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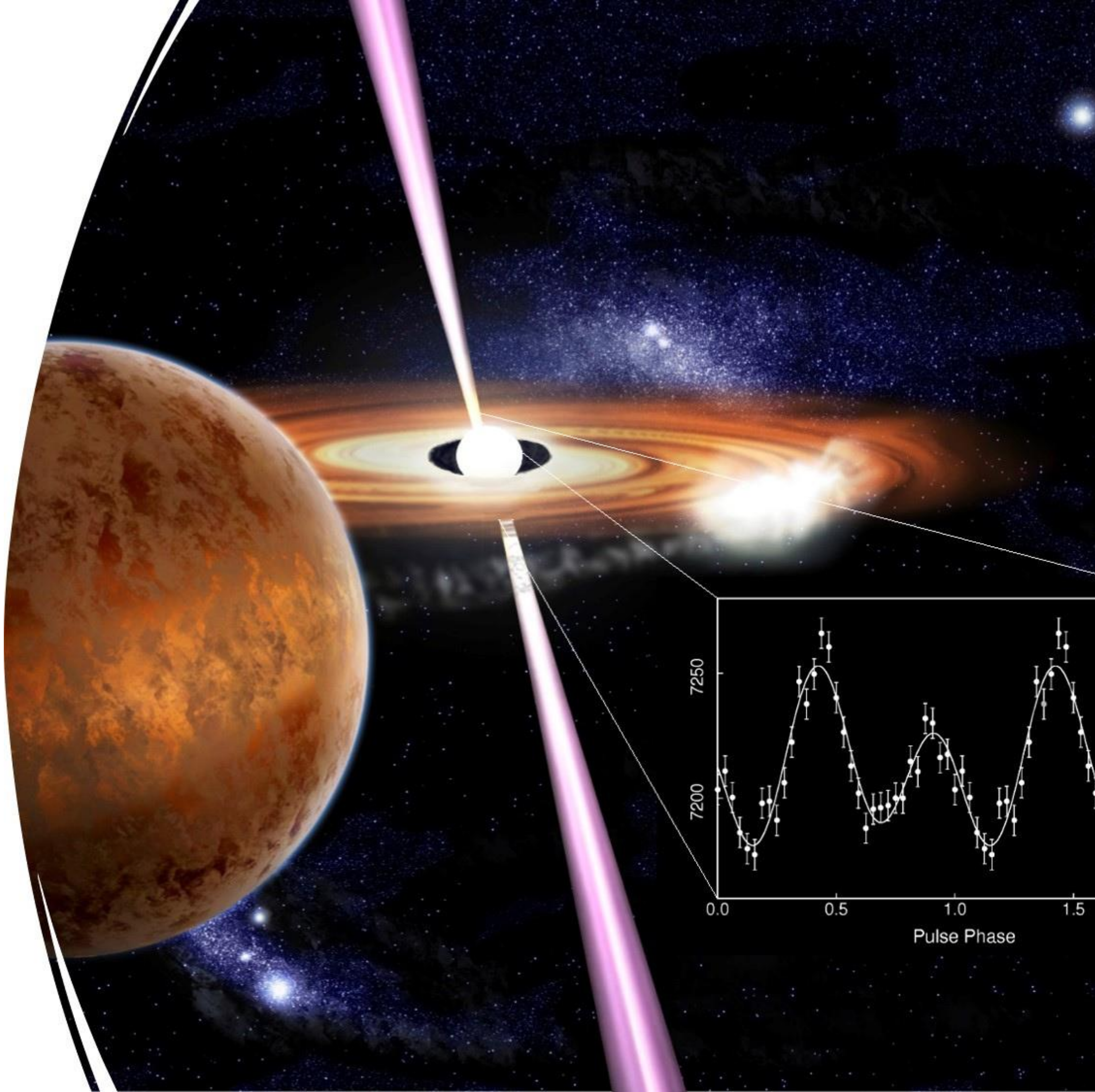
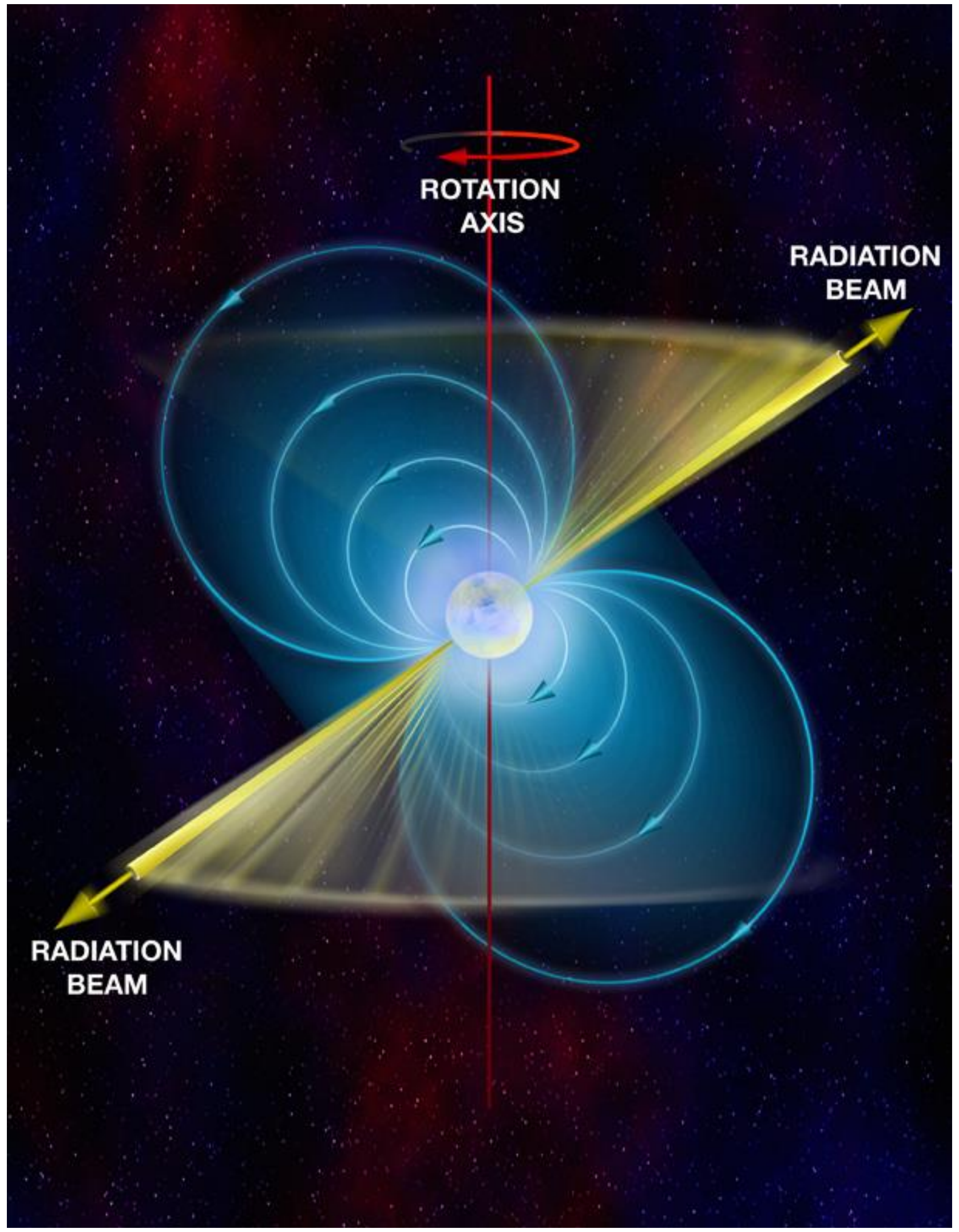
Fast optical photometry as a tool (for CW counterpart searches)

Riccardo La Placa
Giulia Illiano
Alessandro Papitto
Filippo Ambrosino
Arianna Miraval Zanon



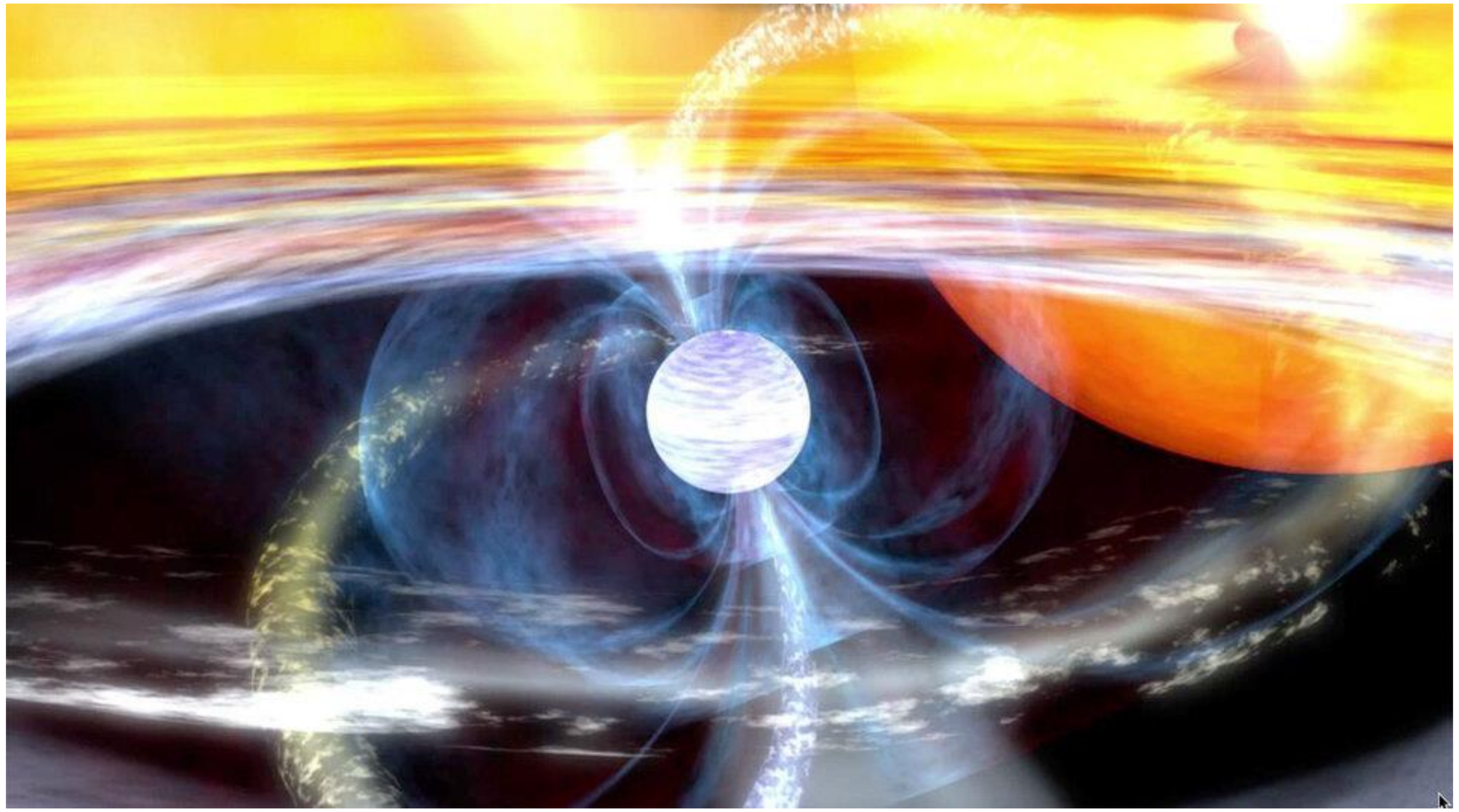
Classical pulsar scenarios

Rotation-powered



Credit: Bill Saxton, NRAO/AUI/NSF

Accretion-powered

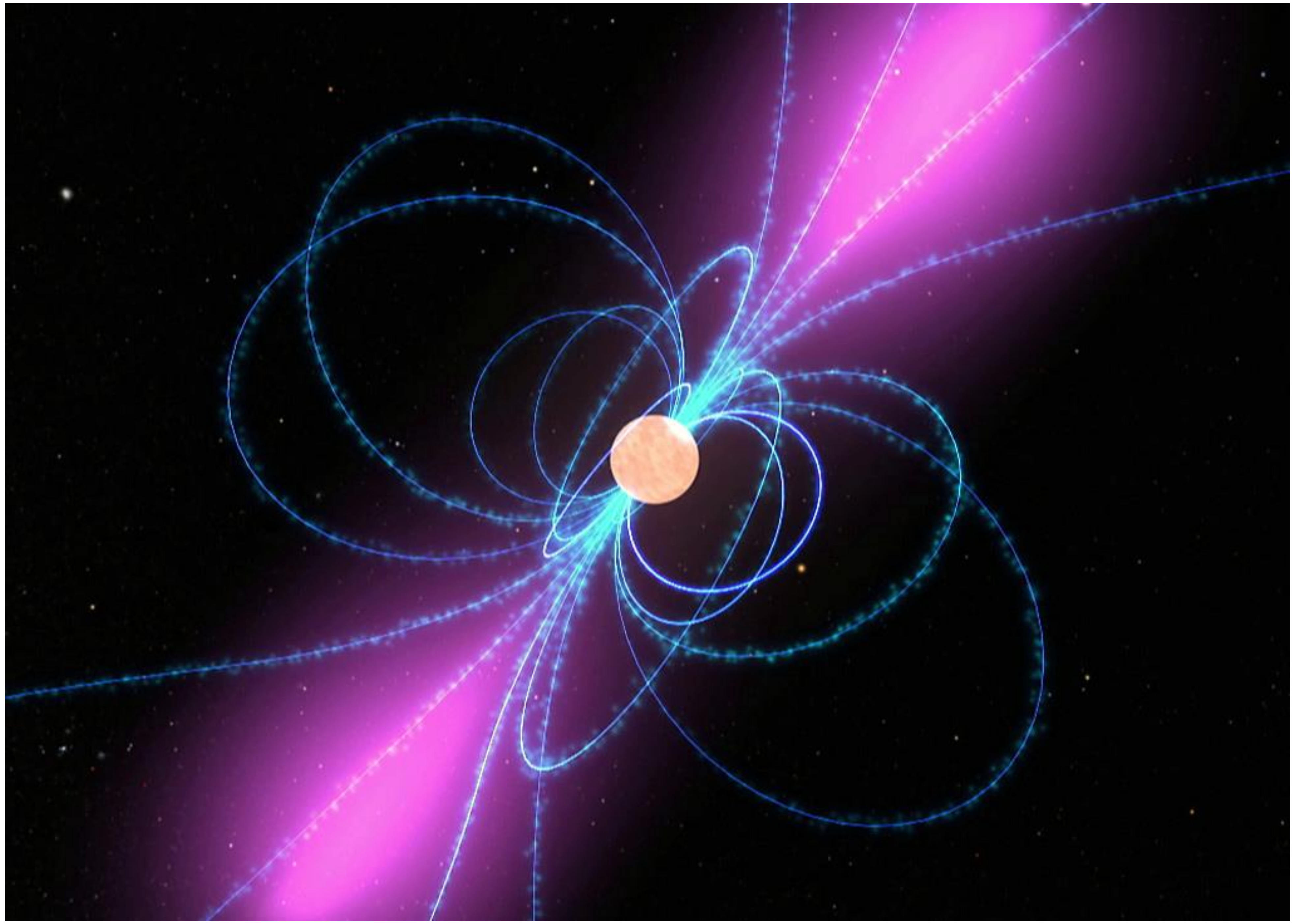


Credit: Dana Berry NASA/GSFC SVS

High-time resolution optical astronomy

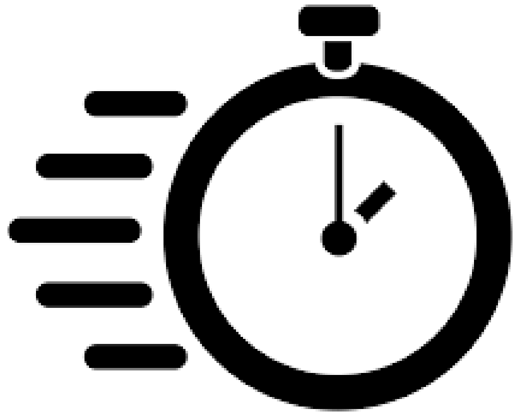
Fast time variability probes geometry and emission mechanisms

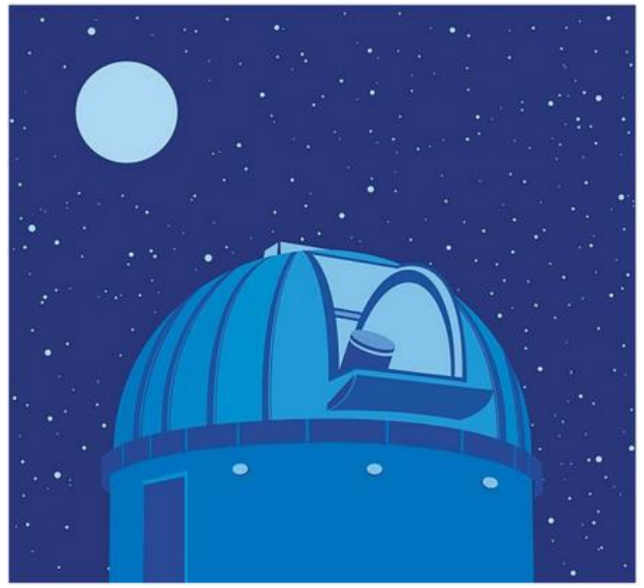
- Millisecond pulsars
- Accreting neutron stars



Detectors for fast optical photometry

$$A \sim \frac{1}{\sqrt{N_{\text{photon}}}}$$

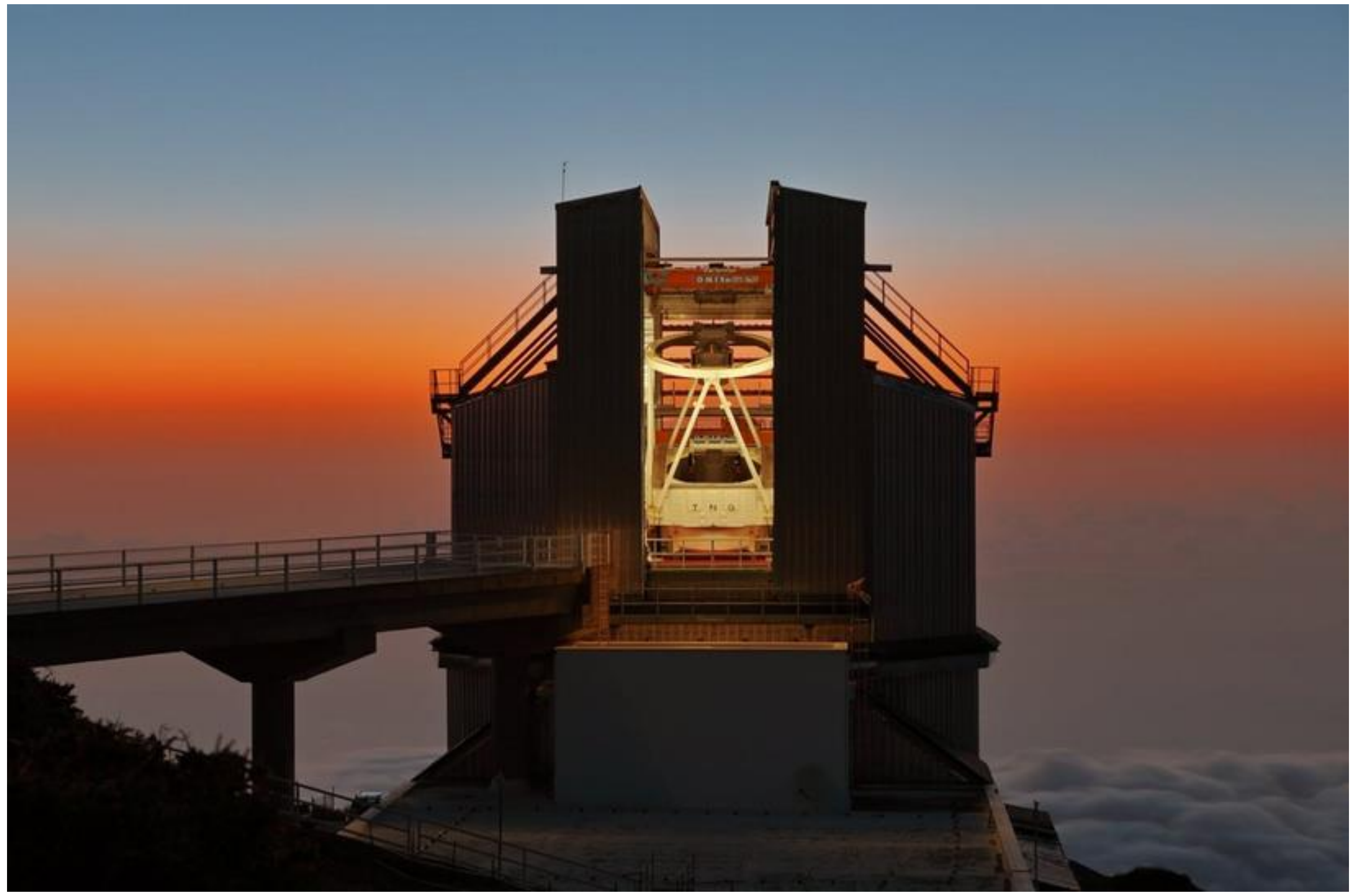


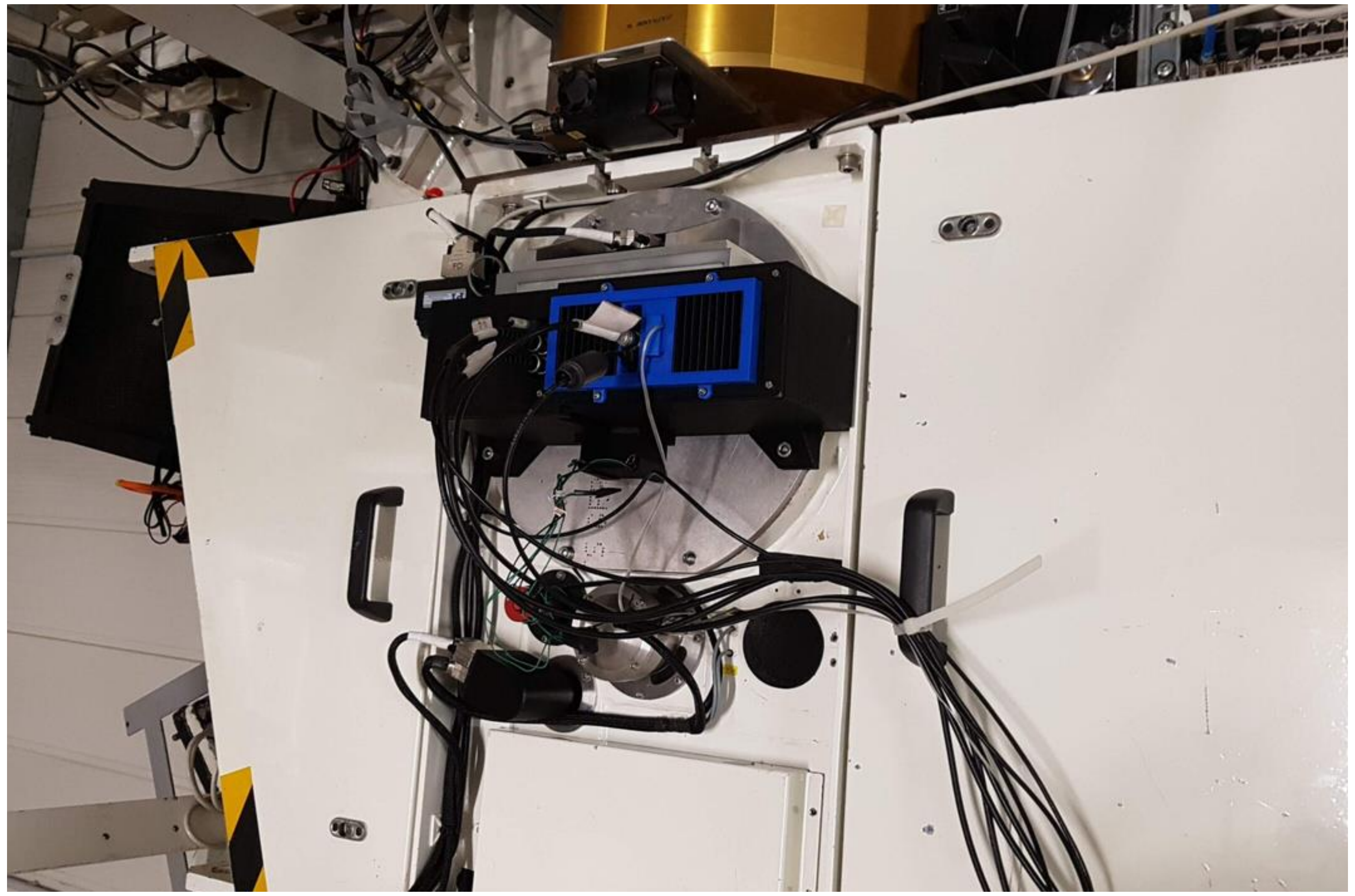


Instrument	Detector	Group	Time res [s]	Mode	Telescope
SiFAP2/4XP	**SiPM**	**INAF Rome / FGG**	**8E-11**	**Timing/Polarimetry**	**3.6m TNG**
Aqueye+/Iqueye	SPAD	INAF Padua	1E-10	Fast timing	1.8m Copernicus
HiPERCAM	CCD	Sheffield/IAC	6E-03	5-band imaging	10.4m GTC
ULTRACAM	CCD	Sheffield/Warwick	5E-03	3-band imaging	3.6m ESO NTT
ULTRASPEC	eMCCD	Sheffield/Warwick	1E-03	Spectroscopy	2.4m ThaiNT
GASP	eMCCD	Galway	6E-04	Polarimetry	WHT (past)
Optima	APD	MPE	1E-09	Timing/Polarimetry	1.3m Skinakas

The Silicon Fast Optical Photometer

- Extremely fast photometer based on Silicon Photo-Multipliers (SiPMs)
- Capable to tag single photons with a time resolution of ~~8 ns~~ 80 ps
- Absolute timing accuracy < ~~60~~ 20 μs
- Very good linearity with high count rates (up to 5 Mcps)
- New polarimeter in the calibration phase!



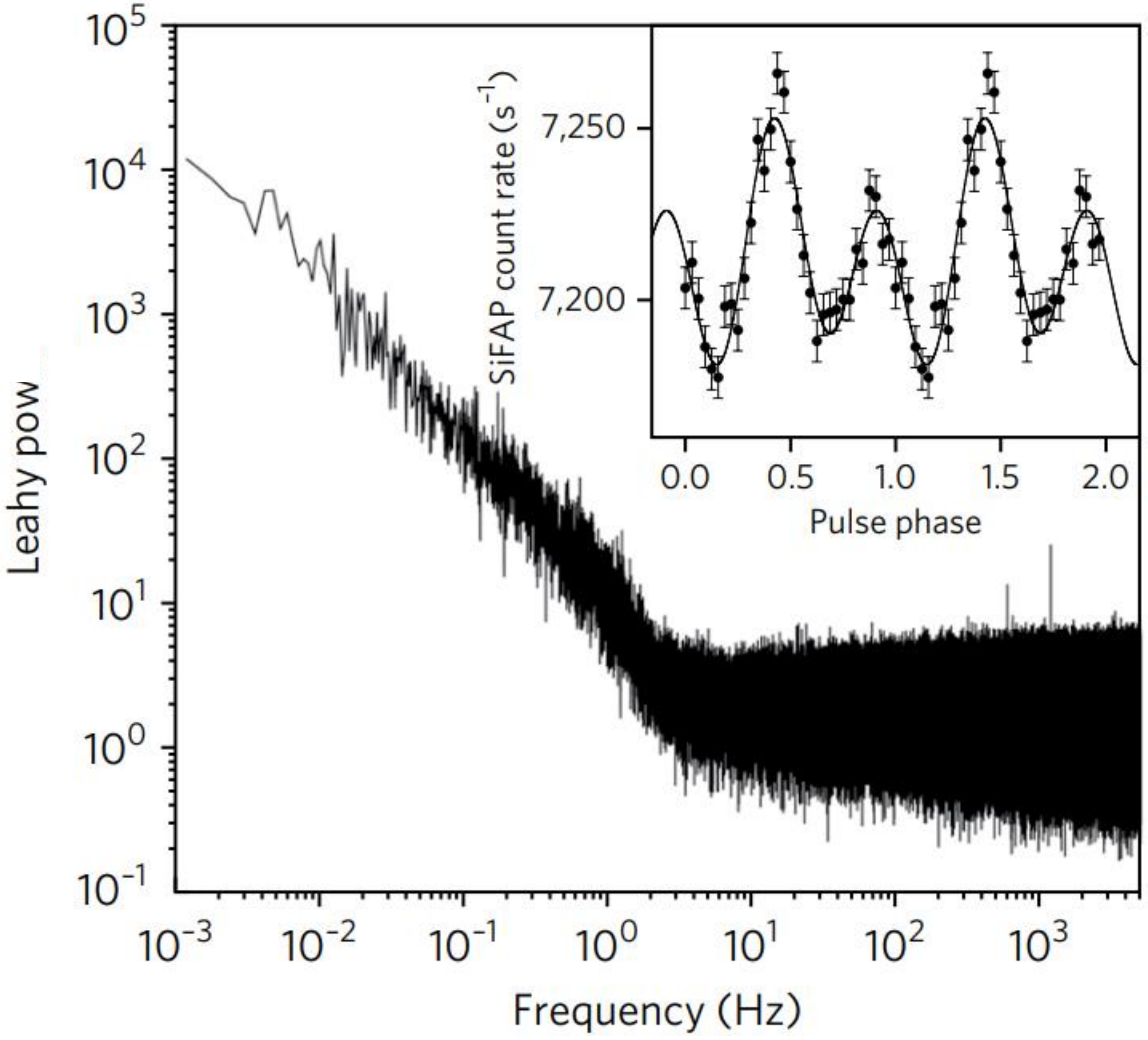


[Meddi+ 2012; Ambrosino+ 2013, 2015; Ghedina+ 2018; Ghedina+ 2022]

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]



PSR J1023+0038

Count rate ~ 10000 c/s (V ≈ 16.5 mag)
Pulse amplitude ~ 1%

L_{pulsed} ~ few x 10^{31} erg/s ≈ 0.03% $L_{SpinDown}$

[The "transitional" comes from their being observed in both accretion-dominated and rotation-dominated regimes, see e.g. Archibald+ 2009, Papitto+ 2013, Stappers+ 2014, Bassa+ 2014]

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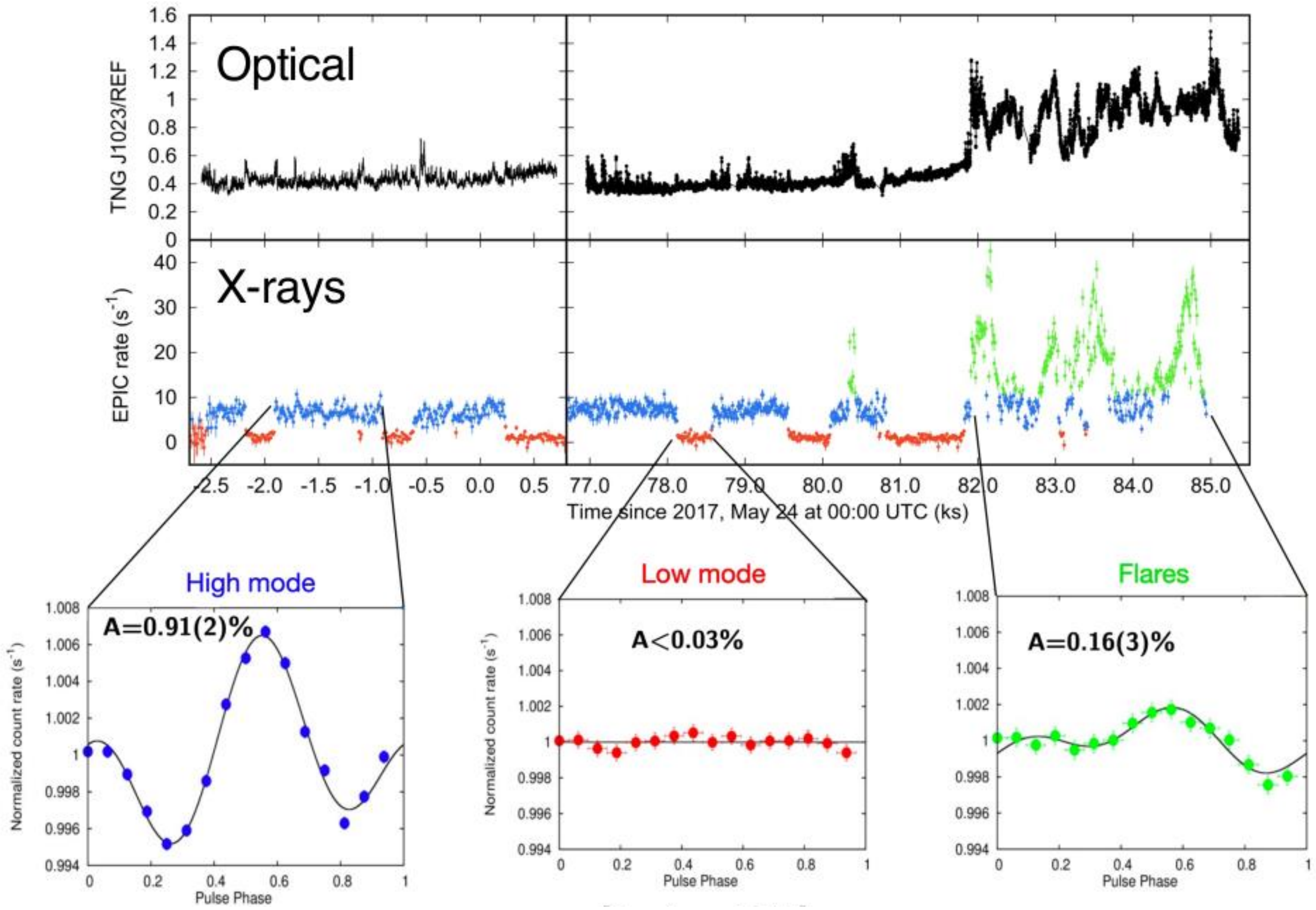
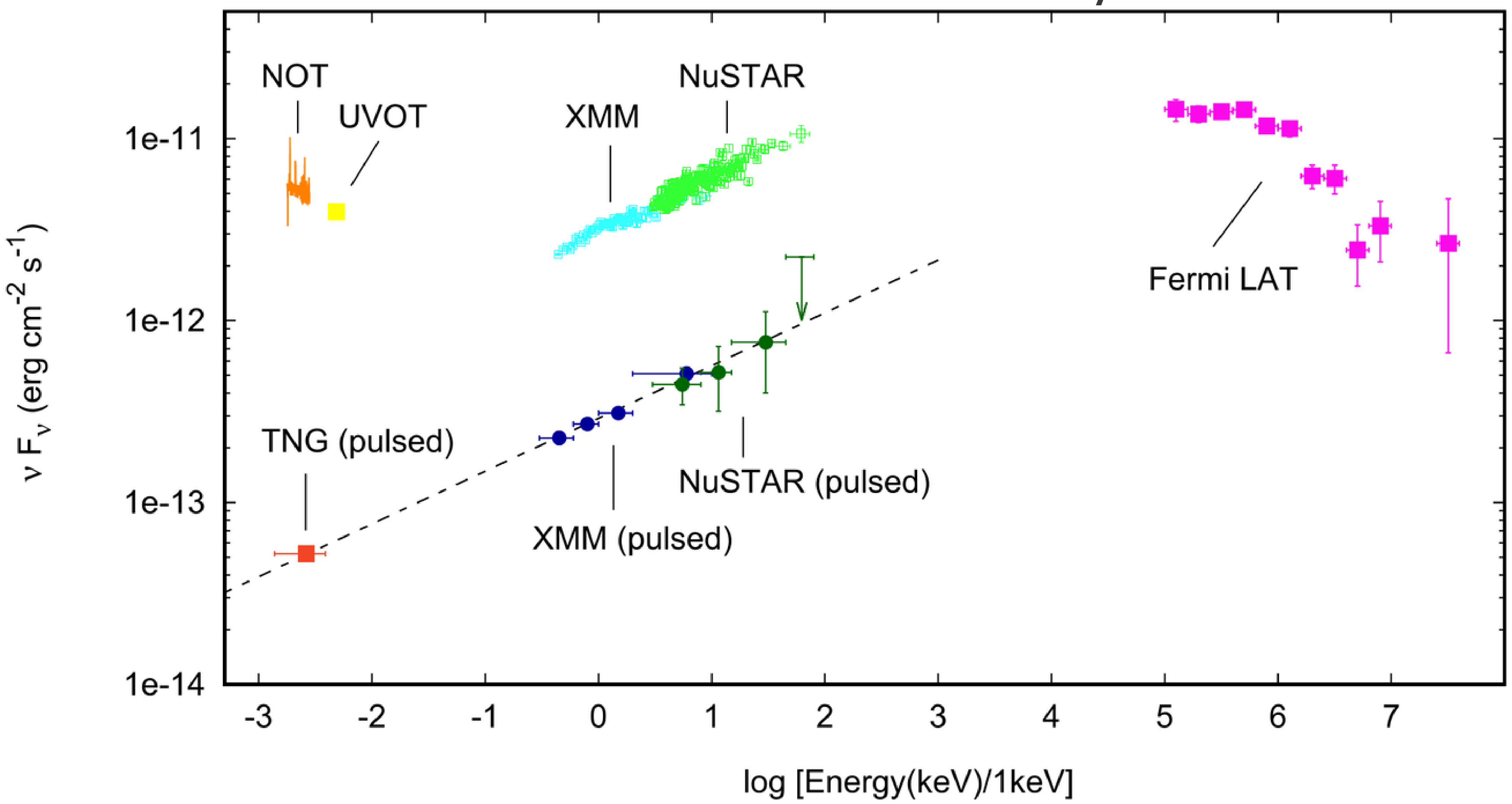


Pulsed flux density

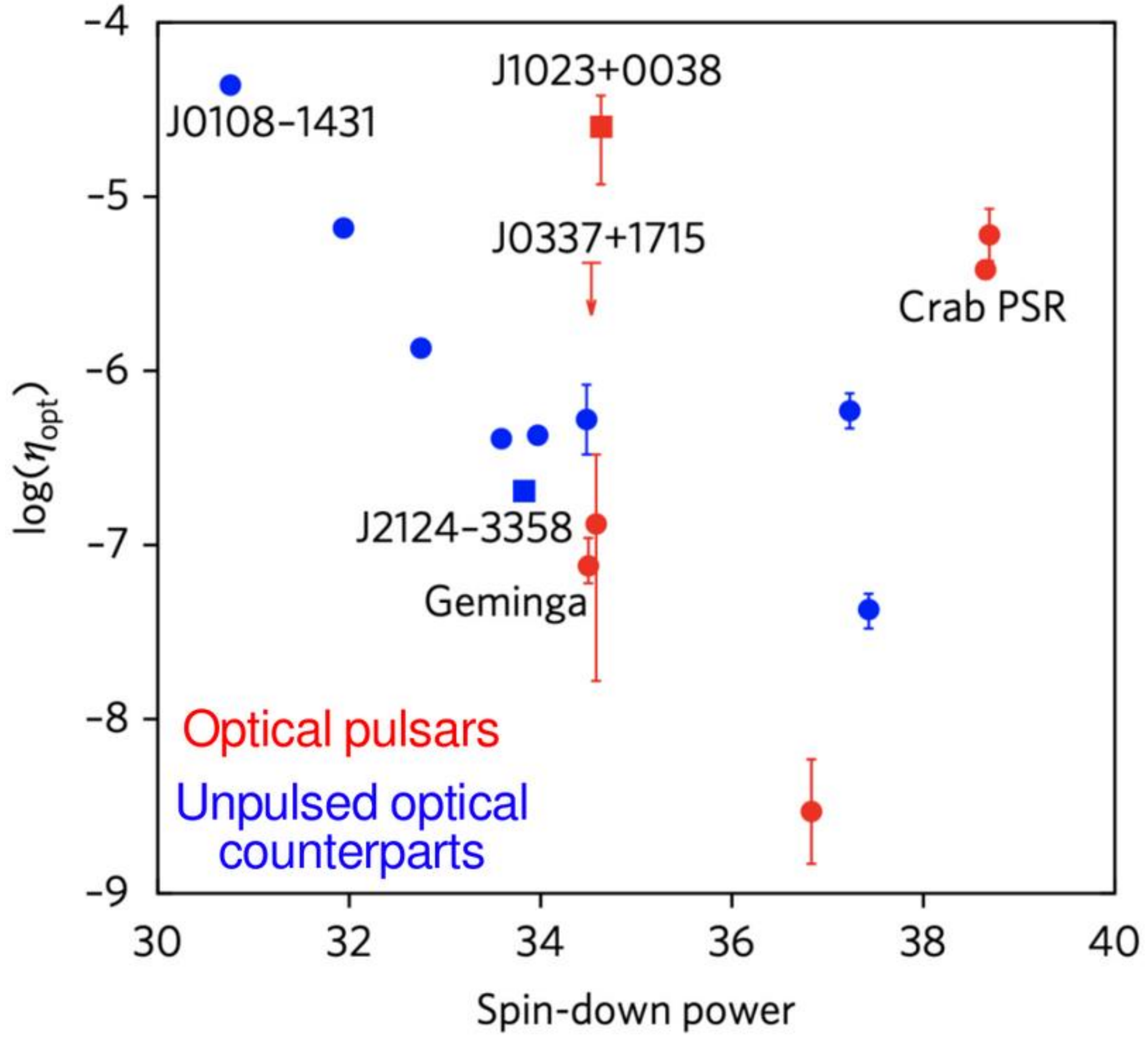


[Papitto+ 2019]

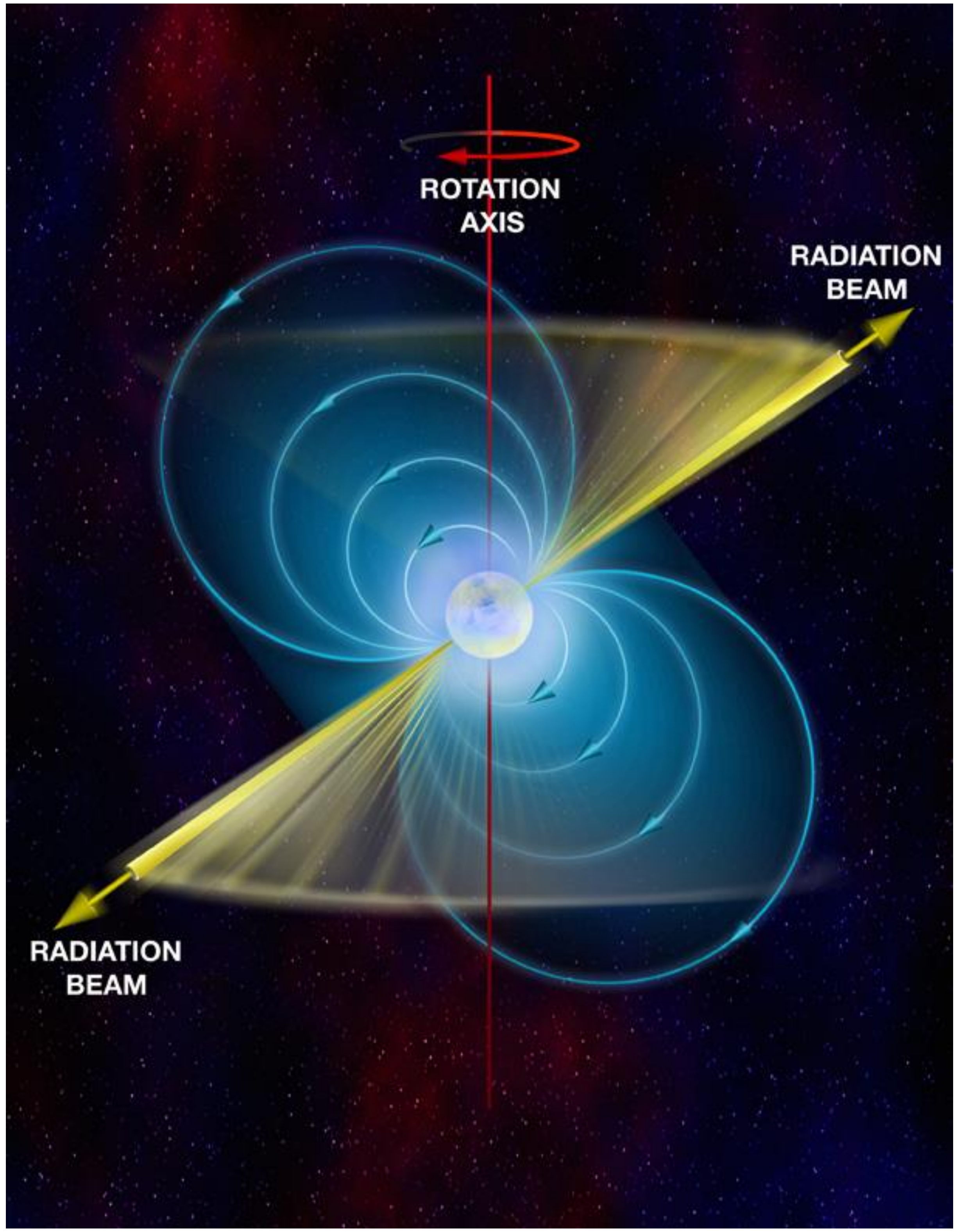
Standard emission mechanisms hardly individually explain the observed optical pulsed luminosity

Rotation power

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



[Ambrosino+ 2017]



Credit: Bill Saxton, NRAO/AUI/NSF

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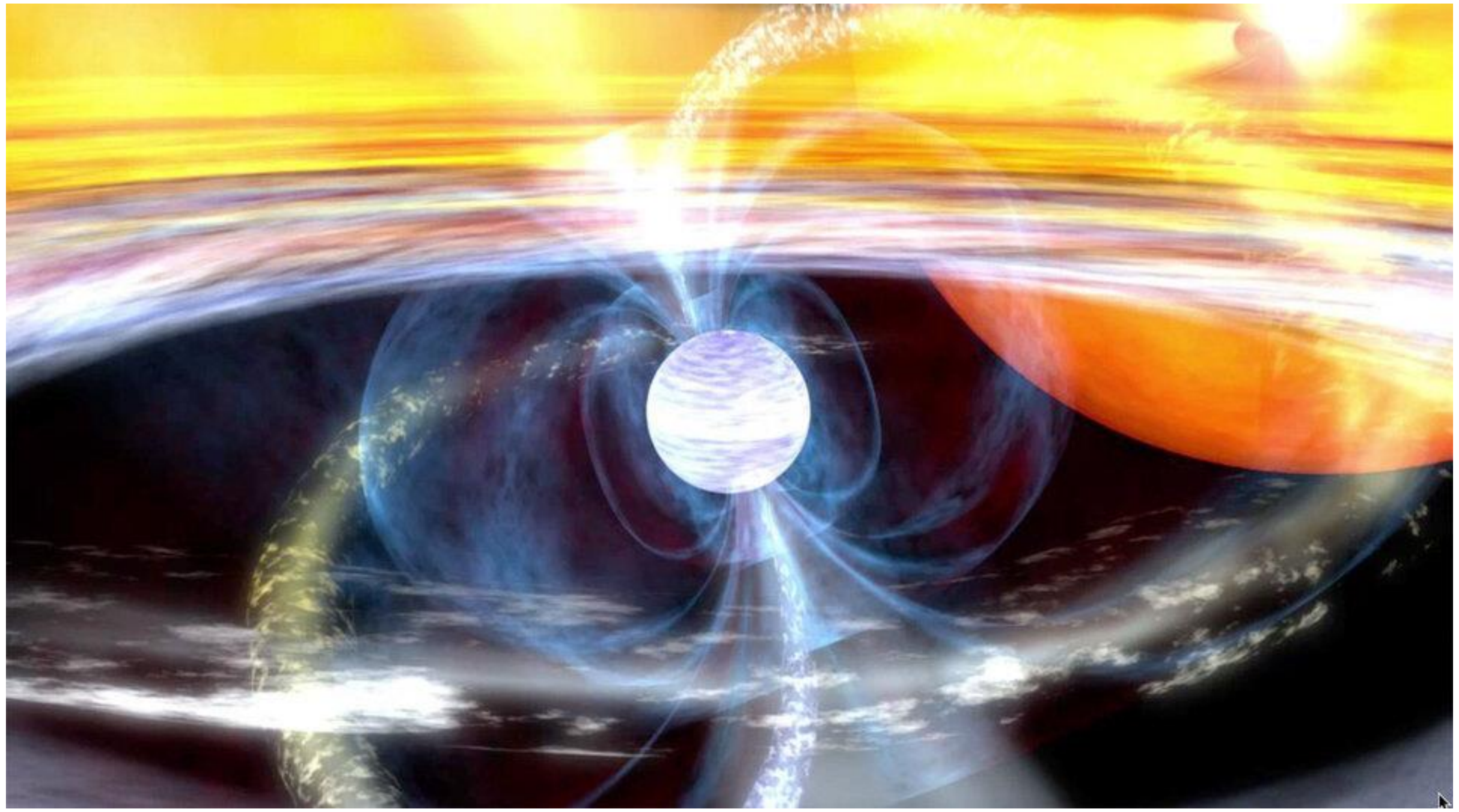


Credit: Dana Berry NASA/GSFC SVS

Accretion power

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

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

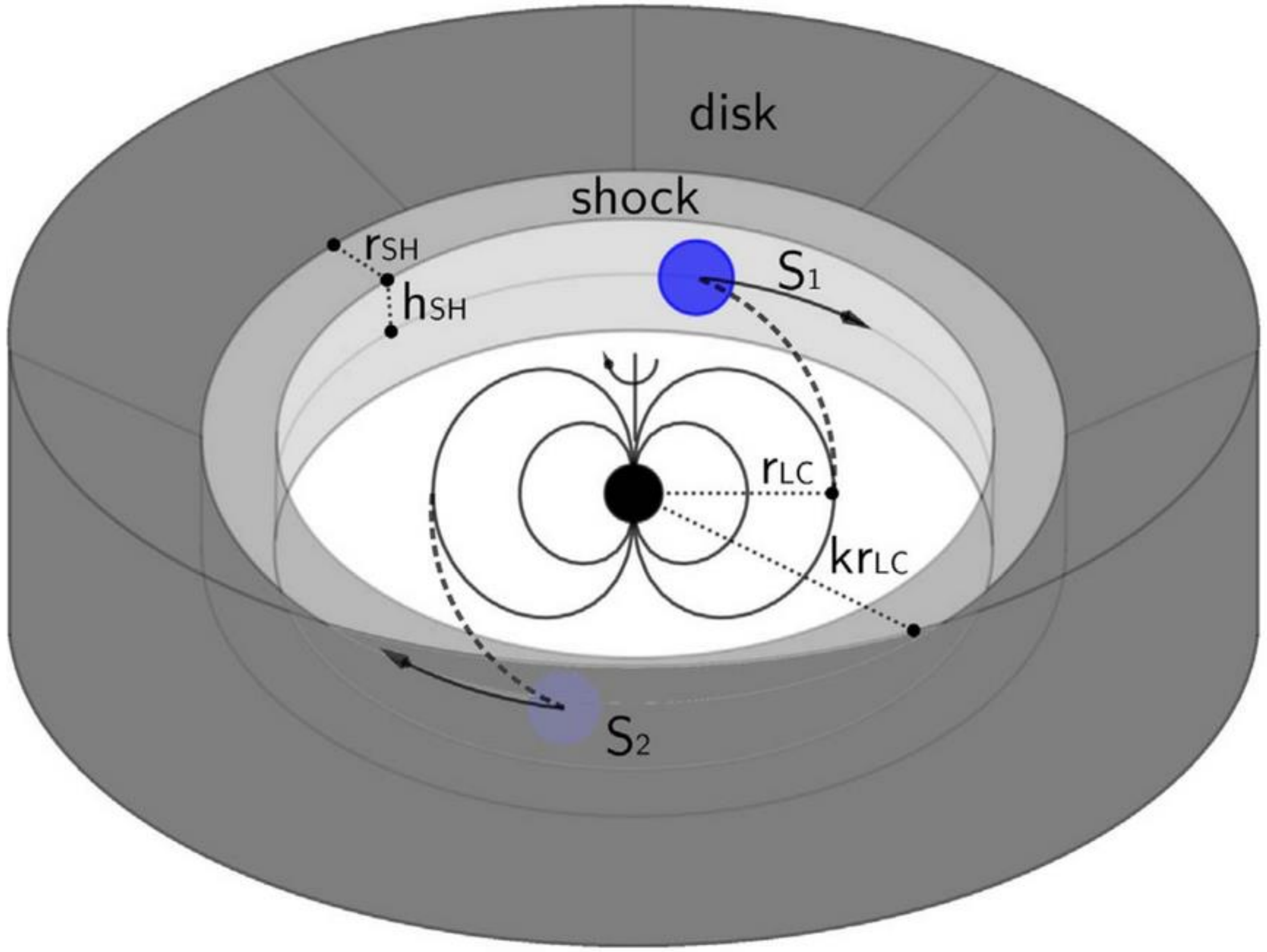
$$L_{\mathrm{pulsed,opt}} \approx 10^{31}\ \mathrm{erg/s}$$

↓

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

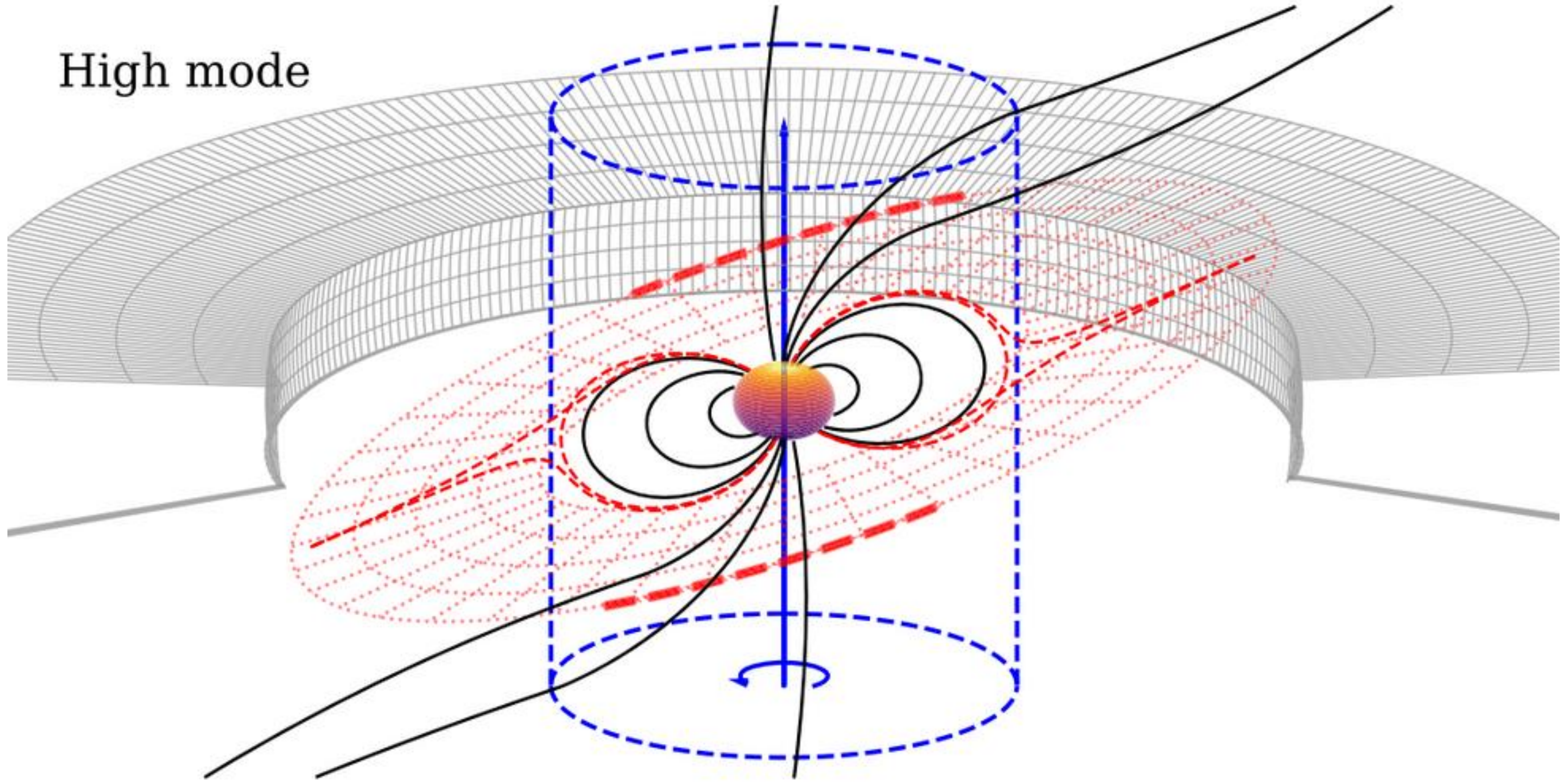
[Ambrosino+ 2017]

Very bright optical pulsations: accretion, spin power, or both?



A pulsar wind heating the accretion disk
Synchrotron radiation from the shock between the striped wind and the accretion disk

[Papitto+ 2019]

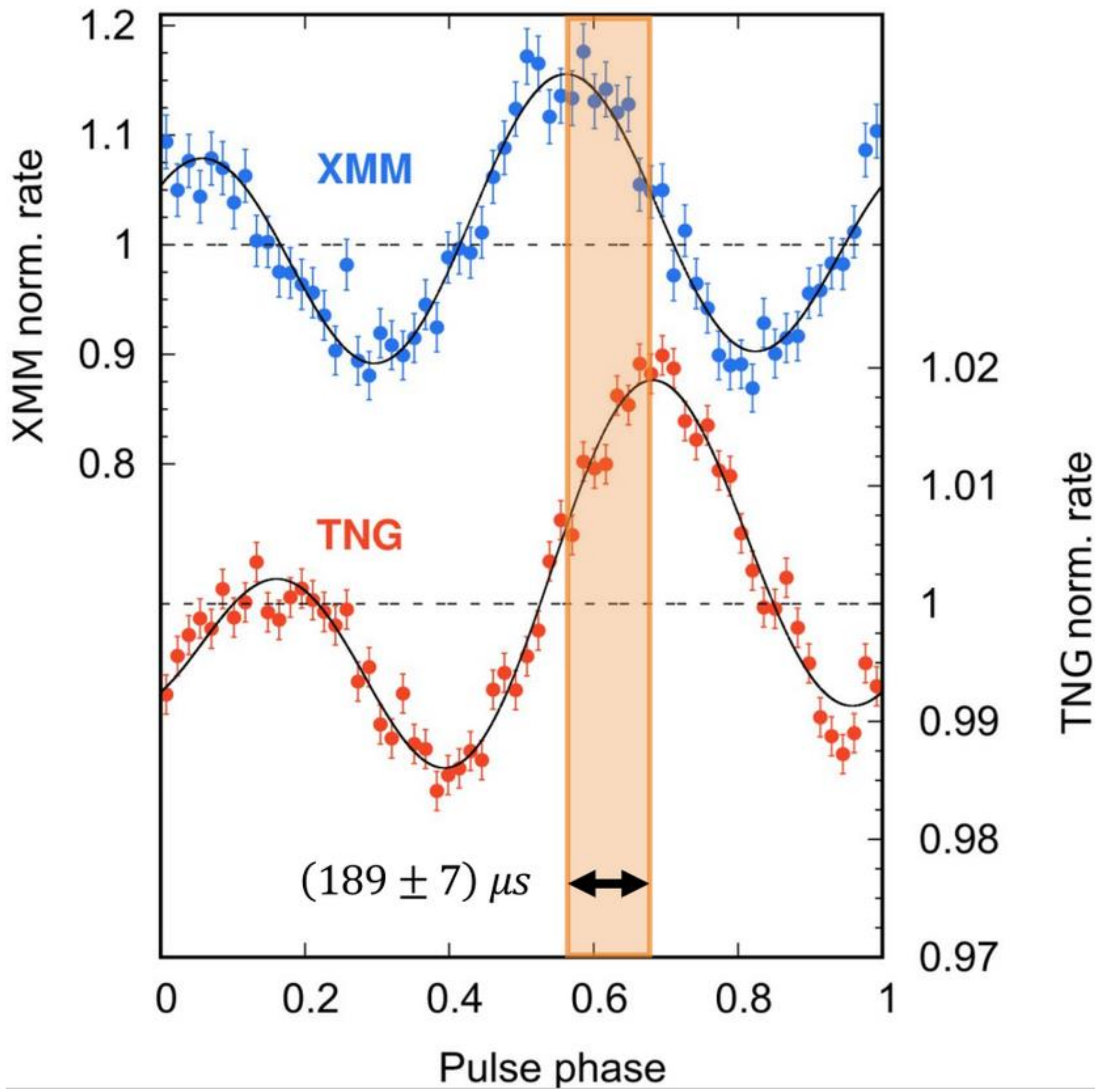


Different synchrotron timescales of optical and X-ray photons:

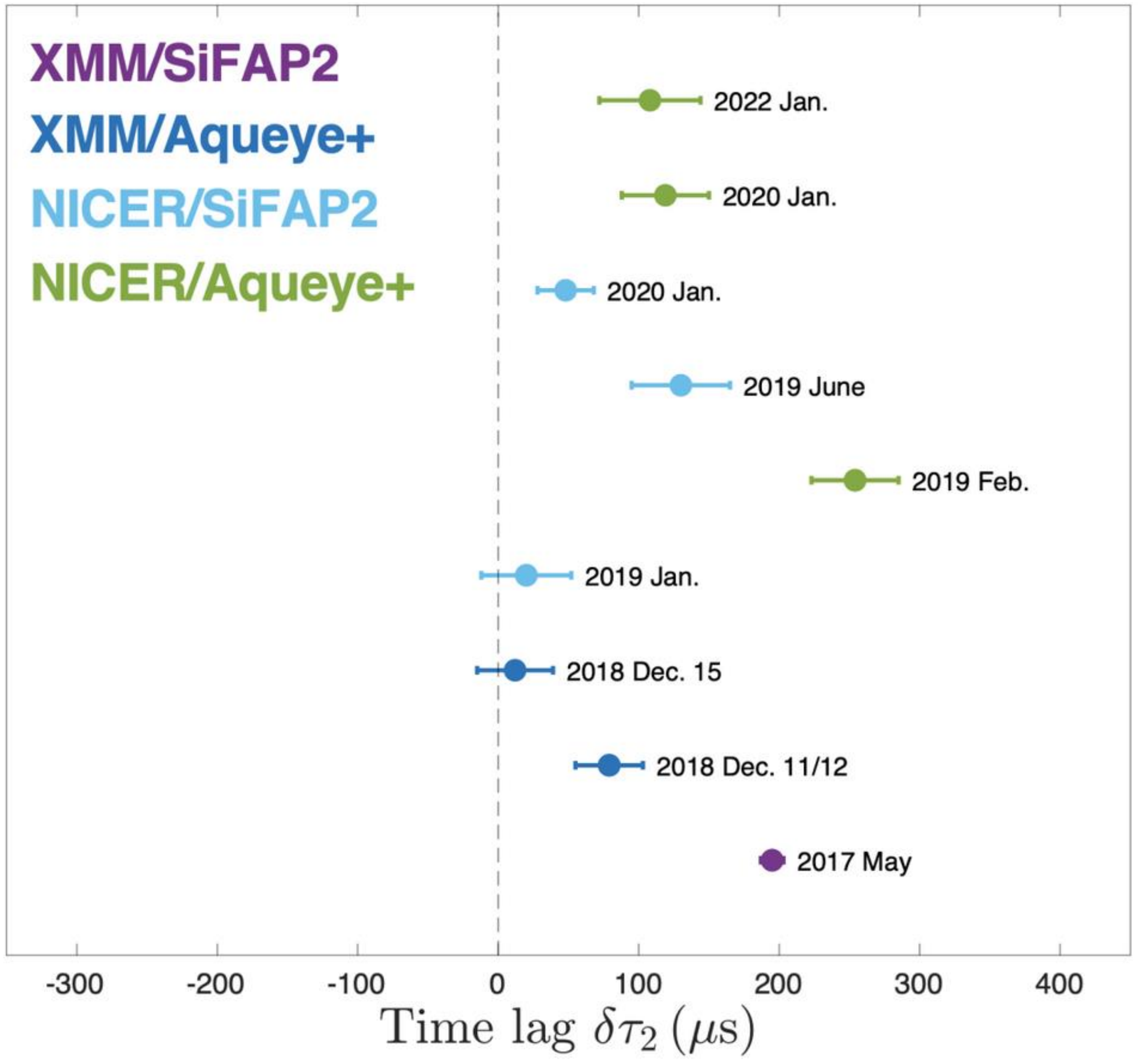
$$t_{sync} \simeq 2.2 \left(\frac{\epsilon}{10\,\mathrm{keV}}\right)^{-1/2} \left(\frac{B_s}{4.5 \times 10^5\,\mathrm{G}}\right)^{-3/2} \mu\mathrm{s}$$

[Veledina+ 2019]

Time lags between optical and X-ray pulsations



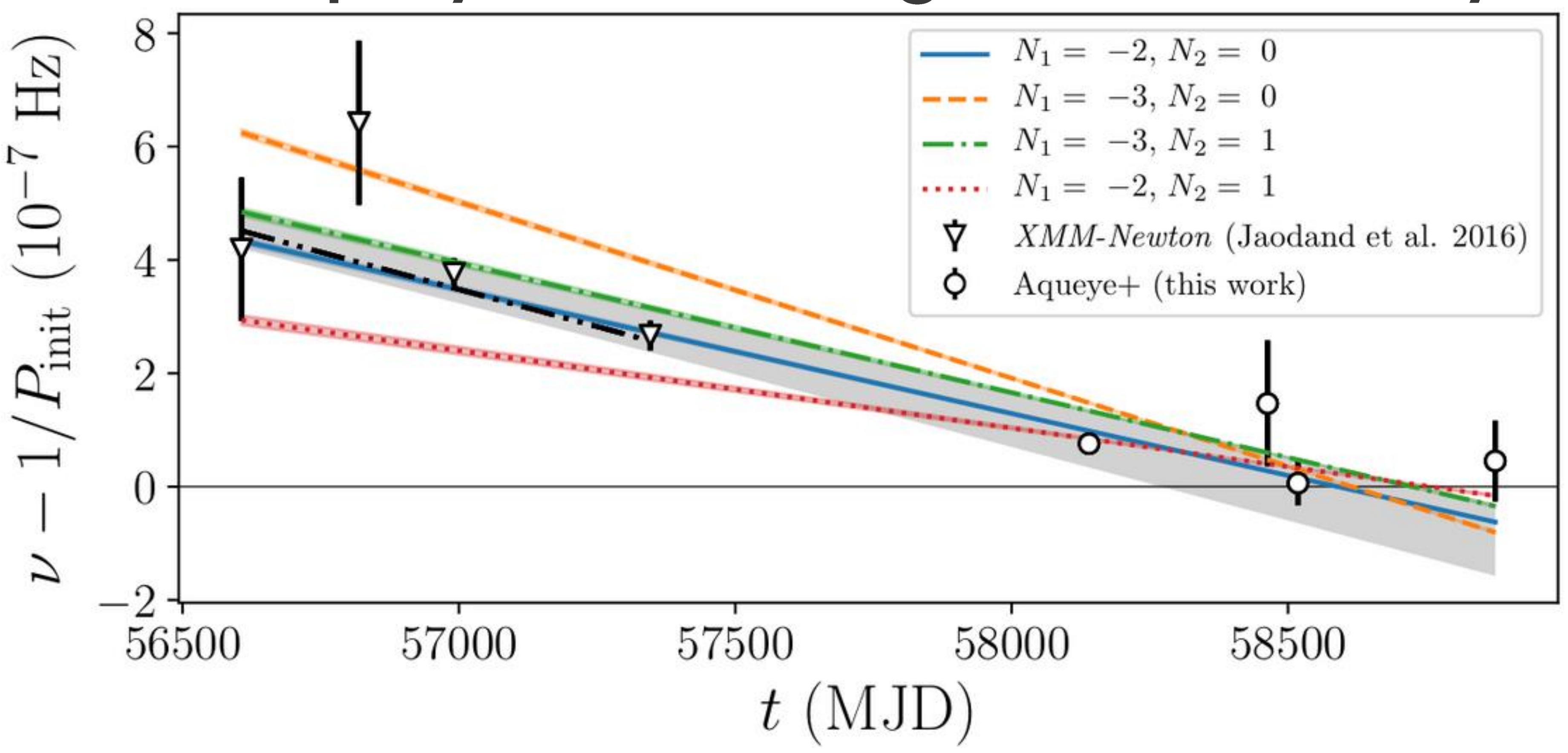
[Papitto+ 2019]



[Illiano+ 2023a]

Millisecond pulsar timing in the optical band

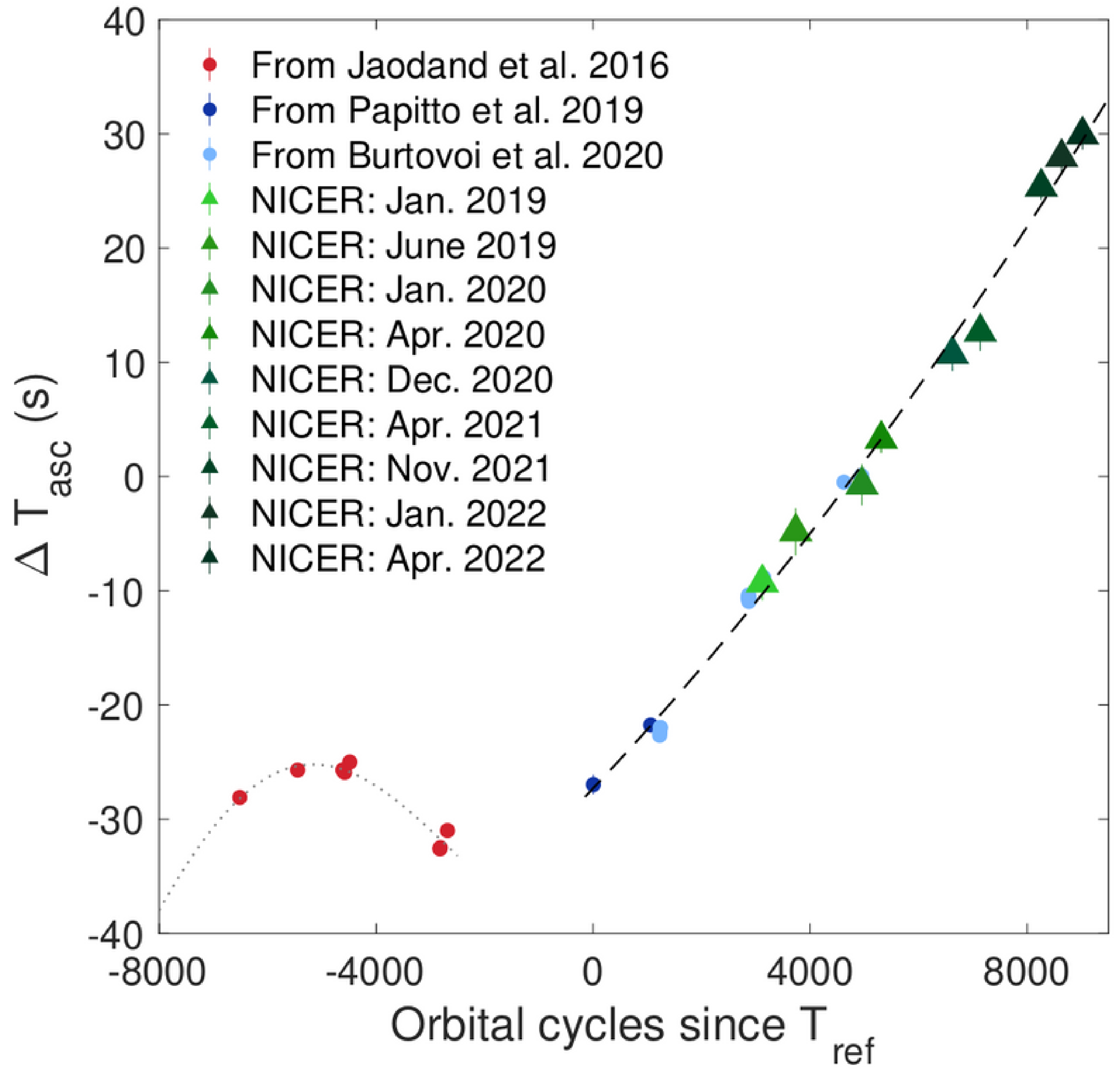
Aqueye+ @ Asiago Observatory



[Burtovoi+ 2020]

$$\dot{\nu}_{\rm DISK} = -2.53(4) \times 10^{-15}\,{\rm Hz/s}$$
$$\dot{\nu}_{\rm DISK}/\dot{\nu}_{\rm RADIO\text{-}PSR} \approx 1.05$$

[see also Jaodand+ 2016, 2021;
Zampieri+ 2019]



Smoother orbital expansion

$$(dP_{\rm orb}/dt)_{\rm app} = +1.6(6) \times 10^{-11}\,{\rm s/s}$$

[Illiano+ 2023a, A&A, 669]

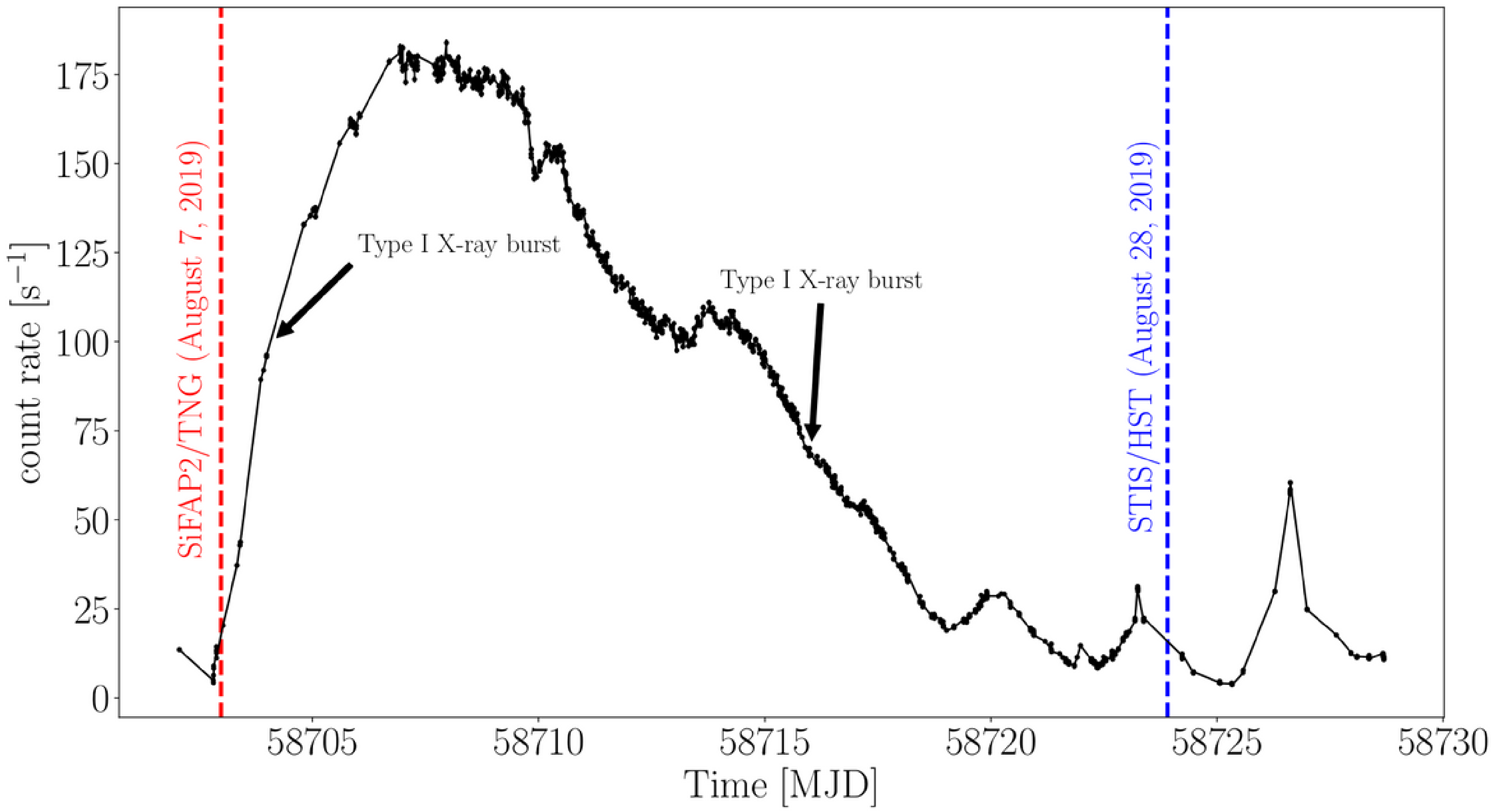
LETTERS
https://doi.org/10.1038/s41550-021-01308-0

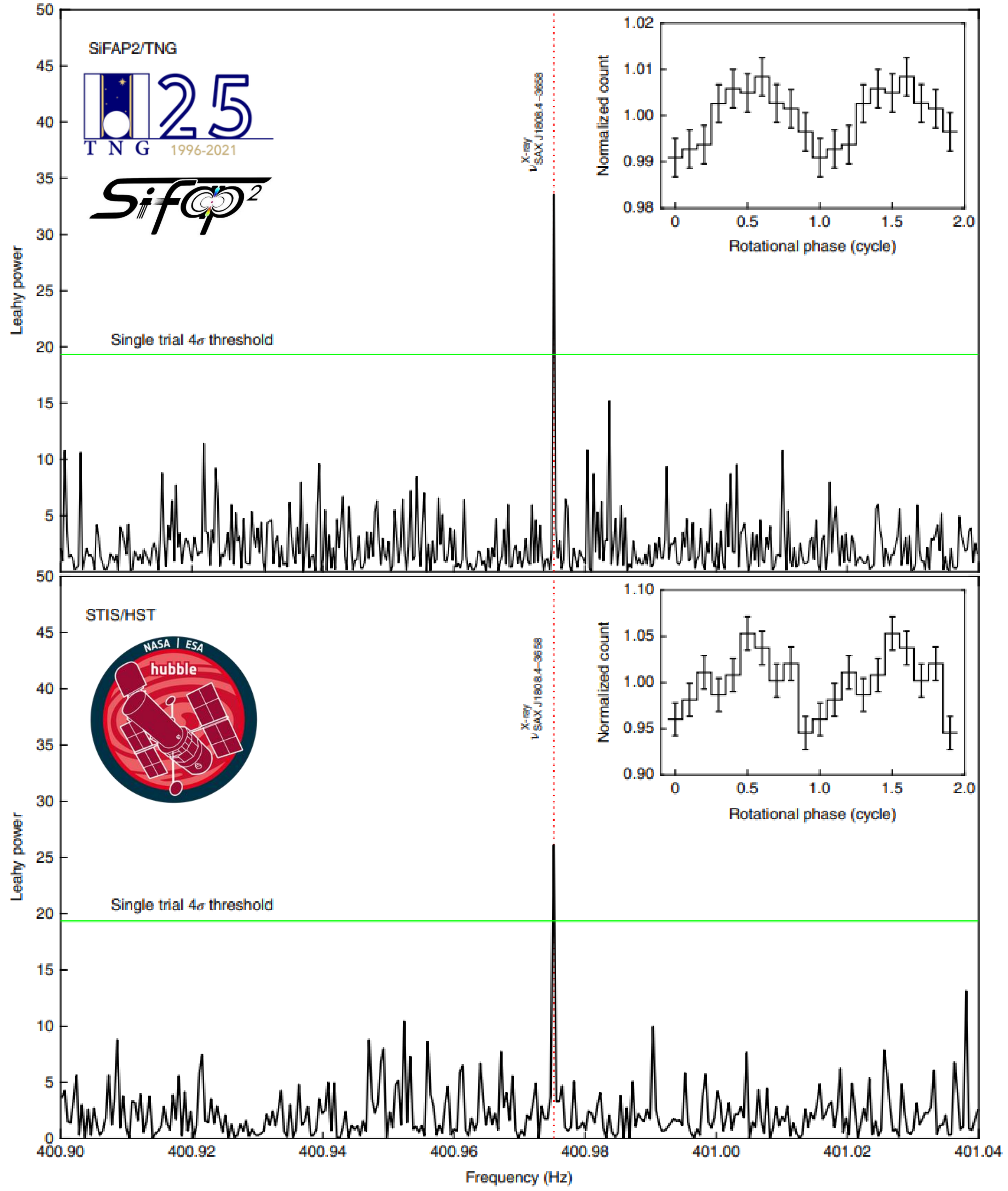
nature astronomy

Check for updates

Optical and ultraviolet pulsed emission from an accreting millisecond pulsar

F. Ambrosino[1,2,3,22] ✉, A. Miraval Zanon[4,5,22] ✉, A. Papitto[1], F. Coti Zelati[5,6,7], S. Campana[5], P. D'Avanzo[5], L. Stella[1], T. Di Salvo[8], L. Burderi[9], P. Casella[1], A. Sanna[9], D. de Martino[10], M. Cadelano[11,12], A. Ghedina[13], F. Leone[14], F. Meddi[3], P. Cretaro[15], M. C. Baglio[5,16], E. Poretti[5,13], R. P. Mignani[17,18], D. F. Torres[6,7,19], G. L. Israel[1], M. Cecconi[13], D. M. Russell[16], M. D. Gonzalez Gomez[13], A. L. Riverol Rodriguez[13], H. Perez Ventura[13], M. Hernandez Diaz[13], J. J. San Juan[13], D. M. Bramich[16] and F. Lewis[20,21]





New outburst of SAX J1808 in August 2022

Multi-wavelength observational campaign

Goals:

- Optical/UV pulse emission mechanism at different mass accretion rates along the outburst
- Coherent X-ray timing and long-term spin and orbital evolution

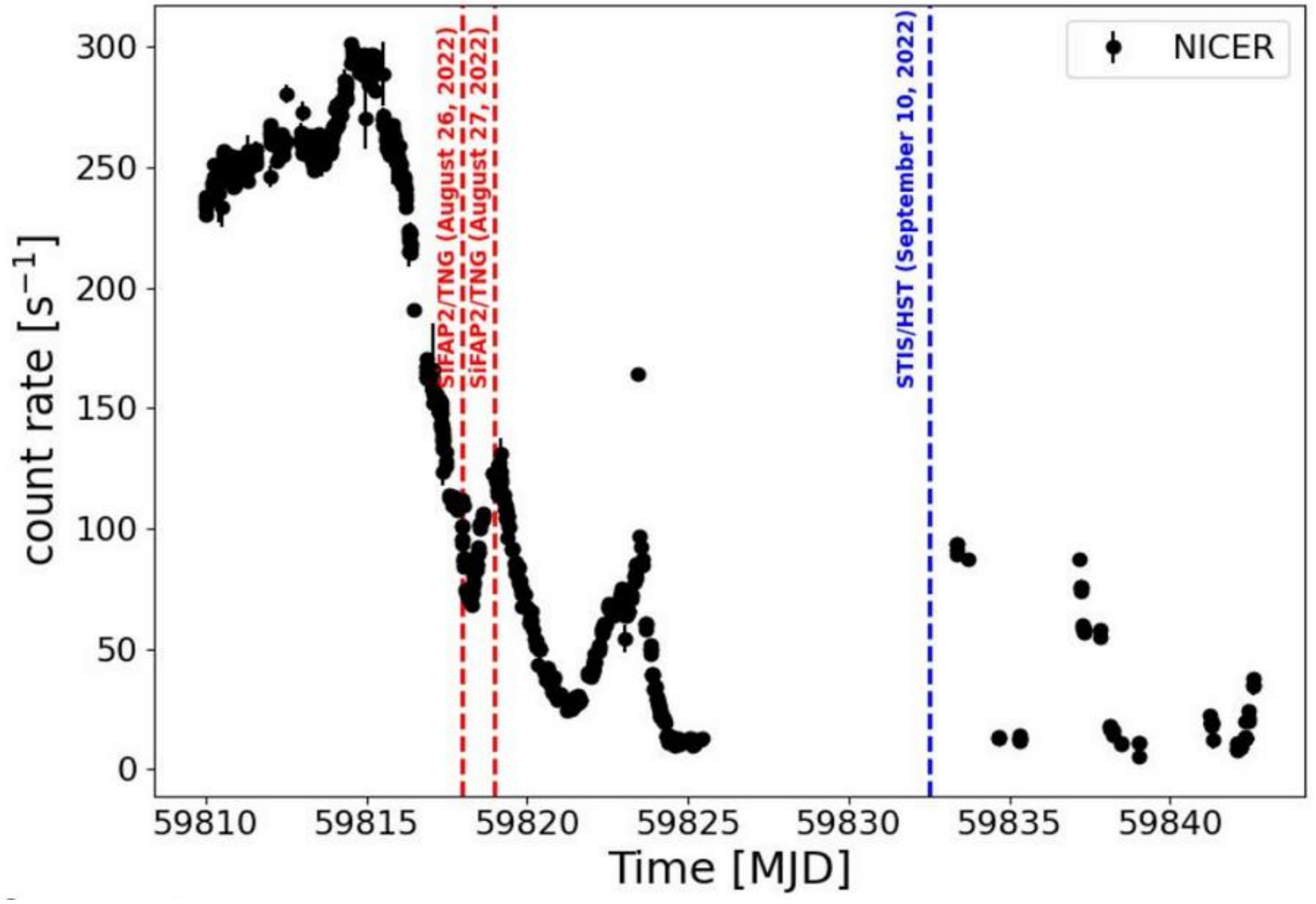
NICER
PI: Papitto
22 Aug.- 31 Oct.
Exp: > 180 ks

NuSTAR
PI: Papitto
22-23 August
Exp: 120 ks

XMM-Newton
PI: Papitto
9-10 September
Exp: 120 ks

TNG/SiFAP2
PI: Miraval Zanon
26-27 August
Exp: 4 hr

HST/STIS
PI: Miraval Zanon
10 September
Exp: 2240 s



[Illiano+ 2023b]
[Miraval Zanon+, subm.]

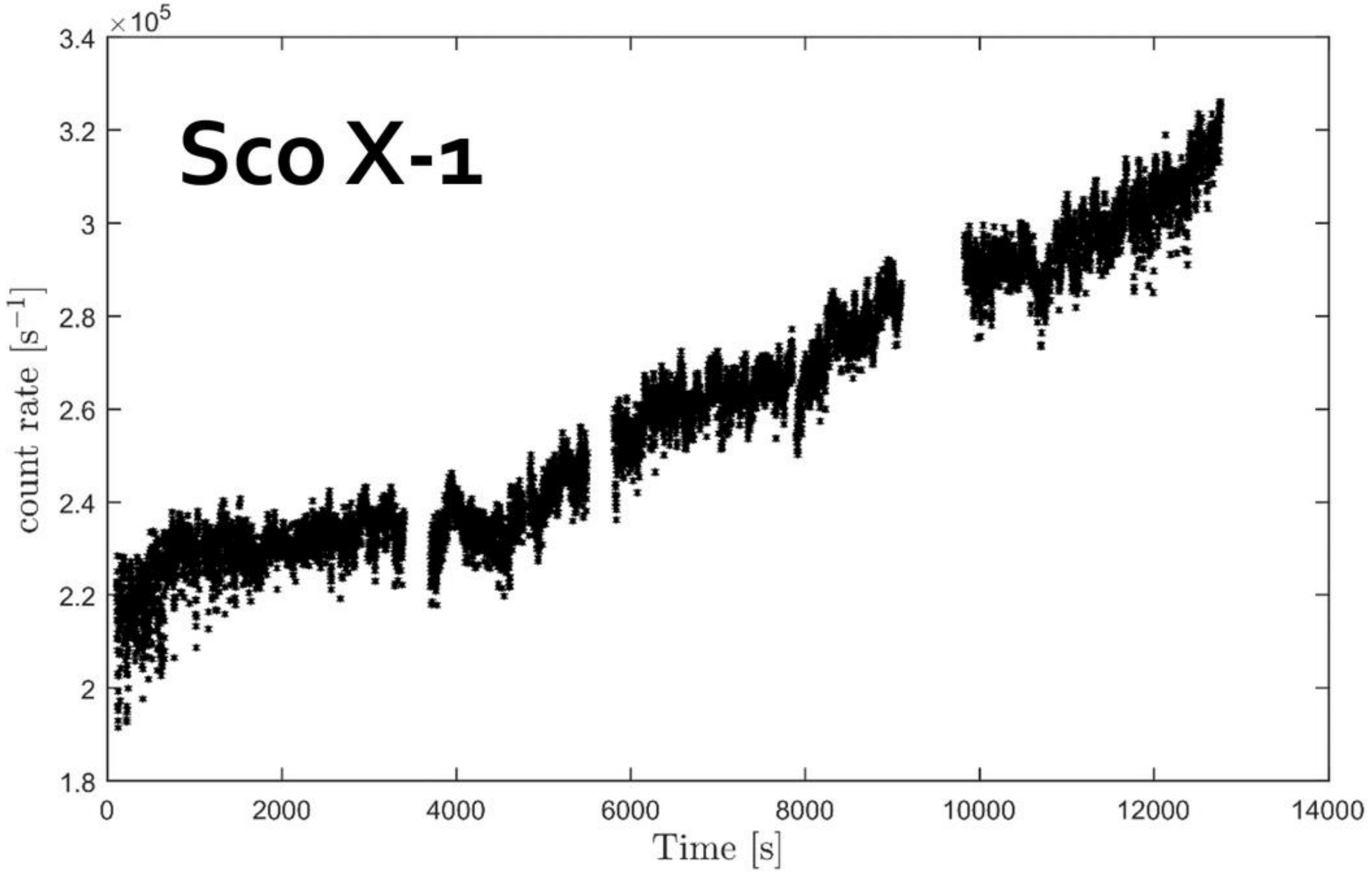
	PSR J1023+0038	SAX J1808.4-3658
X-ray Luminosity (10^{33} erg/s)	5	30-60
Optical Luminosity (10^{33} erg/s)	1	5
Optical rms amplitude	1%	0.5%
Optical/X-ray phase shift	0.1	0.5
UV Luminosity (10^{33} erg/s)	1.5	7.6
UV pulse amplitude	1%	2.6%

Do accretion and rotation power coexist?

Does accretion produce optical pulsations much brighter than expected?

Searching for pulsations from the brightest accreting NSs

- Only 10% of accreting neutron stars show X-ray pulsations
- Pulse sensitivity $\propto 1/\sqrt{N_\gamma}$ (A~0.01-0.05% in a hours from the brightest sources)
- Detection would greatly enhance continuous GW (directed to targeted searches)

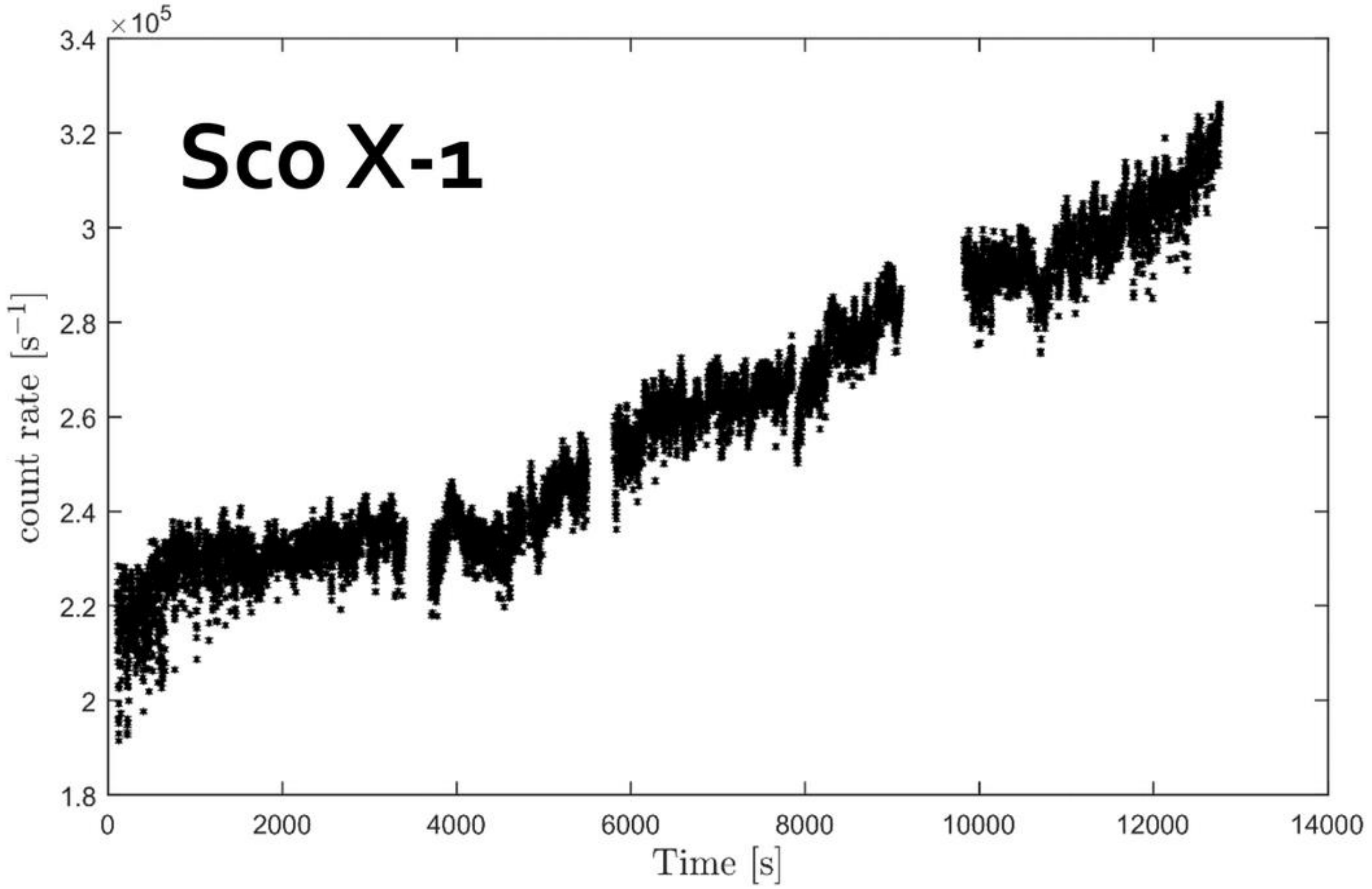


Searching for pulsations from Scorpius X-1

Obs. Date	Instrument	PI	Exp. [s]	MJDREF	N_γ	Ephem.	File size [GB]
2018 July 18 (N1)	SiFAP2	Papitto	3297.8	58317.94516	727115361	DE405	5.4
2018 July 19 (N2)	SiFAP2	Papitto	2397.8	58318.02016	324755950	DE405	2.4
2019 March 3 (N1)	SiFAP2	Motta	3298.3	58543.13266	772856836	DE405	5.8
2019 March 3 (N2)	SiFAP2	Motta	1798.2	58543.17433	435249516	DE405	3.3
2019 March 3 (N3)	SiFAP2	Motta	3298.3	58543.19863	900960703	DE405	6.8
2019 March 3 (N4)	SiFAP2	Motta	3298.3	58543.24516	1006292476	DE405	7.5
2019 April 10	SiFAP2	Papitto	3124.2	58583.07884	429986263	DE405	3.3
2019 June 4 (N1)	SiFAP2	Papitto	3598.0	58638.08058	1502582911	DE405	12.0
2019 June 4 (N2)	SiFAP2	Papitto	3598.0	58638.12468	1323457013	DE405	9.9
2022 June 28 (N1)	SiFAP2	Papitto	8219.6	59758.90069	3974900556	DE405	30.0
2022 June 29 (N2)	SiFAP2	Papitto	7945.6	59759.00178	2759500899	DE405	21.0
2023 April 19 (N1)	SiFAP2	Tempo Tecnico	6840.4	60053.13958	2060187287	DE405	16.0
2023 April 23 (N2)	SiFAP2	Tempo Tecnico	7200.4	60058.13611	741060012	DE405	5.6

← Commensal science!

- Total exposure 2018 July: $T_{\rm obs,2018} = 5695.6\,\rm s \sim 1.6\,hr$
- Total exposure 2019 March: $T_{\rm obs,2019Mar} = 11693.1\,\rm s \sim 3.2\,hr$
- Total exposure 2019 April: $T_{\rm obs,2019Apr} = 3124.2\,\rm s$
- Total exposure 2019 June: $T_{\rm obs,2019June} = 7196\,\rm s \sim 2\,hr$
- Total exposure 2022 June: $T_{\rm obs,2022} = 16165.2\,\rm s \sim 4.5\,hr$
- Total exposure 2023 April: $T_{\rm obs,2023} = 14040.8\,\rm s \sim 3.9\,hr$.



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- Simple searches

$$T_{\rm best} = 298\,{\rm s}\left(\frac{P_{\rm orb}}{1\,{\rm day}}\right)^{2/3}\left(\frac{P_{\rm spin}}{1\,{\rm ms}}\right)^{1/2}\left(\frac{4}{m}\right)^{1/2}\left(\frac{M_2}{0.3M_\odot}\right)^{-2/5}(\sin i)^{-1/2}$$

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- Accelerated searches

$$T_{\rm best}^{\rm acc} = 1948\,{\rm s}\left(\frac{P_{\rm orb}}{1\,{\rm day}}\right)^{7/9}\left(\frac{P_{\rm spin}}{1\,{\rm ms}}\right)^{1/3}\left(\frac{4}{m}\right)^{1/3}\left(\frac{M_2}{0.3M_\odot}\right)^{-4/15}(\sin i)^{-1/3}$$

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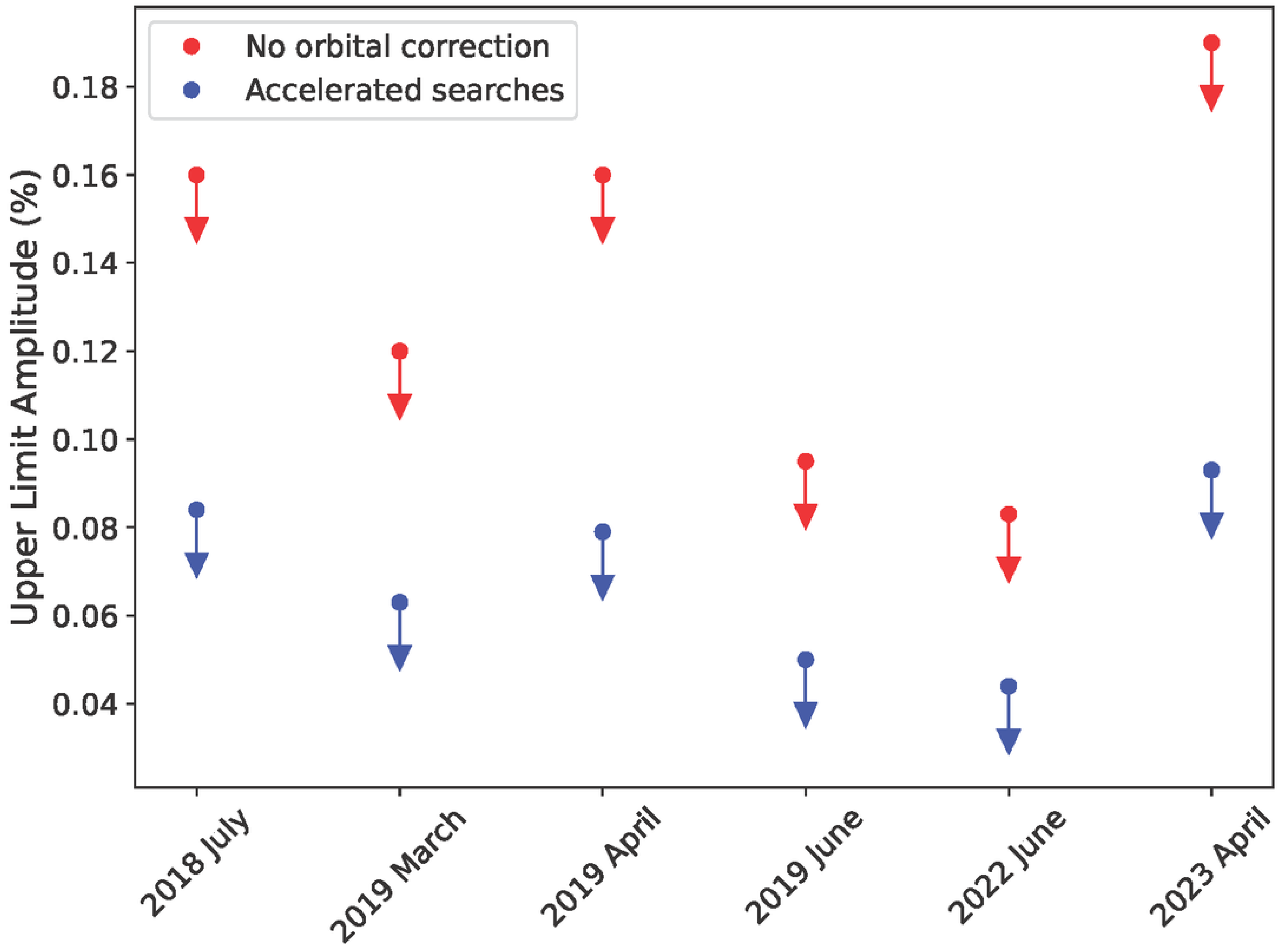
- Simple PS, no orbital correction
- Accelerated searches



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2019 March 3 (N2)	SiFAP2	Motta	1798.2	58543.17433	435249516	DE405	3.3
2019 March 3 (N3)	SiFAP2	Motta	3298.3	58543.19863	900960703	DE405	6.8
2019 March 3 (N4)	SiFAP2	Motta	3298.3	58543.24516	1006292476	DE405	7.5
2019 April 10	SiFAP2	Papitto	3124.2	58583.07884	429986263	DE405	3.3
2019 June 4 (N1)	SiFAP2	Papitto	3598.0	58638.08058	1502582911	DE405	12.0
2019 June 4 (N2)	SiFAP2	Papitto	3598.0	58638.12468	1323457013	DE405	9.9
2022 June 28 (N1)	SiFAP2	Papitto	8219.6	59758.90069	3974900556	DE405	30.0
2022 June 29 (N2)	SiFAP2	Papitto	7945.6	59759.00178	2759500899	DE405	21.0
2023 April 19 (N1)	SiFAP2	Tempo Tecnico	6840.4	60053.13958	2060187287	DE405	16.0
2023 April 23 (N2)	SiFAP2	Tempo Tecnico	7200.4	60058.13611	741060012	DE405	5.6

- Simple PS, no orbital correction
- Accelerated searches
- Blind searches

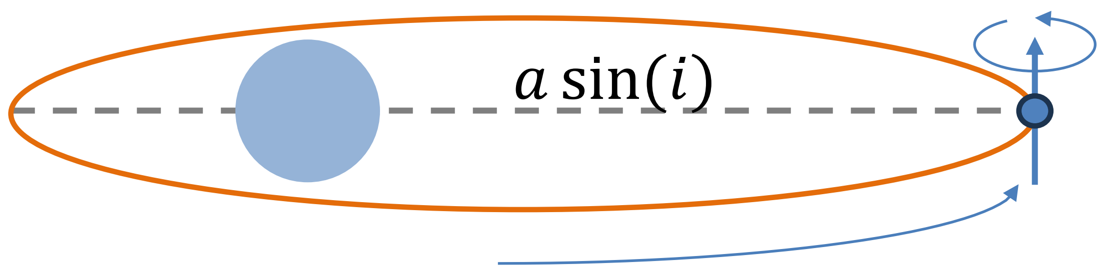
No parameters known *a priori*
(or large uncertainties)

At least 4 parameters (f_{spin} , P_{orb} , $a \sin(i)$, t_{asc})

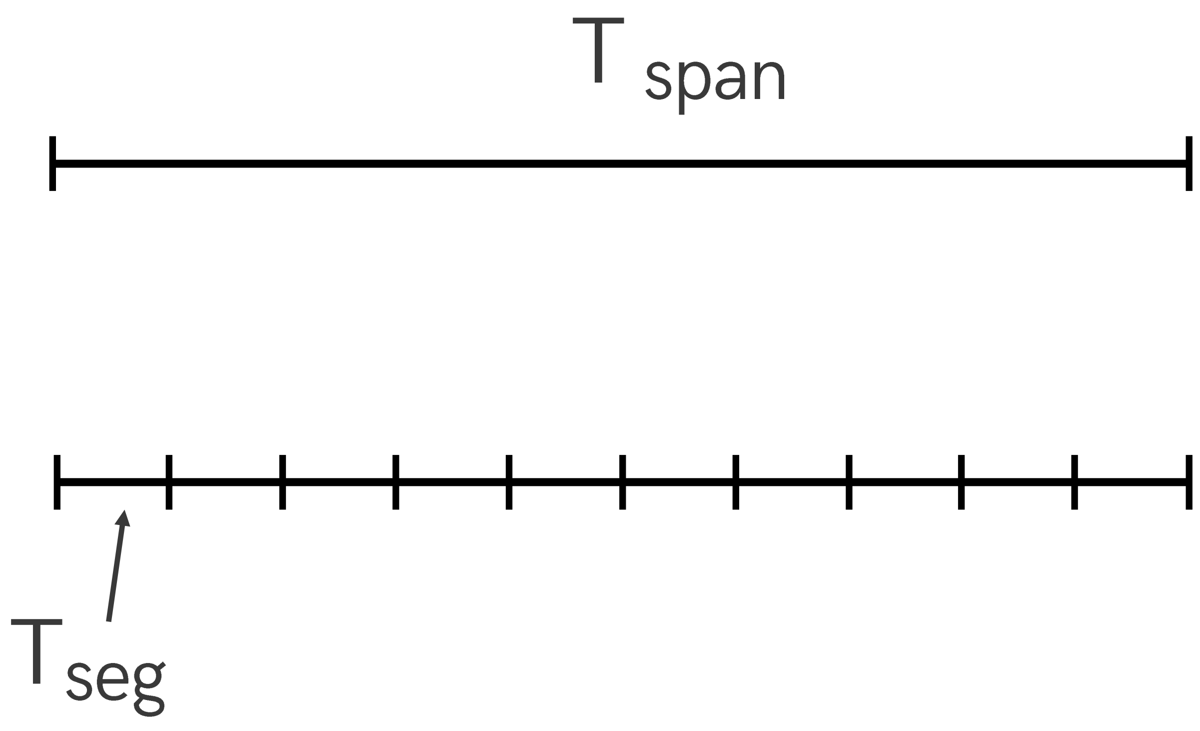
From Wang et al. 2018 (Table 2) [5], we know:

- $P_{orb} = (0.7873132 \pm 0.0000005)$ days $= (18.89552 \pm 0.00001)$ hr $= (68023.86 \pm 0.04)$ s
- inclination of $i = (44 \pm 6)^o$
- $M_1 = 1.4^{+1.4}_{-0.5}\, M_\odot$ (95 per cent)
- $M_2 = 0.7^{+0.8}_{-0.3}\, M_\odot$ (95 per cent)

From Killestein et al. 2023 [3] we have $P_{orb} = (0.7873139 \pm 0.0000007)$ d $= (68023.92 \pm 0.06)$ s.



Semi-coherently searching for pulsations from Sco X-1



- Split T_{span}-long interval in M segments
  - Coherent analyses on each segment
    - Statistics summed incoherently

Already carried out in the X-ray band, but to no avail

[Messenger&Patruno 2015, Patruno+ 2019, Galaudage+ 2022]

Why do it?

$$N_{\mathrm{temp}} \propto T_{\mathrm{coh}}^{5} f_{\mathrm{spin}}^{2} \mathrm{d}^{4}\boldsymbol{\lambda}$$

$$A \propto N_{\mathrm{phot}}^{-1/2} \left(T_{\mathrm{seg}} T_{\mathrm{span}} D\right)^{-1/4}$$

(and always think of your number of trials…)

Semi-coherently searching for pulsations from Sco X-1

Following Messenger [2011], Leaci & Prix [2015], we further split into:

A semi-coherent space

$$\phi(\boldsymbol{\lambda}) = 2\pi f_{\rm spin}\left[t - t_0 - a_* \sin\left(\Omega(t - t_0) + \gamma\right)\right]$$

$$\gamma = \frac{2\pi}{P_{\rm orb}}(t_0 - t_{\rm asc}) = \Omega(t_0 - t_{\rm asc})$$

$$a_* = \frac{a \sin i}{c}$$

A coherent space

$$\phi_j(\boldsymbol{\nu}^{(m)}) \simeq \phi_0^{(m)} + 2\pi \sum_{s=1}^{s*} \frac{\nu_s^{(m)}}{s!}(t_j - t_{\rm mid}^{(m)})^s$$

$$\nu_s = \frac{\mathrm{d}^s \nu}{\mathrm{d}t^s}$$

Generally much smaller!

(All in Matlab ...for now at least)

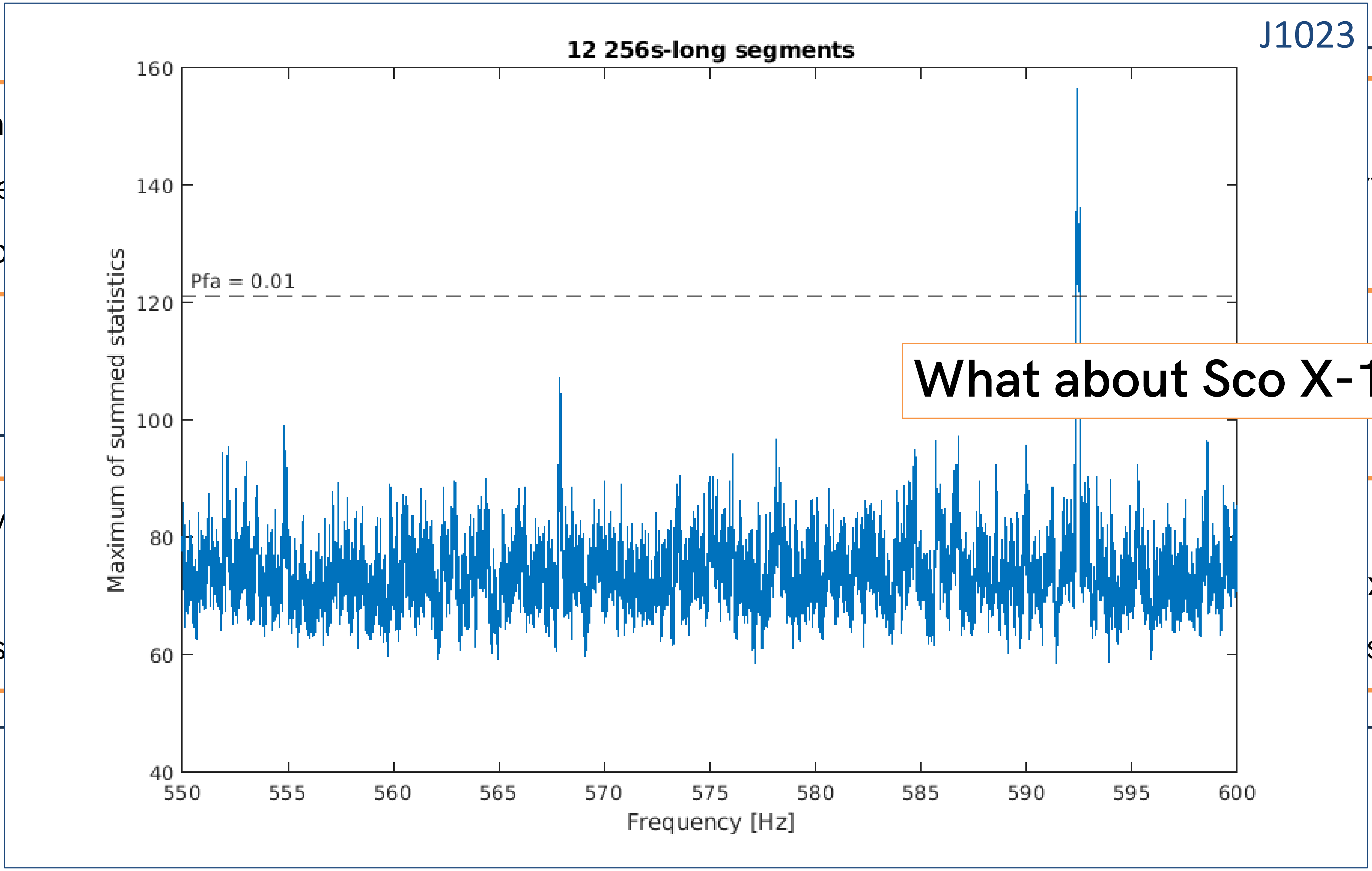
Semi-coherently searching for pulsations

Coherent temp. ba
extrema of possible
and density given b

from t to τ and
ward FFT (no RoI

Take the respectiv
to the previous on
move to the next s

Λ, do it all again
xt frequency and
s combination



What about Sco X-1?

Fast optical photometry for:

- **Optical millisecond pulsars**
  The transitional PSR J1023+0038
  The accreting SAX J1808.4-3658
  Accretion vs Rotation power (or both?)

- **Optical pulsations from bright low-mass X-ray binaries**
  Sco X-1 and other candidate sources for continuous GW searches
  Large collection of archival data (searches underway, one particularly interesting source…)

- **And many more…**
  Magnetars, CCOs, repeating FRBs, etc.