電波・可視光同時観測による カニパルサーの巨大電波パルス 放射機構解明に向けて

Toward unraveling the emission mechanism of Giant Radio Pulses from Crab pulsar by simultaneous observation with radio and optical bands

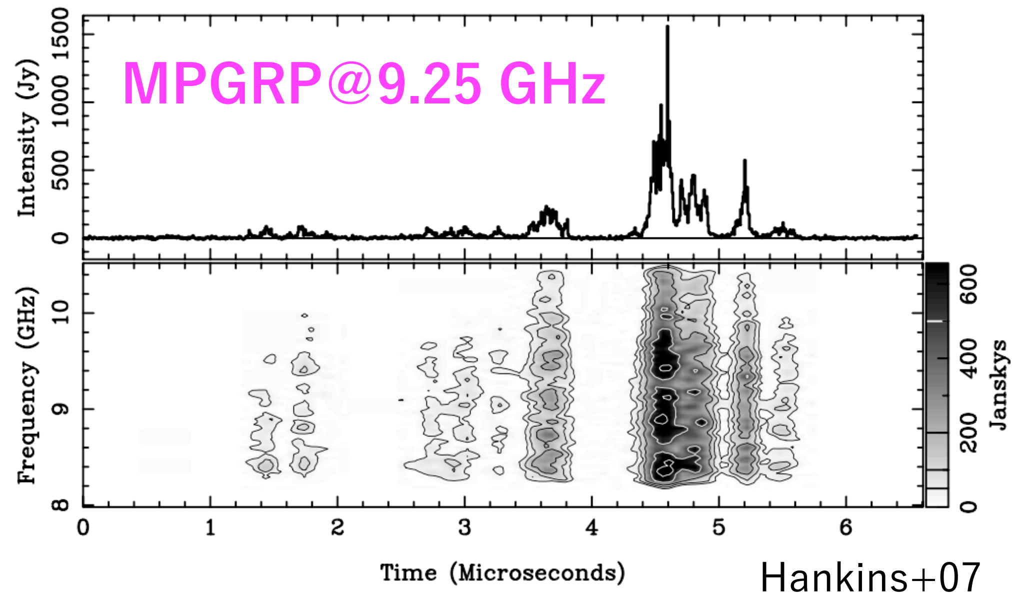
Univ. of Tokyo / Yamagata Univ. D2

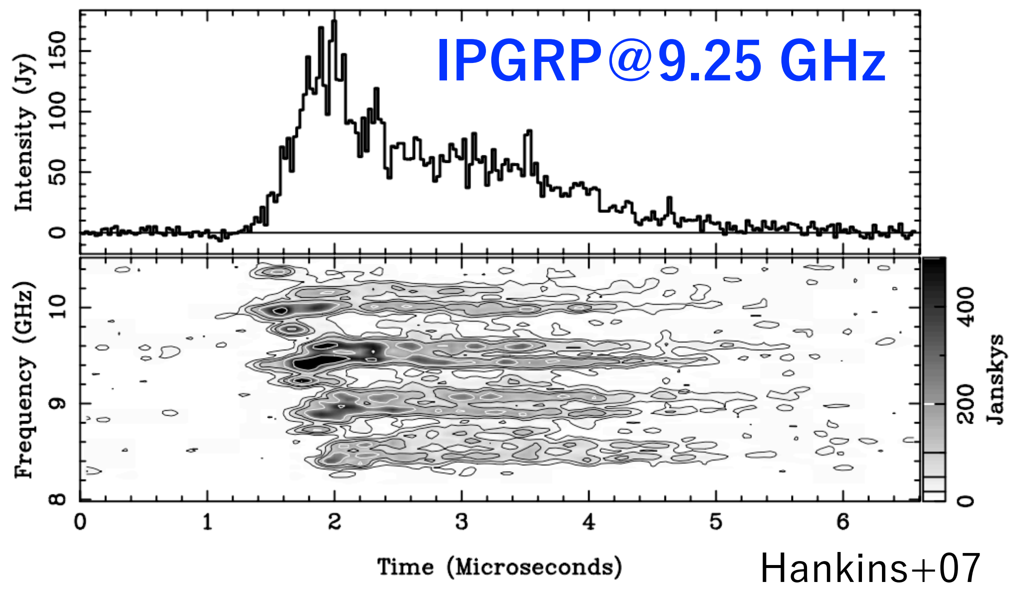
Kazuaki Hashiyama

Neutron Star Workshop 2023 @ Kyoto Univ.

What is "Giant Radio Pulse (GRP)" ?

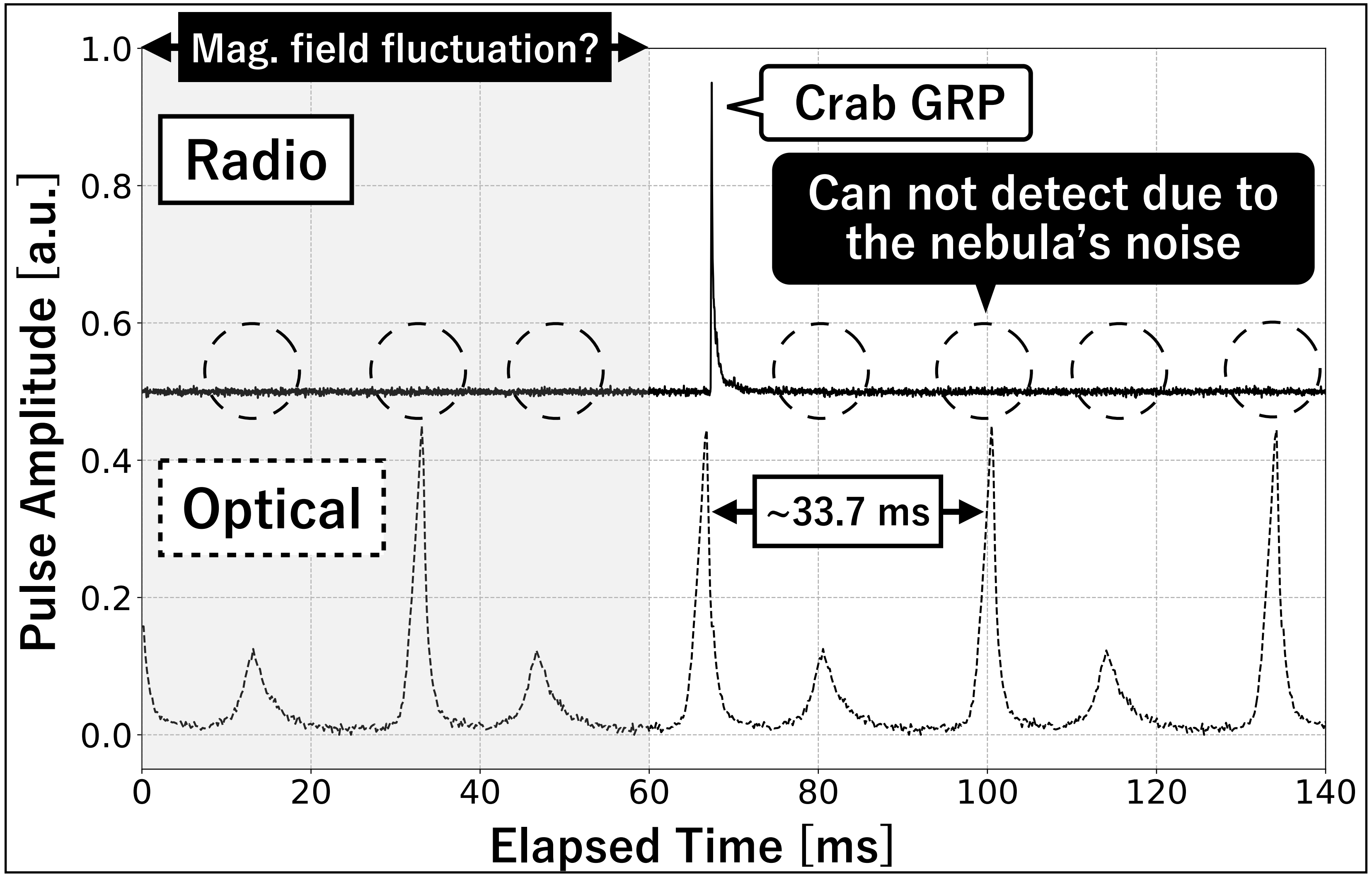
- **GRP is a transient-bright radio pulses**
  - >100 times brighter than the normal pulse
    - Two types: Main Pulse GRP (MPGRP) and Inter Pulse GRP (IPGRP)
  - <u>Unpredictable and unexplained</u>
  - Detection rate is variable because of the disturbance of the plasma
    e.g.) **1000–3200 GRPs/1 hour @300 MHz**
  - Detected at ~0.1 % of pulsars
    - **Crab pulsar is a suitable object because it is brighter than other pulsars!**

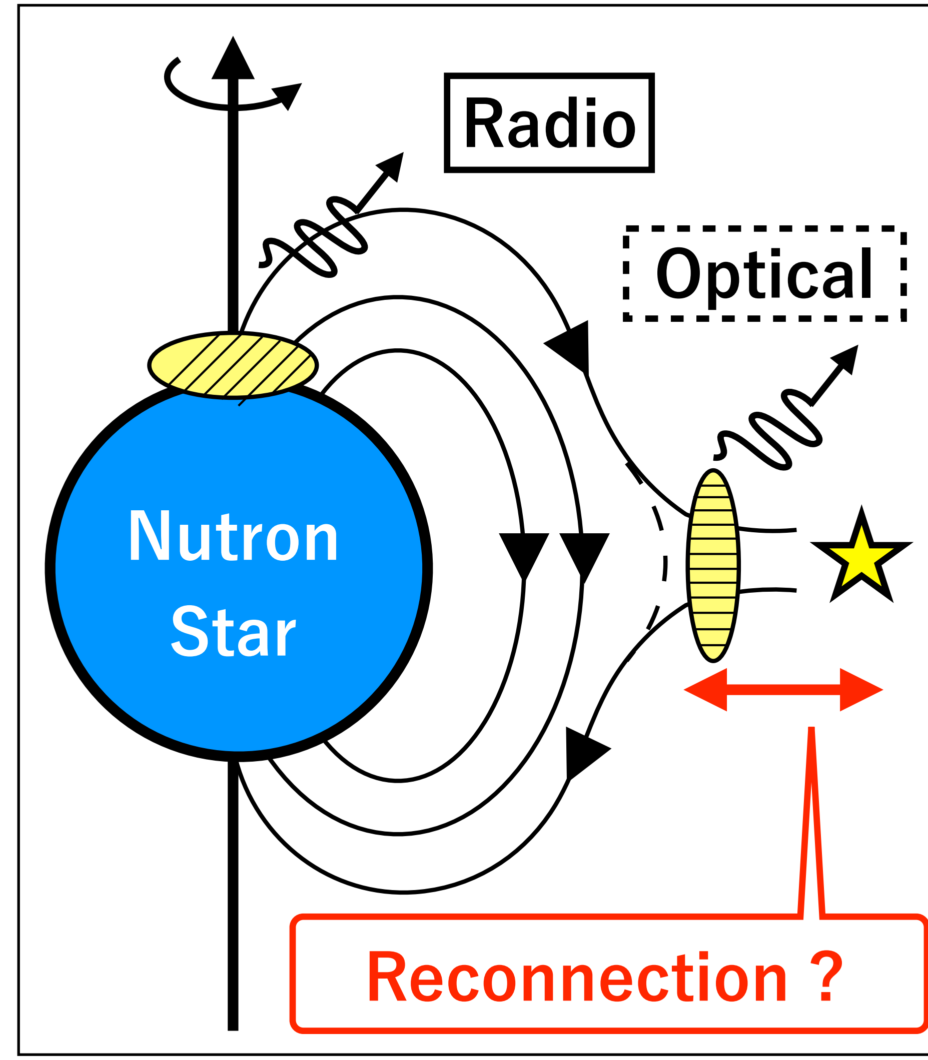




First, we have to understand Crab-GRPs to unveil the widely emission mechanism

Trigger for emitting GRPs ..?



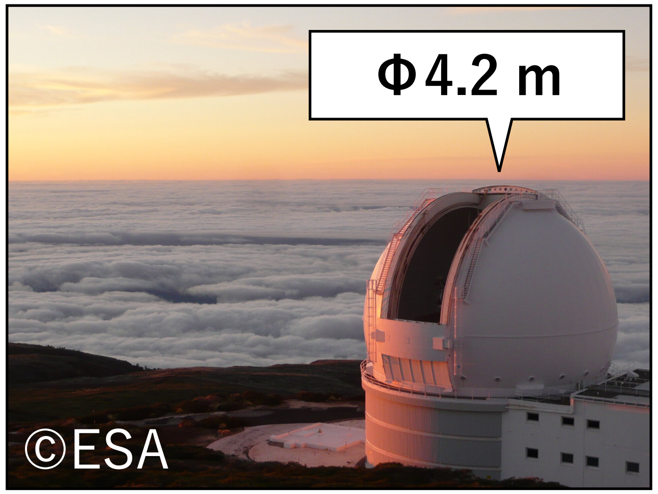


- **Release energy by magnetic reconnection** (e.g. Lyubarsky+19)
  - **Does the magnetic filed structure change before emitting GRPs?**
    - ▸ **Single Pulse (SP)** will be useful to investigate the variance
  - ✤ Time averaged pulse will reduce the change i.e. **SP is important!**

Importance of optical observation

- **Observation of Single Pulses (SPs)**
  - Radio: Nebula emission is stronger than crab pulsar = difficult!
  - X-ray・γ-ray: Less photon statistics = difficult!
  - **Optical: Tough requirement for detectors, but there're some precedents**

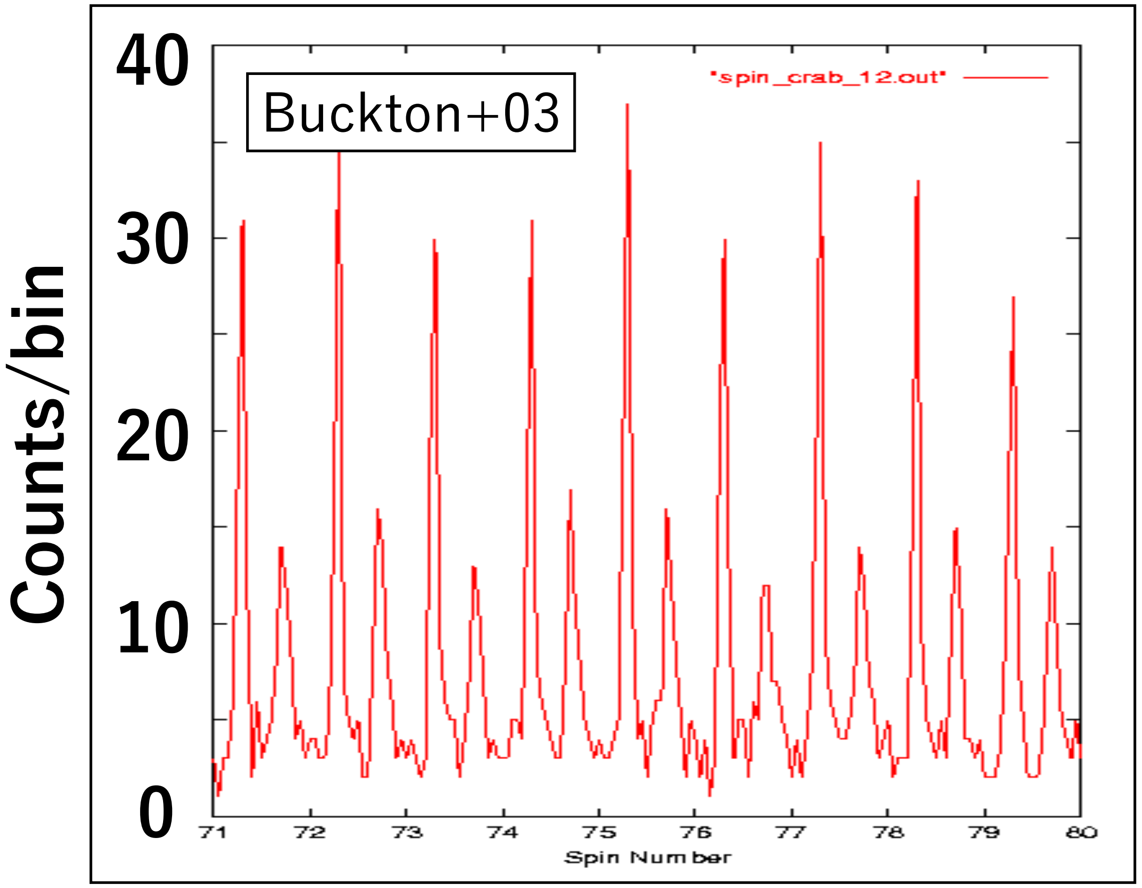
William Herschel Telescope @La Palma



＋

High time resolution TRIFFID system

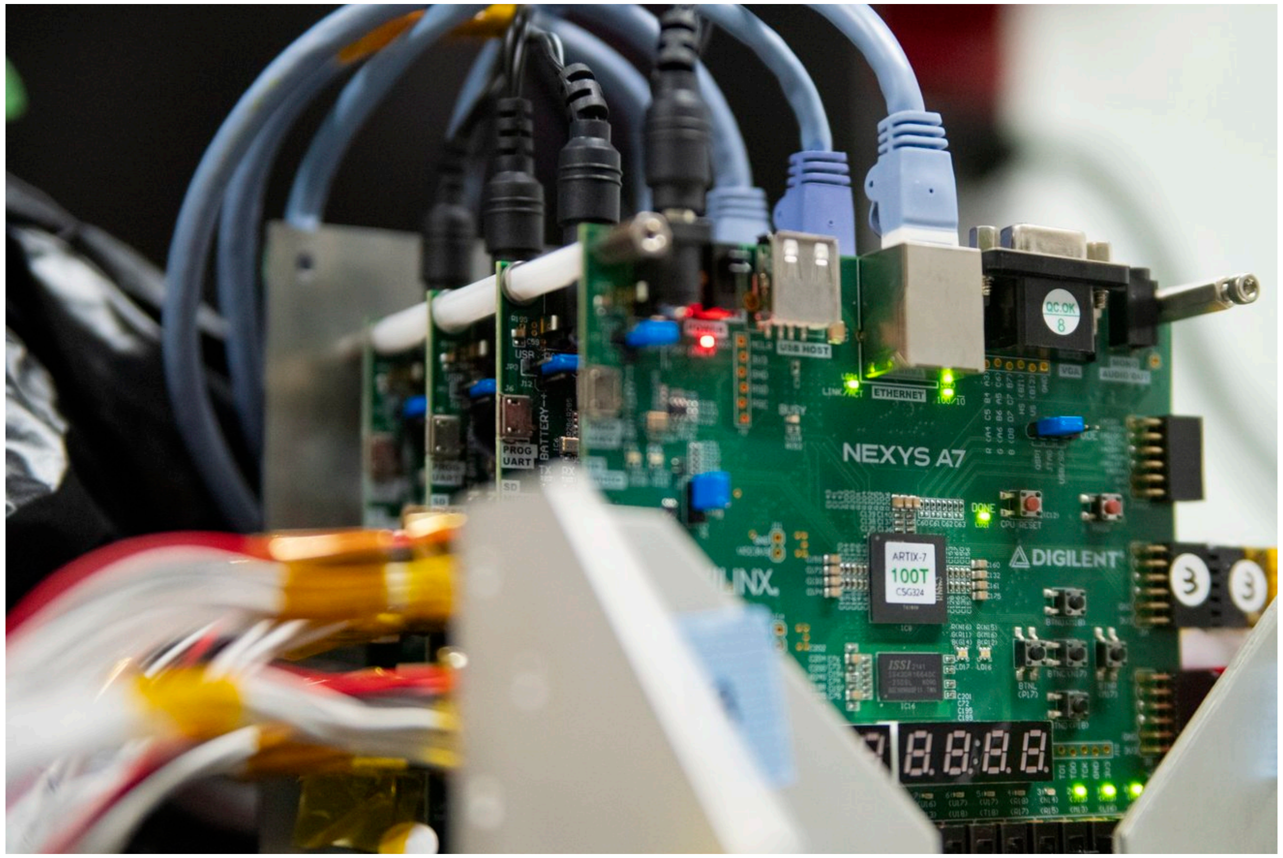
- **Sensor:** APD
  - ✦ Single px observation
    25 um/px, ~2.2 arcsec
- **Efficiency:** max. 70%
- **Time resol.:** ~100 ns

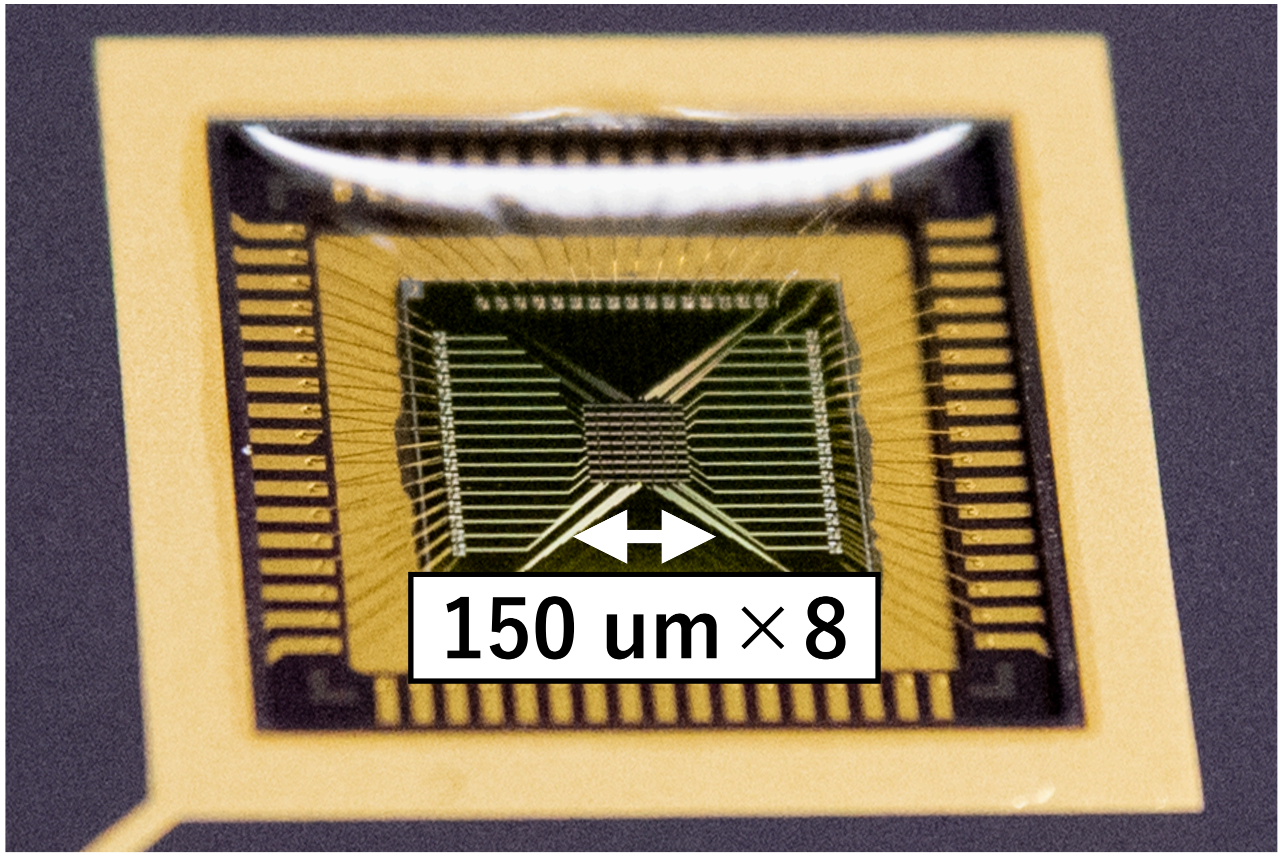


High sensitivity camera
＋Large telescope are needed!

IMONY

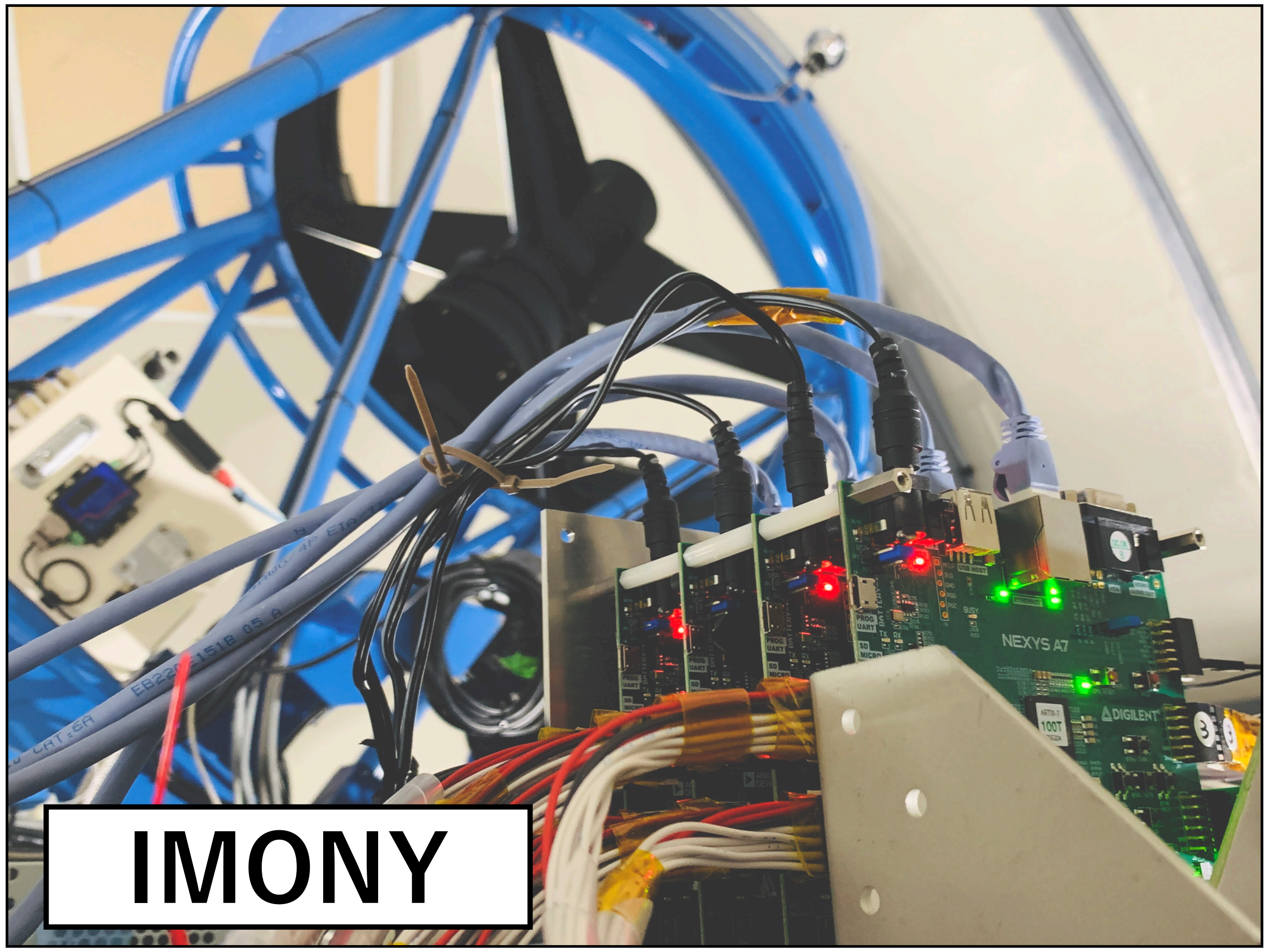
- **<u>I</u>mager of <u>M</u>PPC-based <u>O</u>ptical photo<u>N</u> counter from <u>Y</u>amagata**
  - Sensor: MPPC made with a semiconductor
    - ▸ **Detection of the single-photon is possible** by customized the Geiger APD
  - High sensitivity and high time resolution
    - ✓ Efficiency: <u>max. 60% @450 nm</u> (Range: 270–900 nm)
    - ✓ Time resolution: <u>max. 100 ns</u>





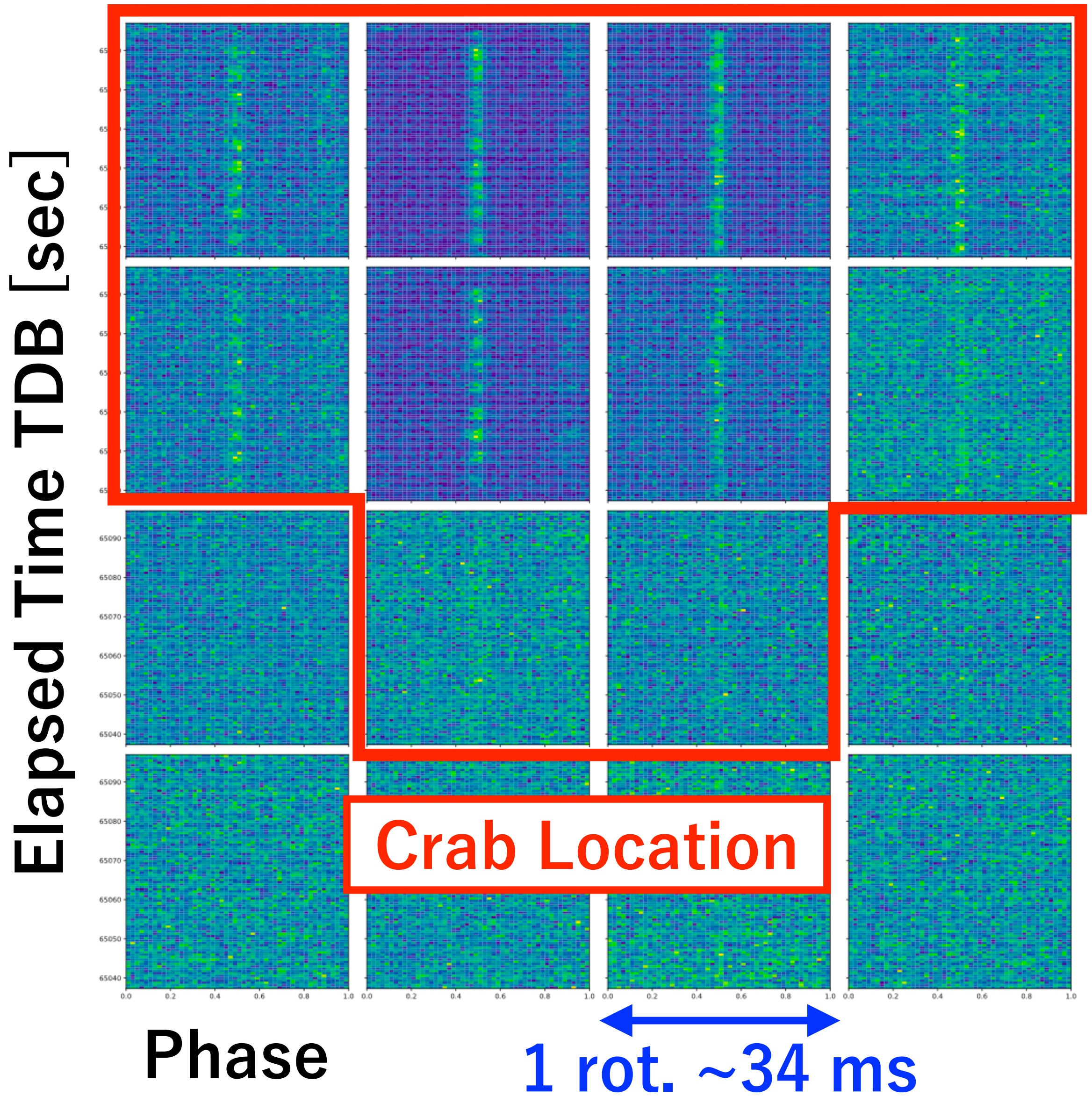
Higashi Hiroshima Observatory

- **Kanata telescope**
  - Aperture: 1.5 m and Focal length: 18300 mm
  - Set IMONY at Nasmyth focus
    - FY2021: □100 um sensor 4×4 array
    - FY2022: □150 um sensor 8×8 array ←**Expanded the FoV!**

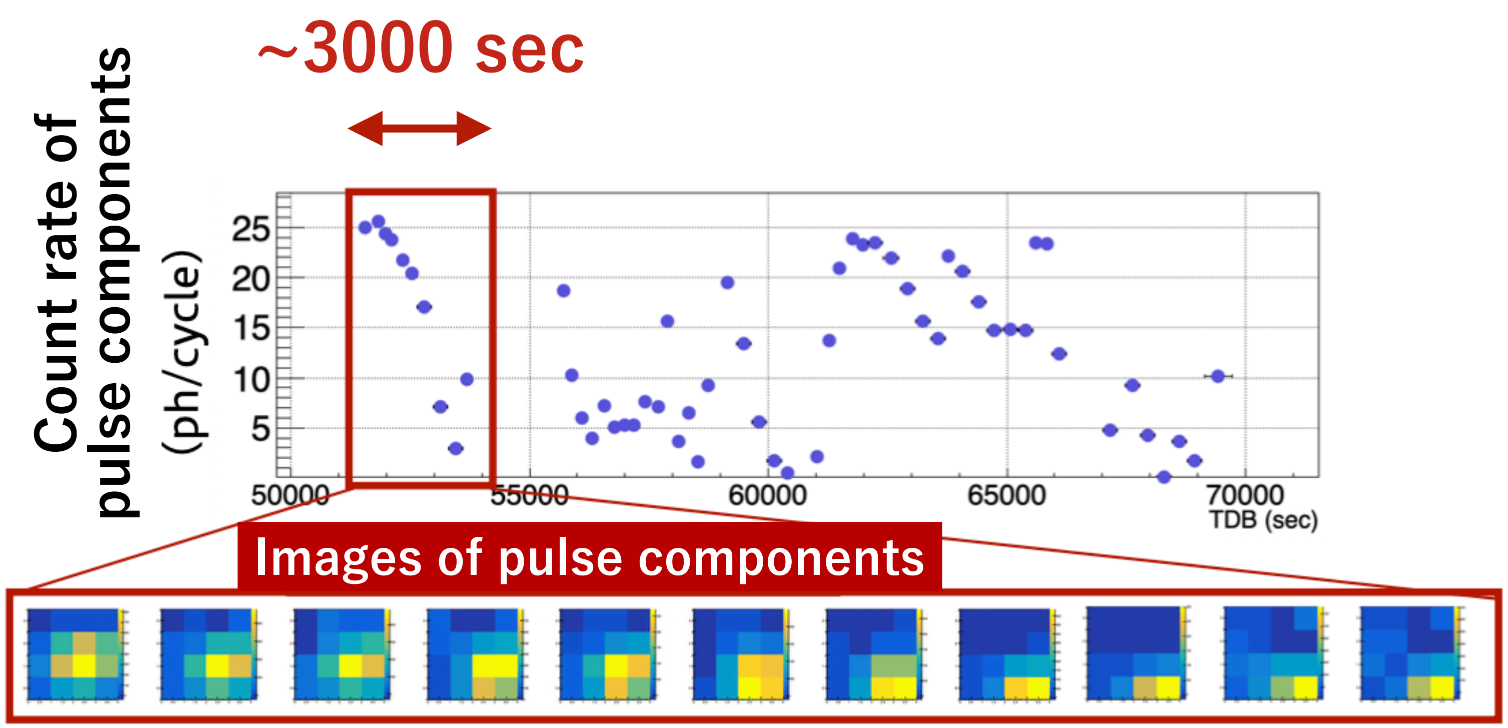


Observation in FY2021

- **Assignment: A star image came out of the sensor**
  - Using □100 um sensor and 4×4 array, FoV will be ~4” = **Narrow**
  - Could not execute the stable observation because the tracking accuracy is limited and the FoV is narrow



← **Example of 60 sec observation**

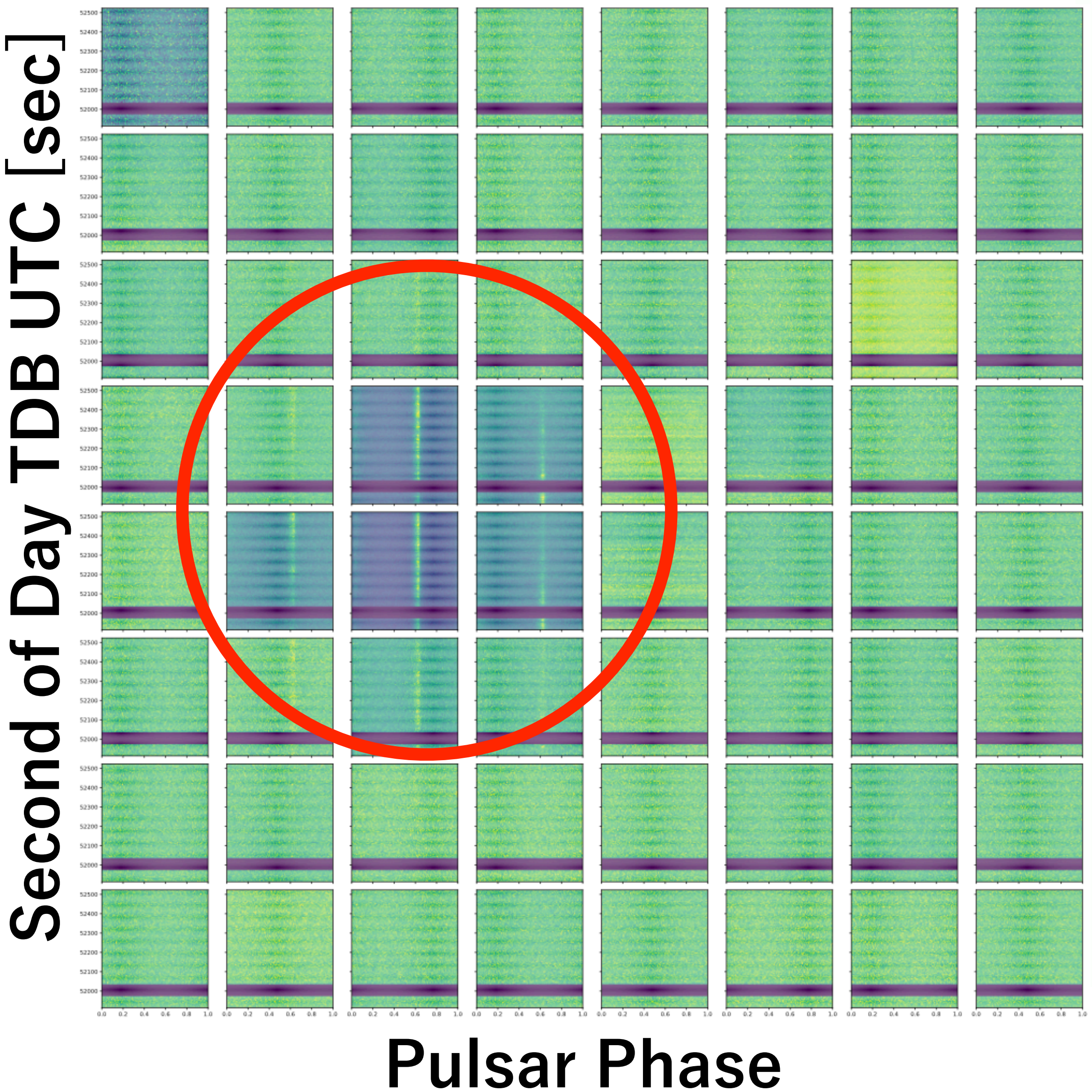


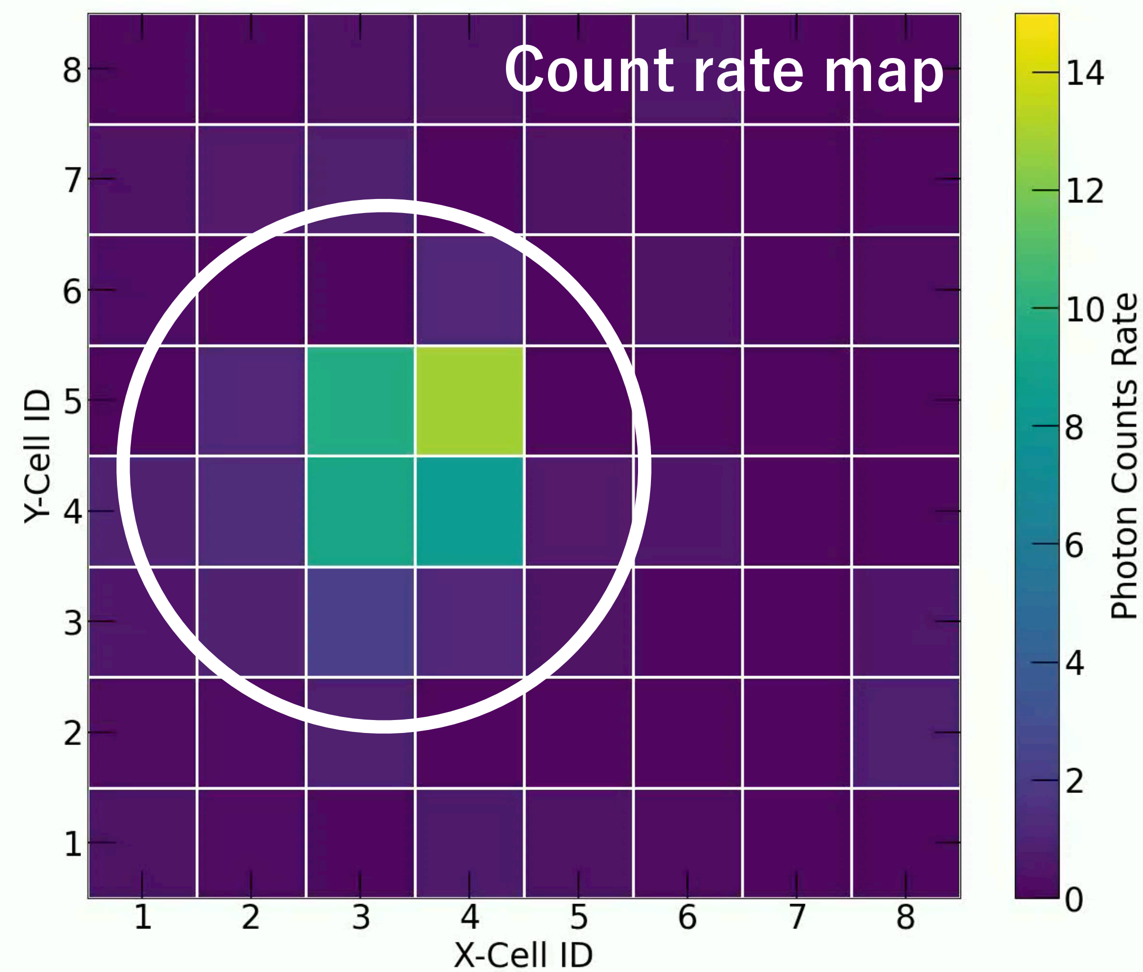
Imaging position was came out of the sensor in less than 1 hour

Credit: Takeshi Nakamori, 2022 JPS

FY2022: Test for the stable observation

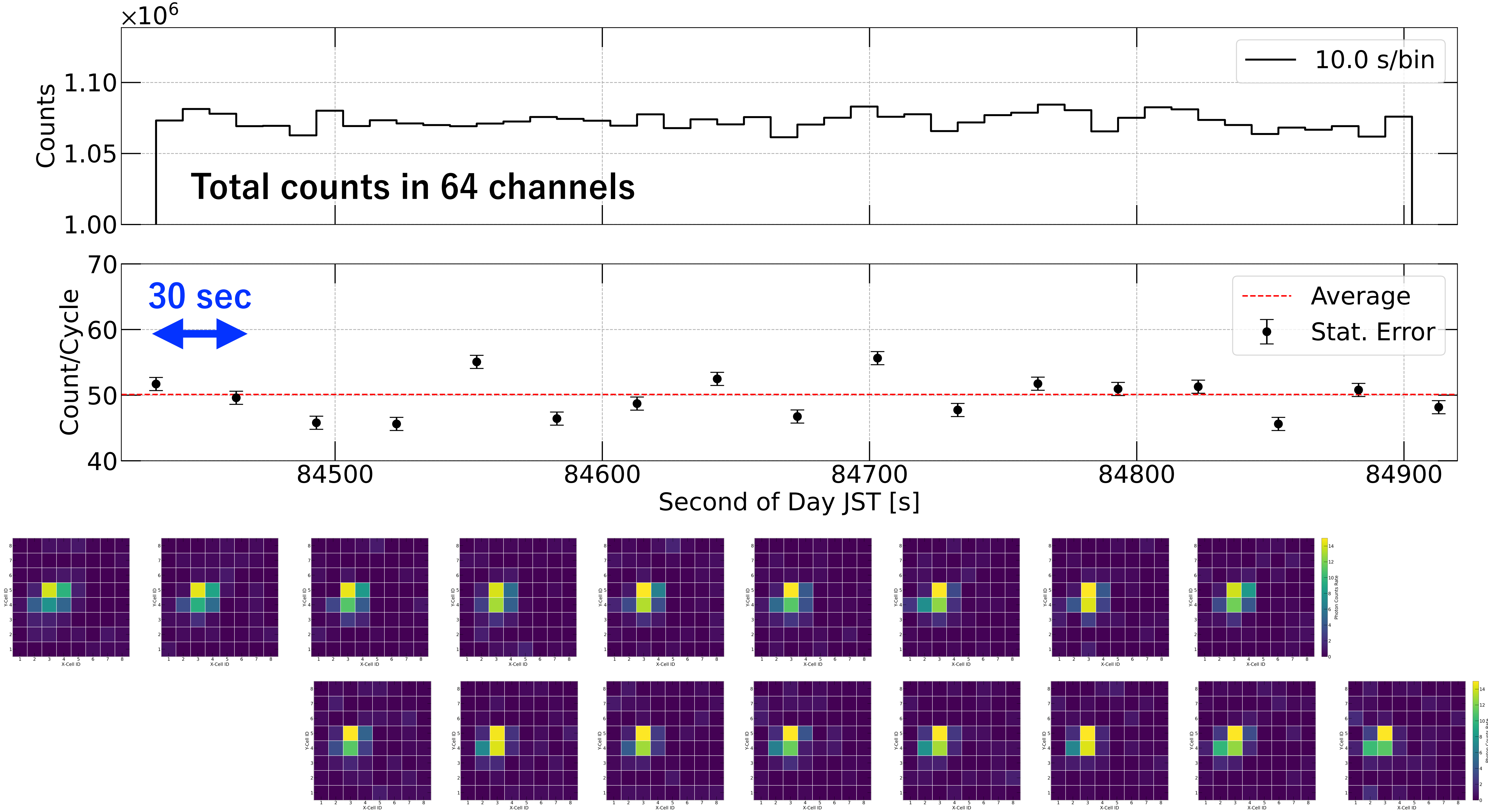
- **Aimed the stable observation to expand the sensor area**
  - 4×4 array to 8×8 array (FoV is 2 times wider)
  - The Crab imaging position is gradually shifting toward the left side
    - ▸ But the image is in the sensor at least 10 min observation





← Example of ~10 min observation (removed some part of data)

FY2022: Evaluation of the stability

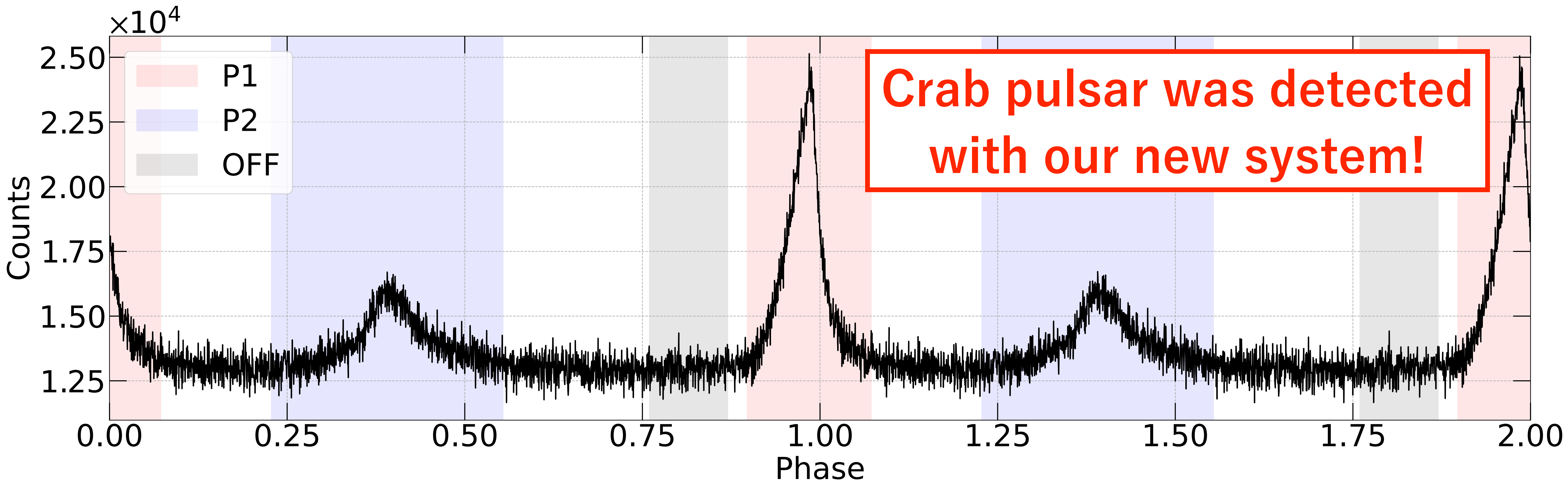


Detection rate was stable <10 min (Needs to estimate!)

FY2022: Crab pulsar observation

- **Observation**
  - Valid obs. time was 2010 sec (~34 min)
- **Data analysis**
  - Converted the photon detection time to the barycentric dynamical time
  - Dark / Flat correction
  - Convolution with a pulsar rotating period

Date	JST	Target	Observation time [s]
1/21	19:46:17	Flat	61/61
	21:24:41	Dark	61/61
	22:42:17	Crab	11/11
	22:47:15	Crab	547/610
	22:57:24	Crab	488/610
	23:25:13	Crab	547/610
	23:38:53	Crab	417/480
		Total	2010/2321



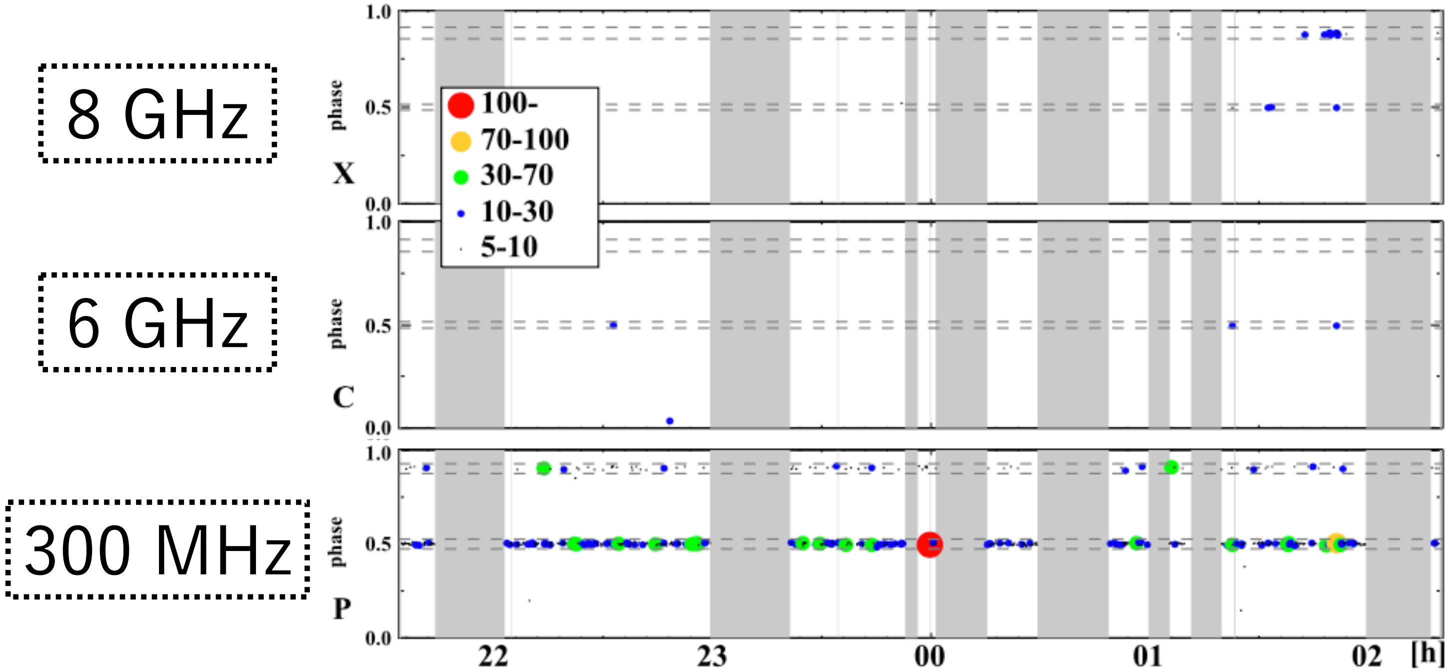
Crab pulsar was detected with our new system!

Radio Observation

- **Motivation: Investigate the optical SPs before and after GRPs**
  - Need to develop the analysis environment for radio data
    - ▸ Pulse **de-dispersion analysis** was needed
- **Iitate radio telescope**
  - Frequency: **317.1–333.1 MHz** (BW=16 MHz)
  - **High detection rate at a lower frequency**
    - ▸ Observing at the ~300 MHz is better!

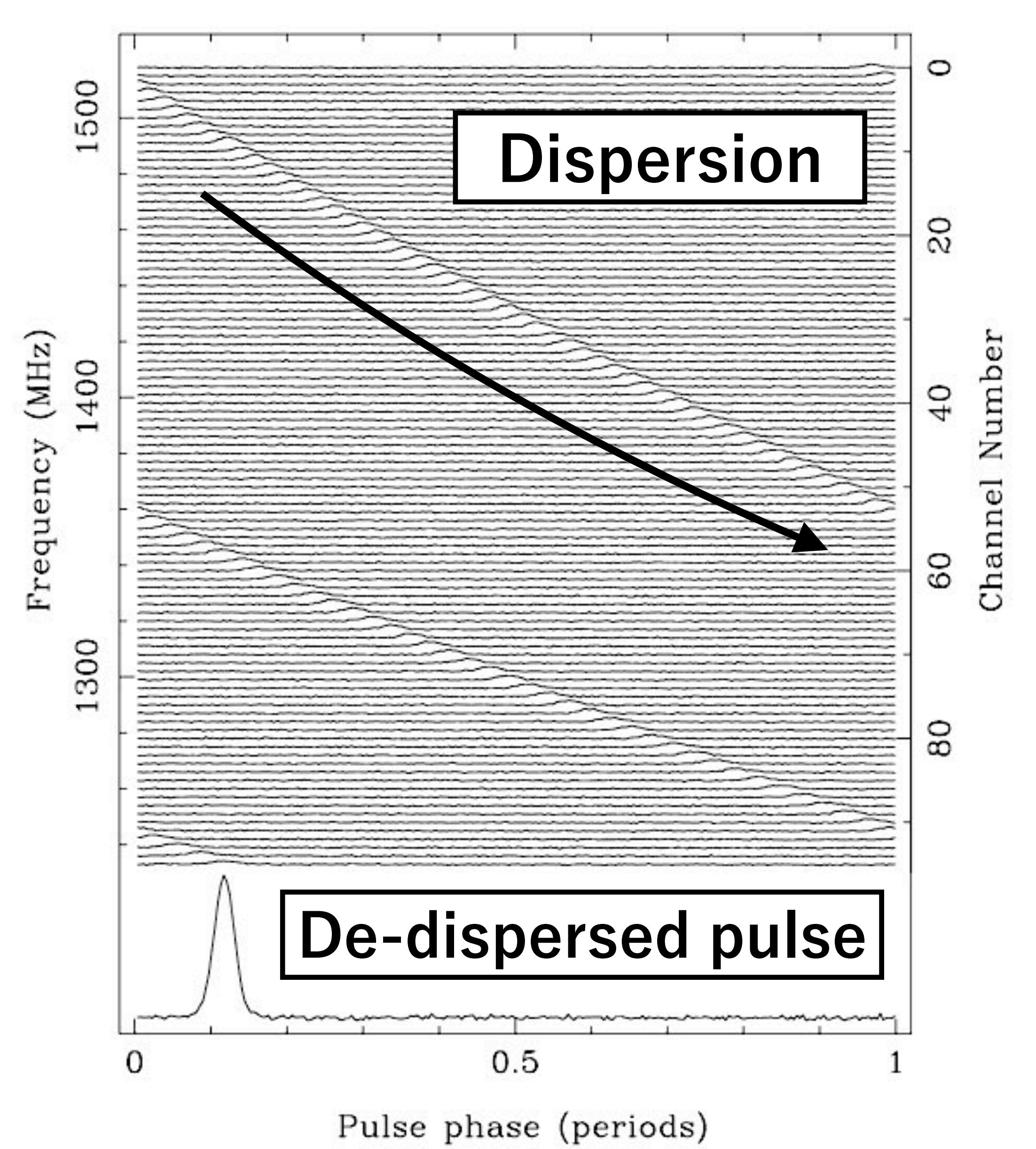
Iitate radio telescope

GRP detection rate at each freq. band (Mikami+16, partially modified)

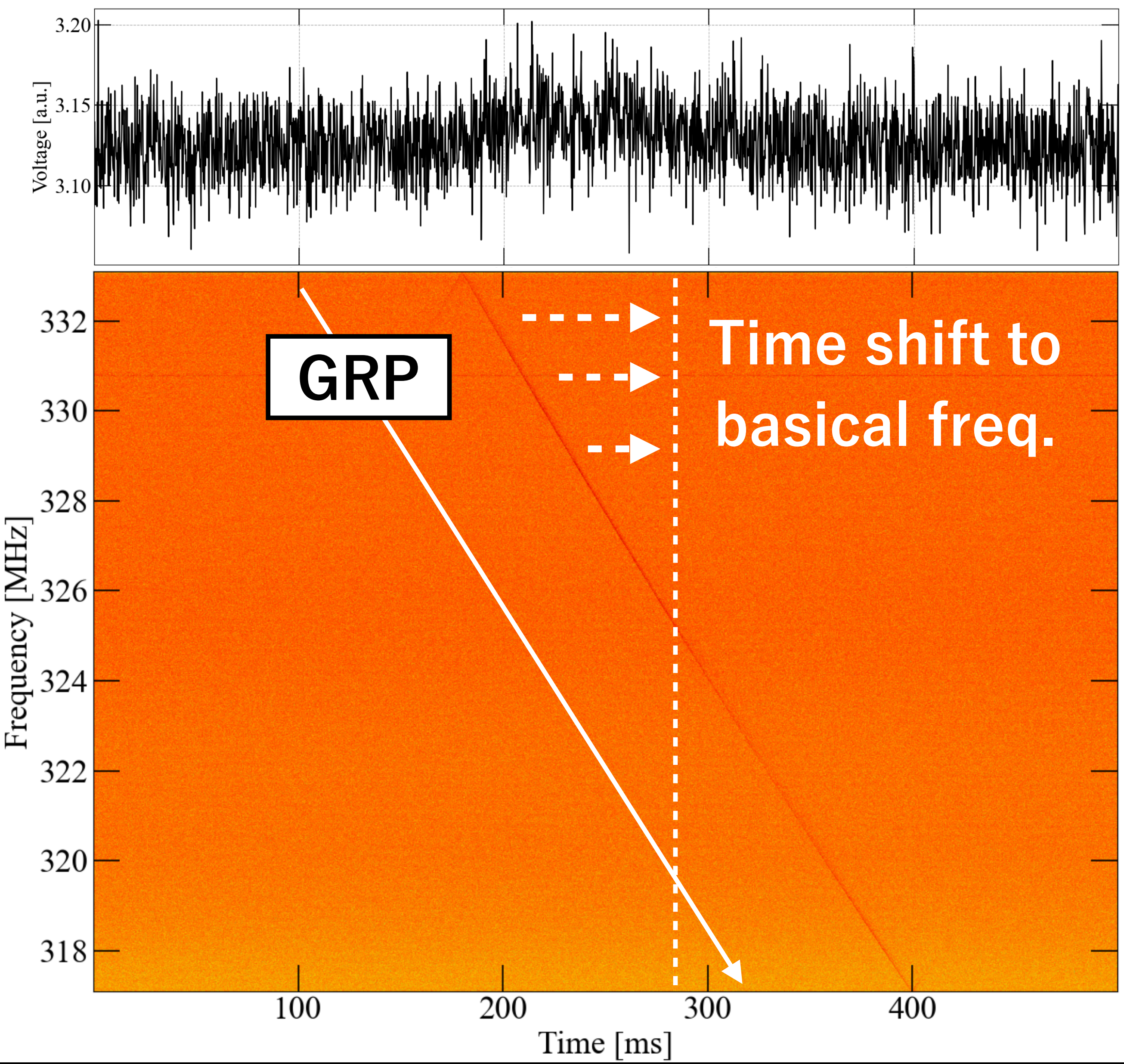


Pulse dispersion

- **Pulse arrival time was delayed by the inter stellar plasma**
  - The higher the frequency component, the earlier the arrival time
    - ▸ Data correction is needed: **De-dispersion analysis**

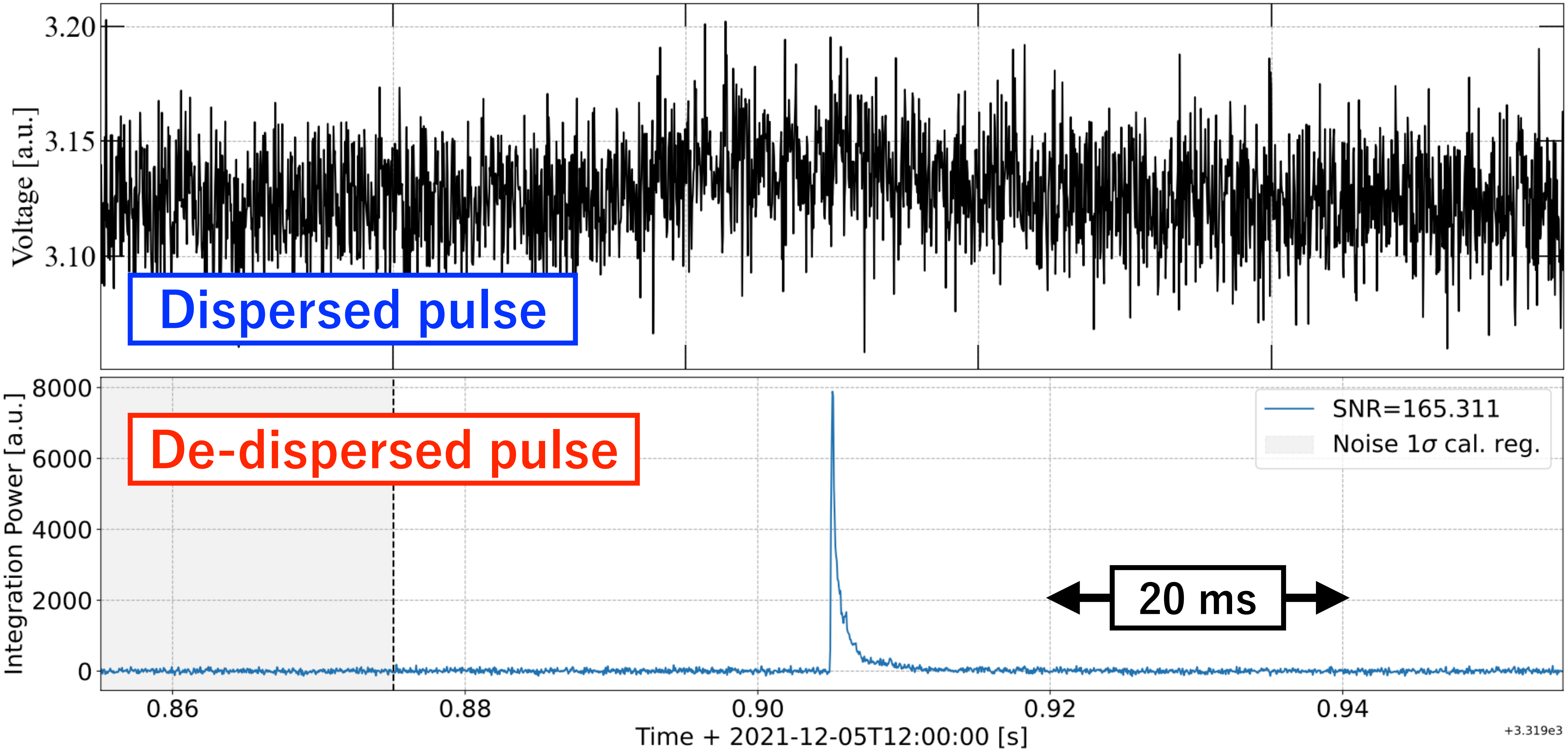


Source: Lorimer Kramer@Handbook of Pulsar Astronomy



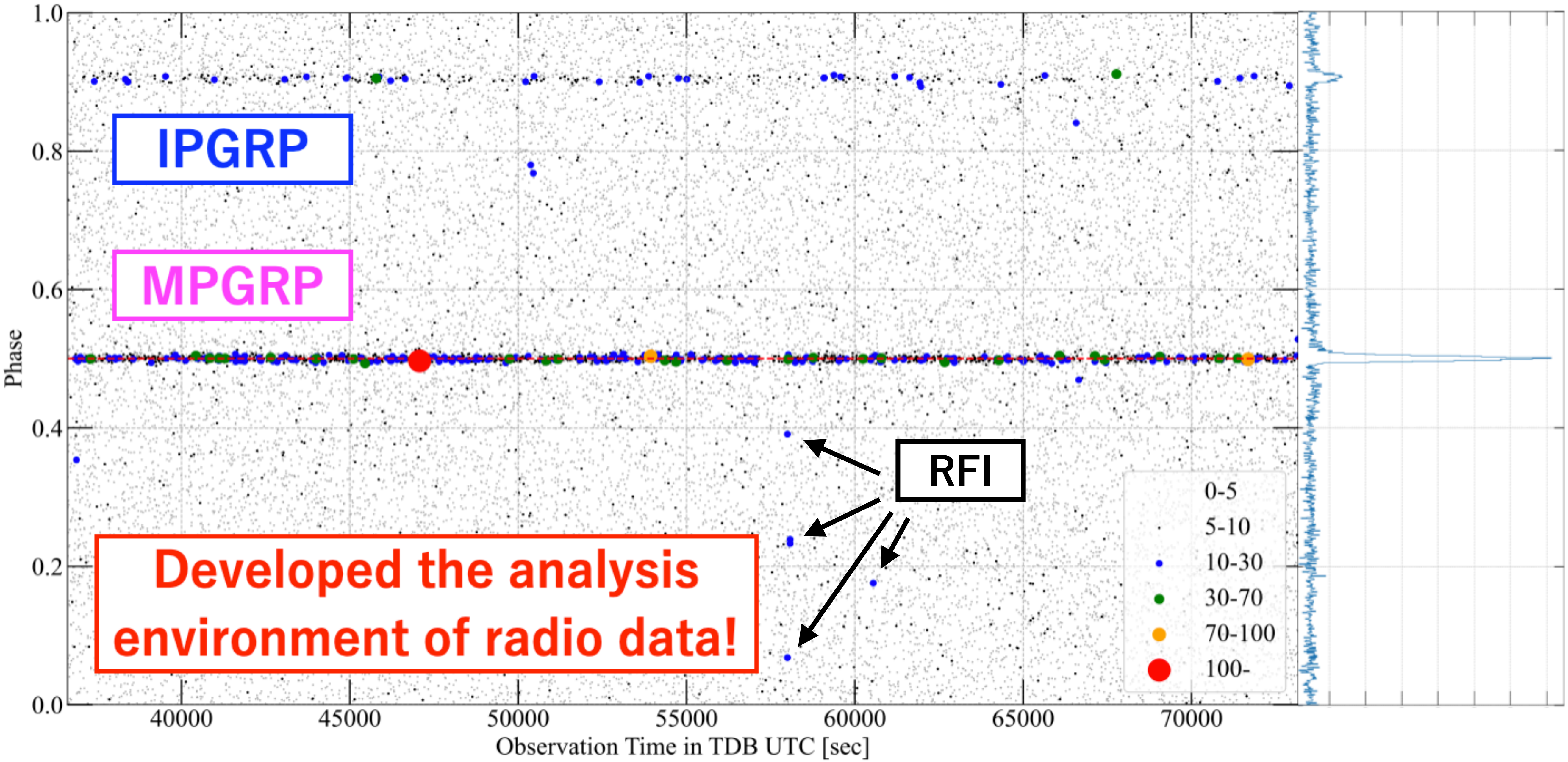
GRP waveform after de-dispersion

- **2021/12/5 12:56:19 GRP @Iitate**
  - 165 times stronger than the 1σ fluctuation of the Crab Nebula emission
  - GRP waveform was restored by de-dispersion analysis



Analysis result of the sample data

- **Observation time vs. phase vs. SNR**
  - GRP detection time was matched in 10 us accuracy with collaborators



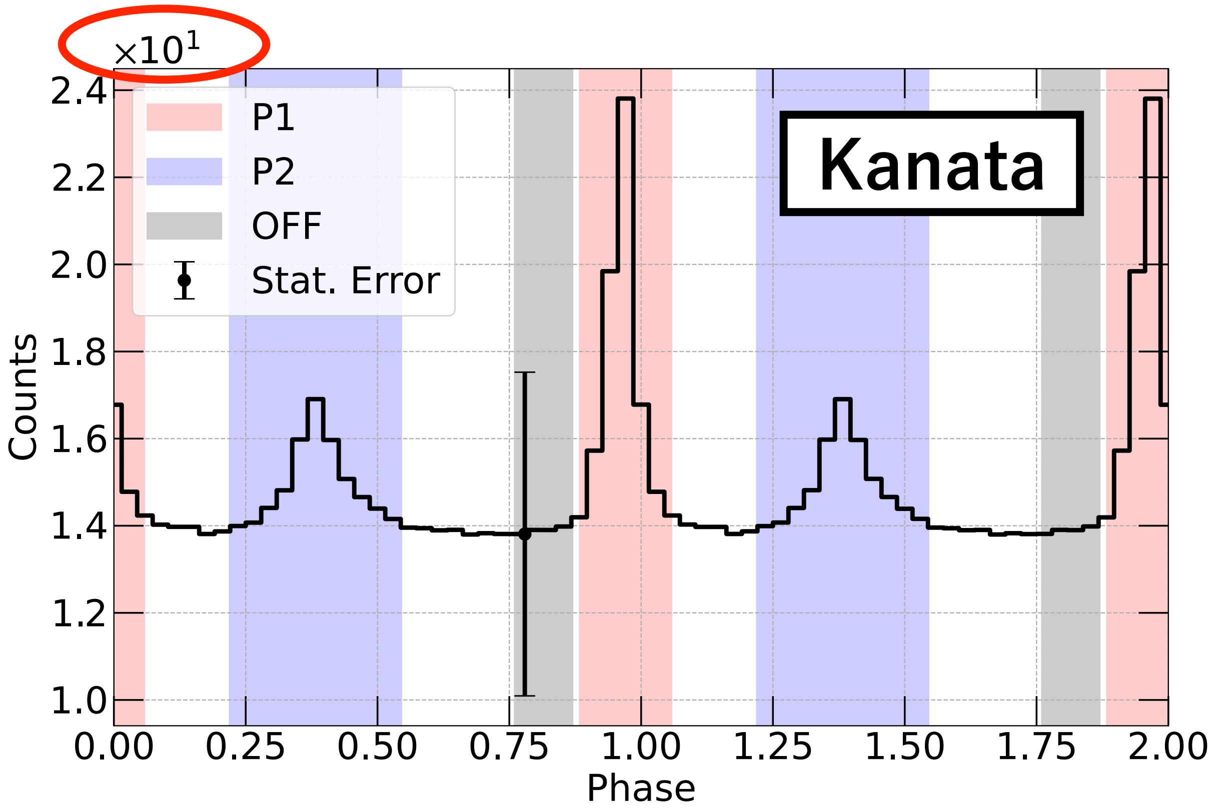
Summary

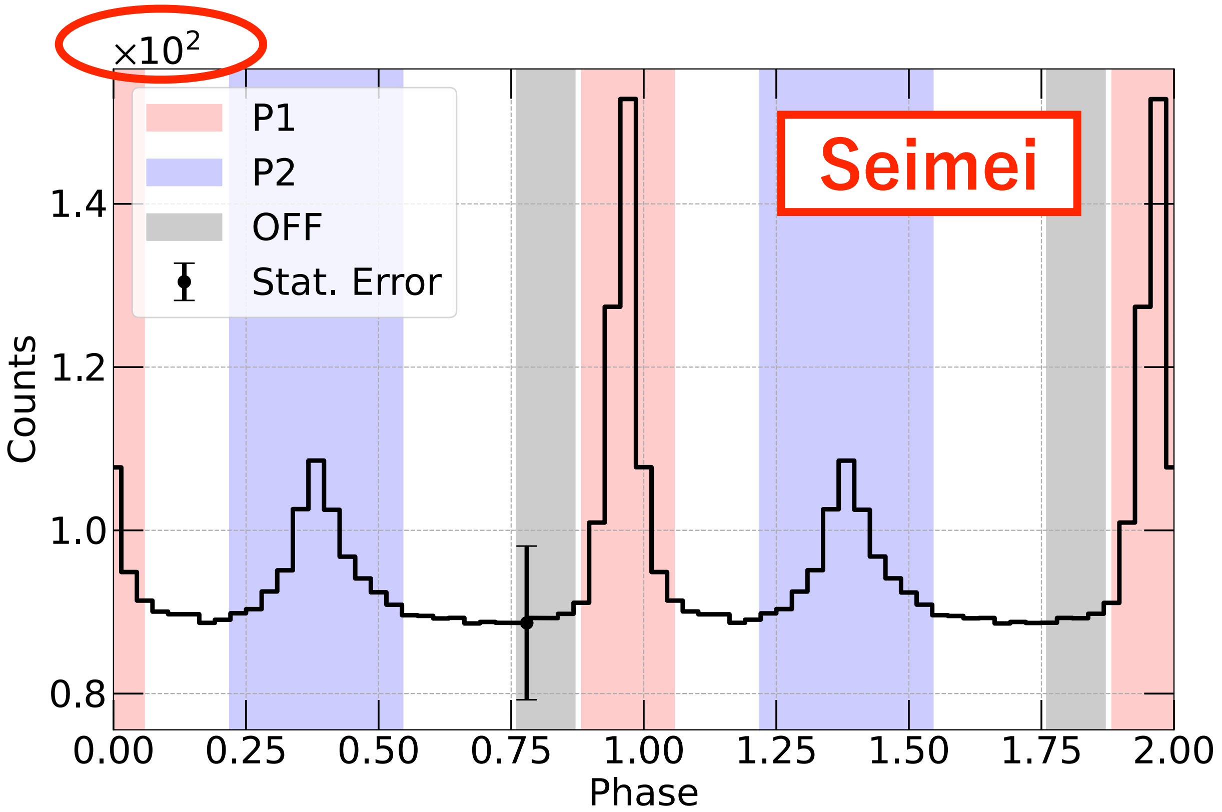
- **Motivation**
  - **Understand the GRP trigger presence and unveiling the GRP emission mechanism by radio-optical simultaneous observation**
    - ▸ Investigate the optical SPs before and after GRPs
      - **Radio:** Difficult to detect SPs because the nebula emission is stronger than the crab pulsar
      - **Optical:** **Possible** with the **high sensitivity & time resolution camera + Large telescope**
- **Observation with IMONY × Kanata Telescope**
  - FY2021: Detected the Crab pulsar with 4 × 4 array
    - ▸ Imaging position was came out of the camera sensor: ~1 h
  - FY2022: Expand 4 × 4 array to **8 × 8 array**
    - ▸ Was being in the sensor at least ~**10 min** observation
- **For the radio observation**
  - De-dispersion system was developed
    - ▸ Detection time was **matched in 10 us accuracy** with collaborators

Because the Integration time was 50–100 us

Future prospects

- **SP observation with Kanata Telescope**
  - Photon counts are not enough to get a significance of SPs
    - ▸ **Want more photons!**
- **Observation with Seimei Telescope ..?**
  - Φ=3.8 m and 6.24 times higher light gathering power
  - Preparing for the observation is ongoing!
  - **Simulation shows that we can detect >4 σ for P1**

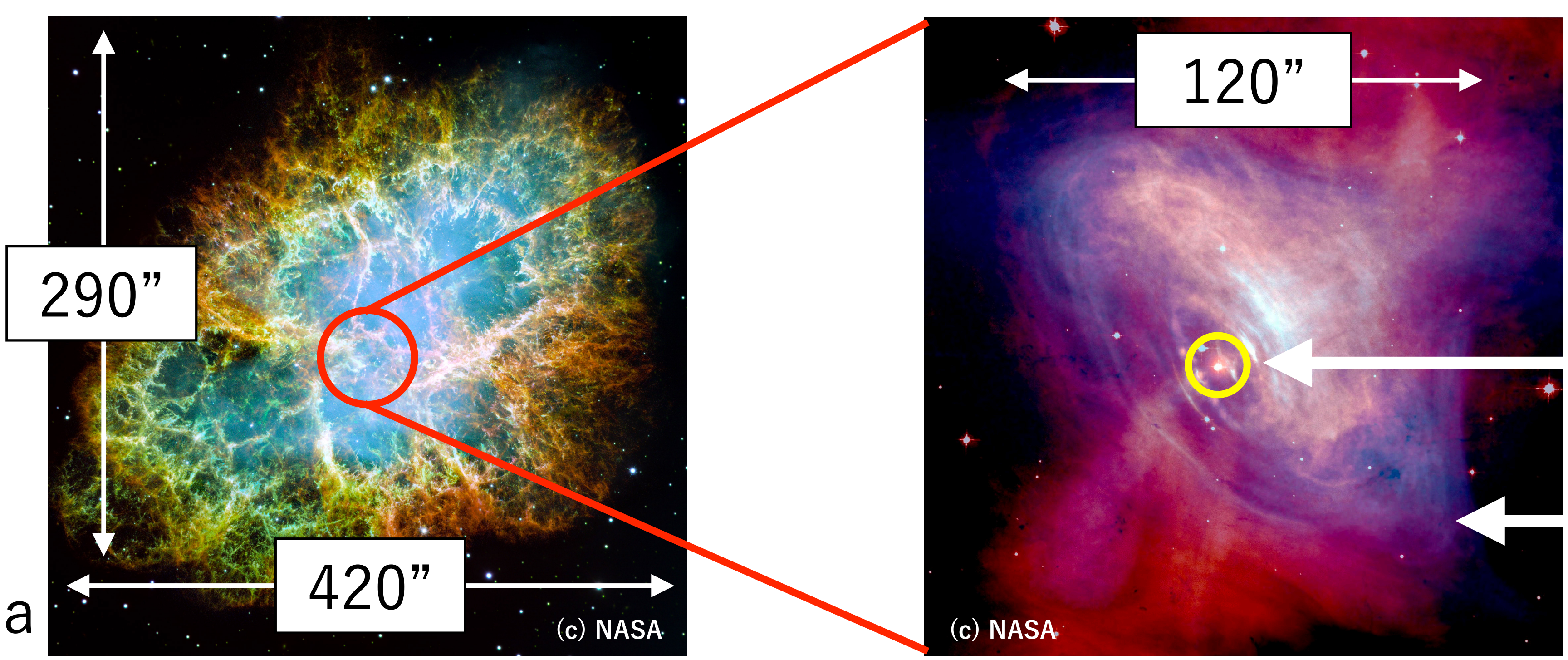




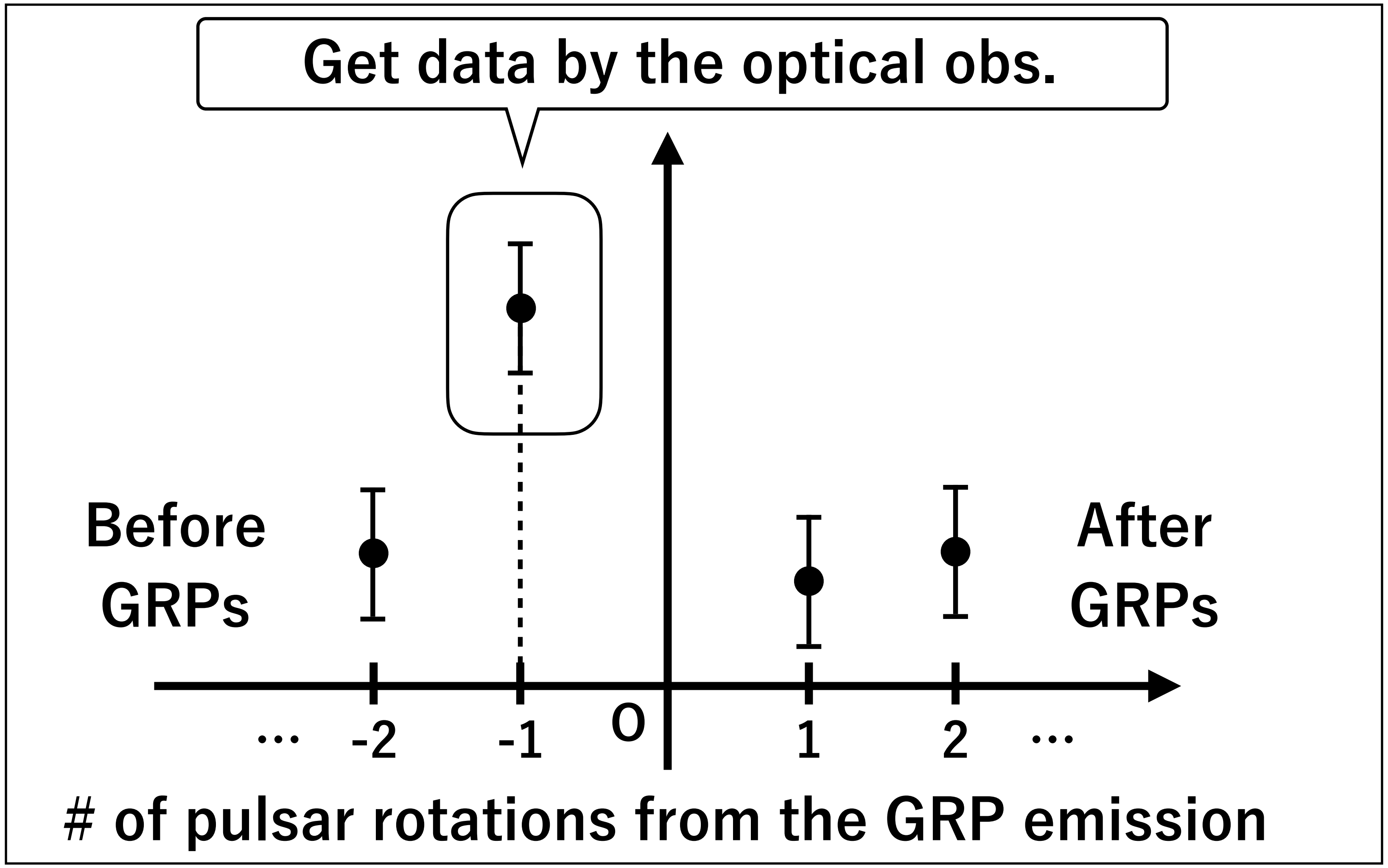
Backup

What is pulsar?

- **Pulsar**
  - Has a strong magnetic field (>10^{12} G) and a fast rotation period (ms–sec)
  - When the emission axis towards the earth, we detect it as a "PULSE"
  - Famous pulsars: **B0531+21**, B0833–45 (Vela), B0633+17 (Geminga)
- **B0531+21 (Crab pulsar)**
  - $P \sim 33.8$ ms , $\dot{P} \sim 4.2 \times 10^{-12}$ s/s
  - Convert the rotation energy to the emission energy $L_{\mathrm{spin-down}} \sim 4.8 \times 10^{38}$ erg/s



Methods of detecting fluctuation



- **Fluctuation of the peak phase**
  - **Emission region** may change due to the fluctuation of the magnetic field
- **Fluctuation of the pulse flux**
  - **Strength of the magnetic field** may change (assuming the synchrotron emission)

De-dispersion analysis

- **Dispersion**
  - Time delay of radio pulses which depends on the radio frequency
    - ▸ Caused by the interaction with the interstellar plasma

$$\Delta t_{\mathrm{f}_1<\mathrm{f}_2} = \frac{e^2}{2\pi m_{\mathrm{e}} c} \times \int_0^L n_{\mathrm{e}}(s)\, ds \times \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right)$$

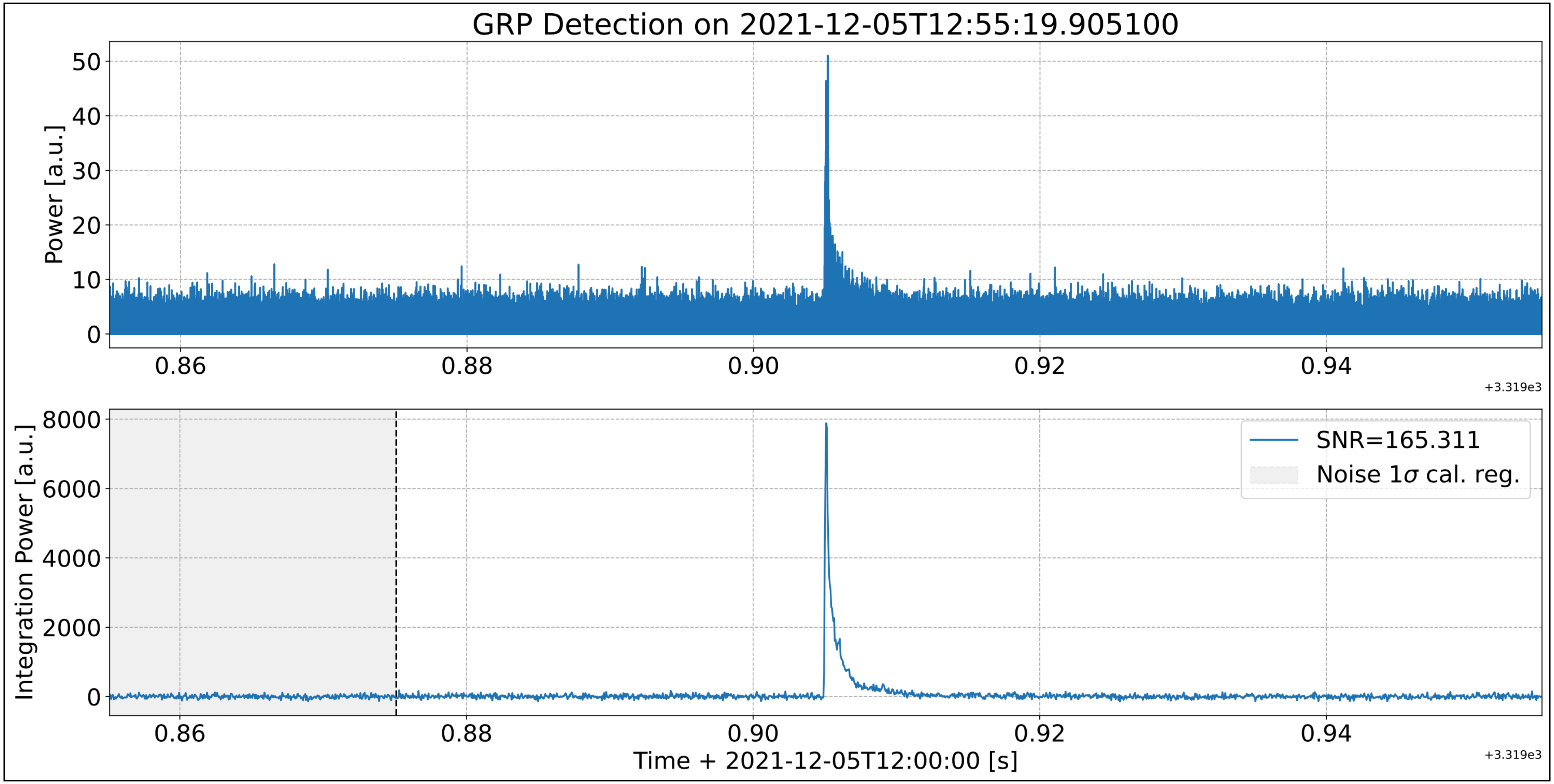
- **Coherent de-dispersion method**
    - ▸ Execute FFT → multiply the phase shift term → IFFT

✤ FFT of the time-shifted function: if let Δt as t_0

$$\begin{aligned} \int_{-\infty}^{\infty} p(t-t_0) e^{-i\omega t} dt &= \int_{-\infty}^{\infty} p(\tau) e^{-i\omega\tau} d\tau \times e^{-i\omega t_0} \\ &= P(\omega) e^{-i\omega t_0} \end{aligned}$$

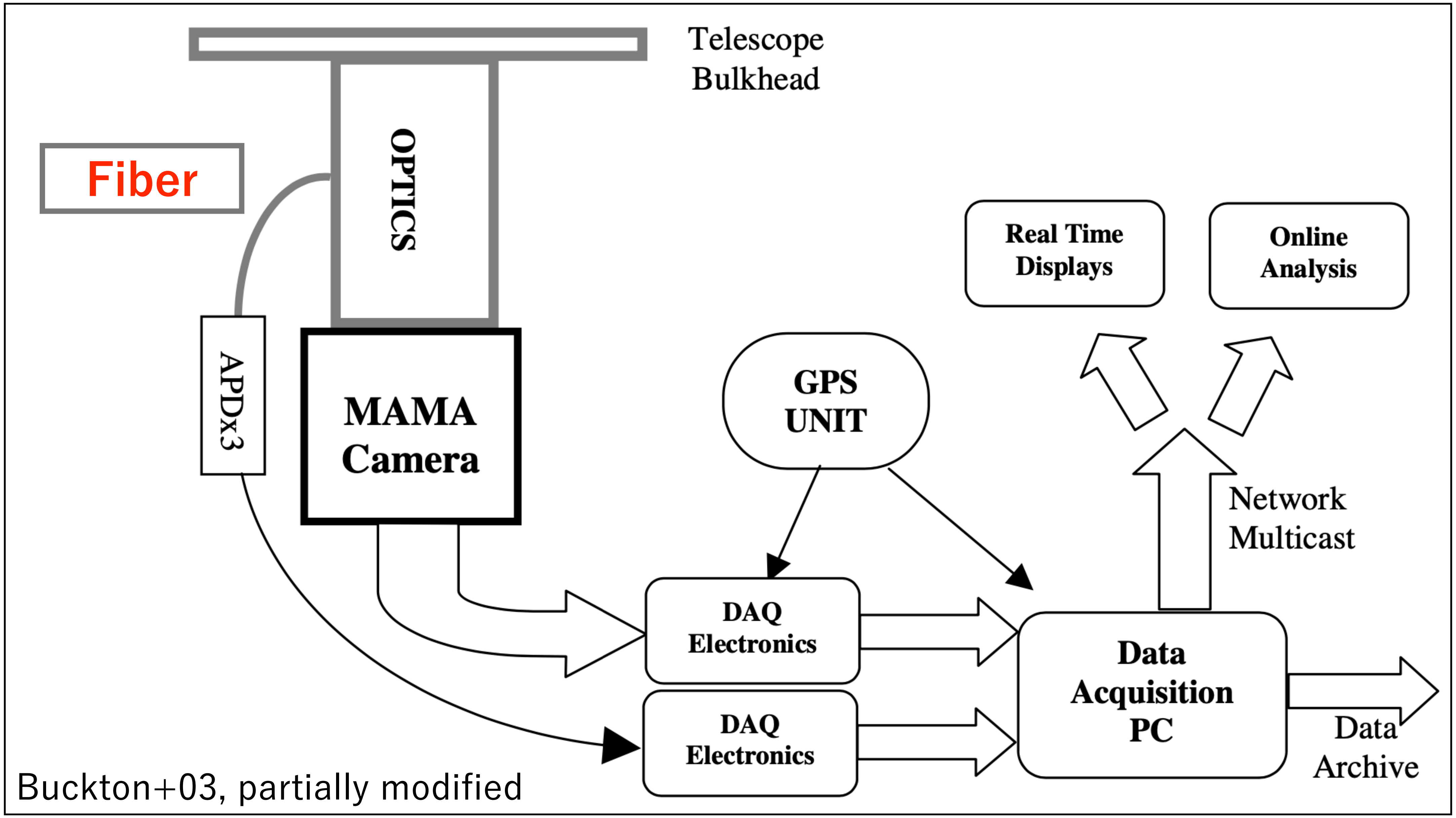
$$\therefore p(t-t_0) = \int_{-\infty}^{\infty} P(\omega) e^{-i\omega t_0} e^{i\omega t} d\omega$$

De-dispersed pulse integration



- **Gain the signal to noise ratio**
  - Set the integration time for 50 us

TRIFFID System



- **MAMA camera**
  - Imaging system (1024×256 px)
  - FoV is 28.5 arcsec (0.15 arcsec/px)
- **Avalanche Photo Diodes (APD)**
  - Time-tag for each photon
  - Connecting with each fiber