# New Insights Into Accretion Physics from Transitional Millisecond Pulsars

Slavko Bogdanov

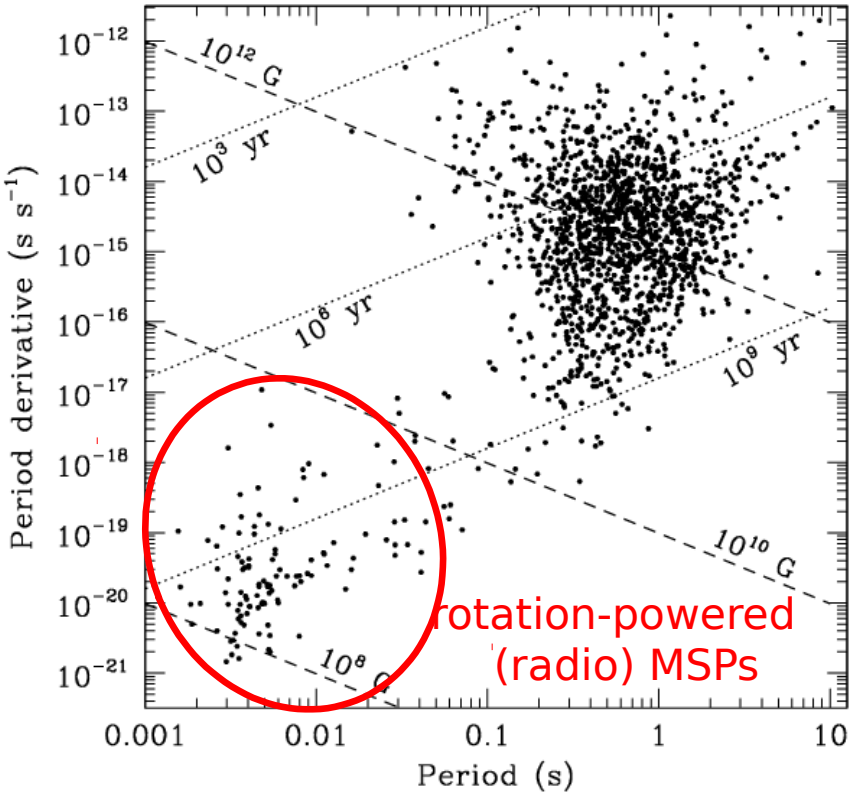
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

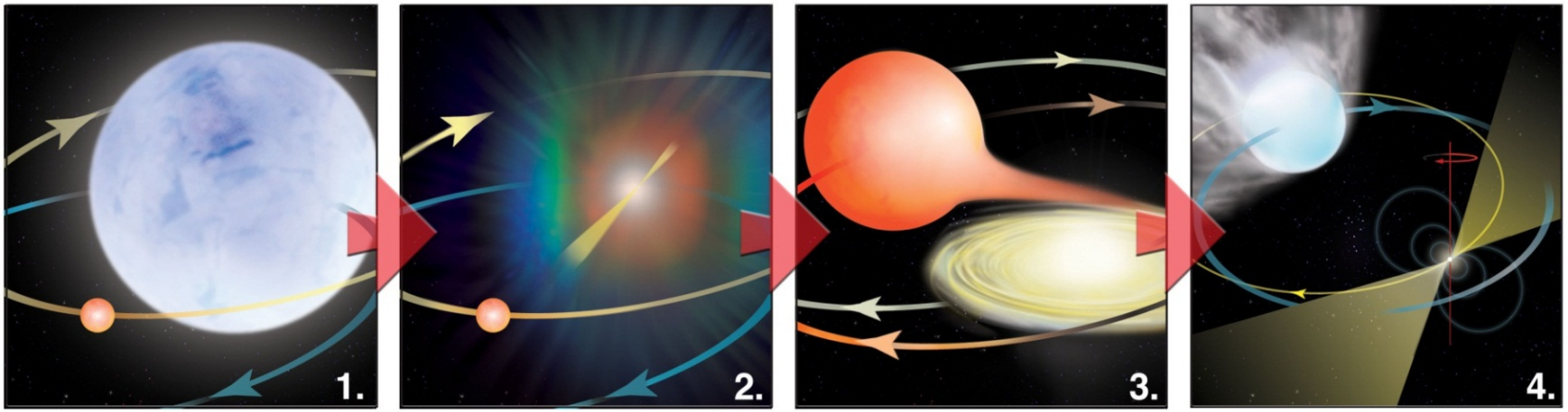
# In collaboration with:

- Anne Archibald
- Cees Bassa
- Adam Deller
- Caroline D’Angelo
- Jules Halpern
- George Heald
- Jason Hessels
- Amruta Jaodand
- Gemma Janssen
- Manu Linares
- James Miller-Jones
- Javier Moldón
- Zsolt Paragi
- Alessandro Patruno
- Ben Perrera
- Ben Stappers
- Shriharsh Tendulkar
- Rudy Wijnands

# Rotation- and accretion-powered millisecond pulsars

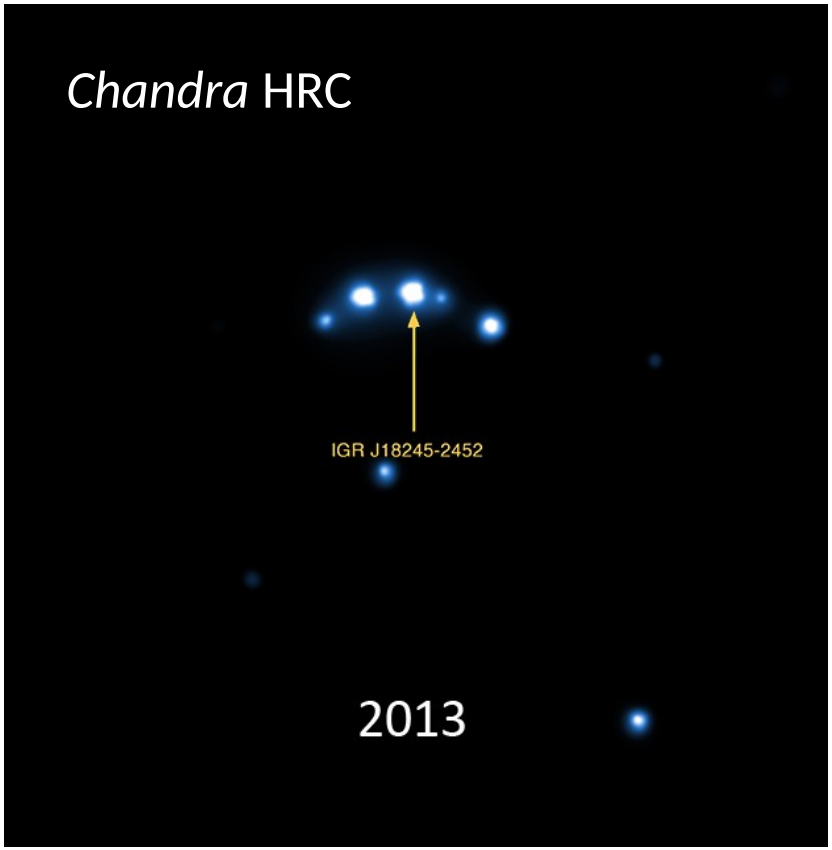
- MSPs discovered at radio frequencies : PSR B1937+21 with Arecibo (Backer et al. 1982)
- Most rotation-powered (radio) MSPs are in binaries
- Accretion-powered MSPs discovered in X-rays: SAX J1808.4- 3658 with *RXTE* (Wijnands & van der Klis 1998)
- Spin-up (“recycling”) by accretion in LMXBs (Alpar et al. 1982)



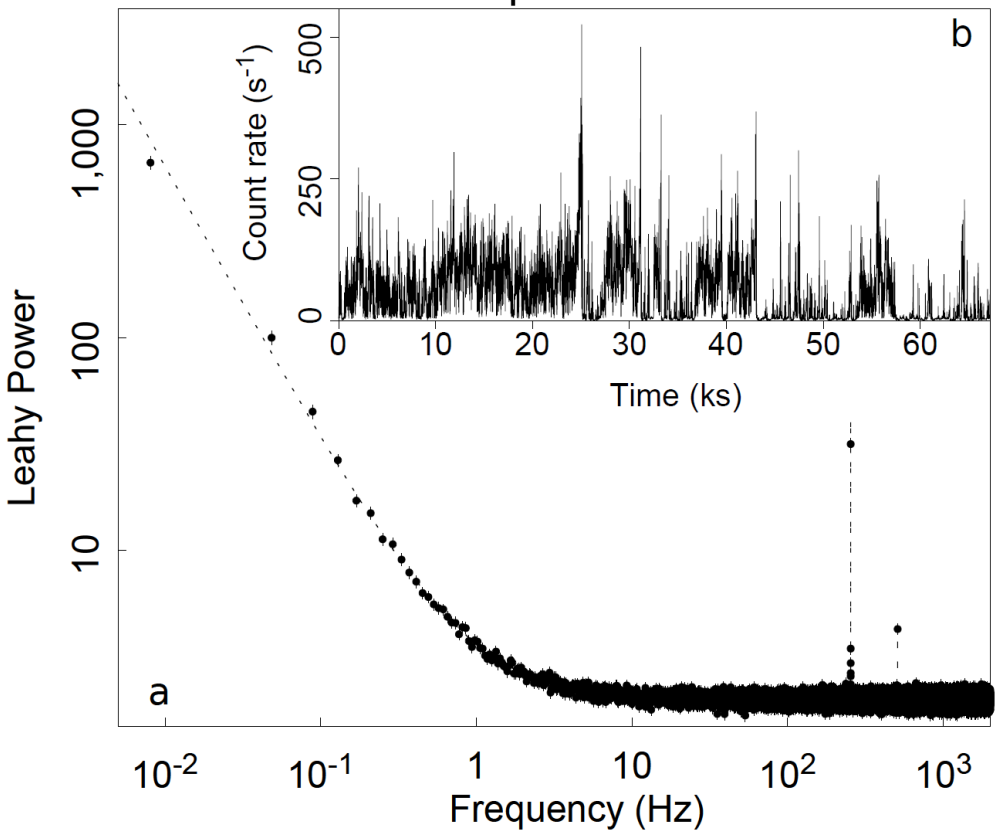



# PSR J1824-2452I / IGR J18245-2452 (M28)

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



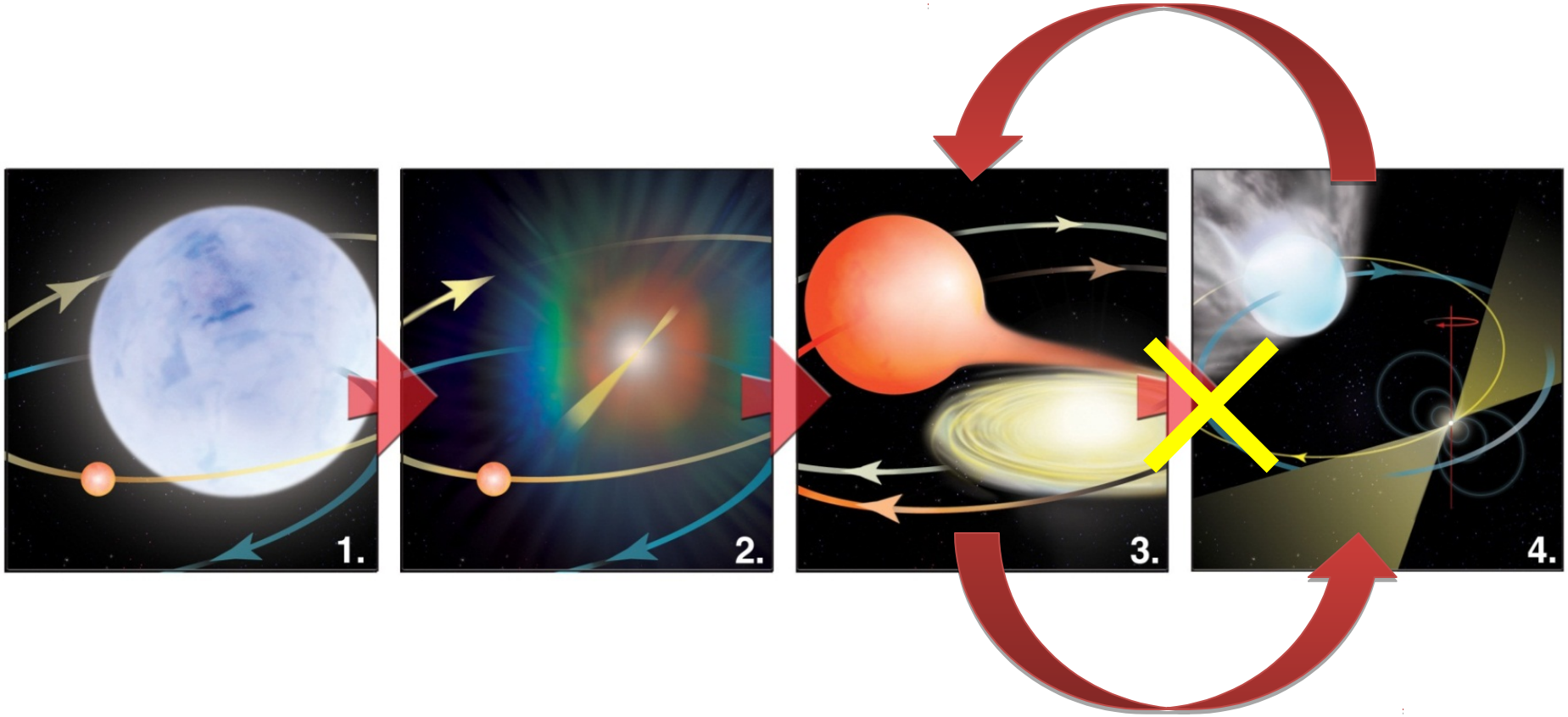

*XMM-Newton* EPIC pn




apitto et al. 2013, Nature, 501, 517

A bona fide transitional millisecond pulsar

# Transitional Millisecond Pulsars



# The Transitional MSP Sample

- **PSR J1023+0038** – d=1.38 kpc

  - Eclipsing ("redback") binary radio MSP ($P$ =1.69 ms, $P_b$ =4.8 h) discovered in 2009

  - System had accretion disk in 2001 but not after 2003

  - Accretion disk returned in 2013

- **XSS J12270-4859** – d≈1.4 kpc

  - Low-mass X-ray binary with *Fermi* LAT counterpart: 2FGL J1227.7-4553

  - In Nov/Dec 2012 accretion disk disappeared and radio and $\gamma$-ray pulsations appeared with $P$=1.69 ms

- **PSR J1824-2452** – d=5.5 kpc

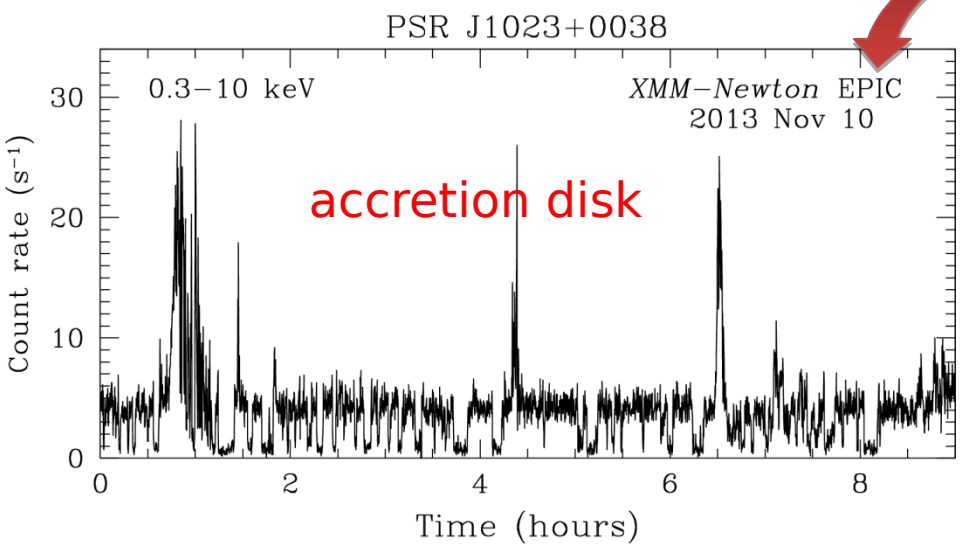
  - Originally discovered as a radio pulsar (P=3.94 ms, $P_b$ =11 h)

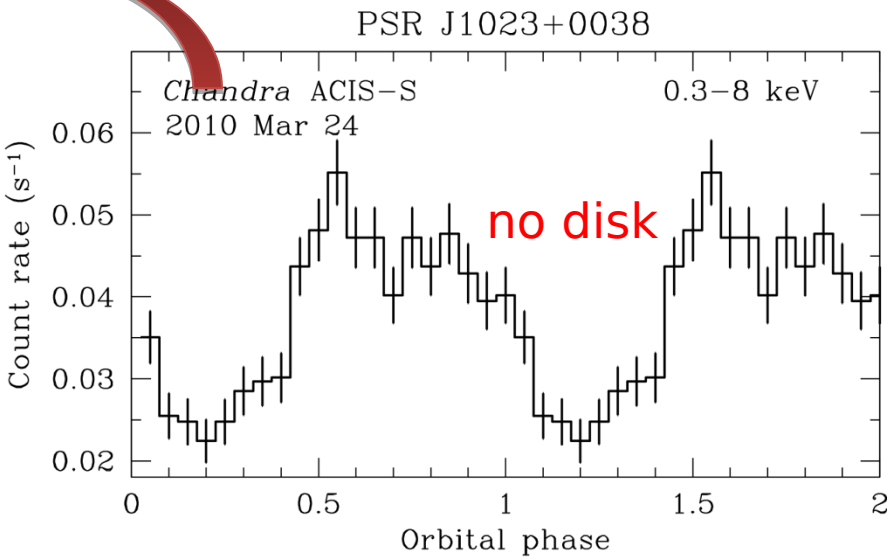
  - System was in low-luminosity accreting state c. 2008

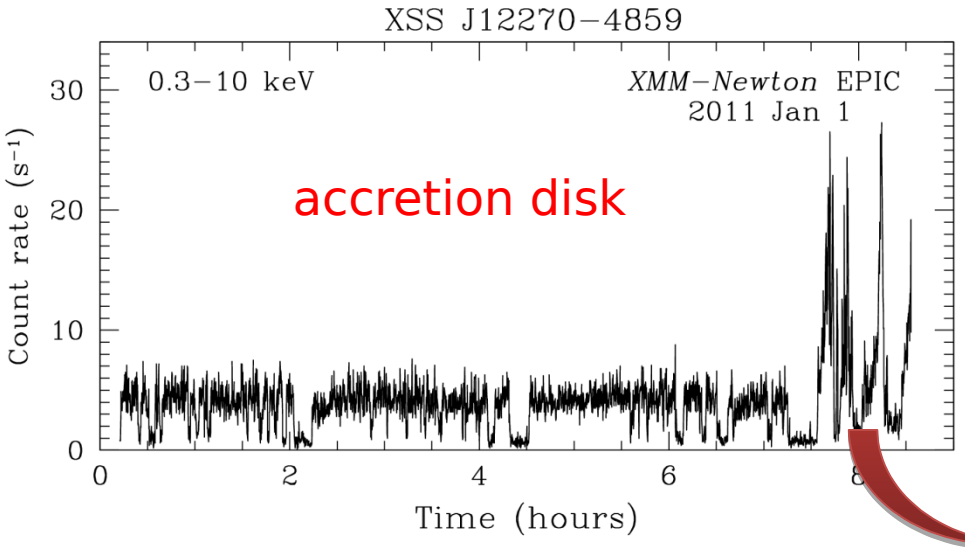
  - Type I thermonuclear burst in 2013

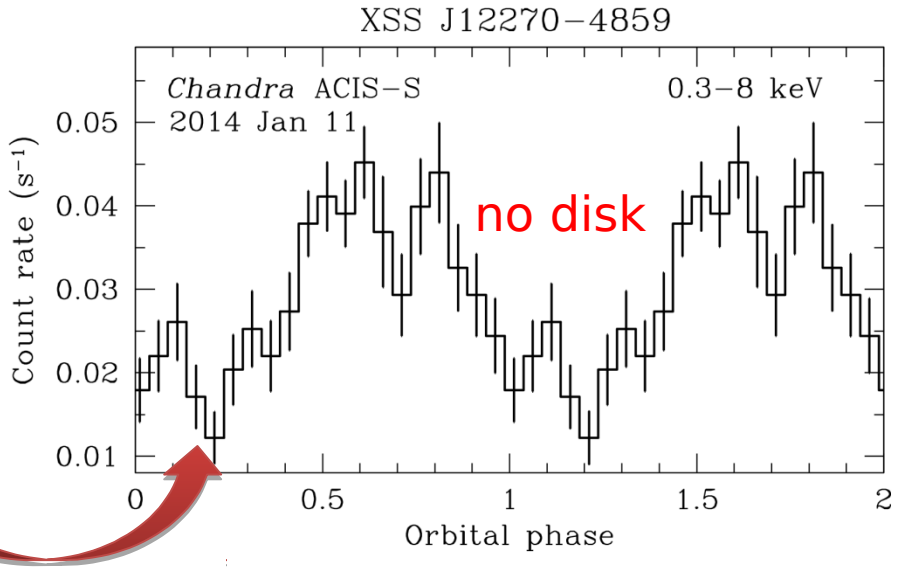
  - Presently in radio pulsar state

# ‘Transitional’ MSP Binaries



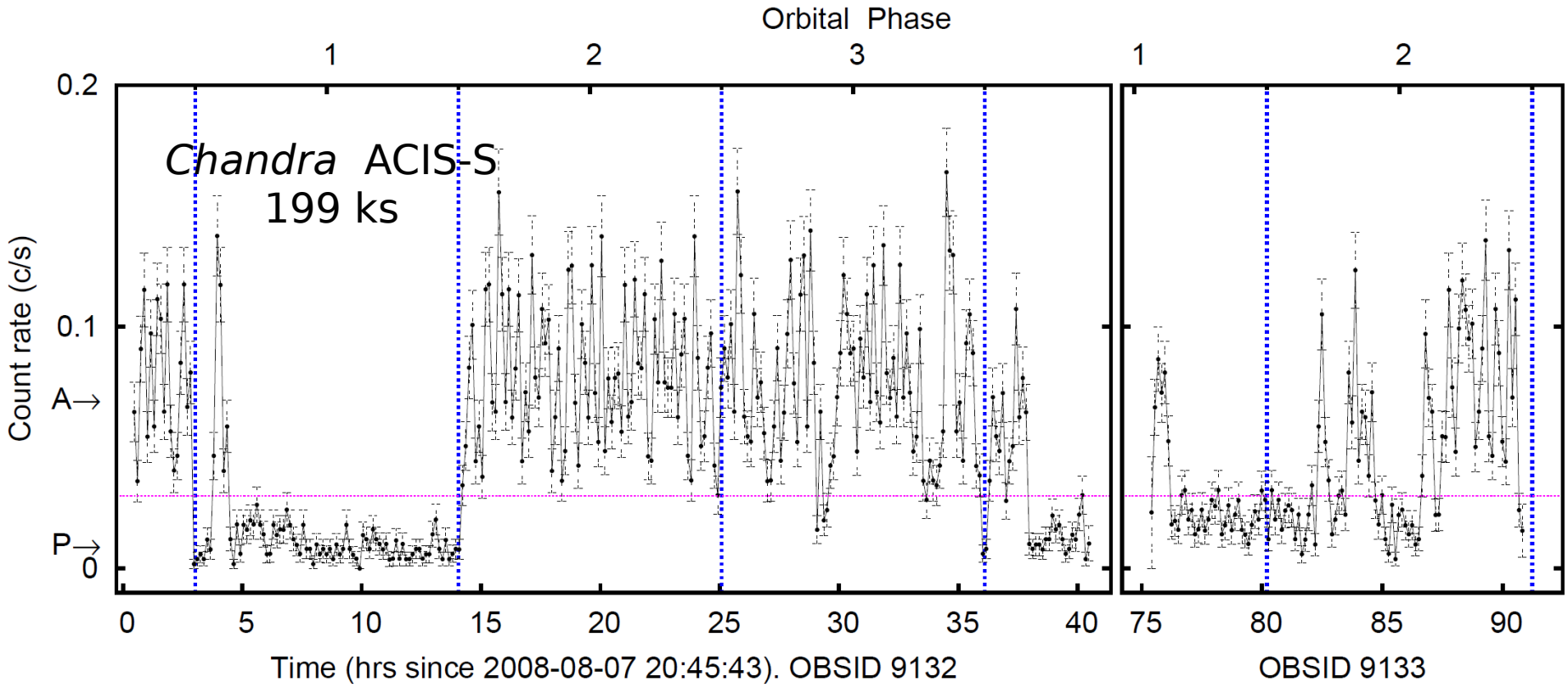

Bassa et al. 2014, MNRAS, 441, 1825

Bogdanov et al. 2014, ApJ, 789, 40

# PSR J1824−2452I/IGR J18245−2452 (M28)

Most of time in accreting state is spent in low luminosity state (~$10^{-5}L_{ed}$

X-ray flux alternates rapidly between two clearly distinct levels

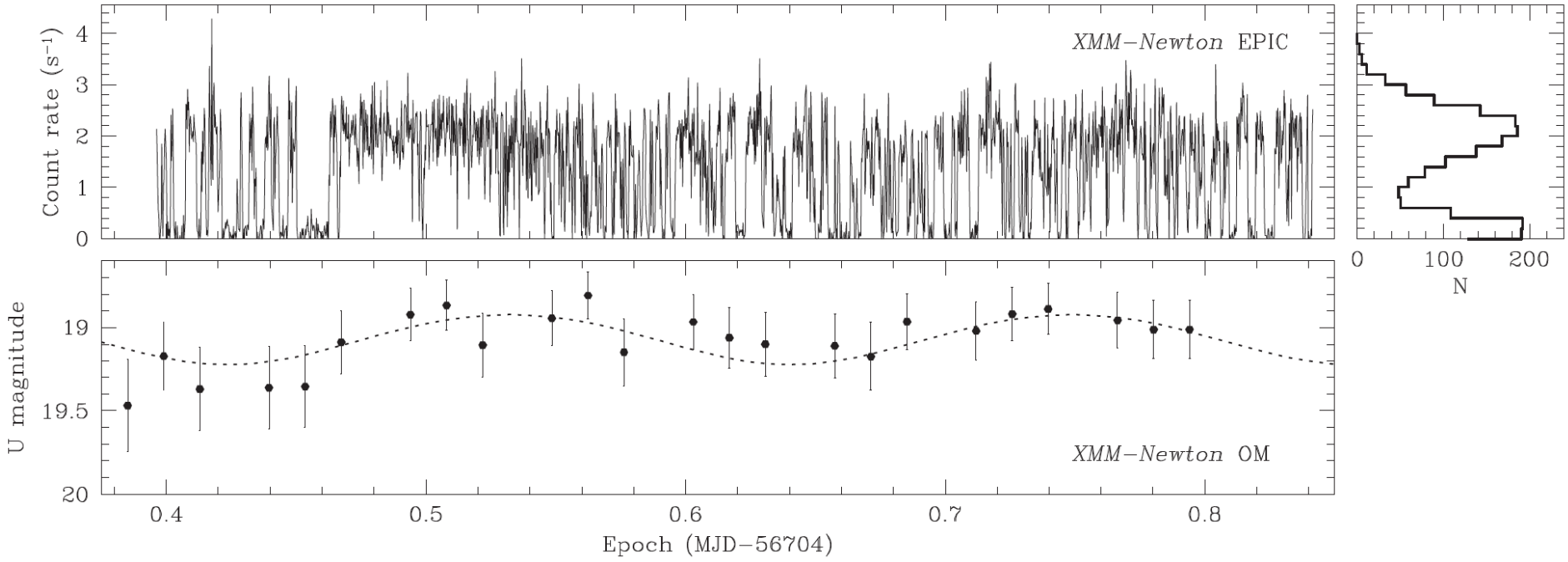



Linares et al. 2014, MNRAS, 438, 251

# 3FGL J1544.6−1125 / 1RXS J154439.4−112820

## A transitional MSP candidate

*XMM-Newton* (40 ks)

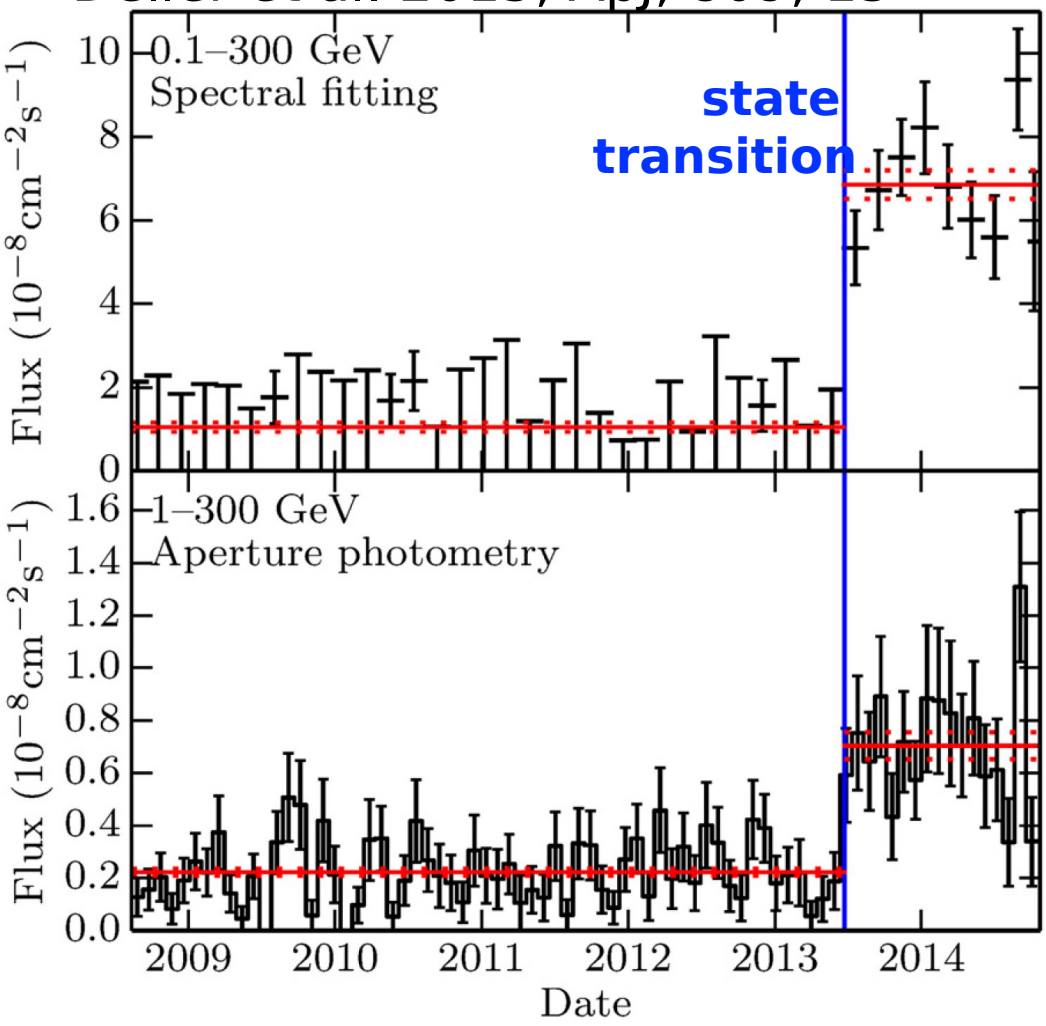



Bogdanov & Halpern 2015, ApJ, 803, L27

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

- Radio pulsar emission ceased at the end of June, 2013
- Optical brightness increased by ~1 mag
- Double-peaked H and He optical emission lines reappeared
- Average X-ray flux increased by ~order of magnitude
- *Fermi* LAT 0.1-300 GeV flux increased ~5-fold!

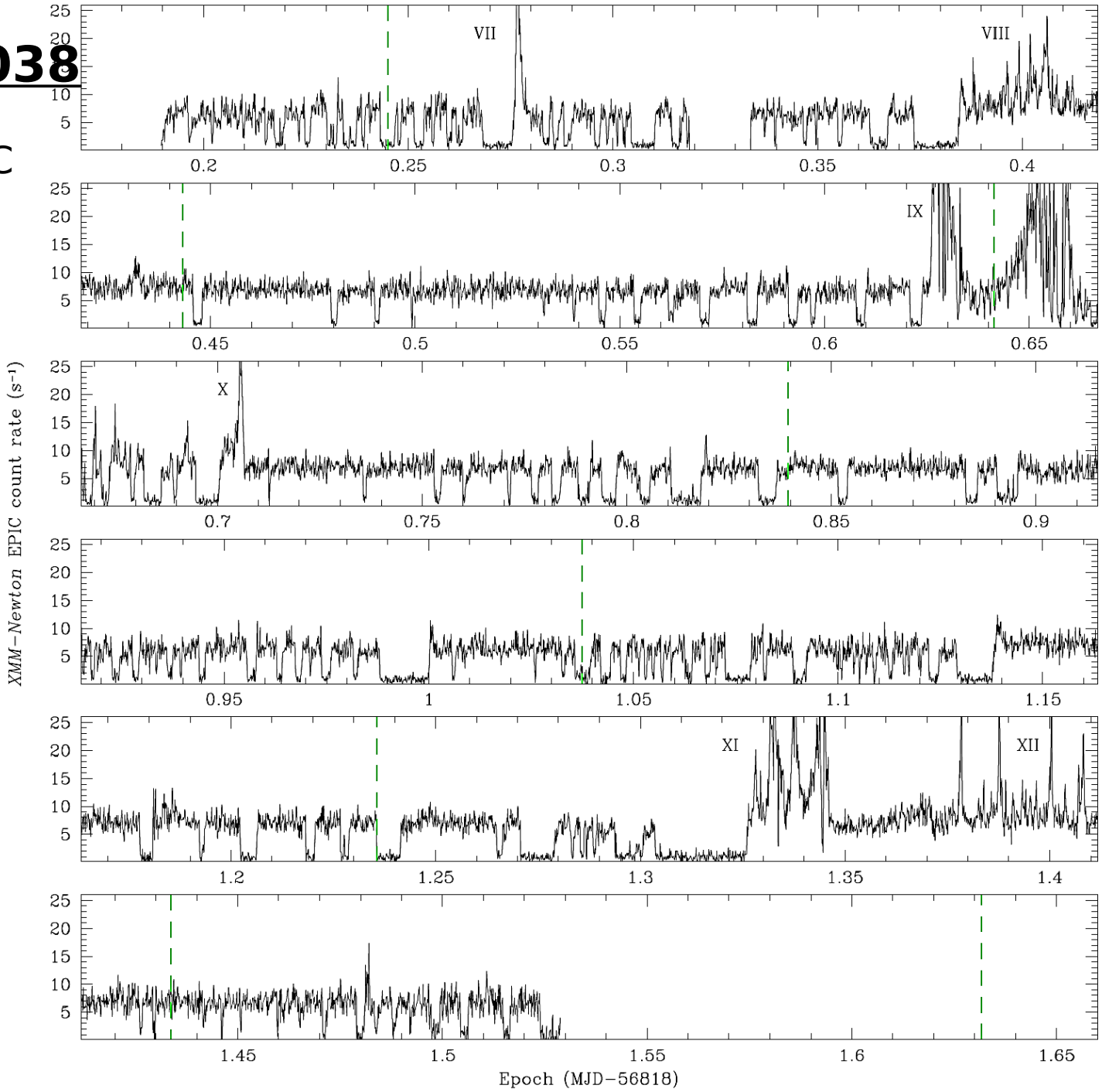
Deller et al. 2015, ApJ, 809, 13



# PSR J1023+0038

*XMM-Newton* EPIC MOS1/2+pn

$L_X \approx 10^{32\text{-}34}$ erg s$^{-1}$ (0.3-10 keV)




Bogdanov et al. 2015, ApJ, 806, 148

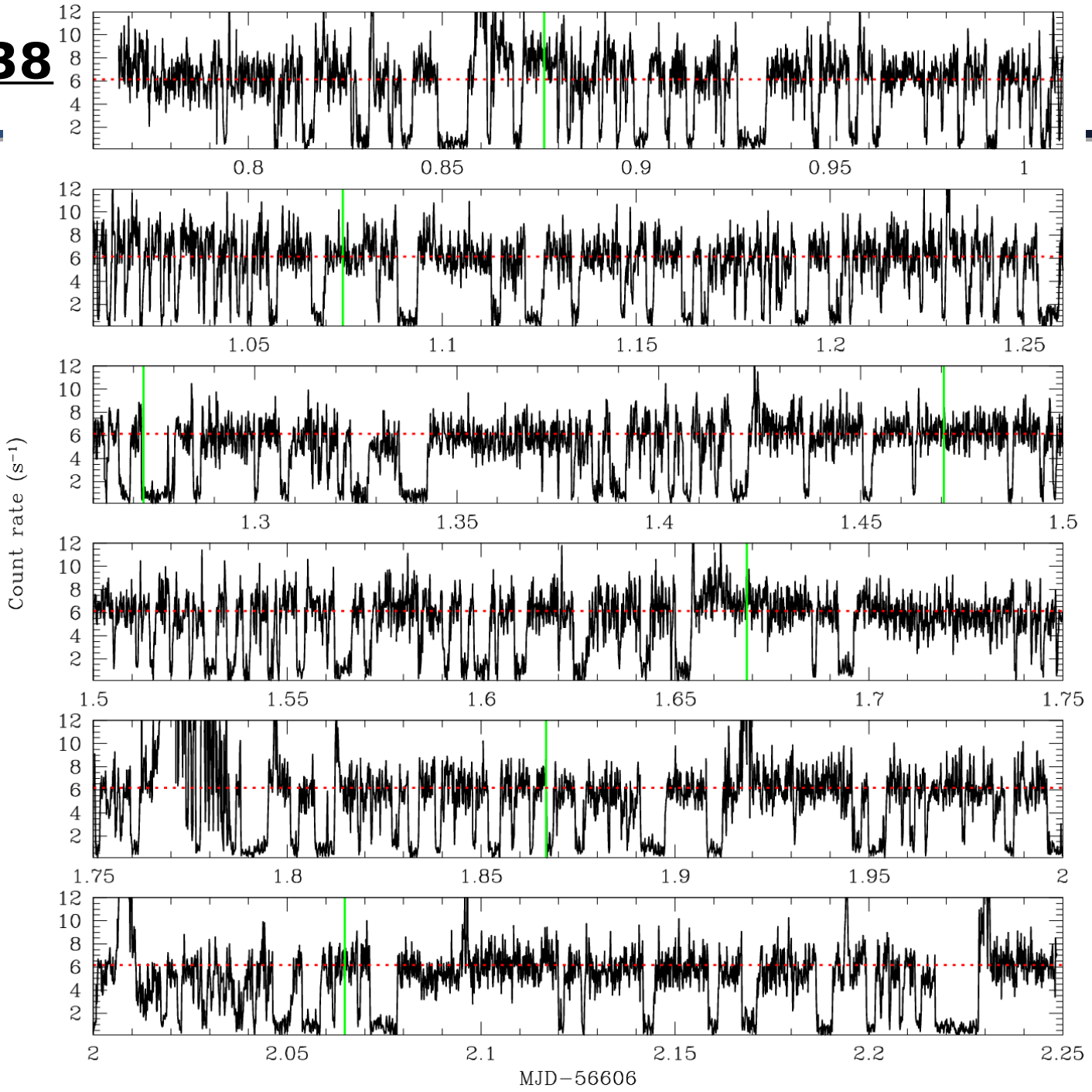
# PSR J1023+0038

*XMM-Newton* EPIC MOS1/2+pn

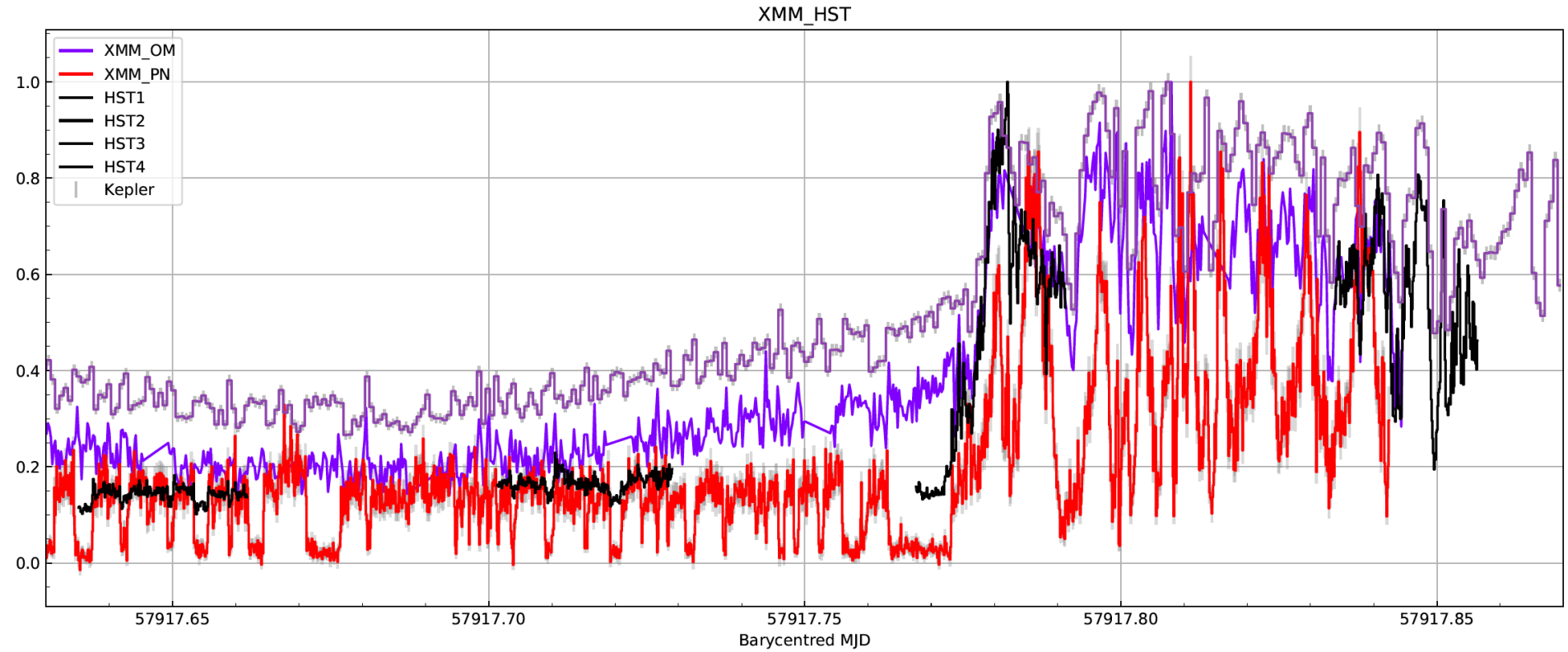
$L_X \approx 10^{32\text{-}34}$ erg $s^{-1}$ (0.3-10 keV)

- high and low X-ray mode luminosities steady over several years!
- two metastable accretion modes?

Bogdanov et al. 2015, ApJ, 806, 148



# Correlated X-ray/UV/Optical Variability in PSR J1023+0038



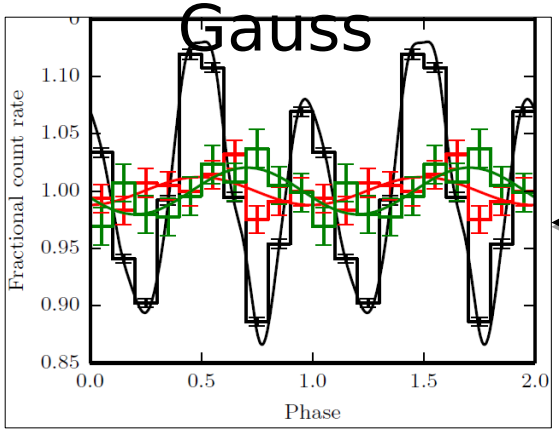

Courtesy of Amruta Jaodand

# Accretion-powered X-ray (and Optical) Pulsations!

PSR J1023+0038

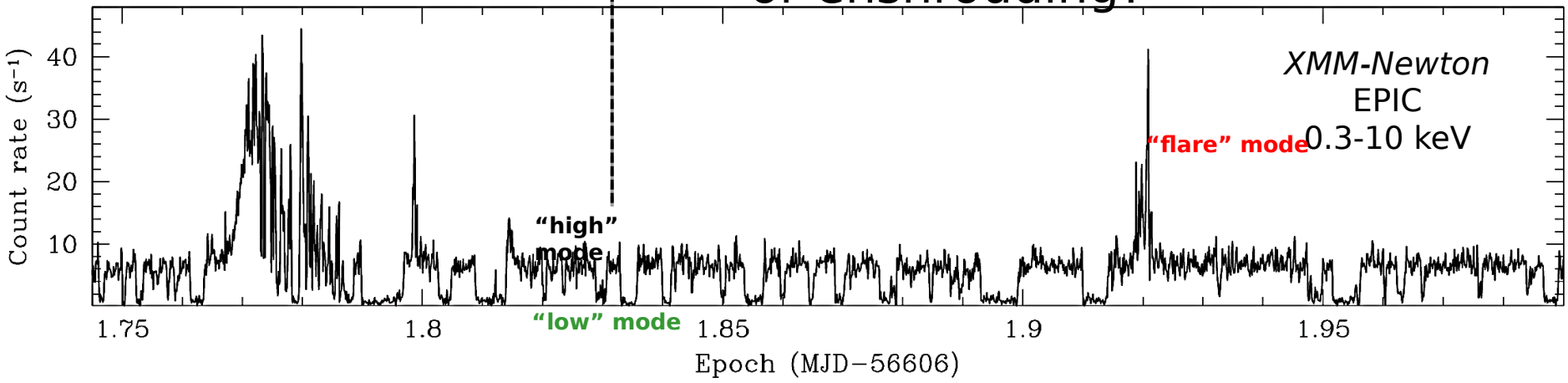
$\nu$=592 Hz

$B_{surf} \approx 10^8$ Gauss



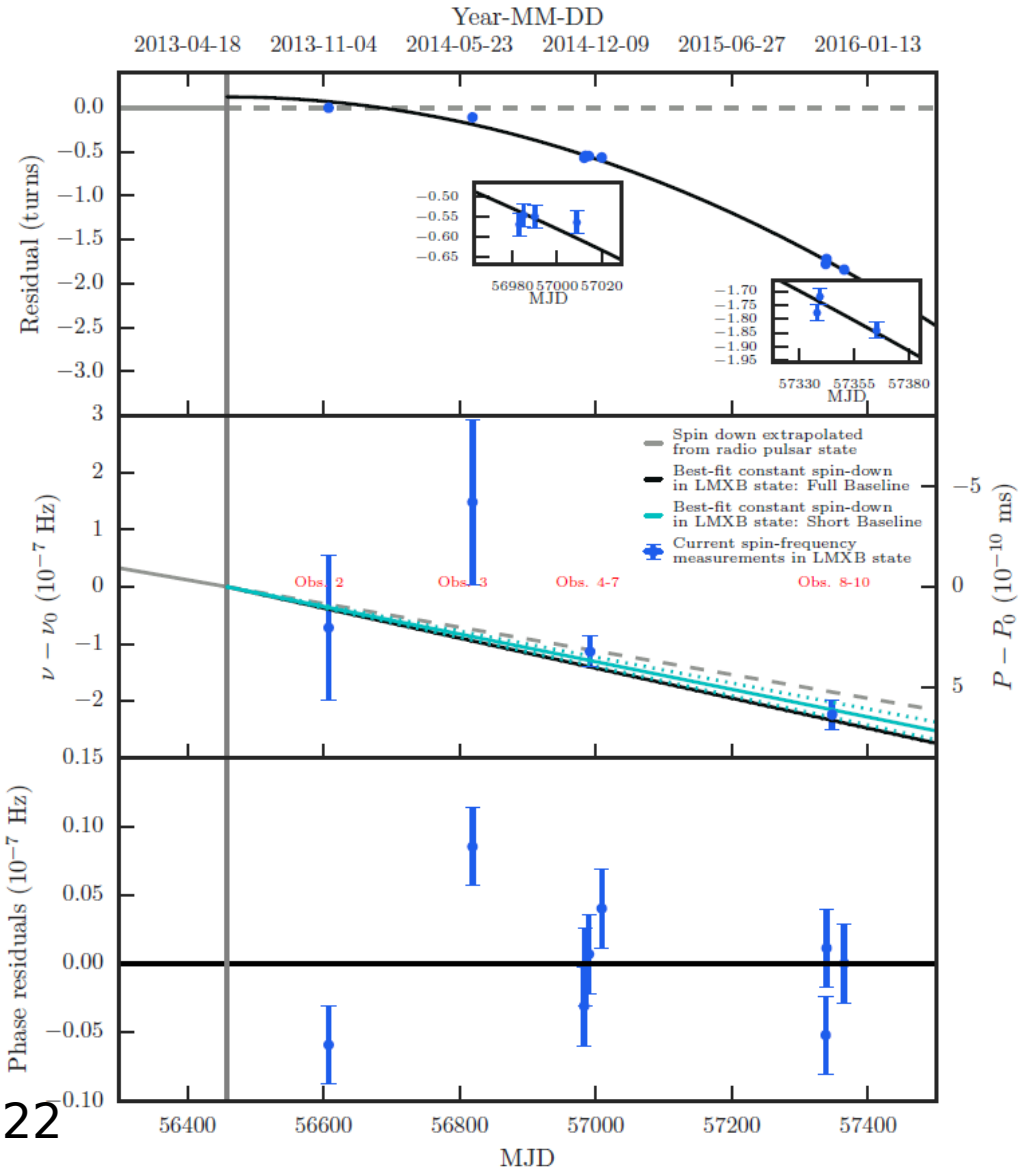

Archibald et al. (2015)

- Coherent X-ray pulsations only in "high" mode ⇒ channeled accretion onto NS (?) at $L_X \approx 10^{33}$ erg $s^{-1}$ (only $\sim 10^{-5} L_{edd}$)
- Too luminous to be only rotation-powered
- Accretion-induced pulsar emission?
- No radio pulsations - quenching or enshrouding?



# Spin-down measurement for PSR J1023+0038 in accreting state

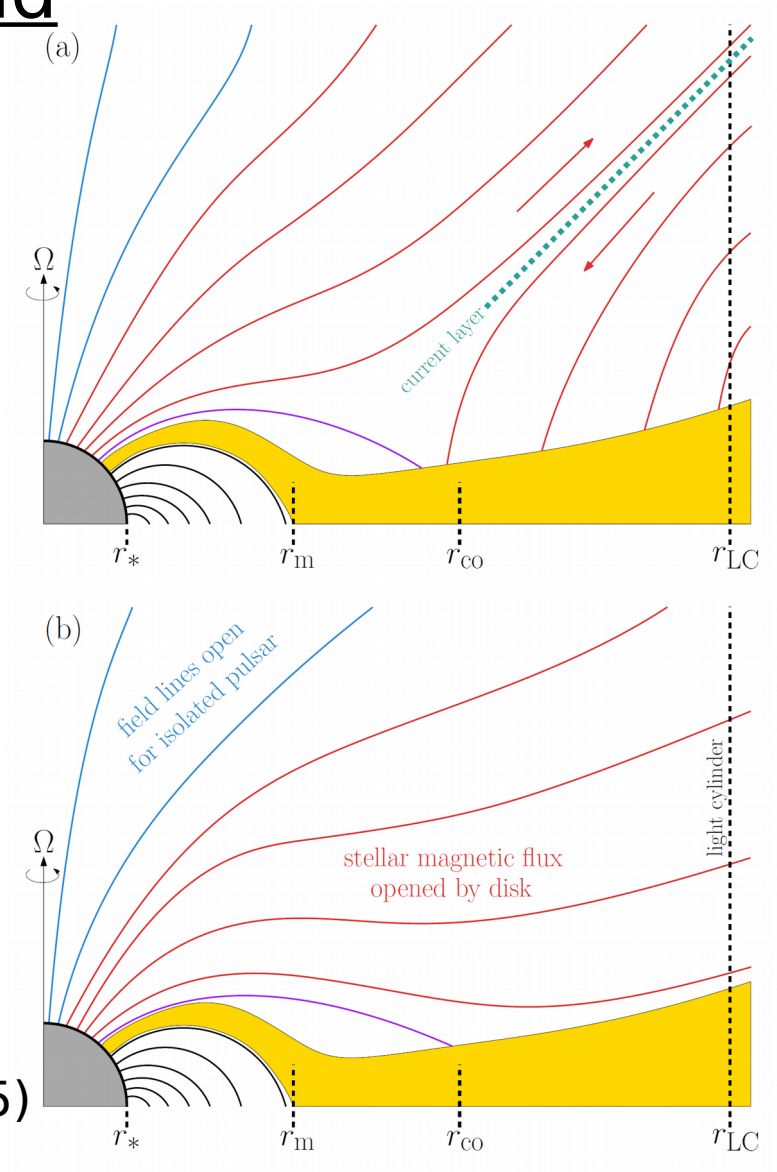
- X-ray timing with *XMM-Newton* over ~2 years ⇒ phase-coherent timing solution of the accreting state
- Average spin-down rate as an LMXB is only 26.8% faster compared to radio pulsar state
- Pulsar wind continues to operate at largely unmodified level ⇒ disk and pulsar magnetic field do not couple well




Jaodand et al. 2016, ApJ, 830, 122

# Effect of Accretion Disk on Pulsar Magnetic Field and Wind

- If accretion flow is not along all open field lines, pulsar wind should still be active
- Opening of stellar magnetic flux due to differential rotation along field lines coupling the star and disk
- The pulsar spin-down rate should increase ~×10 due to opening of additional outward stellar flux

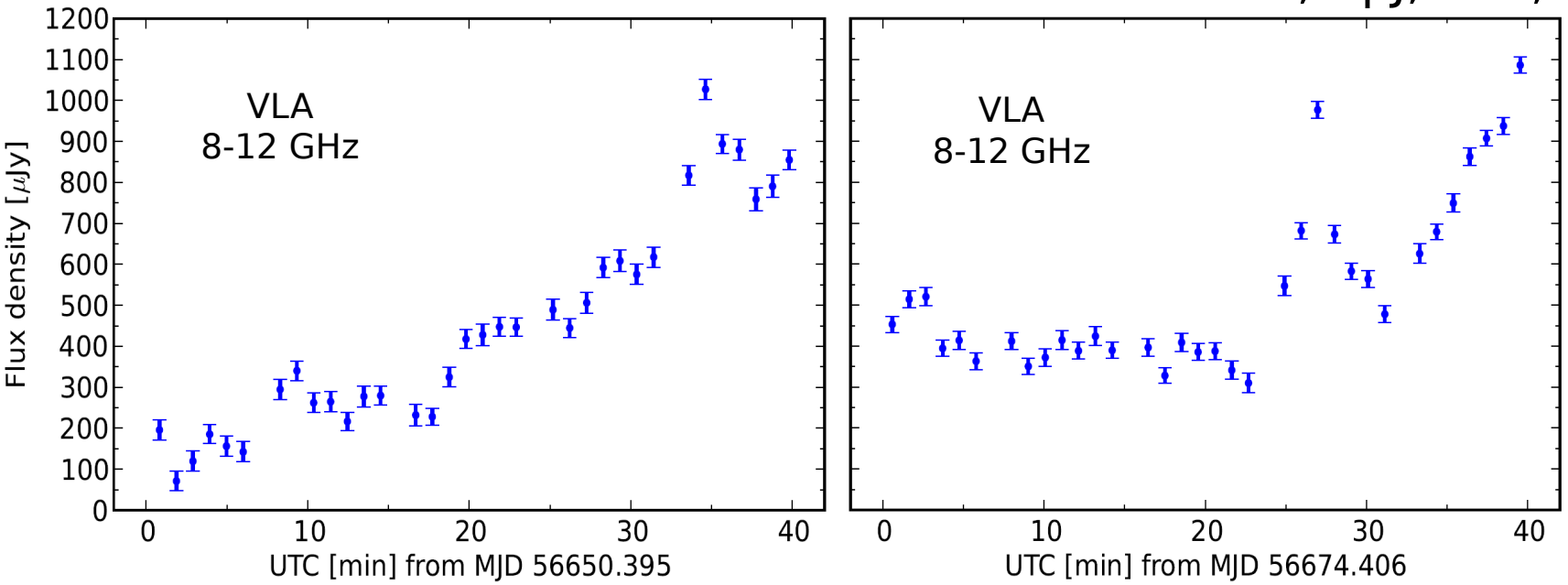



Parfrey et al. (2015)

# Faint flat-spectrum, variable radio emission

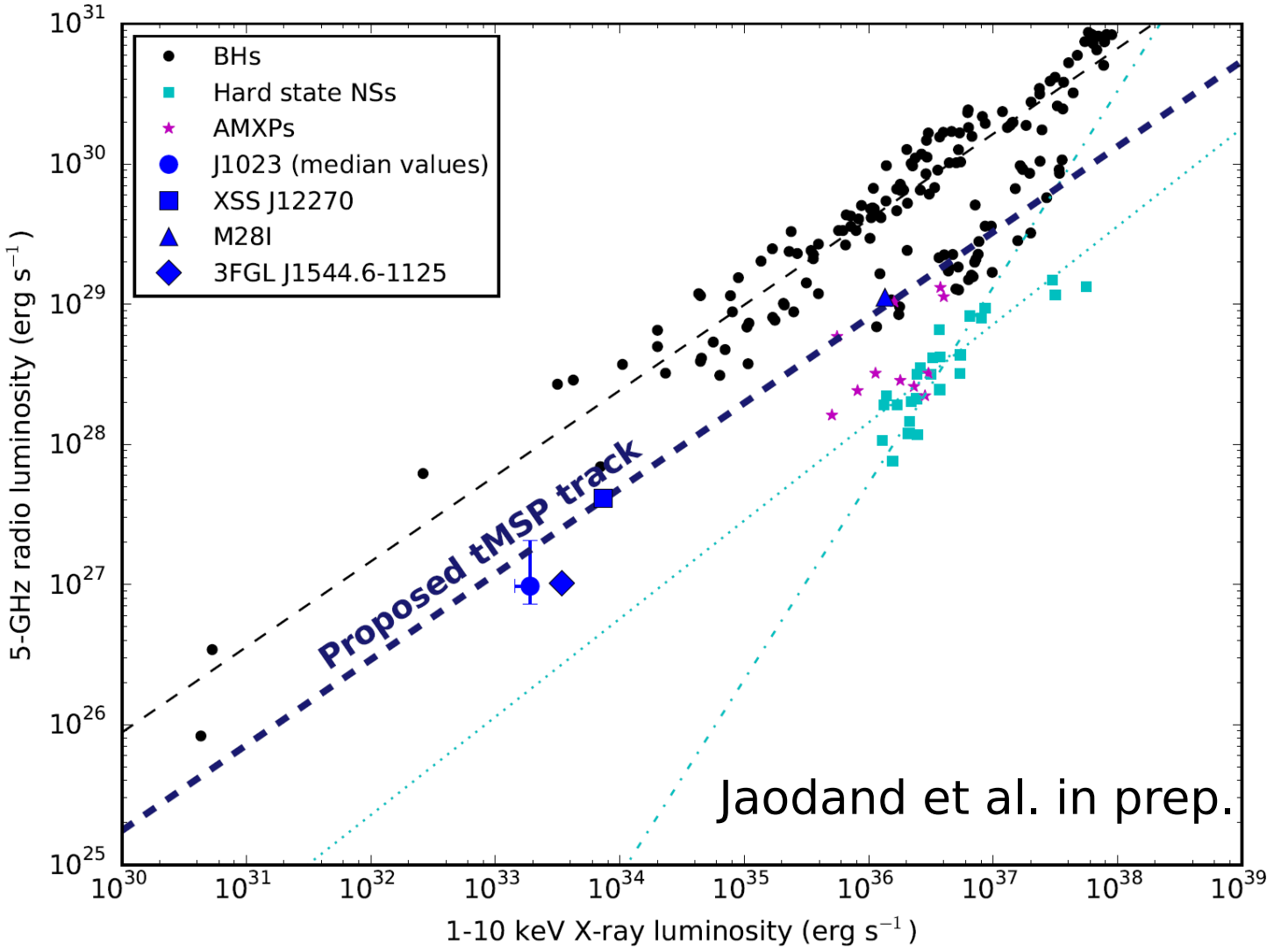
## PSR J1023+0038

Deller et al. 2015, ApJ, 809, 13




Synchrotron from a compact, partially self-absorbed jet?

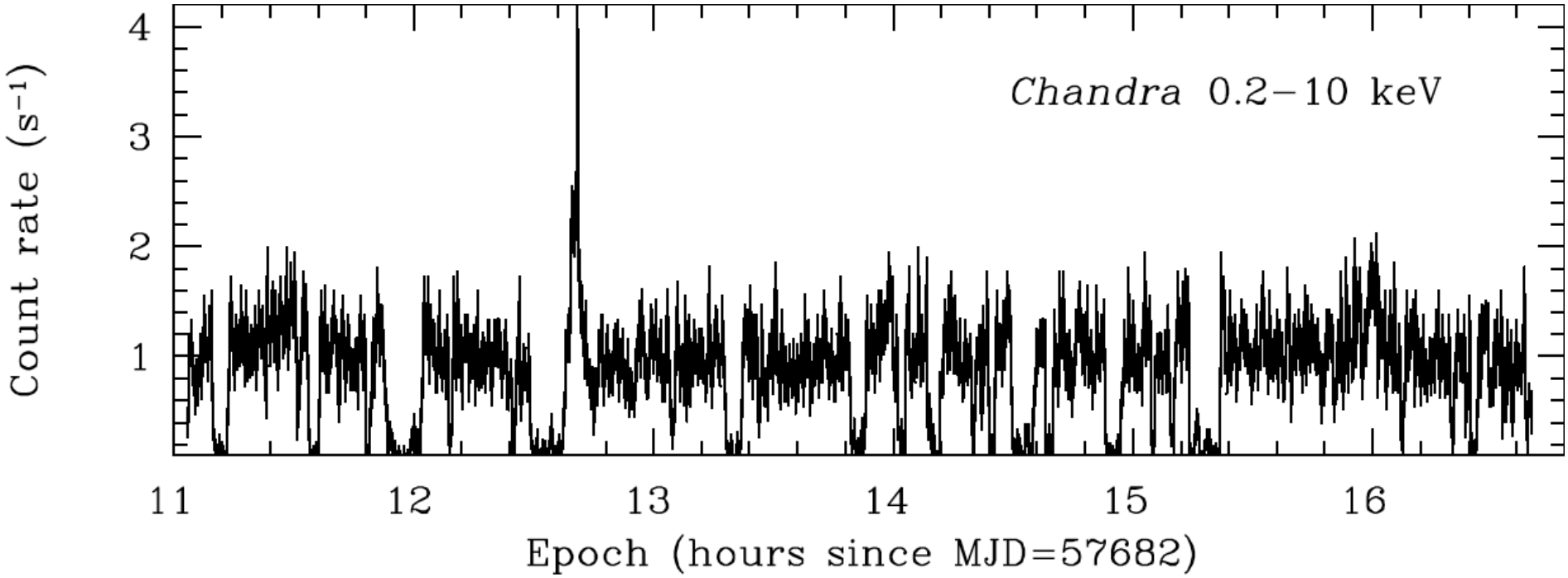
# An X-ray/Radio Luminosity Correlation for accreting MSPs?



# Strictly Simultaneous X-ray and Radio Observations

## PSR J1023+0038

Bogdanov et al. 2018, ApJ, 856, 54



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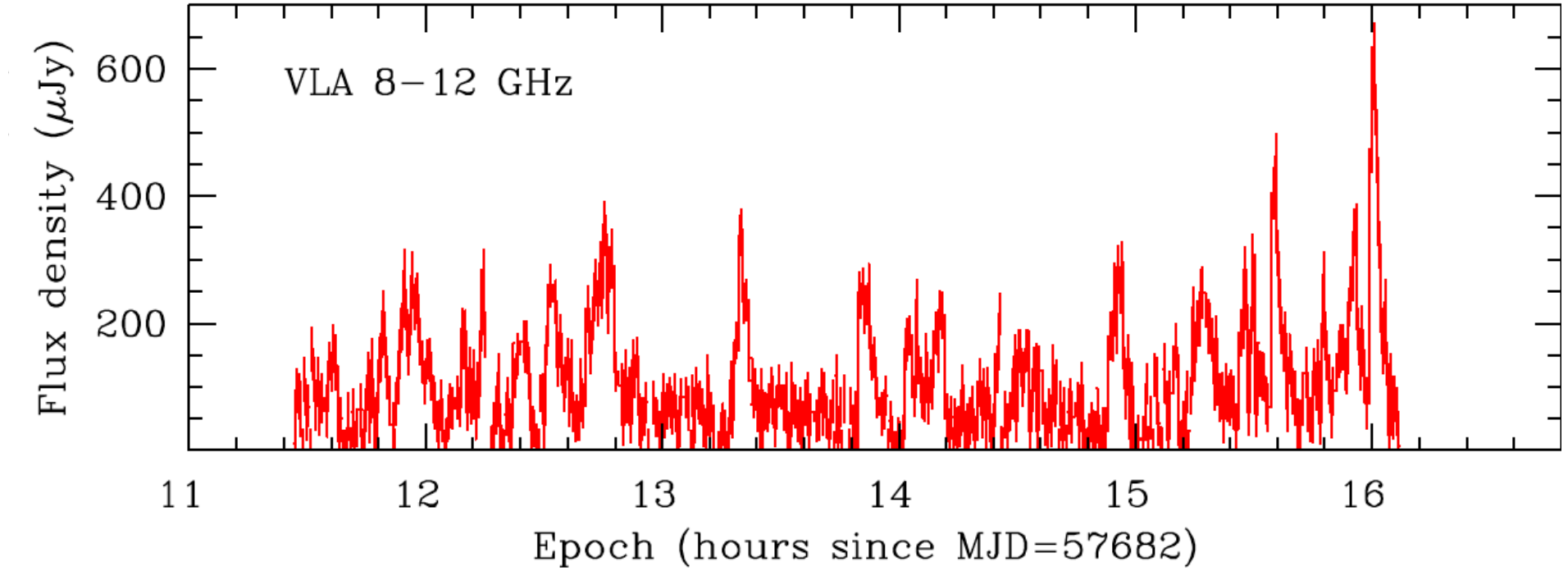
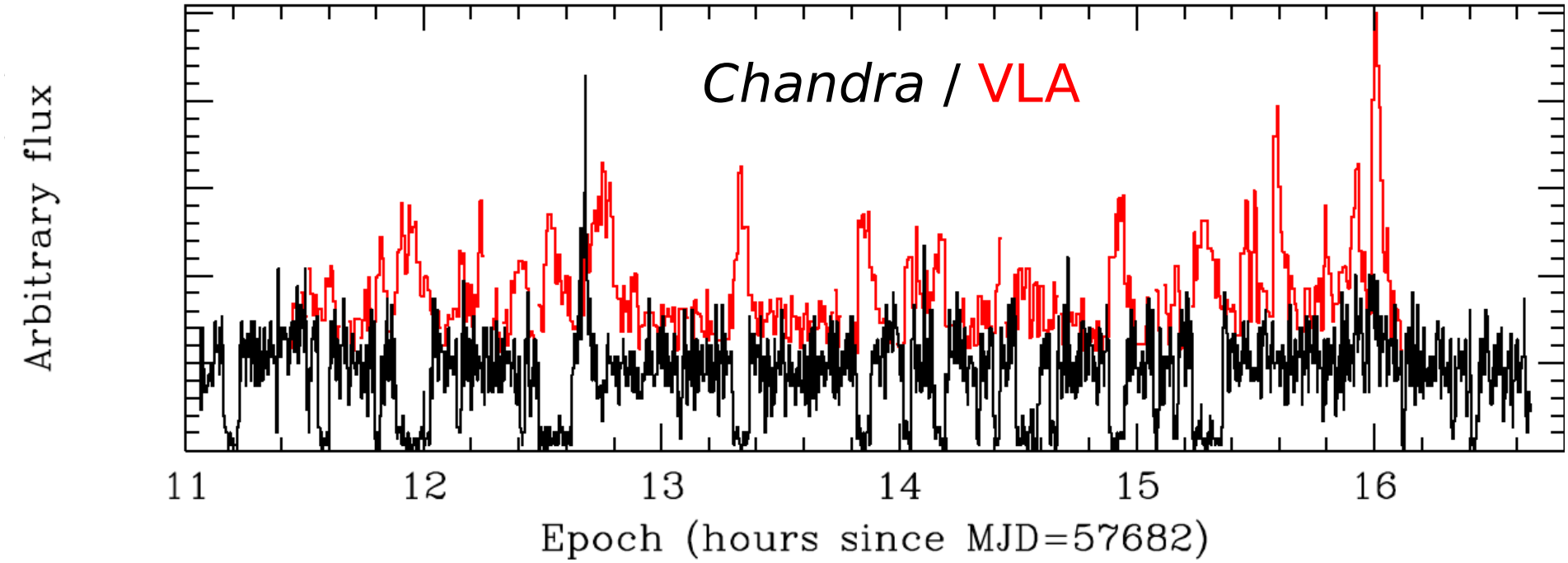



Rapid large amplitude radio variability

# Anti-correlated X-ray and Radio Variability!

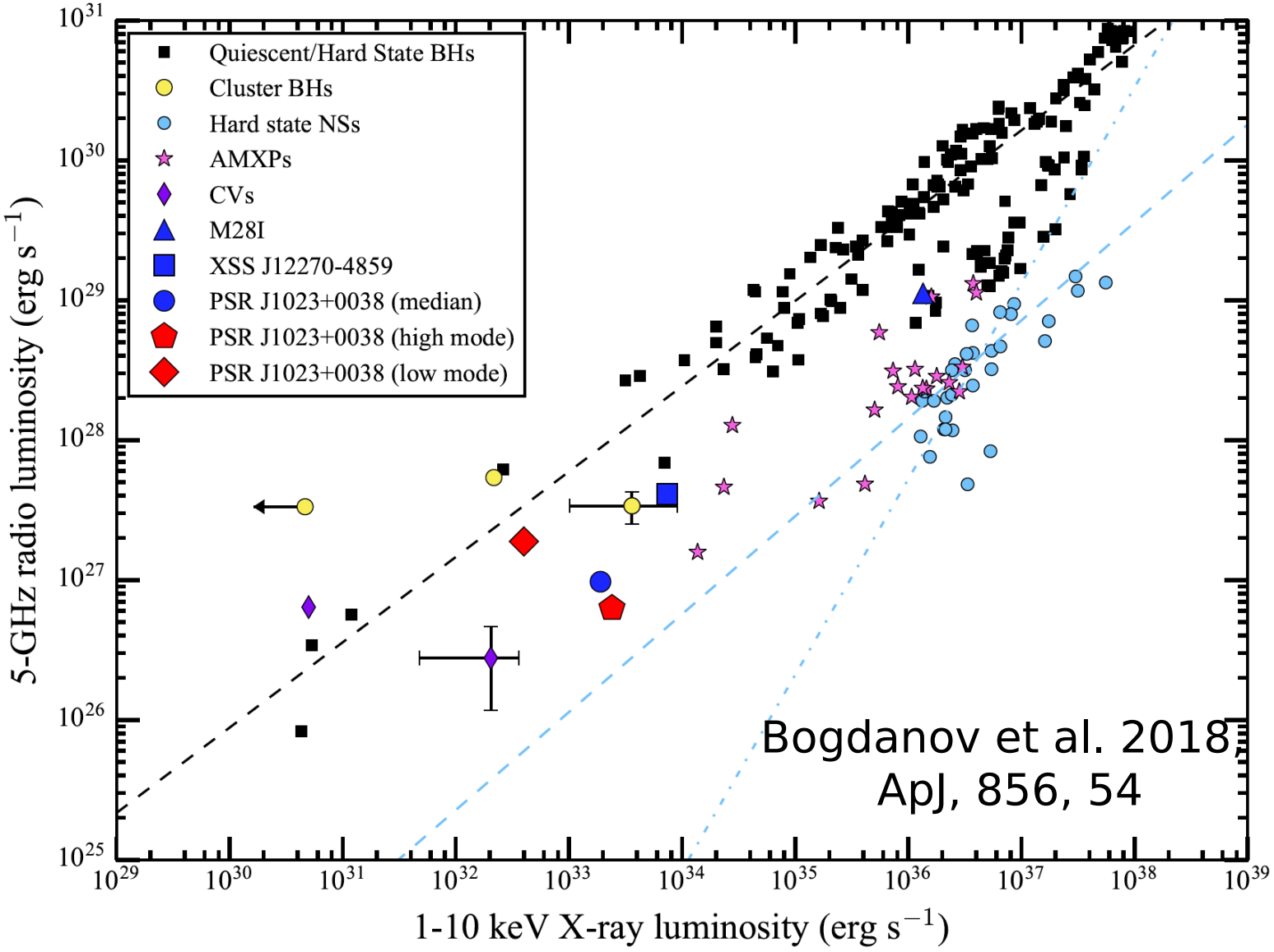
## PSR J1023+0038

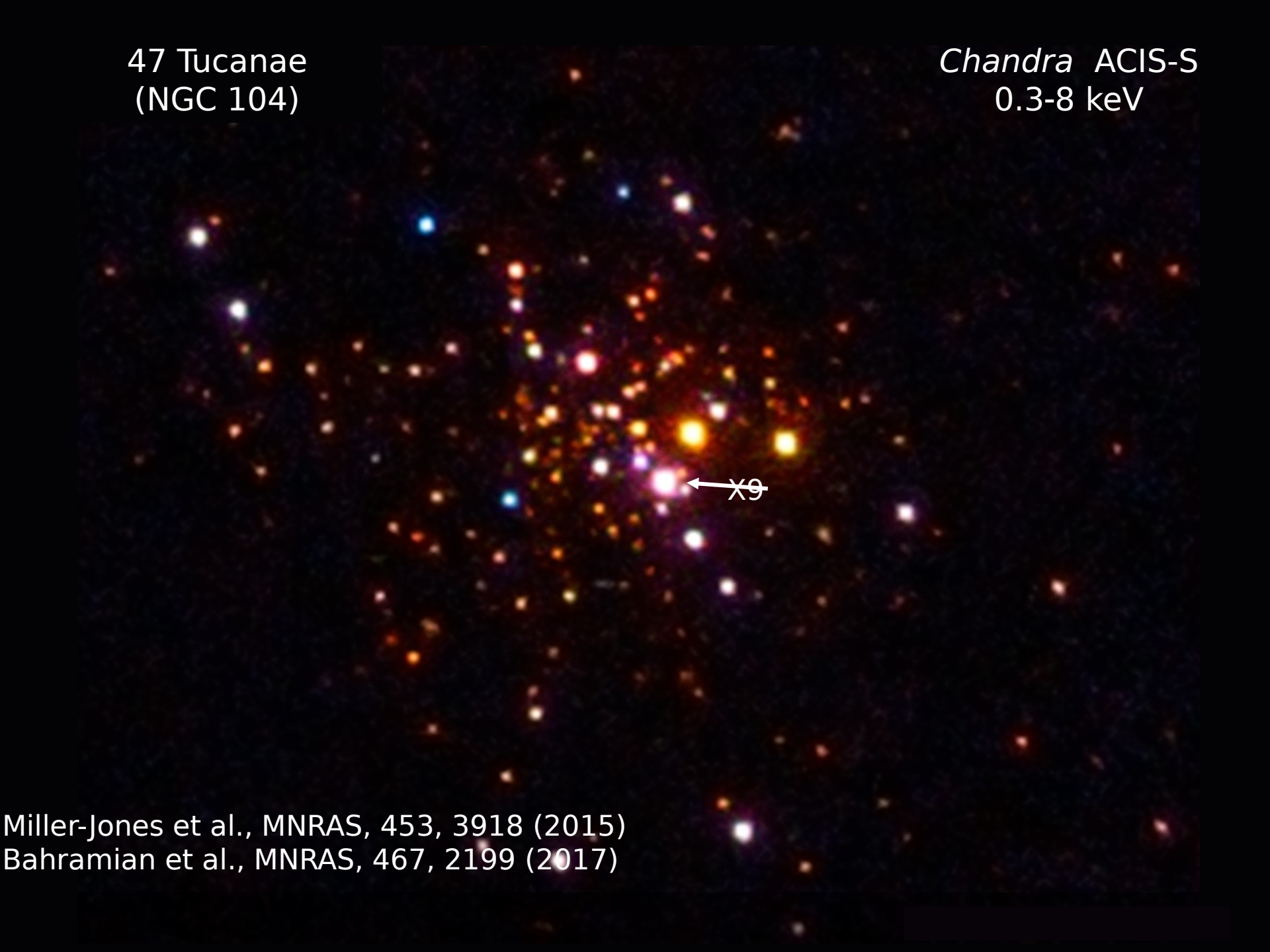
Bogdanov et al. 2018, ApJ, 856, 54




- Causal connection between X-ray mode switches and radio “flares”
- Cannot be jet outflow
- Radio emission must originate in vicinity of neutron star
- Plasma discharges from pulsar magnetosphere? A tiny pulsar

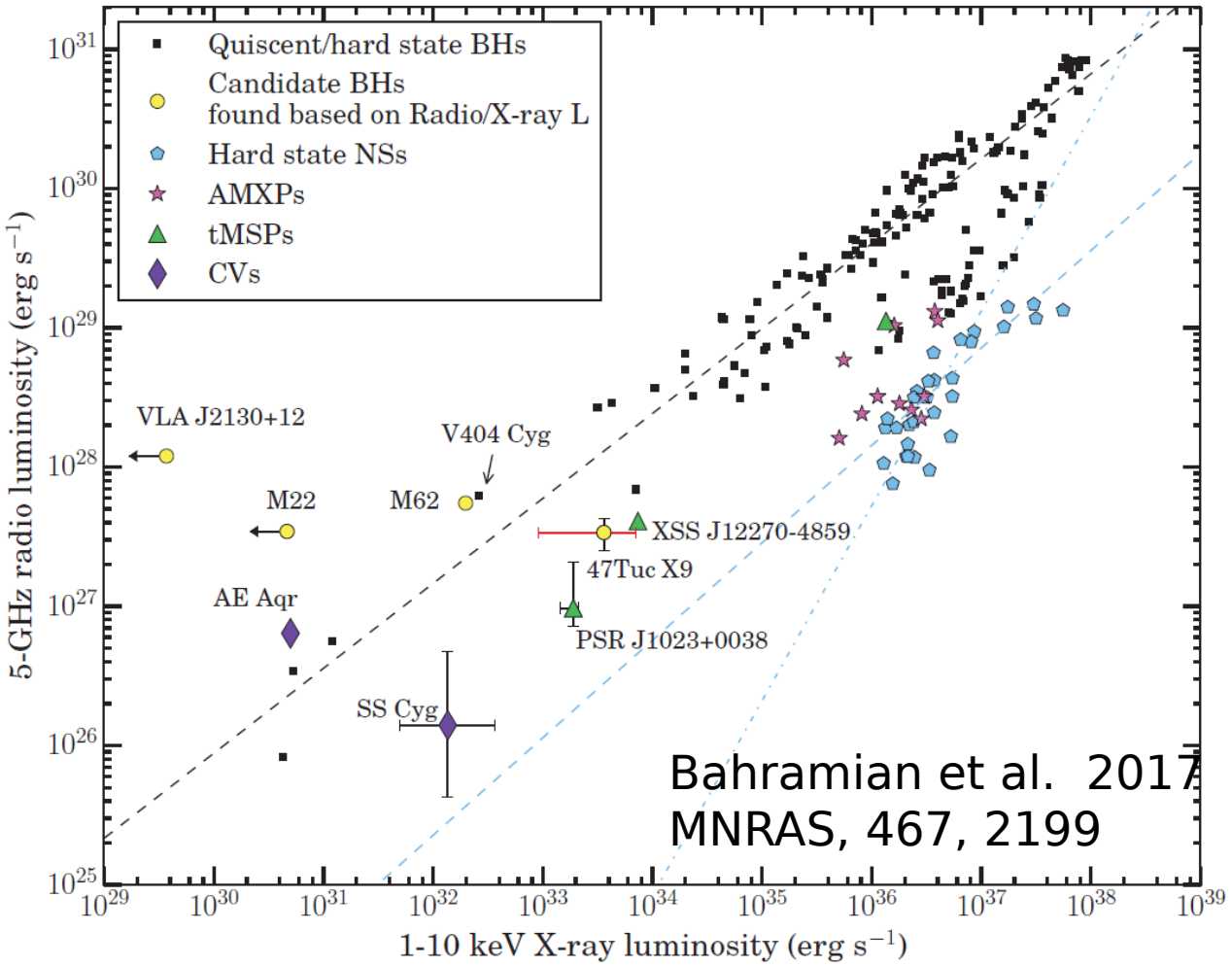
# The X-ray/Radio Luminosity Relation




47 Tucanae
(NGC 104)
*Chandra* ACIS-S
0.3-8 keV
X9
Miller-Jones et al., MNRAS, 453, 3918 (2015)
Bahramian et al., MNRAS, 467, 2199 (2017)

# 47 Tuc X9: An Ultracompact X-ray Binary

simultaneous *Chandra* + *NuSTAR* + ATCA observations




- A 28 minute binary with a WD donor and BH accretor?
- Or a transitional MSP?

# Open Questions

- What causes transitions to/from accreting state?
- Lack of radio pulsations when accreting – enshrouding or quenching due to accretion?
- GeV $\gamma$-ray emission in accreting state – intra-binary shock or propeller ejection? Accretion-stimulated magnetospheric pulsar emission?
- X-ray/UV/optical flares – enhanced ejection or accretion onto neutron star?
- X-ray mode switching – emptying and refilling of inner accretion disk or interruptions in low-level accretion? Reconfiguration of