Spectral–Timing Insights into Millisecond Variability in 4U 1728–34 from AstroSat

Kewal Anand

Fellowship for Academic and Research Excellence (FARE) Fellow

Indian Institute of Technology Kanpur, India

08 September 2026

Collaborators:

Ranjeev Misra (IUCAA)

J. S. Yadav (IIT Kanpur; ex- TIFR)

Pankaj Jain (IIT Kanpur)

Umang Kumar (Ashoka University)

Dipankar Bhattacharya (Ashoka University; ex-IUCAA)

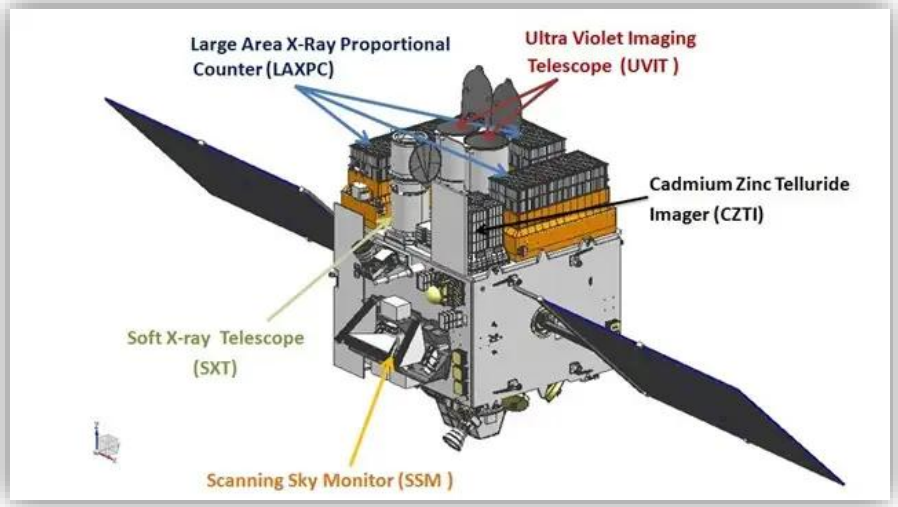
Introduction

Source 4U 1728-34:

- NS-LMXB of atoll type
- Mass of the NS ~ 1.2-1.6 $M_\odot$ (Shaposhnikov et al. 2003)
- Distance ~ 4.4 - 5.2 kpc (Di Salvo et al. 2000; Galloway et al. 2003)
- $N_H = 2.4 - 4.5 \times 10^{22}$ cm^{-2} (Egron et al. 2011; Wang et al. 2019)
- kHz QPOs at ~ 700 and 1000 Hz from RXTE (Strohmayer et al. 1996)
- kHz QPO at ~ 800 Hz from AstroSat (Chauhan et al. 2017)
- Spin frequency 363 Hz (Strohmayer et al. 1996; Chauhan et al. 2017)

Instruments Used:

- LAXPC; 3-80 keV; 10 μs; 6000 cm^2
- SXT; 0.3-8 keV; ~2.4 s; ; 90 cm^2 at 1.5 keV



4U 1728-34: QPO Triplet Detection

AstroSat observed 4U 1728-34 from 7-8 March 2016 (Obs. ID: 9000000362).

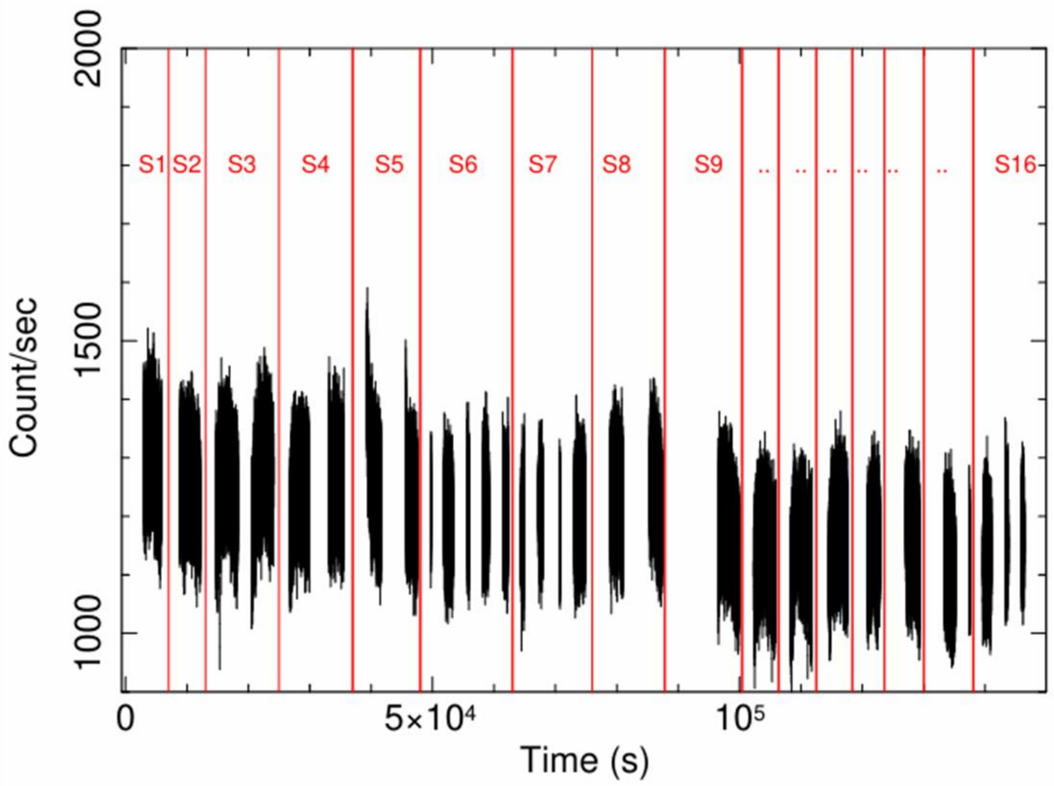


Figure: 3-30 keV LAXPC light curve of 4U 1728-34

FFT

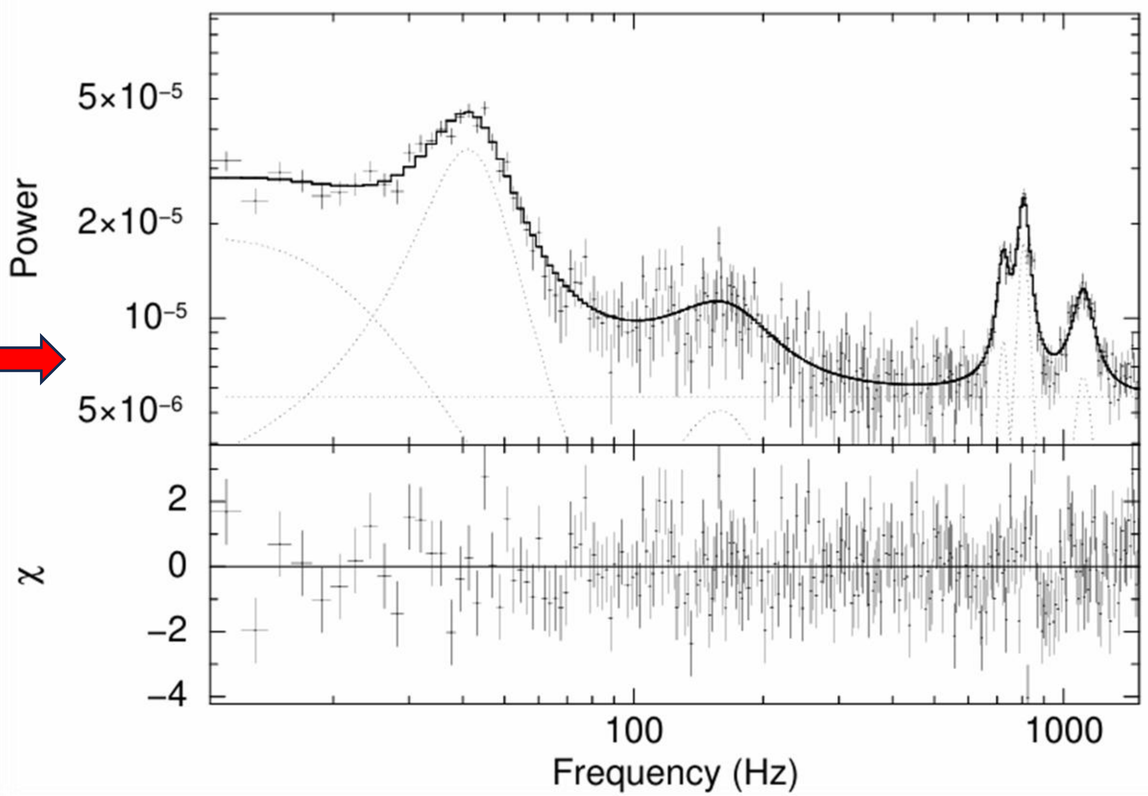
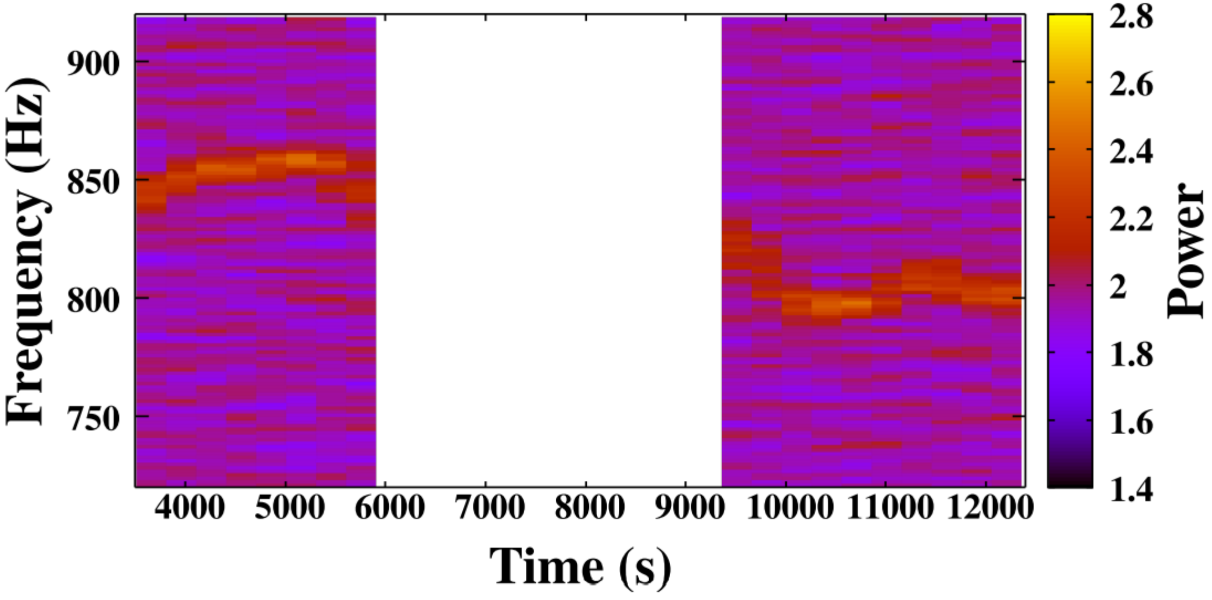
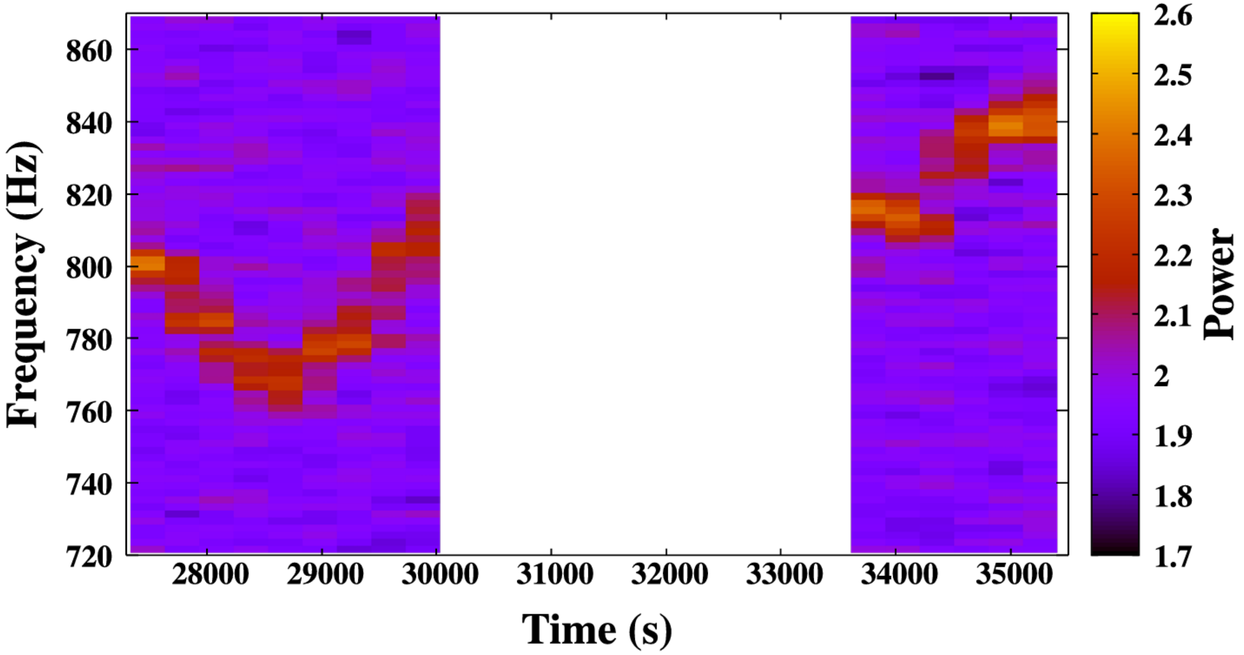


Figure: PDS shows QPOs at ~ 40 Hz (Q = 1.96), ~ 800 Hz (Q = 14), and ~ 1100 (Q = 7) along with a broad feature at ~ 150 Hz.

Ref: K. Anand, R. Misra et al., ApJ, 967(2),129, 2024

4U 1728-34: Drifting kHz QPO





4U 1728-34: QPO Triplet Detection

The orbital frequency (ν_ϕ) of a particle moving around a KBH can be written as [SVM99]

$$\nu_\phi = \pm M^{1/2} r^{-3/2} \left[2\pi (1 \pm \tilde{a} M^{1/2} r^{-3/2}) \right]^{-1} . \tag{1}$$

Now, if the particle is perturbed by an external agent giving it the slight momenta along θ and r. [OKF87, Kat90]

$$\nu_r^2 = \nu_\phi^2 \left(1 - 6Mr^{-1} \pm 8\tilde{a} M^{1/2} r^{-3/2} - 3\tilde{a}^2 r^{-2} \right) , \tag{2a}$$

$$\nu_\theta^2 = \nu_\phi^2 \left(1 \mp 4\tilde{a} M^2 r^{-3/2} + 3\tilde{a}^2 r^{-2} \right) . \tag{2b}$$

$$\tilde{a} = \frac{J}{M} = 2\pi \nu_s \frac{I}{M}$$

$$\nu_s = 363 \text{ Hz}$$

Ref: Bardeen et al. 1972; Okazaki et al. 1987; Kato 1990

$$\nu_{\rm per} = \nu_\phi \left[1 - \sqrt{1 - \frac{6GM}{c^2 r} \pm \frac{16\pi \nu_s (GM)^{1/2}}{c^2 r^{3/2}} \left(\frac{I}{M} \right) - \frac{12\pi^2 \nu_s^2}{r^2 c^2} \left(\frac{I}{M} \right)^2 } \right] \tag{5}$$

$$\nu_{\rm nod} = \nu_\phi \left[1 - \sqrt{1 \mp \frac{8\pi \nu_s (GM)^{1/2}}{c^2 r^{3/2}} \left(\frac{I}{M} \right) + \frac{12\pi^2 \nu_s^2}{r^2 c^2} \left(\frac{I}{M} \right)^2 } \right] . \tag{6}$$

$\nu_{per} = \nu_\phi - \nu_r$ $\quad$ $\nu_{nod} = \nu_\phi - \nu_\theta$

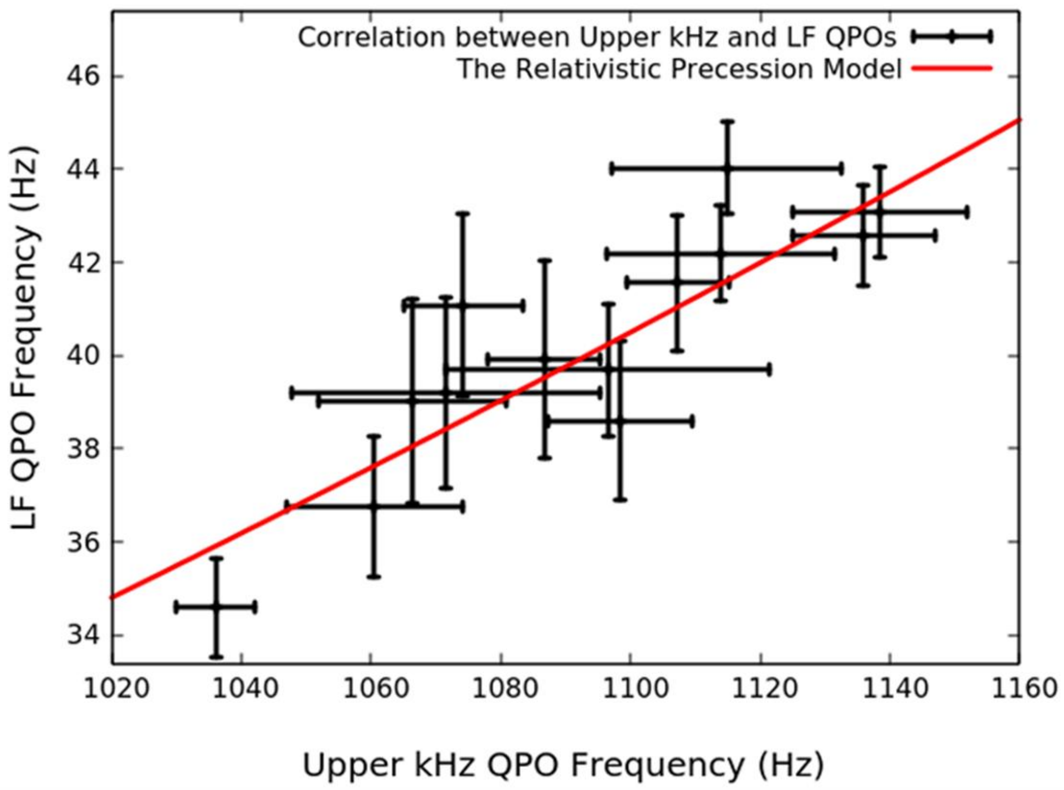
The RPM (Ref: Stella et al. (1999))

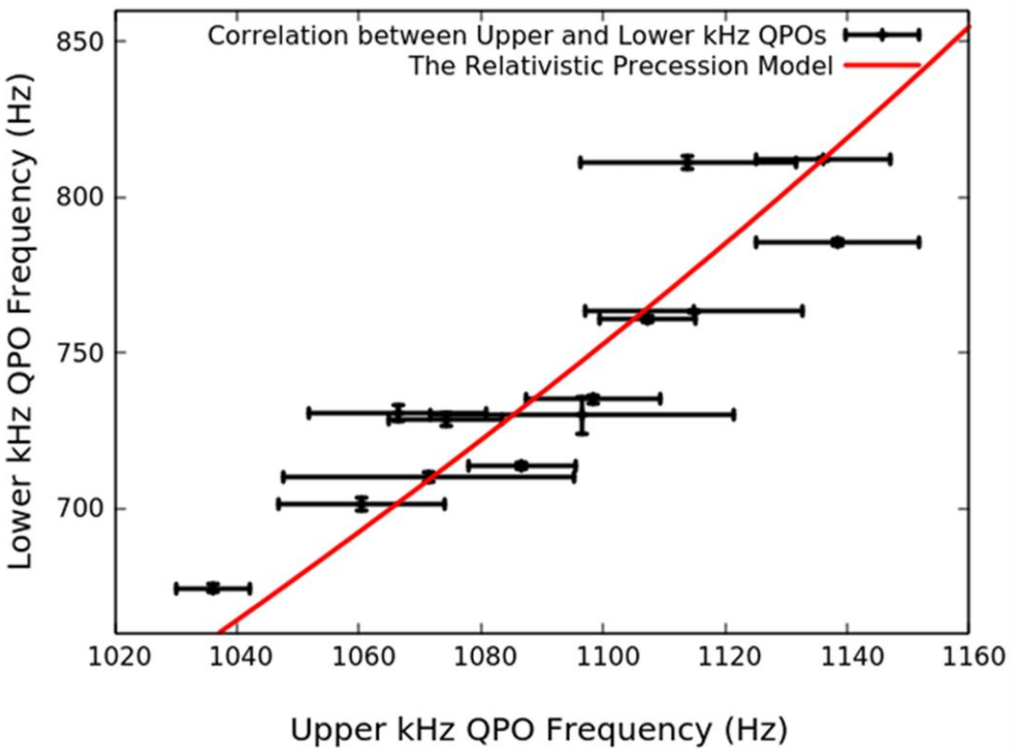
Orbital motion $\rightarrow$ **Upper kHz QPO**

Periastron precession $\rightarrow$ **Lower kHz QPO**

Nodal precession $\rightarrow$ **LF QPO**

4U 1728-34: QPO Triplet Detection

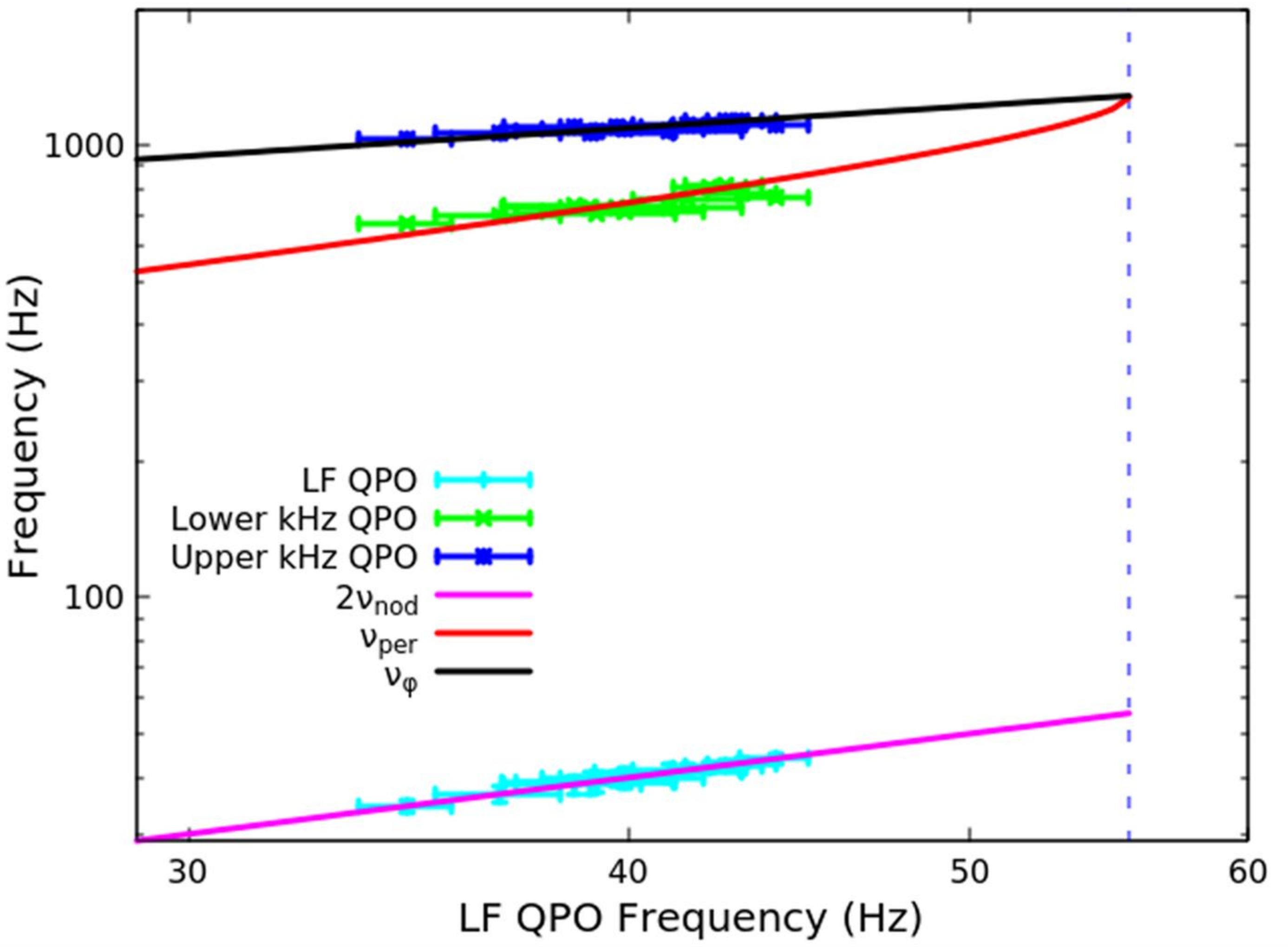




Ref: K. Anand, R. Misra et al., ApJ, 967(2),129, 2024

4U 1728-34: QPO Triplet Detection

- Using RPM, we get $\mathbf{M^*_\odot = 1.92 \pm 0.01}$ and $\mathbf{I_{45}/M^*_\odot = 1.07 \pm 0.01}$.
- The estimated neutron star parameters favors stiffer Equations of State.

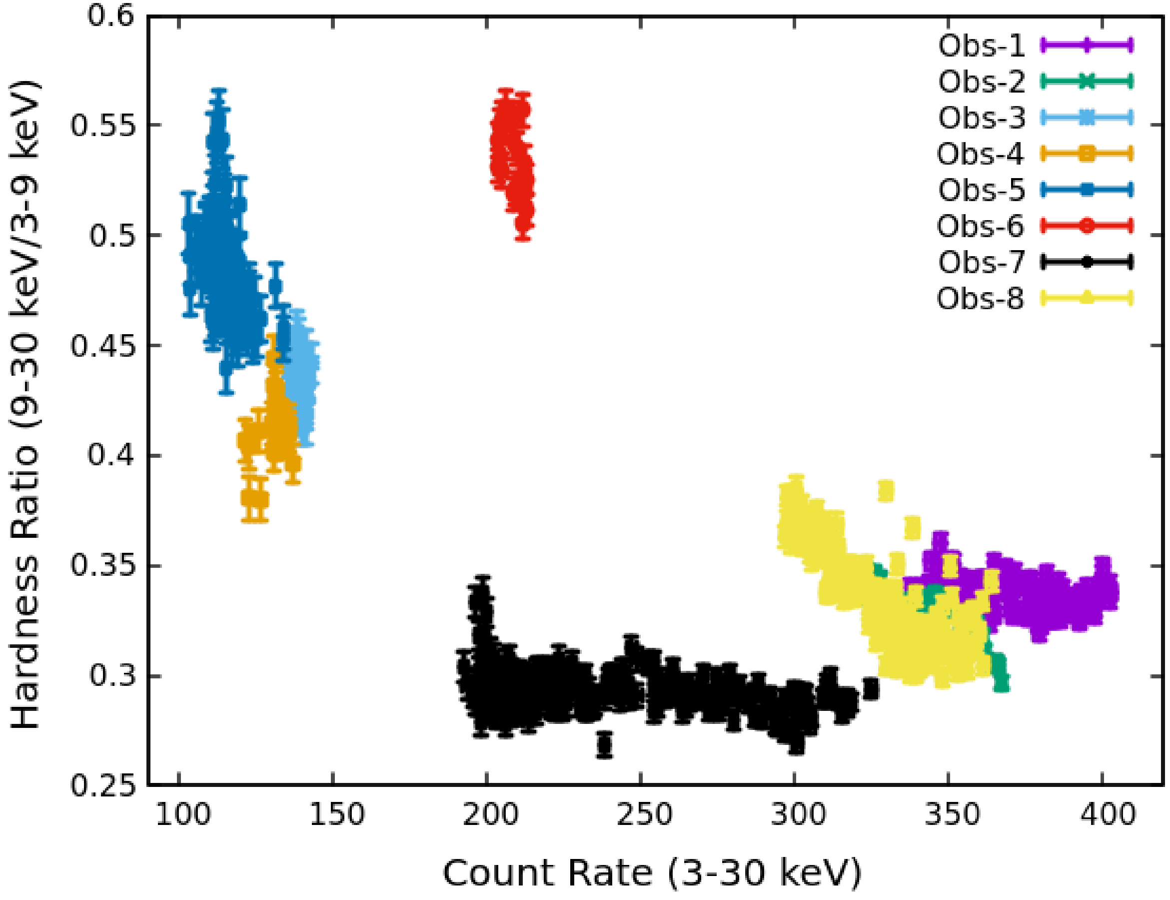


Ref: K. Anand, R. Misra et al., ApJ, 967(2),129, 2024

All AstroSat Observations of 4U 1728-34 from 2016-2019

The detail of all the AstroSat observations of 4U 1728-34 used in this work.

Obs-#	Obs. ID	Obs. Start Date (YYYY-MM-DD)	Exp. Time (ks) LAXPC	Exp. Time (ks) SXT
Obs-1	9000000362	2016-03-07	56.1	18.0
Obs-2	9000000578	2016-08-05	19.3	9.79
Obs-3	9000001904	2018-02-19	7.64	2.93
Obs-4	9000002234	2018-07-17	10.2	7.59
Obs-5	9000002254	2018-07-25	38.6	0
Obs-6	9000002268	2018-08-01	7.45	2.00
Obs-7	9000002890	2019-05-04	84.1	0
Obs-8	9000003134	2019-08-29	81.1	35.3



Ref: K. Anand, R. Misra et al., ApJ, 1001(2), 223, 2026

All AstroSat Observations of 4U 1728-34 from 2016-2019

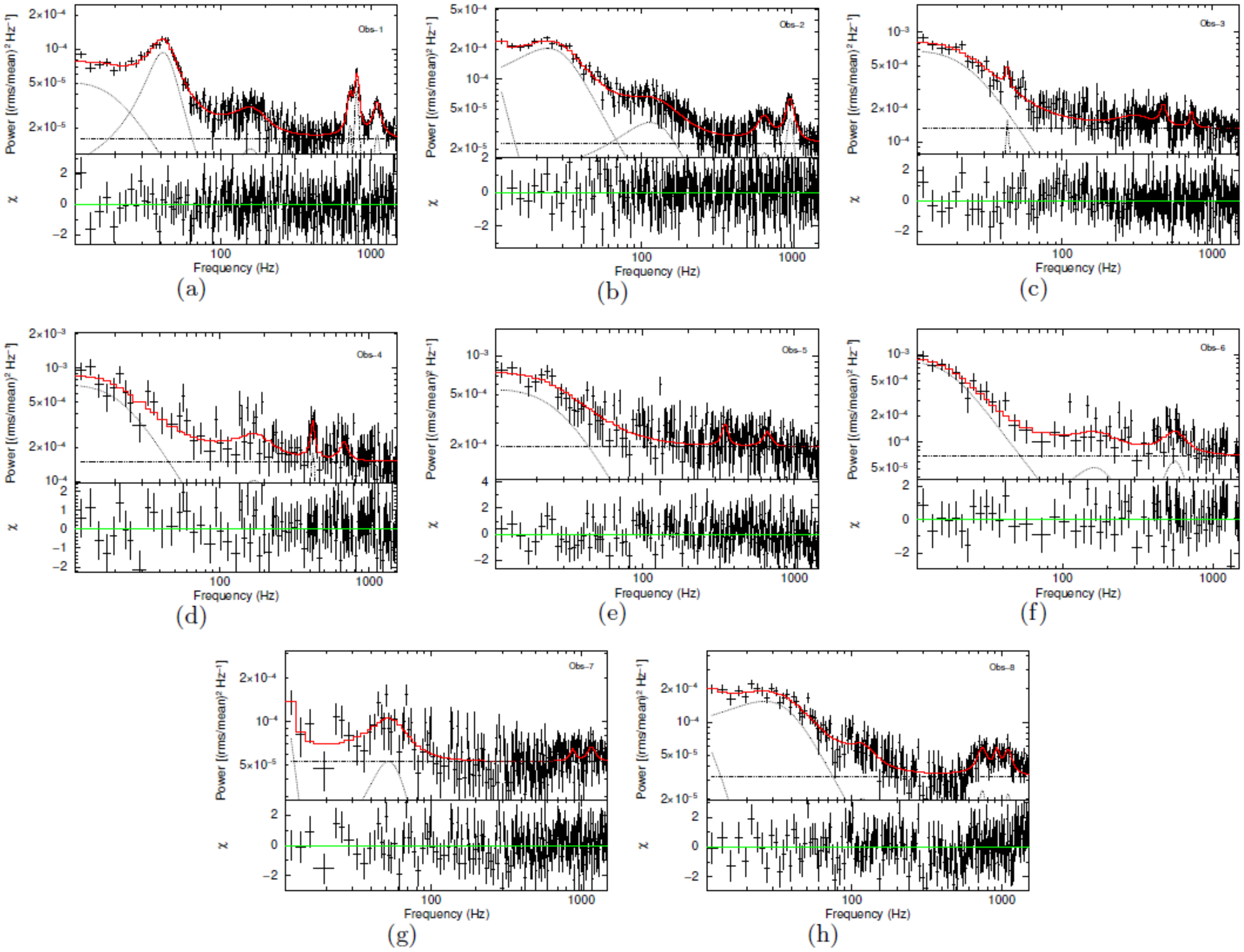
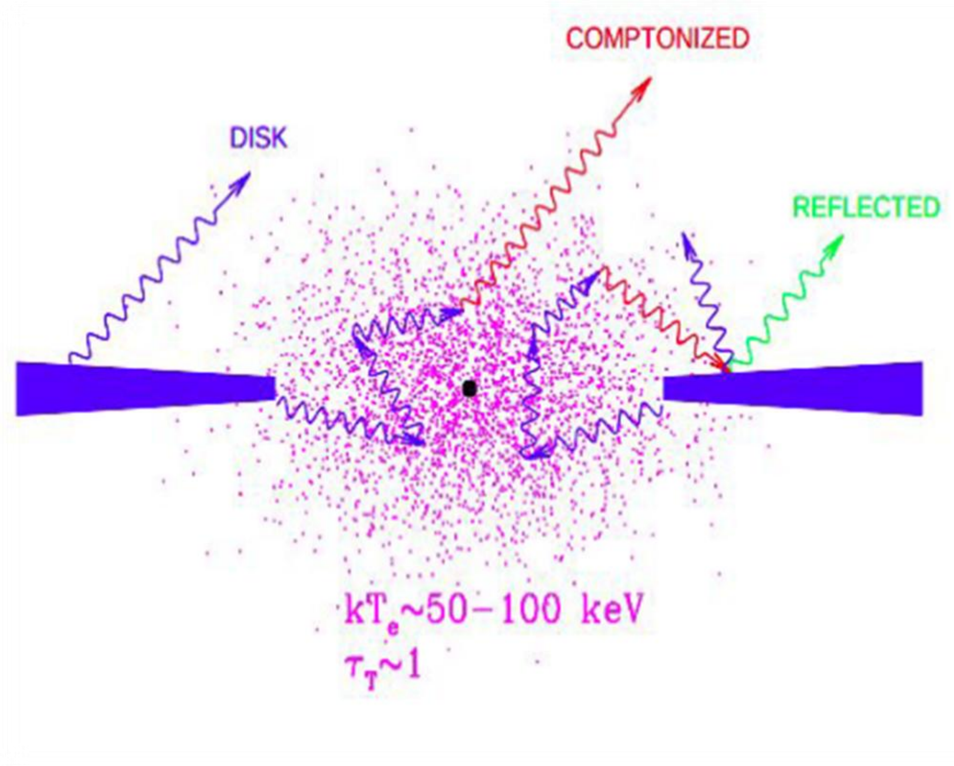
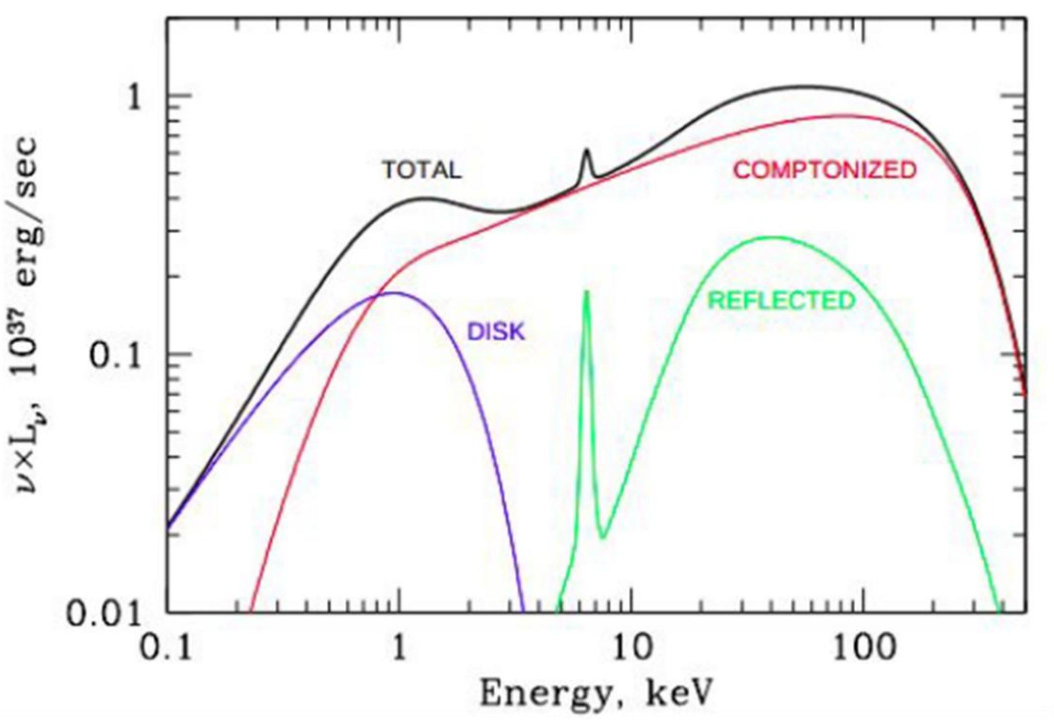


Figure: The 3-30 keV PDS of all eight individual observations. **Ref: K. Anand, R. Misra et al., ApJ, 1001(2), 223, 2026**

Energy Spectra:

A typical energy spectrum of an XRB

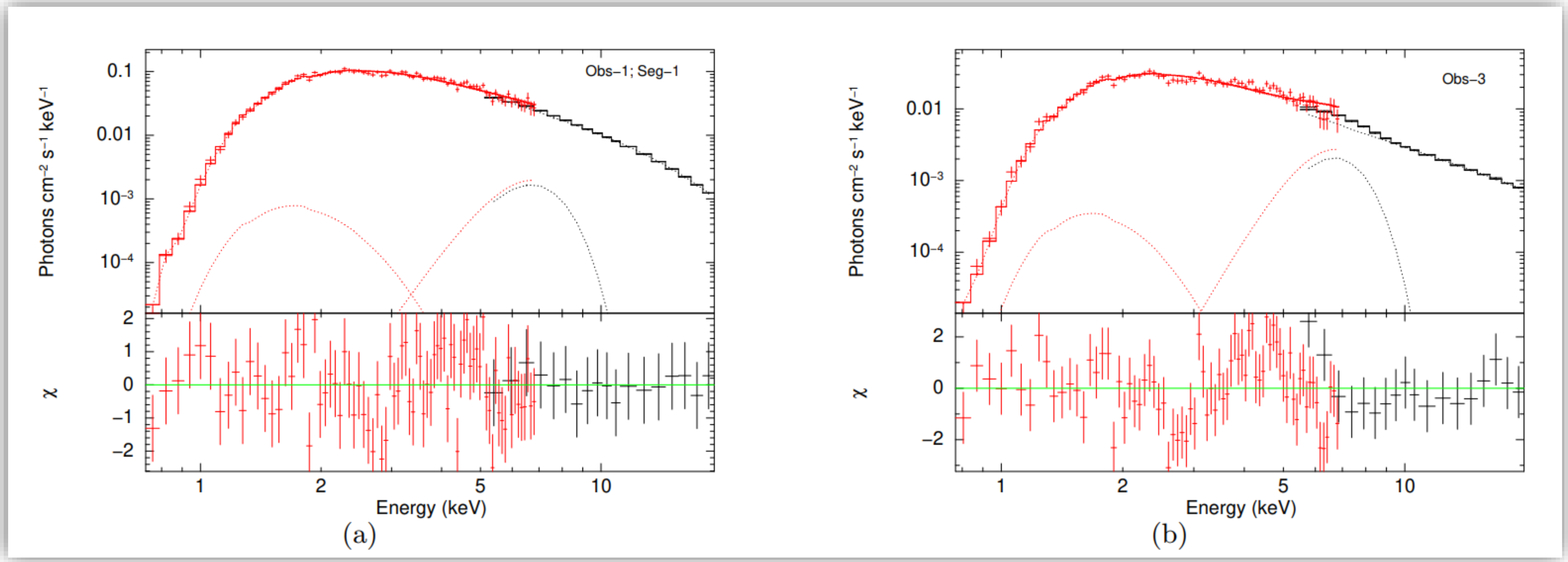




Ref: Gilfanov M., 2010, LNP, 17

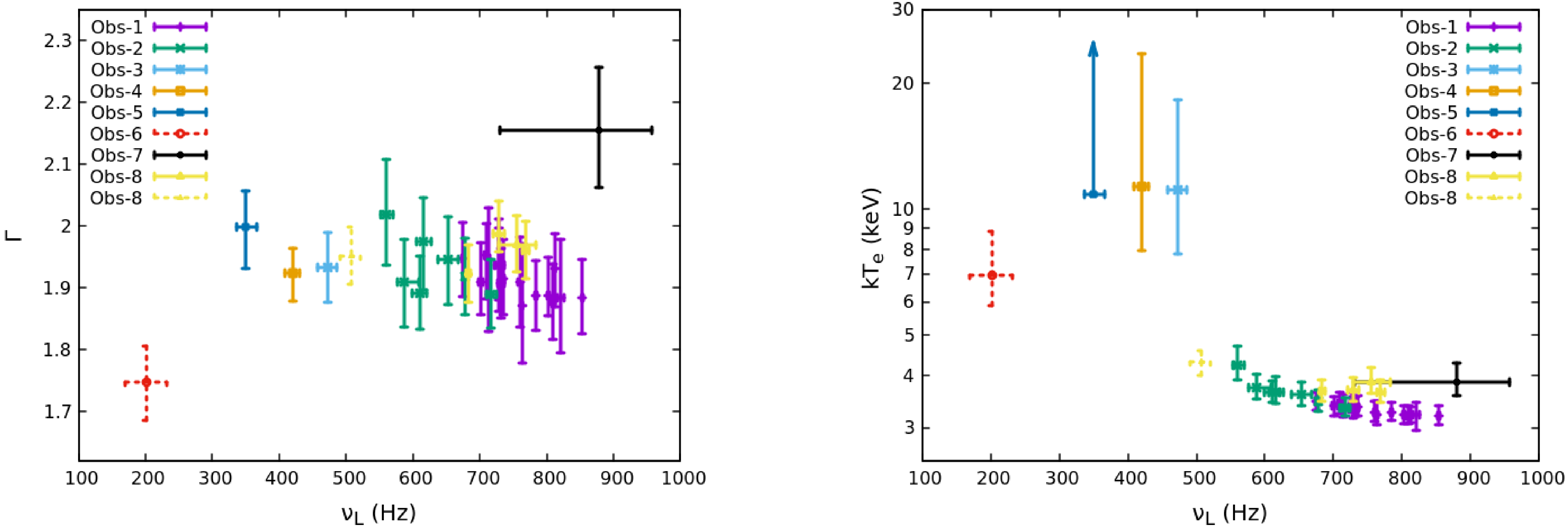
Energy Spectra

Model: constant*tbabs*(thcomp*diskbb + bbodyrad + gaussian); Energy Ranges: SXT (0.7-7.0 keV) and LAXPC20 (5.0-20.0 keV).



Ref: K. Anand, R. Misra et al., ApJ, 1001(2), 223, 2026

QPO Correlations with Spectral Parameters

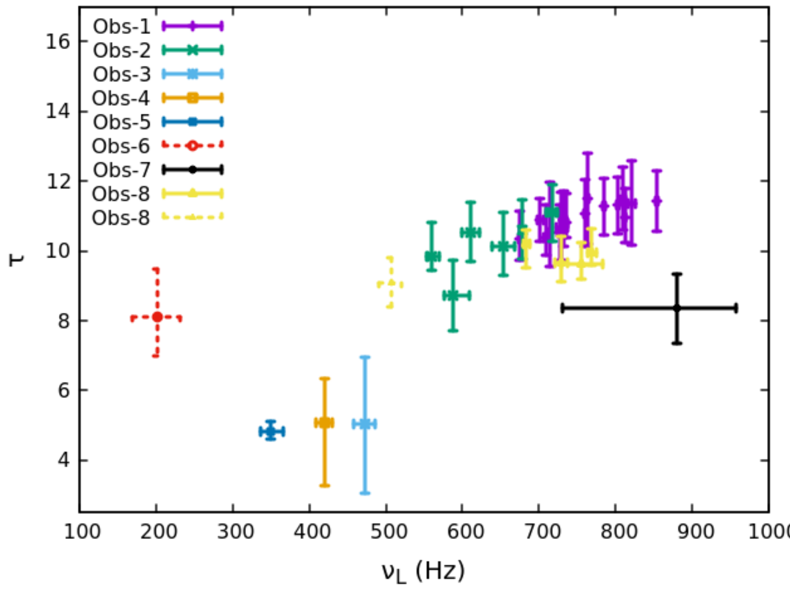


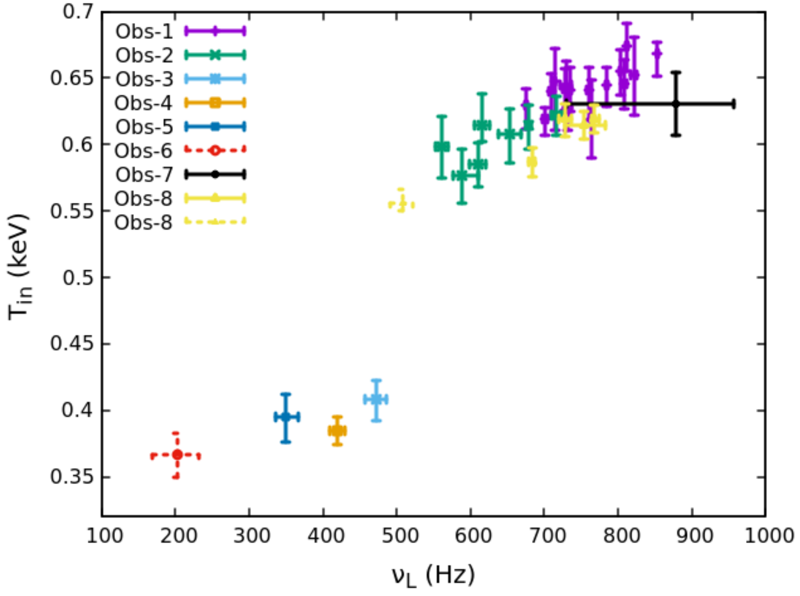
Γ ——→ spectral index

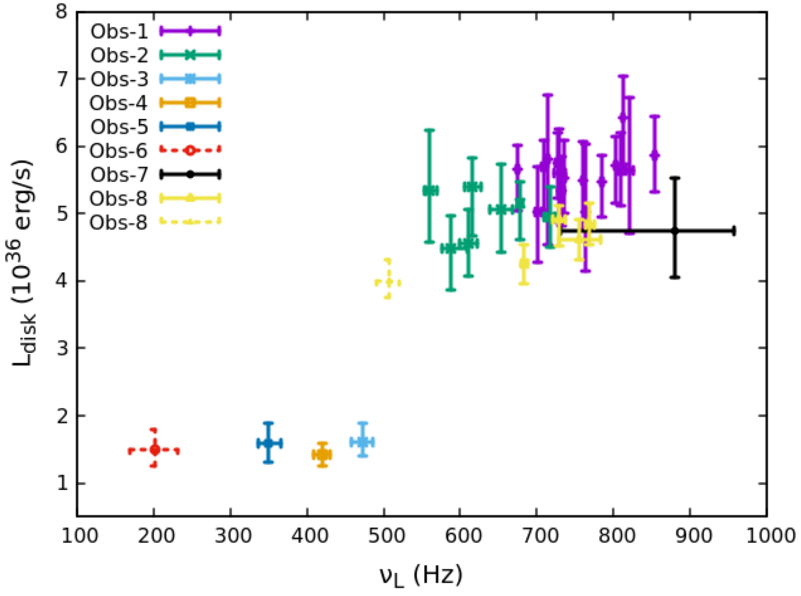
kT_e ——→ electron temperature of the corona

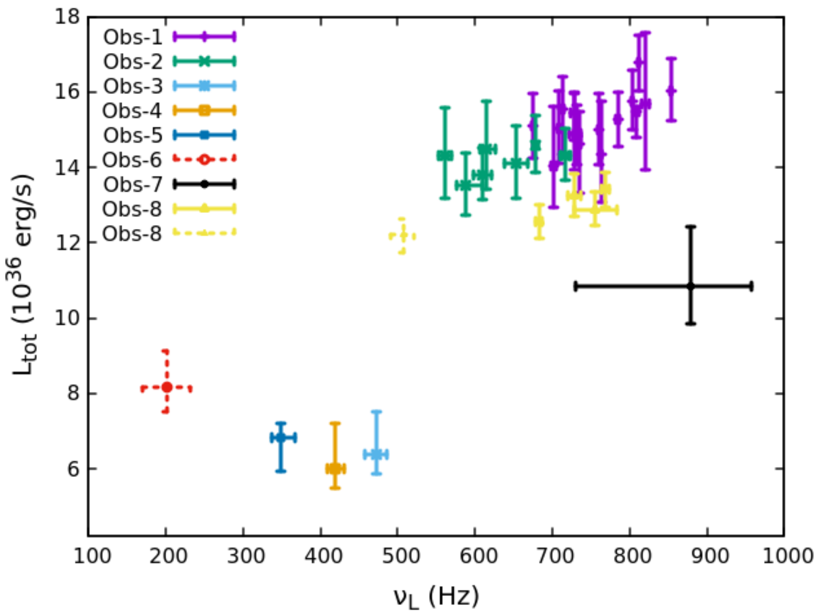
Ref: K. Anand, R. Misra et al., ApJ, 1001(2), 223, 2026

QPO Correlations with Spectral Parameters









τ ‒‒‒→ optical depth of the corona

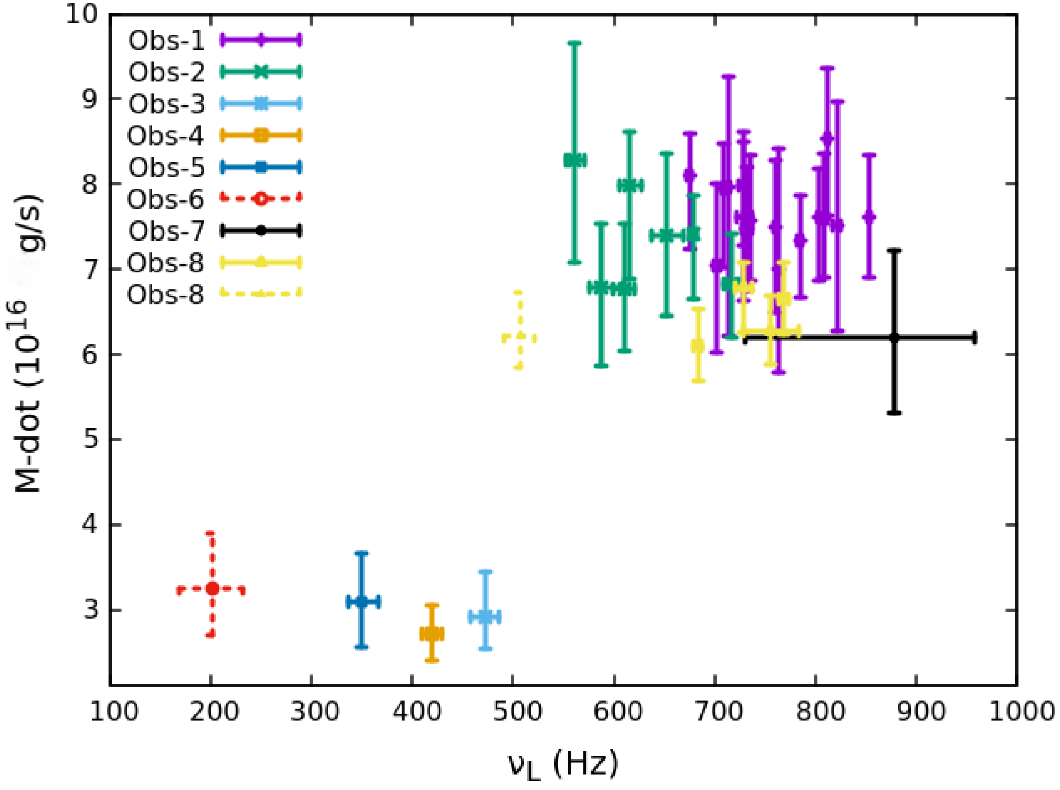
kT_{in} ‒‒‒→ inner disk temperature

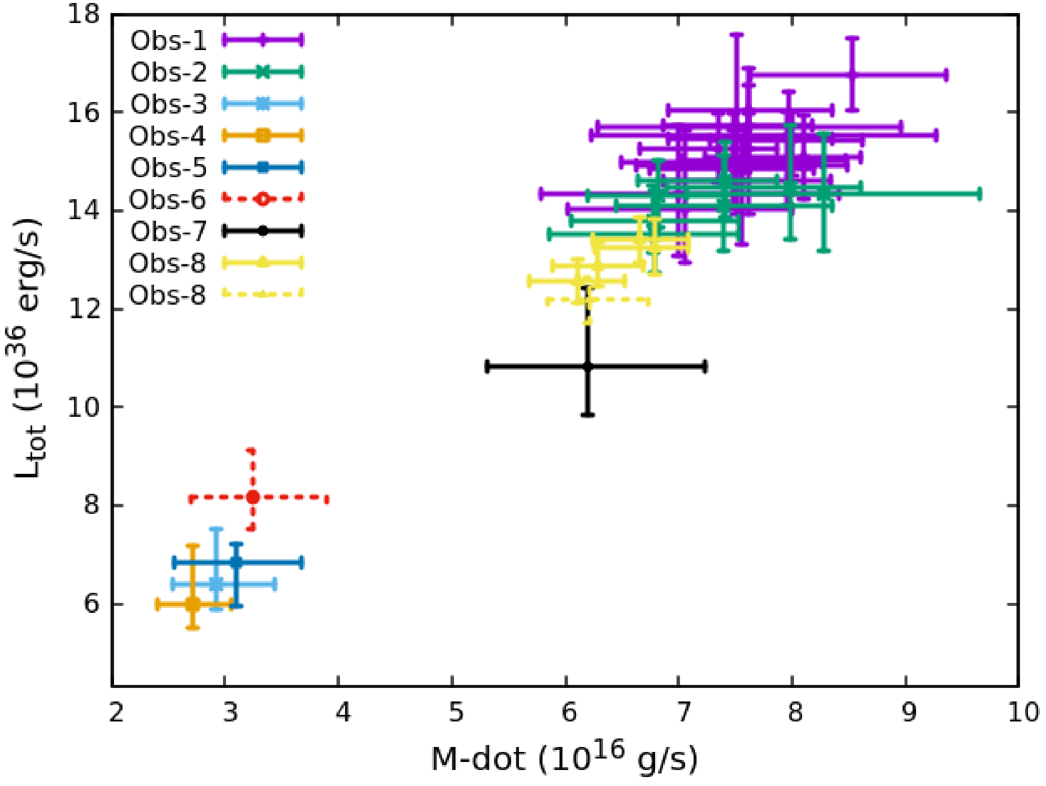
L_{disk} ‒‒‒→ disk luminosity

L_{tot} ‒‒‒→ total luminosity

Ref: K. Anand, R. Misra et al., ApJ, 1001(2), 223, 2026

QPO Correlations with Spectral Parameters





M-dot ——→ accretion rate

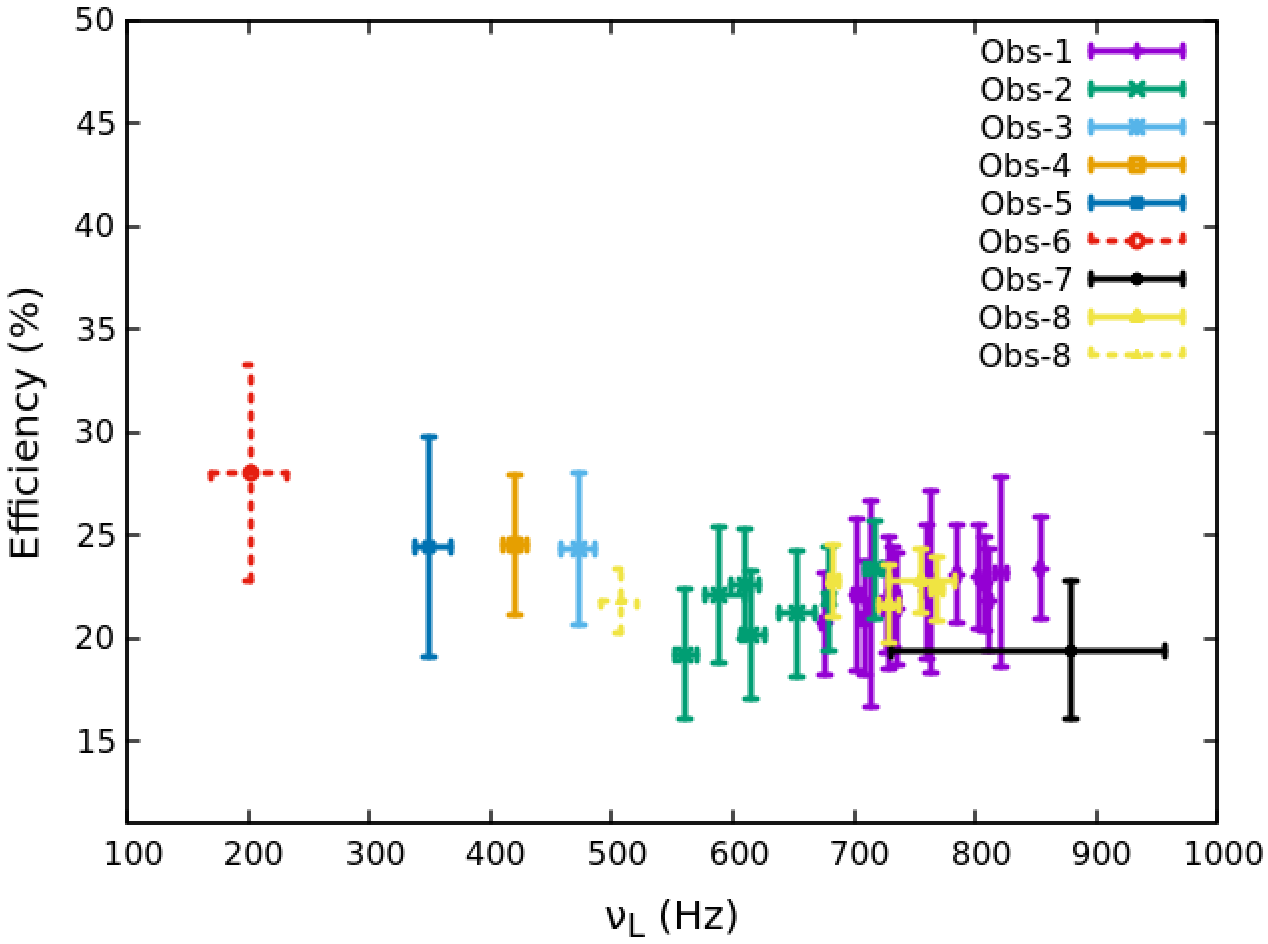
There exists a critical QPO frequency at ~ 500 Hz.

Ref: K. Anand, R. Misra et al., ApJ, 1001(2), 223, 2026

QPO Correlations with Spectral Parameters

$$\eta = \frac{L_{tot}}{\dot{M}c^2}$$

- We found that the radiative efficiency is constant at ~22 % and does not depend upon the source's spectral state.



Ref: K. Anand, R. Misra et al., ApJ, 1001(2), 223, 2026

Summary

- For the very first time, AstroSat/LAXPC detects multiple sets of QPO triplets (time-varying) from a single observation.
- Using RPM, we get well-constrained mass and moment of inertia to be $\mathbf{M}_{\odot}^{*} = \mathbf{1.92 \pm 0.01}$ and $\mathbf{I_{45}/M_{\odot}^{*} = 1.07 \pm 0.01}$, **respectively**, which favour stiffer EOS.

- We detect kHz QPO(s) in all AstroSat observations of 4U 1728-34 from 2016-2019.
- Using LAXPC and SXT, we find that the lower kHz QPO frequency shows correlations with the spectral parameters.
- We find that there exists a critical QPO frequency, below and above which the source has two distinct spectral states.
- The accretion efficiency remains constant at ~ 22 % and shows no dependence on the spectral state.

Thank you for your attention!

Acknowledgements: I thank LAXPC and SXT Payload Operation Centres, ISRO, AstroSat Science Support Cell, IUCAA, all my collaborators, and many others.

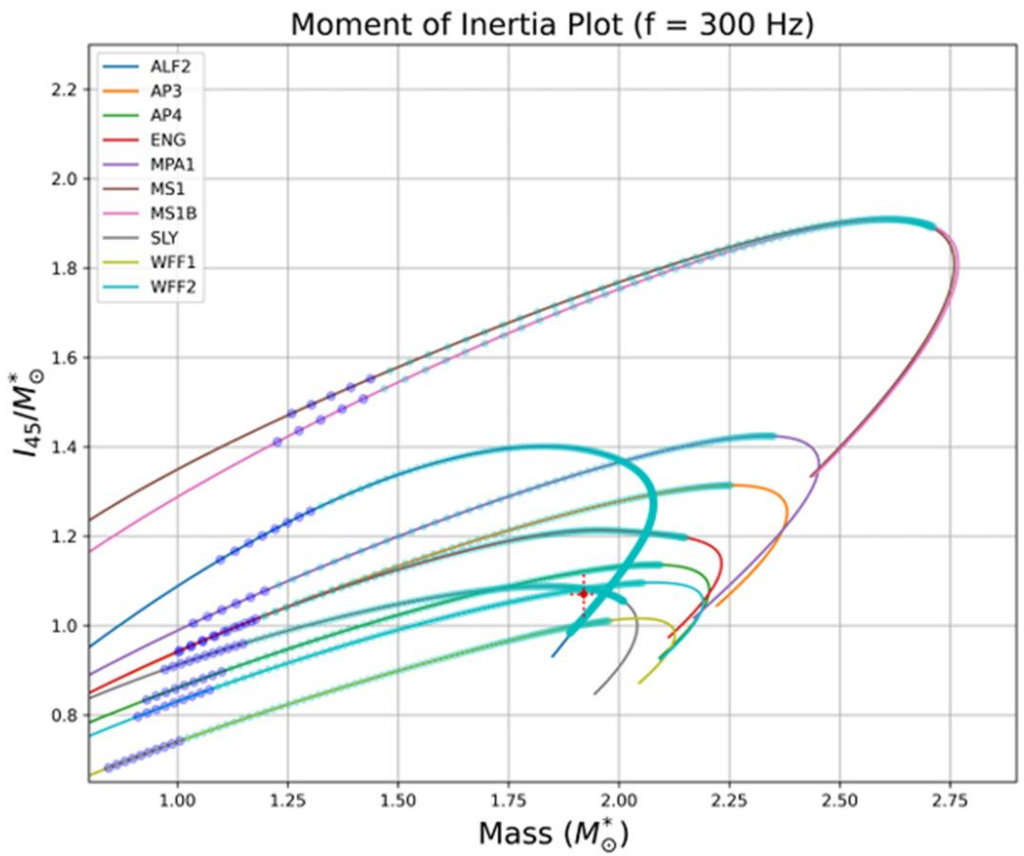
For any question and/or suggestion & comments, please feel free to reach out me at the email ID:

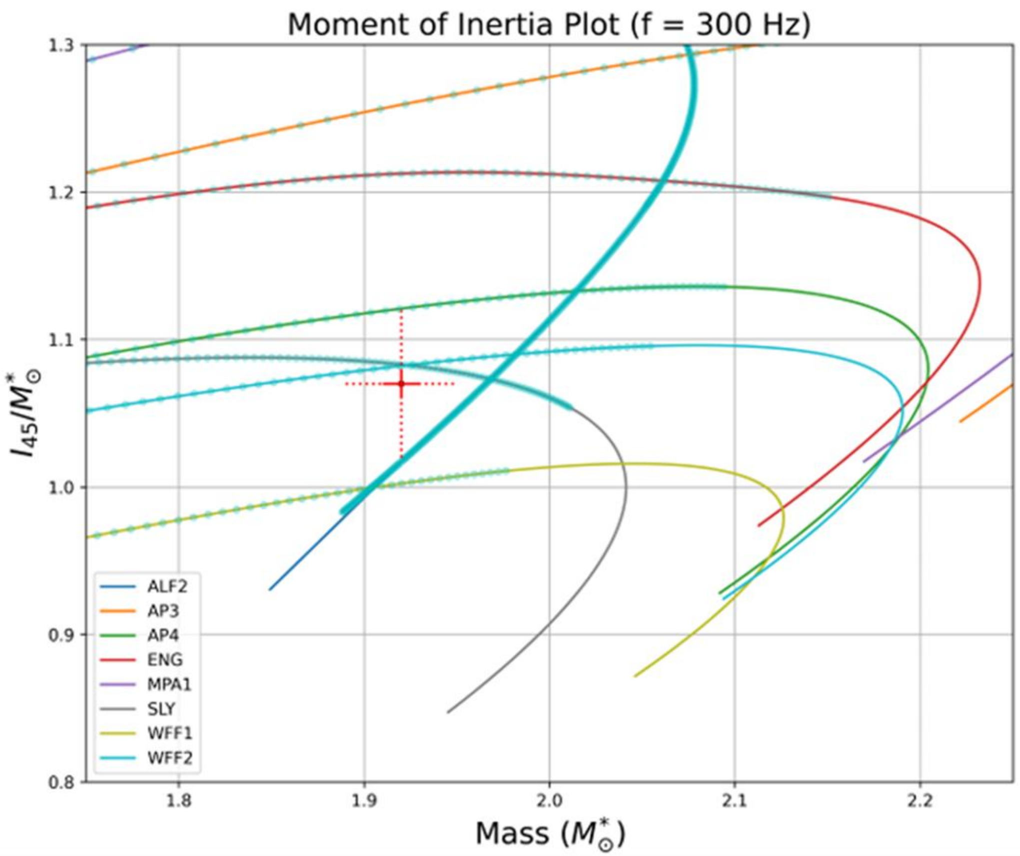
kanand@iitk.ac.in

Papar-1

Papar-2

Back-up Slide 1:





Ref: K. Anand, R. Misra et al., ApJ, 967(2),129, 2024

Back-up Slide 2:

$$I = \frac{J}{1 + \frac{2GJ}{R^3c^2}}; \quad J \equiv \frac{8}{3}\pi \int_0^R r^4\left(\rho(r) + \frac{P(r)}{c^2}\right)\alpha(r)dr,$$

$$\text{where } \alpha(r) = \left(1 - \frac{2GM(r)}{Rc^2}\right)^{-1}.$$

Ref: Ravenhall & Pethick 1994