A search for periodicities from a ULX in the LINER galaxy NGC 4736

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Ultraluminous X-ray sources (ULXs) :

ULXs are off-nuclear point-like sources that have X-ray luminosities ($L_x > 3 \times 10^{39}$ erg/s) above the Eddington limit of a $20 M_{\odot}$ black hole(BH).

- **The true nature of these objects is not clear** …
- much like X-ray binaries

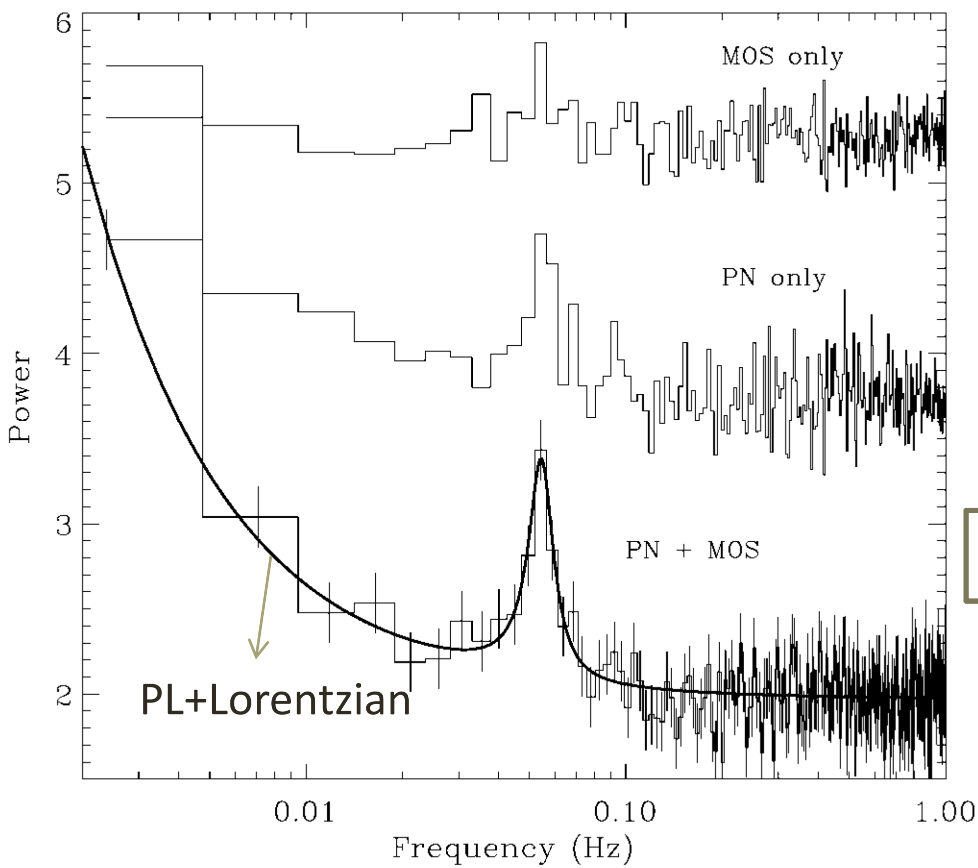
Current models propose several alternatives to explain their high luminosities :

- It could either be due to the geometric beaming if ULXs are powered by an accreting stellar BH (King et al. 2001)
- the super-Eddington fluxes originating from disks (Begelman 2002).
- some ULXs could be powered by intermediate-mass BHs (Miller & Colbert 2004).

X-ray spectral and temporal analyses allow us to study the nature of ULXs and to constrain BH masses in ULXs .

main purpose is to search Quasi-Periodic Oscillations (QPOs) …

Up to now, QPOs have been detected from a few ULXs in nearby galaxies.



The First ULX (X-1) (X41.4+60) showed QPO in M82 (**Strohmayer& Mushotzky , 2003 ; Mucharelli + 2006, Feng&Kaaret, 2007**)

- 30 ks XMM-Newton data
- power-density spectrum (PDS) shows a prominent QPO peak at

54 mHz rms 8.5% in the (2–10) keV

- RXTE observations (2-20 keV):

107 mHz QPO

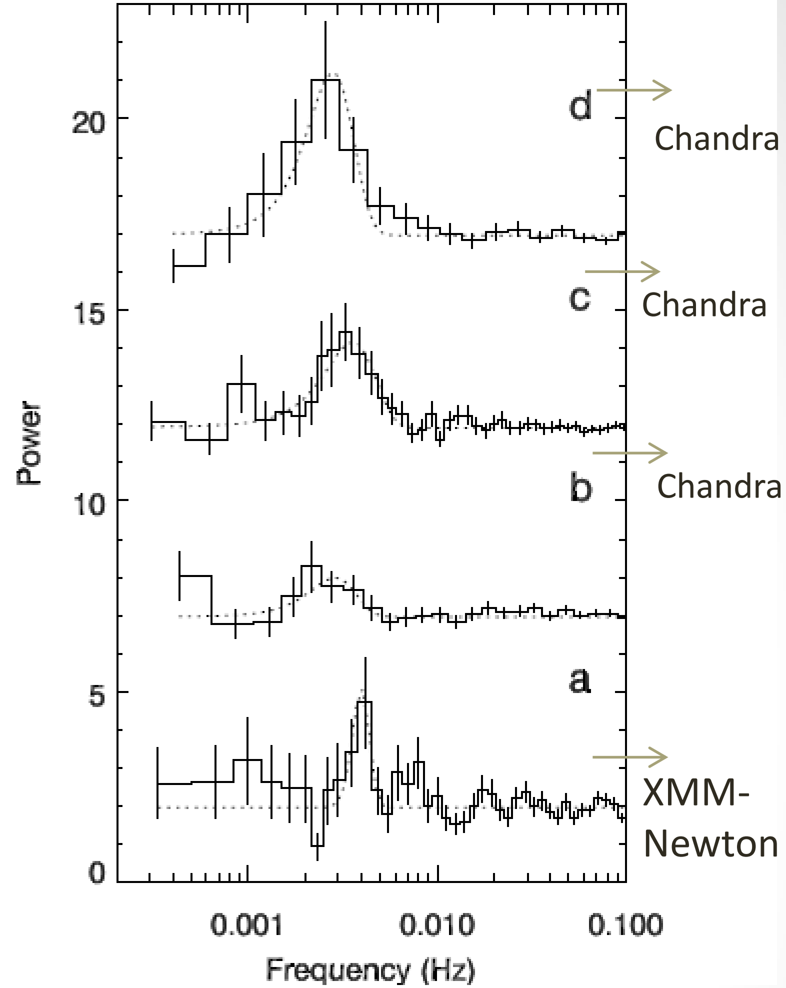
from the same ULX

- BH mass in source **X-1** $<1.87 \times 10^4\ M_\odot$ based on the Schwarzschild geometry, (using the highest QPO frequency)

The second ULX   X-2 (**X42.3+59**) in M82

- QPOs at **(3–4) mHz** from this transient source (Feng et al. , 2010)
- three Chandra and two XMM-Newton obs.
- the BH mass in the range of $(1.2-4.3)\times10^4$ **M☉**

by scaling the QPO frequency to that of their type (A/B) of QPOs in stellar mass BHs.



X-ray power spectra of X42.3+59 in the 1-8 keV.

The **dotted line** indicates the **Gaussian + constant model** that fit the spectrum. Powers are normalized according to Leahy et al. (1983).

Table 1
List of ULXs

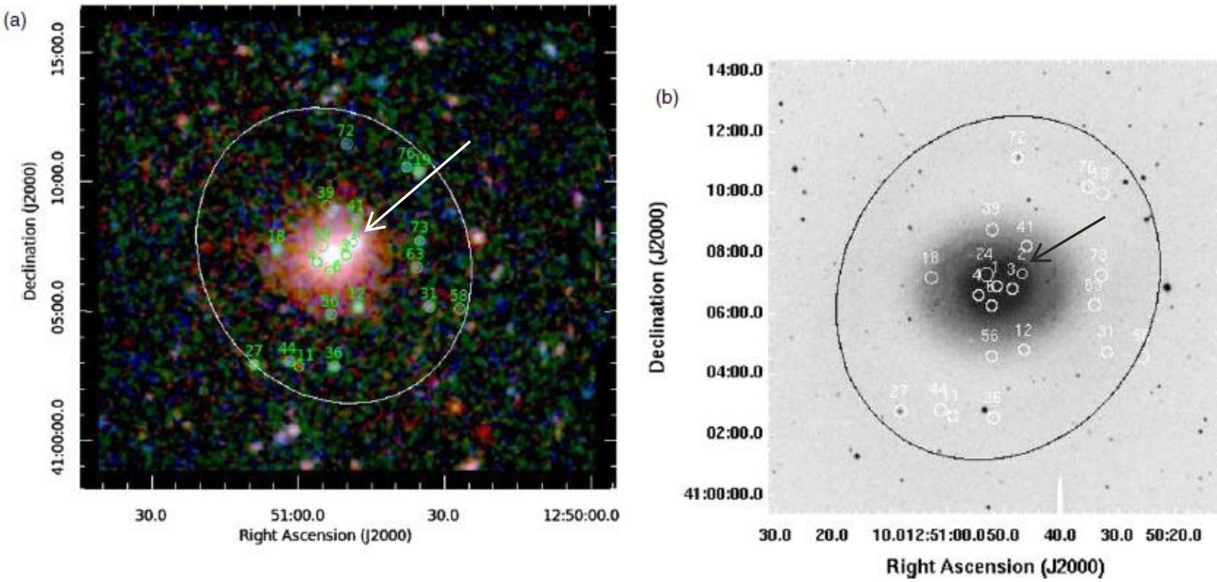
Galaxy	ULX	R.A.	Dec.	L_x	QPO Frequency	Period	Ref.
				(10^{39} erg s^{-1})	(mHz)	(hour)	
M82	CXO J095550.2+694047	09:55:50	+69:40:47	40−50	50−166	1488	1
	CXO J095551.1+694045	09:55:51	+69:40:45	10−25	3−4	-	2
M74 (NGC 628)	CXOU J013651.1+154547	01:36:51	+15:45:47	0.5−1.3	0.1−0.4	-	3
Holmberg IX	X-1	09:57:54	+69:03:46	8.3−8.4	202.5	-	4
NGC 5408	X-1	14:03:20	-41:22:60	8.7	10−40	2760	5
NGC 6946	X-1	20:35:01	+60:11:31	8.4−12	8.5	-	6
M51 (NGC 5194)	X-7	13:30:01	+47:13:44	0.1−2	-	1.7−2.1	7
NGC 3379	Source 6	10:47:50	+12:34:57	3.	-	8−10	8
NGC 1313	X-2	03:18:20	-66:29:10	30	-	146.88	9
NGC 4490	CXOU J123030.3+413853	12:30:30	+41:38:53	0.2−1.1	-	6.4	10

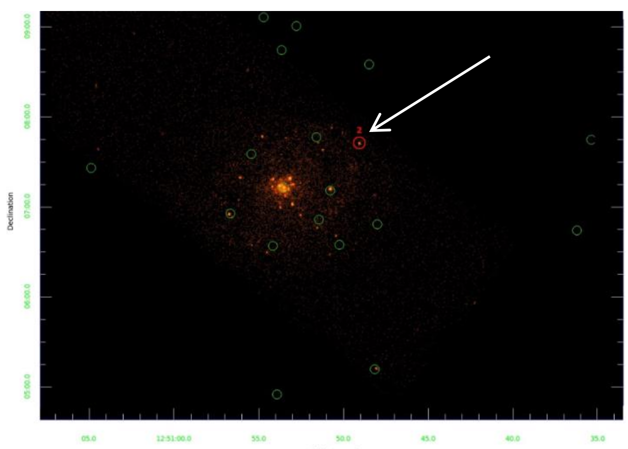
Note.—(1) Strohmayer & Mushotzky 2003; Fiorito & Titarchuk 2004; Dewangan et al. 2006; Kaaret et al. 2006; Mucciarelli et al. 2006; Kaaret et al. 2006; Feng & Kaaret 2007. (2) Feng et al. 2010. (3) Liu et al. 2005. (4) Dewangan et al. 2006. (5) Strohmayer et al. 2007; Strohmayer 2009; Dheeraj & Strohmayer 2012. (6) Rao et al. 2010. (7) Liu et al. 2002; Dewangan et al. 2005 (8) David et al. 2005. (9) Liu et al. 2009. (10) Esposite et al. 2013

List of ULXs exhibit X-ray QPO frequencies or periodicities

ULX X-2

Galaxy	Source	Separation (arcmin)	*ROSAT* ID	*Chandra* ID
NGC 4736	XMM-2	0.9		CXOU J125048.598+410742.49[e]





- **(Liu 2011)** detected as a point source using the Chandra archival data with no reference to its transient nature.

- **Akyuz et al.2013** , XMM-Newton and Chandra archival data reveal its transient nature

- **Lin et al. (2013)** report a highly variable persistents source or recurrent transient with flux variation factror of > 100 with ROSAT, XMM-Newton and Chandra archival data

Table 2

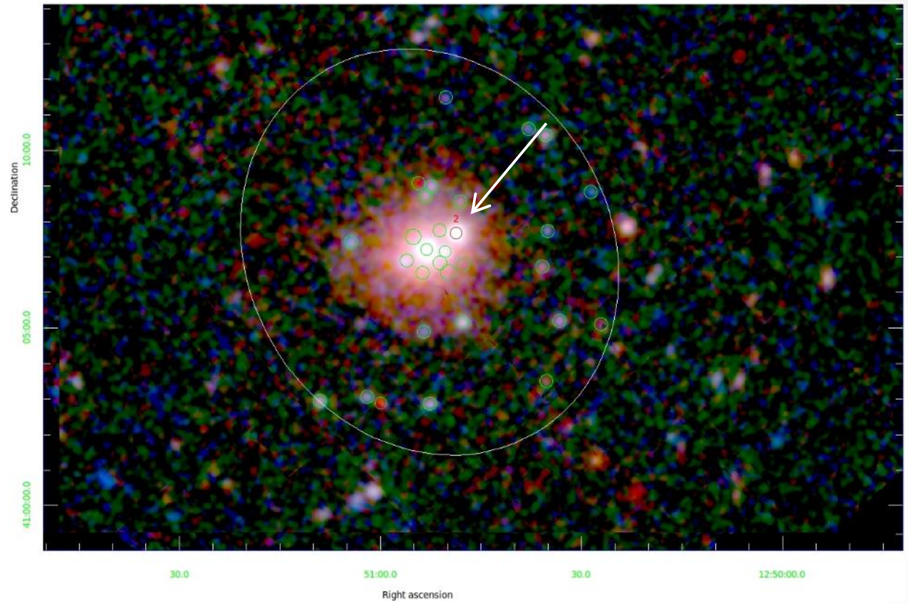
List of Observations that used in this study

	ObsID	Exposure (ks)	Date
Chandra	808	49.8	2000.05.13
XMM-Newton	0404980101	55	2006.11.27

- ❑ we used the XMM-Newton and the Chandra archival observations which have the longest exposure for the source.
- ❑ high background flarings from XMM-Newton (ObsID 0404980101) data set, which removed the last ~ 17 ks of the observation.
- ❑ the shorter exposures (XMM-Newton ObsID 0094360701, Chandra ObsID 9553) also searched however, there was no indication of significant QPOs or periodicities at any frequency

Data reductions

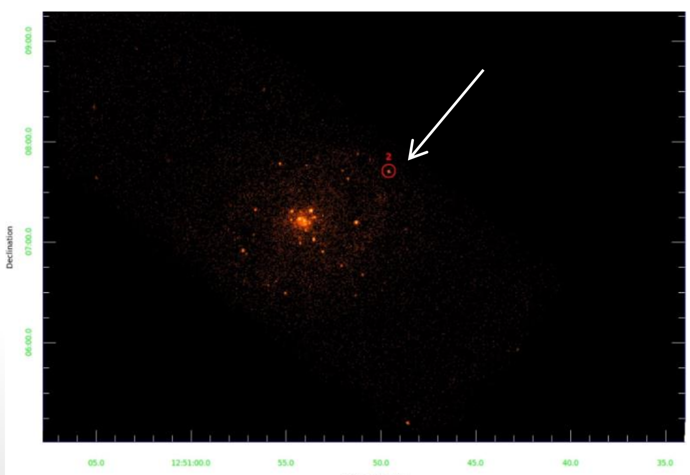
- the SAS (Science Analysis Software) v.12.0 for XMM -Newton
- the CIAO (Chandra Interactive Analysis of Observations) v4.3 with the CALDB (Calibration Database) version 4.4.2 for Chandra.



❖ In XMMNewton:

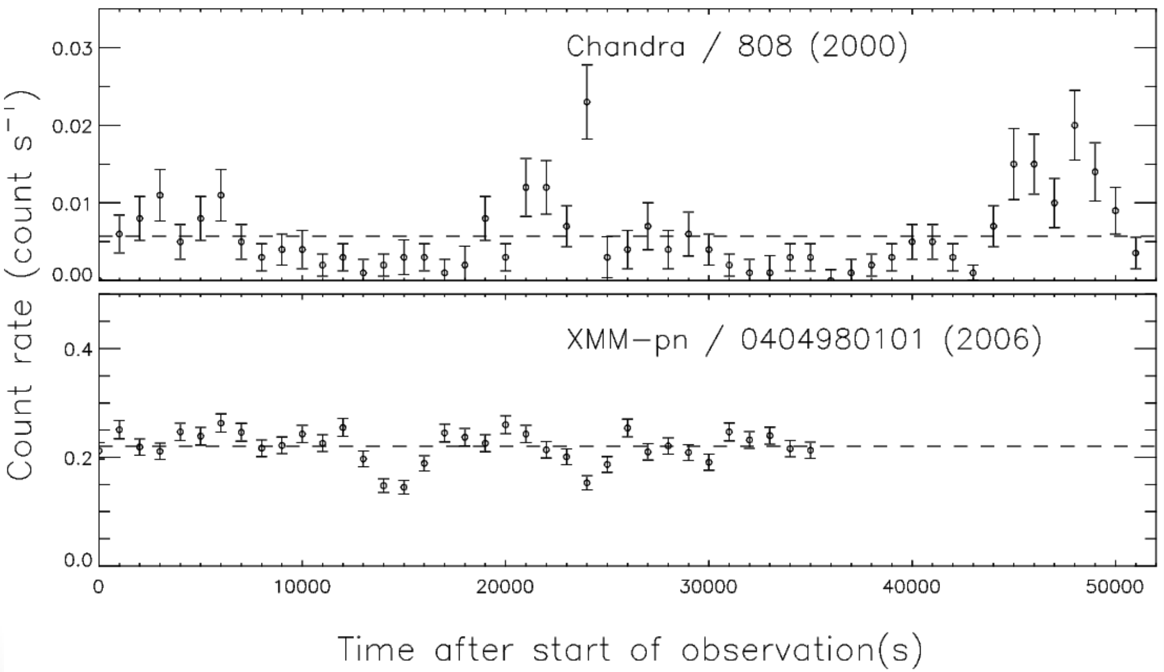
Extraction region --- 18′′ the source
(R.A. = 12h 50m 48s.6, Dec = 41◦ 07′43′′)

❖ In the Chandra observation,
extracted from a circular region of 2′′
the source (R.A. = 12h 50m 48s.6, Dec = 41◦ 07′42′′.5) in Chandra.



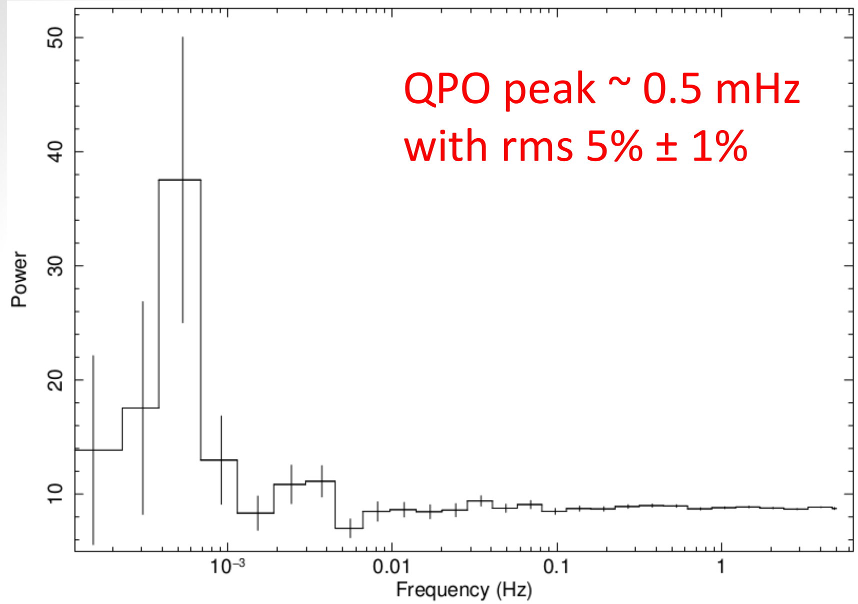
Background photons were extracted using a proper region from a location with no source contamination.

the X-ray timing variations and spectral properties of the **ULX X-2** in the were searched in the LINER galaxy NGC 4736.



X-ray light curves of X-2 in the 0.2-10 keV

Both light curves have a bin size of 1000 s.



To search the QPO the averaged power spectrum obtained using the XMM-Newton pn observation

Light curve was sampled at **0.1 s**

Miyamota normalization in units **(rms/mean)²/Hz** (Miyamoto et al. 1991).

The best fitting composite model

- **(Lorentzian+ constant)**

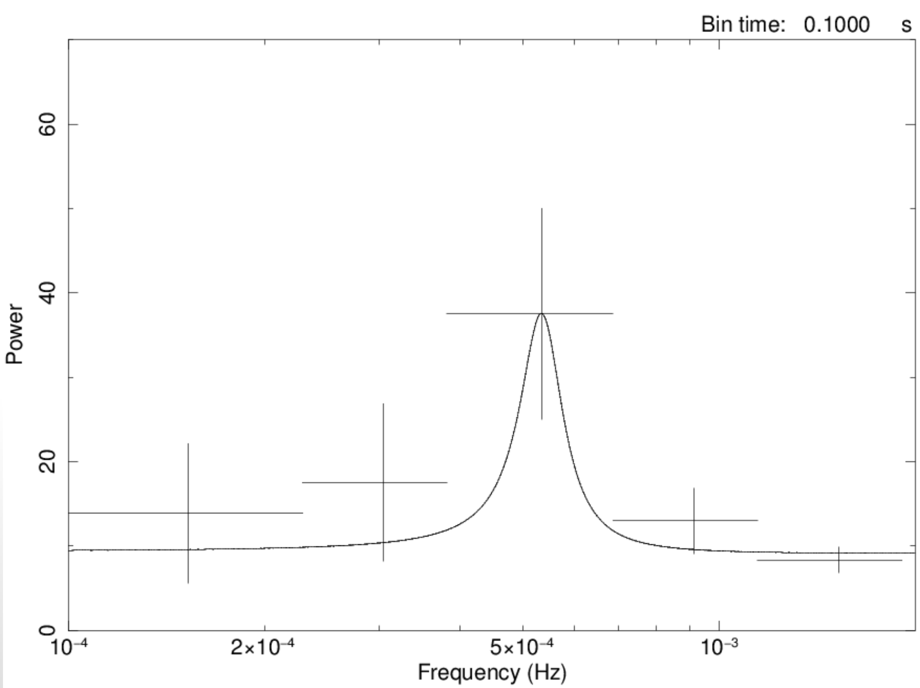
gives the centroid frequency of

- **QPO = $0.53^{+0.09}_{-0.35}$ mHz** with
- **σFWHM = 0.10 mHz.**

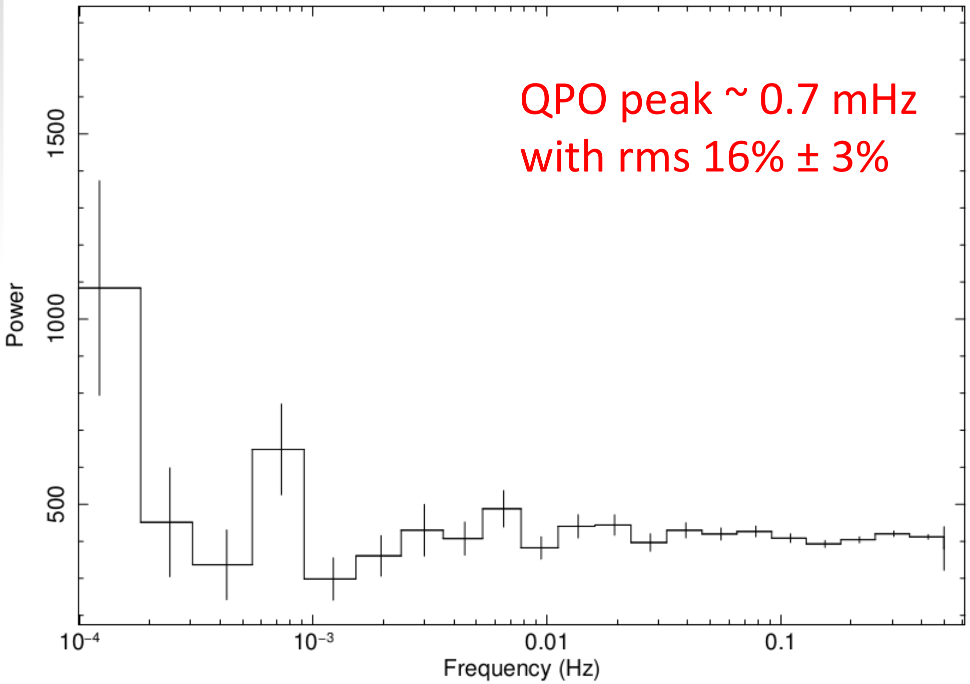
Quality factor:

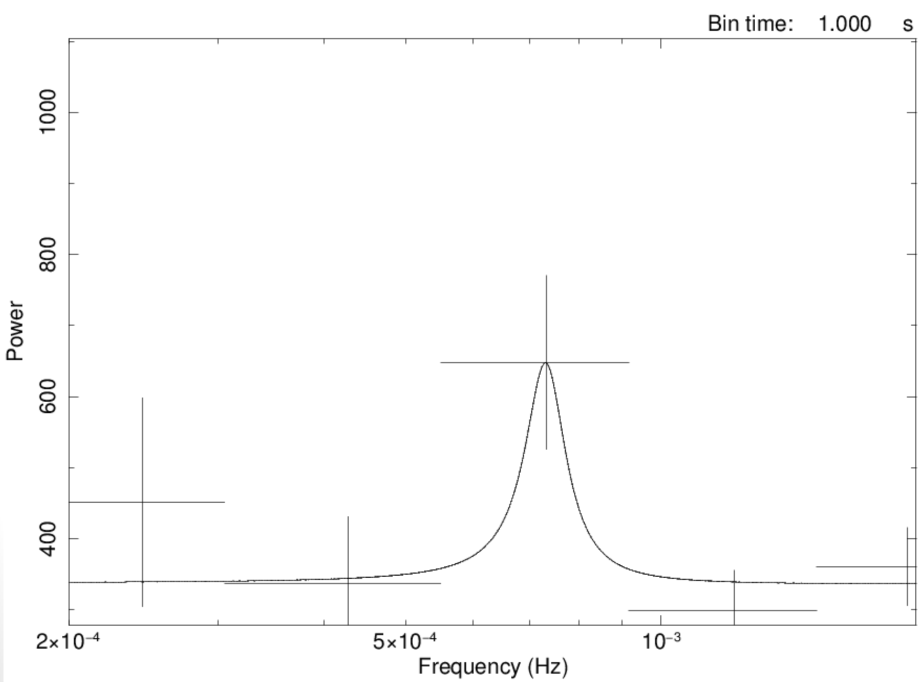
- **Q = QPO/σFWHM = 5.3**

(signals with Q > 2 are called QPOs)



The constant model component which represents the continuum value in the PDS has a value of ~9





the same analysis for the Chandra (ObsID 808) data.

The light curve was sampled at 1 s

fitted the PDS using the same

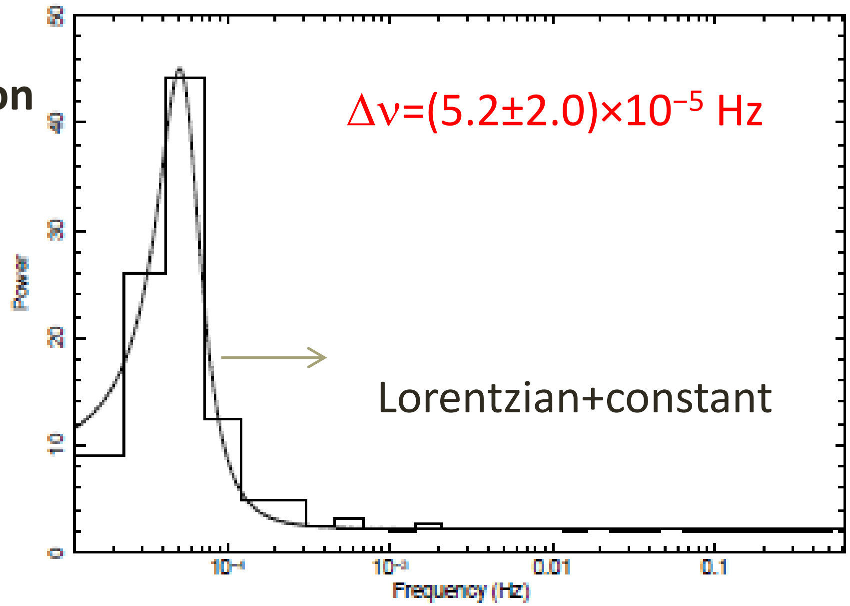
(Lorentzian + constant) model

the best fitting model has a QPO centroid frequency of

- **QPO=$0.73^{+0.16}_{-0.14}$ mHz**
- **σ_{FWHM} = 0.10 mHz (Q = 7.3)** and

a constant model value **of ~336 (rms/mean)^2/Hz.**

Chandra observation (ObsID 808)



Leahy normalization for power
Leahy et al. (1983)

In addition, we detected <u>a possible periodic oscillation or another QPO</u>

$\boxed{\sim 5.2 \times 10^{-5}\ \text{Hz}\ (\sim 5.4\ \text{hrs}) \ > 3\sigma}$

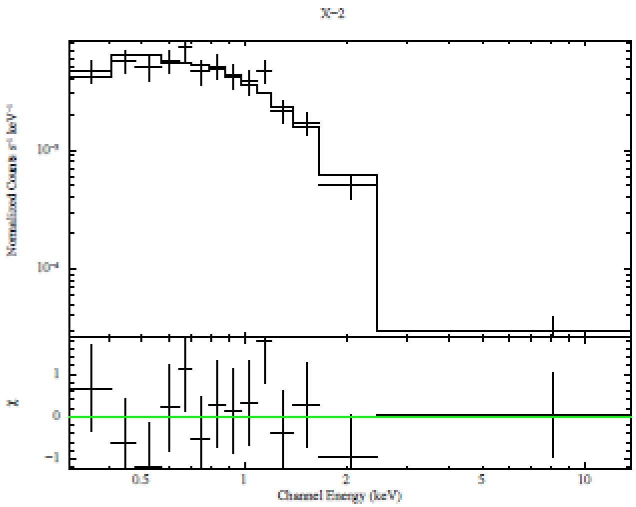
the PDS obtained from a single Fast Fourier Transform (FFT).

- The best fitting model has a centroid frequency of

$\boxed{(5.2 \pm 2.0) \times 10^{-5}\ \text{Hz}, \quad \text{width of } \sigma_{FWHM} = 0.42 \times 10^{-4}\ \text{Hz}}$

- **constant noise level of ~2.22**

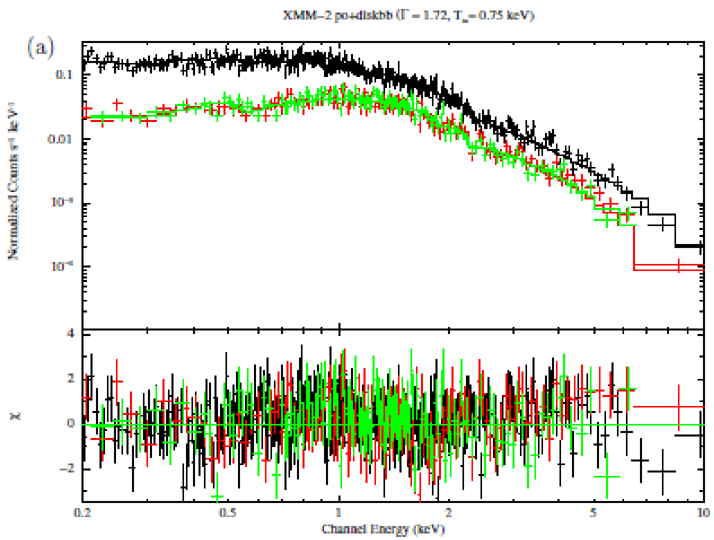
in the XMM-Newton data such low frequencies were not revealed.



Energy spectrum of X-2 obtained with the ACIS-S observatin (ObsID 808)

Spectral Model Parameters For NGC 4736 X-2

	XMM-Newton[a]	*Chandra*
$N_H (10^{22})\ cm^{-2}$	$0.02^{+0.01}_{-0.01}$	$0.07^{+0.06}_{-0.03}$
Γ	$1.72^{+0.14}_{-0.13}$	$2.55^{+0.38}_{-0.26}$
kT (keV)	$0.75^{+0.06}_{-0.04}$	-
$K_{PL}{}^{b}\ (10^{-5})$	$5.79^{+1.40}_{-1.10}$	$0.77^{+0.28}_{-0.18}$
$K_D{}^{c}$	$0.05^{+0.02}_{-0.01}$	-
χ^2/dof	530.81/517	8.27/11
$F^d\ (10^{-13})\ erg\ cm^{-2}\ s^{-1}$	7.57	0.37
$L^e\ (10^{38})\ erg\ s^{-1}$	16.73	0.85



PL+DISKBB for XMM-Newton , PL for Chandra

Note.—(a) *XMM-Newton* model parameters were taken from Akyuz et al. (2013). (b) Normalization parameter of the PL model in units of photon $cm^{-2}\ s^{-1}\ keV^{-1}$ at 1 keV. (c) Normalization parameter of the DISKBB model. $K_D = [(R_{in}/km)/(D/10kpc)]^2 \times cos\theta$, where R_{in} is the inner disk radius, D is the distance to the source and θ is the angle of the disk. (d) Unabsorbed flux in the (0.3–10) keV energy band. (e) These values have been calculated using a distance of 4.3 Mpc (Winter et al. 2006).

Avdan et al, 2014

EPIC pn data points and best-fitting model are shown in **black**, data from MOS1 and MOS2 are shown green and red, respectively.

Considering the inverse proportionality between the BH mass and the QPO frequencies

$M_{BH}(ULX) \sim [\frac{v_{QPO}(X)}{v_{QPO}(ULX)}] \times M_{BH}(X)$ X : reference source (Dewangan et al. 2006a)

the same scaling argument :

ULX	Luminosity (10^{38} erg s^{-1})	QPO Frequency (10^{-4} Hz)	Mass ($M_{\odot}$)
NGC 628 (Liu et al. 2005)	4.5−13.4	1−4	$(2-20)\times10^{3}$
NGC 4736 (Avdan et al. 2014)	0.8−16.7	5−7	$(2-400)\times10^{2}$

- assuming the source emits at the Eddington limit (**L_{Edd} $\sim 1.3 \times 10^{38}$(M/M ⊙)erg/s**)

M_{BH}~10 M⊙ (using **Lx** $\sim 1.7 \times 10^{39}$ **erg /s**).

- Also considering the dominant contribution from the disk and Disk Black Body model parameters,

$$K_D=[(\frac{R_{in}}{km})/(\frac{D}{10\ kpc})]^2 \times \cos\theta$$

the inner disk radius, $R_{in} \sim 96(cos\theta)^{-0.5}$

$$\boldsymbol{M_{BH}} \sim (R_{in}/\mathbf{8.86\alpha})\,\mathbf{x\ M_{\odot}}$$

(α =1 Schwarzshild BH θ= 89° for upper limit)

$\boldsymbol{M_{BH} < 80\ M_{\odot}}$ (Makishima et al. 2000).

Considering this mass range of $\boxed{\mathbf{10\ M_{\odot}} < \boldsymbol{M_{BH}} < \mathbf{80\ M_{\odot}}}$

- the compact source in X-2 is probably a stellar mass BH ($M \leq 20M_{\odot}$) or a massive-stellar BH ($20M_{\odot} \leq M \leq 100M_{\odot}$)(Feng & Soria 2011).

Summary

- Power density spectrum of this source reveals a **QPO peak at ~ 0.73 mHz** (rms variability of 16%) using the **Chandra** data (in the year 2000-lower state of the source).

- **The XMM-Newton** data analysis indicates a peak **at ~ 0.53 mHz** (rms variation of 5%) (in the year 2006-higher state of the source).

These recovered QPOs overlap within errors and may be the same oscillation.

- In addition, we detect a long periodicity or a QPO **in the Chandra data** of **about** $\sim \mathbf{5.2 \times 10^{-5}}$ **Hz (~5.4 hrs)** $> 3\sigma$ confidence level.

- If this is **a QPO**, it is the **lowest QPO** detected from a ULX.

- it is also possible that this is the orbital period of the underlying binary which, then, it will be more consistent with a stellar/massive- stellar size BH.

- the source shows low and high states of luminosity and there is not enough data to conclusively decide its classification.

THANK YOU …