Development of a CCD-CMOS Hybrid Sensor for High-speed X-ray Imaging Spectroscopy in X-ray Astronomy

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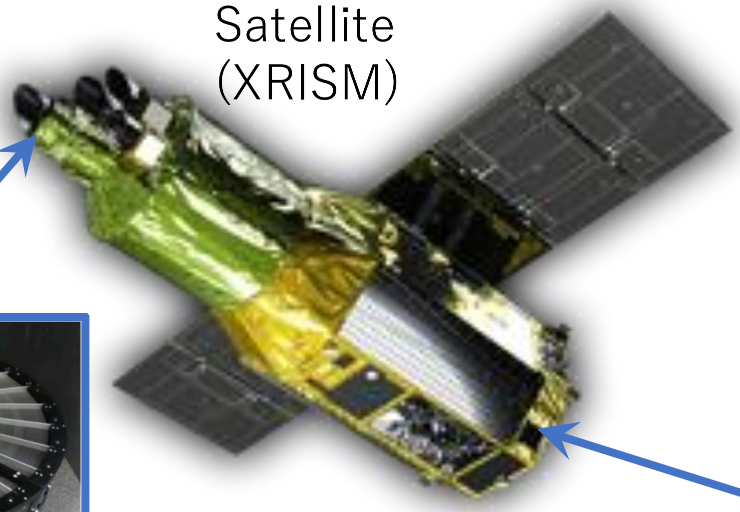
Outline

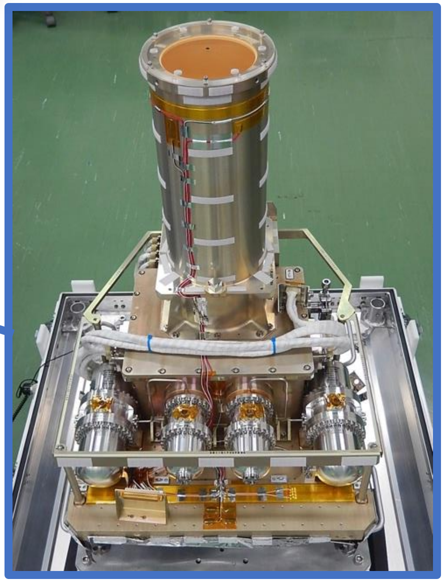
- Background : CCD as soft X-ray imager in X-ray observatories
    - Issues : timing resolution and pile-up
    - Requirements for future onboard sensors
- Proposed sensor
    - CCD (imager) + CMOS (ROIC)
- Initial result of X-ray imaging spectroscopy
- Summary and planned updates

Backgrounds : X-ray CCD as cosmic soft X-ray imaging spectrometer

Satellite
(XRISM)

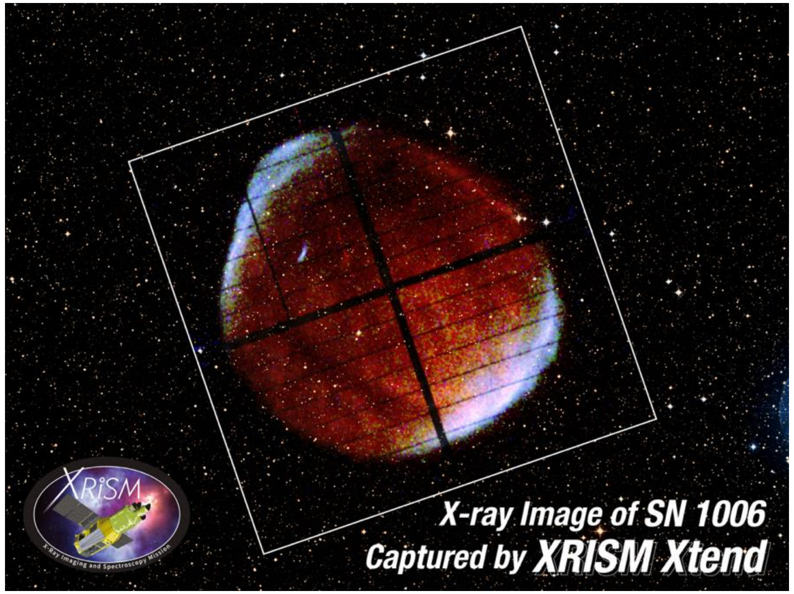


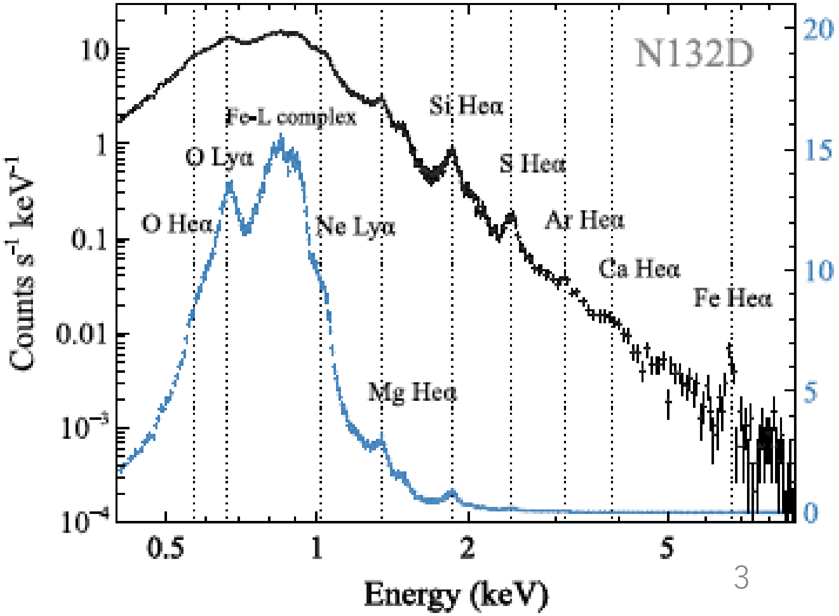
X-ray mirror



CCD camera
(SXI)

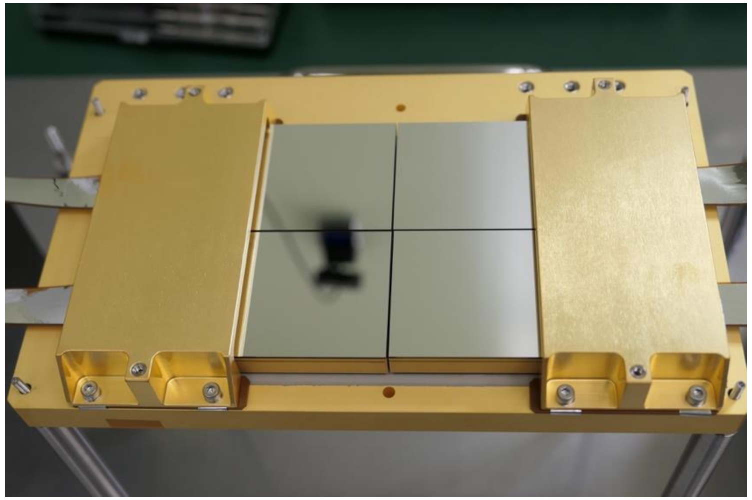
Noda+25





- ➢ CCD is standard detector in X-ray observatory (e.g., XRISM/Xtend, Chandra, Swift, XMM-Newton, etc.)
- ➢ Small pixel size (10～50 μm□) enables high spatial resolution imaging of celestial objects combined with X-ray mirror.
- ➢ Operated with photon-counting mode for imaging-spectroscopy, which enables us to investigate plasma properties, electron energy distribution around blackholes, etc.

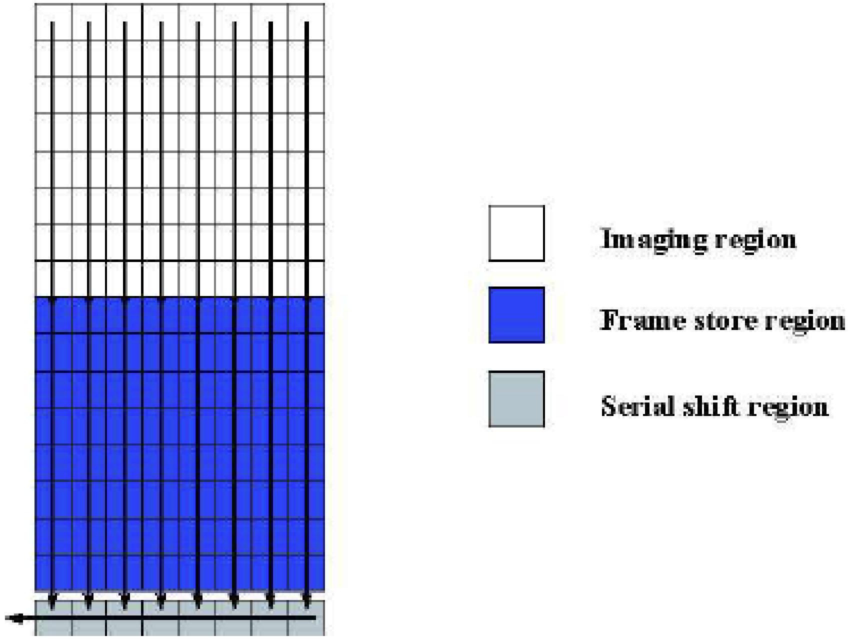
Backgrounds : X-ray CCD as cosmic soft X-ray imaging spectrometer



CCD for XRISM
Tanaka+18
HN+18

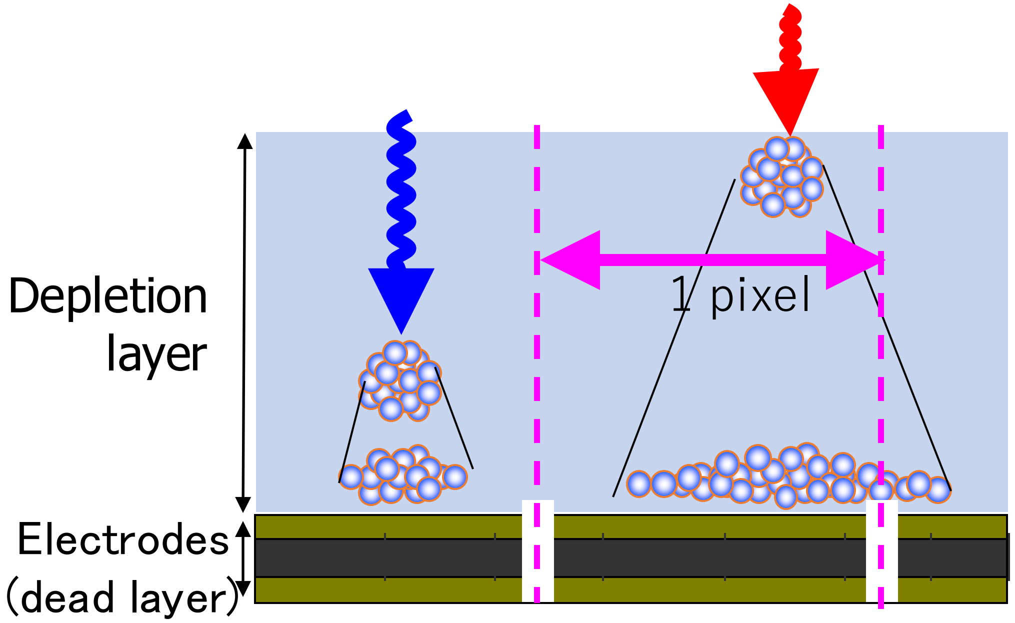
CCD for XRISM

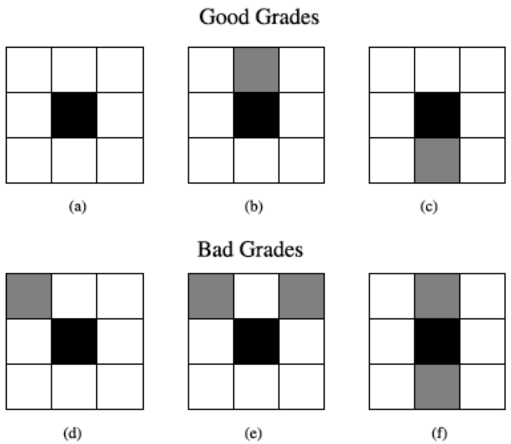
Pixel size	24 μm□
Pixel format	1280 × 1280
Channel type	Buried P-channel
Resistivity	>10 kΩcm
D_dep	200 μm
Transfer clock	2-phase
Dark current	500e-/pix/sec @0°C
RON	5-6 e- rms typical



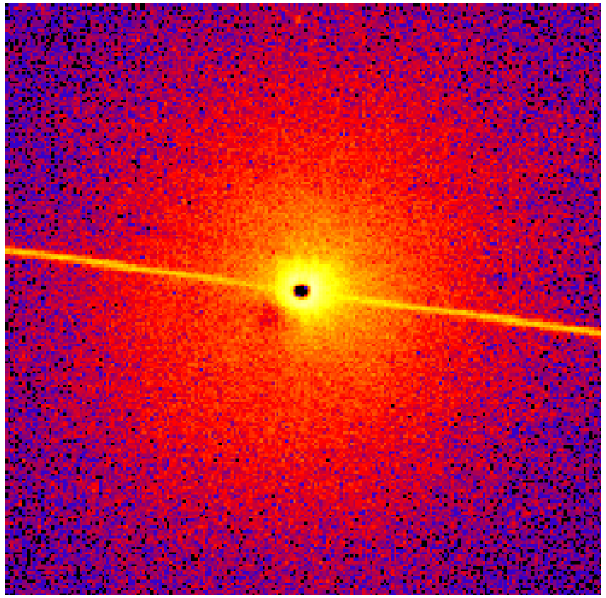
- Large number of pixels (typically 1kx1k) and commonly buttable packages enables high resolution imaging throughout wide field of view.
- Increasing resistivity and/or E-field, 100-500 μm depletion layer have been achieved and sensitive up to 100keV.
- Adopting back-illumination structure makes us effectively detect soft X-rays sensitive down to 0.3keV.
- Frame transfer is often adopted : exposure in imaging region followed by vertical and horizontal transfer in the frames store region.

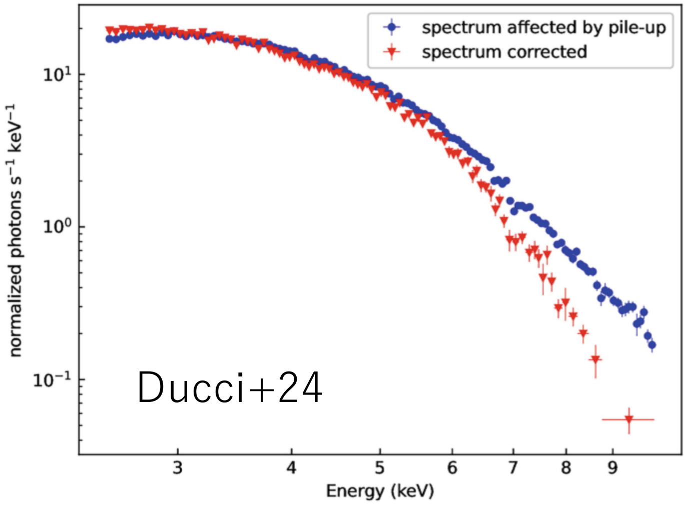
Issues of conventional focal plane CCDs：pile-up





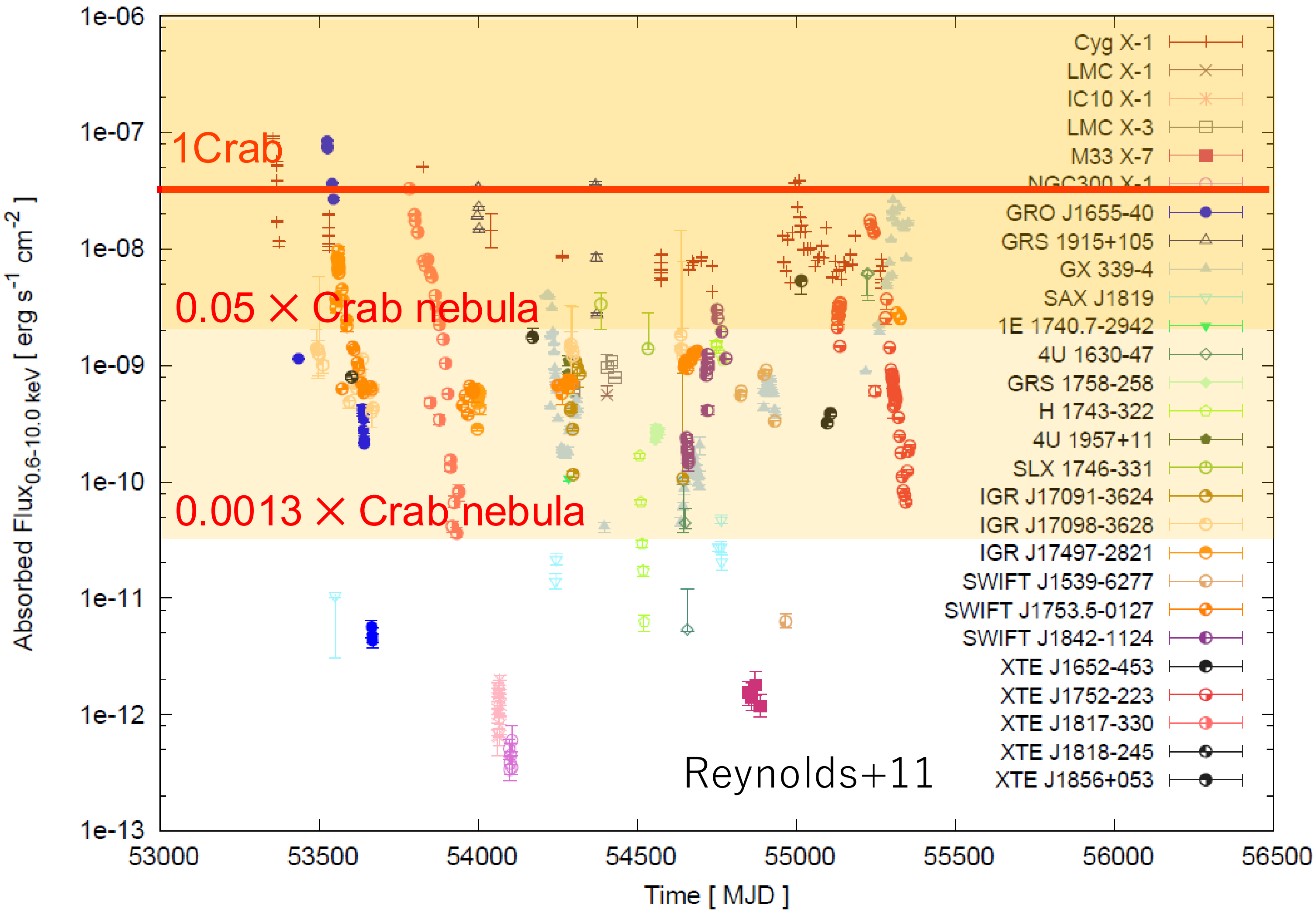
Davis 01

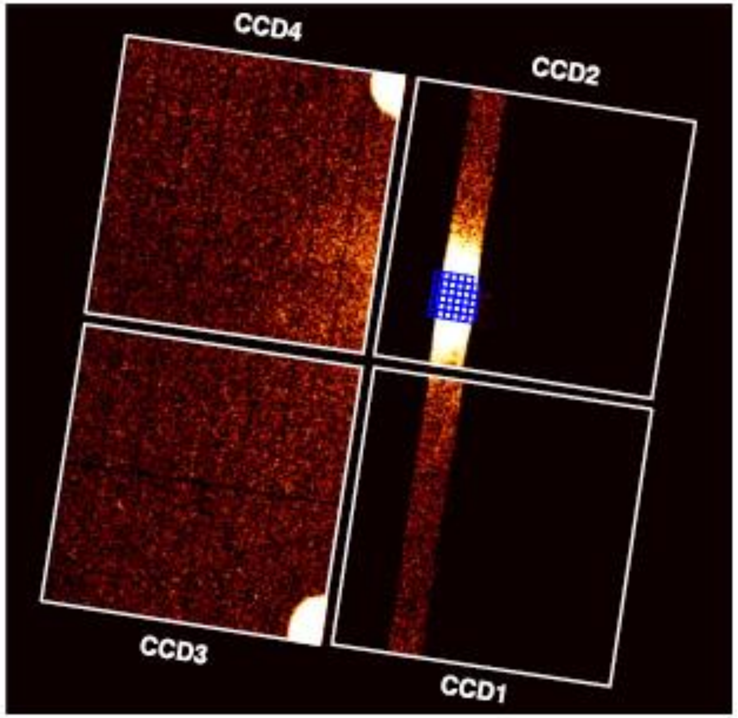




- Pile-up is the recording of multiple photons during single exposure that is regarded as single event, which leads to changes in the spectrum and the rejection of some events due to a change.
- Pile-up of continuum photons will skew the spectral shape to yield higher fitted plasma temperatures.
- Future X-ray mirror with large effective area will make pile-up occur easily for many objects.

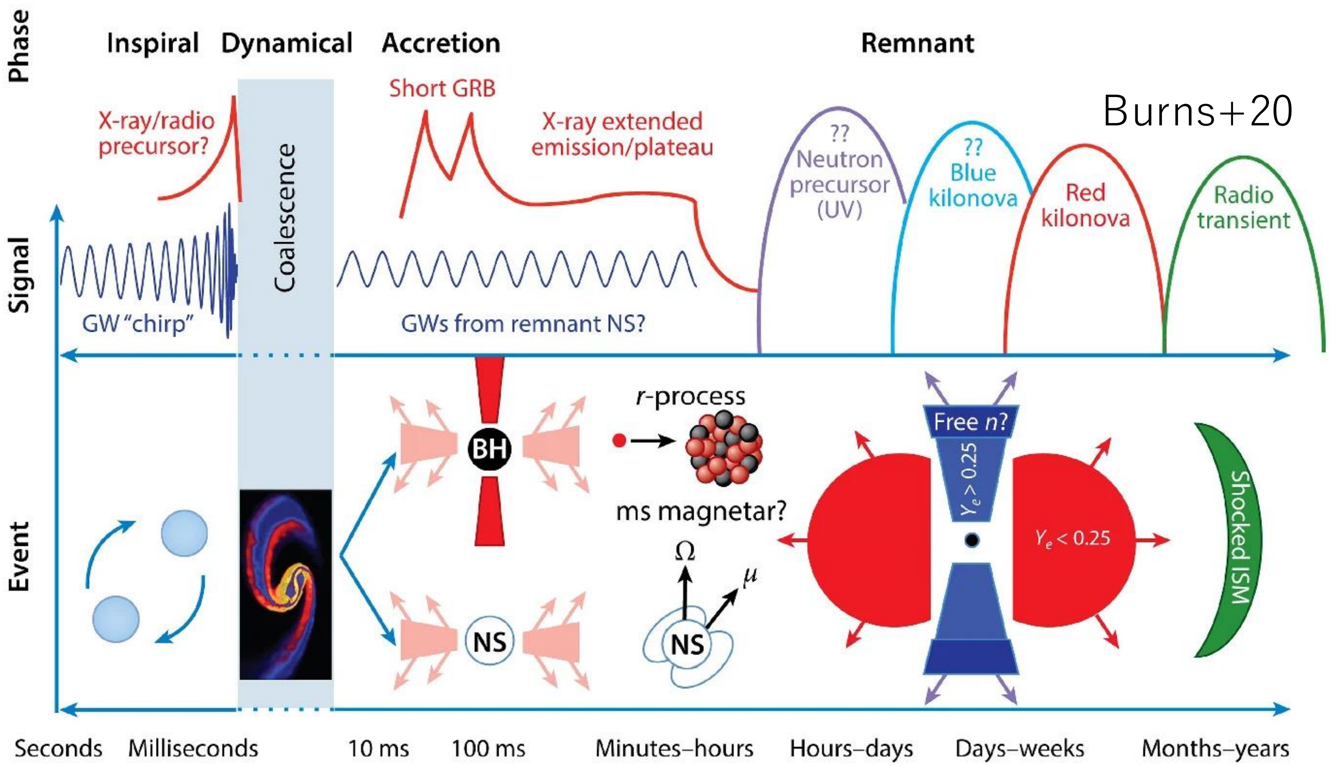
Issues of conventional focal plane CCDs：pile-up

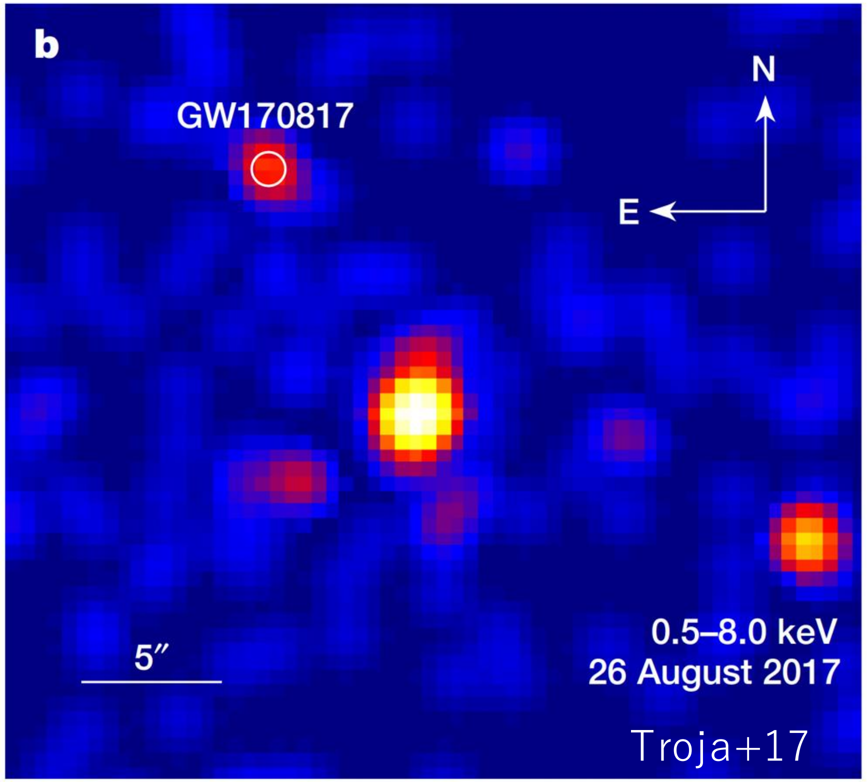




- CCD camera often suffers from pile-up for many X-ray binaries due to the long readout time per frame.
- We are forced to perform intermittent exposure (e.g., 0.1sec/4sec in the case of XRISM CCD camera) and/or reading out only a part of the image.

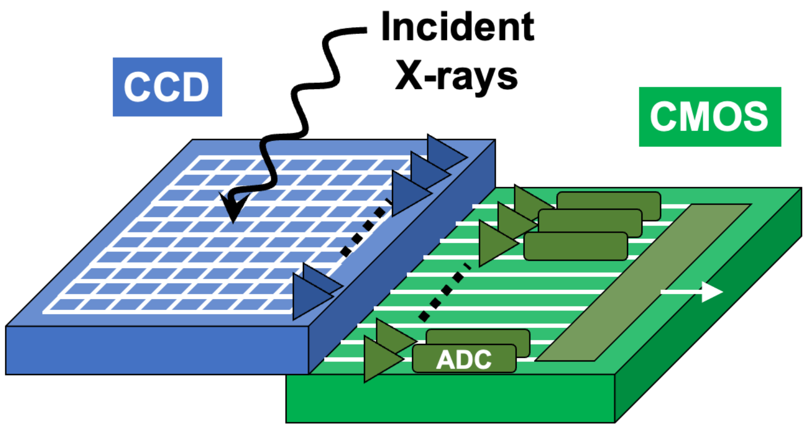
Objectives : Imaging spectroscopy for time domain astronomy

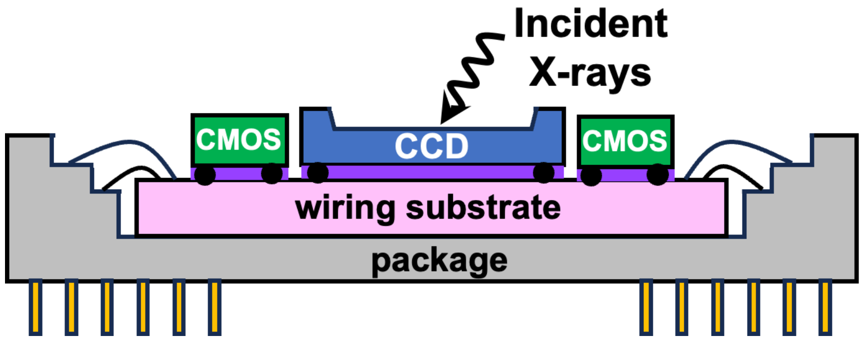


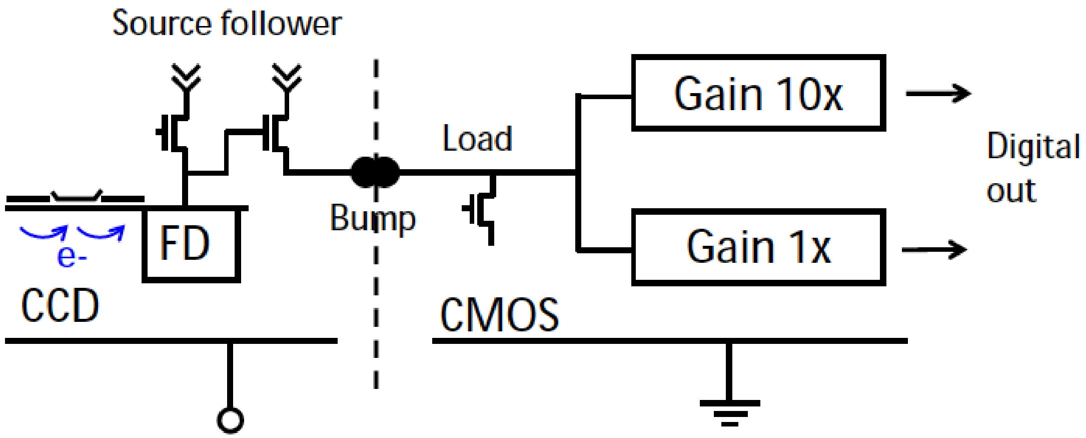


- Obtaining intense time variability before and after the merging events without any intermittency is essential, although we need to put an assumption that we point a telescope at region of candidate.
- Being adaptable to crowded region (requiring ～5arcsec HPD) with sufficient spectroscopic performance is needed for future focal plane detector.
  - CCD: several readout nodes for ～1 Mpixels with speed of ～100kHz → several sec/frame
  - CMOS image sensor: high frame rate with large number of pixels, but thickness of depletion layer ≦ ～ 30 μm → limited efficiency for > 2 keV.

Methods : CCD + CMOS hybrid sensor

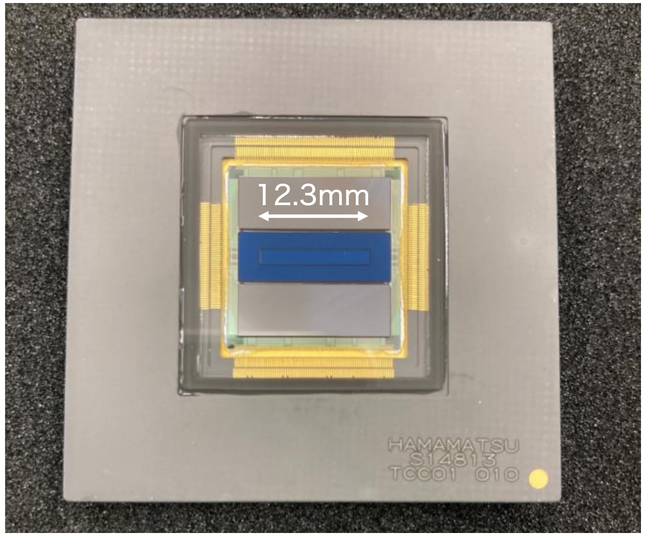


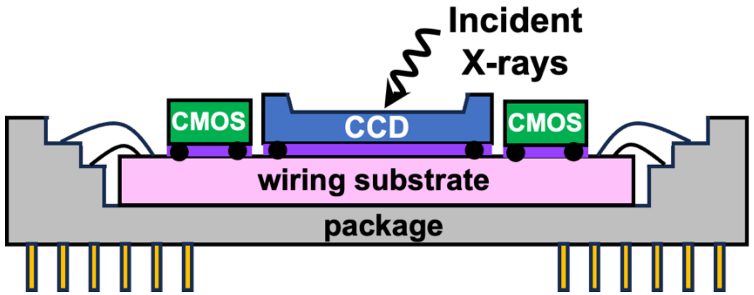




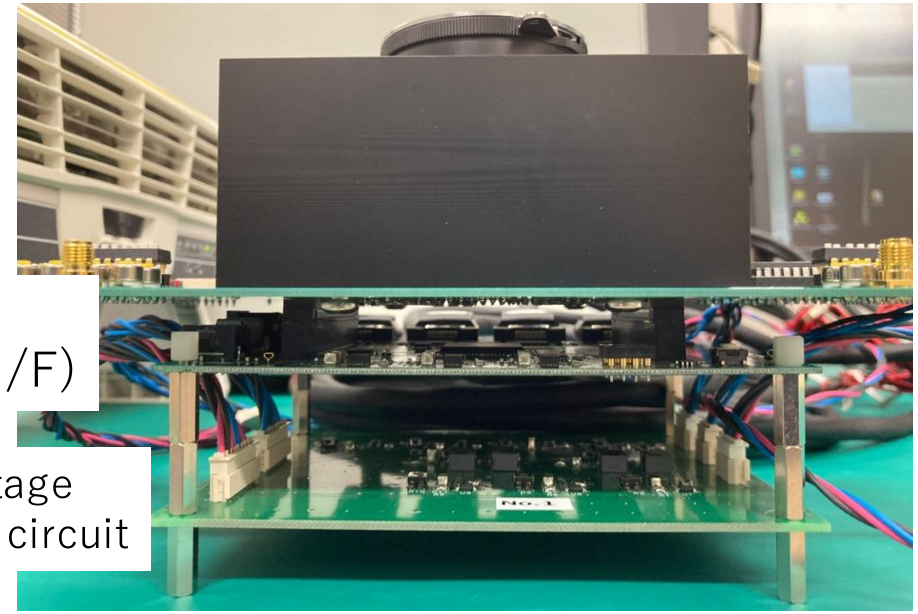
- CCD : readout nodes are implemented for every columns
  - ～100 times quicker readout rate
  - Back-side illumination type CCD makes high sensitivity for soft X-rays
- CMOS : column-parallel AD conversion and transfer signals after serialization
  - Implementing RO circuit in another wafer makes the circuit flexible
- CCD and CMOS are connected via bumps and wiring substrate
  - No shorting by adopting individual ground

TDICCD + CMOS (HPK S14813)



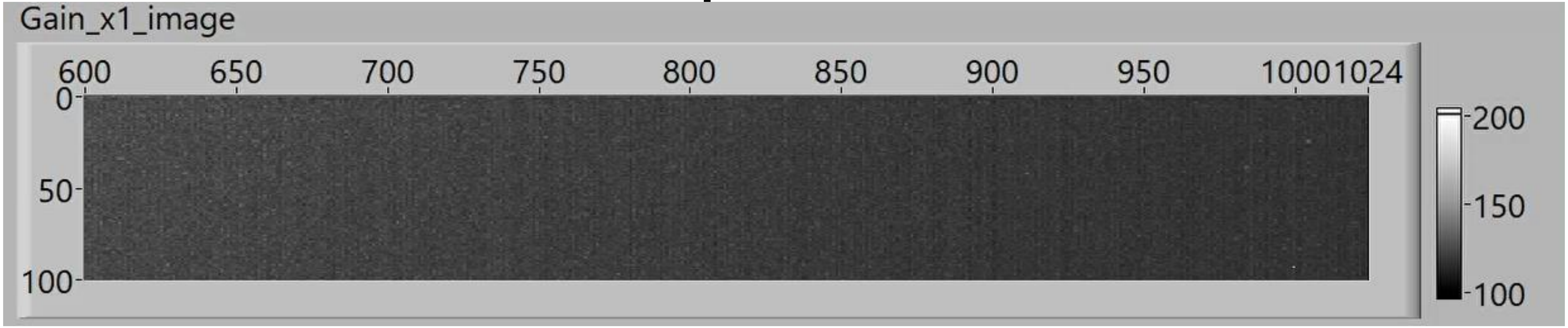


Pixel size	12 μ m□
Pixel format	1024 × 128
Channel type	Buried N-channel
Transfer clock	2-phase
Transfer speed	100 kHz
Full well	6.1 ke-
Dark current	500e-/pix/sec @0°C
RON	12 e- rms
D_dep	To be measured (～10 μ m expected)
output	10bit ADC



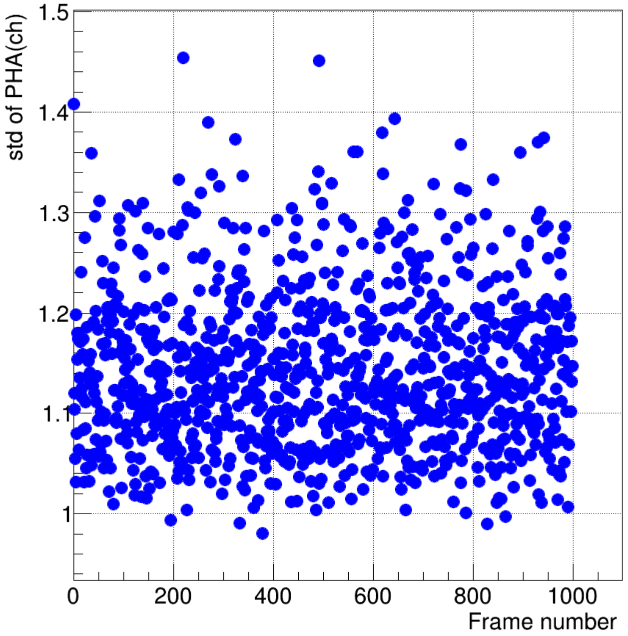
- Analog driving voltages (for CCD charge transfer・ground for CCD・output amplifier, etc.) are generated with individual ICs.
- CMOS output data are fetched via Camera link.

Initial operation test



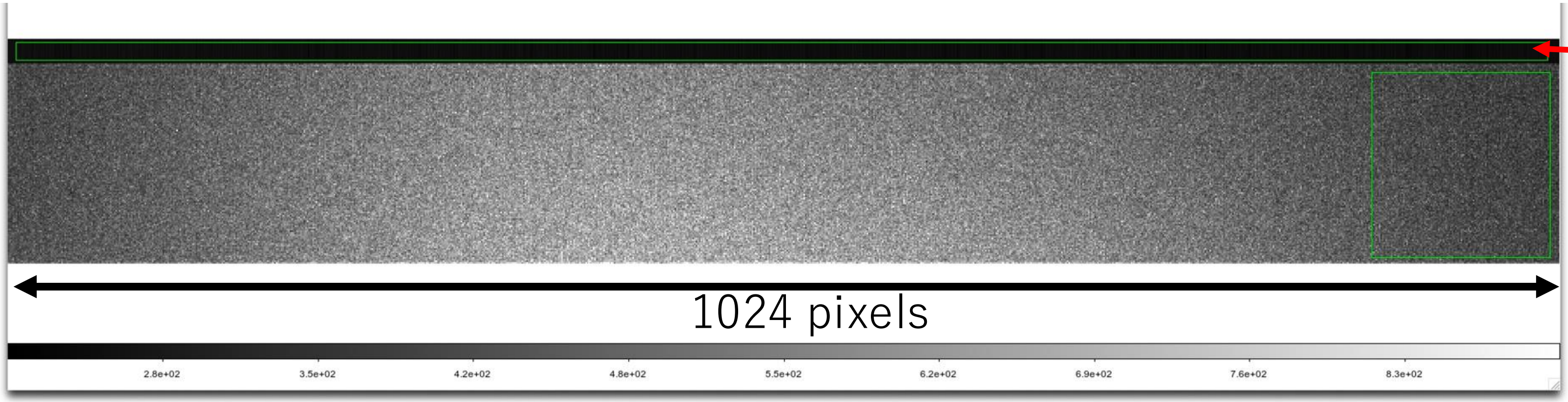
➢ Detect monochromatic X-ray from ^{109}Cd

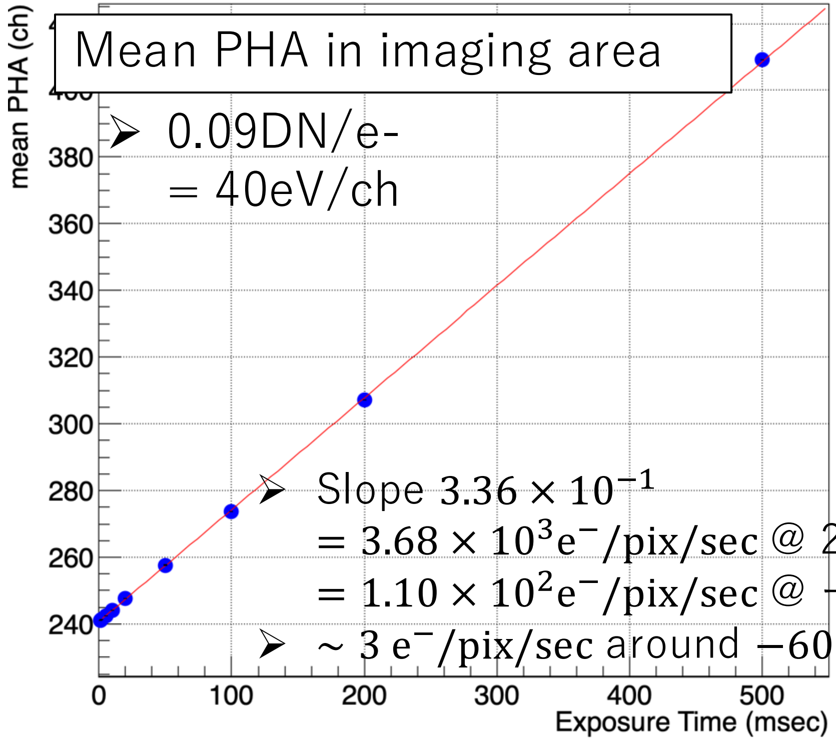
Operation mode	Area scan (vertical transfer after exposure)
Exposure time	0.2sec
No. of frames	1000 frames
Operation temperature	-20°C



Vertical over clock region
Mean: 244.2 ch
Std: 1.1 ch (≅12e-)

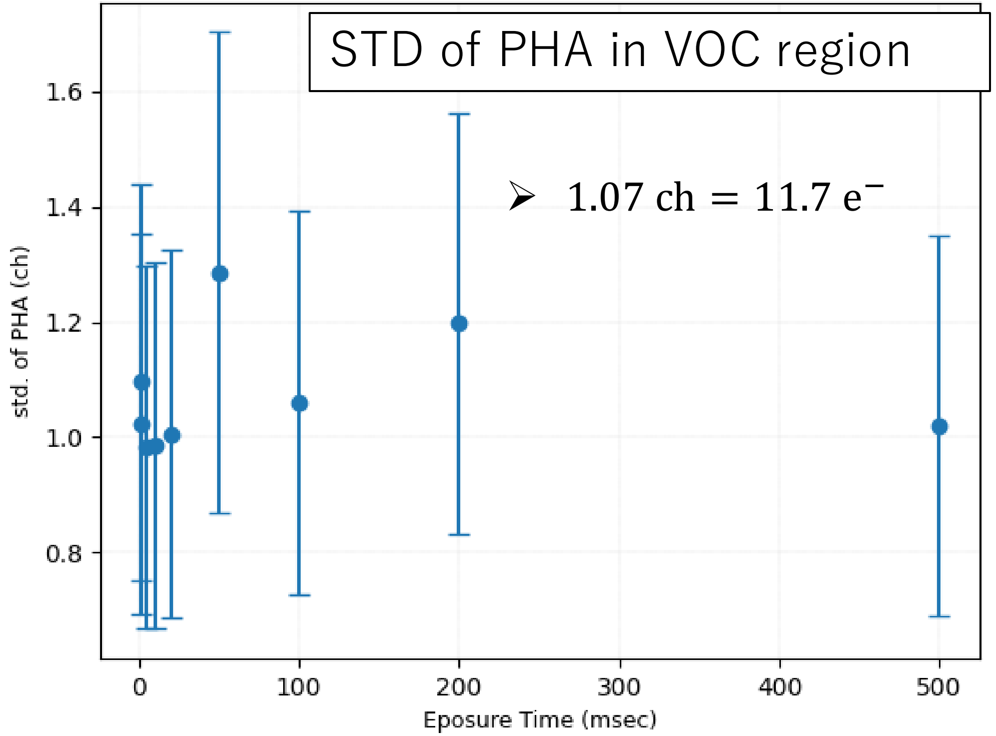
Dark current and readout noise level





Mean PHA in imaging area

- 0.09DN/e- = 40eV/ch
- Slope 3.36×10^{-1} $= 3.68 \times 10^{3} e^{-}/pix/sec$ @ 20°C $= 1.10 \times 10^{2} e^{-}/pix/sec$ @ −20°C
- $\sim 3\ e^{-}/pix/sec$ around −60°C

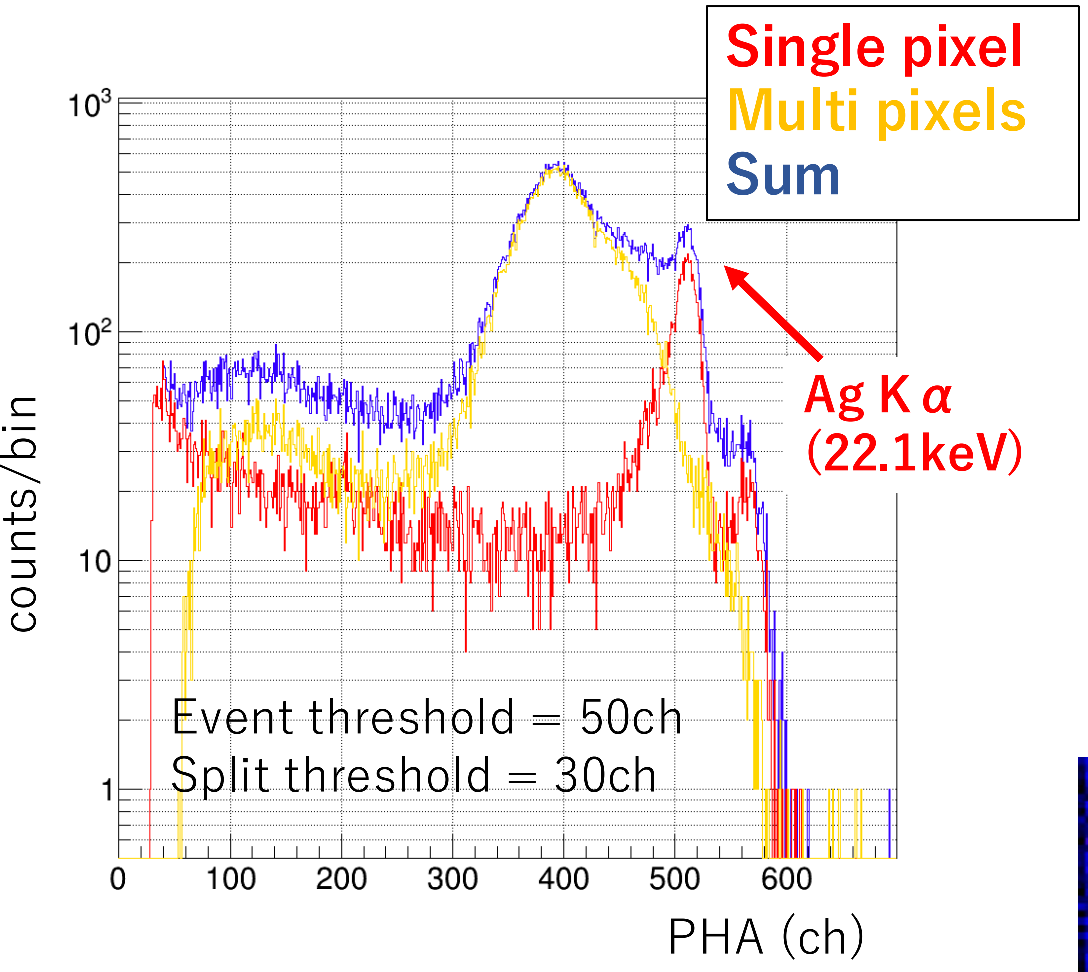


STD of PHA in VOC region

- $1.07\ \mathrm{ch} = 11.7\ e^{-}$

- Sufficiently low dark current (if cooled down below 0°C) and readout noise.

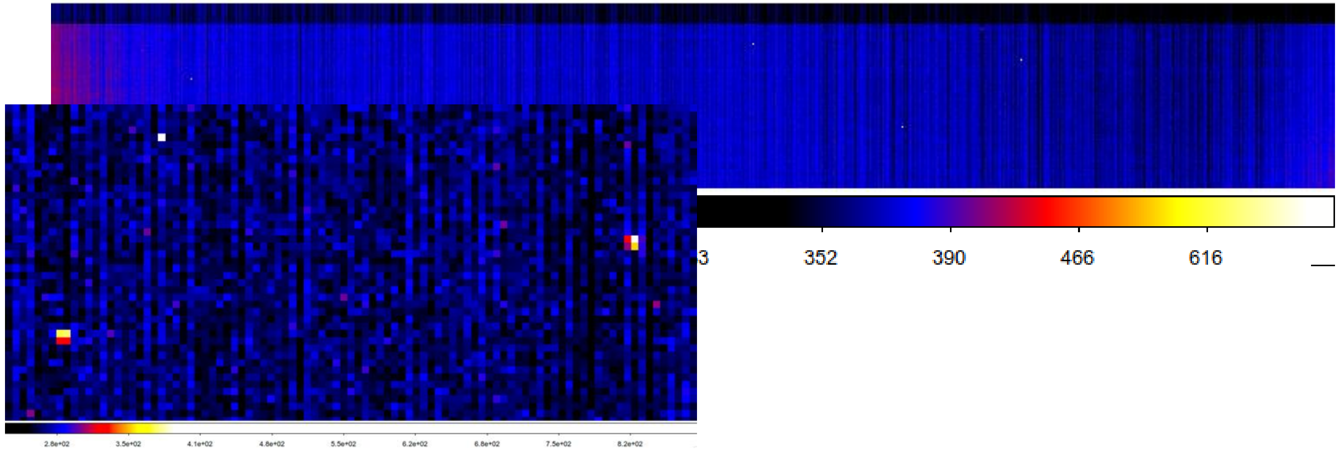
^{109}Cd spectrum



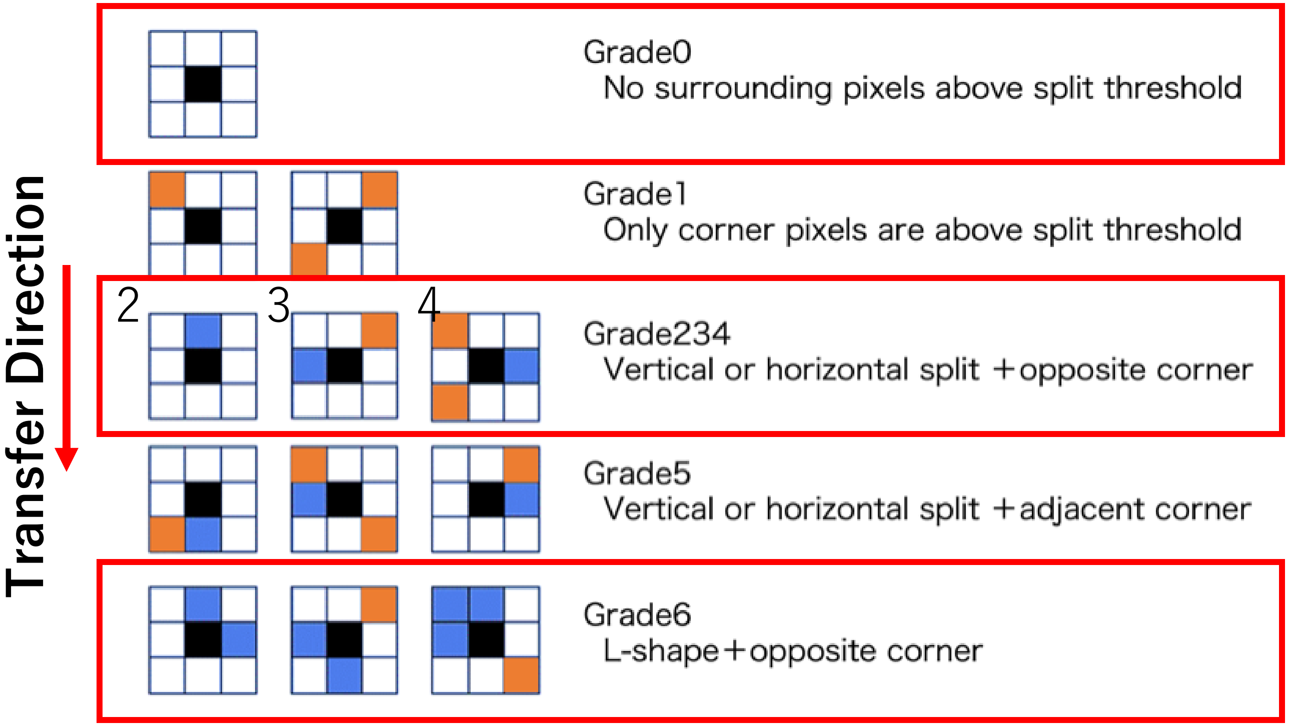
- Successfully detect Ag K α line from ^{109}Cd
- Δ E (FWHM) = 4.4% = 0.97keV

$$\Delta E = 2.35 \times W \times \sqrt{\left(\frac{EF}{W}\right)^2 + N_{noise}^2}$$

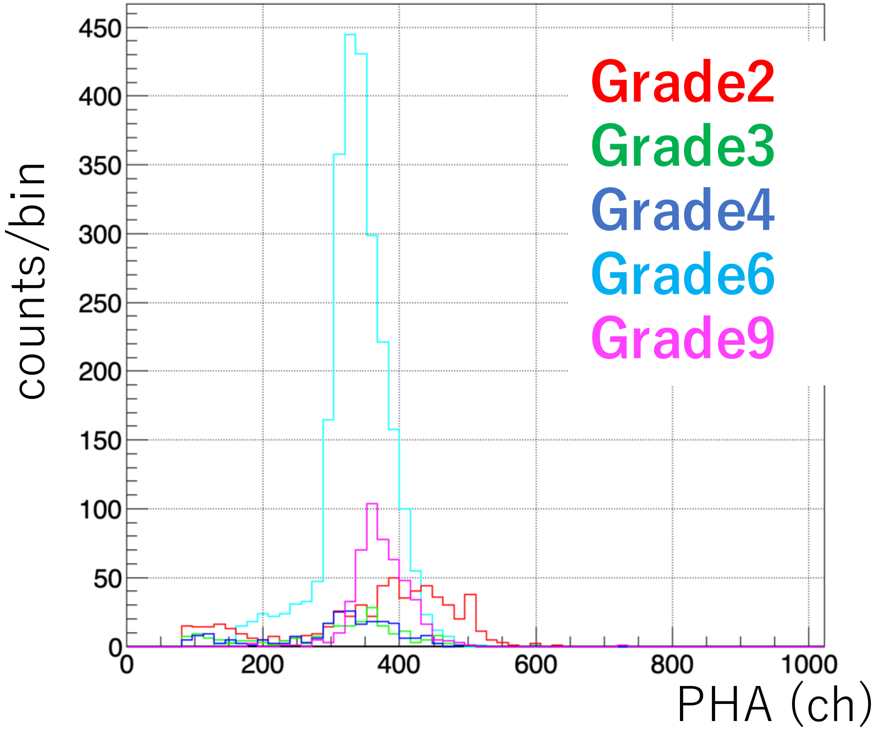
- $N_{noise} = 165e^-$ is slightly larger than expected (dark current + RON).
- Multi-pixel events lose 30～40% of signal charges.

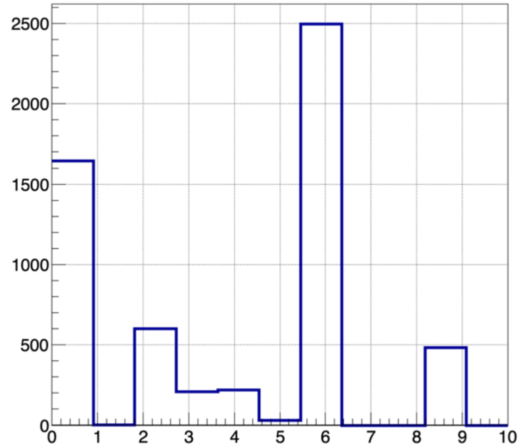


Grade-separated events



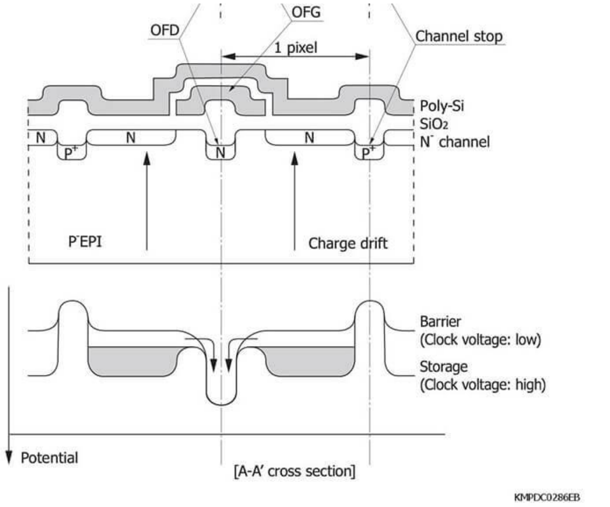
Spectra for each grade



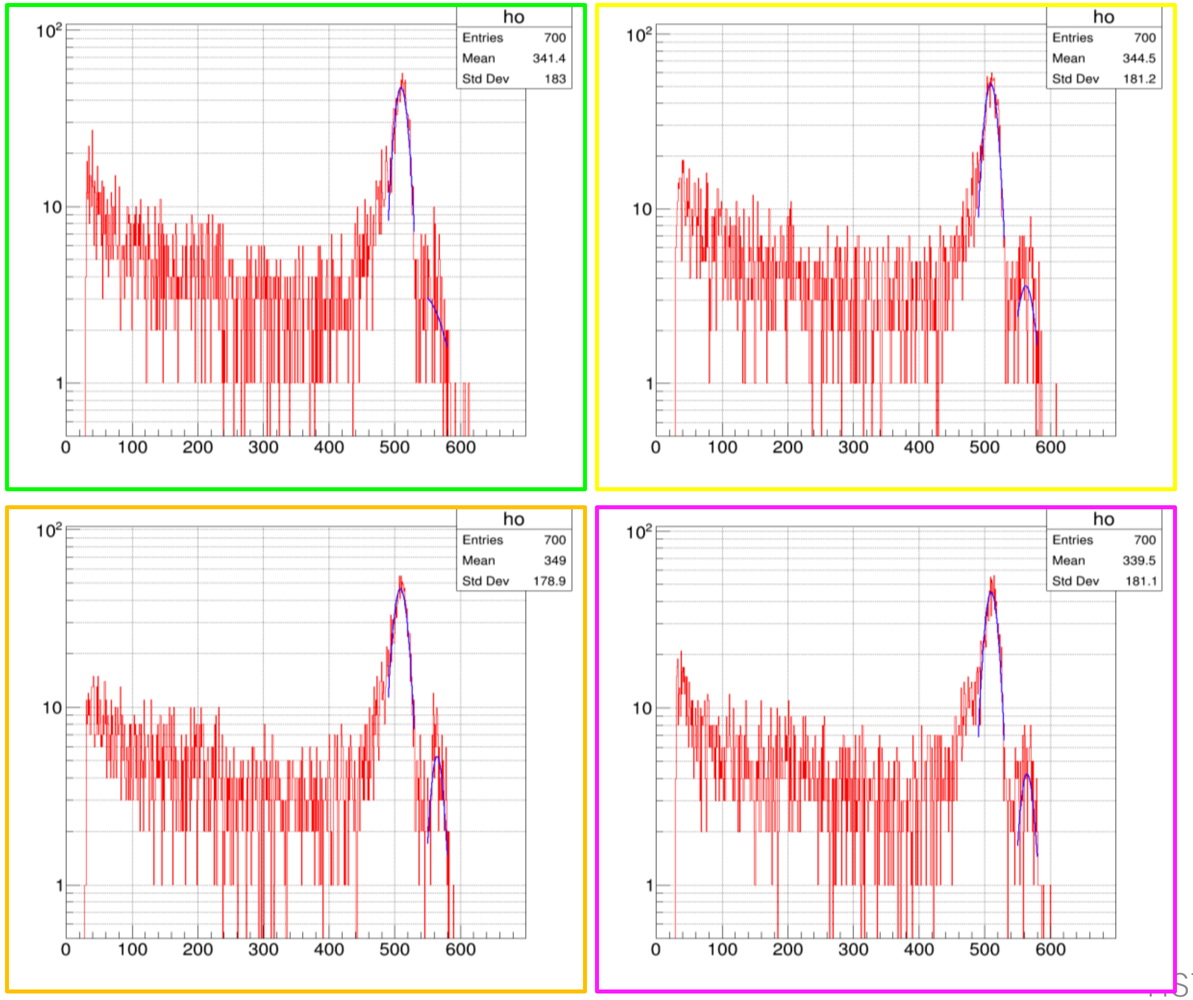


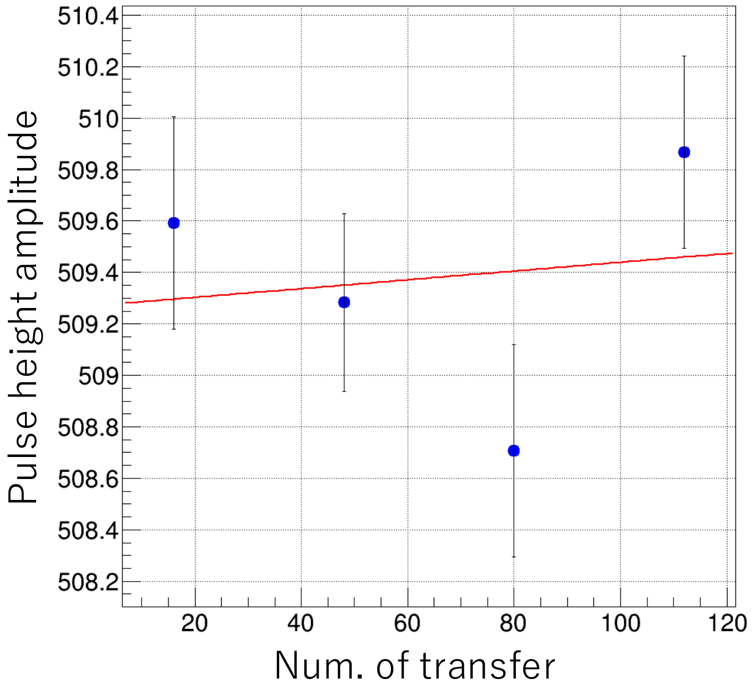
Grade branching ratio

- Horizontally split events (Grade 3 and 4) lose larger amounts of signal charges than Vertically split events (Grade2).
- It is possibly due to the anti-blooming drain structure along the transfer path.



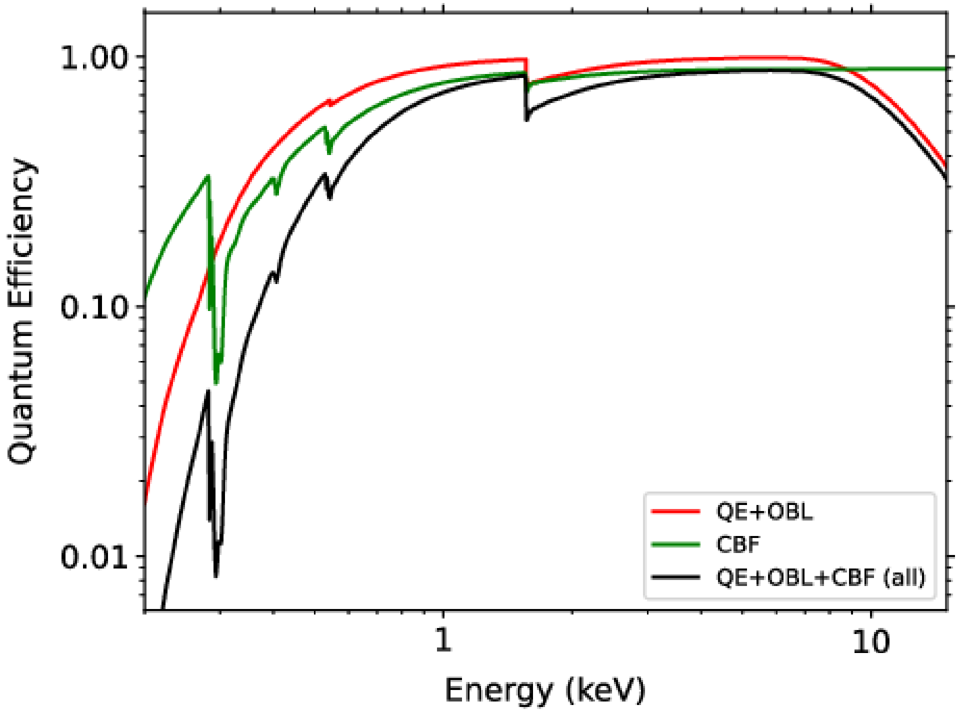
Charge transfer efficiency



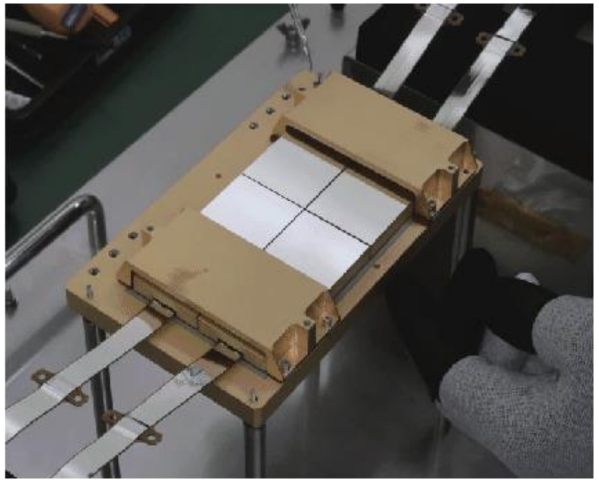


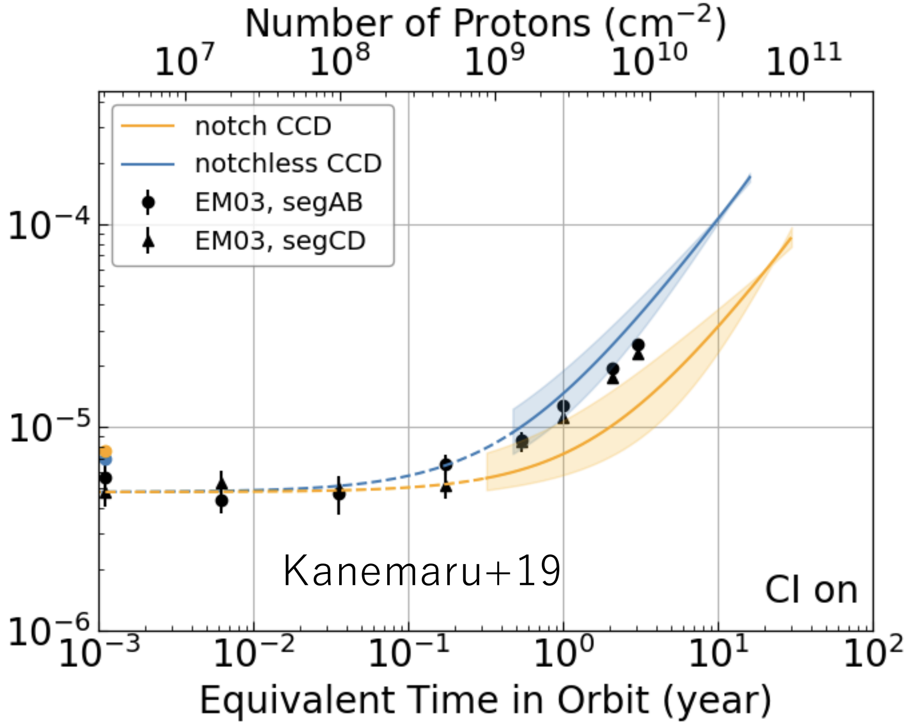
- In general pulse height amplitude ($\propto$ amount of signal charges) decrease as a function of number of transfer due to the charge traps inside the path.
- No significant charge loss has been observed (no more than 1.8×10^{-5} per transfer = XRISM CCD camera results)

Planned update



architecture	frame-transfer
channel type	p-channel
clock phase	2
pixel size	$24 \times 24\ \mu m^2$
pixel format	$320(H) \times 256(V)$
imaging area size	$7.7 \times 6.1\ mm^2$





- ➢ CCD is planned to be substituted by the one that has the same imaging area with XRISM.
- ➢ 200 μ m thick depletion layer extend the effective energy band up to 20keV.
- ➢ Large imaging area of 15.4 mm □ that conform to any focal plane of X-ray mirror.
- ➢ Radiation tolerance has already been verified with 100MeV proton (up to 10 years of satiffying performance in low earth orbit).
- ➢ CMOS ROIC resolution will be improved separately.
- ➢ These update will make this sensor strong candidate for next generation satellite in terms of all parameters (imaging/spectroscopy/timing).

Summary

- We are developing high-speed X-ray CCD sensor for full-size imaging with timescale of well below 1sec.
- Our hybrid sensor implements column-parallel readout for CCD and CMOS ROICs for AD conversion and multiplexing.
- Initial test results verified moderate readout noise of 12e- and energy resolution of 0.96keV@22keV.

Future works

- CCD
  - Increase in size to be adaptable to focal plane of mirrors
  - Optimize wafer thickness for appropriate effective energy range.
  - We will utilize XRISM CCD parameters in future.
- CMOS
  - Increase resolution of AD converter from 10 to 12bit.