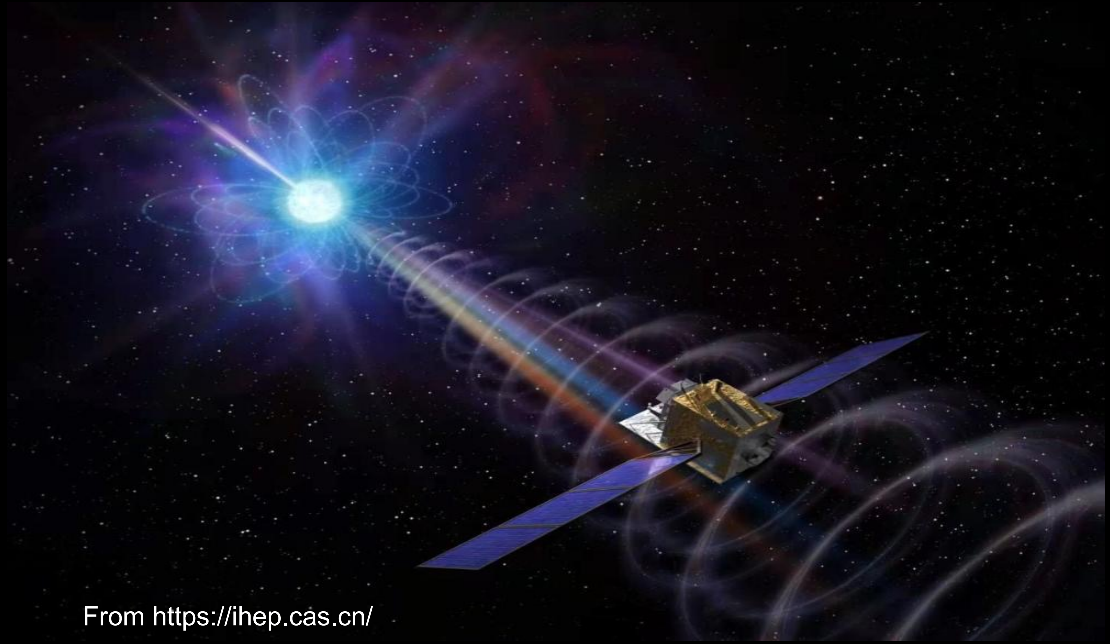
中国科学院大学
University of Chinese Academy of Sciences

中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

慧眼 – HXMT

A Phase-resolved View of the Low-frequency Quasi-periodic Oscillations from Black Hole X-ray Binary MAXI J1820+070



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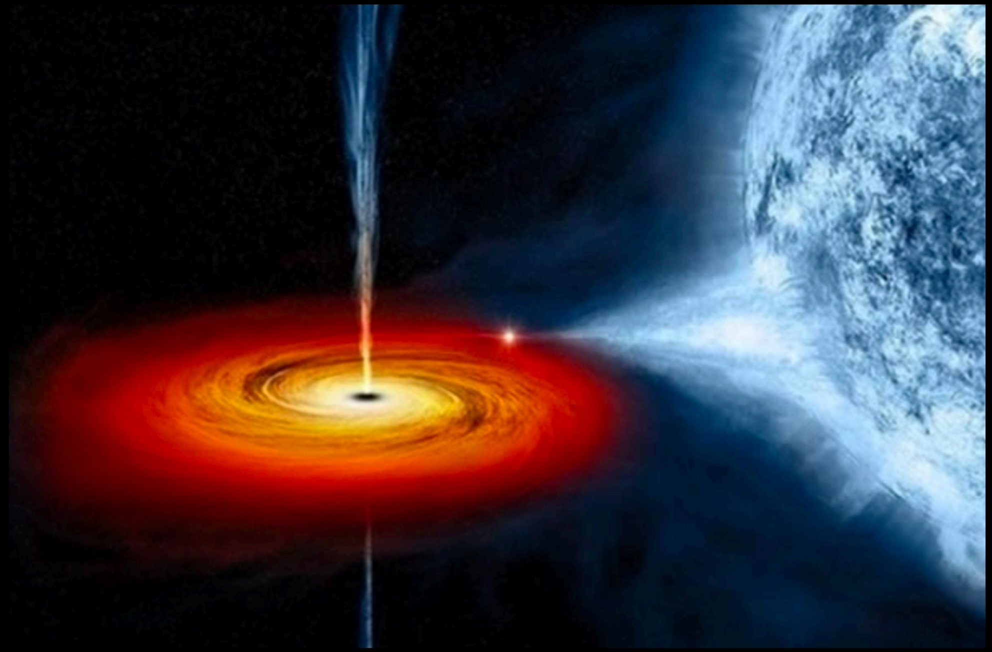
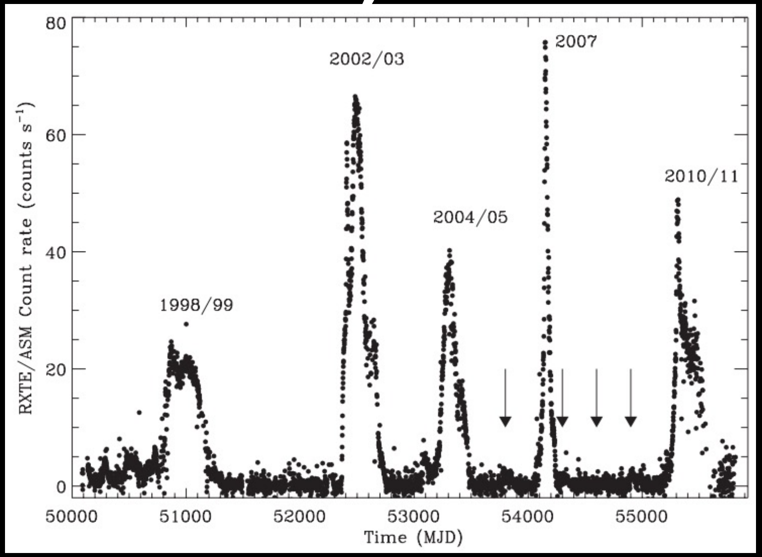
Institute of High Energy Physics, Chinese Academy of Sciences

The 32nd Texas Symposium on Relativistic Astrophysics@Shanghai, China
2023.12.11-15

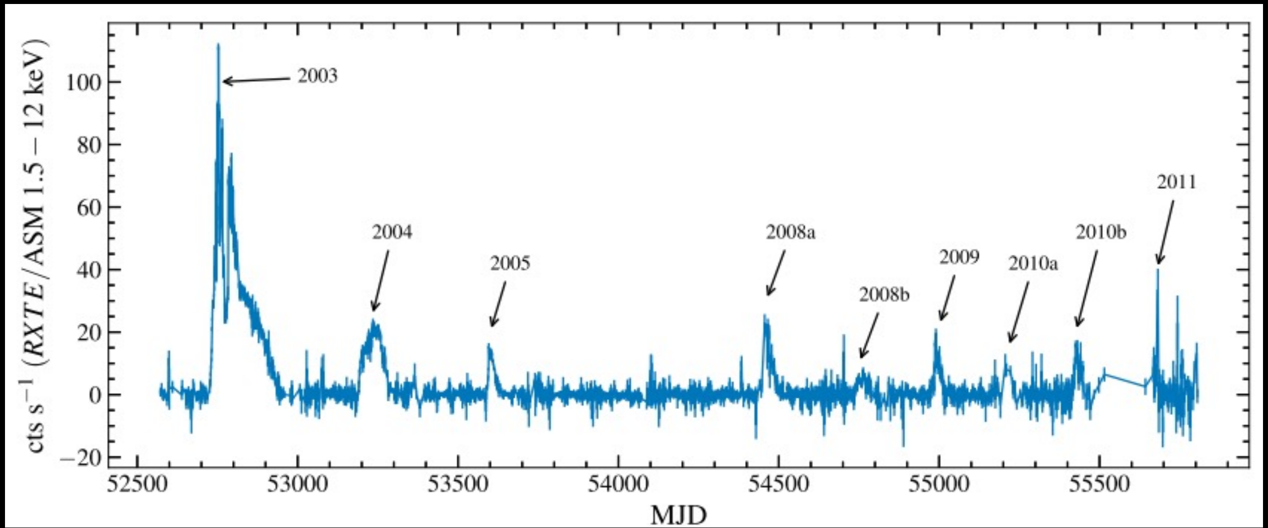
Black Hole X-ray Binary (BHXRB)





GX 339-4, S. Corbel et al. (2013)

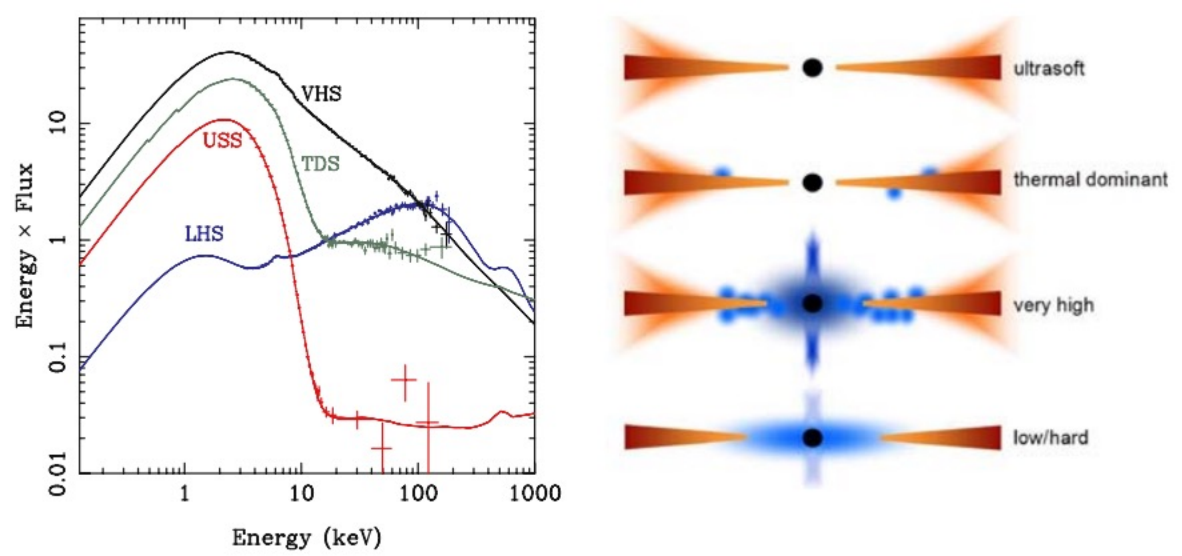
Undergoing outbursts occasionally after staying with faint luminosity for a long time in quiescence is the primary feature of low-mass black hole X-ray binaries.



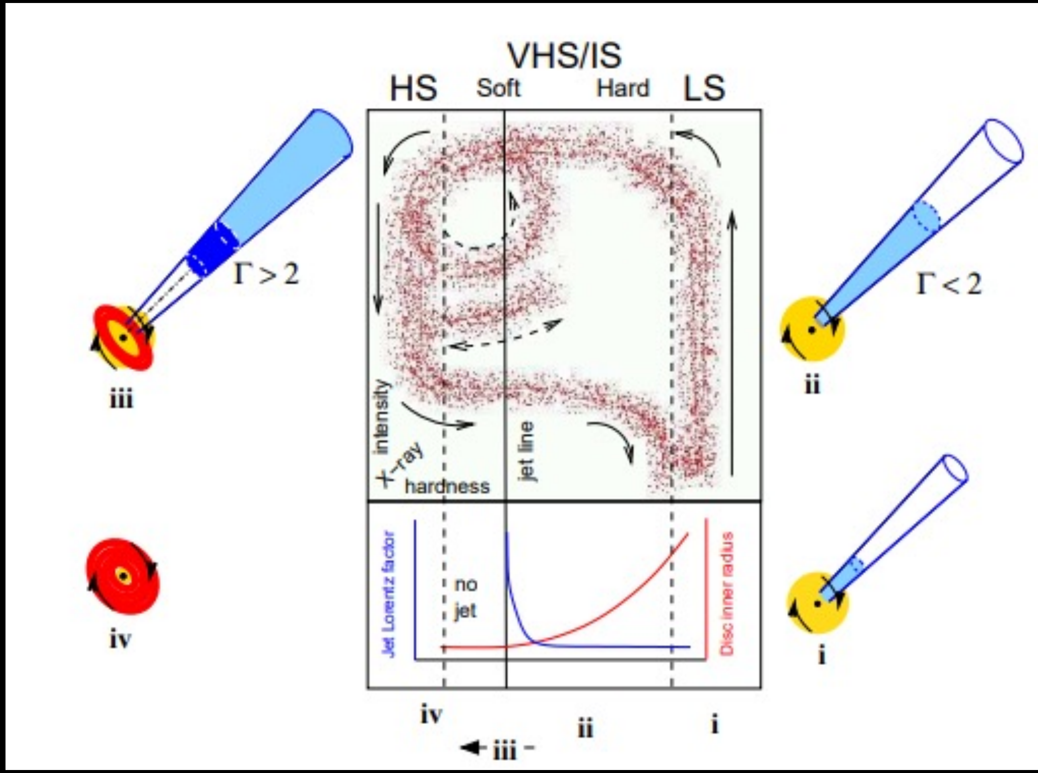
H 1743-322, Shui et al. (2023a)

Black Hole X-ray Binary (BHXRB)

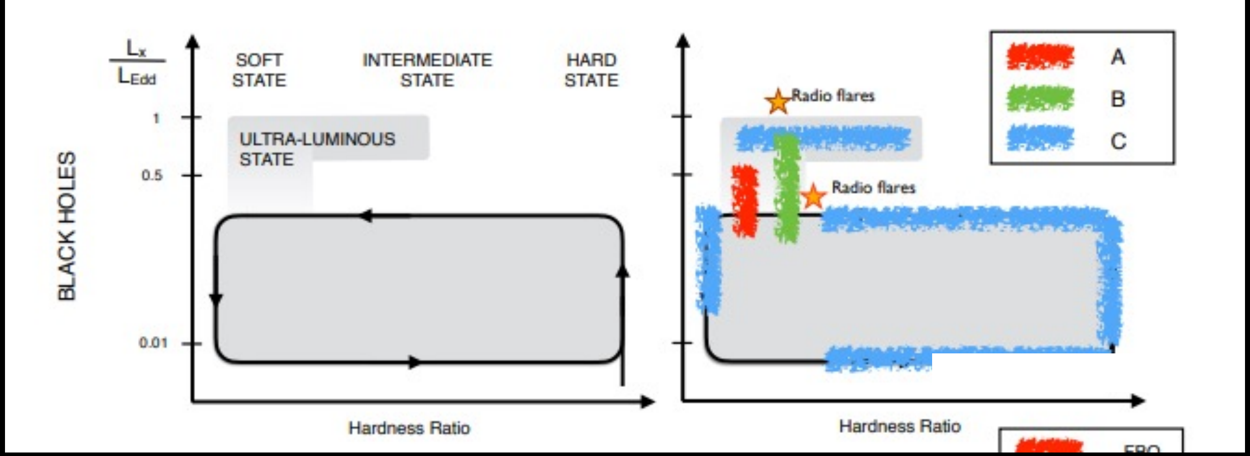
Most complete outbursts are observed to have four typical states: the low/hard state (LHS), hard intermediate state (HIMS), soft intermediate state (SIMS), and high soft state (HSS).



Chris Done et al. (2007)



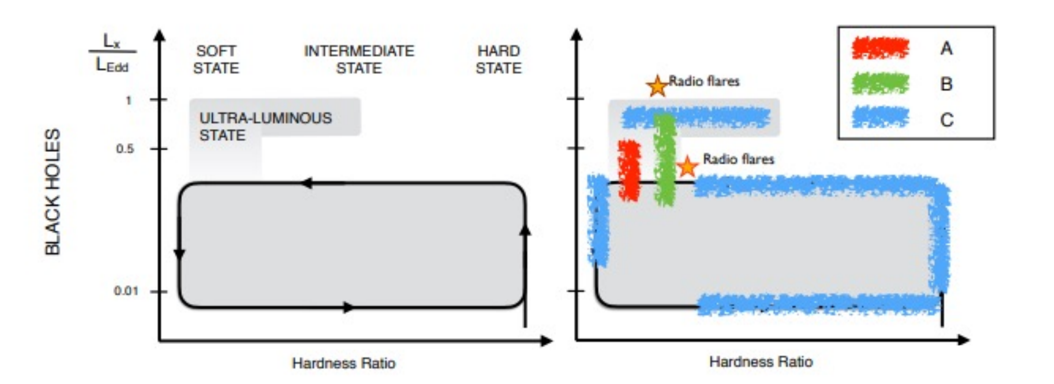
Fender et al. (2004)



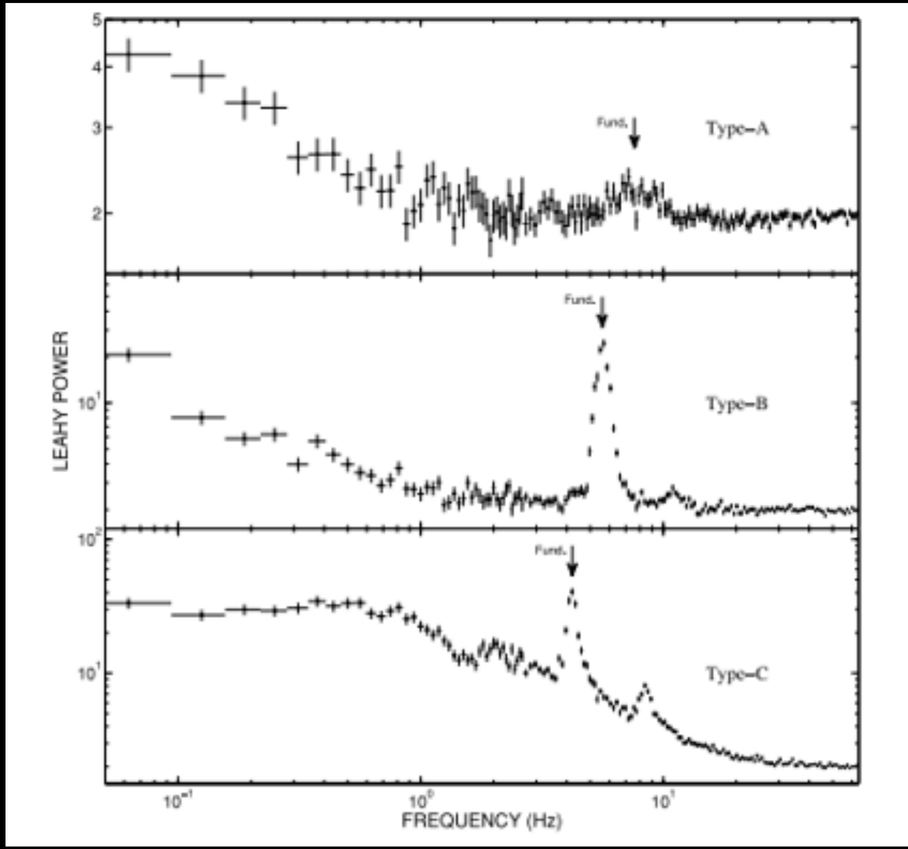
Ingram et al. (2019)

Low-frequency Quasi-periodic Oscillations

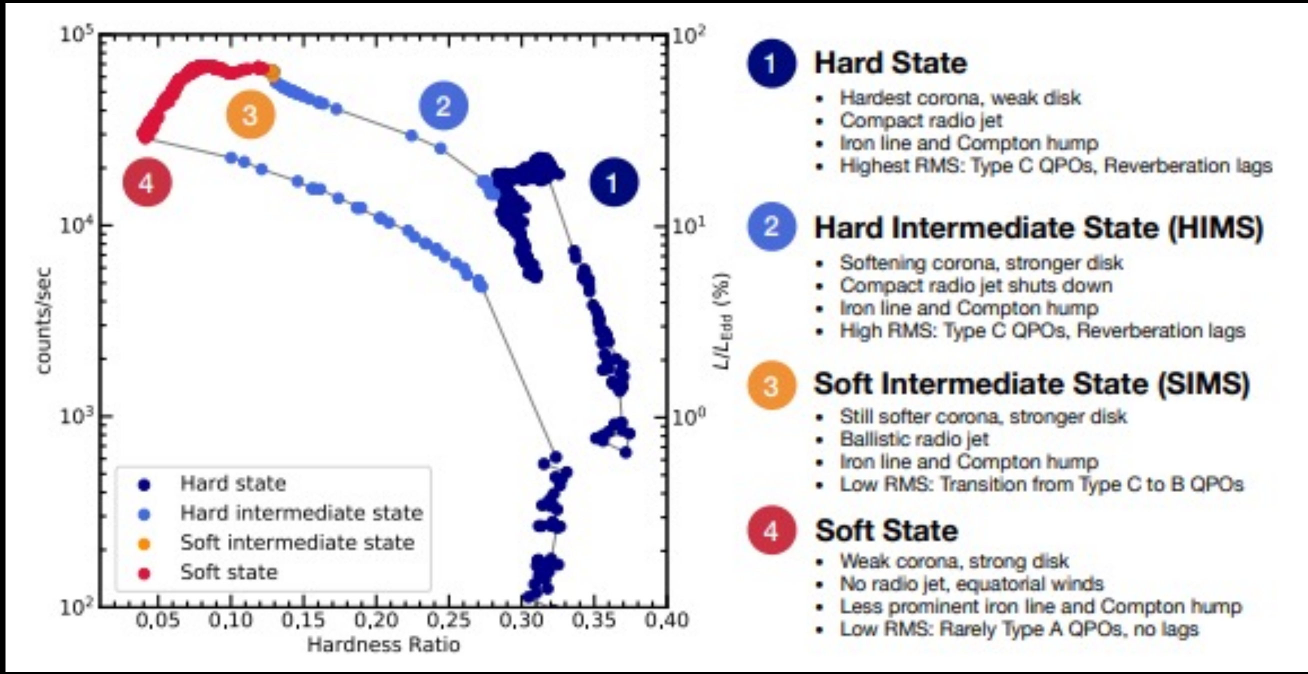
Low frequency quasi-periodic oscillations (LFQPOs) are usually detected in BHXRBs, with characterized by a narrow peak with the finite width in the power density spectra (PDS).



Ingram et al. (2019)



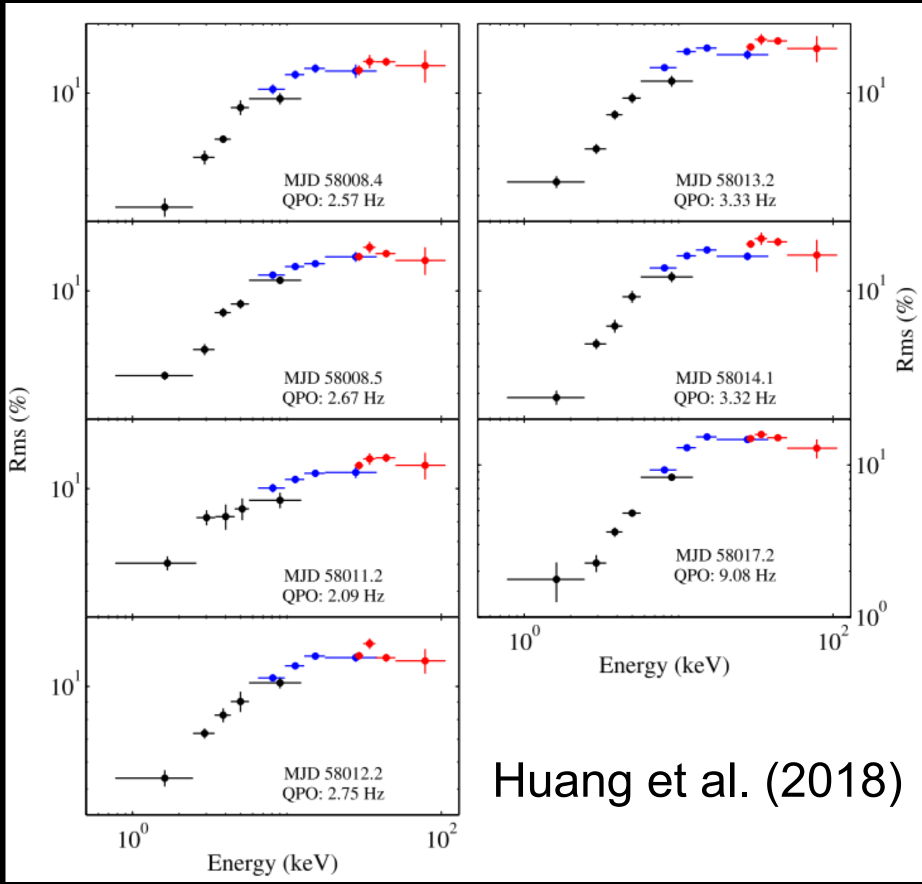
S. E. Motta et al. (2011)



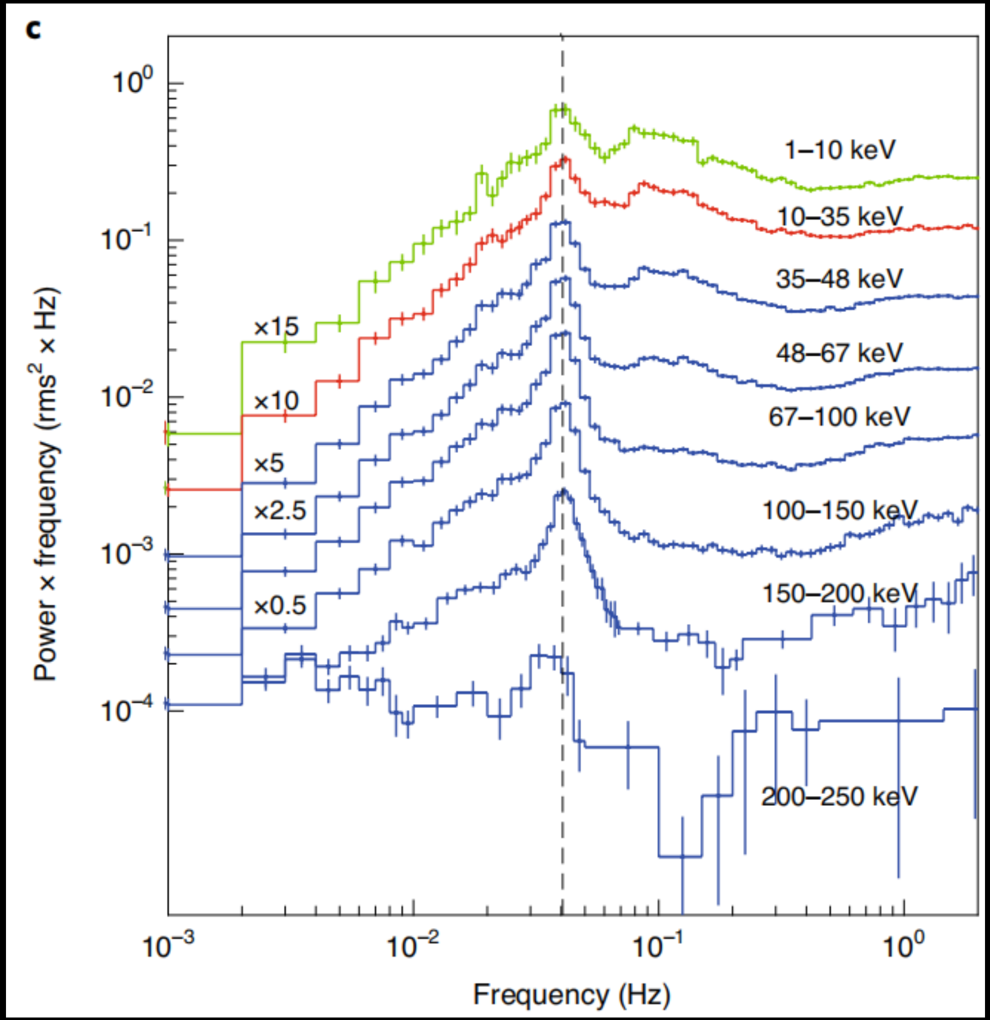
Emrah Kalemci et al. 2022

Low-frequency Quasi-periodic Oscillations

Many observational studies have revealed that the variability of type-C QPOs generally increases with the photon energy. And more importantly, QPO signals above 200 keV have been detected by *Insight*-HXMT. These results indicate that type-C QPO should be strongly related to the Comptonized emission.



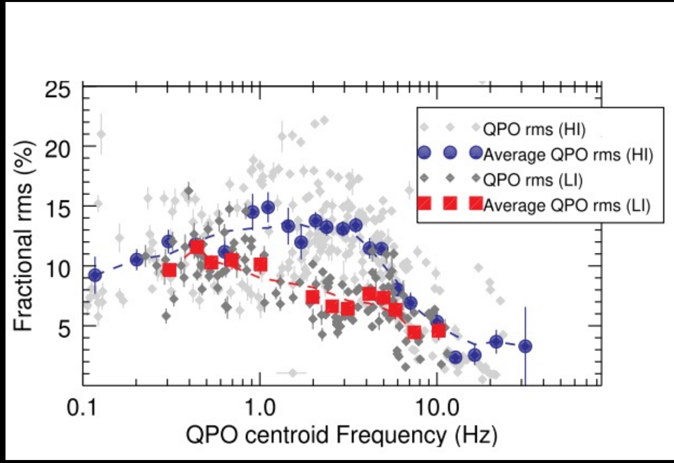
Huang et al. (2018)



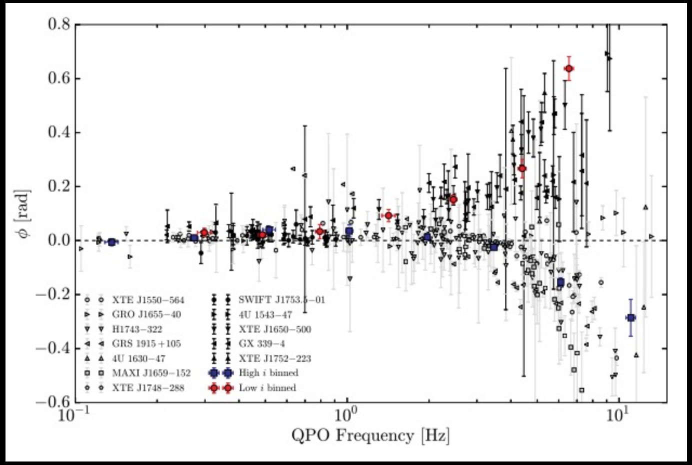
Ma et al. (2021)

Low-frequency Quasi-periodic Oscillations

The inclination dependence of **amplitudes and time lags** add support to a **geometrical origin**.



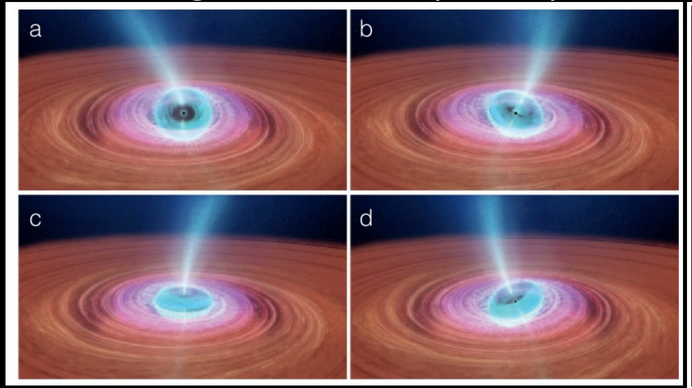
Motta et al. (2015)



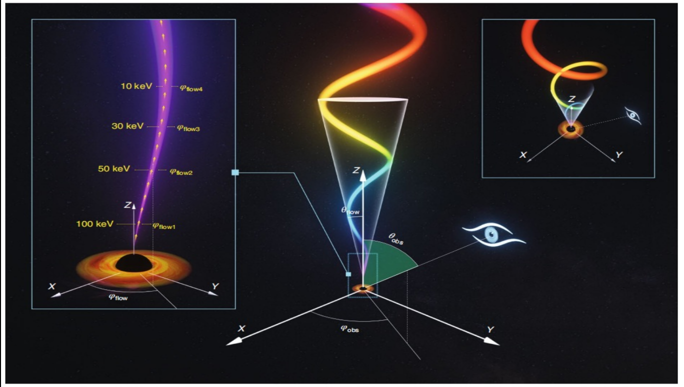
van den Eijnden et al. (2017)

Geometric Model: **Coronal precession** & **Jet precession**

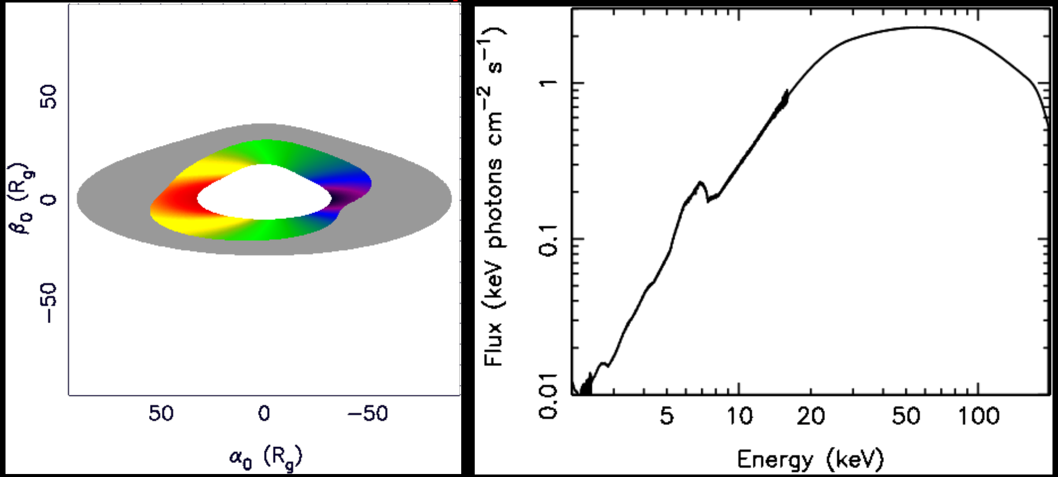
Ingram et al. (2019)

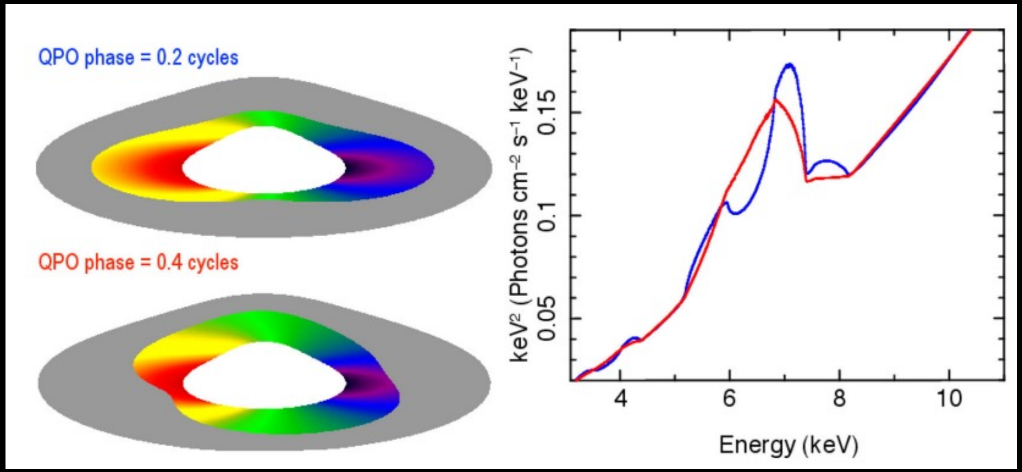


Ma et al. (2021)



Phase-resolved analysis: provides valuable insights into the properties of QPOs by examining the phase-dependent behavior of the spectrum.

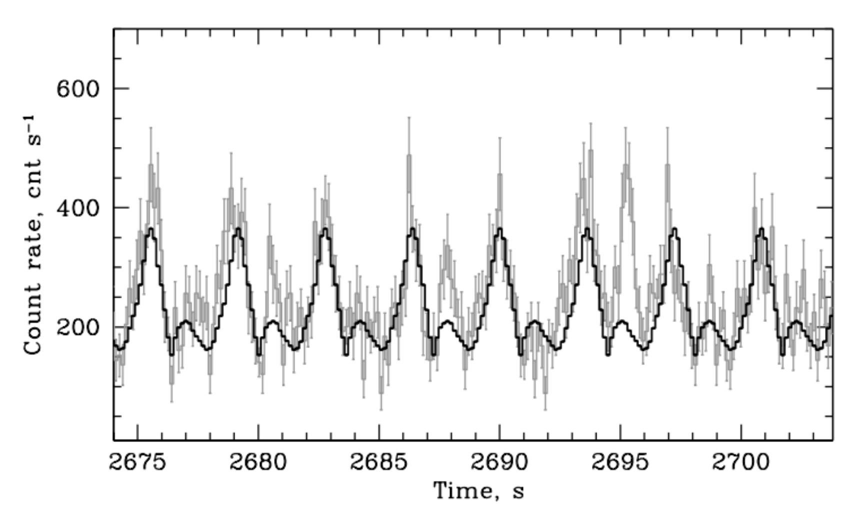




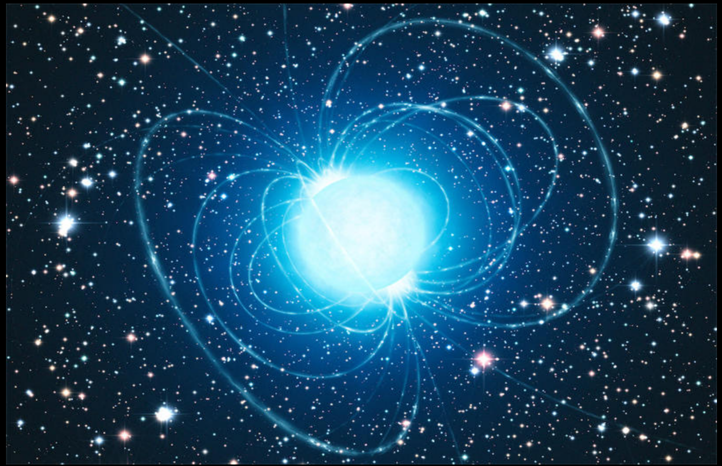
Ingram et al. (2016, 2017)

Low-frequency Quasi-periodic Oscillations

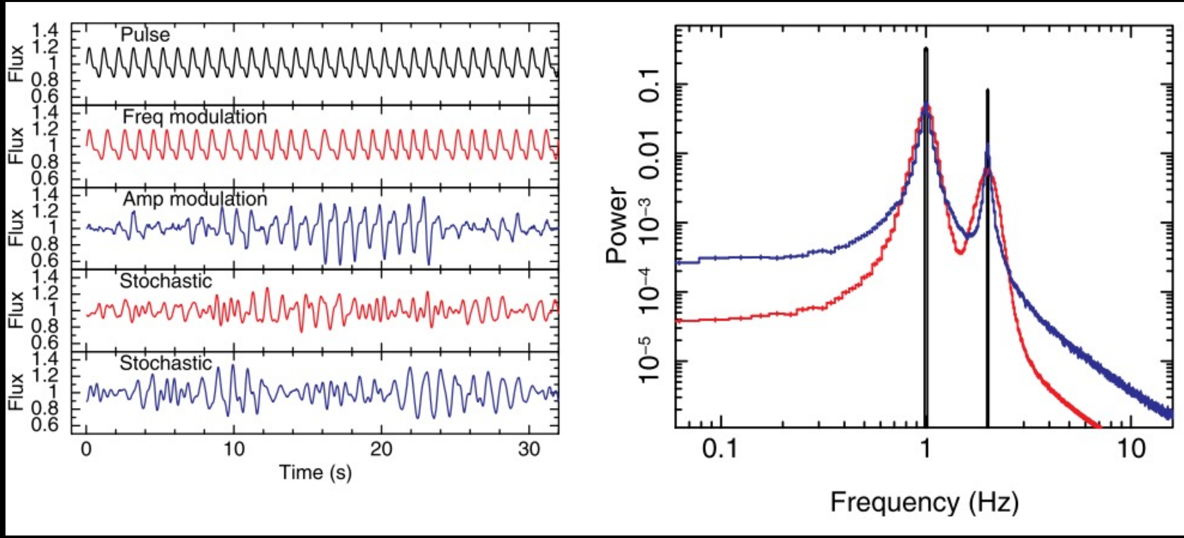
In studies of X-ray pulsars, the phase-resolved analysis has been extensively conducted by **folding on a period**.



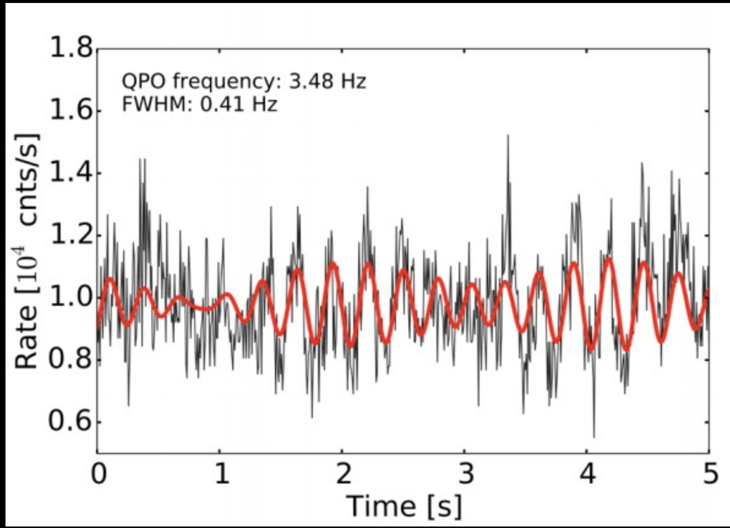
Tsygankov et al. (2007)



Differing from the pulsation in X-ray pulsars, the QPO is characterized by a narrow peak with finite width in the PDS.



Ingram et al. (2019)



QPO frequency changes on a short time scale.

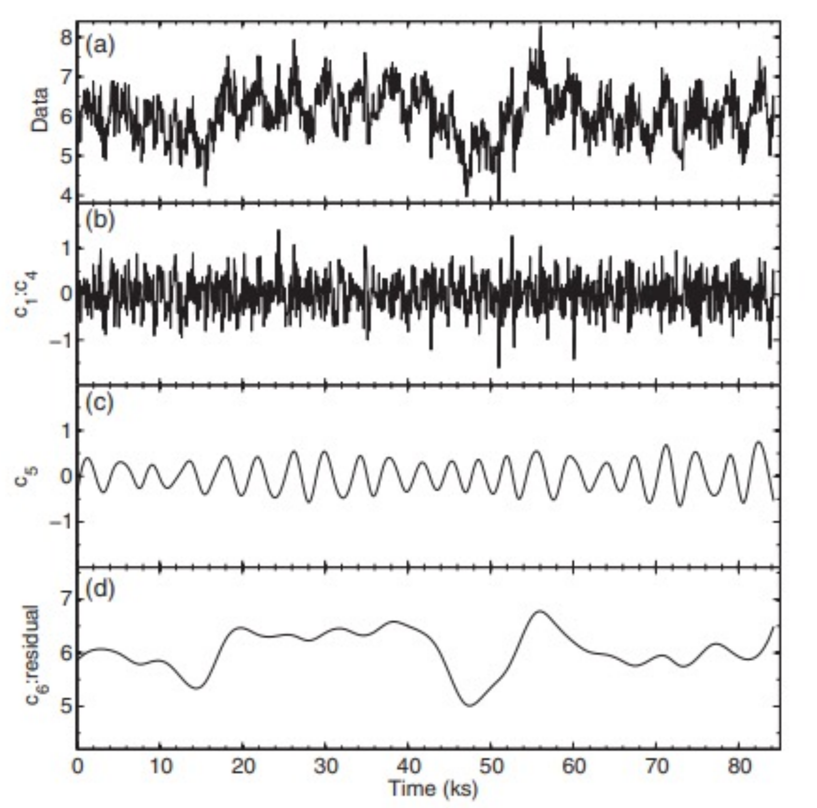
van den Eijnden et al. (2017)

Phase-resolve Analysis of QPOs: HHT

Hilbert-Huang Transform = Mode Decomposition + Hilbert Spectral Analysis

See Huang et al. (1998) for details

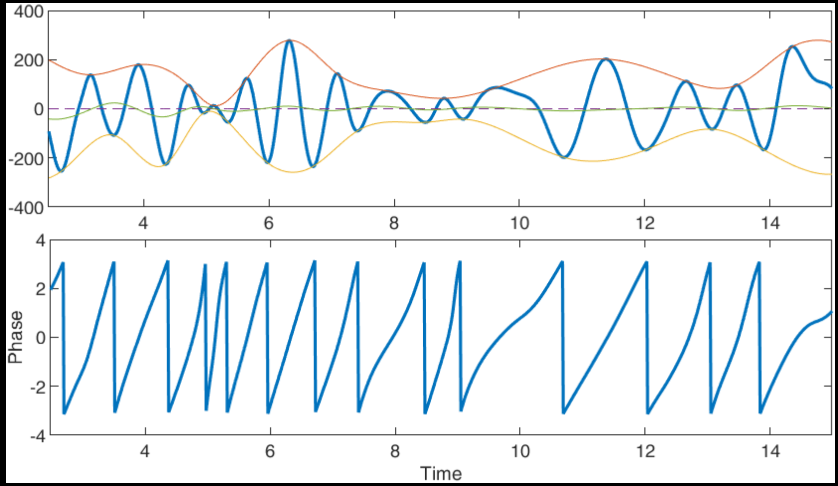
Mode Decomposition (e.g. EMD, VMD)



Intrinsic Mode Functions (IMFs)

Hu et al. (2014)

Hilbert Spectral Analysis



$$\mathscr{H}[u(t)] = \frac{1}{\pi}\text{p.v.}\int_{-\infty}^{+\infty} \frac{u(\tau)}{t-\tau}d\tau = u(t) * \frac{1}{\pi t}$$

$$\phi(t) = \arctan\left\{\frac{\mathscr{H}[f(t)]}{f(t)}\right\}$$

The QPO waveform can be constructed by the HHT phase-folding.

MAXI J1820+070

MAXI J1820+070 is one of the brightest BHXRB systems observed by Insight-HXMT.

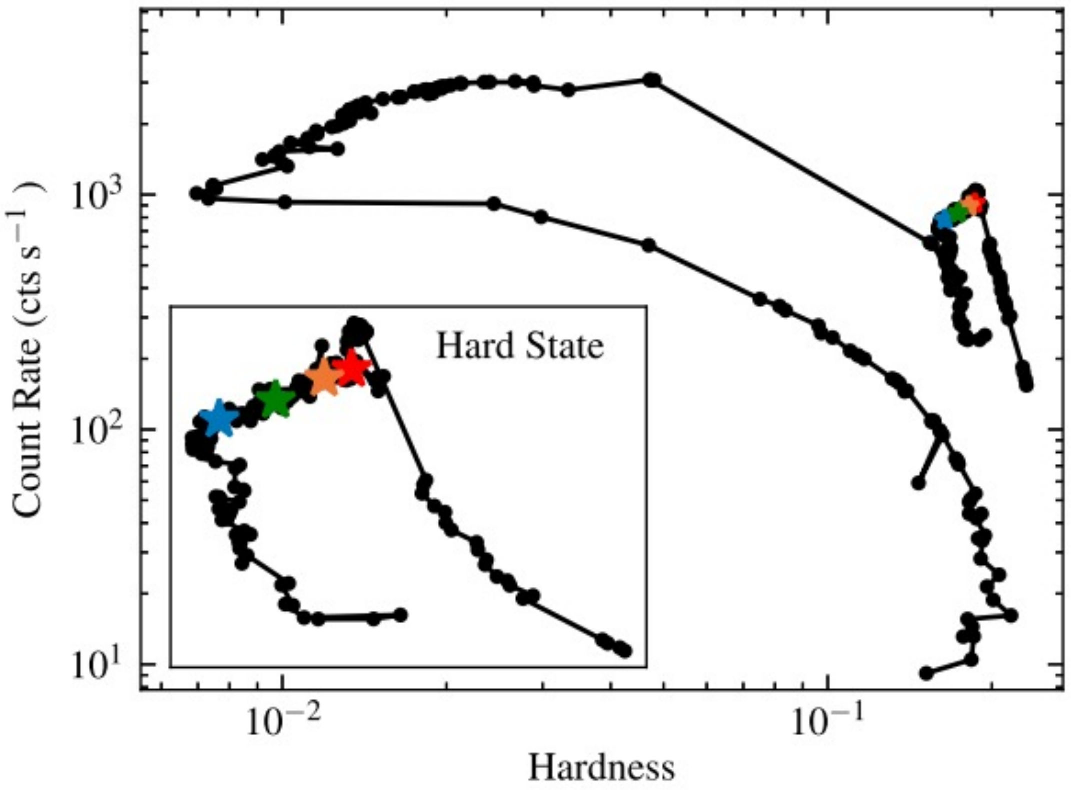
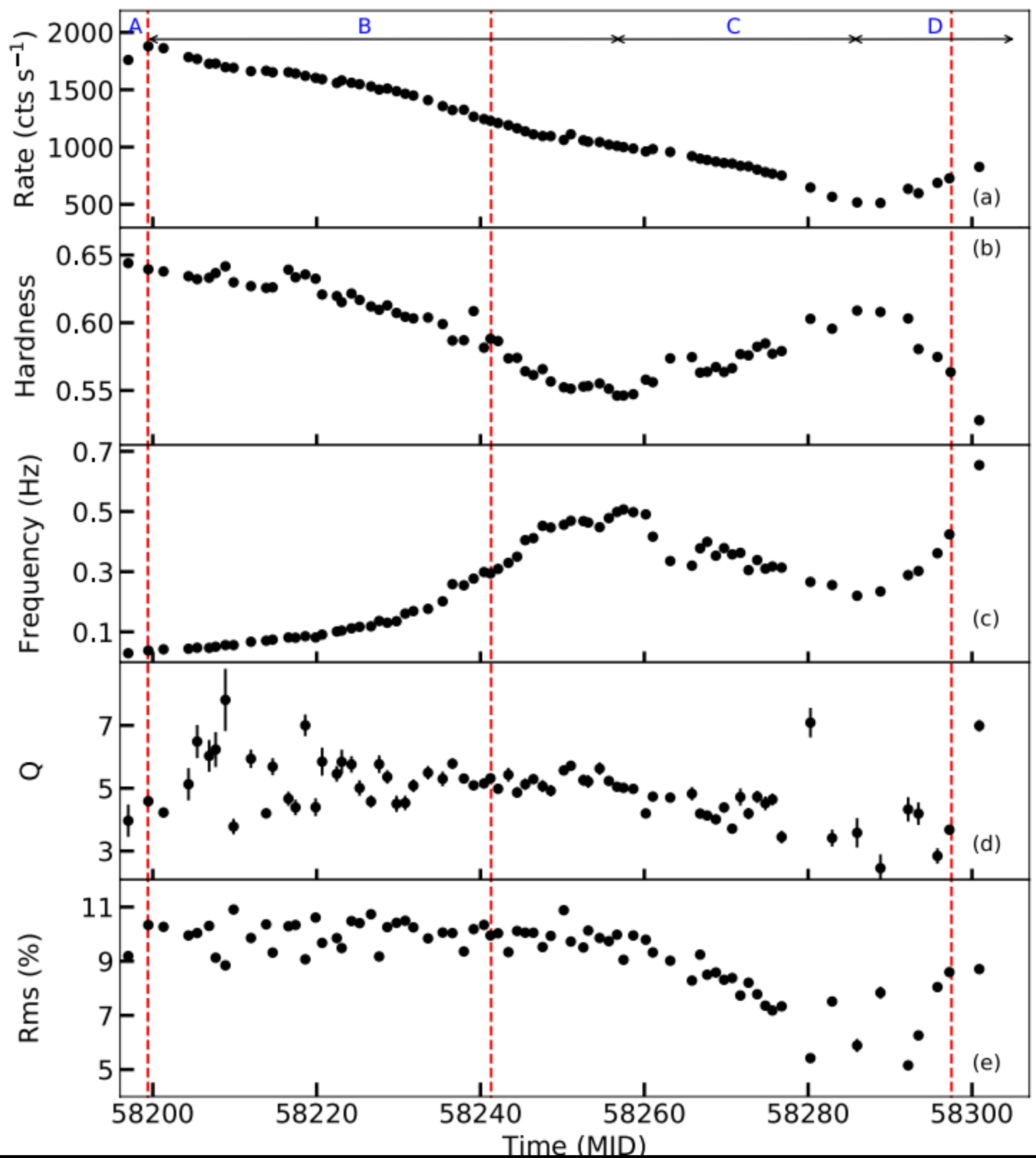


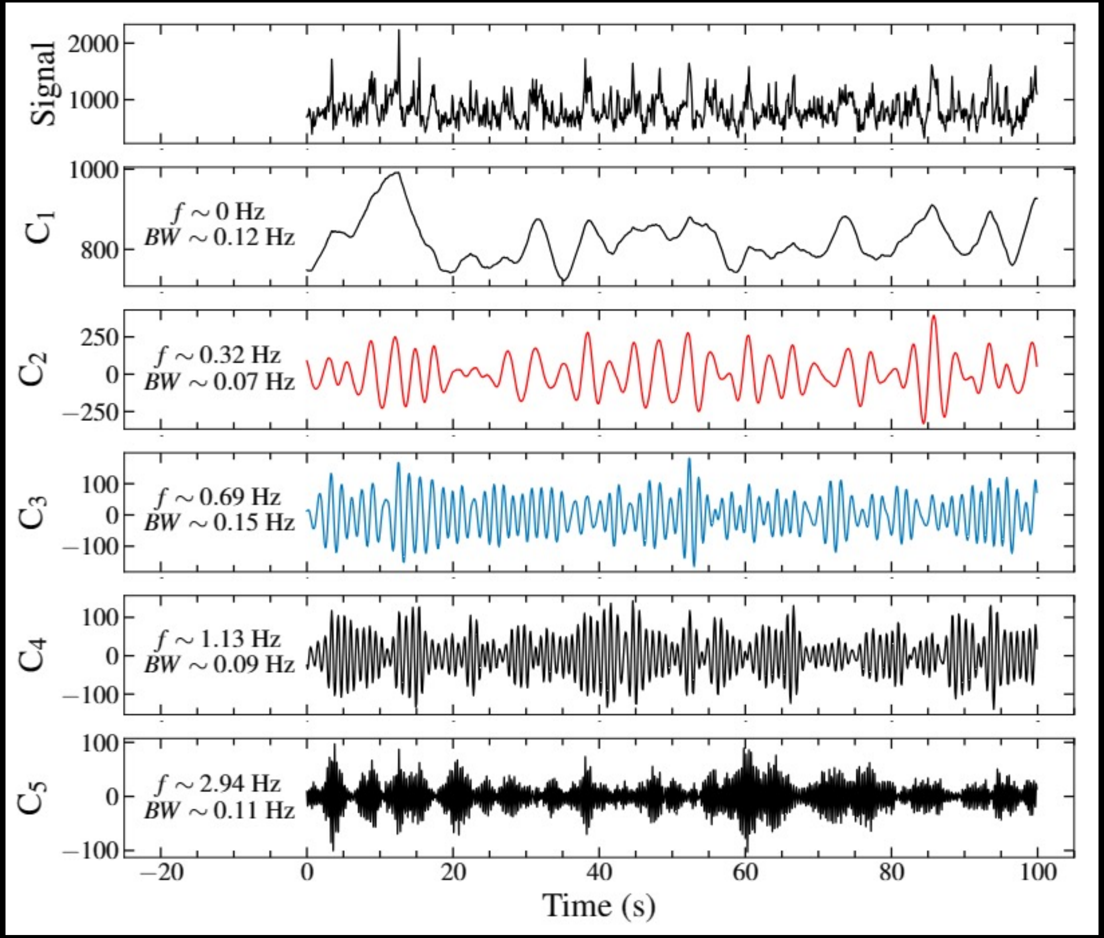
Figure 1. HID of Insight-HXMT, where the hardness ratio is defined as the count ratio between the hard band (5–10 keV) and the soft band (1–5 keV), and the count rate is measured in the 1–10 keV energy range. The colored stars indicate the averaged results for each epoch.



Ma et al. (2021)

Phase-resolve Analysis of QPOs

Variational Mode Decomposition Algorithm

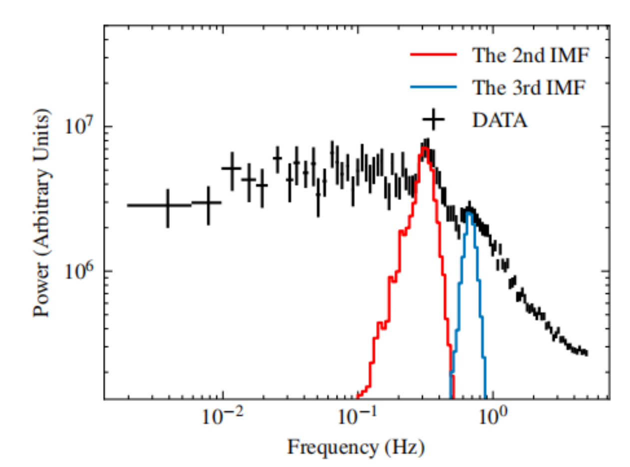


HXMT Light Curve

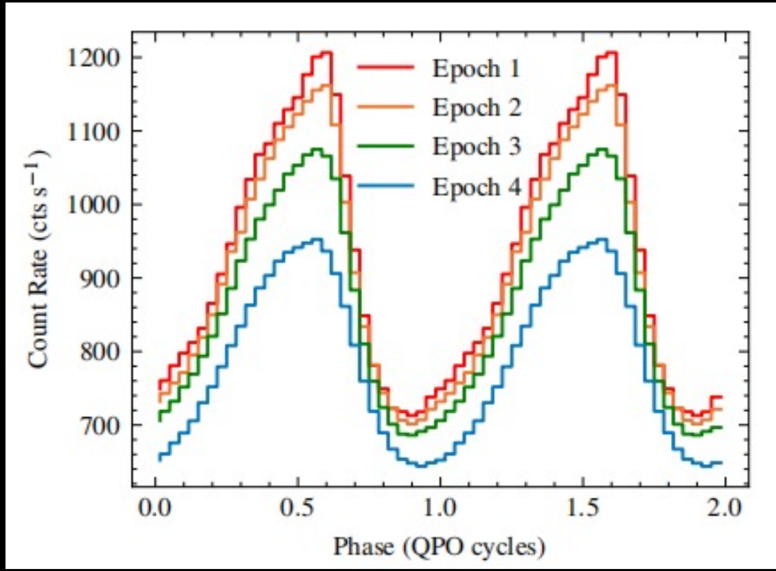
~0.3 Hz QPO

QPO Harmonic

Representative example of a 100-s-long lightcurve of LE in energy range of 1–10 keV and its corresponding IMFs.



Power density spectra (PDS) of the original light curve (black dots) and IMF C_2 (red line)

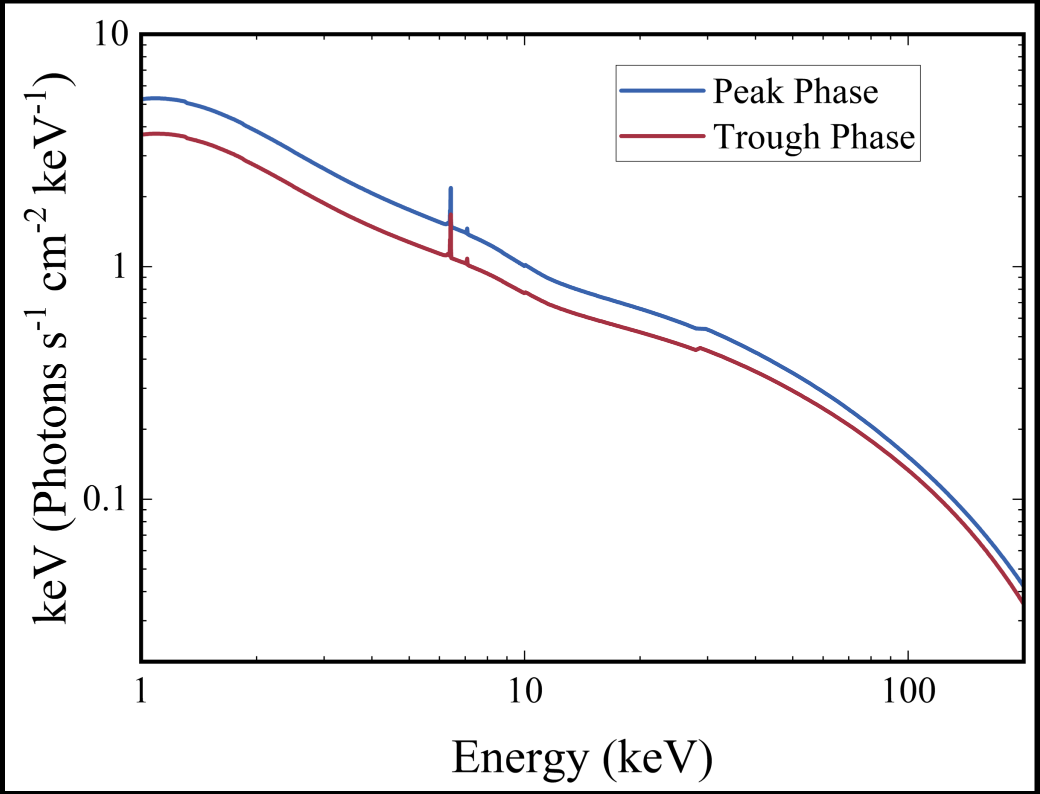


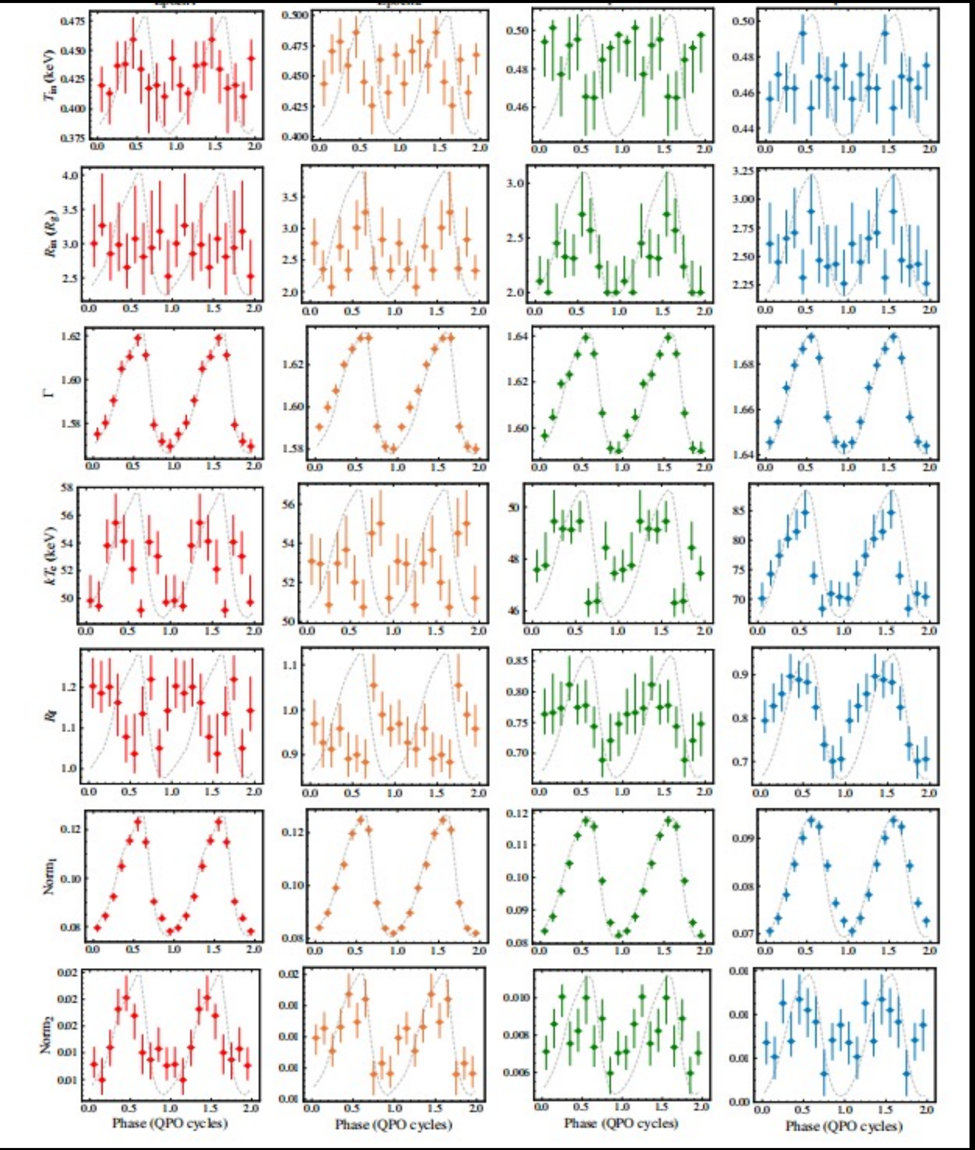
Phase-folding QPO waveforms

Phase-resolve Analysis of QPOs

Spectral Model (You et al. 2021):

constant*tbabs*(diskbb+relxillCp+xillverCp)





Disk tempreture

Inner radius

Spectral index

Electron tempreture

Reflection fraction

Norm of relxillCp

Norm of xillverCp

Phase-resolve Analysis of QPOs

T_{in} (keV)

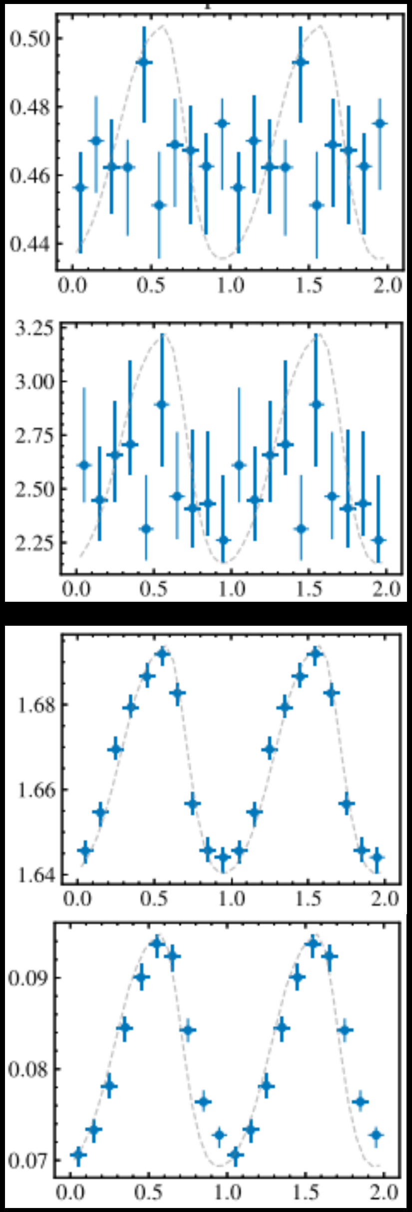
R_{in} (R_g)

Thin Disk

Gamma

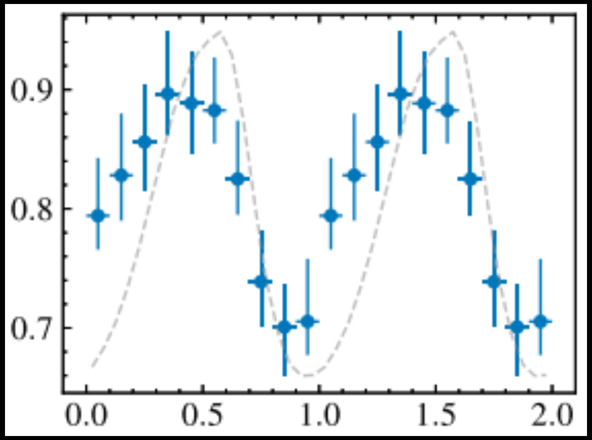
Normalization

Comptonization



Phase (QPO Cycles)

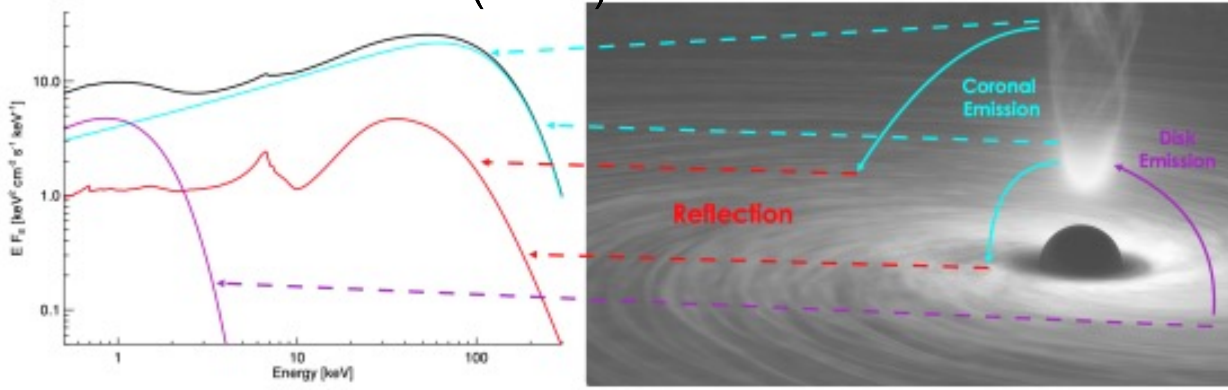
R_f



Phase (QPO Cycles)

Reflection

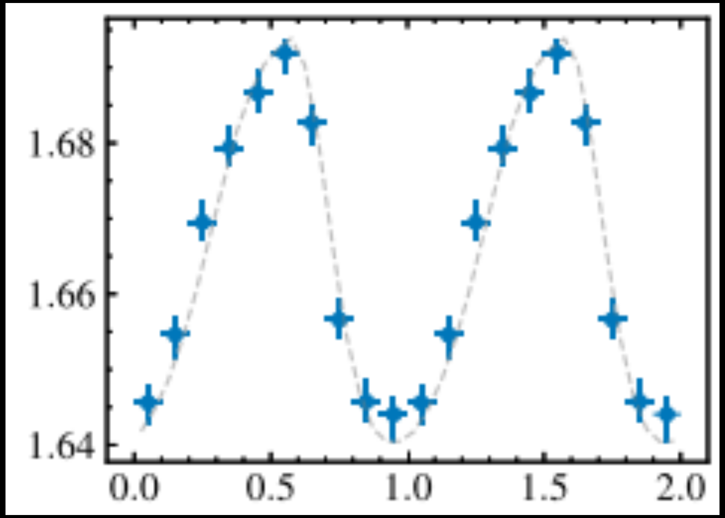
Emrah Kalemci et al. (2022)



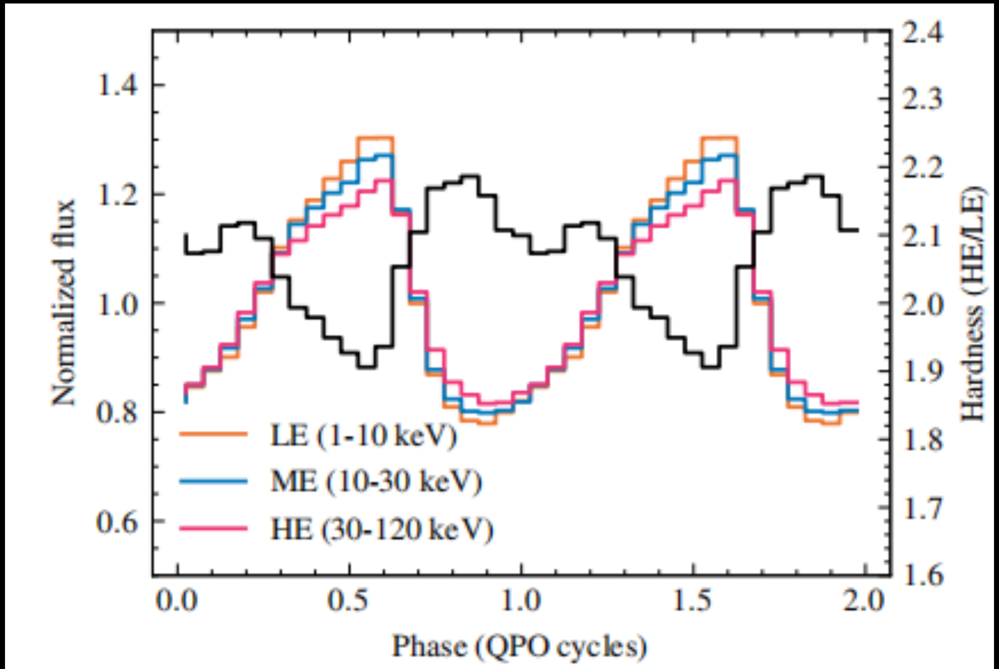
Since the reflection fraction (R_f) is tied to the intrinsic accretion geometry, the observed modulation of R_f provides strong support for the geometric origin of the QPO, e.g. the jet precession model (see Ma et al. 2021, 2023).

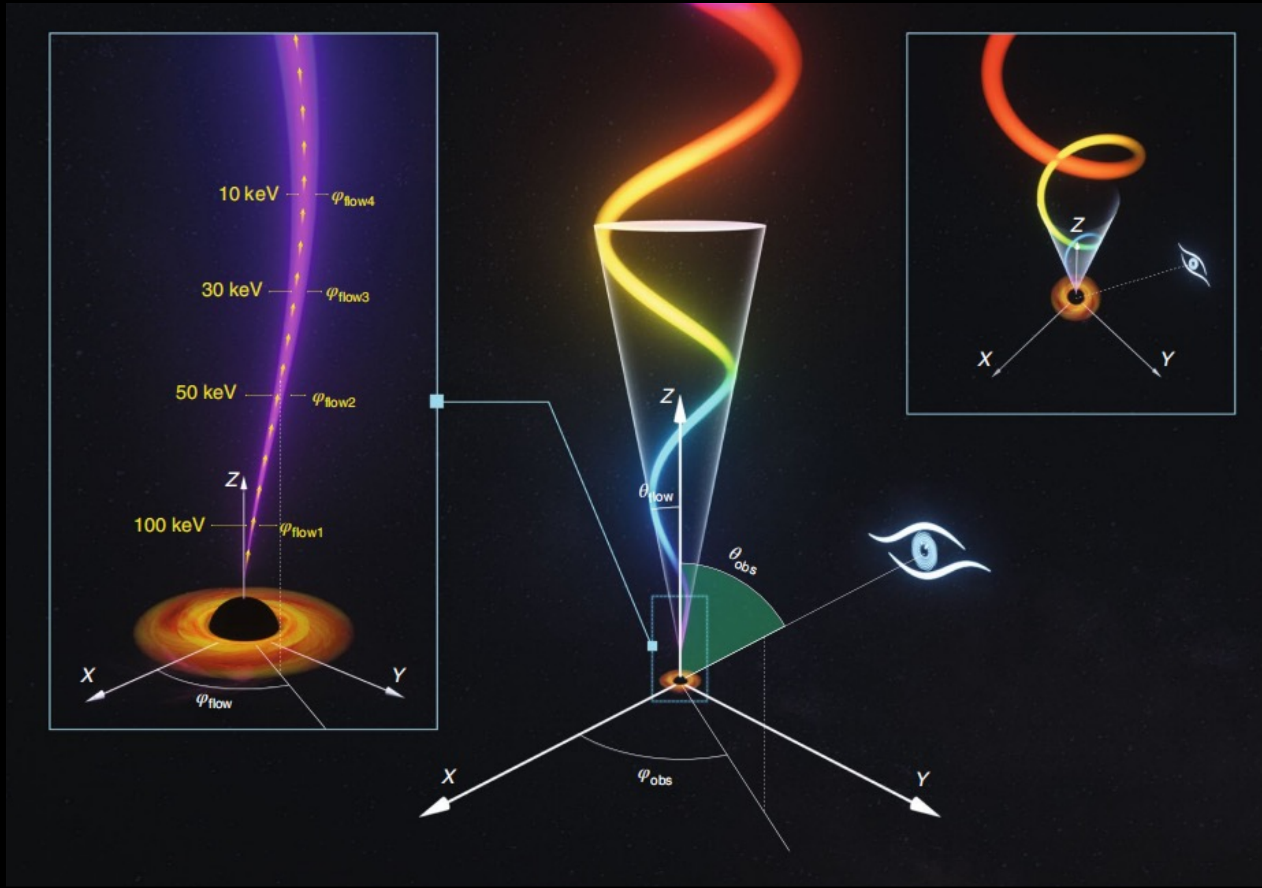
Phase-resolve Analysis of QPOs

Gamma



Phase (QPO Cycles)





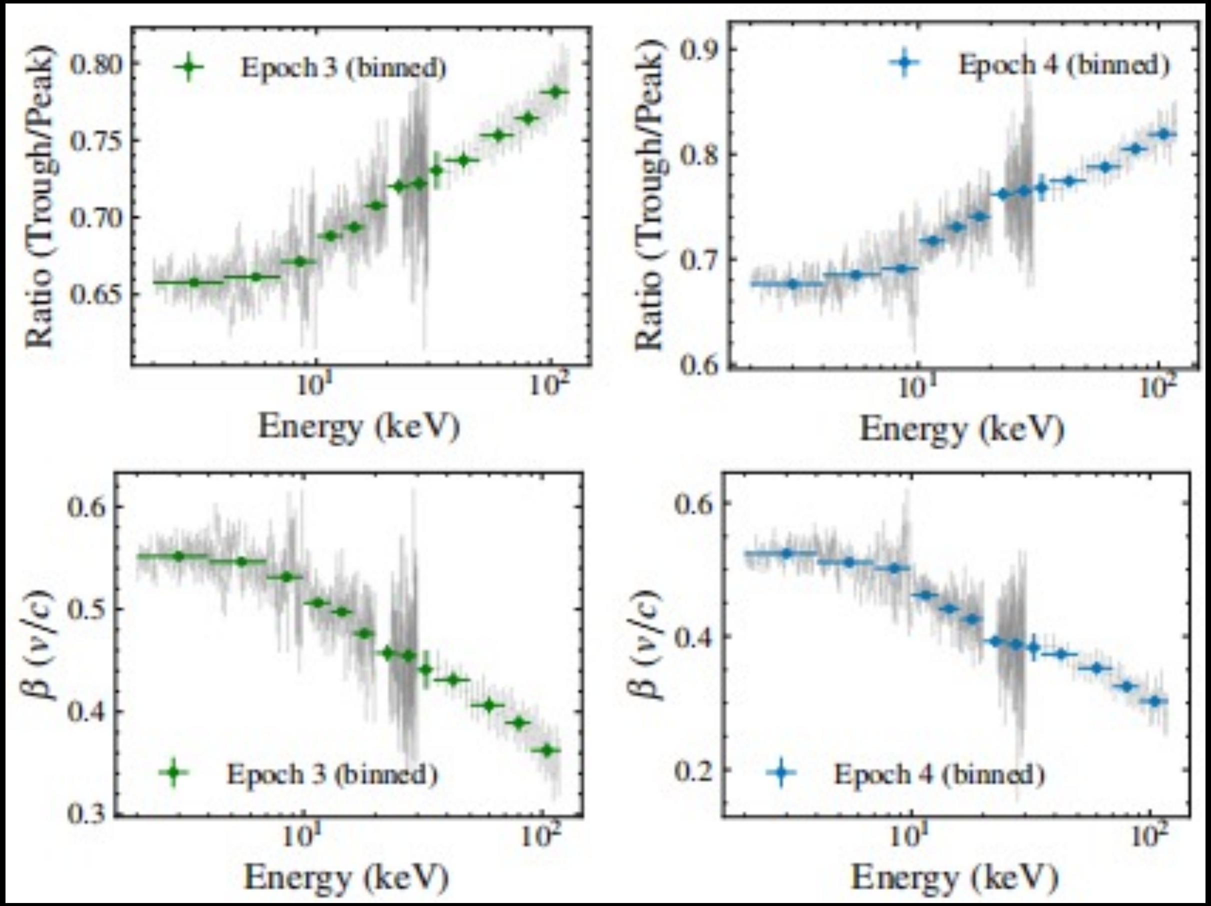
Ma et al. 2021

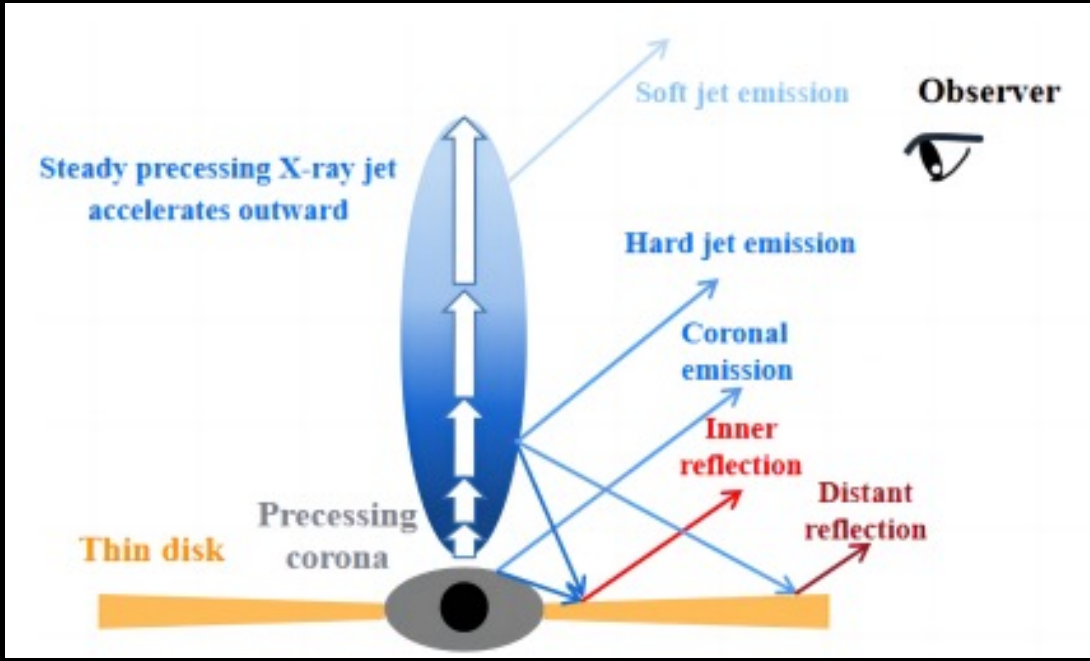
Phase-resolve Analysis of QPOs

$$F_{\text{obs}} = F_{\text{int}} D^{\Gamma+2}, \text{ where } D = \frac{(1-\beta^2)^{1/2}}{1-\beta\cos\theta}$$

$$\beta(E) = \left[R^{1/(\Gamma+2)} - 1\right] \cdot \left[R^{1/(\Gamma+2)} \cos\theta_t - \cos\theta_p\right]^{-1}, \text{ where } R = F_t/F_p$$

The obtained **anti-correlation between β and the energy** indicates that as the **jet material is ejected away from the black hole, the speed of the jet material increases.**





Summary

- We utilize the Hilbert-Huang transform to perform the phase-resolved analysis of LFQPOs in MAXI J1820+070.
- The phase-resolved analysis reveals strong concurrent modulations of the spectral index and flux across the bright hard state.
- Significant modulations in the reflection fraction are also detected but exclusively during the later stages of the bright hard state.
- The modulation of the reflection fraction provide a support for the geometric origin of LFQPOs.
- The modulation of the spectral index could potentially be explained by the jet precession model, with requiring the efficient acceleration within the jet.

Thank you!