Enhanced X-ray Emission Coinciding with Giant Radio Pulses from the Crab Pulsar

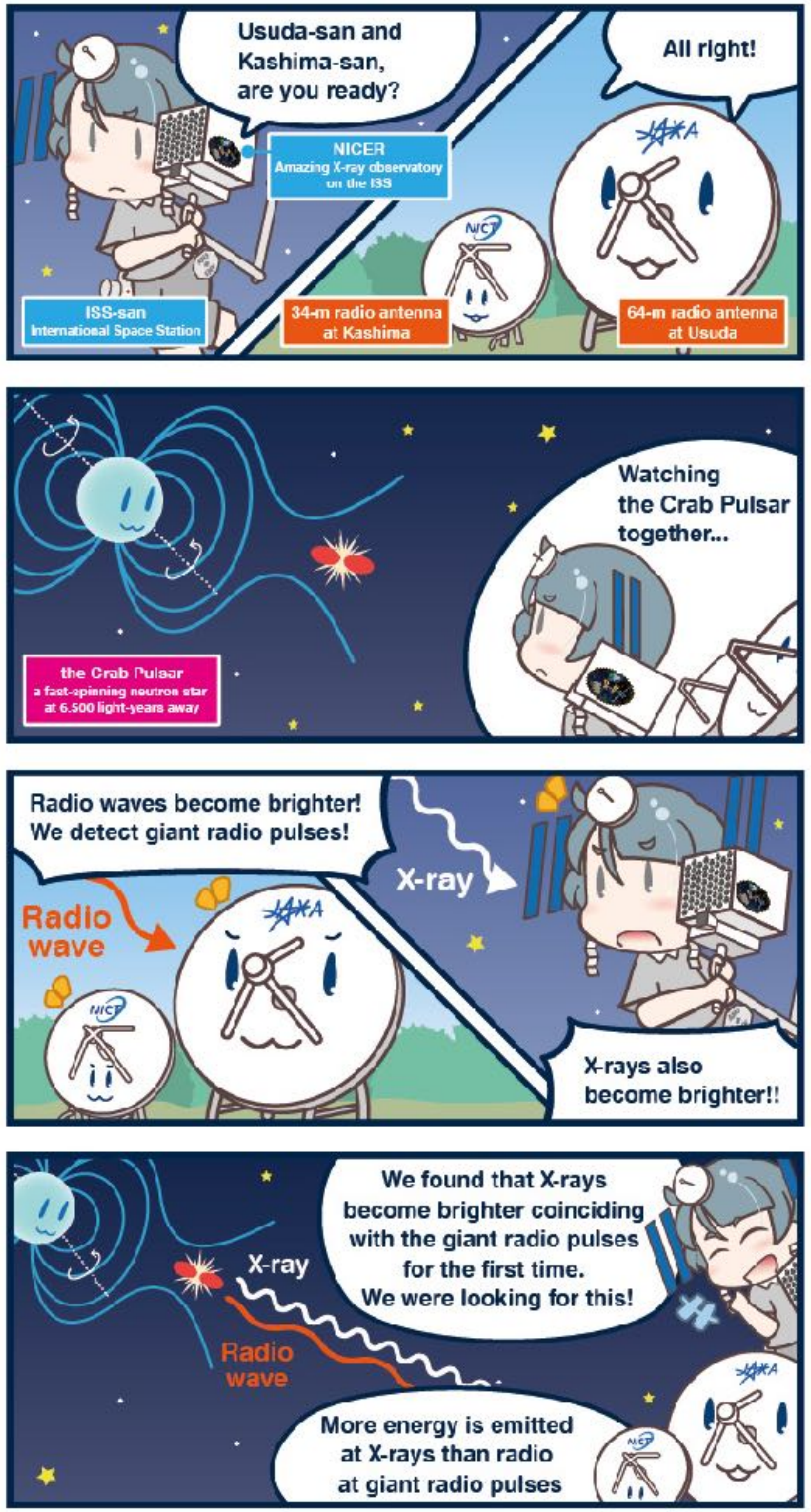
Teruaki Enoto (RIKEN, NICER M&M team)

Toshio Terasawa, Shota Kisaka, Chin-Ping Hu, Sebastien Guillot, Natalia Lewandowska, Christian Malacaria, Paul S. Ray, Wynn C.G. Ho, Alice K. Harding, Takashi Okajima, Zaven Arzoumanian, Keith C. Gendreau, Zorawar Wadiasingh, Craig B. Markwardt, Yang Soong, Steve Kenyon, Slavko Bogdanov, Walid A. Majid, Tolga Guver, Gaurava K. Jaisawal, Rick Foster, Yasuhiro Murata, Hiroshi Takeuchi, Kazuhiro Takefuji, Mamoru Sekido, Yoshinori Yonekura, Hiroaki Misawa, Fuminori Tsuchiya, Takahiko Aoki, Munetoshi Tokumaru, Mareki Honma, Osamu Kameya, Tomoaki Oyama, Katsuaki Asano, Shinpei Shibata and Shuta J. Tanaka

Enoto et al., Science, 372, 187-190 (2021) [arXiv: 2104.03492]

NICER Analysis Workshop, Spring 2021 @ 2021-05-13 9:00-9:20 EDT (22:00-23:00 JST)

NICER on the ISS, Usuda, and Kashima antennas are watching the Crab Pulsar



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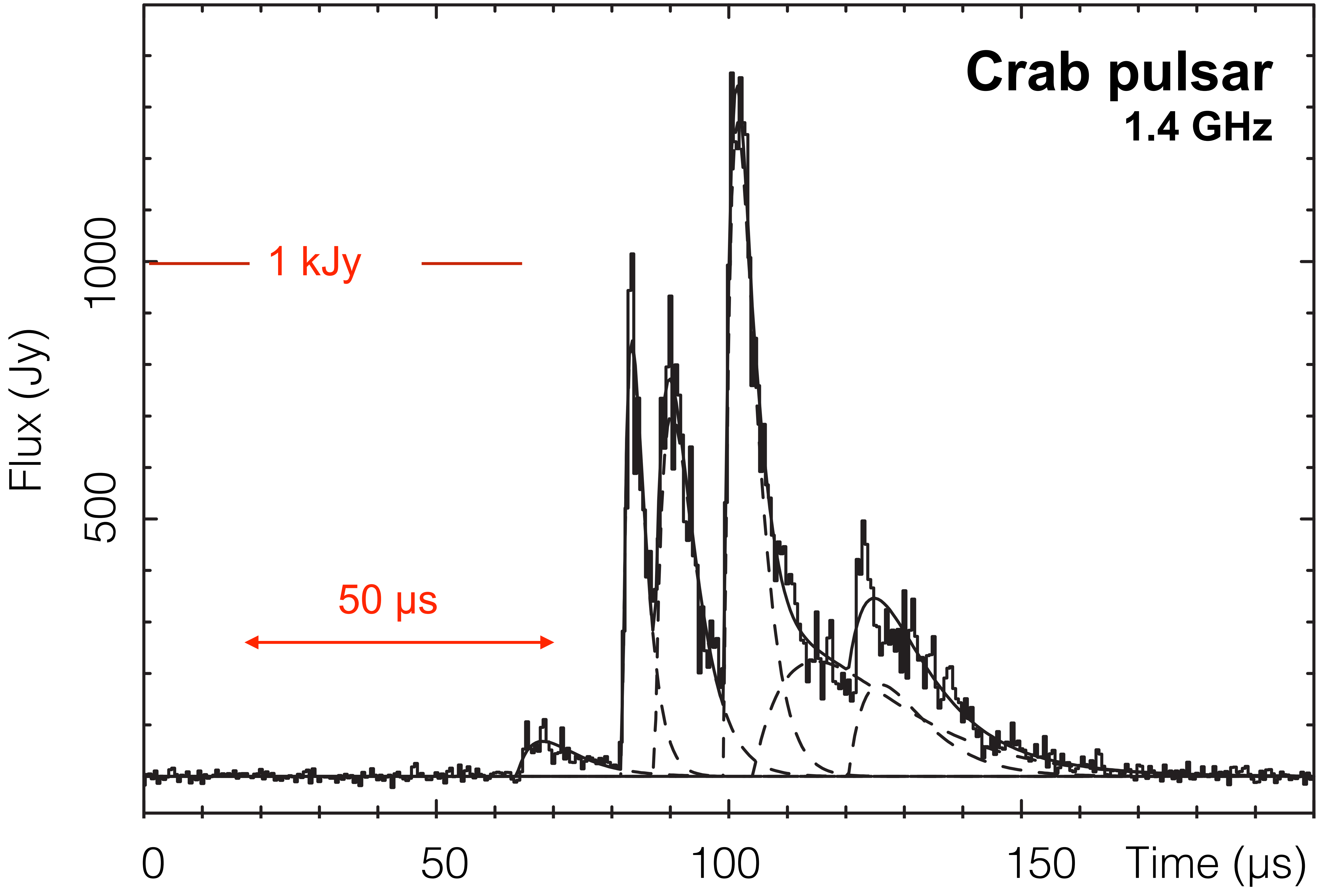
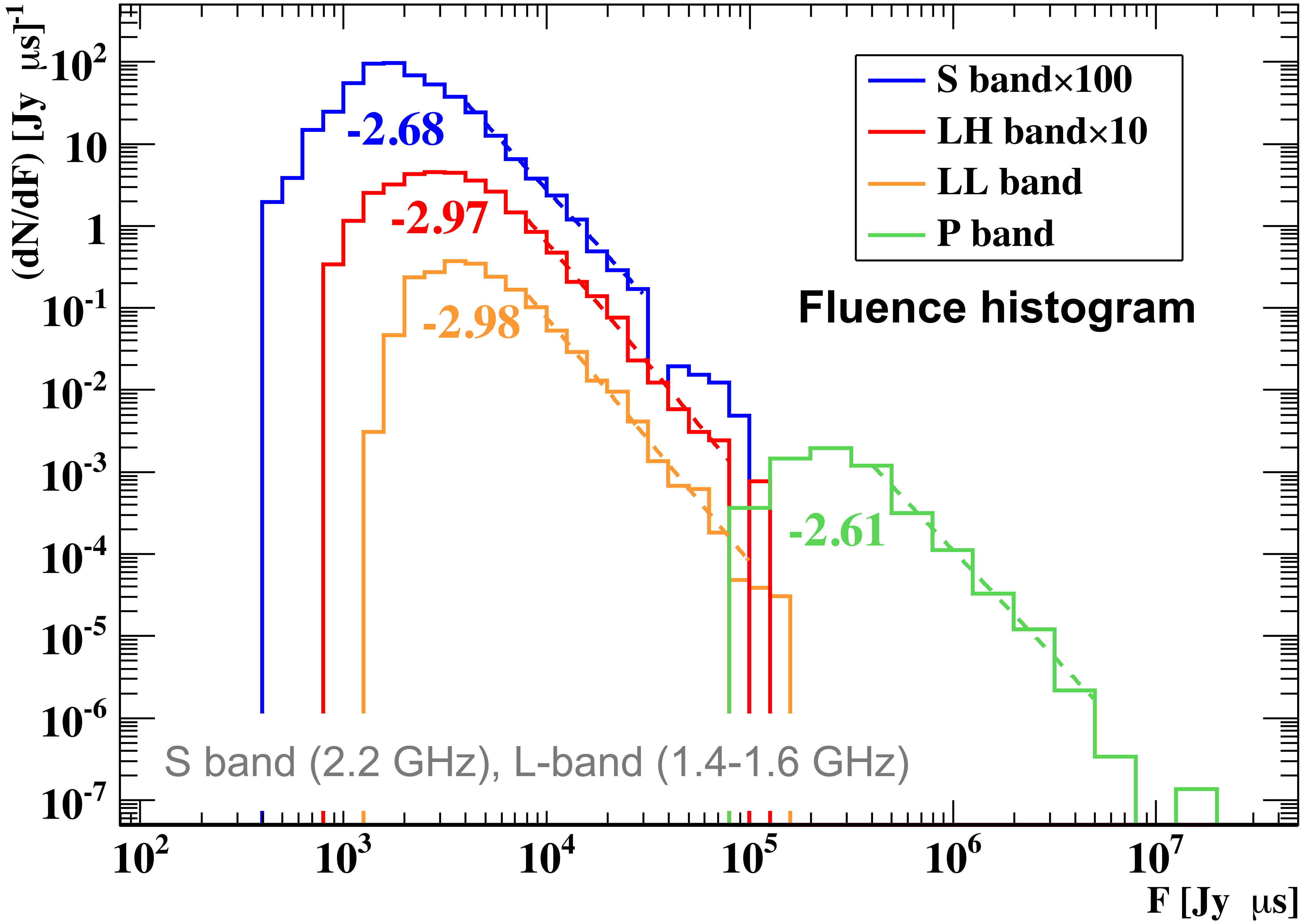
Giant radio Pulses (GPs) from rotation-powered pulsars

- 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?

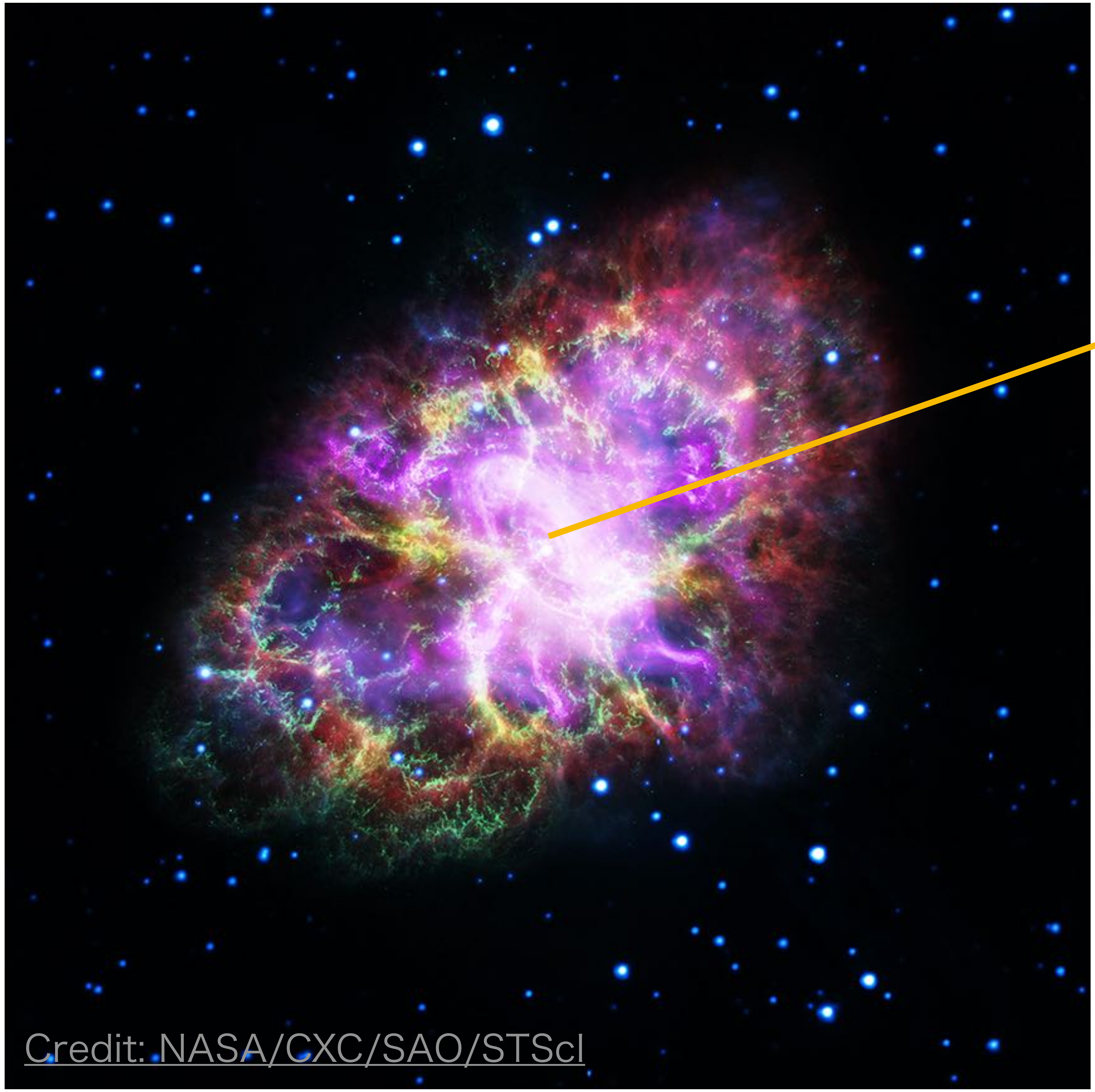


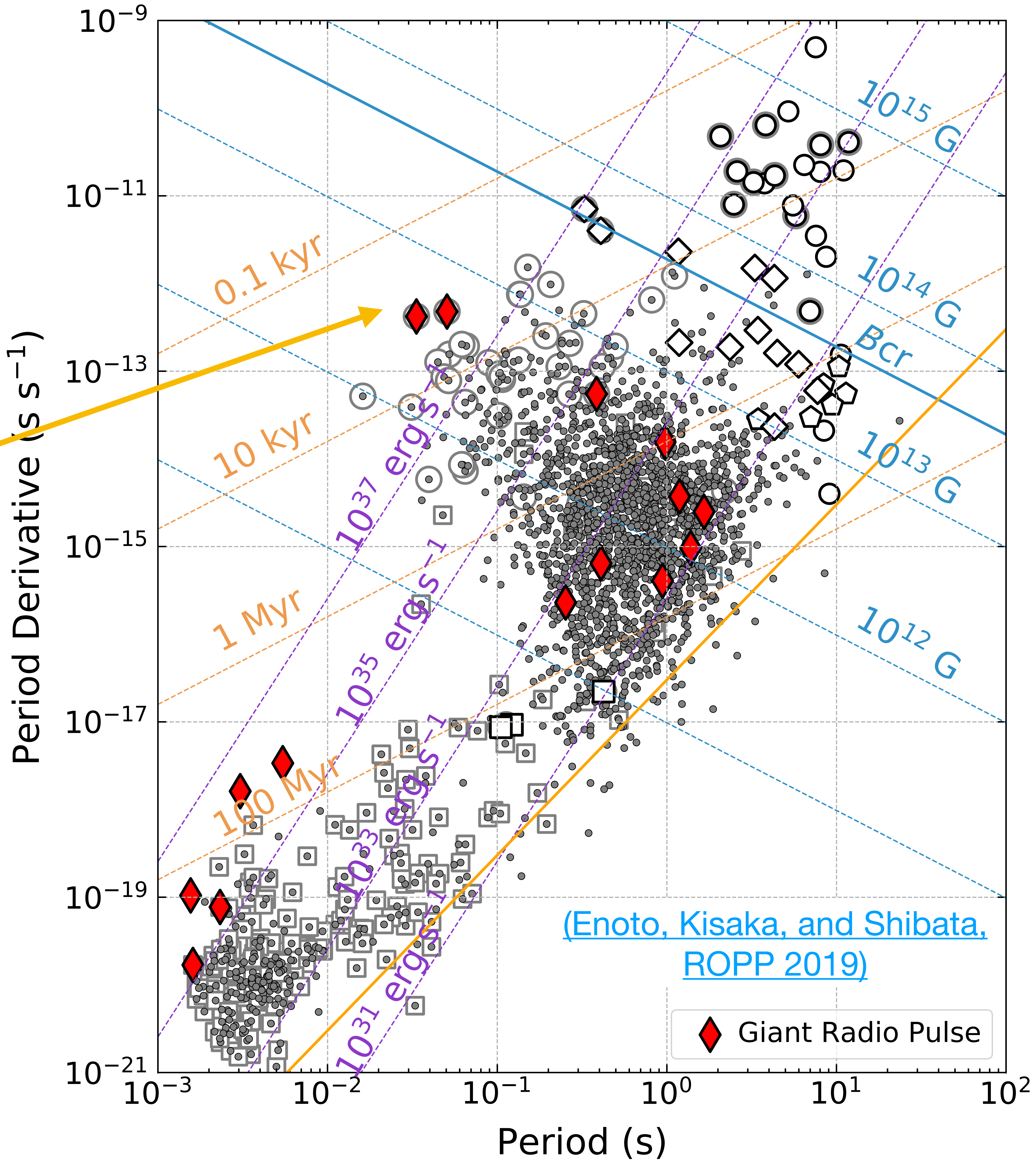
(Sallmen et al., 1999)



(Mikami et al., 2016)

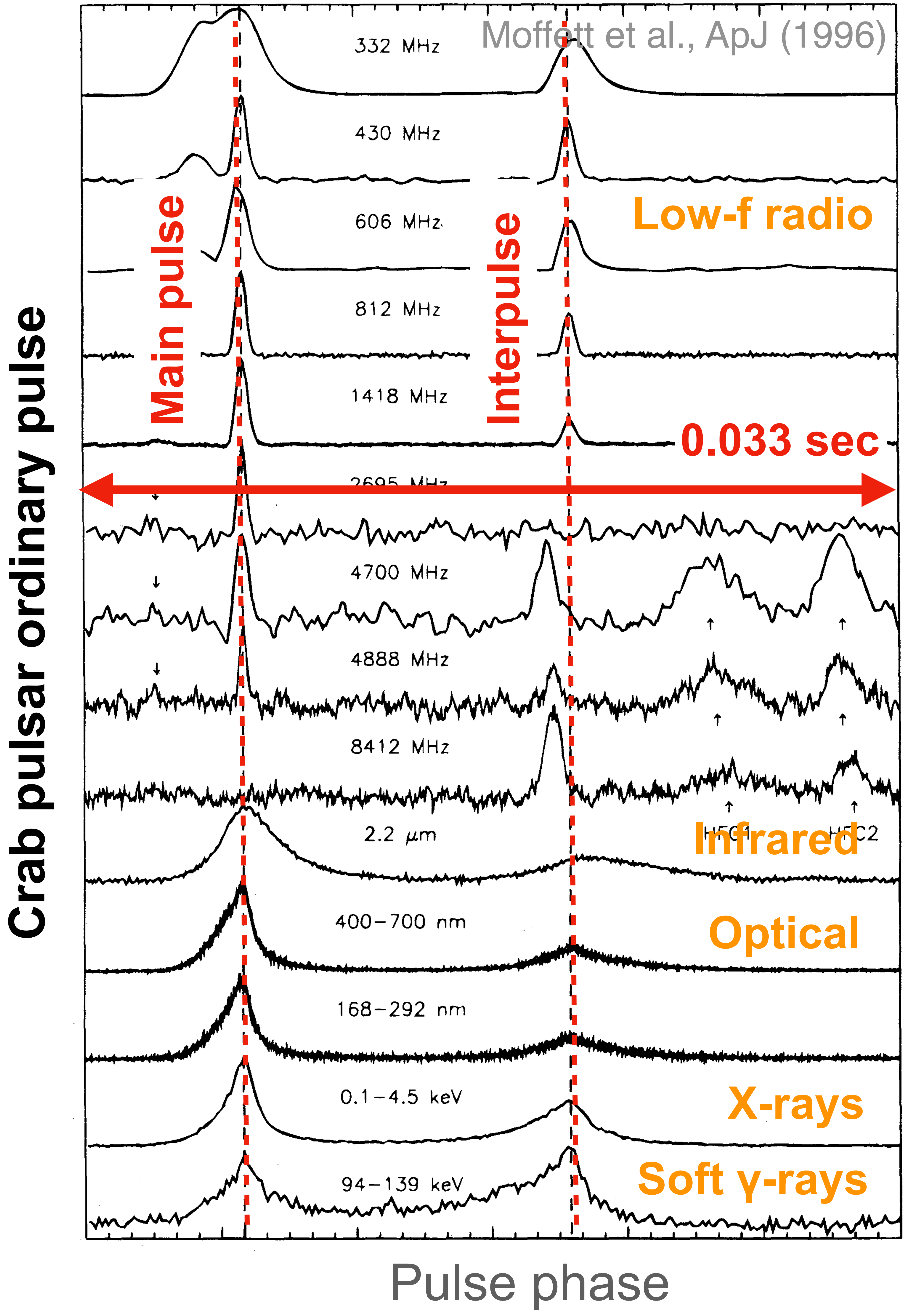
GPs from the Crab Pulsar





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…).



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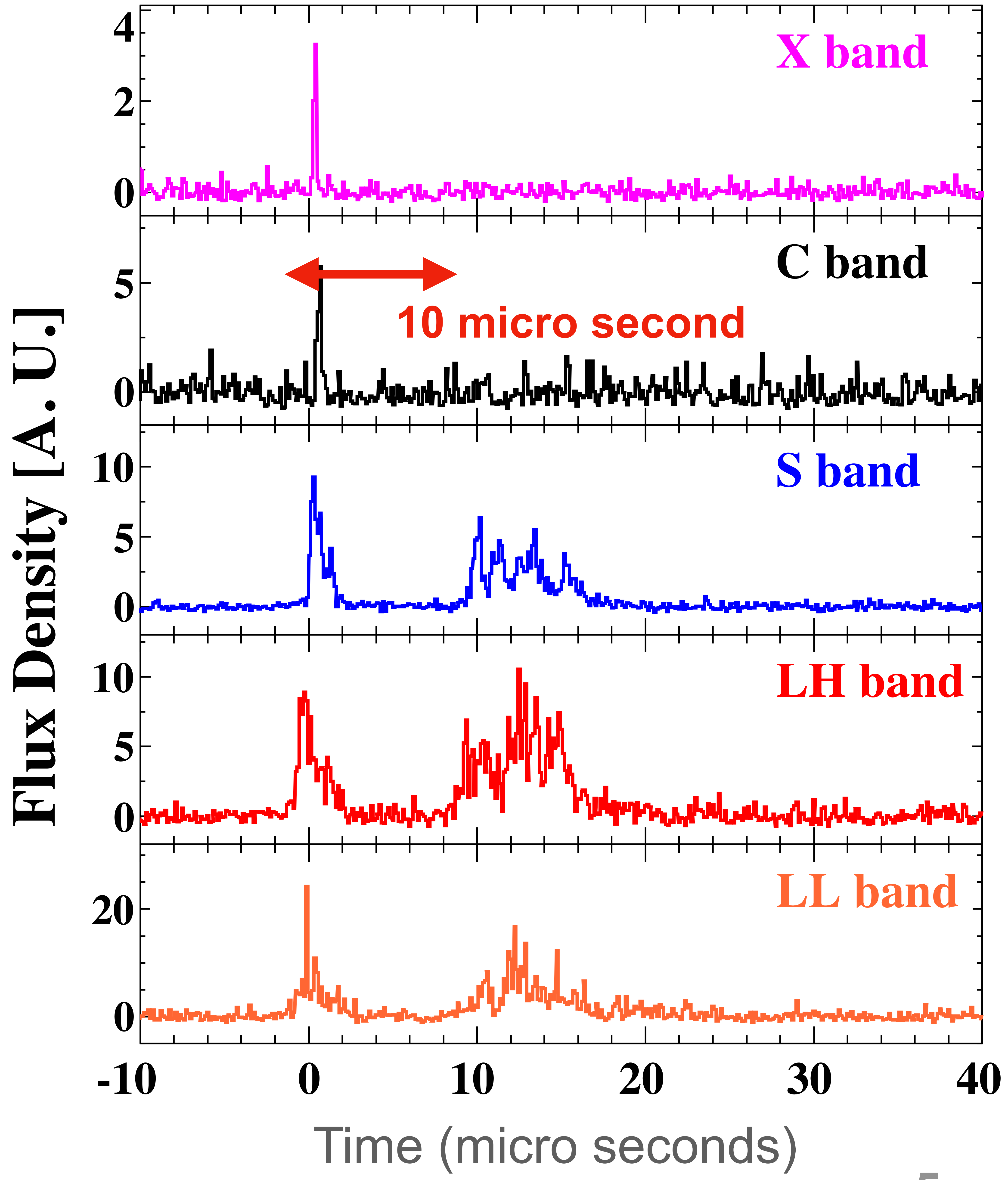
Example of a GP



Mikami et al., ApJ (2016)

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)!

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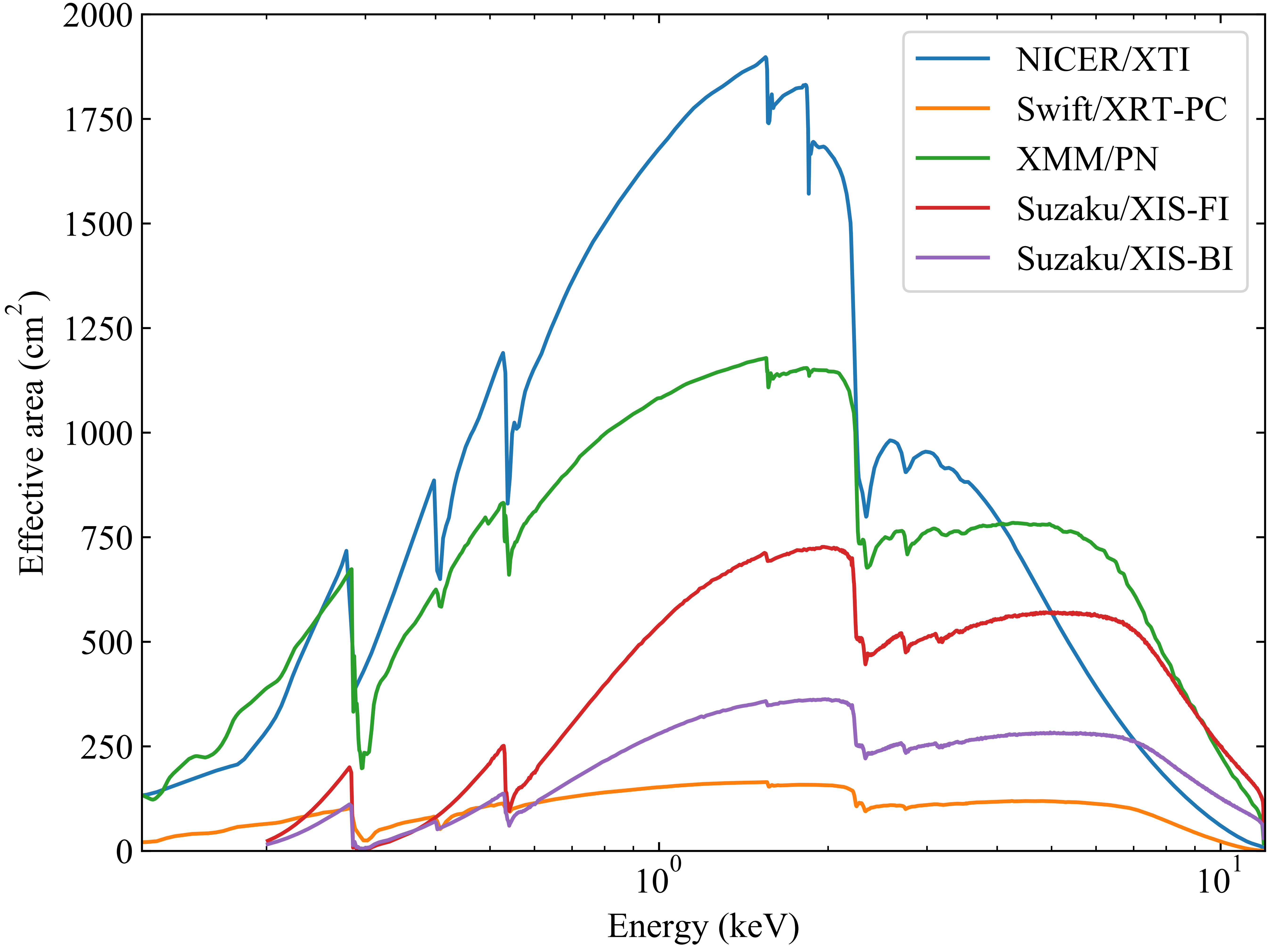
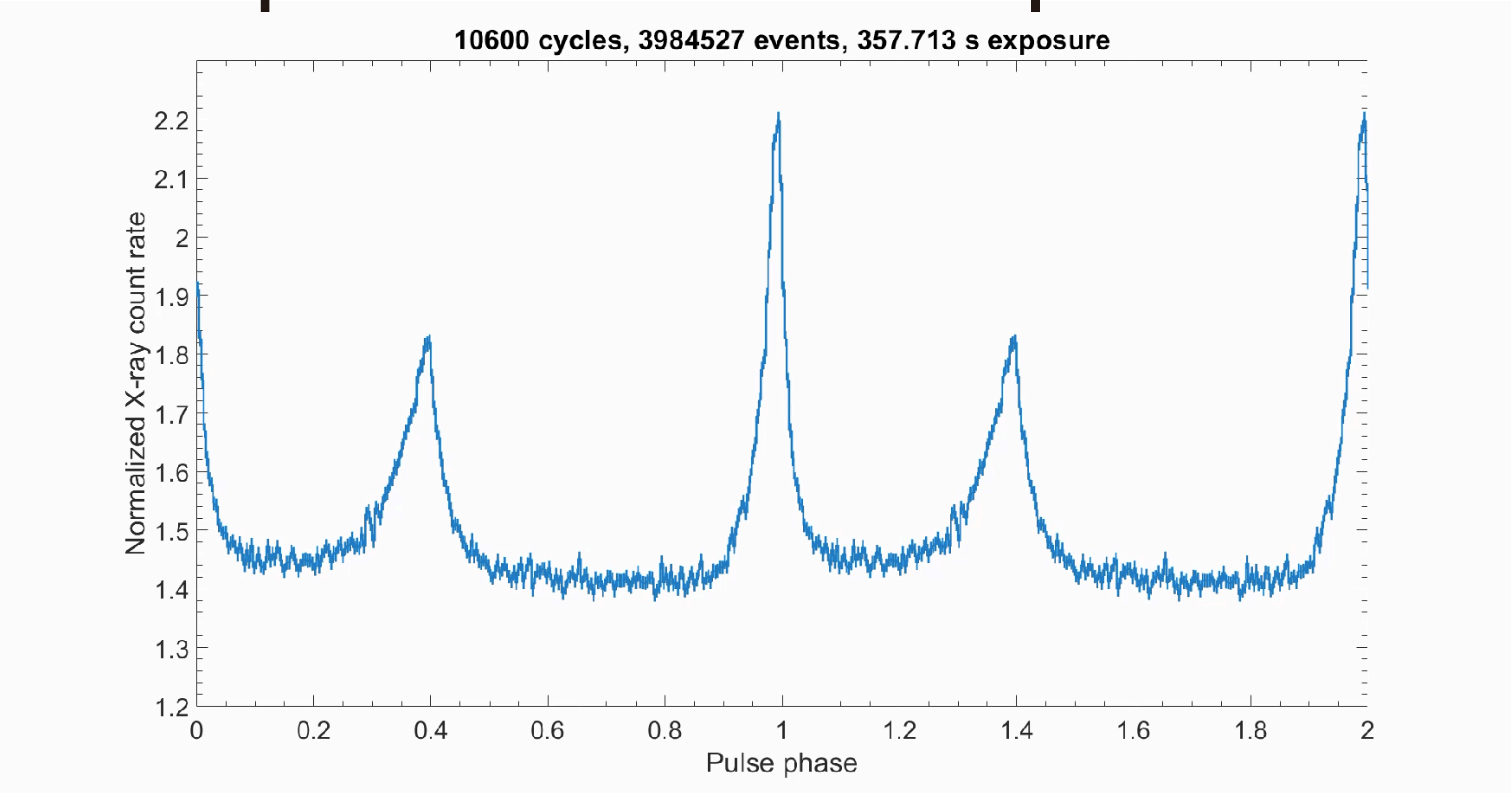


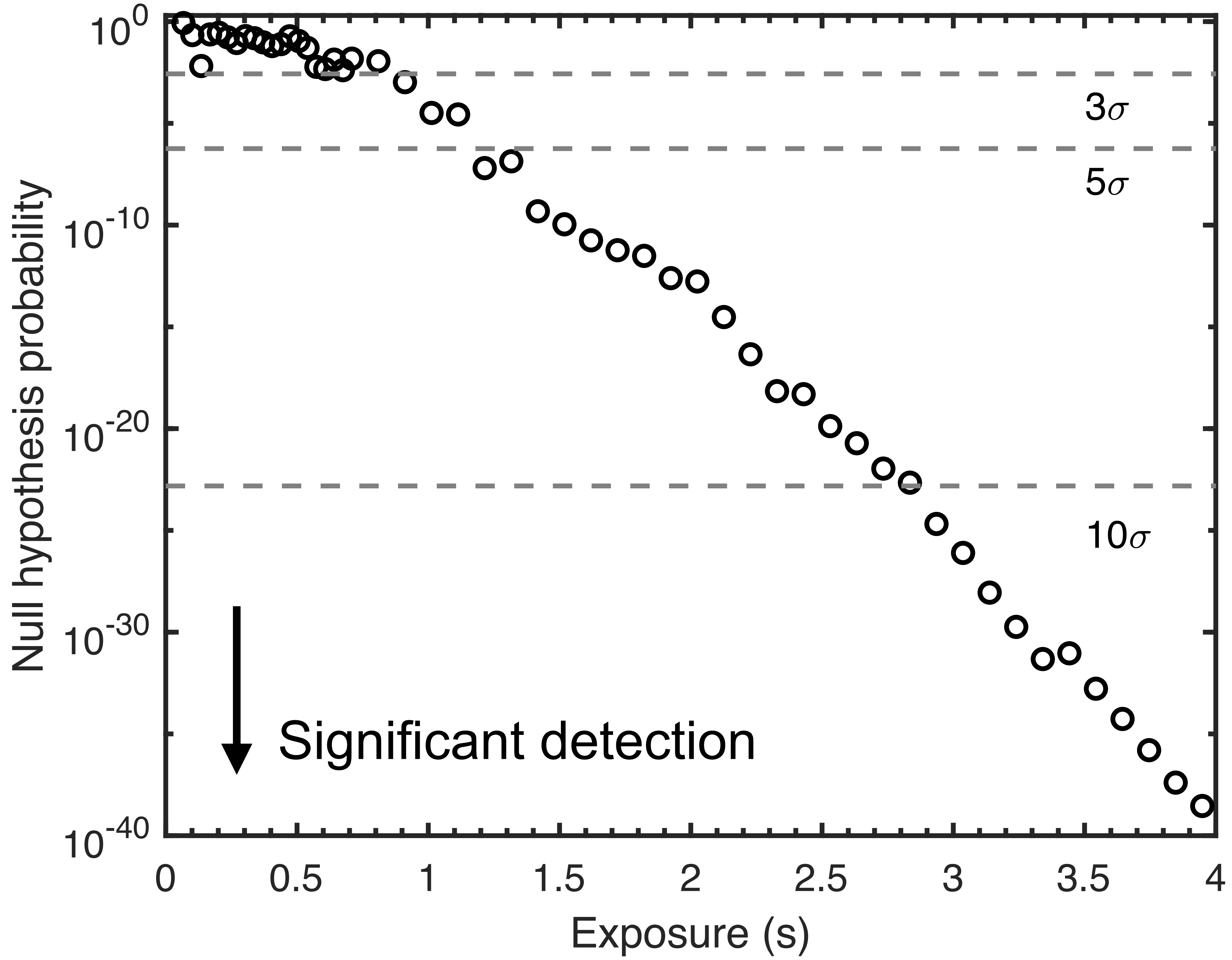
(K. Gendreau, et al., SPIE, 2012; Z. Arzoumanian, et al., SPIE, 2014)

Short exposure to detect the Crab pulsation

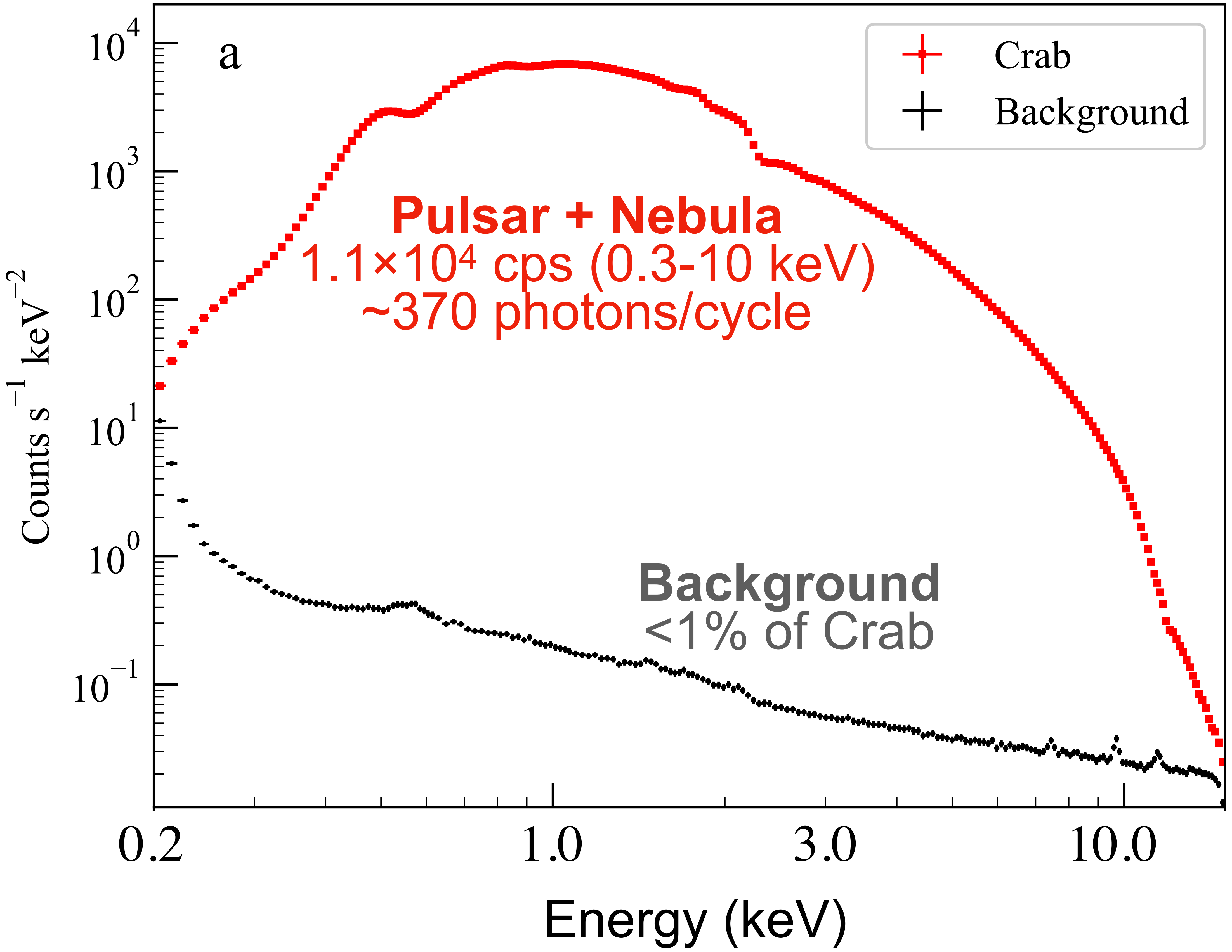


Short exposure to detect the Crab pulsation

Detection significance of X-ray pulses



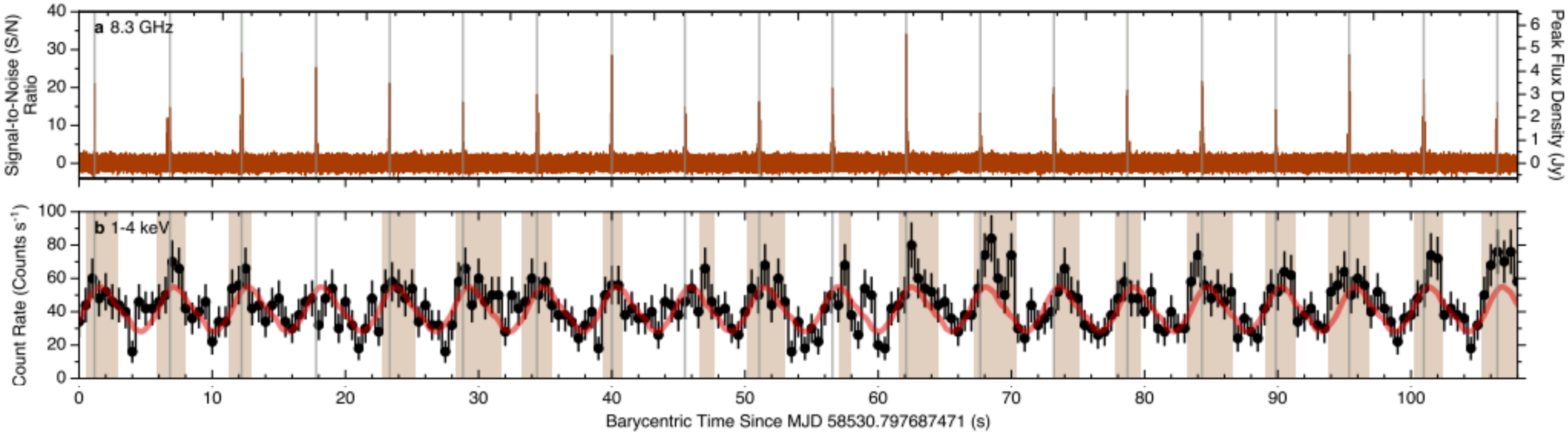
NICER X-ray spectrum of the Crab pulsar and nebula



- Pulse signals are detectable within 1 sec, ×50 larger photon statistics than Hitomi.
- Free from pileups, dead time, and data transfer loss (throughput 3.8×10^4 cps).

NICER Magnetar and Magnetosphere (M&M) Group

- has collaborating with radio telescopes for magnetars and highly magnetized pulsars including the Crab pulsar for simultaneous radio-Xray observations.
- Example (1) Detection of single X-ray pulses from a transient and radio loud magnetar XTE J1810-197



Pearlman et al., 2020, arXiv:2005.08410

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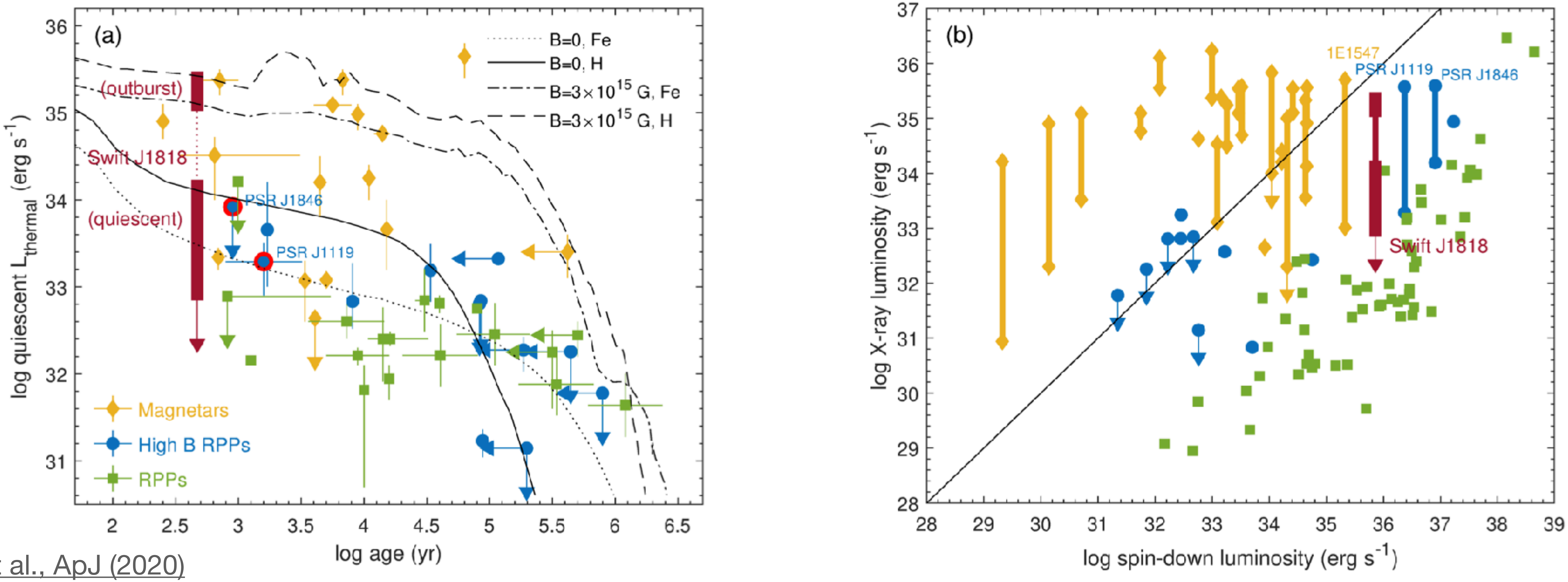
- Example (2) A new magnetar Swift J1818.0-1607 with young characteristic age of ~470 yr , as a missing link between magnetars and high-B pulsars.



Hu et al., ApJ (2020)

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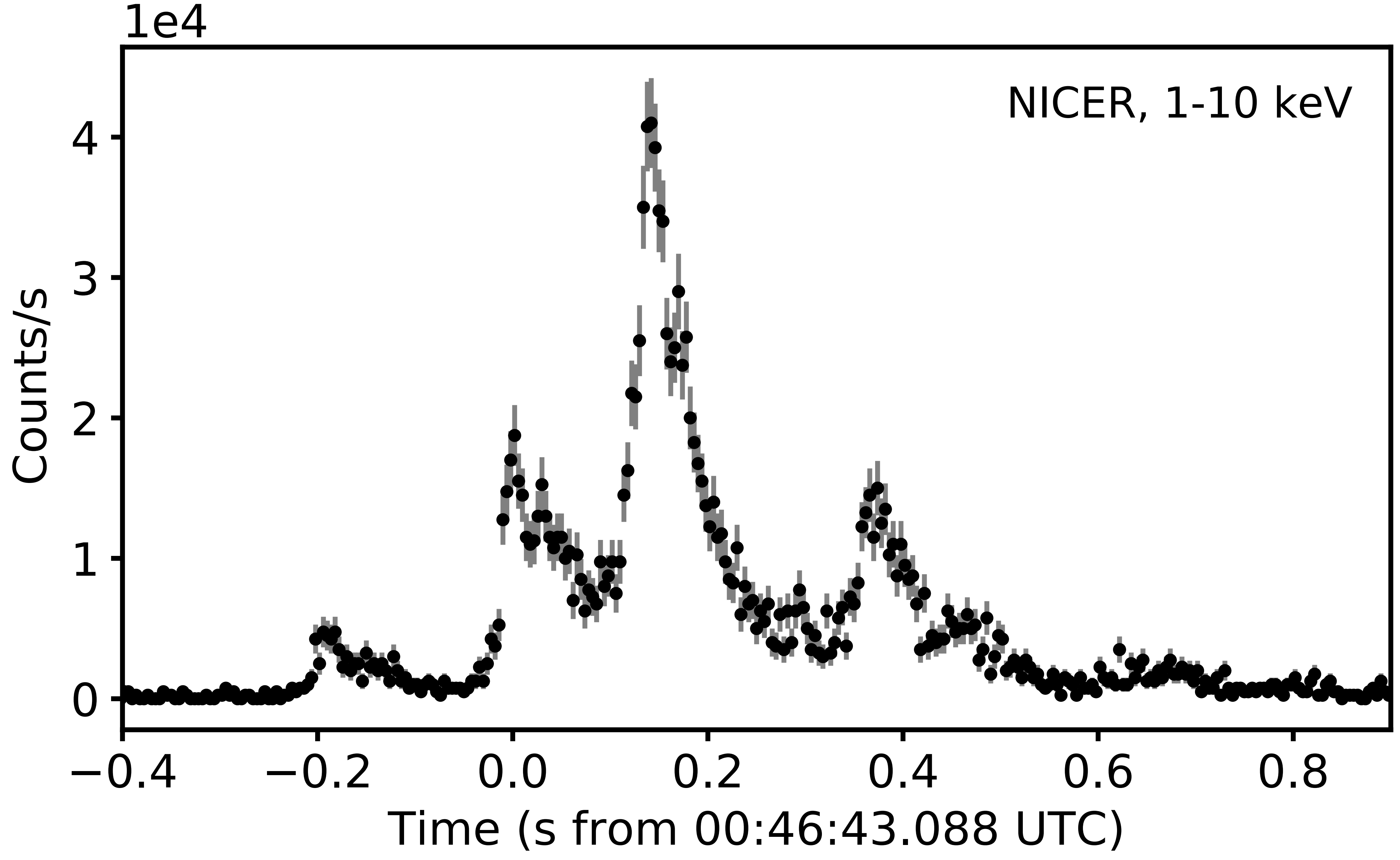
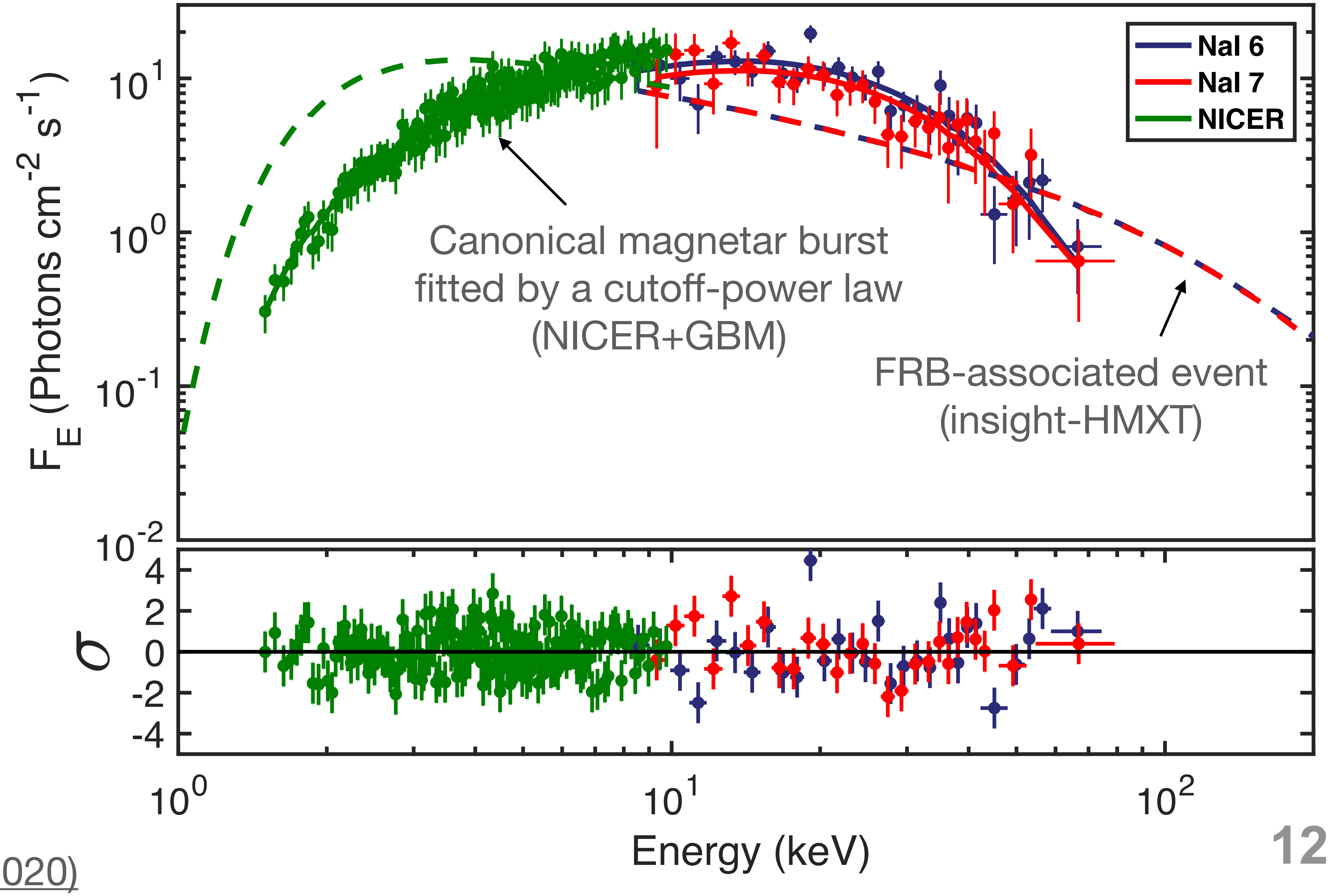
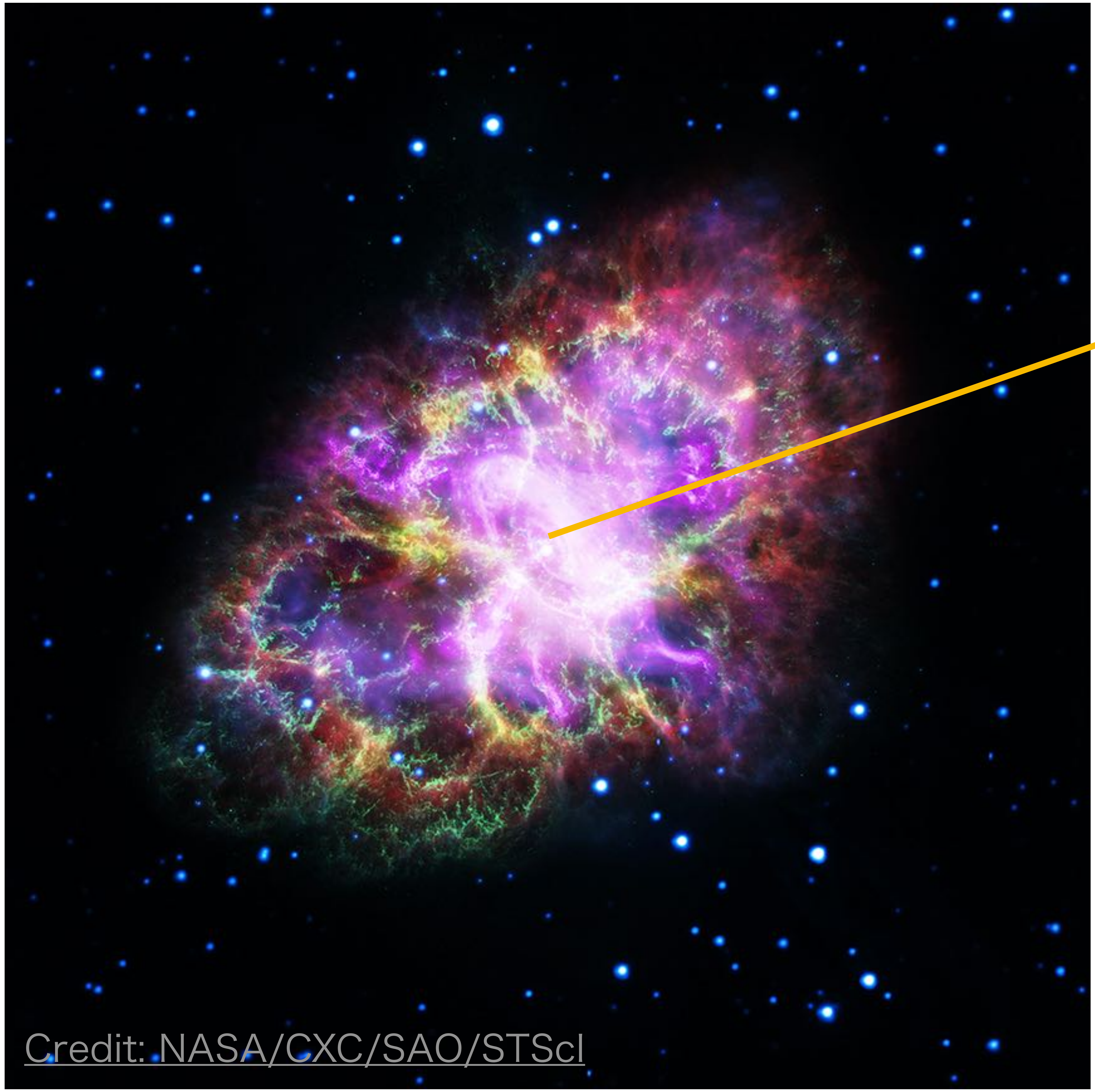
- Example (3) Galactic magnetar SGR 1935+2154 as a FRB source!

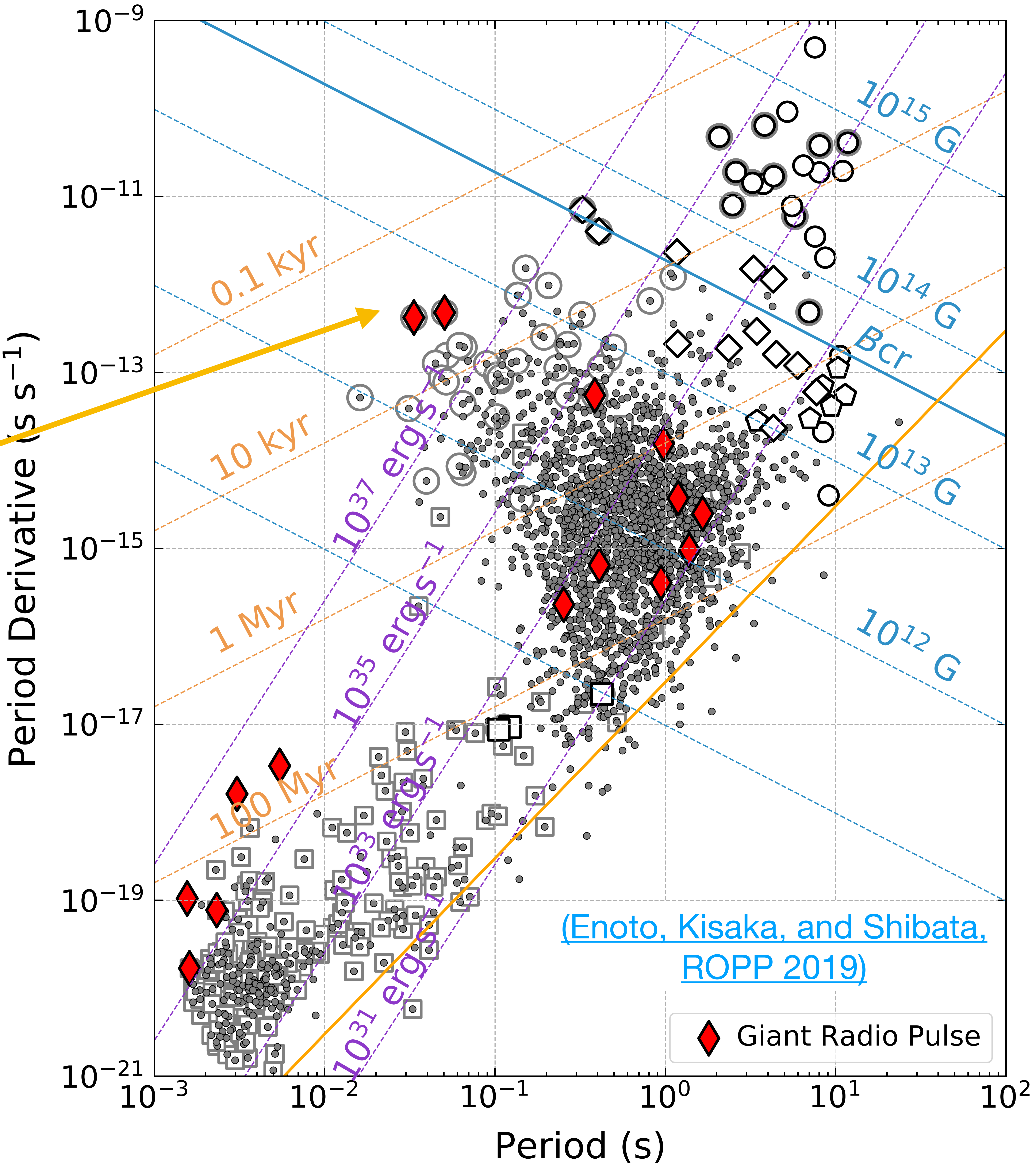




Younes et al., Nature Astronomy (2020)   Younes et al., ApJ (2020)

GPs from the Crab Pulsar





Two Radio Observatories (2 GHz) in Japan

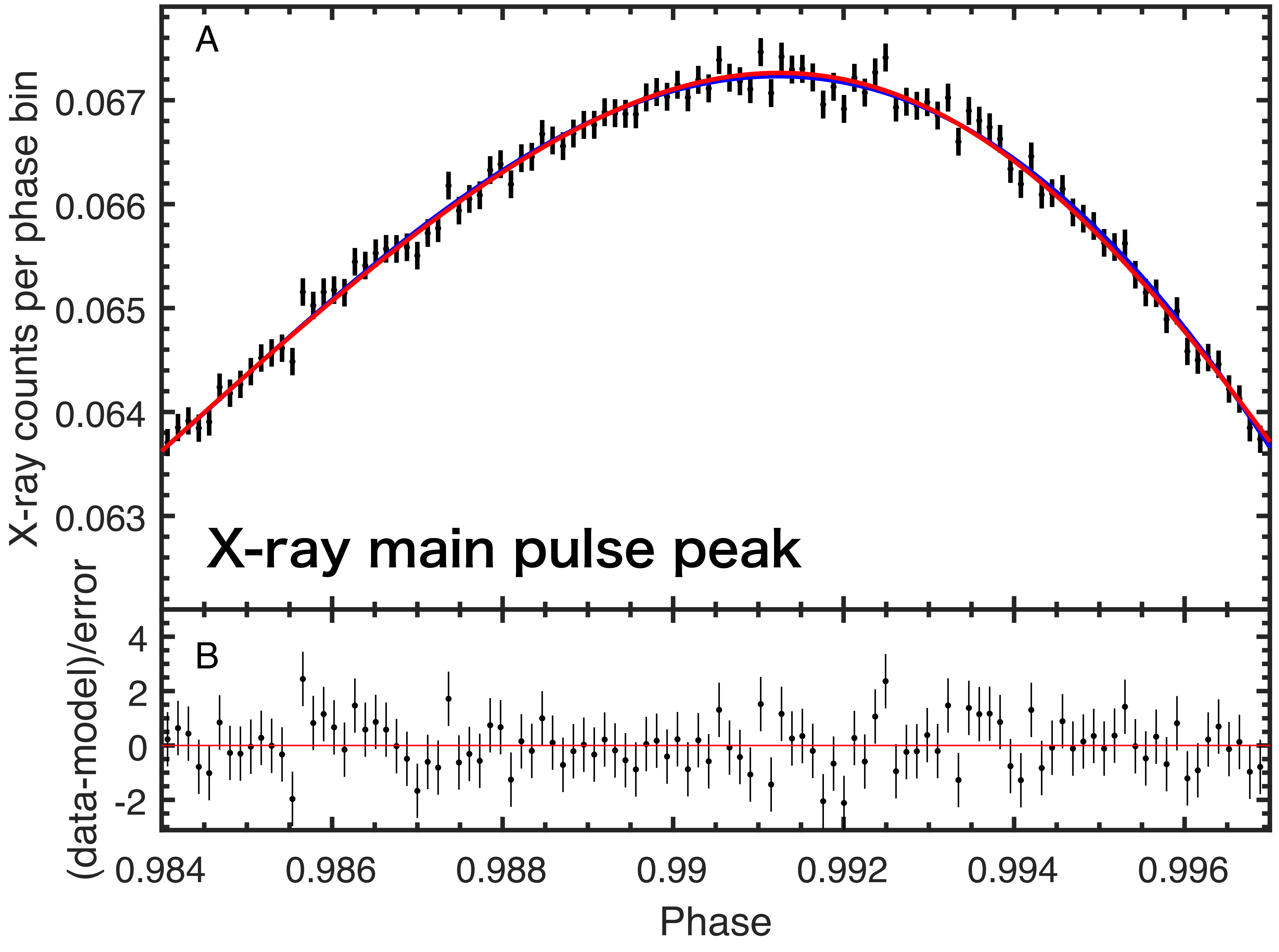
(Credit) NICT/Kashima

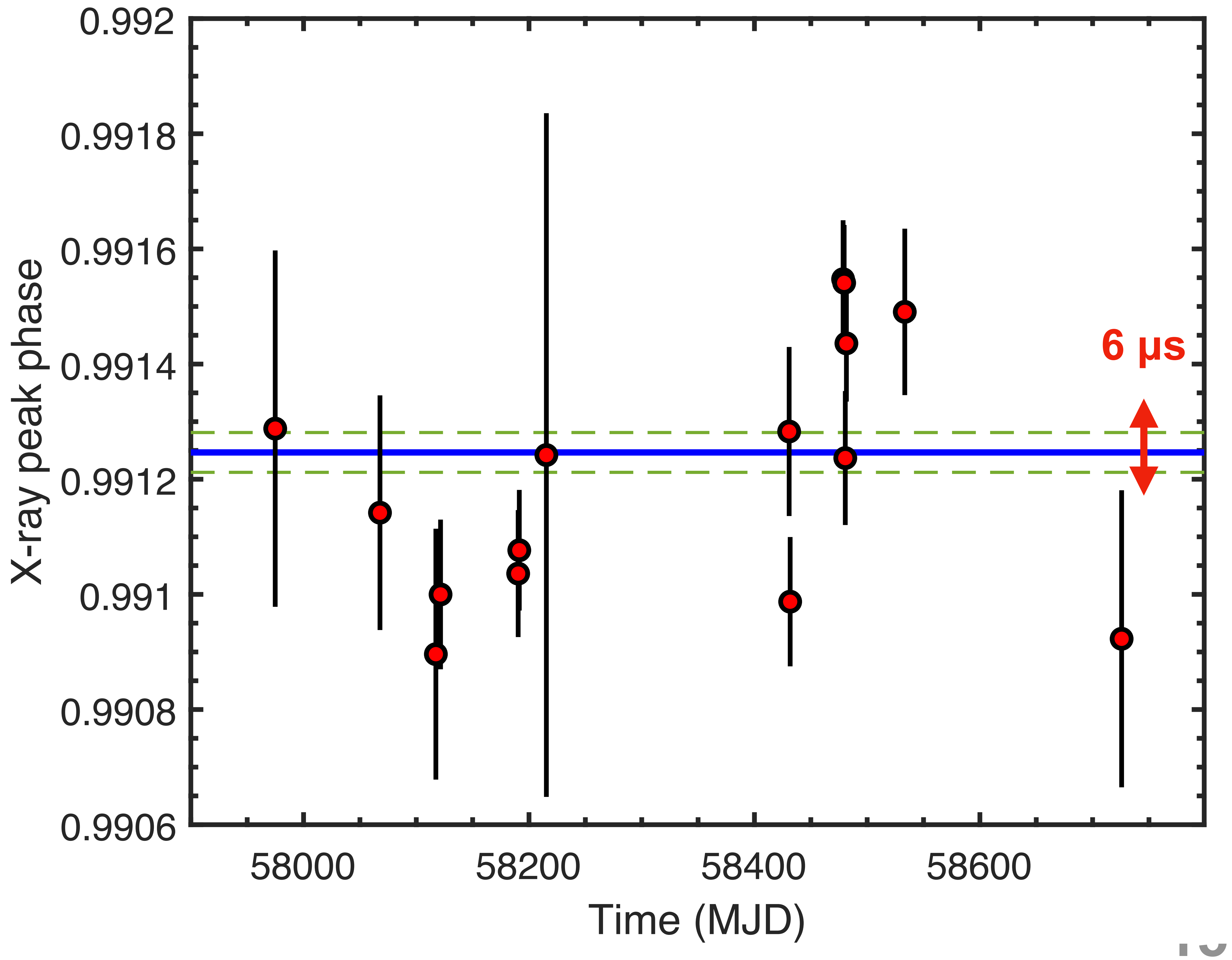

(Credit) JAXA/Usuda

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

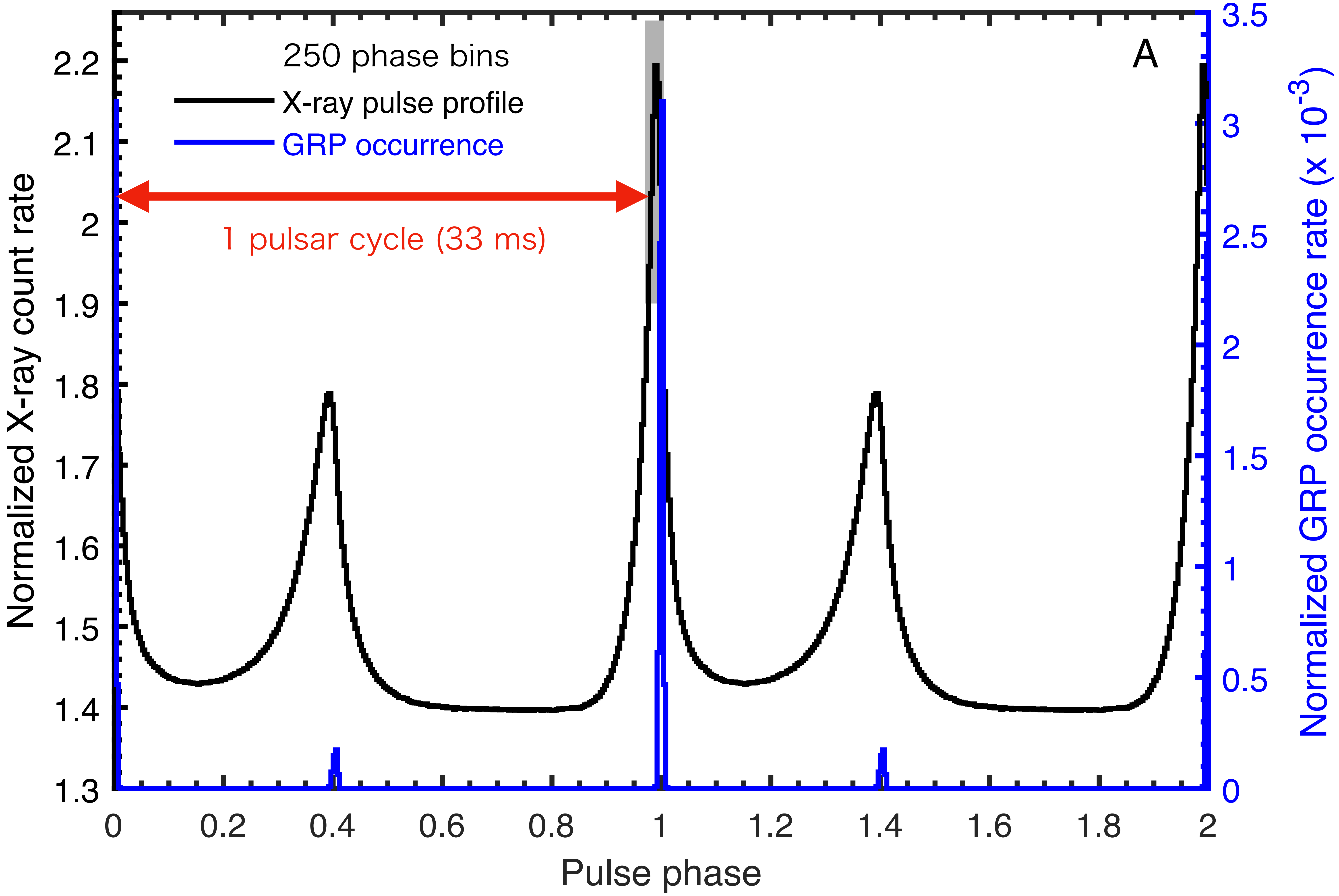
Long-term monitoring simultaneous in radio and X-rays

- Coordinated 15 observations with the two radio telescopes in 2017-2019
- The X-ray main pulse peak ϕ=0.9915±0.00004 relative to the radio peak, corresponding to the source-intrinsic 304 us radio delay.



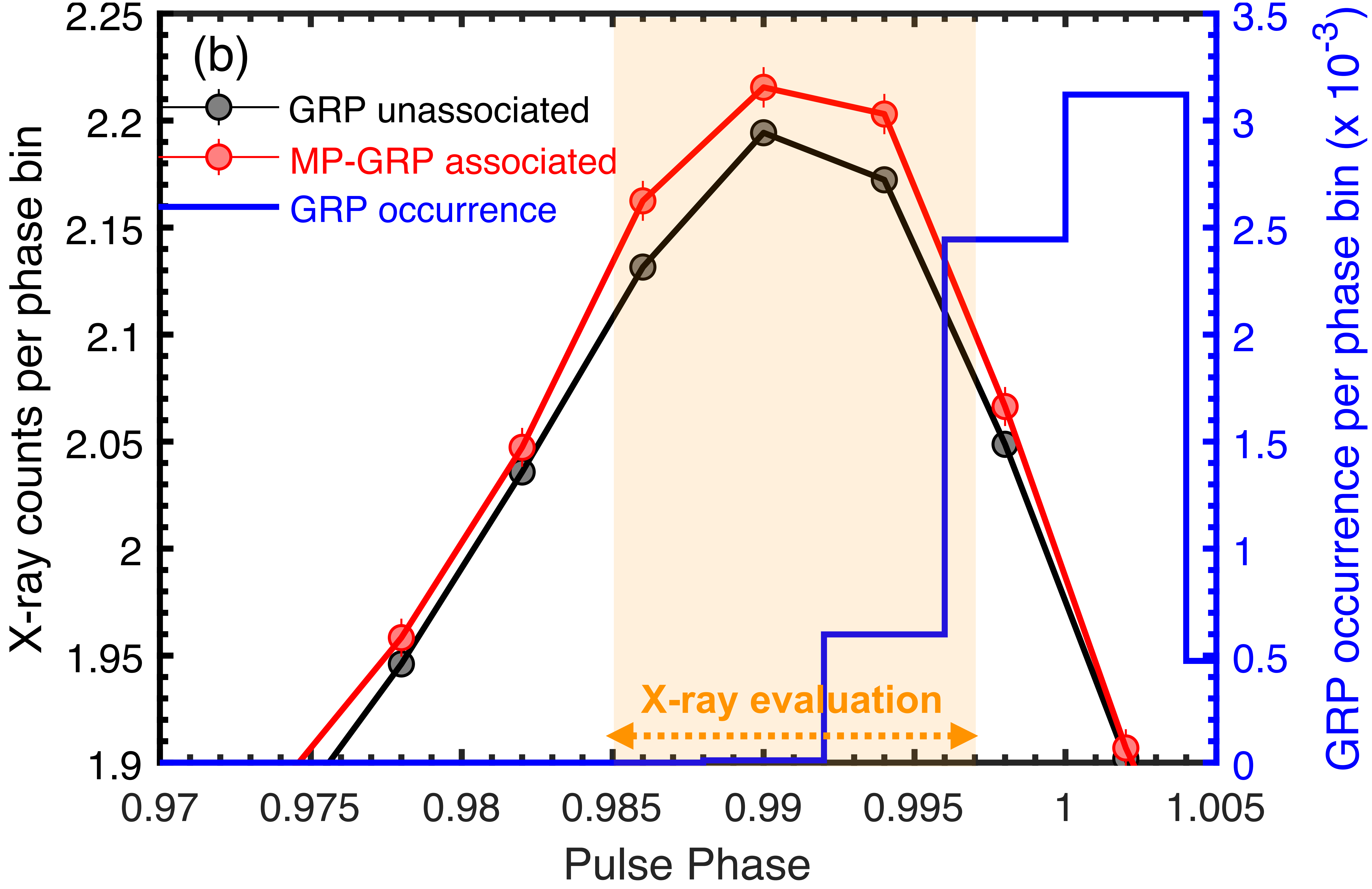


Discovery of X-ray enhancement coinciding with GPs



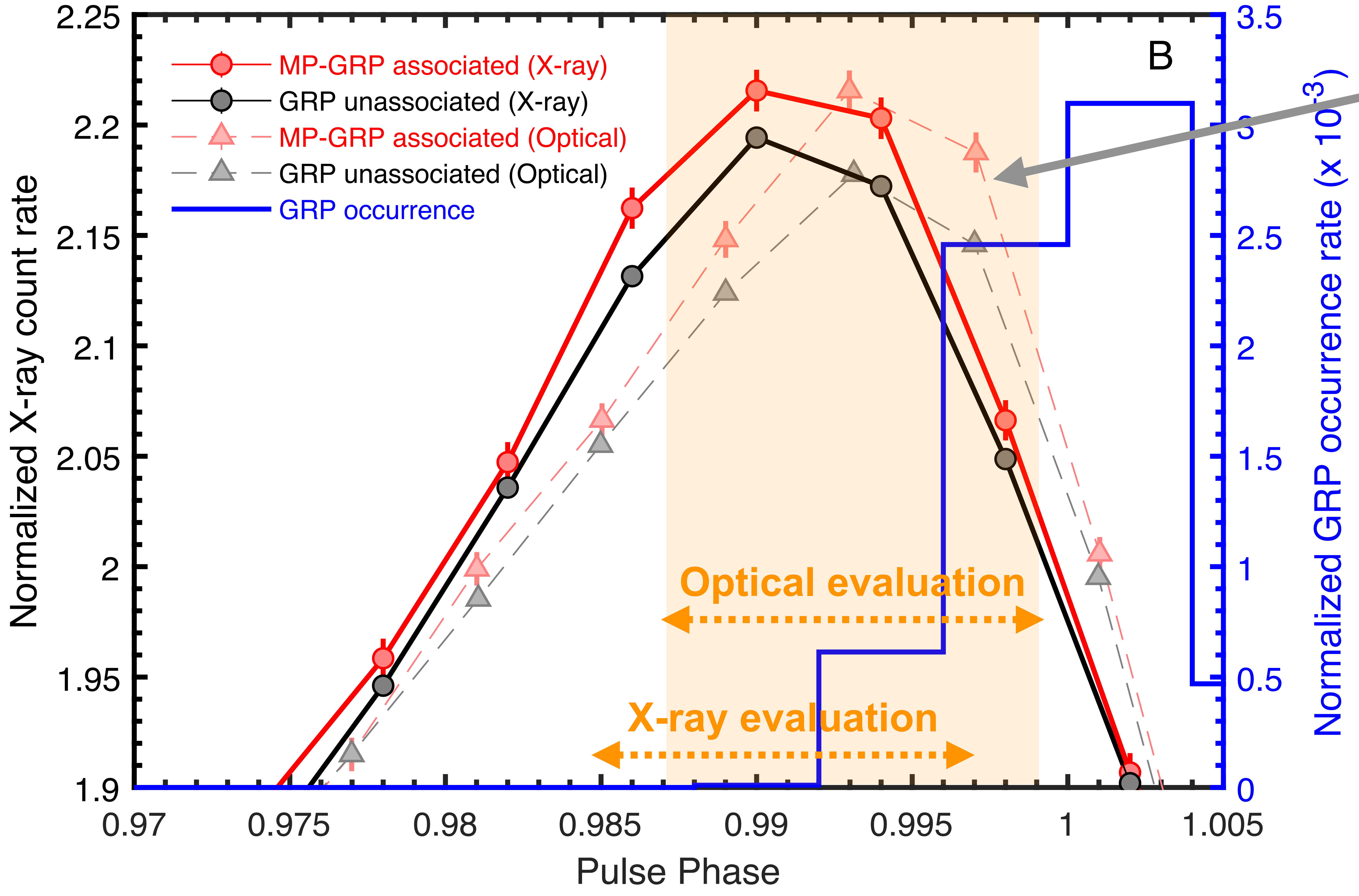
- Detected ~2.5×10^4 GPs at the main pulse phase with the 1.5-day exposure in total accumulated in 2017-2019.

Discovery of X-ray enhancement coinciding with GPs



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

Discovery of X-ray enhancement coinciding with GPs

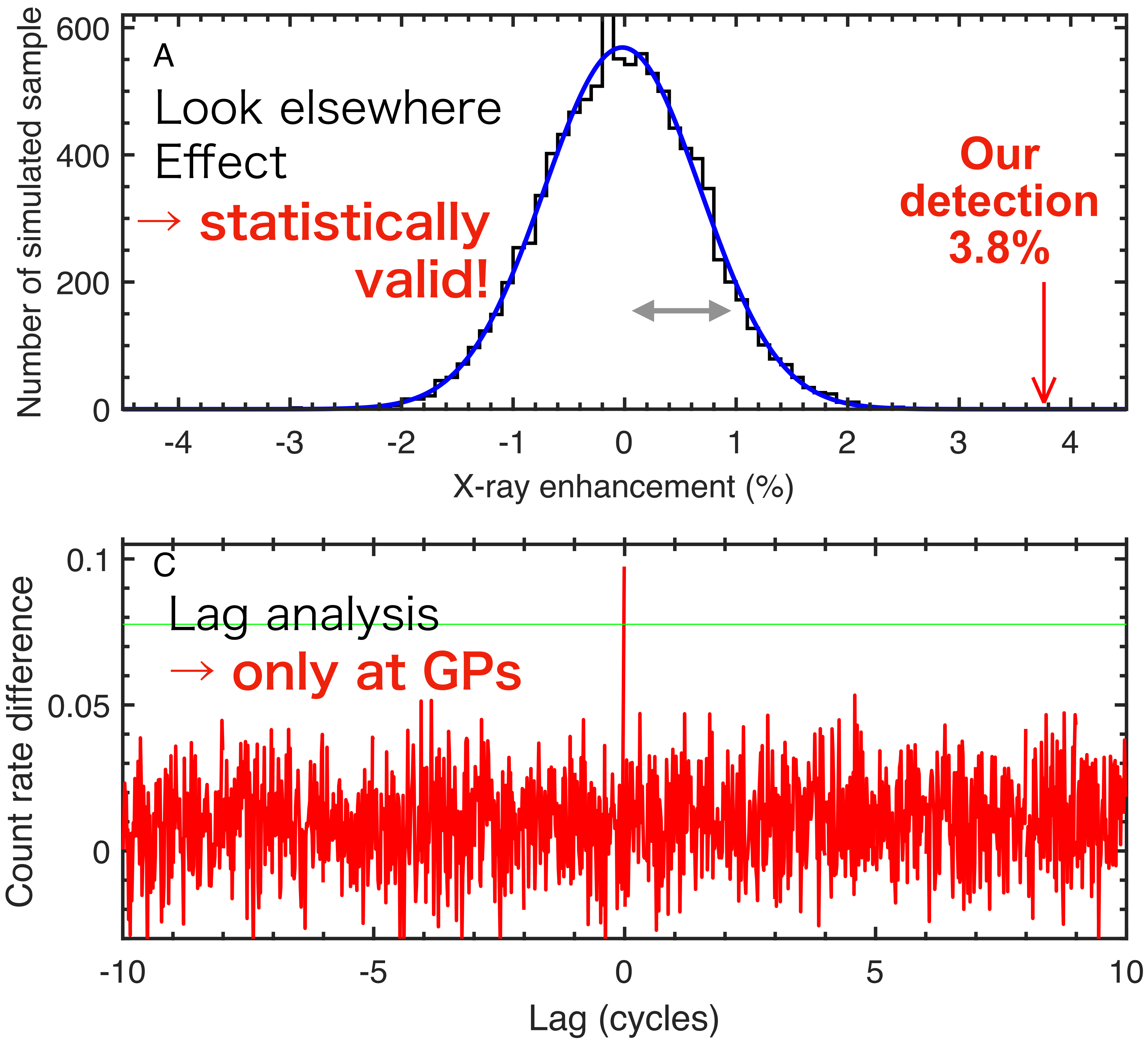


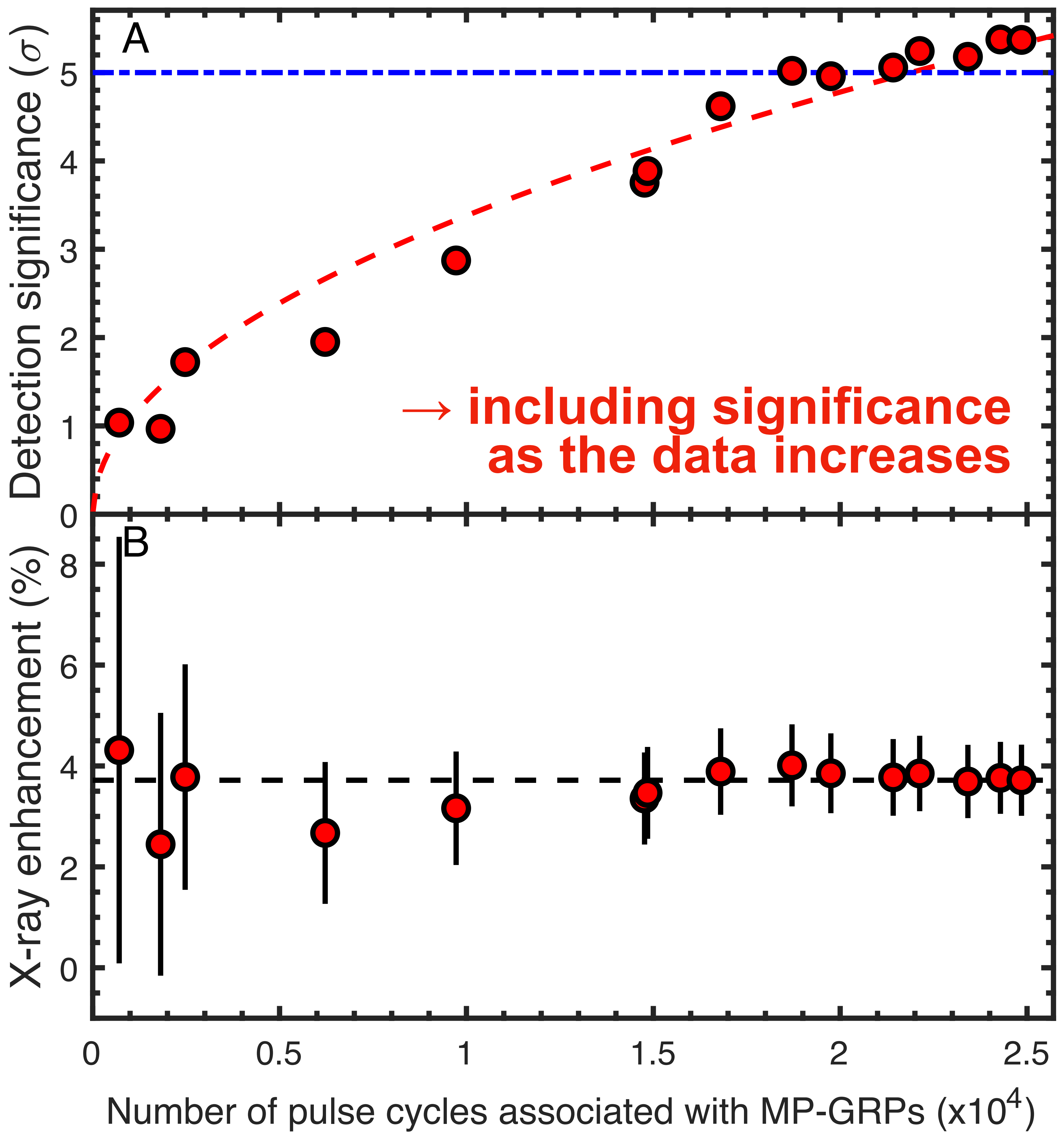
Optical enhancement
(Strader et al., ApJ 2013)

3.2±0.5%
(φ=0.987-0.999)

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

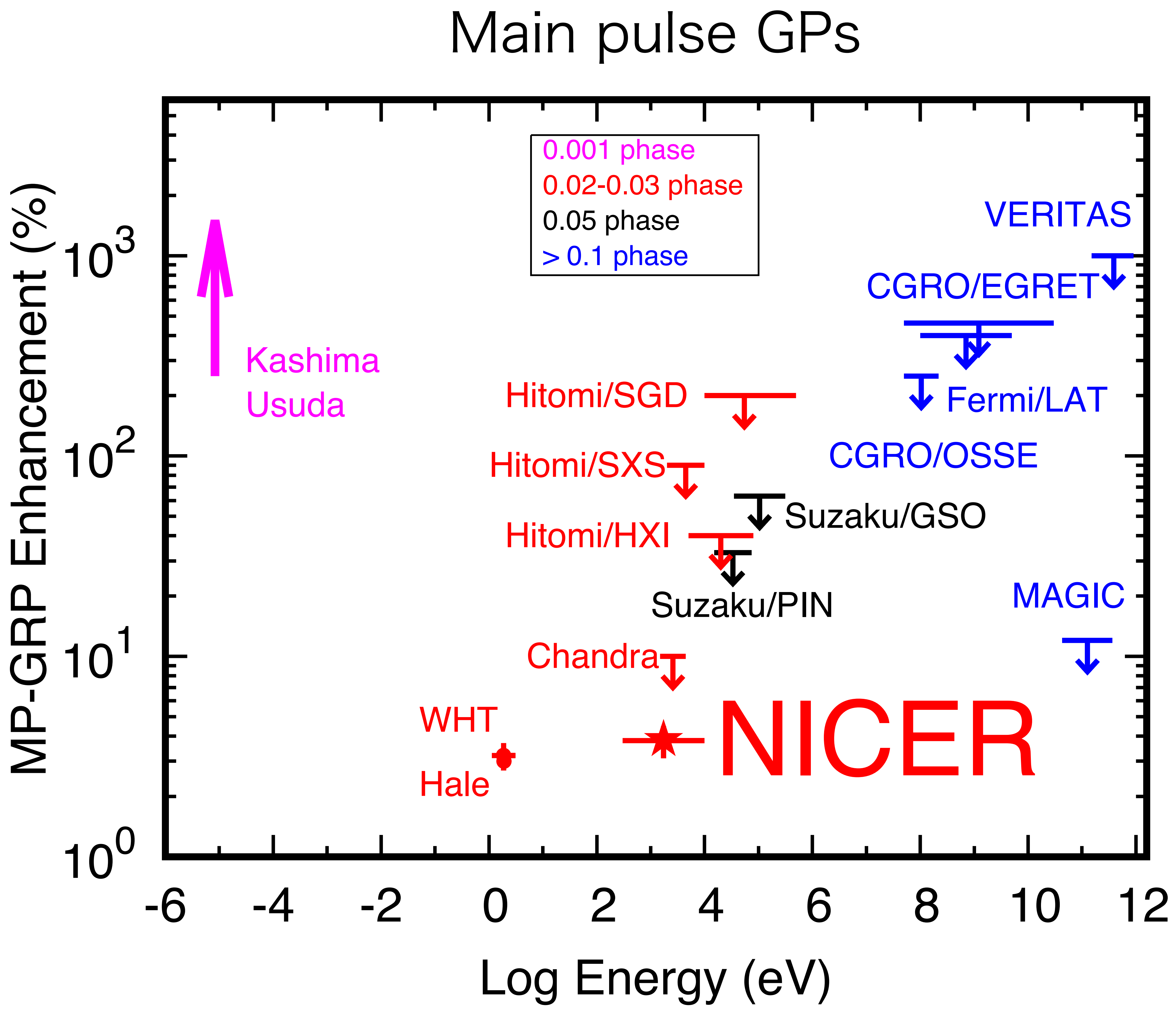
Verified our X-ray detection





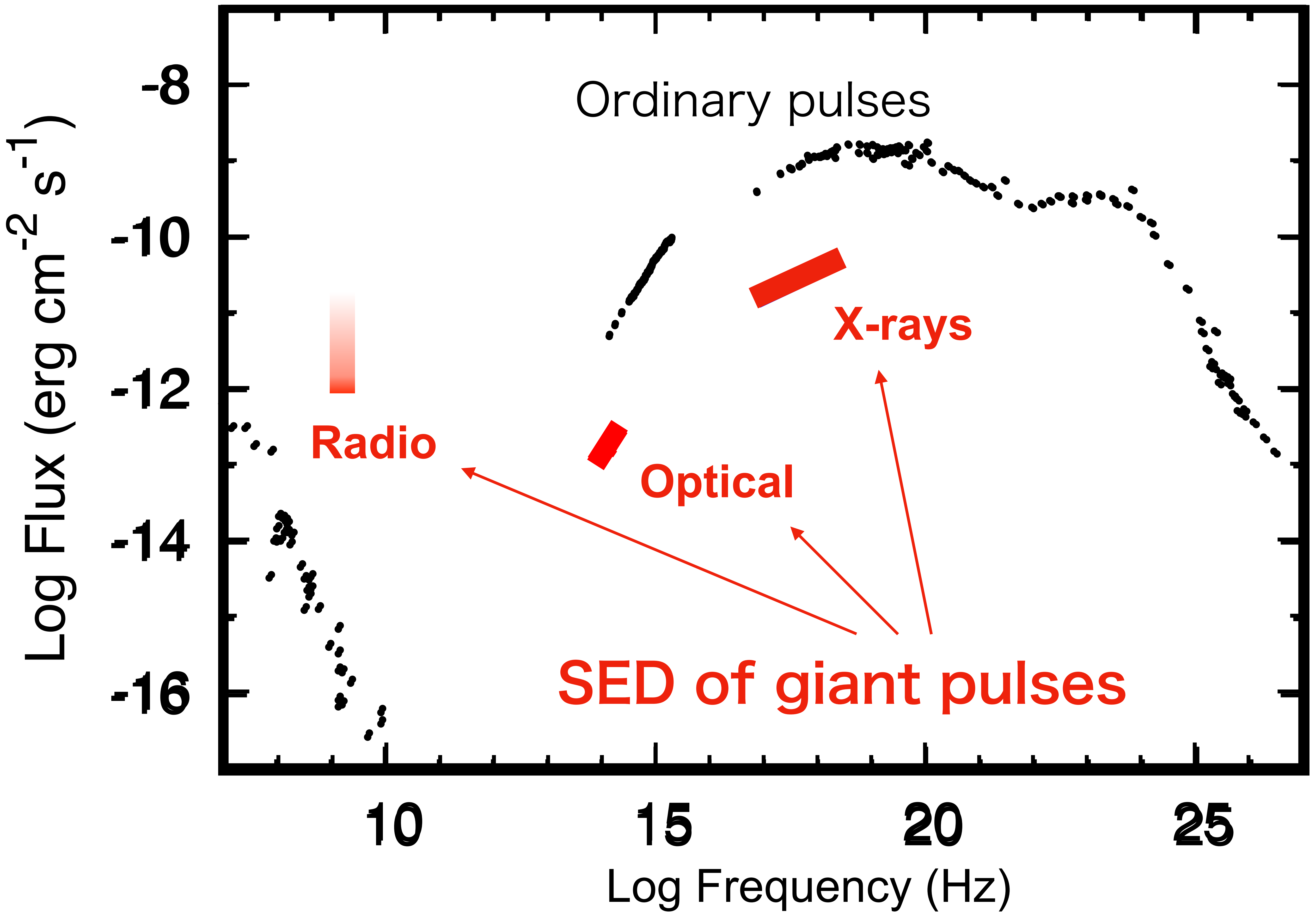
- We confirmed this detection via different verifications (see the paper).

Compared with previous observations



- Our X-ray detection is consistent with the previous upper limits in the X-rays (~10% or higher limits)
- X-ray enhancement (3.8%) is at the same as that in the optical detection (3.2%).
- Only the upper limit (<10%, 3σ) for the interpulse GPs at ϕ= 1.378-1.402.

Compared with previous observations

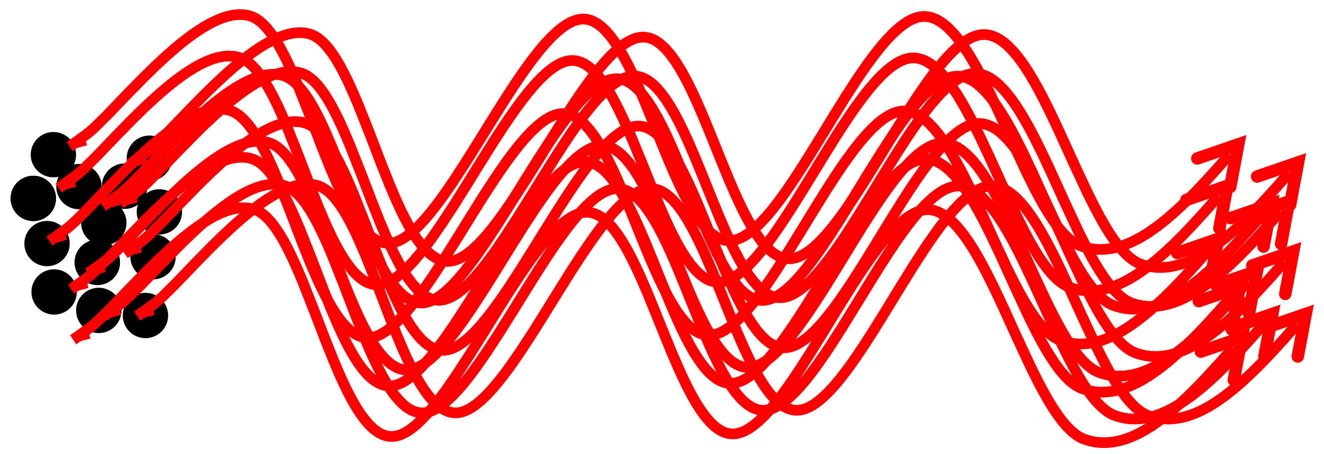


- High-energy pulsar component (optical and X-rays) is distinct from the radio coherent component.
- No difference of the GP-associated X-ray spectrum from the normal pulses.
- X-ray flux of the pulsar component 4.4×10^{-9} ergs/s/cm2 (0.3-10 keV) is 10^3 and 10^7 times higher than those at the optical (5,500A) and radio (2 GHz) bands, respectively.
- **Despite ~4% enhancement, the total emitted energy at GPs is 10-10^2 larger than we previously know.**

Emission mechanism of GPs?

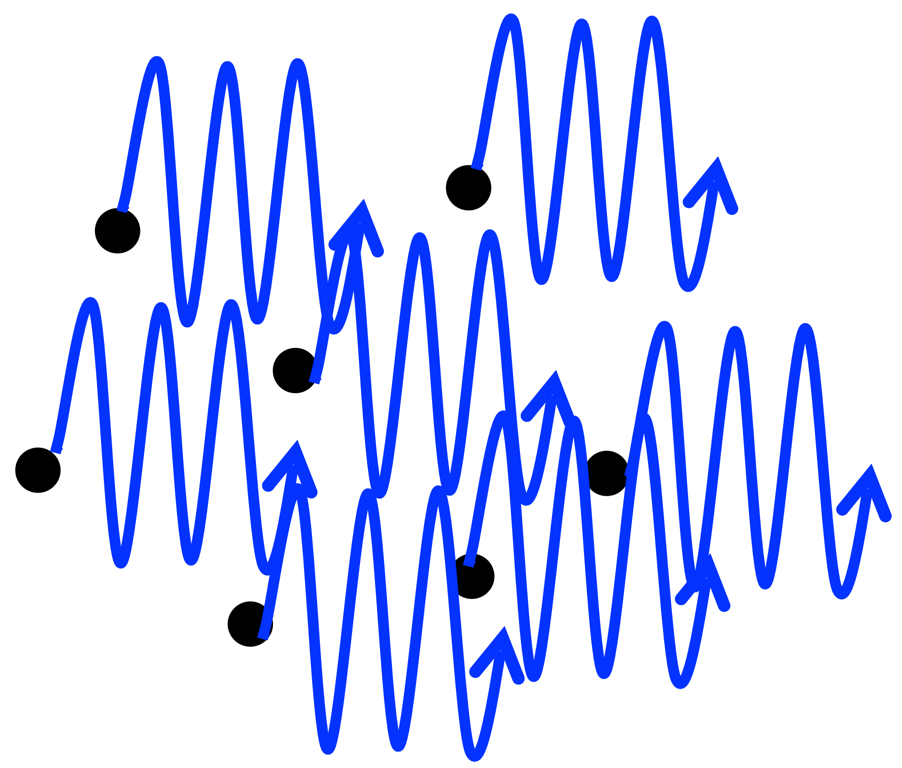
- The emission mechanism of normal radio pulses and GPs is still a mystery.
- Amplification factor at GP is ~10^2-10^3 times at the radio band, while those for the optical and X-rays are an imbalance at only 4%!
- Since radio waves are coherent radiation, they require aligned motions, states and a dense plasma.

Coherent radiation
(radio)



Since the phase is nearly aligned,
the intensity is proportional to
the **square** of the number of particles.

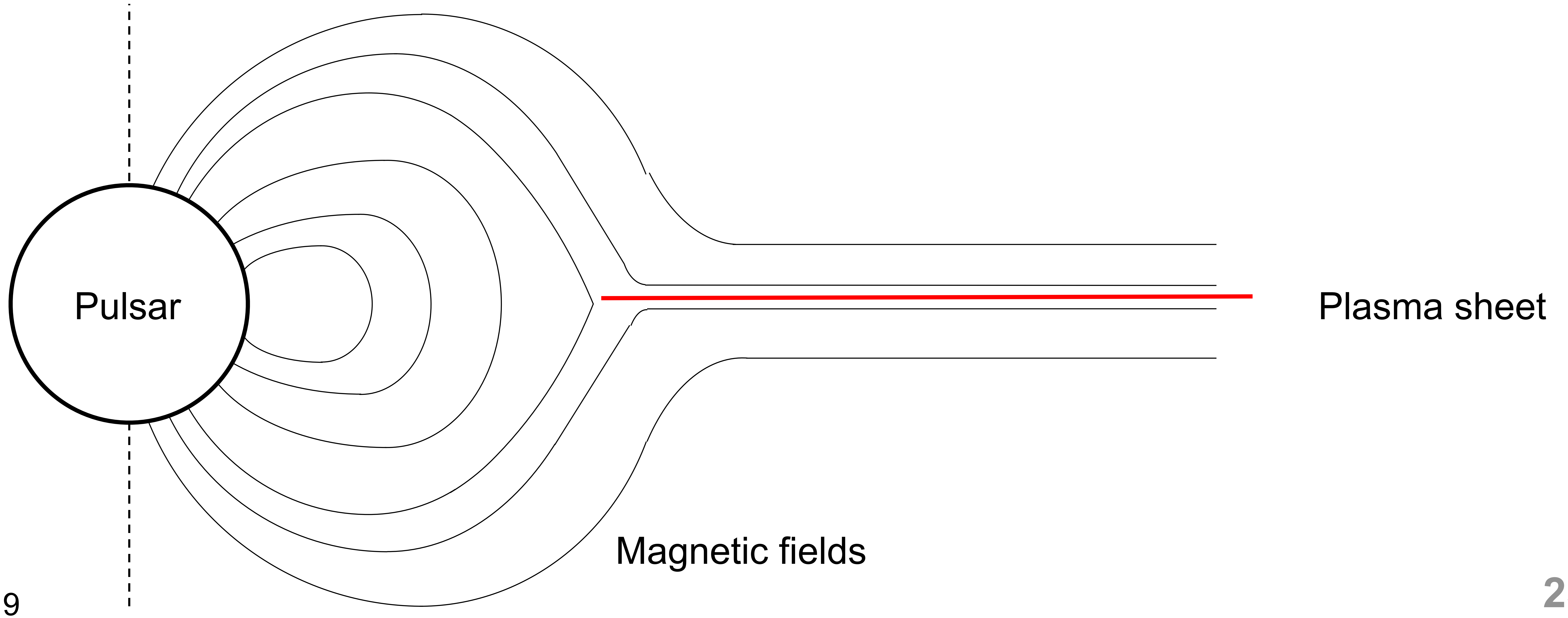
Incoherent radiation
(Optical and X-rays)



Since the phase is not aligned,
the intensity is proportional to
the number of particles.

Emission mechanism of GPs? (One Hypothesis)

- A sheet of dense plasma is formed in the outer part of the pulsar magnetosphere.
- The plasma sheet is structurally unstable and tear apart to form plasma blobs.
- The blobs repeatedly collide and merge, and sometimes grow to ~100 times (thickness).
- As the blobs coalesce, radio pulses are generated in the dense region, while X-rays are emitted from the entire sheet.



Based on
Philippov et al. ApJL 2019

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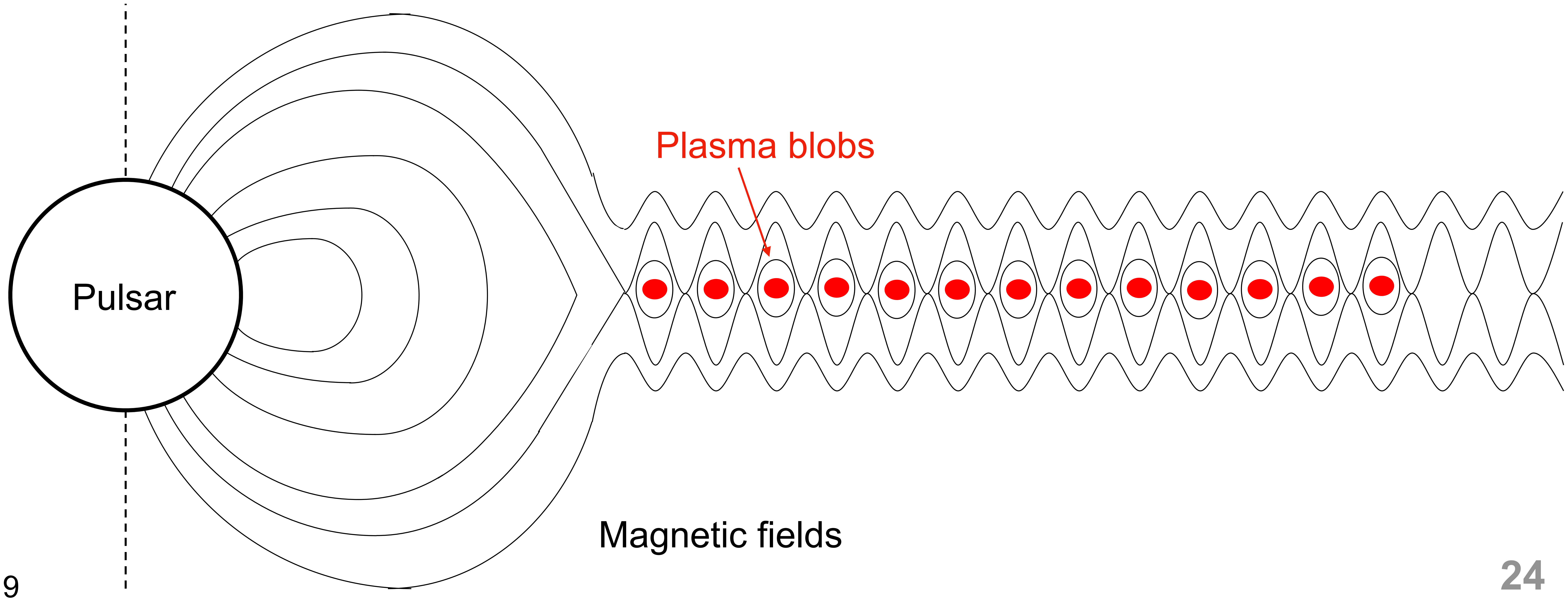

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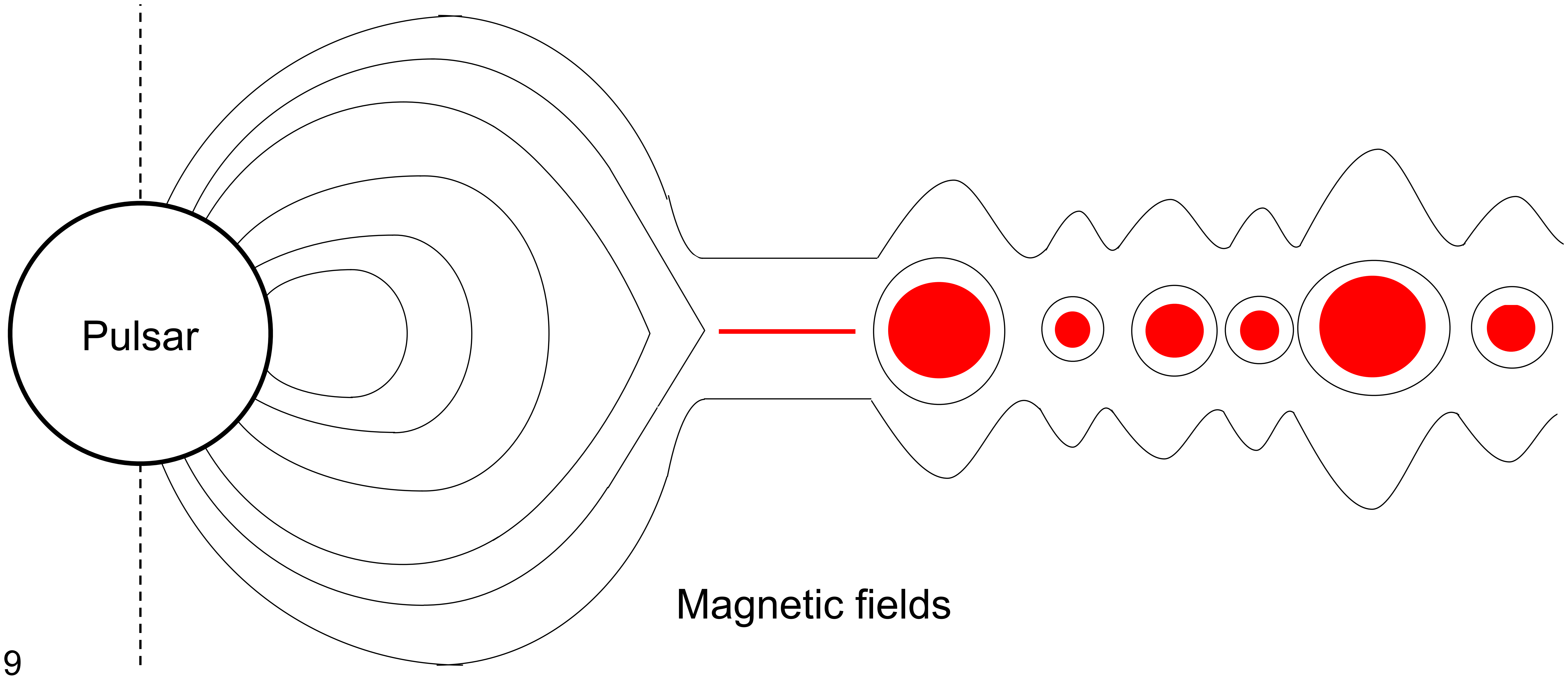

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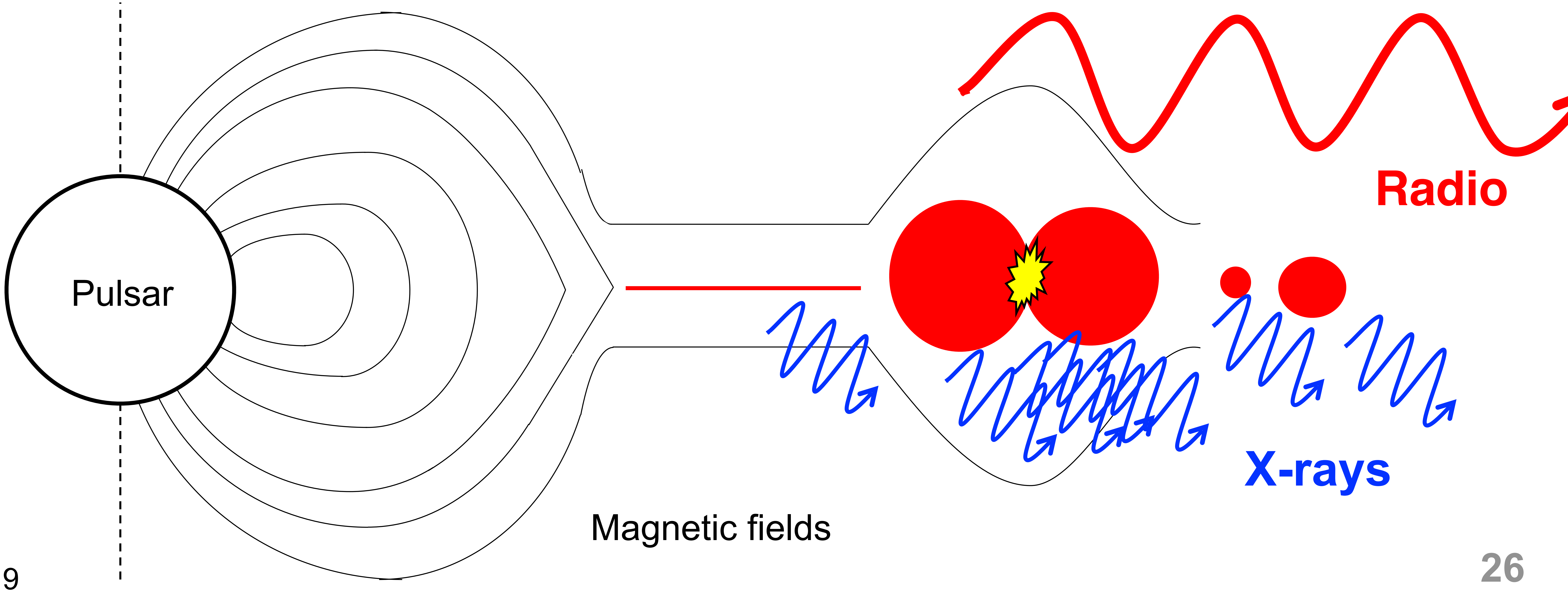


Based on
Philippov et al. ApJL 2019

Implication for the mystery of FRBs

- Hypothetical bright GRP 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 GRP 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. This is also shown the FRB-associated bursts from SGR 1935+2154. Burst activities of magnetars (magnetic energy release) is more favored for FRBs?

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

… End of the Kashima Radio Observatory Operation

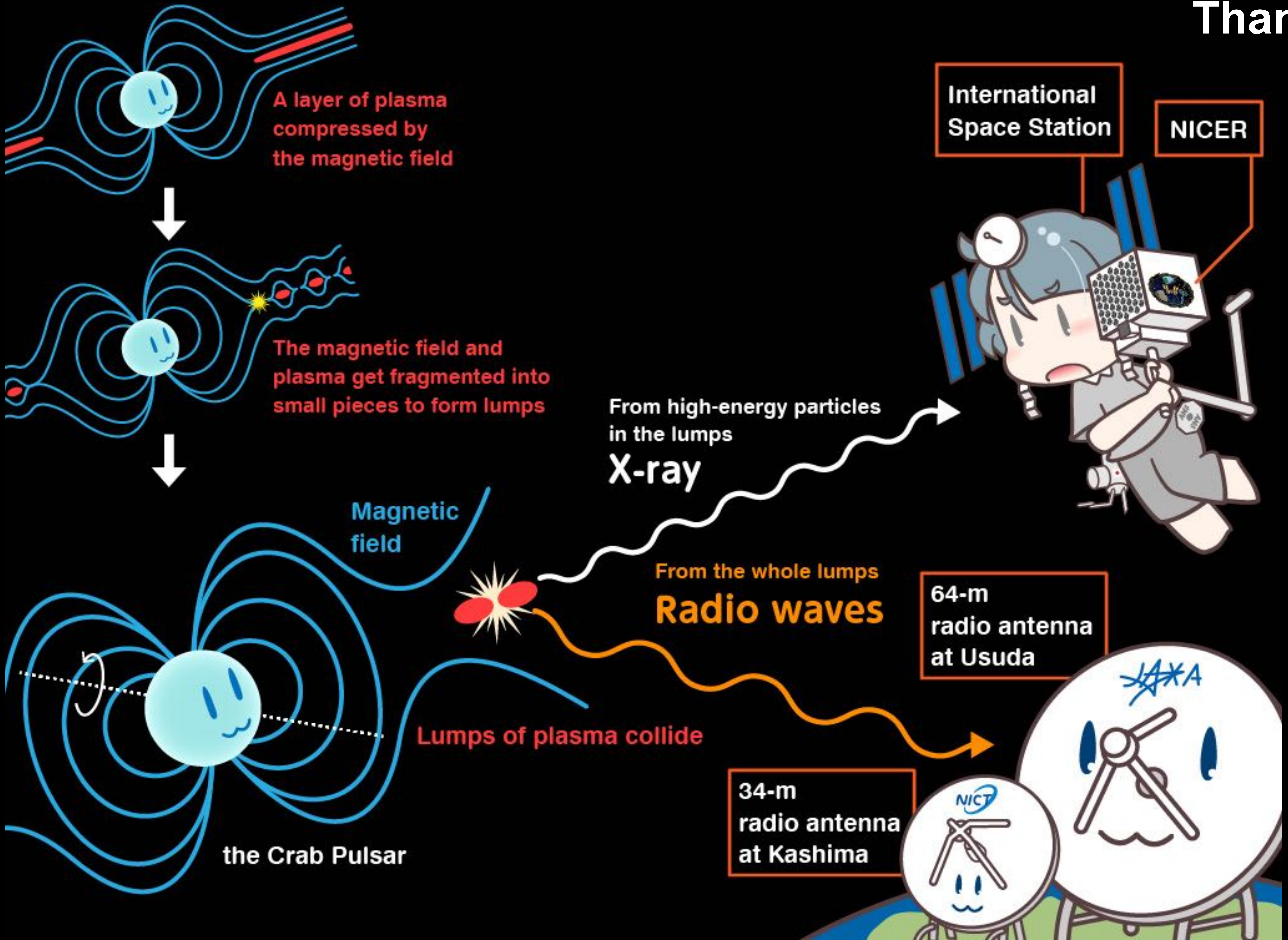
- The Kashima 34-m radio telescope, operated by the National Institute of Information and Communications Technology (NICT), has been an important instrument for radio astronomy.
- It was severely damaged by Typhoon No. 15 in 2019 and its operation was terminated.
- This achievement is one of the last precious legacies left by the Kashima 34 m radio telescope.
- We are looking forward to have another chance to collaborate with other radio telescopes as well.

Panel removal (September 2019)

Summary

1. The electromagnetic radiation mechanism from pulsars still has many unsolved problems. Giant pulses (GPs) are sporadic radio bursts 100-1000 times brighter than the normal radio pulses, and thus a powerful probe to investigate a pulsar magnetosphere within a single rotation.
2. NICER Magnetar and Magnetosphere (M&M) working group coordinated a simultaneous X-ray and radio observation campaign for the Crab pulsar in 2017-2019. We detected the X-ray enhancement by $3.8\pm0.7\%$ (5.4σ detection) coinciding with radio GPs at the main pulse phase.
3. This implies that the total emitted energy from GPs is tens to hundreds of times higher than previously known. Repeating fast radio bursts are difficult to be explained by a model based on hypothesized bright GPs powered by the rotational energy loss. Young magnetars are favored?

Thank you!



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