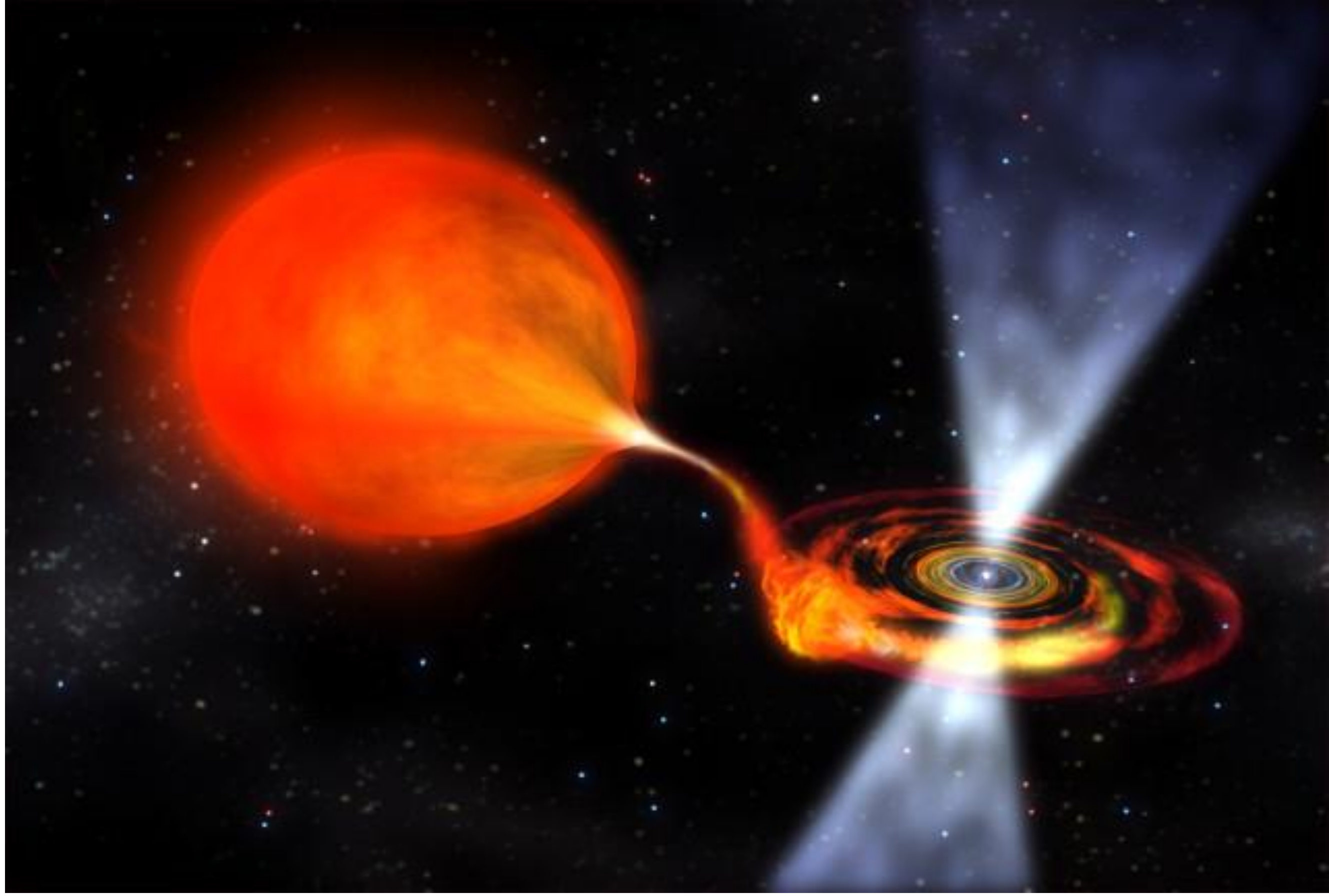
XMM-Newton Workshop, ESAC/ESA, 06/06/2024

THE FIRST SIMULTANEOUS X-RAY/UV TIMING STUDY OF THE ACCRETING MILLISECOND PULSAR SAX J1808.4-3658



Caterina Ballocco

Collaborators: Dr. Alessandro Papitto and Dr. Arianna Miraval Zanon, Giulia Illiano, Dr. Filippo Ambrosino and Dr. Riccardo La Placa

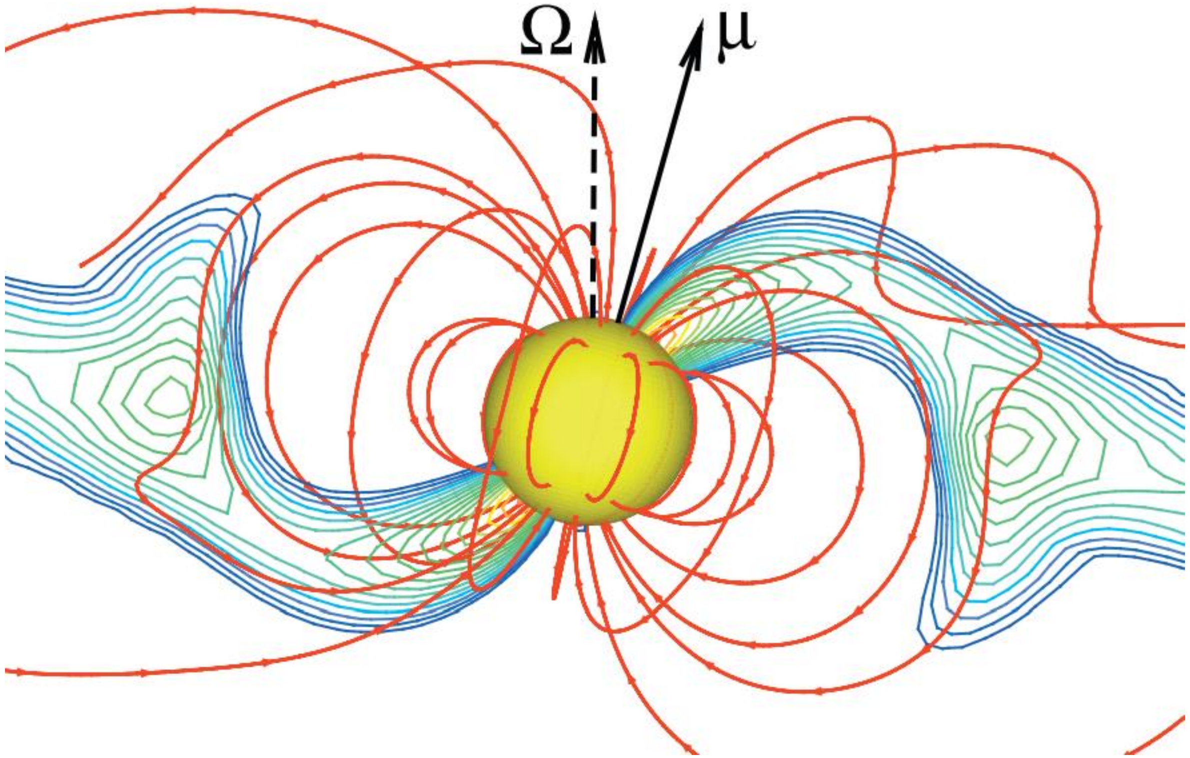
SAPIENZA UNIVERSITÀ DI ROMA

INAF ISTITUTO NAZIONALE DI ASTROFISICA

OAR

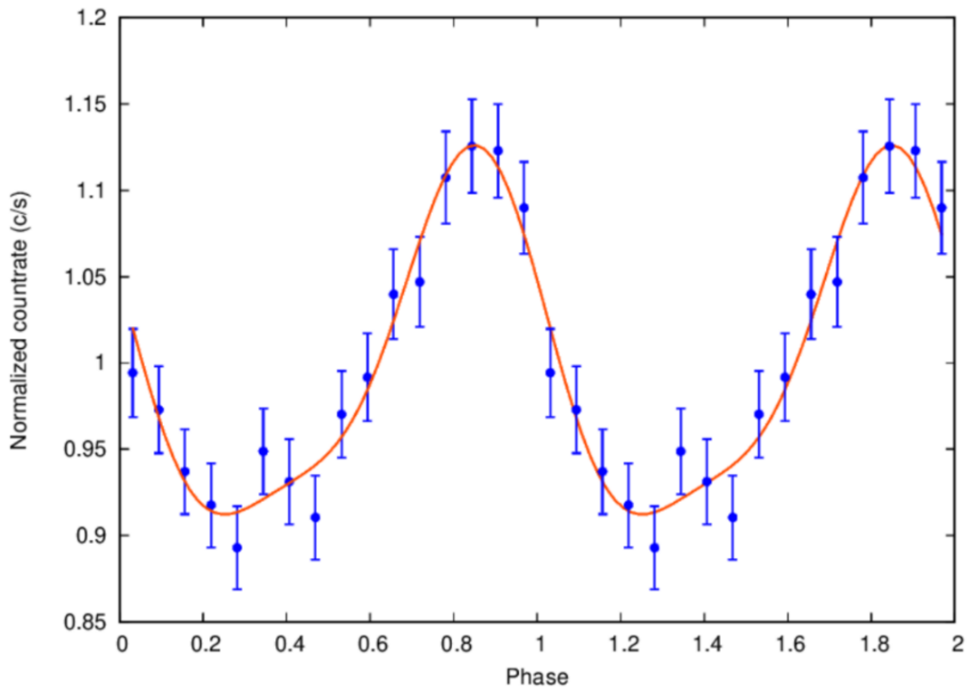
X-ray pulsations in AMPs

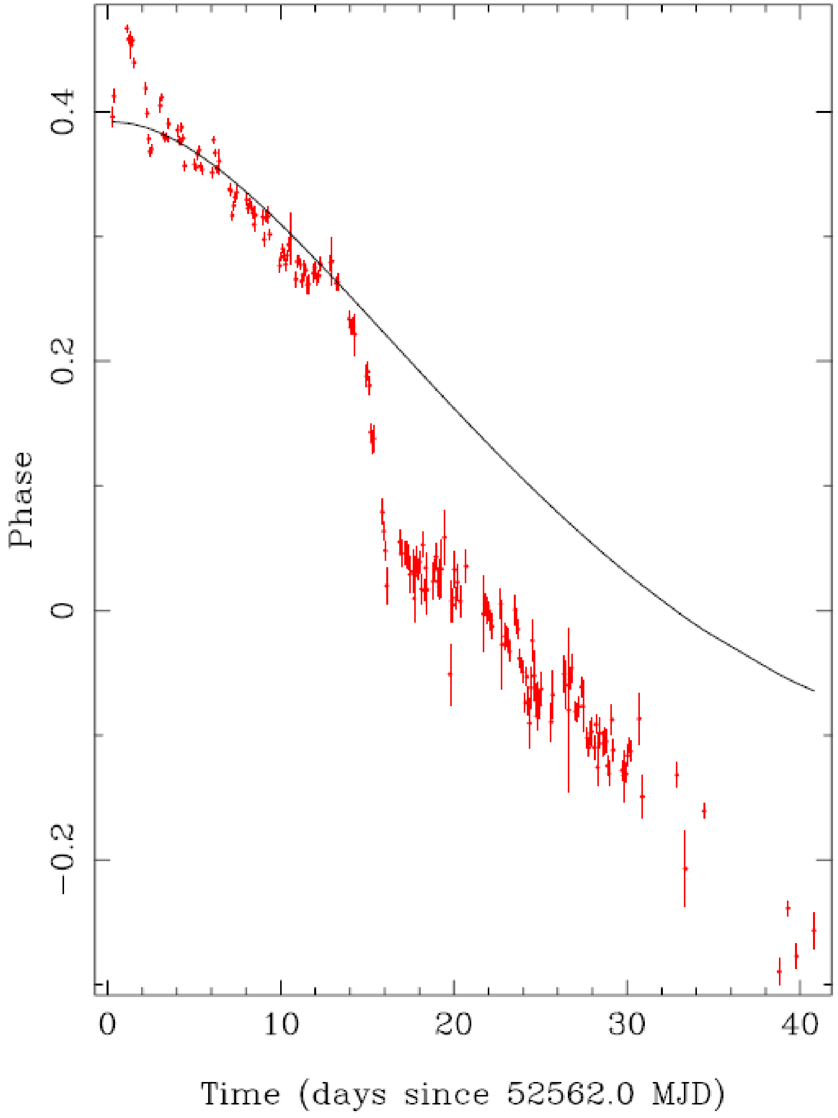
- mass and radius of the NS
- accretion torques acting on these systems



TIMING NOISE OF SAX J1808.4-3658

Too rapid variations to be due to changes in the accretion rate!





[Burderi et al., 2006]
[Patruno & Watts, 2021]

SAX J1808.4-3658

1996
Discovery X-ray transient
[in ‘t Zand+ 1998, 2001]

1998
Discovery of 401 Hz pulsations: FIRST AMXP
[Wijnands & van der Klis 1998]

2000
[Papitto+ 2005; Hartman+ 2008]

2002
[Papitto+ 2005; Burderi+ 2006; Hartman+ 2008]

2005
[Hartman+ 2008]

2008
[Hartman+ 2009; Burderi+ 2009; Patruno 2009]

2011
[Patruno+ 2012]

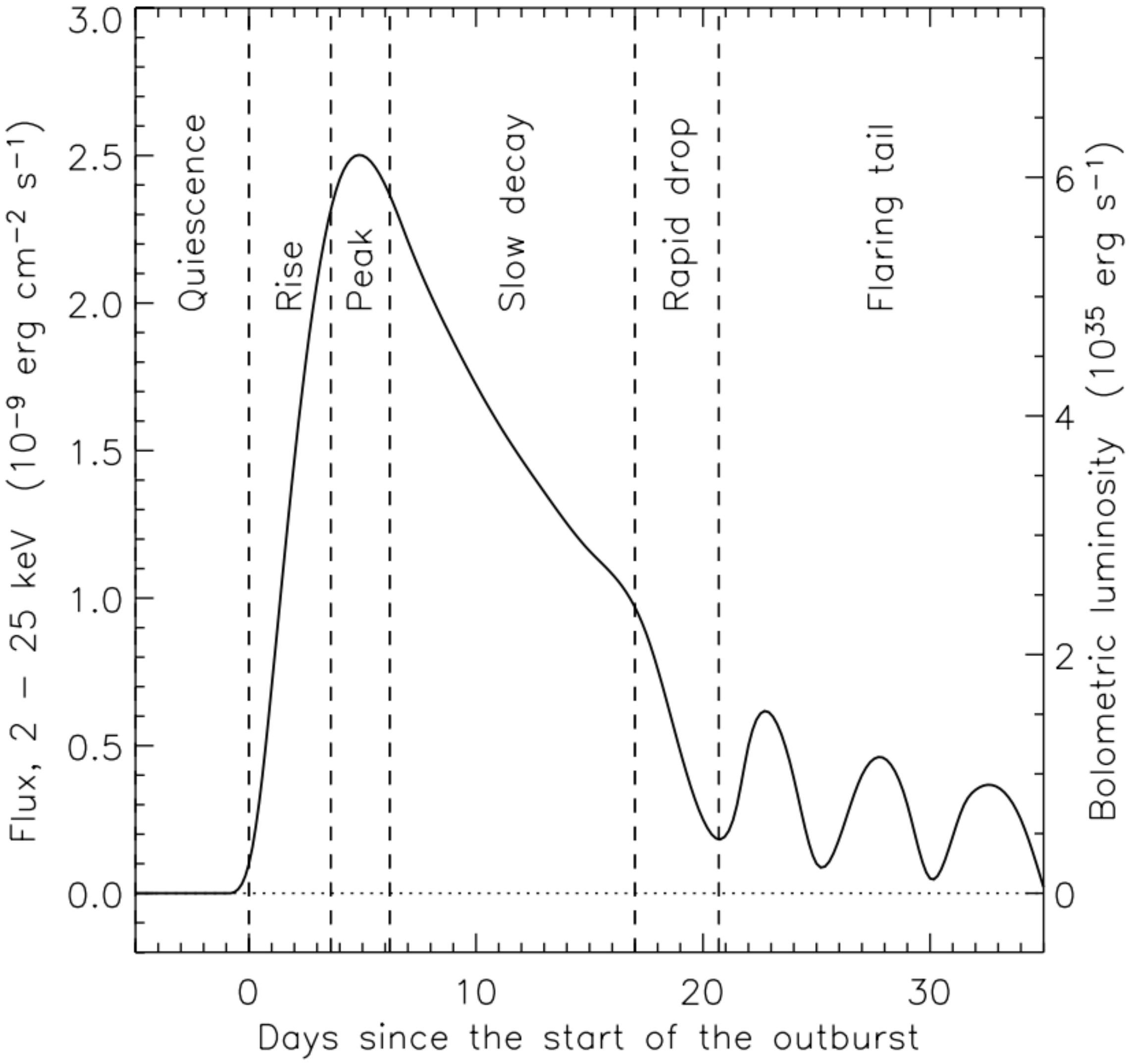
2015
[Sanna+ 2017; Patruno+ 2017; Di Salvo+ 2019]

2019
[Bult+ 2020; Baglio+ 2020]
Discovery of optical and UV pulsations
[Ambrosino, Miraval Zanon+ 2021]

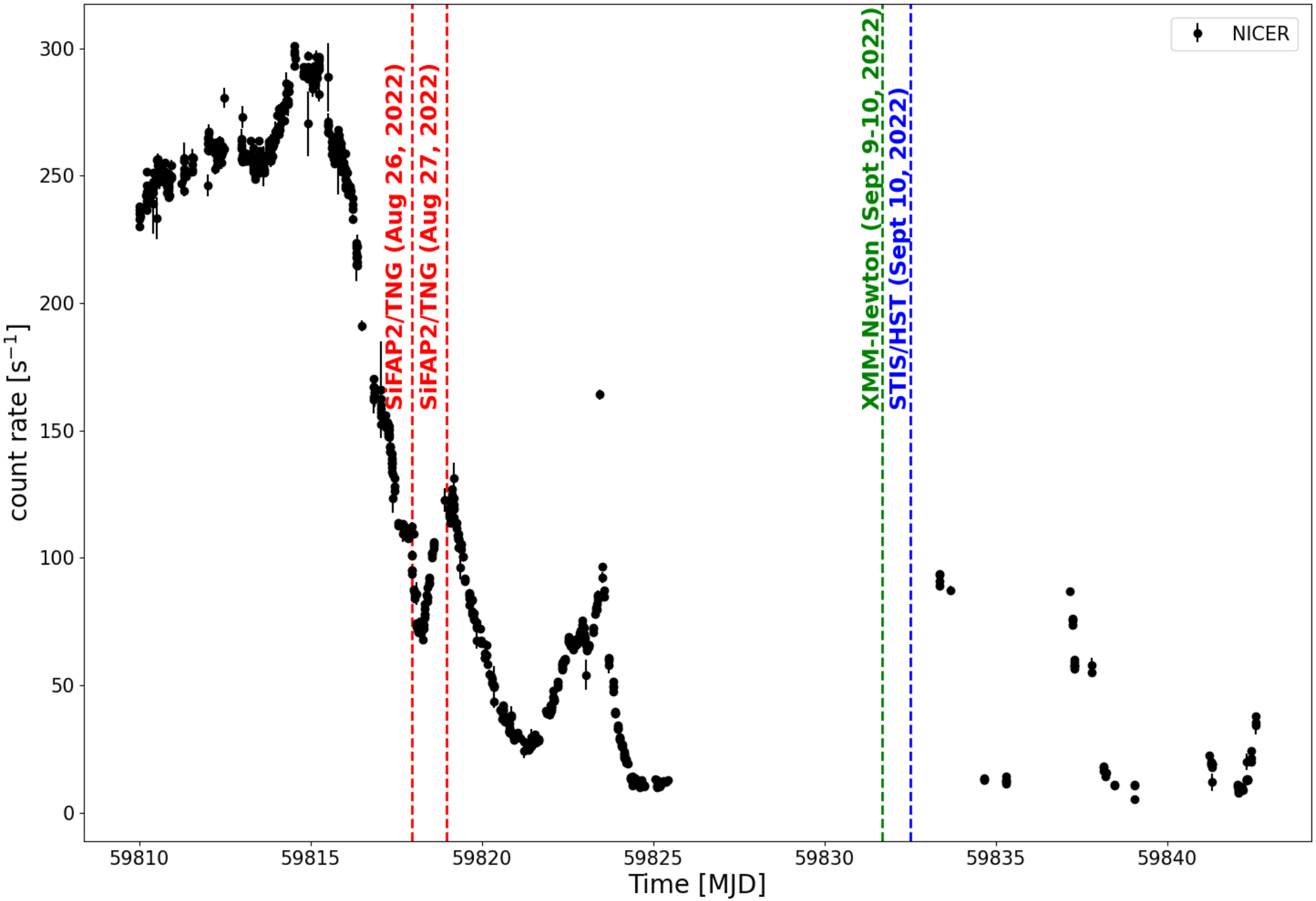
2022
Latest outburst
[**Illiano+ 2023, ApJL**; Miraval Zanon+ (in prep.)]

SAX J1808.4-3658

- P_{spin}=2.49 ms [Wijnands & van der Klis 1998, Nature]
- M_{comp} = 0.04 solar masses
- P_{orb}= 2h [Chakrabarty & Morgan 1998, Nature]
- 10 outbursts since 1996



[Hartman et al.,2008]



2022 OUTBURST

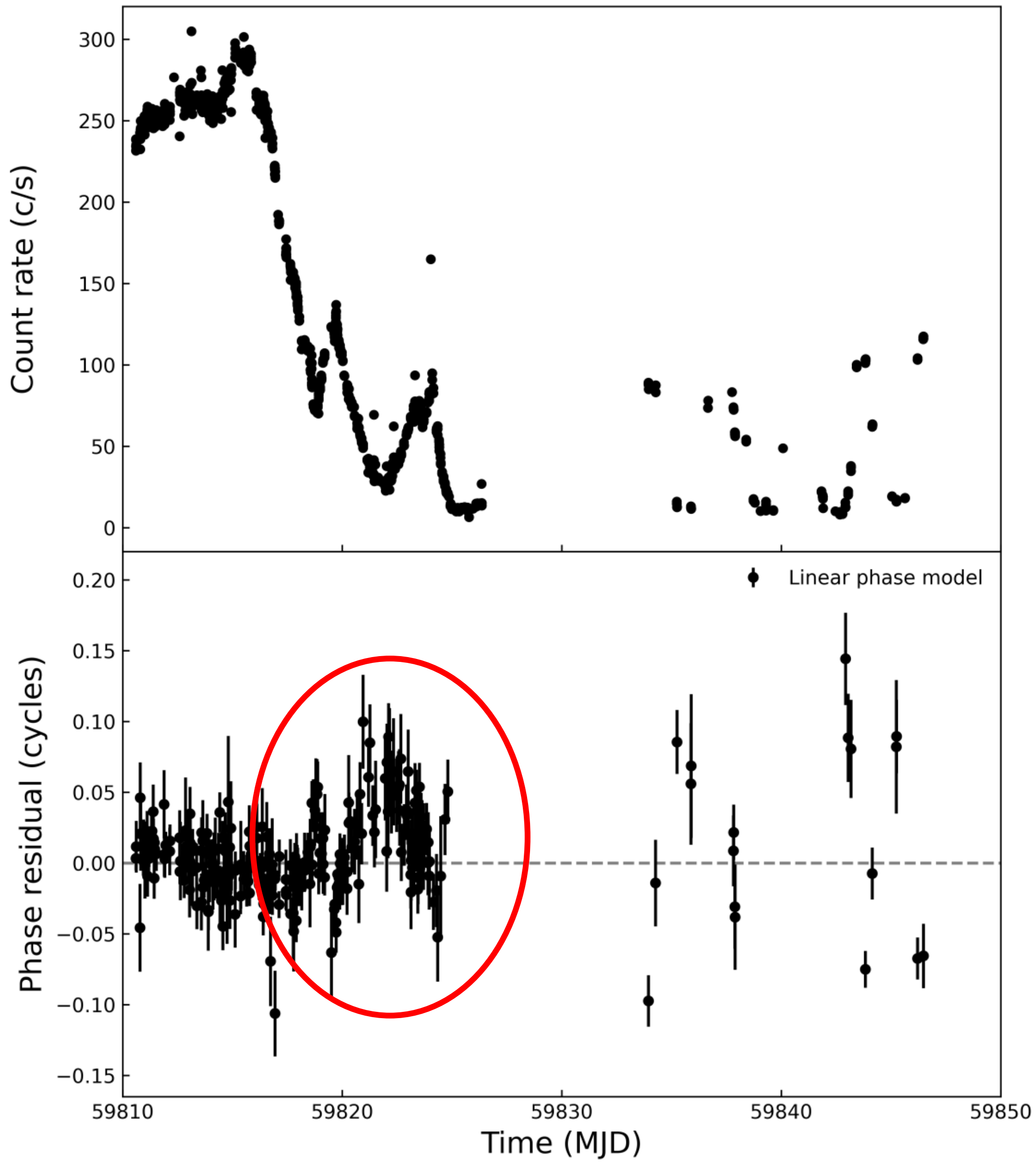
- - - - SiFAP2/TNG (320-900 nm)

- - - - XMM-Newton (0.3-10 keV)

- - - - STIS/HST (160-300 nm)

[Illiano+ 2023, ApJL]
[Miraval Zanon+, (in prep.)]

NICER observation

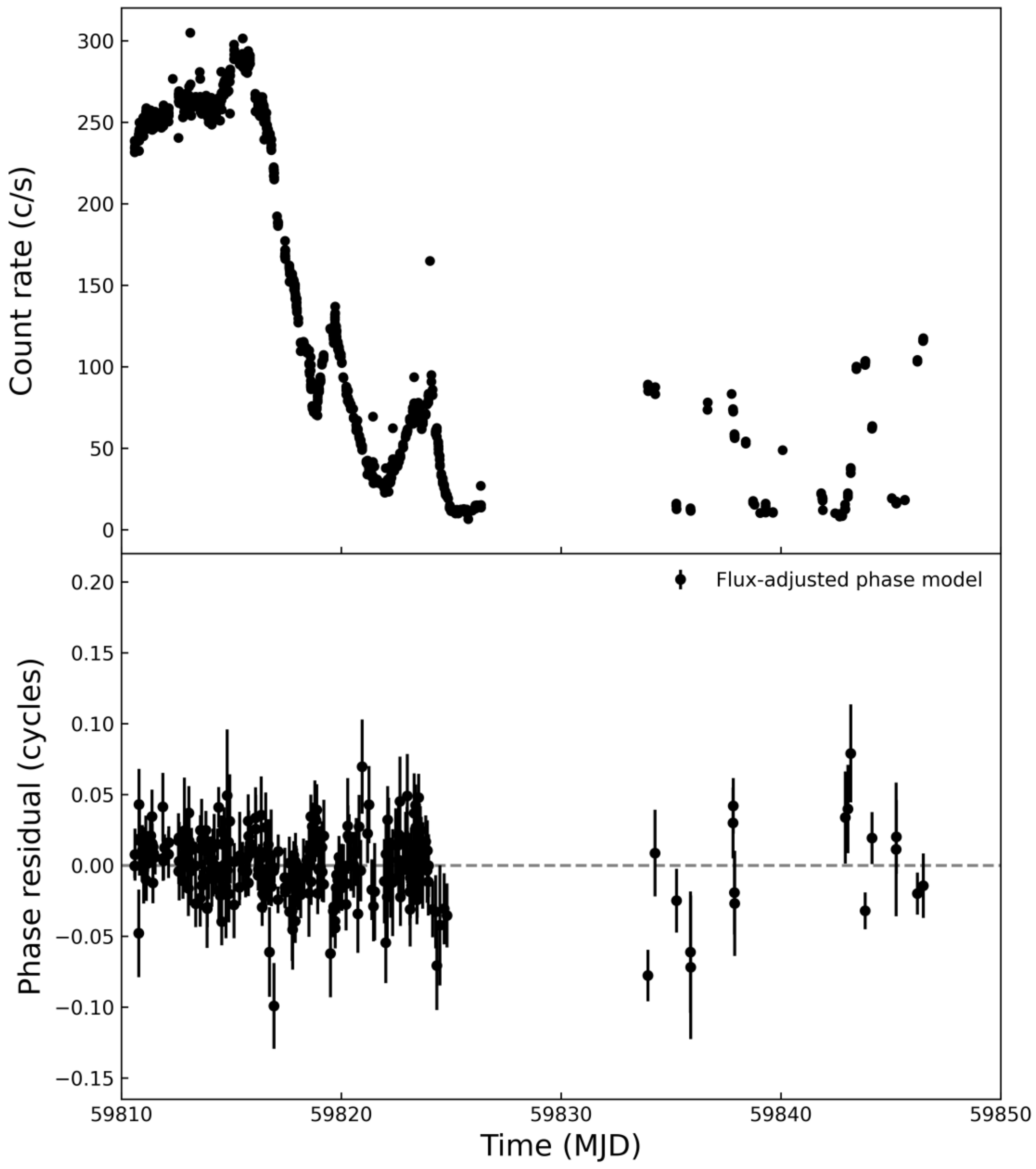


TIMING ANALYSIS

$$\Delta\phi(t) = \phi_0 - \Delta\nu(t - T_0) - \frac{1}{2}\,\dot{\nu}\,(t - T_0)^2 + R_{\rm orb}(t)$$

Parameter	Value
Epoch (MJD)	59810.5956860
$a_1 \sin i$ (lt-s)	0.0628033(57)
$P_{\rm orb}$ (s)	7249.1600(13)
$T_{\rm asc}$ (MJD)	59810.6179996(17)
Linear phase model	
ν (Hz)	400.975209557(50)
χ^2/dof	699.1/285

[Illiano+ 2023, ApJL]



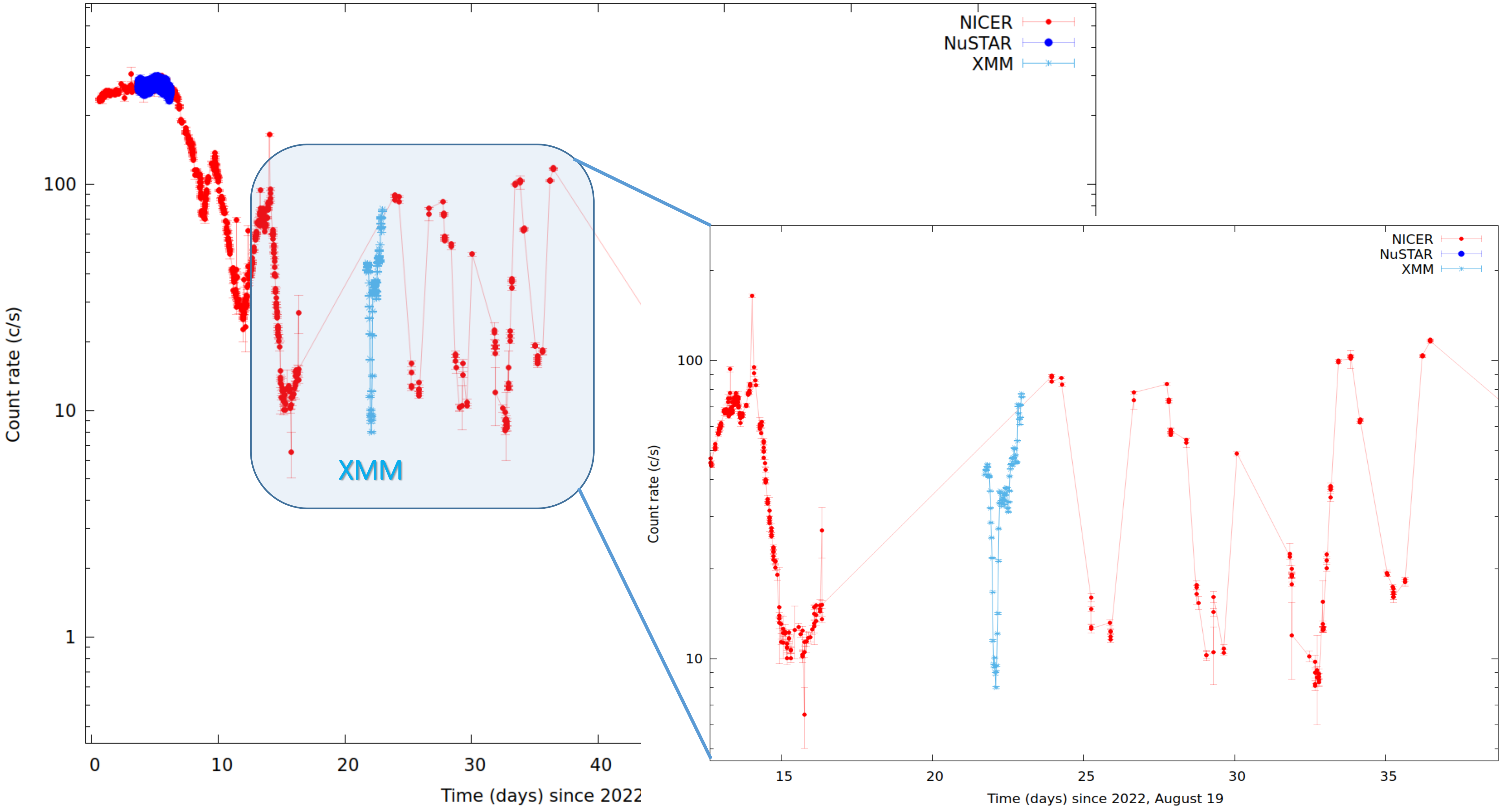
$$\Delta\phi(t) = \phi_0 - \Delta\nu(t - T_0) - \frac{1}{2}\,\dot{\nu}\,(t - T_0)^2 + R_{\rm orb}(t) + R_{flux}(t)$$

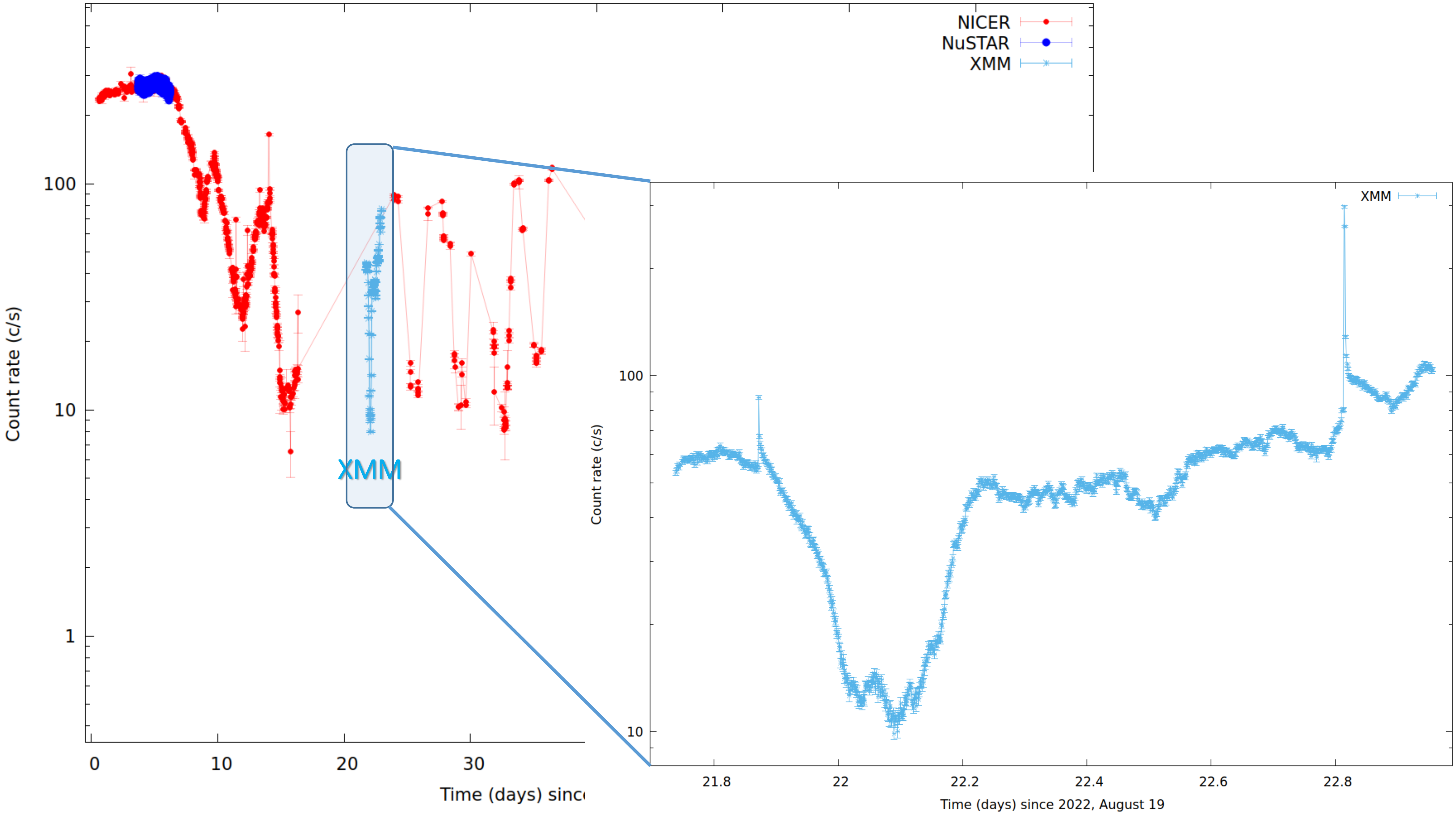
[Bult+ 2020, ApJL]

$$R_{flux}(t) = b(F_x/F_0)^{\Gamma}$$

Flux-adjusted phase model	
ν (Hz)	400.975209535(50)
b	1.44(49)
Γ	−0.81(12)
χ^2/dof	450.0/283

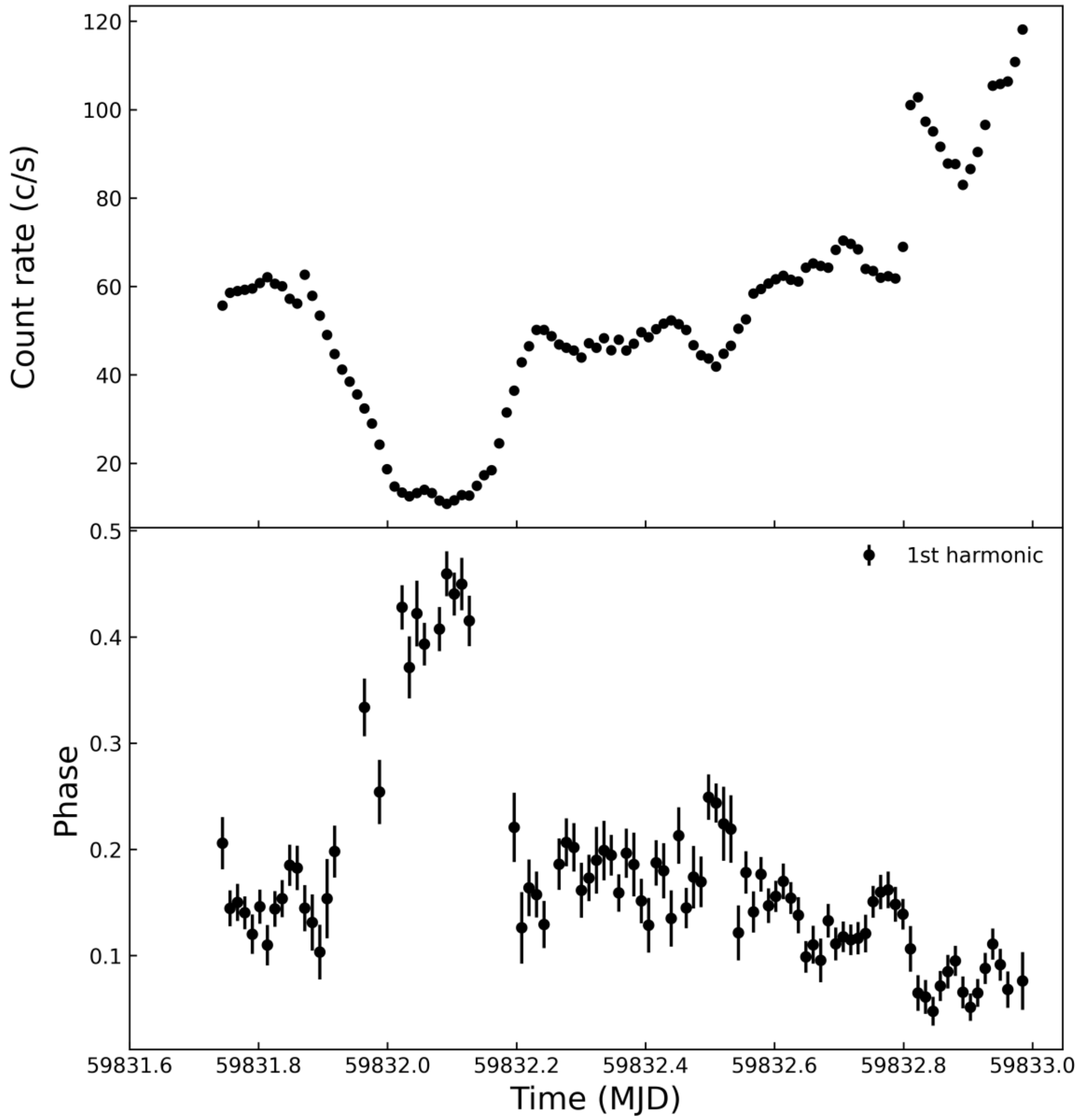
[Illiano+ 2023, ApJL]


NICER
NuSTAR
XMM
Count rate (c/s)
100
10
1
0
10
20
30
40
Time (days) since 2022
XMM
NICER
NuSTAR
XMM
Count rate (c/s)
100
10
15
20
25
30
35
Time (days) since 2022, August 19


NICER
NuSTAR
XMM
Count rate (c/s)
100
10
1
0
10
20
30
Time (days) sinc
XMM
XMM
100
10
Count rate (c/s)
21.8
22
22.2
22.4
22.6
22.8
Time (days) since 2022, August 19

XMM-Newton
9-10 September 2022

Anti-correlation between phase and flux

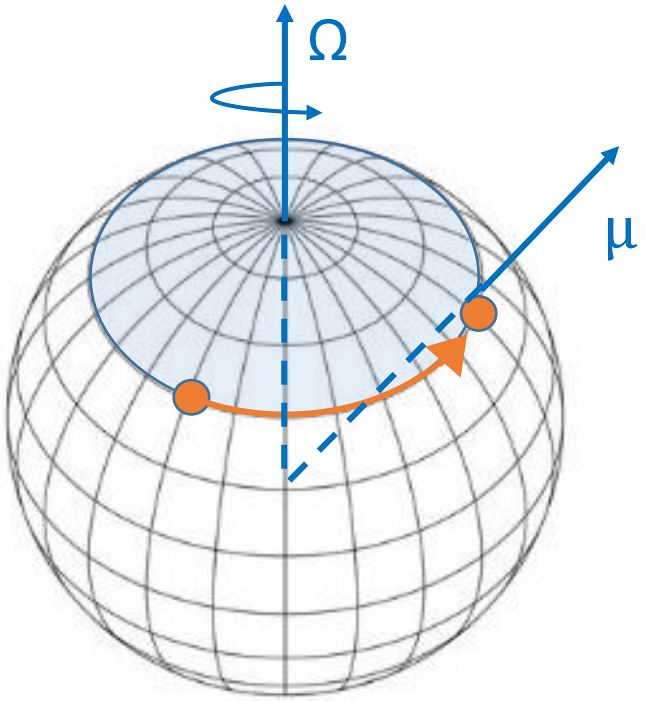


[Ballocco+,in prep.]

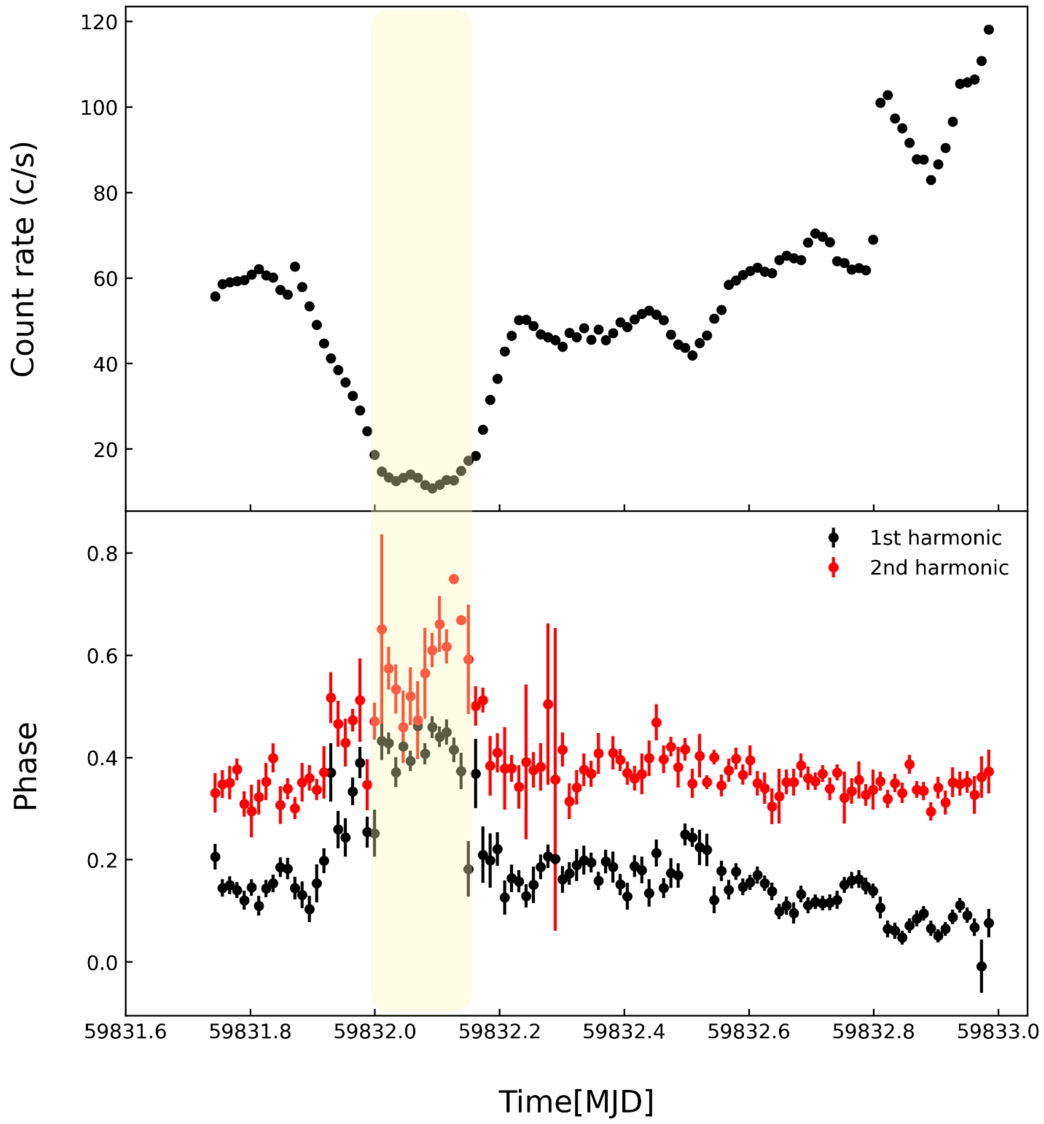
When the source flux hits the minimum

Phase 1st harmonic 0.15 → 0.45
Phase 2nd harmonic 0.35 → 0.60

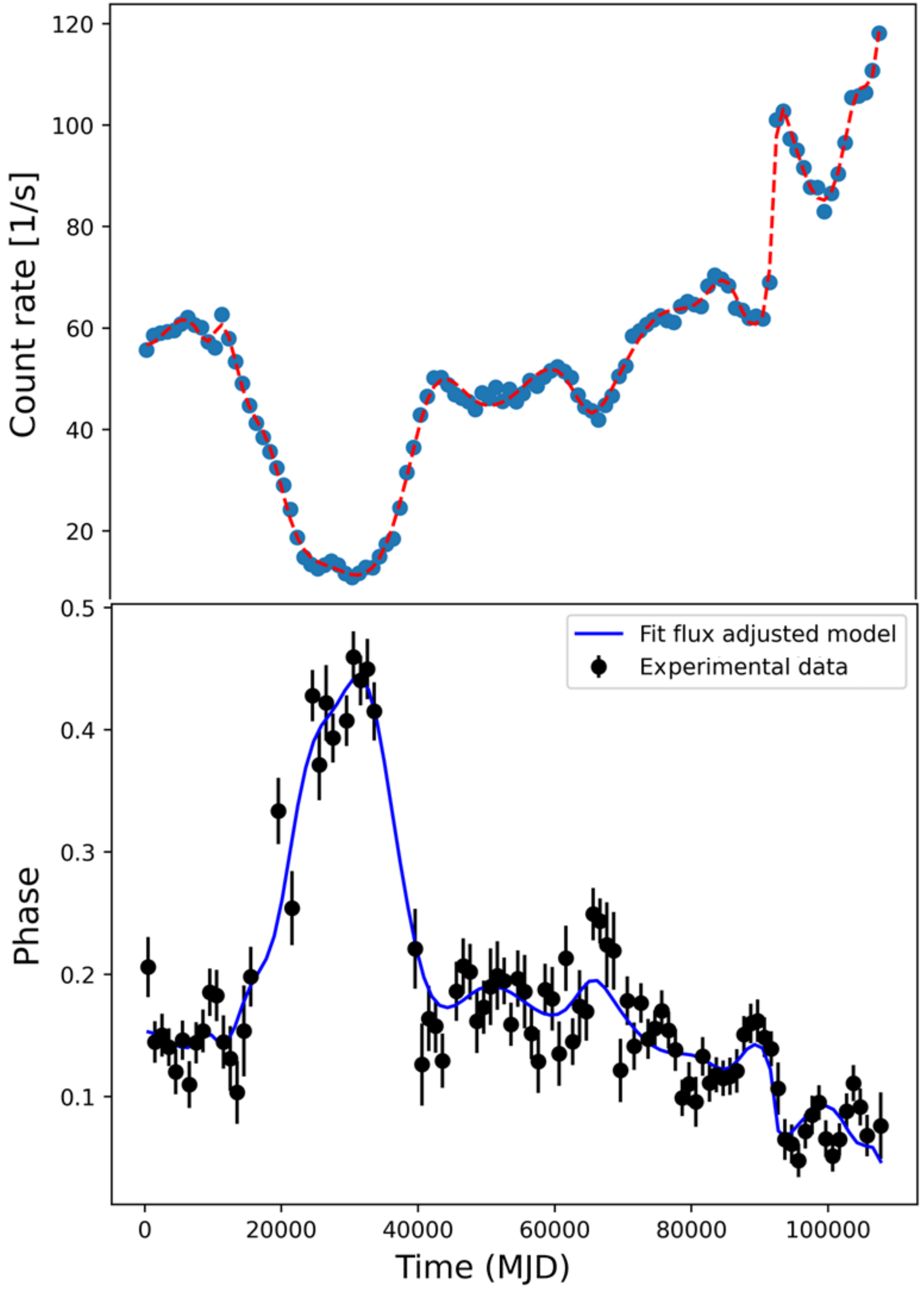
Equivalent to a hot-spot displacement of ≈100°



XMM-Newton
9-10 September 2022



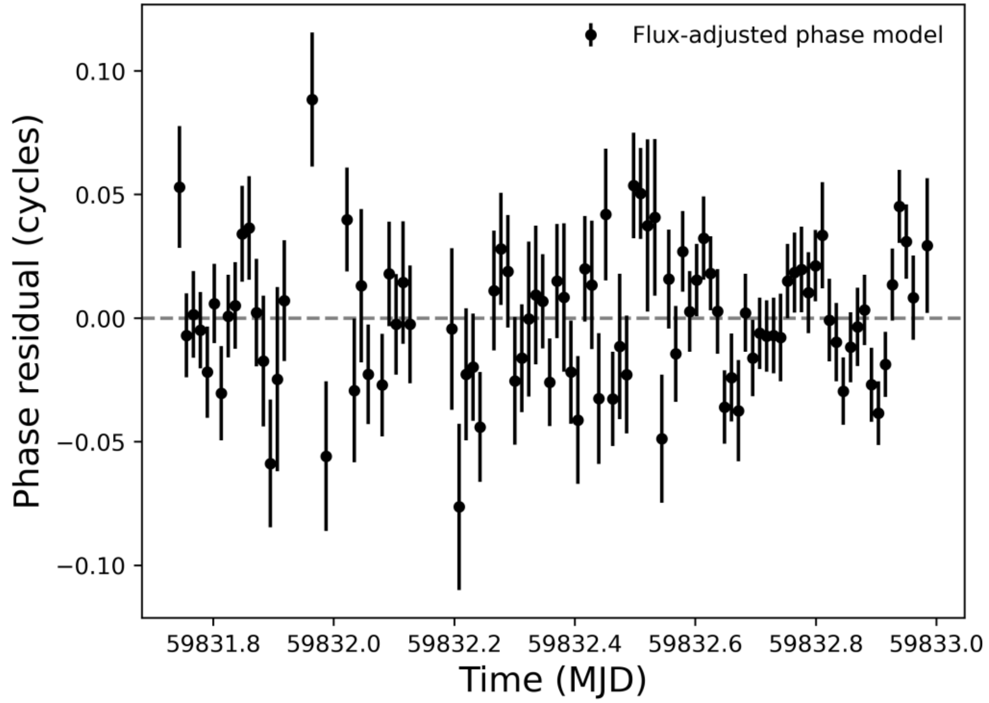
[Ballocco+,in prep.]



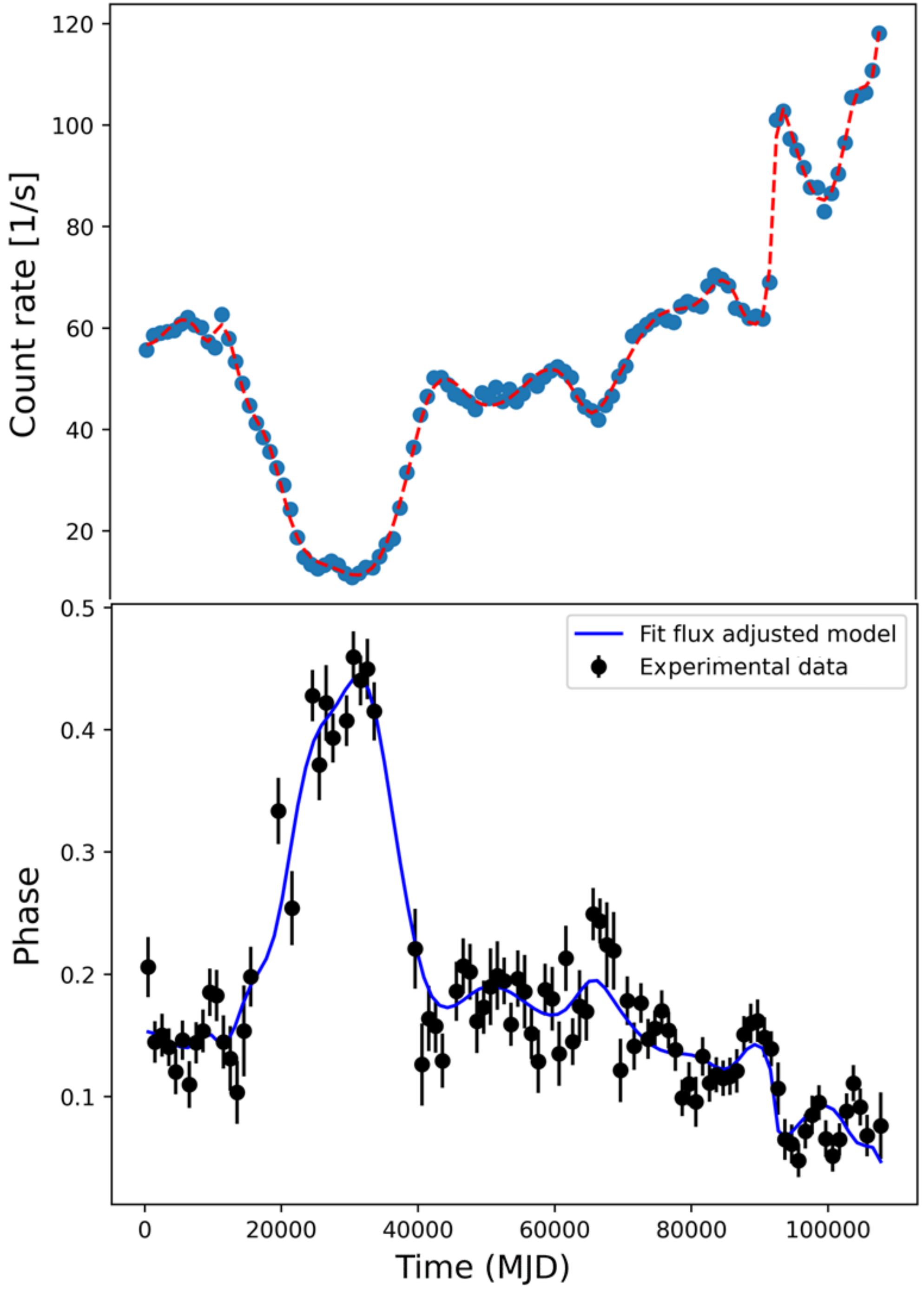
Anti-correlation between phase and flux

$$R_{flux}(t) = b(F_x/F_0)^{\Gamma}$$

$$\Gamma = (-0.19 \pm 0.08), b = (0.8 \pm 0.4)$$
$$\chi^2/dof = 162.5/91$$



[Ballocco+,in prep.]



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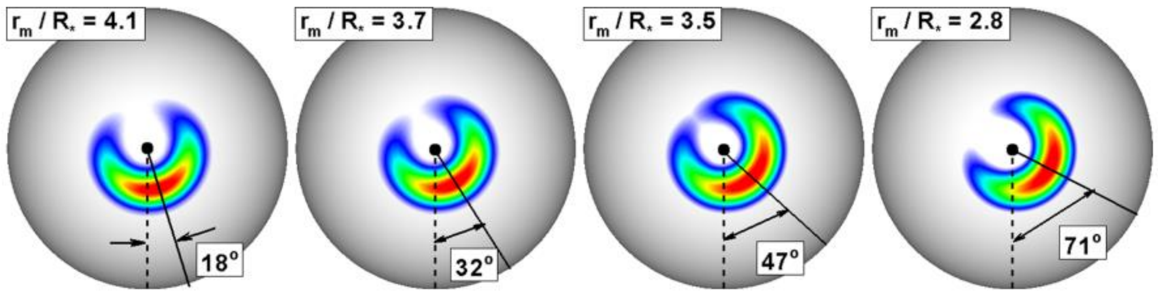
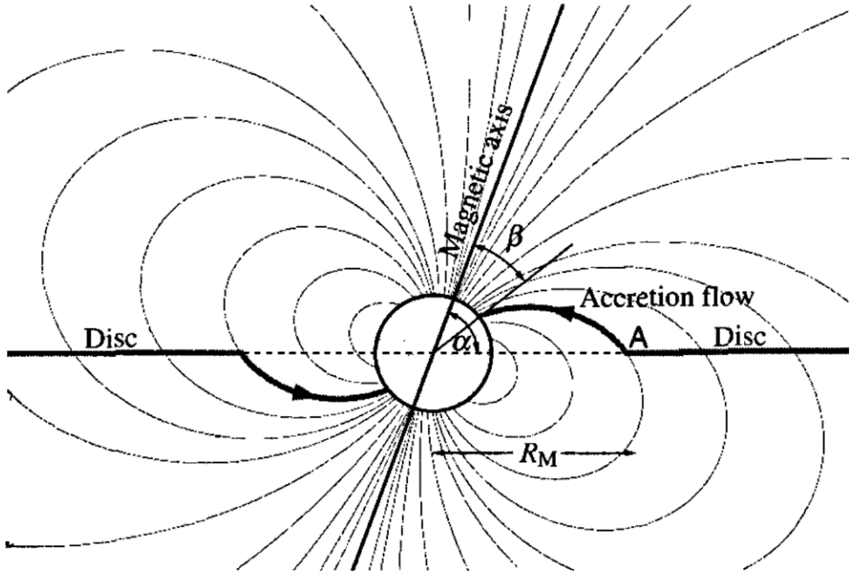


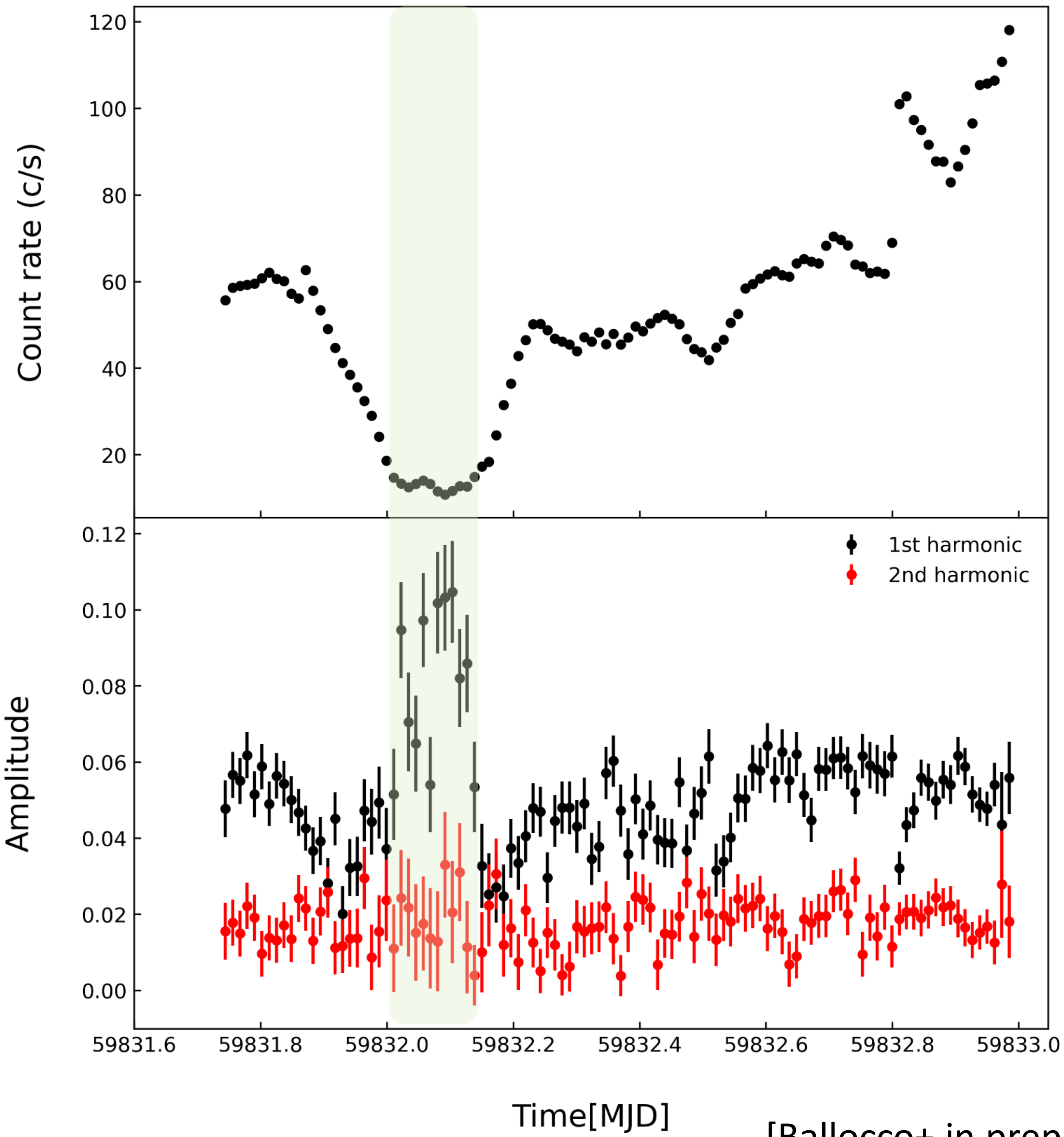
Numerical simulations of accretion onto a fast-rotating NS (Kulkarni & Romanova, 2013)

$$r_m \propto \dot{M}^{-1/5} \quad \rightarrow \quad \phi_0 \propto r_m \propto \dot{M}^{-1/5}$$

When the source flux hits the minimum

Amplitude of 1st harmonic 4% → 10%
Amplitude of 2nd harmonic ≈ constant (2%)



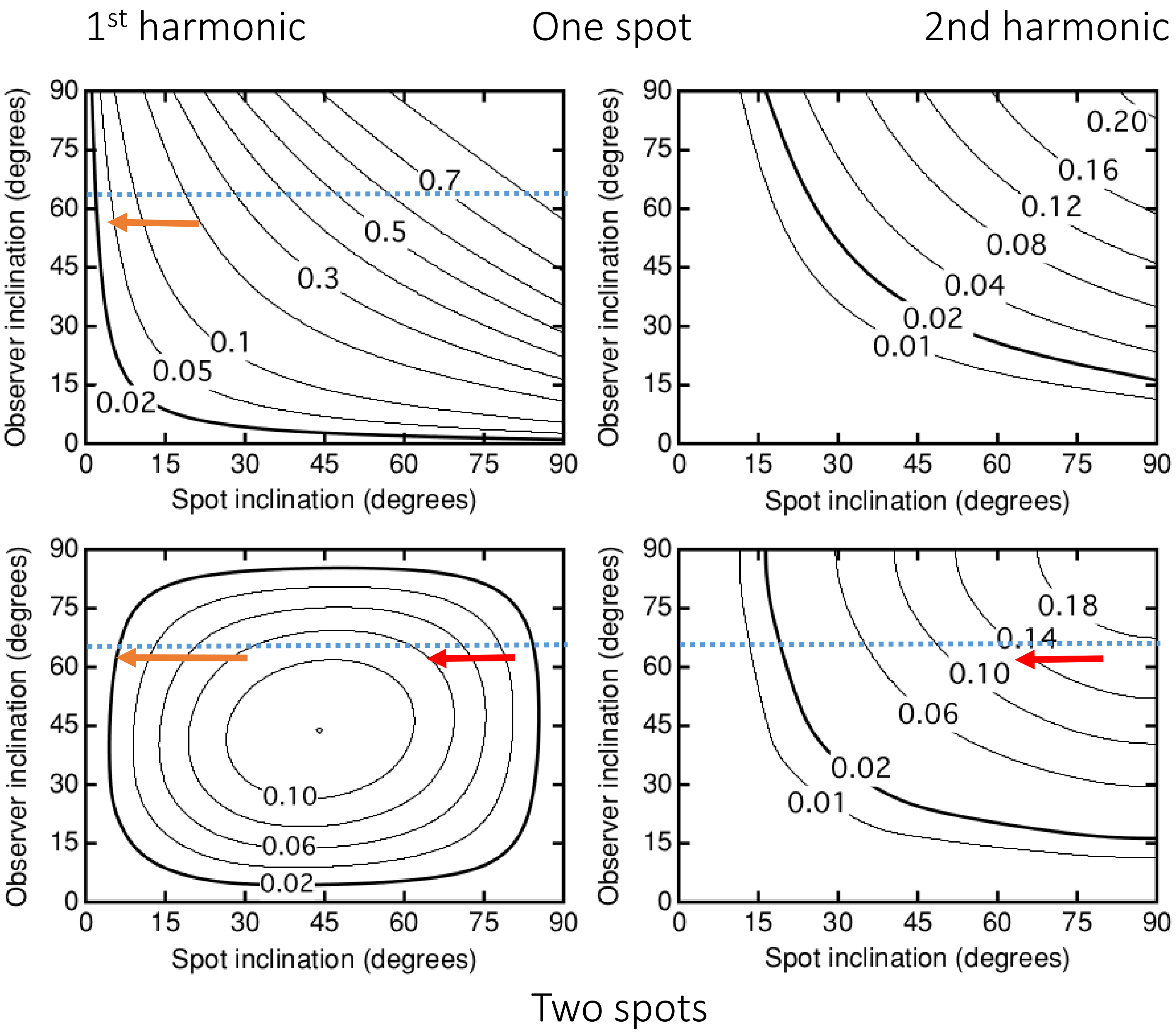


[Ballocco+,in prep.]

The only configuration that gives an amplitude increase when the spot inclination decreases is for

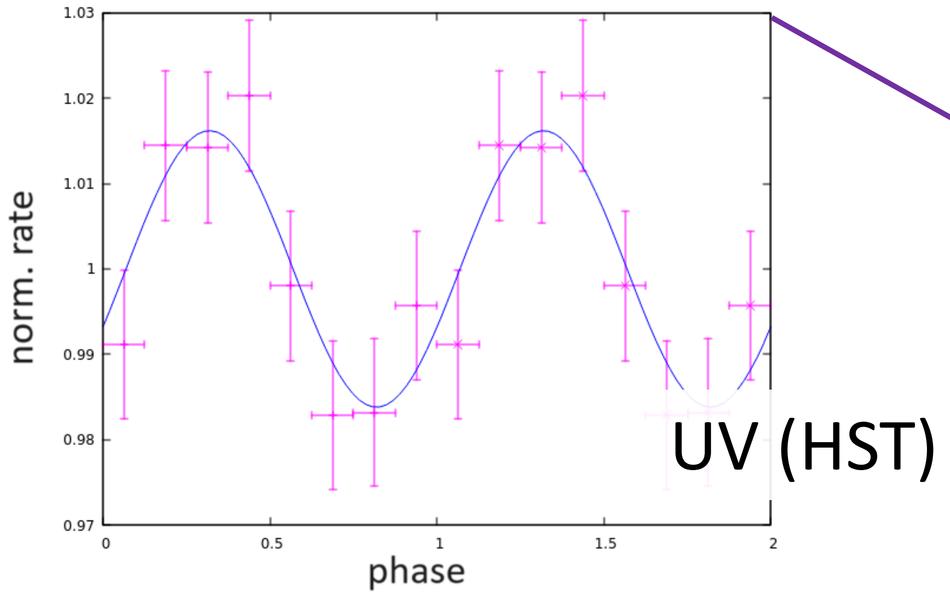
- Two visible spots
- $\theta \approx$ 60-75 degrees

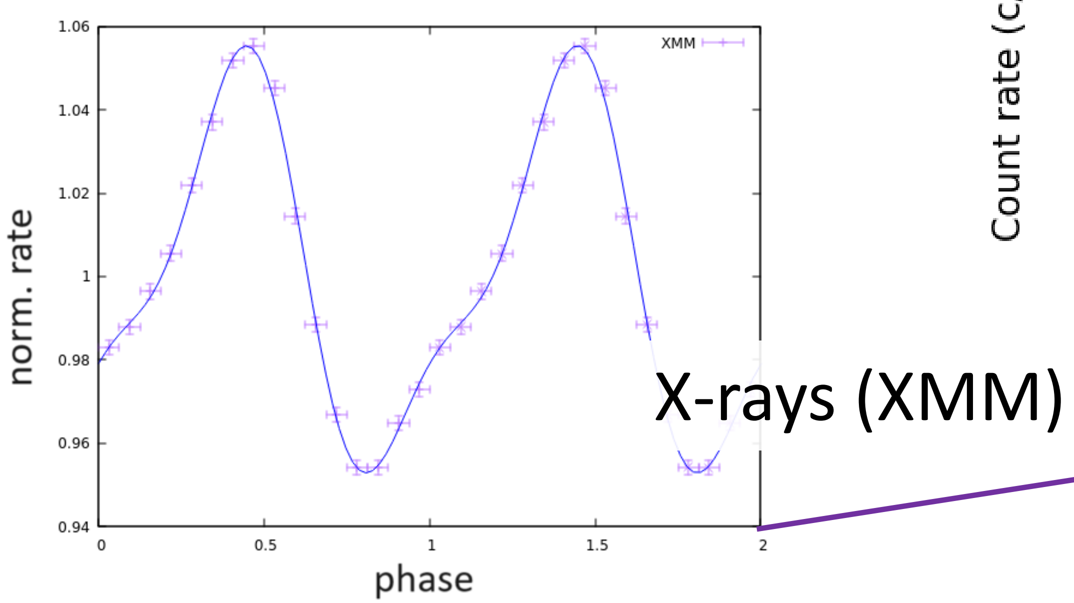
However, the expected 2[nd] harmonic amplitude should be much larger

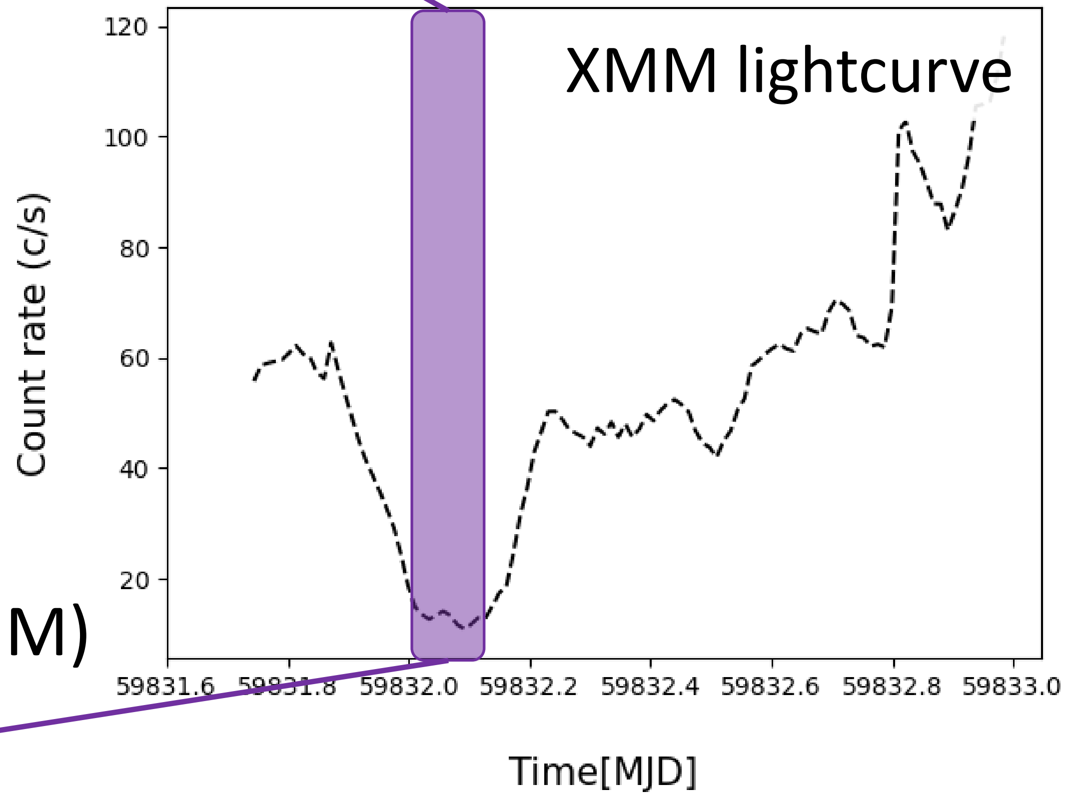


[Lamb et al.,2009]

X-rays/UV pulsations in the flaring state

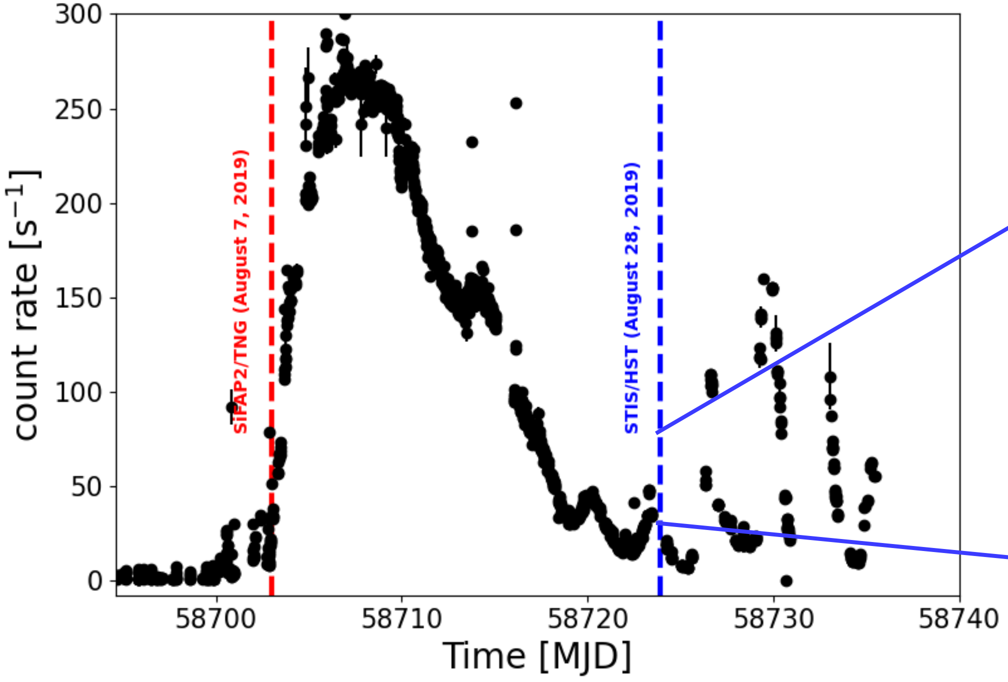




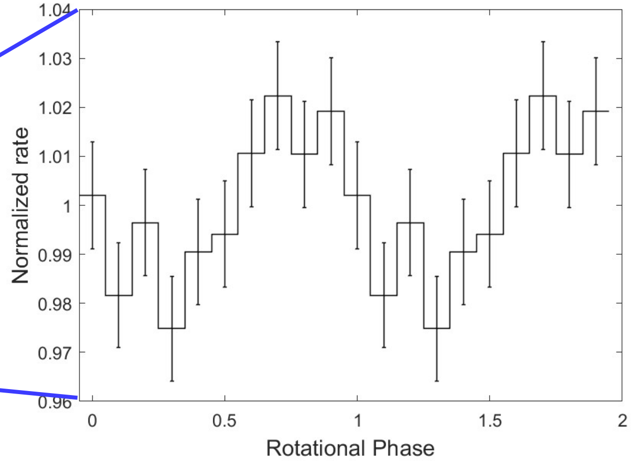


[Miraval Zanon, Papitto, in prep.]

UV PULSATIONS



2019

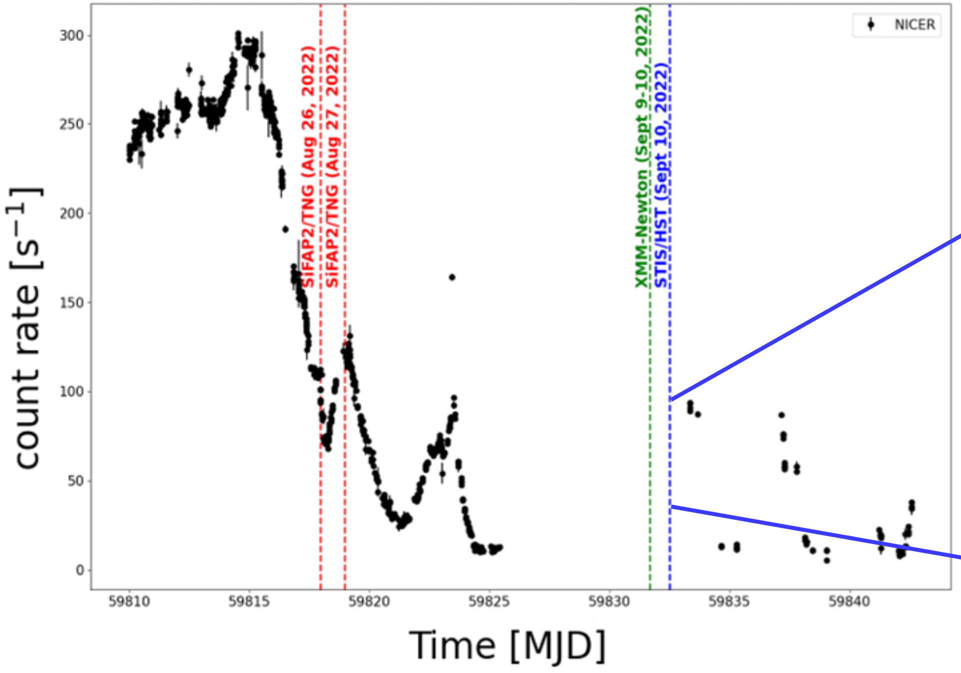


L_{uv} ~ 7.7 x 10^{33} erg/s

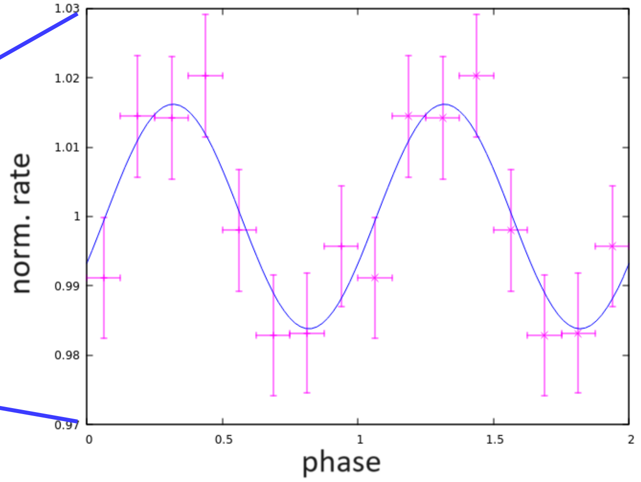
RMS UV amplitude ~ (2.6±0.7)%

$L_{uv\,(pulsed)}$ ~ 2 x 10^{32} erg/s

[Ambrosino, Miraval Zanon+ 2021, NatAstro]



2022



L_{uv} ~ 8.15 x 10^{33} erg/s

RMS UV amplitude ~ (1.6±0.3)%

$L_{uv\,(pulsed)}$ ~ 1.4 x 10^{32} erg/s

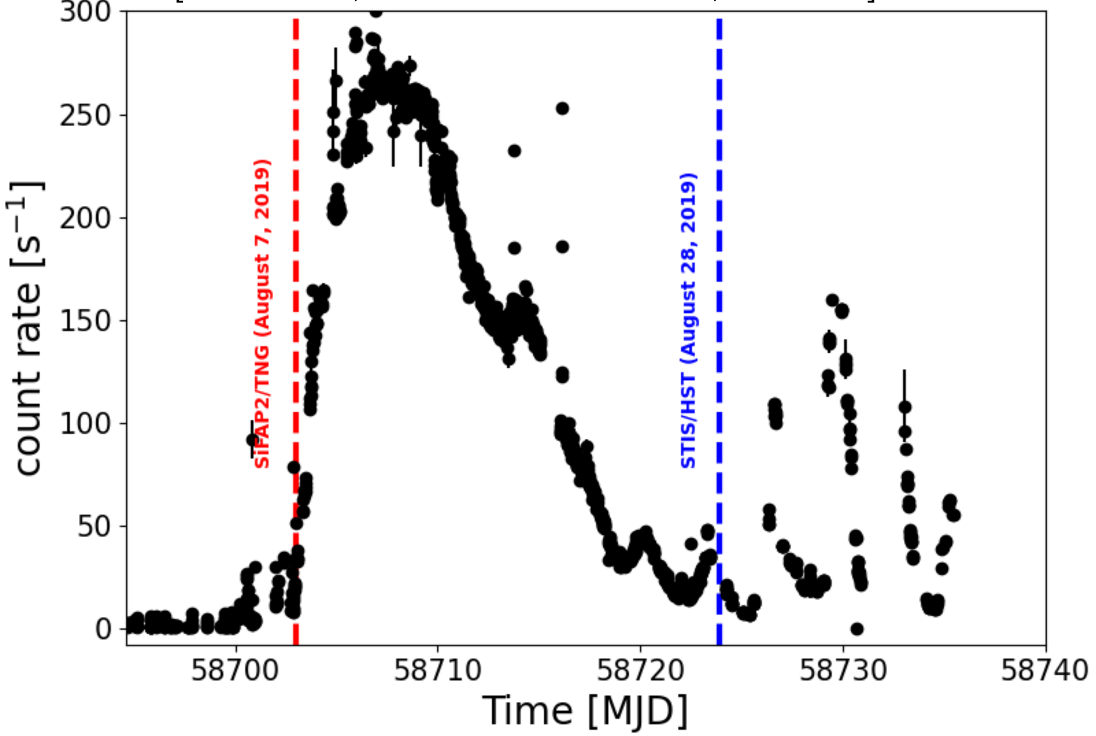
[Miraval Zanon+, in prep.]

OPTICAL PULSATIONS

2019

$L_X \sim 5 \times 10^{34}$ erg/s
$L_{opt} \sim 5 \times 10^{33}$ erg/s
RMS opt. amplitude ~ (0.55±0.06)%
$L_{opt\ (pulsed)} \sim 2.7 \times 10^{31}$ erg/s

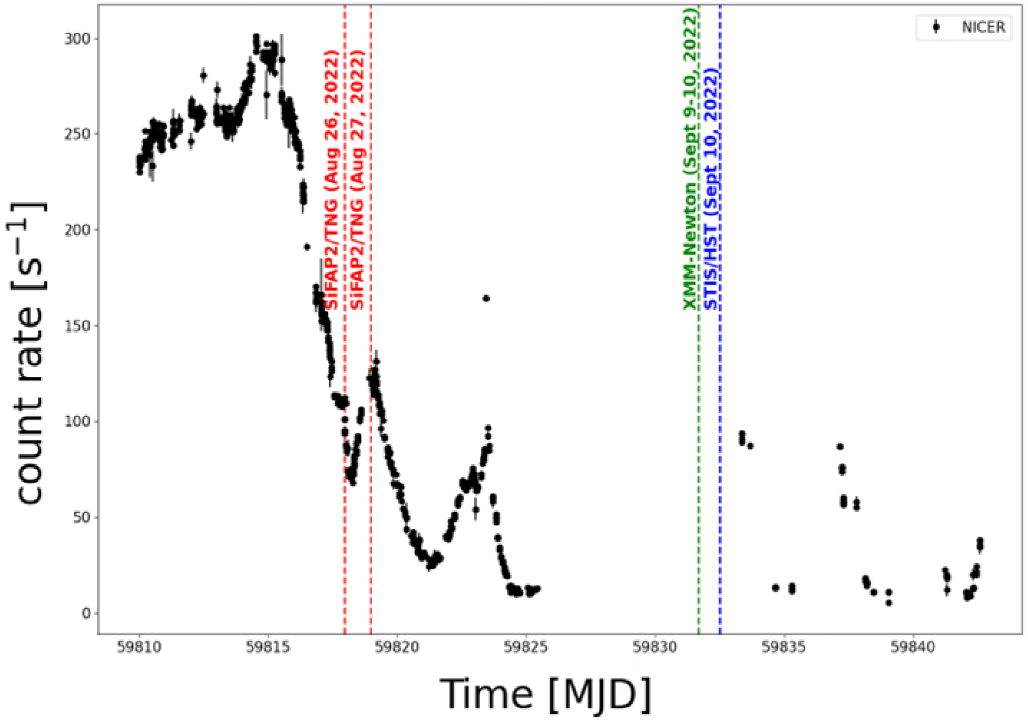
[Ambrosino, Miraval Zanon+ 2021, NatAstro]



2022

$L_X \sim$ 6-7 x 10^{35} erg/s
$L_{opt} \sim 3.6 \times 10^{33}$ erg/s
RMS opt. amplitude ~ (0.23±0.02)%
$L_{opt\ (pulsed)} \sim 10^{31}$ erg/s

[Miraval Zanon+, in prep.]

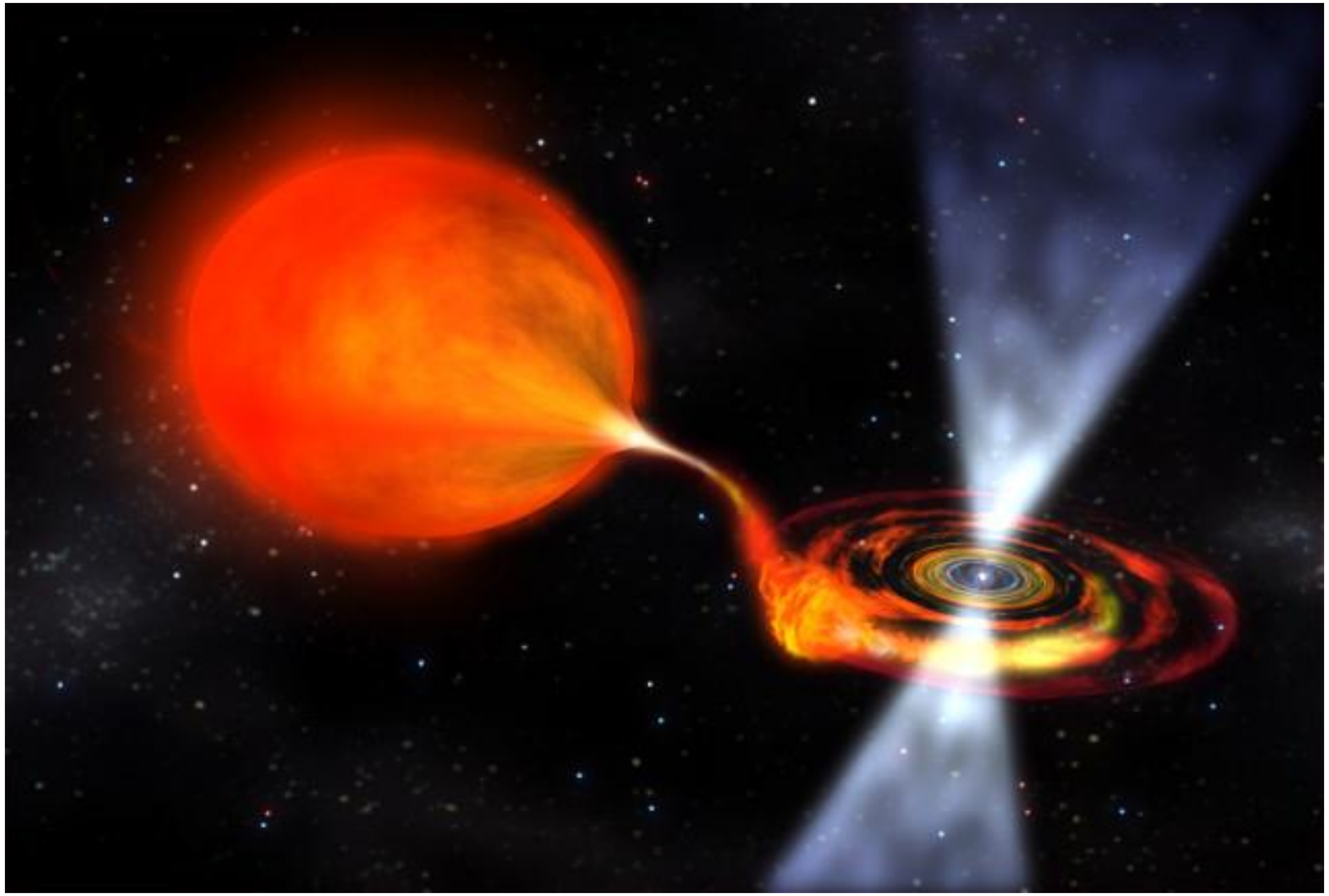


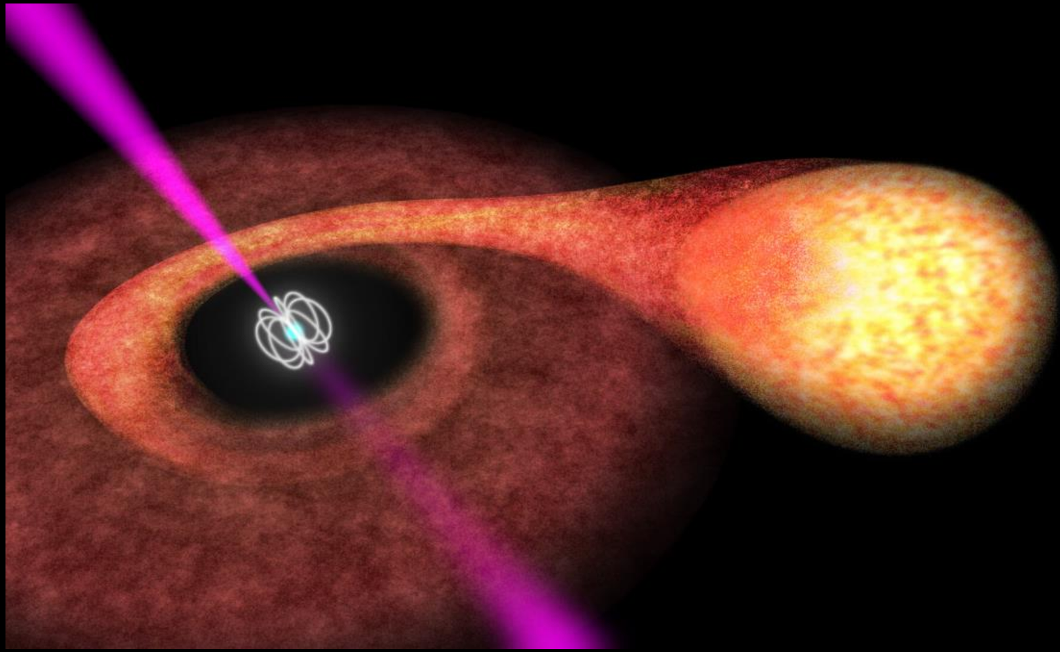
- **Optical pulsations are still present** at high X-ray luminosity **when the mass accretion is active**
- Higher X-ray luminosity → lower optical amplitude

OPEN QUESTIONS

- Why the rapid flux change in the decay phase after the peak of the outburst does not affect the phases as it does in the reflaring phase?

- What is the process that produces the optical and UV pulses in AMXPs?





THANK YOU FOR YOUR TIME AND ATTENTION!

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