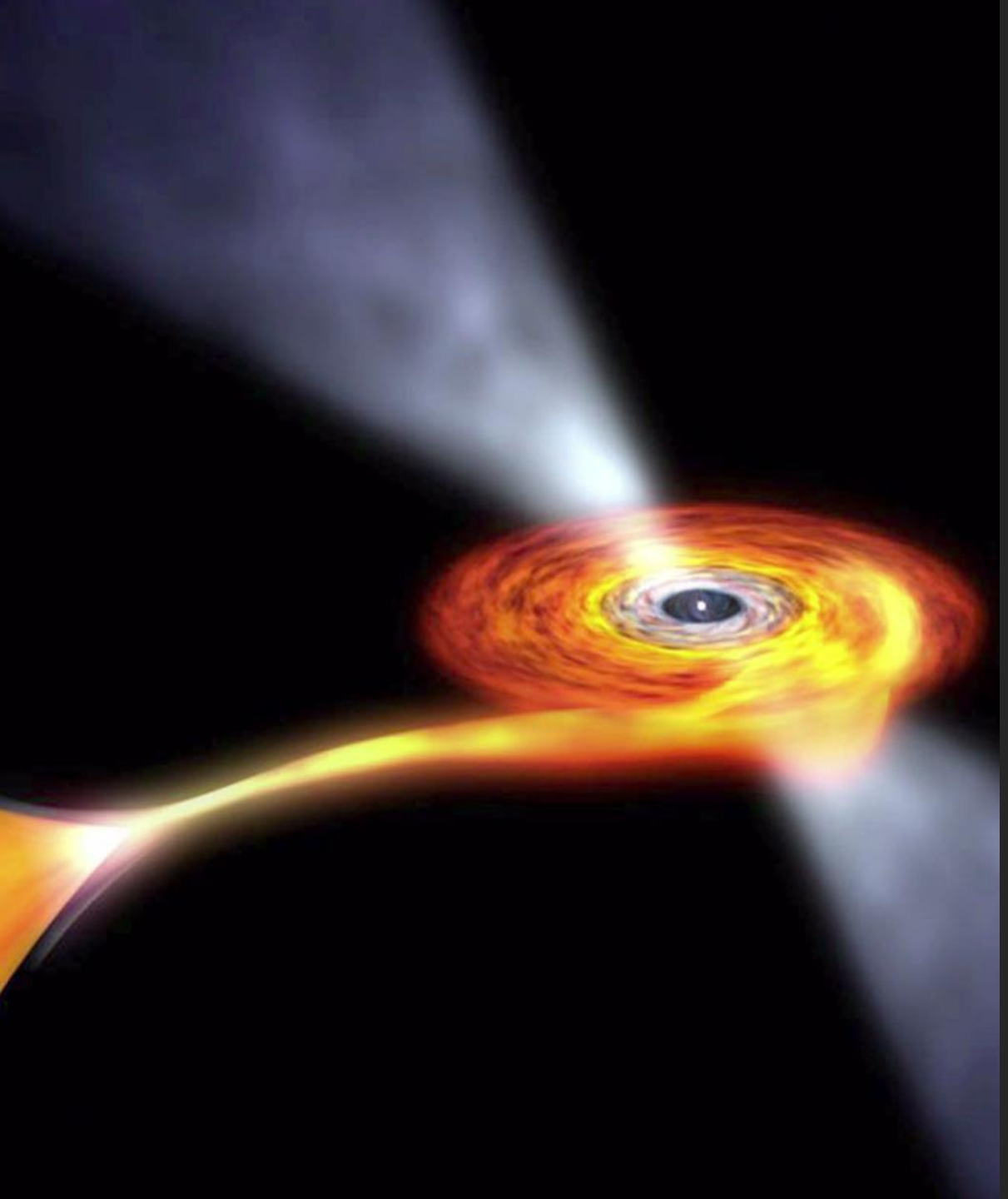


TIME LAGS BETWEEN OPTICAL AND X-RAY PULSATIONS OF THE TRANSITIONAL MILLISECOND PULSAR PSR J1023+0038

GIULIA ILLIANO

Supervisor: Alessandro Papitto

Collaborators: Filippo Ambrosino, Arianna Miraval Zanon, Luigi Stella

CNOC XII – Cefalù – 27/09/2022

INAF ISTITUTO NAZIONALE DI ASTROFISICA

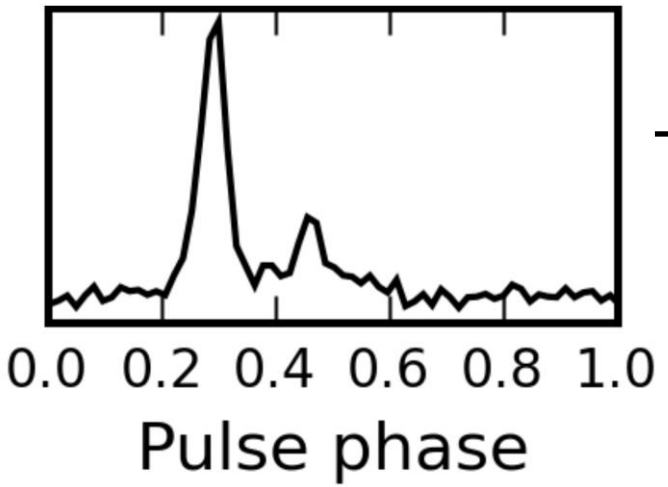
TOR VERGATA UNIVERSITÀ DEGLI STUDI DI ROMA

SAPIENZA UNIVERSITÀ DI ROMA

J1023: THE PROTOTYPE OF TRANSITIONAL MILLISECOND PULSARS

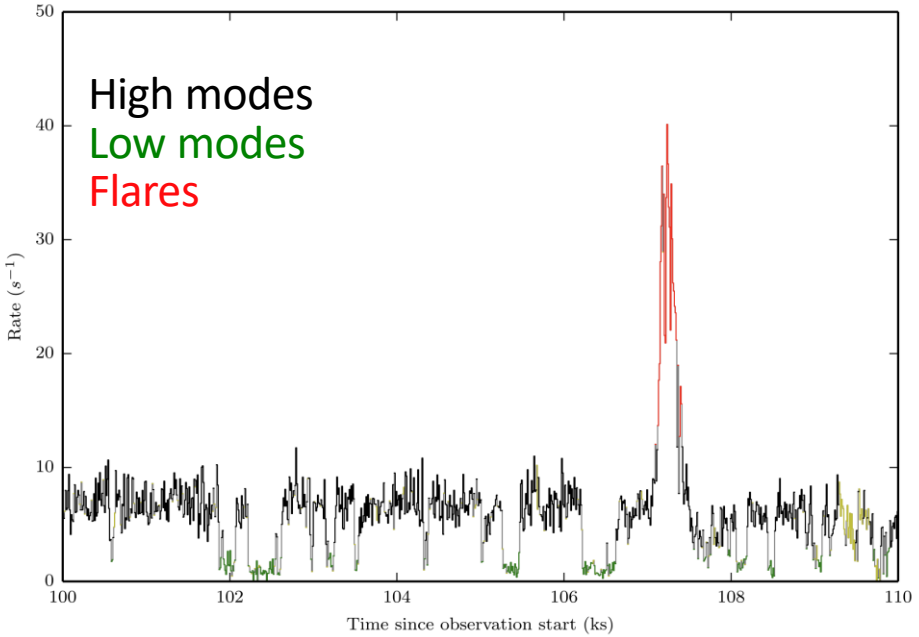
Discovered as a **radio pulsar**
(P=1.69 ms, d=1.4 kpc)

[Archibald + 2009]



— 2008

2001 — Accretion-disk state



[Archibald + 2015]

2013 — Transition to the **accretion-disk state**

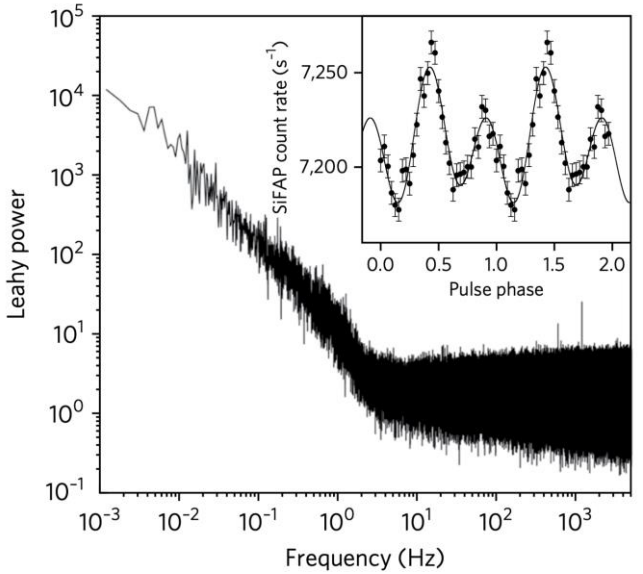
[Patruno+ 2014, Stappers+ 2014, Bogdanov+ 2015]

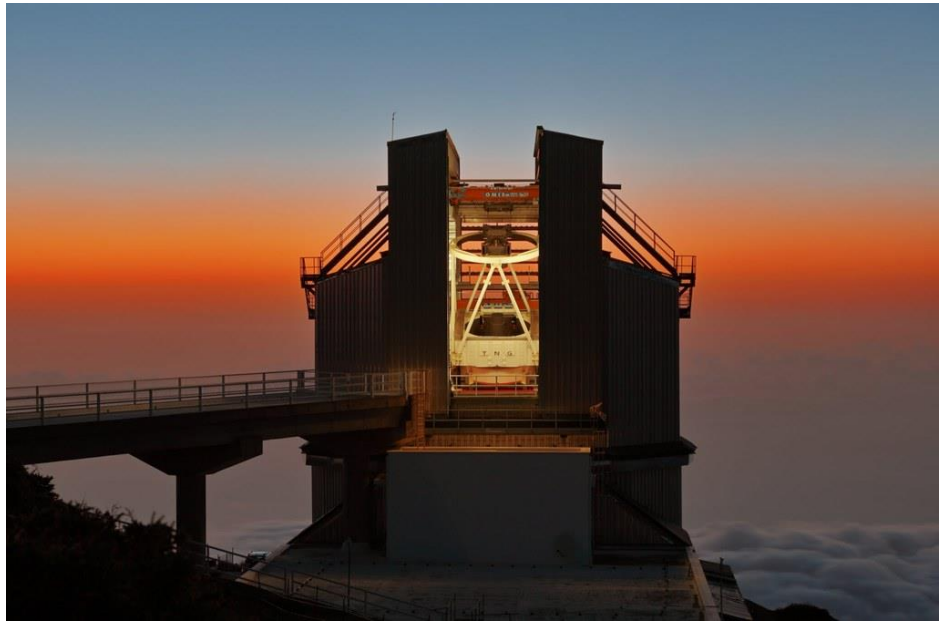
DISCOVERY OF OPTICAL PULSATIONS FROM J1023

LETTERS
DOI: 10.1038/s41550-017-0266-2
nature astronomy

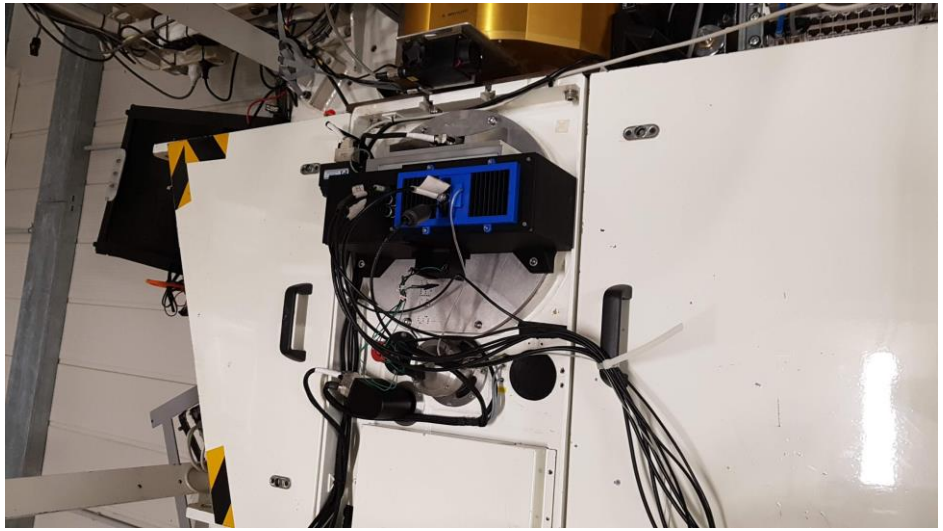
Optical pulsations from a transitional millisecond pulsar

F. Ambrosino[1,2], A. Papitto[3]*, L. Stella[3], F. Meddi[1], P. Cretaro[4], L. Burderi[5], T. Di Salvo[6], G. L. Israel[3], A. Ghedina[7], L. Di Fabrizio[7] and L. Riverol[7]





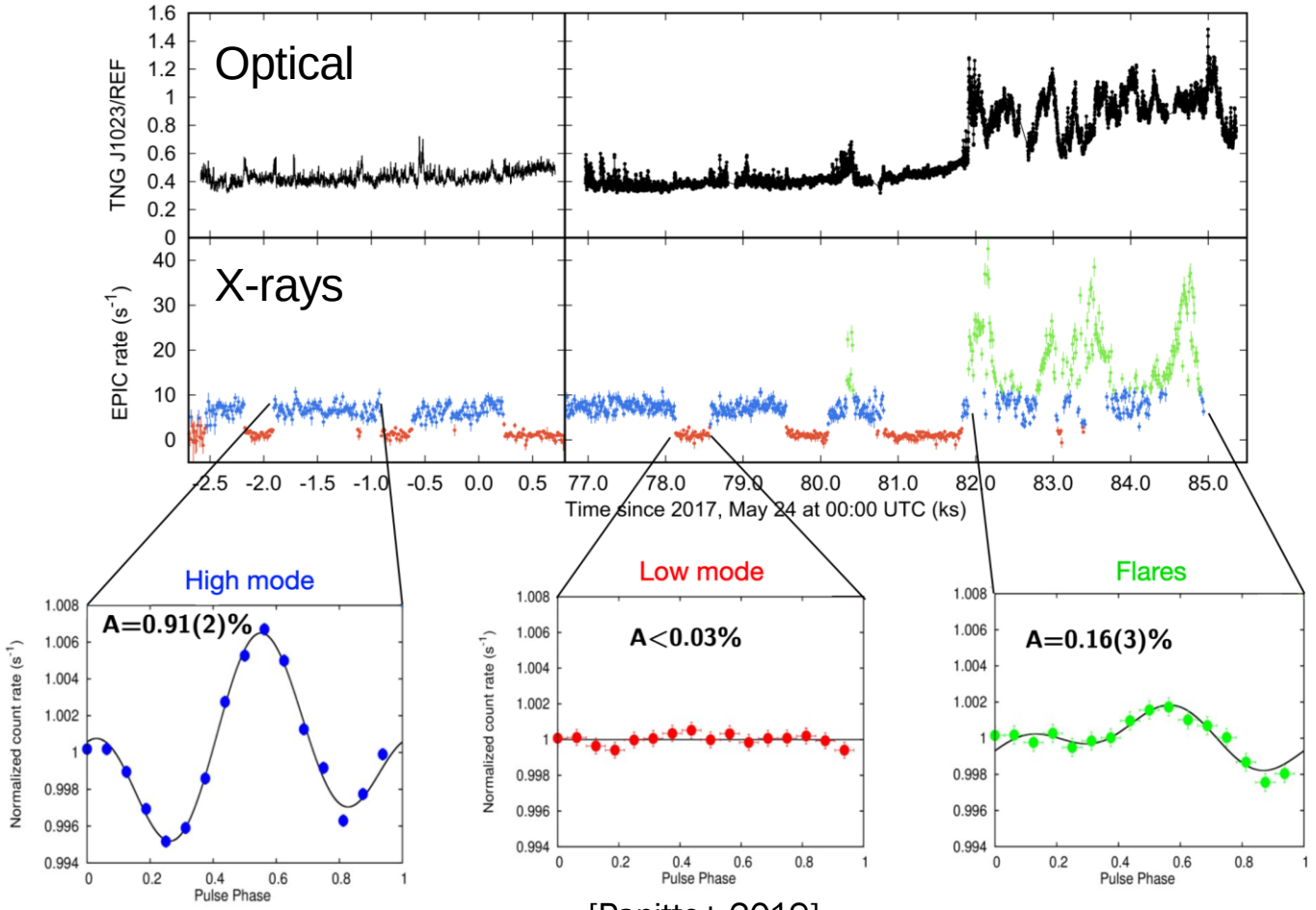
[Credit to G. Tessicini]



[Credit to A. Ghedina]

OPTICAL/X-RAY PULSATIONS FROM J1023

- Detected simultaneously during the X-ray high modes
- Similar pulse shapes
- Same power-law relation ($F_\nu \propto \nu^{-0.7}$) in the pulsed spectral energy distribution



[Papitto+ 2019]

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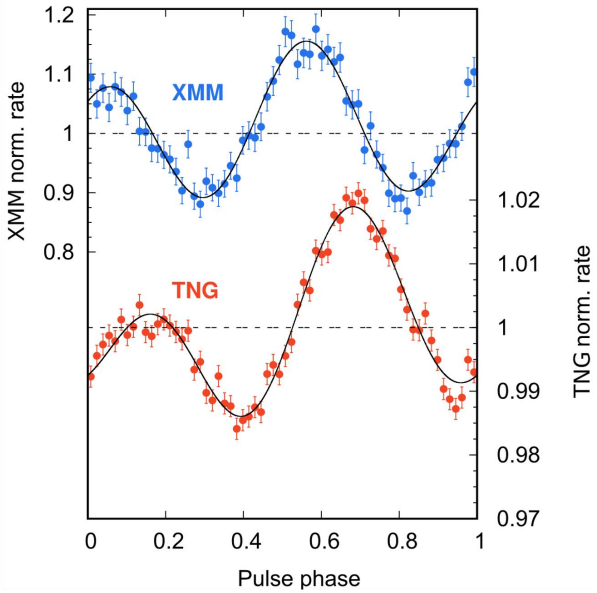
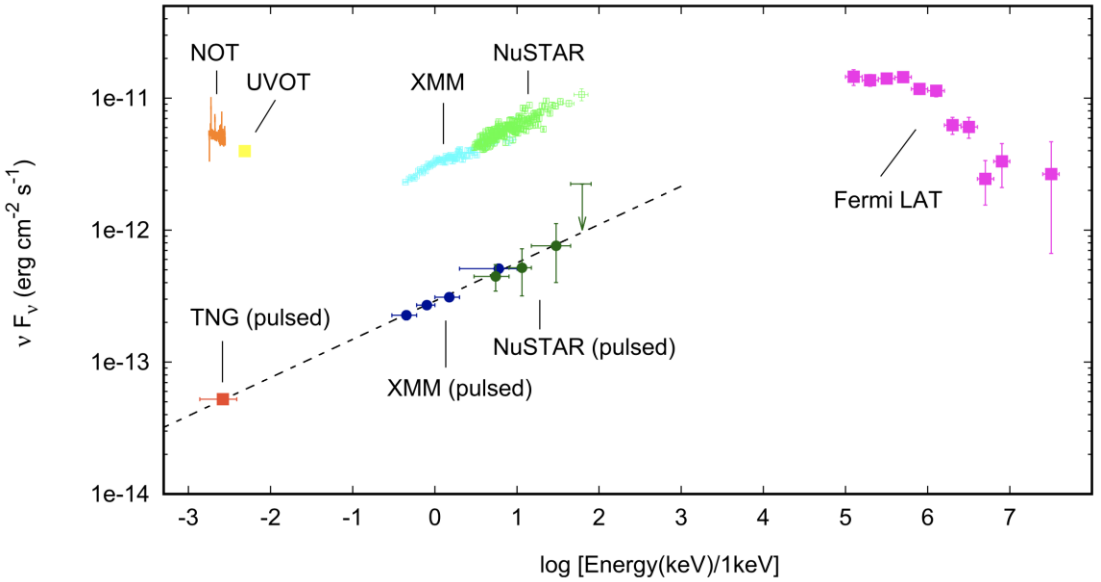
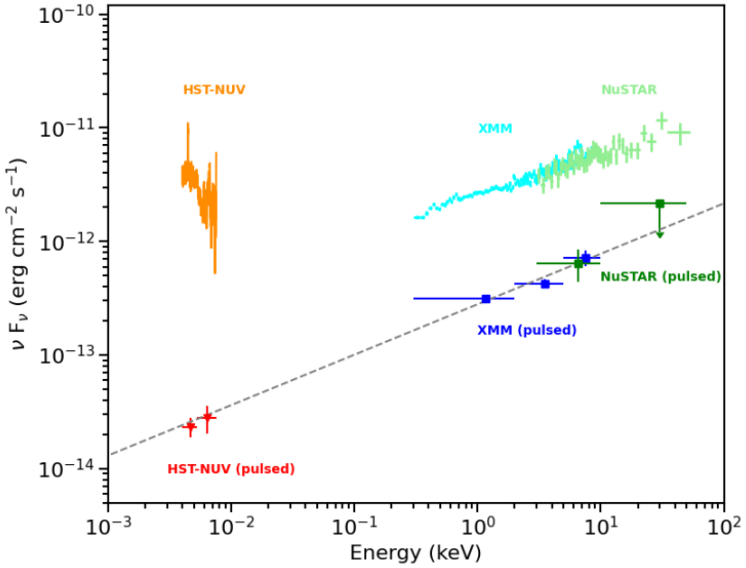


[Papitto+ 2019]



[Papitto+ 2019]



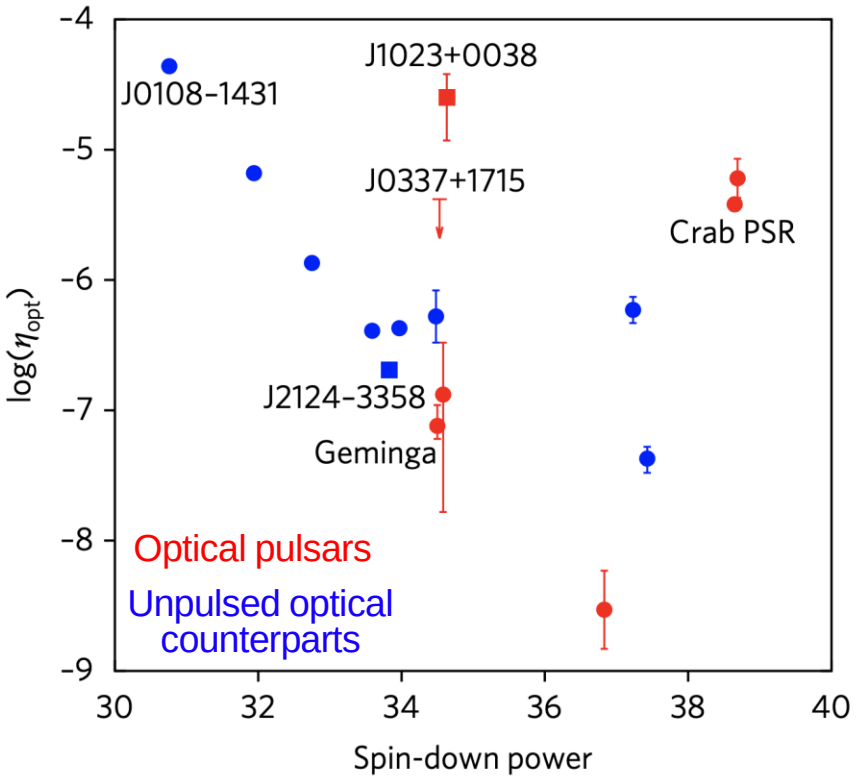
[Miraval Zanon+ 2022]

OPTICAL/X-RAY PULSATIONS FROM J1023

Standard mechanisms hardly individually explain the observed optical pulsed luminosities

Rotation-powered mechanism

Optical efficiency: $\eta_{opt} = L_{opt} \,/\, \dot{E}_{sd}$



[Ambrosino, Papitto+ 2017]

Accretion columns

Optical pulses due to **cyclotron emission** by infalling electrons in the accretion columns

$$L_{cyc,opt} \sim 3 \times 10^{29}\ \mathrm{erg/s}$$

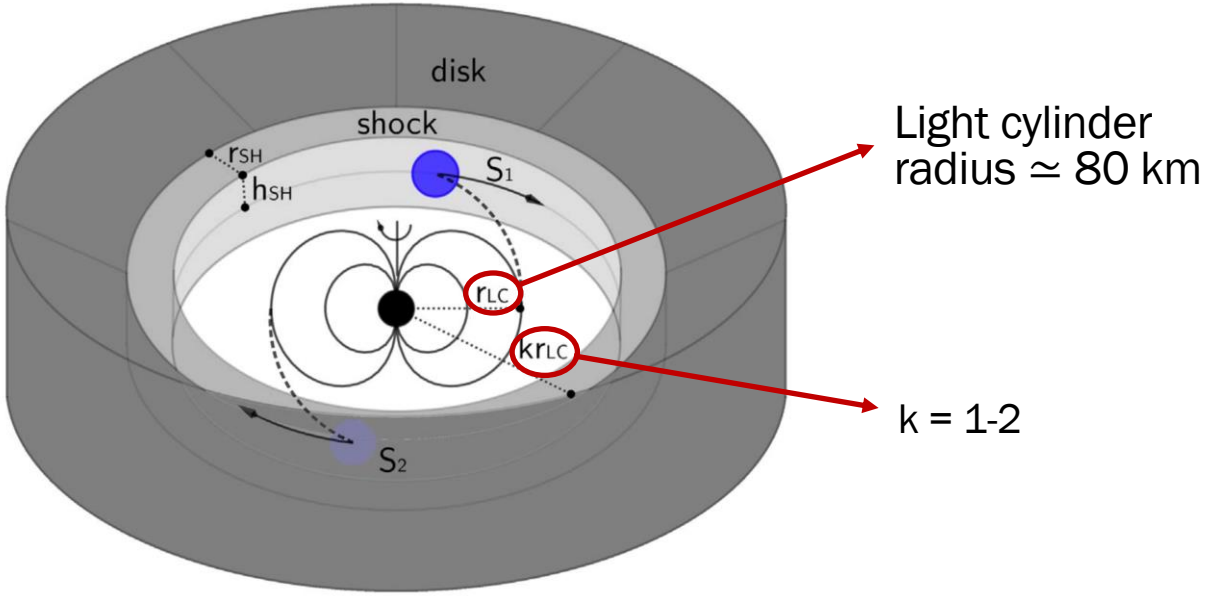
$$L_{pulsed,opt} \approx 10^{31}\ \mathrm{erg/s}$$

[Ambrosino, Papitto+ 2017]

$$L_{cyc,opt} \ll L_{pulsed,opt}$$

SHOCK-DRIVEN MINI PULSAR NEBULA

Synchrotron radiation from the shock between the pulsar wind and the accretion disk

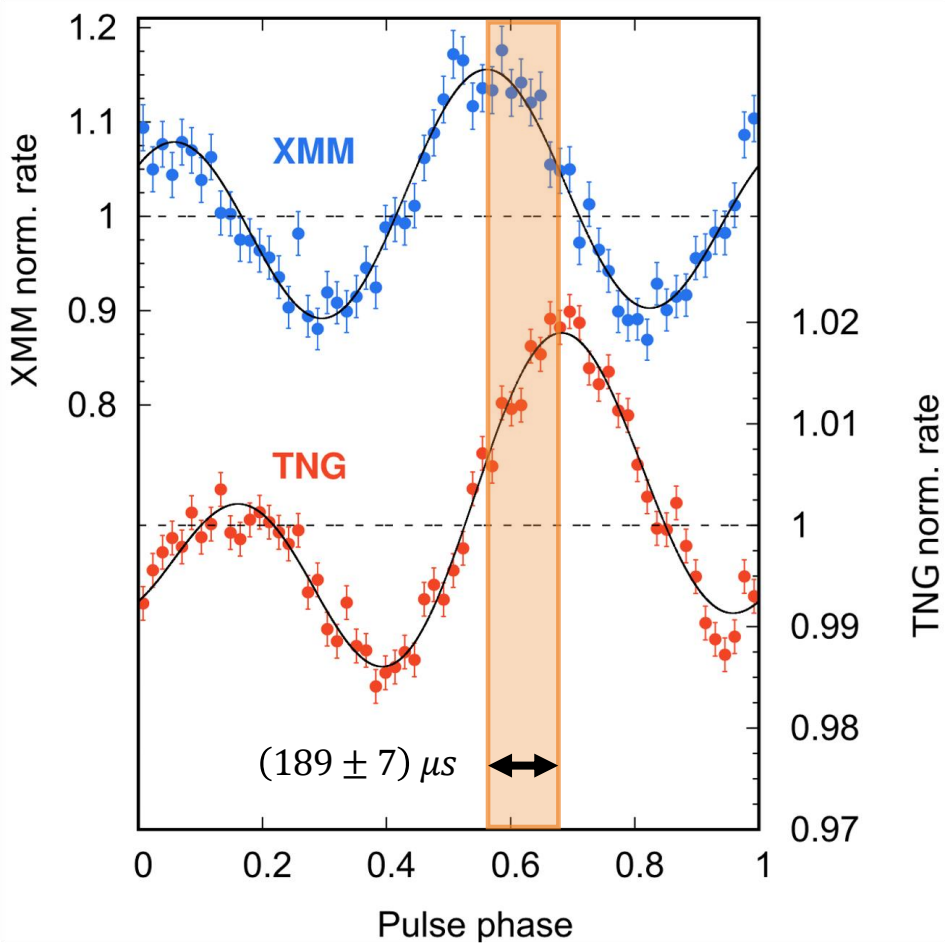


[Papitto+ 2019; Veledina+ 2019]

Different synchrotron timescales of optical and X-ray photons

$$t_{\rm sync} \simeq 2.2 \left(\frac{\epsilon}{10\,{\rm keV}}\right)^{-1/2} \left(\frac{B_{\rm s}}{4.5\times10^5\,{\rm G}}\right)^{-3/2} \mu{\rm s}$$

OPTICAL/X-RAY PULSATIONS FROM J1023



[Papitto+ 2019]

Previous analysis in May 2017: delay between optical pulses and X-ray ones of ~200 μs

[Papitto+ 2019]

Absolute timing accuracy:

- SiFAP2: ~60 μs

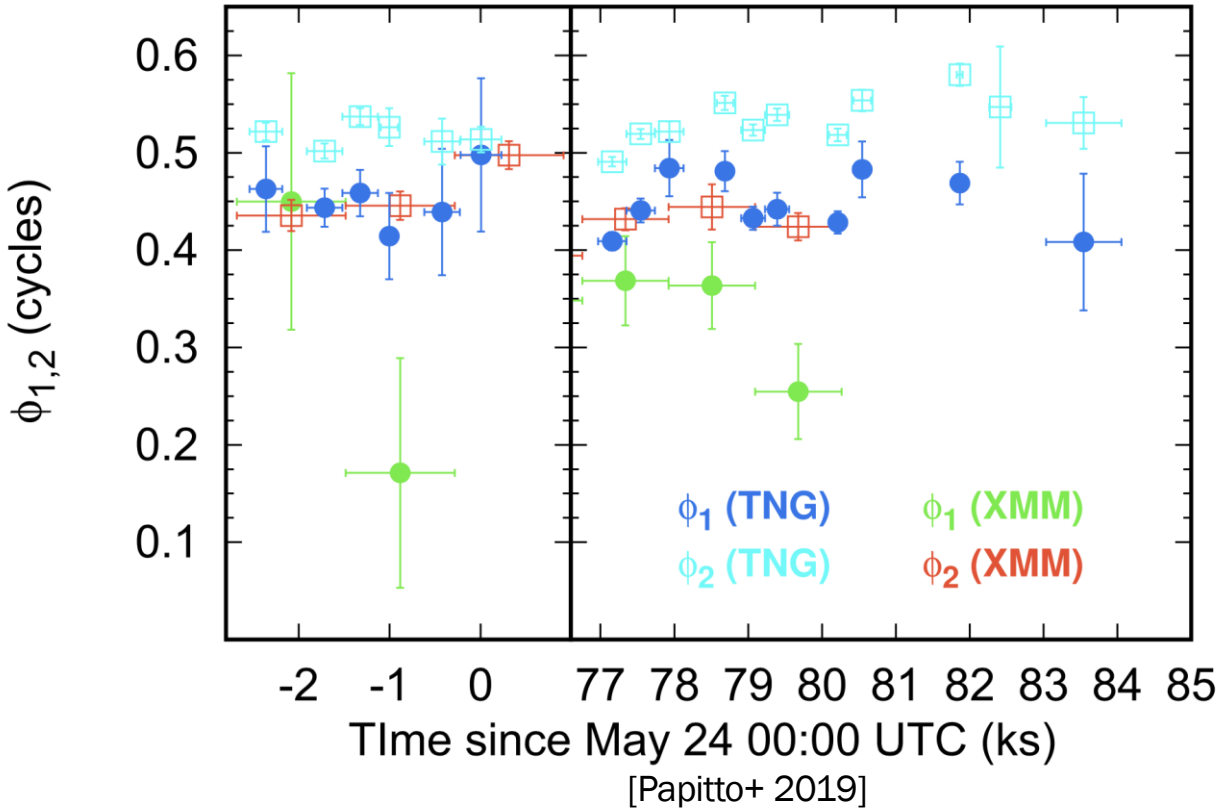
[Papitto+ 2019]

- XMM-Newton: ~100 μs

[XMM Calibration Technical Note 2021]

This work: data acquired using instruments with negligible absolute timing uncertainties

OPTICAL/X-RAY PULSATIONS FROM J1023



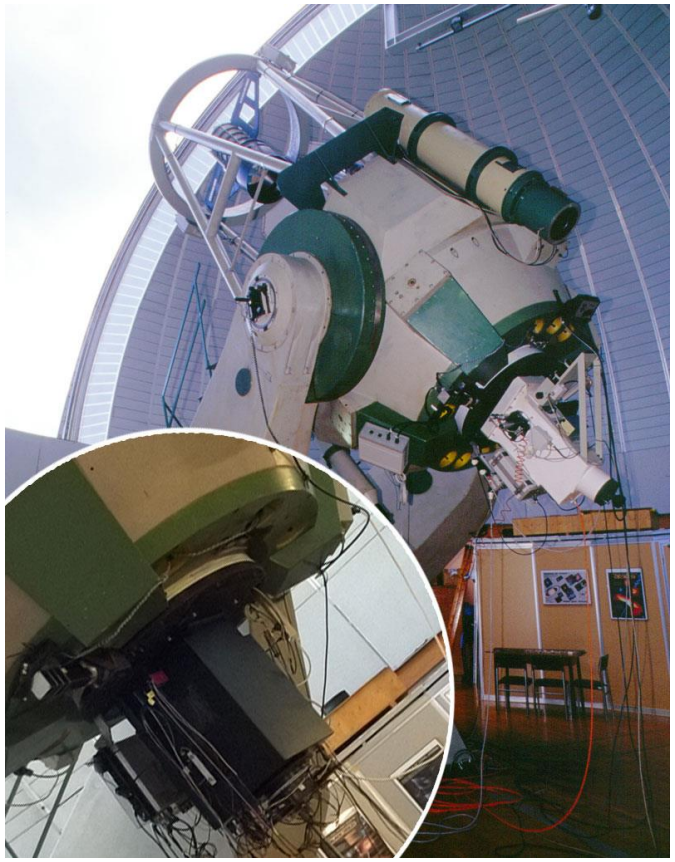
[Papitto+ 2019]

Optical and X-ray pulses during simultaneous observations in 2017: phase shift of ≈0.1 always present

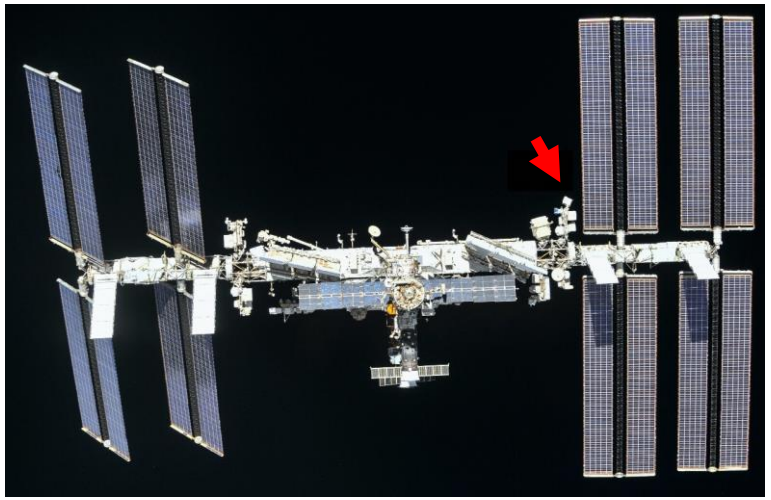
This work: five years of data to verify that the phase relation is maintained over time

OPTICAL/X-RAY OBSERVATIONS

Nine sets of (quasi-) simultaneous observations
from May 2017 to January 2022

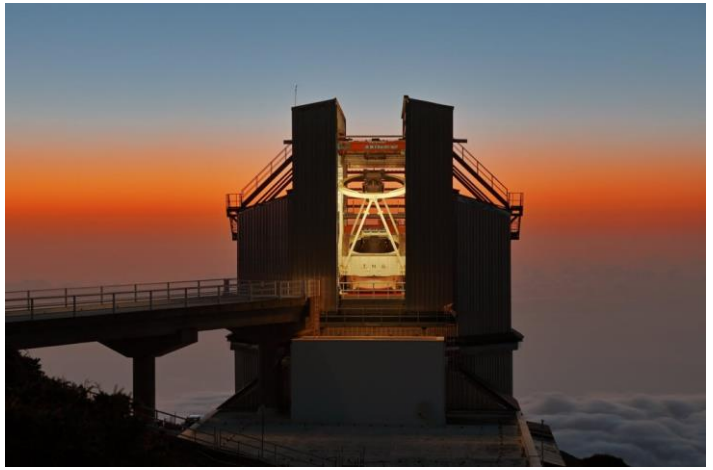


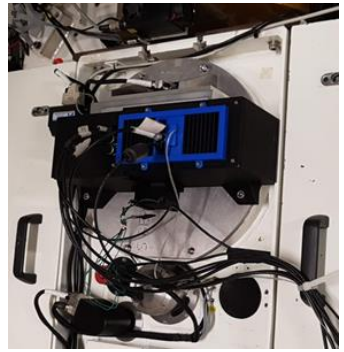
Copernicus/Aqueye+
[Credit to MEDIA INAF]



NICER on the ISS
[Credit to NASA]

XMM-Newton
[Credit to NASA]





TNG/SiFAP2
[Credit to G. Tessicini, A. Ghedina]

PHASE ANALYSIS

We model the folded pulse profiles using two sinusoidal harmonics

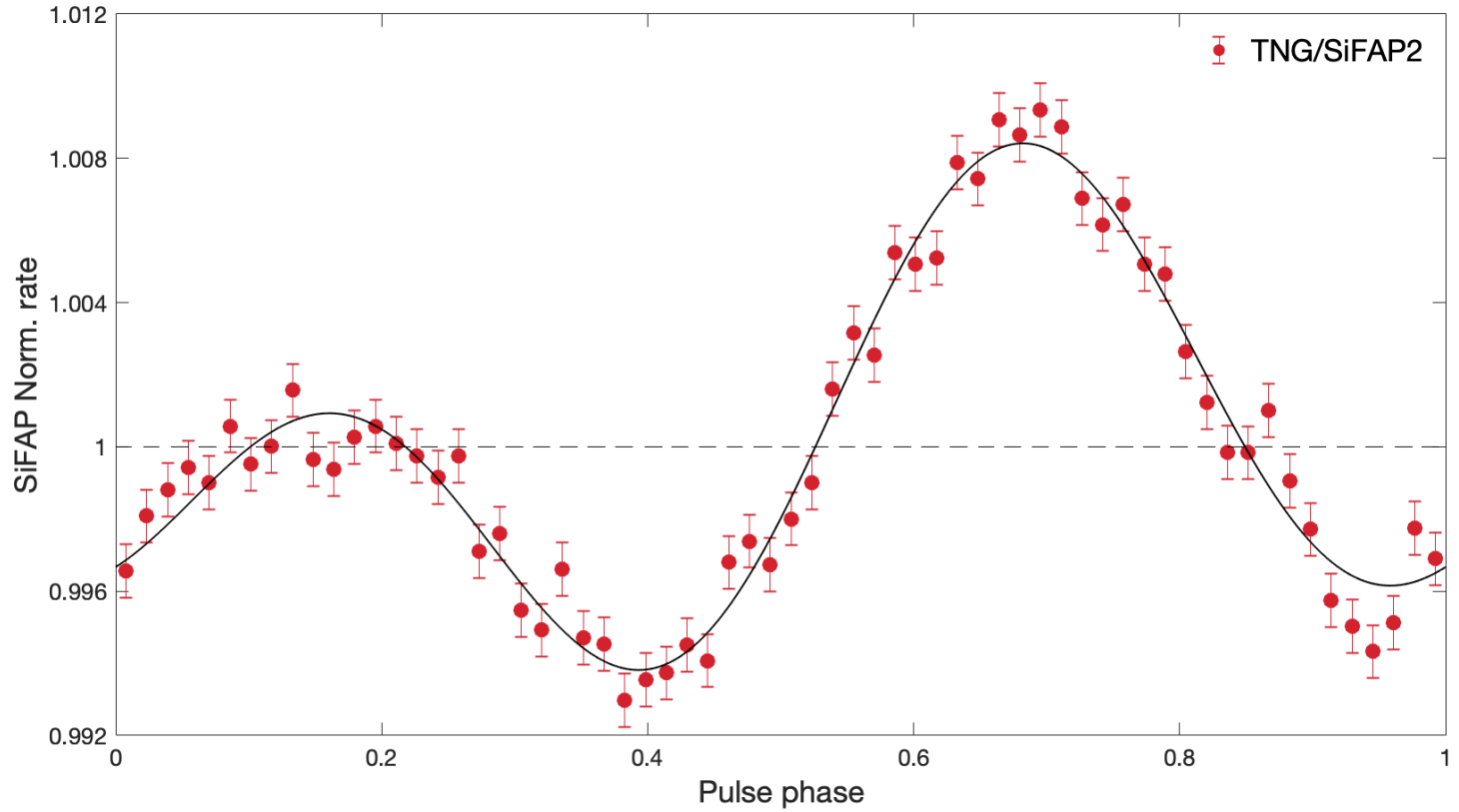
$$F(\phi) = const. + r_1 \sin[2\pi(\phi - \phi_1)] + r_2 \sin[4\pi(\phi - \phi_2)]$$

r_1: 1st harmonic's amplitude

ϕ_1: 1st harmonic's phase

r_2: 2nd harmonic's amplitude

ϕ_2: 2nd harmonic's phase



Pulse profile of the SiFAP observation in May 2017

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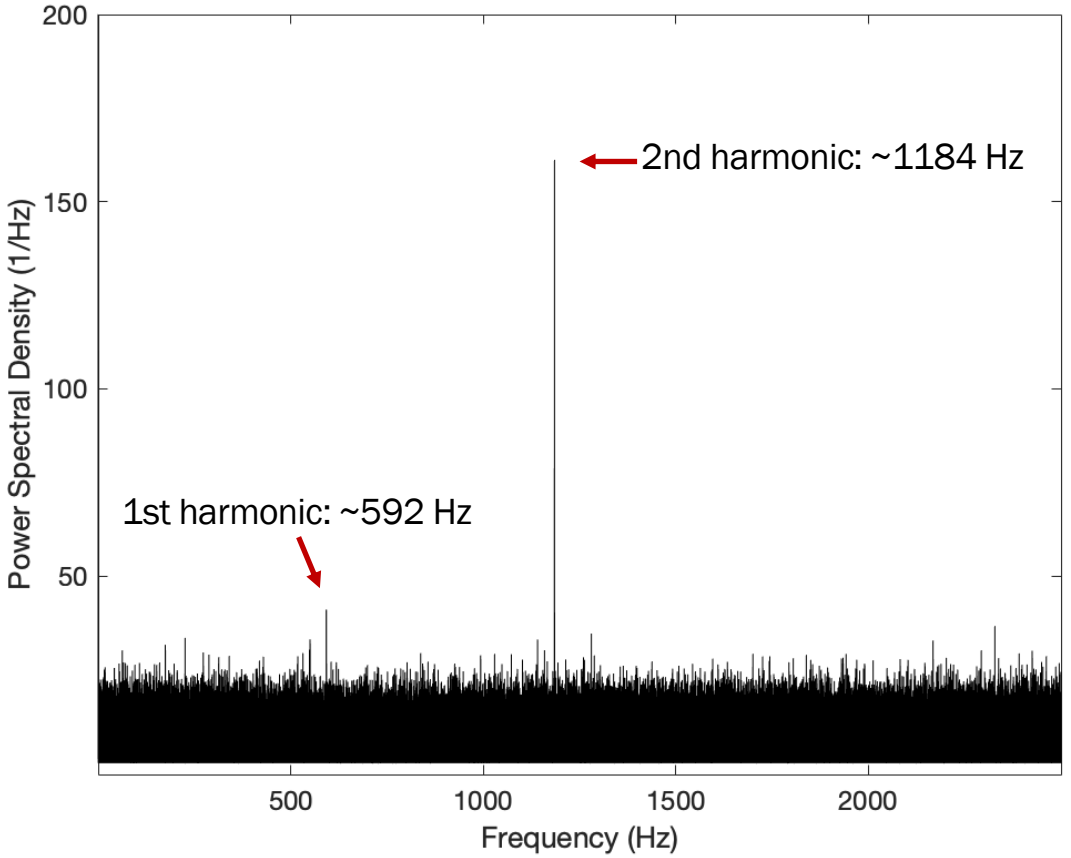
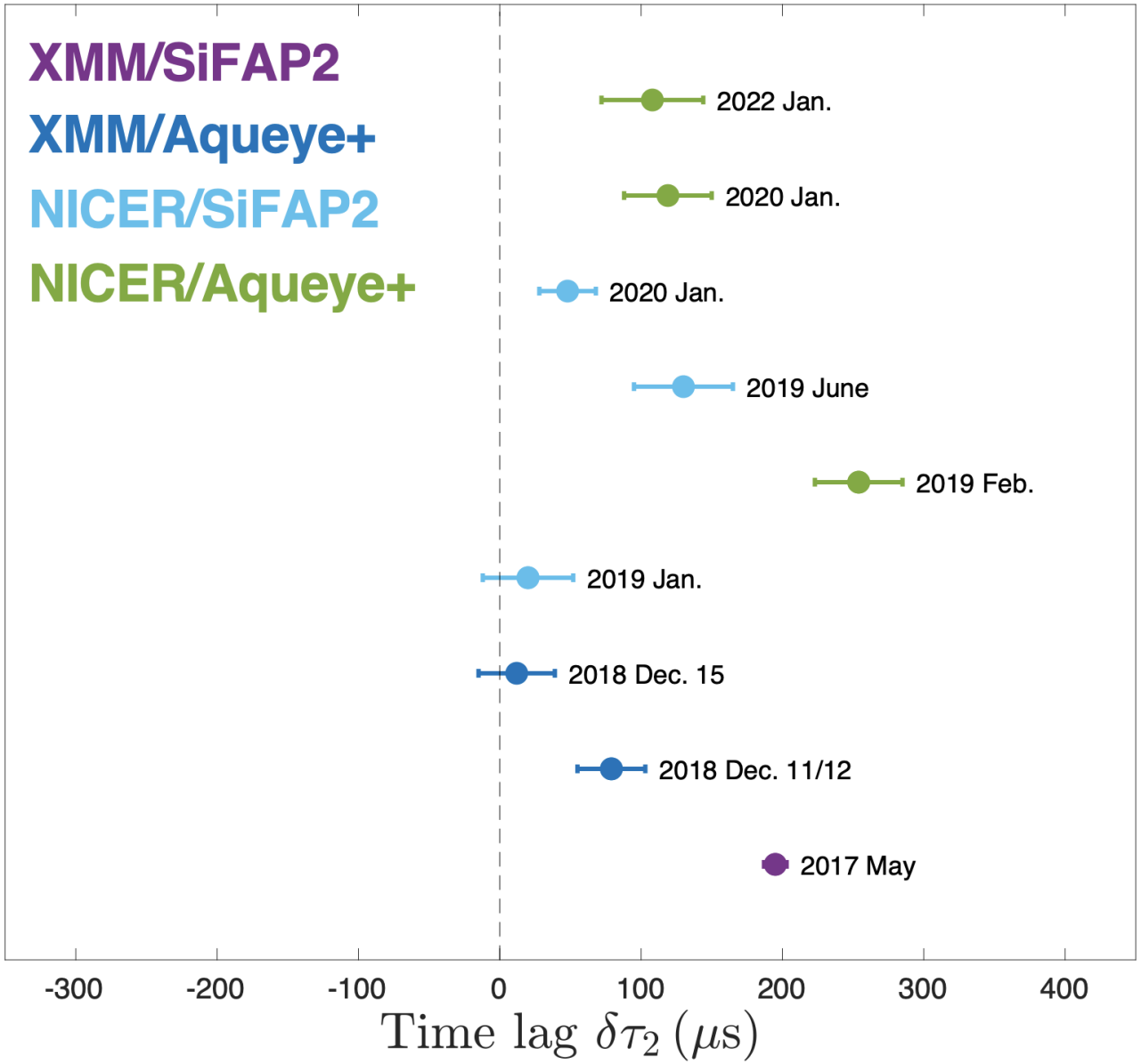


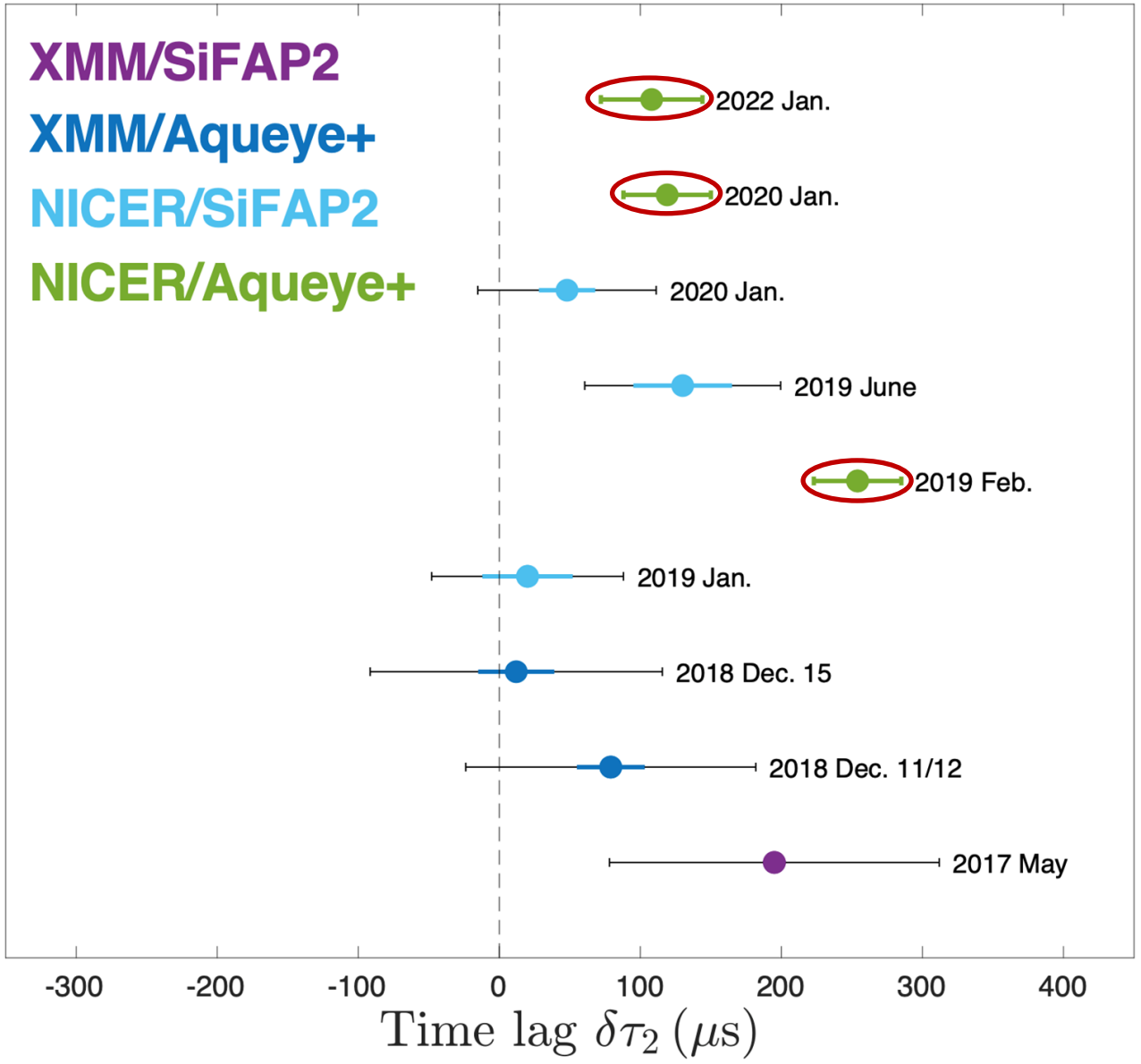
Power spectrum of a XMM-Newton observation

TIME LAGS



[Illiano+, submitted]

TIME LAGS



[Illiano+, submitted]

MODELLING

Estimation of **physical parameters** of the system within the chosen model

Parametric value of the time lag: $\delta\tau_p \sim 150\ \mu s$

- Synchrotron timescale for X-ray ($\sim 3\ \mu s$) and optical photons ($\sim 220\ \mu s$) :

[Papitto+ 2019]

$$t_{\rm sync} \propto \epsilon^{-1/2}\, B_{\rm s}^{-3/2} \Longrightarrow \delta t_{\rm sync} \simeq 200 \left(\frac{B_{\rm s}}{4.5 \times 10^5\ {\rm G}} \right)^{-3/2} \mu{\rm s}$$

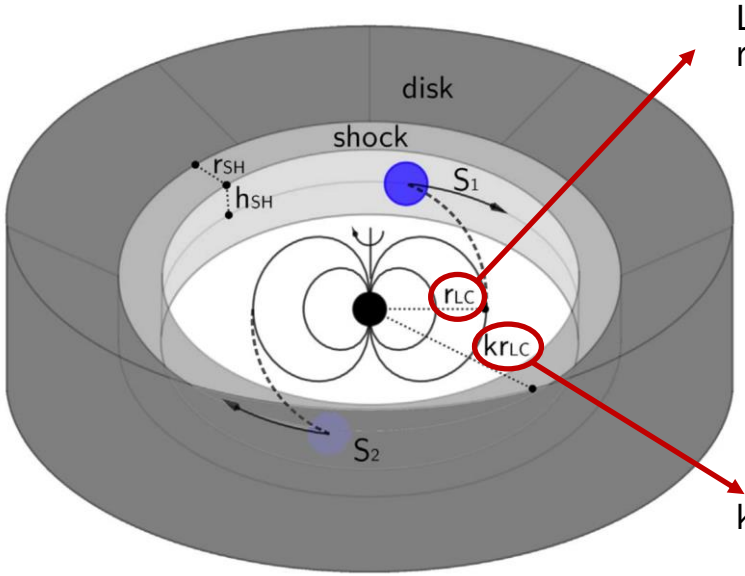
Photon energy

- Magnetic field behind the shock for $k \gtrsim 1$:

[Arons & Tavani 1993]

$$B_{\rm s} \propto f_p^{-1/2}\, r^{-1} \Longrightarrow f_p \lesssim 0.6$$

Collimation factor of the pulsar wind

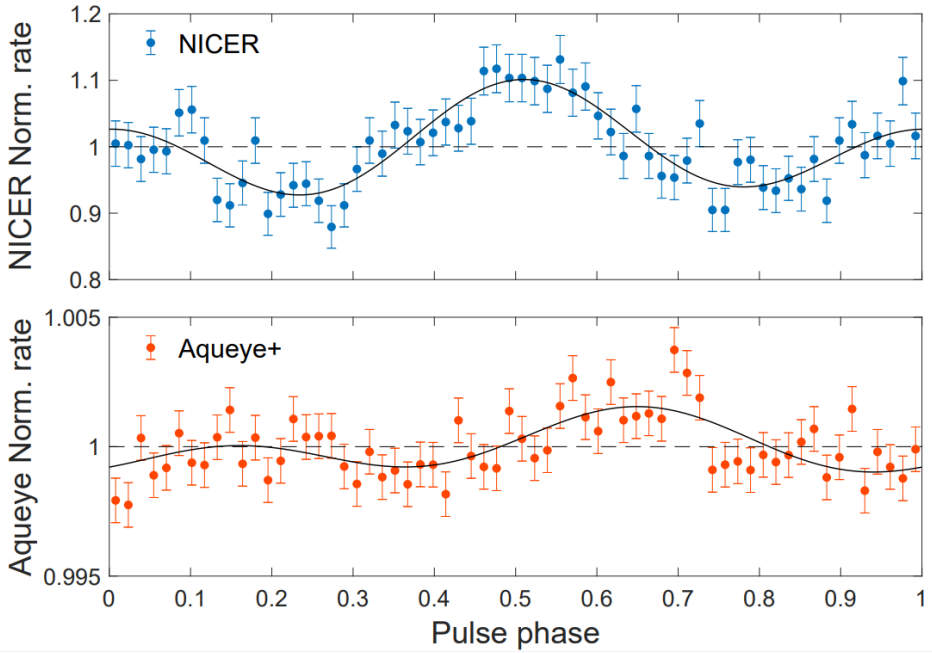


Light cylinder radius ≃ 80 km

k = 1-2

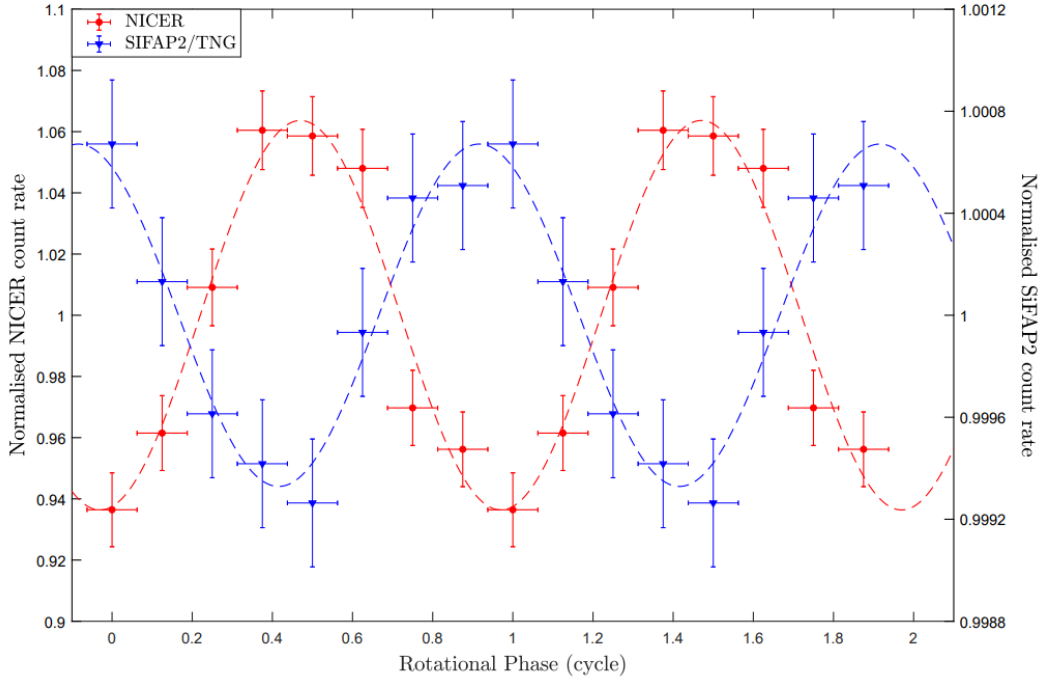
[Papitto+ 2019; Veledina+ 2019]

CONCLUSIONS AND FUTURE PROSPECTS



J1023 X-ray and optical pulse profiles
[Illiano+, submitted]

- **Optical/X-ray pulsations** of the tMSP J1023:
  - Time lags at most of a few hundred μs
  - Phase relation maintained over time
  - Results interpreted in the *shock-driven mini pulsar nebula*



SAX J1808 X-ray and optical pulse profiles
[Ambrosino+, 2021, Miraval Zanon+ (in prep.)]

- Future projects:

- Search for **new transitional millisecond pulsars** (e.g., 3FGL J1544.6-1125)
- Investigate the relation between **optical and X-ray pulses in other ms pulsars**: almost **in phase** (J1023) or **in anti-phase** (SAX J1808)?