NICER WORKSHOP | May 14th, 2021

A two-component Comptonisation model for the type-B QPO in MAXI J1348-630 revealed by ***NICER***

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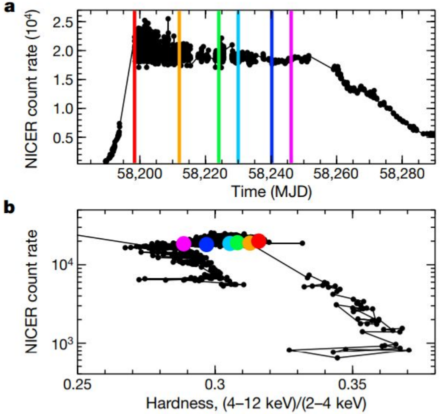
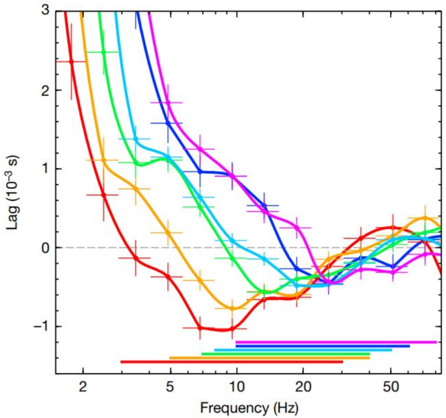
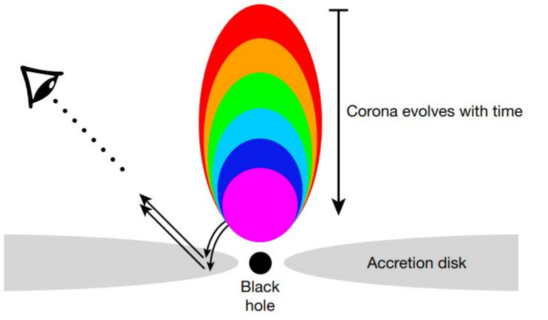
The corona geometry and its evolution is still unknown...

(wonderful NICER datasets of MAXI J1820+070)

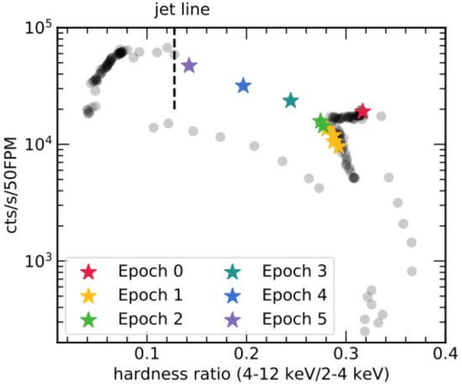


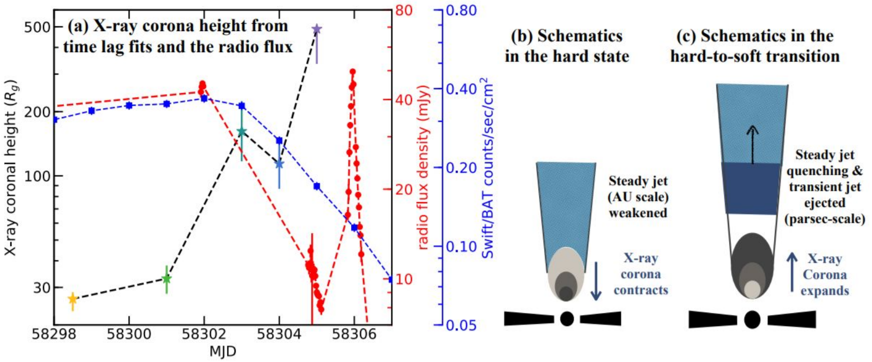




10s Rg

(Kara+2019)



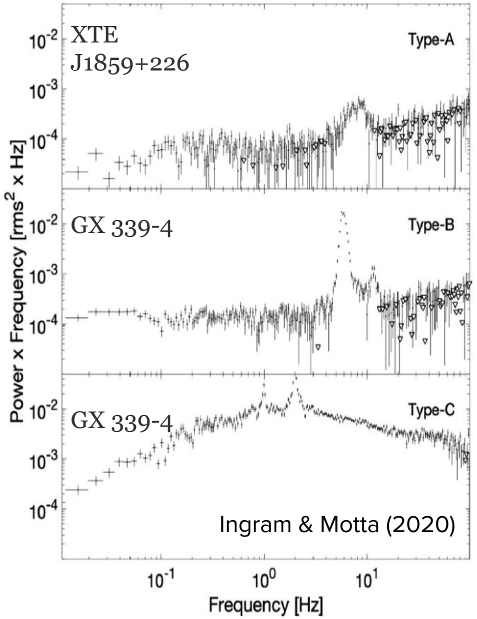


~500 Rg!
during the
state transition

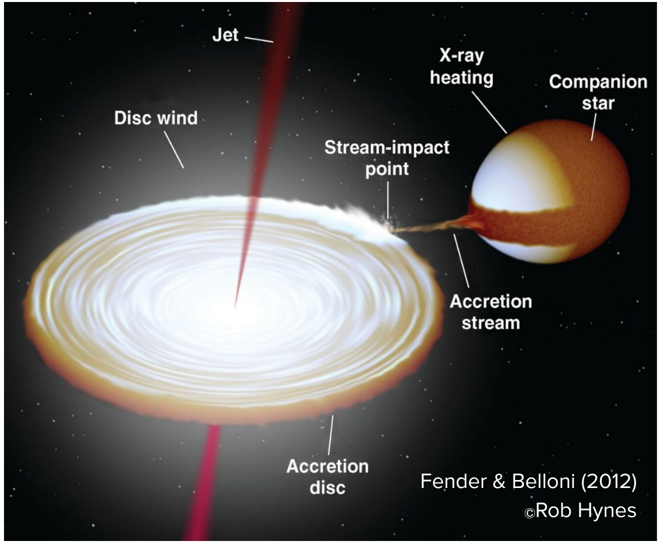
(Wang+2021)

Motivation

- X-ray variability in LMXBs → study physics and geometry of accretion flows
- Power Density Spectra show a variety of QPOs → characteristic frequencies containing dynamical and geometrical information of the innermost regions.
- In this talk, we will focus on the radiative properties of these QPOs and what we can learn from them using a Comptonisation model.



Ingram & Motta (2020)



Fender & Belloni (2012)
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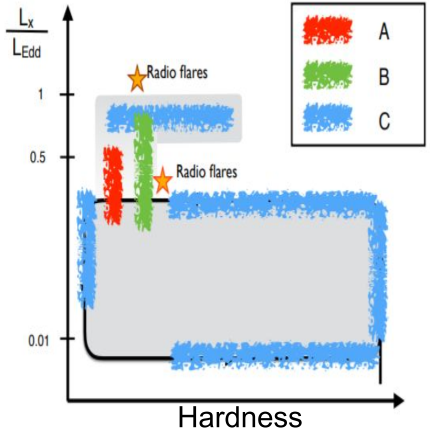
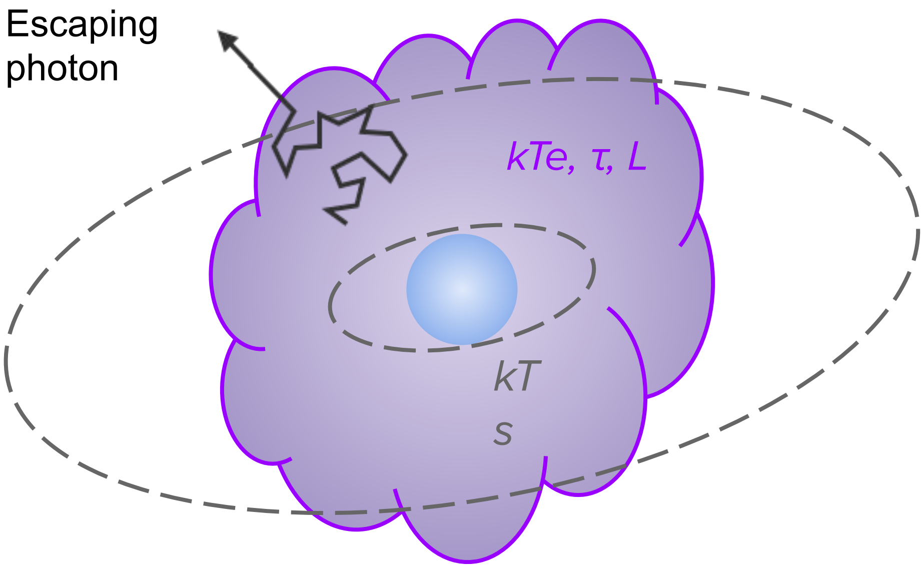
Outline

- The spectral-timing Comptonisation model in a napkin:
  - The lower kHz QPOs in 4U1636-53
- Low-frequency QPOs in BH XRBs:
  - The Type-B QPO in MAXI J1348-630 seen by ***NICER***.



The Comptonisation spectral-timing model



Physical parameters of the model

- Corona temperature, *kTe*
- optical depth, *τ*
- Soft-photons source, *kTs*

- feedback fraction, η
- corona size, *L*

- QPO frequency

The complex spectrum is found solving the linearised time-dependent ***Kompaneets*** eq. for Comptonisation

$$n_\gamma = n_{\gamma,0}(1 + \delta n_\gamma \;\; e^{-i\nu_{qpo}t})$$

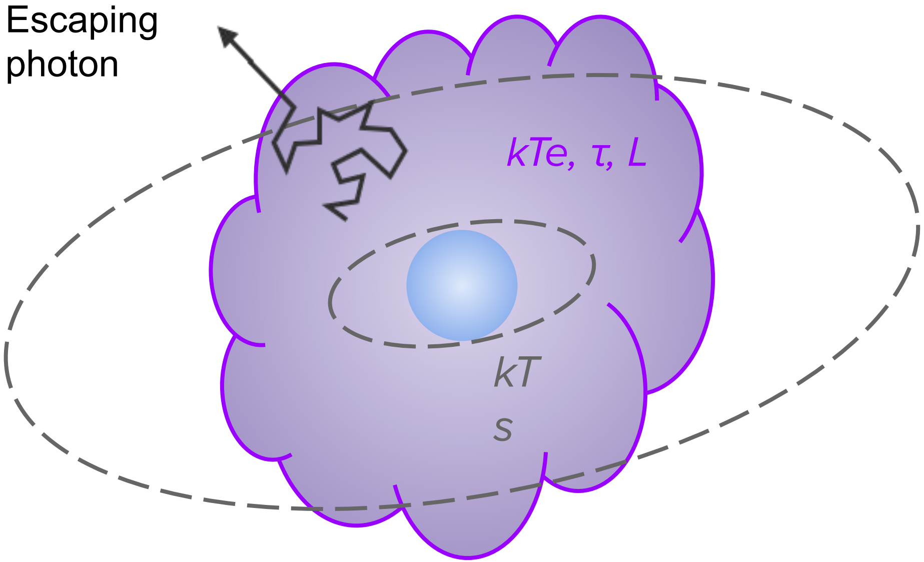
Spectrum = Steady State + Variability at QPO frequency

nthcomp

rms & lags

[Karpouzas+(2020)](#)
[Kumar & Misra (2014)](#)
[Lee & Miller (1998)](#)

The Comptonisation spectral-timing model



Physical parameters of the model

- Corona temperature, *kTe*
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- feedback fraction, η
- corona size, *L*

→ ***Geometry***

- QPO frequency

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$$n_\gamma = n_{\gamma,0}(1 + \delta n_\gamma \; e^{-i\nu_{qpo}t})$$

Spectrum = Steady State + Variability at QPO frequency

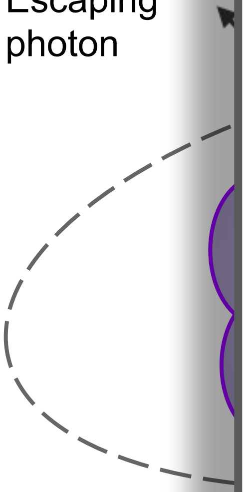
Steady State ↑ nthcomp

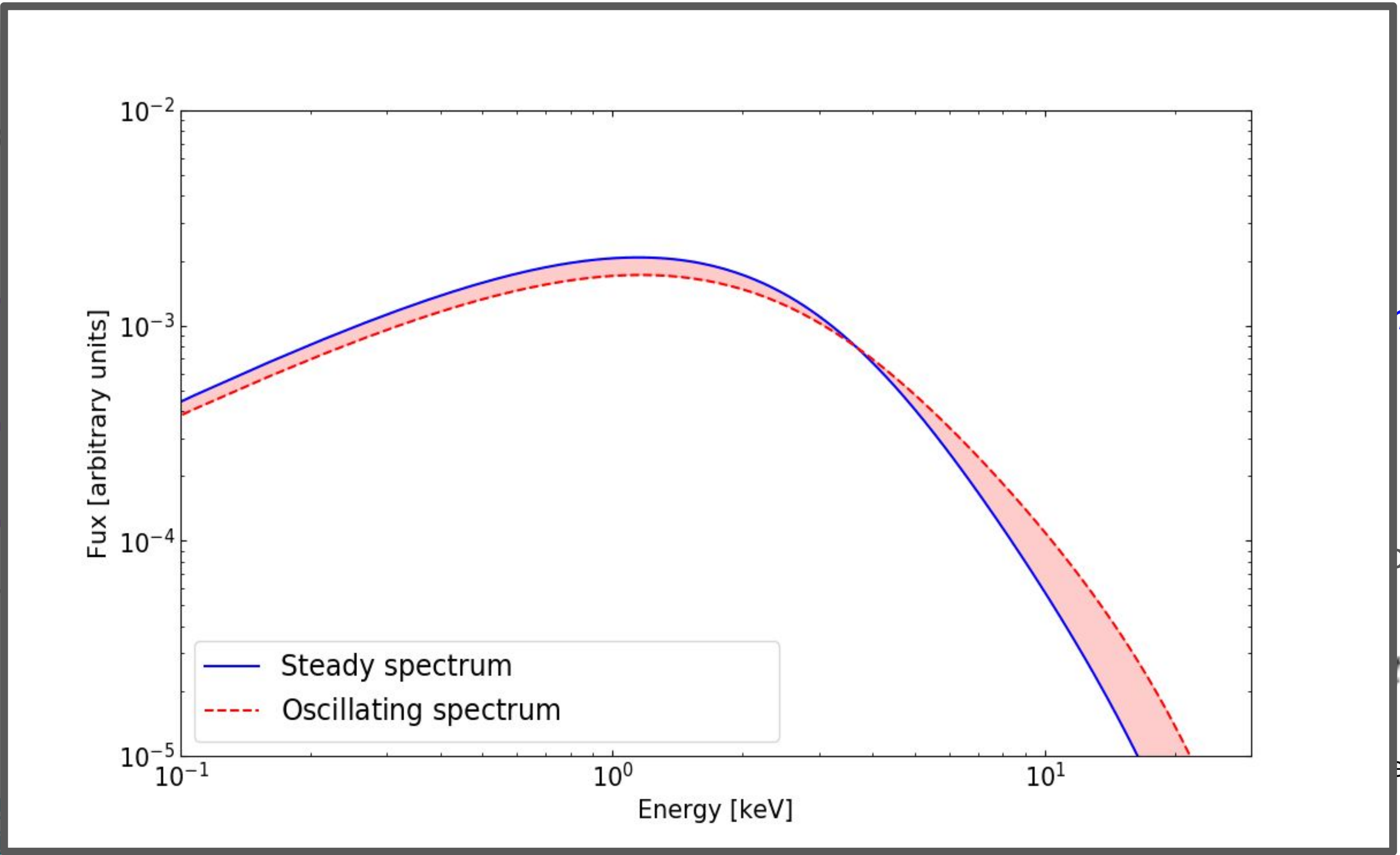
Variability at QPO frequency ↑ rms & lags

Karpouzas+(2020)
Kumar & Misra (2014)
Lee & Miller (1998)

The Comptonisation spectral-timing model

Escaping photon





netry

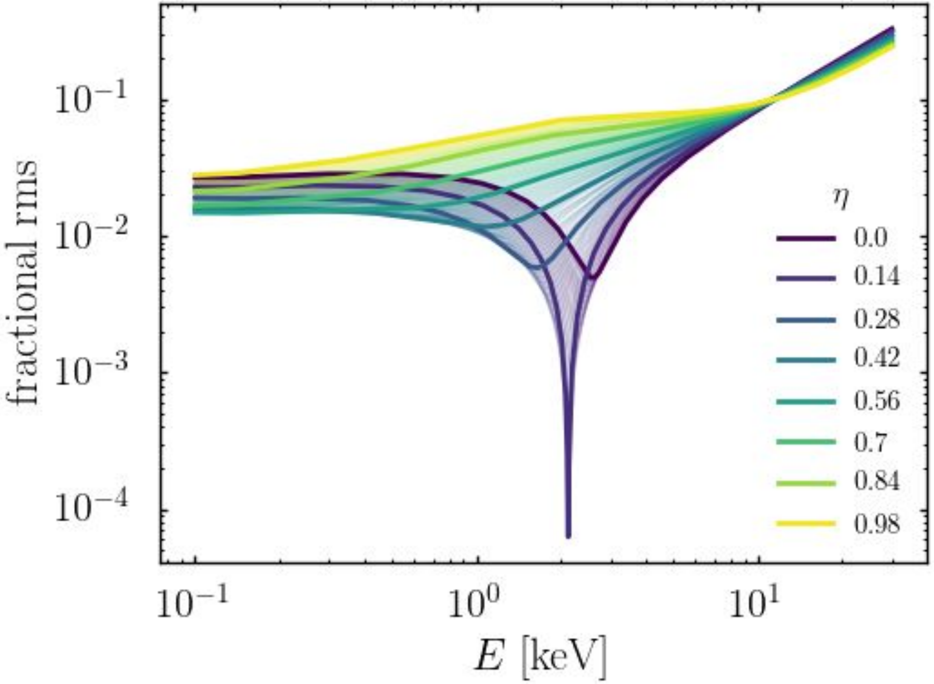
linearised
otonisation

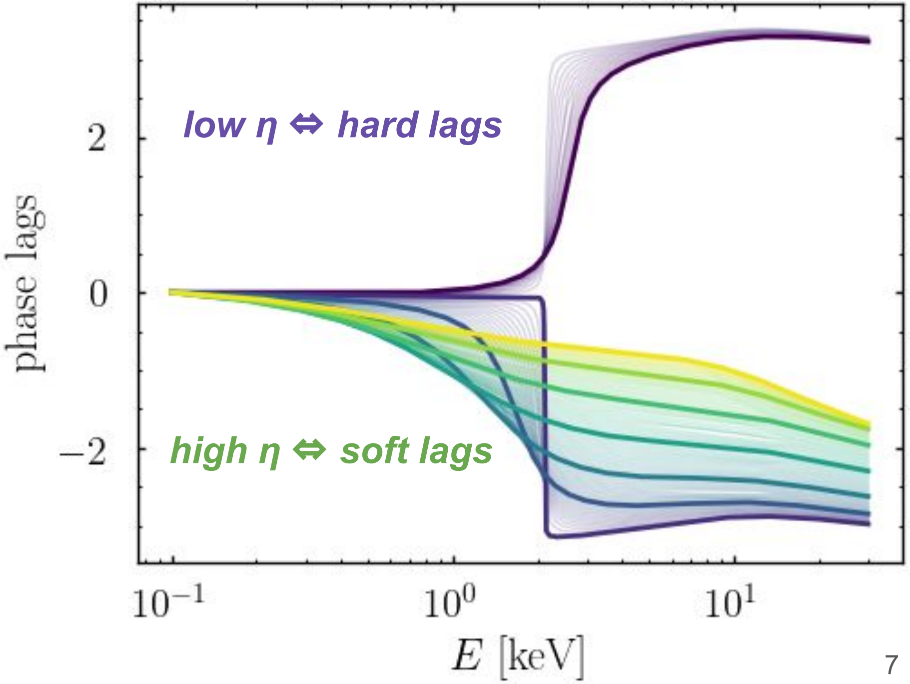
ency

Karpouzas-
Kumar & Mi
Lee & Miller (1998)

Energy-dependent variability (rms) and phase-lags

- *rms* increases with energy, showing a *pivot point at low energies* for *low feedback* (η)
- *lags* strongly depend on the feedback (η):
    - **low η ⇔ *hard lags*** whereas **high η ⇔ *soft lags***





low η ⇔ *hard lags*

high η ⇔ *soft lags*

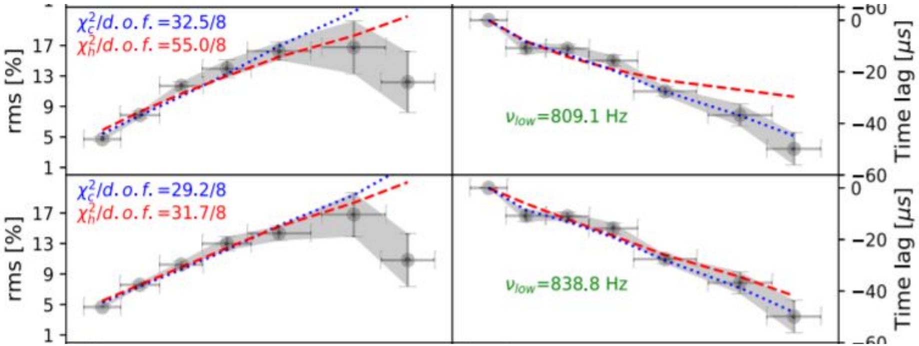
The lower kHz QPO in 4U 1636–53

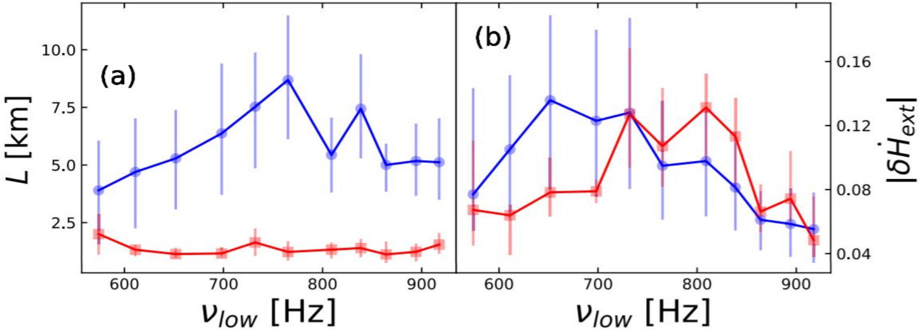
(Karpouzas+2020, MNRAS 492, 1399-1415)

Zhang+2017 and Ribeiro+2017 measured the energy-dependent *rms* and *lags* of the lower kHz QPOs in the NS XRB 4U 1636–53 in the 570–920 Hz frequency range.

We fitted these data for 11 QPO frequencies, to study the frequency-dependent properties of the compact Comptonising region surrounding the NS.

We found two solutions: cold seed (blue) and hot seed (red). The cold seed (blue) leads to more reliable power-law indices and shows that the frequency-dependent properties are mainly driven by the **size *L* evolution** of the thick (τ~10) and compact (L ~ 5–10 km) corona.





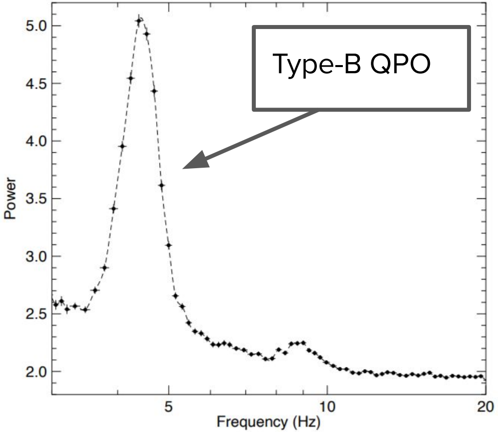
Karpouzas, Méndez, .., FG (2020)

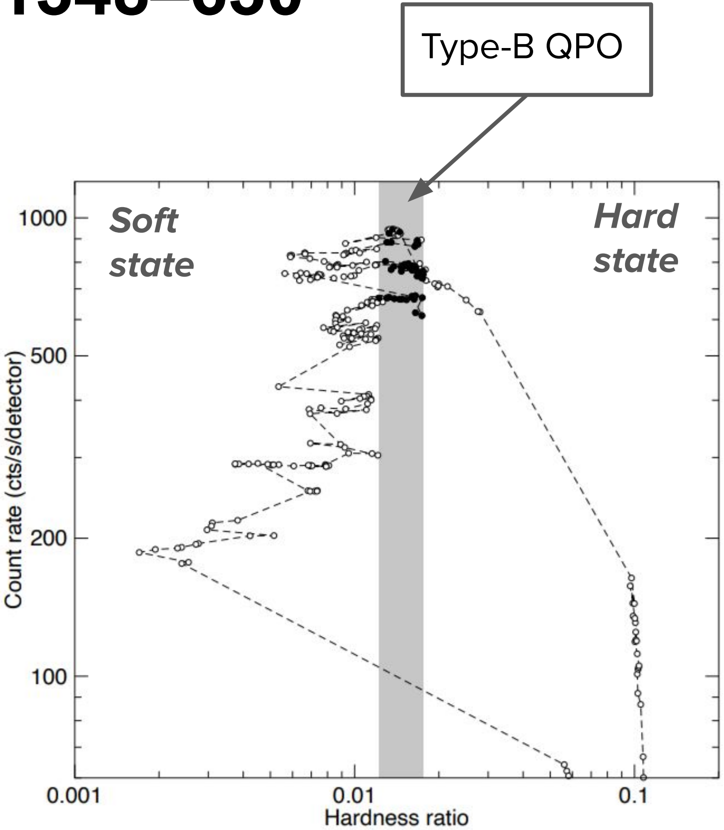
The recent outburst of MAXI J1348–630

- MAXI J1348 is a recently-discovered BH transient (Yatabe+2019, Tominaga+2020).

- It went into outburst in Jan 2019 and transitioned from the Hard to the Soft State ~1 week later (Nakahira+2019, Cangemi+2019).

- During the transition, it showed a prominent Type-B QPO in the 4–5 Hz frequency range.





Belloni+2020

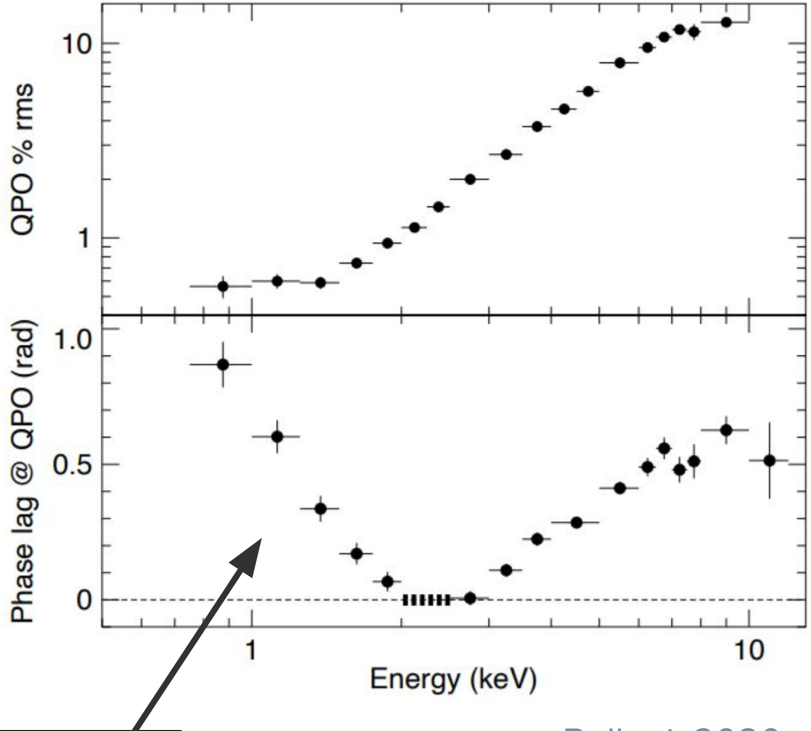
The type-B QPO in MAXI J1348–630

- In a recent paper (Belloni+2020) measured the spectral-timing properties of this QPO using NICER data (down to low energies ~0.8 keV).

- They found increasing-with-energy fractional variability (rms) and a particular lag-energy spectrum, with *positive* phase-lags with respect to a reference band at mid energies of 2–2.5 keV.

- They also fitted the time-averaged spectra with a *diskbb*simpl* model and found:

  $kT_{dbb} \sim 0.6$ keV , $\Gamma \sim 3.5$ (with $kT_e > 10$ keV)



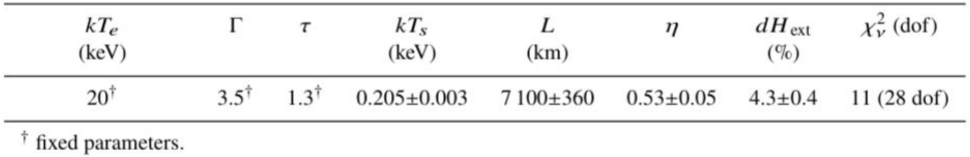
Belloni+2020

New NICER window

Fitting our variable-Comptonisation model

- We used our Comptonisation model to fit the spectral-timing data of the QPO.

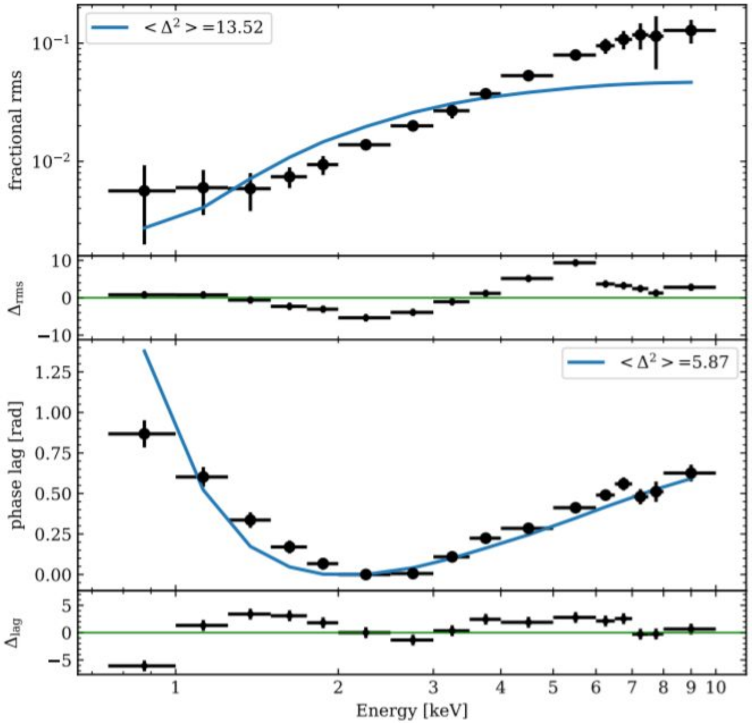
- Our model can roughly describe the data:
  - Overall rms trend is found (increasing rms with *E*).
  - Lag spectrum shape is recovered (but with bad χ^2).



kT_e (keV)	Γ	τ	kT_s (keV)	L (km)	η	$dH_{\rm ext}$ (%)	χ^2_ν (dof)
$20^\dagger$	$3.5^\dagger$	$1.3^\dagger$	0.205±0.003	7 100±360	0.53±0.05	4.3±0.4	11 (28 dof)

† fixed parameters.

- The data is fitted using a single Comptonisation region of ~7000 km (~400 Rg for 10 Msun BH) with intermediate feedback (η ~ 50%) which explains the change from soft to hard lags at E ~ 2.5 keV



F. García et al. (2021, MNRAS 501, 3173)

A *two-component* variable-Comptonisation model

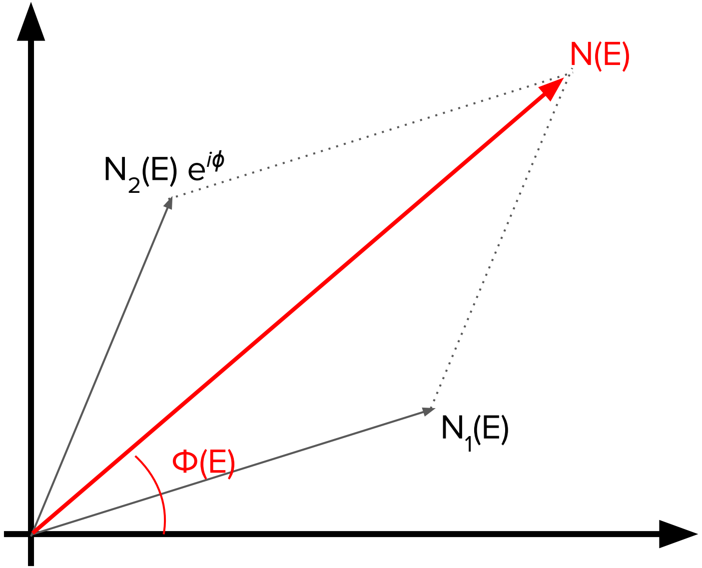
- We then explored the possibility that the QPO spectrum arises from two Comptonisation regions:

$$\begin{aligned} N(E,t,\omega_0) &= N_1(E)e^{i\omega_0 t} + N_2(E)e^{i(\omega_0 t+\phi)} \qquad (1) \\ &= \left(N_1(E) + N_2(E)e^{i\phi}\right) e^{i\omega_0 t} = |N(E)|e^{i\Phi(E)}e^{i\omega_0 t}, \end{aligned}$$

- By doing this, we can get the variability amplitudes and phase-lags by combining two Comptonisation models, this way:

$$\begin{aligned} |N(E)| = \big[&|N_1(E)|^2 + |N_2(E)|^2 \\ &- 2|N_1(E)||N_2(E)|\cos(\phi_2(E) - \phi_1(E) + \phi)\big]^{1/2} \end{aligned}$$

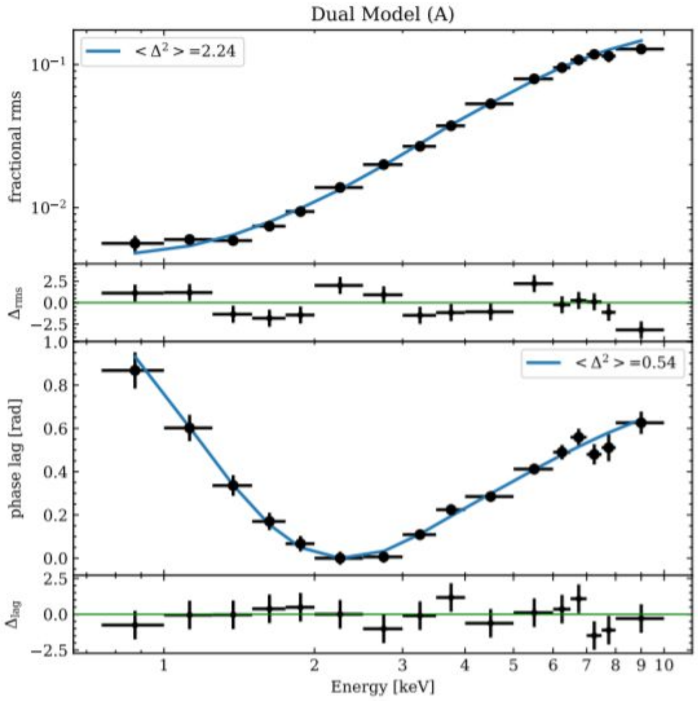
$$\tan(\Phi(E)) = \frac{\mathrm{Im}\{N_1(E)\} + \mathrm{Im}\{N_2(E)e^{i\phi}\}}{\mathrm{Re}\{N_1(E)\} + \mathrm{Re}\{N_2(E)e^{i\phi}\}}$$

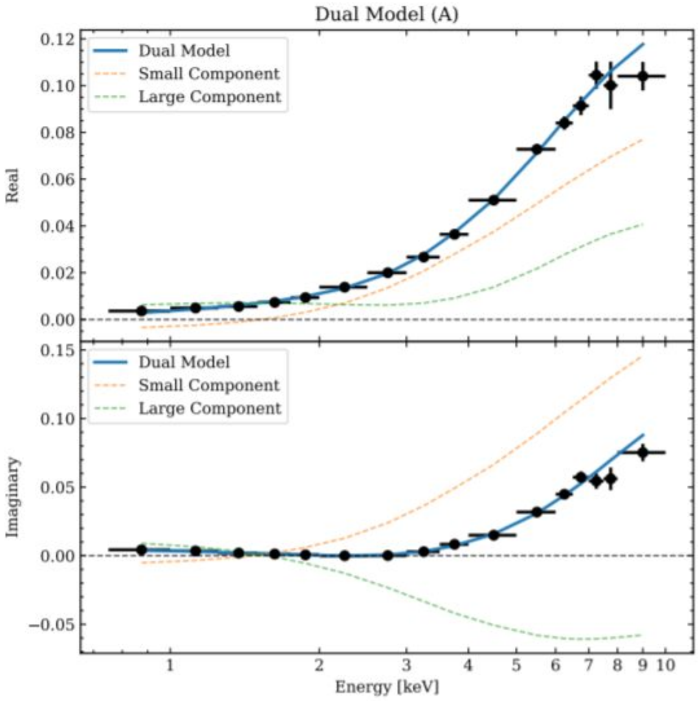


García+2021

Fitting a two-component Comptonisation model

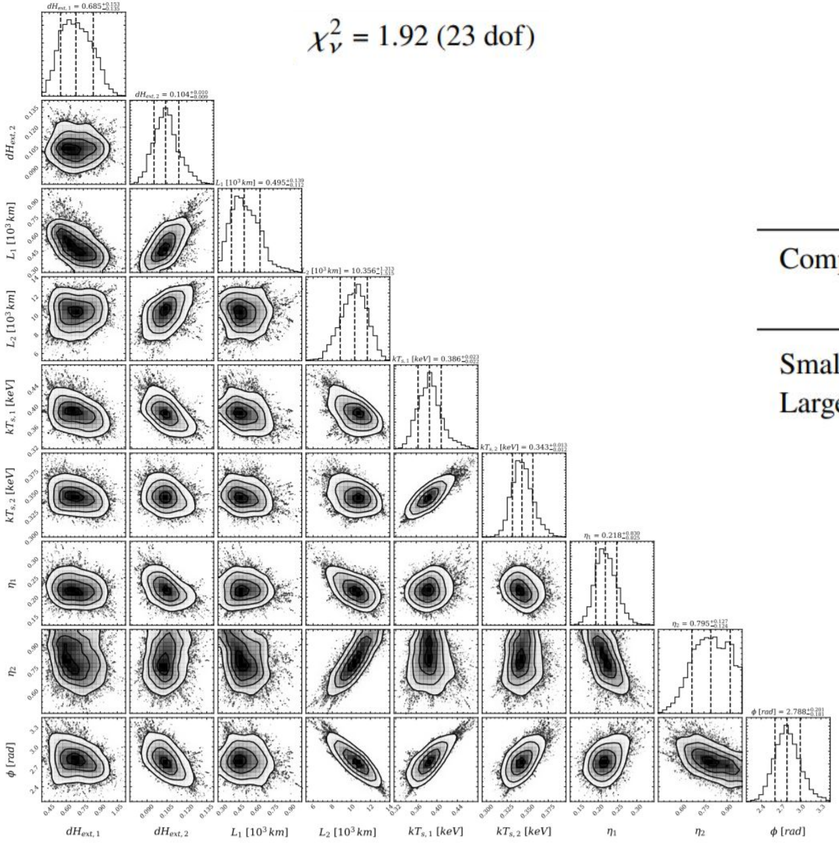
- With this model, we obtain remarkably better fits to both the *rms* and *lag* spectra.





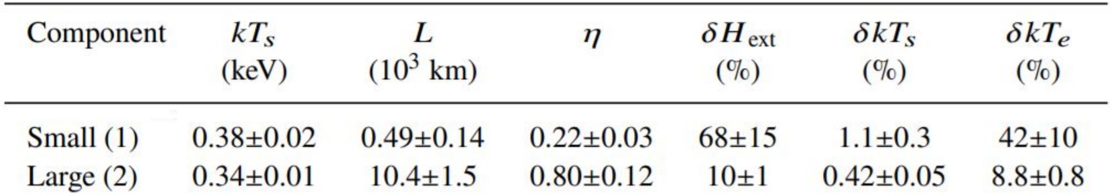
García+2021

Fitting a *two-component* Comptonisation model



$\chi^2_\nu = 1.92$ (23 dof)

- The data is well fitted invoking two Comptonisation regions of ~500 km (25-30 Rg) and ~10 000 km (550 Rg).



Component	kT_s (keV)	L (10^3 km)	η	$\delta H_{\rm ext}$ (%)	δkT_s (%)	δkT_e (%)
Small (1)	0.38±0.02	0.49±0.14	0.22±0.03	68±15	1.1±0.3	42±10
Large (2)	0.34±0.01	10.4±1.5	0.80±0.12	10±1	0.42±0.05	8.8±0.8

- In the fits, we recover compatible temperatures for the soft-photon source (*kTs*) with the time-avg spectrum, in both cases.

- This points to the innermost parts of the disk as the main source of soft-photons (and variability).

García+2021

Fitting a *two-component* Comptonisation model

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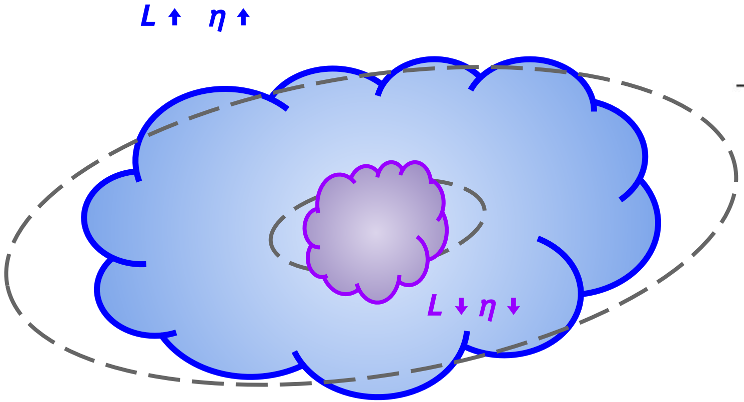

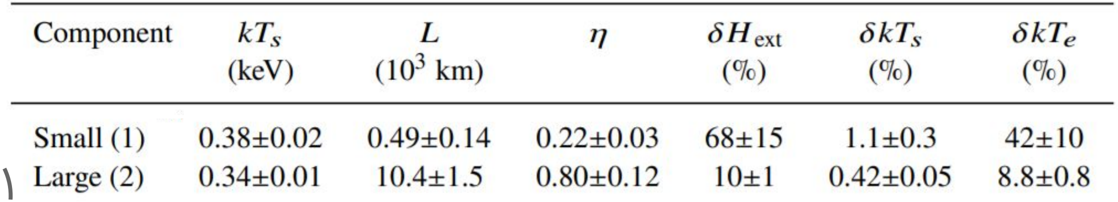

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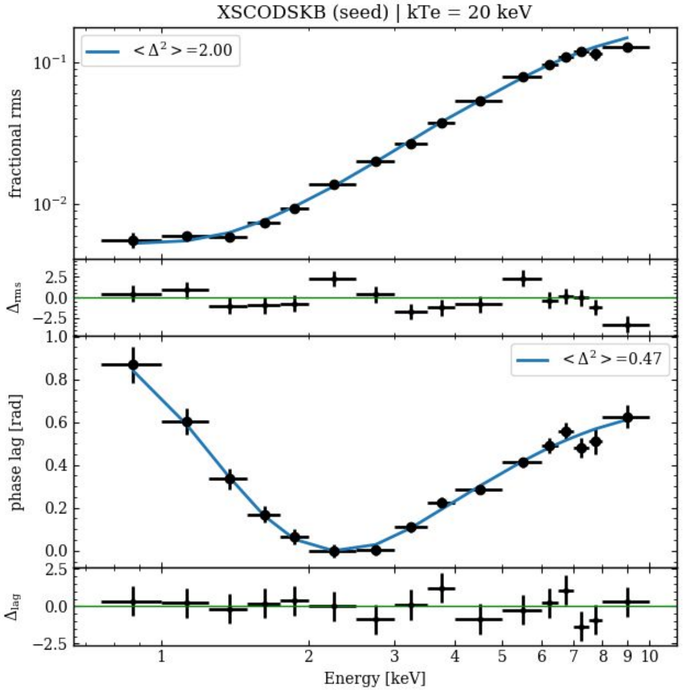
García+2021

Switching to a *diskBB* as the soft-photon source *(preliminary results)*

χ^2 = 1.71 (23 dof)



- The data is ***best fitted*** invoking two Comptonisation regions of ~350 km (20 Rg) and >12 000 km (>650 Rg).

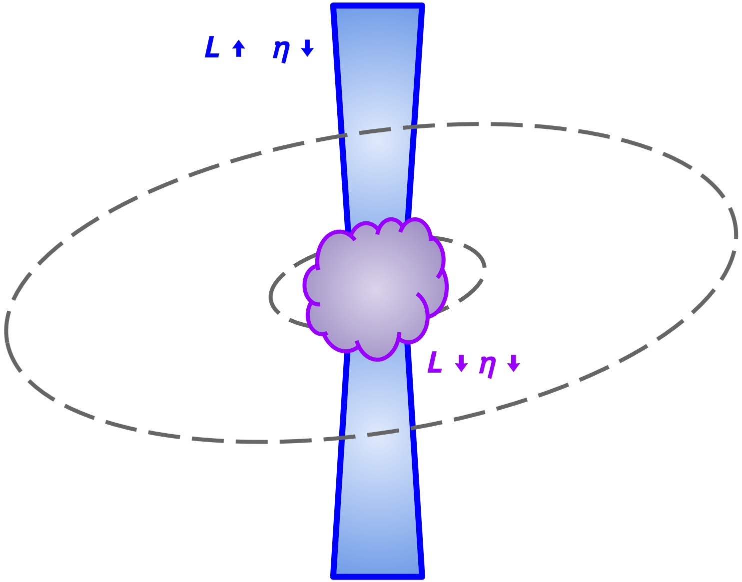
Component	kT_s (keV)	L (10^3 km)	η	$\delta H_{\rm ext}$ (%)
Small (1)	0.48(2)	0.34(5)	0.47(3)	67(10)
Large (2)	0.75(4)	>12.0	<0.10	12(2)

- In the fits, we recover compatible temperatures for the soft-photon source (*kTs*) with the time-avg spectrum (0.6 keV for a diskBB).

- The most important change is in the feedback fraction of the large component.

Bellavita+in prep.

Switching to a *diskBB* as the soft-photon source *(preliminary results)*



(see Carotenuto+2021)

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Bellavita+in prep.

Summary

- Comptonisation dominates the spectra in the hard and intermediate states in BH XRBs.
- We have shown that a spectral-timing Comptonisation model can fit well the energy-dependence of the low-frequency QPOs in these sources.
- The QPO lags can be used to constrain the size of the Comptonising region, information that cannot be attained from the typical time-averaged spectra.
- A feedback term is required to produce soft QPO lags as those seen in the low energy band in the type-B QPO of MAXI J1348.
- In this case, a good fit is obtained when two Comptonisation regions are considered, possibly revealing a more complex underlying corona structure (García+2021).
- Finally, we note that thanks to recent spectral-timing analyses, new evidence has been gathered regarding the evolution of the size of the Comptonisation region (corona) during BH outbursts, mainly thanks to ***NICER*** (Kara+2019, Wang+2021, and see our recent... ***Karpouzas+2021***).

Thank you very much for your attention!

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