X-ray Studies of Transitional Millisecond Pulsars

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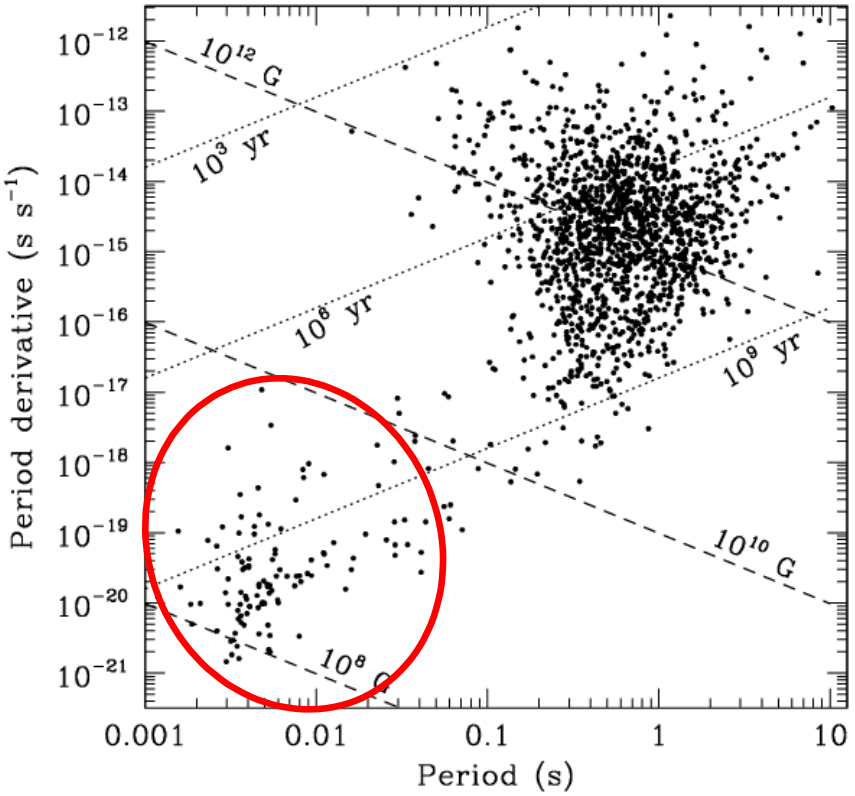
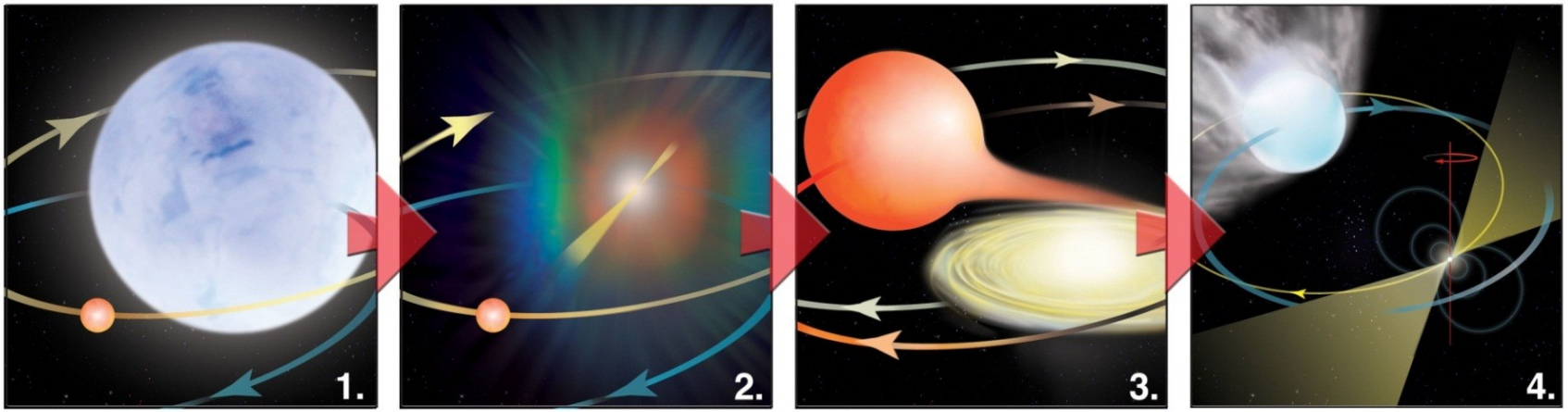
Rotation-powered ("recycled") millisecond pulsars

- Discovered at radio frequencies
  - PSR B1937+21 with Arecibo (Backer et al. 1982)

- Most radio MSPs are in binaries

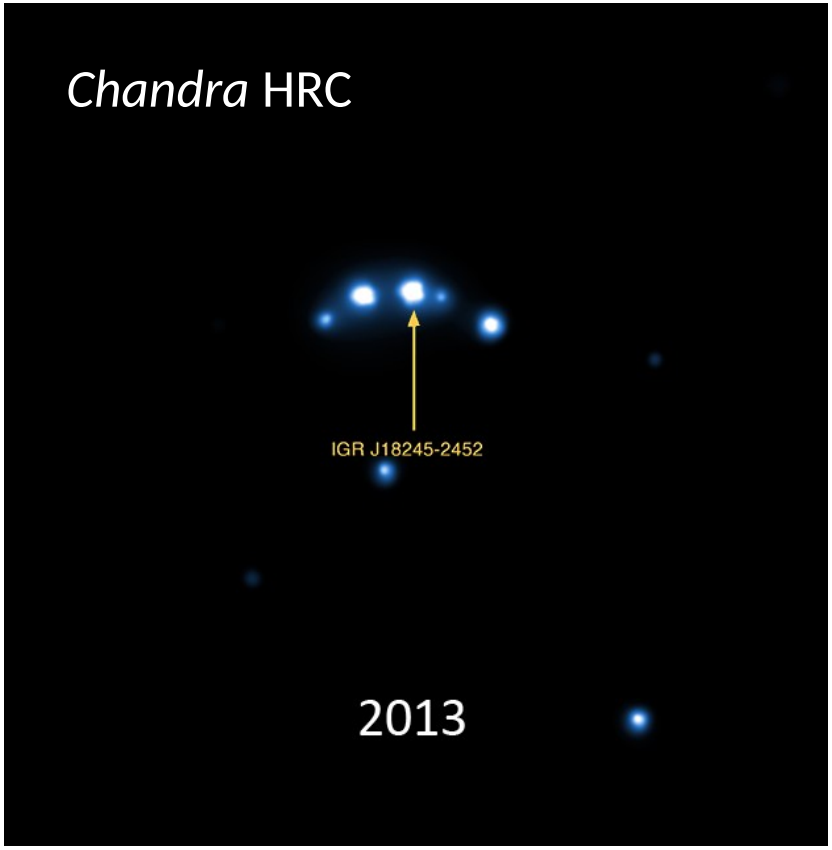
- Spun-up ("recycled") by accretion in LMXBs (Alpar et al. 1982)



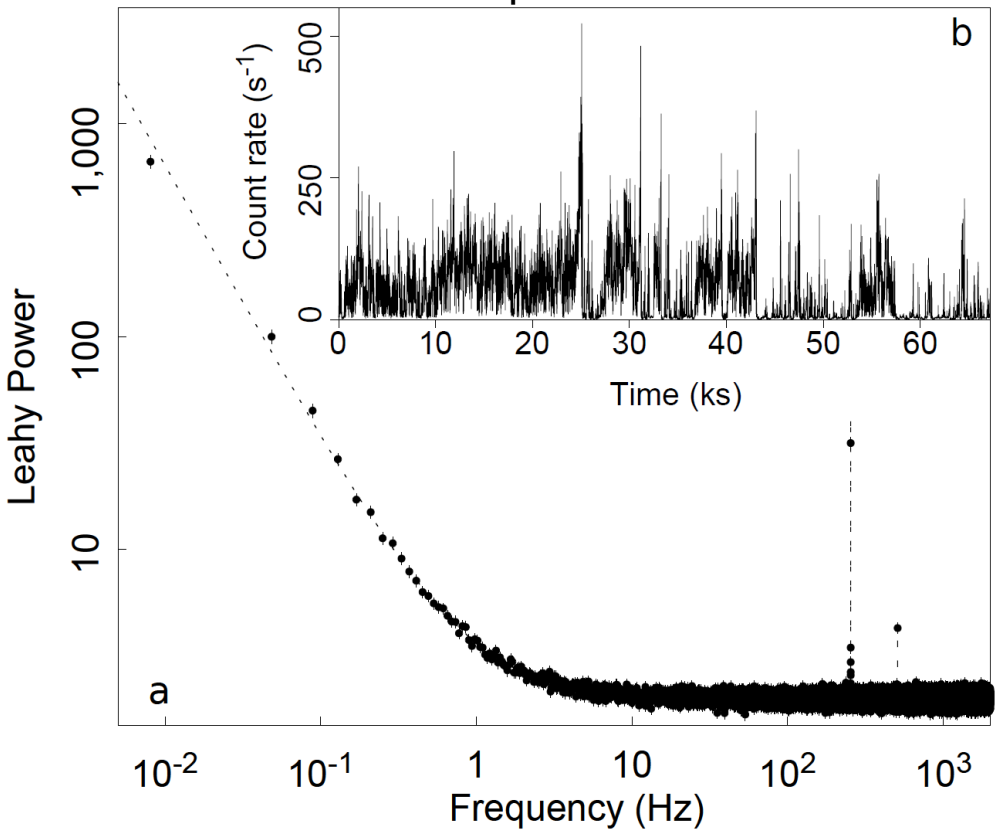


PSR J1824–2452I / IGR J18245–2452 (M28)

Rotation-powered (radio) MSP ▯ Luminous accretion-powered (X-ray) MSP



XMM-Newton EPIC pn

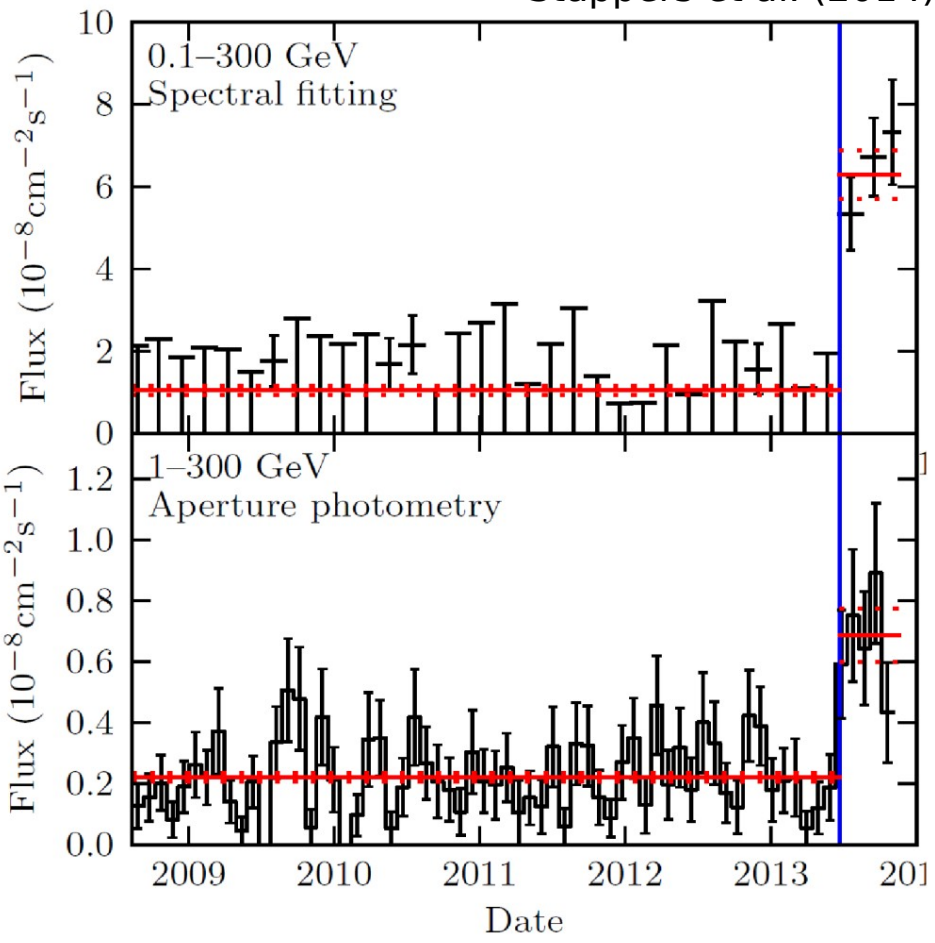


Papitto et al. (2013)

The "Missing Link" PSR J1023+0038: The Accretion Disk Returns

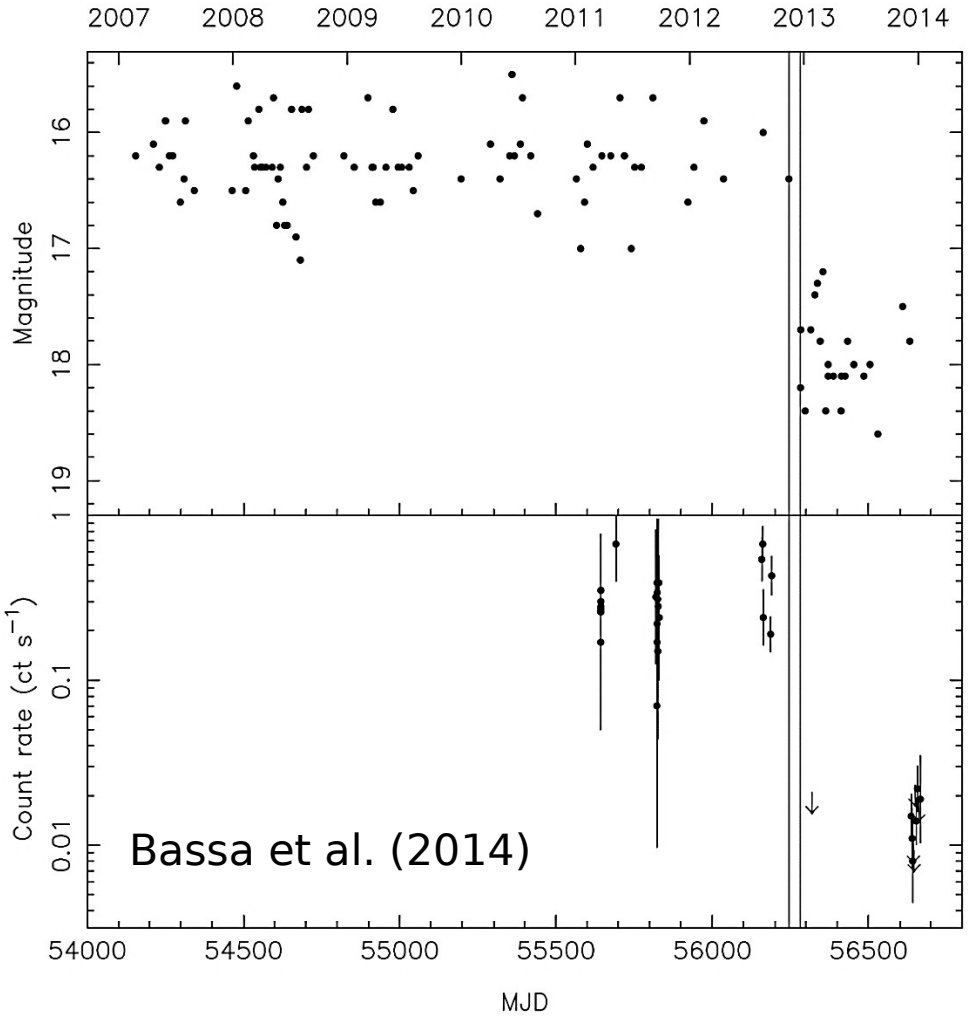
- Radio pulsar emission ceased on June 23rd, 2013
- Optical brightness increased by ~1 mag
- Double-peaked optical emission lines reappeared
- ***Fermi* LAT flux increased ~5-fold!**
- **Average X-ray flux increased by ~order of magnitude**

Stappers et al. (2014)

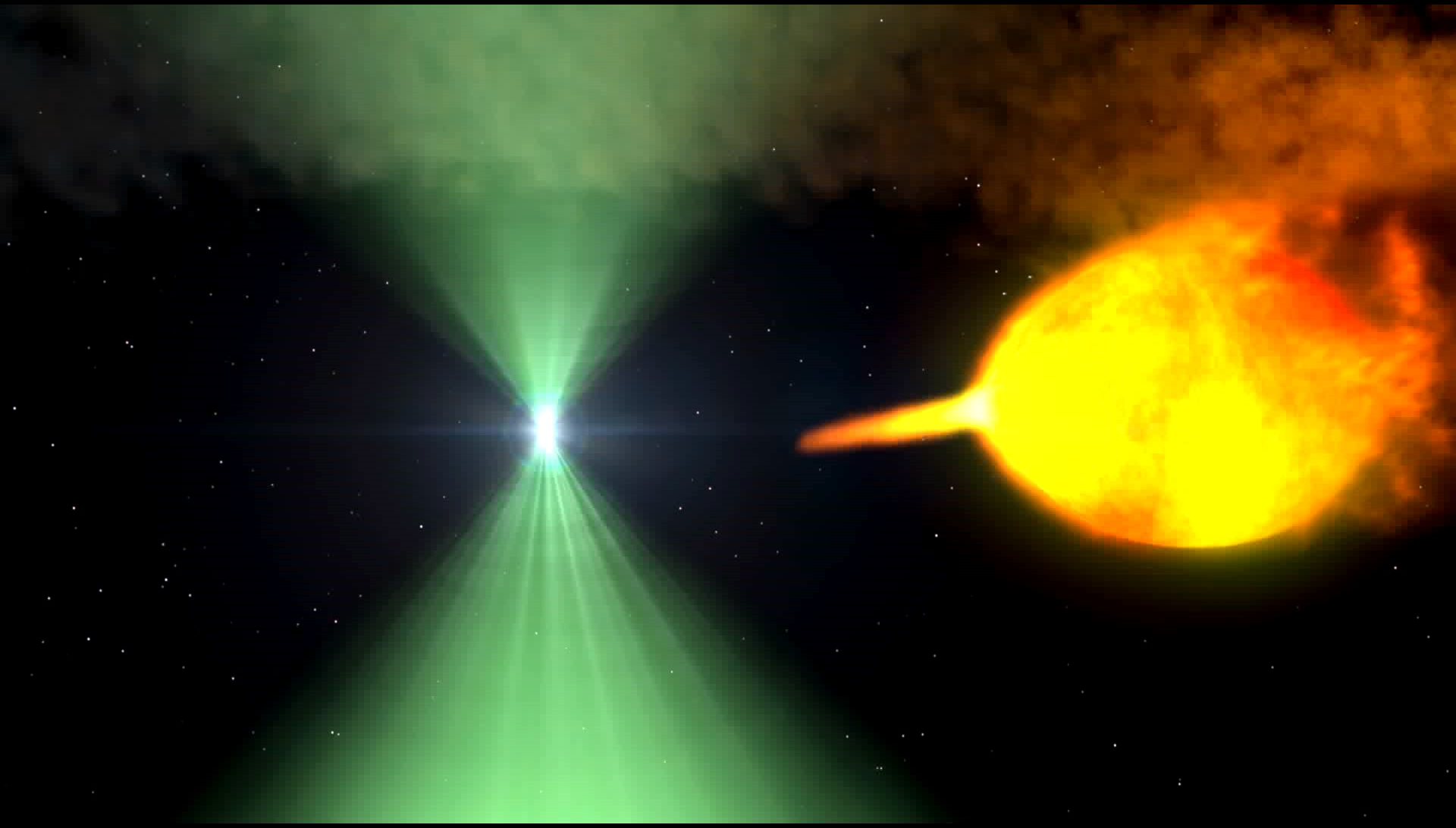


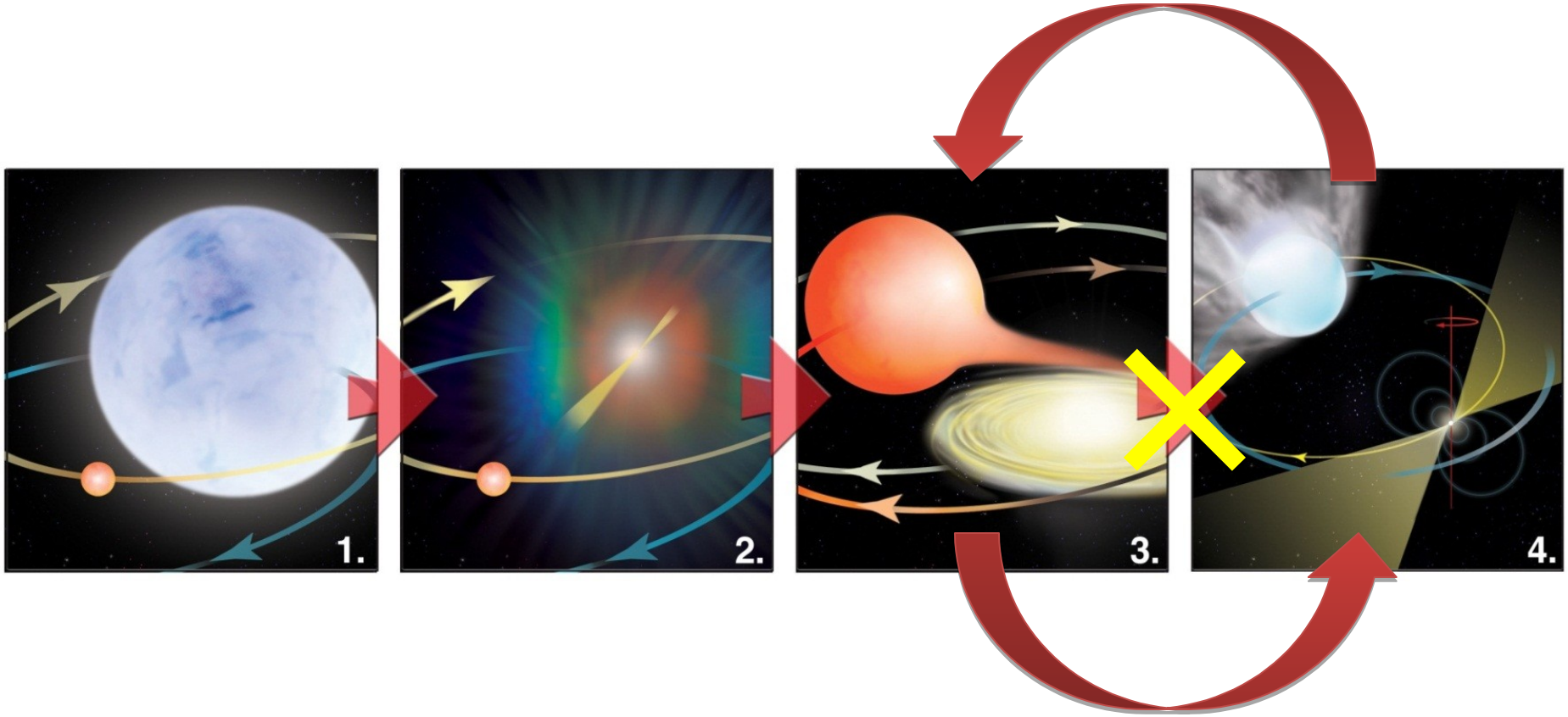
XSS J12270–4859: Another Transitional MSP System

- Low-mass X-ray binary with *Fermi* LAT counterpart: 2FGL J1227.7−4553 (Hill et al. 2011; de Martino et al. 2010,2013)
- In Nov/Dec 2012, optical flux declined by ~1.5 mag (Bassa et al. 2014)
- **X-ray flux decreased by ~order of magnitude**
- Optical emission lines disappeared (de Martino et al. 2015)
- Radio and γ-ray pulsations detected in non-accreting state at P=1.69 ms (Roy et al. 2014; Johnson et al. 2015)



Transition from low-luminsity LMXB to “redback” radio MSP




1.
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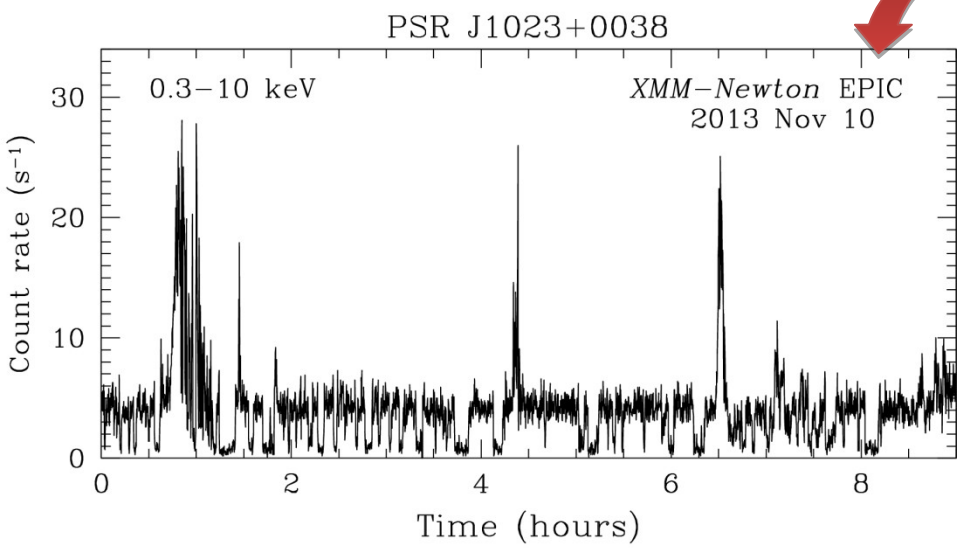
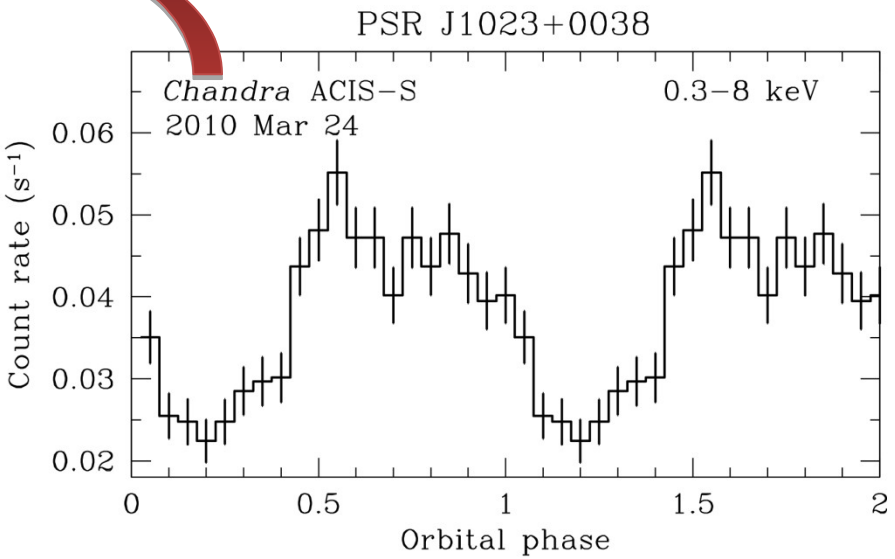
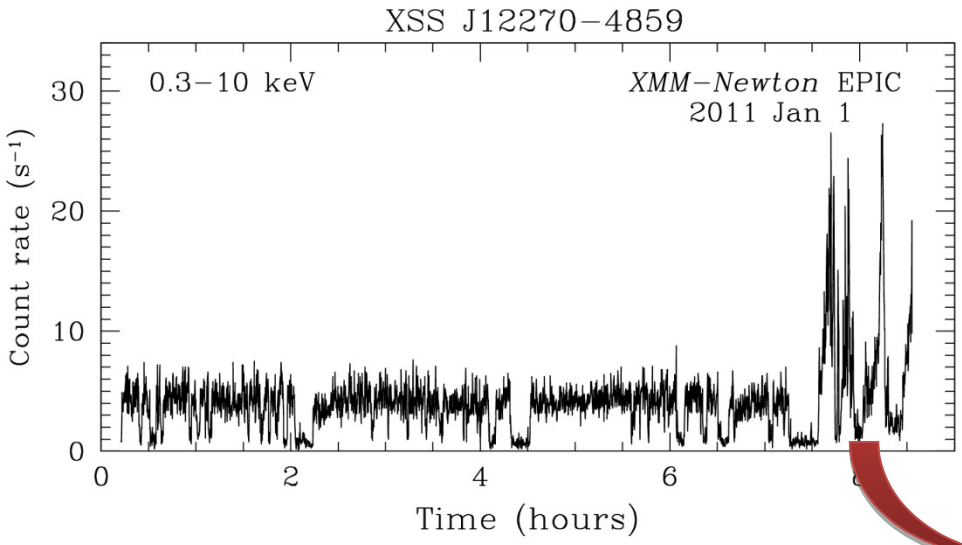
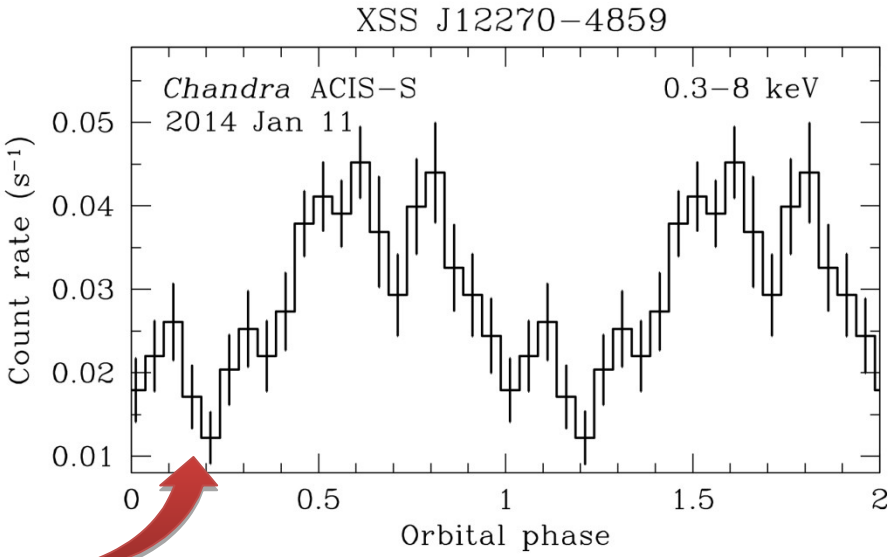
‘Transitional’ MSP Binaries





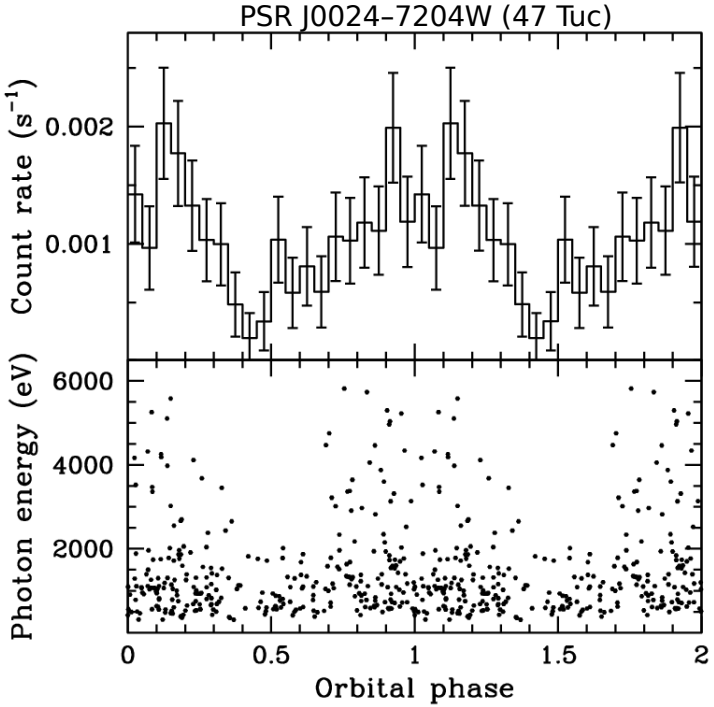




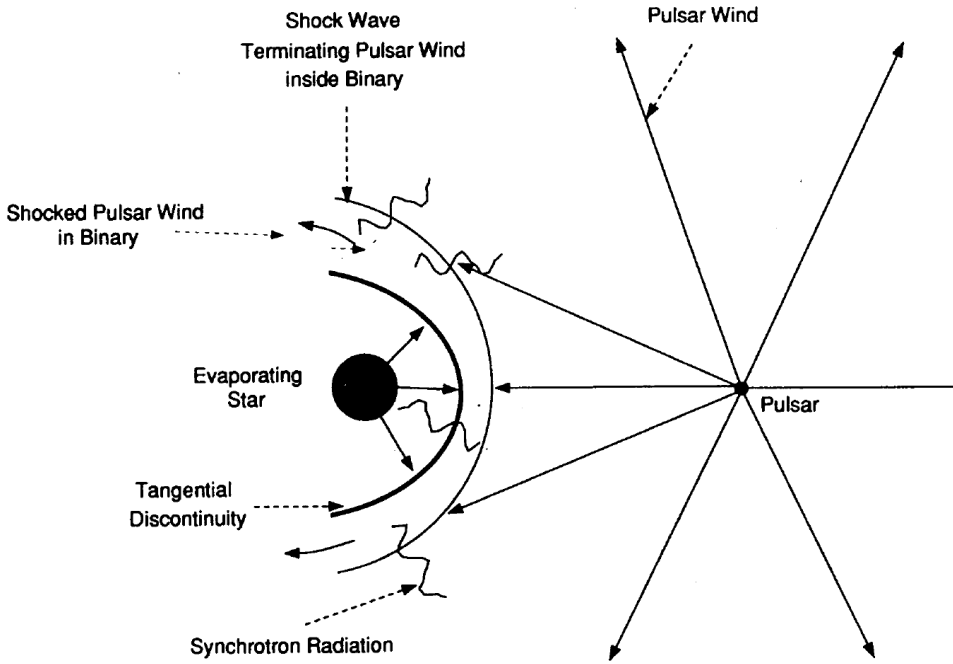
Bassa et al. MNRAS, 441, 1825 (2014)
Bogdanov et al. ApJ, 789, 40 (2014)

“Redback” Millisecond Pulsars

- MSP binaries with non-degenerate ≥0.2 $M_\odot$ secondary stars
- $L_X \approx 10^{31–32}$ erg s^{-1}
- Non-thermal emission with orbital variability ⇒ intra-binary shock due to interaction of pulsar wind with companion
- **Parent population of transitional**



Bogdanov et al. ApJ, 630, 88 (2005)



Arons & Tavani, ApJ, 403, 249 (1993)

AN X-RAY VARIABLE MILLISECOND PULSAR IN THE GLOBULAR CLUSTER 47 TUCANAE: CLOSING THE LINK TO LOW-MASS X-RAY BINARIES

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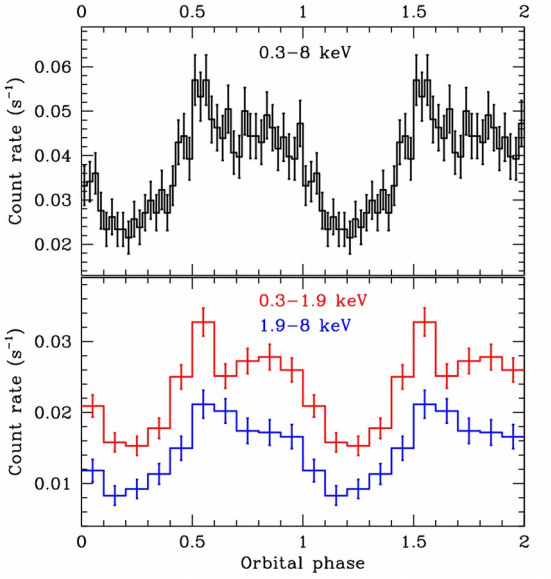
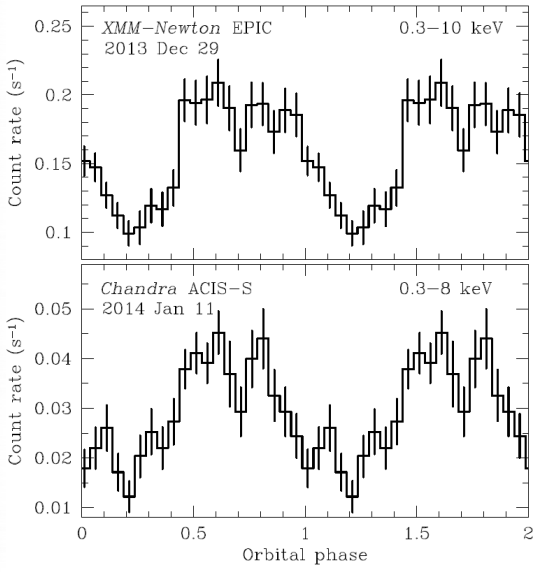
Received 2005 February 7; accepted 2005 May 25

PSR J1023+0038



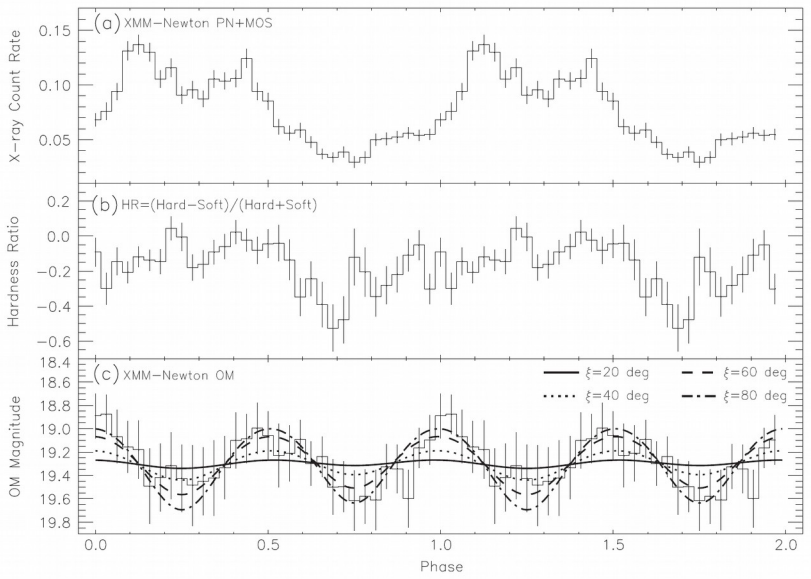
Bogdanov et al. ApJ, 762, 96 (2011)

XSS J12270–4859



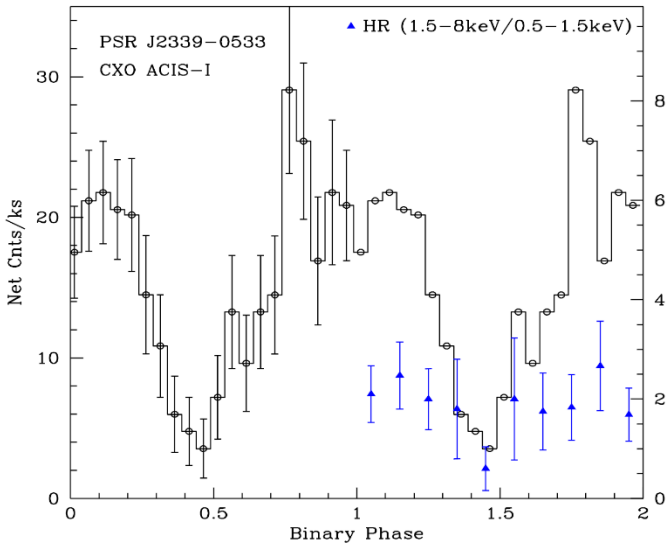
Bogdanov et al. ApJ, 789, 40 (2014)

PSR J2129–0429



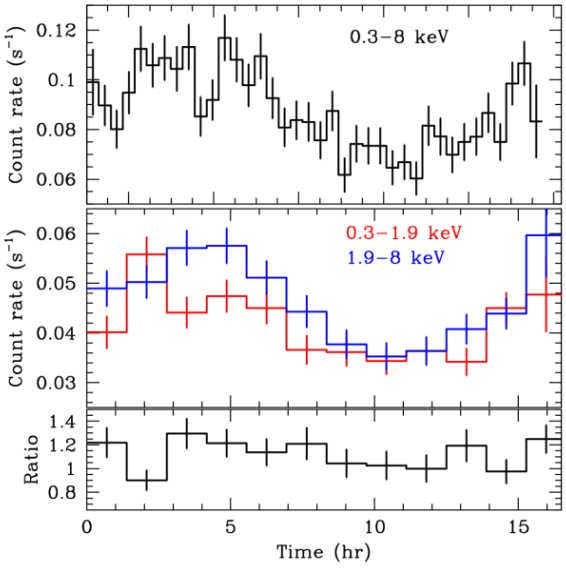
Hui et al. ApJ, 801, L27 (2014)

PSR J2339–0533



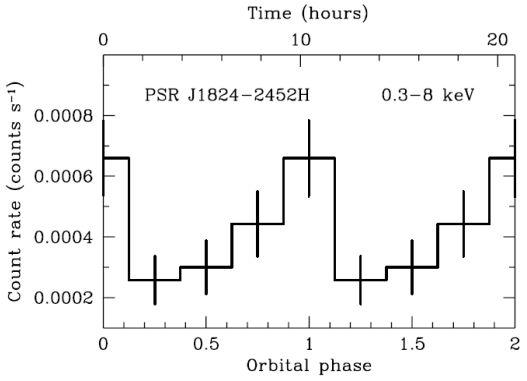
Romani & Shaw, ApJ, 743, L26 (2011)

PSR J1723–2837



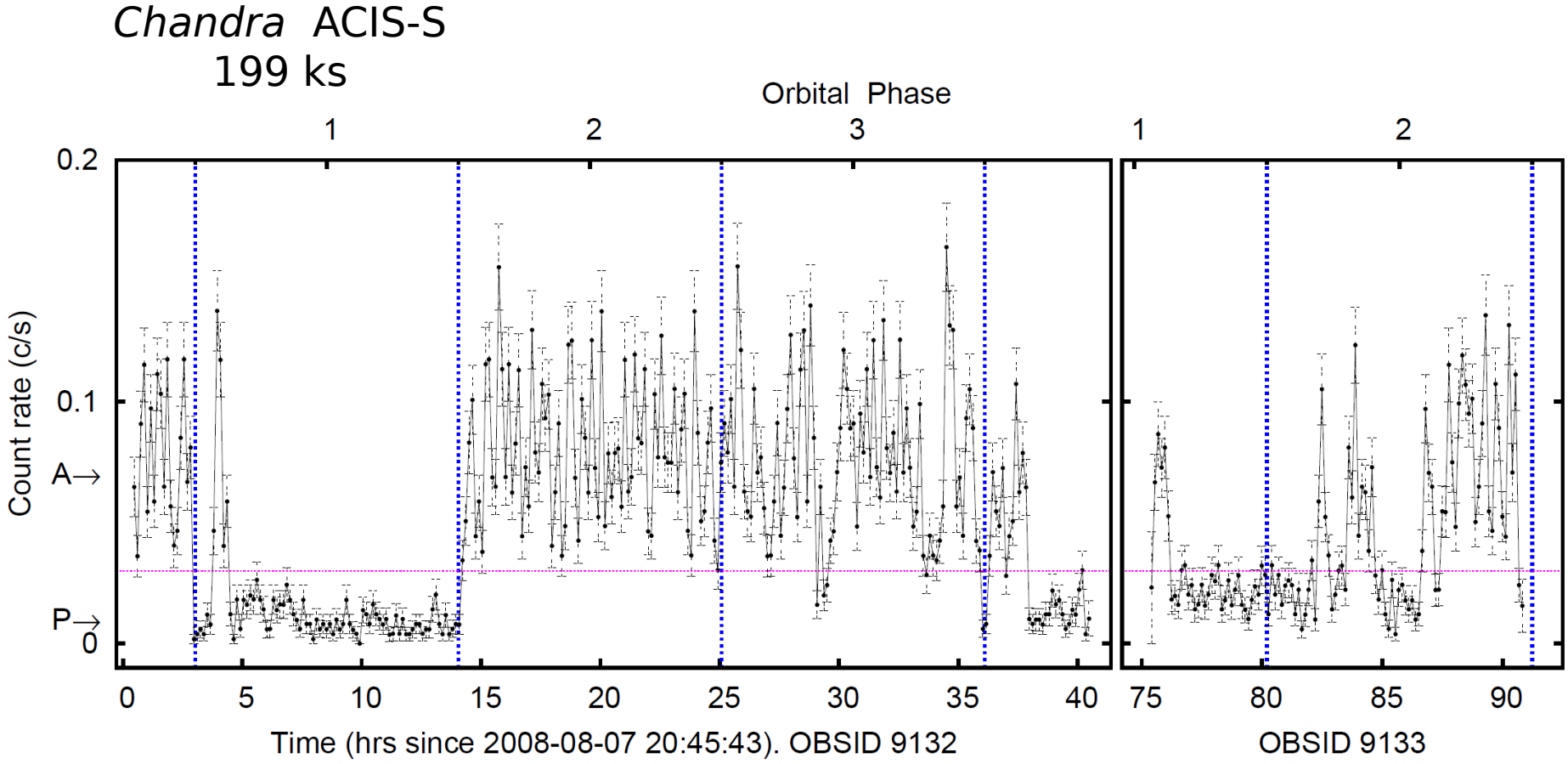
Bogdanov et al. ApJ, 781, 6 (2014)

PSR J1824-2452H (M28)



Bogdanov et al. ApJ, 730, 81 (2011)

PSR J1824-2452I/IGR J18245-2452: Accreting State



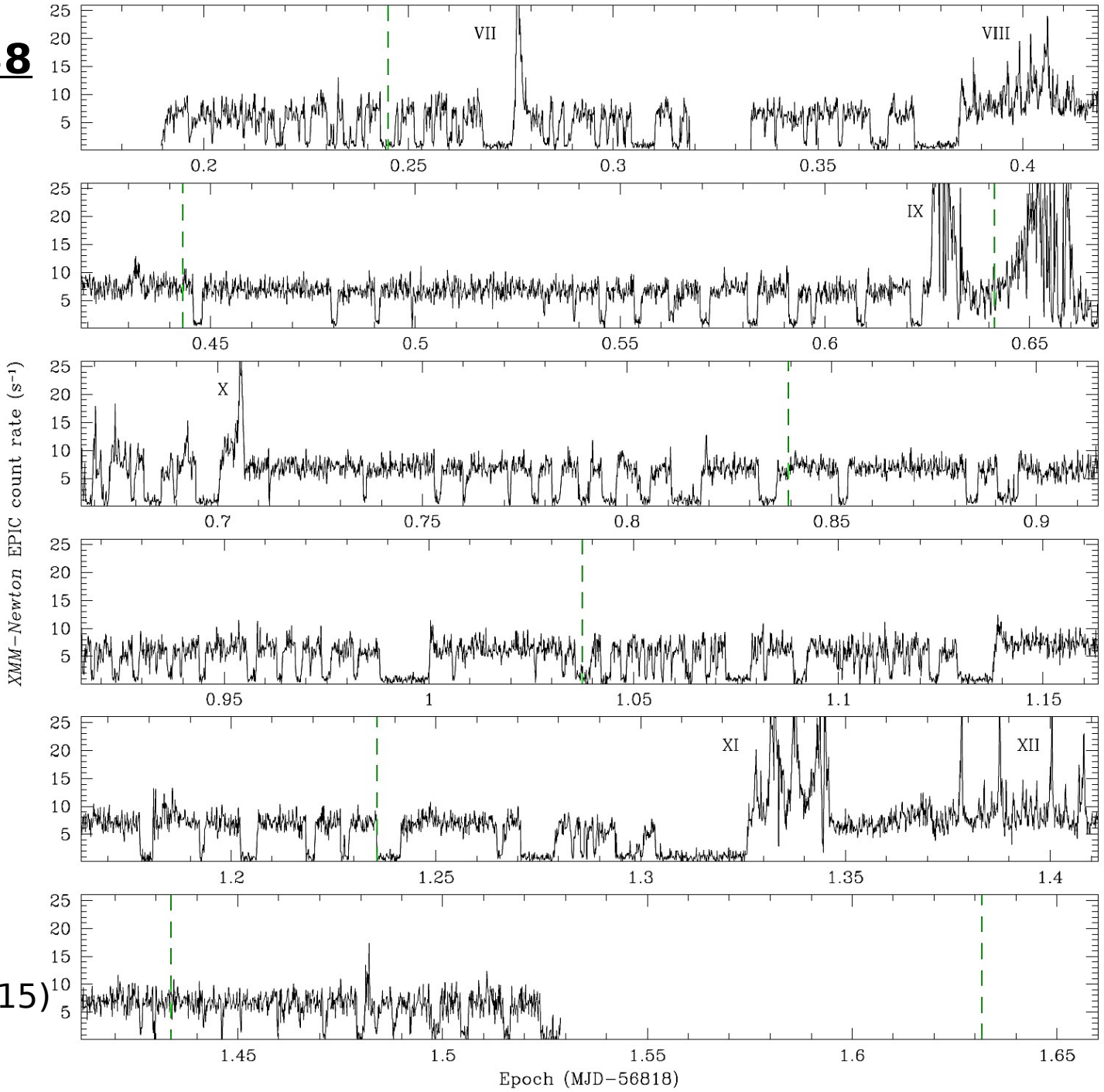
$L_X \approx 10^{32-33}$ erg s^{-1} (0.3–8 keV)

Linares et al. (2014)

PSR J1023+0038

XMM-Newton EPIC

$L_X \approx 10^{33–34}$ erg s^{-1}
(0.3–10 keV)

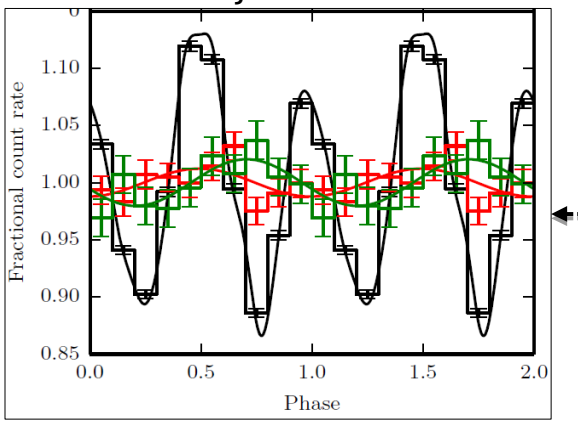


Bogdanov et al. (2015)

Accretion-powered X-ray Pulsations!

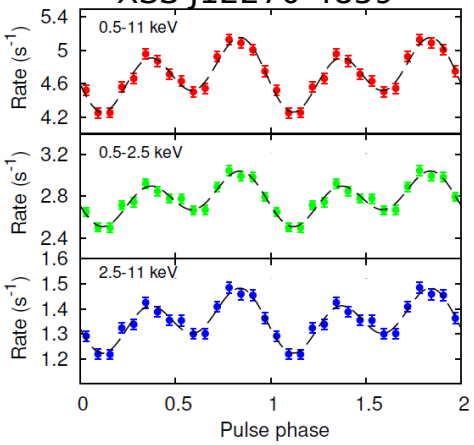
- Coherent X-ray pulsations only in “high” mode
  ⇒ channeled accretion onto star at quiescent levels - $L_X \approx 10^{33}$ erg s^{-1} ($\sim 10^{-5} L_{edd}$)

PSR J1023+0038

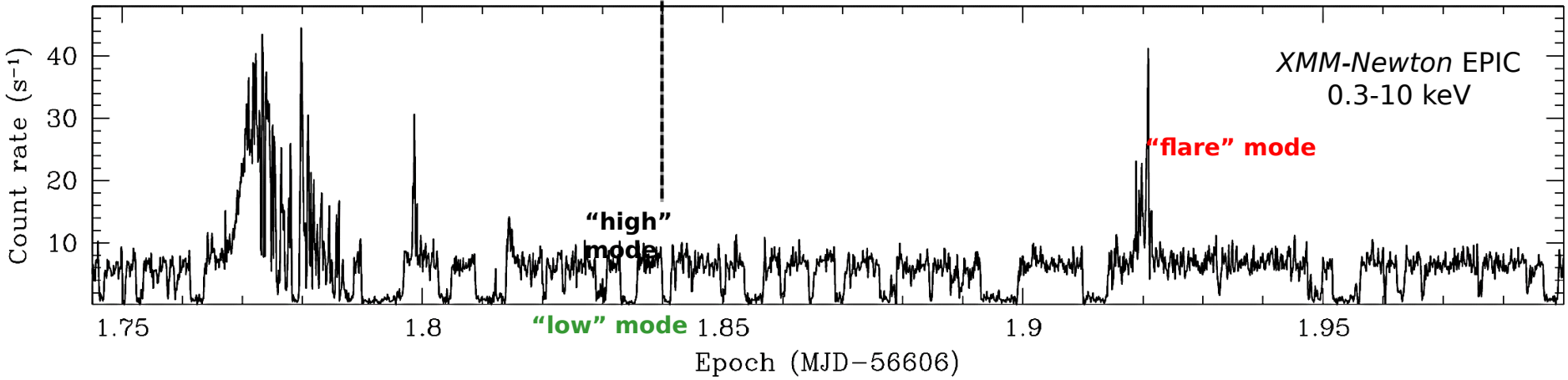


Archibald et al. (2015)

XSS J12270-4859



Papitto et al. (2015)

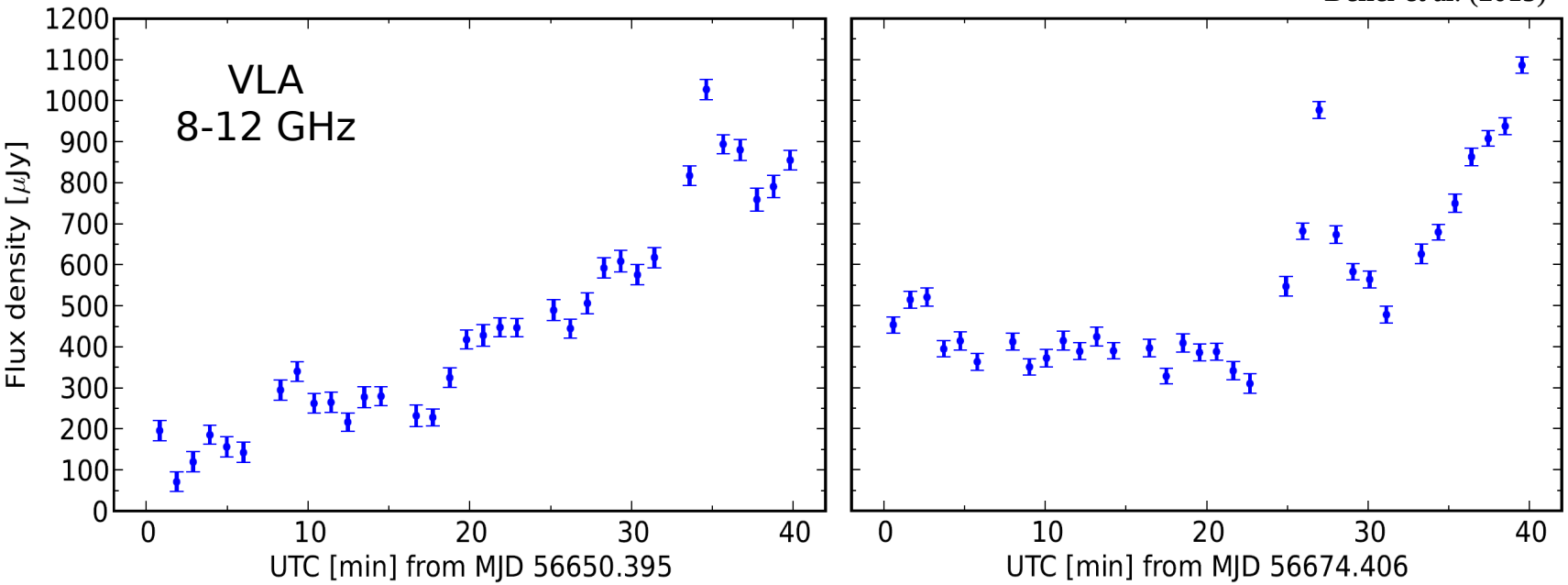


No accretion model can explain this behavior!

Faint flat-spectrum, variable radio emission

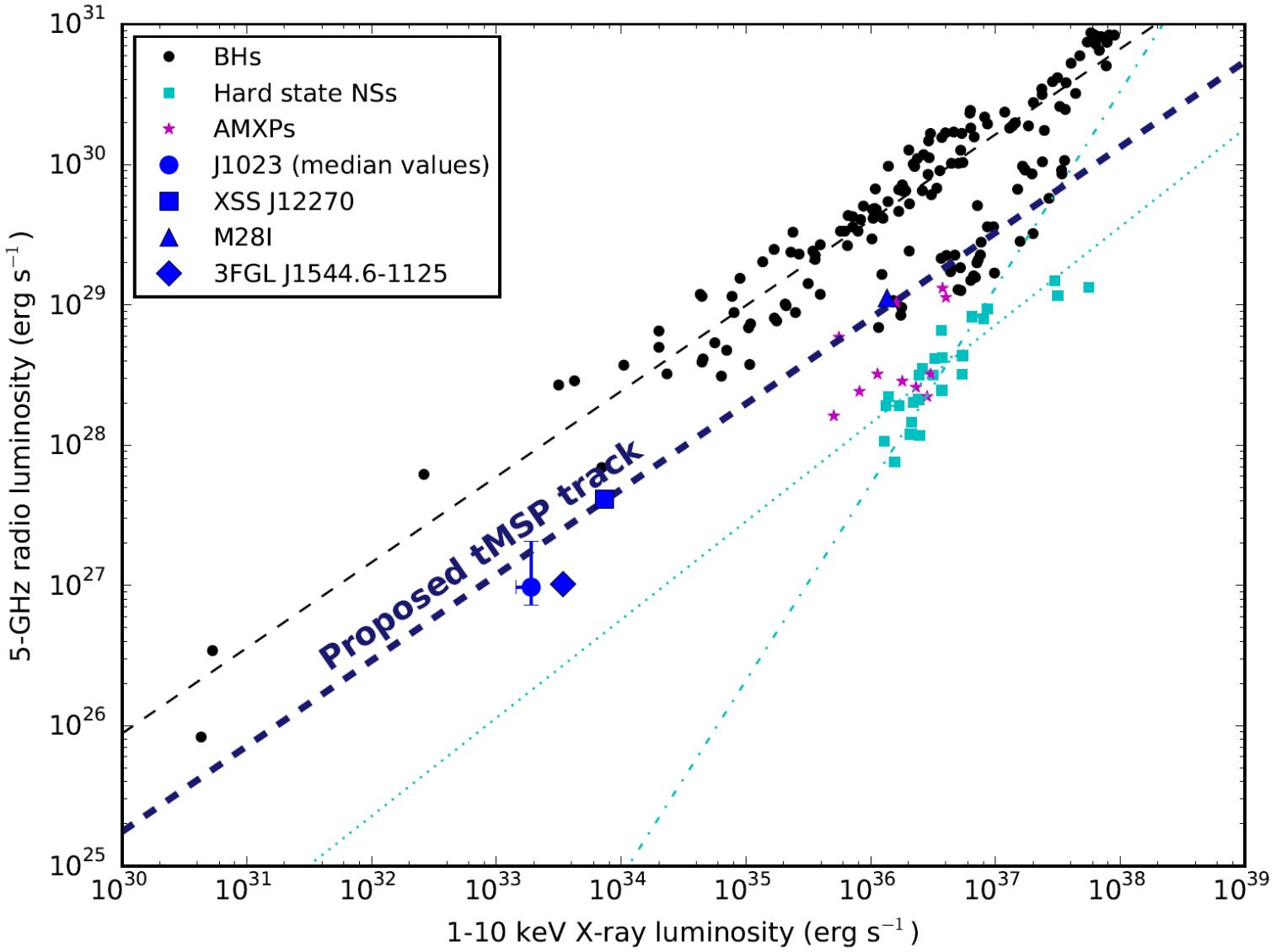
PSR J1023+0038

Deller et al. (2015)



Synchrotron from a compact, partially self-absorbed jet?

An X-ray/Radio Luminosity Correlation for accreting MSPs?

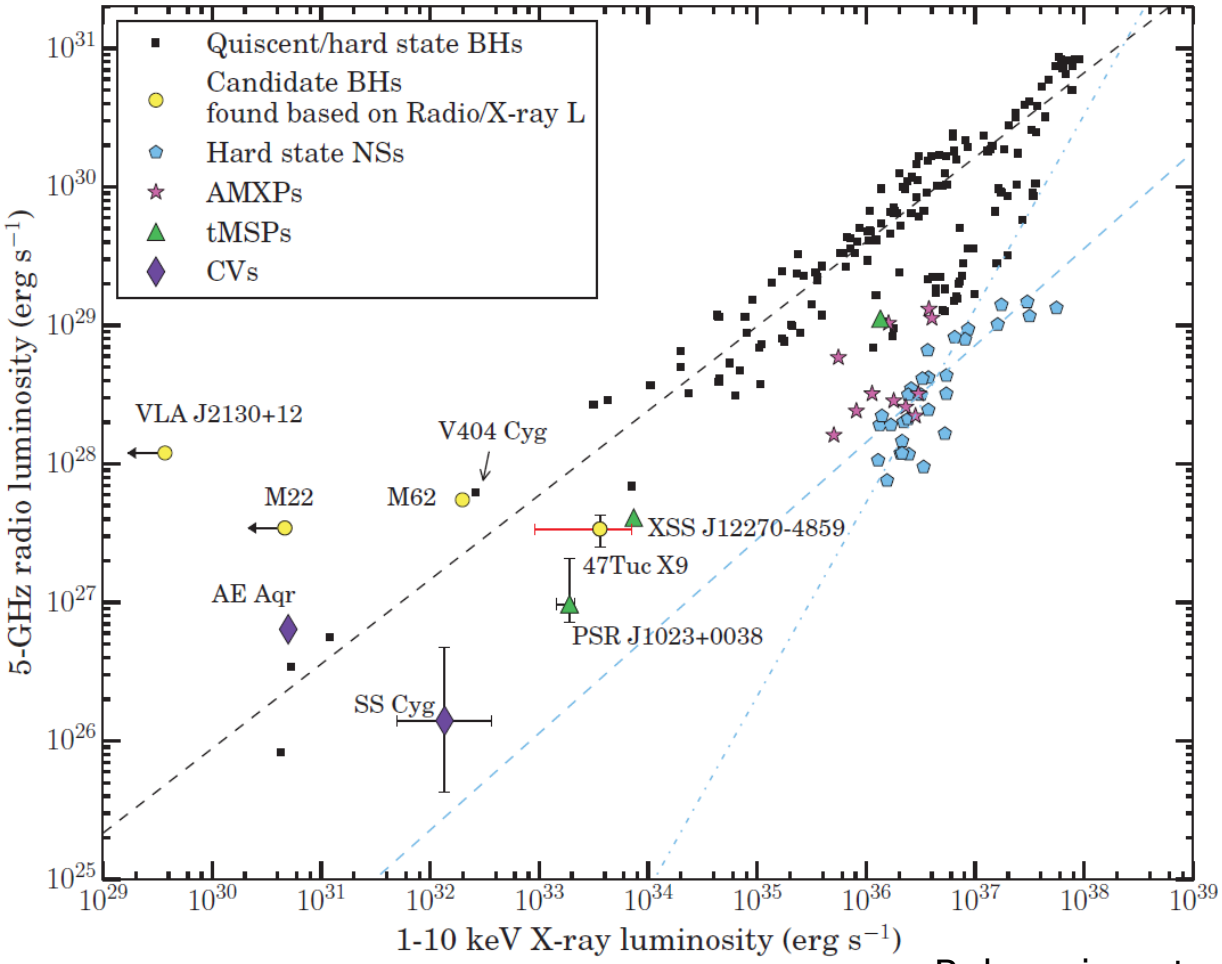


Jaodand et al. in prep.

47 Tuc X9: An Ultracompact X-ray Binary

- A 28 minute binary with a WD donor and tMSP or BH accretor!

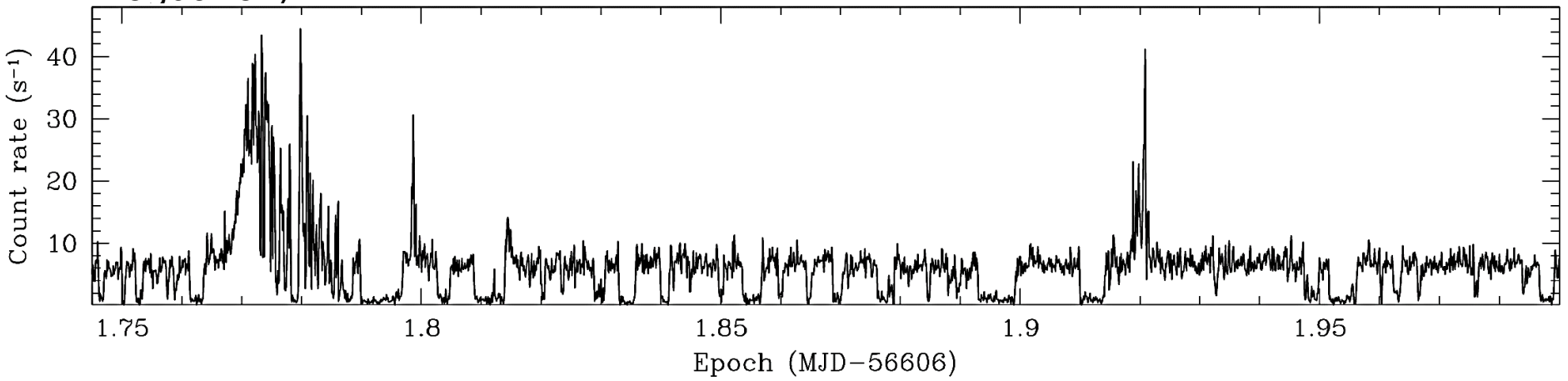
simultaneous *Chandra* + *NuSTAR* + ATCA observations



Bahramian et al. MNRAS, submitted

Transitional Millisecond Pulsars Observing Programs

- *Chandra*+GBT monitoring of PSR J1824–2452I in M28 (Cycle 16, PI Linares)
- *XMM-Newton*+*Swift*+VLA+VLT+LOFAR+Lovell+e-EVN+WSRT observations of PSR J1023+0038 (Bogdanov et al. 2015)
- *Chandra* follow-up of transitional MSP candidates in *Fermi* LAT sources (Cycle 17, PI Halpern)
- Long-term timing of PSR J1023+0038 with *XMM-Newton* (Jaodand et al. in press)
- *Swift* X-ray/UV monitoring of nearby “redbacks” (Cycle 12, PI Bogdanov)
- VLA/*Fermi* LAT survey for transitional MSPs (Fermi GO Cycle 9, PI Bogdanov)
- Contemporaneous *Chandra*+VLA observations of PSR J1023+0038 (Cycle 17, PI Bogdanov)



Open Questions

- What causes transitions to/from accreting state?
- Why is accretion flow able to reach neutron star surface?
- X-ray mode switching – emptying and refilling of inner accretion disk or interruptions in low-level accretion? Pulsar moding?
- Lack of radio pulsations when accreting – enshrouding or quenching due to accretion?
- GeV γ-ray emission in accreting state – intra-binary shock or propeller ejection?
- What mechanism drives jet-like outflow?
- X-ray flares – enhanced ejection or accretion onto neutron star?

- Only 3 *bona fide* tMSPs identified so far

  $\Rightarrow$ <u>Necessary to extend the sample of transitional MSPs</u>

- Detailed behavior of tMSP accreting state is telling us something important about disk-wind/magnetosphere interactions and jet production

  $\Rightarrow$ <u>Further multi-wavelength studies of known transitional MSPs are essential!</u>