Highs, Lows, and Flares
A Multi-band View of Shocks and Outflows in transitional millisecond pulsars

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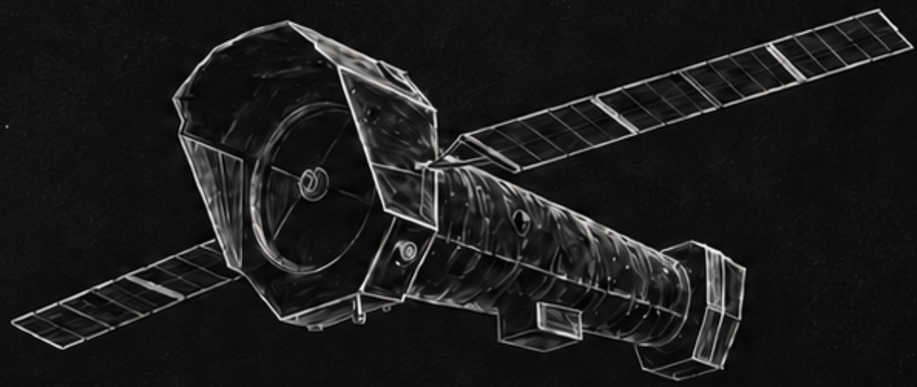
S. Campana, P. D'Avanzo, M. Messa (INAF - OAB),
A. Papitto, P. Casella (INAF -OAR)....



Barcelona, 3 June 2026

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)
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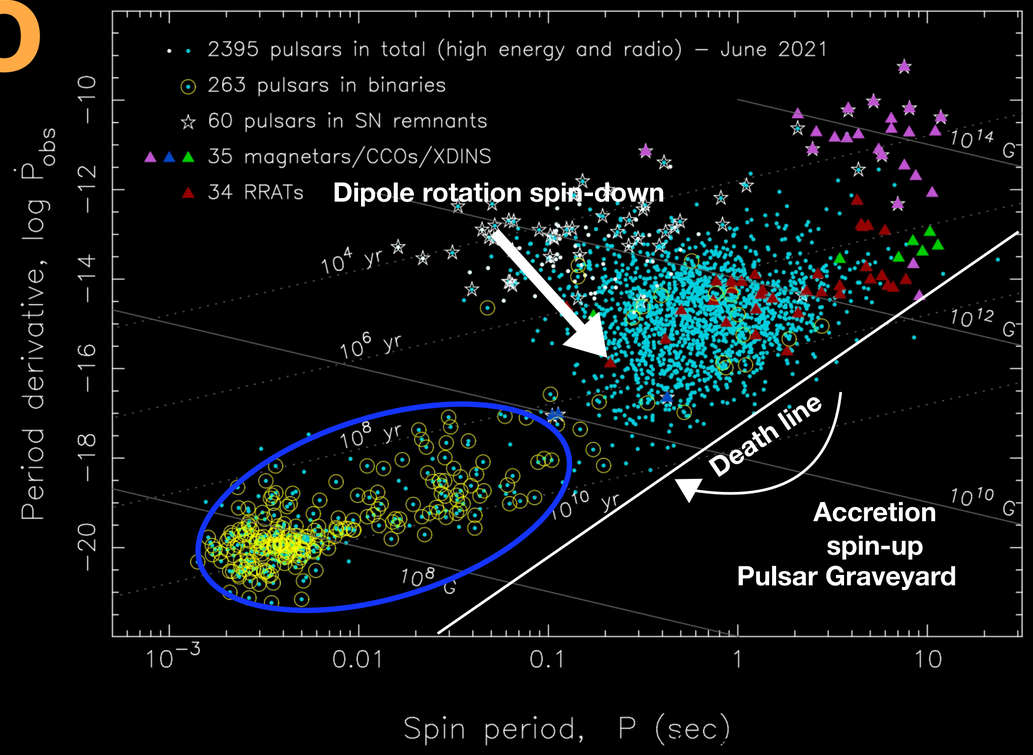
MSPs: Fast-spinning, weakly magnetized NSs

Often found in globular clusters (old objects)

Often in binaries (low-mass companion)



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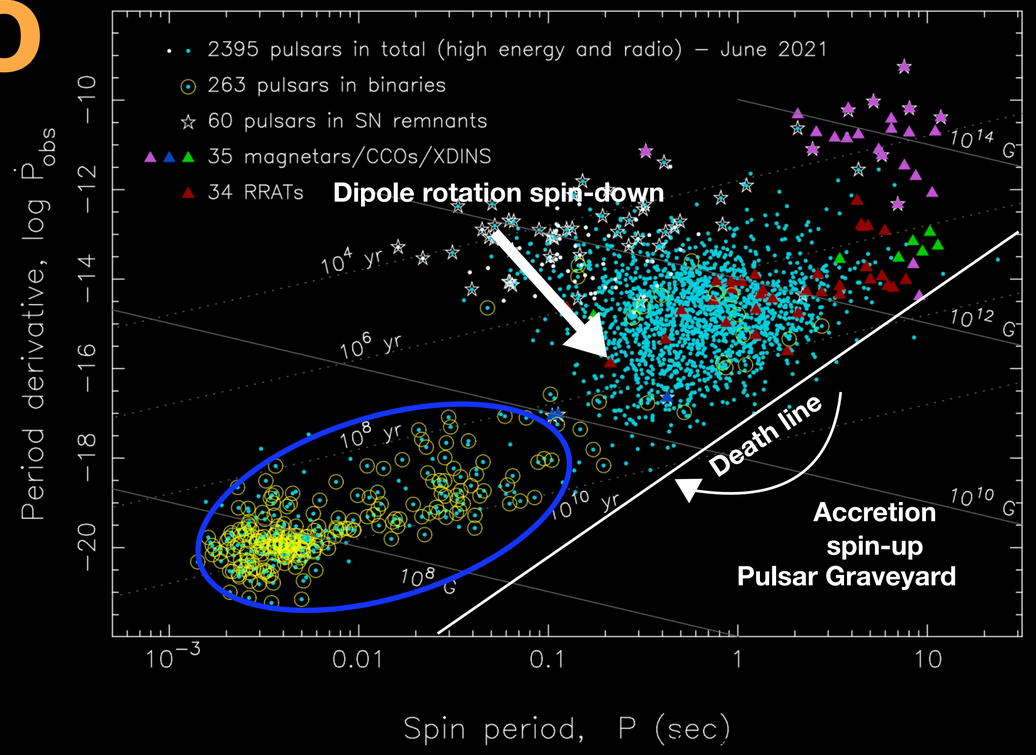
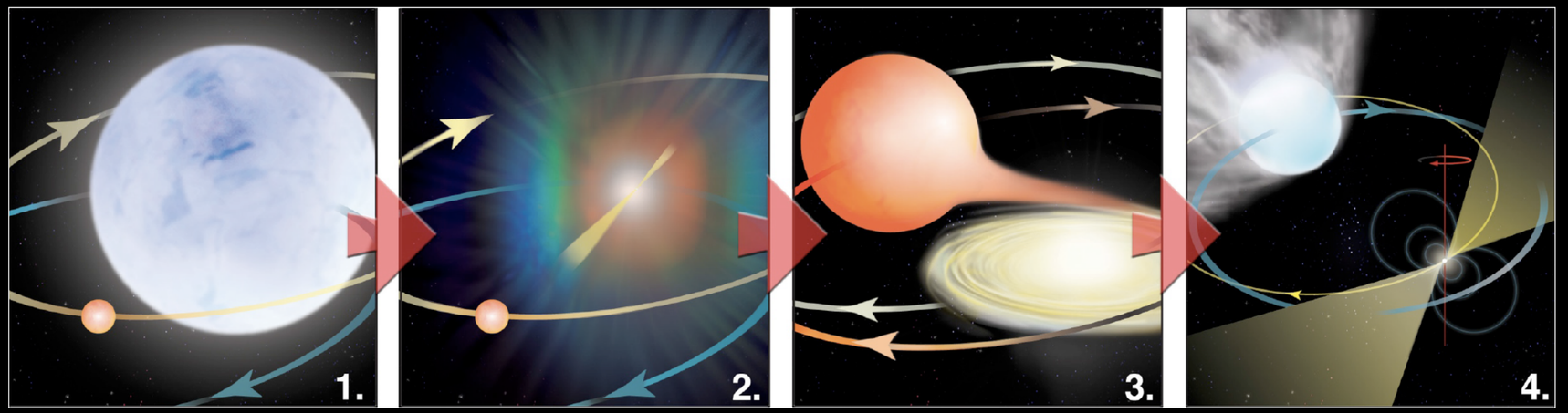


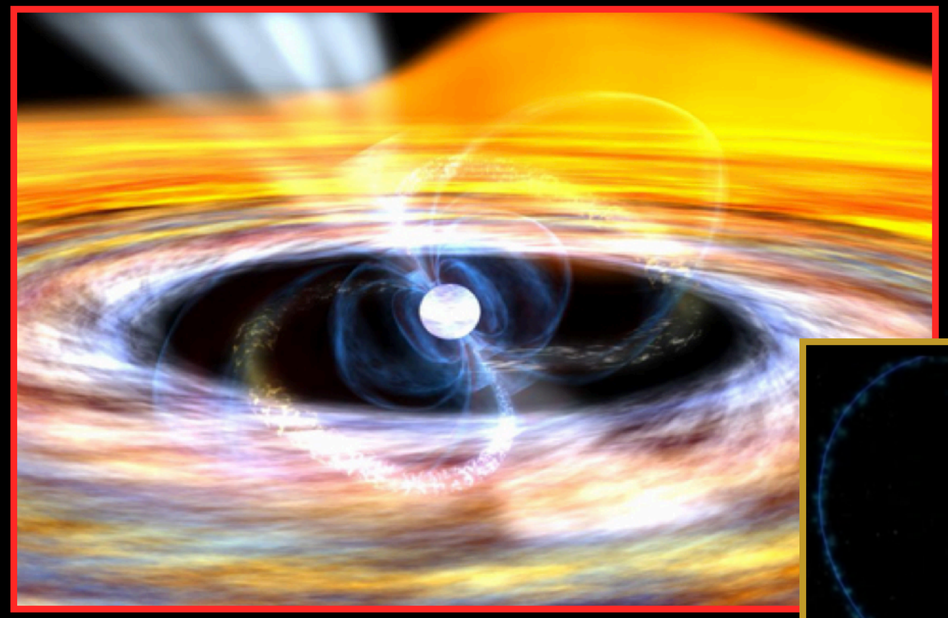
Recycling scenario of MSPs
[Bisnovatyi-Kogan & Komberg 1974, Backer+1982, Alpar+1982, Radhakrishnan+ 1982, Wijnands & van der Klis 1998]



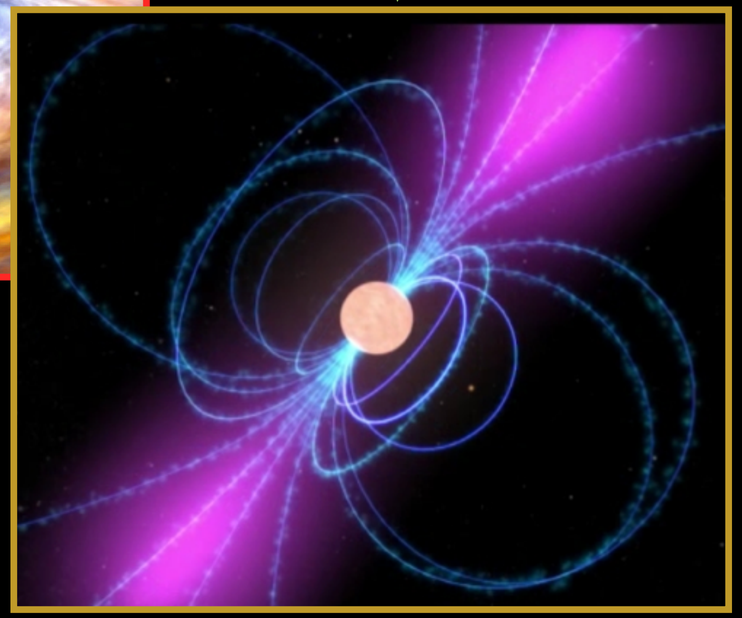
Saxton, NRAO

The “missing link” pulsar

Systems undergoing transitions between accretion states and radio pulsar states were observed!



Accretion stops: rotation of NS magnetic field powers radio and high energy pulsed emission. Matter from the donor is ejected at the shock with the relativistic pulsar wind

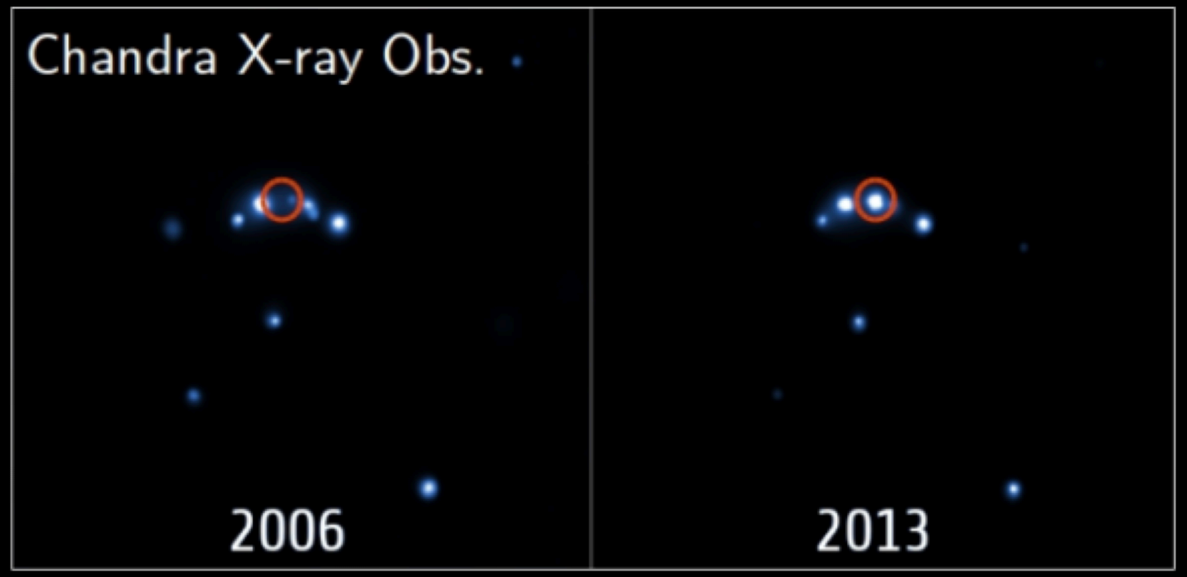


Accretion of mass from the donor (disk); signatures of the accretion disc observed from spectroscopy. No radio pulsation detected.

The first system to be discovered was PSR J1023+0038 (the missing link pulsar; Archibald et al. 2009), followed by XSS J1227-4859

However, none of these systems was showing X-ray pulsations due to the lack of proper outbursts.

First direct confirmation: IGR J1824-2452



IGR J18245-2452: discovered as an X-ray transient in outburst in M28
Pulsations at 3.93 ms detected with XMM-Newton: accreting X-ray pulsar!
Coincidentally, a radio pulsar at the same coordinates and spin was present in the radio archives…

Papitto+2013, Nature, 501, 517

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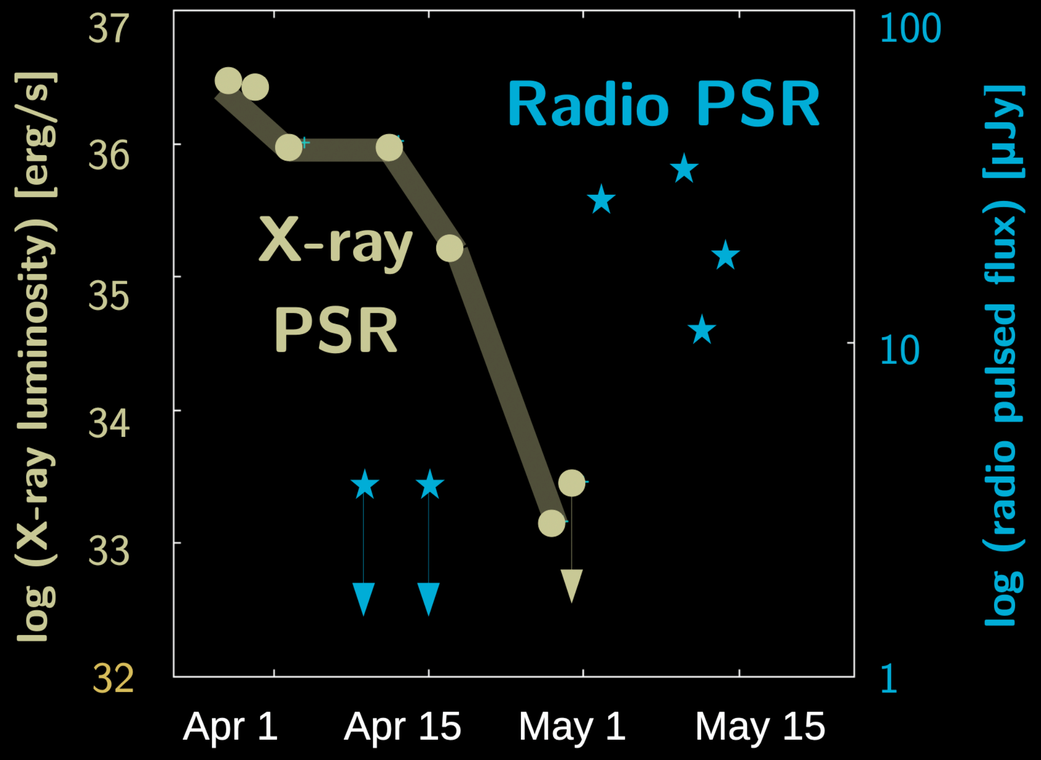

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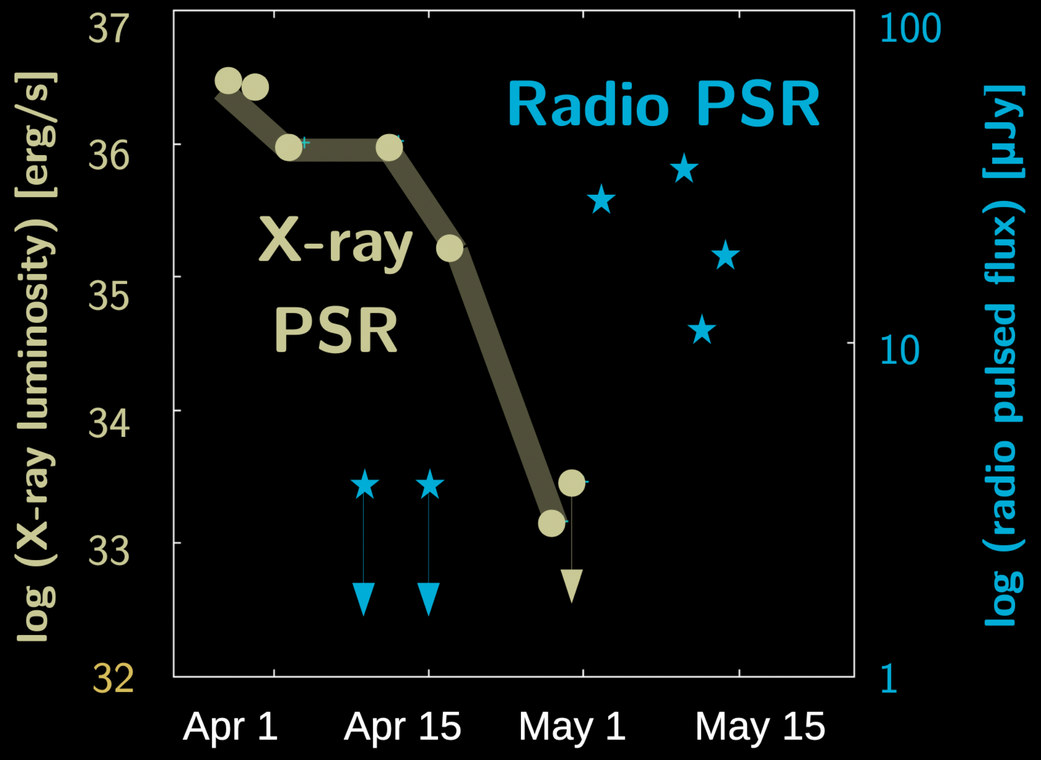

20 days after the end of the outburst, radio pulses were back!

The chain is closed: the first pulsar ever detected at radio and X-ray frequencies!

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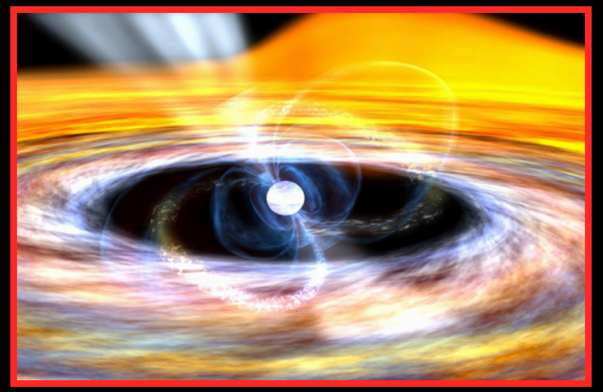
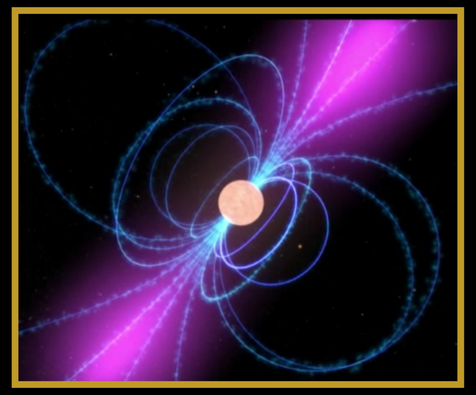
Accretion-powered
X-ray pulsar
(X-ray pulsations observed due to channelled plasma onto the magnetic poles)



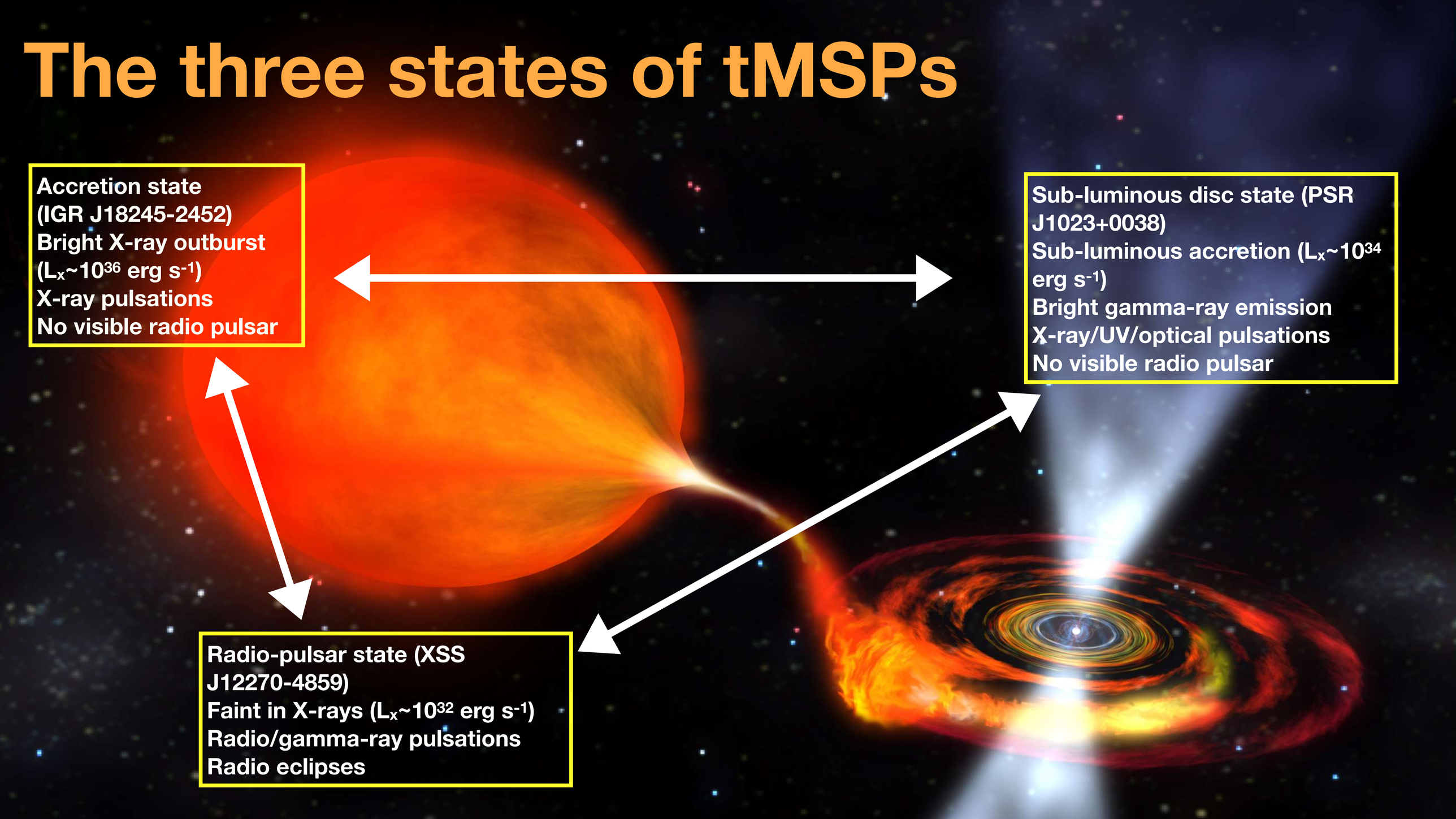


Rotation-powered
radio pulsar

Mass in-flow rate

Papitto+2013, Nature, 501, 517

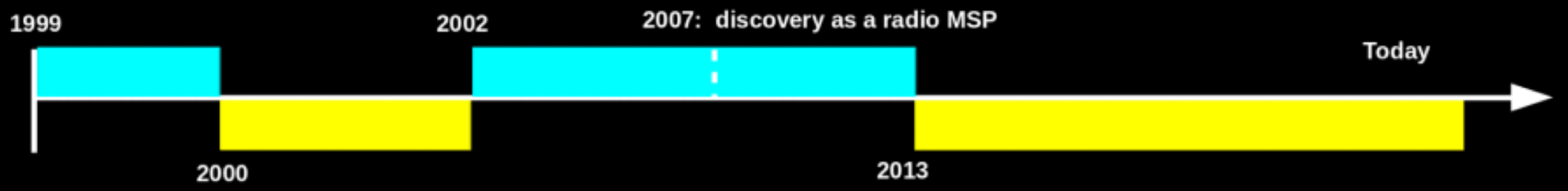
The three states of tMSPs



Three confirmed transitional 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; Baglio et al. 2023]

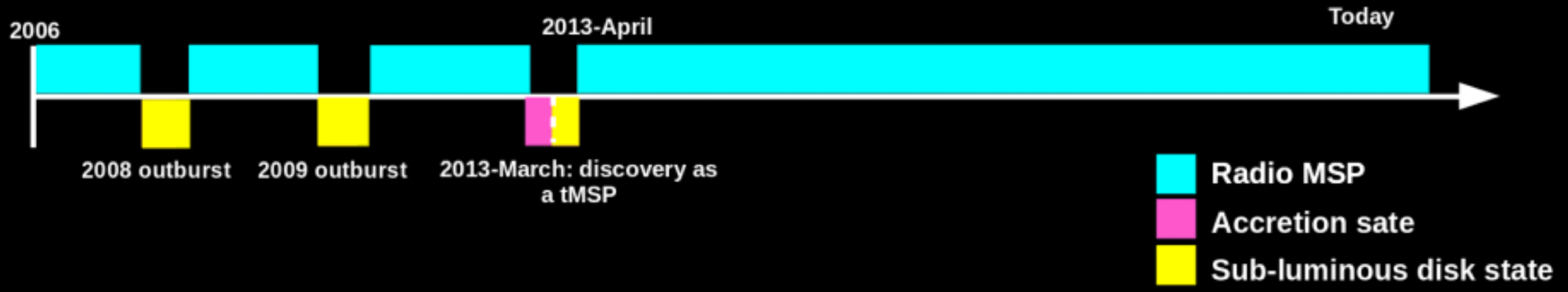
PSR J1023+0038

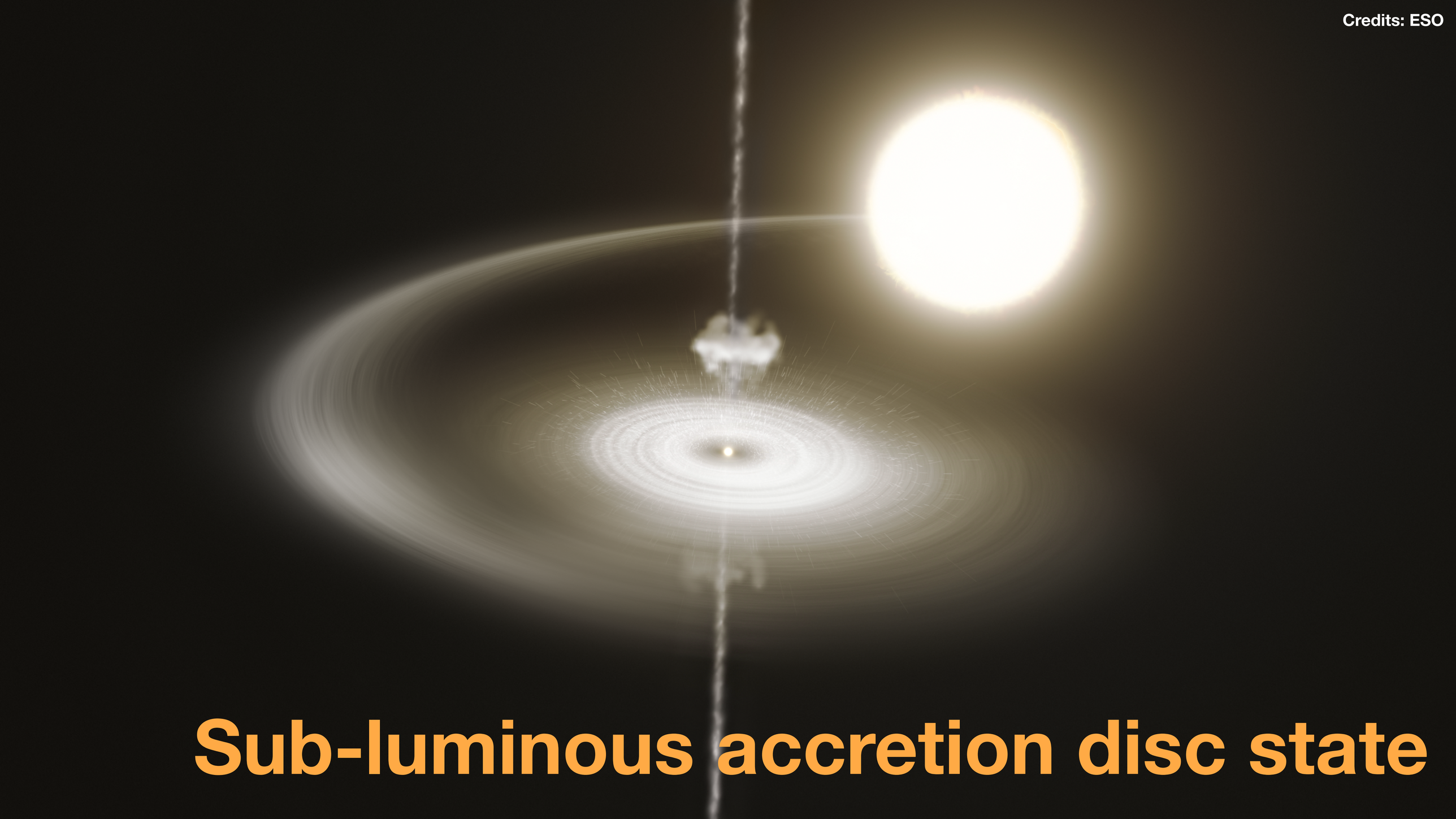


XSS J12270-4859

[**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]

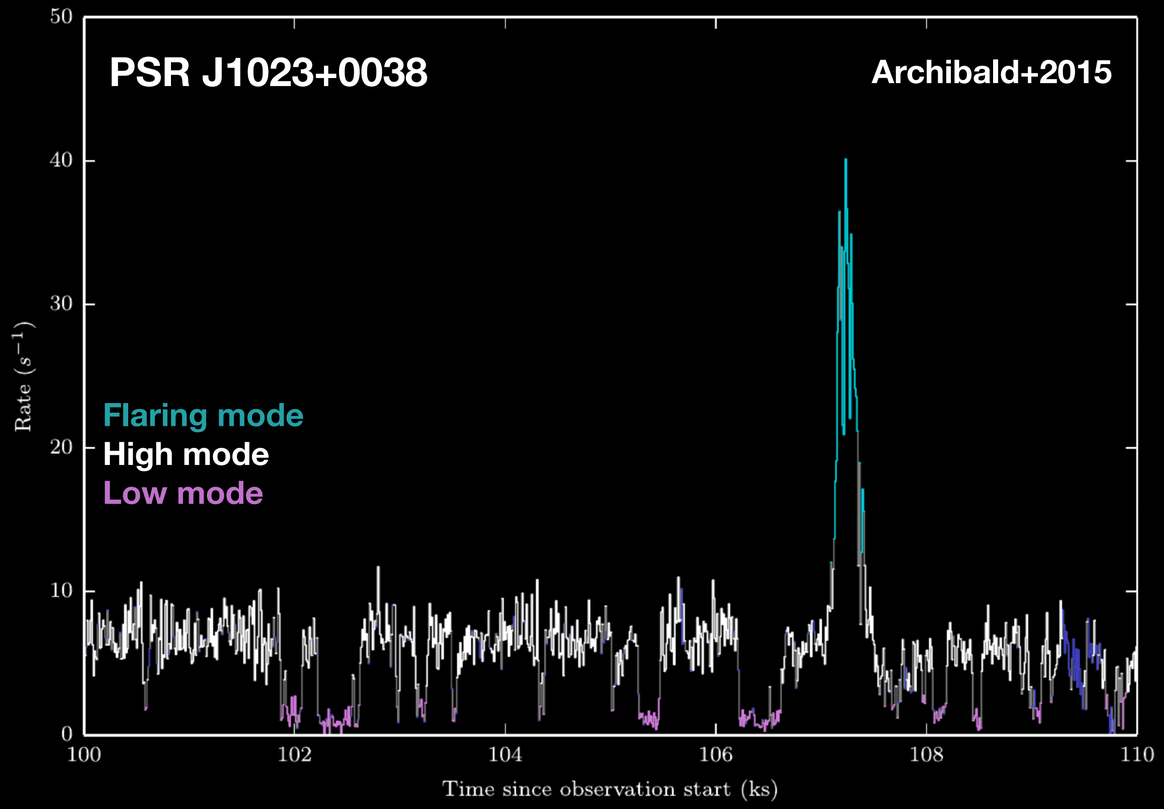


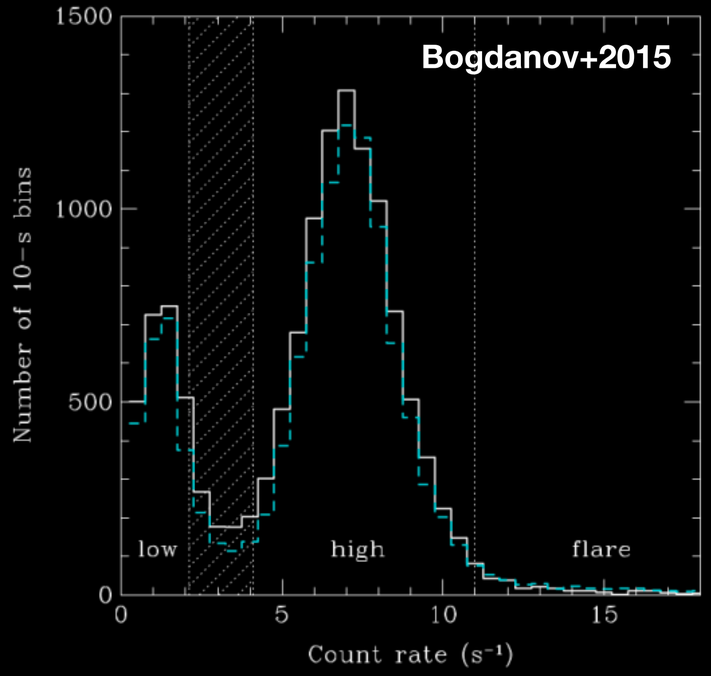


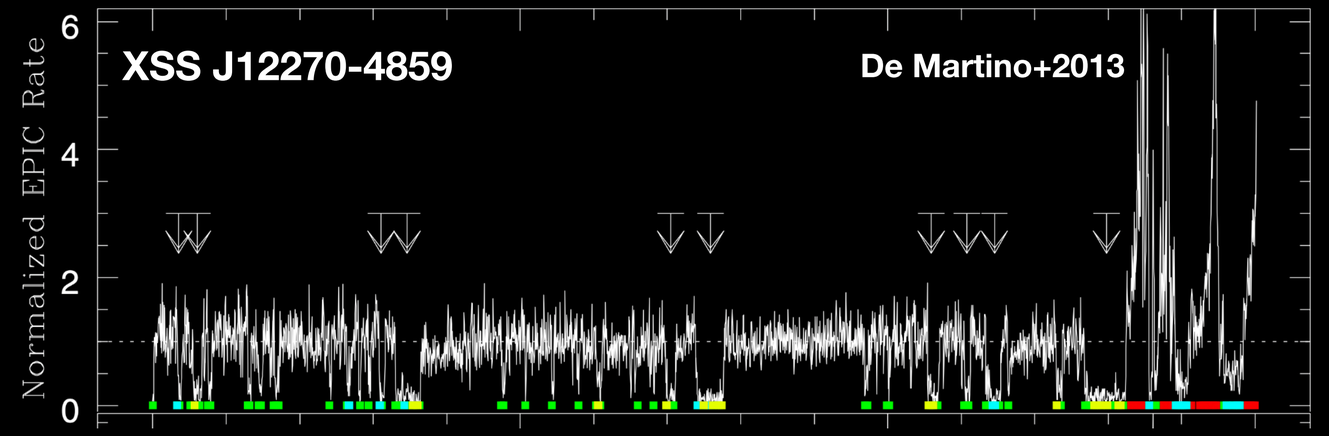
Credits: ESO

Sub-luminous accretion disc state

X-ray variability

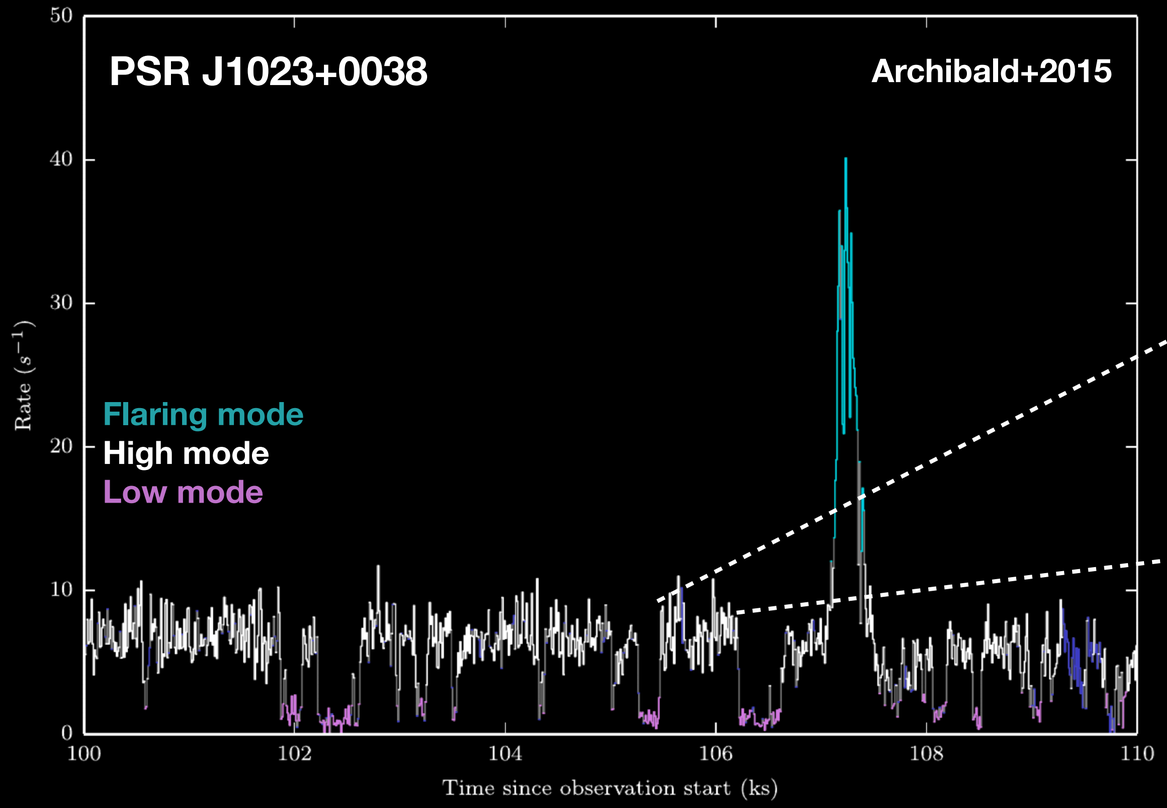




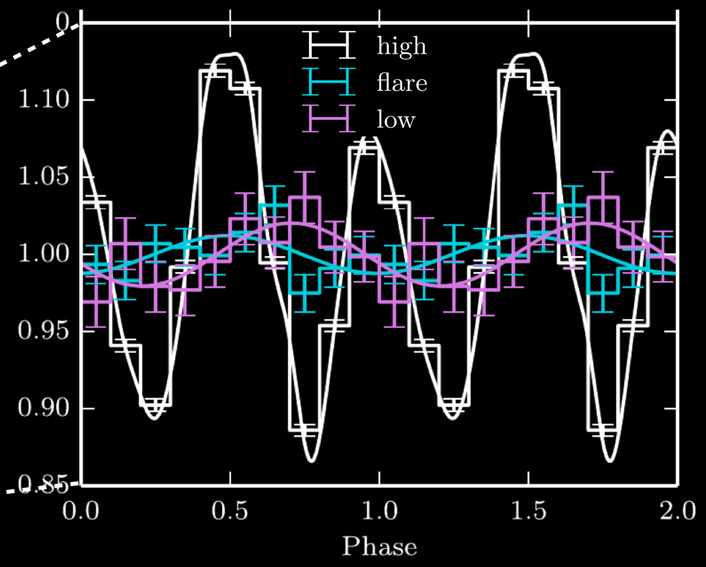


(See also Papitto+2013, Linares+2014)

X-ray variability



Papitto+ 2019

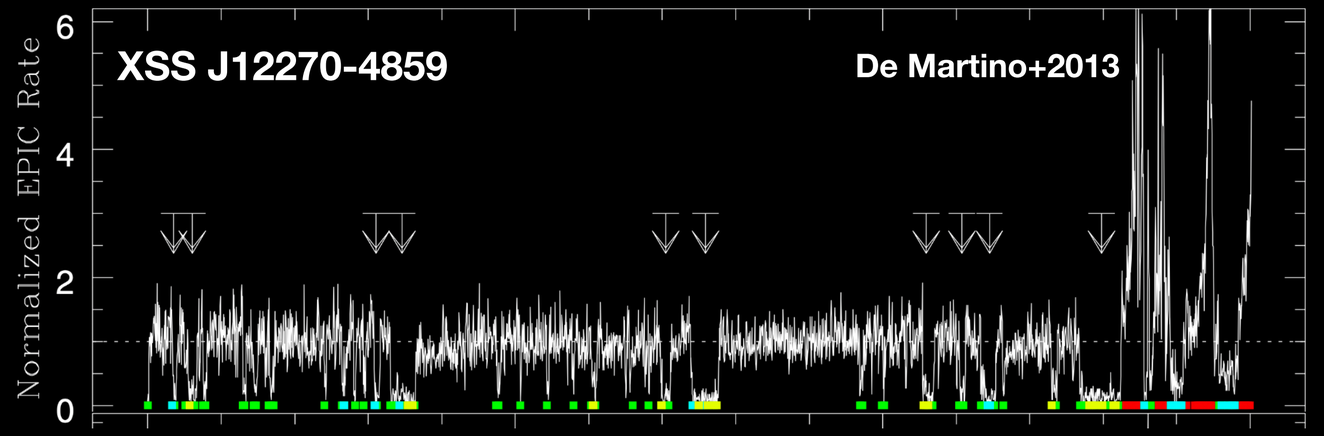


RMS pulse amplitudes of PSR J1023+0038:

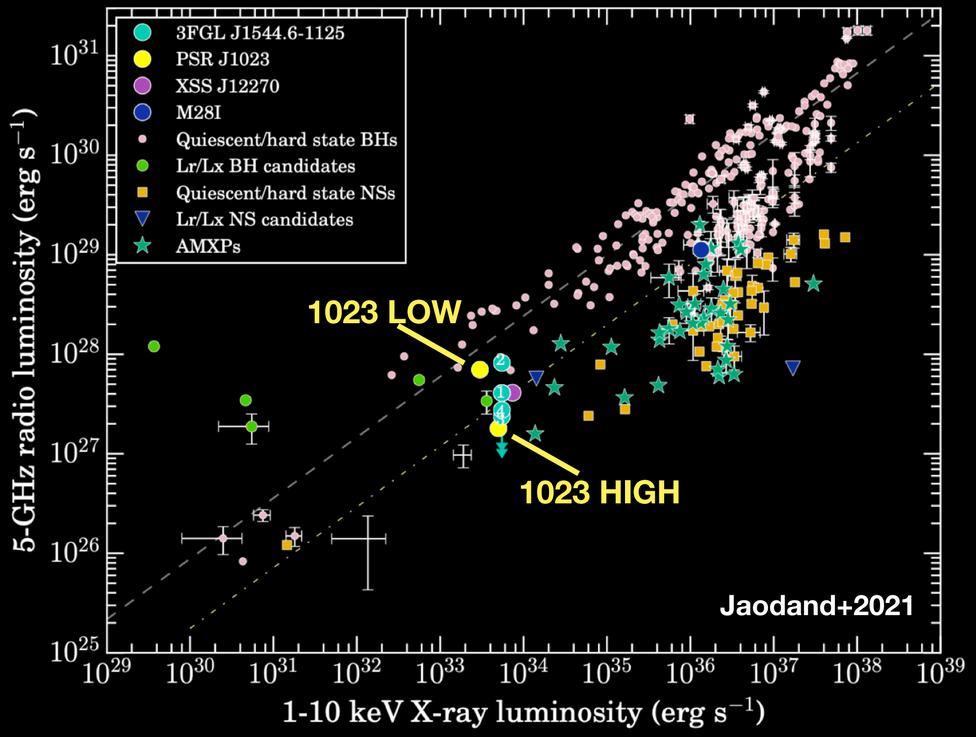
- **High mode: ~8%**
- **Low mode: <2.4%**
- **Flaring mode: 2 sigma detections (?)**

Sporadic accretion happening?

(See also Papitto+2013, Linares+2014)

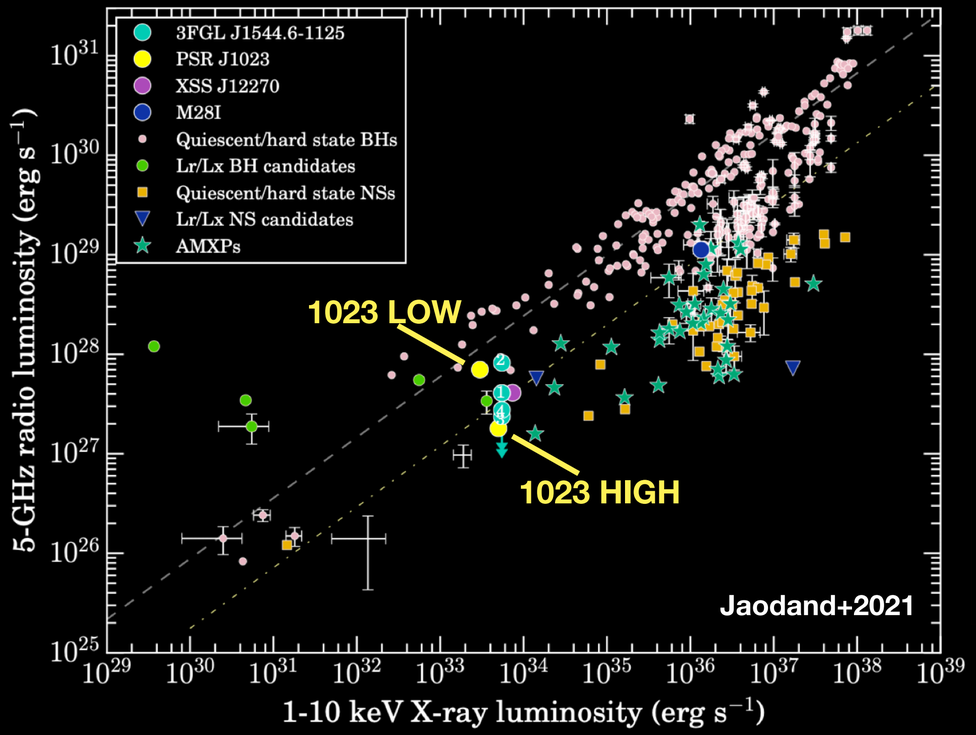


Radio emission

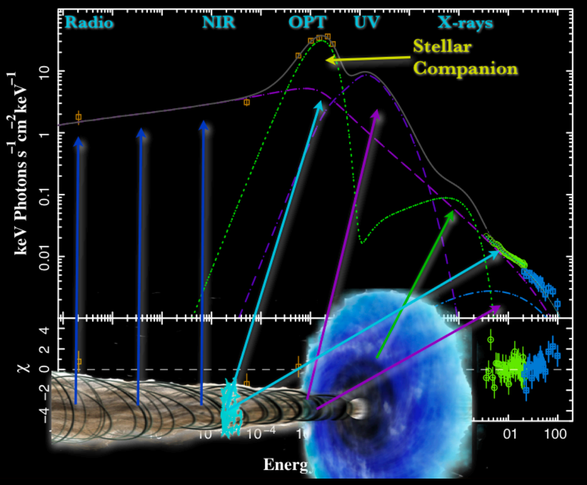


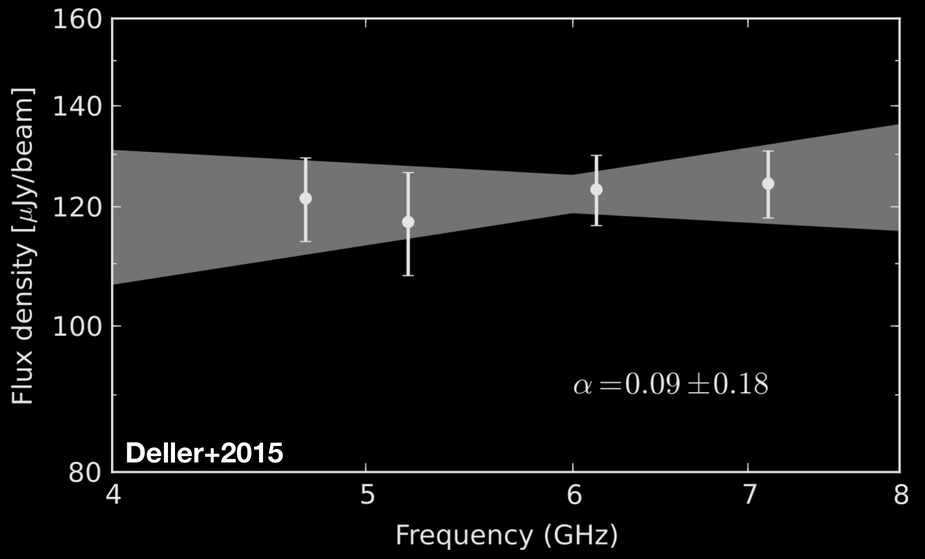
Correlation radio-X: black hole or neutron star?!

Radio emission



RADIO continuum emission with flat spectral shape: possible compact self-absorbed jet.





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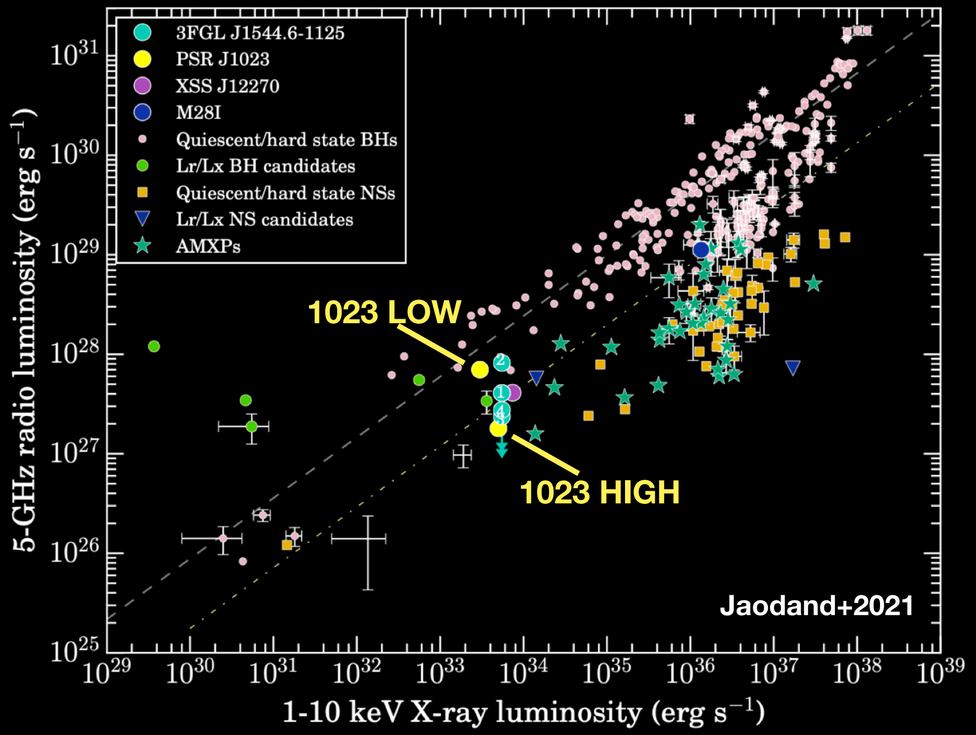

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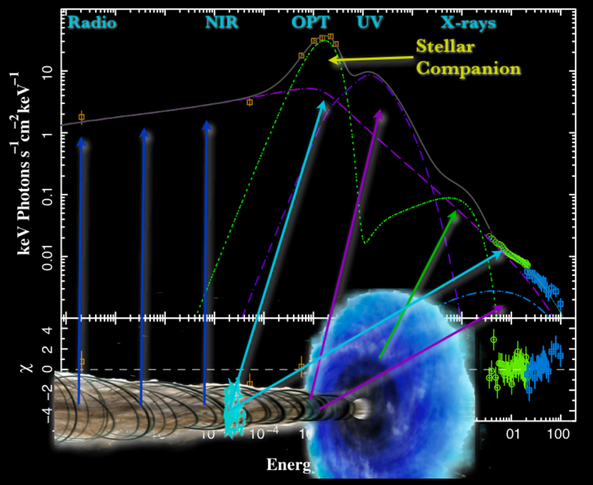
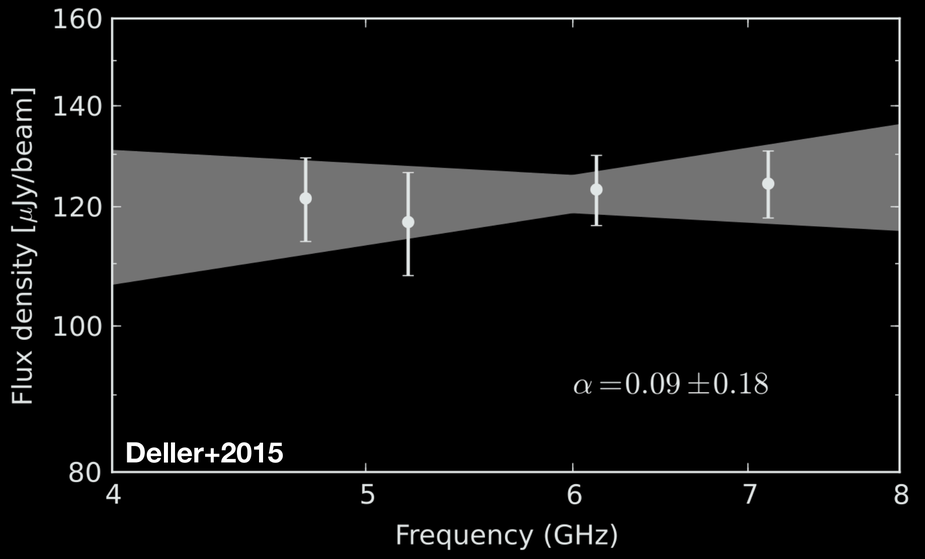
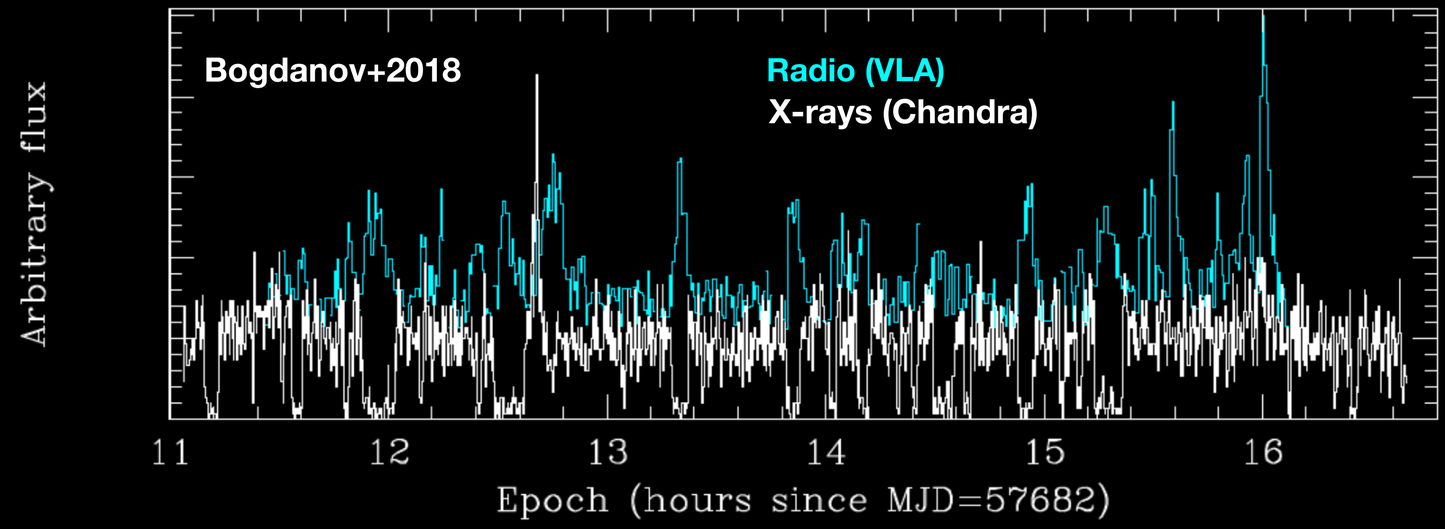


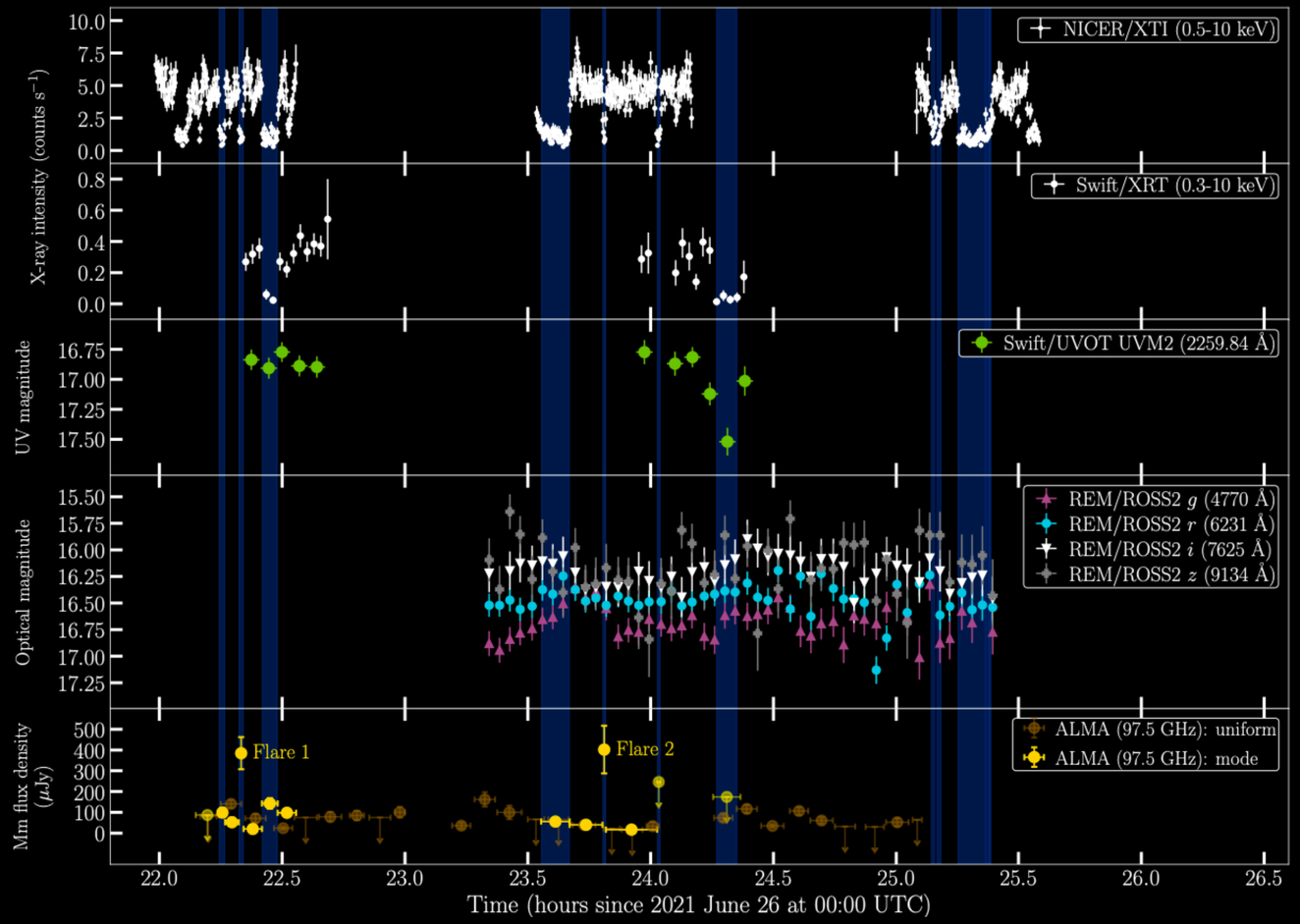


Correlation radio-X: black hole or neutron star?!

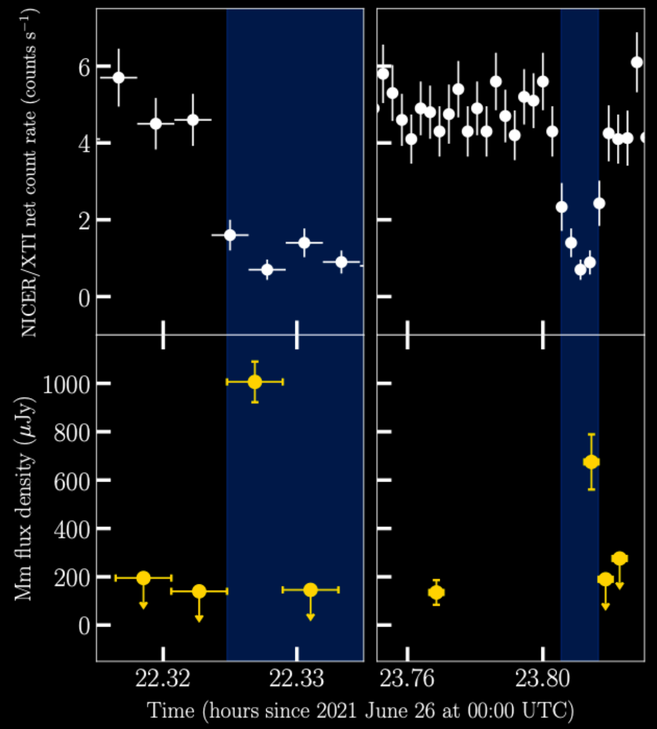
RADIO flares during low X-ray modes: possible ejection of optically thin plasmoids (Bogdanov+2018).

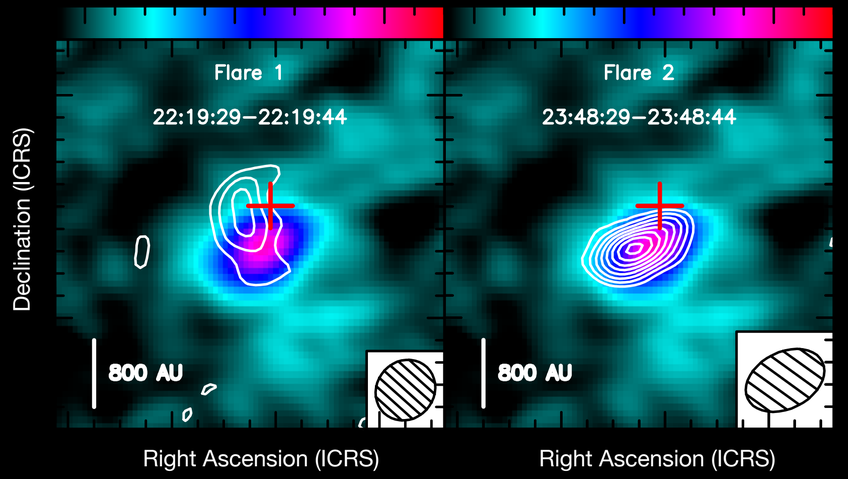


Millimeter emission



Baglio, Coti Zelati et al. 2023





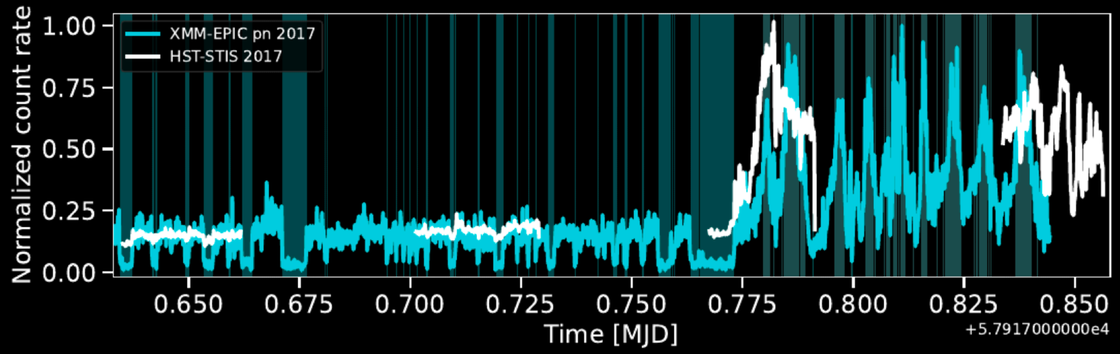
Two mm flares observed during low-modes

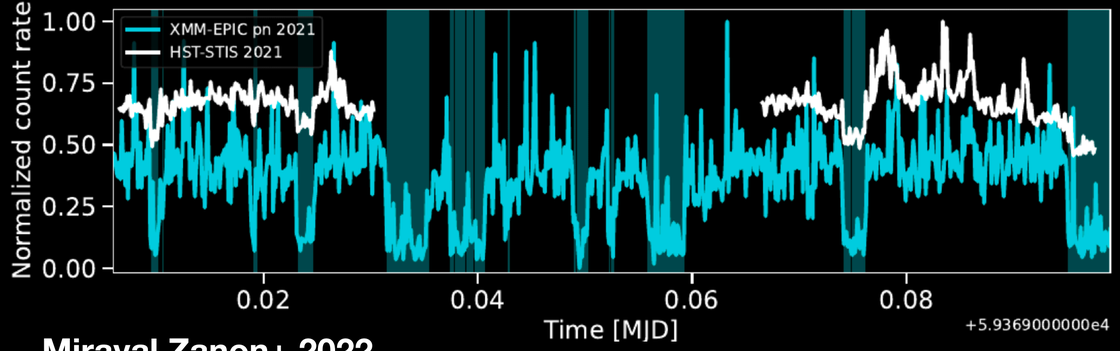
The observed flares (mm-radio) properties can be reproduced by simulating ejecta that propagate from the base of the jet towards the outer regions.

See also Koljonen et al. 2025 for mm obs

UV, Optical, NIR

UV

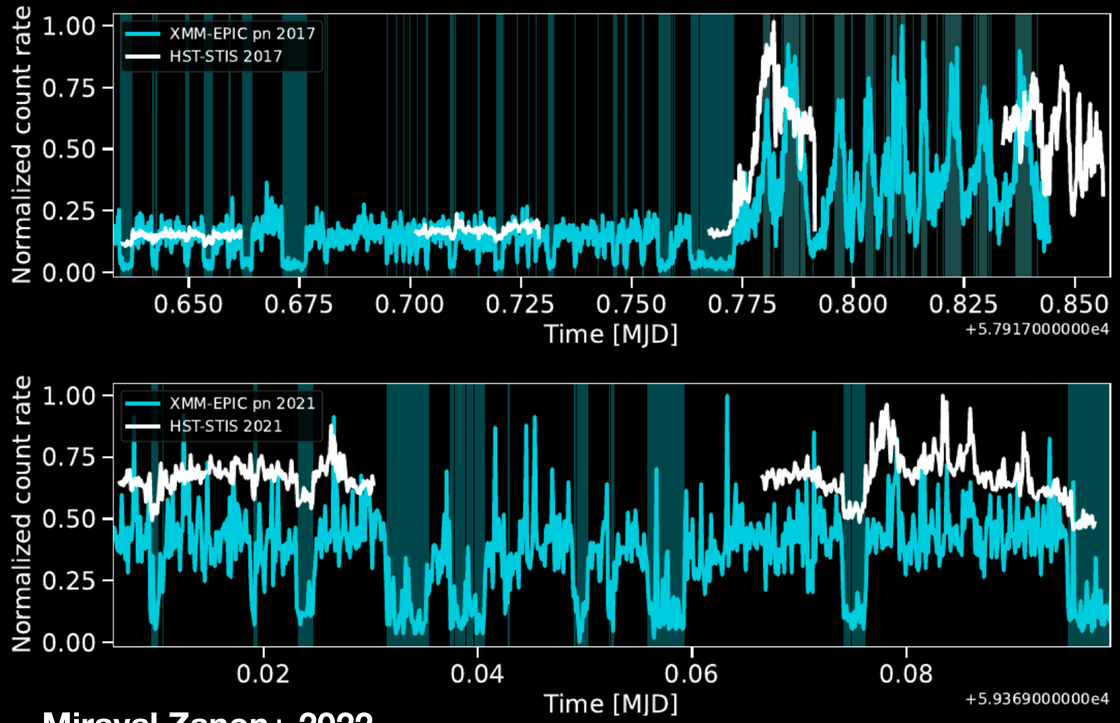




Miraval Zanon+ 2022

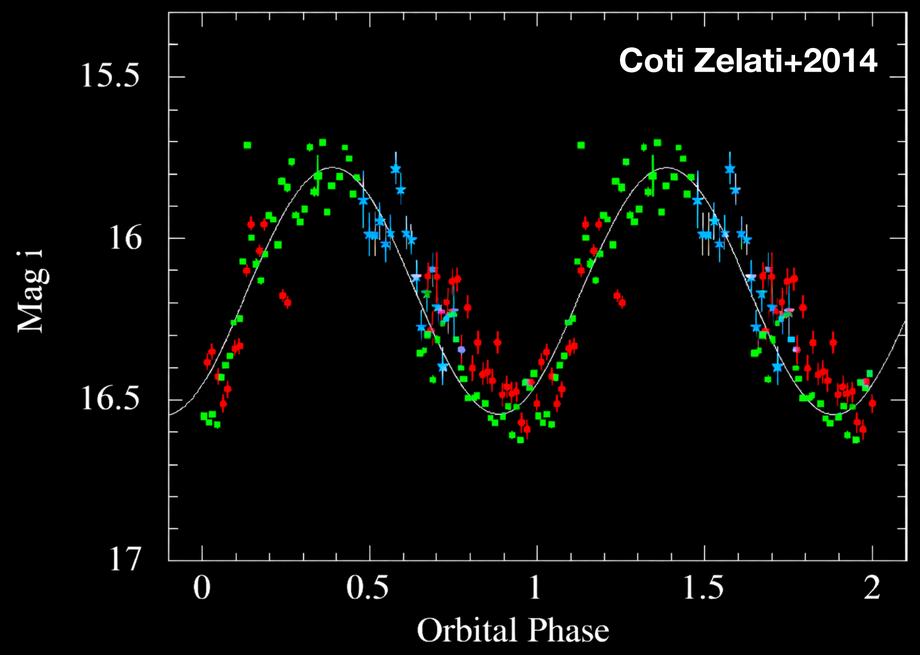
UV, Optical, NIR

UV



Miraval Zanon+ 2022

Optical



UV, Optical, NIR

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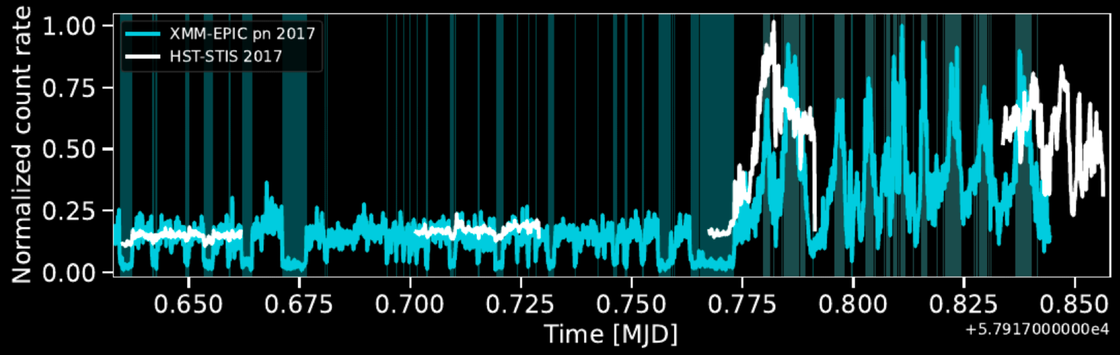
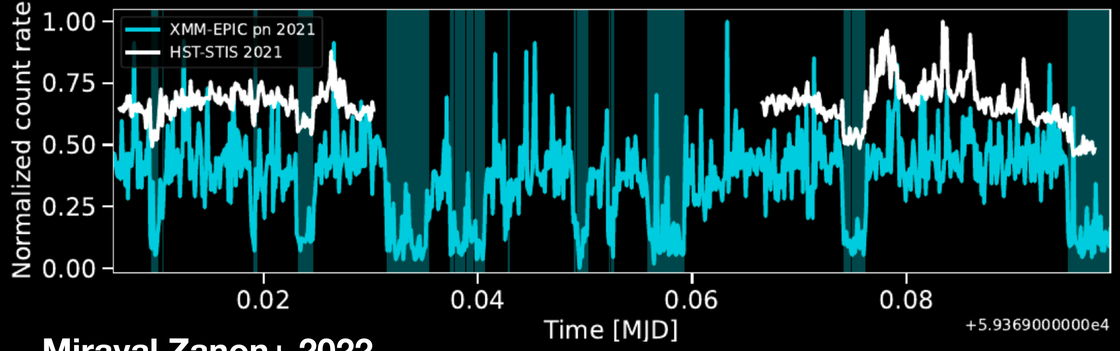
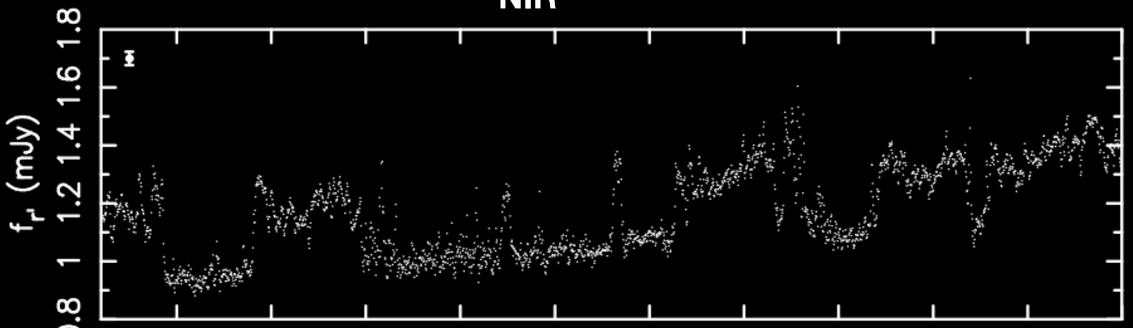




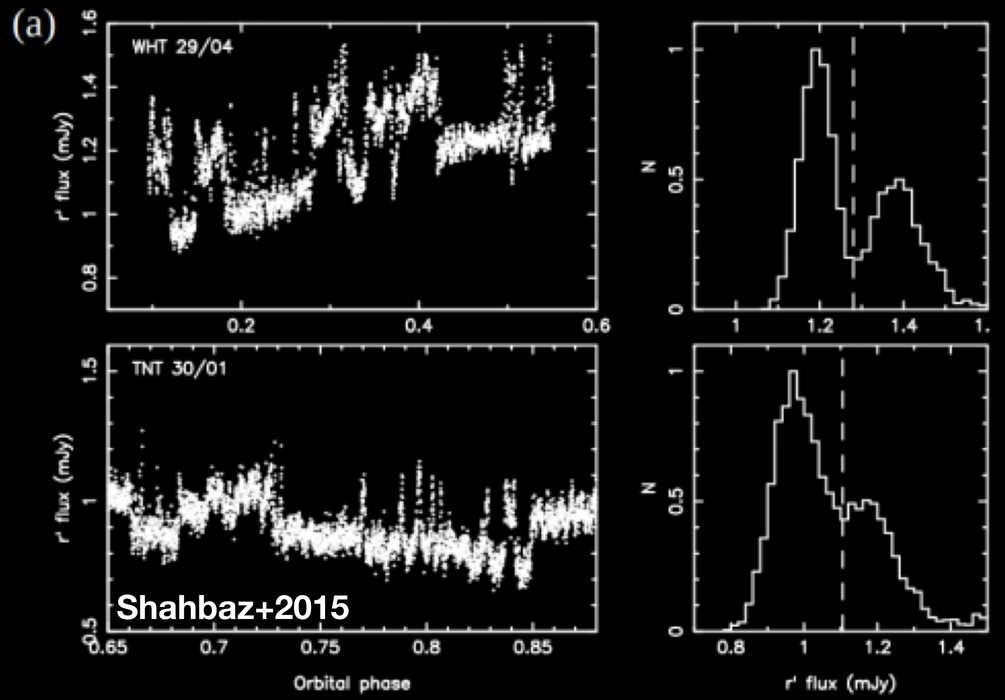
Miraval Zanon+ 2022

NIR

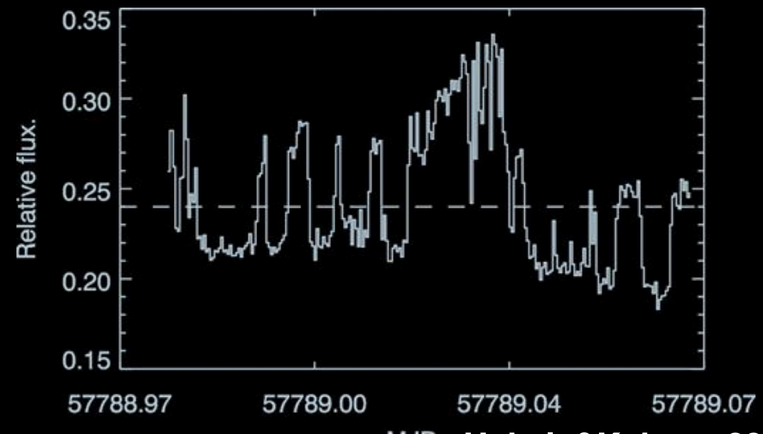


Shahbaz+2015

Optical



Shahbaz+2015

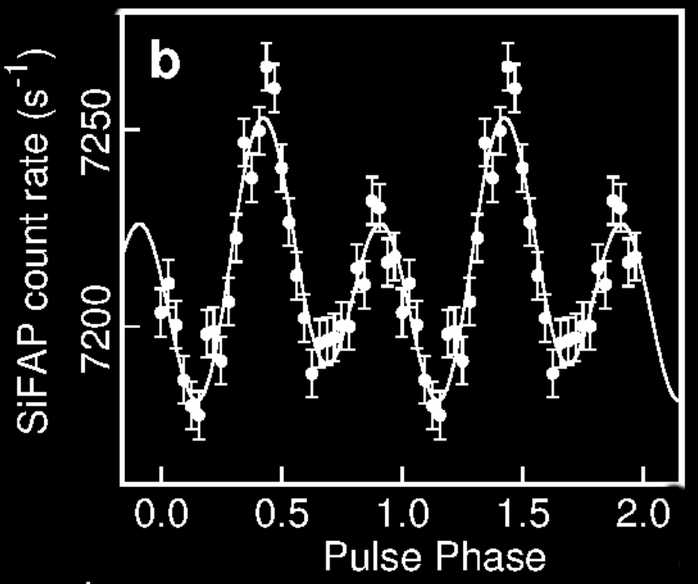


Hakala&Kajava+2018

Optical pulsations

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

Optical pulsations from a transitional millisecond pulsar



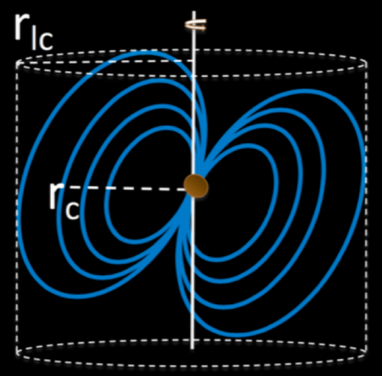
Ambrosino et al. 2017, Nature Astronomy

The region of emission of the pulsations must be:

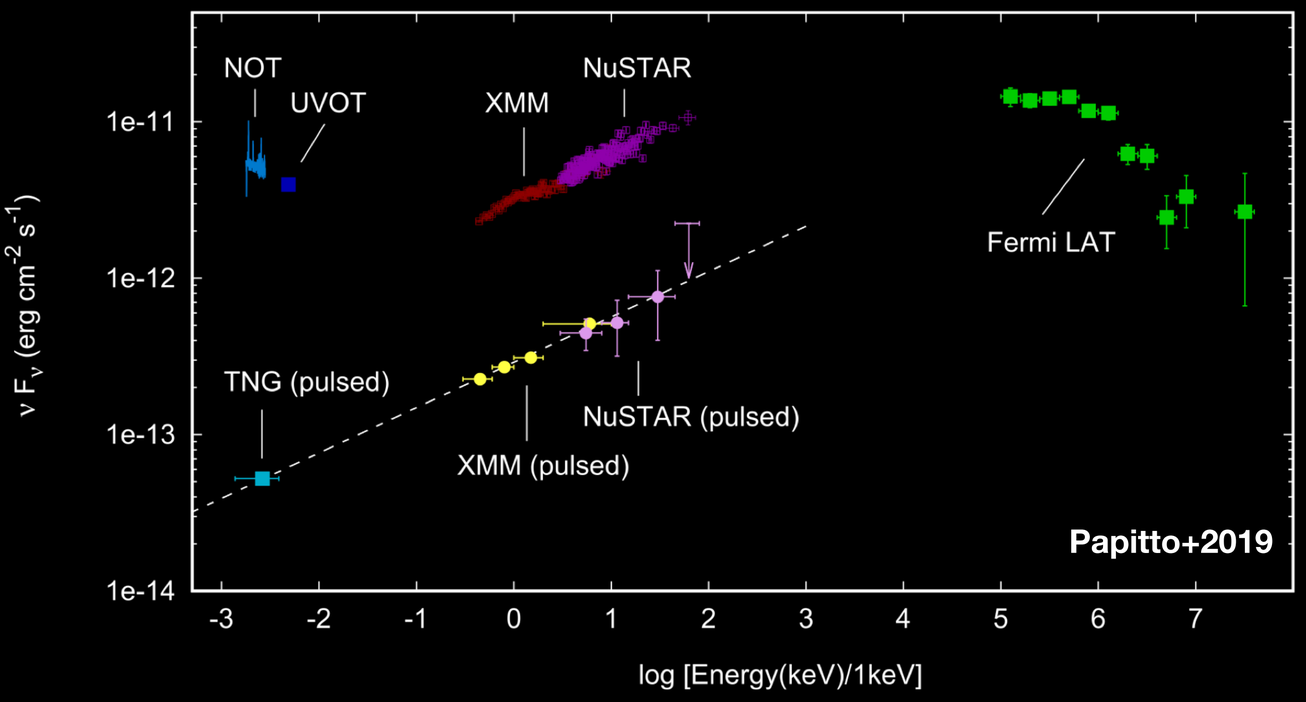
- Maximum 500km (c x P_{spin}) big
- Between ~60 and ~600 km away from the pulsar (> r_{co} and r_m)

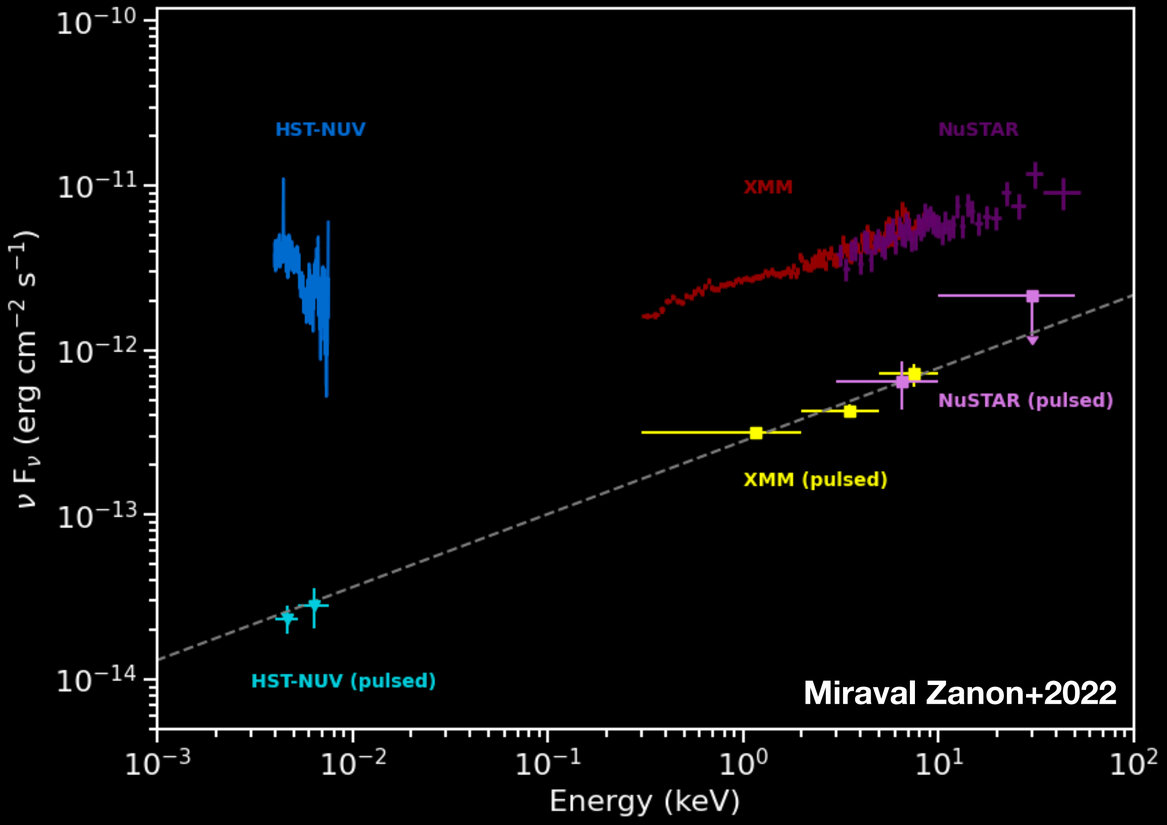
No reprocessing of X-ray pulsations at the companion star surface and/or in the disc.

Cyclotron in the polar regions would give a pulsed luminosity ~30 times lower than observed.



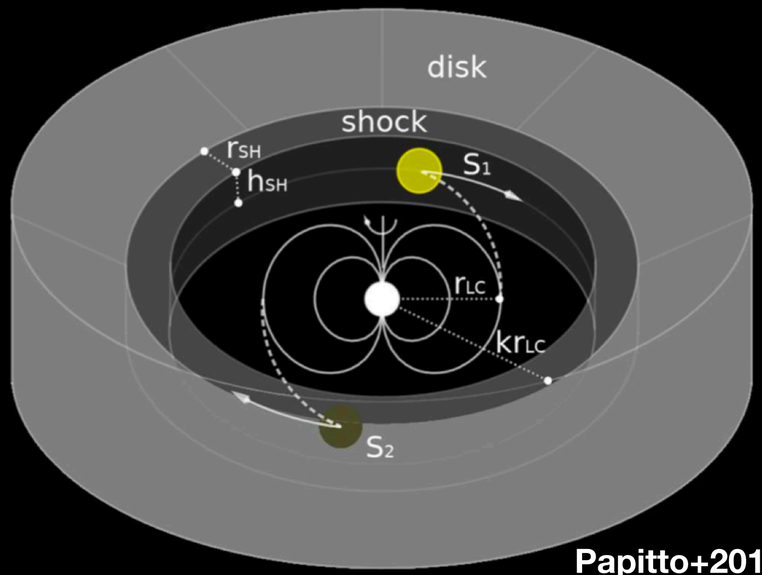
Pulsed spectral energy distribution





PSR J1023+0038 → Optical,UV and X-ray pulses are produced by the same process

Most recent interpretations



Papitto+2019

Mini pulsar wind nebula

HIGH MODE

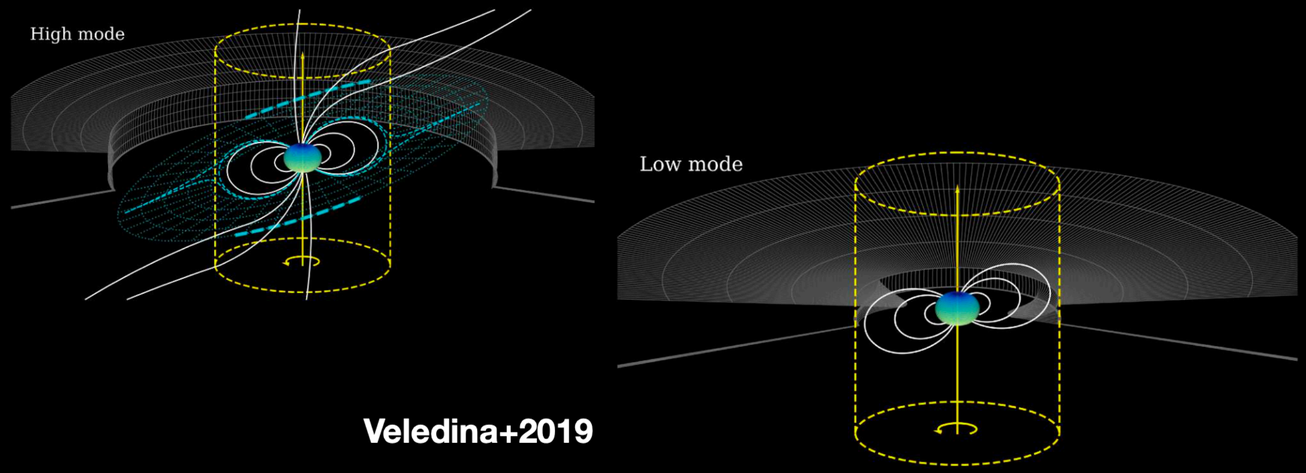
The radio pulsar is active

The pulsar wind interacts with the disc close to the pulsar

A shock is generated

Ms pulsations from optical to X-rays are produced

(Papitto+2019, Veledina+2019)



Veledina+2019

LOW MODE

The boundary region moves outside the lc radius

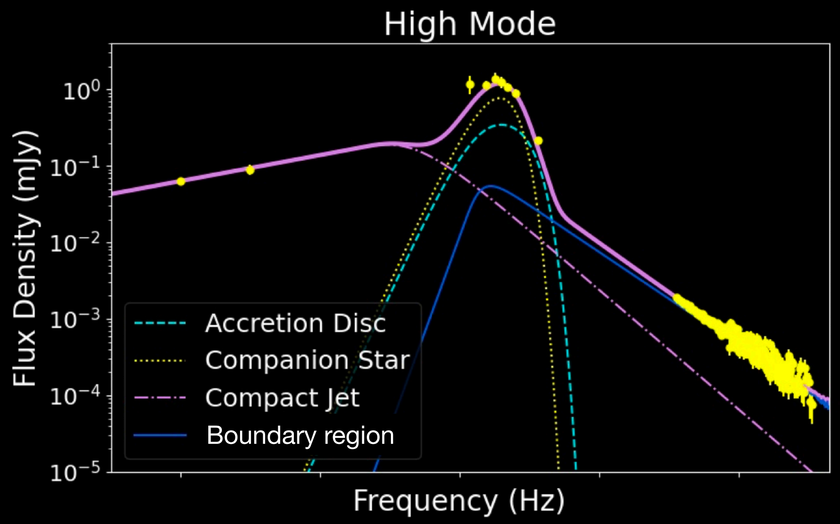
No pulsations are observed (Papitto+2019)

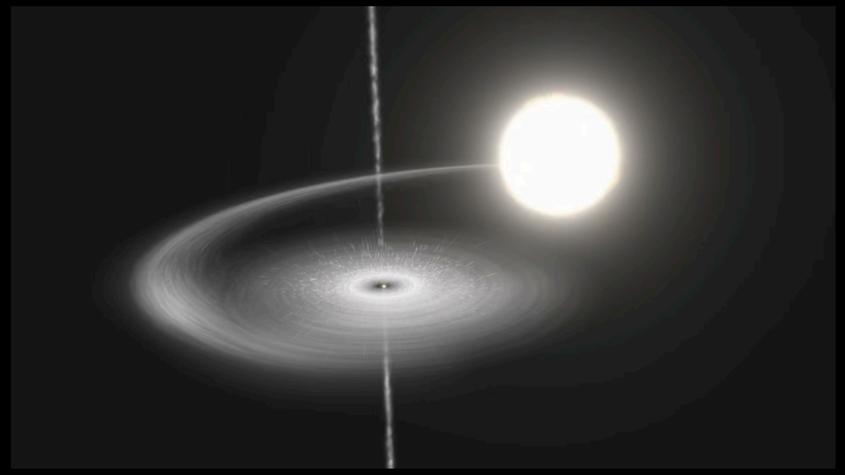
or

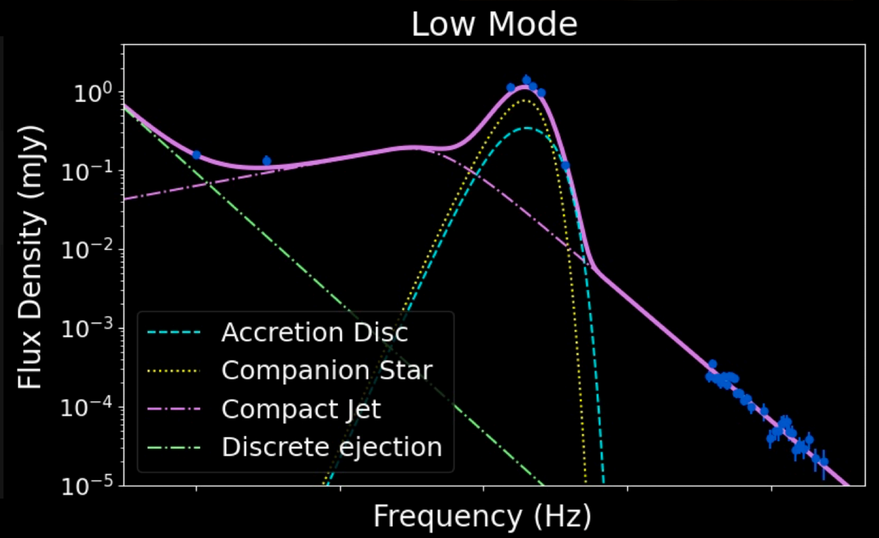
The disc penetrates the lc radius.

The system enters the propeller regime. (Veledina+2019)

A scenario to rule them all…

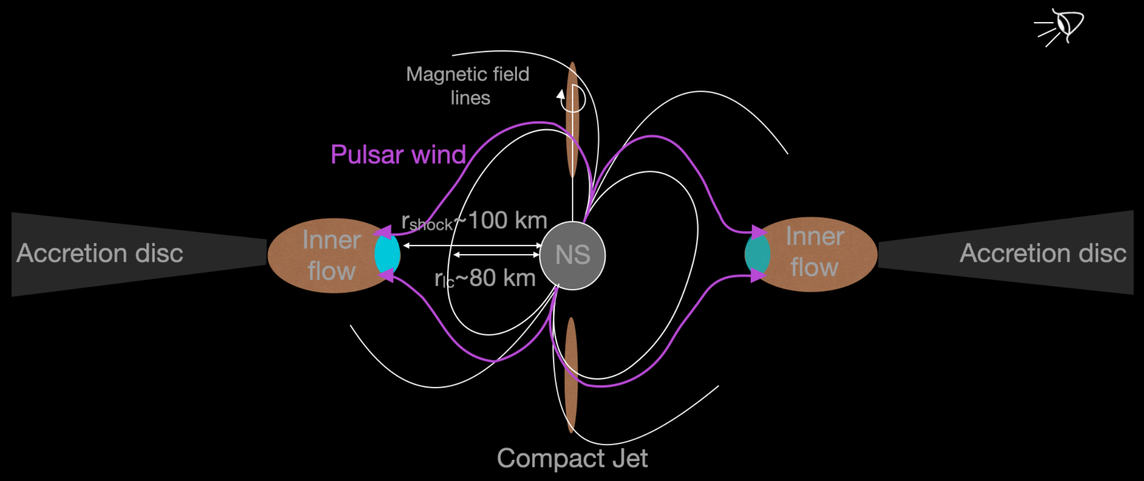




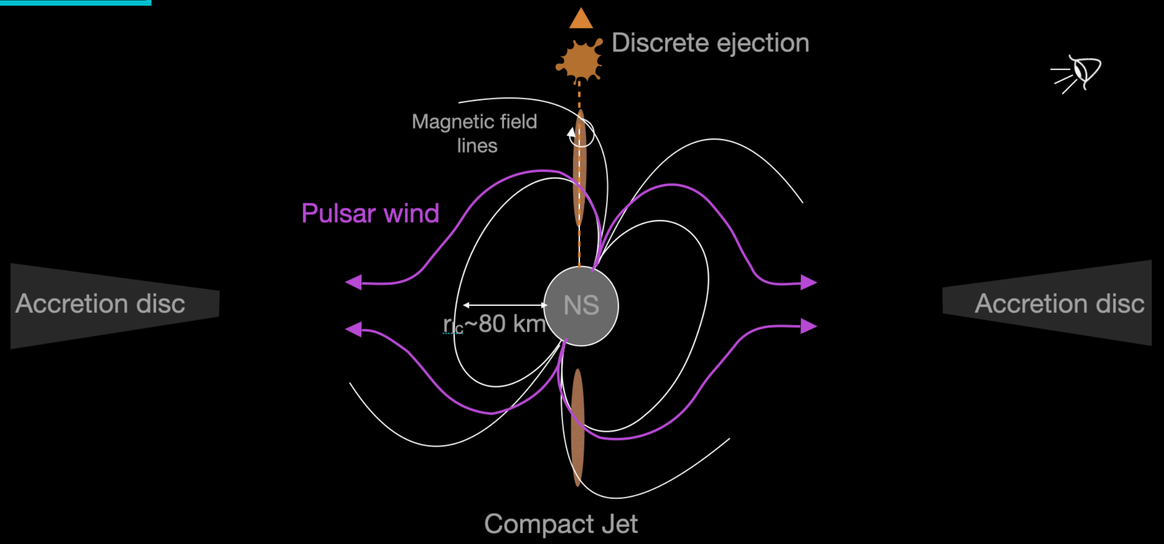


Baglio, Coti Zelati et al. 2023

HIGH MODE

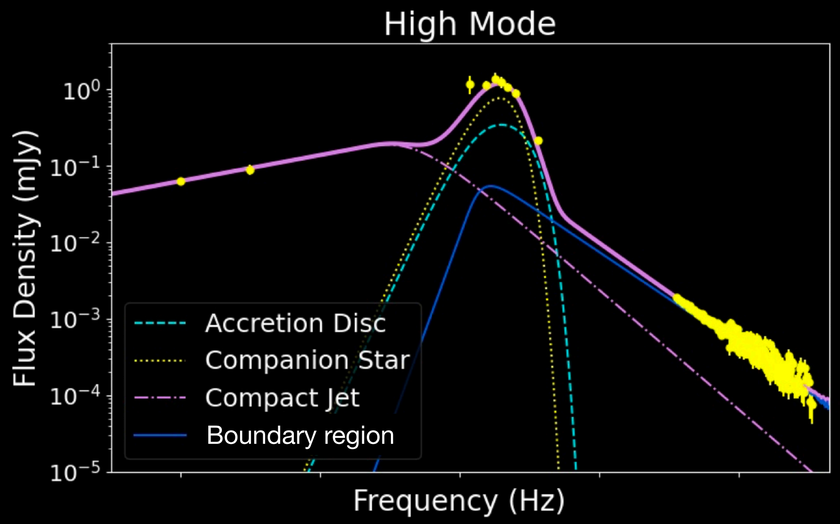


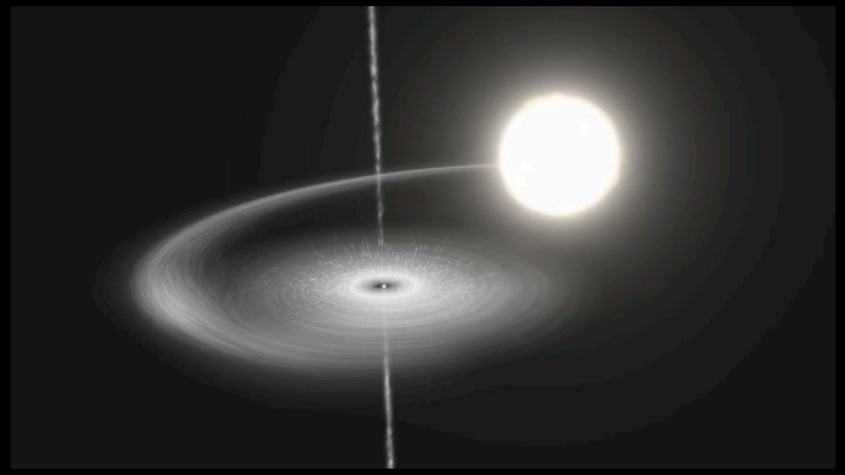
LOW MODE

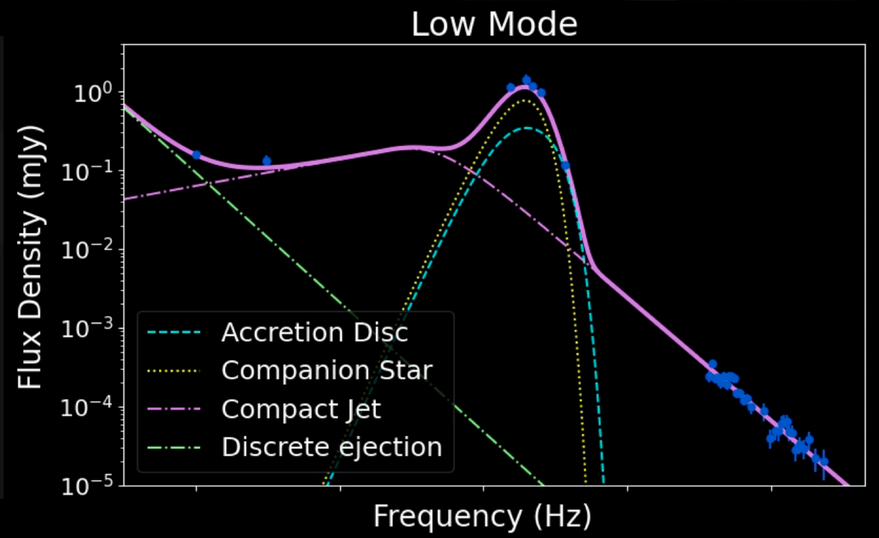


The shock moves out (of a factor ~20): its contribution in the X-rays is negligible.

A scenario to rule them all…







Baglio, Coti Zelati et al. 2023

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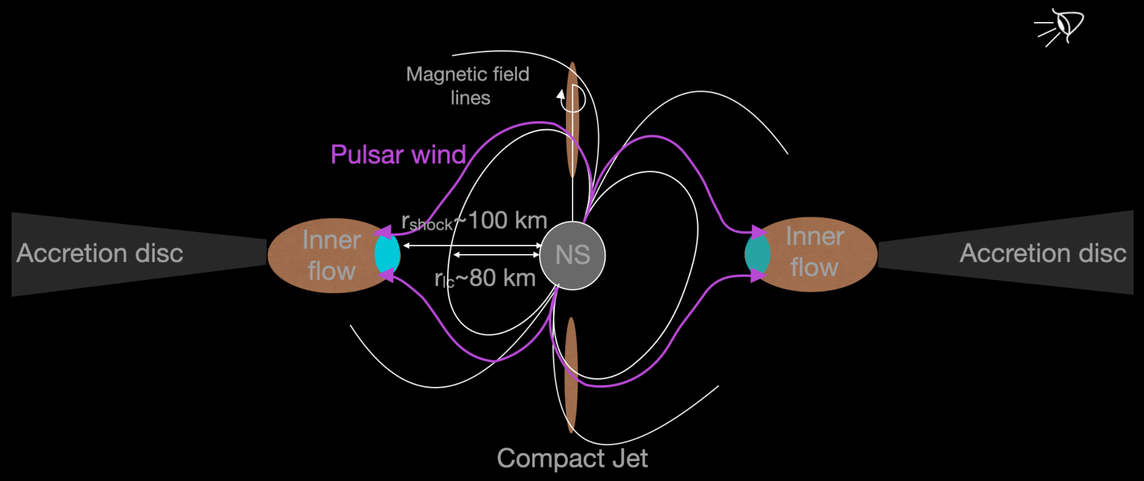

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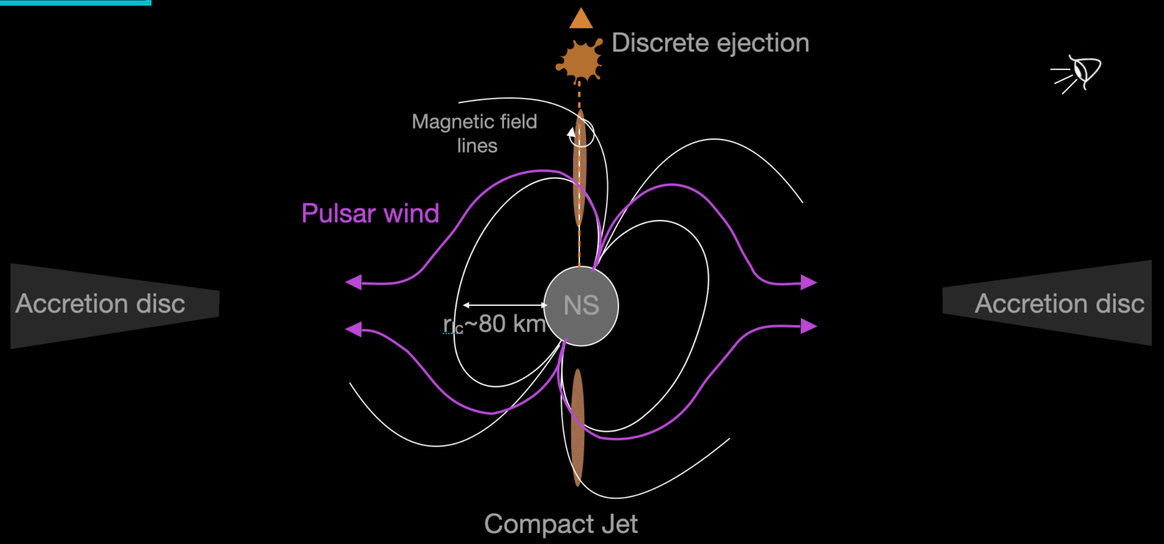

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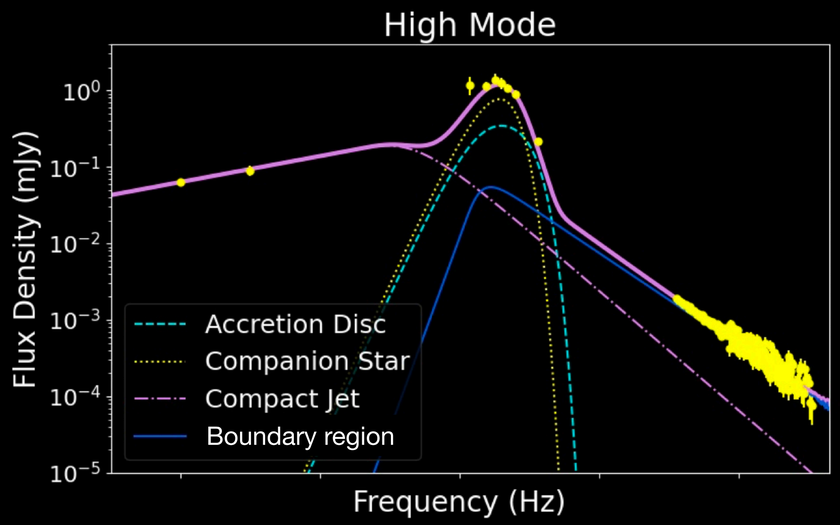
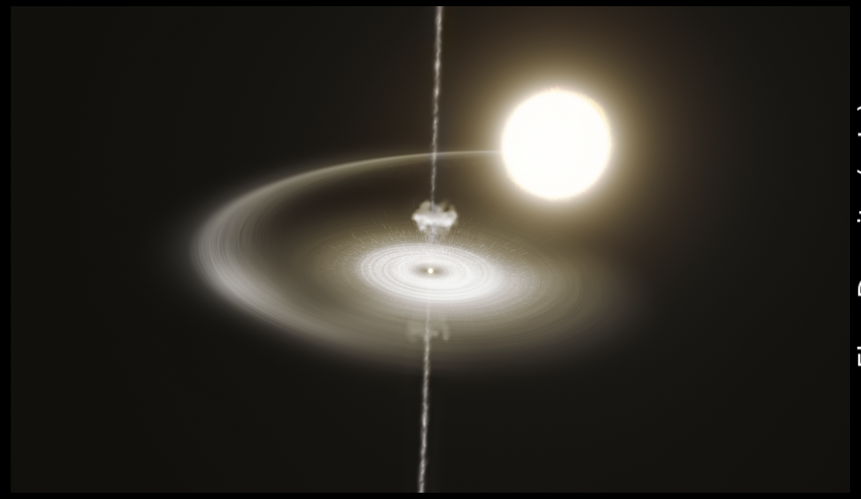
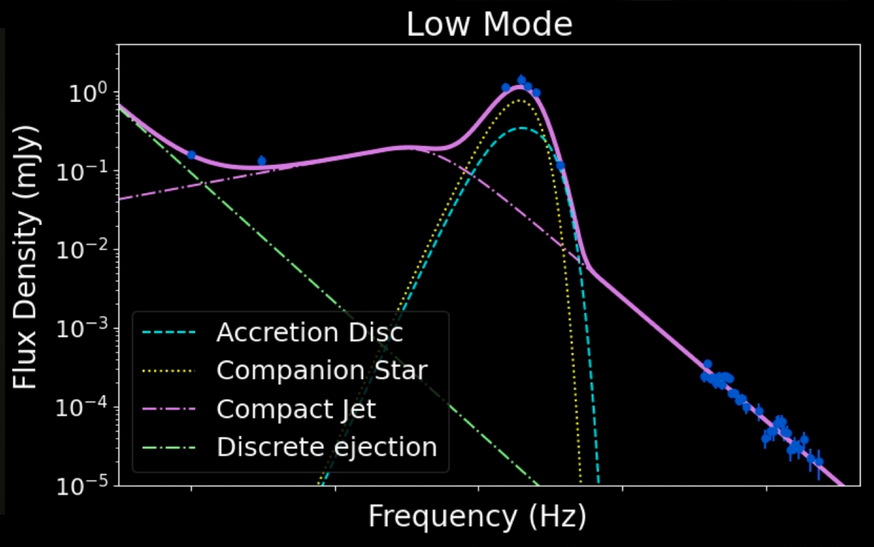
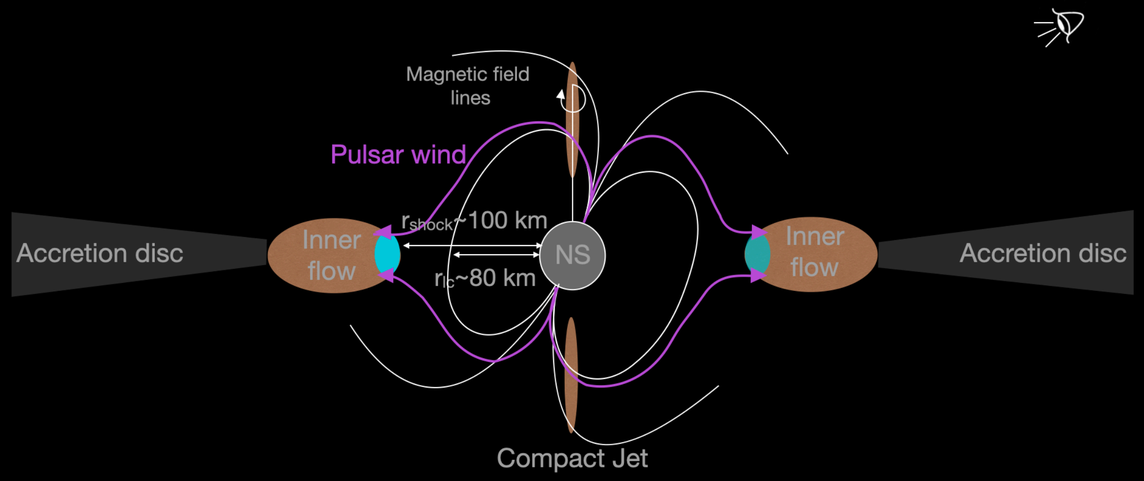






Baglio, Coti Zelati et al. 2023

HIGH MODE



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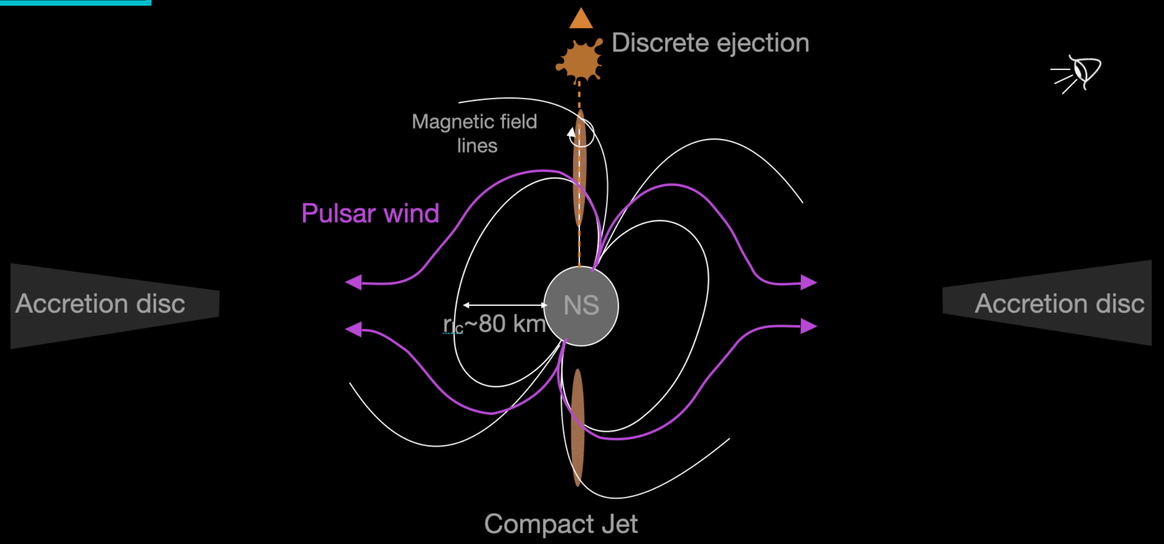

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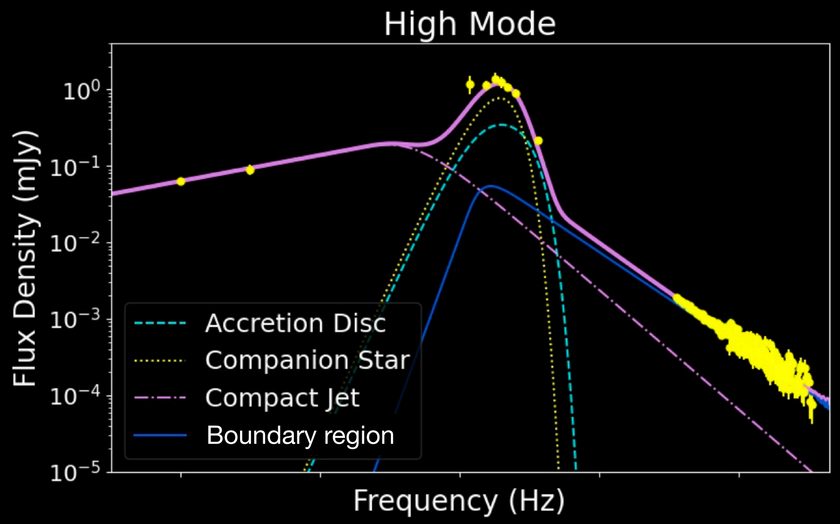

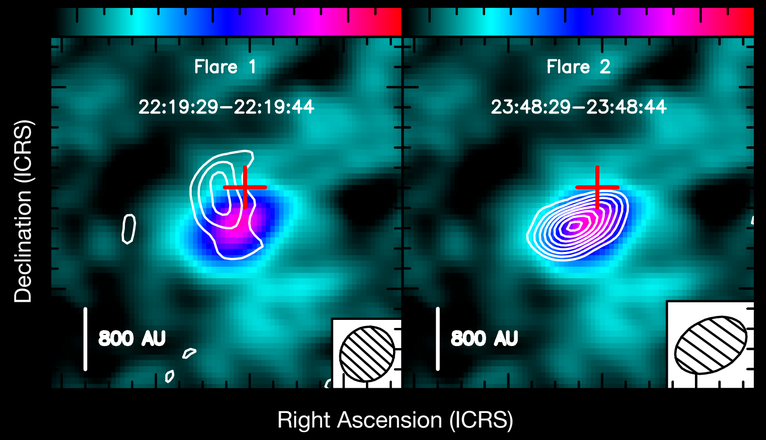

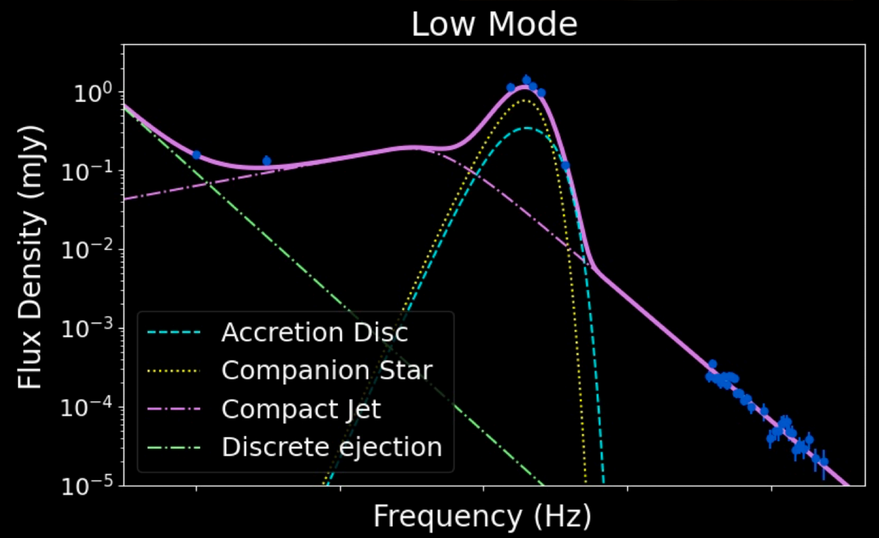

Baglio, Coti Zelati et al. 2023

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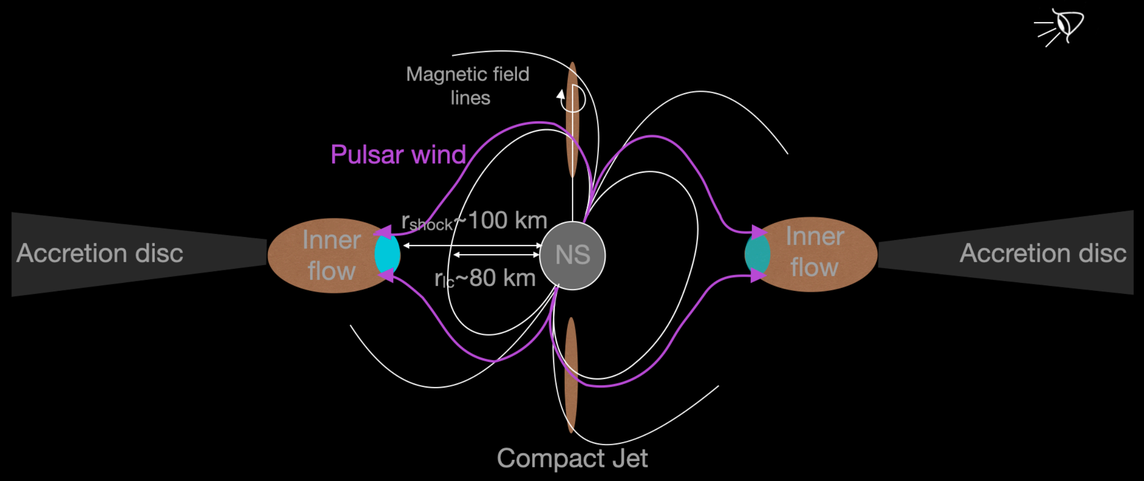

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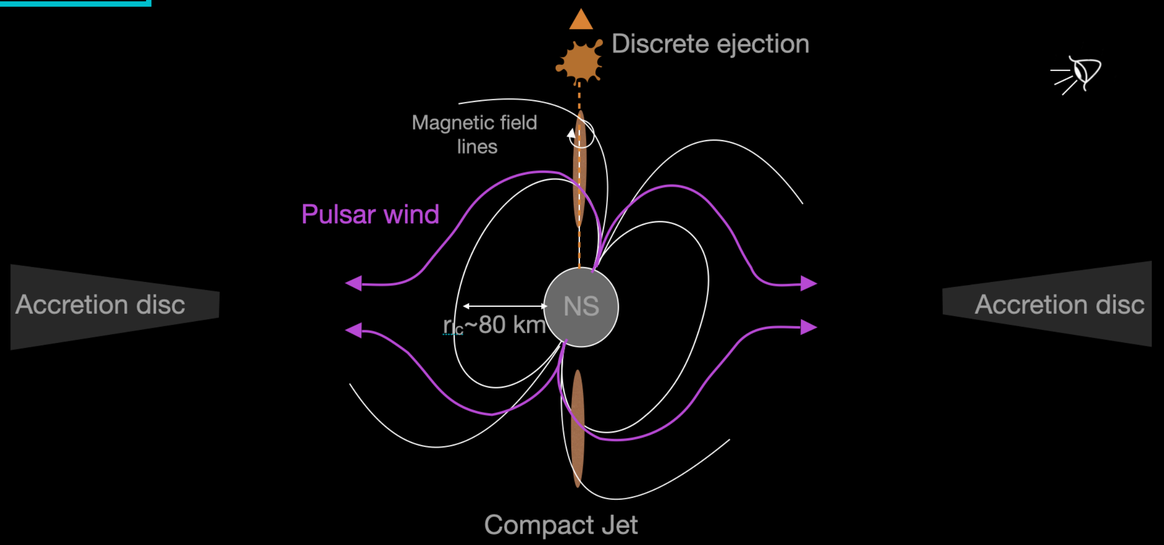

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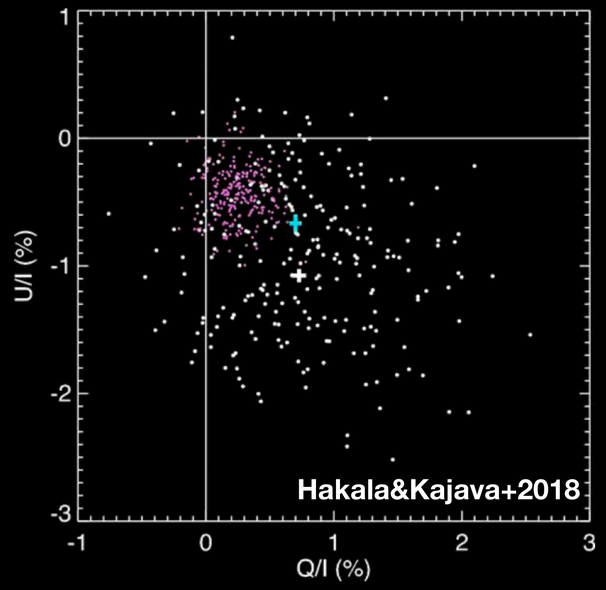
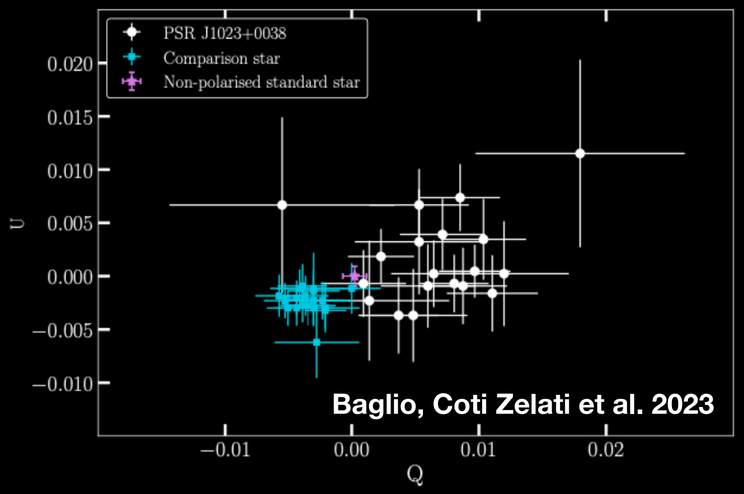
Polarization of tMSPs

Optical polarization measured in different works
(Baglio et al. 2016; Hakala&Kajava+2018; Baglio et al. 2023, 2025)



$P_{low}=(0.4\pm0.3)\%$
$P_{high}=(0.7\pm0.4)\%$



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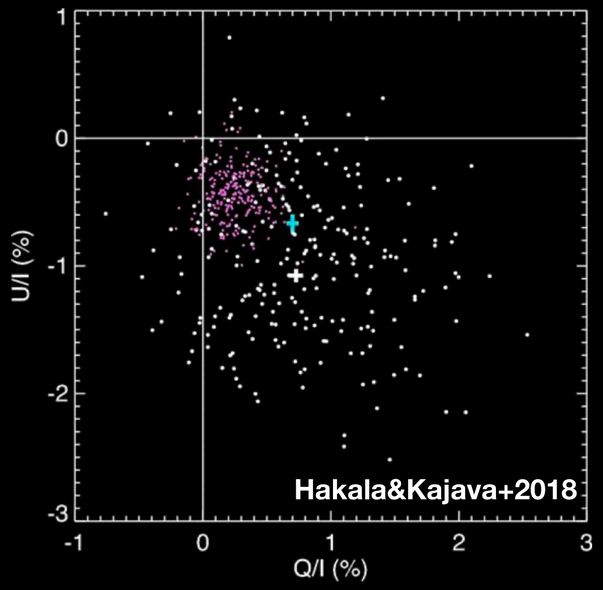

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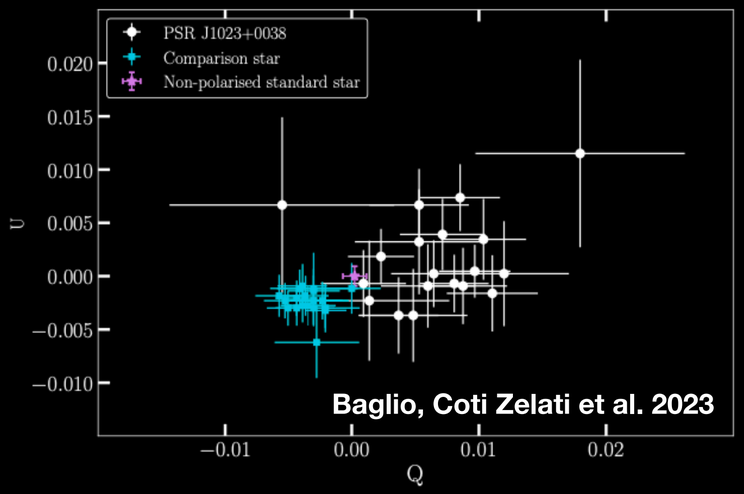
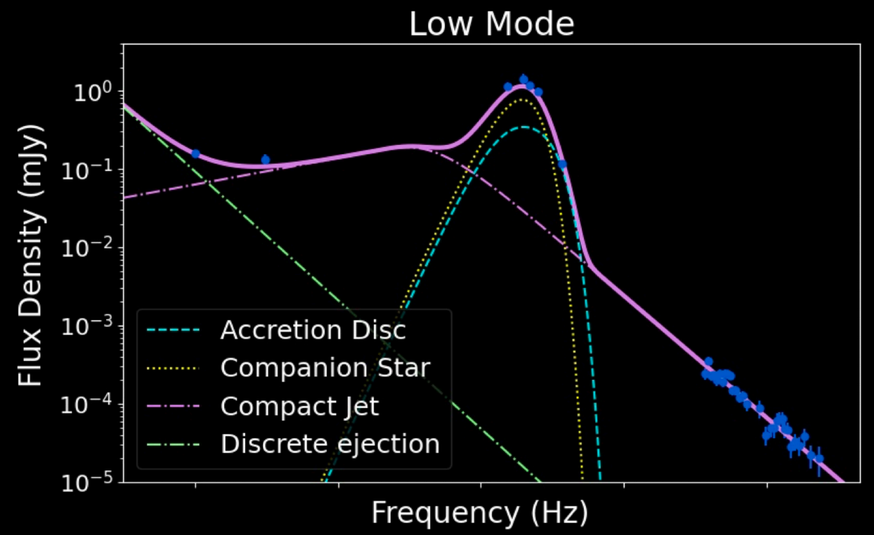
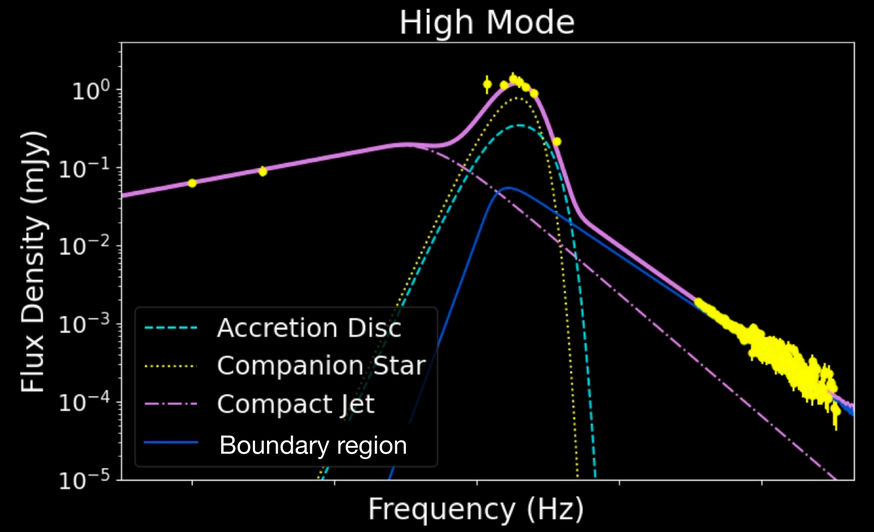


Origin uncertain.
Synchrotron at the boundary between the pulsar wind and the accreting matter?

Synchrotron contribution of ~90% in X: X-ray pol of ~15% with IXPE.



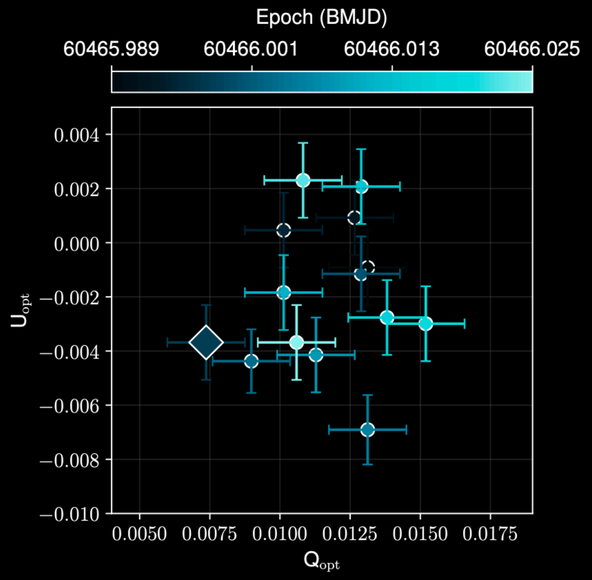
Baglio, Coti Zelati et al. 2023

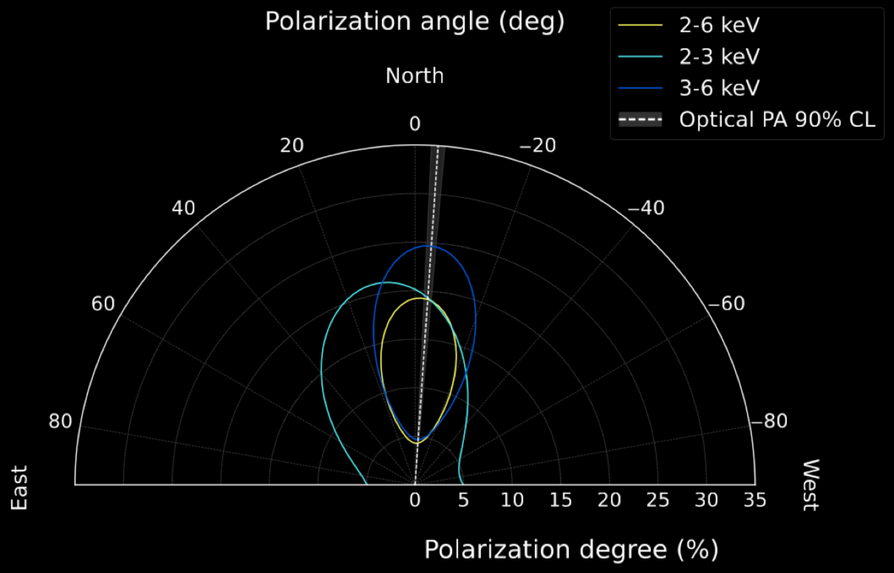


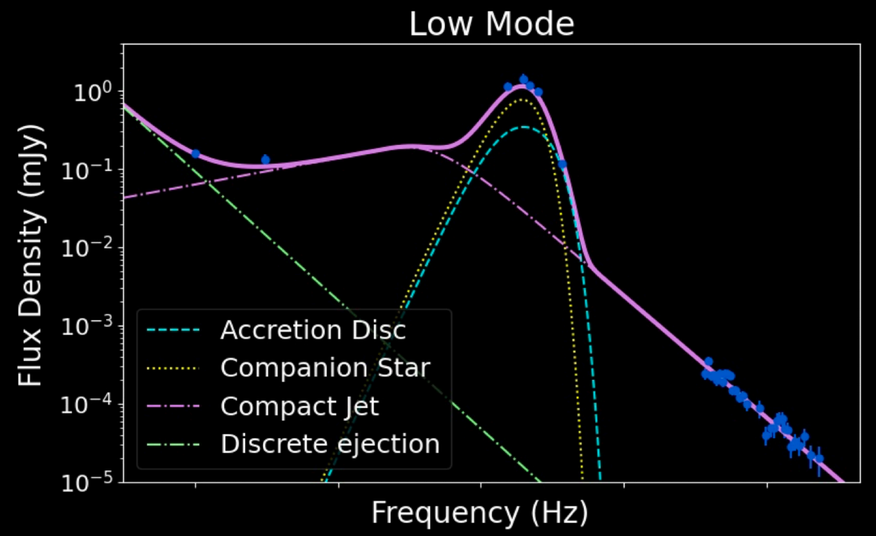
Multi-band polarization

We predicted ~15% polarization in the IXPE band.

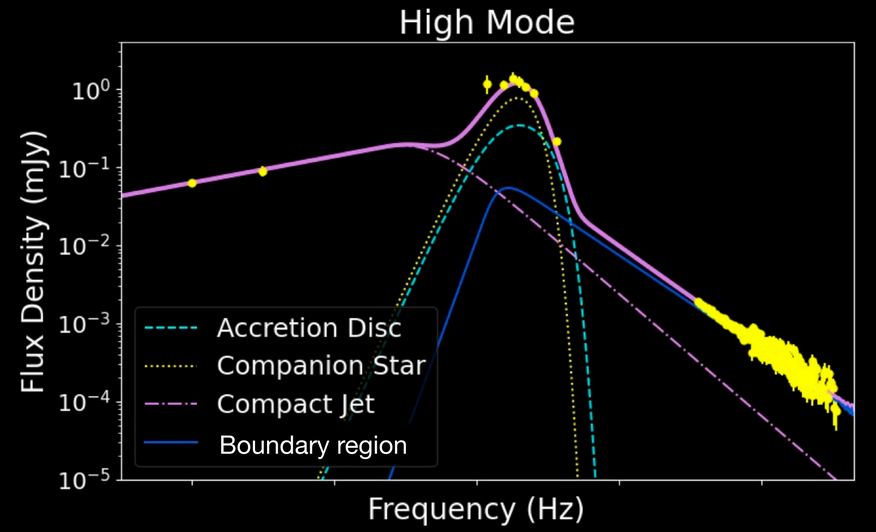
2024 campaign: multi-band polarimetry (IXPE, VLT, VLA).







Baglio, Coti Zelati et al. 2023



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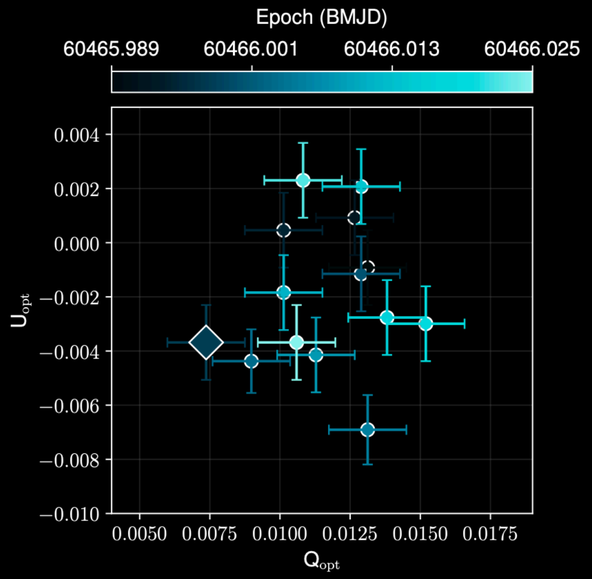
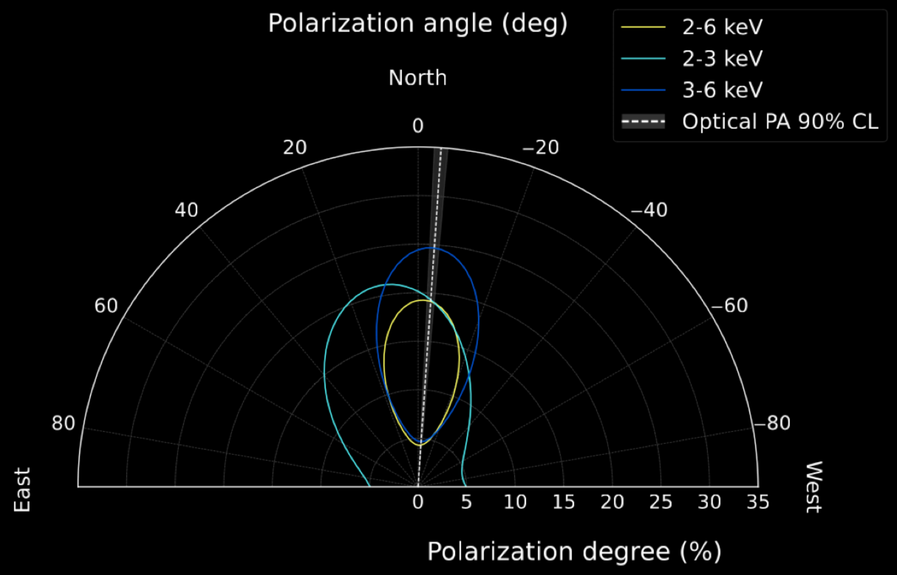
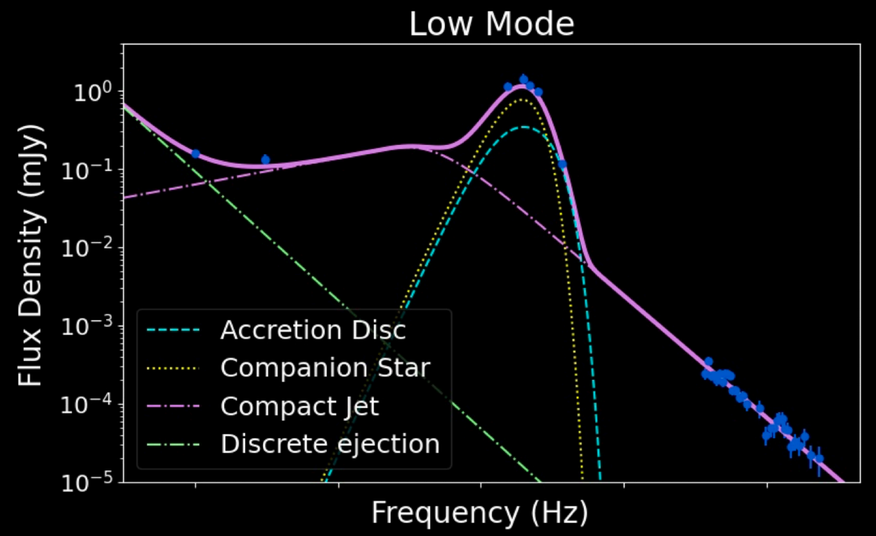
X-ray polarization of 12+/-3 % in the 3-6 keV energy band in high mode aligned with the 1% optical LP.

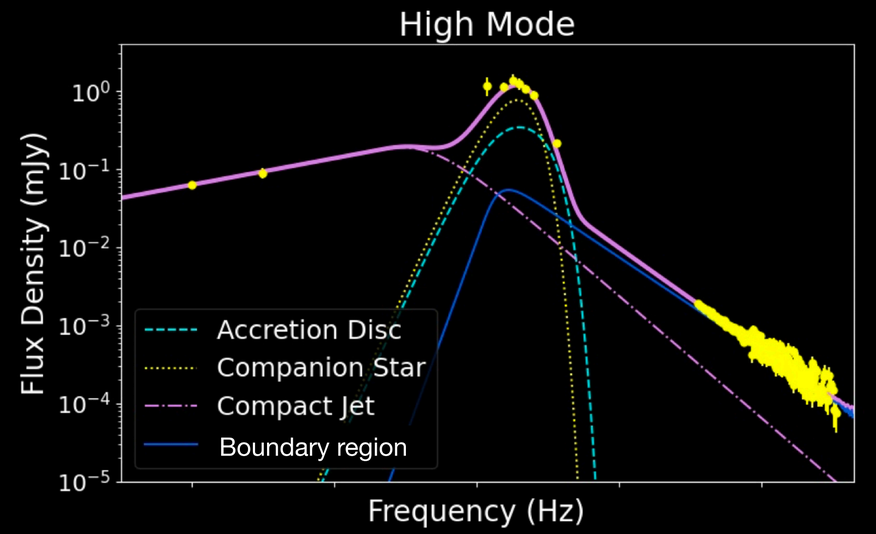




Baglio, Coti Zelati et al. 2025, ApJL



Baglio, Coti Zelati et al. 2023



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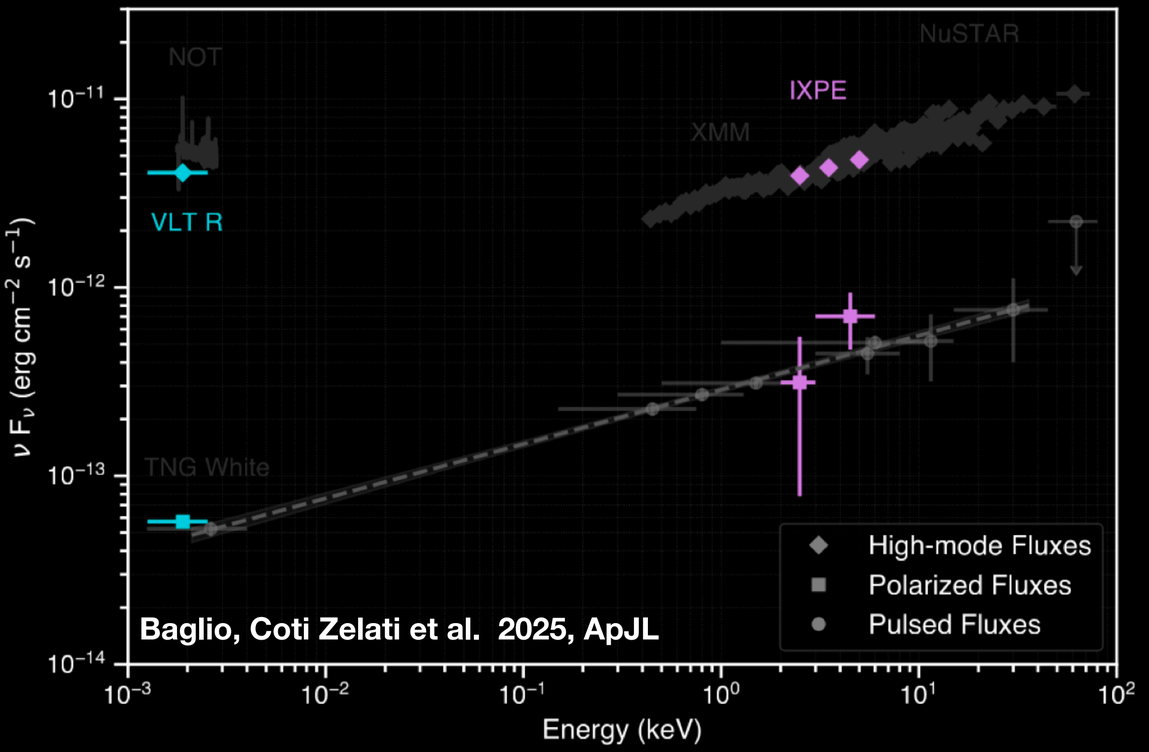


The polarized flux follows a flux distribution that is coincident with the pulsed flux distribution: common origin?

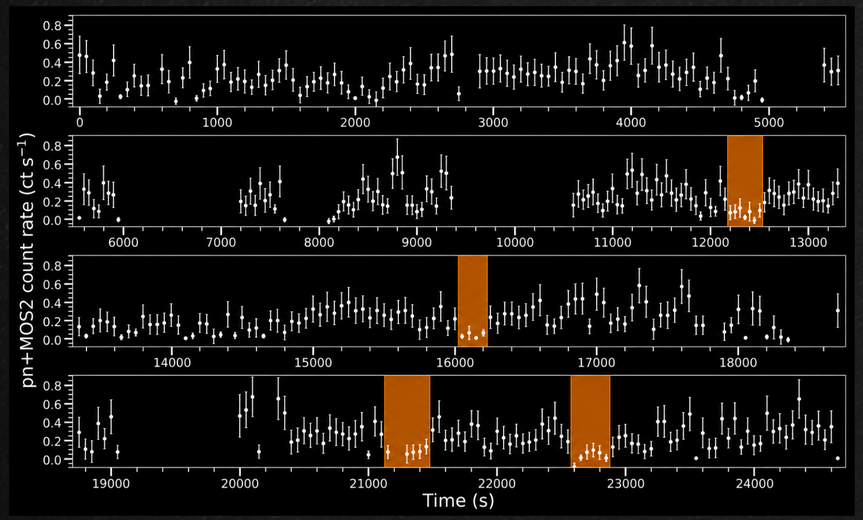
Very high polarization of the pulsed flux is expected at both optical and X-ray frequencies….

NewAthena: a new window into tMSPs

Many open questions still stand:

- **Can we add new candidates to the pool?**

Identifying high/low mode tranistions in faint/far sources

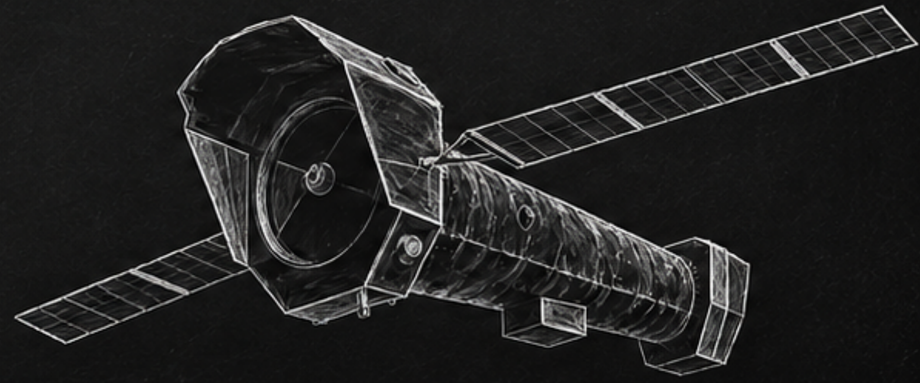


Kyer et al. 2025 — 4FGL J0639.1–8009

See talk by G. Illiano

High mode: ~0.3 ct/s
Low mode: a factor of 7 lower, should be ~0.04 ct/s (2 counts in 50s bins)
-> impossible with XMM/Newton
XMM/Newton EPIC: ~1,500 cm2 @ 1keV

NewAthena WFI: ~10,000 cm2 @ 1keV
Low mode count rate: 0.04 ct/s -> 0.3 ct/s (15 counts in 50s bins)
-> cleanly detectable in 50s bins, at 4sigma



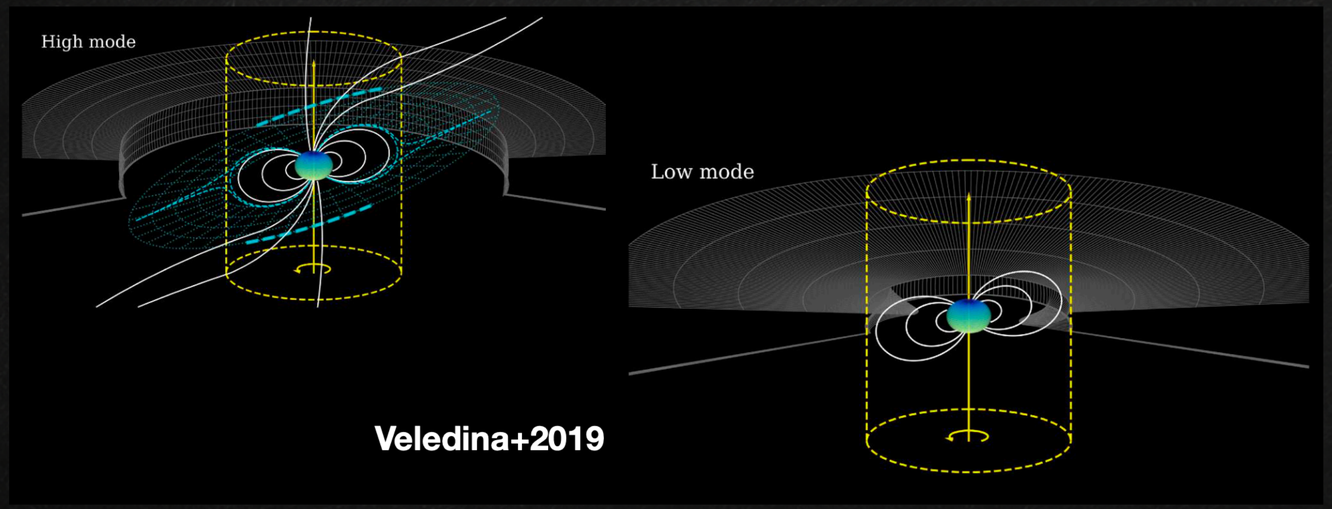
NewAthena: a new window into tMSPs

Many open questions still stand:

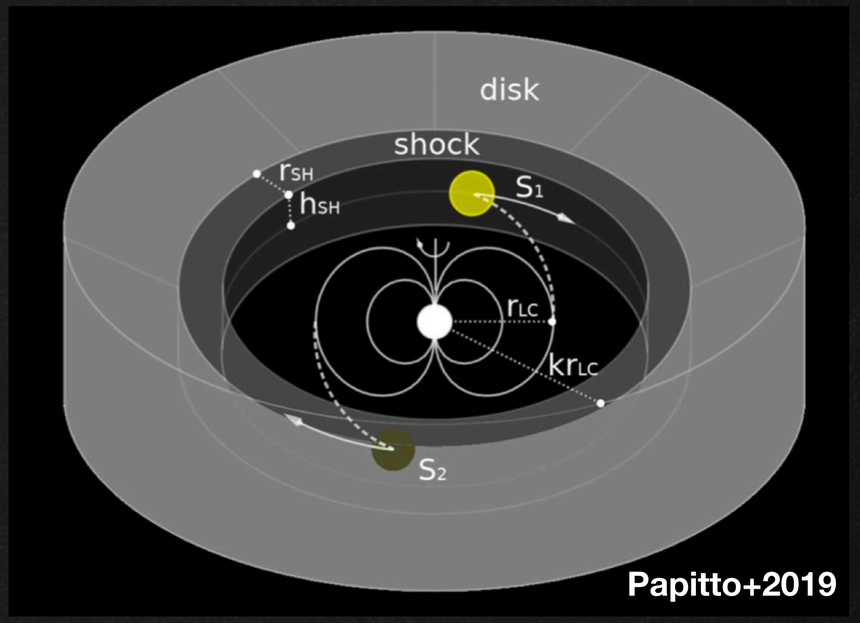
- **Can we add new candidates to the pool?**
- **Are X-ray pulsations present only in high (and maybe flaring) modes?**

XMM upper limit in low mode: <2.4% rms.
NewAthena sensitivity: ~0.9% rms
—> it will probe whether pulsations switch off in low mode, or fade below current detectability.

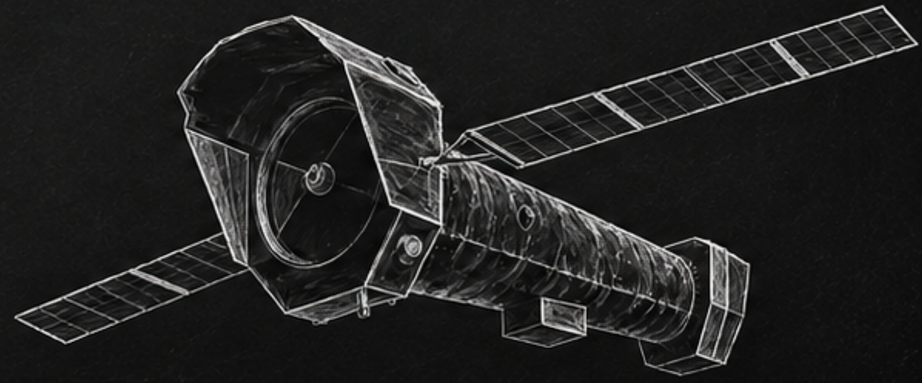
Essential to disentangle between current models!



Veledina+2019



Papitto+2019



NewAthena: a new window into tMSPs

Many open questions still stand:

- **Can we add new candidates to the pool?**
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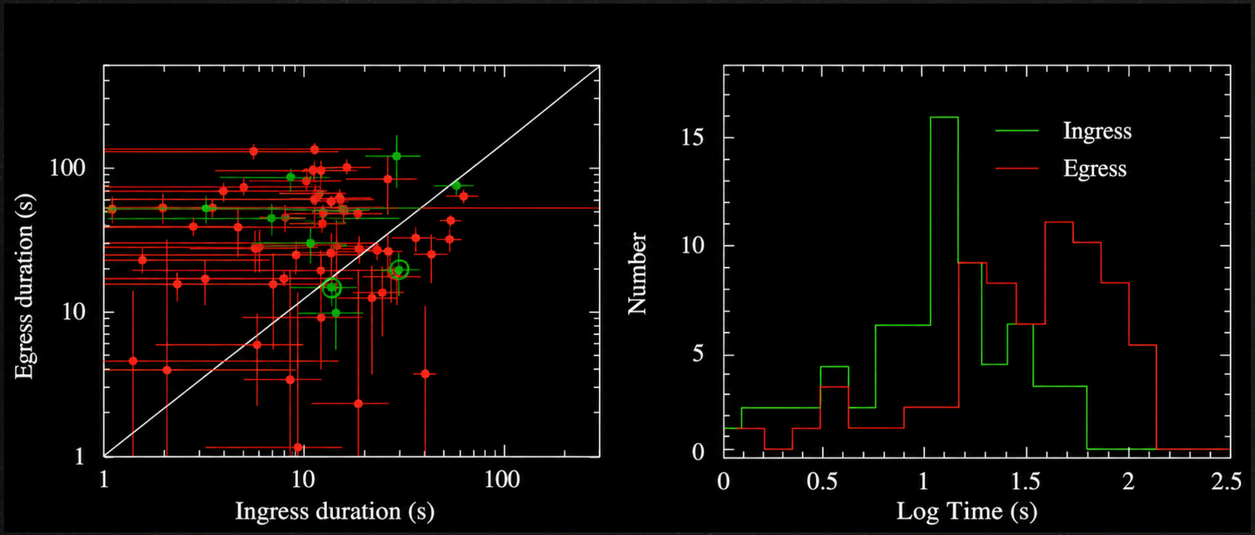
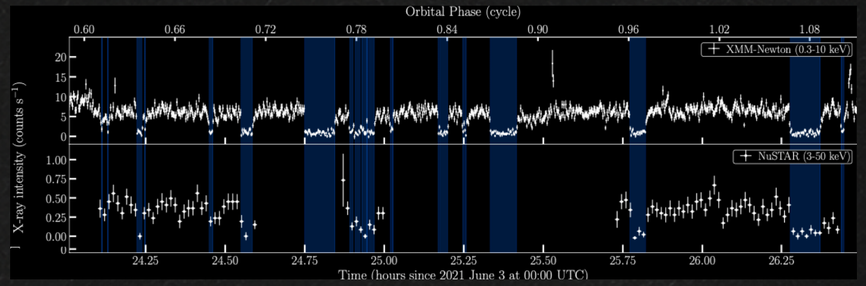
- **What is the duration of the ingress phase to low modes?**



NewAthena will resolve the transitions down to 1-4s.

Not the dynamical timescale — but a factor ~5–7 improvement on current limits.

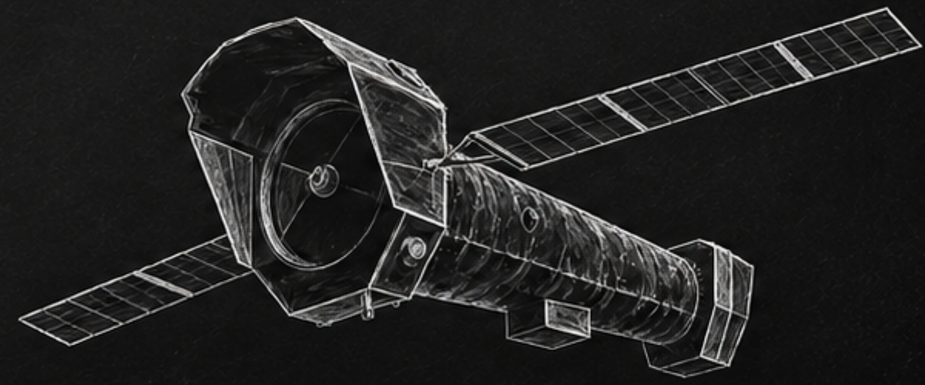


Baglio, Coti Zelati et al. 2023 analyzed all the transitions observed by XMM-Newton in the past ~10 years.

INGRESS: ejection of innermost disc -> dynamical timescale (~0.1 s at 20 R_{LC})

EGRESS: the innermost disc must be refilled -> viscous timescale (~20 s)

XMM-Newton resolves mode transitions down to ~10-25s.



NewAthena: a new window into tMSPs

Many open questions still stand:

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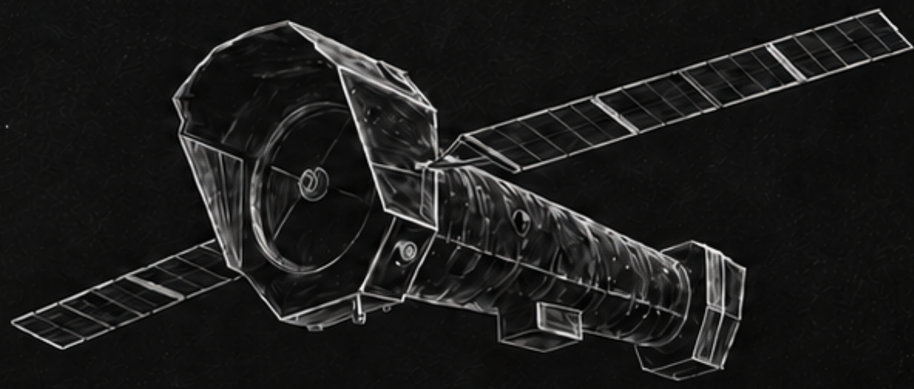
NewAthena will be instrumental to answer all these questions and disentangle between models!



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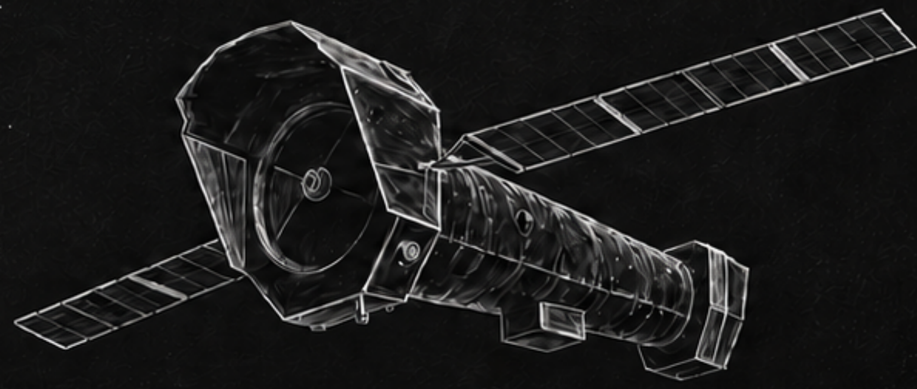

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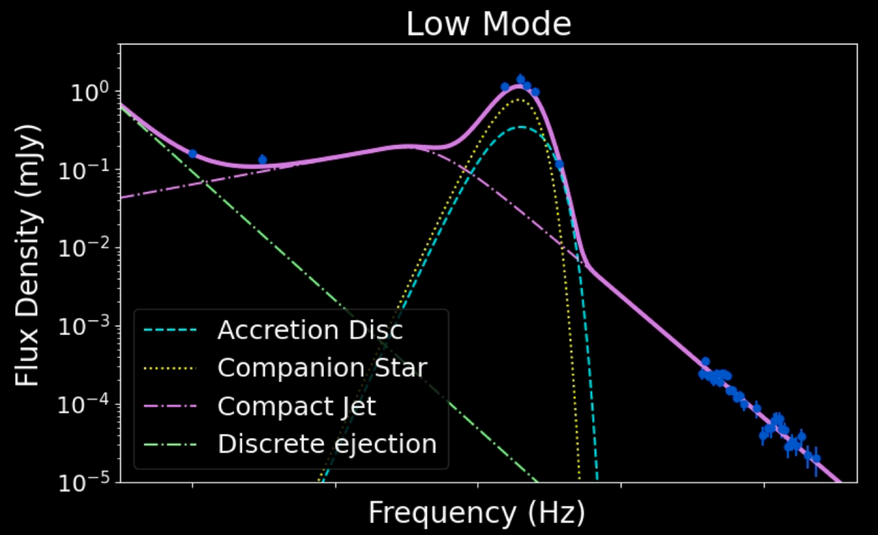
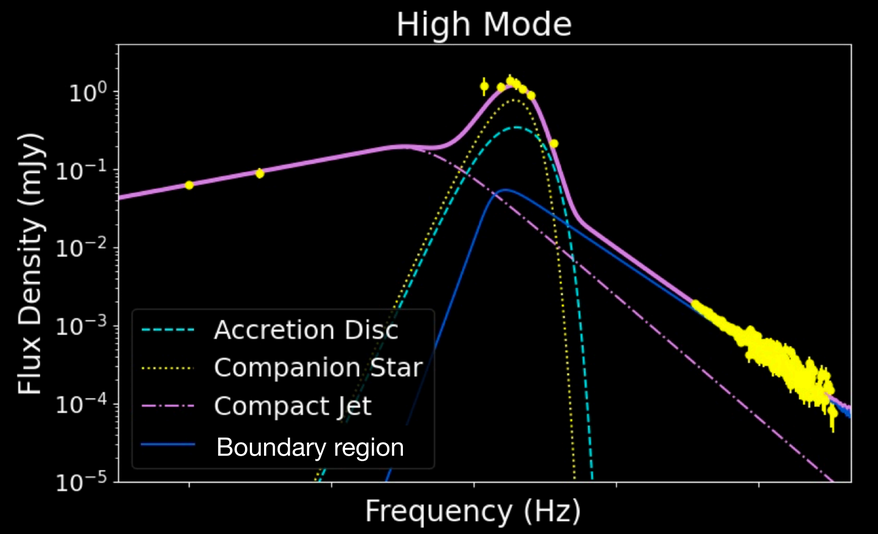
Thank you!

Optical Polarization of tMSPs



Baglio, Coti Zelati et al. 2023

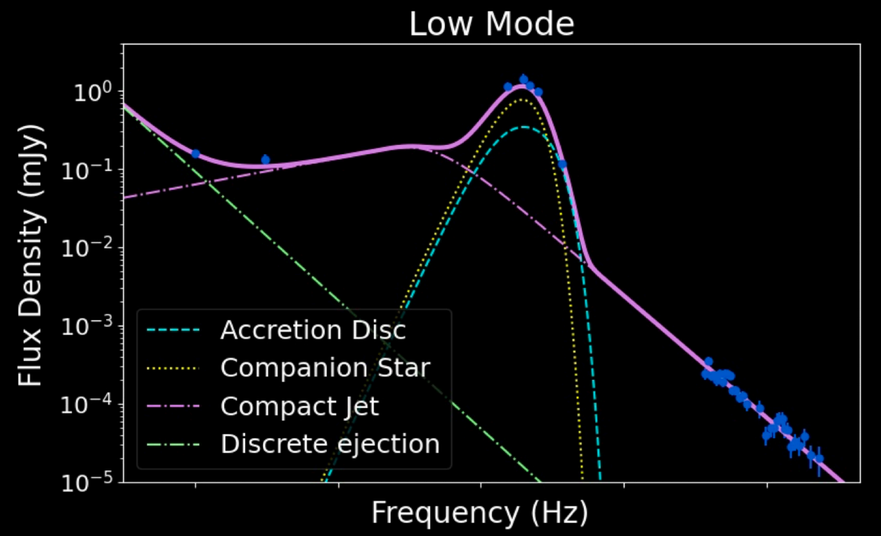


Optical Polarization of tMSPs

Scenario consistent with the ~lower P in low mode

$P_{low}=(0.4\pm0.3)\%$ $P_{high}=(0.7\pm0.4)\%$

Synchrotron contribution in r-band ~2.7%: intrinsic LP of ~23% in high mode.

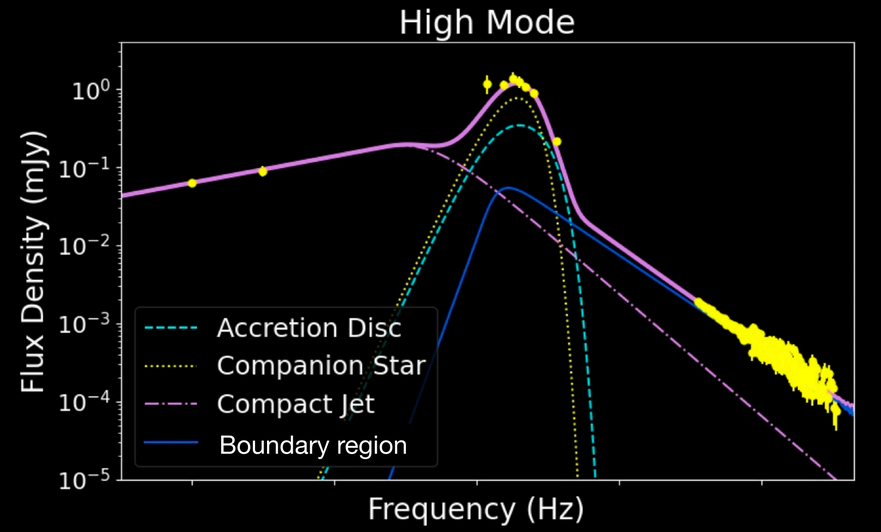


Baglio, Coti Zelati et al. 2023

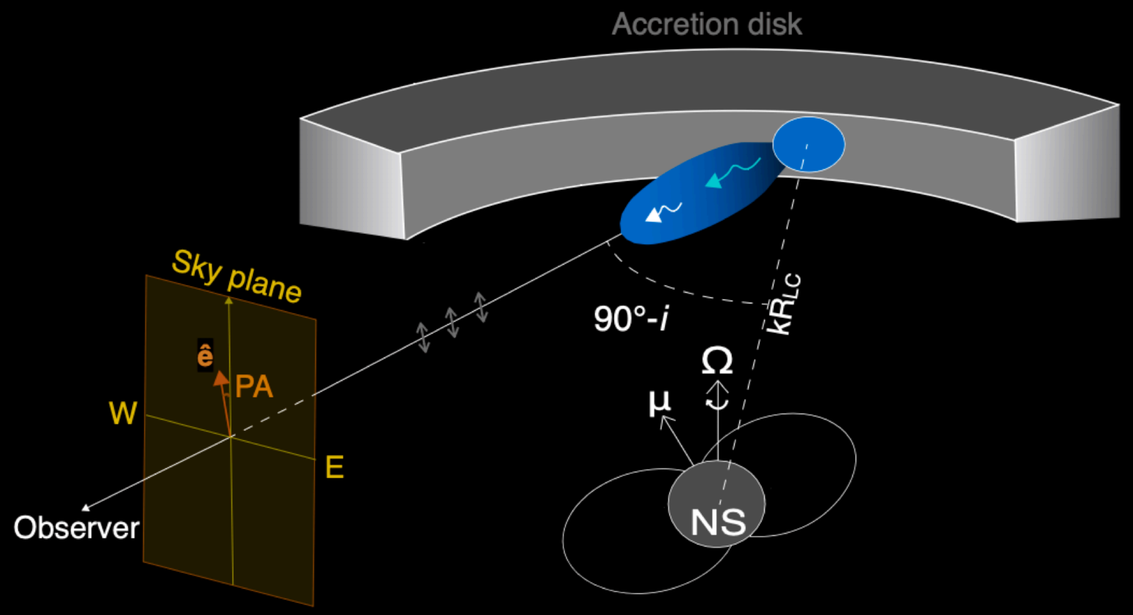
<u>If polarization is due to the impulse only (1% of total)</u>, then the pulse will be ~65-90% polarized!

This can be tested with high time-resolution optical polarimetry: e-SiFOP

Synchrotron contribution of ~90% in X: X-ray pol of ~15% with IXPE.

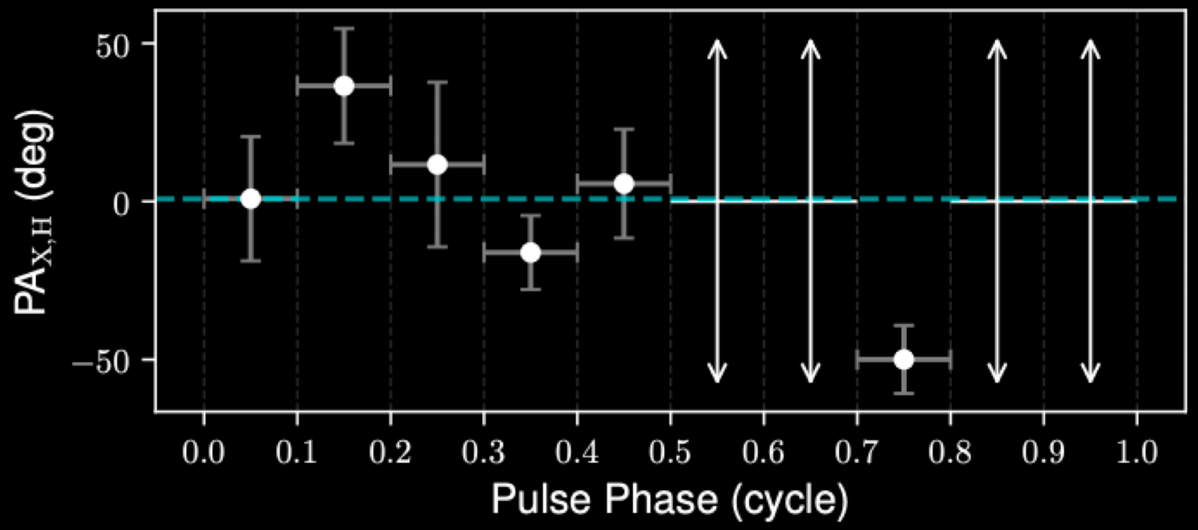


Multi-band polarization



Polarization likely originates from the boundary between the pulsar wind and the accretion flow.

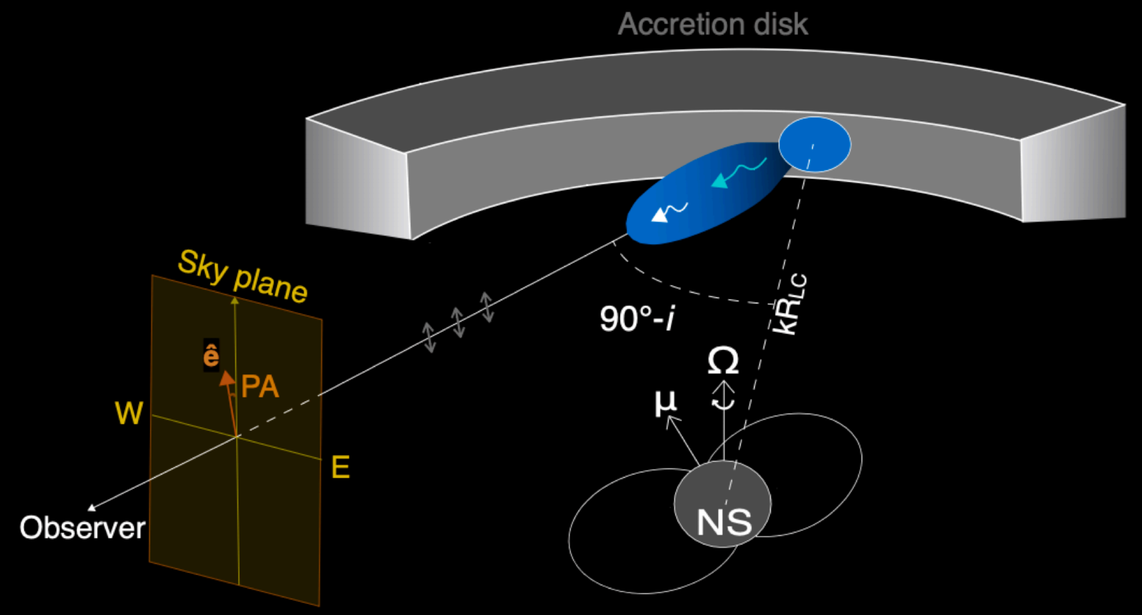
The polarization angle does not show significant variations with the pulse phase, which suggests that the magnetic field at the boundary has a dominant poloidal component (Veledina+2025).



A toroidal geometry cannot be entirely excluded due to the large error bars.

See also the talk by Valentina

Multi-band polarization



Baglio, Coti Zelati et al. 2025, ApJL

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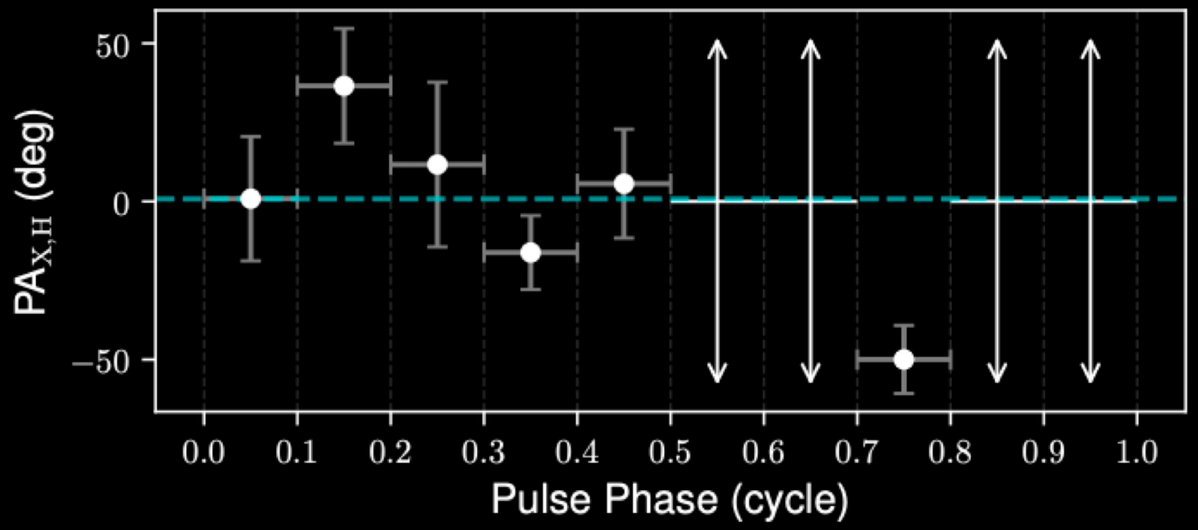

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Poorly investigated so far.

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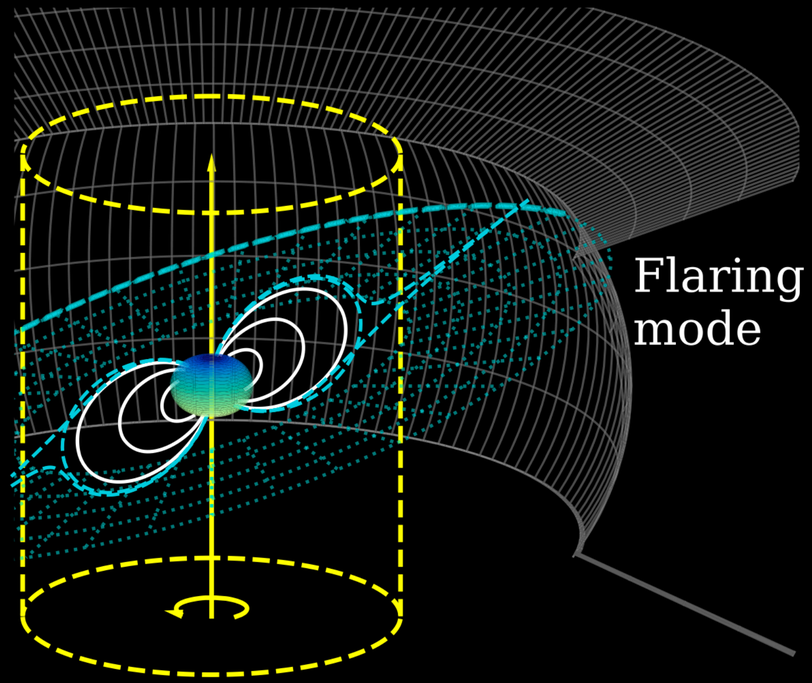
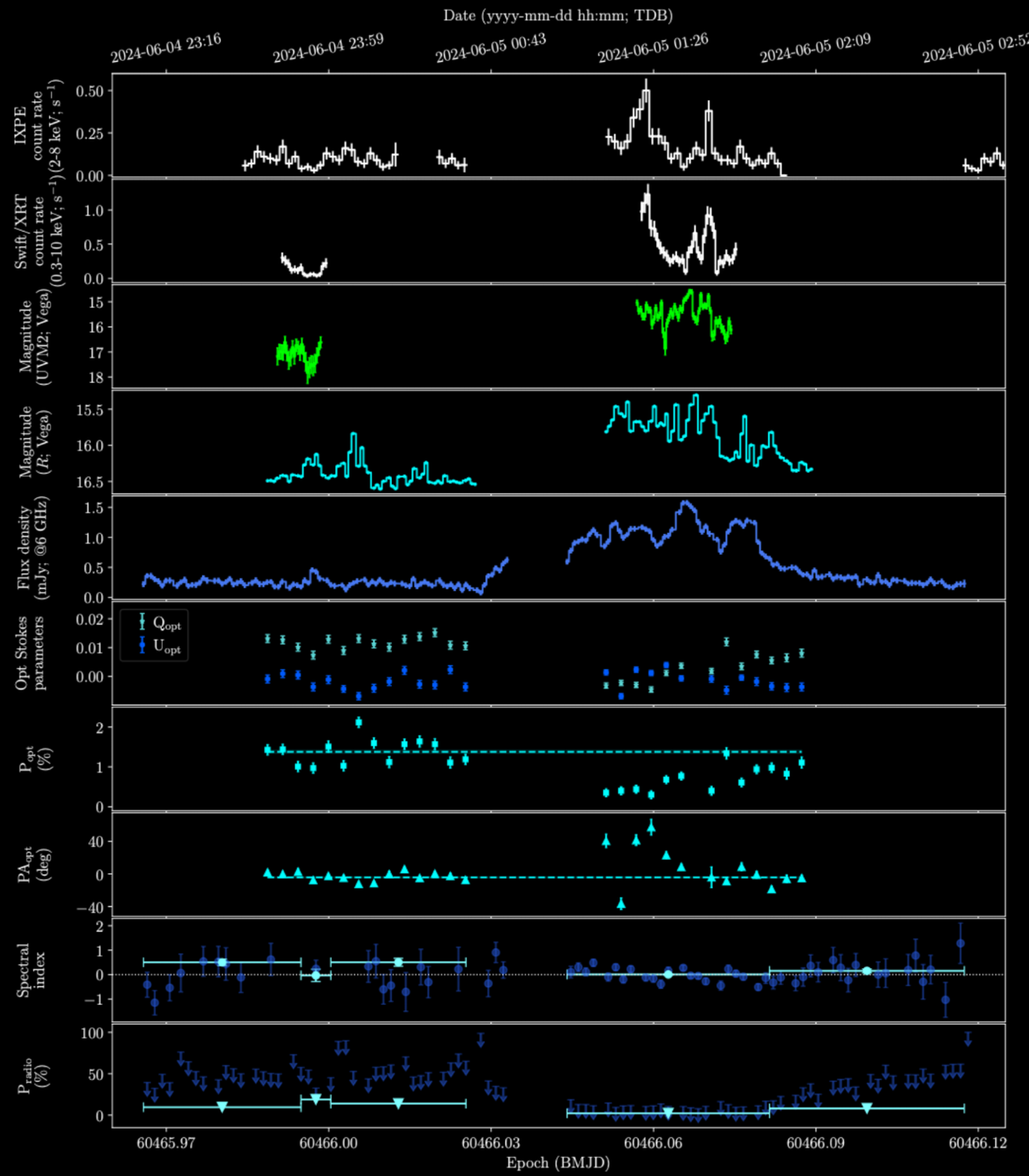


Veledina et al. 2019



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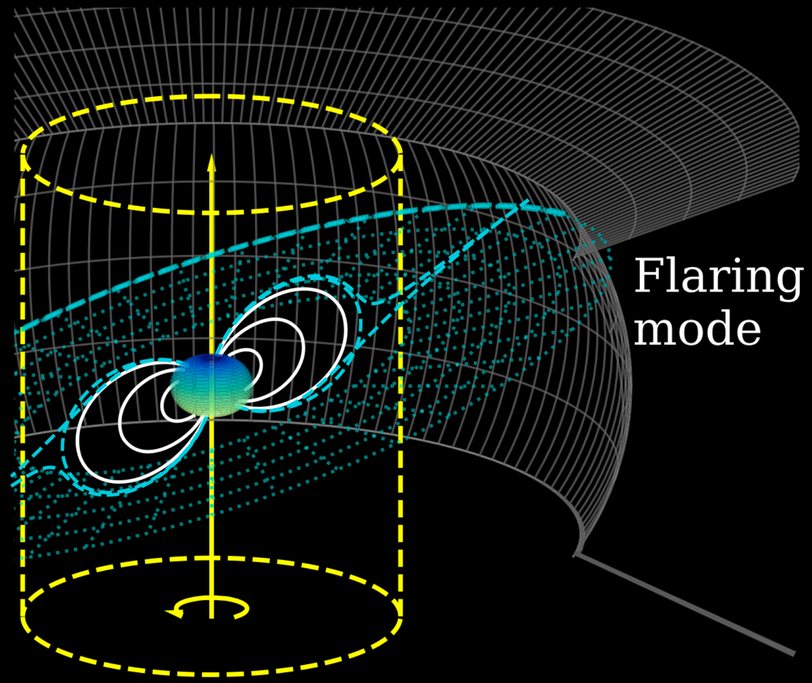

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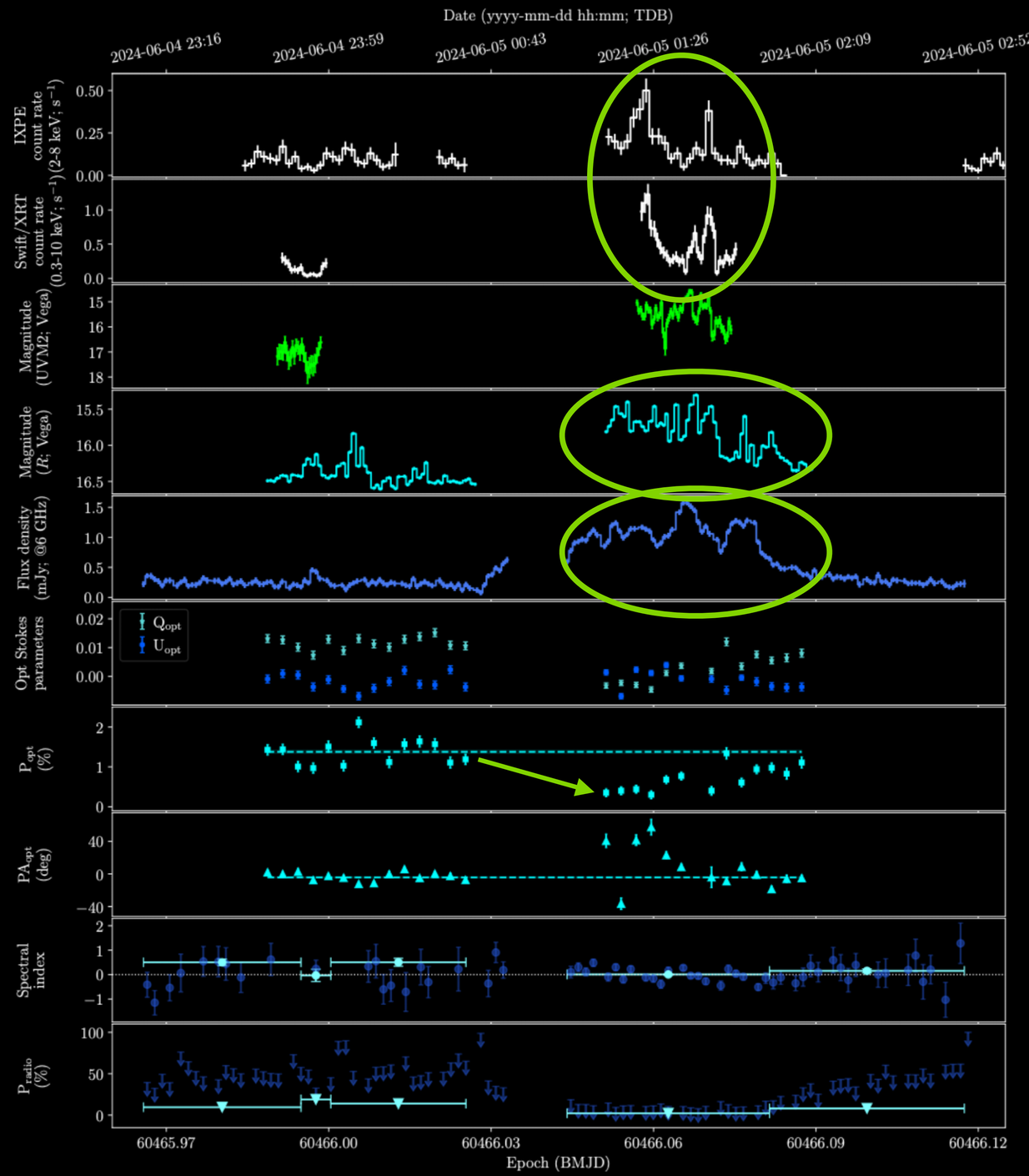

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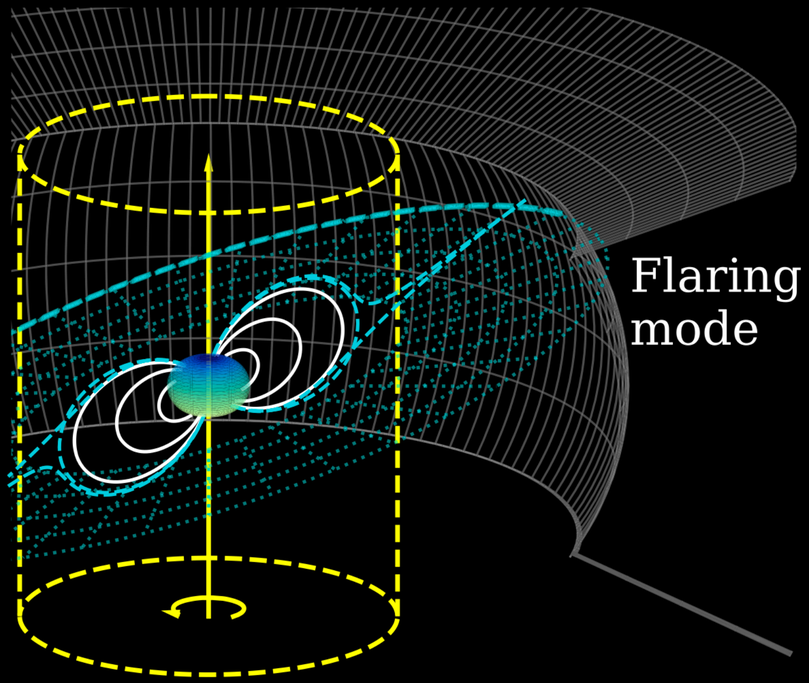
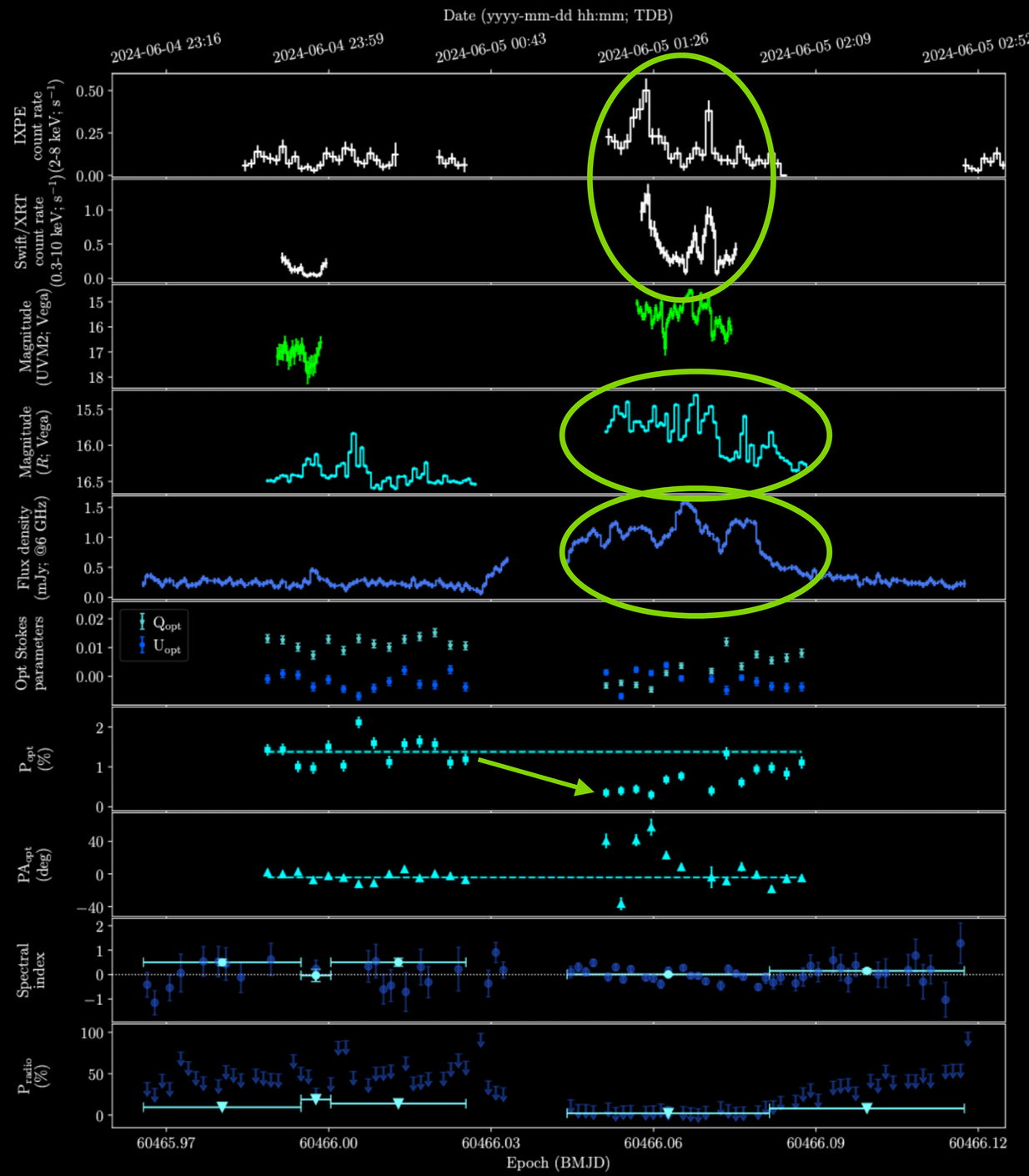


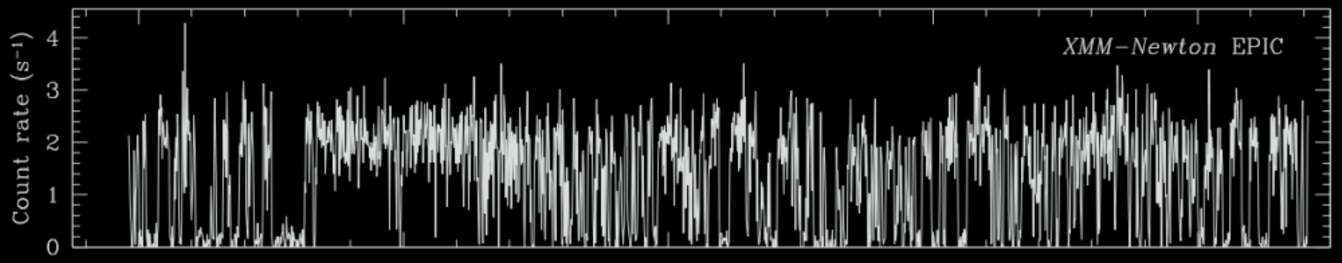
Veledina et al. 2019

Increased jet mass-loading?

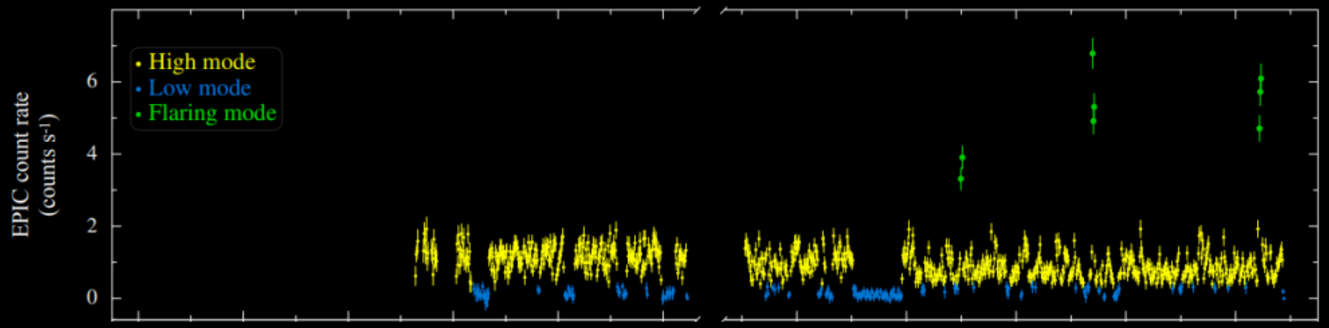


Candidates transitional pulsars

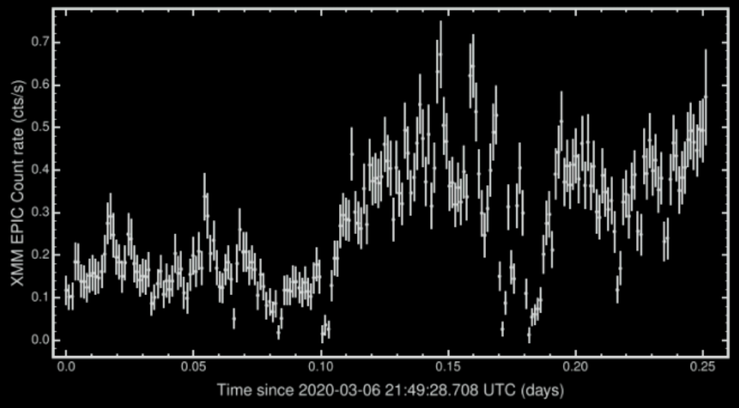
RXS J154439.4-112820
[Bogdanov+ 2015, 2016; Britt+ 2017]

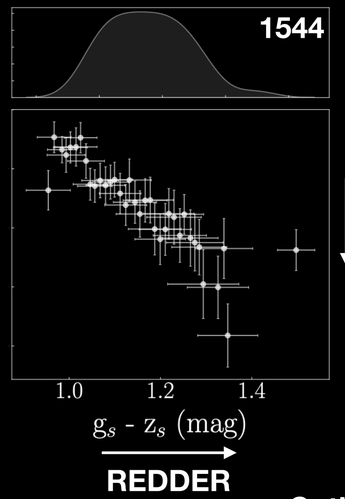


CXOU J110926.4-650224
[Coti Zelati+ 2019, 2021]

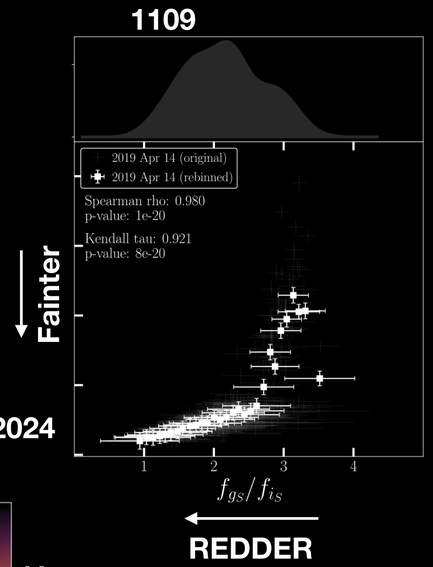


4FGL J0407.7–5702
[Li+ 2020; Miller+ 2020]

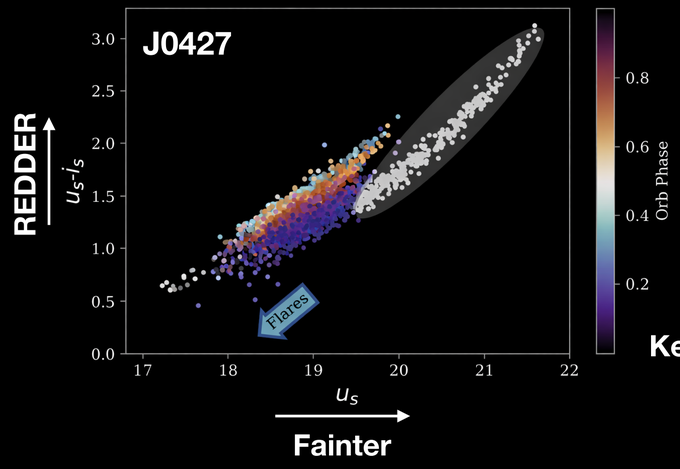




Illiano et al. 2025



Coti Zelati et al. 2024



Kennedy et al. 2020

4FGL J0427.9-6704, Terzan 5 CX10, XMM J174457-2850.3
[Strader+ 2021; Kennedy+ 2020; Deller+ 2014] and others…