Accreting and Transitional Millisecond Pulsar Binaries

Time Domain Astronomy WG

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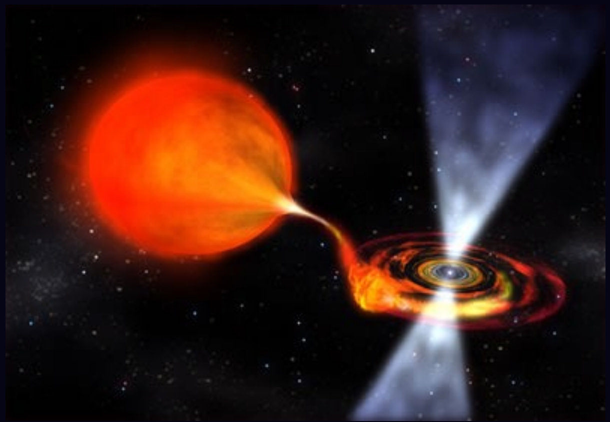
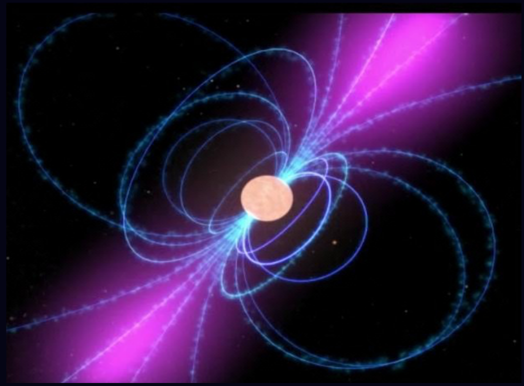
&
A. Papitto, T. Di Salvo, A. Sanna, L. Burderi, A. Marino, A. Riggio, R. Iaria, A. D'Aì, E. Ambrosi,.....





Fundamental Plane of Pulsars

Millisecond pulsars:

- Low field NSs: $B \approx 10^8 - 10^9$ G
- Many in Globular Clusters

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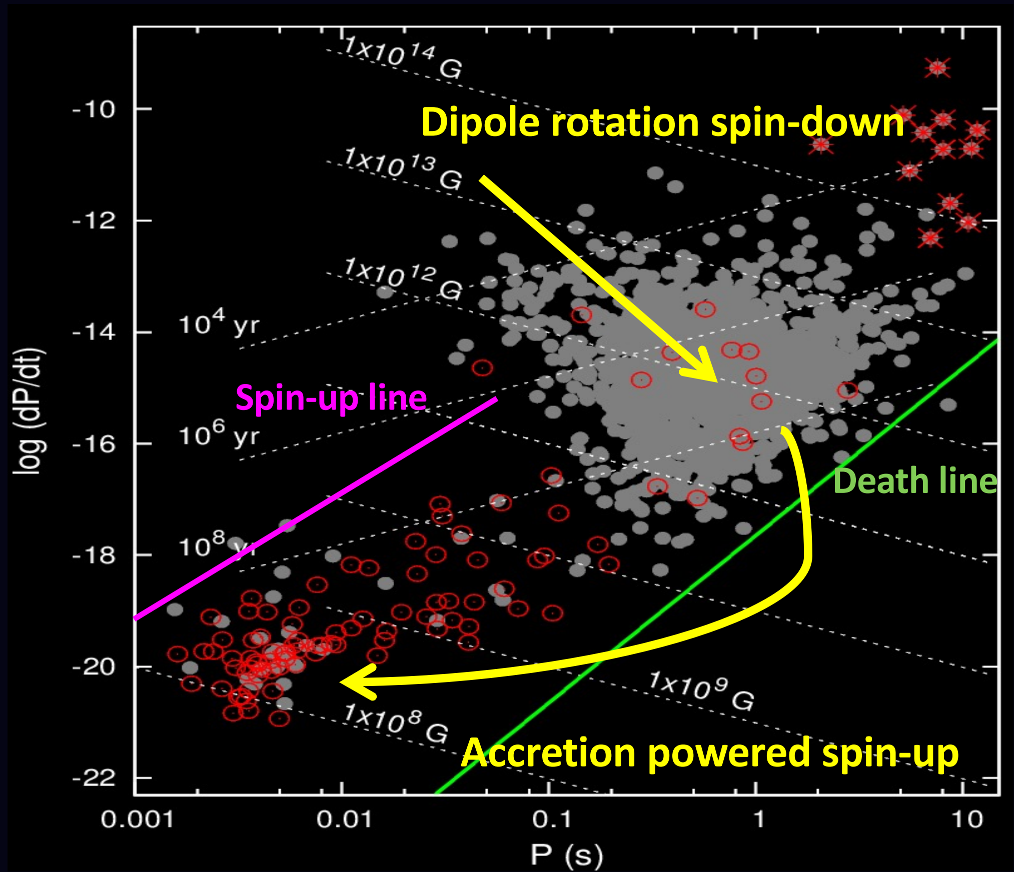
Old Neutron Stars

- Most found in binaries
- Spin-up due to accretion



Recycling scenario:

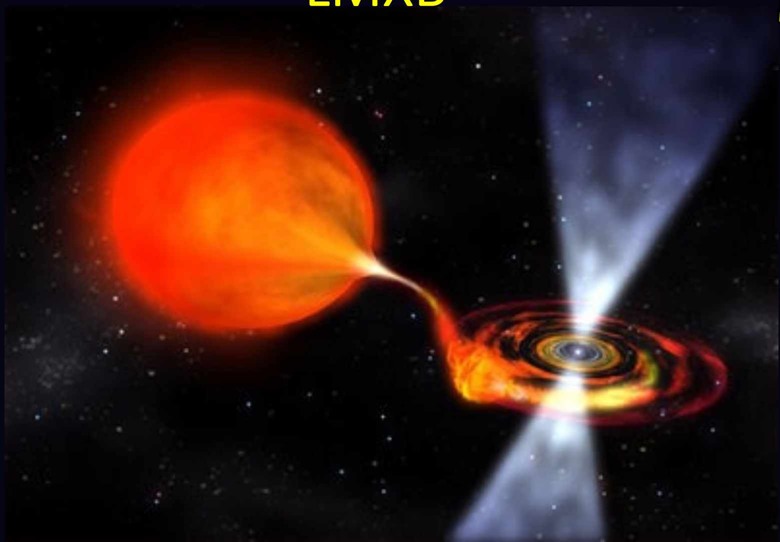
MSPs descendant of previous Gyr-long LMXB phase (Baker 1982; Alpar et al. 1982)

Millisecond Pulsars Binaries

AMXPs
Accretion-powered X-ray ms Pulsars

X-ray bright & radio quiet

LMXB



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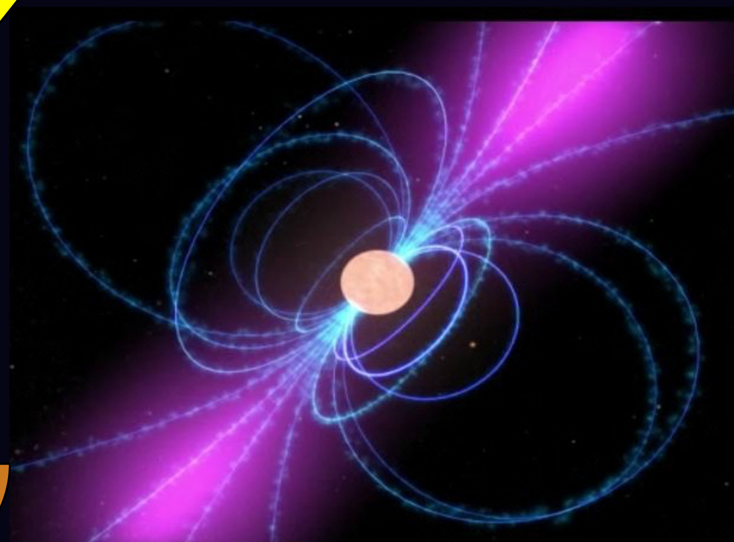
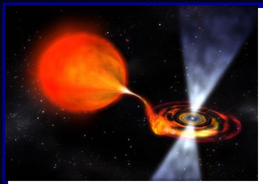
RMSPs
Rotation-power radio ms Pulsars

Radio loud & X-ray faint
Y-ray bright





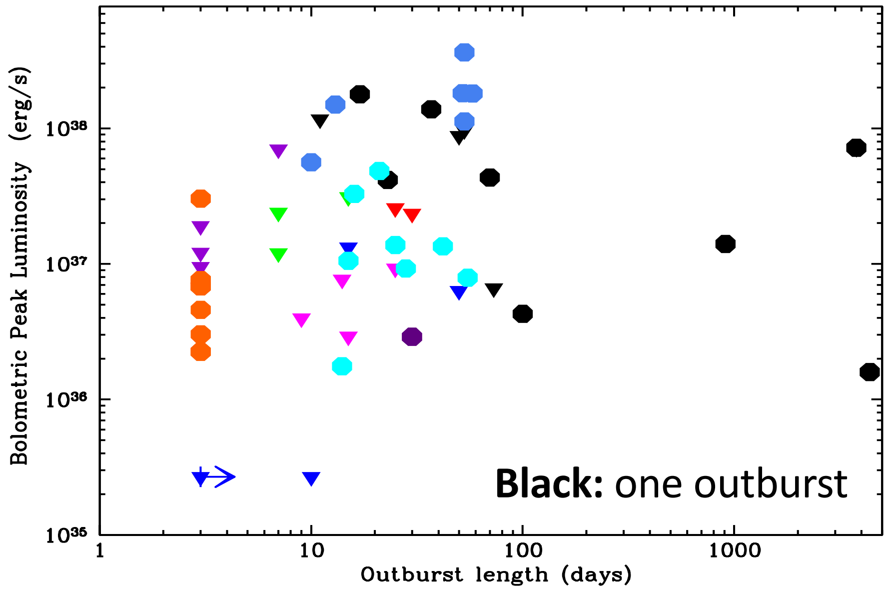
LMXBs hosting AMXPs

- Subclass of LMXBs: 21 systems - P_{spin}<10ms; B≈10^8 – 10^9G (Patruno & Watts 2012; Di Salvo & Sanna 2020; Ng et al. 2021)
- Compact binaries: P_{orb} < 1d with RLOF MS, WD or BD
- Long quiescence: years–decades - Lx ≈ 10^{31} – 10^{34} erg/s
- **All transients**: Lx,peak ≈ 10^{36} – 10^{38} erg/s

  Outburst duration ≈ few days - months – years (a few)

  ≈ Half show multiple outbursts – with recurrence of a few yrs

  Hard spectra – BBs + Comptonization components



Luminosity not related to outburst length

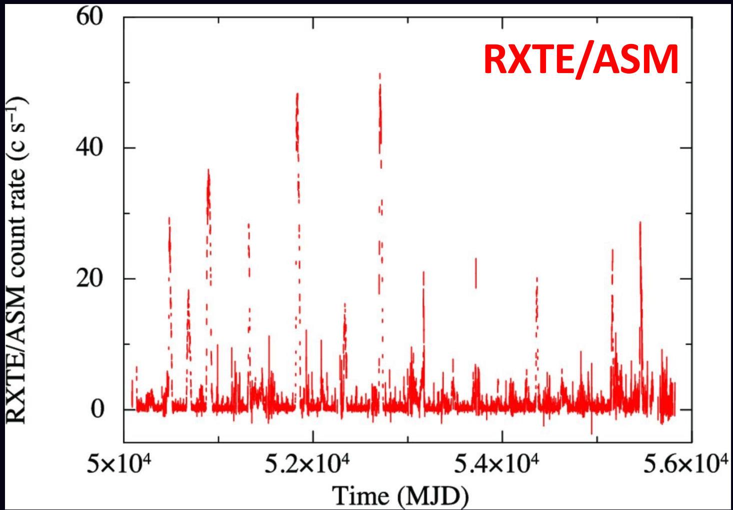
Thermonuclear (Type-I) bursts in half of the systems

After Marino et al. 2019

Outbursts in AMXPs: a few examples

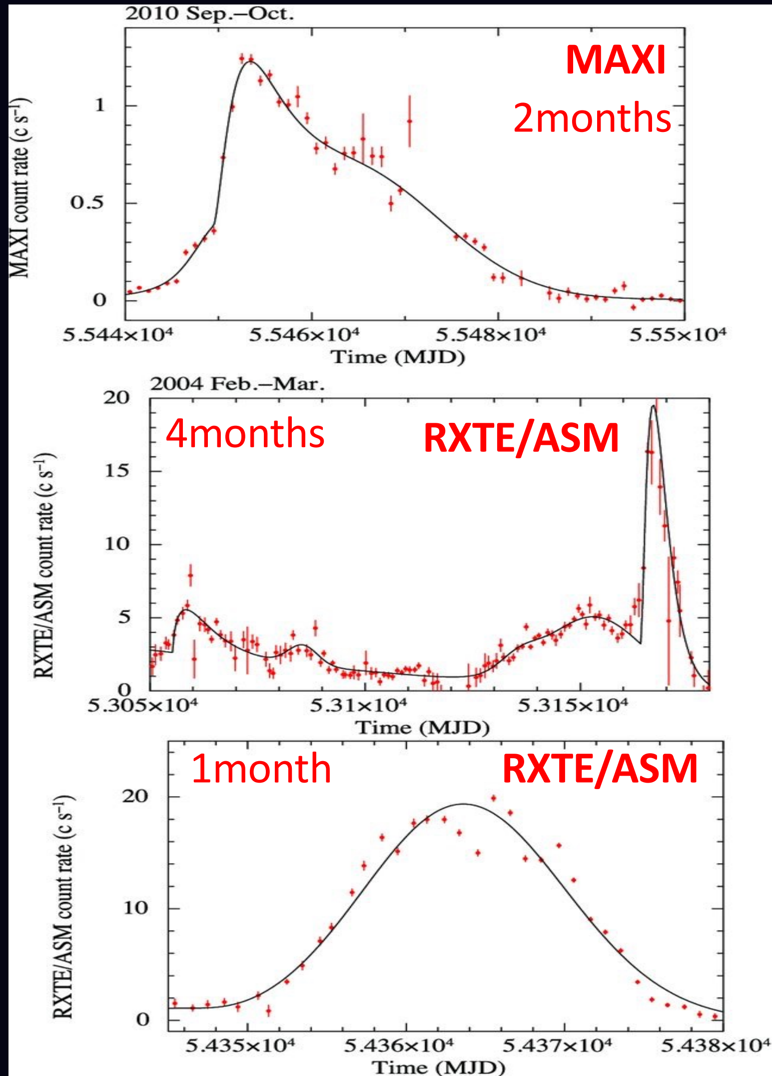
Aql X-1

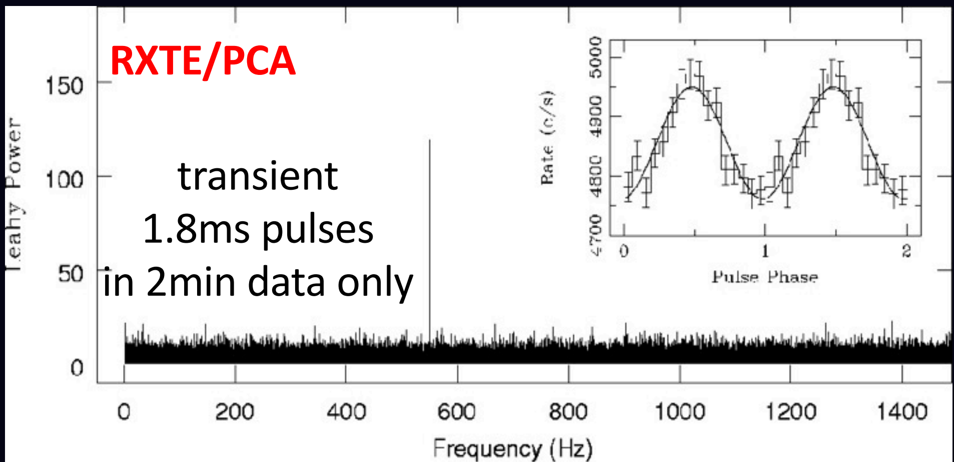
Porb=18.8h



Different morphologies: DIM - Irradiation

Campana et al. 2013



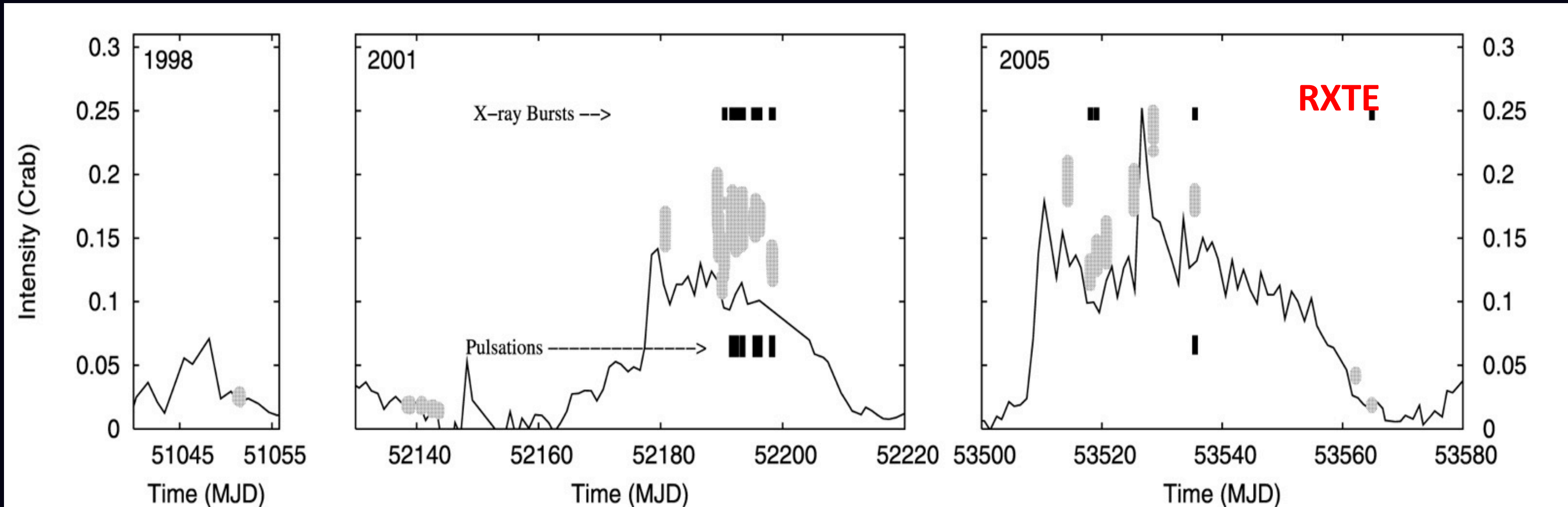


Casella et al. 2008

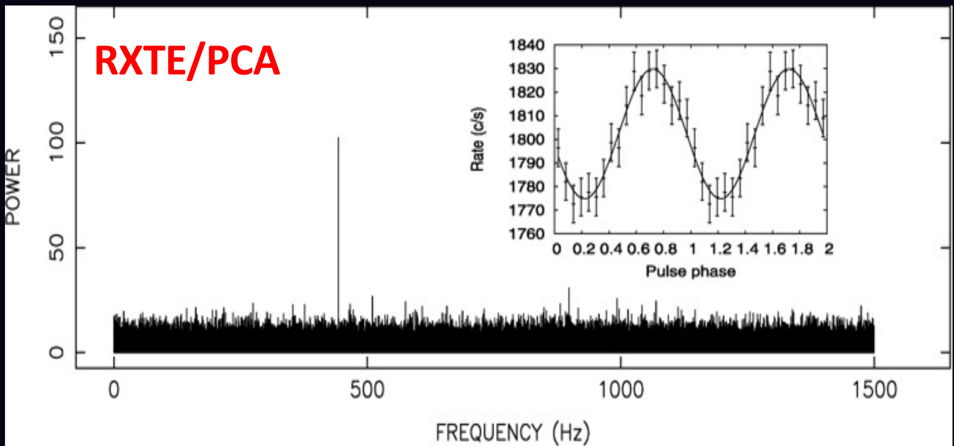
Outbursts in AMXPs: a few examples

Exceptions:

SAXJ1748.9-2021



Altamirano et al. 2008



Porb= 8.8h

Intermittent 2.3ms pulses

appearing/disappearing

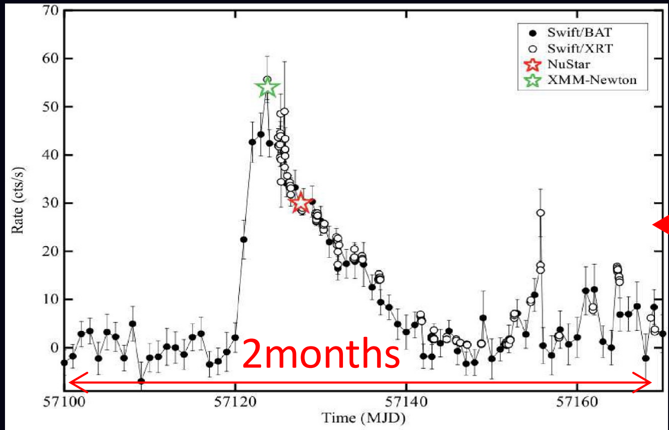
over hundreds of seconds

most just after Type-I bursts

Outbursts in AMXPs: a few examples

SAXJ1808.4-3658

Porb=2.01h
Pspin=2.5ms



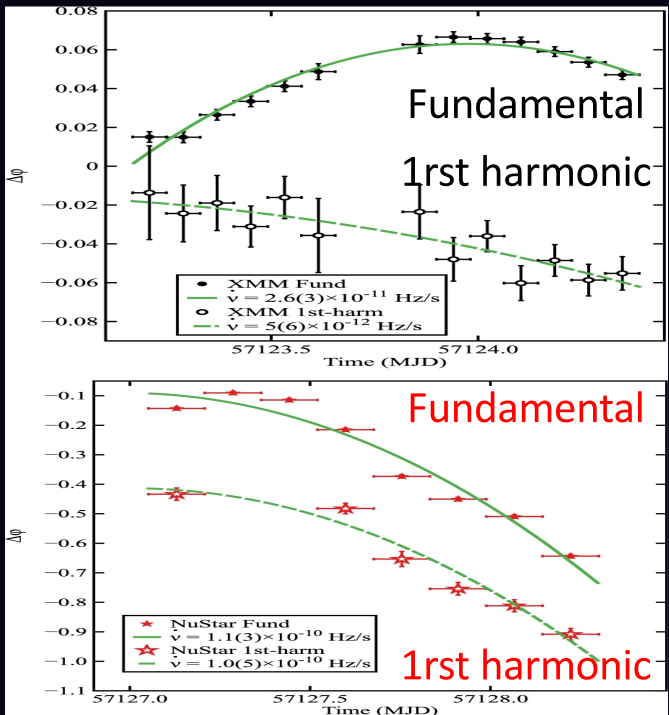
Di Salvo et al. 2019

Recent outbursts
2015
&
2019

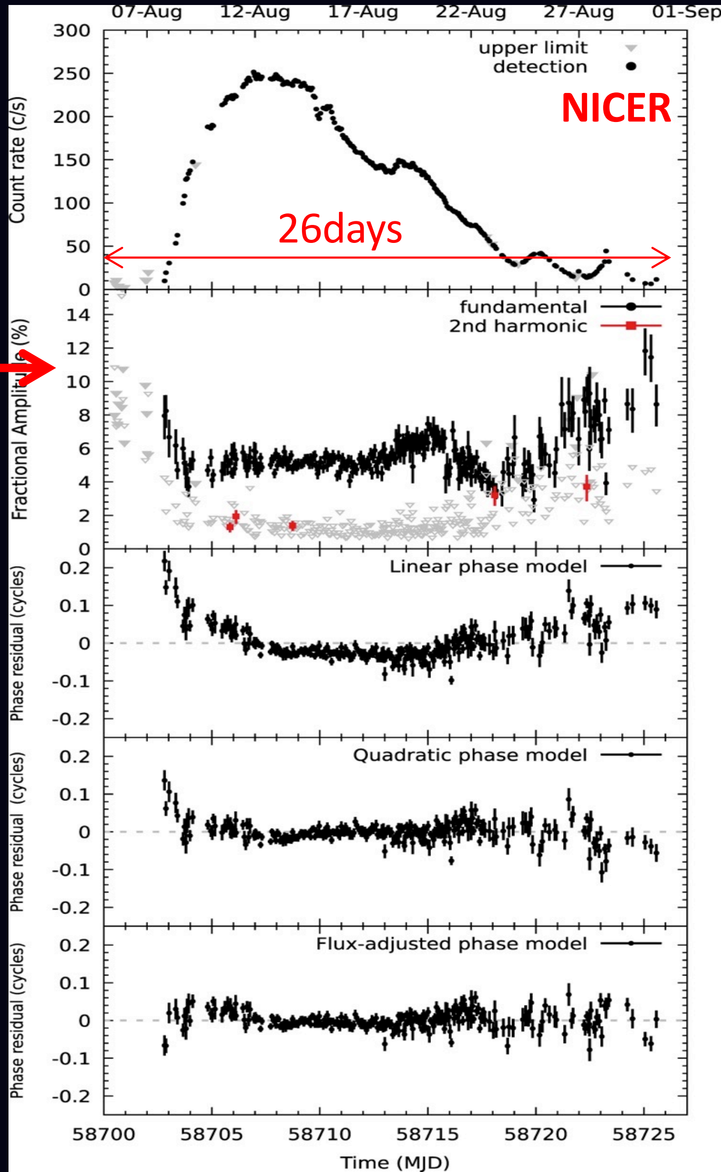
Long-term spin-down

Long-term orbital expansion
↓
Non-conservative mass transfer

Radio ejection scenario
(Burderi et al. 2003)

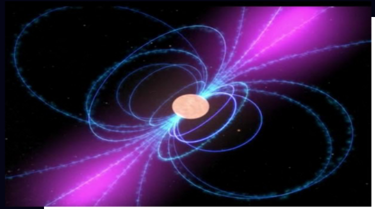


Sanna et al. 2017



Bult et al. 2019

What link between LMXBs and radio MSP?



Rotation-power ms pulsars (RMSPs)

- ≈ 340 radio MSPs: P_{spin}< 30ms; B≈10^7-10^9G; $\dot{E}_{spin-down}$ ≈ 10^{34}- 10^{35}erg/s
- ≈ 200 are in compact binaries : P_{orb} < 1 d
- ≈ 70 show irregular radio eclipses → mass loss from ablated companion star:

44 "Black widows" (**BW**) - $M_2 < 0.04 M_\odot$ (degenerate)
26 " Redbacks" (**RB**) - $M_2 \approx$ 0.1 -0.5 $M_\odot$ (MS)

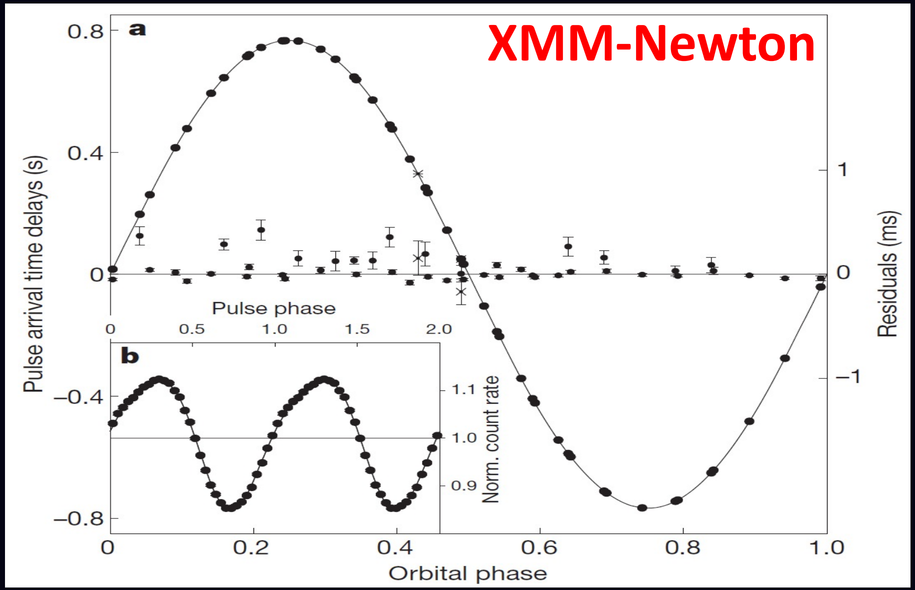
} **Spiders** Roberts 2013

- ≈ 80 MSP binaries detected as Gamma-ray **Fermi-LAT** sources

(Abdo et al. Science 2009, Pietsch et al Science. 2012, Acero et al. 2015,Deneva etal.2021)

IGR J18245-2452: A transient in the GC M28

An AMXP
discovered in outburst
by INTEGRAL
March 28, 2013



$L_x \approx$ 1-4 x 10^{36} erg/s

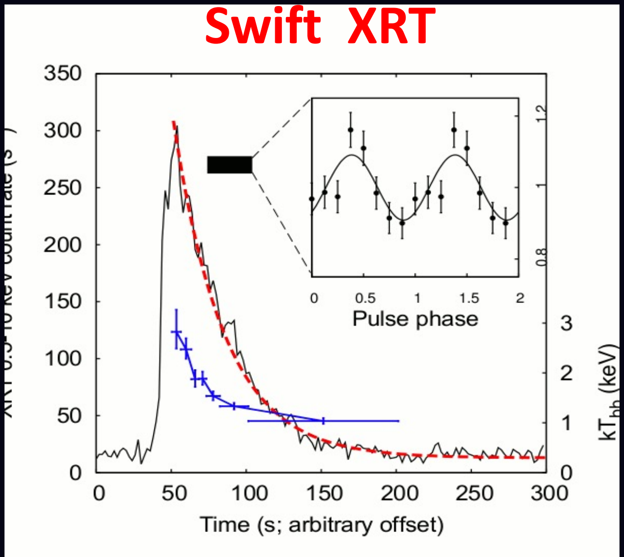
X-ray Pulses (4-16%) @ 3.9ms

Porb = 11. 0h

$M_{2,min}$ = 0.17 → **Redback**

Thermonuclear Bursts

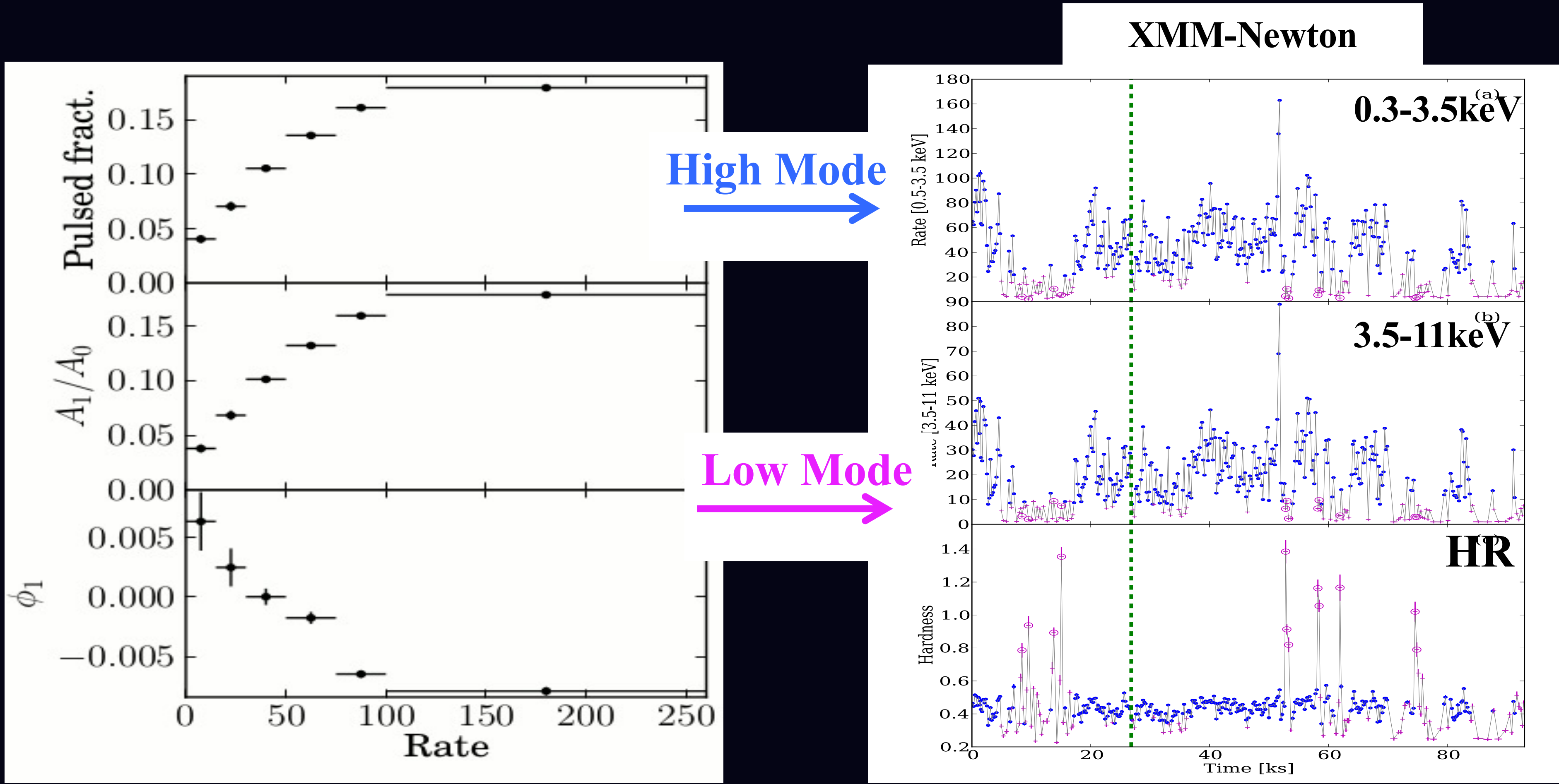
Peculiar short term X-ray variability



Papitto et al. 2013, Nature

IGR J18245-2452: A transient in the GC M28

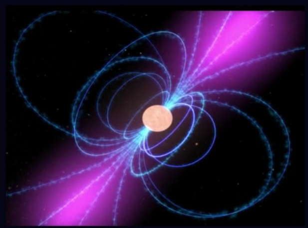
Peculiar X-ray Variability in Outburst

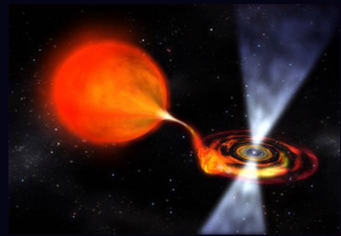


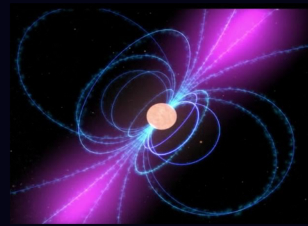
Ferrigno et al. 2014

The first swinging MSP binary

IGRJ 18245-2452/PSRJ1824-24521

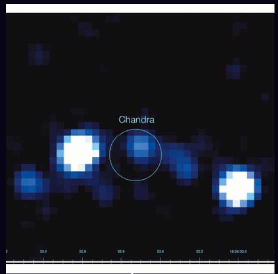




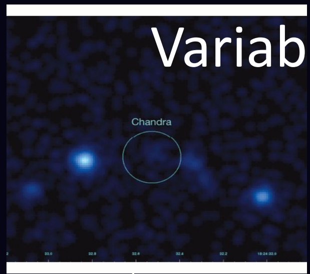


Chandra, XMM-Newton,Swift

ACIS – S

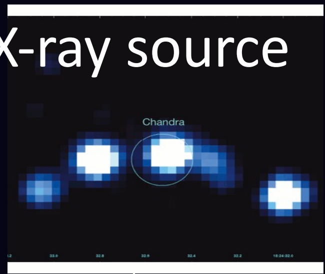


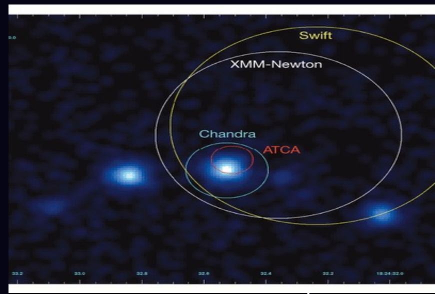
Chandra
HRC



Variable X-ray source

ACIS-S





2002 2006 2008 2009 March-April 2013 time (yrs)

ATNF Catalog

PSRJ1824-2452
3.9ms radio pulsar

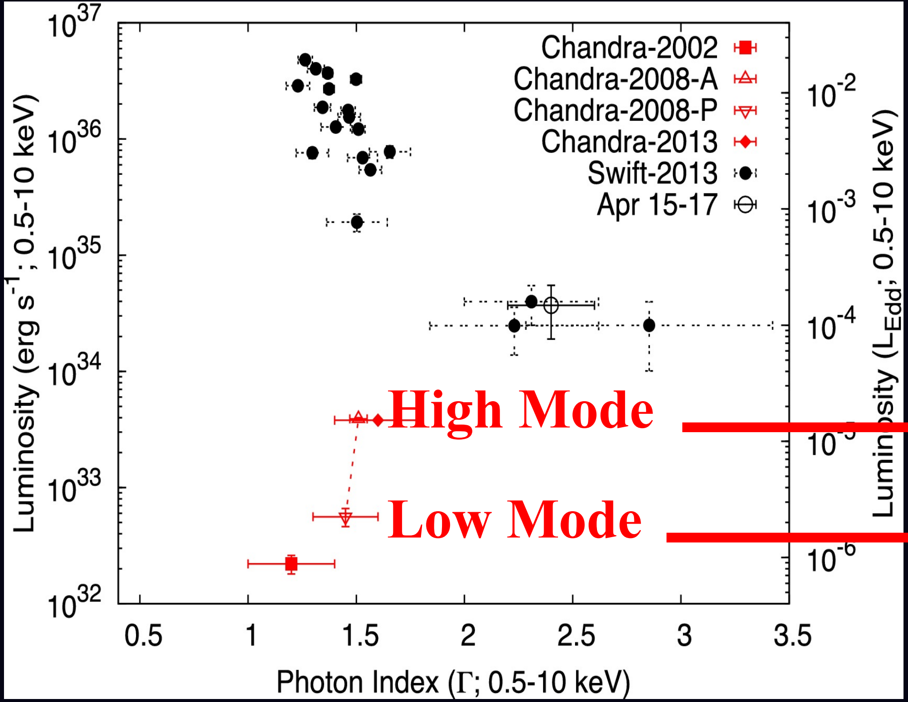
X-ray pulsar

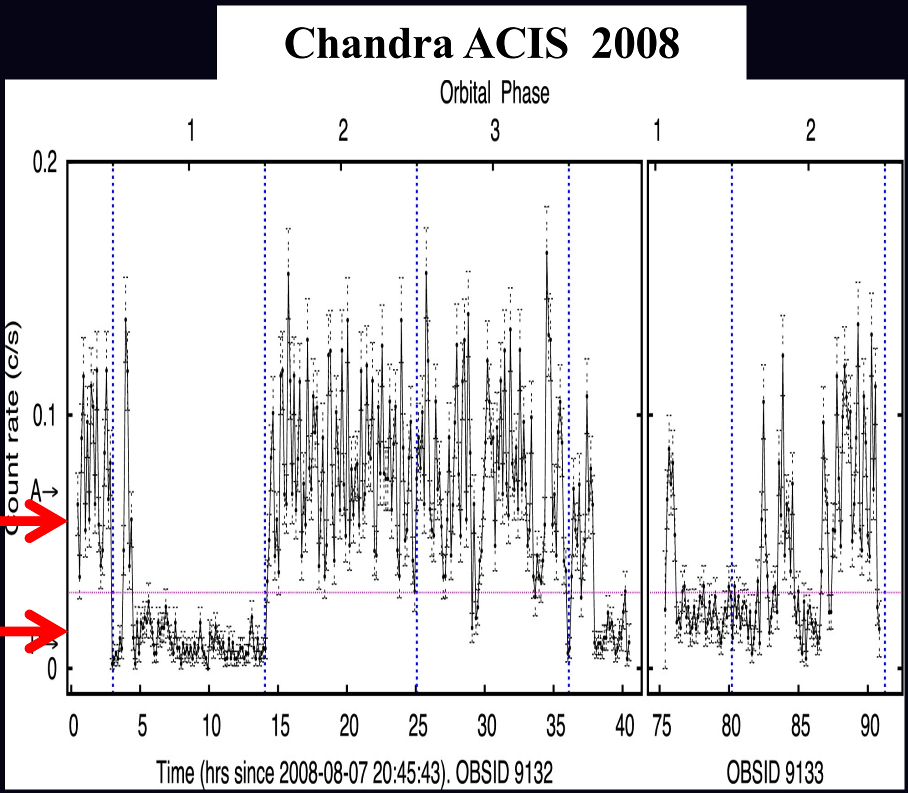
radio pulsar

Papitto et al. 2013, Nature

The first swinging MSP binary

Peculiar X-ray Variability also in a sub-luminous state





Mode switching

Accretion ⟷ Inhibition of accretion

Linares et al. 2014
Papitto et al 2013
Ferrigno et al. 2014

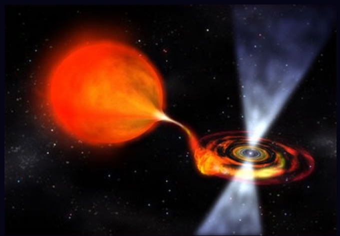
PSRJ 1023+0038

a transitional MSP in the Galactic field

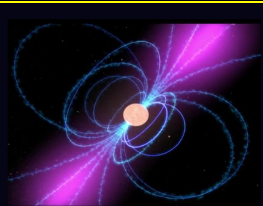
Archibald et al. 2009, Science

1.69ms Radio Pulsar
Radio Eclipses @4.75h

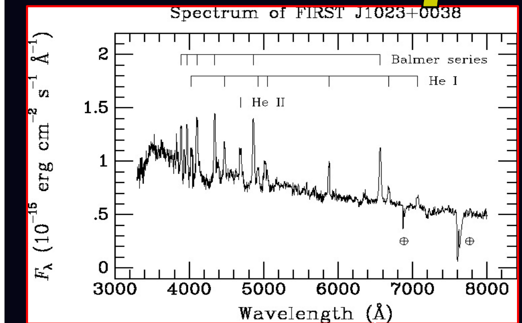
X-ray modulation @ 4.75h
Intrabinary shock

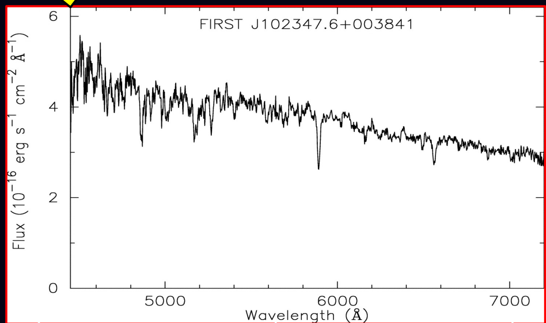


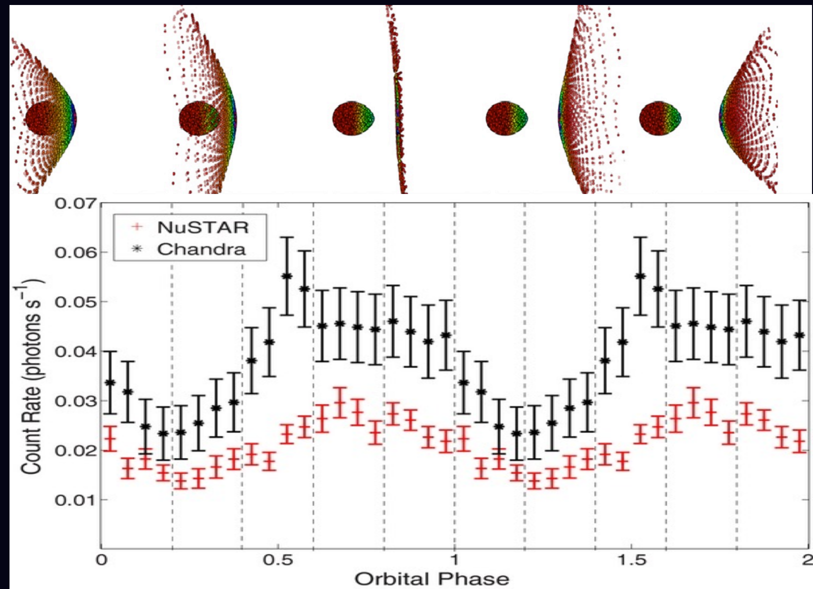
LMXB



RMSP







2000 2001 2002 2003 2004 2007 2008

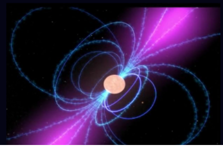
time (yrs)

Bond et al. 2002
Szkody et al. 2003

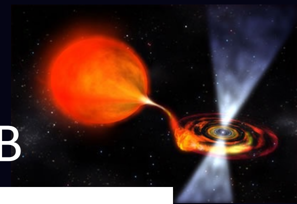
Homer et al. 2004,
Thorstensen&Halpern2005

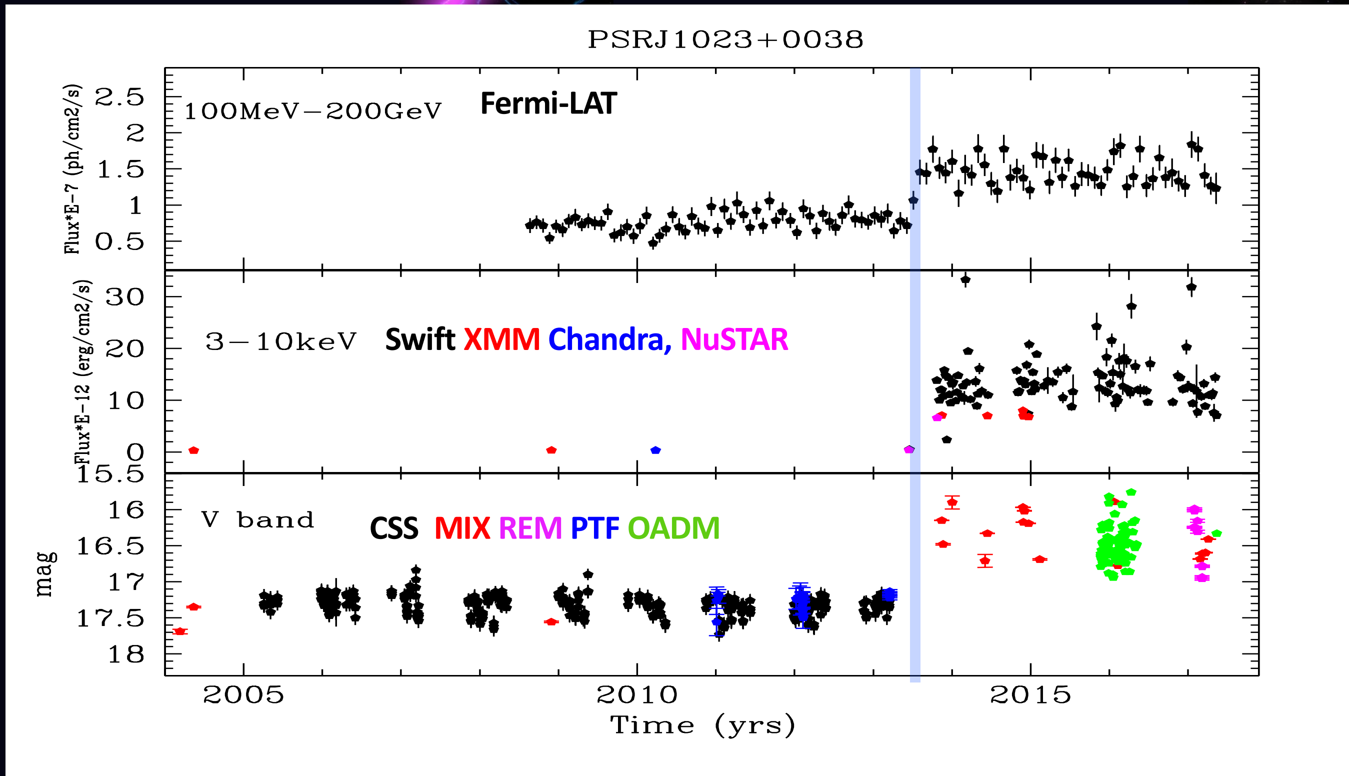
Bogdanov et al. 2011
Tendulkar et al. 2014

PSR J1023+0038: a new state transition in 2013



RMSP → LMXB





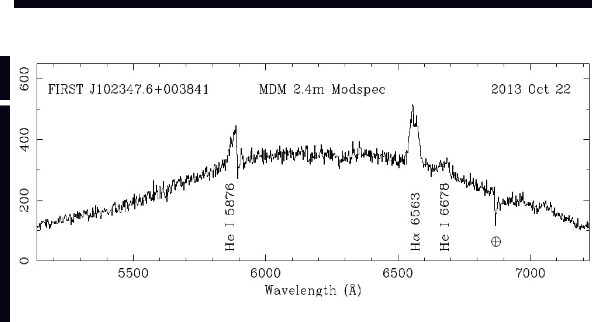
RMSP OFF

$L_{\gamma} \approx 0.1 \rightarrow 1.2\text{x}10^{34}$ erg/s

$L_{X} \approx 0.5 \rightarrow 6\ \text{x}10^{33}$ erg/s

$V_{Opt} \approx 17.5 \rightarrow 16.2$ mag

Accretion Disc

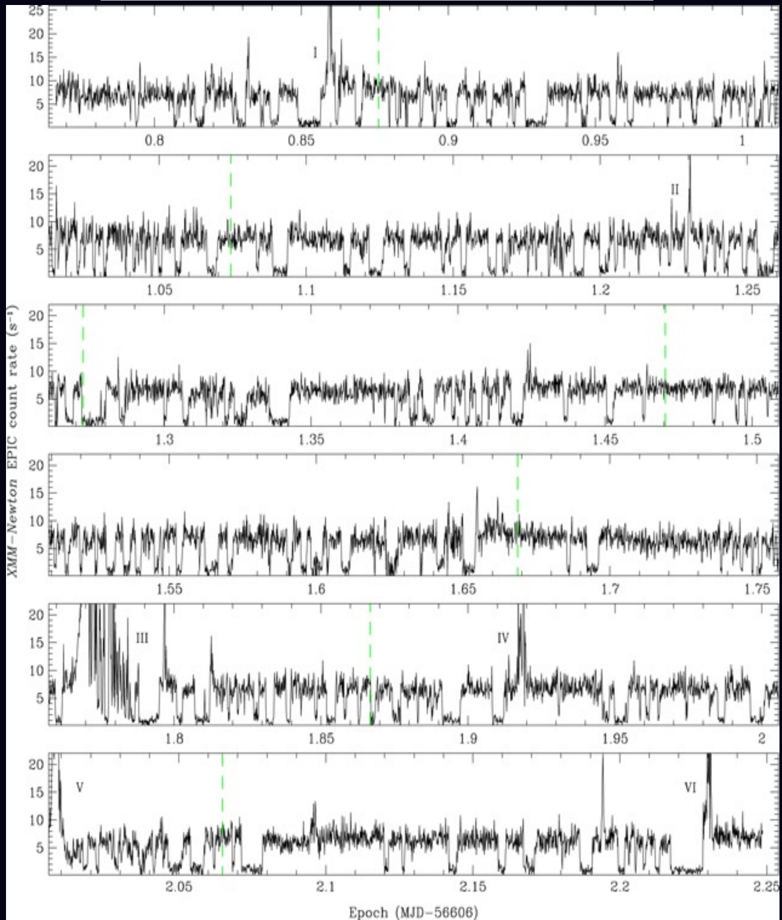


2004 **mid 2013** 2017

Stappers et al. 2014
Tendulkar et al. 2014
Patruno et al. 2014
Bogdanov et al. 2015

PSR J1023+0038: the sub-luminous LMXB state

XMM-Newton Nov.2013



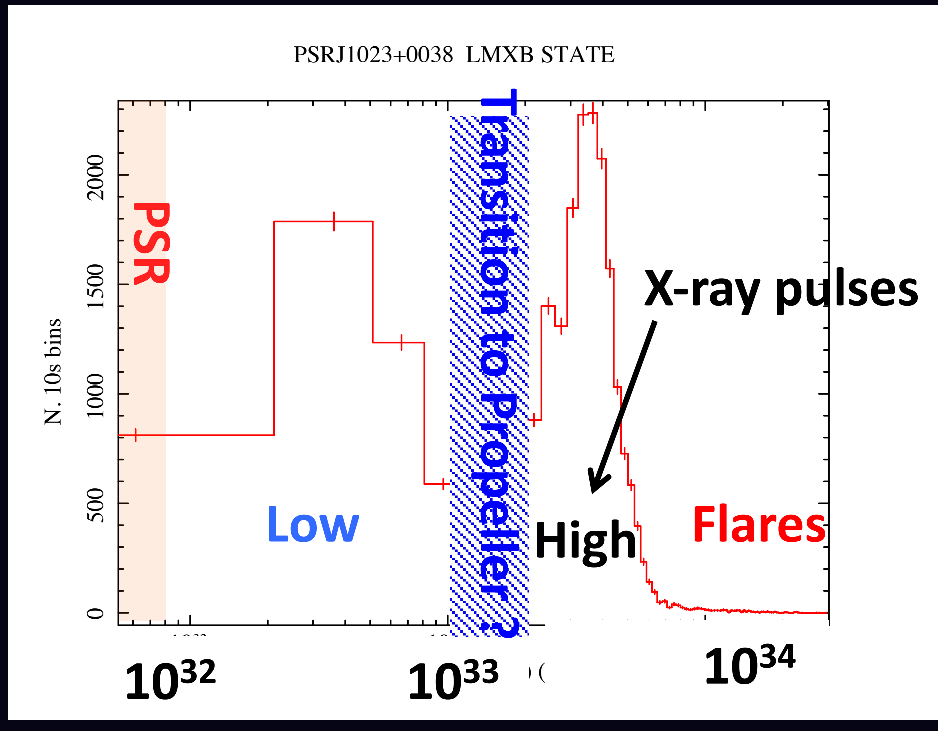
Tendulkar et al. 2014
Bogdanov et al. 2015
Archibald et al. 2015

X-ray Tri-modal behaviour:

Erratic Flares ≈ tens mins up to 10hr

Erratic Dips = Low Mode ≈ secs-mins

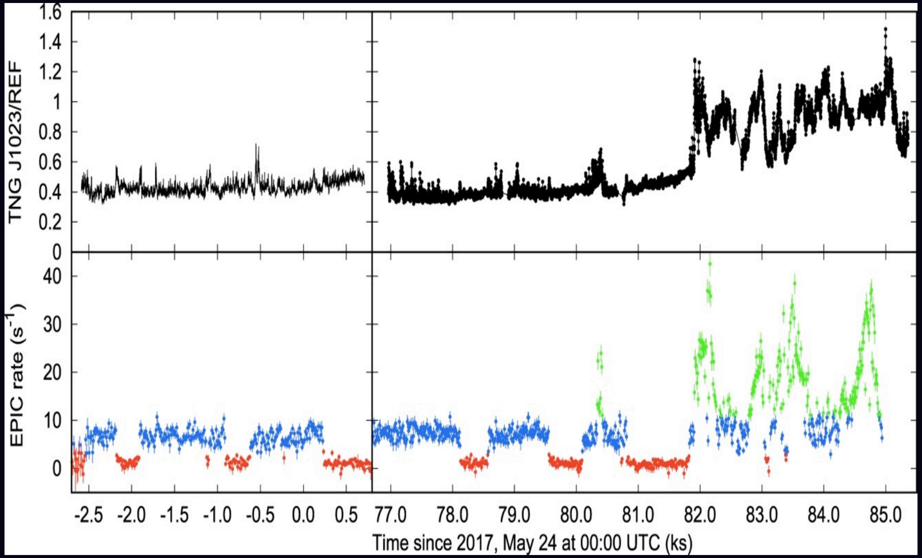
Persistent level = High Mode



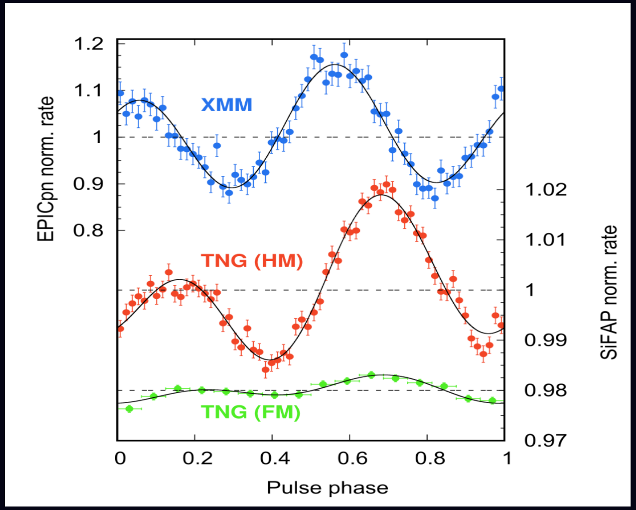
Luminosity (0.3-10keV) (erg/s)

PSR J1023+0038: the puzzling LMXB state

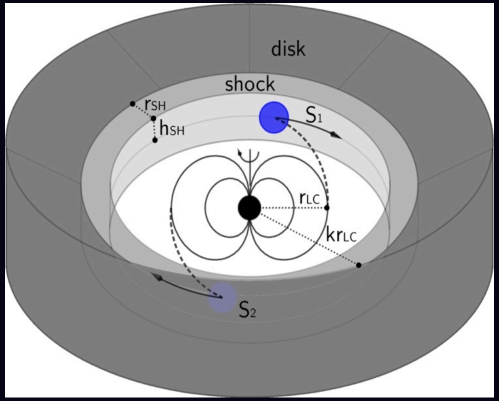
XMM-Newton & TNG 2017



X-ray pulses in high mode only



Optical pulses in high and flare mode



Challenging accretion ?

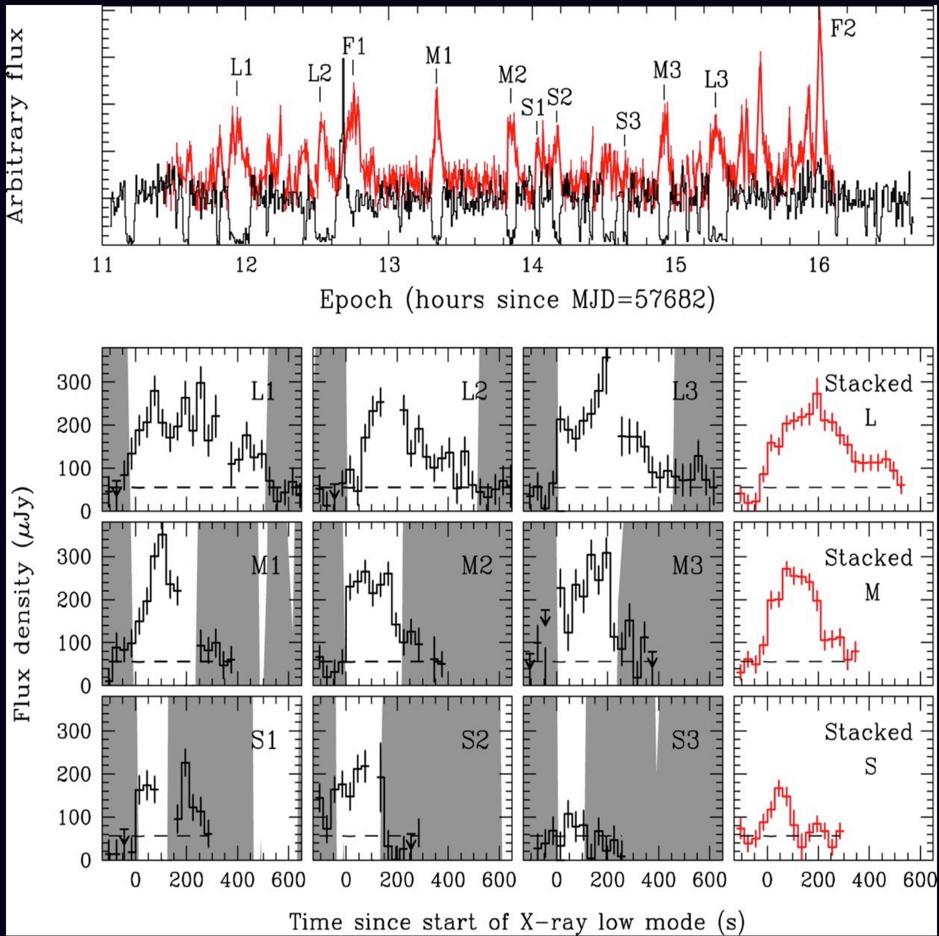
Synchroton emitting shock at a few R_{LC} radii

Ambrosino et al. 2017, Nature Ast.

Papitto et al. 2019

PSR J1023+0038: the puzzling LMXB state

XMM-Newton & VLA 2016



Bogdanov et al. 2018

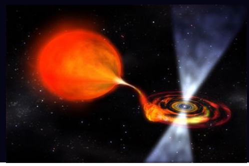
Anti-correlation X-ray – Radio emission:

X-ray low-modes & radio flares

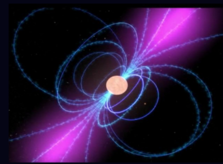
↓

Outflow/jet launching

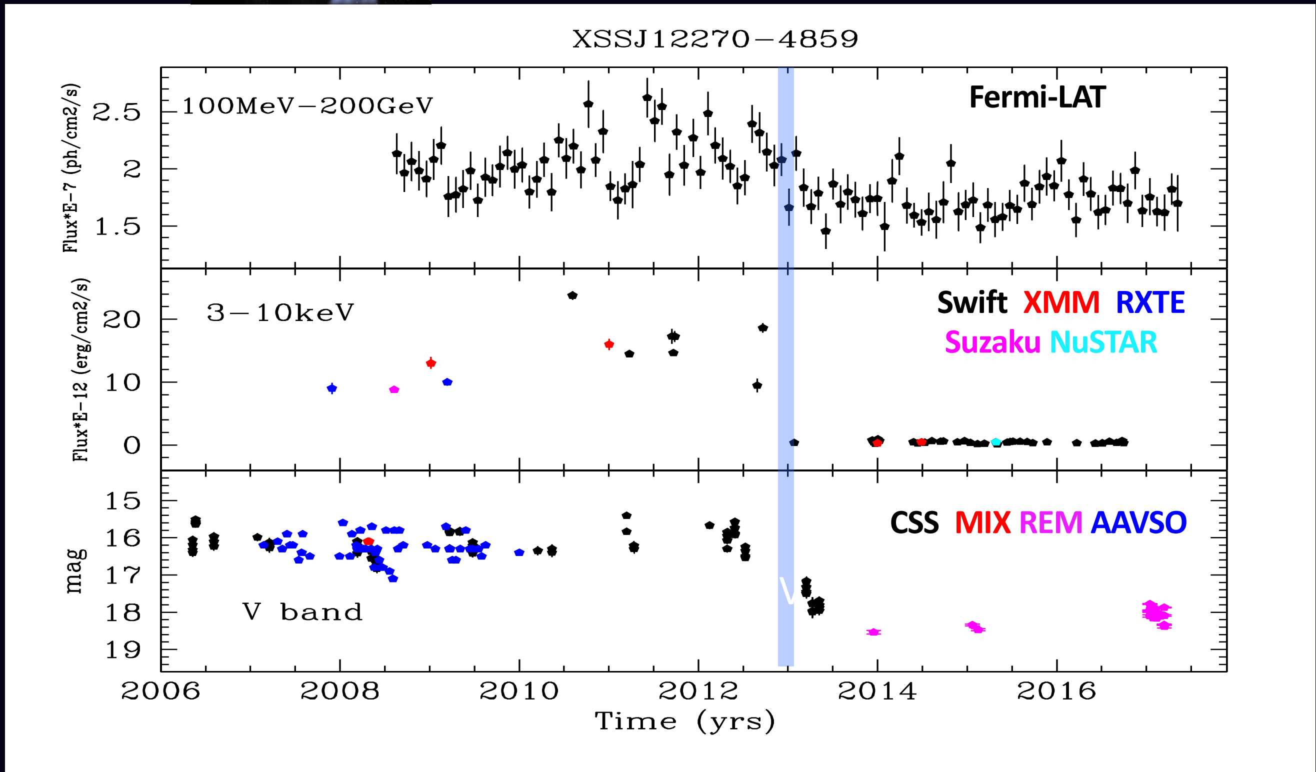
XSS J1227-4859: a late recognised twin transitional MSP binary



LMXB → RMSP



Radio pulses@1.69ms



$L_{\gamma} \approx$ 1.1 → 0.4 x10^{34} erg/s

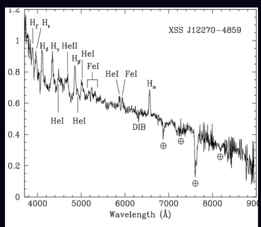
$L_X \approx$ 6 → 0.2 x10^{33} erg/s

$V_{Opt} \approx$ 16 → 18 mag

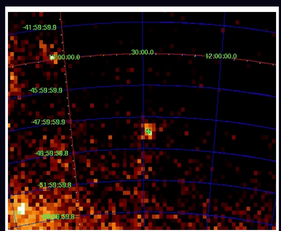
G-type optical spectrum

No disc

2006 | Nov-Dec 2012 | 2017 | time (yrs)



Fermi-LAT

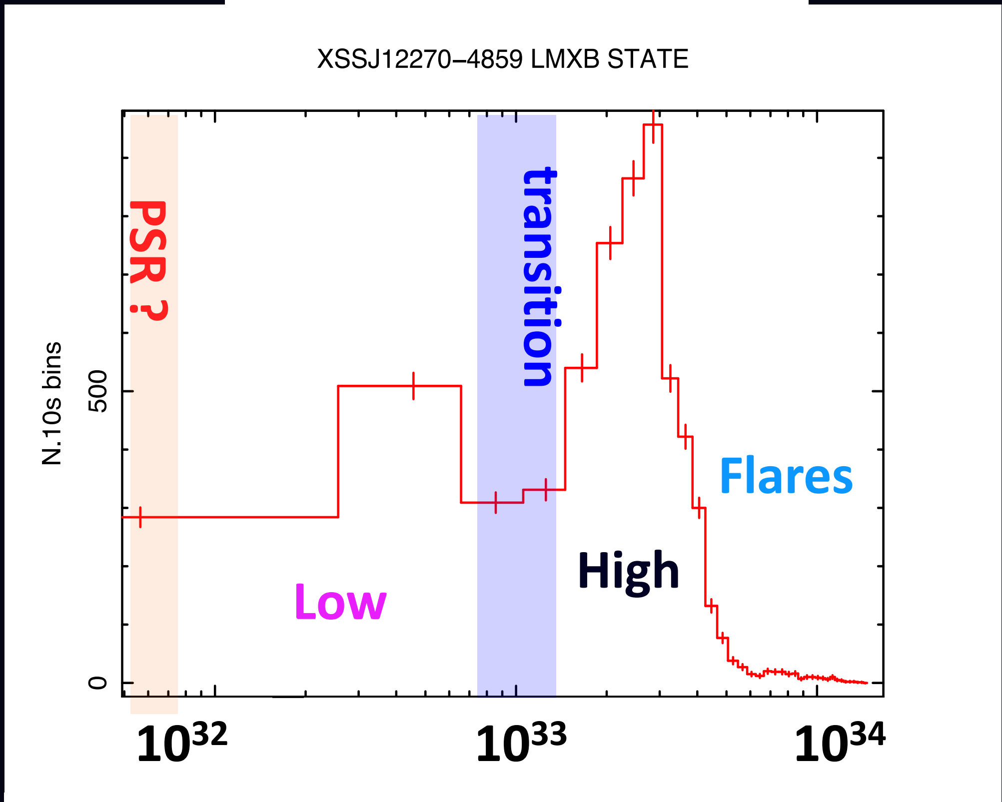


Masetti et al. 2006
de Martino et al. 2010,2013

Bassa et al. 2014
de Martino et al. 2014
Roy et al. 2015
Torres et al. 2017

XSS J1227-4859: a late recognised twin transitional MSP binary

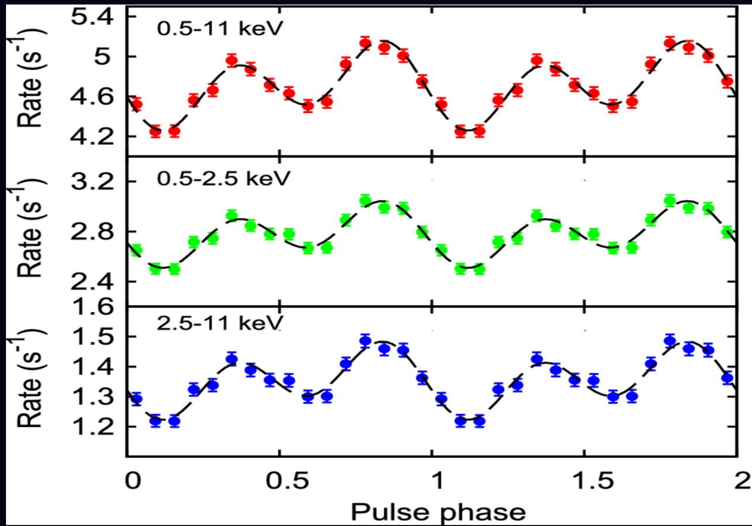
XMM-Newton 2009-2011



Mode switching

de Martino et al. 2010,2013

X-ray pulses in high mode only



$A \approx 8\%$	High	
$A < 2\%$	Flares	3σ
$A < 5.9\ \%$	Low	3σ

Papitto et al. 2015

Millisecond Pulsars Binaries with THESEUS

TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

The transient behaviour of MSPs binaries requires monitoring facilities

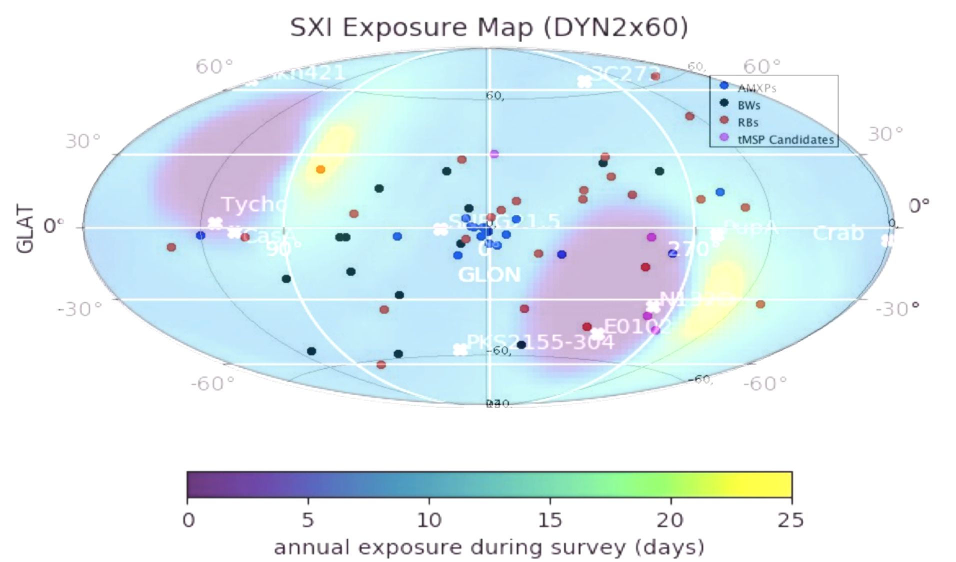
Crucial aspects:

- ❑ Catching ourbursts from known and new AMXPs
- ❑ Catching state-transition from/to LMXB/RMSP states

How many at reach of THESEUS?

> > 70 detected in X-rays :
> 21 AMXPs, 24 RBs, 21 BWs
> 4 transitional candidates
> 3 RBs at long (>1d) Porb

Courtesy: A. Beardmore



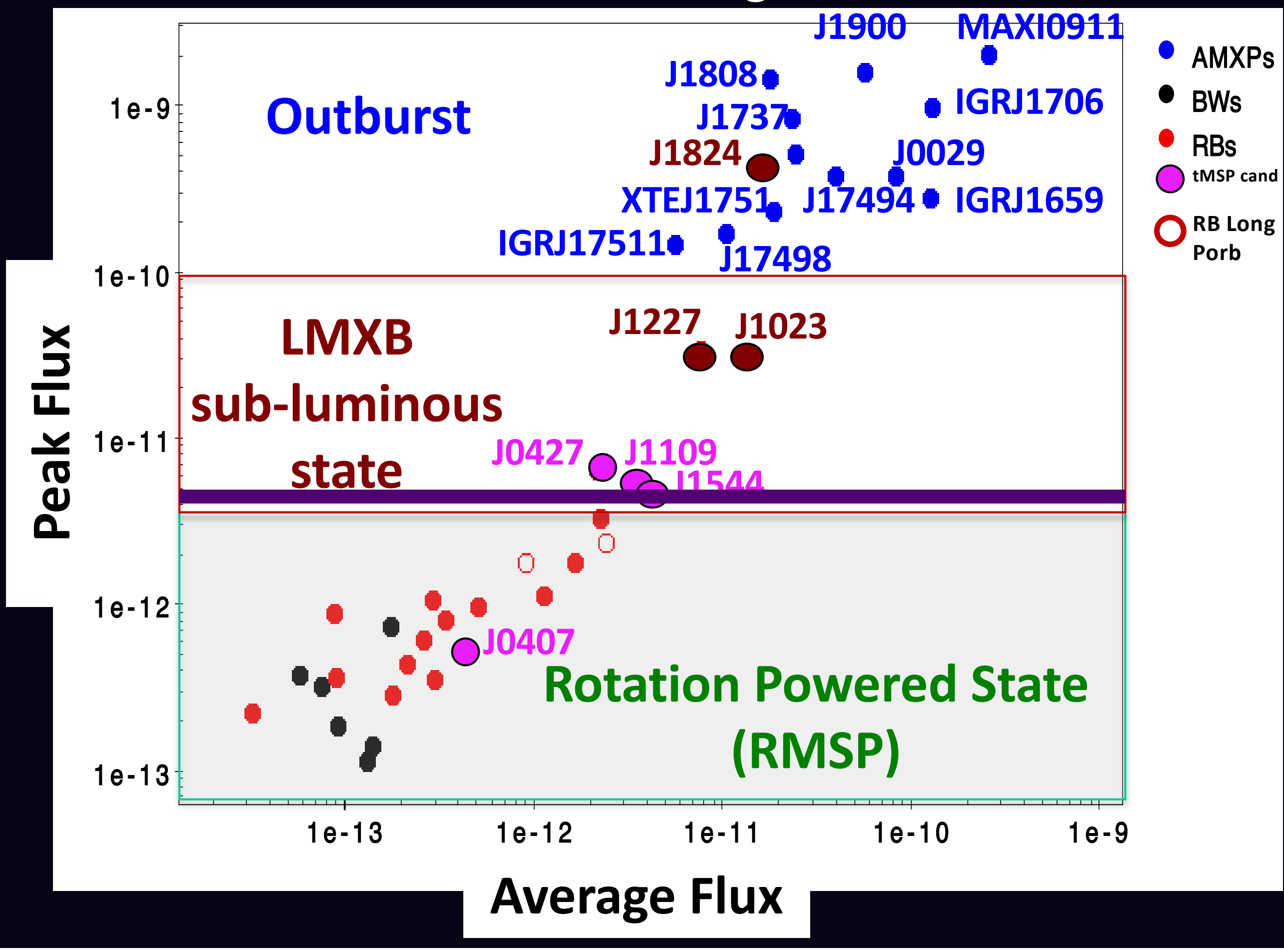
Millisecond Pulsars Binaries with theseus

TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

How many at reach of THESEUS?

Match with Swift/XRT 2SXPS catalogue clean version (Evans et al. 2020)

Swift/XRT Peak vs Average flux 0.3-10keV



AMXPs
tMSP
tMSP Cand
RBs
BWs

Setting Limit to SXI 0.3-5keV flux of 5E-12 cgs for 80ks expo

Millisecond Pulsars Binaries with THESEUS

TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

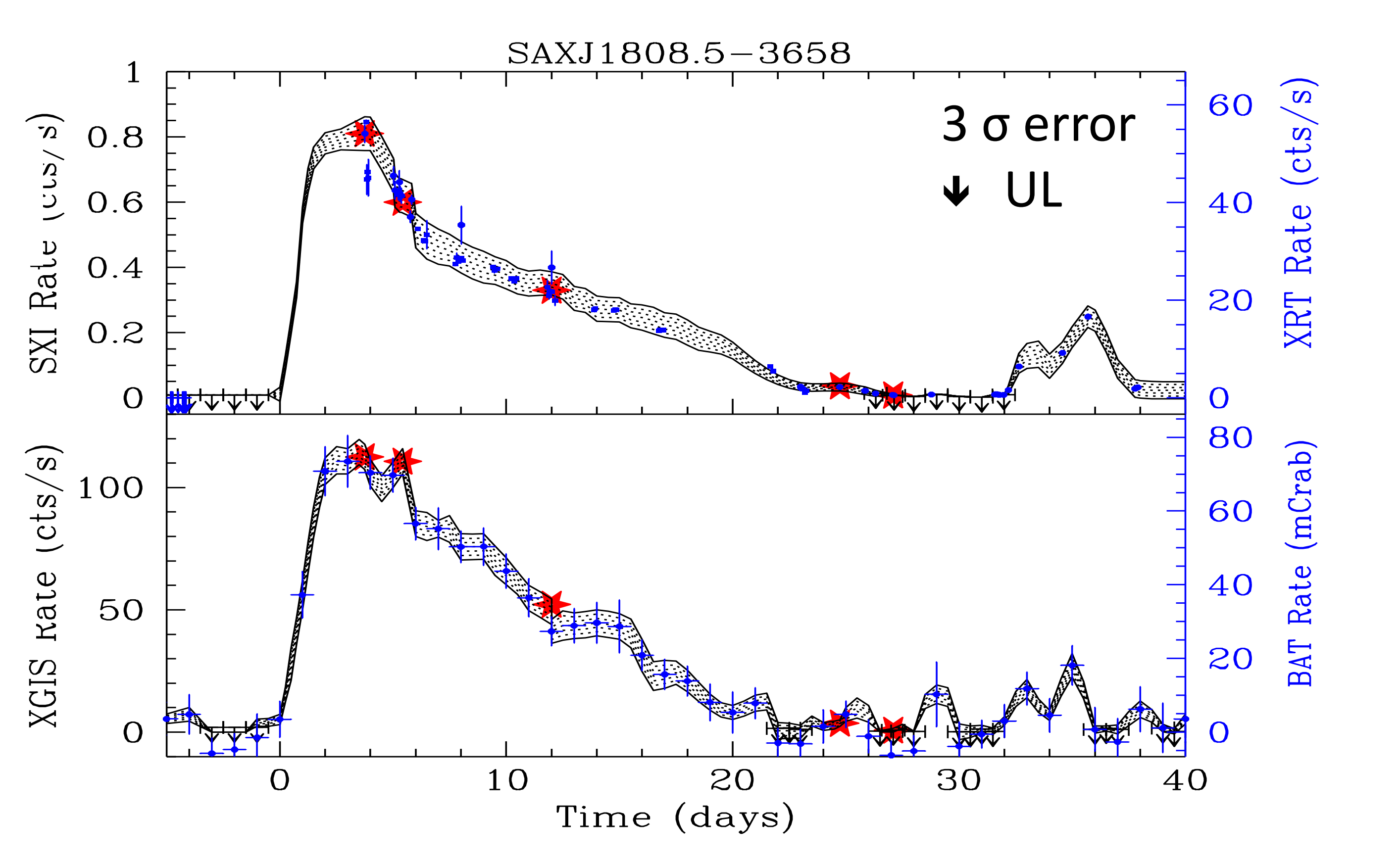
How many at reach of THESEUS?

AMXPs will be detected at outbutst

- Example of simulated SAXJ1808-3658 outburst in 2015

SXI BKG ARF
675 arcmin^2

XGIS BKG RESP
On-axis

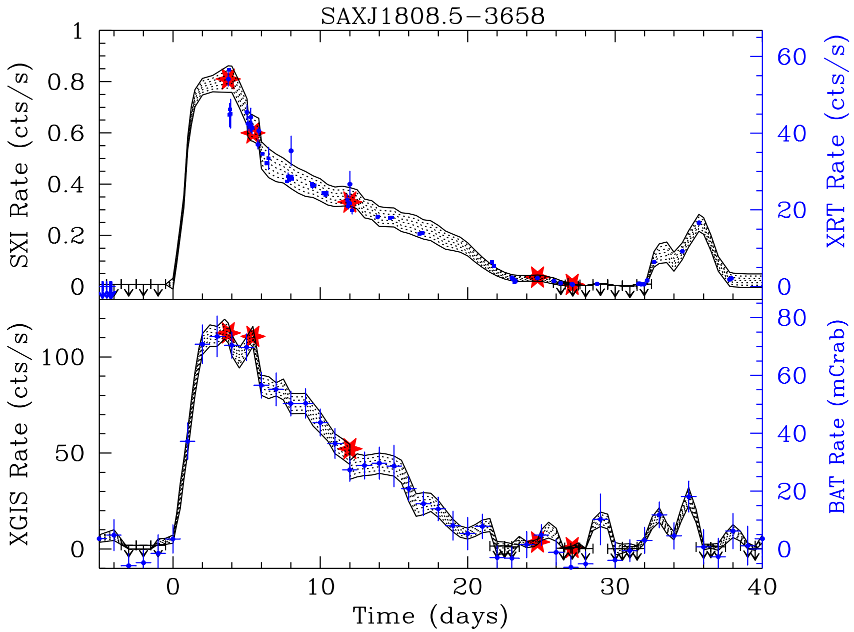


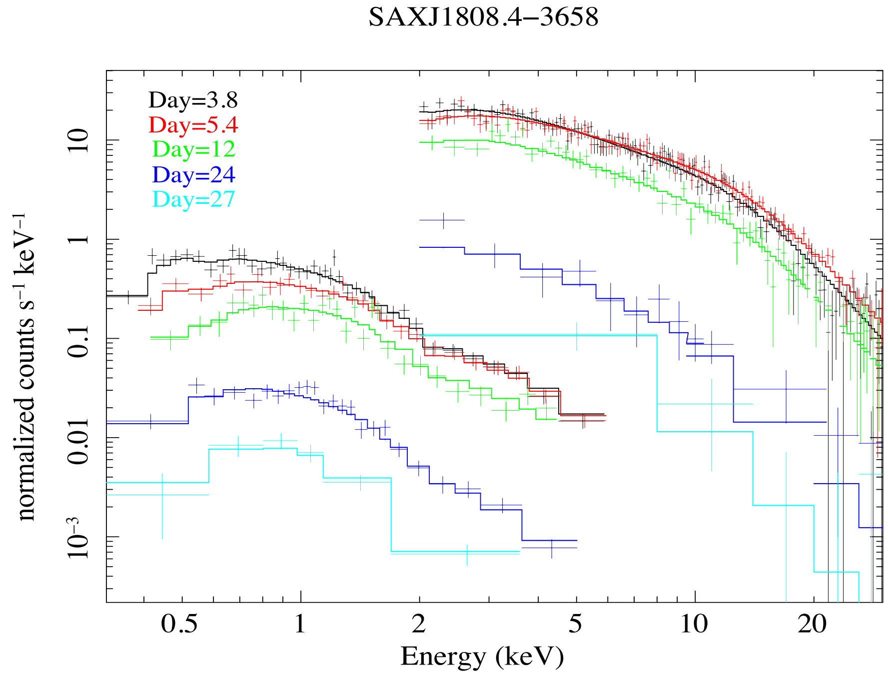
Swift/XRT

Swift/BAT

OUTBURST COVERAGE of AMXPs

Example of SAXJ1808.4-3658 outburst in 2015





Simulated SXI and XGIS spectra at 5 epochs of outburst adopting an absorbed **PL** with **Nh** and **Γ** as derived from SWIFT/XRT fits and Texpo=2ks (first 3 epochs); Texpo=30ks (4th epoch) and Texpo=30ks (SXI) and 100ks (XGIS) (5th epoch)

Parameters recovery:

Day	**Nh**	**Γ**	**Day**	**Nh**	**Γ**
3.8	2%	2%	24	30%	7%
5.4	2%	2%	27	----	----
12	4%	4%			

Complex simulated spectrum at peak not necessary (e.g. tbabs*(bb+nthcomp+3diskline) (see Di Salvo+19)

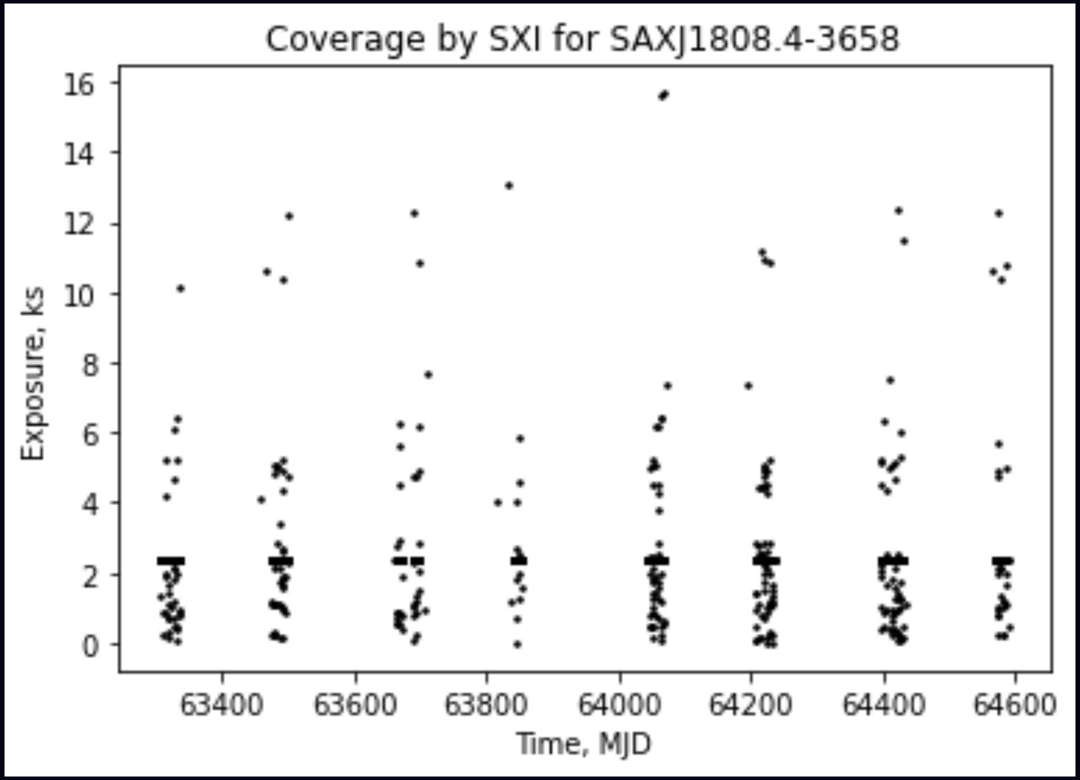
Millisecond Pulsars Binaries with theseus

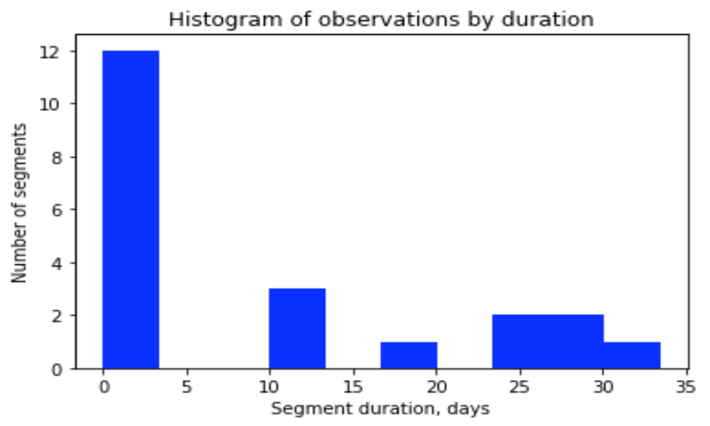
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

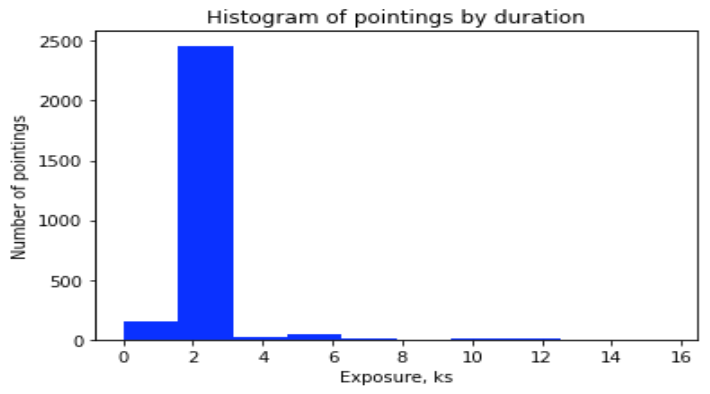
SAXJ1808-3658 coverage with SXI

SXI VISIBILITY tool with GRBs

credit: V. Doroshenko







Millisecond Pulsars Binaries with THESEUS

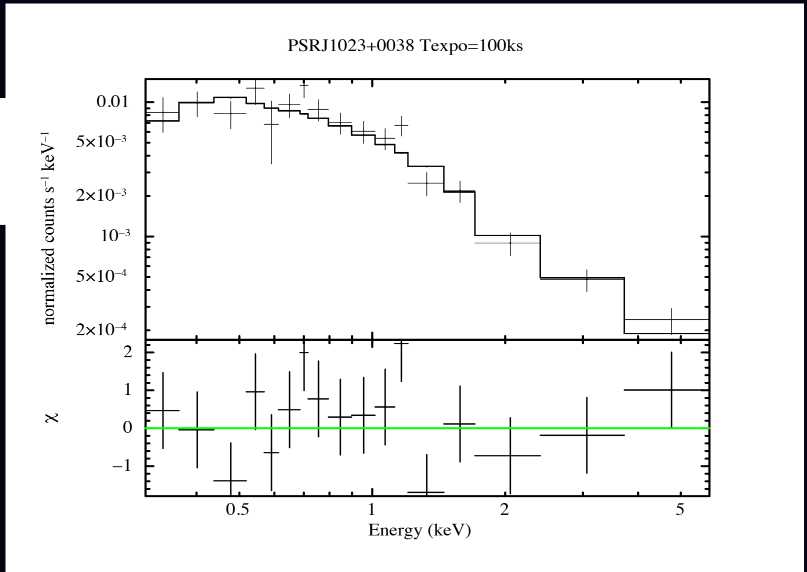
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

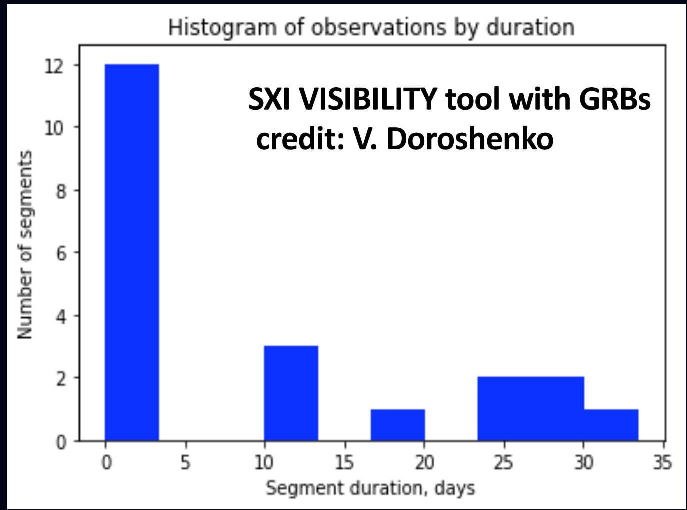
How many at reach of THESEUS?

At least 6-8 RBs transiting to/from sub-luminous state

- Example of simulated SXI spectrum of PSRJ1023-0038 in LMXB state

SXI BKG ARF
675 arcmin^2





SXI rate: 0.0102cts/s in 0.3-6keV
Power law Index Γ = 1.7 recovery at 15% in 100ks

Conclusions

theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

Millisecond pulsar binaries have transient behaviour

Outbursts ⟷ (LMXB) Sub-luminous states ⟷ (RMSP) IB dominated states

Need to increase statistics to answer:

- How accretion and magnetic field rotation power loss compete?
- Do transitional MSPs represent an intermediate evolutionary stage?

THESEUS will offer a great opportunity to find state transitions
- simultaneous IRT coverage for sources within a few deg from pointing

Synergies with facilities like: Athena, SKA, LSST, CTA