A spectral and timing study of the LMXRB MAXI J1820+070

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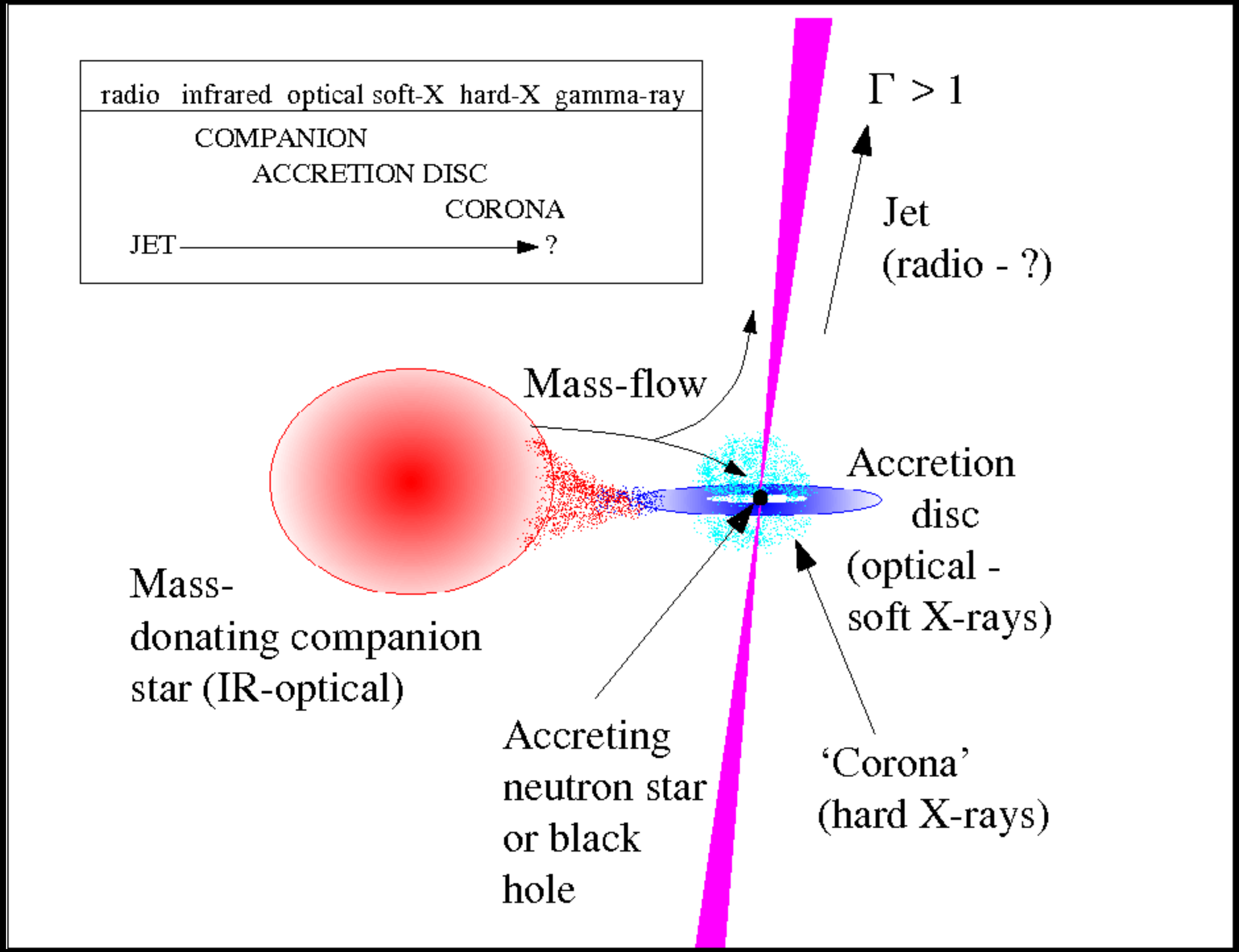
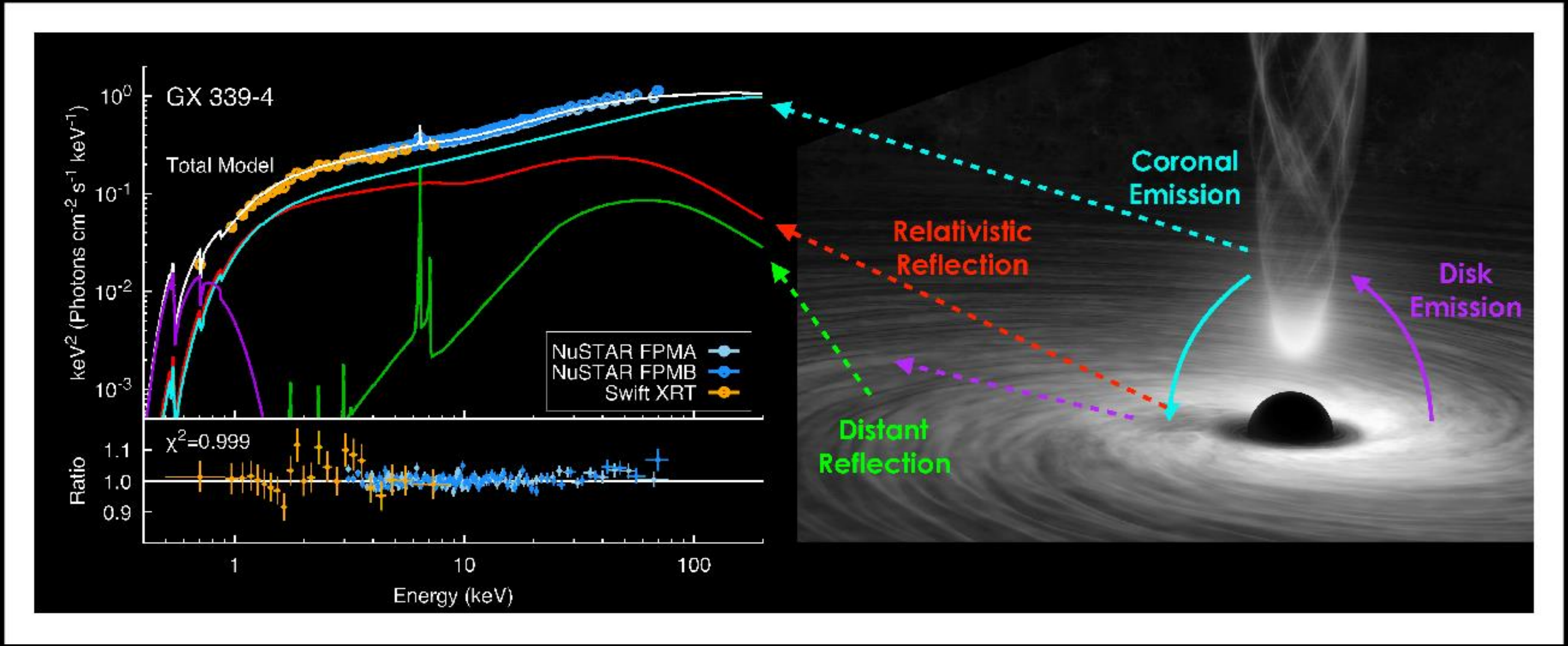
WHAT ARE XRBS?

- Consist of a compact object (black hole or neutron star) and a companion star.
- **Thermal**: Emission from accretion disk (~1 keV).
- **Non-thermal**: Power-law extending to ~100 keV - Compton scattered photons from corona/jet.
- **Disk Reflection**: Spectral bump (10-30 keV) & Fe Kα line.



R. Fender, 2001

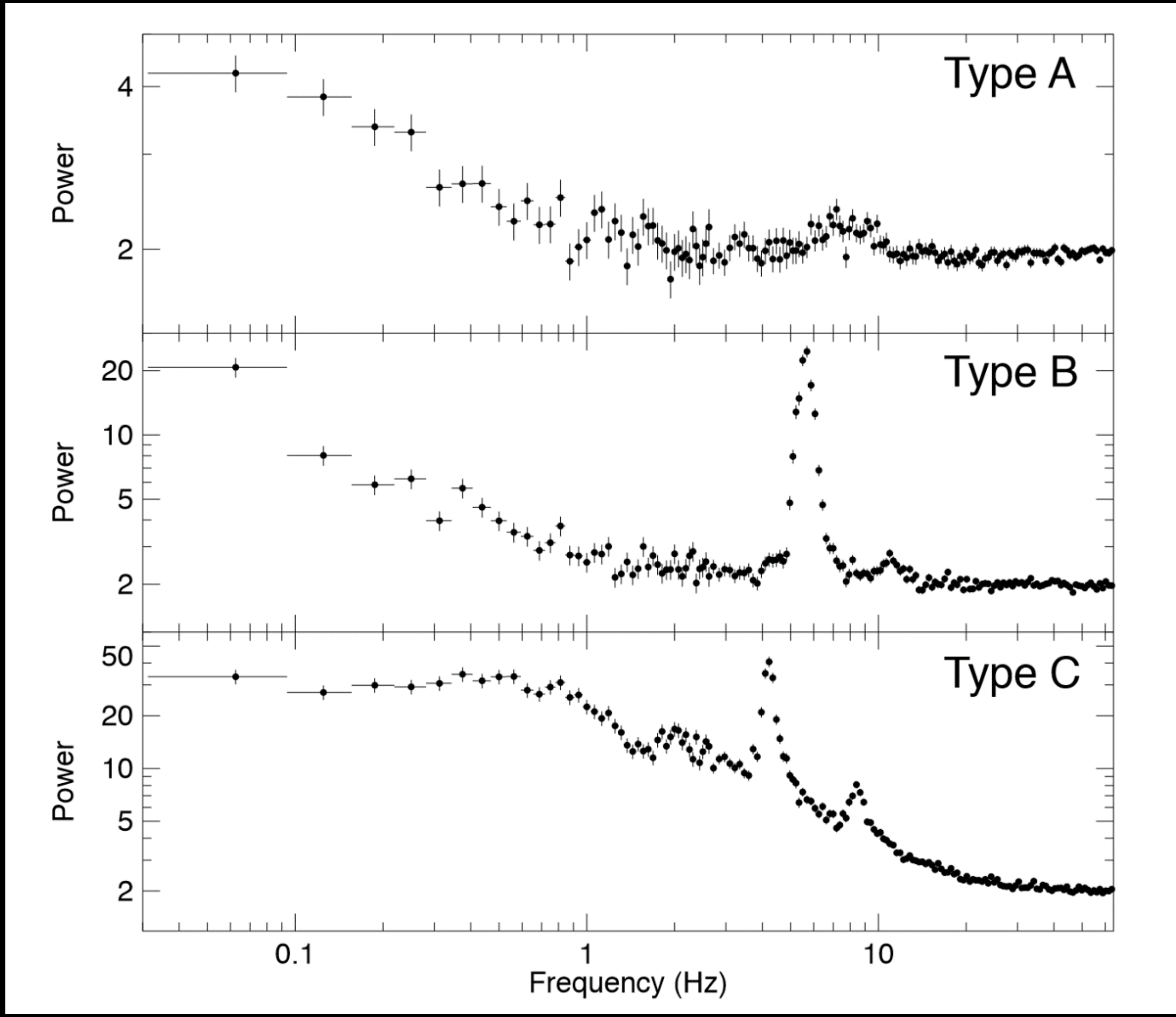


Swift and NuSTAR Spectrum of GX 339−4 during its 2017 outburst (Credit: García et al.,2019)

- **Spectral Components:** Compton continuum (blue), relativistic reflection (red), distant reflection (green), and thermal disk emission (violet).

X-RAY TEMPORAL PROPERTIES

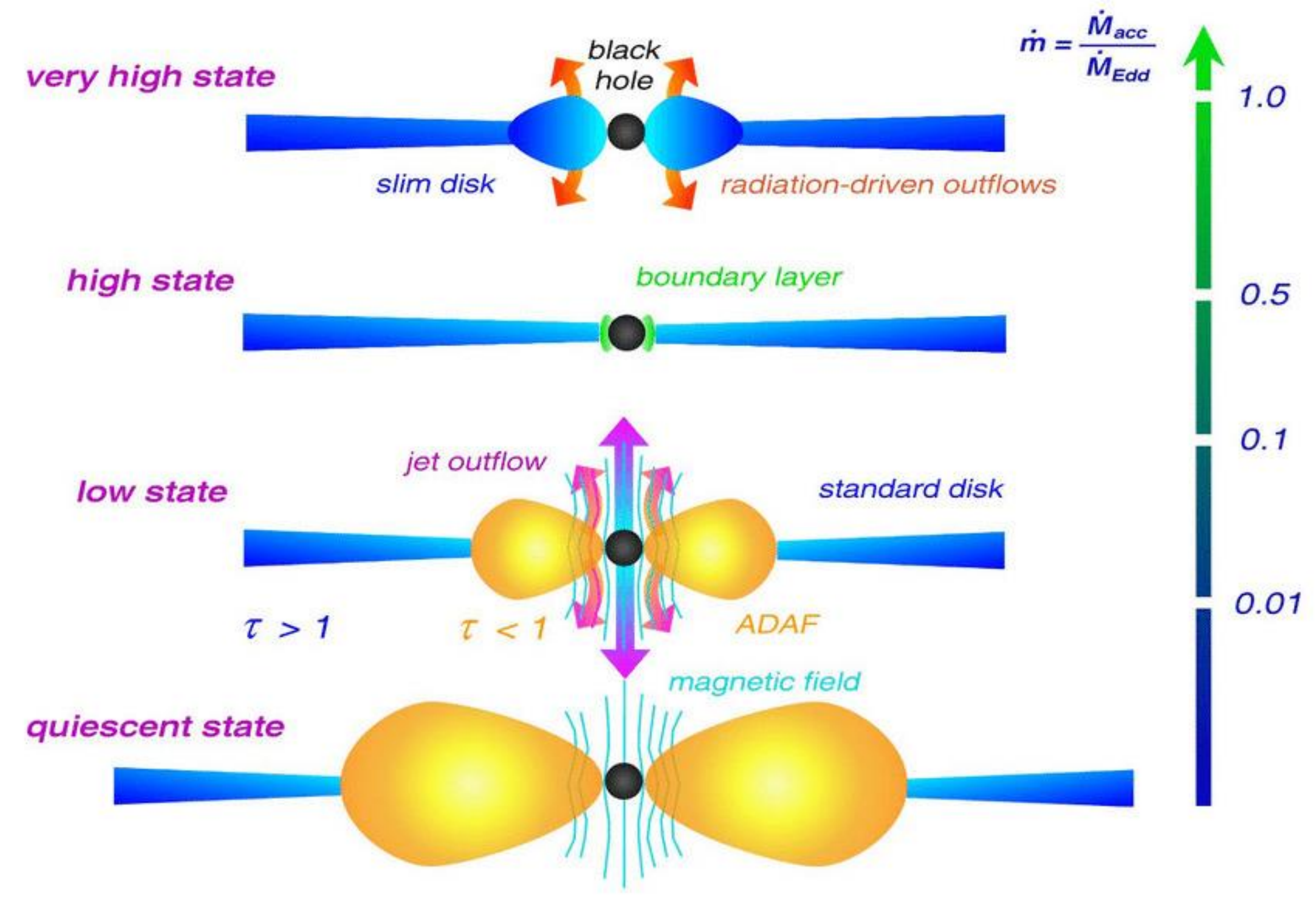
- **Quasi-Periodic Oscillations (QPOs):**
  - Transient, discrete features in frequency ranges of $\sim 0.01 - 450$ Hz
  - Source not fully understood – instabilities (e.g. AEI) or geometrical effects (e.g. disk precession).
  - Modeled with multiple Lorentzian profiles.
- **Soft-vs-hard time lags:**
  - Cause by mass accretion fluctuations and/or the light travel time delay between corona and disk.
  - Provide information about the geometry and dynamics of the accretion flow.



S. Motta et.al., 2001

OUTBURSTS

- BHBs undergo outbursts characterized by different spectral states where either thermal (**high/soft**) or non-thermal (**low/hard**) components dominate.
- Unifying spectral states:
  - Low $\dot{m}$ **: Hard state** – Truncated accretion disk + ADAF & Jet.
  - High $\dot{m}$: **Soft state** - Disk extends to ISCO.



T. Belloni et. al., 2005

OBJECTIVES

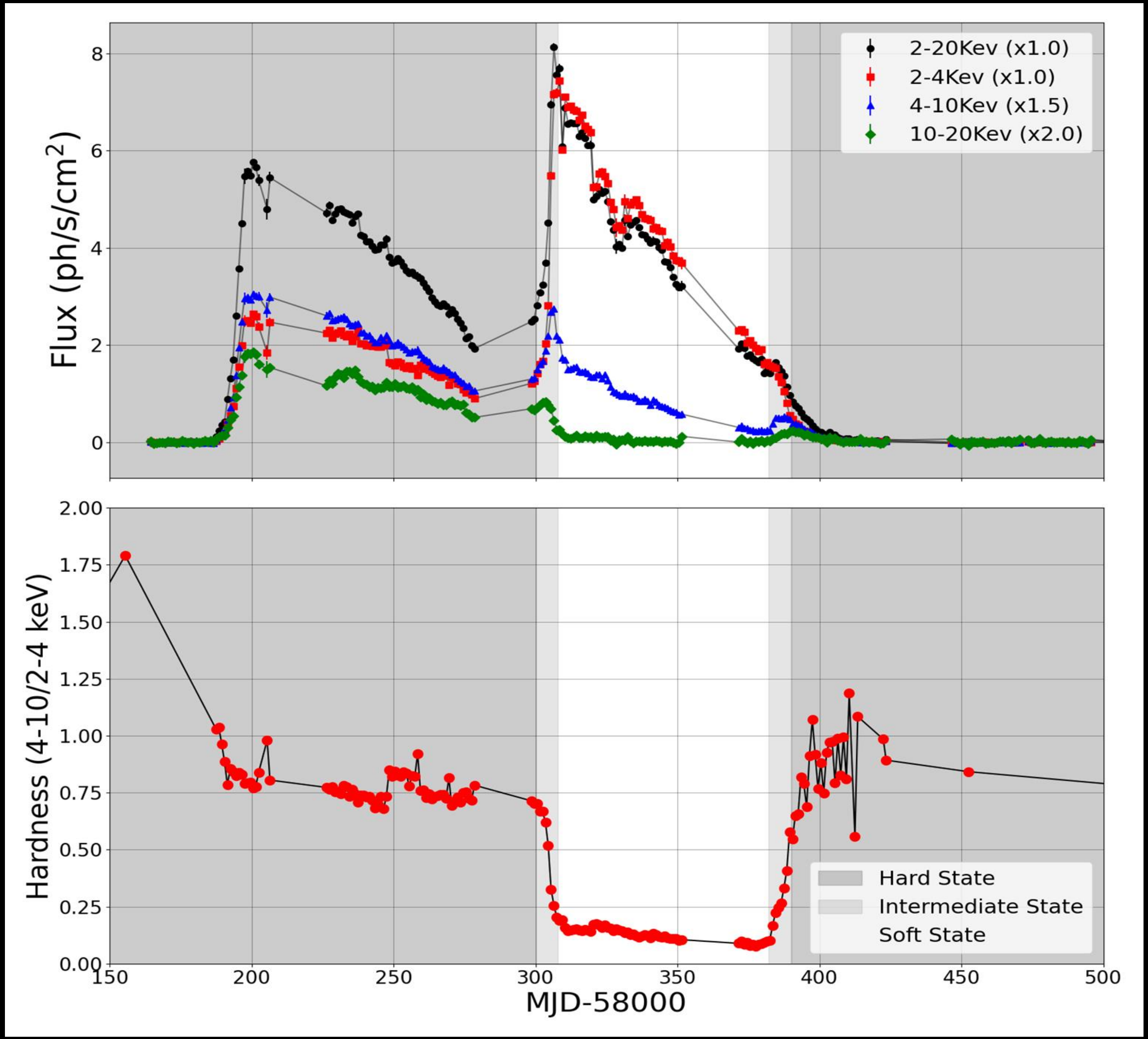
- Study MAXI J1820+070 during its outburst to independently validate and corroborate existing research.
- Better understand the X-ray spectral evolution of BHBs throughout their outburst.
- Analyse the evolution of temporal variability to better understand emitting region's geometry.
- Test and identify limitations of using a single spectral model throughout the outburst.

WHY MAXI J1820+070?

- MAXI J1820+070 underwent a bright, extended outburst in 2018
  - Clear transitions between hard and soft accretion states.
  - Collimated jets detected during state transitions.
  - Dynamic QPOs and time-lags observed.
- Abundant literature and observational data across the X-ray band.
- Ideal laboratory to study parameter evolution as a function of accretion flow.

MAXI LIGHTCURVES

- Light curve exhibits a rapid initial rise followed by a consistent decrease in flux.
- Notable instances of re-brightening observed during state transitions.
- State transitions are marked by rapid changes in spectral hardness.

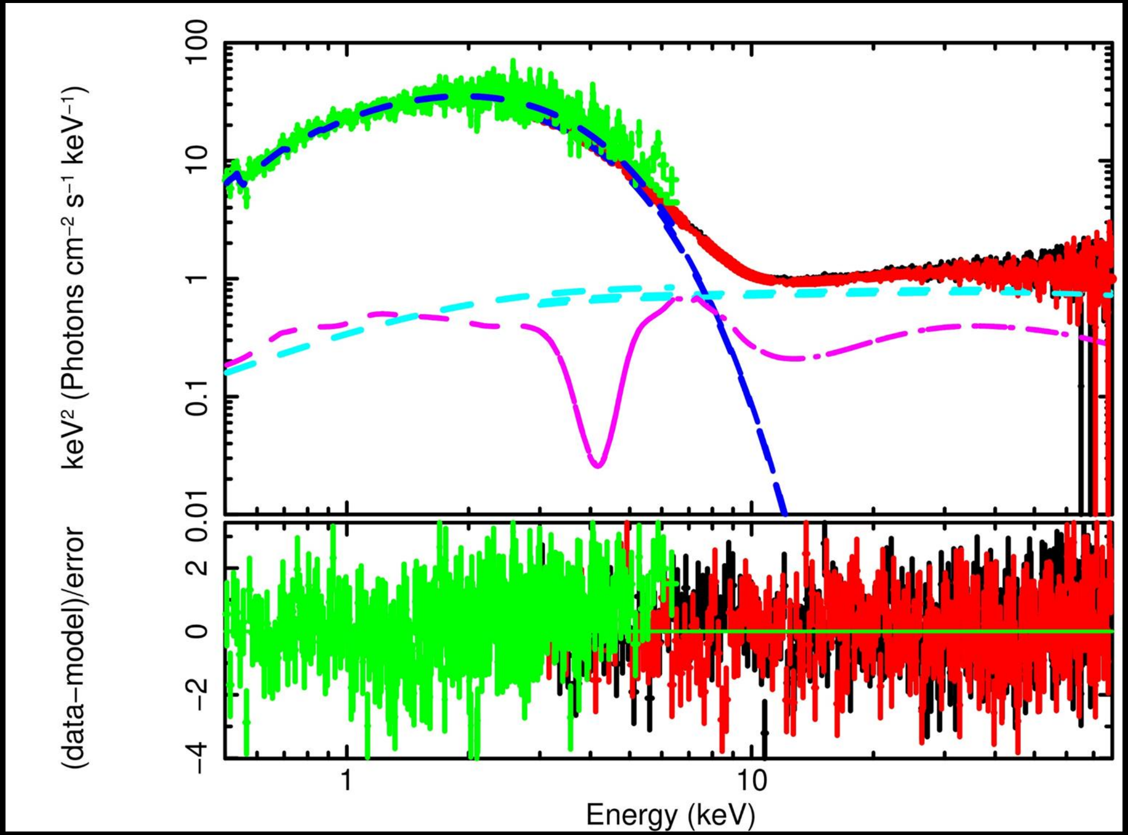


SPECTRAL ANALYSIS

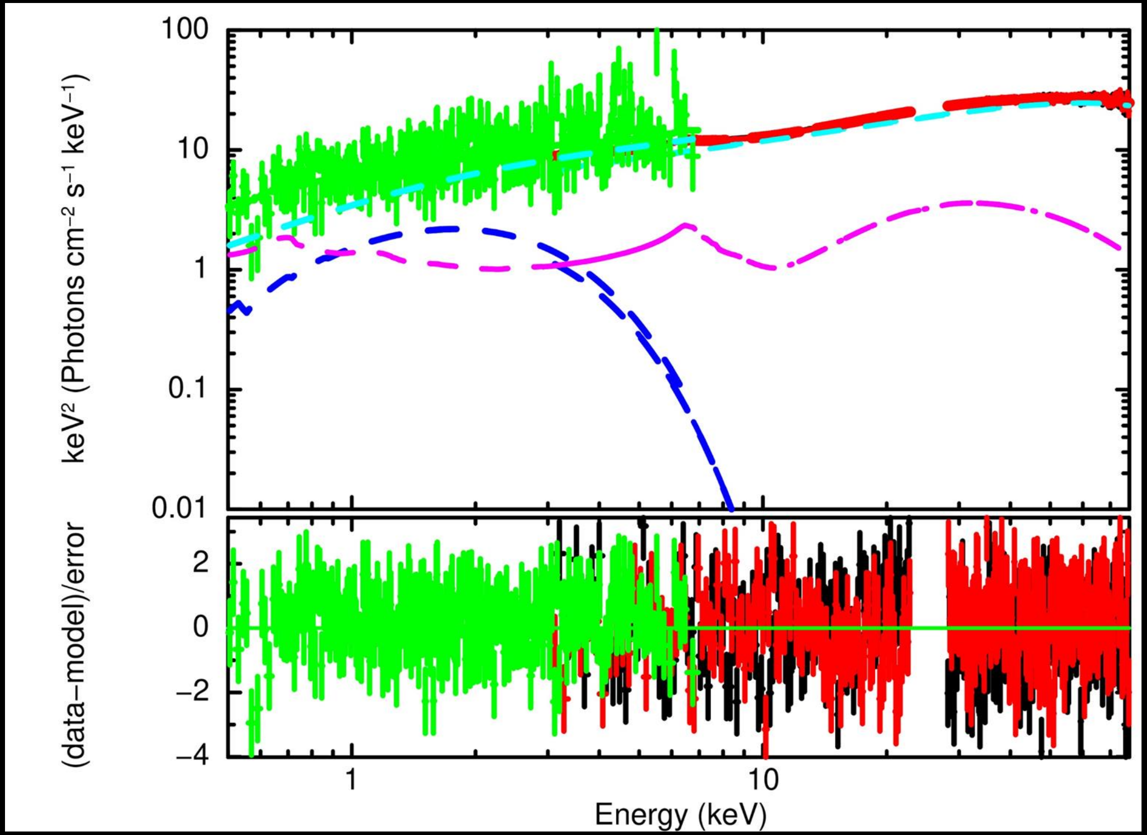
- **Spectral Modeling for MAXI J1820+070**:
  - Utilized NuSTAR and Swift-XRT spectral data.
  - Aimed to characterize the thermal and non-thermal X-ray emission simultaneously.
- **Model Components:**
  - Incorporated multiple spectral components to capture different physical processes.
  - XSPEC models:
    - **Diskbb**: Model thermal emission from the accretion disk, providing key temperature and emission data.
    - **Nthcomp**: Model non-thermal continuum with a thermal Comptonization model.
    - **Relxillcp**: Model relativistic effects near the black hole.

MAXI J1820+070 SPECTRAL FITS

Soft state



Hard state

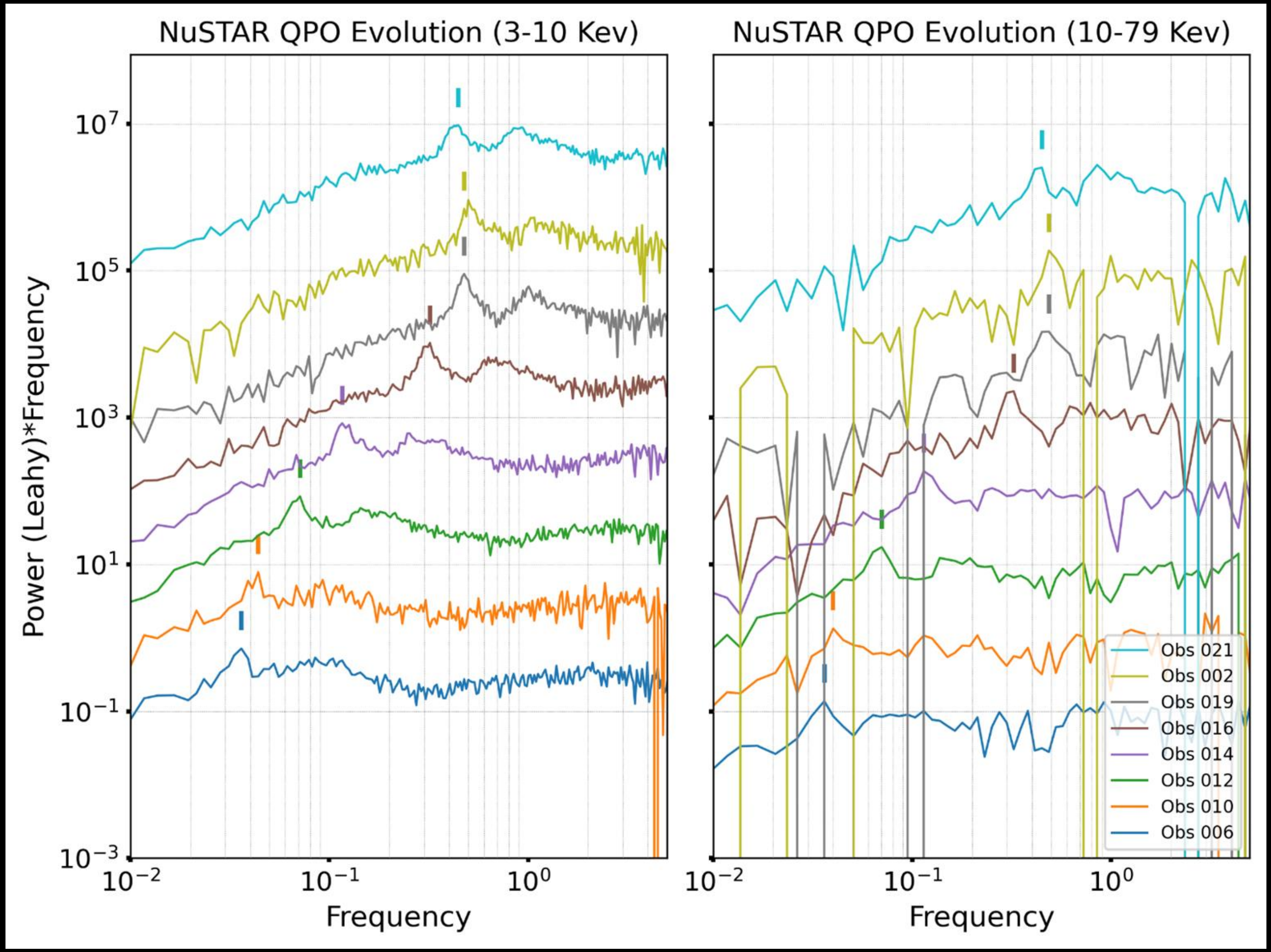


- Spectrum: **Swift-XRT** in green**; NuSTAR** FPMA/B in red/black
- Model**: Tbabs** * (**Diskbb** [blue] + **Nthcomp** [cyan] + **Rexillcp** [magenta])

TIMING ANALYSIS

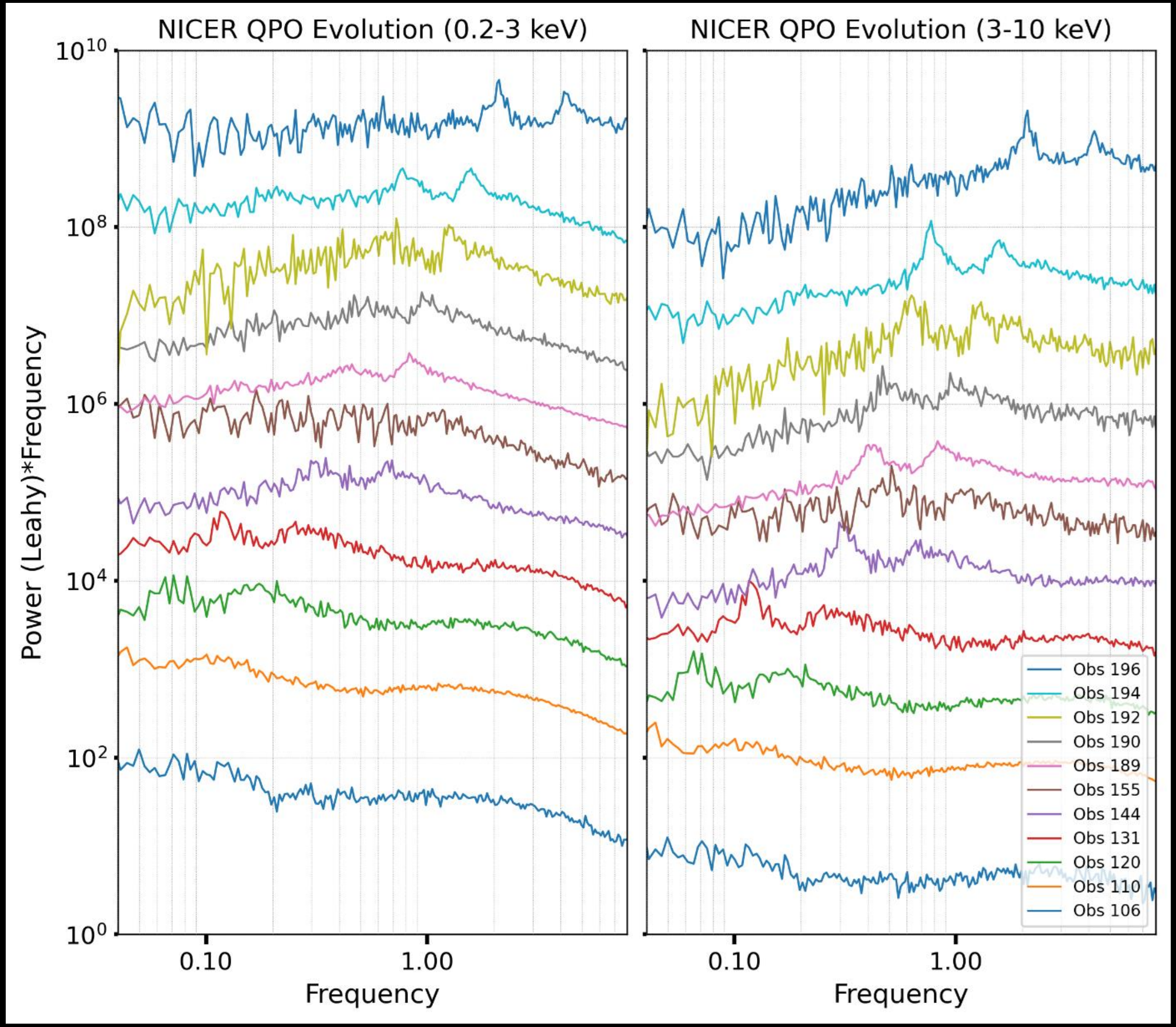
- Incorporated both NuSTAR and NICER temporal data.
- Utilized spectral-timing software package‘**Stingray**’ for time-series analysis.
- Perform Fourier transform to create PDS to analyze QPOs.
- Divided PDS into different energy bands to explore QPO-energy dependence.
- Compute the Cross-spectrum between hard and soft bands and extract frequency dependent time-lag.

NUSTAR QPO EVOLUTION



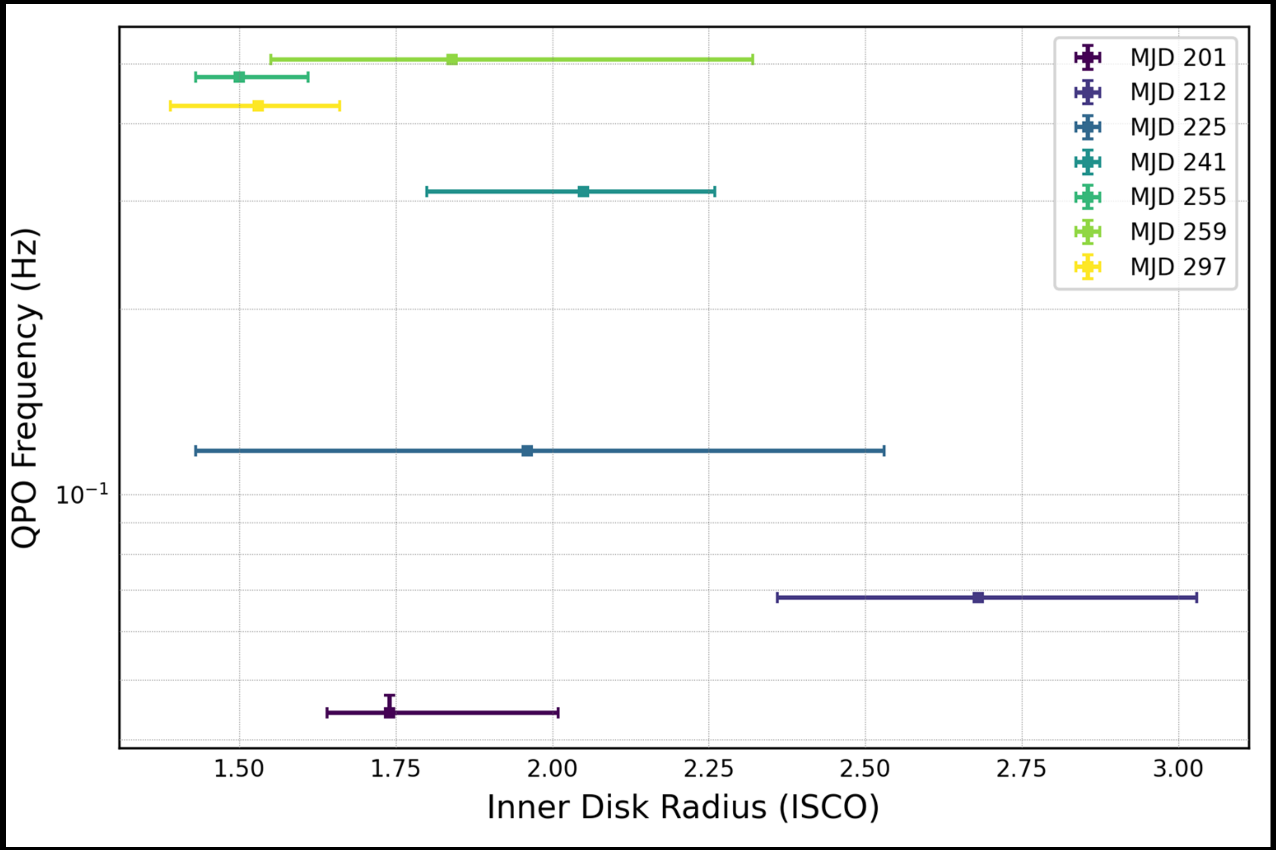
- LFQPO with harmonic present during hard state.
- Centre QPO frequency shifts to higher frequency, with increasing EW.
- Weakened QPO in 10-79 keV.
- No QPOs present in NuSTAR data in soft state.

NICER QPO EVOLUTION



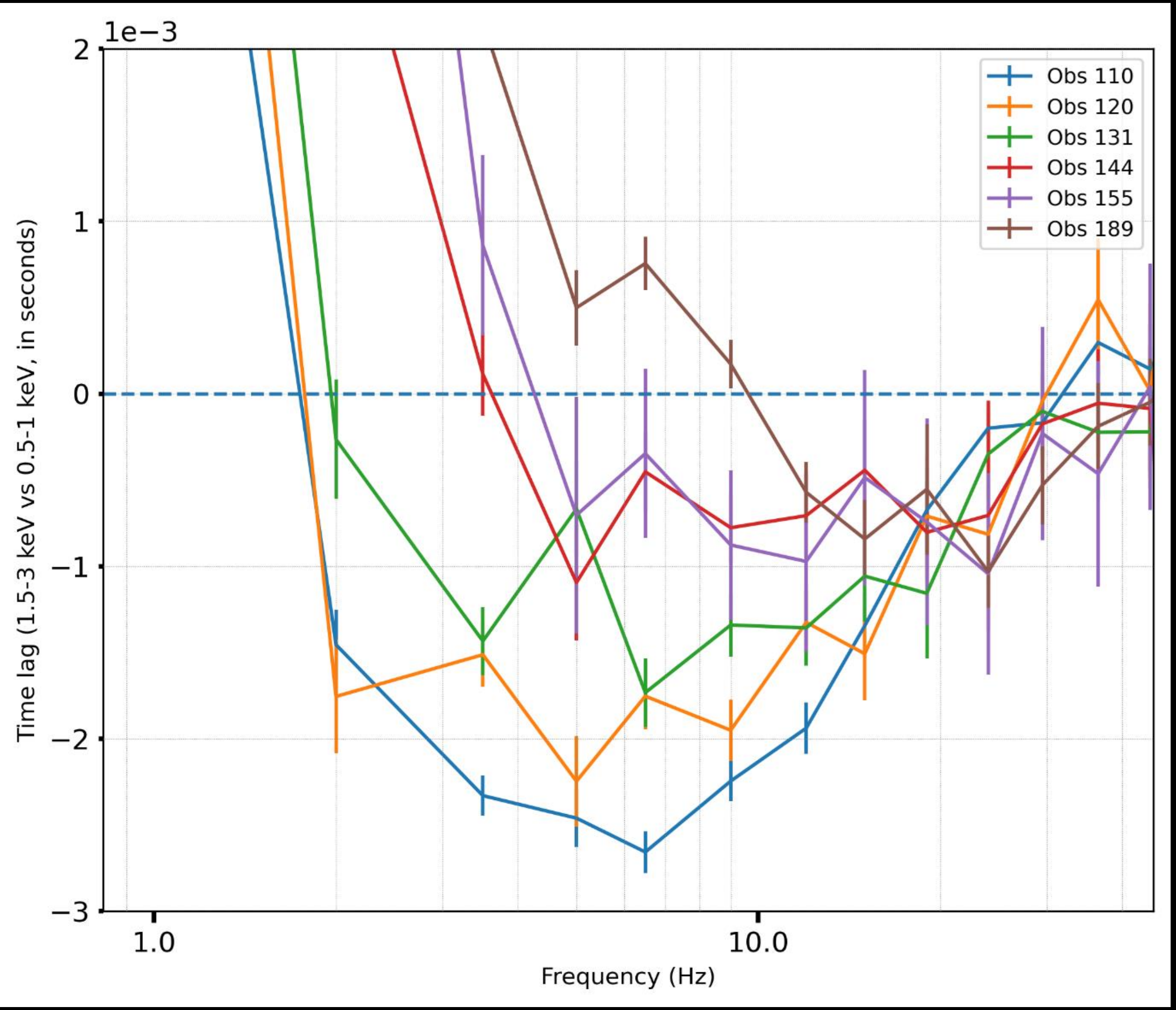
- QPOs present < 3 keV.
- Weakened main QPO present in 0.2-3 keV with stronger harmonic.
- Broadband noise dominates in 0.2-3 keV band.

QPO-DISK CONNECTION



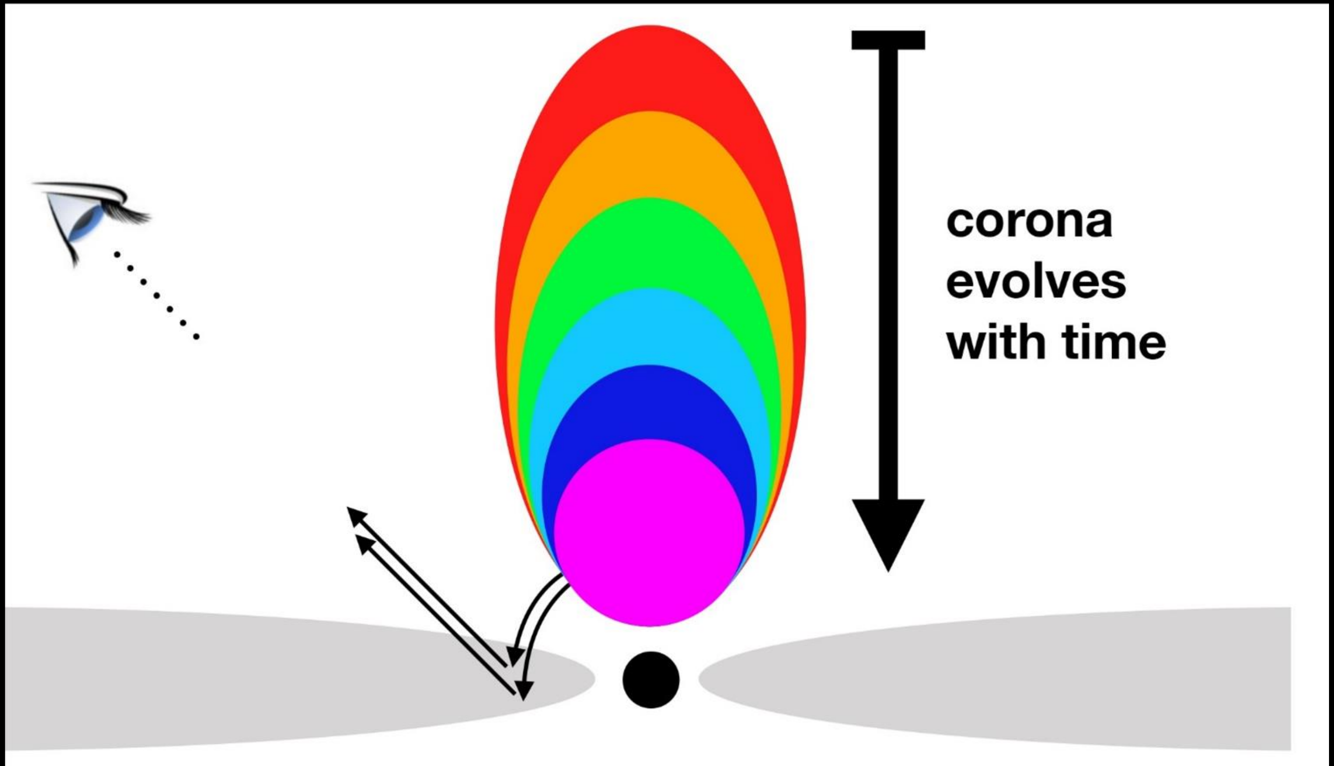
- Minimal variation in disk radius with dynamic QPO frequency.
- Suggests QPO frequencies are not correlated with inner-disk geometry.
- Diverges from models predicting QPOs originating from geometric changes in inner-disk.
- Other theories propose connection to temporal evolution of the corona.

THE CORONA CONTRACTS



- Soft/reverberation lag – light travel time delay between direct coronal emission and reflected emission.
- Soft lag evolves to higher frequencies and smaller amplitude during hard state -> implies a contracting emitting region.
- Spectral modelling show no evolution of disk truncation radius, suggesting a contracting corona.

THE CORONA CONTRACTS



Kara et. al., 2019

- Contracting corona proposed in a ‘lamp-post corona’ geometry (Kara et. al, 2019).
- Compact, magnetized region above black hole – base of jet.
- Corona contracts $\Longrightarrow$ closer to disk $\Longrightarrow$ diminishing soft lag amplitude.
- Smaller, hotter corona $\Longrightarrow$ increased variability (higher soft-lag frequency)
- If QPO originate from corona $\Longrightarrow$ smaller & hotter corona could increase QPO frequency as observed.

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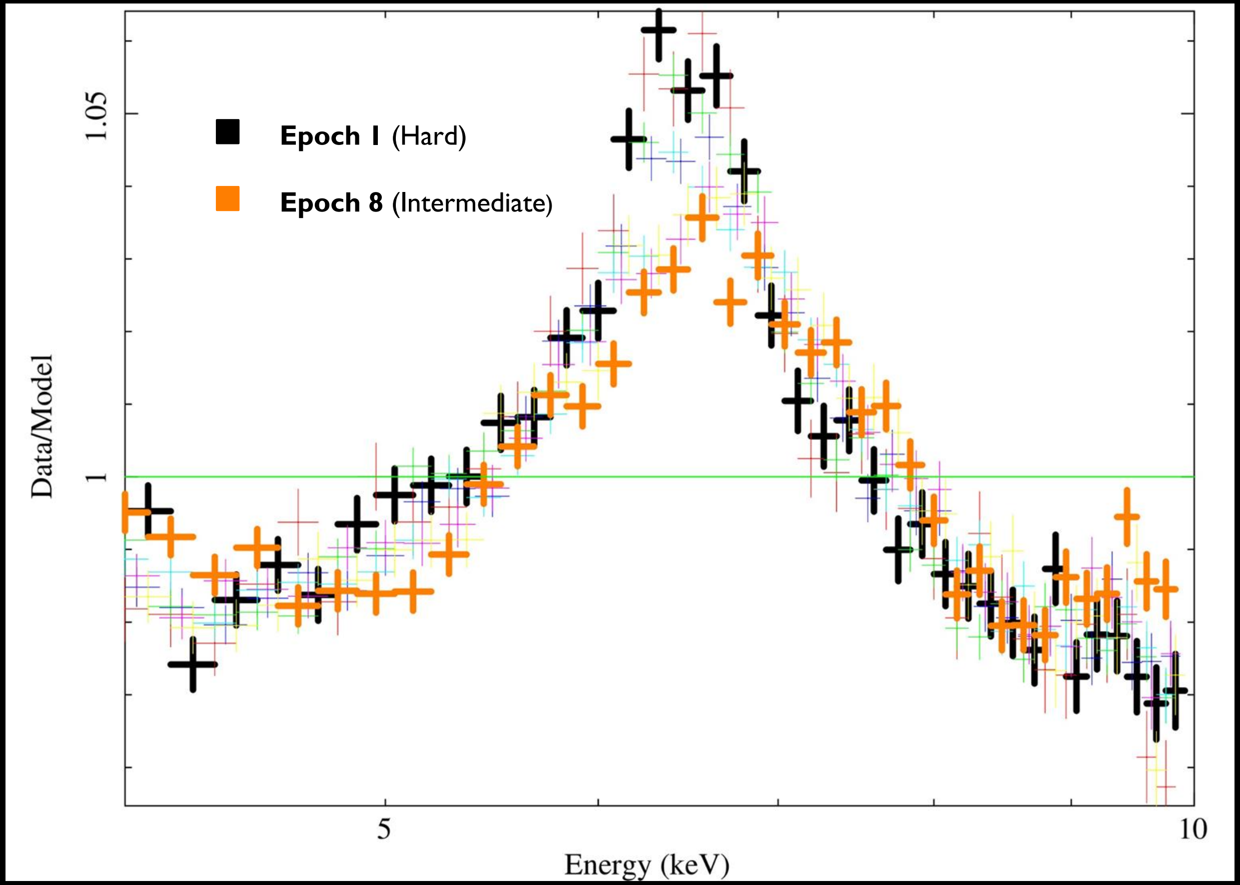
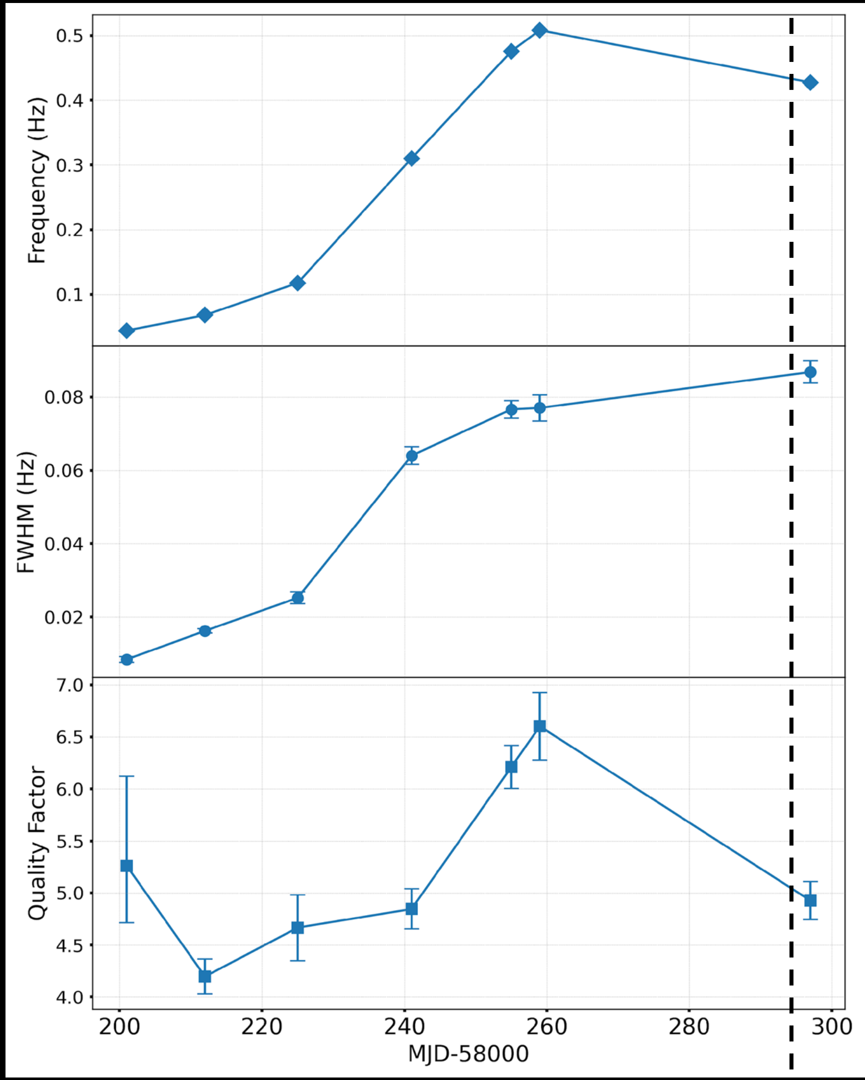


- Fit NuSTAR spectra with disk and corona models – leaves reflection residuals.
- Fe K**α** - narrow component (outer disk) superimposed onto broad component (inner-disk)
- Corona contracts ⟹ reduced irradiation of outer disk regions ⟹ narrow Fe K**α** component diminishes & unchanged broad component.

THE CORONA EXPANDS



- QPO peak shifts to lower frequencies during transition.
- Soft lag frequencies during IMS (black) regress to lower values, lag amplitude increases.
- Smaller corona oscillates at higher frequencies $\Longrightarrow$ expanding corona shifts QPO and soft-lag to lower frequencies.
- Increased soft-lag amplitude due to larger solid angle irradiating outer disk.

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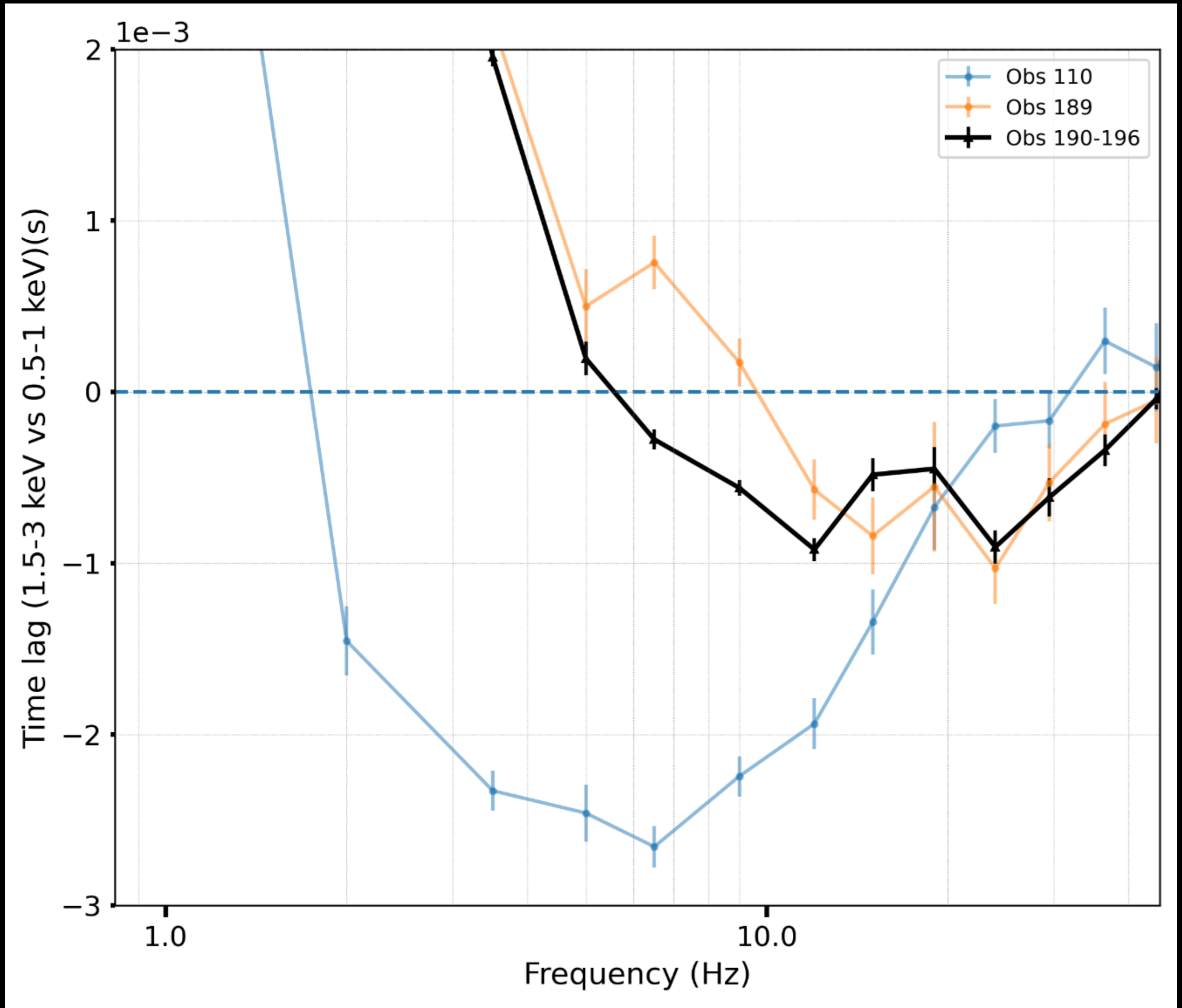

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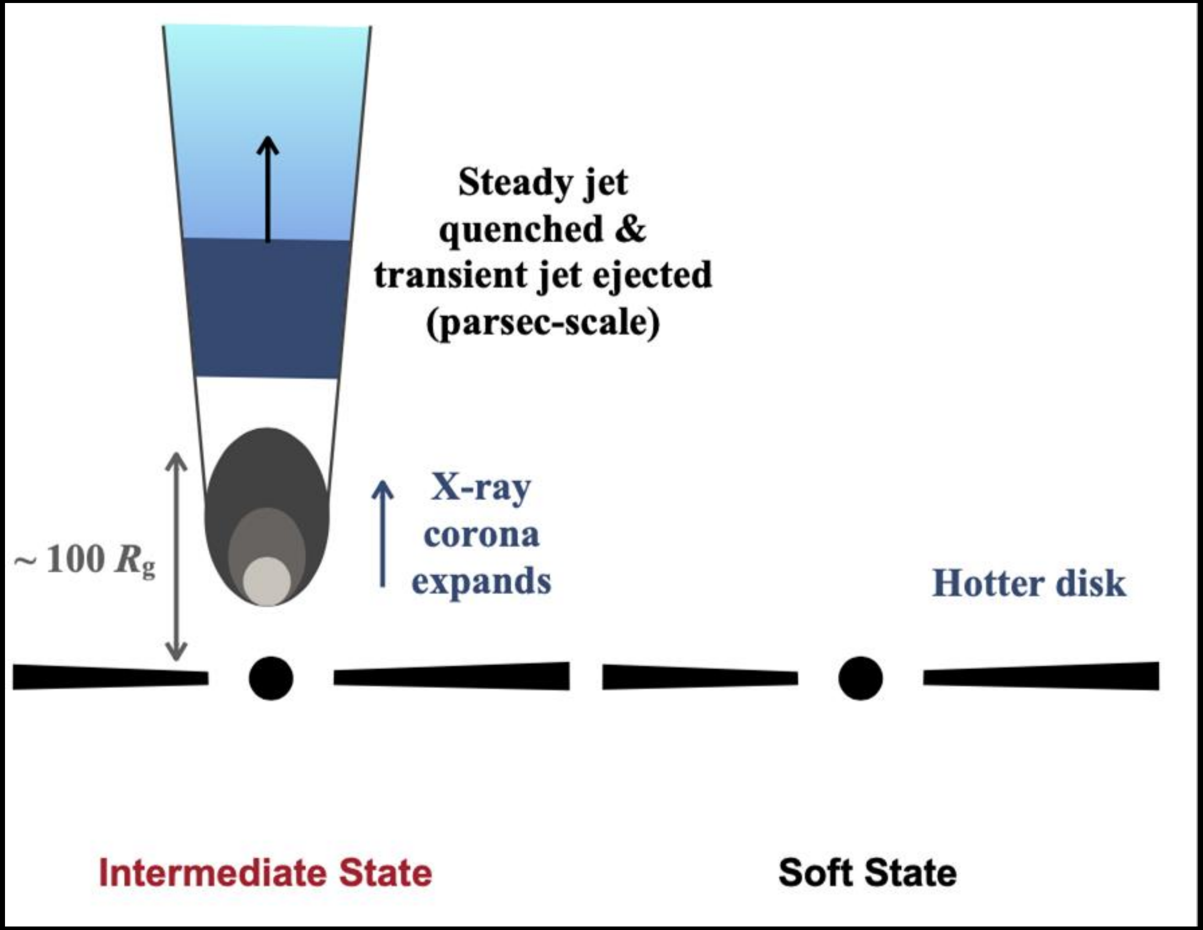


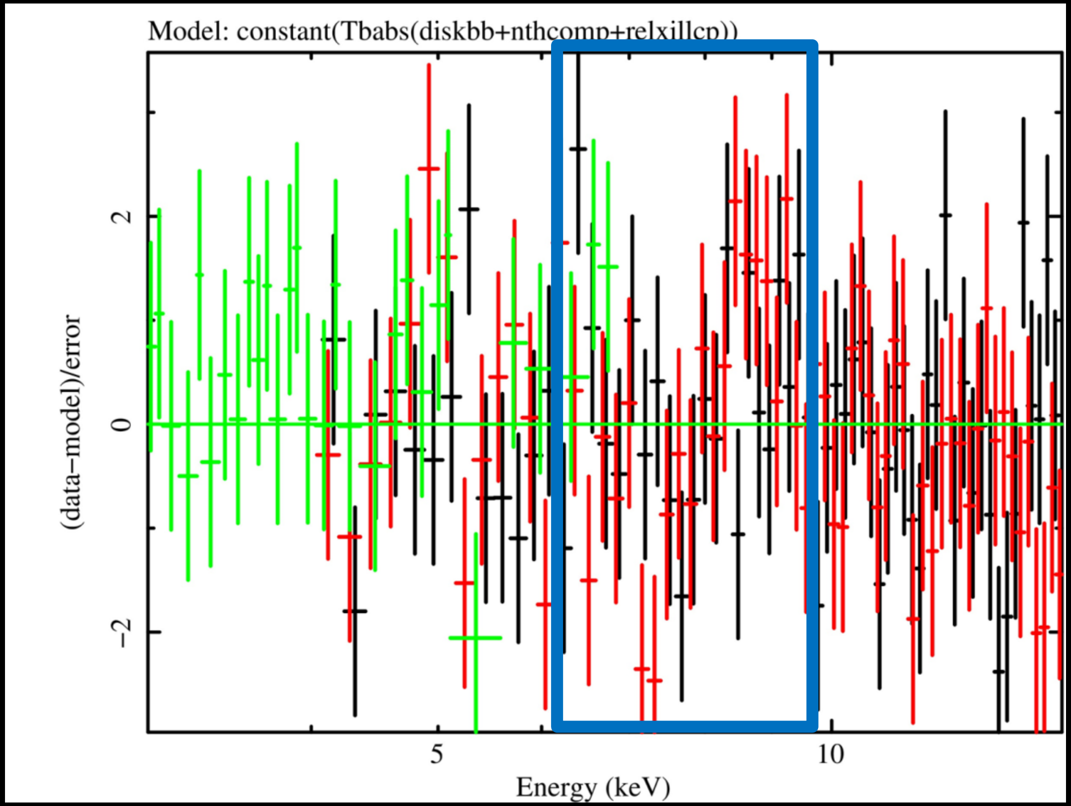
Wang et. al., 2022

- Radio flare observed ~5 days after hard-to-soft transition, correlating with the expanding corona and launch of bi-polar relativistic ejecta (Bright et al., 2020).
- X-ray corona height possibly linked to radio jet behaviour - corona forms as the jet base, expanding and ejected before state transition. (Wang et. al, 2021).

INCLINATION VARIATION

- **Inclination changes observed:**
  - Spectral models prefers a low inclination at the onset (~40°), increasing during the intermediate state (~70°)
  - Extreme variation likely due to model limitations instead of physical phenomena
- **Reflection Model Limitations:**
  - *RelxillCp* does not assume coronal geometry.
  - Change in coronal height possibly compensated through inclination parameter.
  - Lower inclination yields a stronger narrow Fe K**α** component.
  - Corona contracts ⟹ Weaker narrow Fe K**α** line ⟹ higher inclination parameter.

POTENTIAL OUTFLOWS



- Historical Context on Disk Winds:
  - Observed in BHB systems like GRO J1655-40 and GRS 1915+105.
  - Identified through highly ionized Fe Kα lines (e.g. Fe XXV at ~6.72 keV, Fe XXVI at ~7.0 keV).
- Gaussian Absorption Line:
  - Incorporated in the 6.9-7.3 keV.
  - Suggests presence of photo-ionized absorbing material, likely equatorial accretion disk winds.

POTENTIAL OUTFLOWS

- **Absorption Features in Hard State:**
  - Hard-state spectra absorption feature resembles hydrogen-like Fe XXVI kα line.
  - Challenges paradigm of hard state being jet-dominant and wind-free.
  - Disk winds typically associated with soft state and high inclination (Ponti et al., 2012).

- **Spectral Resolution problem:**
  - NuSTAR and Swift-XRT have limited spectral resolution.
  - Grating spectra needed for accurate modelling and detailed information on outflows.
  - Necessity of absorption feature may indicate model limitations in characterizing the spectrum.

FUTURE PERSPECTIVES

- Incorporate more complex spectral models to study MAXI J1820+070 in greater detail.
- Apply spectral and timing analysis techniques to other X-ray binaries.
- Study disk winds, radio jets, and accretion-disk truncation.
- High-Resolution Spectroscopy:
  - Utilize XMM-Newton's RGS and XRISM telescope.
  - Examine absorption and emission features to investigate outflows in detail.
- Combine radio, optical and X-ray data to understand jet formation and accretion-ejection dynamics.

SUMMARY

- Observed dynamic type-c Low-Frequency QPO during hard state.
- Apply spectral and timing analysis techniques to other X-ray binaries.
- Confirmed contracting corona in hard state, leading to higher QPO and soft lag frequencies.
- During state transition, the corona expanded, correlating with ejecta and quenching of jet.
- Detected absorption features suggesting equatorial disk winds, however, further detailed spectroscopy is required.
- **Future Research Directions**: Incorporate more complex models and extend techniques to other XRBs. Conduct high-resolution spectroscopy and multiwavelength observations.

Thank you!