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Development of the X-ray imaging polarimeter using micro-pixel CMOS imager

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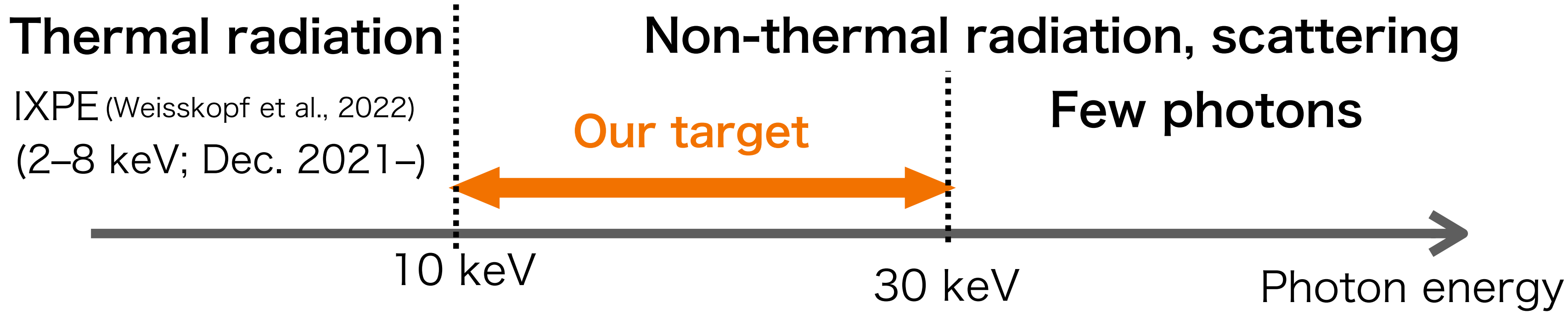
X-ray polarimetry in astrophysics

X-ray polarimetry in astrophysics

➡ understanding the structure of celestial objects

- Synchrotron radiation ➡ Magnetic field
- Scattering ➡ Geometrical structure



Hard X-ray (10-30 keV) polarimetry
is a frontier of X-ray astronomy

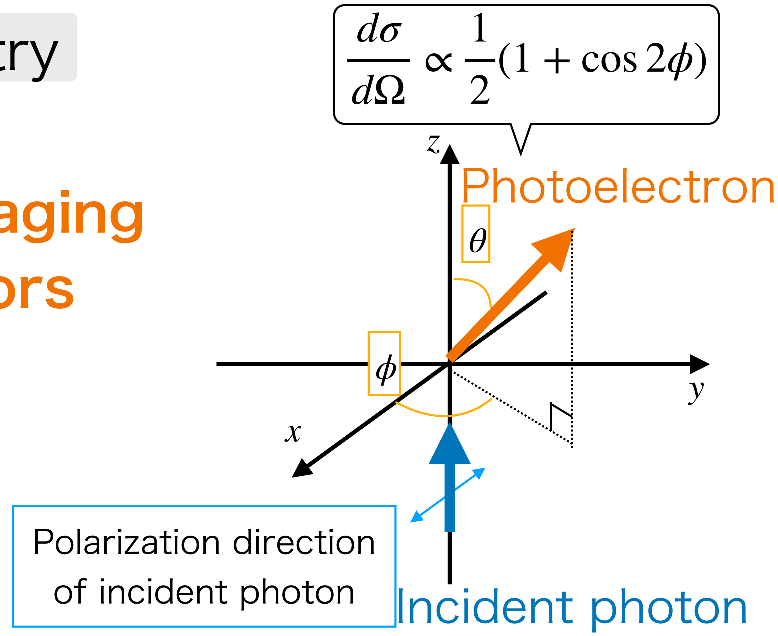
cipher

(Coded Imaging Polarimetry of High Energy Radiation; Odaka et al. 2020)

micro-pixel CMOS sensor + coded mask

➡ hard X-ray (10–30 keV) imaging polarimetry

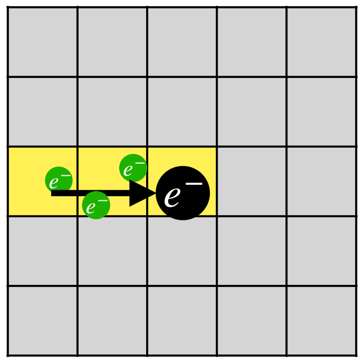
Trying to realize **hard X-ray (10-30 keV) imaging polarimetry using micro-pixel CMOS sensors**



CMOS sensor as polarimeter

- Photoelectrons tend to be emitted to the polarization angle of incident photons.
- distribution of the photoelectron direction

➡ polarization degree and polarization angle



Progress so far and purpose of this study

Progress so far

- Development of readout system specialized for X-ray measurement
- Successful proof-of-principle experiment

Master thesis: Kasuga (2019)、Aizawa (2020)、Hatauch (2021)、Watanabe (2022)

Problem

Evaluation of **polarization sensitivity** of CMOS sensors by combining **modulation factor (MF)** and **detection efficiency (DE)**

MF: modulation amplitude for perfectly polarized incident radiation

Purpose of this study

Evaluate and compare the MF/quality factor (QF) of two CMOS sensors with different pixel sizes and detector thicknesses.

Quality factor (QF) = $\mathrm{MF}\sqrt{\epsilon}$

*ϵ: Quantum efficiency (#events subject to polarization analysis /#incident photons)

→ Polarization sensitivity

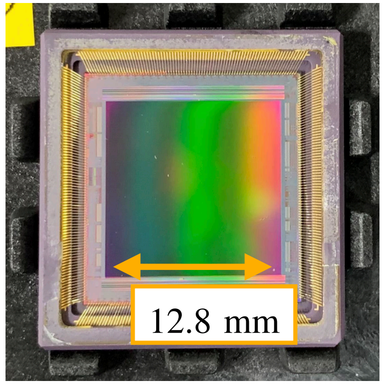
Sensor to be evaluated

CMOS sensor used in the experiments

Front-illuminated micro-pixel sensors for visible light

	2.5 μm sensor (Gpixel)	1.5 μm sensor (Canon)
Pixel size	2.5 μm	1.5 μm
NIR enhanced	O	X

2.5 μm sensor

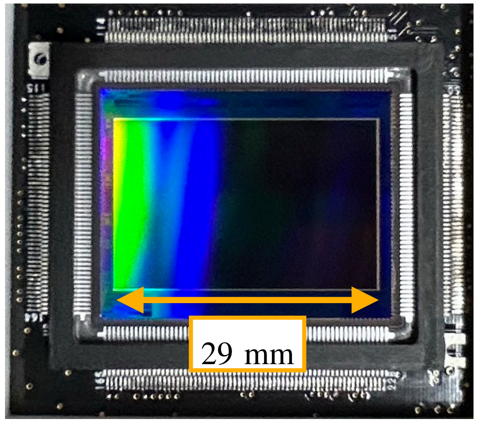


GMAX0505RF

Expectation

- 1.5 μm sensor
  higher photoelectron tracking accuracy ➡ larger MF
- NIR-enhanced 2.5 μm sensor
  thicker detection layer ➡ higher DE

1.5 μm sensor



LI8020SA

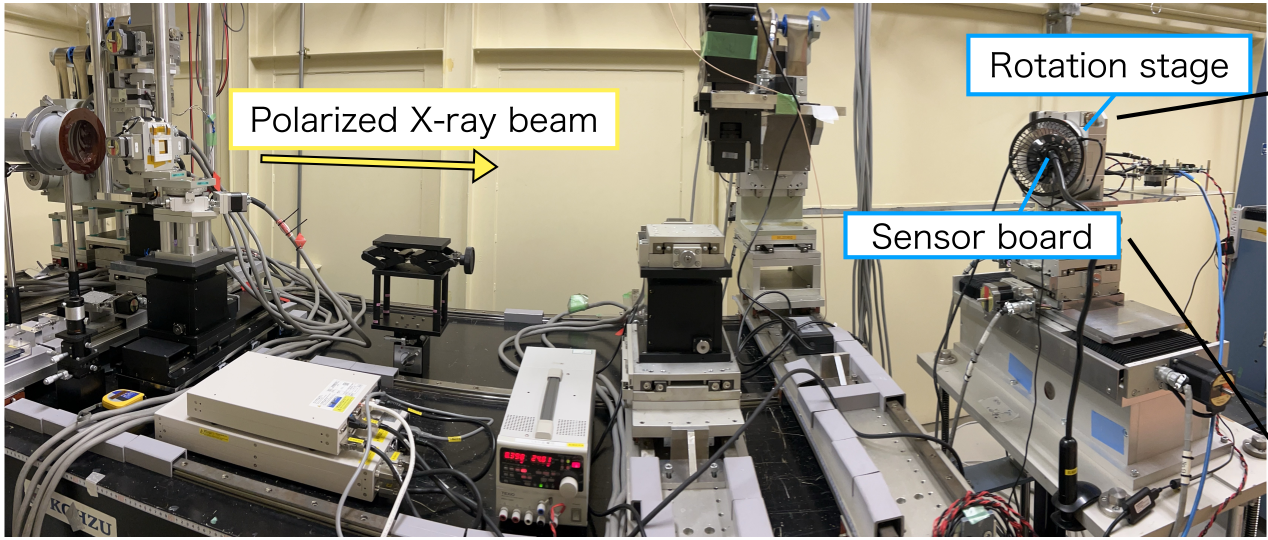
Evaluation items

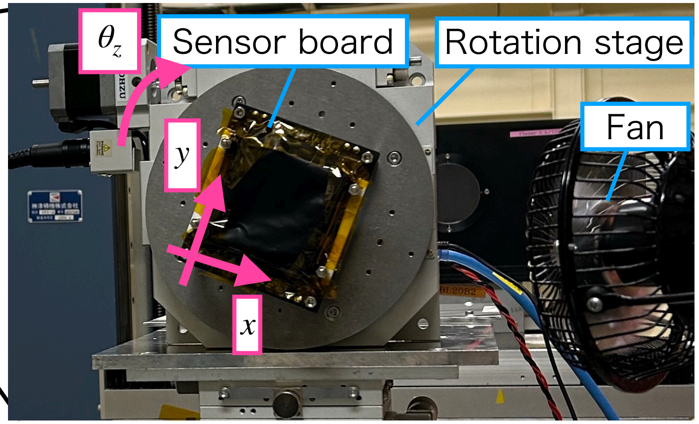
① MF (modulation factor)

② DE (detection efficiency)

→ ③ QF ($= \mathrm{MF}\sqrt{\epsilon}$)

① MF measurement: beam experiments





Nov. 2022, Jun. 2023 SPring-8 beam line BL20B2

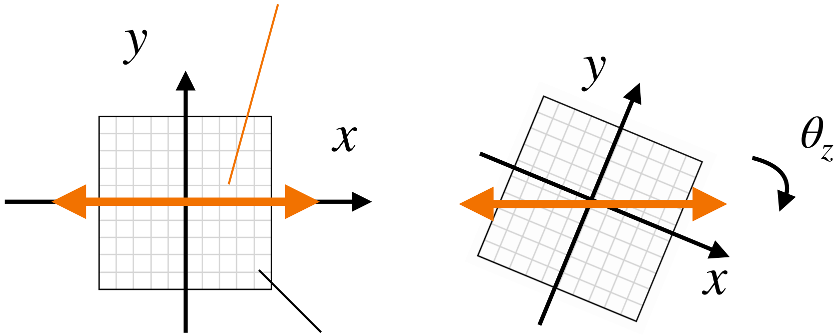
Purpose

- Measurement of MF at 10–22 keV

Measuring conditions

- Almost 100% horizontally polarized monochromatic beam
- Acquired data at multiple energies
- Rotated the stage to change the incident polarization angle

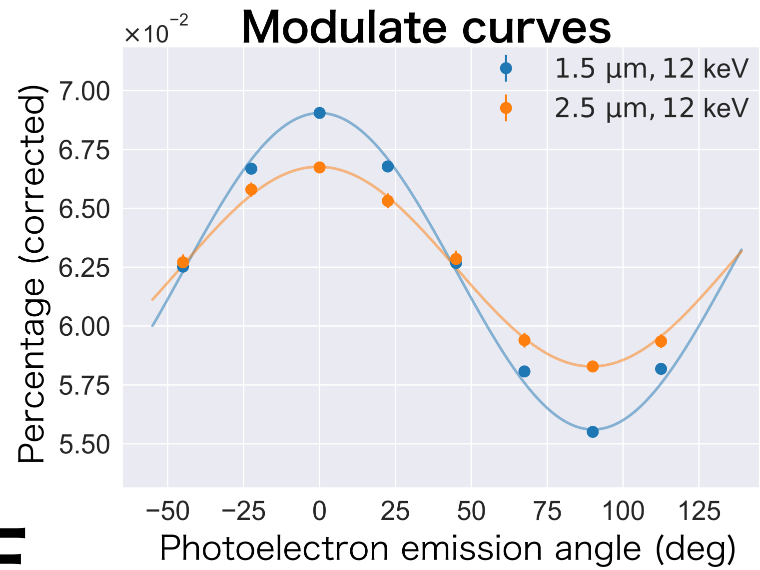
Polarization direction of incident beam



① MF Measurement: analysis

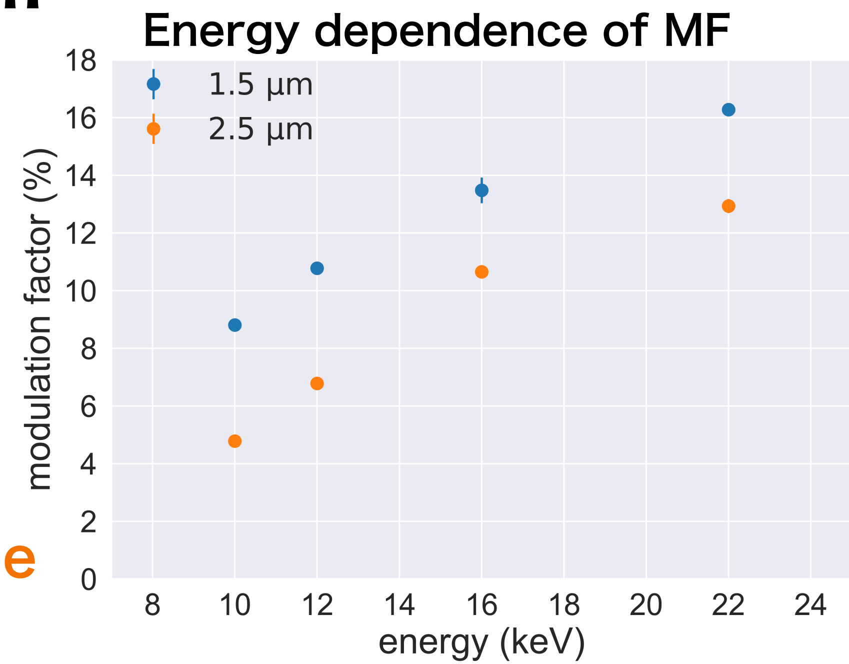
MF at each energy

- The second moment of the charge distribution
  ➡emission direction of photoelectron
- The distribution of photoelectron direction after correction
  ➡MF



Energy dependence of MF

- The higher the energy, the larger the MF.
- MF is larger for 1.5 μm sensor at all energies
- The lower the energy, the greater the ratio of increase in MF



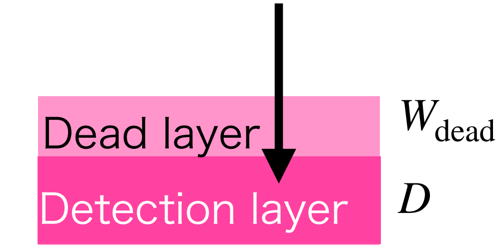
We have confirmed that reducing the pixel size significantly improves MF

② DE measurement: experiment

Detection layer thickness D

<u>Assumption:</u>

There is a dead layer of Si in front of the detection layer

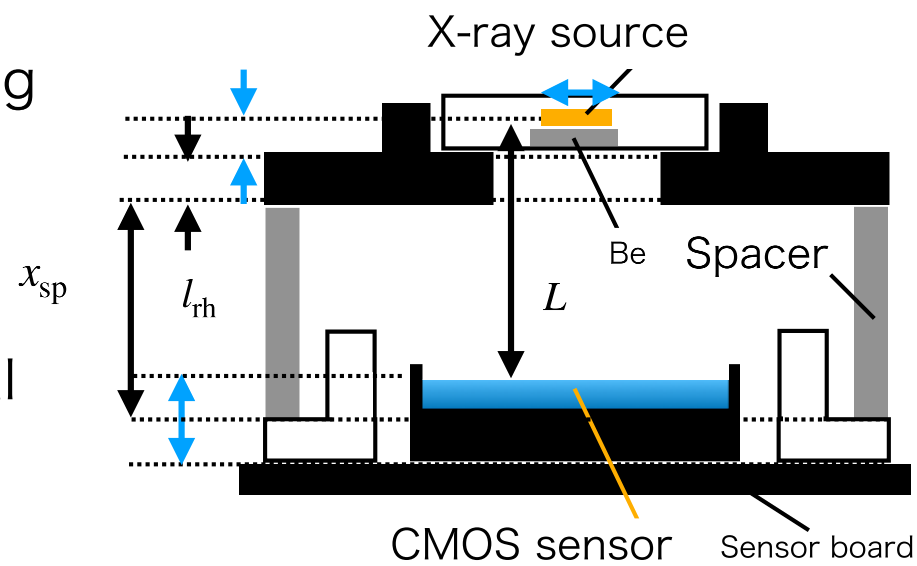


$$\mathrm{DE} = \underbrace{\exp\left(-\frac{W_{\mathrm{dead}}}{l_{\mathrm{mean}}}\right)}_{\text{Transmittance}} \cdot \underbrace{\left[1 - \exp\left(-\frac{D}{l_{\mathrm{mean}}}\right)\right]}_{\text{Absorption probability}}$$

*l_{mean}: mean free path for photoelectric absorption of Si

Outline of Experiment

1. Measure the X-ray count rate, using X-ray sources $^{55}\mathrm{Fe}$ and $^{109}\mathrm{Cd}$.
2. Calculate theoretical count rate.
3. Compare measured and theoretical values to obtain D and W_{dead}



Perform experiments with several x_{sp}

➡ obtain distance correction (l) and the size of the X-ray source (r).

② DE measurement: analysis

Estimation of detector thickness

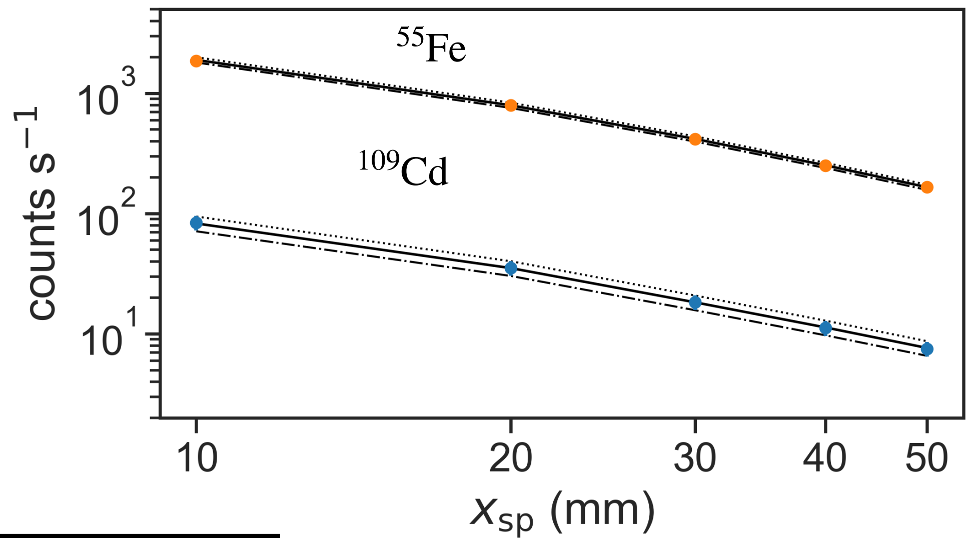
10 data points: 5 for ^{109}Cd, 5 for ^{55}Fe

4 free parameters: D, $W_{\rm dead}$, l and r

Uncertainties on X-ray source intensity and event criteria

➡ Errors in D and $W_{\rm dead}$

Data points and fitting curve (1.5 μm sensor)



Results

	2.5 μm sensor	1.5 μm sensor
D	16.04 ± 0.81 μm	2.56 ± 0.37 μm
$W_{\rm dead}$	10.3 ± 1.8 μm	3.2 ± 4.2 μm

NIR-enhanced 2.5 μm sensors have a thicker detection layer

③ Quality factor (QF) and future plans

Estimation of ϵ

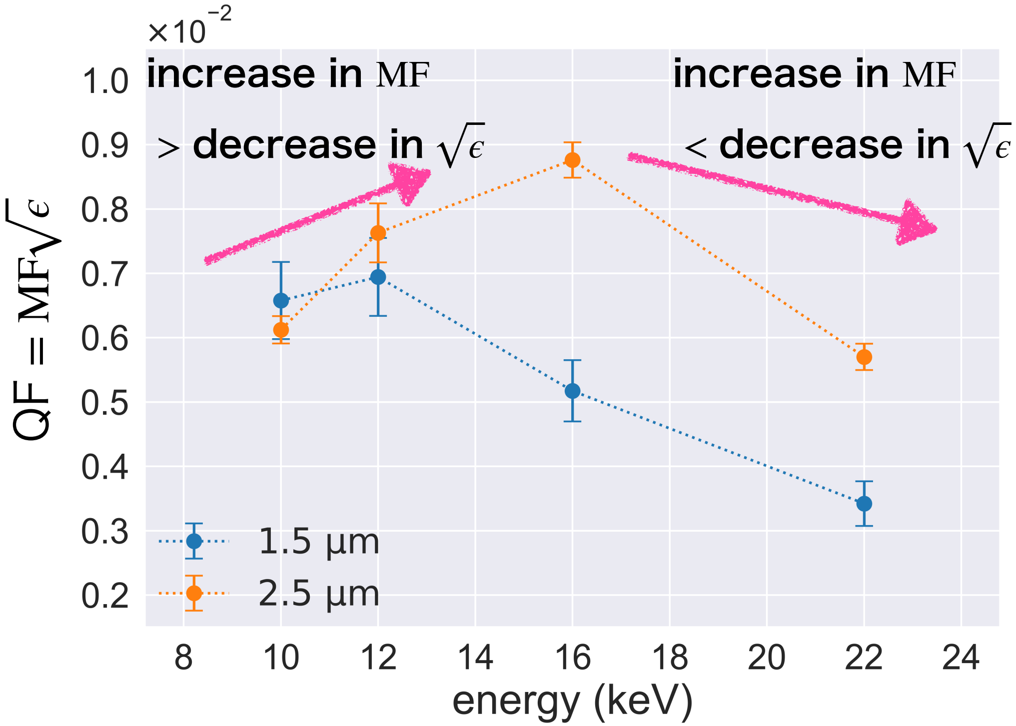
- D and W_{dead}

➡ DE and ϵ at each energy

*ϵ: Quantum efficiency
$=$ DE $\cdot$ (#events subject to polarization analysis /#detected events)

QF of the sensors

- Peak QF energy is lower for the 1.5 μm sensor
- **2.5 μm sensor has higher polarization sensitivity above 10 keV**



Future tasks

- Understanding the relation between $\left\{\begin{matrix}\text{pixel size} \\ D\end{matrix}\right.$ and $\left\{\begin{matrix}\text{MF} \\ \text{QF}\end{matrix}\right.$
- Improve polarization analysis method

➡ Improve MF especially for 1.5 μm sensor

Summary

- We aim to **realize polarization observation of hard X-rays (10-30 keV) using micro-pixel CMOS sensors (cipher).**
- **The MF, detector thickness, and quality factor of sensors with pixel sizes of 1.5 μm and 2.5 μm were evaluated and compared.**
- MF was measured at 10-22 keV in beam experiments at SPring-8.
  MF was greatly improved by using a 1.5 μm sensor.
- The measured detection layer thickness was
  $D = 16.04 \pm 0.81\ \mu\mathrm{m}$ for the 2.5 μm sensor and
  $D = 2.56 \pm 0.37\ \mu\mathrm{m}$ for the 1.5 μm sensor.
  The NIR-enhanced 2.5 μm sensor had a thicker detection layer.
- **The 2.5 μm sensor has a higher polarization sensitivity above 10 keV**.