Gain measurements of eight-inch photomultiplier tubes at field and laboratory toward Fluorescence detector Array of Single-pixel Telescopes

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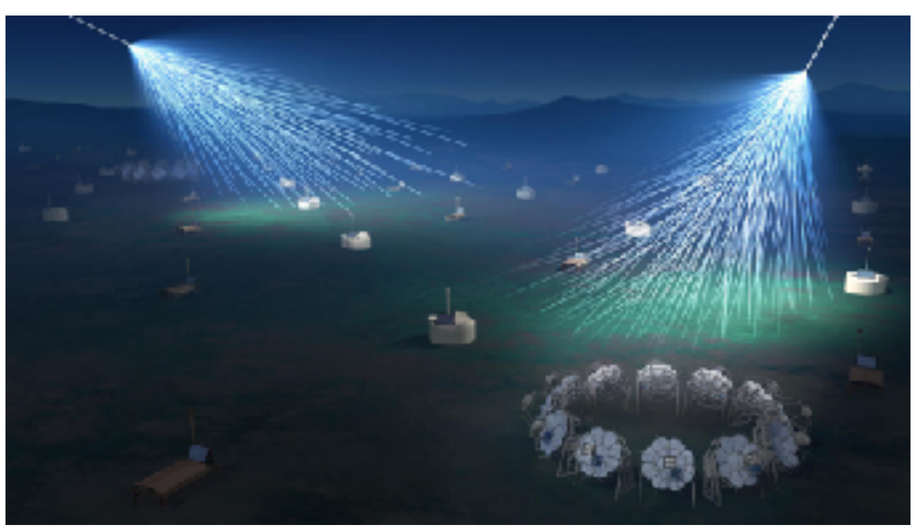
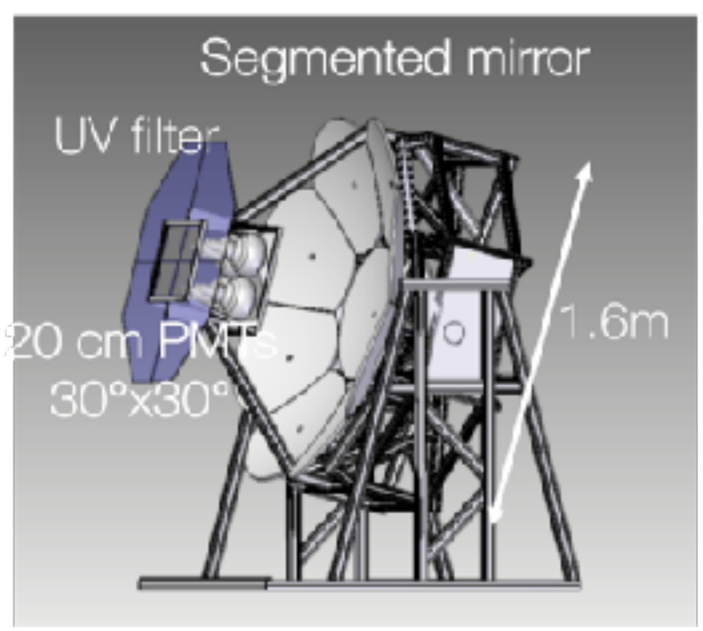
FAST

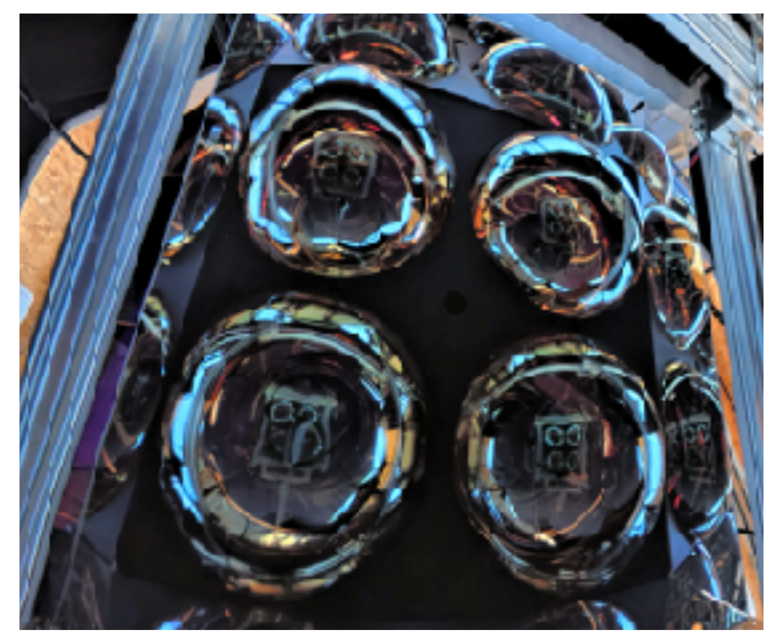
Fluorescence detector Array of Single-pixel Telescopes

- As a candidate for the **GCOS-FD**, FAST aims to observe ultra-high-energy cosmic rays (UHECRs) with energies of $E > 10^{19}$ eV with high statistics by deploying a large number of fluorescence telescopes over a wide area.

- The telescope has a segmented mirror and **four 8-inch photomultiplier tubes (PMTs)**.
  The field of view of each PMT is $15° \times 15°$.







Current Status of FAST Prototypes

FAST@Telescope Array

2016~

- Telescope Deployment:
  - 2017: 2 telescopes
  - 2018–present: 3 telescopes
- Trigger: External trigger from TA FD
- Planned drone-based on-site calibration in Autumn 2026

FAST@Pierre Auger

- Installed two new telescopes
- Data acquisition:
  - External trigger from Auger
  - Internal trigger (self-trigger) for stereo observation

2019~

2026~

Distance ~11.2km

PMT Calibration

- **Purpose**
  To prepare for future long-term operation of FAST, I aim to investigate long-term fluctuations and stability of PMT gain. It directly affects the primary cosmic-ray energy reconstruction.

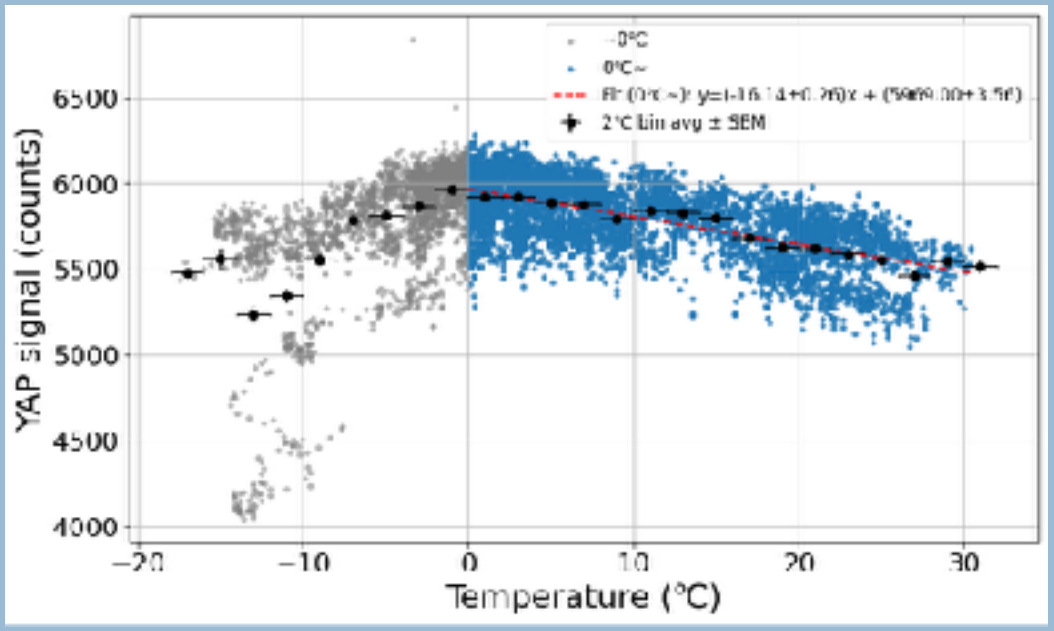
- **Approach ①: Field Measurement**

  . Analysis of **YAP** data collected by FAST@TA

  > YAP: A **stable UV light source** consisting of an alpha source and a scintillator.
  > YAP Installed on the photocathodes of PMT00 (FAST1) and PMT07 (FAST2) at FAST@TA.

Temperature Dependence of YAP Signals

YAP signal measured with FAST@TA



Temperature coefficients

-20 to 10 °C : ± 10 %

10 to 20 °C : -0.47 ± 0.02 %/°C

≧ 0 °C : **-0.278 ± 0.004 %/°C**

Expected YAP temperature response [Rozsa+ (1999)]

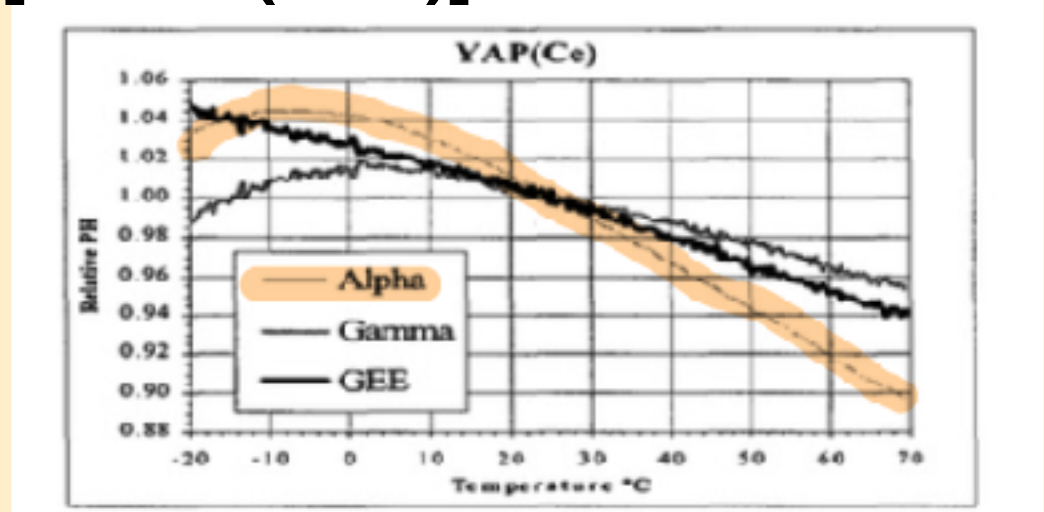


Figure 6. The normalized response of YAP(Ce) to alpha and gamma ray stimulation.

Temperature coefficients

- 20 to 10 °C : ±1%

10 to 20 °C : -0.21%/°C

YAP is not stable enough.

Problem

Observed YAP signal contains:

PMT multiplication gain, YAP light yield, quantum efficiency effects ...

→ Their temperature dependences are mixed

Motivation for Single Photoelectron Measurements

- **Measuring Single-Photoelectron (SPE) signals**
  → Provides the absolute PMT gain, since the amplification per photoelectron can be directly determined.

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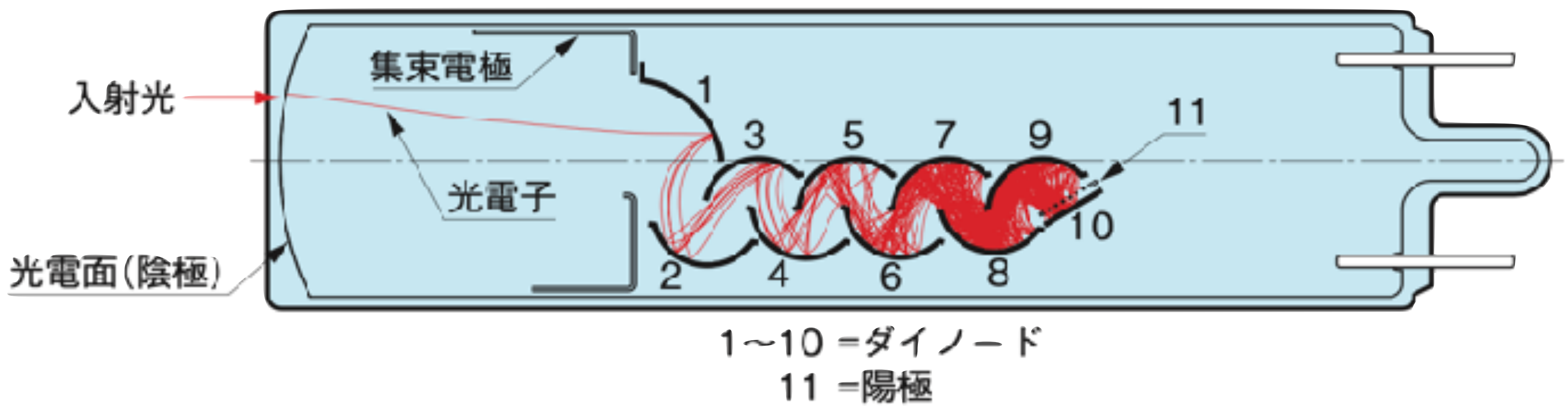
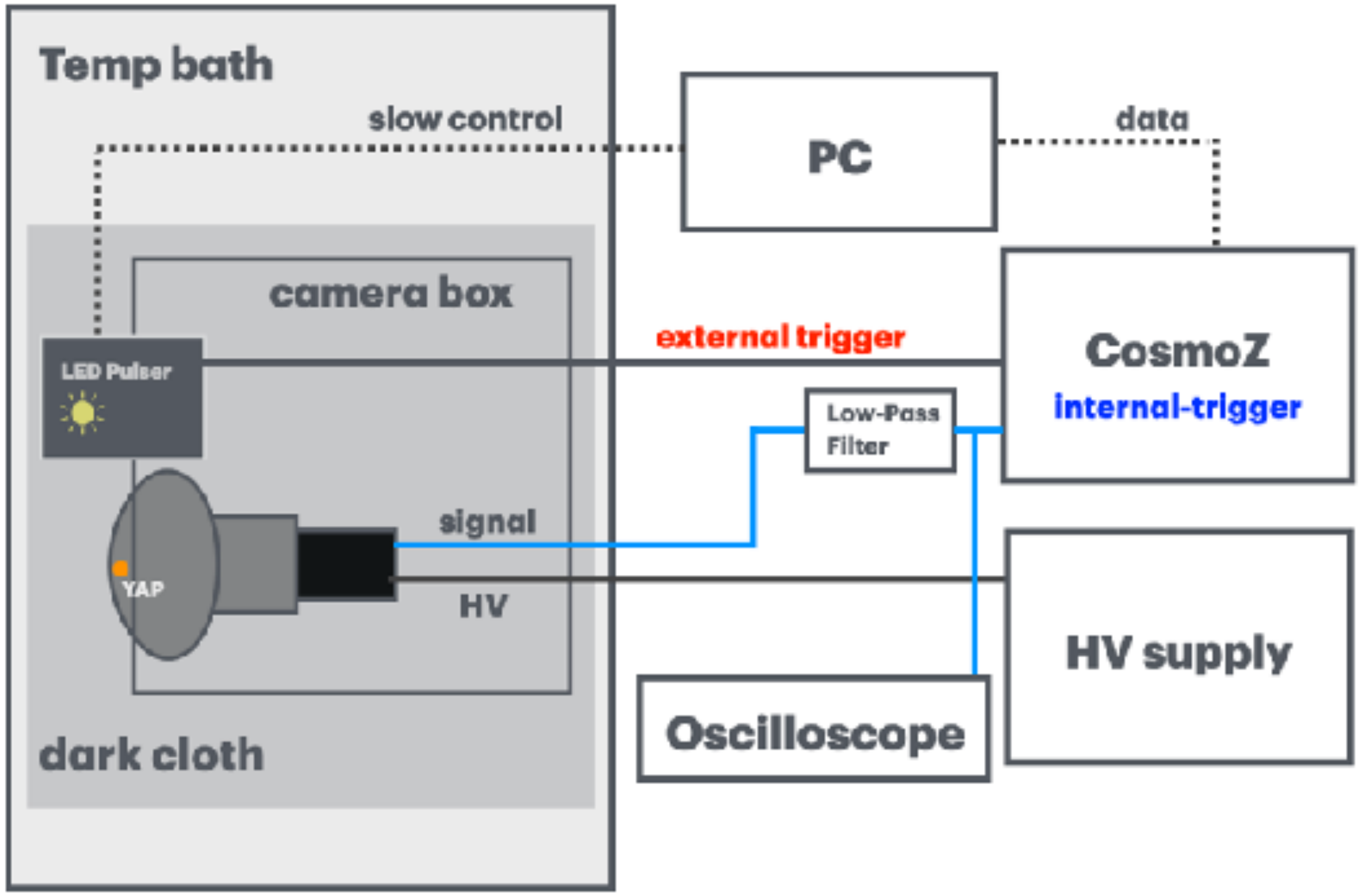
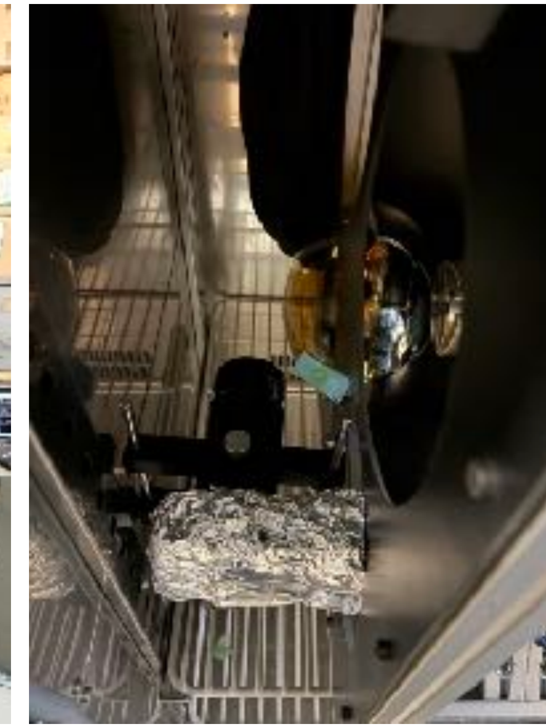


- **Approach ②: Laboratory Measurements**

  Measure absolute PMT gain (SPE) and YAP signals under controlled temperature conditions.
  → Enables separation of individual temperature dependences (PMT vs. YAP).

SPE Measurement Setup





PMT：R14688 ZC2969

LPF：15MHz

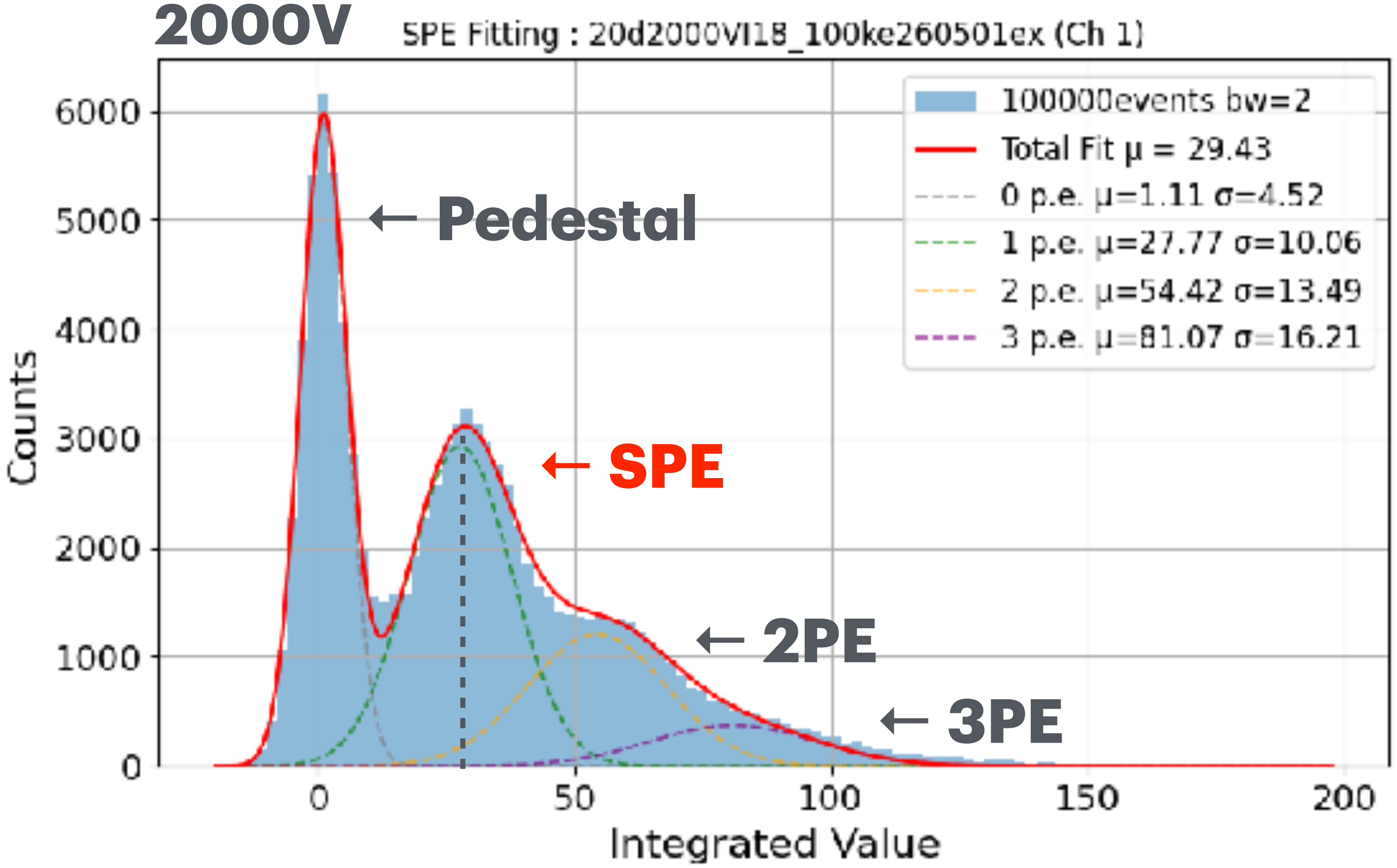
temp bath：-10 ~ 60 °C (use -10 to 35)

CosmoZ：80MHz

LED pulser: Max 20mW, 365 nm (+-5 nm), temperature stabilized

SPE fitting and HV dependence of Gain

2000V



Fitting

$$S(x) = A \sum_{n=0}^{\infty} P(n;\mu) \cdot G_n(x)$$

Peak positions and dispersion of n (≧ 2) photons.

$$Q_n = Q_0 + nQ_1 \qquad \sigma_n = \sqrt{\sigma_0^2 + n\sigma_1^2}$$

Determine the optimal parameters [μ, q0, σ0, q1, σ1, amplitude] using the least squares method.

HV dependence of Gain

$$GN_{\mathrm{pe}} = \frac{1}{eR} \int V(t)\, dt$$

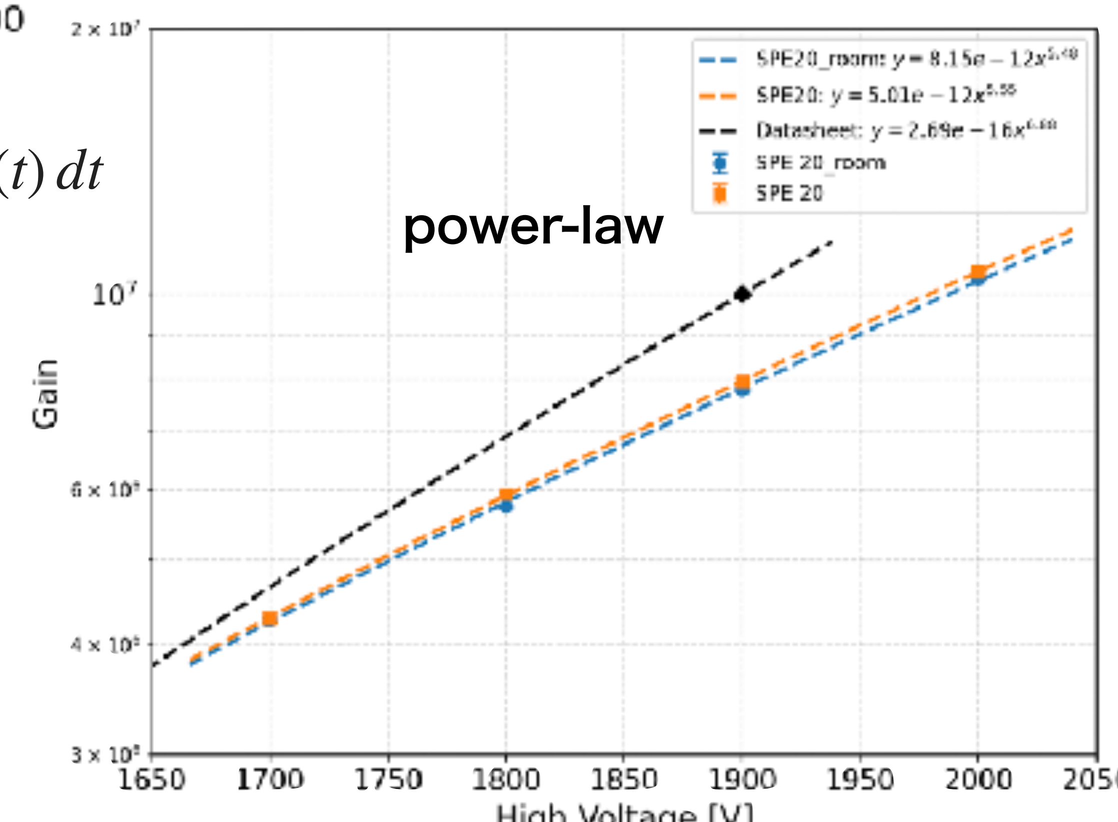
① HAMAMATSU data sheet

880V: G=5×10^4

1900V: G=10^7

② temp bath: off ~ 20°C

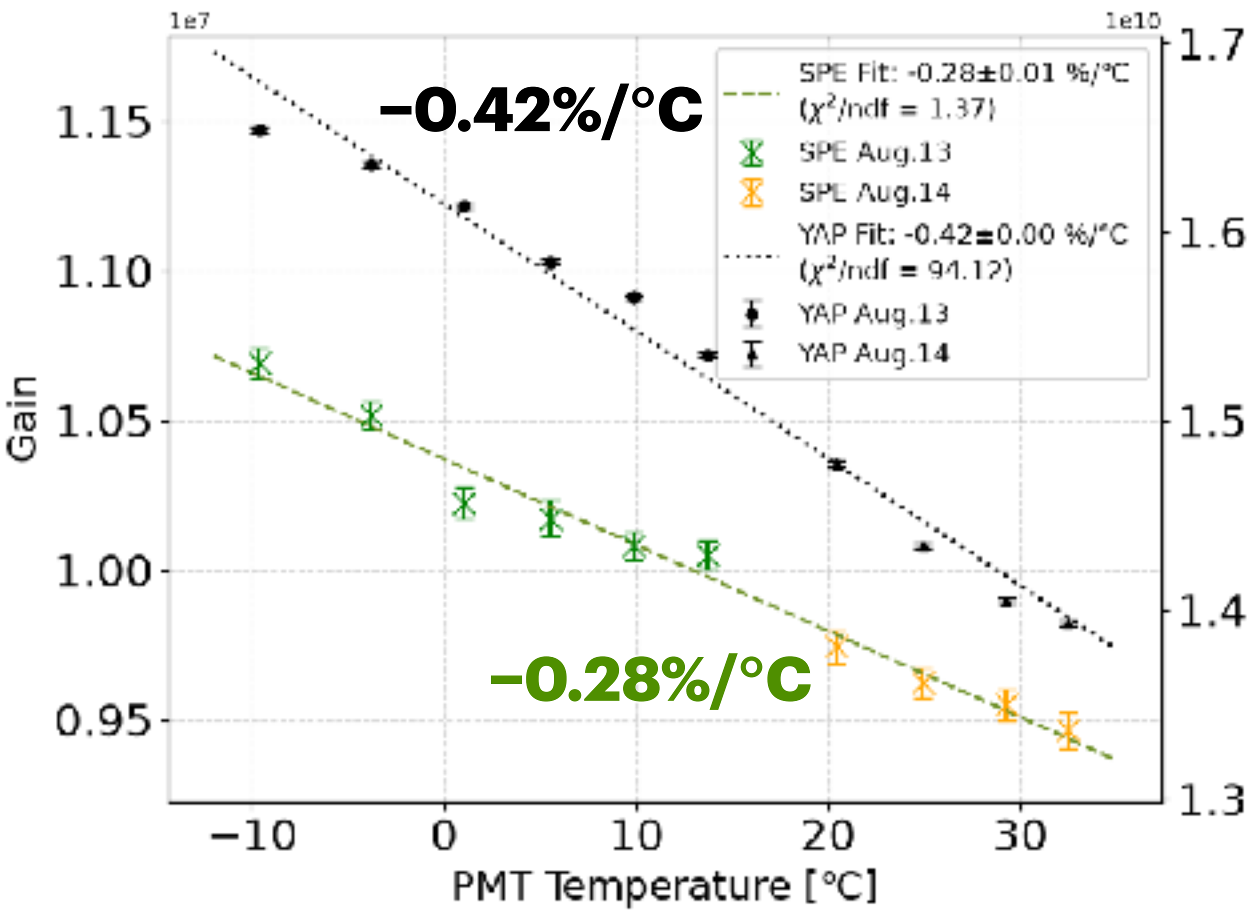
③ temp bath: on, 20°C

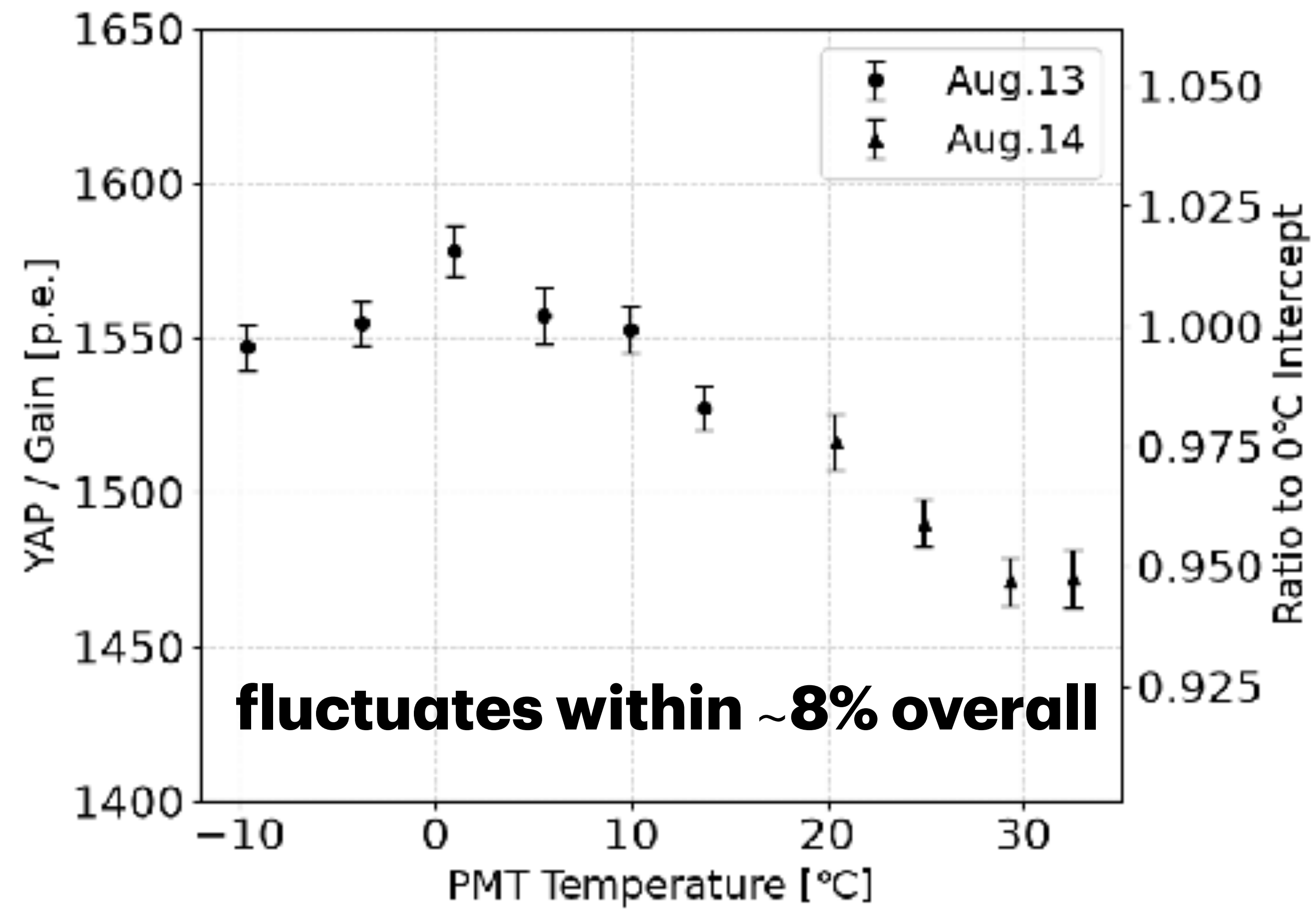


Temperature dependence of Gain

Procedure: Lowered in 5°C steps (1-hour wait)

→ SPE & YAP measurements (with 2000V)





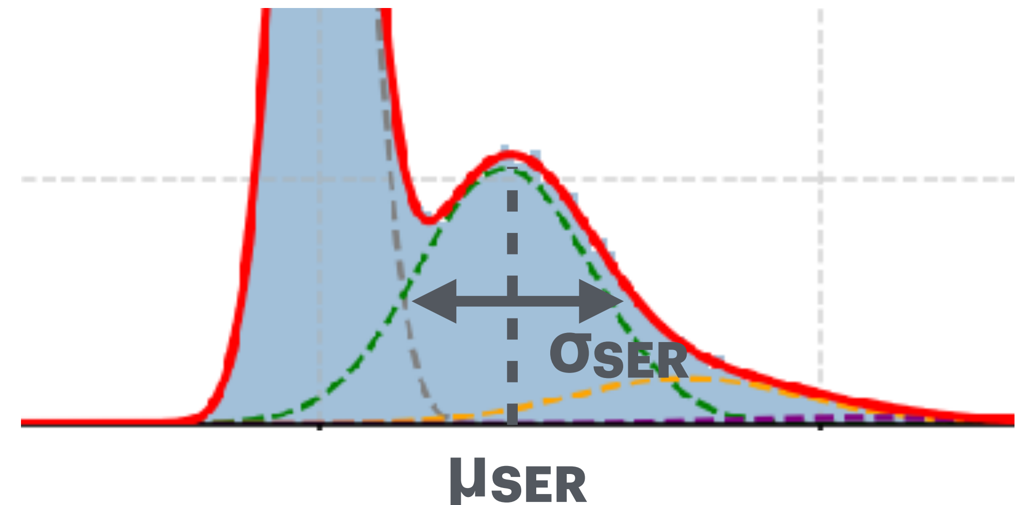
- The steeper temperature decrease in YAP confirms that the observed signal is a superposition of PMT gain and true YAP light yield.
- The calculated YAP/Gain ratio shows a similar temperature dependence to that reported by Rozsa et al. (1999).

Gain Estimation via Excess Noise Factor

ref. B.Bencheikh 1992 NIMA

Excess Noise Factor (**$F = 1 + \delta^2_{SER}$**)

Accounts for gain fluctuation in the PMT dynode multiplication process.
Defined by Single-Electron Response (SER): **$\delta_{SER} = \sigma_{SER} / \mu_{SER}$** .



Gain Estimation Principle
Signal variance (σ^2) vs. Mean signal ($\langle R \rangle$)

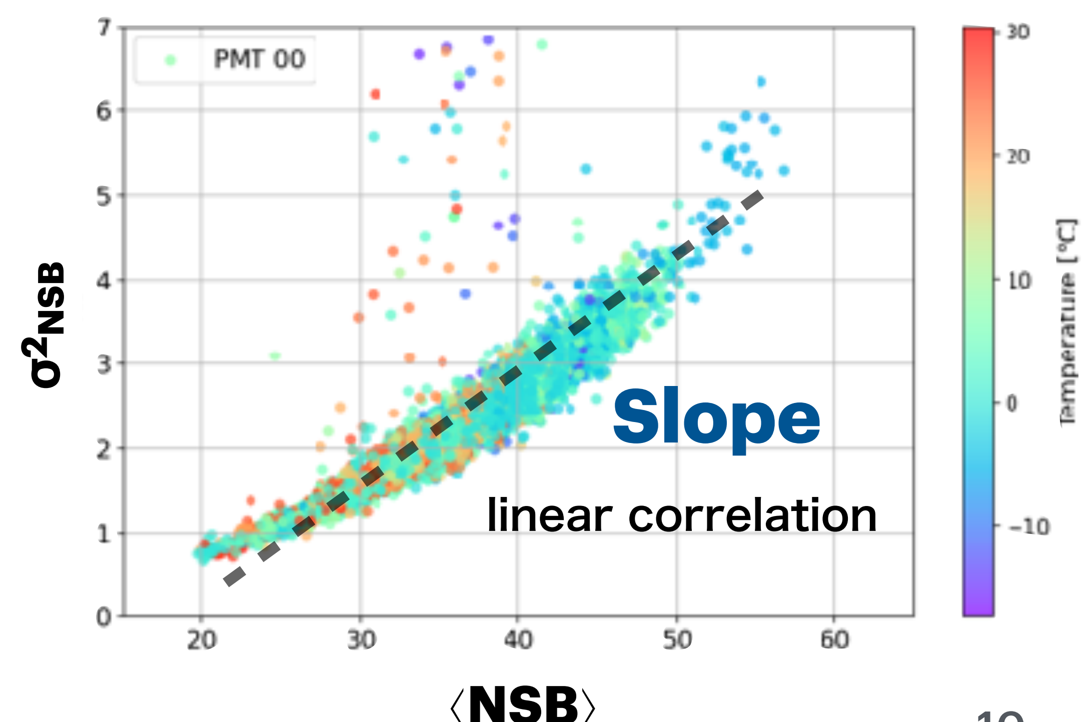
$$\sigma^2_R = \mathbf{S} \cdot \langle R \rangle + \sigma^2_{elec}$$

Slopes: $S = \langle G \rangle (1 + \delta^2_{SER})$

→ Mean Gain $\langle G \rangle$ can be determined directly from the slope S

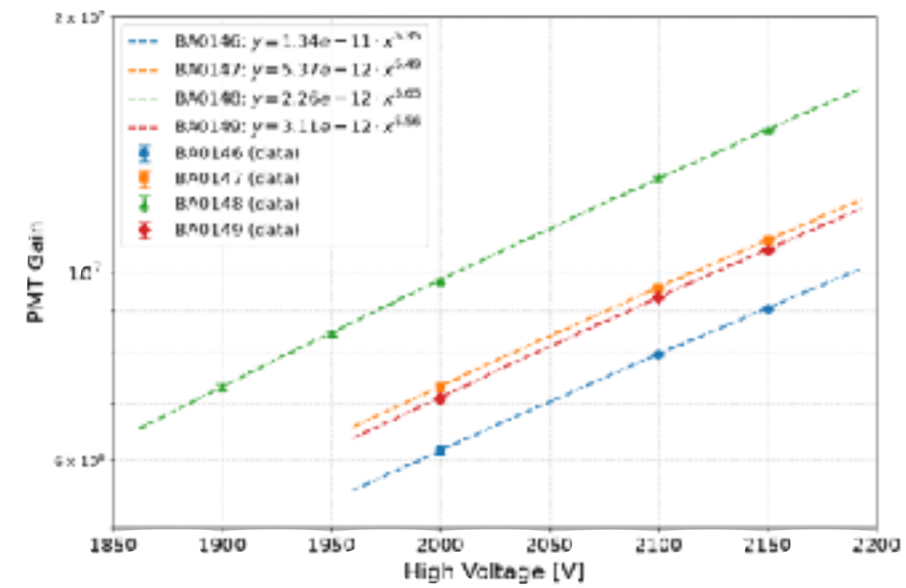
σ^2_{NSB} vs. NSB
(All-period data from FAST@TA)

The **slope S** extracted for each period can potentially be used to estimate PMT gain shifts.
→**Potential in-situ calibration**



HV dependence of Gain and Stability of the Factor

- **4 PMTs**: R14688 (BA0146 - BA0149)
  HV: 2000, 2100V, 2150V



- **Stability of Excess Noise Factor (1+δ²):**

$1+\delta^2$	2000V	2100V	2150V
BA0146	1.122 ± 0.005	1.137 ± 0.004	1.137 ± 0.004
BA0147	1.180 ± 0.006	1.205 ± 0.005	1.200 ± 0.004
BA0148	1.163 ± 0.005	1.172 ± 0.004	1.189 ± 0.004
BA0149	1.144 ± 0.004	1.153 ± 0.004	1.136 ± 0.005

- Stable within 2–3% for each PMT across different high voltages.
- If this stability holds around the operational voltage (~1000 V), **this method can be used to track in-situ PMT gain variations in the field.**

Summary

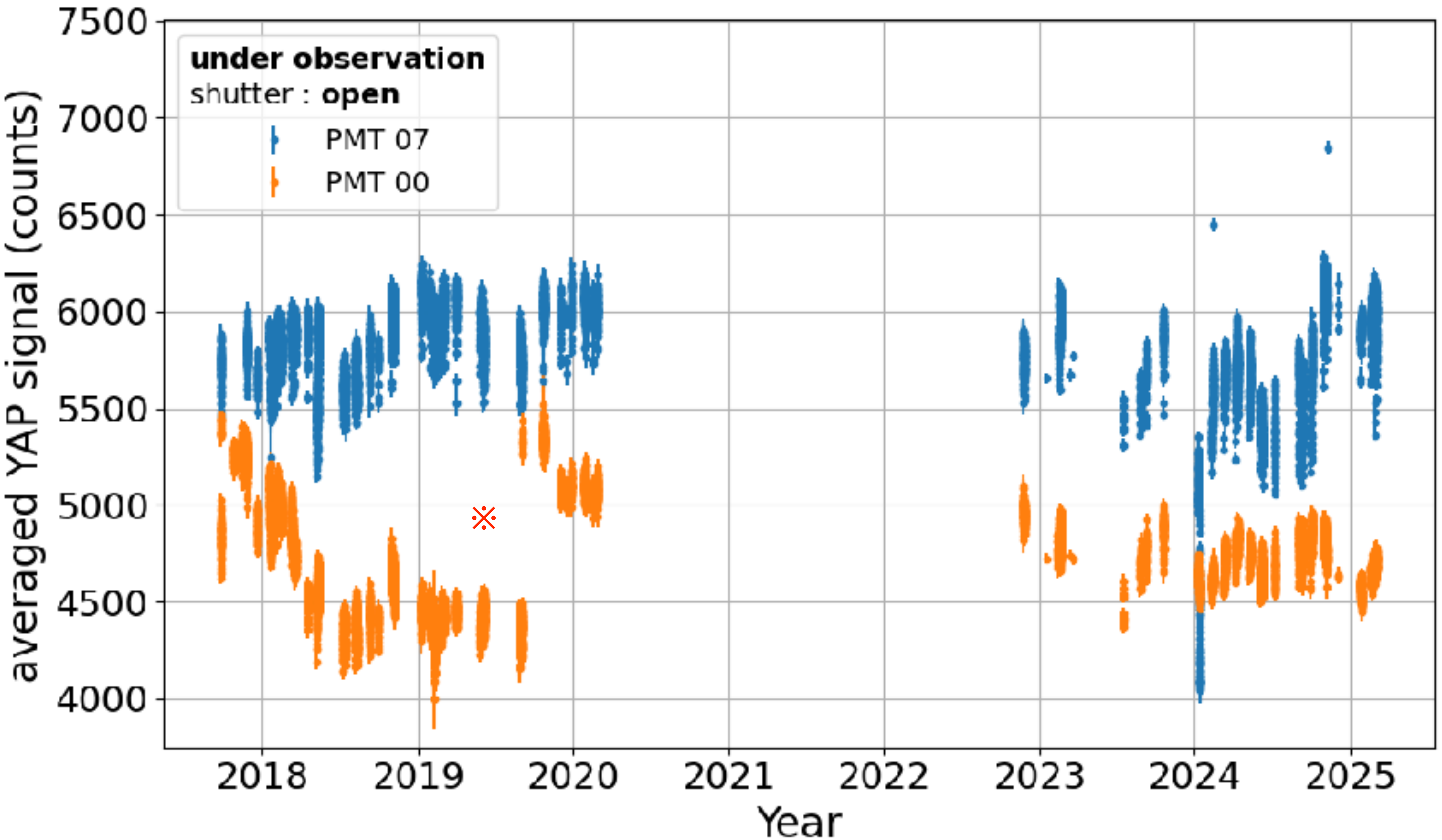
- **Separation of Temperature Dependence (YAP vs. PMT)**
  - PMT gain changes by −0.28%/°C → main cause of the field trend.
  - True YAP light yield is fluctuate within ~8% (−10°C to 35°C).

- **Gain Monitoring via Excess Noise Factor**
  - Excess noise factor is stable within 2–3% across PMTs and HVs.
  - NSB slope (σ^2_{NSB} vs. NSB) can be used for continuous in-situ calibration.

- **Future Outlook**
  - Apply the Excess Noise Factor method to period-by-period field data for long-term gain calibration.
  - Test temperature dependence on more PMTs and YAPs to evaluate individual differences.

Temperature Dependence of YAP Signals

YAP signal measured with FAST@TA PMTs



Disentangling G and Np.e. (Theory)

Real Detector case

ref. B.Bencheikh 1992 NIMA

Gain fluctuates from photon to photon.
Electronics noise is present.
→ Account for gain fluctuations using Single Electron Response measurements.

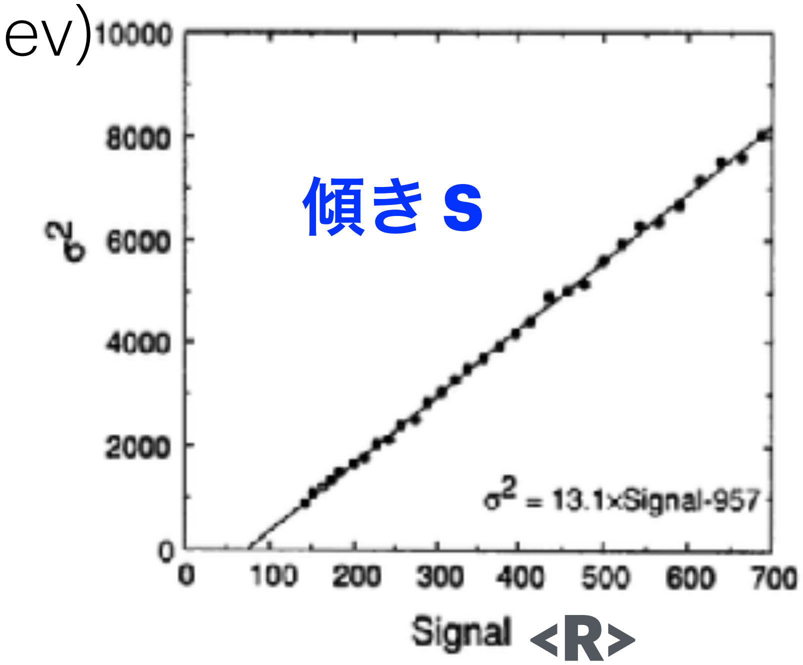
$$\langle R\rangle_{real} = \langle G\rangle\langle N_{pe}\rangle + P$$

$$\sigma_R^2 = \langle G\rangle^2\langle N_{pe}\rangle + \langle G\rangle^2\langle N_{pe}\rangle\, \delta^2_{SER} + \sigma^2_{elec}$$

$$\delta_{SER} = \sigma_{SER} / A_{SER}$$

↑ 第1項：光信号の統計的ゆらぎ, 第2項：ゲインのゆらぎ, 第3項：電子ノイズ

(Where P: ADC pedestal, ASER ,σSER : SER mean & std dev)



Plotting ⟨R_i⟩ real vs. σ_i^2 for various light intensities yields a linear slope S:

$$S = \langle G\rangle\underline{(1 + \boldsymbol{\delta^2_{SER}})}$$

Excess Noise Factor

→ **Knowing δ^2_{SER} , the mean gain ⟨G⟩ can be determined from the slope S.**

Individual differences in PMT

2000V | 2100V | 2150V

BA0146

BA0147

BA0148

BA0149