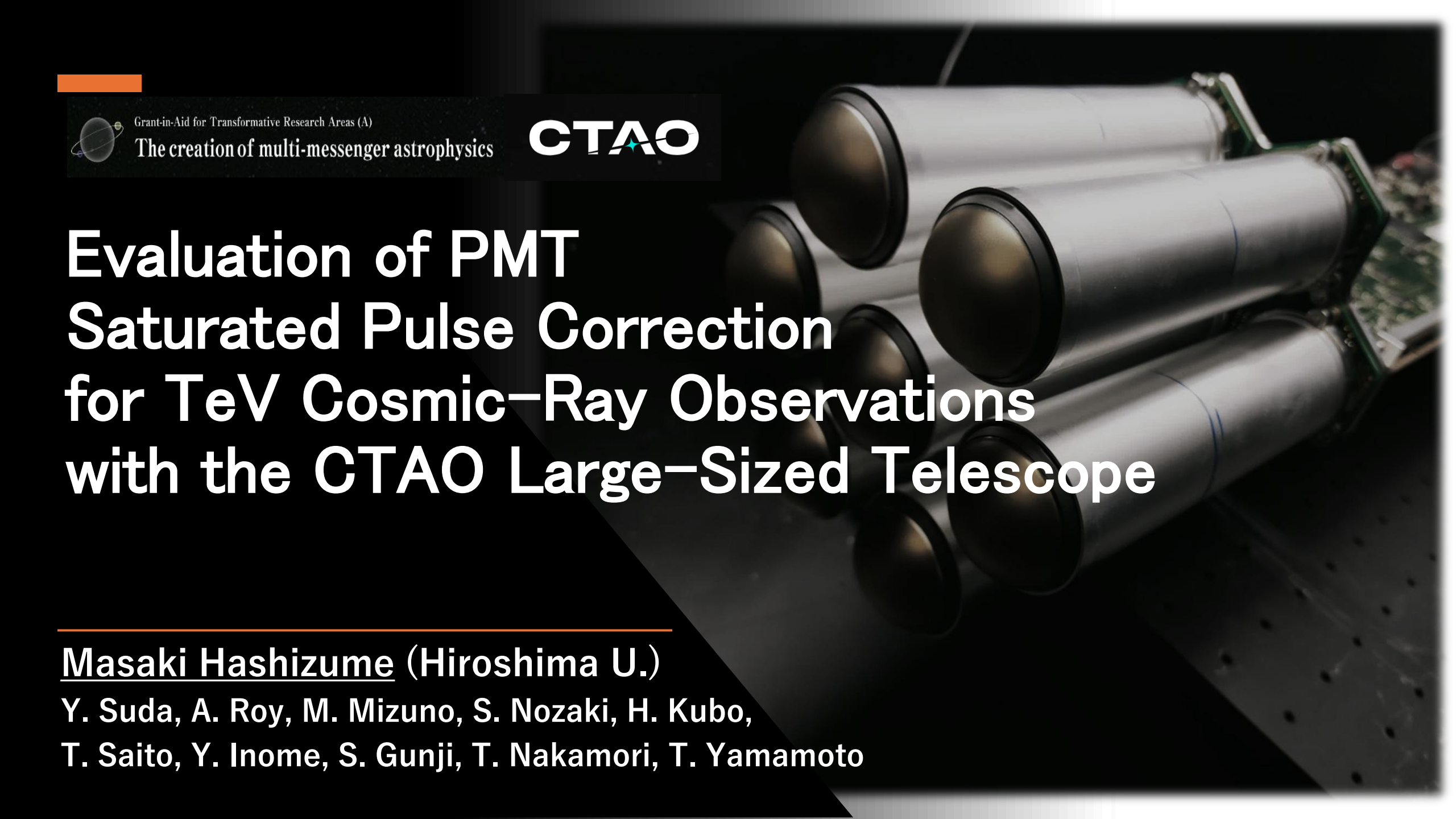

Grant-in-Aid for Transformative Research Areas (A)
The creation of multi-messenger astrophysics

CTAO

Evaluation of PMT Saturated Pulse Correction for TeV Cosmic-Ray Observations with the CTAO Large-Sized Telescope

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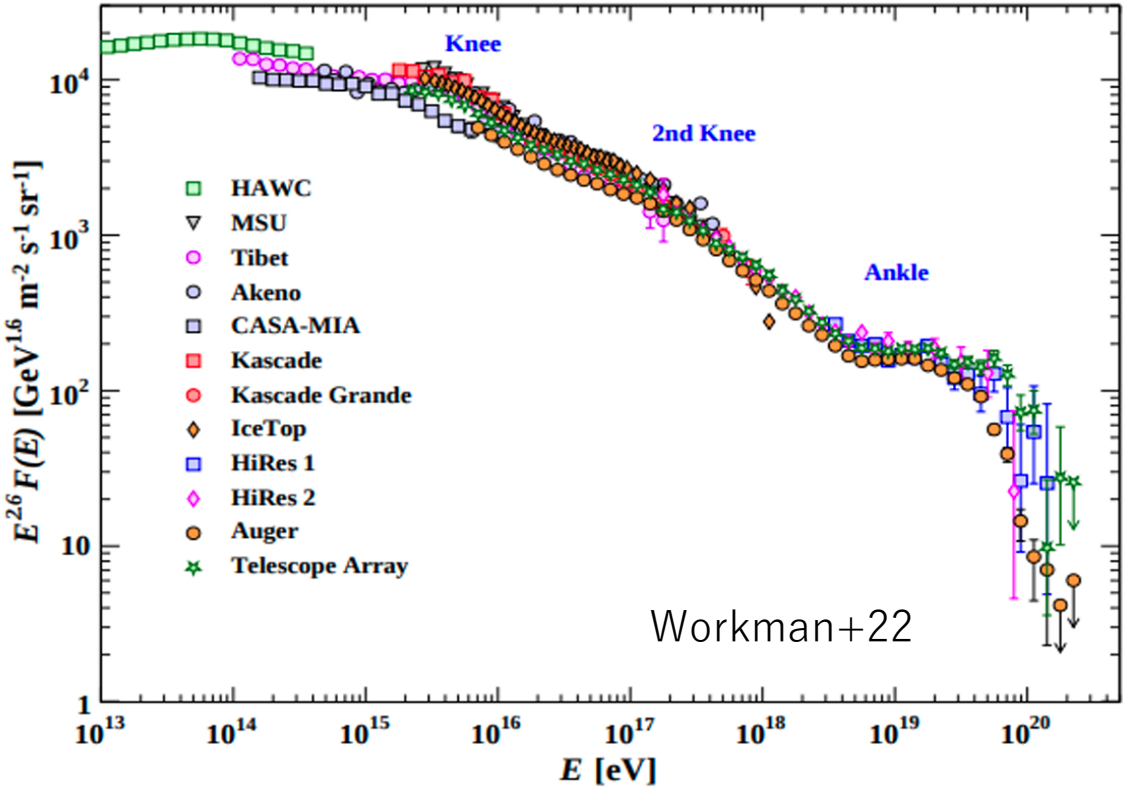
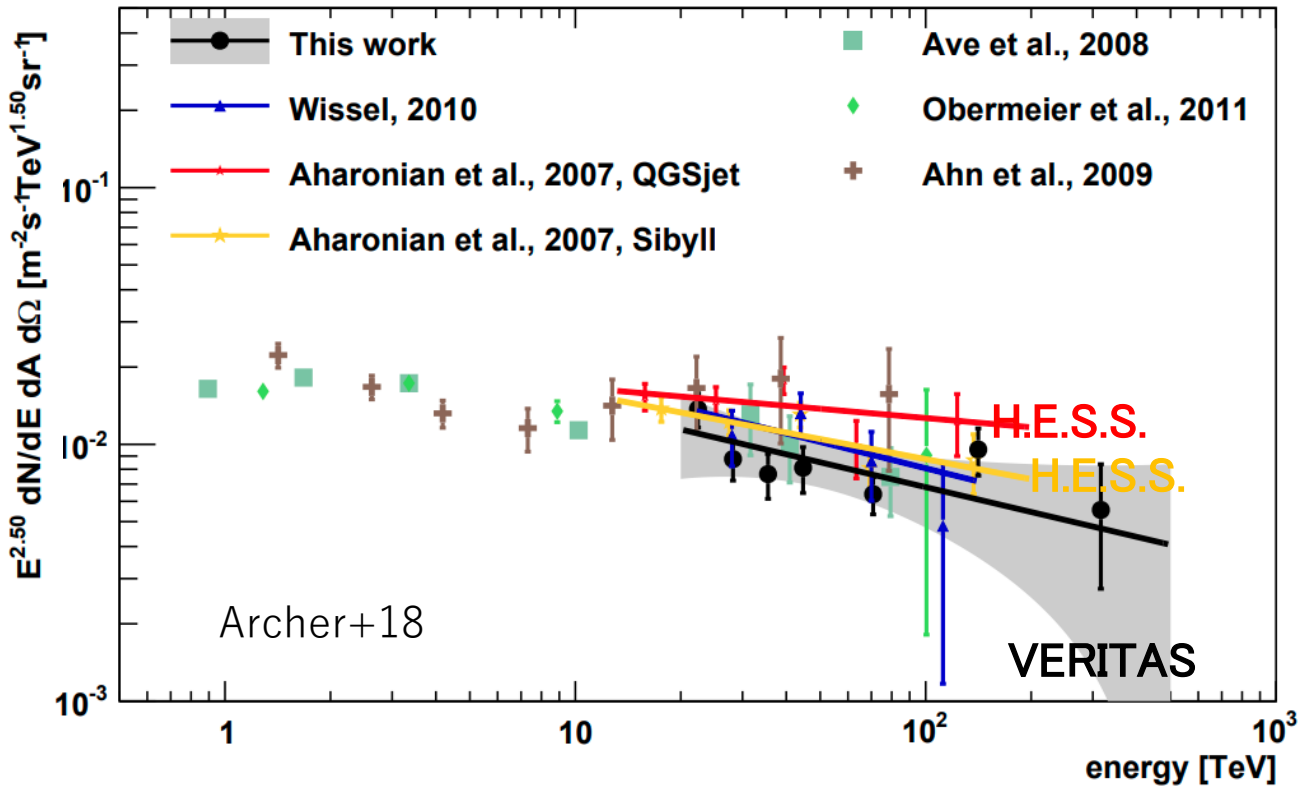
T. Saito, Y. Inome, S. Gunji, T. Nakamori, T. Yamamoto

TeV Cosmic-Ray Observation

Cosmic-Ray spectrum

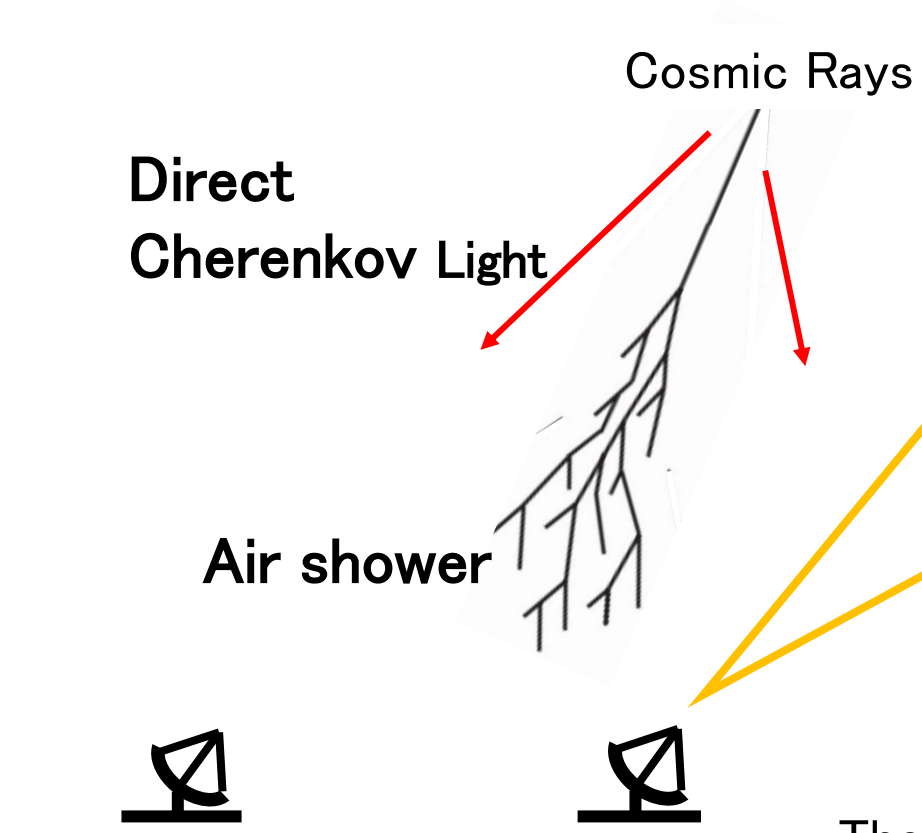


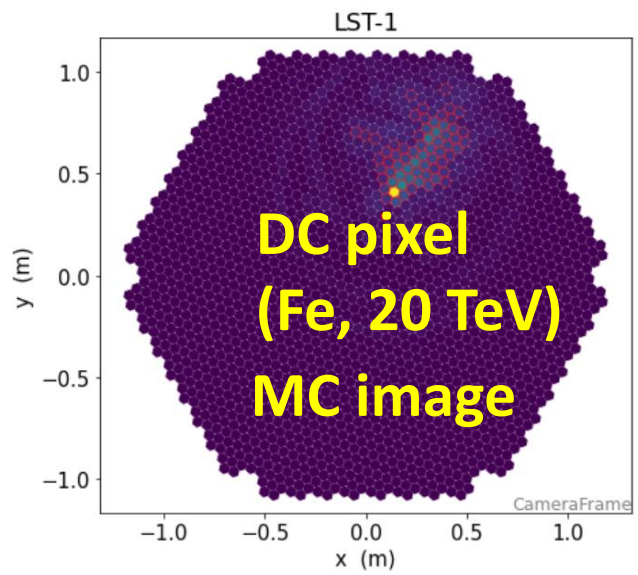
Cosmic-Ray Iron specrtrum (VERITAS, H.E.S.S.)

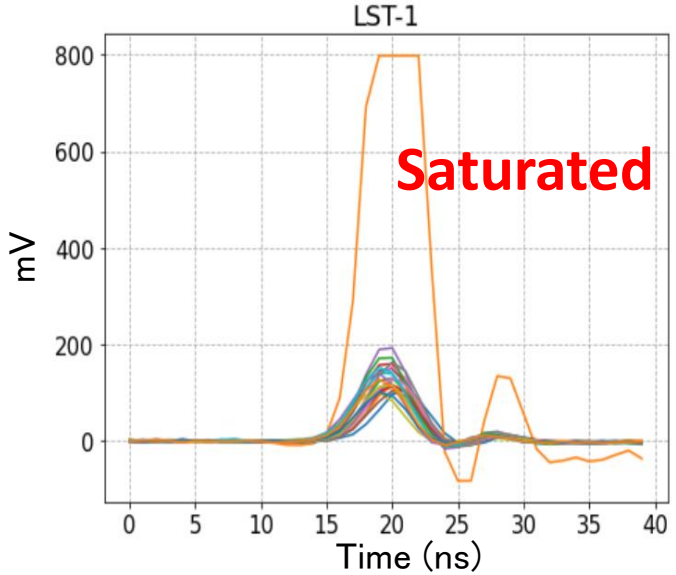


- The composition of cosmic rays in the TeV to PeV energy range is crucial to understand the source of Galactic cosmic rays.
- In particular, obtaining an accurate energy spectrum of iron which is the third most abundant element after hydrogen and helium is essential.
- We aim to obtain a much more precise cosmic-ray iron spectrum by observing with the LSTs of CTAO.

Direct Cherenkov Light

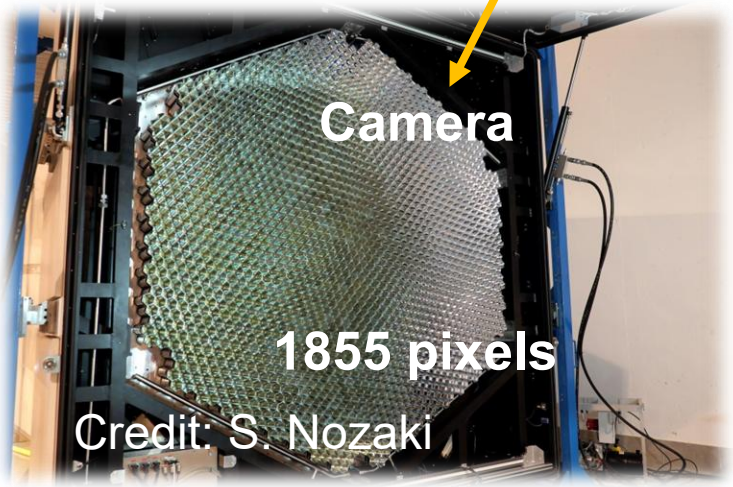




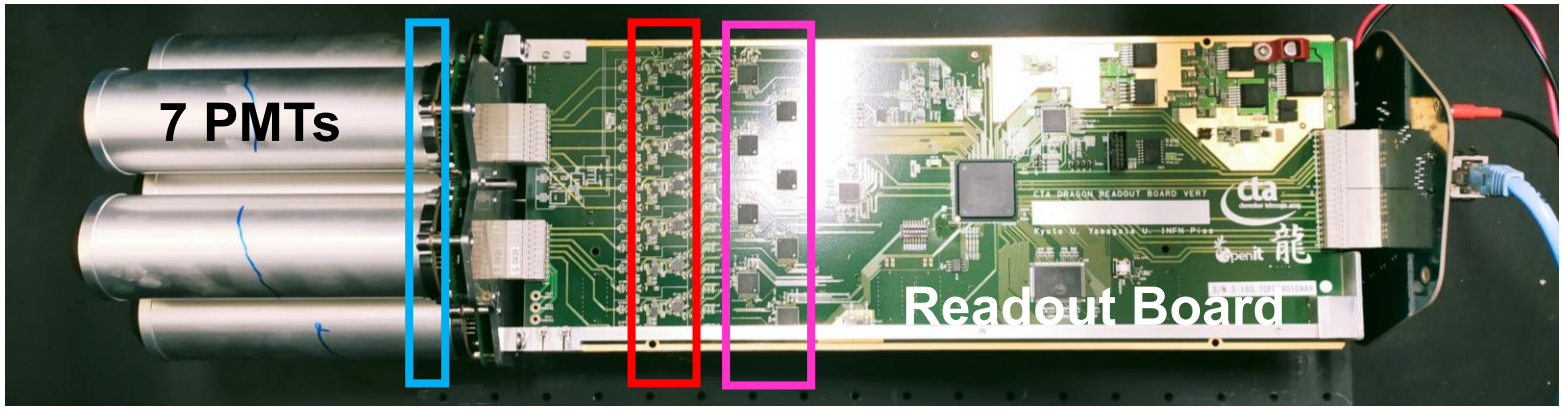


- The cosmic-ray particle itself emits Cherenkov light (Direct Cherenkov: DC) before the first interaction.
- DC light is proportional to the square of the atomic number, and iron DC is very bright so the pulse can be saturated.
- MC show that about 40% of DC light events become saturated.

LST Camera



PMT module

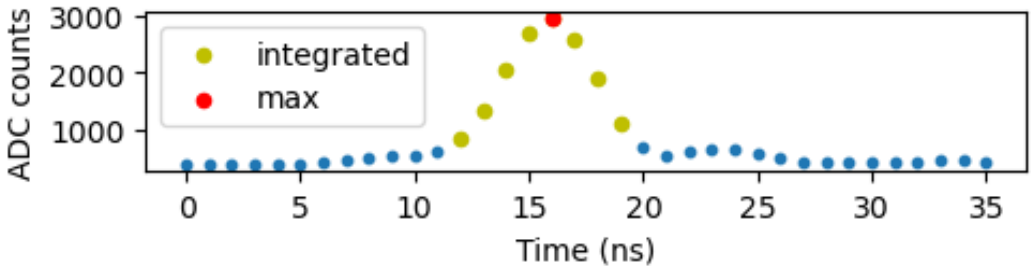


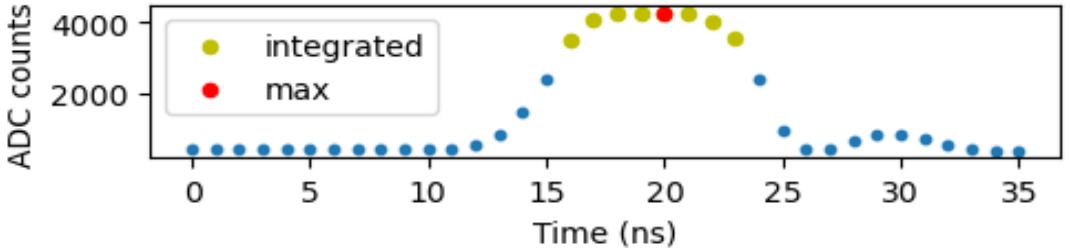
Pre-Amp **Main-Amp (HG/LG)** **DRS4 (ASIC)**

- The LST camera consists of 1,855 PMTs.
- On the readout board, there are main amplifiers with two gain channels (high gain and low gain) and also ASICs called DRS4, which samples the signal at the GHz rate.

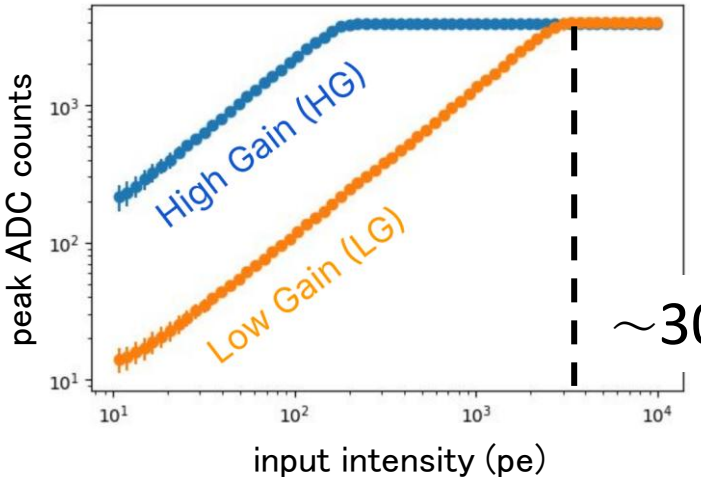
Saturation Effect

If the signal is saturated…





- In the default LST analysis, the charge sampled by the DRS4 is integrated over 8 ns (8 samples) around the peak position.
- If the signal is saturated, the charge can be underestimated.
- From test-pulse measurements, we know that saturation occurs even in the LG channel when the input corresponds to about 3,000 photoelectrons.



~3000 pe

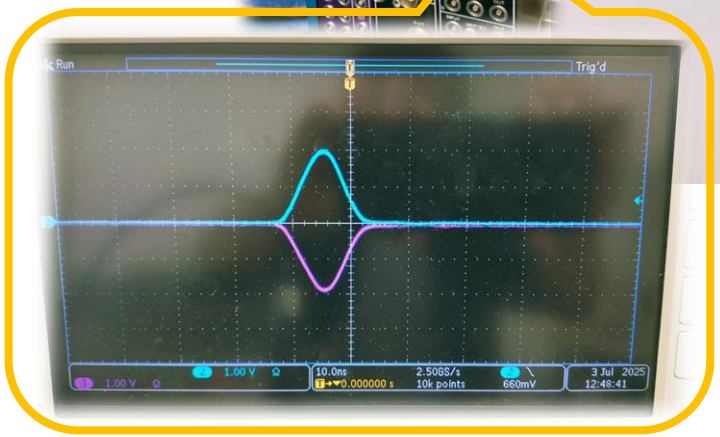
In this talk…

- To first understand saturated pulse behavior, we used a pulse generator to identify parameters that show correlations when saturation occurs.
- We evaluated the output linearity and pixel-to-pixel variations to explore the possibility of applying corrections using LST-1 calibration Laser.

Setup (Pulse Generator experiment)

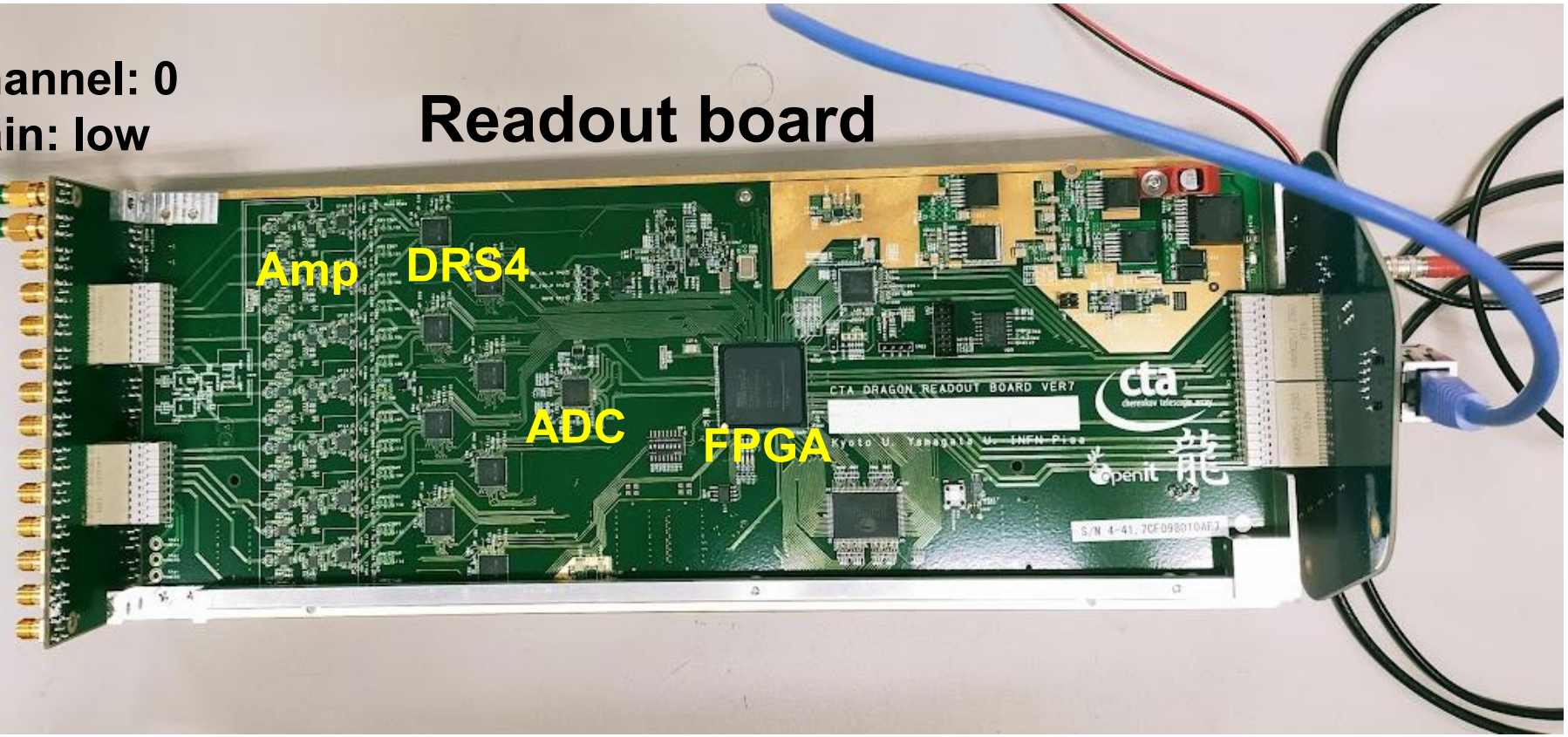
Pulse Generator

FAN-in/out



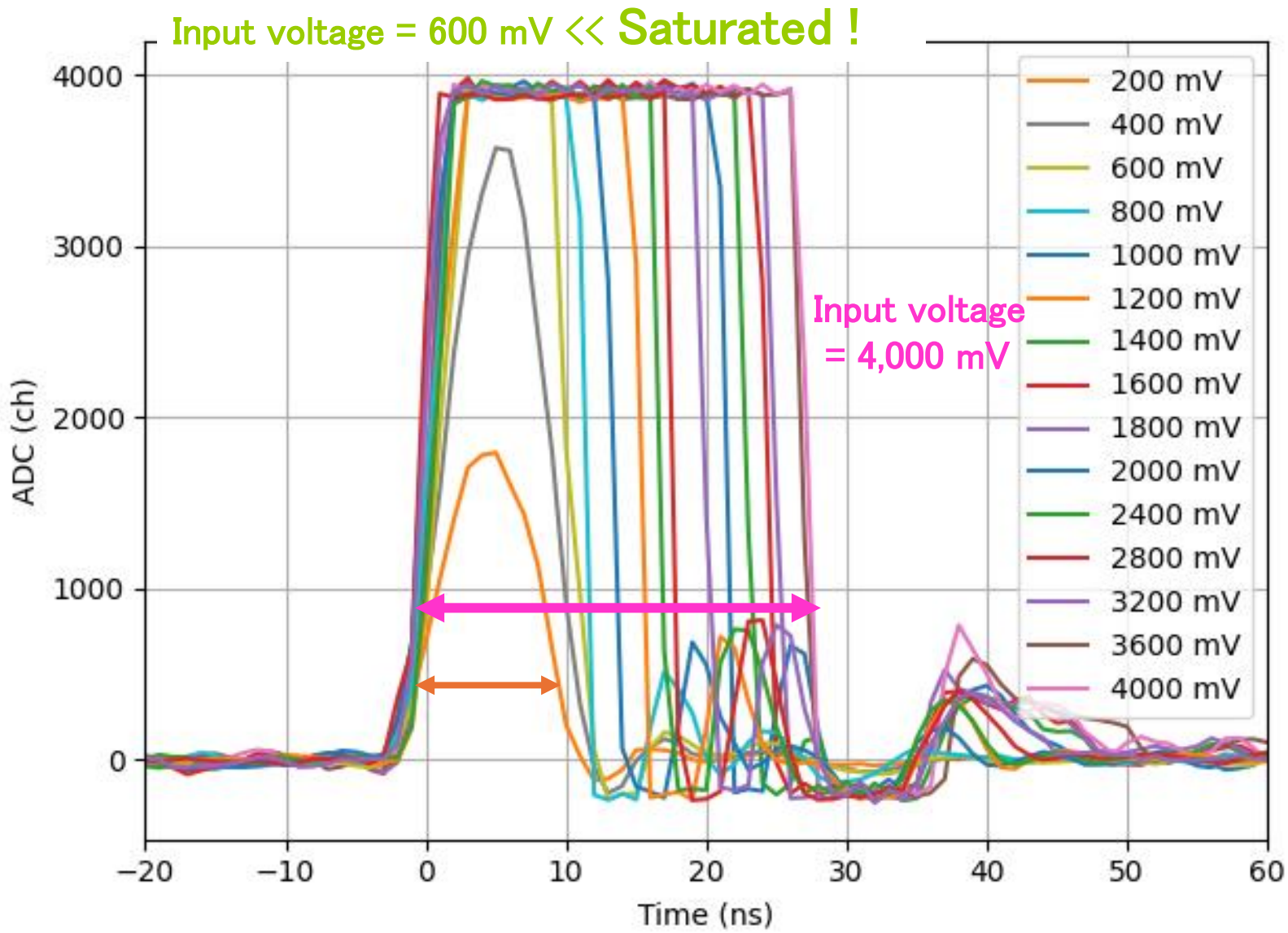
Channel: 0
Gain: low

Readout board



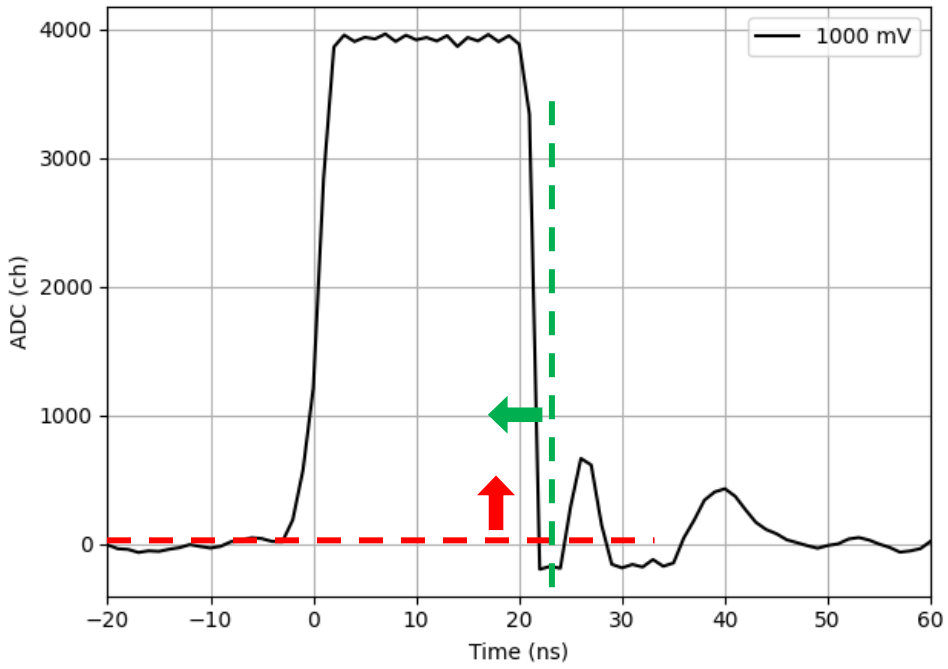
- Input voltage: 200, 400, 600, ・・・ , 10,000 mV
- Width: 8 ns

Result

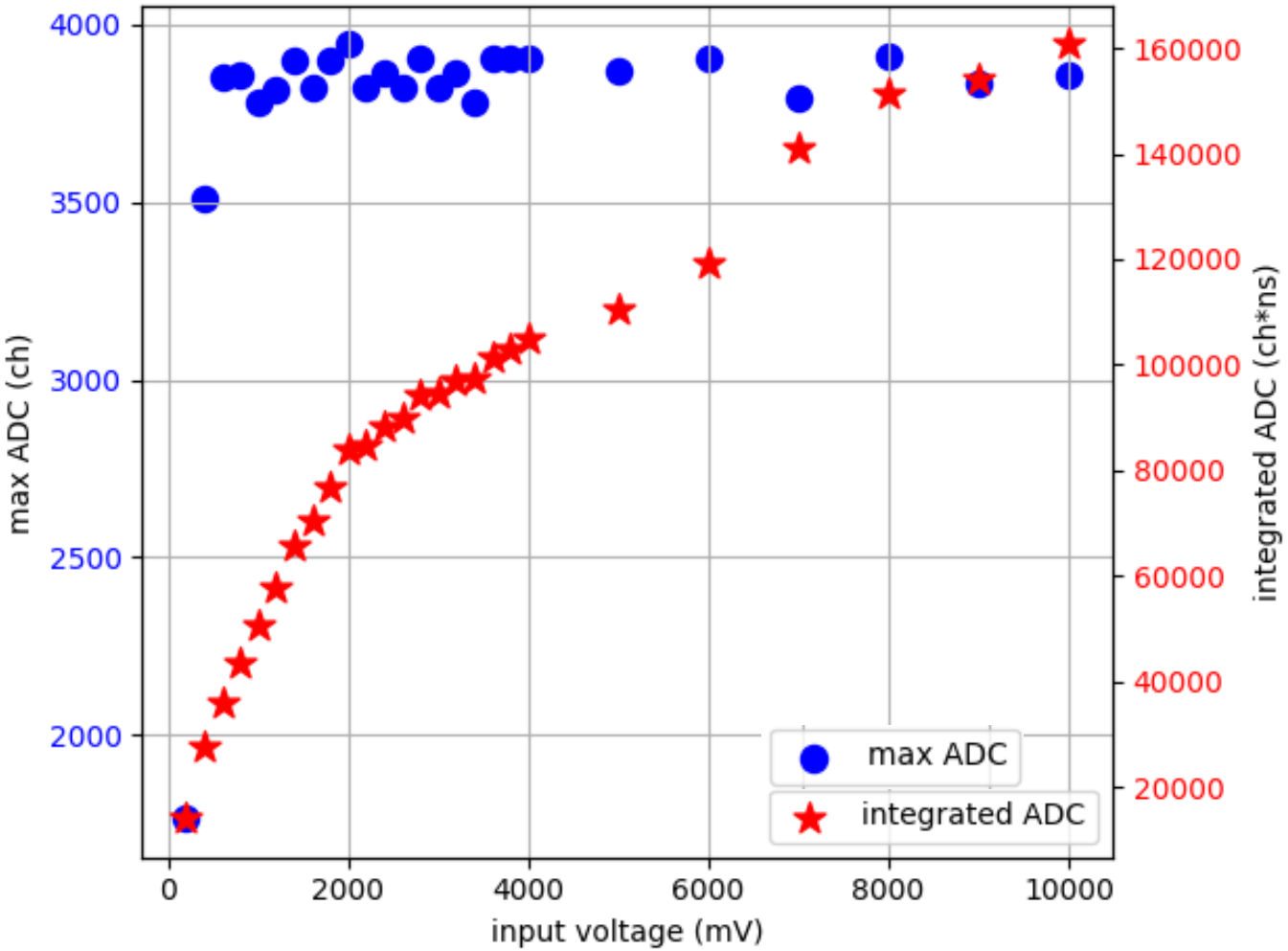


After saturation, the pulse height can not increase, but the pulse width continues to grow.

Result



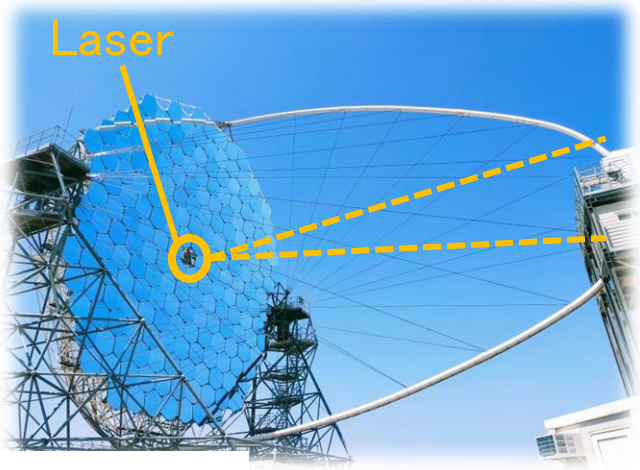
We integrated the ADC counts of each pulse in range of ADC ch > 0 and Time < undershoot.



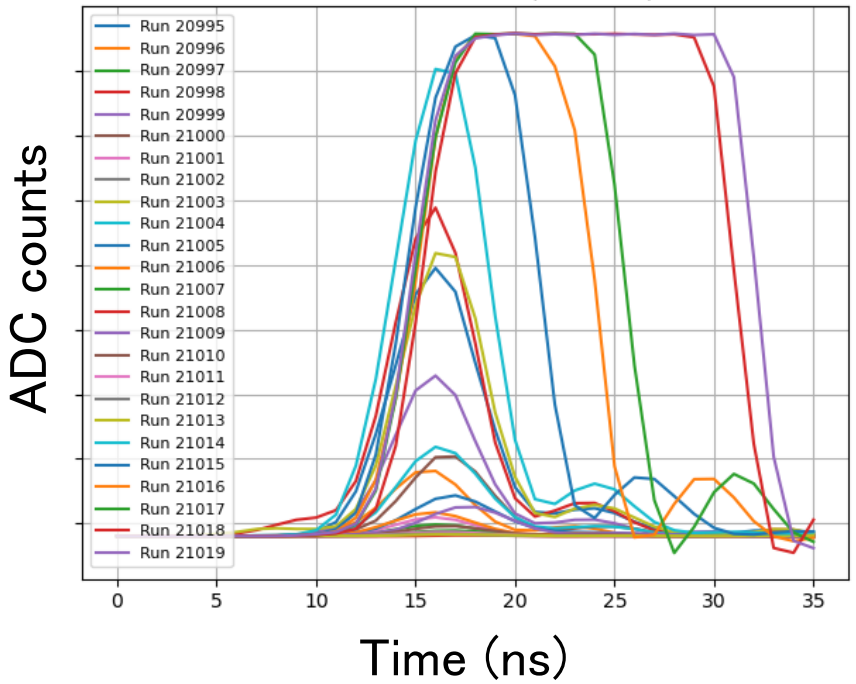
- Even after the pulse height becomes saturated, the pulse intensity continues to increase without saturation.
- We can focus on the pulse intensity as a parameter that remains correlated with the input signal when the pulse height is saturated.

Test with LST-1 calibration Laser

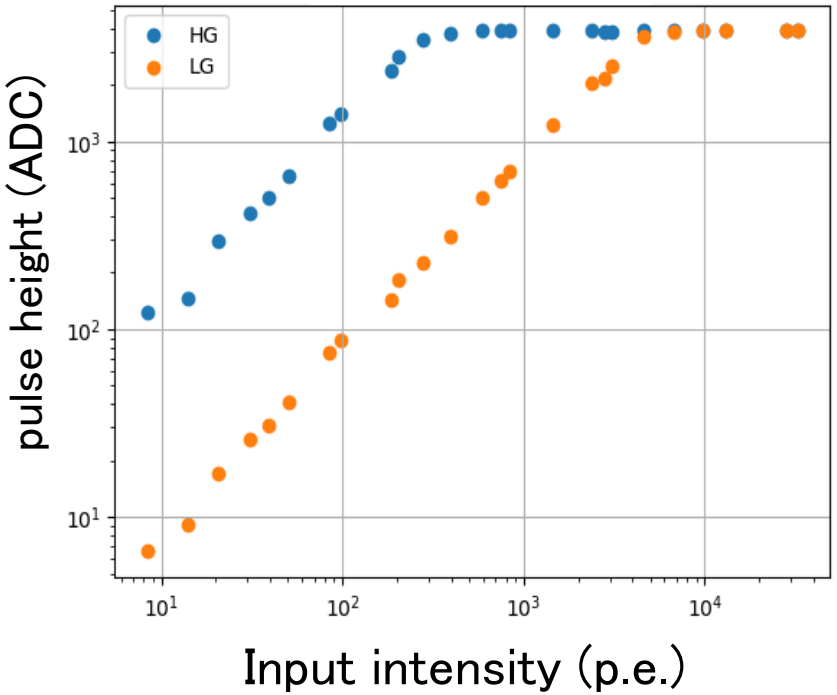
- This summer, we acquired calibration laser data with LST-1.
- By adjusting the laser filters, we changed the transmittance and injected light intensities of up to 3.5 × 10^4 photoelectrons.



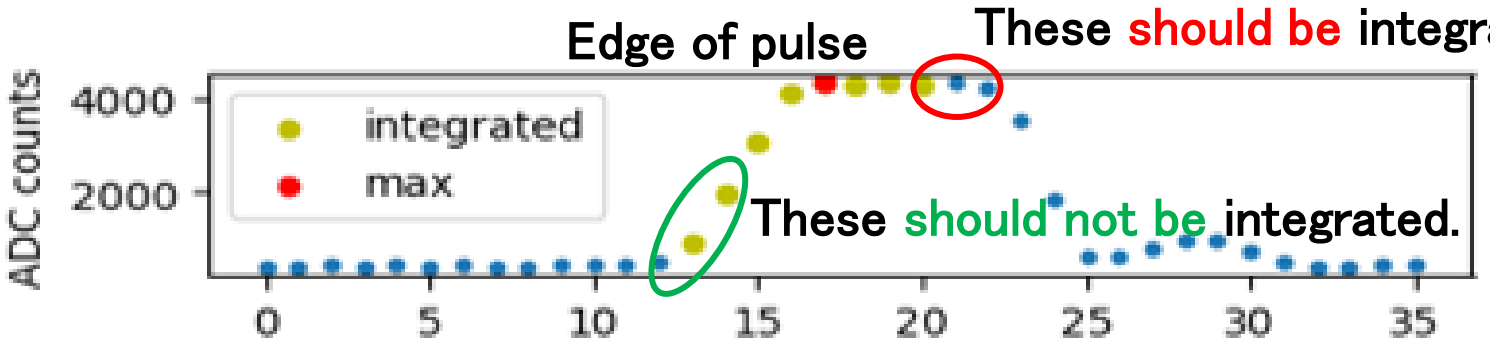
Waveforms



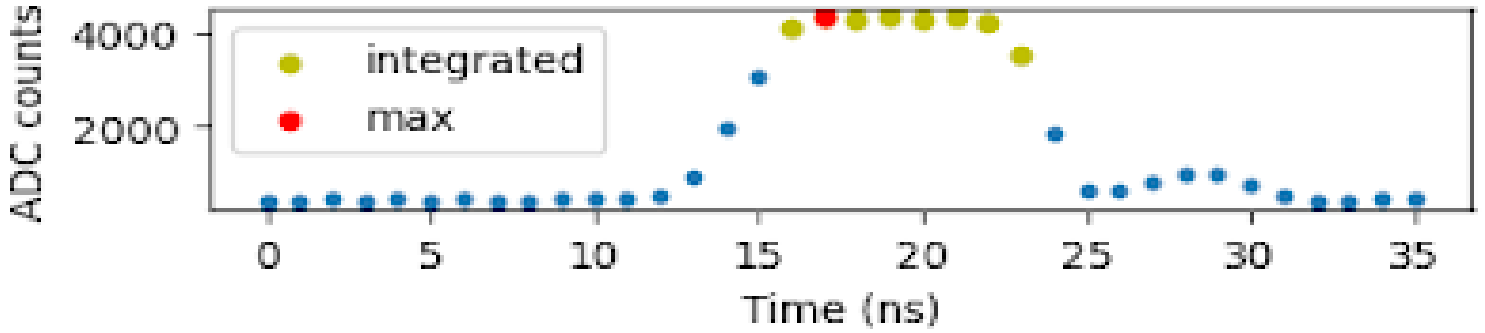
Pulse height



8ns integration

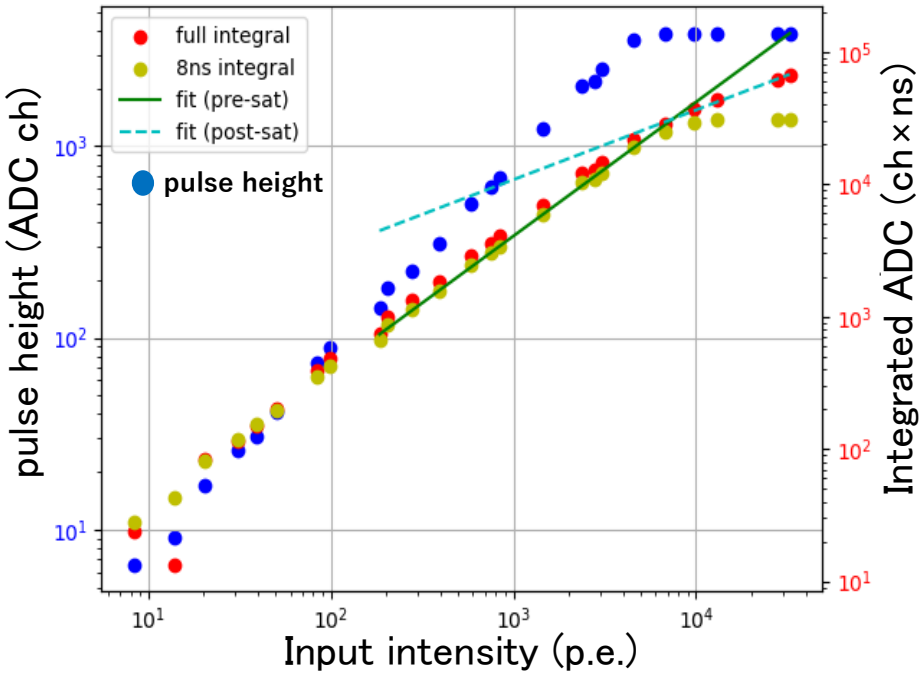


Sliding the integration window and selecting the sample combination…

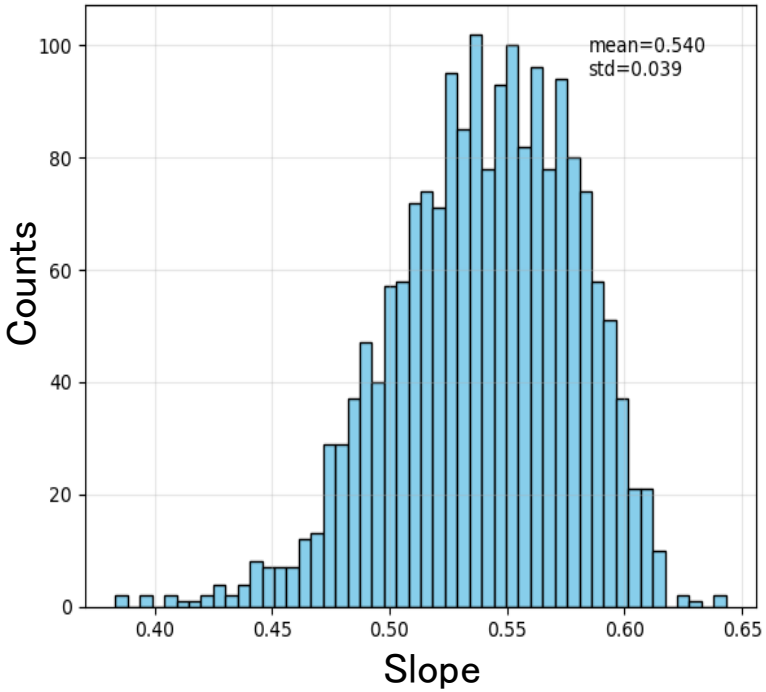


- When saturation occurs, the true pulse peak can not be identified correctly.
- If the peak is mistakenly taken to be the waveform edge, the rising part of the pulse will be included in the integration window.
- We slide the 8-sample integration window by up to ±4 ns and choose the combination of samples that gives the maximum integrated value.

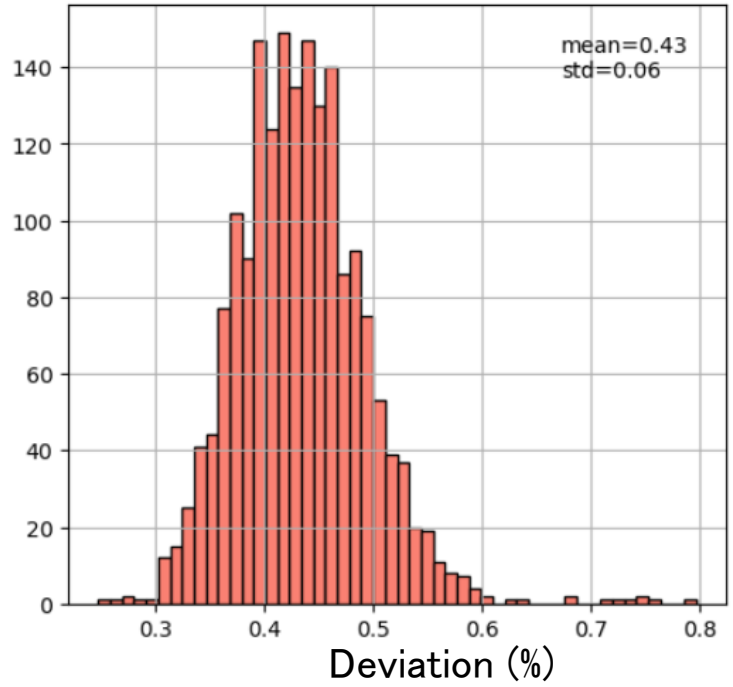
Linearity



Slope (all pixels, after saturation)



Deviation (all pixels, after saturation)



- Even after the pulse height becomes saturated, the pulse intensity continues to increase.
- The full integration remains linear up to the maximum input intensity, without saturation.
  From this, we expect that the number of photoelectrons we can reconstruct can be increased by a factor of ten compared to the conventional limit.
- The pixel–to–pixel variation is small and can be almost ignored.

Summary

- We conducted experiments using the PMT modules employed in the CTAO-LST in order to correct the number of photoelectrons with saturation.
- Even after the pulse height becomes saturated, the pulse intensity continues to increase.
- Linearity is maintained up to an input of 35,000 photoelectrons, suggesting that the number of photoelectrons we can reconstruct can be increased by a factor of ten compared to the conventional limit.
- The pixel-to-pixel variation is small.

Future works

- Fitting with single function across both the unsaturated and saturated regions, thereby completing the response function for saturated signals
- Appling this method to cosmic-ray showers and gamma-ray analyses


Thank you for your attention!!