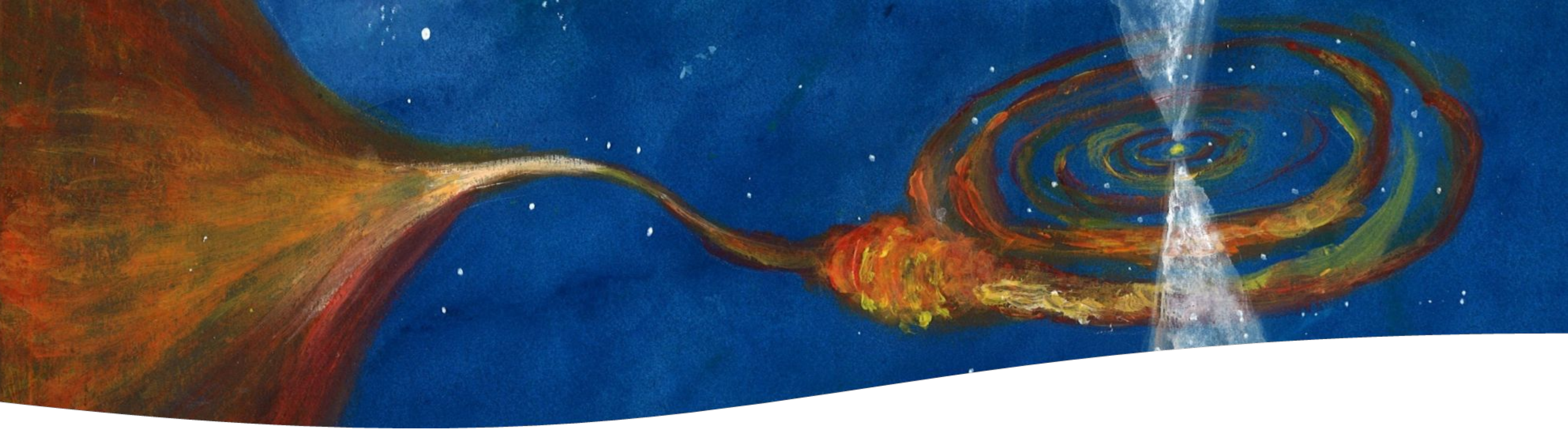


Fast optical variability in the sky: millisecond pulsars and more

Arianna Miraval Zanon

Collaborators: A. Papitto, F. Ambrosino, R. La Placa, G. Illiano, C. Ballocco

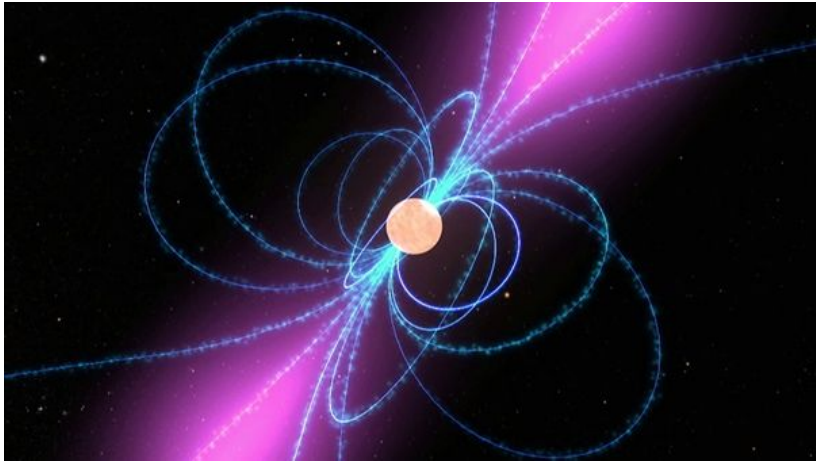
Agenzia Spaziale Italiana

INAF ISTITUTO NAZIONALE DI ASTROFISICA

GEMMA2 Congress - Rome

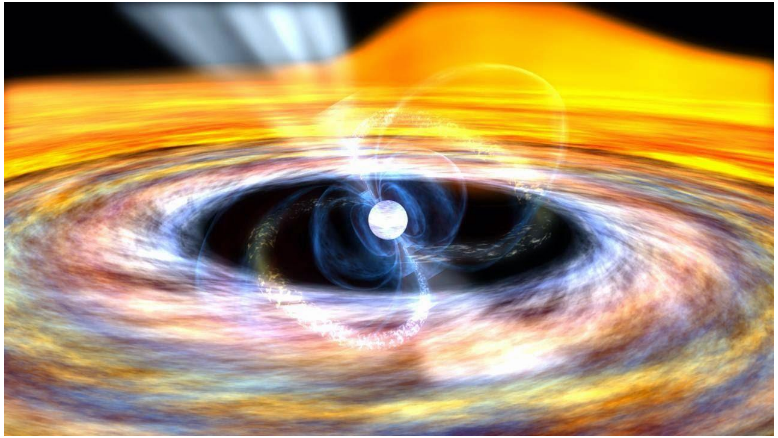
16-19/09/2024

Rotation and accretion powered pulsars



Rotation-powered (radio) pulsars
Rotation of the electromagnetic field
→ particle acceleration
→ radio/gamma-ray pulses

Accretion-powered (X-ray) pulsars
Accretion of matter lost by a companion star channeled by the NS magnetic field
→ X-ray pulses



NASA/Goddard Space Flight Center/Dana Berry

Millisecond (radio) pulsars: the recycling scenario

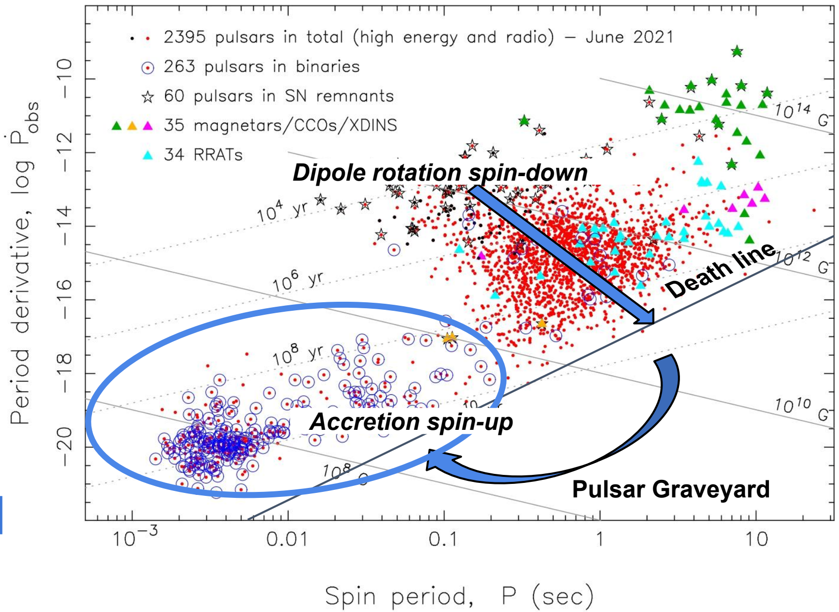
Letter

A millisecond pulsar

D. C. Backer, Shrinivas R. Kulkarni, Carl Heiles, M. M. Davis & W. M. Goss

Nature **300**, 615–618 (16 December 1982)
doi:10.1038/300615a0
Download Citation

Received: 22 November 1982
Accepted: 25 November 1982
Published: 16 December 1982

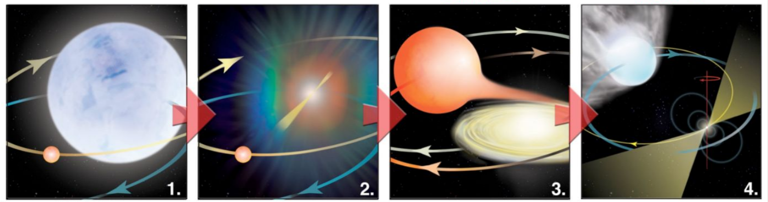


[Tauris & van den Heuvel, 2022]

- Low magnetic fields (~ 10^8 -10^9 G)
- Often in **globular clusters → very old objects**
- Often in **binary systems**

Recycled low-mass X-ray binaries

[Bisnovatyi-Kogan & Komberg 1974, Backer+1982, Alpar+1982, Radhakrishnan+ 1982, Wijnands & van der Klis 1998]

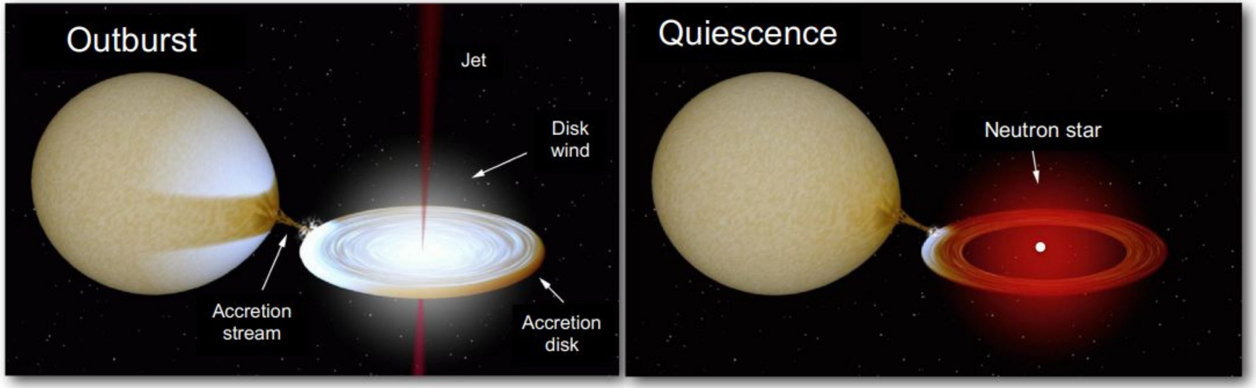


Accreting millisecond X-ray pulsars

- Transient LMXBs showing coherent ms X-ray pulsations
- Alternate cycles of outburst and quiescence
  - **outburst** –> dominated by accretion disc
  - **quiescence** –> thermal emission from the companion star

Main features:

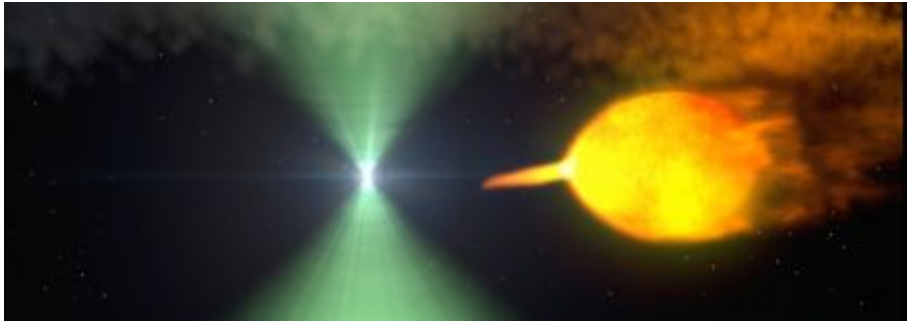
- ➢ companion star mass $M < 1M_\odot$;
- ➢ orbital periods $P_b < 1$ day;
- ➢ mass accretion spins-up the NS to ms periods;
- ➢ rare systems (~ 24 discovered) [Patruno & Watts 2021; Di Salvo & Sanna 2022]

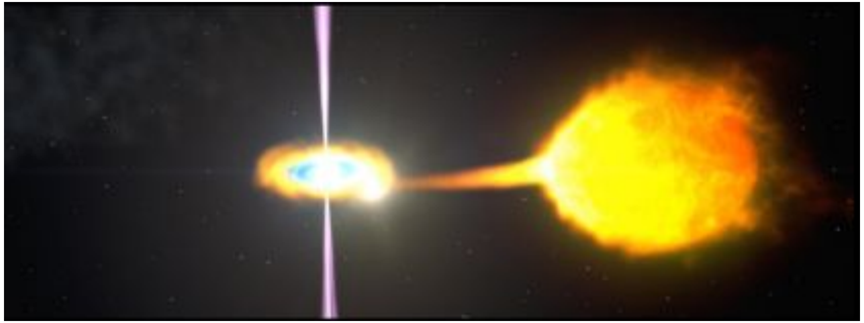


[Credit: R. Hynes]

The missing link: transitional millisecond pulsars

Rotation-powered (radio) pulsars





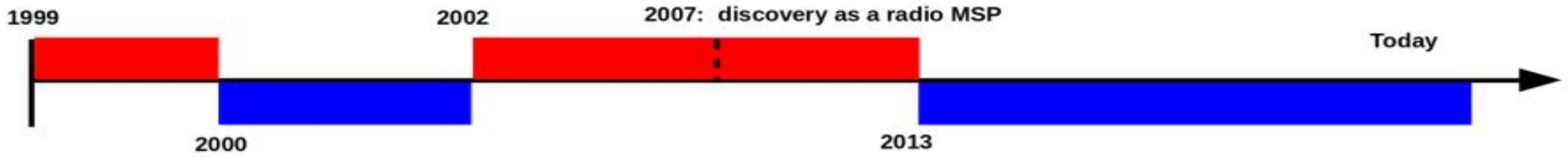
Accretion-powered (X-ray) pulsars

[Archibald+ 2009; Papitto+ 2013; Bassa+ 2014]

3 confirmed transitional millisecond pulsars

[**Archibald+ 2009**, Bogdanov+ 2011, 2015, 2016; Coti Zelati+ 2014,2018; Stappers+ 2014; Takata+ 2014; Campana+ 2016, 2019; Papitto+ 2015, 2018, 2019; Ambrosino, Papitto+ 2017; Shahbaz+ 2015, 2018, 2019, 2022; Kennedy+ 2018; Jaodand+ 2016, 2021; Deller+ 2012, 2015; Tendulkar+ 2014; Hakala+ 2018; Patruno+ 2014; Baglio+ 2019; Burtovoi+ 2020; Miraval Zanon+ 2022]

PSR J1023+0038



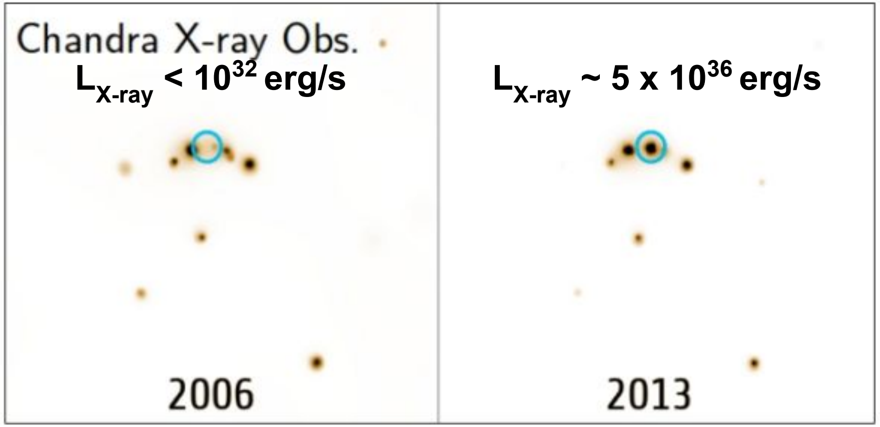
XSS J12270-4859

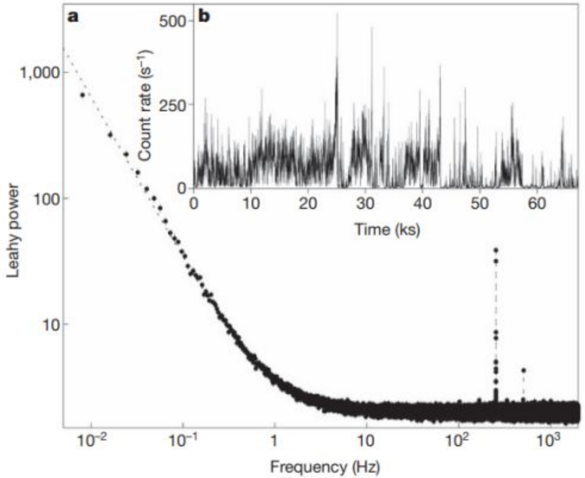
[**Bassa+ 2014**, de Martino+ 2010, 2012, 2013, 2014, 2015, 2020; Baglio+ 2016; Deller+ 2013; Roy+ 2015; Johnson+ 2015; Papitto+ 2014, 2015; Bogdanov+ 2015; Miraval Zanon+ 2020]

IGR J18245-2452

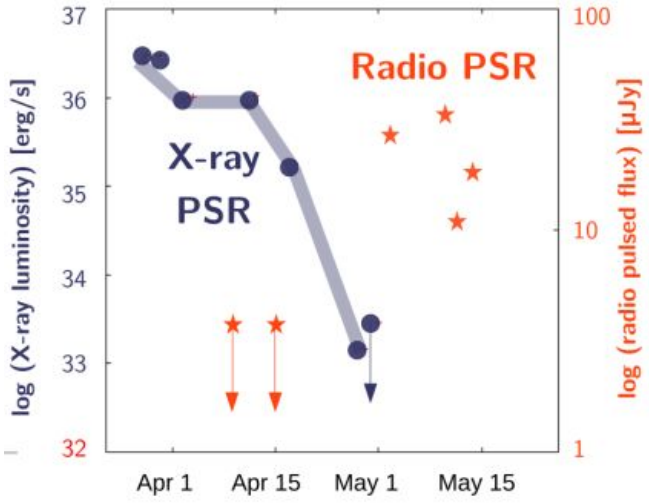
[**Papitto+ 2013**, Ferrigno+ 2014; Linares+ 2014; De Falco+ 2017]

IGR J18245-2452 in the globular cluster M28





Weak radio pulsar signal (~10-50 microJy) detected less than two weeks after the X-ray pulsar detection



[Papitto+ 2013, Nature]

The three states of transitional millisecond pulsars

Sub-luminous disk state
(PSR J1023+0038 & XSS J12270-4859)

Sub-luminous accretion (~10^{34} erg/s)
Brighter gamma-ray emission
X-ray/UV/optical pulsations
No visible radio pulsar

Accretion state
(IGR J18245-2452)

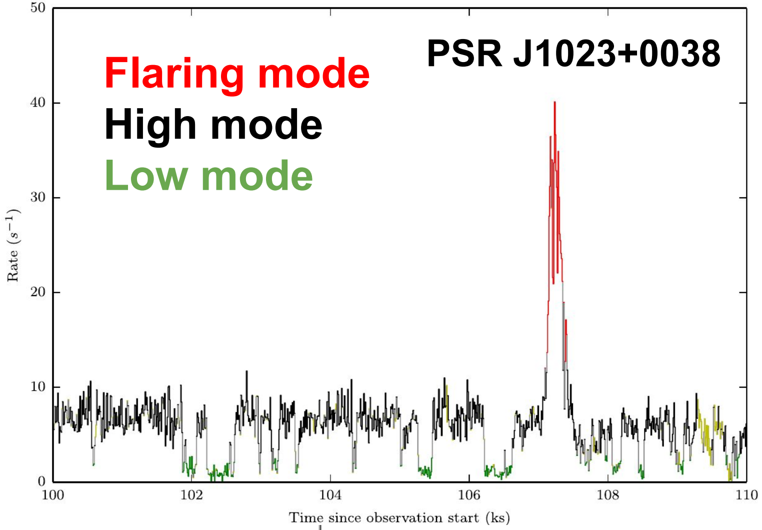
Bright X-ray outburst (~10^{36} erg/s)
X-ray pulsations
No visible radio pulsar

[Papitto+ 2013; Ferrigno+ 2014; Linares+ 2014; See review by Papitto & de Martino 2022]

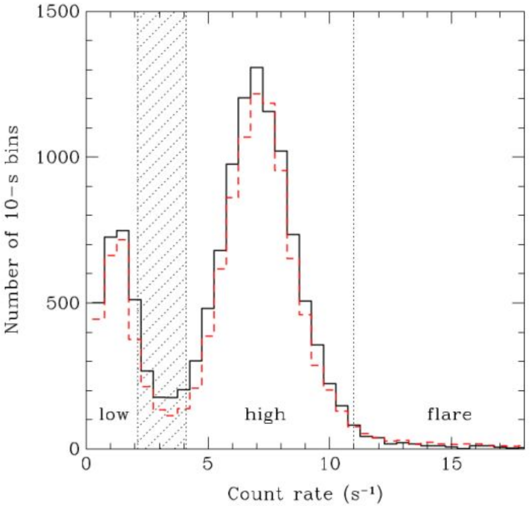
Radio pulsar state (redbacks)

Faint in X-rays (~10^{32} erg/s)
Radio/gamma-ray pulsations
Radio eclipses

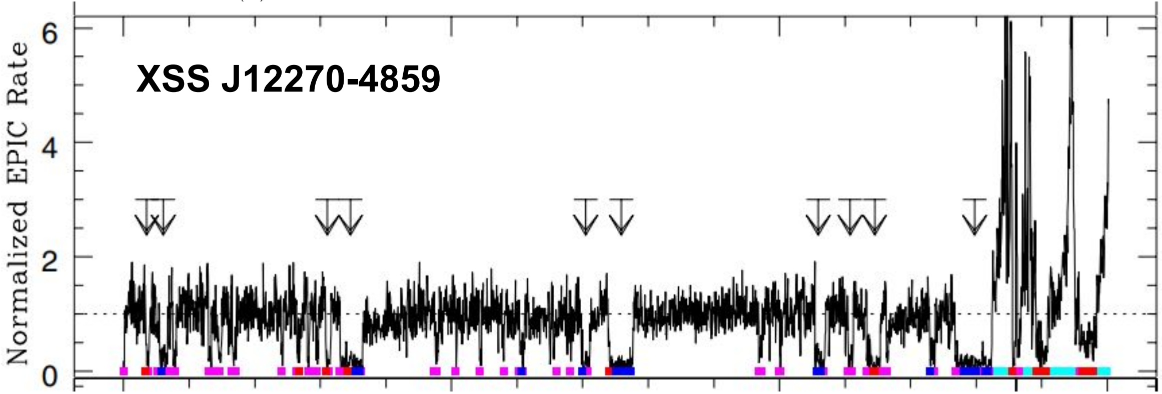
Sub-luminous disk state: X-ray variability



[Archibald+ 2015, ApJ]



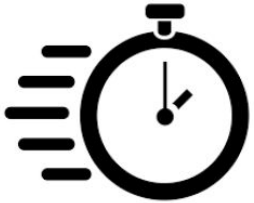
[Bogdanov+ 2015, ApJ]



[de Martino+ 2013, A&A]

Detectors for fast optical photometry

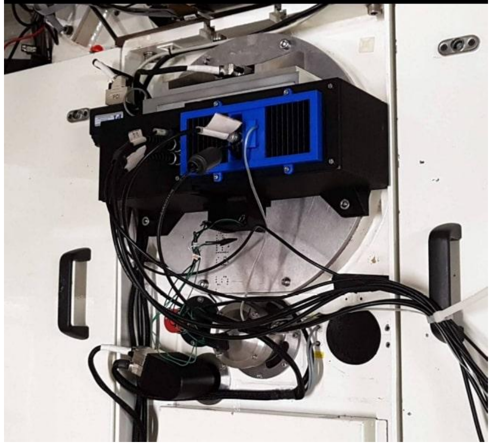
$$A \sim \frac{1}{\sqrt{N_{\text{photon}}}}$$



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

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



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GASP	eMCCD	Galway	6E-04	Polarimetry	WHT (past)
Optima	APD	MPE	1E-09	Timing/Polarimetry	1.3m Skinakas

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

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

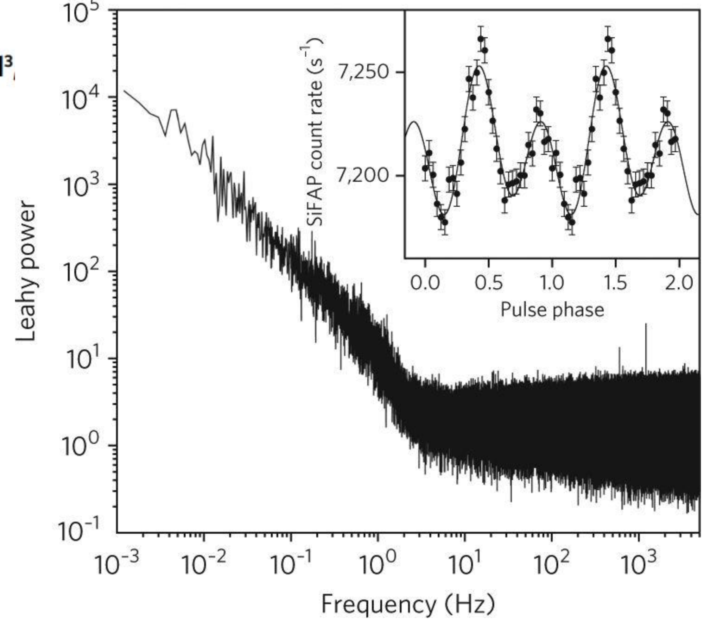
Optical pulsations from a transitional millisecond pulsar

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]

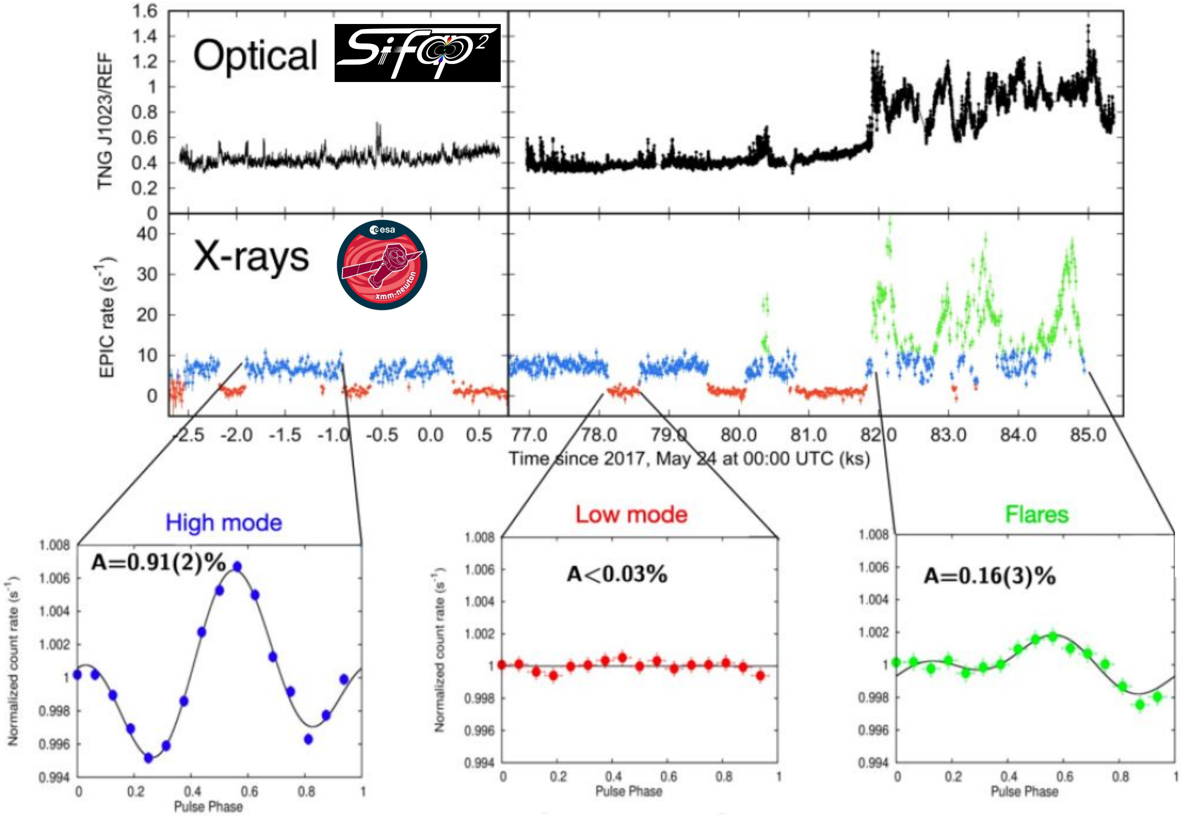
PSR J1023+0038

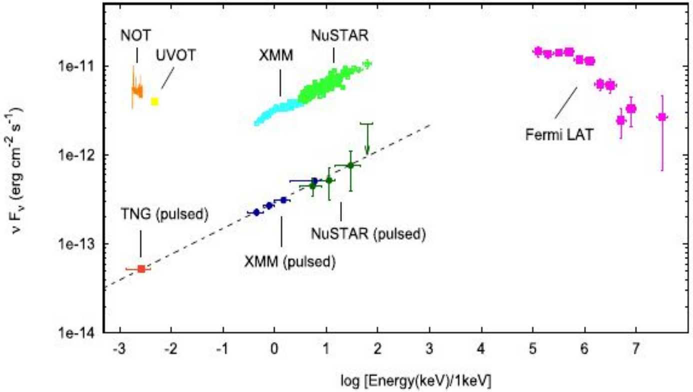
- Optical pulsations discovered when the source was surrounded by an accretion disk and also showed X-ray pulsations

- Optical pulse profile very similar to the X-ray one



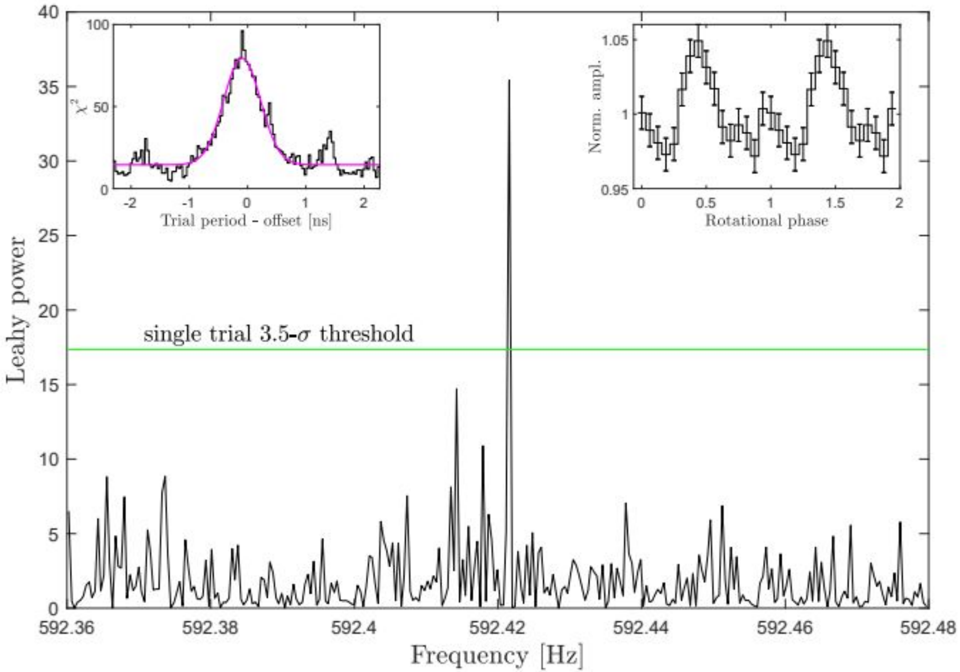
Pulsating in unison at optical and X-ray energies

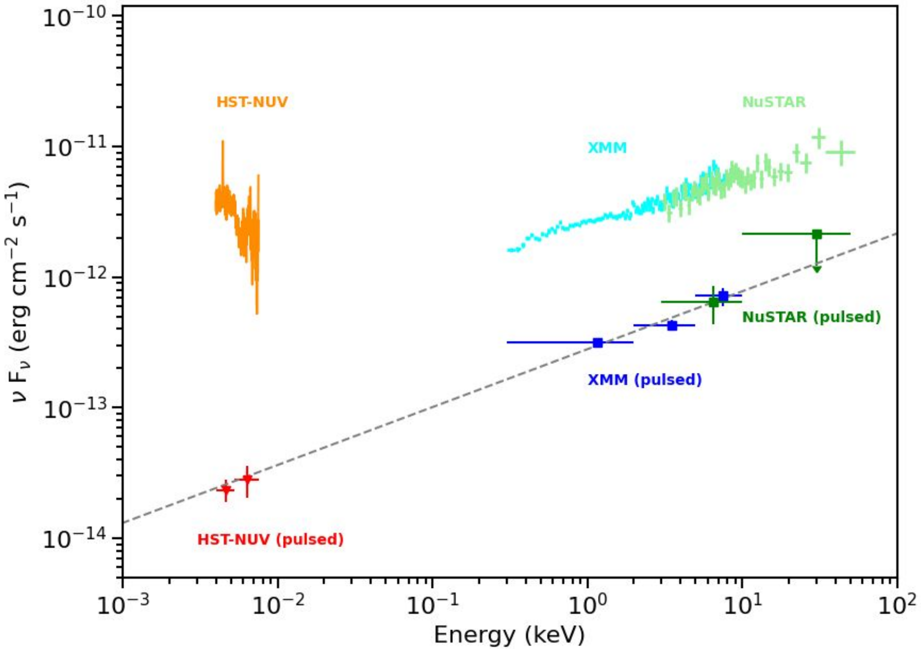




[Papitto+ 2019]

UV pulsed emission with Hubble Space Telescope

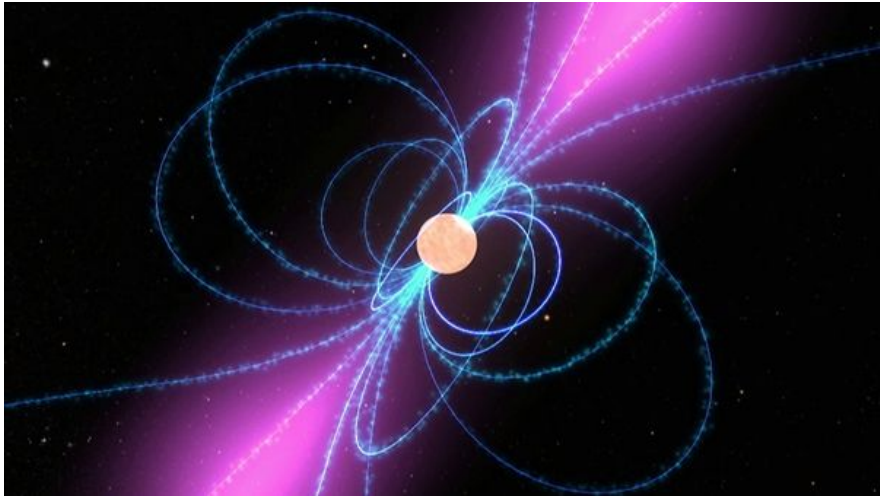




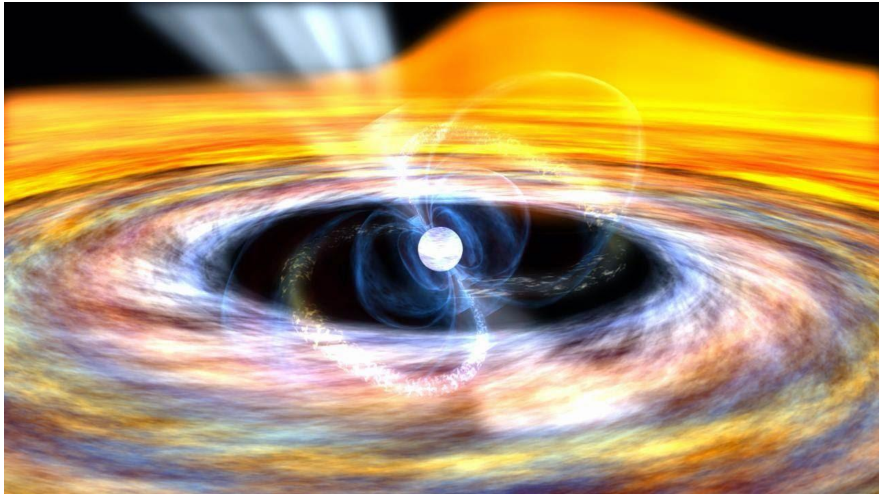
[Miraval Zanon+ 2022]

Standard emission mechanisms hardly individually explain the observed optical pulsed luminosity

Rotation-powered

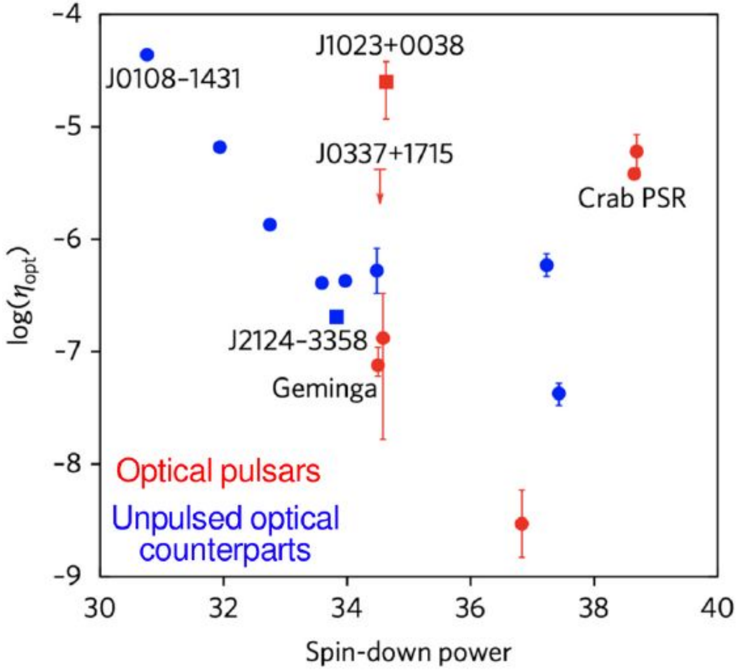


Accretion-powered



Rotation-powered pulsar

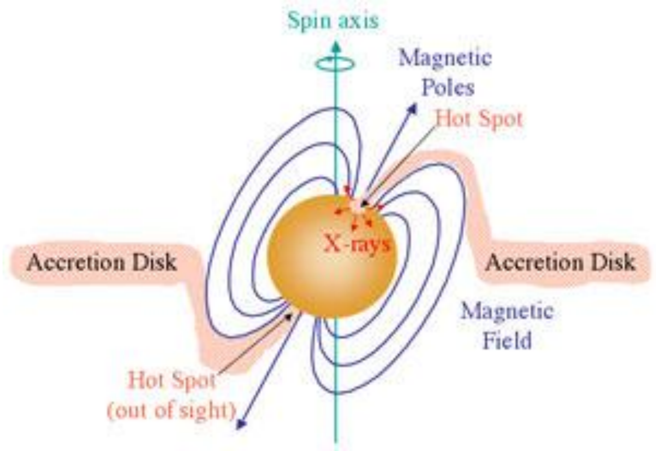
Optical efficiency $\eta_{opt} = L_{pulsed\ (opt)}/\dot{E}_{sd}$ ~ 2×10^{-5}



[Ambrosino+ 2017]

Credit: X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Infrared: NASA-JPL-Caltech

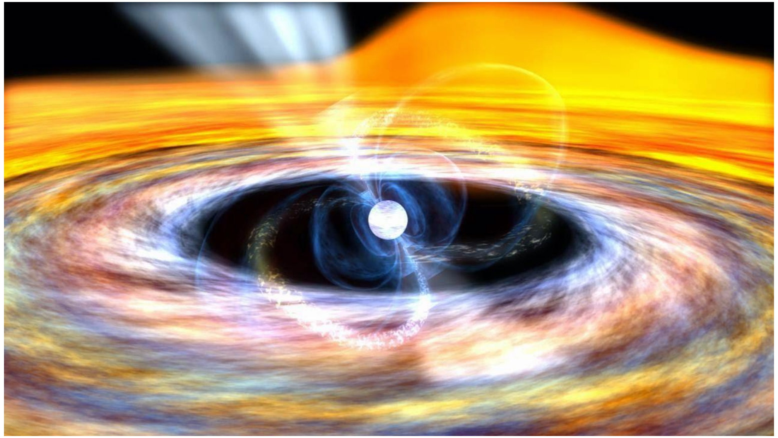
Accretion-powered pulsar



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

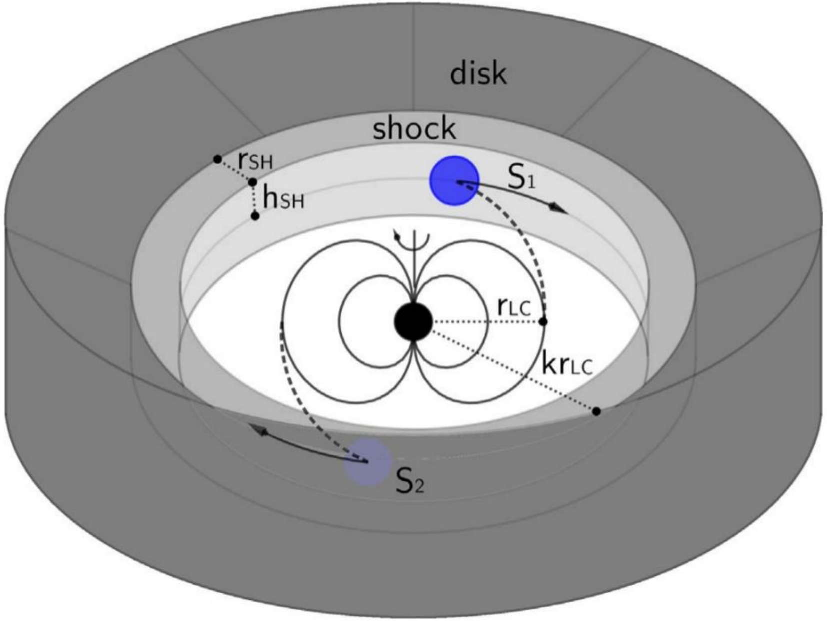
❖ $L_{cyc(opt)} \sim 3 \times 10^{29}$ erg/s

● $L_{pulsed(opt)} \sim 1.6 \times 10^{31}$ erg/s



$L_{cyc(opt)} \ll L_{pulsed(opt)}$

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



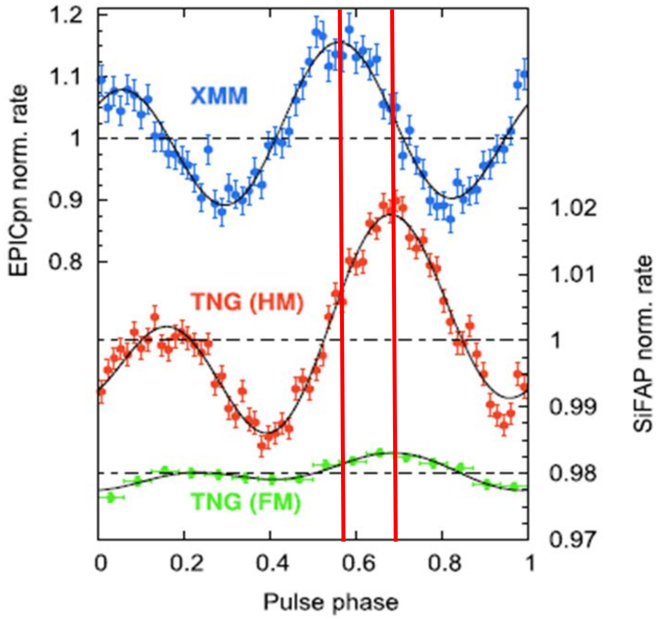
[Papitto+ 2019; Veledina+ 2019]

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

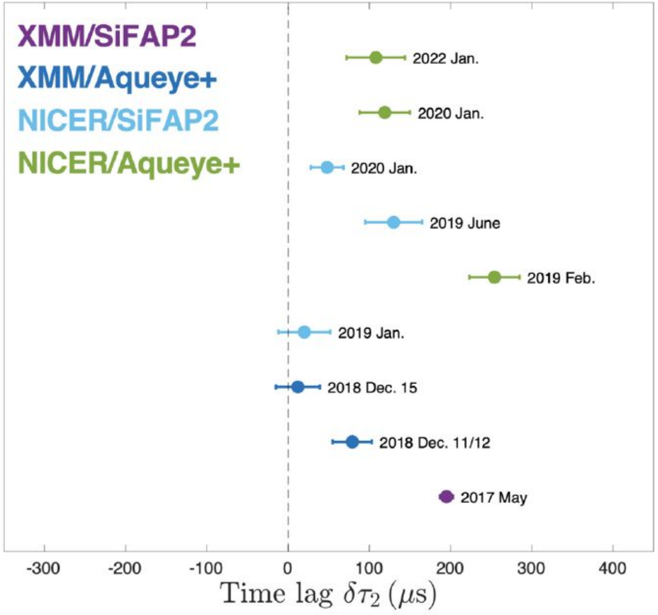
- Radio pulsar is always active
- Optical,UV and X-ray pulses are produced by the same process

Time lags between optical and X-ray pulsations

Different synchrotron timescales of optical and X-ray photons: $t_{sync} \simeq 2.2 \left(\frac{\epsilon}{10\,\mathrm{keV}}\right)^{-1/2} \left(\frac{B_s}{4.5 \times 10^5\,\mathrm{G}}\right)^{-3/2} \mu s$



[Papitto+ 2019]



[Illiano+ 2023]

nature astronomy
LETTERS
https://doi.org/10.1038/s41550-021-01308-0
Check for updates

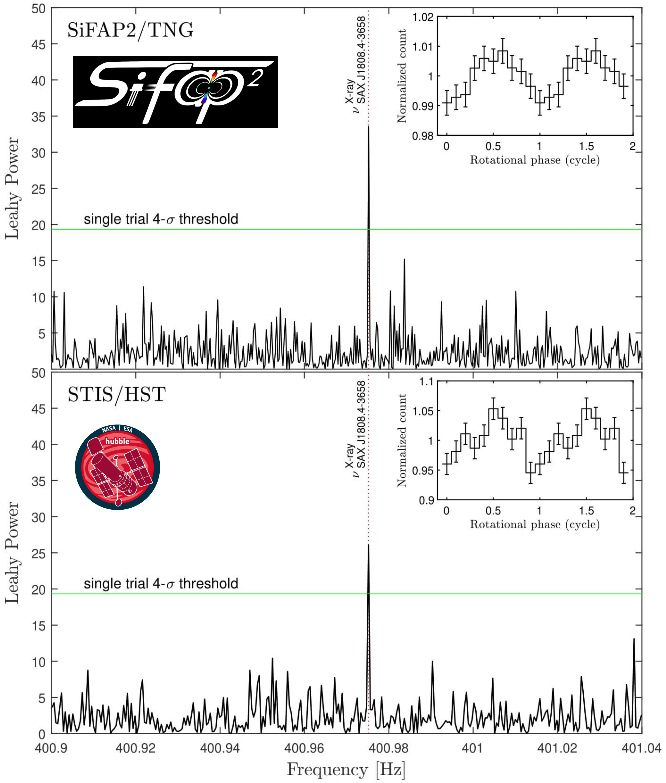
Optical and ultraviolet pulsed emission from an accreting millisecond pulsar

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]

SAX J1808.4-3658

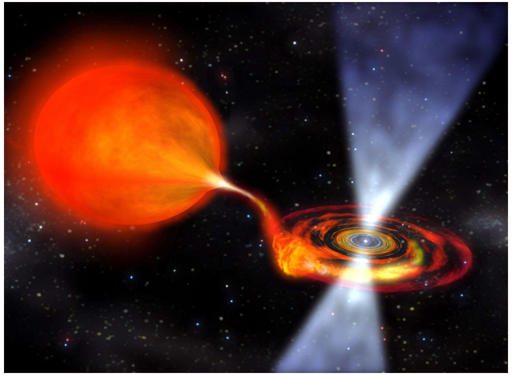
- Optical and UV pulsations discovered when the source was surrounded by an accretion disk and also showed X-ray pulsations

- Optical emission lags X-rays by ~ 1.38 ms

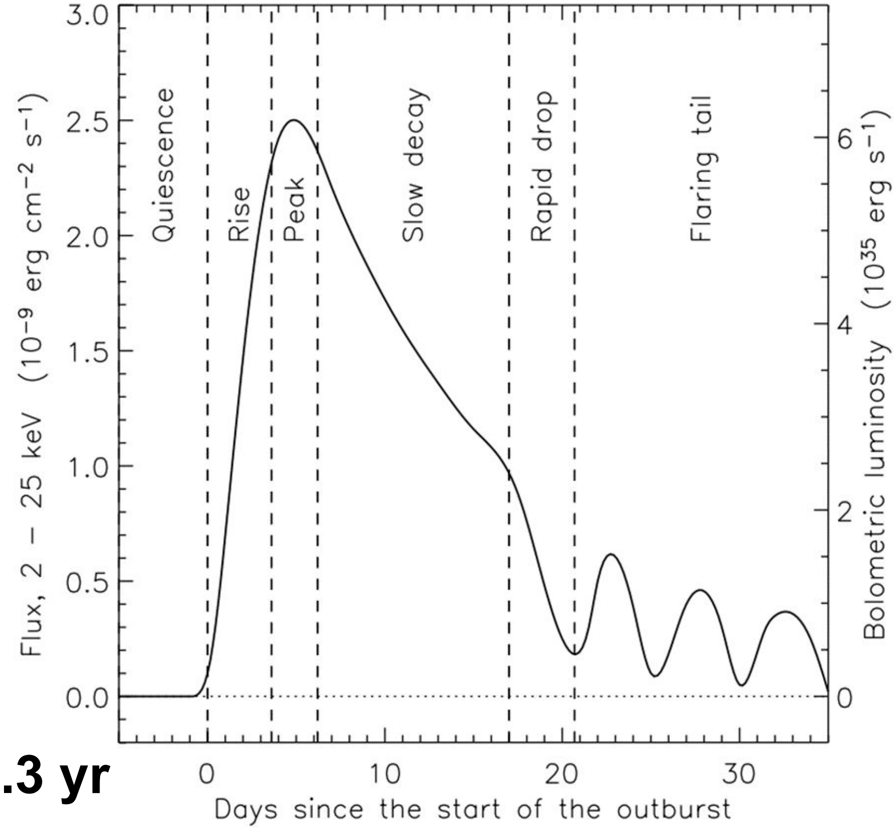


SAX J1808.4-3658

First discovered accretion-powered millisecond pulsar (ν~401 Hz)

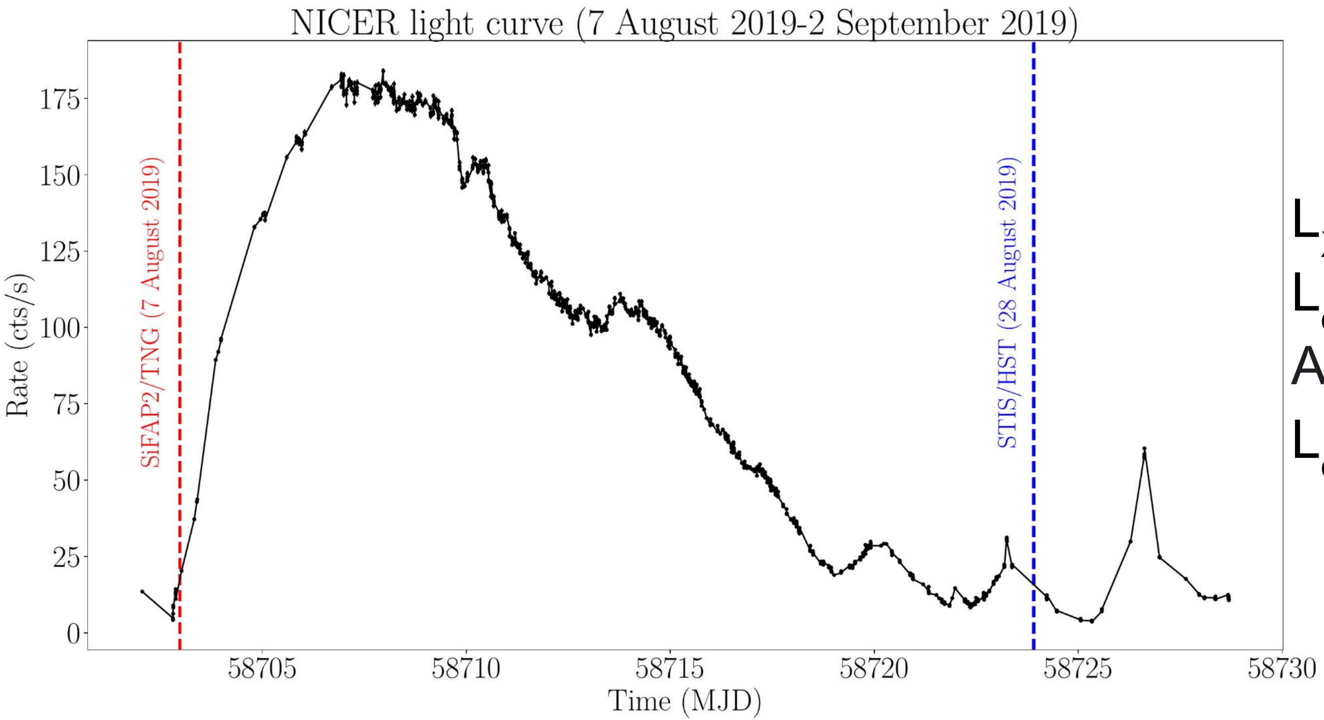


- **orbital period of ~2 hours**
- **outburst recurrence of about 1.6-3.3 yr**



[Hartman+ 2008]

Outburst of SAX J1808 in August 2019



$L_X \sim 5 \times 10^{34}$ erg/s

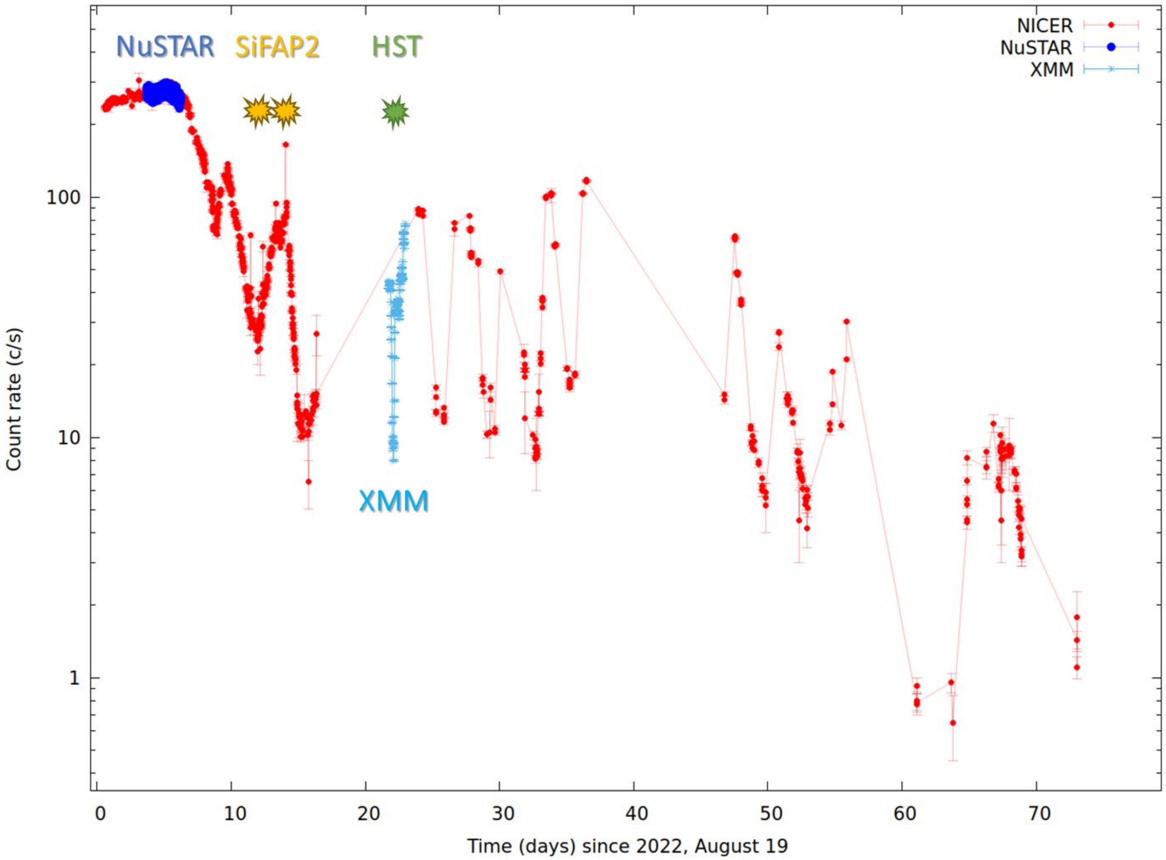
$L_{opt} \sim 5 \times 10^{33}$ erg/s

$A_{opt} \sim (0.55\pm0.06)\%$

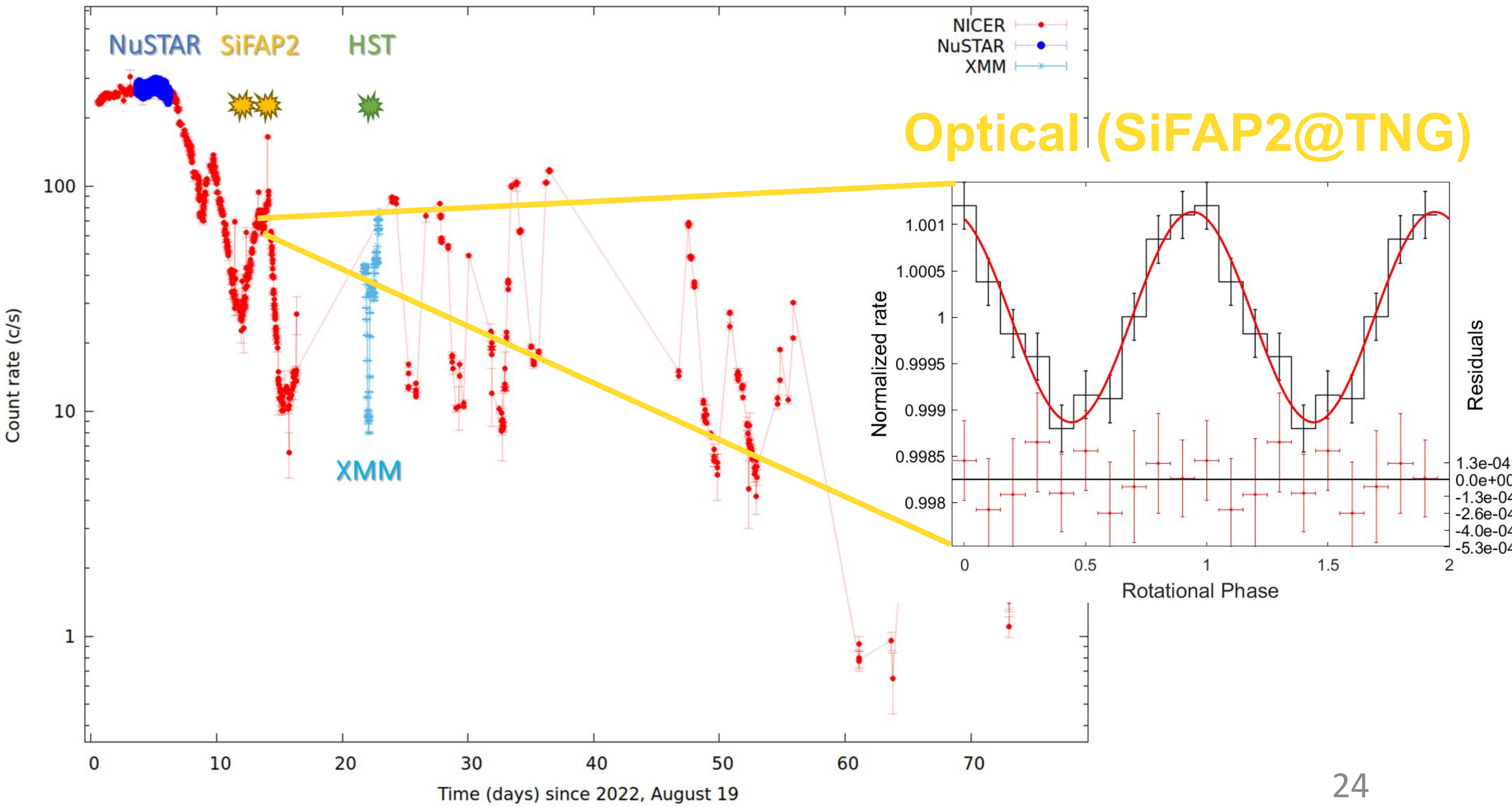
$L_{opt\ (pul)} \sim 2.7 \times 10^{31}$ erg/s

[Ambrosino, Miraval Zanon+ 2021]

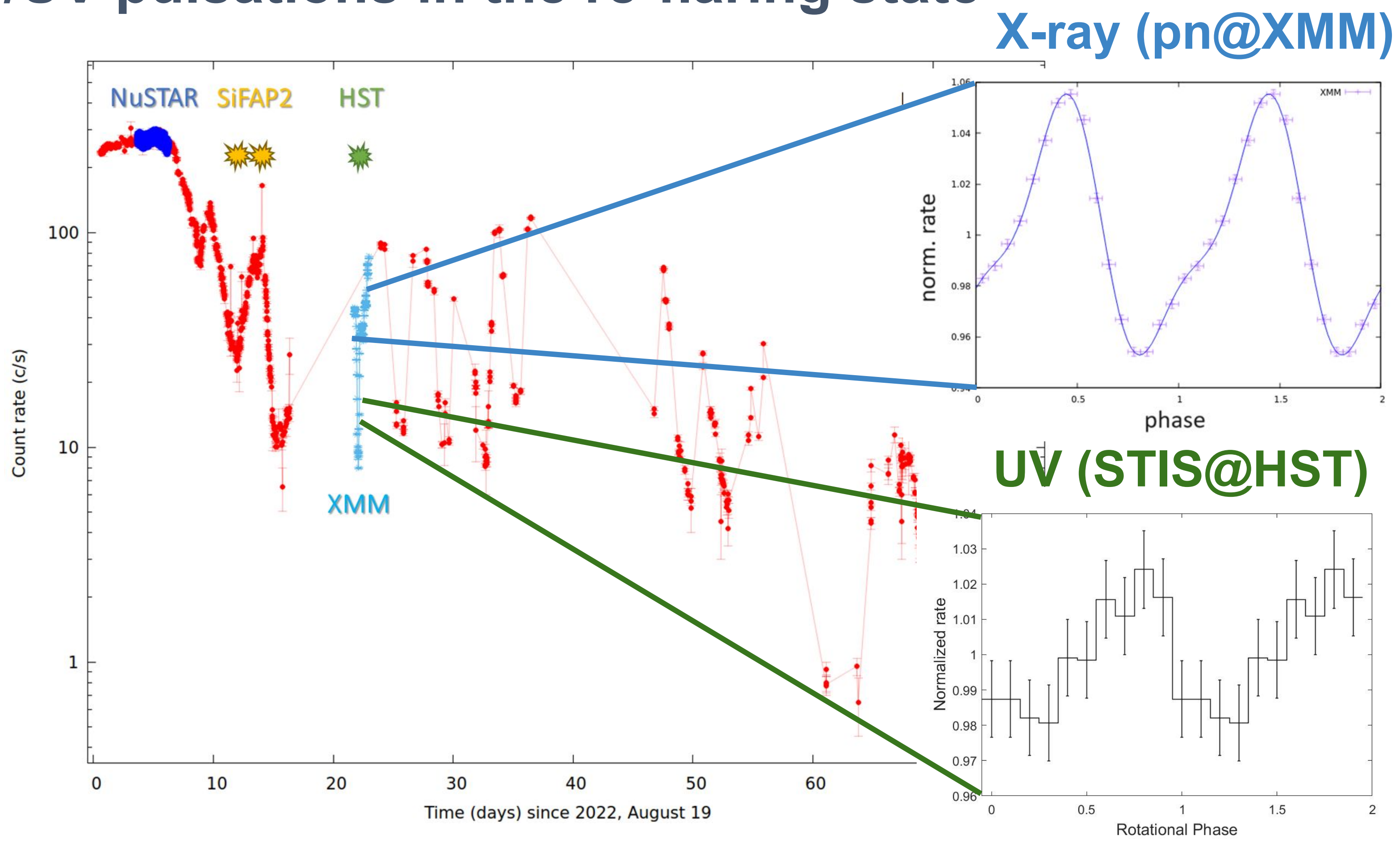
New outburst of SAX J1808 in August 2022



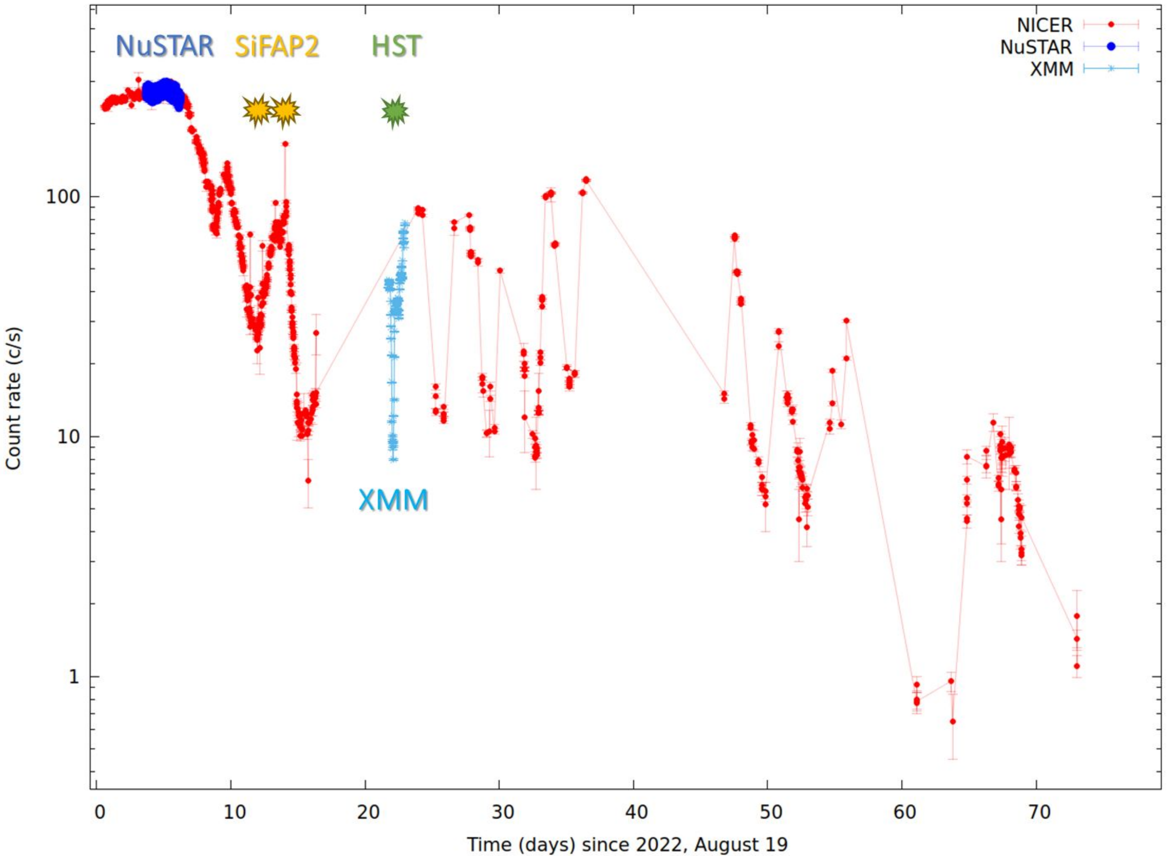
New outburst of SAX J1808 in August 2022



X-rays/UV pulsations in the re-flaring state



New outburst of SAX J1808 in August 2022



$L_X \sim$ 6-7 x 10^{35} erg/s

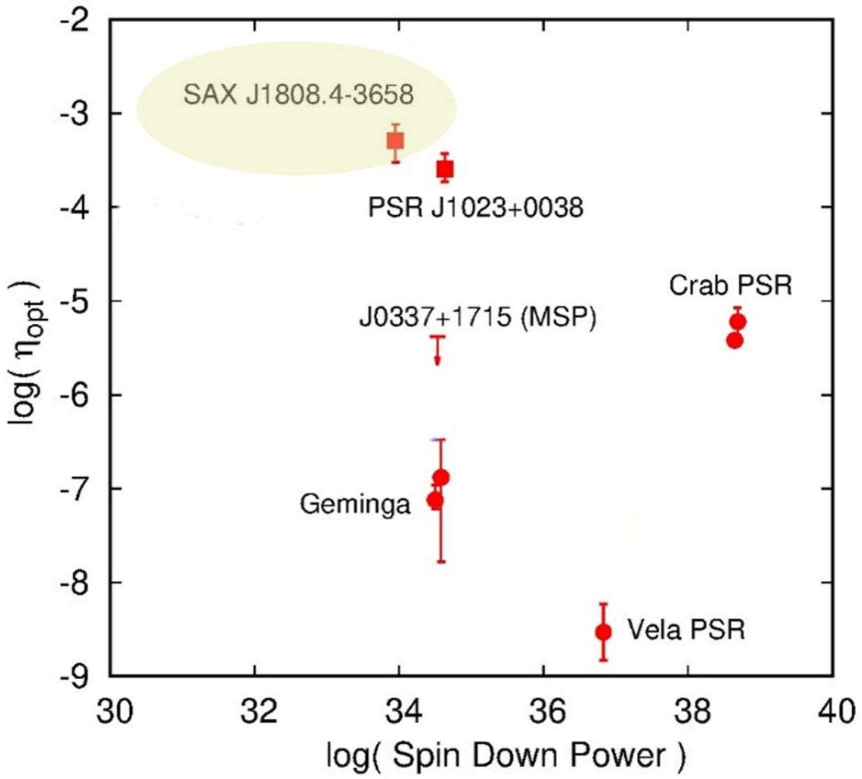
$L_{opt} \sim$ 3.6 x 10^{33} erg/s

$A_{opt} \sim (0.23 \pm 0.02)\%$

$L_{opt\ (pulsed)} \sim 10^{31}$ erg/s

[Miraval Zanon, in prep]

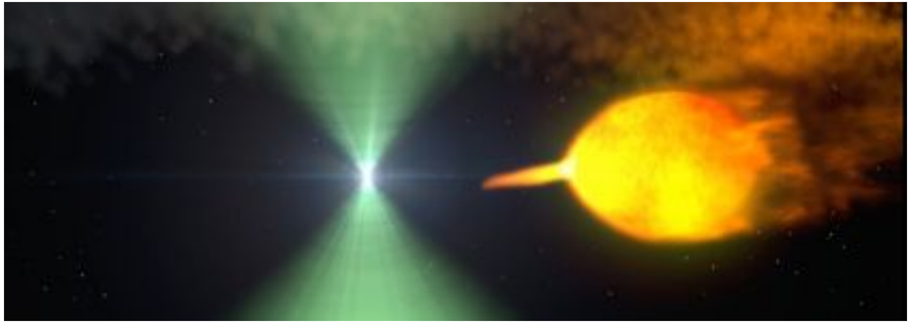
Standard emission mechanisms inadequate for explaining very bright optical pulsations



Do **accretion** and **rotation power** coexist?

Does **accretion** produce optical pulsations much brighter than expected?

How many optical millisecond pulsars are out there?



Rotation-powered MSPs

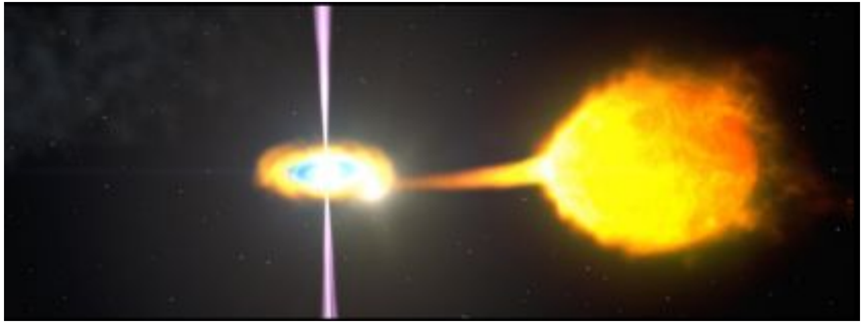
Redbacks and black widow pulsars

A_{opt} < 0.1 %

Candidate Transitional MSPs

A_{opt} < 1.5 % (in PSR J1023+0038 was 1%)

Possible detection in longer exposure



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 (see Riccardo La Placa's talk)**

Thank you for your time