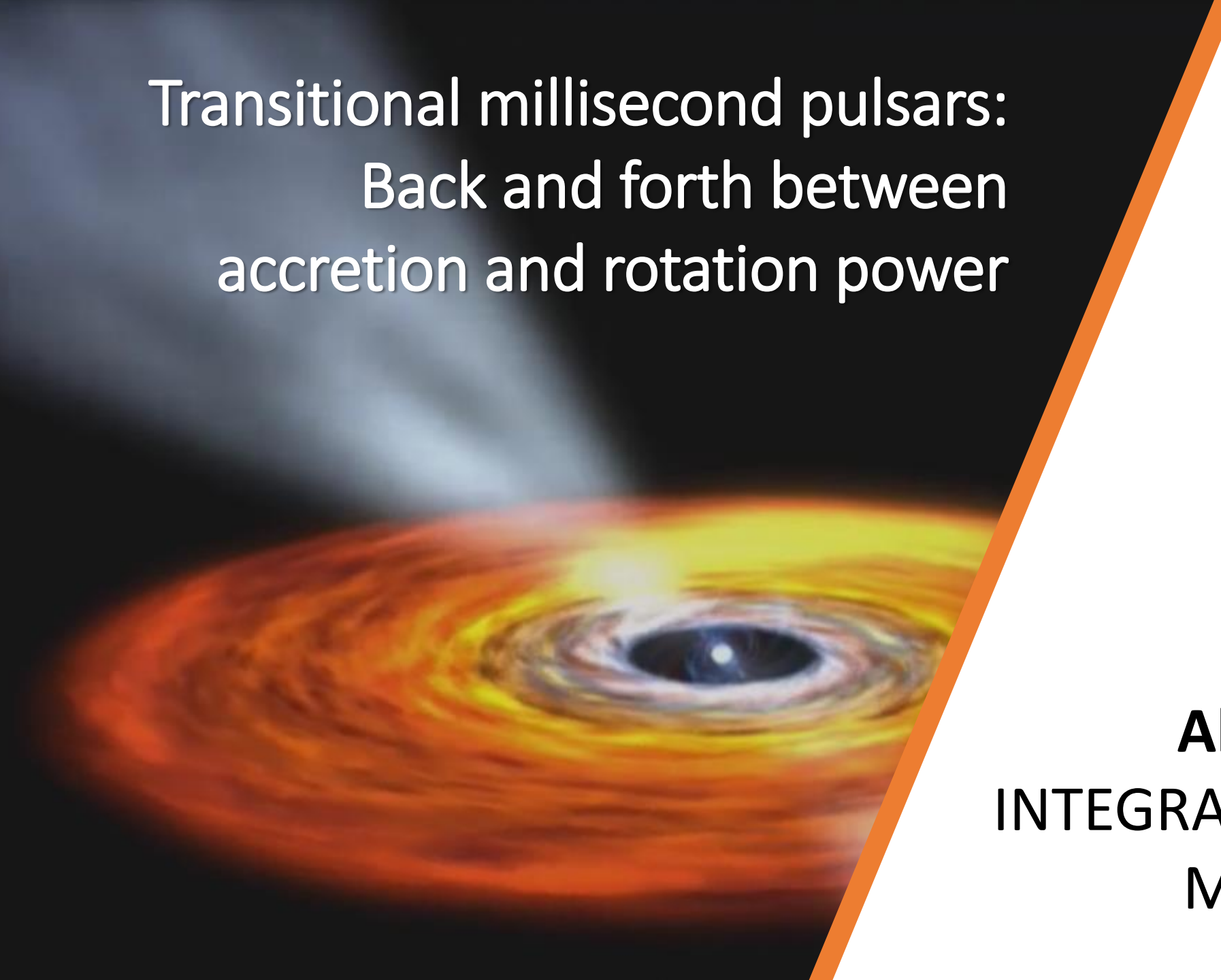
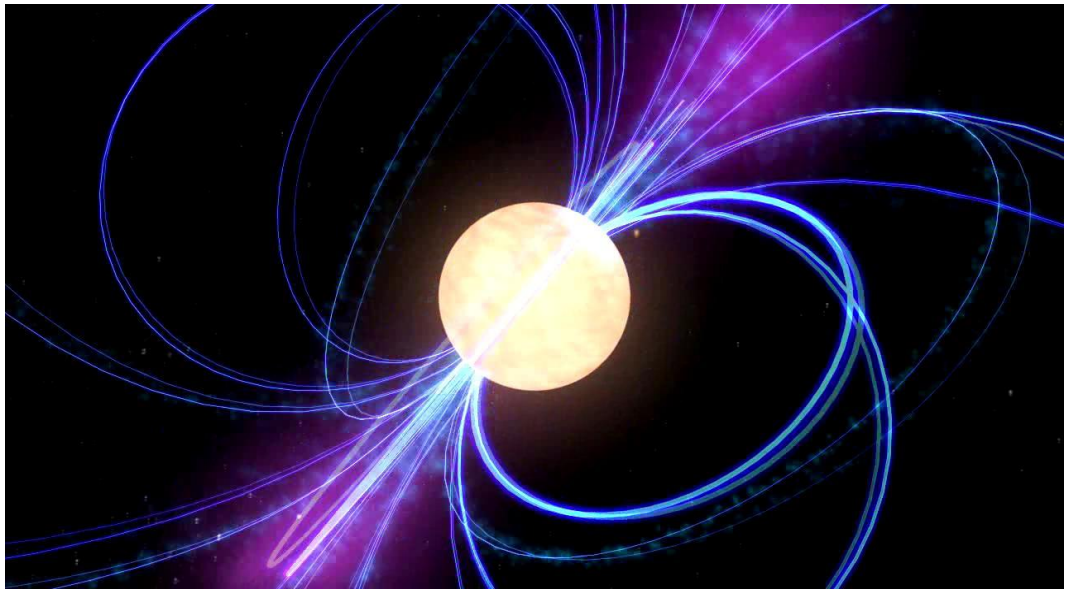
Transitional millisecond pulsars: Back and forth between accretion and rotation power



Alessandro Papitto

INTEGRAL Workshop 2024

Madrid 23.10.2024



Rotation-powered Pulsars

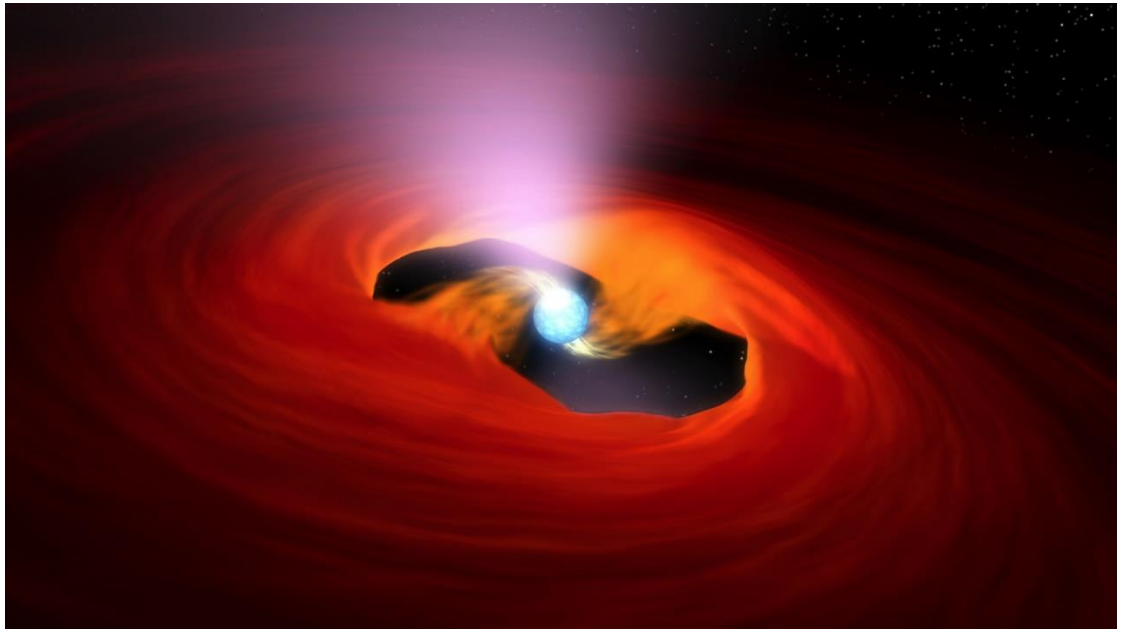
Rotation of the electromagnetic field

→ **Radio/Gamma-ray pulses**

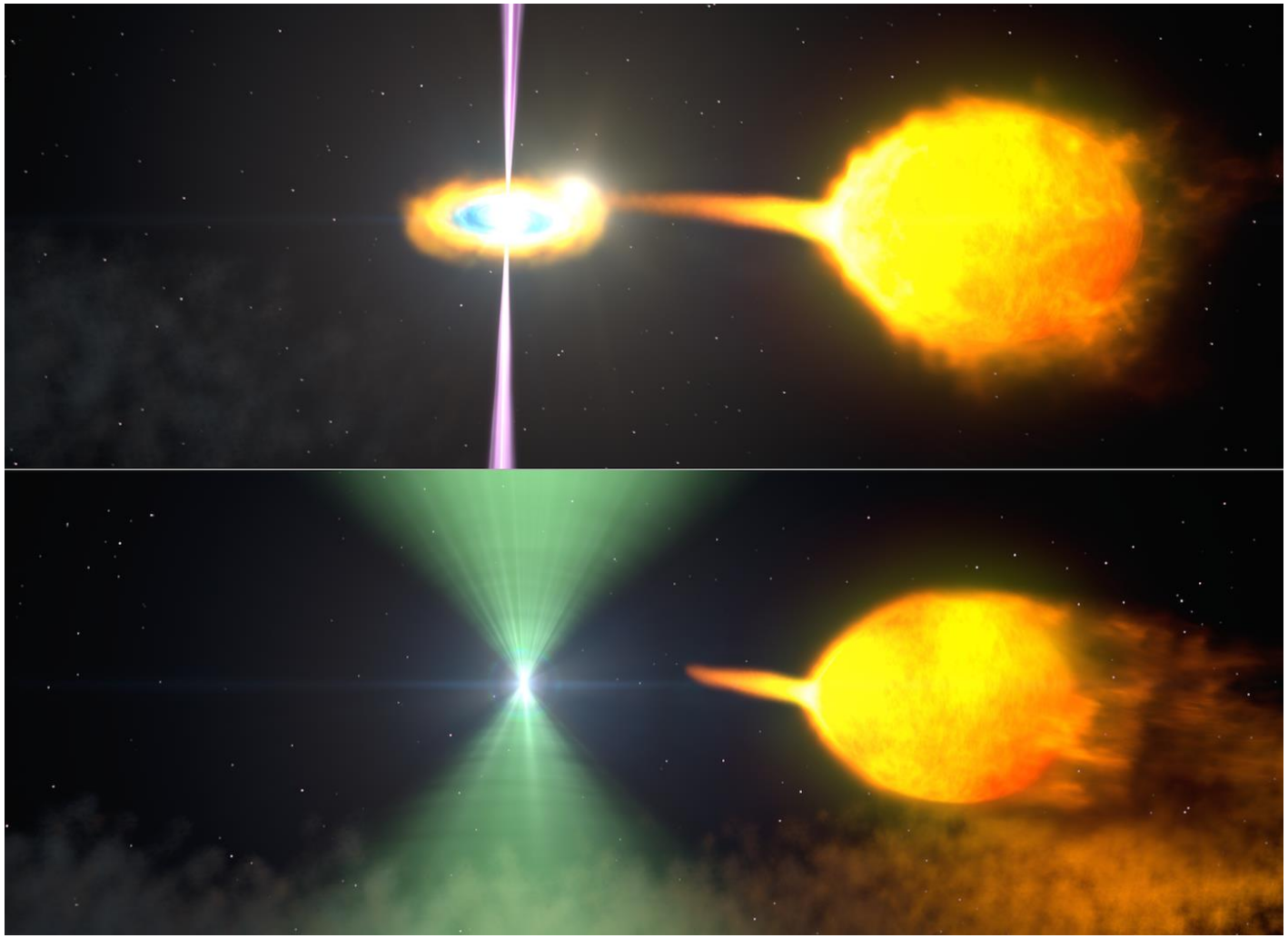
Accretion-powered Pulsars

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

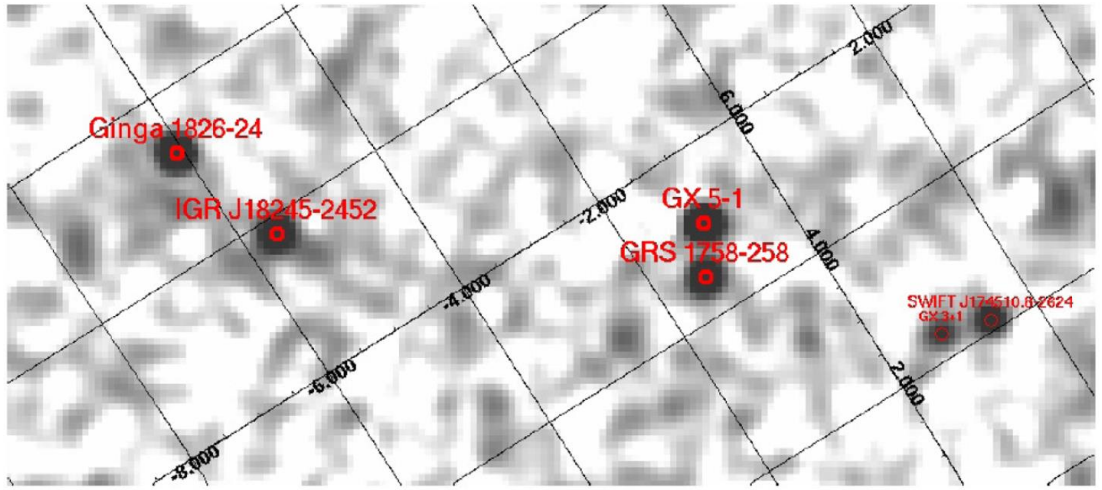
→ **X-ray pulses**

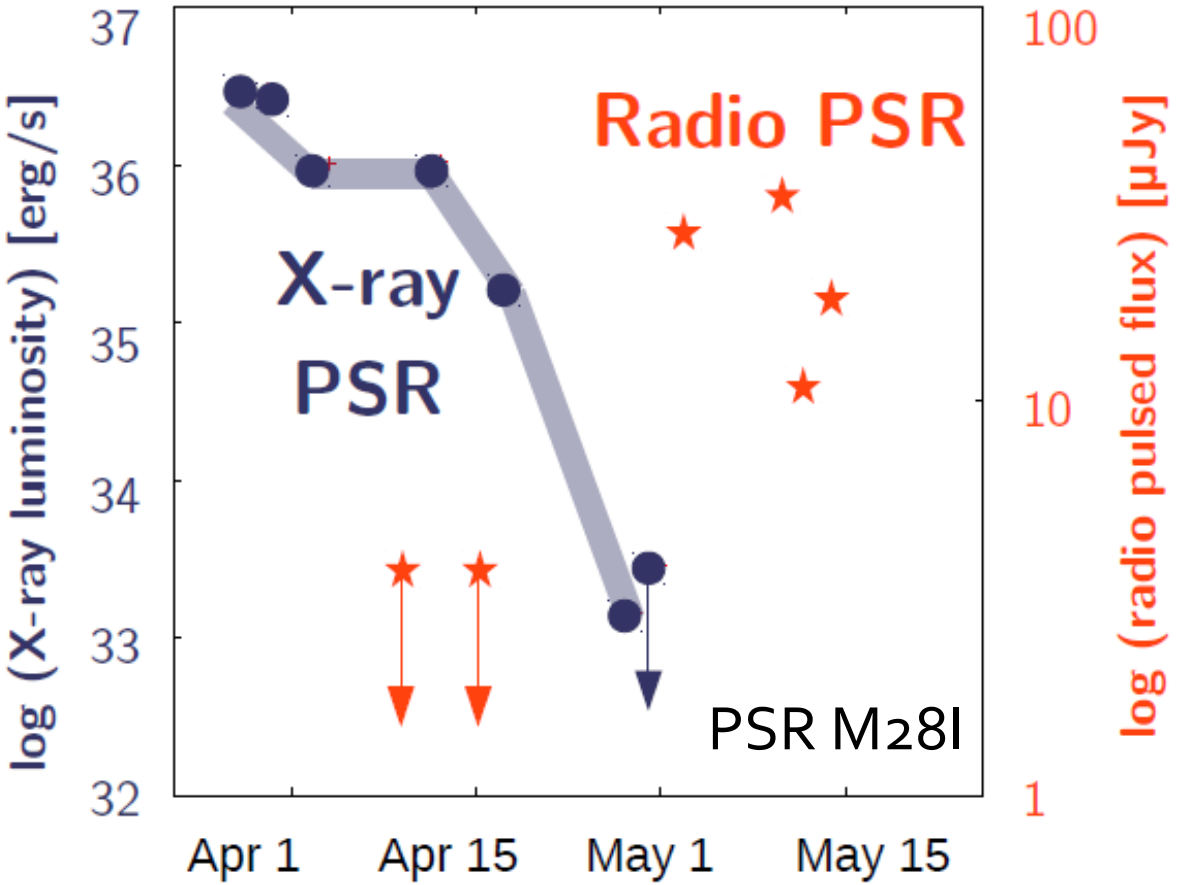


Can rotation and accretion power coexist?



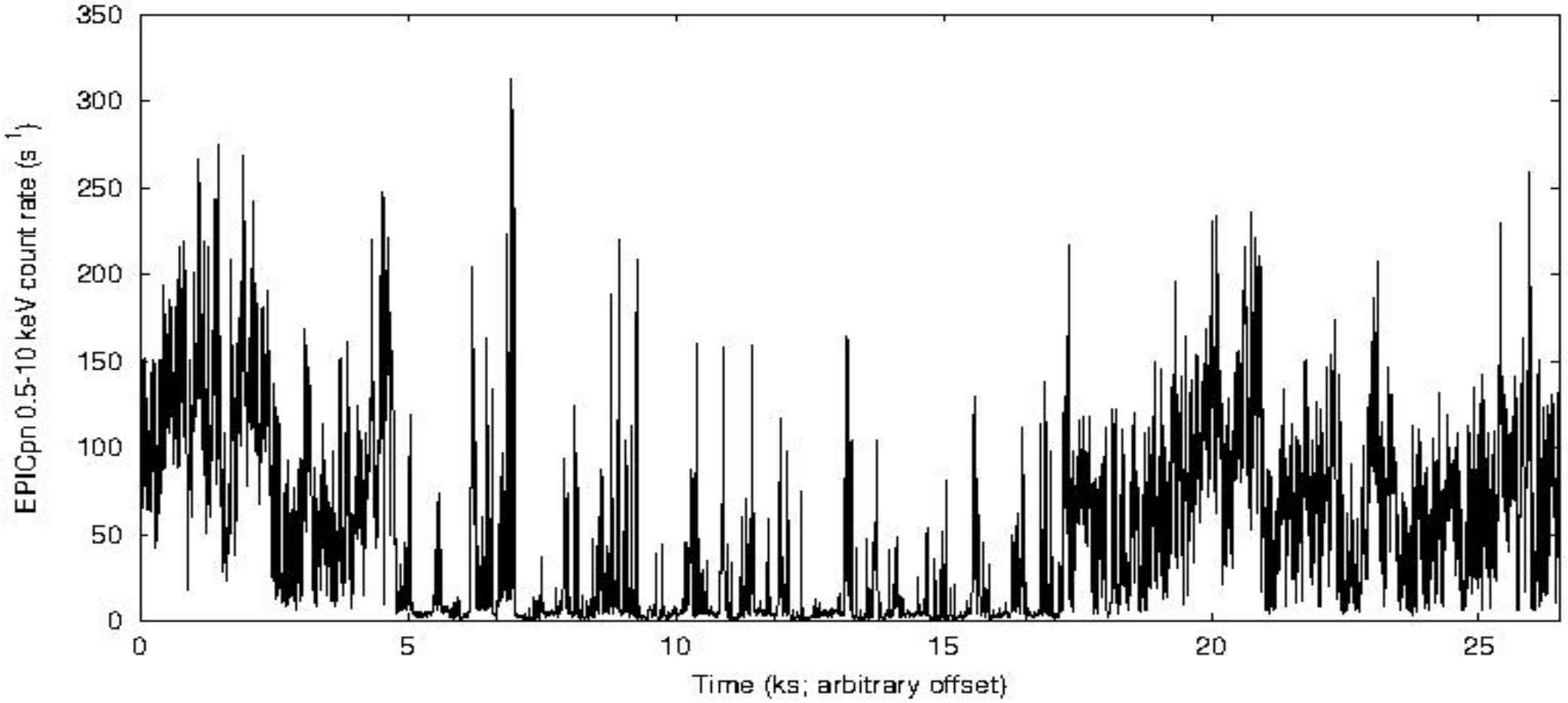
Swings between rotation and accretion power in a transitional millisecond pulsar: IGR J18245-2452





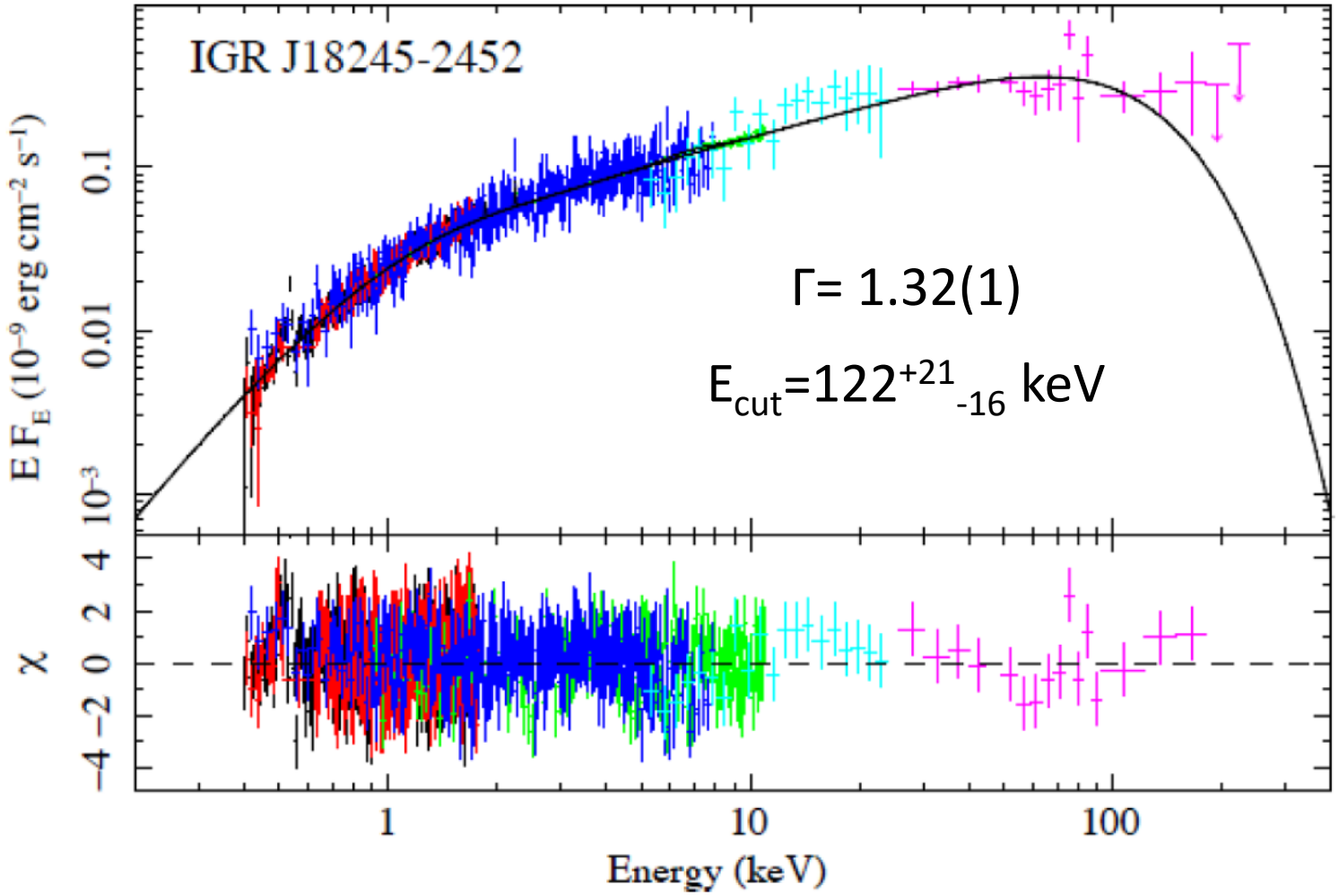
Papitto+ 2013, Nature, 501, 517; **Ferrigno**+ 2014; **Linares**+ 2014

Hiccups of a peculiar accreting millisecond pulsar



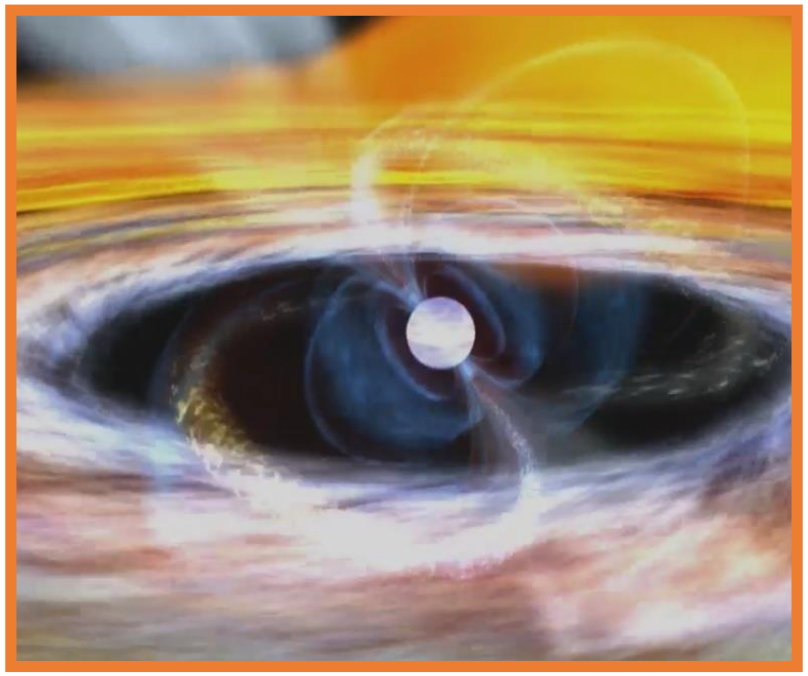
Papitto+ 2013; **Ferrigno**+ 2014

The hardest spectrum for an accreting ms pulsar

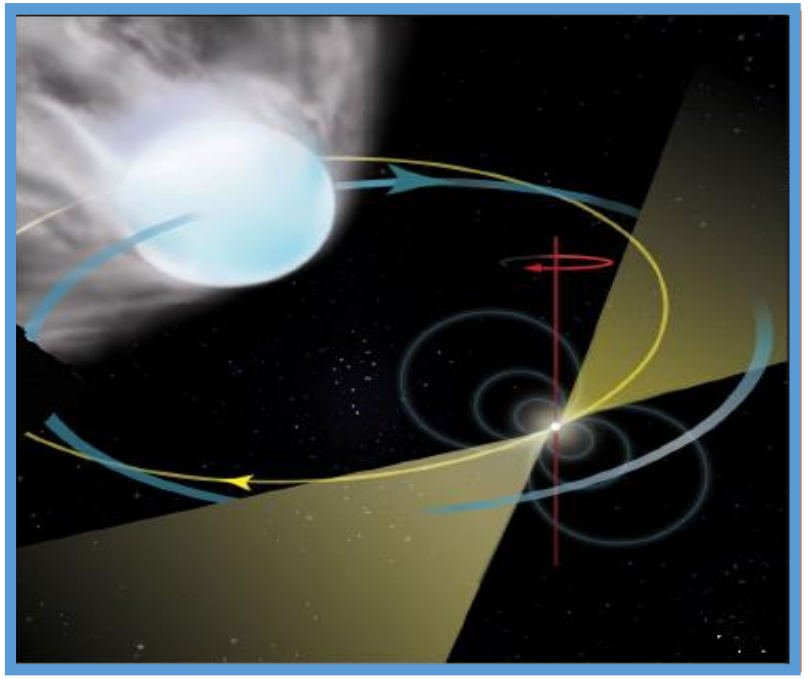


De Falco+ 2017

Mass in-flow rate



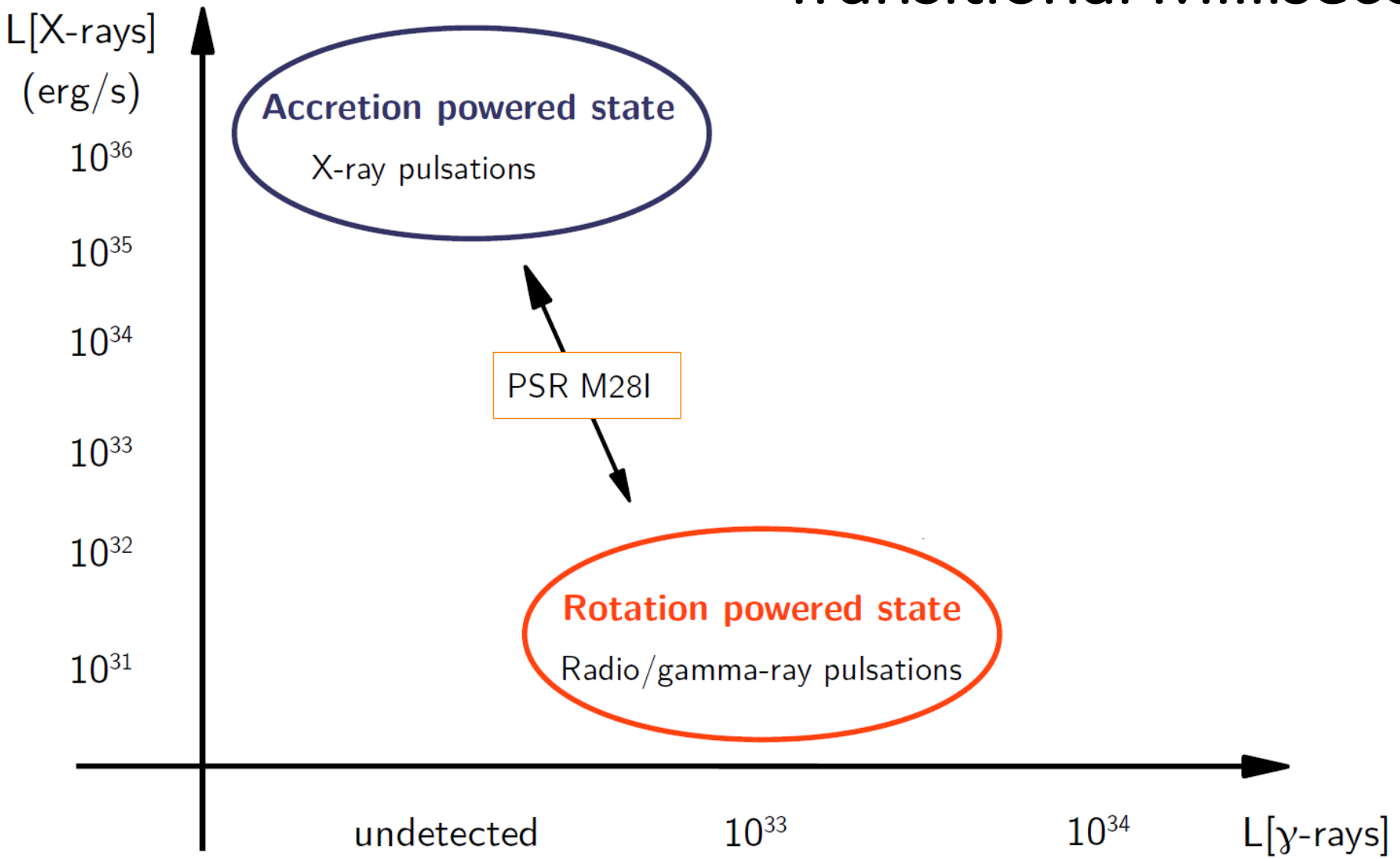
High mass in-flow rate
Gravity dominates
Accretion-powered (X-ray) PSR



Low mass in-flow rate
Pulsar wind dominates
Rotation-powered (radio) PSR

Stella+ 1994; **Campana**+ 1998; **Burderi**+ 2001

Transitional Millisecond Pulsars

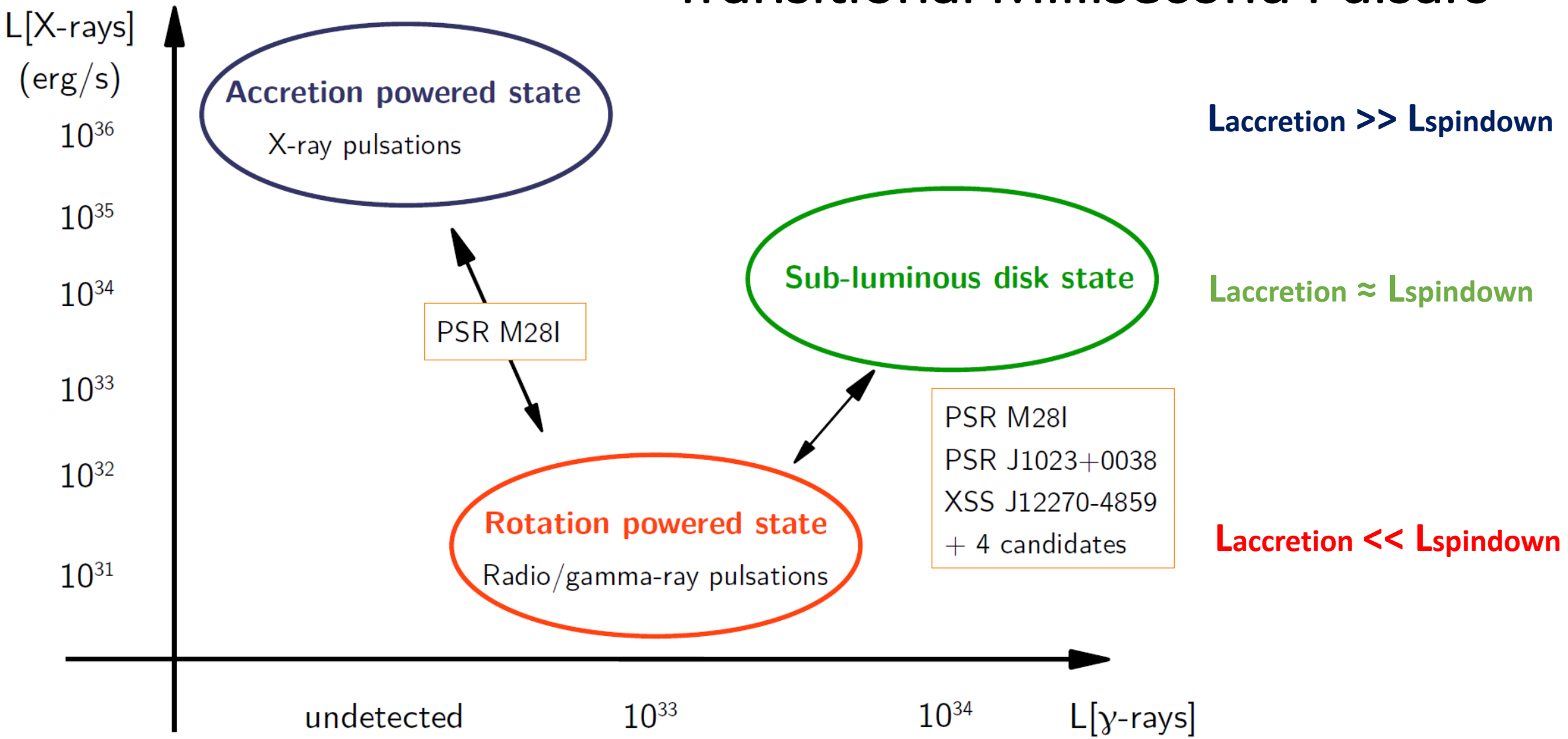


Laccretion >> Lspindown

Laccretion << Lspindown

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

Transitional Millisecond Pulsars



Laccretion >> Lspindown

Laccretion ≈ Lspindown

Laccretion << Lspindown

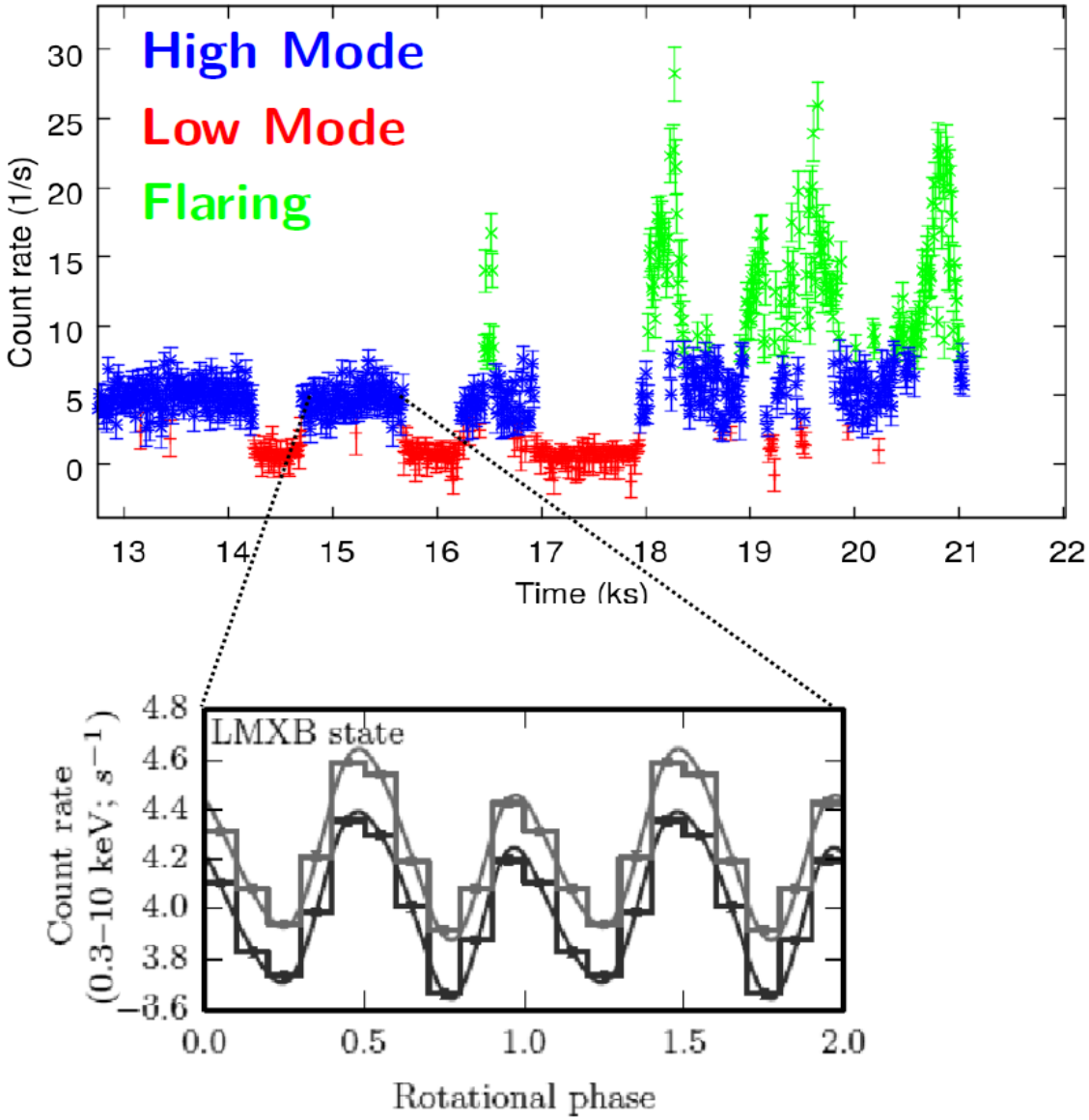
Archibald+ 2009; **Papitto+** 2013; **Bassa+** 2014; **Linares+** 2014; See review by **Papitto & de Martino** 2022

A sub-luminous disk state

Accretion-power features

Disk emission lines

X-ray pulsations & sudden variability



Linares+ 2014**, Patruno**+ 2014, **Bogdanov**+ 2015, **Archibald**+ 2015, **Papitto**+ 2015, **Campana**+ 2016

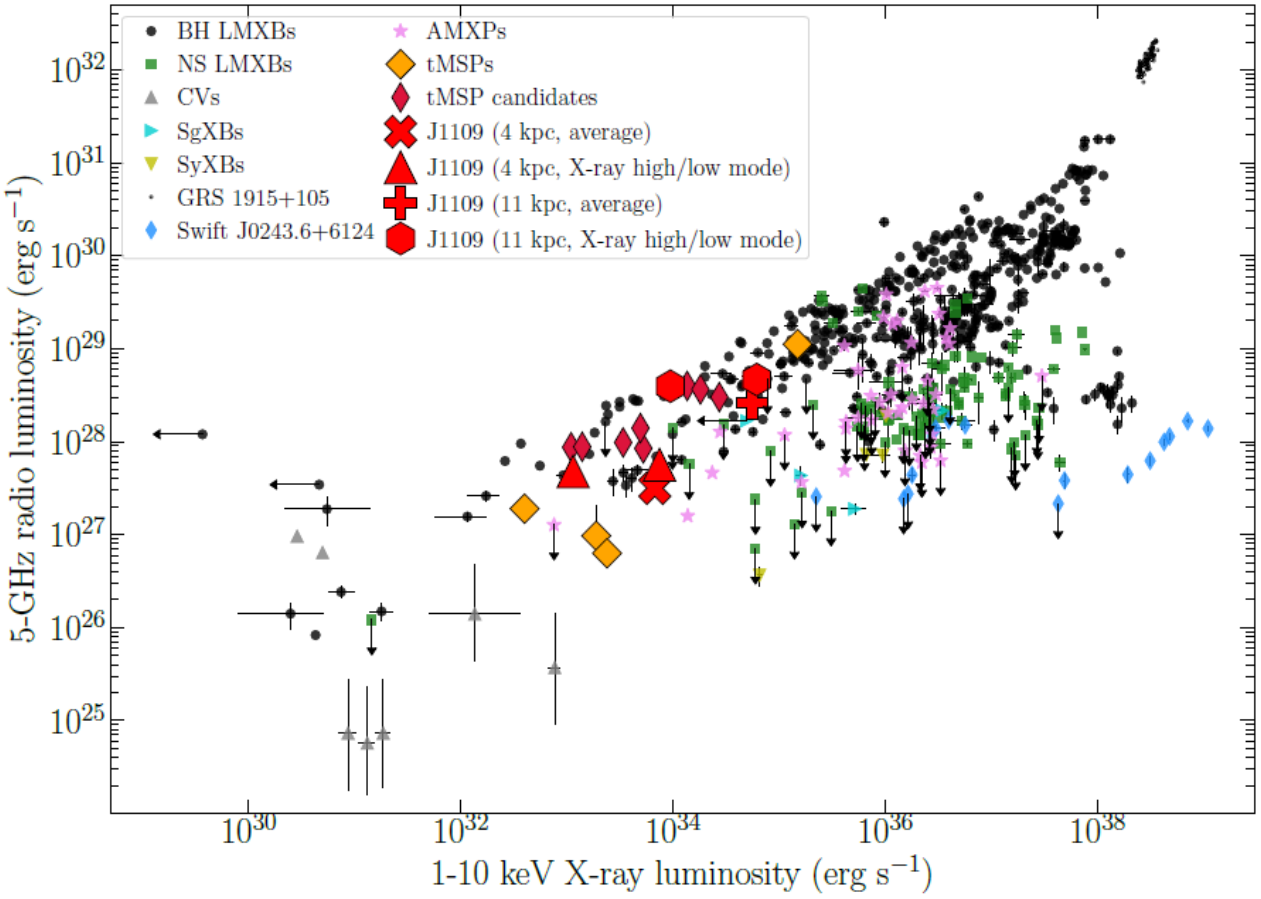
A sub-luminous disk state

Accretion-power features

Disk emission lines

X-ray pulsations & sudden variability

Bright radio jets



Deller+ 2015, **Bogdanov**+ 2018, **Coti Zelati**+ 2021, **Baglio**+ 2023

A sub-luminous disk state

Accretion-power features

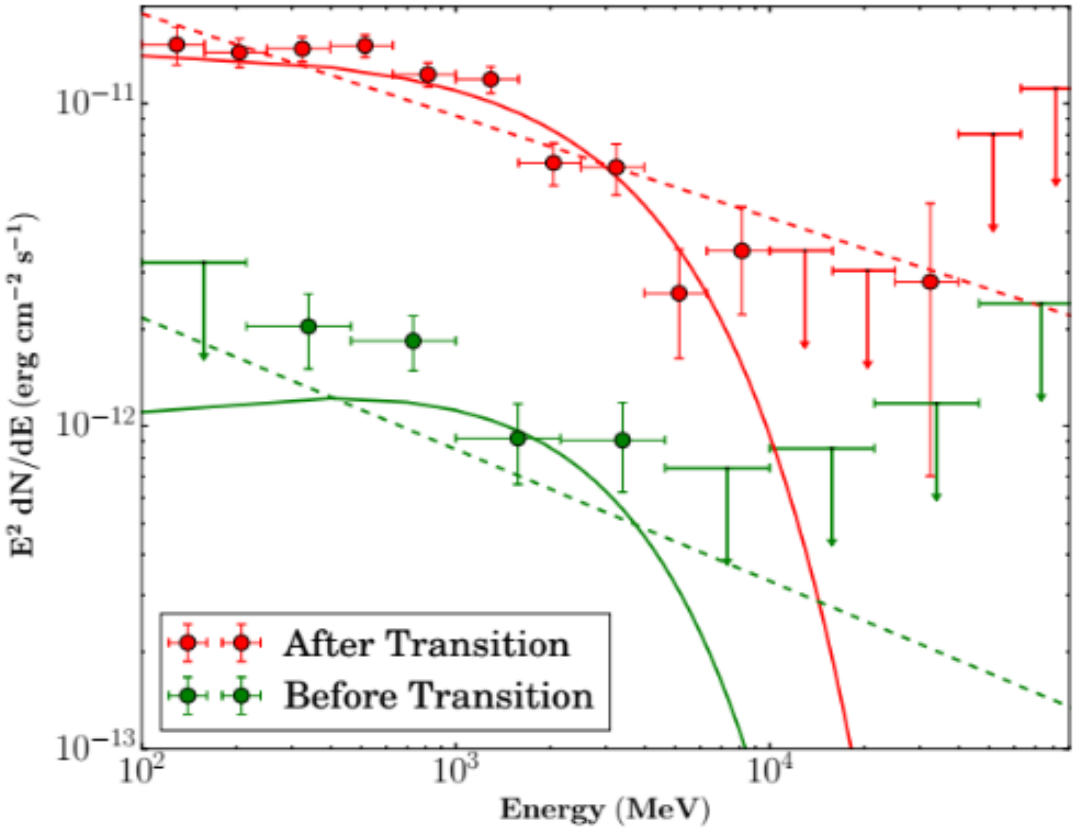
Disk emission lines

X-ray pulsations & sudden variability

Bright radio jets

Rotation-power features

Bright gamma-ray emission



de Martino+ 2010, **Stappers**+ 2014, **Torres**+ 2018

A sub-luminous disk state

Accretion-power features

Disk emission lines

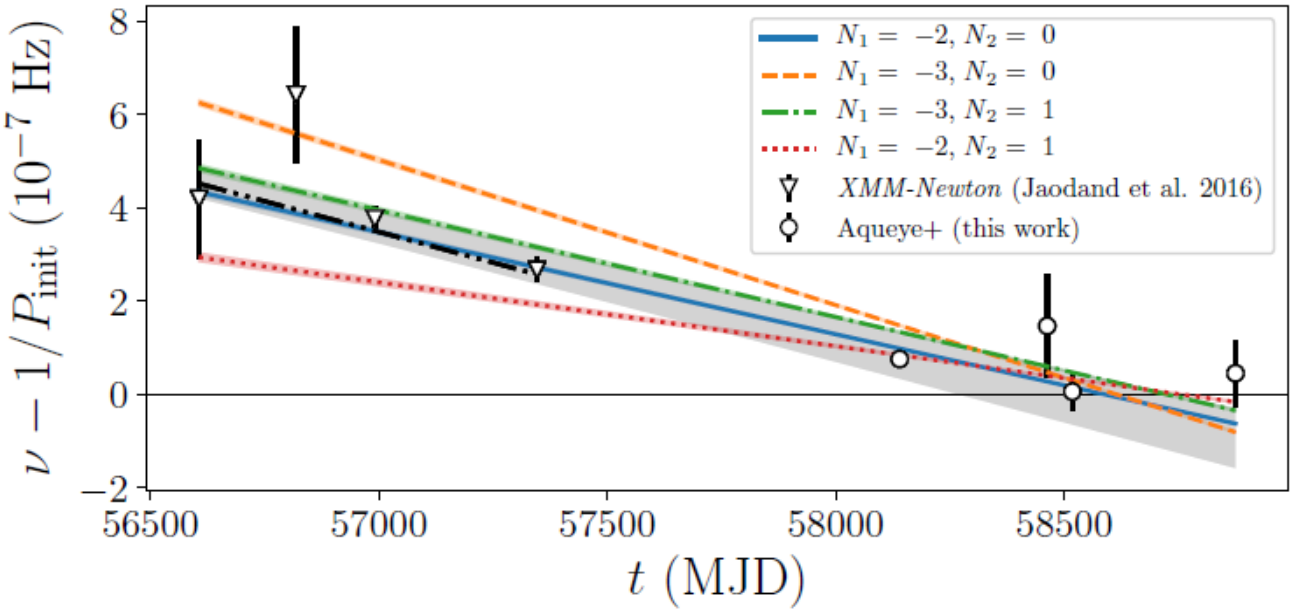
X-ray pulsations & sudden variability

Bright radio jets

Rotation-power features

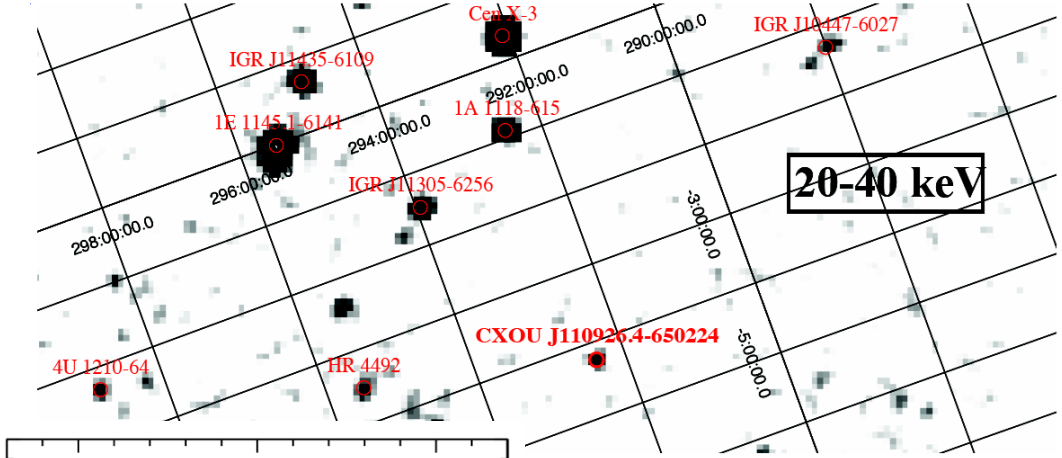
Bright gamma-ray emission

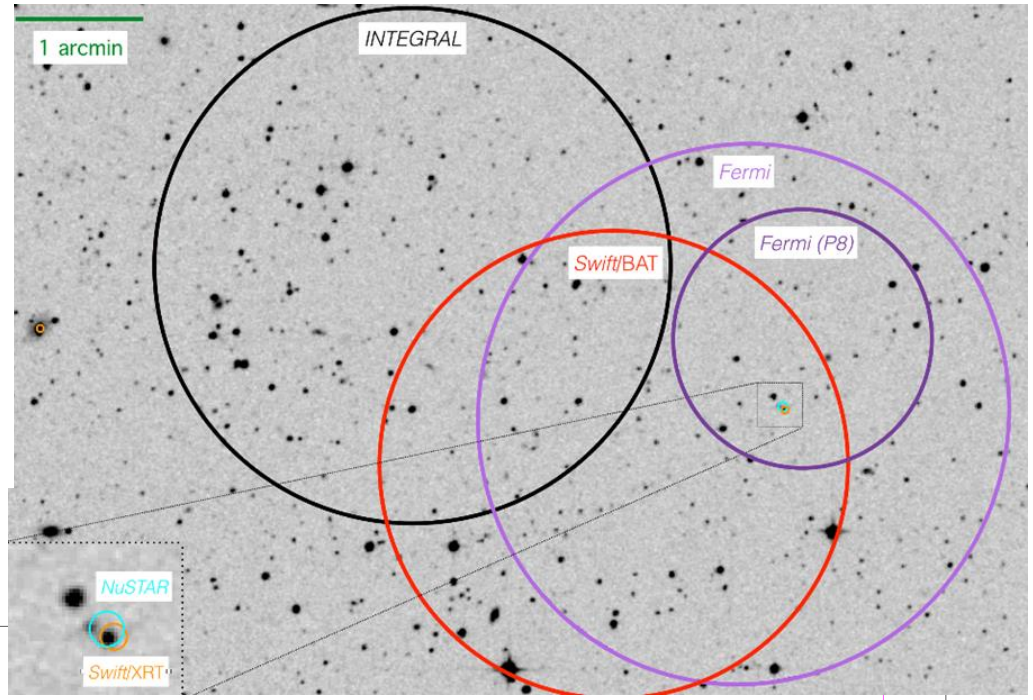
Radio pulsar-like spin down

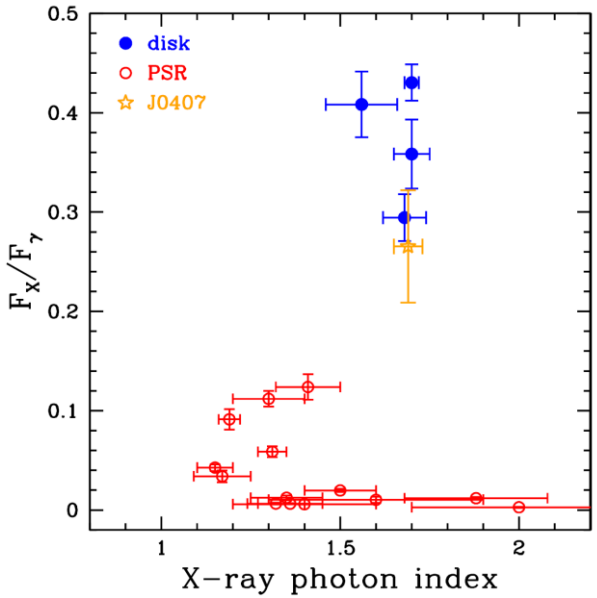


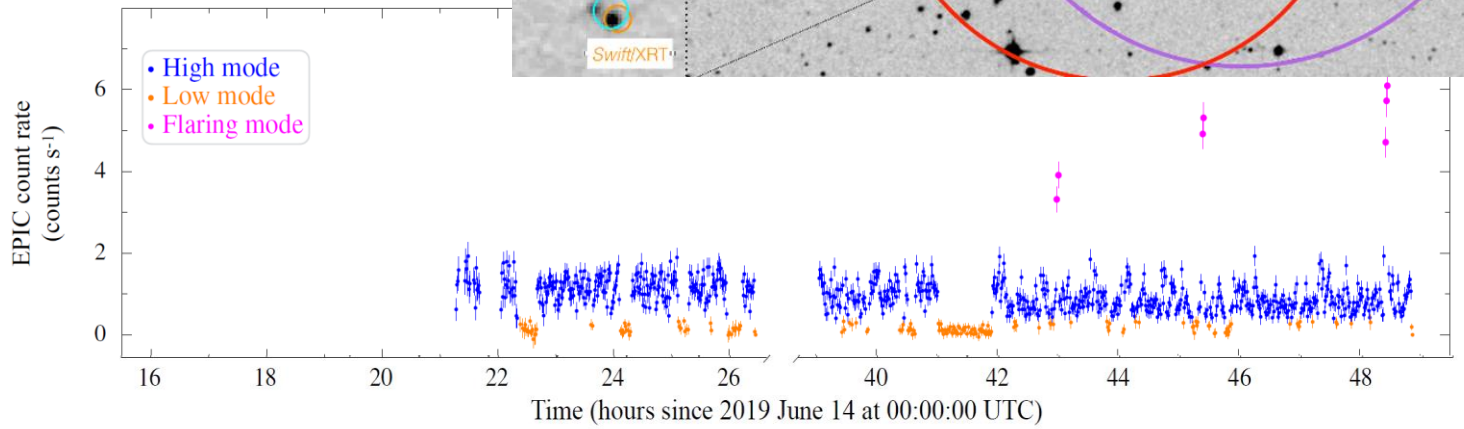
Jaodand+2016, **Burtovoi**+ 2021

How to identify a candidate transitional MSP?







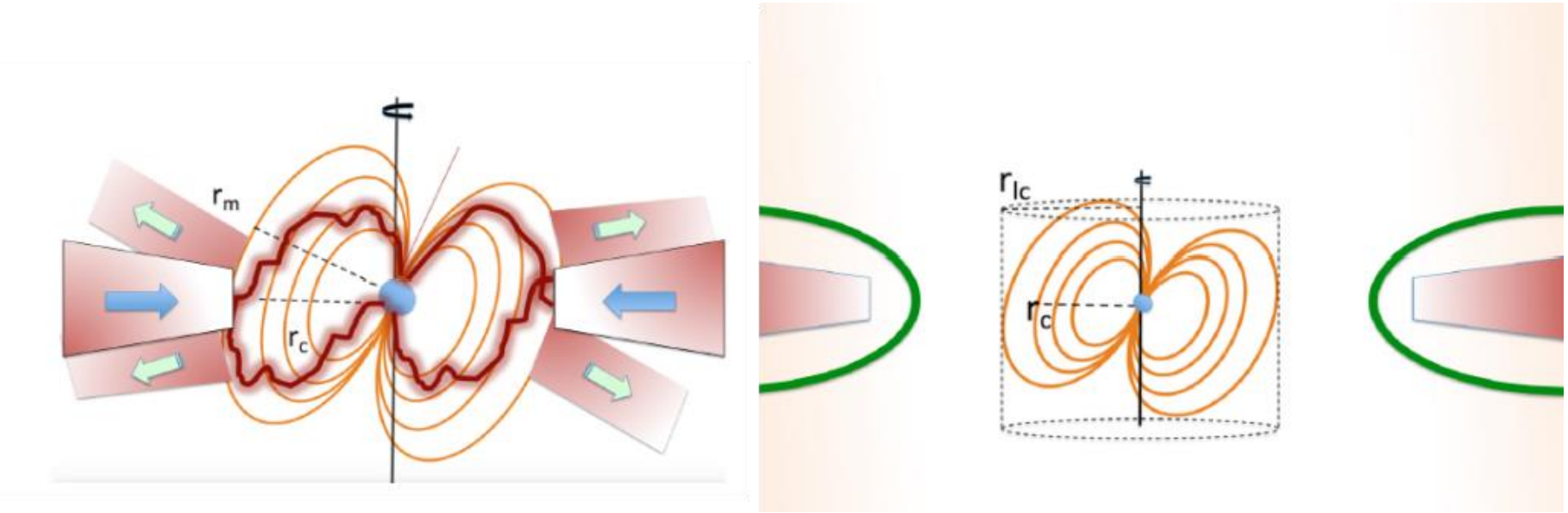


Halpern & Bogdanov 2018; **Miller**+2020, **Coti Zelati**+ 2021

What powers the sub-luminous disk state emission?

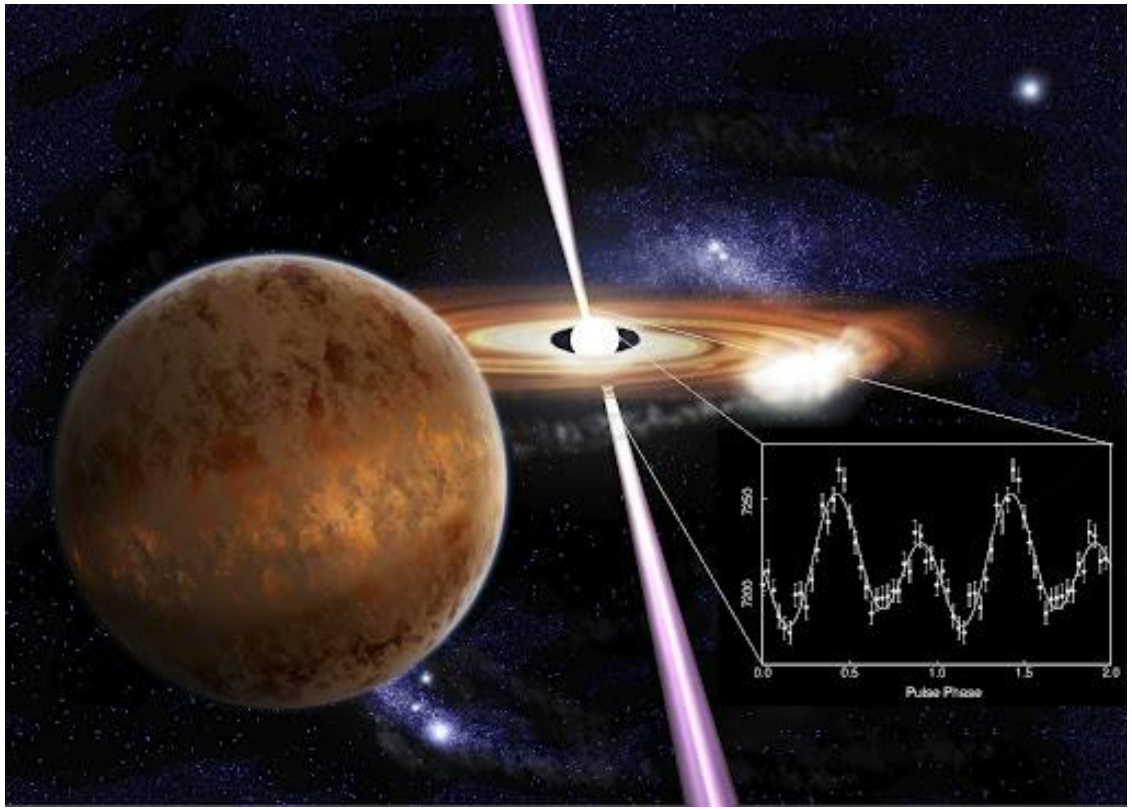
- Enshrouded rotation-pwd pulsar
- Propellering pulsar
- Low Mdot accretion

What drives the high/low mode switching?



Coti Zelati+2014, **Takata**+ 2015, **Papitto**+ 2014, 2015, **Linares**+ 2014, **Campana**+ 2016, **Papitto & de Martino** 2022

Discovery of an Optical/UV transitional millisecond pulsar



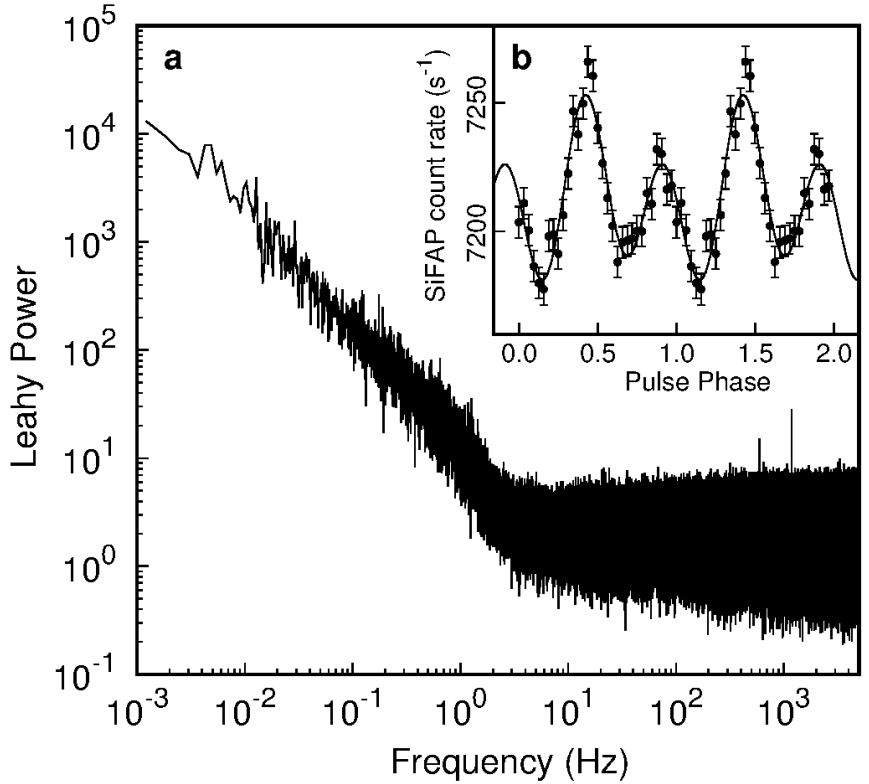
Ambrosino, Papitto+ 2017, Nature Astr.; **Zampieri+** 2019; **Karpov+** 2019; **Miraval Zanon+** 2022

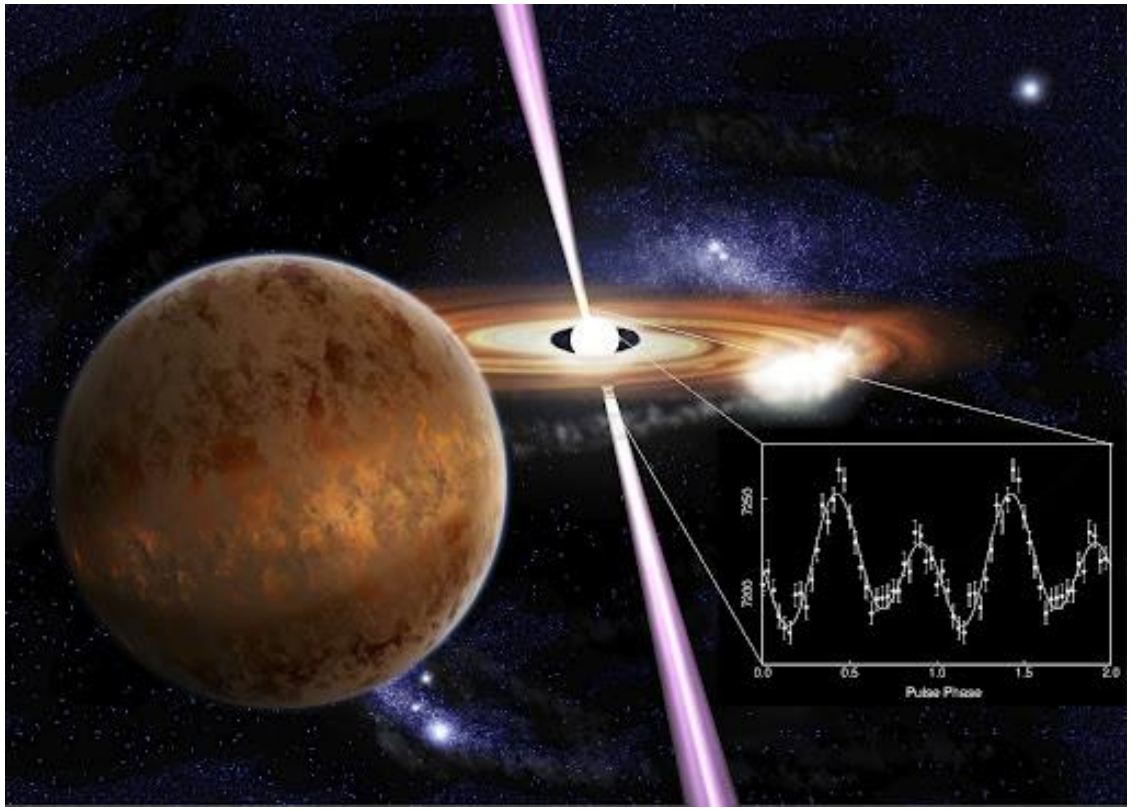
Discovery of an Optical/UV transitional millisecond pulsar

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

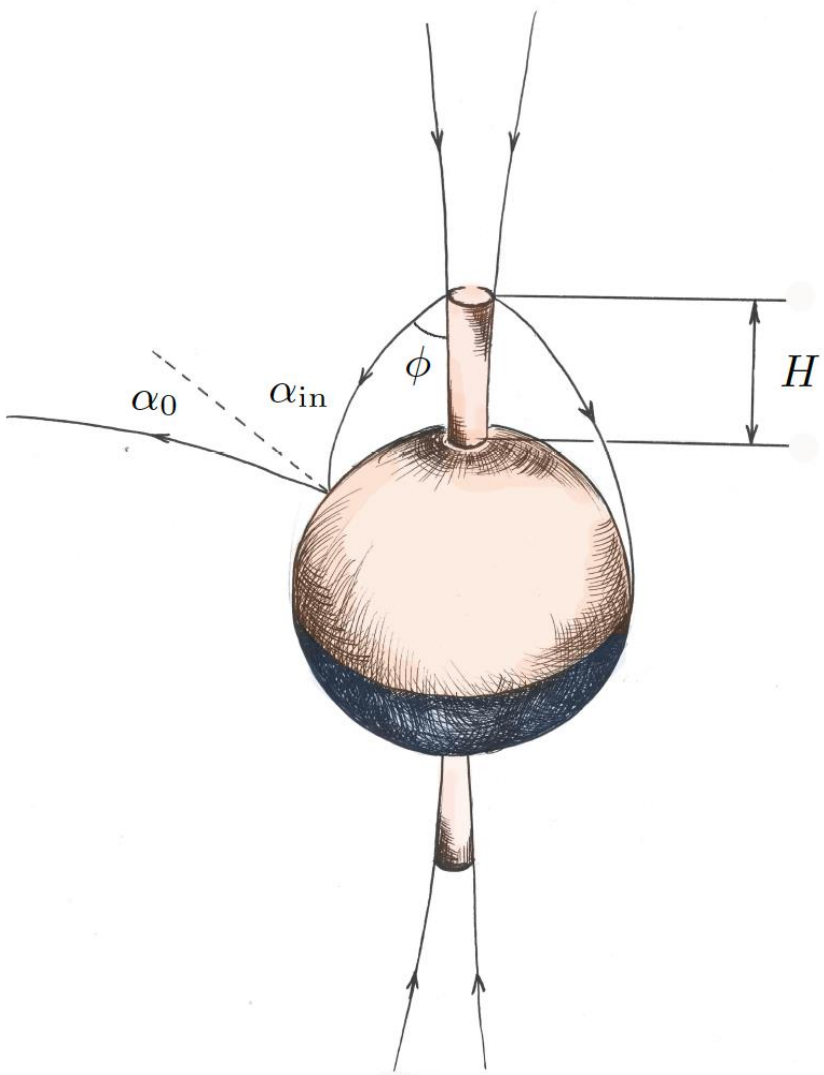
Stunningly bright optical pulsations accretion-powered?

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?

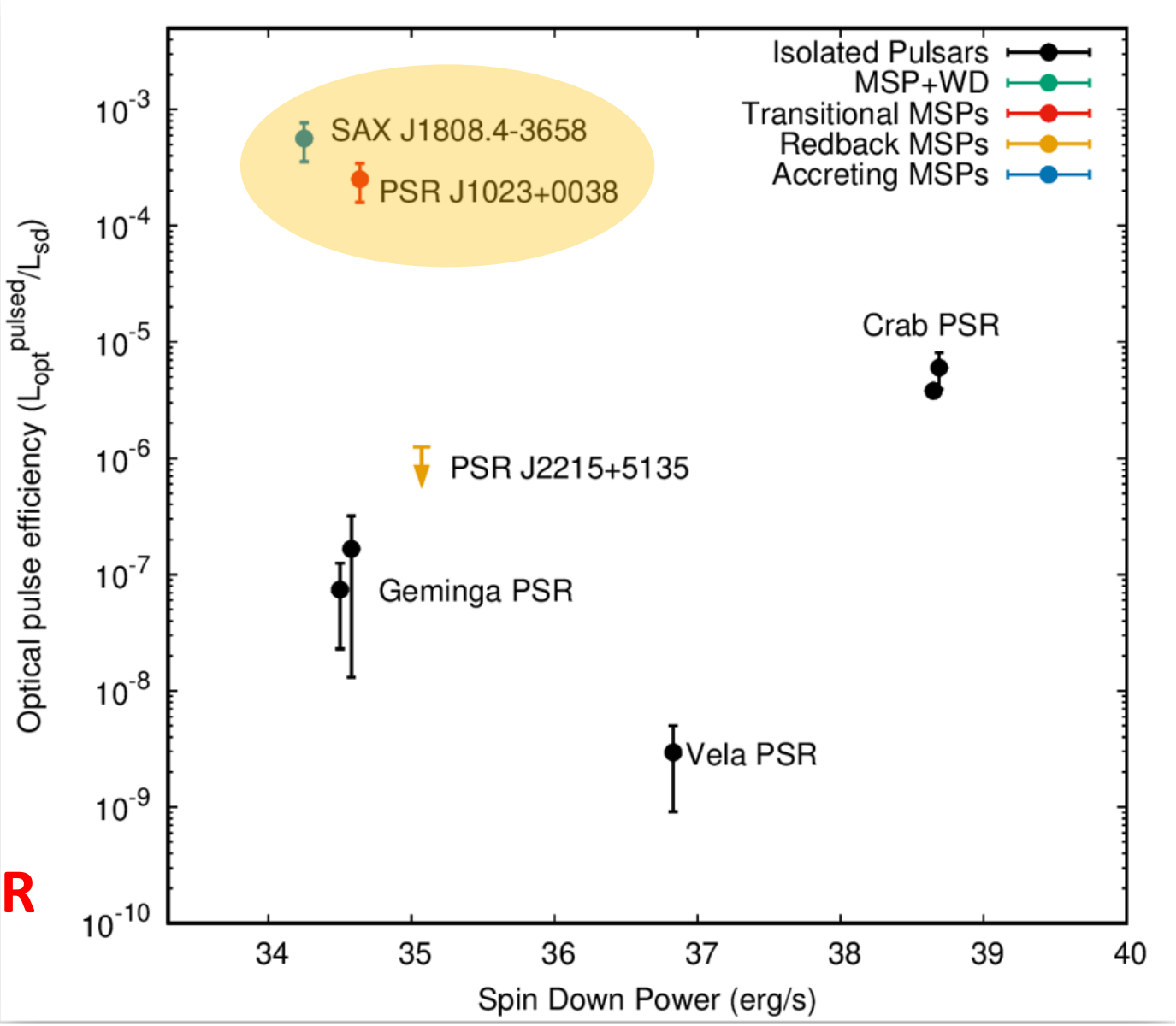
Radio pulsars

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

PSR J1023

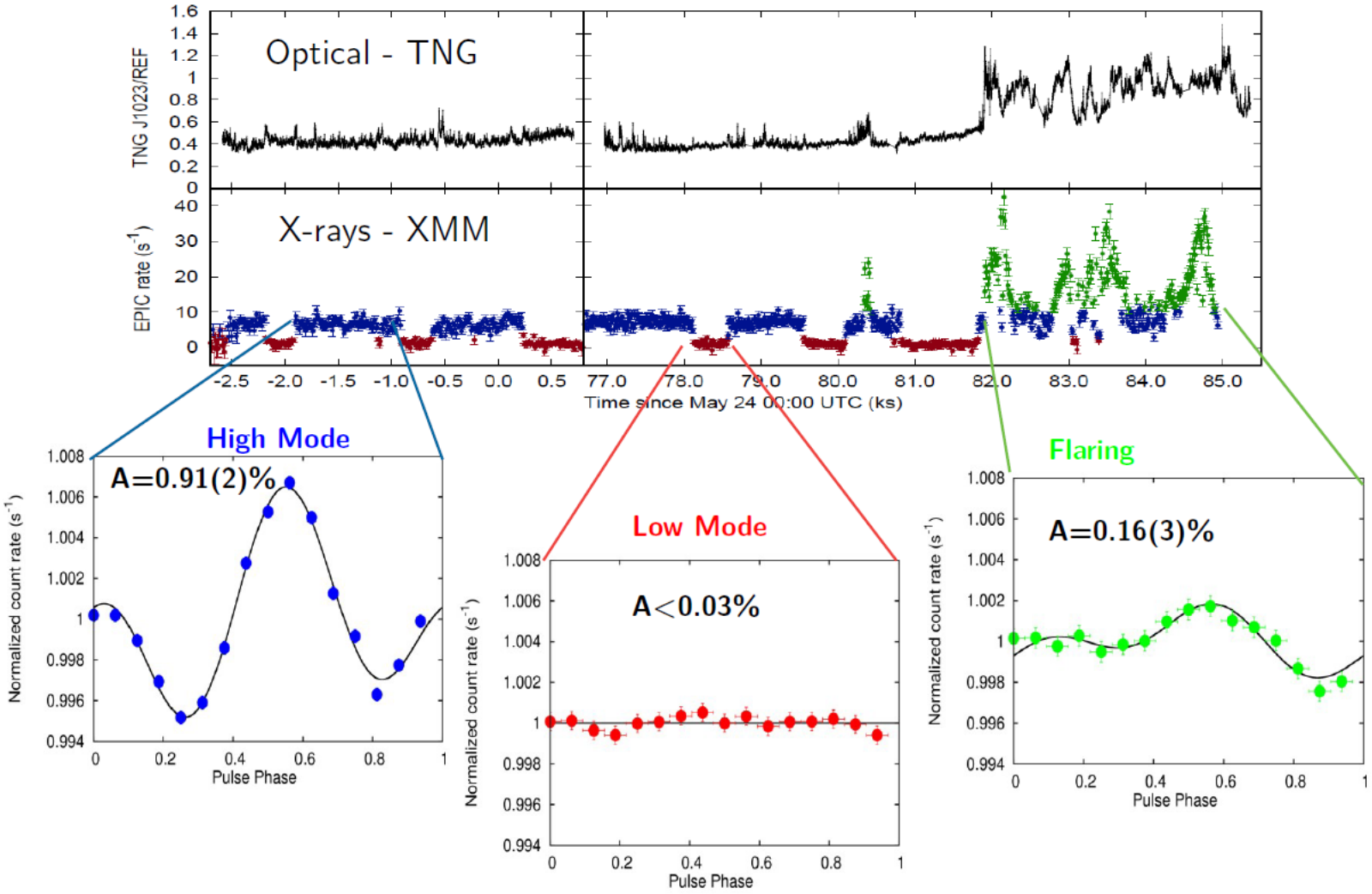
$L = 2x10^{-4}$ L_{sd}

>50x more efficient than Crab PSR



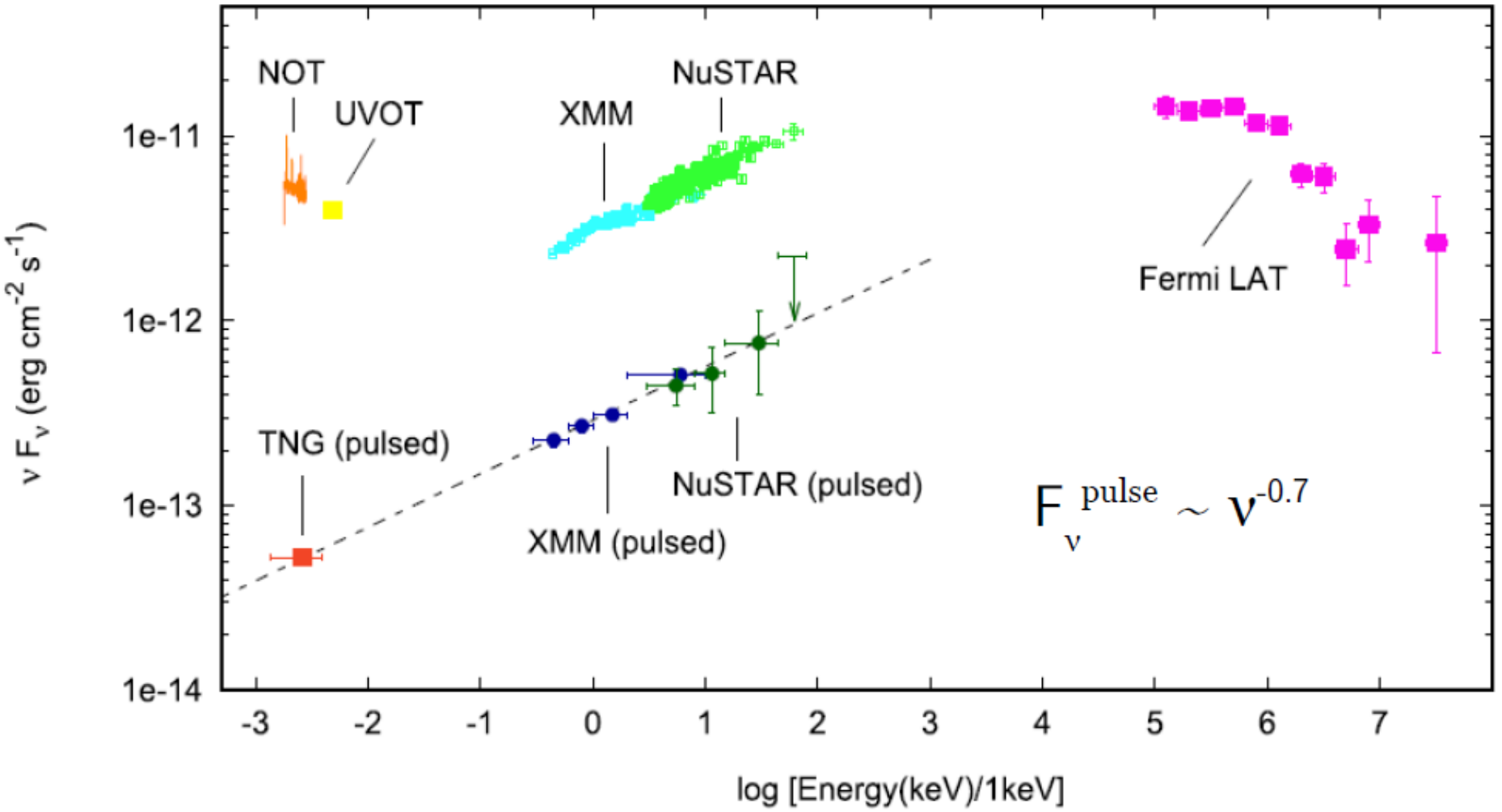
Ambrosino, Papitto+ 2017, Nature Astr.; **Ambrosino, Miraval Zanon, Papitto** et al. 2021, Nature Astr.

Pulsating in unison at optical and X-ray energies



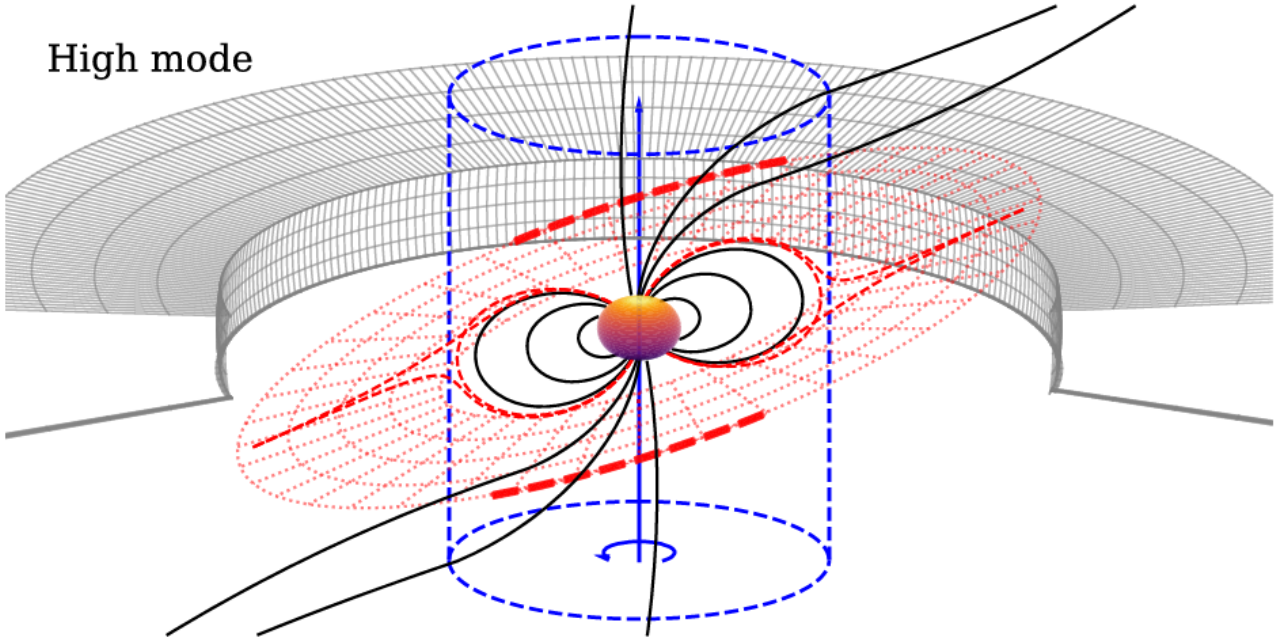
Papitto+ 2019; **Illiano+** 2023

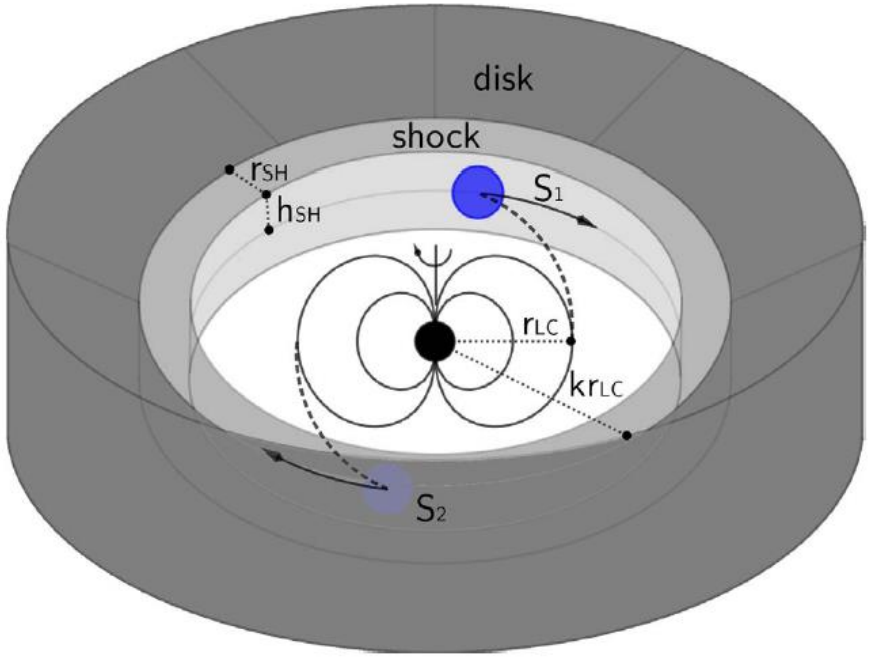
Pulsating in unison at optical and X-ray energies



Papitto+ 2019; **Miraval Zanon+** 2022

Coexistence of Rotation & Accretion-power



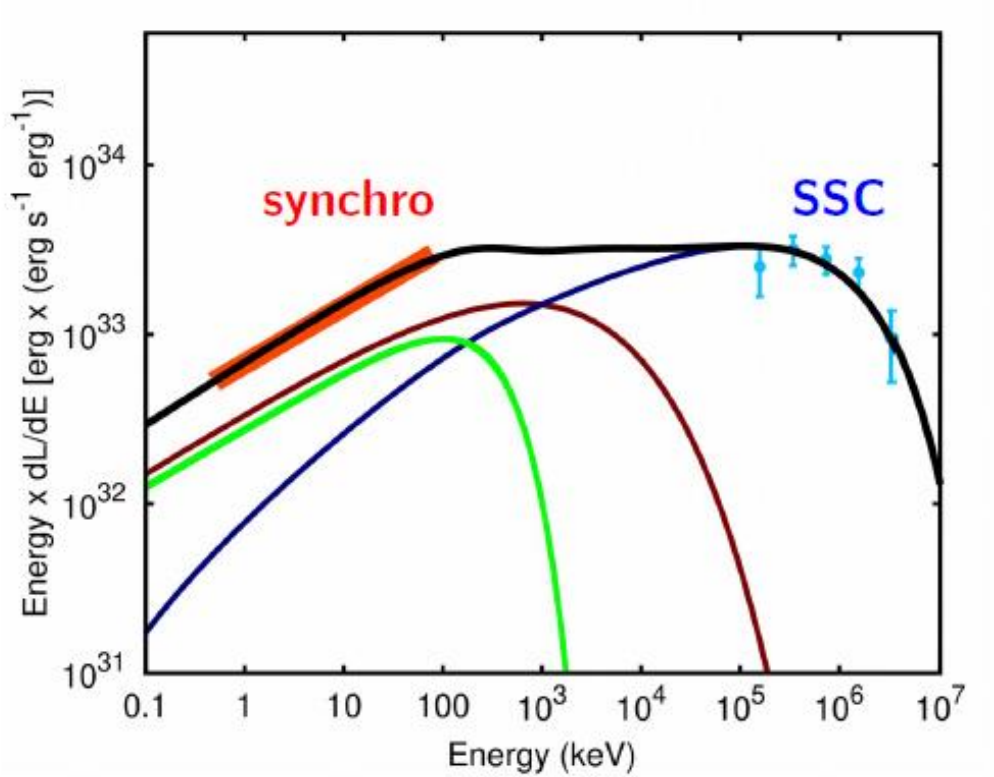


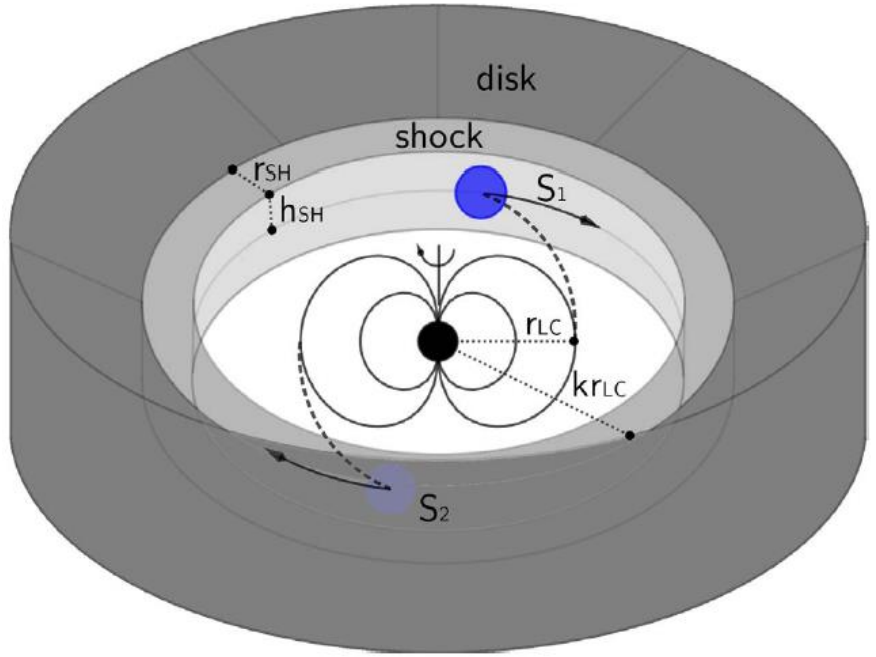
Veledina, Nättila, Beloborodov 2019; **Papitto+** 2019

Coexistence of Rotation & Accretion-power

Synchrotron → Optical/X-rays

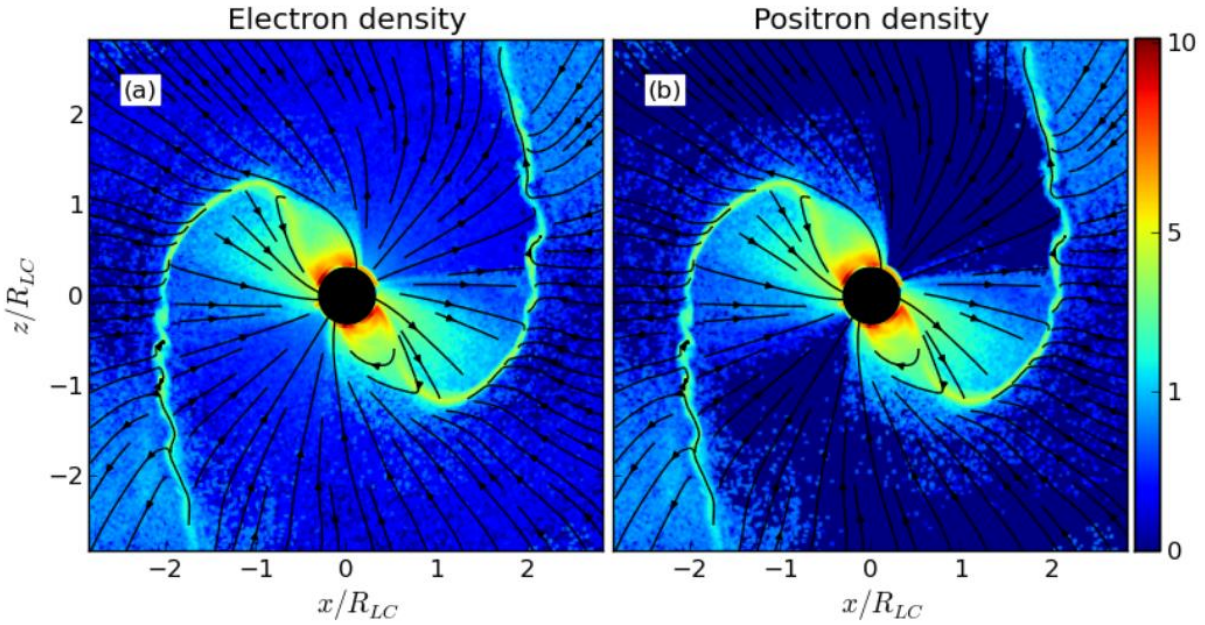
Self Synchrotron Compton → Gamma-rays





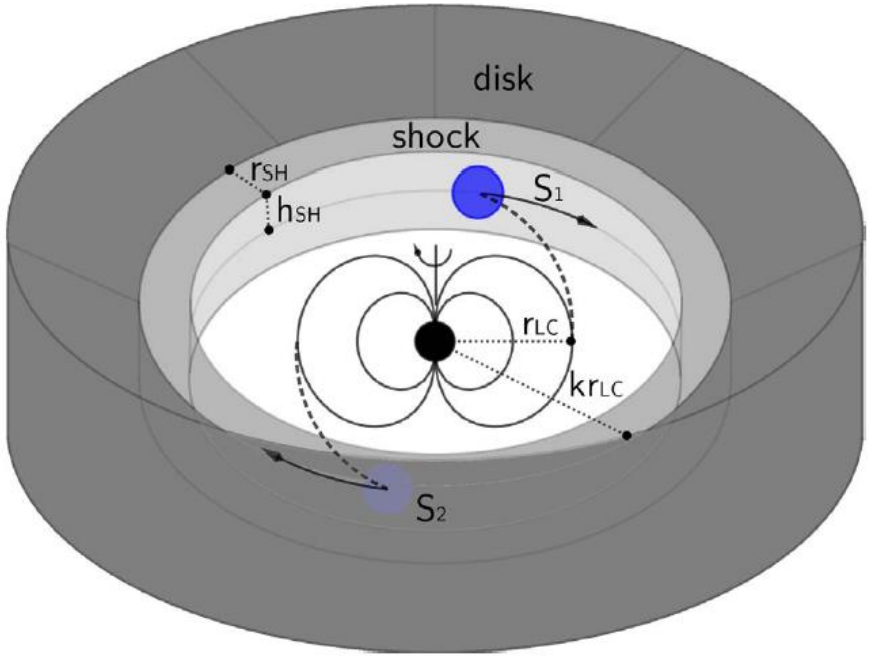
Veledina, Nättila, Beloborodov 2019; **Papitto+** 2019

Coexistence of Rotation & Accretion-power



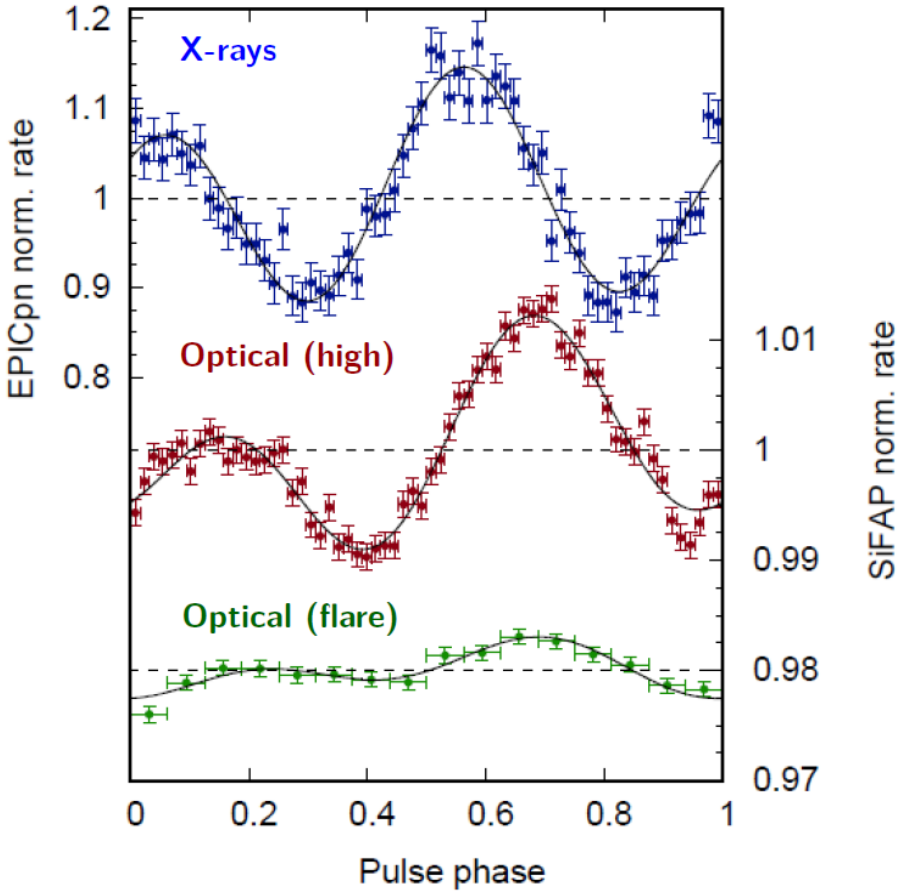
Optical and X-ray pulses from the interaction between the **pulsar striped wind** and the termination shock

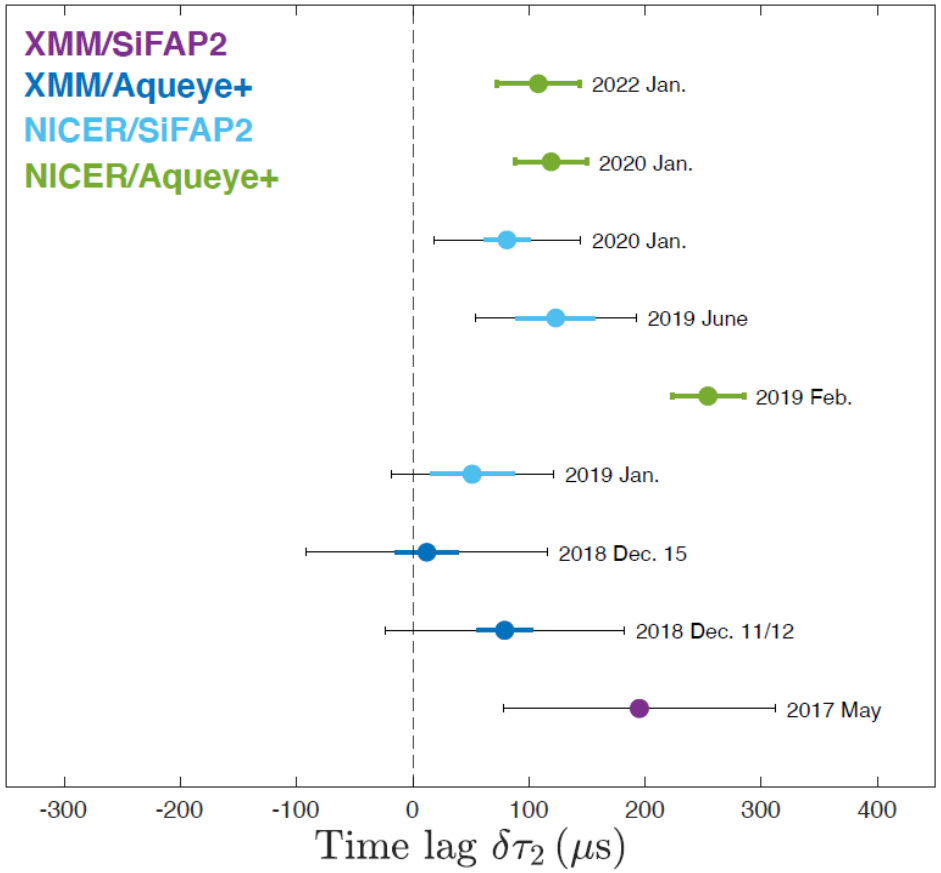
Pulsar wind terminated by the accretion disk at r≈100 km



Cerutti & Beloborodov 2017; **Papitto**+ 2019

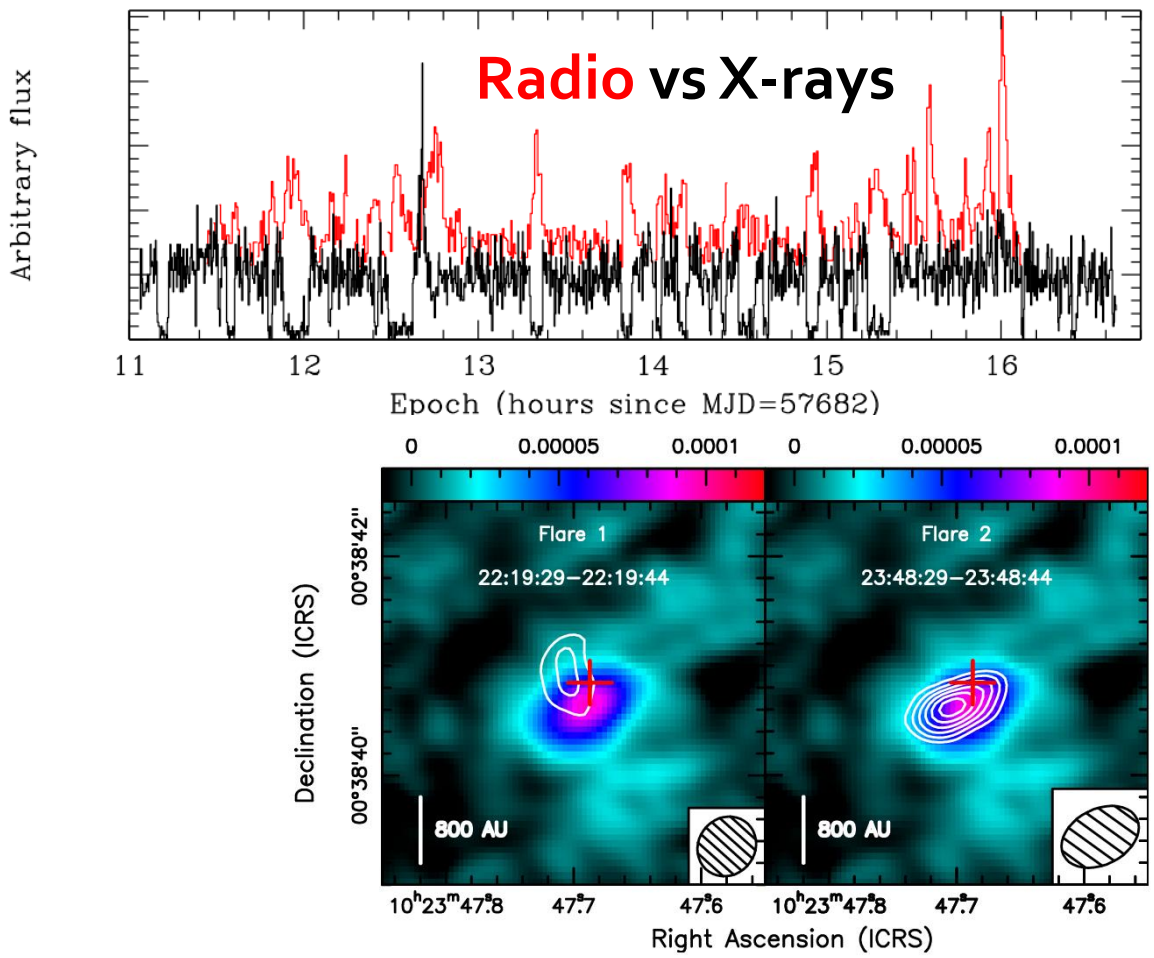
Optical pulses lag X-ray pulses by 100-200s

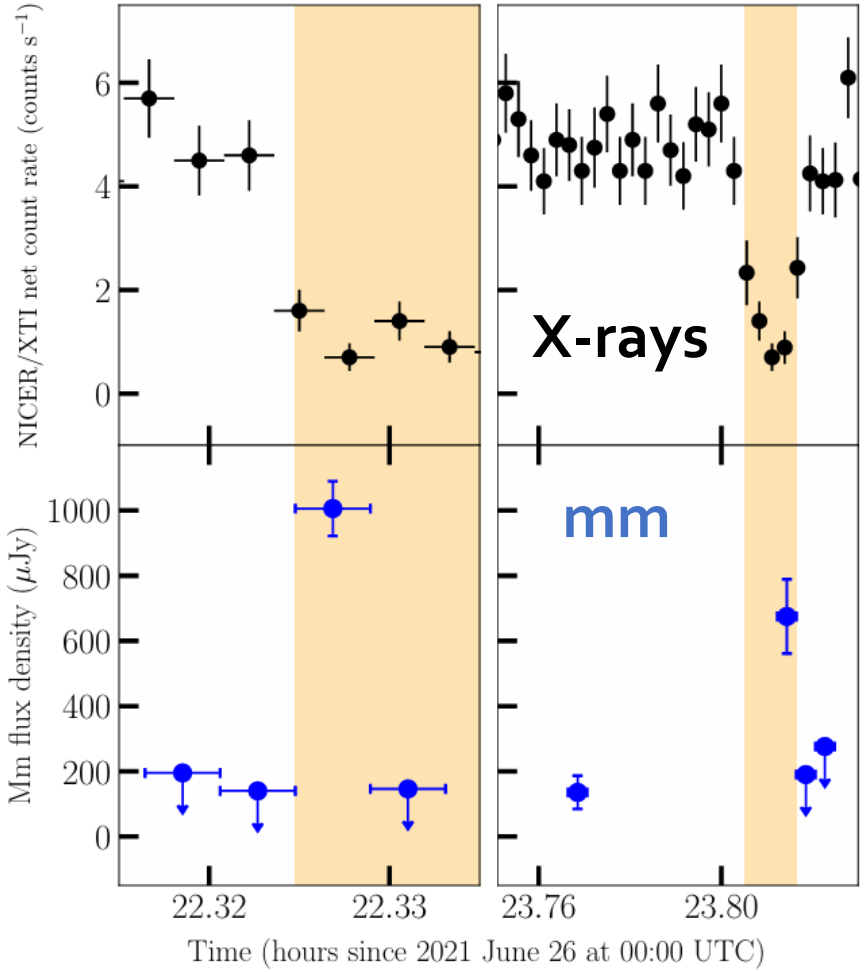




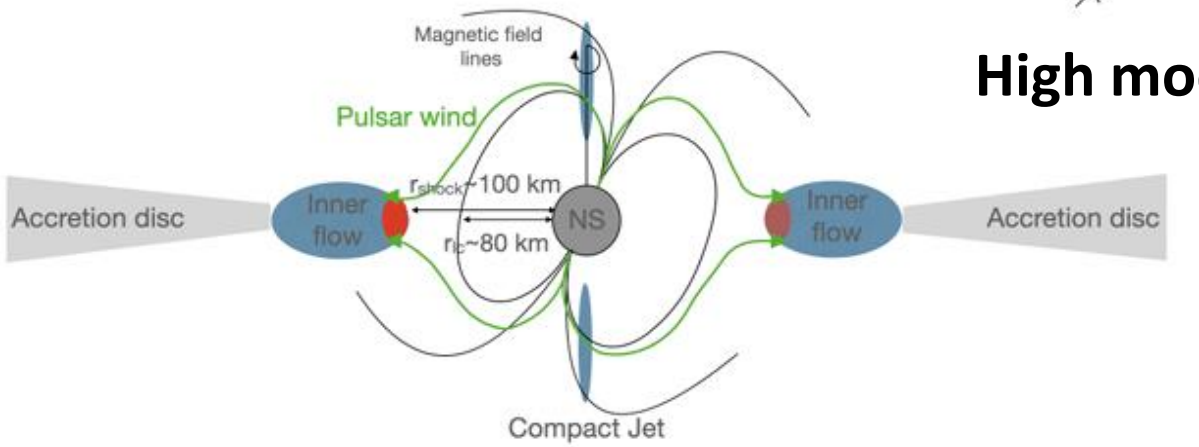
Papitto+ 2019; **Illiano, Papitto+** 2023

Radio and mm flares during X-ray low modes

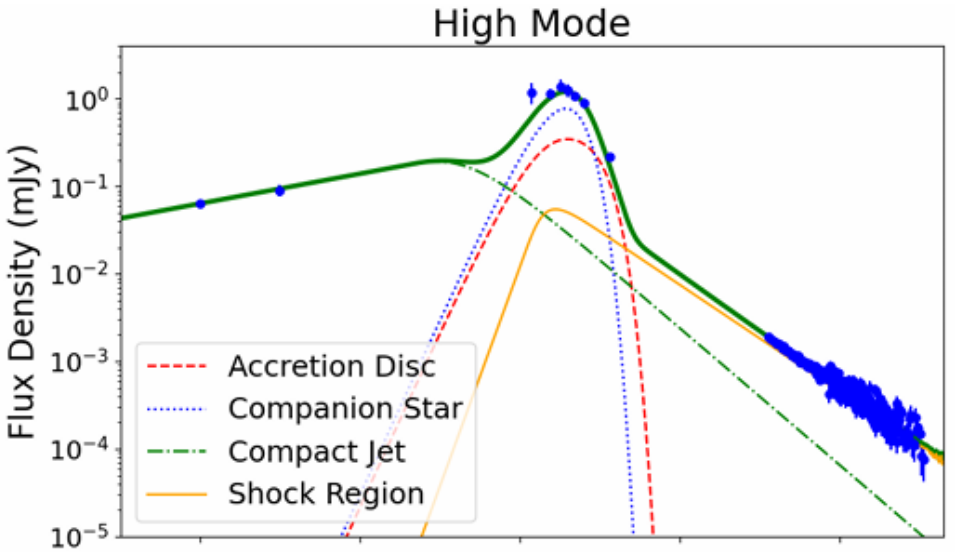


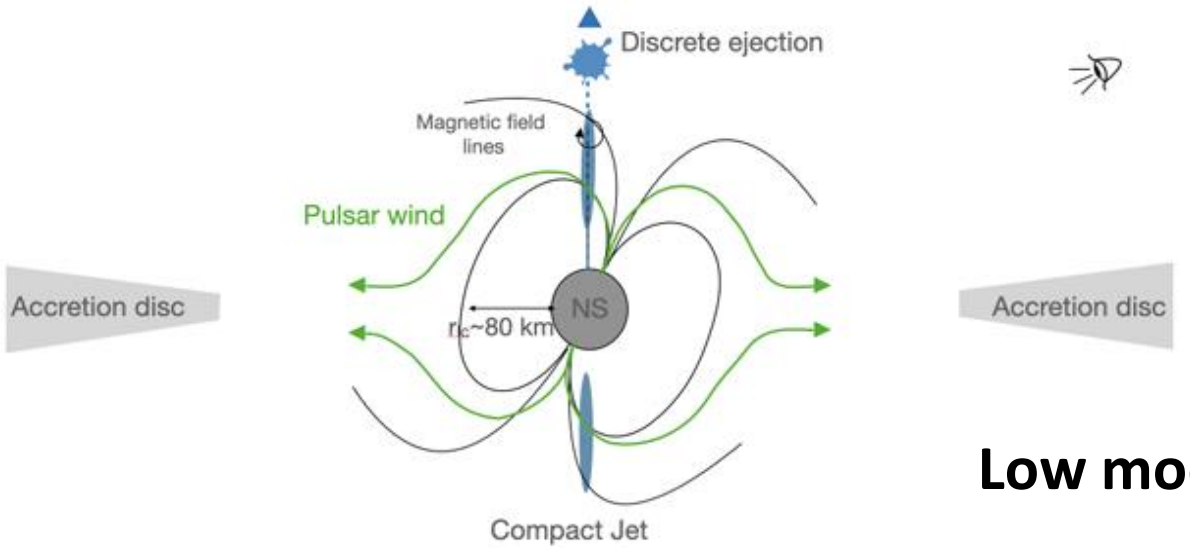


Bogdanov+ 2018; **Baglio+** 2023

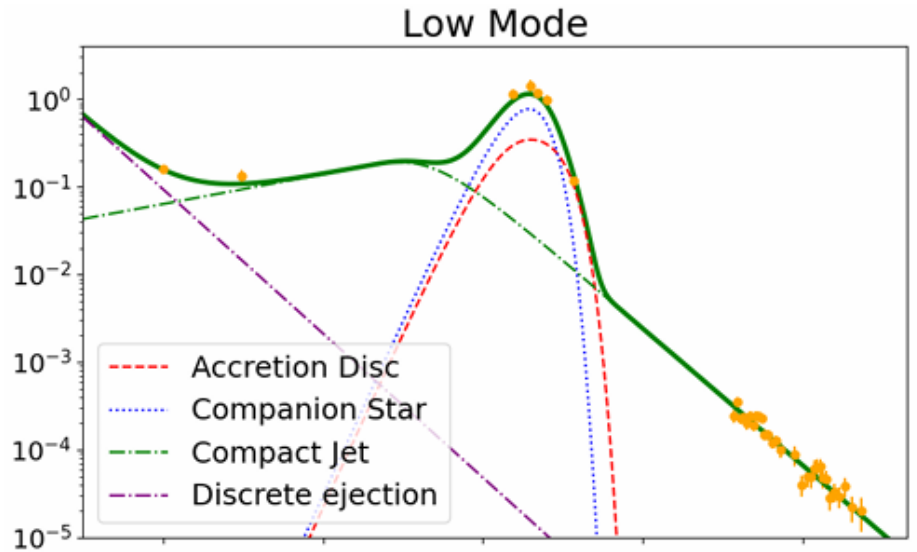


High mode



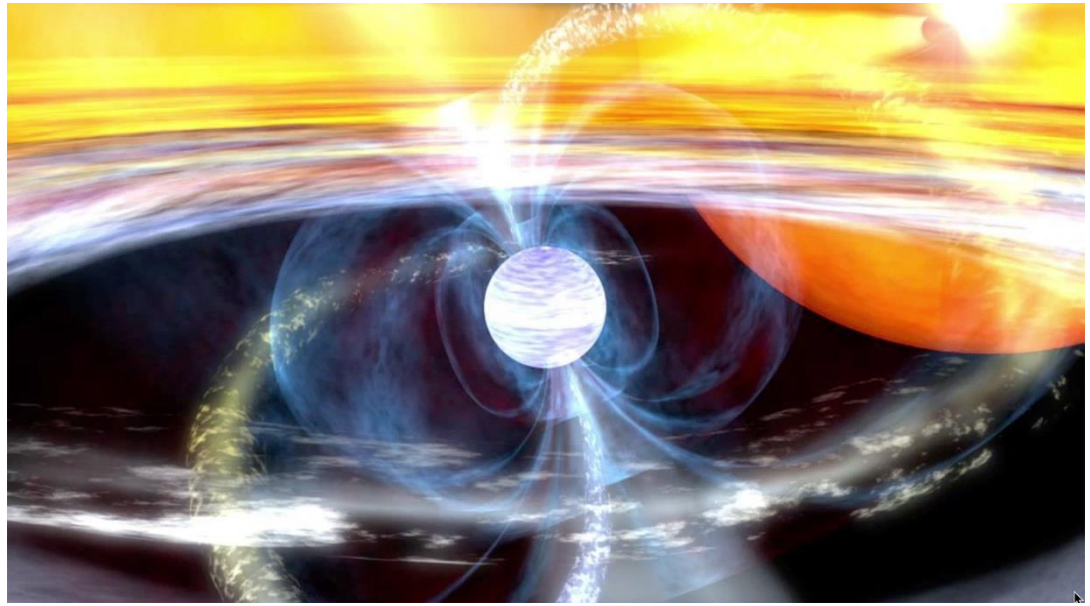


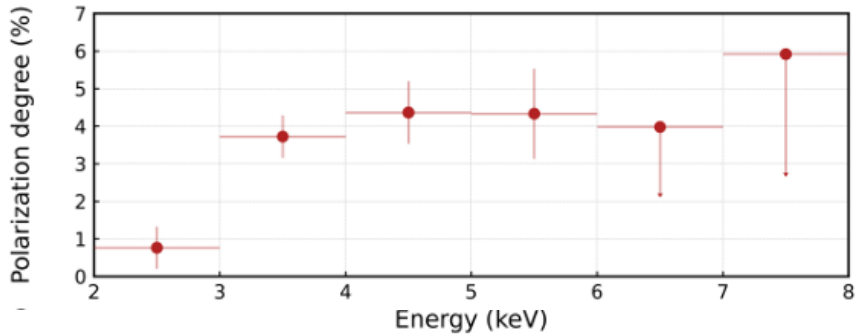
Low mode

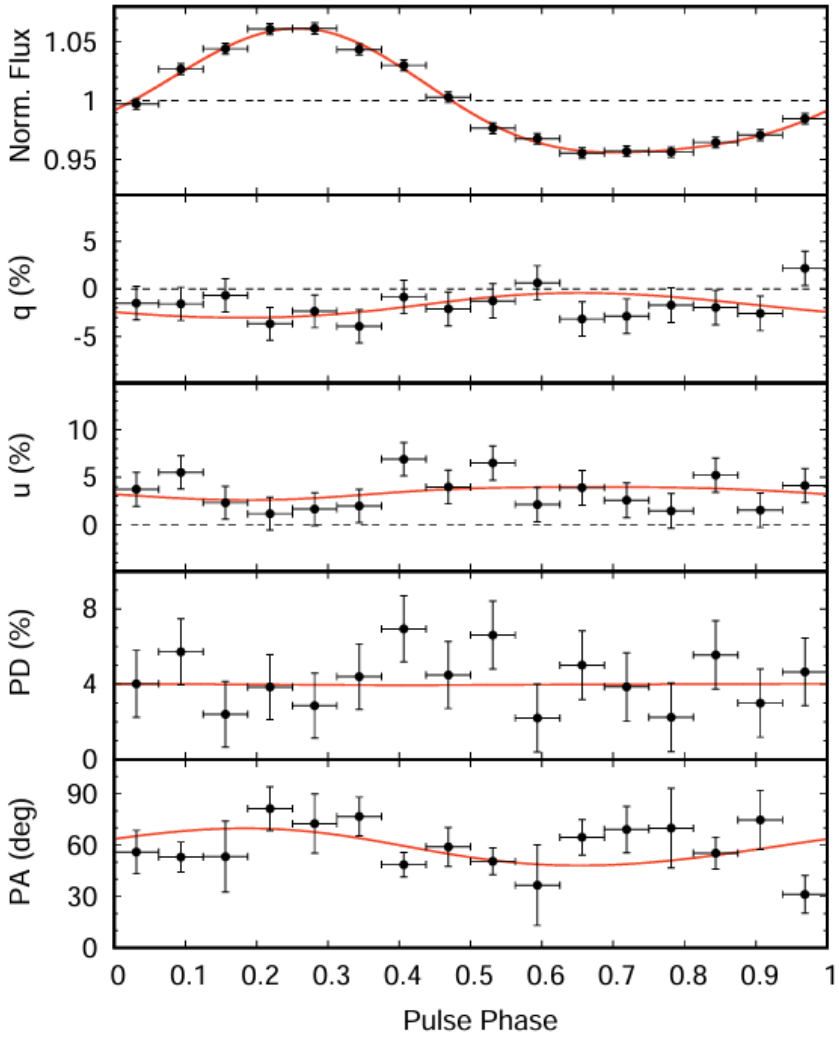


Papitto+ 2019; **Baglio+** 2023; **Baglio**+ 2024 in prep.

X-ray polarization from an accreting ms pulsar







Papitto+ 2024, arXiv:[2408.00608]

Summary

So far, accretion outburst & radio pulsations in quiescence seen **only in IGR J18245-2452**

Sub-luminous disk state of transitionals suggest **coexistence of rotation and accretion power**

A rotation-powered pulsar surrounded by accretion matter close to the light-cylinder radius
(a **scaled down pulsar wind nebula**?)

The MSP@OAR team

www. oa-roma.inaf.it/heag

Filippo Ambrosino, Caterina Ballocco, Giulia Illiano, Riccardo La Placa, Christian Malacaria, Arianna Miraval Zanon, Alessandro Papitto

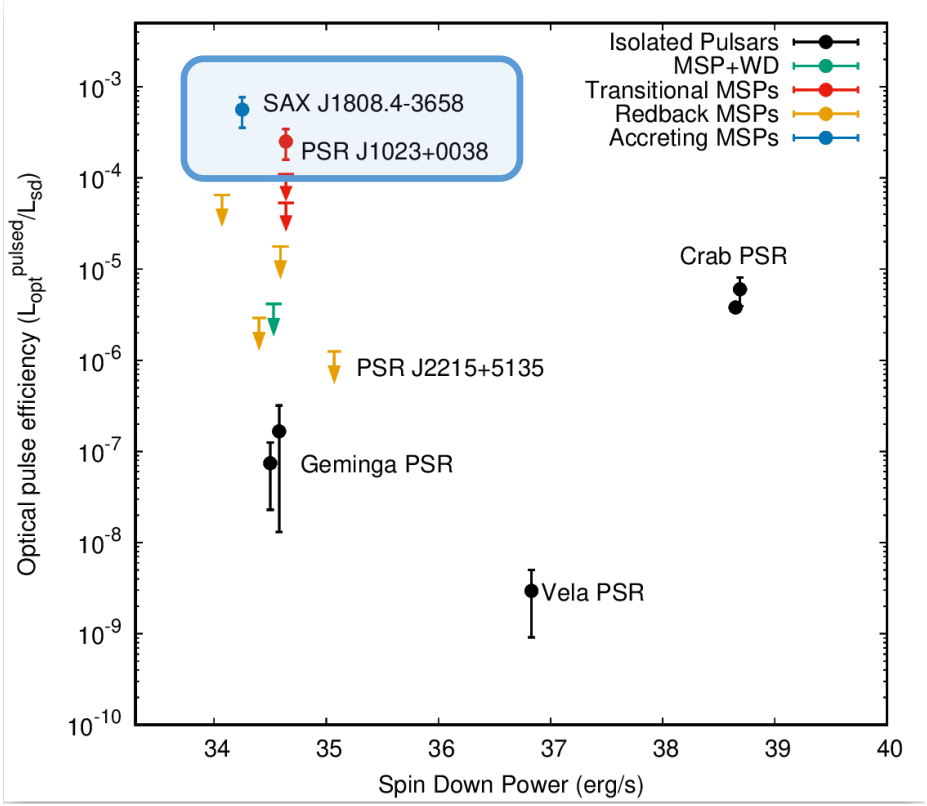
Supprted by PRIN MUR 2020 (GEMS - 2020BRP57Z) & INAF Large Grant (FANS)

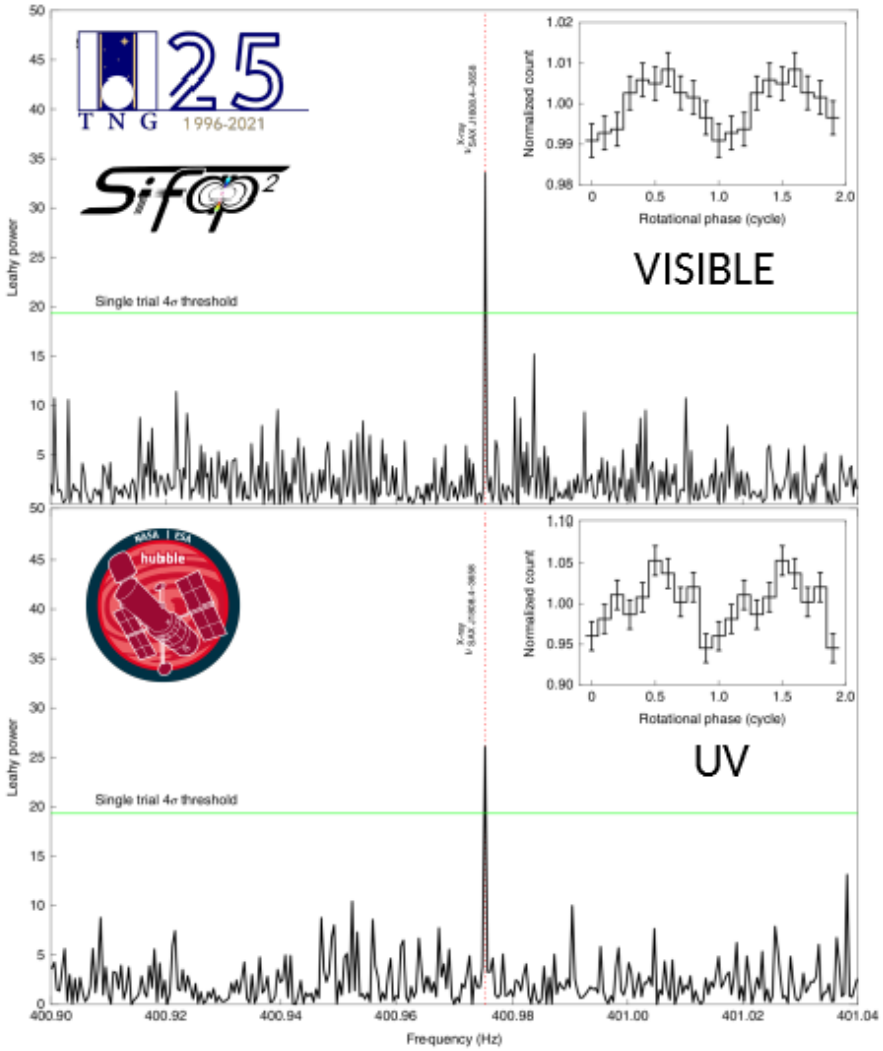
Optical and UV pulsed emission from an Accreting millisecond pulsar

SAX J1808.4-3658 – August 2019 outburst

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

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





Ambrosino, Miraval Zanon, Papitto+ 2021, Nature Astr.; Ballocco, Papitto+ 2024, in prep.