Discovery of a soft X-ray 8 mHz QPO from the accreting millisecond pulsar IGR J00291+5934

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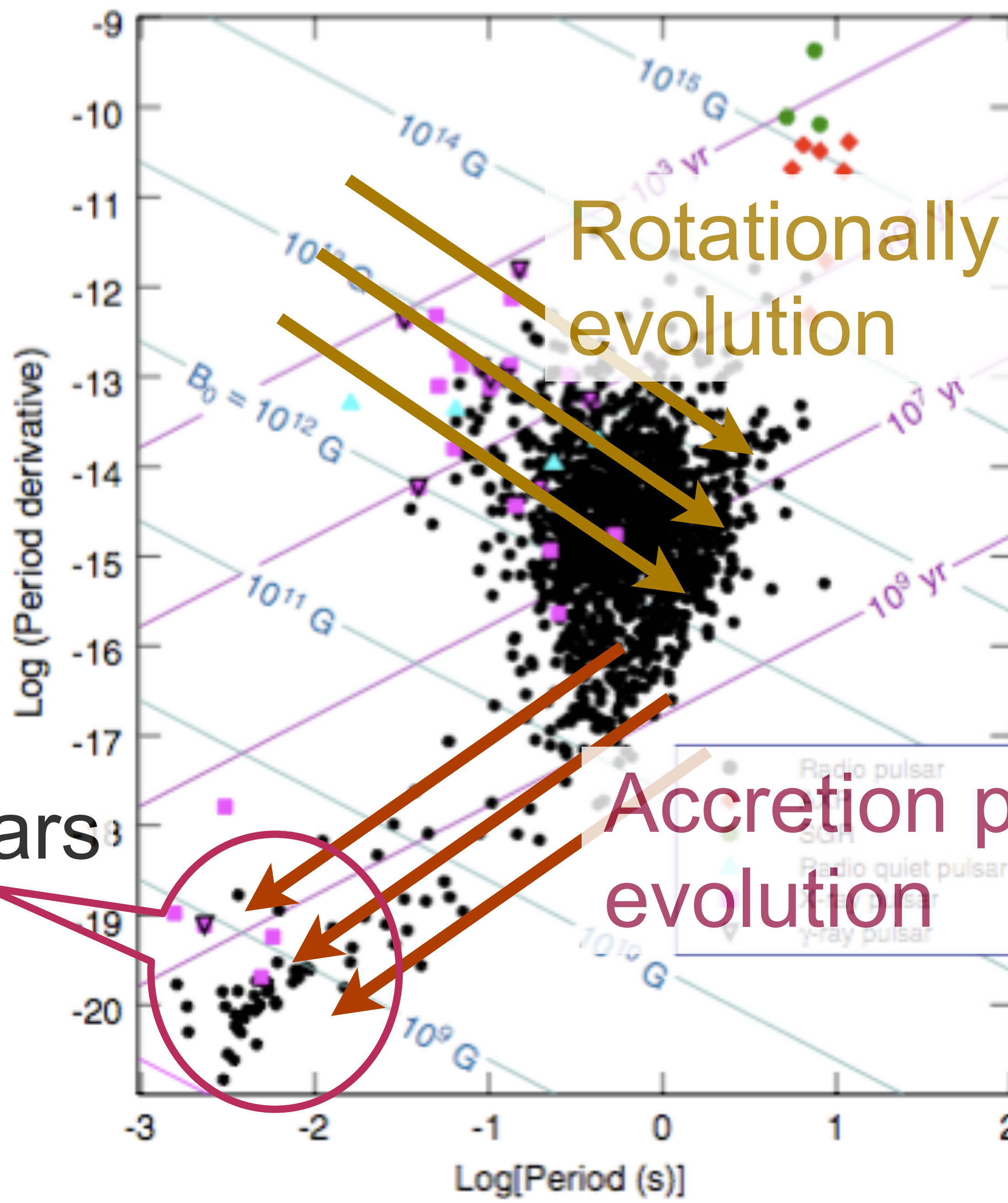
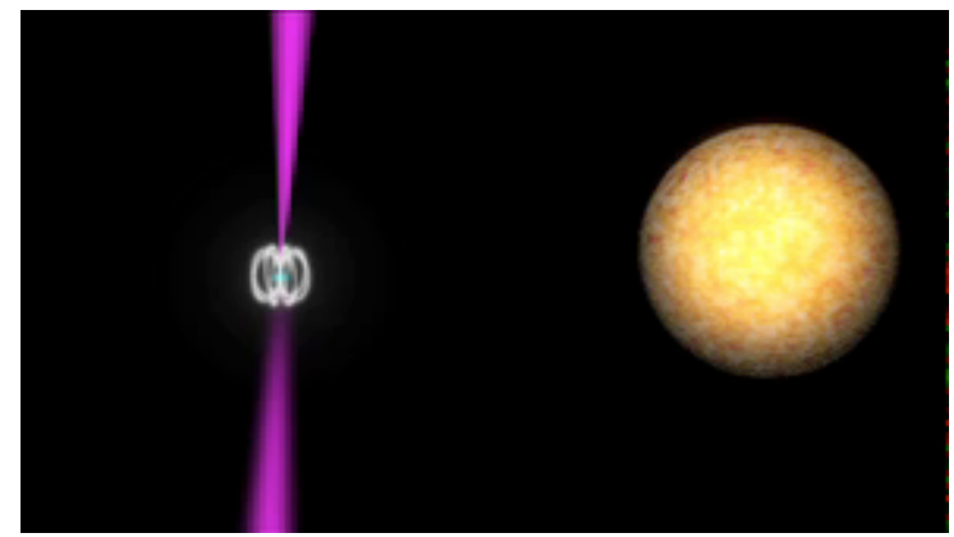
The context



Rotationally powered evolution

Accretion powered evolution

Recycled pulsars



- Accretion of material brings angular momentum and spins-up the pulsar.

The growing family of Accreting MilliSecond Pulsars

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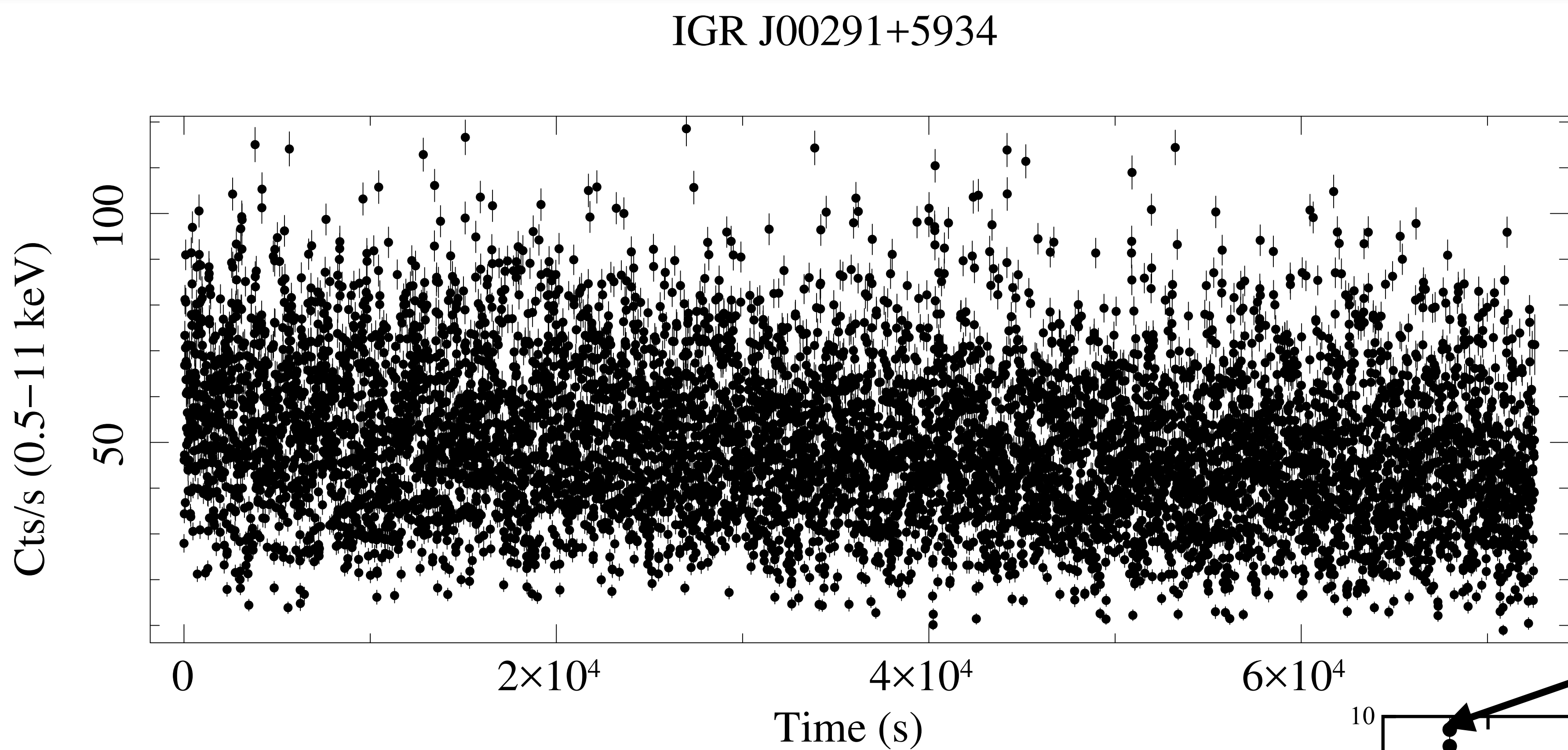
Name	P_{Spin} [ms]	P_{Orb} [min]	$M_{C,Min}$ [M_{sol}]	Discovered
SAX J1808.4-3658	2.5	120	0.043	Apr. 1998
XTE J1751-306	2.3	42	0.014	Apr. 2002
XTE J0929-314	5.4	44	0.083	Apr. 2002
XTE J1807-294	5.2	40	0.0066	Feb. 2003
XTE J1814-338	3.2	258	0.17	Jun. 2003
IGR J00291+5934	1.67	150	0.039	Dec. 2004
HETE J1900.1-2455	2.6	84	0.016	Jun. 2005
Swift J1756.9-2508	5.5	54	0.007	Jun. 2007
NGC 6440 X-2	4.86	57	0.0067	Aug. 2009
IGR J17511-3057	4.1	208	0.13	Sep. 2009
Swift J1749.4-2807	1.9	530	0.6	Apr. 2010
IGR J17498-2921	2.5	230.4	0.17	Aug 2011
IGR J18245-2452	3.9	661.5	0.17	March 2013
MAXI J0911-655	2.9	44.3	0.024	February 2016

+ 2 Intermittent pulsars: Aql X-1 and SAX J1748.9-2021

IGR J00291

- Fastest AMSP: 600 Hz (fastest pulsar 716 Hz, Hessels et al. 2006)
- Compact binary, similar to SAX J1808.4 companion mass 0.04-0.16 M_{sol}
- Measured spin-up in accretion phase (8.4 10^{-13} Hz/s, Falanga et al, 2005)
- Zero orbital period derivative, limit compatible with Gravitational Wave emission (Patruno et al., 2016)
- A Type-C QPO was found in 2004 outburst (Linares et al. 2007). Frequency at 44 mHz with hard spectrum.
- In 2015 (outburst studied here), a Thermonuclear burst was detected for the first time with Swift (De Falco et al., 2016). This is the brightest of the source outbursts.
- Distance estimate (4 kpc, De Falco et al., 2016).

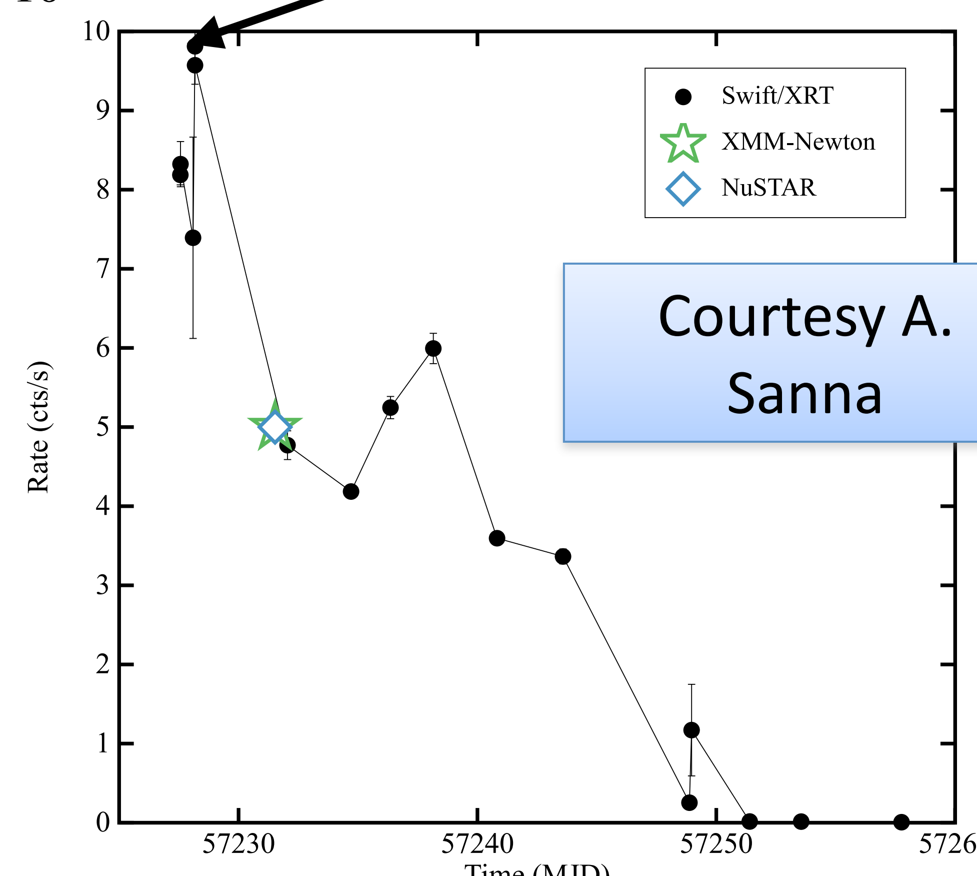
Light curve and Hardness ratio



Ferrigno et al. (MNRAS 2017)

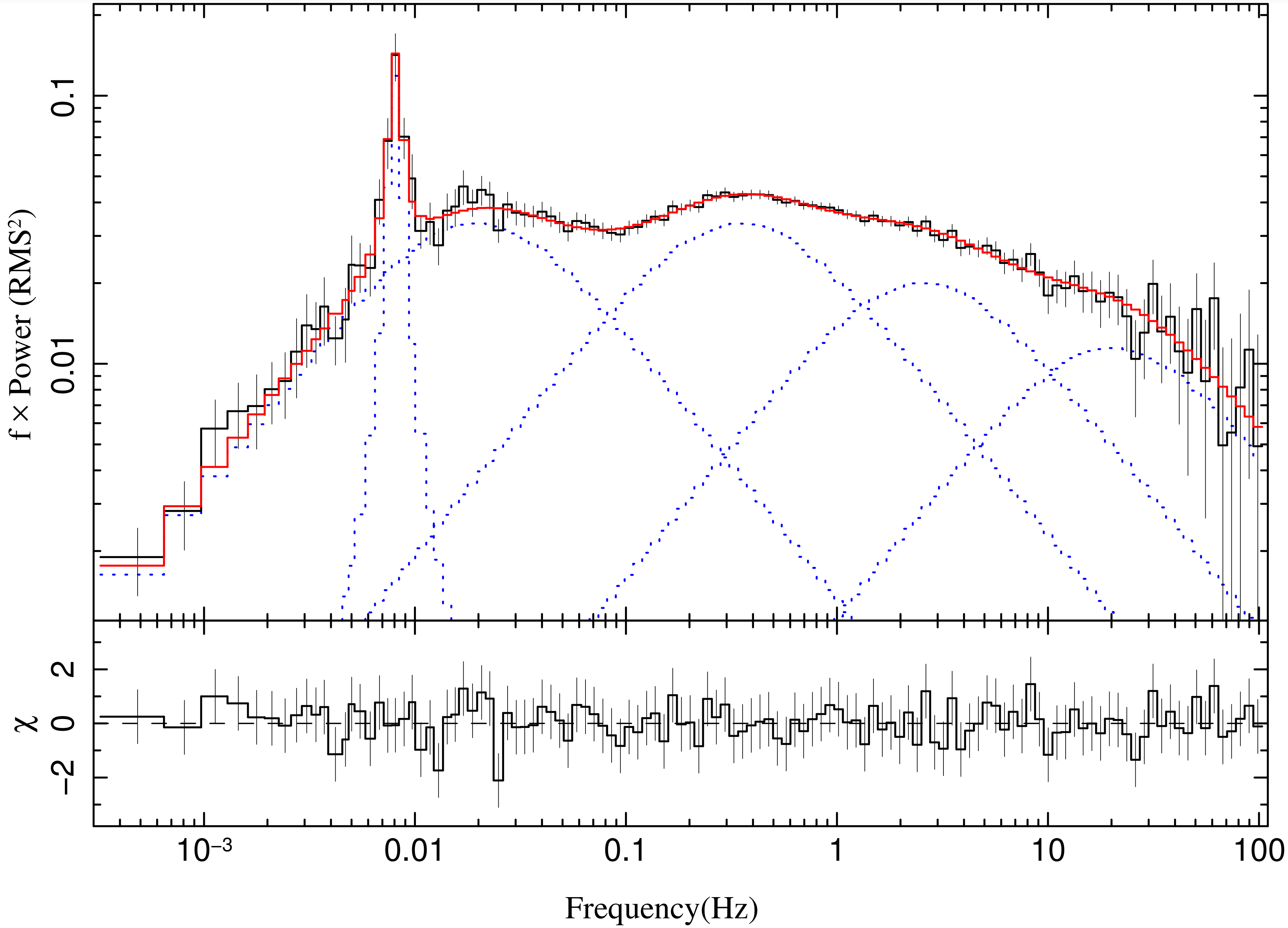
Thermonuclear burst

- 2015: 70 ks XMM Epic
  86 ks RGS
- 40 ks Contemporary Nustar
- Decay of the outburst



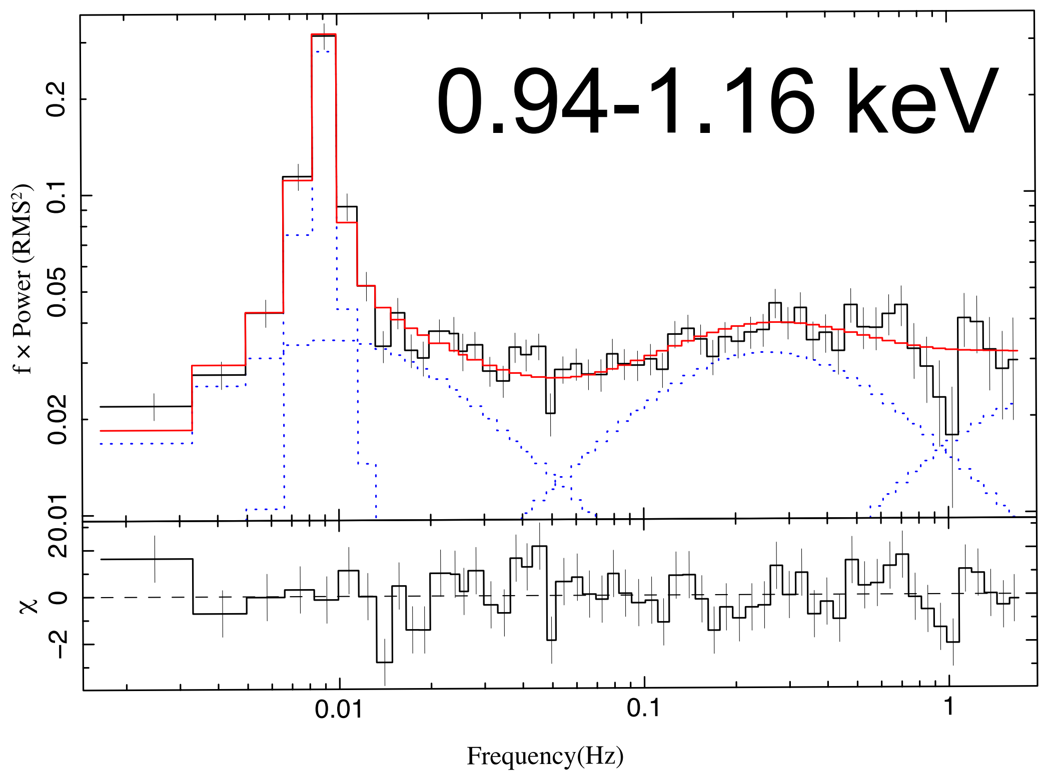
Courtesy A. Sanna

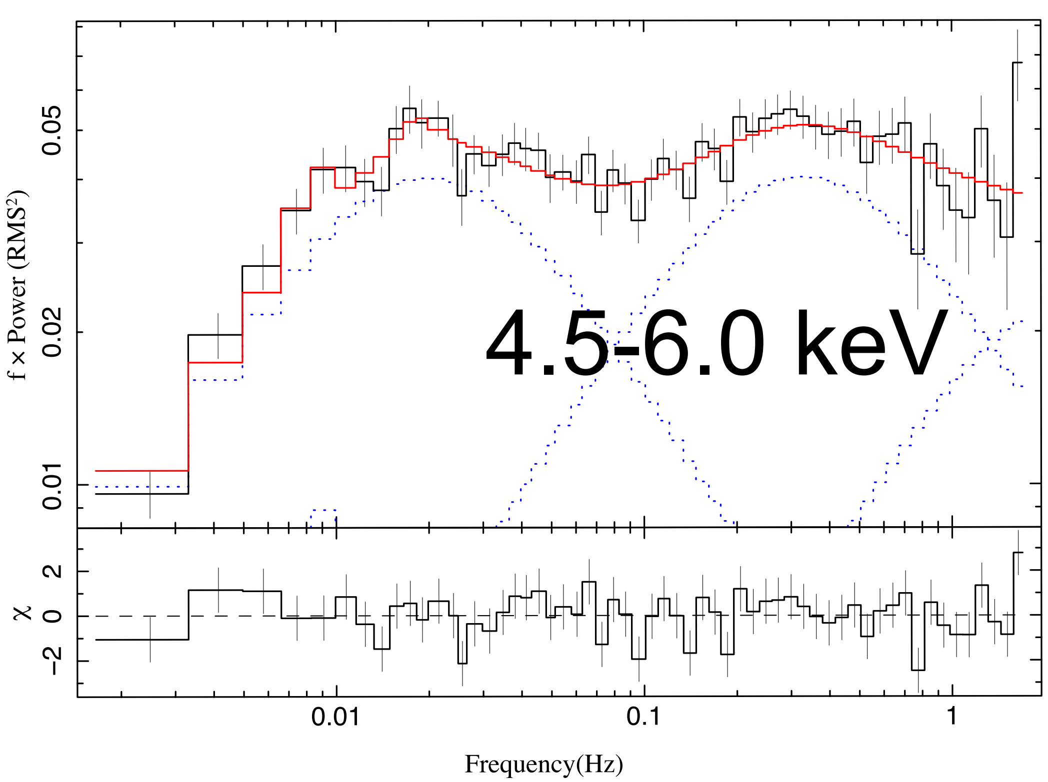
Power density spectrum

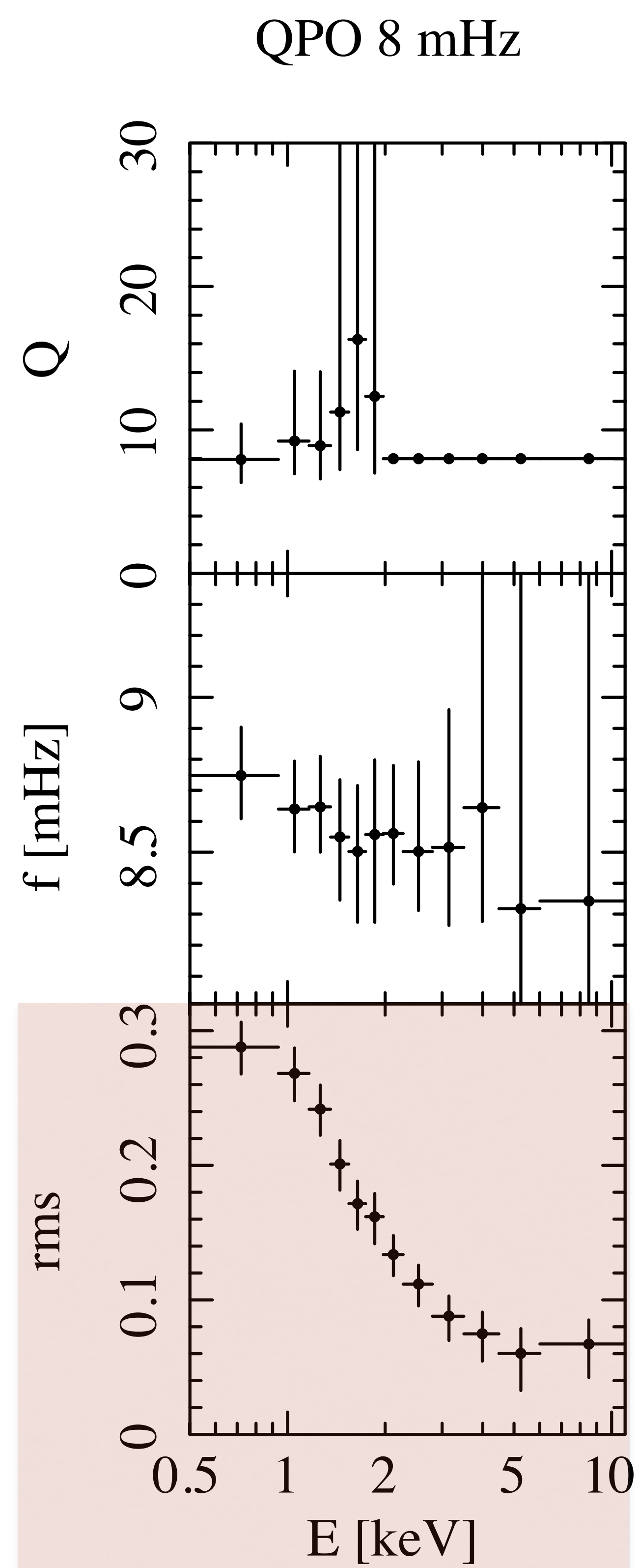


- 0.5 -11 keV XMM EPIC-pn
- Four broad Lorentzians and one QPO: f=8 mHz Q=9 rms=15%

Energy-resolved analysis

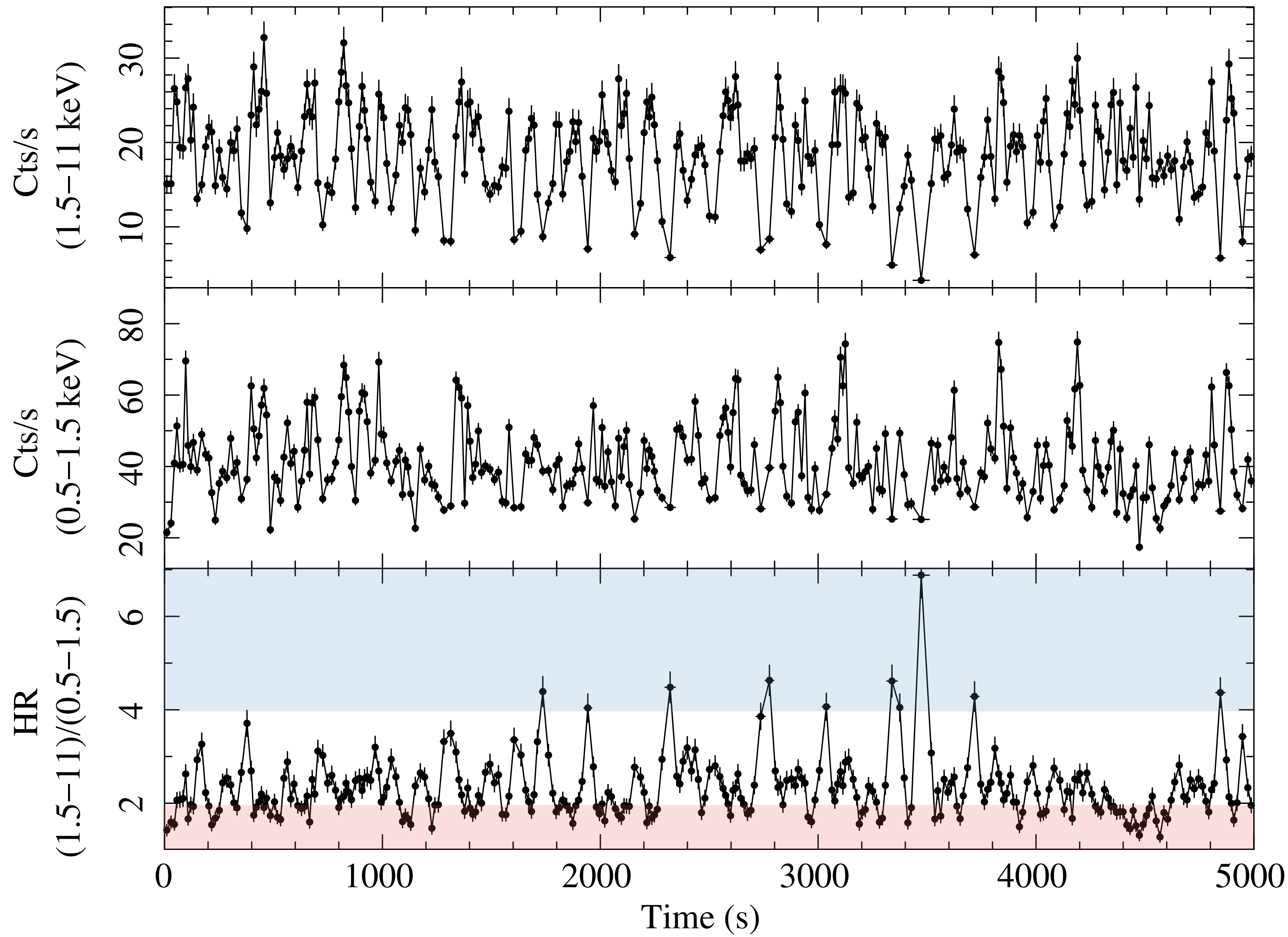






- Divided in 12 energy bins with equal number of photons.
- Frequency at 8.5 mHz
- A very soft QPO !
- Rather high Q-factor

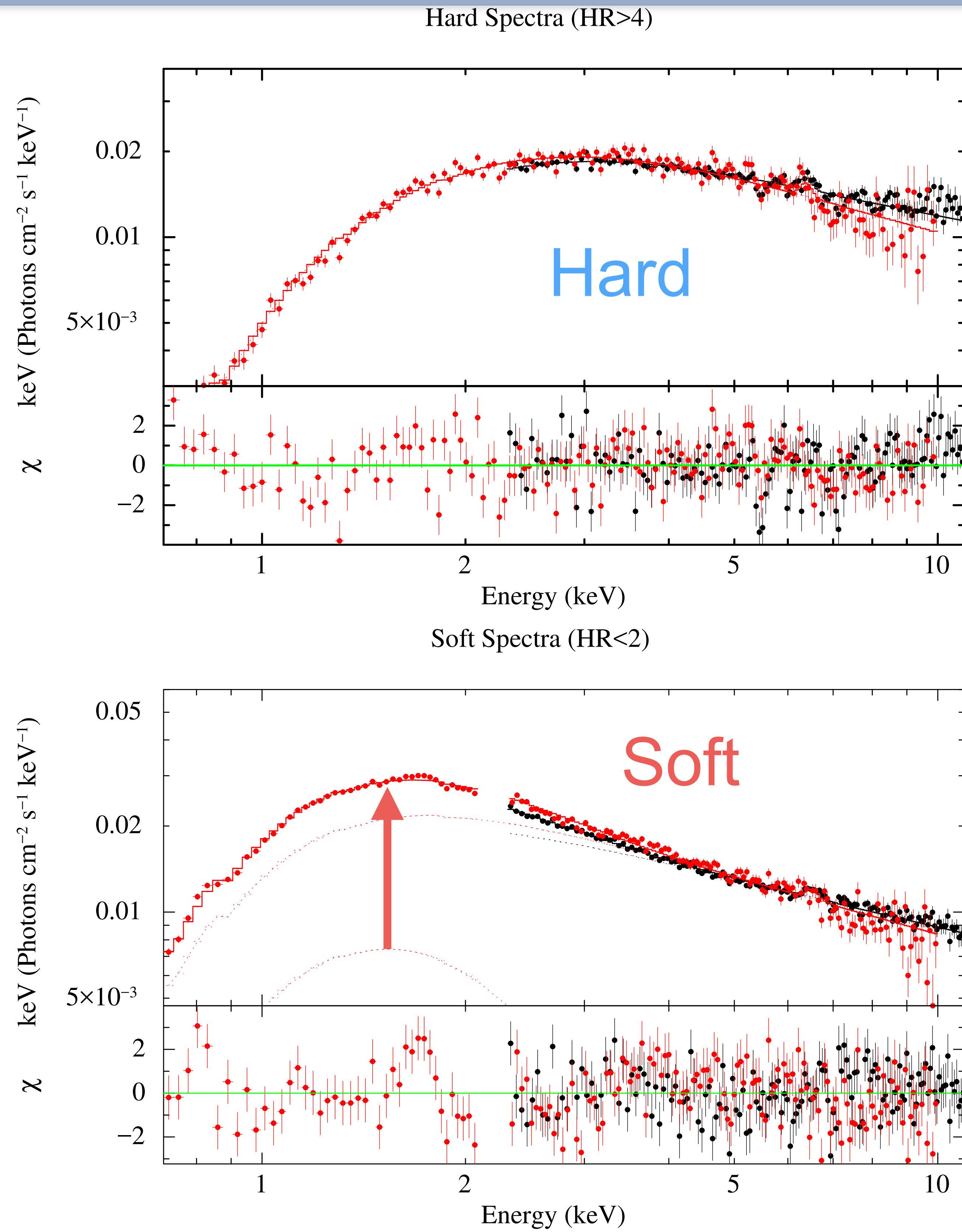
Zoomed light curve



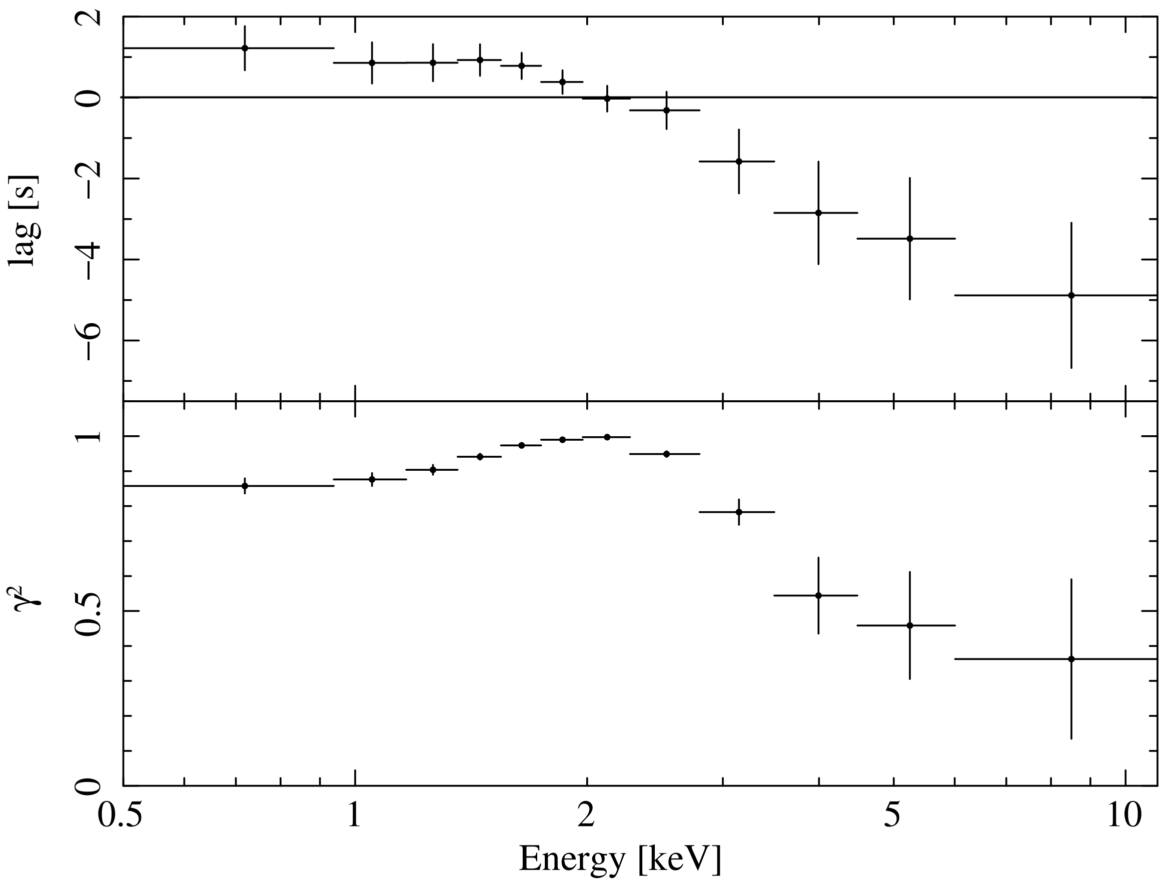
- At low luminosity, sometimes hard, sometimes soft.

Hardness-resolved spectra

- As for the average spectrum (Sanna et al. 2017), we use *(Tbabs *(nthComp (kT_s= 1, kT_e = 28 keV + BlackBody (0.5 keV))*
- We exploit the hardness to guess the origin of variability.
- Softening due to additional black-body and lower seed-photon temperature in Comptonization. Almost equal power-law slope.



QPO-resolved spectroscopy

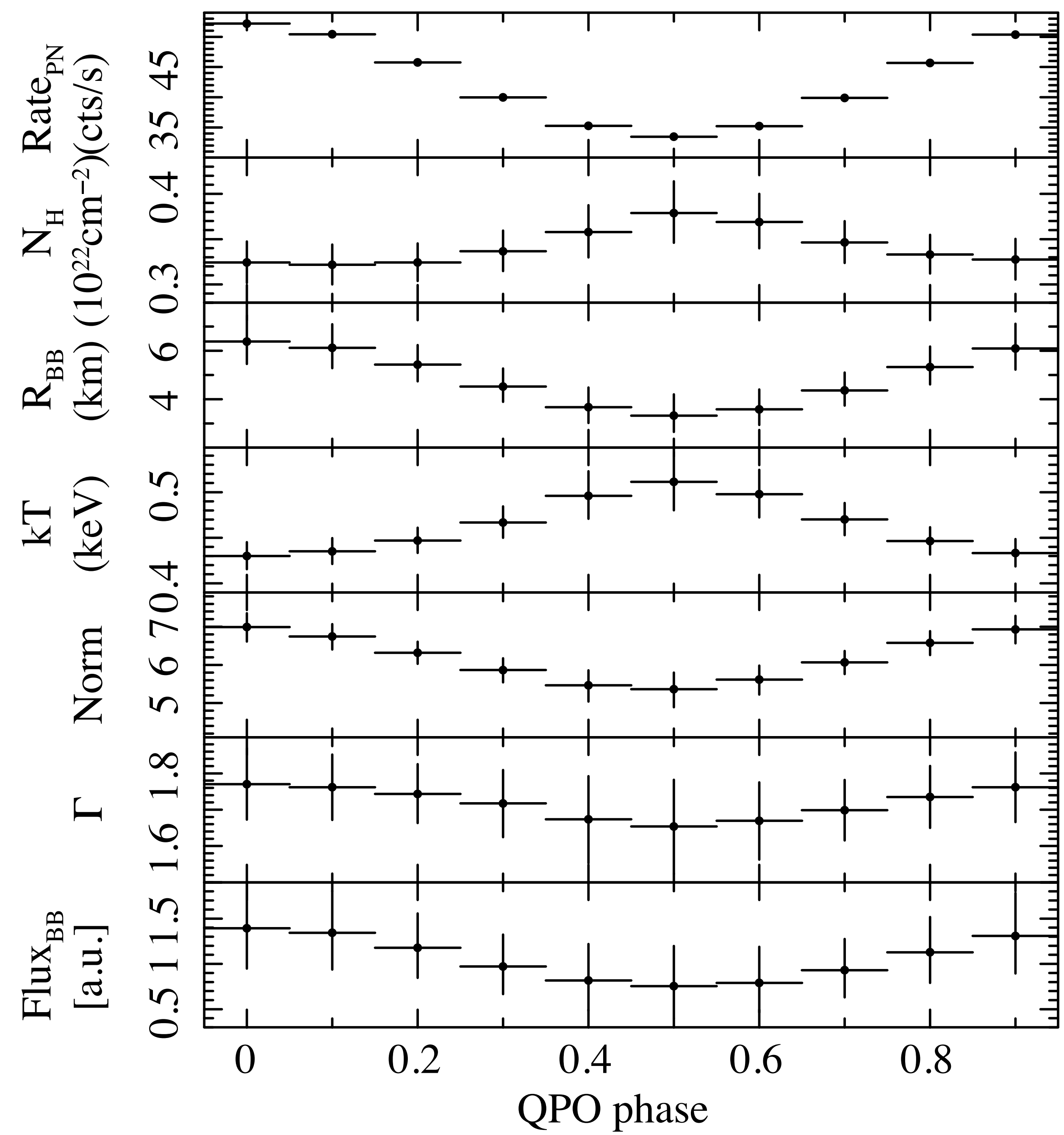


rms

$$w(E,\phi) = \mu(E)\left(1 + \sqrt{2}\sigma_1 \cos[\phi - \Phi_1(E)]\right).$$

mean spectrum

lag



- Lags at QPO frequency
- Reconstruct energy-dependent QPO front from rms and lag (1.5% systematic).
- Black Body (both T and R) drives variability

The accretion phase

Kulkarni & Romanova (2013)

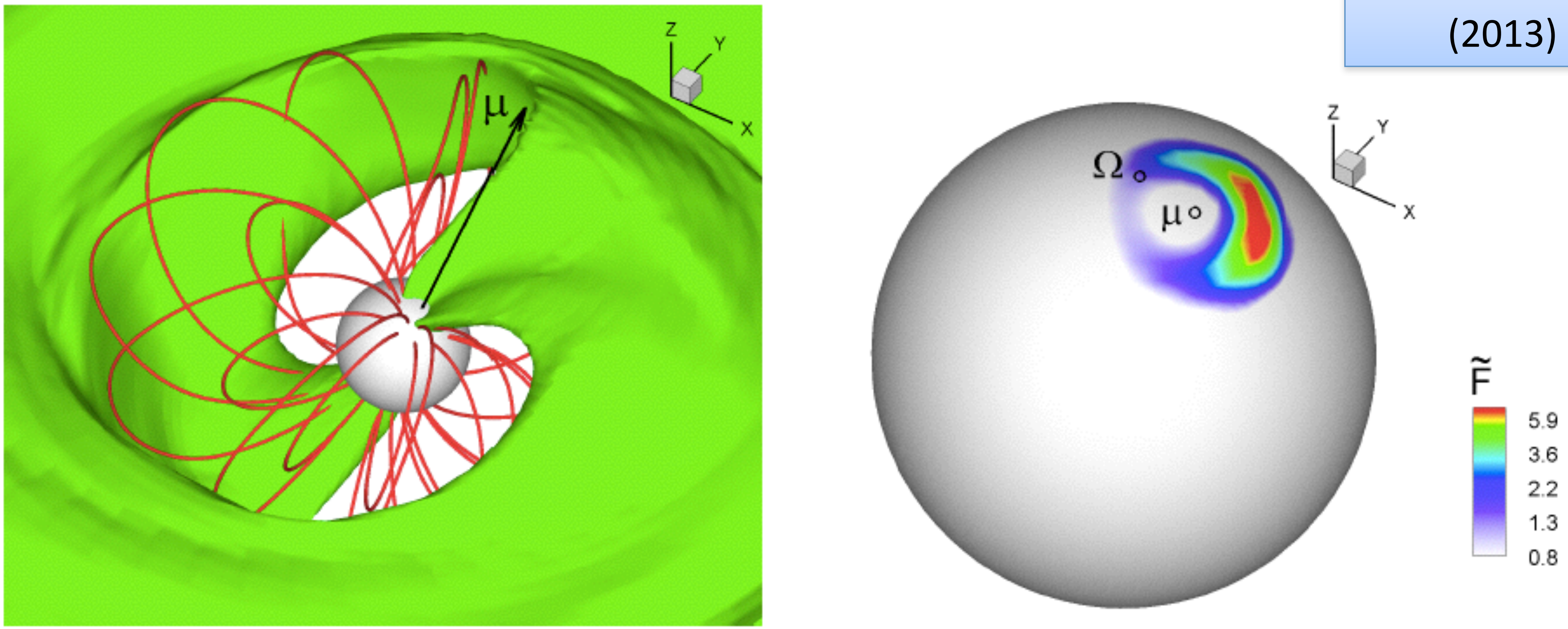
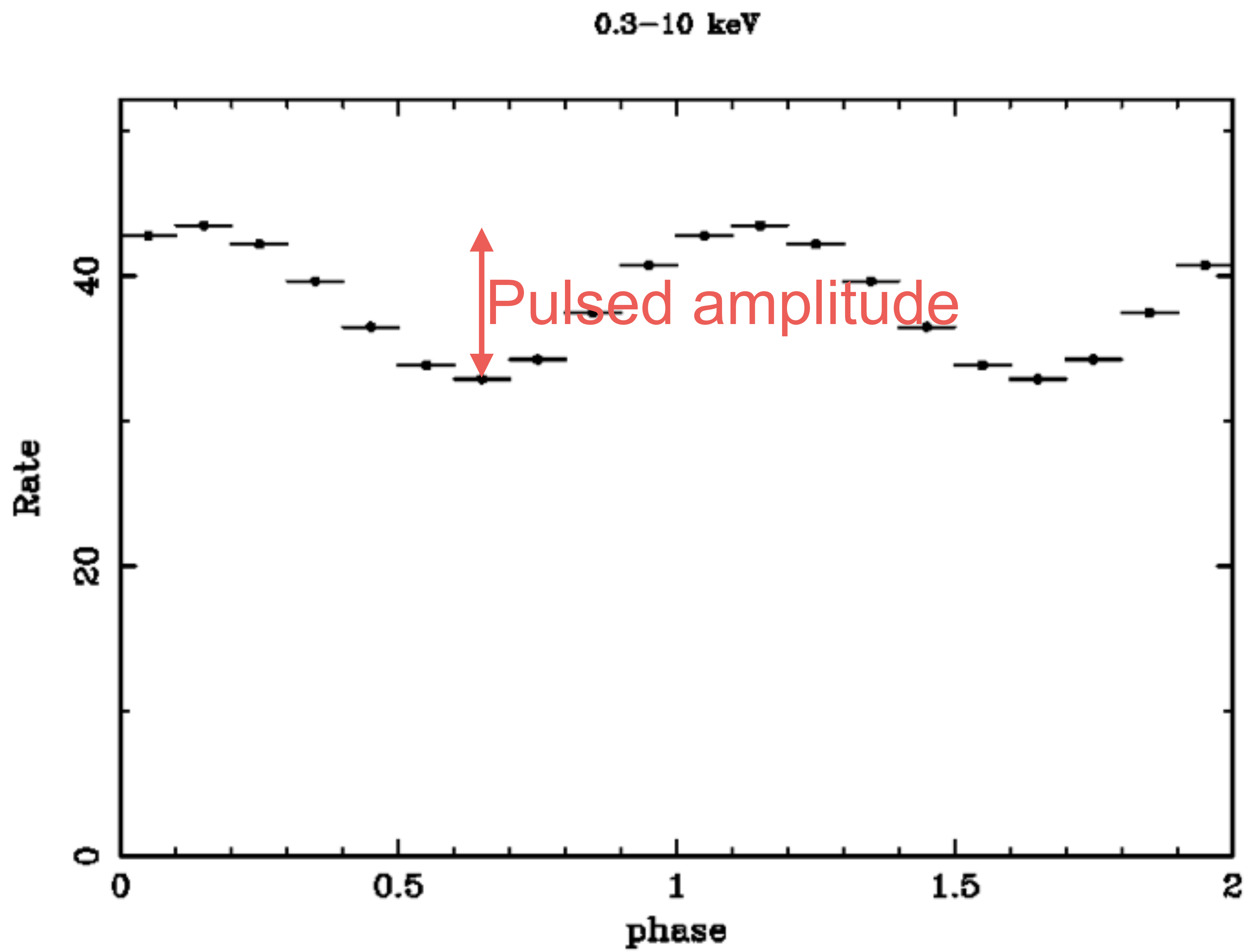


Figure 1. *Left panel:* A 3D view of the funnel flow from the disc to a magnetized star, where the dipole moment μ is tilted by $\Theta = 20^\circ$ about the rotational axis. One of the density levels is shown in green; sample field lines are shown in red. *Right panel:* the energy flux distribution on the

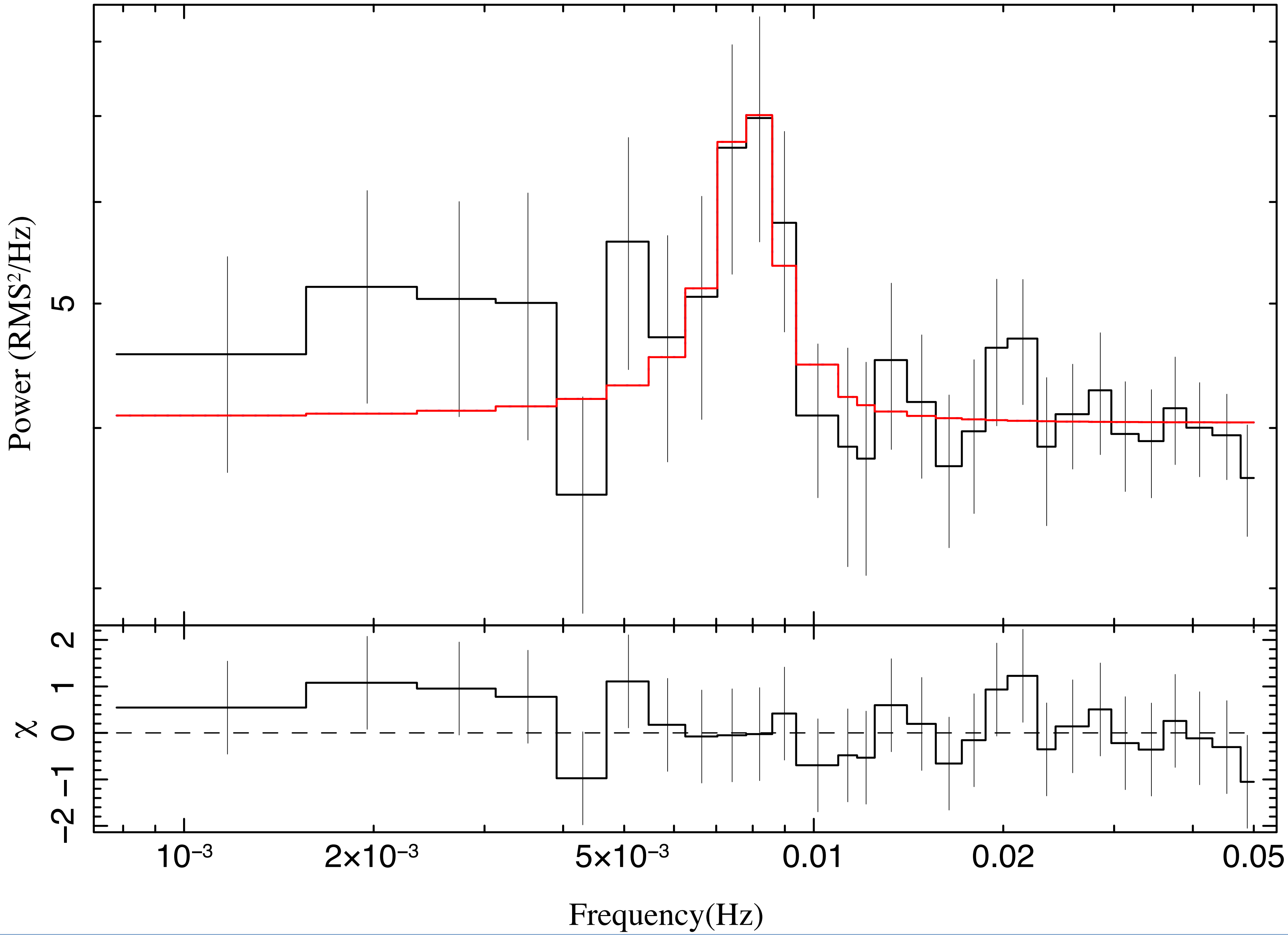
Pulse profile

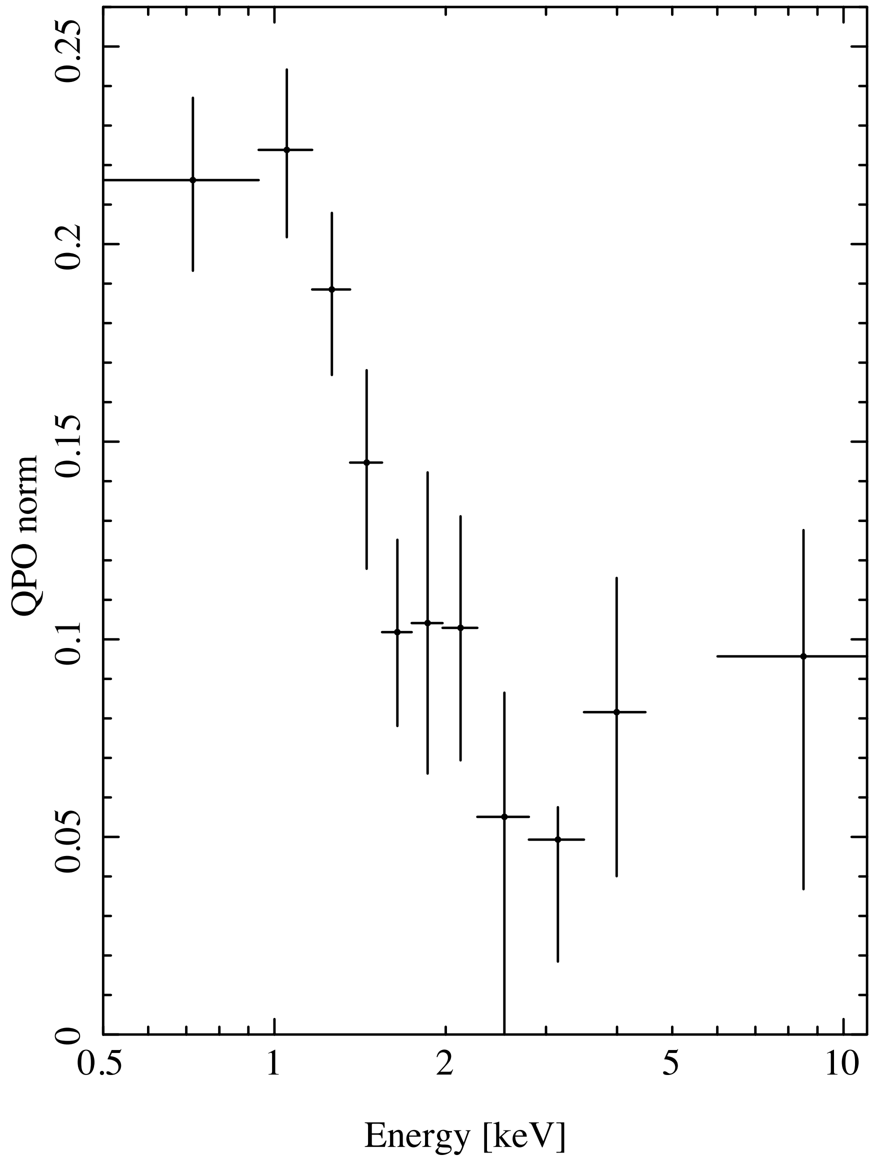


- Nearly sinusoidal. Only one pole is probably seen.

Pulsation and QPO

- Take a time series of *fractional* amplitudes of the 600 Hz spin, measured every ten seconds.
- Make a Power density spectrum. QPO ! Same energy dependency.





Observational summary

- Strong and Soft QPO at 8 mHz
- Driven mainly by a soft spectral Component, identified as a black body with a few km radius and ~0.5 keV temperature
- Fractional pulsed amplitude is modulated by a QPO

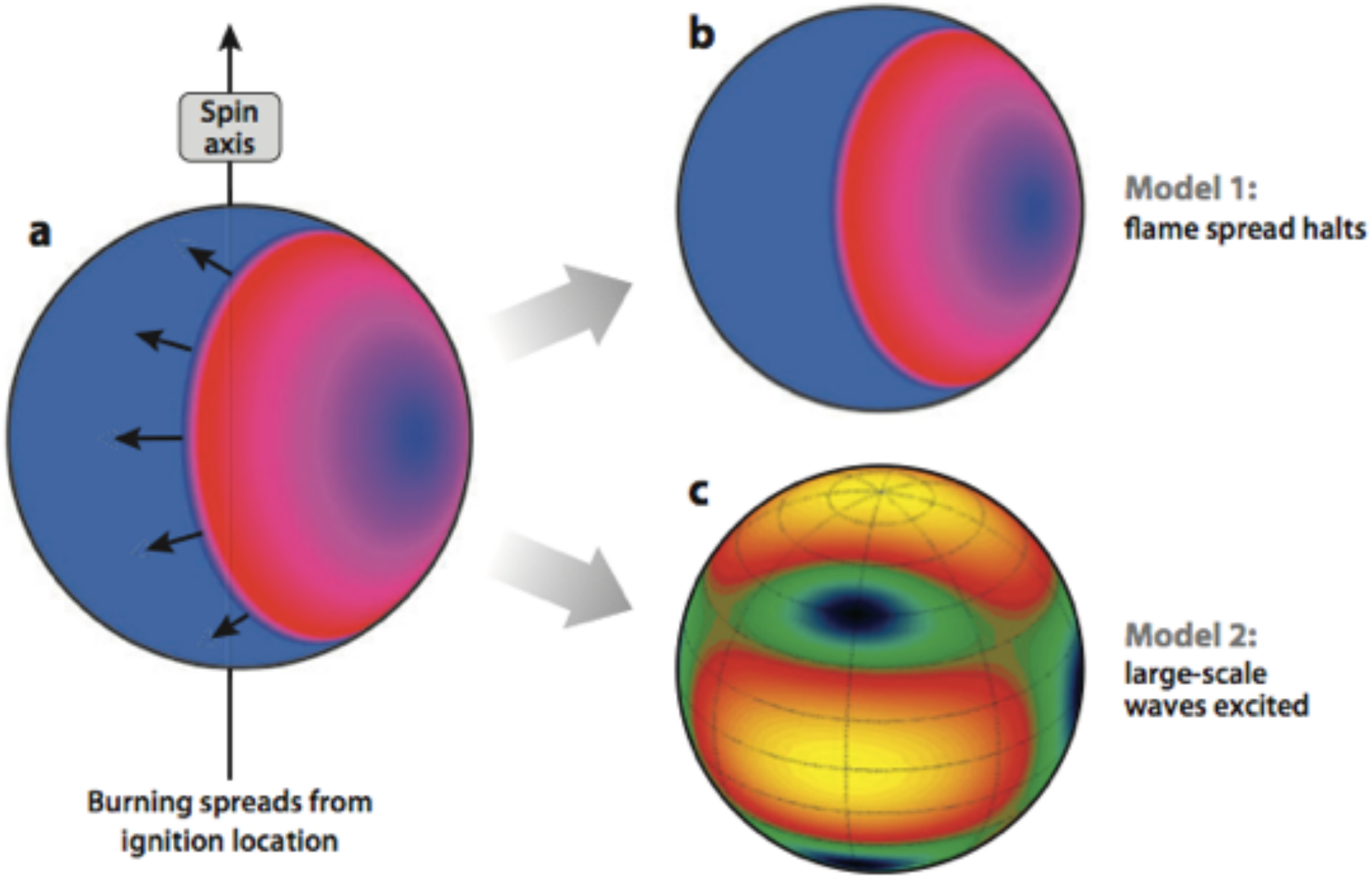
- Is it a phenomenon inherent to the accretion flow or is it linked to thermonuclear burning, or is it ~~due to absorption~~ ?

- Absorption is irrelevant, as showed by spectra resolved in hardness or QPO phase

Parameter	HR> 4	HR<2
N_{H} (10^{22} cm^{-2})	0.35±0.02	$0.31^{+0.03}_{-0.05}$

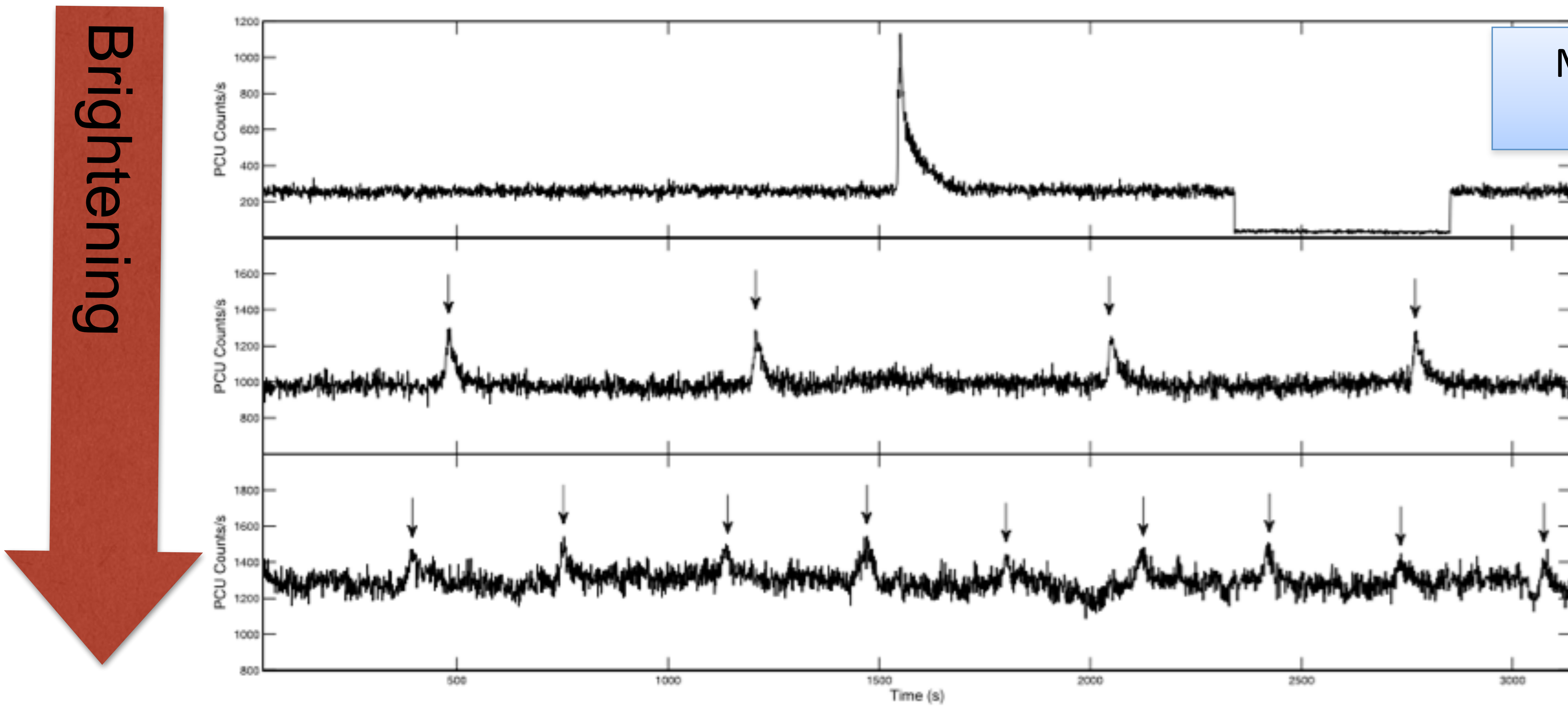
Thermonuclear bursts

Watts et al. (2012)



- Material accumulated on the NS surface undergoes catastrophic nuclear burning and the object becomes very bright.

Regular bursts



Motta et al. (2011)

- IGR J17480-2446 (Terzan 5) transitioned from Atoll to Z-states. Becoming extremely bright, the Thermonuclear bursts became quasi periodic flares with recurrence of ~300 s.
- Our source is dimmer, spectrum is NOT BB dominated, LC is more “dipping” than flaring

Marginally stable burning

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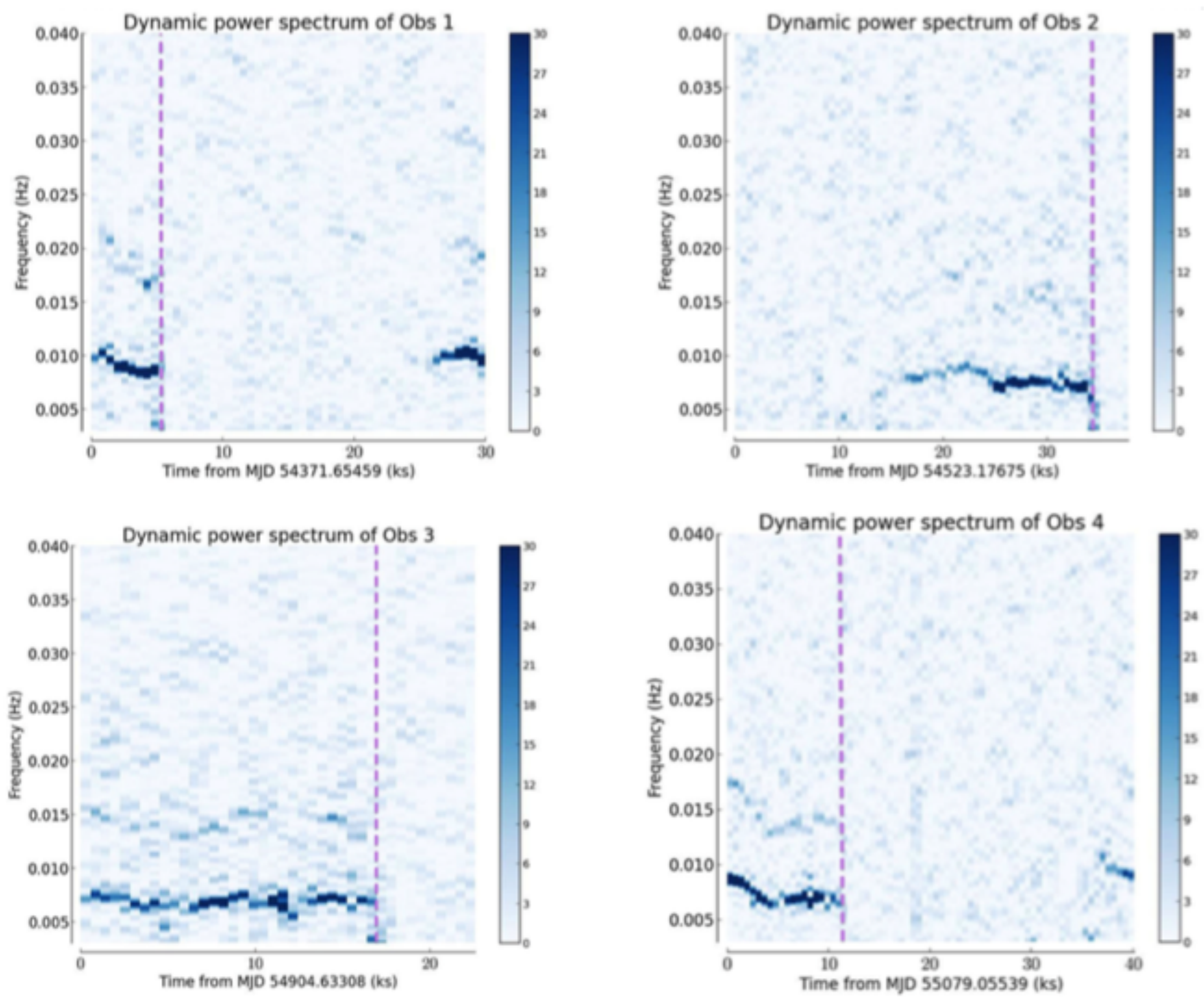
- 4U 1636-53 shows QPO at 8 mHz with a very soft spectrum, interrupted by thermonuclear bursts. Discovered in 2001 by Revnivtsev
- Spectrum has a strong BB with kT~2 keV
- Only in a (broad) range of luminosity

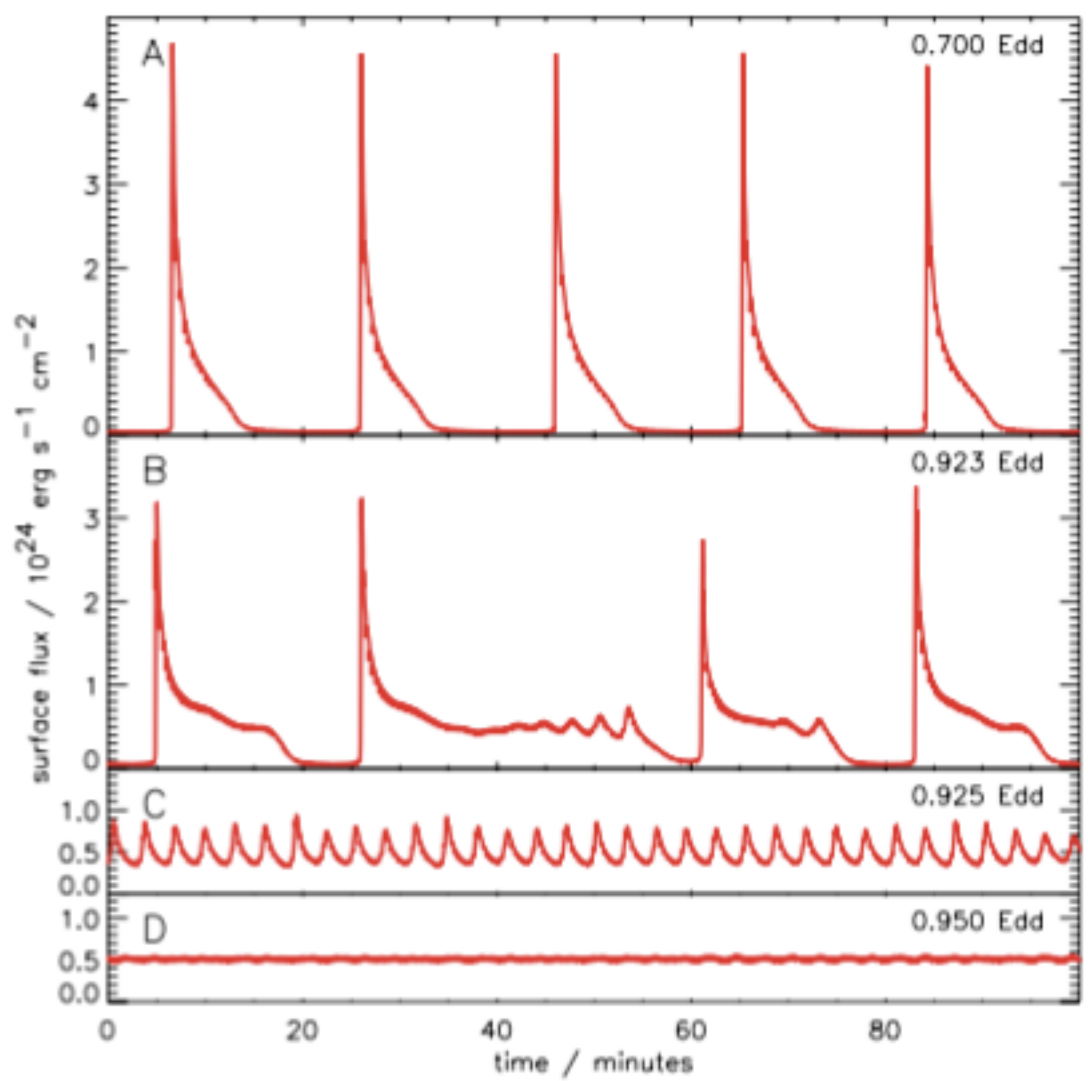


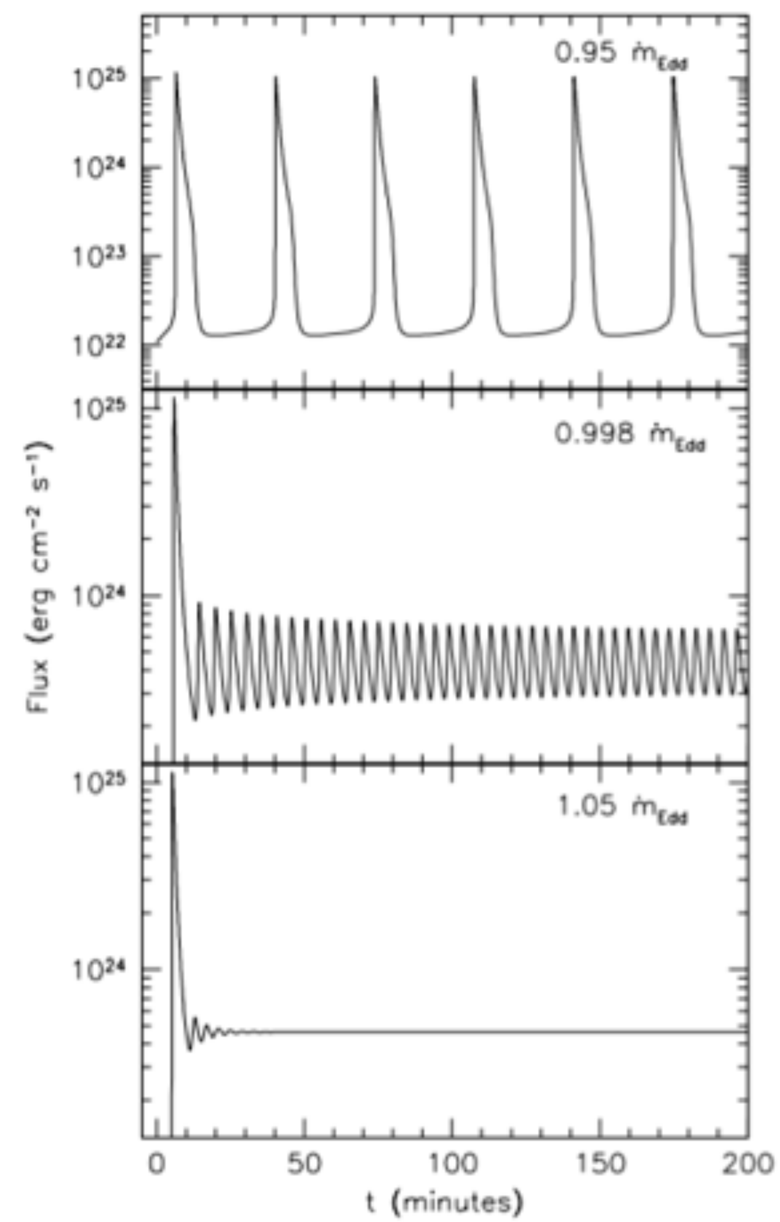
Altamirano et al. (2008)

Lyu et al. (2015)

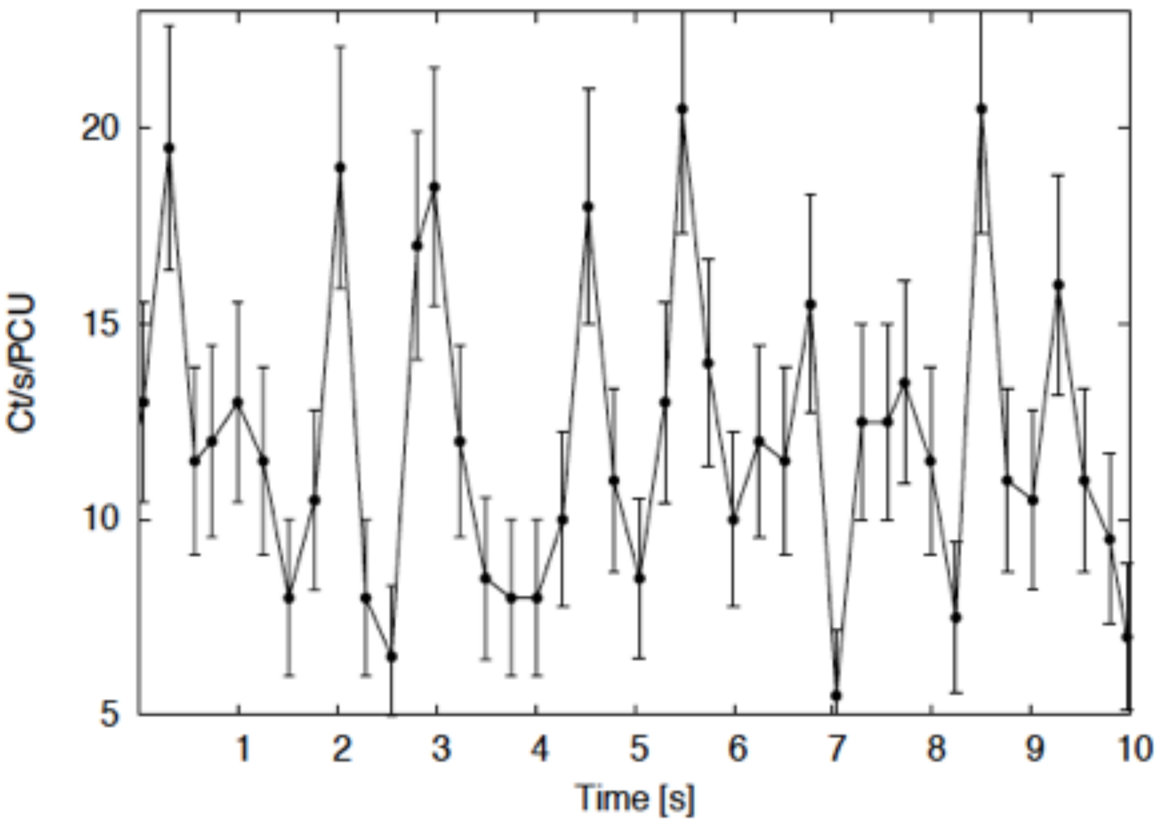
Modeling

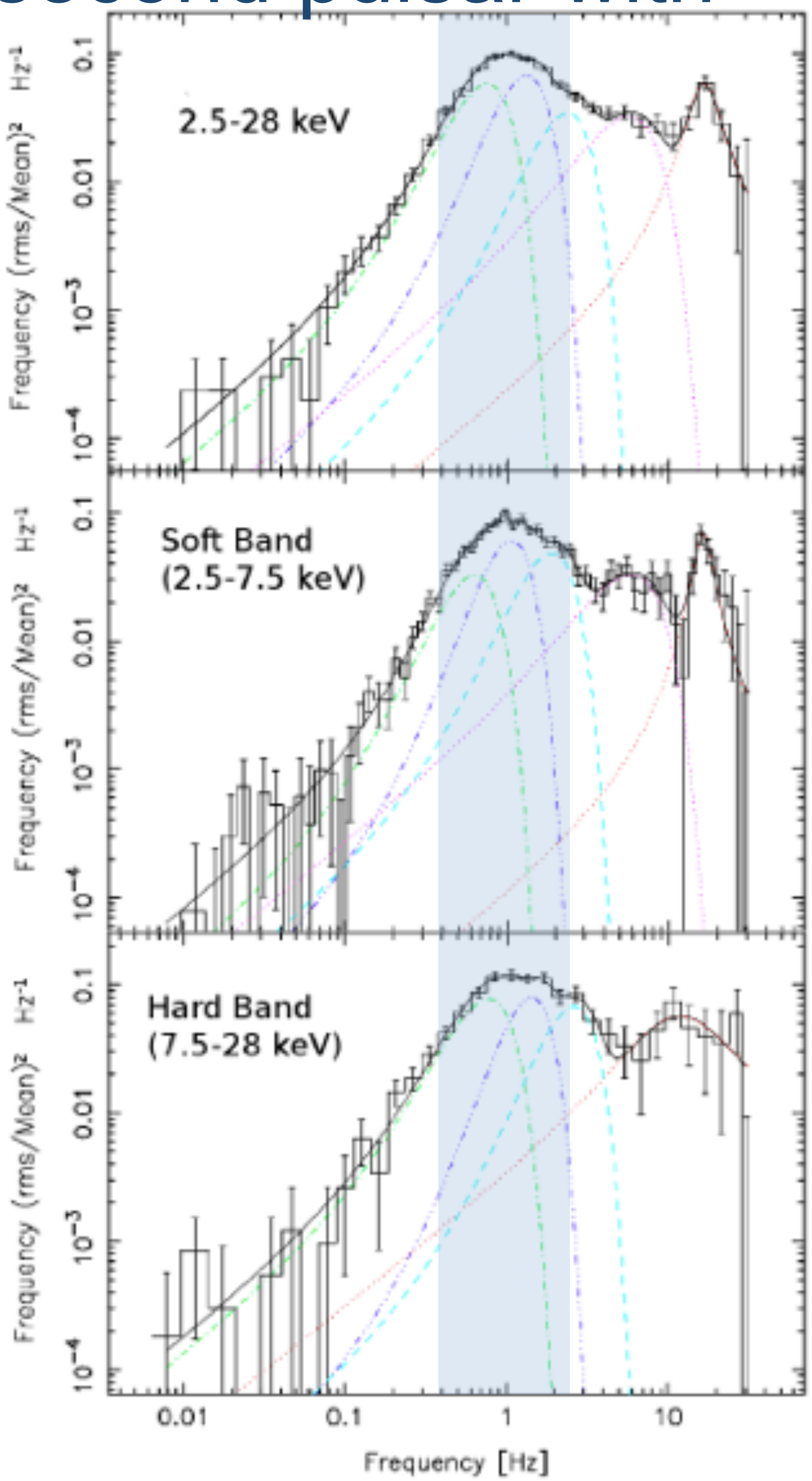
- It requires a high (Eddington) and very narrow range of mass accretion rate (1%). Obs. show a range of 50%.
- To lower luminosity, it is argued that burning take place in a narrow equatorial zone. Heger (2007). Ashes of H burning.





- NGC 6440 X-2 is a transient accreting millisecond pulsar with a 4.86 ms spin period and 57 min orbit

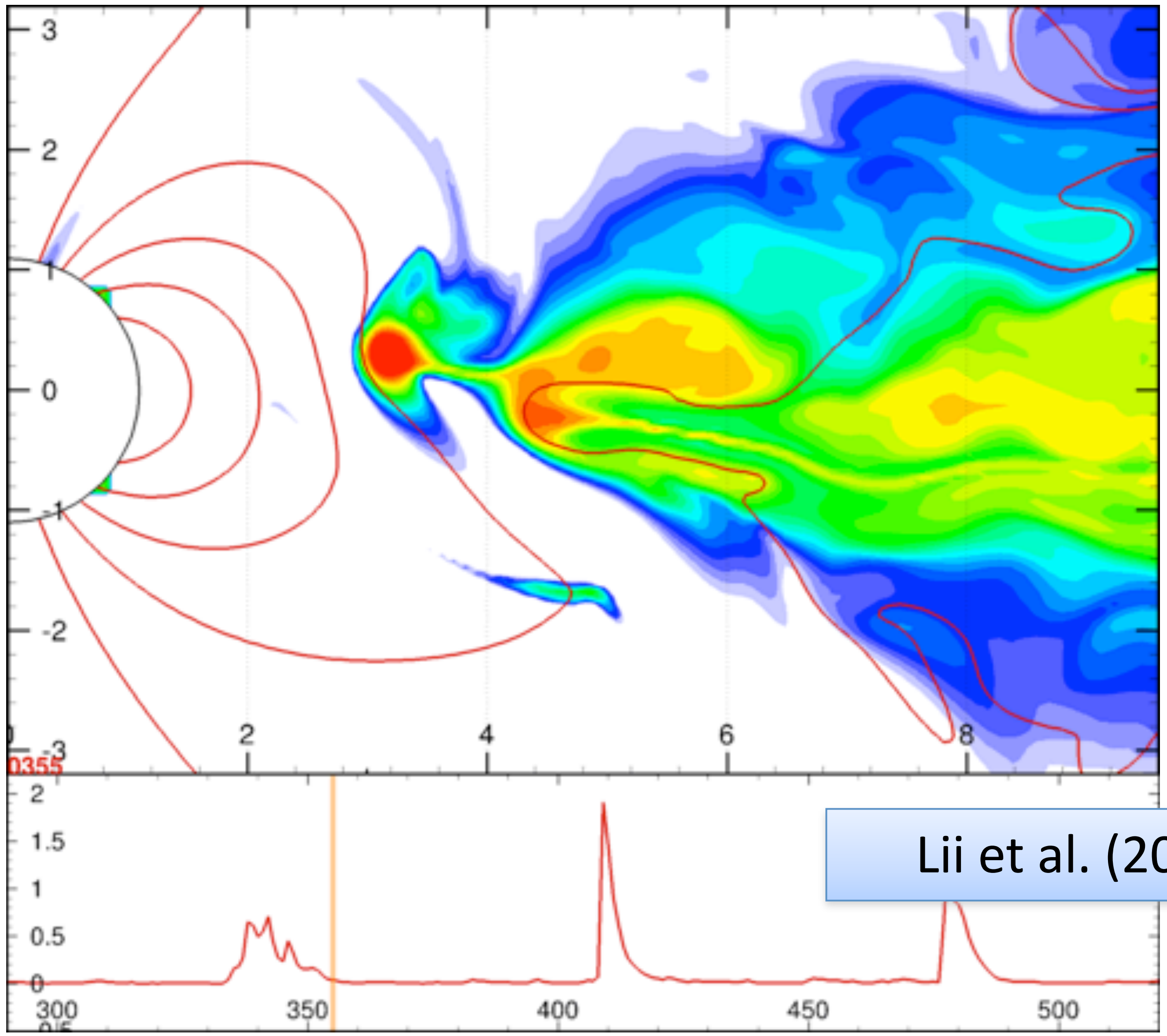




Patruno & D'Angelo (2013)

  - Strong semi-period modulation at a frequency of ~1 Hz.
  - PSD fitted with 3 harmonic Gaussians (1 Hz) + Lorentzian (10 Hz QPO)
  - Similar to SAX J1808.4-3658

Cyclic accretion



Lii et al. (2014)

- Matter accumulates and then is accreted in cyclic fashion
- Contemporary ejections of material
- Much lower time scale (10^3 lower)

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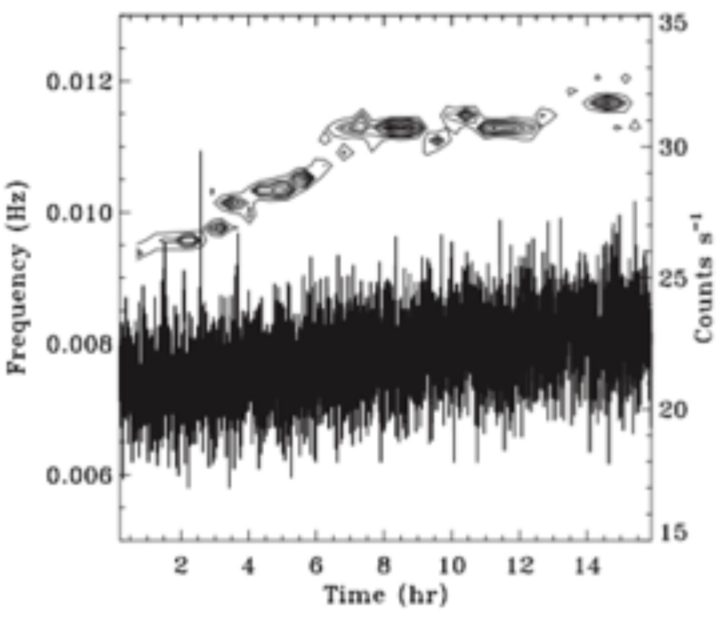
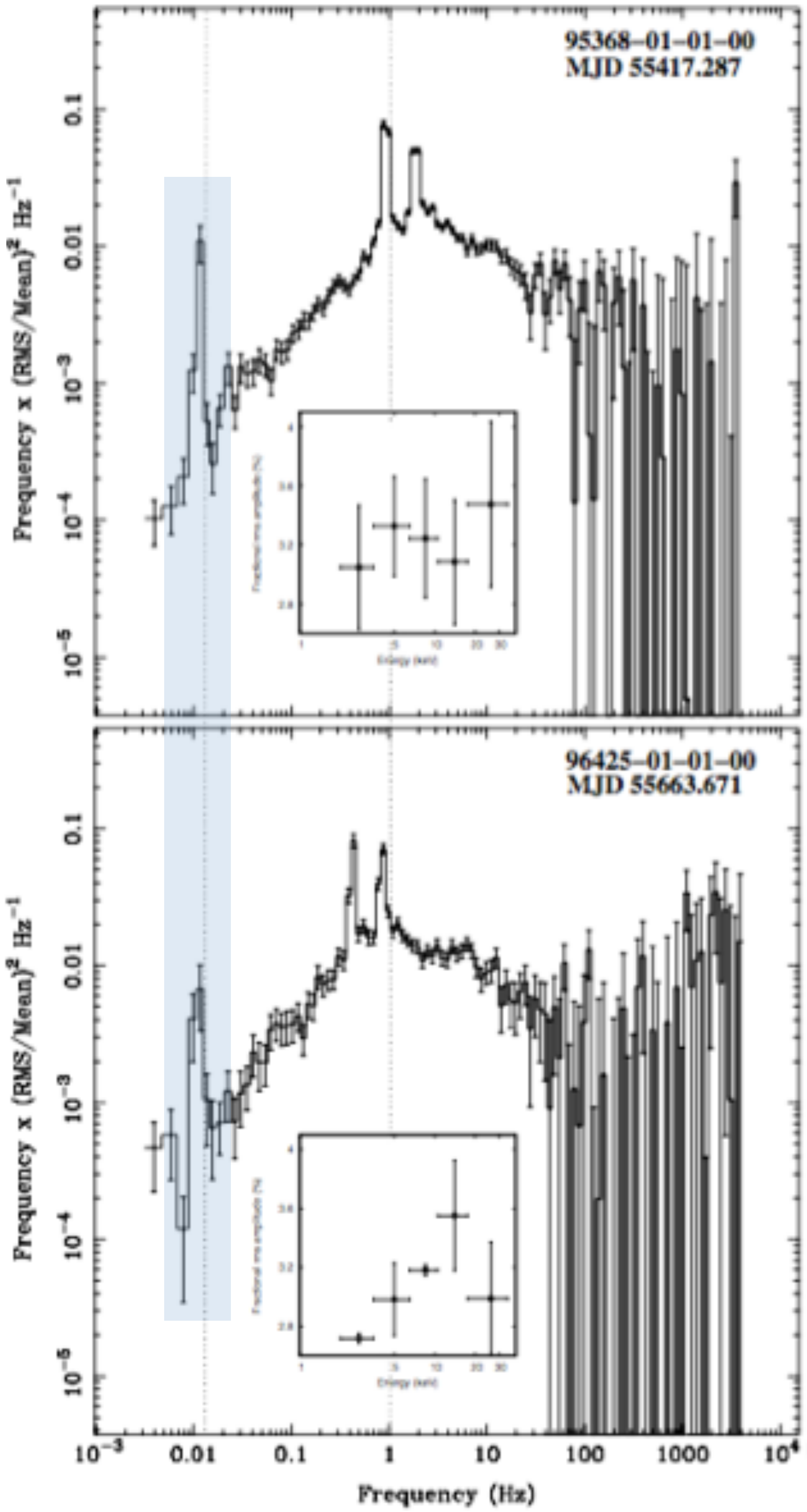
A similar QPO in BH





Altamirano et al. (2011)

- A very similar signature in the power spectrum of the black-hole binary H1743–322 was found in the 2010-2011 outburst using Chandra.
- They argue it is similar to the 1 Hz QPO seen in neutron star and interpreted as the movement of the disc in and out of the coronation radius.
- QPOs are harder (seen in RXTE above ~3 keV) and variable in frequency.

Conclusions

- Found a very pronounced variability in the XMM-Newton observation of IGR J00291, reflected in the presence of a soft QPO (<3 keV, *below RXTE band but in eXTP energy range!*).
- This variability resembles the QPOs in 4U 1608-52, 4U1636-536, and Aql X-1, interpreted as *marginally stable nuclear burning*. However, only one thermonuclear burst in IGR J00291 history and well apart both in flux and time from the QPO.
- Variability is reflected in the pulsed fraction: shape of accretion driven emission region? Change of the surface thermonuclear emission pattern leading to a modulation in pulsed fraction?
- Possibility that it is an accretion-flow mediated modulation of the accretion rate as in H1743–322 (or GRS 1915+105). However, why would it be so soft?
- Multi-Messenger eXTP data will solve these degeneracies.