

X-ray Spectro-Polarimeters Enabled by Fine-Pixel CMOS Imaging Sensors

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Polarization is a fundamental property of a photon

Operators of the quantized radiation fields

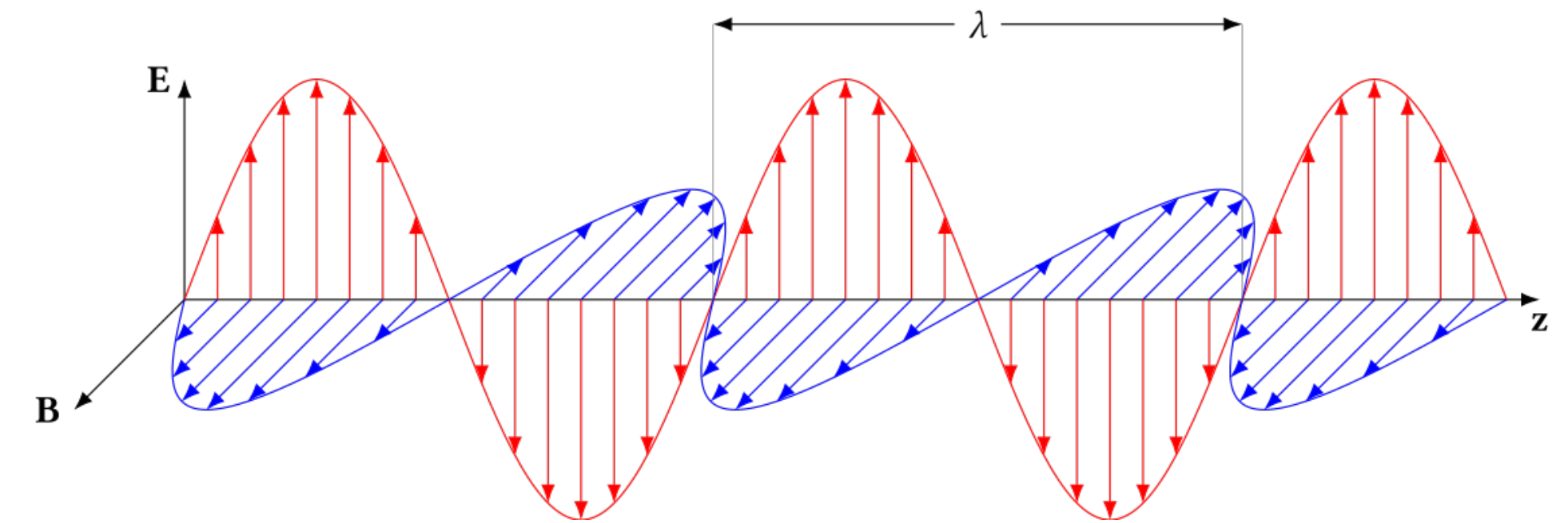
$$\mathbf{A}(\mathbf{r}) = \sum_{\mathbf{k}, \mu} \sqrt{\frac{\hbar}{2\omega V \epsilon_0}} \left\{ \mathbf{e}^{(\mu)} a^{(\mu)}(\mathbf{k}) e^{i\mathbf{k} \cdot \mathbf{r}} + \bar{\mathbf{e}}^{(\mu)} a^{\dagger(\mu)}(\mathbf{k}) e^{-i\mathbf{k} \cdot \mathbf{r}} \right\}$$

$$\mathbf{E}(\mathbf{r}) = i \sum_{\mathbf{k}, \mu} \sqrt{\frac{\hbar\omega}{2V \epsilon_0}} \left\{ \mathbf{e}^{(\mu)} a^{(\mu)}(\mathbf{k}) e^{i\mathbf{k} \cdot \mathbf{r}} - \bar{\mathbf{e}}^{(\mu)} a^{\dagger(\mu)}(\mathbf{k}) e^{-i\mathbf{k} \cdot \mathbf{r}} \right\}$$

$$\mathbf{B}(\mathbf{r}) = i \sum_{\mathbf{k}, \mu} \sqrt{\frac{\hbar}{2\omega V \epsilon_0}} \left\{ (\mathbf{k} \times \mathbf{e}^{(\mu)}) a^{(\mu)}(\mathbf{k}) e^{i\mathbf{k} \cdot \mathbf{r}} - (\mathbf{k} \times \bar{\mathbf{e}}^{(\mu)}) a^{\dagger(\mu)}(\mathbf{k}) e^{-i\mathbf{k} \cdot \mathbf{r}} \right\}$$

$\mathbf{k}$: wave vector

$\mu = \pm 1$: polarization mode

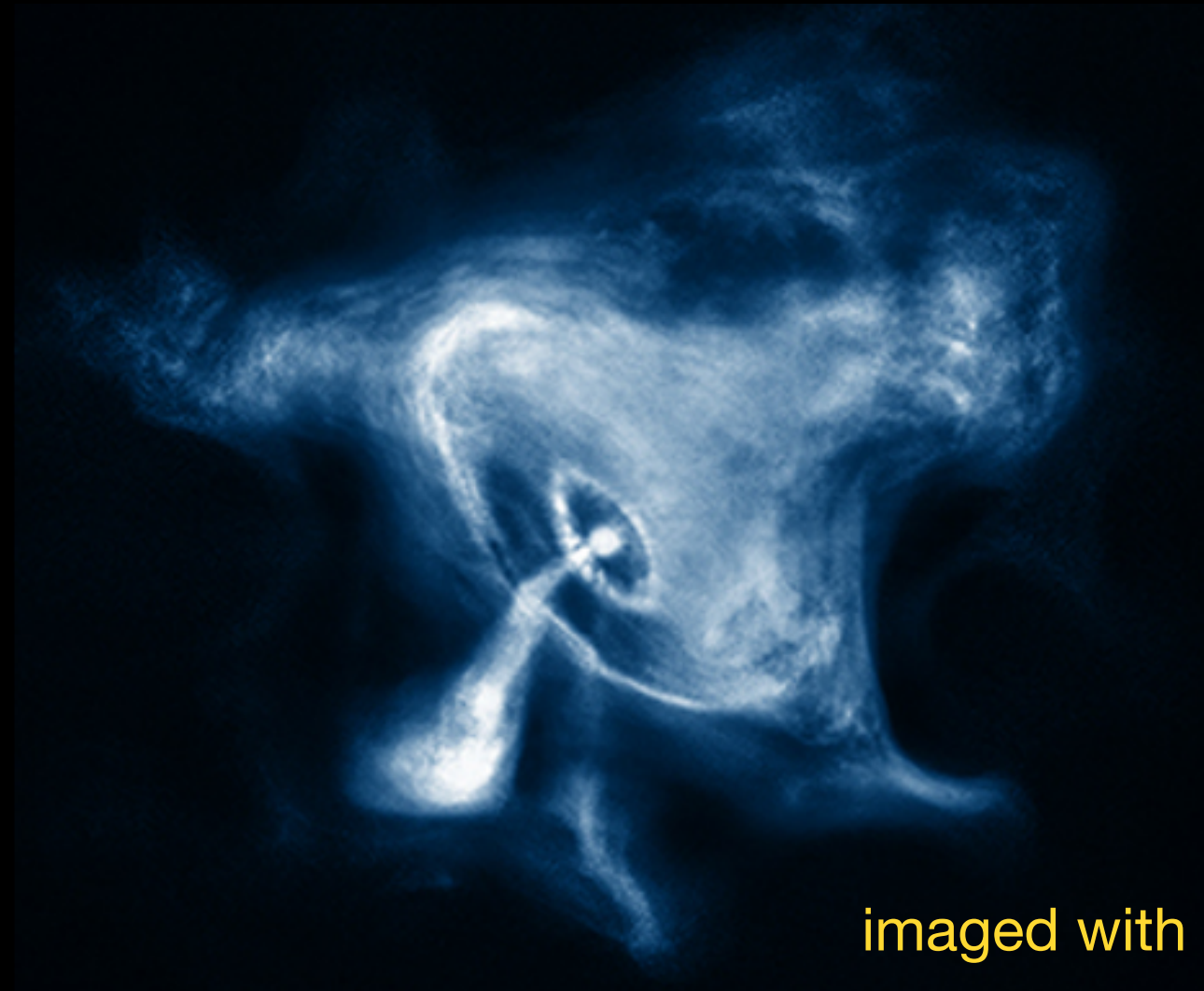


The state of a photon is determined by the wave vector and the polarization.

Polarization is a probe of **anisotropy** of astrophysical systems and physical processes associated with the systems.

- ✓ configuration of a magnetic field
- ✓ geometry of a scattering/reflecting medium around a neutron star and a black hole
- ✓ properties of a gravitational field in the vicinity of a black hole

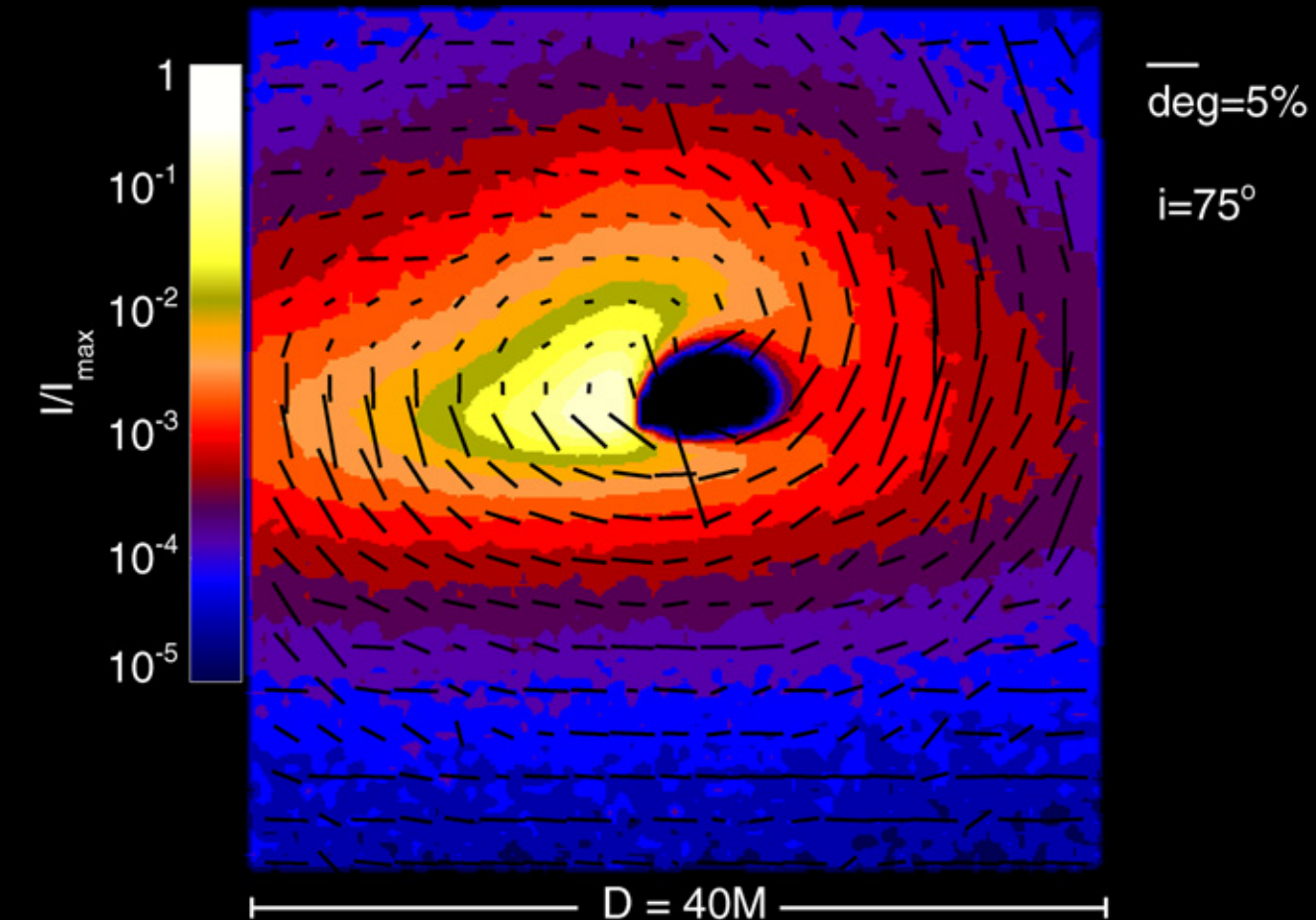
Interesting objects in X-ray polarimetry



imaged with CXO (NASA)

The Crab Nebula (pulsar wind nebula)

- ✓ a cosmic lepton accelerator up to **1 PeV** powered by a rapidly rotating neutron star
- ✓ shining via synchrotron radiation in the X-ray band
- ✓ polarization traces the configuration of magnetic field which plays a key role in the mysterious acceleration mechanism



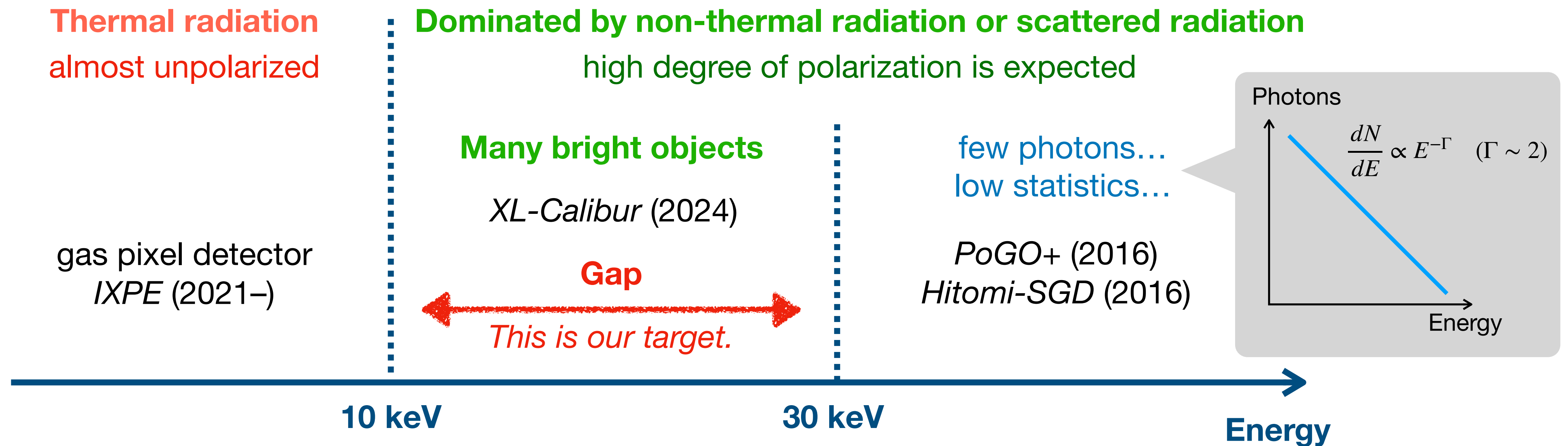
Black hole

- ✓ a theoretical polarimetric image in X-rays of an accretion flow onto a spinning black hole
- ✓ polarization will reveal physical properties of the falling flow and the gravitational field in the closest vicinity of **the event horizon**

Hard X-rays are more important

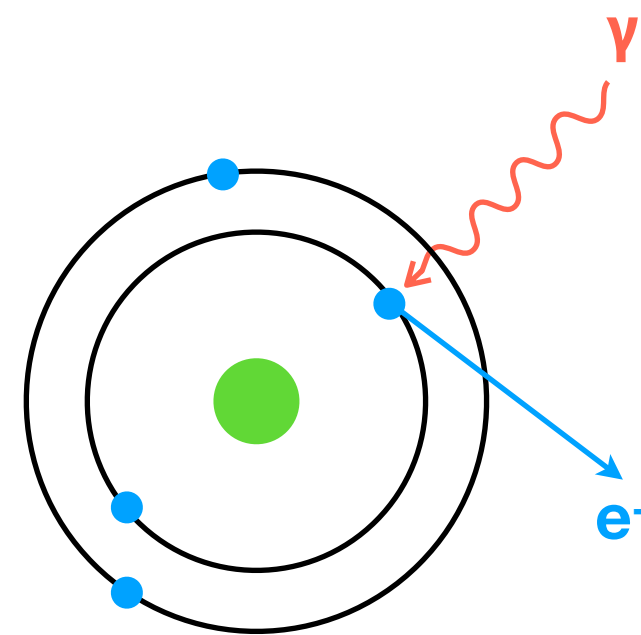
The Imaging X-ray Polarimetry Explorer (IXPE, NASA), launched in 2021, has opened a new window of X-ray polarization.

However, the hard X-ray band, i.e., above 10 keV, still remains unexplored in spite of its great scientific importance.



Methods of X-ray polarimetry

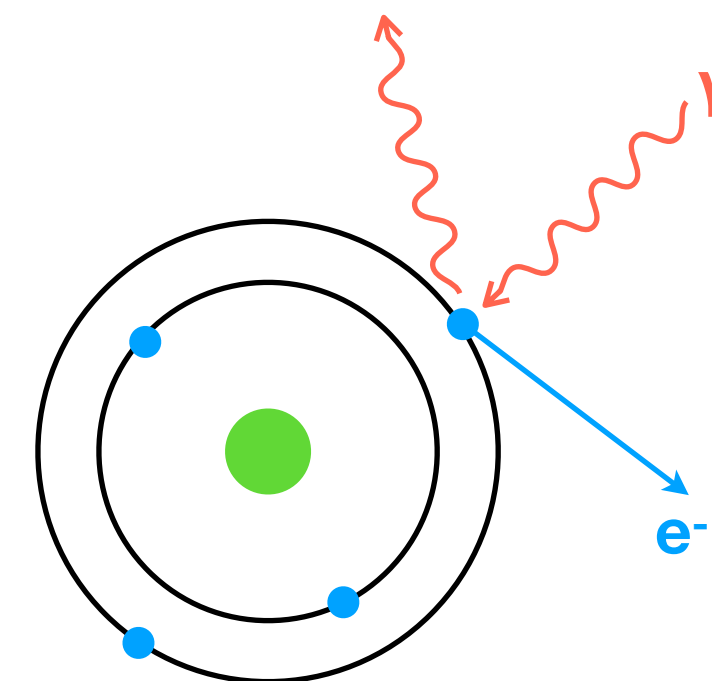
Photoelectric effect



$$\frac{d\sigma}{d\Omega} \propto \frac{\sin^2 \theta \cos^2 \phi}{(1 - \beta \cos \theta)^4}$$

The photo-electron tends to be ejected to the polarization angle

Compton scattering



$$\frac{d\sigma}{d\Omega} \propto \frac{E_1}{E_0} + \frac{E_0}{E_1} - 2 \sin^2 \theta \cos^2 \phi$$

The photon tends to be scattered perpendicular to the polarization angle

The observation gap, namely the low energy part of hard X-rays, is between these two.

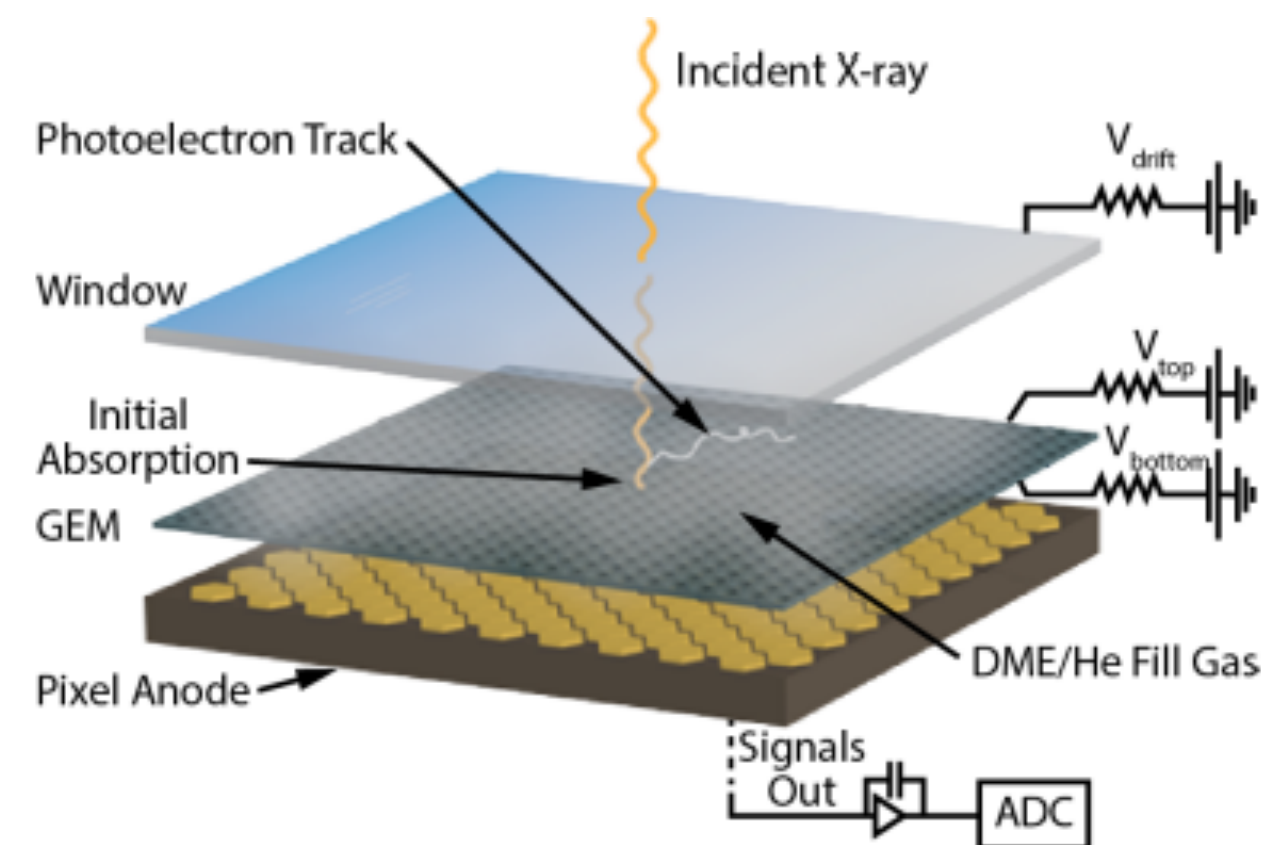
✓ X-Calibur adopts low-Z (beryllium) scatterer.

✓ Our choice is going to the **photoelectric** type using **a silicon pixel detector**.

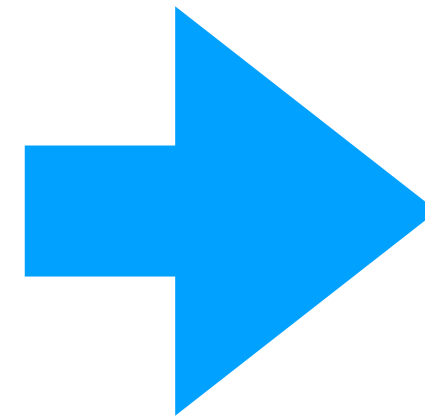
Semiconductor sensors for polarimetry

Gas pixel detector

- ✓ A **standard** detector for soft X-ray polarimetry.
- ✓ An electron range is long enough thanks to low detector density.
- ✓ Pixel readout realizes the capability of tracking a photoelectron.



IXPE (NASA) website



Silicon semiconductor detector

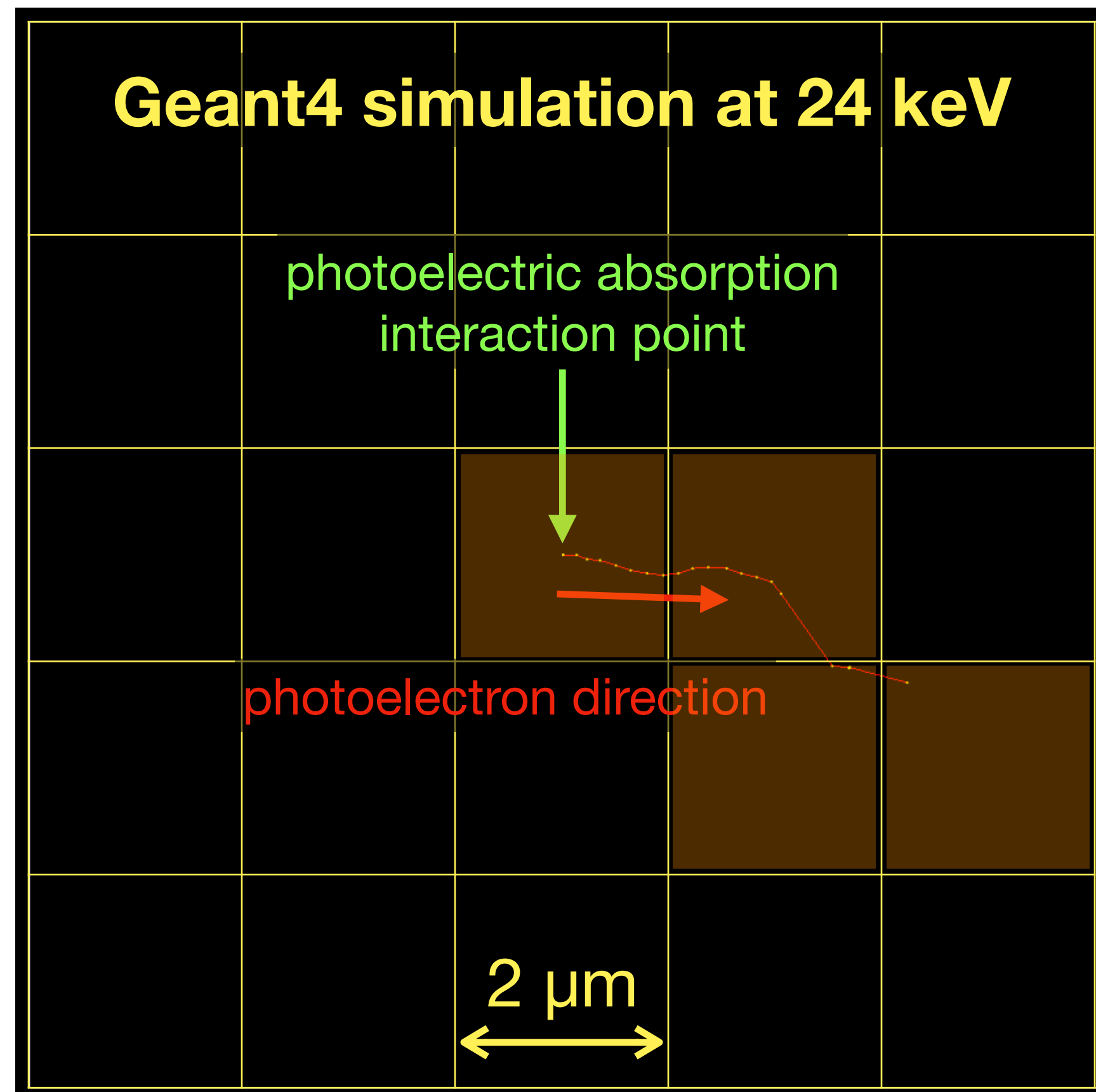
- ✓ **High energy resolution**
- ✓ High position resolution
- ✓ Easier handling
- ✓ High density (x1000 higher than gas)
 - thin detector
 - good for combination with optics with thin focal depth

However, an even shorter electron range makes it difficult to track photoelectrons.

→ We need **very small pixels!**

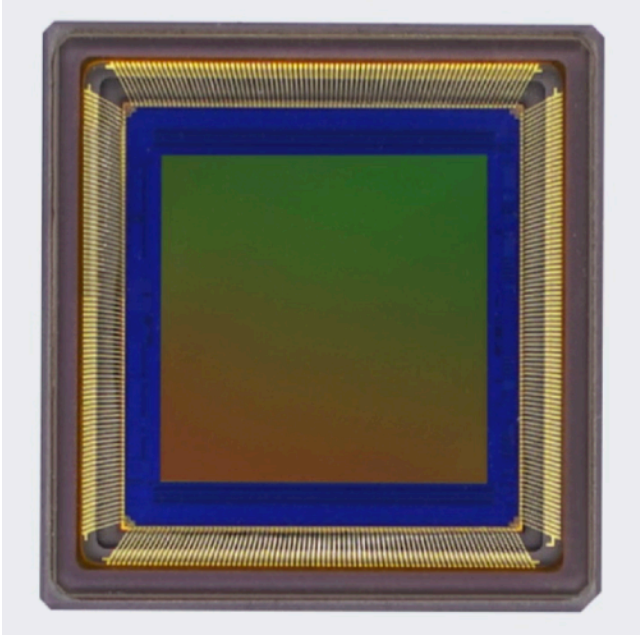
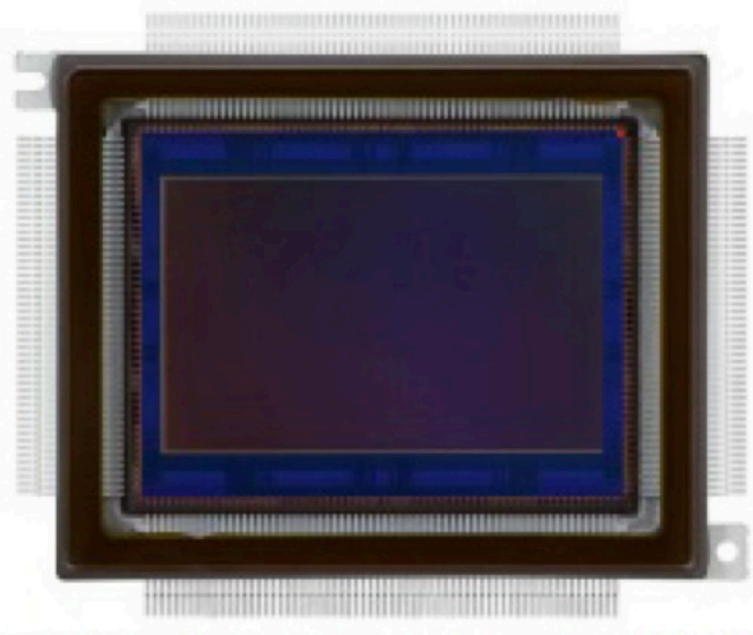
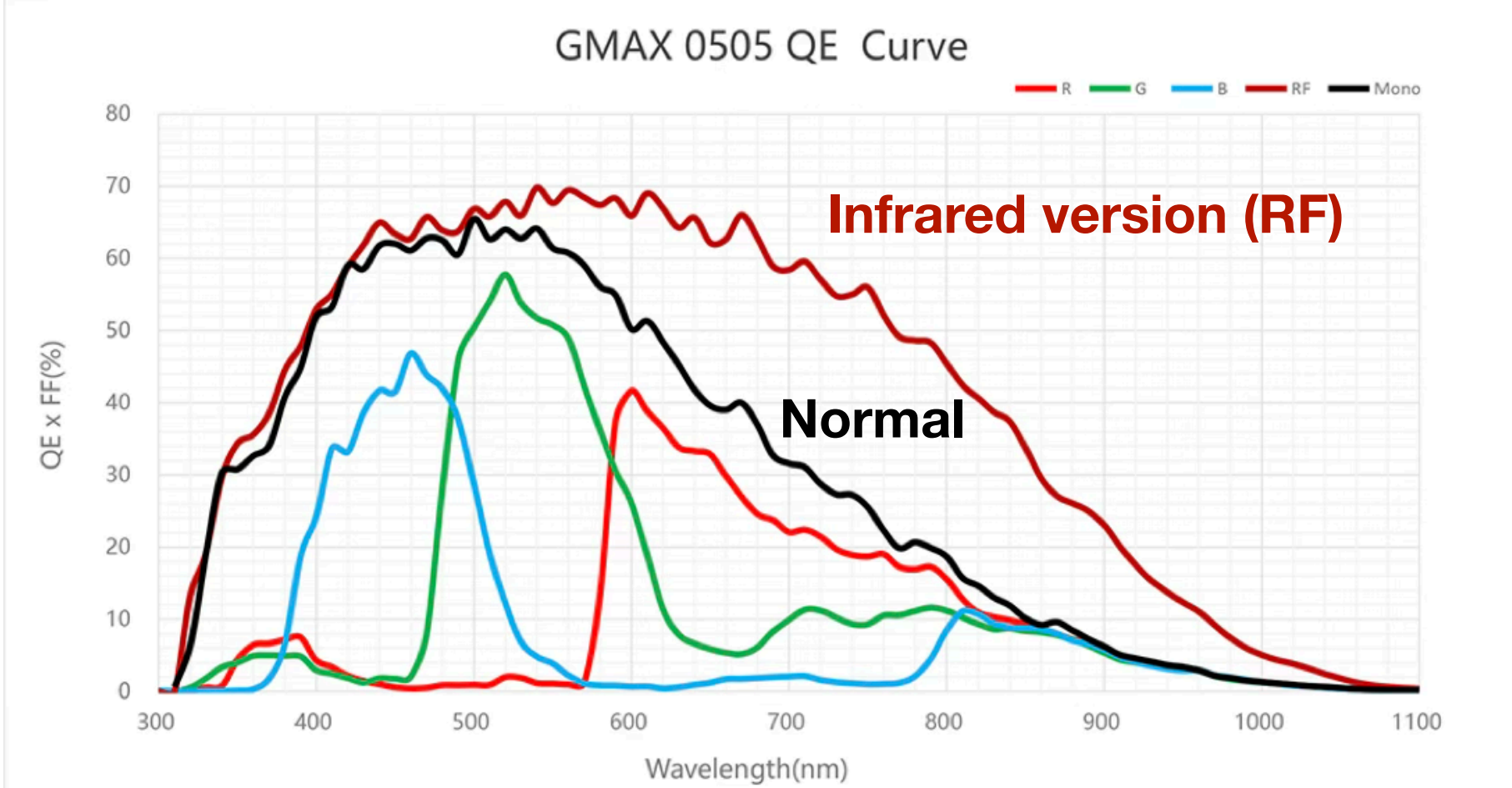
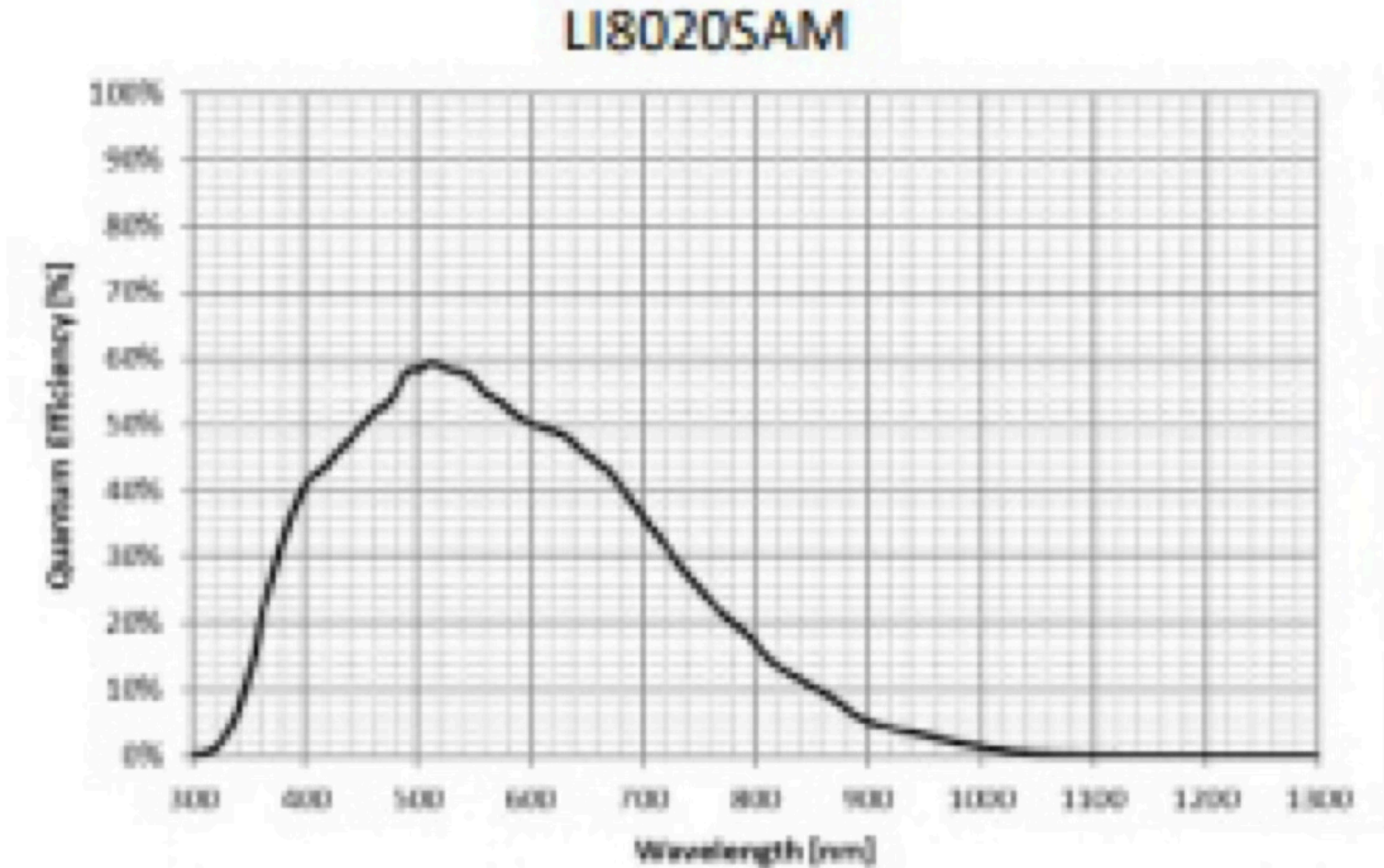
CIPHER project

CMOS-based Imaging Polarimetry for High-Energy Radiation



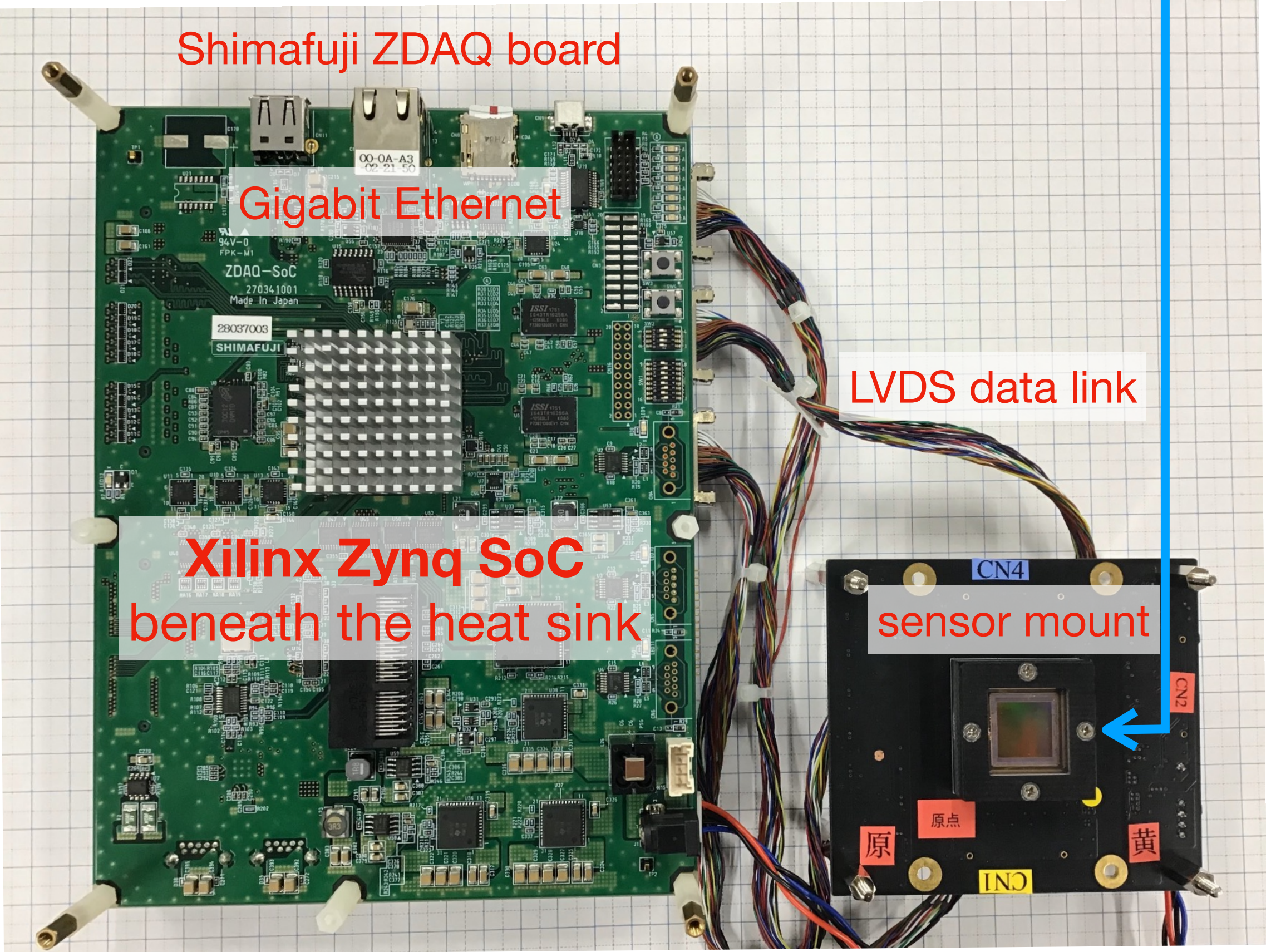
- Odaka et al. (2020) proposed the first concept of CIPHER, which employed a CMOS-based active pixel sensor for high-resolution visible light inspection with very fine-pitch pixels.
- A similar idea was proposed by Asakura, Hayashida et al. (2019) for a high-resolution X-ray imaging mission.
- The first concept was a CubeSat-based X-ray imaging polarimetry mission using the combination of a fine-pixel CMOS sensor and a narrow field-of-view coded aperture mask.
- We also plan a solar X-ray mission using a similar detector design with high-resolution X-ray mirrors. (Hagino et al. 2025)

CMOS imaging sensors with small pixels

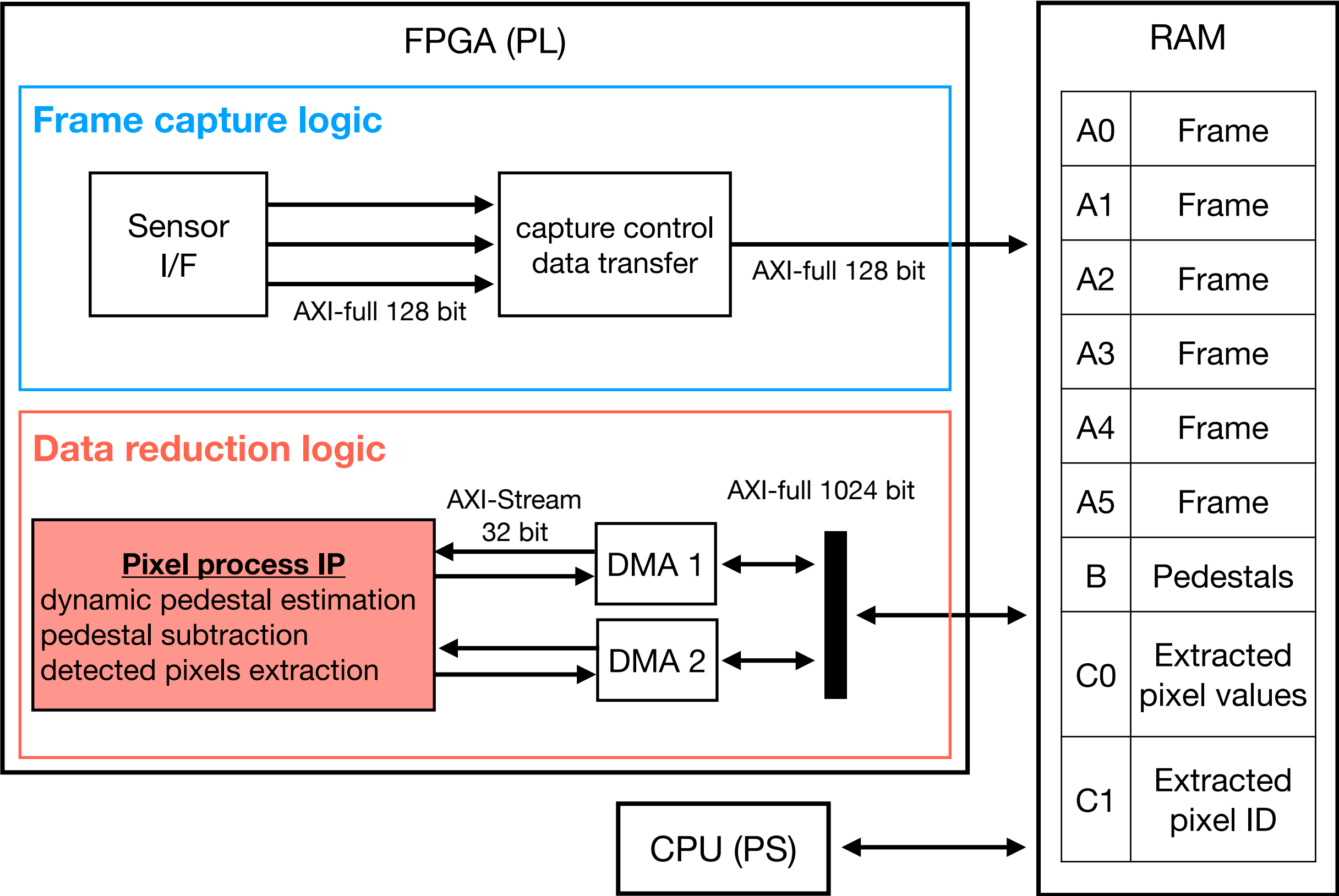
GPixel GMAX0505	Canon LI8020SA
	
2.5 μm pixel	1.5 μm pixel
25M pixels, 1" format, 12.8 mm $\times$ 12.8 mm	250M pixels, APS-H format, 29.4 mm $\times$ 18.9 mm
	

Our detector system

GPixel GMAX0505 (RF) series
pixel size: 2.5 μm
pixel number: 25 million = 5k x 5k
area: 12.8 x 12.8 mm^2



FPGA extracts X-ray events from an entire frame image for data reduction.

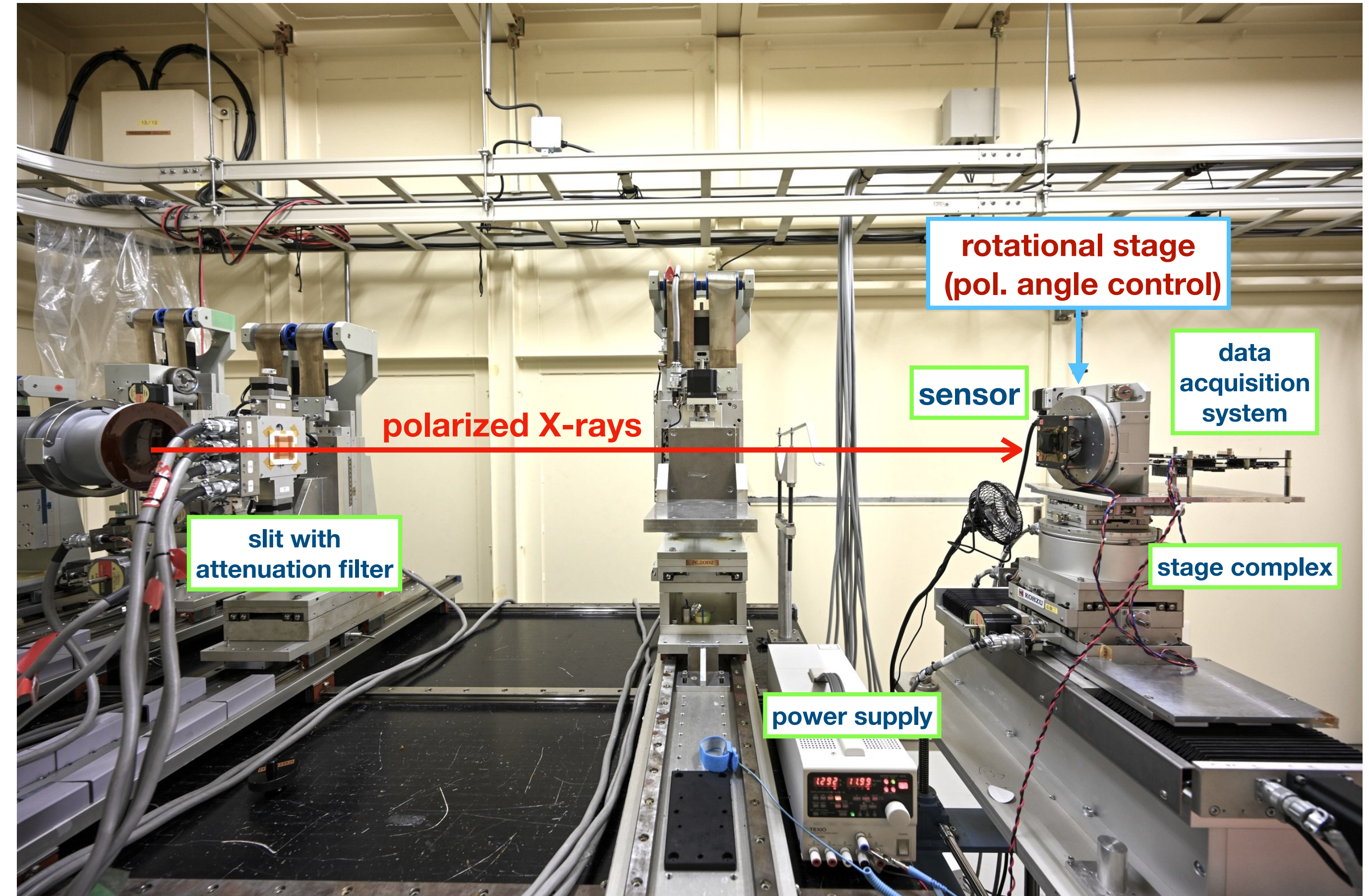


Proof-of-concept experiment



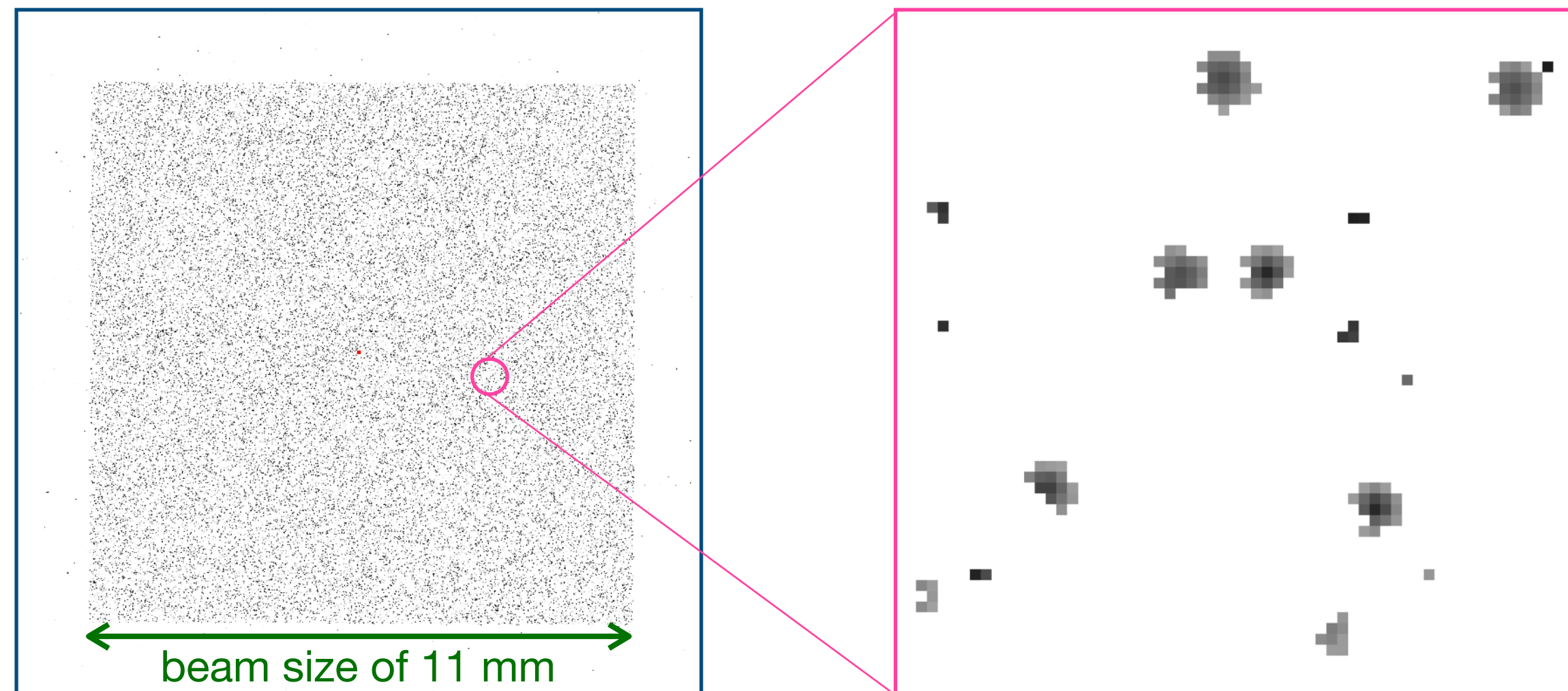
SPring-8 synchrotron radiation facility
in Hyogo, Japan

200 m long beamline BL20B2
for a large-area uniform X-ray beam
Beam size: 300 mm (H) x 20 mm (V)



- ✓ Monochromatic 100% linearly polarized photon beams
- ✓ Energies between 6 keV and 30 keV

X-ray event shapes



One-frame image at 16 keV

5000 x 5000 pixels.

Many X-ray events.

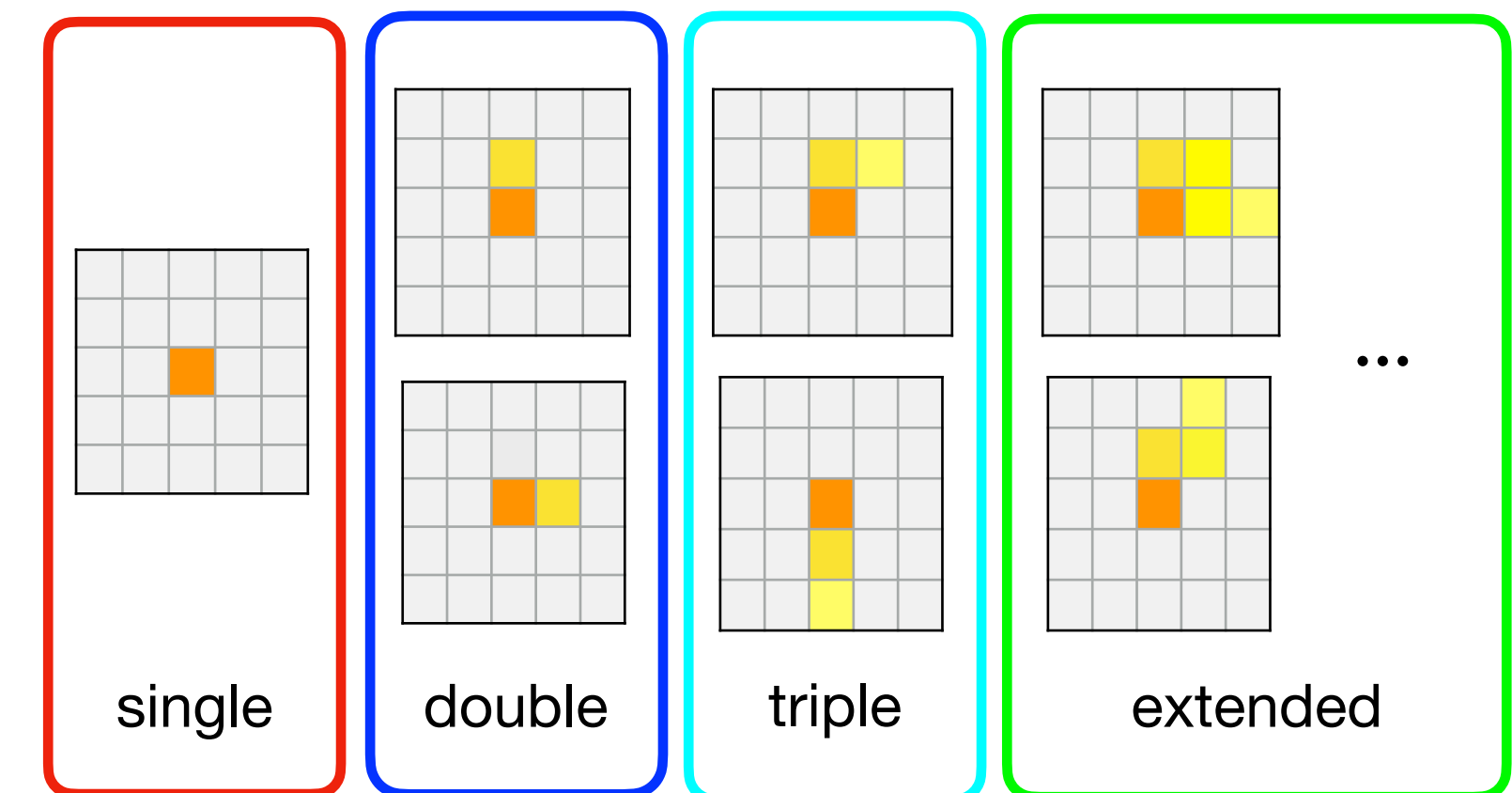
Grey scale is enhanced for visibility.

X-ray events

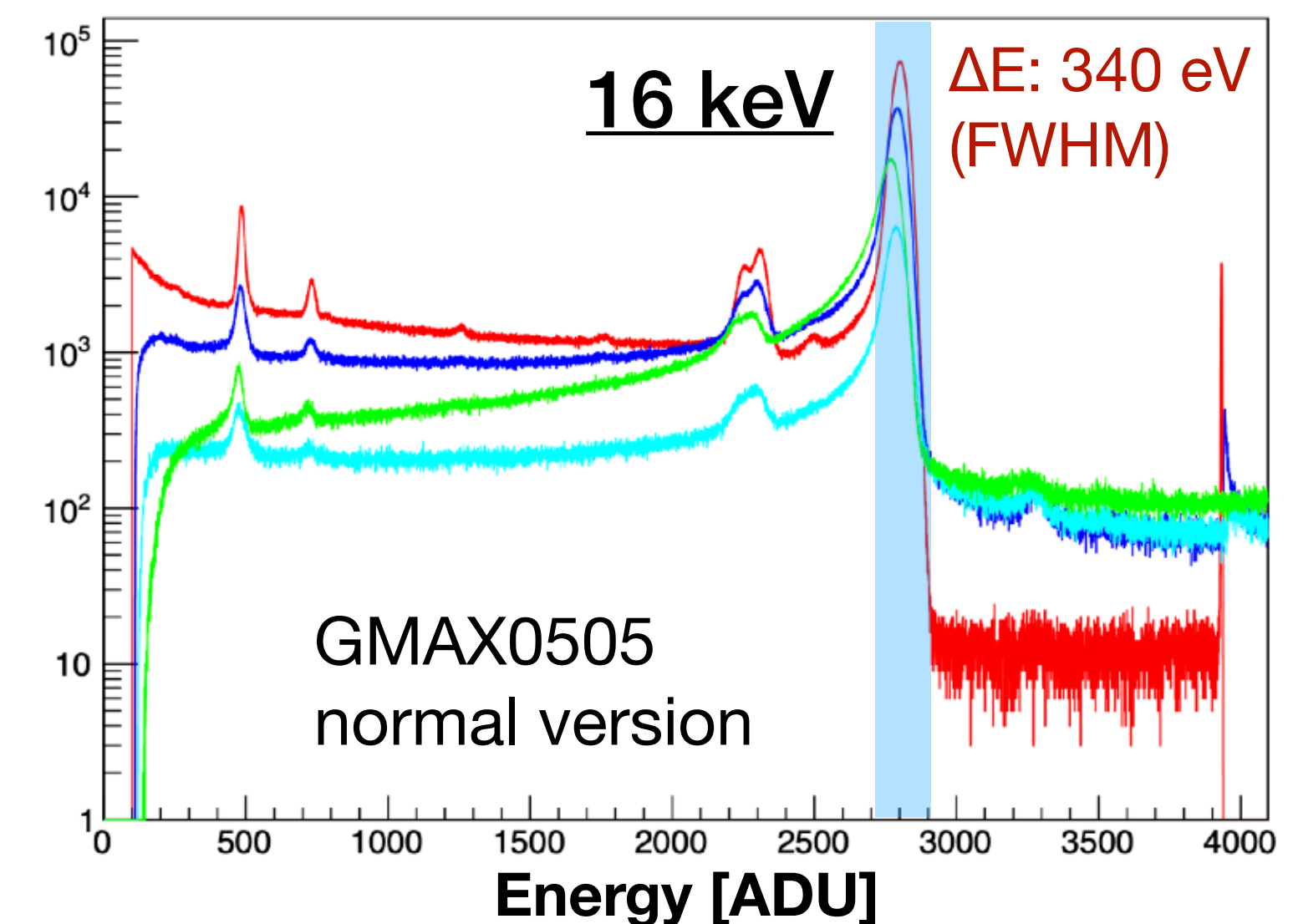
Various shapes from a single point to very extended.

Grey scale is logarithmic.

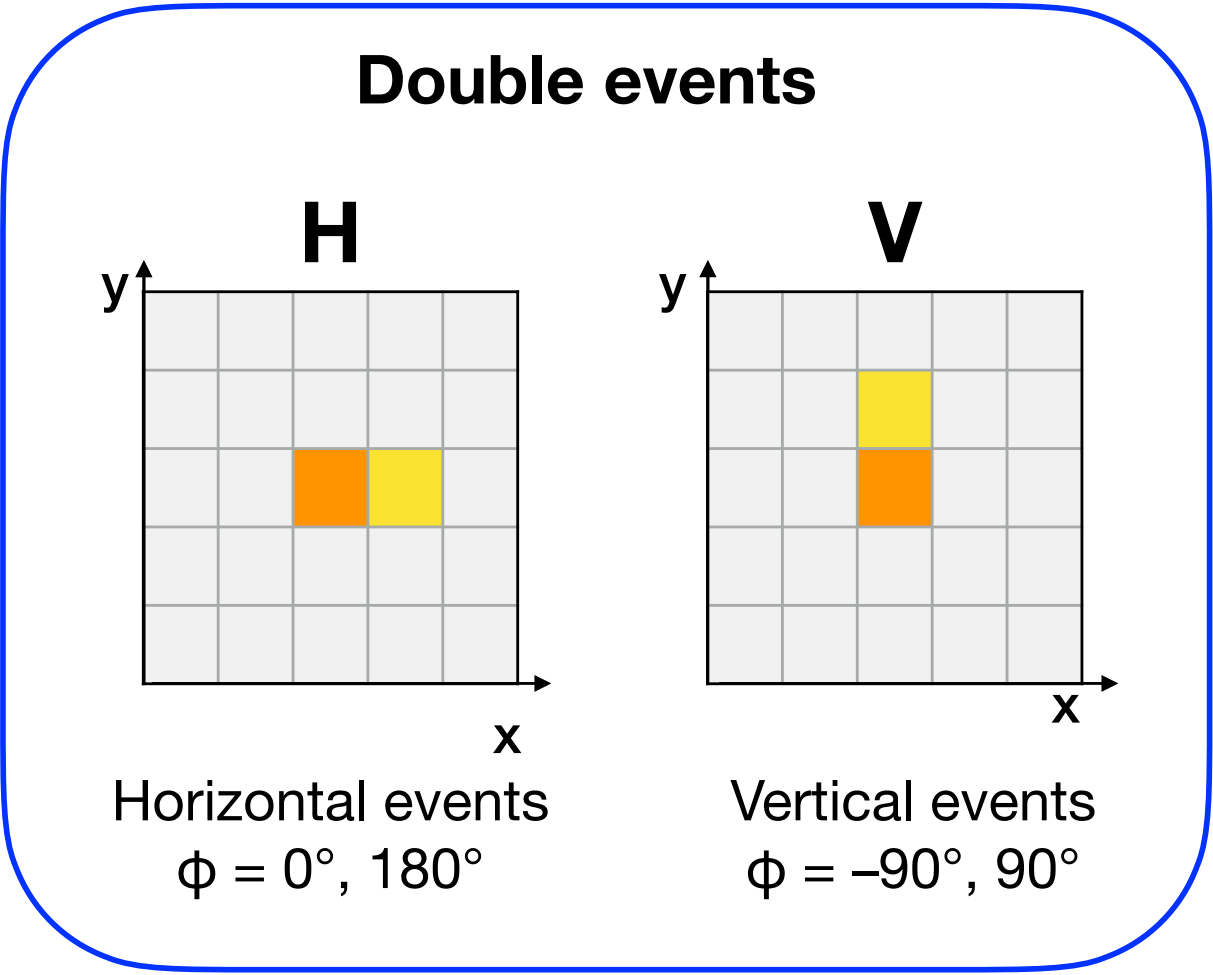
Extended events are probably due to diffusion in the low-field layer.



Multi-pixel events can be used for polarimetry.



Modulation factor

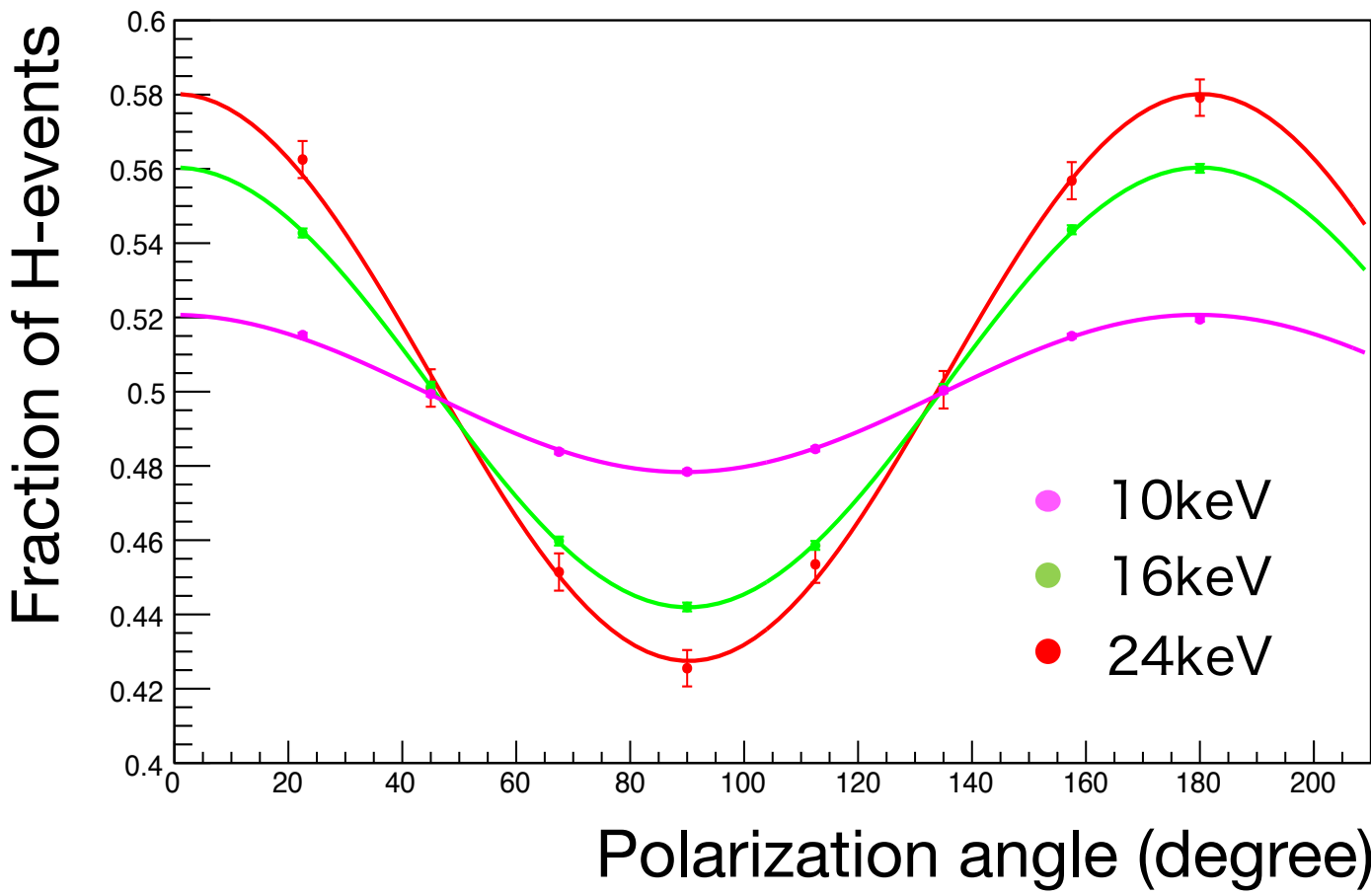


The fraction of the H-events

$$f = \frac{N_H}{N_H + N_V}$$

is a measure of polarization.

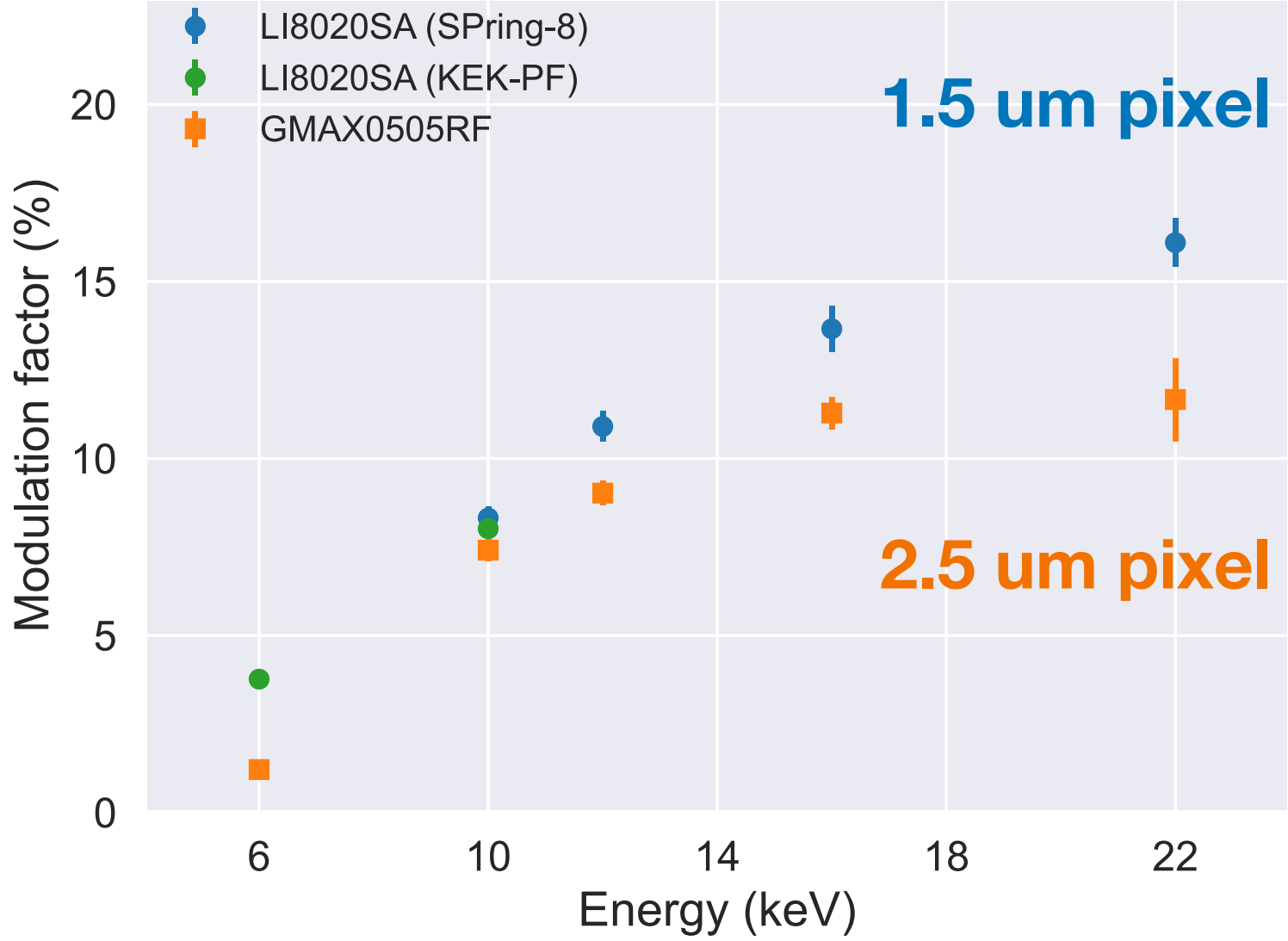
We corrected an intrinsic bias for unpolarized data of $f = 0.5$.



Energy	Modulation factor
10 keV	4.24% ± 0.03%
16 keV	11.82% ± 0.06%
24 keV	15.15% ± 0.25%

The H-event fraction is measured as a function of the polarization angle.

These modulation curves clearly show that the sensor has **high sensitivity to polarization**.



Modulation factor using multi-pixel events

- Uses 2-4 pixel events for 2.5 um sensor
- Uses 2-6 pixel events for 1.5 um sensor
- The modulation factor increases with energy, as expected.
- Consistent with Geant4-based simulation

Sensitivity of polarization

Minimum detectable polarization (confidence level of 99%)

$$\text{MDP}_{99} = \frac{4.29}{\sqrt{N} \cdot \mu} \quad (N: \text{count}, \mu: \text{modulation factor})$$

is a widely used for polarization sensitivity.

Thus, a figure of merit called the quality factor can be introduced:

$$q = \sqrt{\epsilon} \cdot \mu \quad (\epsilon: \text{quantum efficiency}, \mu: \text{modulation factor})$$

As energy gets higher,

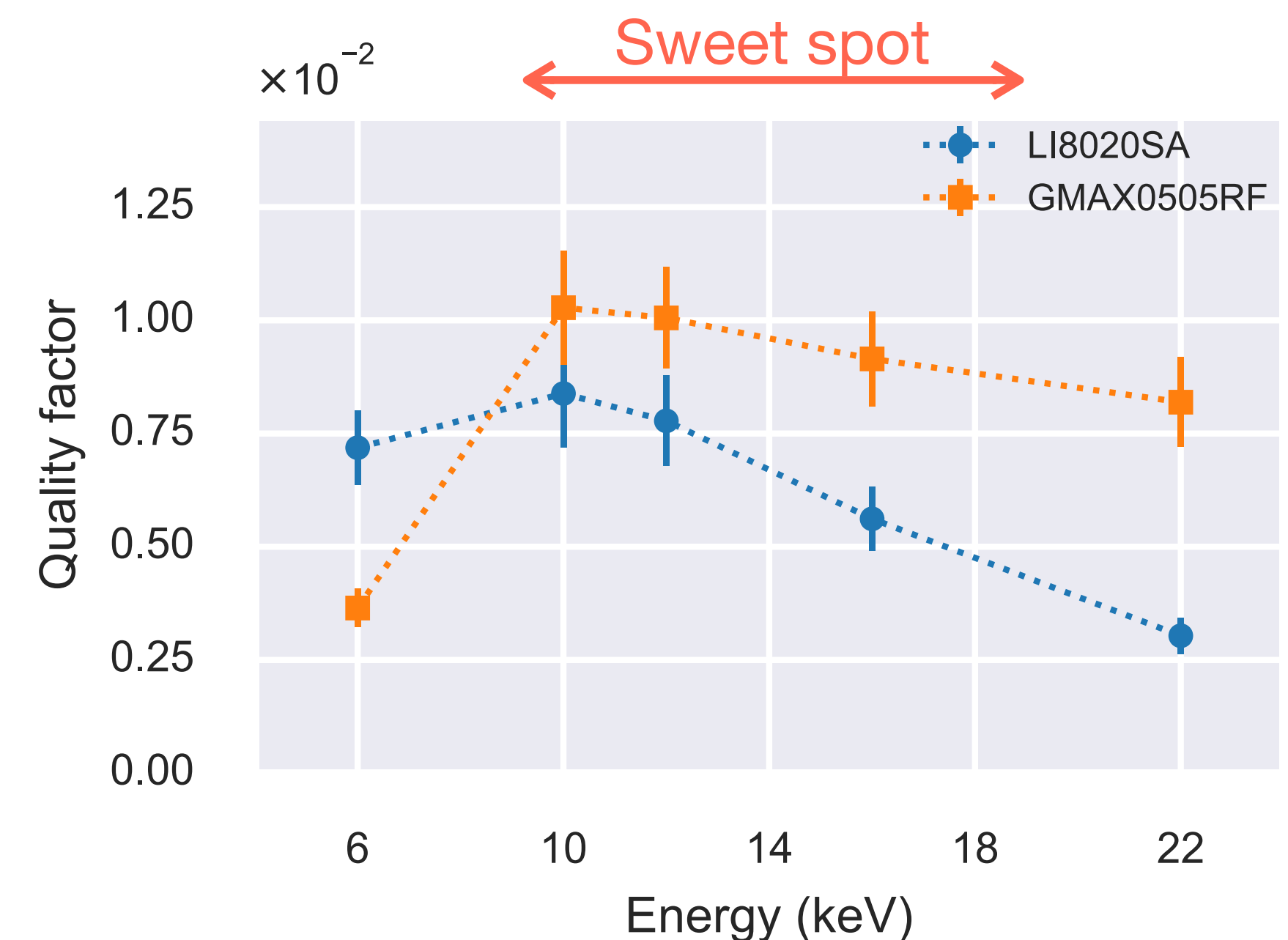
- the electron range gets longer (good for modulation factor),
- photoabsorption cross section decreases (bad for statistics),

Thus, ideally, we need a sensor with

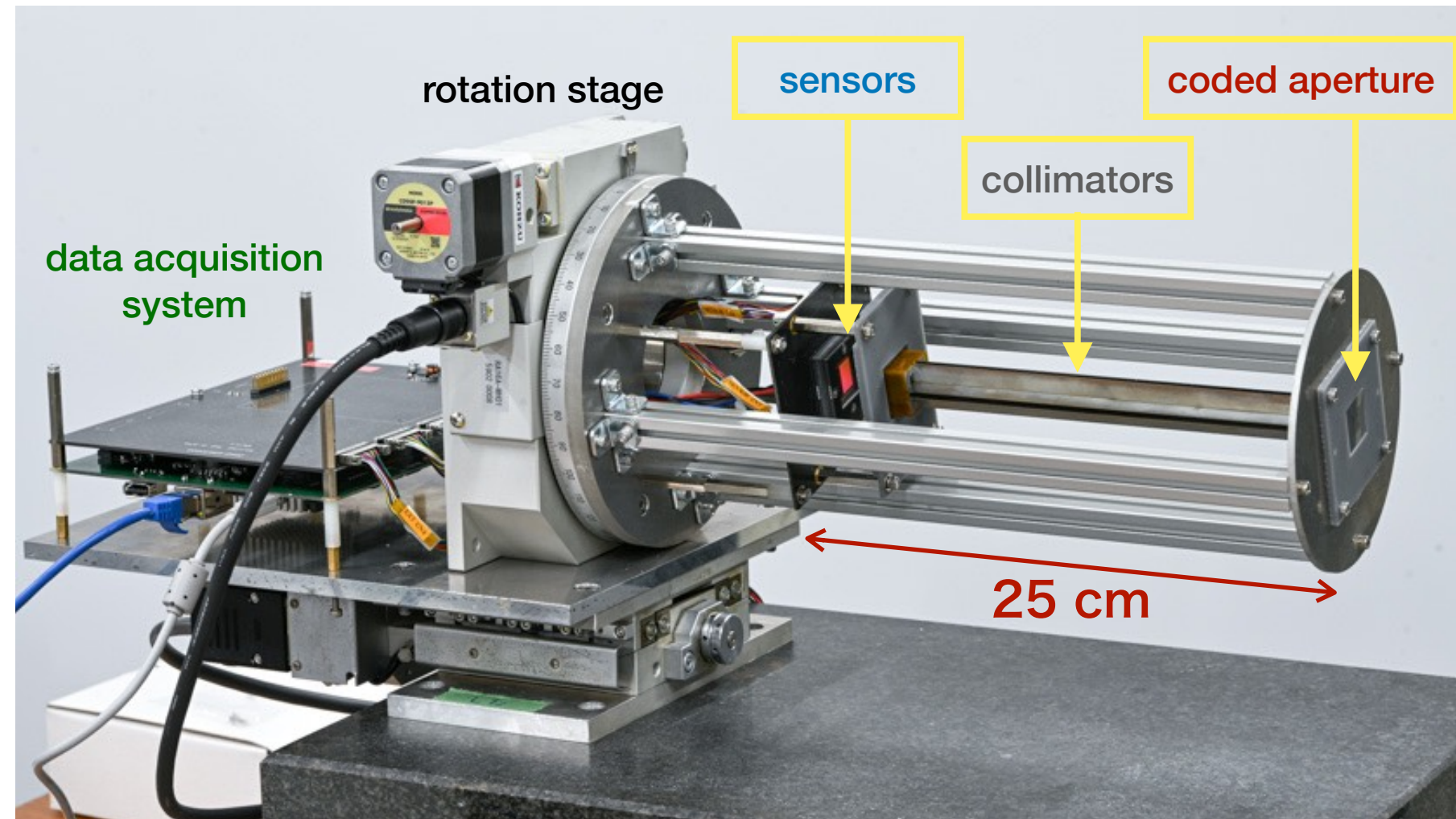
- small pixel size < 2.5 μm
- thick depletion layer > 40 μm with backside bias

Currently we use optical sensors but need real X-ray sensors.

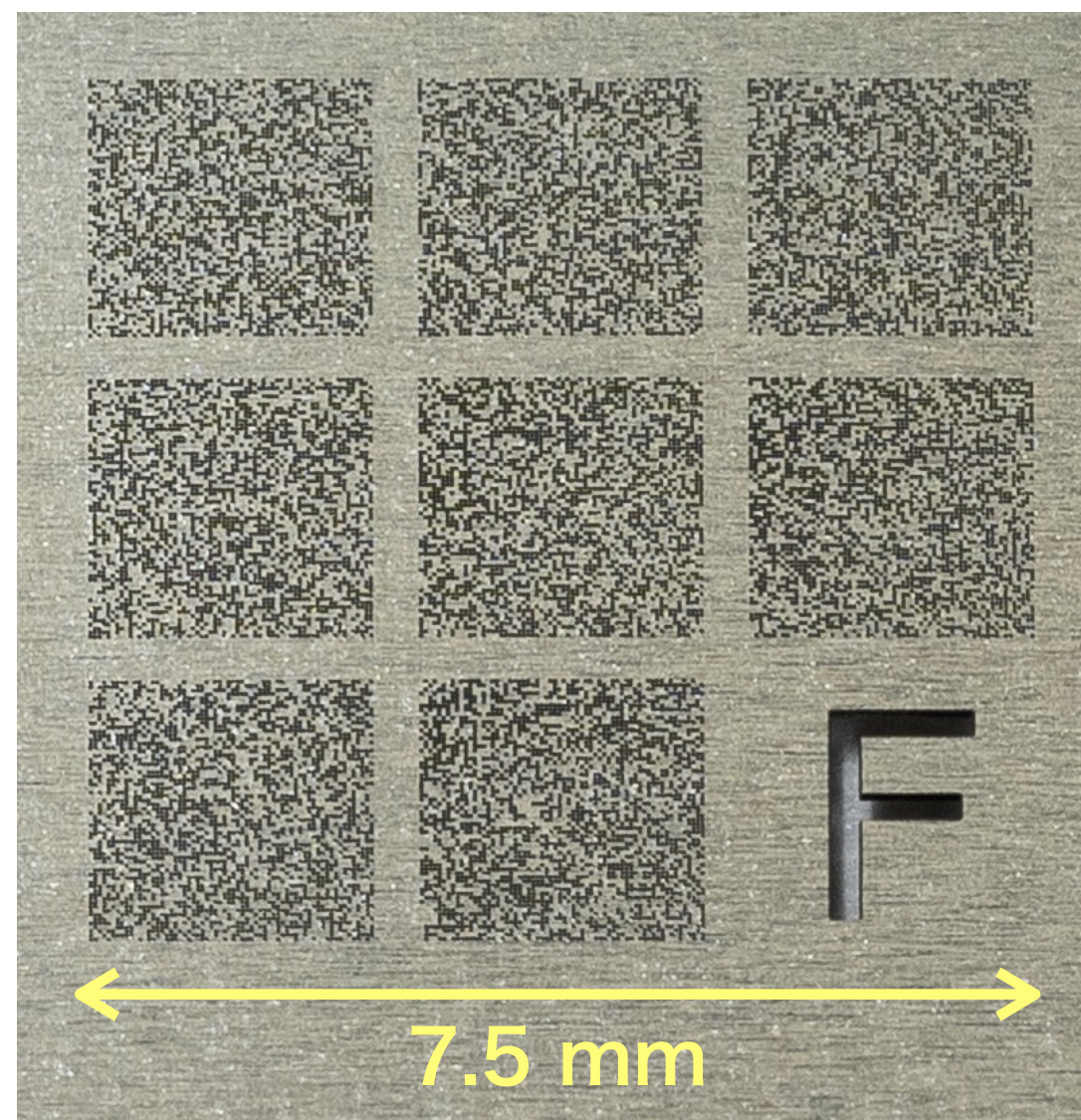
$$\text{Quality factor } q = \sqrt{\epsilon} \cdot \mu$$



Demonstration of polarimetric imaging

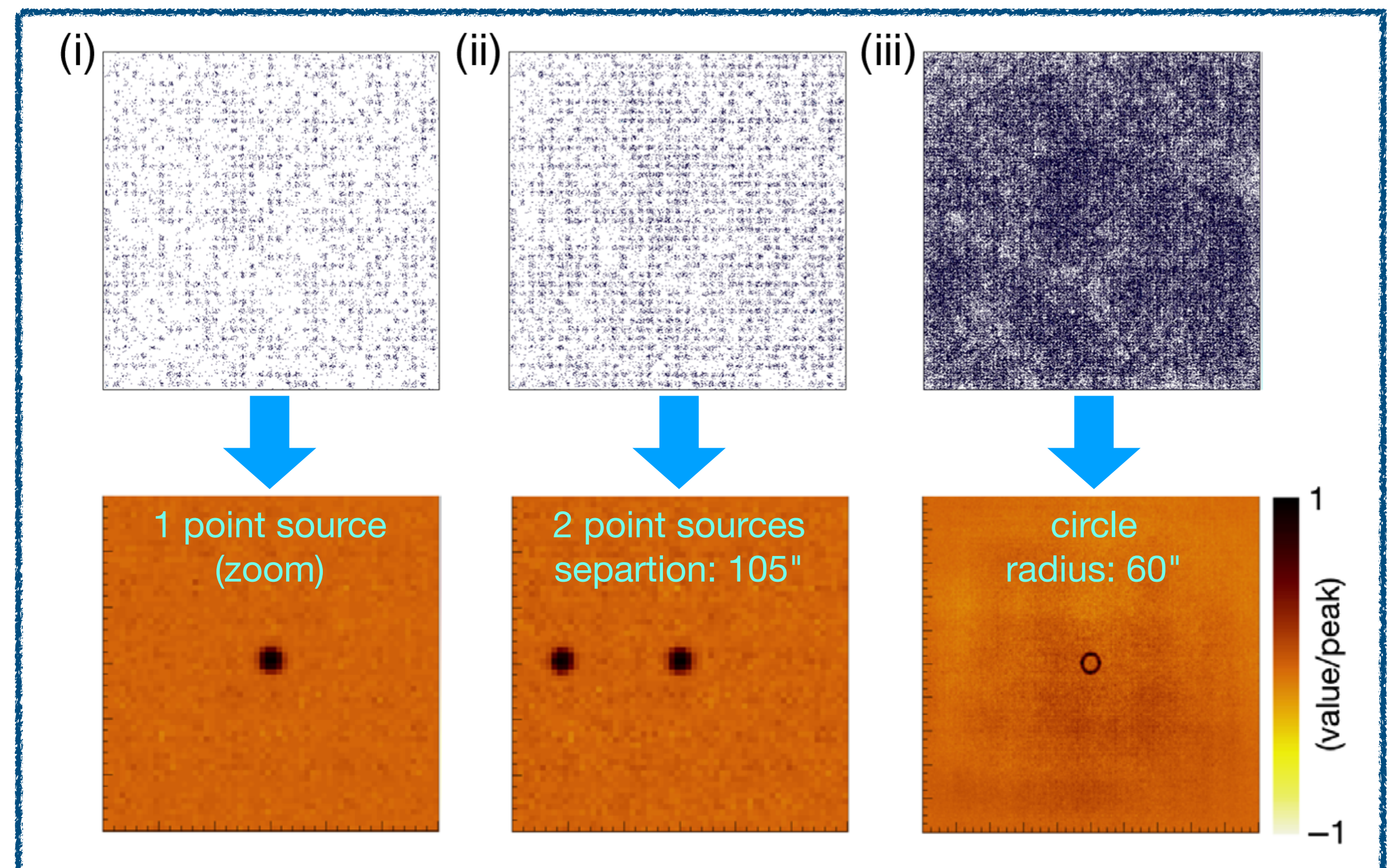


- ✓ Optics is necessary. A mirror is a straightforward way, but it requires large system size for its long focal length.
- ✓ Coded aperture imaging—a kind of computational imaging method. A shadow image is reconstructed into an object image.
- ✓ High angular resolution of 30" with a small system size of 25 cm



Coded aperture

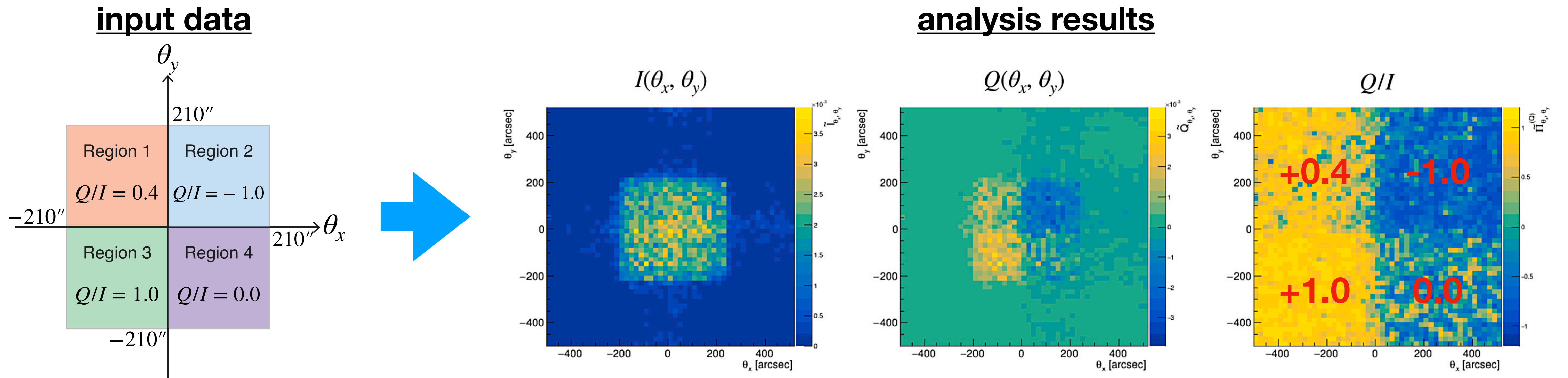
- ✓ femto-second laser microfabrication
- ✓ SUS304
- ✓ 100 μm thick
- ✓ 35 μm pitch



Polarimetric imaging with coded aperture mask

We successfully obtained a polarimetric image by the combination of a CMOS polarimeter and a coded aperture imaging.

We develop a new analysis technique using EM algorithm.



Tamba et al. 2024

Data: counts on the detector $v = (k, p_x, p_y, \phi)$ where k : pattern ID, (p_x, p_y) : pixel coordinates, $\phi \in \{\text{H-type, V-type}\}$: photoelectron angle
 Model: intensities in the sky $u = (\theta_x, \theta_y, \chi)$ where (θ_x, θ_y) : sky coordinates, $\chi \in \{0^\circ, 90^\circ\}$: polarization angle (here we assume Stokes-U is zero)

$$\text{E-step: } \tilde{Y}^{(l)} = \sum_u T_{uv} \tilde{X}_u^{(l)} \rightarrow \text{M-step: } \tilde{X}_u^{(l+1)} = \sum_v Y_v \frac{T_{uv} \tilde{X}_u^{(l)}}{\tilde{Y}_v^{(l)}} \quad (l : \text{iteration step})$$

Concluding remarks

- ✓ CMOS imaging sensors with fine pixels for visible light have great capability of X-ray spectro-polarimetric imaging.
- ✓ Small pixels are essential: we used 2.5 μm pixels (GPixel GMAX0505) and 1.5 μm pixels (Canon LI8020SA).
- ✓ We completed the proof-of-concept experiments using linearly polarized X-ray beam at SPring-8 and KEK-PF in 6–30 keV.

Ongoing projects and future prospects of CIPHER

- We are planning to use this sensor system for solar X-ray polarimetry mission and to deploy it into atomic physics experiments.
- For higher polarimetric sensitivity, we need a “real” X-ray detector with thicker sensitive layer.
→ hybrid sensor of fine-pitch CMOS readout + X-ray sensing high-resistivity (FZ) Si layer would be promising.