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Aql X-1 "from dawn 'til dusk":

Observing an entire outburst from early rise to decay with Einstein Probe, NICER, NuSTAR and LCO

(Marino et al., A&A, in prep.)

Alessio Marino (he/him)

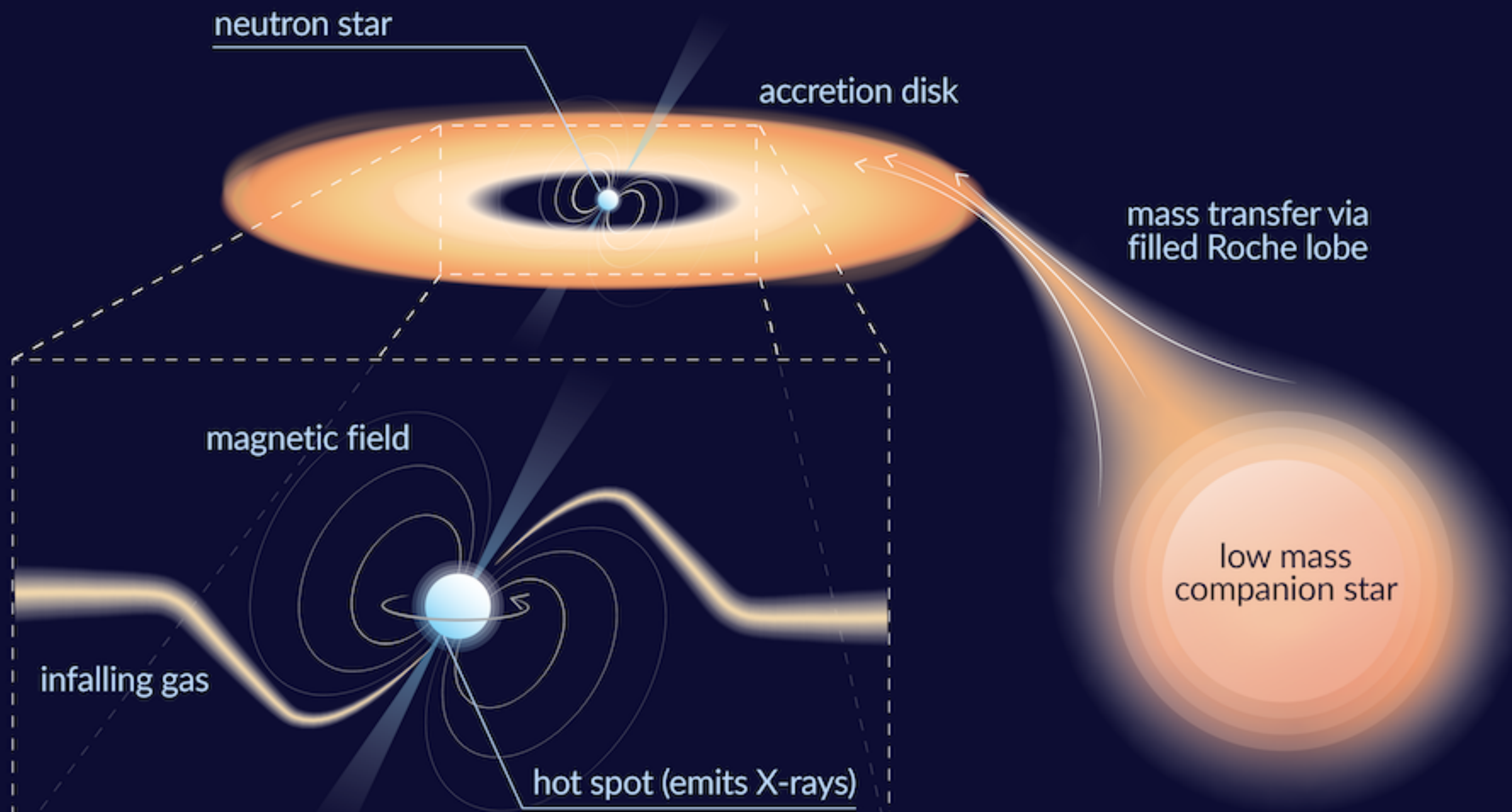
Postdoctoral fellow, Institute of Space Sciences (Barcelona)

Einstein Probe associate member

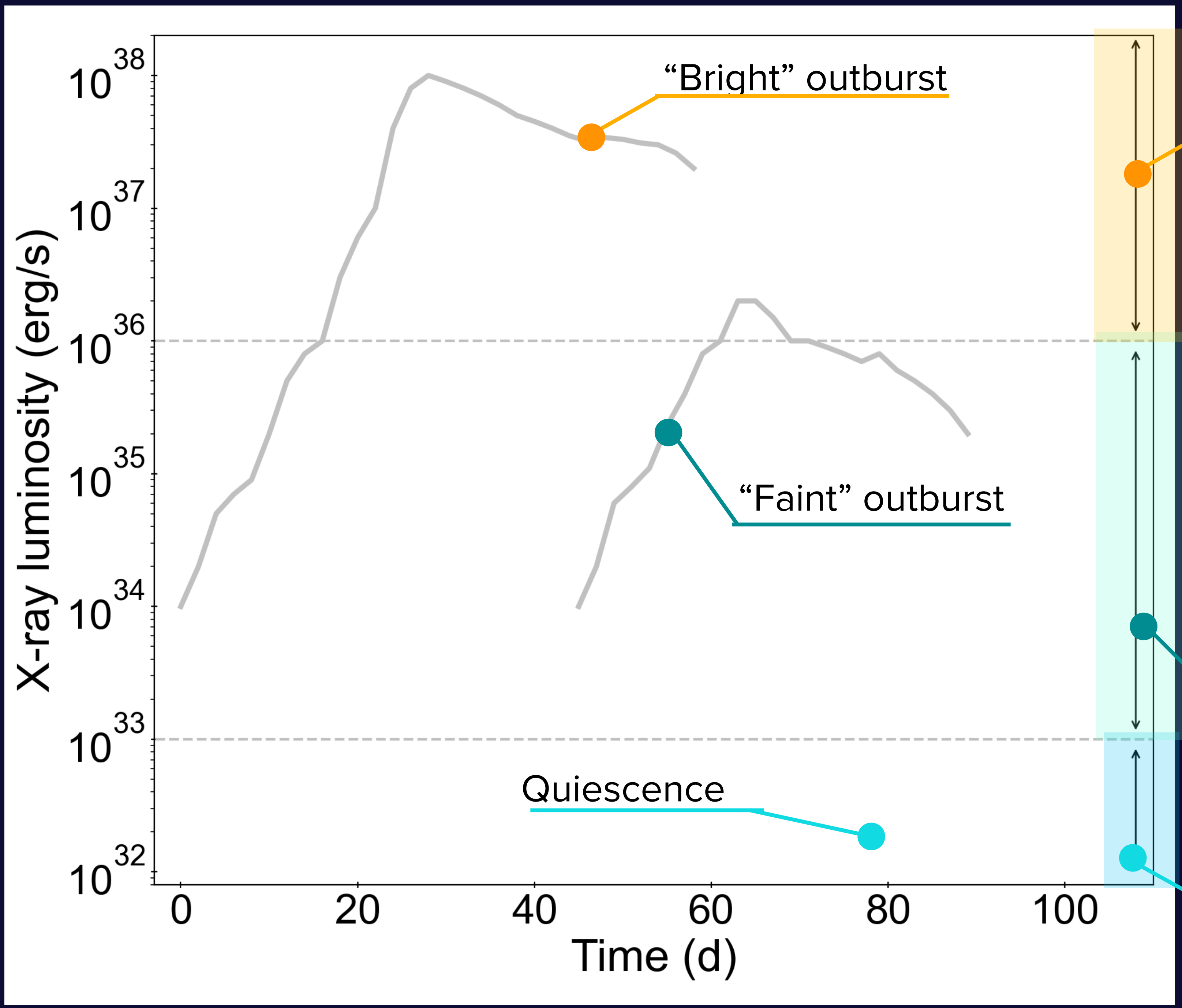
Collaborators: F. Coti Zelati, N. Rea, D. Russell, K. Alabarta, Y. L. Wang, A. Jurado and many more....

CSIC Consejo Superior de Investigaciones Científicas | Institute of Space Sciences 25th Anniversary | Excelencia María de Maeztu | 爱因斯坦探针 einstein probe | INAF | EXOTIC Extreme Compact Objects in the Transient Multi-Messenger Sky

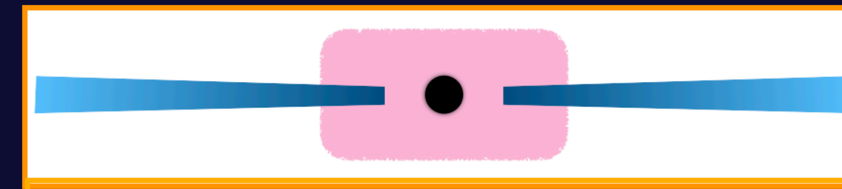
Di Salvo, Papitto, AM+2023; Bahramian & Degenaar 2022; Avakyan+2023



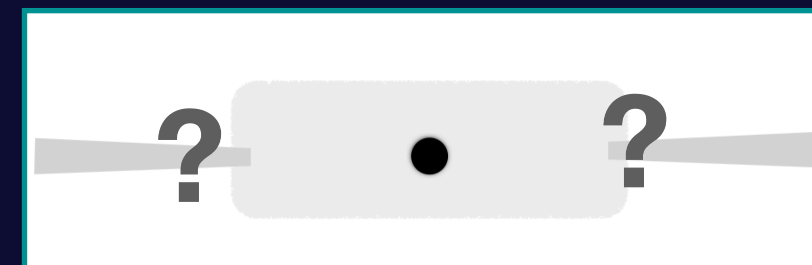
- Binary systems hosting old (Gyr), low-magnetised ($B=10^8$-10^9 G) neutron stars;



- Hypothetical light curves of two outbursts of a NS LMXB



High mass-accretion rate;
(10^{36}-10^{38} erg/s)



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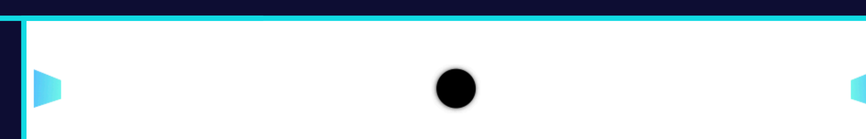
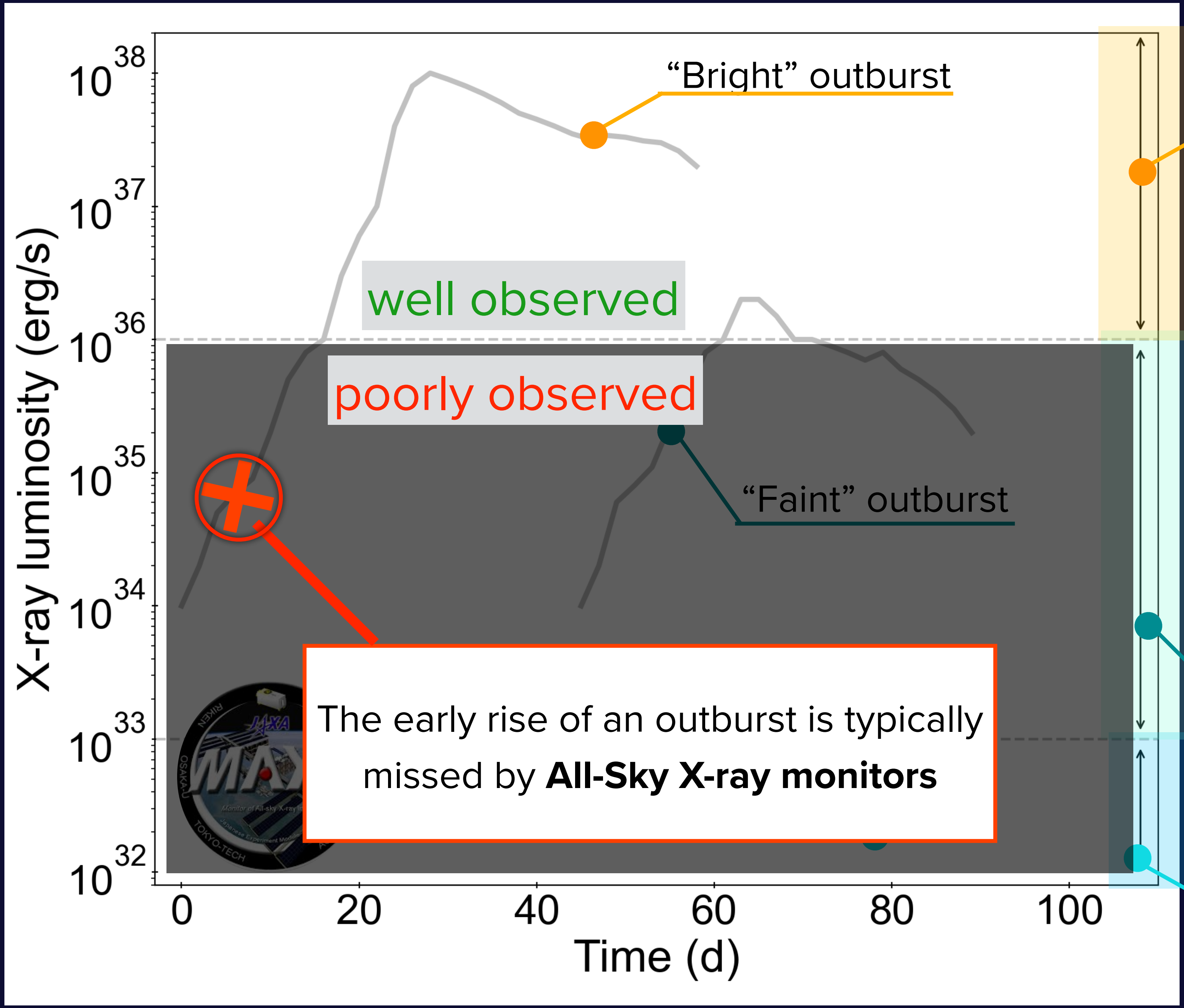
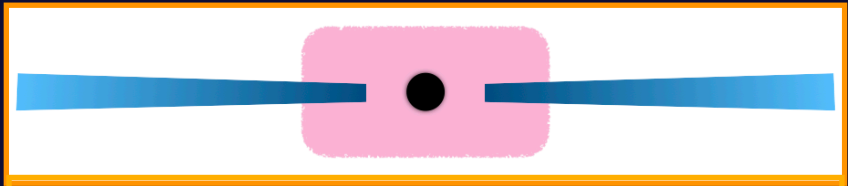


Accretion (almost) shut-off;
($<10^{33}$ erg/s)





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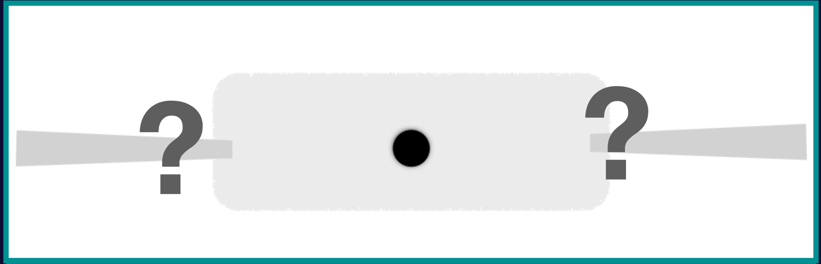

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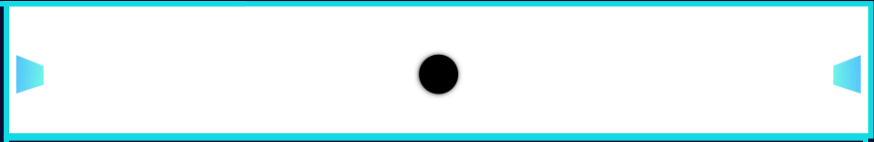

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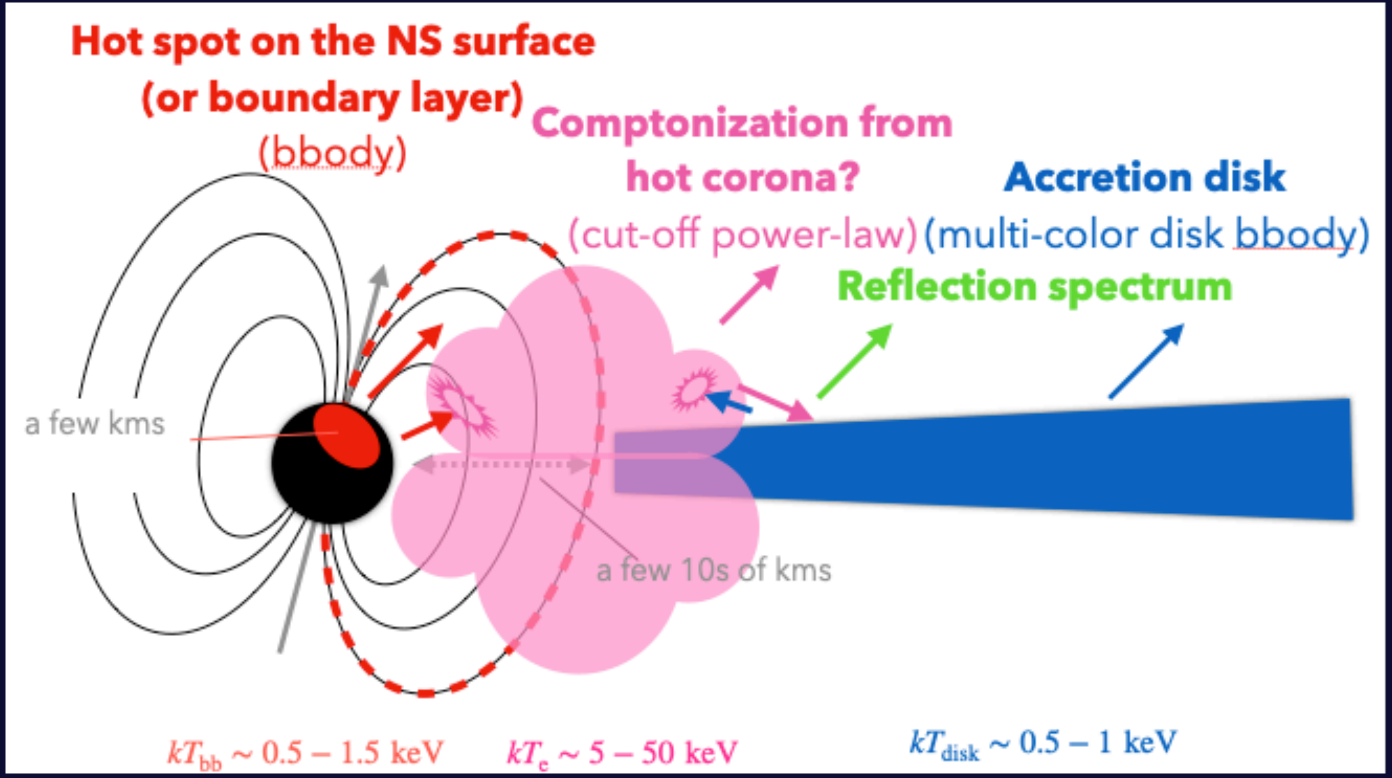
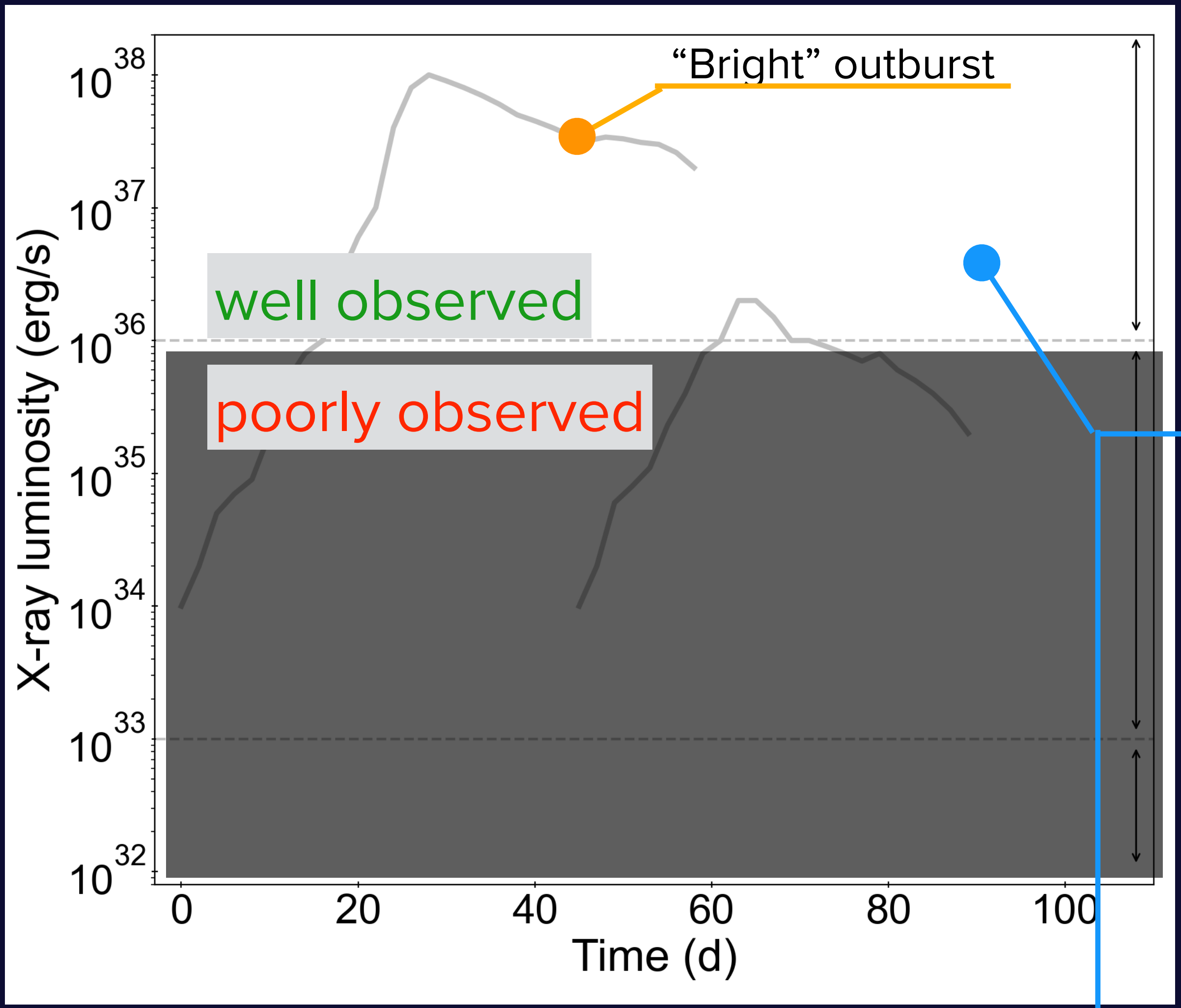


- Toy model of the accretion flow



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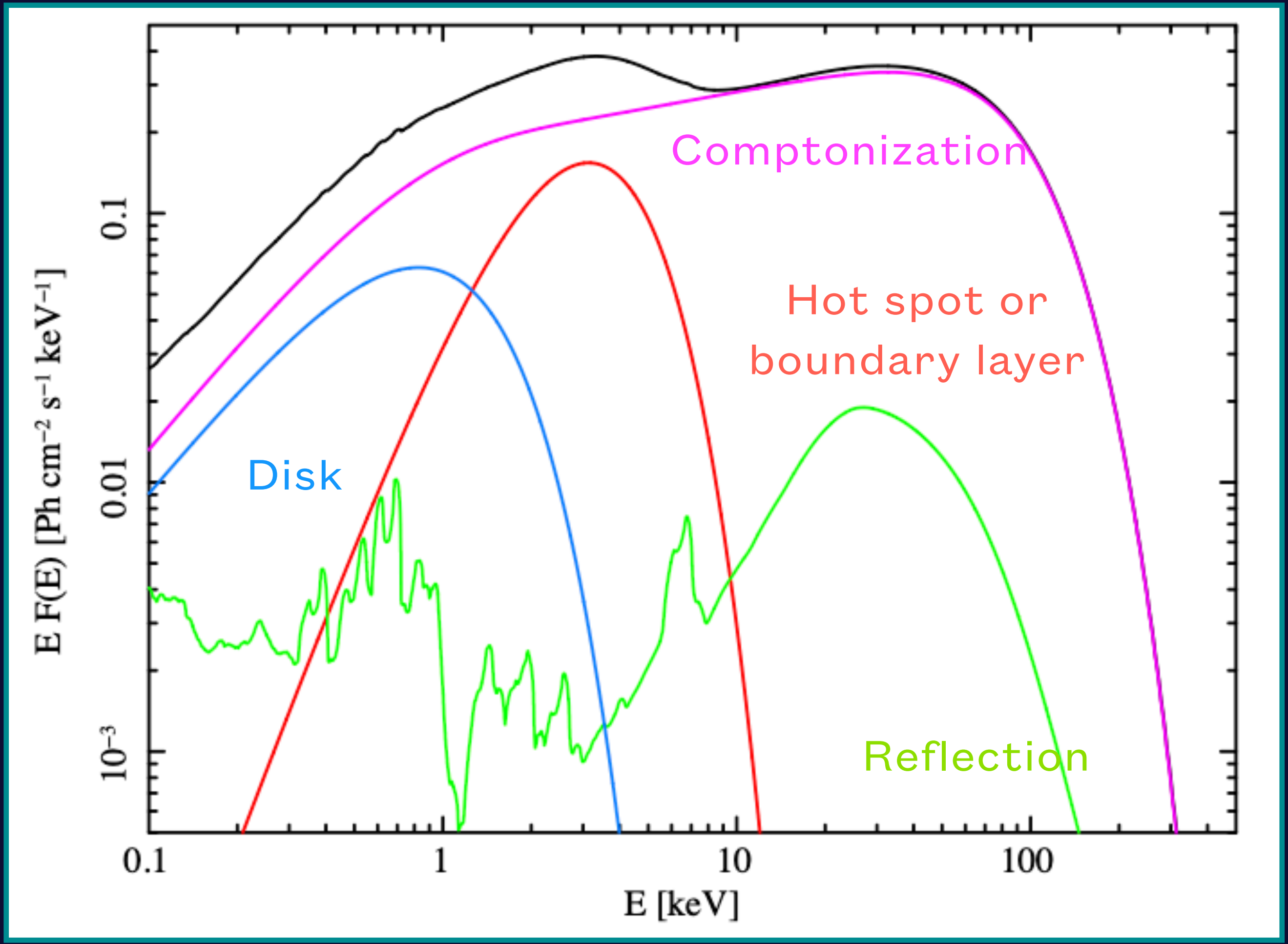
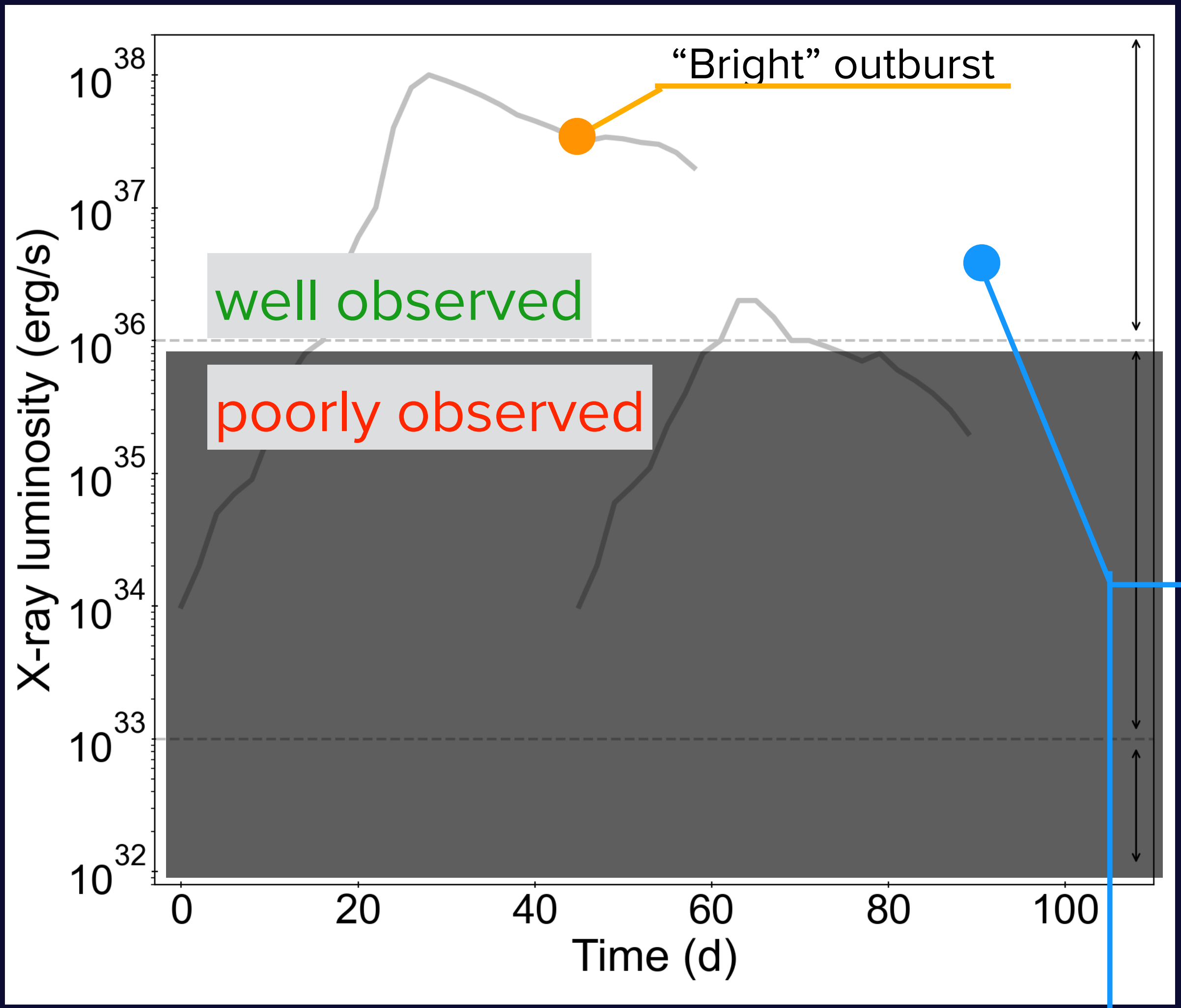


- Best-fit model for an ideal spectrum

Gierlinski & Poutanen 2005; Papitto+2009, 2010; Armas Padilla+2017; van den Eijnden+2018; Pintore+2017; Di Salvo+2019; Sharma+2019; Marino+2022; Illiano +2024b; Malacaria+2025 *just to name a few…*



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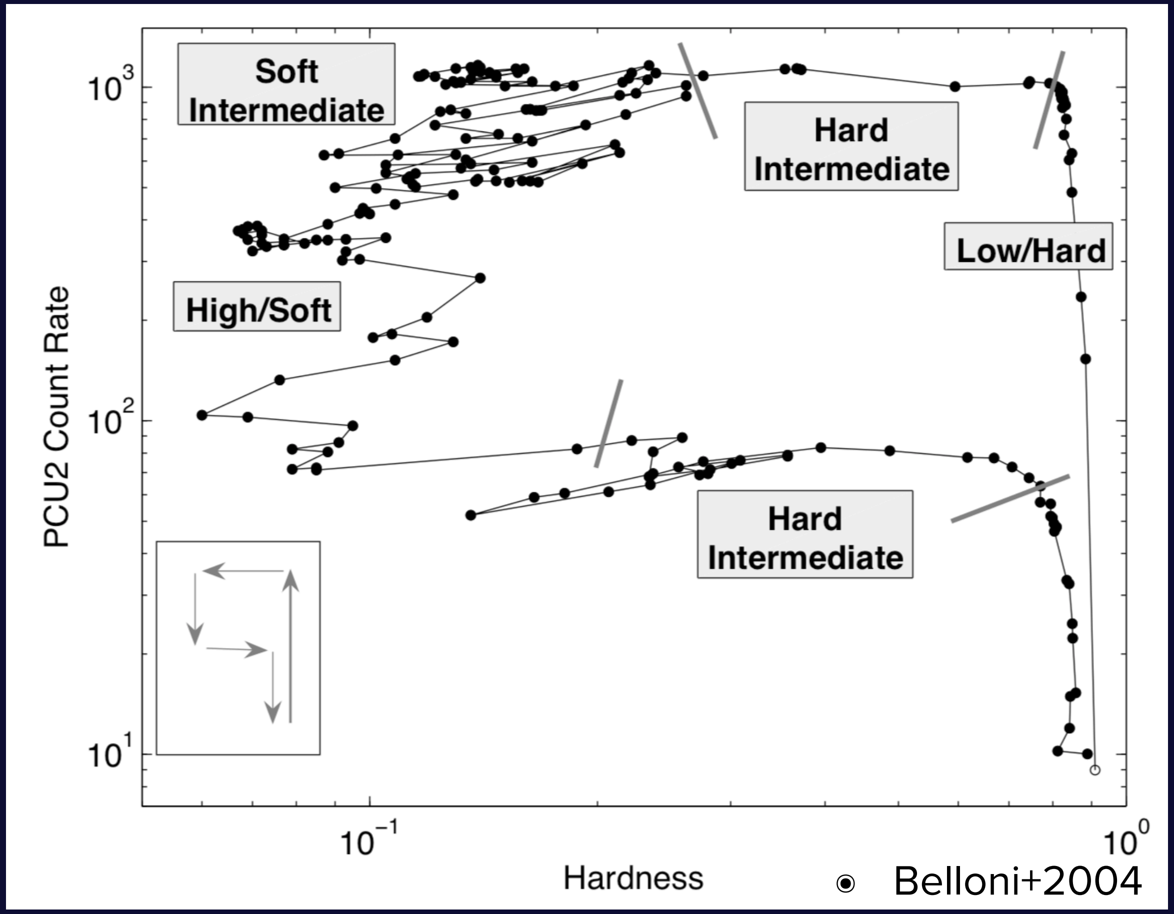
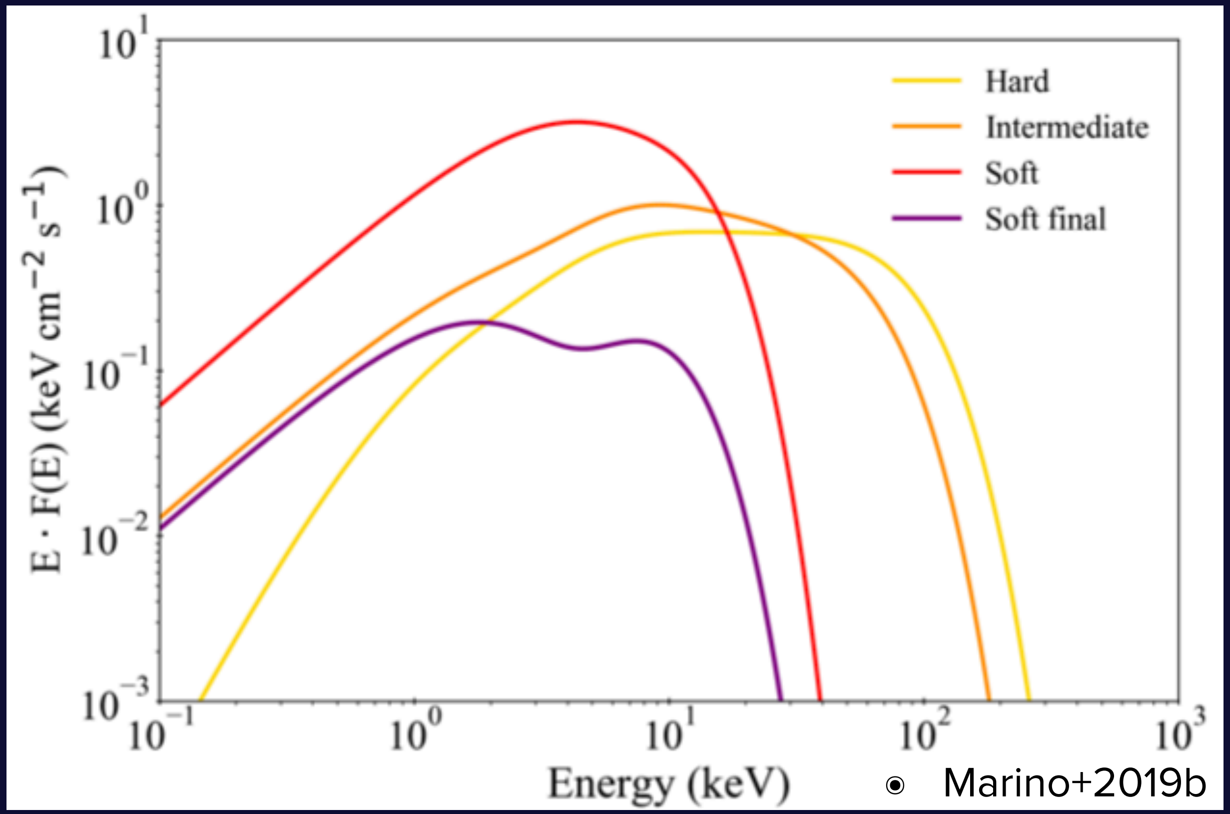


- Schematic illustration of the q-track in LMXBs

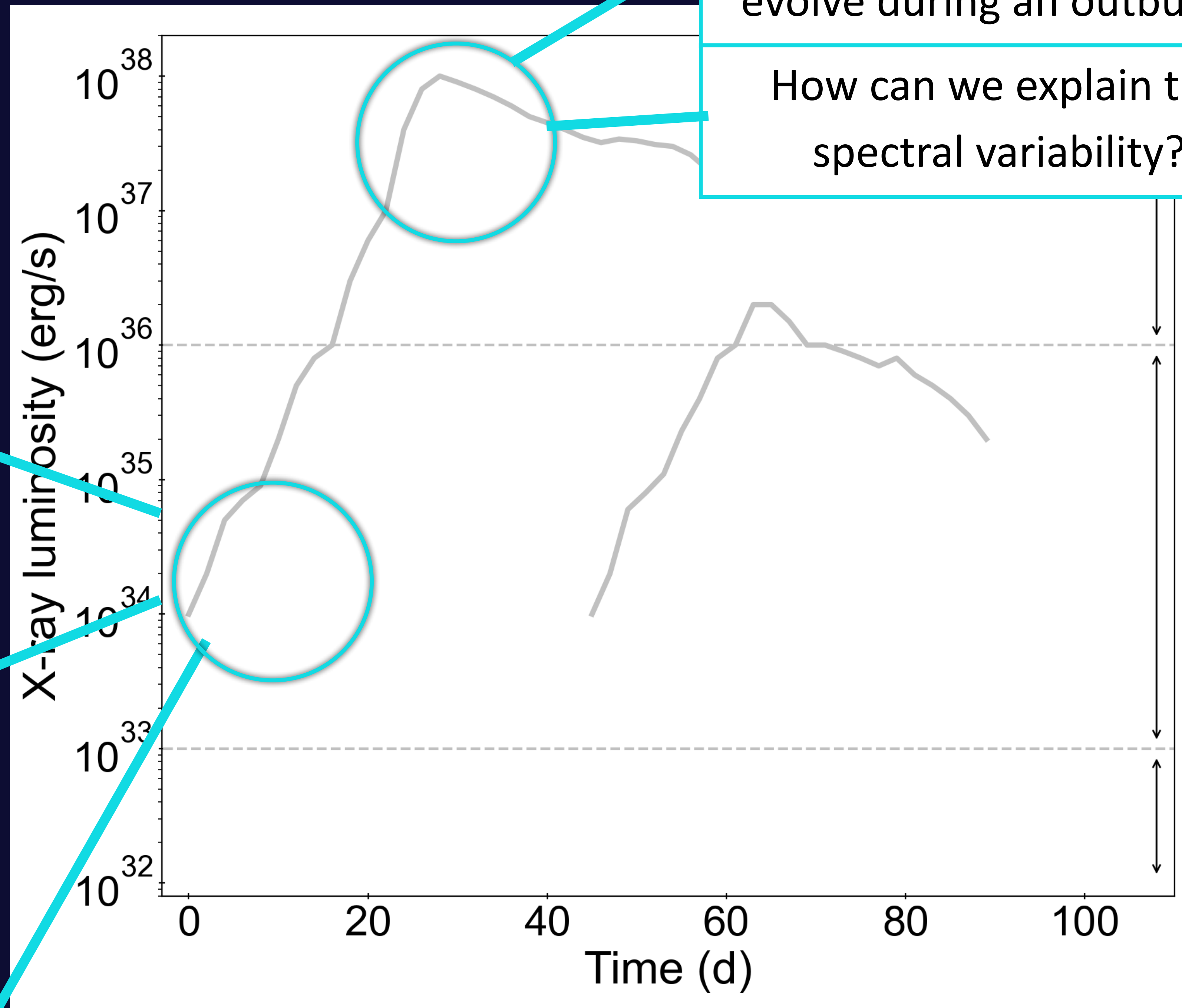


- Models of spectral states in a NS LMXB

Di Salvo, Papitto, AM+2023; Done & Gierlinski 2007; Gladstone+2007; Muñoz-Darias+2014; Lin & Yo 2017; Ludlam+2017; Manca+2023a; *just to name a few…*

How does the accretion flow evolve during an outburst?

How can we explain the spectral variability?



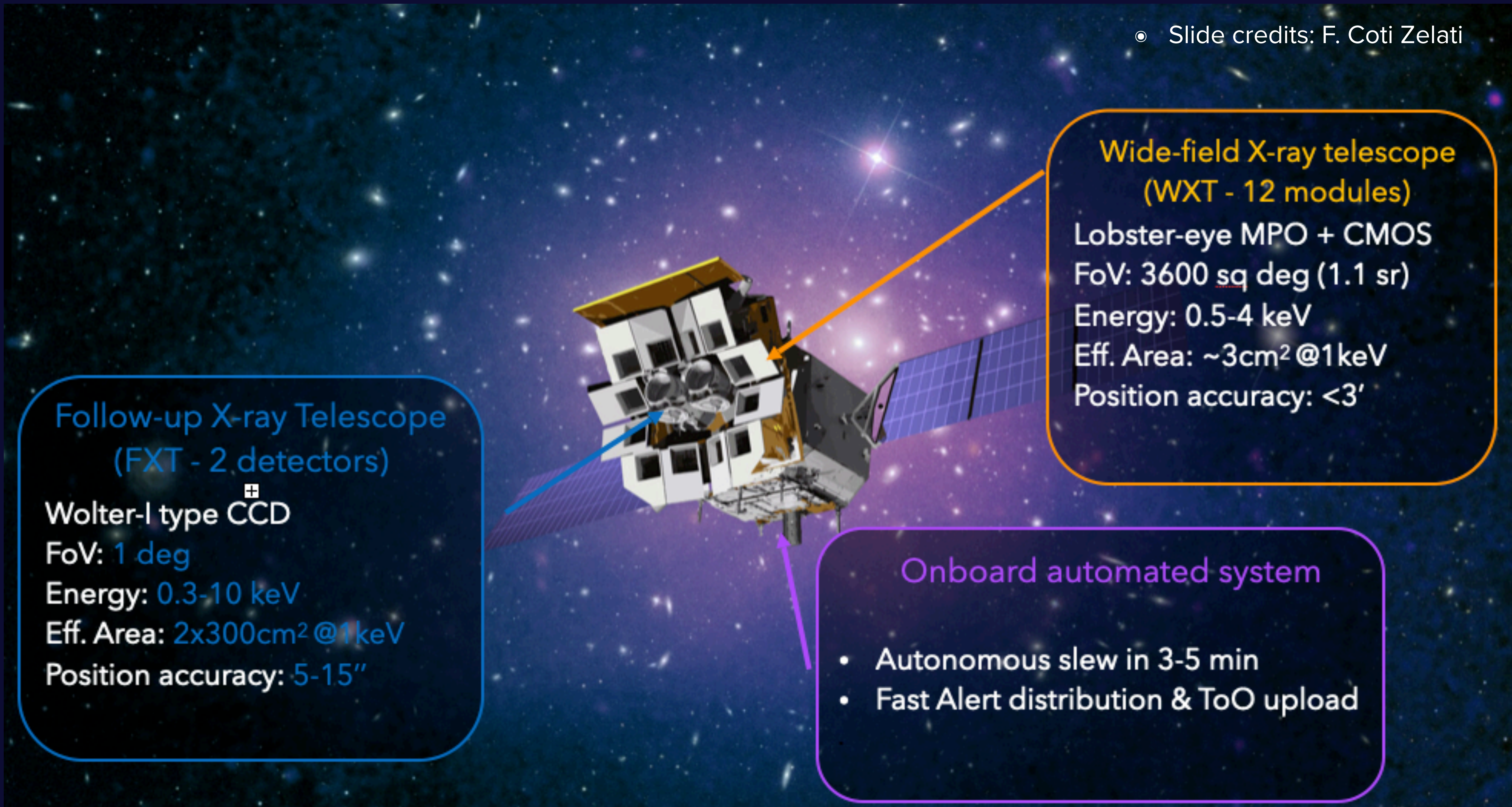
How and when outbursts starts?

How does the early stage of an outburst proceed at different wavelengths?

What circumstances determine the peak luminosity, duration and recurrence time of an outburst?

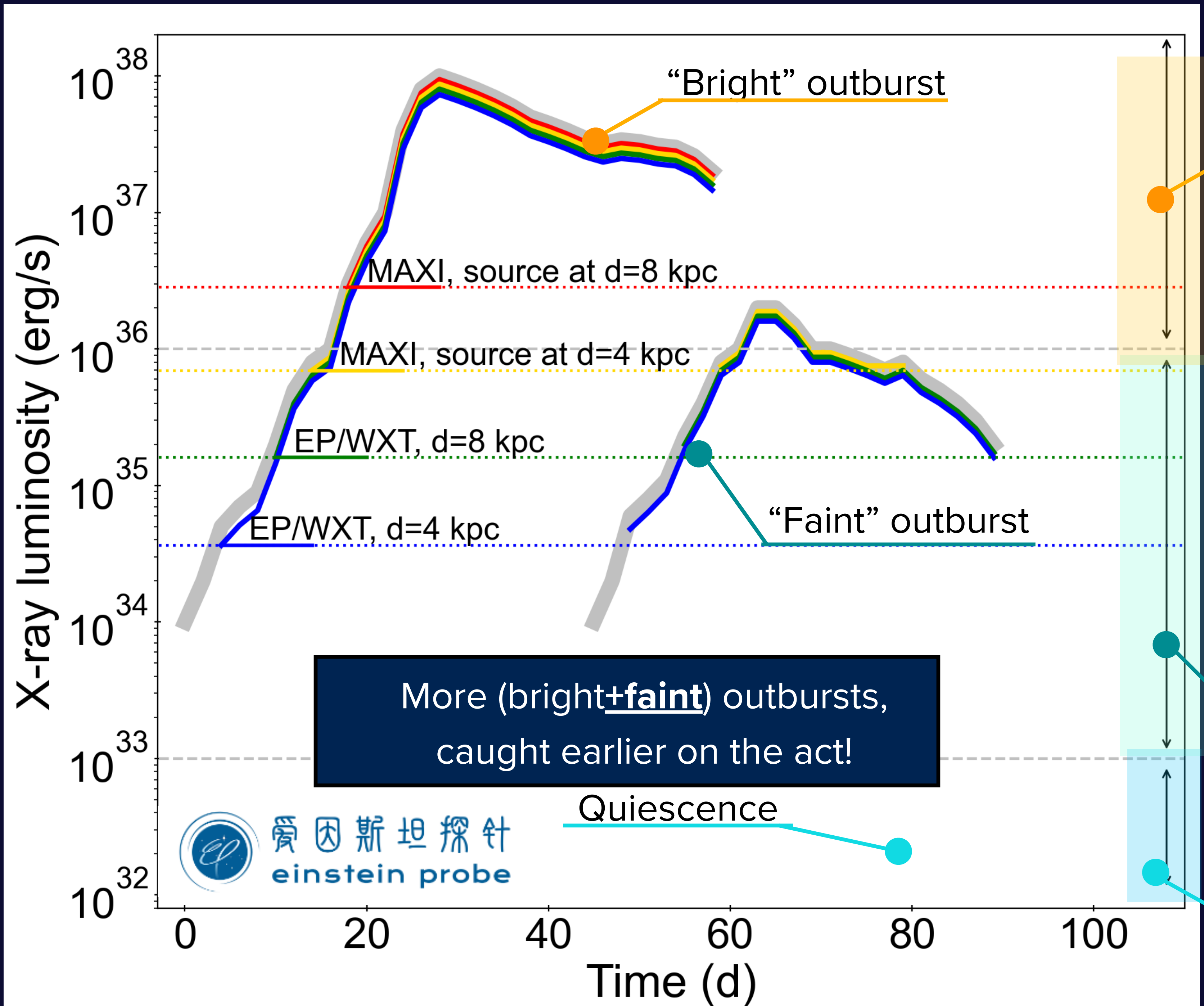
Are the answers to those questions **the same** for BHs and NSs?

Yuan+2022; 2025; Cheng+2025



- A new time-domain X-ray mission, launched in 2024 (Chinese Academy of Sciences + ESA & MPE);
- The **WXT** (the monitor) has the best **grasp*** ever - can detect new transients once they get to a few mCrabs!

*Grasp: FoV*Effective area



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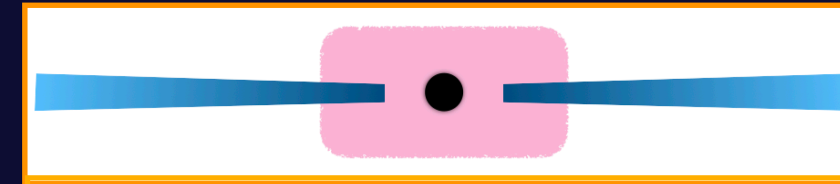

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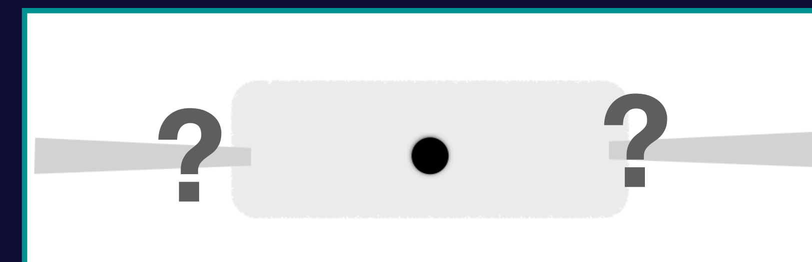

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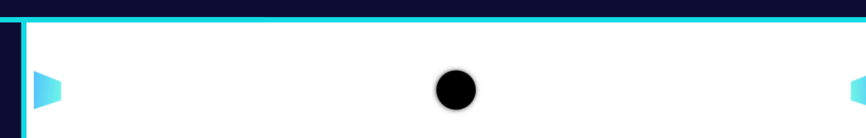
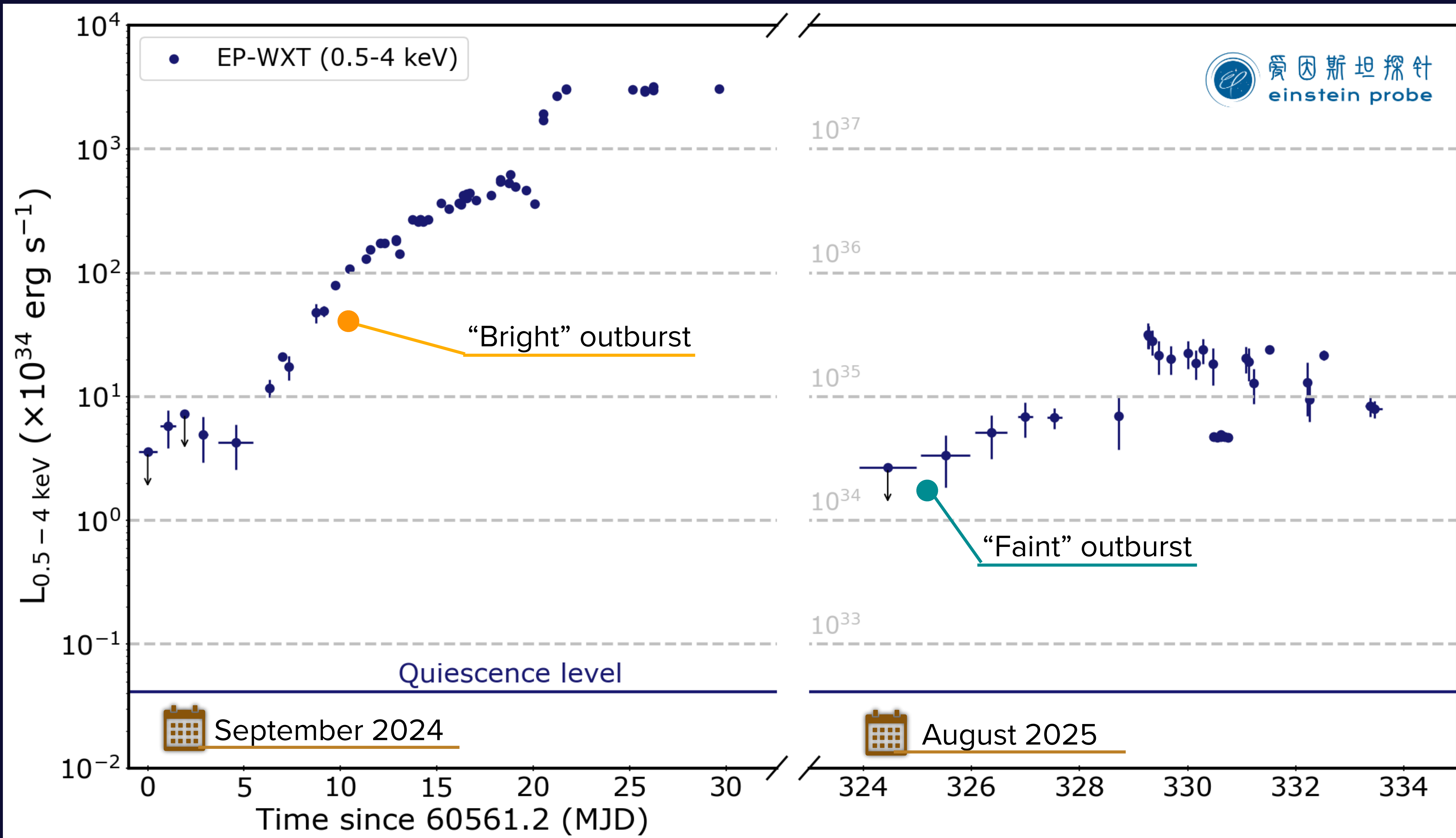


Accretion (almost) shut-off; (<10^{33} erg/s)

Kunte+1973, Coti Zelati+2014, Mata Sanchez+2017, Diaz Trigo+2018, Mandal+2025 *just to name a few…*

- In outburst almost every year;
- P_{orb}=18.95 hr (Chevalier+1991), P_{spin}=1.8 ms (Casella+2008), d=4.5 kpc (Galloway+2008);



Atels by: Liu+2024, Rout+2024, Russell+2024, Alabarta+2025, Rout+2025;

Kunte+1973, Coti Zelati+2014, Mata Sanchez+2017, Diaz Trigo+2018, Mandal+2025 *just to name a few…*

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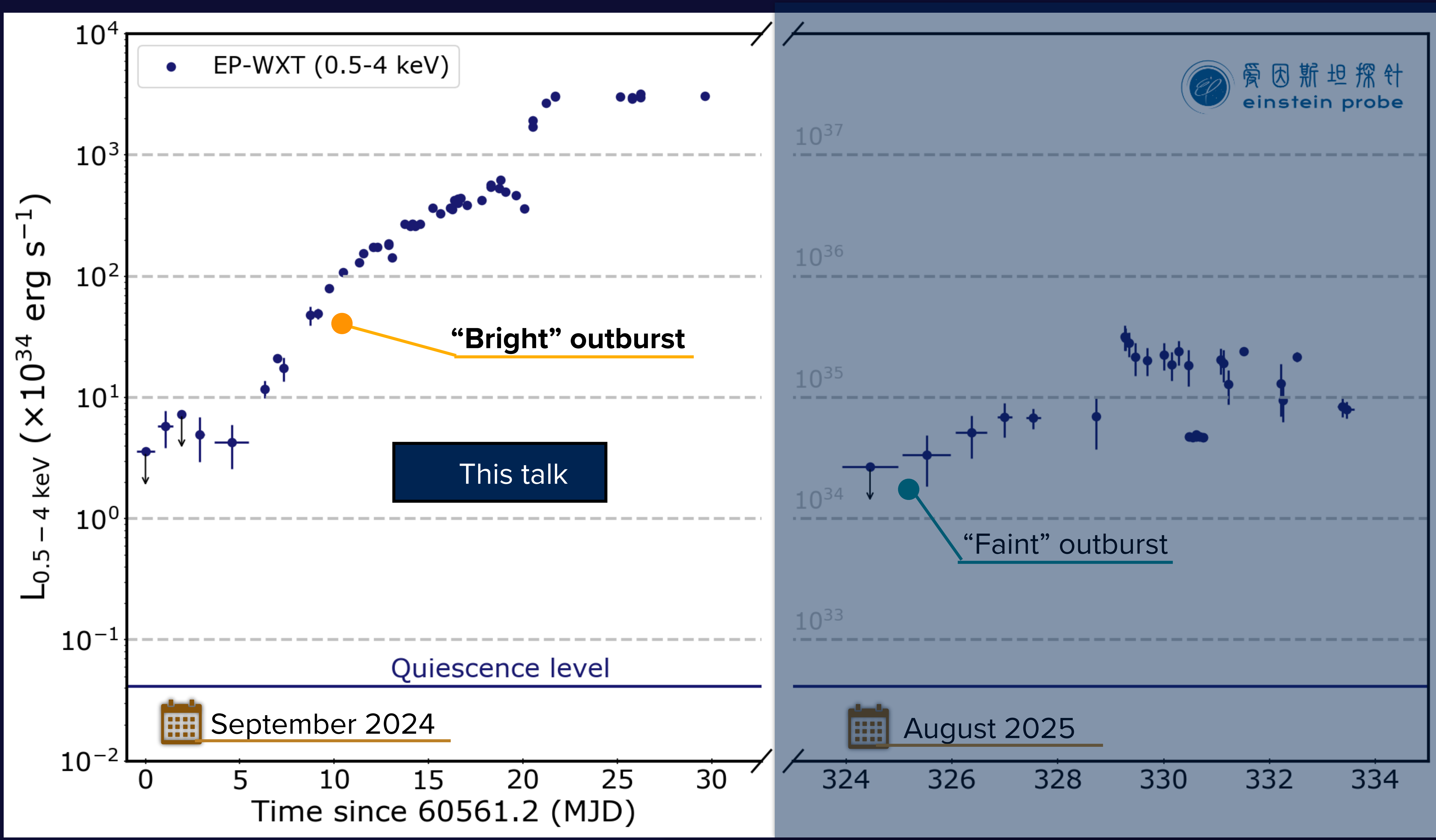

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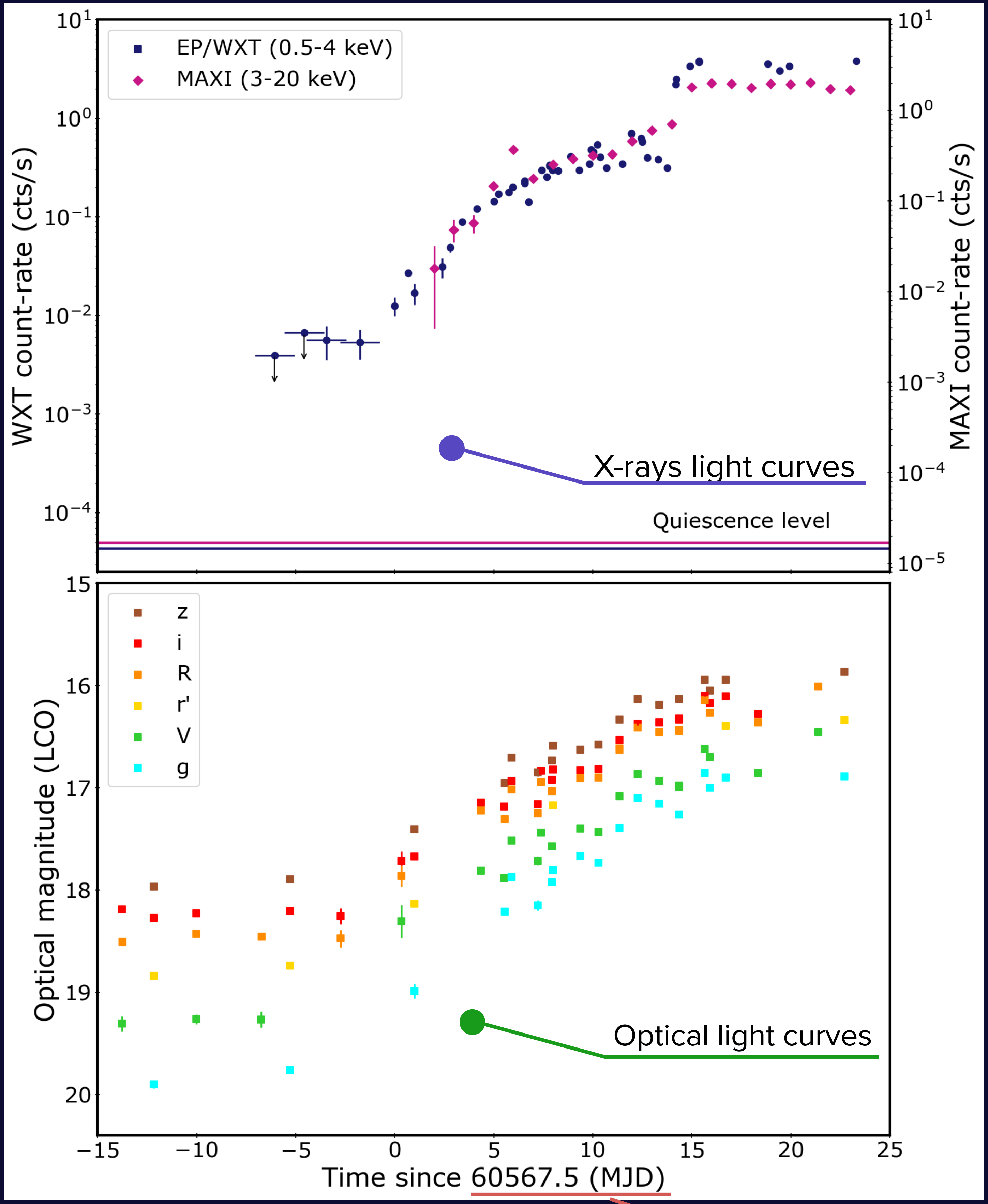
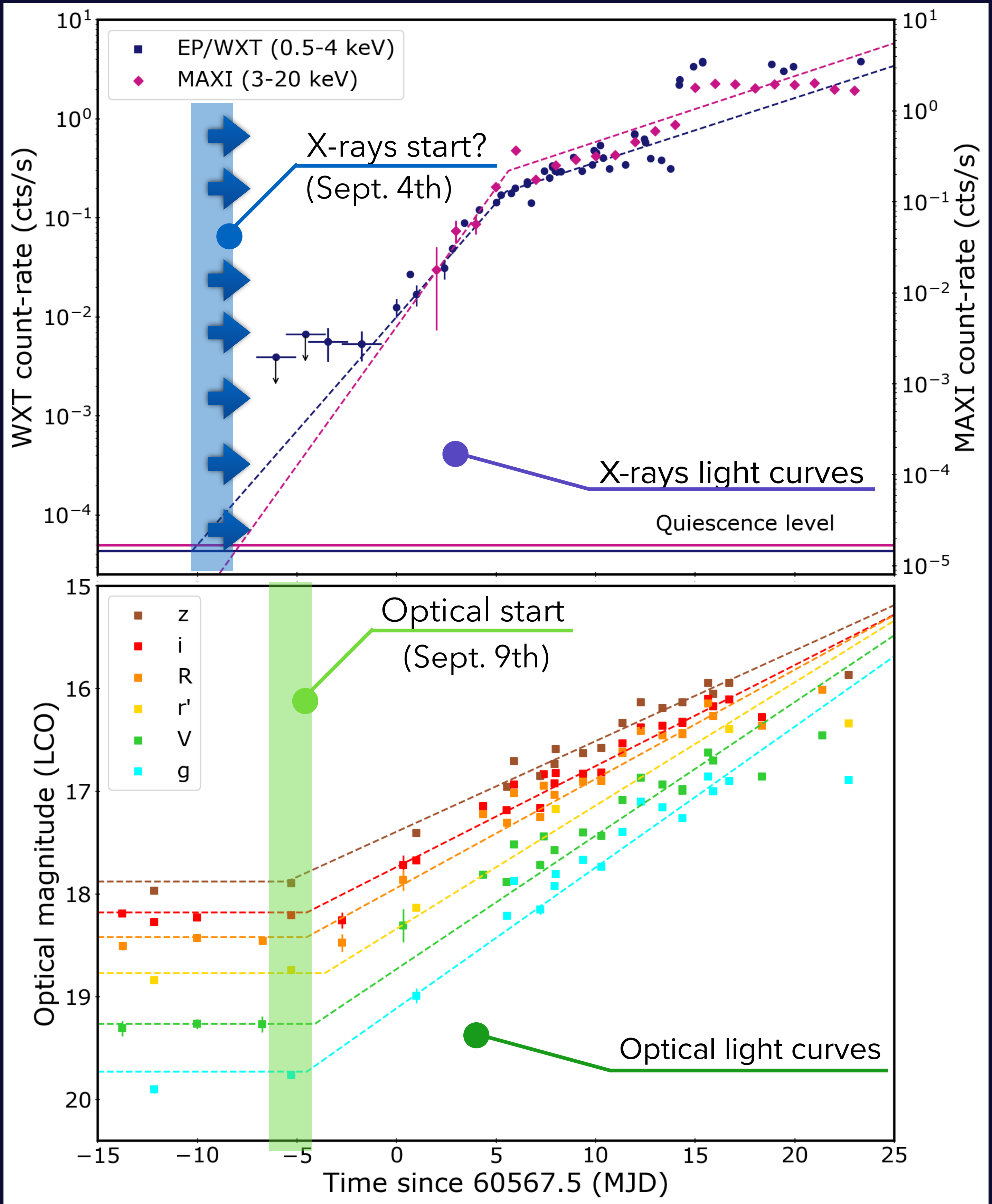


- We were able to observe the onset of the outburst with Einstein Probe, MAXI and Las Cumbres Observatory thanks to the XB-NEWS program (Russell+2019);

More about XB-NEWS on Kevin Alabarta's talk after the break!

- Marino+, in prep.



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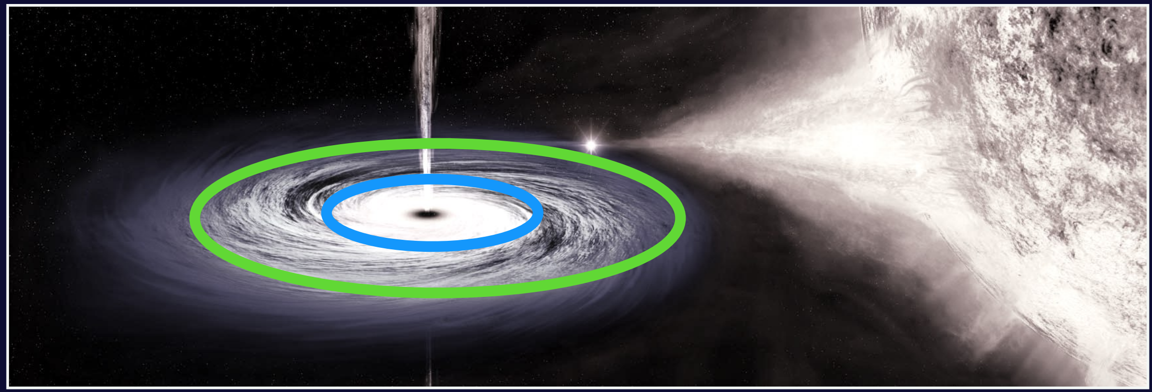
- We parametrised the light curves with phenomenological models to individuate the **start time** of the outburst in the different bands;



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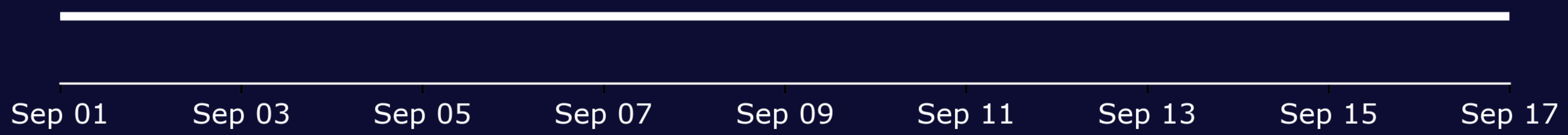
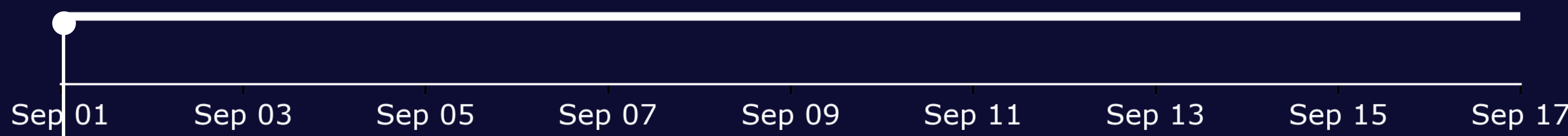
PRELIMINARY

The day the outburst was first caught by EP

PRELIMINARY





(Taken in Croatia, last year)

My holidays were over :(

PRELIMINARY

Sep 01 Sep 03 Sep 05 Sep 07 Sep 09 Sep 11 Sep 13 Sep 15 Sep 17

EP first detects Aql X-1

(Taken in Croatia, last year)

My holidays were over :(

PRELIMINARY

Sep 01 Sep 03 Sep 05 Sep 07 Sep 09 Sep 11 Sep 13 Sep 15 Sep 17

EP first detects Aql X-1

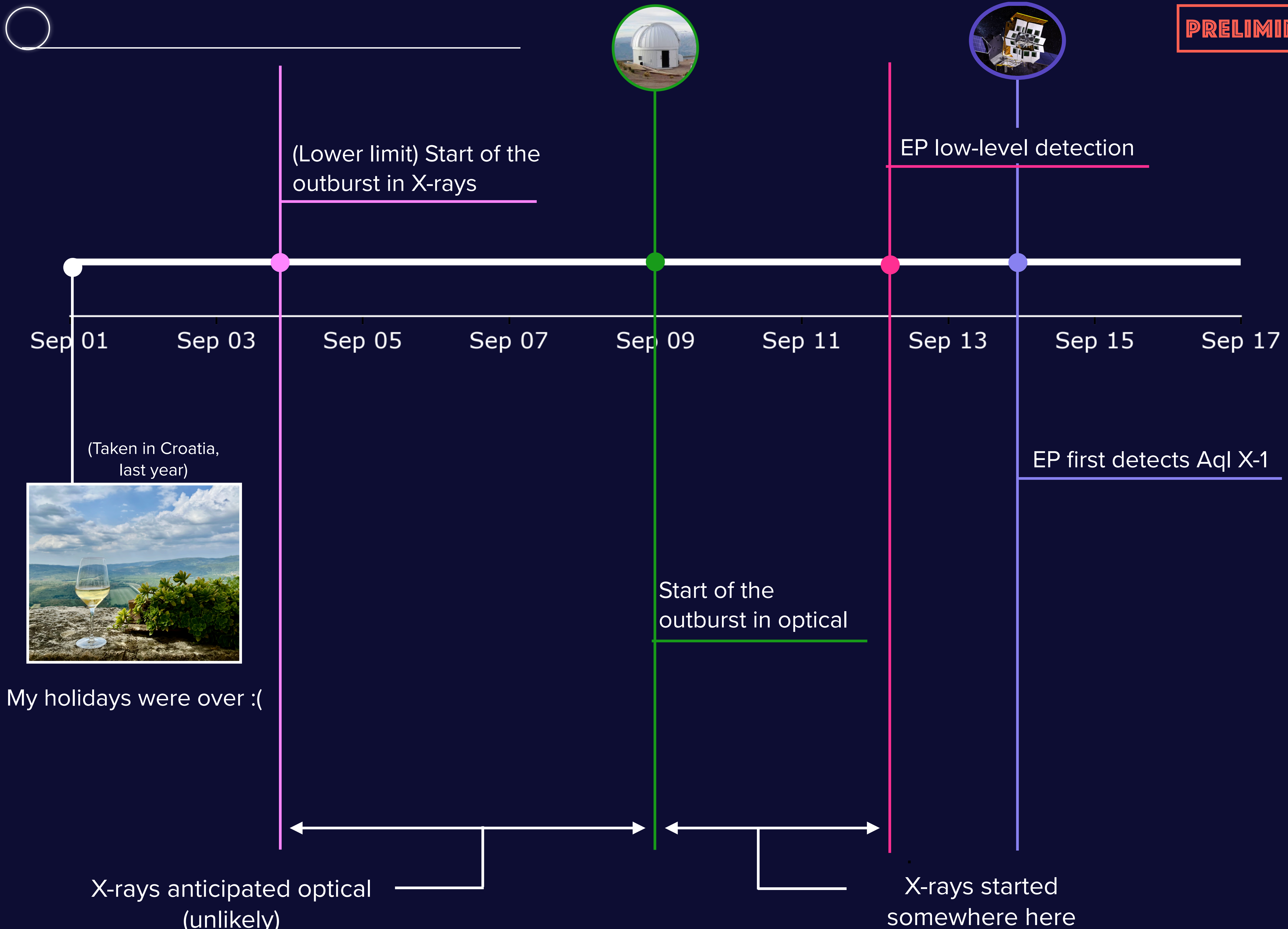
(Taken in Croatia, last year)

Start of the outburst in optical

My holidays were over :(


PRELIMINARY
(Lower limit) Start of the outburst in X-rays
EP low-level detection
Sep 01
Sep 03
Sep 05
Sep 07
Sep 09
Sep 11
Sep 13
Sep 15
Sep 17
(Taken in Croatia, last year)
EP first detects Aql X-1
Start of the outburst in optical
My holidays were over :(
X-rays anticipated optical (unlikely)
X-rays started somewhere here

PRELIMINARY



An optical-to-X-rays delay of 3 d or less?

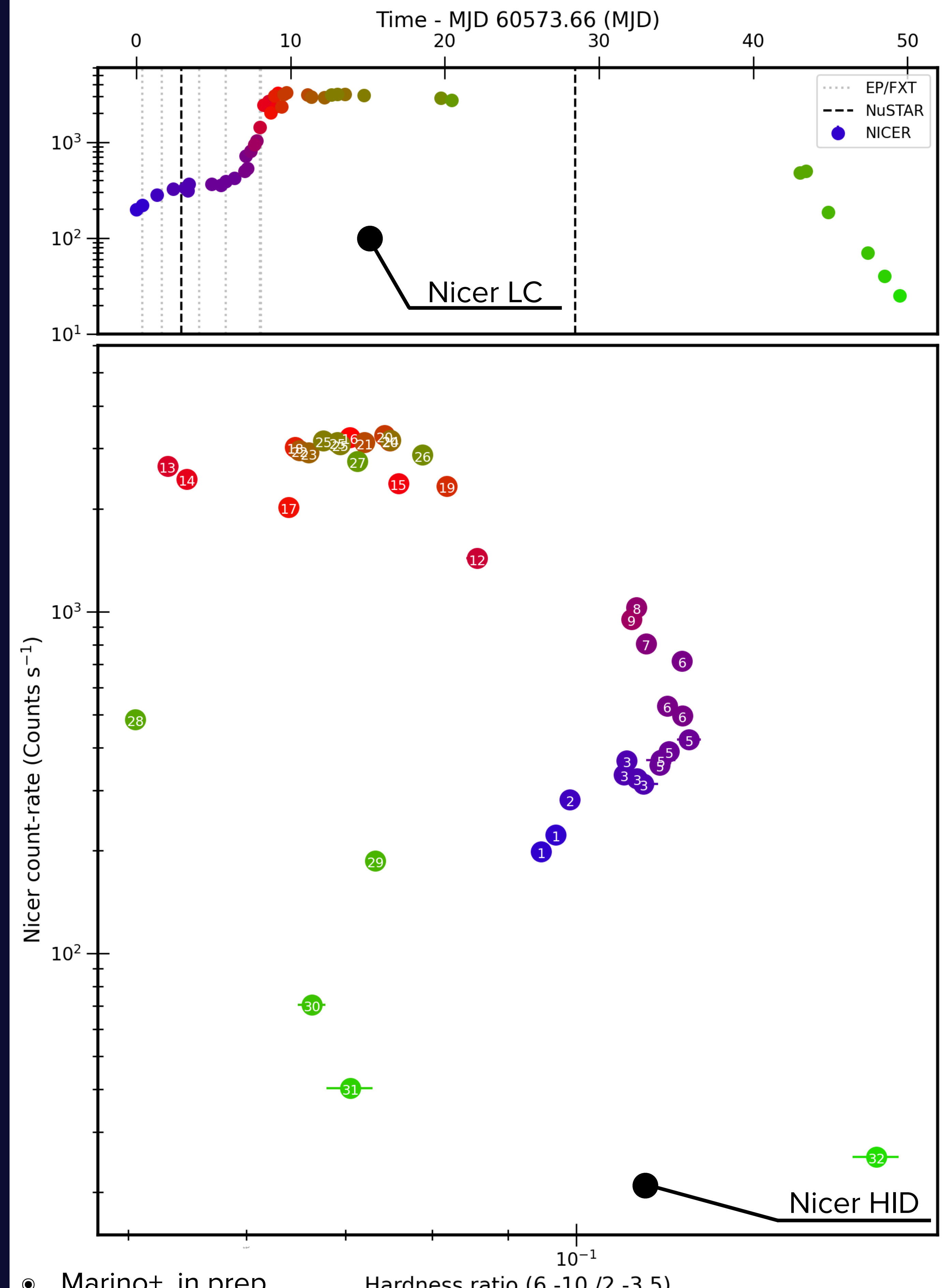
- Lasted for about 2 months;

5 Einstein Probe/FXT obs.

44 Nicer obs.

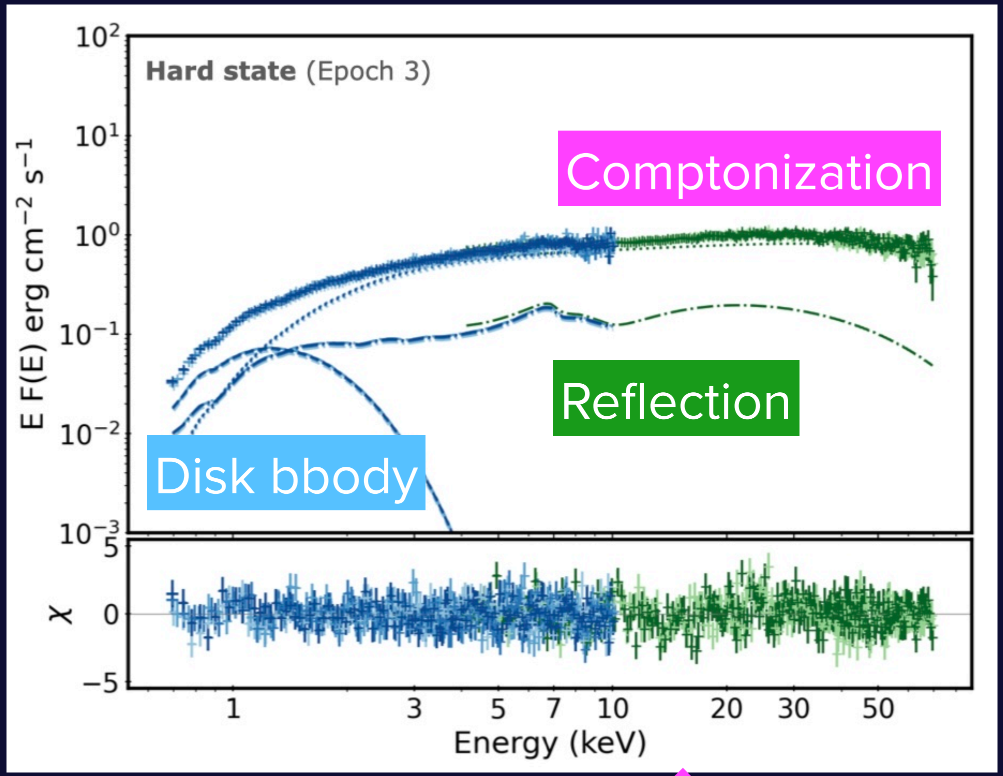
2 NuSTAR obs.

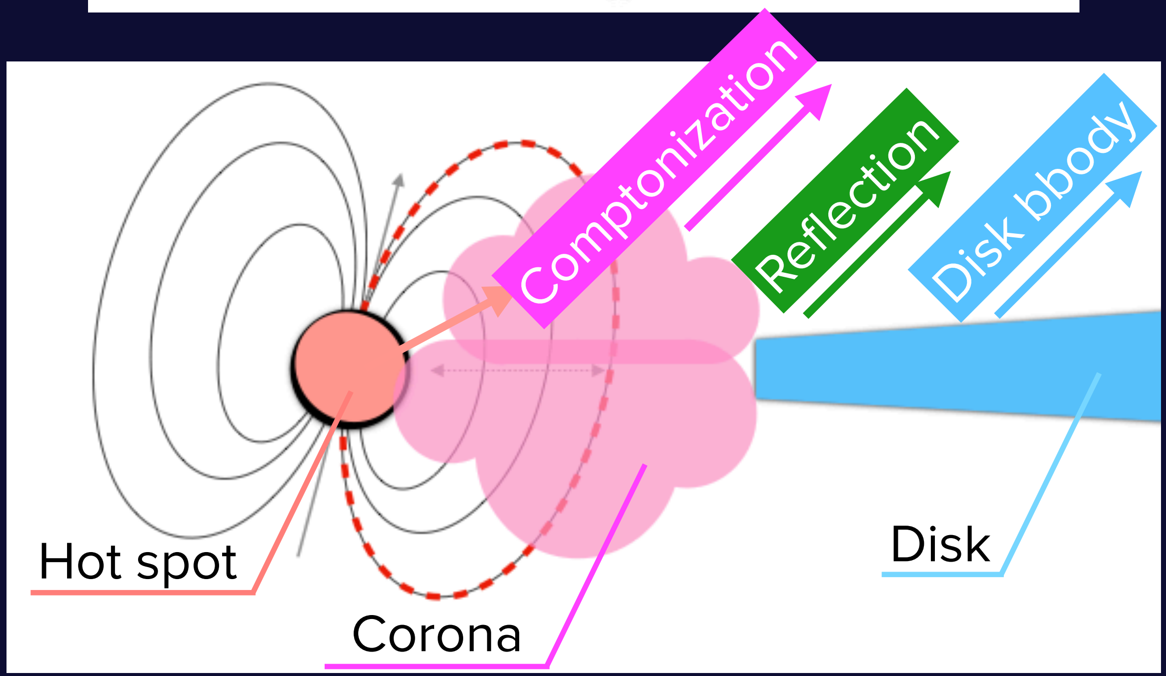
- Showed the typical q-diagram shape;



- Marino+, in prep.

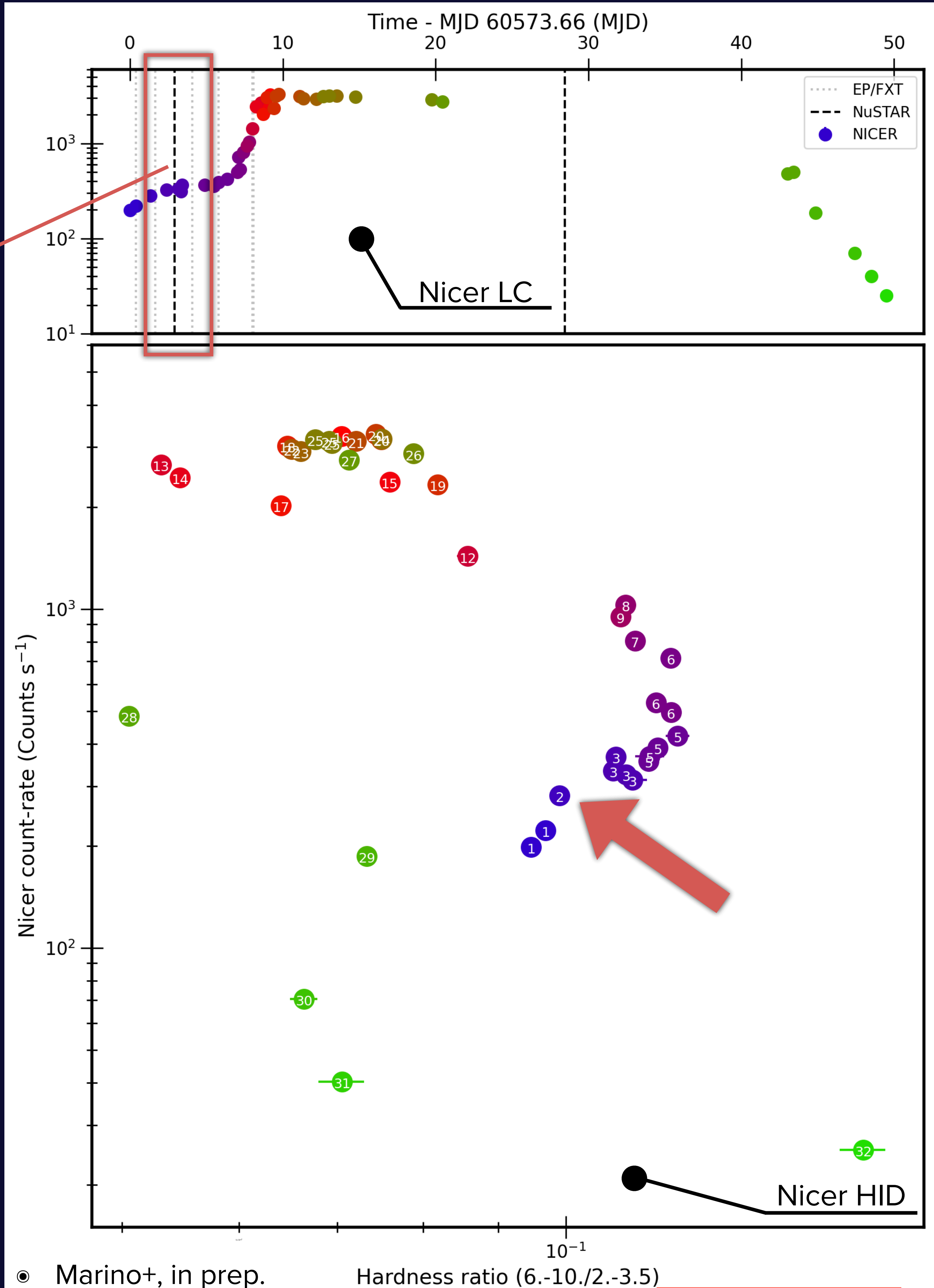
- Best-fit model including:





Xspec

Comptonization -> `thcomp*bbodyrad`
Disk bbody -> `diskbb`
Reflection -> `relxillCp` or `relxillNS`



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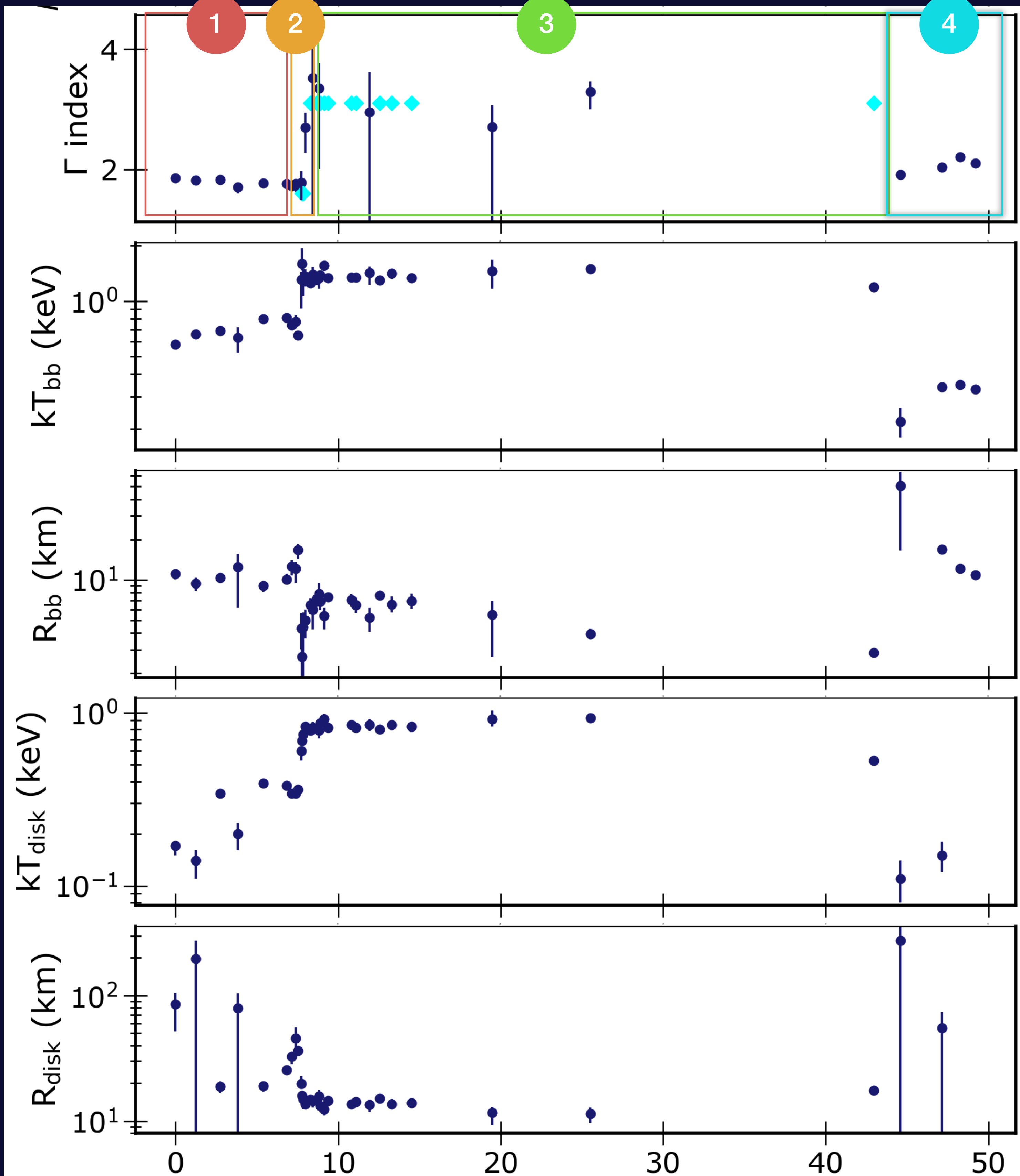

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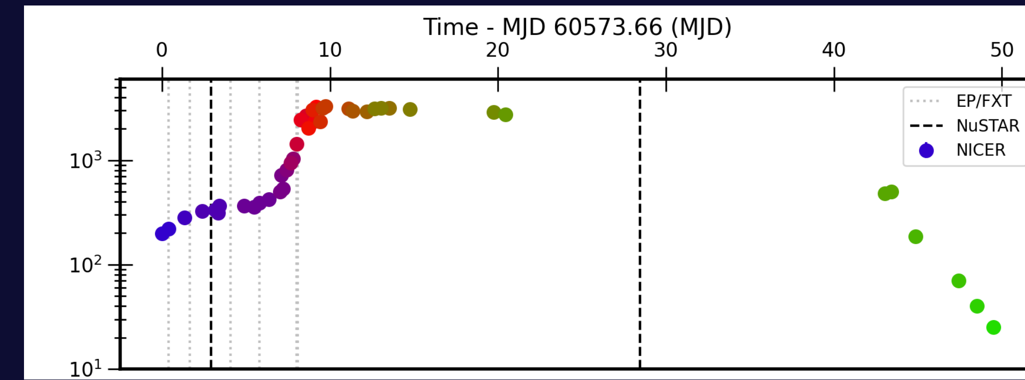
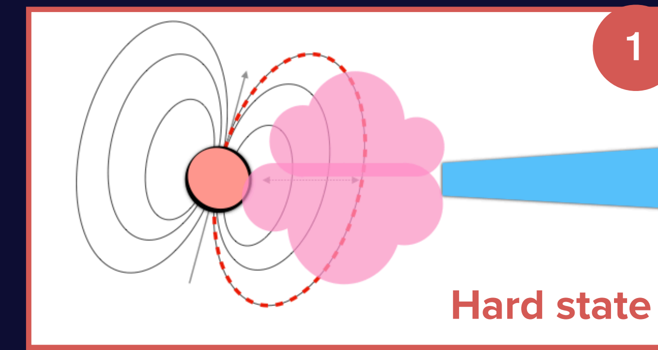
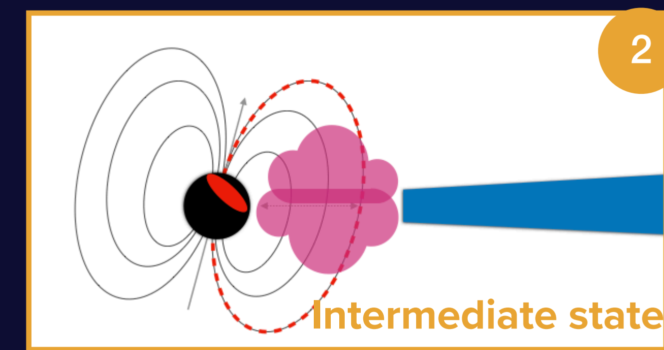


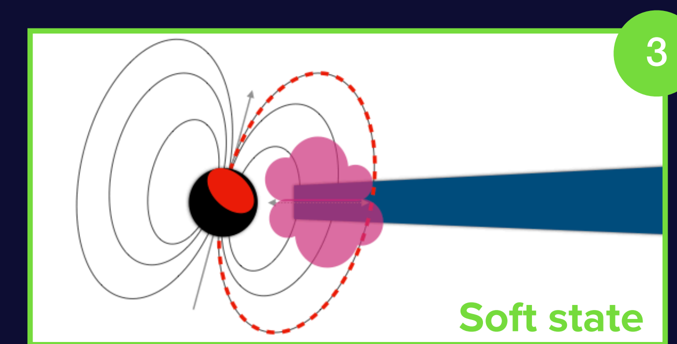
$\Gamma \sim 1.8$
$kT_{bb} \sim 0.7$ keV
$kT_{disk} \sim 0.4$ keV
$R_{bb} \sim 10$ km
$R_{disk} \sim 50$ km



$\Gamma \sim 1.5 - 3.0$
$kT_{bb} \sim 1.0$ keV
$kT_{disk} \sim 0.7$ keV
$R_{bb} \sim 3$ km
$R_{disk} \sim 20$ km



$\Gamma \sim 3.1$
$kT_{bb} \sim 1.3$ keV
$kT_{disk} \sim 1.0$ keV
$R_{bb} \sim 8$ km
$R_{disk} \sim 15$ km



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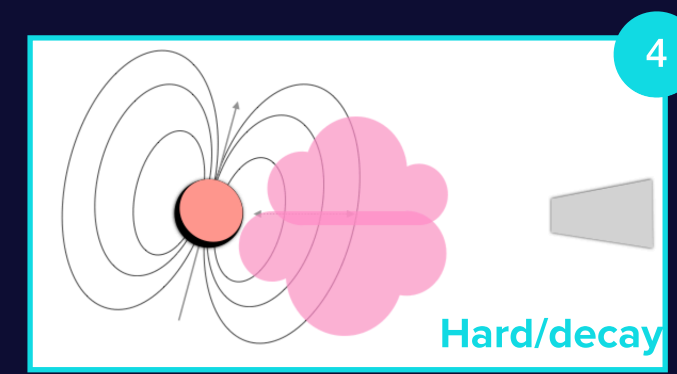

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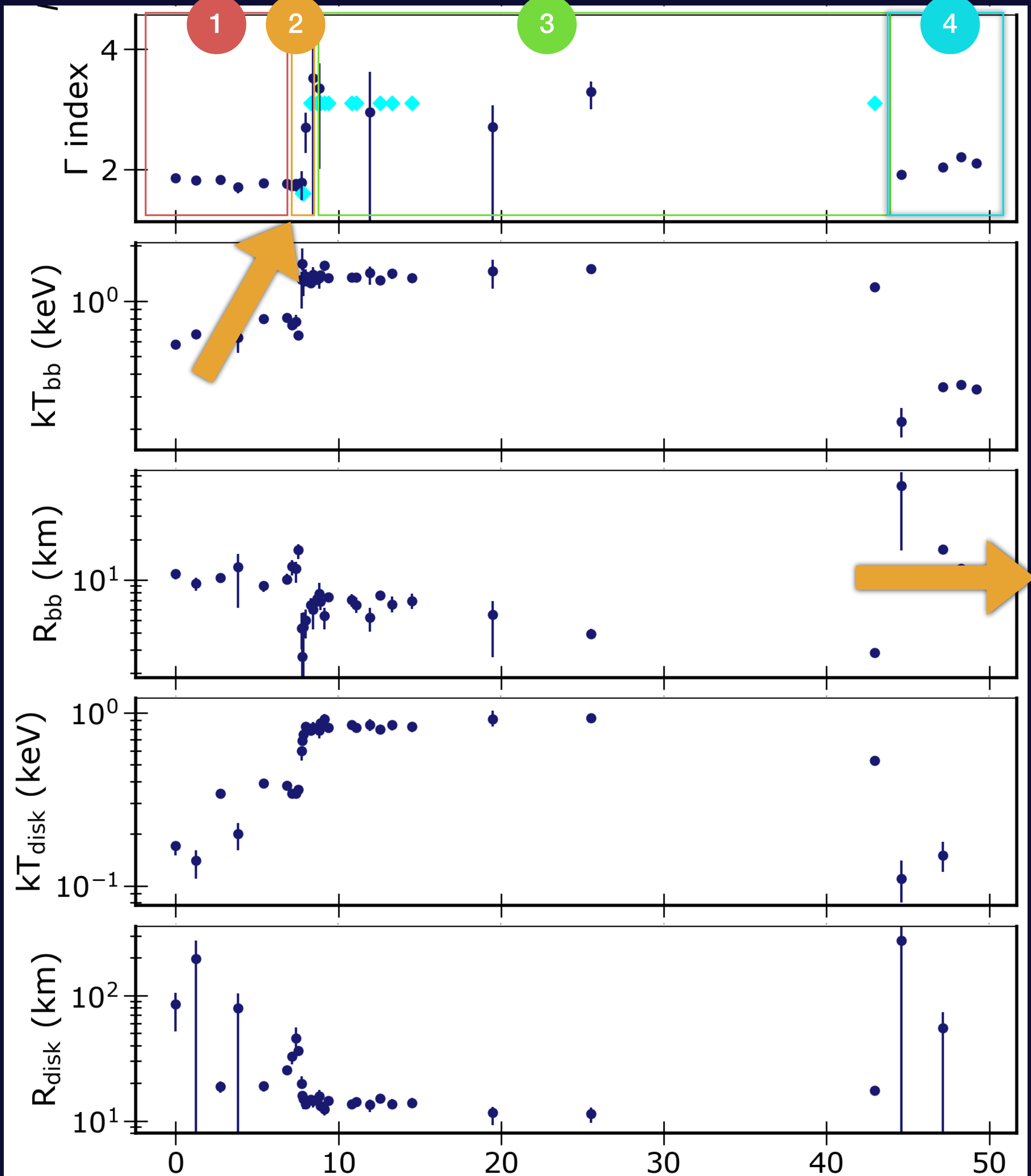
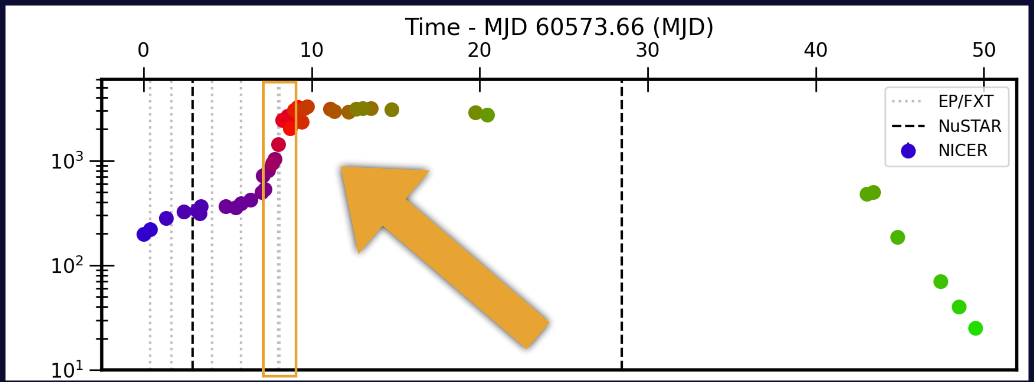


Marino+, in prep.



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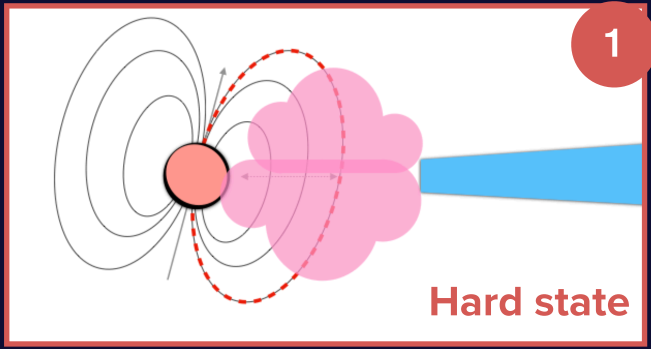

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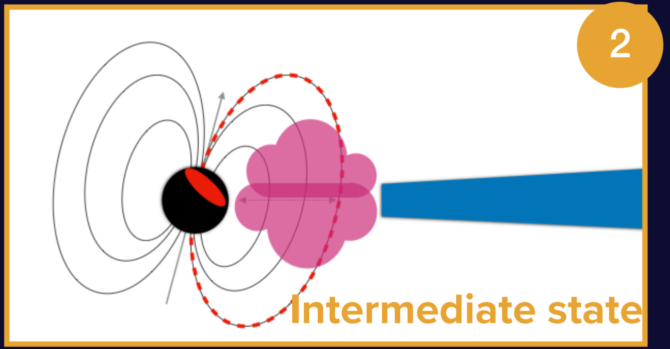

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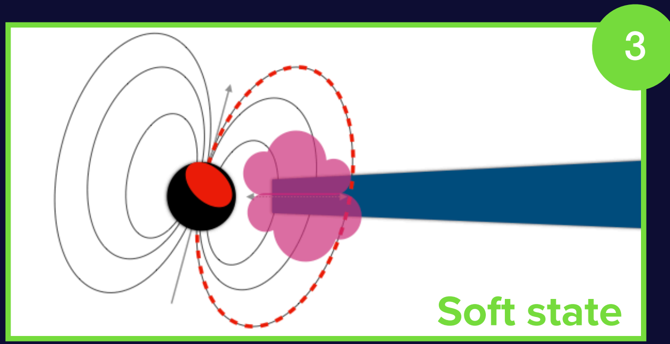

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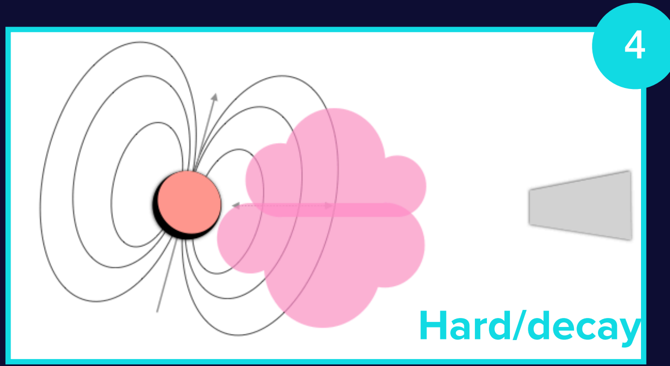
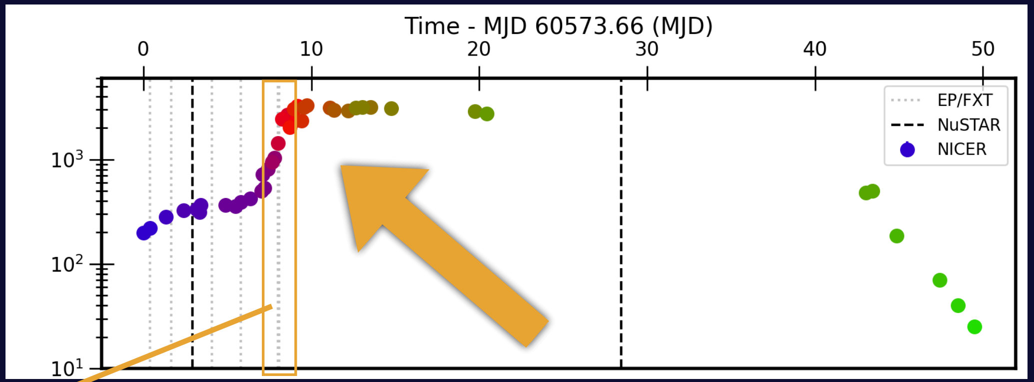


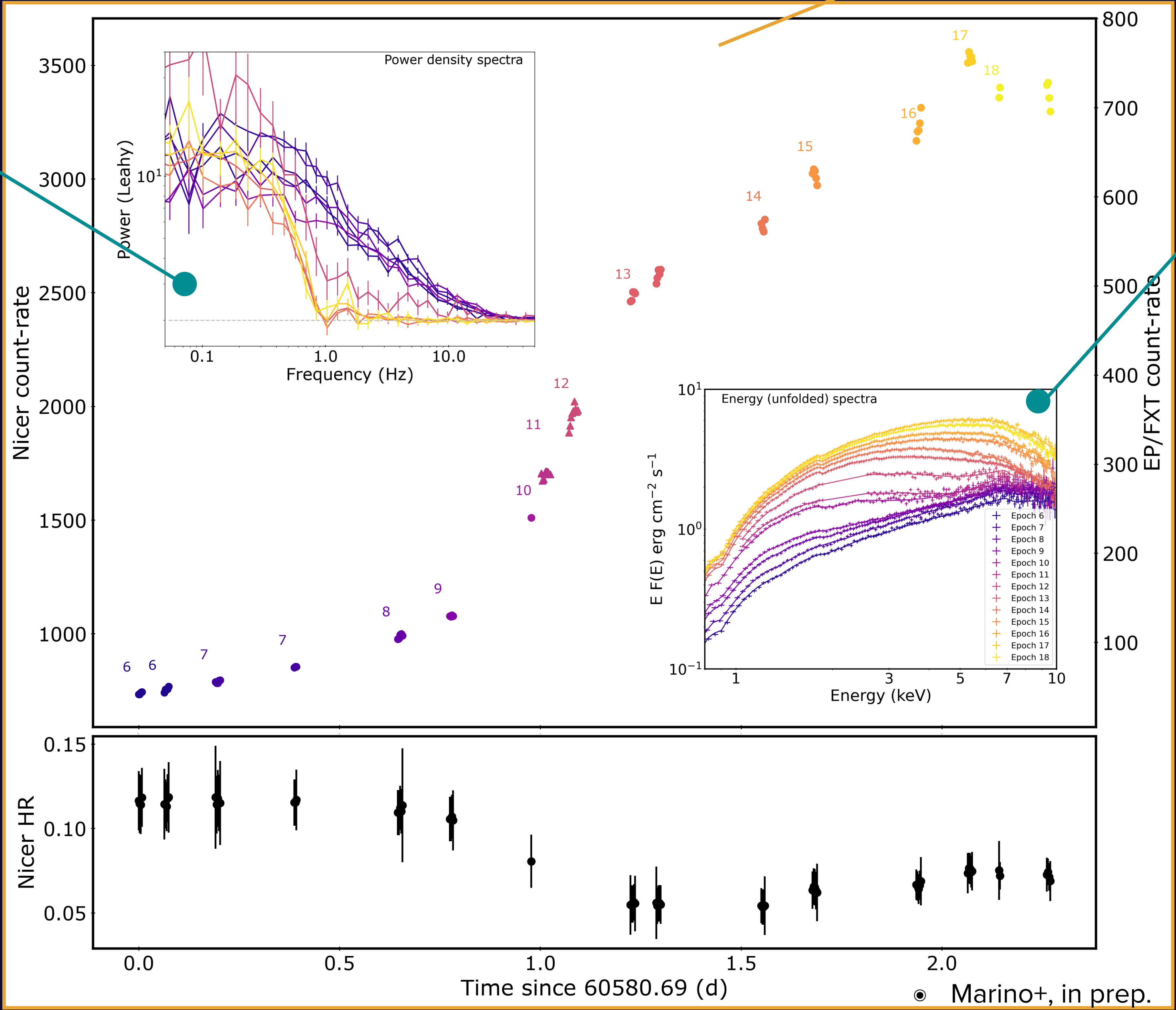
PRELIMINARY

- A spectacularly rapid state transition confirmed by both spectral and timing properties of the source;



Noise drop

Cooling down of the corona?



Spectral softening

An energy exchange from disk to hot spot?

- Marino+, in prep.

PRELIMINARY

i) Thanks to EP, we were able to follow the 2024 outburst by Aql X-1 already since it reached a triggering X-ray luminosity of less than 10^{35} erg/s.

ii) By comparing the X-rays and optical (LCO) light curves, we suggest that the **X-rays and optical outbursts started about 3-days (or less)** apart, consistent with similar works (e.g. Bernardini+2016, Goodwin+2020, Rout+2025); to be sure about these numbers we need even more sensitive X-rays monitors.

iii) The spectral evolution of the source followed the canonical q-track and displayed the typical spectral states, but the hard-to-soft transition was extremely quick (about half a day)!

iv) Intermediate states are harder to catch in NS with respect to BHs? (see also Muñoz-Darias+2014, Marino+2019b, Fiocchi+2019);

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Thanks for the attention! Questions?

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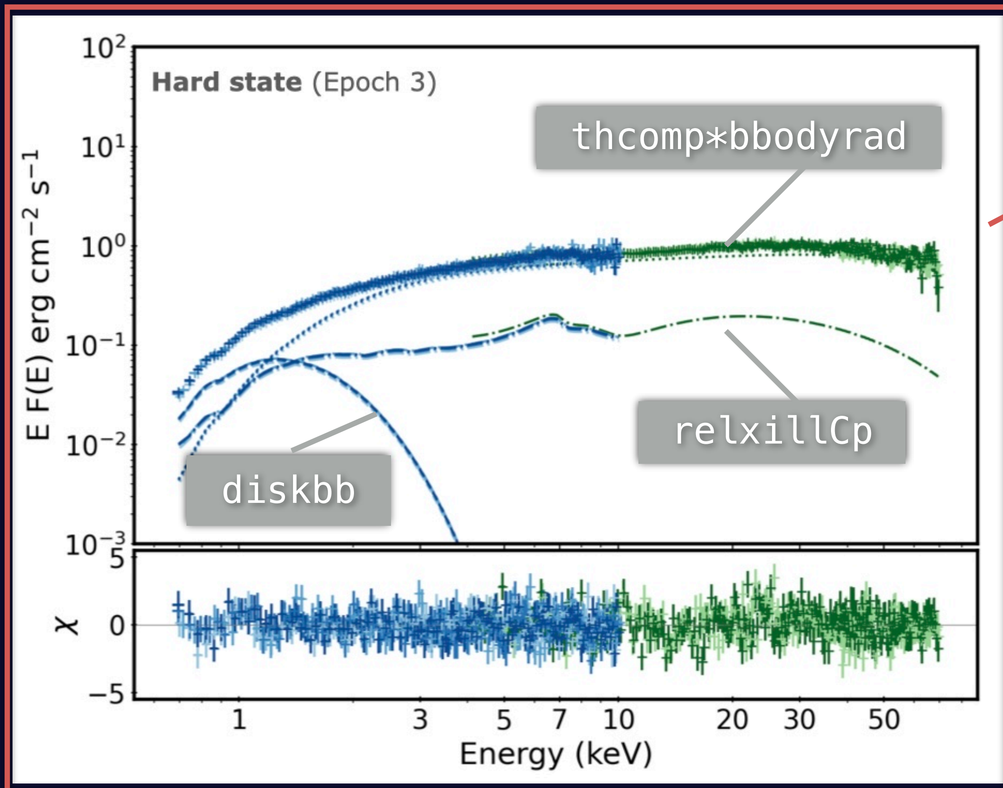
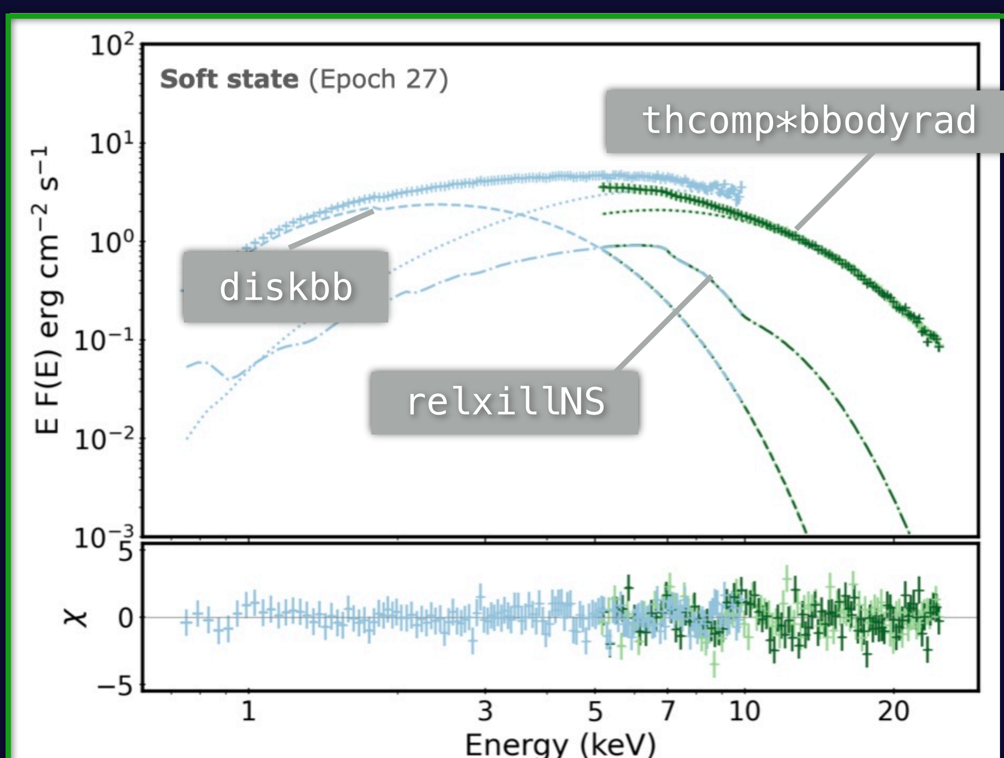
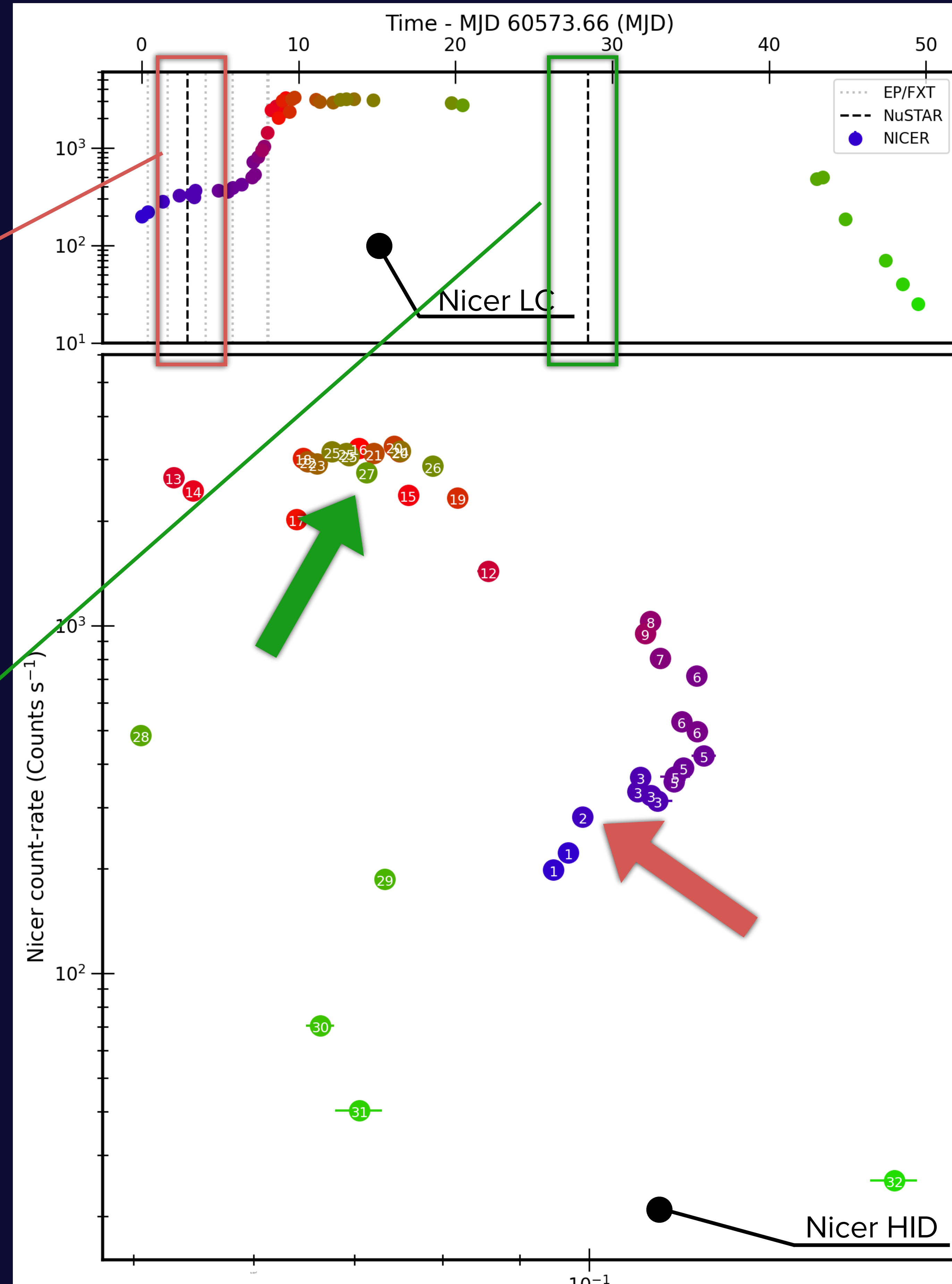
Extra-slides

- NICER+NuSTAR quasi-simultaneous spectra;







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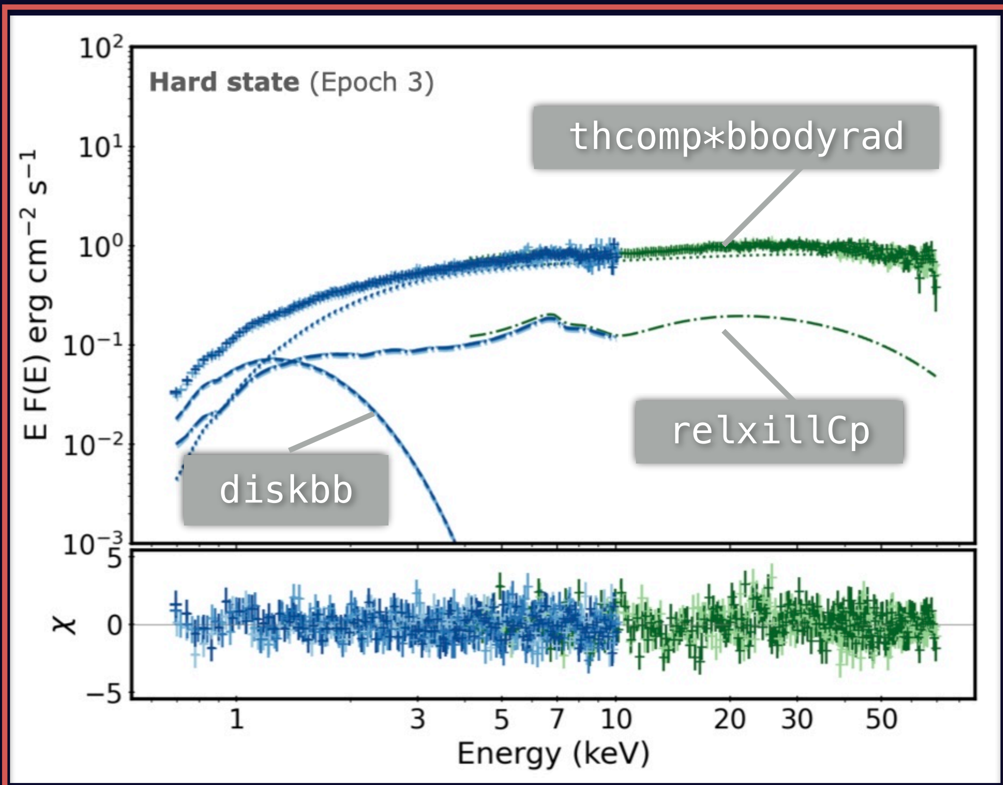
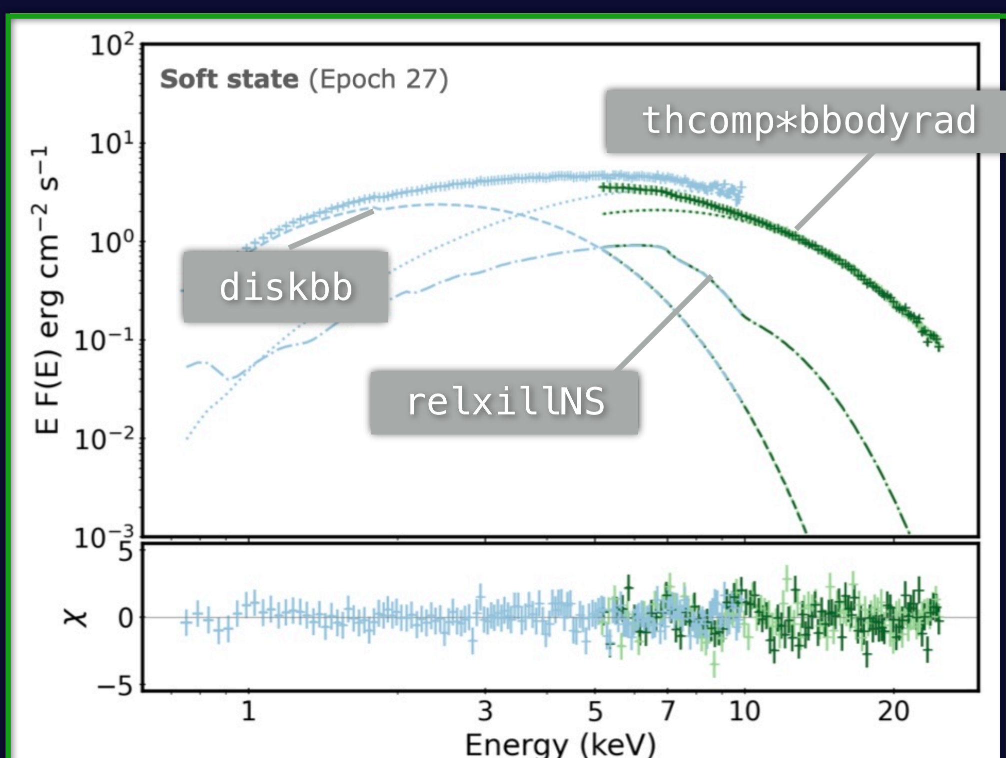
PRELIMINARY





Broadband spectral analysis

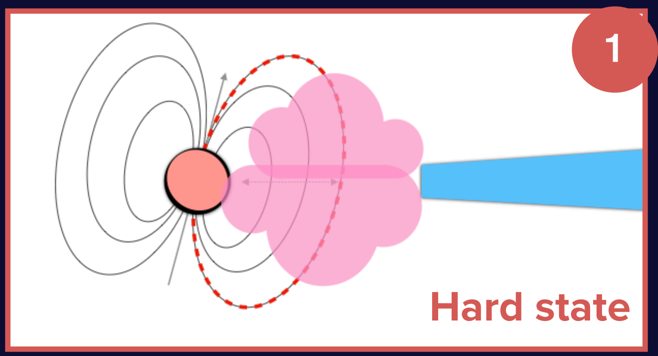
Component	Parameters		Description	Epoch 3	Epoch 27
constant	$c_{\rm cal}$		Intercalibration constant	(1.0)	
TBabs	N_H	10^{22} cm^{-2}	Equivalent hydrogen column density	(0.50)	
thComp	Γ		Power-law index of the Comptonization spectrum	1.820±0.002	$3.4^{+0.3}_{-0.2}$
	kT_e	keV	Electron temperature of the corona	$22.2^{+1.3}_{-0.8}$	$3.3^{+0.3}_{0.2}$
	$f_{\rm cov}$		Covering fraction	(1.0)	
bbodyrad	$kT_{\rm bb}$	keV	Blackbody temperature	$0.69^{+0.03}_{-0.02}$	$1.50^{+0.06}_{-0.03}$
	$K_{\rm bb}$		Blackbody radius†	10.4±0.6	$4.0^{+0.2}_{-0.4}$
diskbb	$kT_{\rm disk}$	keV	Inner disk temperature	0.340±0.020	$0.93^{+0.05}_{-0.04}$
	$R_{\rm disk}$	(km)	Disk inner radius†	$18.9^{+2.0}_{-1.9}$	$11.4^{+1.8}_{-1.4}$
expabs	$E_{\rm cut-off,low}$	keV	Low energy cut-off	$=kT_{\rm bb}$	-
relxillCp	i	°	System inclination	$26.0^{+3.0}_{-2.0}$	-
	$a*$		Spin parameter	(0)	-
	$R_{\rm in}$	$R_{\rm G}$	Inner disk radius	<10.0	-
	$R_{\rm out}$	$R_{\rm G}$	Outer disk radius	(1000) -	
	ϵ		Disk emissivity	(3.0)	-
	z		Redshift to the source	(0)	-
	$\Gamma_{\rm relxill}$		Power-law index of the incident spectrum	$=\Gamma$	-
	$\log \xi$		Disk ionisation	$2.97^{+0.04}_{-0.06}$	-
	$\log N$	cm^{-3}	Disk density	(20.0)	-
	$A_{\rm Fe}$		Fe abundance of reflecting material	(1.0)	-
	$kT_{\rm e,refl}$	keV	Electron temperature of the corona	$=kT_{\rm e}$	-
	$f_{\rm refl}$		Reflection fraction	(-1.0)	-
	$K_{\rm refl}$	$(\times 10^3)$	Reflection normalization	1.97±0.17	-
relxillNS	i	°	System inclination	-	$31.1^{+2.0}_{-1.7}$
	$a*$		Spin parameter	-	(0)
	$R_{\rm in}$	$R_{\rm G}$	Inner disk radius	-	$13.0^{+5.0}_{-4.0}$
	$R_{\rm out}$	$R_{\rm G}$	Outer disk radius	-	(1000)
	ϵ		Disk emissivity	-	(3.0)
	z		Redshift to the source	-	(0)
	$kT_{\rm bb,relx}$		Blackbody temperature of the incident spectrum	-	$=kT_{\rm bb}$
	$\log \xi$		Disk ionisation	-	$3.01^{+0.12}_{-0.06}$
	$\log N$	cm^{-3}	Disk density	-	(20.0)
	$A_{\rm Fe}$		Fe abundance of reflecting material	-	(1.0)
	$kT_{\rm e,refl}$	keV	Electron temperature of the corona	-	$=kT_{\rm e}$
	$f_{\rm refl}$		Reflection fraction	-	(-1.0)
	$K_{\rm refl}$	$(\times 10^3)$	Reflection normalization	-	$2.2^{+0.3}_{-0.2}$
cflux	$F_{1-10\ \rm keV}$	$(\times 10^{-09})$ erg cm^{-2} s^{-1}	X-ray unabsorbed flux	2.290±0.004	11.800±0.014
	χ^2	(dof)		873(960)	299(309)

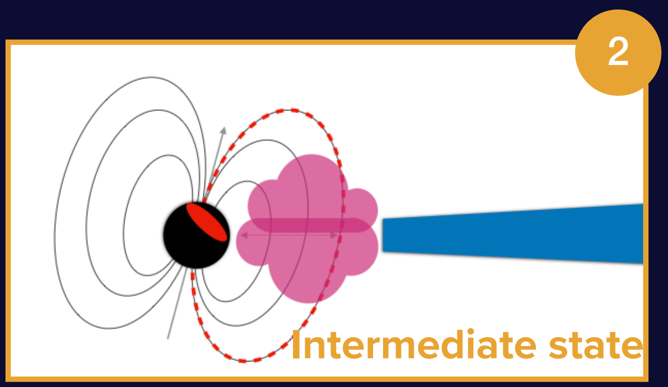
Table 3. Results of the spectral analysis of our broadband spectra. Quoted errors reflect 90% confidence level. The parameters that were kept frozen during the fits are reported between round parentheses. $R_{\rm G}$ represents the gravitational radius. The reported flux values correspond to the 1–10 keV energy range. †: estimated from the parameter normalization (see text for more details).

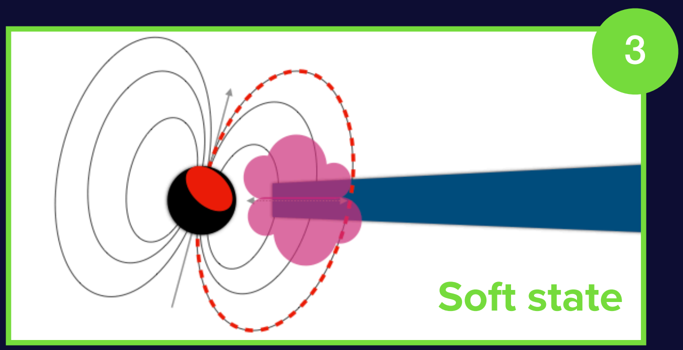
- Marino+, in prep.

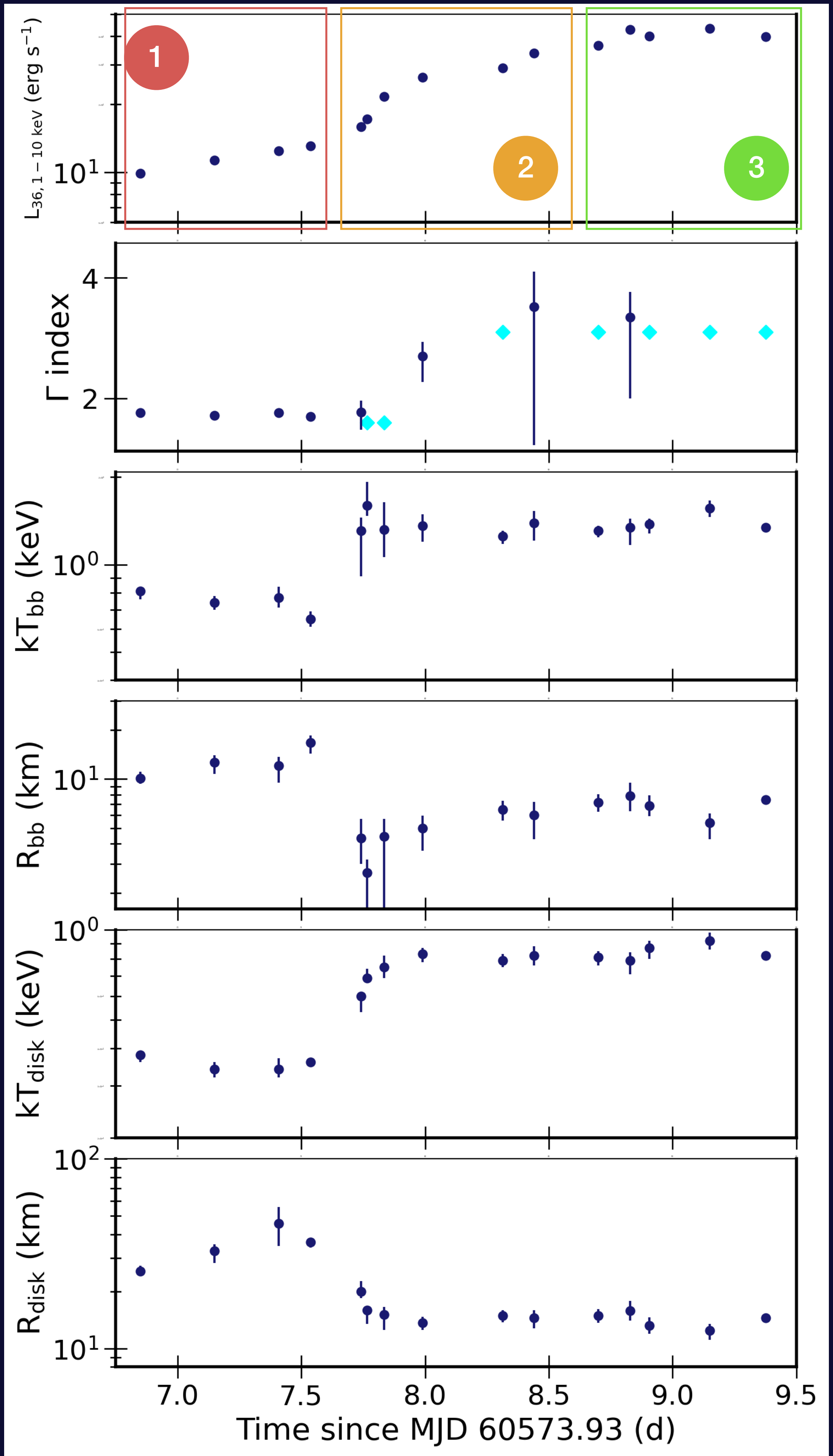
Marino+, in prep.

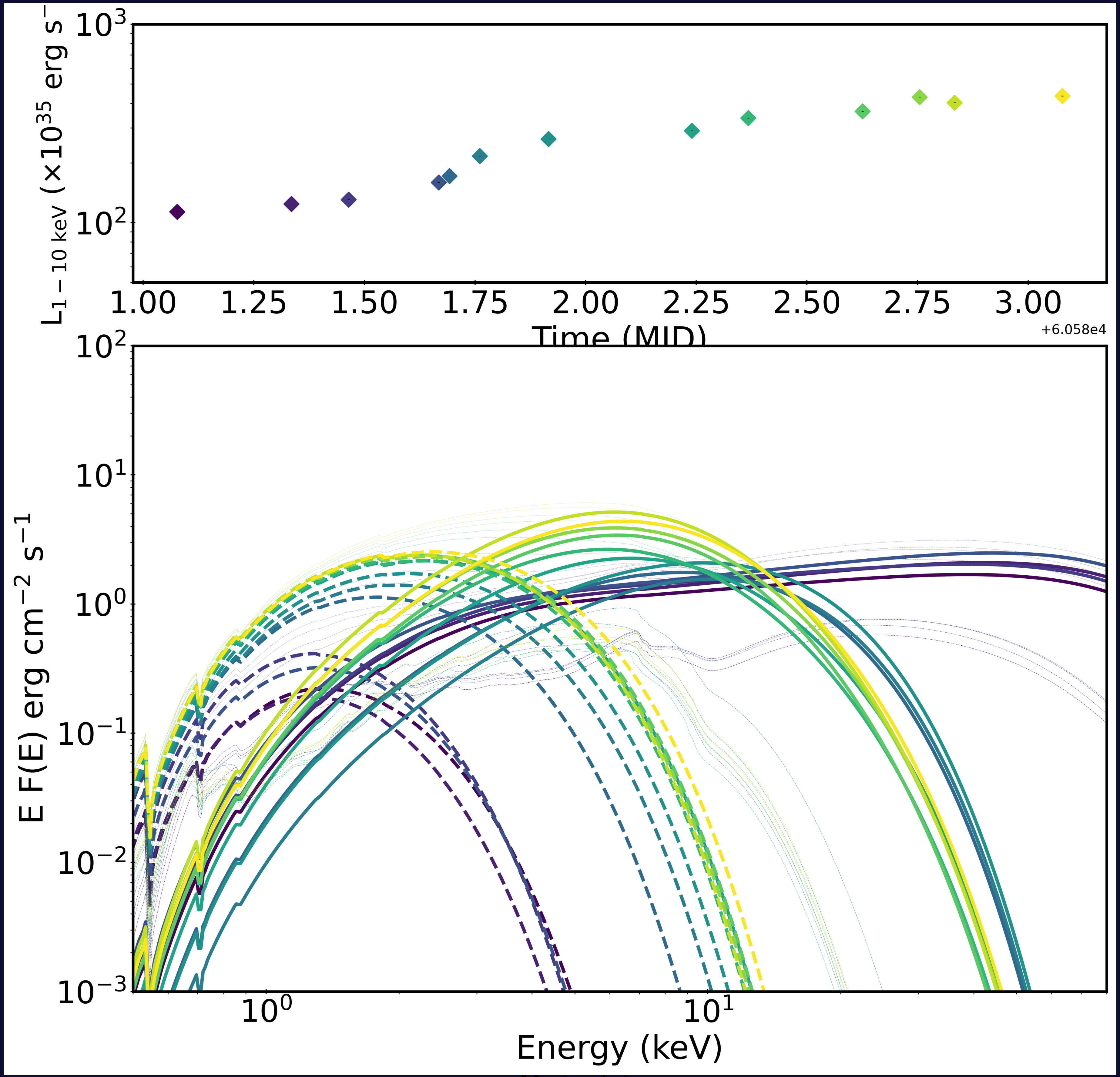
PRELIMINARY


1
Hard state

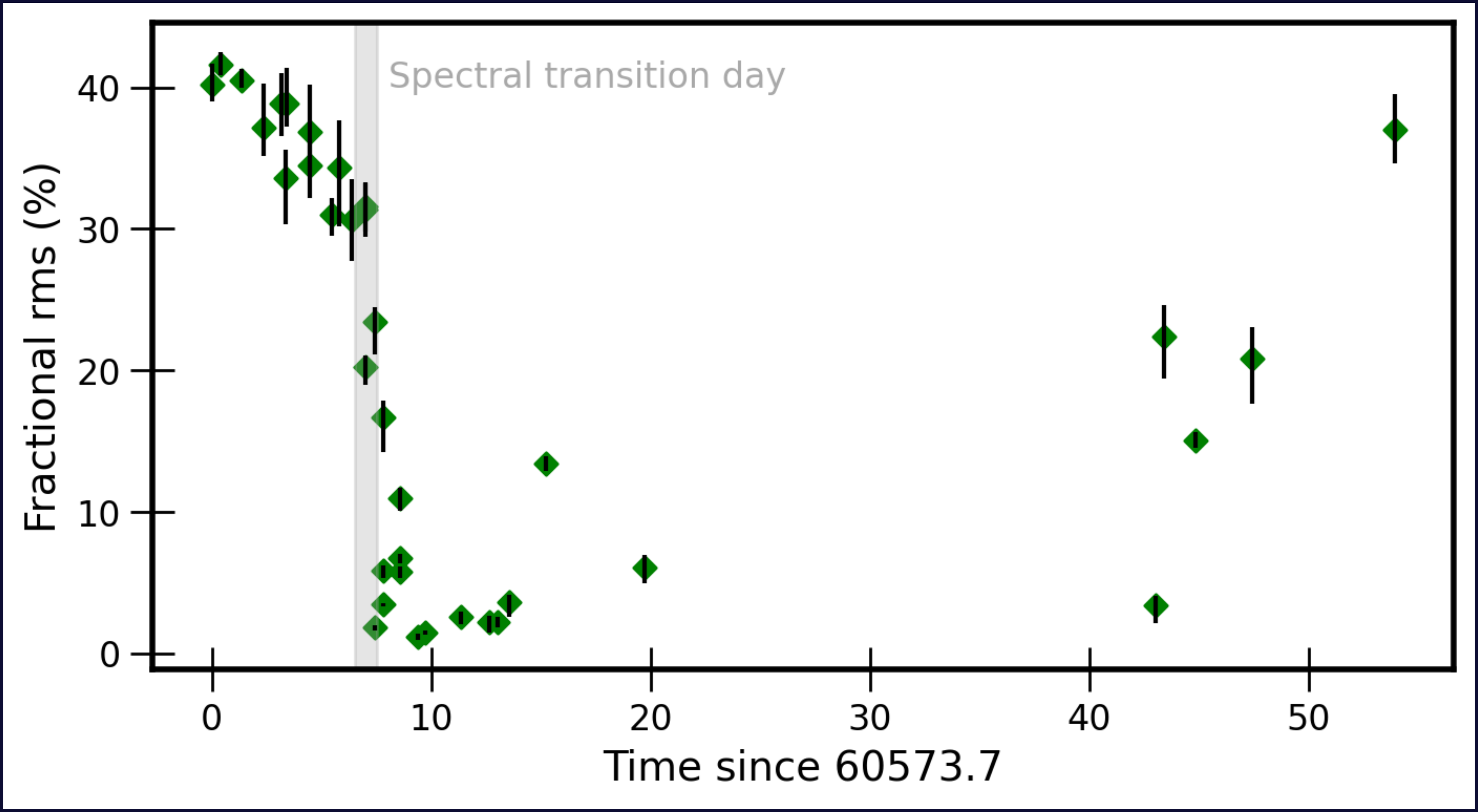

2
Intermediate state


3
Soft state


$L_{36,1-10\ \mathrm{keV}}$ (erg s^{-1})
10^1
1
2
3
Γ index
4
2
kT_{bb} (keV)
10^0
R_{bb} (km)
10^1
kT_{disk} (keV)
10^0
R_{disk} (km)
10^2
10^1
7.0
7.5
8.0
8.5
9.0
9.5
Time since MJD 60573.93 (d)

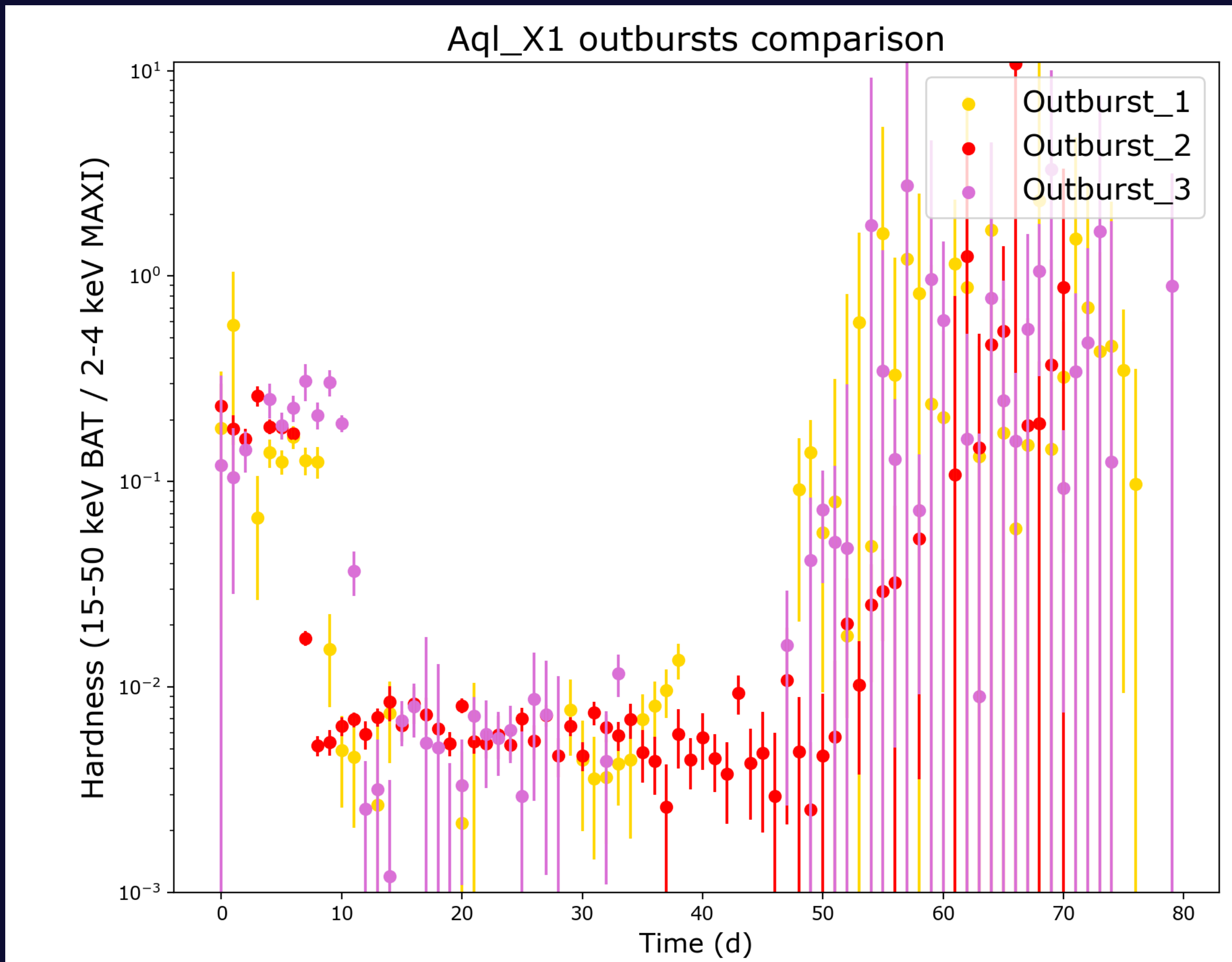


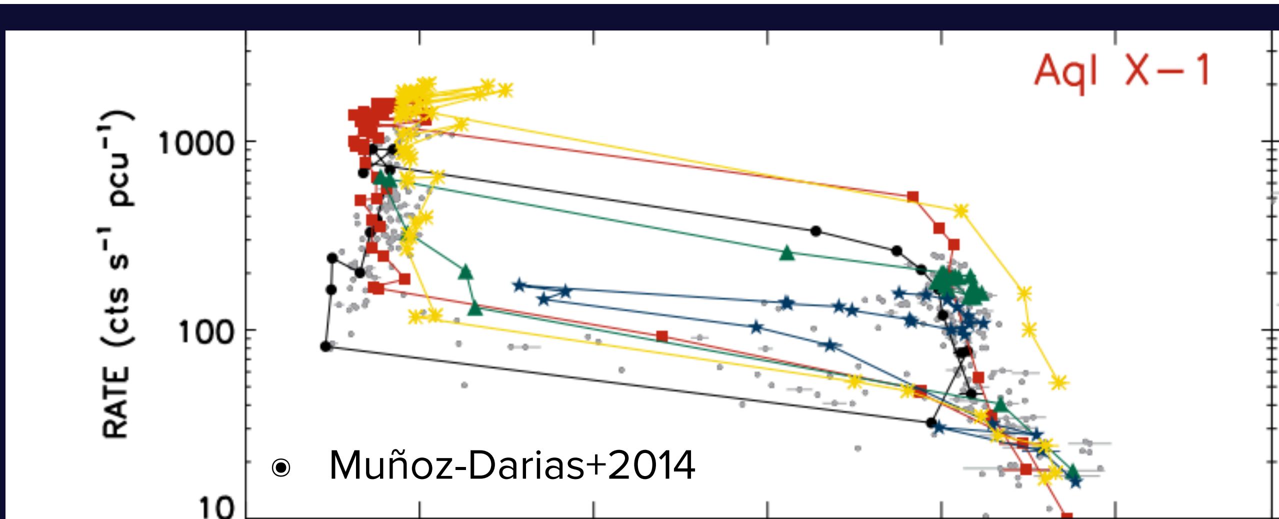
- Marino+, in prep.



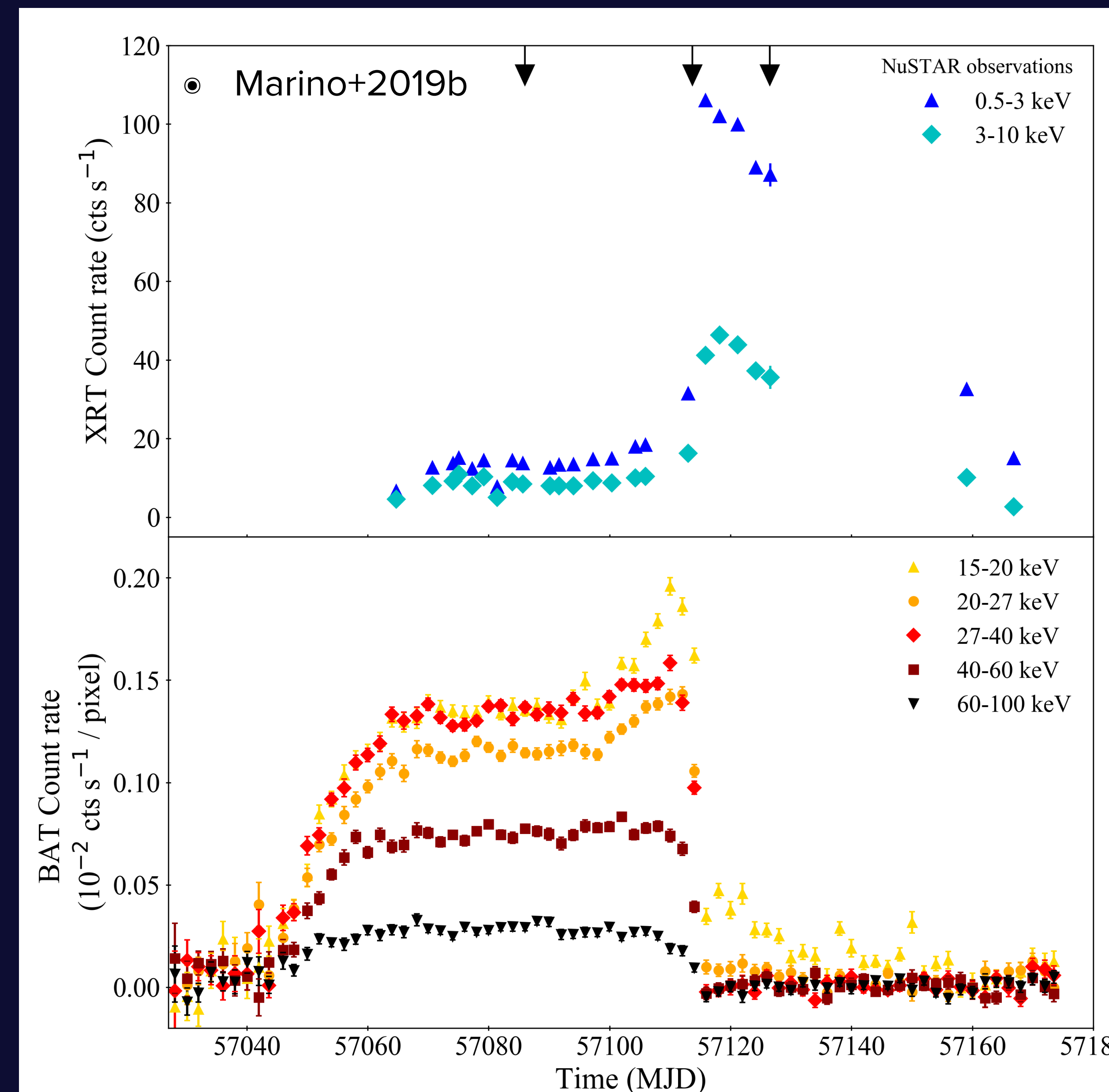
- Marino+, in prep.

PRELIMINARY





- Rapid state transition also in 1RXS J180408.9-365028 (Marino+2019b, Fiocchi+2019)



See also Tudose+2009, Diaz Trigo+2018

- Marino+, in prep.

Muñoz-Darias+2014

Table 1. Transient (top) and persistent (bottom) sources showing full hysteresis loops.

NS-LMXB	$N_{\rm H}$ ($\times 10^{22}$ cm^{-2})	Behaviour *	Loop duration (d)	Hard-to-Soft times (d) **	Soft-to-Hard times (d) **
EXO 0748-676	0.06 (1)	LTT, ML	60–90	<50	<2 / <8
Aql X-1	0.34 (2)	T, ML	30–60	<2 / 1–4	<1 / <4
EXO 1745-278	1.2 (3)	T, SL	90	< 3	
4U 1608-52	1.6 (4)	T, ML	25–90	< 3 / 2-6	2-4 / < 7
IGR 17473-2721	4 (5)	T, SL	110	2–6	3–5
4U 1820-303	0.28 (4)	P, SL	> 56	<16	
4U 0614+09	0.3 (4)	P, SL	90	< 13	< 23
4U 1636-53	0.43 (4)	P, ML	35–50	< 2 / 2–6	< 4 / 6–12
4U 1705-44	1.8 (6)	P, ML	50–300	< 4 / < 8	4–16
4U 1728-34	2.5 (7)	P, ML	20–60	< 4 / 2–6	< 2 / 4–8

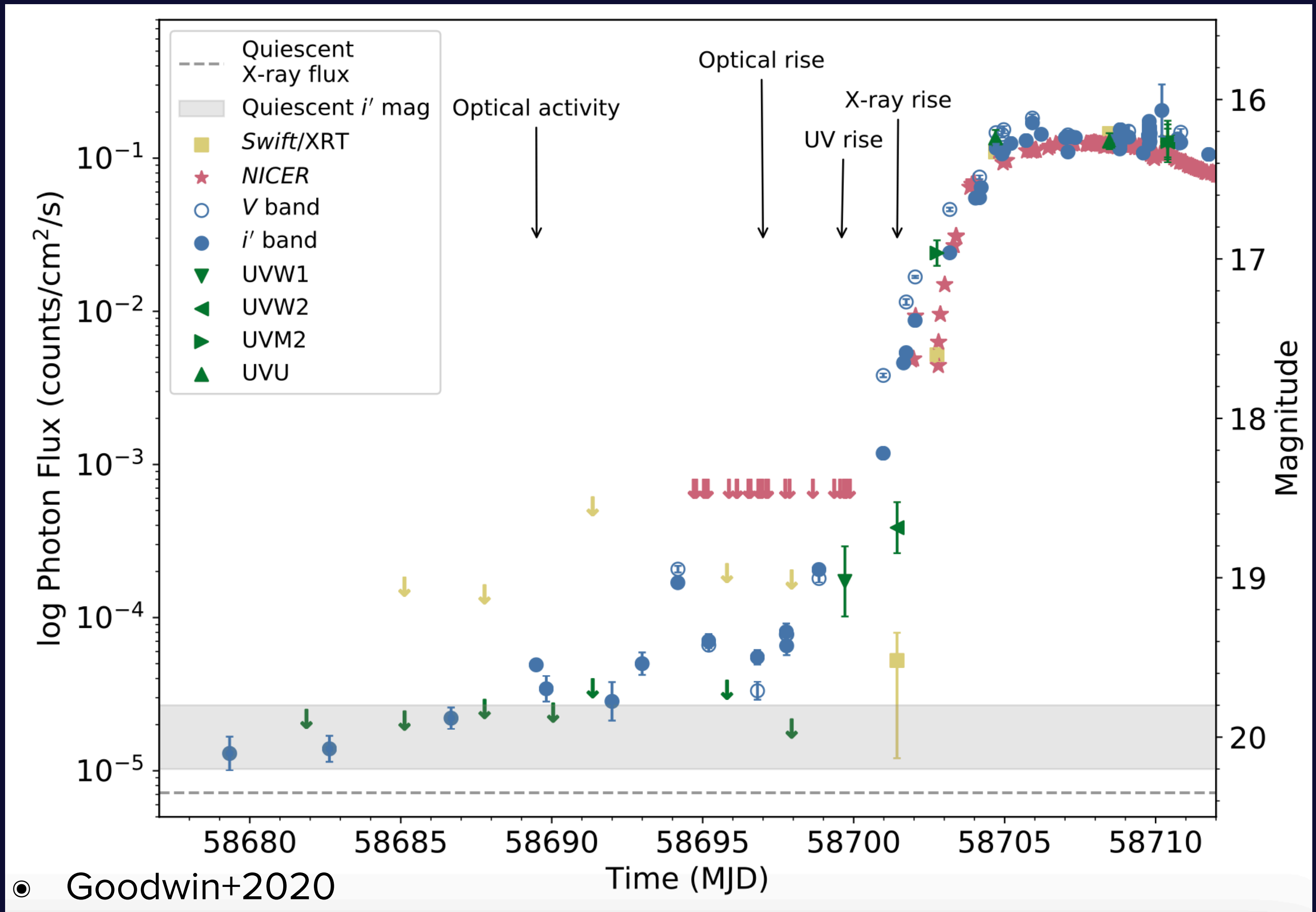
* T: transient; LTT: long-term transient; P: persistent; ML: multiple loops; SL: single loop

** Minimum / maximum transition time scales are quoted if more than one loop is seen.

REFERENCES: (1) Díaz Trigo et al. (2011); (2) Maccarone & Coppi (2003); (3) Heinke et al. (2003); (4) Christian & Swank (1997); (5) Chenevez et al. (2011); (6) di Salvo et al. (2009); Di Salvo et al. (2000)

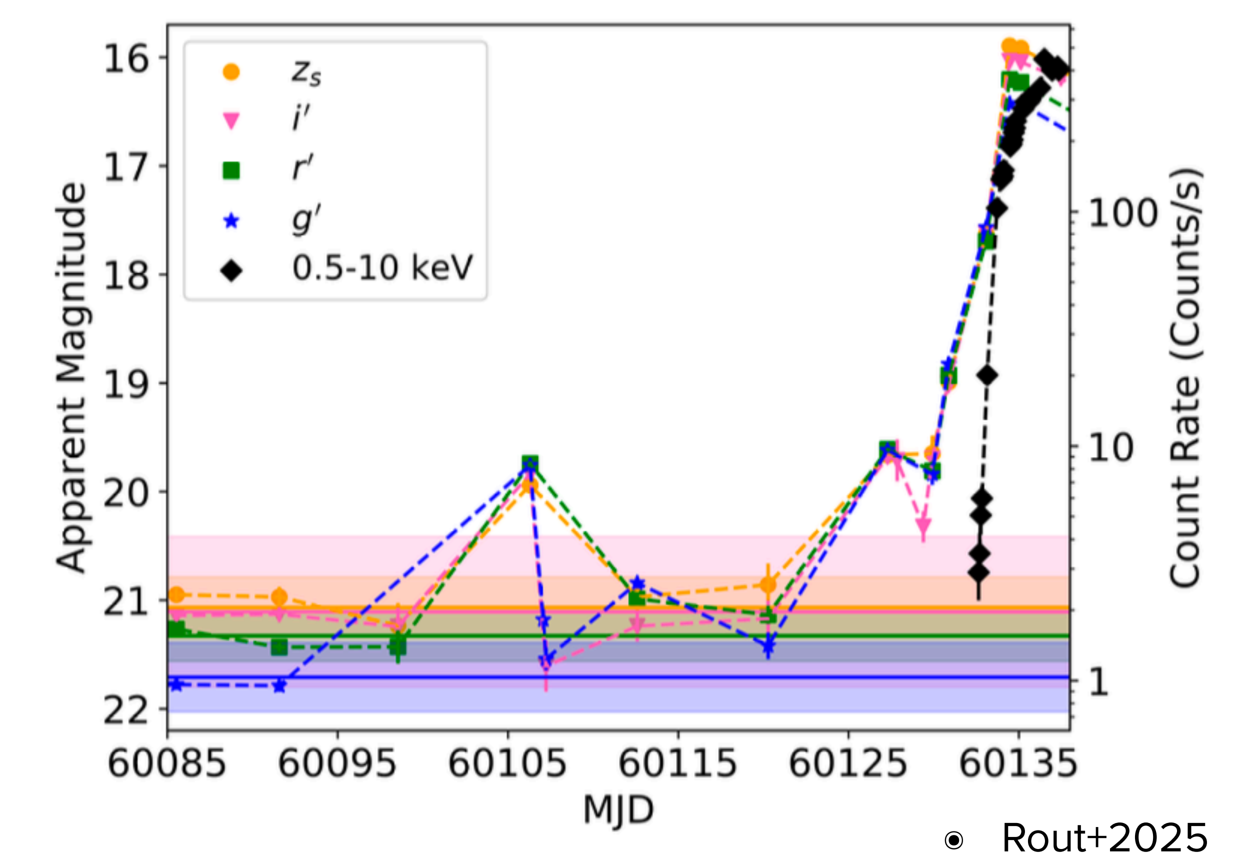
Marino+, in prep.

4 d - SAX J1808.4-3658



Goodwin+2020

4-12 d - MAXI J1807+132



Rout+2025