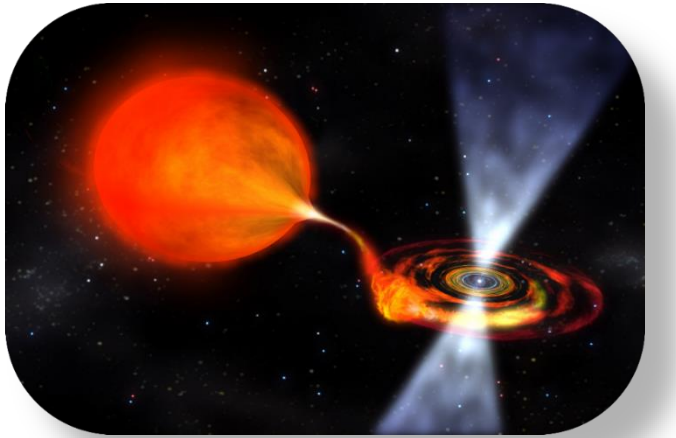
Millisecond pulsars in the ultra-fast optical domain



Filippo Ambrosino – **CNOC XII**

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Collaborators: Alessandro Papitto, Piergiorgio Casella, Gianluca Israel, Arianna Miraval Zanon, Luigi Stella, Giulia Illiano, Matteo Imbrogno (INAF/OAR)
Franco Meddi (Sapienza Università di Roma), Franco Leone (Università di Catania)
Adriano Ghedina, Massimo Cecconi, Manuel Gonzales, Ennio Poretti (INAF/Fundacion Galileo Galilei)
Sergio Campana, Paolo D'Avanzo (INAF/OAB)

Outline

- Millisecond pulsars (MSPs)
  - The recycling scenario
  - Rotation-powered MSPs
  - Accretion-powered MSPs
  - Transitional MSPs
- Observational results
  - SiFAP2@TNG
  - Transitional ms pulsar PSR J1023+0038
  - Accreting ms pulsar SAX J1808.4-3658
  - RB pulsar PSR J2339-0533
  - Intermittent accreting X-ray pulsar Aql X-1
  - Other observations of MSPs
- Open questions and future perspectives

Millisecond pulsar evolution: the recycling scenario


Letter

A millisecond pulsar

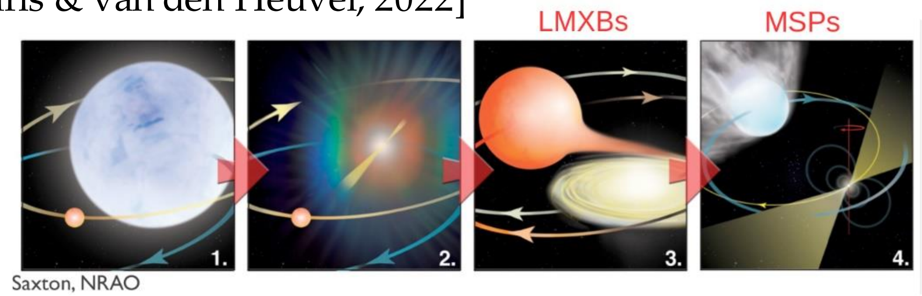
D. C. Backer, Shrinivas R. Kulkarni, Carl Heiles, M. M. Davis & W. M. Goss

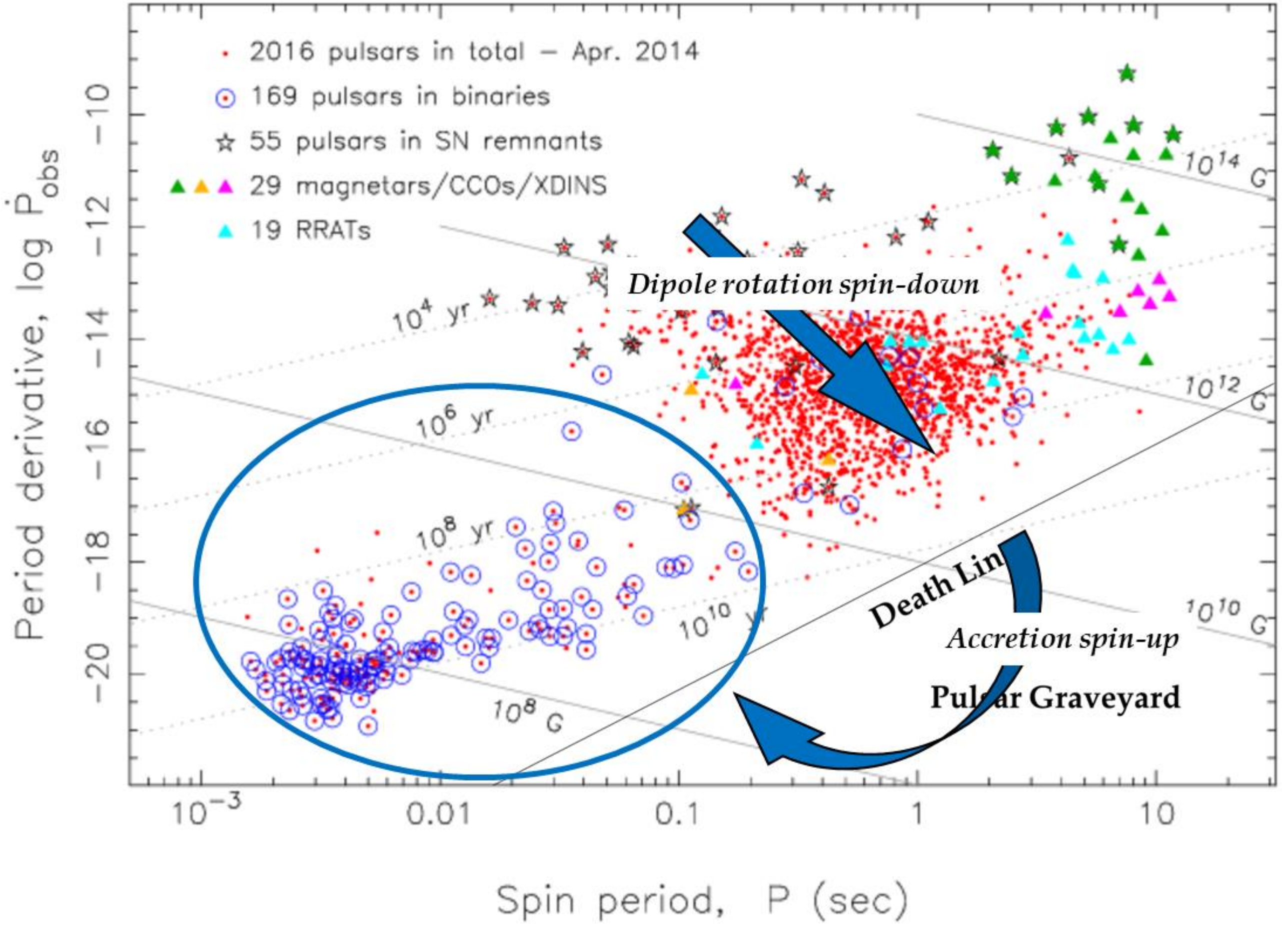
Nature **300**, 615–618 (16 December 1982)
doi:10.1038/300615a0
Download Citation

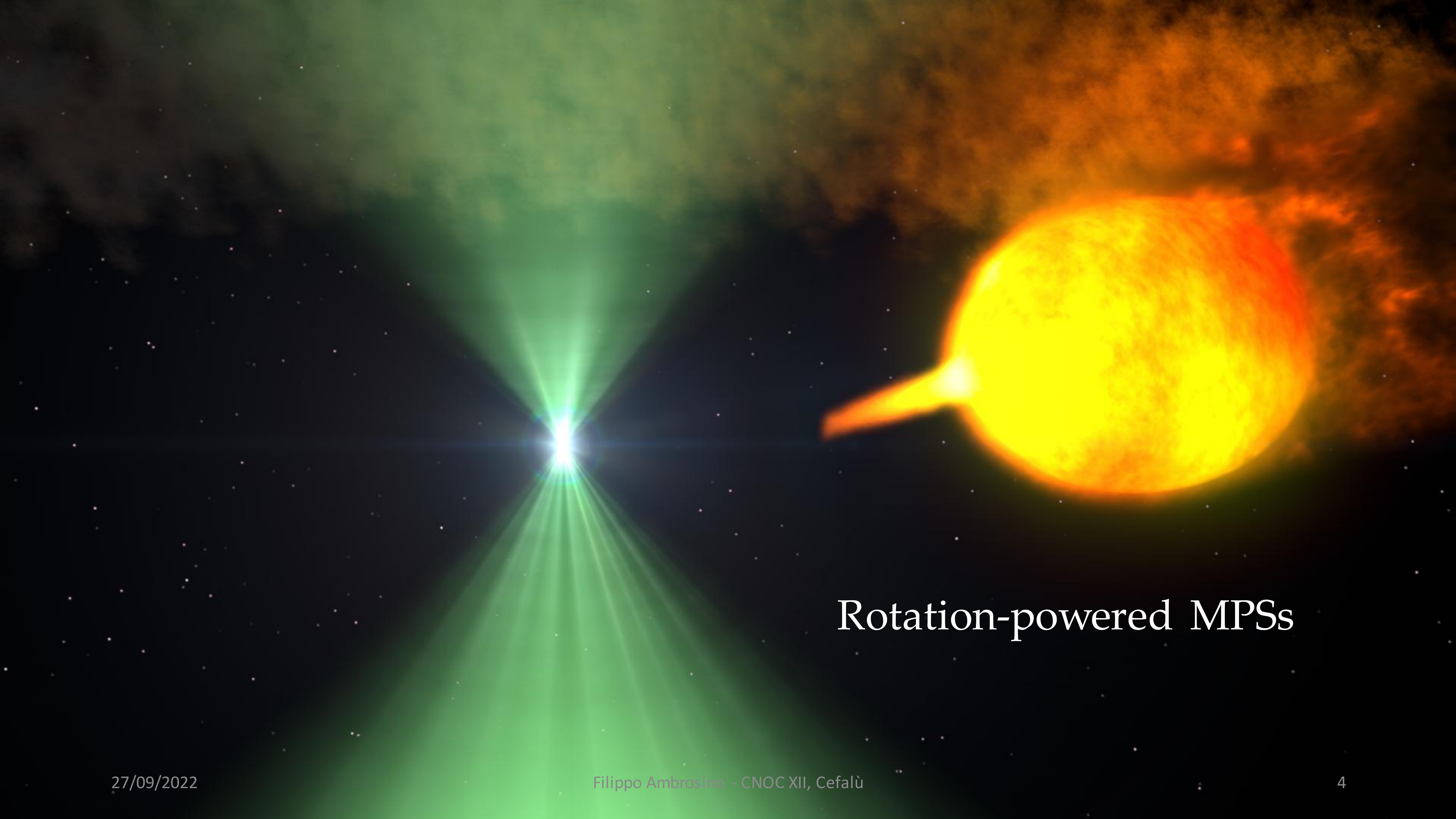
Received: 22 November 1982
Accepted: 25 November 1982
Published: 16 December 1982

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

[Tauris & van den Heuvel, 2022]







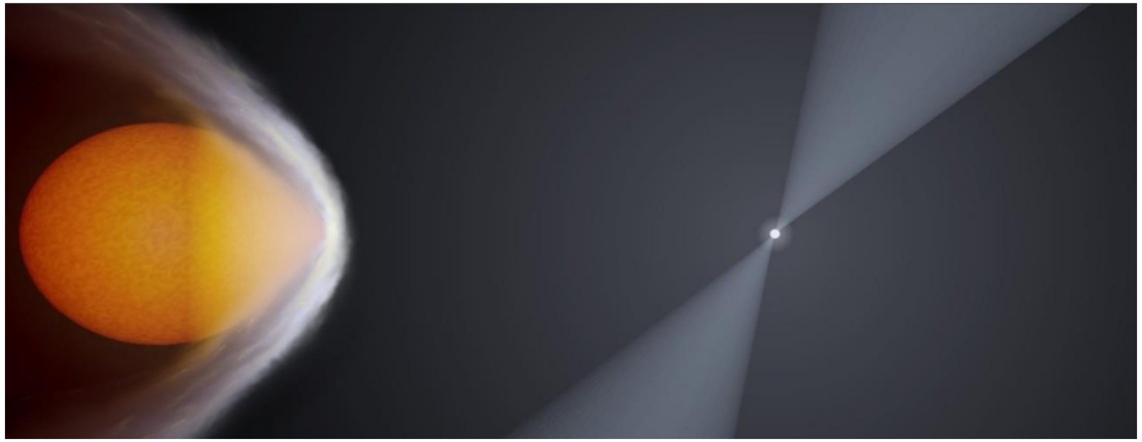
Rotation-powered MPSs

Eclipsing binary MSPs: Black Widows & Redbacks

MSPs in binary systems sometimes show **eclipses** of their pulsed **radio signal**

➔ Black widows (BWs): $M_c < 0.1\ M_\odot$.
- Semi-degenerate companion star
- Eclipses cover a small fraction (< 20%) of the orbit

➔ Redbacks (RBs): $0.1\ M_\odot < M_c < 0.7\ M_\odot$.
- Low-mass Main Sequence companion star
- Eclipses cover a significant fraction (up to 80%) of the orbit

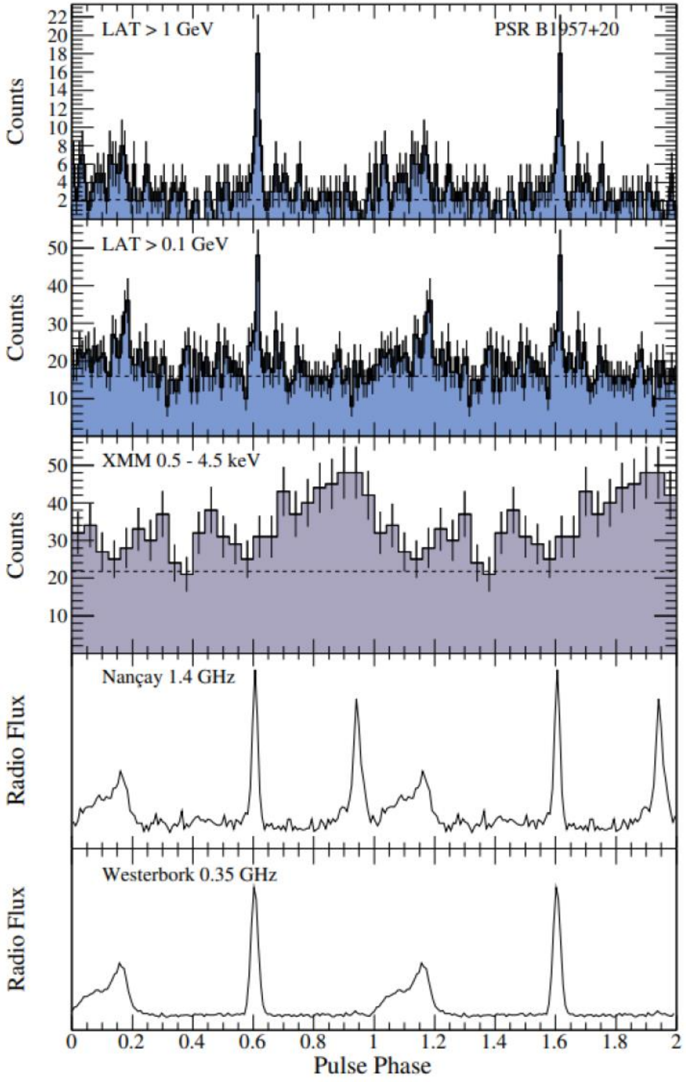


These systems can swing between rotation and accretion powered states in very short timescales (~ weeks)

⬇

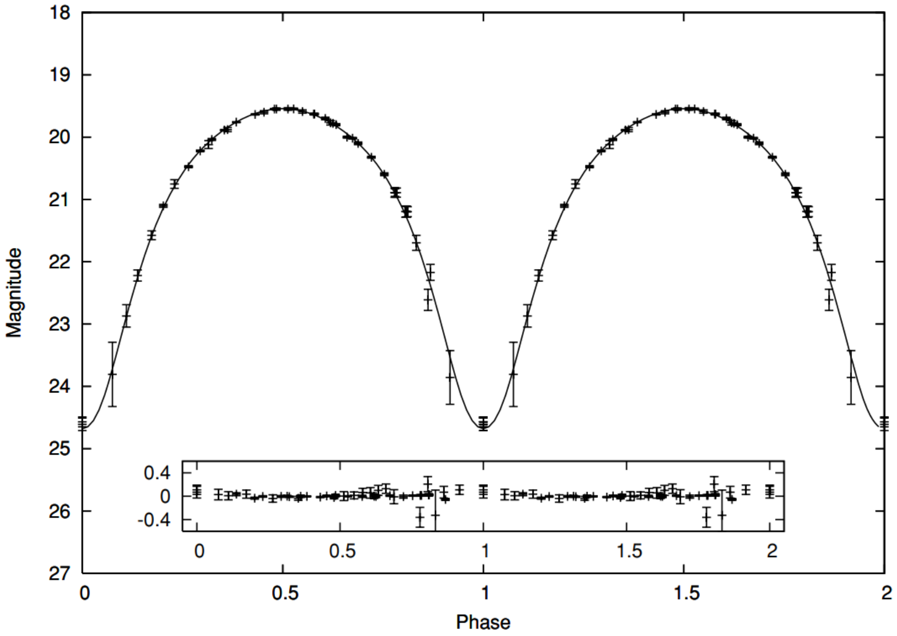
Transitional millisecond pulsars (tMSPs)
The three transitional pulsars discovered so far are RBs

Black widow pulsars: PSR B1957+20



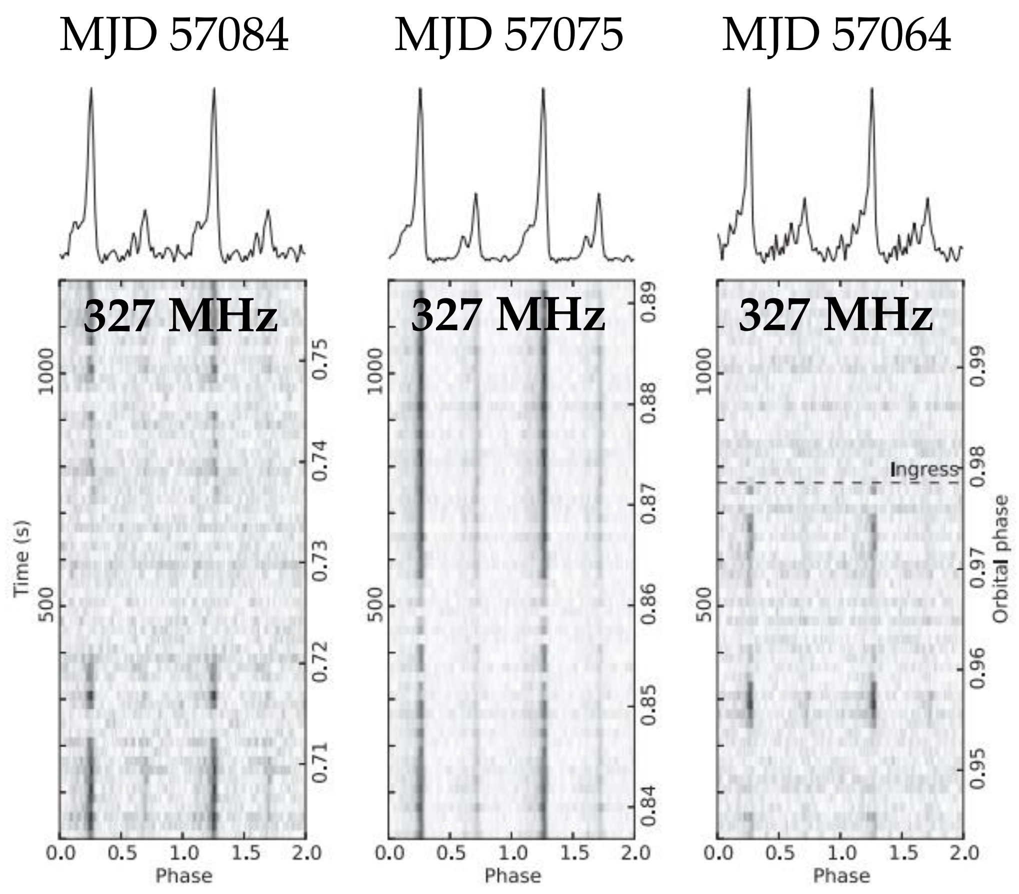
[Guillemot et al., 2012]

- P_{spin} ~ 1.61 ms
- P_{orb} ~ 9.17 hr
- Radio eclipses within 0.19 - 0.39 orbital phase
  - ➔ near NS superior conjunction, no radio pulsations
- Eclipse length ~20% of the orbit
- $M_c \sim 0.022\ M_\odot$
- Shows γ/X-ray pulsations



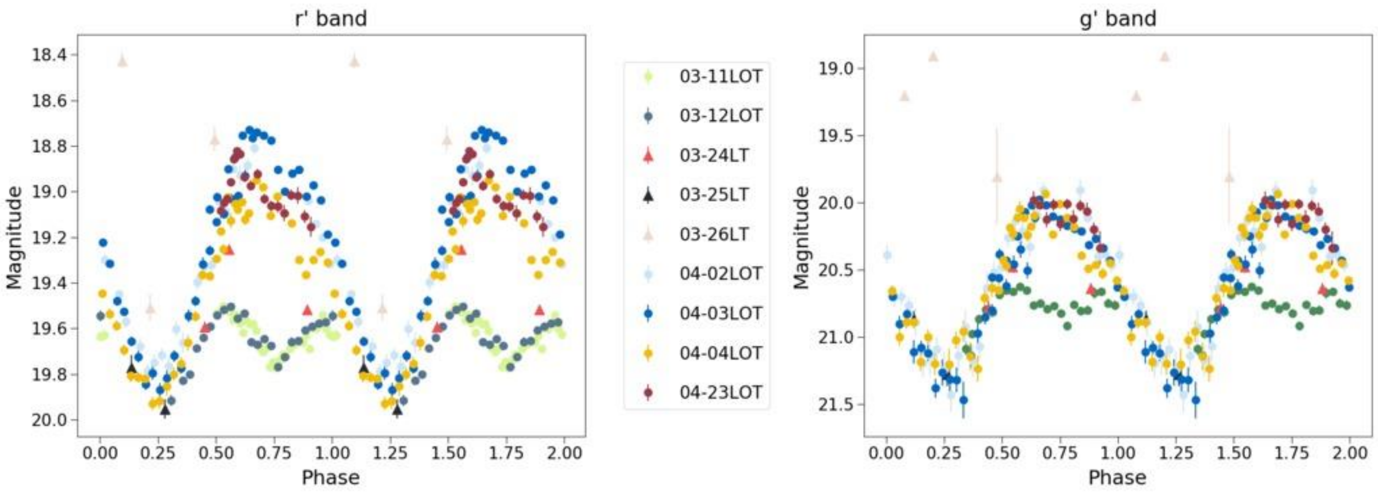
[Reynolds et al., 2007]

Redback pulsars: PSR J1048+2339



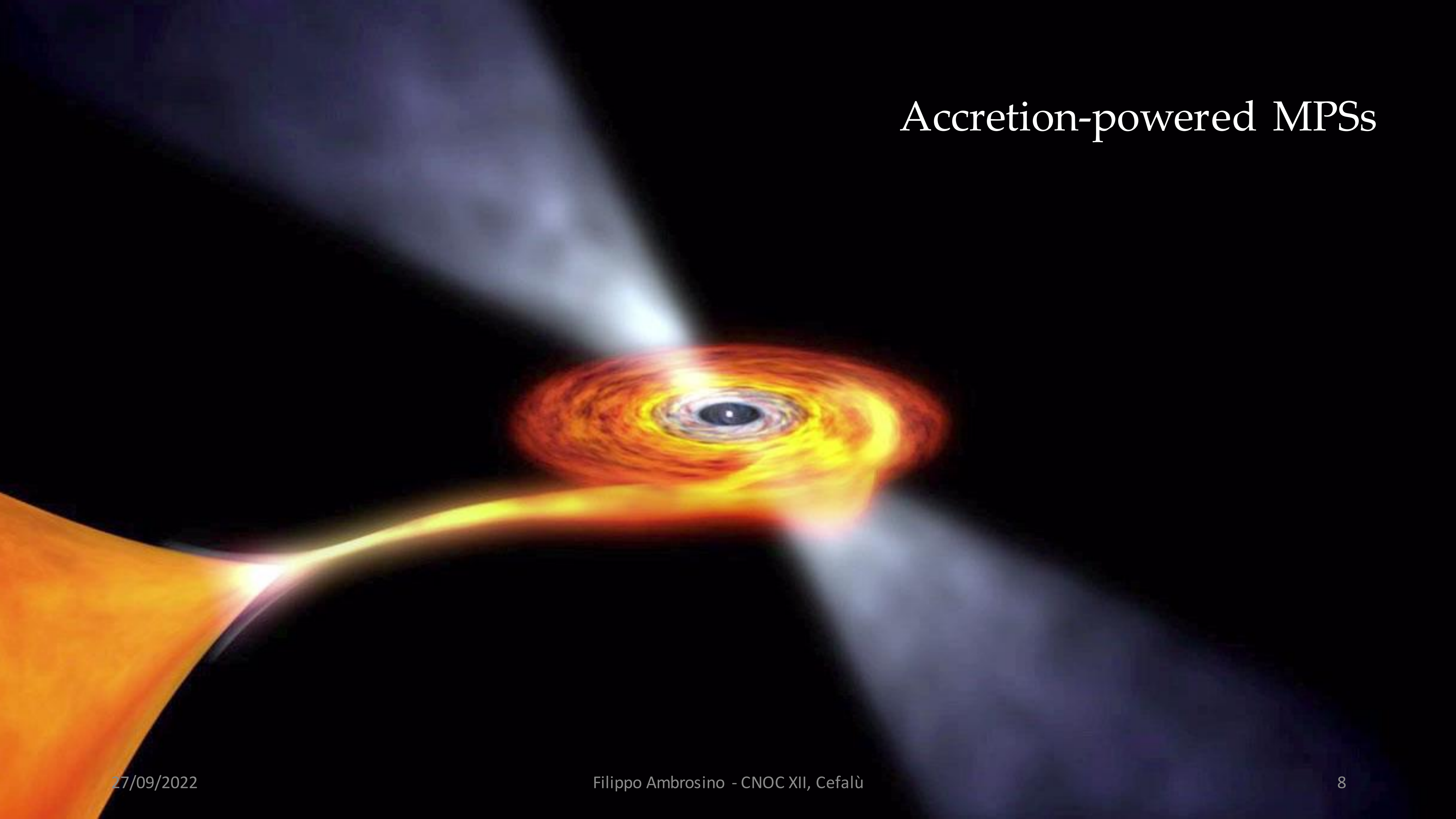
[Deneva et al., 2016]

- P_{spin} ~ 4.66 ms
- P_{orb} ~ 6 hr
- Radio eclipses within 0.02 - 0.49 orbital phase
  - ➔ near NS superior conjunction, no radio pulsations
- Eclipse length ~47% of the orbit
- $M_c > 0.3\ M_\odot$
- No significant γ/X-ray pulsations nor optical ones

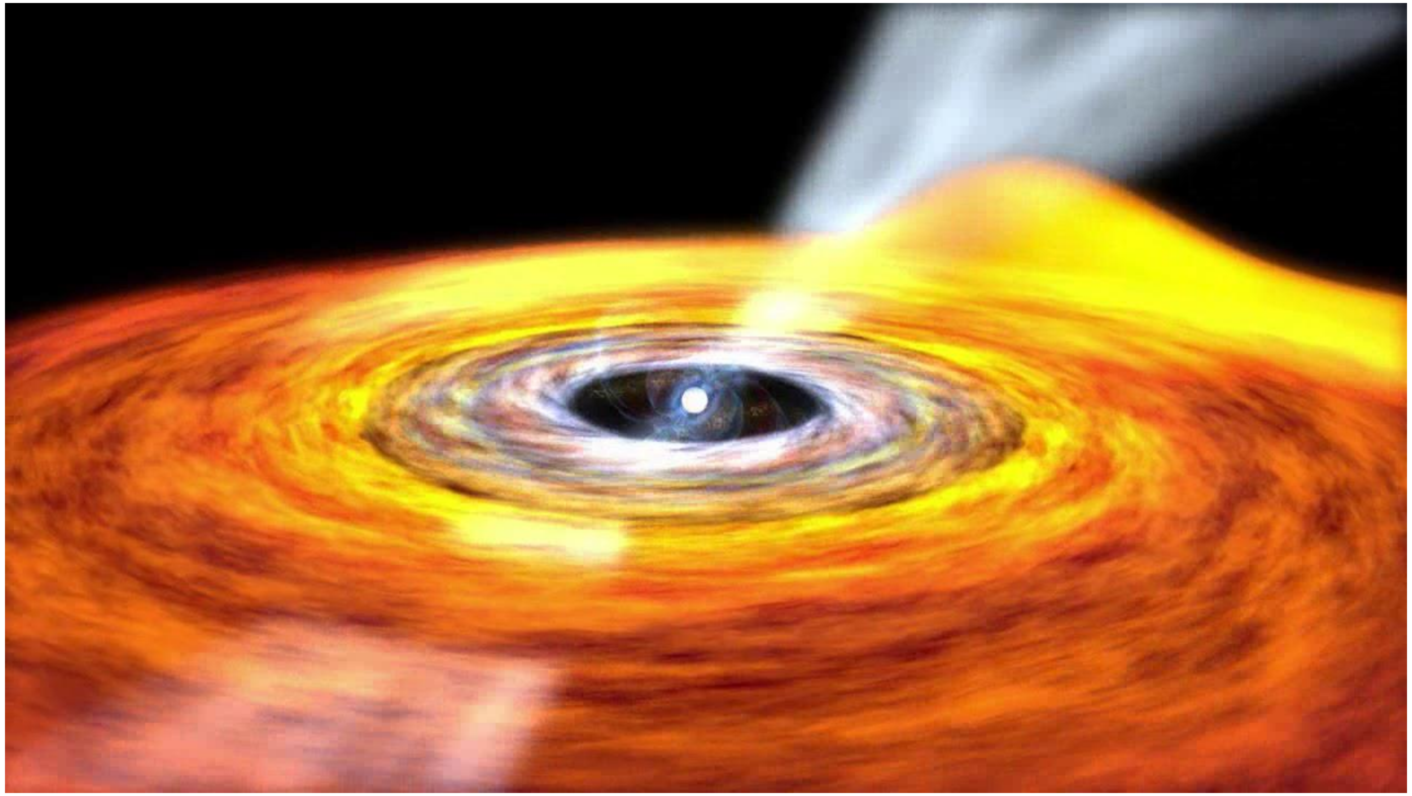


[Yap et al., 2019]

Accretion-powered MPSs



Accreting X-ray MSPs



[Credit: NASA]

- Old systems (1-10 Gyr)
- Low-mass companion stars (< 1 $M_\odot$)
- Brightest X-ray sources in the Galaxy
- Powered by accretion
- Possible type I X-ray bursts
- Few (~20) of them show X-ray pulsations
  ➔ Accreting X-ray MSPs

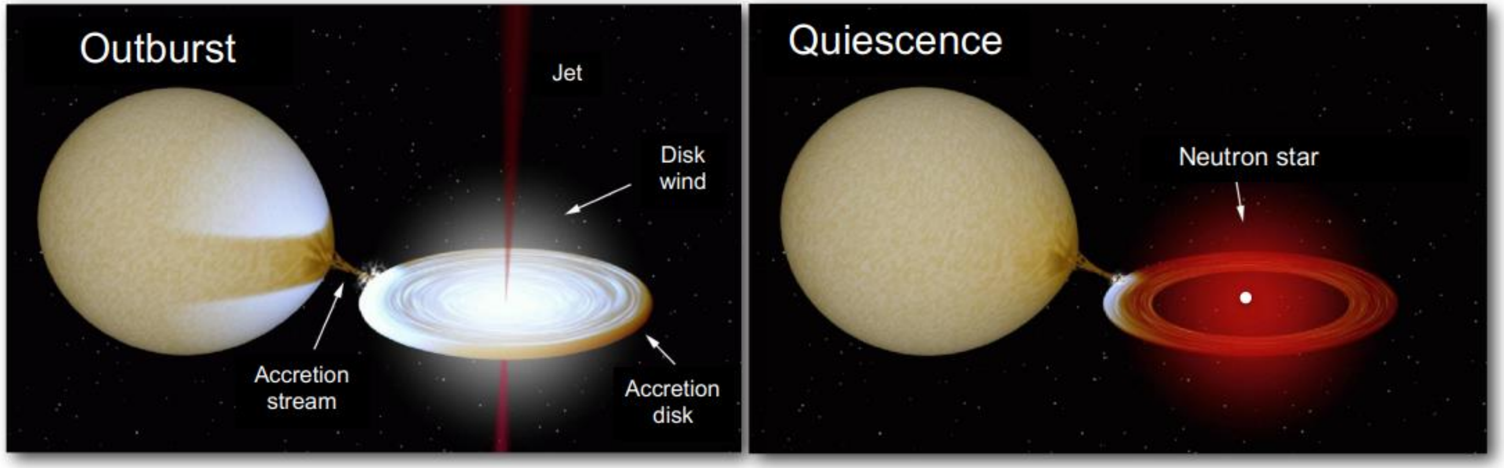
Accreting X-ray MSPs

- **Transient LMXB showing coherent ms X-ray pulsations**
- **Alternate between quiescence and outburst pahses**

Quiescence ➔ dominated by the thermal emission of the companion star
Outburst ➔ dominated by the accretion disk

Main properties

- Low-mass companion stars ($< 1\ M_\odot$)
- Short orbital periods ($P_{orb} < 1$ d)
- NS spun-up to ms spin periods due to mass accretion
- Only ~20 systems known



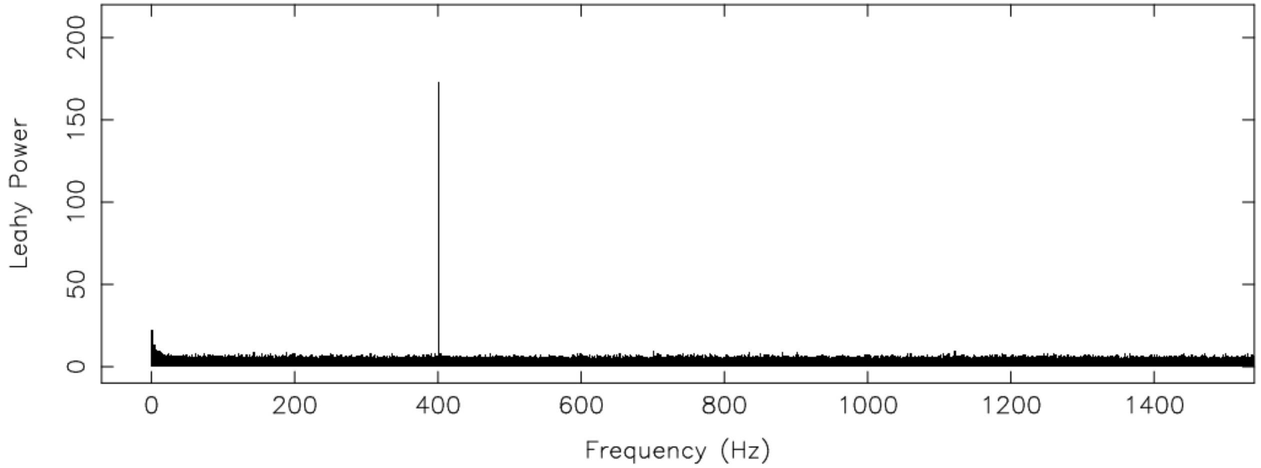
[Credit: Haynes]

Accreting MSPs: SAX J1808.4-3658

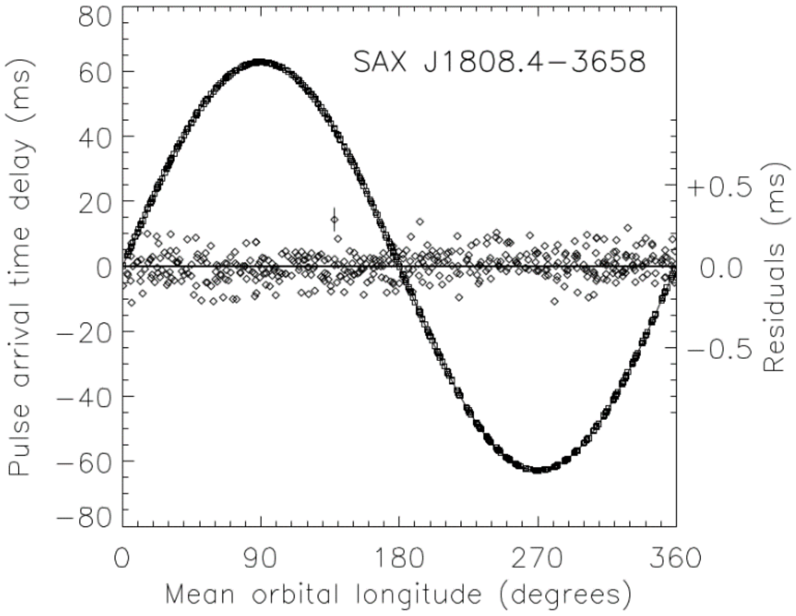
First discovered accretion-powered millisecond pulsar

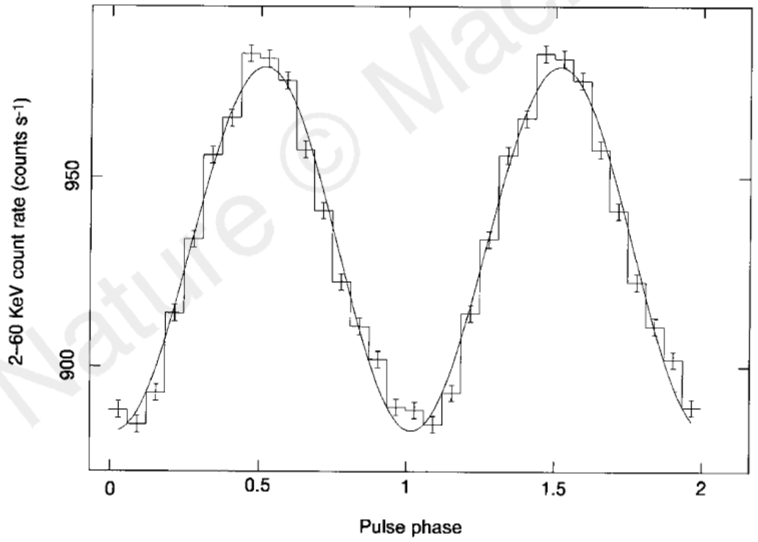
- P_{spin} ~ 2.5 ms
- P_{orb} ~ 2 hr
- $M_c \sim 0.4\ M_{\odot}$
- X-ray/optical/UV pulsations
- Recurrent outbursts (1.6 – 3.3 yr)

[Wijnands & van der Klis 1998, Nature]

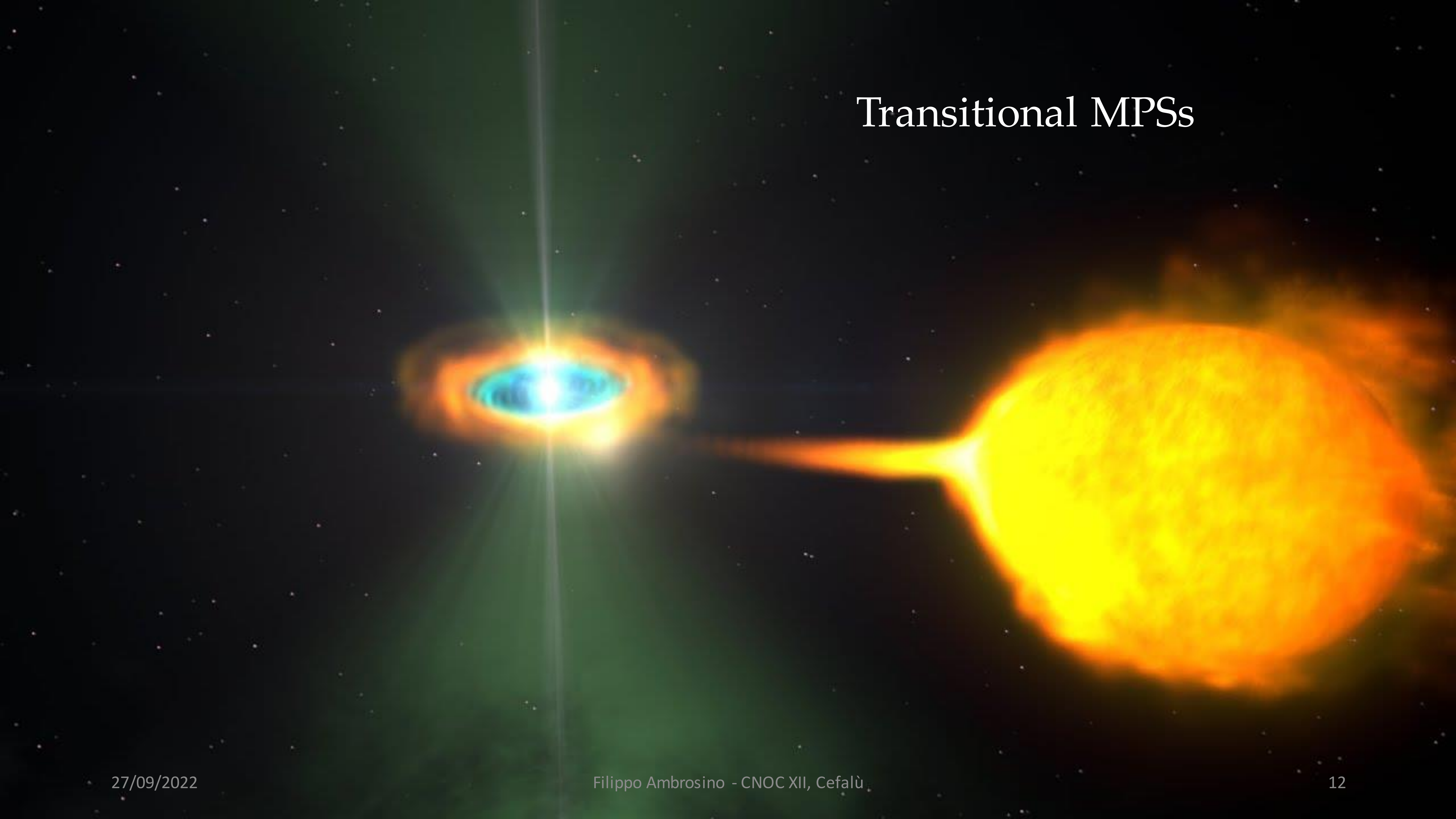


[Chakrabarty & Morgan 1998, Nature]





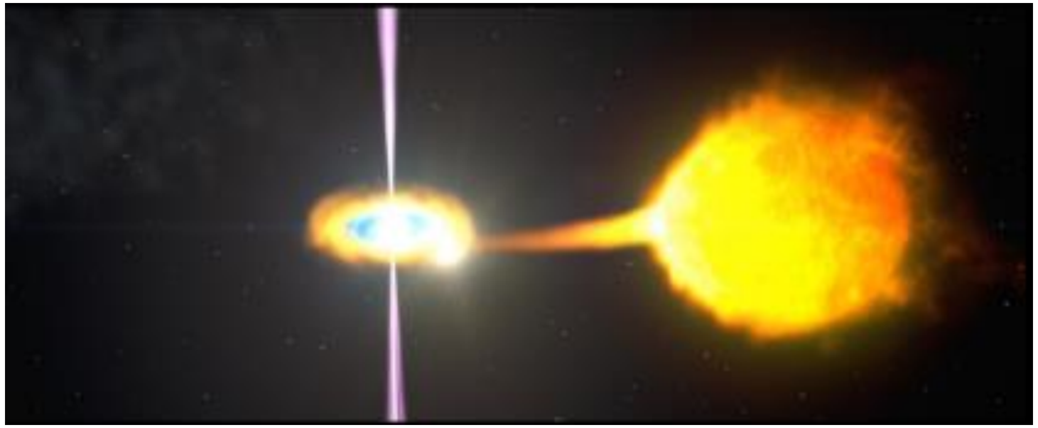
Transitional MPSs

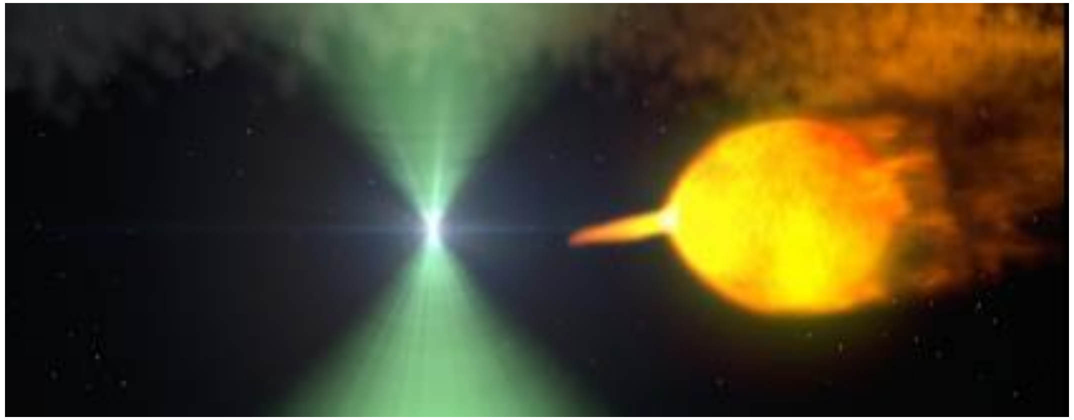


Transitional MSPs: the missing link

Accretion state

Accretion-power X-ray millisecond pulsars
X-ray bright & radio quiet





Radio pulsar state

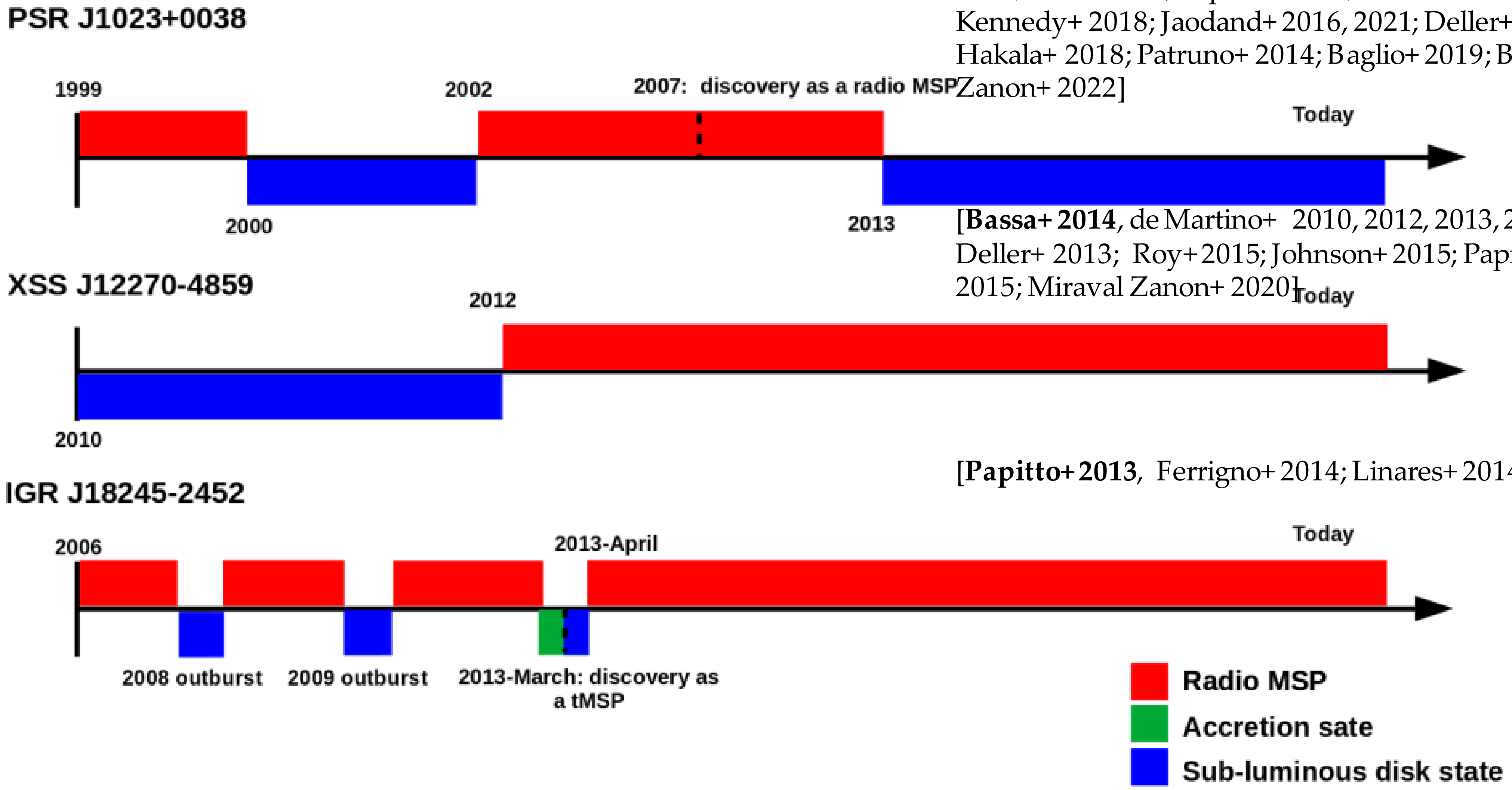
Rotation-power radio millisecond pulsars
Radio loud & X-ray faint

Three confirmed tMSPs

[**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]

[**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]

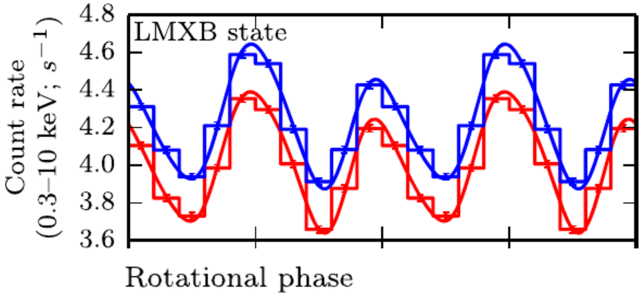
[**Papitto+2013**, Ferrigno+ 2014; Linares+ 2014; De Falco+ 2017]

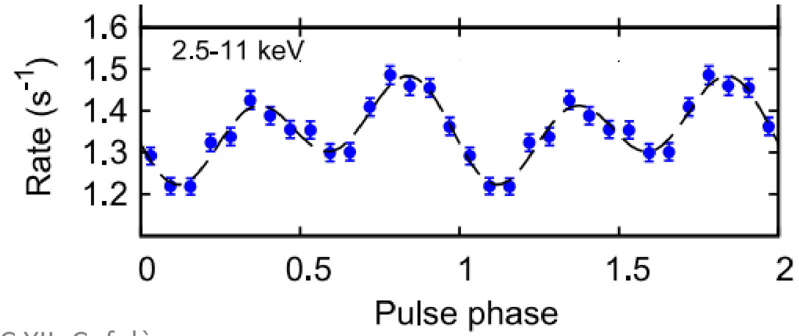


The opposite twins: PSR J1023+0038 & XSS J12270-4859

	J1023+0038	J1227−4859
P_{orb}	4.75 h	6.91 h
P_{spin}	1.69 ms	1.69 ms
Spin-down luminosity	$\approx 5.6\times 10^{34}$ erg/s	$\approx 9\times 10^{34}$ erg/s
Magnetic field	$\approx 9.6\times 10^{7}$ G	$\approx 1.4\times 10^{8}$ G
Pulsar age	$\approx$ 5.0 Gyr	$\approx$ 2.4 Gyr
Distance	1.37 kpc	1.4 kpc
Inclination	42 deg	46-65 deg
Mass ratio (q)	0.14	0.11-0.26
Companion mass	0.24 $M_\odot$	0.2-0.4 $M_\odot$
Companion Sp. Type	G5 $\rightarrow$ G9	G5 $\rightarrow$ F5

[Papitto et al., 2015]

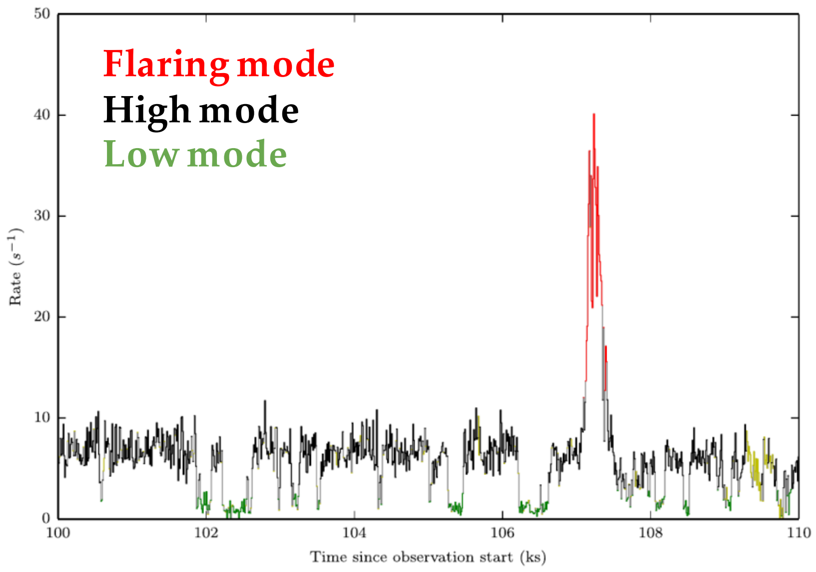




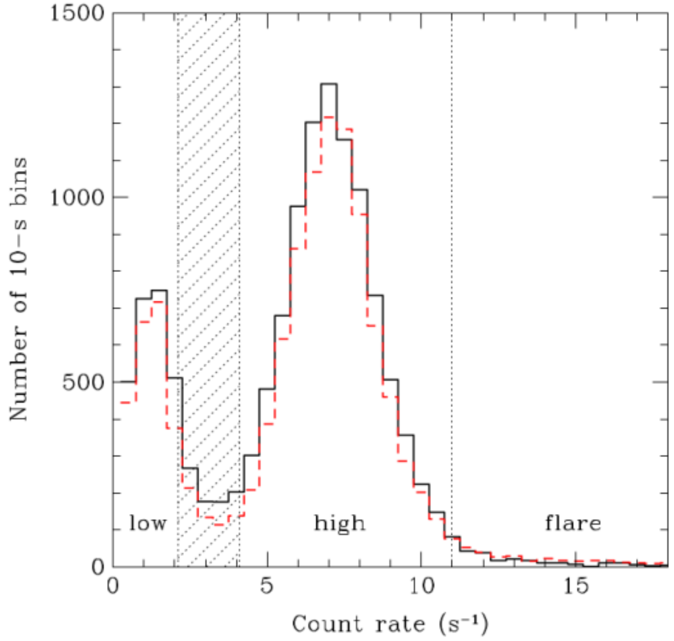
[Archibald et al., 2015]

X-ray variability in the sub-luminous disk state

PSR J1023+0038

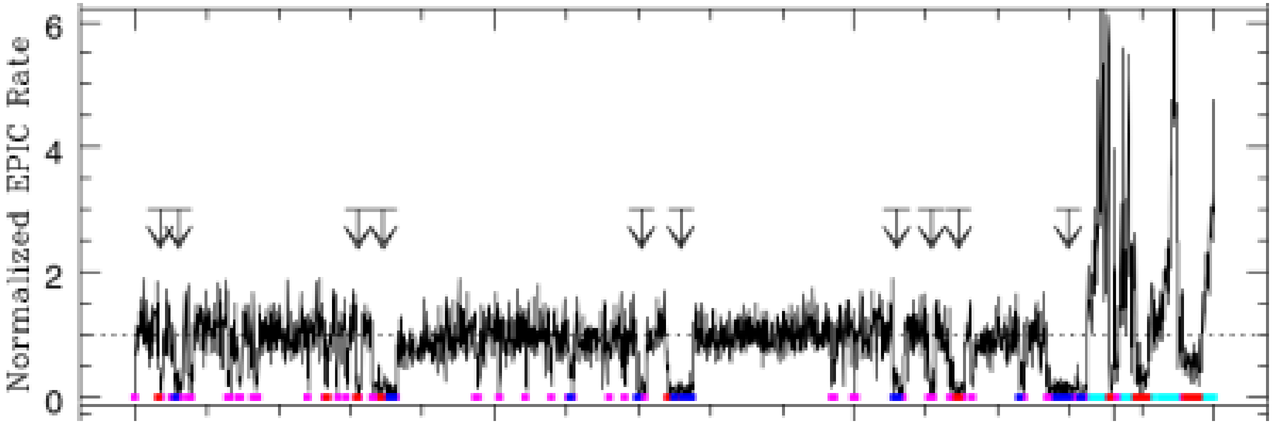


[Archibald+ 2015, ApJ]



[Bogdanov et al., 2015]

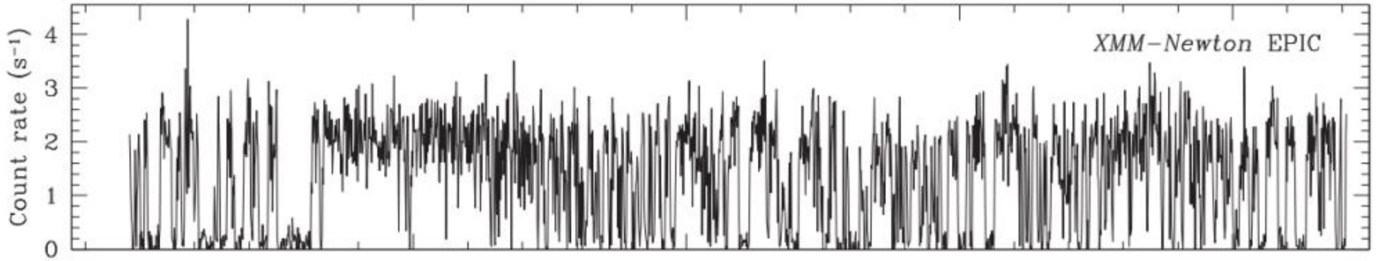
XSS J12270-4859



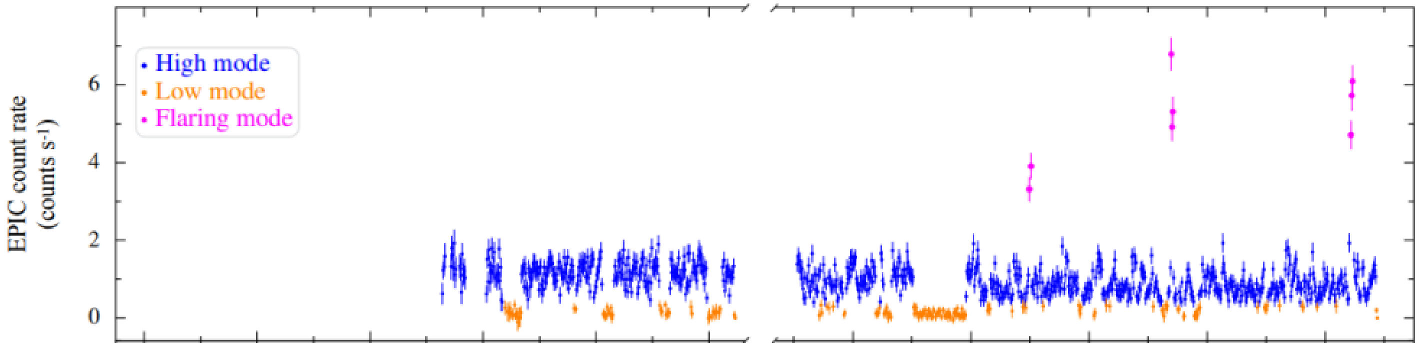
[De Martino et al., 2013]

Candidate tMSPs

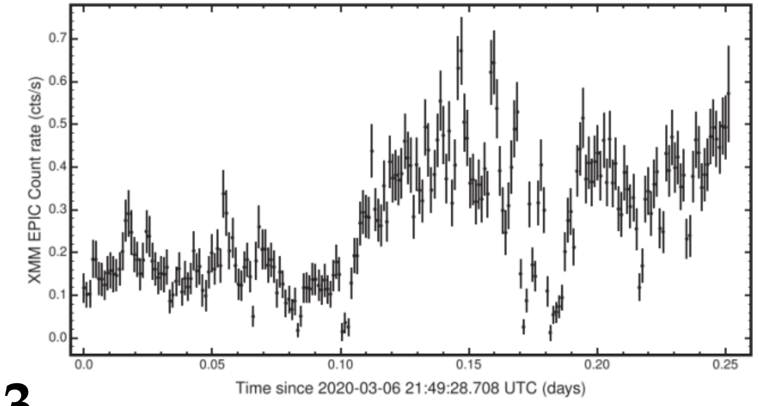
RXS J154439.4-112820
[Bogdanov et al., 2015, 2016; Britt et al., 2017]



CXOU J110926.4-650224
[Coti Zelati et al., 2019, 2021]



4FGL J0407.7-5702
[Li et al., 2020; Miller et al., 2020]



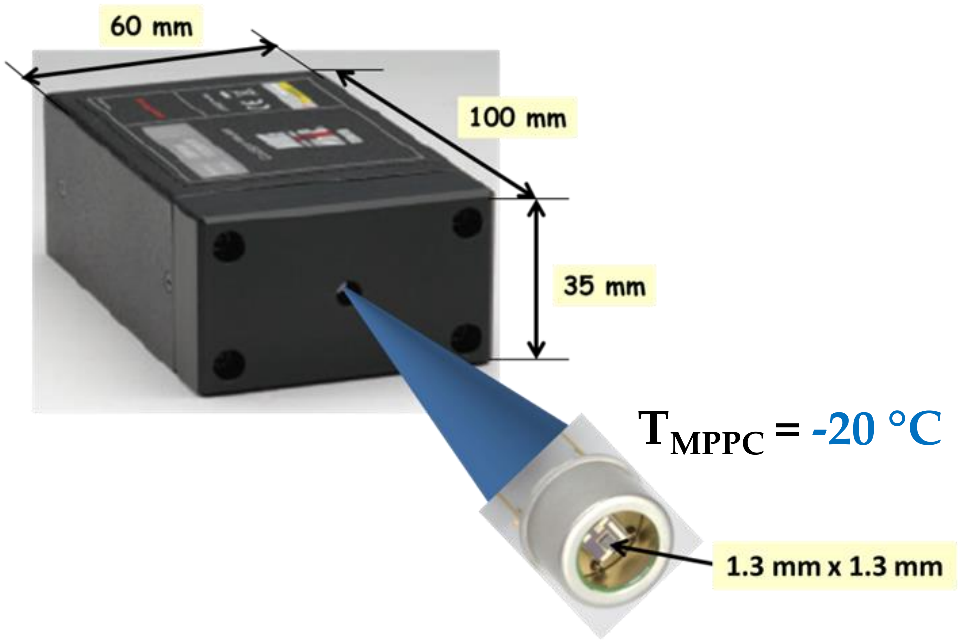
3FGL J0427.9-6704, Terzan 5 CX10, XMM J174457-2850.3
[Strader et al., 2021; Kennedy et al., 2020; Deller et al., 2014]

Fast optical photometry: SiFAP2@TNG

https://www.tng.iac.es/instruments/sifap2/

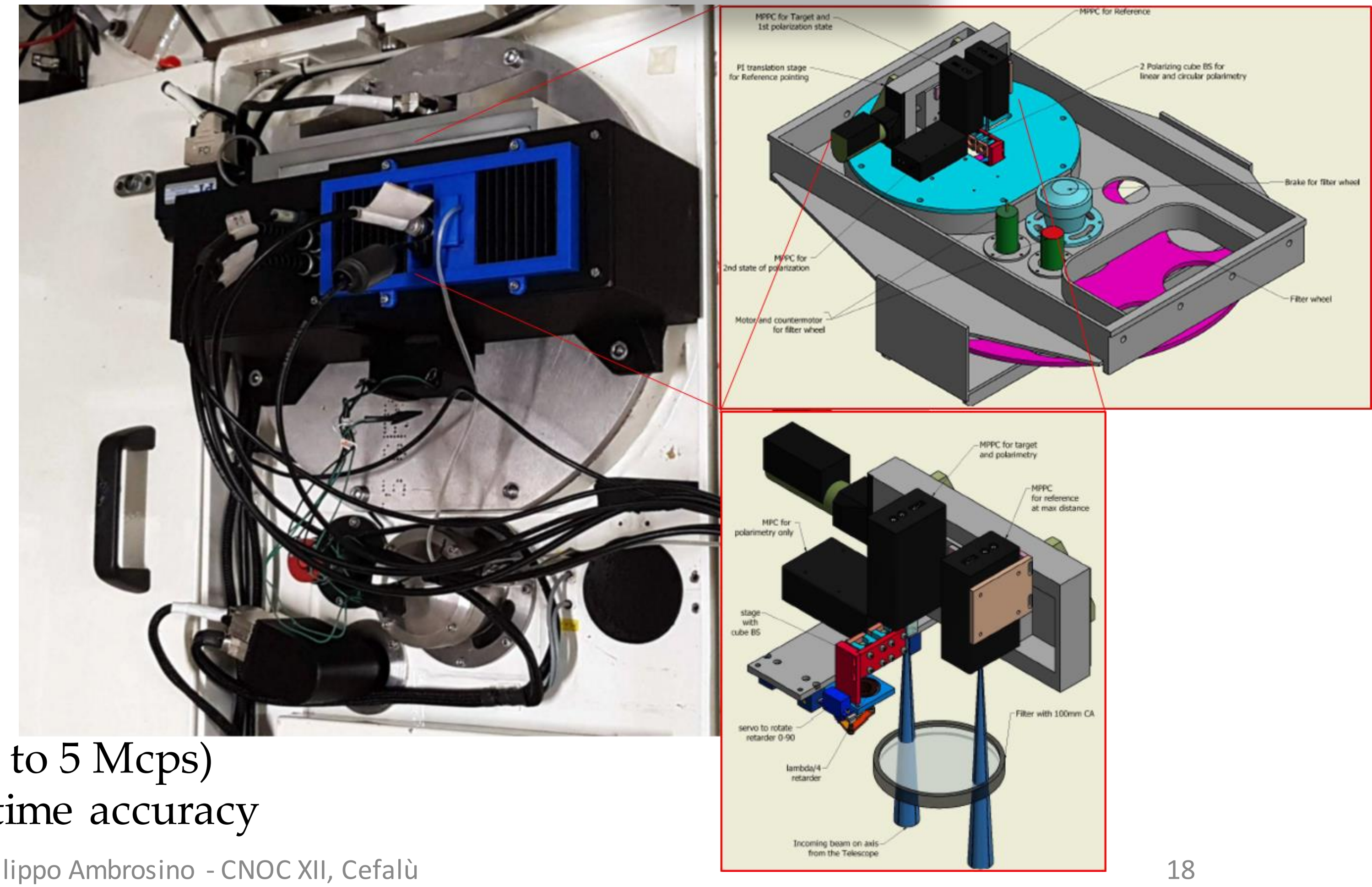
SiPM/MPPC

(320 – 900 nm band)



T_{MPPC} = -20 °C

Nasmyth A focus



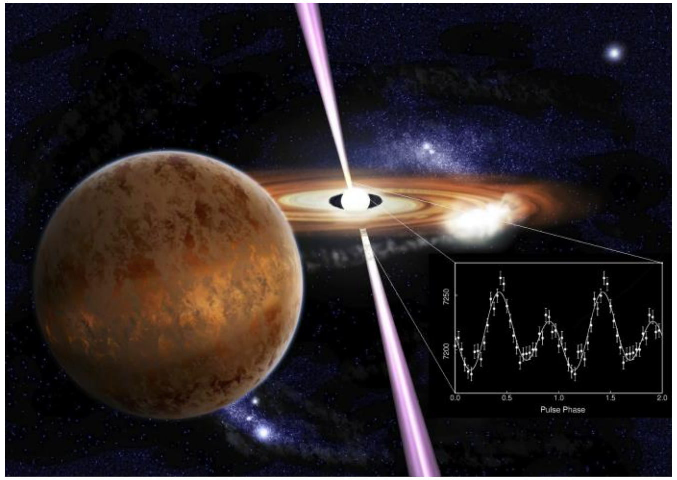
- Single photon counting capability
- Fast rise time (~2-5 ns)
- PDE up to 40%@450 nm
- Low dark count (~2 kcps)
- Very good linearity with high count rates (up to 5 Mcps)
- 8 ns relative time resolution; ~10 μs absolute time accuracy

Observational results: PSR J1023+0038

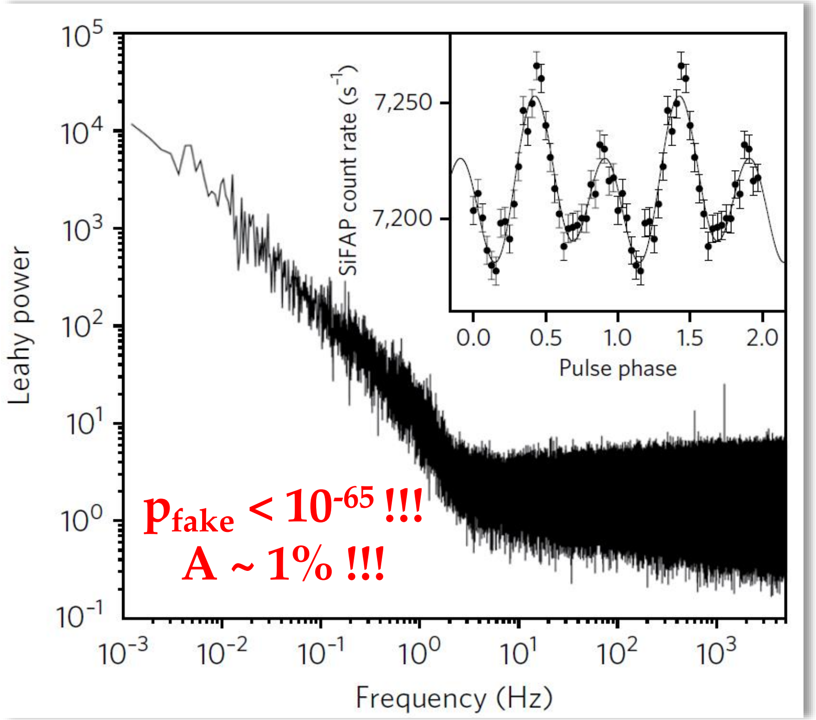
nature astronomy
LETTERS
DOI: 10.1038/s41550-017-0266-2

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]



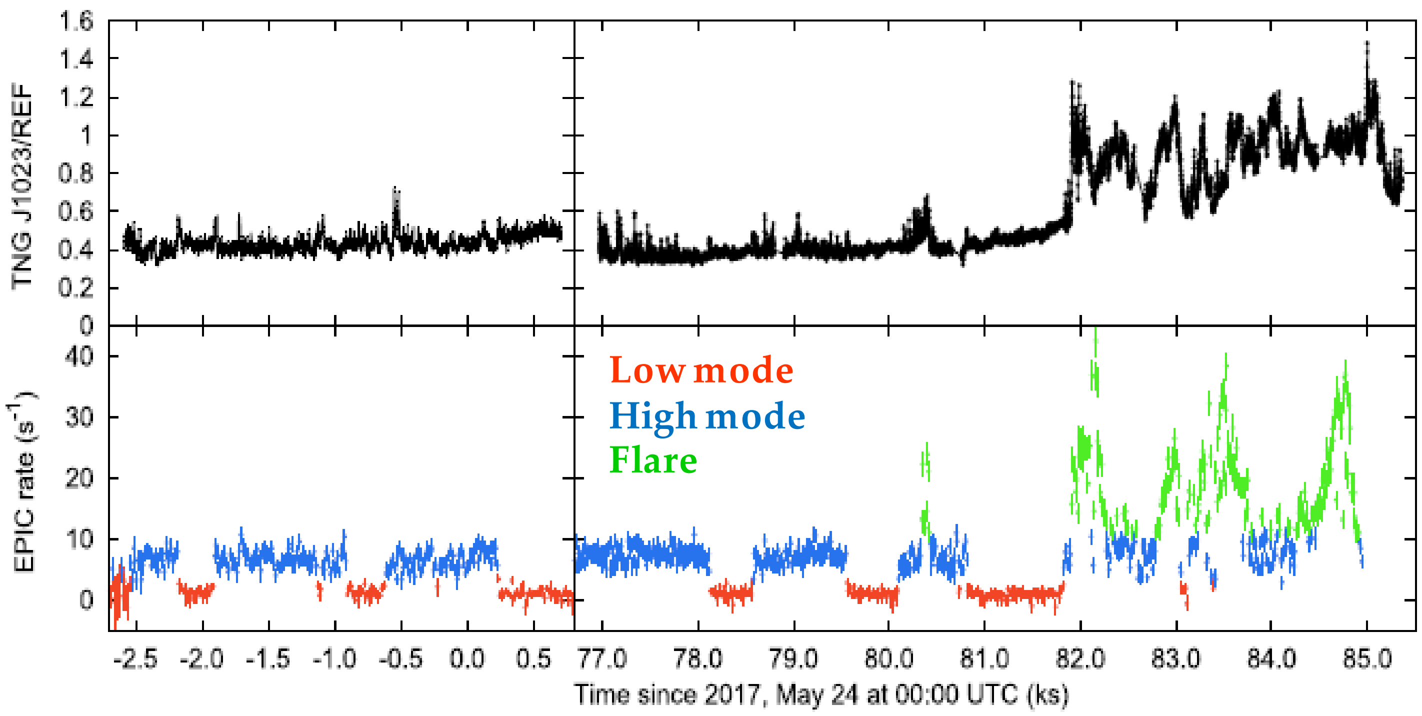
[Ambrosino, Papitto et al. 2017, Nature Astronomy]

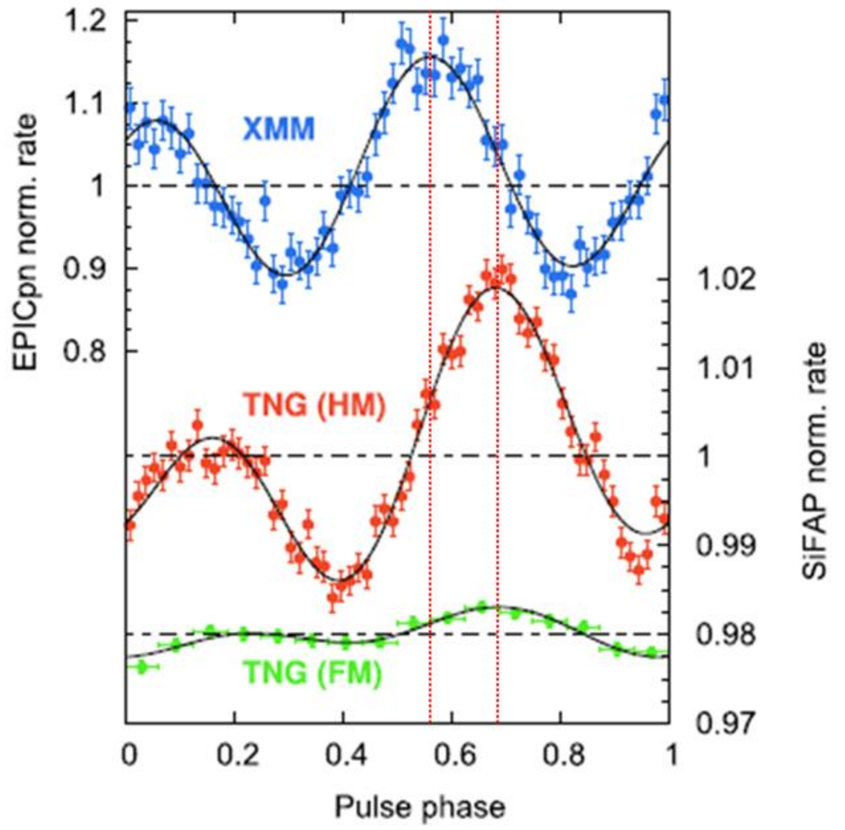


First optical pulsations from a tMSP discovered!!!

Observational results: PSR J1023+0038

[Papitto et al. 2019, ApJ]





Optical emission lags X-ray one by ~ **200 μs**

➔ **Common region** for both the optical and X-ray pulsed emissions

See Alessandro/Cristina/Giulia's talks

Observational results: SAX J1808.4-3658

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]

First optical/UV pulsations from an AMXP discovered!!!

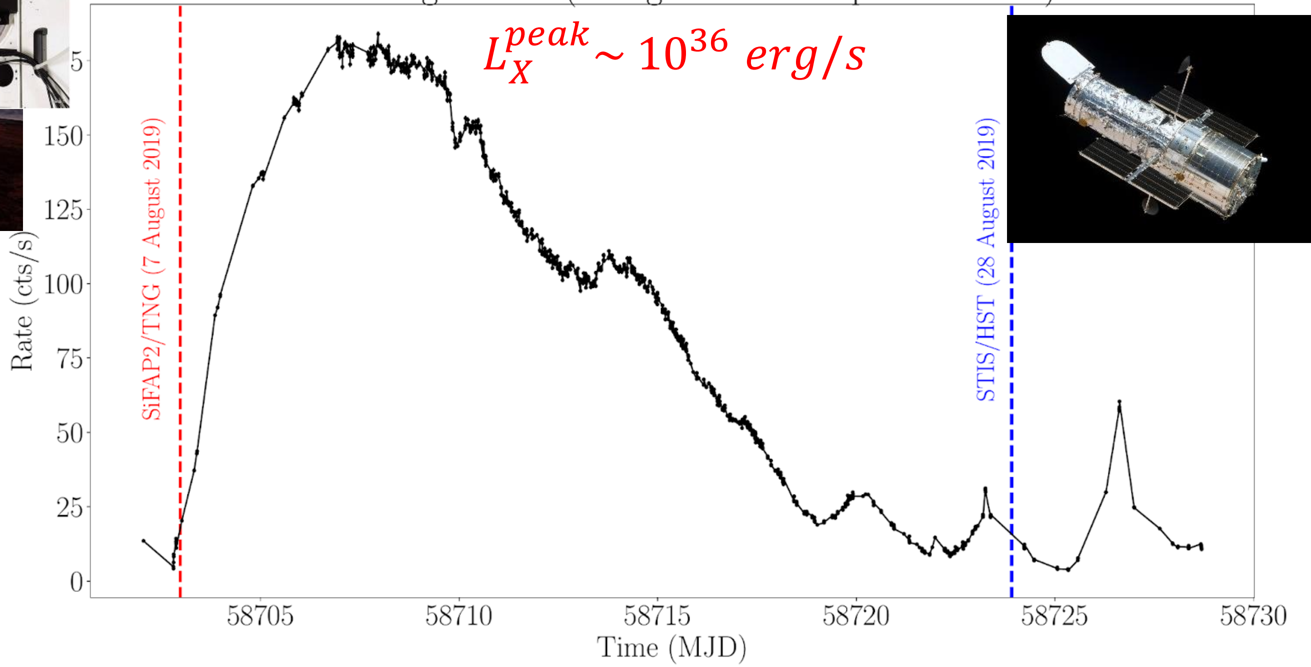
MULTI-WAVELENGTH CAMPAIGN OF SAX J1808.4-3658

- High time resolution **TNG/SiFAP2** observation (PI. Papitto)
  - 320-900 nm band
  - **7 August 2019**
  - duration: 3300 s
- Hubble Space Telescope **STIS/NUV-MAMA** observation (PI. Miraval Zanon)
  - spectroscopic observation in TIME-TAG mode
  - 157-318 nm band
  - **28 August 2019**
  - duration: 2240 s

SAX J1808.4-3658

➔ Orbital period: 2.01 hr
➔ Pulsar spin period: 2.5 ms

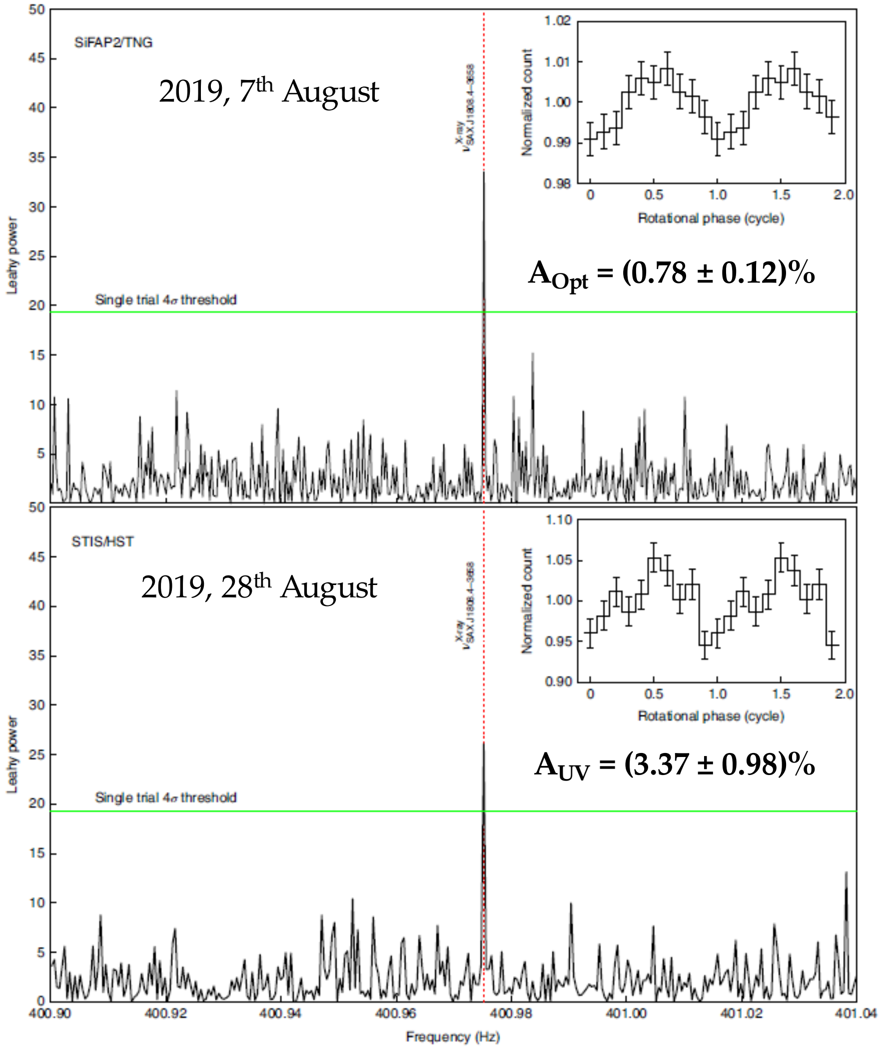
NICER light curve (7 August 2019-2 September 2019)

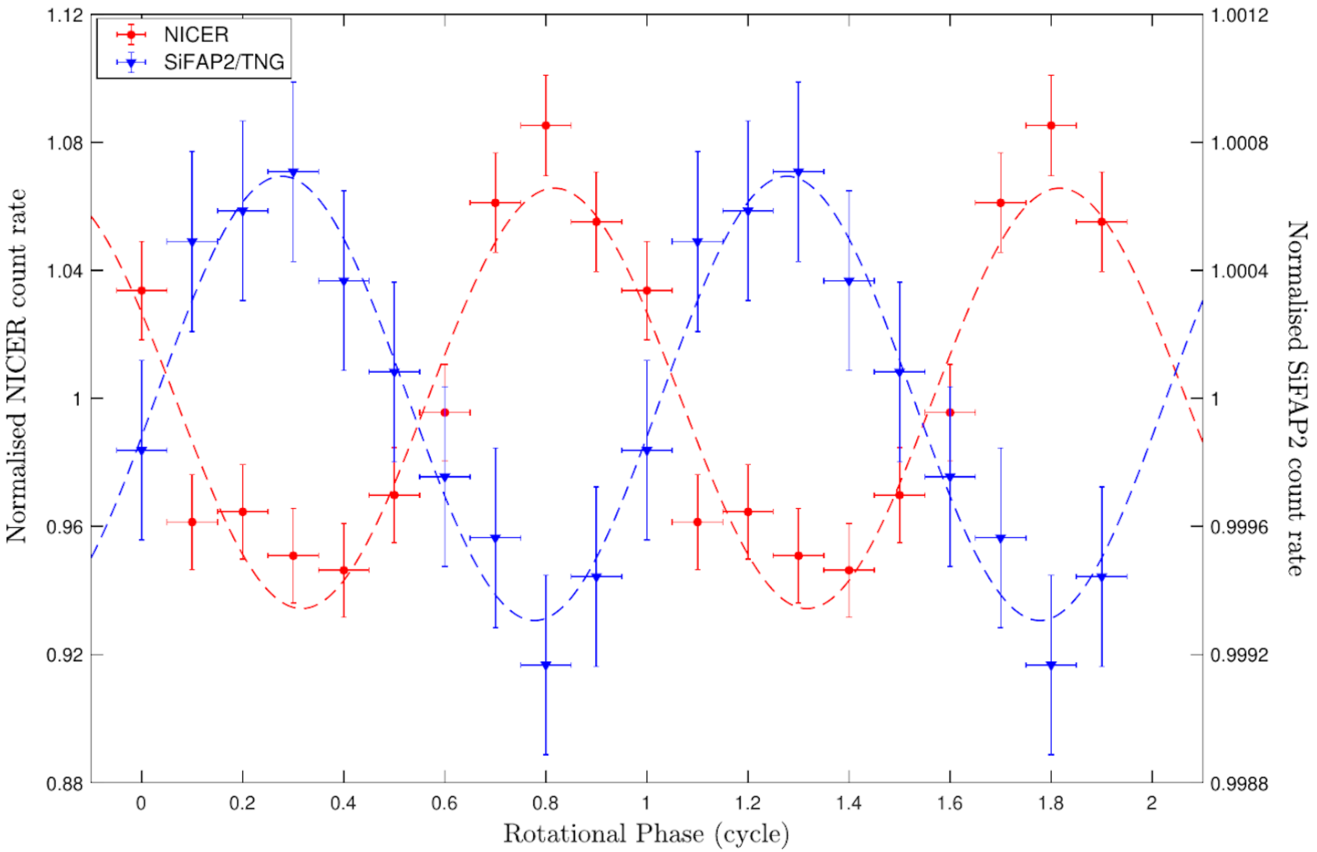


NICER observations

➔ monitoring of SAX J1808 in **outburst** from August to September

Observational results: SAX J1808.4-3658





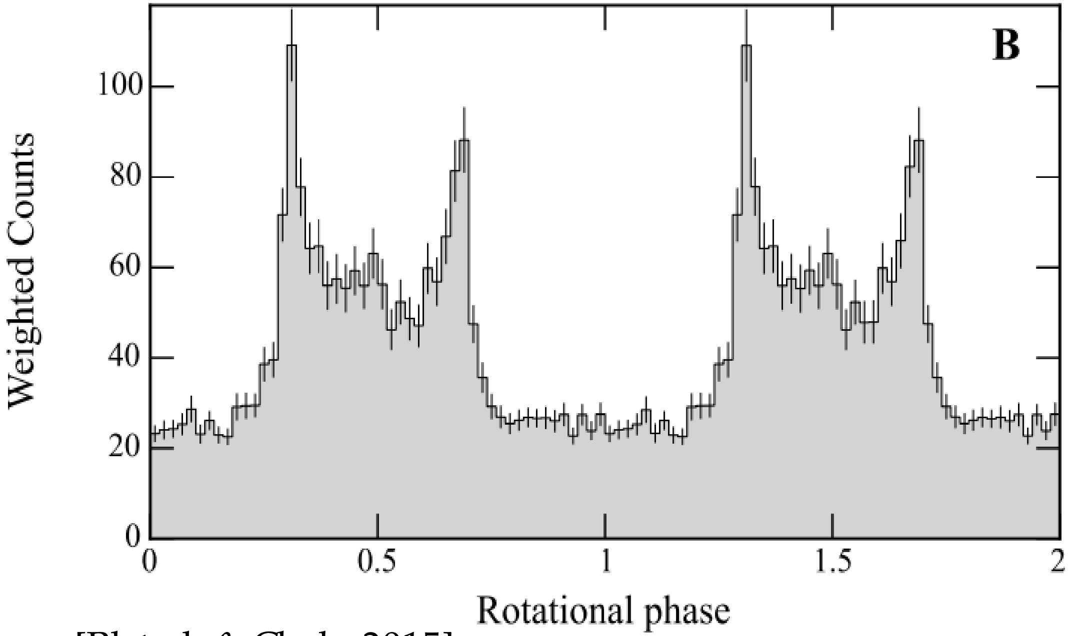
Optical and X-ray pulsed emissions
➔ **almost in antiphase**

August 2022 ➔ The source again in outburst See Arianna's talk

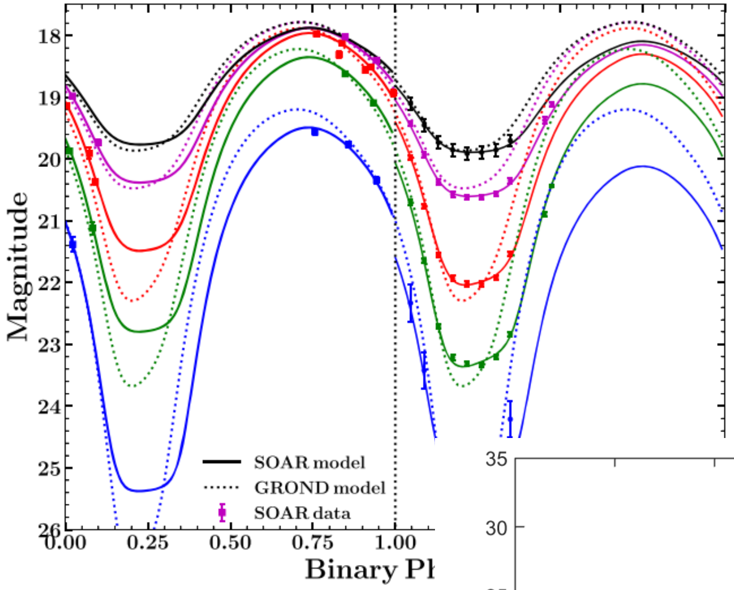
Observational results: PSR J2339-0533

(γ-ray/radio) RB pulsar with known orbital parameters

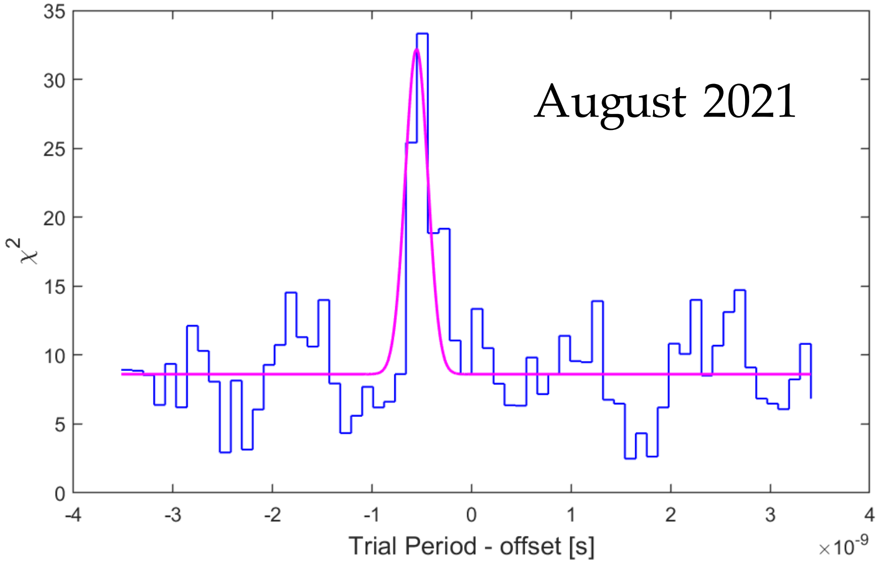
- Porb = 16683.7 s
- asin(i)/c = 0.611 lt-s
- ν_{spin} = 346.713 Hz



[Pletsch & Clark, 2015]



Using long-term timing solution

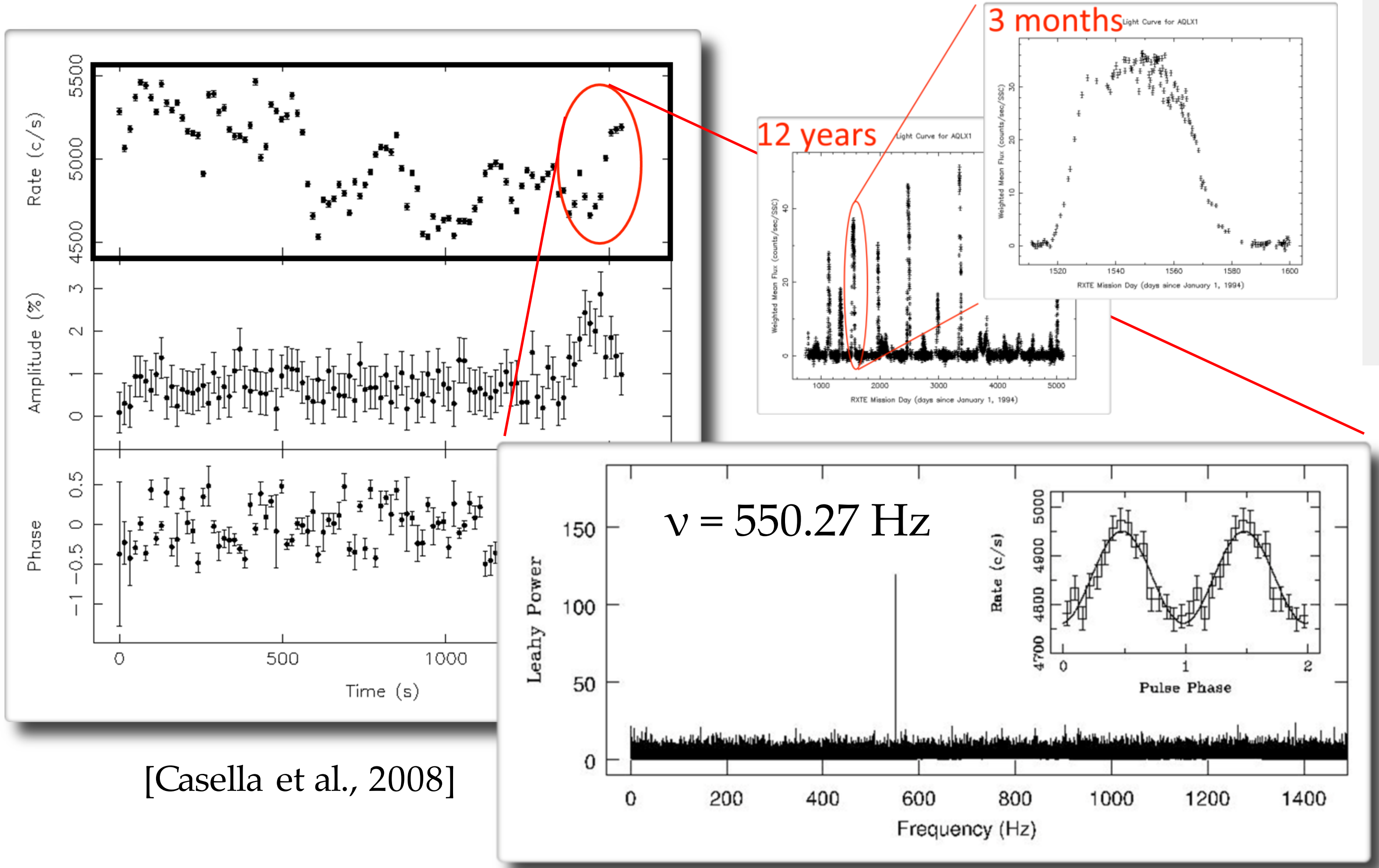


Waiting for **radio ephemeris** derived from the last (August 2022) **quasi-simultaneous observations** to fold optical data

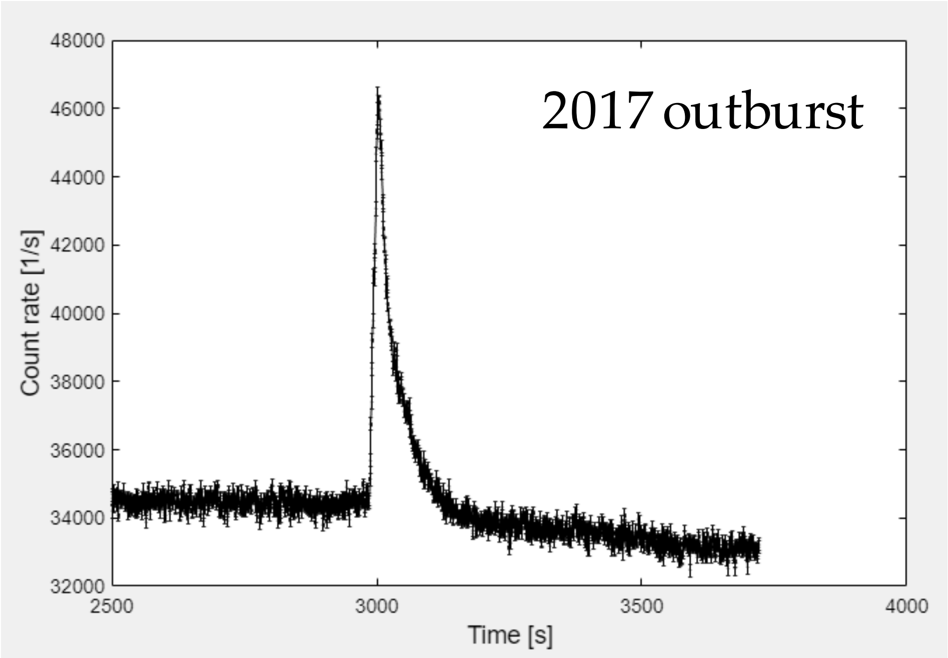
Observational results: Aql X-1

Intermittent accreting MSP

➔ X-ray pulsations found during outburst only once in 0.01% of total RXTE data



[Casella et al., 2008]



Search for optical pulsations from the burst with dynamic PSD

No pulsations found

Search for optical pulsations from MSPs with SiFAP2

- **RXS J154439.4-112820:** Candidate tMSP. Blind search on orbital parameters is still going on. We are trying to use genetic algorithms to search for pulsations (see Nicolò's talk)

- **PSR J1723-2837:** Eclipsing MSP with known radio orbital parameters. Candidate RB system with no γ-ray emission. Search on T_{asc} but no optical pulsations found.

- **PSR J1048+2339:** RB pulsar with known orbital parameters. Search on T_{asc} but no optical pulsations found.

- **PSR B1957+20 & PSR J1653-0158:** BW pulsars with known orbital parameters. Search on T_{asc} but no optical pulsations found so far. Analysis is still going on.

- **PSR J2129-0429:** RB pulsar with known orbital parameters. Many hours of observation, search on T_{asc} to be completed.

Open questions and future perspectives

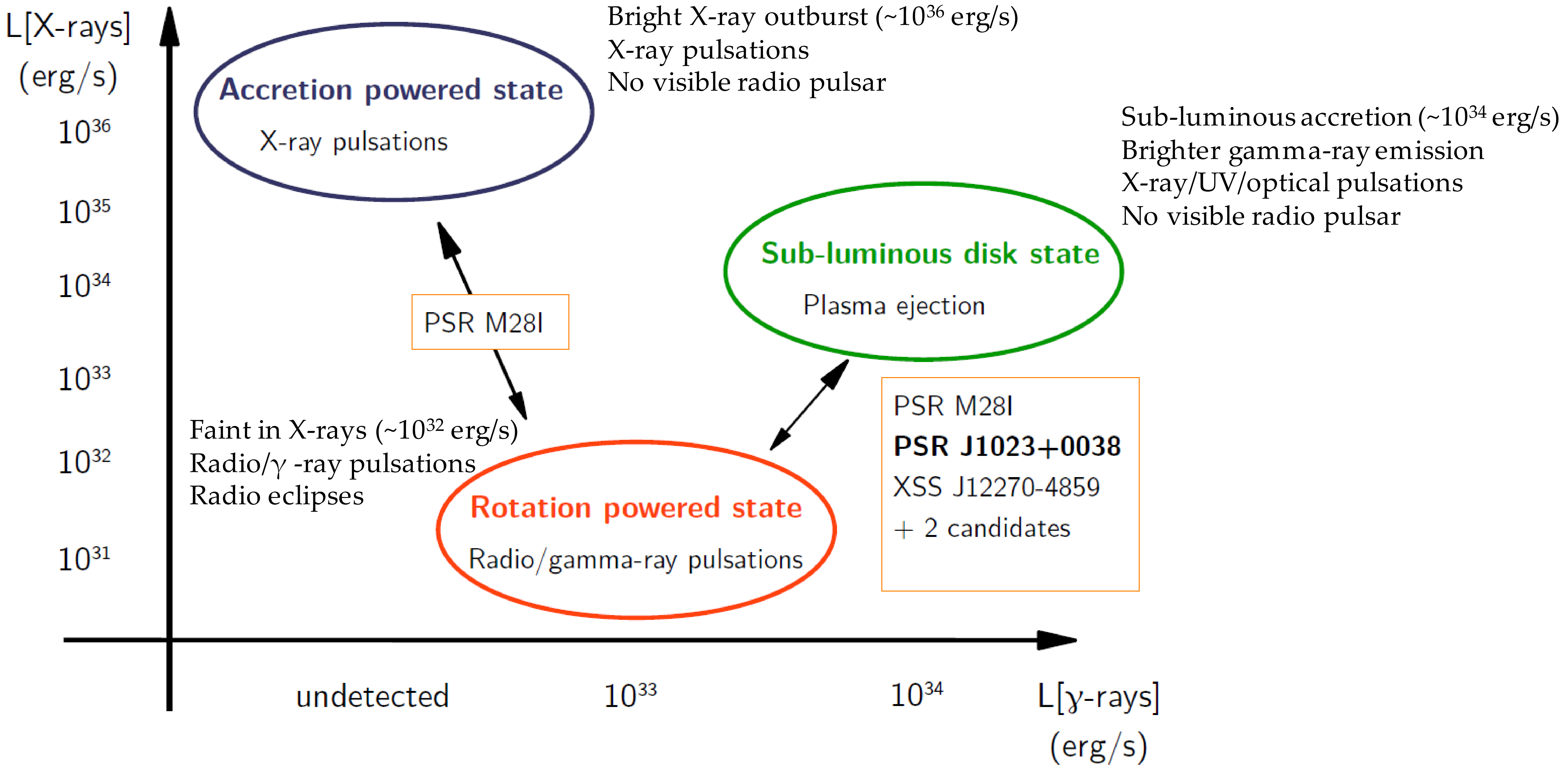
- *What is the process that produces the optical, UV and X-ray pulses in tMSPs and AMXPs?*
- *Do the optical/UV pulsations persist at the peak of the outburst, during the radio pulsar state or the quiescence?*
- *Can rotation-powered and accretion-powered mechanisms coexist?*

➔ Searching for optical and UV pulsations in other AMXPs (HST/XMM-Newton/TNG)
➔ Optical observations of SAX J1808.4-3658 during quiescence with SiFAP2/TNG
➔ Optical observations of binary millisecond radio pulsars (RBs and BWs)

- SiFAP4XP ➔ new instrument for simultaneous polarimetric measurements with IXPE
- Feasibility study of nIR photometry ➔ **PRIN MUR**
- **e-SiFAP** funded by **PNRR** ➔ optical/nIR photopolarimetry

Back-up slides

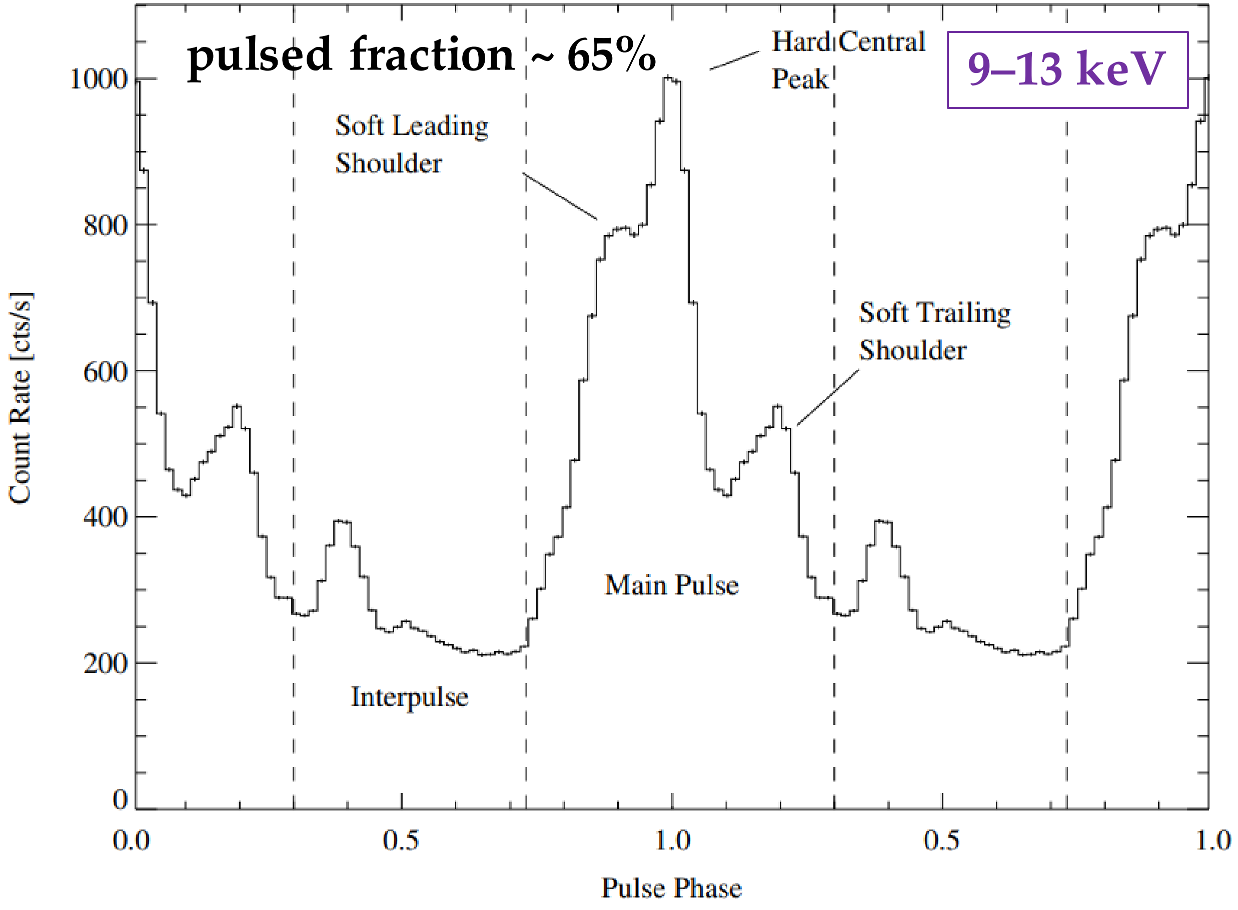
Three states of tMSPs



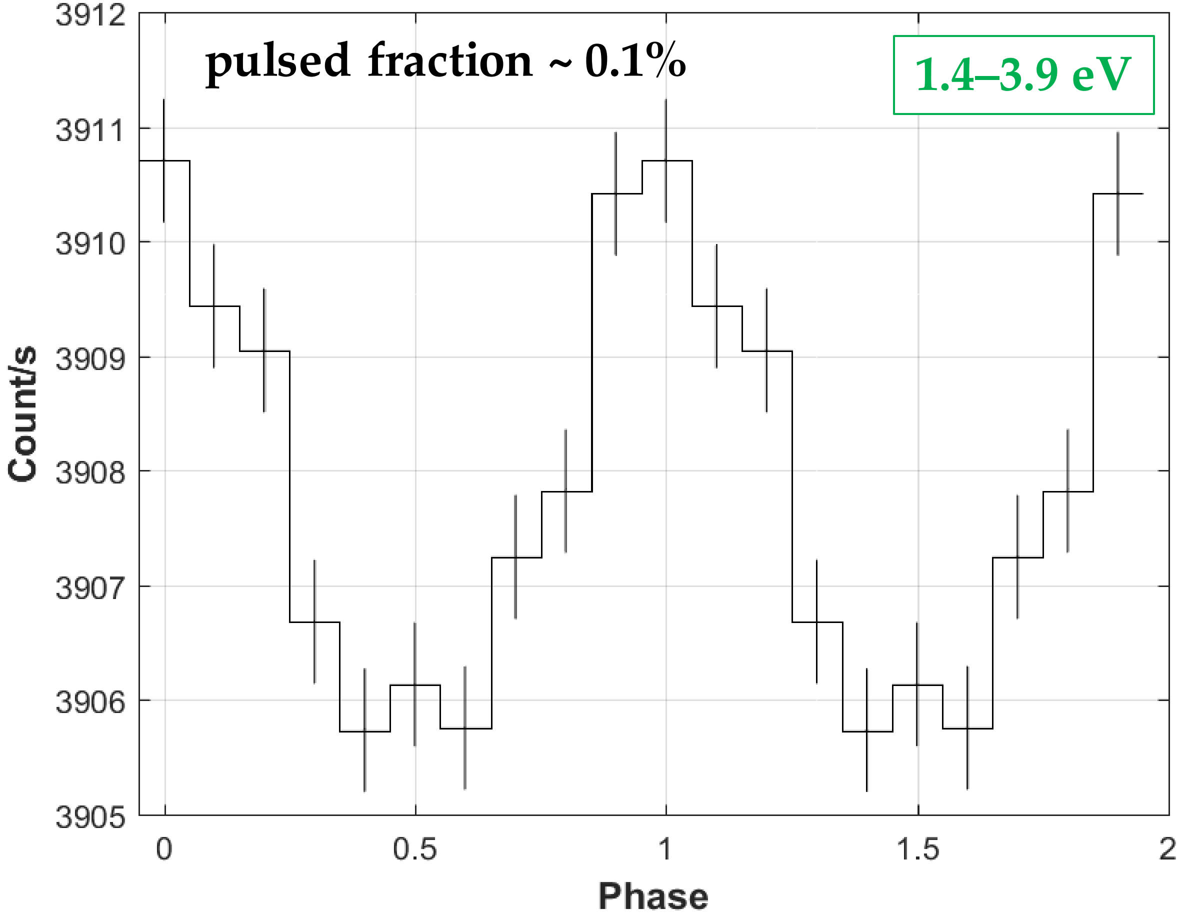
First observational Results:

Her X-1/HZ Her binary system

RXTE satellite light curve



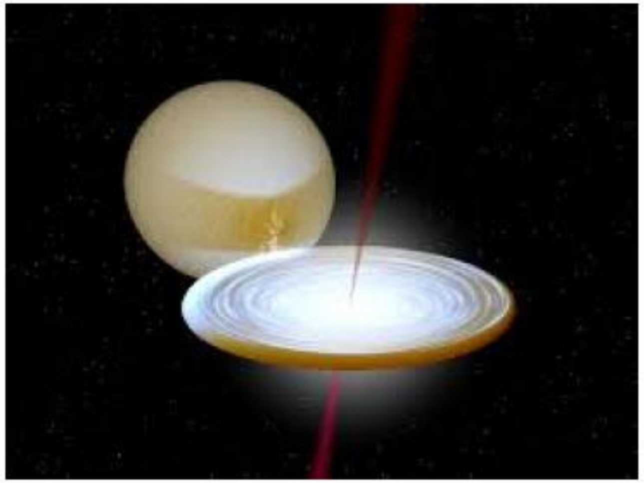
SiFAP light curve

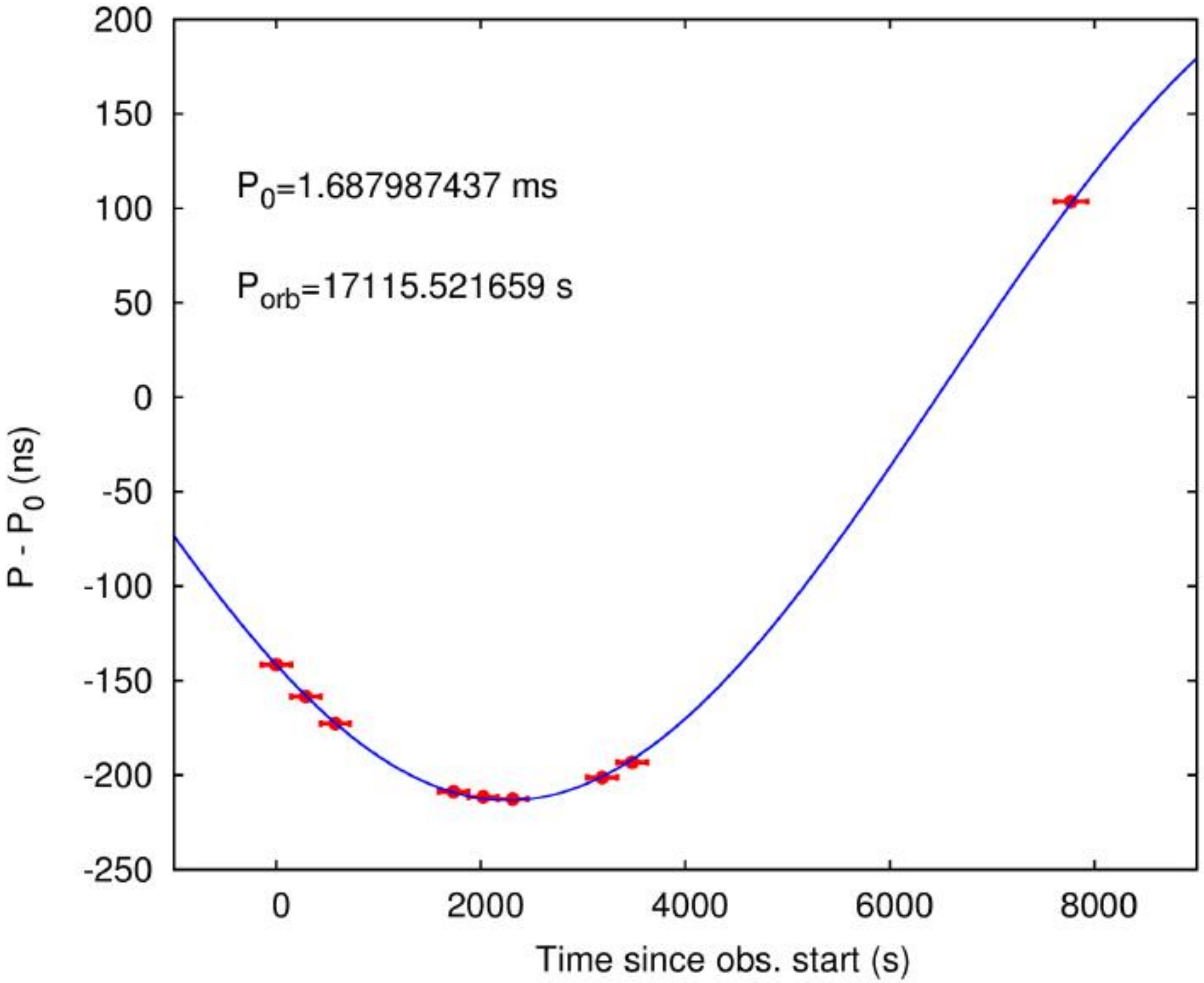


Observational results:

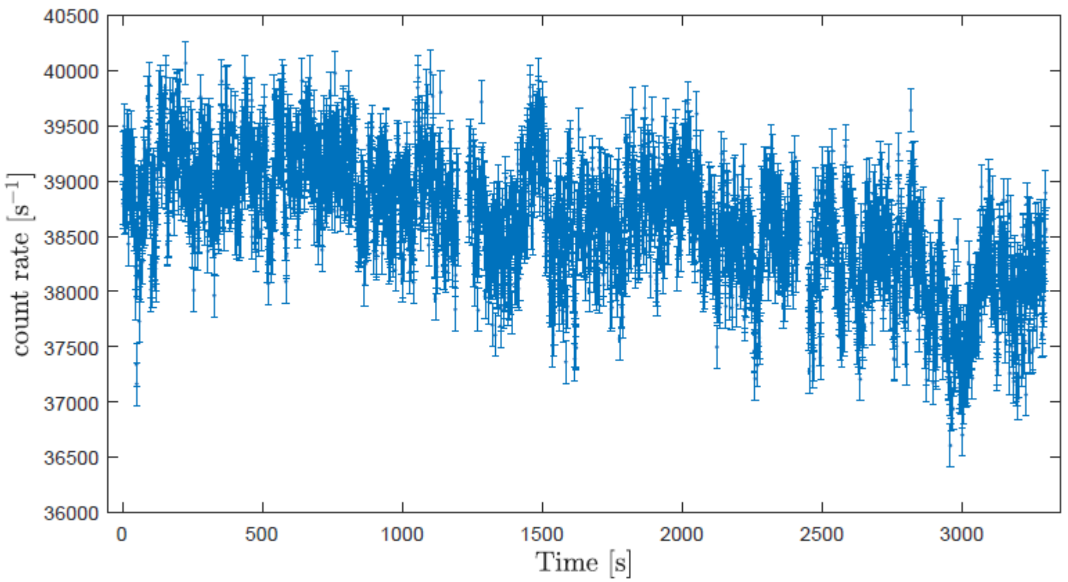
PSR J1023+0038

Spin period variations as a function of the orbital phase



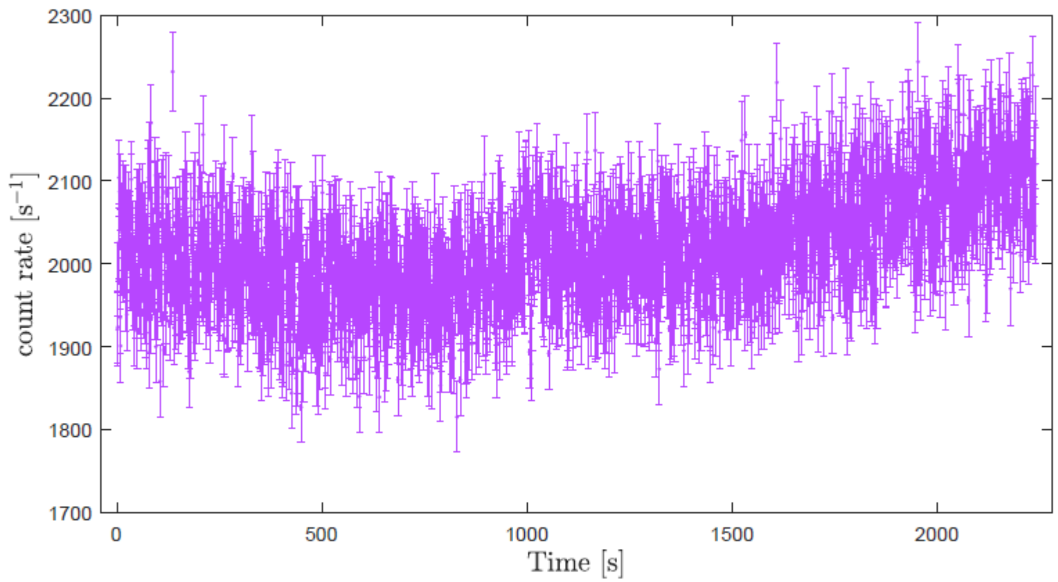


Observational results: SAX J1808.4-3658



SiFAP2/TNG

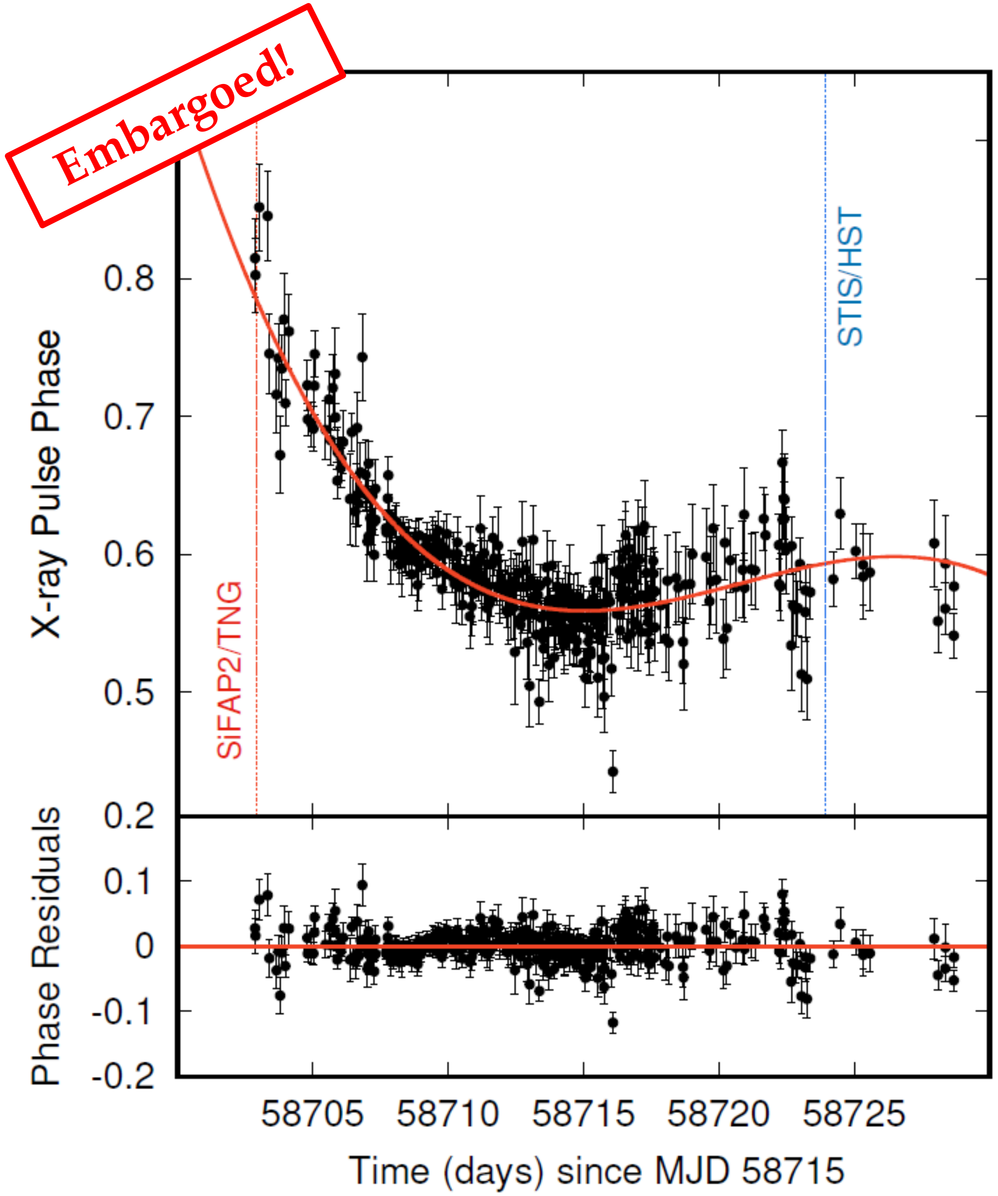
⇒ T exp: 3.3 ks
⇒ Time-tag mode (8 ns resolution)
⇒ Clear filter (320 - 900 nm)
⇒ Variable seeing: 0.5 - 0.9 arcsec
⇒ Airmass: 2.5
⇒ Moon: 47° angular distance



STIS(NUV-MAMA)/HST

⇒ T exp: 2.2 ks
⇒ Time-Tag mode (125 μs resolution)
⇒ G230L grating (165 - 310 nm)

Observational results: SAX J1808.4-3658



NICER observations during the whole outburst

➔ measurement of SAX J1808.4-3658 ephemeris, crucial to **reconstruct** UV/optical **pulse profiles**

Table 1 | X-ray, UV and optical ephemeris of SAX J1808.4−3658 during the August 2019 outburst

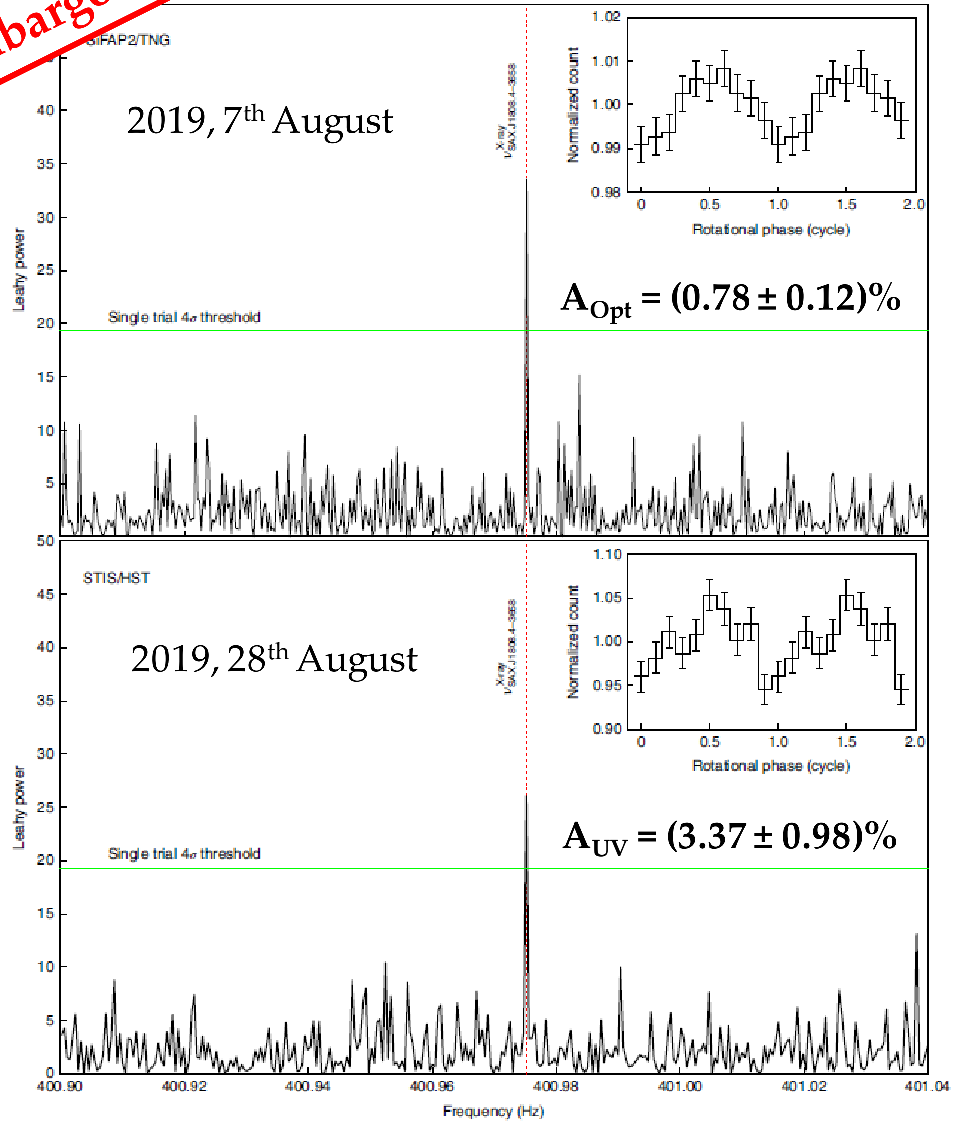
Parameter	X-ray	UV	Optical
Right ascension[a] (α, J2000)	18 h 08 m 27.62 s	–	–
Declination[a] (δ, J2000)	−36° 58′ 43.3″	–	–
Validity range (MJD)	58702-58726		
Reference epoch T_{ref} (MJD)	58715.0	–	–
Time system	TDB	TDB	TDB
Planetary ephemeris	DE405	DE200	DE405
Spin frequency ($\nu(T_{ref})$) (Hz)	400.975209660(9)	–	–
Spin frequency ($\nu(T_{TNG})$)[b] (Hz)	400.975210179(63)	–	400.975225(72)[d]
Spin frequency ($\nu(T_{HST})$)[c] (Hz)	400.975209618(36)	400.97517(10)[d]	–
Spin frequency first derivative ($\dot{\nu}$) (Hz s^{-1})	$-(2.43 \pm 0.21) \times 10^{-13}$	–	–
Spin frequency second derivative ($\ddot{\nu}$) (Hz s^{-2})	$(4.9 \pm 1.1) \times 10^{-19}$	–	–
Orbital period (P_b) (s)	7249.1572(14)	–	–
Time of ascending node ($T^{\star}$) (MJD)	58715.0220987(32)	–	–
Projected semi-major axis (light seconds)	0.0628099(35)	–	–
χ^2/d.o.f.	550/378	–	–

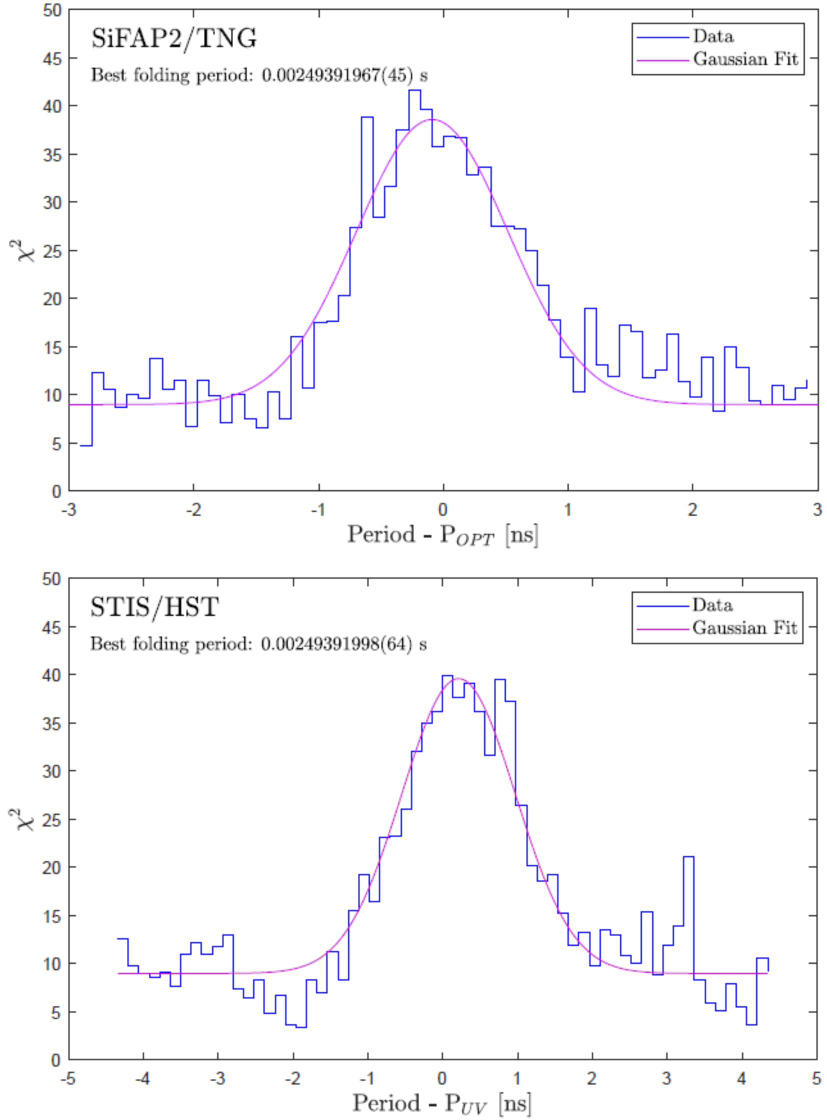
[a]Values taken from ref. [39]. [b]Observation carried out on 7 August 2019 (T^{TNG}_{Start} = 58702.9382176 MJD(UTC)) with SiFAP2/TNG. [c]Observation carried out on 28 August 2019 (T^{HST}_{Start} = 58723.9080081 MJD(UTC)) with STIS/HST. [d]Obtained with the epoch folding search technique. d.o.f., degrees of freedom; MJD, modified Julian date; TDB, barycentric dynamical time.

Observational results: SAX J1808.4-3658

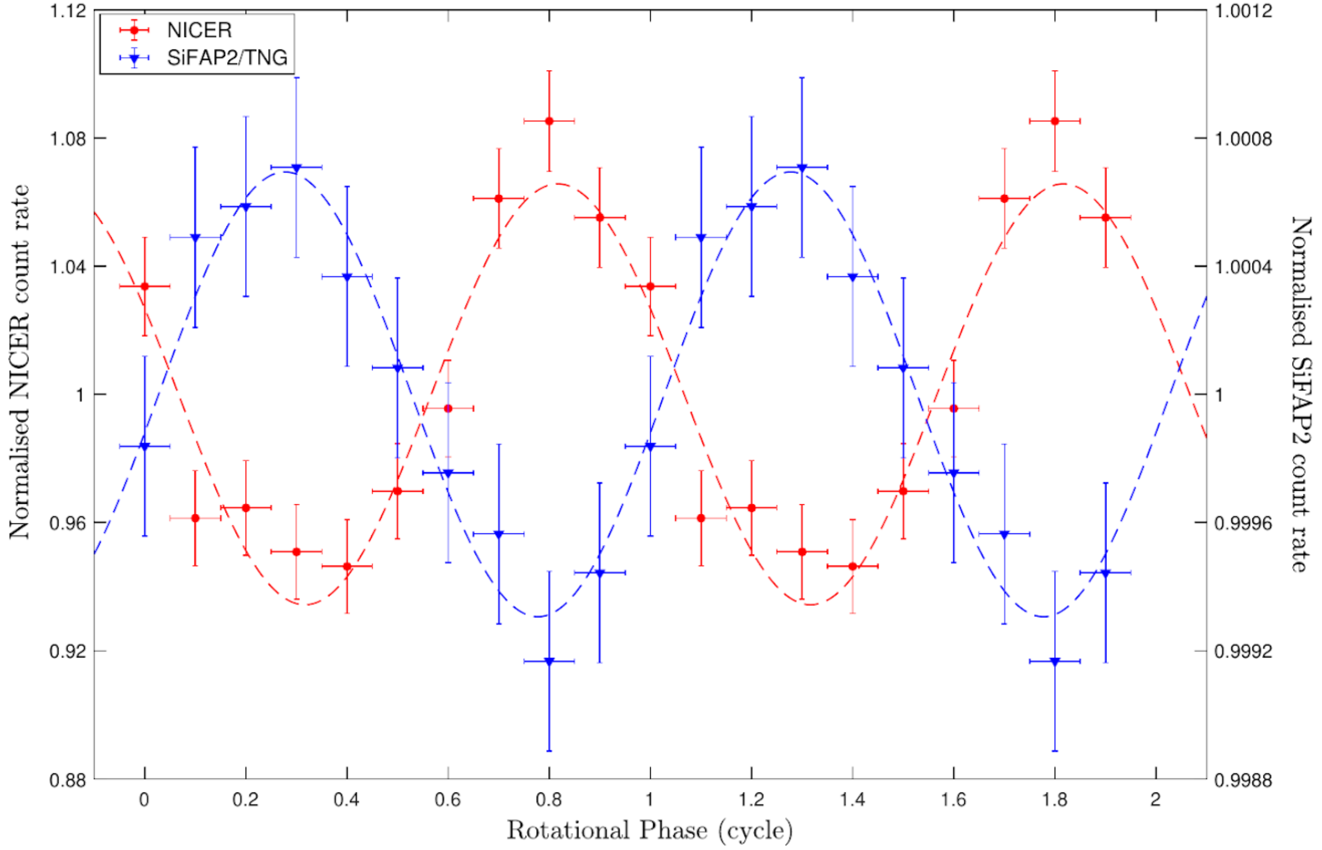
First optical/UV pulsations from an AMXP discovered!!!

Embargoed!





Observational results: SAX J1808.4-3658



Possible models

Cyclotron emission?

(matter accreting onto the polar caps of the NS)

➔ **not powerful enough** to explain pulsed optical luminosity!

Thermal emission?

(from hot concentric rings surrounding the polar caps of NS)

➔ **Fitting with a blackbody** gives a temperature **≳ 1 MeV!**

Reprocessing?

(the emission region of optical/UV pulsations must be $< f\,cP_{spin} \sim 350$ km)

➔ **Fitting with a blackbody** gives a temperature **≳ 1 MeV!**

Our interpretation for Optical & UV pulsed emission

Star-disk interaction with high magnetic diffusivity in the disk can open the NS field lines, causing:

- the increase in the strength of the relativistic pulsar wind
- a high efficiency in the rotation-powered emission
- the observed spin-down during outbursts

- X-ray pulsed emission from accretion-powered mechanism
- UV/optical pulsed emission from rotation-powered mechanism

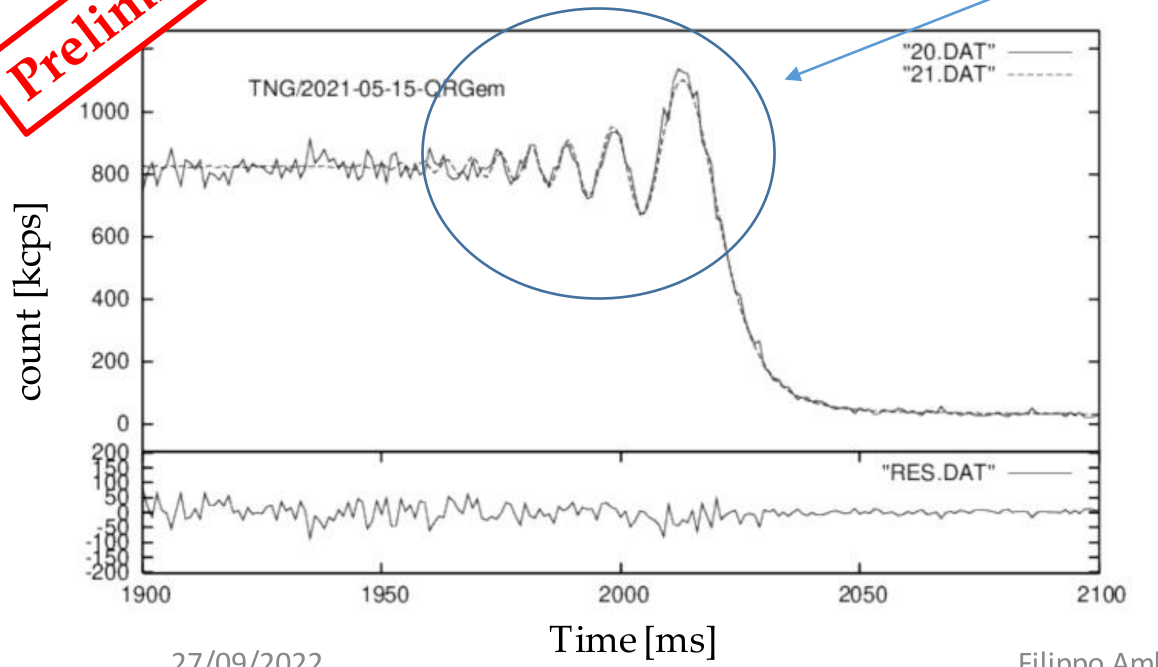
Observational results: Lunar Occultations

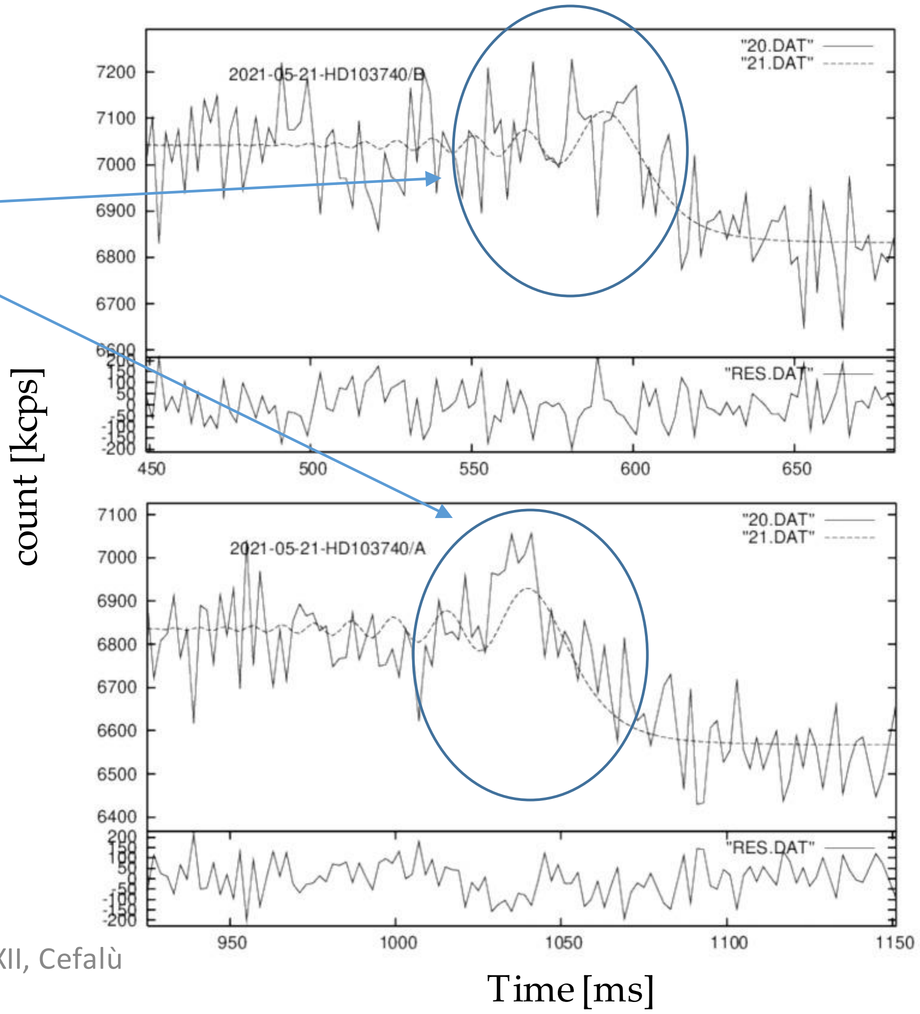
QR Gem: V = 7.65
Occultation on 13th May 2021 @21:37:43.028 UT
Mag drop: 3.5
Moon Phase: 15%
Filter: Hα (800 kcps down to 50 kcps)
Angular size: 2.05(1) mas (UL) with an empirical estimate of 1.7(1) mas
S/N: 30

HD103740: V = 7.60, double star
Occultation on 21th May 2021 @20:23:48.617 and @20:23:49.066 UT
Moon Phase: 73%
Filter: Hα (7100 kcps down to 6600 kcps and saturation)
S/N: 3

Preliminary

Diffraction fringes visible!!!



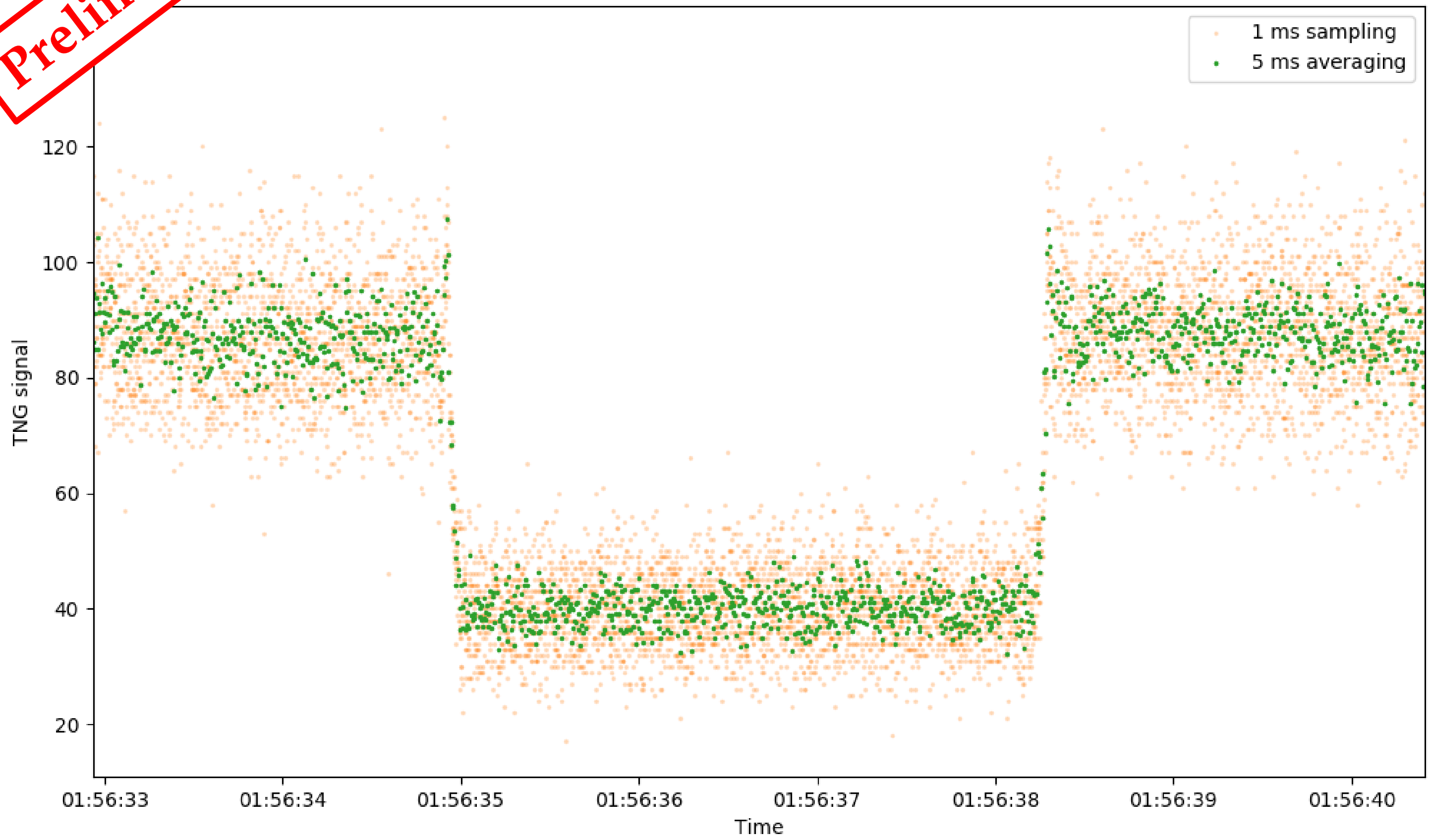


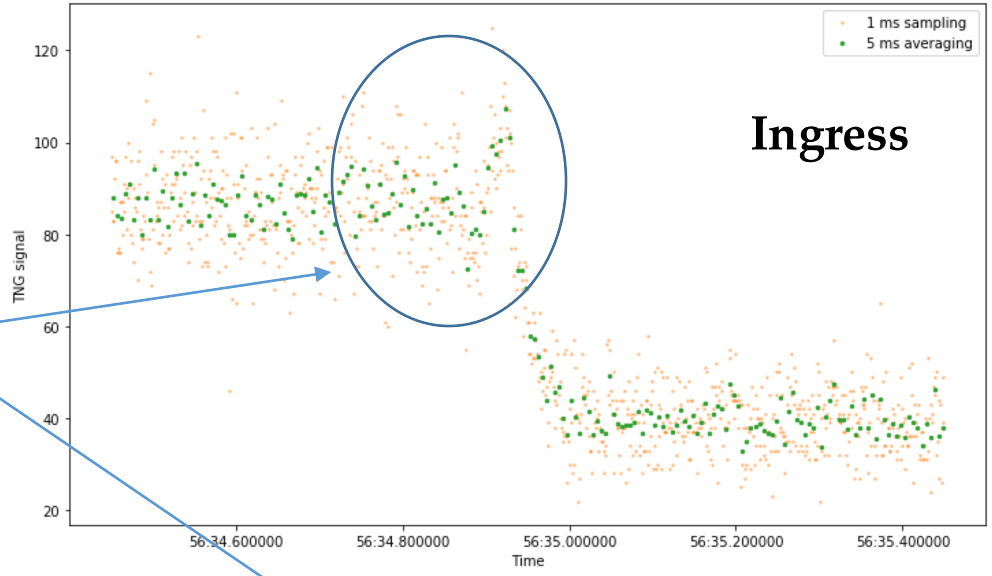
Observational results: an asteroidal Occultation

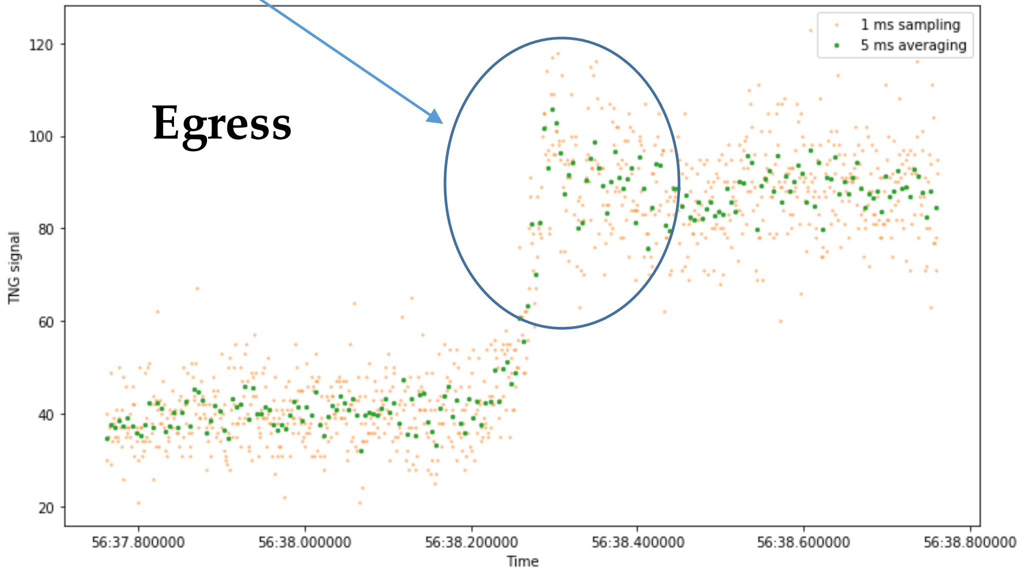
UCAC4 340-082004: V = 11.7
Occultation on 21th May 2021 @01:56:35 UT
Mag drop: 1.3
Moon Phase: 73%
Filter: Sloan r (90 kcps down to 40 kcps)

Preliminary

Two diffraction fringes visible!!!

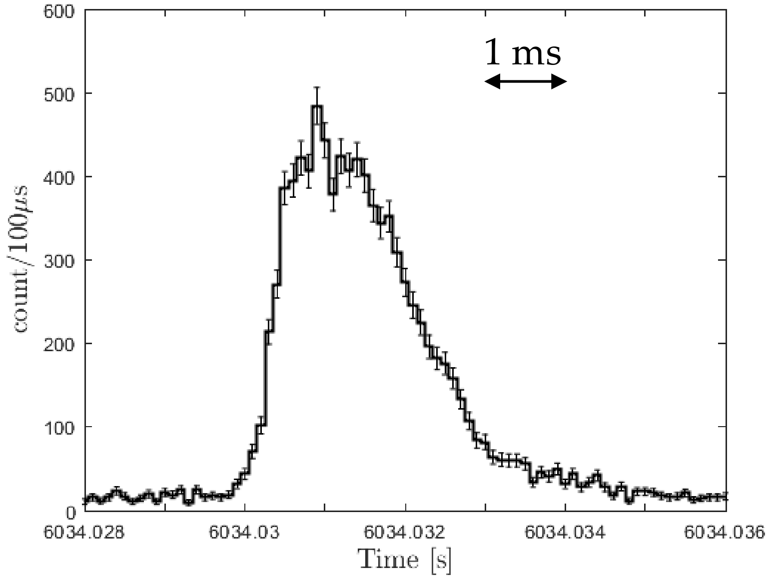




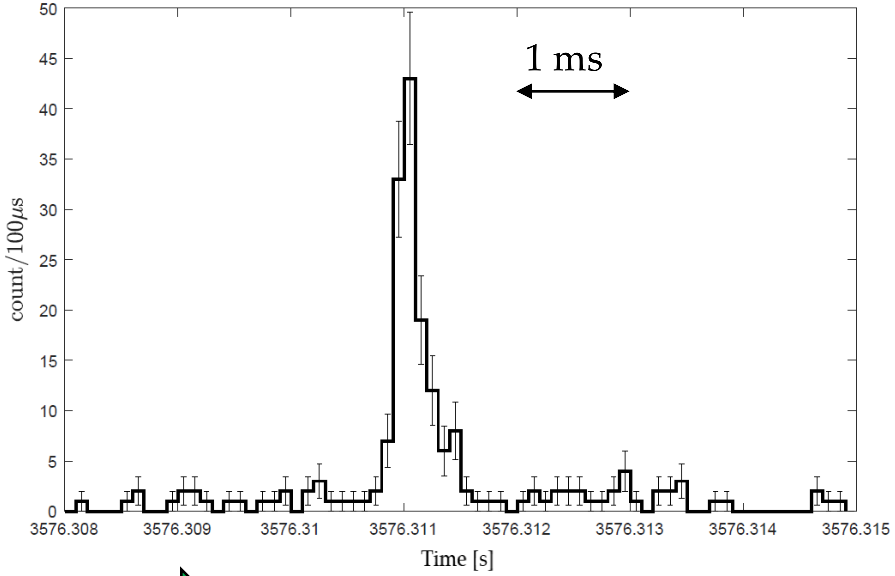


Observational results: Fast Optical Bursts (FOBs)

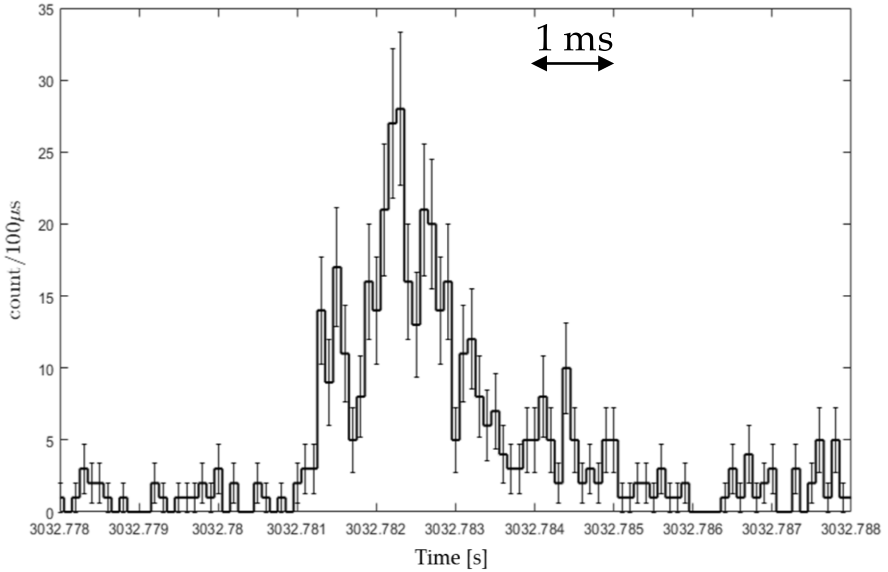
Pulsar



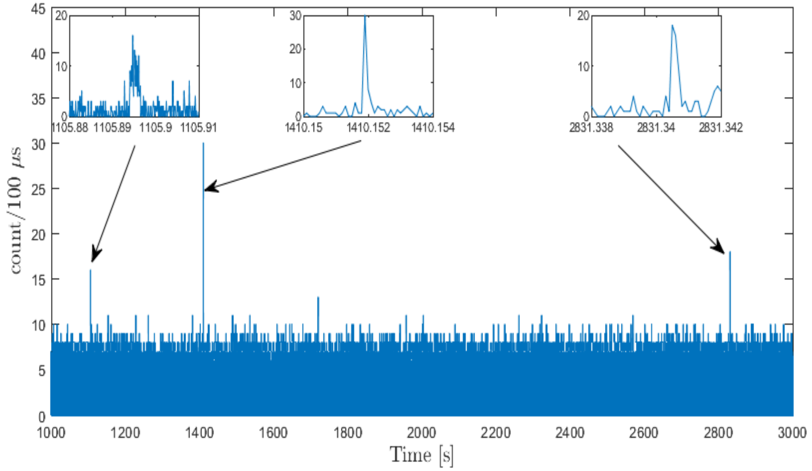
FRB



Magnetar



Pulsar



A new class of fast (~ ms) optical transients?

Rate of ~1/hr!!!

- Meteor? (rate of FOBs several orders of magnitude higher than that expected for meteors from MAGIC estimates)
- Space debris?
- Satellites passages?
- Atmospheric origin (optical flashes)?

Need for more statistics to identify the optical counterpart of impulsive events without simultaneous MWL campaigns!

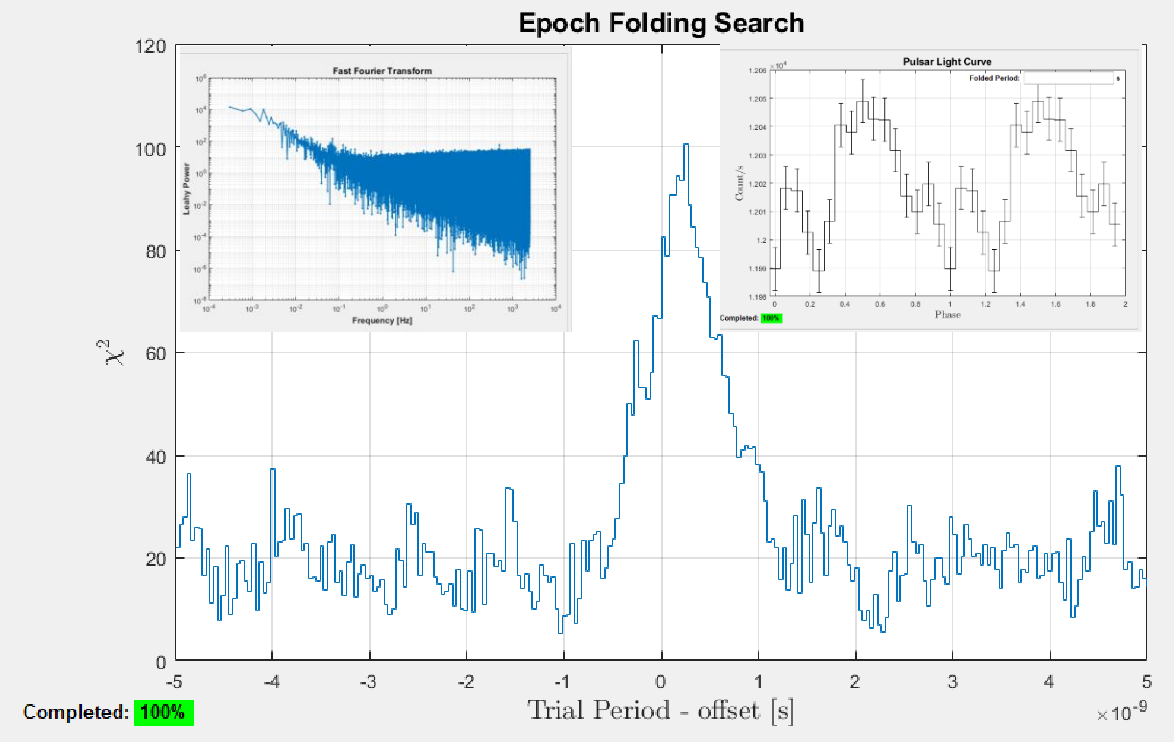
Observational results:

3FGL J1544.6-1125

A candidate transitional millisecond pulsar

- ➔ Light curve similar to PSR J1023+0038
- ➔ Unknown projection of semi-major axis (a·sin(i)/c)
- ➔ P_{orb} = 20868.7 s
- ➔ No X-ray/radio pulsations ever detected

Searching for optical pulsations…



SiFAP acquisition on April 2018

- ➔ Restricted blind search on T_{asc} and a·sin(i)/c
  - Found a not significant peak at ~ 2.1 ms spin period
- ➔ Not reproducible result in further observations

Work in progress to extend the blind search on

- ➔ T_{asc}
- ➔ a·sin(i)/c
- ➔ No search on P_{orb}

Need for a huge amount of

- ➔ computational resources
- ➔ computational time