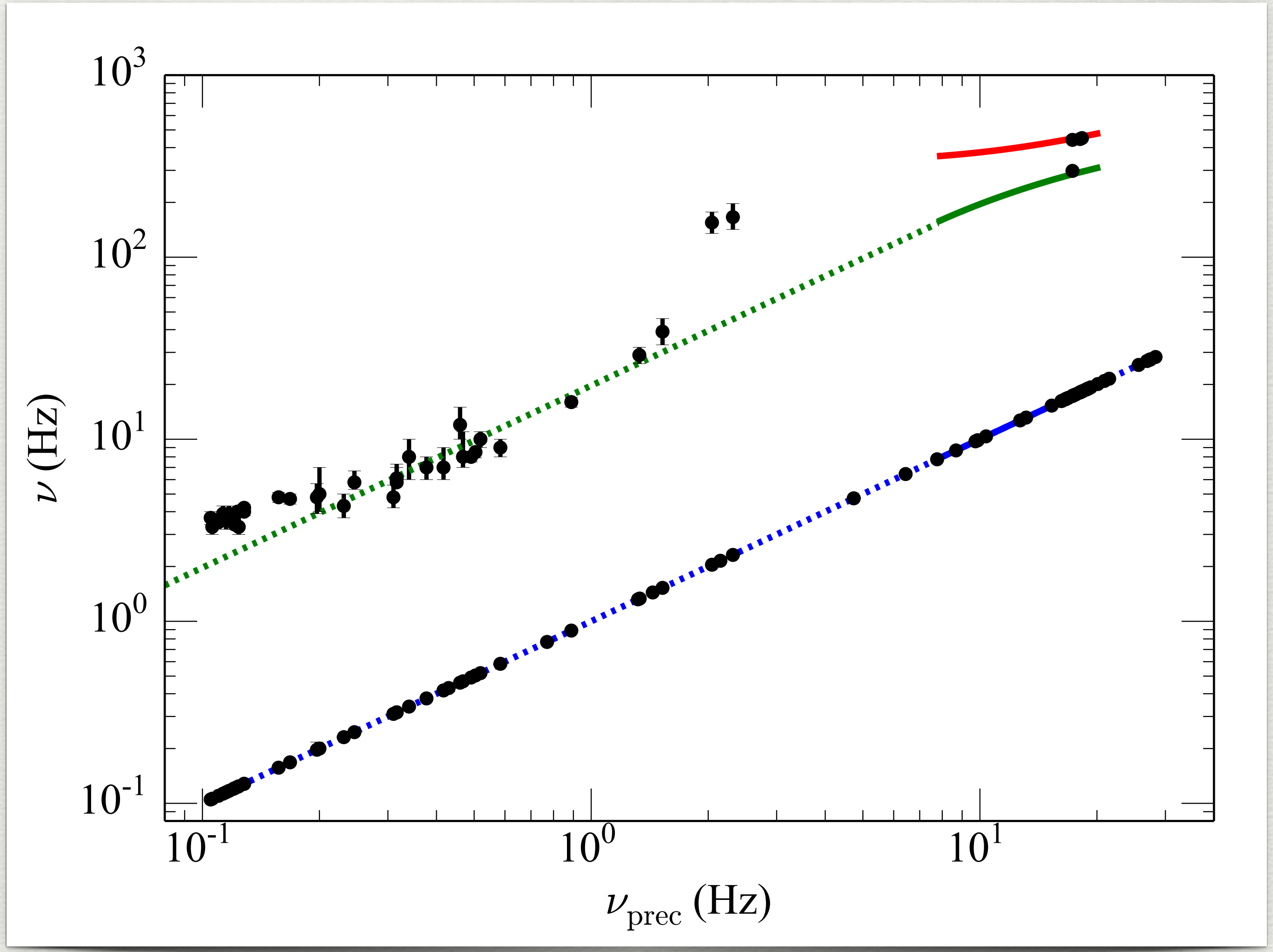
- GRO J1655-40:
  3 simultaneous QPOs
  and a dynamical measurement of the mass
- XTE J1550-564:
  2 simultaneous QPOs
  and a dynamical measurement of the mass

Bonus: in both cases, you get a BH spin!

Oscillating, Precessing torus model Field Testing

Type-C QPO	⟷	Relativistic precession (nodal)
LOWER HFQPO	⟷	Vertical Frequency
UPPER HFQPO	⟷	Breathing Mode

GRO J1655-40



Fragile, Straub, Blaes 2016

Take home message n.2

- **HFQPOs** are very **rare** in black hole binaries (but very common in neutron star binaries)
- They appear only at **very high luminosities**
- Their **frequencies** are close enough to the **keplerian values**.
- We need to test the models!
- You can do amazing things with X-ray **timing** and **QPOs!**

...if you understand them...

Thank you!