MAXI J1348-630 : Detection of high frequency quasi-periodic oscillation during hard state

Raj Kumar[1,2] , Nilay Bhatt[2] ,Subir Bhattacharyya[1,2]
[1]Homi Bhabha National Institute (HBNI), Mumbai, India
[2]Bhabha Atomic Research Centre (BARC) Mumbai, India

Email : arya95raj@gmail.com

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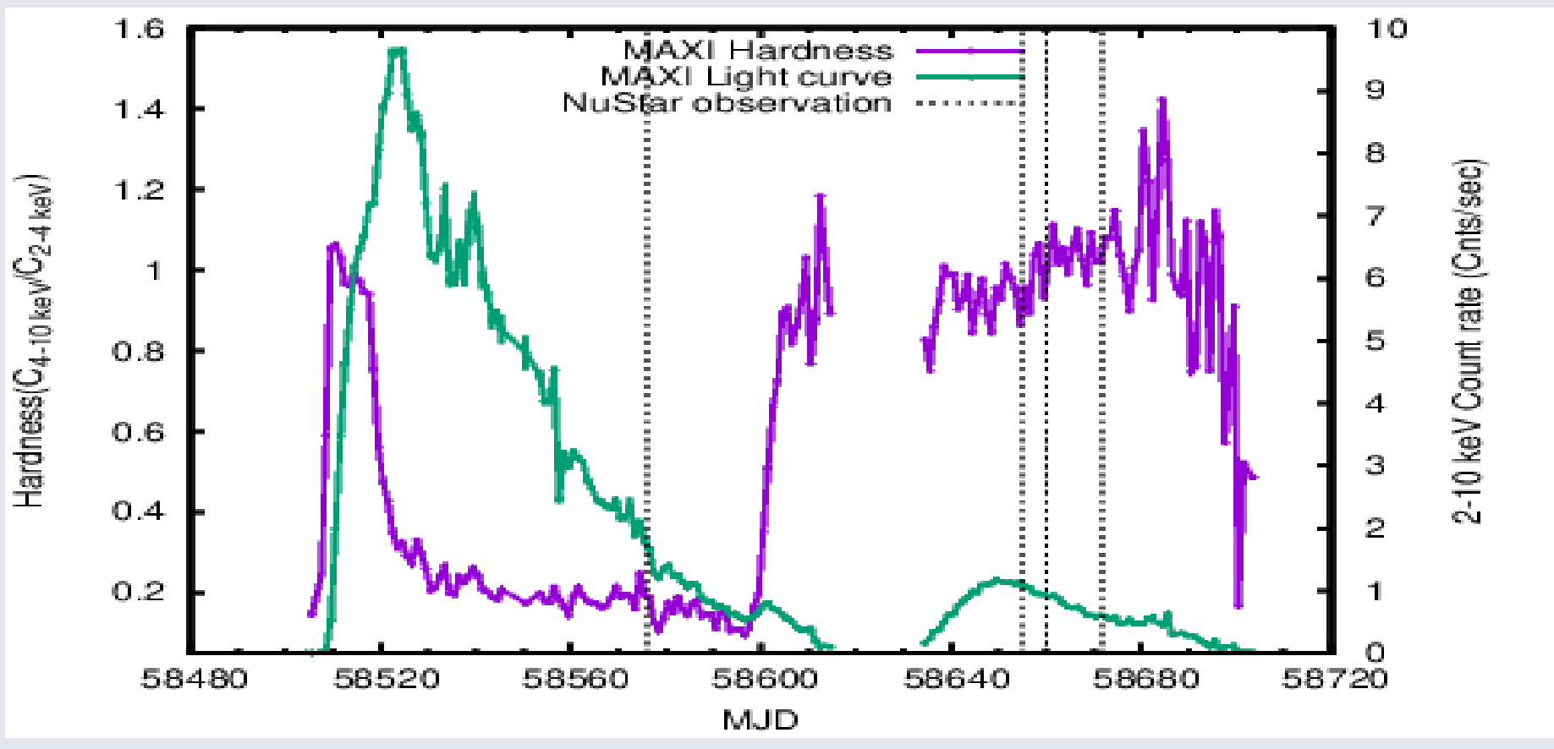
ABSTRACT

High frequency quasi-periodic oscillations is a rare phenomena in black hole X-ray binaries. Mostly, HFQPO were observed in soft state. In this work, we report the detection of high-frequency quasi-periodic oscillation (QPO) in the black hole x-ray binary MAXI J1348-630 in its hard spectral state. MAXI J1348-630 went through a reflare during MJD 58634 to MJD 58674 after a 104 days long outburst which began on MJD 58509. During the reflare the binary system evolved through a series of hard states of varying luminosity. We detected a high-frequency QPO at 98.3 Hz with a significance of 3.7σ in one of the NICER observations during its evolution. It was argued that the QPO frequency might be related to the Keplerian frequency of the accretion flow at the inner radius around a Kerr black hole.

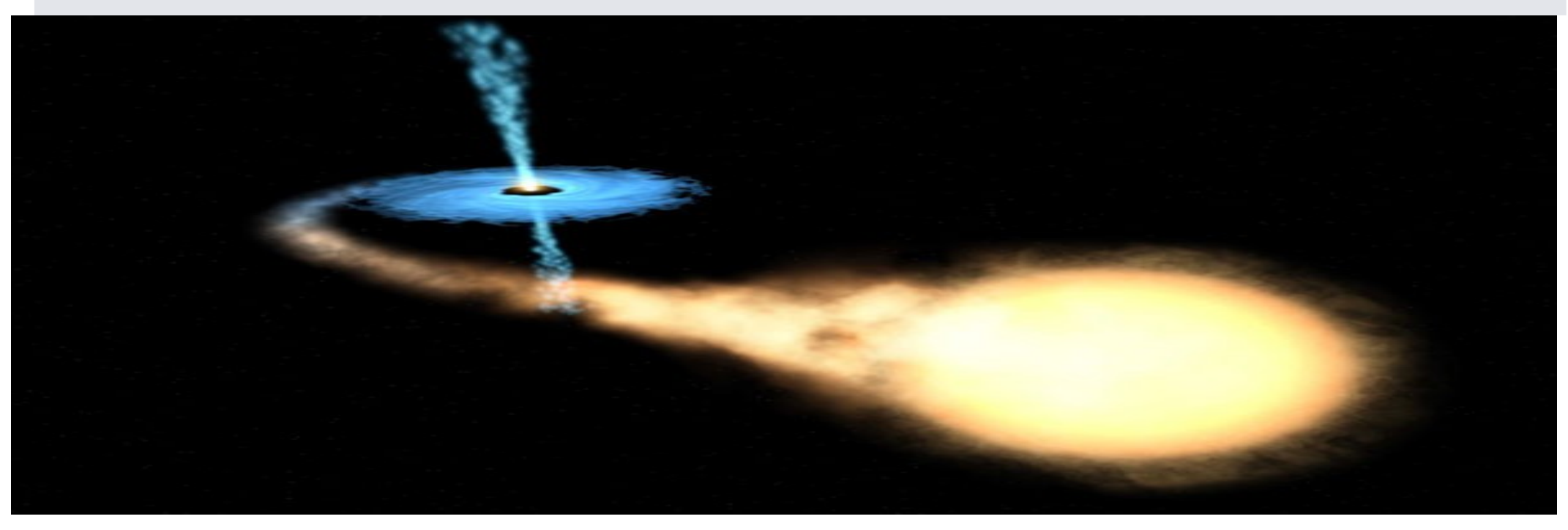
Introduction

- MAXI J1348-630 is a BH LMXB.
- It underwent an outburst in 2019 followed by a reflare.
- Source was observed in low/hard state during reflare.



- **Generally HFQPO is a rare in BHXRBs and it is seen only in their high flux soft states.**

- Belloni et al (2012) reported QPO like features at high frequency in the low hard state power spectral densities of GX 339-4 and XTE J1752-223, but the final chance probability of QPO detection were reported to be high.



Methods

Lewin et al. (1998) and Van der klis (1989)	**Benlloch et al (2001)**	**Vaughan et al (2005)**
When QPO is buried in Poissonion noise in PDS.	Broad continuum of the PDS was described by a power law and the quasi-periodic component was superposed on the continuum.	Estimate the significance of possible periodicity superposed on red noise spectrum, it it was assumed that the red noise continuum described by a power-law.
✓	✗	✗

The power corresponding to the frequency ν_i consists of the power associated with the signal and the power associated with the nise.

$P_i(\nu_i) \rightarrow P_{i,s} + P_{i,n}$
S→signal
n→ noise

Noise power follows the χ^2-distribution with 2 dof.

The probability that the noise power exceeds a certain threshold P_{th} is given by

$$Prob(P_{i,n} > P_{th}) = Q(MW\ P_{th}|2MW)$$

M is number of segments used to estimate the average power spectrum, W is the number of consecutive frequency bins over which the power spectrum was re-binned and Q is the *χ^2-distribution.*

In the limit MW → ∞,
The *χ^2-distribution converges to the Gaussian distribution*

$$Prob(P_{i,n} > P_{th}) = Q_{Gauss}\left(\frac{P_{th}-2}{2/\sqrt{MW}}\right)$$

$$Q_{Gauss}(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-t^2/2}\,dt$$

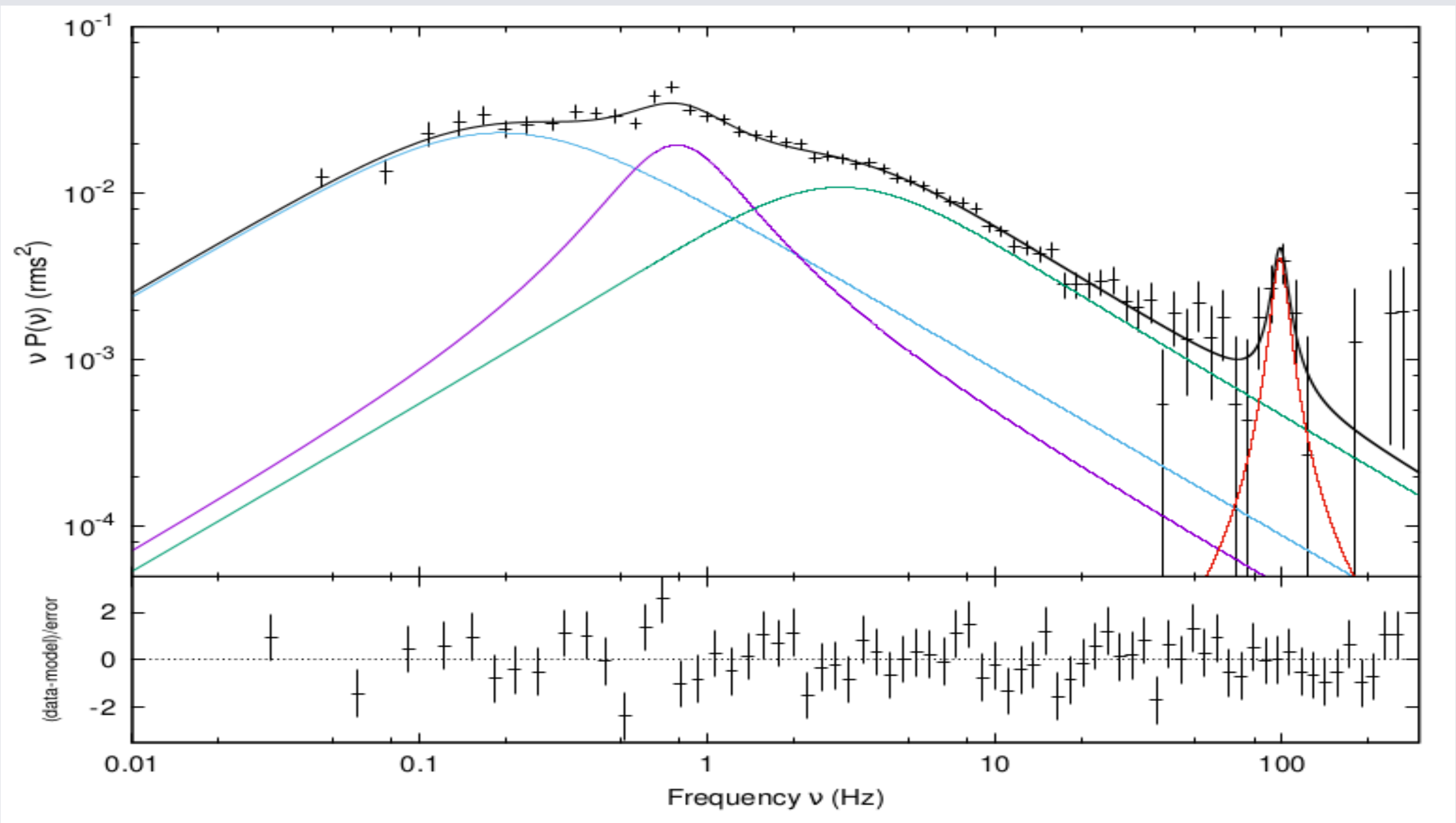
If P_d (detected power) has small probability ε that will be exceeded by the noise power Then any power $P_i > P_d$ will have large probability (1-ε) that will be due to the signal.

If there are N trials then the chance per trial,

$$\epsilon/N \approx Q_{Gauss}\left(\frac{P_d-2}{2/\sqrt{MW}}\right)$$

Results

Power Spectral density for the NICER observation on **MJD 58660** (Obsid: 2200530165). Different Lorentzian components used in the fitting are also shown here

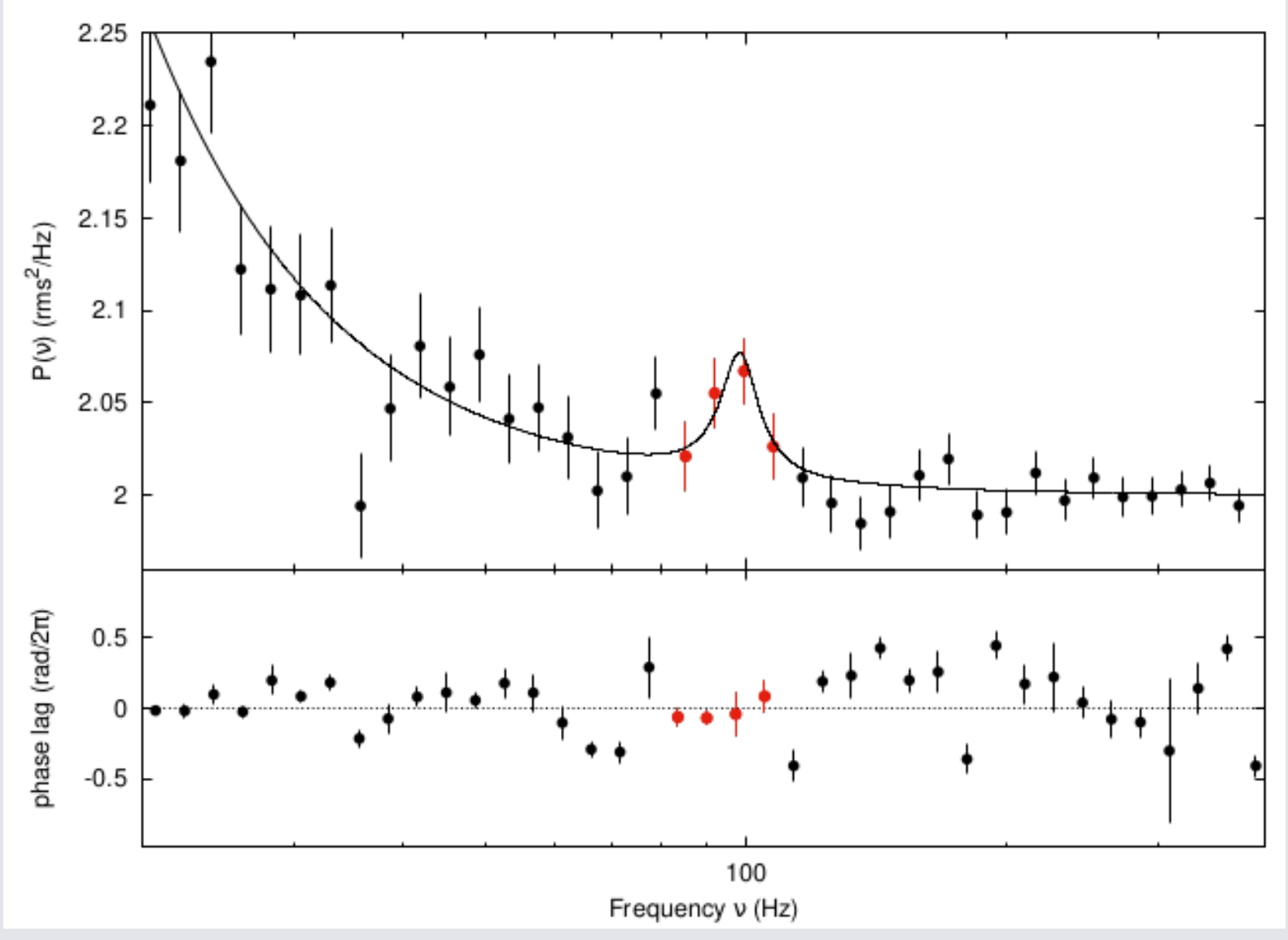


A HFQPO at 98.3 Hz with Q value ~ 14.9 and rms ~ 0.029±0.009 was observed in Poisson noise dominated region of the power spectrum, so, We estimated the significance using method discussed above.

For our case,
M = 51, W ~ 295 → MW ~ 15000
P_d ~ 2.06, N~1

Calculated chance probability for noise power to exceed detected power is ε ~ 0.000117 . This translates to ~ 3.7σ detection of the QPO signal.

We calculated the phase lag between Energy bands
S → 0.7 - 2.0 keV
H → 2.0 - 10.0 keV



The expression of Cross-power spectrum is, ***C(f) = <S*(f)H(f)>***

Phase lag is given by,
tan φ(f) = Im[C(f)] / Re[C(f)]

Time lag was calculated by
τ(f) = φ(f) / 2*pi*f

Estimated time lag at QPO frequency ~ 0.8 ms
Time travel-time distance ~ 240 km ~ 6 Risco

Estimated inner radius of accretion disk from spectral fitting ~ $5.4^{+3.5}_{-4.3}\ R_{ISCO}$ (**Kumar et al 2022**).

Origin of HFQPOs

Germana et al. (2009) : Keplerian frequency of the Radiation-emitting clump of Matter orbiting around a Schwarzschild black hole can produce HFQPO.

Tagger and Varniere (2006): Magnetohydrodynamic (MHD) instabilities in the disk.

Kato (2004,2008): Excitation due to nonlinear Resonance between the0 Oscillations within the accretion disk.
Tagger and Varniere (2006) and Kato (2004,2008) used to explain the twin QPOs With their peak frequencies at a ratio of 3:2 or 5:3. Not applicable in our case.

Conclusions

- **We observed a HFQPO in MAXI J1348-630 at 98.3 Hz with a significance of 3.7σ during low flux hard state.**

- **Light travel time distance agreed with the inner radius of accretion flow as estimated from spectral modeling.**

- **The frequency of QPO is consistent with the Keplerian orbital frequency around the black hole.**

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