# Transitional Pulsars and Low-Mass X-ray Binaries: Some Additional Open Questions

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# Classes of Objects Discussed At This Meeting

- Low-mass X-ray binaries (LMXBs)
  - Persistent versus transient
  - Quiescent (transient) LMXBs
  - Accreting millisecond X-ray pulsars (AMXPs) (transient, not by definition)
  - Very-faint X-ray binaries (VFXBs) (some transient)

- Eclipsing millisecond radio pulsars (MSPs) (“spiders”)
  - “Black widow” systems (semidegenerate companion)
  - “Redback” systems (non-degenerate companion)
  - Romani’s “Tidderan” systems (H-poor degenerate companion)

- Transitional millisecond pulsars (t-MSPs, switching between LMXB and MSP)
  - PSR J1023+0038
  - PSR J1824-2452I = M28I
  - XSS J12270-4859

# Objects to Compare Different Classes

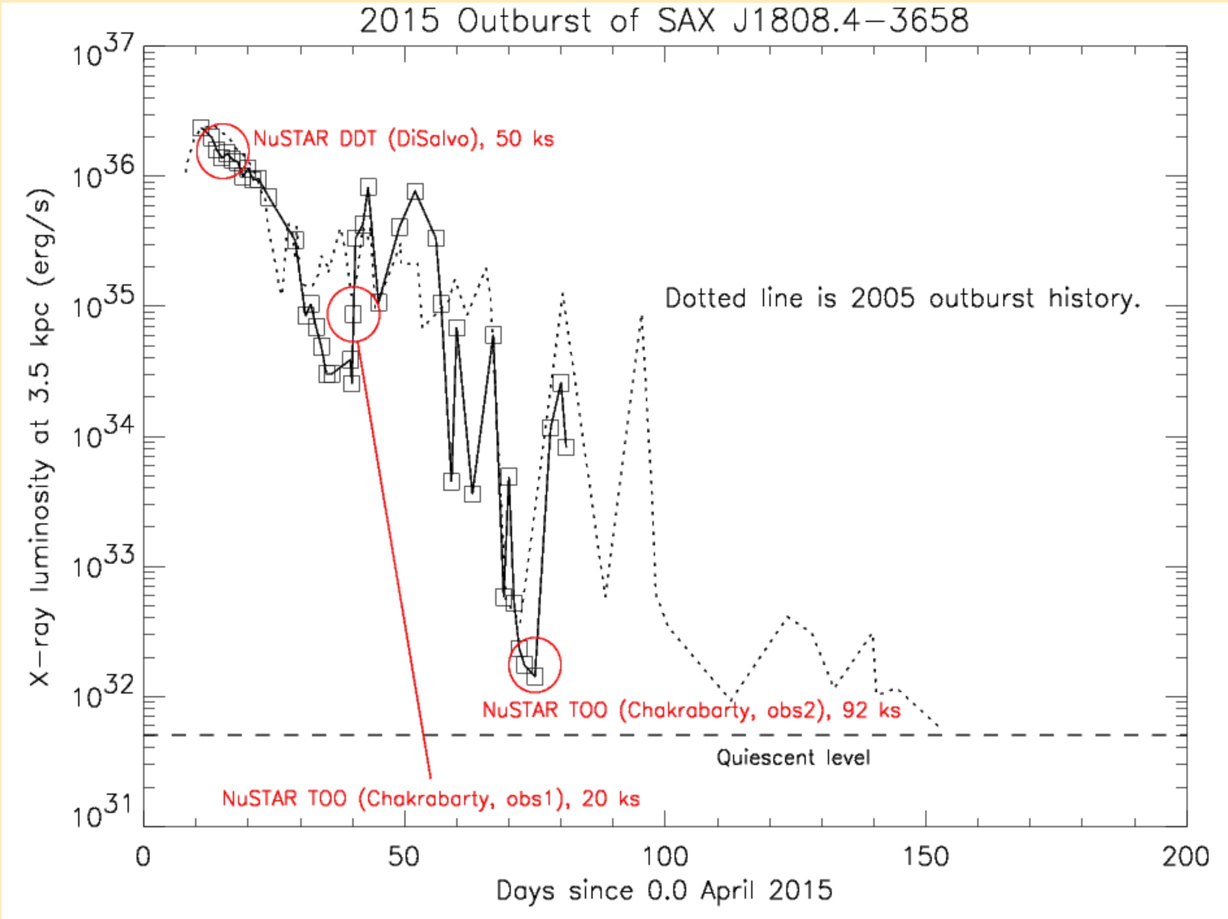
| Source | Class | D (kpc) | $L_x$ (erg/s) | $M_c$ ($M_{sun}$) | $P_{spin}$ (ms) | $P_{orb}$ (hr) |
|---|---|---|---|---|---|---|
| PSR J1023+0038 | trans-MSP | 1.37 | $10^{32}$-$10^{34}$ | ~0.2 | 1.7 | 4.7 |
| SAX J1808.4-3658 | AMXP | 3.5 | $10^{31}$-$10^{36}$ | ~0.05 | 2.5 | 2.01 |
| Cen X-4 | qLMXB | < 1.2 | $10^{31}$-$10^{37}$ | ~0.3 | ? | 15.1 |

# Transitional PSR J1023+0038

- **LMXB state** (Archibald et al. 2015, Bogdanov et al. 2015)
  - Power-law X-ray spectrum, $\Gamma$=1.7, weak thermal component
  - Flat-spectrum radio emission, no radio pulsations
  - Bright gamma-ray emission
  - <u>Low mode</u>: steady X-ray, ~ $5 \times 10^{32}$ erg/s, 20% of data, unpulsed
  - <u>High mode</u>: steady X-ray, ~ $3 \times 10^{33}$ erg/s, 80% of data, pulsed
  - <u>Flaring mode</u>: erratic X-ray, ~ $3 \times 10^{34}$ erg/s, ~1% of data, unpulsed

- **Radio pulsar state** (Archibald et al. 2010, Bogdanov et al. 2011)
  - Millisecond radio pulsar active, steep radio spectrum
  - Gamma-ray emission
  - Possible X-ray pulsations (Archibald et al. 2010)
  - Power-law X-ray spectrum, $\Gamma$=1.1, weak thermal component. Interpreted as polar cap emission plus intrabinary synchrotron shock emission
  - X-ray luminosity ~ $1 \times 10^{32}$ erg/s, modulated at orbital period

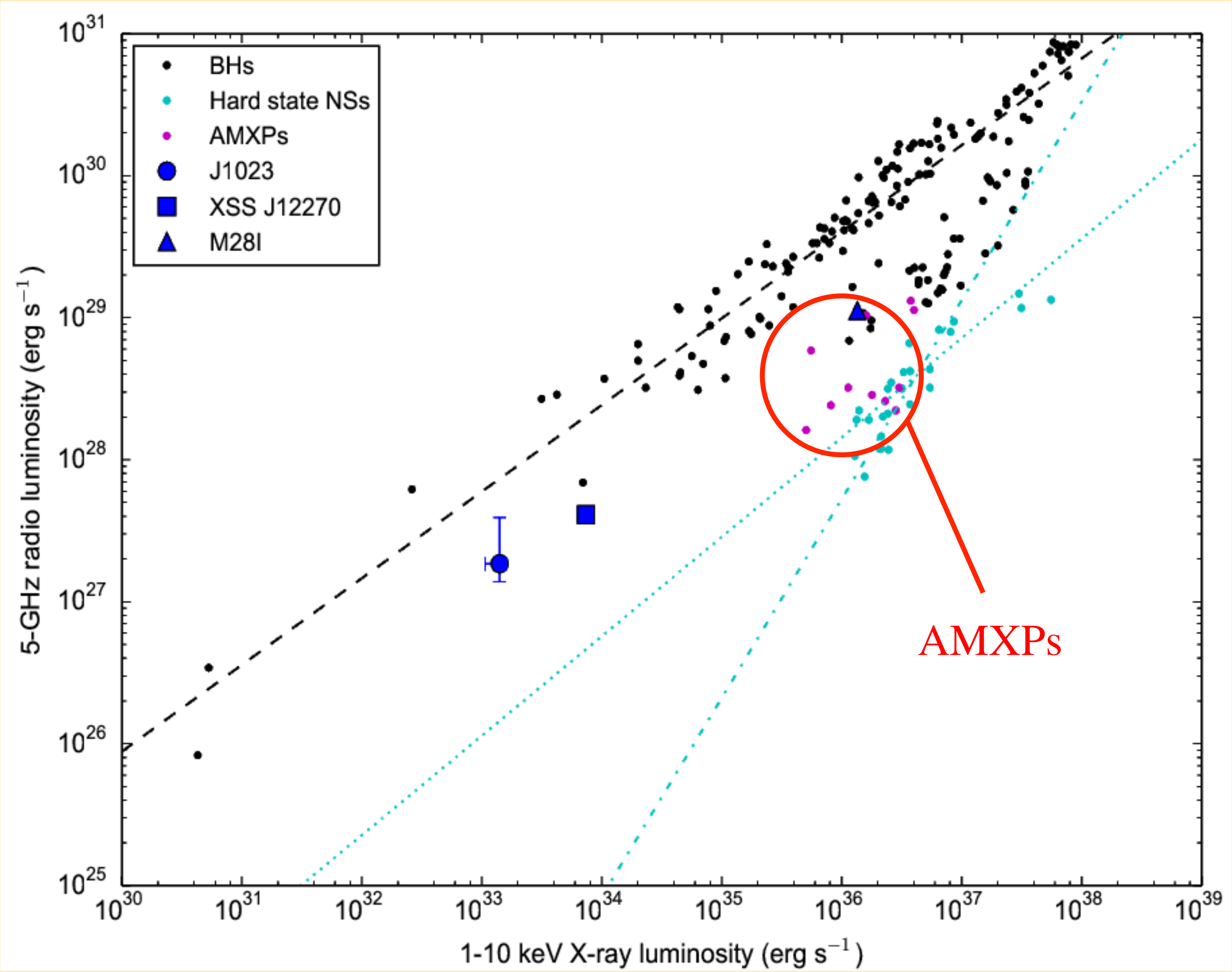
# SAX J1808.4-3658 (AMXP)




- Pulsations detected at $>10^{34}$ erg/s. (Lower luminosities not probed yet.)
- Black-widow-like binary period variations.
- Flat-spectrum radio detected during outburst.
- Indirect evidence for radio pulsar turn-on during X-ray quiescence (Burderi et al. 2003; Campana et al. 2004; Deloye et al. 2008)
- Possible gamma-ray detection (Xing et al. 2015)

# Radio/X-ray Correlation

(Deller et al. 2015)



# Possible *Fermi* Detection of the Accreting Millisecond Pulsar Binary SAX J1808.4−3658

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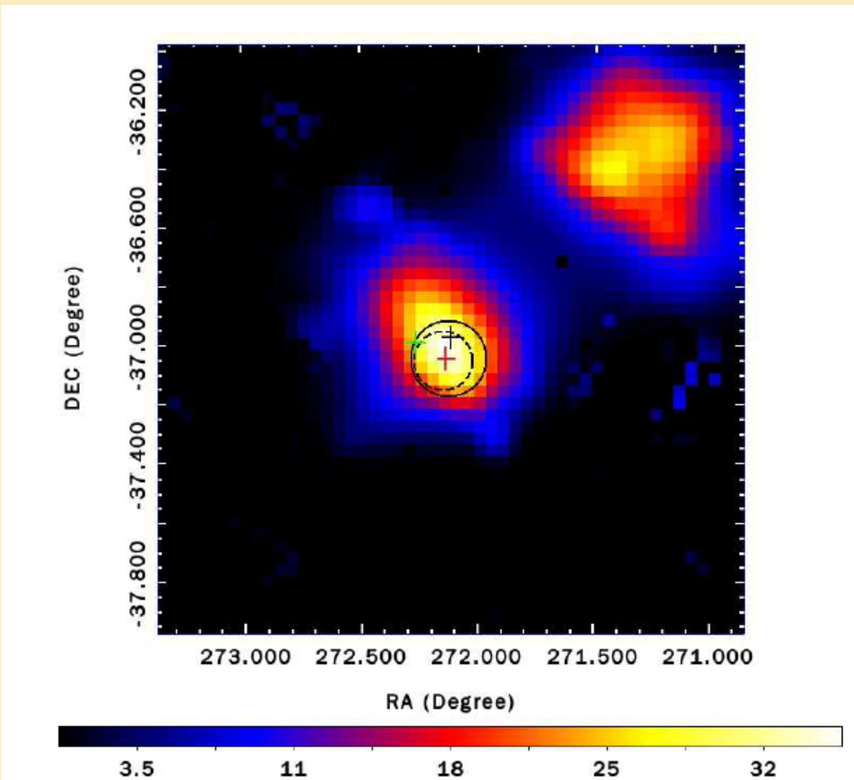
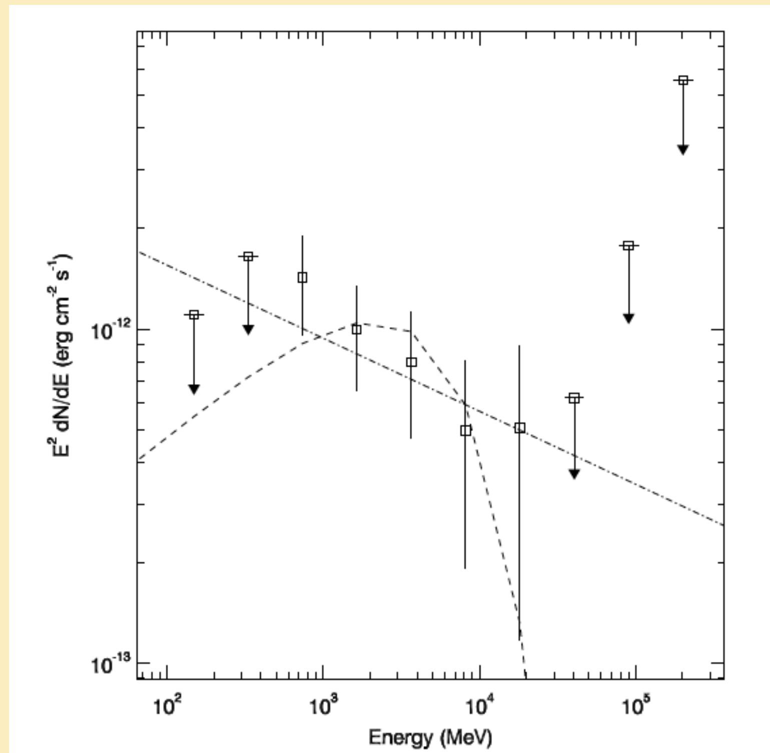
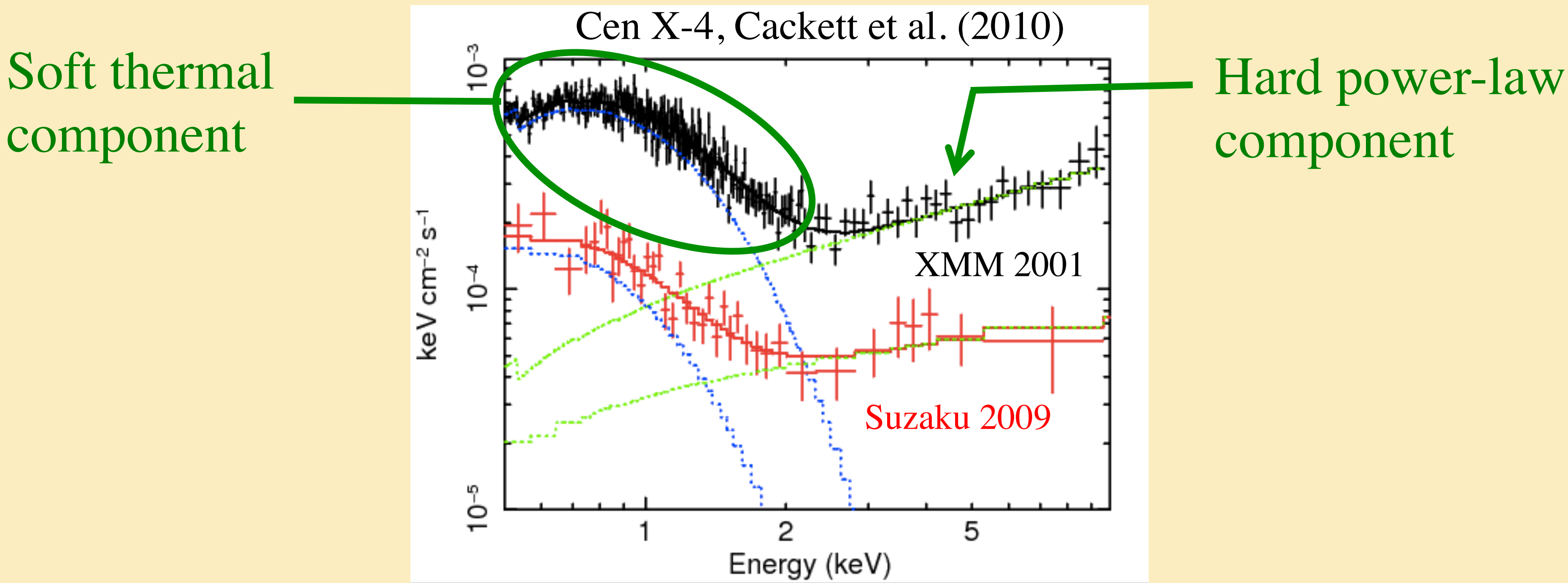


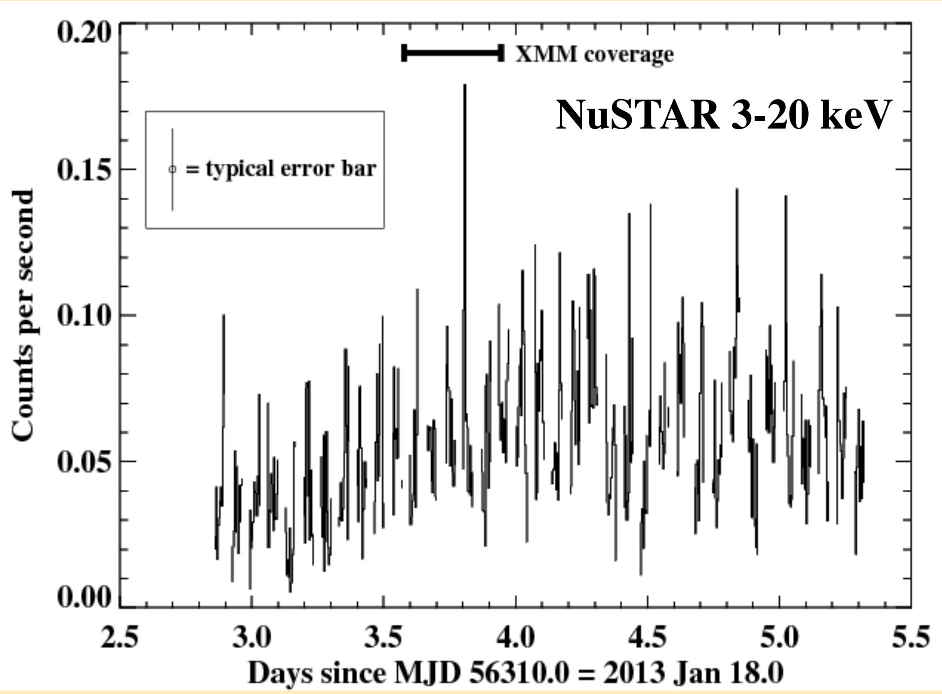



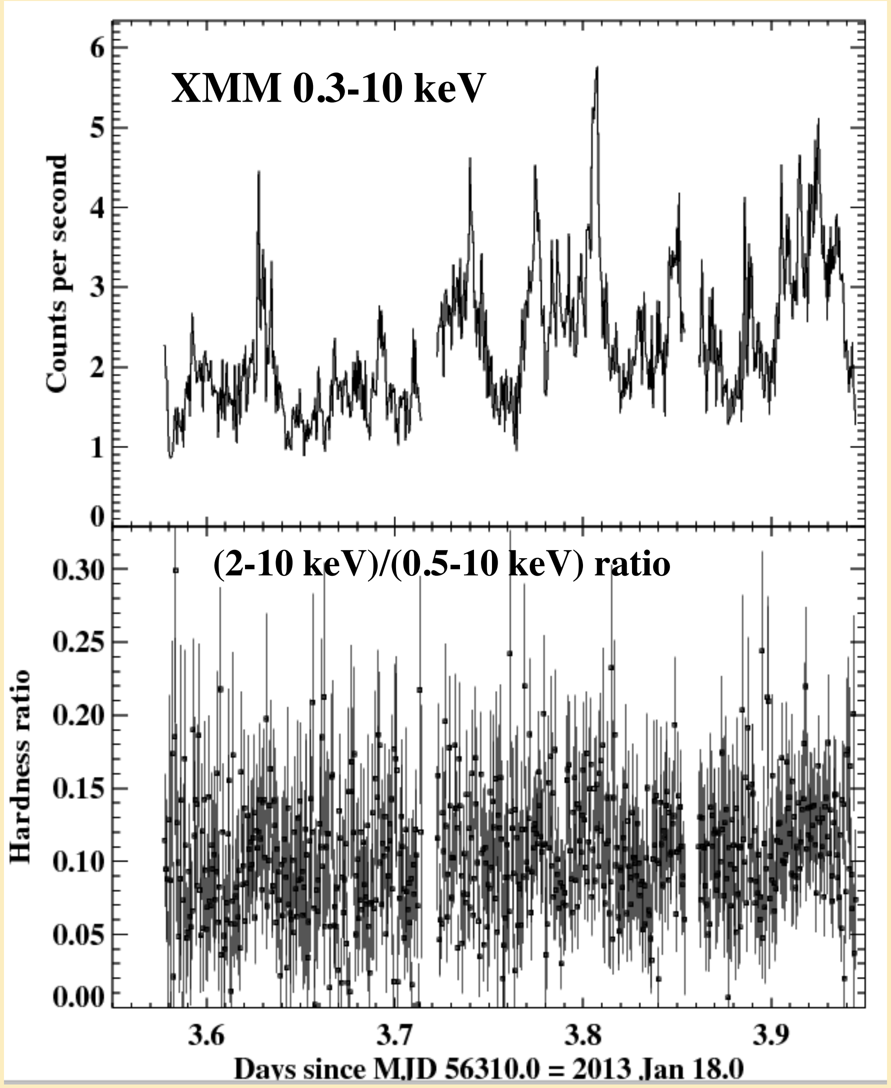
# Typical 2-Component Spectrum of Quiescent NS/LMXB Transients




- Soft ~0.1 keV thermal component from NS atmosphere.
- Hard power-law component with photon index $\Gamma$ = 1-2. Origin unclear. Spectrum above 10 keV unknown until recently (too faint until NuSTAR)
- Thermal fraction varies from source to source, and sometimes even from observation to observation for the same source. May reflect importance of accretion.
- Quiescent flux can vary on both short (hours) and long (months) time scales.

# Joint NuSTAR/XMM Observation of Cen X-4 in 2013 Jan



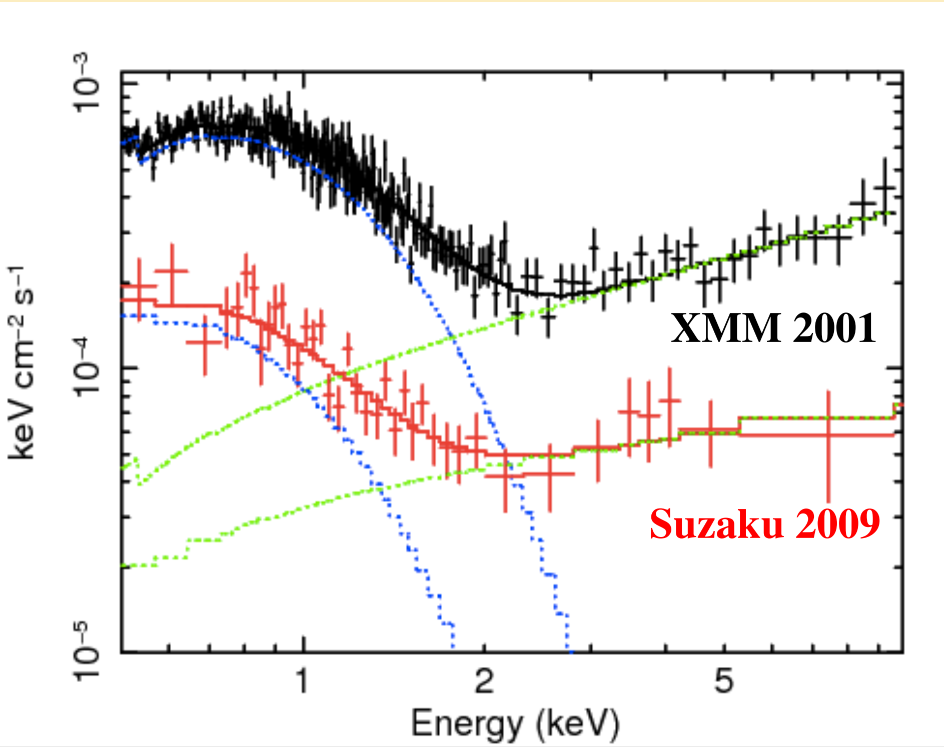




- 116 ks with NuSTAR, 26 ks with XMM.
- Lumimosity ~$10^{33}$ erg/s (0.3-79 keV)
- Strong flickering and flaring (factor of 5) seen in both XMM and NuSTAR data.

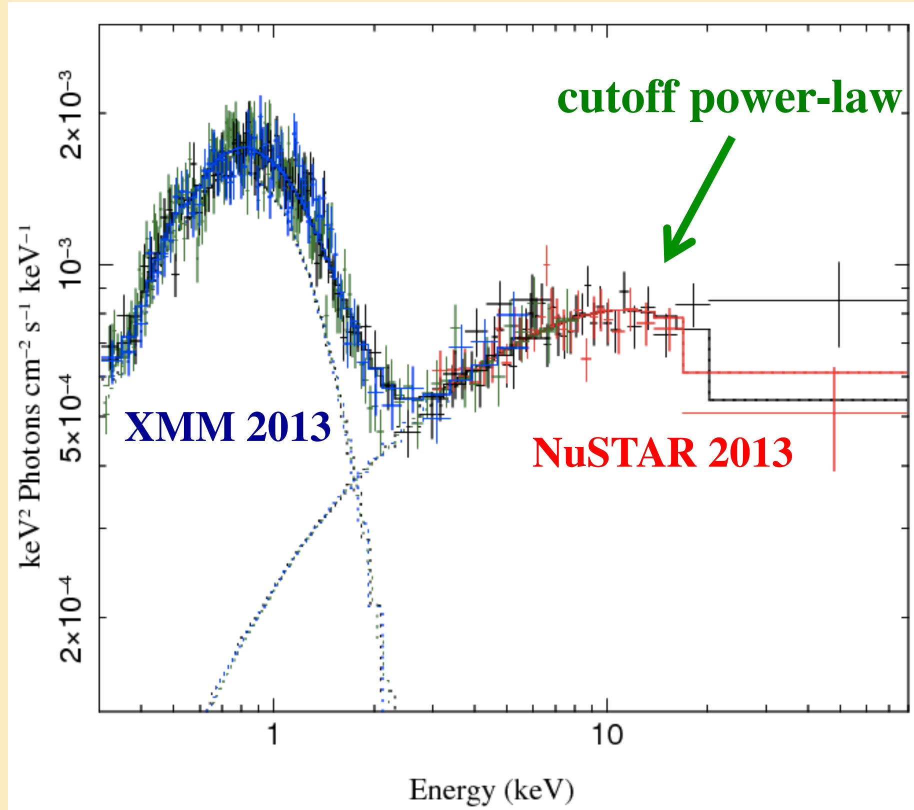
Chakrabarty et al. 2014

# Cutoff of Hard Power-Law Component Detected in Cen X-4

Previous observations (Cackett et al. 2010)




2013 observation (Chakrabarty et al. 2014)




- First X-ray power-law cutoff in a quiescent LMXB (Chakrabarty et al. 2014).
- Both Comptonization and synchrotron shock ruled out by the low cutoff energy.
- Hard emission is bremsstrahlung from the NS atmosphere or the accretion flow.
- D'Angelo et al. (2015) show that the NS atmosphere origin is more likely.

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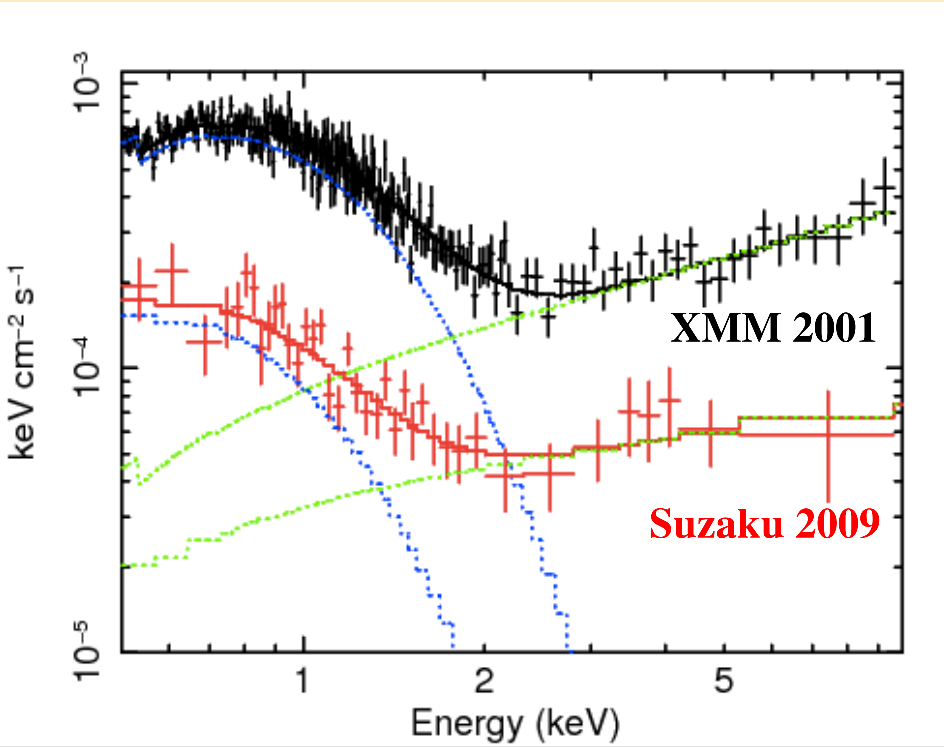
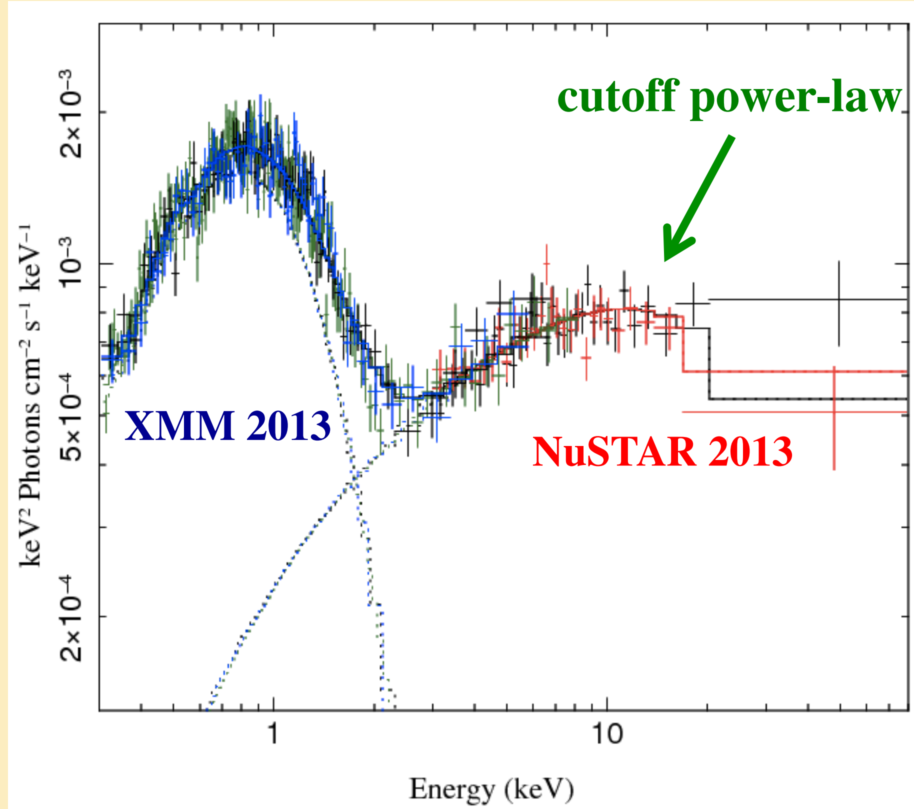
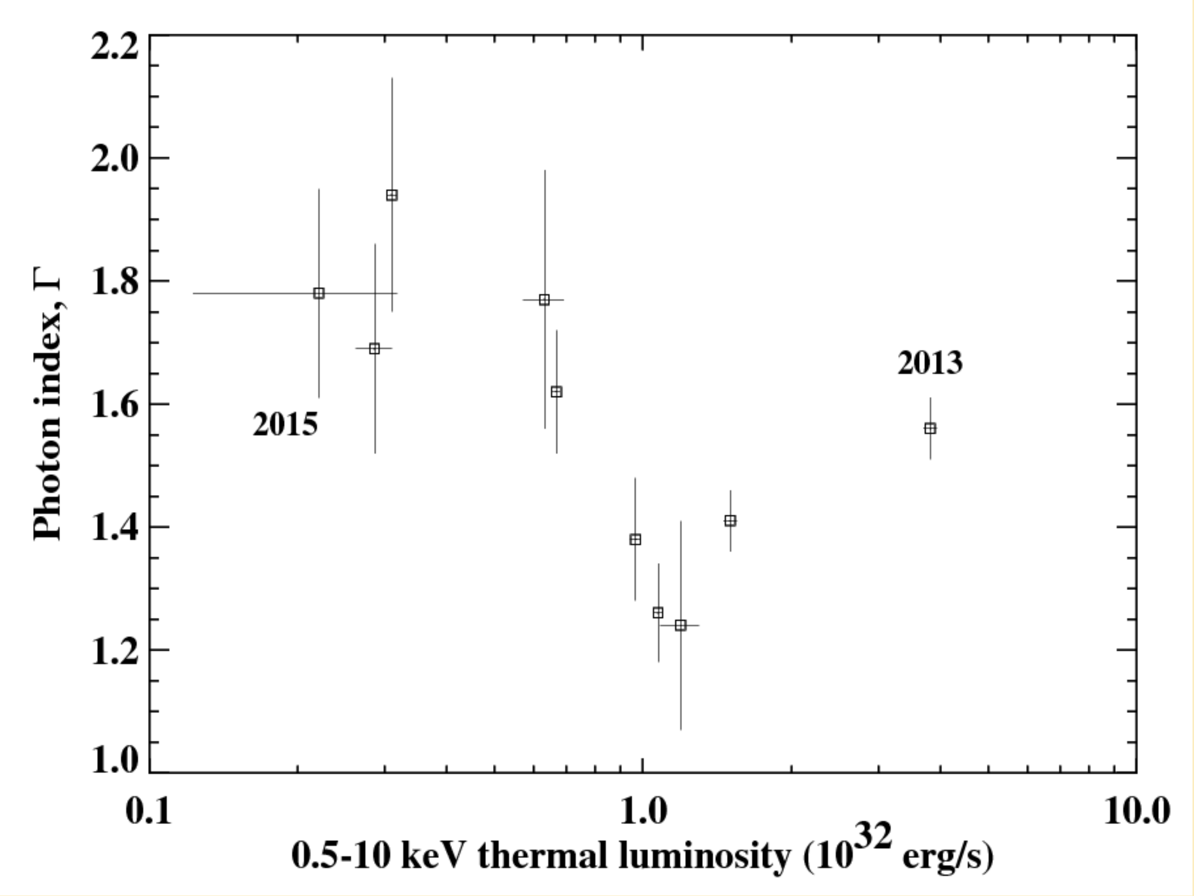



2013 observation (Chakrabarty et al. 2014)




- 2013 observation was brightest recorded quiescent flux from Cen X-4. Evidence for cutoff is visible even in just the XMM data alone (below 10 keV).
- Similar cutoff evidence not seen in previous (fainter) observations, suggesting that cutoff energy is variable.
- Second NuSTAR observation made in 2015 to look for change in cutoff energy.

# Power-law index versus luminosity in Cen X-4




Chakrabarty et al. 2014

- Above $10^{32}$ erg/s, source hardens as it gets fainter, but it softens at the lowest luminosities.
- Jonker et al. (2004) proposed that the power-law component in qLMXBs is accretion-driven at higher Mdot but arises from some non-accretion component at low Mdot, like synchrotron shock emission.

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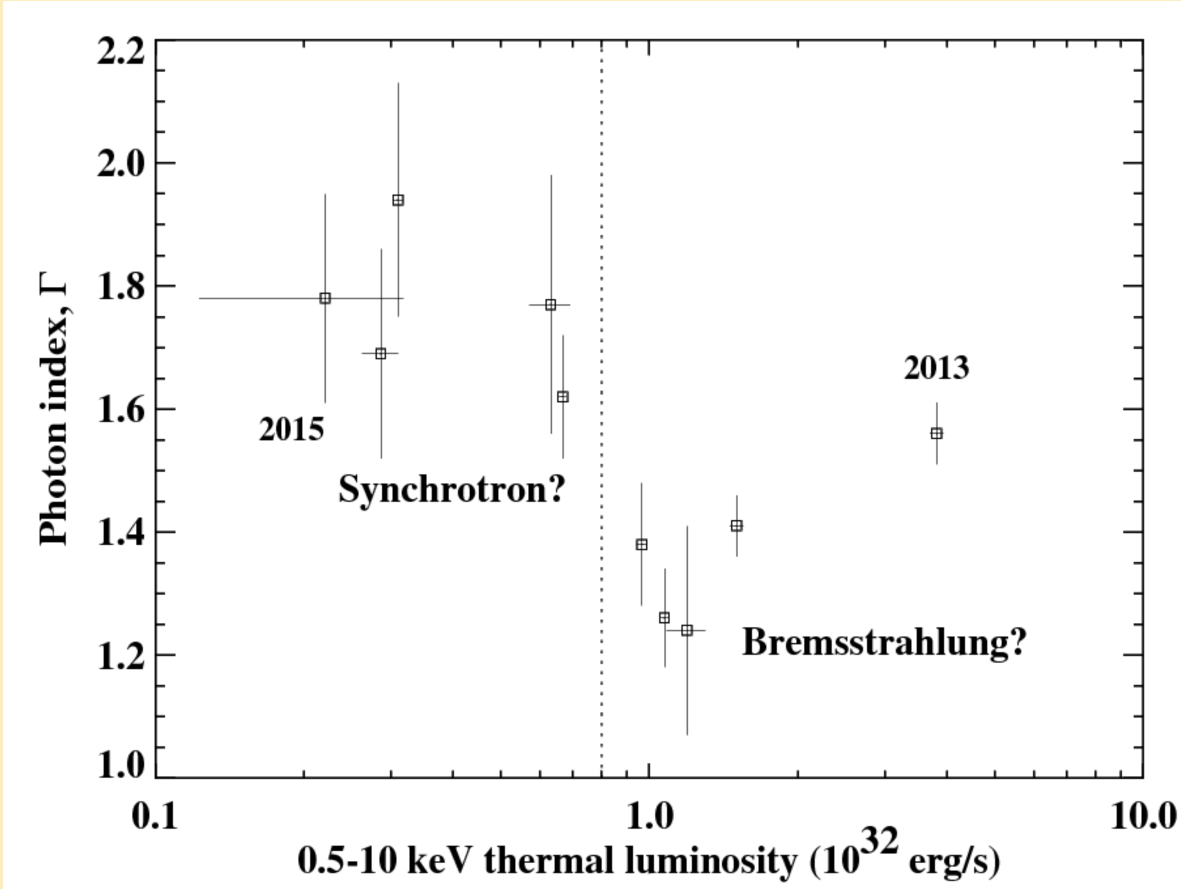



Chakrabarty et al. 2014

- 2015 observation was historically faint, consistent with earlier measurements.
- Thermal component still significant (cf Suzaku data from 2009).
- The t-MSPs are already in the radio pulsar state at $10^{32}$ erg/s, unlike Cen X-4.
- If shock emission at faint end, look for evidence of radio pulsar turn-on?

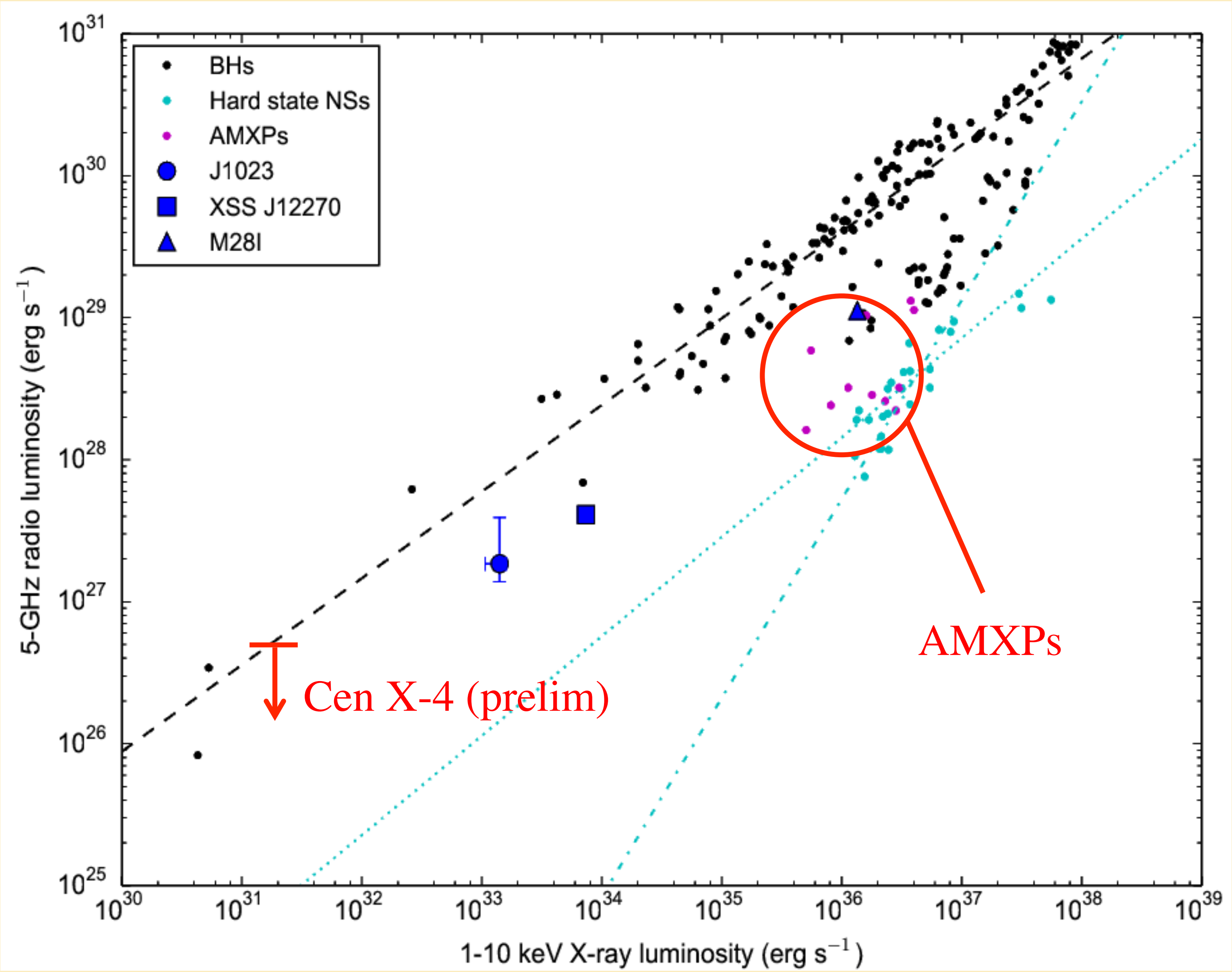
## Preliminary Results for New Cen X-4 Observations in 2015

(Chakrabarty et al. 2015, in prep)

- Quiescent X-ray luminosity historically low
- Searched for radio pulsations (with Paul Ray) at GBT, 1-hour each at 820 MHz and 2 GHz. Observed near optimal phase of 19-hr orbit, acceleration search applied. No pulsations detected.
- Searched for radio continuum emission (with Stephane Corbel) at ATCA at 5.5 and 9 GHz. No source detected.
- Cen X-4 is also not a known Fermi gamma-ray source. (It is the closest known quiescent LMXB, so the best target in this class.)
- We have a no evidence supporting any sort of outflow in this system, in contrast to SAX J1808.4-3658 and PSR J1023+0038.

# Radio/X-ray Correlation

(Deller et al. 2015)

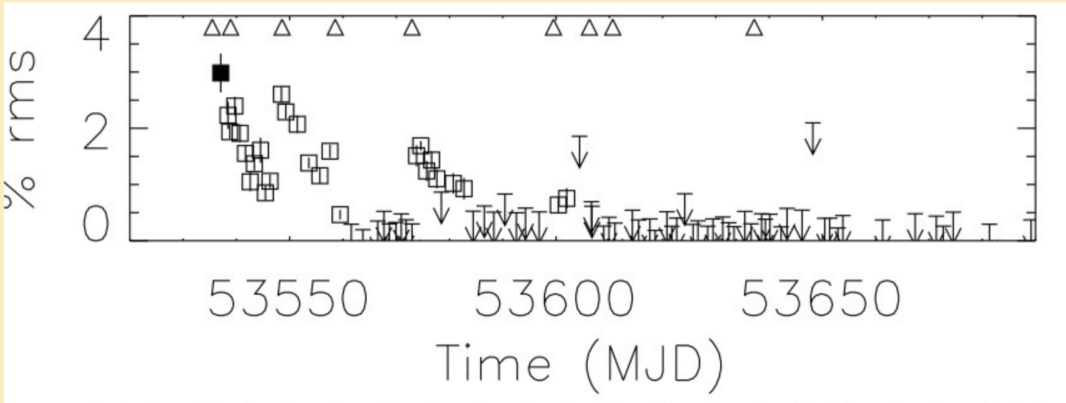


## Comparing LMXBs to AMXPs and t-MSPs

- Cen X-4 seems to behave very differently from both PSR J1023+0038 and SAX J1808.4-3658 at the same X-ray luminosities. What is the difference?
- D'Angelo et al. (2015) suggested that the magnetic field may be well below $10^8$ G in Cen X-4 and thus dynamically unimportant. Presumably, the magnetic field plays a role in any outflow in AMXPs and tMSPs.
- This connects to a very old problem: why are most LMXBs not AMXPs? Or, why do we only find AMXPs among low-luminosity LMXB transients? We know many have millisecond spins (burst oscillations).
- Non-magnetic accretion flows in the non-pulsing LMXBs?
    - Intrinsically weak magnetic fields? How to reconcile with millisecond radio pulsar population?
    - Could there be a population of rotation-powered NSs with $B<10^8$ G? Would they be active as radio pulsars or beyond the death line?
    - Screening of magnetic field by accretion? (Cumming, Zwiebel, & Bildsten 2001) Fields only penetrate for very low accretion rates, intrinsic field reemerges when accretion ends. Critical rate around 0.01 $L_{Edd}$
- Another complication: What about "intermittent" AMXPs?

# “Intermittent” accretion-powered millisecond pulsars

First example was HETE J1900.1-2455 (Galloway et al. 2007).




- Luminosity ~ $10^{36}$ erg/s.
- Active outburst for >1 yr but pulsations only during first few months.
- Drops in pulsed fraction uncorrelated with changes in flux or spectrum.
- Episodes of enhanced pulsed fraction following Type 1 (thermonuclear) X-ray bursts.

Why are these pulsations coming and going? Is this some sort of gradual magnetic screening effect?

Cautionary tale when searching for AMXPs...

## Summary

- The discovery of t-MSPs finally allows us to study the detailed path between the LMXB and radio pulsar states. It has also thrown a new light on the problem of understanding why most LMXBs are not pulsed X-ray sources (AMXPs).

- The seemingly important role of outflows in both the tMSPs and AMXPs during accretion-powered pulsation modes suggests an avenue for focus. Theoretical progress in interpreting the radio and gamma-ray emission, and in understanding extremely low-rate accretion flows and the details of propeller and trapped disk models for the disk-magnetosphere interaction will be crucial.