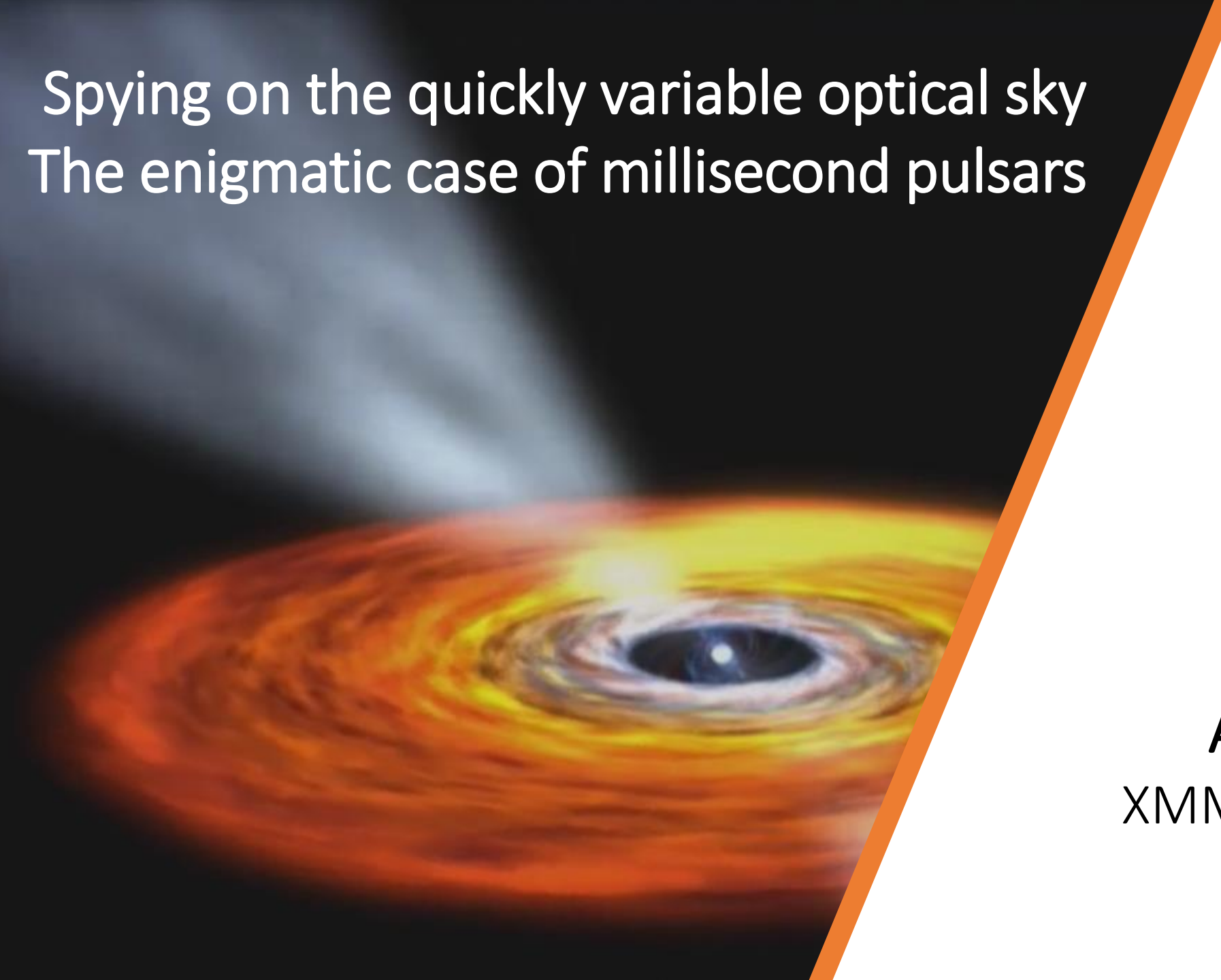
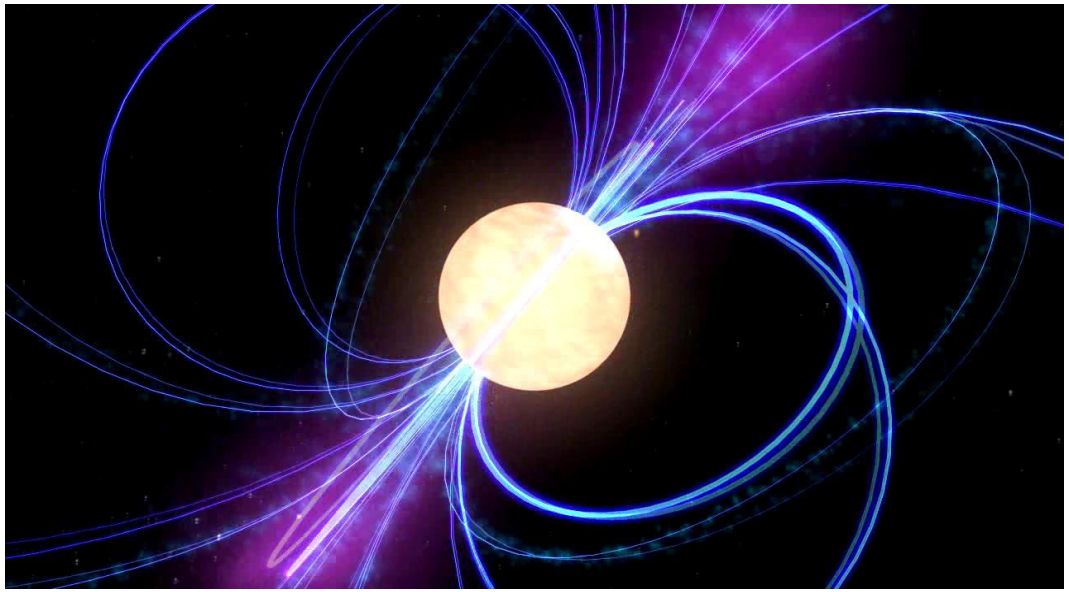
Spying on the quickly variable optical sky
The enigmatic case of millisecond pulsars



Alessandro Papitto

XMM Science Workshop

ESAC 6.6.2023



Rotation-powered Pulsars

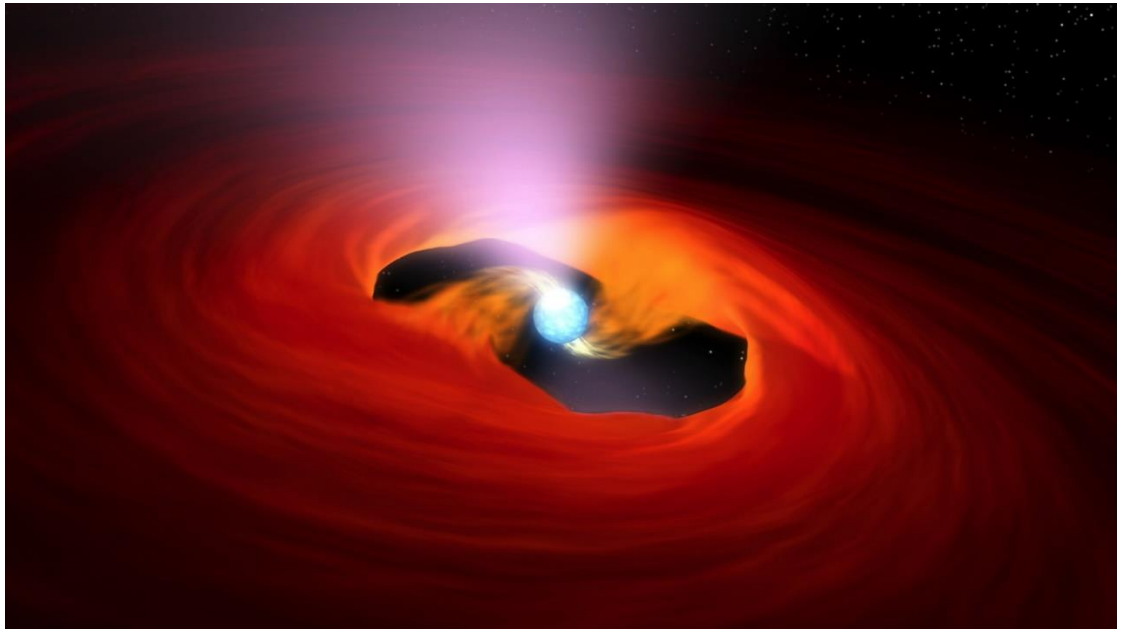
Rotation of the electromagnetic field

→ **Radio/Gamma-ray pulses**

Accretion-powered Pulsars

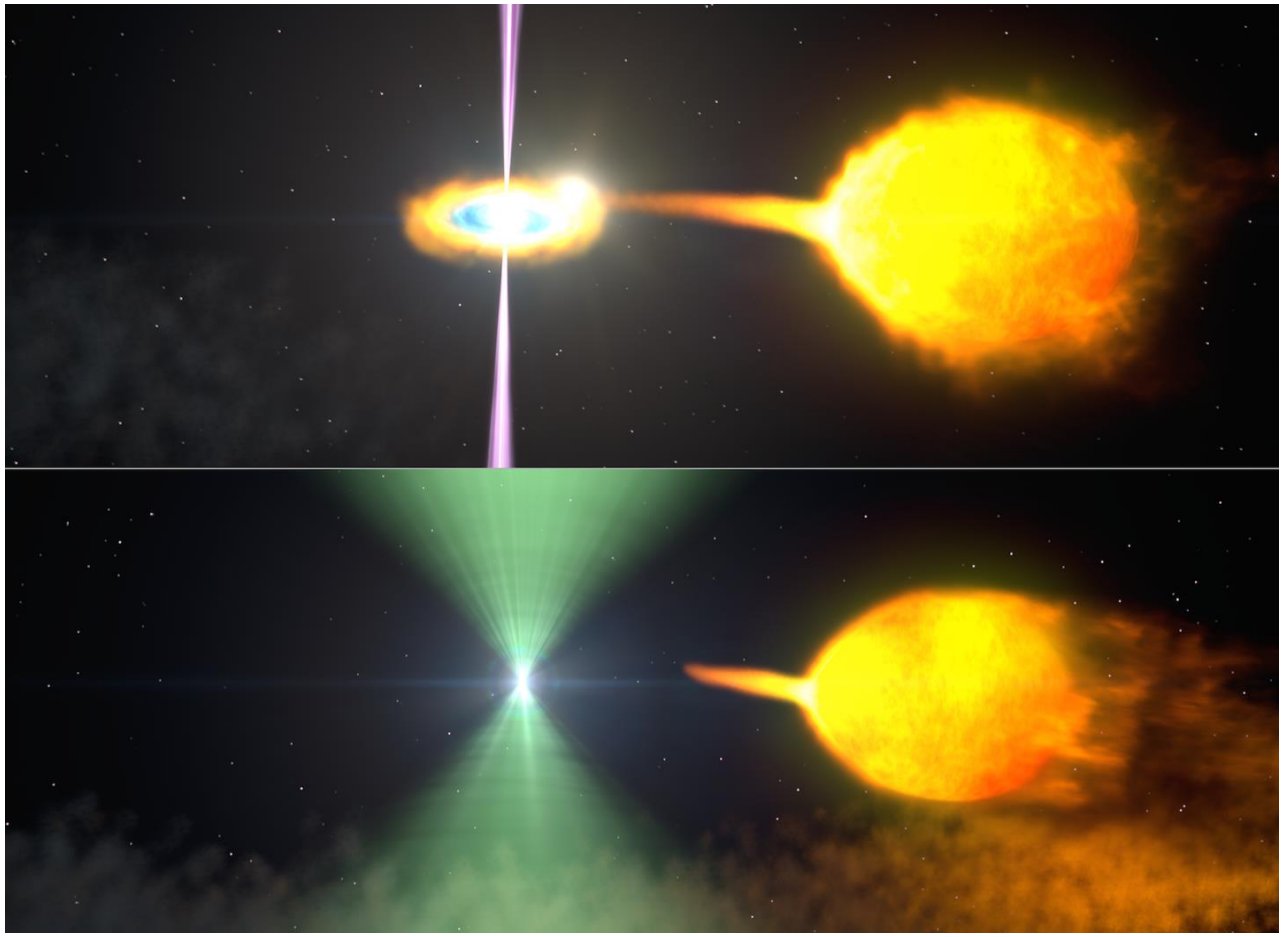
Accretion of Matter lost by a companion star channeled by the NS magnetic field

→ **X-ray pulses**

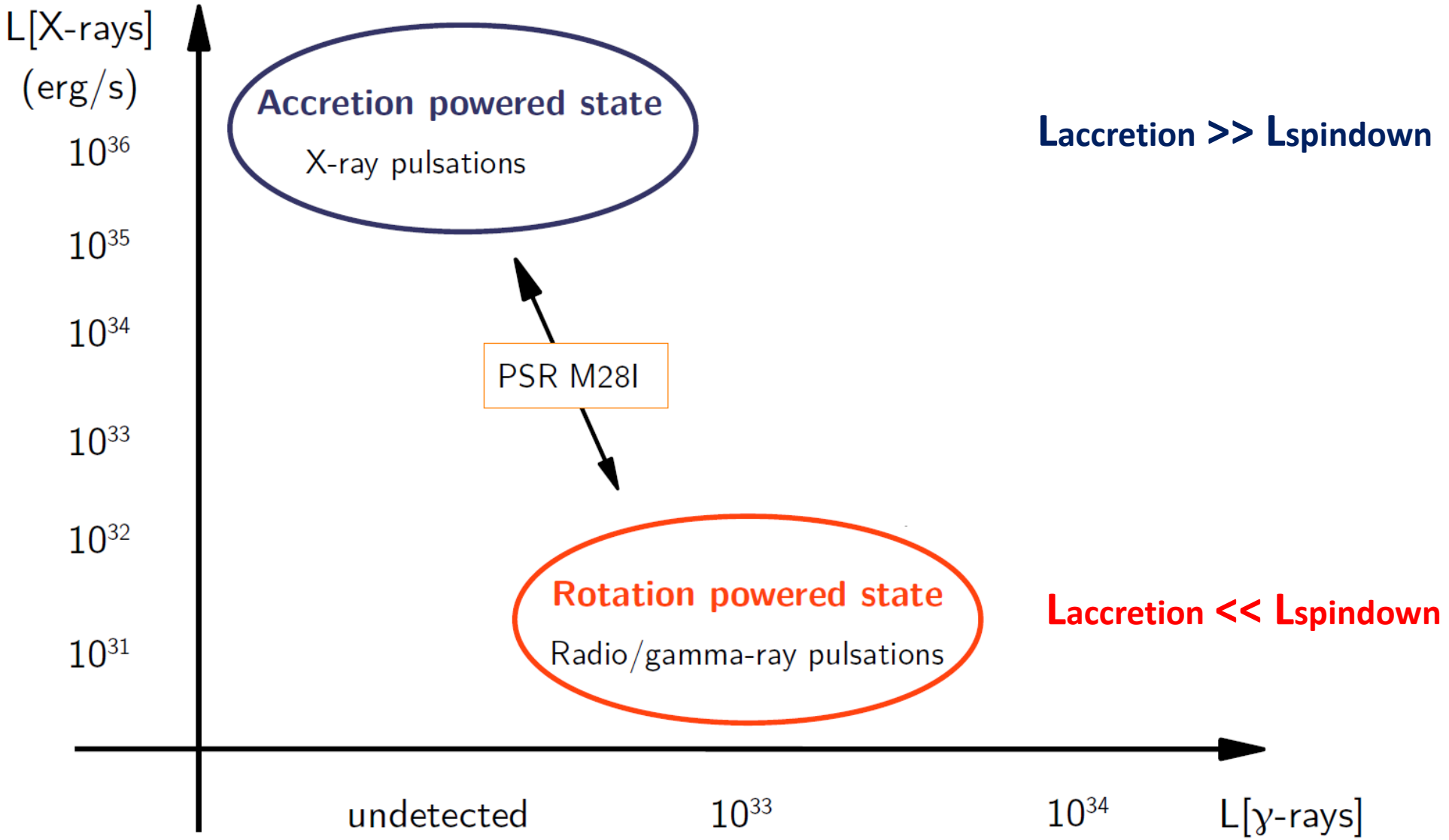


Can rotation and accretion power coexist?

Optical/UV millisecond pulsars support the hypothesis



Transitional Millisecond Pulsars

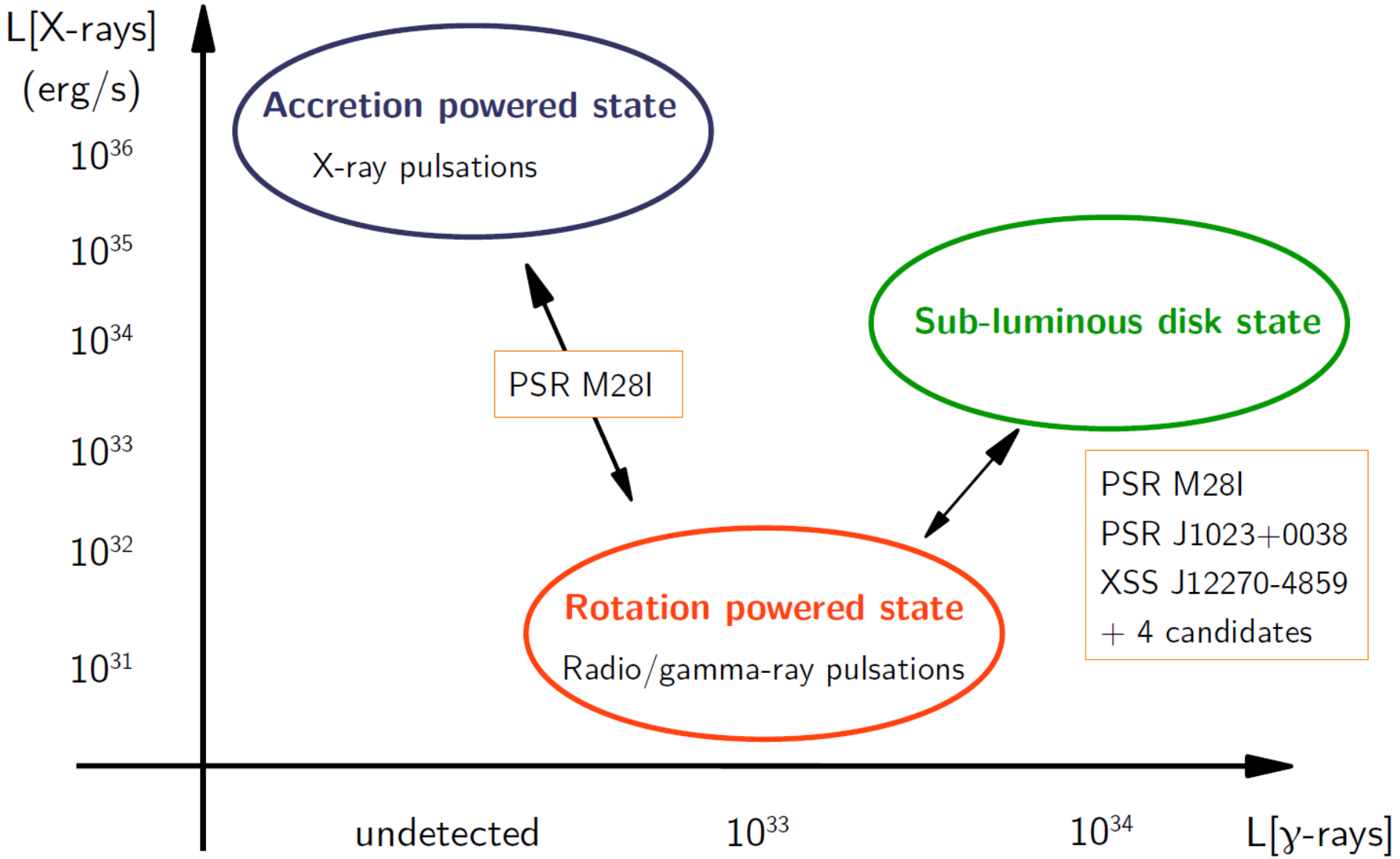


Laccretion >> Lspindown

Laccretion << Lspindown

Papitto+ 2013, Nature; **Ferrigno**+ 2014; **Linares**+ 2014; See review by **Papitto & de Martino** 2022 (arXiv:2010.09060)

Transitional Millisecond Pulsars



Laccretion >> Lspindown

Laccretion ≈ Lspindown

Laccretion << Lspindown

Archibald+ 2009, Science; **Papitto**+ 2013; **Bassa**+ 2014; **Linares** 2014

An enigmatic sub-luminous disk state

Accretion-power features

Disk emission lines

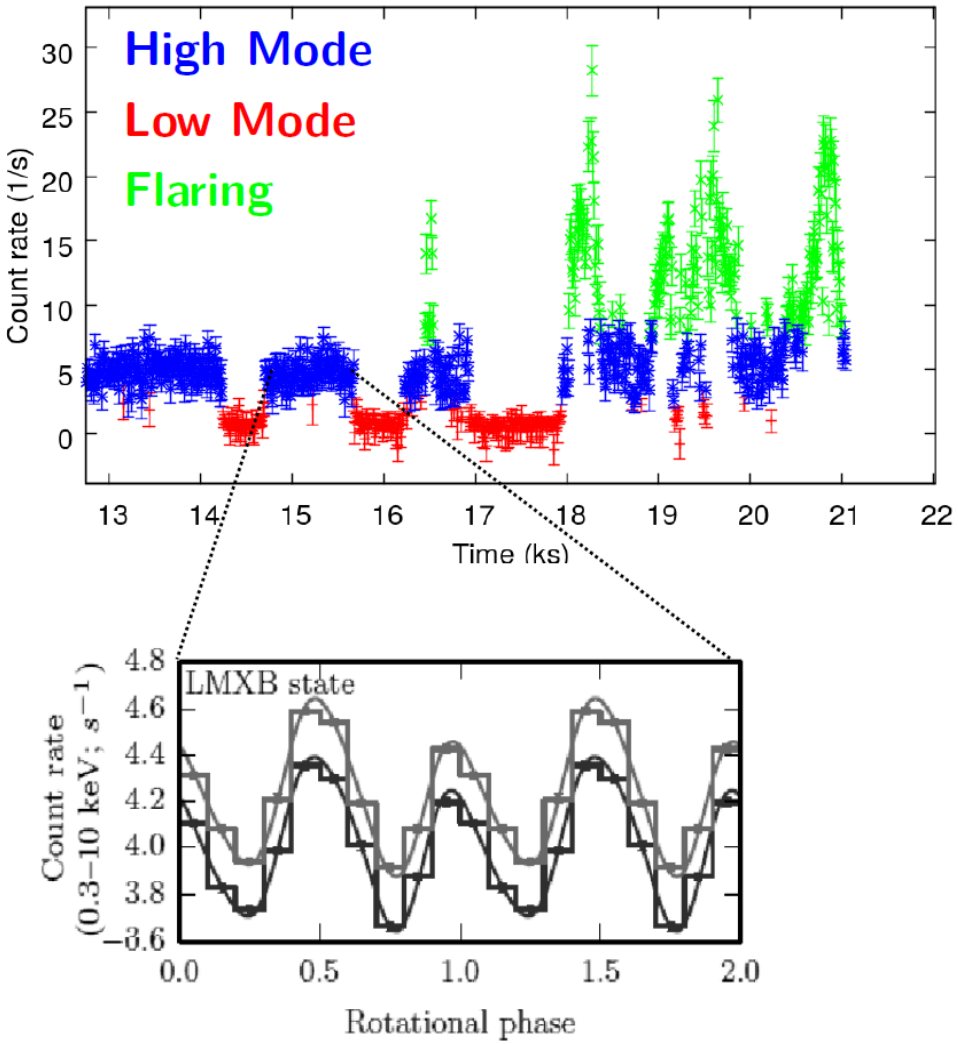
X-ray pulsations & sudden variability

Bright radio jets

Rotation-power features

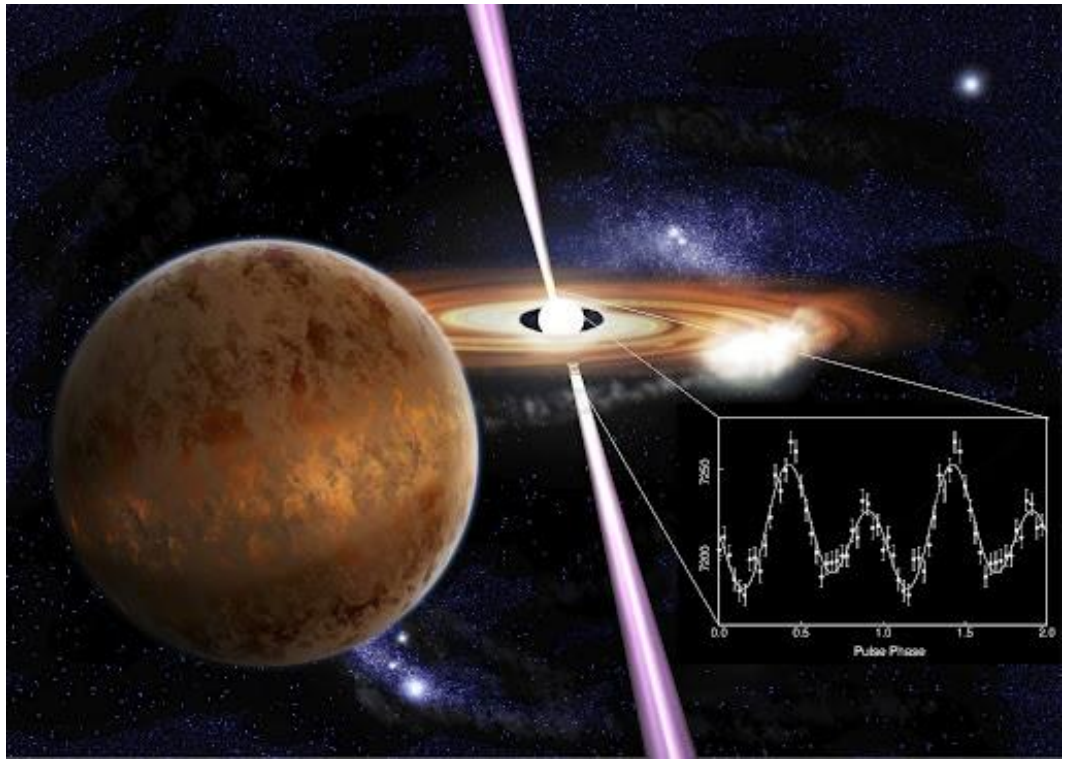
Bright gamma-ray emission

Spin-down



Patruno+ 2014, Stappers+ 2014, Bogdanov+ 2015, Archibald+ 2015, Papitto+ 2015, Deller+ 2015, Jaodand+2016, Torres+ 2018

Discovery of an Optical/UV transitional millisecond pulsar



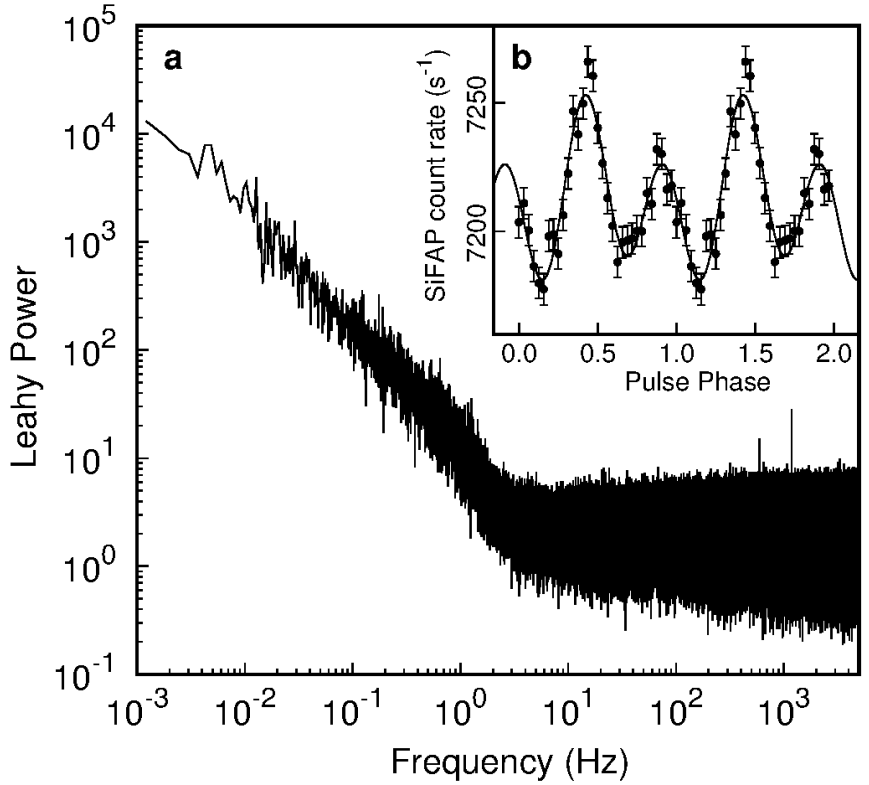
Ambrosino, Papitto+ 2017, Nature Astr.; **Zampieri+** 2019; **Karpov+** 2019; **Miraval Zanon+** 2022

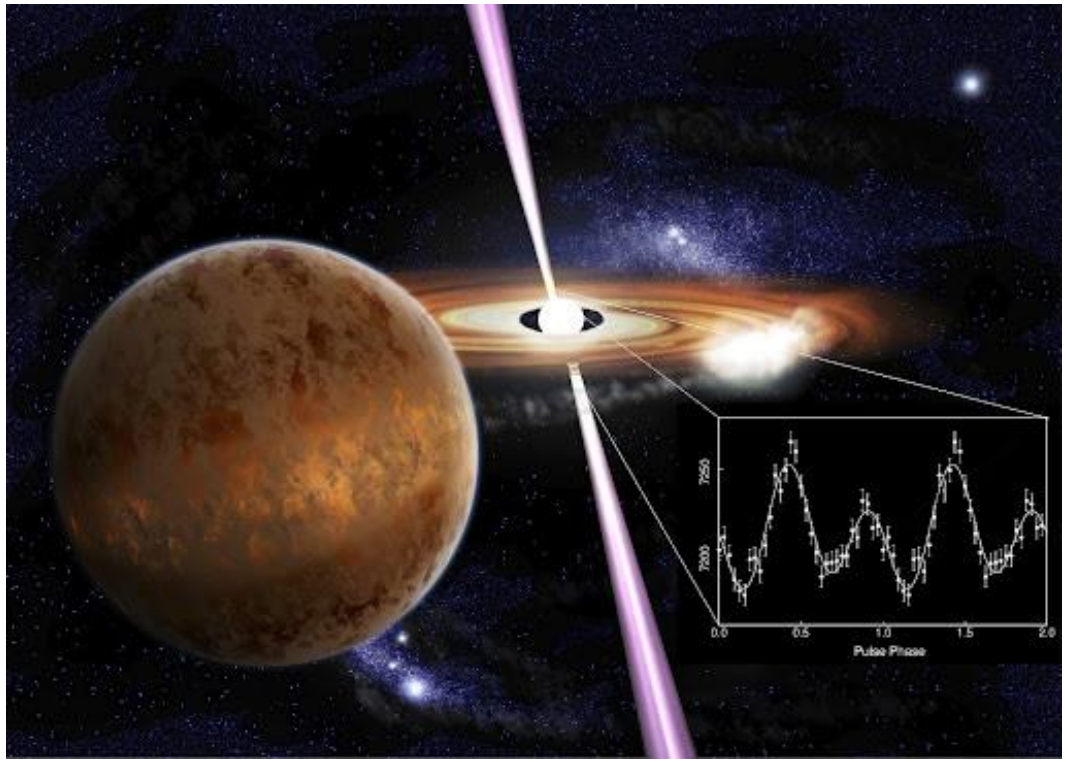
Discovery of an Optical/UV transitional millisecond pulsar

PSR J1023+0038: ~ 10000 c/s (V ≈ 16.5 mag), Pulse amplitude ~ 1%

L_{pulsed} ~ few x 10^{31} erg/s

≈ 0.03% $L_{SpinDown}$





Ambrosino, Papitto+ 2017, Nature Astr.; **Zampieri+** 2019; **Karpov+** 2019; **Miraval Zanon+** 2022

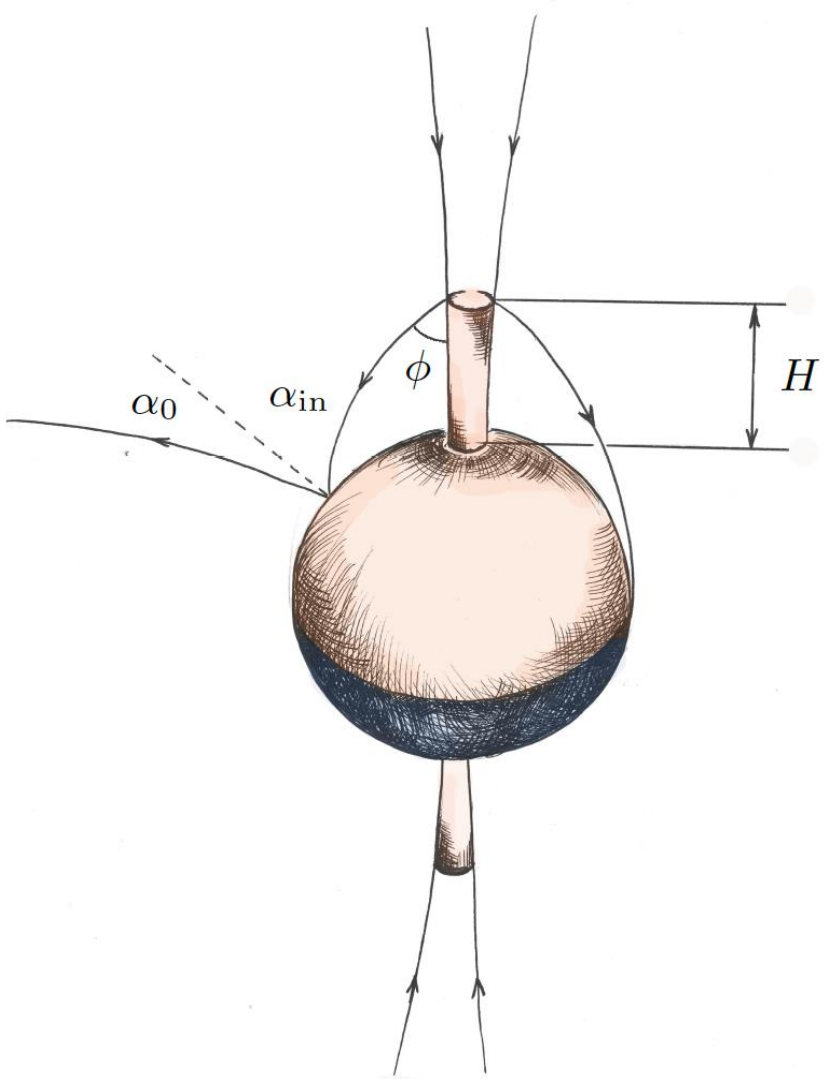
Stunningly bright optical pulsations accretion-powered?

Cyclotron emission from **accretion column**?

$$E_{cyc} = 1\,(B / 10^8\ \mathrm{G})\ \mathrm{eV}$$

$$L_{\rm cyc} = A_{\rm spot} \int_{\nu_l}^{\nu_h} (2\pi k T_e \nu^2 / 3c^2)\, d\nu$$

$$= 2.9 \times 10^{29} \left(\frac{A_{\rm spot}}{10^{12}\ \mathrm{cm}^2} \right) \left(\frac{kT_e}{100\ \mathrm{keV}} \right) \mathrm{erg\ s^{-1}}$$



PSR J1023 L_{pulsed} = few x 10^{31} erg/s

50x beaming required

Lamb & Masters 1979

Stunningly bright optical pulsations rotation-powered?

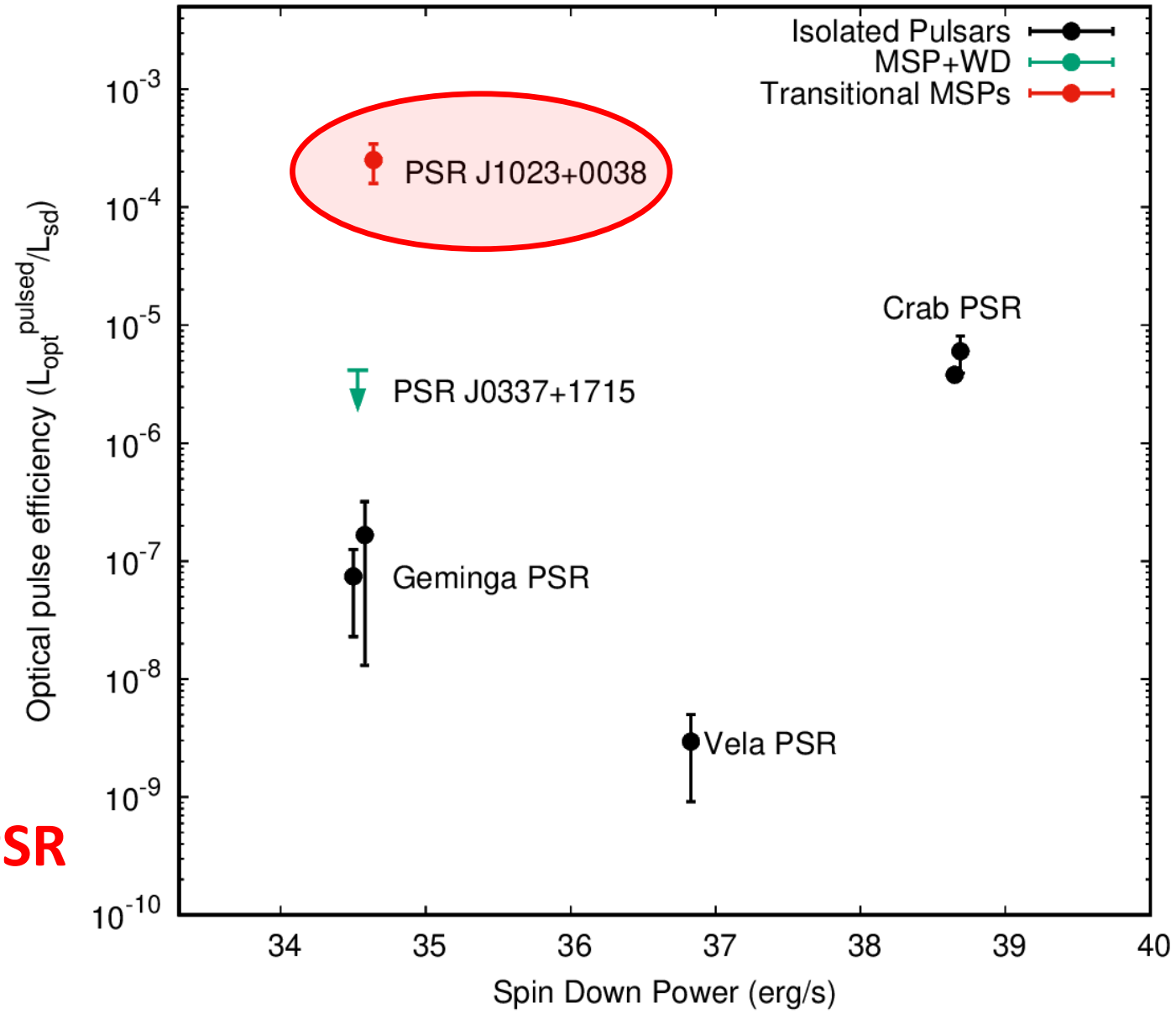
Radio pulsars

$L=10^{-5}$-10^{-8} L_{sd}

PSR J1023

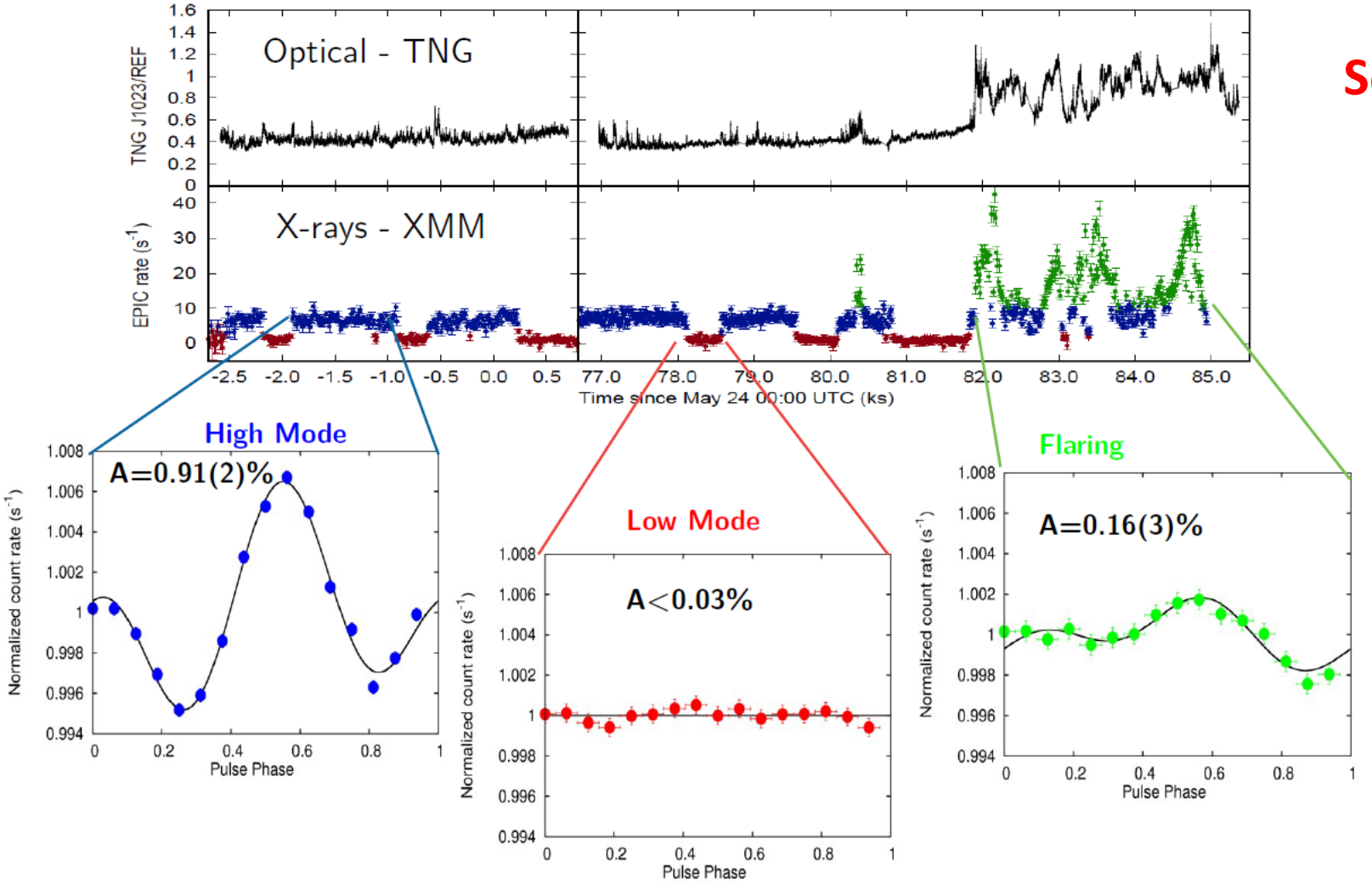
$L = 2x10^{-4}$ L_{sd}

>50x more efficient than Crab PSR



Updated from **Ambrosino, Papitto+** 2017, Nature Astr.

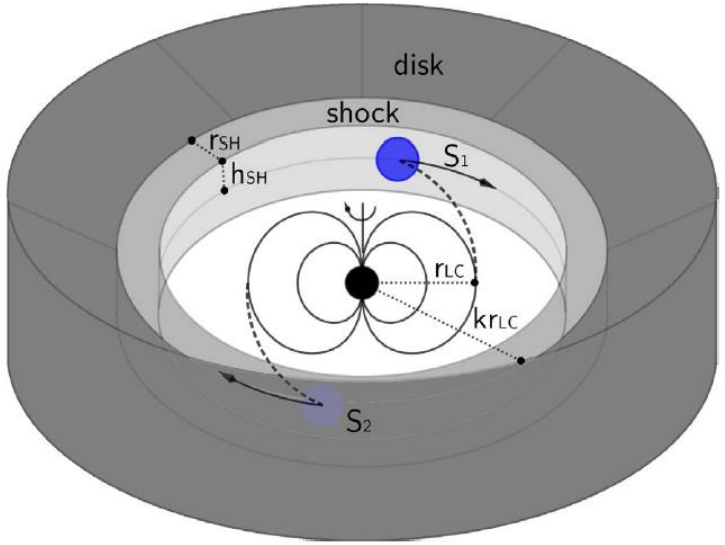
Pulsating in unison at optical and X-ray energies



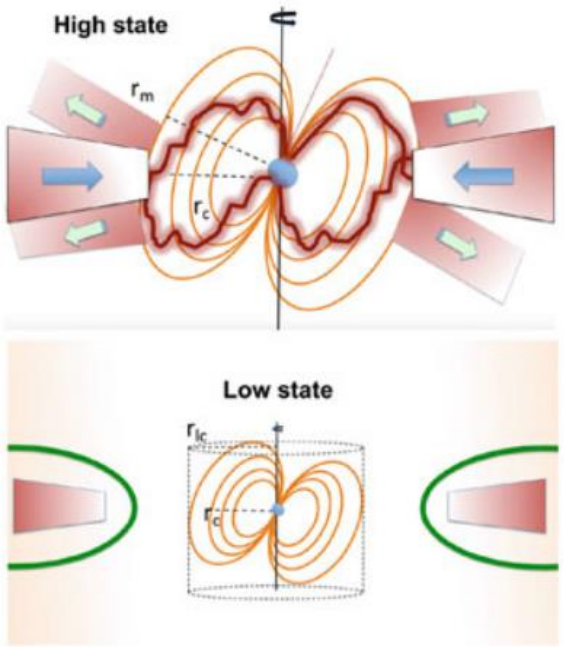
See Giulia Illiano's talk later on

Papitto+ 2019; **Illiano+** 2023

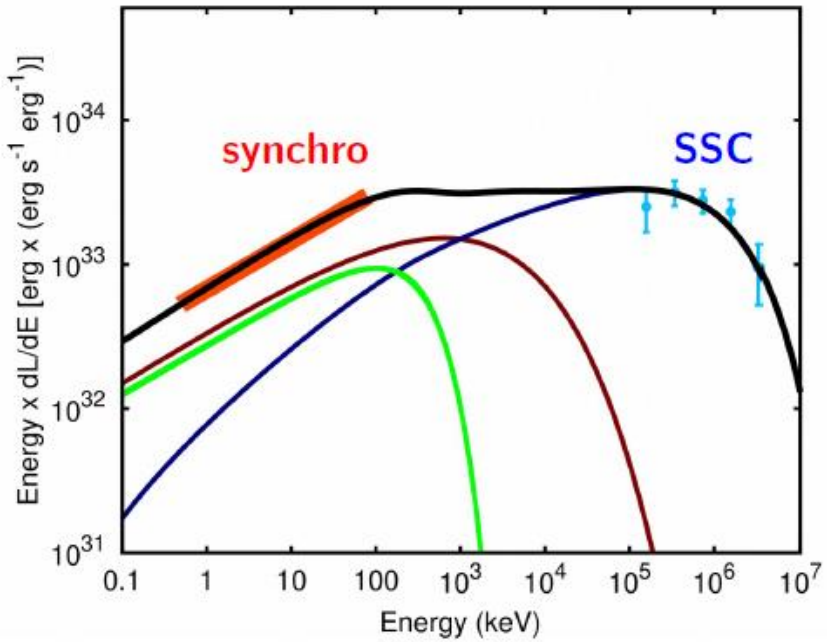
Coexistence of Rotation & Accretion-power



Pulsar wind terminated by the accretion disk at r≈100 km

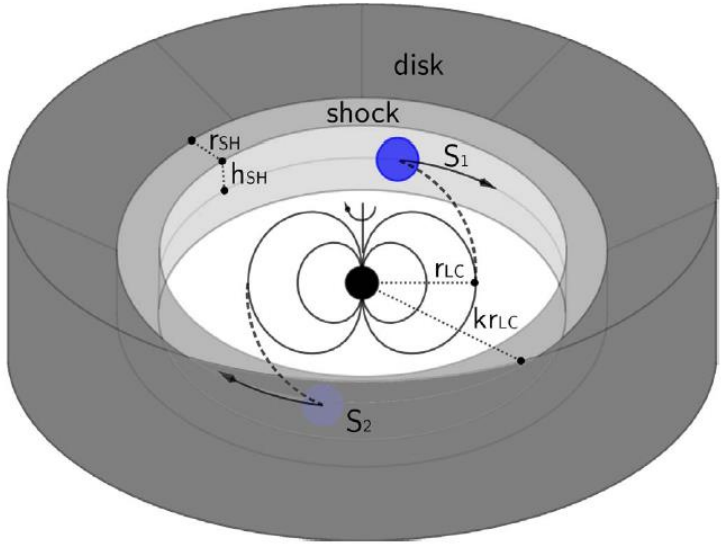


Synchrotron → Optical/X-rays
Inverse Compton → Gamma-rays



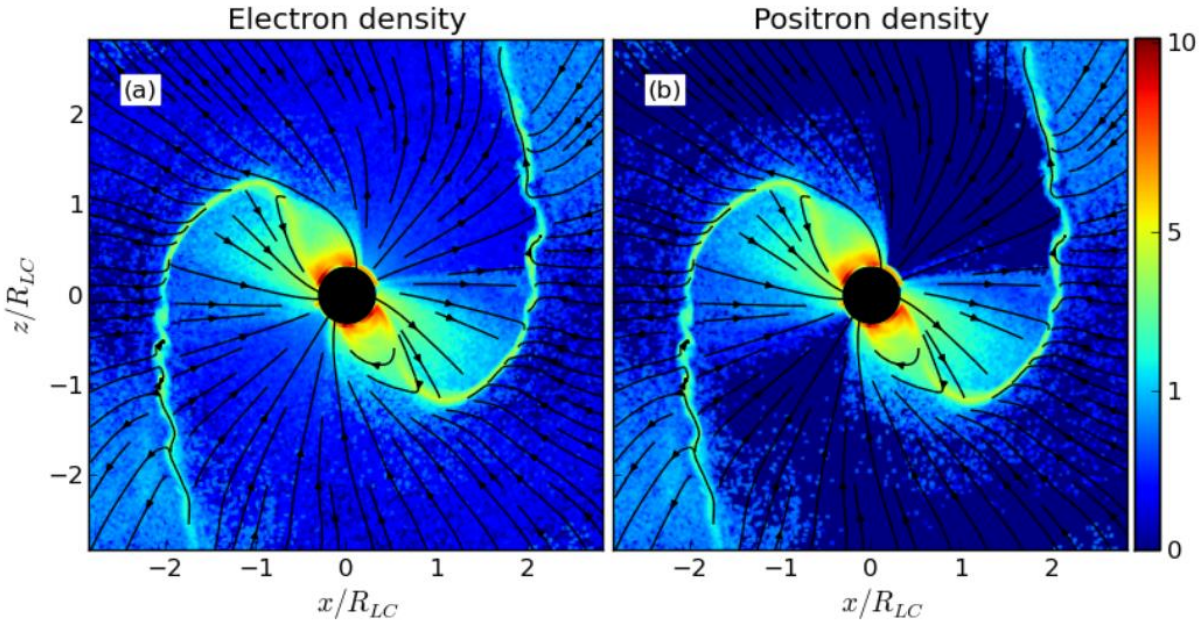
Papitto+ 2019; **Veledina+** 2019; **Papitto+** 2014, 2015; **Campana**+ 2016

Coexistence of Rotation & Accretion-power



Pulsar wind terminated by the accretion disk at r≈100 km

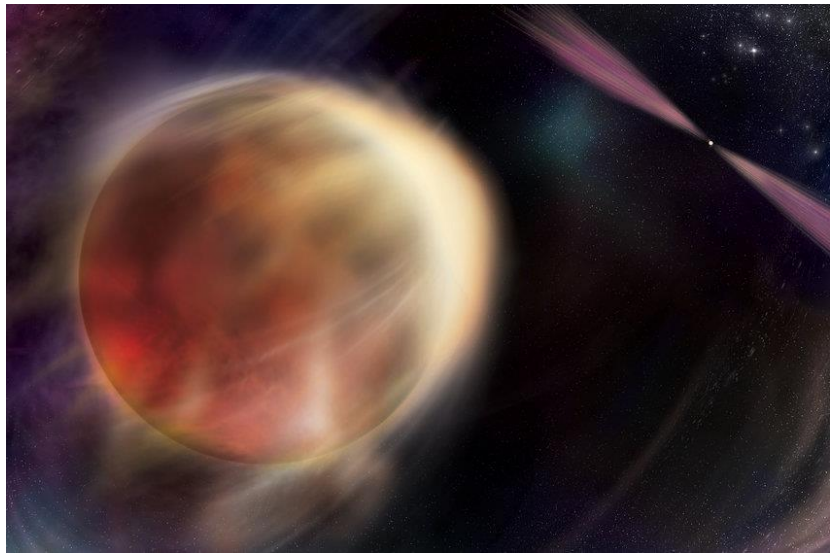
Optical and X-ray pulses from the interaction between the **pulsar striped wind** and the termination shock

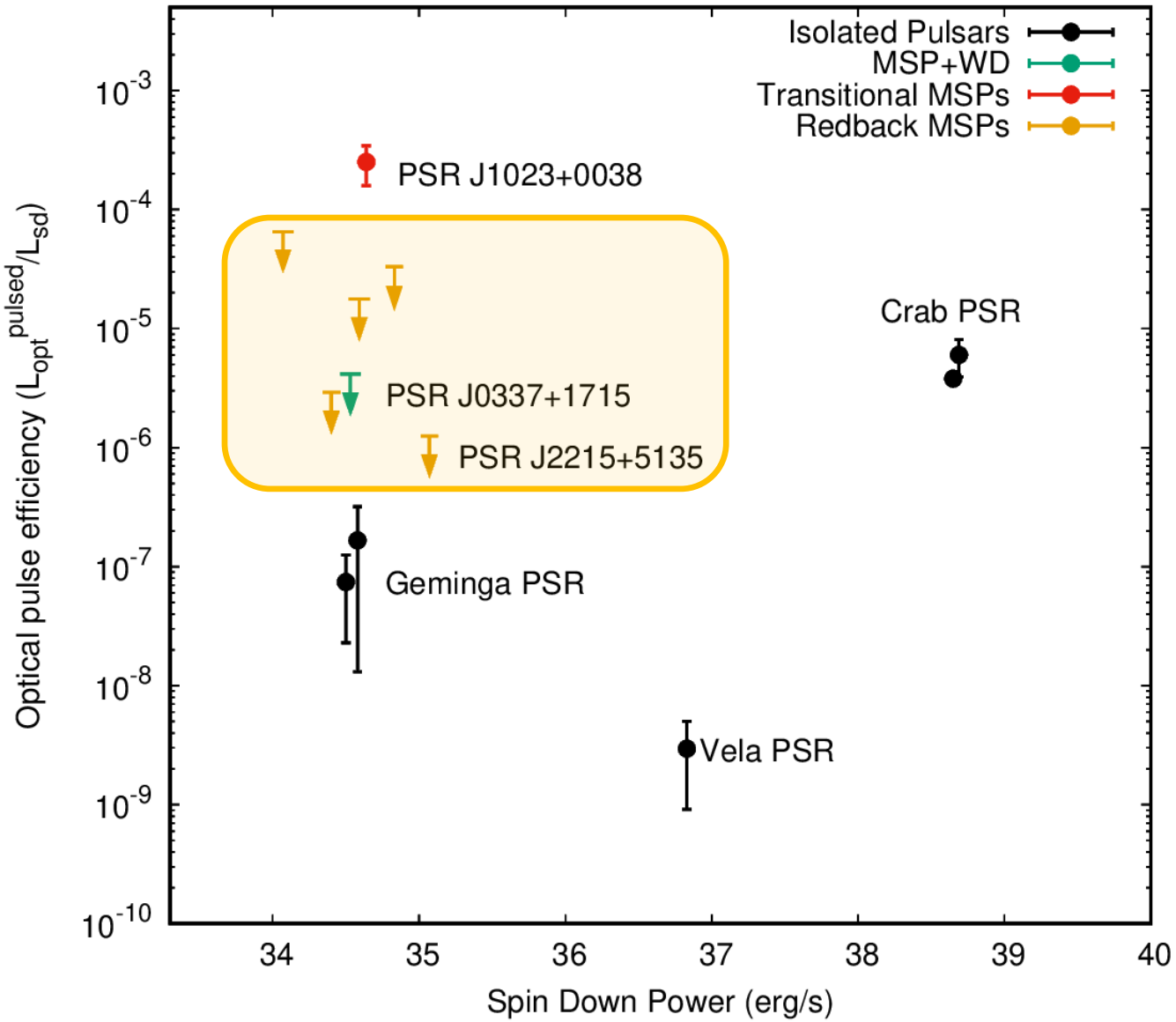


Cerutti & Beloborodov 2017

Optical pulsations from redbacks?

PSR J2215+5135
Efficiency < 10^{-6}



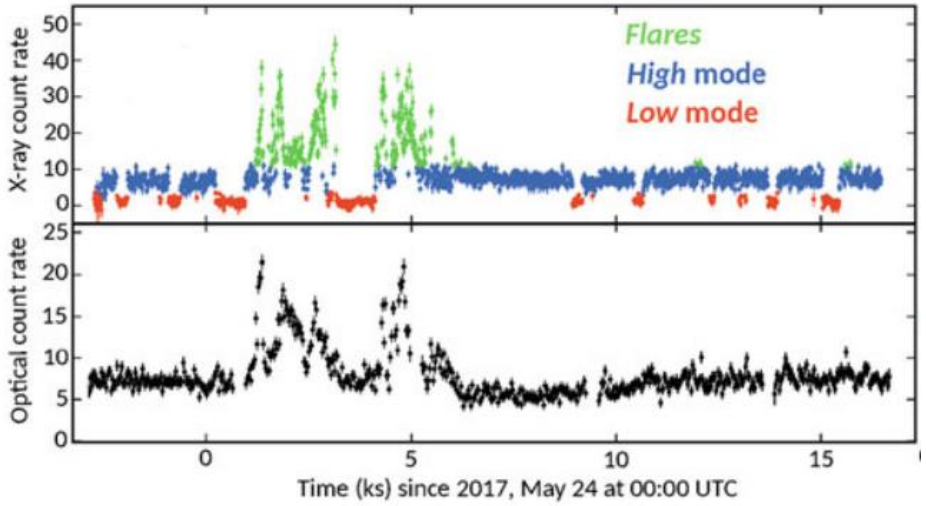


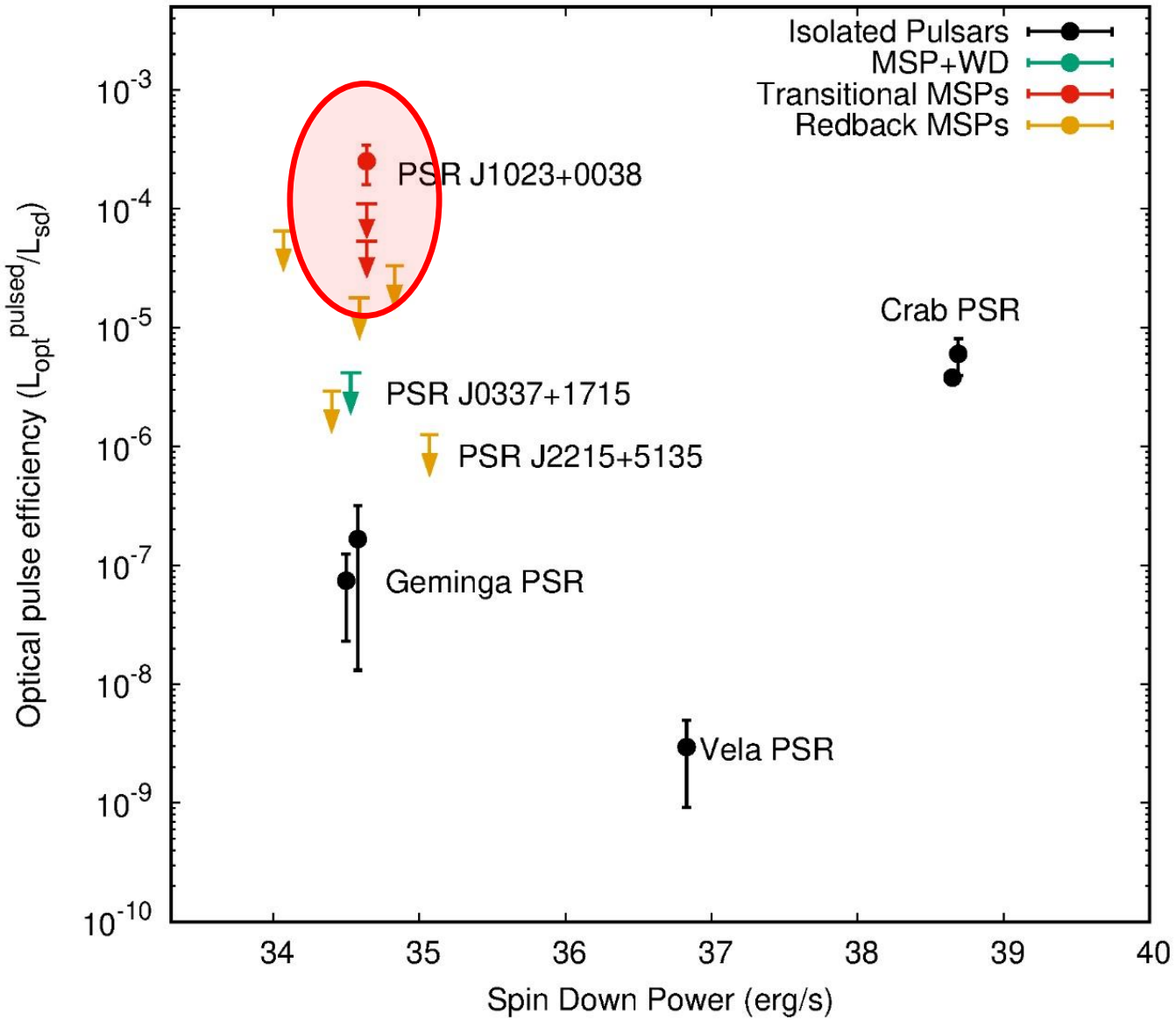
Turchetta 2020, **Ambrosino+** in prep., **La Placa+** in prep.

Candidate transitional ms pulsars?

3FGL J1544.6-1125
Amplitude < 0.024

Semi-coherent searches ongoing
Switch to radio PSR state?





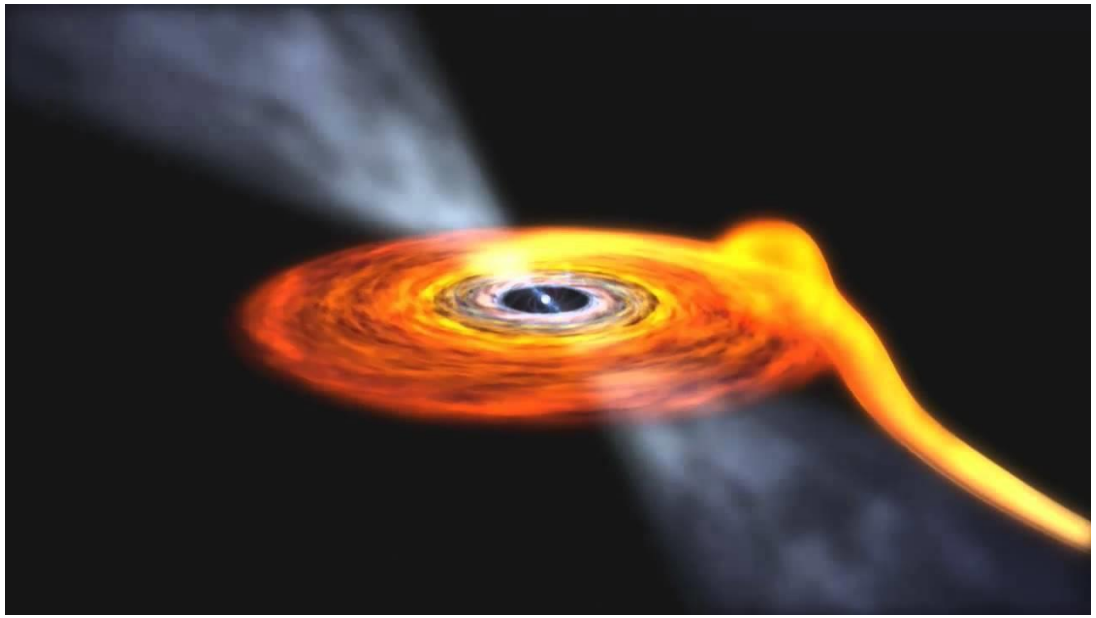
Illiano+ in prep.

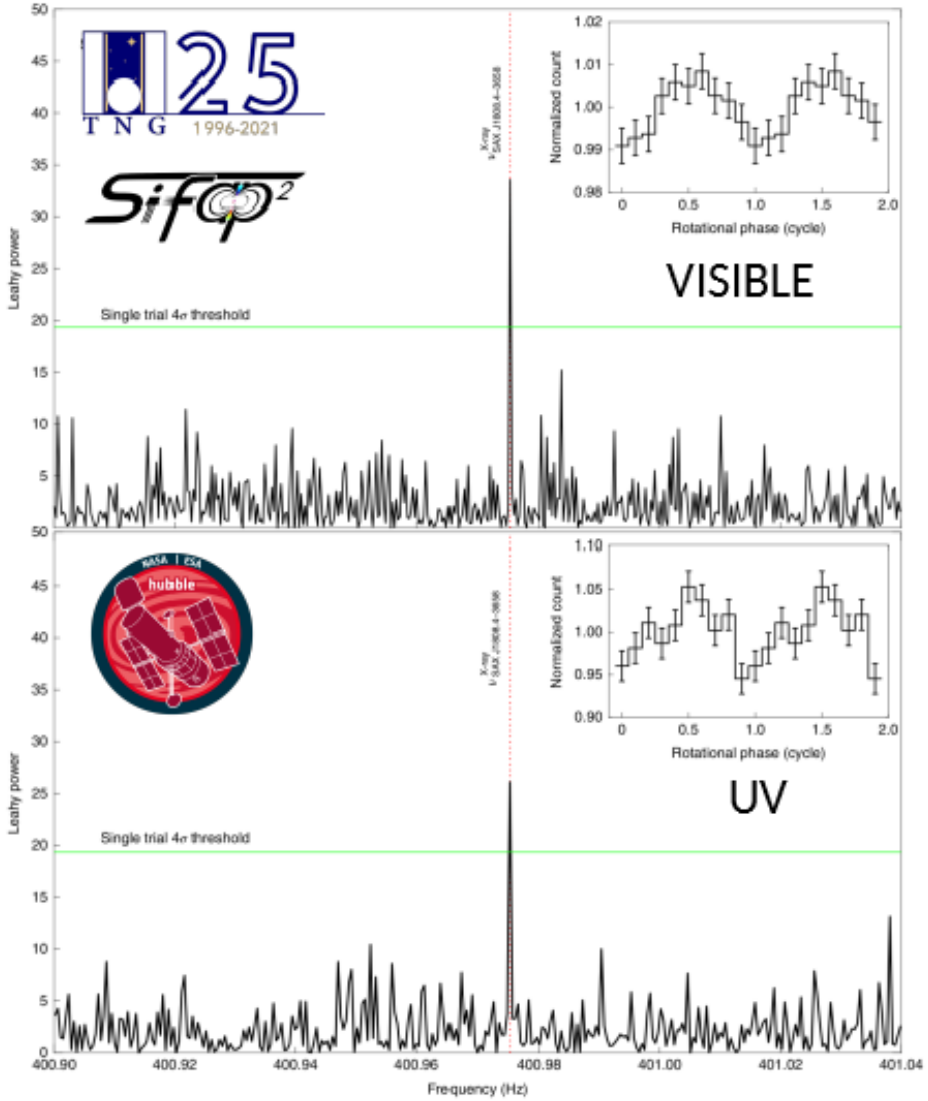
Optical and UV pulsed emission from an Accreting millisecond pulsar

SAX J1808.4-3658 – August 2019 outburst

$L_{X\text{-rays}} = 10^{35}$ erg/s

$A_{opt} \approx A_{UV} \approx 1\text{-}2\%$





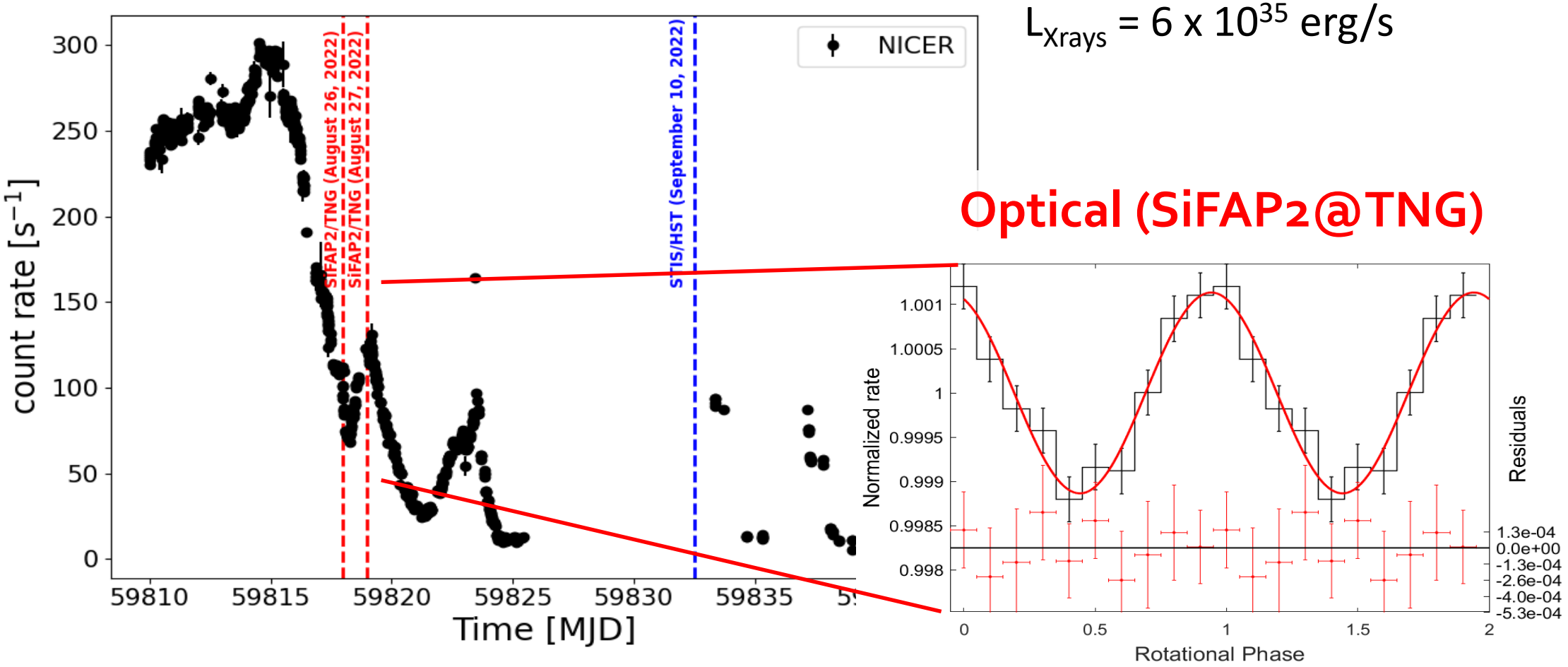
Ambrosino, Miraval Zanon, Papitto+ 2021, Nature Astr.

Optical pulses also in August 2022 outburst

See Caterina Ballocco's talk later on

$L_{opt} = 1 \times 10^{31}$ erg/s

$L_{Xrays} = 6 \times 10^{35}$ erg/s



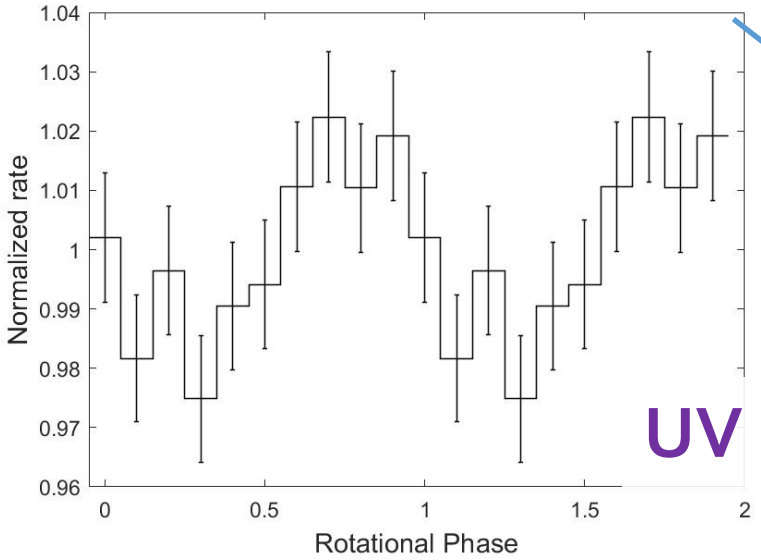
Ballocco, Papitto+ in prep.

Xrays/UV pulsations in the flaring state

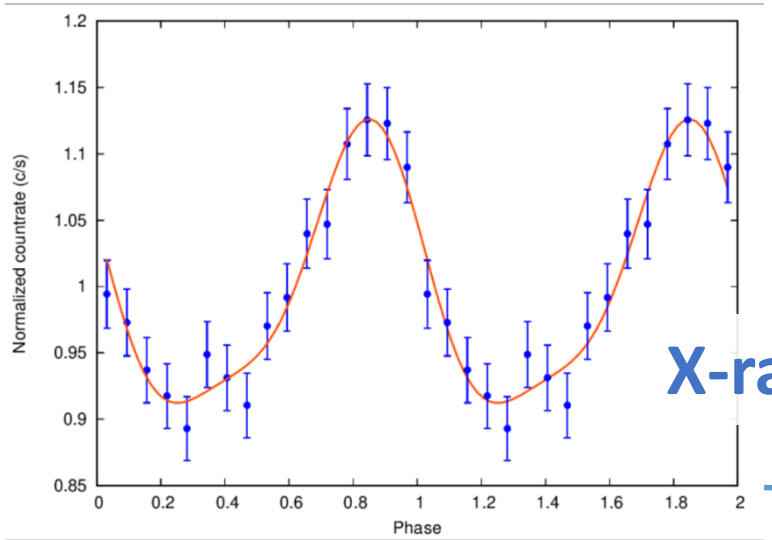
See Caterina Ballocco's talk later on

$L_{UV} = 2 \times 10^{32}$ erg/s

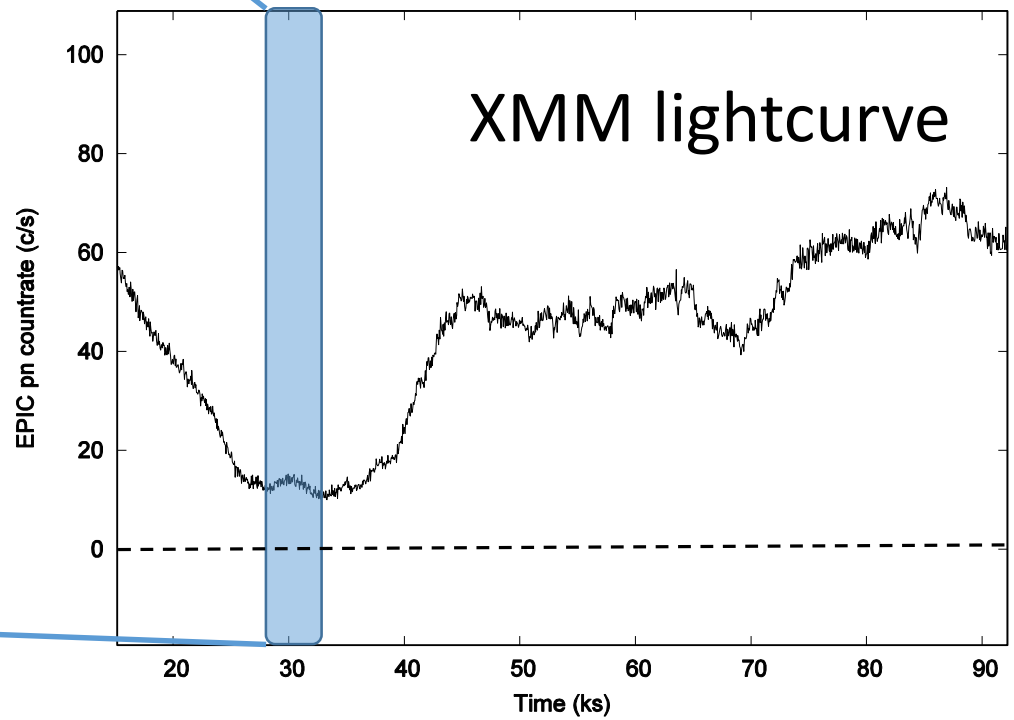
L_{Xrays} = few x 10^{34} erg/s



UV (HST)



X-rays (XMM)



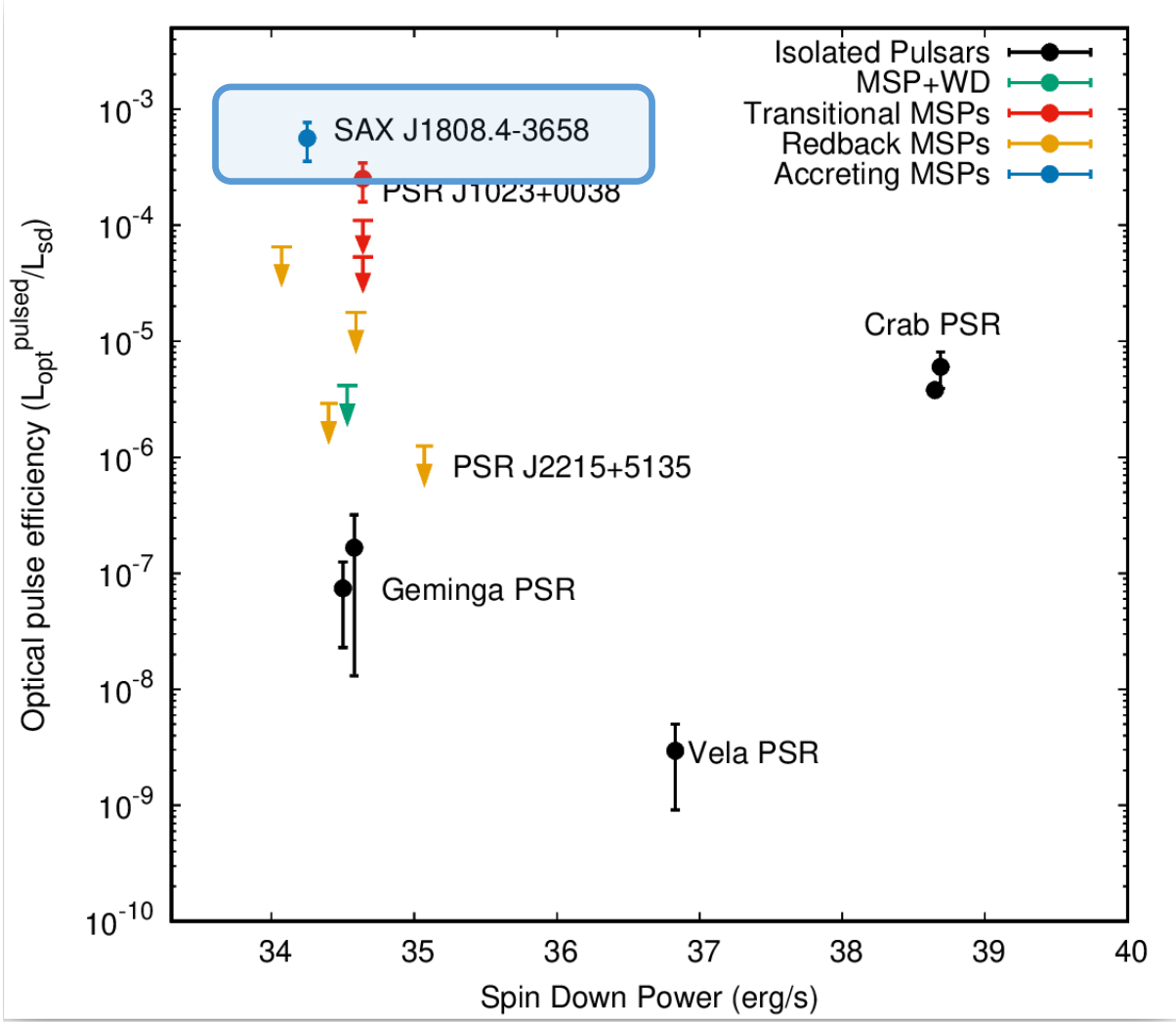
Ballocco, Papitto+ in prep.

Optical and UV pulsed emission from an Accreting millisecond pulsar

- Accretion-powered (L_X>>Lsd)
- Most efficient optical pulsar

Coexistence of **accretion** and **rotation** power?

Accretion-powered optical pulses much brighter than expected?



Ballocco, Papitto+ in prep.

Summary

Optical/UV pulses add a new dimension to MSP studies

They suggest coexistence of rotation and accretion power

Detection of more sources in different states required

The MSP@OAR team

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CALL FOR PROPOSALS TNG and REM