The interaction between the relativistic pulsar wind and the accretion flow in transitional systems

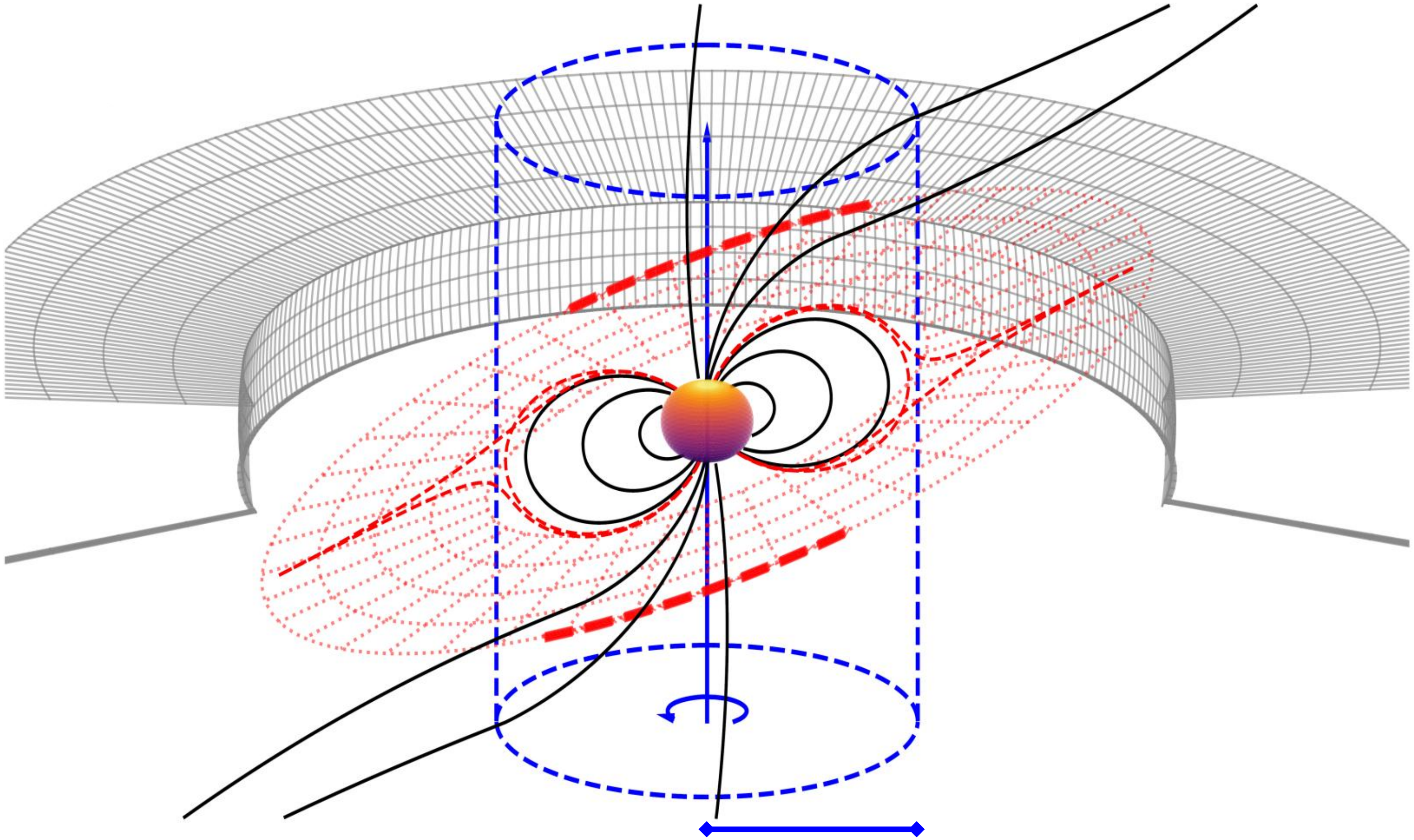
Alessandro Papitto

OA Roma

Feeling the pull and pulse of relativistic magnetospheres

Les Houches 10.4.2025

A millisecond pulsar surrounded by an accretion disk



$P = 1.6$ ms

$B_0 = 10^8$ G

$L_{sd} = 4.4\text{x}10^{34}$ erg/s

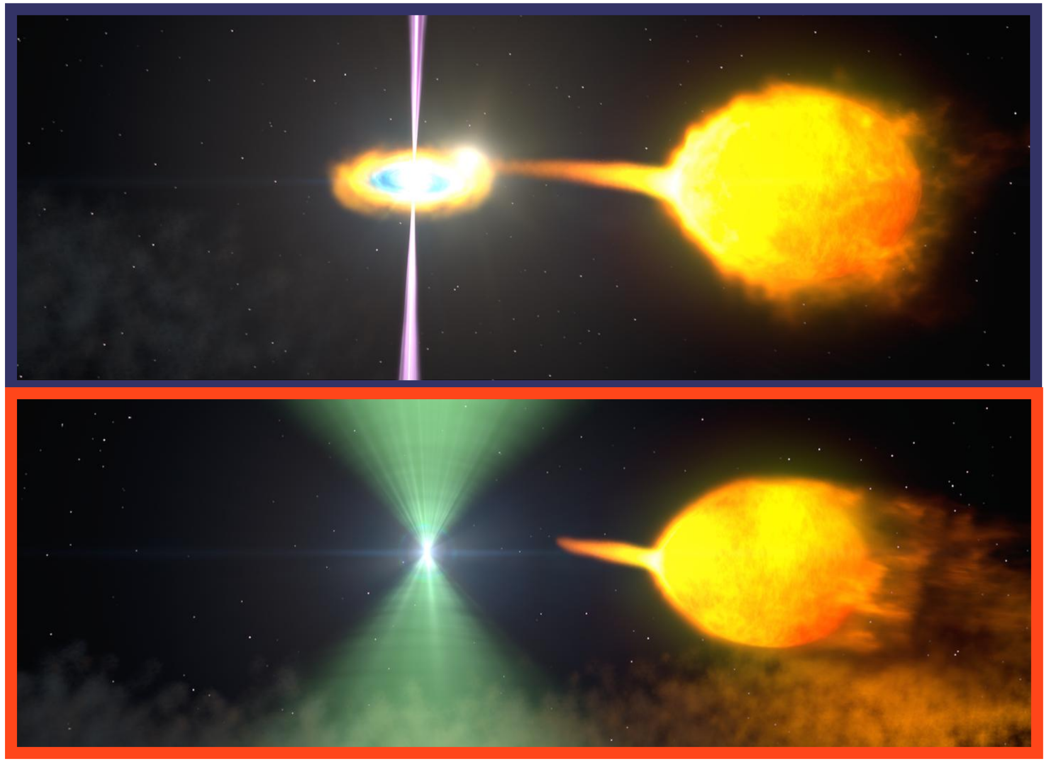
$R_{LC} = 80$ km

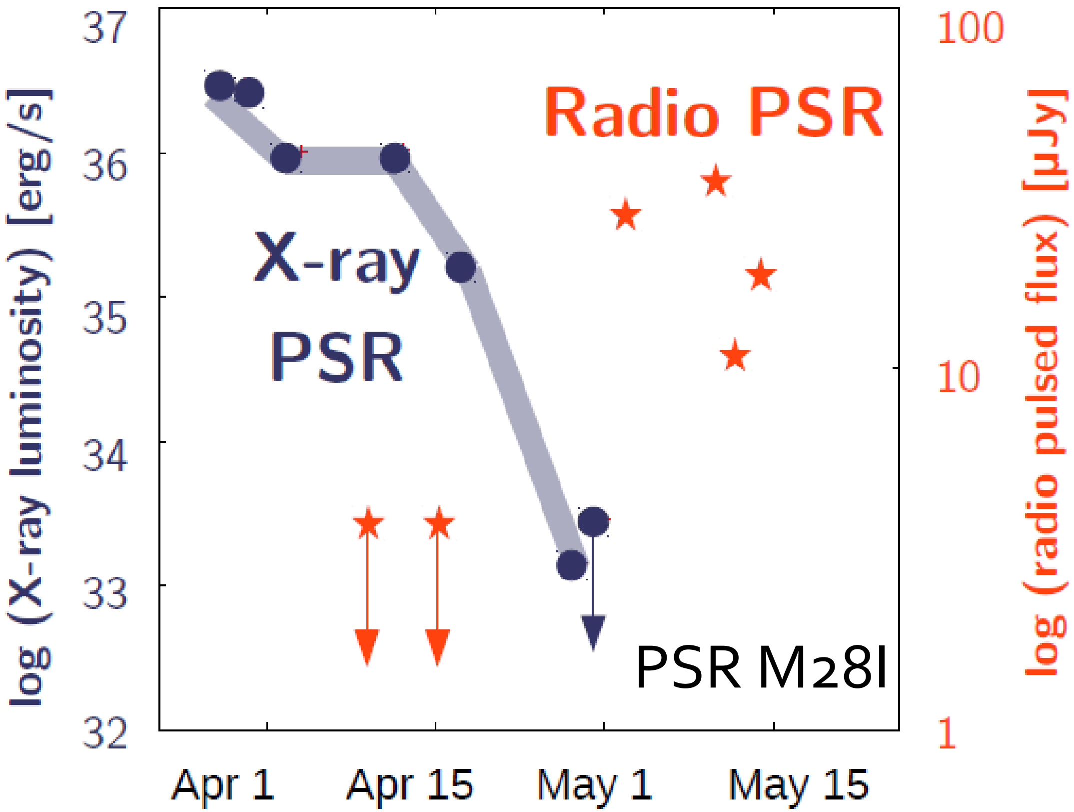
$R_{disk} = 100\text{-}200$ km

cartoon from **Veledina, Nättilä, Beloborodov** 2019

Swinging between rotation and accretion power in transitional ms pulsars

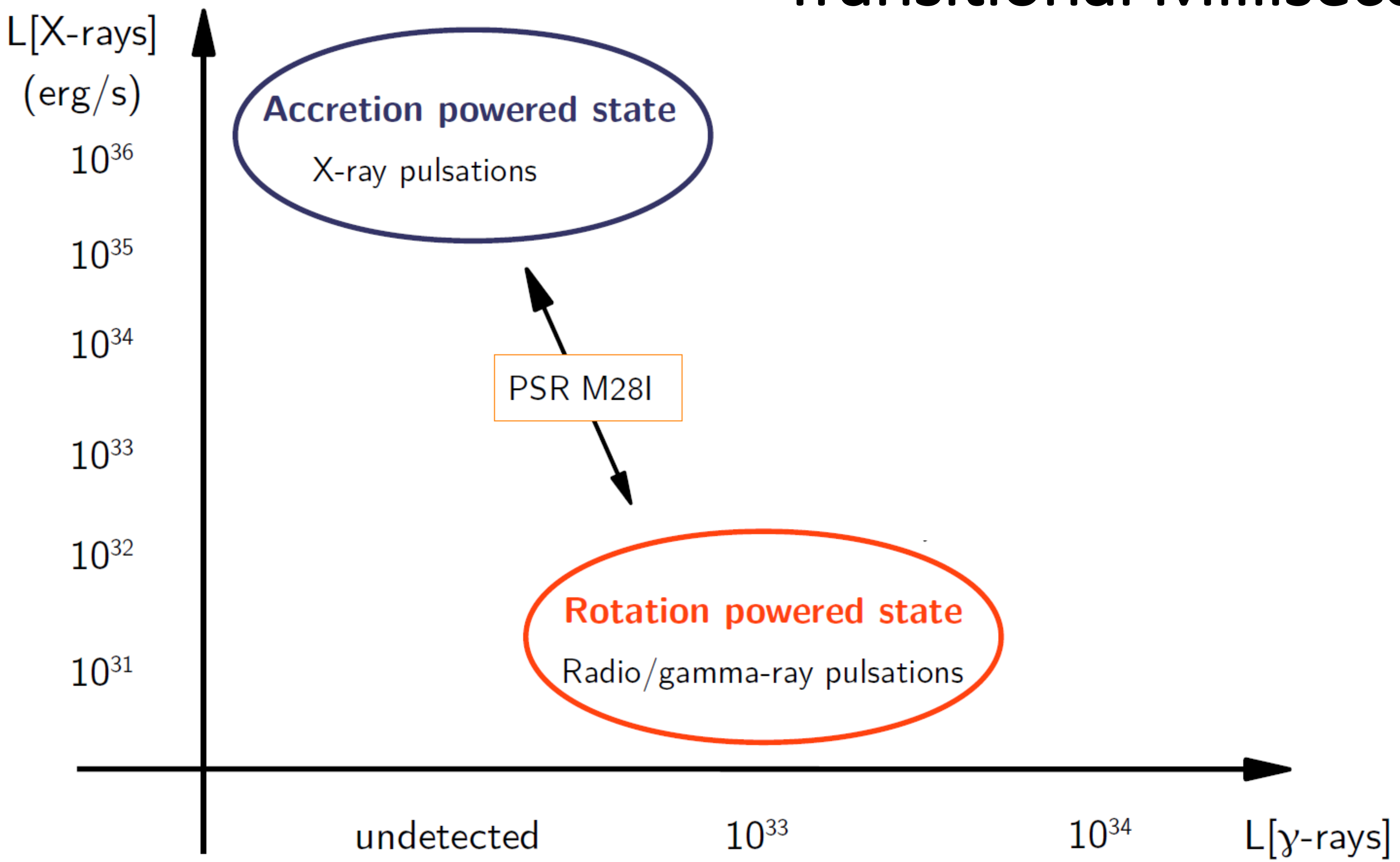
Mass in-flow rate





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

Transitional Millisecond Pulsars

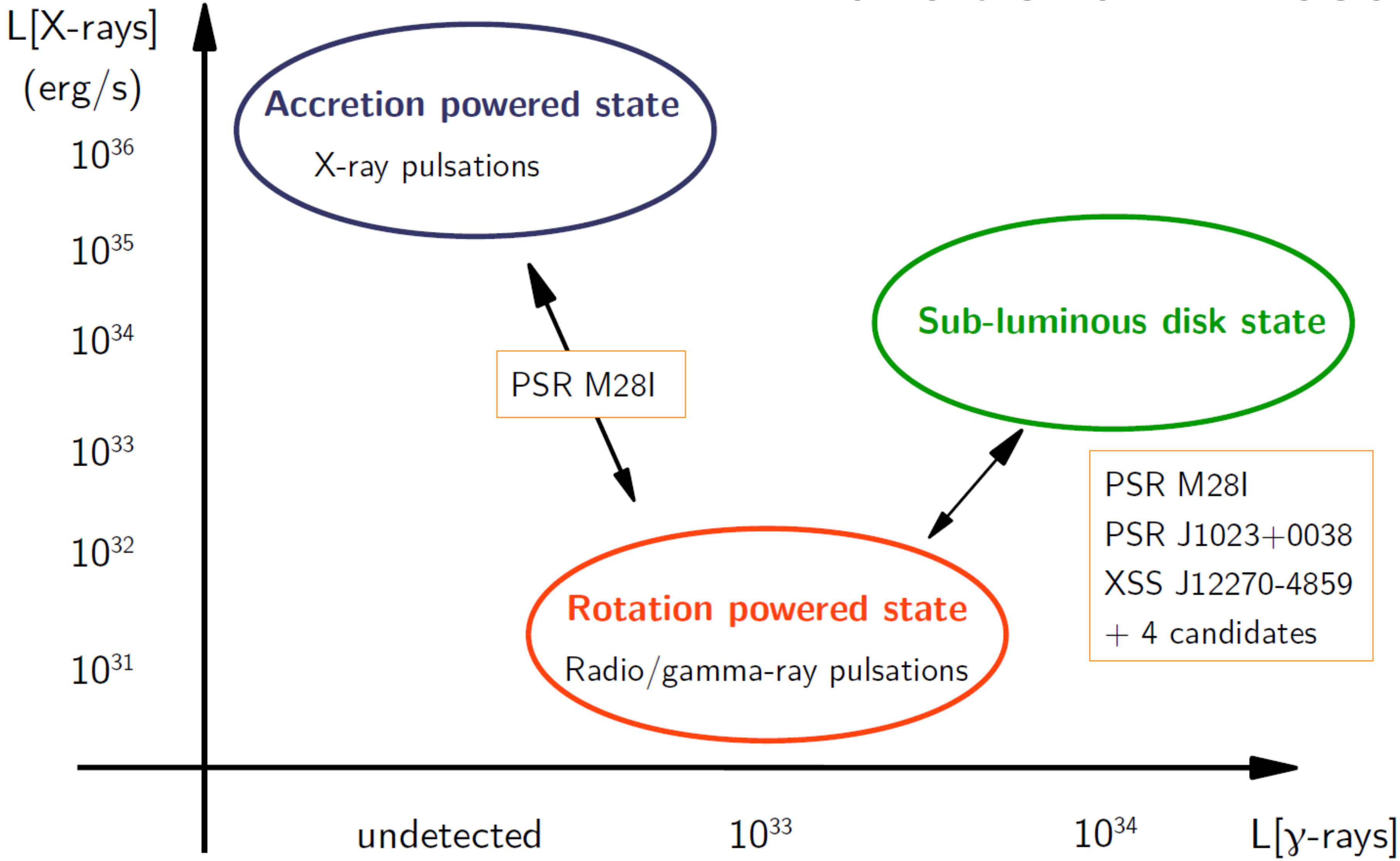


Laccretion >> Lspindown

Laccretion << Lspindown

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

Transitional Millisecond Pulsars



$L_{accretion} >> L_{spindown}$

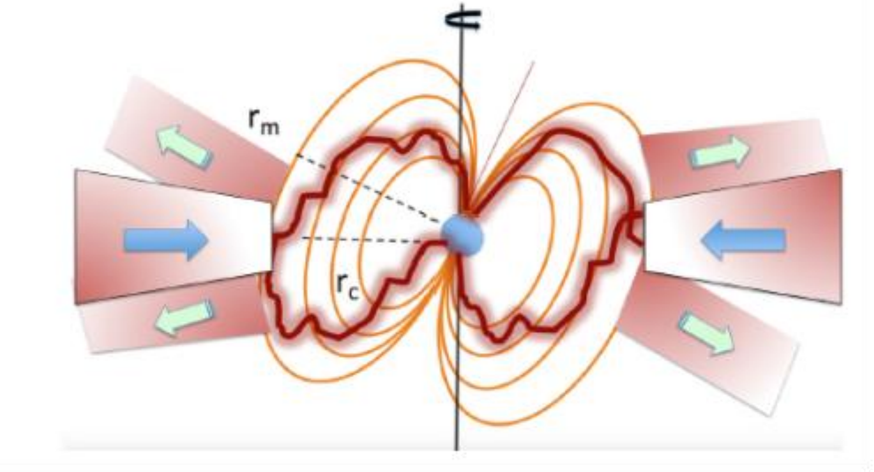
$L_{accretion} \approx L_{spindown}$

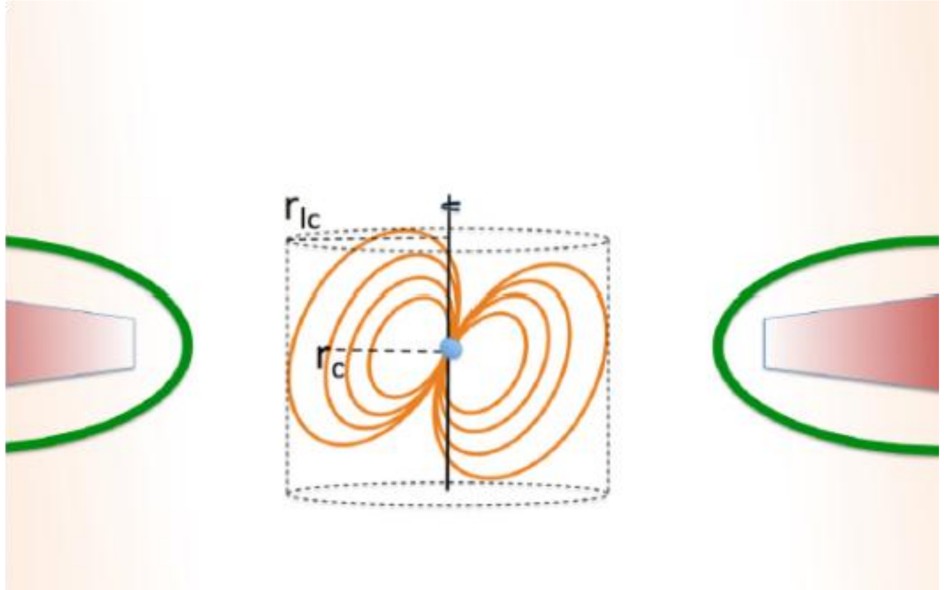
$L_{accretion} << L_{spindown}$

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

What powers the sub-luminous disk state emission?

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



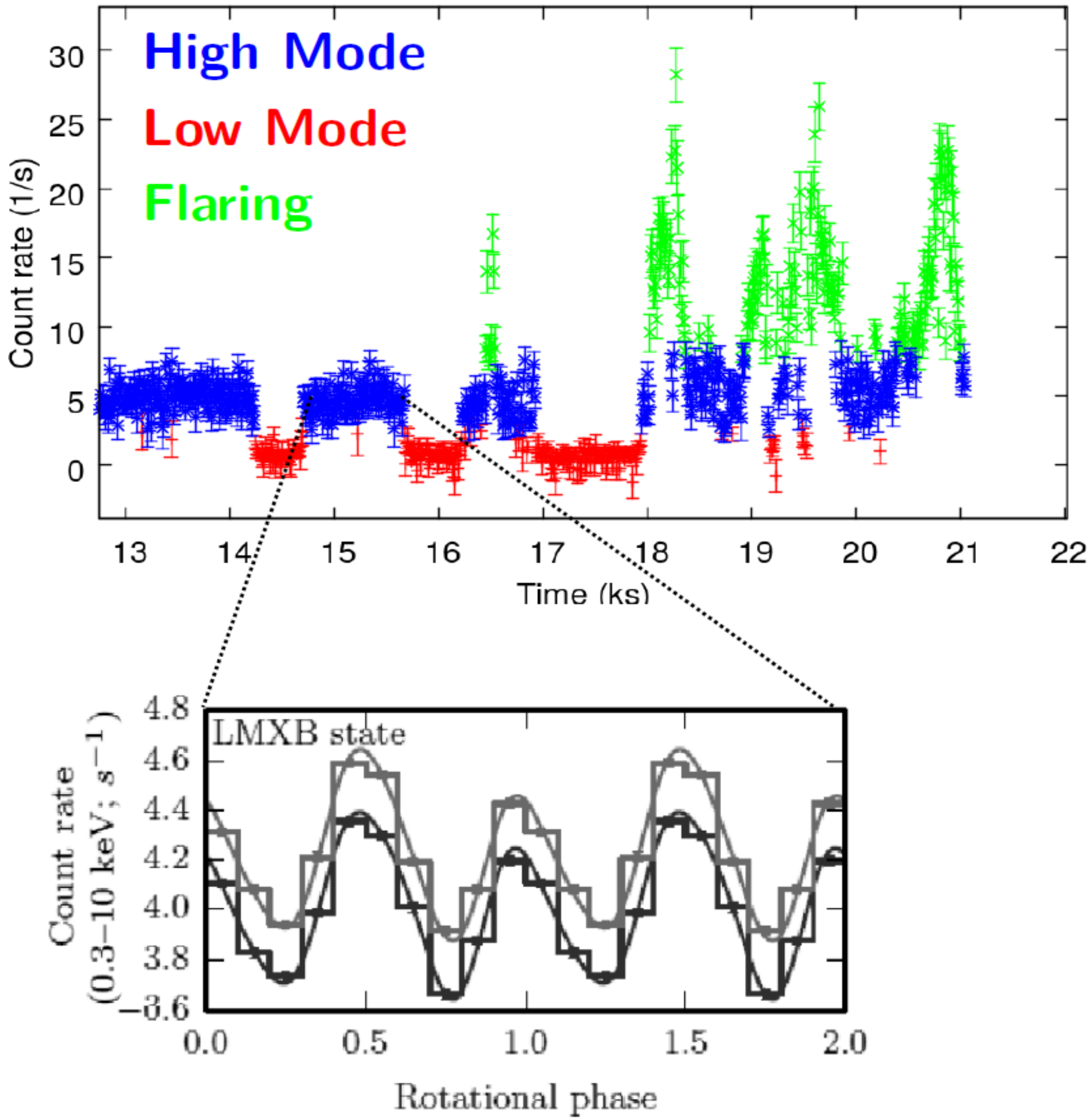


Coti Zelati+2014, **Takata**+ 2015, **Papitto**+ 2014, 2015, **Linares**+ 2014, **Campana**+ 2016, **Papitto & de Martino** 2022

A sub-luminous disk state

Accretion-power features

Disk emission lines
X-ray pulsations & sudden variability
Bright compact radio jets



Patruno+ 2014, Bogdanov+ 2015, Archibald+ 2015, Campana+ 2016

A sub-luminous disk state

Accretion-power features

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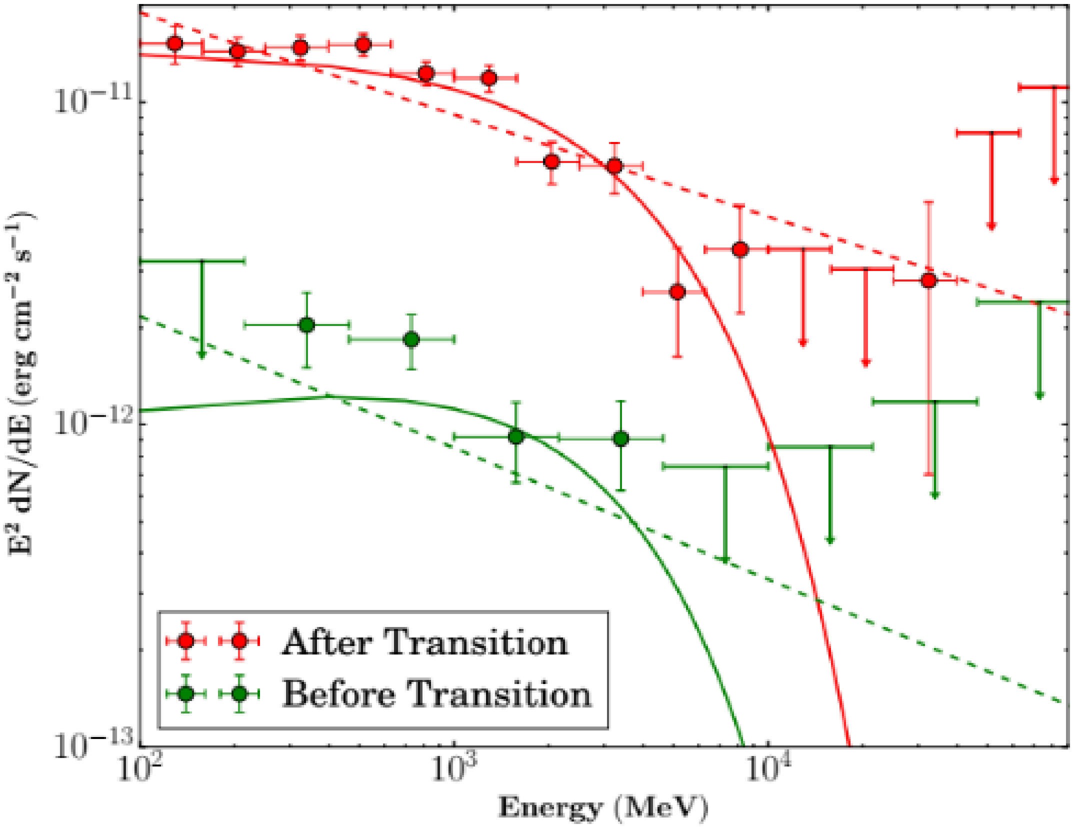


Rotation-power features

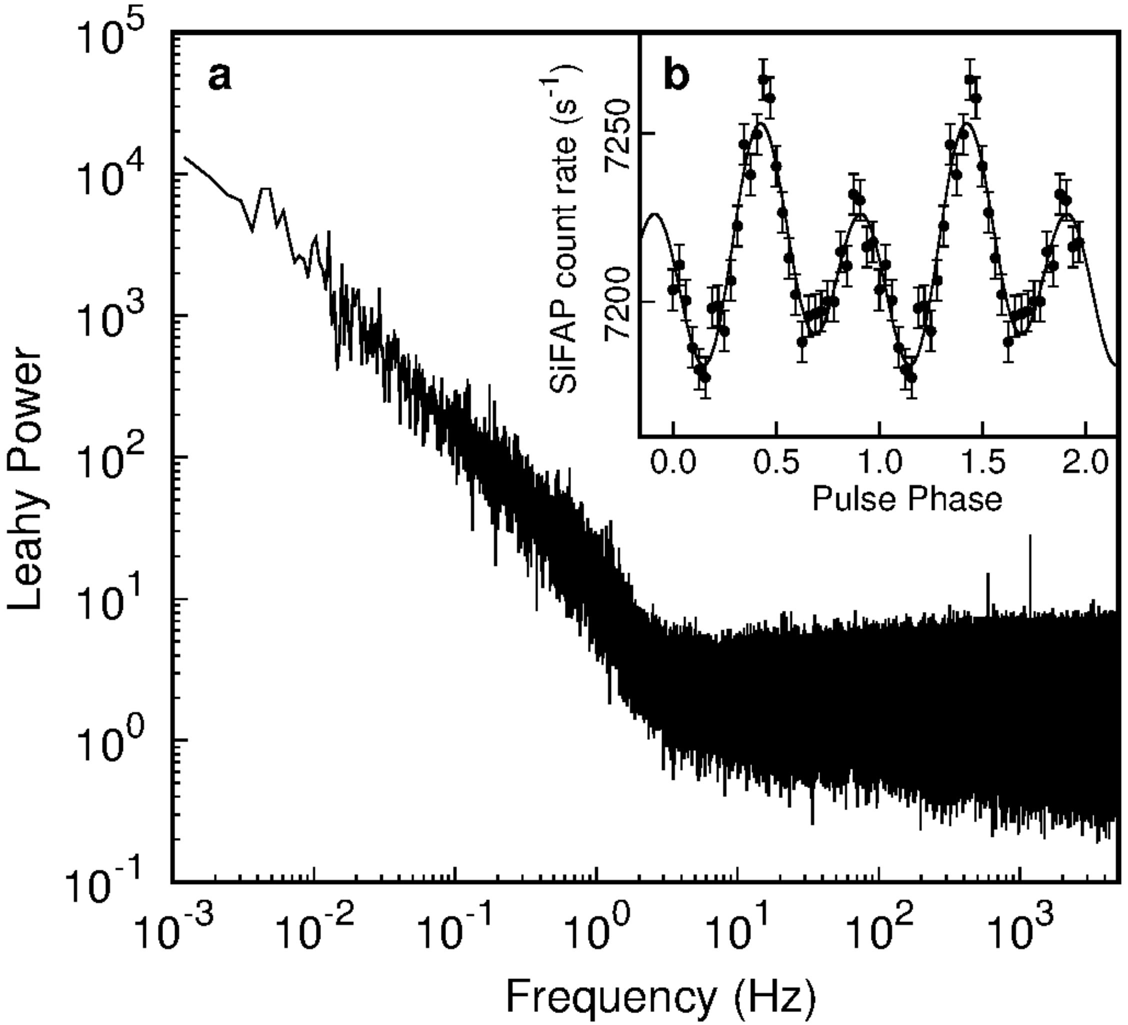
Bright gamma-ray emission (as bright as Xrays)

Radio pulsar-like spin down (within 5%)

de Martino+ 2010, **Stappers**+ 2014, **Torres**+ 2018; **Jaodand**+2016, **Burtovoi**+ 2021; **Baglio**+ 2025

Optical/UV pulsations from a transitional millisecond pulsar

Detected by SiFAP2@TNG
from PSR J1023+0038
~ 10000 c/s (V ≈ 16.5 mag)
Pulse amplitude ~ 0.1-1%
L_{pulsed} ~ few x 10^{31} erg/s ≈ 0.1% $L_{SpinDown}$



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

Stunningly bright optical pulsations accretion-powered?

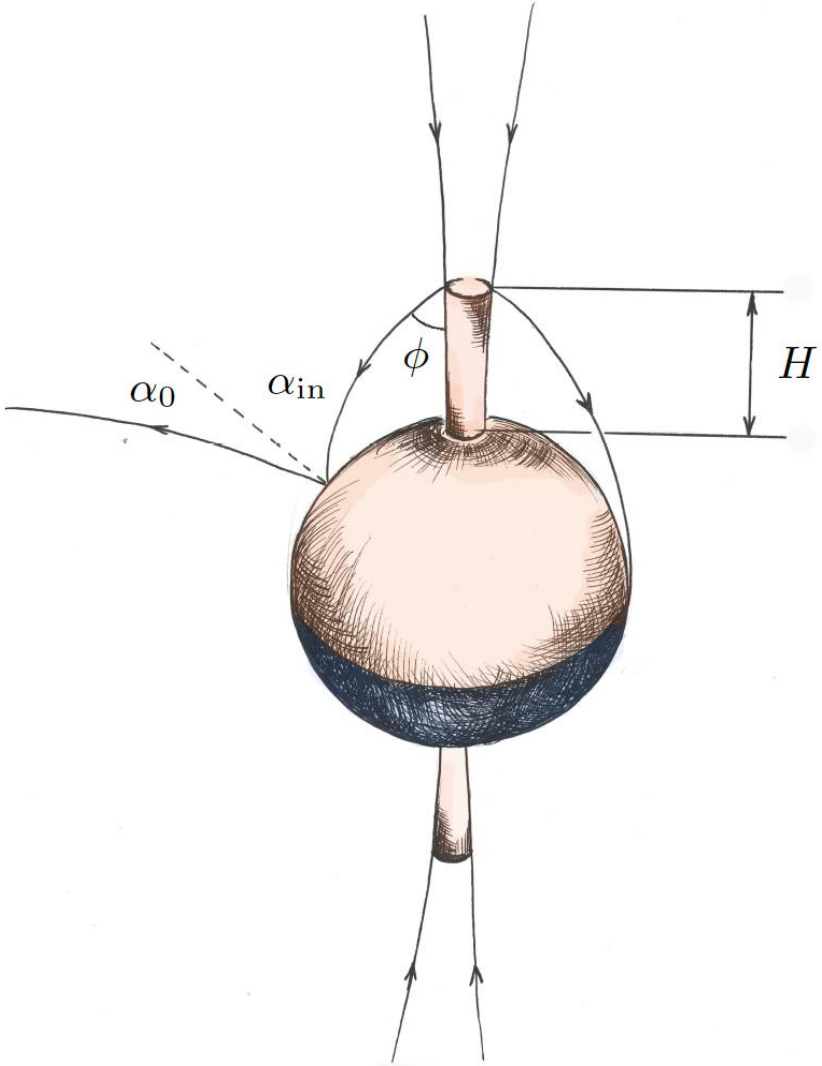
Cyclotron emission from **accretion column**?

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

$$\begin{aligned} L_{\rm cyc} &= A_{\rm spot}\int_{\nu_l}^{\nu_h}(2\pi kT_e\nu^2/3c^2)d\nu \\ &= 2.9\times10^{29}\left(\frac{A_{\rm spot}}{10^{12}\ {\rm cm}^2}\right)\left(\frac{kT_e}{100\ {\rm keV}}\right)\ {\rm erg\ s^{-1}}, \end{aligned}$$

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

50x beaming required



Lamb & Masters 1979

Stunningly bright optical pulsations rotation-powered?

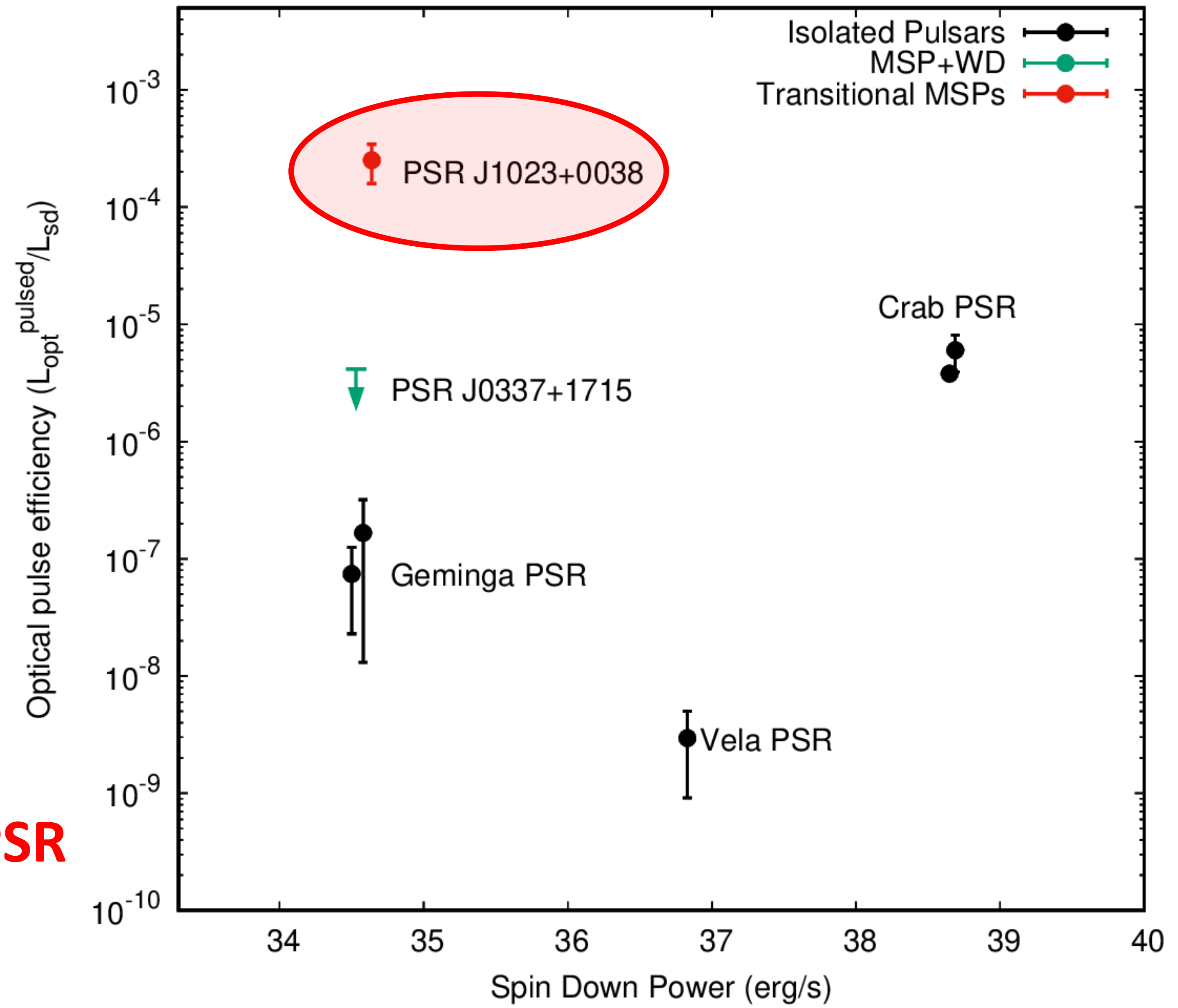
Radio pulsars

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

PSR J1023

$L = 2 \times 10^{-4}\ L_{sd}$

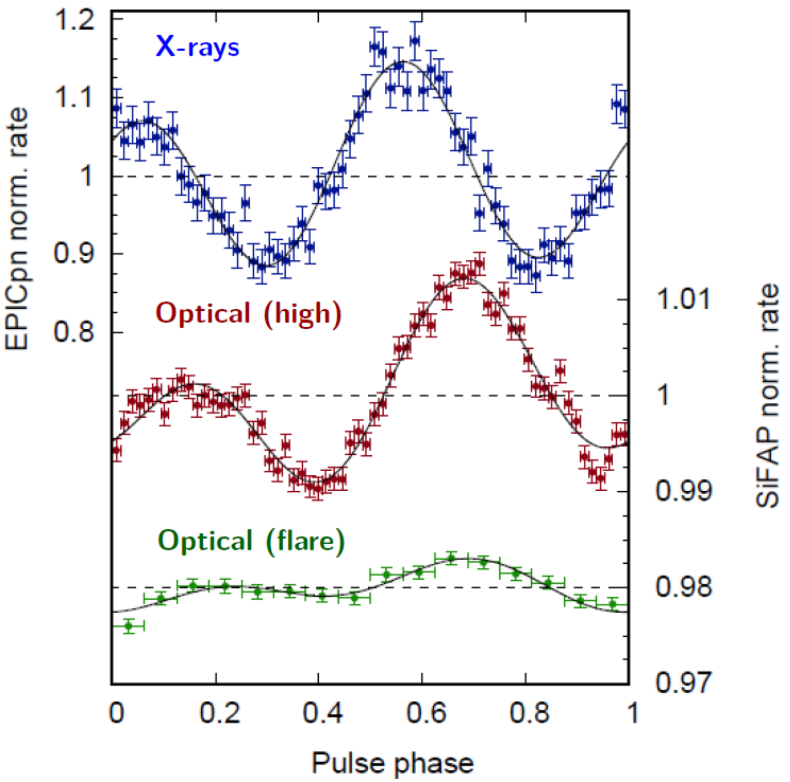
>50x more efficient than Crab PSR

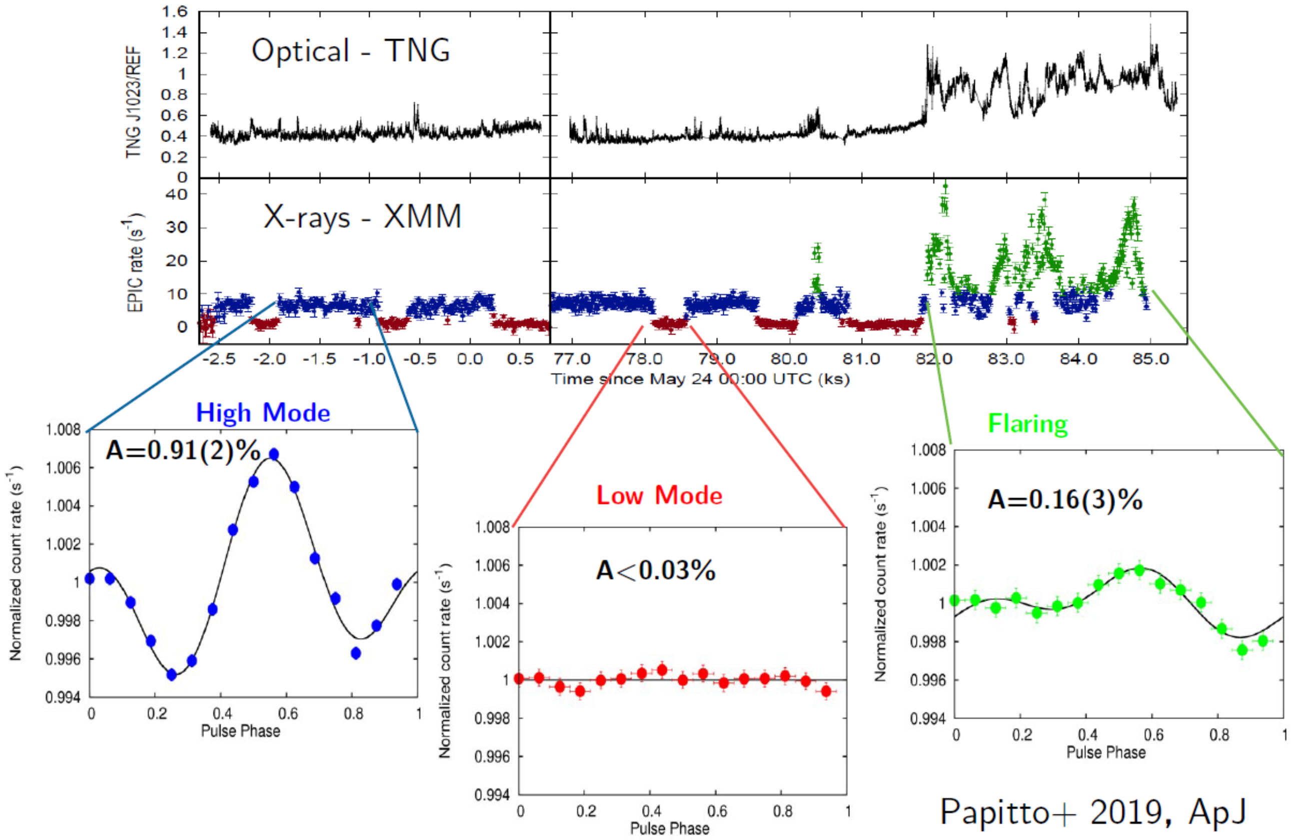


Updated from **Ambrosino, Papitto+** 2017, Nature Astr.

A single process to explain optical/UV/X-ray pulses

Similar shape and simultaneous disappearance during low modes

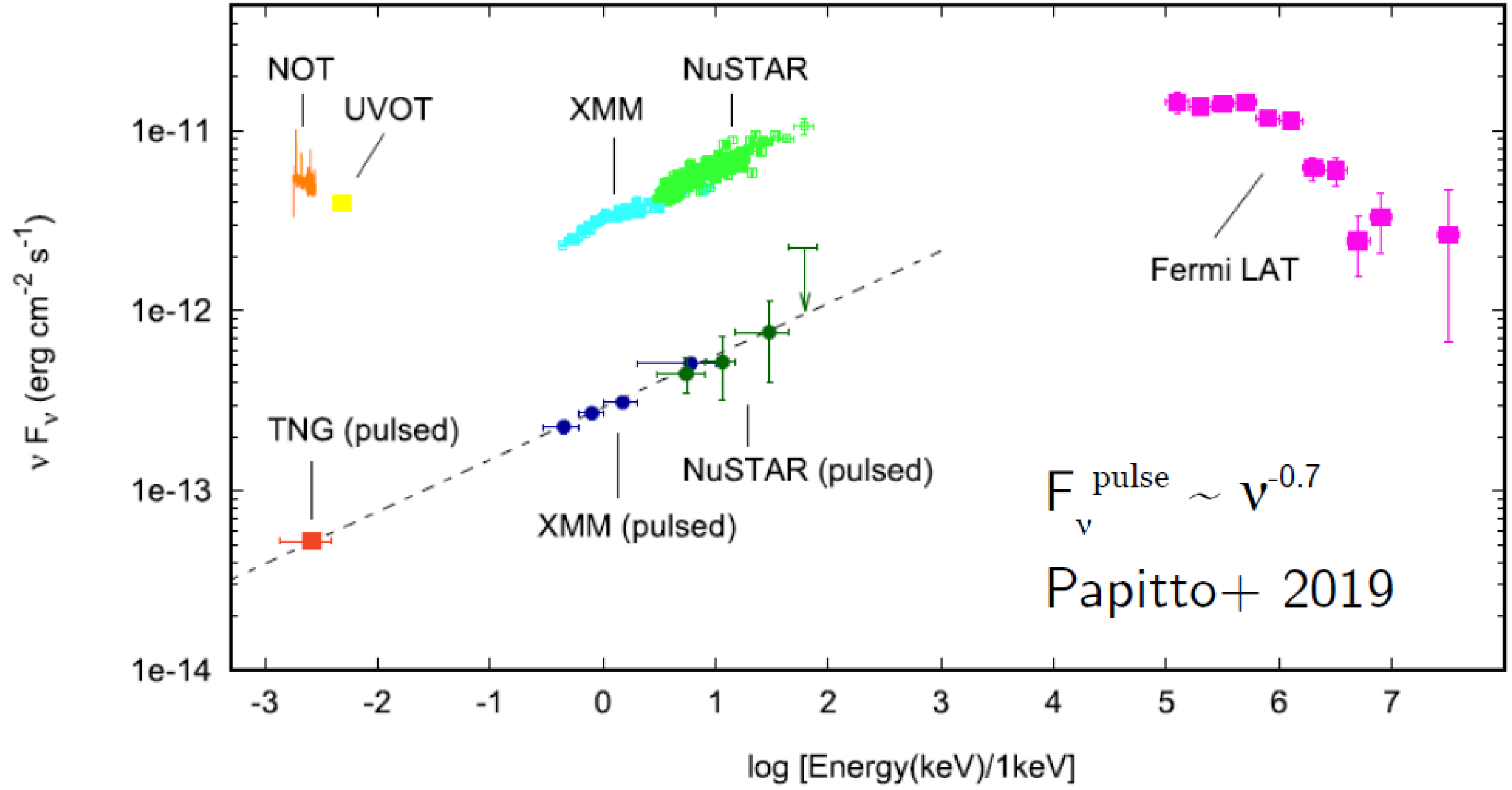




Papitto+ 2019, ApJ

A single process to explain optical/UV/X-ray pulses

Energy spectrum of pulsed emission suggests single synchrotron process



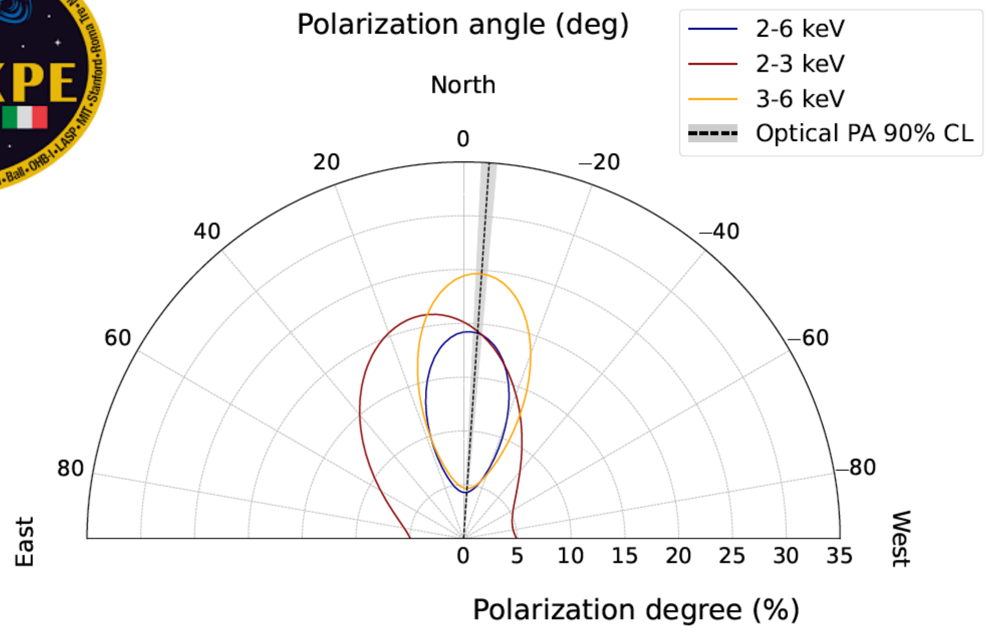
Papitto+ 2019; **Miraval Zanon+** 2022

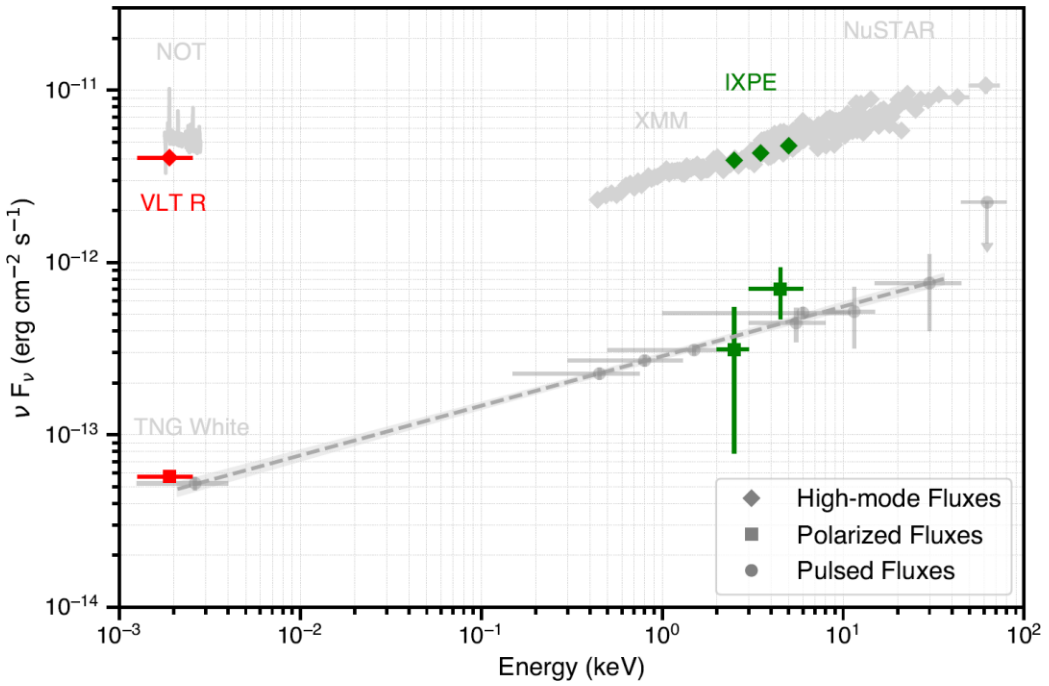
A single process to explain optical/UV/X-ray pulses

Polarization degree of X-rays in high mode = (12+/-3)%

Pol. Angle = (-2+/-9)° consistent with optical band (-3.9+/-0.7)°

SED of polarized and pulsed emission compatible from the optical to Xrays

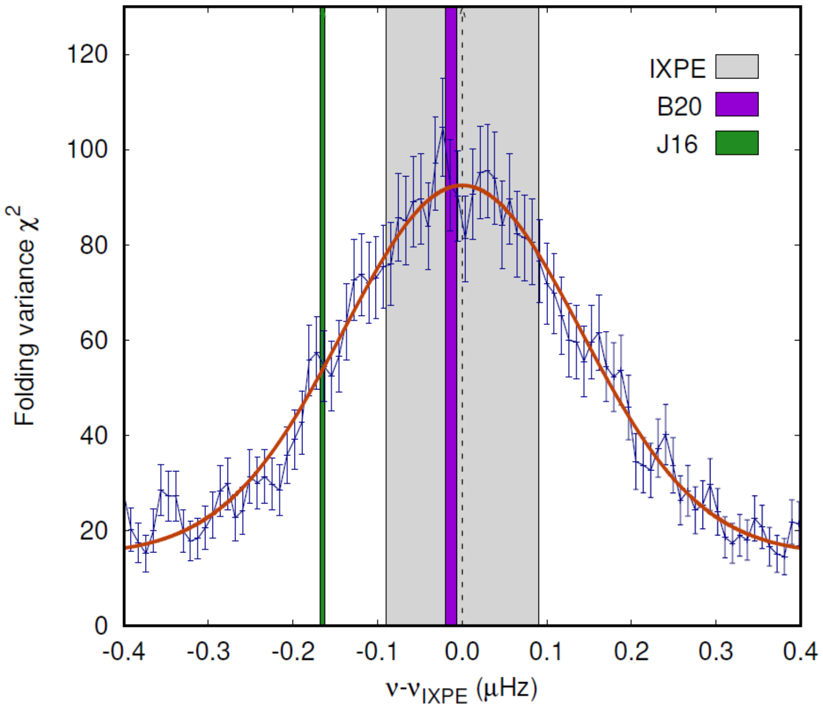


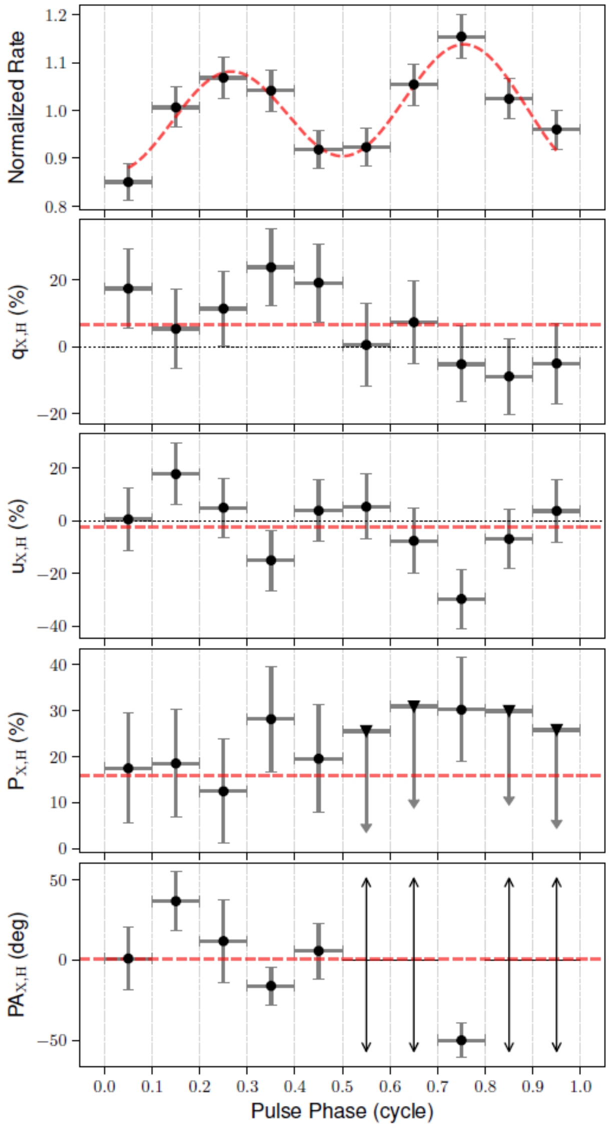


Baglio+ 2025, arXiv: 2412.13260

X-ray/optical/polarization

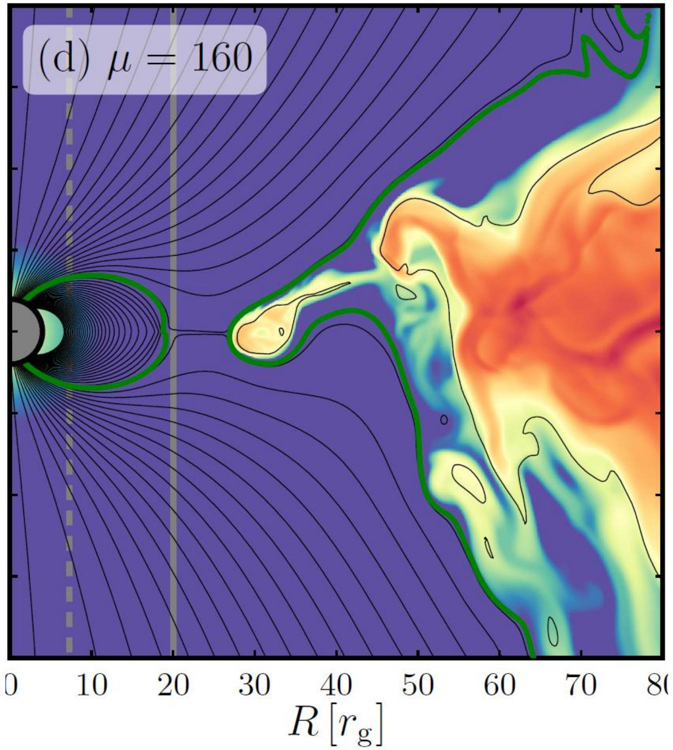
Energy band (keV)	Average emission P_X (%)	PA_X (°)	χ^2(dof)	High mode $P_{X,H}$ (%)	$PA_{X,H}$ (°)	χ^2(dof)
2–6	11 ± 3	-7 ± 8	175(166)	12 ± 3	-2 ± 9	164(166)
2–3	8 ± 5	20 ± 20	32(31)	8 ± 6	10 ± 20	25(31)
3–6	15 ± 4	-9 ± 8	120(121)	15 ± 5	-3 ± 9	120(121)

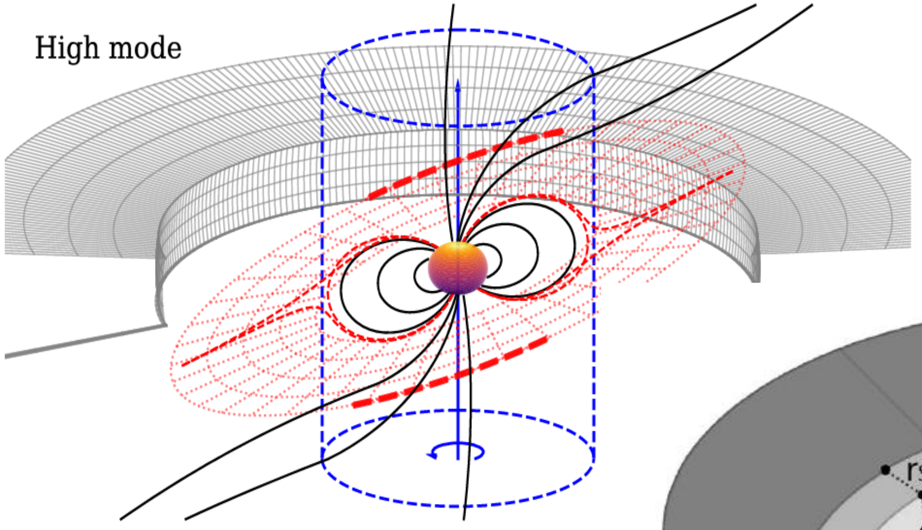


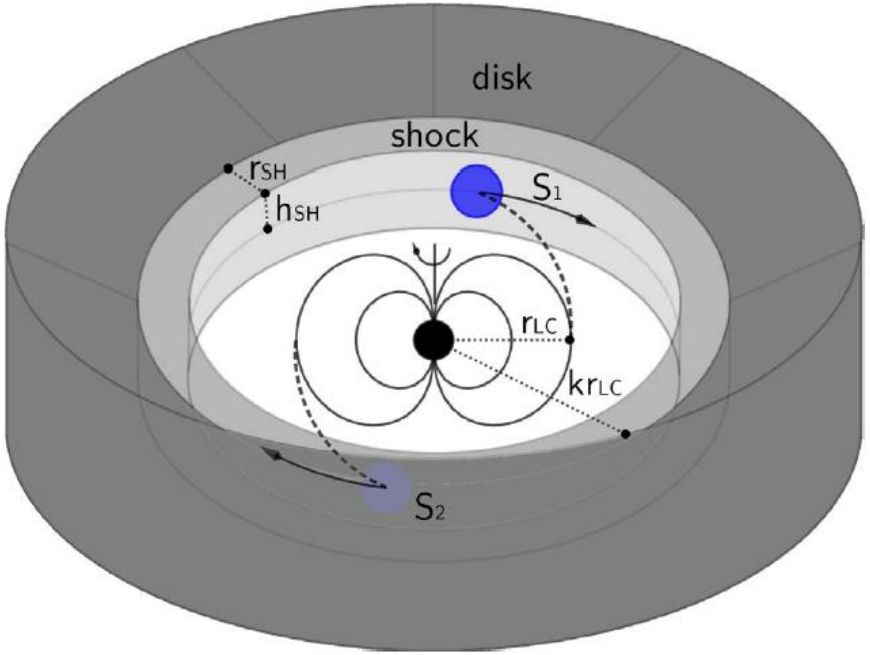


Baglio+ 2025, arXiv: 2412.13260

Coexistence of Rotation & Accretion-power



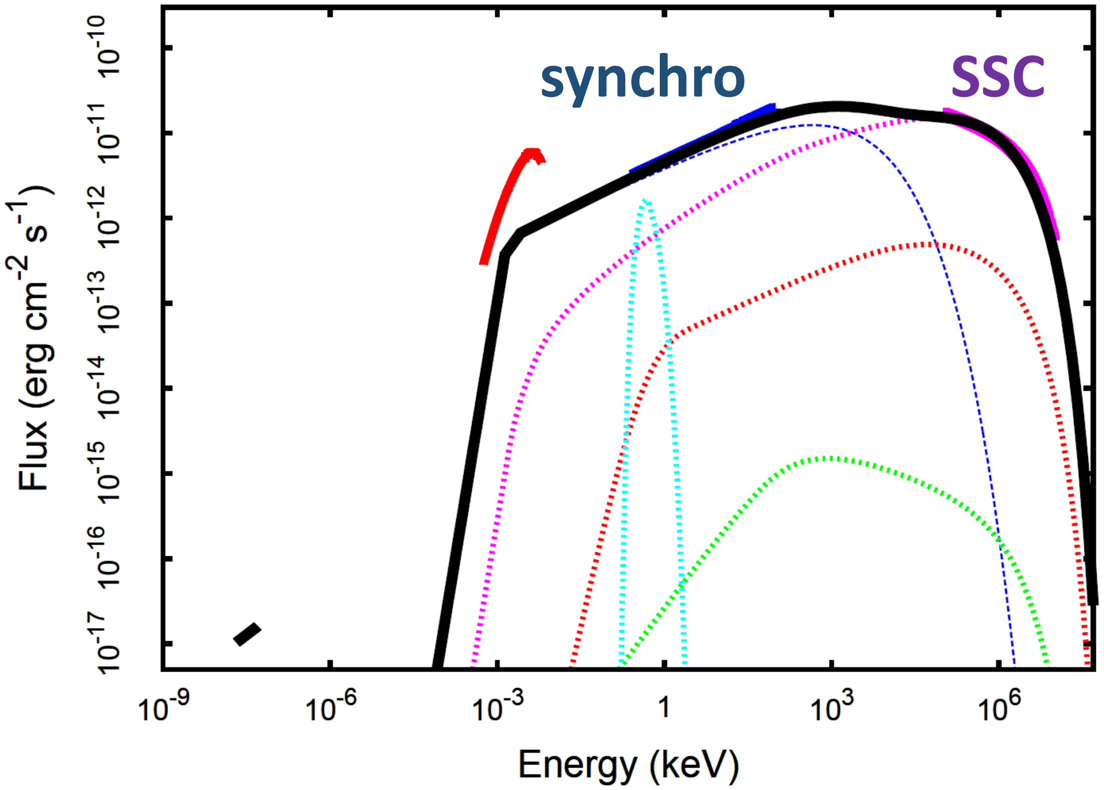


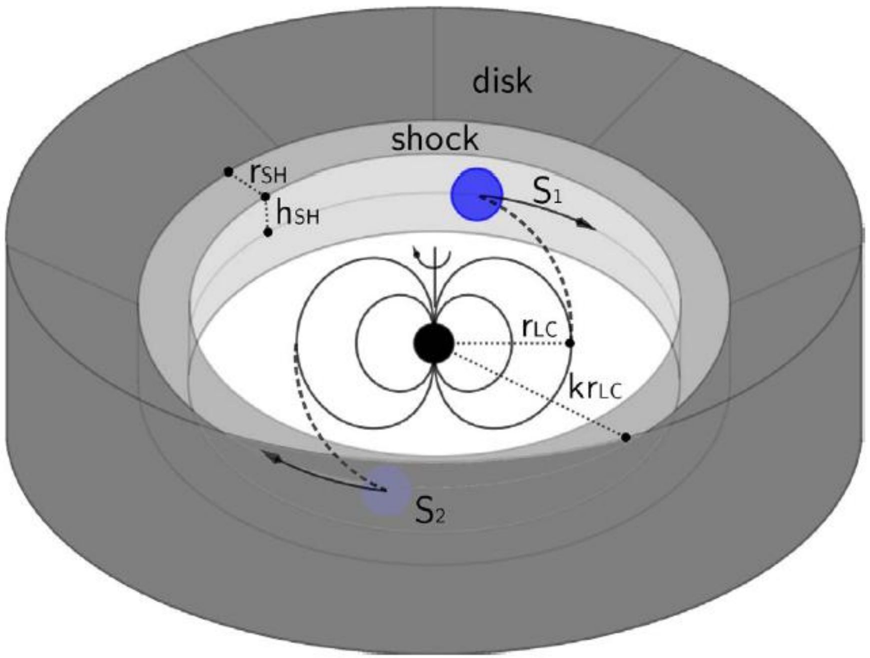


Parfrey+ 2017**; Veledina, Nättila, Beloborodov** 2019; **Papitto+** 2019

Coexistence of Rotation & Accretion-power

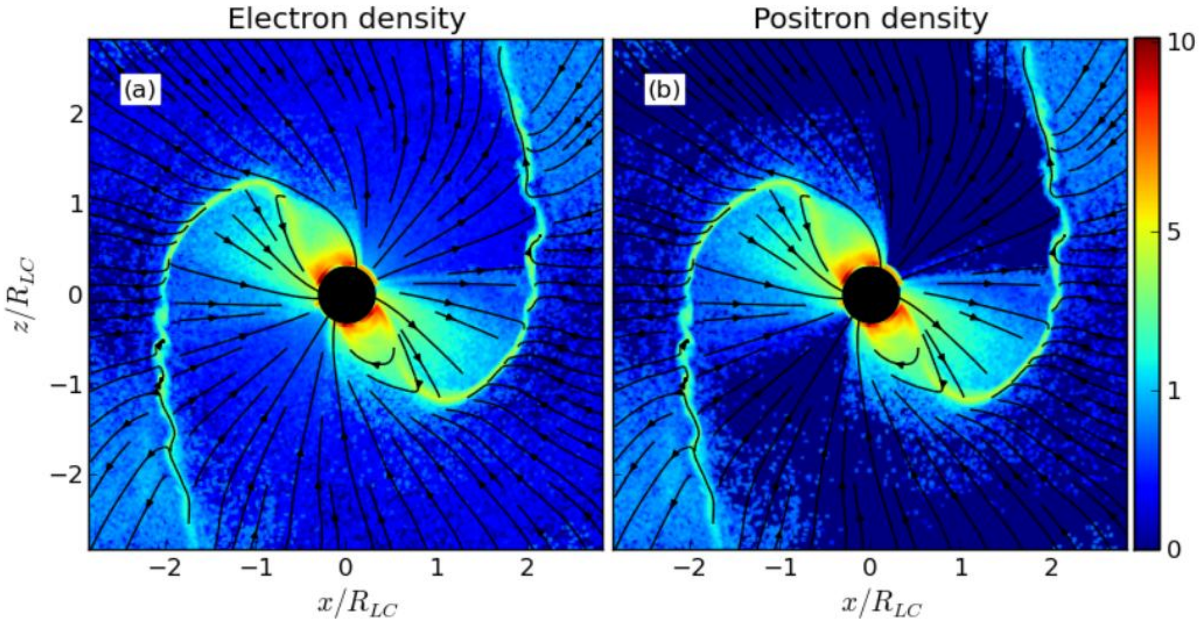
Synchrotron → Optical/X-rays
Self Synchrotron Compton → Gamma-rays



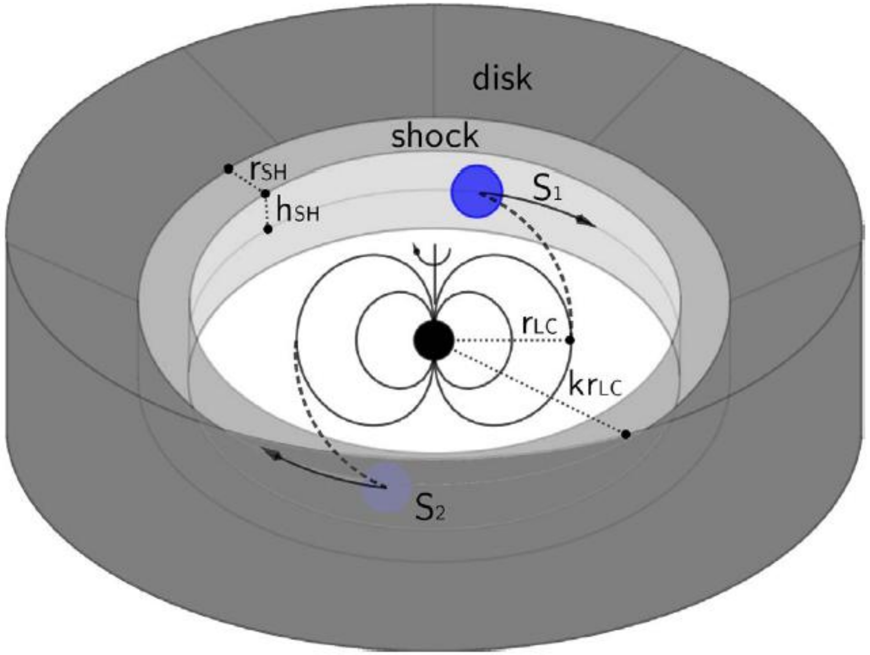


Veledina, Nättila, Beloborodov 2019; **Papitto+** 2019, **Papitto & Torres** 2013, 2014

Coexistence of Rotation & Accretion-power



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

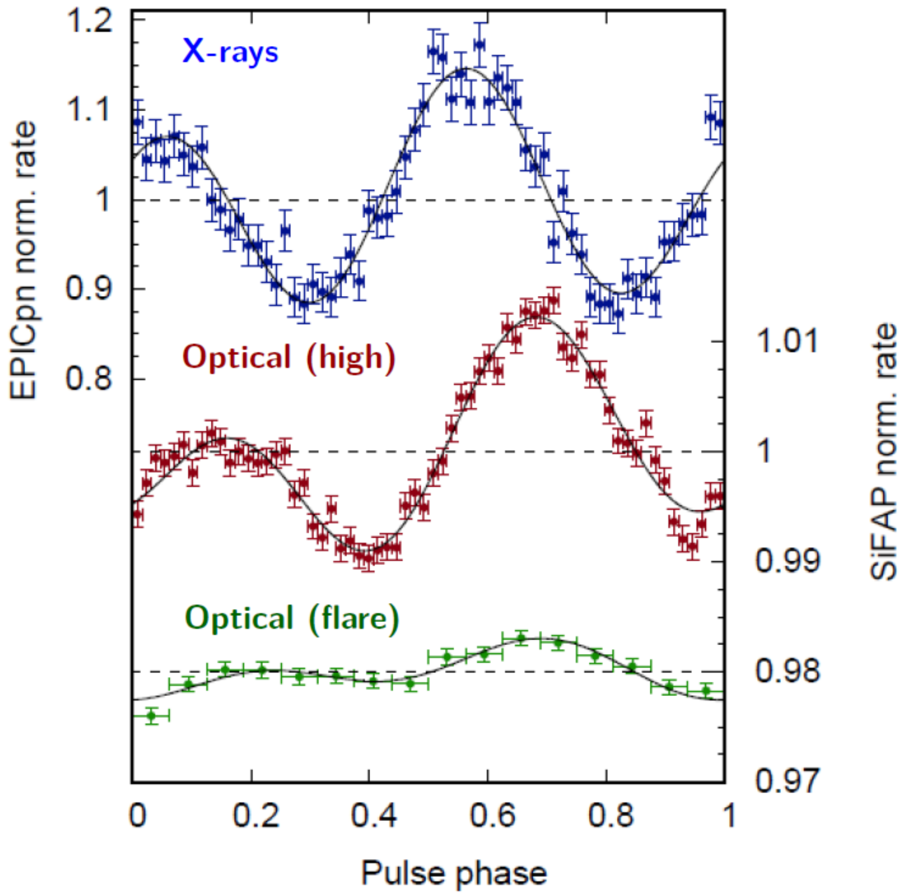


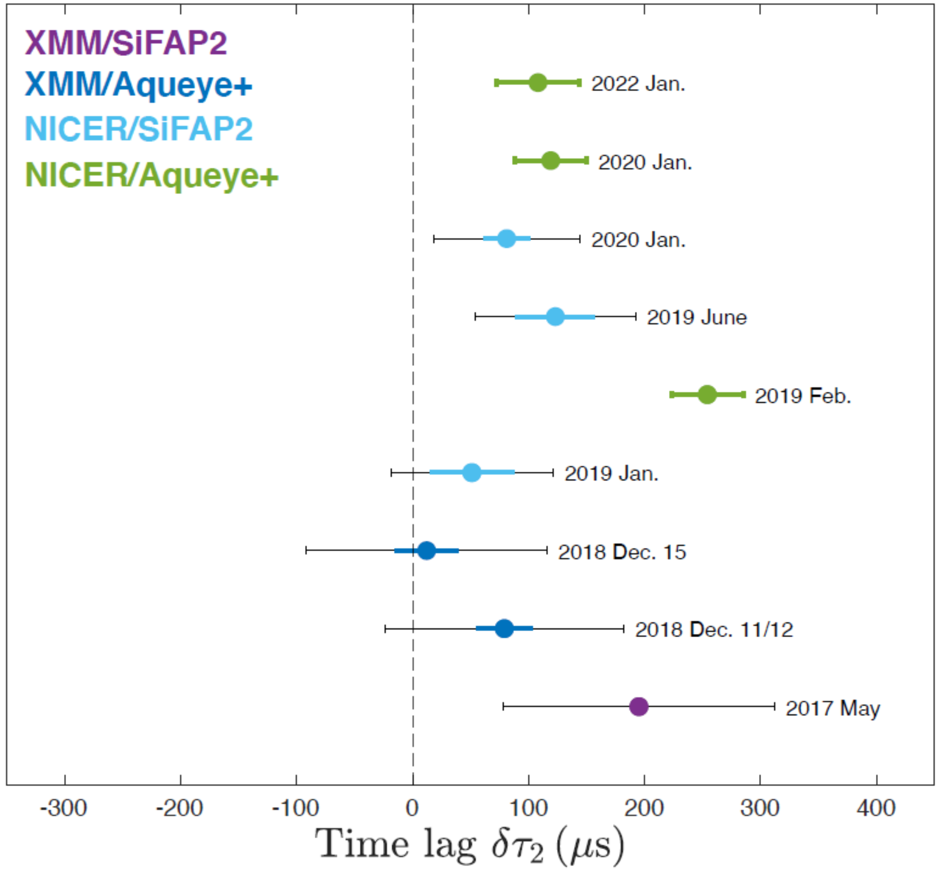
Pulses from the interaction between the **<u>pulsar striped wind and the mass in-flow</u>**

See Valentina Richard-Romei's talk later on

Cerutti & Beloborodov 2017; **Papitto+** 2019; **Veledina, Nättila, Beloborodov** 2019

Optical pulse lags X-ray pulse by ~ 100-200 μs



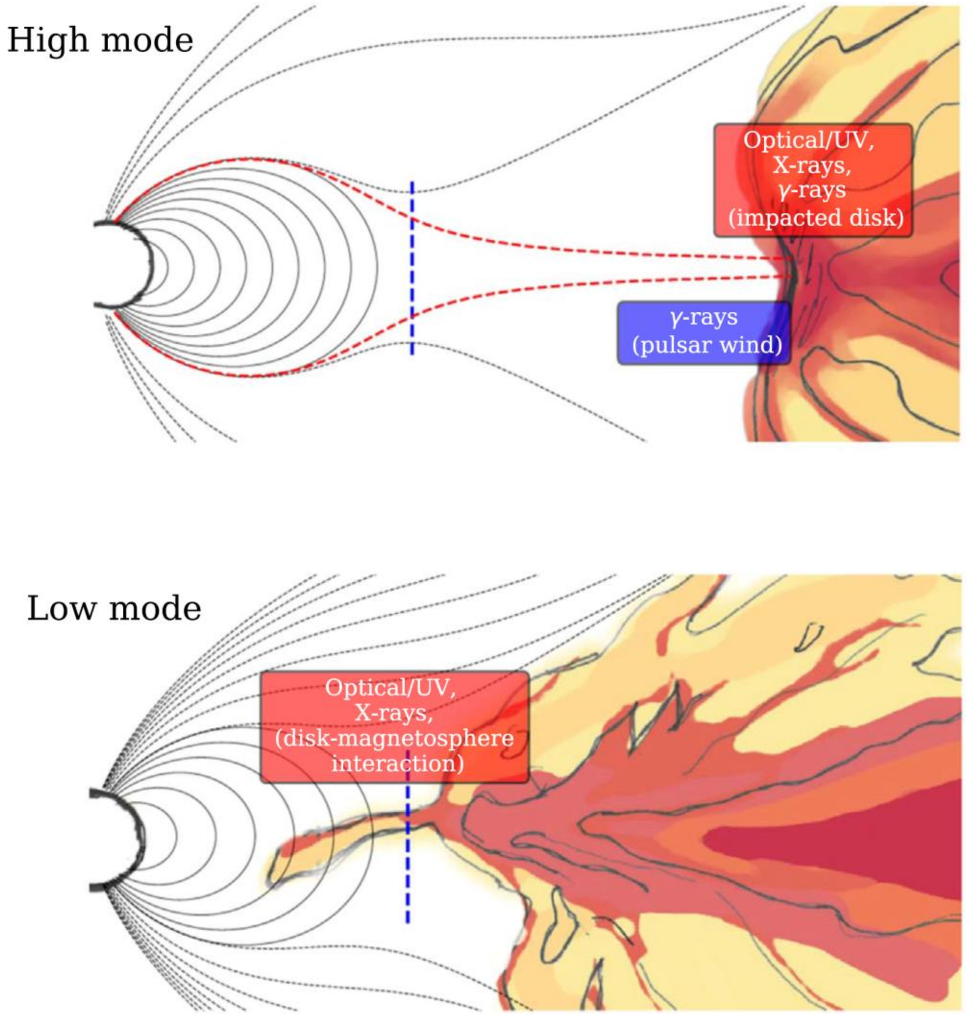


Illiano, Papitto+ 2017

What drives the high/low mode switching?

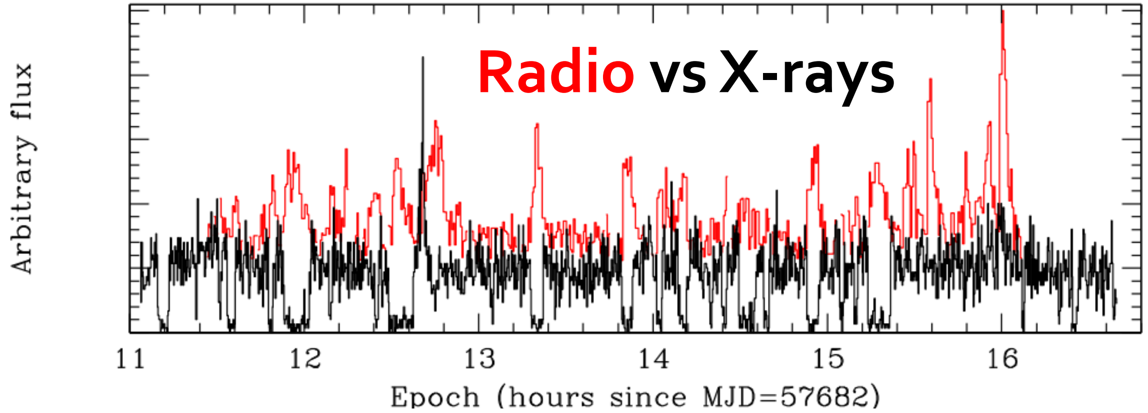
Accretion flow enters the light cylinder in the low mode.

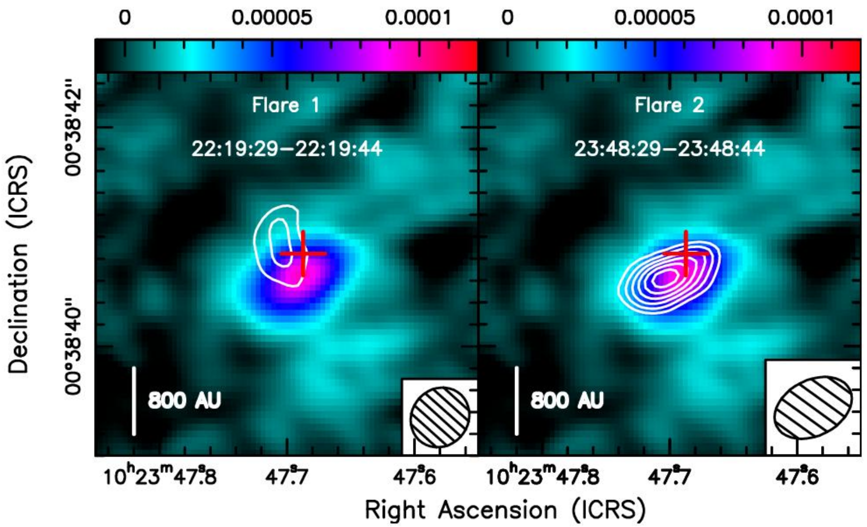
- propeller inhibition of accretion
- Switch off of pulsar wind related emission

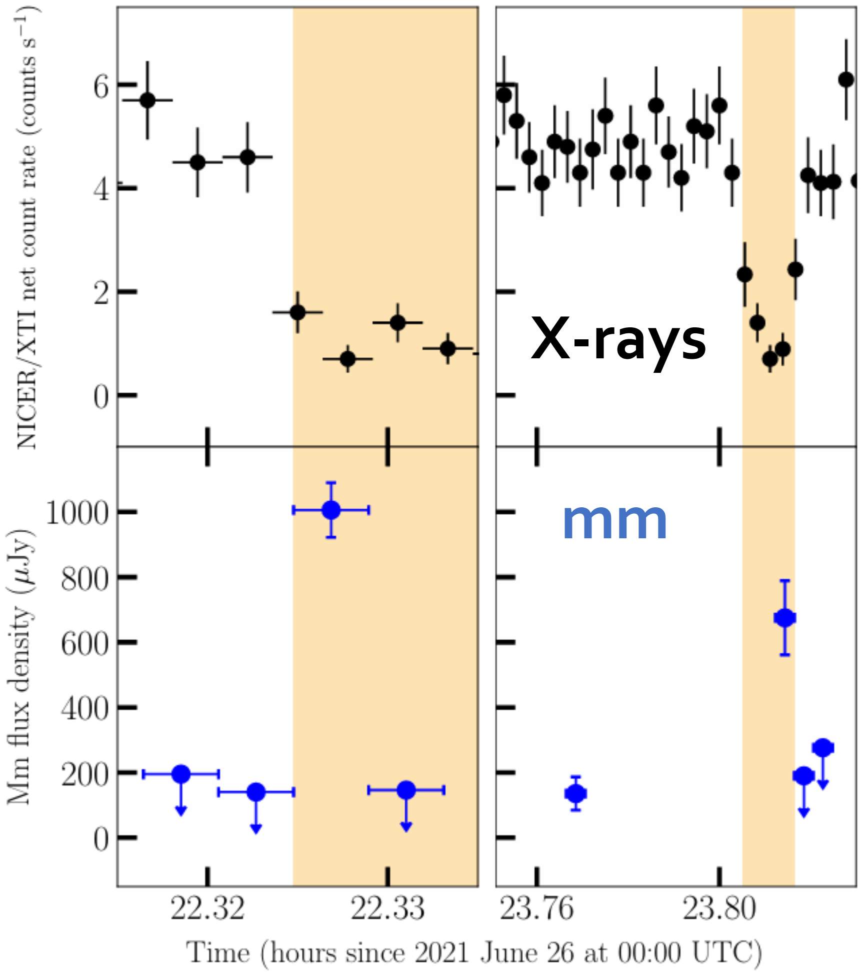


Veledina+ 2019

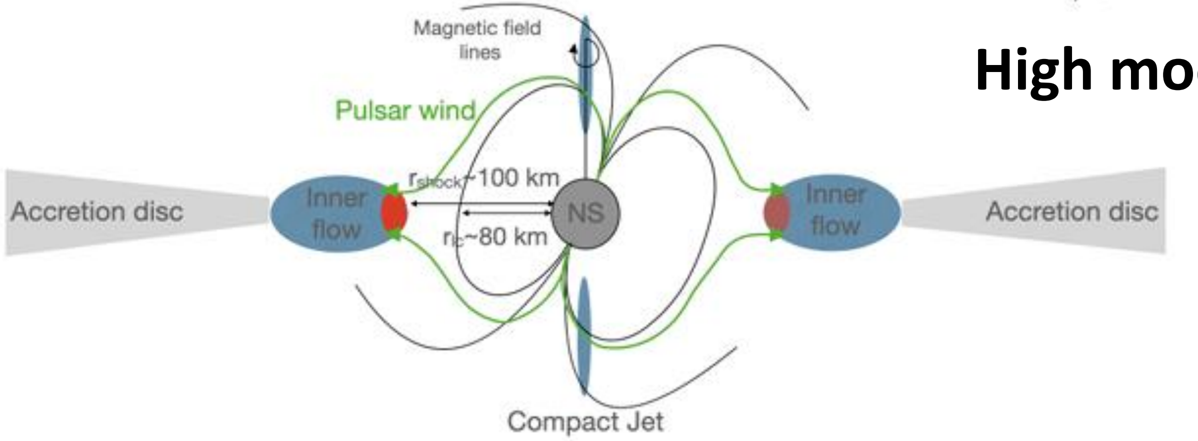
Radio and mm flares during X-ray low modes



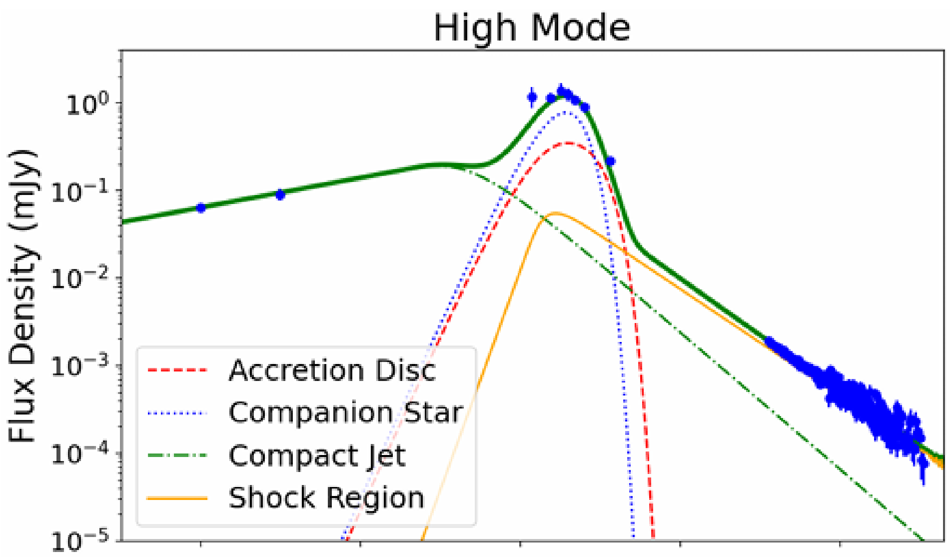


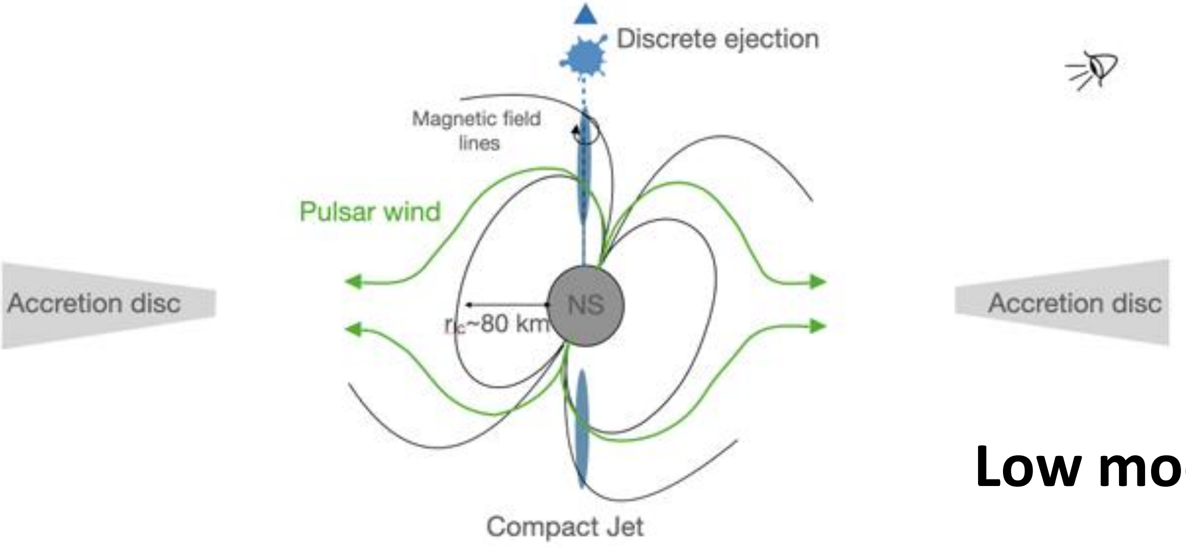


Bogdanov+ 2018; **Baglio+** (incl. Papitto) 2023

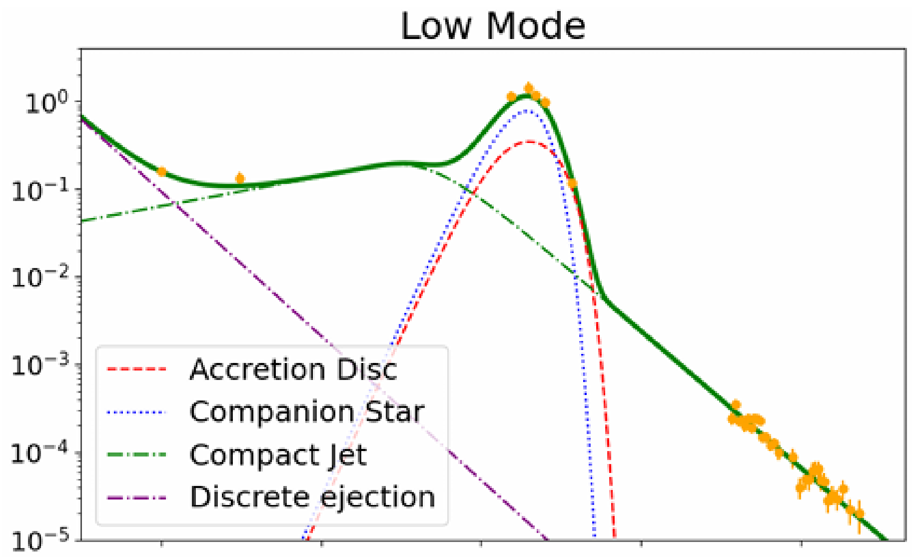


High mode





Low mode



Papitto+ 2019; **Baglio+** 2023 (incl. Papitto); **Baglio**+ (incl. Papitto) 2025

Open questions

Can simulations of the pulsar wind/disk interaction reproduce the observed patterns?

What causes high/low mode variability?

Why are transitional ms pulsars different than accreting/rotation-powered systems?

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The MSP@OAR team

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