Kyoto's Event-Driven X-ray Astronomical SOI Pixel Sensor

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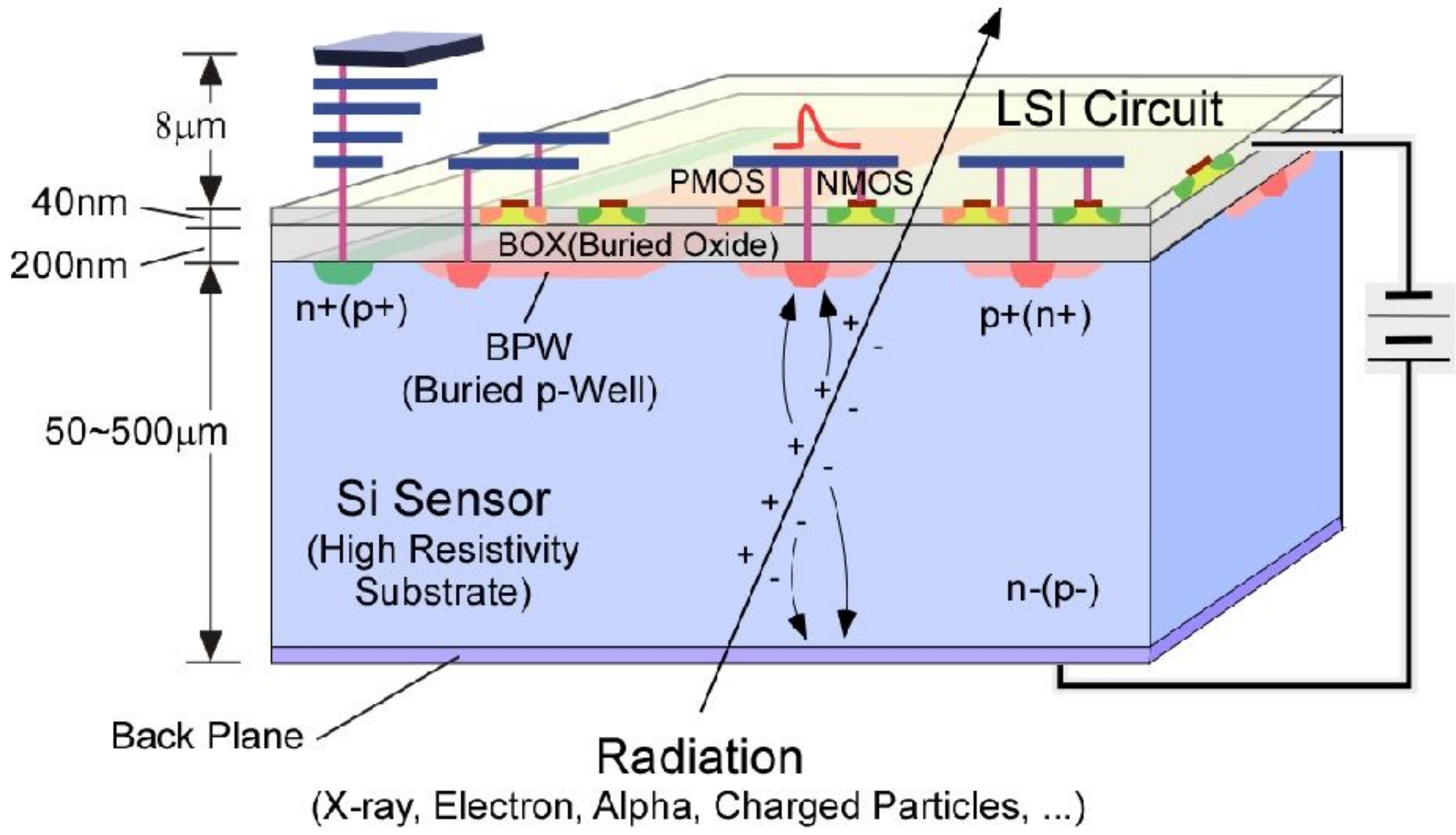
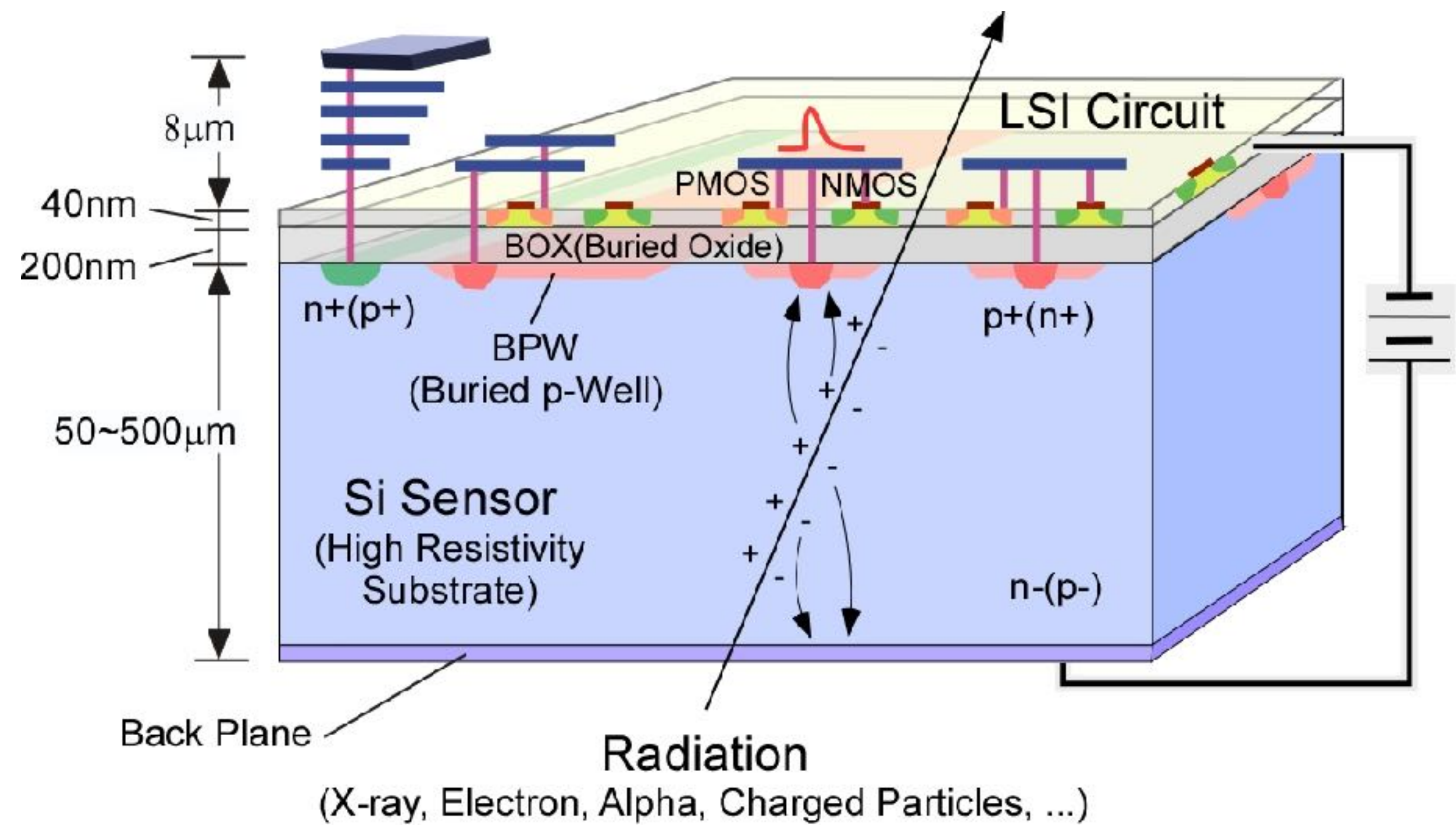
We are developing Silicon-On-Insulator Pixel (SOIPIX) Detectors



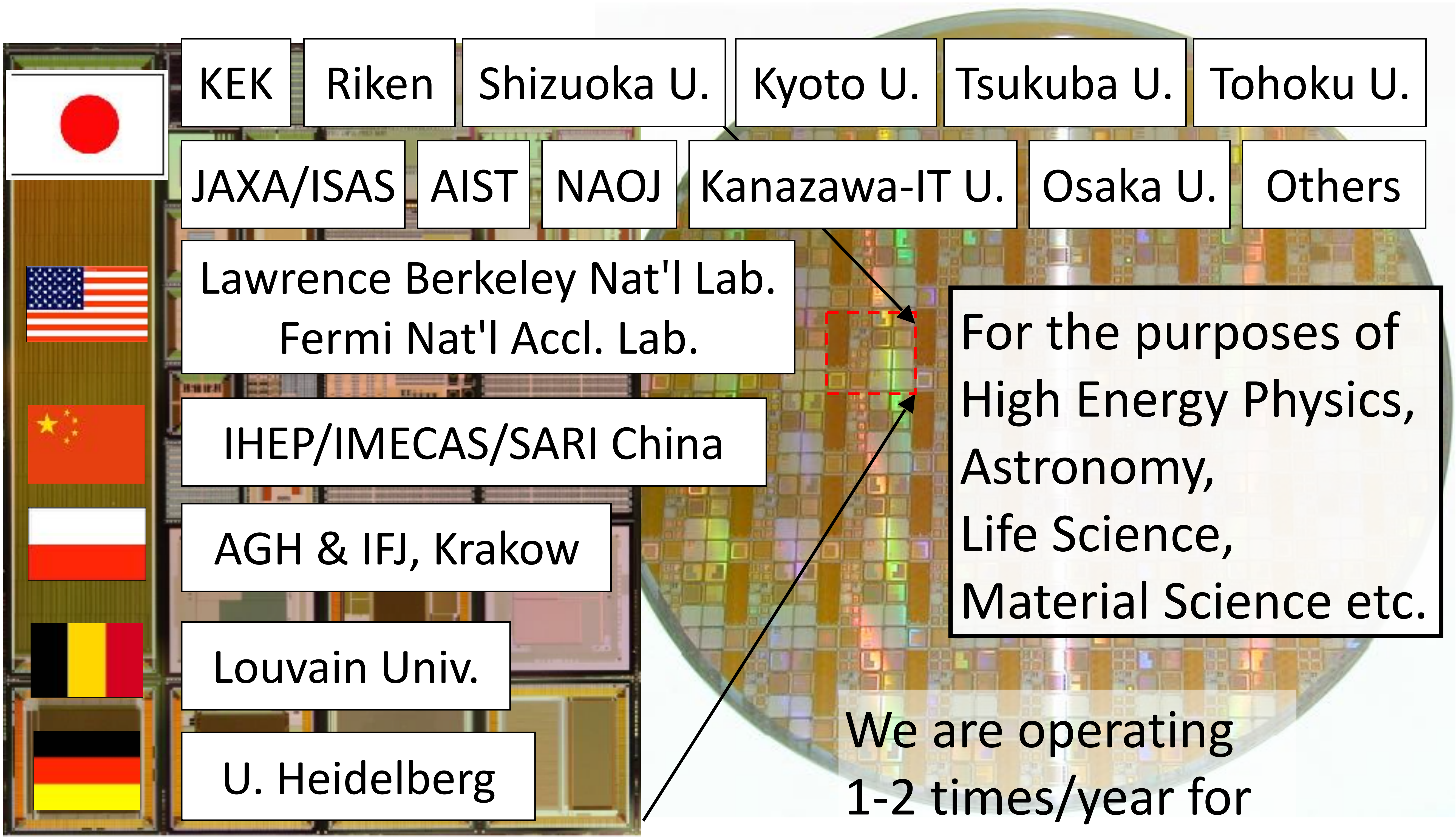
Features of SOI Pixel Detector



- Monolithic device. No mechanical bonding. Small pixel size.
- Fabricated with semiconductor process only and based on Industry Standard Technology. → High reliability and Low Cost.
- High Resistive fully depleted sensor (50um~700um thick) with Low sense node capacitance. → High S/N.
- In-pixel processing with CMOS circuits.
- No Latch up and very low Single Event cross section.
- Can be operated in wide temperature range (1K-570K).

SOIPIX MPW (Multi-Project Wafer) run

Lapis Semiconductor 0.2 μm FD-SOI Pixel Process



For the purposes of High Energy Physics, Astronomy, Life Science, Material Science etc.

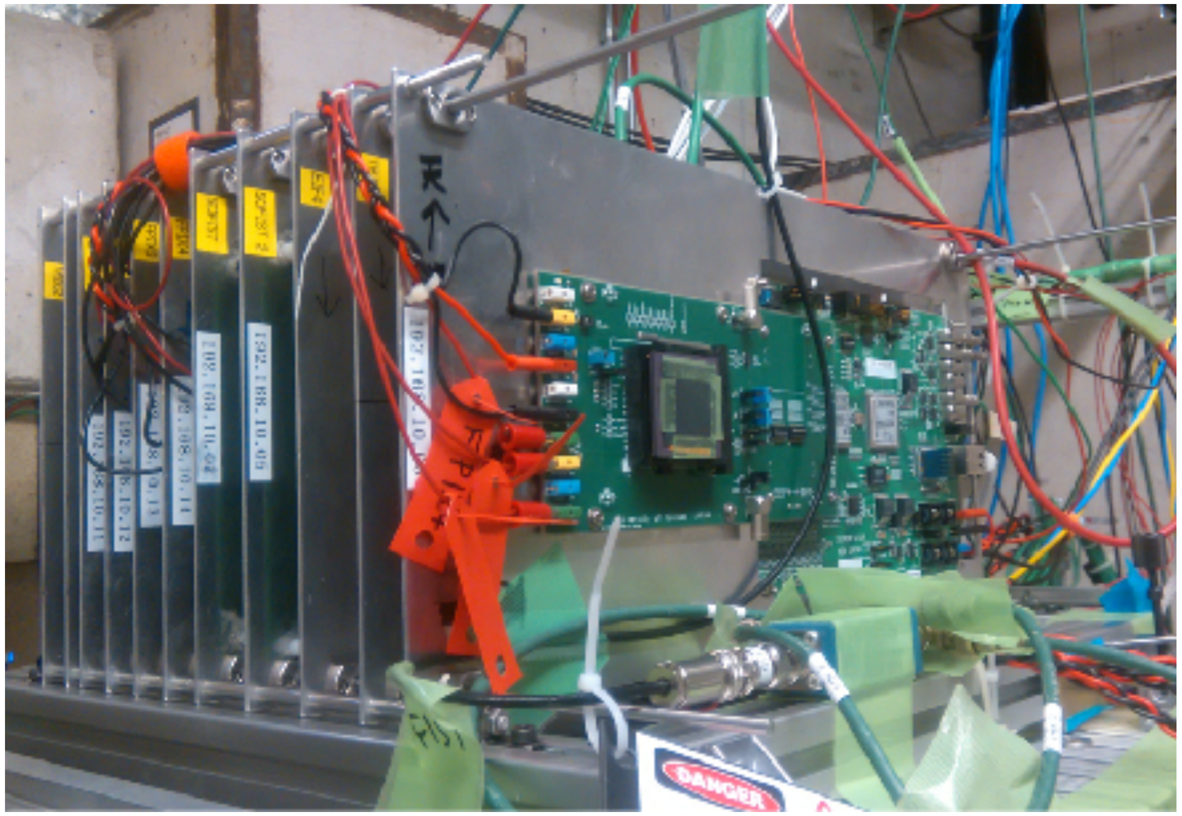
We are operating 1-2 times/year for academic users.

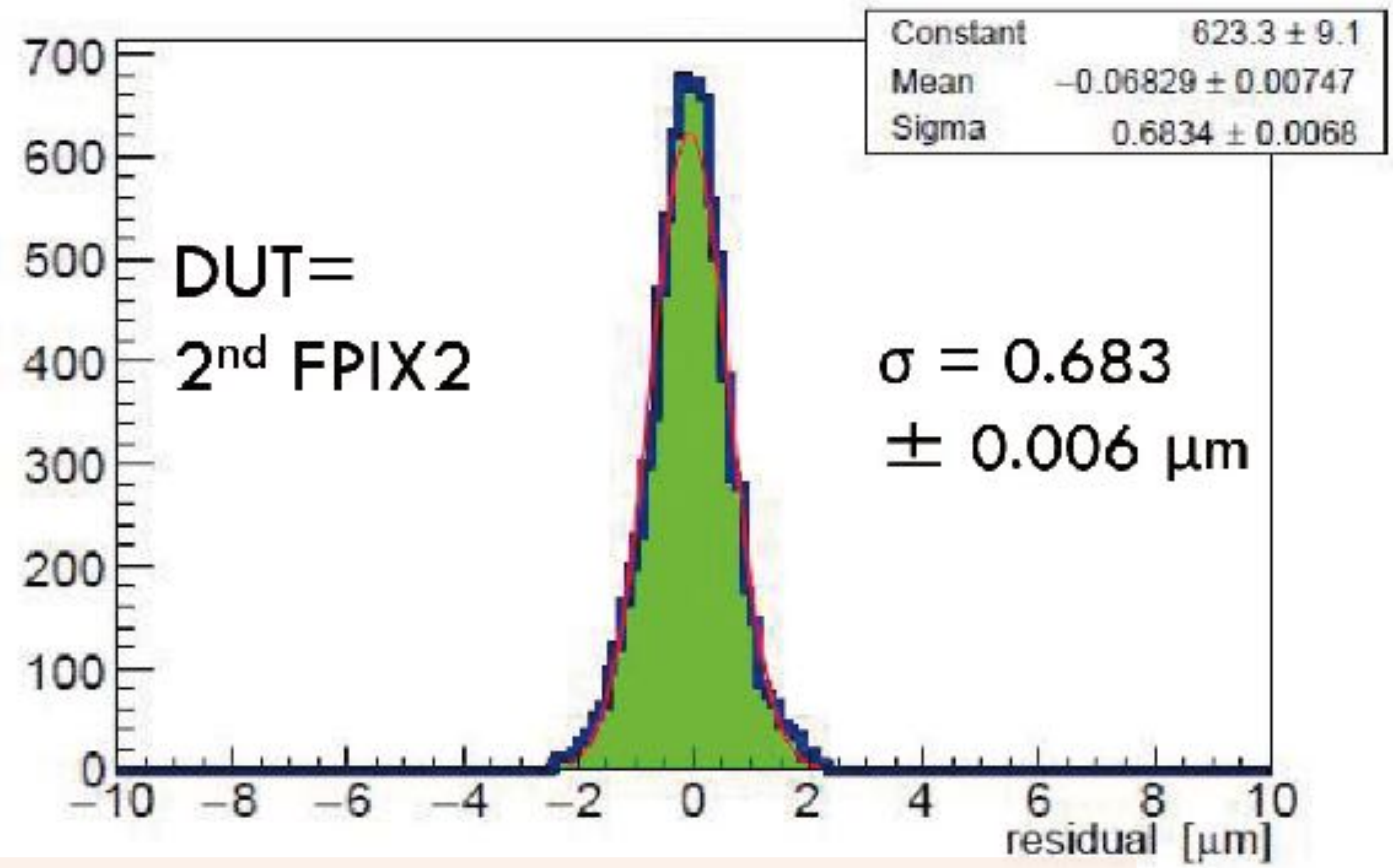
Mask Size 24.6 x 30.8 mm

Tracking Resolution of FPIX2
Proton Beam (120 GeV/c) test @FNAL

Two kinds of SOIPIX-DSOI detectors are used:

- FPIX2 x 4 8 μm square pixel detector
- SOFIST1 x 2 20 μm square pixel detector

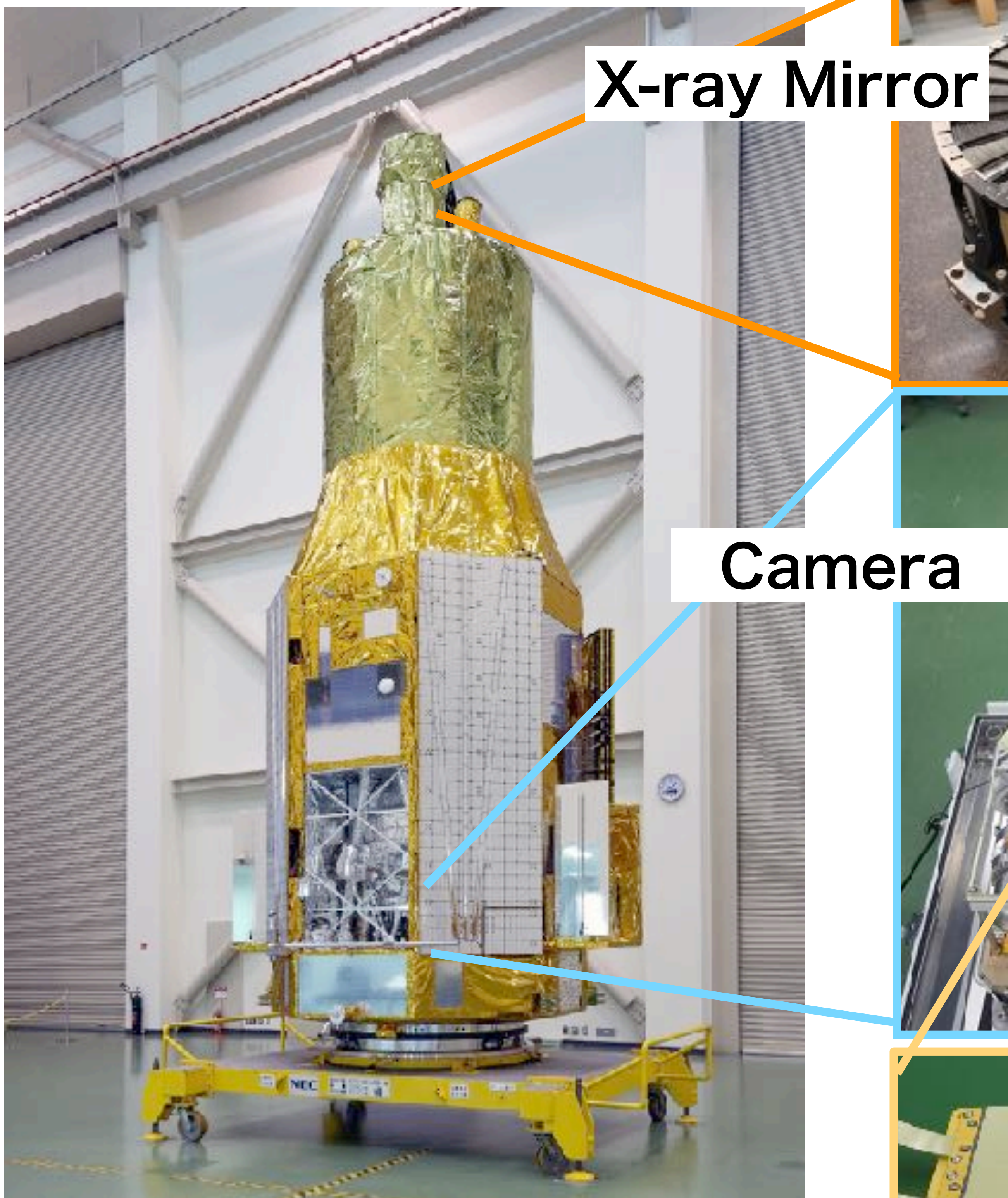


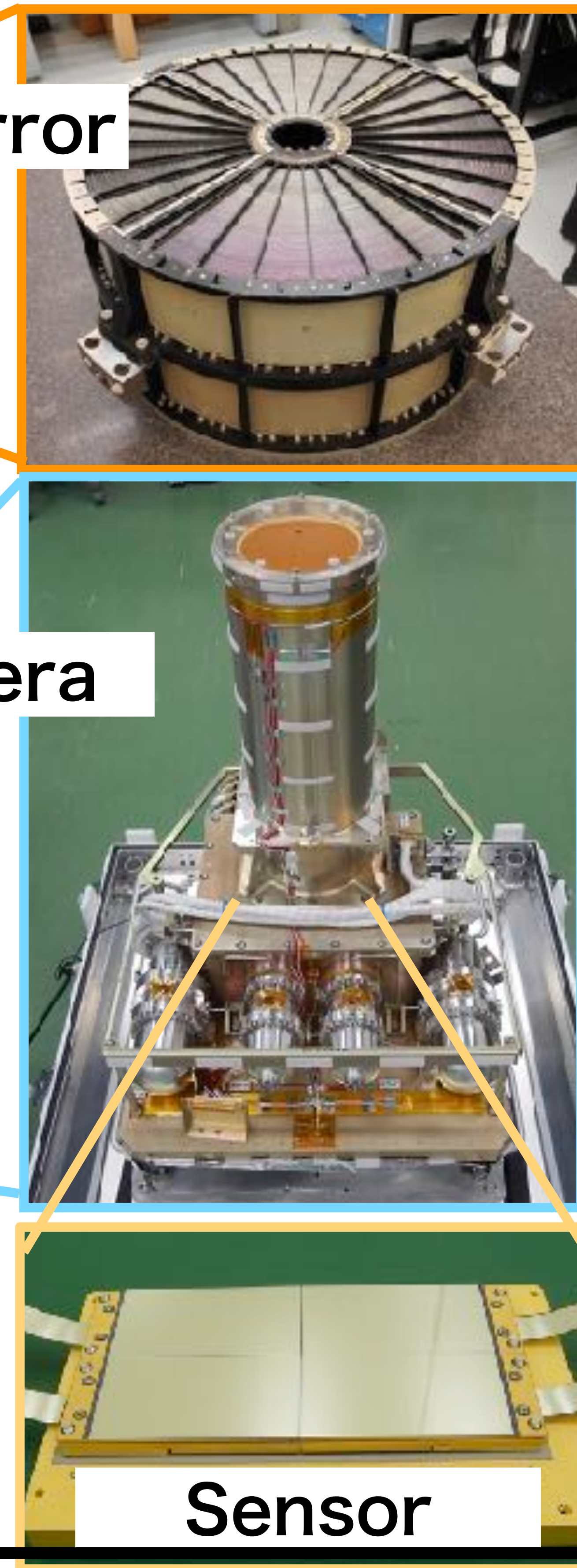


Achieved Less than 1 μm Position Resolution for high-energy charged particle first in the world .

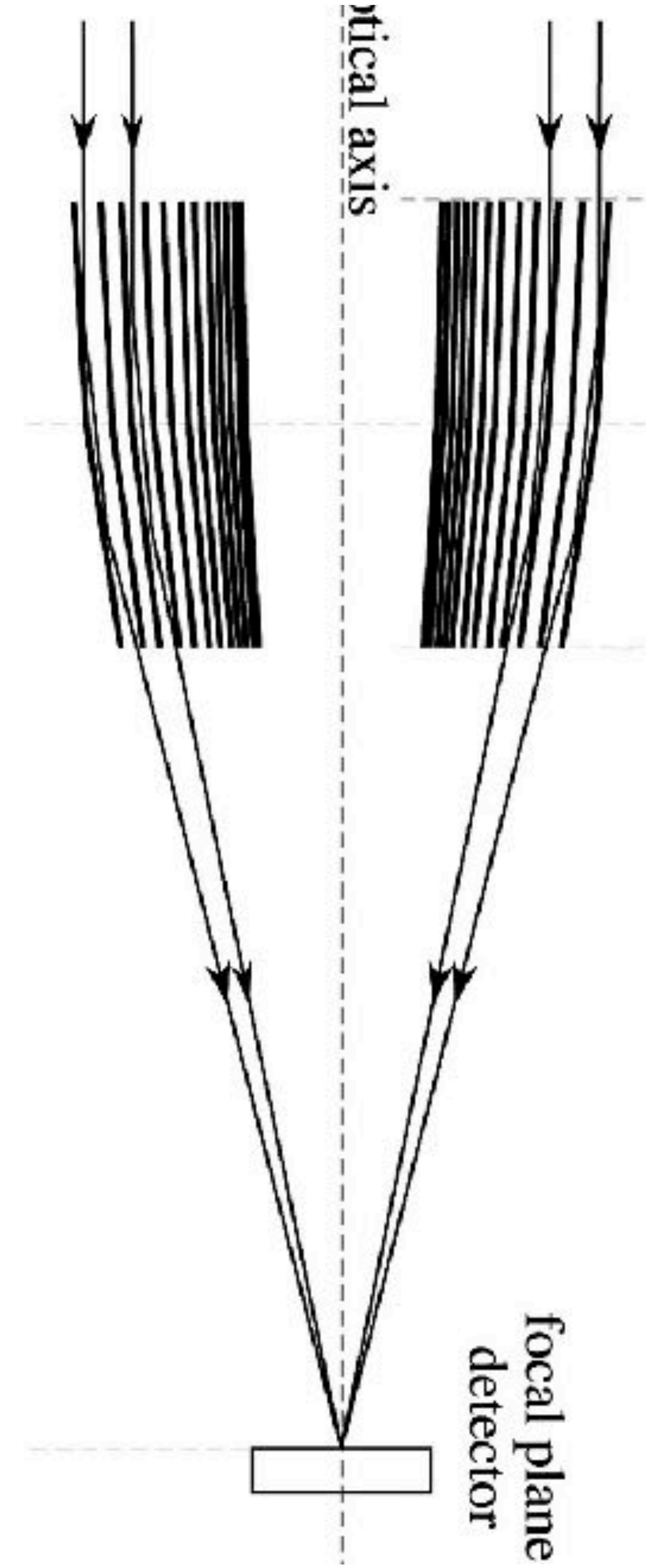
(K. Hara et al., Development of Silicon-on-Insulator Pixel Detectors, Proceedings of Science, to be published)

X-ray Imaging System



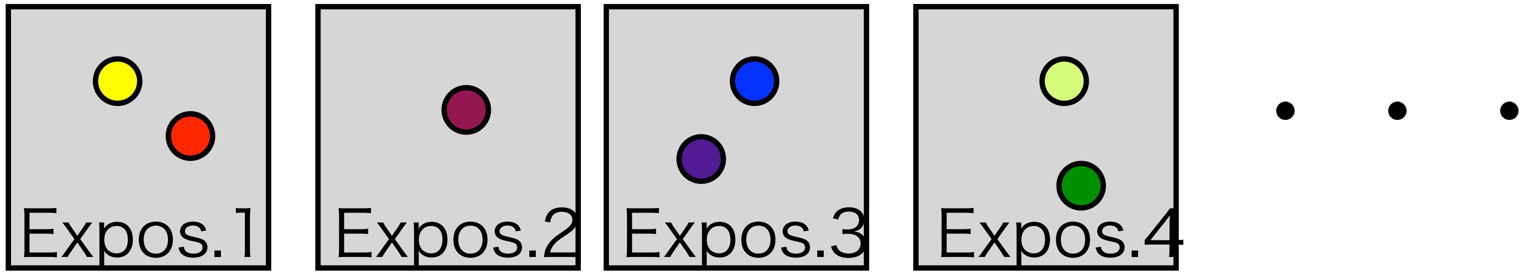


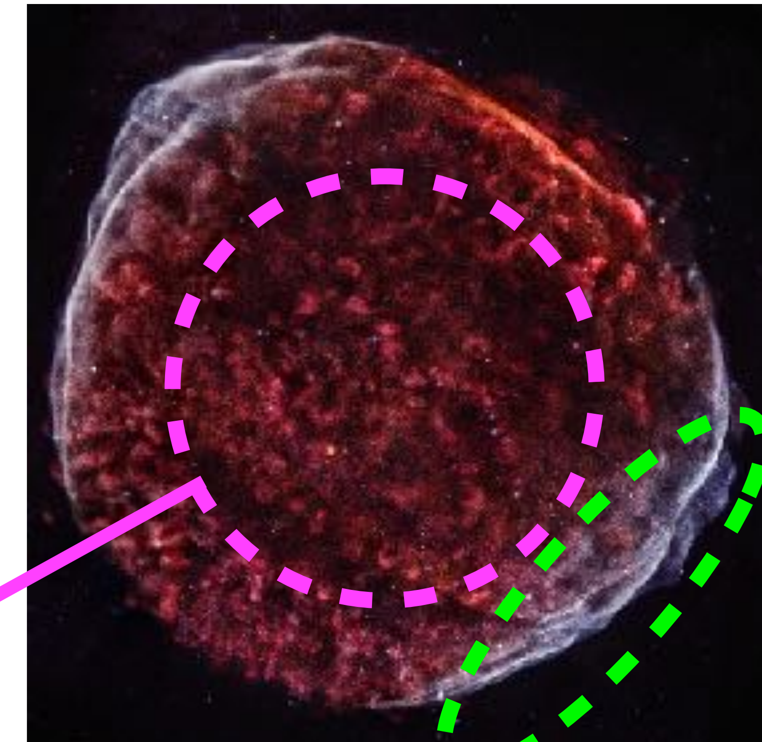
http://astro-h.isas.jaxa.jp/diary/1329/
https://user.spring8.or.jp/sp8info/?p=2925



X-ray CCDs as Standard Imaging Spectrometers at 0.3–10keV.

X-ray Photon Counting

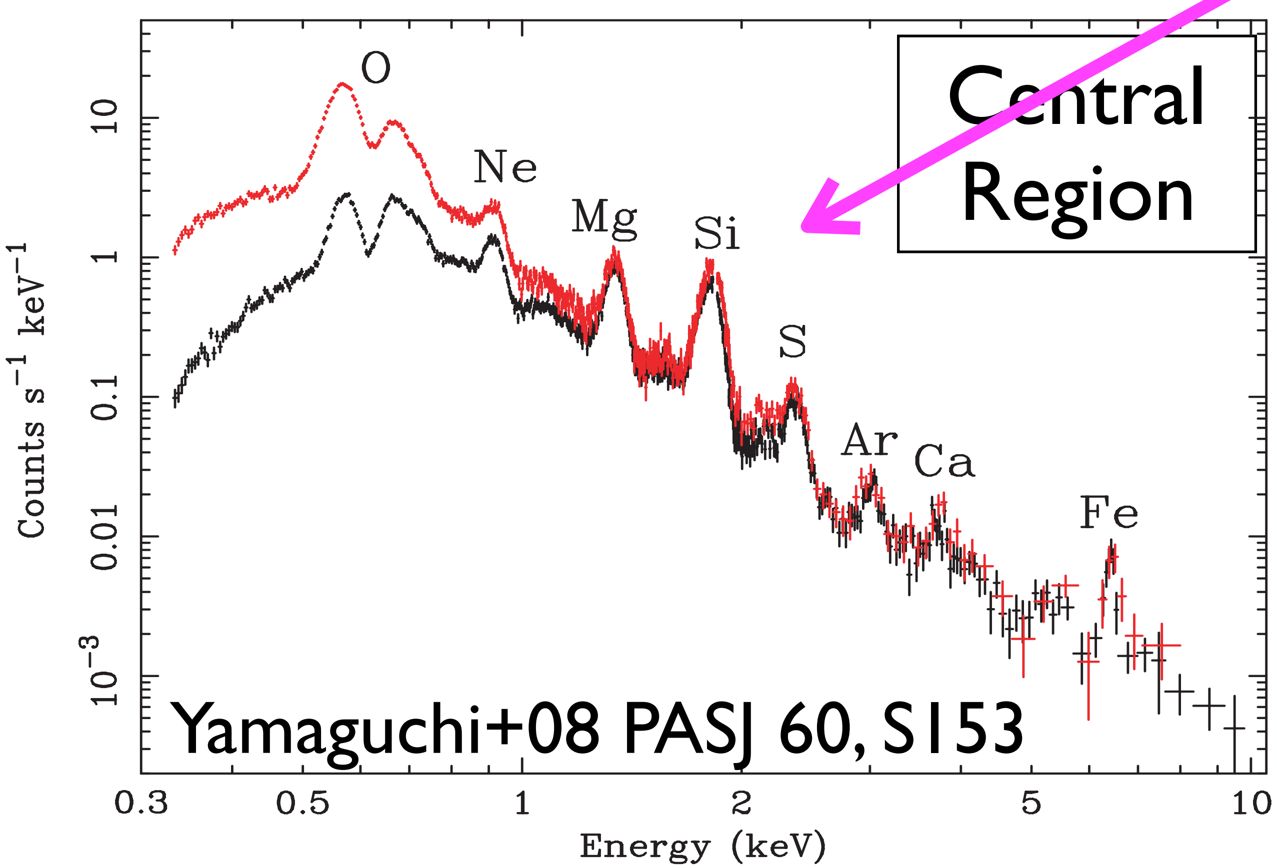


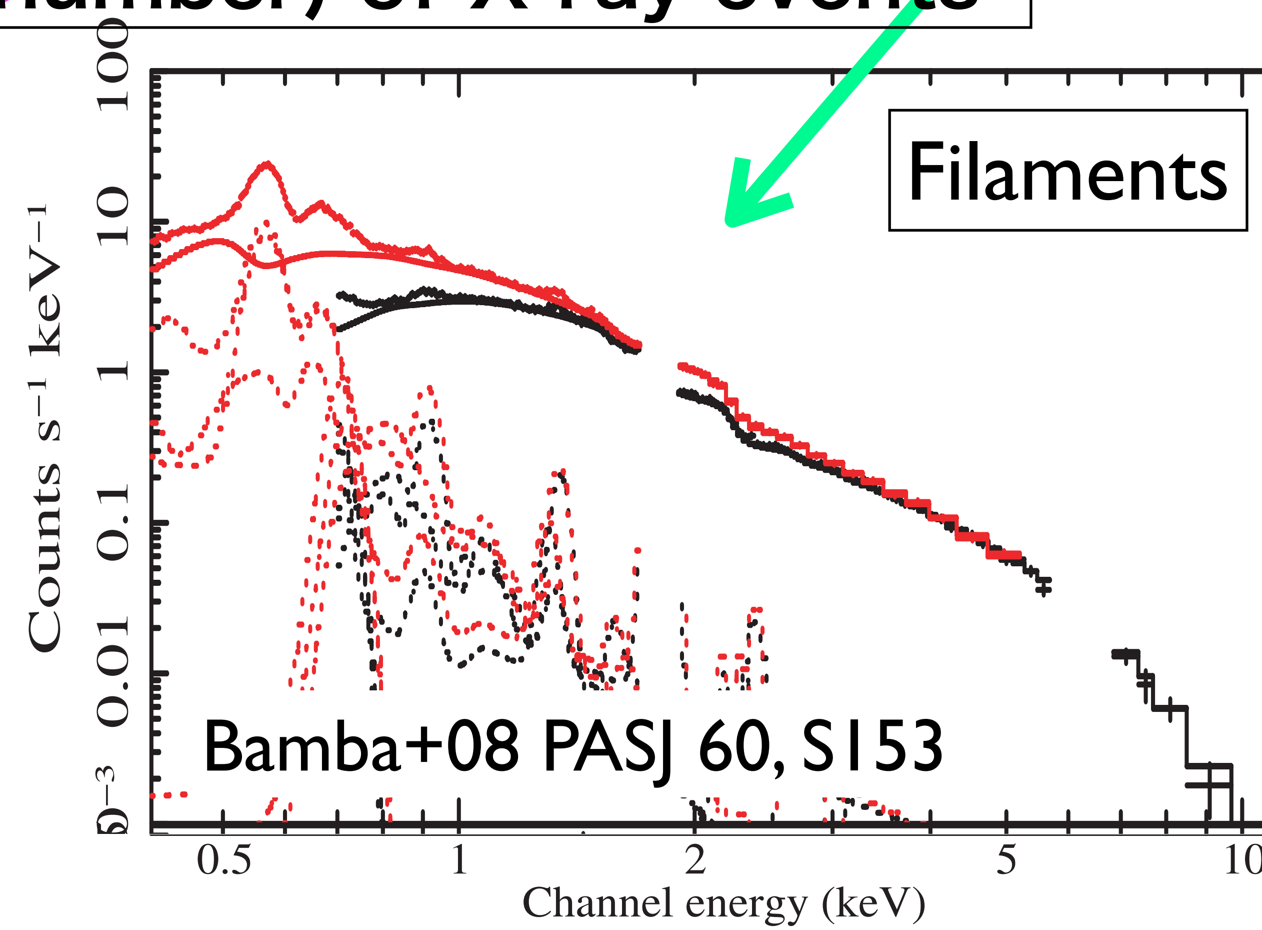


- Detect an X-ray photon as one-by-one event.
- Measure position, energy and time of each X-ray event.
- Make exposures of ~10^4 times.

Map of the number of X-ray events

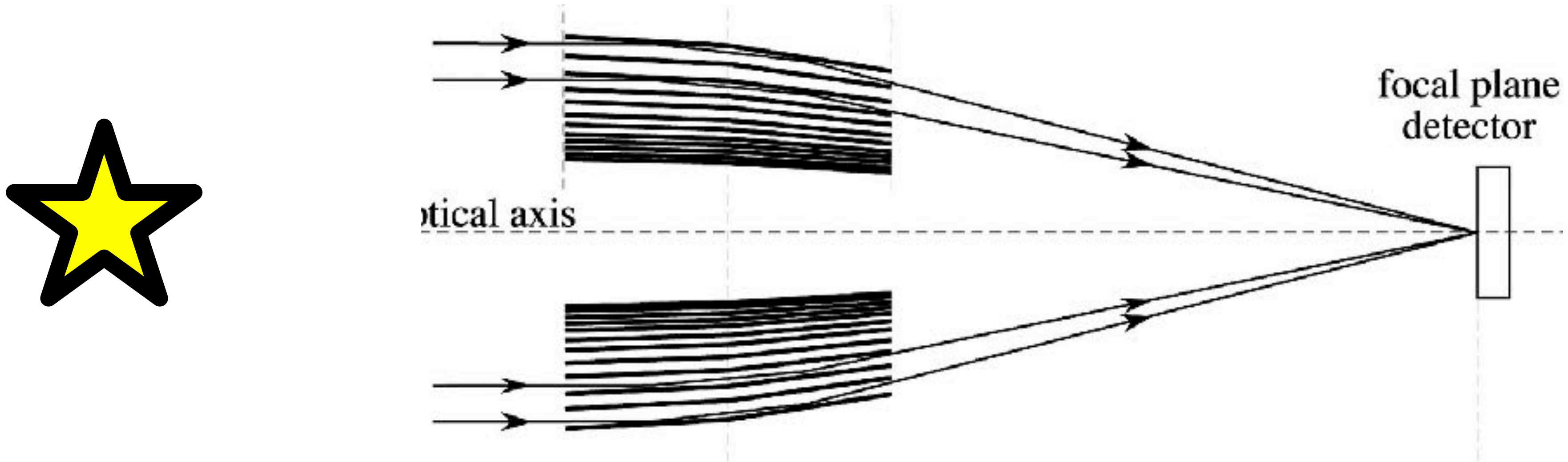
Histogram of energy (electron number) of X-ray events





Limitation due to low time resolution of CCD (~1sec)

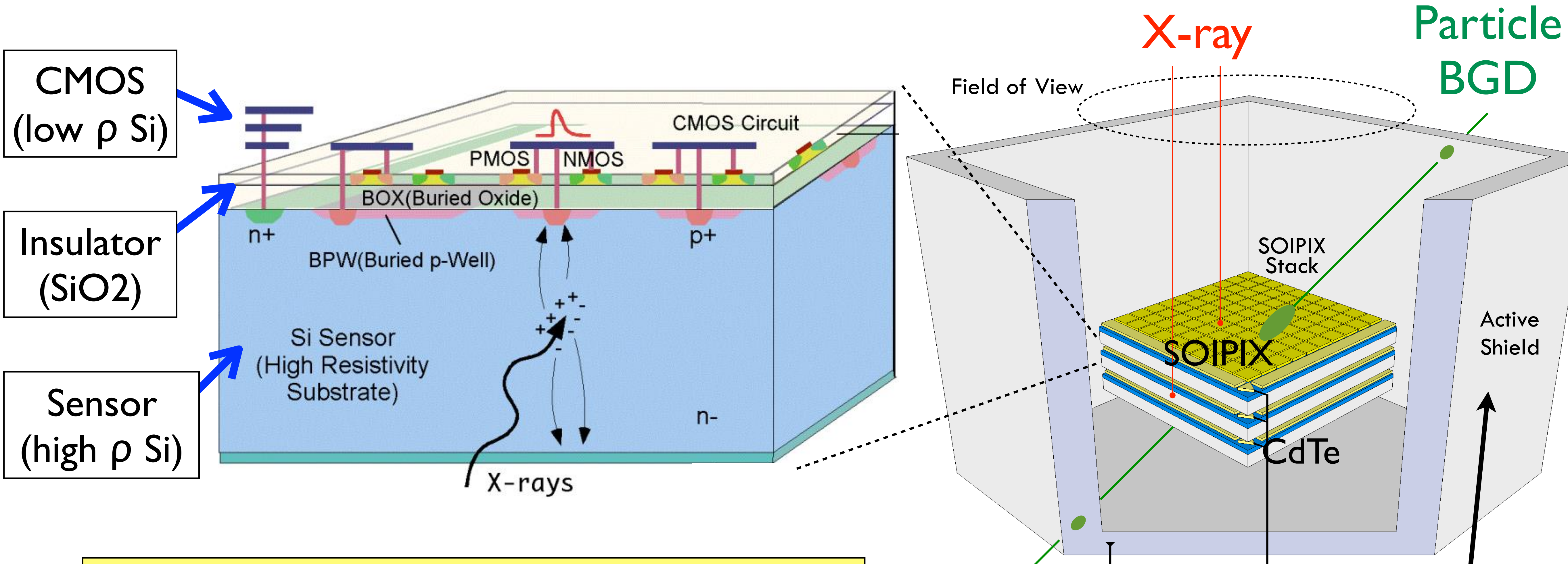
- Unable to make good use of the performance of large collecting area and high angular resolution of the latest mirrors.
  - Event pileup occurs. Photon counting is impossible.



- Unable to resolve fast variability of compact objects such as blackholes and neutron stars.
- Unable to apply anti-coincidence technique
  - Unable to make use of the excellent performance of Si in the band above 10keV due to the high particle background

High Frame Rate and High Time Resolution are Key Issues for Next Generation of X-ray Astronomical Imagers

"XRPIX" = SOI pixel sensor for X-ray Astronomy



Each pixel has its own trigger logic and analogue readout CMOS circuit.

Anti-coincidence Shield by Scintillators Rate ~10kHz

- realize very low non-Xray BGD by anti-coincidence with surrounding scintillators
- event rate from the scintillators is about ~10kHz
- XRPIX is required to have time resolution much faster than ~10kHz.

Target Specification of the Device

same performance as CCD

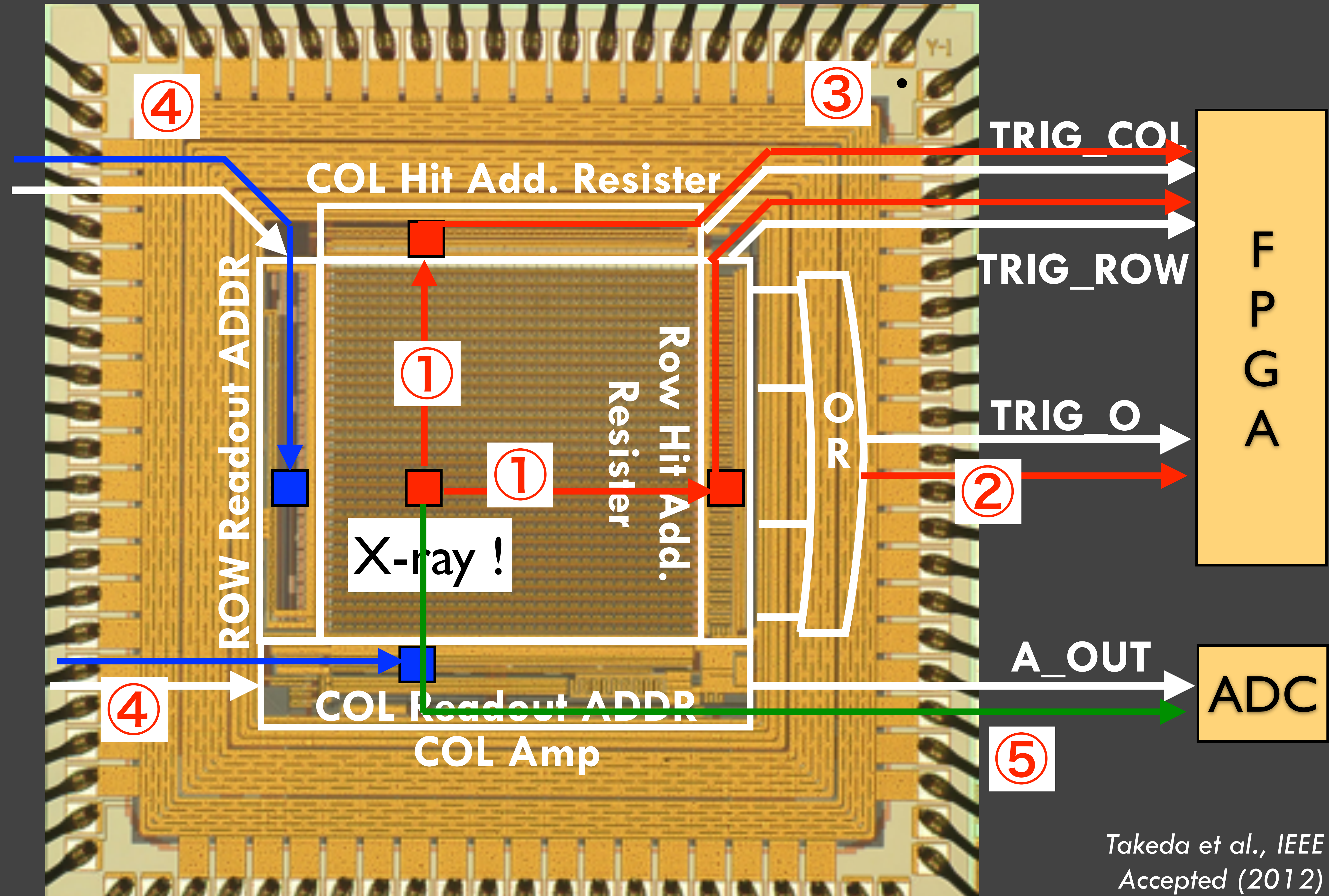
Imaging	area ~ 15x45mm^2 pixel ~ 30-60μm□ (1" @ F=10m)
Energy Band	Req. 1-40 keV, Goal 0.5-40 keV Backside Illumination Req. <1μm, Goal 0.1μm Full Depletion Req. >250μm
Spectroscopy	ΔE : Req. < 300eV, Goal < 140eV @ 6keV ENC: Req. <10e-, Goal < 3e- ← **Most Difficult**
Time Resolution	< 10μsec for the anti-coincidence with the rate of ~10kHz
Max Count Rate	> 2kHz / detector for observation of bright X-ray sources

new features with X-ray SOIPIX

Power Consumption in FEE

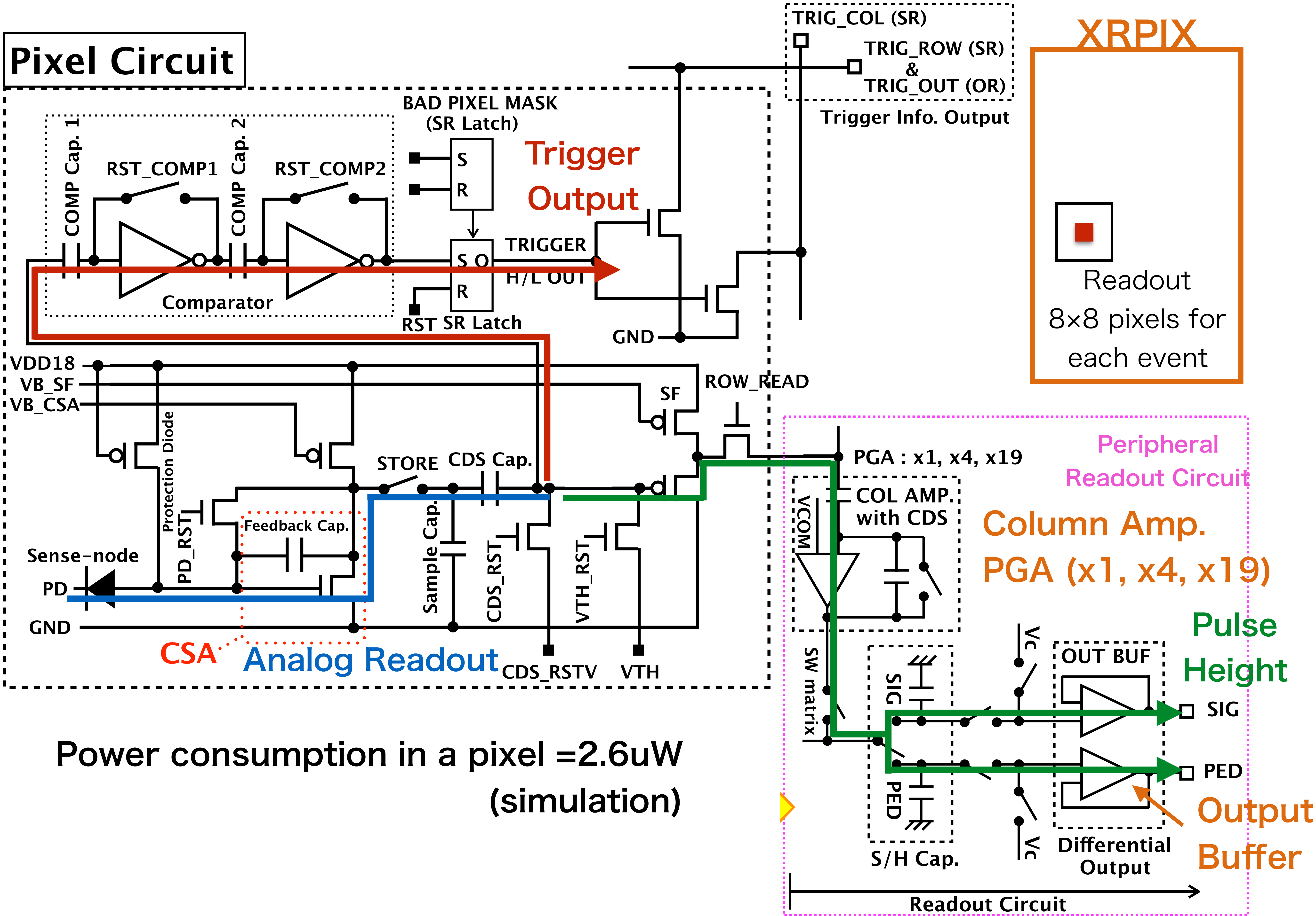
- Counting rate is ~ kHz even in the case of the brightest X-ray star.
- In the case of CCD
  - The pixel rate of CCD is ~MHz (~Mpixel / sec).
  - Most of the pixels have no X-ray information.
  - The power consumption in FEE is proportional to the pixel rate of ~MHz.
- In the case of the Event Driven type
  - Only pixels having X-ray information are read out.
  - The power consumption in FEE is proportional to the counting rate of ~kHz.
- The Event Driven type of detector has advantages in terms of power consumption in FEE.

Event Driven Readout



Takeda et al., IEEE Accepted (2012)

Pixel and Perophéral Circuits (since XRPIX5)



Power consumption in a pixel =2.6uW
(simulation)

Results from the recent developments

Two Readout Modes:

- Frame Readout Mode
  Read out all pixels serially without using the trigger function.
- Event Driven Readout Mode
  Read out 8x8 pixels with a triggered pixel in the center using the trigger function.

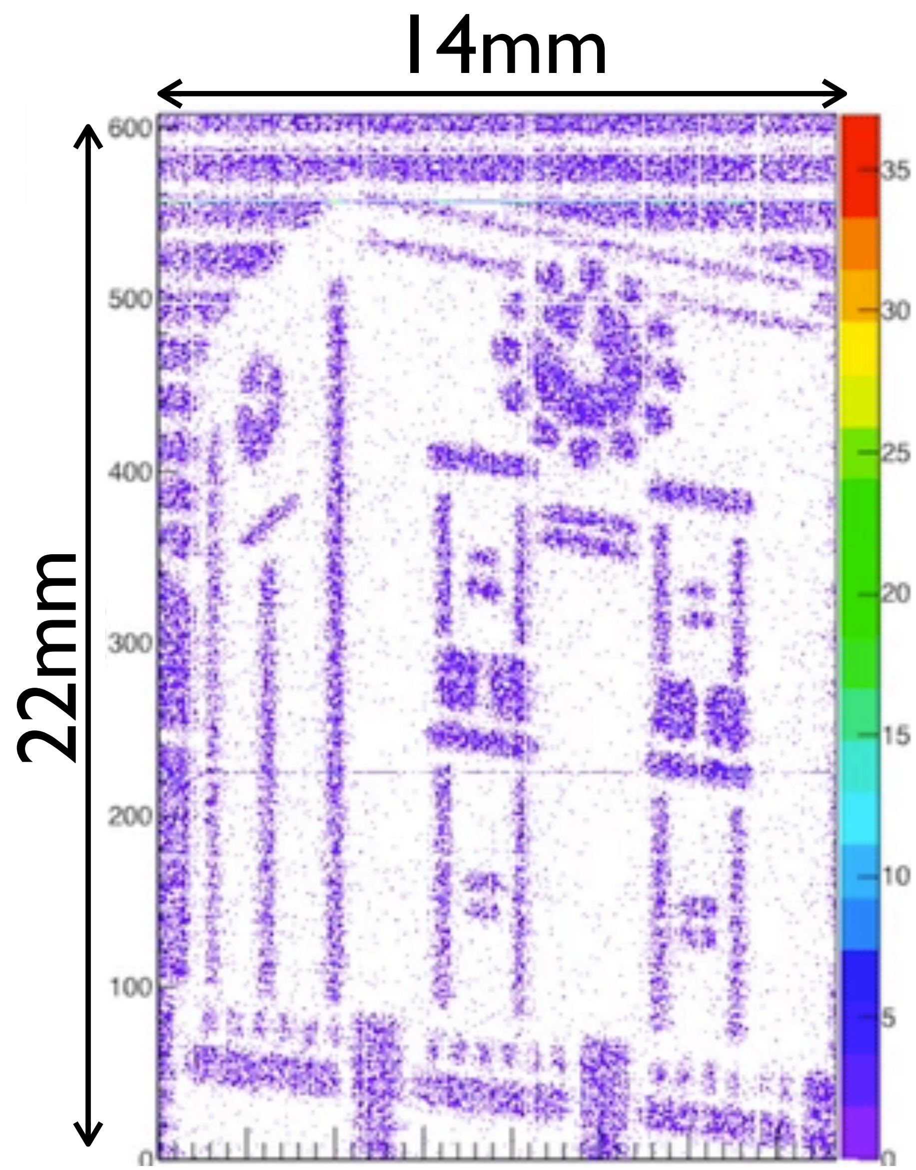
Imaging in Event-Driven Mode (XRPIX5b)

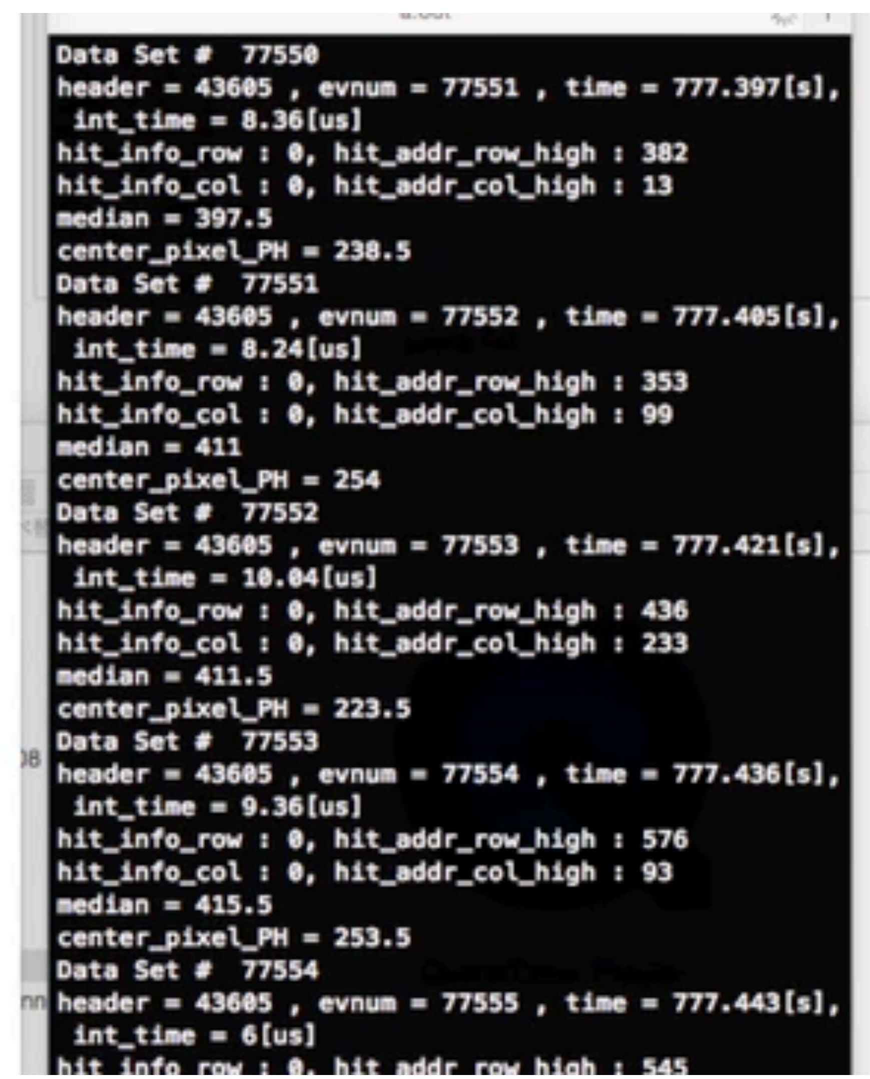
透かし彫り栞/金

SIZE:W35×H85mm

◆純金表面加工◆時計台を透かし彫りにした実用性の高いアイテムです。 **860** 円

https://www.u-coop.net/kyodai/goods/indicate.php?mode=detail&id=27&category=6

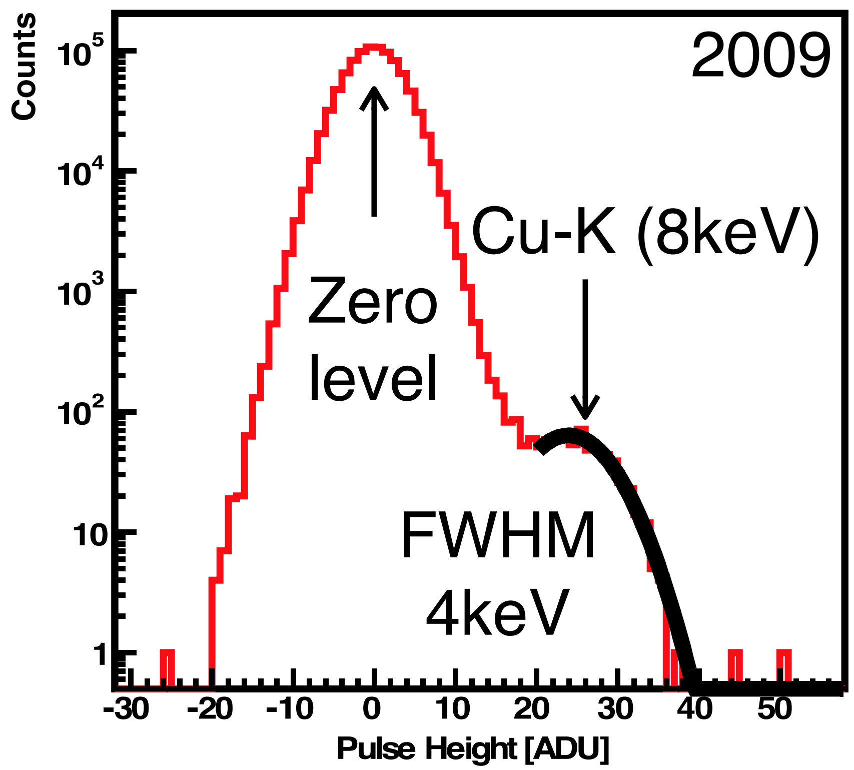




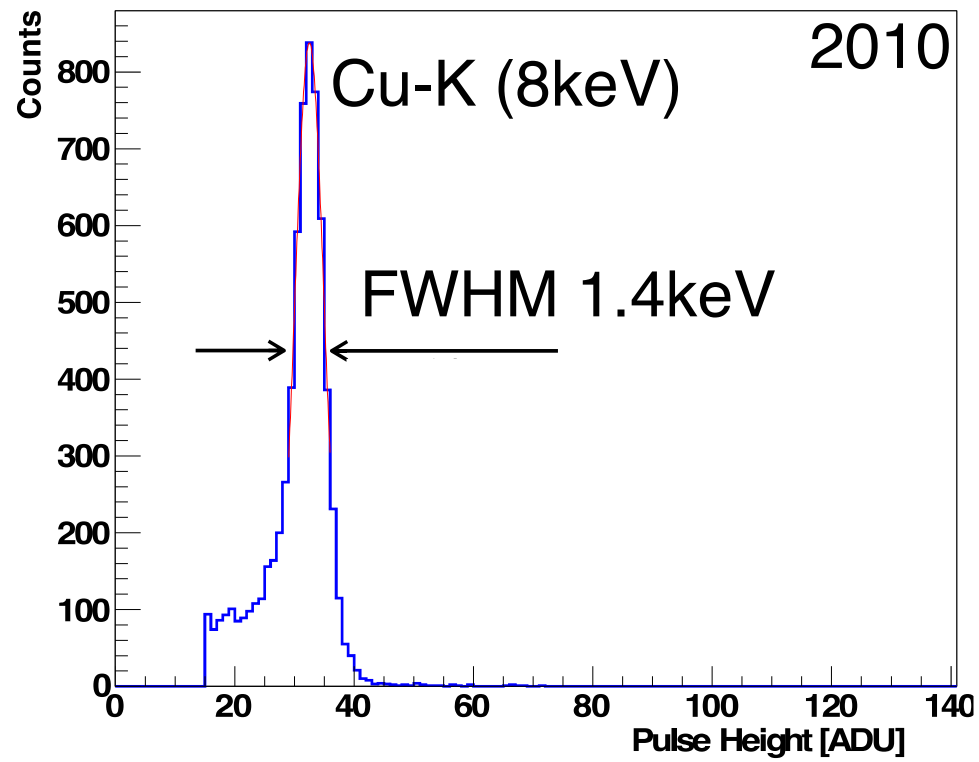
Cd-109, Vbb=10V, Room Temp. (movie in10 times speed)

Capability of event rate > 500Hz is Confirmed

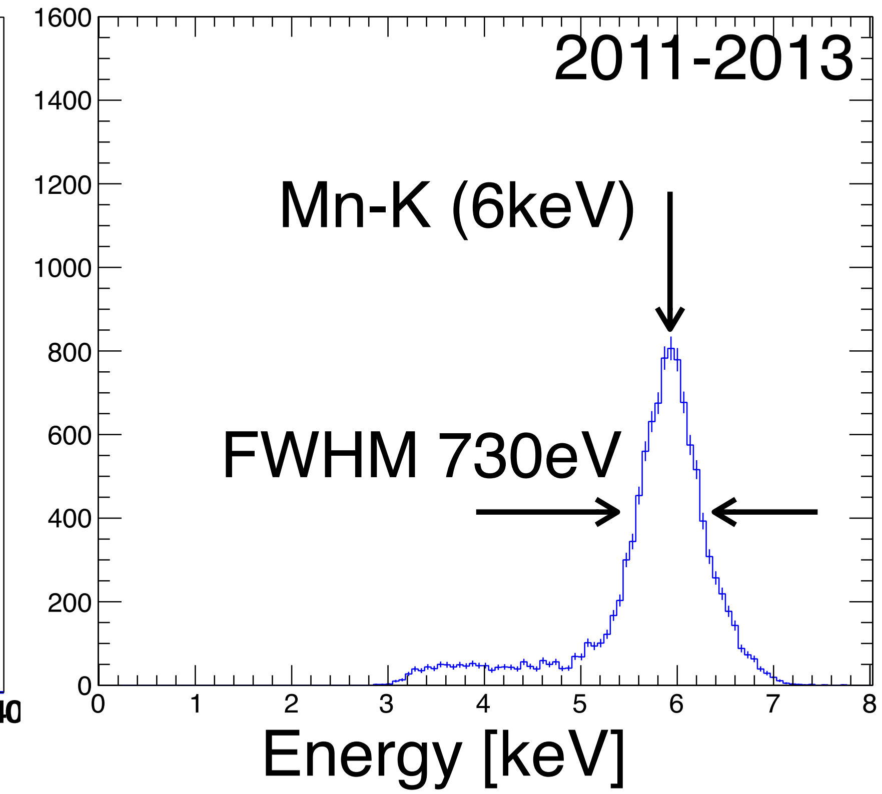
Improvement of Spectral Performance in Frame Mode



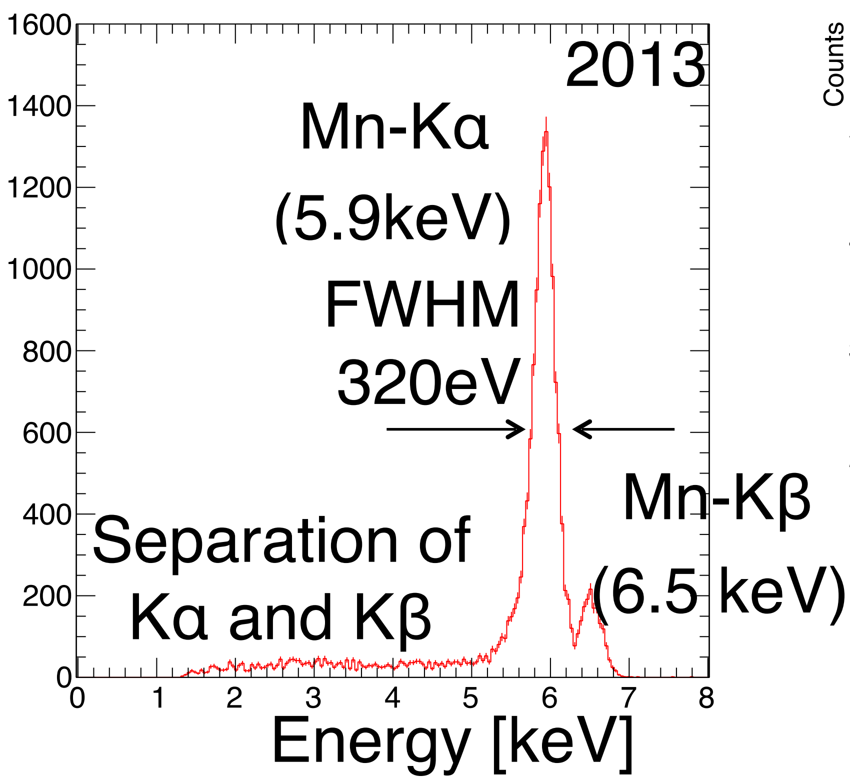
ENC ~600e (rms)



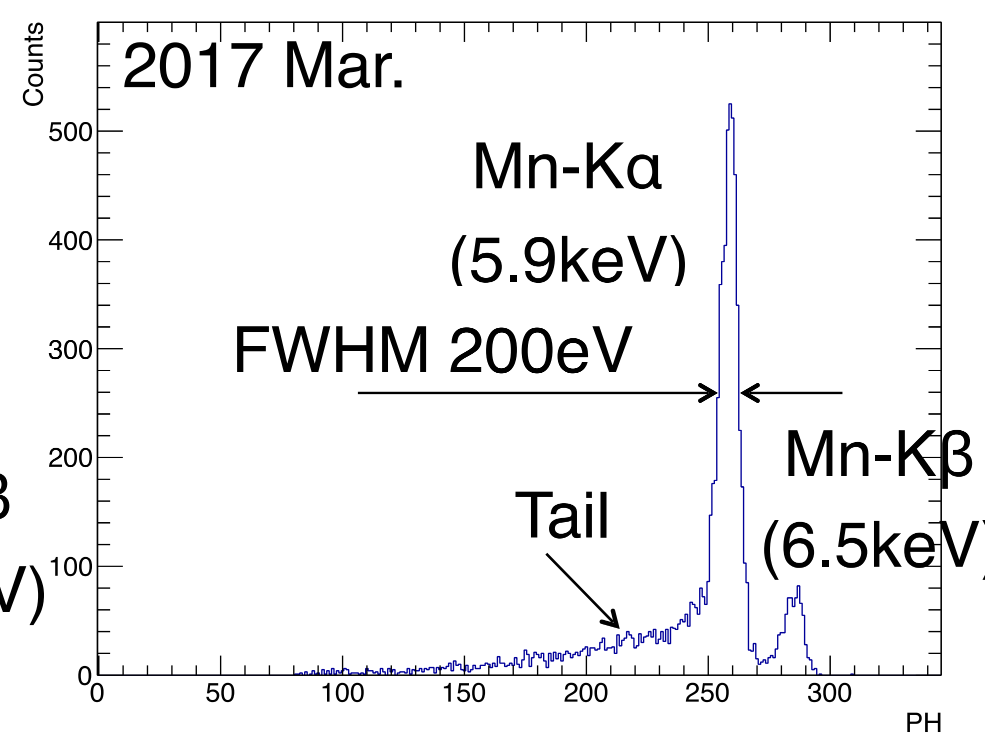
ENC ~130e (rms)



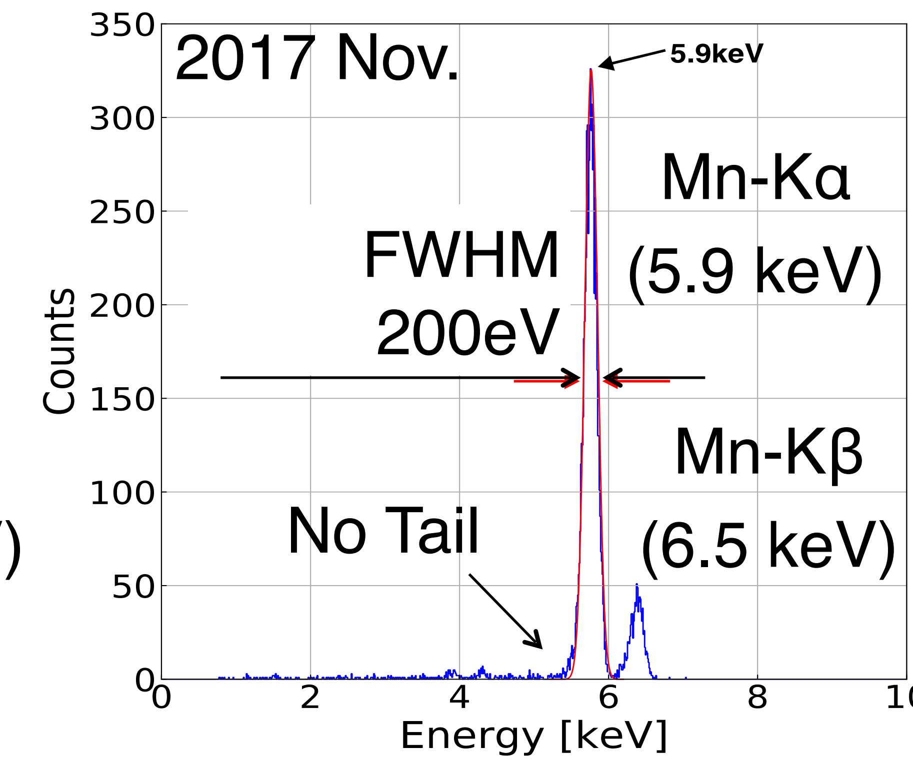
ENC ~68e (rms)



ENC ~35e (rms)



ENC ~16e (rms)

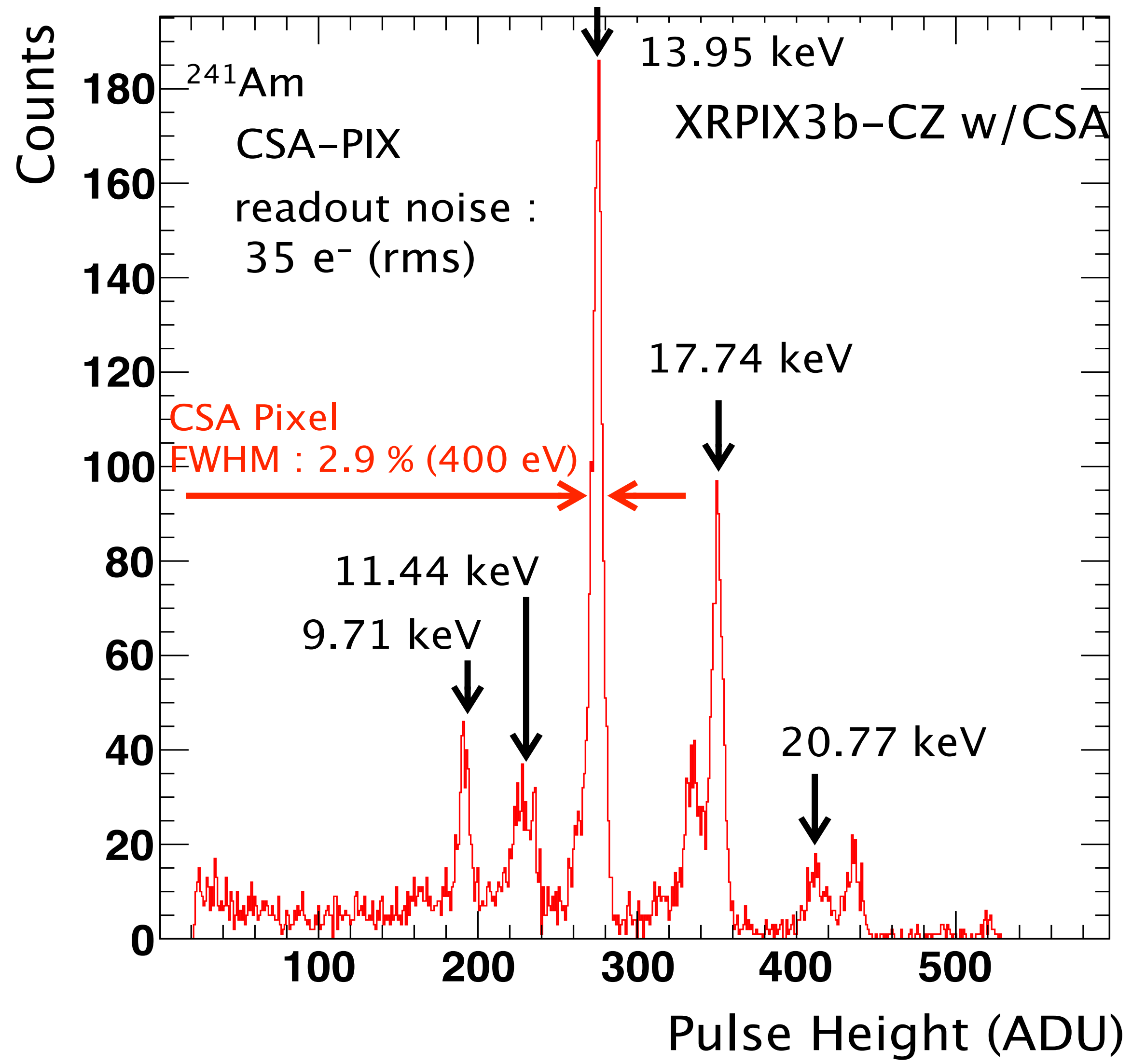


ENC ~10e (rms)

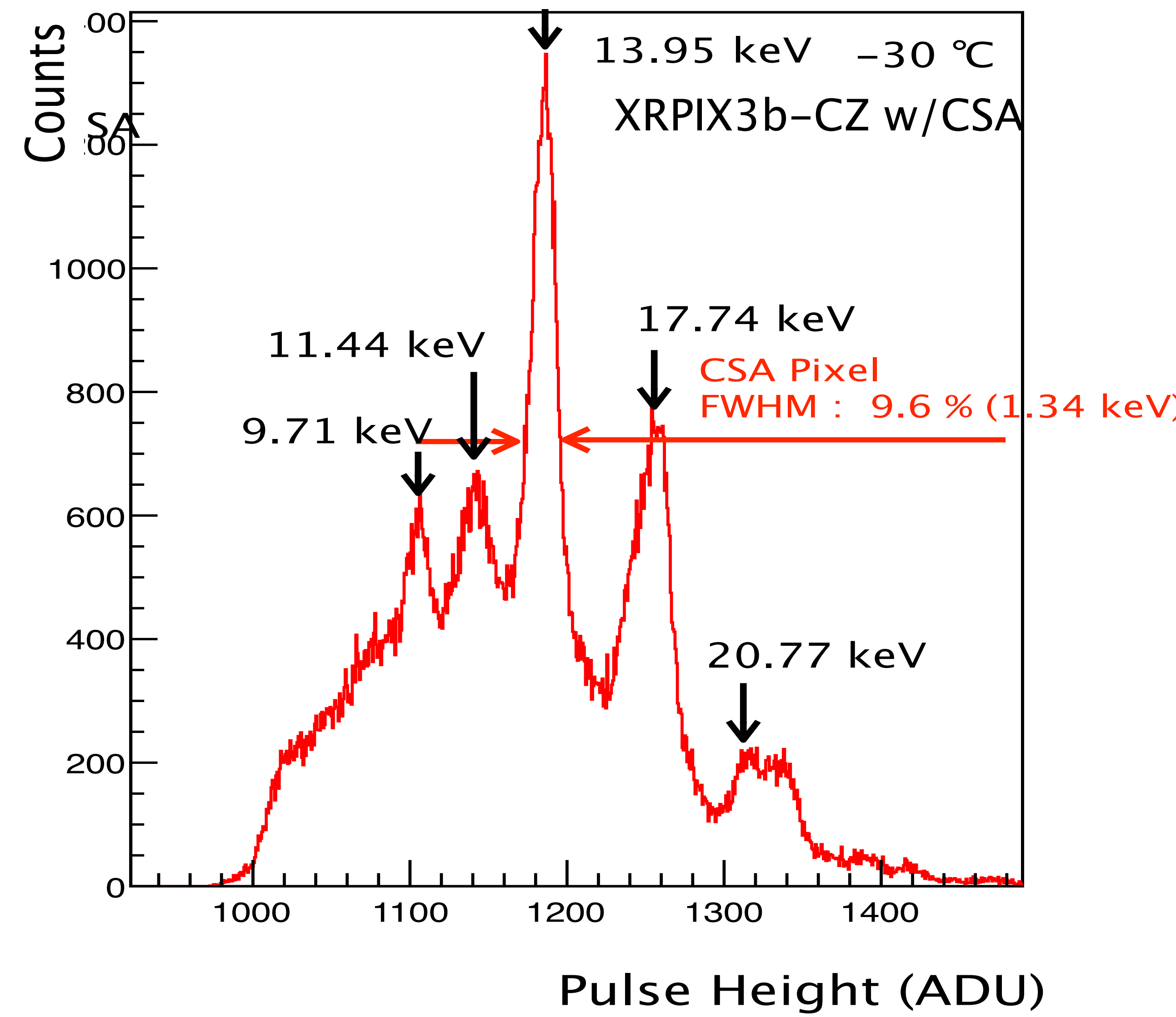
Kamehama, Kawahito+17

Comparison of Frame and Event-Driven Modes

Frame readout mode



Event-Driven readout mode



- in-pixel circuit consists of analog and digital circuits
- operation of digital circuit influences the analog signal in the event-driven readout mode

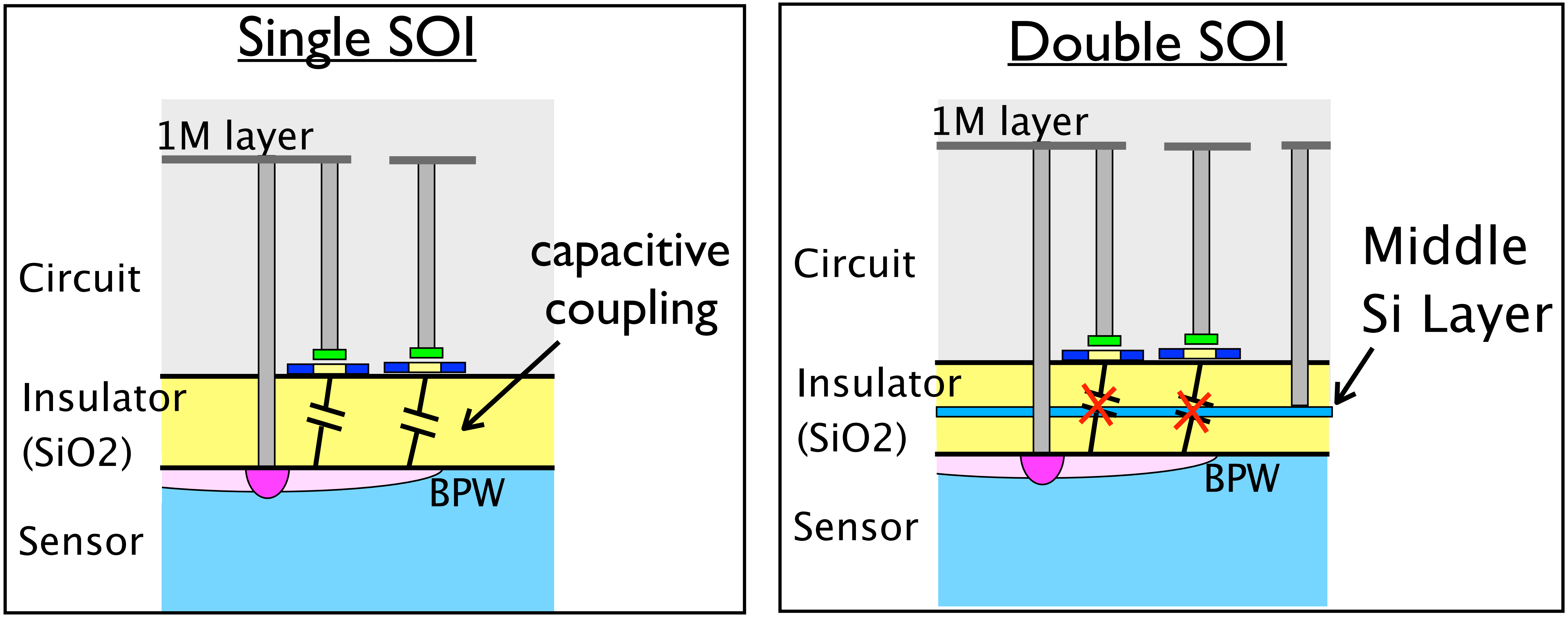
Takeda+2015 JINST, Takeda+2013 IEEE/NSS, Takeda Ph.D Thesis, 20140814_takeda_v0.pdf

Double SOI Structure

Two causes making the spectral performance worse in the Event Driven mode

1) analog and digital circuits have a common power supply line (common impedance coupling) ⇒ modified the power lines

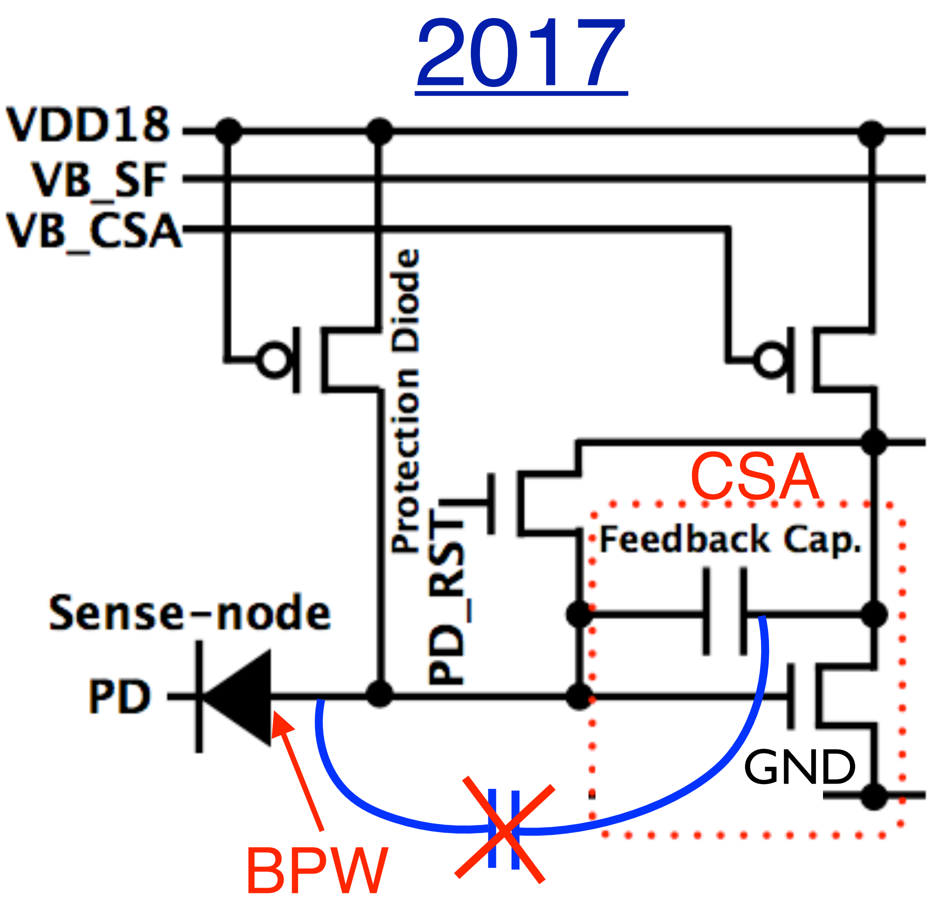
2) crosstalk between digital circuit and BPW (electrically connecting to the sense-node) ⇒ "Double SOI"

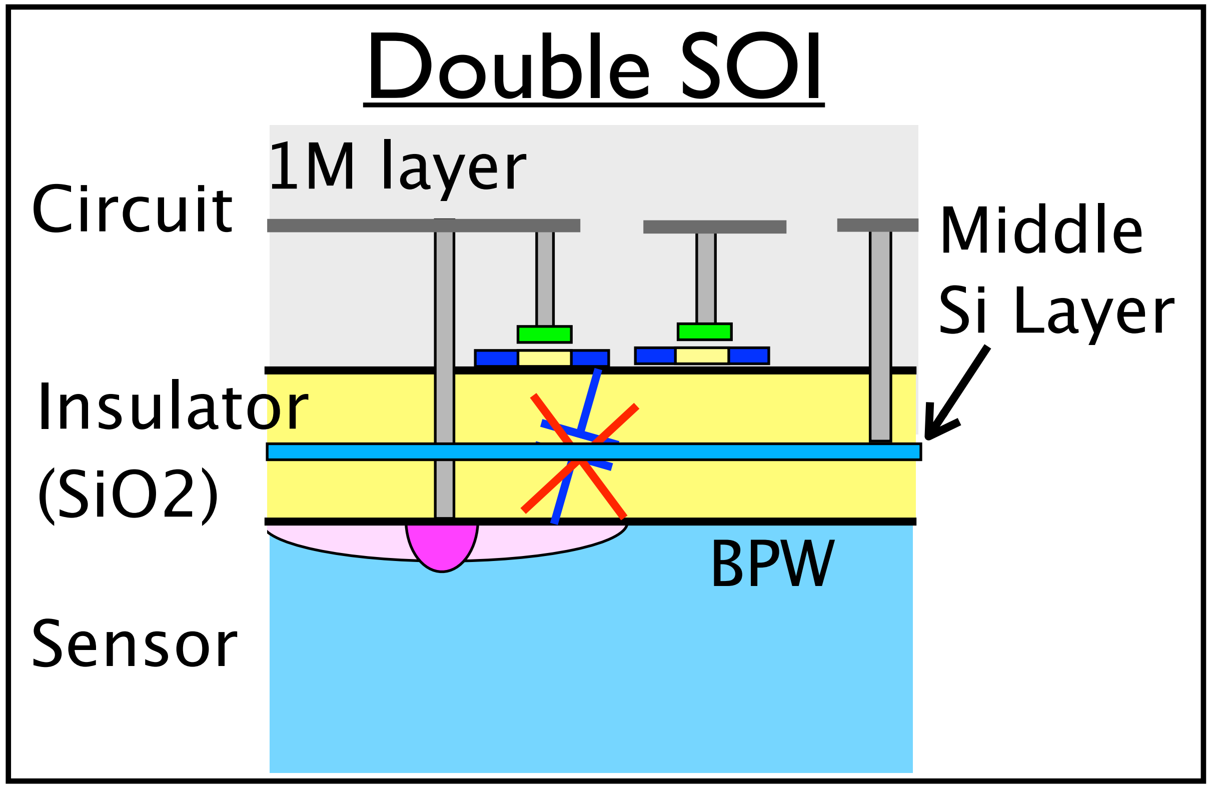


Ohmura+2016 NIM A

Double SOI Structure to increase the Gain

- We found that the gain of the in-pixel CSA was lower than the designed value.
- This is probably because there is parasitic capacitance around the in-pixel CSA.
- We increased the gain about a factor of two by cutting the parasitic capacitance with the DSOI structure.

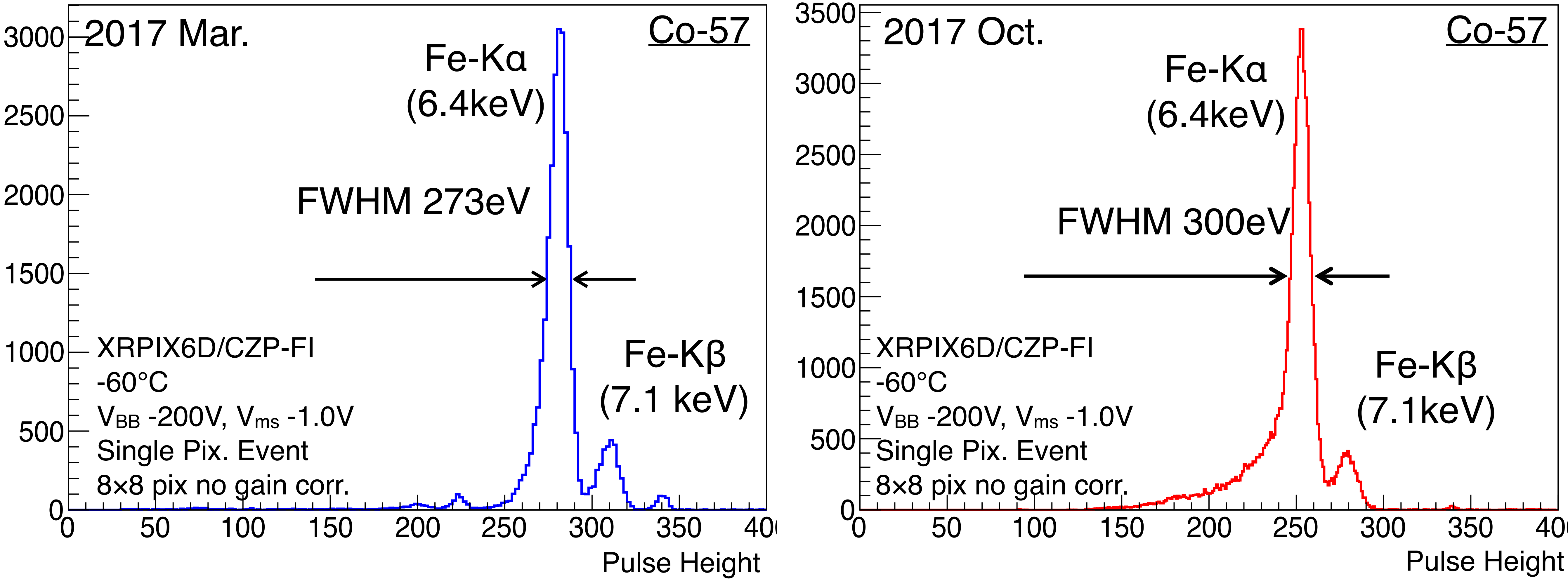




Miyoshi+2017 JINST

Event-Driven Mode with DSOI

Frame readout mode | Event-Driven readout mode

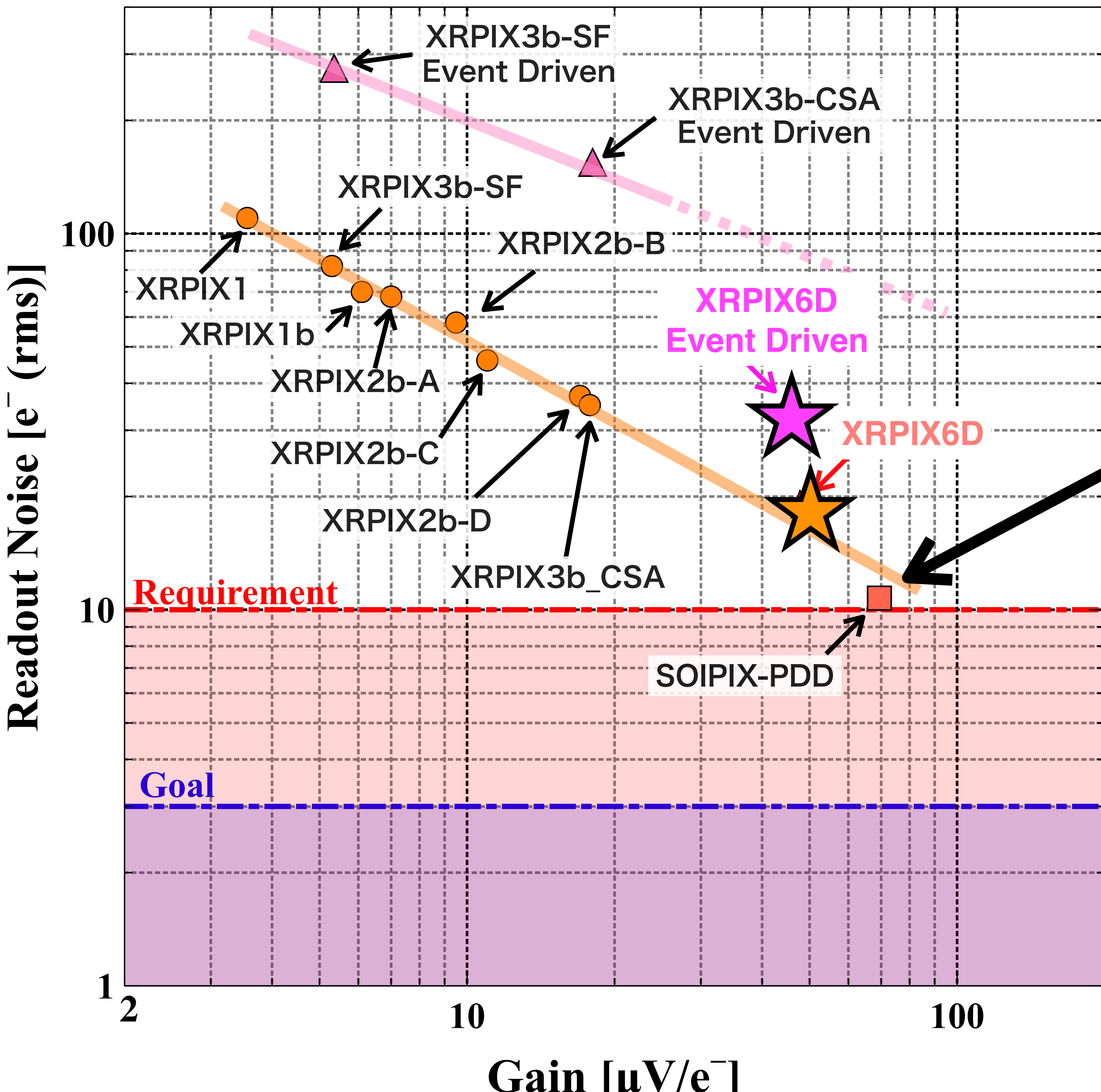


Single-pixel events collected from 8x8 Pixels
No correction of inter-pixel gain variations

- The spectral performance in the frame mode was successfully improved.
- The performance in the event-driven mode is now close to the one in the frame mode.

20171129_XR6D_ed_fr_spectrum_v0.pdf, Hayashi, Takeda+2017

Gain - Readout Noise



SOIPIX-PDD talk by Kawahito-sensei

Summary

- We are developing scientific SOIPIX detectors for particle physics, astrophysics, photon science etc.
- We introduced the status of the development of Event Driven X-ray astronomy SOIPIX (XRPIX).
- Introduction of the DSOI structure (and PDD structure ⇒ Kawahito-sensei's talk) successfully suppress the interference between the circuit layer and sensor layer.
- We reached ENC of ~30-35e (rms) and ΔE of ~300eV (FWHM) at 6keV in the Event Driven readout mode.

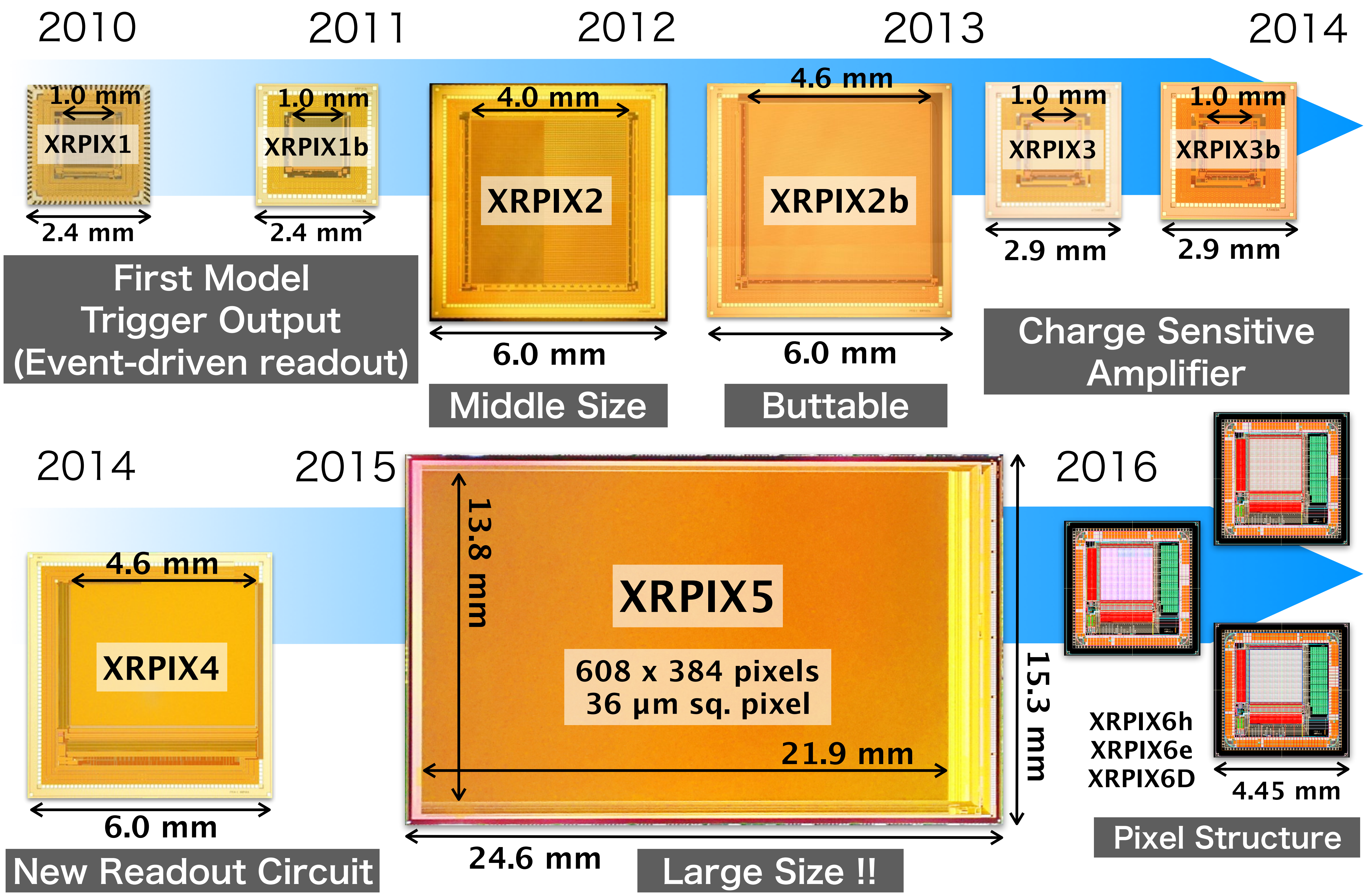
宮崎大学 University of Miyazaki

A-R-Tec Analog and RF Technologies

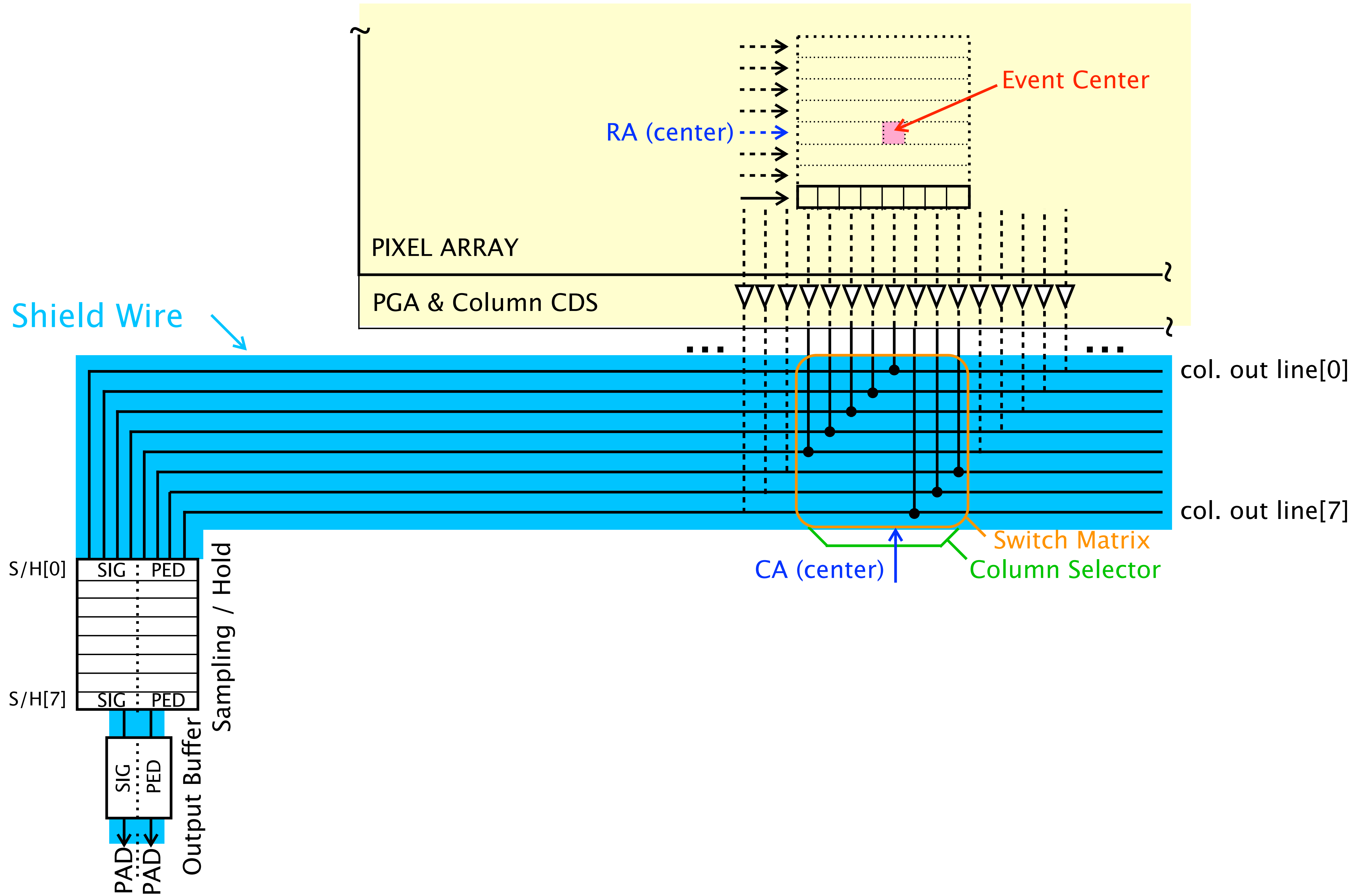
Lapis Semiconductor 0.2 μm FD-SOI Pixel Process

Process	0.2 μm Low-Leakage Fully-Depleted SOI CMOS 1 Poly, 5 Metal layers. MIM Capacitor (1.5 fF/um^2), DMOS Core (I/O) Voltage = 1.8 (3.3) V
SOI wafer (single)	Diameter: 200 mmφ, 720 μm thick Top Si : Cz, ~10 Ω-cm, p-type, ~40 nm thick Buried Oxide: 200 nm thick Handle wafer: Cz (n) ~700 Ω-cm, FZ(n) > 2k Ω-cm, FZ(p) ~25 k Ω-cm etc.
Backside process	Mechanical Grind, Chemical Etching, Back side Implant, Laser Annealing and Al plating

History of XRPIX Series



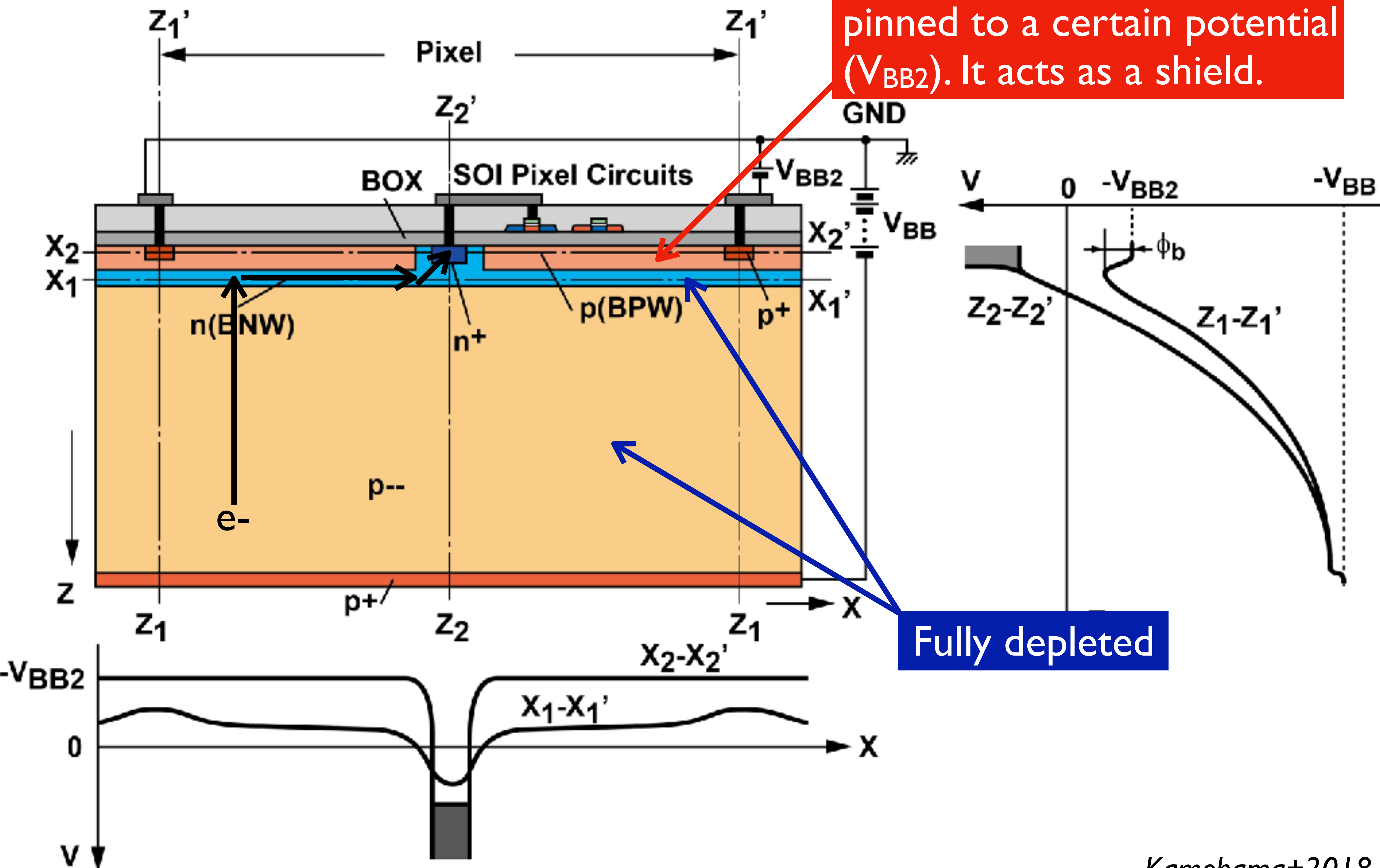
Peripheral Readout (since XRPIX5)



Pinned Depleted Diode, a new device structure

New Device Structures : Pinned Depleted Diode (PDD)

BPW remains neutral and is pinned to a certain potential (V_{BB2}). It acts as a shield.

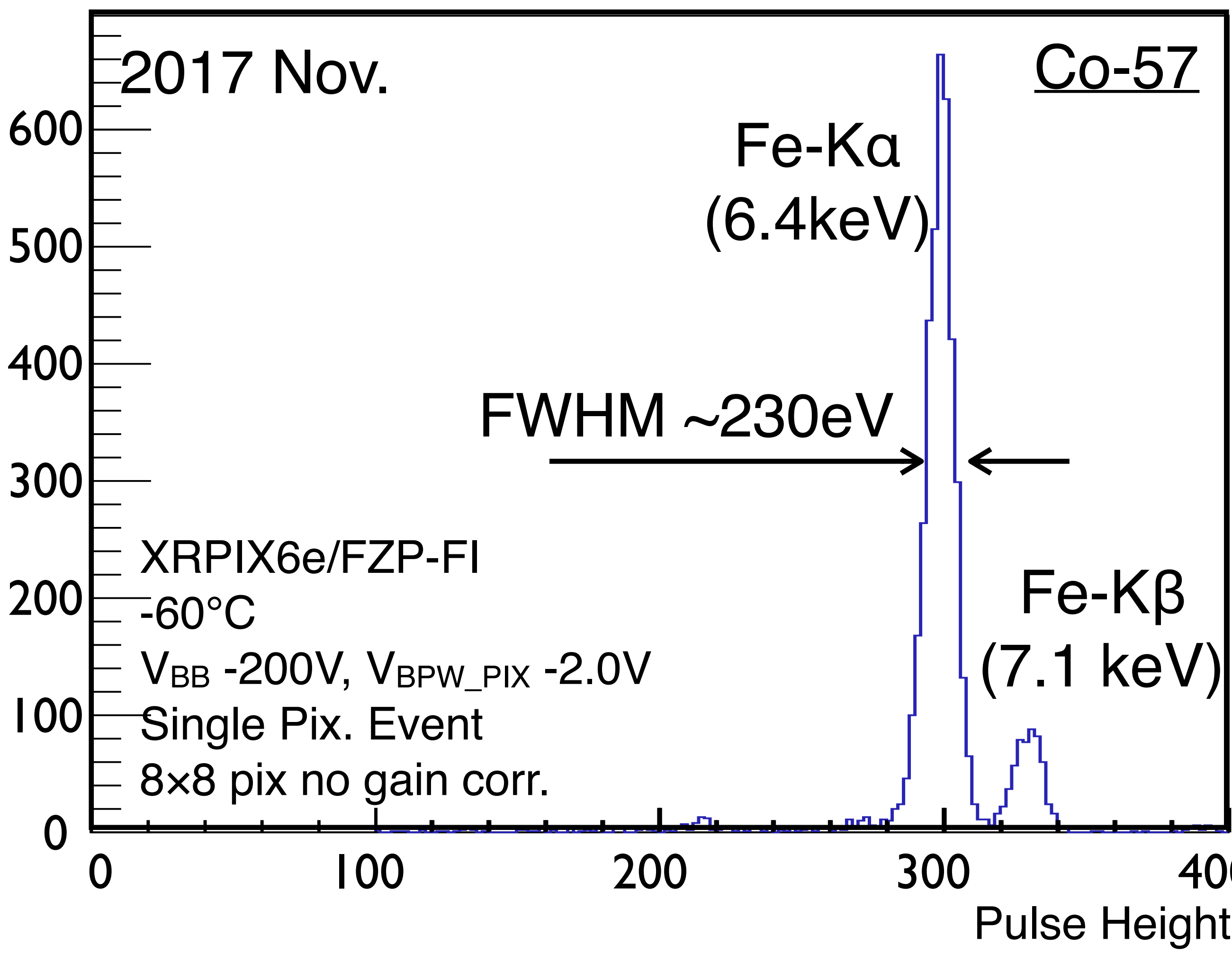


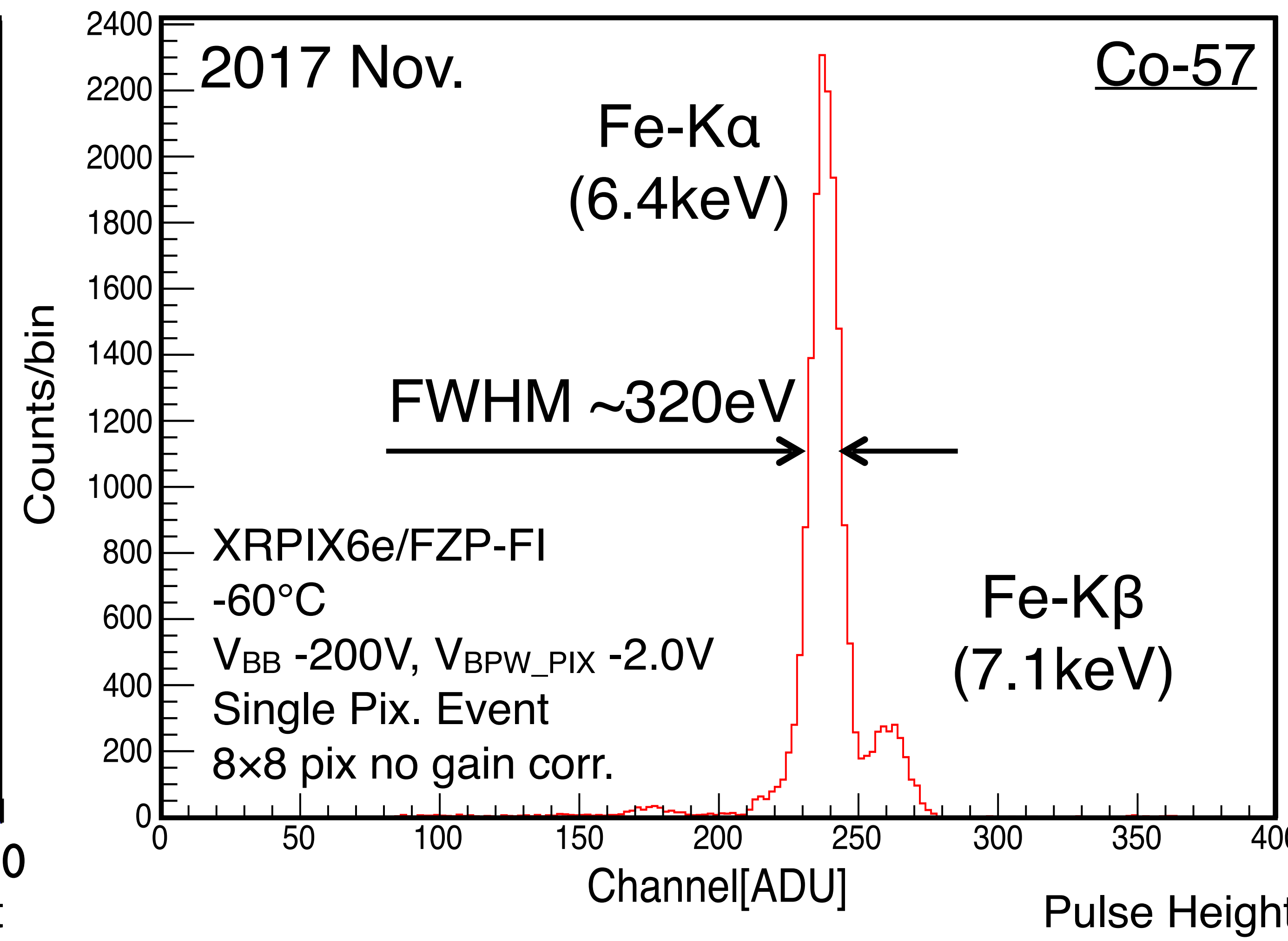
Fully depleted

Kamehama+2018

Event-Driven Mode with PDD

Frame readout mode | **Event-Driven readout mode**



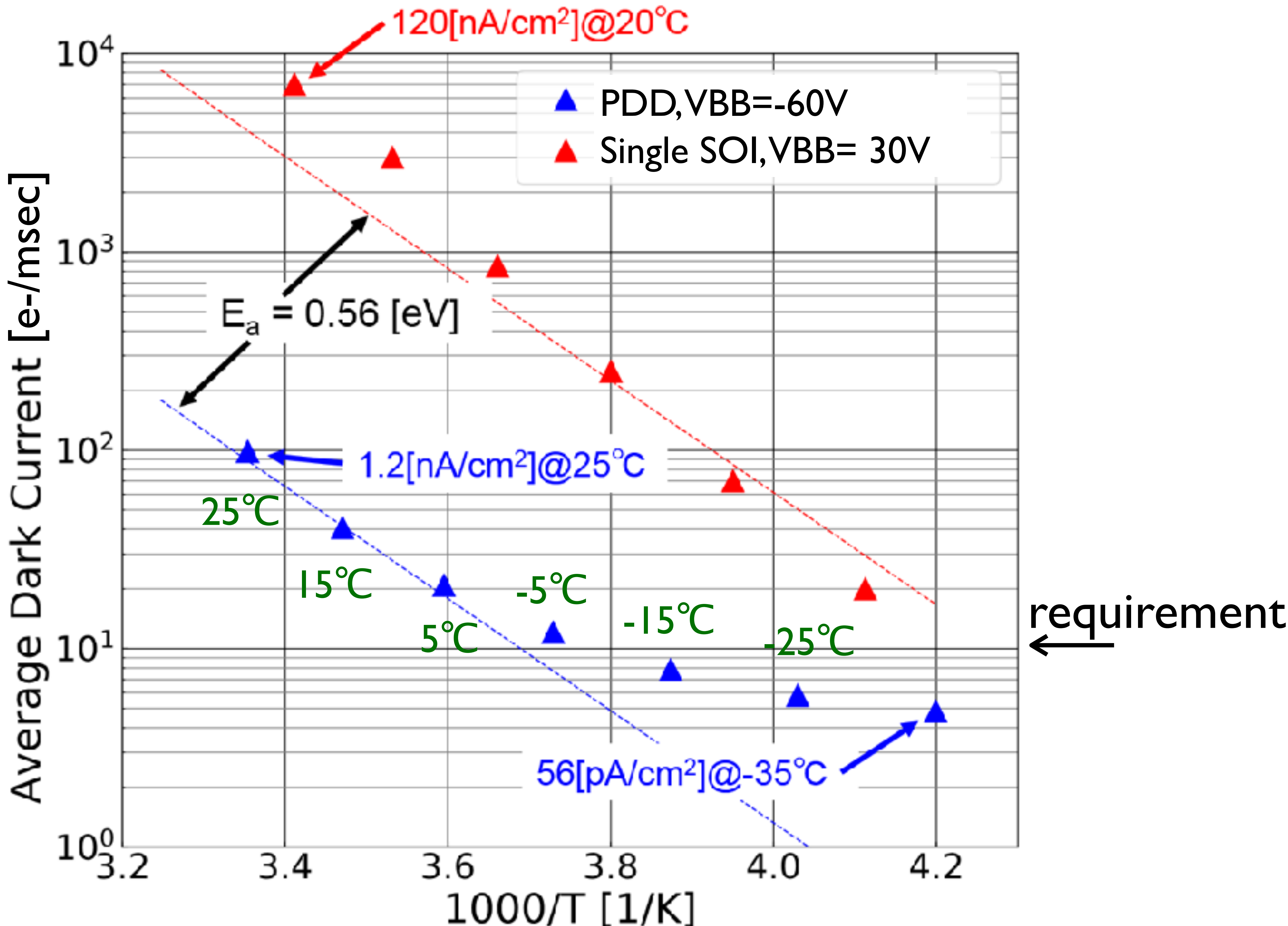


Single-pixel events collected from 8x8 Pixels
No correction of inter-pixel gain variations

- The spectral performance is similar to the one of DSOI version.
- The tail component with PDD is smaller than the one with DSOI.

XR6E_spectrum_harada_171127_v1.pdf, Harada, Kamehama, Hayashi+2017

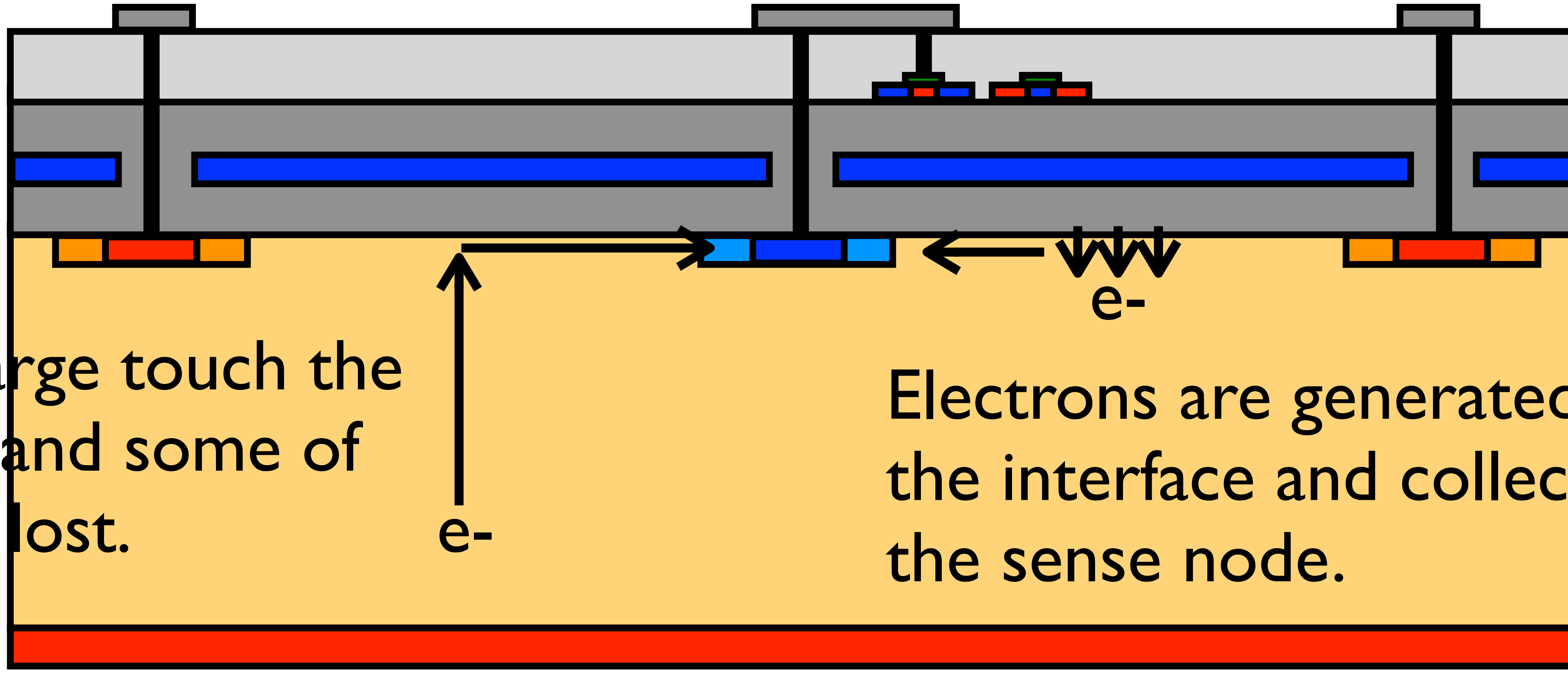
Dark Current



Kamehama+2018

What makes the difference ?

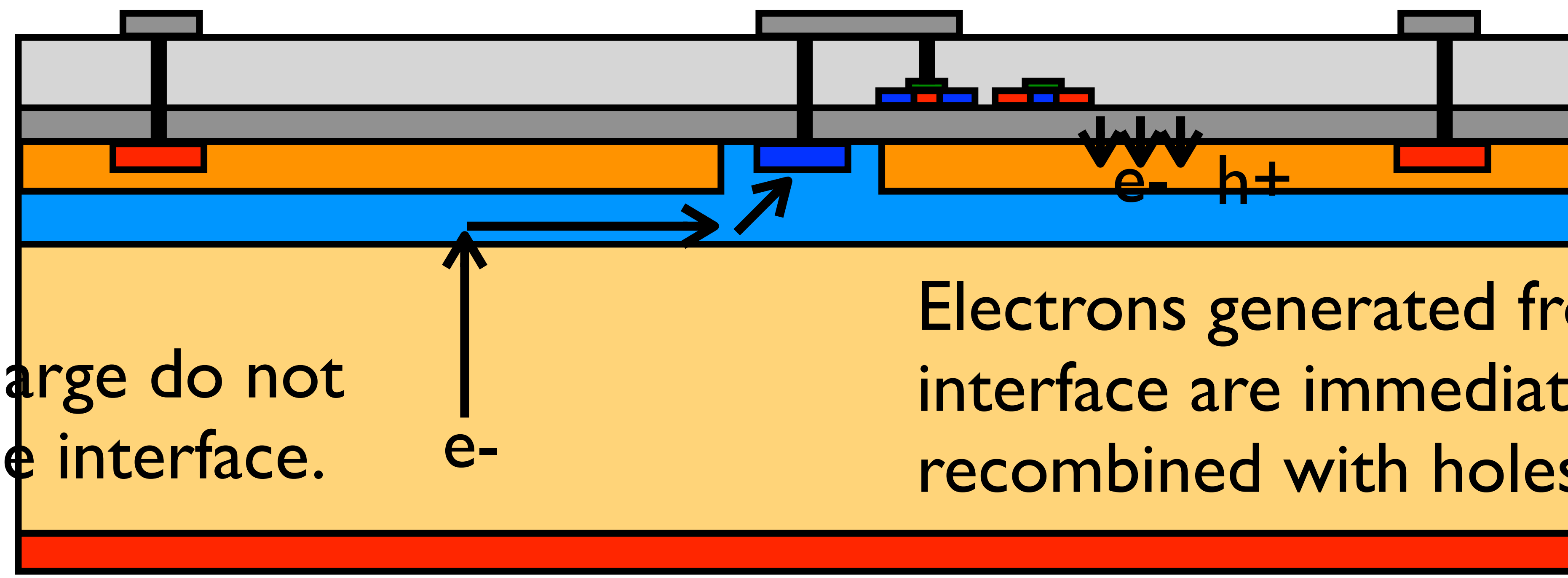
DSOI



Signal charge touch the interface and some of them are lost.

Electrons are generated from the interface and collected by the sense node.

PDD



Signal charge do not touch the interface.

Electrons generated from the interface are immediately recombined with holes.