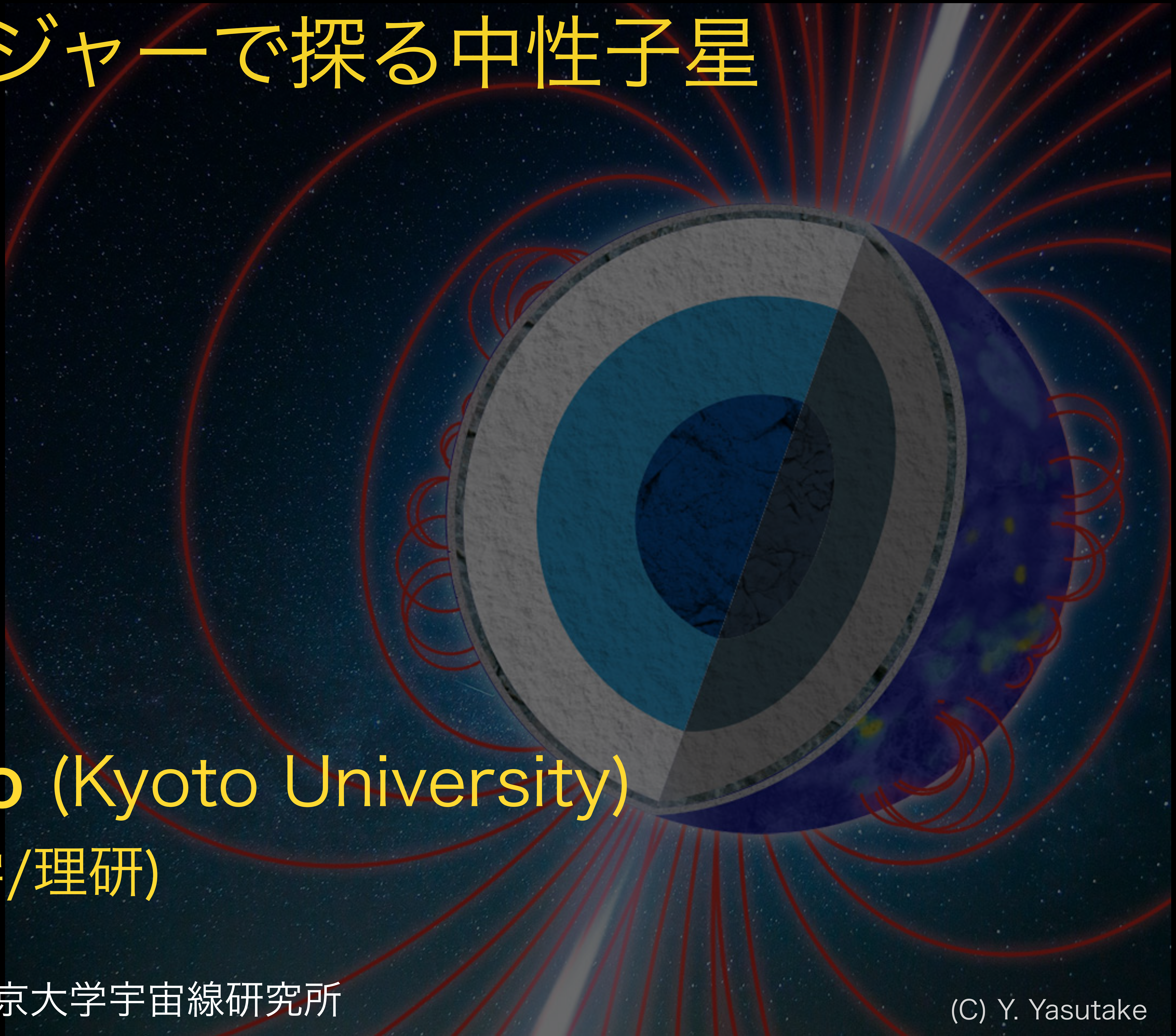
Neutron Stars in the Multi-messenger Era

マルチメッセンジャーで探る中性子星



(C) Y. Yasutake

Teruaki Enoto (Kyoto University)

榎戸輝揚 (京都大学/理研)

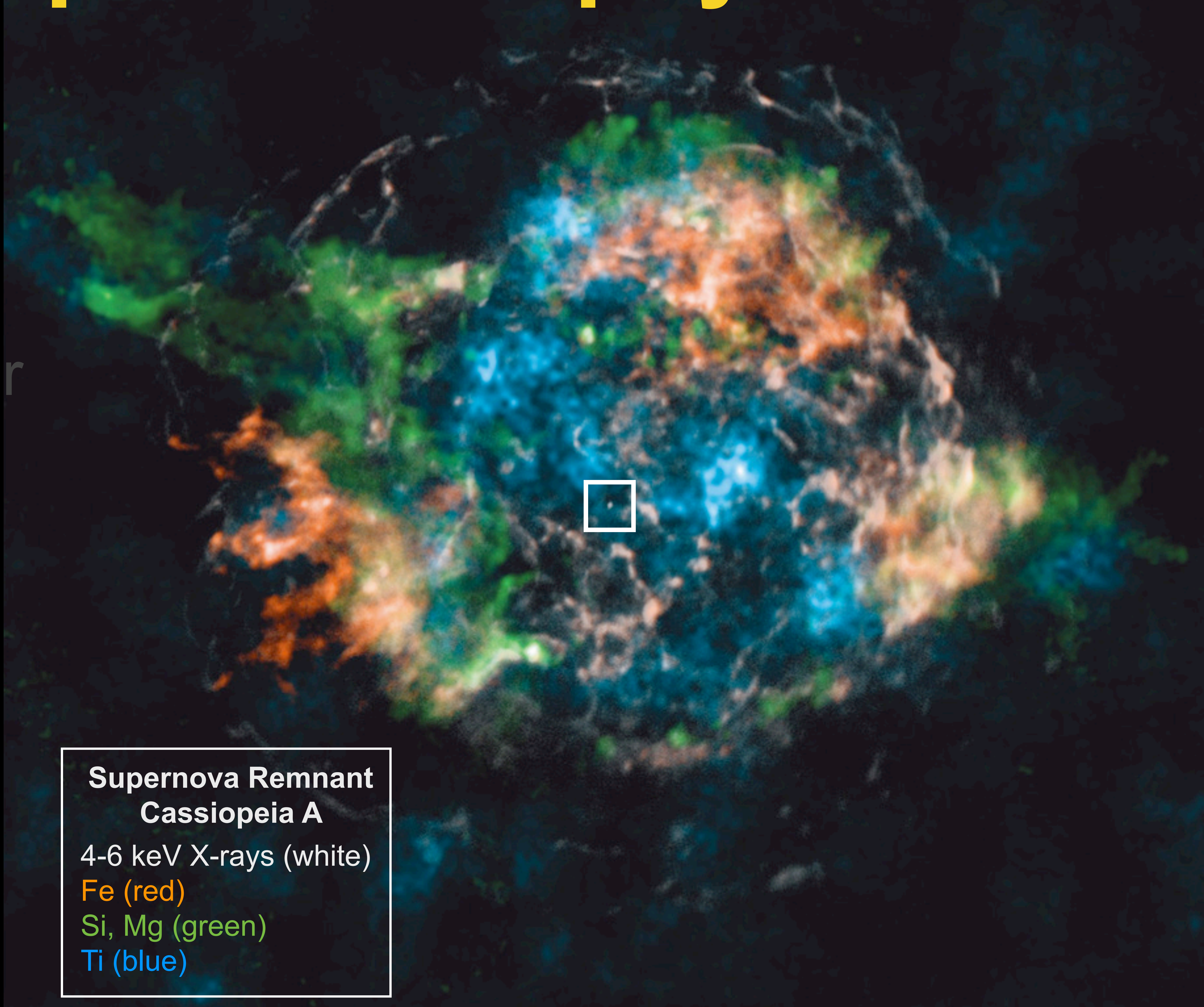
マルチメッセンジャー天文学の展開研究会

2023年11月1日 (水曜日) 16:20-16:45 (25min), 東京大学宇宙線研究所

Neutron star (NS) important for physics

- Neutron star (mass M~1.4 M_{sun} and radius R~10 km) is formed via a gravitational collapse of a massive star

1. High-density interior (> nuclear density 3×10^{14} g/cm^3)
2. Strong gravity to generate gravitational waves (GWU)
3. Rapid rotation (~> a few ms) makes cosmic-ray outflow
4. Strong-magnetic field (QED critical field, $B=4.4\times10^{13}$ G)
5. High-intensity radiation fields



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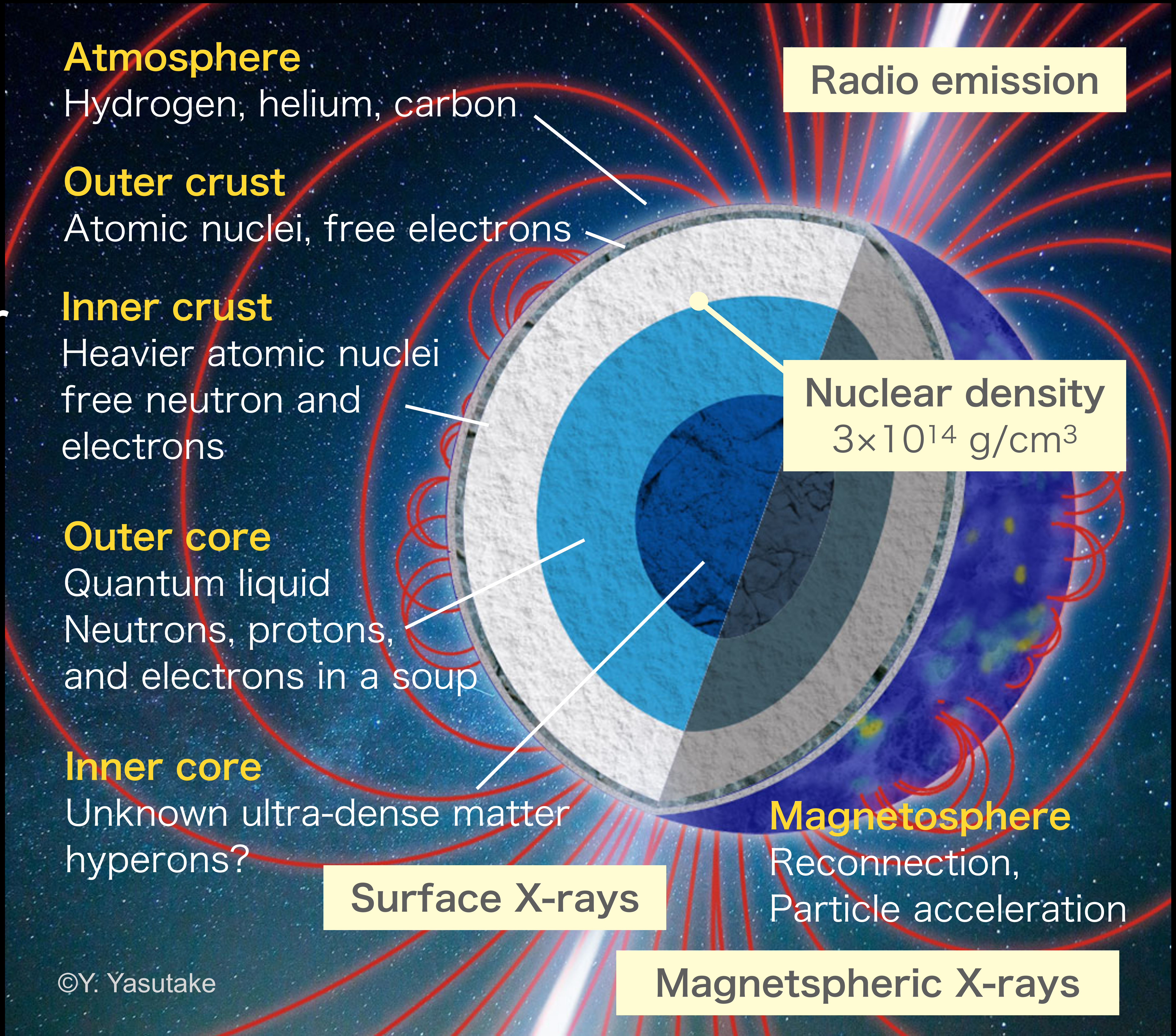
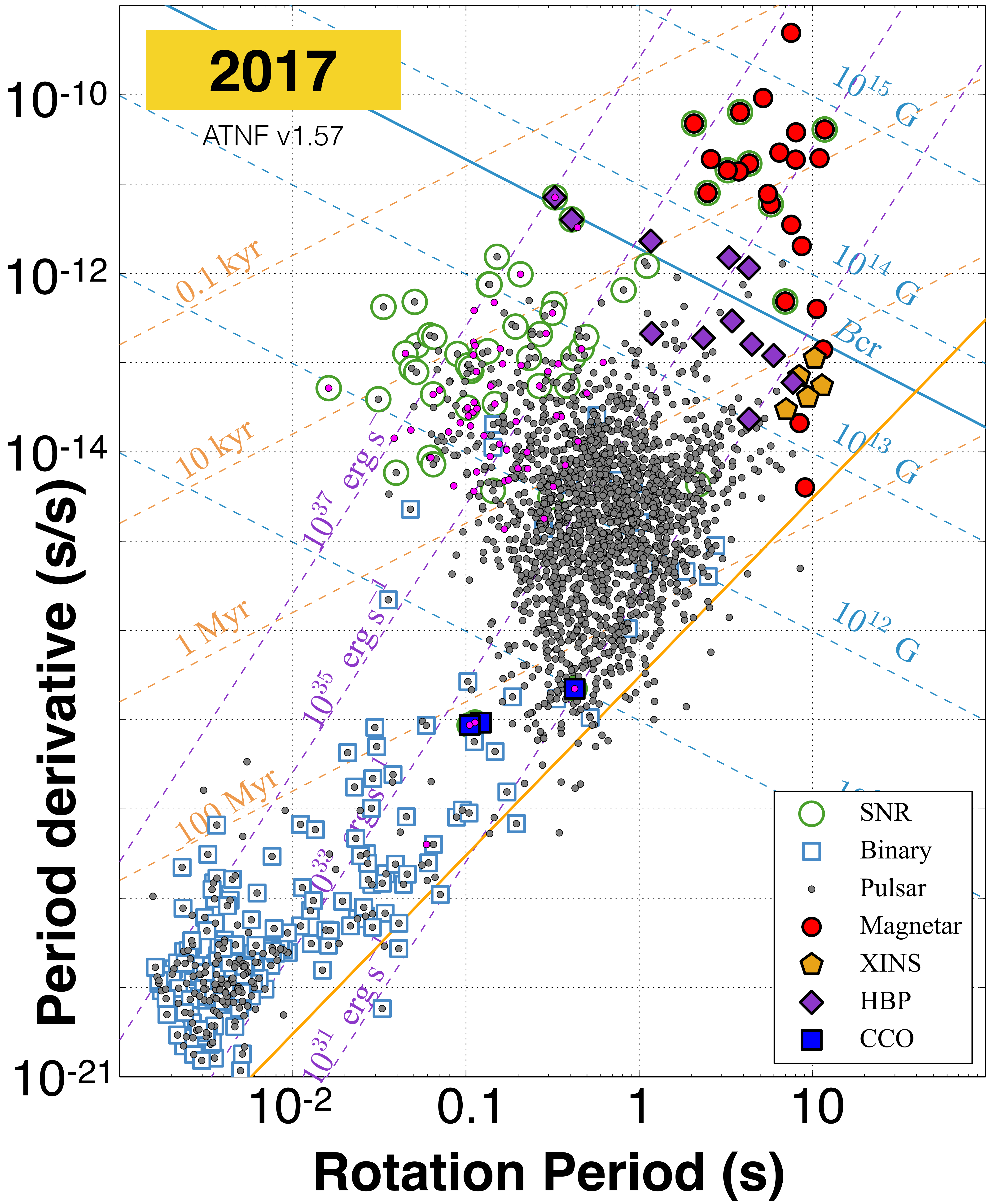


Multi-wavelength observation and diversity of NSs

- >3,300 known pulsars discovered
- 10^5 in our Galaxy?
- Multi-wavelength observation by radio, optical, X-rays, and γ-rays.
- Diverse NS species have been discovered. Challenge to unification of different NS classes
- Multi-wavelength observations have become an essential, and multi-messenger observations have become gradually popular.



Enoto, Kisaka, Shibata, 2019, ROPP

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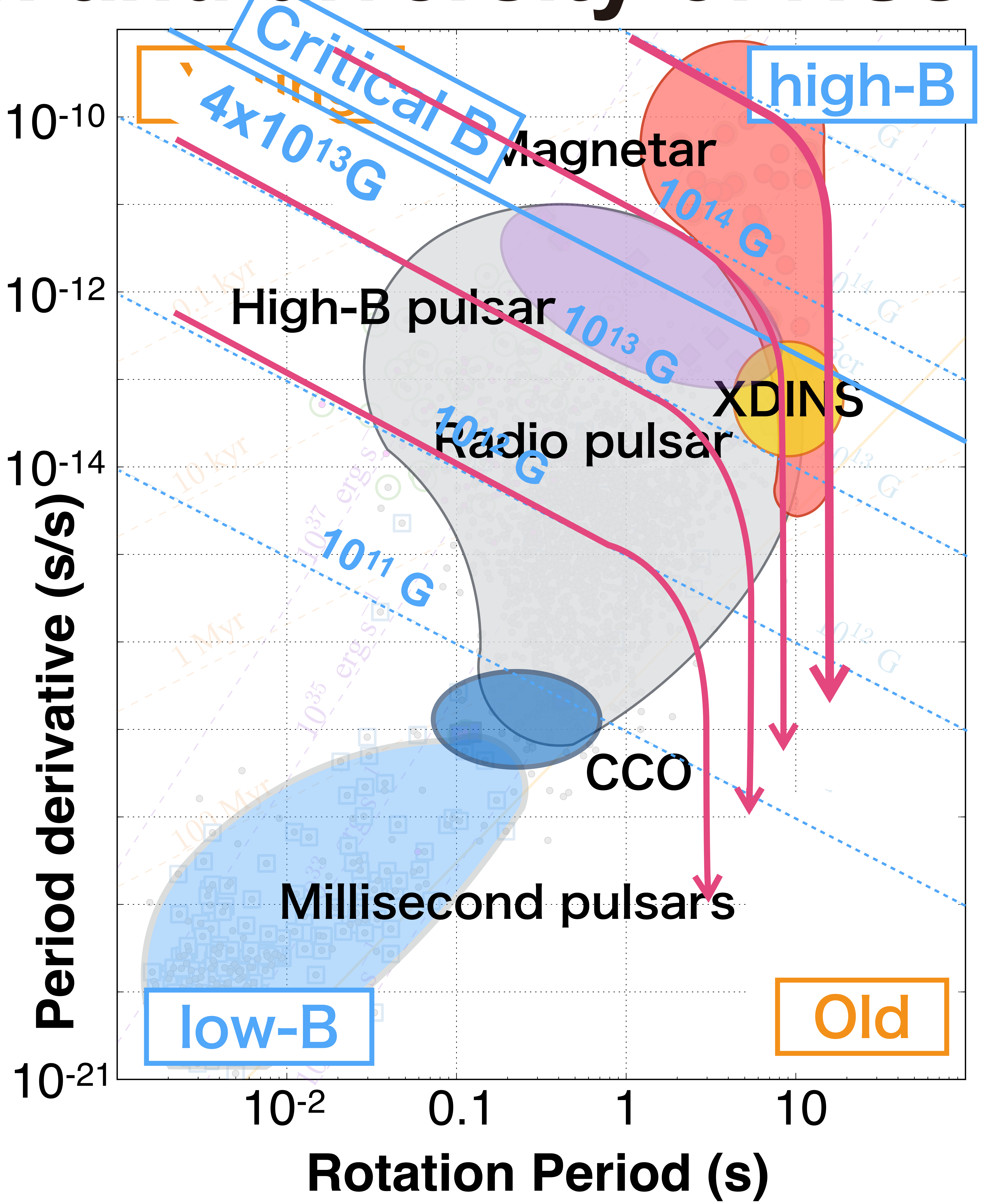
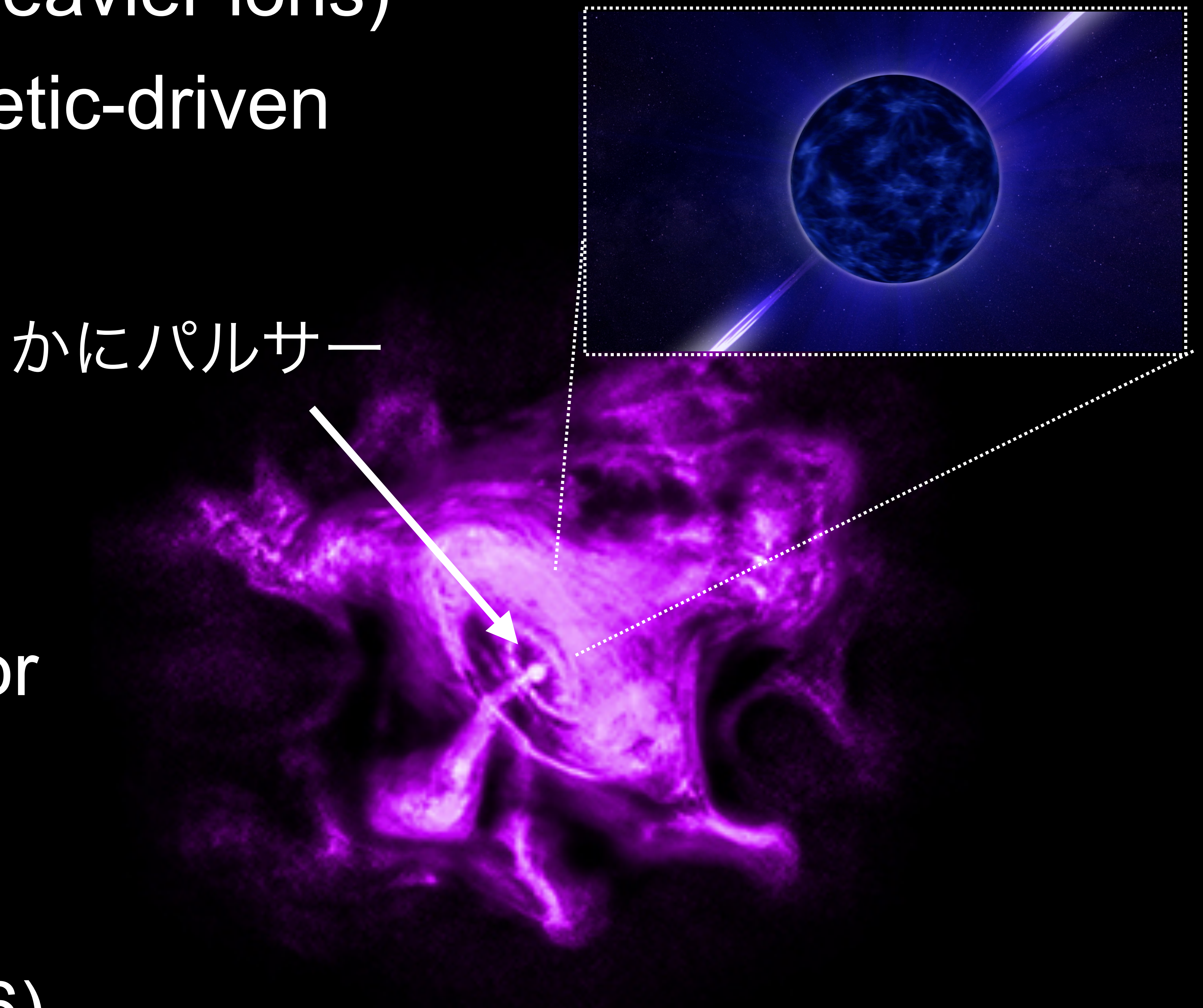


Enoto, Kisaka, Shibata, 2019, ROPP

Neutron stars (NSs) as a multi-messenger source

- **Cosmic rays** (=charged particles, p, e-, e+, heavier ions)
  - Particle acceleration via rotational or magnetic-driven
- **Multi-wavelength photon**
  - Radio, optical, X-rays, and γ-rays
- **Neutrinos**
  - Supernovae (e.g., SN 1987A)
  - Long-term neutrino cooling in the NS interior
  - Hadronic interaction of protons?
- **Gravitational wave (GW)**
  - Indirect GW detection (e.g., PSR B1913+16)
  - Binary NS merger inspiral (e.g., GW 170817)
  - Coherent GW from a fast spinning NS?

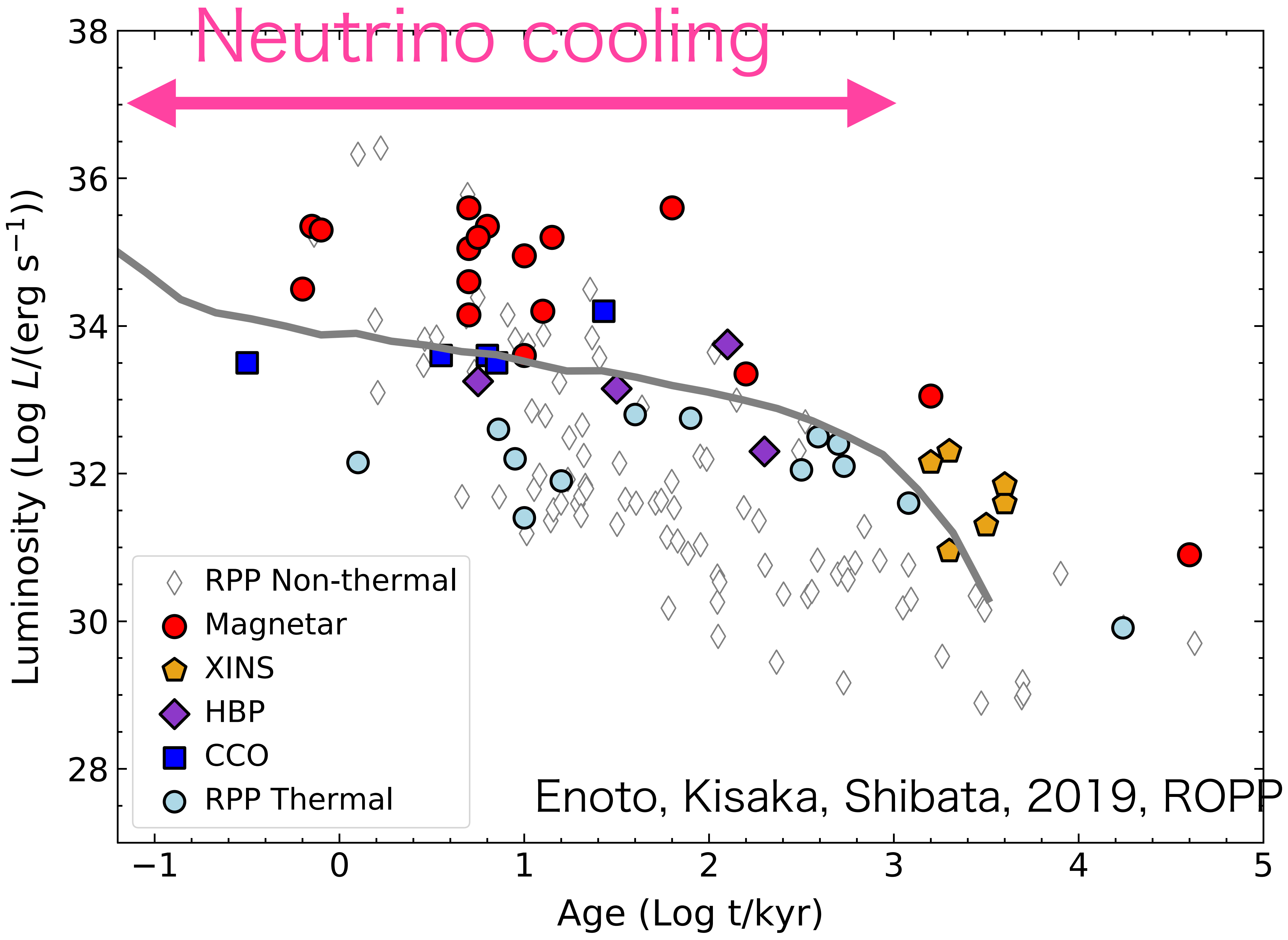


かに星雲 (Crab Nebula)
X線（チャンドラ宇宙望遠鏡）

Credit: NASA/CXC/SAO/STScI

Detected or expected neutrinos from NSs

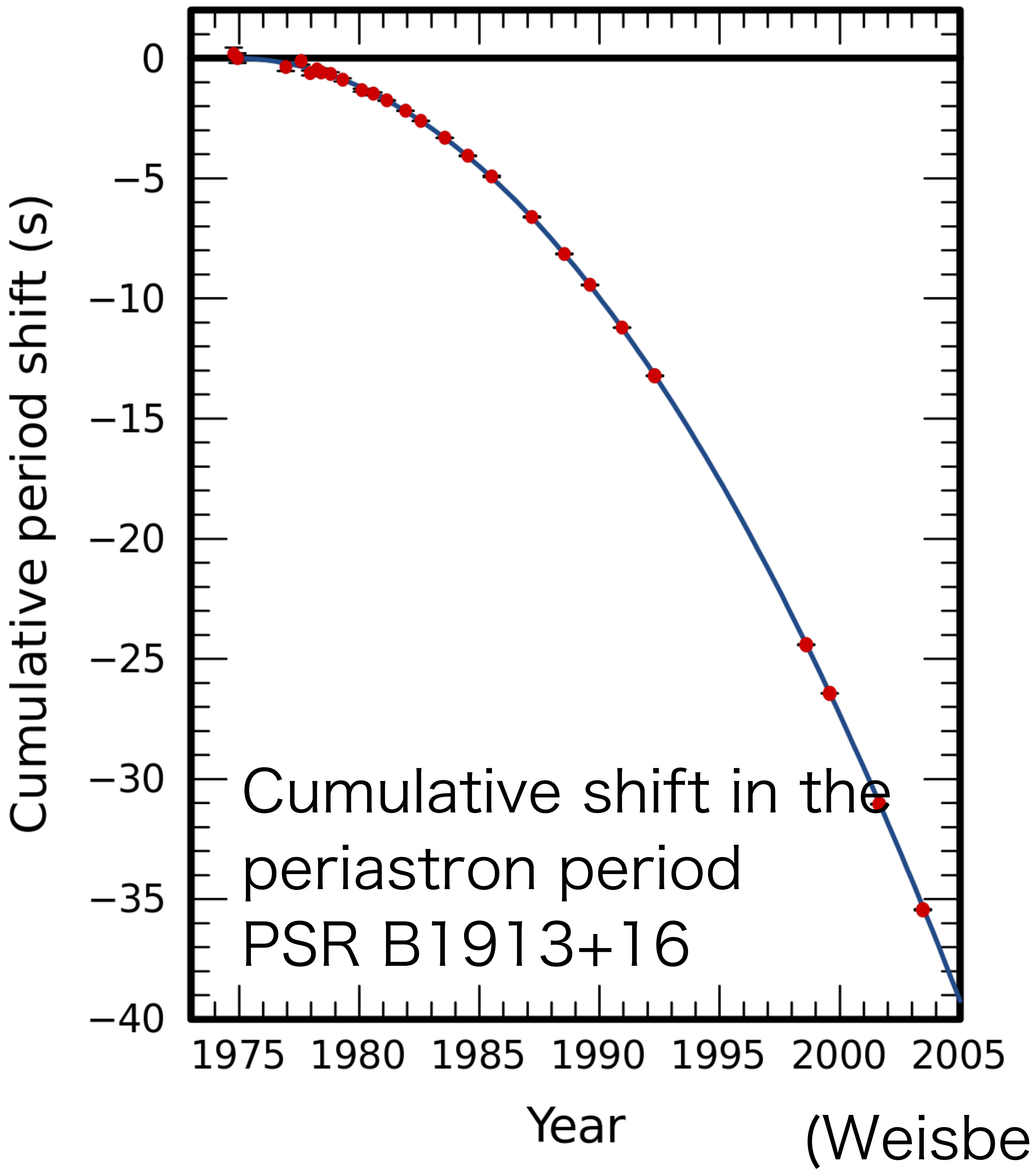
- Neutrino detection at SN 1987A
- Indirect estimation of neutrino emission from the NS core in the long-term NS cooling curve.



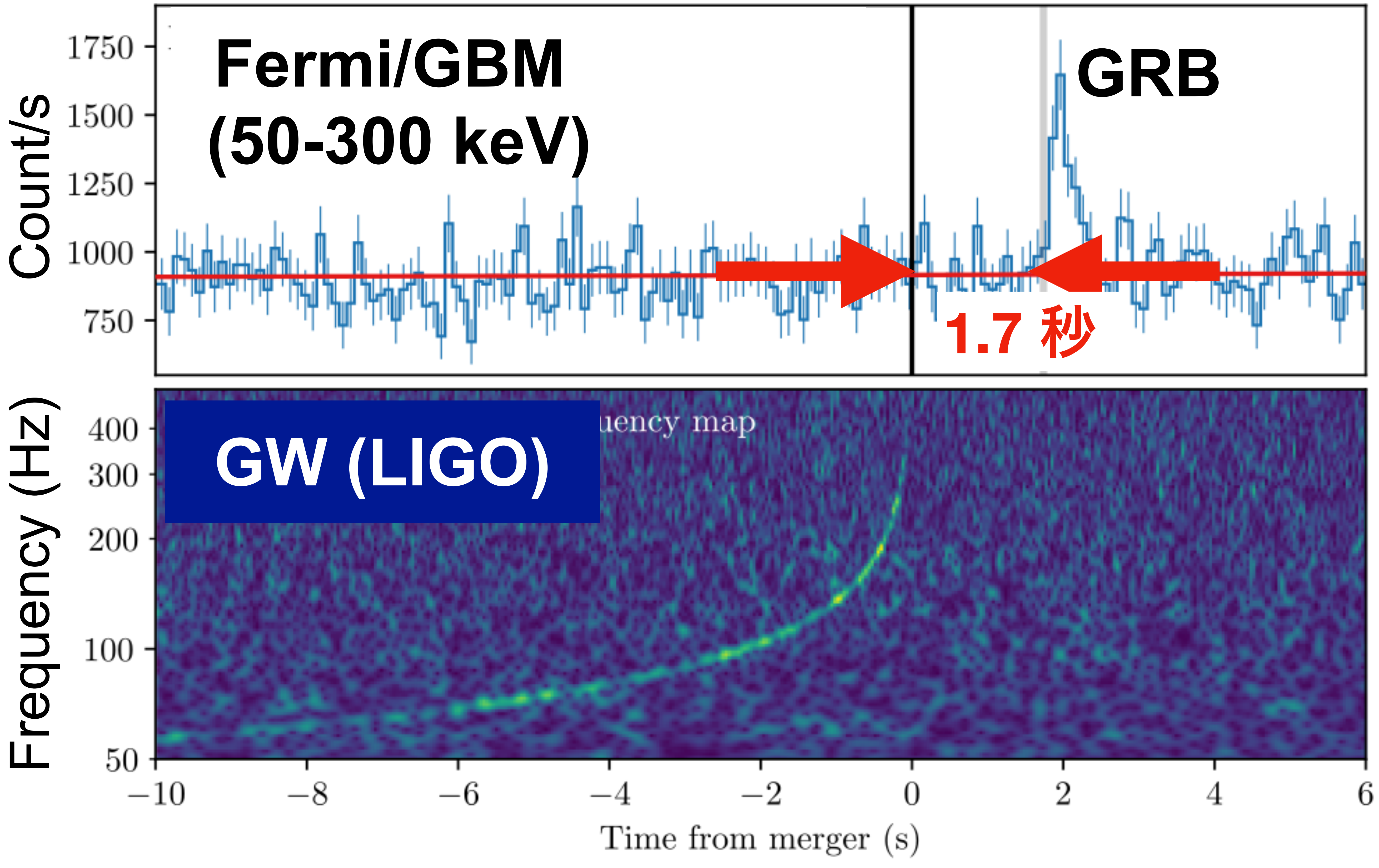
- Ion acceleration (to ~1 PeV) in young rapidly rotating neutron stars, which would become a neutrino source? (Link & Burgio, 2006; Bhadra & Dey, 2009)
  - $p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+ \rightarrow n\nu_\mu\mu^+ \rightarrow n\nu_\mu e^+\nu_e\overline{\nu_\mu}$
- Neutrinos from new born magnetars? (Murase+2009)
- TeV-PeV neutrinos from giant flares of magnetars? (Ioka+2005)
- Thermal neutrinos from the remnant of binary NS merger? (Kyutoku & Kashiyama, 2018)

Gravitational wave (GW) from NSs

- GW discovery via radio observations of the Hulse-Taylor pulsar PSR B1913+16 in 1974, and the direct GW detection of GW 170817 in 2017.
- Glowing sample of GW events —> Measurements of the EoS of NSs and their inertia of moment? (榎戸, 久徳, 原子核研究, 2023)



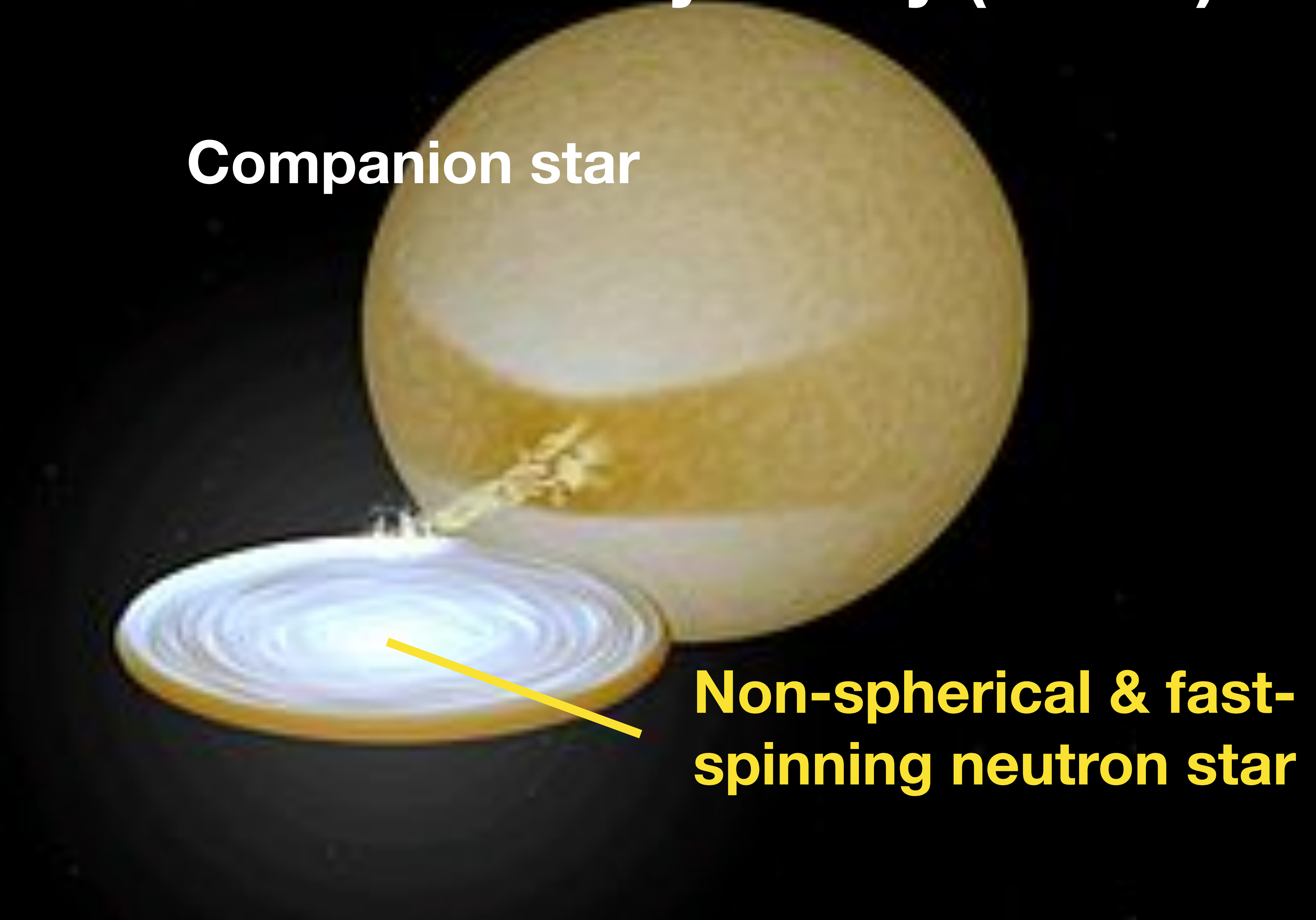
(Weisberg & Taylor, 2005)



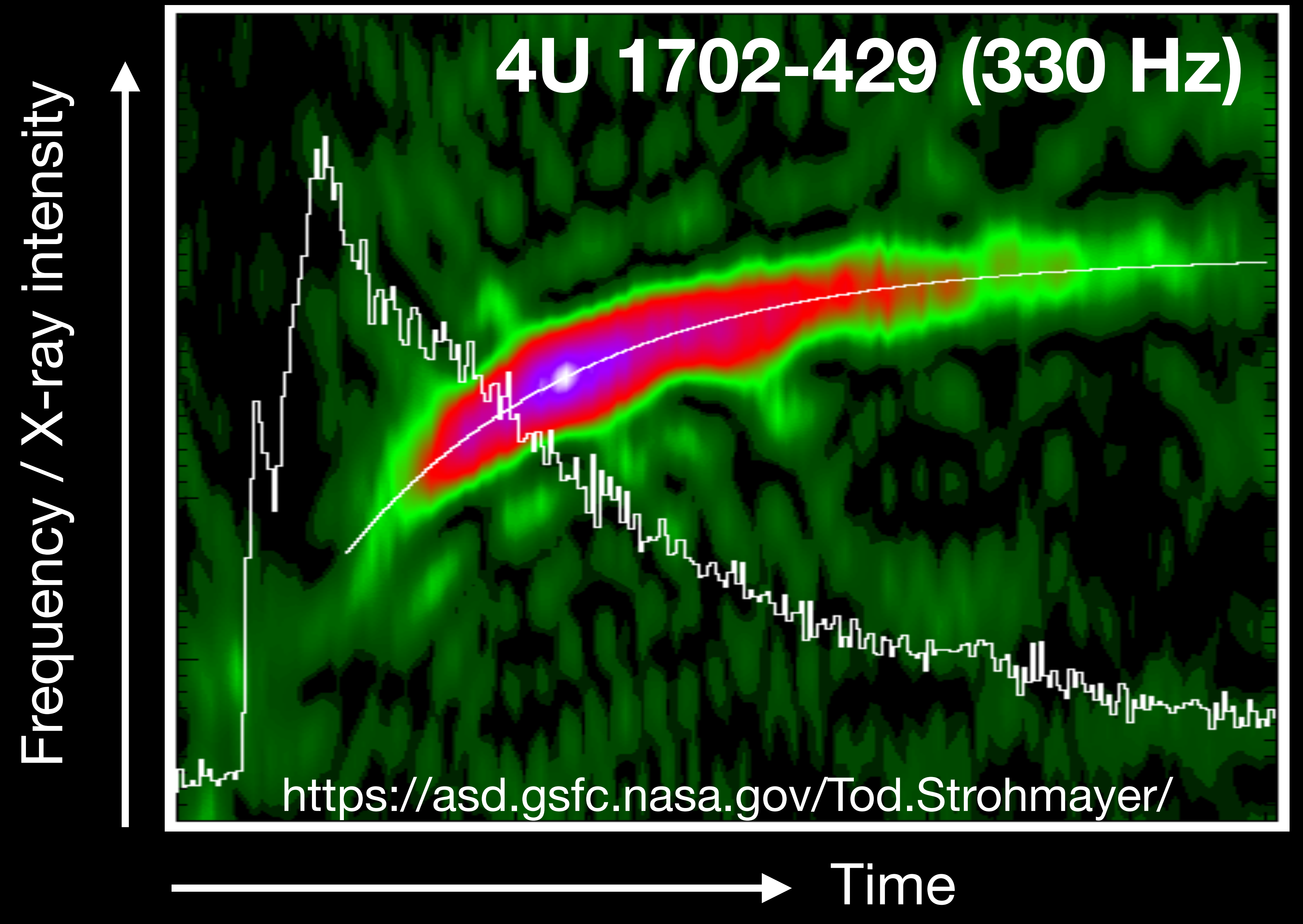
LIGO & Virgo Scientific Collaboration, ApJ (2017)

Scorpius X-1 — Brightest X-ray source in the sky

Artists illustration of
Low-mass X-ray binary (LMXB)



Spin frequency detection in X-ray burst?



- Spin-up of a neutron star due to angular momentum inflow of the accreting matter
- Critical spin frequency at ~1 kHz before a stellar collapse by the centrifugal force
- Observed spin frequencies of weakly-magnetized neutron stars are ~160-620 Hz
- What pulls out the angular momentum? Disk? Continuous gravitational wave?

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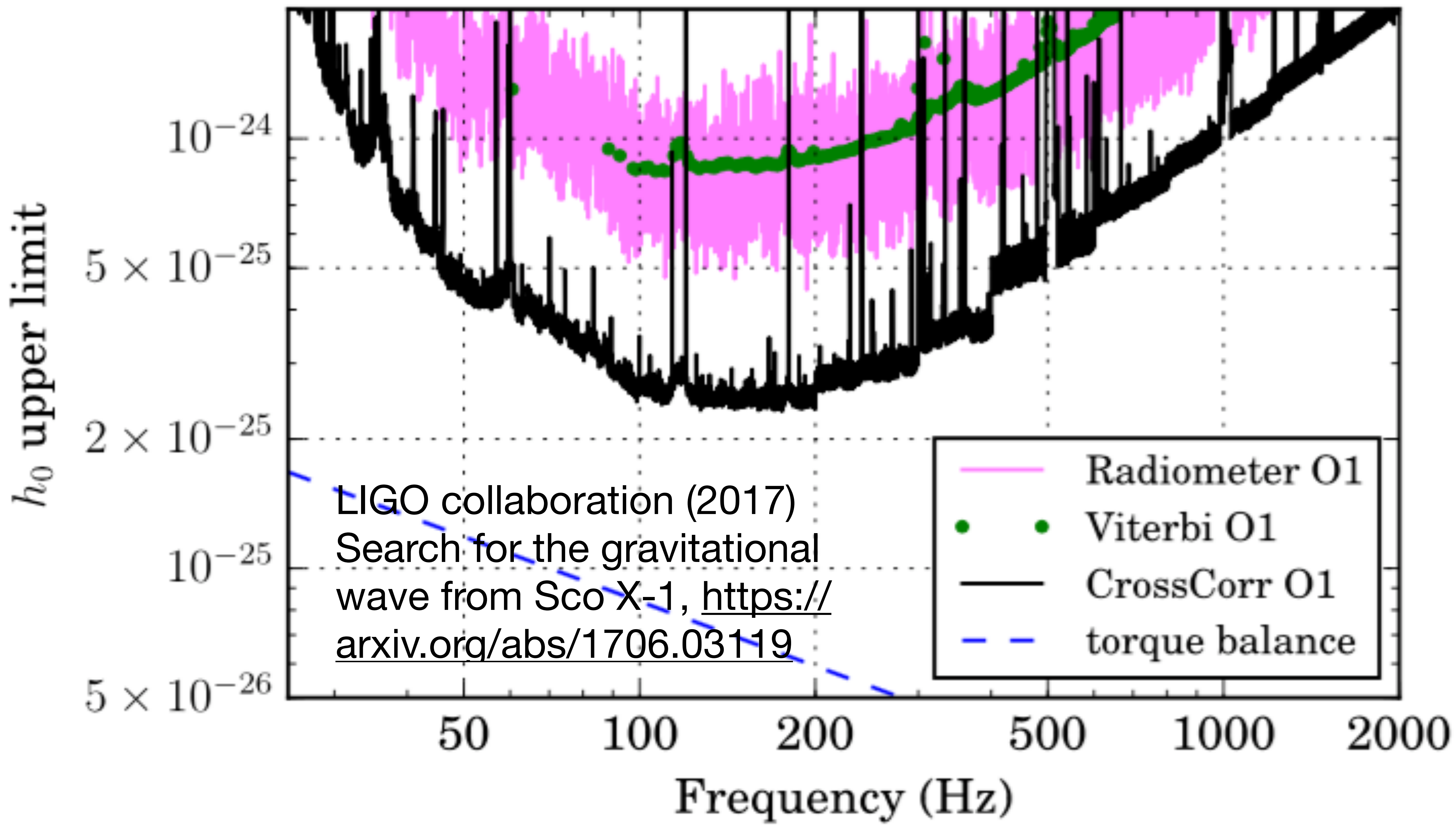
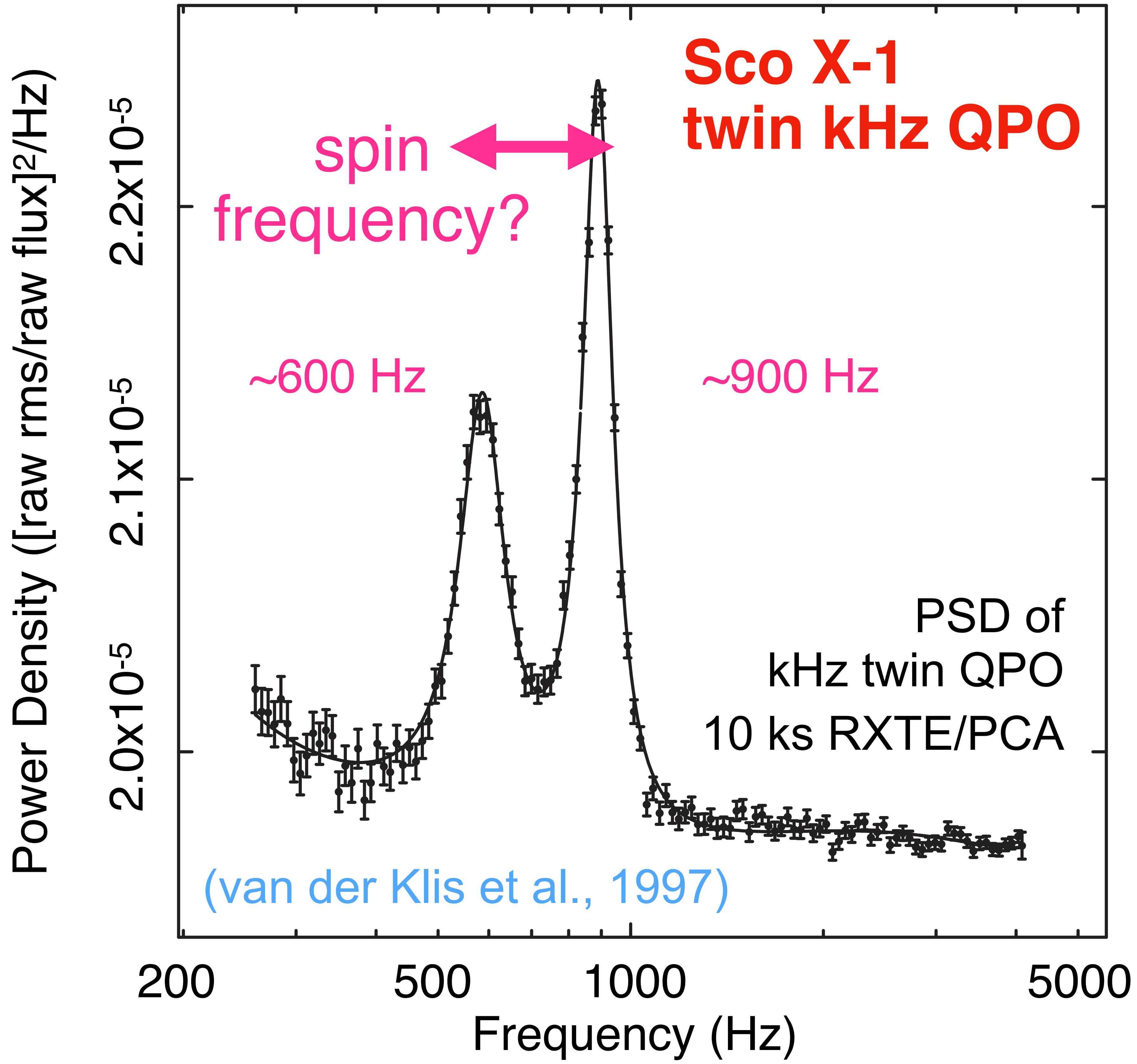
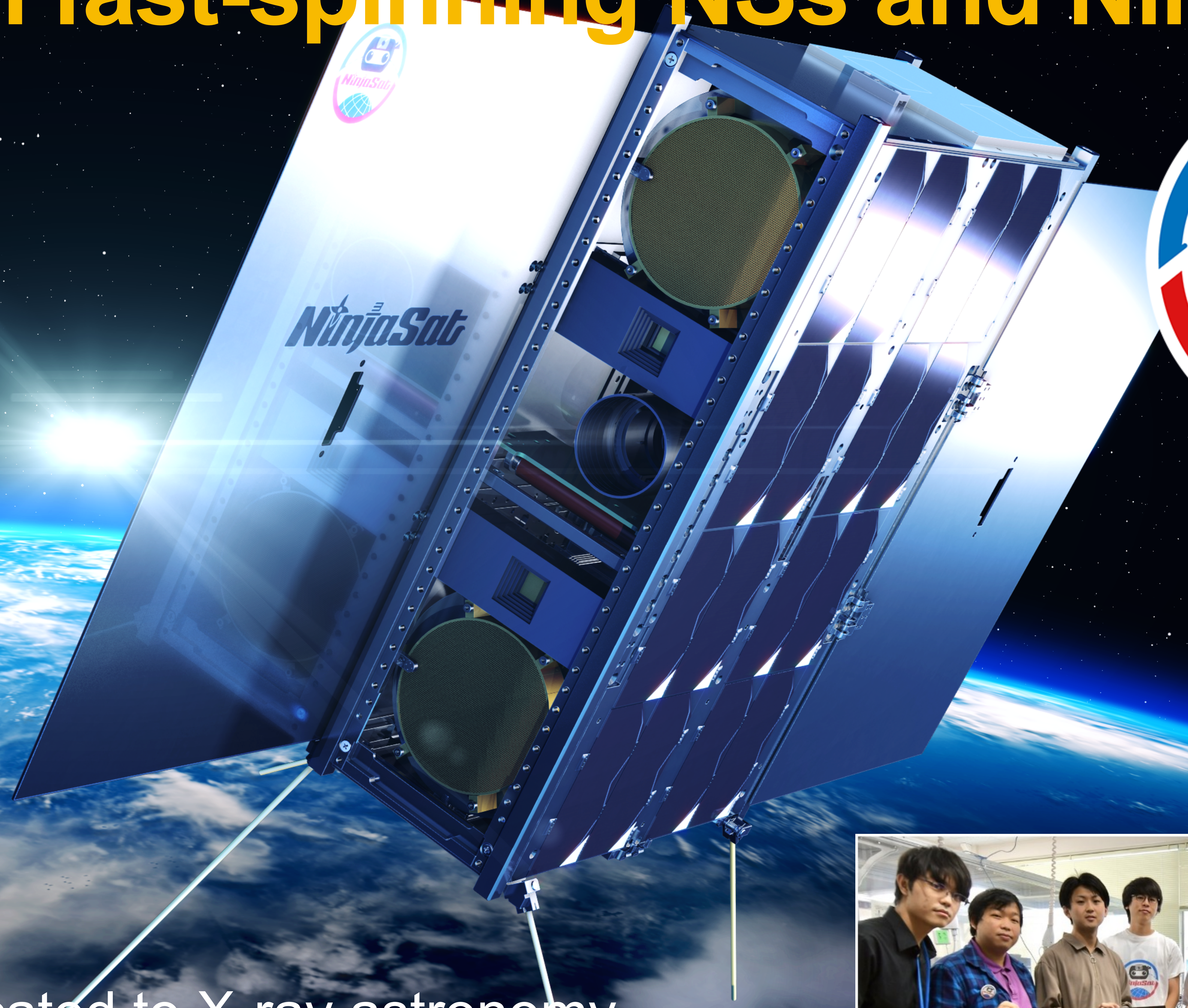




- X-ray variation of Sco X-1 shows the twin kHz Quasi-Periodic Oscillation (QPO), which frequency difference is proposed to correspond with the spin frequency.
- Monitoring of QPOs, which is expected to be fluctuate with mass accretion rate, can be used for the matched-filter template of the gravitational wave search?

Coherent GW from fast-spinning NSs and NinjaSat?



- First Japanese CubeSat dedicated to X-ray astronomy
- Agile and flexible time-domain studies for X-ray sources
- World's largest effective area in CubeSat missions

Enoto et al., Proceedings of the SPIE, Volume 11444, id. 114441V 20 pp. (2020).

Unresolved 6 big problems of NSs (personal view)

1. What is the equation of state for the dense interiors of neutron stars?

   ➡ The problem is close to being solved by X-ray and gravitational wave observations (榎戸, 安武「宇宙観測で見えてきた中性子星の状態方程式」日本物理学会誌2021年10月号).

2. What evolutionary theory provides a unified understanding of the observational diversity of neutron stars?

3. Are magnetars really NSs with extremely strong magnetic fields?

   ➡ ”Magnetars” has been established by the accumulation of observational studies (Enoto, Kisaka, Shibata, ROPP, 2019).

4. What types of cosmic rays are produced in NSs and supplied to our galaxies and reach the Earth?

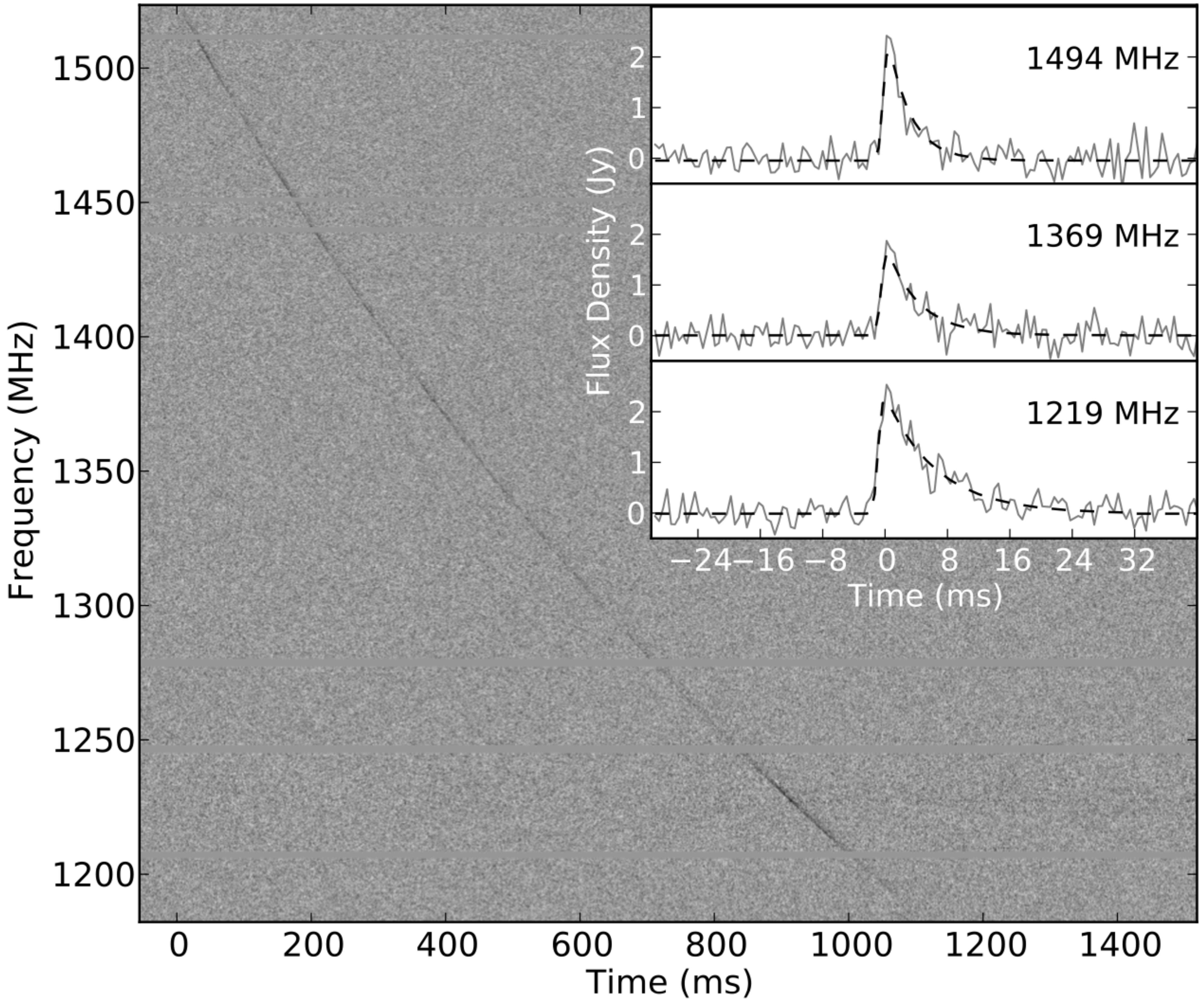
5. What are the GWs produced by NSs (in addition to NS-NS systems)?

6. What are the sources and mechanisms of fast radio bursts?

Mystery of Cosmological Fast Radio Bursts (FRBs)

- Reported in 2007 (Lorimer, Science, 2007)
- FRBs have following characteristics:
  1. Bright radio emission F ~ 0.2-120 Jy @~1 GH
  2. Brightness temperature $T_b = 10^{33\text{-}37}$ K
     ➡ Coherent radio emission
  3. Large DM ~ 300-1600 cm^{-3} pc
     ➡ Cosmological distance (z <~ 1)
  4. Short duration Δt < 1 ms
     ➡ Compact origin? (R~c Δt ~3×10^2 km ~30R_{NS}
  5. Fluence $S = F\,\Delta t$ = 1-10 Jy ms
     ➡ Energetics E ~ 4×10^{39} erg (d / 1 Gpc)^2
  6. High event rate R_{FRB} ~ 10^4 / sky / day
     ➡ R_{FRB} ~ 0.1 R_{SN} ~ 10^4 R_{GRB}
  7. Repeating & Non-repeating?
     ➡ Multi-population?
  8. Host galaxies
     ➡ different at different populations?

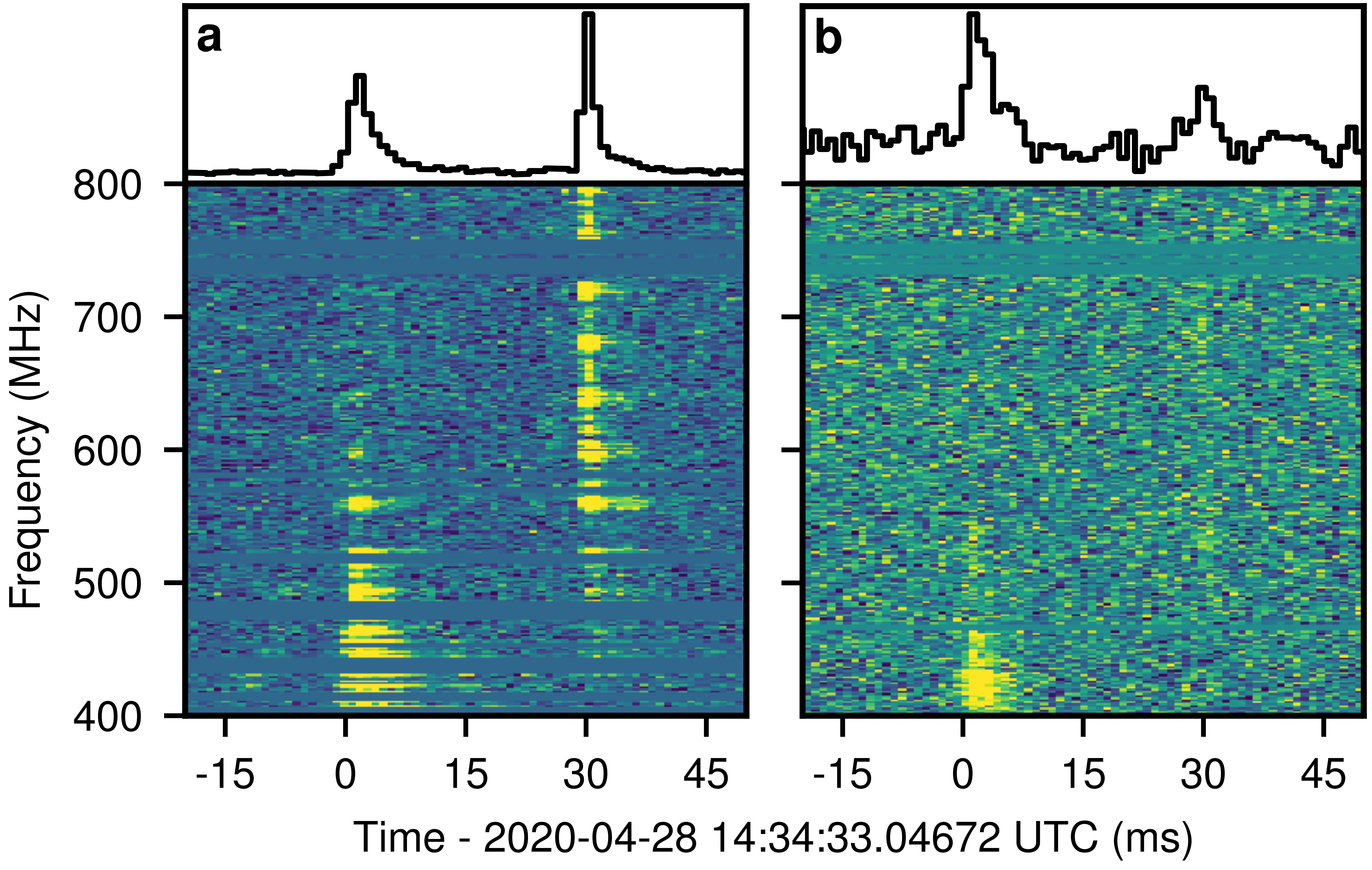
Thronton et al., Science, 2013

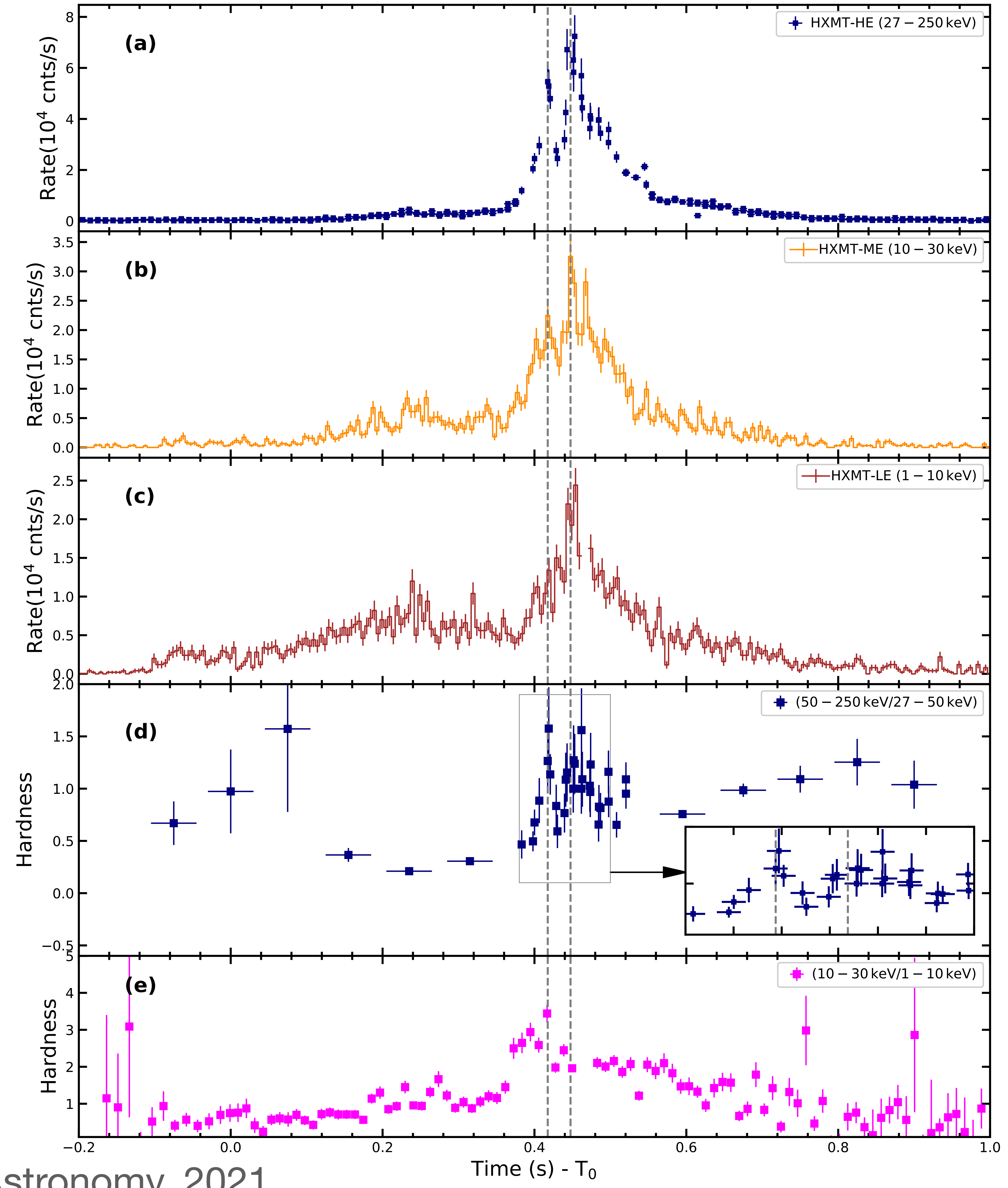


Very likely neutron stars?

Magnetar as a promising candidate of FRBs!

Two-peaked FRB (radio) was found to be coincided with X-ray bursts from a Galactic magnetar SGR 1935+2154 in 2020!





The CHIME/FRB Collaboration, Nature, 2020

Li et al., Nature Astronomy, 2021

Neutron Star Interior Composition Explorer (NICER)

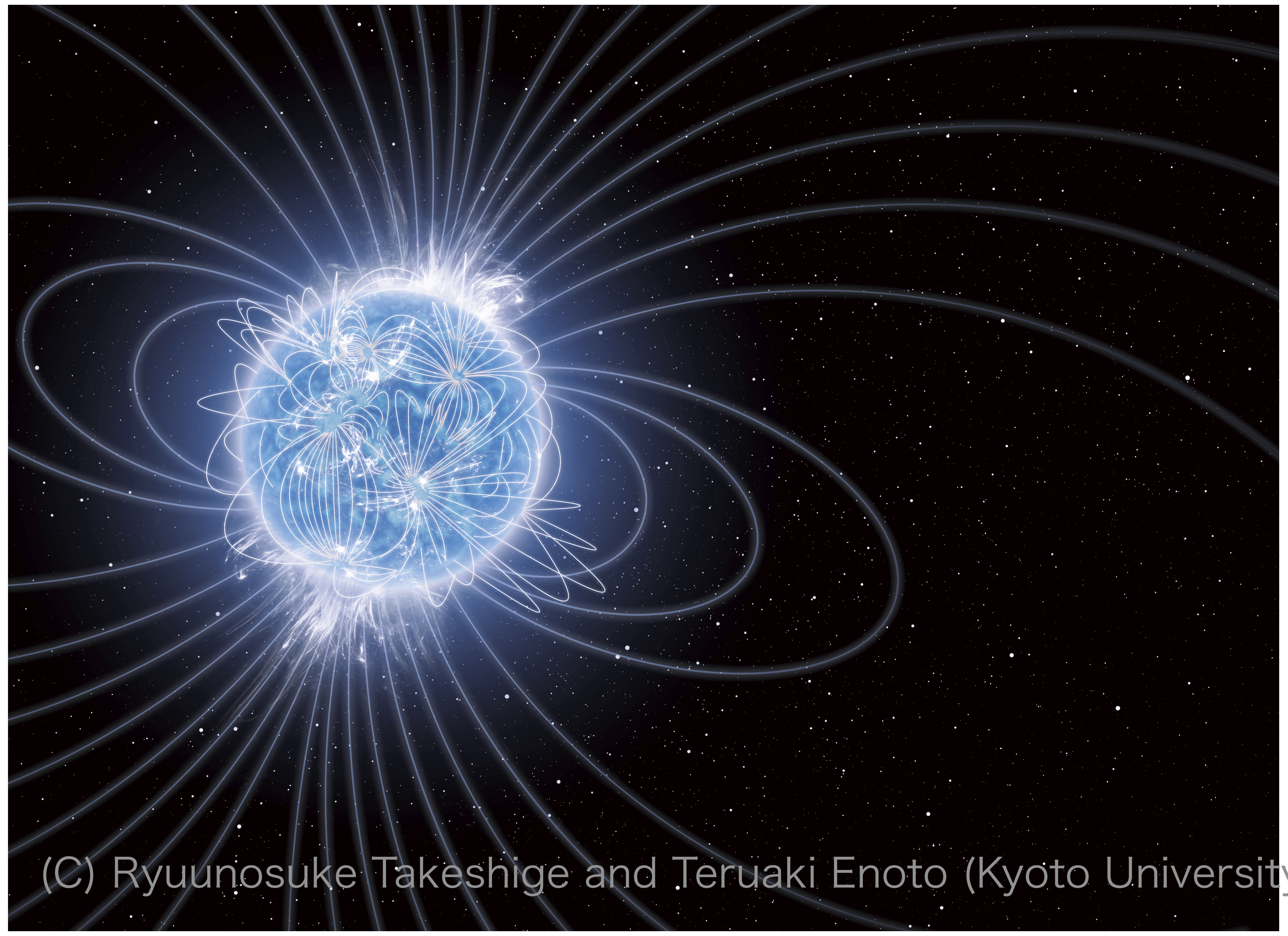
Soft X-ray timing spectroscopy for neutron star structure, dynamics, and energetics as the ISS external attached payload with active pointing, launched on June 3, 2017

- Energy band : 0.2-12 keV (Resolution : 140 eV @ 6 keV)
- Time resolution : <100 ns RMS (absolute)
- Non-imaging FOV 6 arcmin diameter
- Background : < 0.5 cps
- Sensitivity: 1×10^{-13} erg/s/cm^2 (5σ, 0.5-10 keV, 10 ksec exposure for Crab-like)
- Max rate: ~38,000 cps (3.5 Crab)

Gendreau et al., SPIE (2012), Arzoumanian et al., (2014)

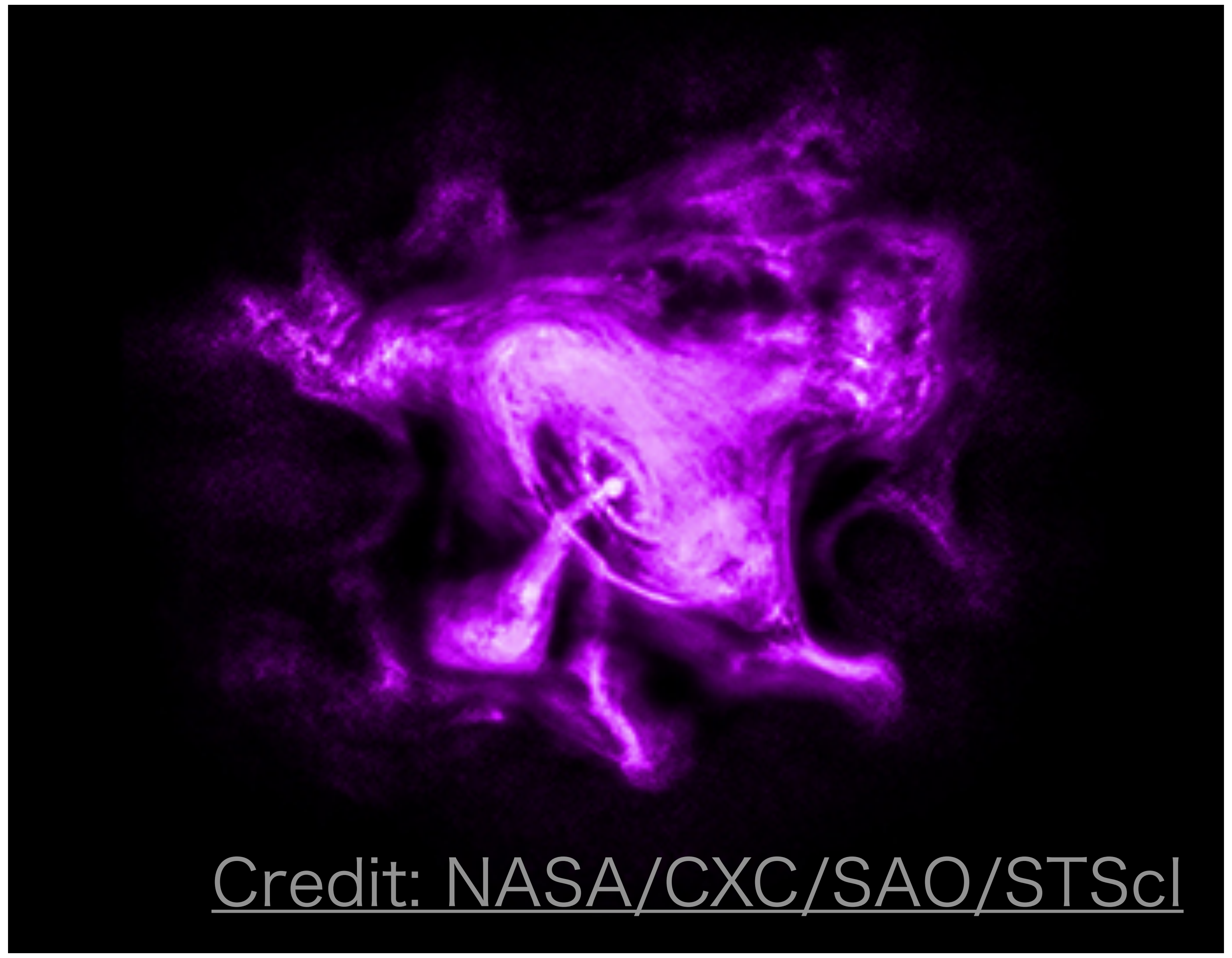
Candidates of the Neutron Star Origin of FRBs

Magnetar bursting activity



- Energy source: **Magnetic energy**
- Mechanism: **Reconnection?**
- Example: **SGR 1935+2154**

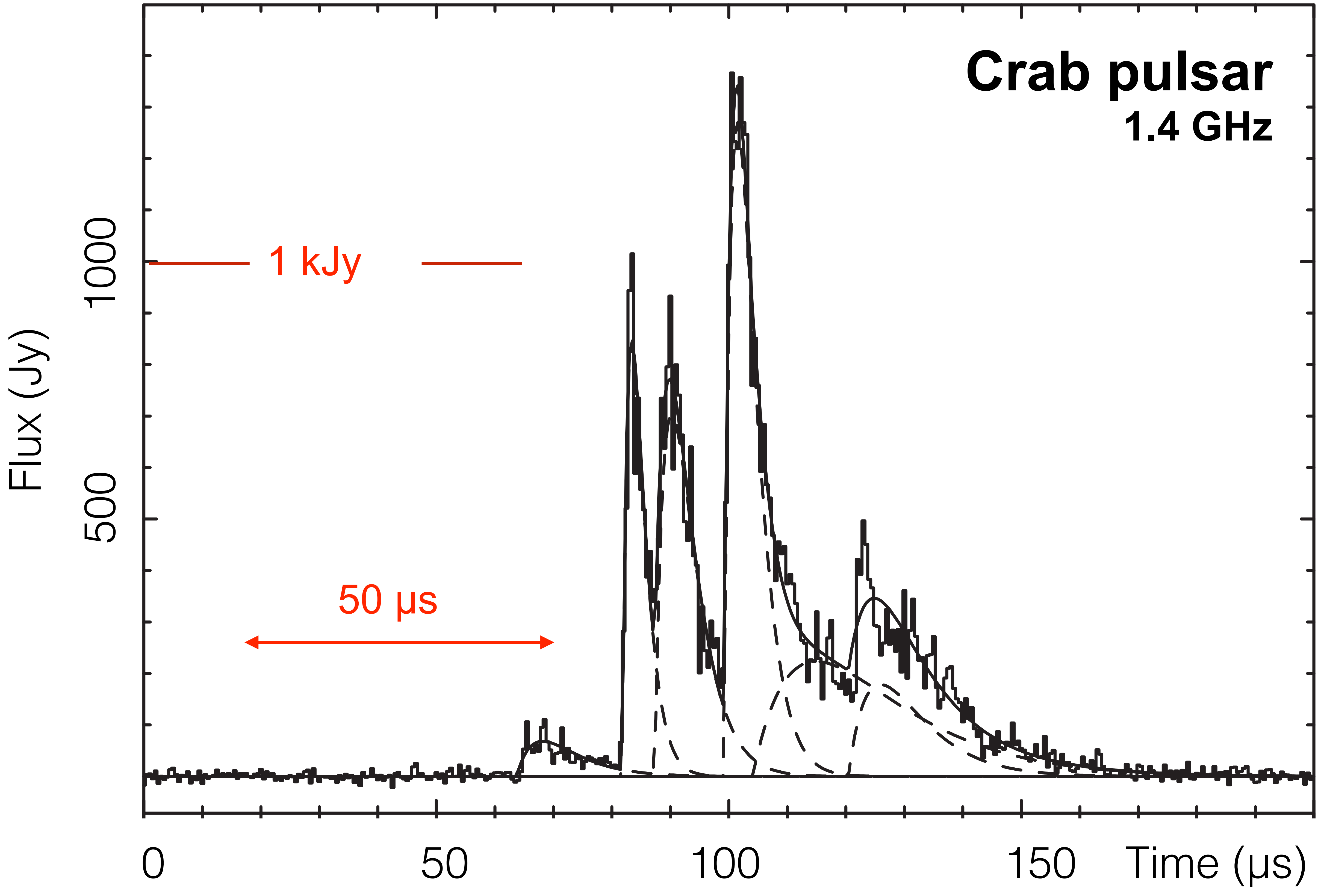
Giant radio pulses



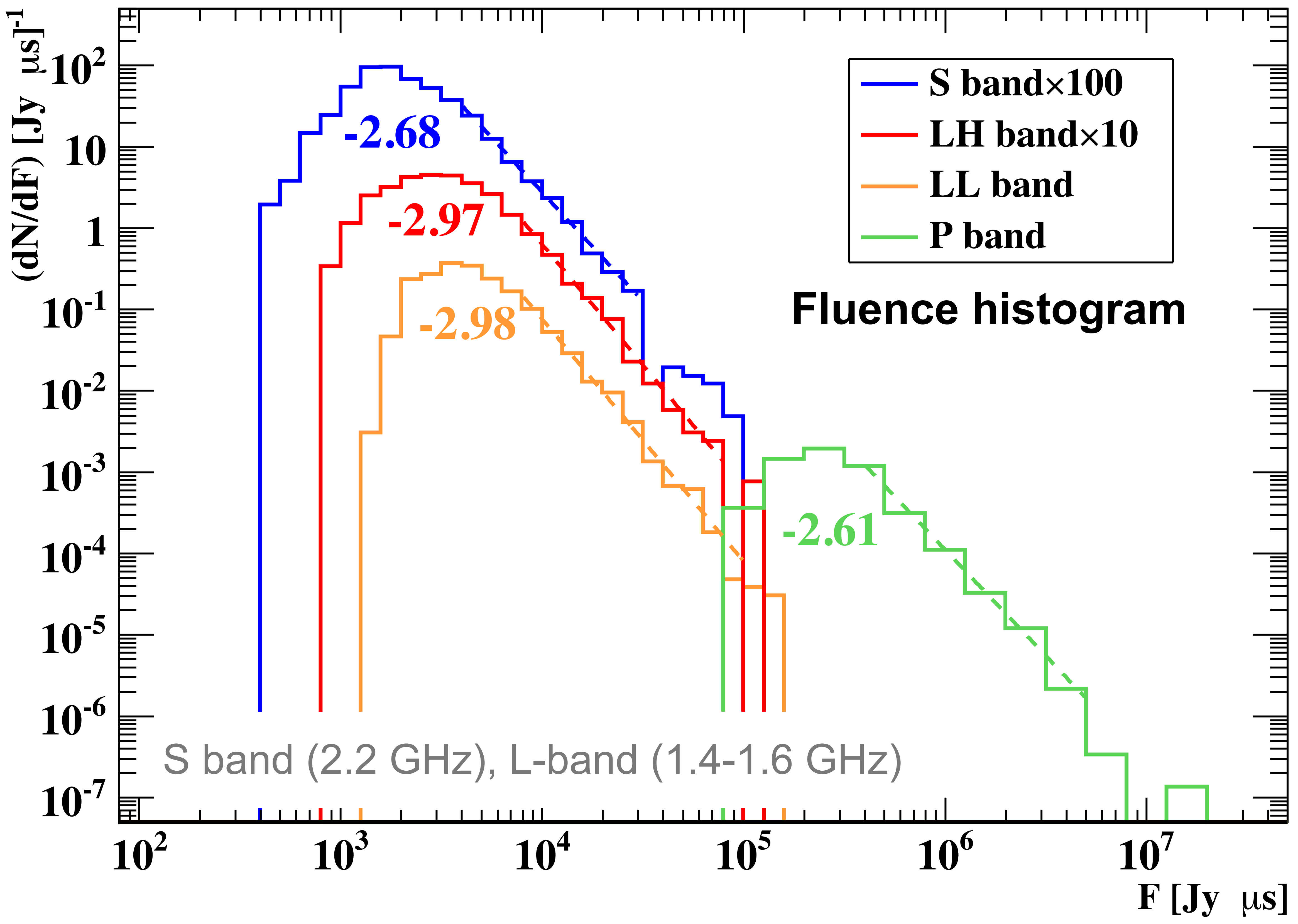
- Energy source: **Rotational energy**
- Mechanism: **Plasma blob collision?**
- Example: **Crab pulsar**

Giant radio pulses as another candidate of FRBs?

- 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?

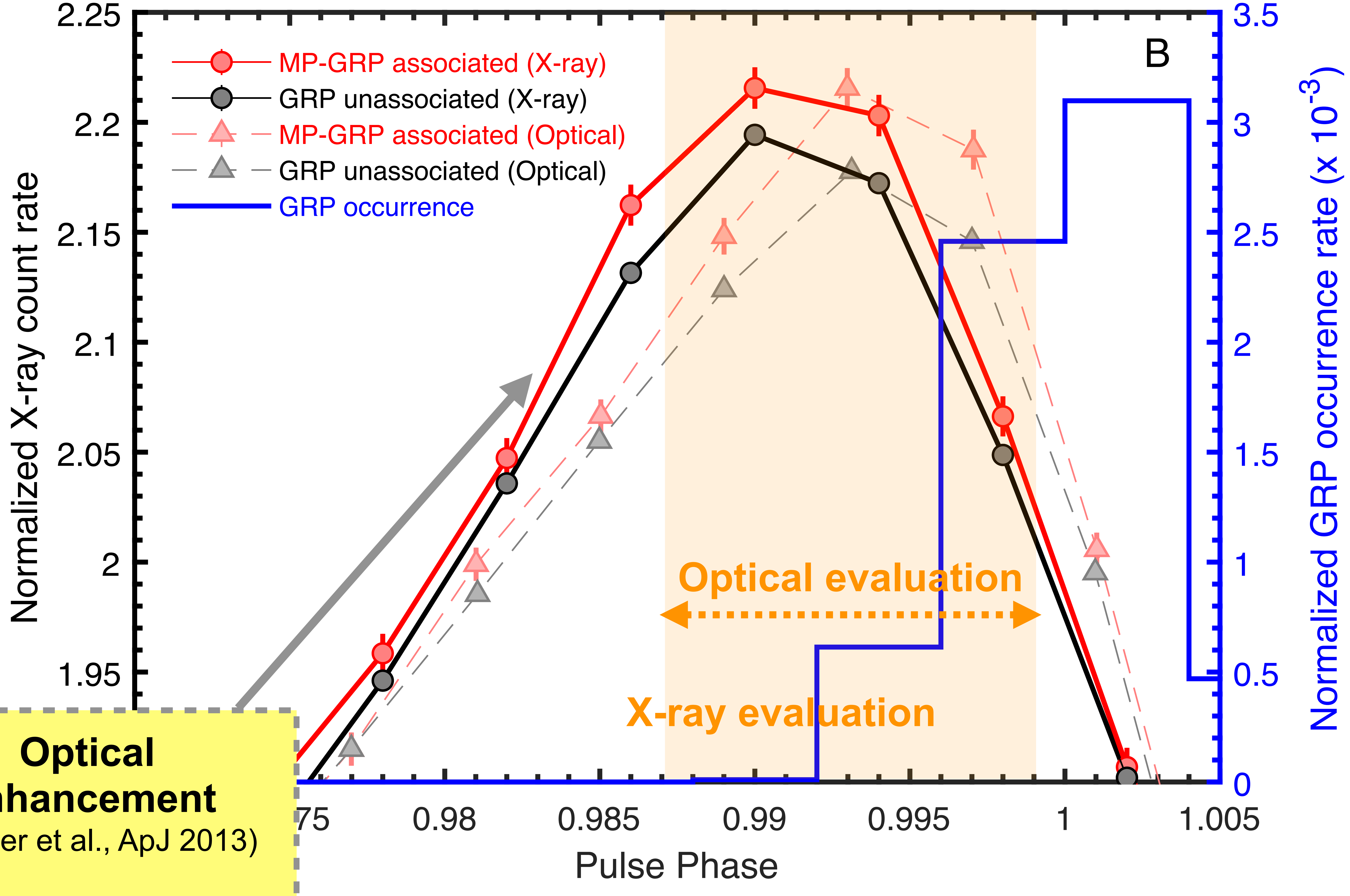


(Sallmen et al., 1999)



(Mikami et al., 2016)

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

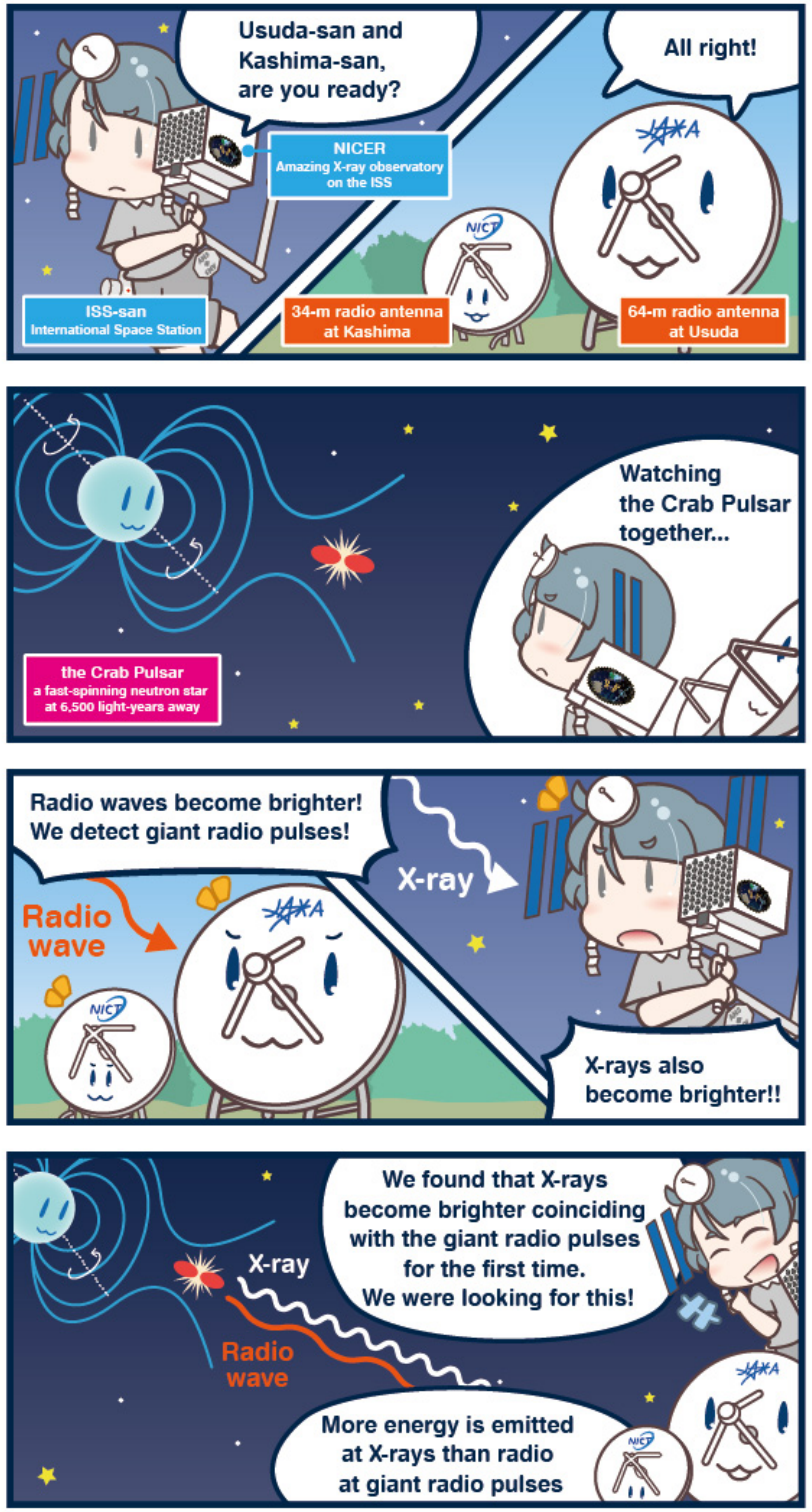


Optical enhancement
(Strader et al., ApJ 2013)

3.2±0.5%
(φ=0.987-0.999)

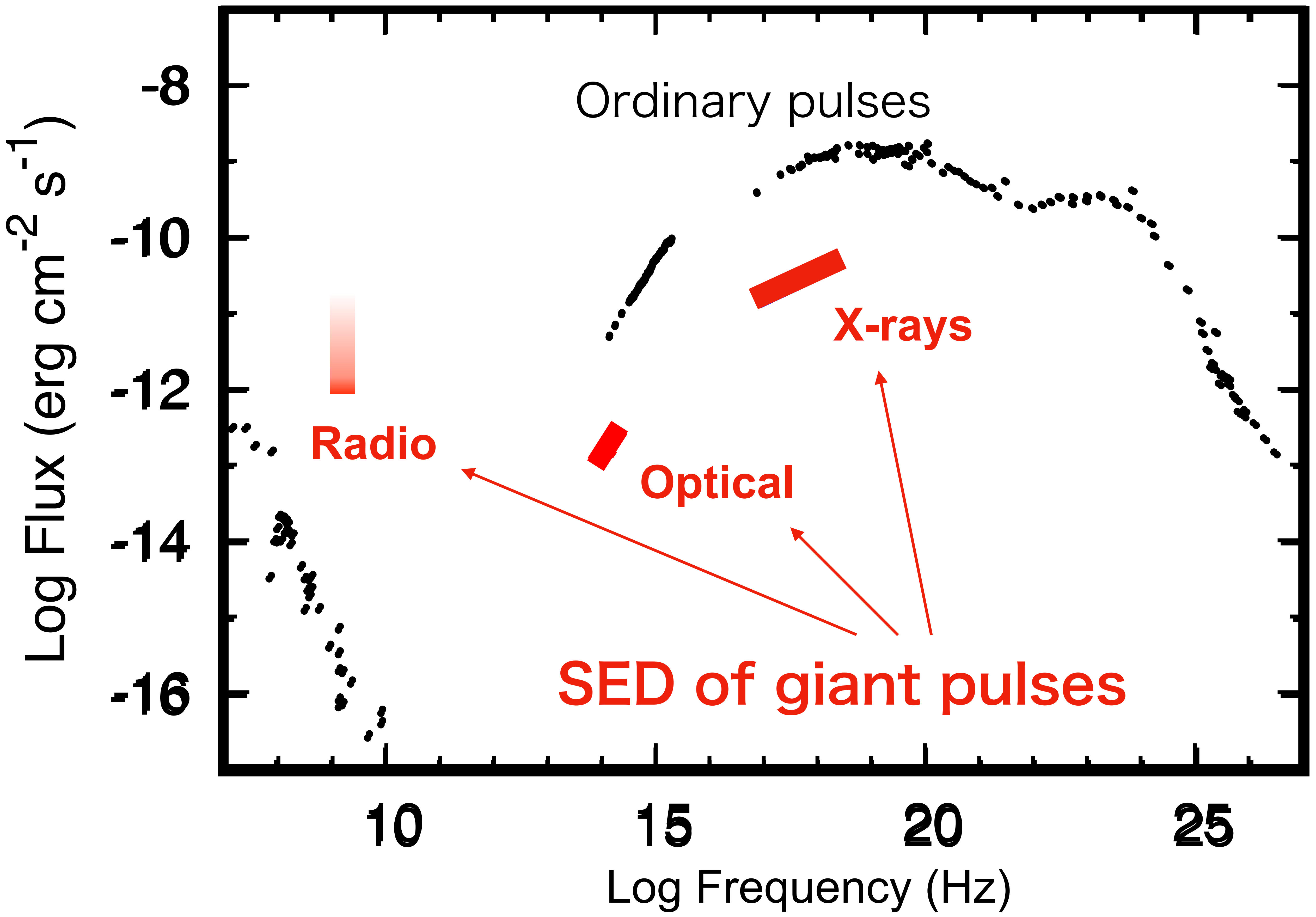
Enoto et al., Science, 372, 187-190 (2021)

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



(Credig) Higgstan.com

Giant Pulses (GPs) can not explain repeating FRBs?

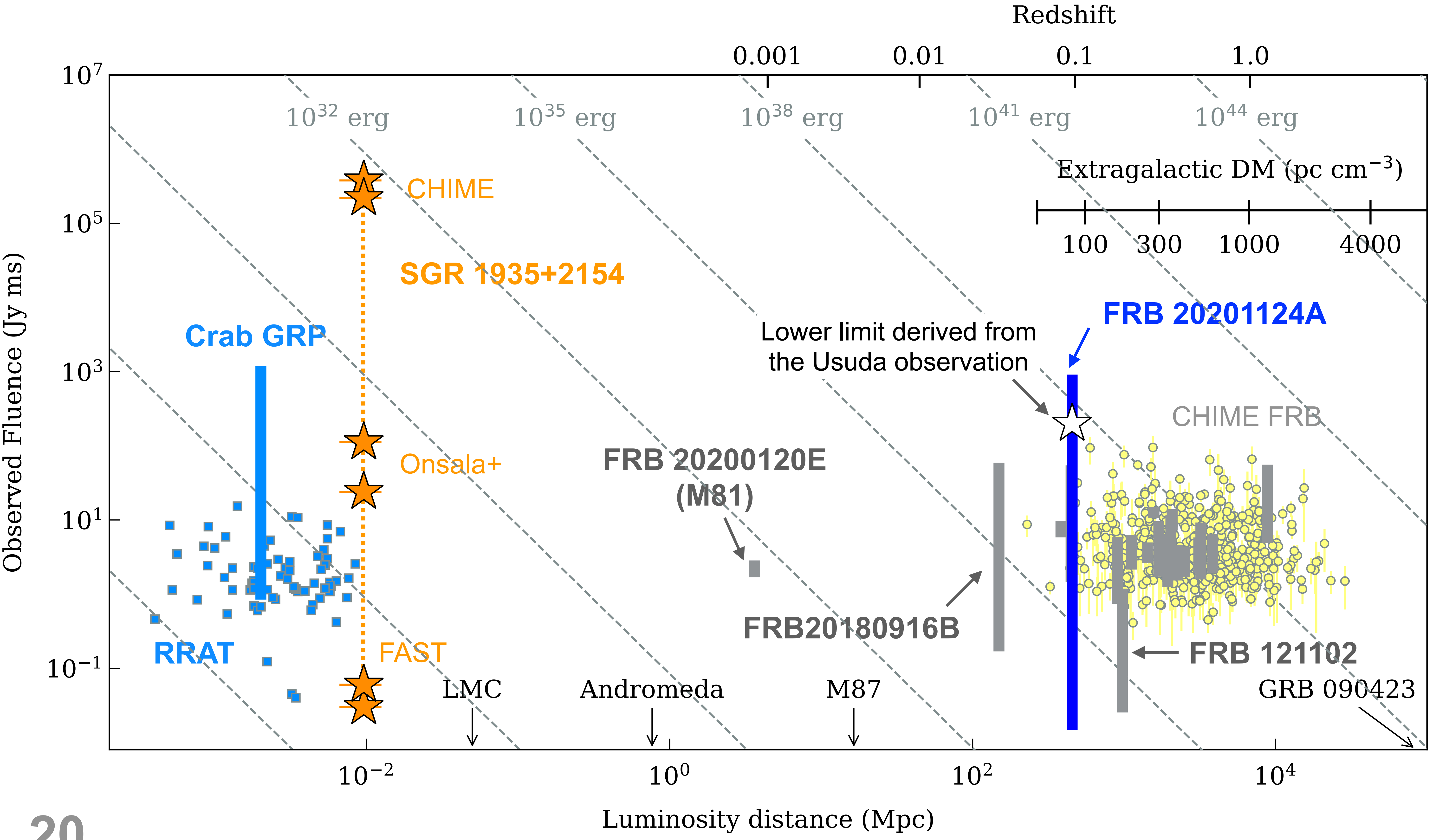


- **Despite ~4% enhancement, the total emitted energy at GPs is 10-10^2 larger than we previously know.**
- Hypothetical bright GRP is a candidate for the origin of FRBs, especially repeating FRB sources (e.g., repeating FRB 121102). The energy source of such FRBs is assumed to be the spin-down luminosity.
- Since bolometric luminosity of GPs, including X-rays, is revealed to be 10$^{2-3}$ times higher than we previously thought, the simple GRP model for FRBs became more difficult because pulsars quickly lose its rotational energy.

Suggesting magnetar-like origin?

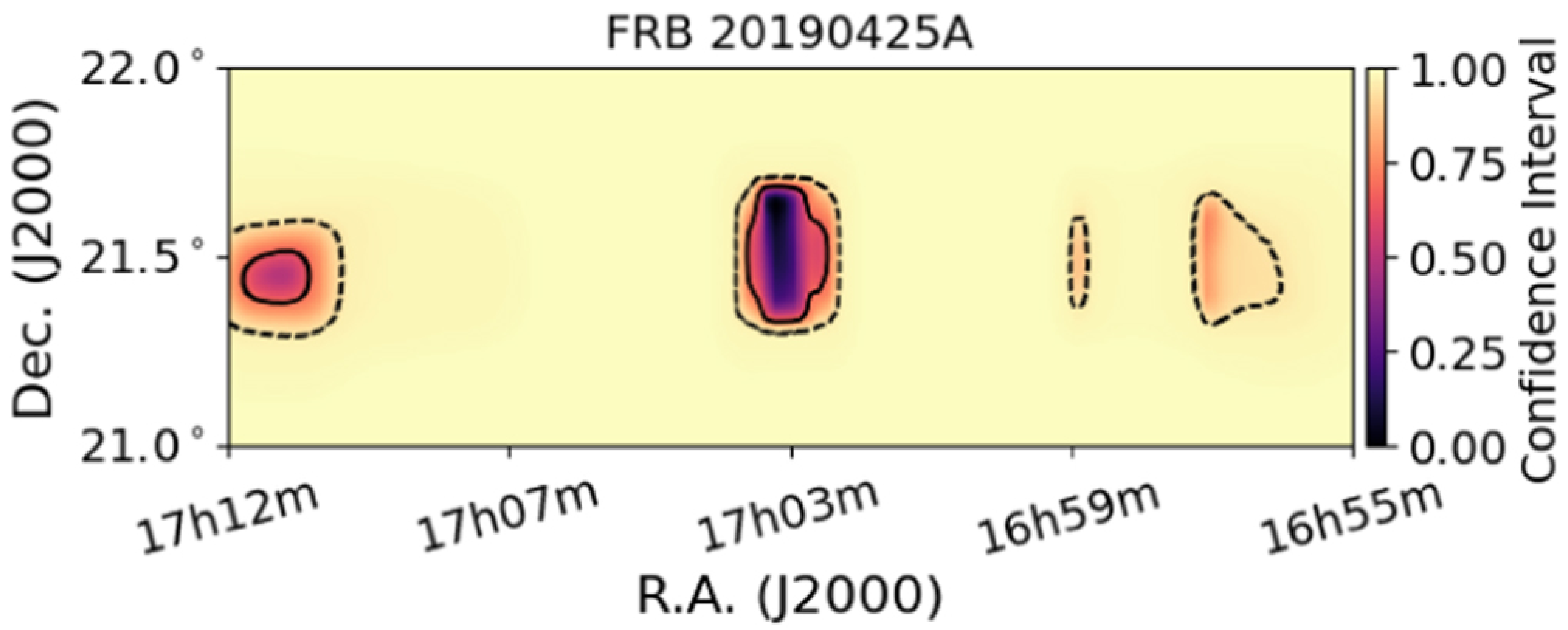
Search FRB events for GW, neutrino, γ emissions

- There are two types of FRBs: one-off and Repeating FRBs.
- Are there any hidden non-magnetar phenomena in the FRB?
- Search the LIGO-Virgo O3a for GW events with FRB (LVK+2022)



Enoto, Kisaka, Terasawa, The Astronomical Herald (2022)

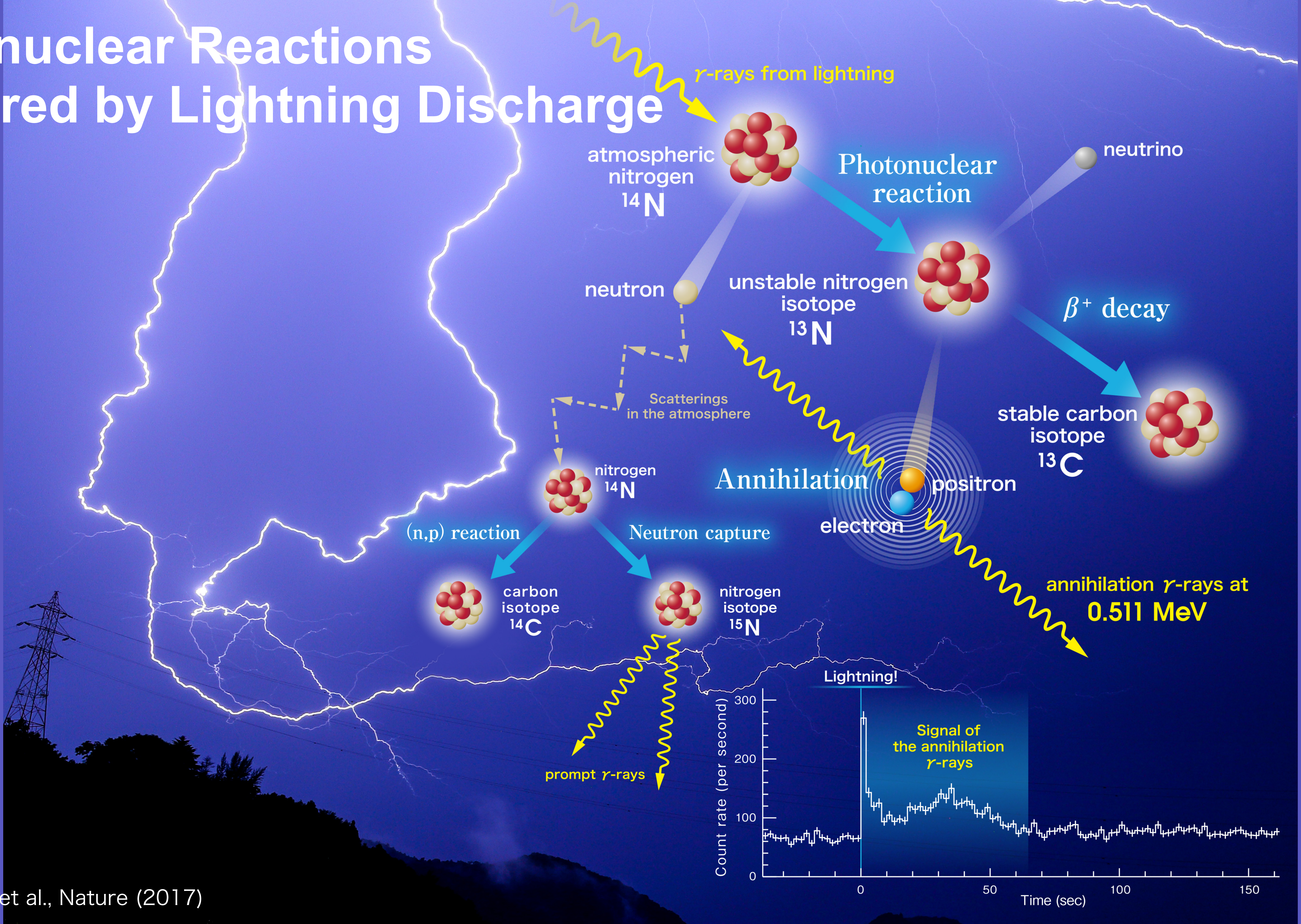
So far, no detection of the GW events associated with FRBs



Summary

- Neutron stars continue to be a driving force in physics through cosmological observations as a testing ground for extreme physics, such as strong magnetic fields and gravity.
- As an example of multi-wavelength astronomy, the FRB study is growing rapidly. Our observations of the Crab pulsar and a magnetar SGR 1935+2154 suggest that magnetar-related phenomena (e.g., glitches) are one of the promising candidates for the origin of FRBs, though other phenomena would be contaminated in FRBs.
- Neutron stars are also expected to become a multi-messenger source, and now we are at the stage where budding attempts can be made. We (X-ray astronomers) want to collaborate with non-electromagnetic radiation (neutrinos, gravitational waves, and cosmic ray physicists).

Photonuclear Reactions Triggered by Lightning Discharge



Enoto, Wada , et al., Nature (2017)