NICER and NuSTAR Spectral Timing analysis of QPOs in GRS 1915+105

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Quasi-periodic oscillations (QPOs) are often observed in the X-ray flux of black hole X-ray binary systems, but their physical mechanism has long remained ellusive. Studying the QPO phase-dependence of the iron Kα line profile provides the best test for whether the QPO is driven by Lense-Thirring precession of the inner accretion flow [1]. In order to reconstruct QPO phase-resolved spectra, we must first measure the energy dependent phase lags and variability amplitude of the QPO's harmonics [2]. We do this for a 30 ks joint NICER + NuSTAR observation of the black hole X-ray binary GRS 1915+105.

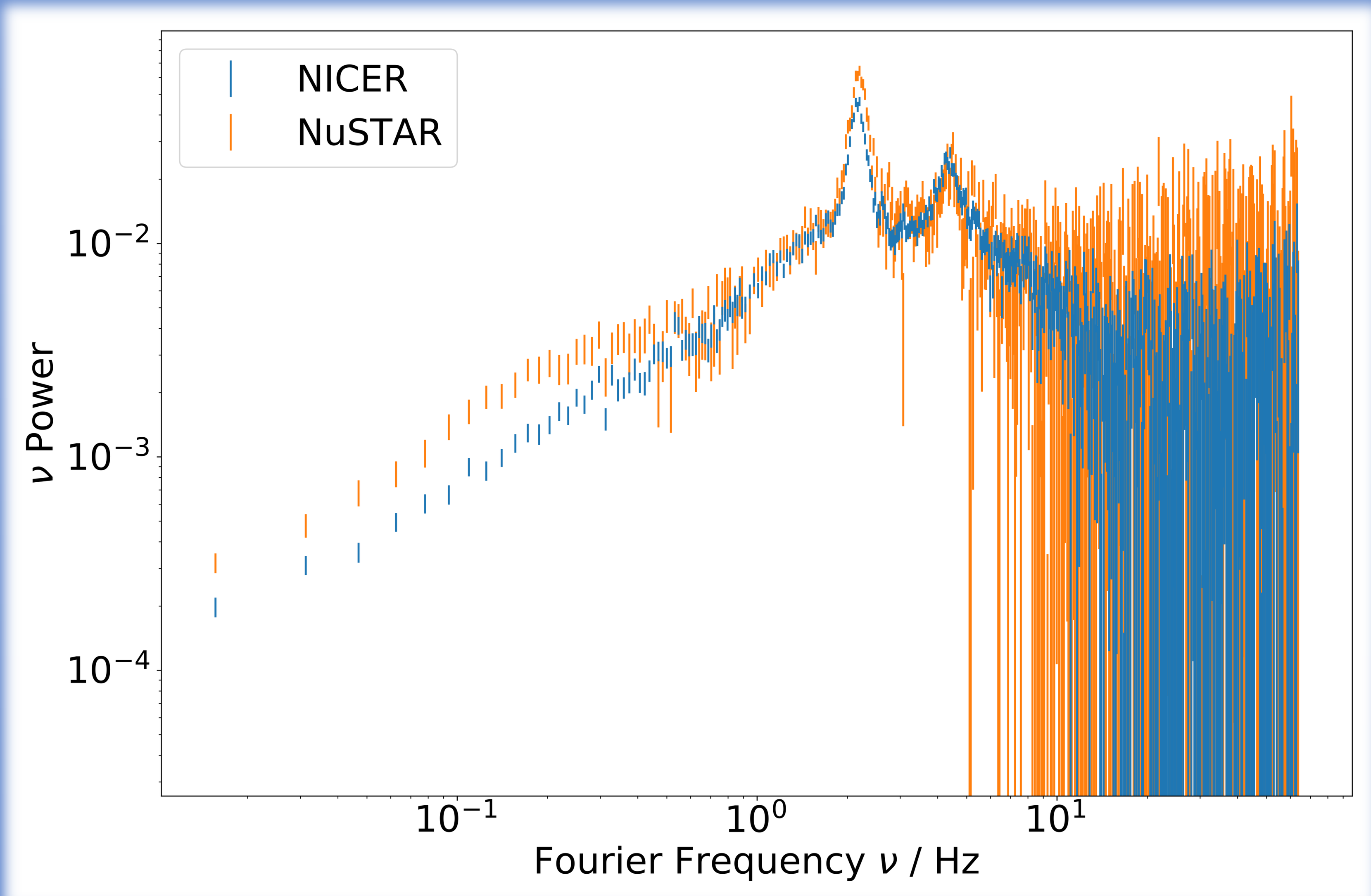

Figure 1: Poison noise subtracted power spectrum of the NICER lightcurve, and co-spectrum of the NuSTAR FMPA and FMPB light curves. The QPO fundamental (first harmonic) is easy to see at ~2.2 Hz in each, along with the the second harmonic at ~4.4 Hz.

GRS 1915+105 is a bright source with a strong iron line and high amplitude QPOs, making it an ideal source for phase-resolved spectroscopy. Simultaneous coverage with NICER and NuSTAR provides high quality data across a broad energy bandpass. Our observation from May 2018 exhibits a QPO with two strong harmonics at ~2.2 Hz and ~4.4 Hz in both the NICER and NuSTAR bands (Fig 1).

In general the QPO frequency is not constant throughout a long observation. To correct for this we track the instantaneous QPO frequency over time using maximum likelihood estimation [3] and shift the frequency of timing products measured for short time intervals to a common QPO frequency before averaging all intervals together.

We create light curves in narrow energy ranges and calculate the fractional rms and phase lag of each light curve (Fig 2). We calculate the rms by fitting a multi-Lorentzian model to the "shifted and added" power spectrum of each light curve. The rms of each QPO harmonic is taken as the integral of the corresponding Lorentzian component. To find the phase lag, we take the shifted and added cross-spectrum between each light curve and a common reference band light curve. The phase lag is the argument of this cross-spectrum. In Fig 2, we see good agreement between NICER and NuSTAR, except for a small systematic offset in the phase lag. This occurs because we use different reference bands for the two observatories (NICER full band for the NICER data and NuSTAR FMP B full band for the NuSTAR data), and can be corrected for by measuring the phase lag between these two reference bands.

We see `wiggles' around the iron line energy (~6.4 keV, grey line) in the rms and phase lag plots, particularly noticable in the higher signal to noise NICER data. This is indicative of a QPO phase-dependence of the iron line profile.

The next step will be to combine the results shown in Fig 2 with the average phase difference between the first two QPO harmonics in order to reconstruct the average underlying waveform of the QPO in each energy band. This will allow phase-resolved spectroscopy: examining the energy spectrum of the source as a function of QPO phase. We will use our own spectral model that parameterises the QPO phase-dependent radial and azimuthal dependence of disc illumination with an analytic function [1]. Our model simultaneously calculates the QPO phase-dependent shape of the full disc reflection spectrum (that includes the iron line feature) and the QPO phase-dependent spectrum of reprocessed photons that thermalise with the disc and are re-emitted in the energy range that NICER is most sensitive to. The QPO phase-dependence of the full reflection spectrum has only previously been studied for one source (H1743-322; [1]). Since GRS 1915+105 is brighter and has a stronger iron line, our analysis promises to provide the best constraints on the QPO mechanism to date.

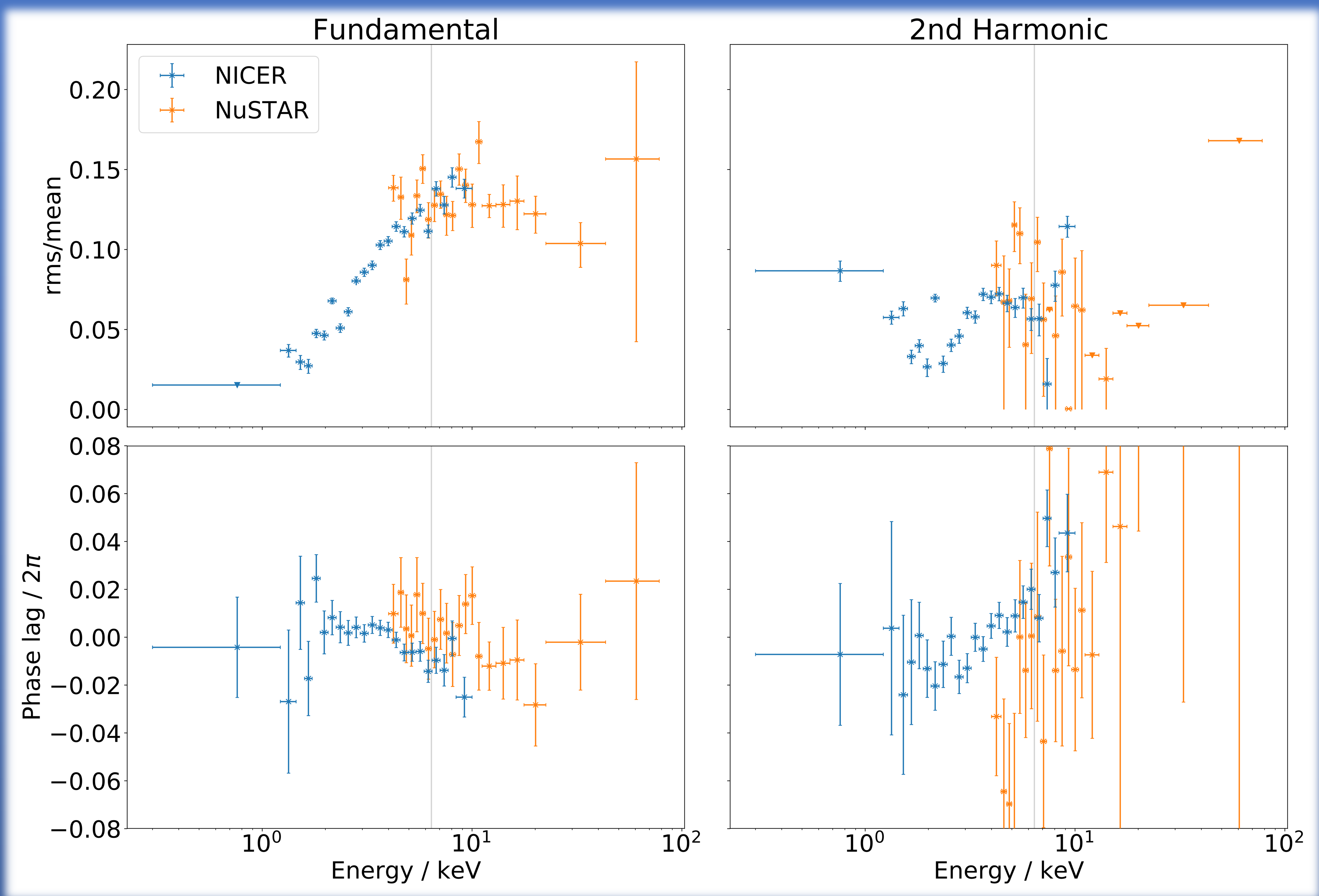

Figure 2: Top: The fractional rms of the first two QPO harmonics in the NICER power spectra and NuSTAR cospectrum, in different energy bands. In some cases only an upper limit can be found for the fractional rms, indicated with a triangle, and if the 1-σ error bars encompass 0 they are truncated without a cap.
Bottom: Phase lag of the harmonics between energy bands. For NICER this is the lag of each energy band to the full spectrum, for NuSTAR this is the lag of each band in FPM A to the entire spectrum in FPM B. On each plot the 6.4 keV Fe Kα line is indicated in grey.

1. A. Ingram, M. van der Kliss, M. Middleton, C. Done, D. Altamirano, L. Heil, P. Uttley, M. Axelsson. A quasi-periodic modulation of the iron line centroid energy in the black hole binary H1743–322. *MNRAS*, 461:1967-1980, 2016.
2. A. Ingram, M. van der Kliss. Phase-resolved spectroscopy of low frequency quasi-periodic oscillations in GRS 1915+105. *MNRAS*, 446:3516-3525, 2015.
3. D. Barret, S. Vaughan. Maximum likelihood fitting of x-ray power density spectra: application to high-frequency quasi-periodic oscillations from the neutron star x-ray binary 4u1608-522. *APJ*, 746:131, 2012.