Power of agile and flexible observations of the large effective area NICER telescope — Examples of magnetars and transients

Teruaki Enoto (RIKEN, Japan)
George Younes, Wynn Ho, Chin-Ping Hu, Wataru Buz Iwakiri, and on behalf of the NICER Magnetar & Magnetosphere team
@teru_enoto

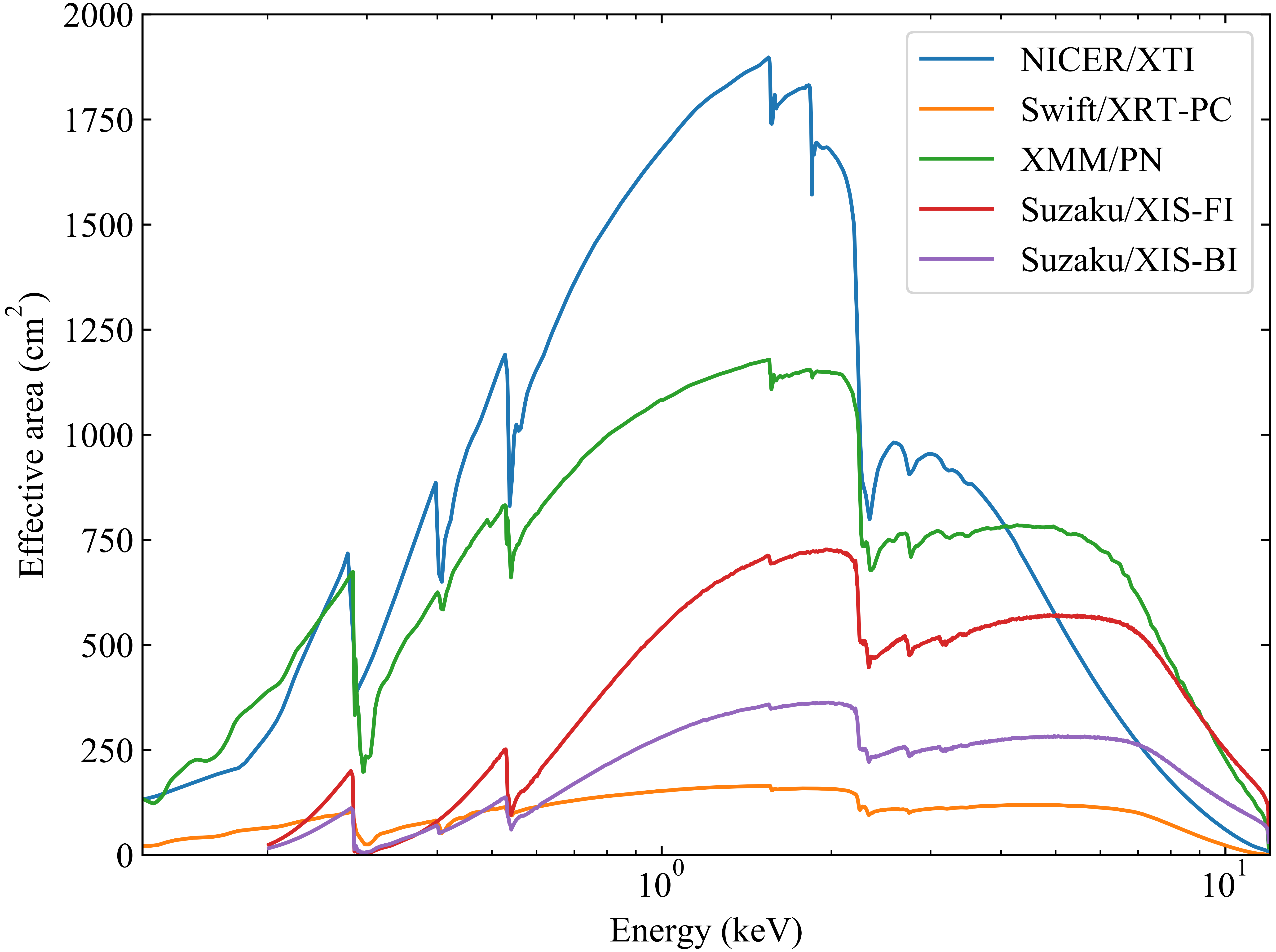
NICER Summer 2022 Science Workshop (18+2 min)
https://heasarc.gsfc.nasa.gov/docs/nicer/data_analysis/workshops/2022/nicer_workshop2022.html

X-ray observatory NICER on the ISS

- The largest effective area 1,900 cm^2 at 1.5 keV with high-time resolution (<100 ns)!

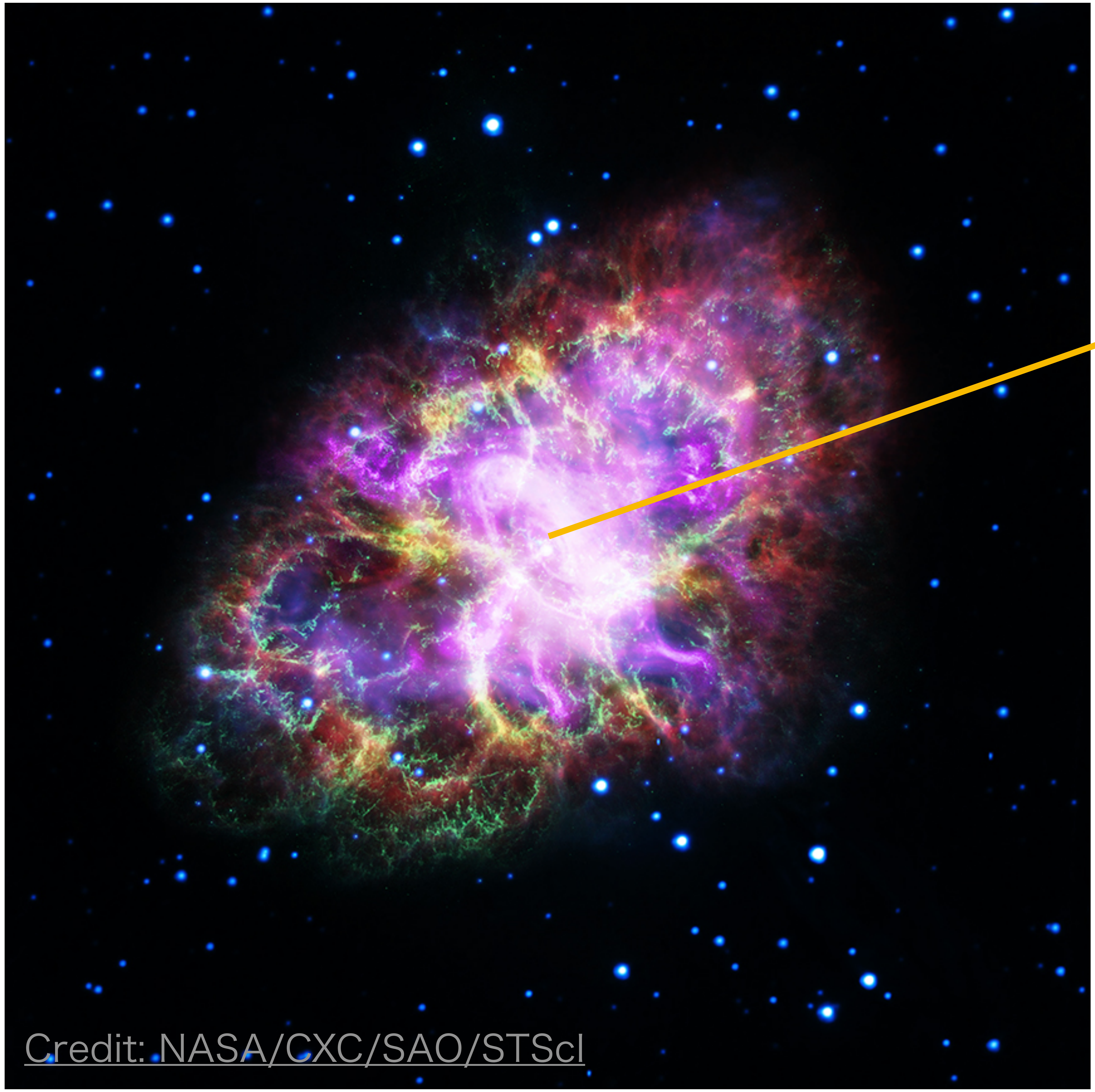
X-ray observatory NICER on the ISS

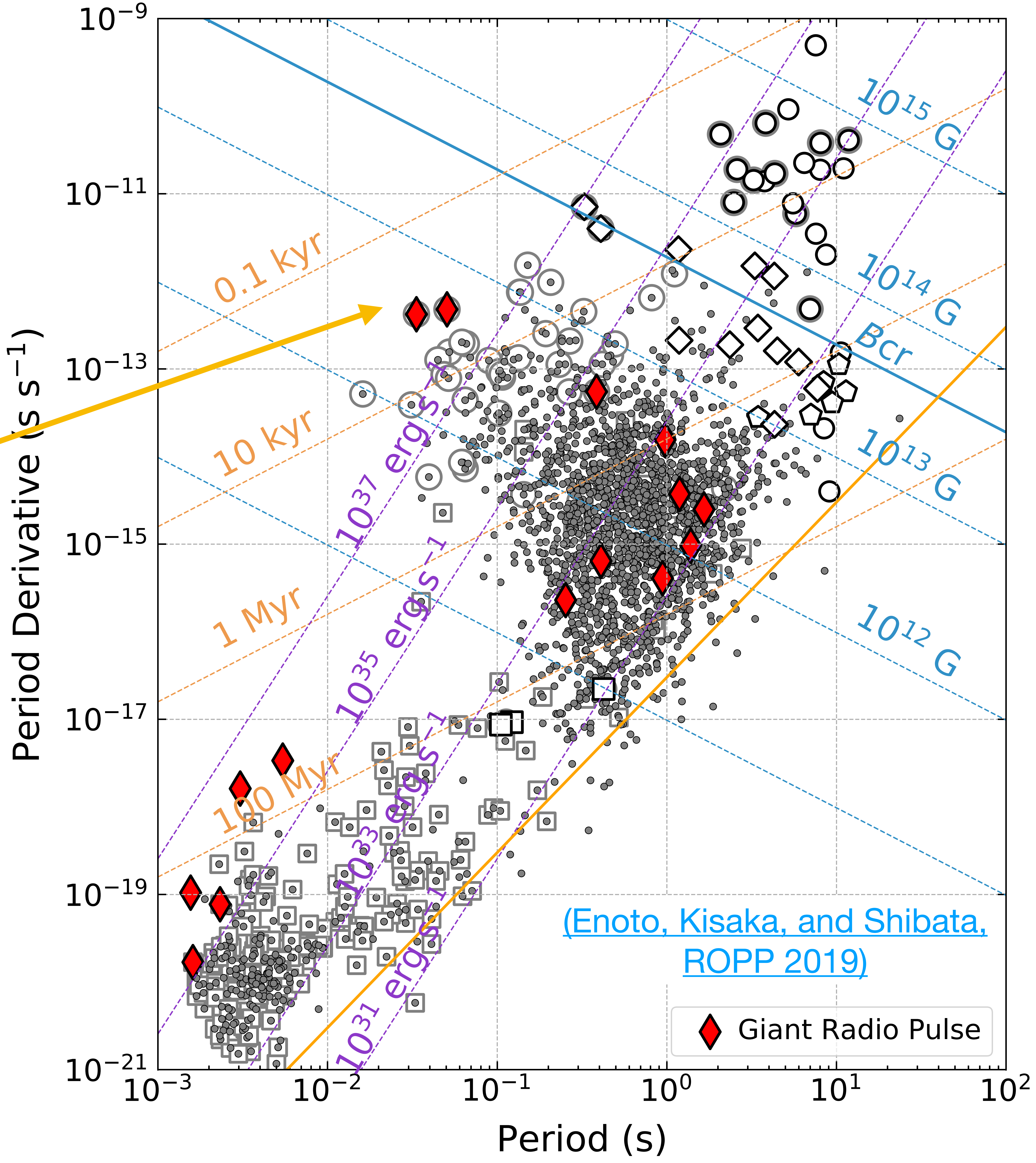
- The largest effective area 1,900 cm^2 at 1.5 keV with high-time resolution (<100 ns)!



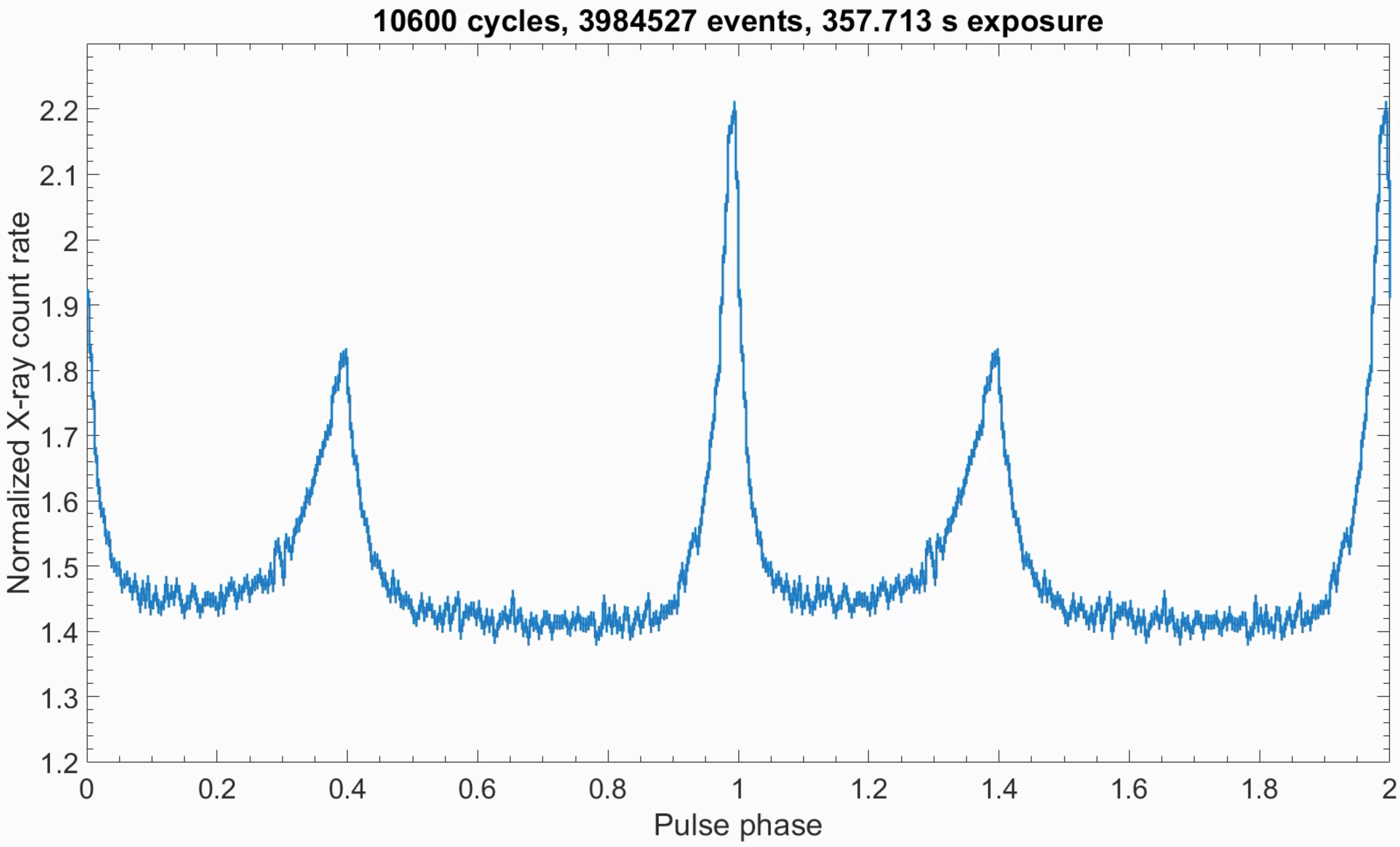
(K. Gendreau, et al., SPIE, 2012; Z. Arzoumanian, et al., SPIE, 2014)

The Crab Pulsar



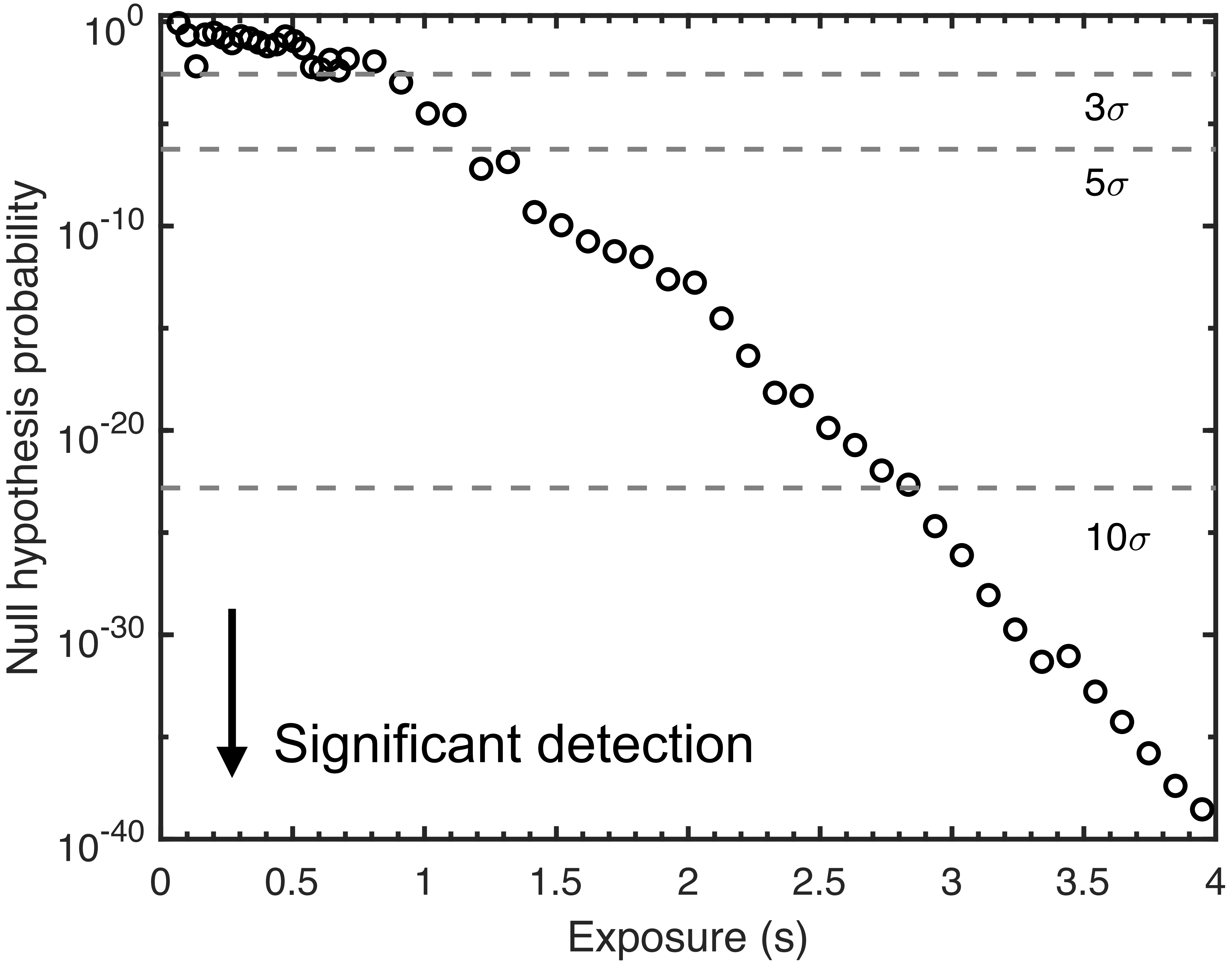


Short exposure to detect the Crab pulsation

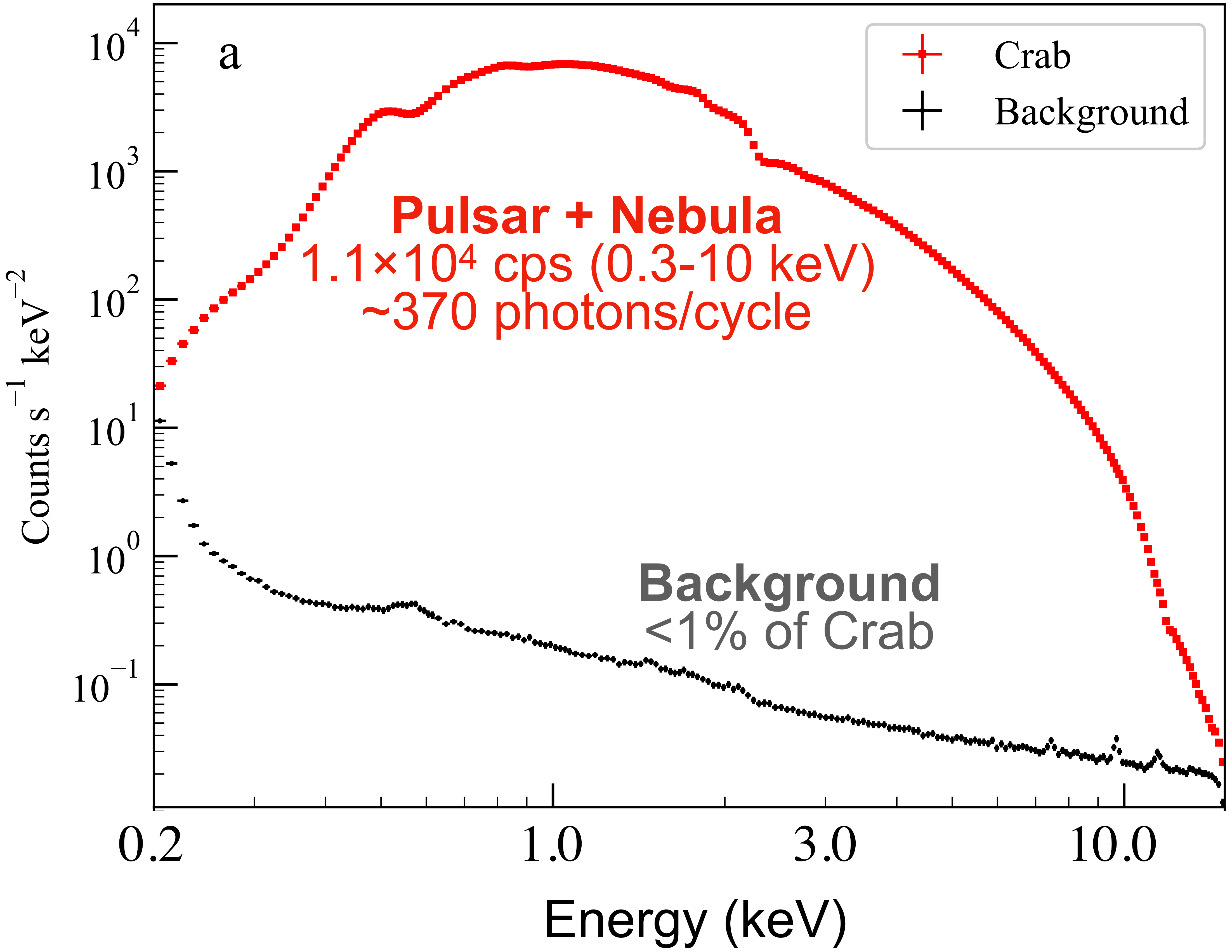


Short exposure to detect the Crab pulsation

Detection significance of X-ray pulses



NICER X-ray spectrum of the Crab pulsar and nebula



- Pulse signals are detectable within 1 sec
- Free from pileups, dead time, and data transfer loss (throughput 3.8×10^4 cps).

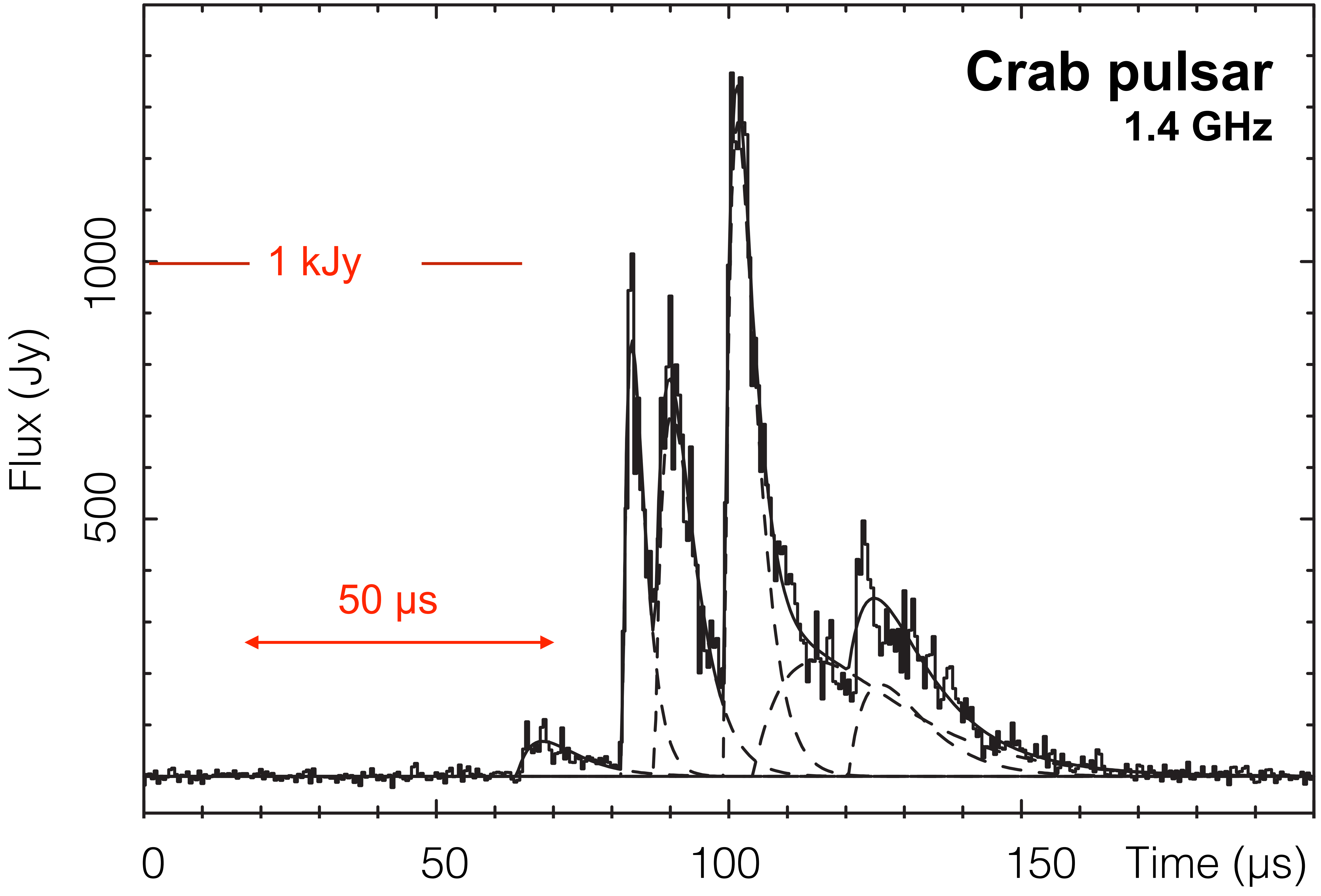
Best Use of the NICER Telescope's Performance?

1. Large effective area (~1900 cm^2 at 1.5 keV)
2. High-time resolution (<100 ns)
3. Free from pileups, dead time, and data transfer loss (up to ~4×10^4 cps)
4. Flexible observations (quick response to ToO, even within a day)

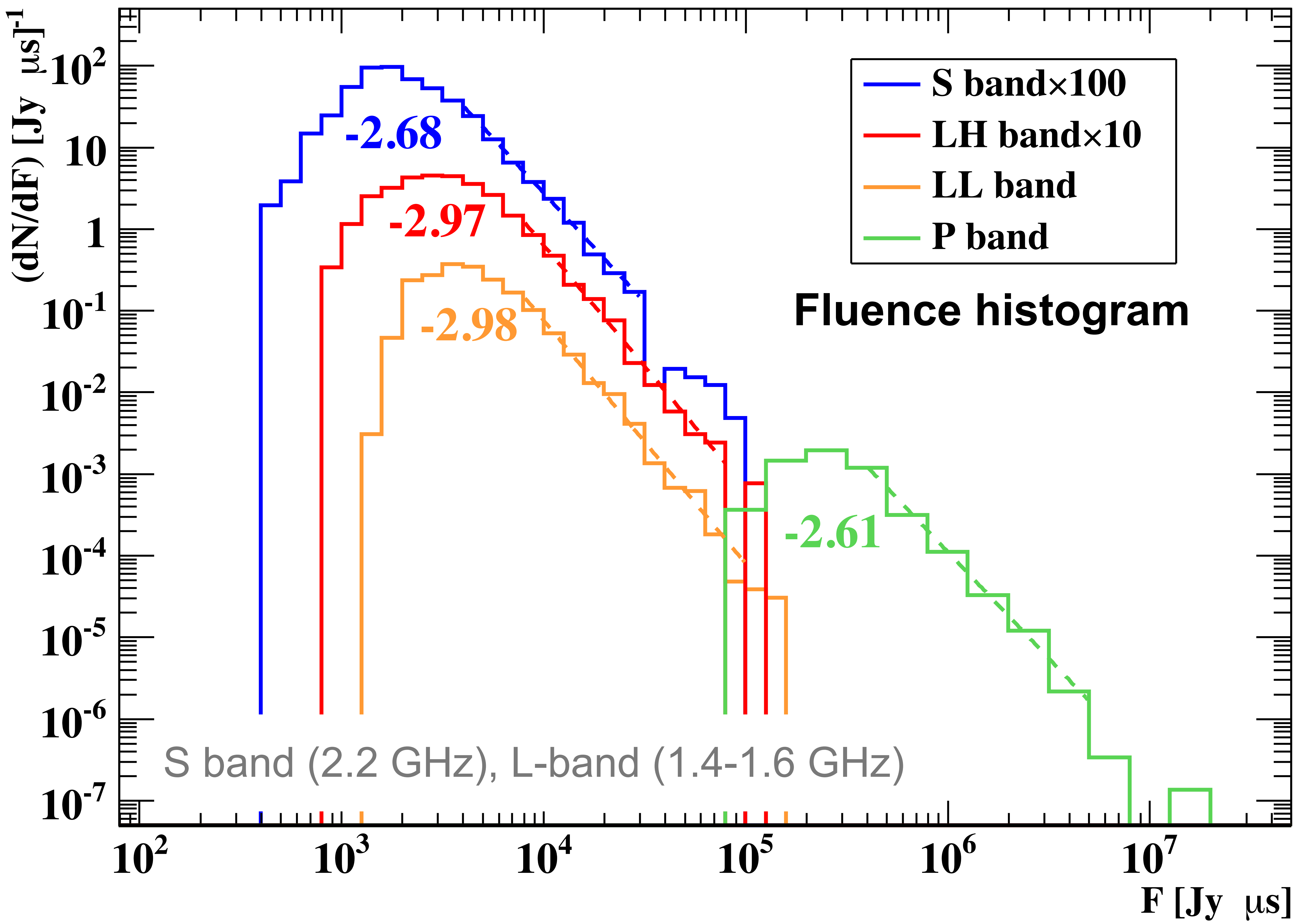
- Examples and applications
  - Discovery of an X-ray enhancement at the Crab giant radio pulses
  - Prompt follow-ups of new magnetars to identify pulsar characteristics
  - Comprehensive studies of magnetar short bursts
  - Search for gravitational waves from rotation powered pulsars
  - Automated transient alert system from MAXI (OHMAN project)

Giant radio Pulses (GPs) from rotation-powered pulsars

- Sporadic sub-millisecond radio bursts $10^{2\text{-}3}$ times brighter than the normal pulses.
- Only from known ~12 sources, power-law distribution of fluence.
- Fast radio bursts (FRBs) are extragalactic GPs from young and energetic pulsars?



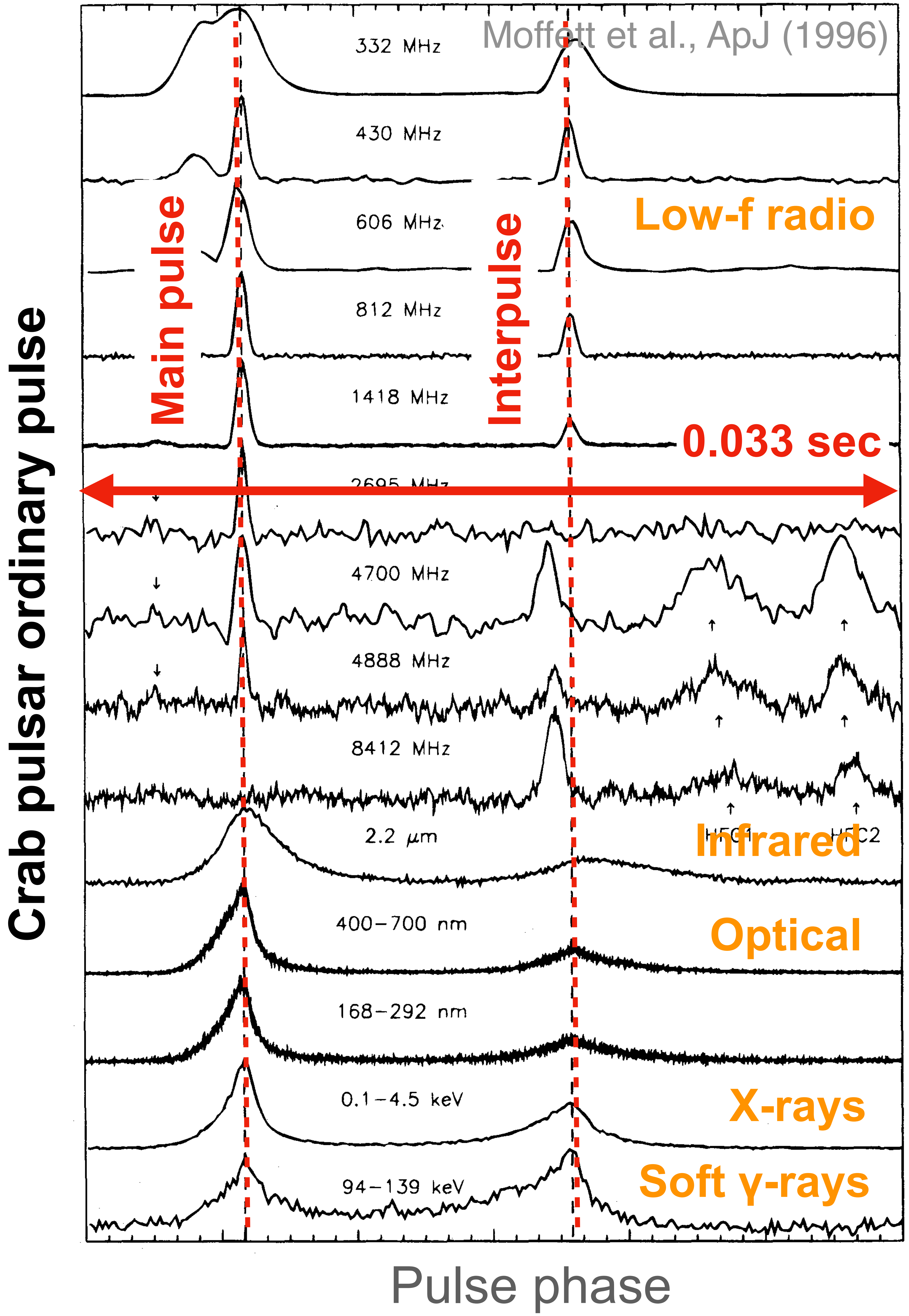
(Sallmen et al., 1999)



(Mikami et al., 2016)

GPs from the Crab Pulsar

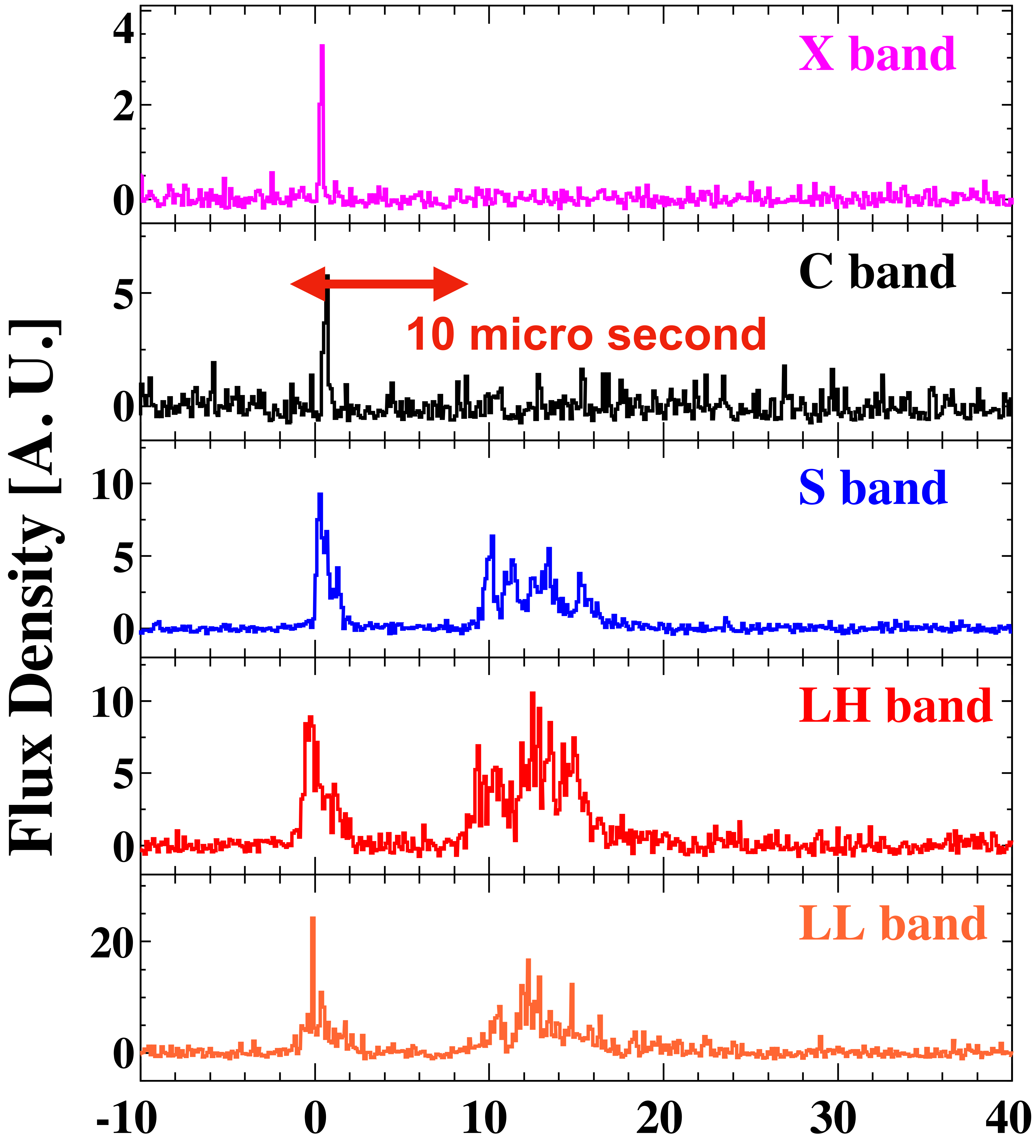
- Crab pulsar has been observed in almost all electromagnetic waves, including radio, infrared, optical, X-rays, and gamma rays.
- GPs of the Crab Pulsar randomly occur in the radio band at the main or inter pulses.
- GPs were thought to be a phenomenon observed only at radio. However optical enhancement coinciding with GPs was discovered (Shearer et al., Science 2003).
- Many teams have been trying to search for an enhancement in X-rays or gamma rays for 20 years, but only the upper limits have been obtained (Chandra, Suzaku…).



GPs from the Crab Pulsar

- Crab pulsar has been observed in almost all electromagnetic waves, including radio, infrared, optical, X-rays, and gamma rays.
- GPs of the Crab Pulsar randomly occur in the radio band at the main or inter pulses.
- GPs were thought to be a phenomenon observed only at radio. However optical enhancement coinciding with GPs was discovered (Shearer et al., Science 2003).
- Many teams have been trying to search for an enhancement in X-rays or gamma rays for 20 years, but only the upper limits have been obtained (Chandra, Suzaku…).

Example of a GP



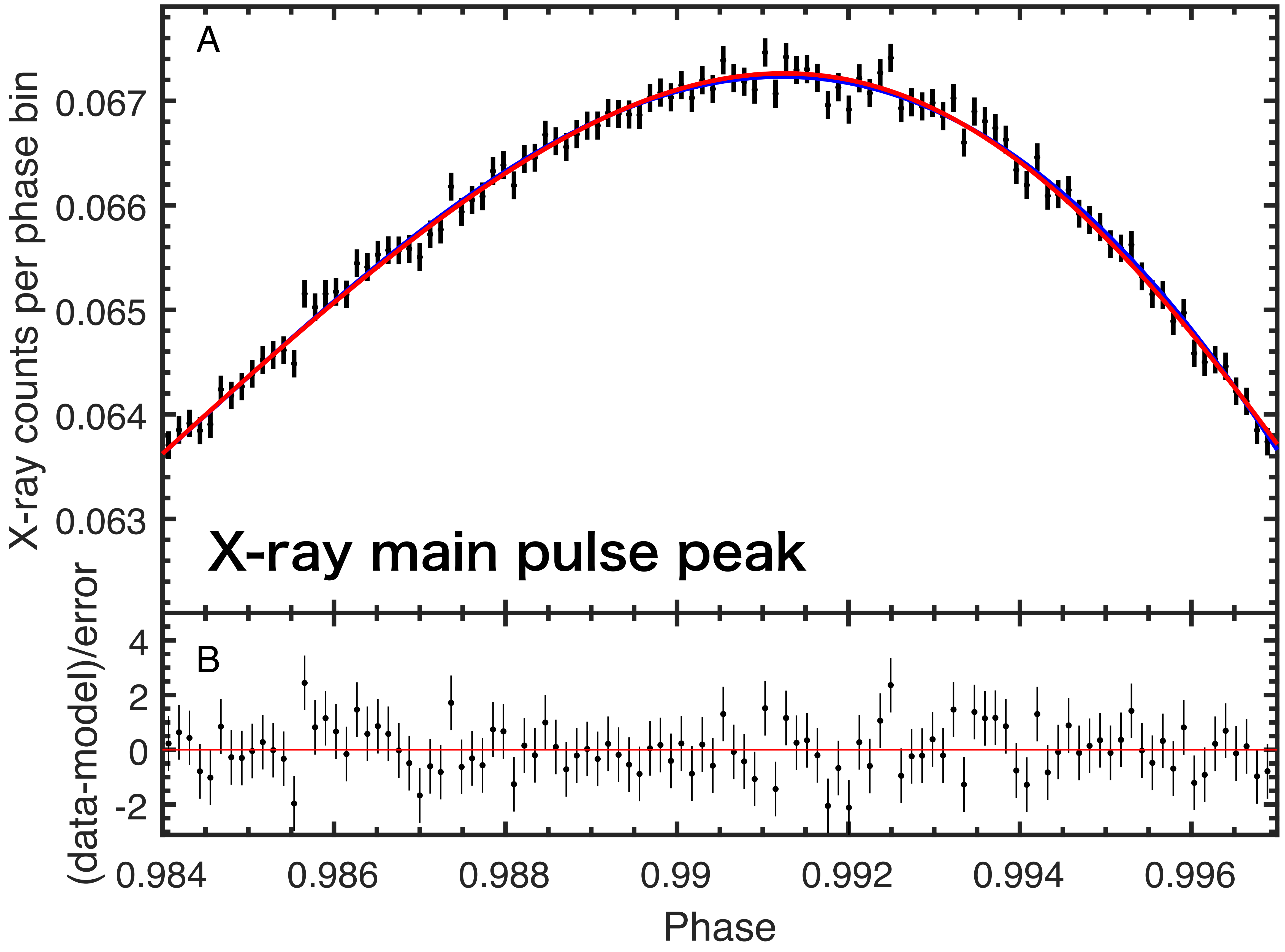
Mikami et al., ApJ (2016)

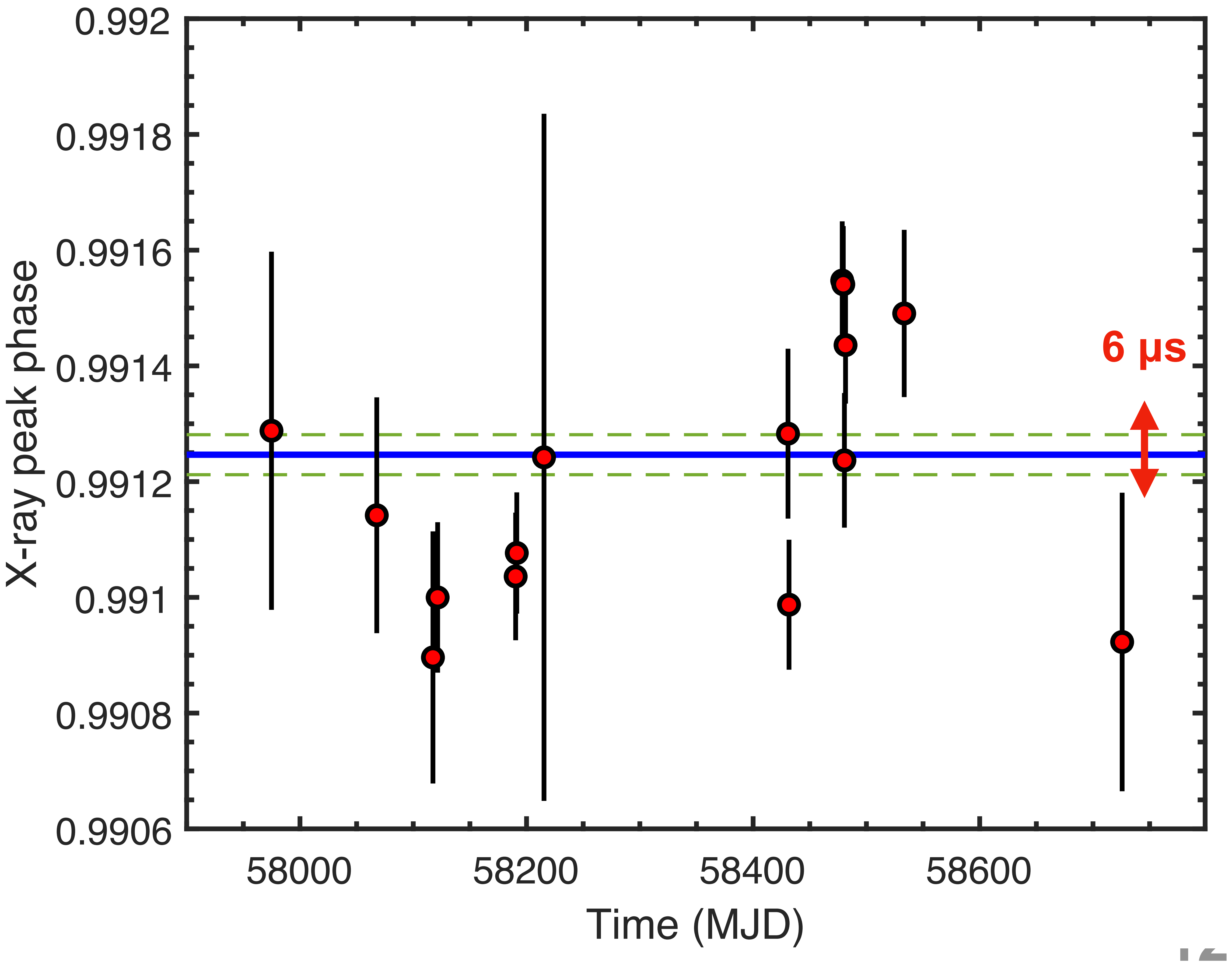
Two Radio Observatories (2 GHz) in Japan

- 34-m radio telescope of the Kashima Space Technology Center (NICT)
- 64-m radio dish of the Usuda Deep Space Center (JAXA)

Long-term monitoring simultaneous in radio and X-rays

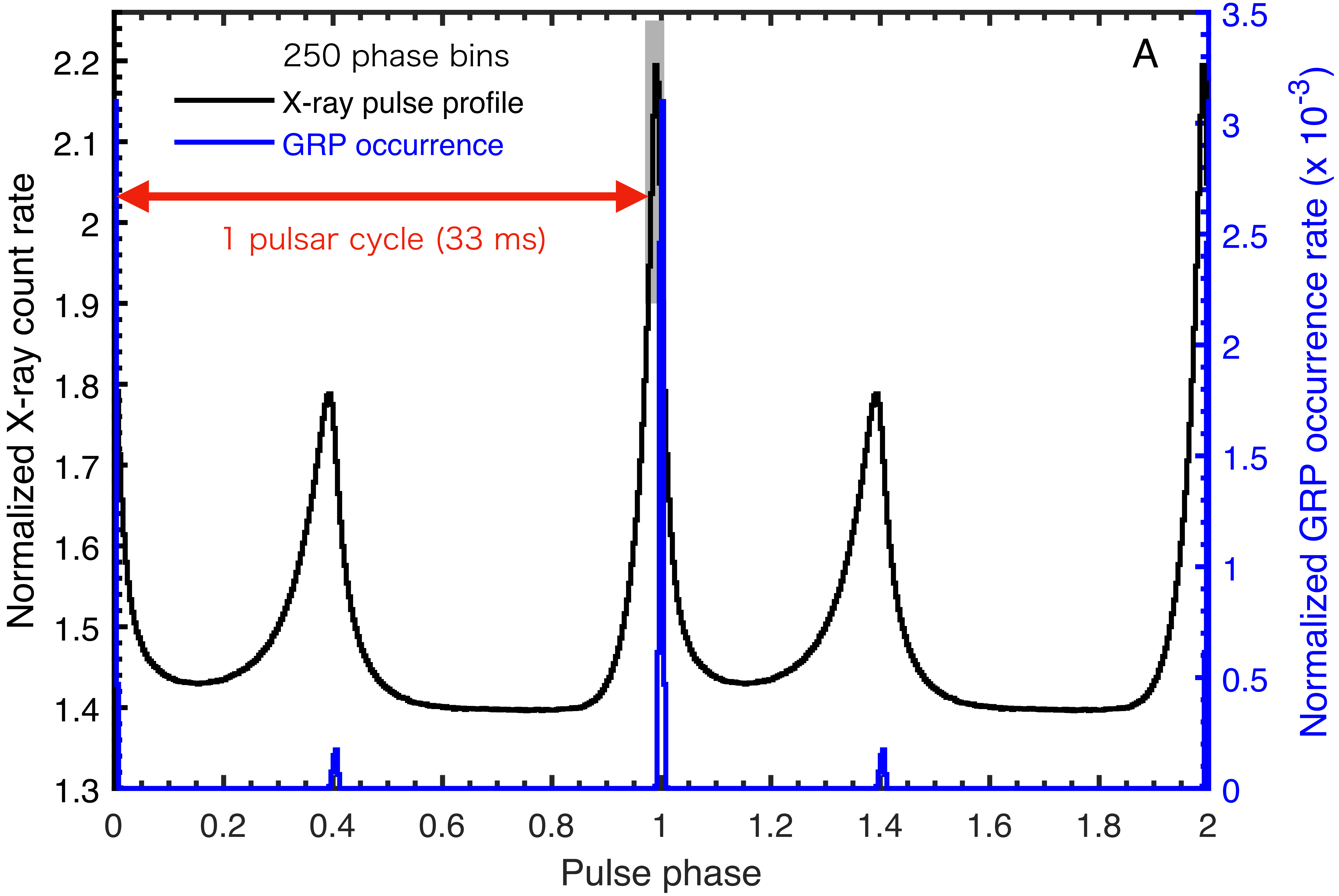
- Coordinated 15 observations with the two radio telescopes in 2017-2019
- The X-ray main pulse peak ϕ=0.99125±0.00004 relative to the radio peak, corresponding to the source-intrinsic 304 us radio delay.





Enoto et al., Science, 2021

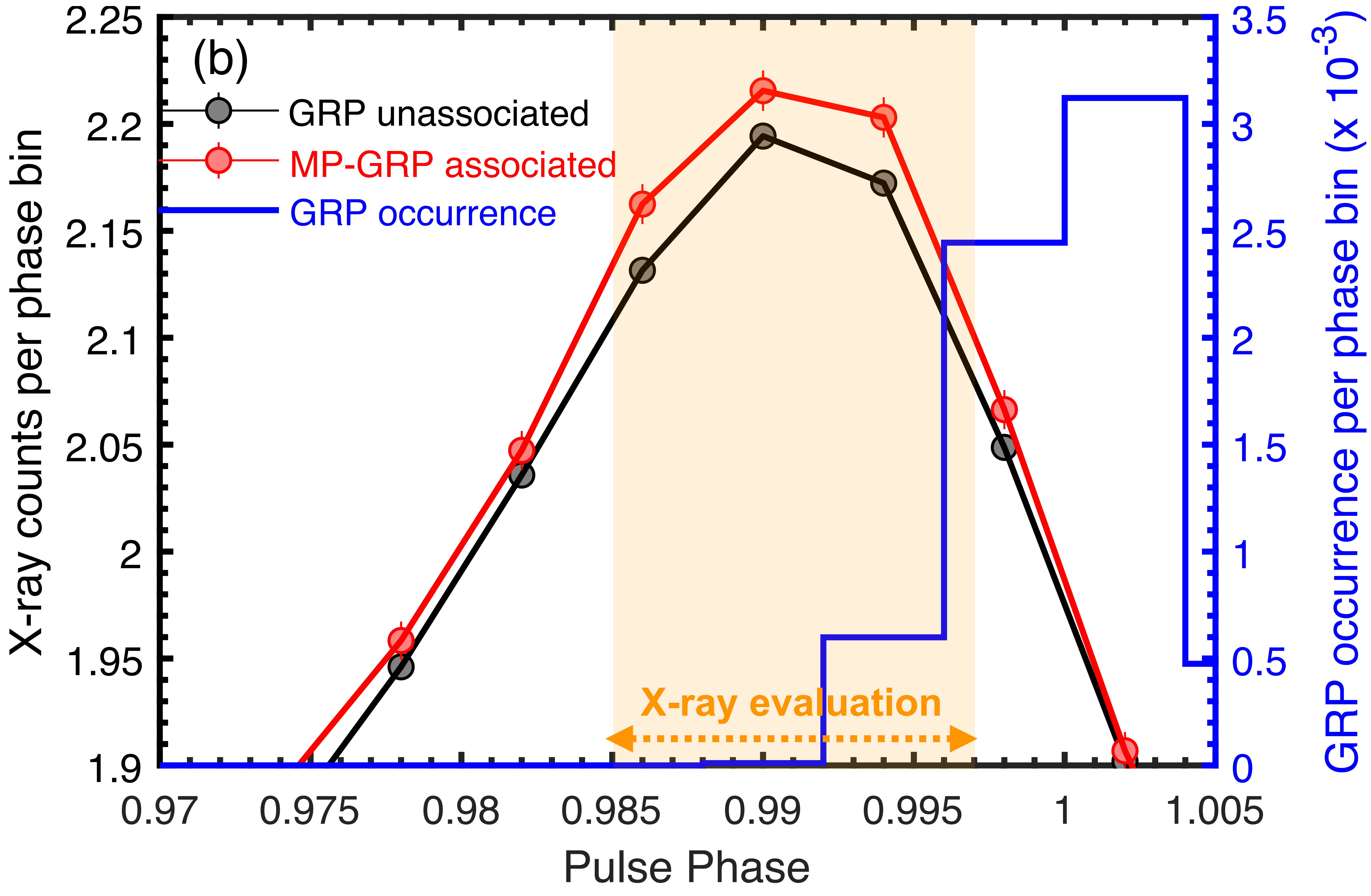
Discovery of X-ray enhancement coinciding with GPs



- Detected ~2.5×10^4 GPs at the main pulse phase with the 1.5-day exposure in total accumulated in 2017-2019.

Enoto et al., Science, 2021

Discovery of X-ray enhancement coinciding with GPs

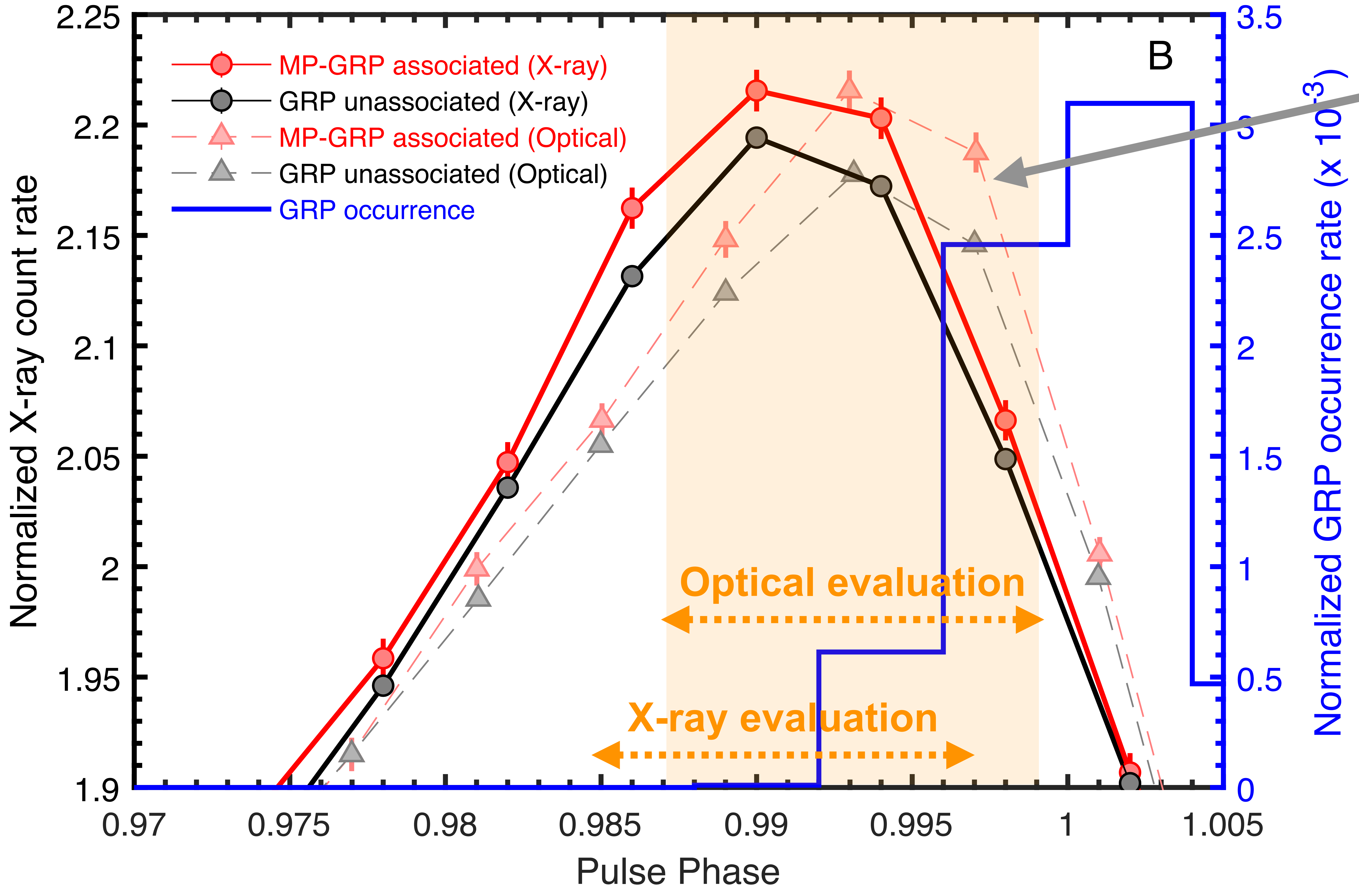


5.4σ Detection

- X-ray enhancement of 3.8±0.7% (1σ error) at the pulse phase ϕ=0.985-0.997.

Enoto et al., Science, 2021

Discovery of X-ray enhancement coinciding with GPs



Optical enhancement
(Strader et al., ApJ 2013)

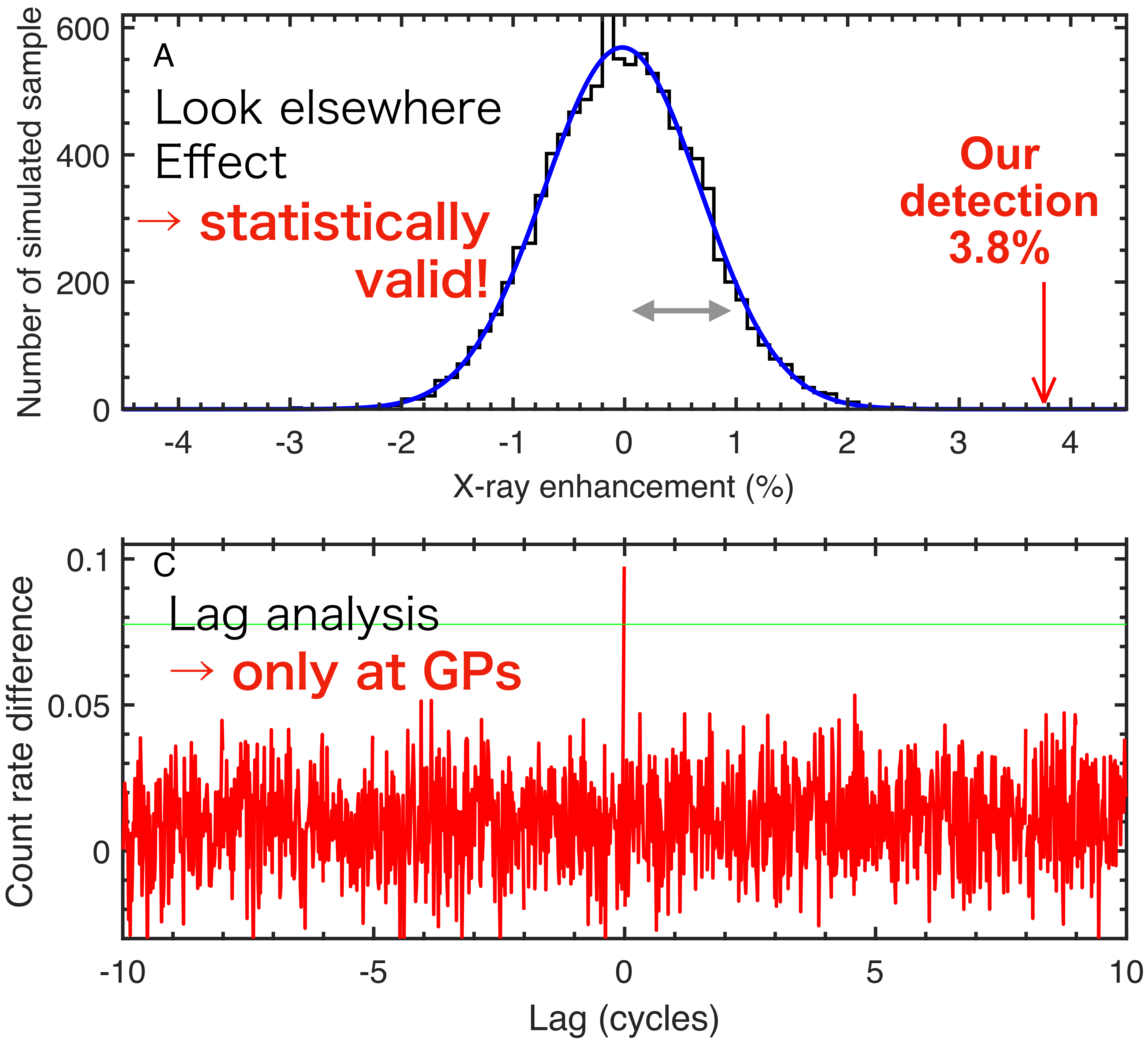
3.2±0.5%
(φ=0.987-0.999)

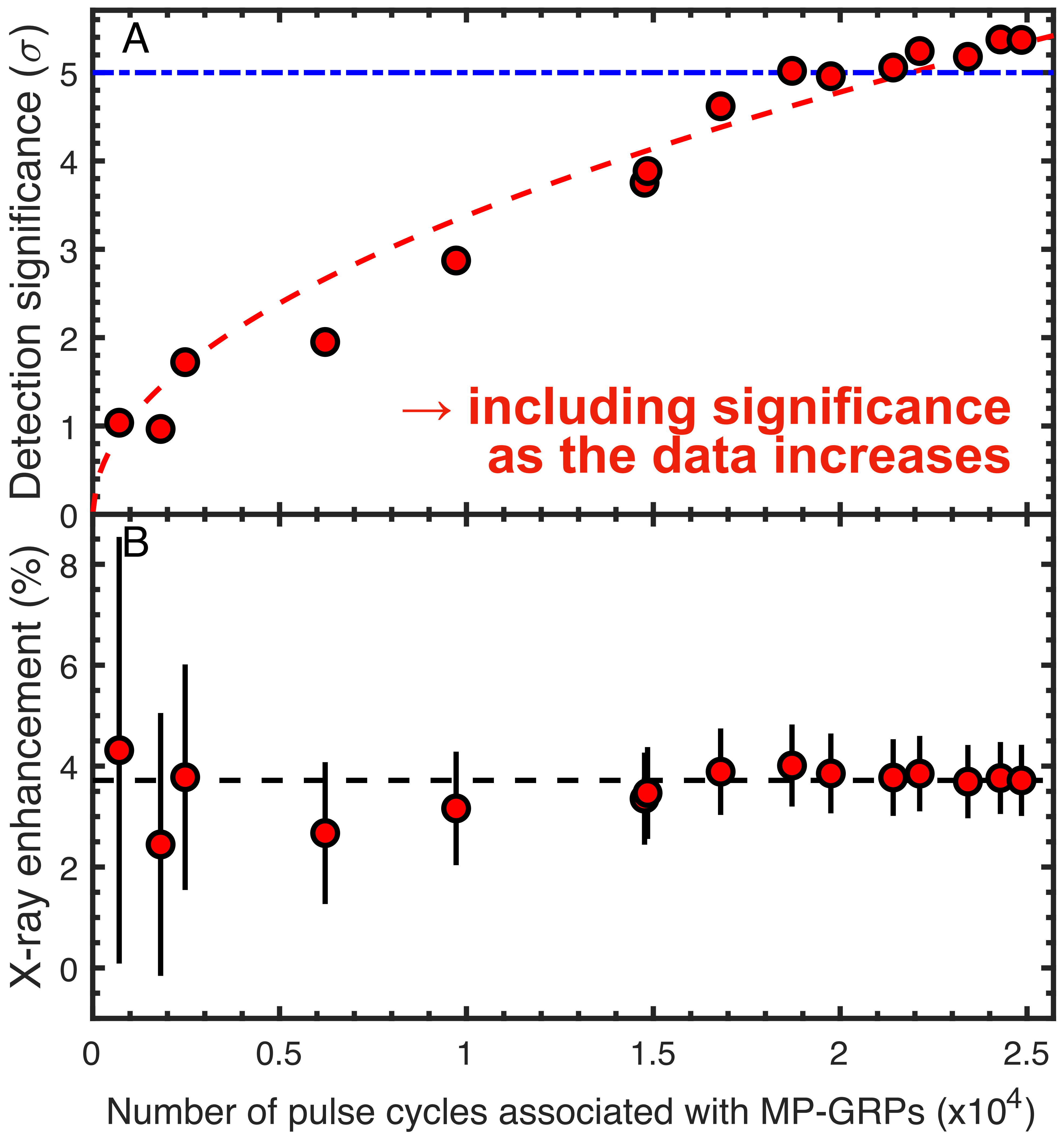
5.4σ Detection

- X-ray enhancement of 3.8±0.7% (1σ error) at the pulse phase φ=0.985-0.997.

Enoto et al., Science, 2021

Verified our X-ray detection





- We confirmed this detection via different verifications.

Enoto et al., Science, 2021

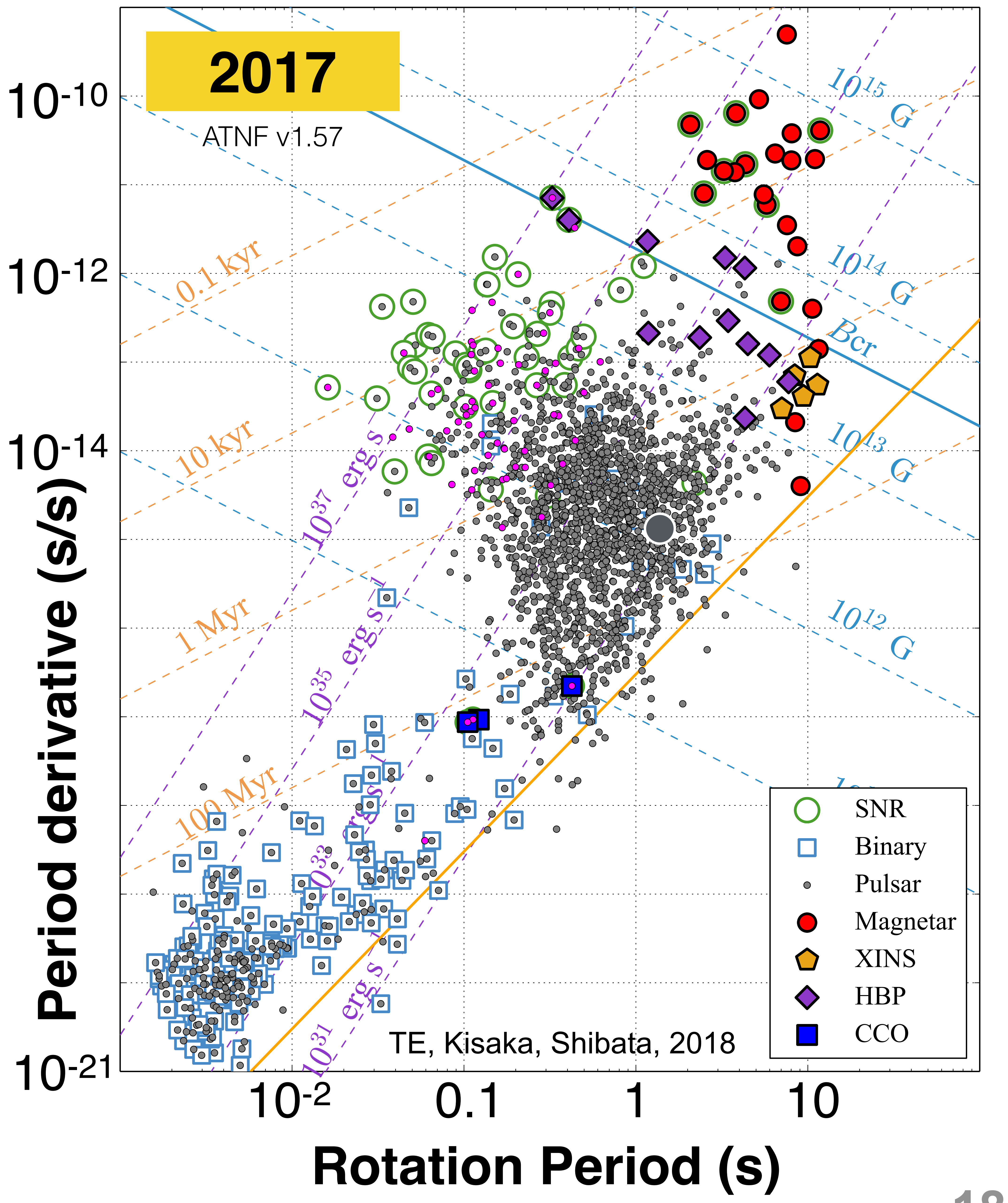
Implication for the mystery of FRBs

- Hypothetical bright GP is a candidate for the origin of FRBs, especially repeating FRB sources (e.g., repeating FRB 121102).
- The energy source of such FRBs is assumed to be the spin-down luminosity.
- The discovery of X-ray enhancement suggests:
    - Since bolometric luminosity of GPs, including X-rays, is revealed to be $10^{2\text{-}3}$ times higher than we previously thought, the simple GP model for FRBs became more difficult because pulsars quickly lose its rotational energy.
    - Another example of the connection between the coherent radio emission and incoherent X-ray radiation in the neutron star magnetosphere.

See the supplementary part of Enoto et al., Science 2021
Kashiyama & Murase, 2017; Kisaka, Enoto, Shibata 2017

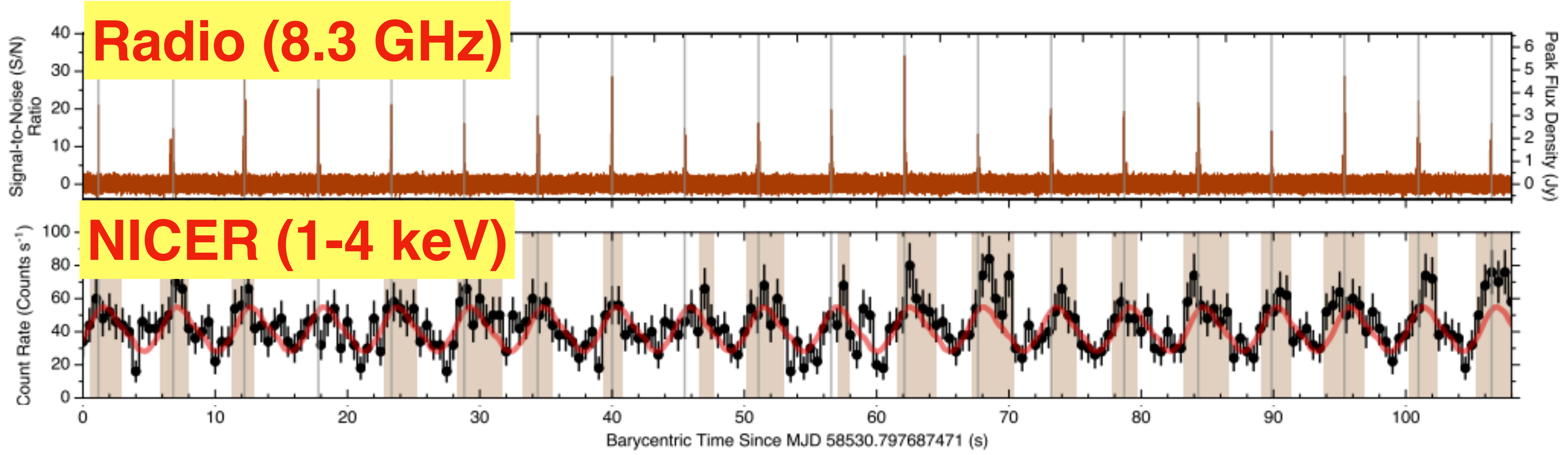
Magnetars seen with NICER

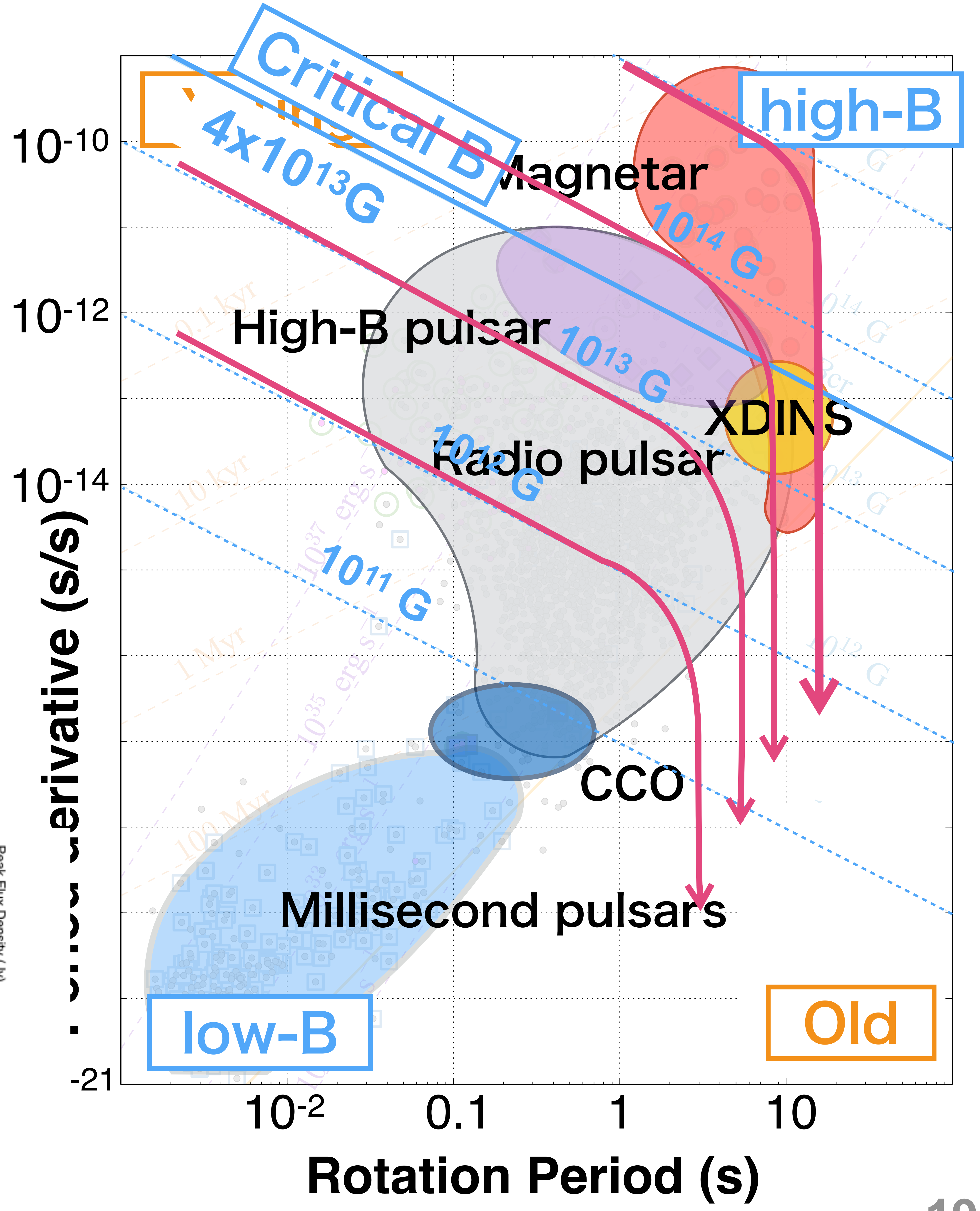
- >2,500 known pulsars (10^5 in our Galaxy?)
  - Challenge to unification of different neutron star classes
- NICER Magnetar and Magnetosphere (M&M) subgroup is focusing on highly magnetized sources.
  - Collaborating with radio telescopes



Magnetars seen with NICER

- >2,500 known pulsars (10^5 in our Galaxy?)
  - Challenge to unification of different neutron star classes
- NICER Magnetar and Magnetosphere (M&M) subgroup is focusing on highly magnetized sources.
  - Collaborating with radio telescopes





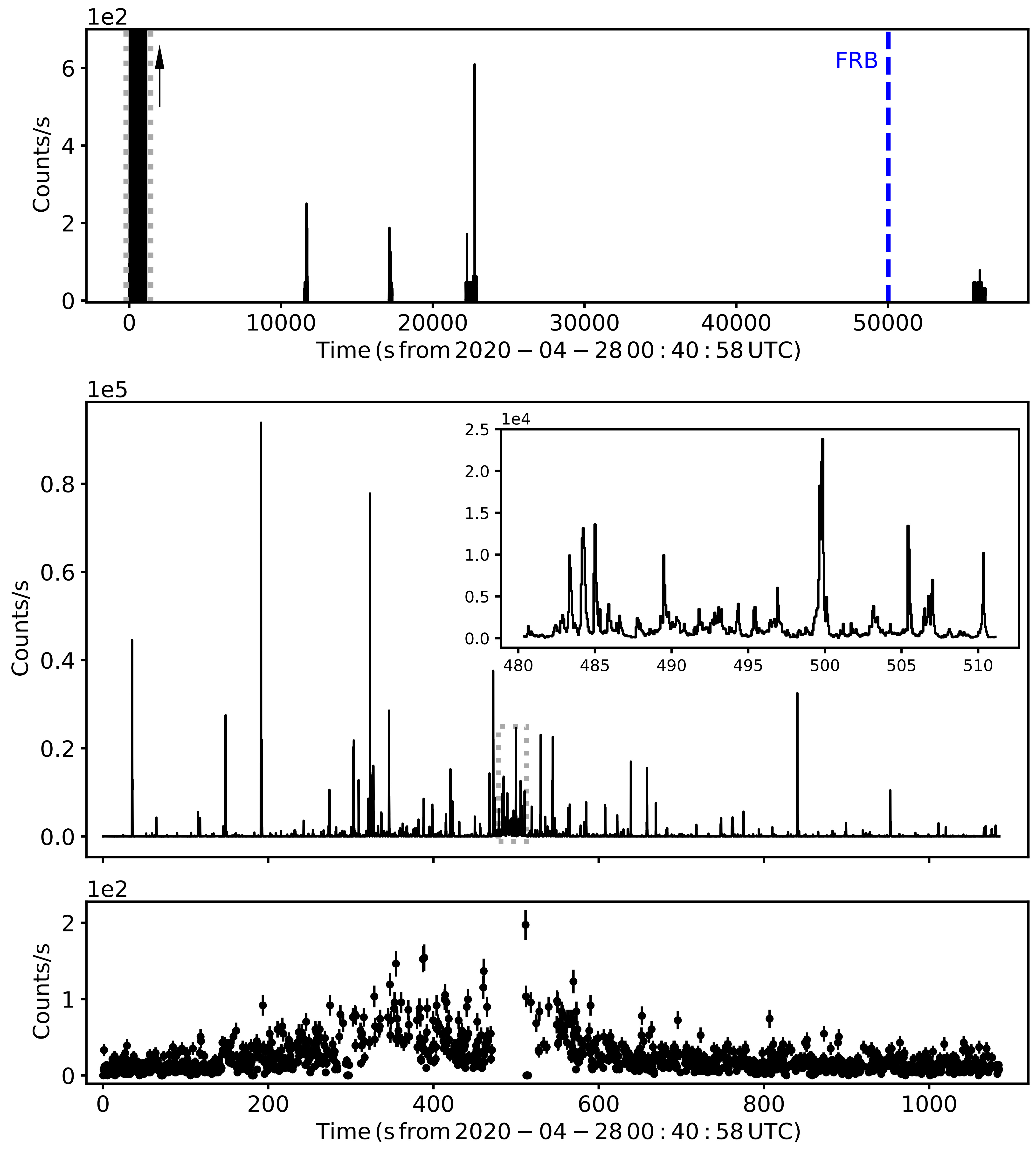
Pearlman et al., 2020, arXiv:2005.08410

NICER Follow-ups of Magnetar Outbursts

- Since the launch in 2017, one transient magnetar campaign per year on average.

Year	Source	Note	Reference
2017 July	**4U 0142+61**	Re-brightening in 2017 Pulse morphology change	
2019 February	**XTE J1810-197**	Re-brightening in 2019 Radio-loud magnetar	Guver et al., 2019 Borgdese et al., 2021
2020 March	**Swift J1818.0-1607**	New magnetar Radio-loud magnetar	Hu et al., 2020, Rajwade et al., 2022
2020 April	**SGR 1935+2154**	Galactic FRB event Burst storm events	Younes et al., 2017, 2021, and many
2020 October	**SGR 1830-0645**	New magnetar Pulse peak migration	Younes et al., 2022a,b Coti Zelati et al. 2021
2021 June	**Swift J1555.2-5402**	New magnetar Long lasting outburst	Enoto et al., 2021

SGR 1935+2154 — Magnetar and FRB connection

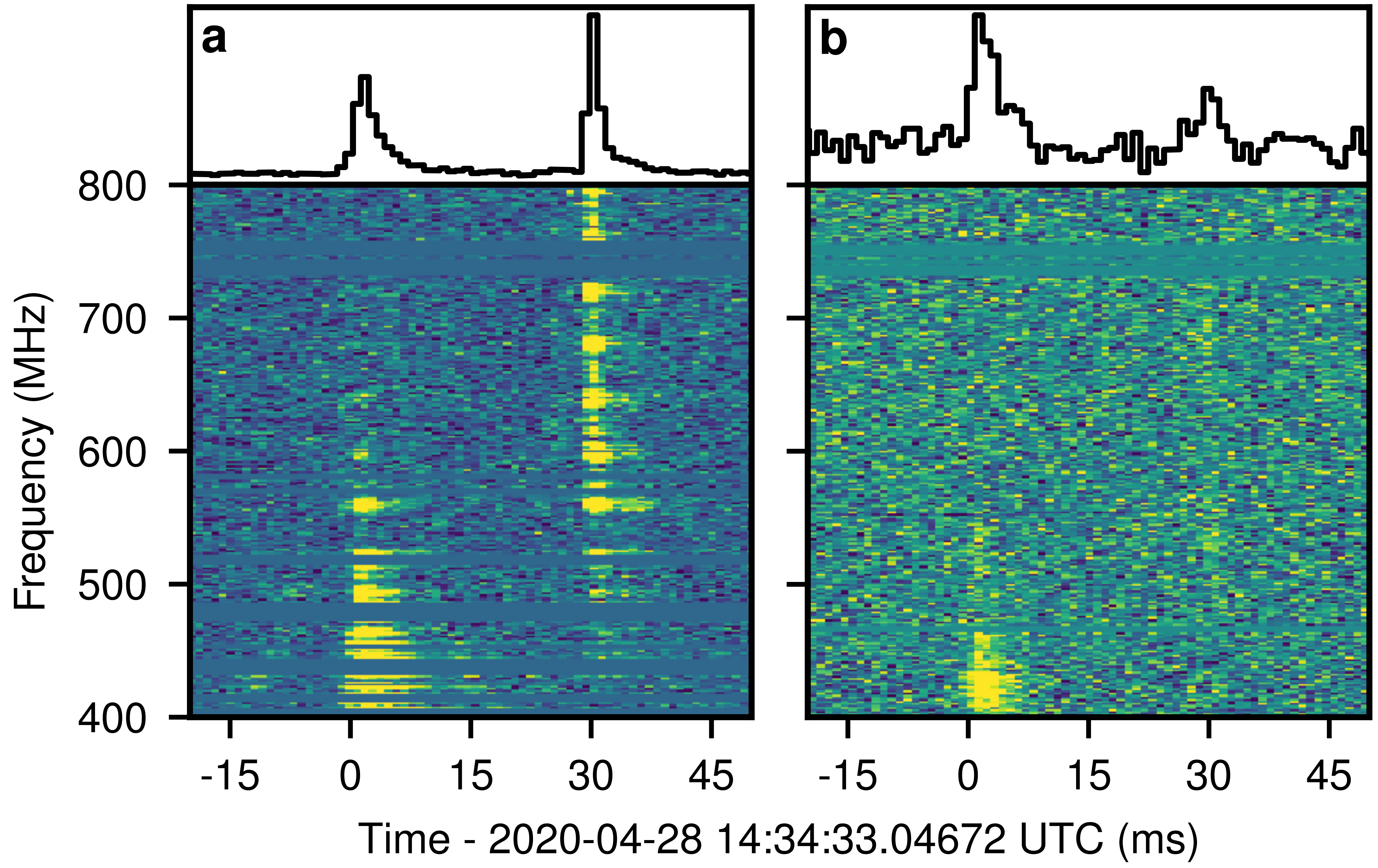


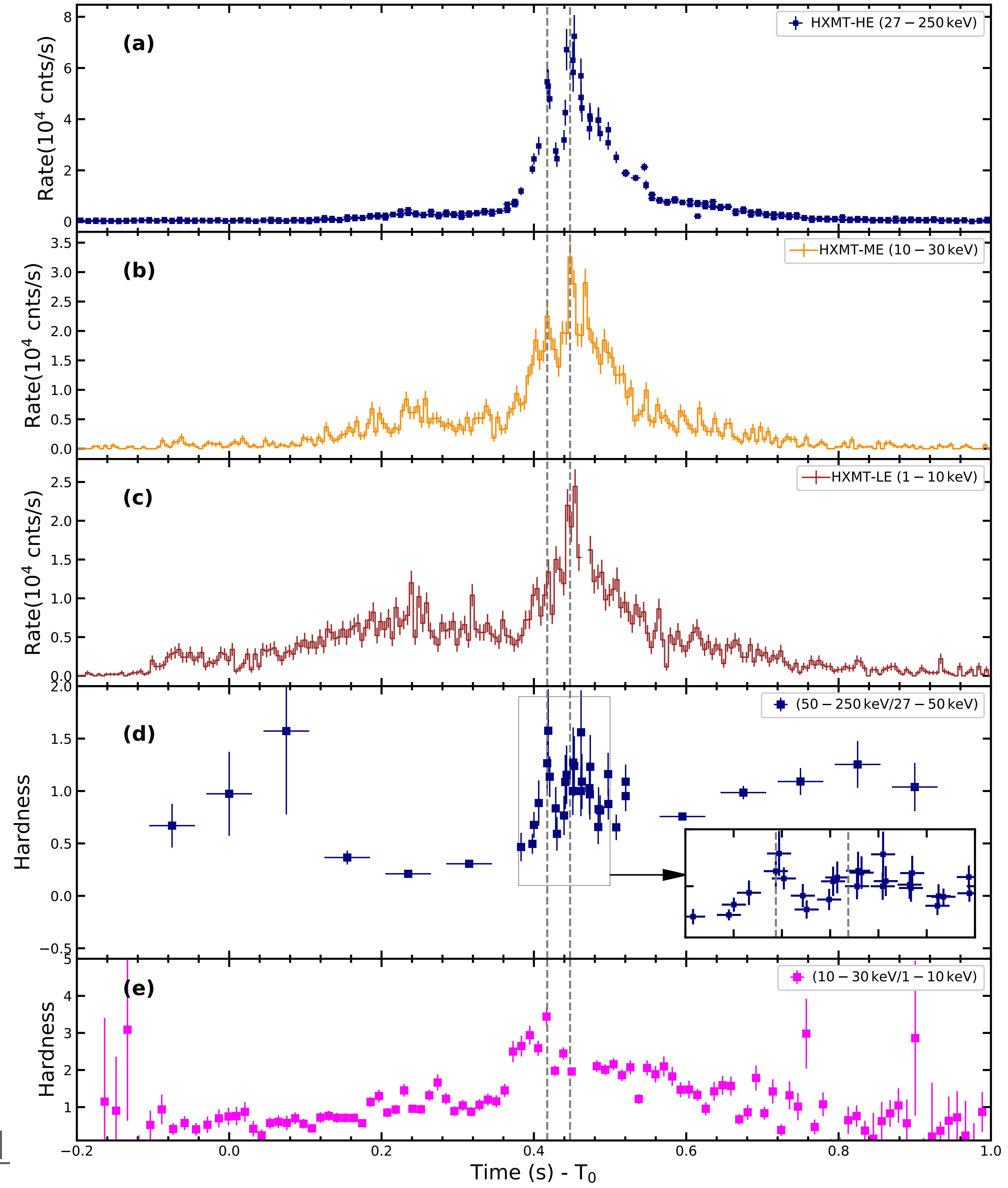
- Galactic magnetar SGR 1935+2154
  - discovered in 2014 (~9 kpc?)
  - P=3.24 s, Pdot=1.43e-11 s/s
  - B ~ 2.2e+14 G
- A burst was detected with Swift/BAT at 18:26 on April 27, 2020.
- X-ray follow-up observations by several X-ray satellite, including NICER (on source 6 hours later on April 28, 00:40).
- Intense bursting activity for at least 7 hours (burst storm): 217+ bursts in 20 minus

Younes et al., arXiv:2009.07886

FRB detected from SGR 1935+2154

- Two-peak FRB coincided with a magnetar X-ray burst (Insight-HMXT, INTEGRAL, AGILE, and Konus-Wind)

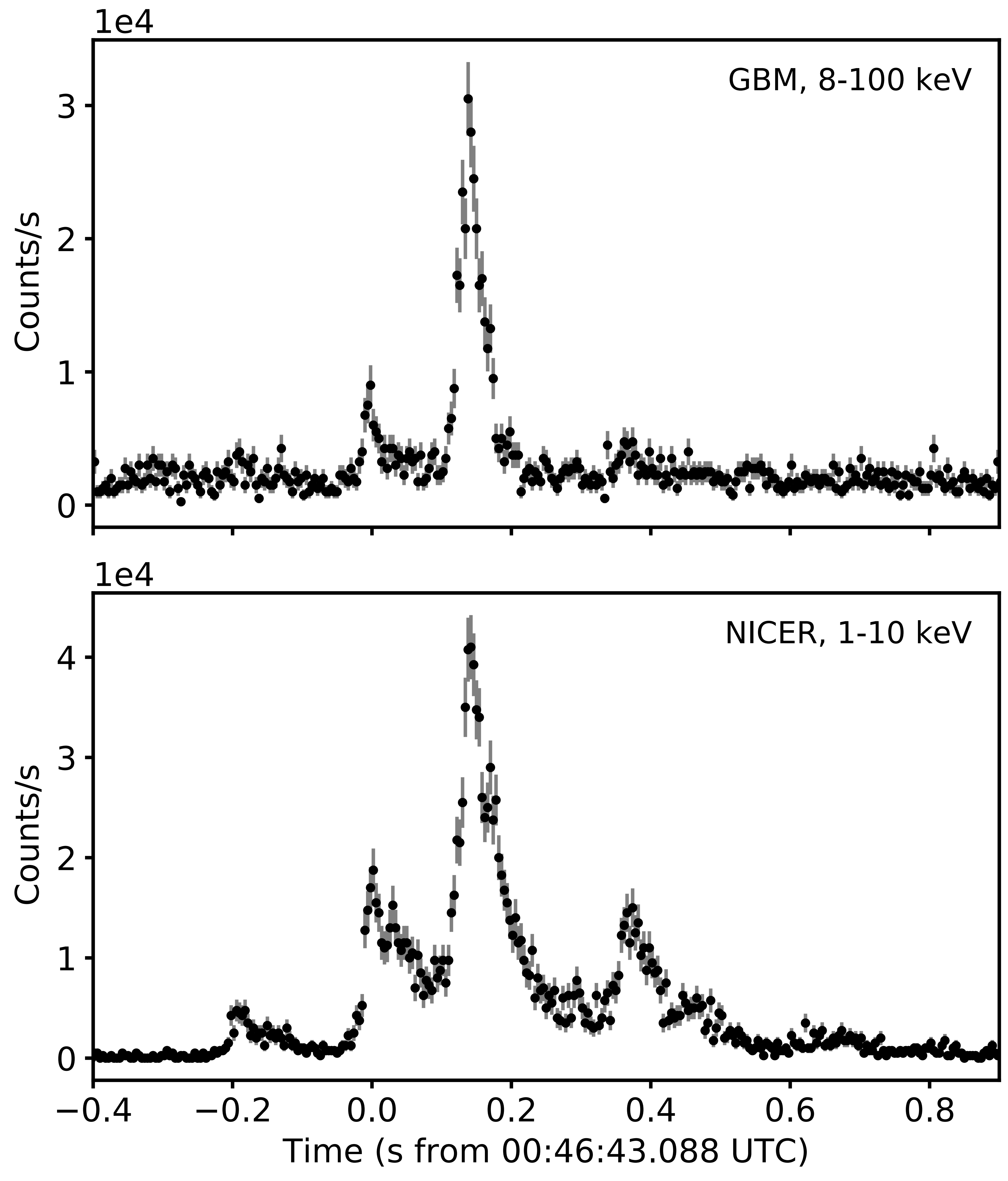


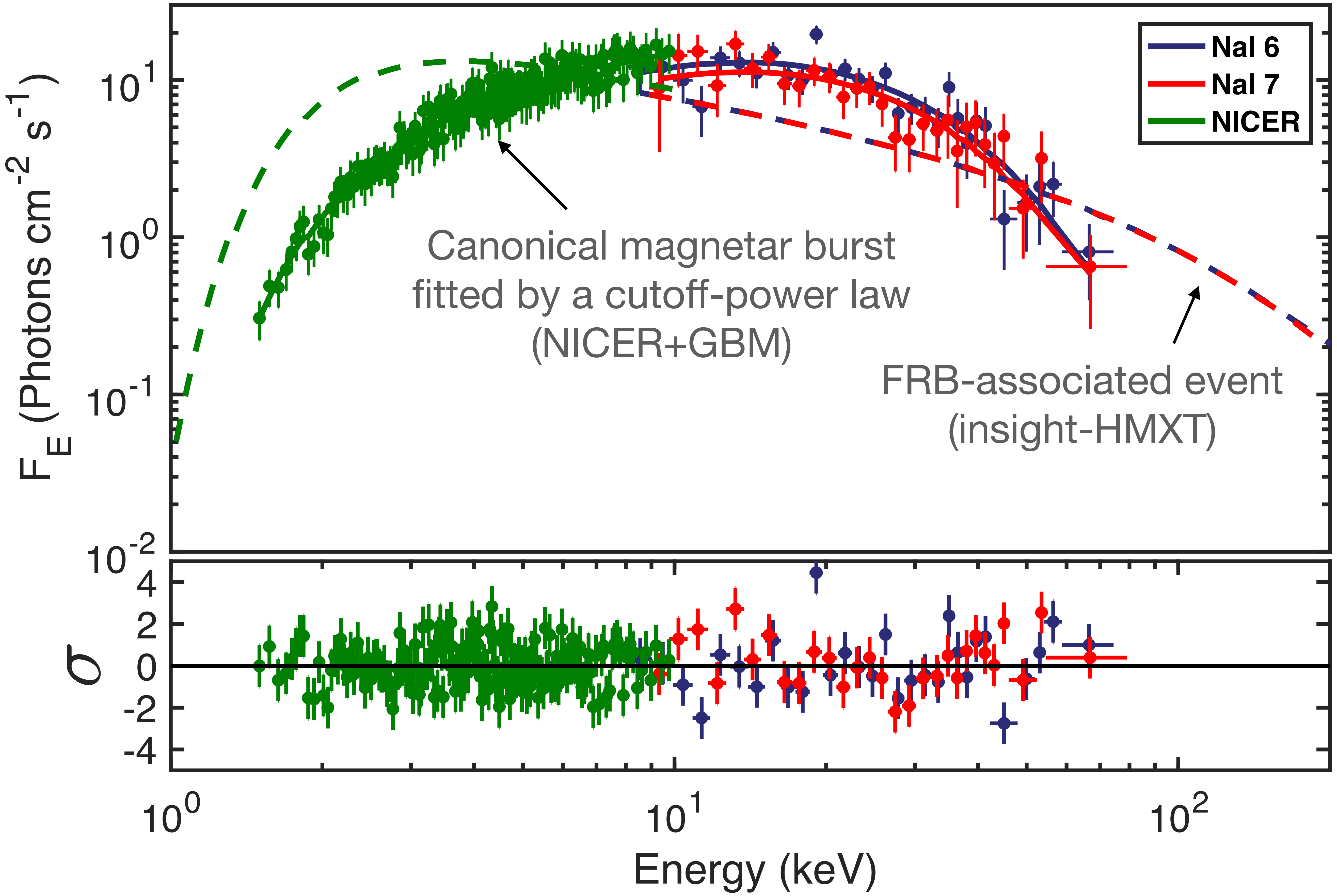


The CHIME/FRB Collaboration, arXiv:2005.10324

Li et al., arXiv 2005.11071

FRB-associated burst vs. Other magnetar bursts

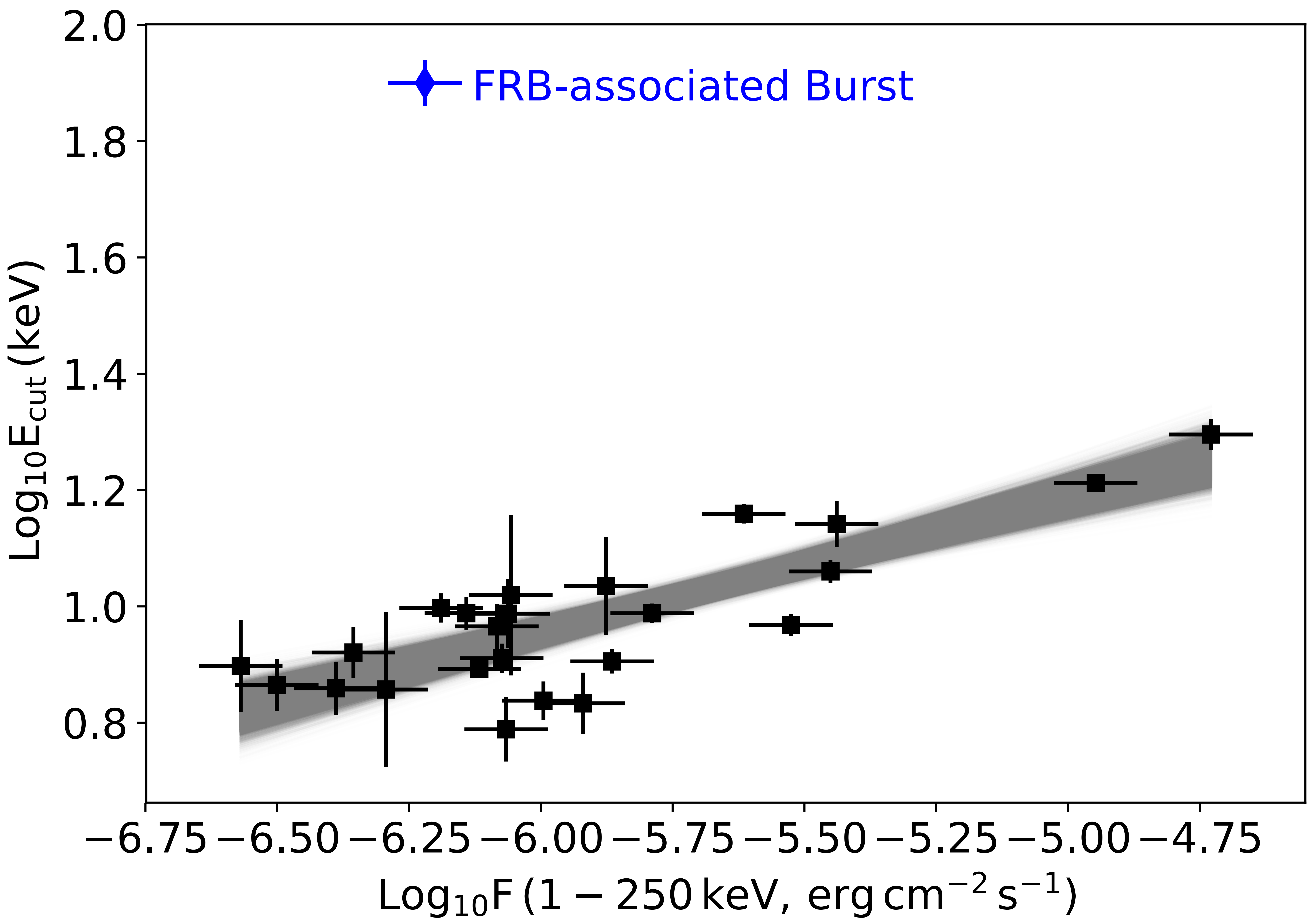




- Example of a magnetar short burst from SGR 1935+2154 observed with NICER+GBM compared with the FRB-associated event.

Younes et al.., arXiv: 200611358

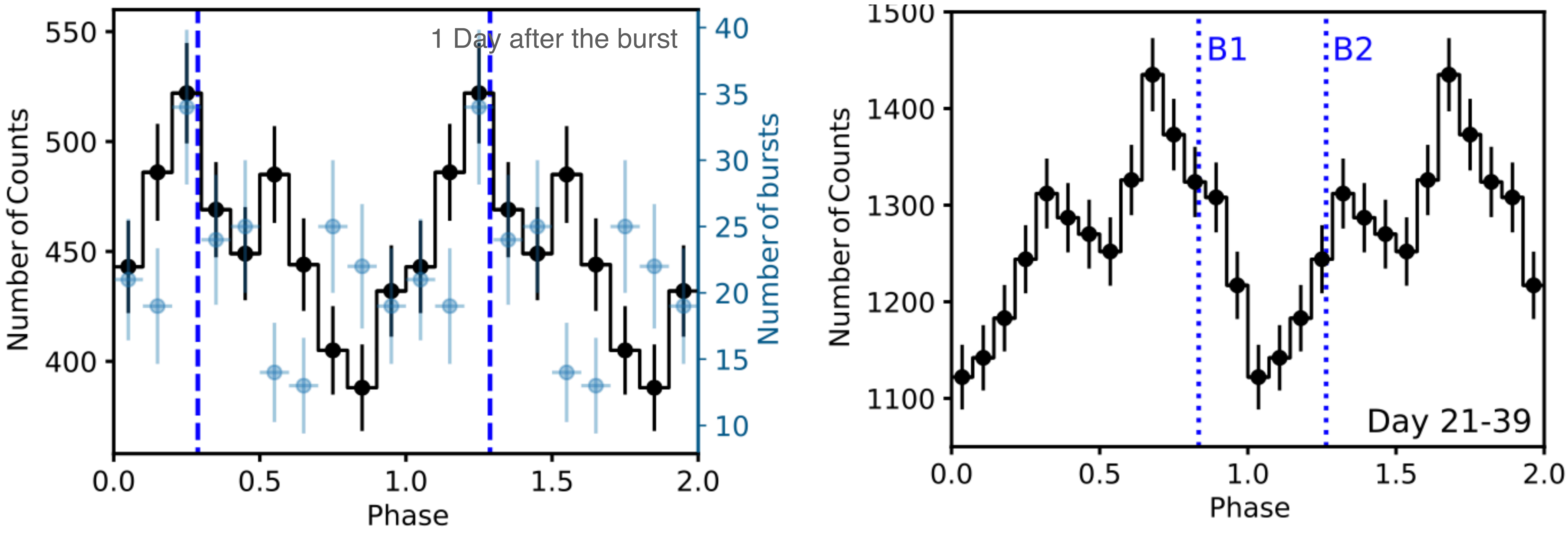
X-ray burst spectrum: FRB-associated vs. others



- Cutoff energy vs. X-ray flux in 1-250 keV.
- Brighter magnetar short burst shows higher cutoff energy.
- X-ray flux of the FRB-associated burst is in the distribution of the other (canonical) magnetar bursts.
- However, the cutoff energy of the FRB-associated one is higher than the others.

Younes et al.., arXiv: 200611358

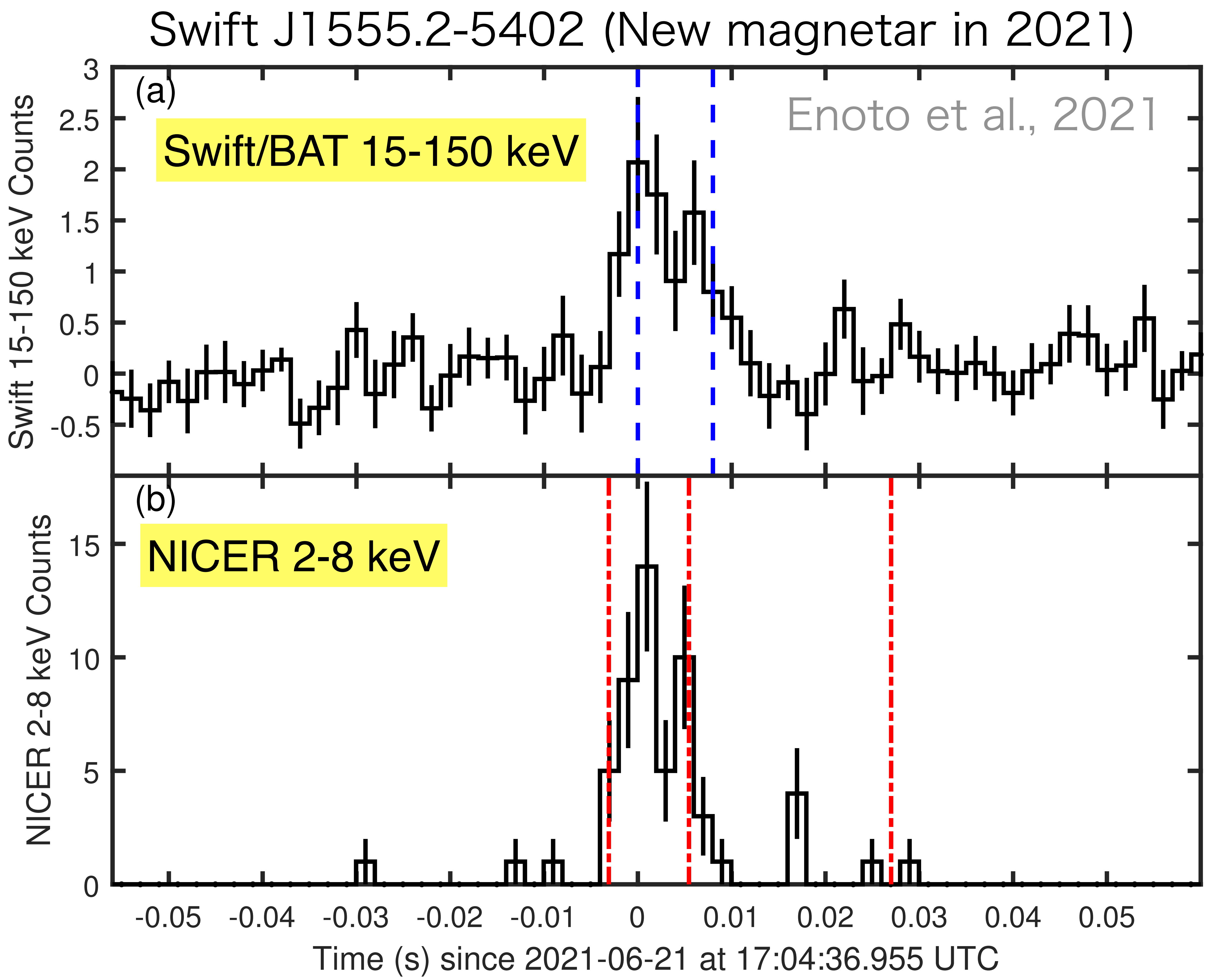
At which pulse phase the FRB event happened?

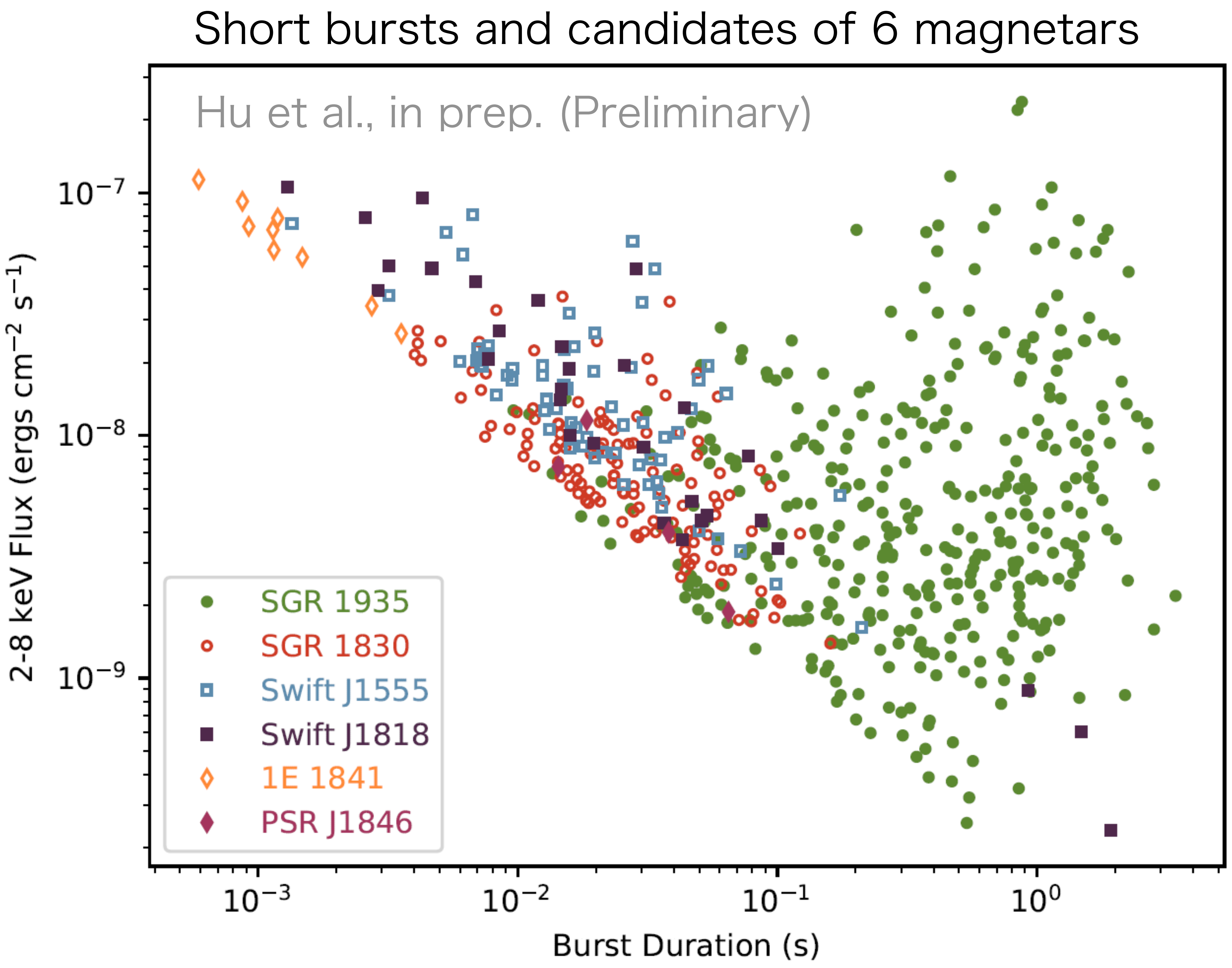


- Pulse profile of SGR 1935+2154 at 1 day and 21-39 days after the burst
- Folded burst peak time (light blue) does not show a clear pulse profile.
- The pulse phase of the FRB event happened at the peak of the pulse profile.

Younes et al., arXiv:2009.07886

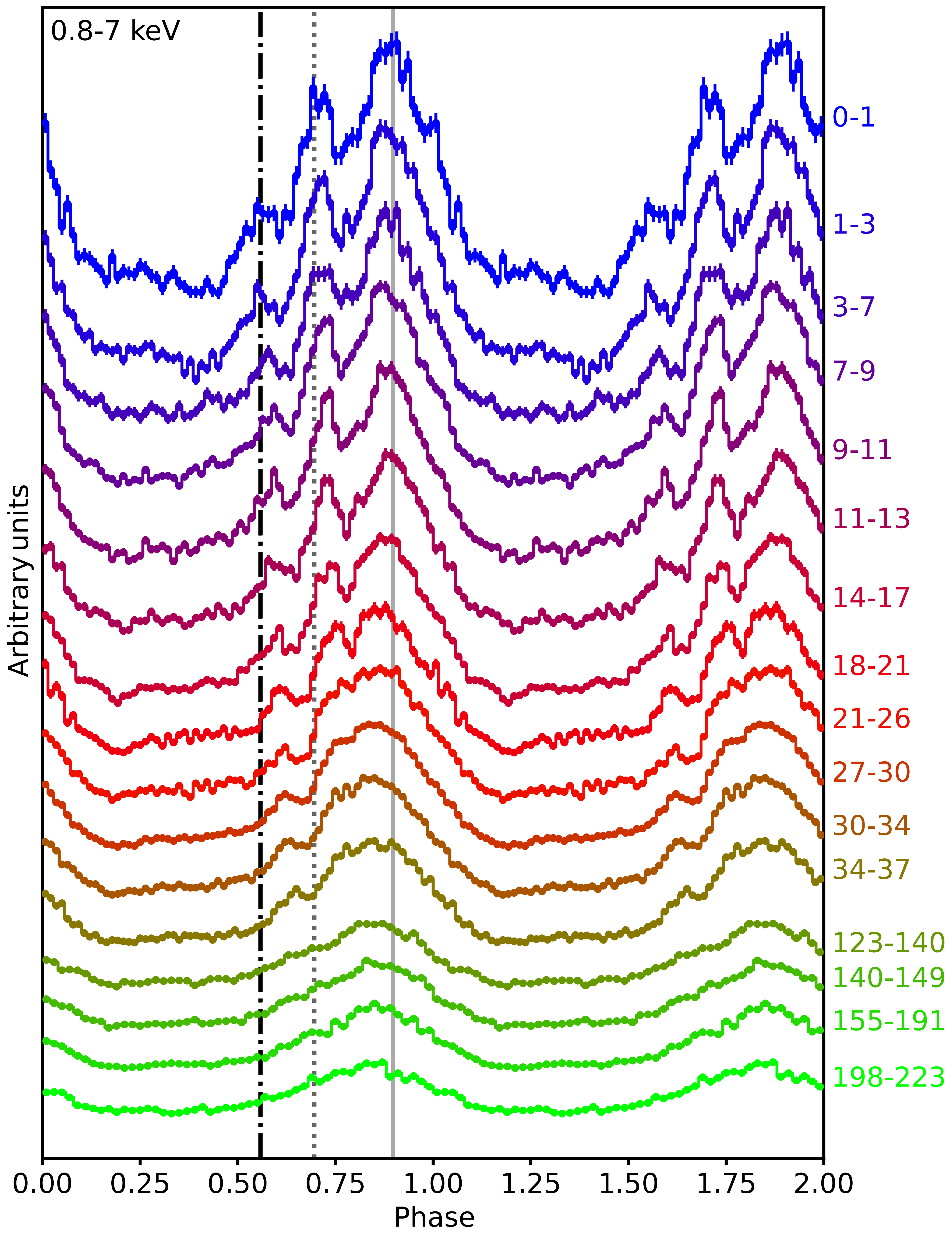
Comprehensive Studies of Magnetar Short Bursts



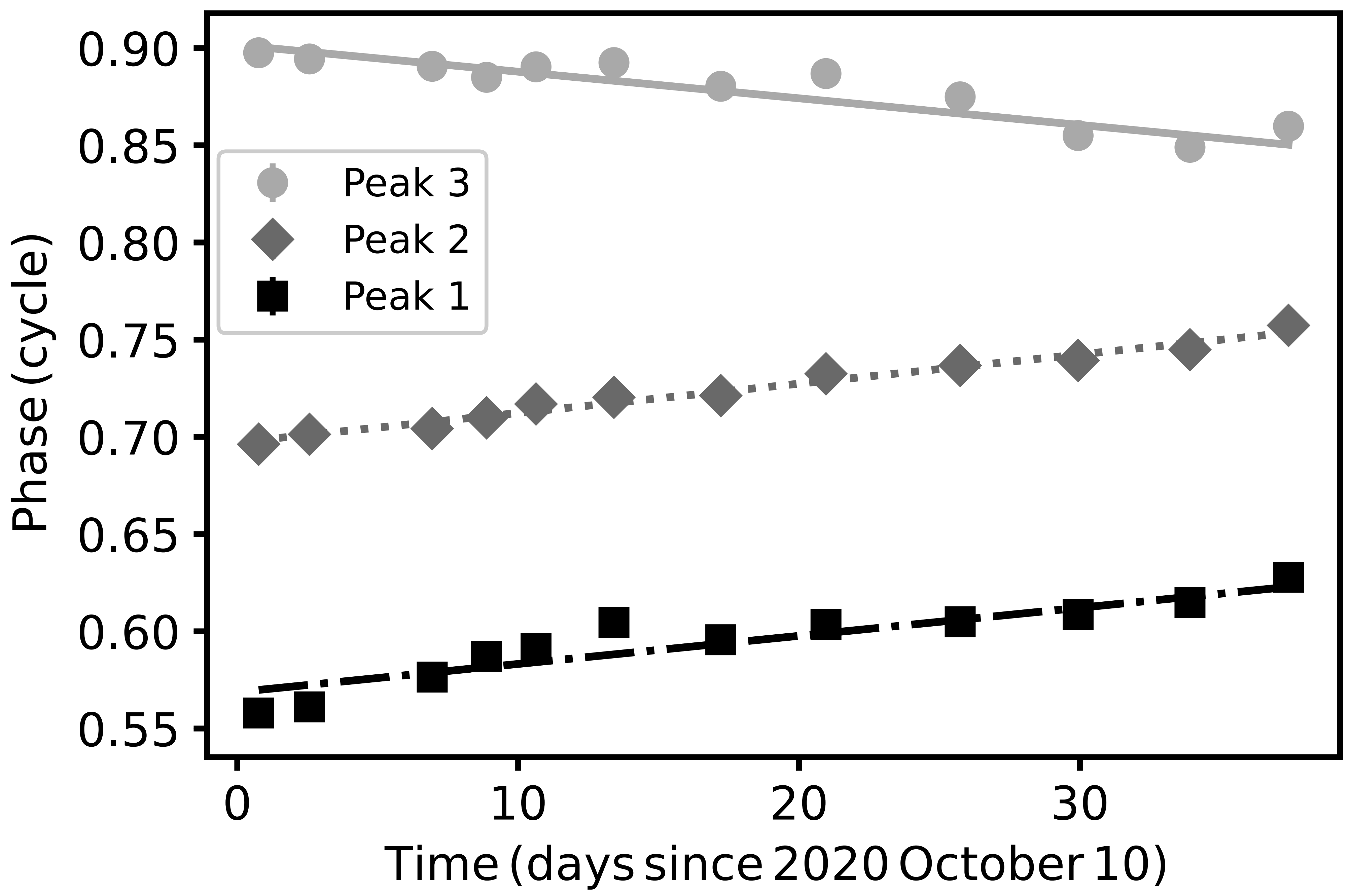


- NICER's large effective area is ideal to search for weak short bursts
- M&M team is working for comprehensive studies of magnetar short bursts.

SGR 1830-0645 — Pulse Peak Migration

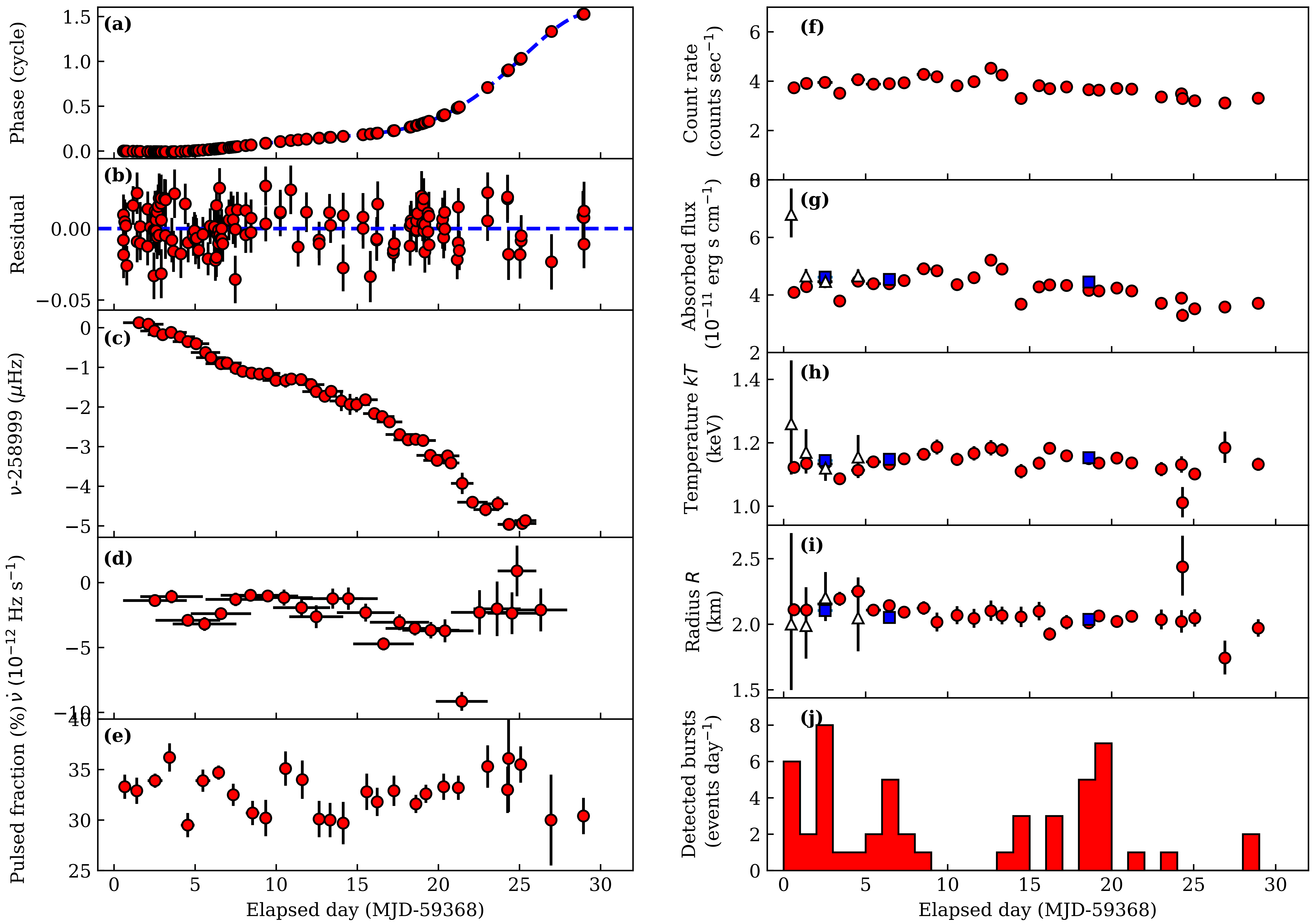


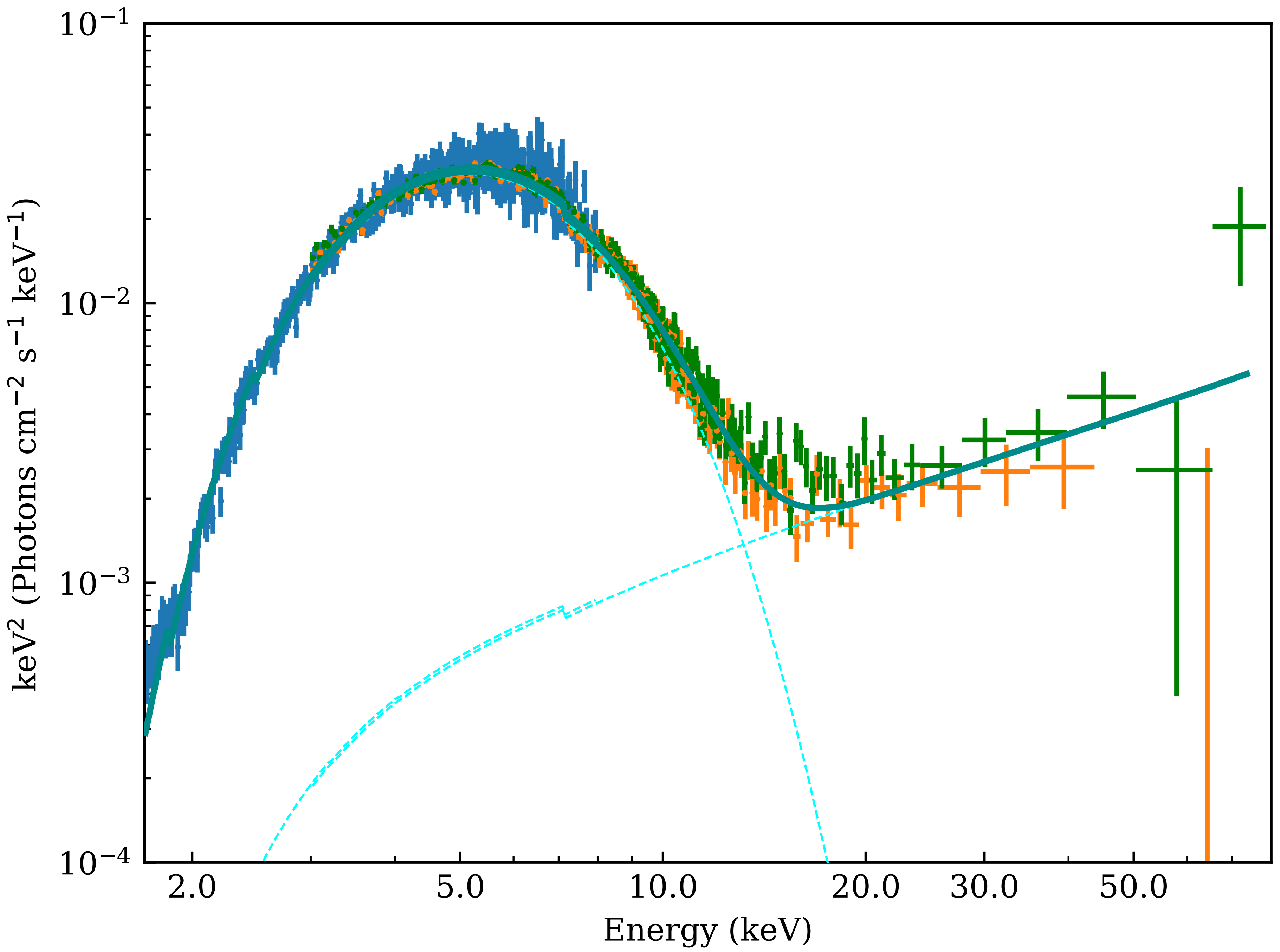
- Near-daily NICER observation during the first 37 days of an outburst suggested pulse peak migration in phase.
- Tectonic motion of the crust? Inferred speed of the crustal motion is <100 m/day.
- Hot spot of particle bombardment from a twisted magnetosphere — untwist and dissipate on 30-40 day timescale?

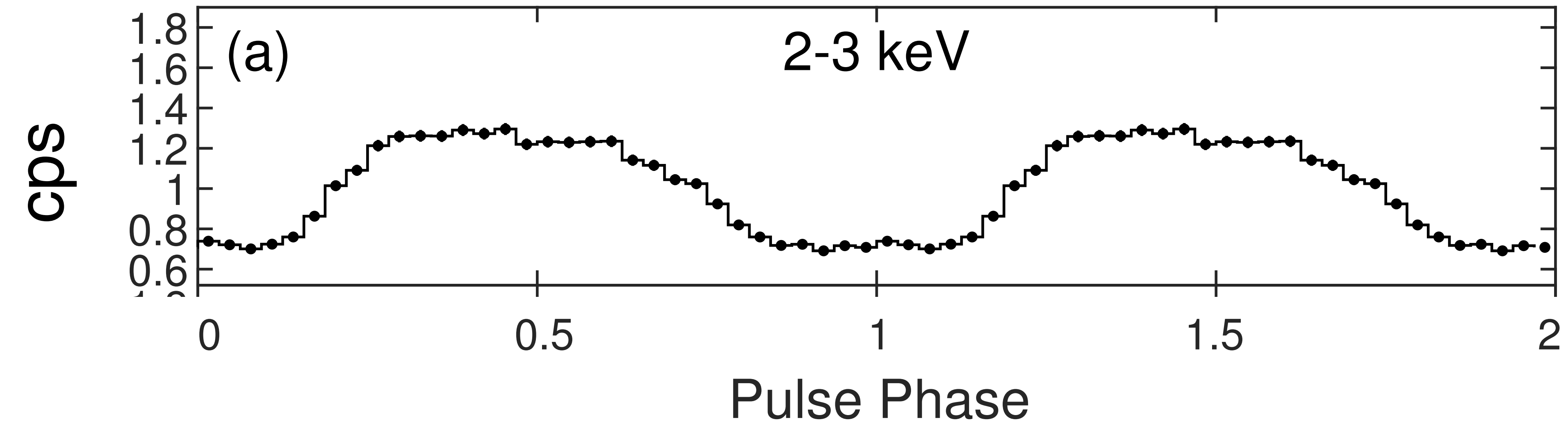


Younes et al., ApJL 2022

Swift J1555.2-5402 — New magnetar in 2021



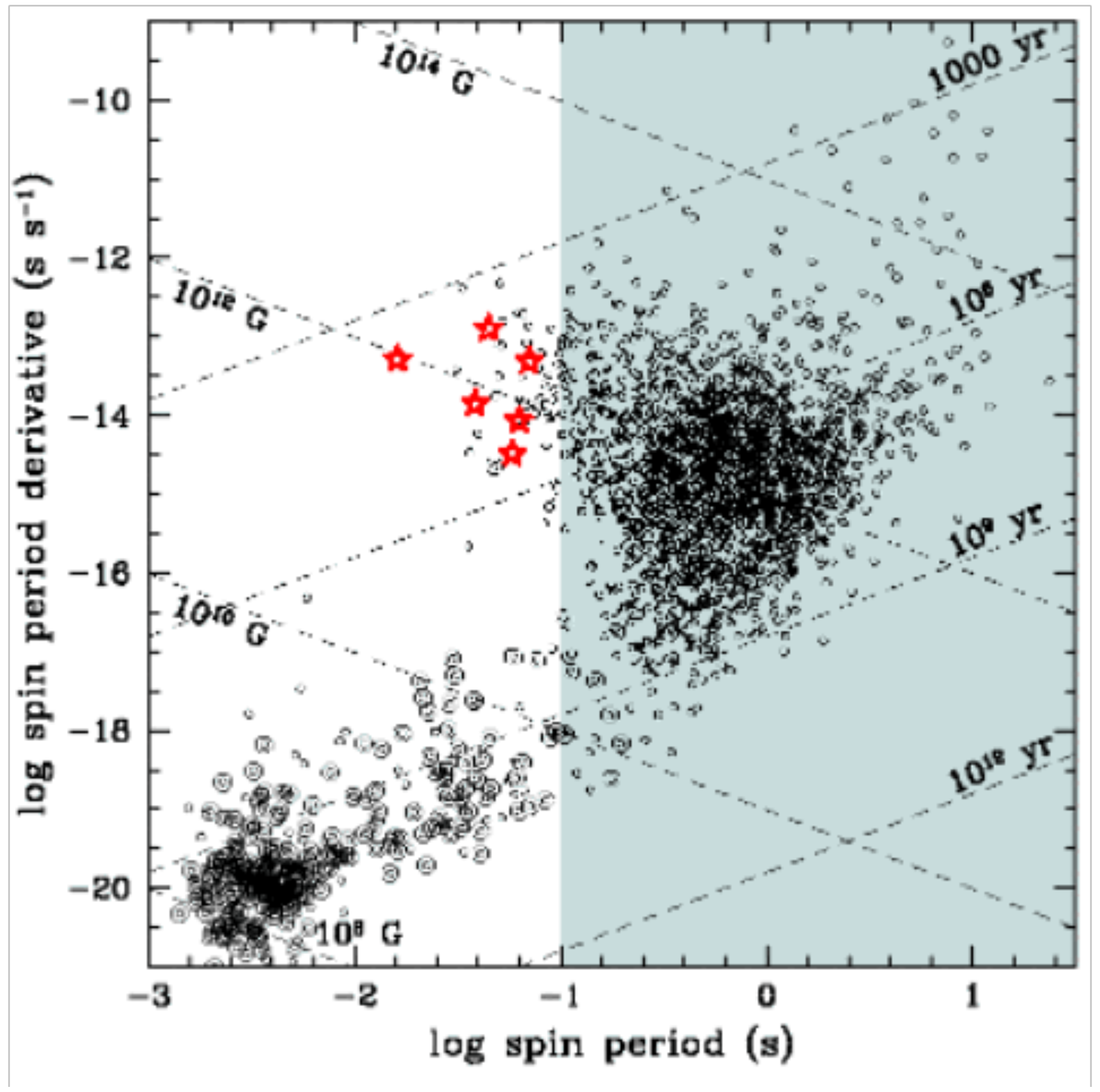


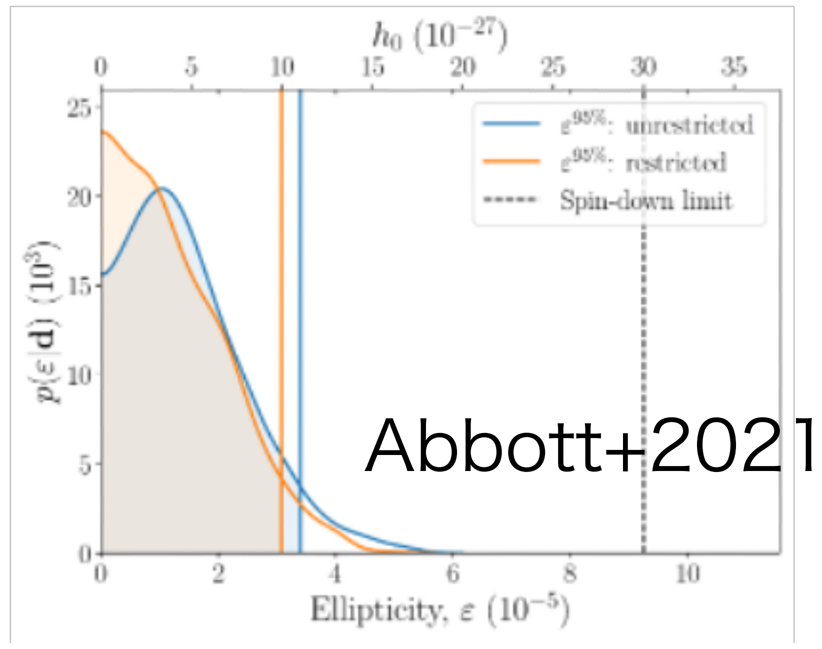


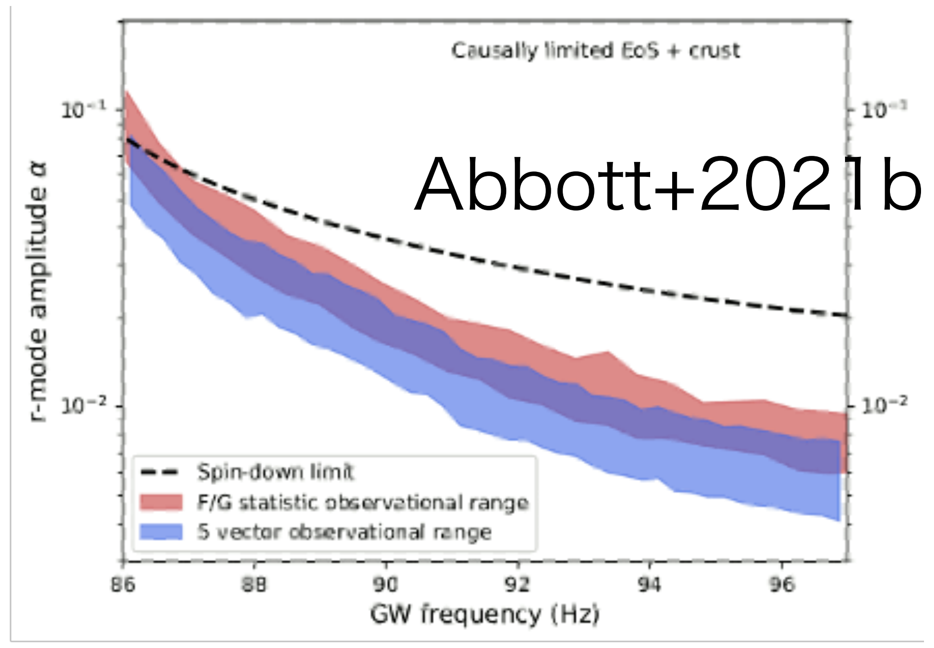
- Burst detected with Swift/BAT on 2021 June 3, followed by NICER 1.6 hours after the burst.
- Long lasting persistent X-ray flux (4e-11 erg/s/cm2 in the 2-10 keV)

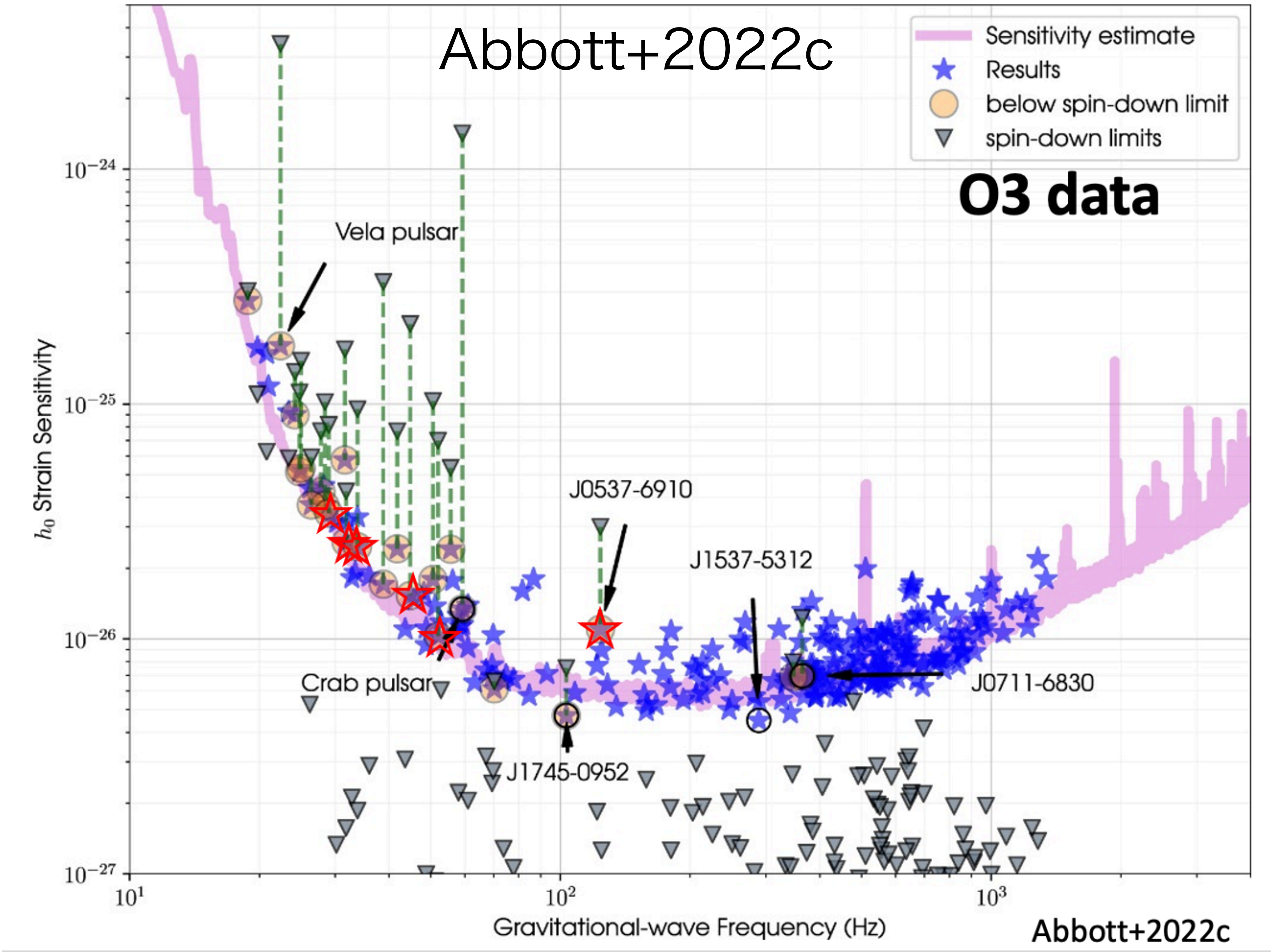
Searching for Gravitational Waves (GW) from Pulsars

- LIGO/Virgo/KAGRA sensitive at $\nu_{gw} > 20$ Hz
  - ~500 pulsars with $\nu_{spin} > 10$ Hz
  - Most sensitive GW searches use simultaneous EM timing observations (tracking of pulsar spin)
- GW searches of O3 data (2019–20)
  - using NICER timing of
    - young magnetic pulsars (Abbott+2021a,b; 2022b,c)
    - pulsar glitches (Abbott+2022b)
    - accreting millisecond pulsars (Abbott+2022a)
  - **6 of 24 below "spin-down limit" are due to NICER timing**
  - constraints on neutron star mountains and oscillations
- **Multi-messenger future with GWs and NICER**
  - O4 to take place 2023 Mar to 2024 Feb
  - NICER pulsar timing project approved thru 2024 Feb



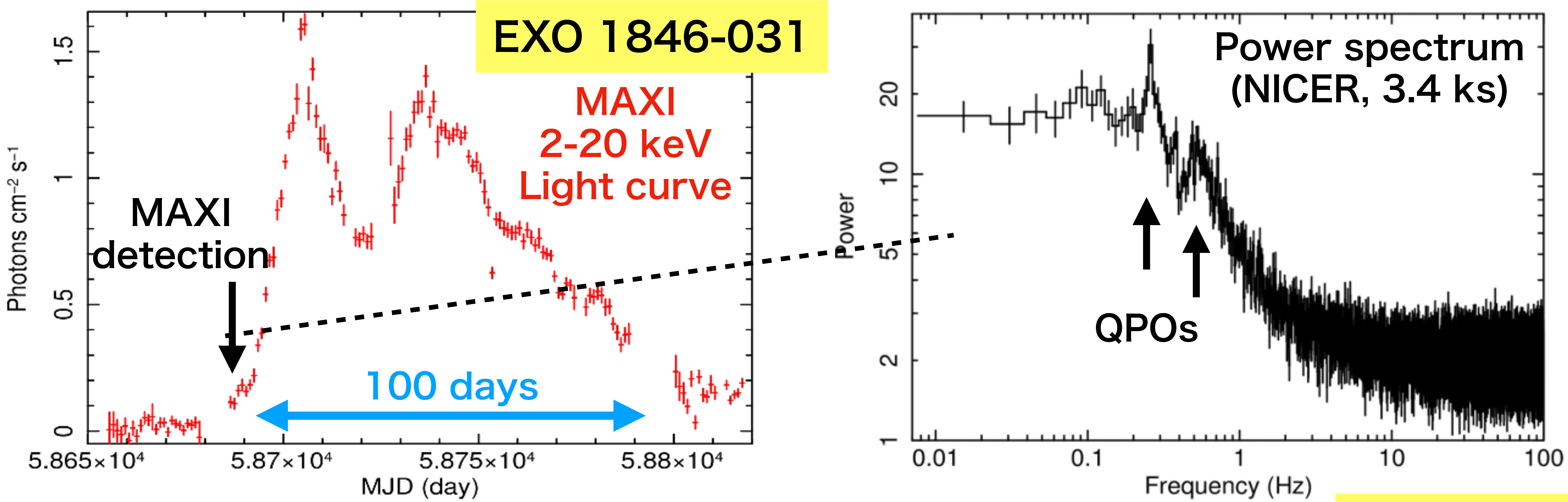


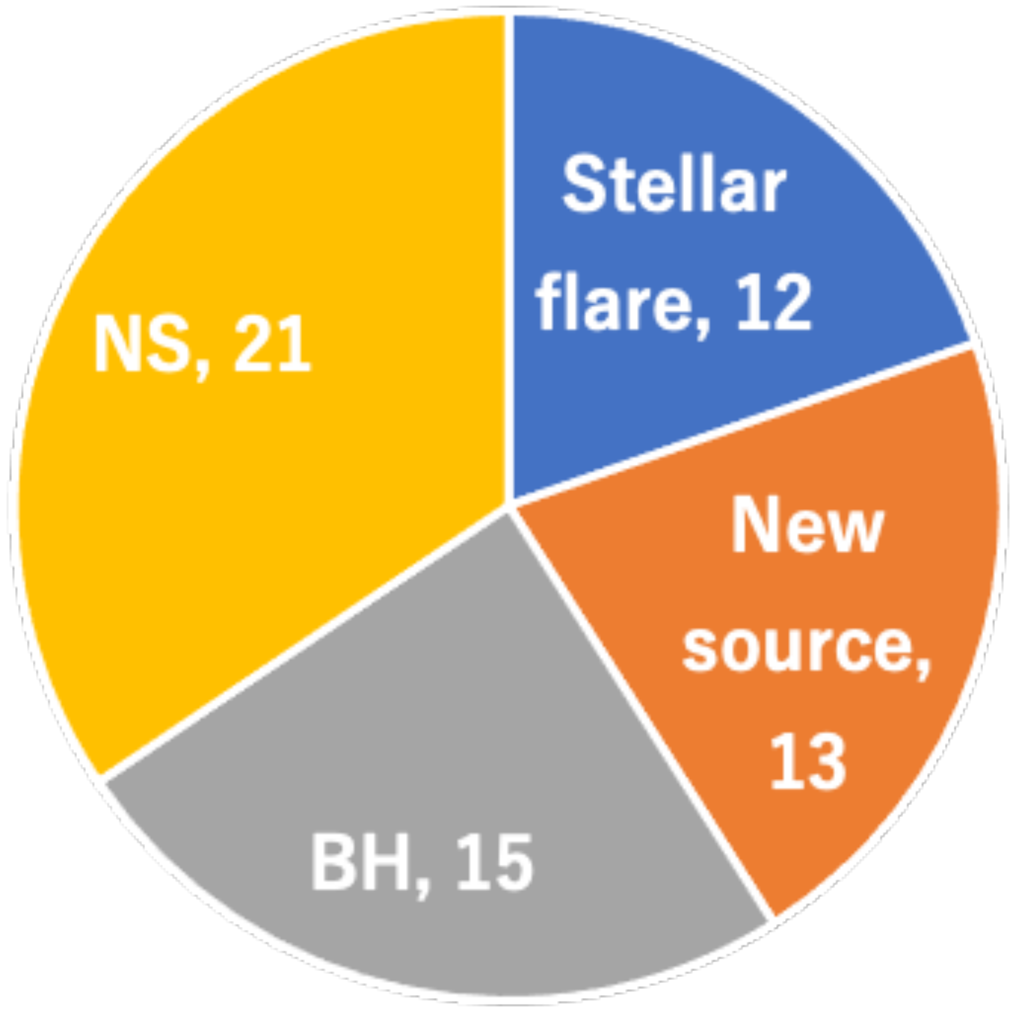




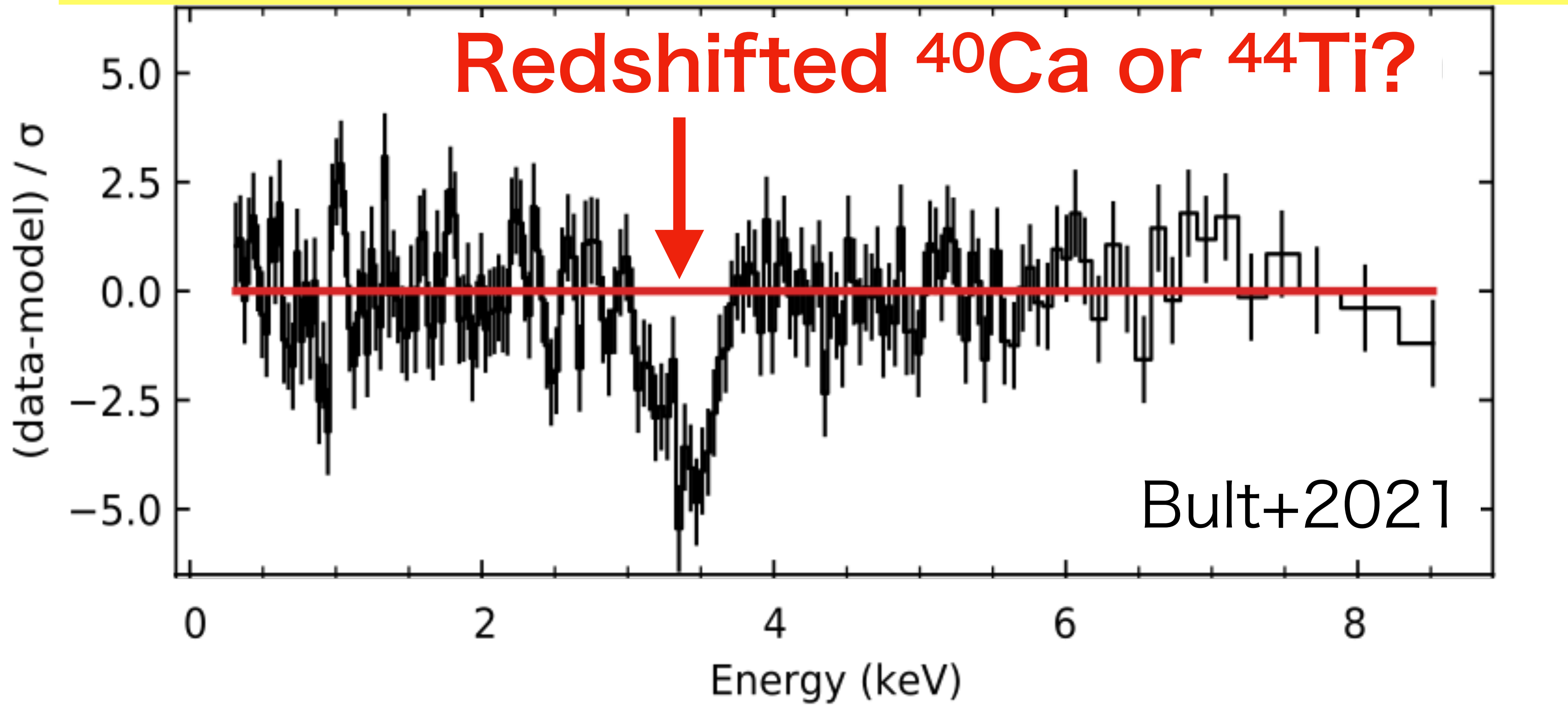
Slide credit: Wynn Ho

NICER Follow-up Observations of MAXI Transients





Burst emission from IGR J17062-6143



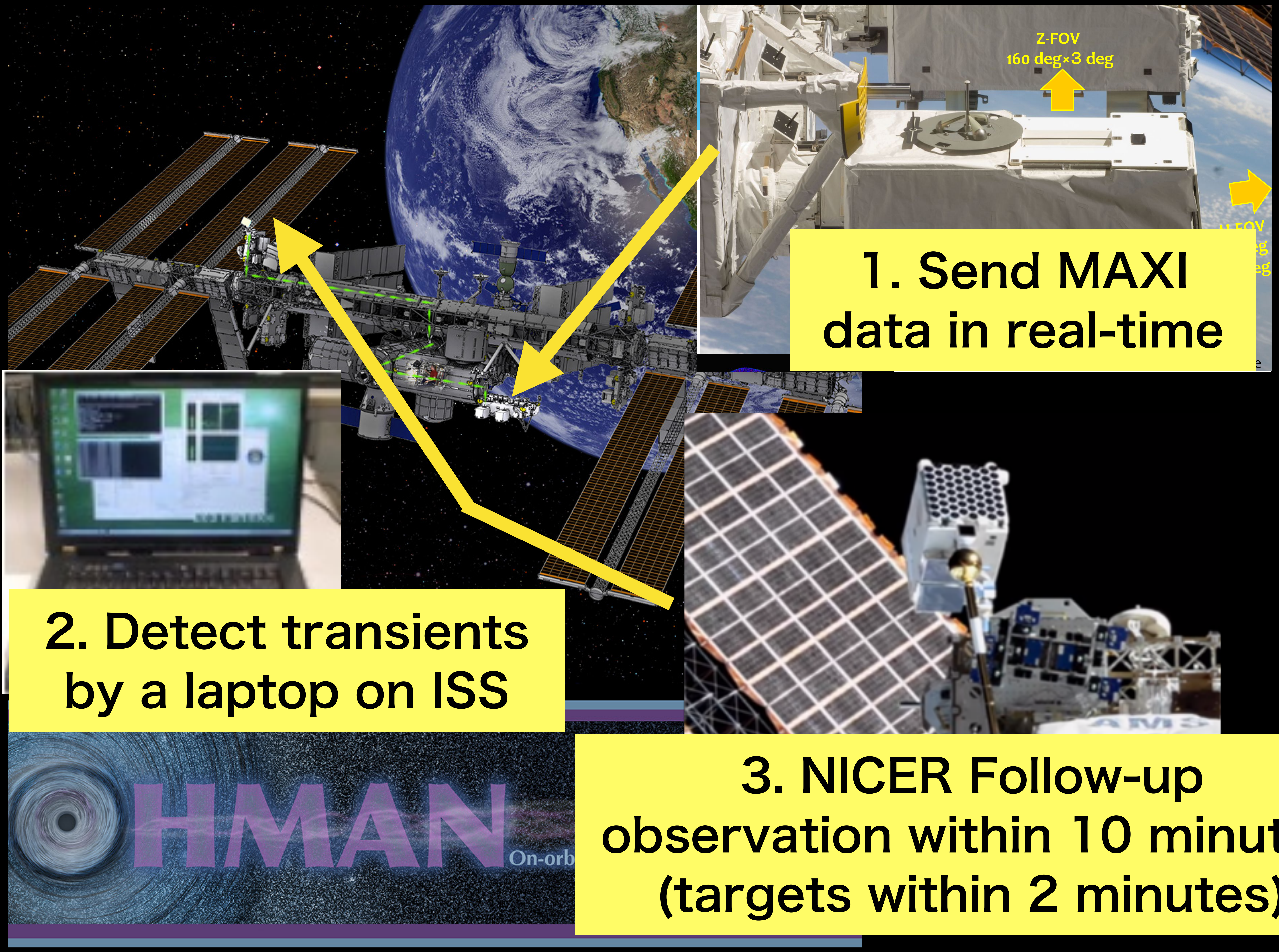
Successful follow-up of a long X-ray burst within 3 hours of the discovery

- NICER and MAXI joint teams have been organizing systematic agile follow-up and subsequent monitoring of MAXI-discovered X-ray transients.
  - This is the key why NICER data sets in early outbursts are available for discoveries.
- 61 transients were observed by Feb 2022, most of which are within 12 hours of their discoveries.

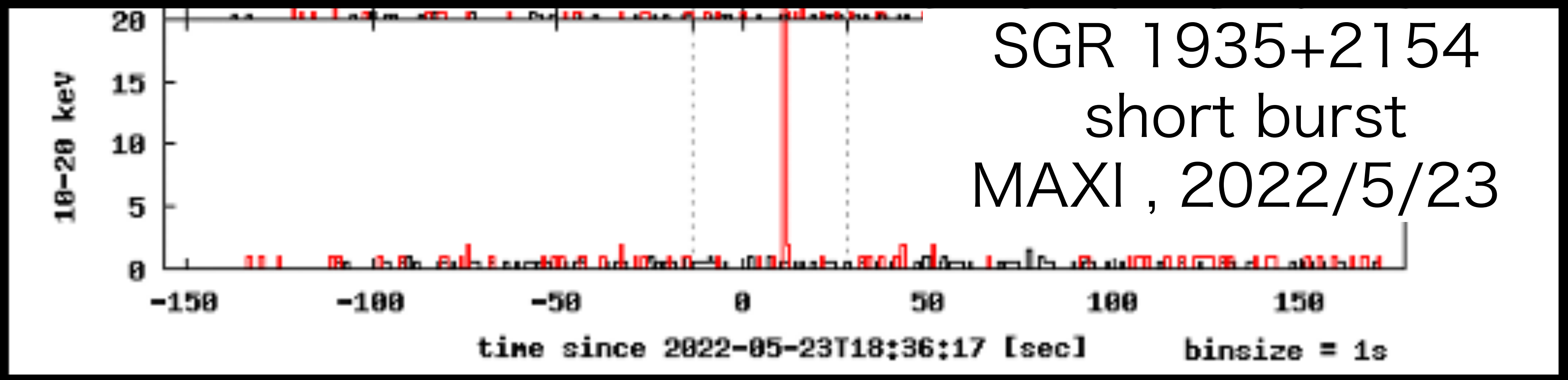
Slide credit: Wataru Buz Iwakiri

OHMAN (On-orbit Hookup of MAXI and NICER)

- Fully automatic follow-up observation system beyond the national border in ISS
- Primarily targets are unknown MAXI transients, stellar flares, long X-ray bursts, etc.
- Started in 2022 June, and expected trigger rate is about once a month



(Future example) application to magnetars



- MAXI has detected 3 short bursts from SGR 1935+2154 since 2020.
- OHMAN will enable NICER to observe persistent emission immediately after a short burst

Slide credit: Wataru Buz Iwakiri

Summary

1. Advantages of the NICER performance are large effective area (~1900 cm2 at 1.5 keV), high-time resolution (<100 ns), high throughput (free from pileups, dead time, and data transfer loss up to $\sim 4\times10^{4}$ cps), and flexible observations (quick response to ToO, even within a day).
2. Here we showed some examples and applications:
   a) Discovery of an X-ray enhancement at the Crab giant radio pulses
   b) Prompt follow-ups of transient magnetars and burst studies
   c) Long-term monitoring of magnetar pulse profile (migration)
   d) Search for gravitational waves from rotation powered pulsars
   e) Automated transient alert system from MAXI (OHMAN project)