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European Space Agency

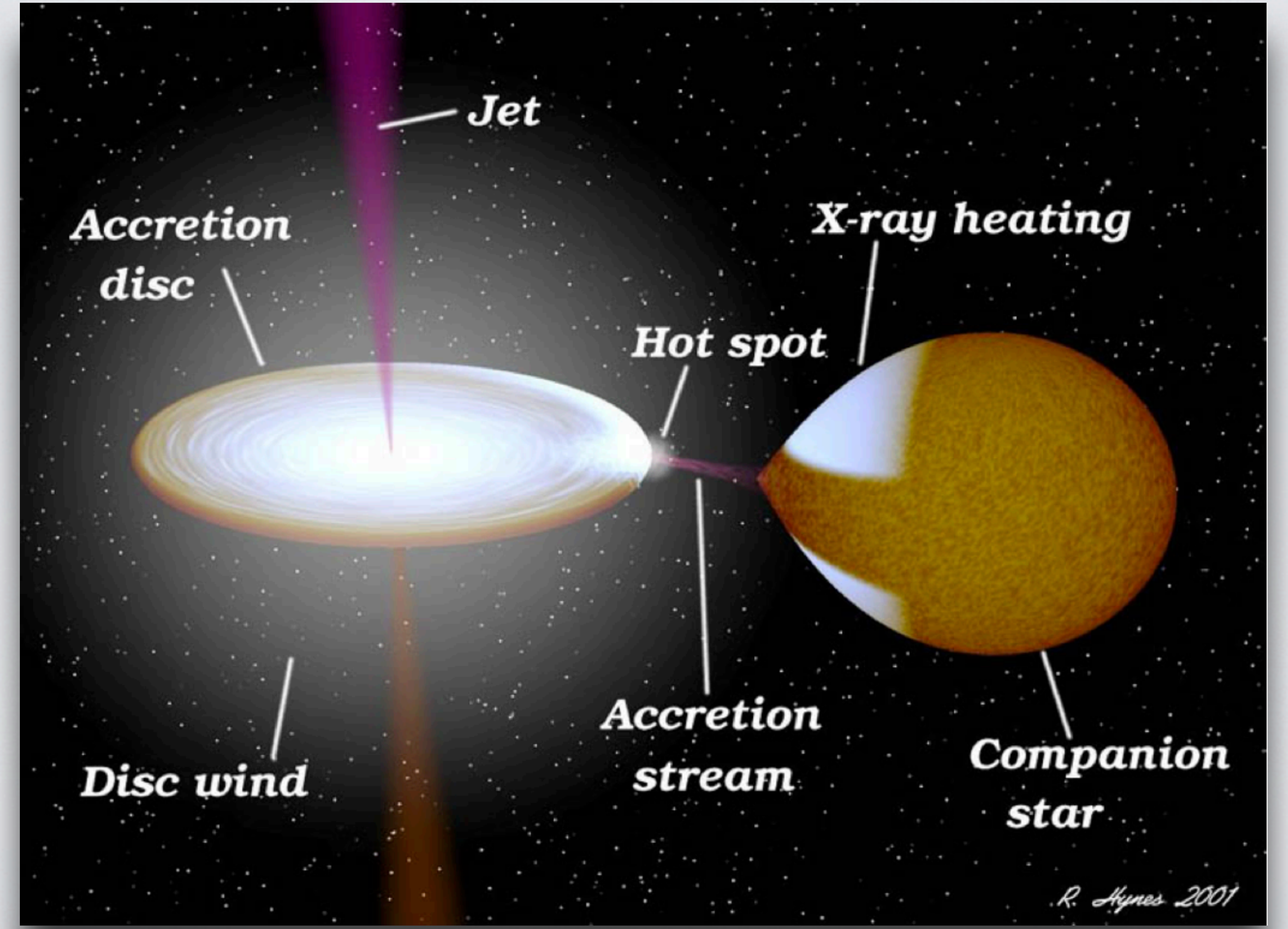
From general relativity to spin and mass measurements through the Relativistic Precession Model

Time to weigh black holes

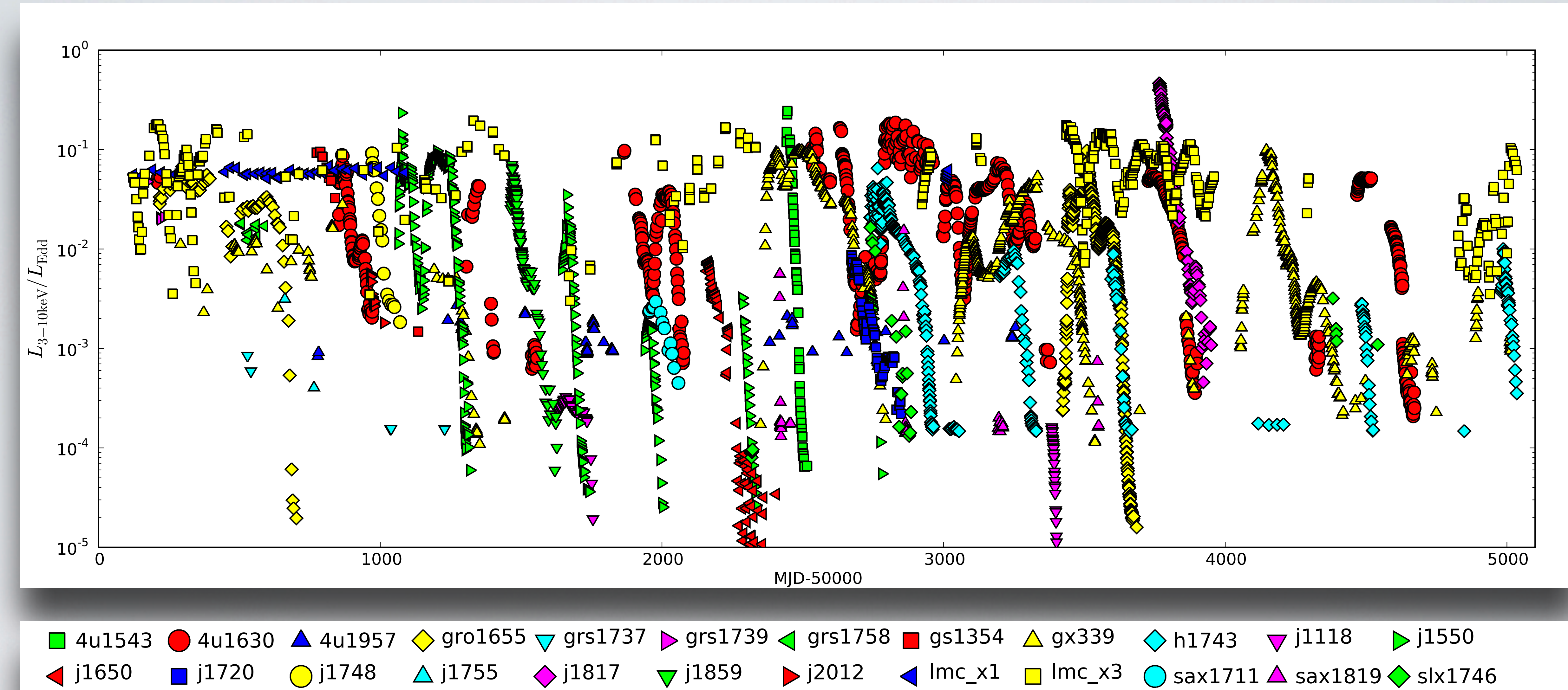
Sara Motta
and Tomaso Belloni, Luigi Stella, Teo Muñoz-Darias, Rob Fender

Aranjuez - November 21, 2013

X-RAY BINARIES



X-RAY BINARIES: THEY VARY!

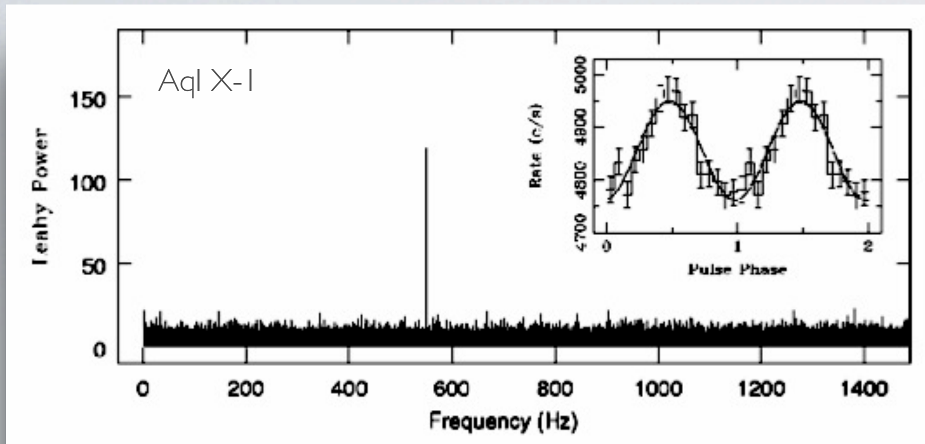


Dunn et al. 2010

X-ray light curves of 24 transient black hole X-ray binaries

(RXTE data over ~15 years)

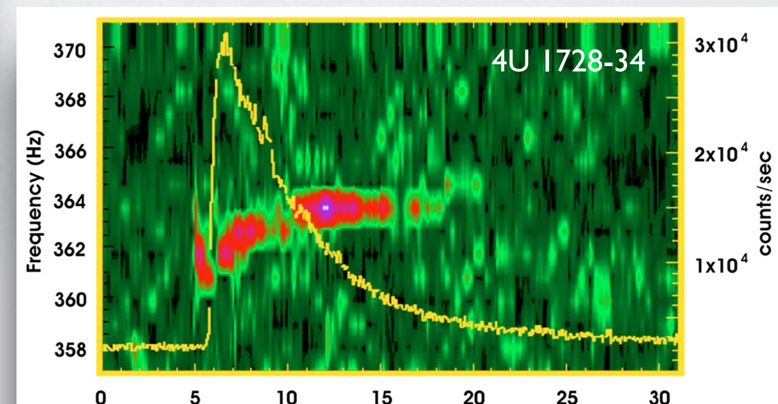
...ON SEVERAL TIMESCALES



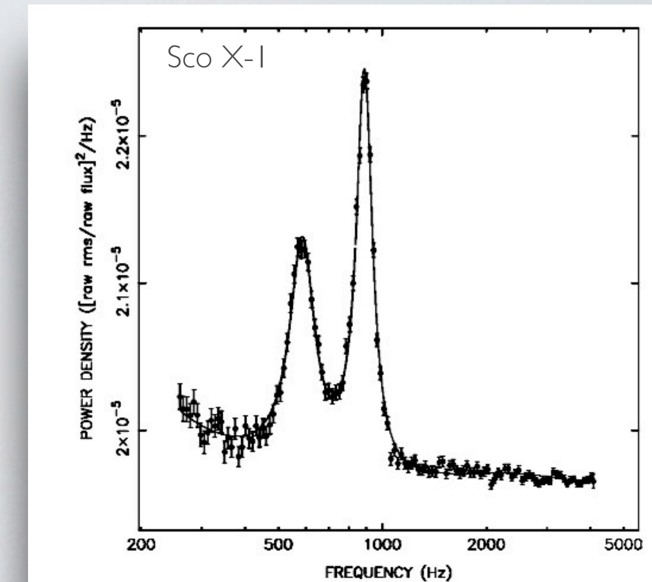
Pulses from accreting X-ray pulsars

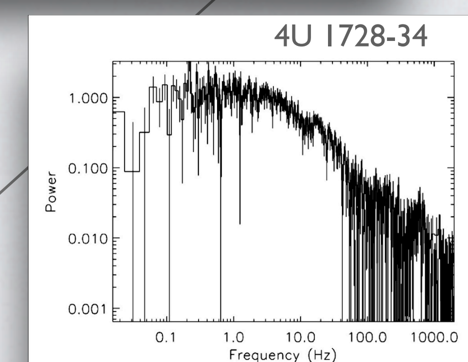
Periodic variability

Burst Oscillations



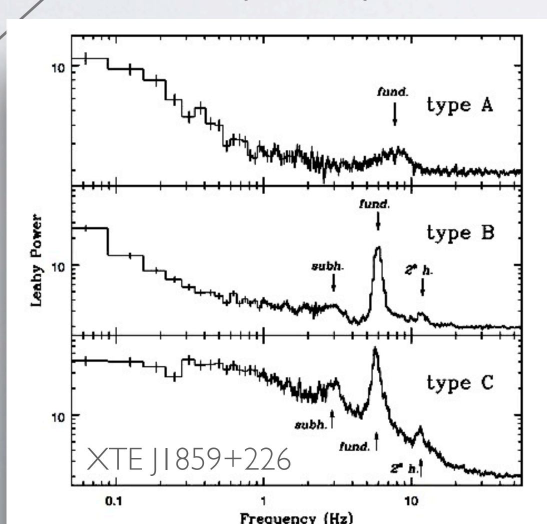
kHz QPOs

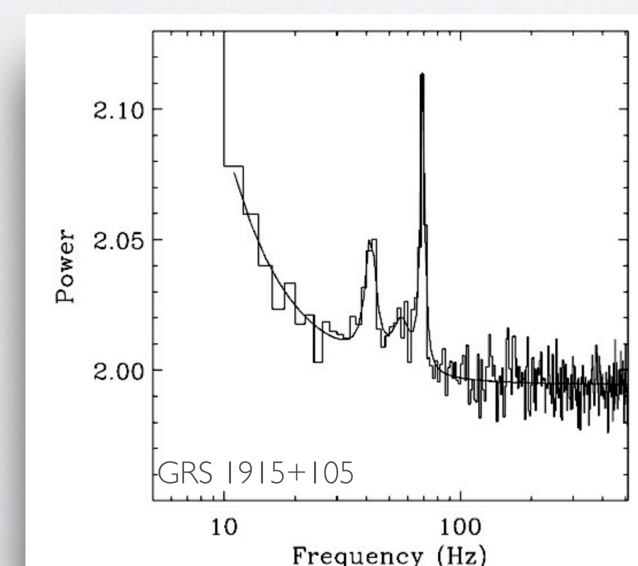




Quasi periodic variability

Low Frequency QPOs

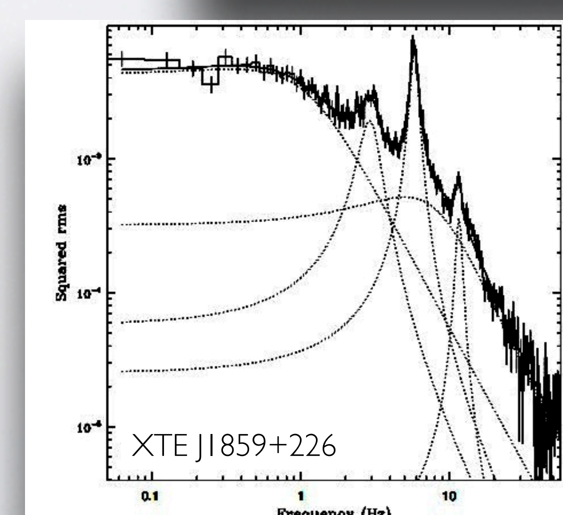




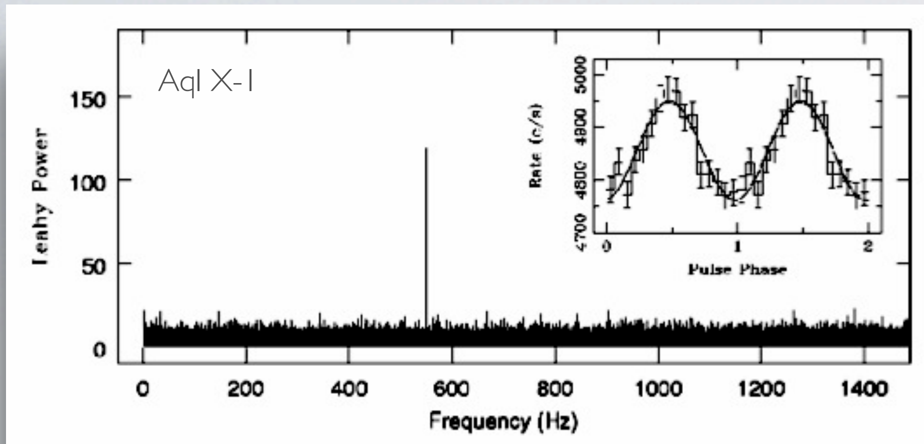
High Frequency QPOs

Aperiodic variability

Broad band Noise



...ON SEVERAL TIMESCALES



Pulses from accreting X-ray pulsars

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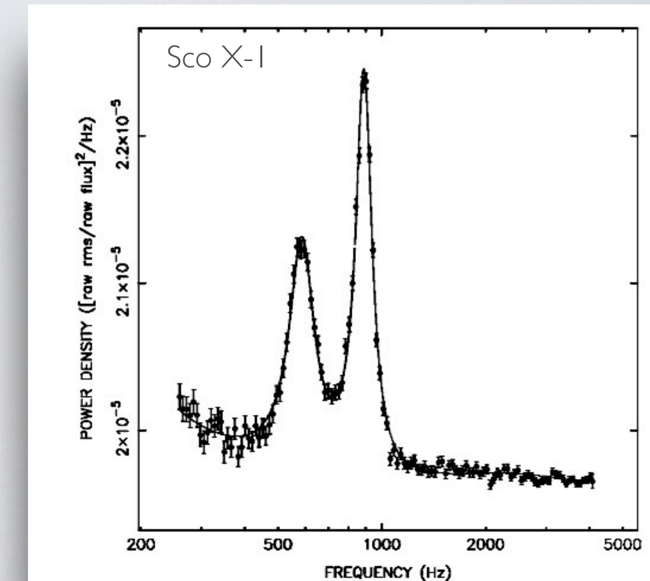
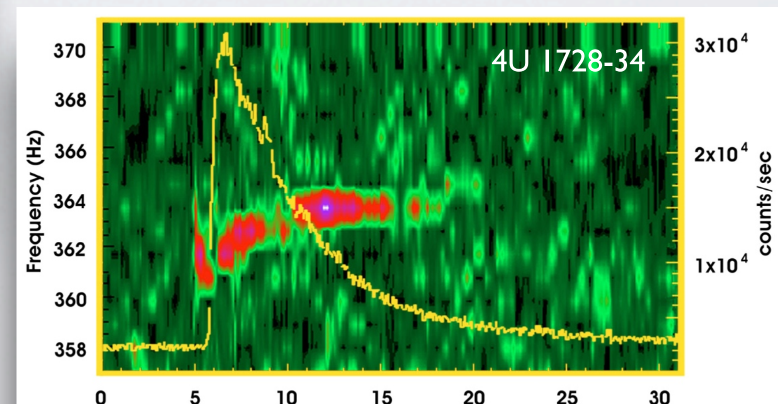
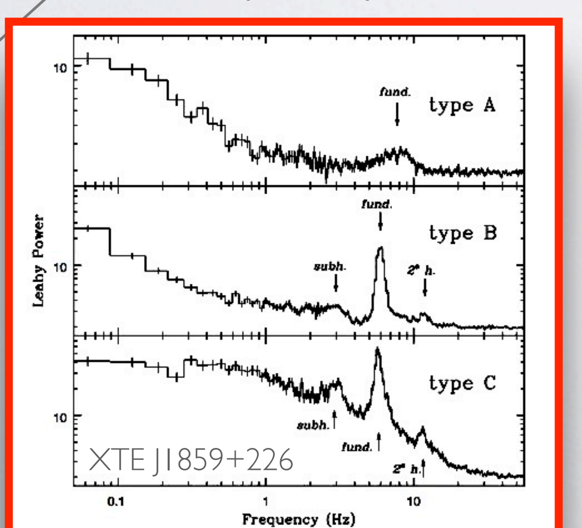


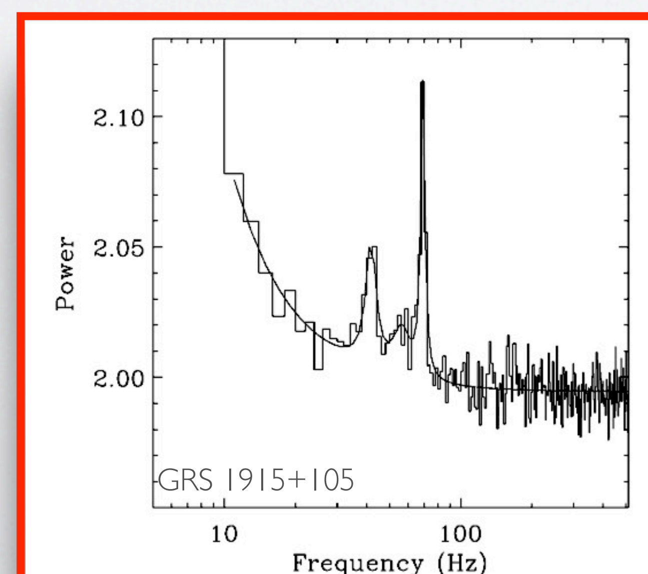
Burst Oscillations



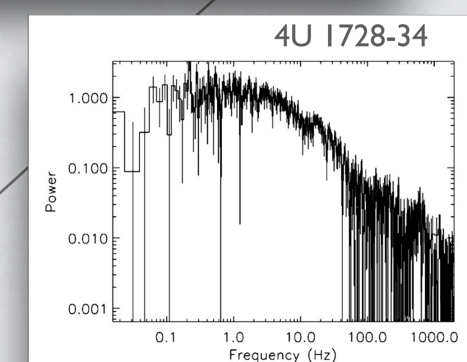
Quasi periodic variability

Low Frequency QPOs





High Frequency QPOs



Aperiodic variability

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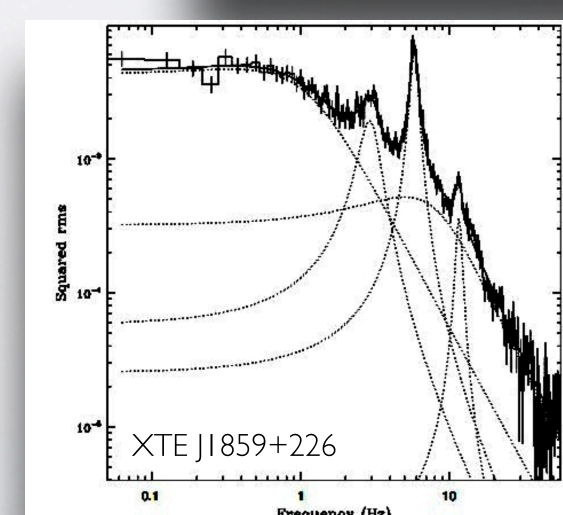
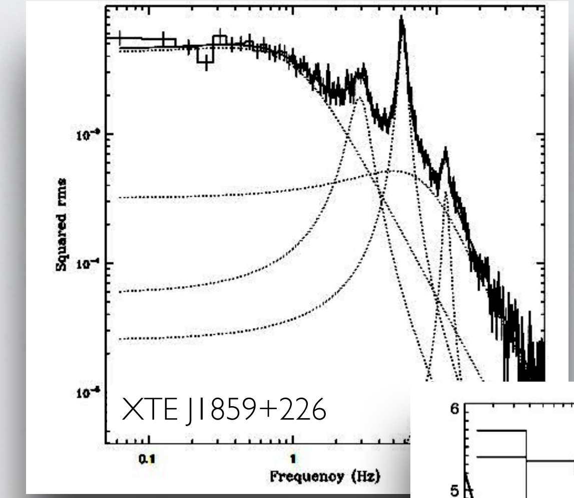


WHAT IS A QPO?
QUASI PERIODIC OSCILLATION

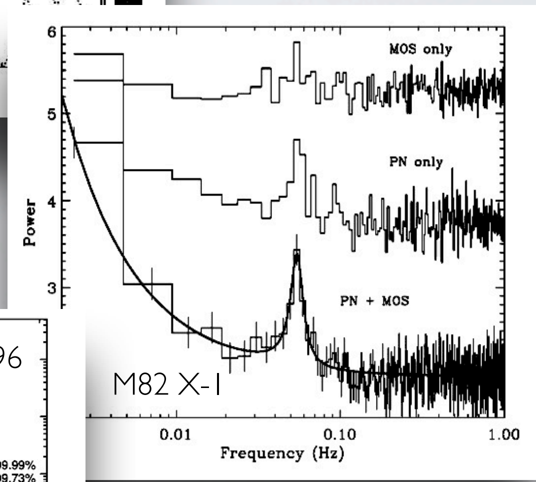
- Quasi periodic signal in a light-curve (BHs, NSs, ULXs, even AGNs)
- Becomes apparent in a power density spectrum
- Associated to noise
- They come in different flavors

Black Hole binary



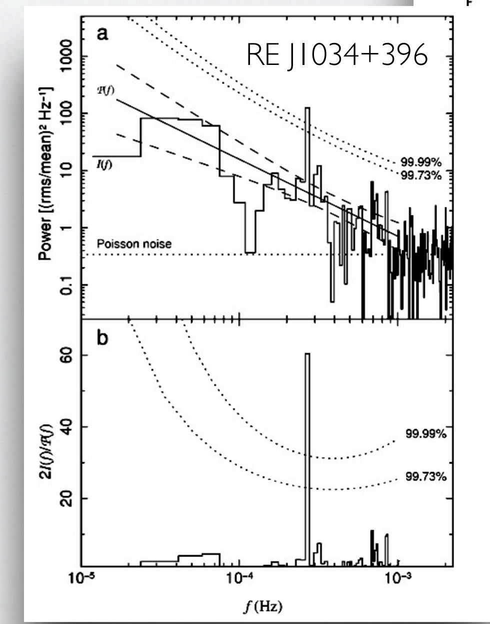
Casella et al. 2004

ULX



Strohmayer & Mushotzky 2003

AGN

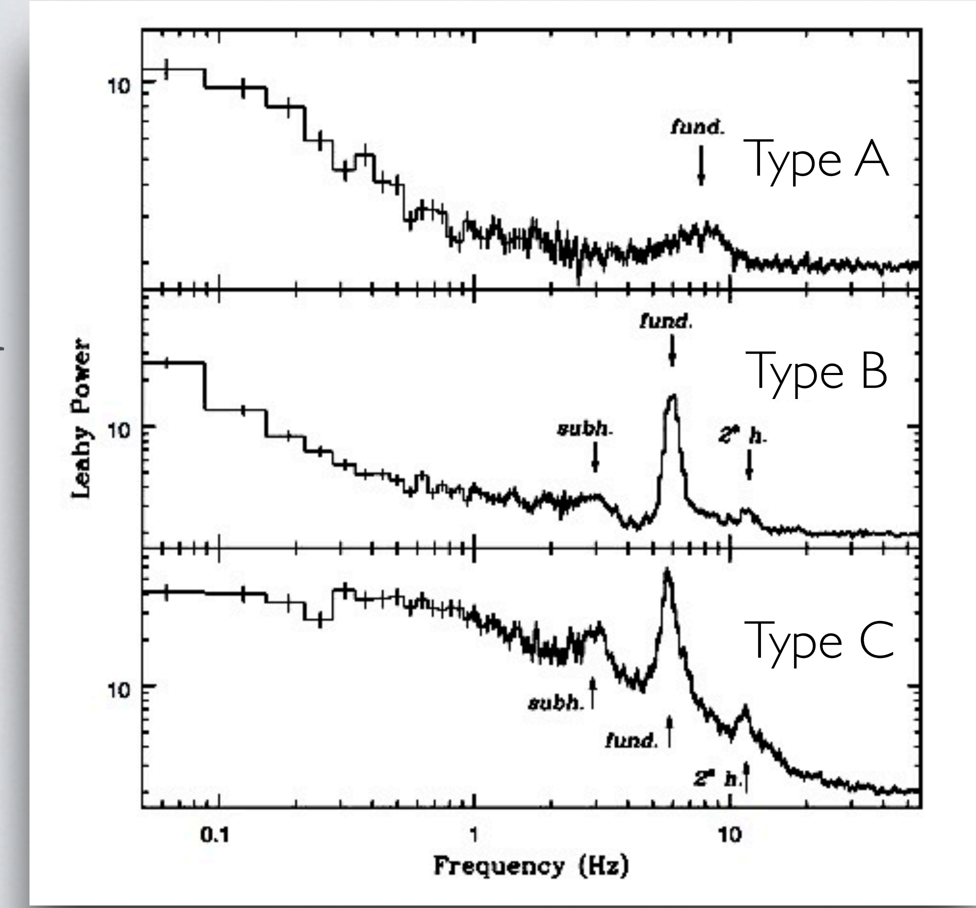


Gierliński et al. 2008

QPOs IN BLACK HOLES

LOW FREQUENCY

Too slow to be keplerian!



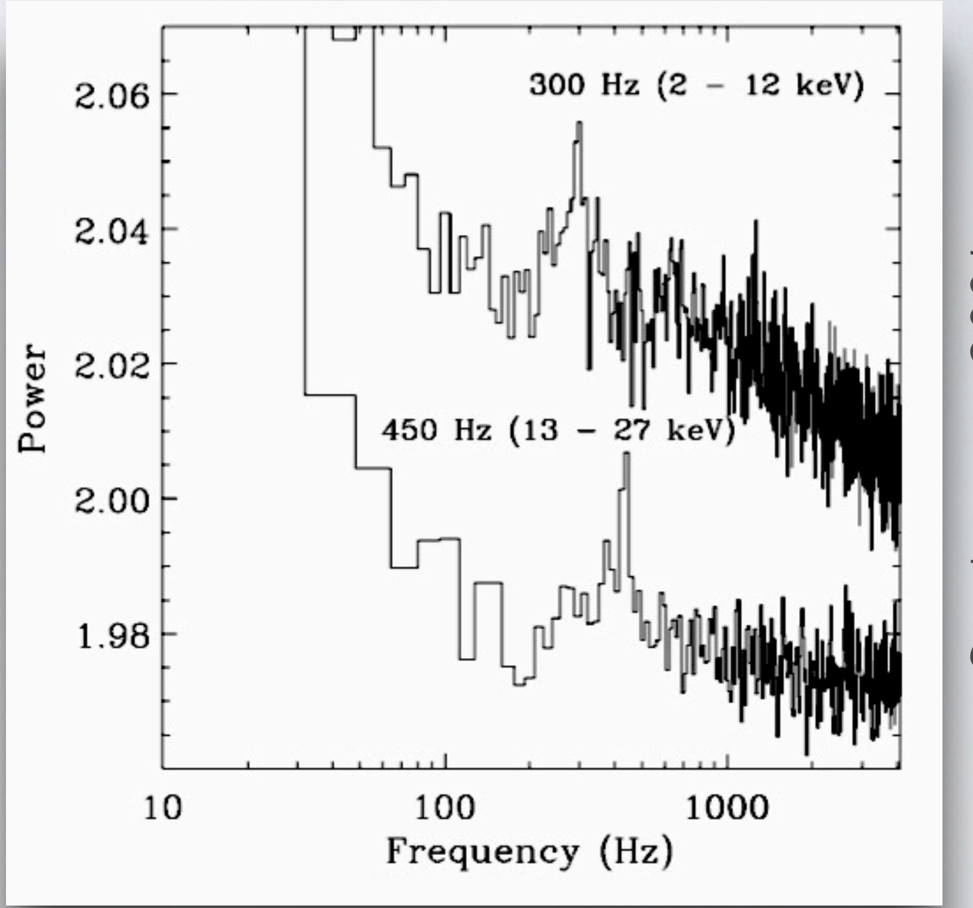
Casella et al. 2004

Very common. Different shapes, frequency ranges, noise level...

We do not know what they are.

HIGH FREQUENCY

Might be keplerian!



Strohmayer 2001

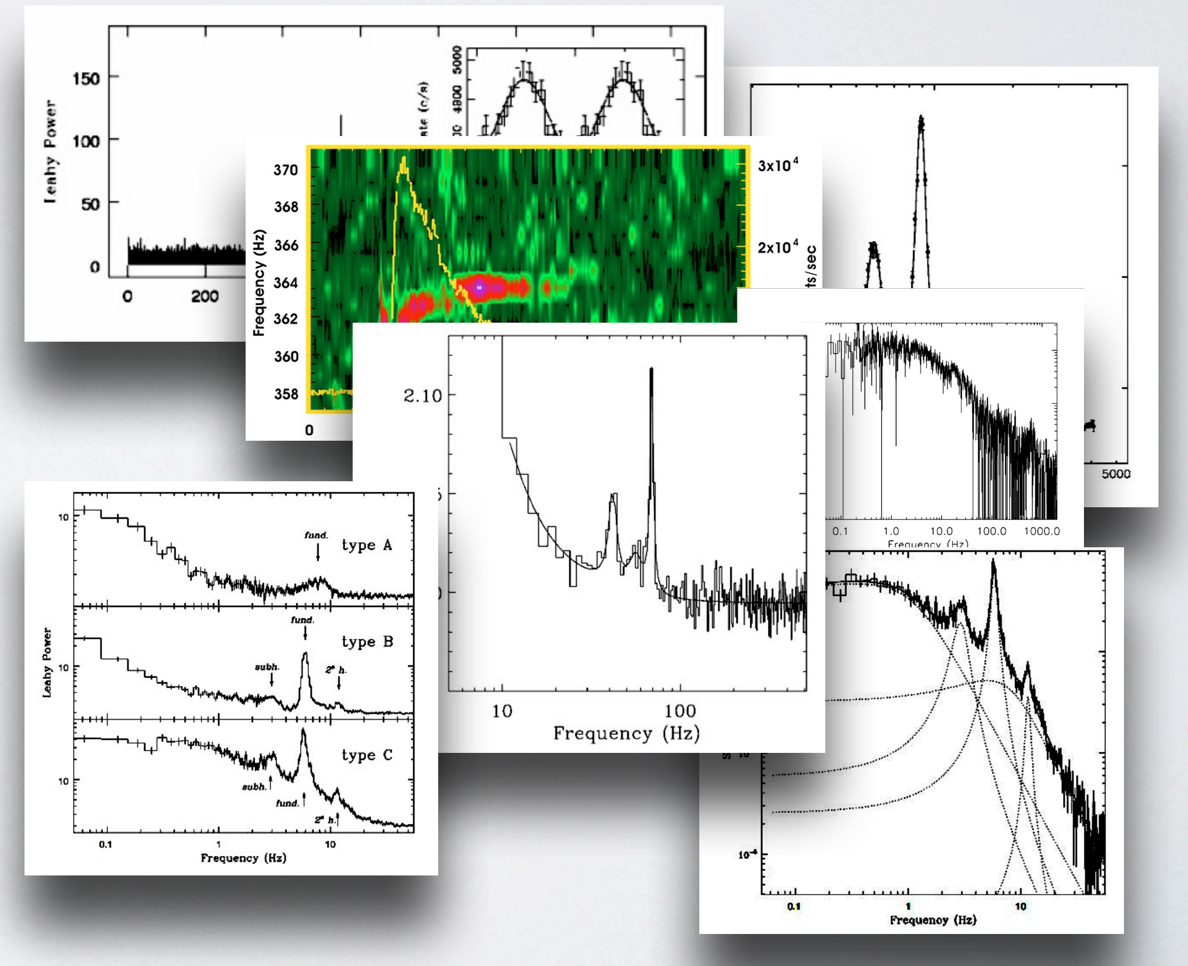
Not common nor easily detectable (especially in pairs), and again...

We do not know what they are.

WHY DO WE CARE ABOUT QPOs?

- produced close to the central compact object
- They are very common
- Easy to study
- They allow to test General relativity!

But collecting pretty peaks is not enough...!



THE RPM
RELATIVISTIC PRECESSION MODEL

Stella & Vietri 1998,1999,1999a

R in the same for all the equations

$$\begin{cases} \nu_\phi = \nu_\phi(M,a,R) \\ \nu_{per} = \nu_\phi - \nu_r = \nu_{per}(M,a,R) \\ \nu_{nod} = \nu_\phi - \nu_\theta = \nu_{nod}(M,a,R) \end{cases}$$

≡ Orbital frequency

≡ Periastron precession frequency
keplerian frequency - radial epicyclic frequency

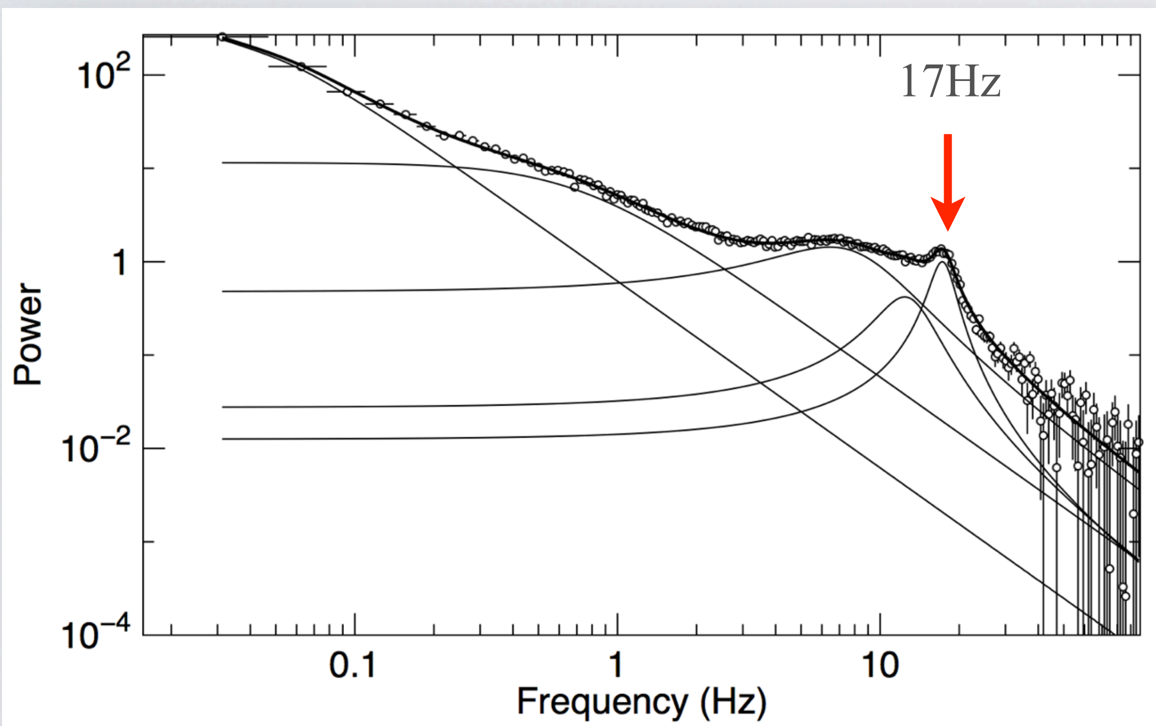
≡ Nodal frequency (or Lense-Thirring)
keplerian frequency - vertical epicyclic frequency

If you have ν_ϕ, ν_{per}, ν_{nod} together
you can solve the system!

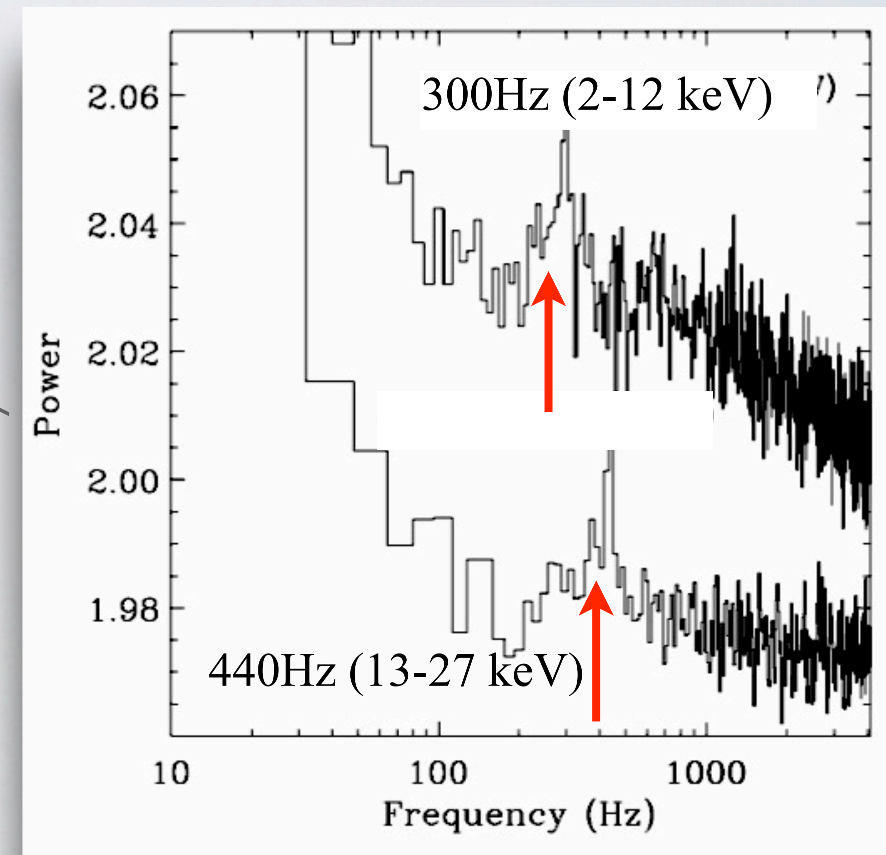
GRO J1655-40

$$
\begin{cases}
\nu_\phi = \nu_\phi(M,a,R) \\
\nu_{per} = \nu_\phi - \nu_r = \nu_{per}(M,a,R) \\
\nu_{nod} = \nu_\phi - \nu_\theta = \nu_{nod}(M,a,R)
\end{cases}
$$

Motta et al 2012



Strohmayer 2001



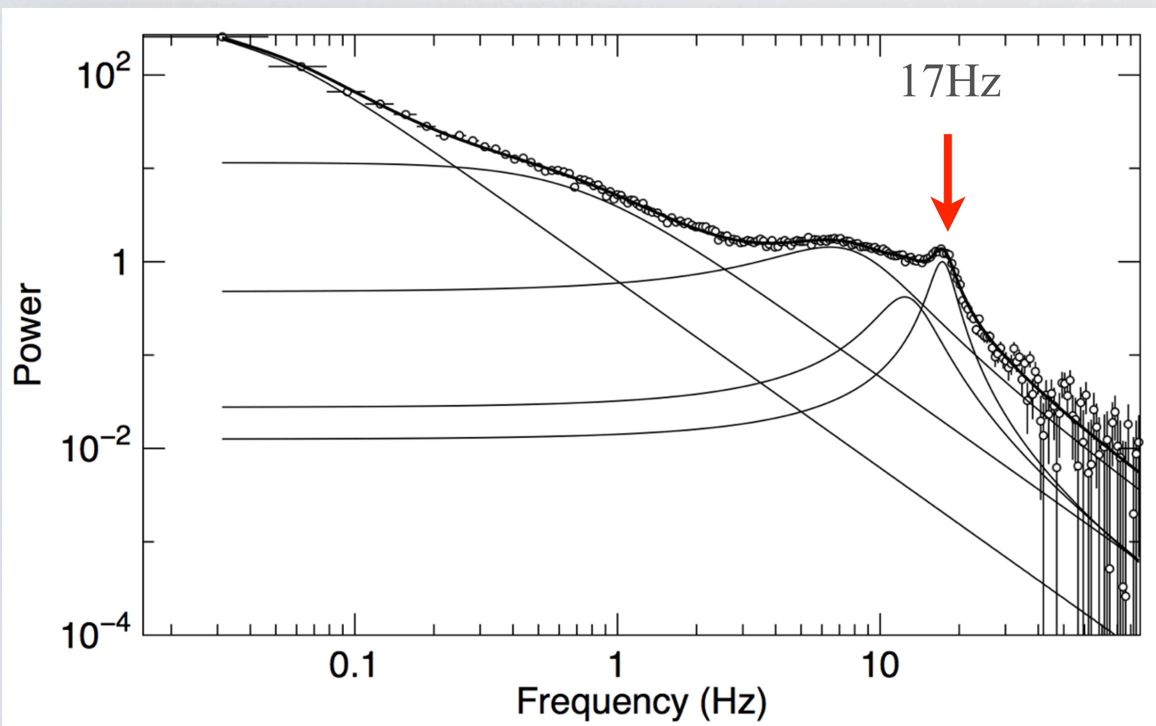
Those peaks are observed ***simultaneously***!

data from RXTE

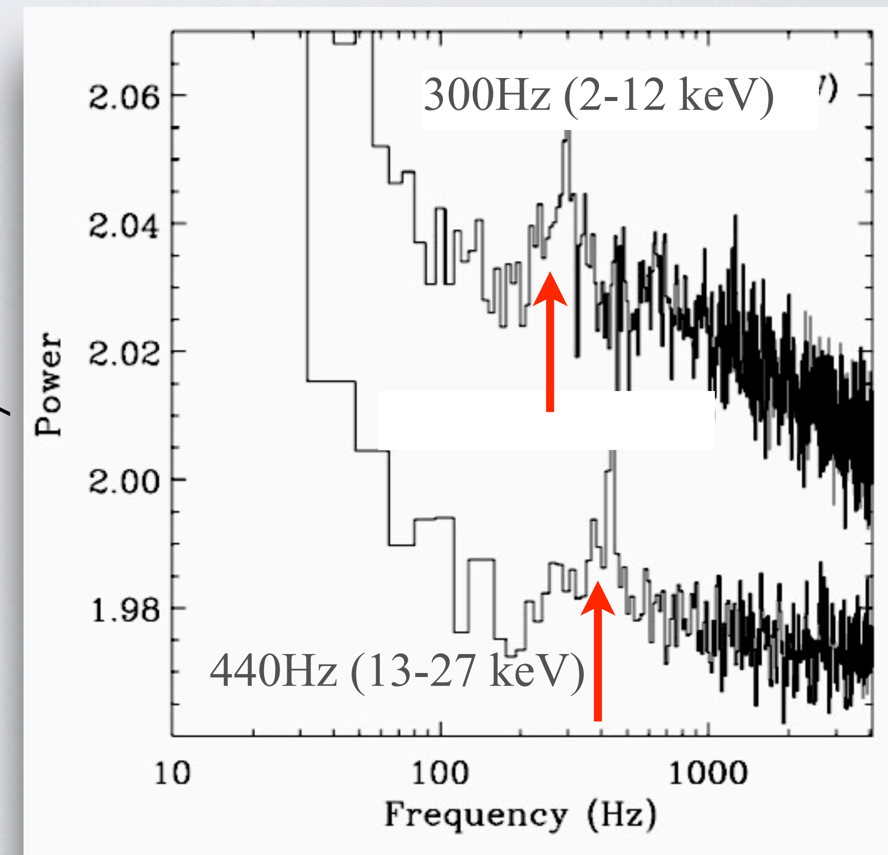
GRO J1655-40

$$\begin{cases} \nu_\phi = \nu_\phi(M,a,R) \\ \nu_{per} = \nu_\phi - \nu_r = \nu_{per}(M,a,R) \\ \nu_{nod} = \nu_\phi - \nu_\theta = \nu_{nod}(M,a,R) \end{cases}$$

Motta et al 2012



Strohmayer 2001



Type-C QPO ν_{nod}□

Nodal Frequency

Lower HFQPO ν_{per}

Periastron precession frequency

Upper HFQPO ν_ϕ

Orbital frequency

YOU GET THE MASS AND THE SPIN!

In Hz

$$\nu_\phi = 17.25 \pm 0.07$$
$$\nu_{per} = 298 \pm 4$$
$$\nu_{nod} = 440 \pm 3$$

Solve the RPM system →

In solar masses and gravitational radii

$$M = 5.31 \pm 0.07$$
$$a = 0.286 \pm 0.003$$
$$R = 5.68 \pm 0.04$$

Beer & Podsiadlowski 2002

From Optical-Infrared

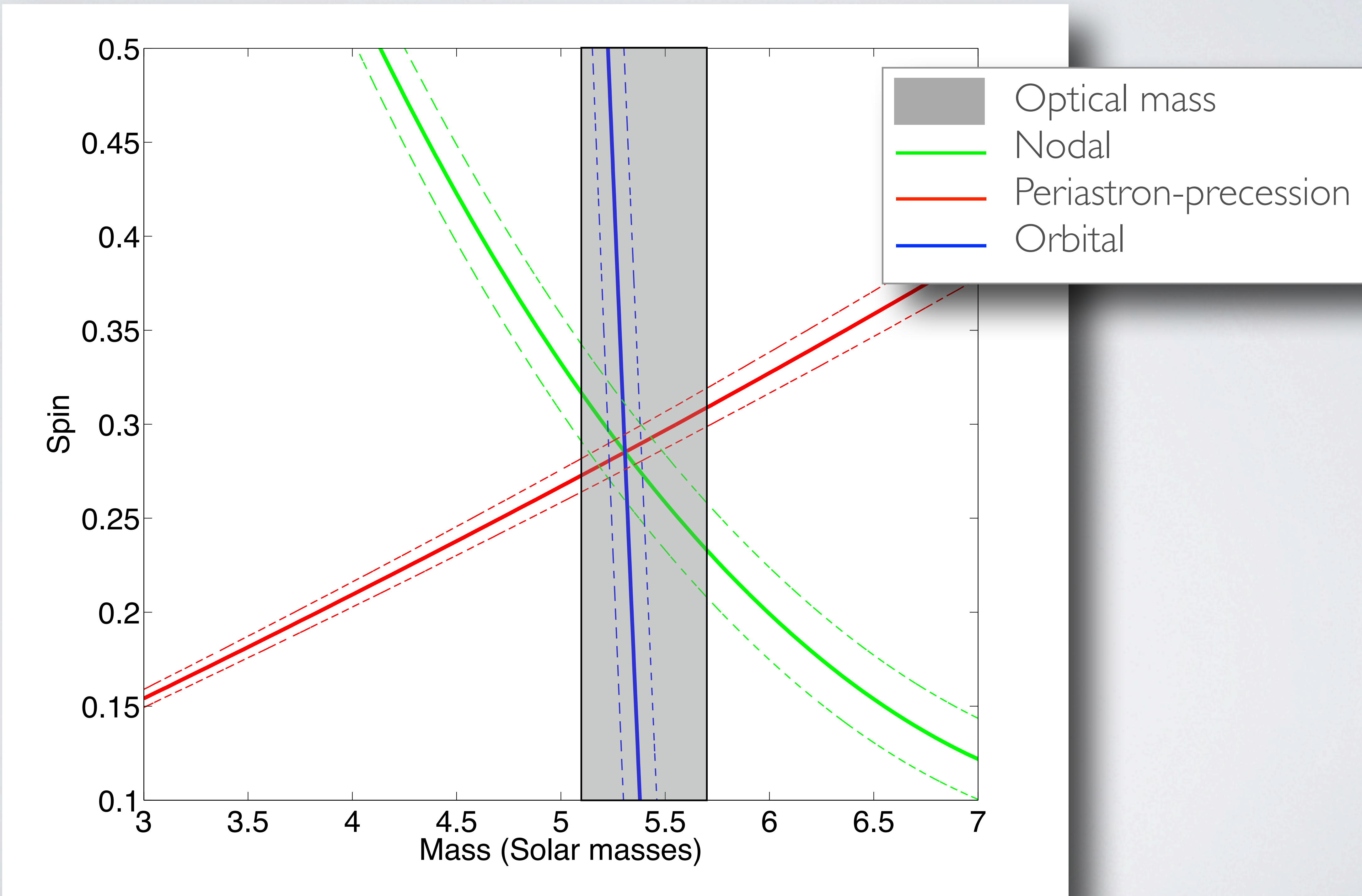
$M = 5.4 \pm 0.3\ M_\odot$

e.g. Shafee et al. 2006

From X-ray spectroscopy

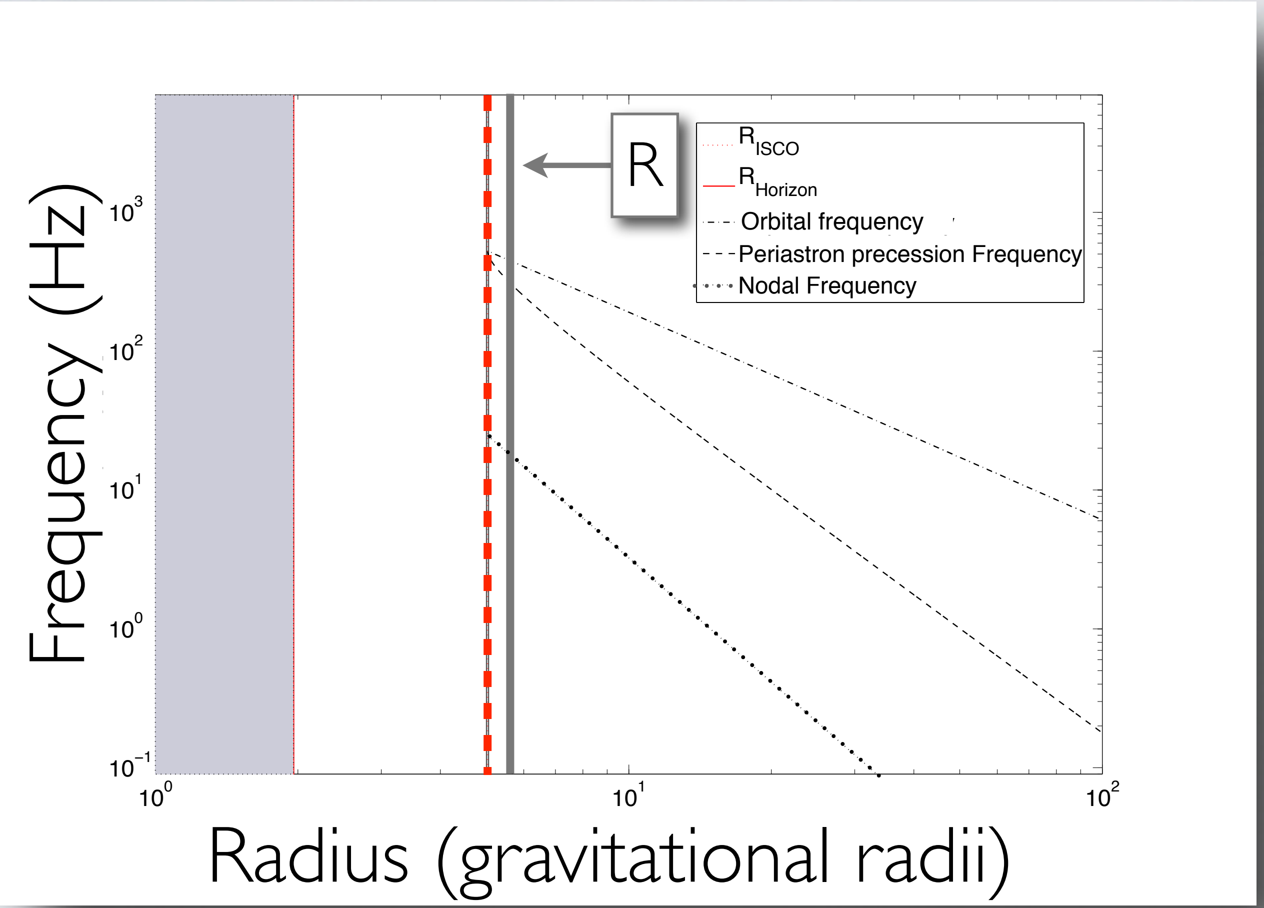
$a = 0.65 \div 0.75$

YOU GET THE MASS AND THE SPIN!

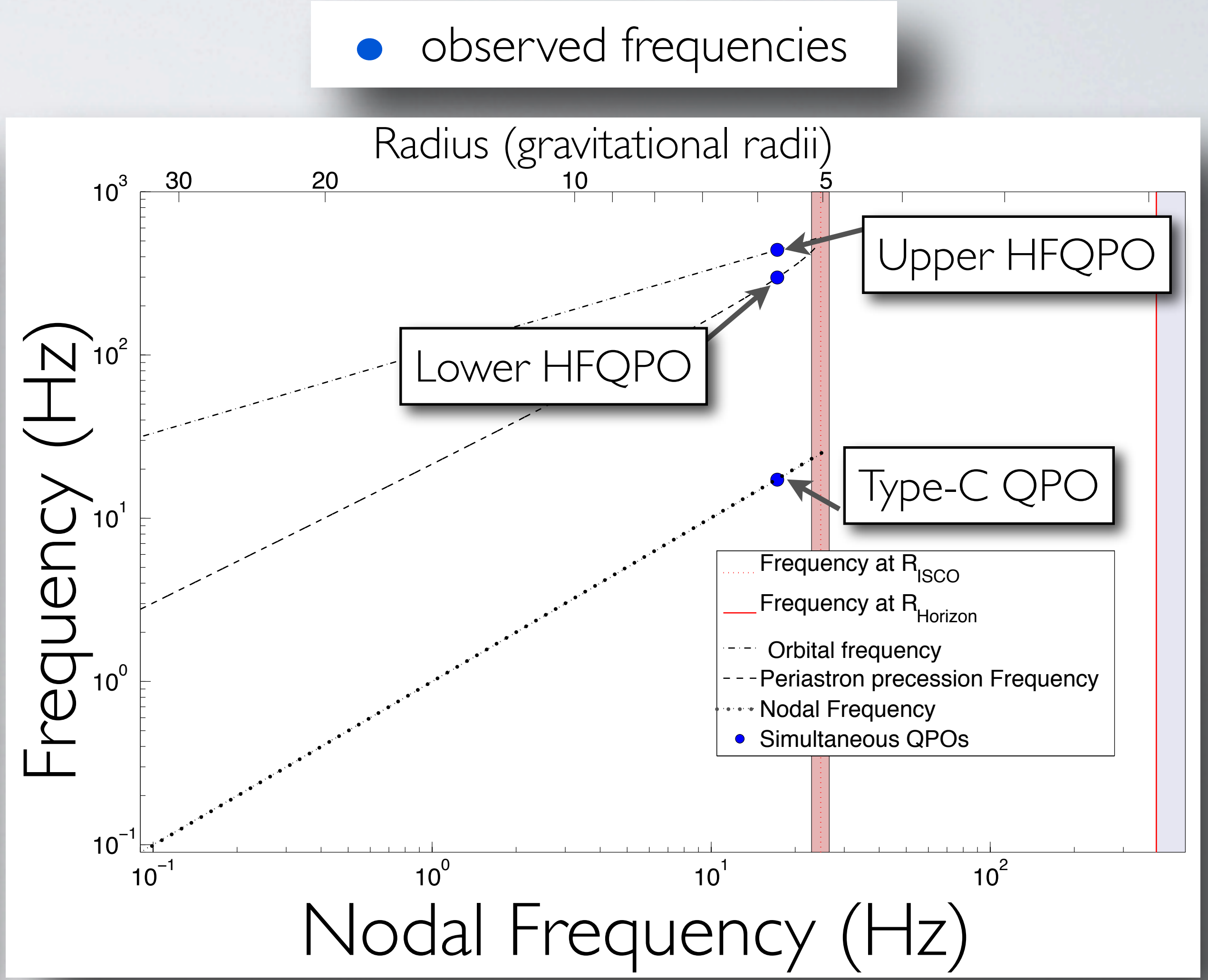


Motta et al. 2013

THE RPM FOR GRO J1655-40



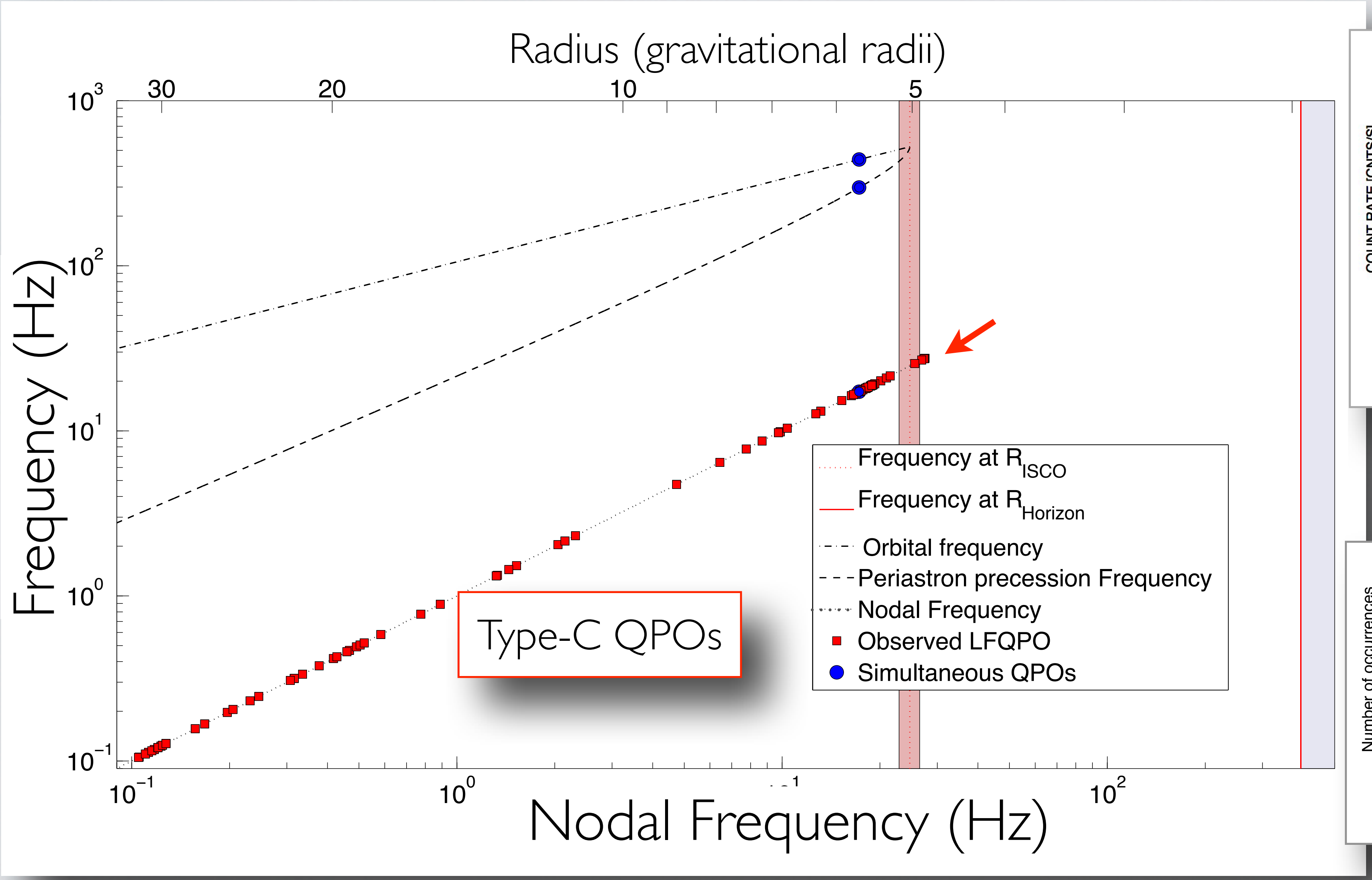
frequency vs radius

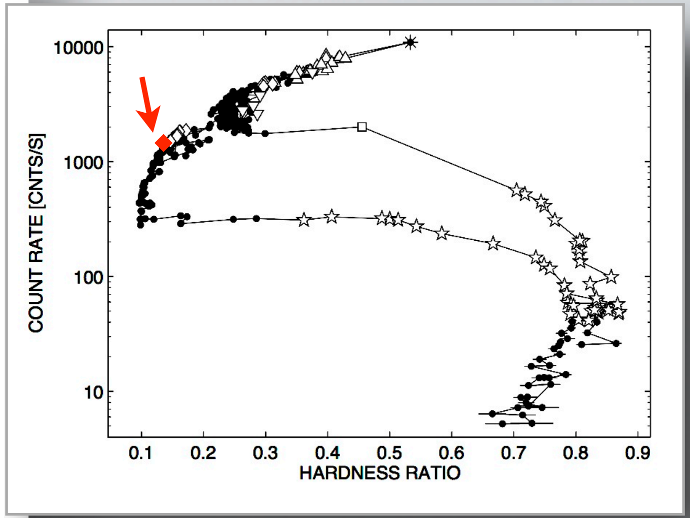


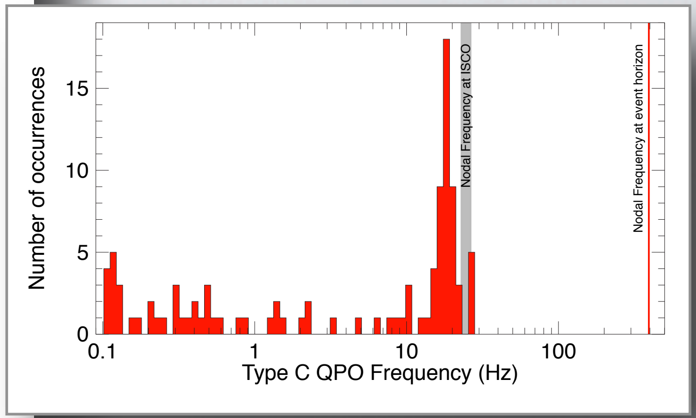
frequency vs nodal frequency

Motta et al. 2013

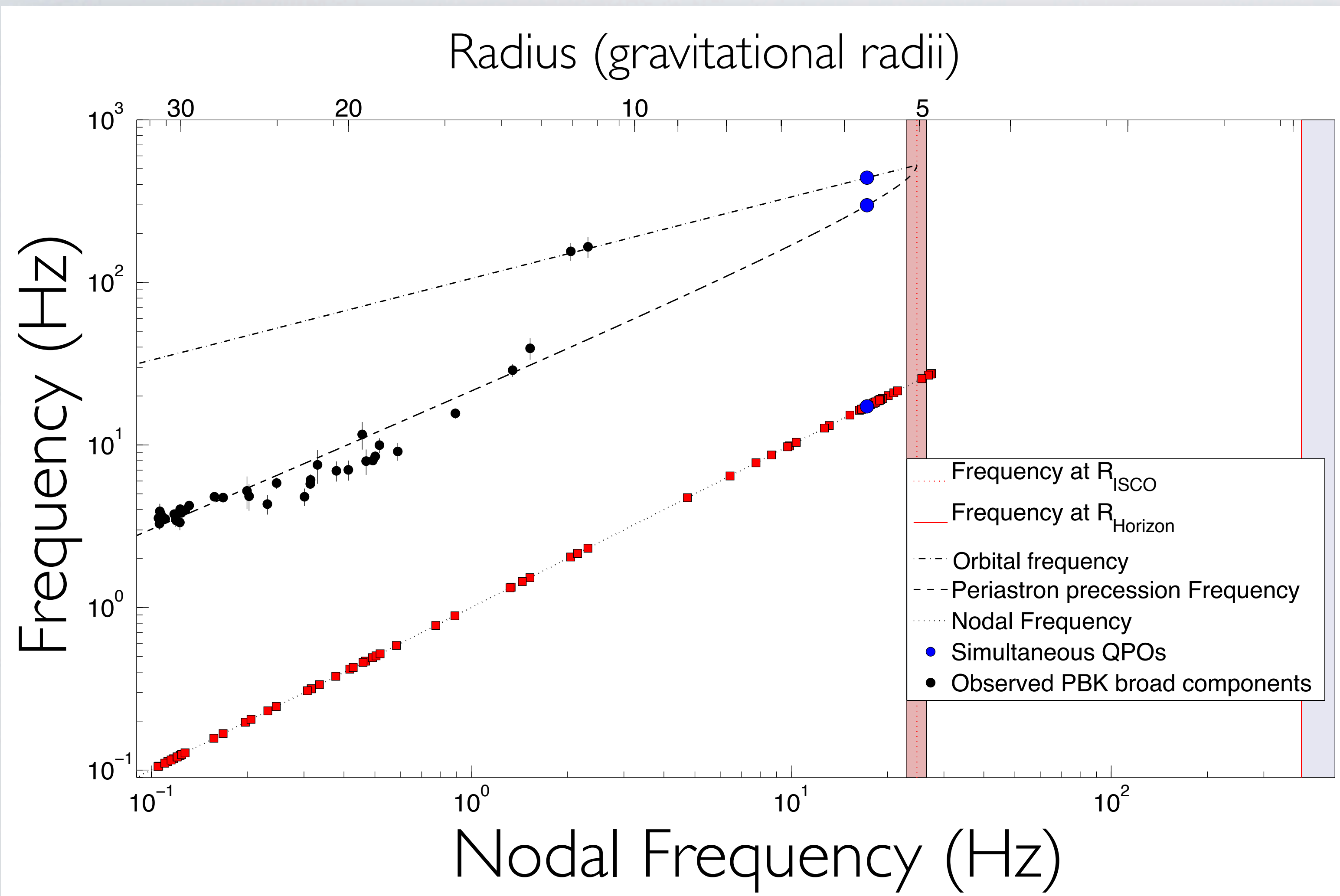
THE RPM + TYPE-C QPOs





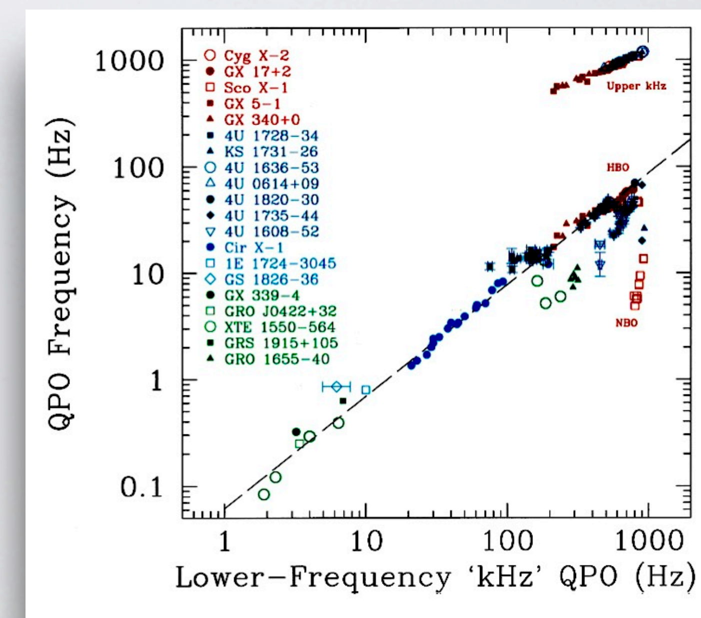


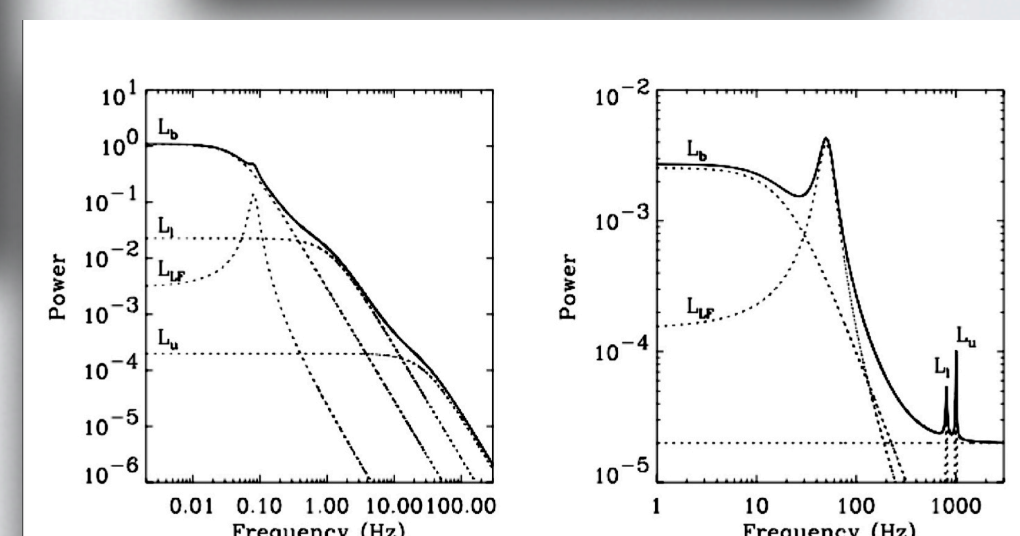
THE RPM + TYPE-C QPOs + PBK RELATION



Motta et al. 2013

Psaltis, Belloni, van der Klis 1999
(PBK correlation)





SUMMARIZING

what you do

- you start from GR
- you measure 3 frequencies
- you solve the RPM system system of equations
- you get reasonable mass and spin
- the predicted frequencies match the data

what you get

- you verify the validity of the RPM (relativistic precession and keplerian motion do explain QPOs!)
- you have a method to measure black hole spin and mass and to track the emission radius
- the PBK broad components and HFQPOs are unified by the RPM

IN CONCLUSION

You can do real hard core physics from timing!

From the timing you get a very precise measure of the fundamental parameters of a Black Hole