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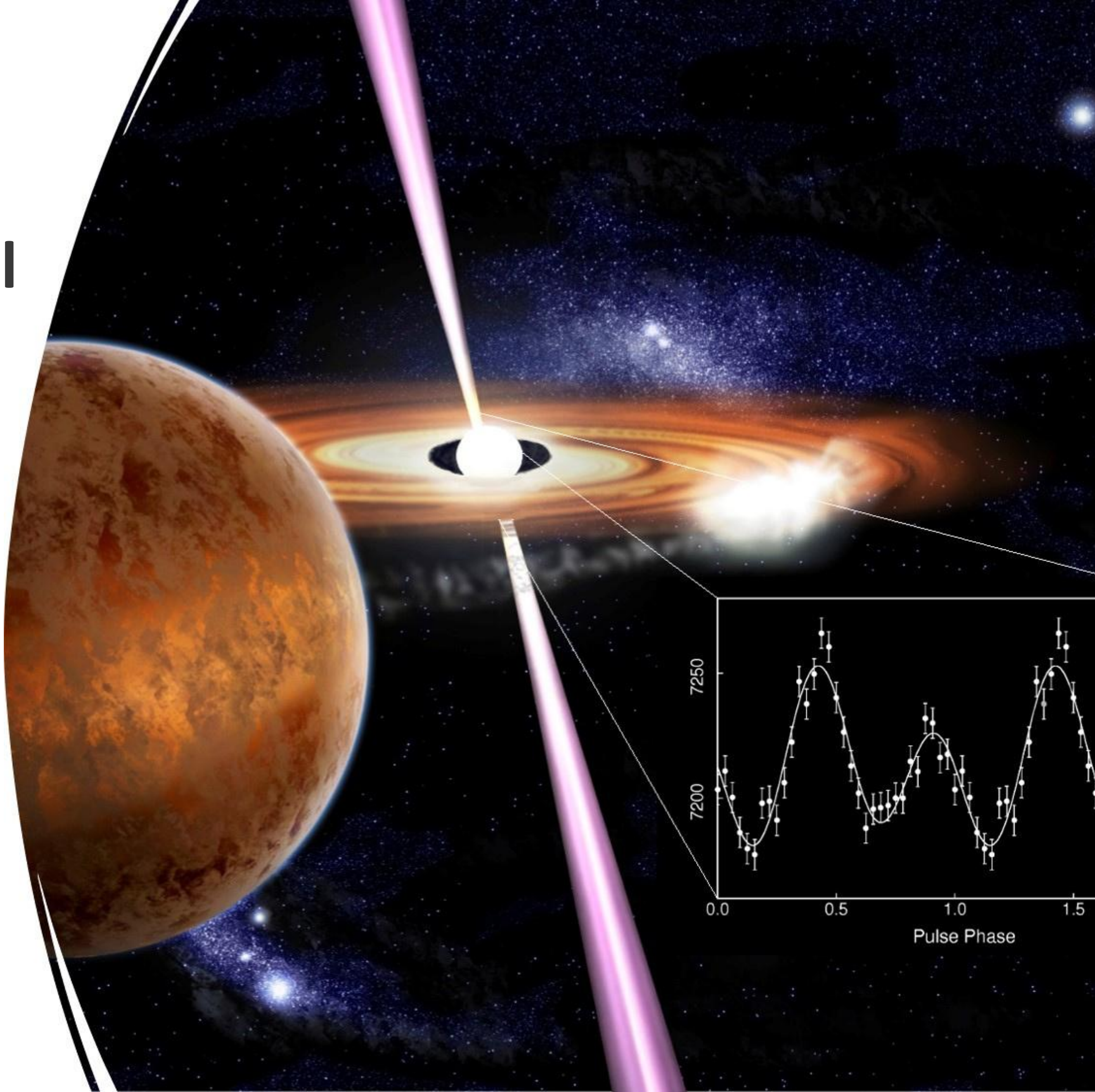
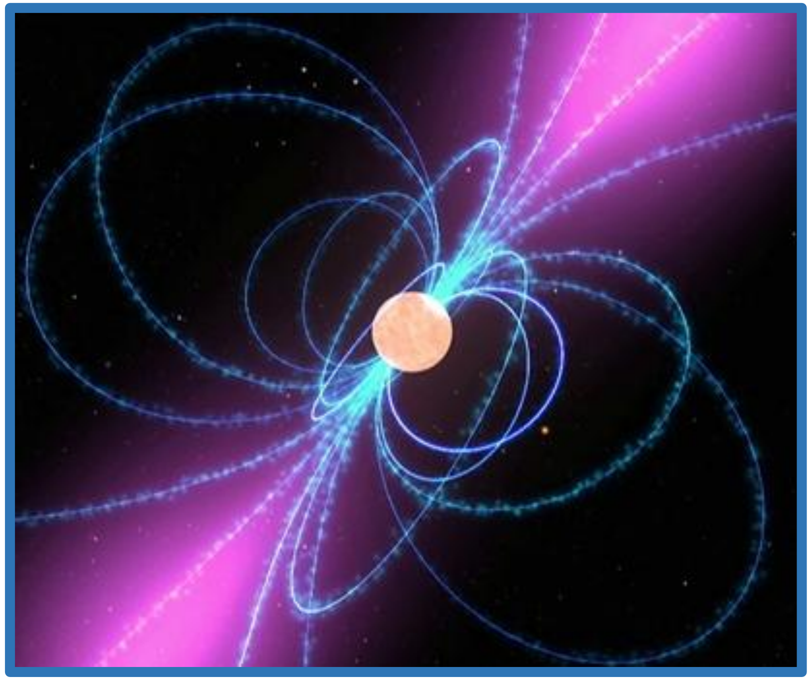
The many facets of transitional millisecond pulsars: can accretion- and rotation-powered states coexist?

Giulia Illiano

In collaboration with A. Papitto, F. Ambrosino, A. Miraval Zanon, F. Coti Zelati and many more

HONEST3 Workshop 26/11/2024





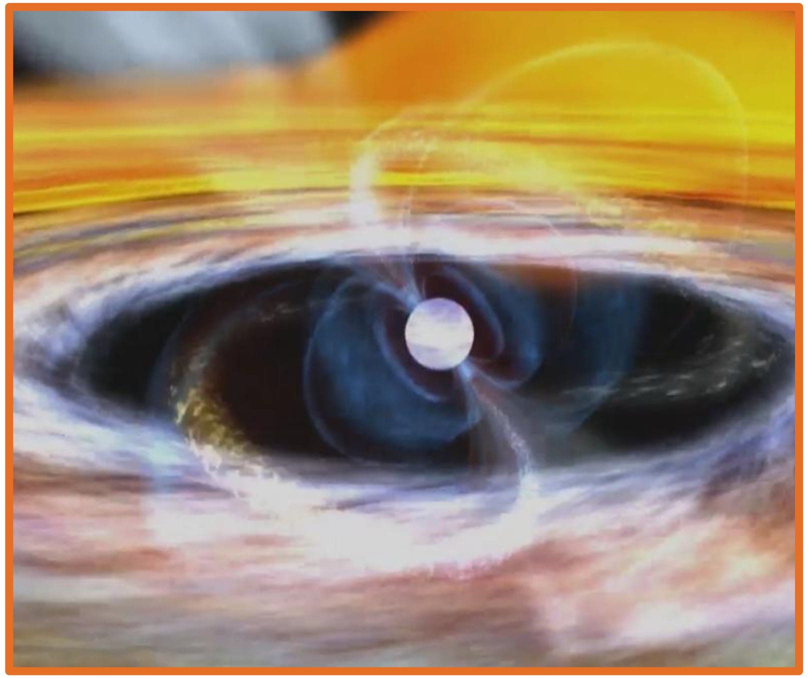
Rotation-powered (radio) ms pulsar

Rotation of the electromagnetic field
→ **Magnetospheric particle acceleration**

→ **Radio/Gamma-ray pulses**
→ **Relativistic pulsar wind**

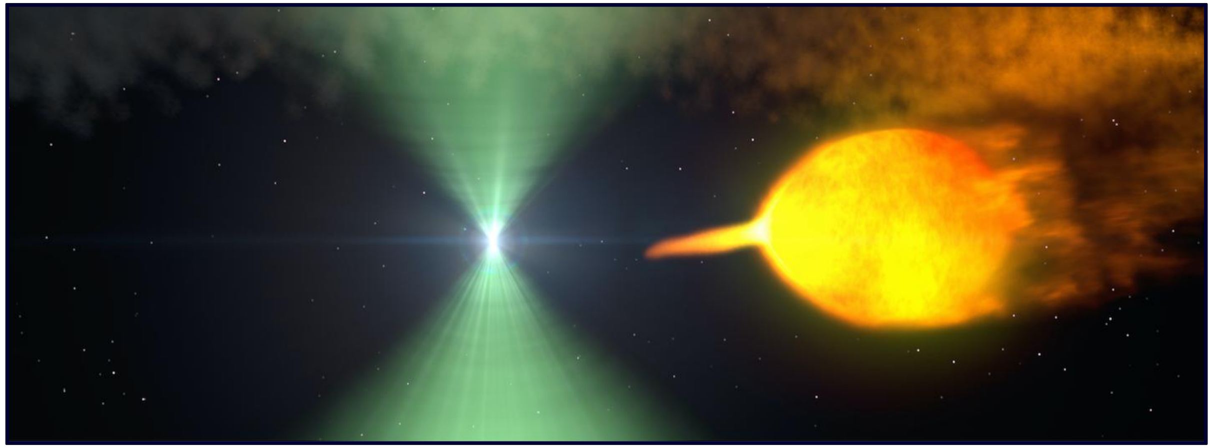
Accretion-powered (X-ray) ms pulsar

Matter lost by a companion star
channeled by the pulsar’s magnetic field
→ **X-ray emitting hotspots/columns**

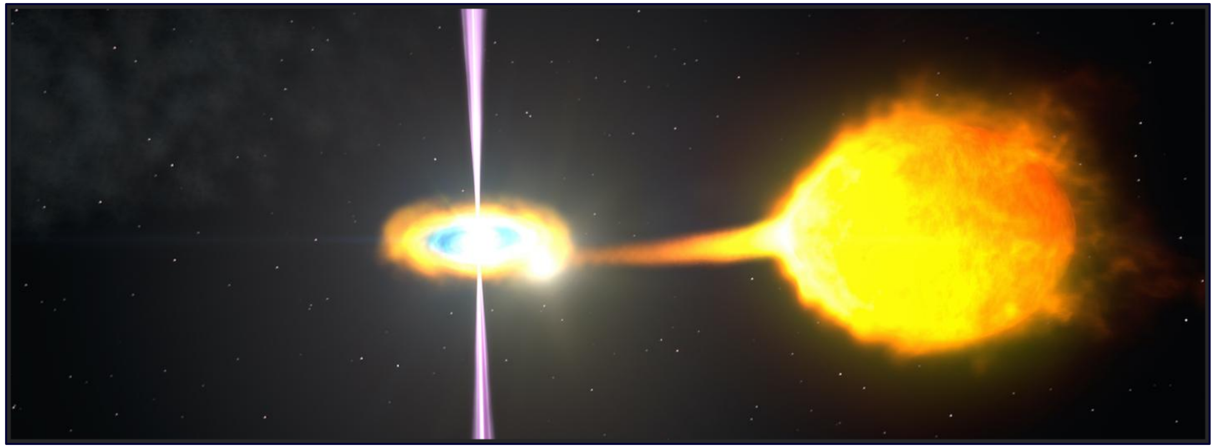


The “missing link”

Rotation-powered (radio) state



[Credit to NASA]

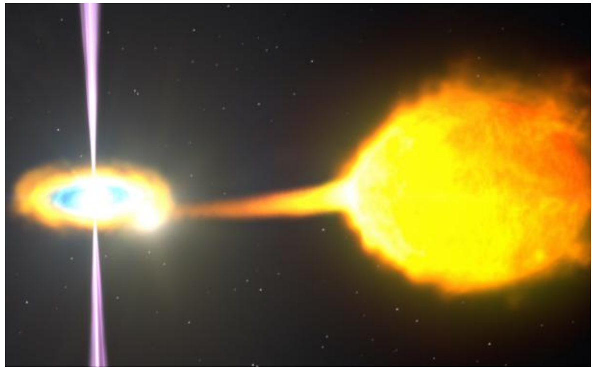


Accretion-powered (X-ray) state

[see Stella+ 1994; Campana+ 1998; Burderi+ 2001]

Transitional millisecond pulsars

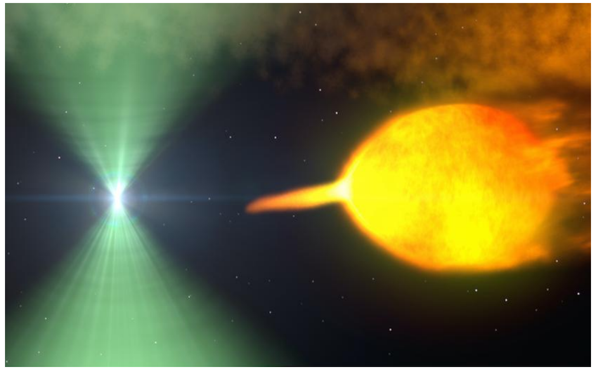
Accretion-powered (X-ray) state



Mass accretion rate

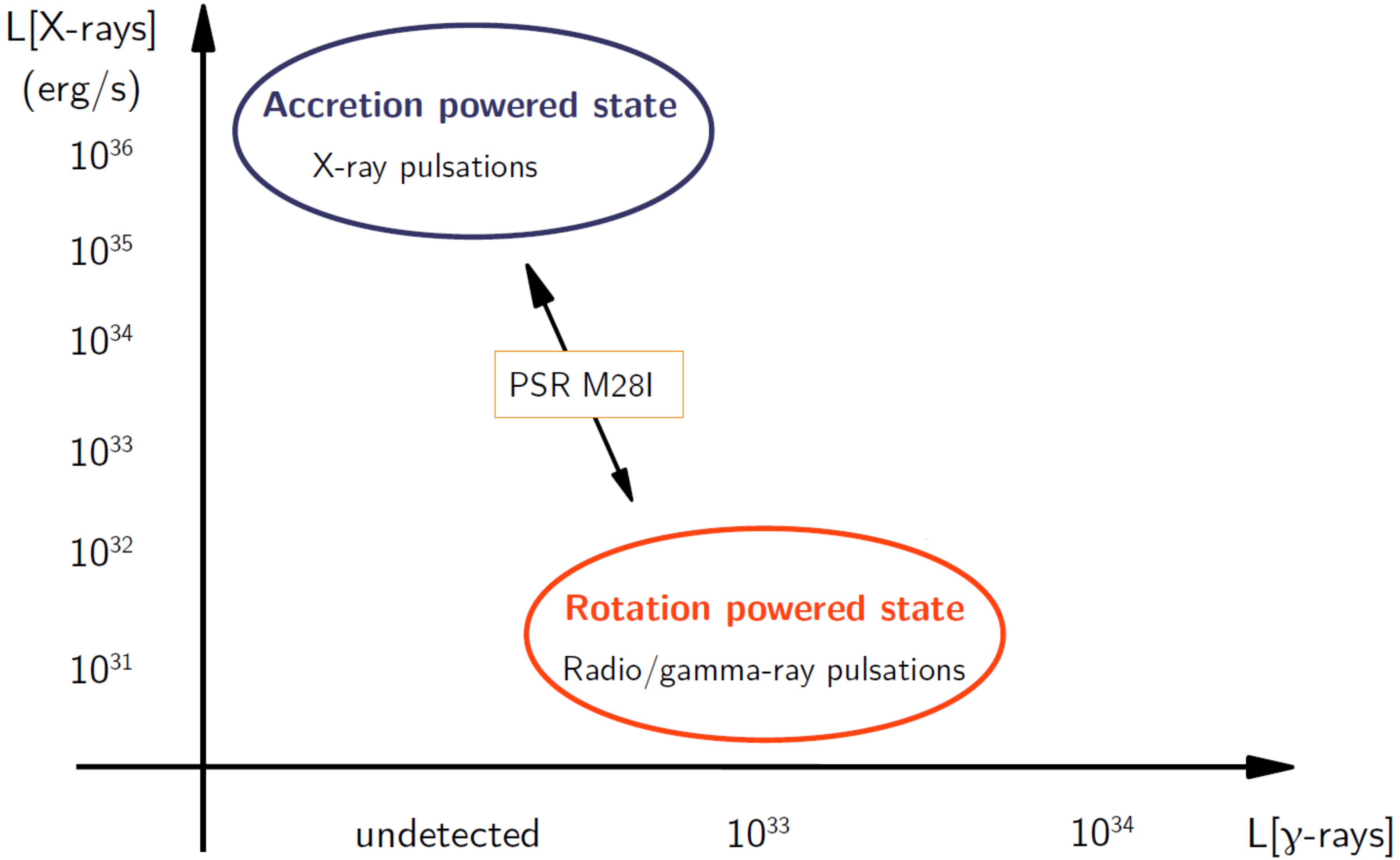
Confirmed transitional millisecond pulsars:

- PSR J1023+0038 [Archibald+ 2009]
- XSS J12270-4849 [Bassa+ 2014]
- IGR J18245-2452 [Papitto+ 2013]



Rotation-powered (radio) state

Transitional millisecond pulsars



$$L_{accretion} \gg L_{spin-down}$$

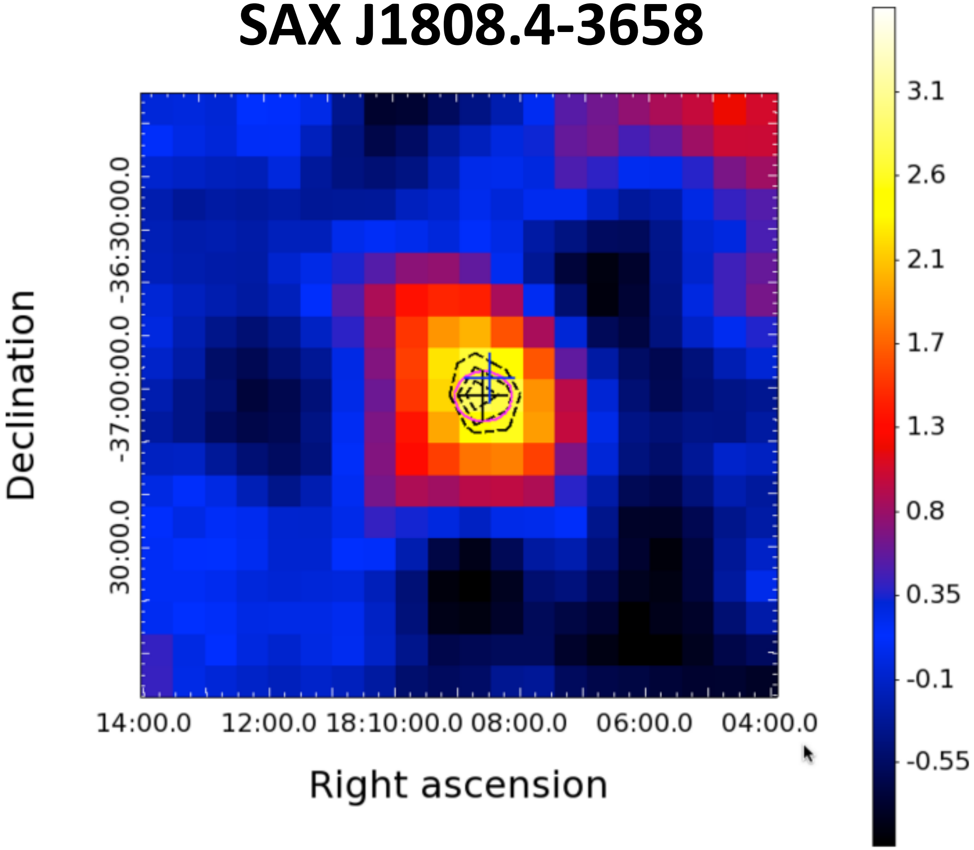
$$L_{accretion} \ll L_{spin-down}$$

[Courtesy of A. Papitto]

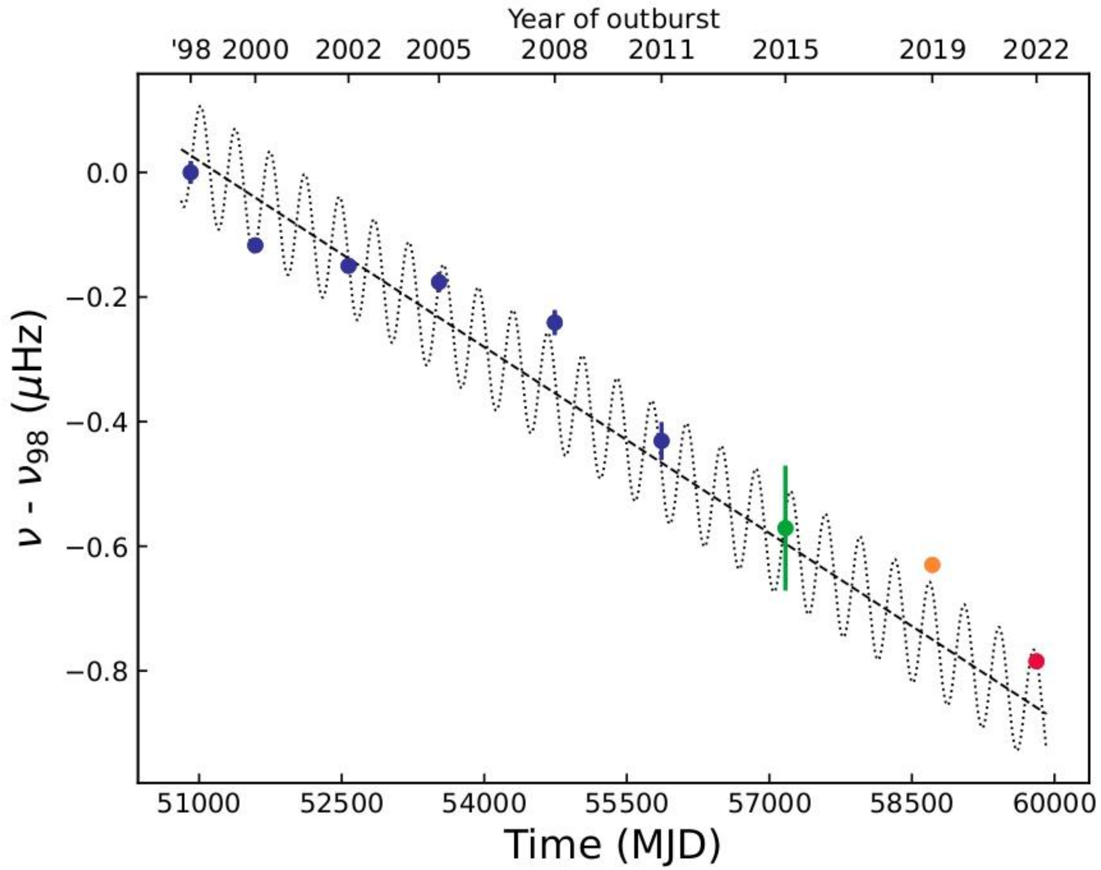
[Papitto+ 2013, Nature; see Papitto & de Martino 2022, ASSL for a review]

An accreting millisecond pulsar shining in gamma rays?

SAX J1808.4-3658



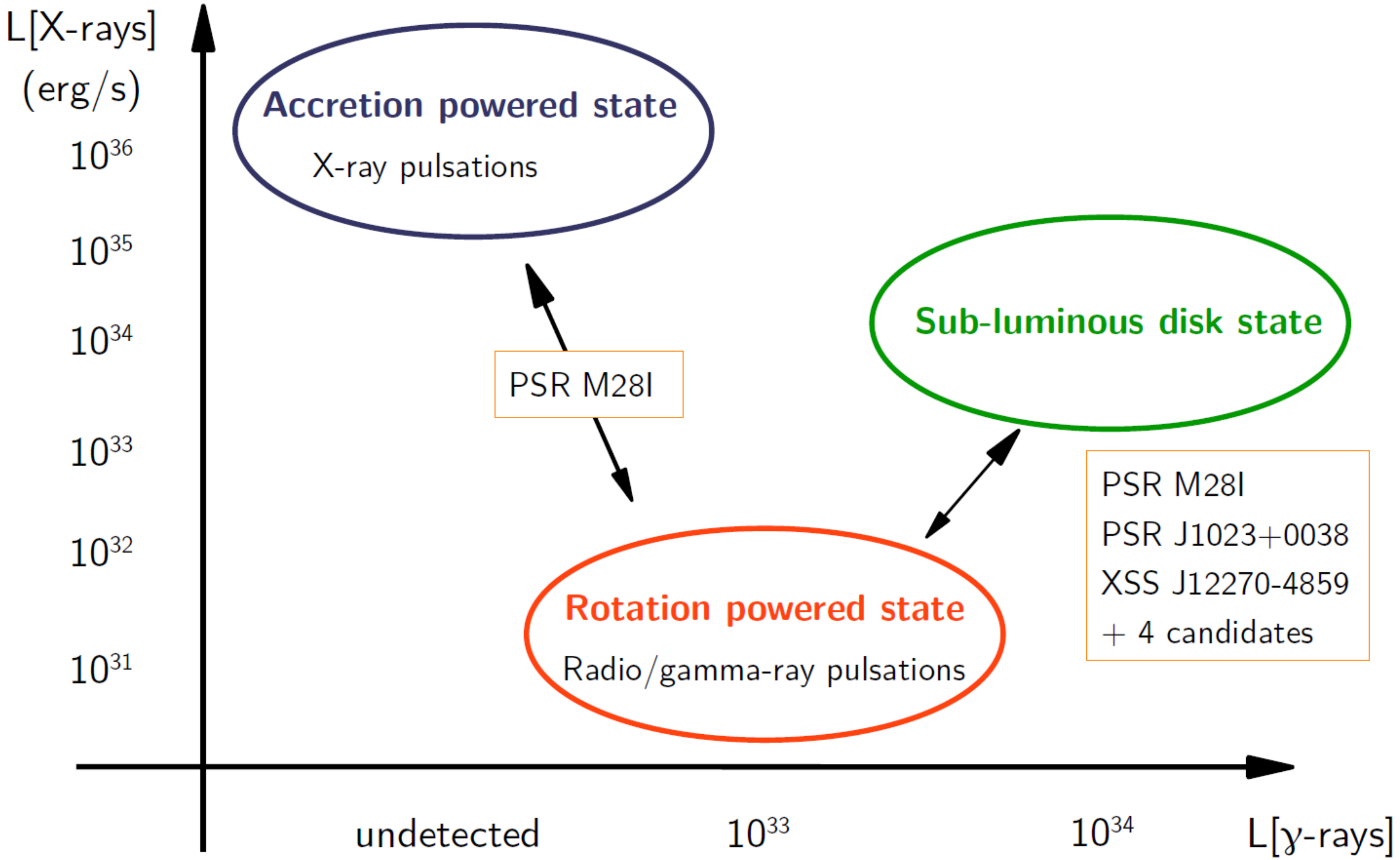
[de Oña Wilhelmi+ 2016]



[Illiano+ 2023b]

A rotation-powered pulsar active during quiescence (i.e., another transitional MSP)?

The sub-luminous disk state



$L_{accretion} \gg L_{spin-down}$

$L_{accretion} \approx L_{spin-down}$

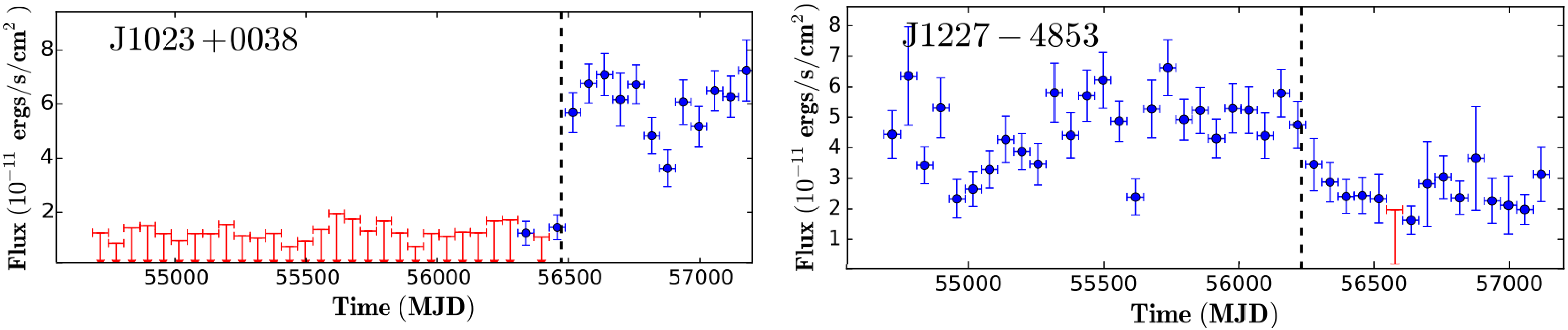
$L_{accretion} \ll L_{spin-down}$

[Courtesy of A. Papitto]

[see Papitto & de Martino 2022, ASSL for a review]

γ-ray emission of tMSPs

J1023+0038 **from radio MSP to sub-luminous disk state** → 0.1-300 GeV flux: >6x **increase**
J1227-4859 **from sub-luminous disk state to radio MSP** → 0.1-300 GeV flux: ~2x **decrease**



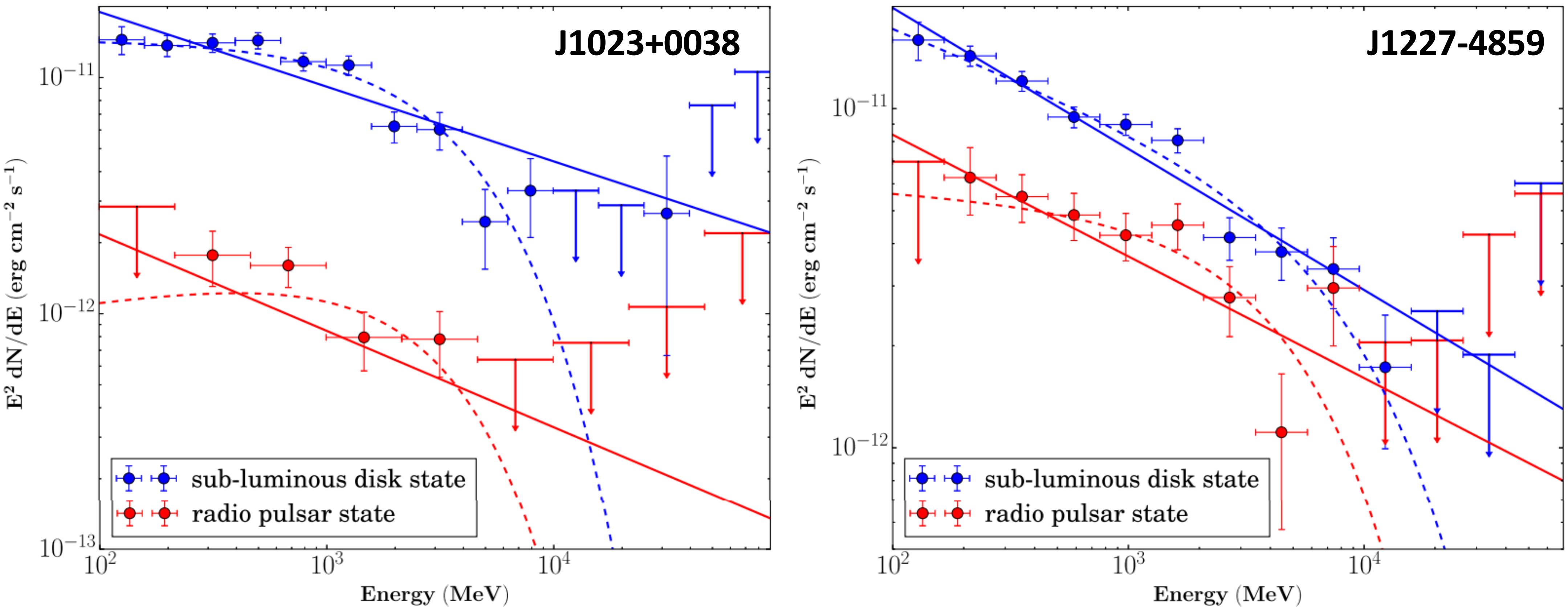
[Torres+ 2017]

[see also Stappers+ 2014; Takata+ 2014; Deller+ 2015; Johnson+ 2015; Xing & Wang 2015]
[see Torres & Li 2022, ASSL for a review]

Fermi-LAT spectra of tMSPs

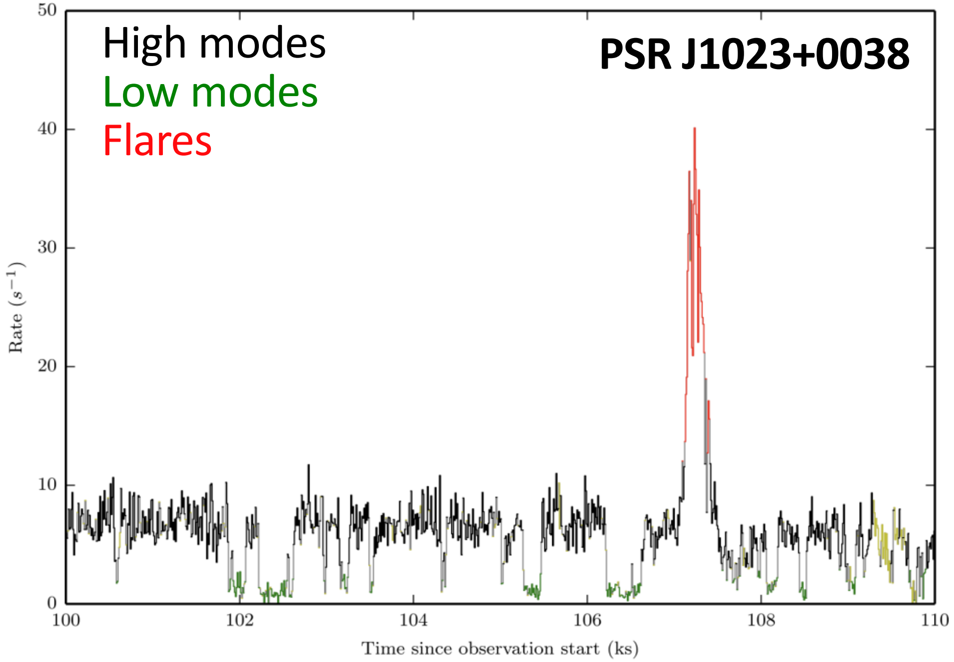
In the **sub-luminous disk state,** power law + exponential cutoff**:**

J1023+0038: $\Gamma = 2.0 \pm 0.1 \pm 0.1$, $E_{cut} = 3.7 \pm 1.3 \pm 0.9$ GeV (~4.3σ)
J1227-4859: $\Gamma = 2.3 \pm 0.1 \pm 0.1$, $E_{cut} = 10.8 \pm 3.7 \pm 5.6$ GeV (~3.7σ)

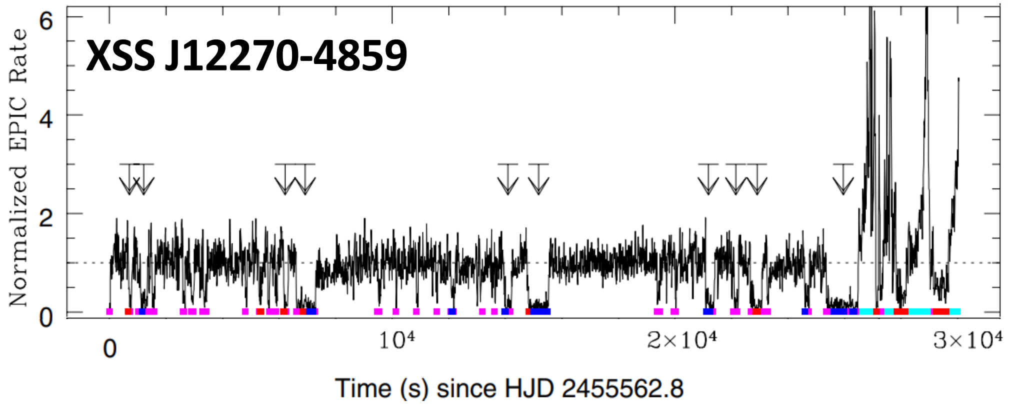


[Torres+ 2017]

X-ray variability



[Archibald+ 2015]

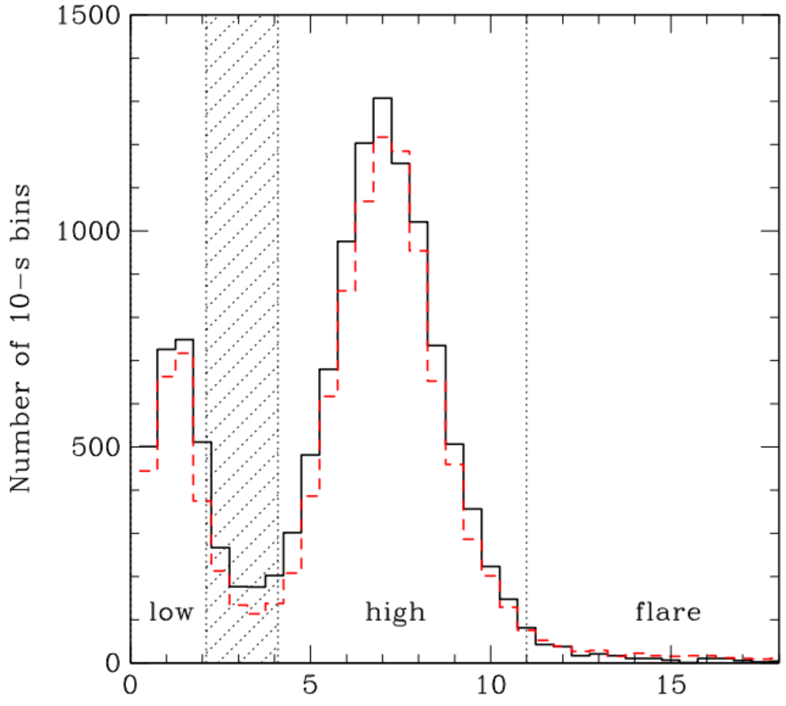


[De Martino+ 2013]

Transition on timescale of ~10 s between:

- High modes ($L_X \sim 7 \times 10^{33} \text{erg s}^{-1}$)
- Low modes ($L_X \sim 10^{33} \text{erg s}^{-1}$)

Sporadic flares ($L_X \sim 10^{34} \text{erg s}^{-1}$)

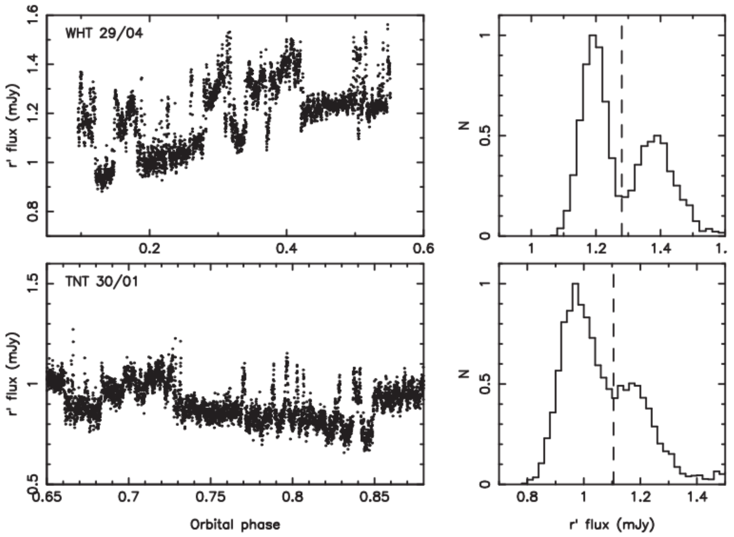


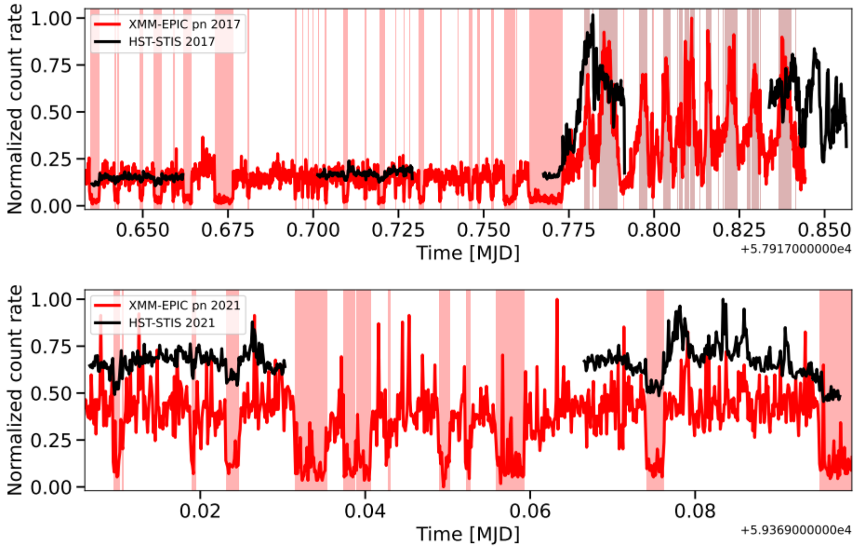
[Bogdanov+ 2015] Count rate (s^{-1})

[see also, e.g., Papitto+ 2013, Linares+ 2014]

Other wavelengths

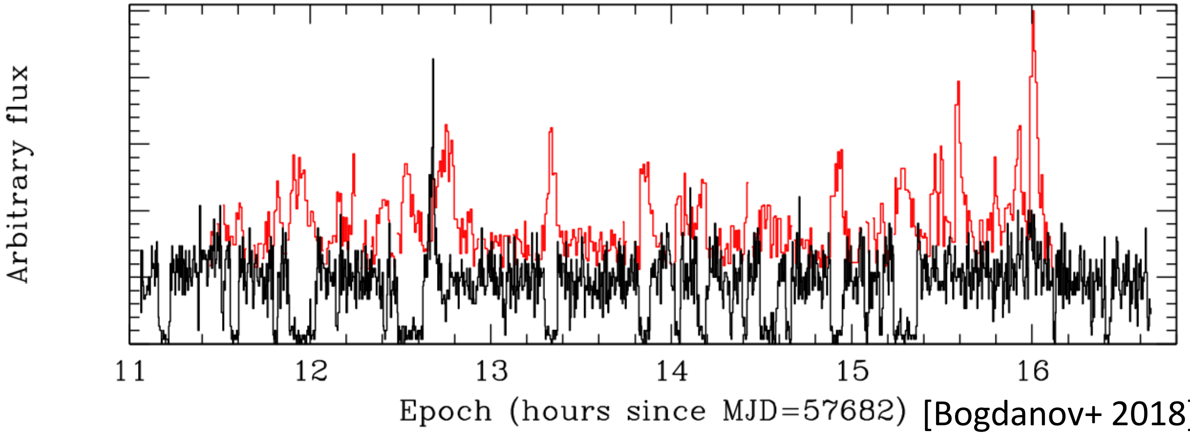
- Optical and UV variability resembling X-ray high and low modes





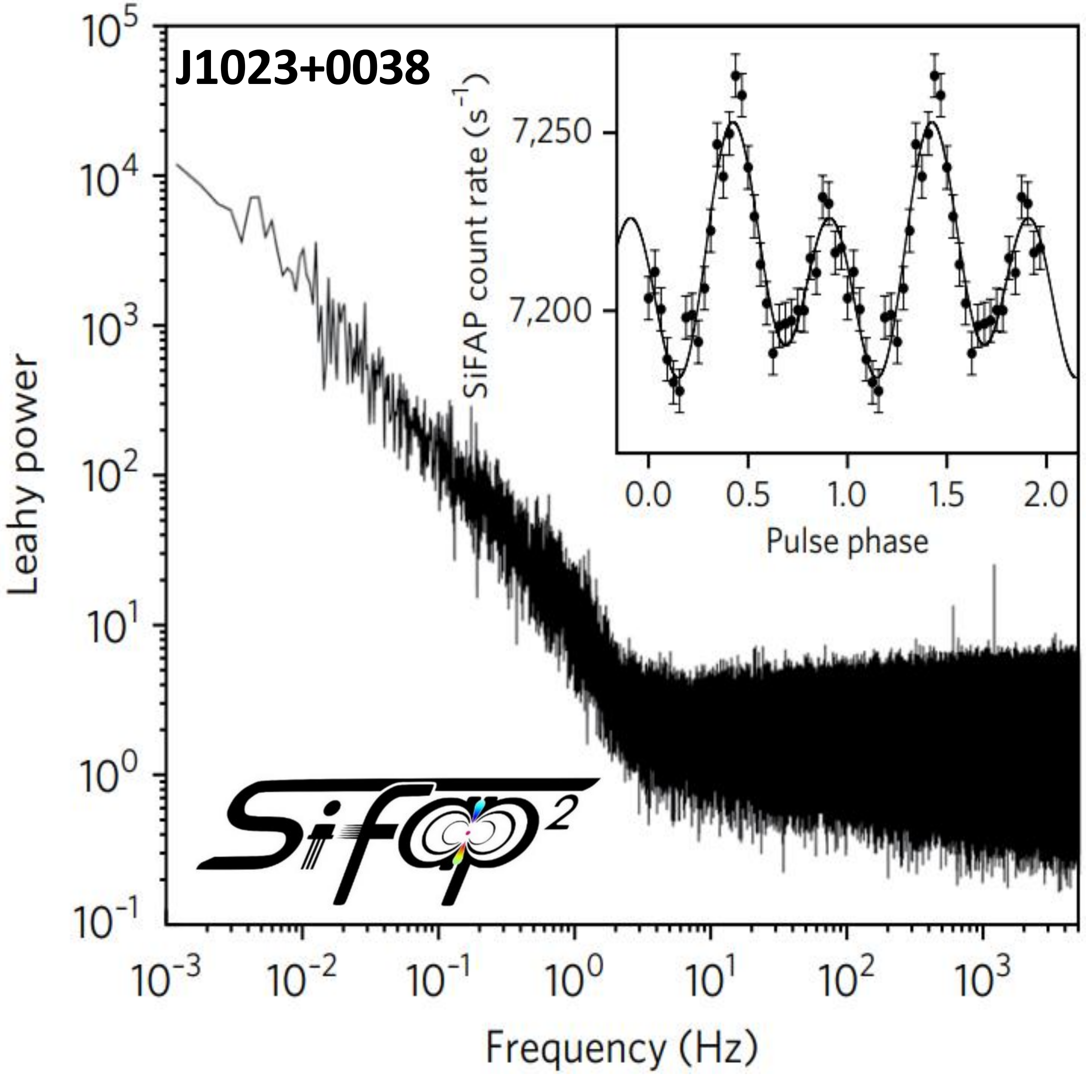
[Shahbaz+ 2015, 2018; Kennedy+ 2018; Papitto+ 2018] [Miraval Zanon+ 2022; see also Jaodand+ 2022, Baglio+ 2023]

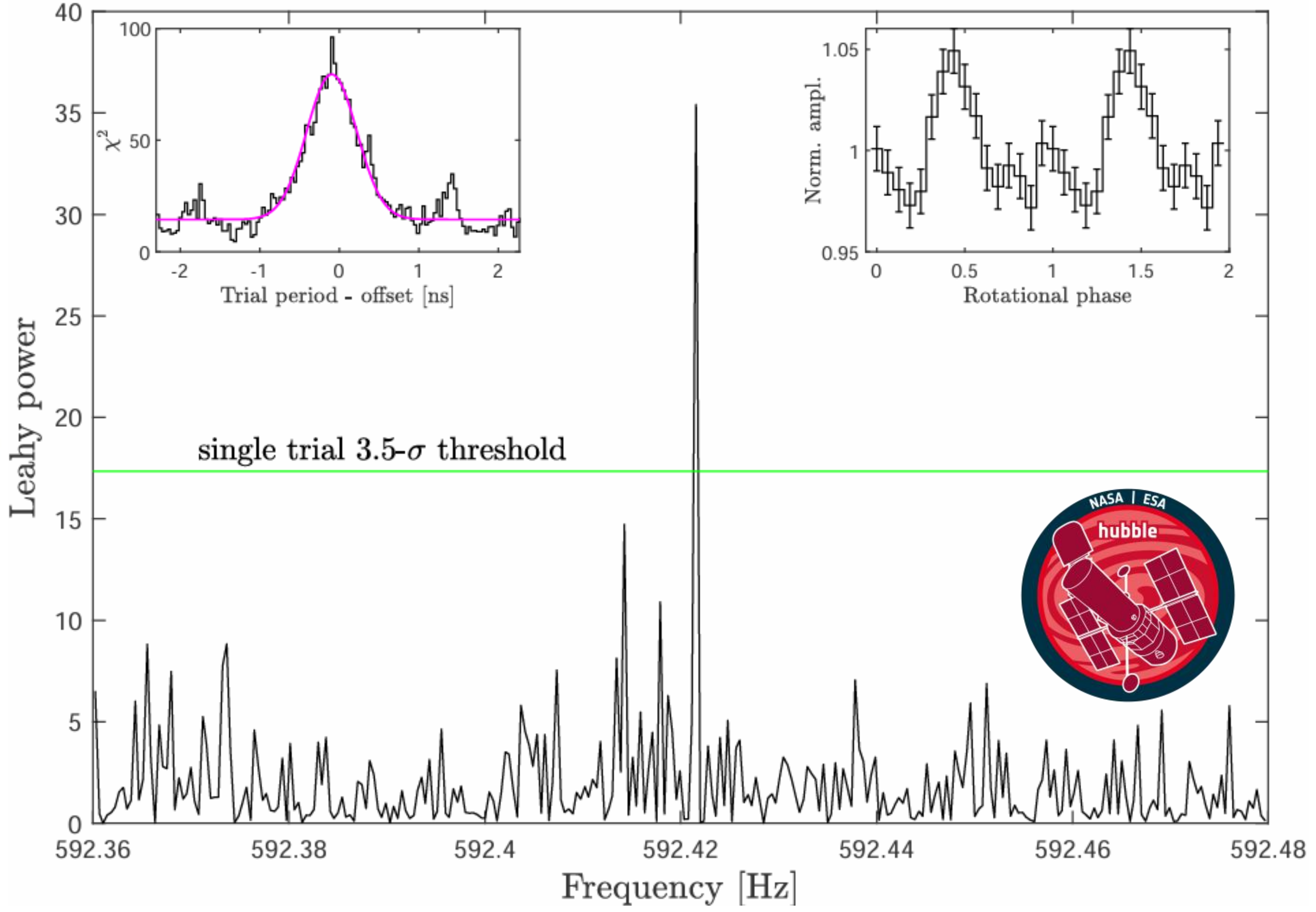
- Anti-correlated radio/X-ray variability



[Bogdanov+ 2018]

Discovery of an optical/UV transitional MSP

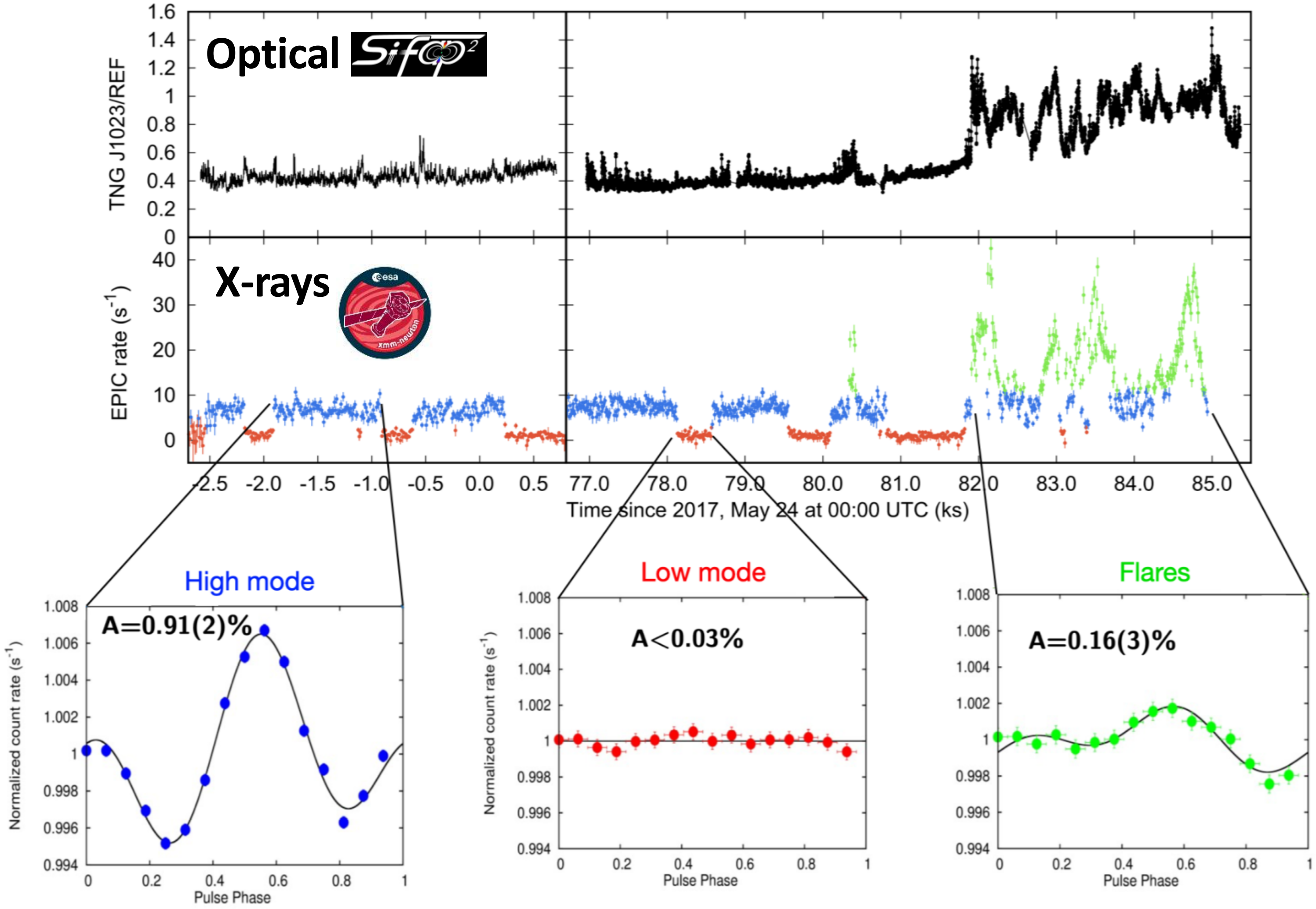




[Ambrosino, Papitto+ 2017; Miraval Zanon+ 2022]

Pulsating in unison at optical, UV and X-ray energies

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



[Ambrosino, Papitto+ 2017; Zampieri+ 2019; Papitto+ 2019; Jaodand+ 2021; Miraval Zanon+ 2022]

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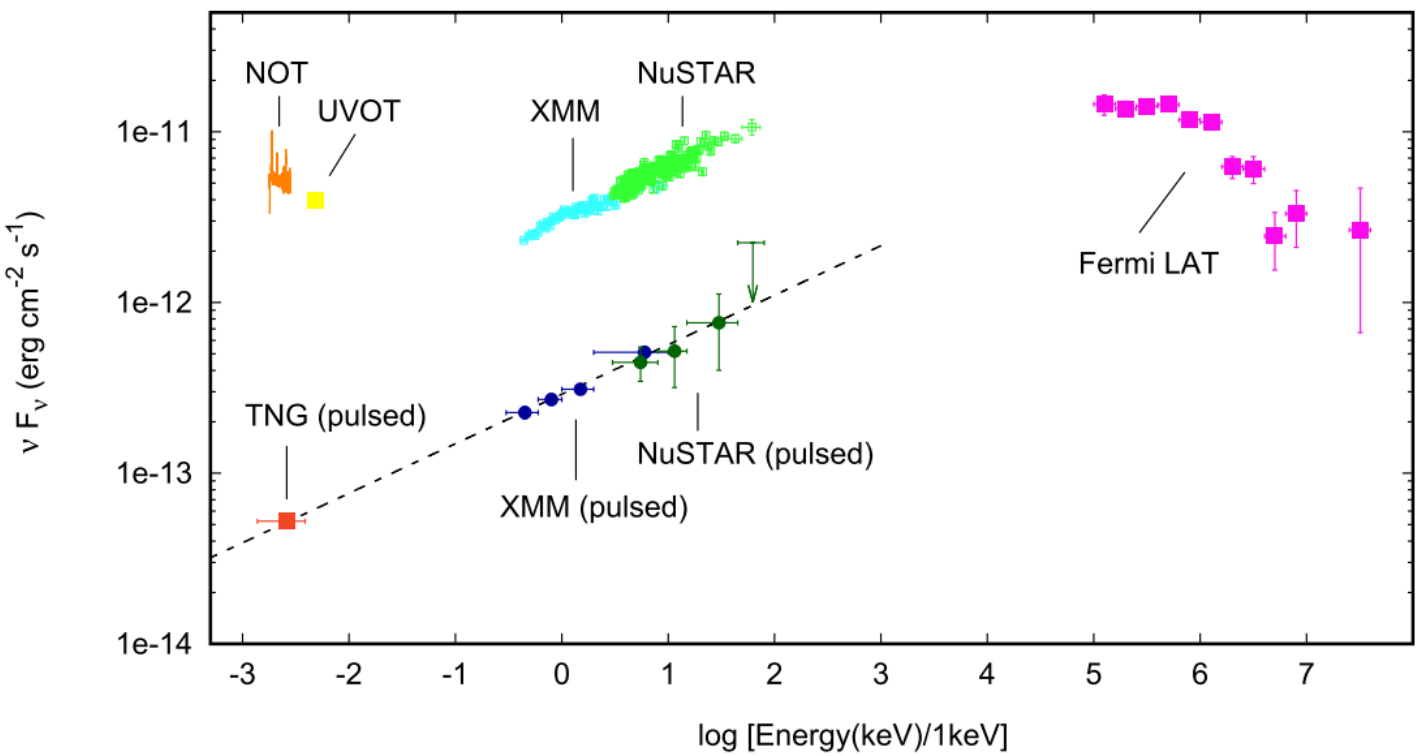
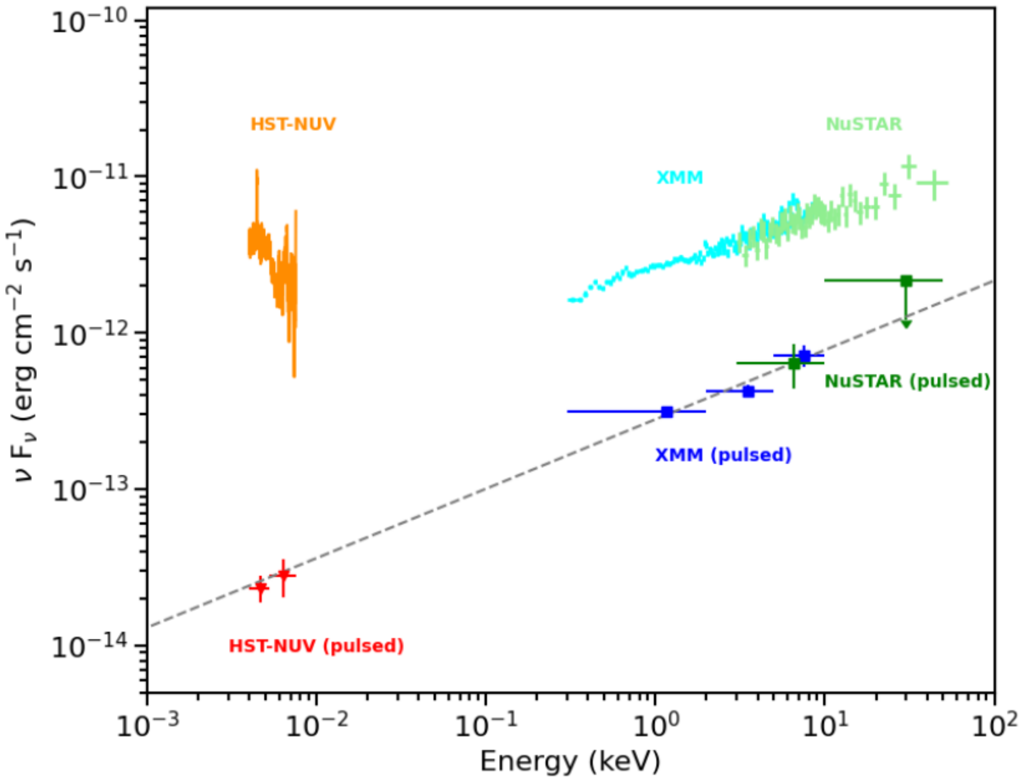


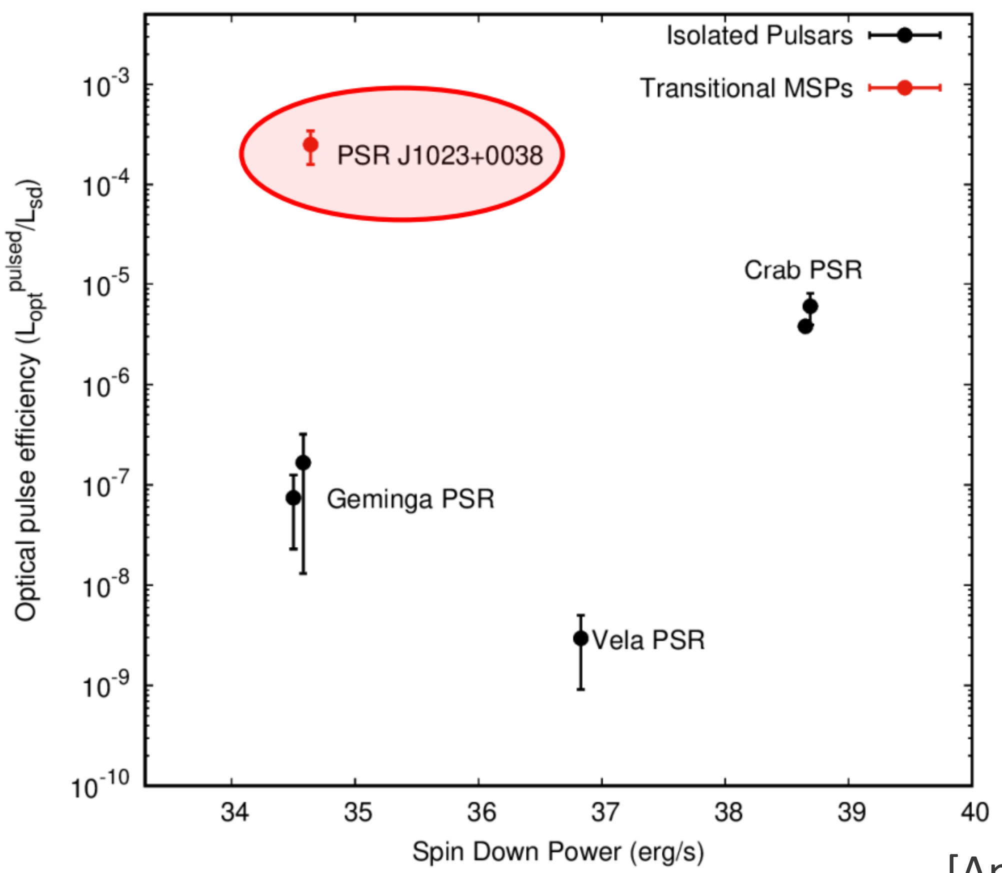


[Ambrosino, Papitto+ 2017; Zampieri+ 2019; Papitto+ 2019; Jaodand+ 2021; Miraval Zanon+ 2022]

Unexpected and (too) bright optical pulsations

Standard emission mechanisms hardly individually explain the observed optical pulsed luminosity

Rotation-powered pulsar



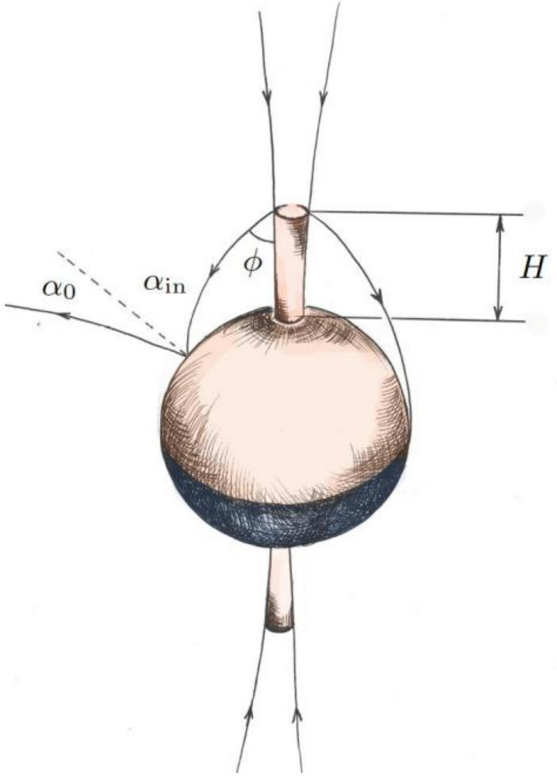
Accretion-powered pulsar

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

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

$$\downarrow$$

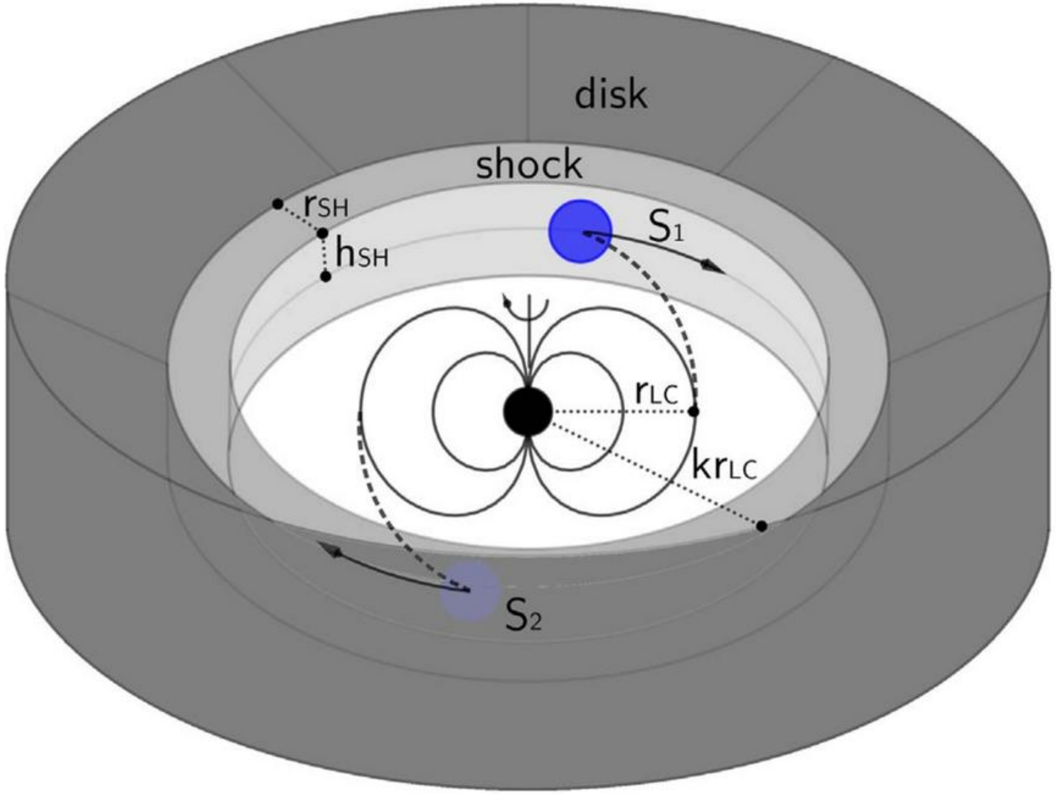
$$L_{\text{cyc,opt}} \ll L_{\text{pulsed,opt}}$$



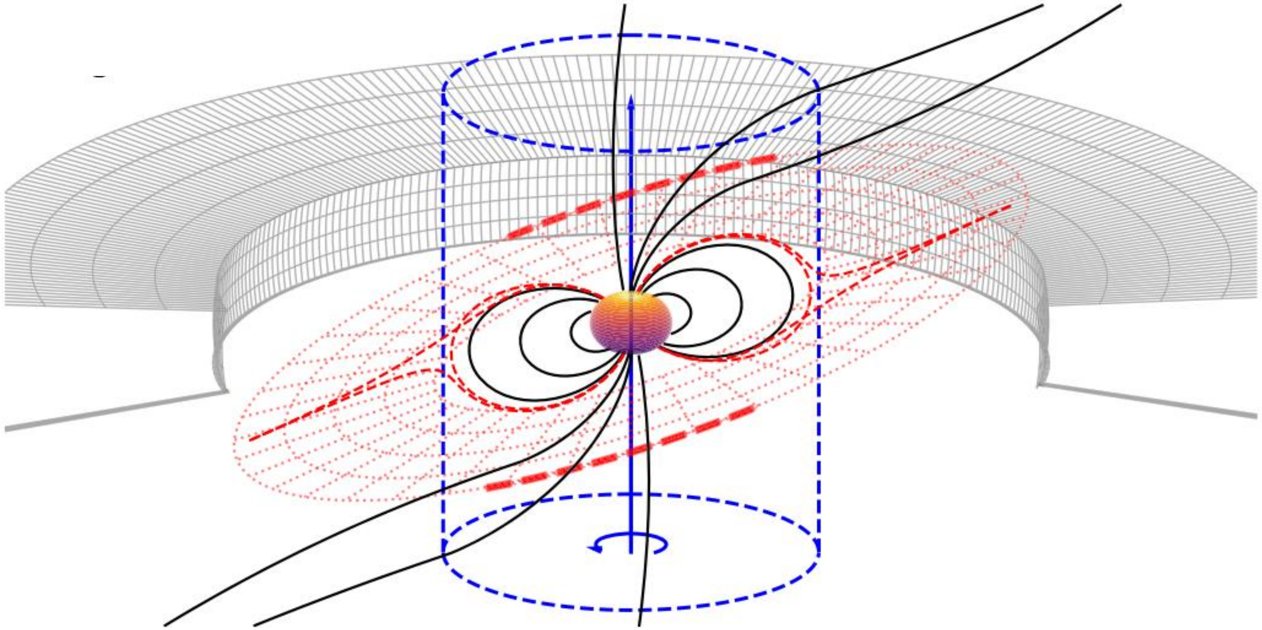
[Ambrosino, Papitto+ 2017]

Co-existence between accretion- and rotation-powered states?

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



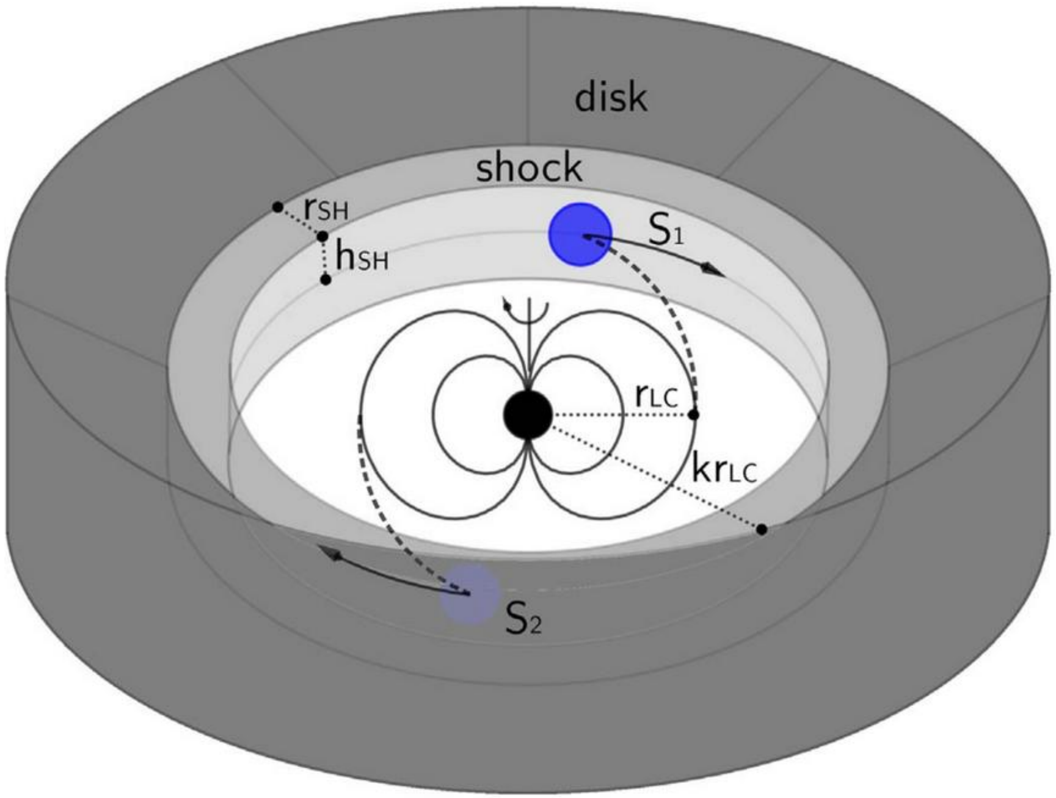
[Papitto+ 2019]



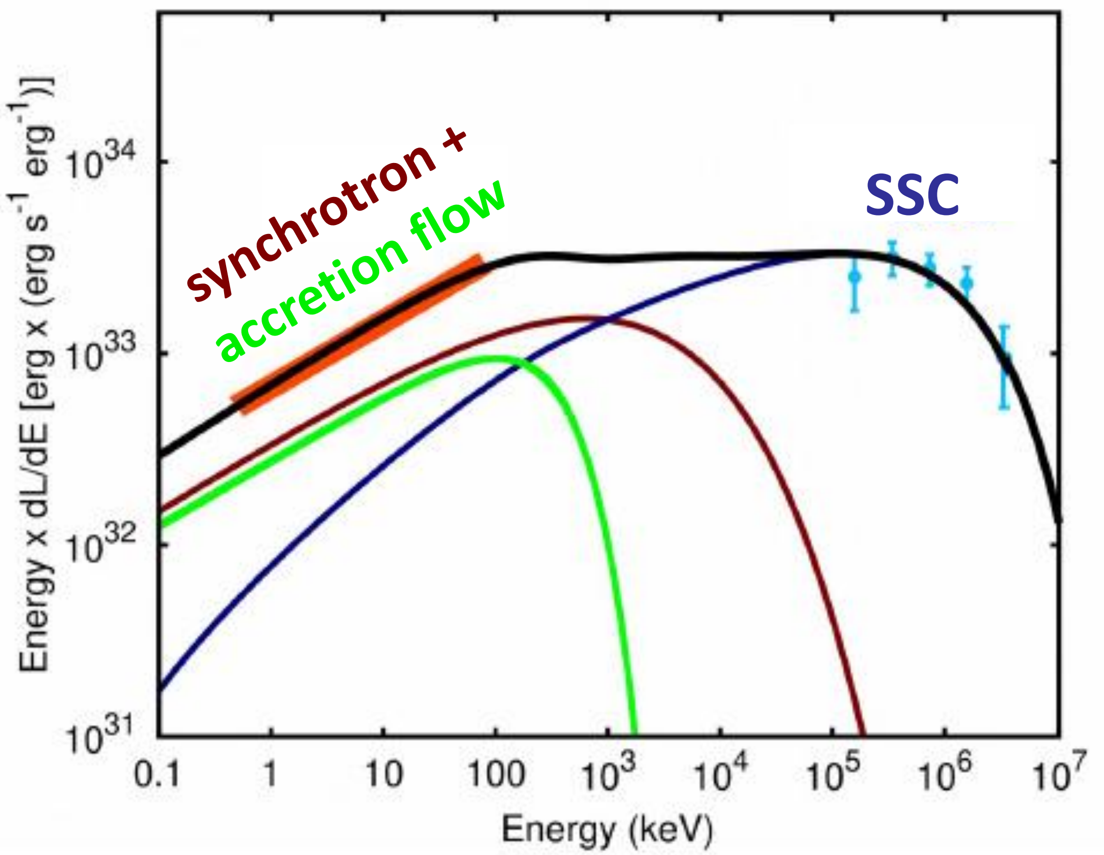
[Veledina+ 2019]

Co-existence between accretion- and rotation-powered states?

Synchrotron → Optical/X-rays
Synchrotron Self-Compton → Gamma-rays



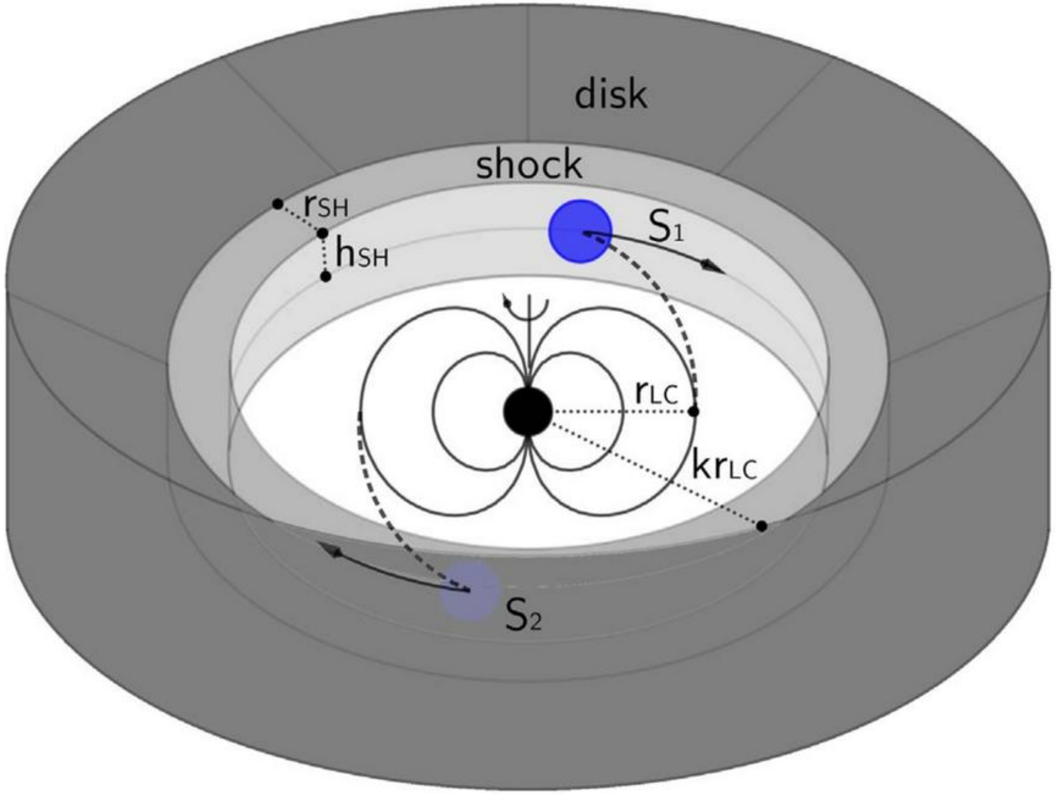
[Papitto+ 2019]



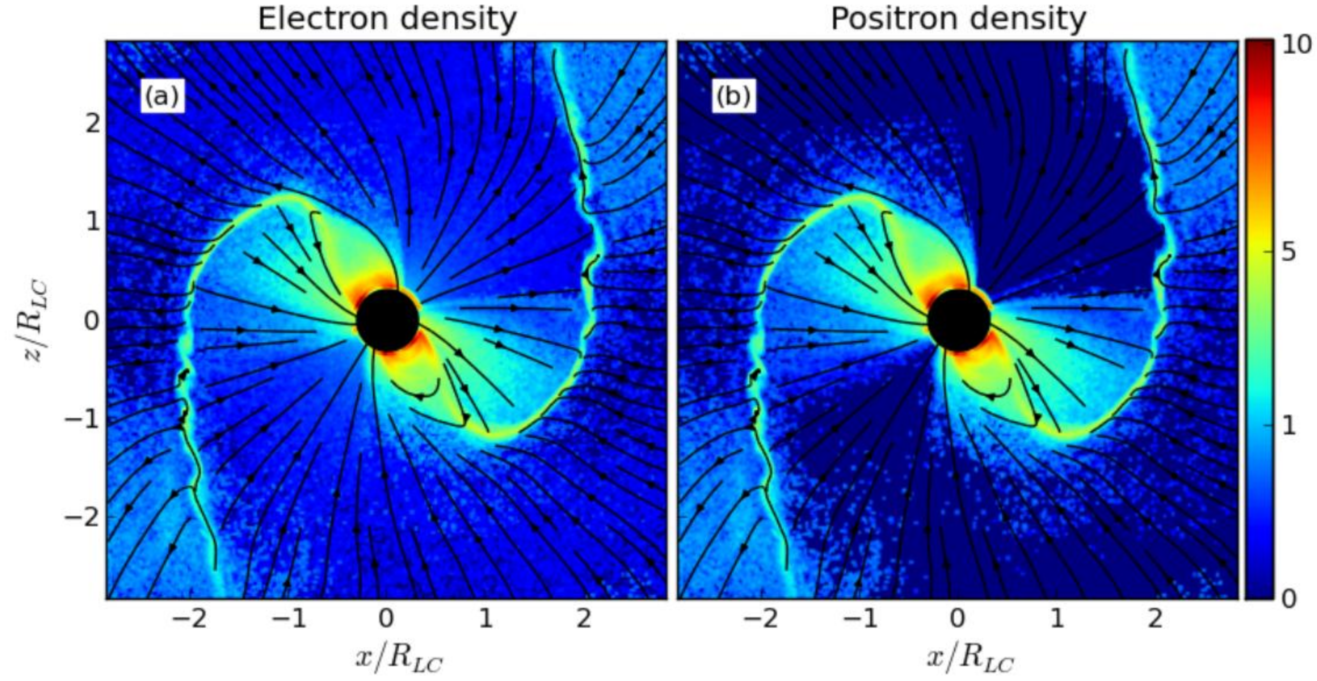
[Papitto & Torres 2015]

Co-existence between accretion- and rotation-powered states?

Optical, UV and X-ray pulsations from the interaction between
the pulsed striped wind and the termination shock



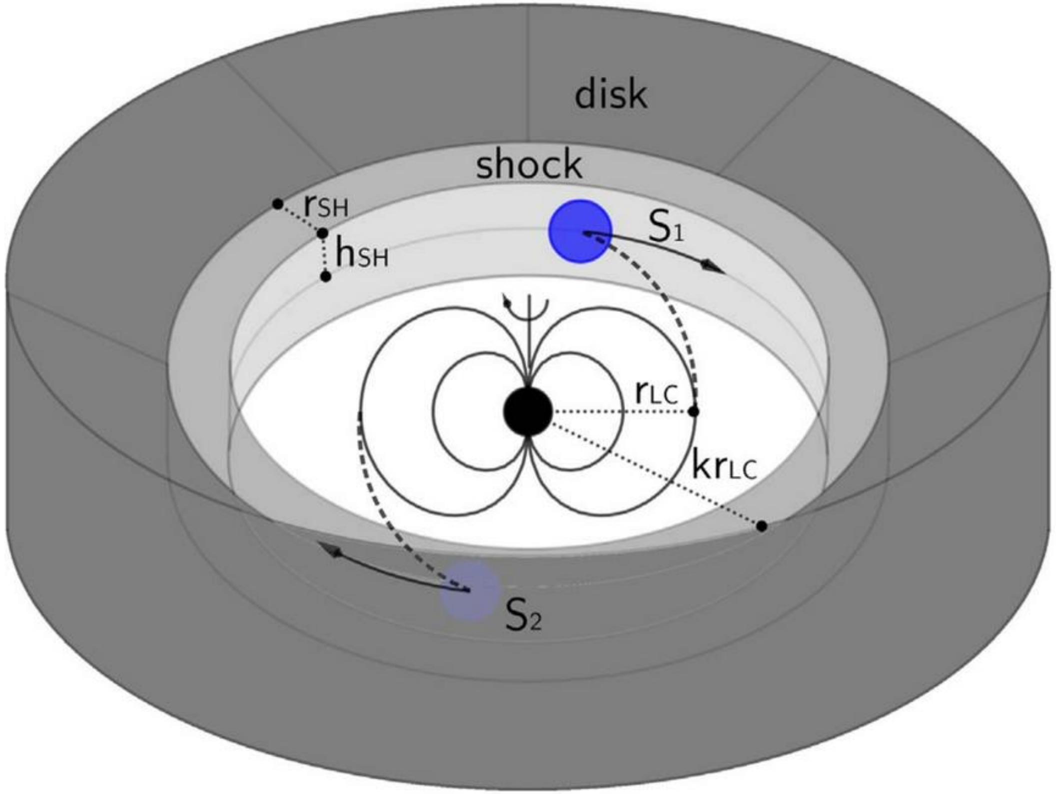
[Papitto+ 2019]



[Cerutti & Beloborodov+ 2017]

Co-existence between accretion- and rotation-powered states?

Optical, UV and X-ray pulsations from the interaction between the pulsed striped wind and the termination shock



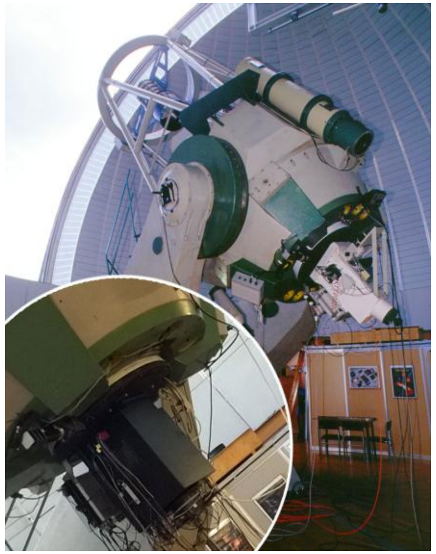
[Papitto+ 2019]

Different synchrotron timescales of optical (~3 μs) and X-ray photons (~220 μs) :

$$t_{\rm sync} \propto \epsilon^{-1/2}\, B_{\rm s}^{-3/2}$$

Five years of optical and X-ray observations

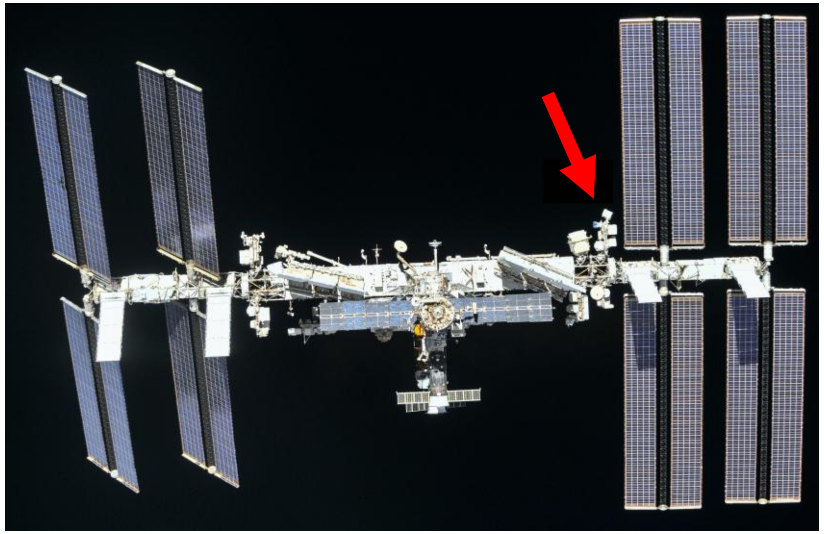
TNG/SiFAP2
[Credit to G. Tessicini]



Copernicus/Aqueye+
[Credit to MEDIA INAF]

Telescope/Instrument
2017 May - overlap: 11.0 ks *XMM-Newton*/EPIC TNG/SiFAP2
2018 December - overlap: 10.8 ks *XMM-Newton*/EPIC Copernicus/Aqueye+
2018 December - no overlap; temporal gap: 41 ks *XMM-Newton*/EPIC Copernicus/Aqueye+
2019 January - overlap: 2.3 ks *NICER* TNG/SiFAP2
2019 February - overlap: 1.1 ks *NICER* Copernicus/Aqueye+
2019 June - overlap: 340 s *NICER* TNG/SiFAP2
2020 January - overlap: 4.6 ks *NICER* TNG/SiFAP2
2020 January - overlap: 520 s *NICER* Copernicus/Aqueye+
2022 January - overlap: 1.7 ks *NICER* Copernicus/Aqueye+

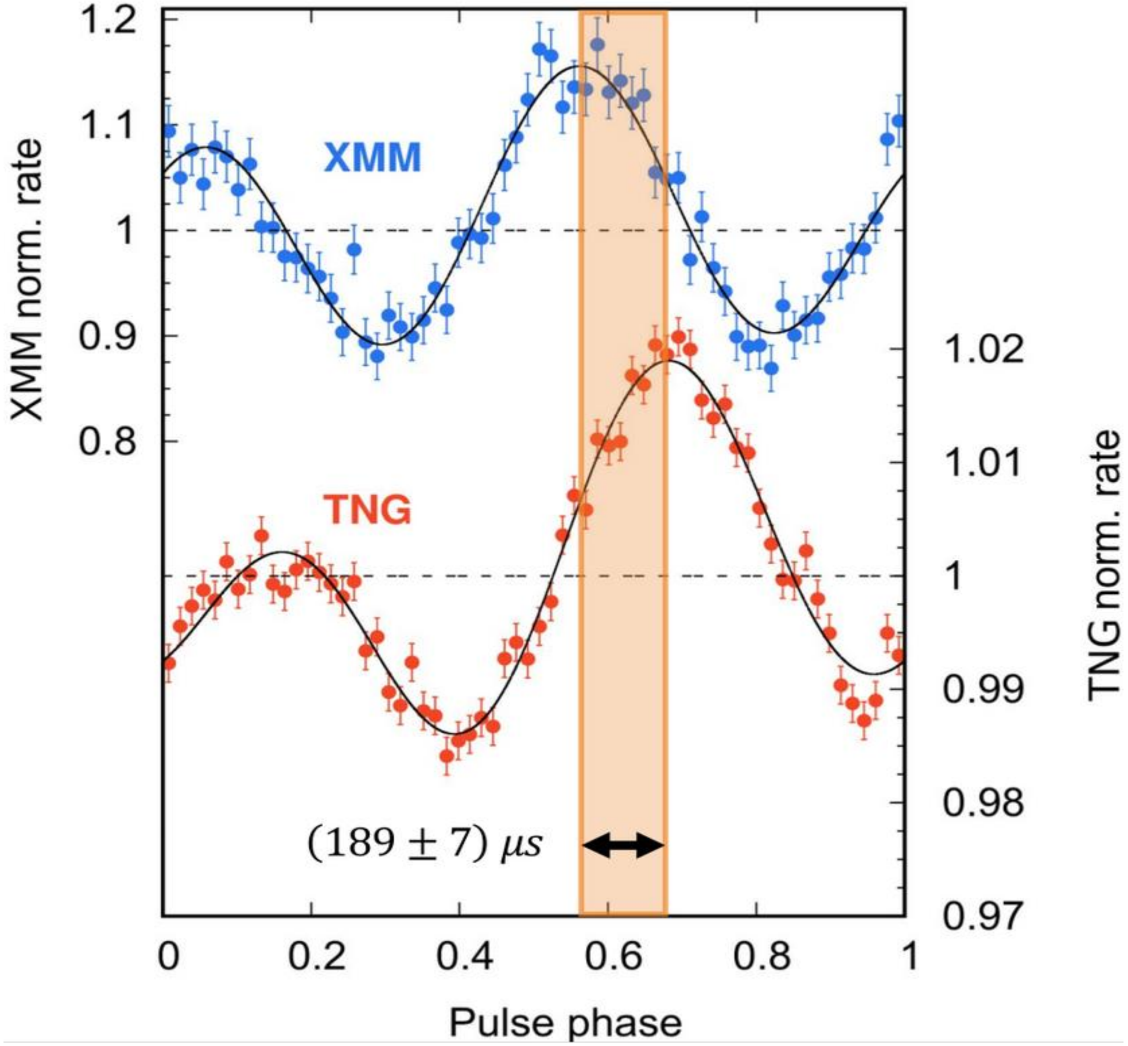
[Illiano+ 2023a]



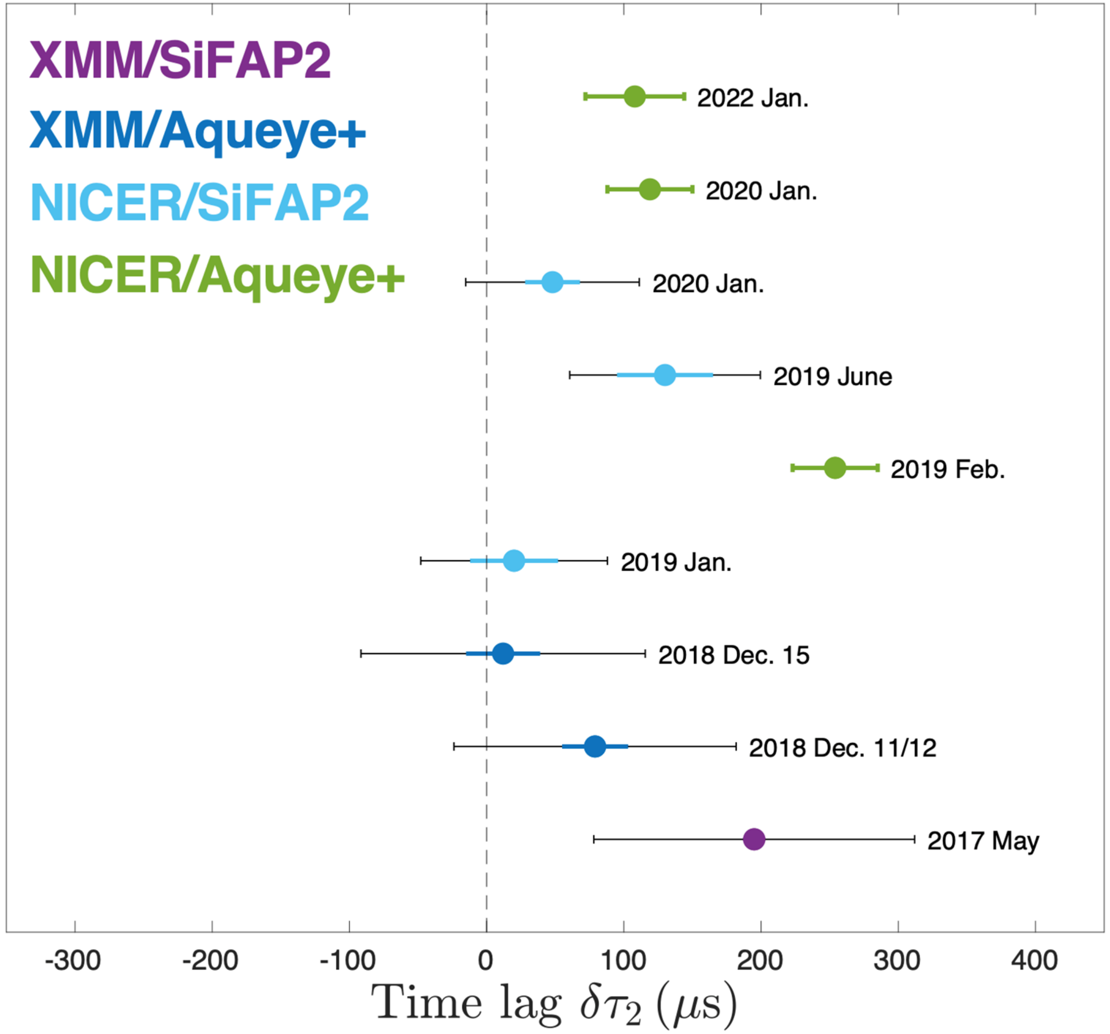
NICER
[Credit to NASA]

XMM-Newton
[Credit to ESA]

Time lags between optical and X-ray pulsations

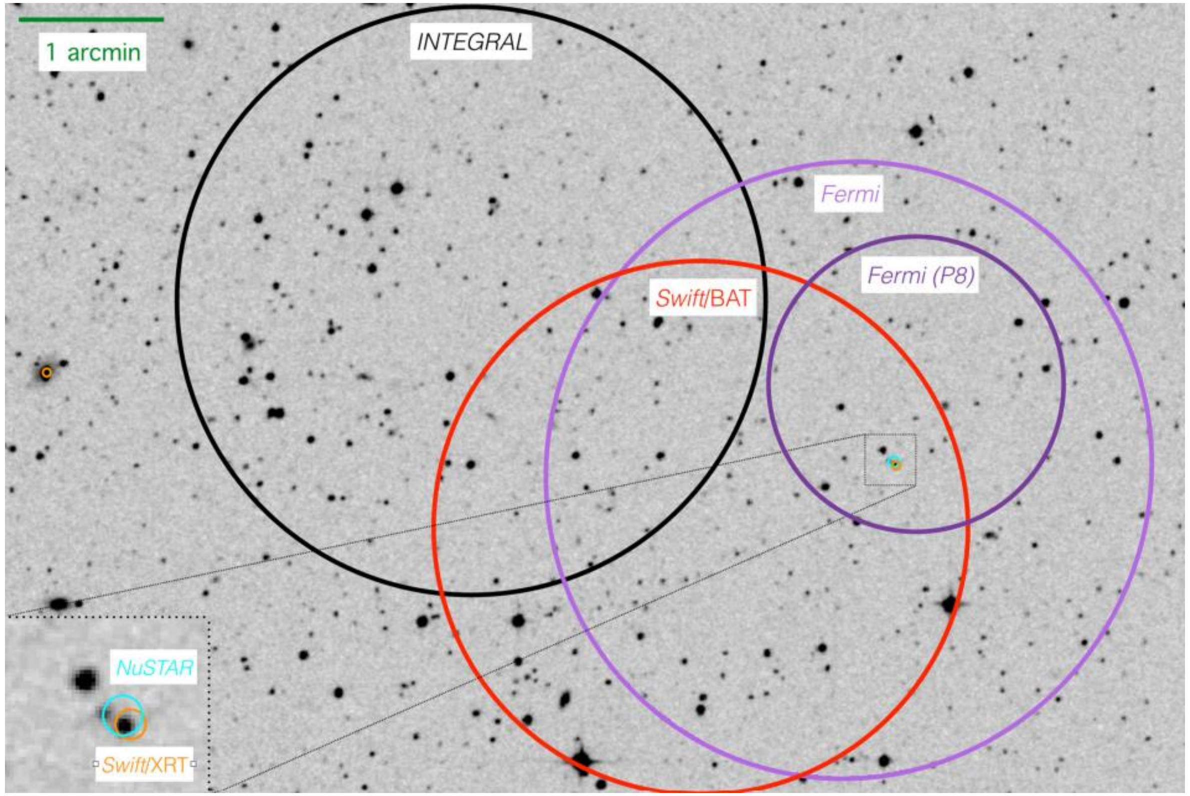


[Papitto+ 2019]

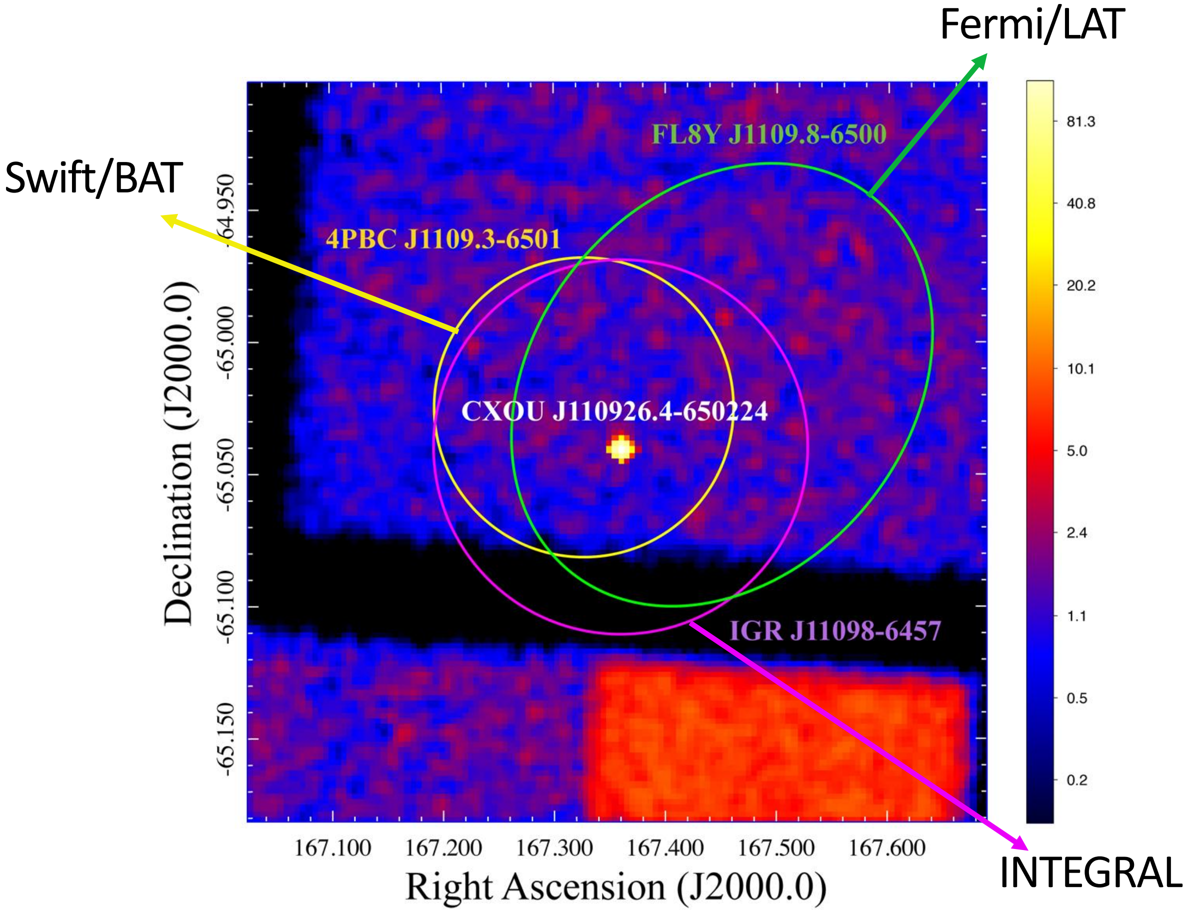


[Illiano+ 2023a]

Searching candidates from unidentified Fermi-LAT sources



3FGL J0427.9–6704 [Strader+ 2016]



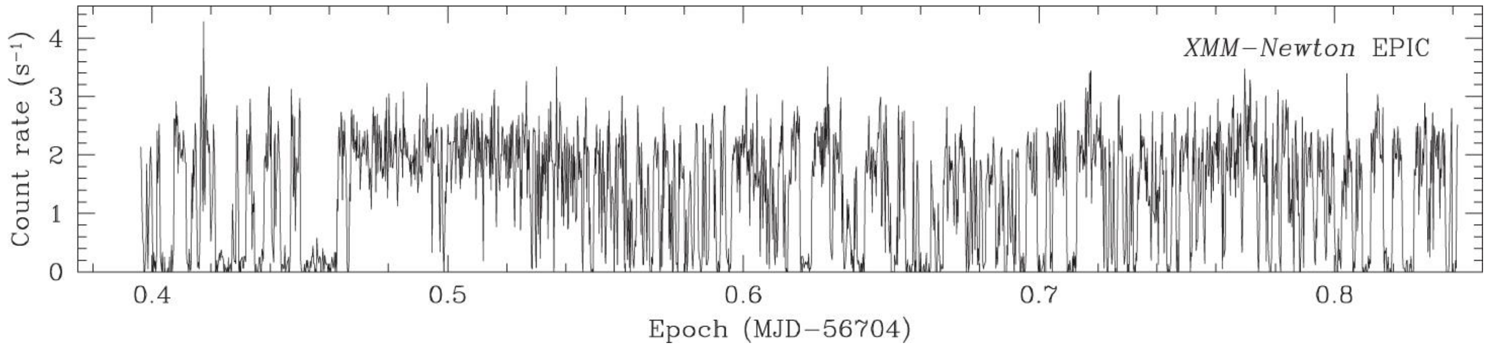
CXOU J110926.4–650224 [Coti Zelati+ 2019]

See A. Manca's contribution

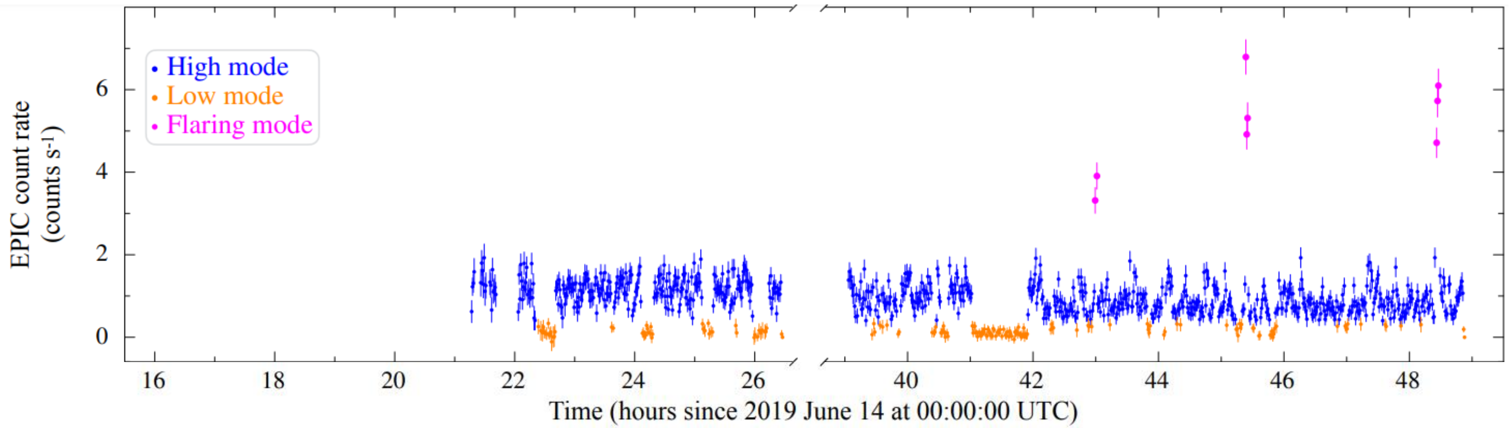
[see also, e.g., Torres+ 2017 for a systematic search in the Fermi-LAT data]

Searching candidates in the sub-luminous disk state

RXS J154439.4-112820
[Bogdanov+ 2015, 2016; Britt+ 2017; Jaodand+ 2021; Gusinskaia+ 2024; Illiano+ in prep.]



CXOU J110926.4-650224
[Coti Zelati+ 2019, 2021,2024]



4FGL J0407.7-5702, 3FGL J0427.9-6704, Terzan 5 CX10, XMM J174457-2850.3

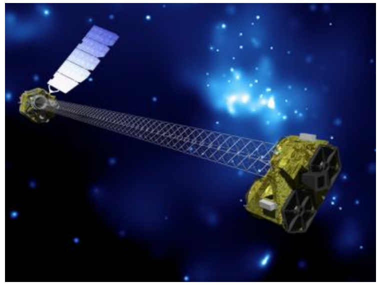
[Li+ 2020; Miller+ 2020, Strader+ 2021; Bahramian+ 2018; Degenaar+ 2014; Kennedy+ 2020, Deller+ 2014]

See C. Rodríguez García's contribution for searching candidates using machine learning techniques

[see also, e.g., Torres+ 2017 for a systematic search in the Fermi-LAT data]

Multi-wavelength campaign on the candidate 3FGL J1544.6-1125



DAY 1

XMM-Newton/EPIC (PI: Miraval Zanon)

HST/STIS (→ *first UV observation of this source ever*!) (PI: Illiano)

XMM-Newton/OM B-band (PI: Miraval Zanon)

TNG/SiFAP2 (PI: Illiano)

REM (PI: Baglio)

VLA (PI: Miraval Zanon)

DAY 2-3-4

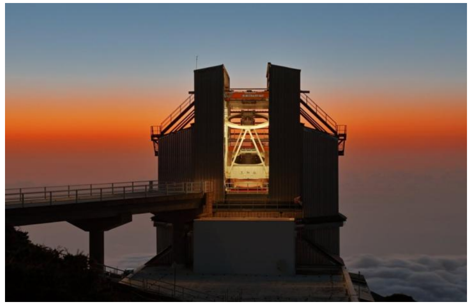
NuSTAR (PI: Miraval Zanon)

NICER (PI: Illiano)

REM (PI: Baglio)

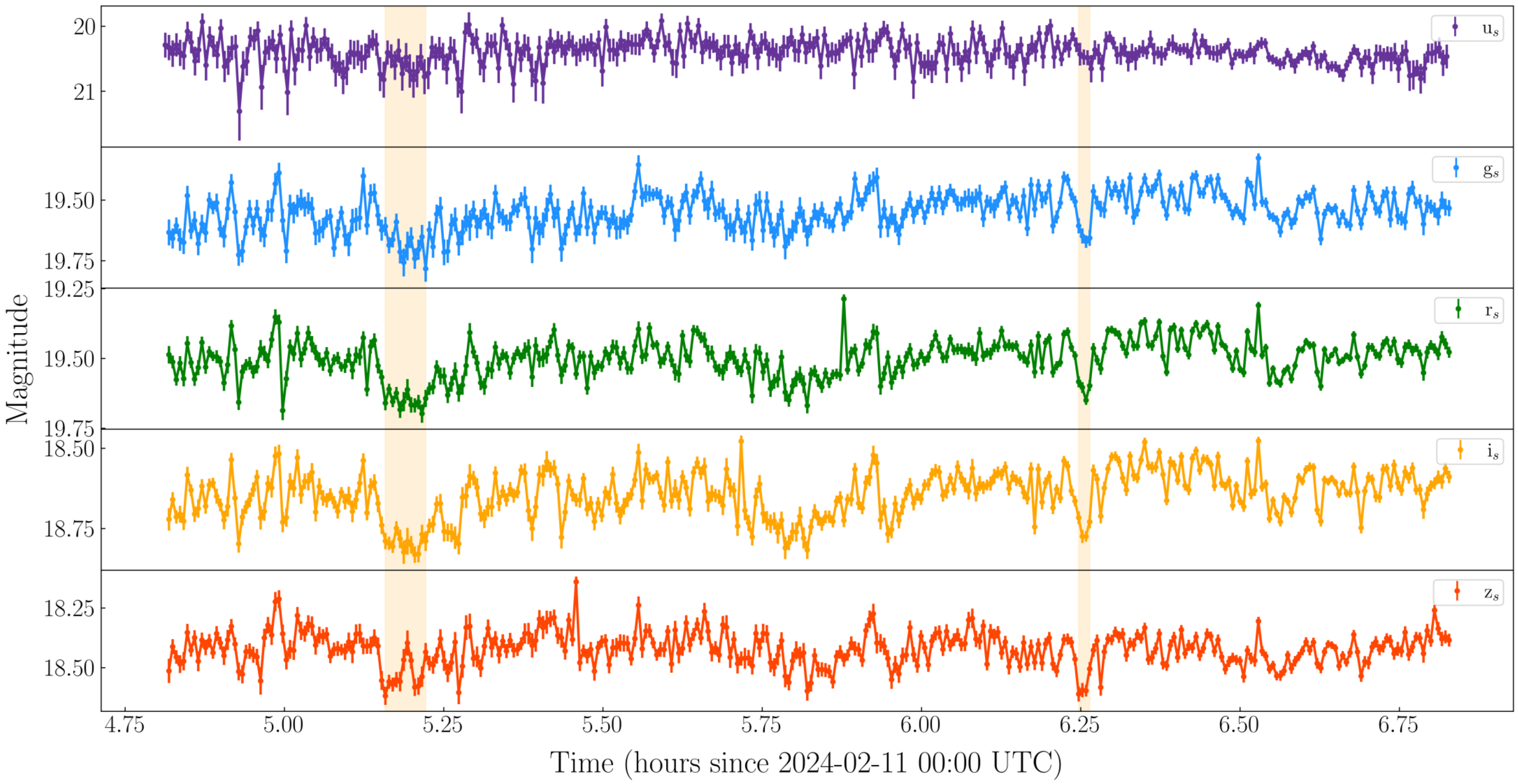
GTC/HiPERCAM (PI: Coti Zelati)



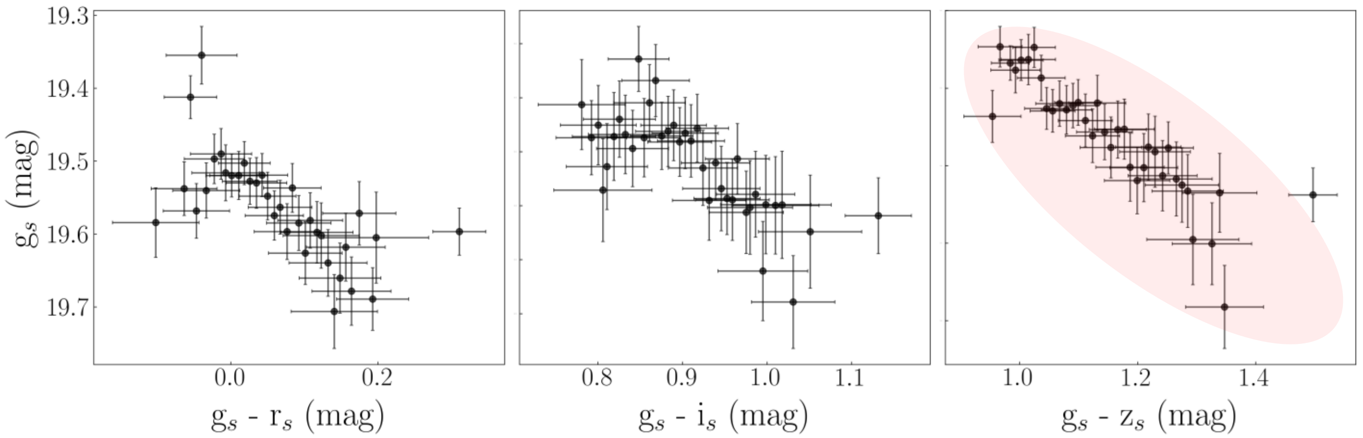
AHEAD Visitor program at ICE-CSIC (Barcelona) with the MAGNESIA group

GTC/HiPERCAM observation in five different filters

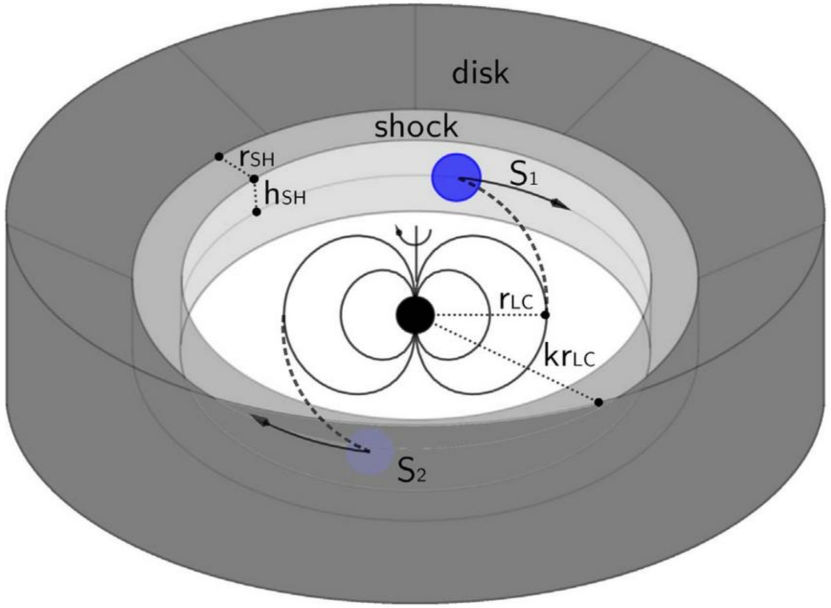


[Illiano, Coti Zelati+, in prep.]

Optical/X-ray emissions from the inner accretion flow

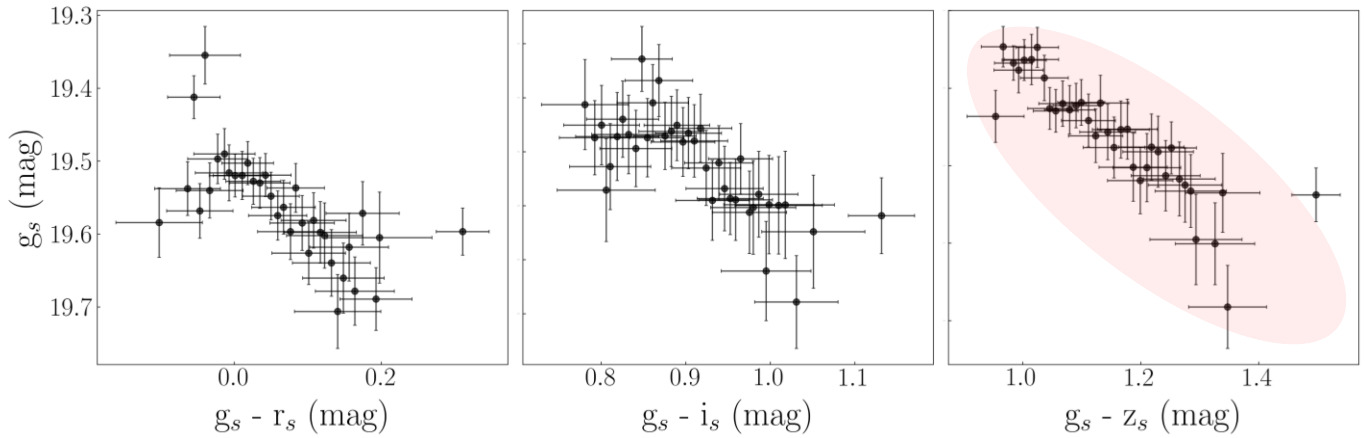


[Illiano+, in prep; see also Coti Zelati+ 2024]



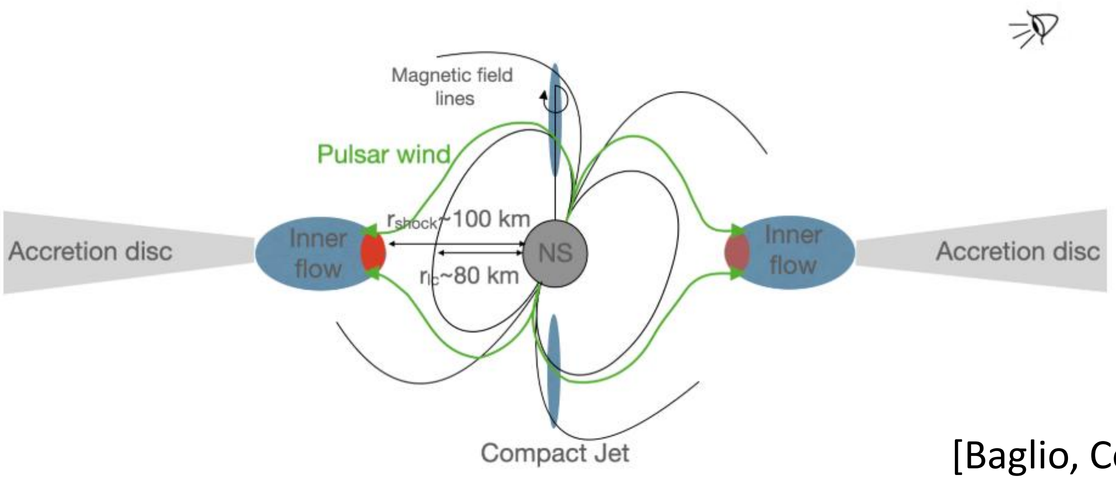
[Papitto+ 2019; see also Veledina+ 2019]

Optical/X-ray emissions from the inner accretion flow

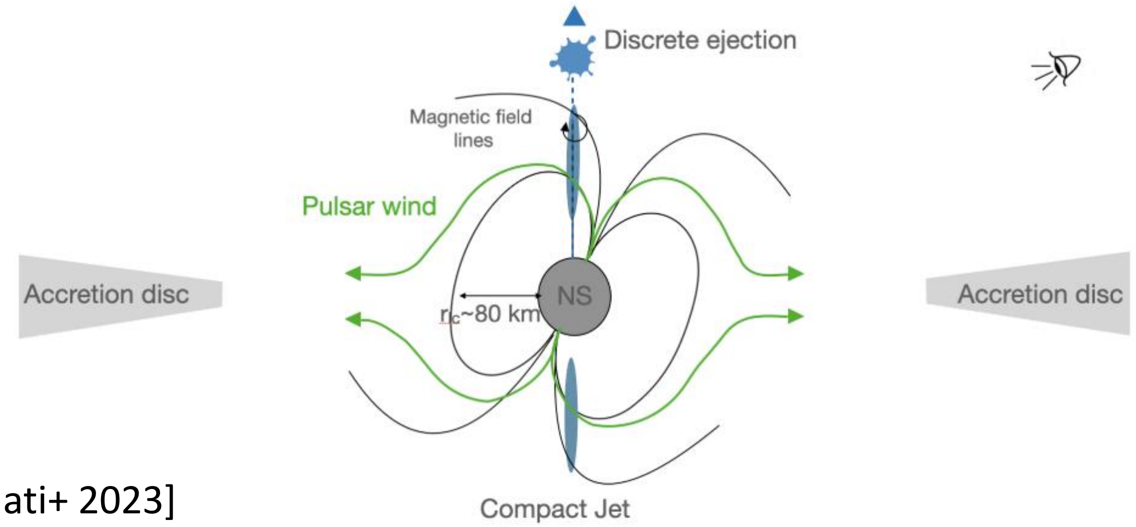


[Illiano+, in prep; see also Coti Zelati+ 2024]

HIGH MODE



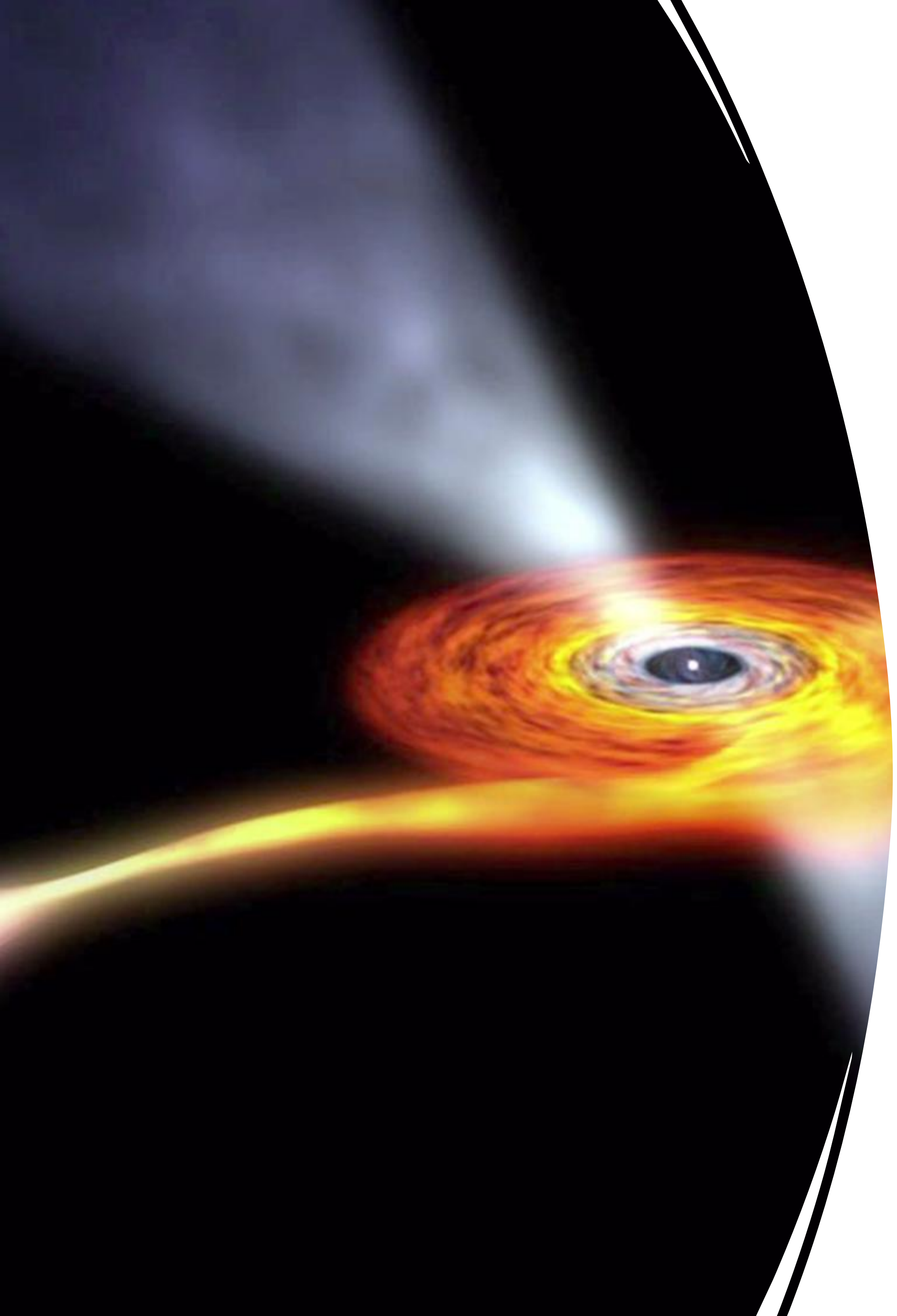
LOW MODE



[Baglio, Coti Zelati+ 2023]

Optical/X-ray emissions at the shock front between the pulsar wind and the accretion disk

[see also Papitto+ 2019; Veledina+ 2019; Campana+ 2019]



Summary & Open Questions

- **Transitional MSPs in the sub-luminous disk state are bright gamma-ray sources**
- Need more confirmed/candidate sources → searches from unidentified Fermi-LAT sources and using machine learning

  See A. Manca and C. Rodríguez García's contributions
- Multi-wavelength campaigns to test the model with a **rotation-powered pulsar active despite the accretion disk**
- Do these transitional MSPs pulse in the gamma rays?
- Do accreting MSPs shine in the gamma rays (→ transition to rotation-powered state during quiescence)?