SOIPIX
Silicon-On-Insulator Pixel Detector Project

SOI Pixel Detectors for X-ray Astronomy

10th International Workshop on Semiconductor Pixel Detectors for Particles and Imaging (PIXEL2022)

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Ayaki Takeda (Univ. of Miyazaki)

takeda @astro.miyazaki-u.ac.jp

on behalf of XRPIX collaboration

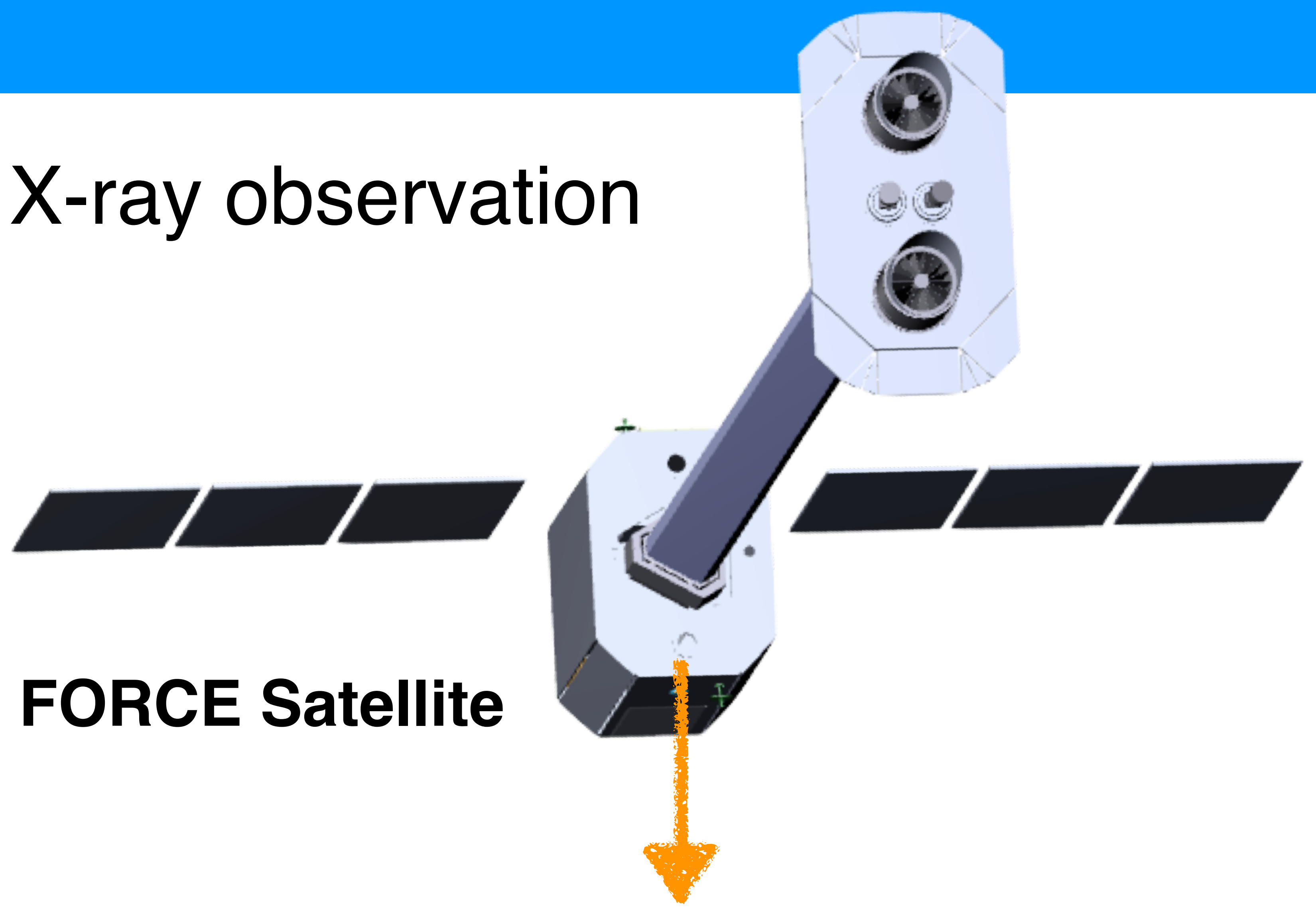
Outline

- Introduction of detector development for X-ray astronomy
- XRPIX series
- on-chip pattern processing for background rejection purpose
- Improved spectroscopic performance by PDD structure
- Summary

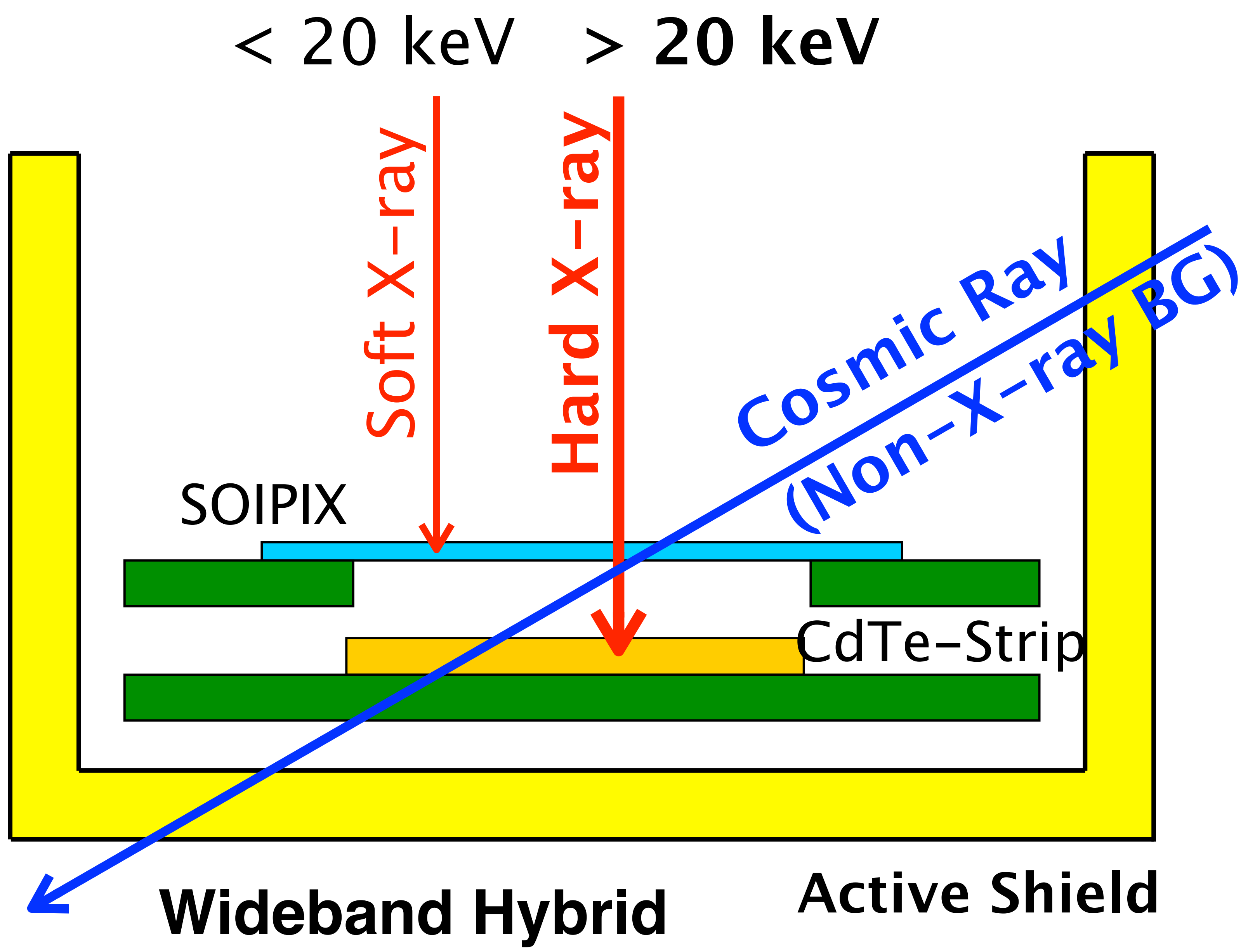
Introduction of detector development for X-ray astronomy

XRPIX for Future X-ray astronomy

- Future satellite missions for wideband (1-79 keV) and low-background X-ray observation in Japan
  → FORCE Satellite Mission (Early 2030s)
  * FORCE : Focusing on Relativistic universe and Cosmic Evolution
- The performance requirements for silicon detectors are...
  → Energy resolution (ΔE): < 300 eV @ 6 keV (requirements)
  → Time resolution: < 10 μs
  → Spatial resolution: < 100 μm
- Current candidates → SOI pixel detector (SOIPIX)
- Developed “Event-driven type SOIPIX” capable of outputting timing and position information at the time of event detection
  → XRPIX Series



FORCE Satellite

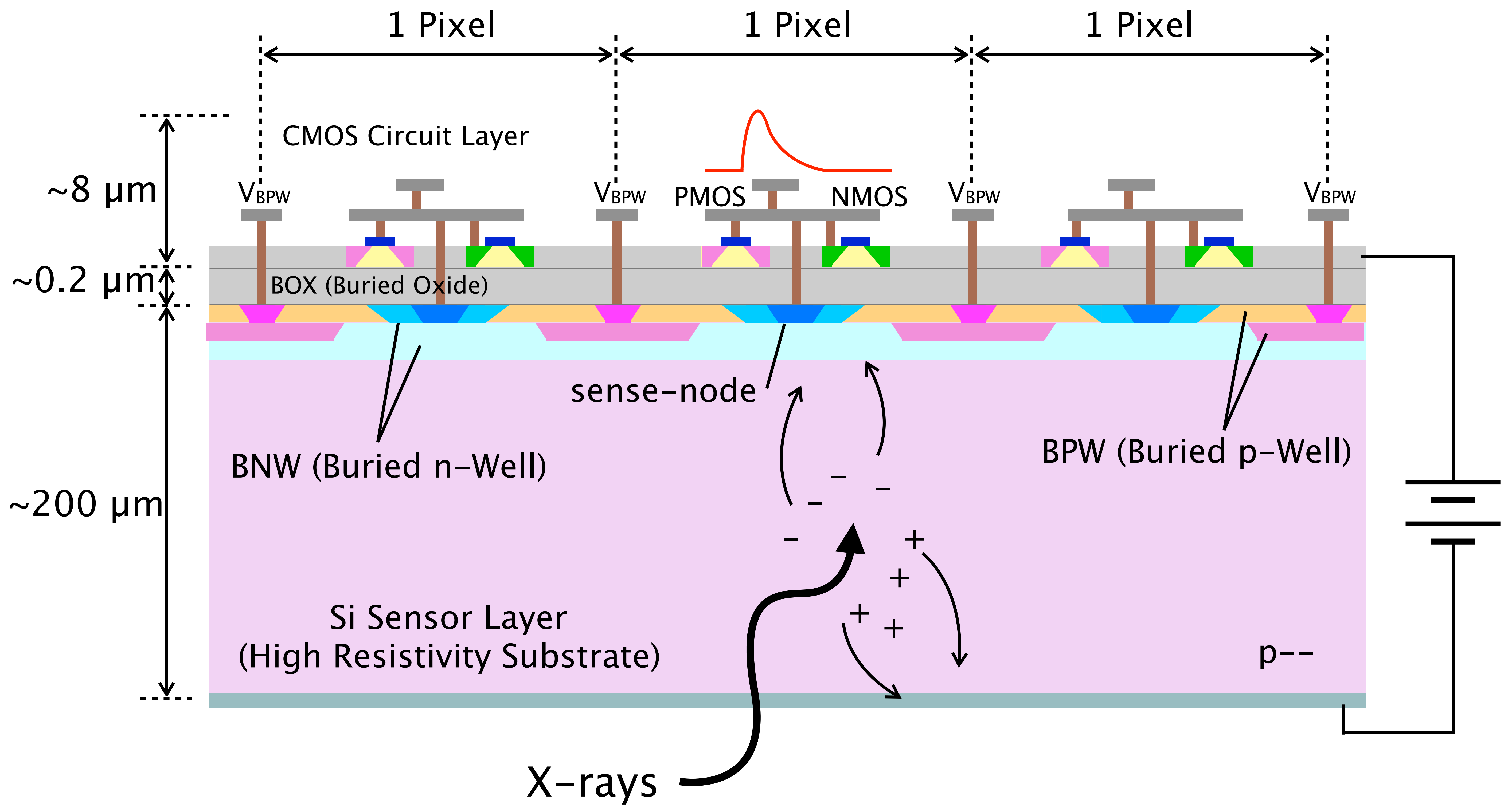


Wideband Hybrid X-ray Imager (WHXI)

Active Shield

SOI Pixel Detector (SOIPIX)

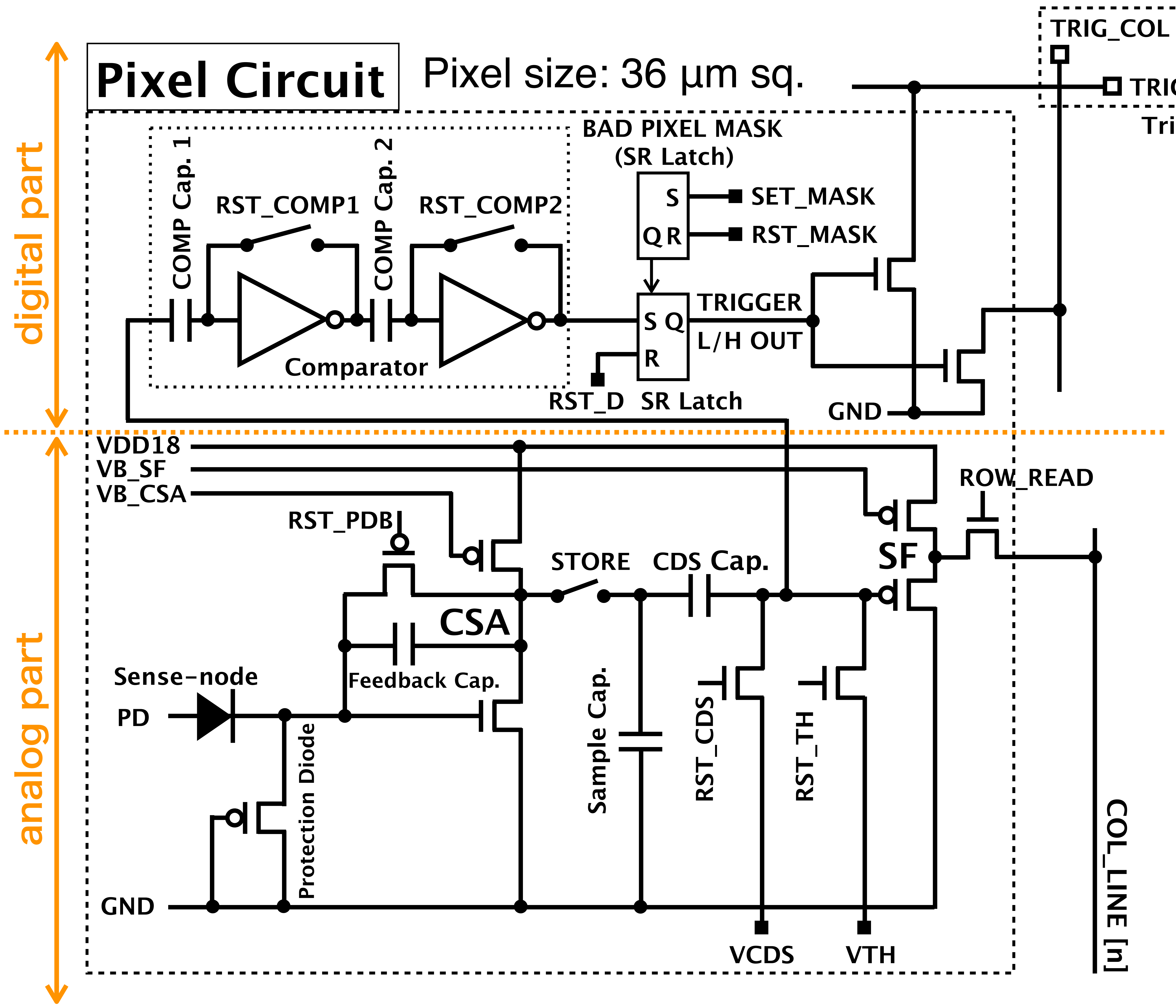
- A monolithic pixel detector with silicon-on-insulator (SOI) CMOS technology
  → 0.2 μm fully-depleted (FD) - SOI pixel process by LAPIS Semi. Co., Ltd.
- Recently, Pinned-depleted Diode (PDD) structures with fixed potential layers introduced at the interface of buried oxide layers have been applied.



XRPIX series

History of XRPIX Series

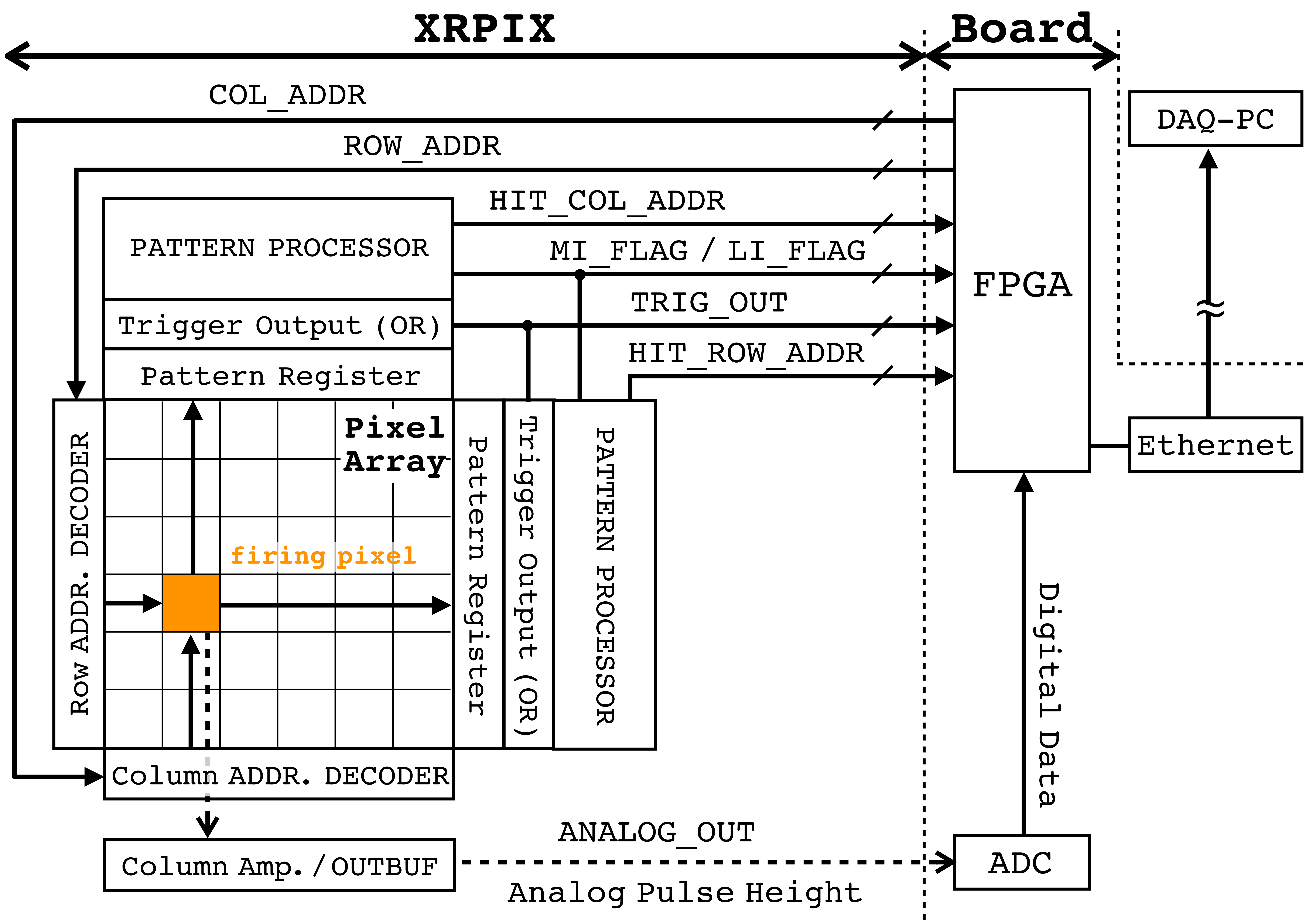
Pixel Circuit



Pixel Circuit consists of …

- Charge-sensitive amplifier (CSA)
- Correlated Double Sampling
- Inverter-chopper type comparator
- SR Latch for bad pixel mask

Event-driven Readout



Flow of Event-driven readout mode

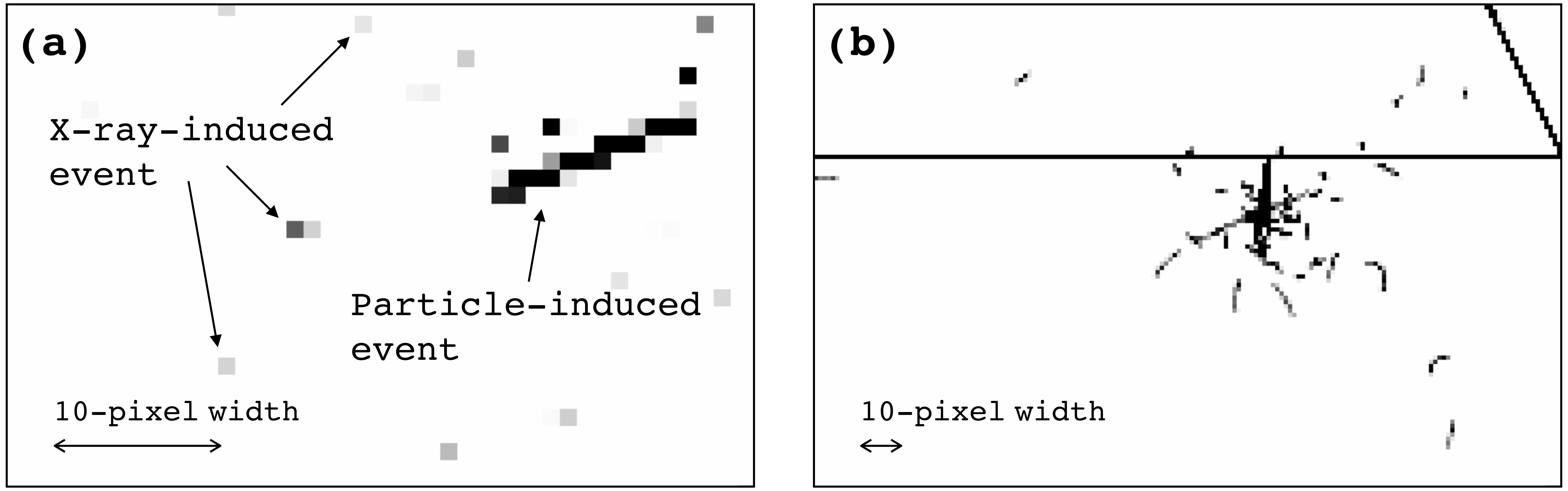
1. When X-ray is injected, X-ray signal is detected by a pixel.
2. If the X-ray signal exceeds a threshold voltage, trigger signals are transferred to row and column direction.
3. The trigger signal is generated.
4. By receiving the signal of “TRIG_OUT”, “MI_FLAG”, and “LI_FLAG”, the FPGA determines which events should be readout.
5. If the event is to be readout, the FPGA obtains and specifies the hit address.
6. The FPGA reads out the analog voltage of the signal and pedestal levels through the ADC.

The pattern processor is a key component !

on-chip pattern processing
for background rejection purpose

Expected pattern of particle-induced events

- Images actually obtained by CCD detectors in space are good references in designing the concept of pattern processing in XRPIX.



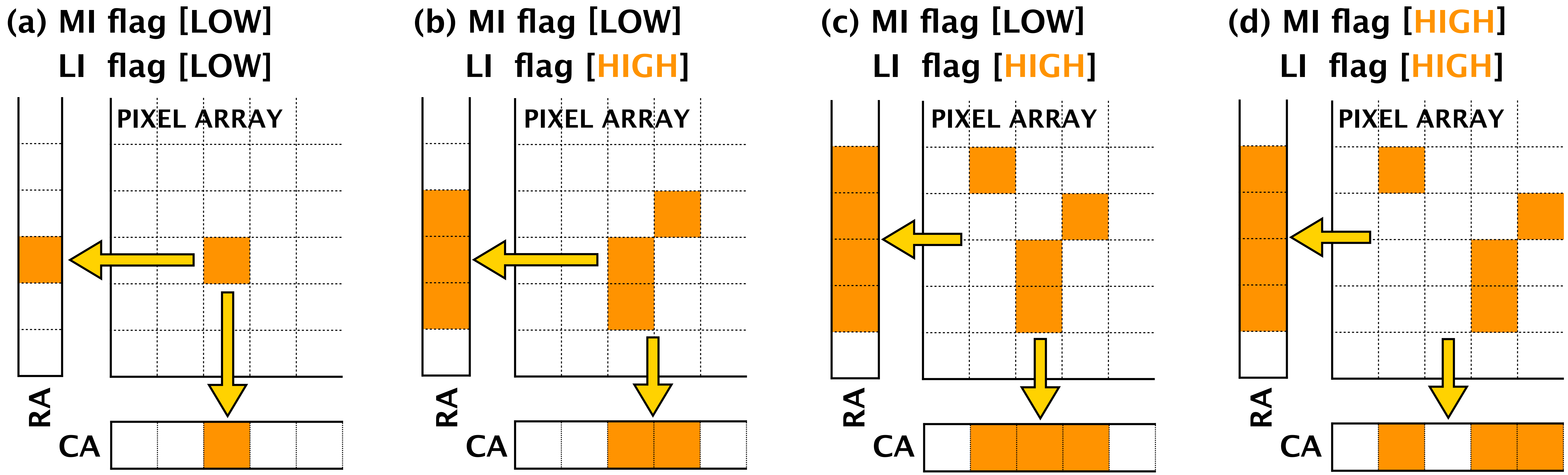
- Two CCD images obtained by Soft X-ray Imager (SXI) aboard Hitomi which is the Japanese X-ray astronomy satellite. (a) shows a close-up view of an image; (b) shows a larger view of a different image.
  * A horizontal black line in (b) indicates a charge injection row, which is an instrumental effect.
- The close-up view in (a) includes isolated one- or two-pixel long islands and an island that is more than 10 pixels long. The former and the latter are typical examples of X-ray- and particle-induced events, respectively.
- In fact, low-energy particles can result in the former pattern, but X-ray events never produce the latter pattern.

Design concept of the pattern processor

- The following concept might be one of the most appropriate and practical ones.
  - The pattern processor to be implemented in XRPIX should send out two types of flags, the multi-island (MI) flag and long-island (LI) flag.
    → MI flag : The triggering exposure contains multiple islands
    → LI flag : The length of a given island is longer than the user-specified threshold length
    * We defined the “island length” of a given island as the sum of its projected RA and CA lengths.
- The hit-pattern data are projected and stored in the pattern register. This information can be used to discriminate detected particles.

Pattern Examples

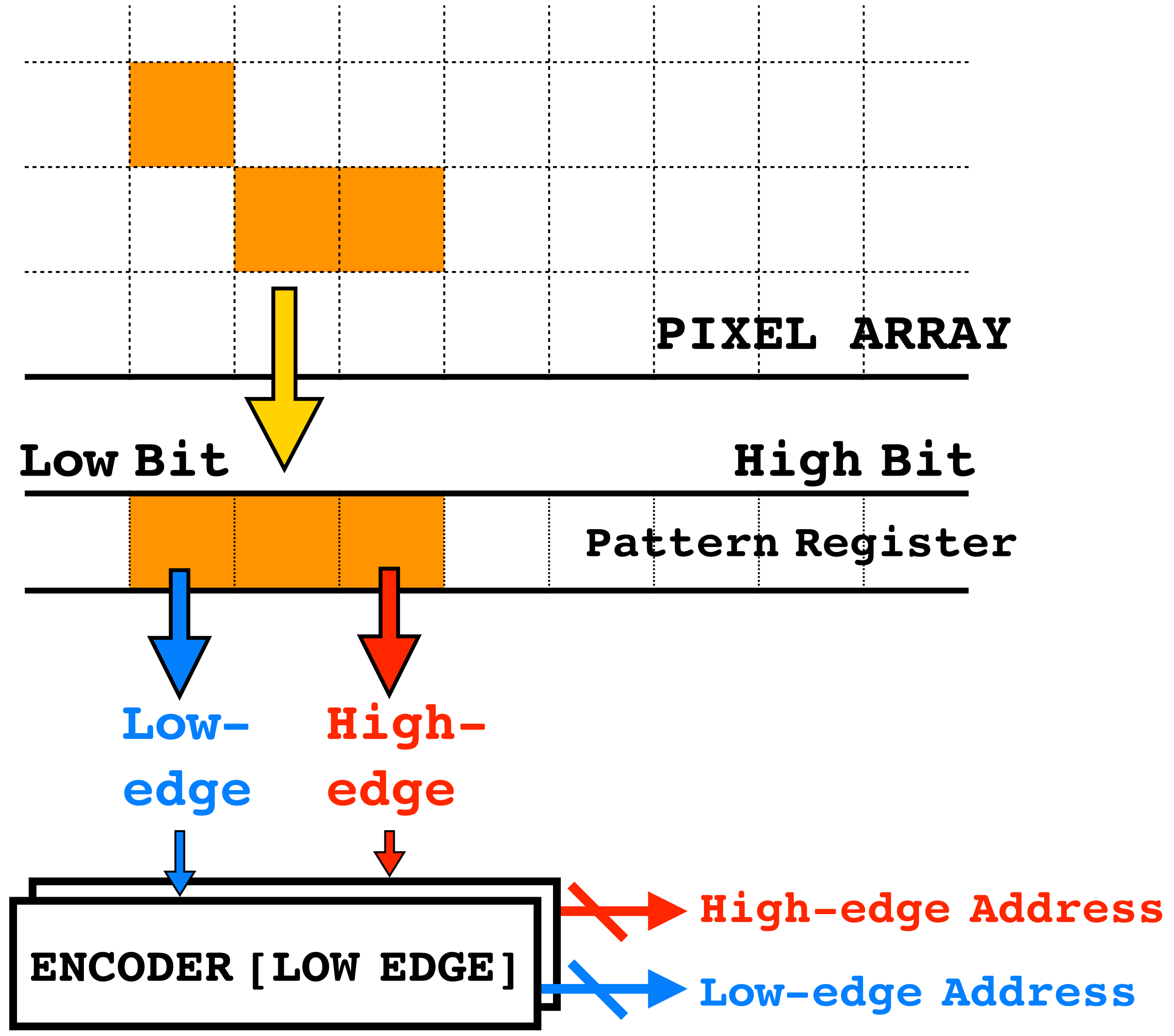
In this example, the user-specified LI flag threshold length was tentatively set to **3**.



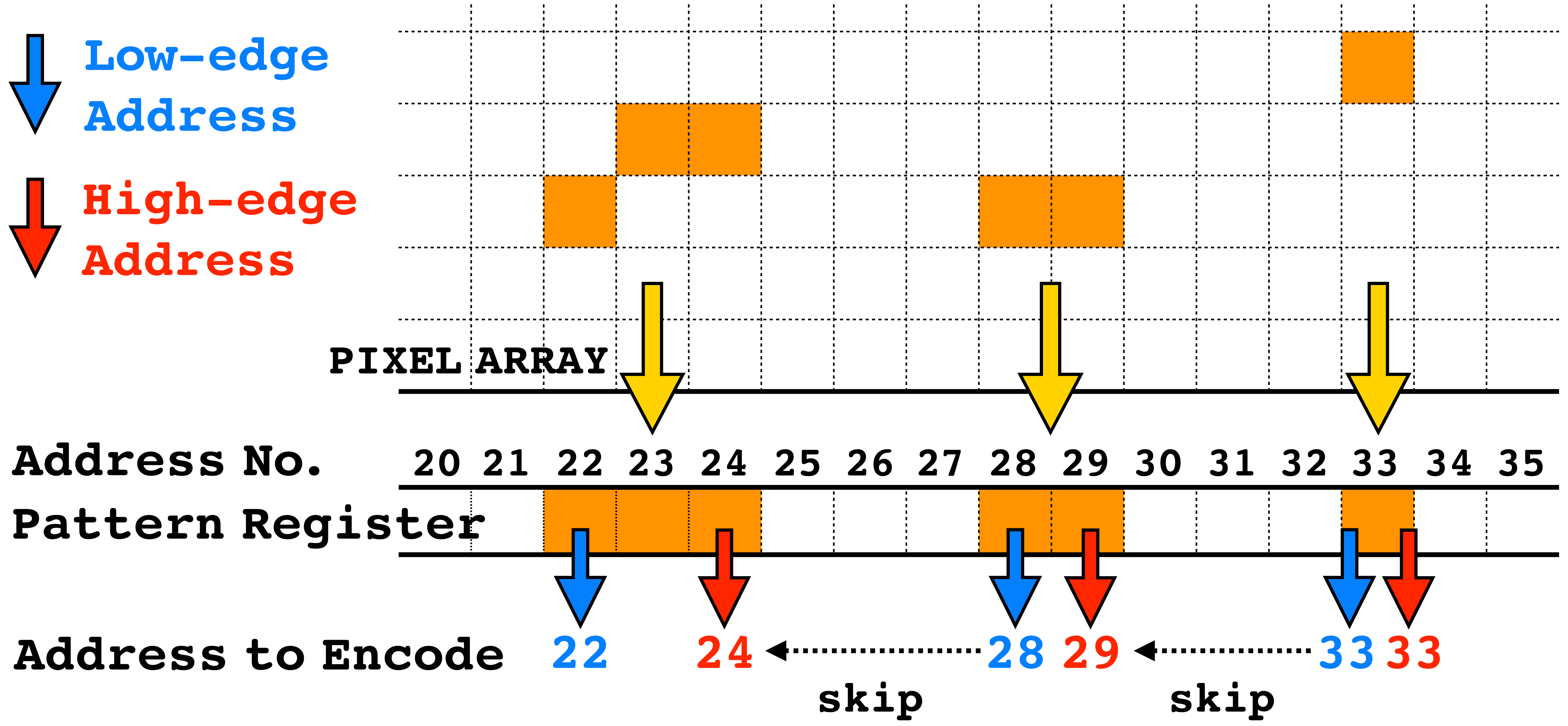
Obtaining hit-pattern addresses

- XRPIX outputs the address of the place where the event is detected through the encoder circuit.
  → Independent of Row Address (RA) side and Column Address (CA)
- The position and size of the detected event can be determined simply by obtaining the address ("Low Edge" and "High Edge").
- The output address is shifted by the input of the scan clock signal.
  → Pattern scan function

Obtain addresses from both edges of a "**HIGH**" bit-string.

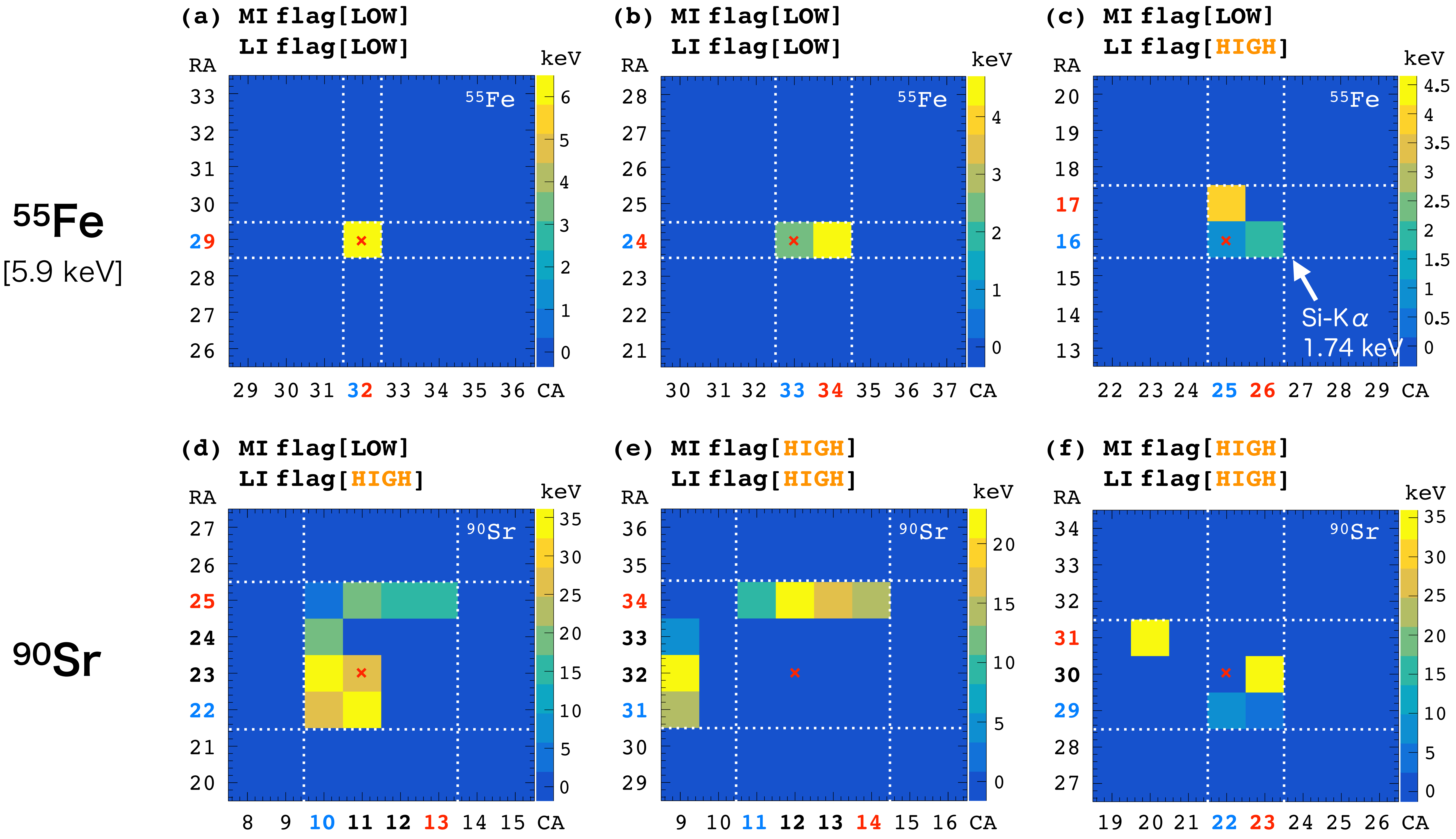


A pattern scan function is implemented to obtain addresses even when multiple islands are detected.



Verification of the pattern-processing function

- Example of event acquisition using XRPIX.
- 8 × 8 pixels analog signal is read out based on the event center information.

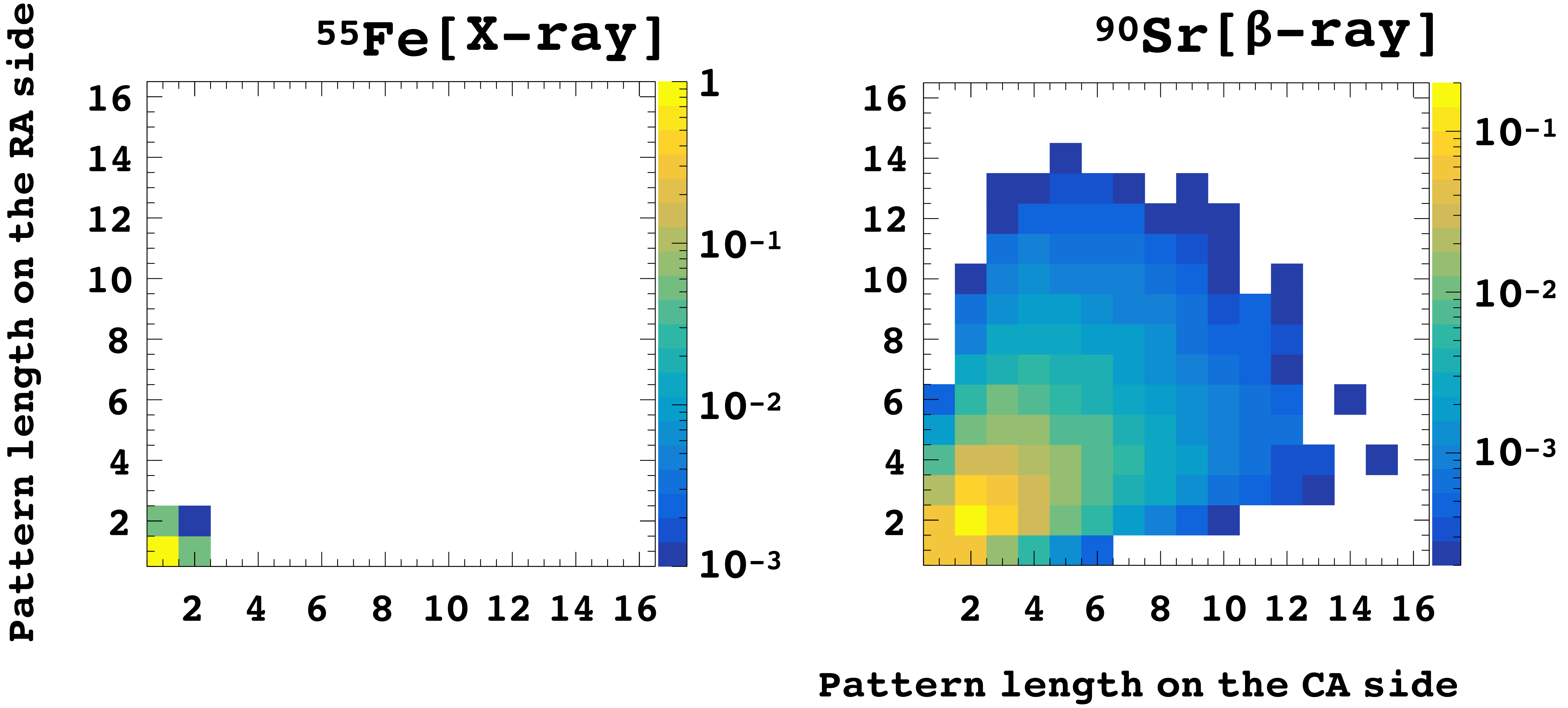


Pixel size: 36 μm sq.
x : event center address
Red: High-edge address
Blue: Low-edge address
Red & Blue: High- & Low-edge addresses are the same

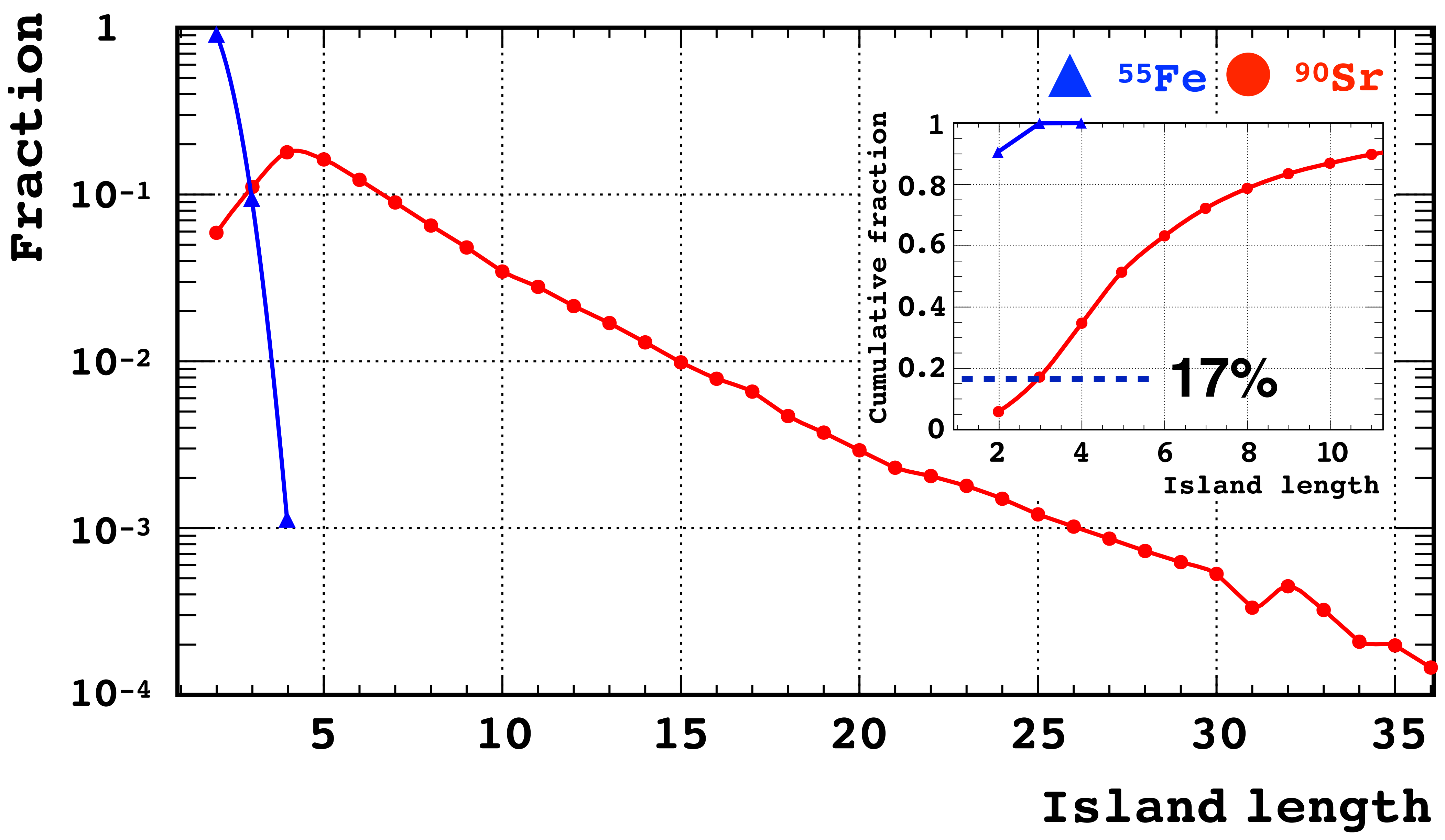
Events from other sources were similarly examined to verify that the pattern processor works as designed.

Pattern length distribution

- We investigated the projected island length distribution of events with MI flag “LOW”
- The distribution of the X-ray events is within the range of 2 x 2 pixels, while that of beta-ray events extends significantly beyond this range.
- It is possible to distinguish between X-ray and beta-ray events by considering the island length.



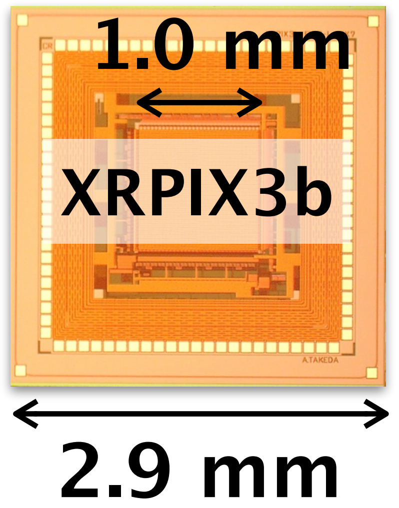
- The plot shows the fraction of events as a function of the island length, i.e., the sum of the projected RA and CA lengths.
- We can reject the remaining **83%** of the beta-ray events without discarding the most of X-ray events when adopting LENGTH_TH = 3 in this case.

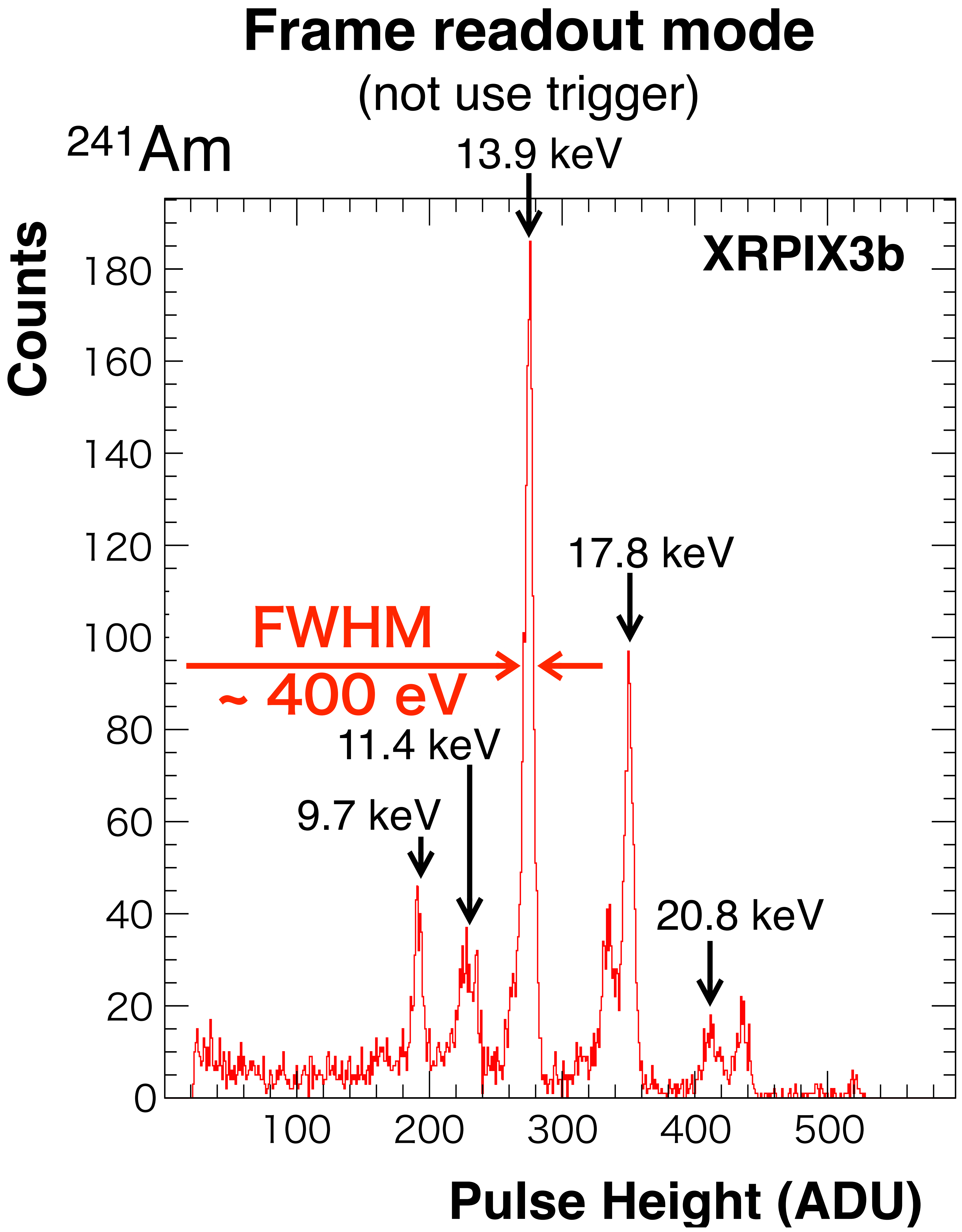


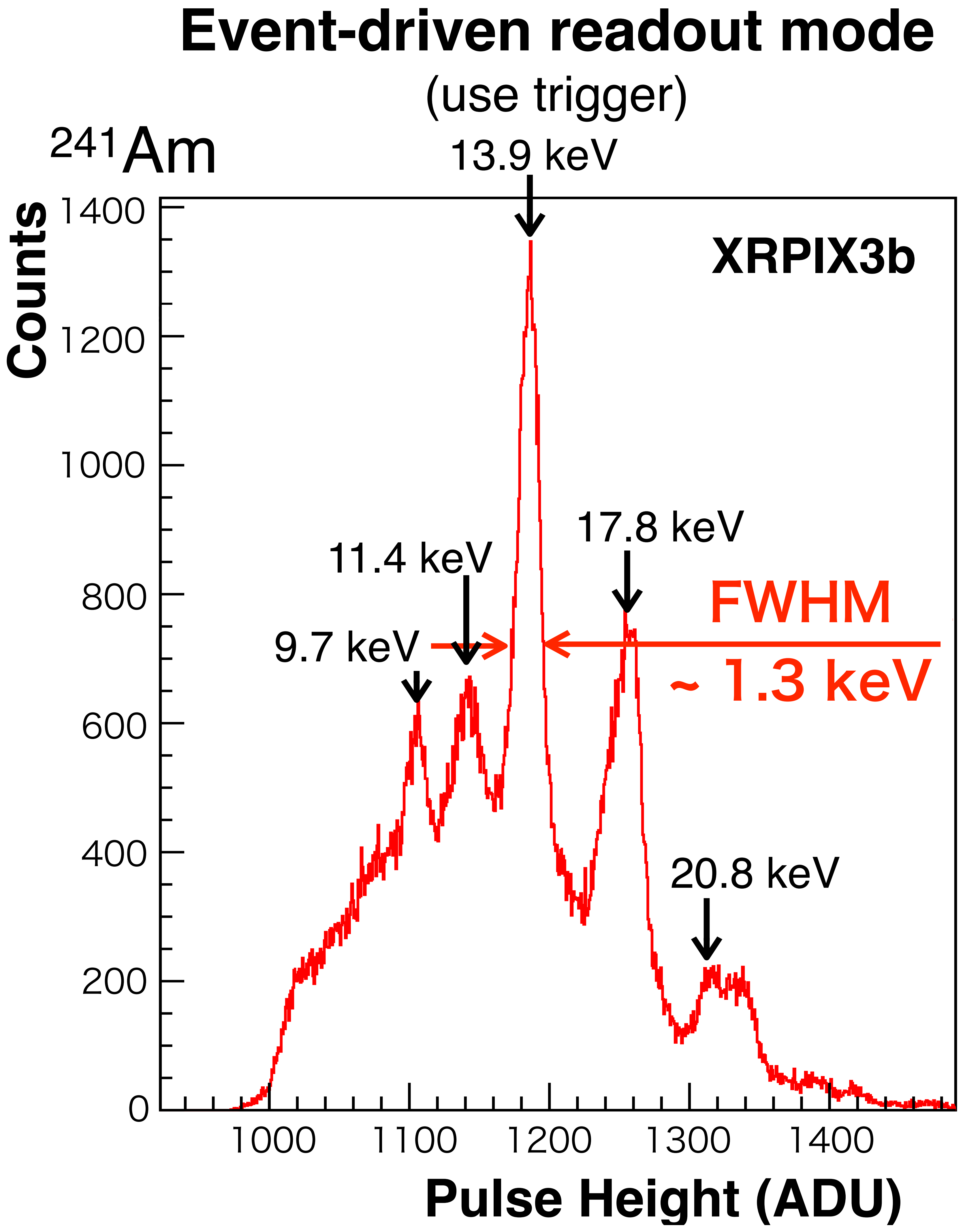
Improved spectroscopic performance by PDD structure

Signal Degradation by Event-driven mode (~2015)

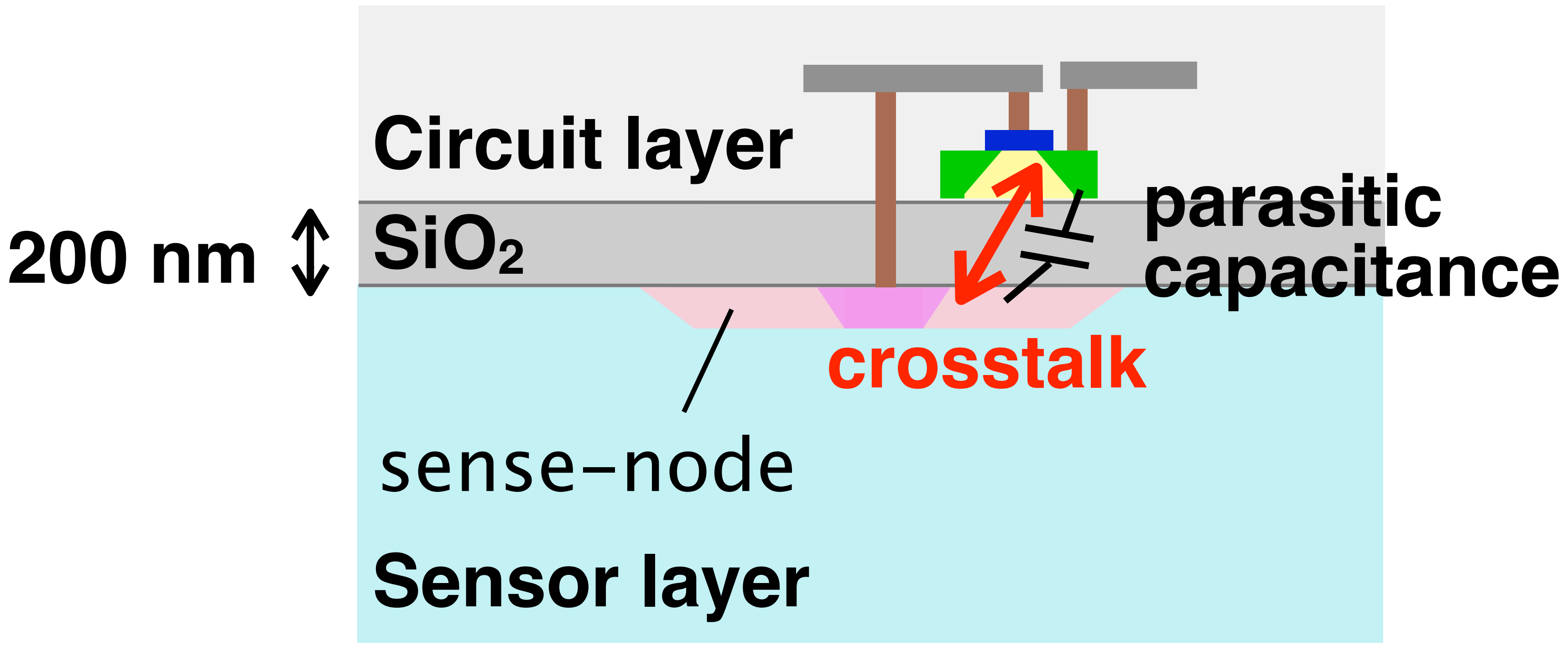
We had a critical issue in event-driven mode… The analog signal is degraded…







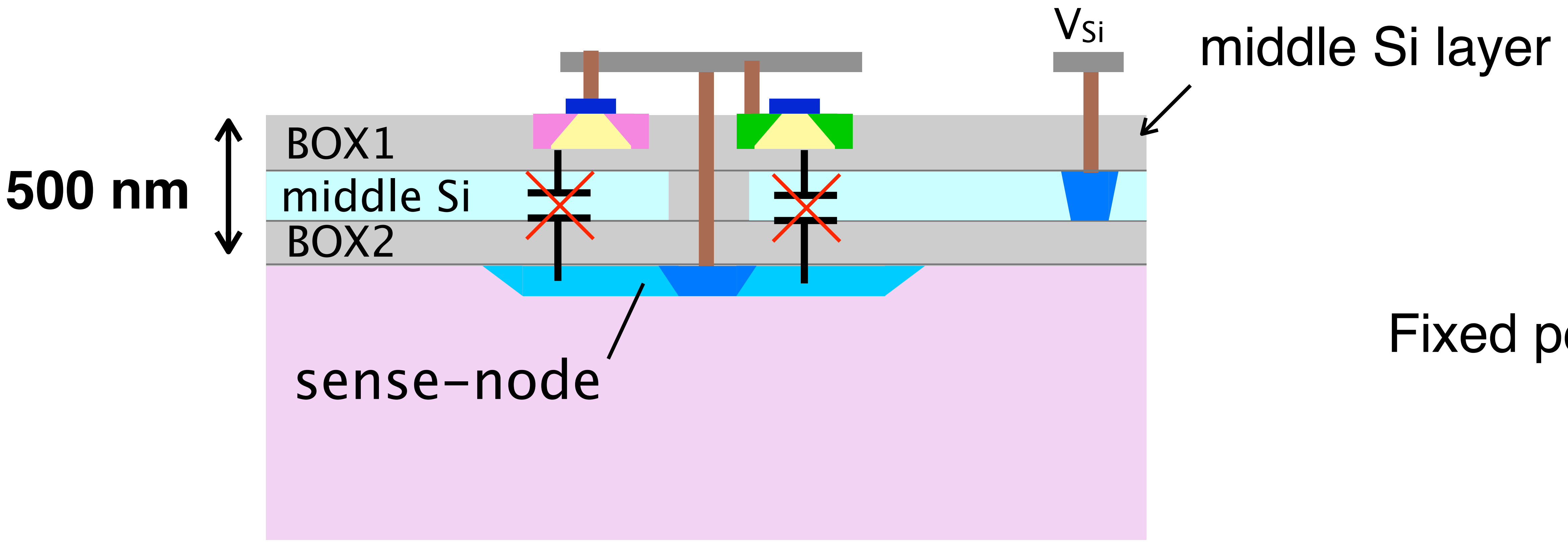
Improvement for interference issue



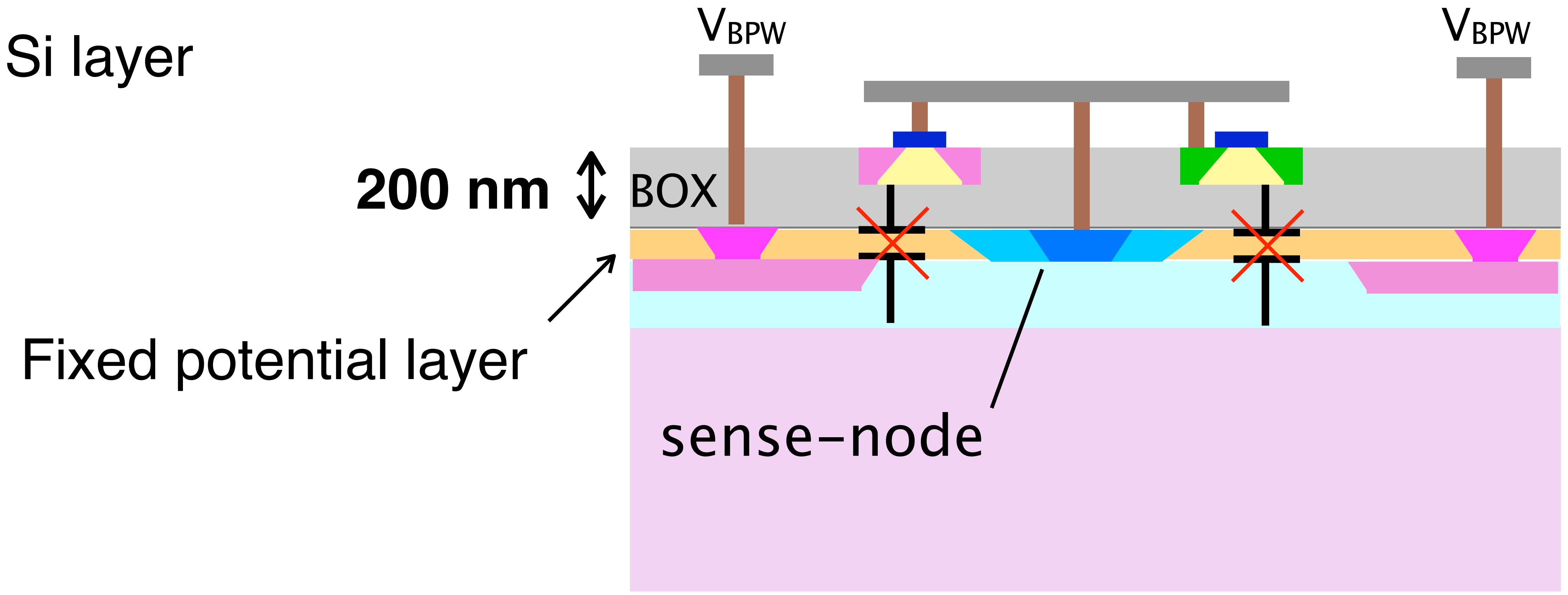
- We understood that the signal degradation was caused by interference of digital signal in the pixel.
- The digital signal transmits a signal change of the comparator inversion to the analog signal via the parasitic capacitance.

→ It is important to suppress capacitive coupling

New approach to suppress capacitive coupling



Double SOI structure



Pinned Depleted Diode structure

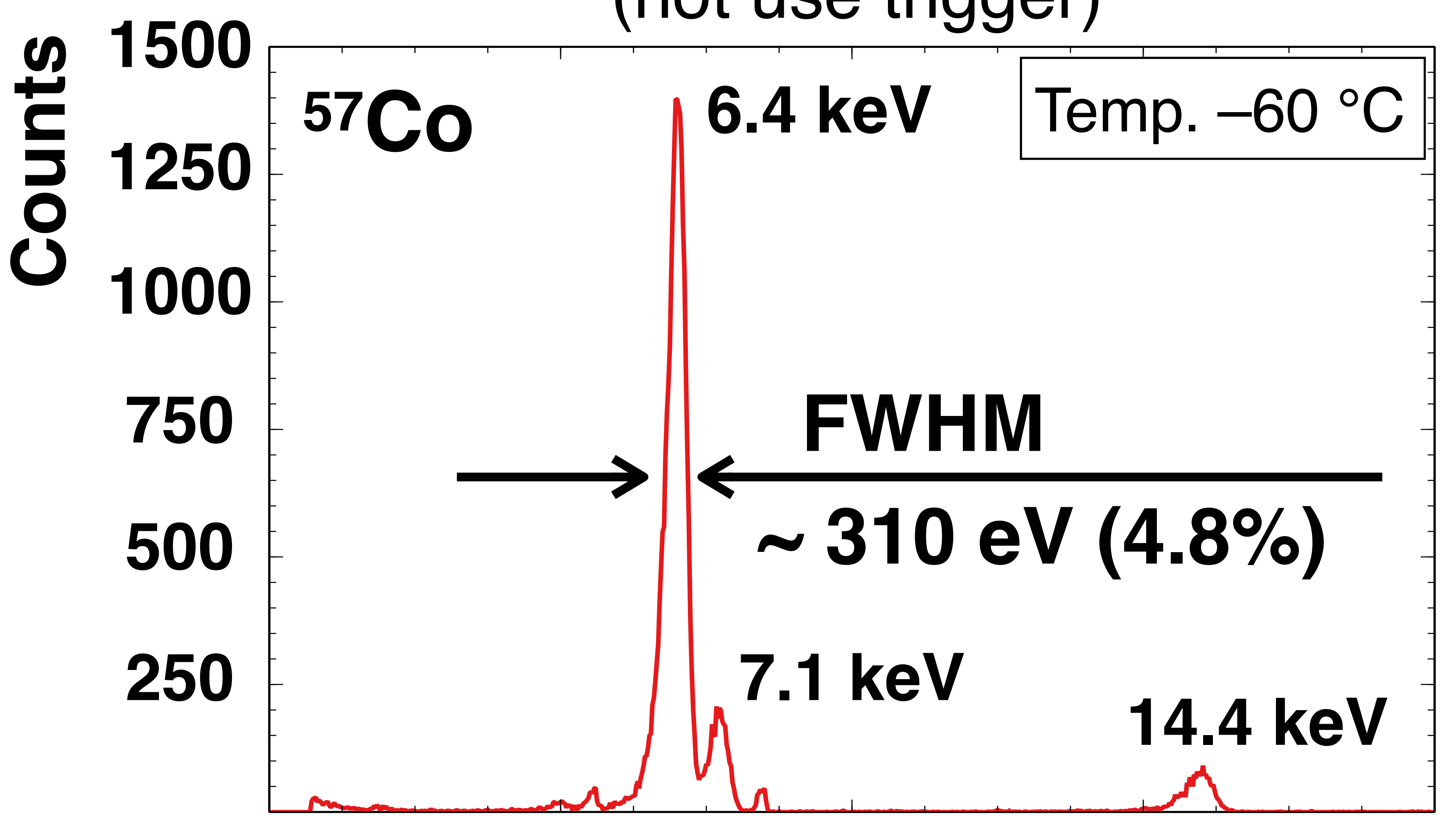
→ Current standard structure

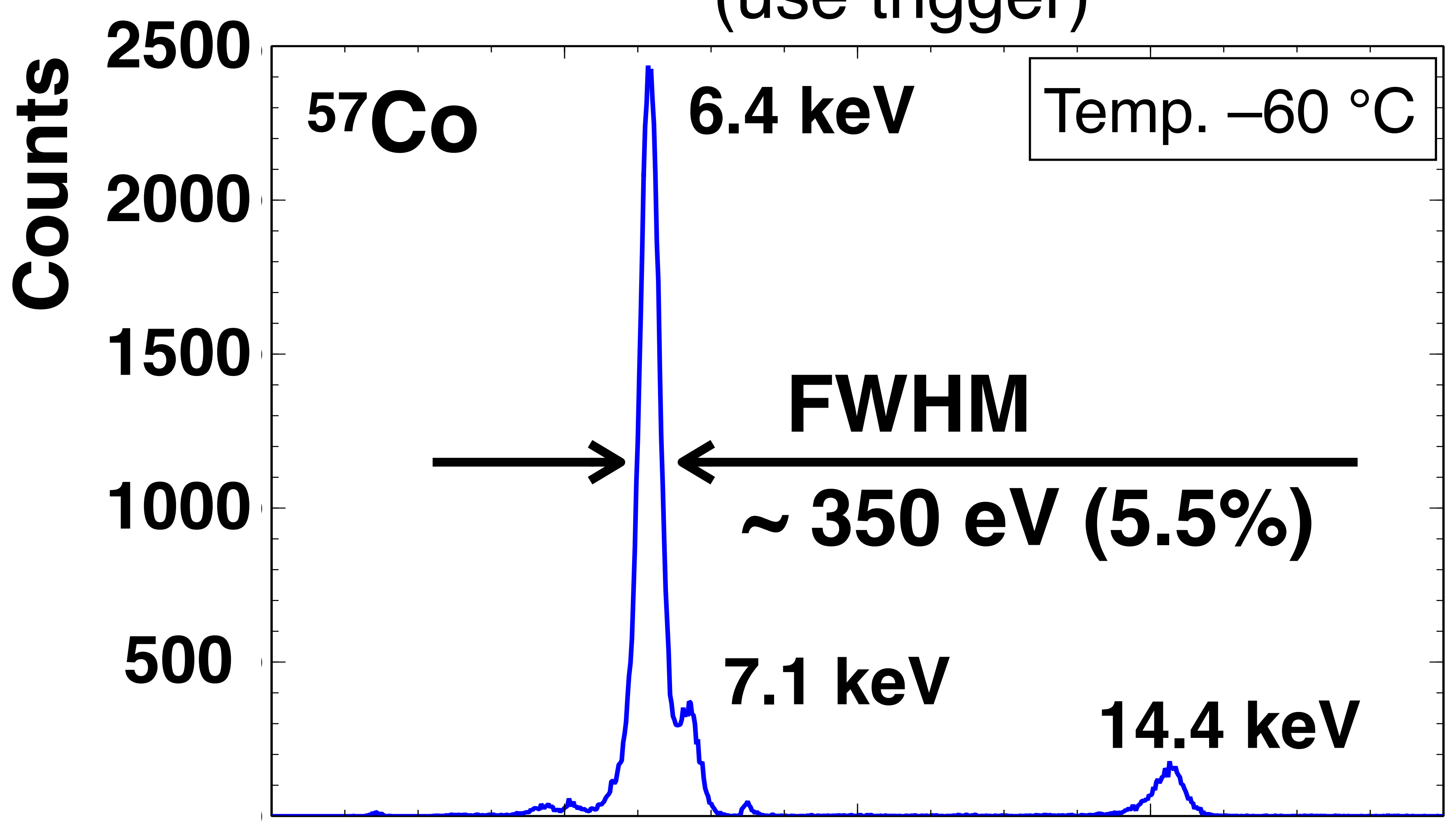
Improved Spectroscopic Performance

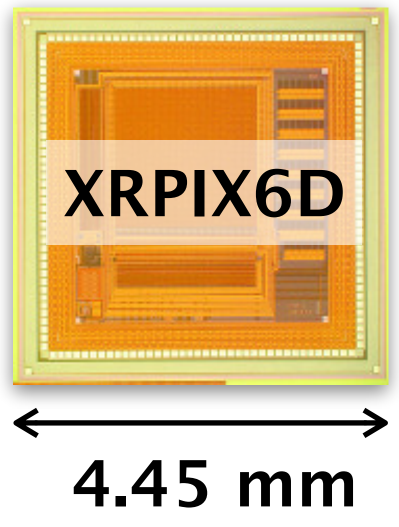
Frame readout mode (not use trigger)

Event-driven readout mode (use trigger)

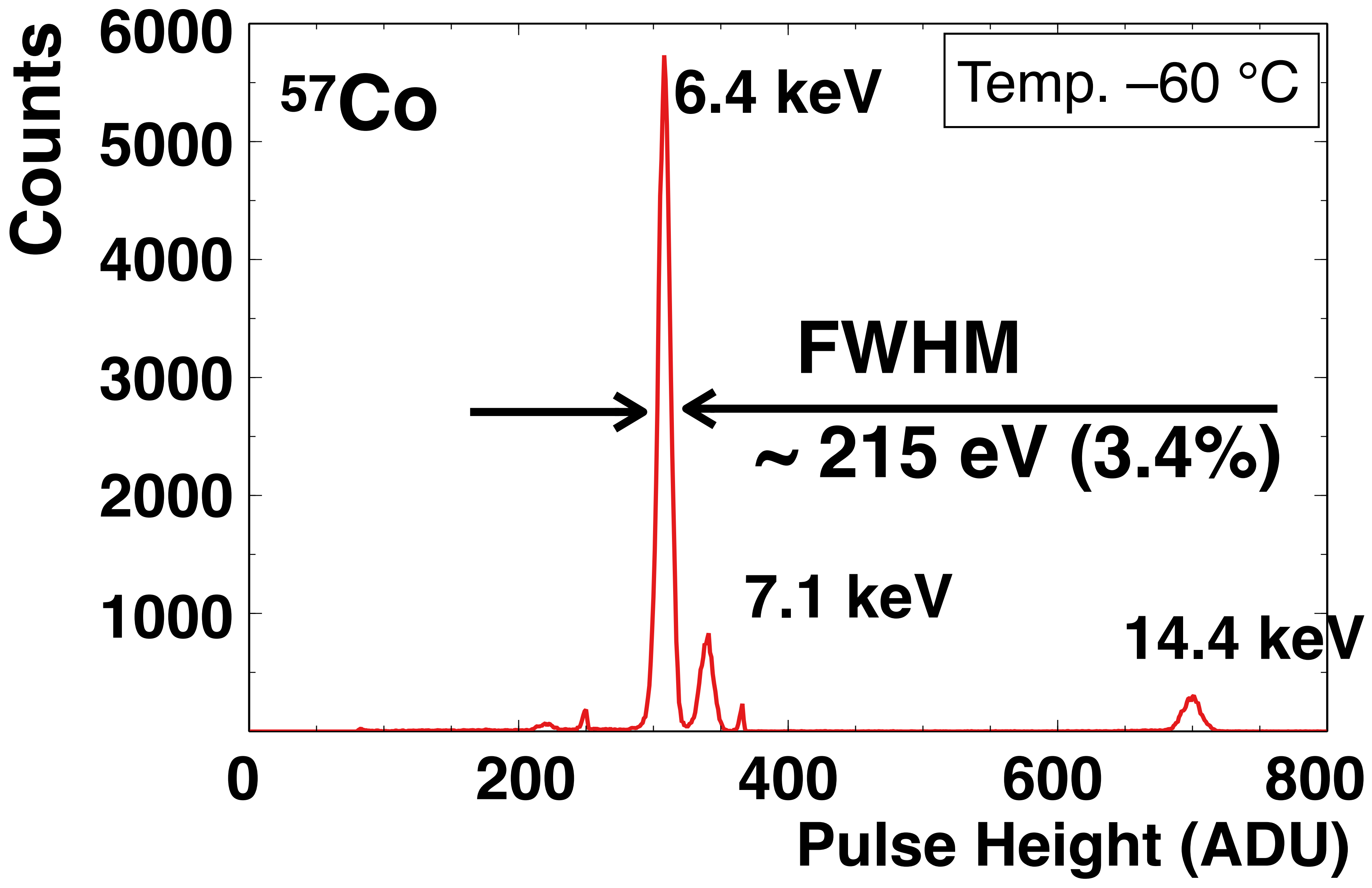
D-SOI

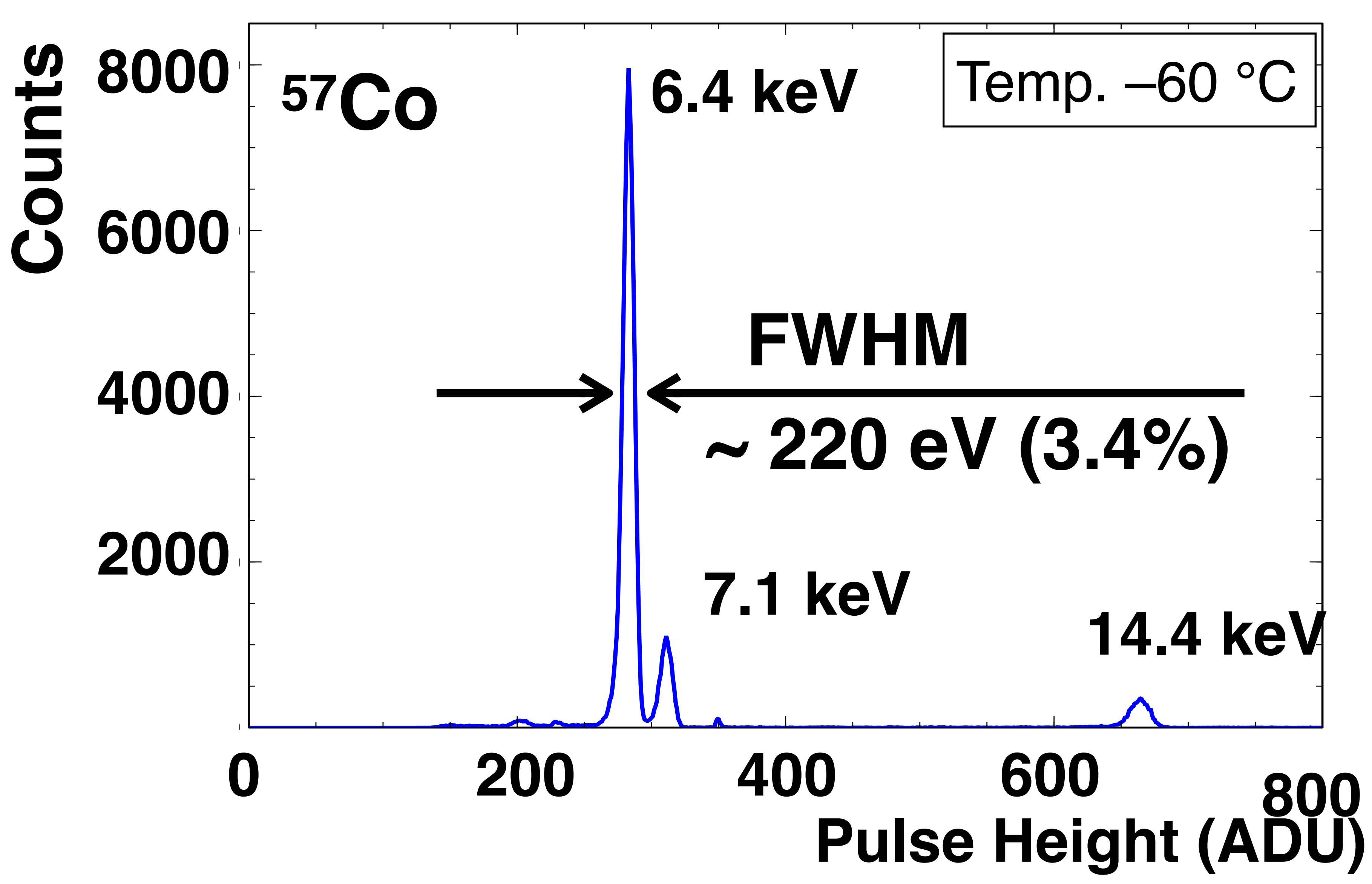


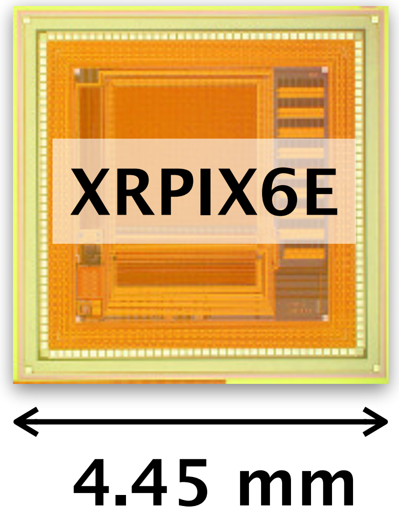




PDD







Room temperature spectra of small-area device "XRPIX8"

Conditions

Device: XRPIX8 **[PDD]**

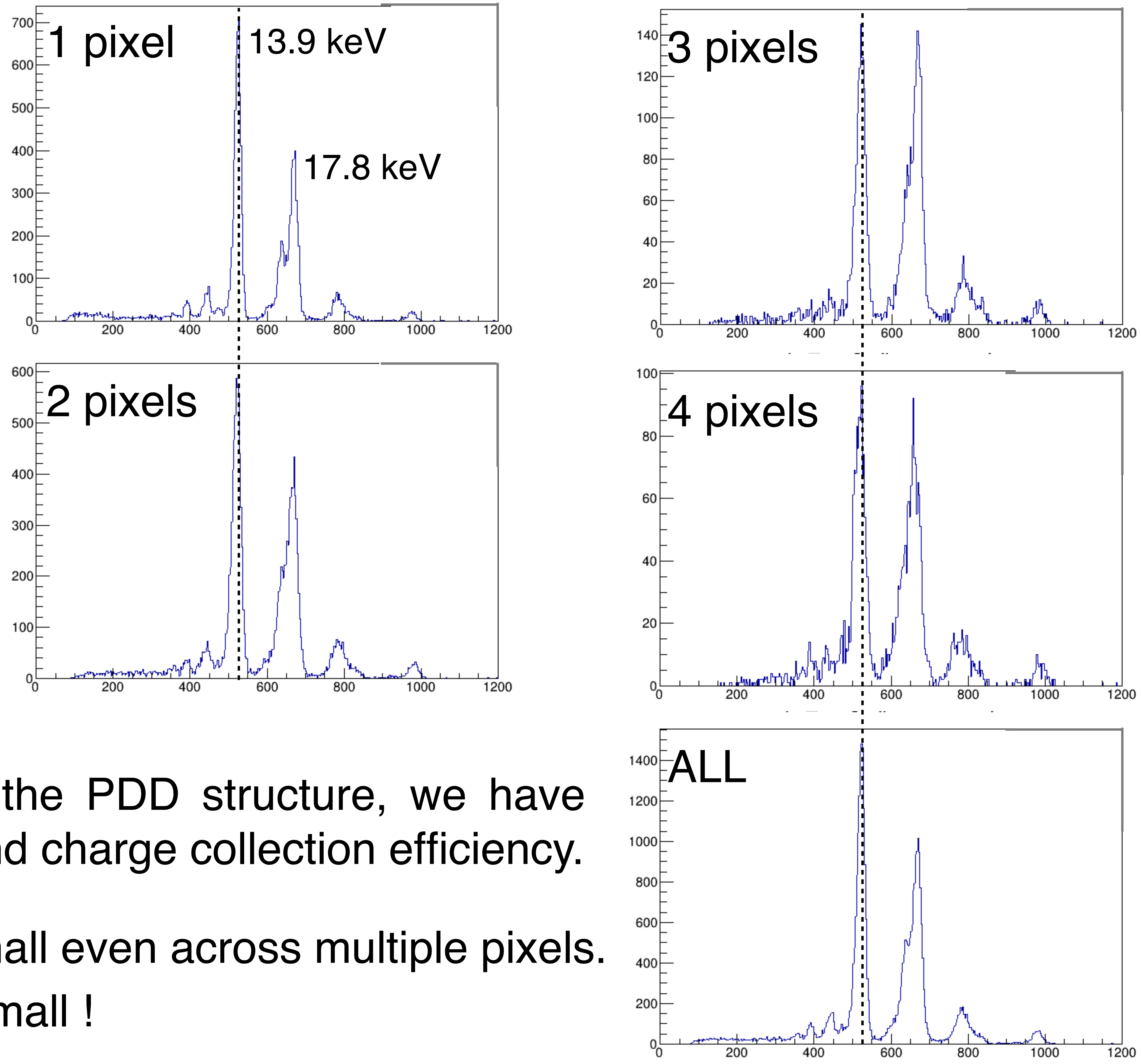
Temperature: 25 deg.

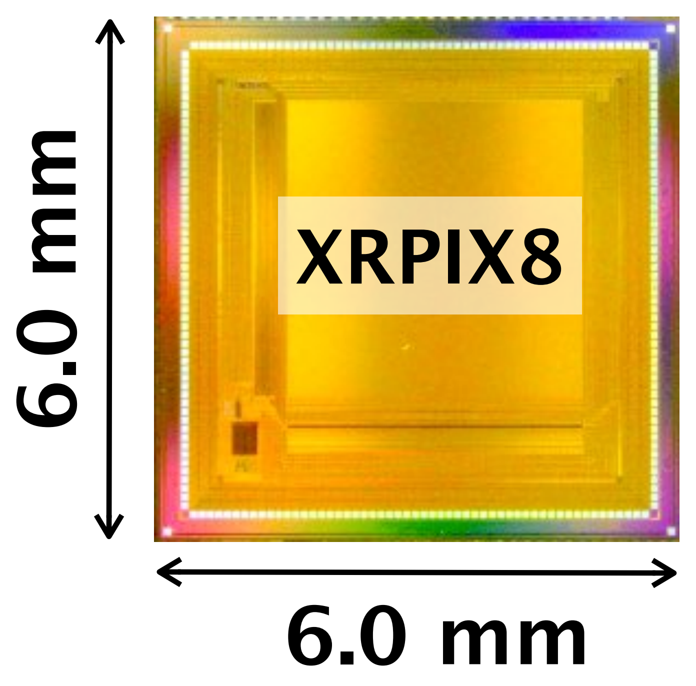
Radiation source: ^{241}Am

Back bias voltage: -300 V

Reset Period: 100 µs

Operation Mode: Event-driven





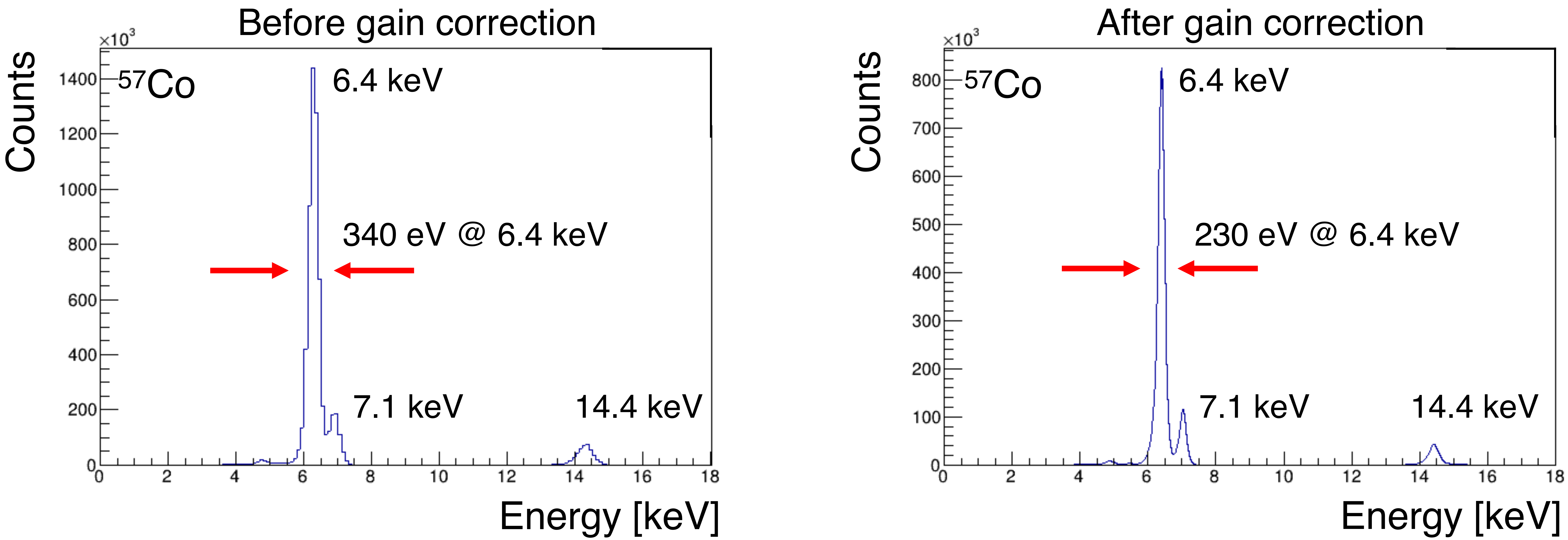
- As a result of further optimized the PDD structure, we have improved the energy resolution and charge collection efficiency.
- The change in peak position is small even across multiple pixels.
  → Pixel boundary charge loss is small !

Gain correction spectra

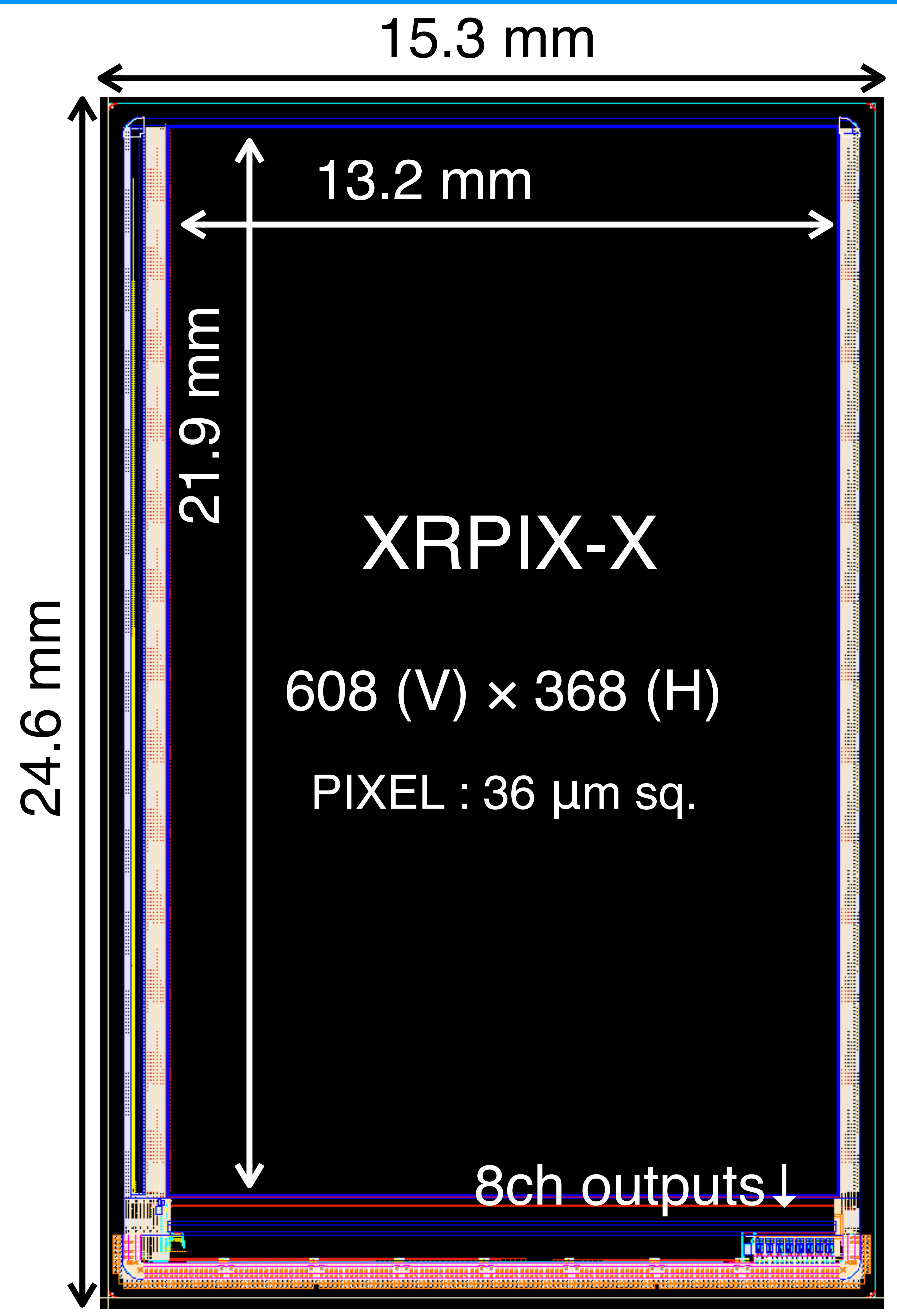
Conditions

Device: XRPIX8, **Temperature: 25 deg.,**
Radiation source: ^{57}Co, **Back bias voltage: -300V,**
Reset Period: 100 μs, **Operation Mode: Event-driven**

- Same spectral performance as at -15 deg.
- Expect to get the same spectra on large area devices at room temperature!



And then to “XRPIX-X” …



Based on the results obtained in this study, we designed a large XRPIX, named “XRPIX-X”. This chip is the culmination of our analog signal output chips.

Components

Chip size: 24.6 mm (V) × 15.3 mm (H)

# of pixels: 608 (V) × 368 (H)

Pixel size: 36 µm sq.

Other

→ Reviewing the configuration of power supply wiring to stabilize.

→ **PDD structure**

→ Analog signal 8ch output (previously 1ch)

→ **Enhanced detection particle pattern processing circuitry.**

etc…

Coming soon...

Summary

- We have been developing an event-driven SOIPIX sensor, “XRPIX” series, for future X-ray astronomical satellite mission in Japan.
- We realize the event-driven readout mode and very low non-X-ray background by the function of the trigger signal output.
- XRPIX has on-chip pattern processing circuitry to efficiently identify X-ray events and eliminate charged particle background.

  → The demonstration showed the possibility of discriminating X-ray “candidates".

  → On-chip pattern processing may also be useful in highly constrained systems such as small satellites.
- We have successfully improved the energy resolution and charge collection efficiency by introducing the PDD structure.

  → event-driven mode / 230 eV (3.6%) @ 6.4 keV (FWHM) / Temperature: 25 deg.

Collaboration

- Univ. of Miyazaki: **A. Takeda**, K. Mori, Y. Nishioka, M. Yukumoto, T. Ishida, U. Iwakiri, D. Izumi, R. Kawashima, K. Magata
- Kyoto Univ.: T. G. Tsuru, H. Uchida, M. Uenomachi, Y. Amano, K. Kayama, M. Matsuda
- Tokyo Univ. of Science: T. Kohmura, Y. Uchida, S. Tsunomachi, T. Doi, Y. Takesue, M. Shimizu
- Konan Univ.: T. Tanaka, H. Suzuki
- Kanto Gakuin Univ.: K. Hagino
- The Univ. of Tokyo: K. Shimazoe, H. Takahashi
- KEK: Y. Arai
- D&S Inc.: I. Kurachi