An atypical X-ray variability component in the black-hole candidate AT2019wey

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A QPO can be weak in the power spectrum yet leave a strong, coherent fingerprint in the cross spectrum, phase lags, coherence function.

1. Background and Motivation: Why look beyond the power spectrum?

Quasi-periodic oscillations (QPOs) are usually identified in the power density spectrum (PDS). Recent joint fits of the PDS and cross spectrum (CS) revealed a hidden component, **during HIMS**, whose **imaginary CS amplitude exceeds the real part**. We call it 'imaginary QPO'. The imaginary QPO coincides with two striking timing signatures (e.g., MAXI J1820+070 (Méndez et al. 2024, Bellavita et al. 2025), Cygnus X–1 (König et al. 2024, Fogantini et al. 2025) and Swift J1727.8–1613 (Brigitte et al. 2025), MAXI J1348–630 (Alabarta et al.2025)):

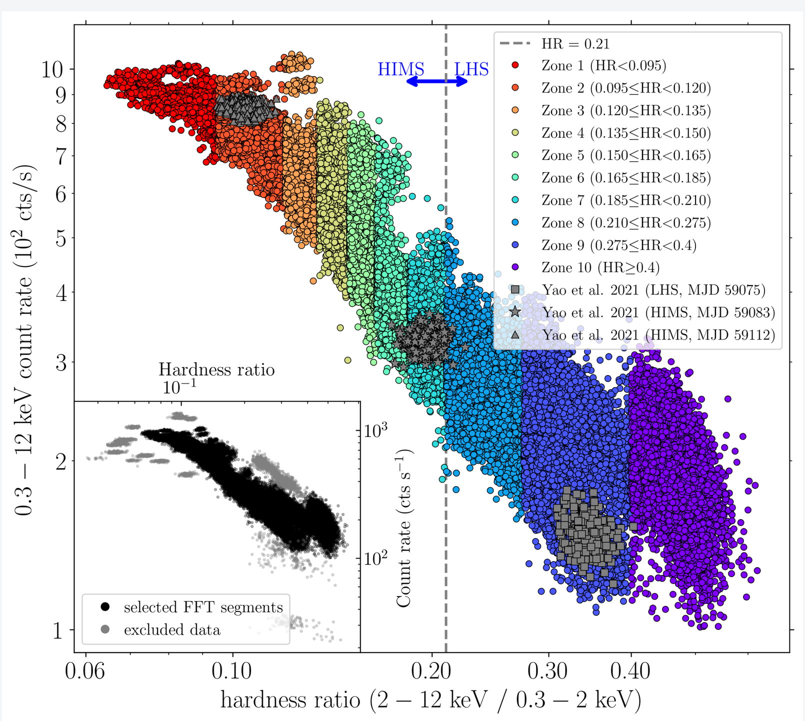
- a sharp increase in phase-lags **('cliff')**;
- a narrow drop of coherence-function **('dip')**.

We explored whether AT2019wey hosts the same phenomenon.

2. Source and data

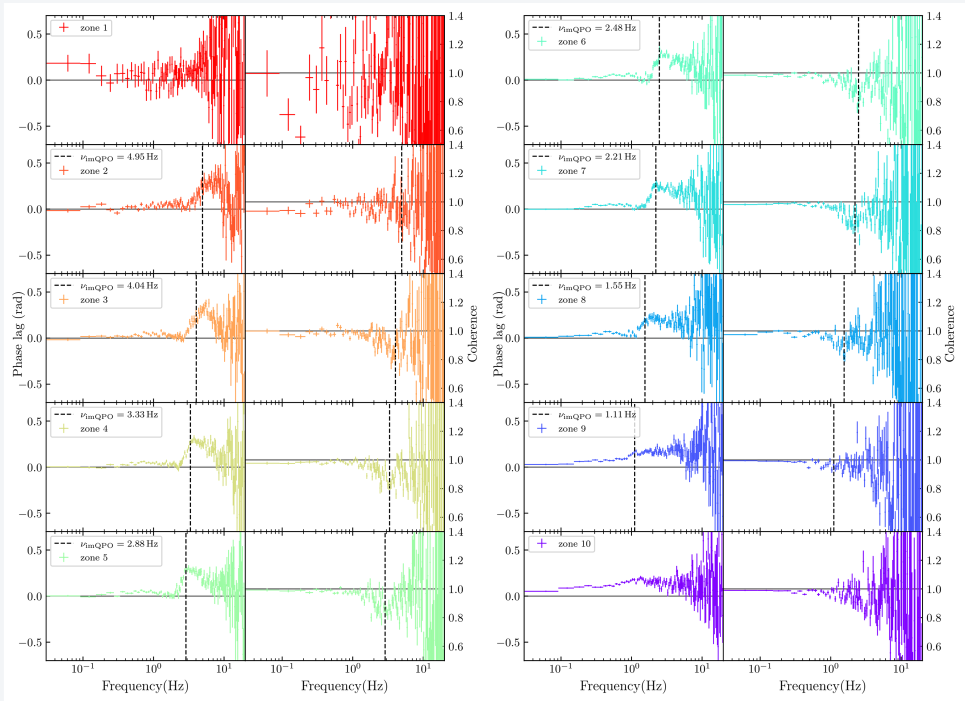
AT2019wey is a black-hole candidate discovered as an optical transient in 2019. NICER monitored it from 2020–2025, mainly in the hard intermediate state (HIMS) and low/hard state (LHS) (Yao et al. 2021).

- Reference band: 0.3–2 keV; subject band: 2–12 keV
- One point per 16.384-s segment; 0.5-ms time resolution
- Data grouped into ten hardness-ratio zones to improve S/N



Hardness–intensity evolution and the ten analysis zones.

3. Timing fingerprint across source states



Phase-lag cliffs (left) and coherence dips (right) across the hardness-selected zones. Dashed lines mark fitted QPO frequencies.

4. Methodology: Simultaneous Fitting of the PDS and CS

We simultaneously fitted the PDS in two energy bands and the rotated real and imaginary parts of the CS with a multi-Lorentzian model (Mendéz et al. 2024). Each variability component is coherent between energy bands but mutually incoherent with the other components. The fitted amplitudes and constant component phase lags predict the total phase-lag and intrinsic-coherence spectra.

PDS model:

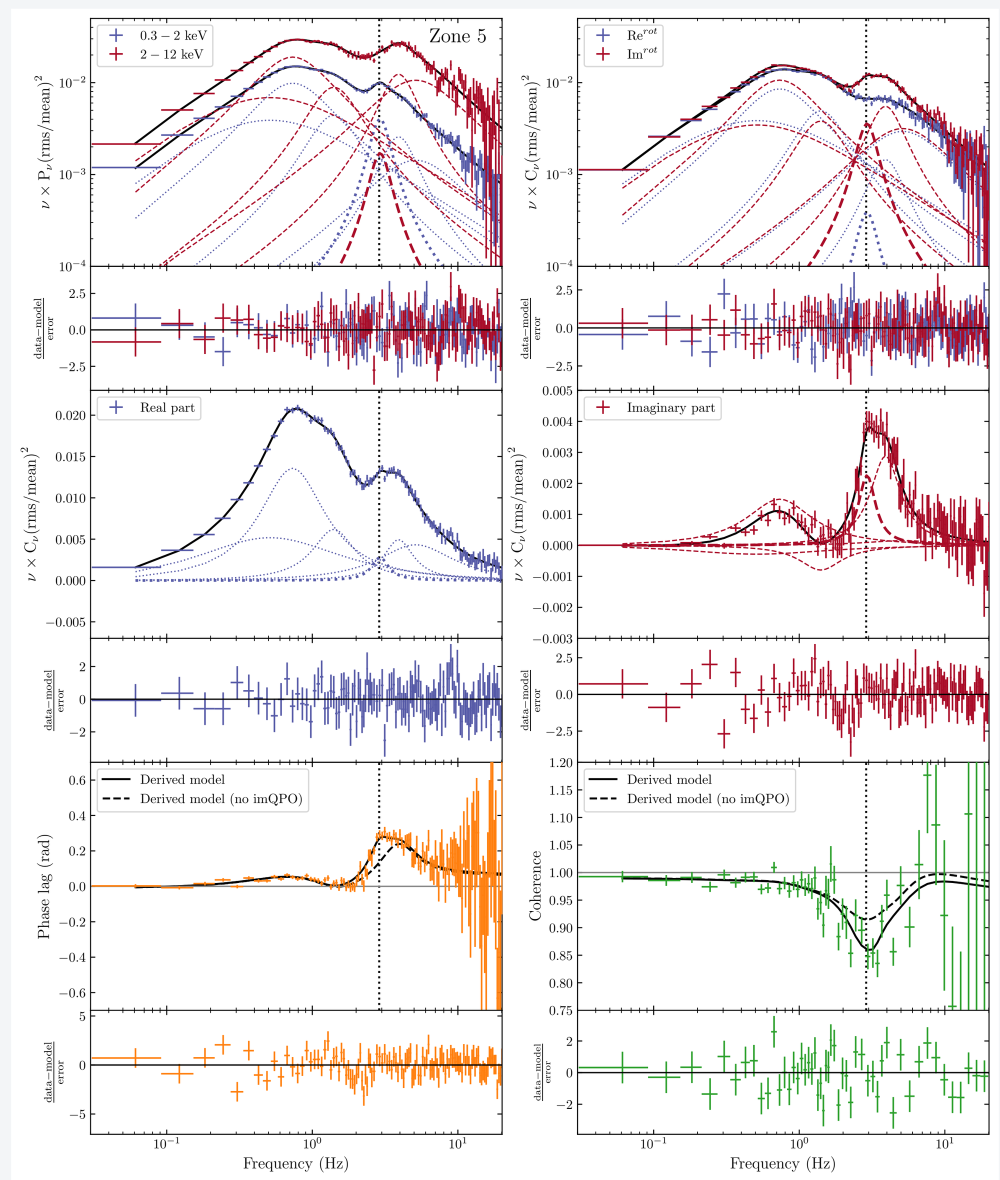
$$G_{xx}(\nu)=\sum_{i=1}^{n} G_{xx,i}(\nu)=\sum_{i=1}^{n} A_i L(\nu;\nu_{0,i},\Delta_i)$$
$$G_{yy}(\nu)=\sum_{i=1}^{n} G_{yy,i}(\nu)=\sum_{i=1}^{n} B_i L(\nu;\nu_{0,i},\Delta_i), \qquad (1)$$

CS model:

$$\mathrm{Re}[G_{xy}(\nu)]=\sum_{i=1}^{n} C_i\, L(\nu;\nu_{0,i},\Delta_i)\cos[\Delta\phi_{xy,i}(\nu)]$$
$$\mathrm{Im}[G_{xy}(\nu)]=\sum_{i=1}^{n} C_i\, L(\nu;\nu_{0,i},\Delta_i)\sin[\Delta\phi_{xy,i}(\nu)], \qquad (2)$$

See Méndez et al. (2024) for details on the derived phase lags and intrinsic coherence function.

5. Detection of the imaginary QPO in CS



Fitting example for Zone 5. Upper left: fitted PDS in two energy bands; Upper right: fitted rotated real and imaginary part of CS. Middle: unrotated CS; Lower: Phase lags and coherence function; The vertical dotted line marks the QPO frequency.

A narrow component at **2.88 Hz** is detected in the CS, with $\mathrm{Im}(CS) > \mathrm{Re}(CS)$. The narrow component is consistently significant in CS, but not always significant in PDS. We call it **imaginary QPO**. At the same frequency, the phase lag rises sharply and the coherence drops. The joint model reproduces both signatures without fitting either diagnostic directly.

6. Evolution with spectral hardening

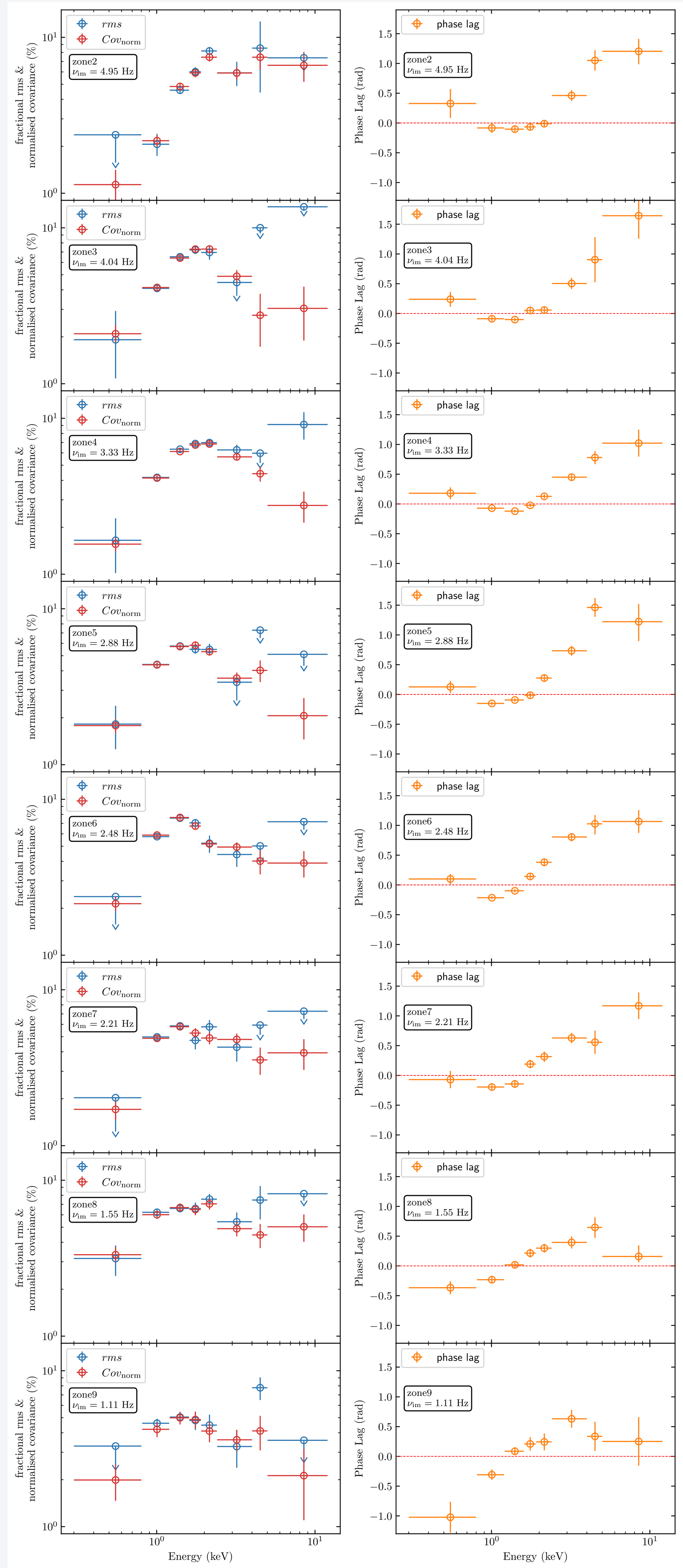
	Zone	ν_{imQPO} (Hz)	FWHM (Hz)	Q factor	$\Delta\phi$ (rad)
HIMS	2	4.95 ± 0.21	3.2 ± 0.7	1.5 ± 0.3	0.33 ± 0.09
	3	4.04 ± 0.08	2.5 ± 0.3	1.6 ± 0.2	0.38 ± 0.15
	4	3.33 ± 0.02	1.3 ± 0.1	2.5 ± 0.2	0.43 ± 0.04
	5	2.88 ± 0.02	0.9 ± 0.1	3.0 ± 0.3	0.68 ± 0.08
	6	2.48 ± 0.02	1.0 ± 0.1	2.5 ± 0.2	0.78 ± 0.08
	7	2.21 ± 0.04	0.7 ± 0.1	3.2 ± 0.4	0.70 ± 0.09
LHS	8	1.55 ± 0.05	0.8 ± 0.2	2.1 ± 0.7	0.47 ± 0.13
	9	1.11 ± 0.03	0.6 ± 0.2	1.9 ± 0.5	0.59 ± 0.19

5 → 1 Hz : QPO frequency decreases as source hardens

0.3 → 0.7 rad : phase lag increases as source hardens

LHS : first detection of imaginary QPO in this state

7. Energy spectrum of the rms, covariance and phase lag

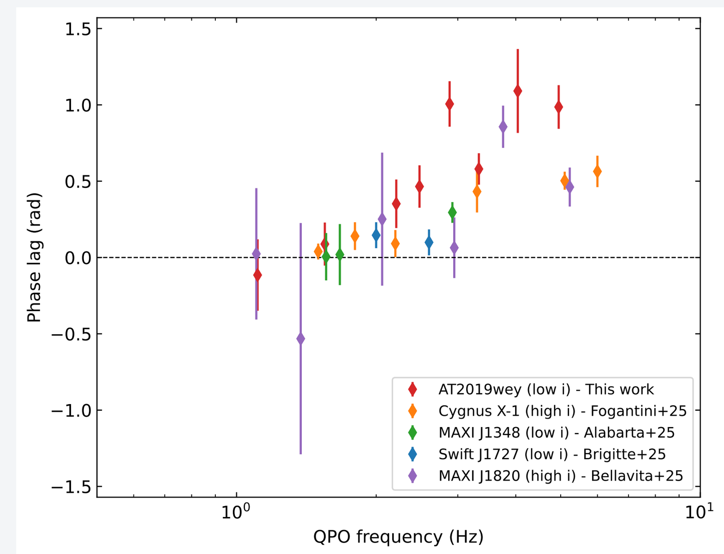


1. The covariance spectrum provides higher S/N (Wilkinson & Uttley 2009) and replaces the rms spectrum in our discussion. The QPO covariance generally rises and then falls, peaking near **1.5–2 keV**. This might indicate a relatively cool Comptonising region, which suppress high-energy variability and shift this maximum to lower energy (vKompth; Bellavita et al. 2022).
2. The phase-lag spectrum is **U-shaped in the HIMS**; its minimum moves to lower energy as the source hardens, and the U-shape is no longer visible in the LHS. This is consistent with a decreasing disc temperature in time-dependent Comptonisation models (Karpouzas et al. 2021, Bellavita et al. 2022).

8. A likely type-C QPO?

1. The anti-correlation between QPO frequency and broadband rms, the high broadband variability (up to about 30%), and the decrease of QPO frequency with spectral hardening all resemble type-C QPOs.
2. Imaginary QPO frequencies are marginally consistent with Type-C QPO frequencies in AT2019wey

9. Extra investigation: Inclination dependence of imaginary QPO ?



Phase lag of the imaginary QPO as a function of QPO frequency. The inclination (high or low) of each source is inferred from X-ray reflection fitting. Phase lag appears to increase with imaginary-QPO frequency, but the inclination dependence remains inconclusive because of the small sample and uncertain inclination estimates.

10. Take-home message

1. Joint PDS–CS fitting exposes an imaginary QPO, with the phase-lag cliff and coherence dip at QPO frequency.
2. AT2019wey extends imaginary-QPO detections into the LHS.
3. A decrease in the covariance of the imaginary QPO above ~ 2 keV, which might indicate a cool corona.
4. U shaped phase lag spectrum appears in the HIMS while disappear in LHS, which might be related to a decreasing disc temperature as source hardens.
5. Some imaginary QPO's properties resemble the Type-C QPO.