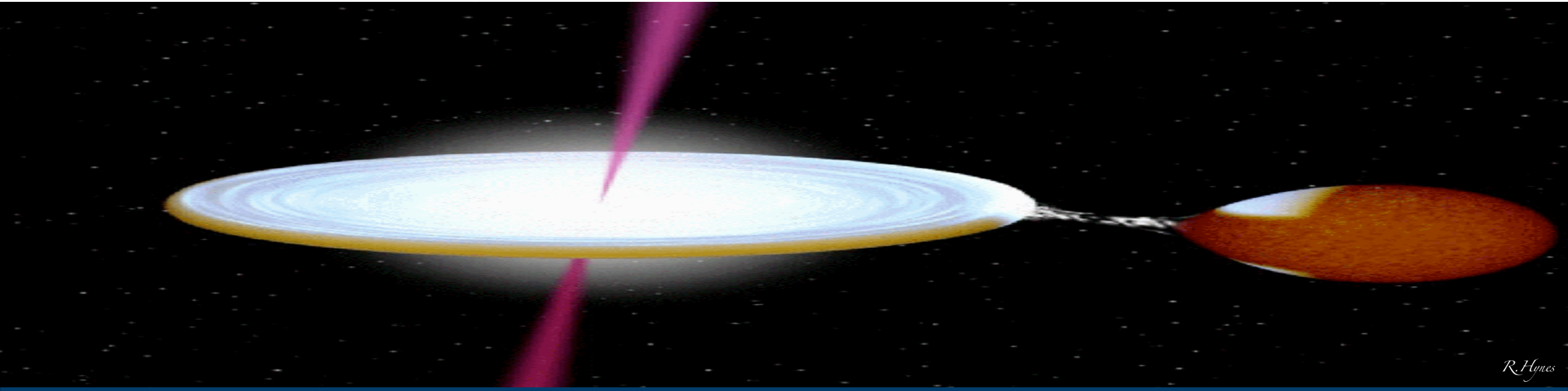


EVOLUTION OF QPOS AND SPECTRAL PROPERTIES DURING X-RAY BINARY OUTBURST

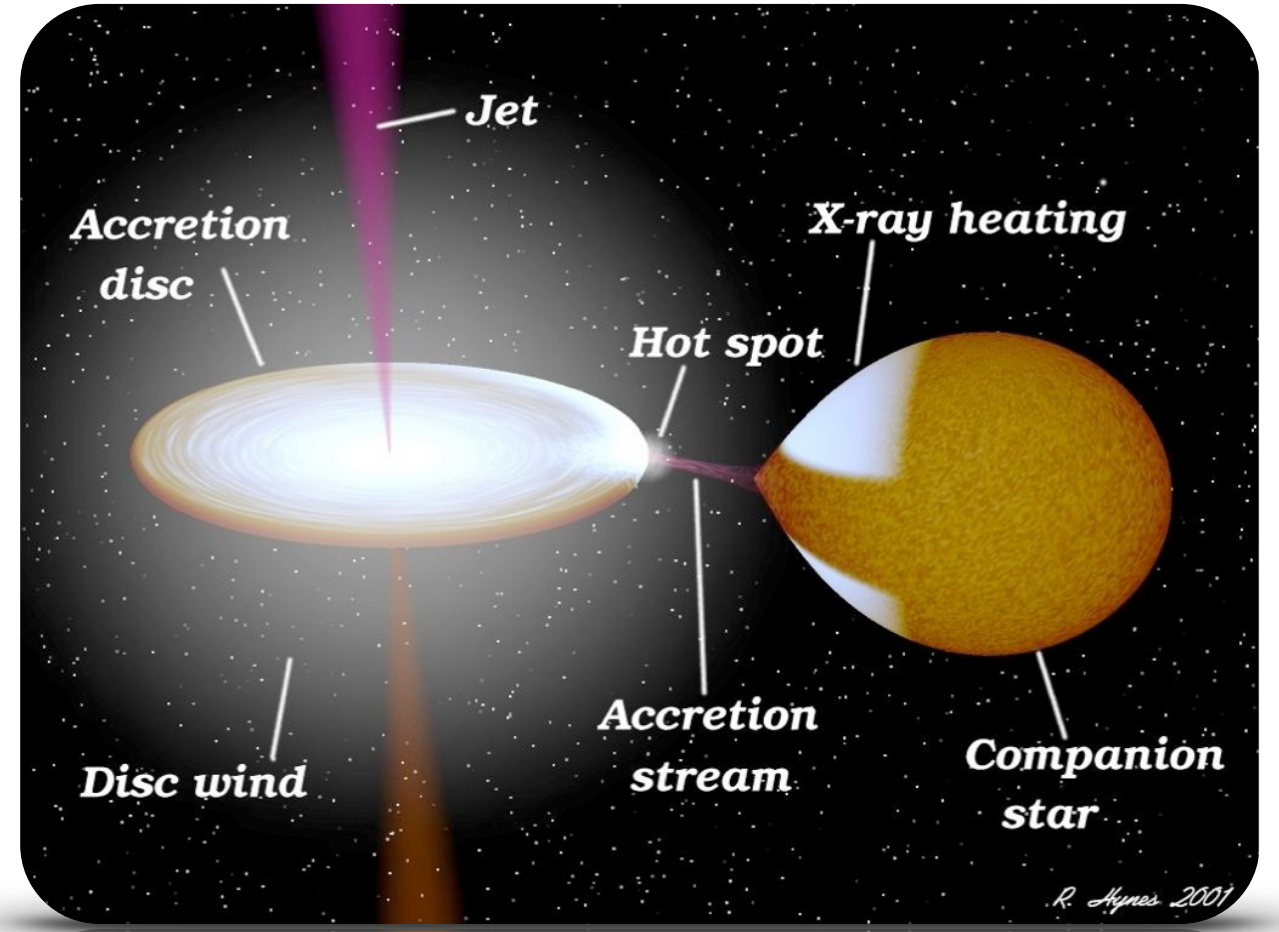
31.07.2024 I HOLGER STIELE (JSC) & ALBERT KONG (NTHU)

MNRAS **522,** 268–274 (2023)
Stiele & Kong 2024, A&A, subm.

JSC: Jülich Supercomputing Centre
NTHU: National Tsing Hua University

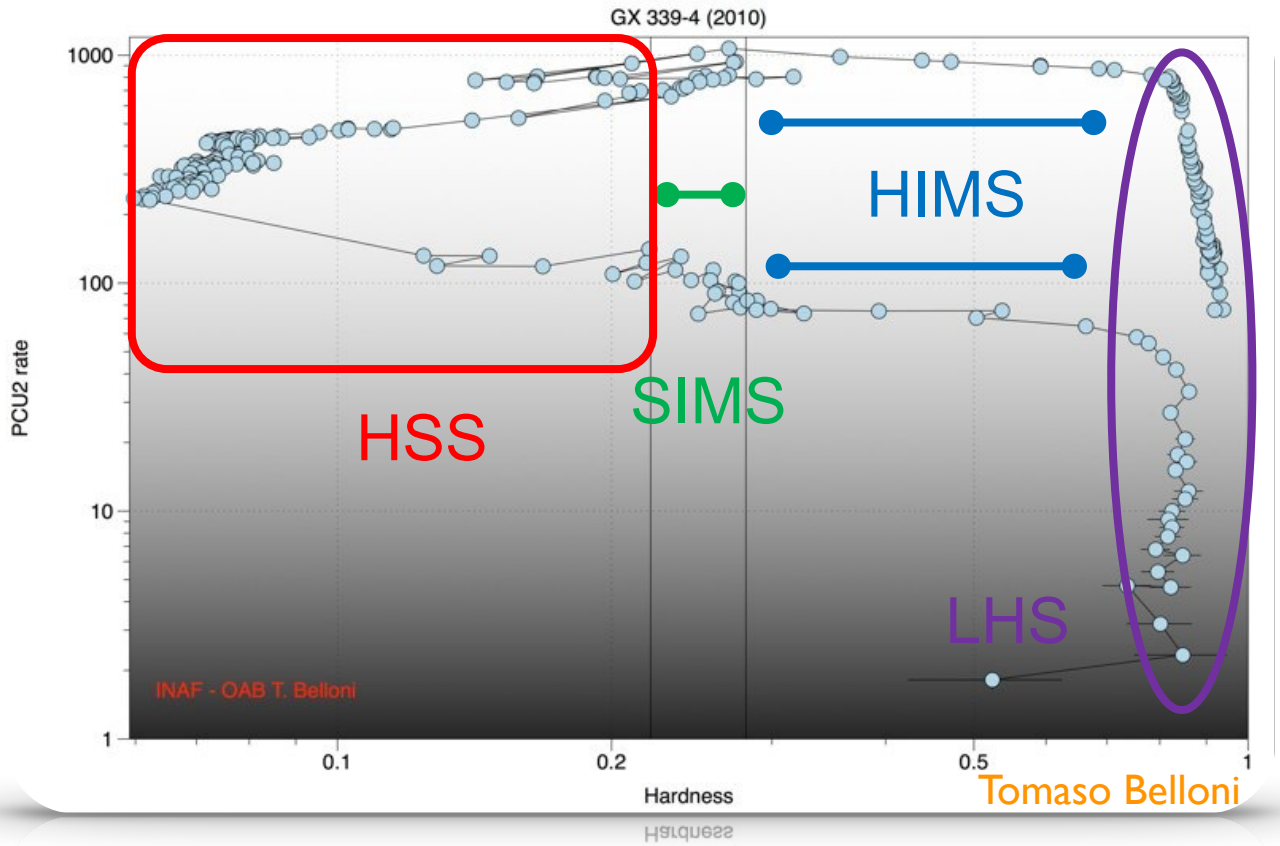
LOW MASS BLACK HOLE X-RAY BINARY

- Central object is a stellar mass (3-20 $M_\odot$) black hole
- Accretes matter from its low mass companion star (Ms ≲ 1 $M_\odot$, type A,F,G,K,M) through a disc (Rochelobe overflow)
- X-ray emitting region close to event horizon RS
- ~200 sources
- ~50 black holes



OUTBURST PROPERTIES OF BHXRBS

Hardness-intensity diagram



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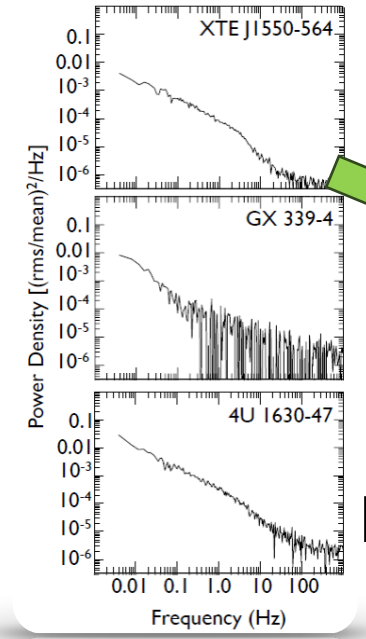
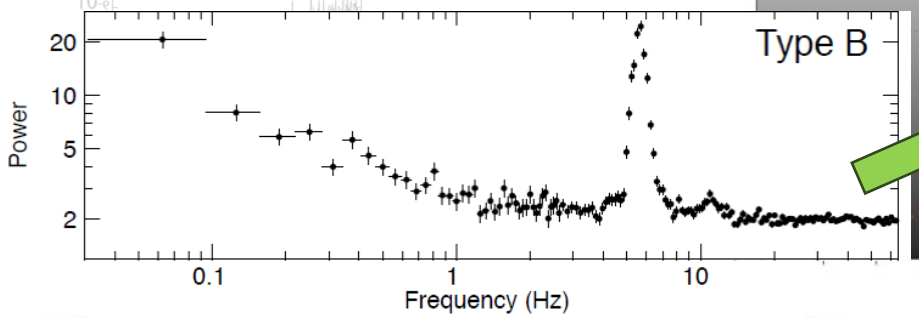


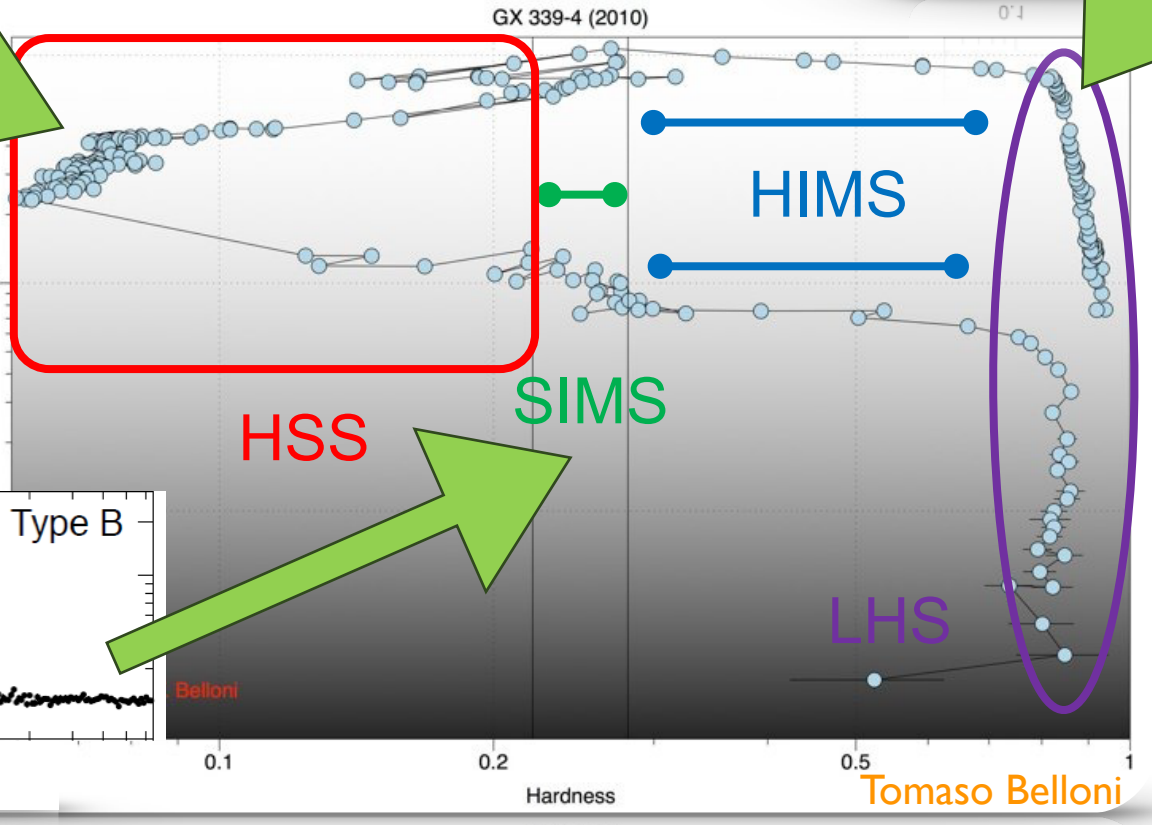
McClintock & Remillard 2006 Black Hole binaries

Power law noise

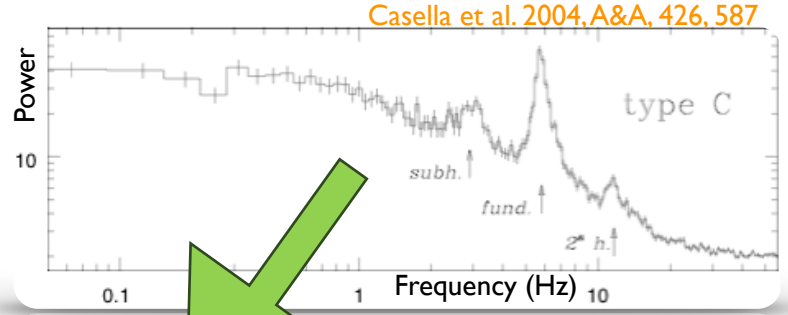


Casella et al. 2004, A&A, 426, 587

Hardness-intensity diagram



Tomaso Belloni



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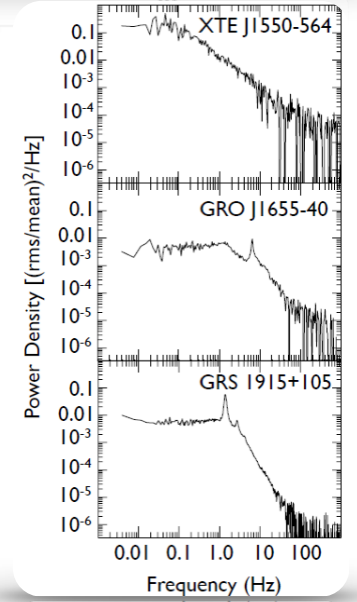
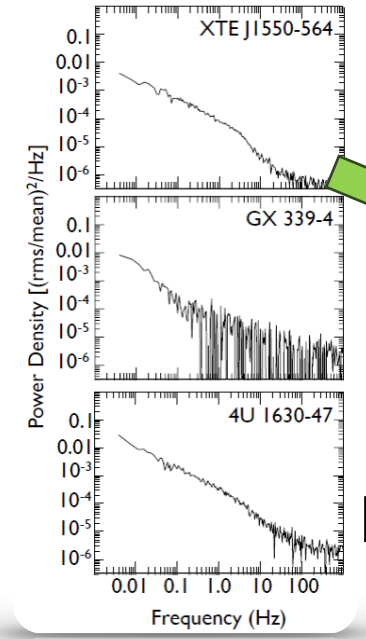


McClintock & Remillard 2006 Black Hole binaries

Band limited noise and QPO

OUTBURST PROPERTIES OF BHXRBS



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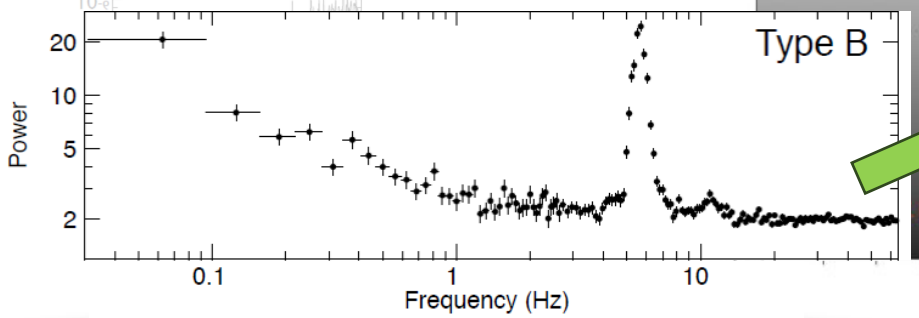

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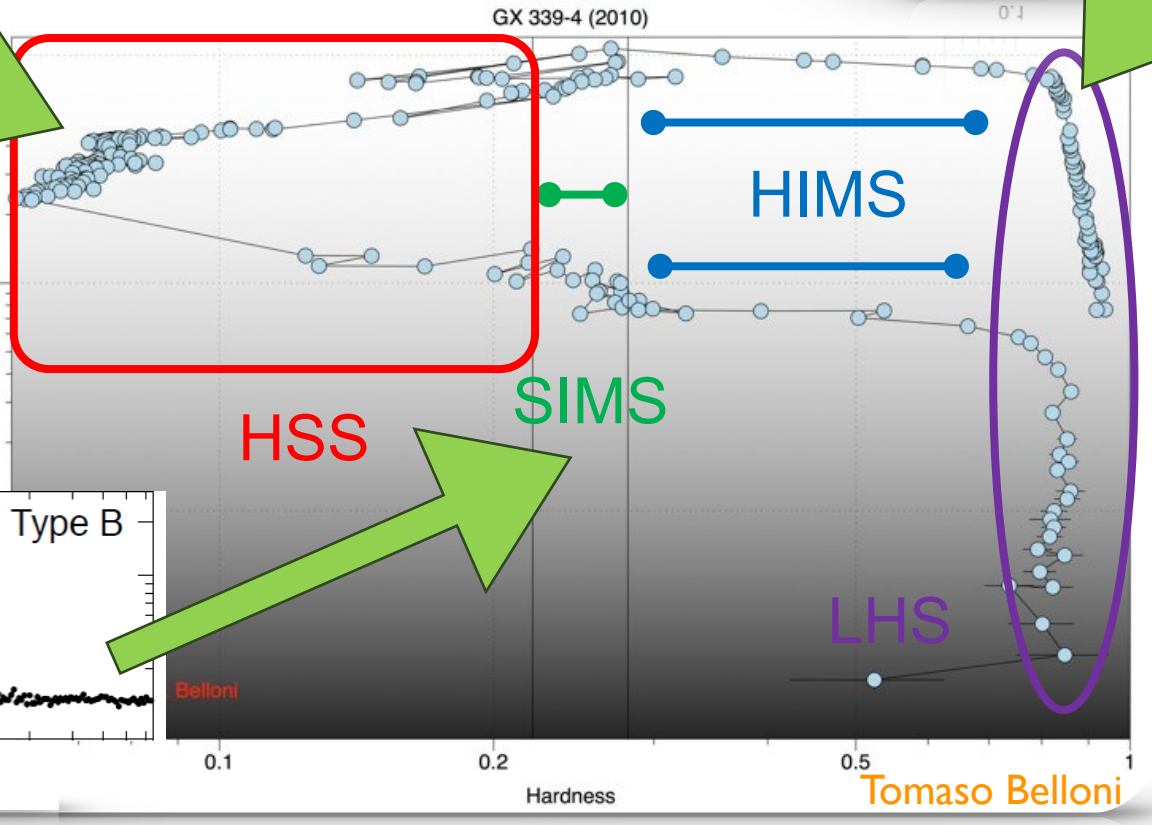
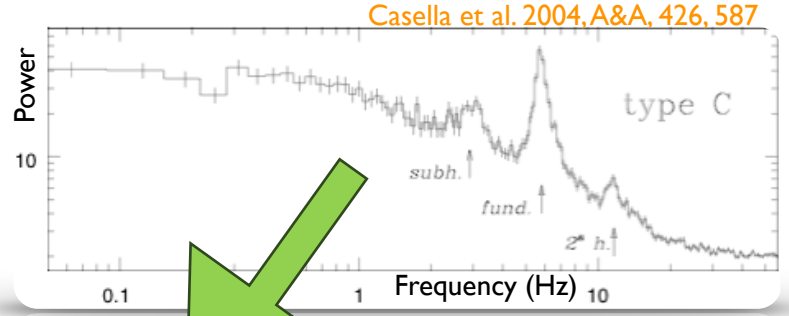


Tomaso Belloni

About 40% of sources remain in the hard state

Tetarenko et al. 2016, ApJS, 222, 15



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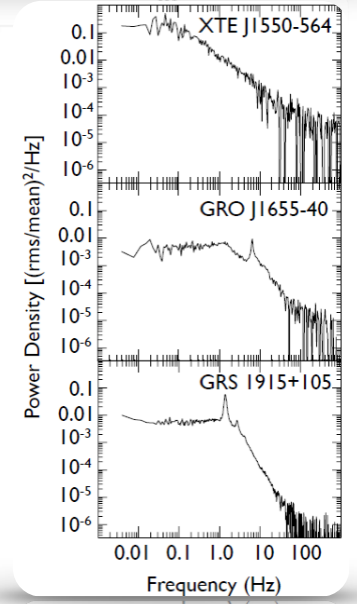
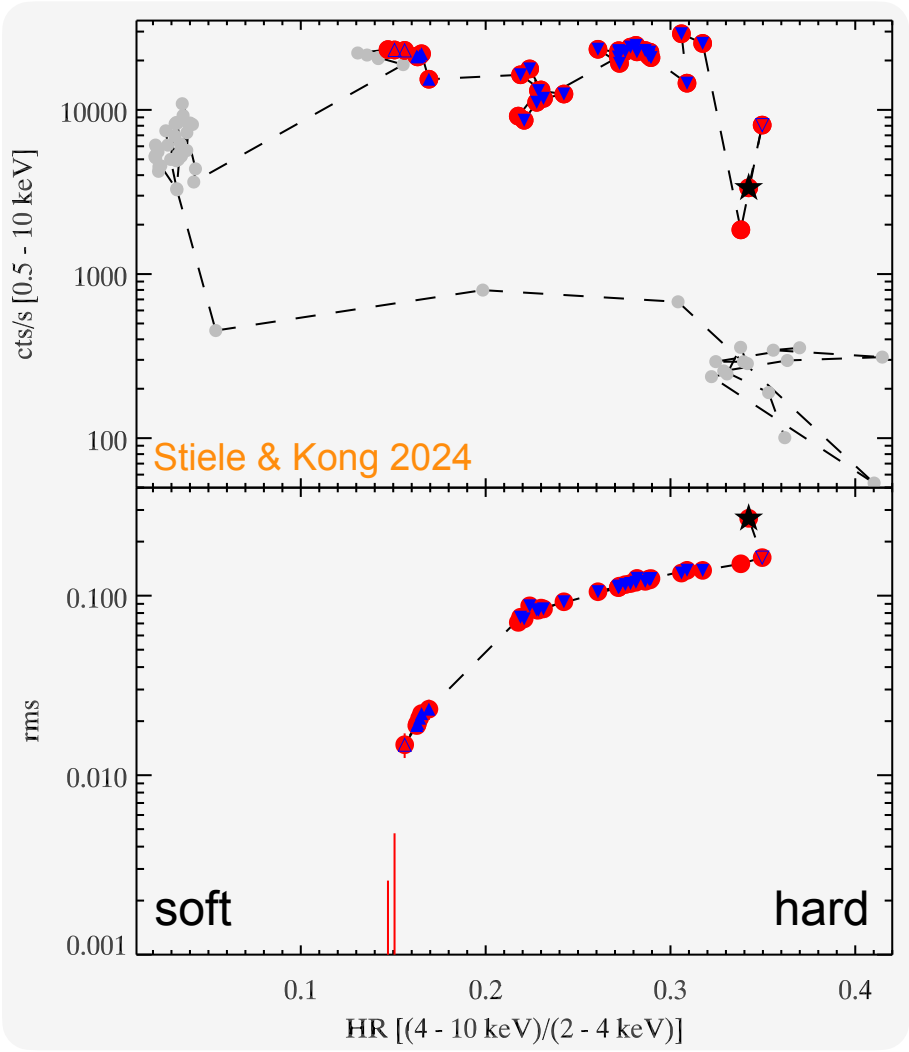


McClintock & Remillard 2006 Black Hole binaries

Band limited noise and QPO

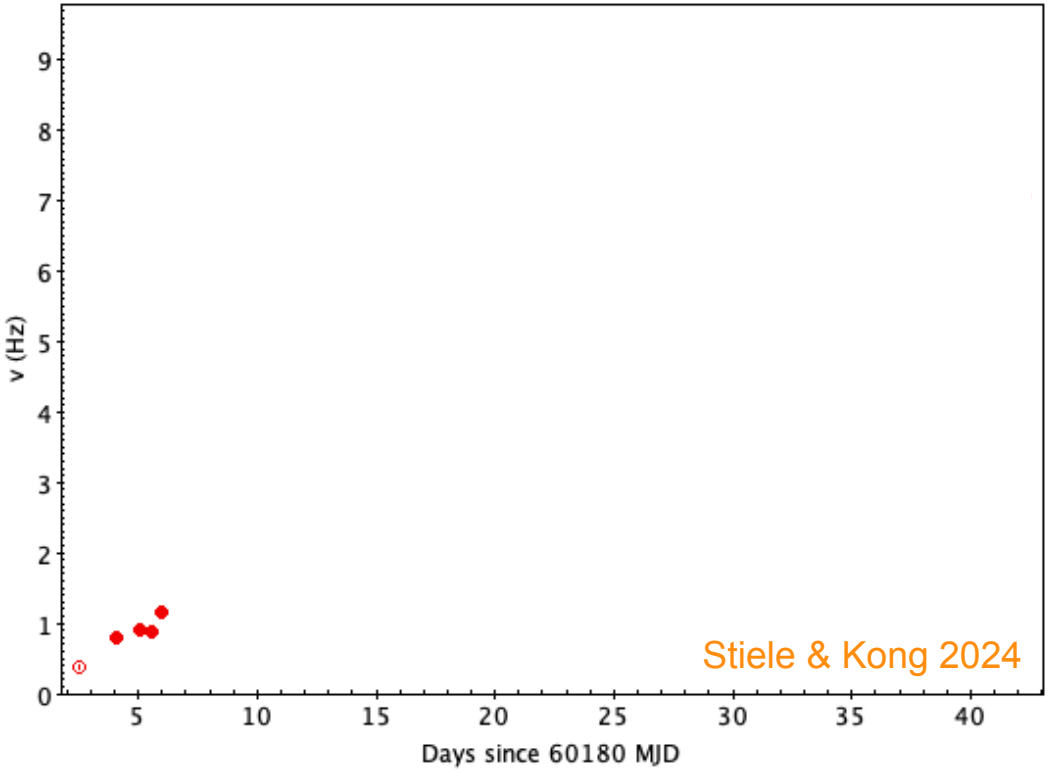
NICER VIEW OF THE 2023/24 OUTBURST OF SWIFT J1727.7–1613

- NICER started observing on 2023 August 25
- **SwiftJ1727.7–1613** shows typical evolution from the hard to the soft state
- Here we focus on observations between 25 August and 9 October



EVOLUTION OF QPOS

- From day 2 to day 42 PDS show two BLN, a QPO and its upper harmonic
- Observe increase in characteristic frequency from about ~0.4 to 1.3 Hz



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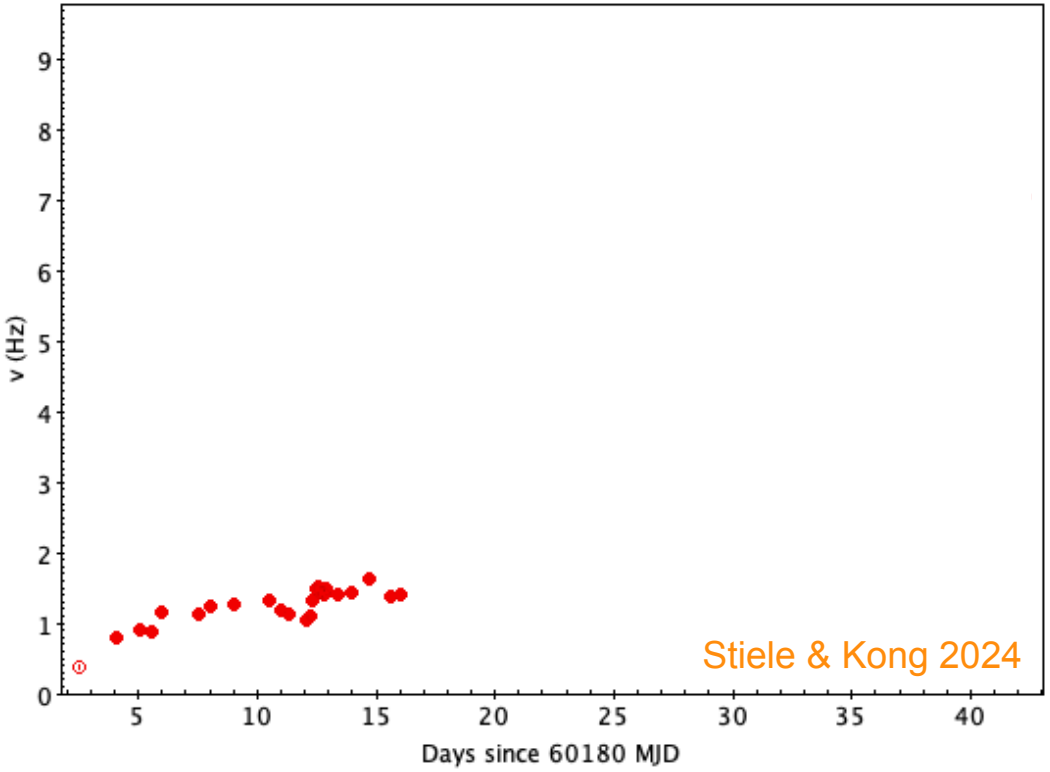

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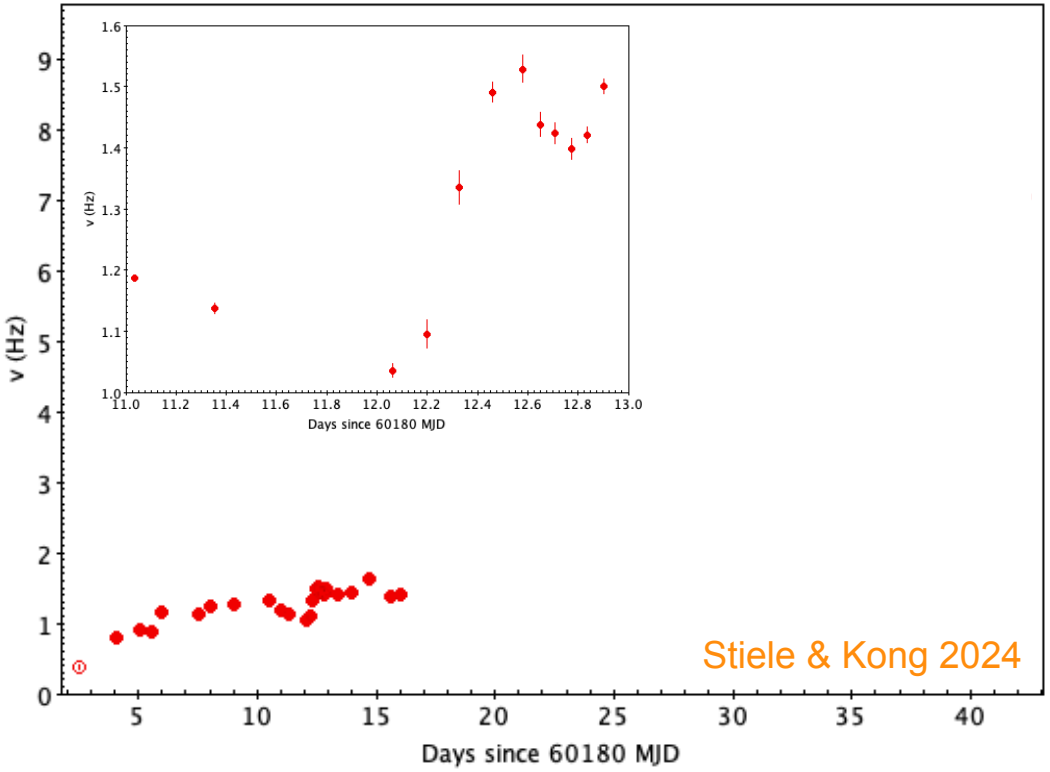

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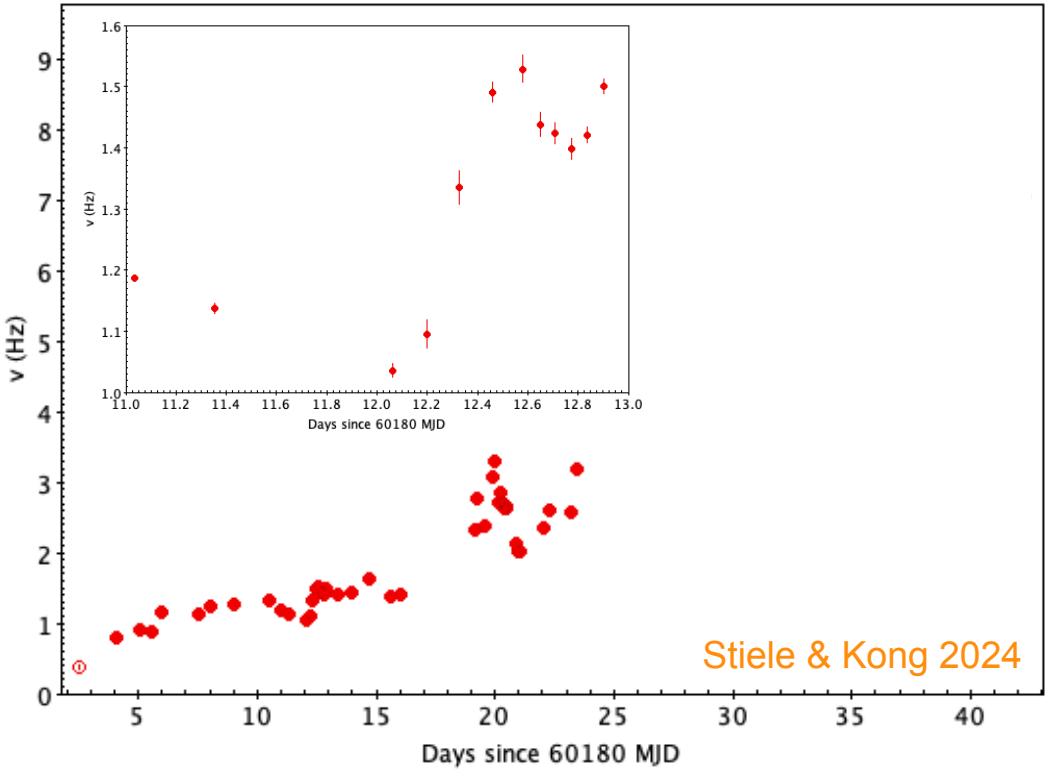

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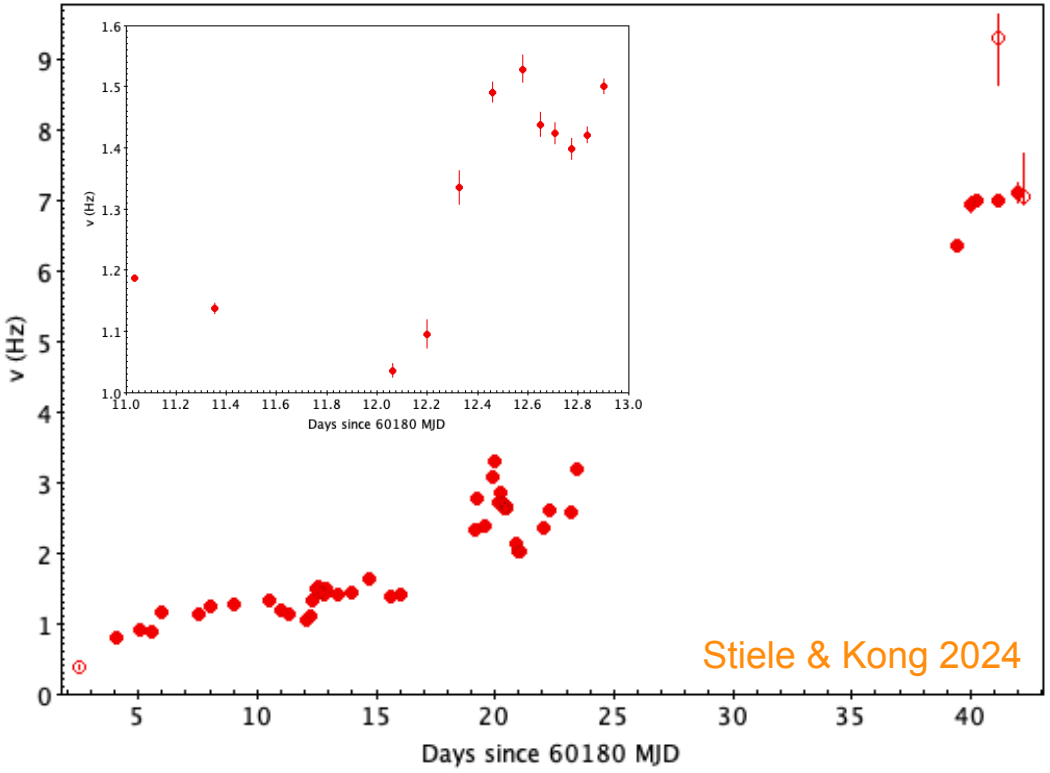

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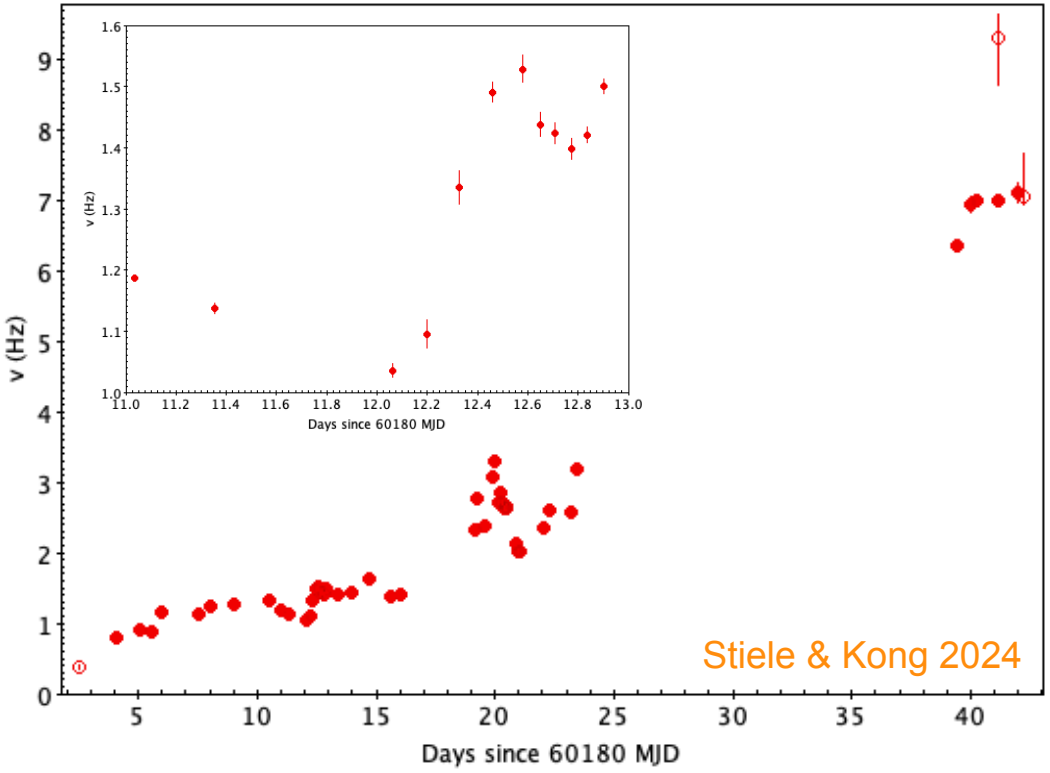
- Consistent with evolution in LHS & HIMS

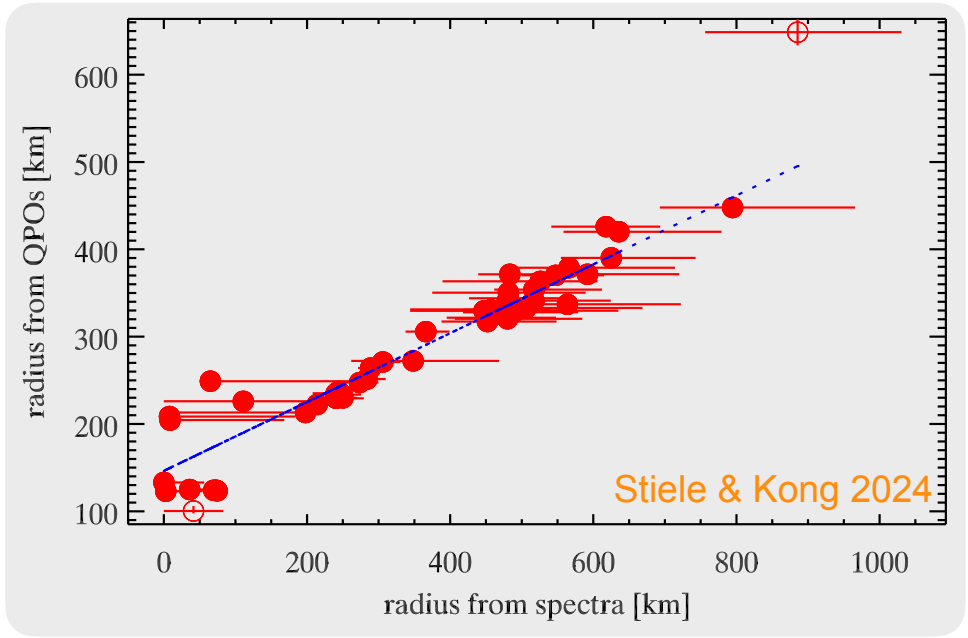


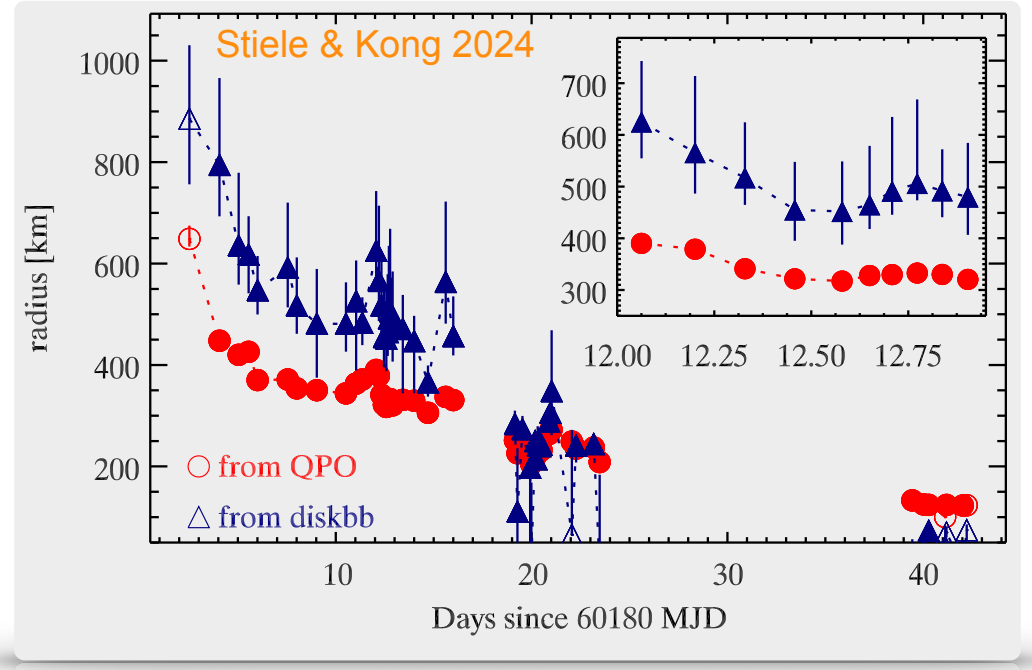
RADIUS FROM FUNDAMENTAL QPO

- One model to explain type-C QPOs: Lense-Thirring precession of a hot inner flow in a truncated accretion disc (Stella & Vietri 1998; Ingram et al. 2009):
- $$\nu_{\mathrm{prec}} = \frac{5-2\zeta}{\pi(1+2\zeta)} \frac{a_* \left[1-(r_i/r_o)^{1/2+\zeta}\right]}{r_o^{5/2-\zeta} r_i^{1/2+\zeta} \left[1-(r_i/r_o)^{5/2-\zeta}\right]} \frac{c}{R_g} \approx \nu_c$$
- $\zeta = 0$; $r_i \sim 2.5(h/r)^{-4/5} a^{2/5}$ with $h/r = 0.2$; $a = 0.9$; $M = 10 M_\odot$
- r_o outer radius of hot flow < inner radius of accretion disc
- ν_c 1.09 ↗ 1.34 Hz within 3.08 h ➜ ΔR ~2.66 R_g or v~12717 m/h
- ν_c 1.14 ↗ 1.41 Hz in 10 day ➜ v~165 m/h

COMPARE EVOLUTION OF RADII

- Radii from fitting energy spectra (0.5 – 10 keV) with diskbb model; distance 10 kpc; cos θ = 1
- Disc radius increase from 370 km to 885 km; decay to a plateau~500 km between days 6 and 16; varies ~216 km days 19 – 24; another plateau ~85 km after day 39



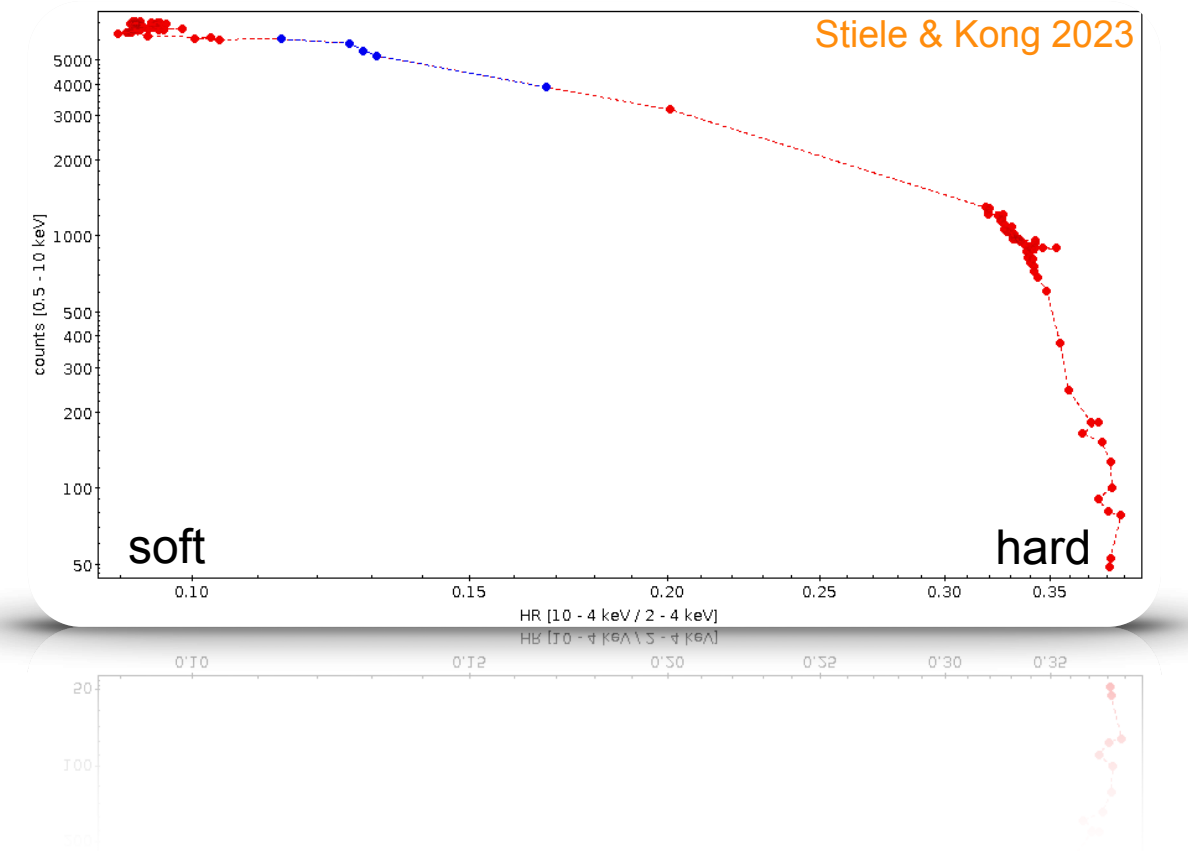


- Similar evolution for the radii obtained by the two methods on days as well as hours timescales

➜ Supports Lense-Thirring precession interpretation

NICER VIEW OF THE 2021 OUTBURST OF GX 339-4

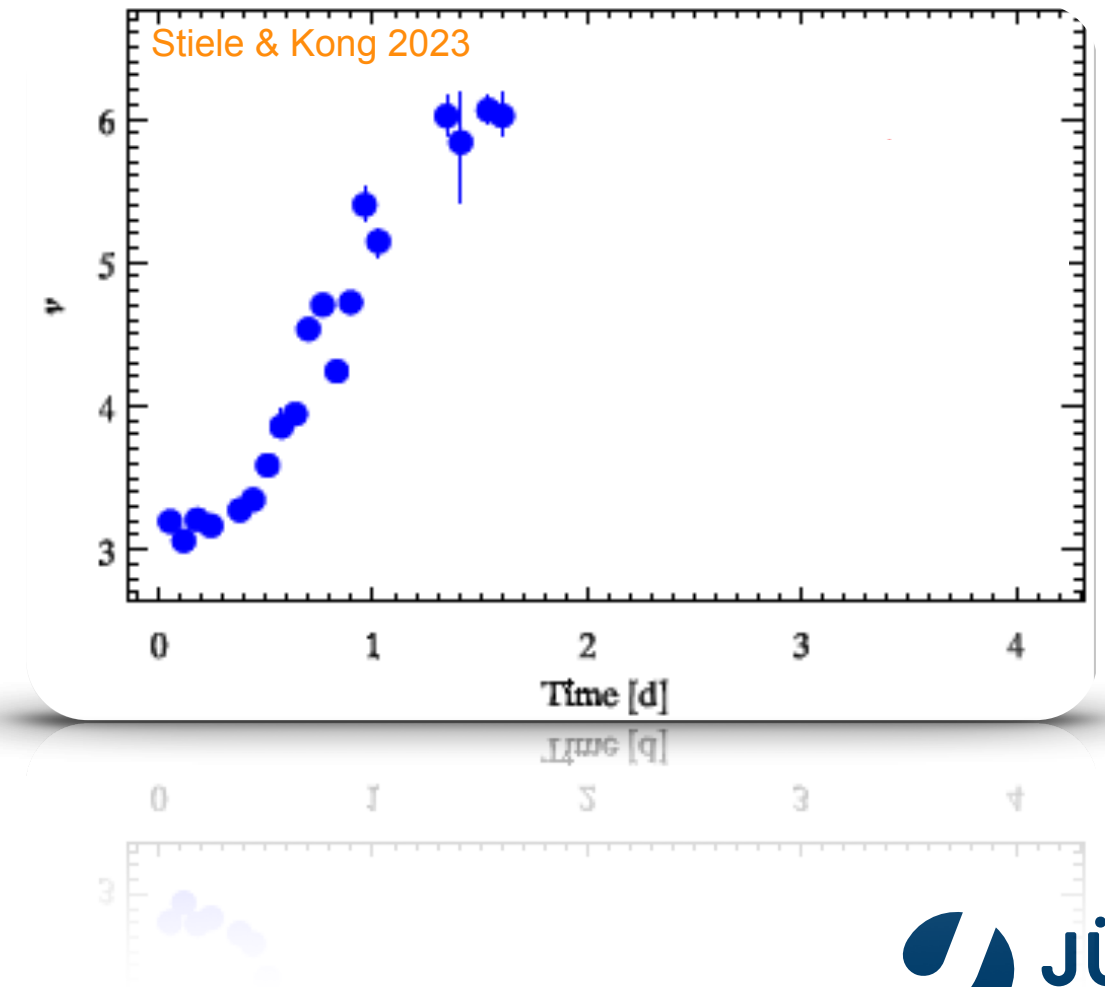
- NICER started observing on 2021 January 25
- **GX 339-4** shows typical evolution from the hard to the soft state
- Here we focus on observations between 27 and 31 March, when GX 339-4 went from the HIMS to the SIMS



JÜLICH Forschungszentrum

EVOLUTION OF QPO FREQUENCY

- Type-C QPO characteristic frequency evolves from 3 to 6 Hz



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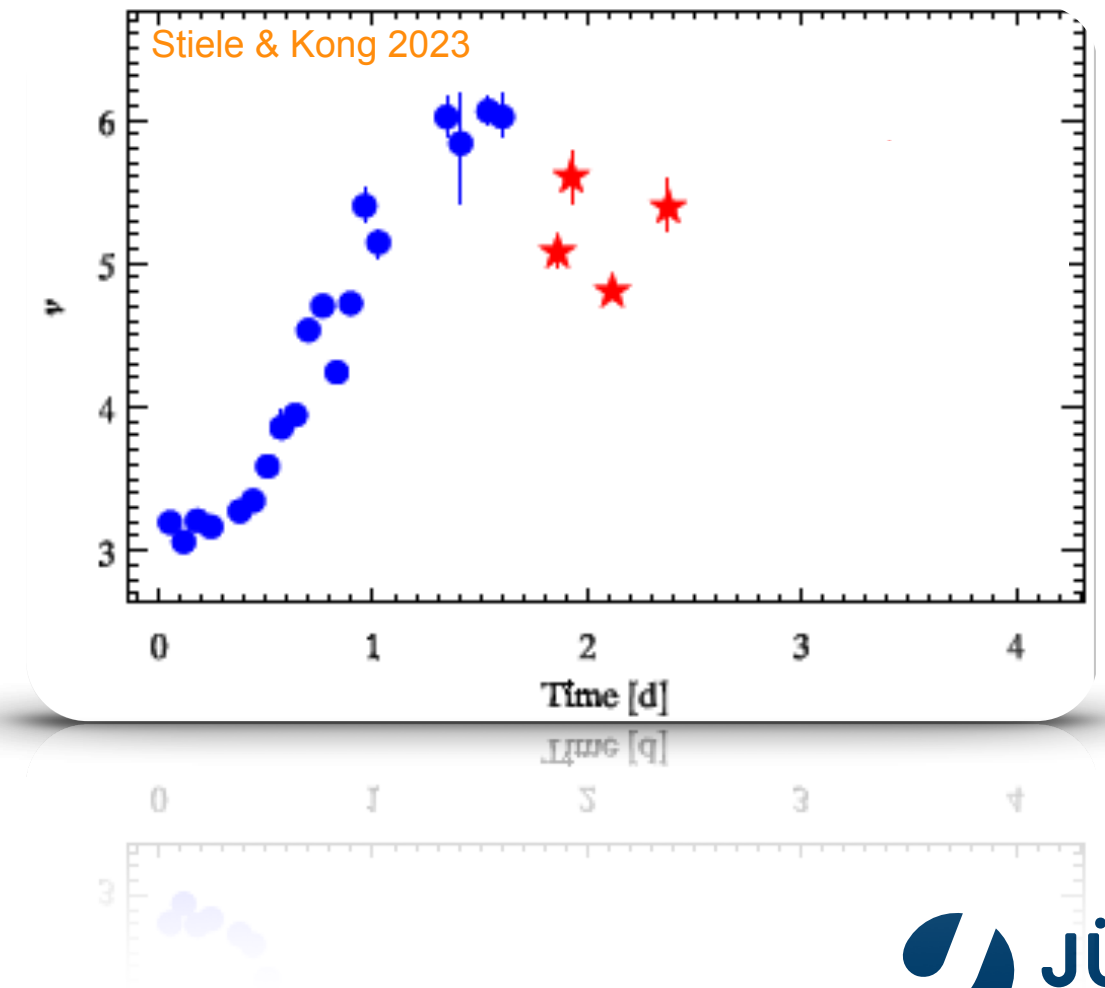
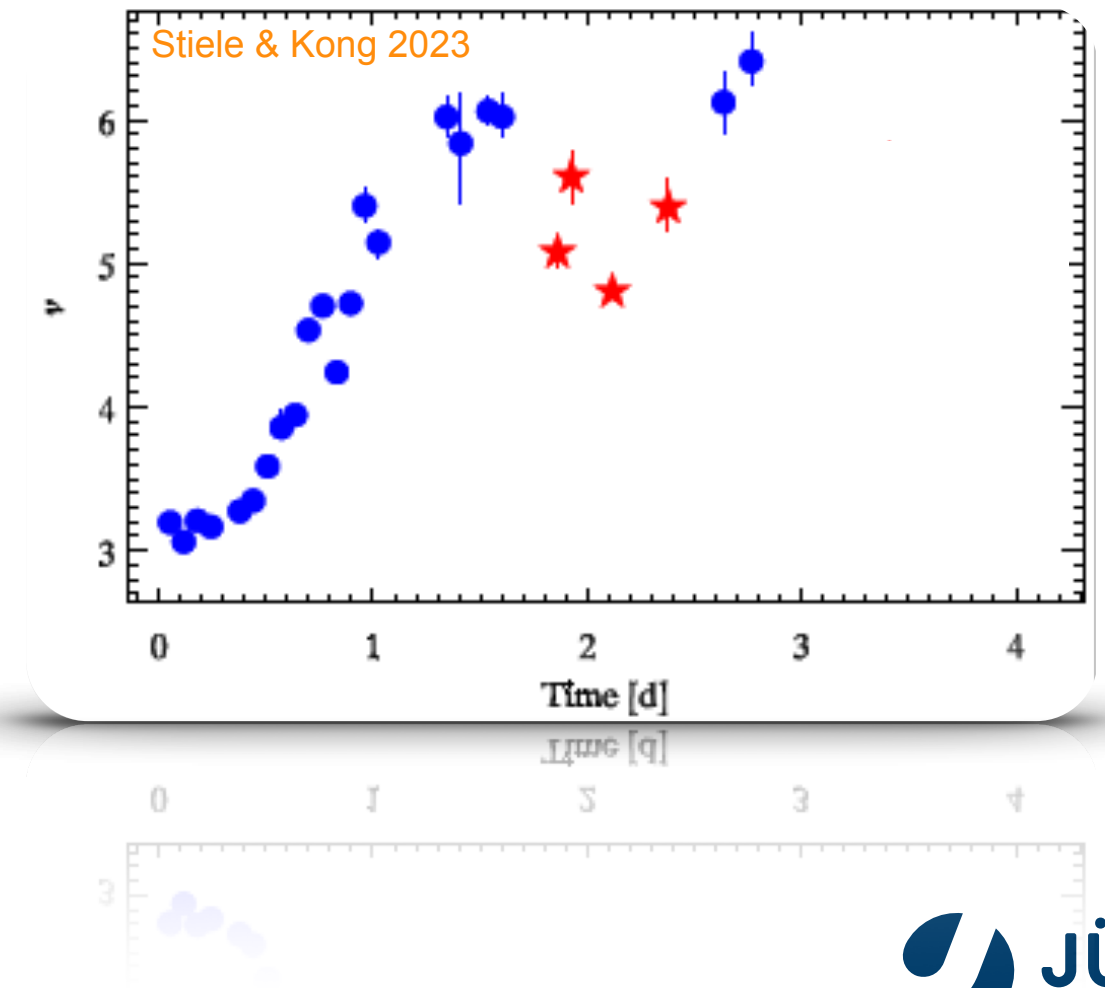
- Type-C QPO characteristic frequency evolves from 3 to 6 Hz
- Then type-B QPO at 5-5.5 Hz appears



EVOLUTION OF QPO FREQUENCY

- Type-C QPO characteristic frequency evolves from 3 to 6 Hz
- Then type-B QPO at 5-5.5 Hz appears
- Type-C QPO reappears at 6-6.5 Hz, continuing the increase in frequency before type-B QPO



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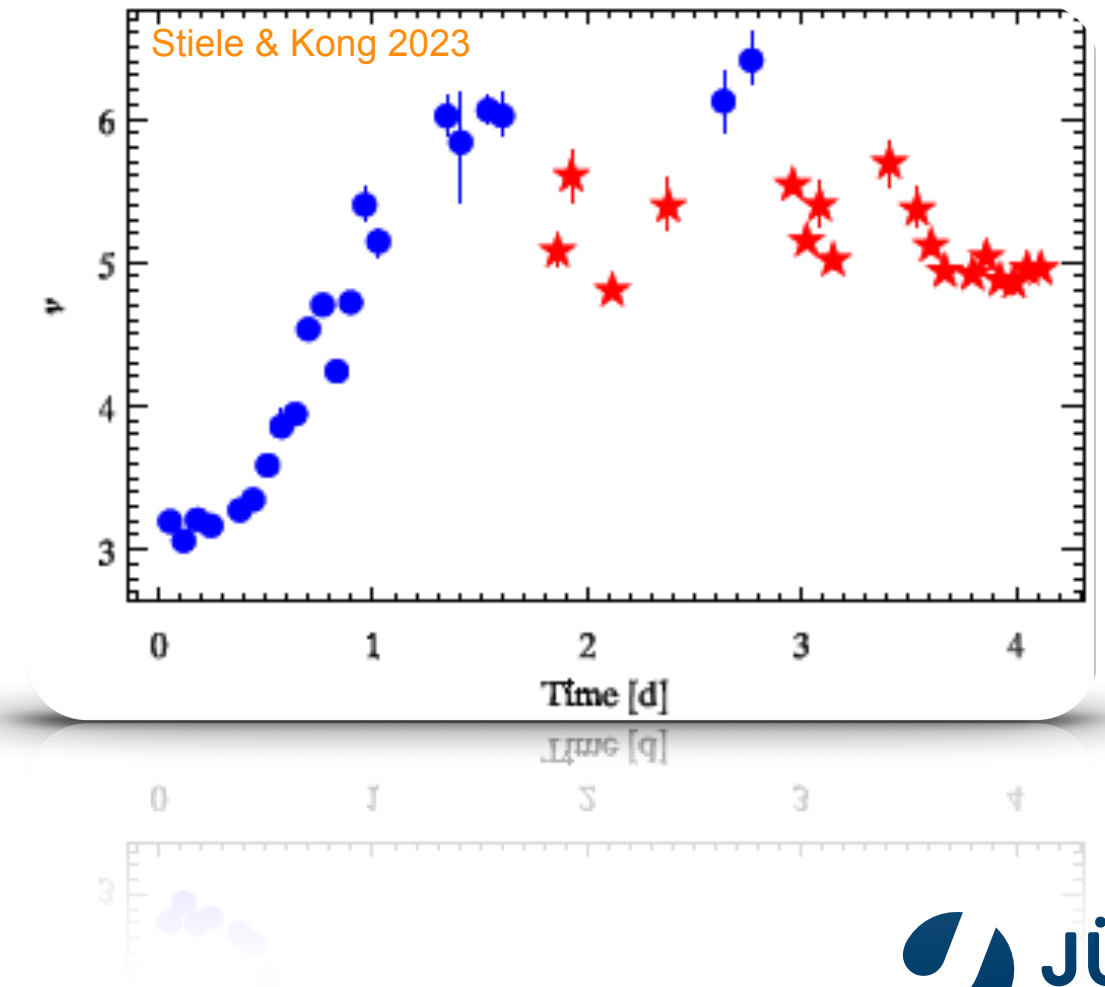
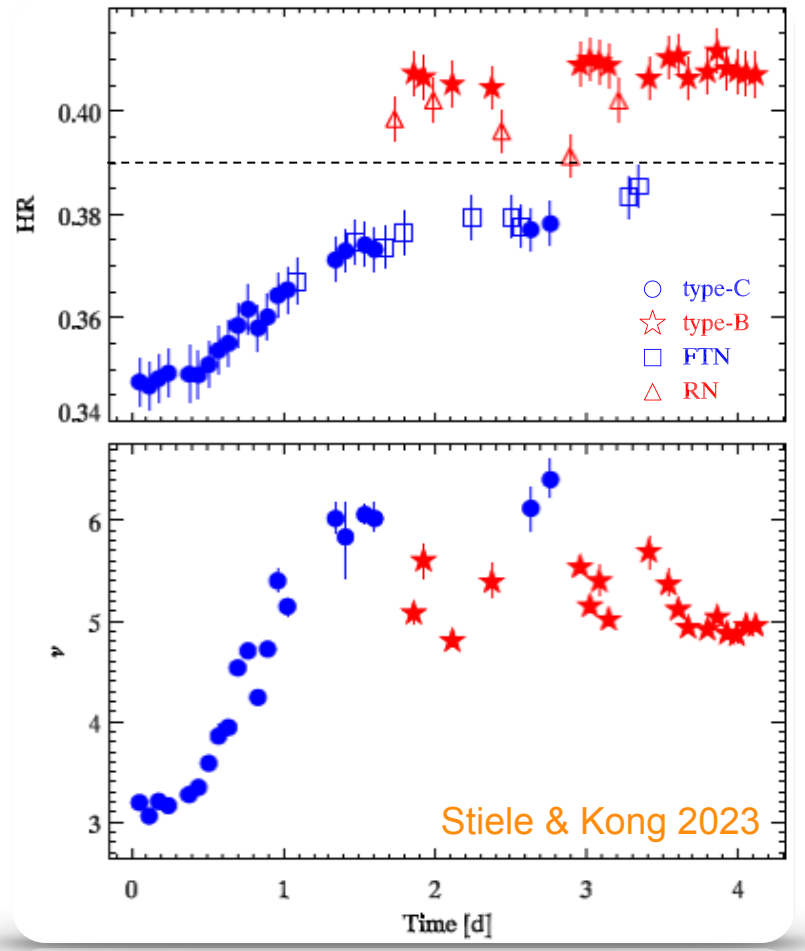
- Type-C QPO characteristic frequency evolves from 3 to 6 Hz
- Then type-B QPO at 5-5.5 Hz appears
- Type-C QPO reappears at 6-6.5 Hz, continuing the increase in frequency before type-B QPO
- Again type-B QPO at 5-5.5 Hz
- Decrease in frequency?



EVOLUTION OF HARDNESS RATIOS

- Hardness ratio: 0.5 – 2 keV / 2 – 10 keV
- Red noise and type-B QPOs appear above a HR value of 0.39
- Flat-top noise and type-C QPOs are observed at lower HR values
- Transition between the two states is related to a change in the accretion geometry that shows up in a change of the spectral properties
- Not changes in the spectral shape, but in the contribution of flux in the hard band (Motta et al. 2011)

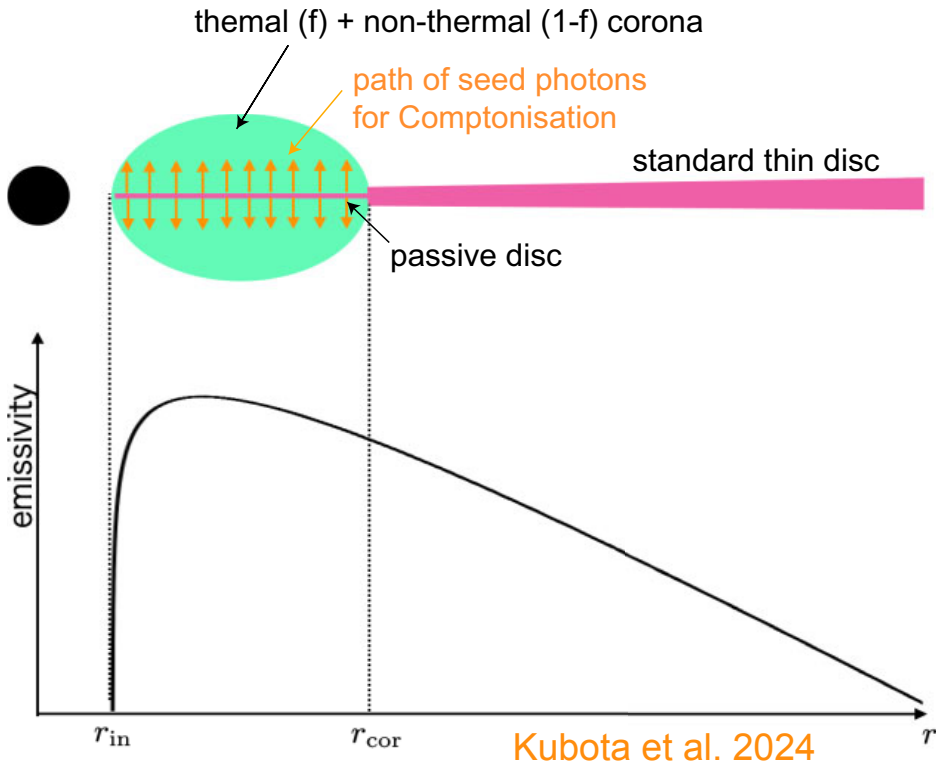


DISCUSSION

- The results shown here, clearly support the idea that the two different QPO types are caused by two distinct mechanisms
- Transition from HIMS to SIMS is a gradual process that is intermitted by excursions back to the HIMS ➔ Changes of QPO type is an interplay between two processes
- Similar results found from RXTE data (Motta et al. 2011), however on a much coarser time scale, compared to the scale of hours that is accessible with NICER
- Type-B QPO forms from or disintegrates into a broad feature, sometimes showing a “sub-harmonic” peak before the source transits in or out of the HIMS ➔ Strong decoherence in the process that causes the type-B QPO
- Simultaneous detection of type-B and C QPOs in one observation of GROJ1655–40 in its ultraluminous state & Presence of a broad feature at frequencies where a type-B QPO forms (Motta et al. 2012)

LENSE-THINNING PRECESSION

- Three components:
  - Hot inner flow that drives type-C QPO
  - Thin accretion disc
  - Transitional region where passive disc is imbedded in outer non-thermal corona
- ν_c anti-correlated to R_{comp}
- Type-C QPO quenched when disc has moved so far inward that hot flow region gets too small to produce detectable QPO; energy spectrum can still show Comptonized emission thanks to transitional region
- Temporary increase in R_{comp} ➜ reappearance of type-C QPO close to last seen ν_c



DYNAMIC CORONA – DISK SYSTEM

- Based on radiative feedback between a hot e^- population in the corona and soft radiation coming from the accretion disc, due to reprocessing of the hard corona radiation (Mastichiadis et al. 2022)
- Type-C QPOs are identified with damped oscillations
- Because of damping oscillations need to be sustained by small fluctuations in the accretion rate
- To quench type-C QPOs, e^- need to escape quickly from corona; happens when corona shrinks and outflow becomes continuously narrower as source moves from HIMS to SIMS; increase in soft disc radiation supports suppression of type-C QPO
- Shrinking of corona **cannot** be **uni-directed process** and/or fluctuations in the soft disc radiation
- *Can changes in the corona size, soft disc happen on the timescales observed here?*
- Observe continuous evolution in ν_c of type-C QPOs after first appearance of type-B
- If increase in accretion rate drives type-C QPOs, this increase may counteract shrinking of corona and explain the reappearance of type-C QPOs

TWO COMPTONIZATION REGIONS

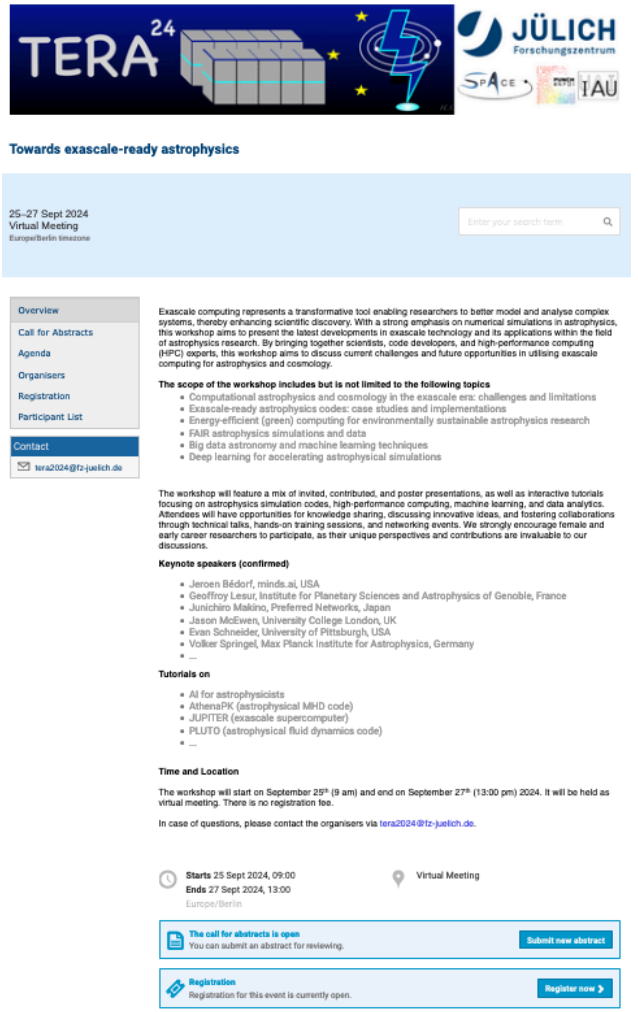
- Two Comptonization regions to explain type-B QPOs (García et al. 2021; Peirano et al. 2023; Kylafis et al. 2020)
- Two component corona for type-C QPOs (Karpouzas et al. 2020, 2021)
- Corona and disc size anti-correlated for $\nu_c \gtrsim 2$ Hz, correlated for lower frequencies (Karpouzas et al. 2021)
- Large size of corona at high frequencies makes it challenging to explain „fast“ transitions between type-C and B QPOs
- If both type-C and B QPOs are caused by two-component corona ➜ kind of „oscillation“ between the two Comptonization regions

SUMMARY

- Follow hard to soft evolution of SwiftJ1727.7–1613 with NICER
- Consistent evolution of radii obtained from ν_c of type-C QPOs assuming Lense-Thirring precession and radii obtained from diskbb model
- Follow GX 339–4 from the HIMS to the SIMS with NICER; PDS and HR for individual snapshots ➜ evolution
- The results shown here, clearly support the idea that type-C and type-B QPOs are caused by two distinct mechanisms
- In dynamic corona - disc system: Can changes in the corona size, soft disc happen on the timescales observed here?
- With two Comptonization regions: Cause of „oscillations“ between them?

TOWARDS EXASCALE-READY ASTROPHYSICS

- 3-day workshop on exascale computing for astrophysics and cosmology
- Features a mix of keynote, contributed, and poster presentations, as well as tutorials focusing on astrophysics codes and high-performance computing
- Audience of scientists, code developers, and HPC experts
- Starts on Sept 25th at 9:00 am
- Ends on Sept 27th at 12:30 pm
- Virtual meeting
- No registration fee
- Webpage: https://indico3-jsc.fz-juelich.de/e/tera2024



EVOLUTION OF THE ENERGY SPECTRUM

- 0.5 – 10 keV range; fitted with XSpec
- Background: SCORPEON model
- Source: tbabs (diskbb + nthcomp + gaussian)

~6.6 keV; iron line

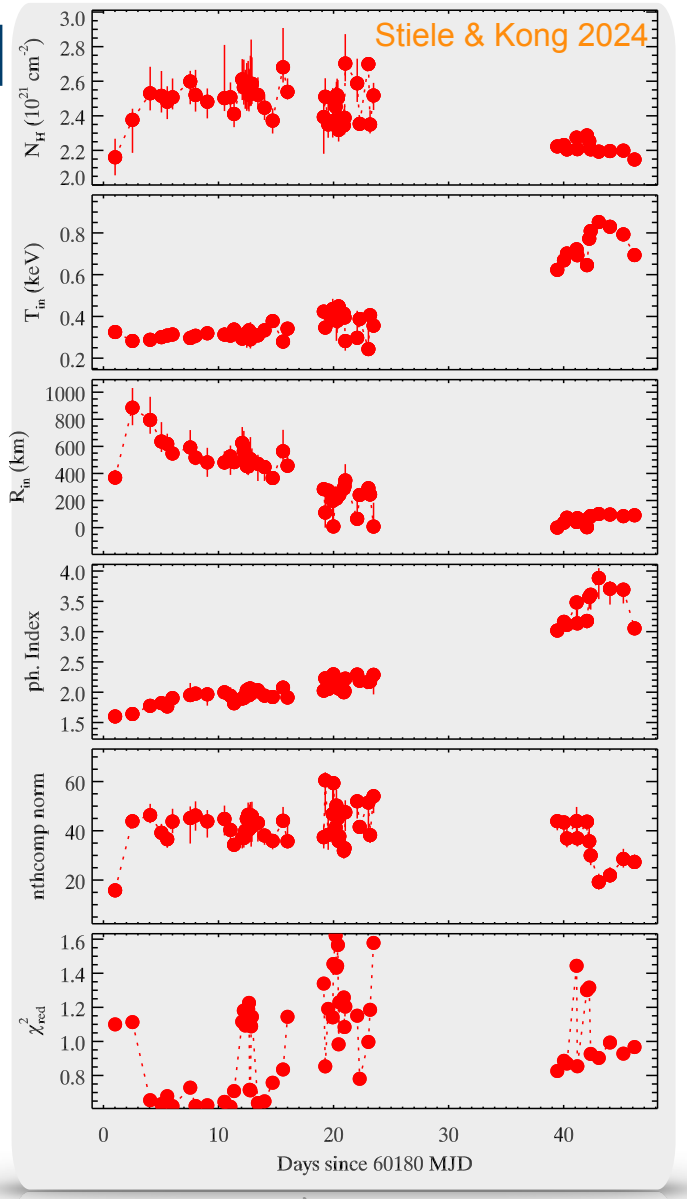
Wilms et al. (2000)

Mitsuda et al. (1984)

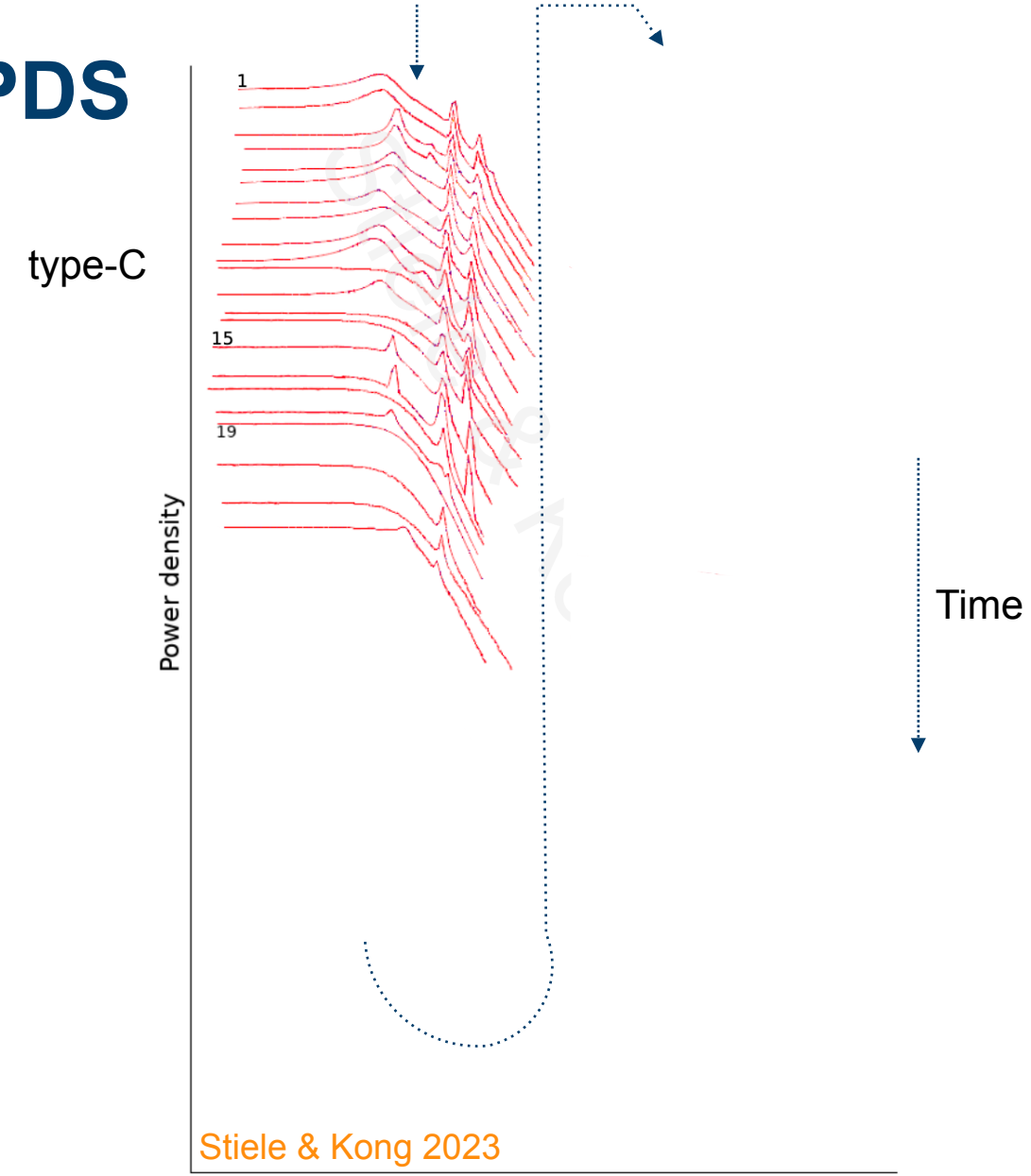
Zdziarski et al. 1996

Życki et al. 1999

- Averaged foreground N_H ~ 2.43x10^{21} cm^{-2} similar to that of other Galactic XRBs
- Accretion disc temperature constant ~0.31 keV up until day 16; varies ~0.38 keV days 19 – 23; 0.62–0.85 keV days > 39
- Disc radius increase from 370 km to 885 km; decay to a plateau~500 km between days 6 and 16; varies ~216 km days 19 – 24; another plateau ~85 km after day 39
- Photon index increases from 1.6 to ~2.3 on day 23; after day 39 Γ ~ 3.0 – 3.9

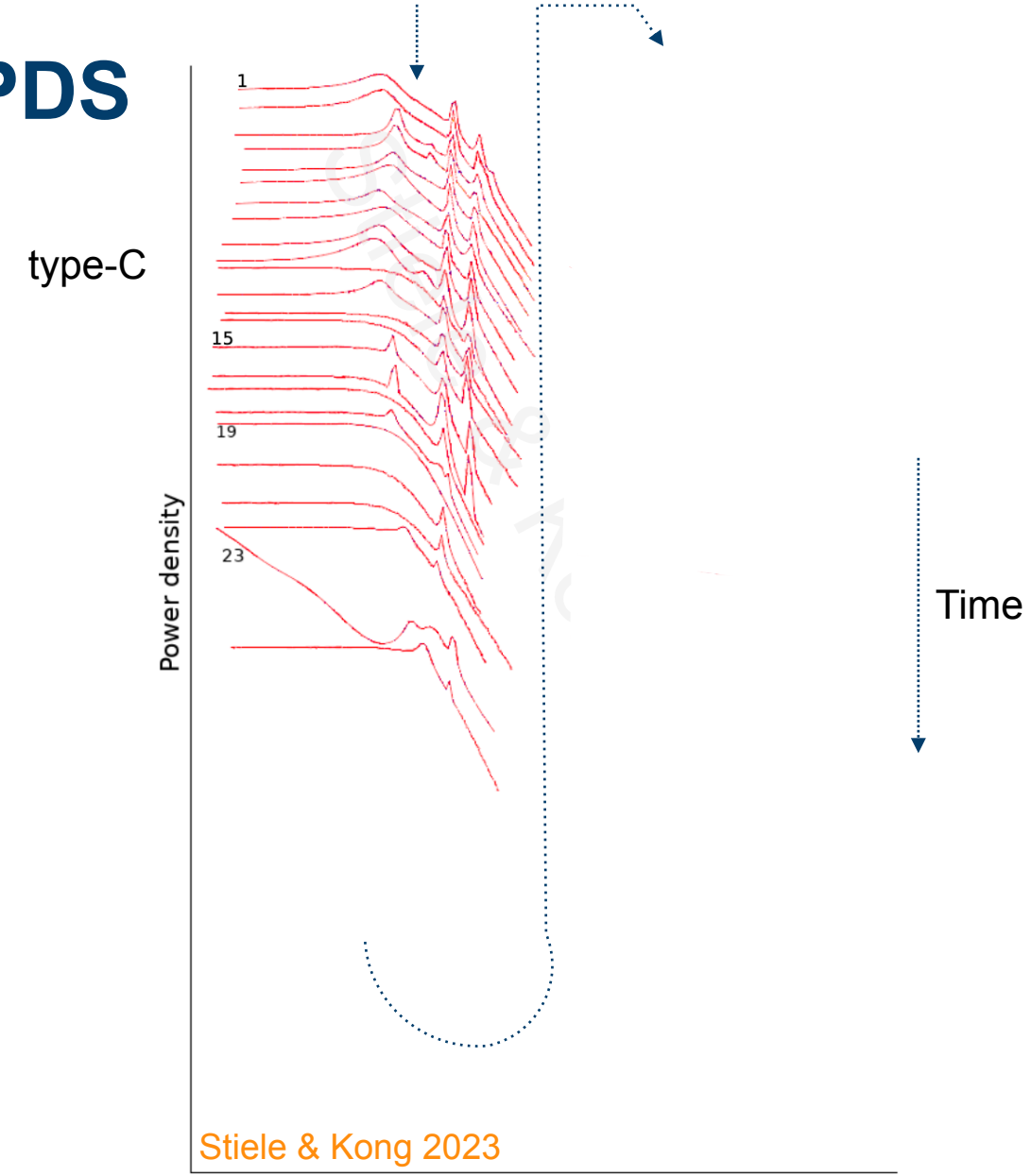


EVOLUTION OF PDS



Stiele & Kong 2023

EVOLUTION OF PDS



Stiele & Kong 2023

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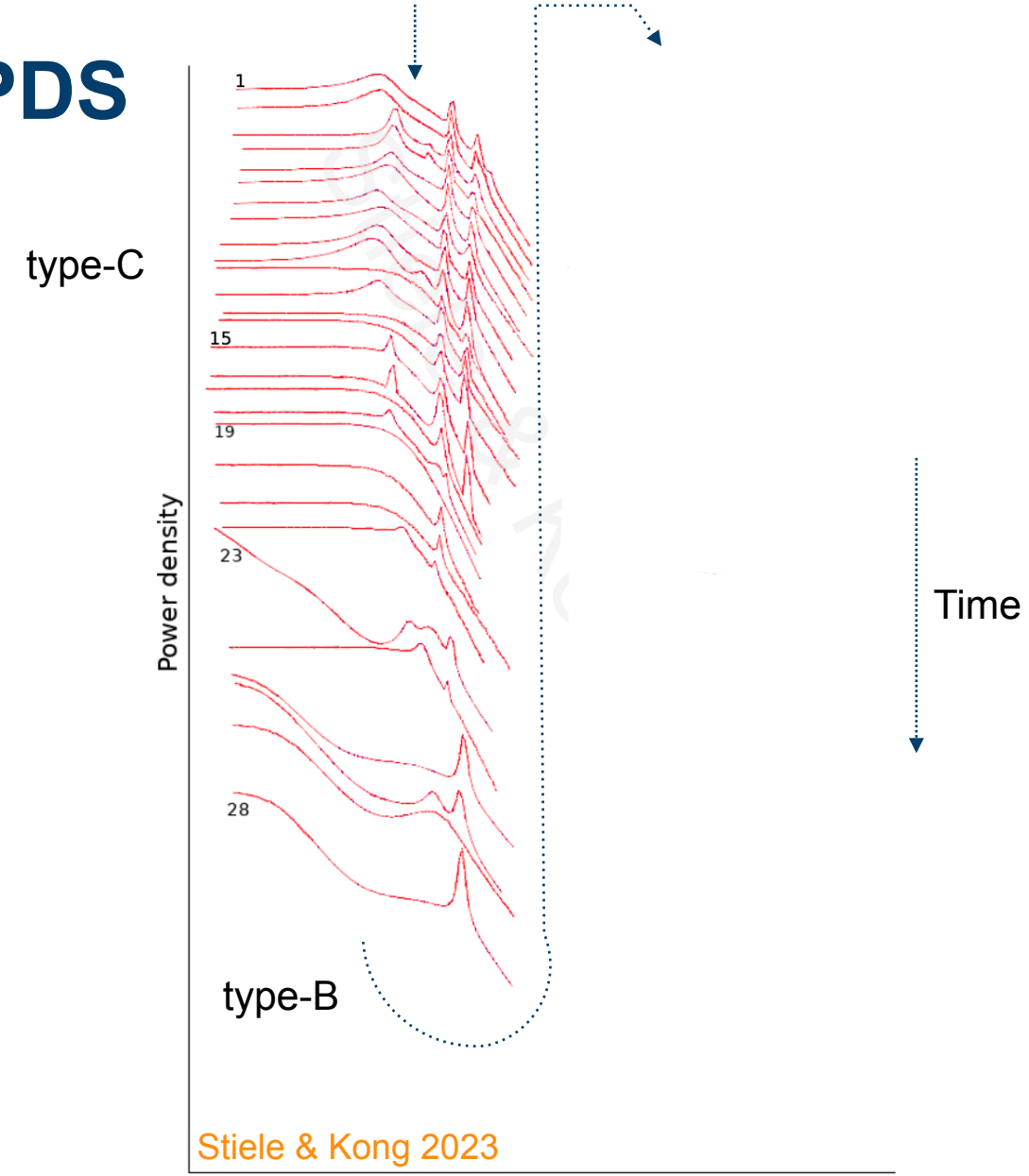

Stiele & Kong 2023

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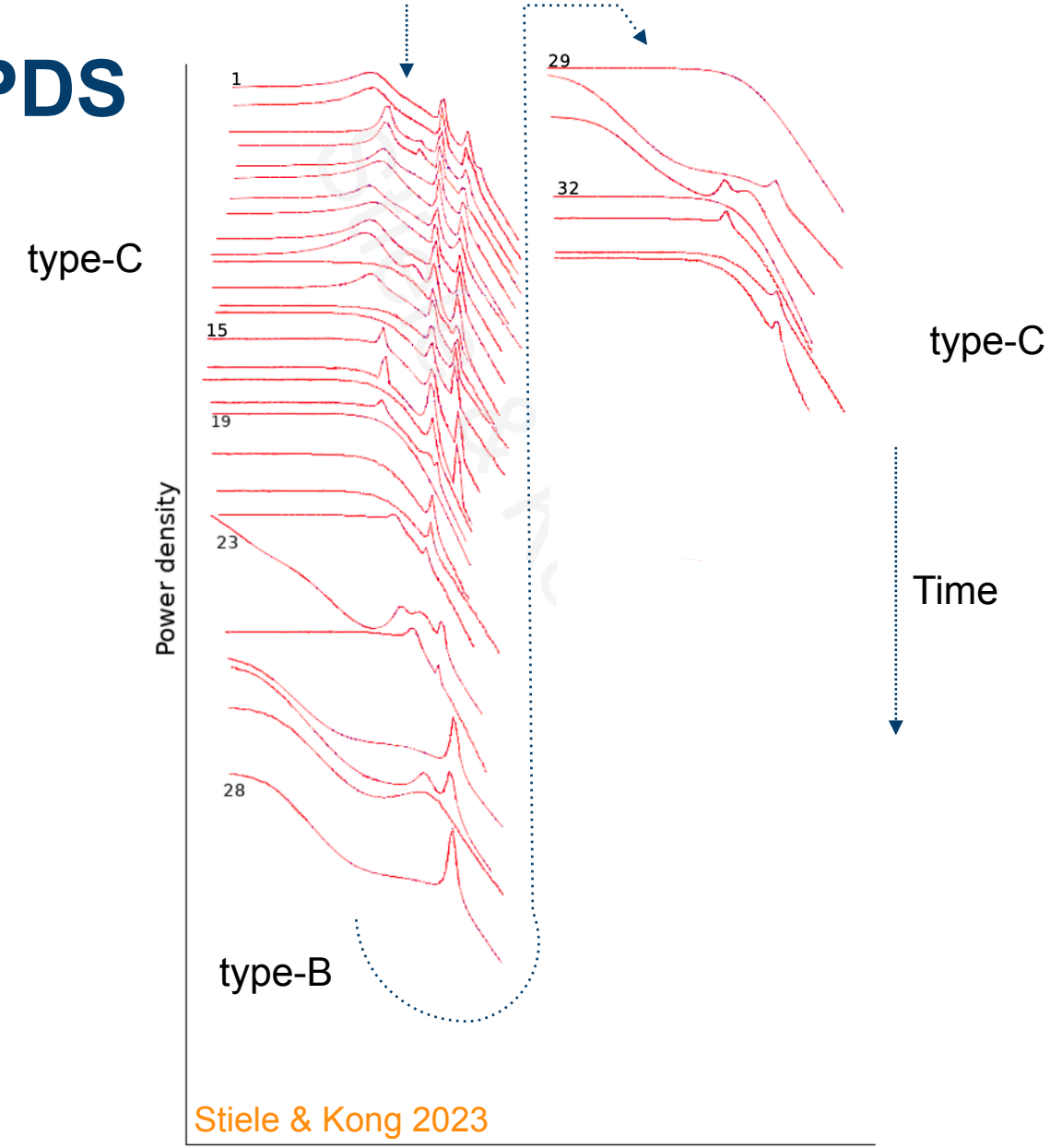

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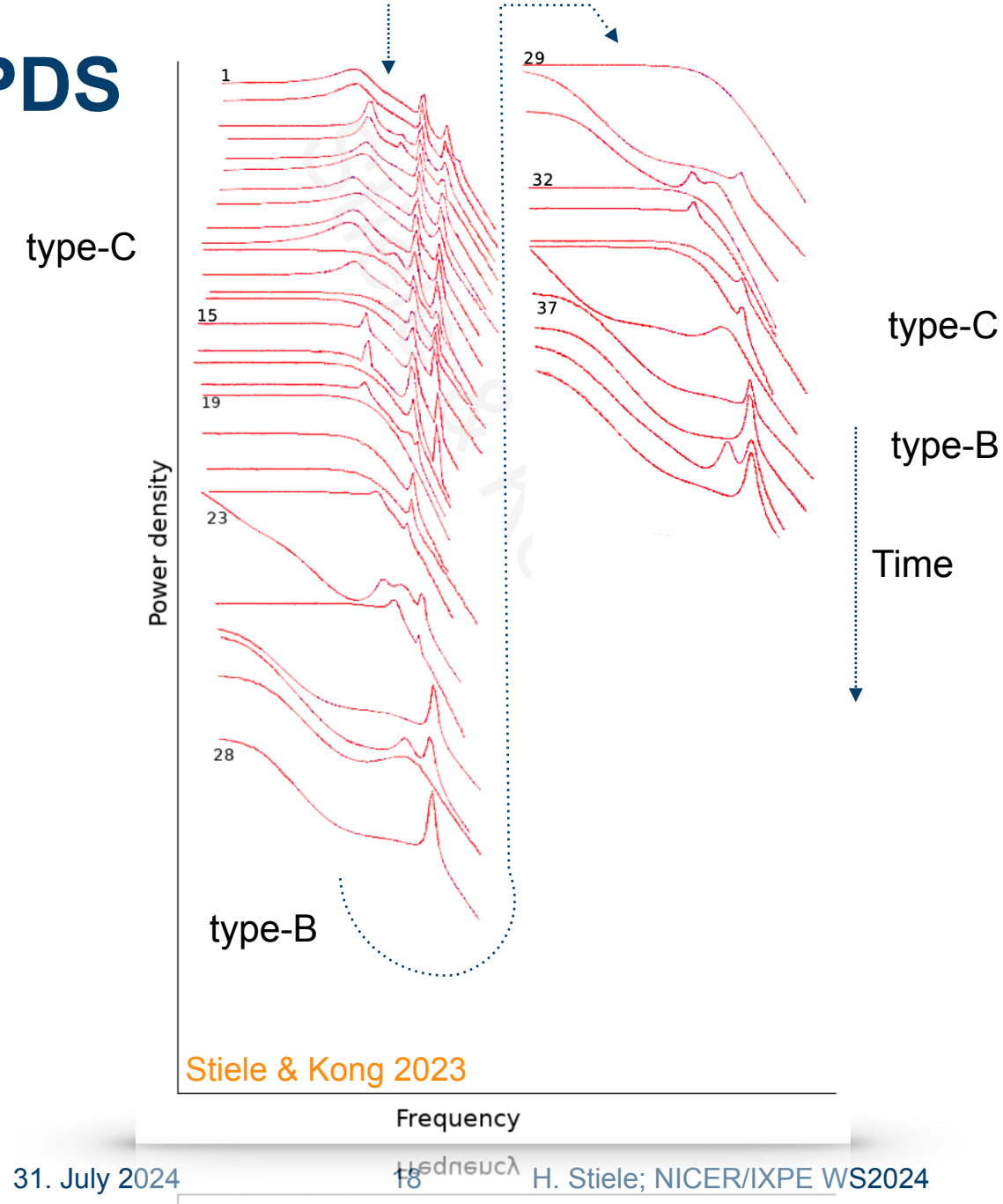
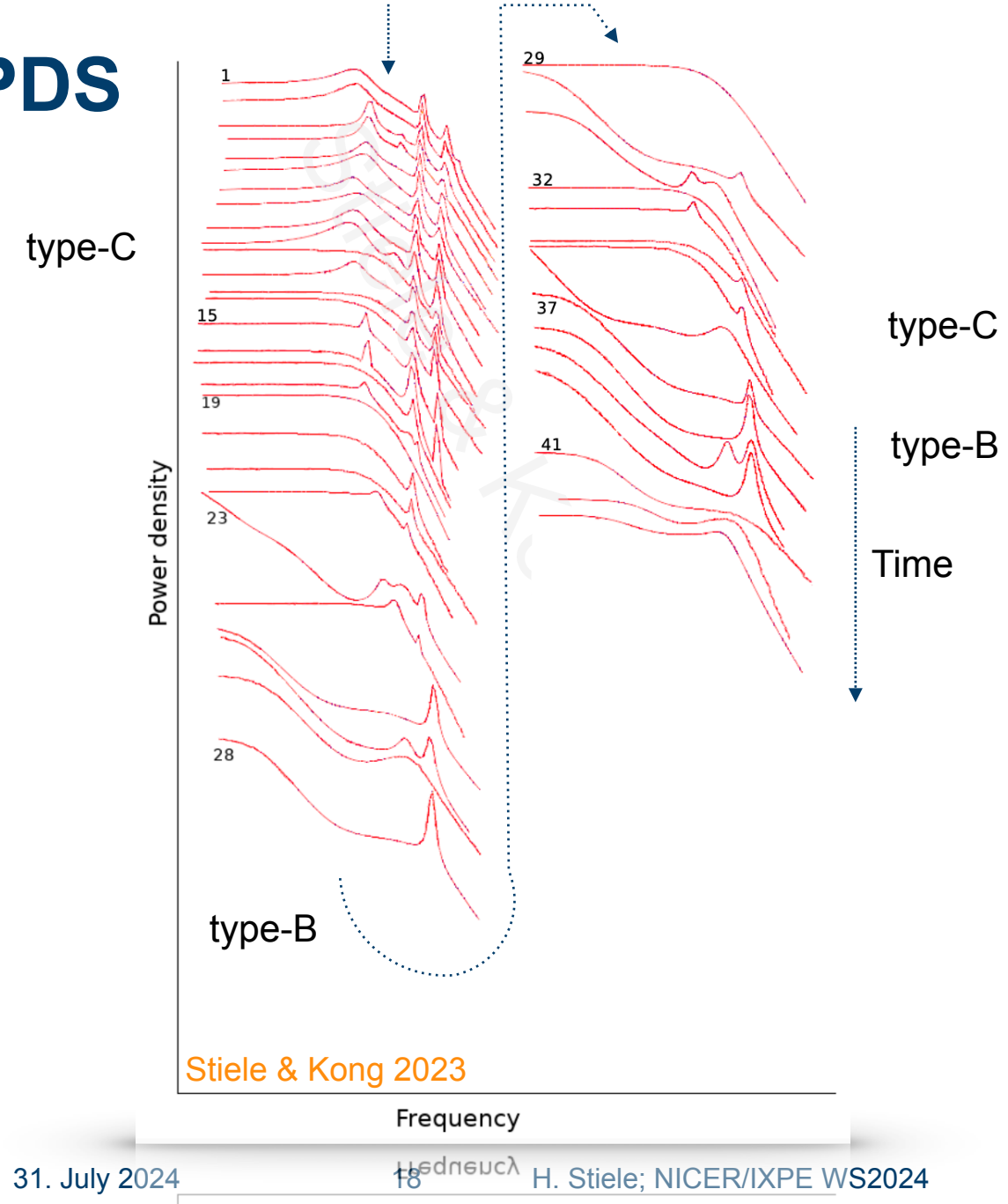


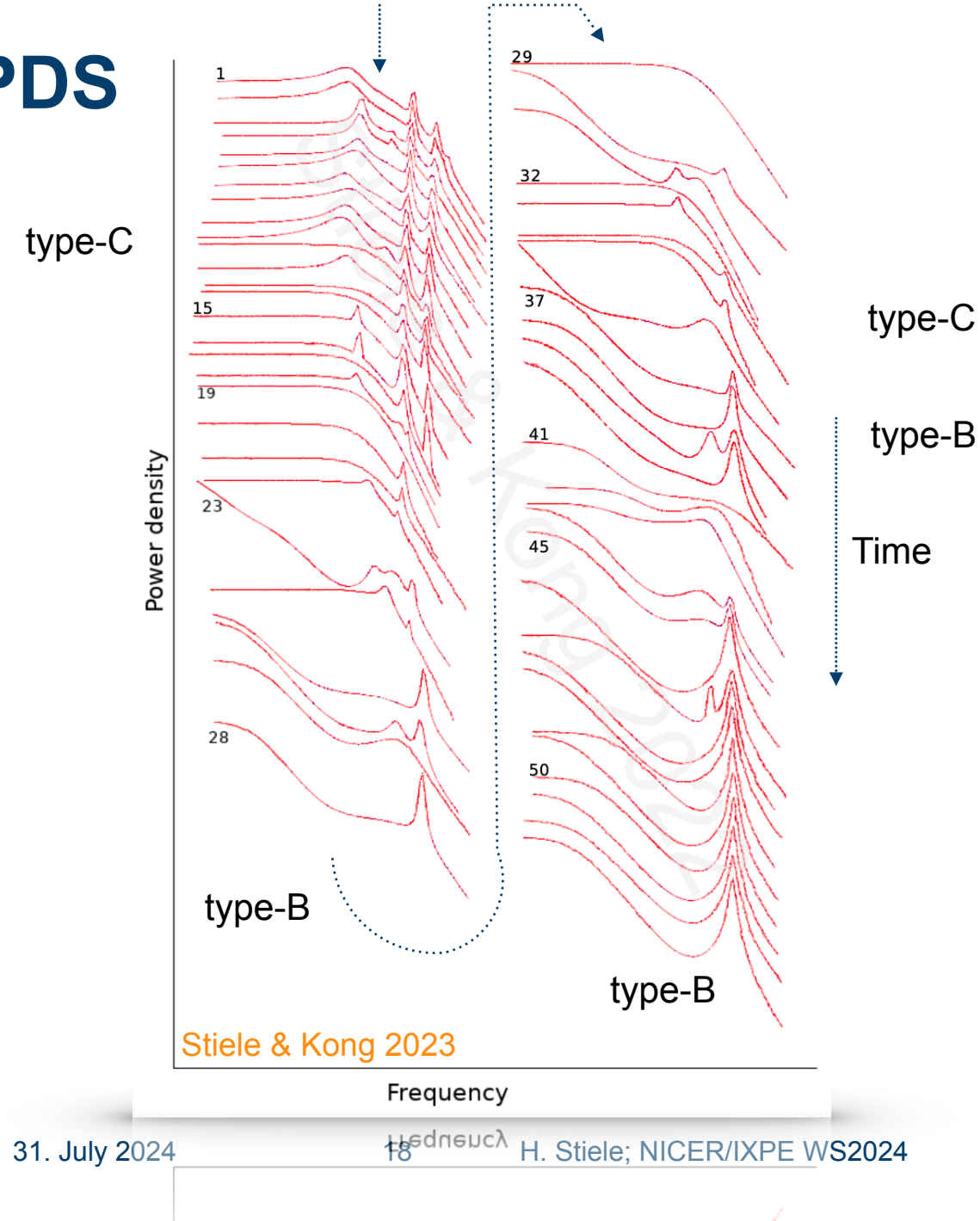
Stiele & Kong 2023

EVOLUTION OF PDS



Stiele & Kong 2023

EVOLUTION OF PDS



EVOLUTION OF RMS VALUES

- Regarding rms values:
- No clear distinction between snapshots that show red noise/type-B QPOs and those that show flat-top noise/type-C QPOs.