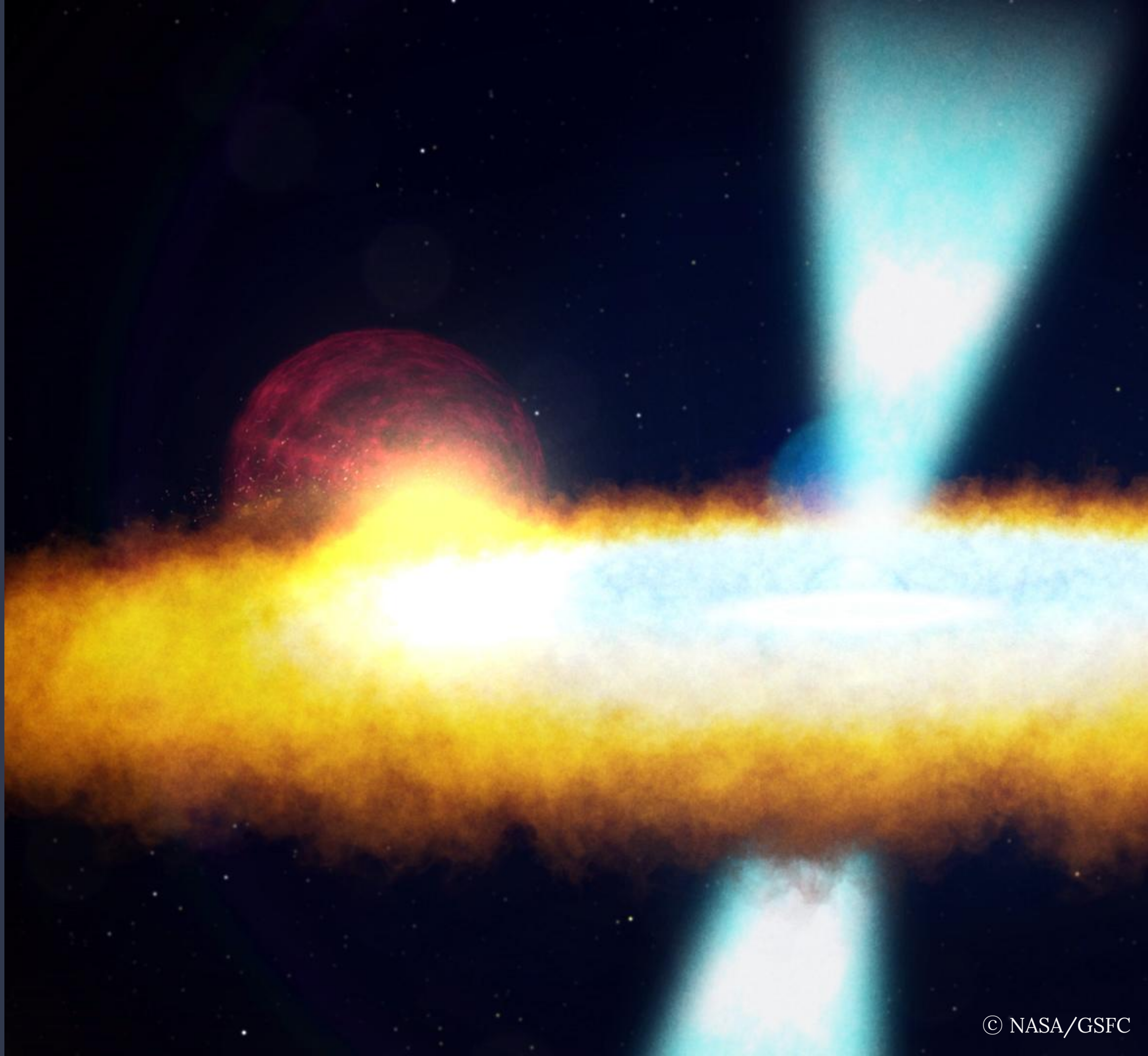
Monitoring Accreting Millisecond X-ray Pulsars with NICER

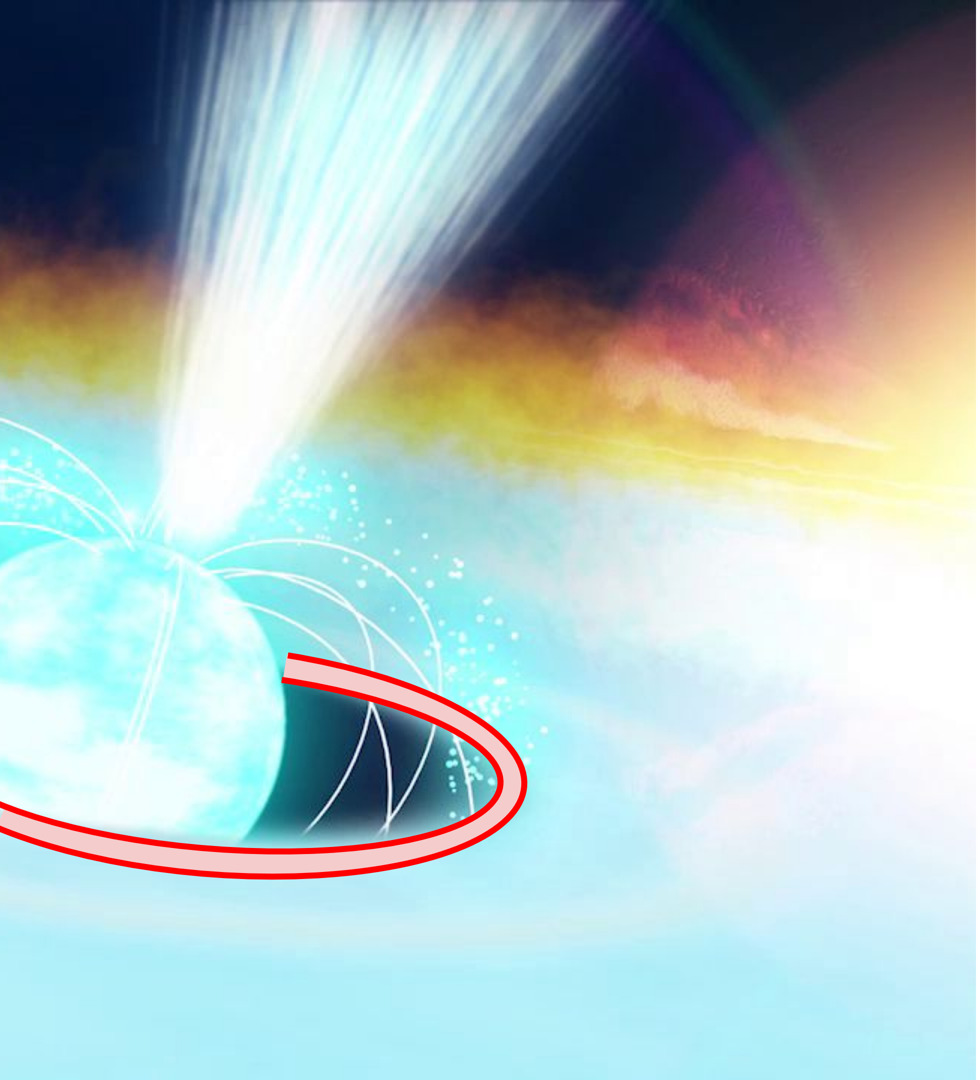
Peter Bult

The anatomy of an AMXP

Binary system where a neutron star draws gas from a low-mass companion star.

Matter flows through an accretion disk that couples to the magnetic field of the neutron star.





Consider the magnetosphere

Magnetically confined accretion causes the formation of a **hotspot**. The stellar rotation then causes a geometric aspect variation: the apparent effective area of the hotspot varies with the rotational phase of the neutron star.

This leads to the appearance of **pulsations**.

Why do we care?

A couple reasons…

1. Pulsations allow for precision measurements of key system parameters such as the spin frequency, the binary orbit, and their respective evolution, as well as the magnetic field strength.

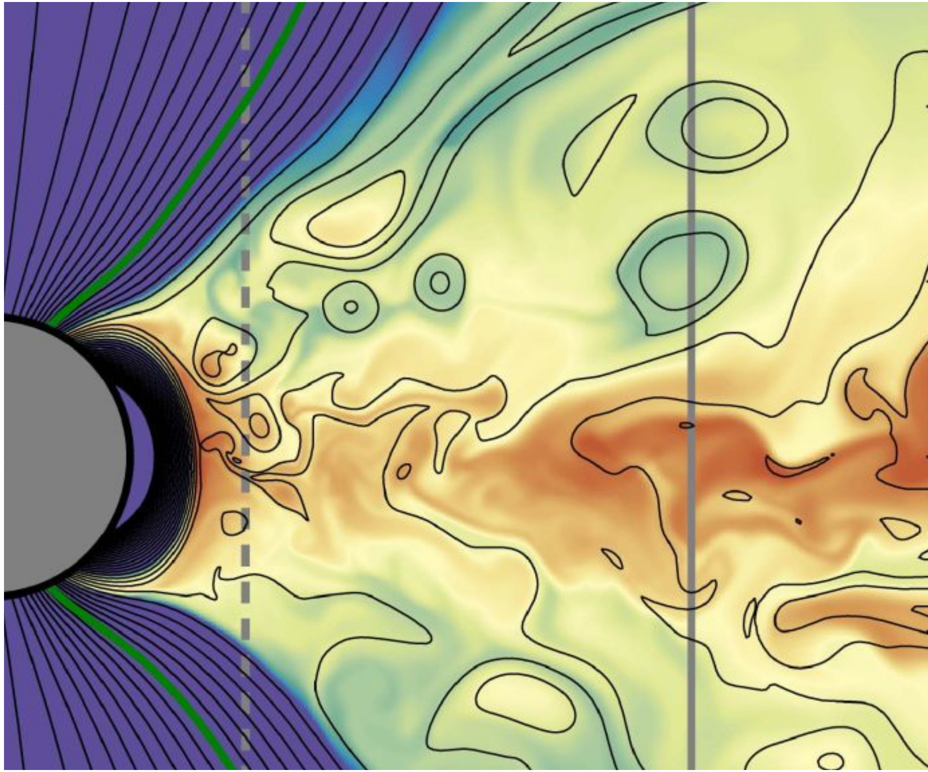
2. Pulsations originate from the stellar surface, so their precise waveform encodes information about the compactness of the neutron star.

3. Pulsations can place a length scale on the accretion process.

Accretion is noisy

The accretion flow is inherently turbulent and that turbulence transfers over to the pulse waveform.

This is both a challenge and an opportunity.



Parfrey & Tchekhovskoy

Why use NICER?

Discovery:

- High timing resolution
- Fast response

Characterization

- Good throughput
- Flexible monitoring capability

Known AMXPs by discovery

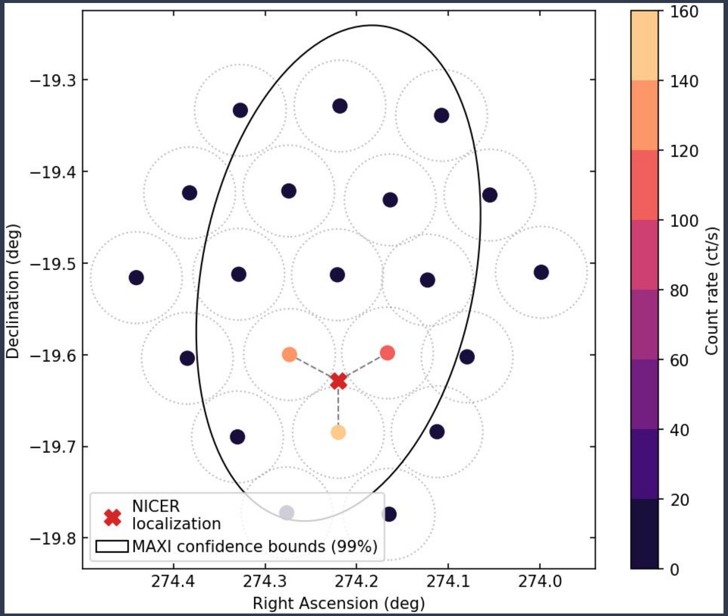
NICER dominates the discovery and subsequent characterization of AMXPs in recent years.

		Year	Source name	Freq. (Hz)	P_orb (hr)	Observatory
1		1998	SAX J1808.4-3658	401	2.01	RXTE
2		2002	XTE J1751-305	435	0.71	RXTE
3		2002	XTE J0929-314	185	0.73	RXTE
4		2003	XTE J1807-294	191	0.68	RXTE
5		2003	XTE J1814-338	314	4.27	RXTE
6		2004	IGR J00291+5934	599	2.46	RXTE
7	*	2005	HETE J1900.1-2455	377	1.39	RXTE
8		2007	Swift J1756.9-2508	182	0.91	RXTE
9	*	2007	SAX J1748.9-2021	442	8.76	RXTE
10	*	2007	Aql X-1	550	18.95	RXTE
11		2009	NGC 6440 X-2	205	0.96	RXTE
12		2009	IGR J17511-3057	245	3.47	RXTE
13		2010	Swift J1749.4-2807	518	8.86	RXTE
14		2011	IGR J17498-2921	401	3.84	RXTE
15	†	2013	IGR J18245-2452	254	11.03	XMM
16	†	2014	XSS J12270-4859	593	6.91	XMM
17	†	2015	PSR J1023+0038	592	4.75	XMM
18	*	2016	MAXI J0911-655	340	0.74	XMM/NuSTAR
19		2017	IGR J17062-6143	163	0.63	RXTE
20		2017	IGR J16597-3704	105	0.77	NuSTAR
21		2018	IGR J17379-3747	468	1.88	**NICER**
22		2018	IGR J17591-2342	527	8.80	**NICER**/NuSTAR
23		2020	IGR J17494-3030	376	1.25	**NICER**
24		2022	MAXI J1816-195	528	4.83	**NICER**
25		2022	MAXI J1957+032	314	1.16	**NICER**

* - Intermittent AMXP

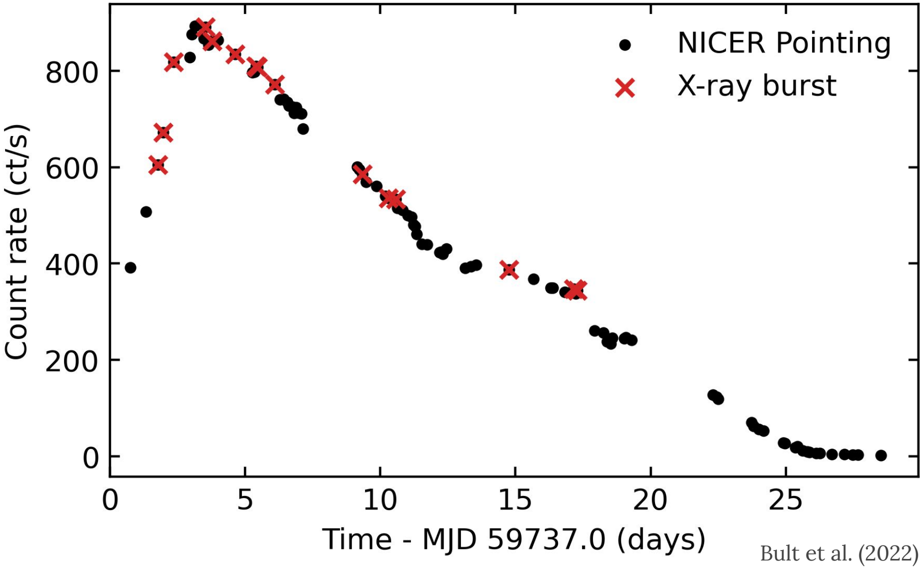
† - Transitional MSP

MAXI J1816−195



A typical timeline

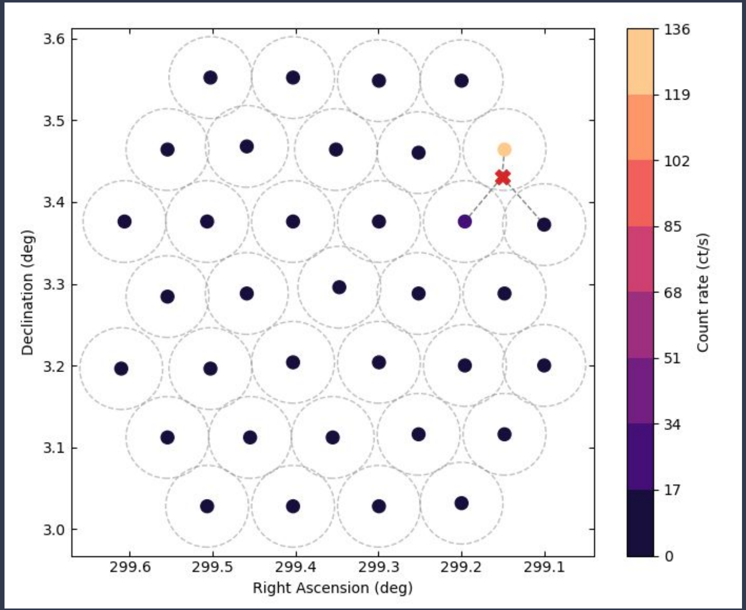
1. All sky monitor alert (MAXI/GSC, Swift/BAT)
2. Refine localization (Swift/XRT, NICER raster)
3. Pointed observation (NICER)

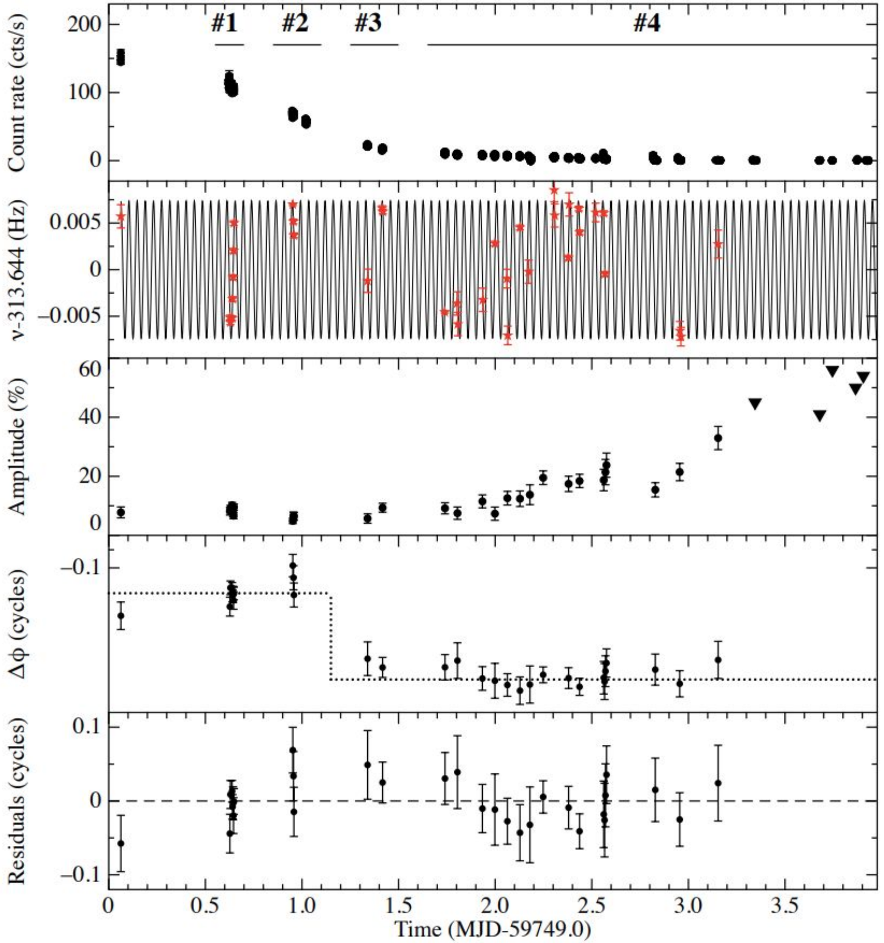


Bult et al. (2022)

MAXI J1957+032

A showcase of rapid discovery and follow-up.





Sanna et al. (2022)

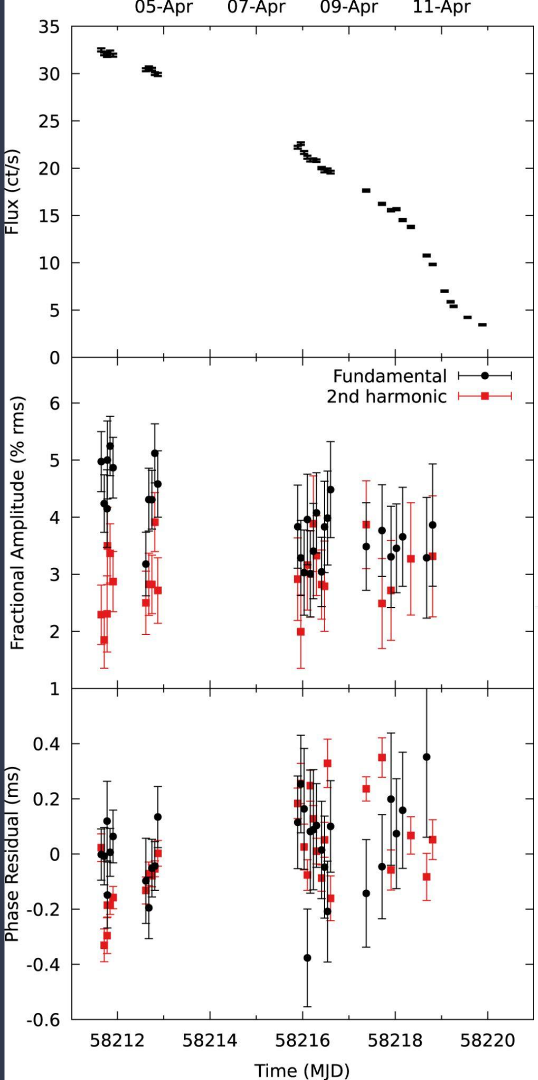
Characterization requirement

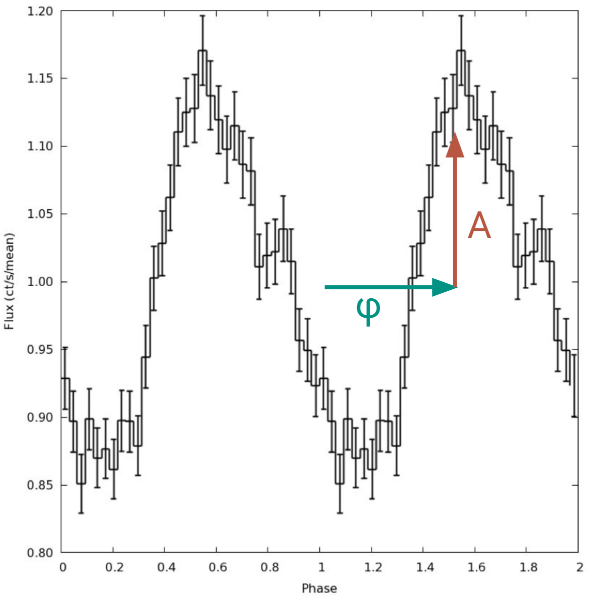
Outburst are transient, typically lasting a few days to weeks.

The pulse requires a couple hundred seconds of integration time to resolve.

The waveform will vary with time, usually over hours.

We need cover all timescales with high cadence.





Our basic observable is the pulse waveform, with some measurable amplitude and phase.

Both vary over time.

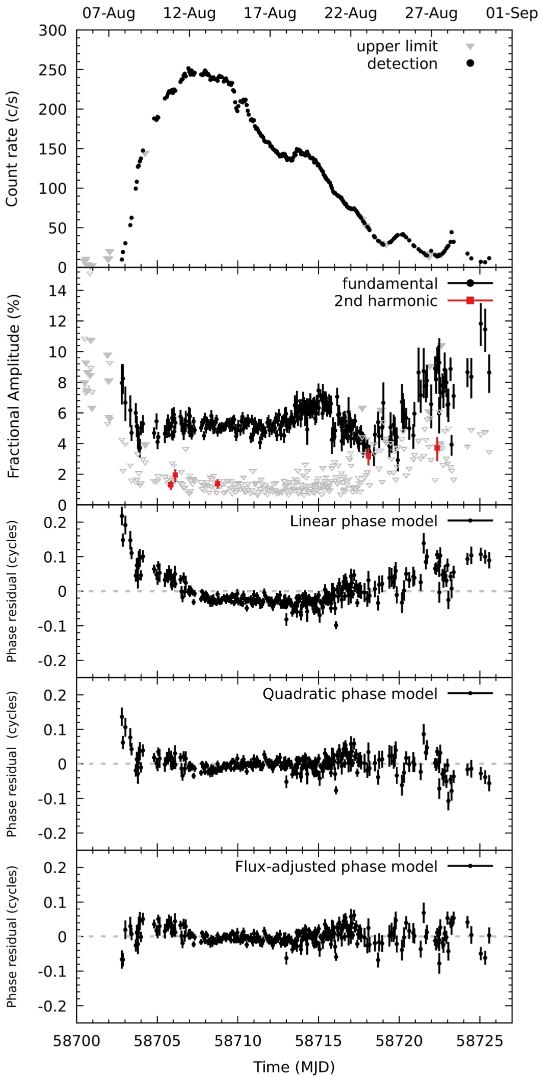
Bult et al. (2018, 2019)

SAX J1808.4-3658

systematic shifts in pulse amplitude

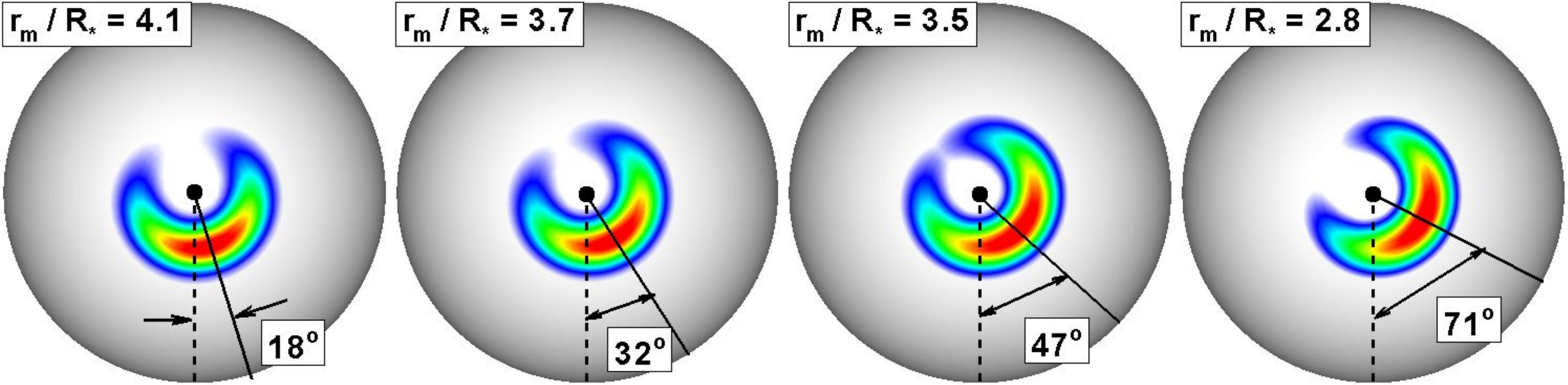
The August 2019 outburst was observed extensively with NICER.

- pulse phase drifts are anti-correlated with flux
- accounting for the flux-phase bias gives the best description of the pulse phase evolution



Bult et al. (2020)

Systematic shifts in pulse phase

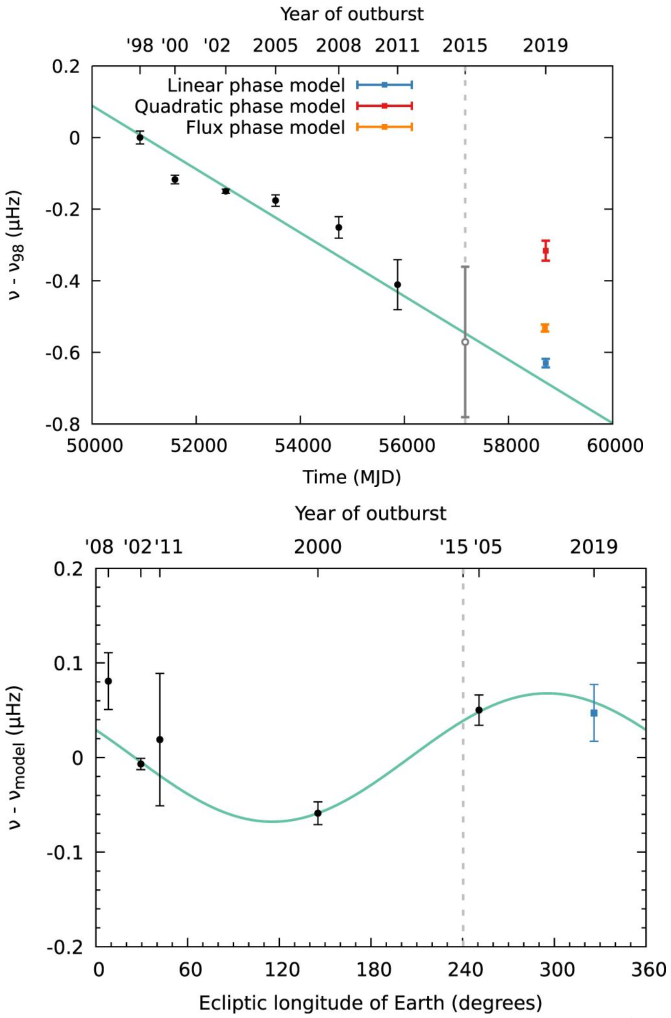


Kulkarni & Romanova (2014)

Long-term spin change

Between outbursts, magnetic dipole radiation spins down the neutron star.

- Spin-down gives a measure of the stellar magnetic field strength.
- Long term monitoring can reveals astrometric position correction.

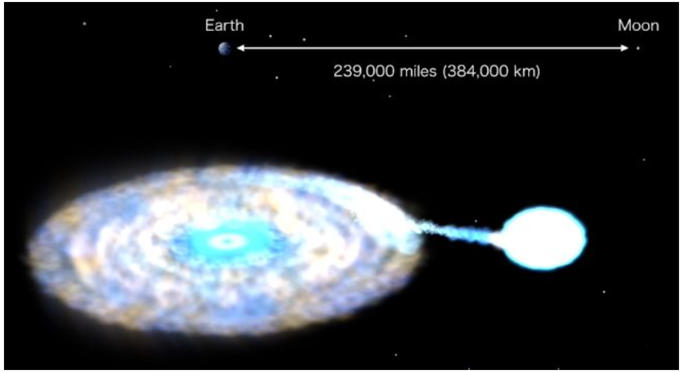


Bult et al. (2020)

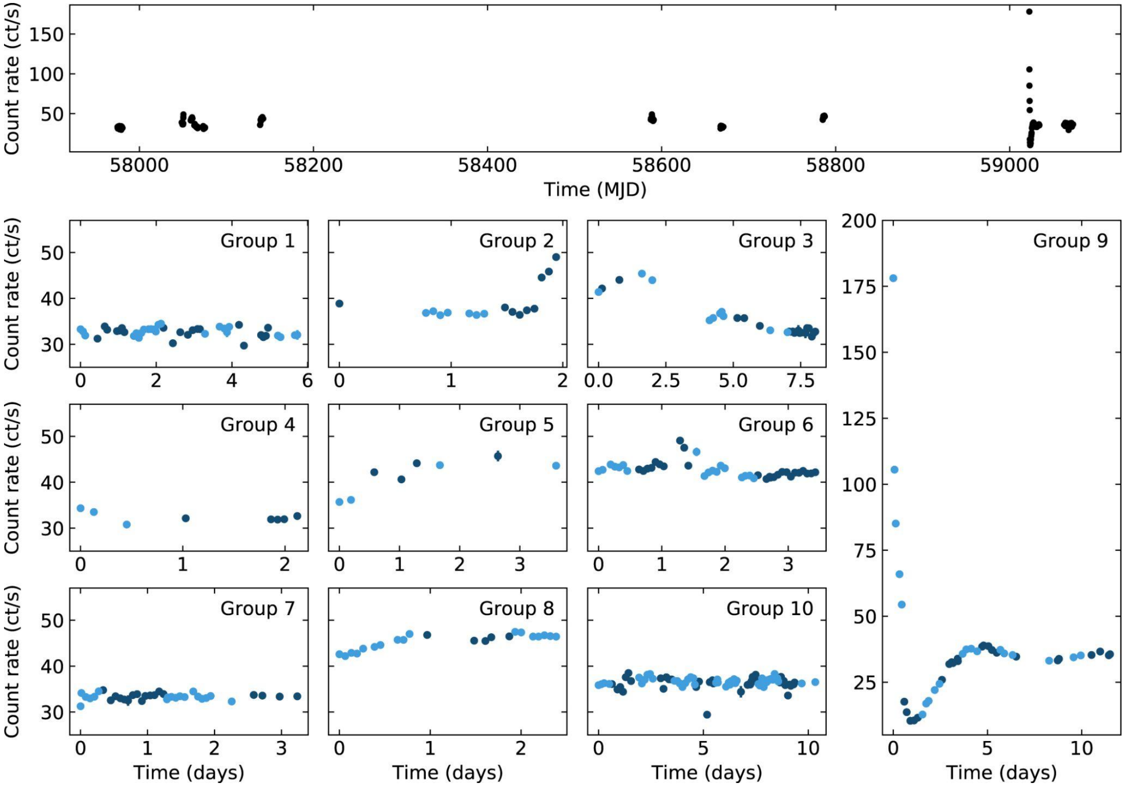
IGR J17062-6143

An ultra-compact binary (38 min orbit) that has been persistently visible since 2007.

Pulsations were only discovered recently, in 2017.



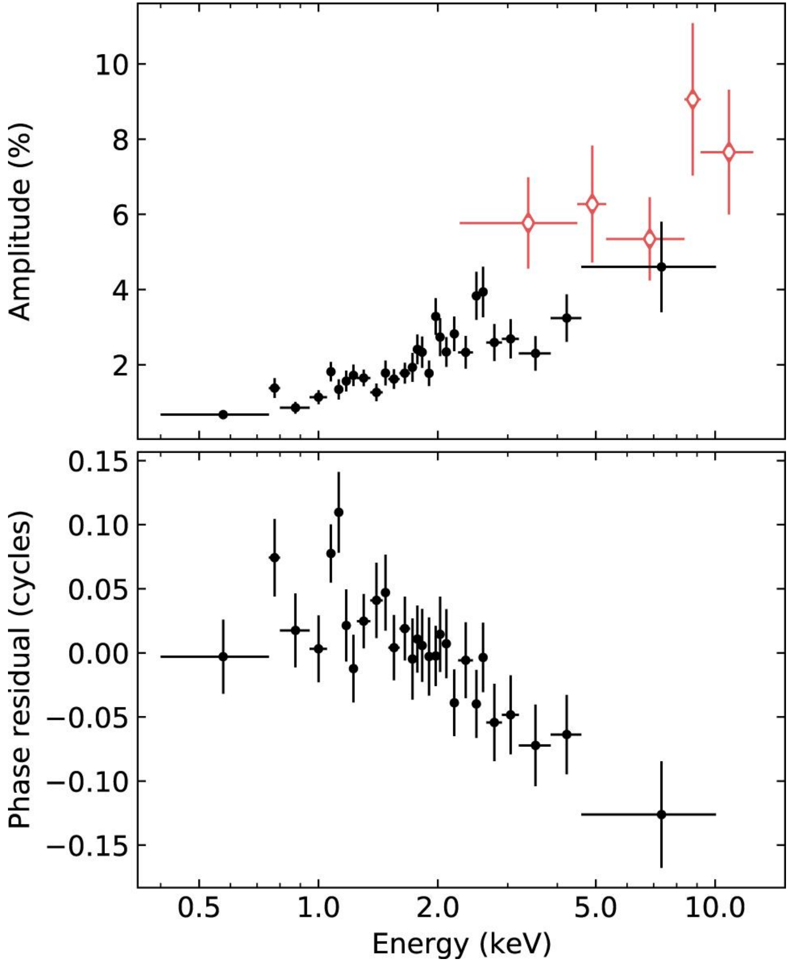
Strohmayer et al. (2018), Bult et al.



IGR J17062-6143

Pulsations were observed at ~9% in RXTE (red), but appear much smaller in NICER (~2%).

This difference appears to be partially due to the very different energy bands.

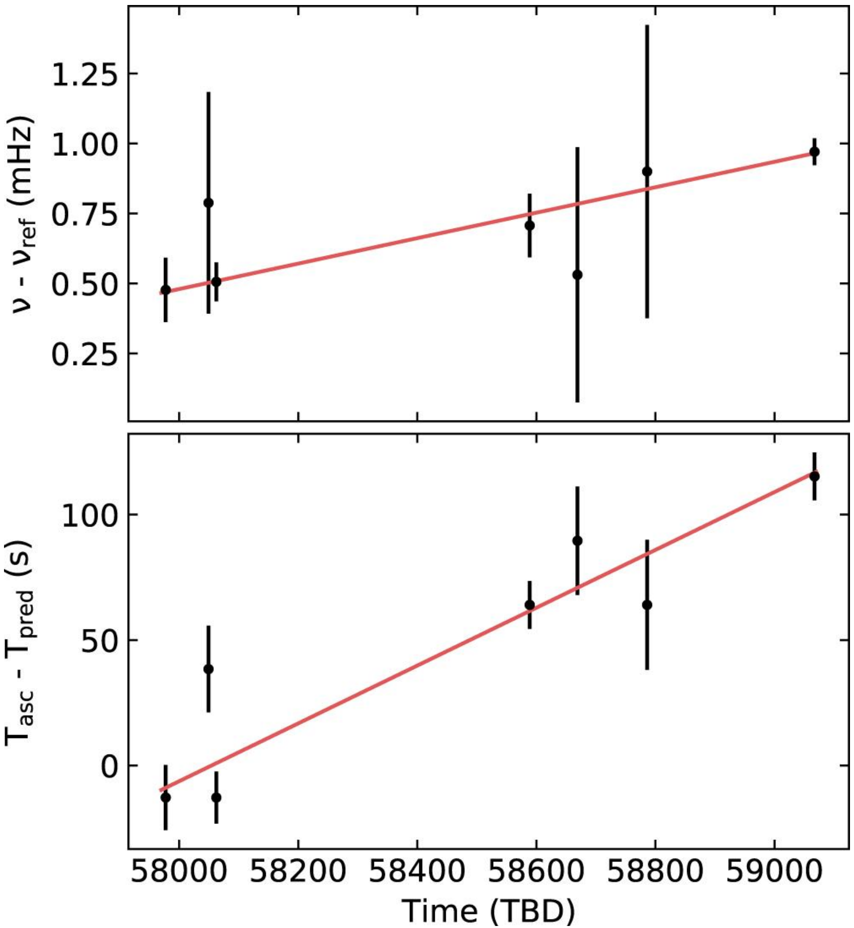


Bult et al. (2021)

IGR J17062-6143

The continuous accretion is steadily spinning up the neutron star. While spin changes have measured for various other AMXPs, J17062 is the only case in which the spin change is measured directly from frequency (as opposed to phase based pulsar timing).

This is completely independent of phase shift uncertainties.



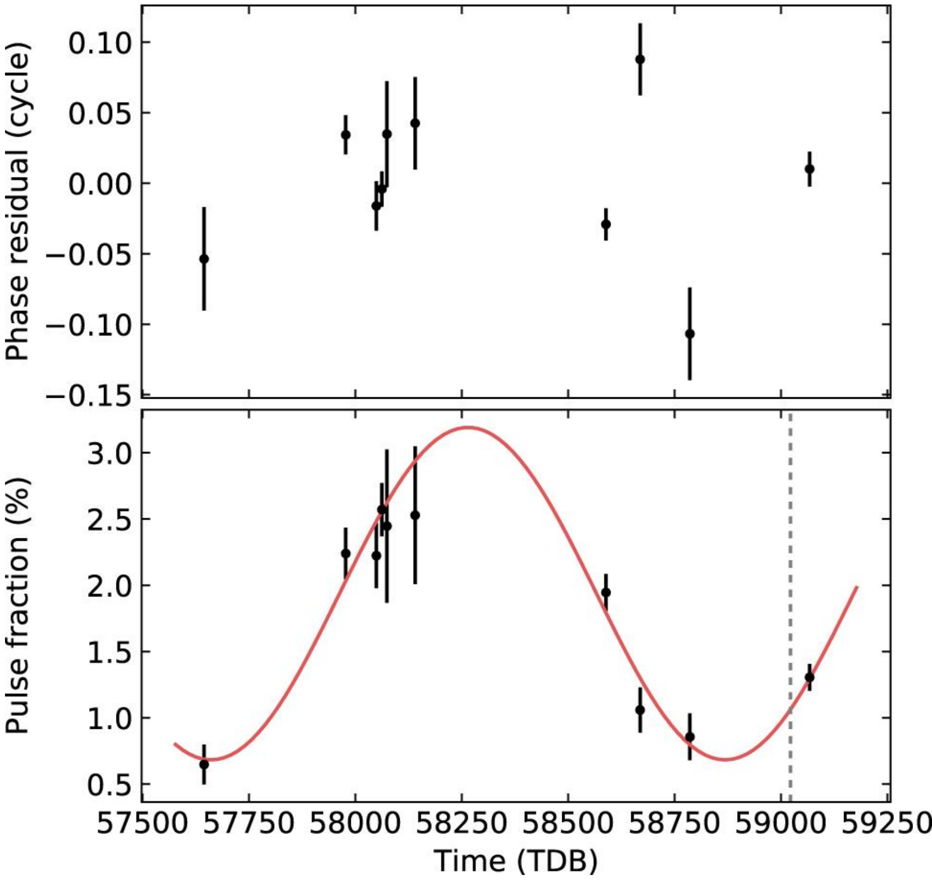
Bult et al. (2021)

Strohmayer et al. (2018), Bult et al.

IGR J17062-6143

The pulse amplitude shows highly unusual behavior, with an apparent oscillation over multiple years.

The origin of these slow amplitude changes is unknown. It could be a geometric effect (some sort of precession); a slow limit cycle related to its X-ray bursts, or something else entirely.



Bult et al. (2021)

Summary

- NICER provides the key capabilities we need to perform detailed studies of AMXPs
  - Rapid response
  - High time resolution
  - Monitoring capability
  - Good sensitivity

- Five new AMXPs discovered in recent year

- Several additional outburst observed from previously known AMXPs