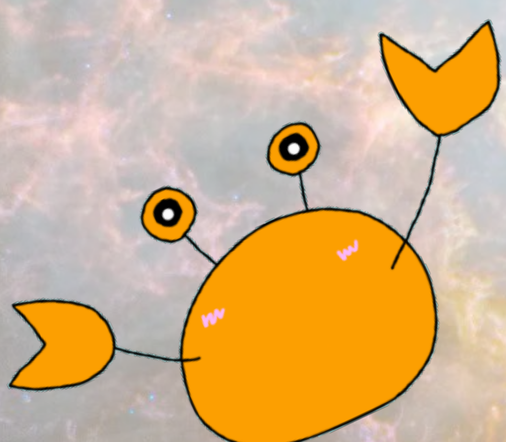
Results of nightly observations of the Crab pulsar with Imager of MPPC-based Optical photoN counter from Yamagata

（高速撮像システムIMONYを用いたカニパルサーの光学連日観測成果）

Hashiyama et al., 2025 in prep.

2025/5/20

Neutron Star Workshop 2025 @RIKEN



Mizusawa VLBI Observatory

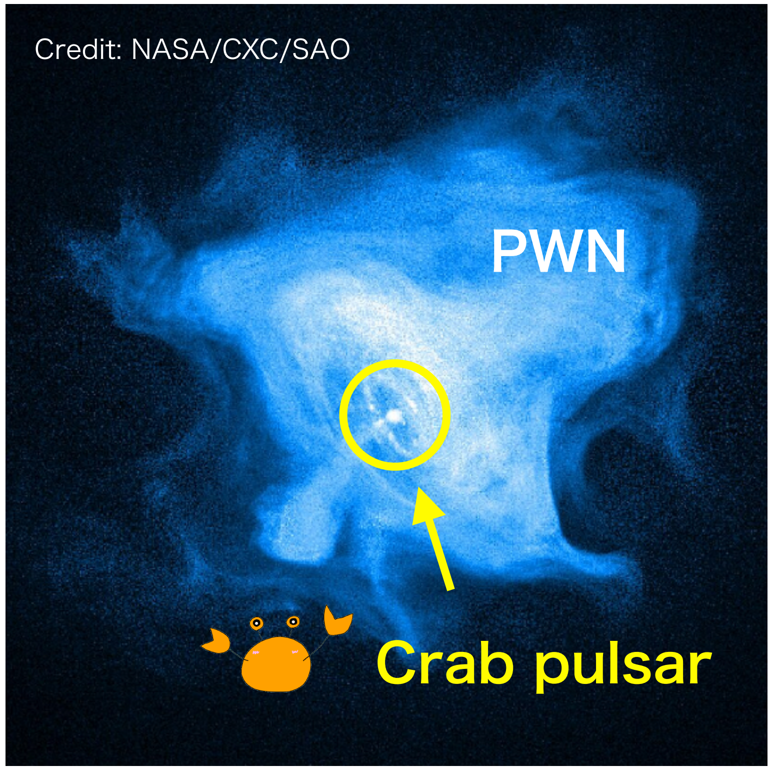
Kazuaki Hashiyama

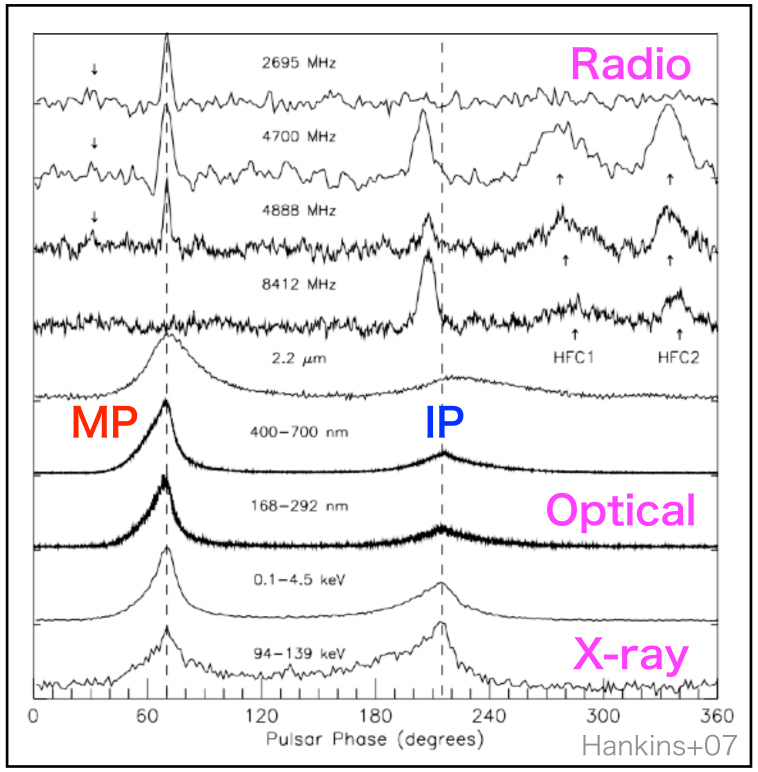
PSR B0534+21 (Crab pulsar)

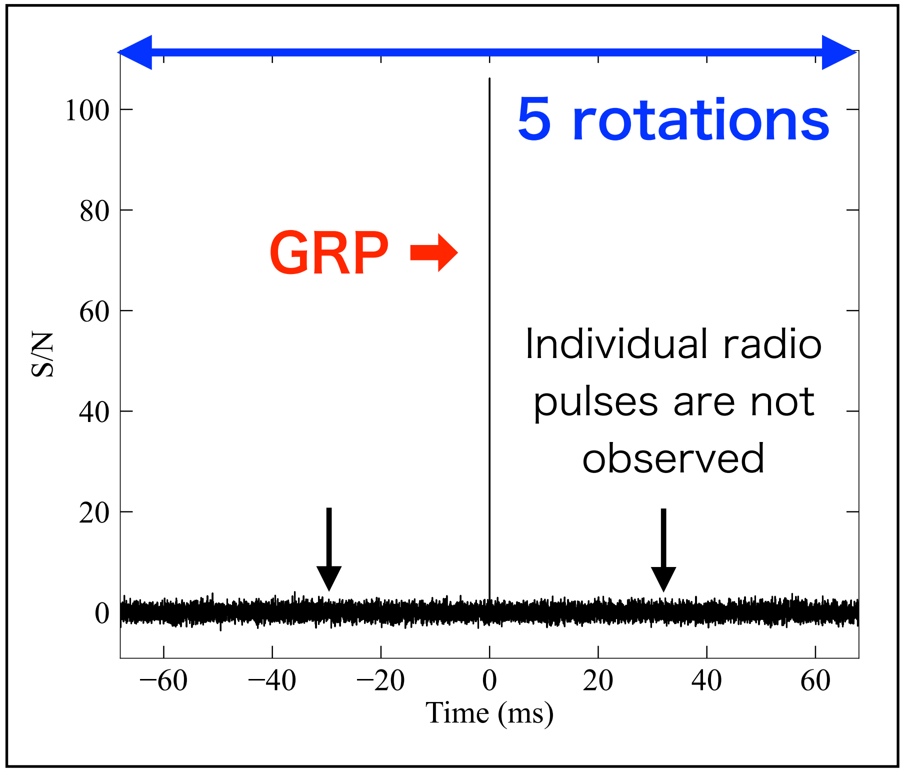
The brightest pulsar from the Earth

- **Located at the center of the Pulsar Wind Nebula (PWN), and emits pulses every 34 ms across multiple wavelengths**
  - Pulse components are divided into Main Pulse (MP) and Inter-Pulse (IP)
  - Individual pulses are difficult to detect, but we can confirm pulsation by time-averaging
- **Unexplained transient radio burst, Giant Radio Pulse (GRP)**

The luminosity is >100 times grater than the radio emission fluctuations from the PWN





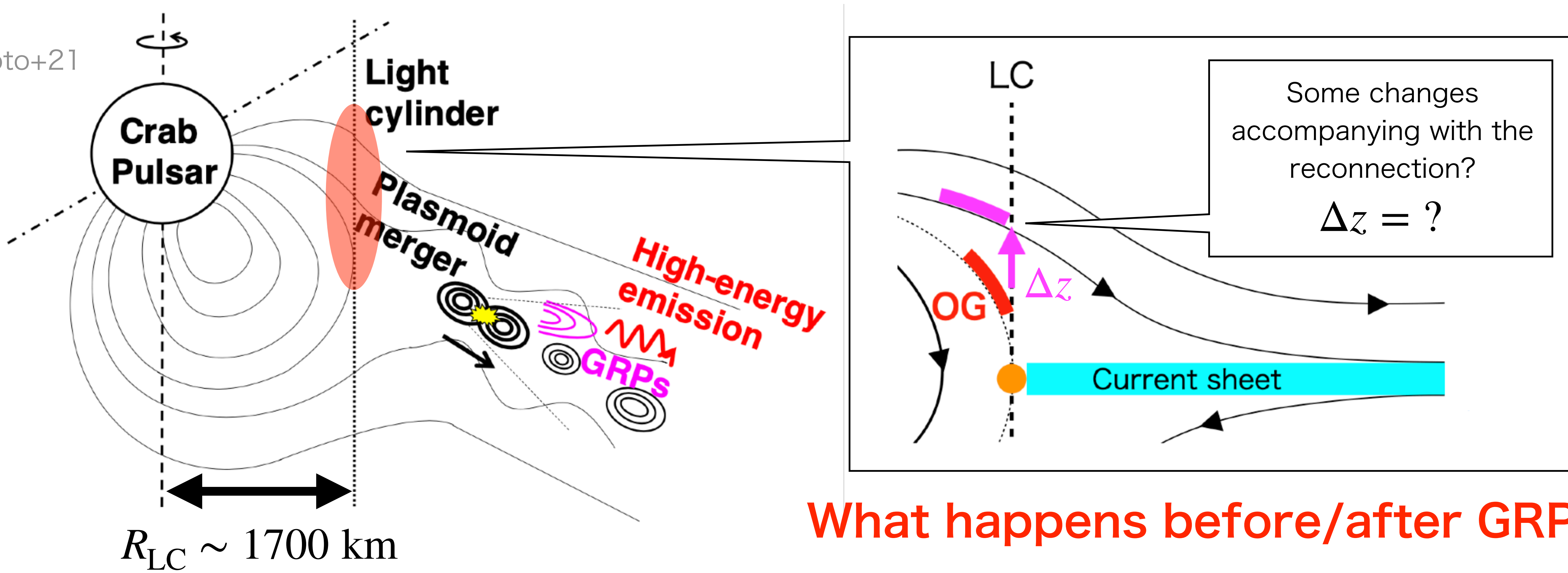


What triggers GRPs ?

Magnetic Reconnection (MR) is one possible model

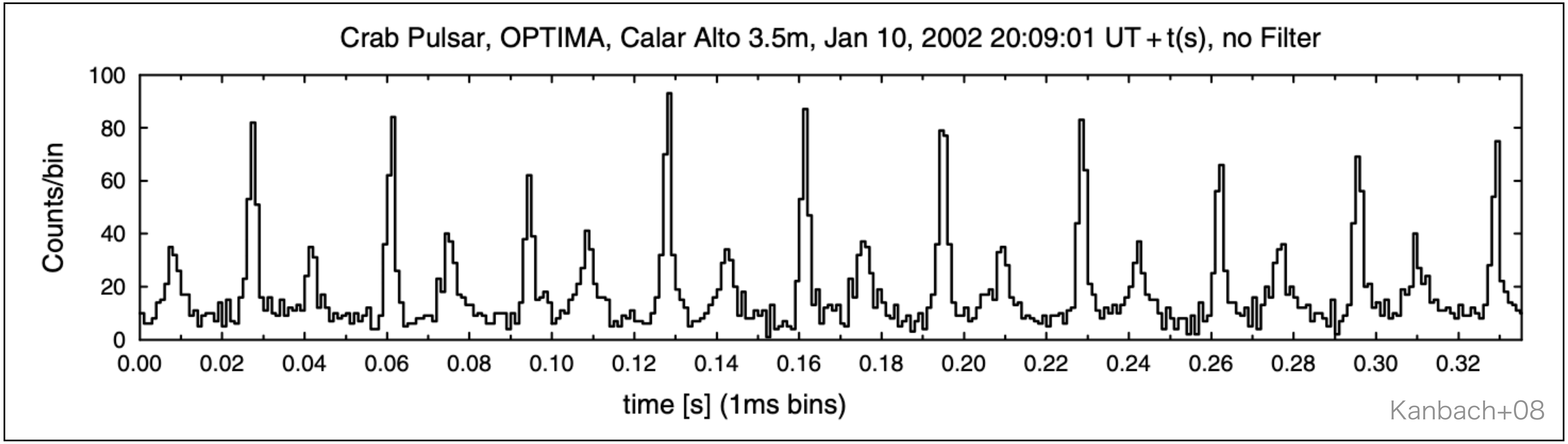
- **Magnetic energy stored near the light cylinder is released through the reconnection and observed as a GRP** (e.g., Philippov+19)
- **Does the magnetic field structure change before or after GRPs?**
  - Individual pulse, <u>Single Pulse (SP)</u>, is useful to validate the reconnection model
  - Time-averaged pulse-profile reduces the structure change, i.e., <u>SP is important</u>

Enoto+21



What happens before/after GRPs?

Single Pulses (SPs)



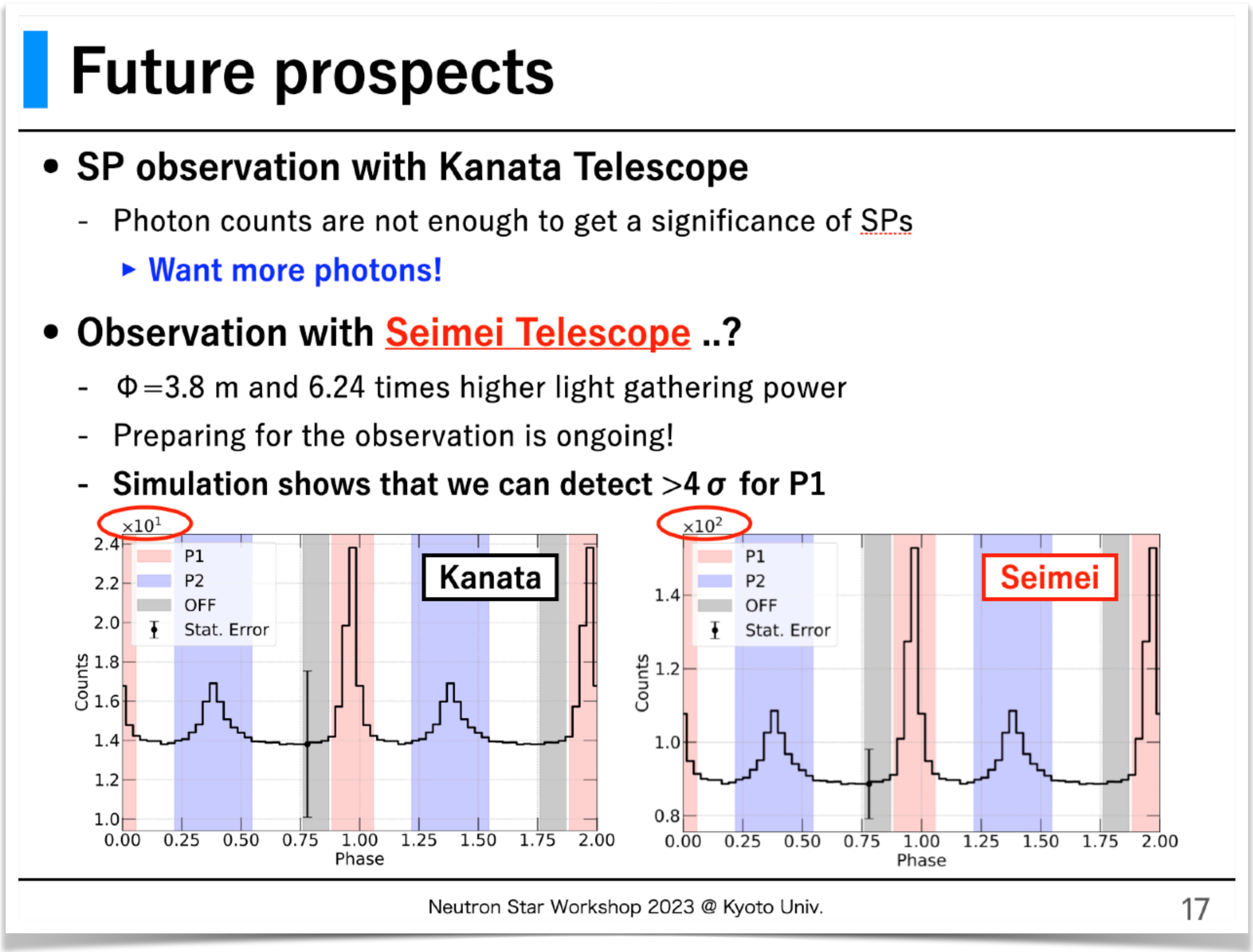
SPs are individual pulses per rotation

- **Important to validate the reconnection model**

  We aim to detect peak timing fluctuations of SPs caused by reconnection events

- **SP observations in multi-wavelength**
  - Radio: Impossible to detect due to the radio emission from the Crab PWN
  - **Optical: Possible, but there are some mechanical constraints** (e.g., Kanbach+08)
  - X-ray & Gamma-ray: Difficult due to the low photon flux (c.f., ~sec w/NICER; Enoto+21)

Previous talk in FY2023



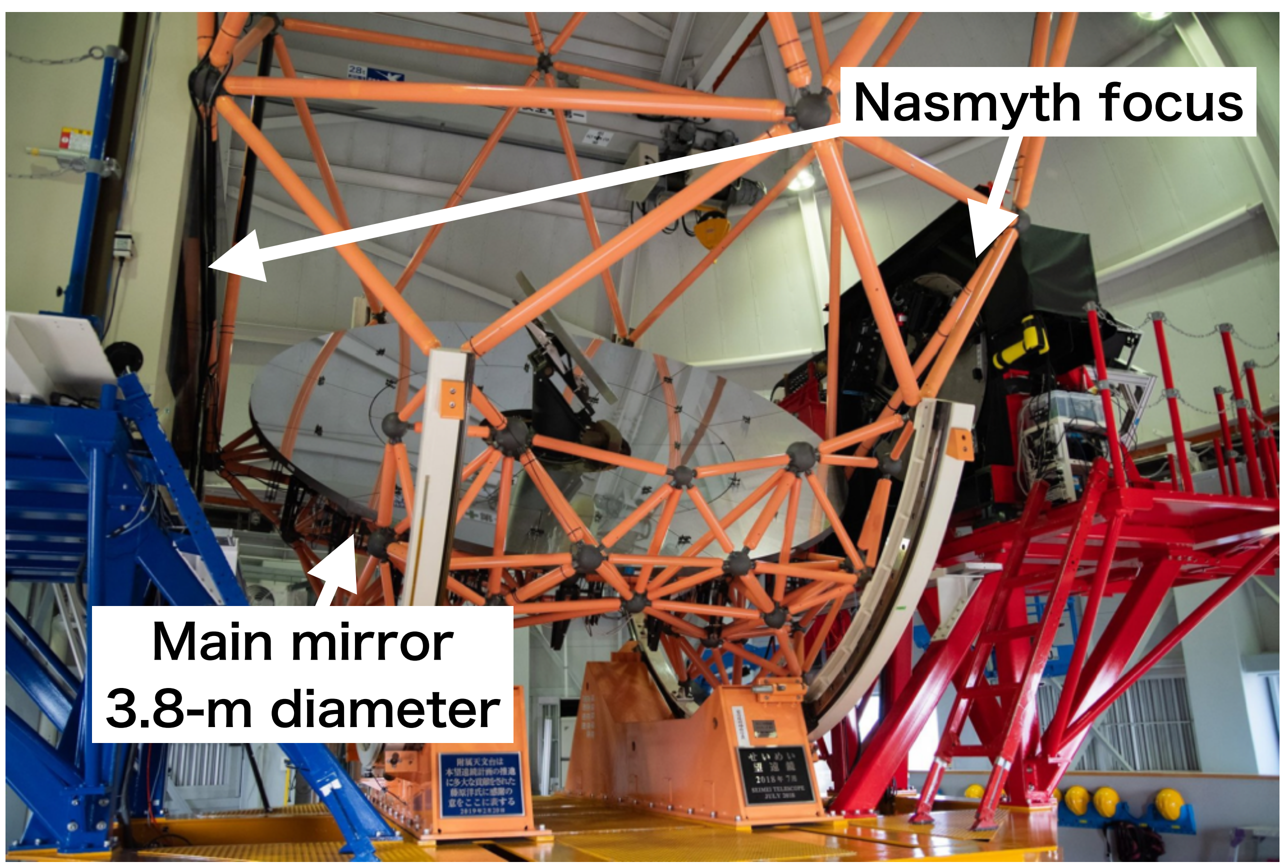
We estimated the detection possibility of SPs

- Test observation results with the 1.5-m Kanata telescope were used
- We concluded that **the 3.8-m Seimei telescope is necessary**

Telescopes

Seimei telescope (Opt.)

- Located at Okayama, Japan
- 3.8-m diameter
- Focal length of 22692 mm (F/D~6.0)



Usuda telescope (Rad.)

- Located at Nagano, Japan
- 64-m single dish
- Dual frequency bands centered at 2.3 & 8.4 GHz

Observation

We observed the Crab pulsar in 2/5–11 Feb. 2024

- **No observation days were lost due to bad weather**
- **We performed Rad./Opt. simultaneous observations in 2/7 & 8**

However, only about 1 hour of simultaneous observation was possible due to cloud cover

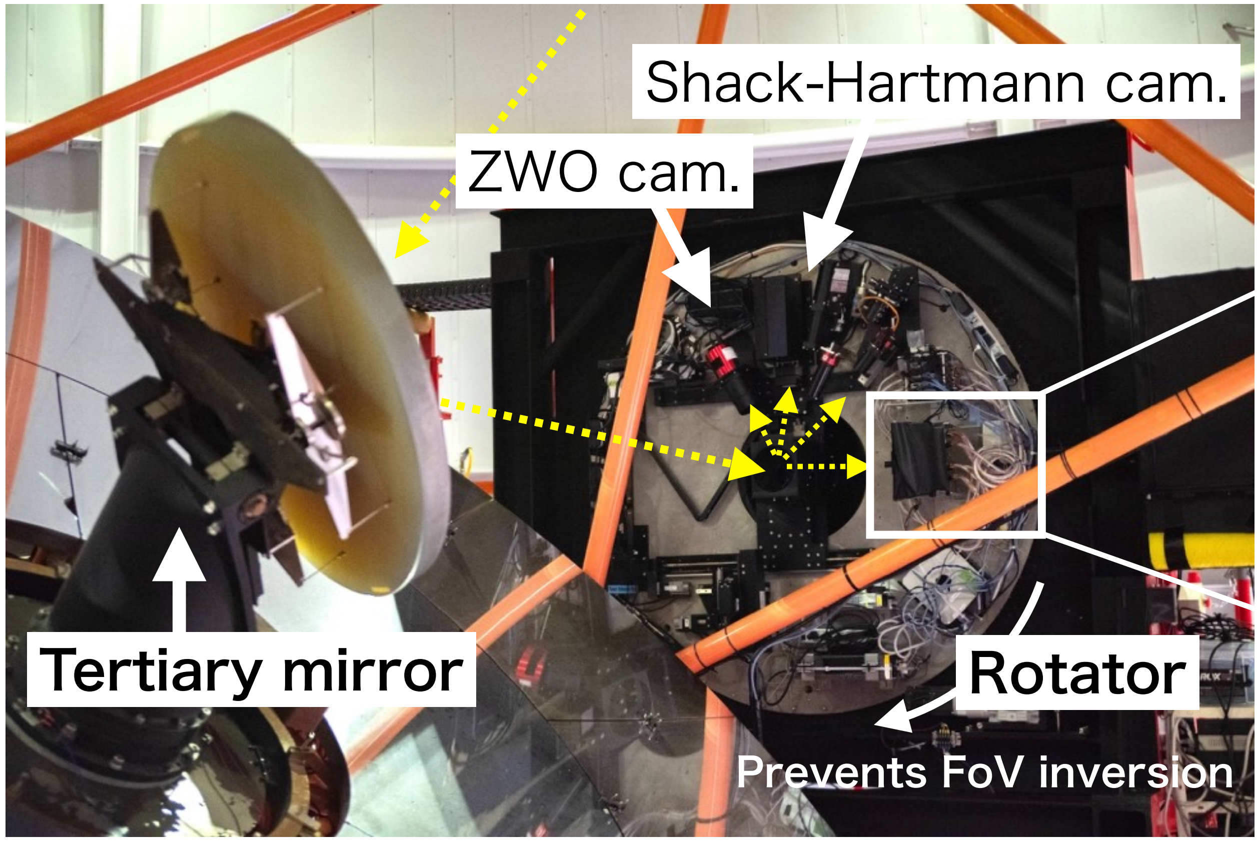
Epoch	Weather	Bands	Eff. Obs. Time (Opt)	Eff. Obs. Time (Rad)
2024/2/5	☀️	Optical	1.2 h	—
2024/2/6	🌥️	Optical	0.37 h	—
2024/2/7	🌥️	Optical/Radio	0.33 h	11.4 h
2024/2/8	🌥️	Optical/Radio	0.53 h	11.4 h
2024/2/9	☀️	Optical	1.9 h	—
2024/2/10	☀️	Optical	2.2 h	—
2024/2/11	🌥️	Optical	1.3 h	—
		Total	**7.8 h**	**22.8 h**

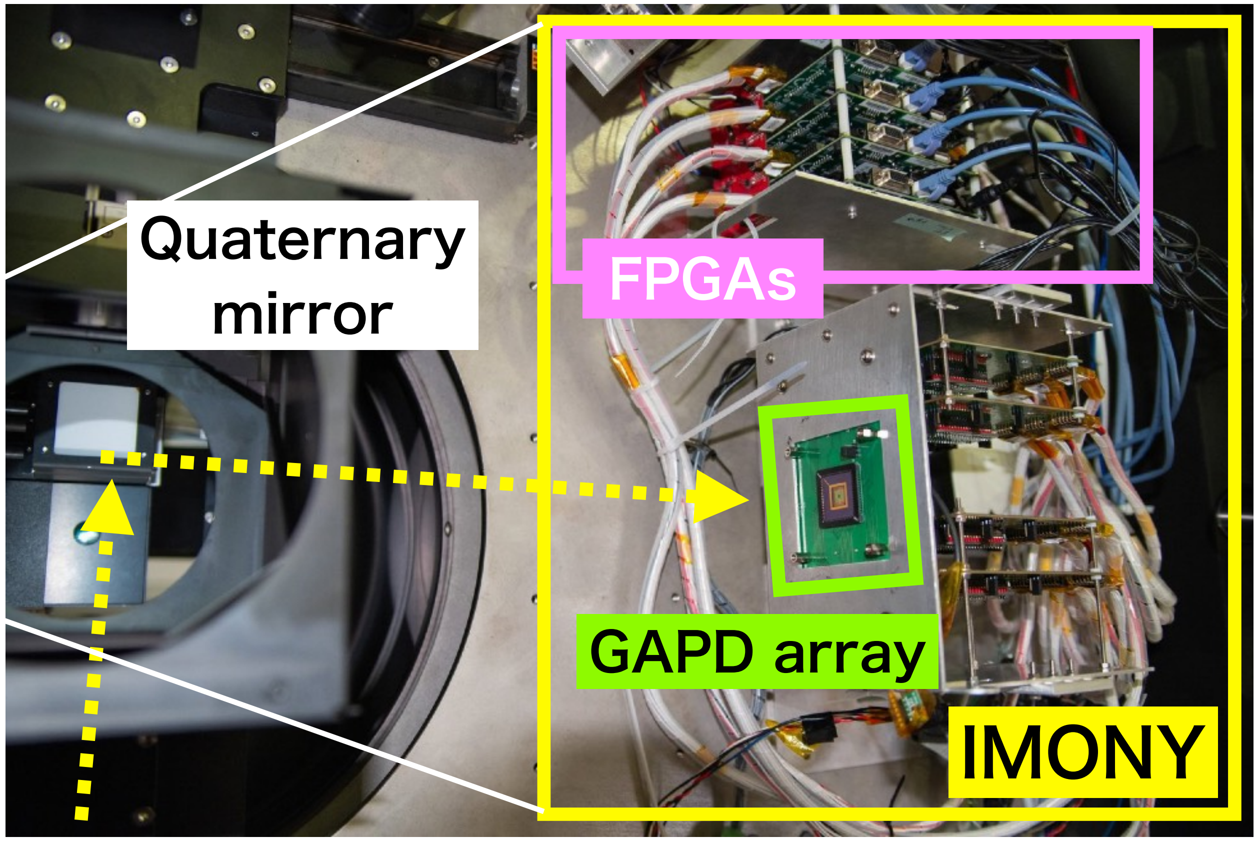
Photometer (System details are introduced in the poster session by M. Hasebe)

Imager of MPPC-based Optical photoN counter from Yamagata (IMONY)

(Nakamori+21, Hashiyama+24, Sato+24, Hasebe+24, and Nakamori & Hashiyama+25, PASJ ←New!)

- **Geiger-APD array of 64 pixels has a sensitivity for a single photon**
  - Sensor size is 200 um/px (Field of View is ~15×15 arcsec)
  - Photon detection efficiency is around 70% @450 nm (No filter)
- **Single pixel readout & time-stamping in 100 ns with FPGAs**





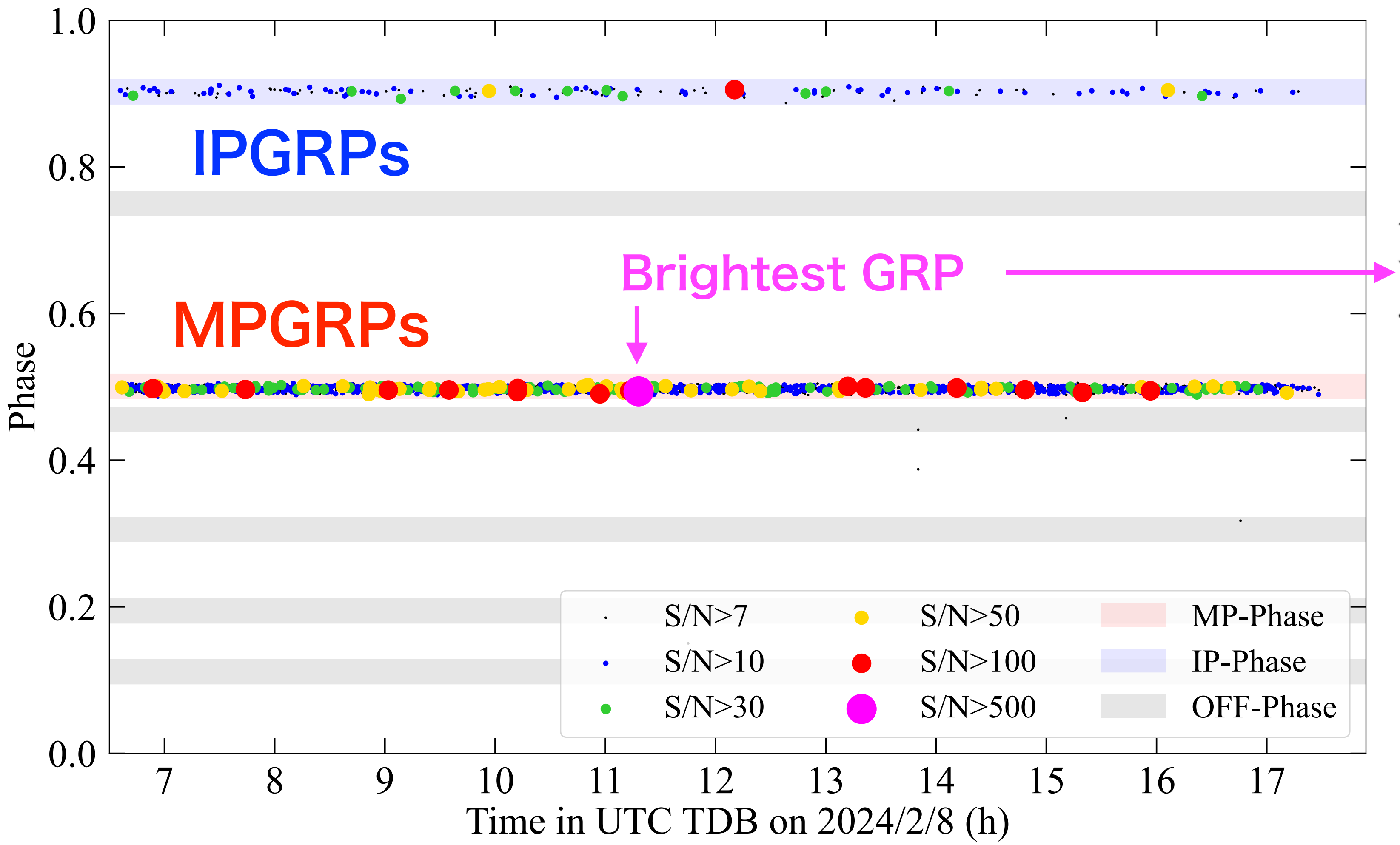
Radio results

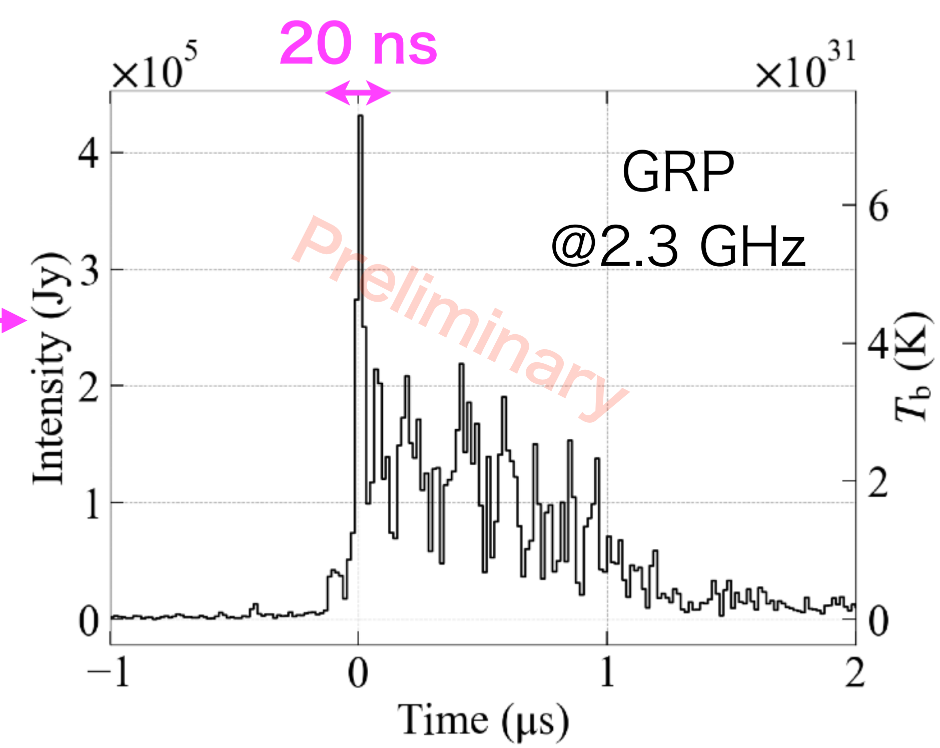
Result on 2024/2/8 @2.3 GHz

We detected 2782 MPGRPs & 175 IPGRPs with ~11 hours observation

- Occurrence rate at 2.3 GHz was **~253 MPGRPs/h** & **~16 IPGRPs/h**
- Peak intensity was ~400 kJy in 20 ns, and **brightness temperature achieved ~10^{31} K**

➡ Inconsistent with the black-body radiation, i.e., non-thermal emission origin

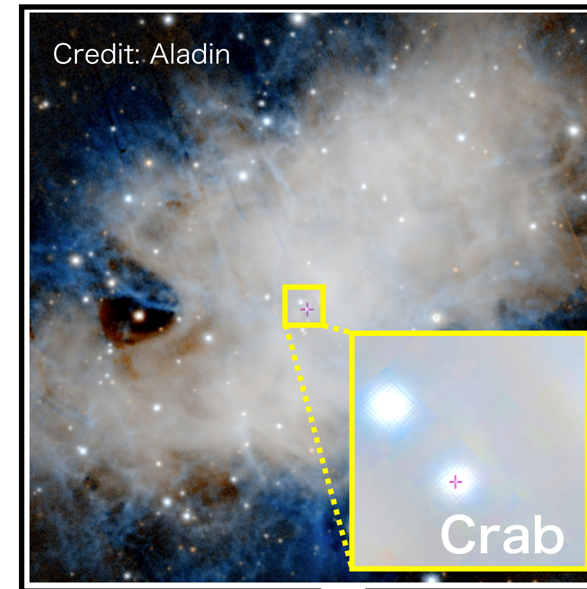




Brightness temperature

$$T_\mathrm{b} = \frac{S_\nu}{2k_\mathrm{B}}\left(\frac{D}{\nu\Delta t}\right)^2$$

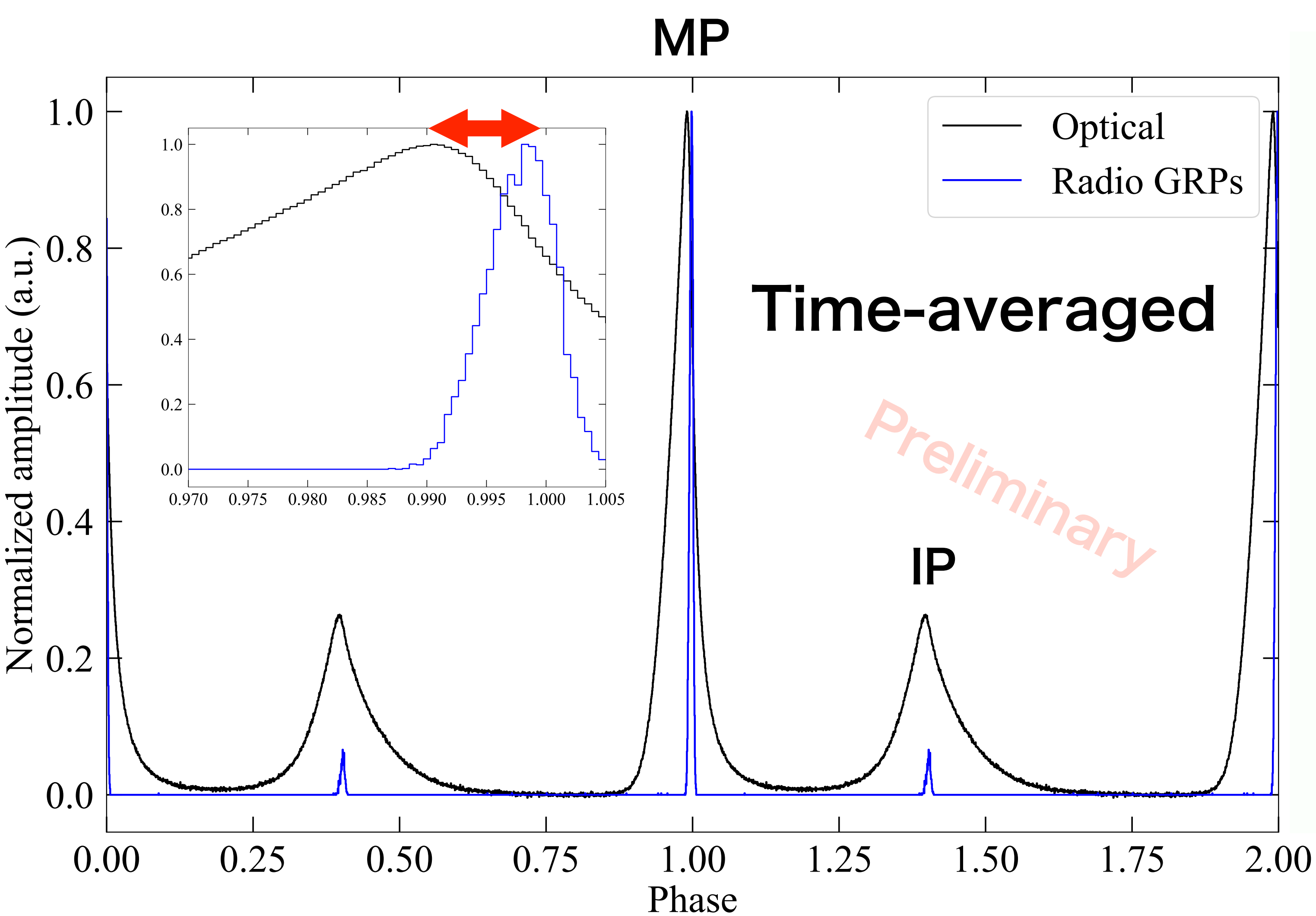
Optical results (i)

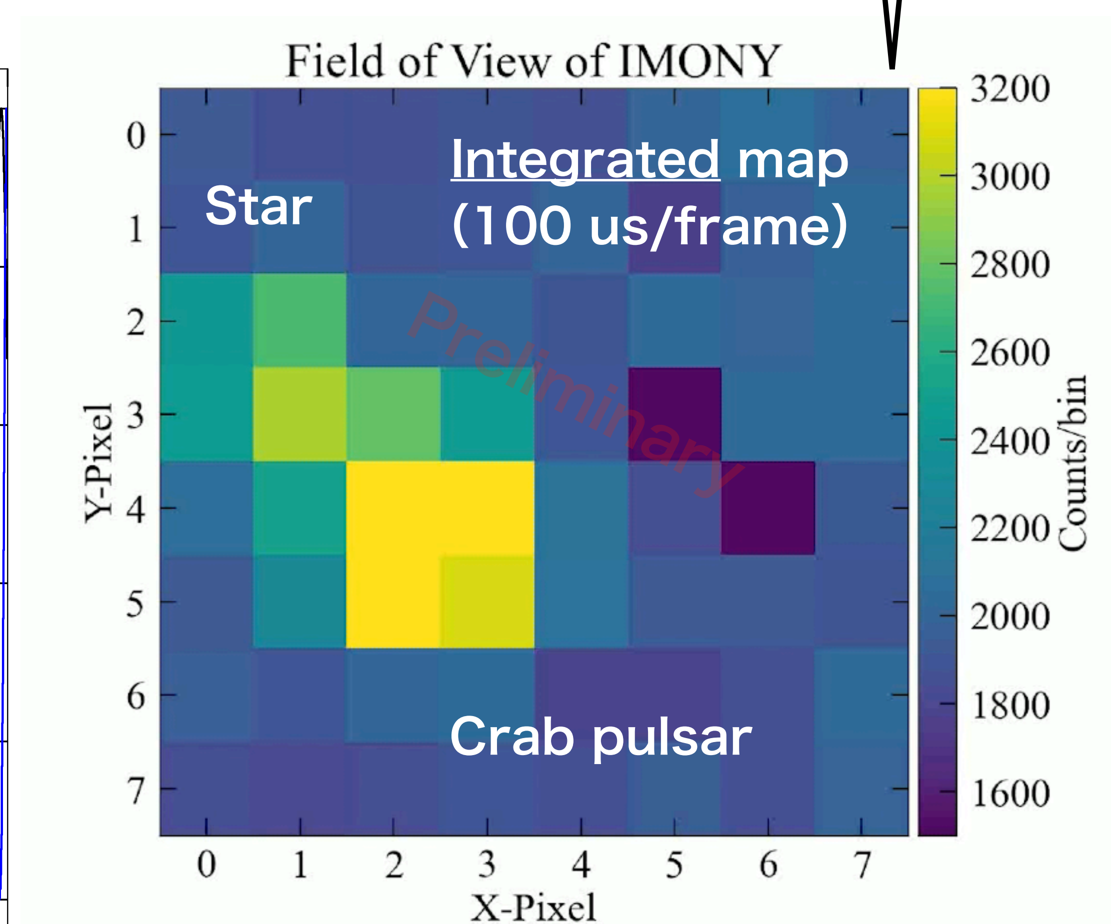


Detection of the averaged pulse-profile

Photon arrival times were aligned with reference timing t_{JPL} on 2/7, and the rad.-opt. time lag was 258±10 us

↔ Our result was consistent with previous studies (e.g., 255±21 us by Oosterbroek+08)



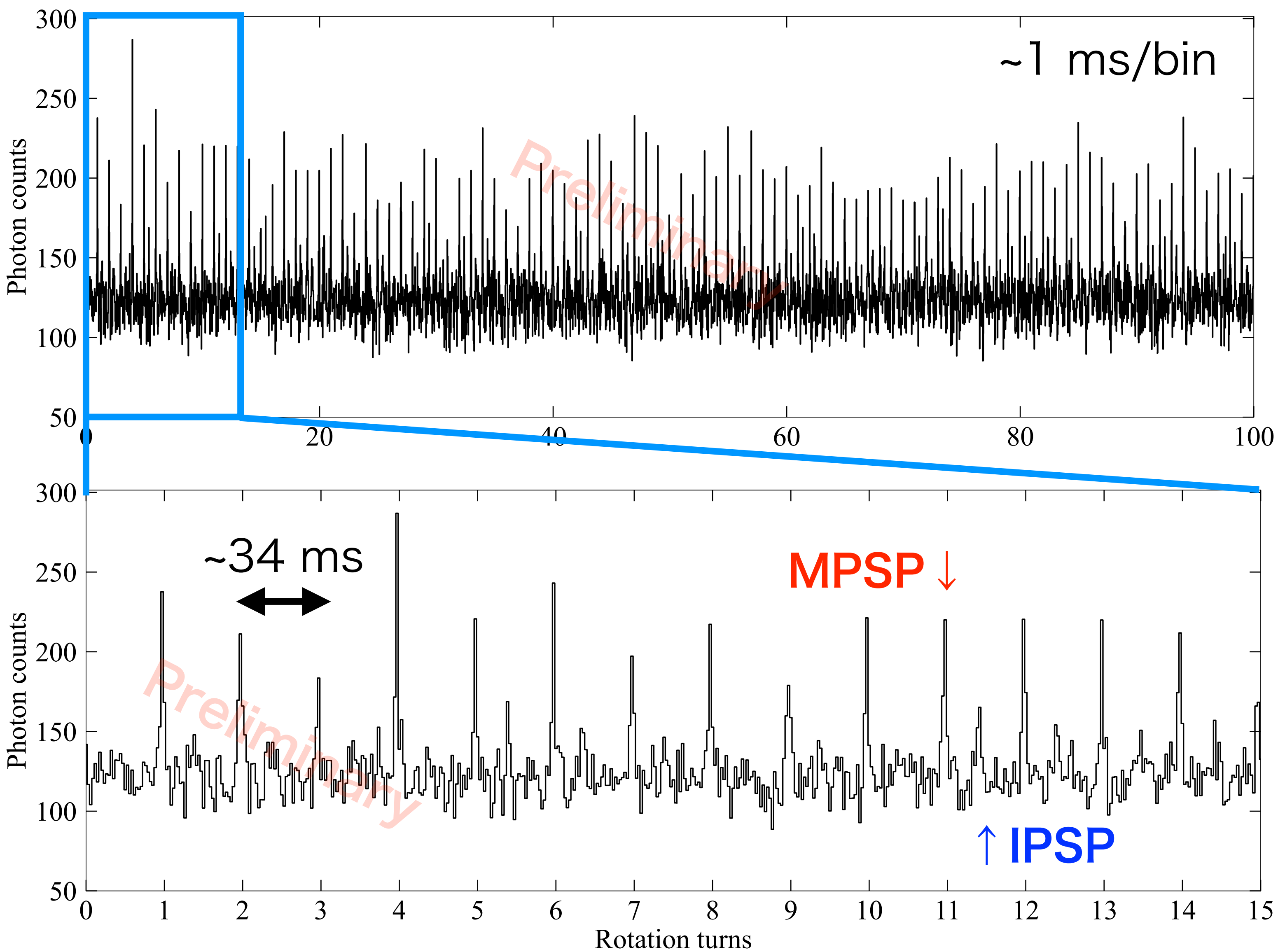


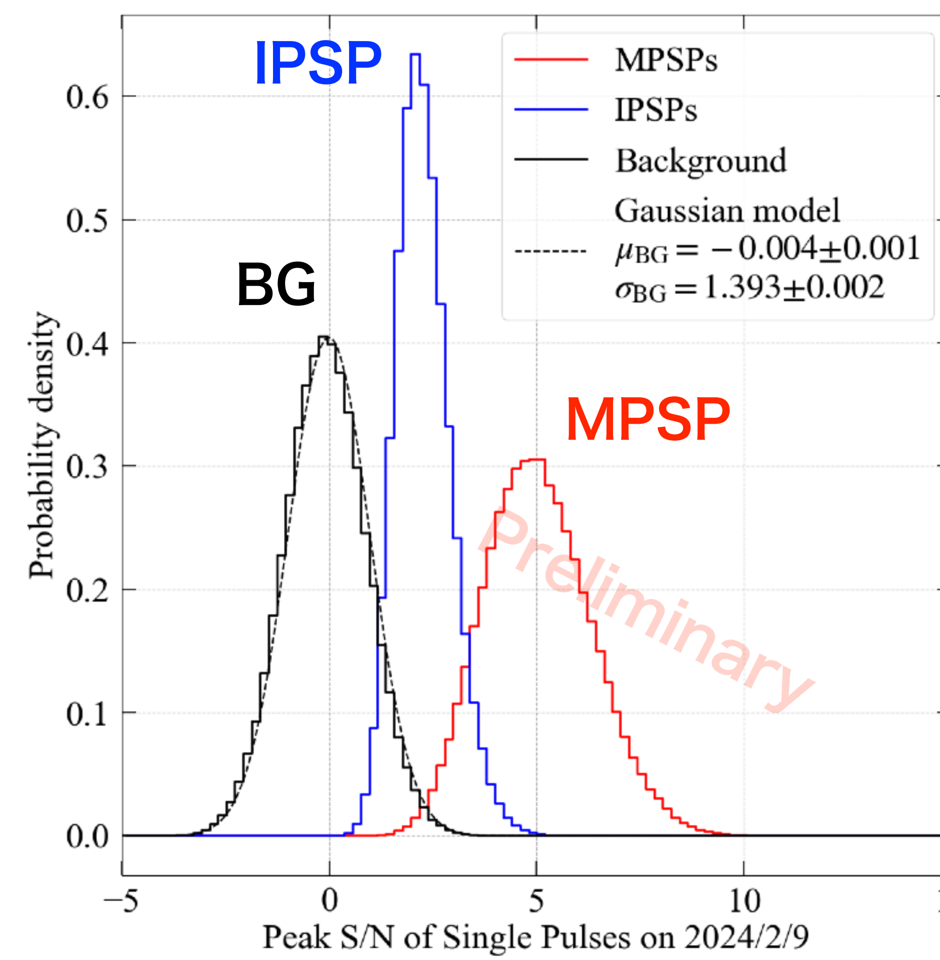
We can reconstruct the folded light curve as a movie

Optical results (ii)

Optical SPs were successfully detected!

- ~5σ for MPSP and ~3σ for IPSP on average
- Considering the photon statistics, we analyzed MPSPs in detail



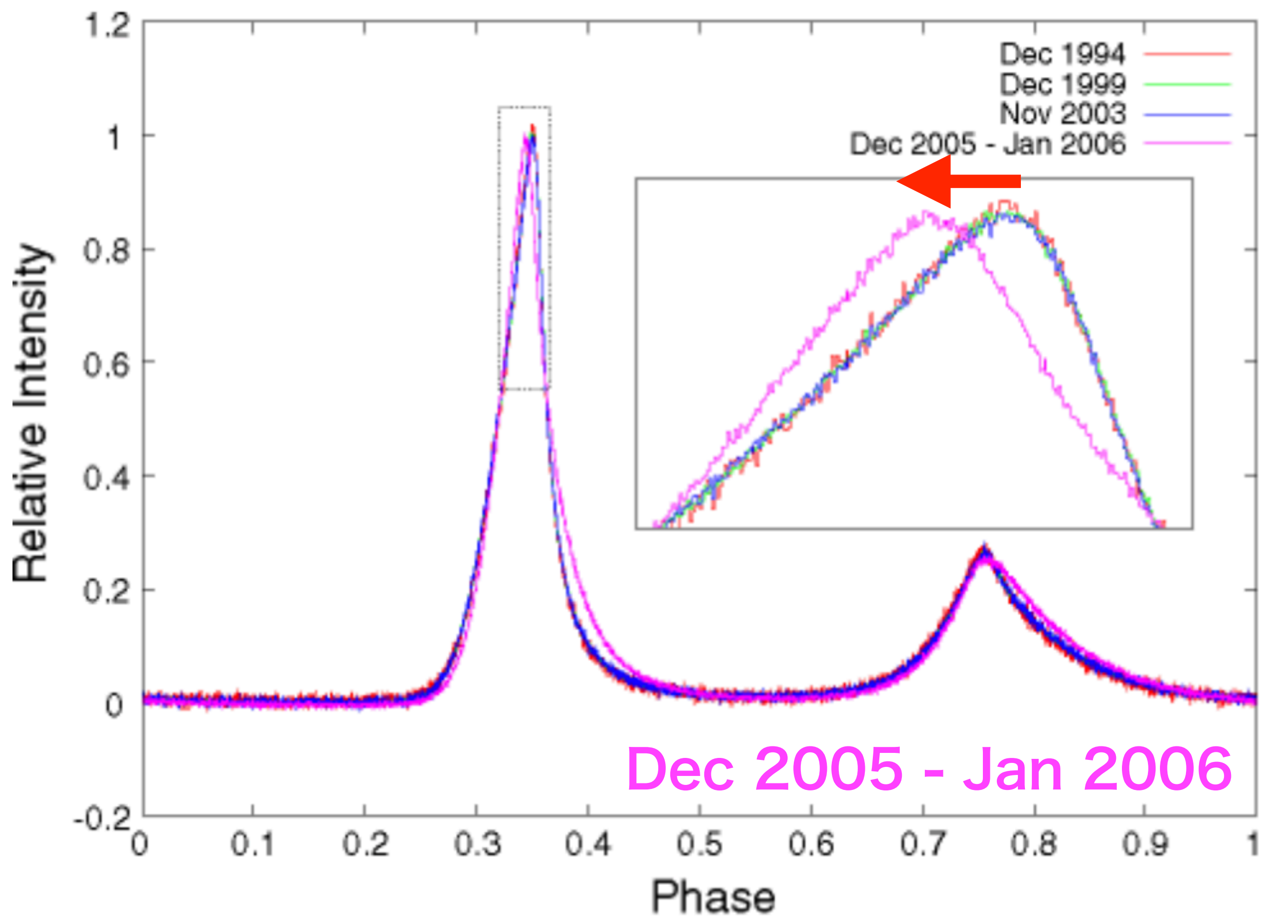


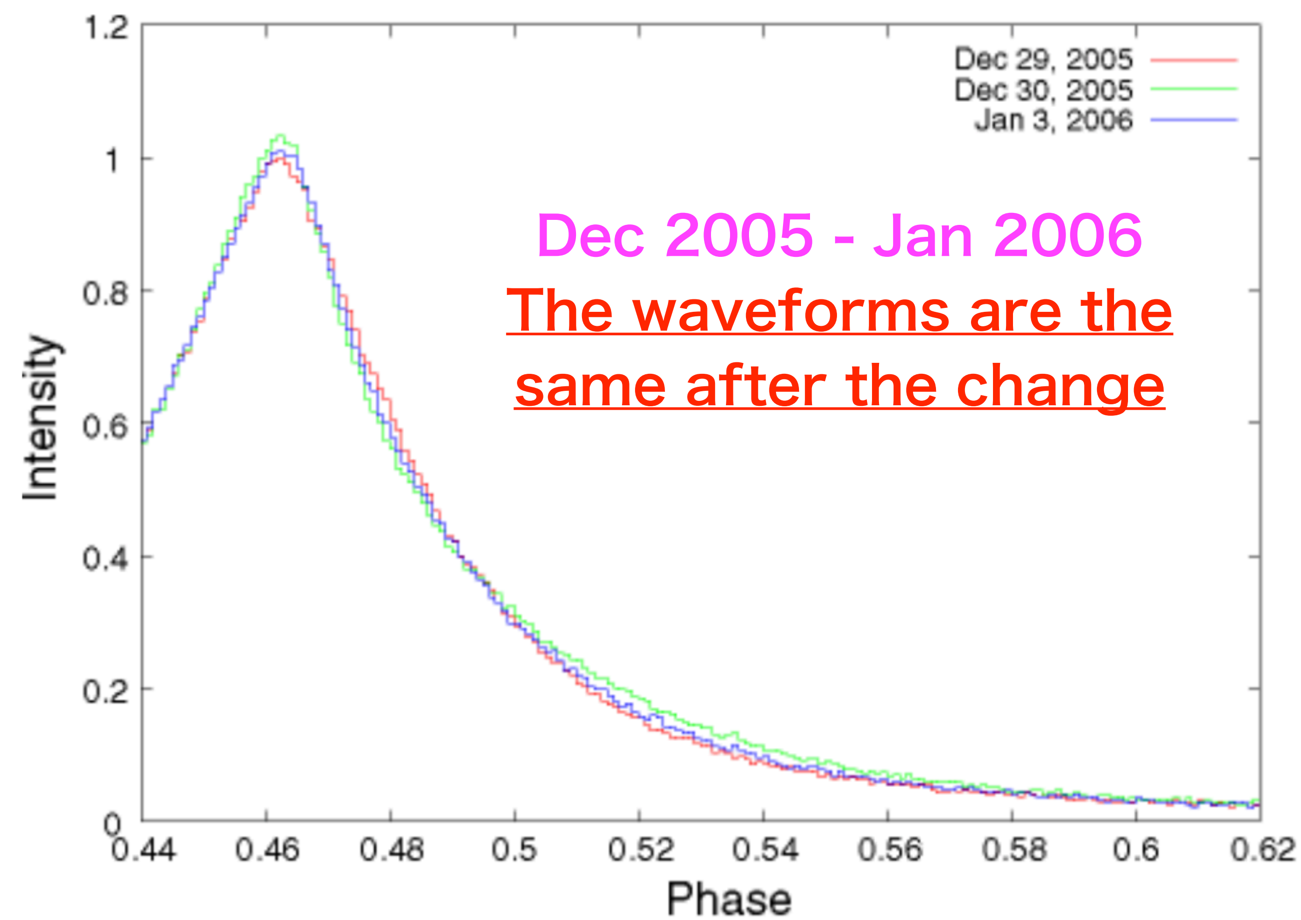
↑
The distribution of peak S/N
of MPSP and IPSP on 9 Fev. 2024

e.g., Hashiyama et al., Proc of SPIE, 2024
and K. Hashiyama, Ph.D thesis, 2025

This page is skipped ..

Stability of pulsation (Karpov+07)





Pulse waveform changed in 2003–2006

- **Quasi-periodic change of the pulse beam orientation?**
  - Caused by the pulsar's glitch?
  - Change of the neutron star's state?

What about our one-week nightly observation data?

This page is skipped ..

This page is skipped ..

Summary

What is the origin of pulsed emission?

- **We focused on the pulsed emission mechanism of the Crab pulsar**
  - Giant Radio Pulse (GRP) is a radio transient emission
  - The mechanism is still unclear, but the magnetic reconnection is one possible idea
- **We focused on timing fluctuations caused my the reconnection**
  - **Optical Single Pulses (SPs) are the key to validate the reconnection model**
  - We performed the radio and optical simultaneous observations with the Usuda radio telescope and the Seimei telescopes with IMONY in 5-11 Feb. 2024
- **No timing fluctuations before or after GRPs were observed**
  - The critical reason was the cloud cover that reduced the effective simultaneous observation time (**we need an additional observation!**)
- **Meanwhile, the peak drift was found through 7 nights observation**
  - We investigated and confirmed that the drift was not caused by pulsar's glitches
  - **The optical emission region might move ~24 km in the Outer Gap**