Transitional Millisecond Pulsar Binaries

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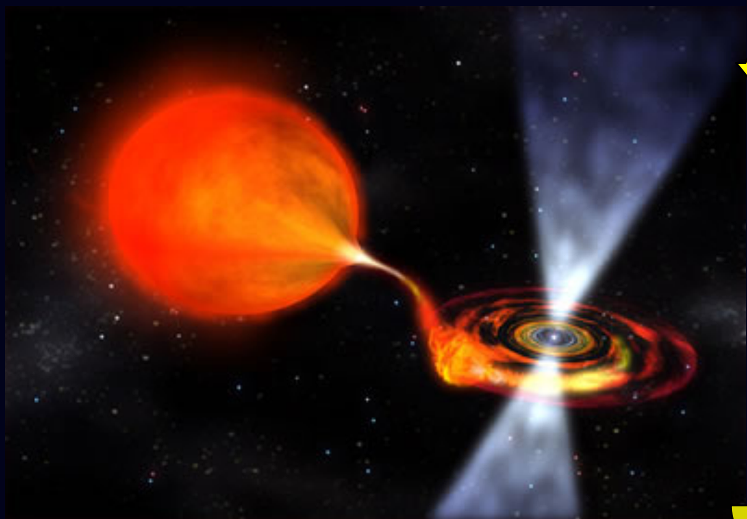
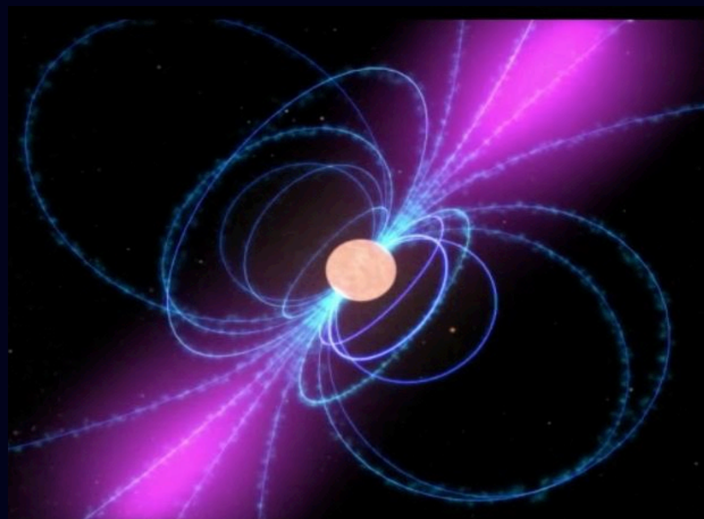




“The X-ray Universe 2017” – Rome , 6-9 June 2017

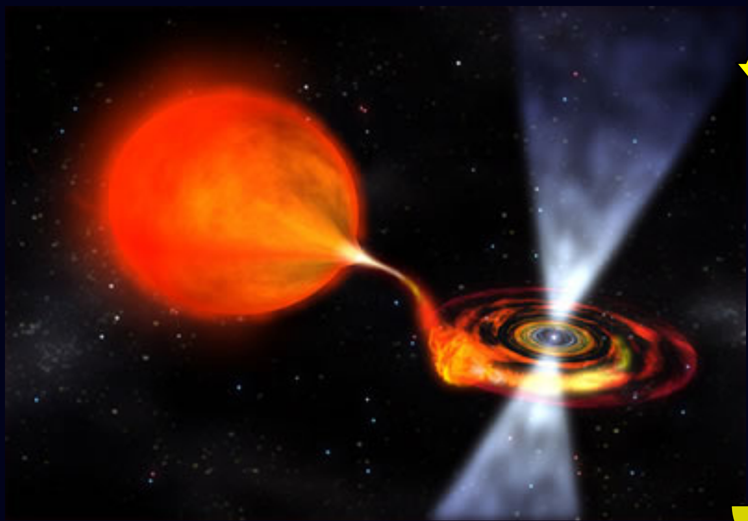
Millisecond Pulsars

AMXPs
Accretion-power X-ray ms Pulsars

X-ray bright & radio quiet

RMSPs
Rotation-power radio ms Pulsars

Radio loud & X-ray faint



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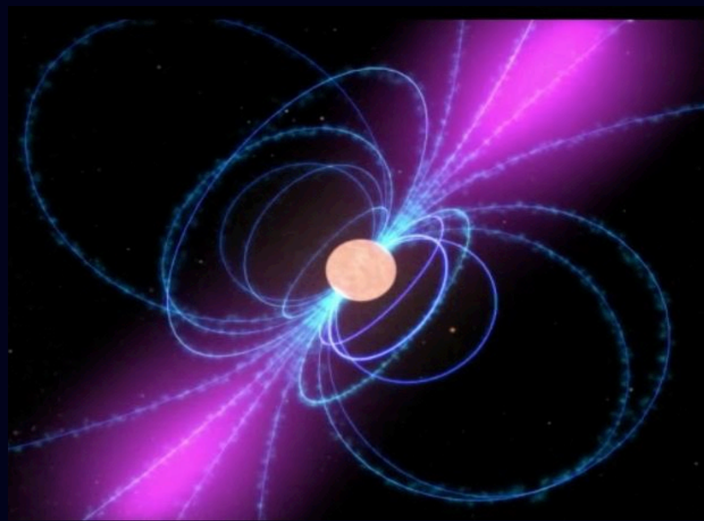


Fundamental Plane of Pulsars

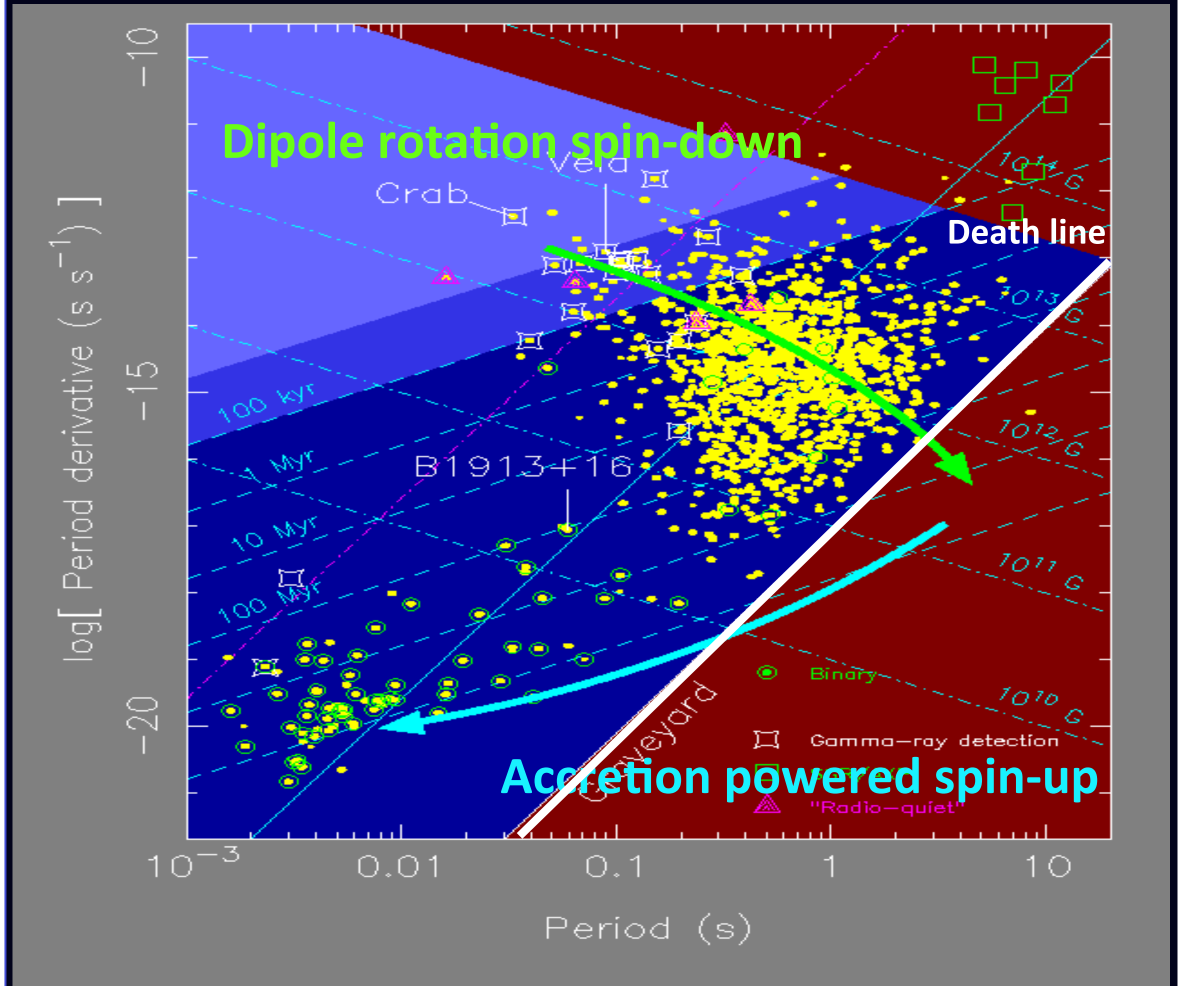
Millisecond pulsars:

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

↓

Old systems

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



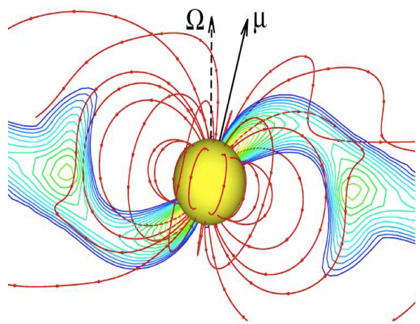
Recycling scenario:

AMXPs believed to be progenitors of RMPS (Baker 1982; Alpar et al. 1982)

What link between LMXBs and radio MSP?

LMXBs hosting AMXPs

- Subclass of LMXBs: 19 systems - P_{spin}<10ms; B≈10^8-10^9G (Patruno & Watts 2012)
- Long quiescence: Lx ≈ $10^{31} – 10^{34}$ erg/s
- Occasional outbursts: ΔT≈ days to yrs Lx ≈ 10^{36} erg/s
- Compact binaries: P_{orb} < 1 d
- RLOF Donors: MS, CO/He WD - M_2<0.2$M_\odot$
- 10 Nuclear-power MSPs: Type-I bursts - Quasi-coherent Oscillations (Watts 2012)



What link between LMXBs and radio MSP?

Rotation-power ms pulsars (RMSPs)

- ≈ 340 radio MSPs: $P_{spin} < 30$ms; $B \approx 10^7$-10^9G; $\dot{E}_{spin\text{-}down} \approx 10^{34}$- 10^{35}erg/s
- ≈ 200 are in compact binaries : $P_{orb} < 1$ d
- ≈ 60 show irregular radio eclipses → mass loss from ablated donor star:

  38 "Black widows" (BW) - $M_2 < 0.04 M_\odot$ (degenerate)

  22 " Redbacks" (**RB**) - $M_2 \approx 0.1$ -0.4 $M_\odot$ (MS) (Roberts 2011,2013)

  [Listen M. Roberts - BINARY III on Wed. afternoon]
- ≈ 50 detected as Gamma-ray **Fermi-LAT** sources

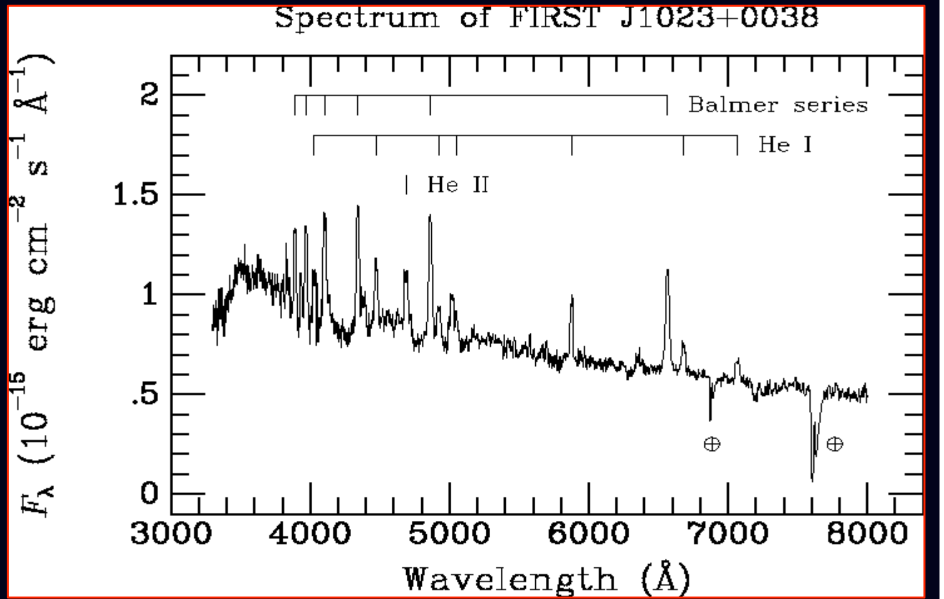
  (Fermi Coll. Science 2009, Pietsch et al Science. 2012, Acero et al. 2015)
- BW believed to descend from RB but not all RB evolve into BW (Benvenuto 2014)

PSRJ 1023+0038: the missing link binary MSP

CV-like optical spectrum!

Optical flickering

Variable radio source



2000 2001

time (yrs)

Bond et al. 2002
Szkody et al. 2003

PSRJ 1023+0038: the missing link binary MSP

CV-like spectrum!

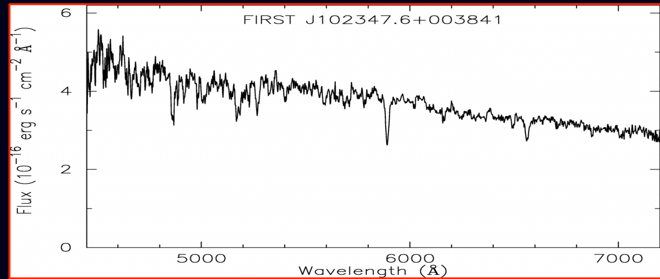
Optical flickering

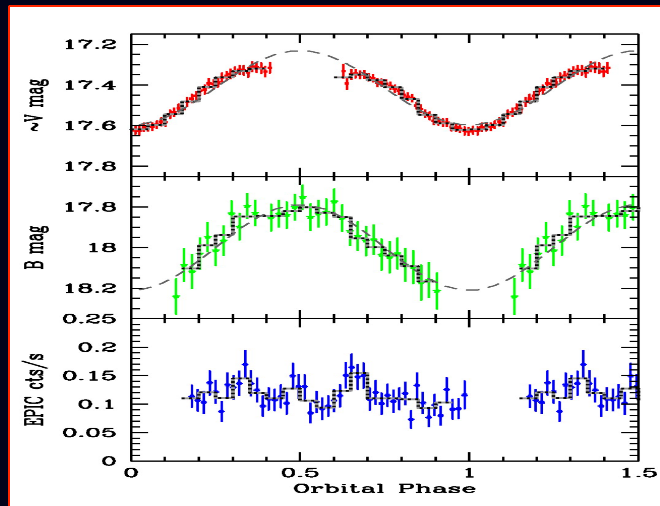
Variable radio source

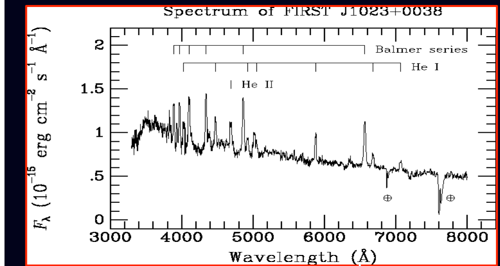
No Accretion disc

Optical modulation @4.75h

Variable X-rays







2000 2001 2002 2003 2004

time (yrs)

Bond et al. 2002
Szkody et al. 2003

Would et al. 2002;
Homer et al. 2004,
Thorstensen&Armstrong2005

PSRJ 1023+0038: the missing link binary MSP

Variable radio source

Optical flickering

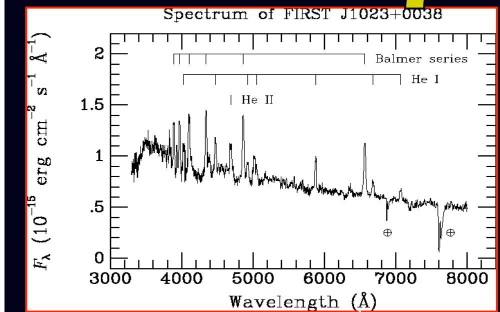
CV-like spectrum !

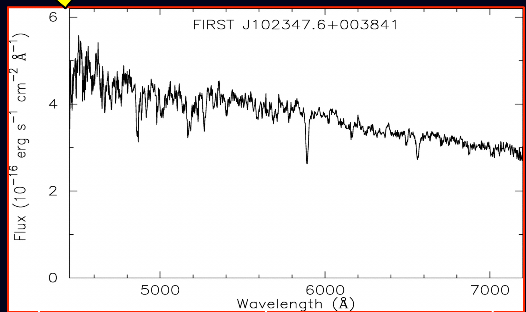
No Accretion disc

Optical modulation @4.75h

Variable X-rays

Change of State





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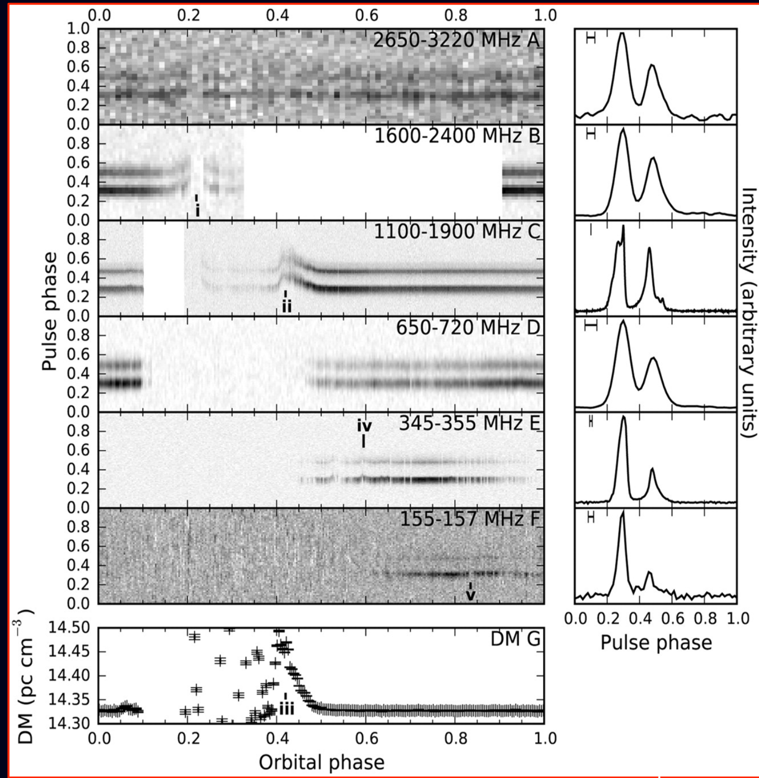
Bond et al. 2002
Szkody et al. 2003

Would et al. 2002;
Homer et al. 2004,
Thorstensen&Armstrong2005

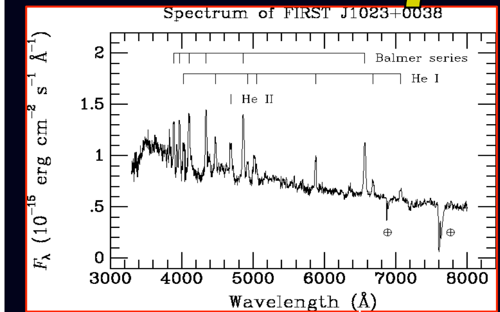
PSRJ 1023+0038: the missing link binary MSP

1.69ms Radio Pulsar
Radio Eclipses @4.75h

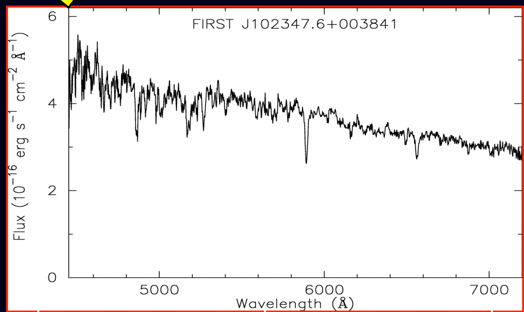
Archibald et al. 2009, Science



LMXB



RMSP



2000 2001 2002 2003 2004 2007 2008

time (yrs)

Bond et al. 2002
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Would et al. 2002;
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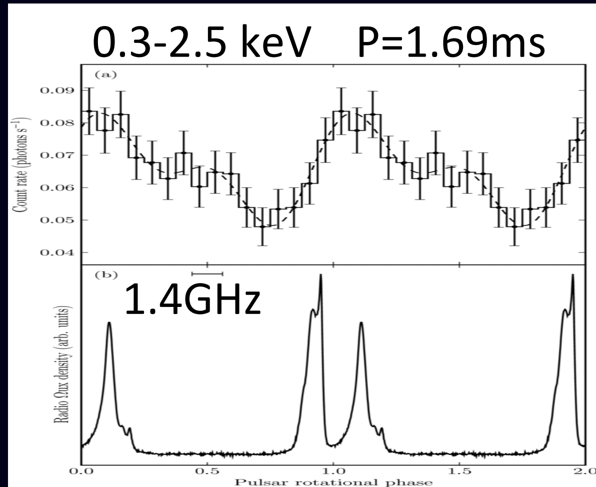
Thorstensen&Halpern2005

PSRJ 1023+0038: the missing link binary MSP

1.69ms Radio Pulsar
Radio Eclipses @4.75h

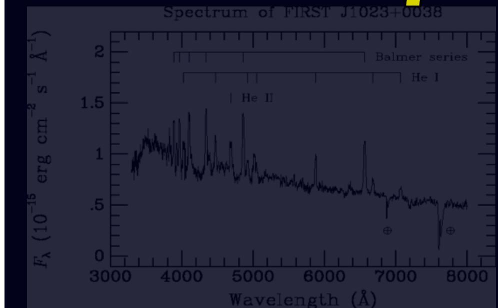
Marginal γ–ray Pulses@ 1.69ms

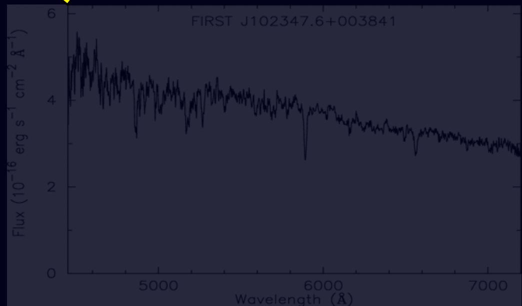
X-ray Pulses @ 1.69ms



LMXB

RMSP





2000 2001 2002 2003 2004

time (yrs)

Archibald et al. 2010, 2013

PSRJ 1023+0038: the missing link binary MSP

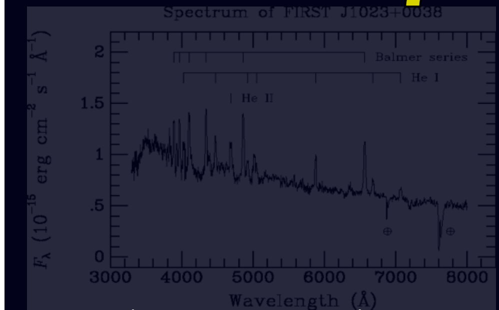
1.69ms Radio Pulsar
Radio Eclipses @4.75h

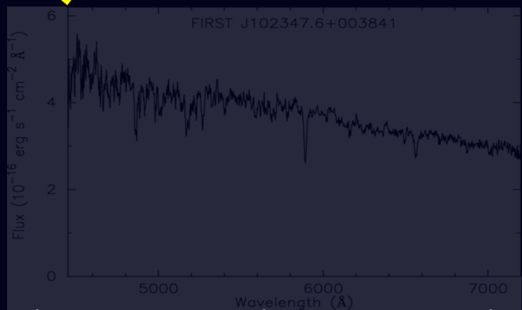
Marginal γ–ray Pulses@ 1.69ms

X-ray Pulses @ 1.69ms
X-ray modulation @ 4.75h

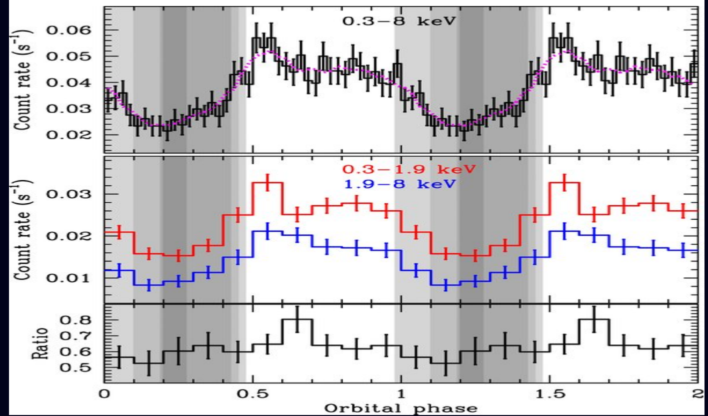
LMXB

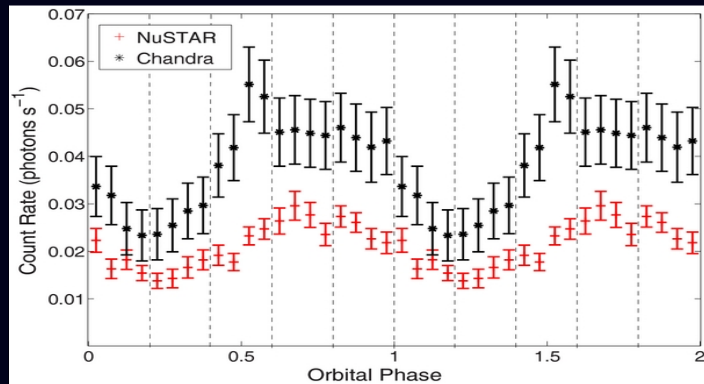
RMSP





Chandra 0.3-8 keV P=4.75h





2000 2001 2002 2003 2004

time (yrs)

Archibald et al. 2010, 2013
Bogdanov et al. 2011
Tendulkar et al.2014

PSRJ 1023+0038: the missing link binary MSP

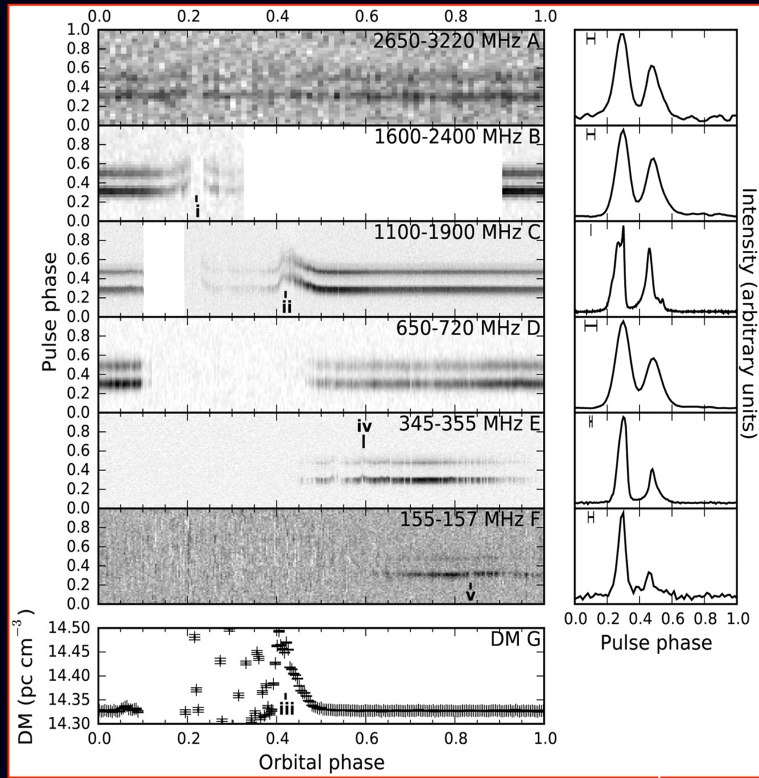
1. 9ms dio Pulsar
R se @4.8h

Recycling
Scenario

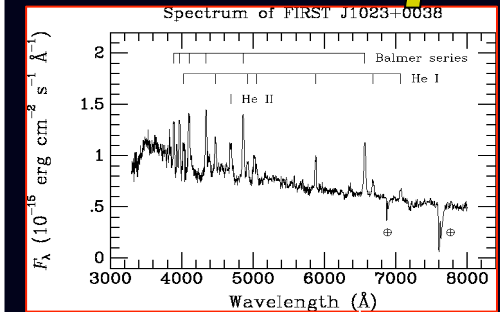
7ms
@ 4.8h

rg al γ – ray Pulse@ 1.7ms

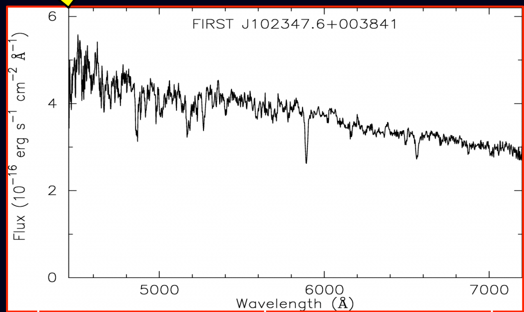
Archibald et al. 2009, Science



LMXB



RMSP



2000 2001 2002 2003 2004 2007 2008

time (yrs)

Bond et al. 2002
Szkody et al. 2003

Would et al. 2002;
Homer et al. 2004,
Thorstensen&2005

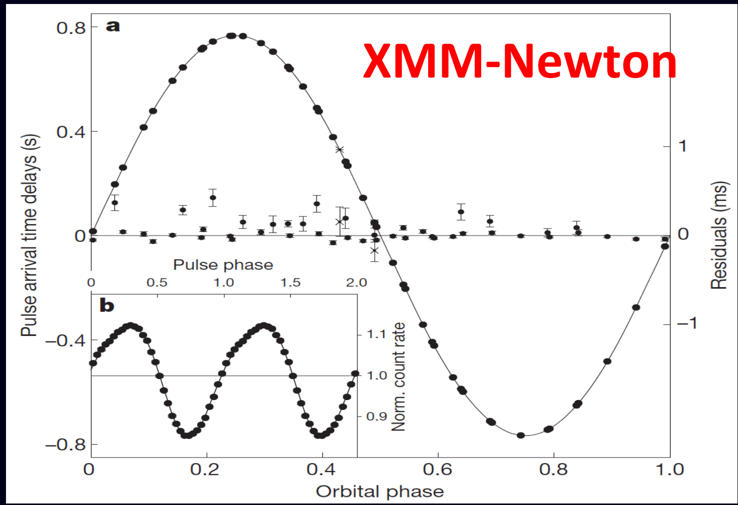
Archibald et al. 2010, 2013

IGR J18245-2452: A transient in the GC M28

Papitto et al. 2013, Nature

An AMXP
discovered in outburst

March 28, 2013



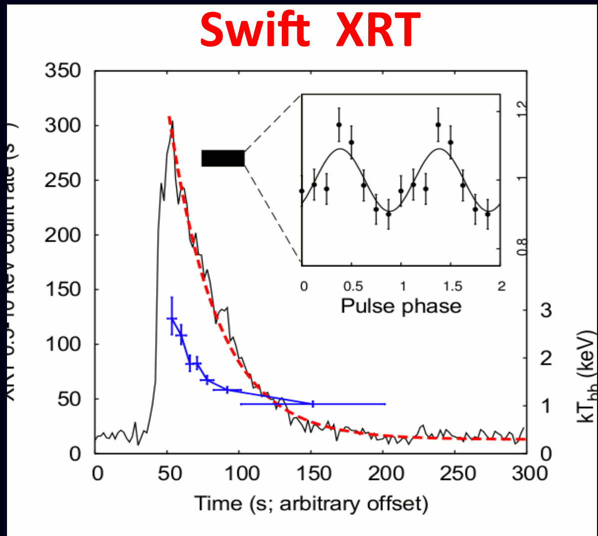
Lx ≈ 1-4 x 10 ^{36} erg/s

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

Porb = 11. 0h

Thermonuclear Bursts

Peculiar short term X-ray variability



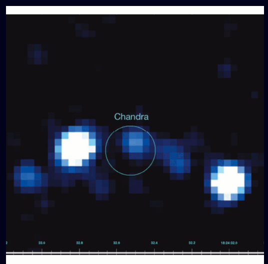
The first swinging MSP binary

PSRJ1824-2452 / IGR J18245-2452

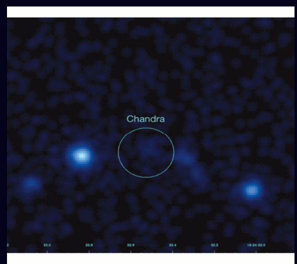
Papitto et al. 2013, Nature

Variable X-ray source

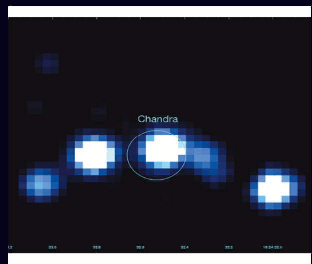
ACIS – S



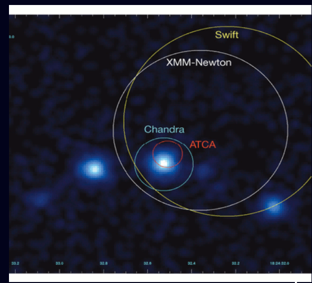
HRC



Chandra
ACIS-S



HRC



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

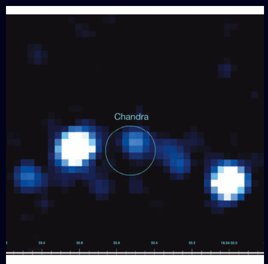
The first swinging MSP binary

PSRJ1824-2452 / IGR J18245-2452

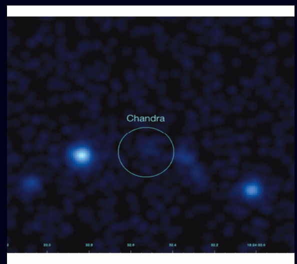
Papitto et al. 2013, Nature

Variable X-ray source

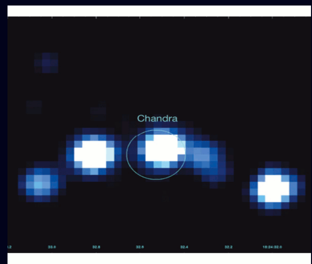
ACIS – S



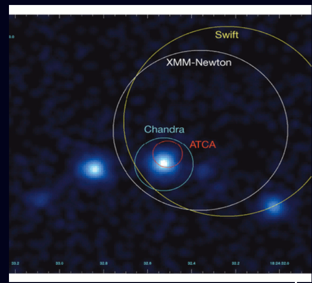
HRC



Chandra
ACIS-S



HRC



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

PSRJ1824-2452

ATNF Catalog: 3.9ms radio pulsar

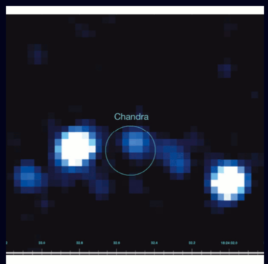
The first swinging MSP binary

PSRJ1824-2452 / IGR J18245-2452

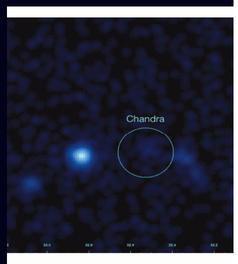
Papitto et al. 2013, Nature

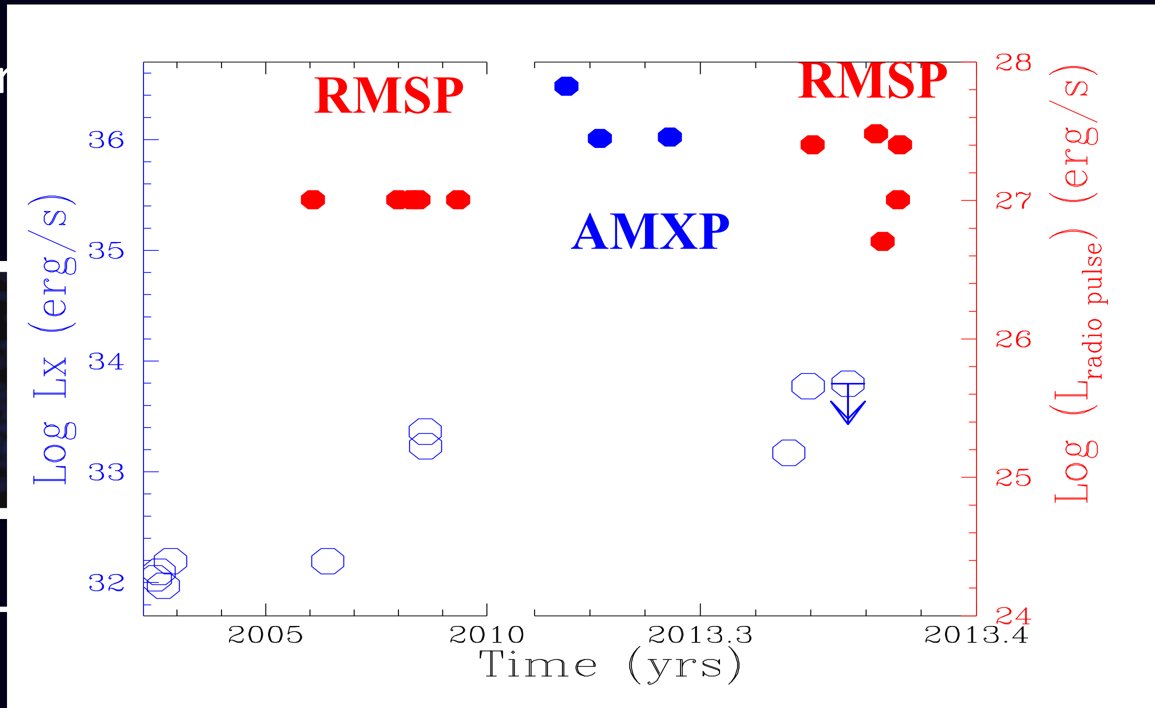
Var

ACIS – S



HRC





2002

2006

time (yrs)

PSRJ1824-2452

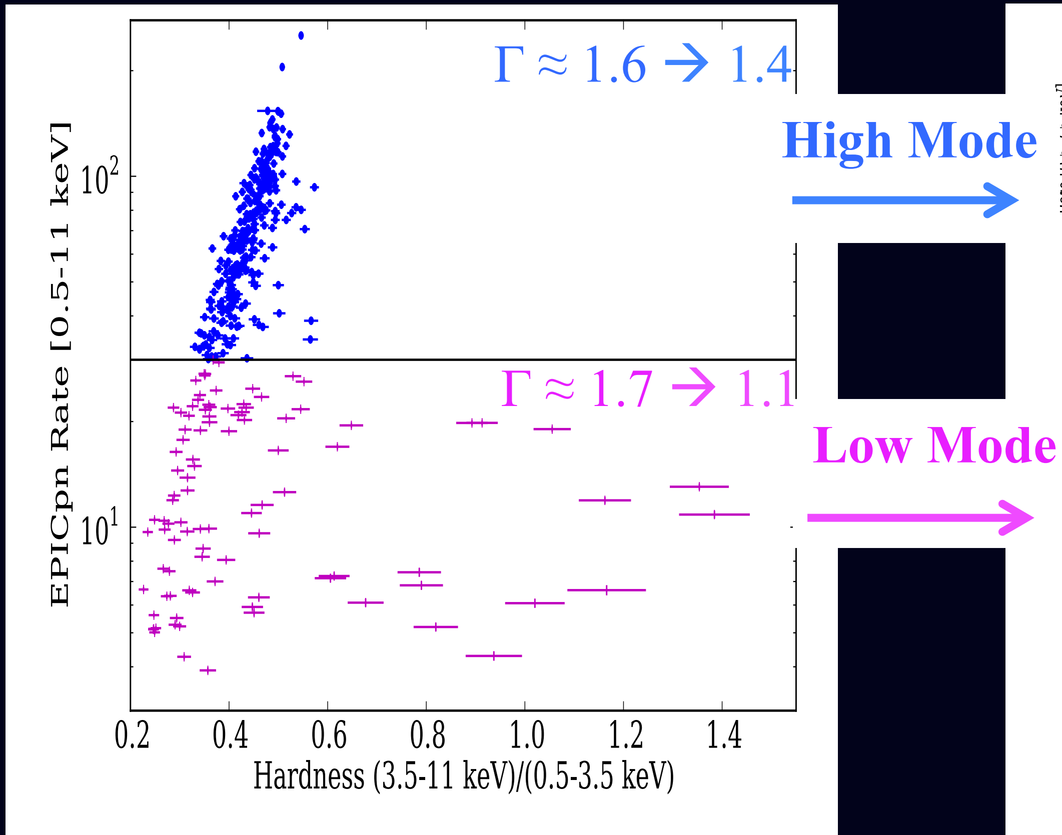
ATNF Catalog 3.9ms radio pulsar

no radio pulsar

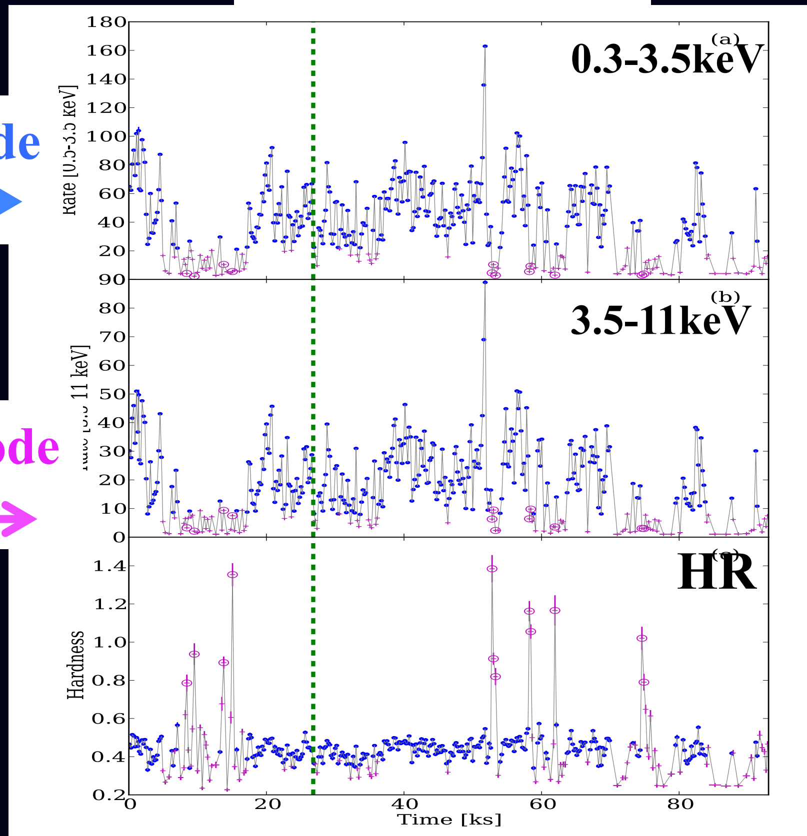
radio pulsar

The first swinging MSP binary

Peculiar X-ray Variability in Outburst



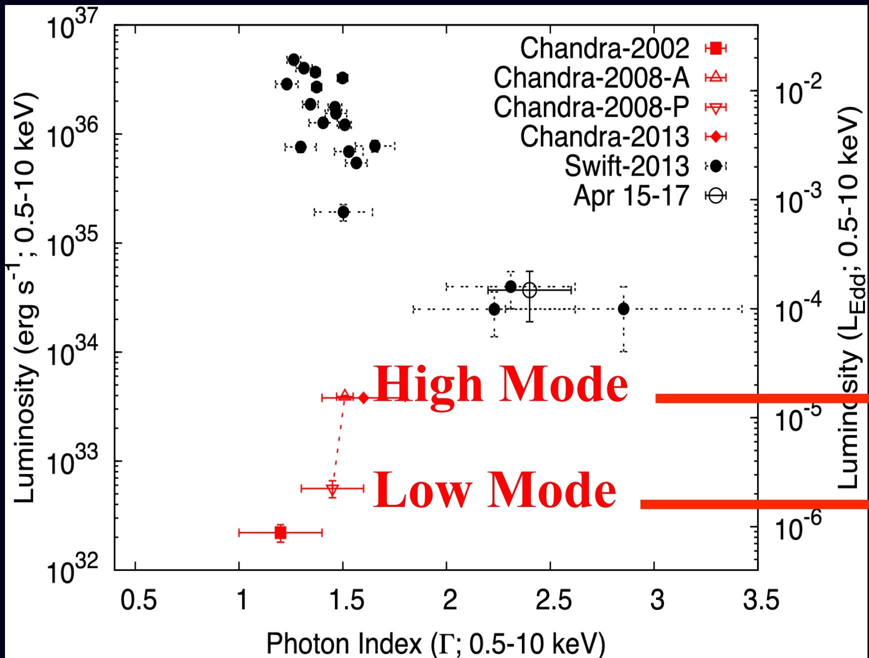
XMM-Newton

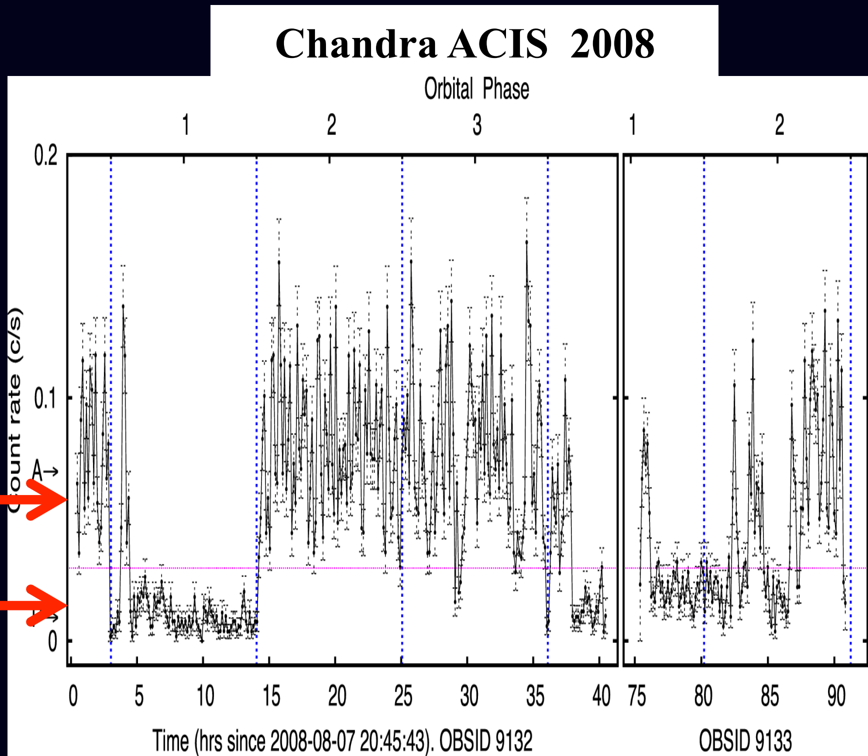


Ferrigno et al. 2014

The first swinging MSP binary

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





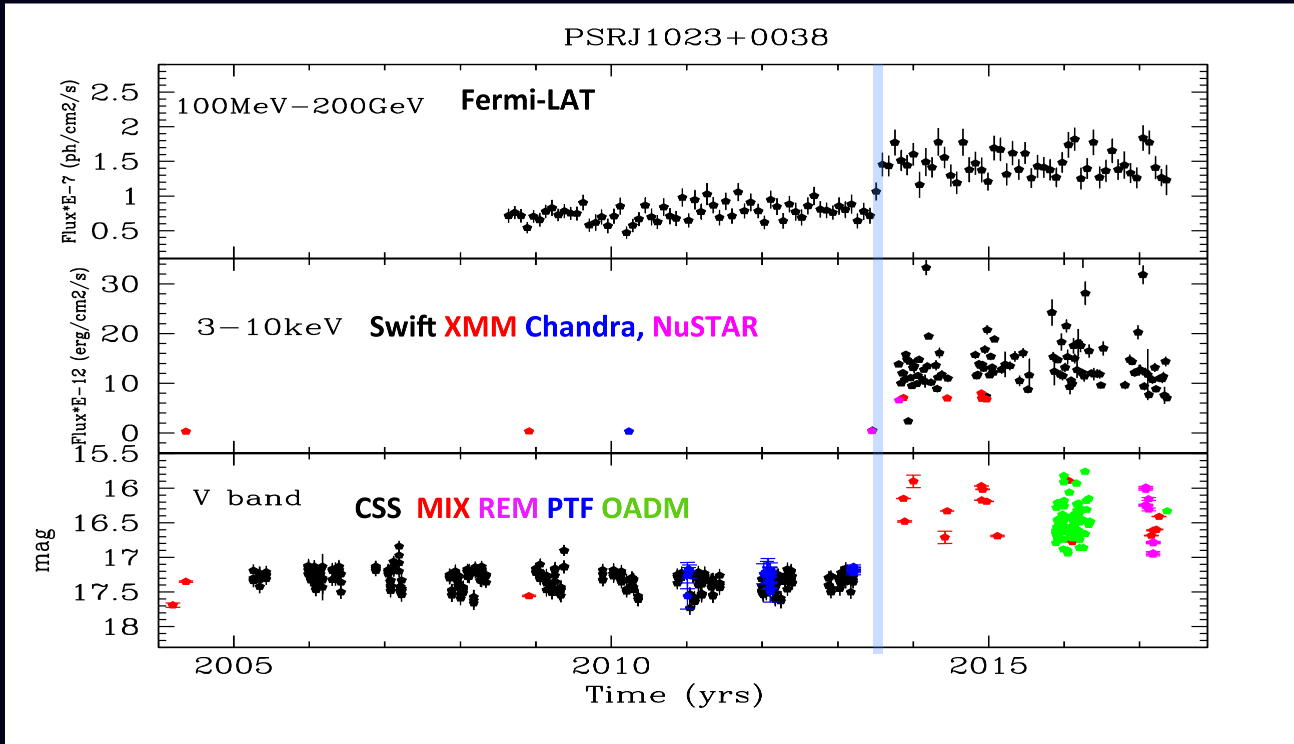
Mode switching

Accretion ↔ Inhibition of accretion

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

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

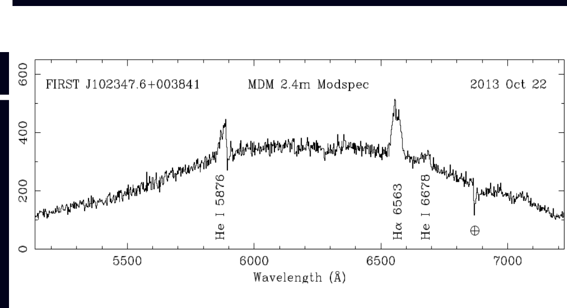
2004 **mid 2013** 2017

Stappers et al. 2014

Tendulkar et al. 2014

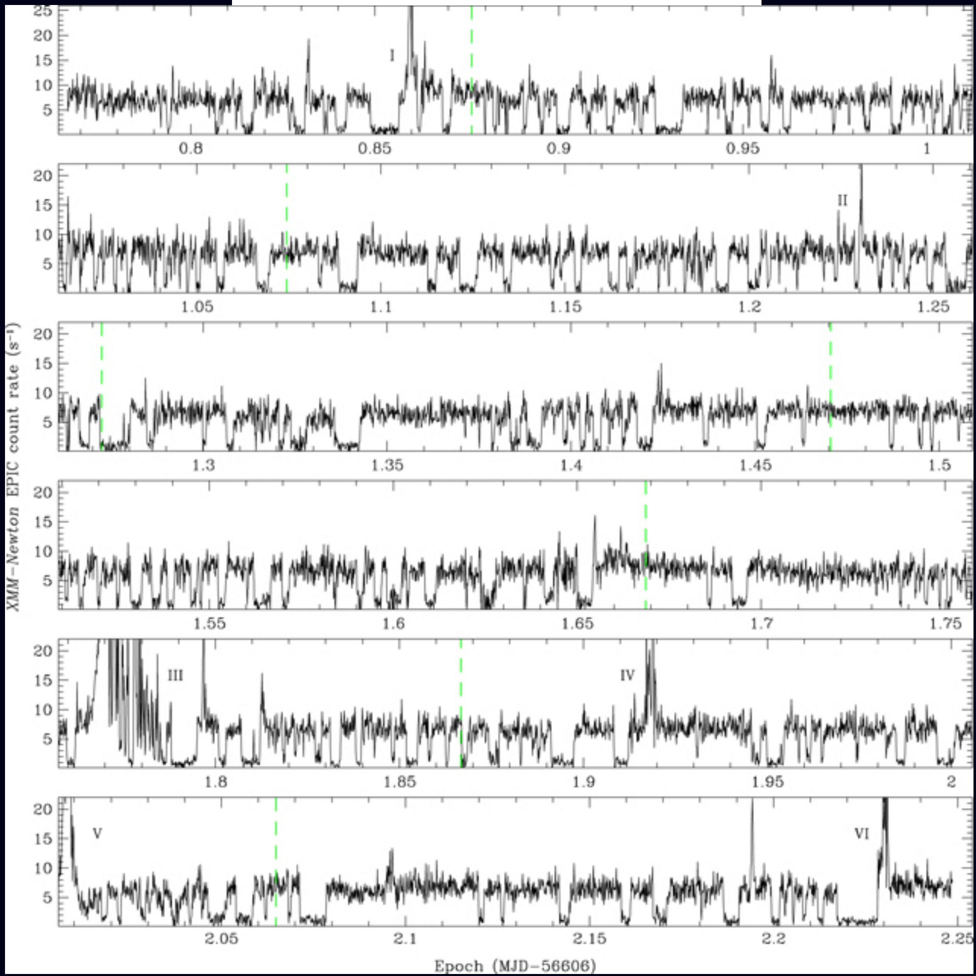
Patruno et al. 2014

Bogdanov et al. 2015



PSR J1023+0038: the LMXB state

XMM-Newton Nov.2013



X-ray Tri-modal behaviour:

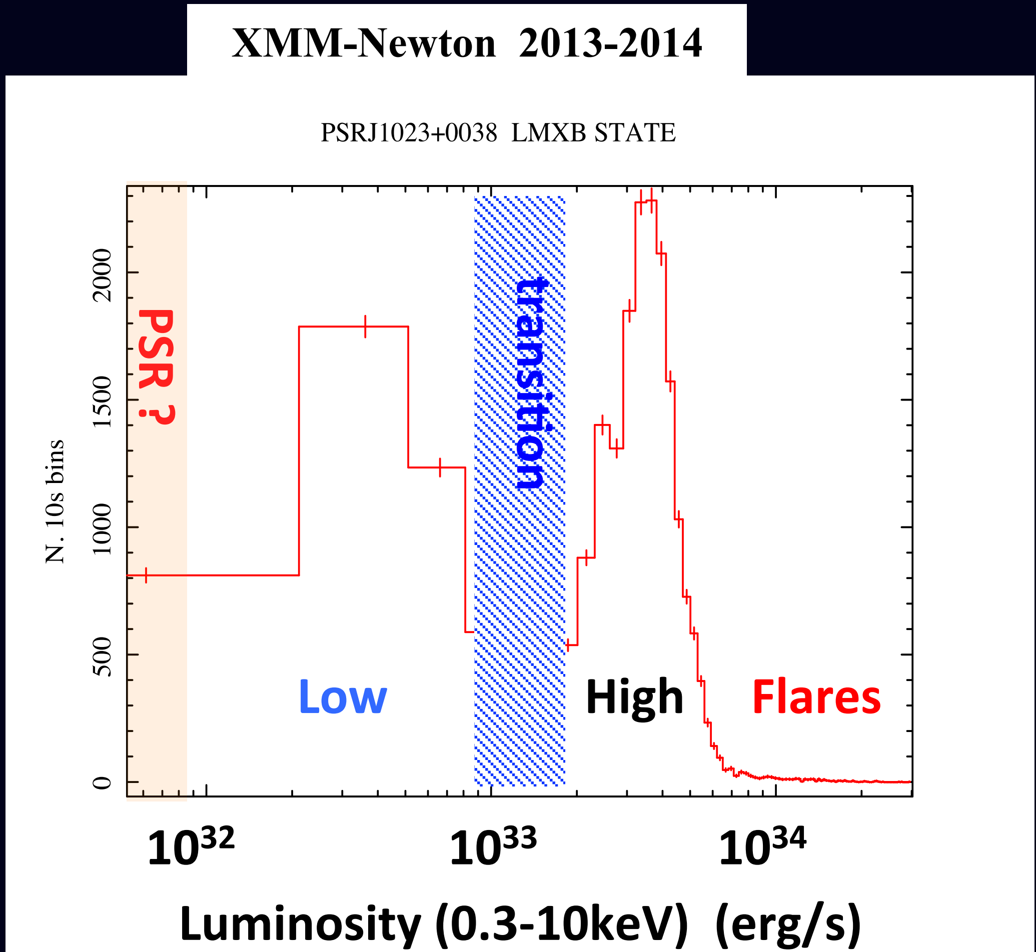
Erratic Flares ≈ tens mins up to 10hr

Erratic Dips = Low Mode ≈ secs-mins

Persistent level = High Mode

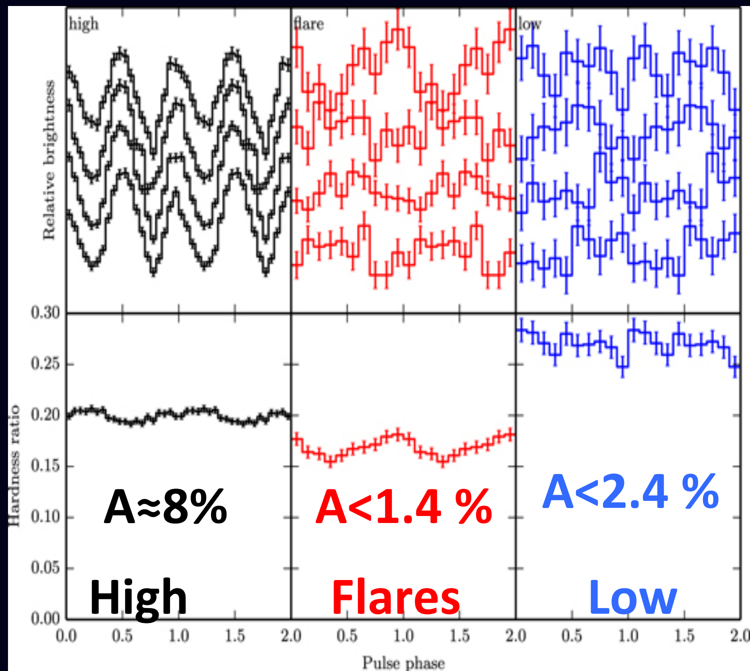
Tendulkar et al. 2014
Bogdanov et al. 2015

PSR J1023+0038: the LMXB state



Mode switching in a few sec

X-ray pulses in high mode only

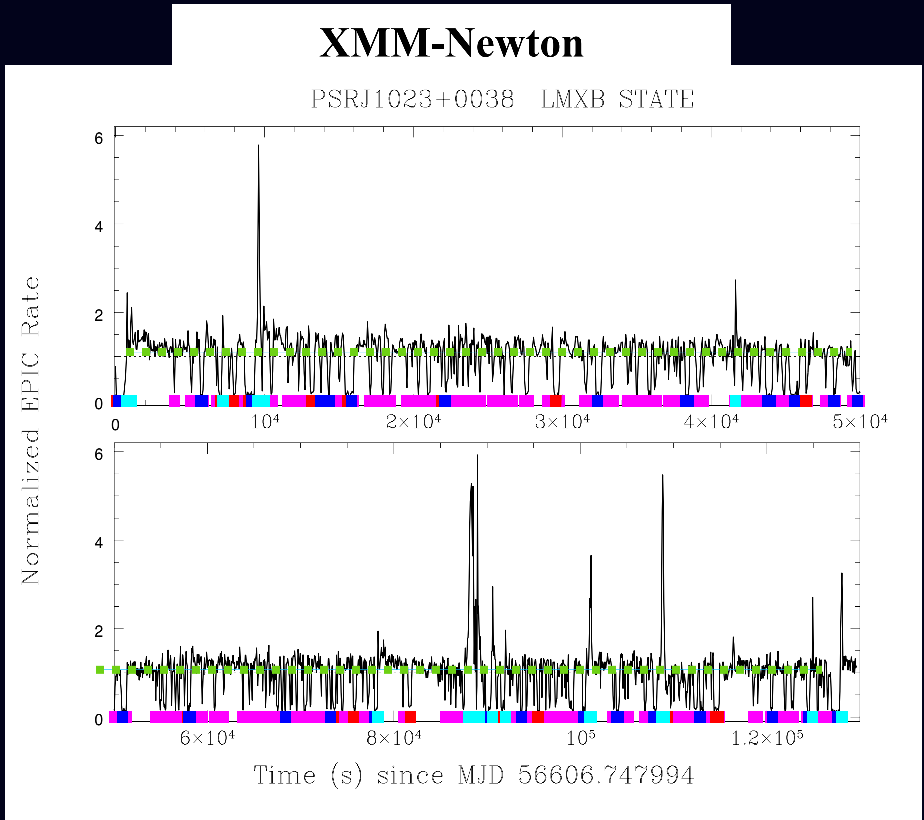


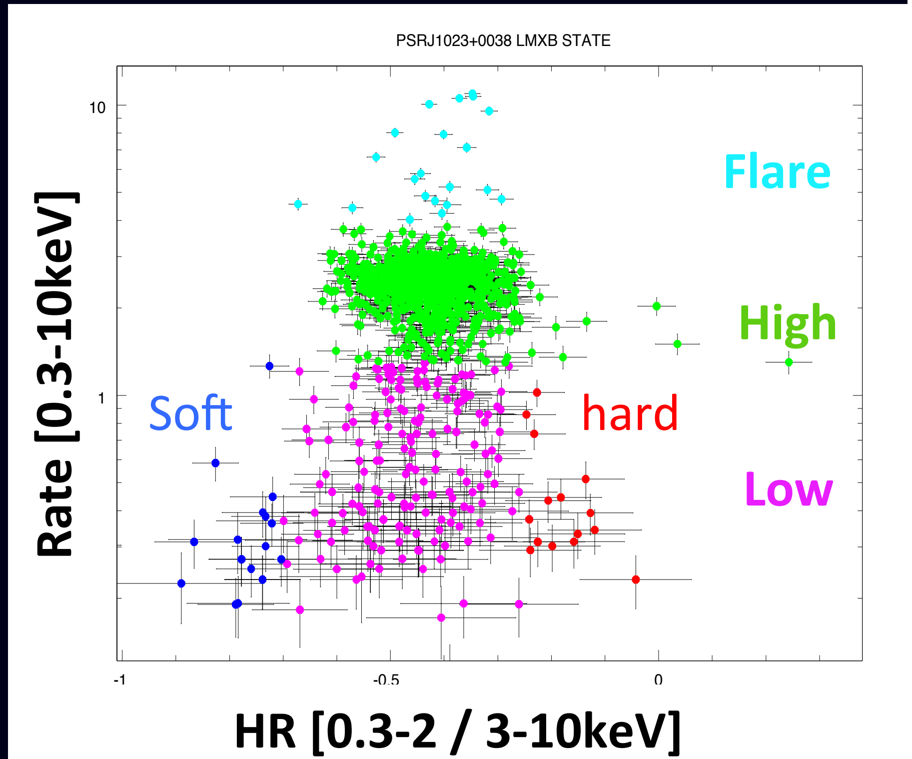
Bogdanov et al. 2015
Archibald et al. 2015

PSR J1023+0038: the LMXB state

No substantial spectral variability

but Soft & hard dips → subtle changes

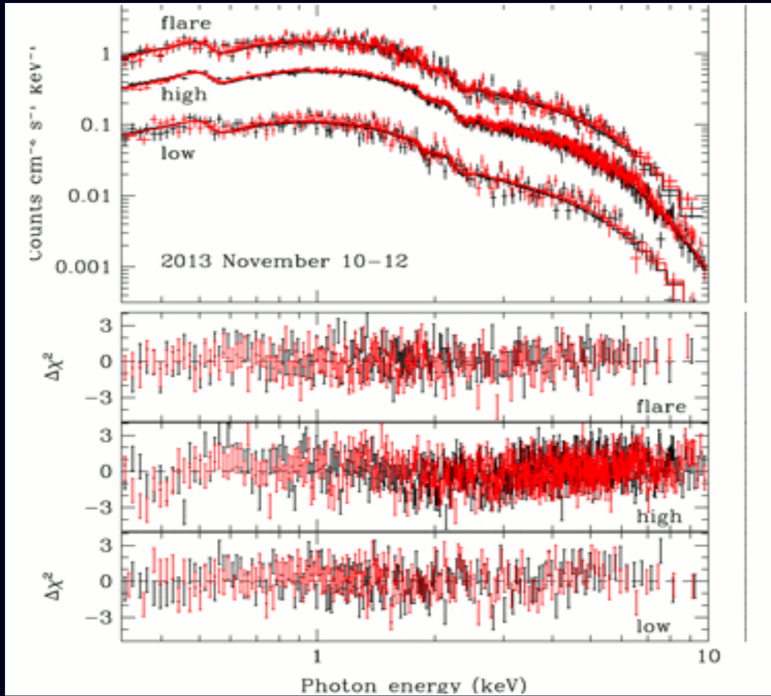




PSR J1023+0038: the LMXB state

Average spectrum featureless : Γ = 1.7 softer than RMSP state Γ = 1.26

No substantial spectral variability - No thermal component



Flare: Γ ≈1.7

High: Γ ≈1.7

Low: Γ ≈1.8

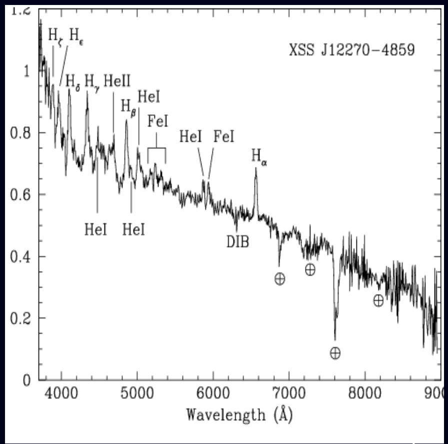
Dominated by outflowing matter ?

Bogdanov et al. 2015

XSS J1227-4859: a peculiar hard low-luminosity source

CV-like optical spectrum!

Variable Hard X-rays



HR

2006 2007 2009 2010

time (yrs)

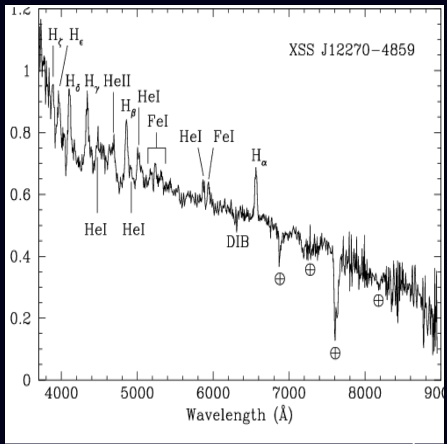
Masetti et al. 2006

Sazonov & Revnivtsev 2008

XSS J1227-4859: a peculiar hard low-luminosity source

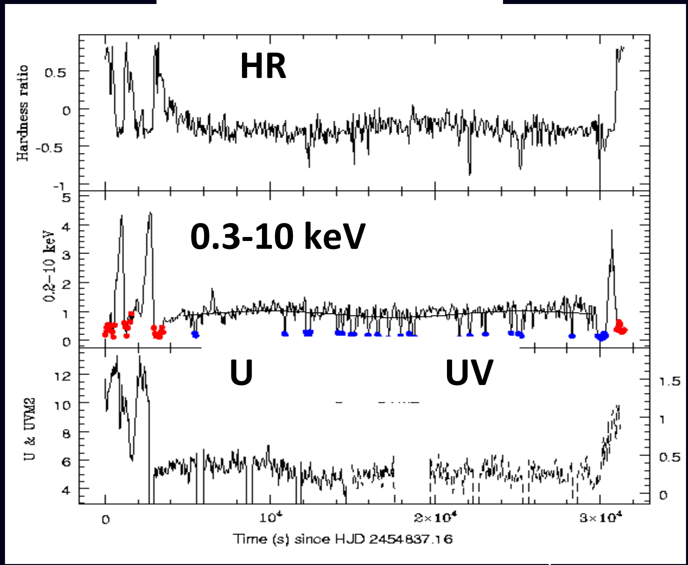
CV-like optical spectrum!

Variable Hard X-rays



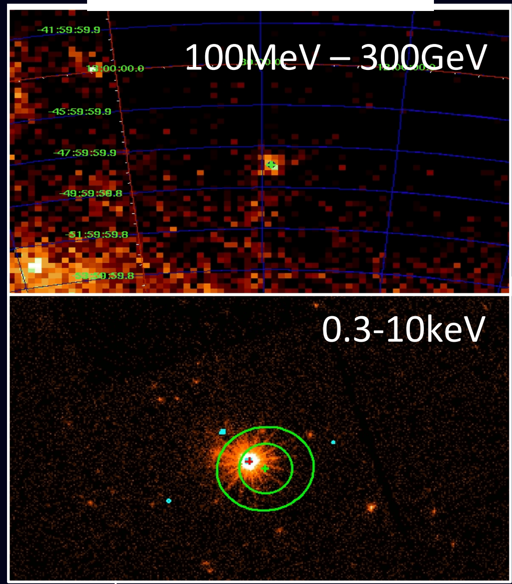
Erratic X-ray - UV/optical variability

XMM-Newton



Fermi-LAT/XMM-Newton association

Fermi-LAT



2006

2007

2009

2010

time (yrs)

Masetti et al. 2006

Sazonov & Revnivtsev 2008

de Martino et al. 2010

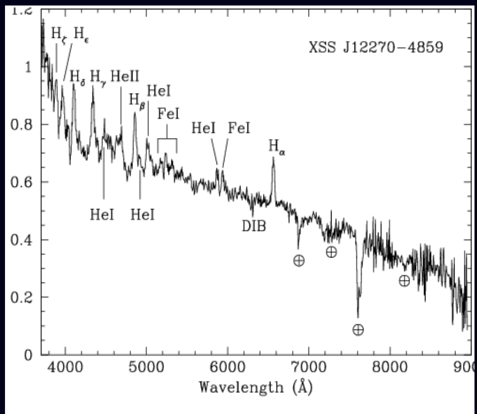
XSS J1227-4859: a peculiar hard low-luminosity source

CV-like optical spectrum!

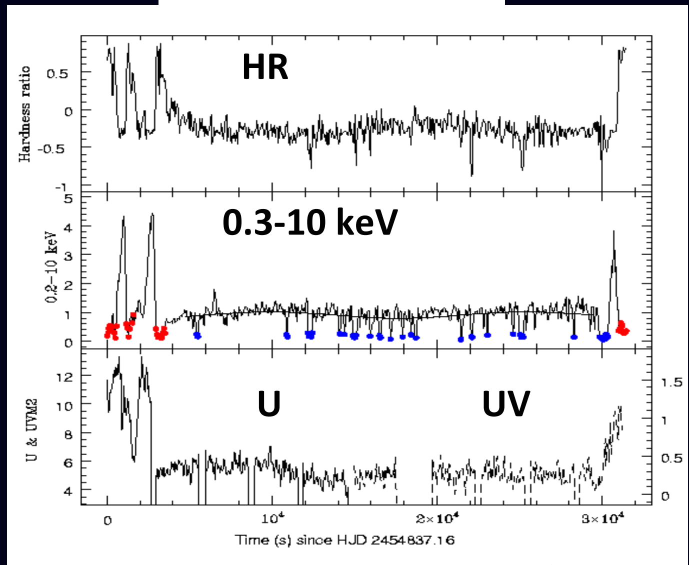
Variable Hard X-rays

Erratic X-ray - UV/optical variability

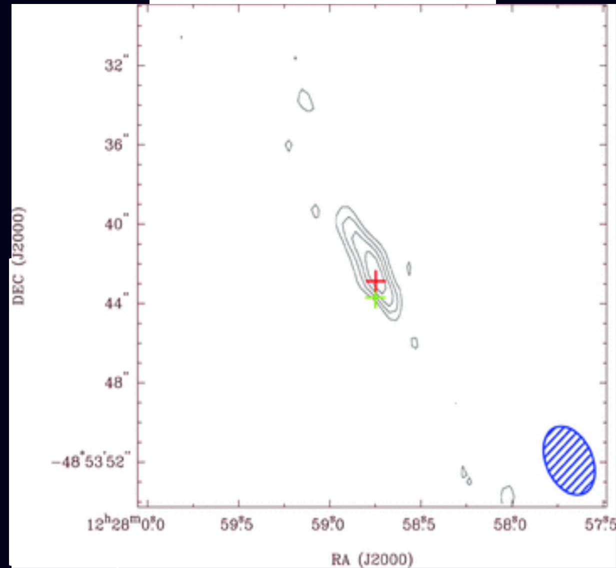
Weak radio source



XMM-Newton



ATCA 9GHz



2006

2007

2009

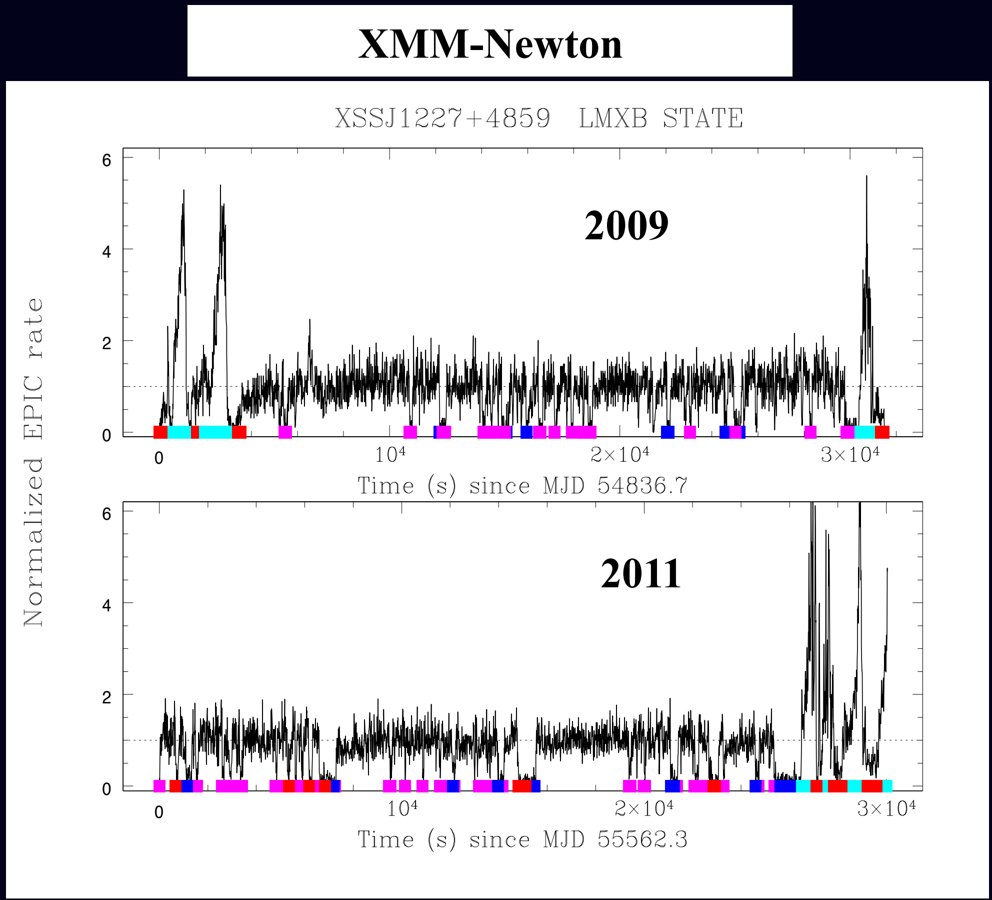
2010

time (yrs)

Masetti et al. 2006
Sazonov & Revnivtsev 2008

de Martino et al. 2010, 2013
Saitou et al. 2010
Hill et al. 2011

XSS J1227-4859: the LMXB state



Tri-modal behaviour:

Sporadic Flares ≈ mins

Erratic Dips = Low Mode ≈ secs-mins

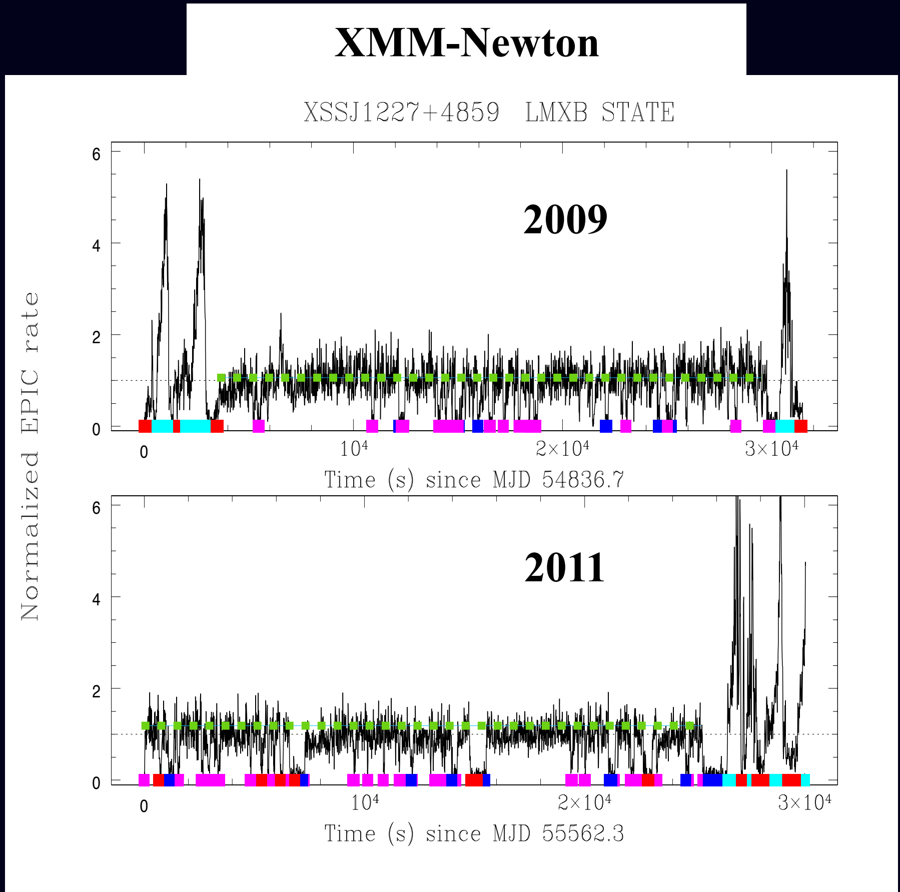
Persistent level = High Mode

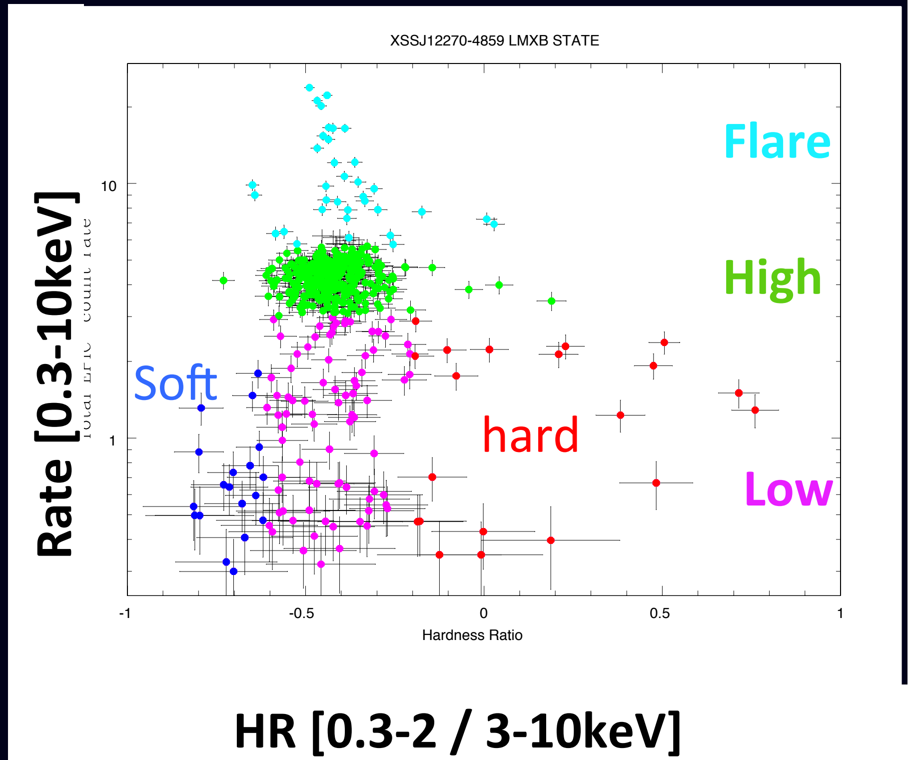
de Martino et al. 2010,2013

XSS J1227-4859: the LMXB state

No substantial spectral variability

but Soft & hard dips → subtle changes



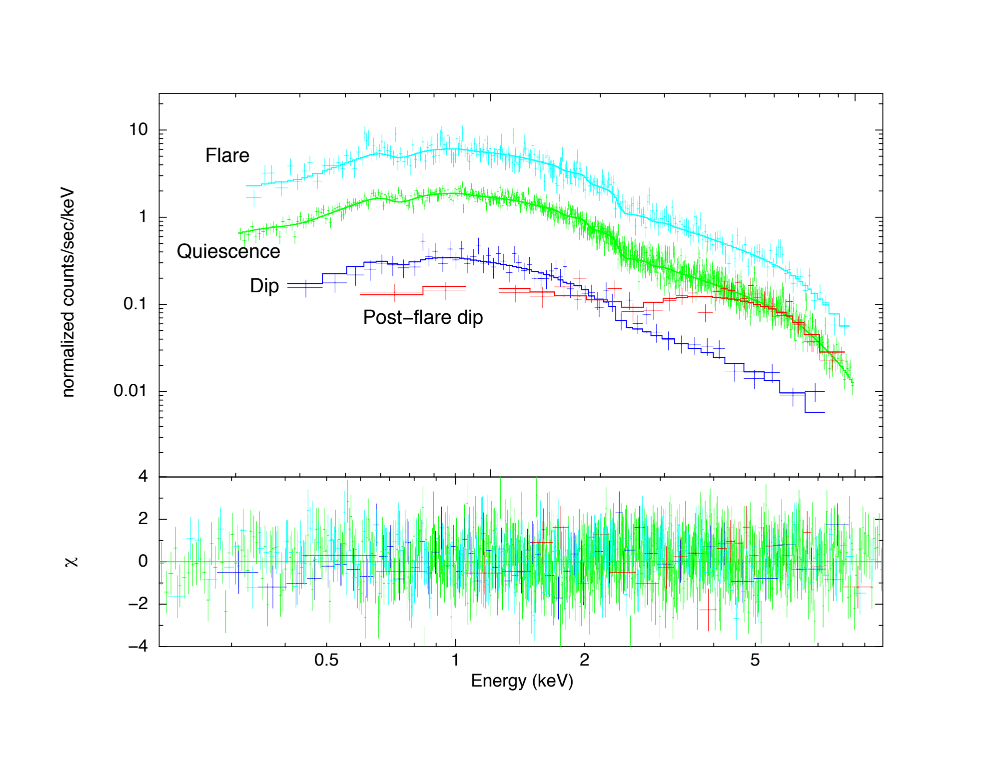


de Martino et al. 2010,2013

XSS J1227-4859: the LMXB state

Average spectrum featureless : Γ = 1.7

No substantial spectral variability except in Post-flare Dips



Flare: Γ ≈1.7

High: Γ ≈1.6

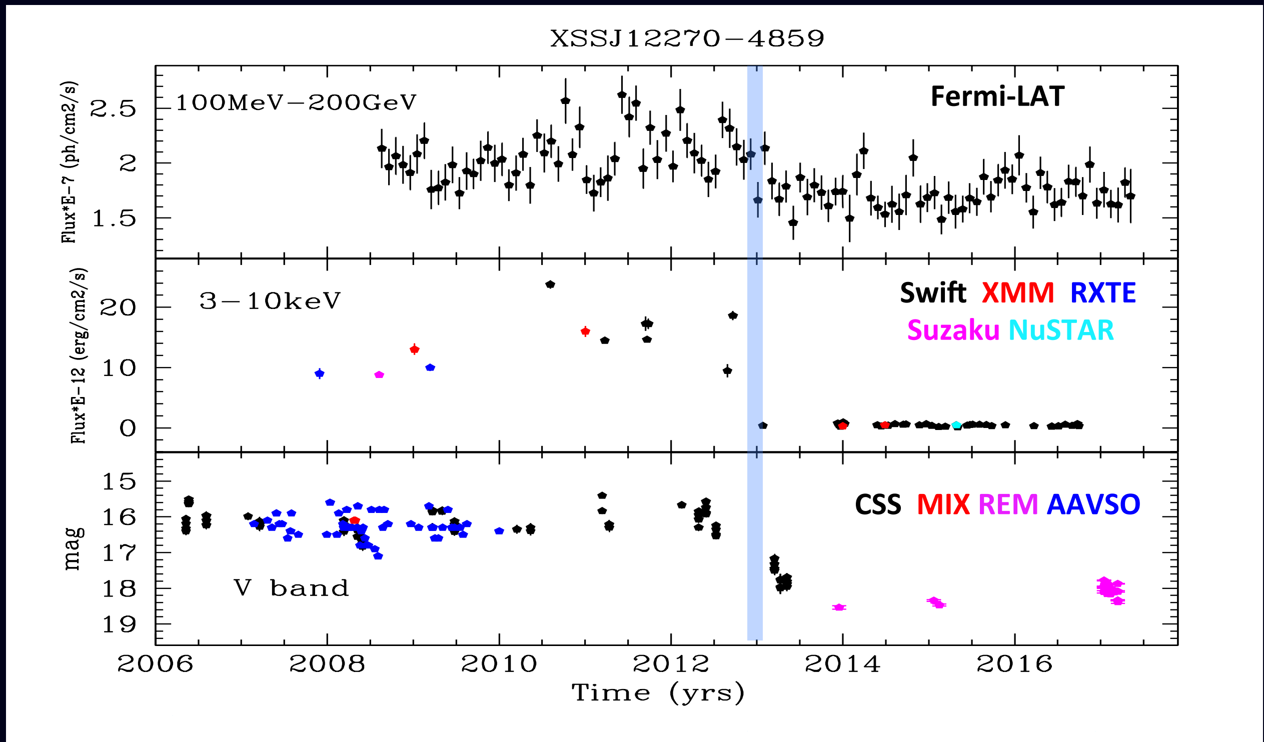
Dips: Γ ≈1.7

Post-flare Dips : Γ ≈0.7 + PCF

de Martino et al. 2010, 2013

XSS J1227-4859: a late recognised transitional MSP binary

Disc → Disc-free



$L_{\gamma} \approx$ 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

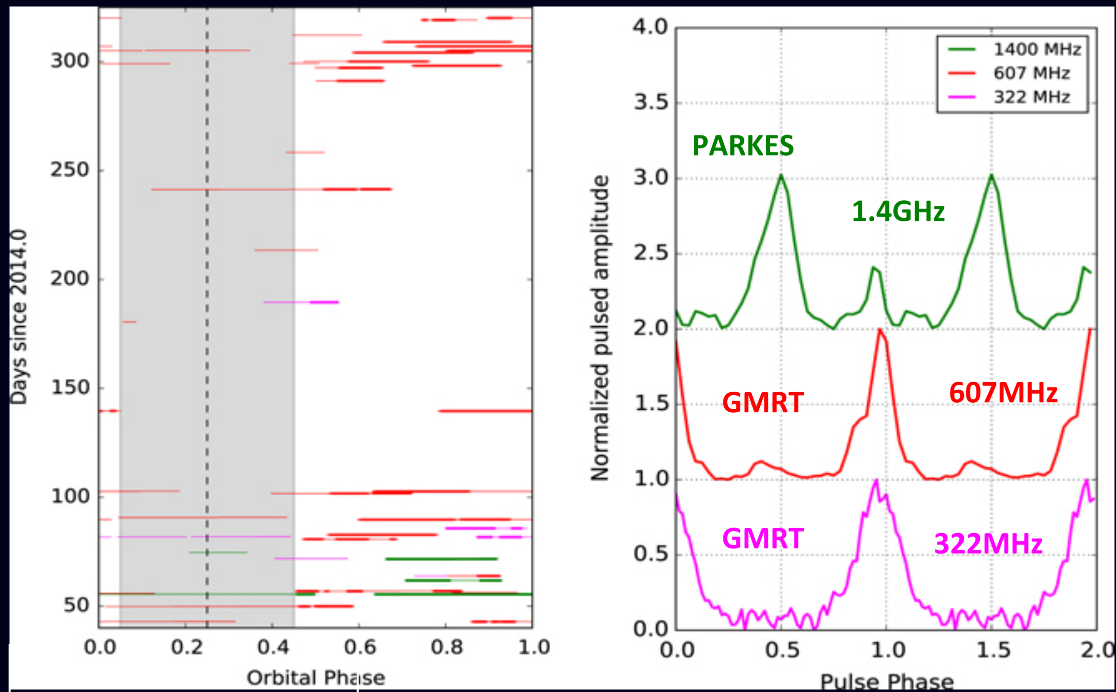
2006 **Nov-2012- Mar.2013** 2017 time (yrs)

Bassa et al. 2014
Bogdanov et al. 2014
de Martino et al. 2014
Torres et al. 2017

XSS J1227-4859: a late recognised transitional MSP binary

LMXB → RMSP

Radio Eclipses @ 6.91h   1.69ms Radio Pulsar



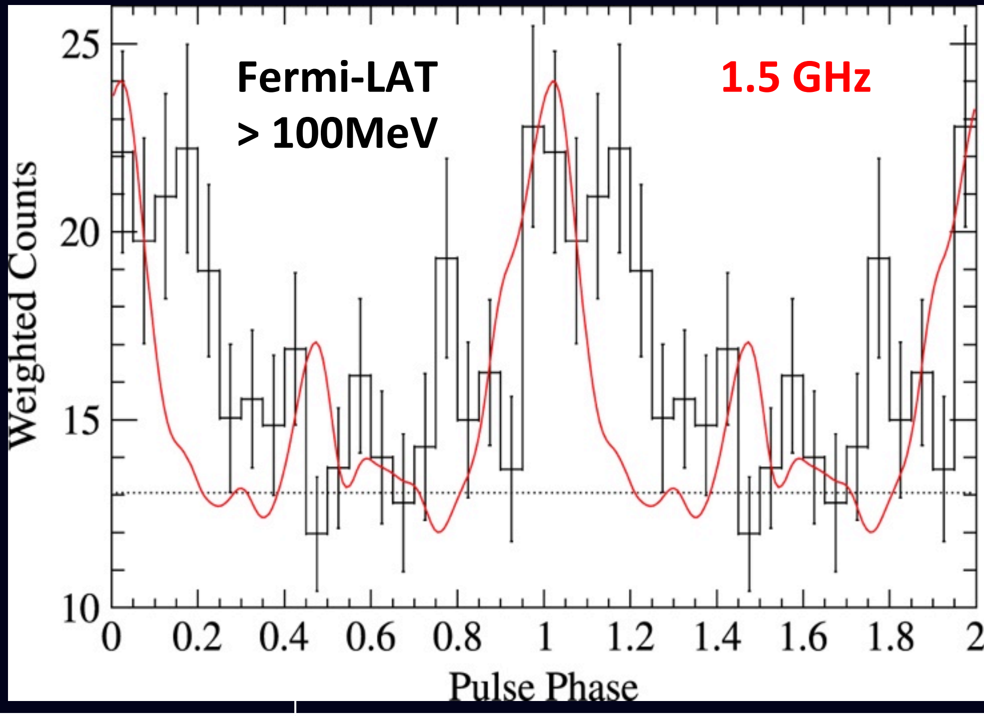
2006   **Nov-2012- Mar.2013**   time (yrs)

Roy et al. 2015

XSS J1227-4859: a late recognised transitional MSP binary

LMXB → RMSP

Gamma-ray PSR @ 1.69ms



2006

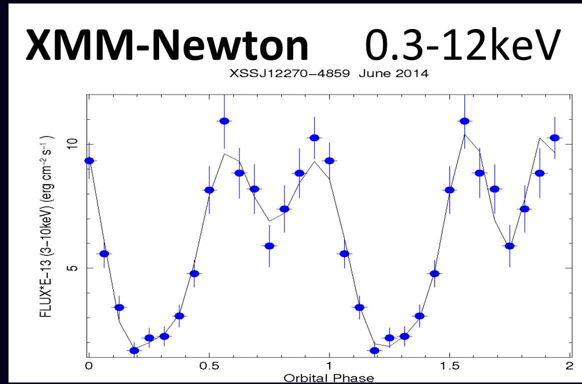
Nov-2012- Mar.2013

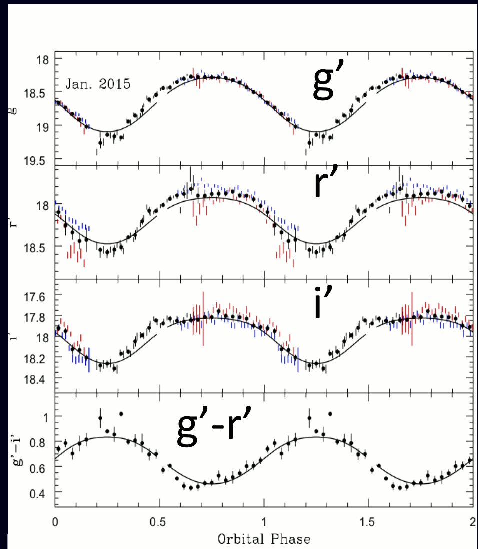
time (yrs)

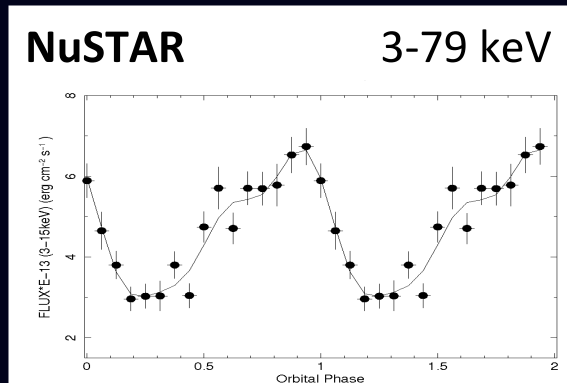
Roy et al. 2015
Johnson et al. 2015

XSS J1227-4859: now a Redback irradiated by Intrabinary Shock

No X-ray Pulses @ 1.69ms
X-ray modulation @ 6.91h
Optical modulation @ 6.91h







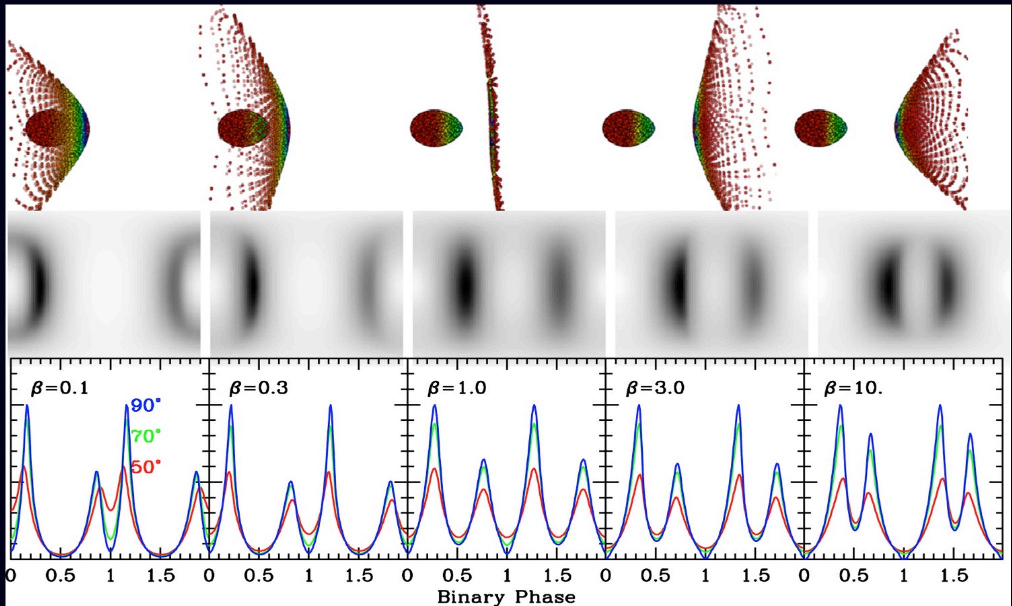
2006 **Nov-2012- Mar.2013** time (yrs)

de Martino et al 2015
Papitto et al. 2015, 2017 inprep

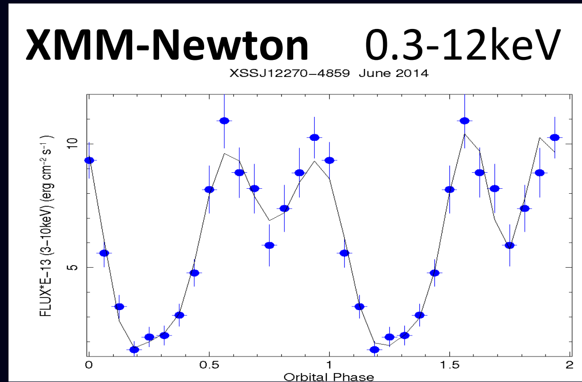
XSS J1227-4859: now a Redback irradiated by Intrabinary Shock

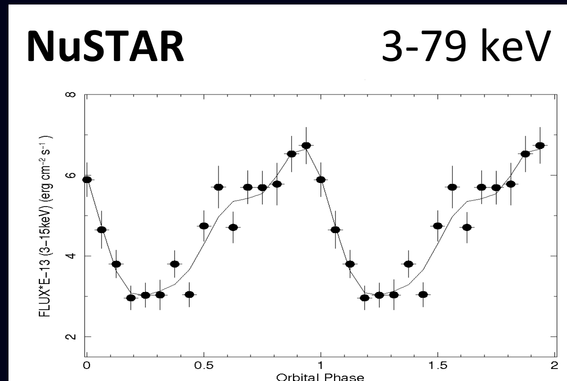
Intrabinary Shock dominates X-rays

Light Curve Shape depends on wind momentum ratio



Romani & Sanchez 2016

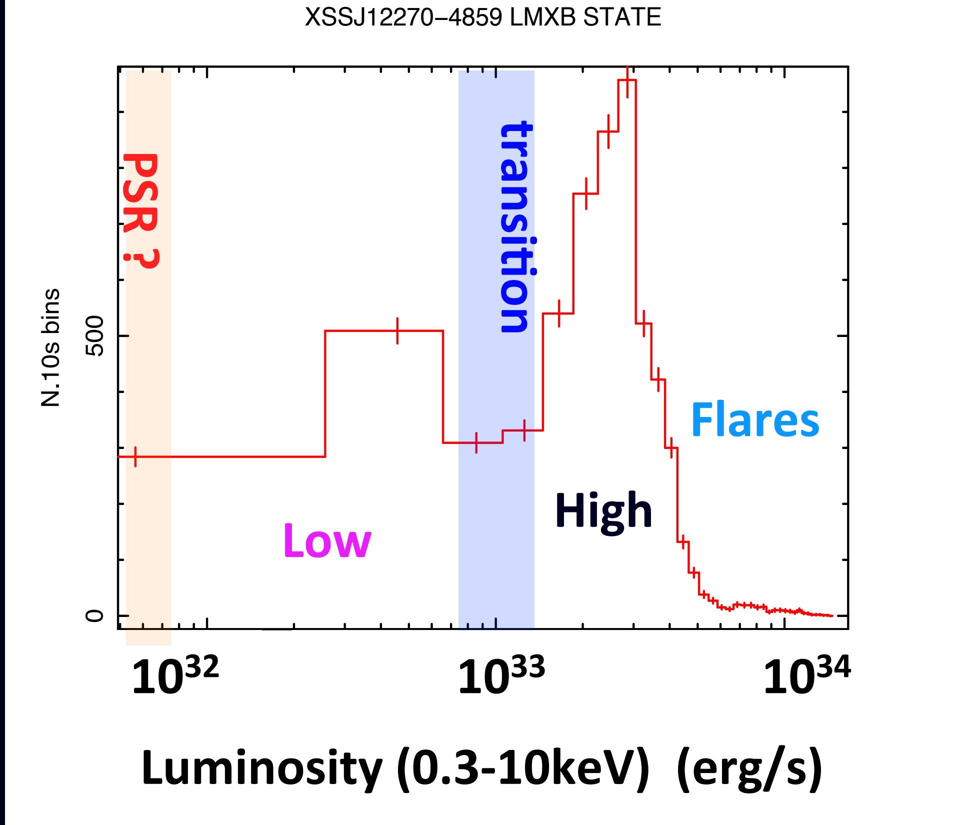




de Martino et al 2015
Papitto et al. 2015, 2017 inprep

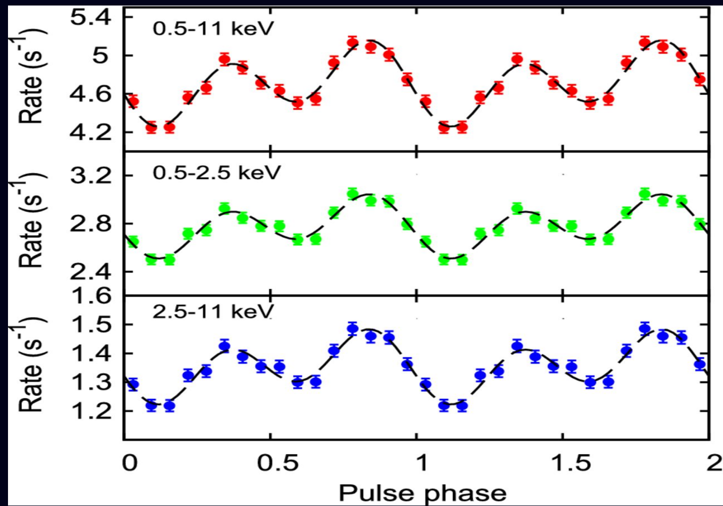
XSS J1227-4859: a late recognised transitional MSP binary

XMM-Newton 2009-2011



Mode switching

X-ray pulses in high mode only

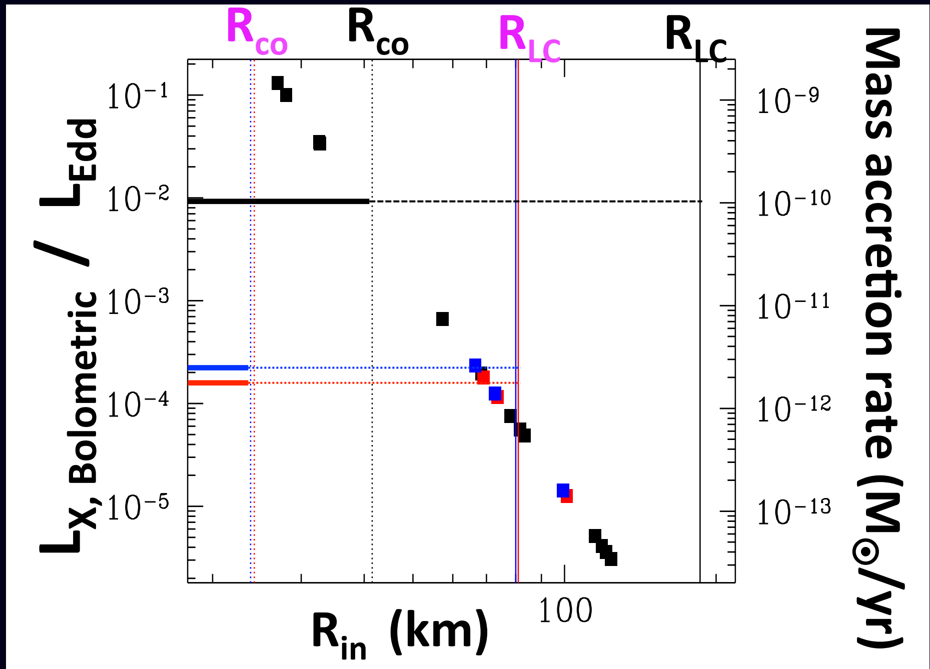


A ≈ 8%	High	
A < 2%	Flares	3σ
A < 5.9 %	Low	3σ

Papitto et al. 2015

Three states of tMSPs

M28I   PSRJ1023   XSSJ1227

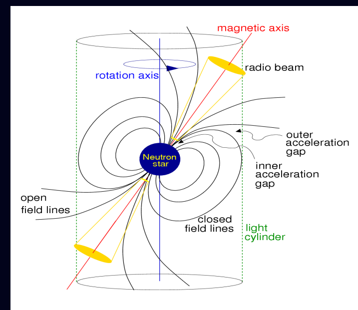


$R_{in} \approx R_{mag} \propto M_{acc}^{-2/7} \mu_B^{4/7}$

$R_{in} \leq R_{co} \leq R_{LC}$ **Accretion state**

$R_{CO} < R_{in} < R_{Lc}$ **Accretion inhibited**
Subluminous state

$R_{in} > R_{LC}$ **Radio Pulsar state**



- Mass inflow rate should be larger to have pulsations
- X-rays do not only trace the mass accretion rate on NS
- Advected energy in the disc powers propeller

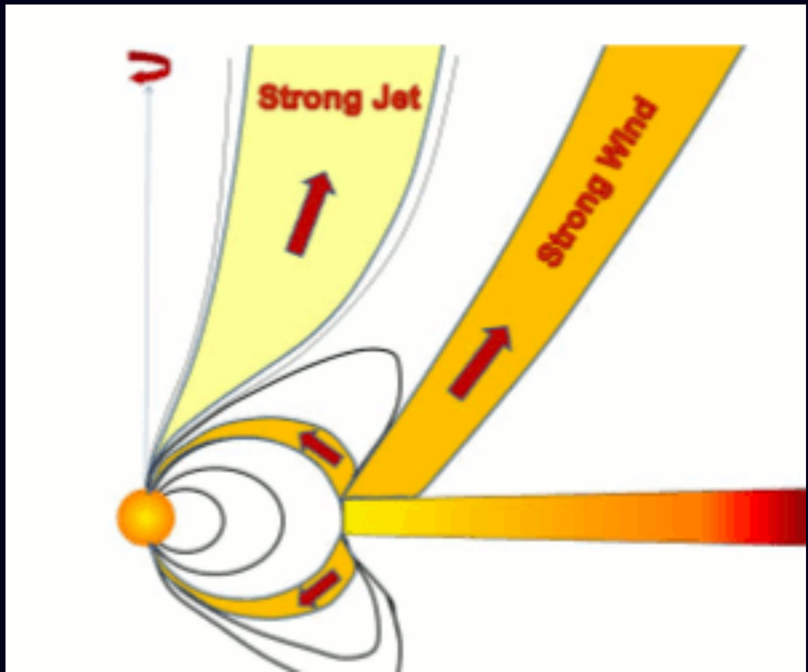
[Listen Papitto – Binaries VI – Thurs. afternoon]

Linares 2014
Campana et al. 1998
Romanova et al. 2014,2017
Papitto & Torres 2014,2015

Outflows in tMSPs

3-D MHD - Propeller driven winds & Jets

Romanova et al. 2014,2017



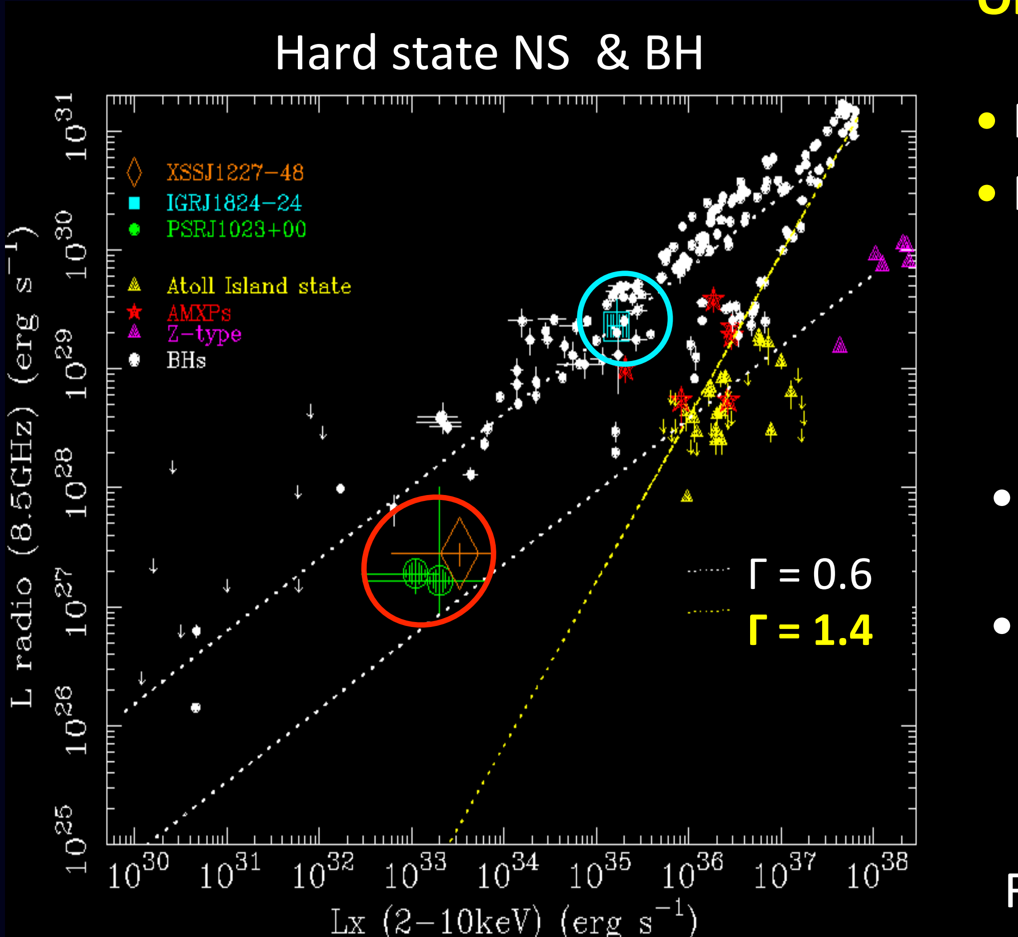
Strong propeller: $\omega_s = \Omega_\star / \Omega_k >> 1$

2 Component Outflow

- Slow dense conical wind
- Low-density high-velocity jet

Accretion onto NS still possible

Outflows in tMSP



BH, **Atoll**, **Z-type, AMXPs,** NS: from Migliari & Fender 2006,2011 Gallo et al. 2014, Miller-Jones et al. 2010; Coriat et al. 2011+ref.therein
PSRJ1023: from Deller et al. 2015, **XSS1227**: from de Martino et al. 2015,
IGR1824: from Ferrigno et al. 2014

Observational Evidence ?

- Radio variability (mins)
- Radio flat-inverted slope:

  $S_\nu \approx \nu^{\alpha}$ $\alpha \approx 0.-05$

Hill et al. 2011
Ferrigno et al.2014
Deller et al. 2015

- tMSPs closer to BH than NS

- tMSPs radio louder than other NS

→ Compact jet in tMSPs likely

Few simultaneous X-ray & Radio obs

Longer simultaneous coverage needed!

tMSPs: an intermediate or atypical evolutionary stage?

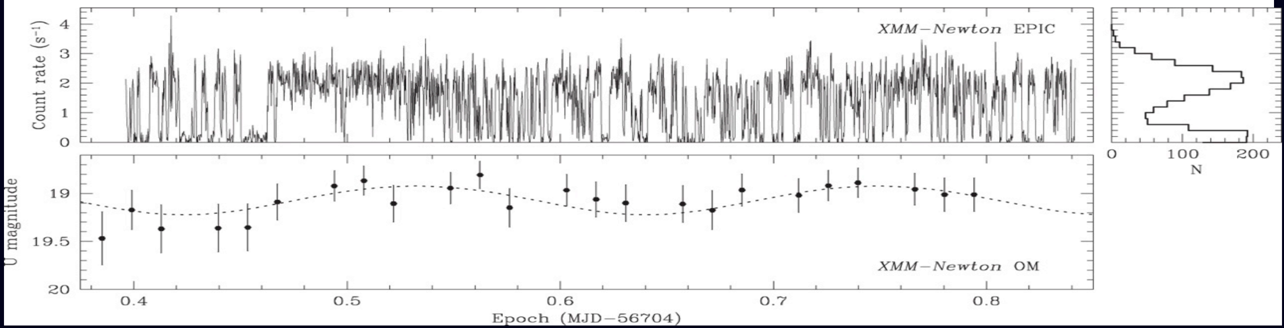
Need to find more !

Ongoing Intense Activities:

- X-ray, Radio & Optical search of counterparts of FERMI-LAT Unidentified sources

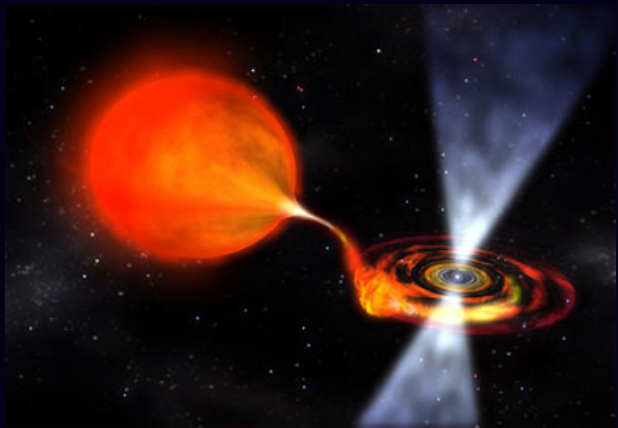
→ RBs, BWs and tMSPs candidates

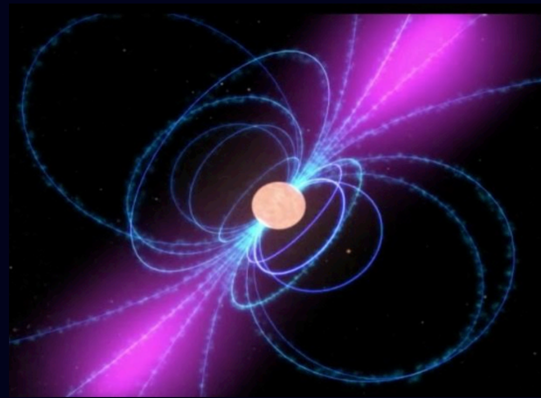
3FGLJ1544-1128 / RXJ1544-1128 Bogdanov & Halpern 2015



- Long-term X-ray & Optical monitoring of known Radio Eclipsing RB
- X-ray deep observations of AMXPs in quiescence may reveal odd modes

Stay tuned!





Thanks:

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