Search for 'rocking' of the iron line in black hole binaries through LFQPO phase-resolved spectroscopy

Seshadri Majumder[1*], Teruaki Enoto[1], Chris Done[2], Megumi Shidatsu[3], Yoshihiro Ueda[1]

[1]Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan
[2]University of Durham, Durham DH1 3LE, UK
[3]Ehime University, Ehime 790-8577, Japan

*majumder.seshadri.75c@st.kyoto-u.ac.jp

Abstract

Context: Quasi-periodic oscillations (QPOs) are coherent X-ray timing features observed in black hole X-ray binaries (BH-XRBs), originating from the innermost disc-corona region. The Lense-Thirring precession model predicts QPO phase-dependent variations in the fluorescent iron line profile and centroid energy due to relativistic frame-dragging.

Aims: The primary aim of this study is to test the Lense-Thirring precession model by investigating QPO phase-dependent modulation of the iron-line centroid energy and broadband spectral properties in several black hole transients using NuSTAR observations.

Methods: We employ the Hilbert-Huang Transform (HHT) techniques to isolate the QPO component from the light curve and construct QPO phase-resolved spectra. These spectra are fitted with physically motivated models to track the evolution of the spectral properties over the QPO cycle.

Results and Conclusions: We detect significant ($> 3\sigma$) 'rocking' of the line-centroid energy between red- and blue-shifted regimes over the QPO cycle, broadly consistent with predictions from the Lense-Thirring precession model, in which QPO phase-dependent illumination of the disc by the precessing corona produces the observed iron line and broadband spectral variability.

1. Background

- BH-XRBs exhibit rapid spectro-temporal variability (milliseconds to tens of seconds) across distinct spectral states, typically traced in the hardness-intensity diagram (HID) during their X-ray outbursts.
- Low-frequency QPOs appear as excess power in the Fourier spectrum in the low-hard state (LHS) and hard-intermediate state (HIMS), when spectrum is dominated by coronal emission.

Credit: Adam Ingram

- The geometry of the X-ray corona remains debated. QPOs provide a key diagnostic for probing the accretion disc-corona geometry.
- Lense-Thirring (LT) precession model of LFQPOs predicts modulation of fluorescent Fe-line energy over the QPO cycle, yet to be tested for a comprehensive sample of BH-XRBs.

2. Source Selection & Observations

NuSTAR archival observations of transient BH-XRBs over last 12 years

GS 1354−64, H 1743−322, GRS 1915+105, GX 339−4, MAXI J1820+070, MAXI J1803−298, Swift J1658.2−4242

Criteria on the selection of sources and observations:

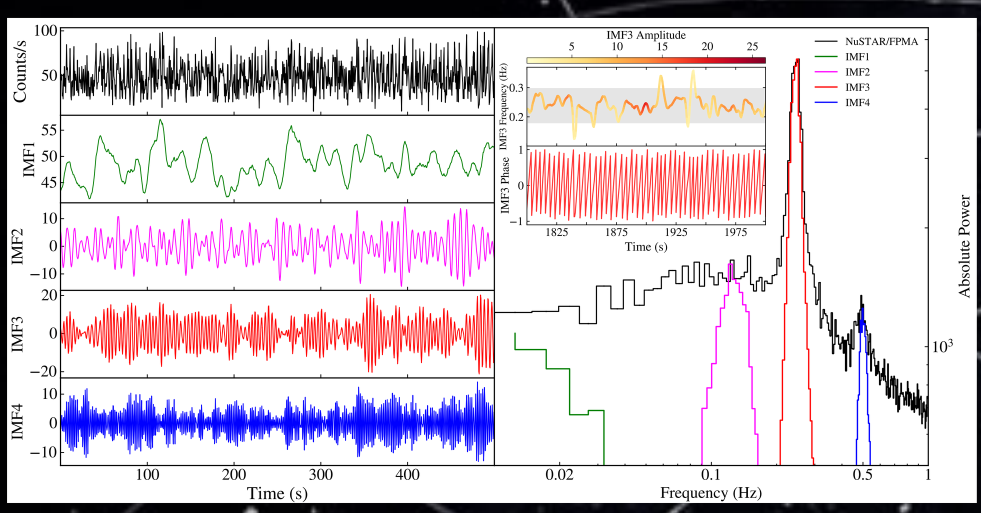
1. Observations in LHS and HIMS
2. Prominent iron line emission detected in both NuSTAR/FPMA and FPMB.
3. Significant detection of LFQPOs in the power spectra
4. Effective NuSTAR exposure per module $\gtrsim$ 10 ks

3. Analysis and Methodology

QPO phase-resolved analysis using the Hilbert-Huang Transform (HHT):

1. Light curves are decomposed into intrinsic mode functions (IMFs) using Variational Mode Decomposition (VMD), and the QPO component is identified in the power density spectrum.

2. The Hilbert transform is applied to derive the frequency, phase, and amplitude of the QPO IMF.



HHT of $g(t)$:

$$\mathscr{H}(g(t)) = \frac{1}{\pi}\mathrm{pv}\int \frac{g(t')}{t-t'}dt'$$

Phase:

$$\phi(t) = \tan^{-1}\left[\frac{\mathscr{H}(g(t))}{g(t)}\right]$$

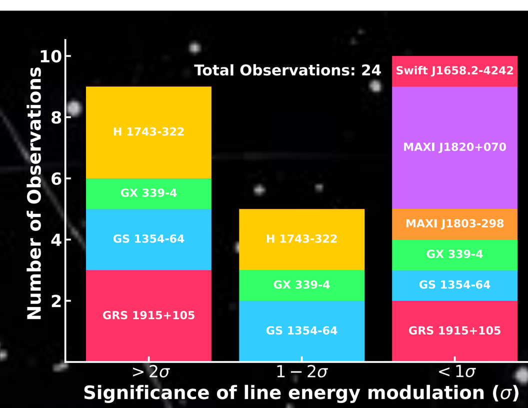
Frequency:

$$f(t) = \frac{1}{2\pi}\frac{d\phi(t)}{dt}$$

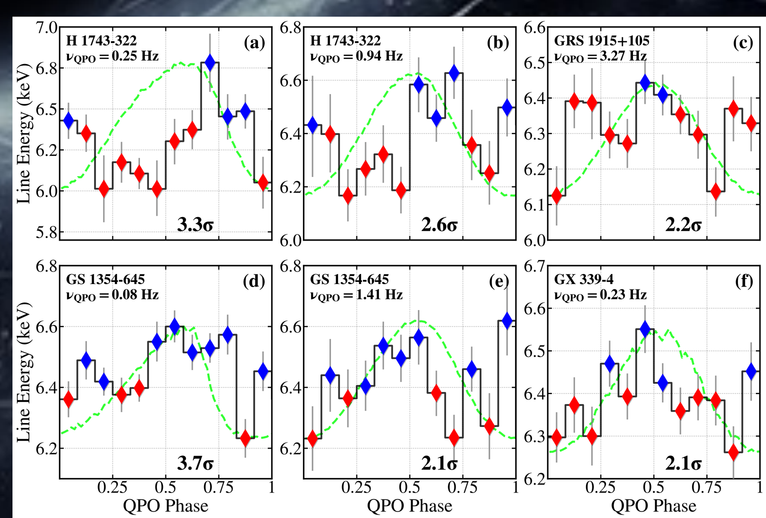
Use $\phi(t)$ to obtain QPO phase-resolved spectra

4. Results: I. 'Rocking' of Iron Line in BH-XRBs

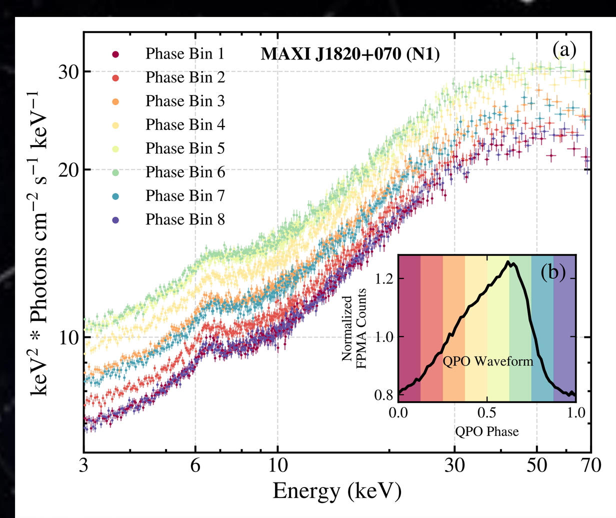
- LFQPO phase-resolved spectroscopy over 12 phase bins using **nthComp** for the continuum and **Gaussian** for Fe-line emission.
- Significance of Fe-line energy variations is assessed using a χ^2test against the weighted mean line energy.



- This study reports the detection of 'rocking' in Fe-line energy for **GS 1354-64 (at 3.7σ)** and **GX 339-4 (at 2.1σ)** for the first time and confirms previous detections in **H 1743-322** and **GRS 1915+105** using time domain analysis.

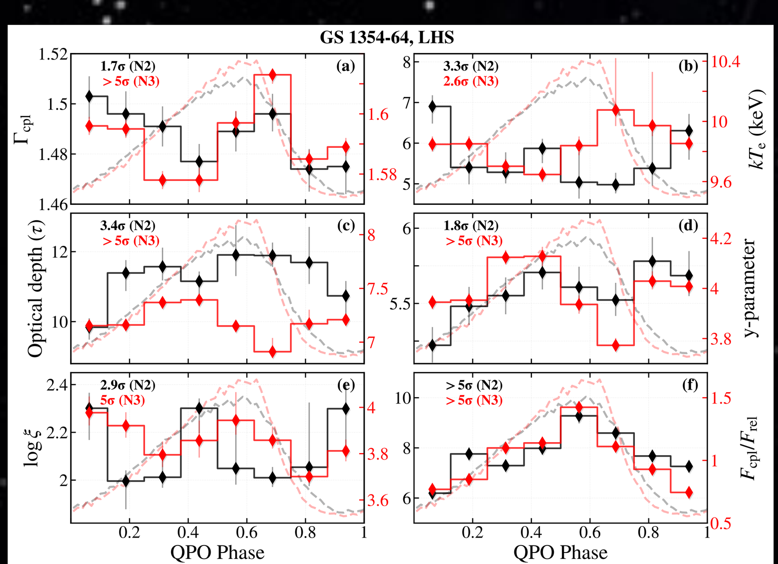


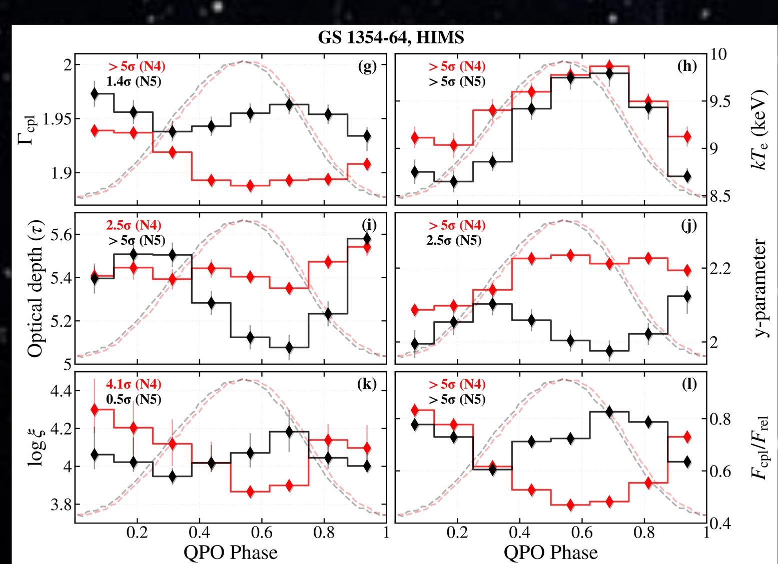
QPO Waveform



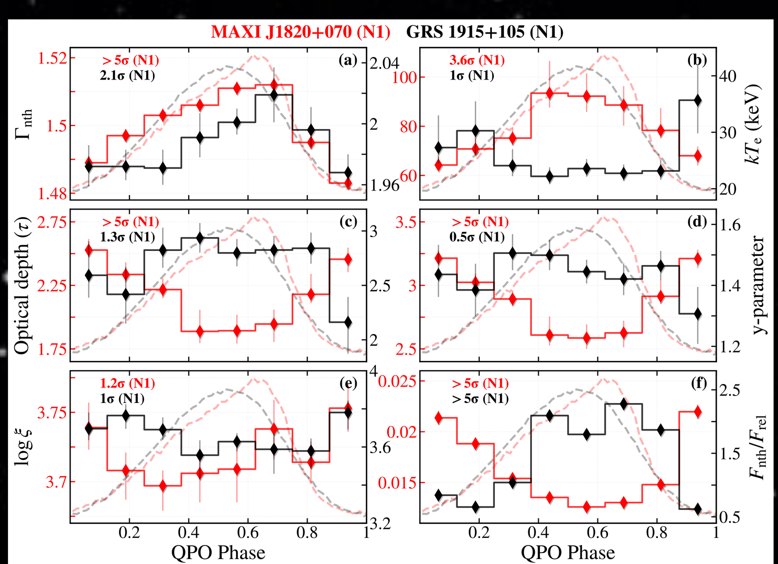
5. Results: II. Variation of Spectral Continuum over QPO Phase

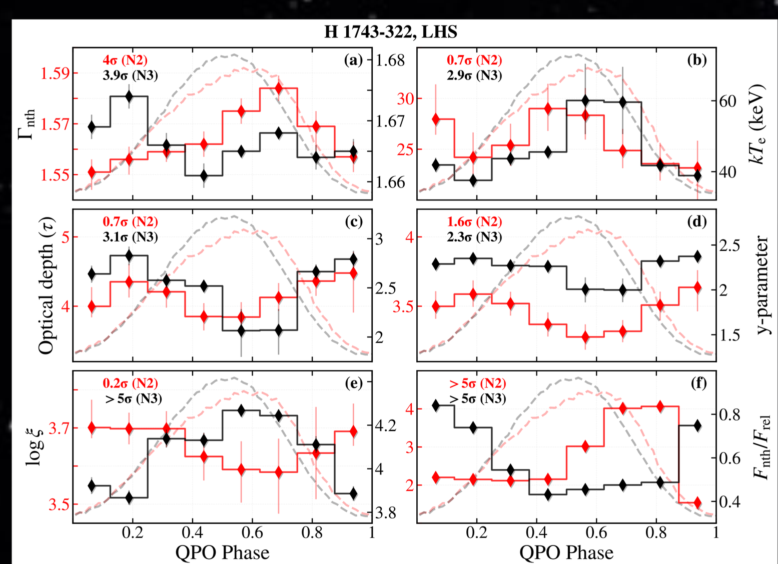
- QPO phase-resolved reflection spectroscopy is performed across 8 phase bins in the respective observations using **nthComp/cutoffpl** for the primary emission and **relxillCp** for reflected emission.





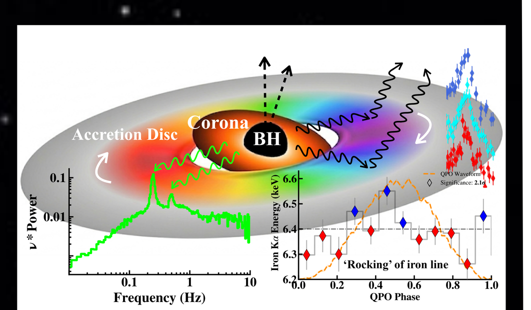
- We observe significant variation in the photon index, electron temperature, optical depth, and y-parameter: Modulation of Comptonization spectral component on QPO timescales.
- Multiple extrema in spectral parameters are observed over a complete QPO cycle, possibly arising from Lense-Thirring precession of the inner flow/corona.





6. Summary

- Significant ($> 2\sigma$) QPO phase-dependent modulation of the Fe-line energy in **GS 1354-64, H1743-322, GRS 1915+105, and GX 339-4**.
- Significant variations in the coronal properties and spectral flux over the QPO phase.



- Consistent with the LT precession scenario, where QPO phase-dependent illumination of disc azimuths produces the observed 'rocking' in Fe-line energy.
- More sophisticated reflection modeling is required for further tests of this effect.

7. Acknowledgments

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8. References

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