X-ray SOIPIXs for the FORCE mission

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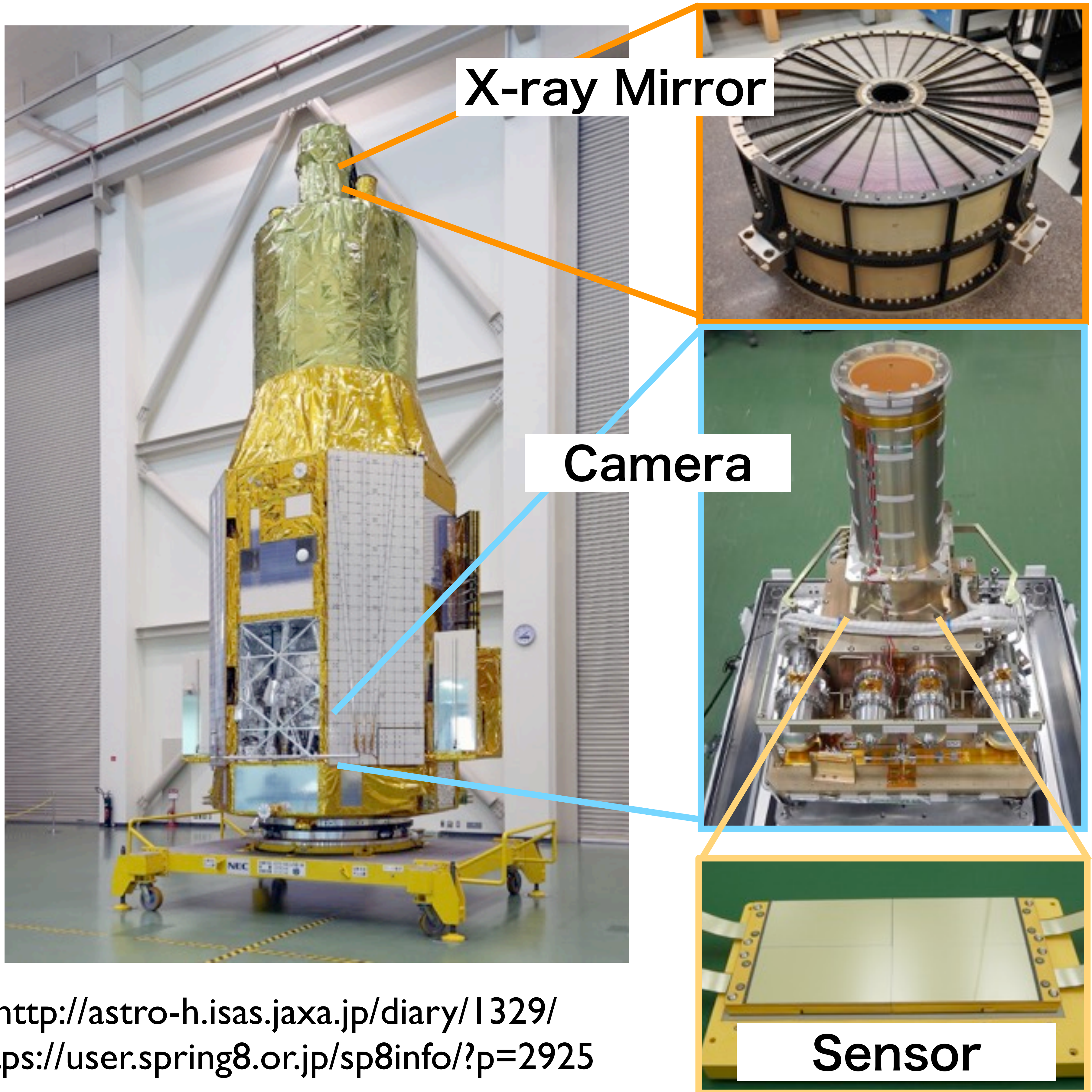
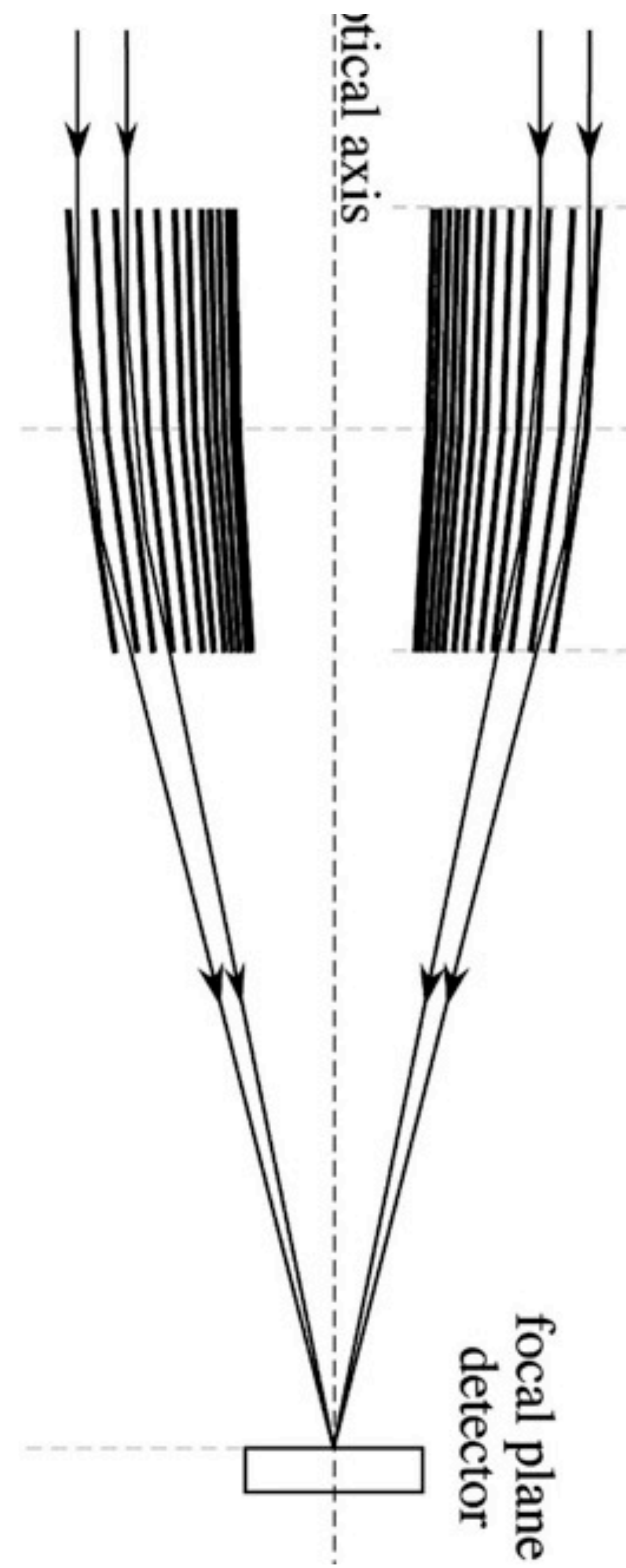
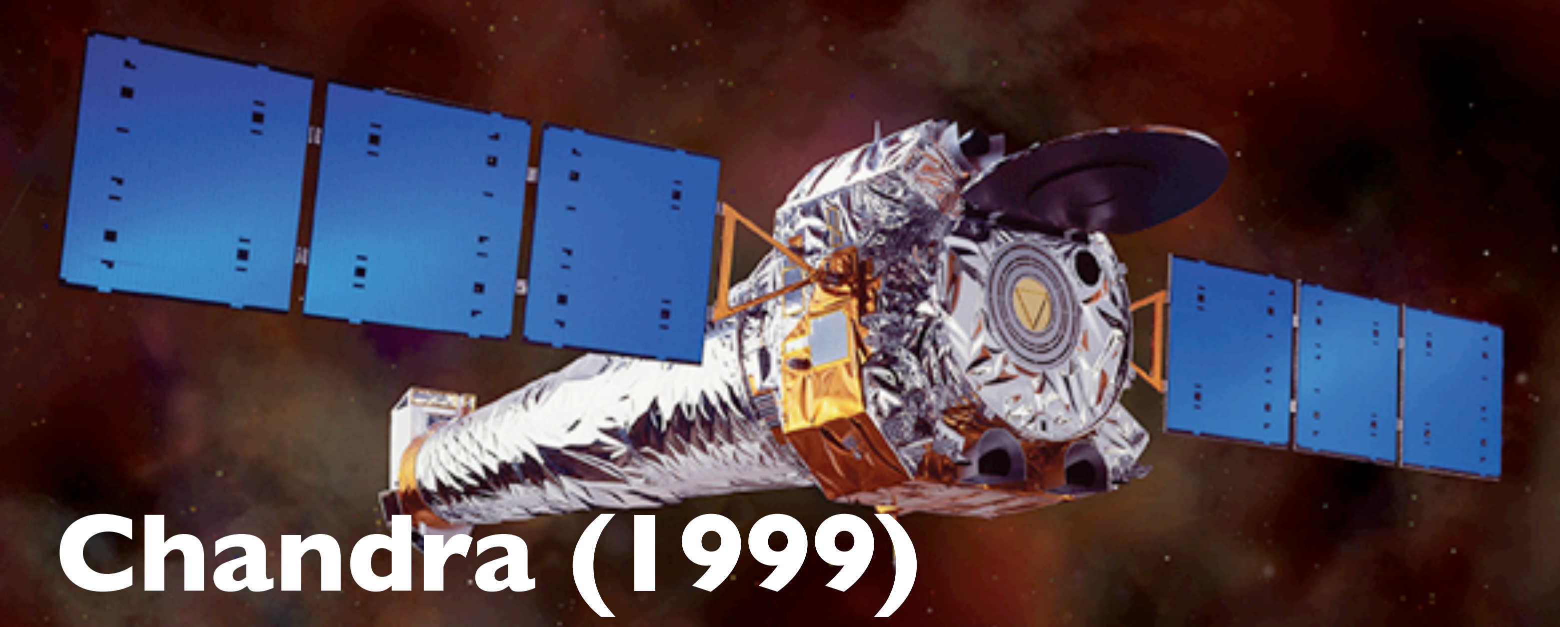
- X-ray Astronomy Imaging System and the FORCE mission
- Basis and Operation of Event-Driven readout mode
- Large Sized Device
- Quantum Efficiency
- Spectral performance

X-ray Imaging System





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



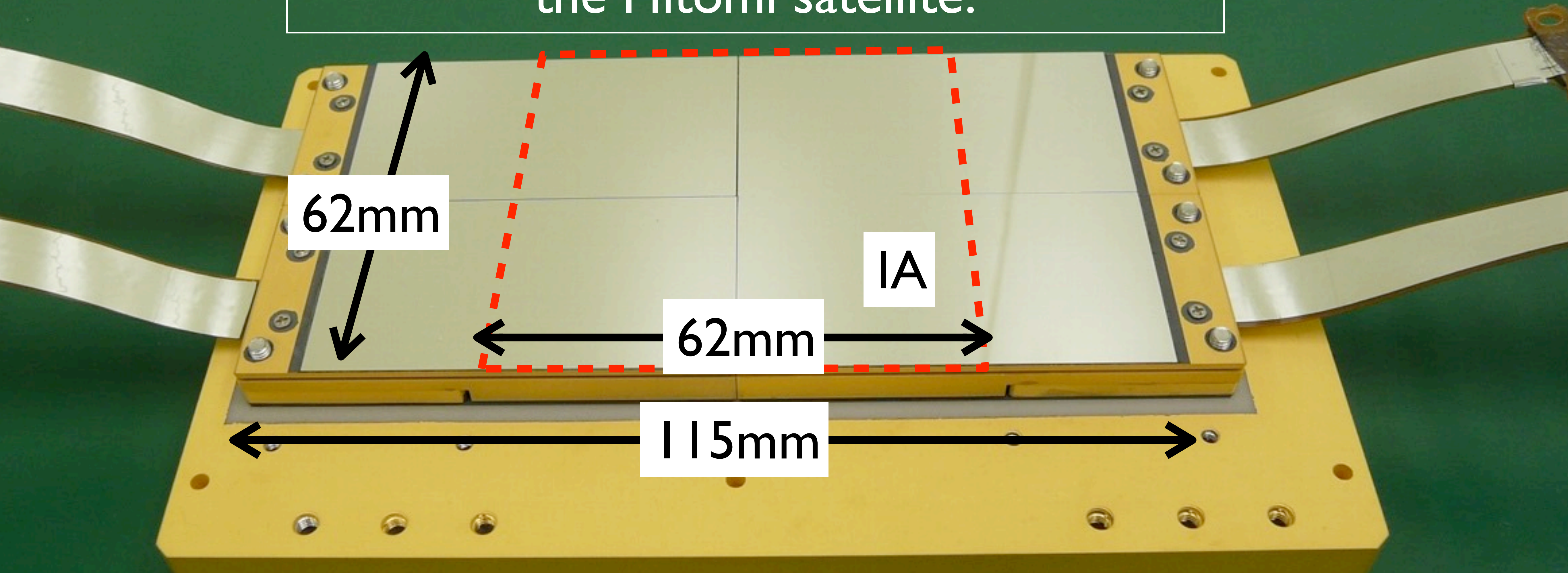
<u>X-ray CCDs</u>

“The” standard Imaging Spectrometer

X-ray Astronomy CCD

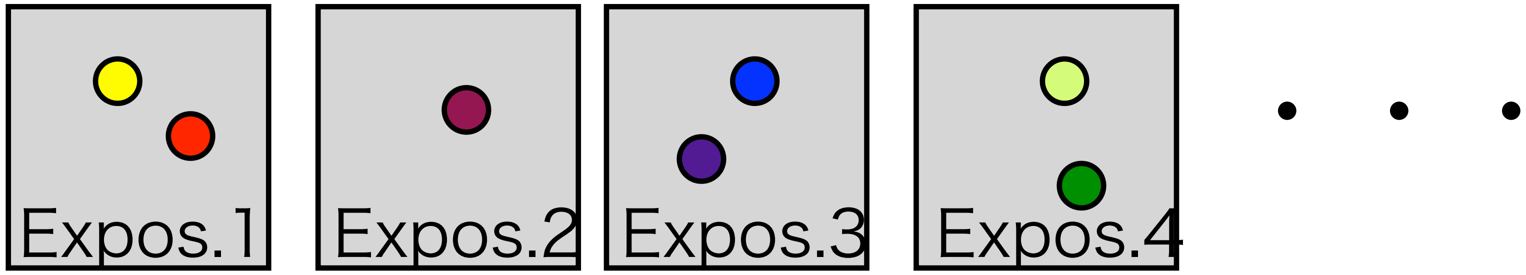
- Standard Imaging Spectrometer at 0.3-10keV.
- Fano limited spectroscopy with the readout noise ~3e- (rms).
- Wide and fine imaging with the sensor size of ~20-30mm□ and the pixel size of ~24μm□

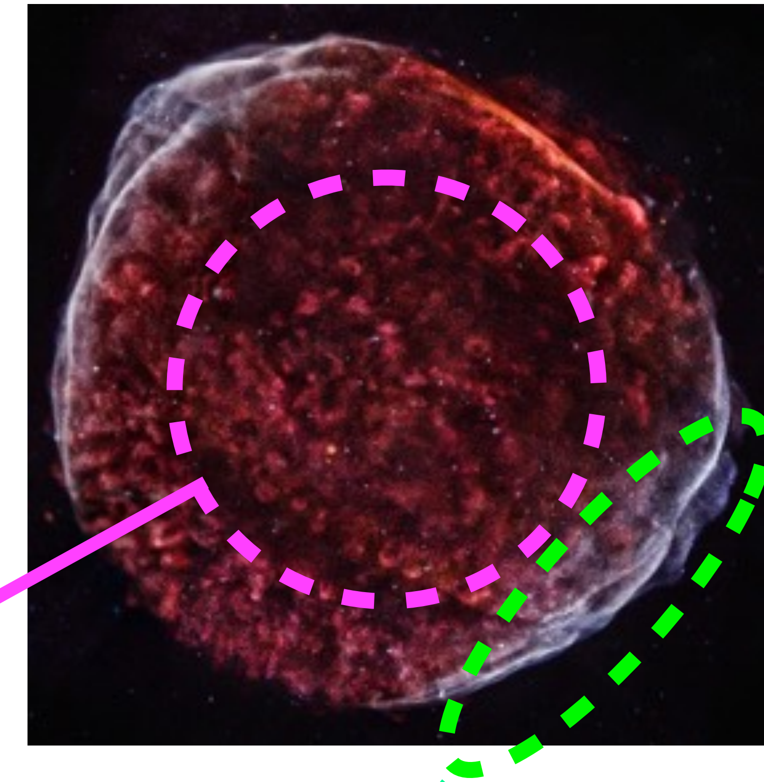
Focal assemply of the CCD camera of the Hitomi satellite.



ASTRO-H, the SXI team

X-ray Photon Counting

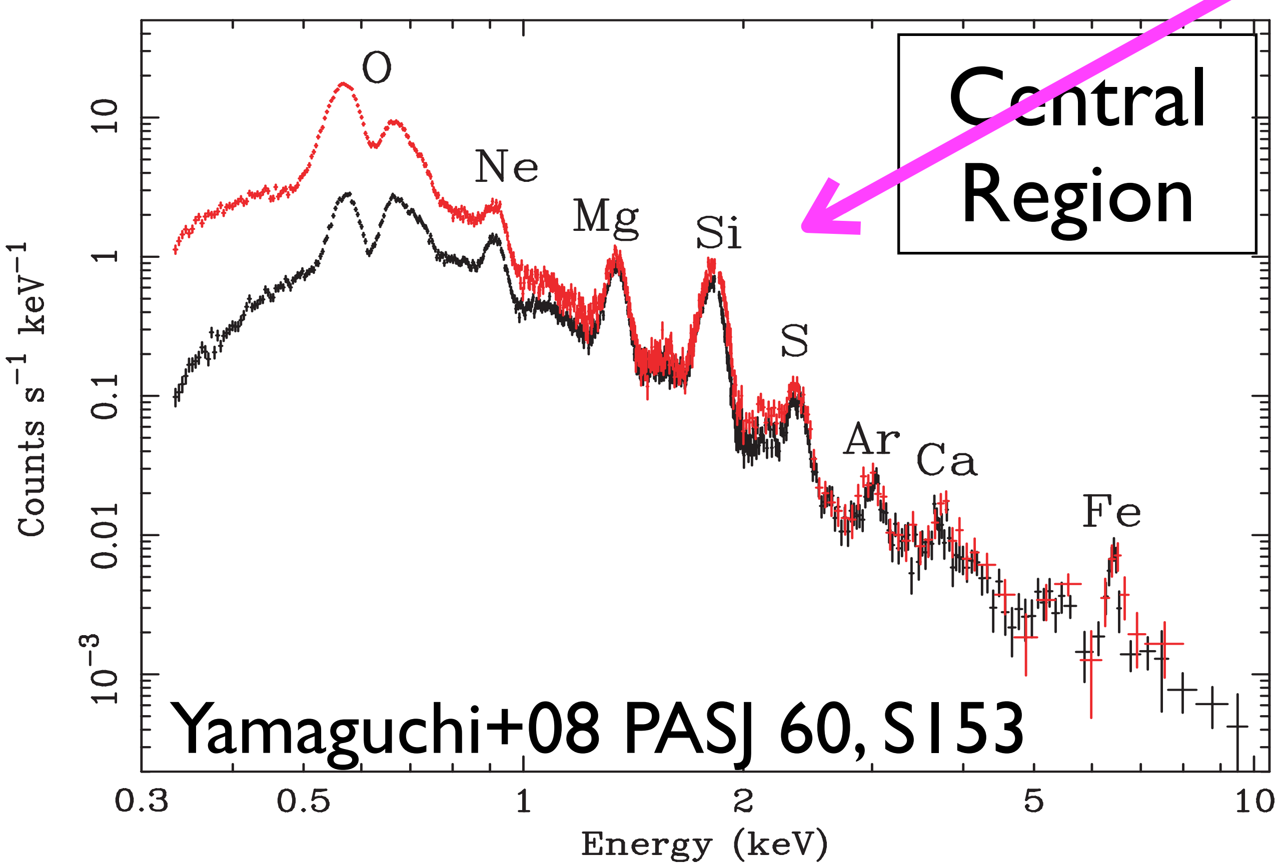


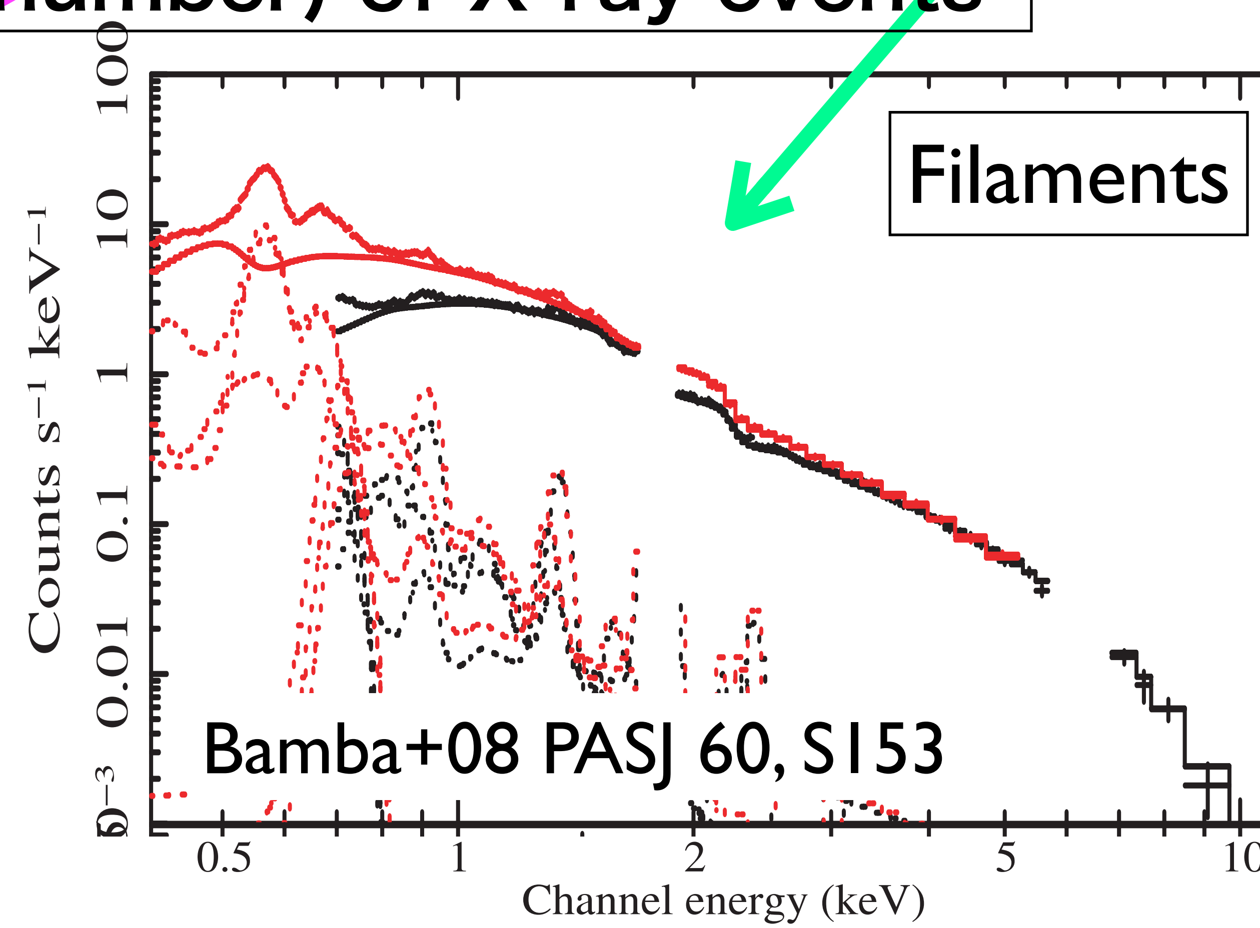


- Detect an X-ray photon as one-by-one event.
- Measure position, energy and time of each X-ray event.
- Make exposures of ~10^4 times.

Map of the number of X-ray events

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

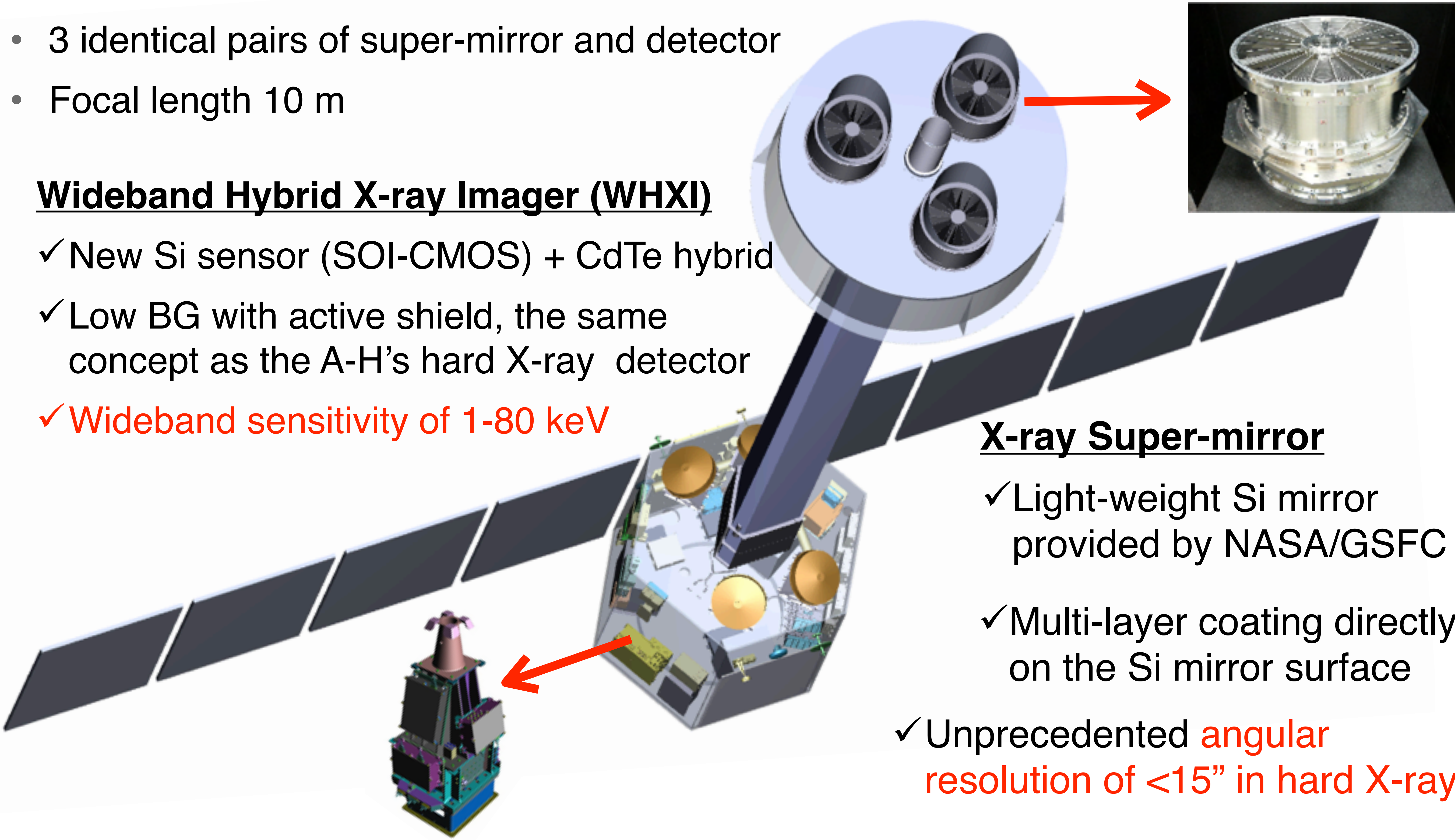




FORCE - a future Japan-lead X-ray mission

FOcusing **R**elativistic universe and **C**osmic **E**volution

- 3 identical pairs of super-mirror and detector
- Focal length 10 m



Wideband Hybrid X-ray Imager (WHXI)

✓New Si sensor (SOI-CMOS) + CdTe hybrid

✓Low BG with active shield, the same concept as the A-H's hard X-ray detector

✓Wideband sensitivity of 1-80 keV

X-ray Super-mirror

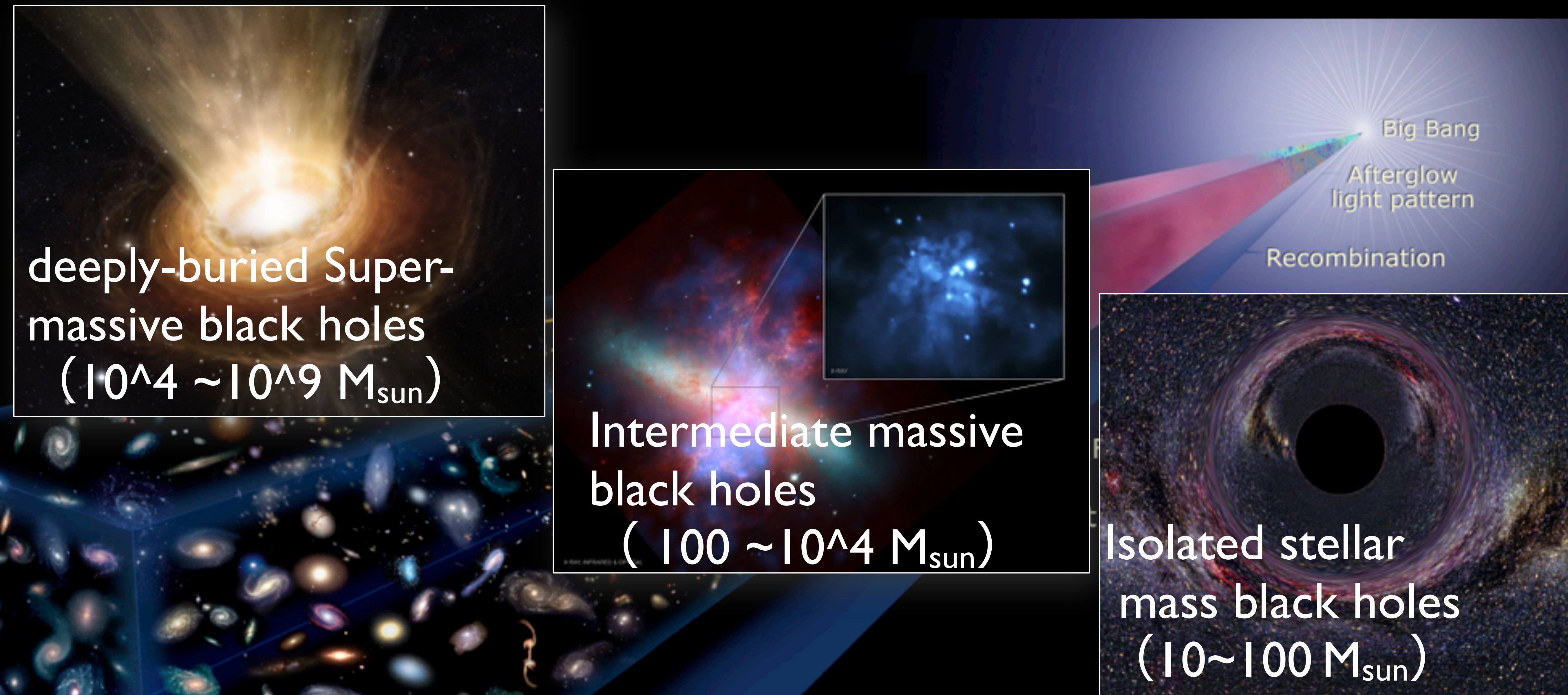
✓Light-weight Si mirror provided by NASA/GSFC

✓Multi-layer coating directly on the Si mirror surface

✓Unprecedented angular resolution of <15" in hard X-ray

Proposing the mission to be realized in mid 2020s.

Hunt for Missing Black Holes



The primary scientific objective is to hunt for "missing black holes" in various mass-scales and to trace their cosmic evolution

Broadband observation (1-80keV) is essential.

Mission Requirement

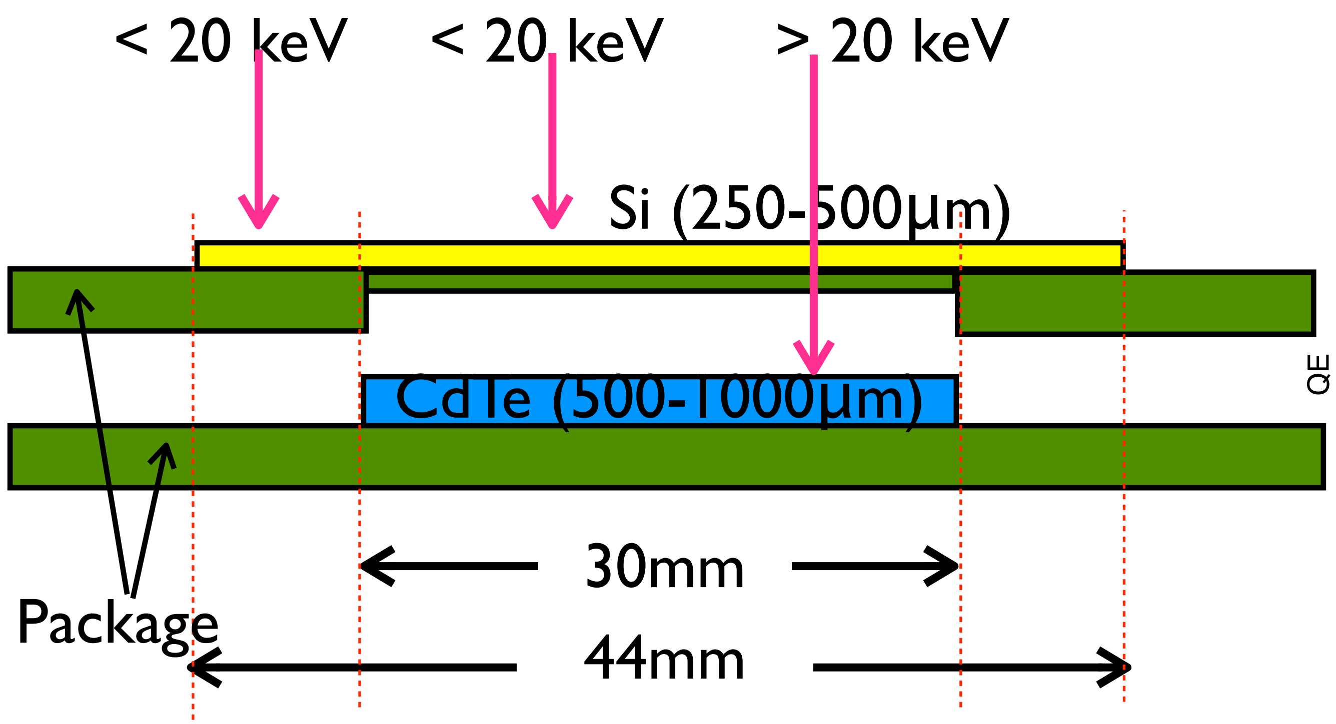
Hitomi

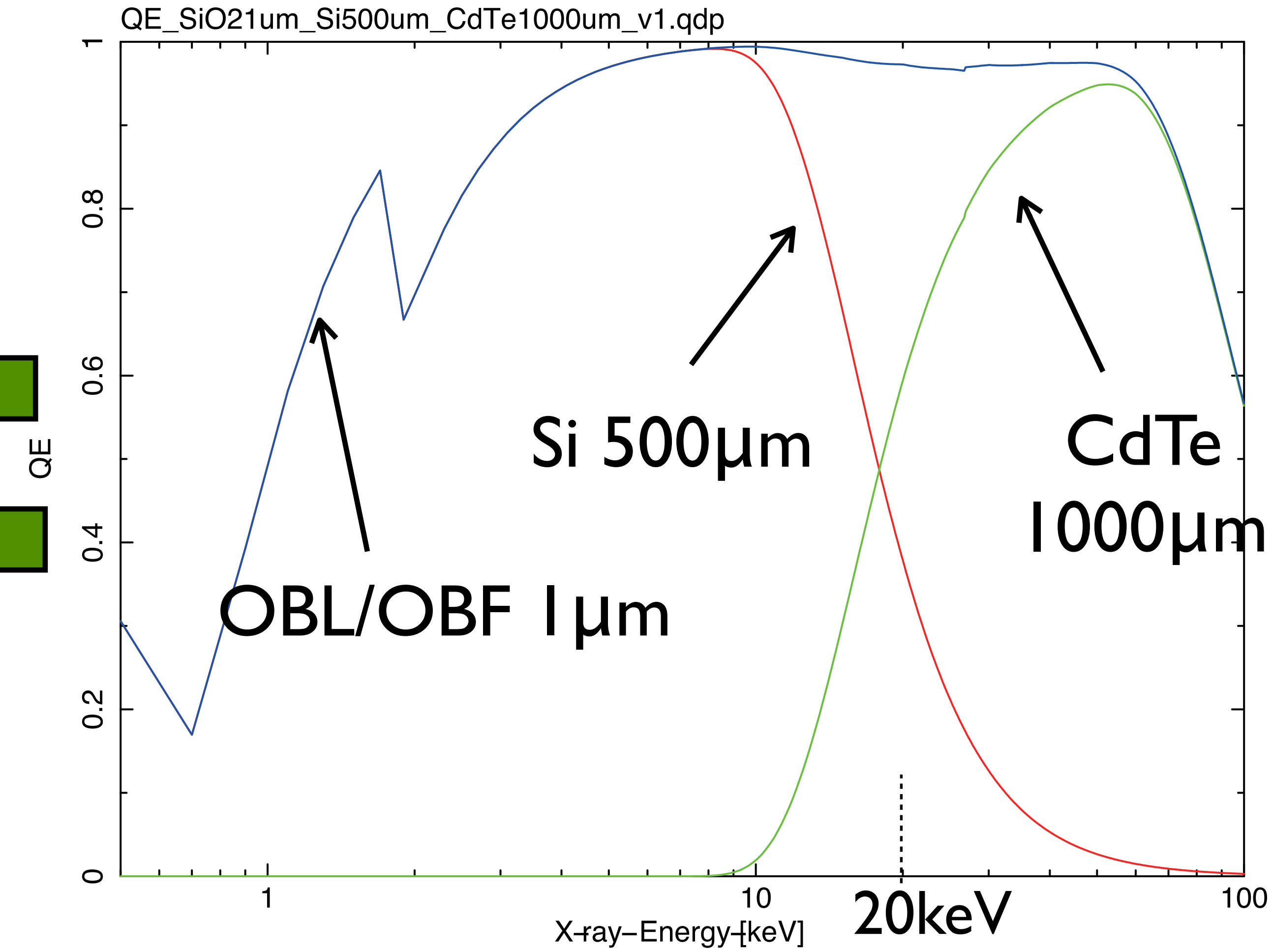
Table 2: Performance Parameters

Parameter	FORCE	NuSTAR	ASTRO-H (HXT & HXI)
angular resolution (HPD)	<15″	58″	1.7′
bandpass (keV)	1–80	3–79	5–80
effective area (cm^2@30 keV)	>350	comarable with HXI	338
fov (50% resp. @30 keV)	$>7' \times 7'$	$\sim 10' \times 10'$	$\sim 6' \times 6'$
timing resolution	several × 10 μs	2 μs	several × 10 μs
energy resolution	<300 eV at 6 keV	400 eV at 10 keV	900 eV at 14 keV
(FWHM)	comparable with HXI	900 eV at 68 keV	1500 eV at 60 keV

- High sensitivity of 2-3x10^{-15} erg/s in 10-40 keV
  - High Angular resolution of 15”
- Broadband response
  - 1-80 keV for requirement (0.5-80 keV for goal)
- High energy resolution for spectroscopy
- Necessary statistics should be obtained during appropriate mission life time

Hybrid Camera with Si and CdTe





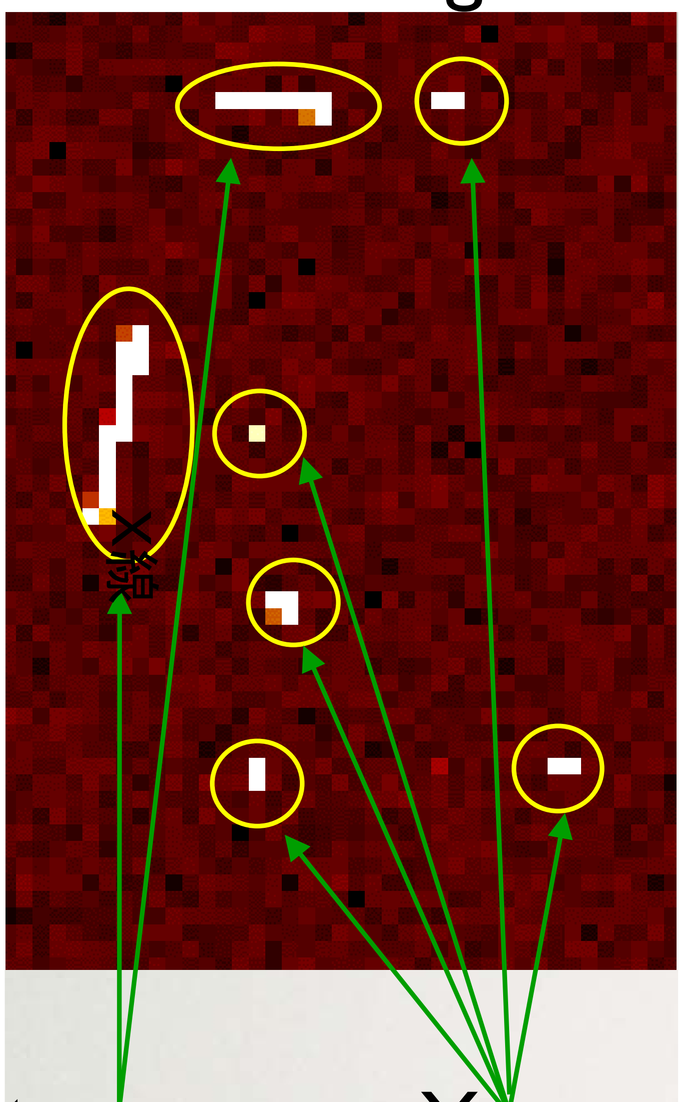
- Si sensor alone can not cover 1-80 keV
- "Hybrid Detector" consisting of Si and CdTe sensors.
  - E_X < 20keV is detected with Si sensor.
  - E_X > 20keV penetrating Si sensor is detected with CdTe placed under Si
- What kind of Si sensor ?
  - DSSD dose not detect X-rays below 5 keV due to high read out noise,
  - X-ray CCD ? ---- No

Non X-ray Background of X-ray CCD

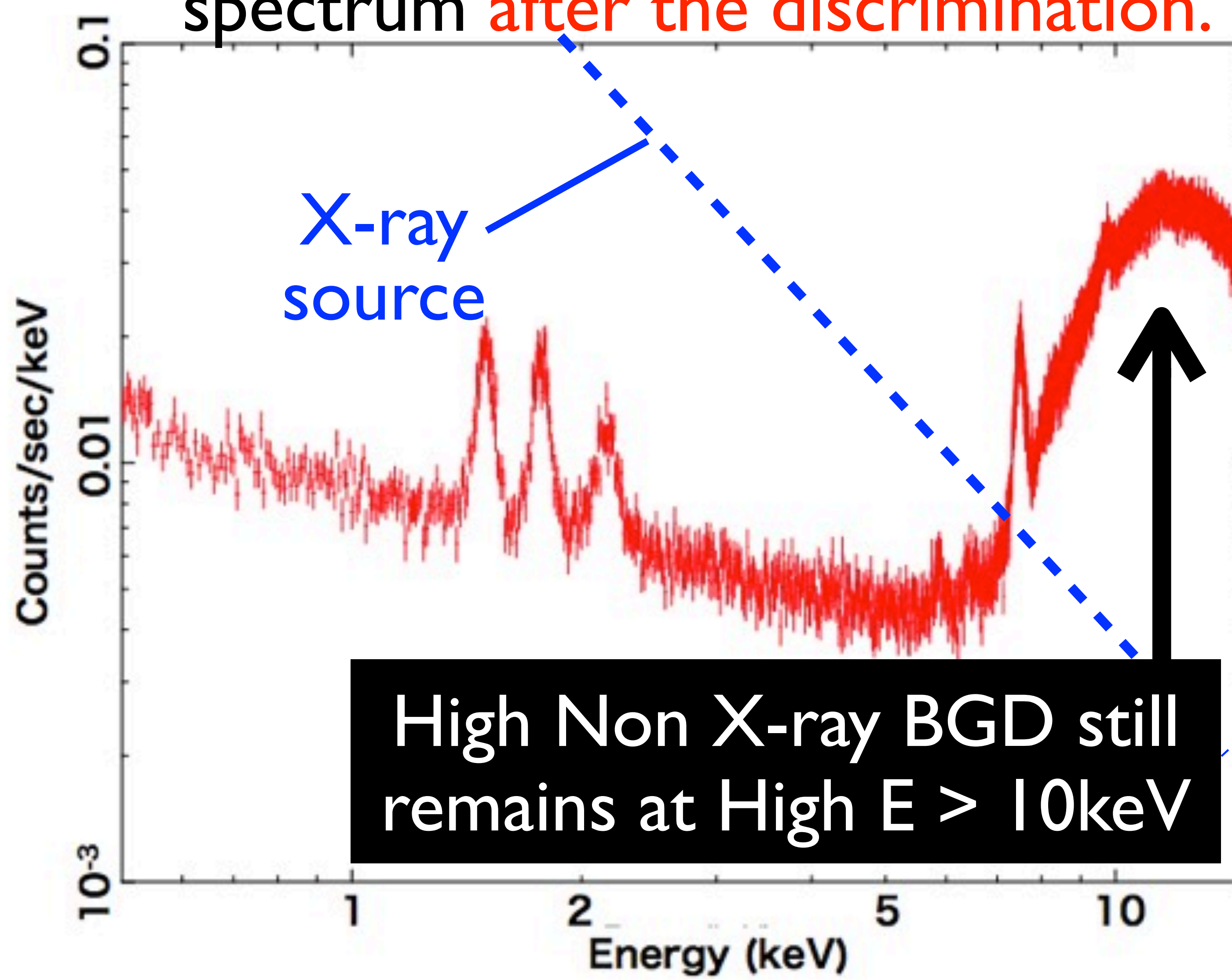
- Particle events which we cannot distinguish from X-ray events.
- Celestial X-ray source is very faint ⇒ Reduction of non-X-ray BGD is vital.

Data from Suzaku 「すざく」 in orbit.

Raw Image



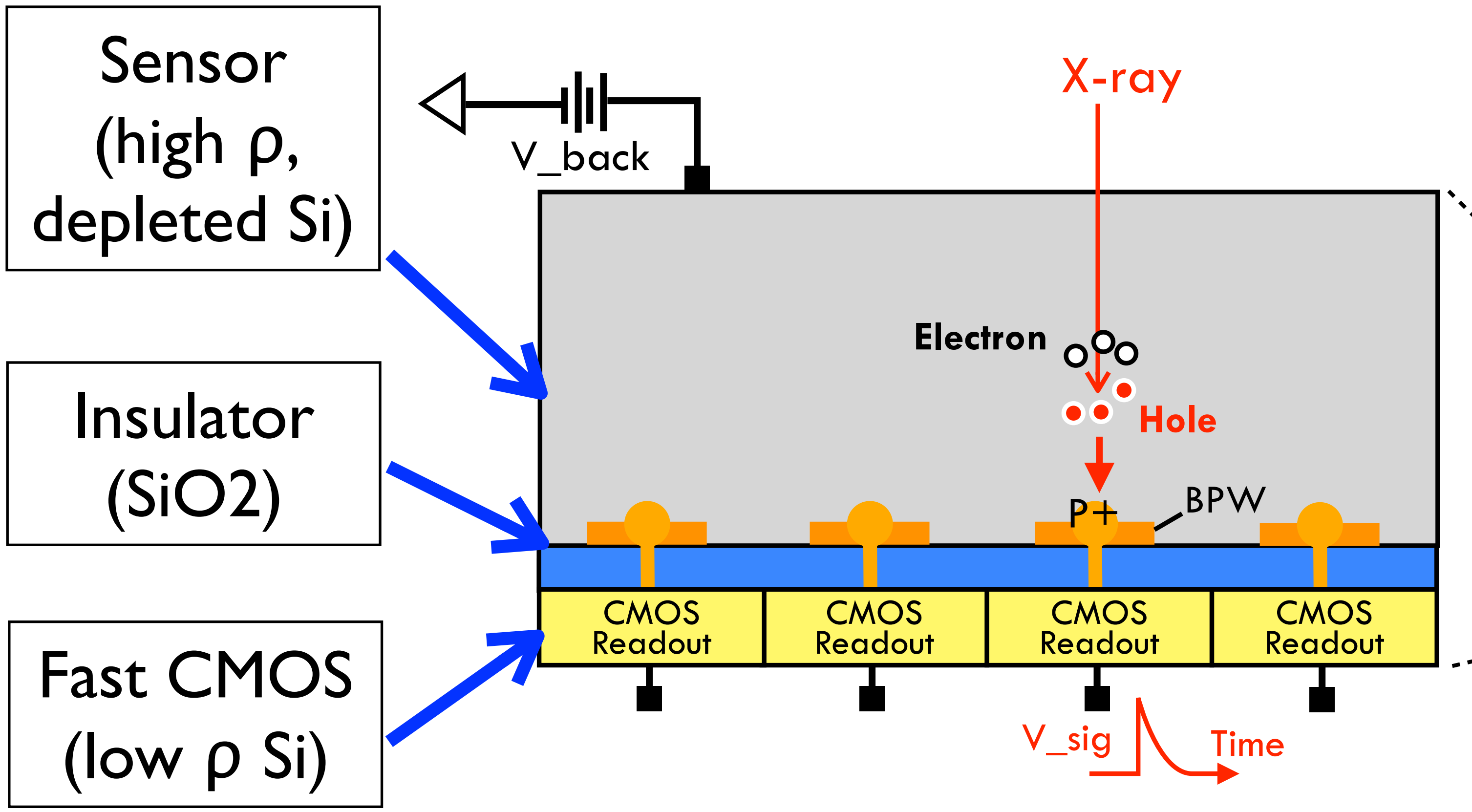
Remaining Non X-ray BGD spectrum after the discrimination.



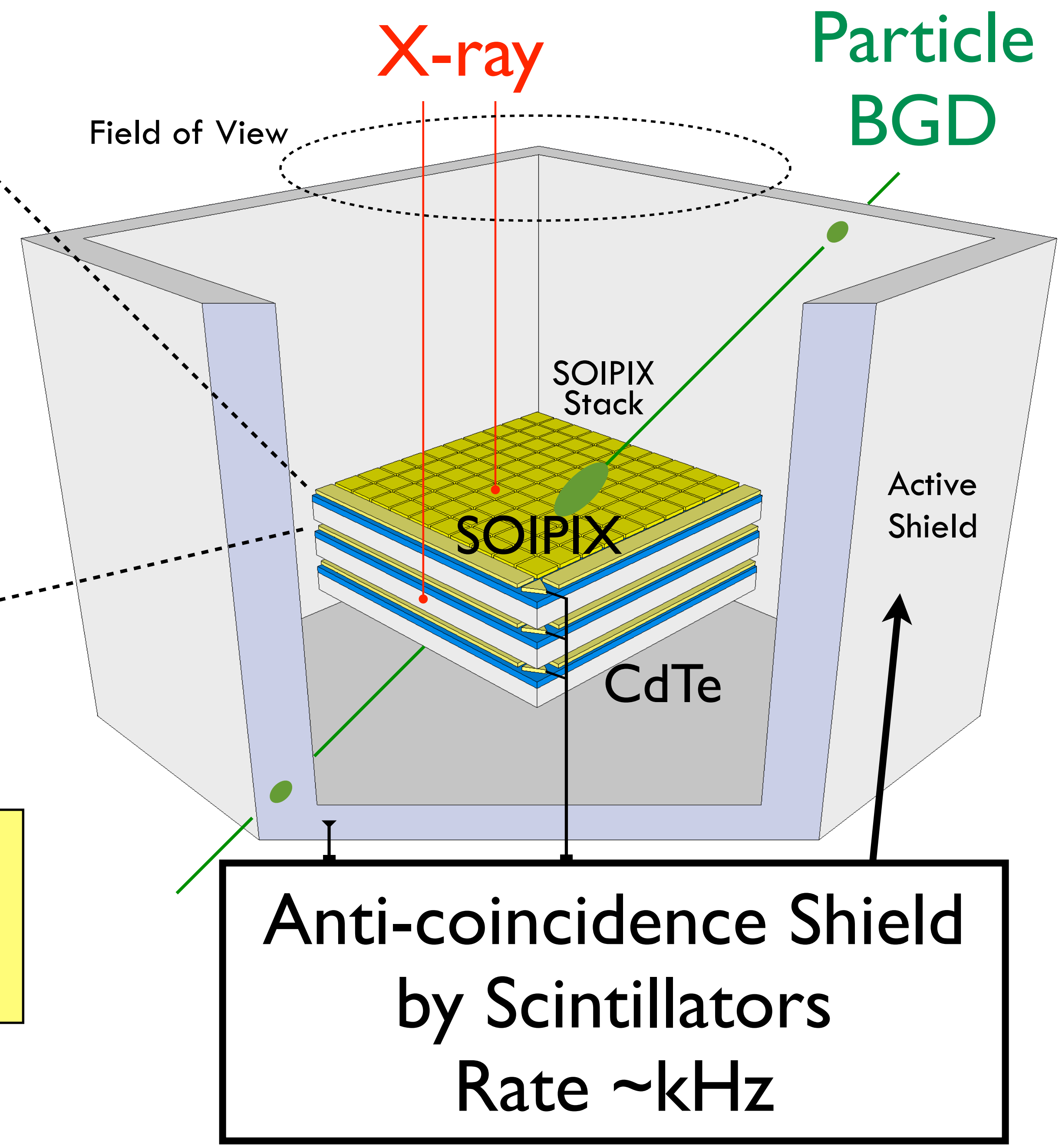
Particle : Track
X-ray : Small spread (single or adjacent pixels)

→ Discrimination with charge spread

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



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



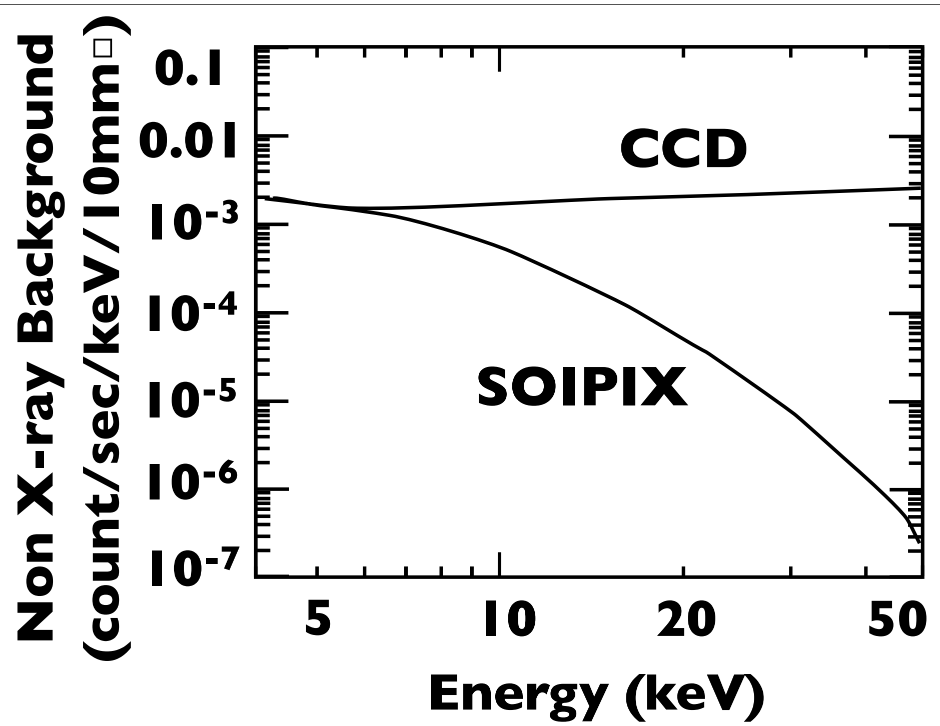
- realize very low non-Xray BGD by anti-coincidence with surrounding scintillators
- event rate from the scintillators is about kHz
- XRPIX is required to have time resolution much faster than kHz.

Target Specification of the Device

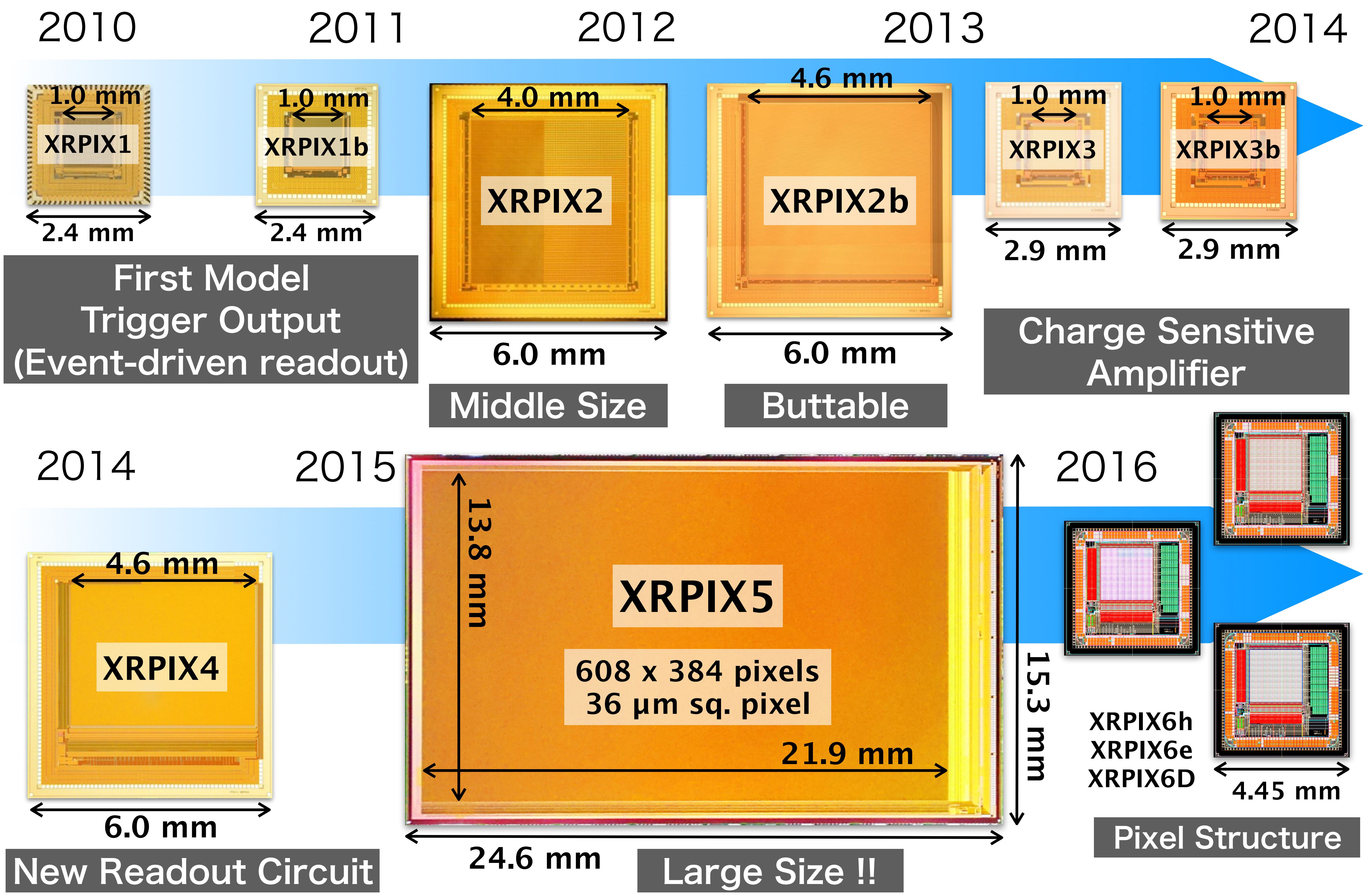
the same as CCD

Imaging	area ~ 15x45mm2, (prototype ~2x2mm2) 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 ~kHz
Max Count Rate	> 2kHz / detector for observation of bright X-ray sources
Non X-ray BGD (anti-coincidence)	1/100 of CCD at 20 keV (5e-5 c/s/keV/10x10mm2)

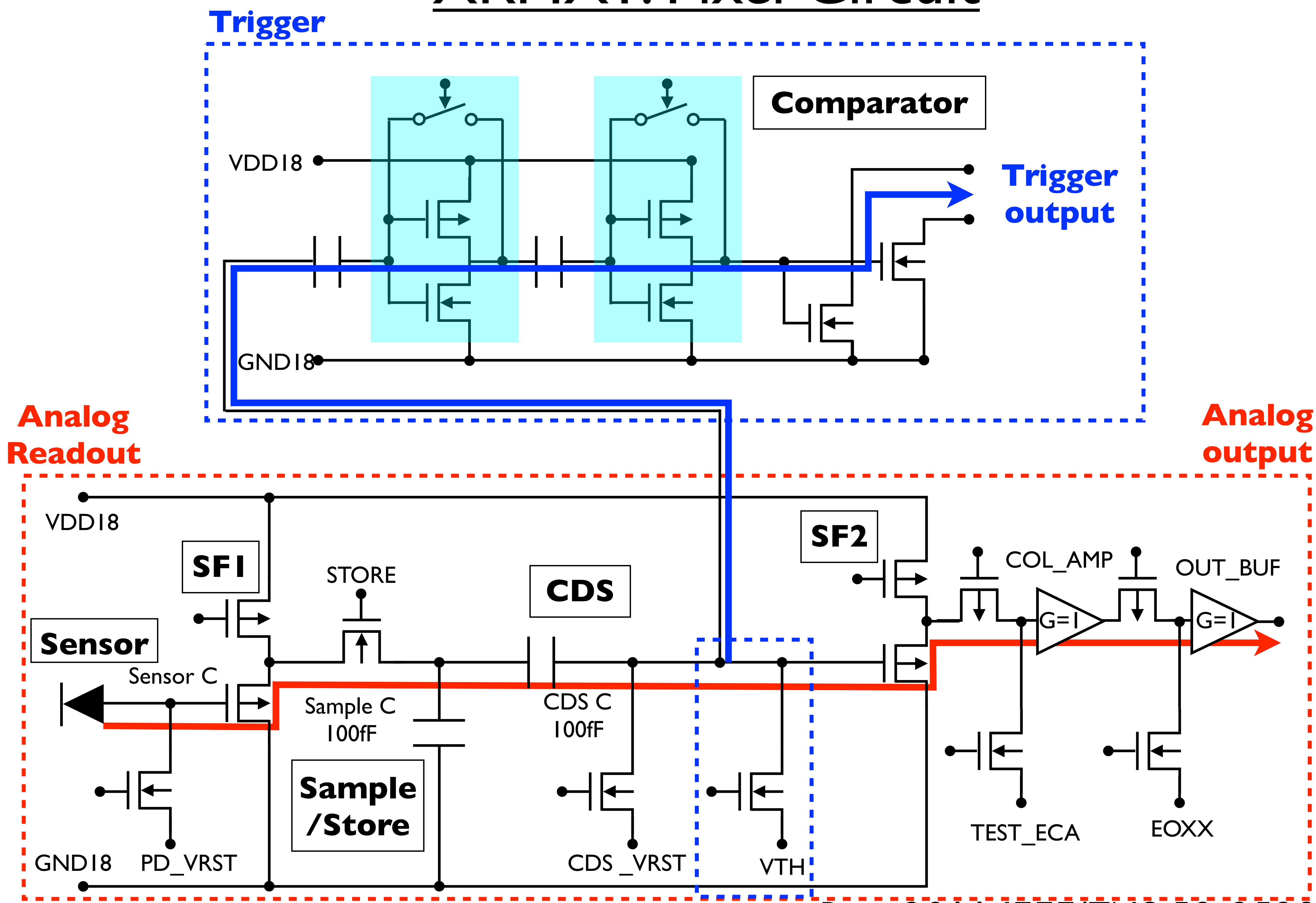
X-ray SOIPIX



History of XRPIX Series

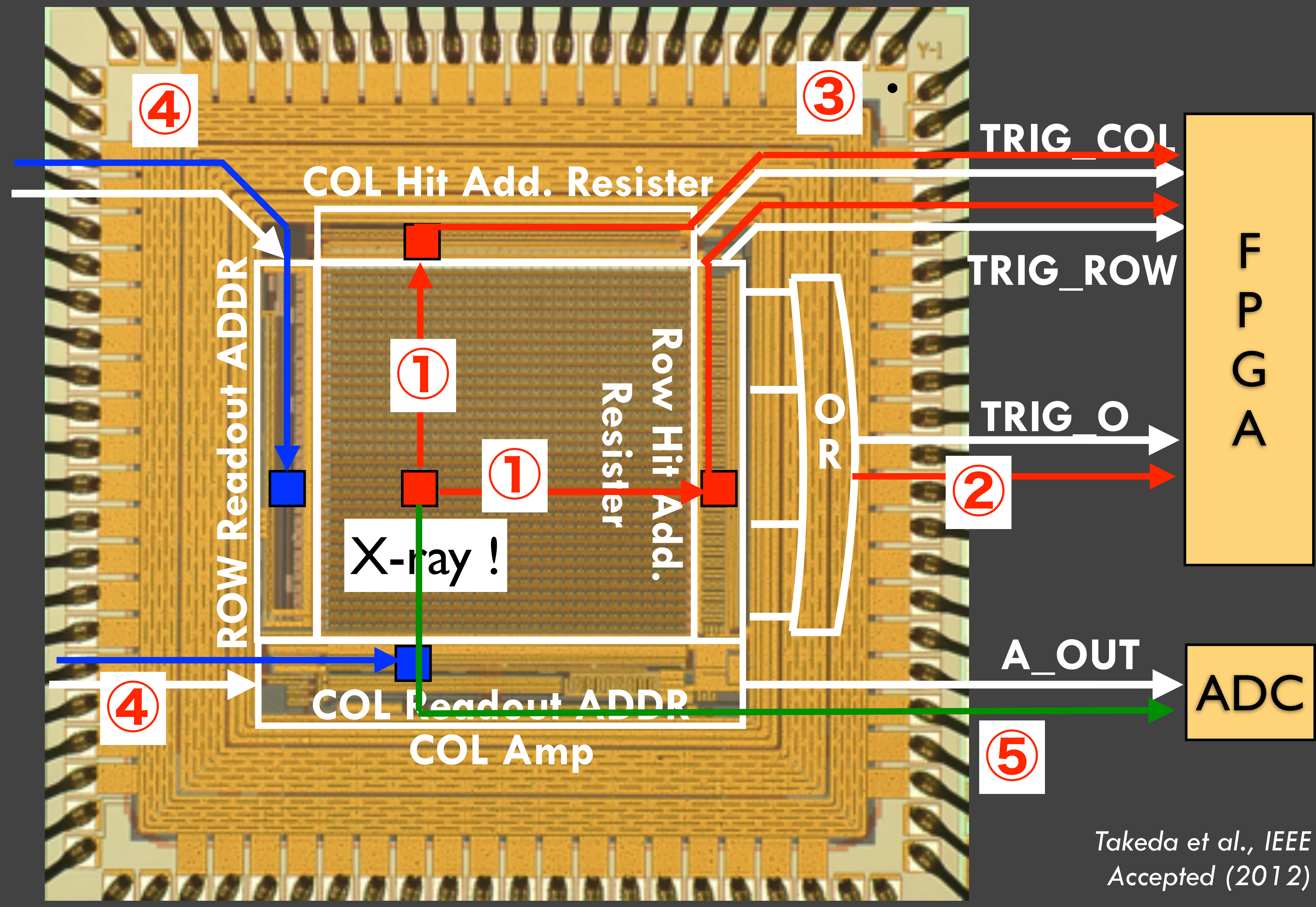


XRPIX1: Pixel Circuit



Ryu+2011 IEEE/TNS 58, 2528

XRPIX1b-CZ : Event Driven Readout



Takeda et al., IEEE Accepted (2012)

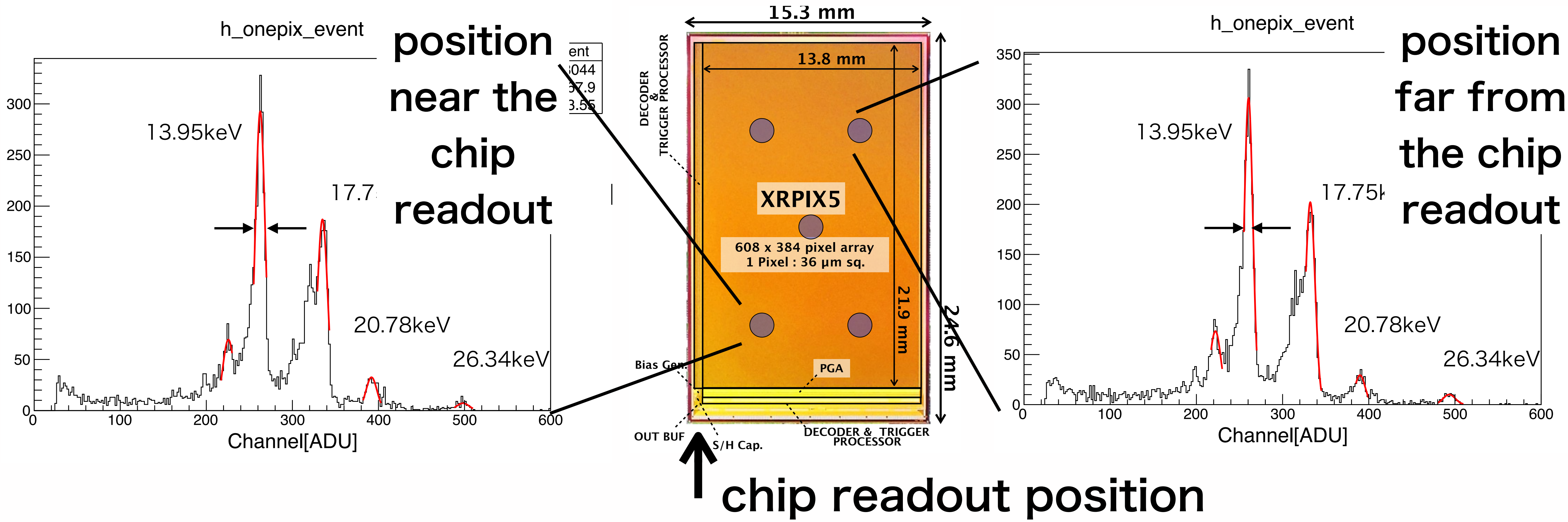
Demonstration of Event-driven

XRPIX2b
30um□, 64x64 pixel
Room Temperature
(thin depletion layer with VBB=5V)

XRPIX5 - IA of 14x22mm2, 3-sides Buttable.

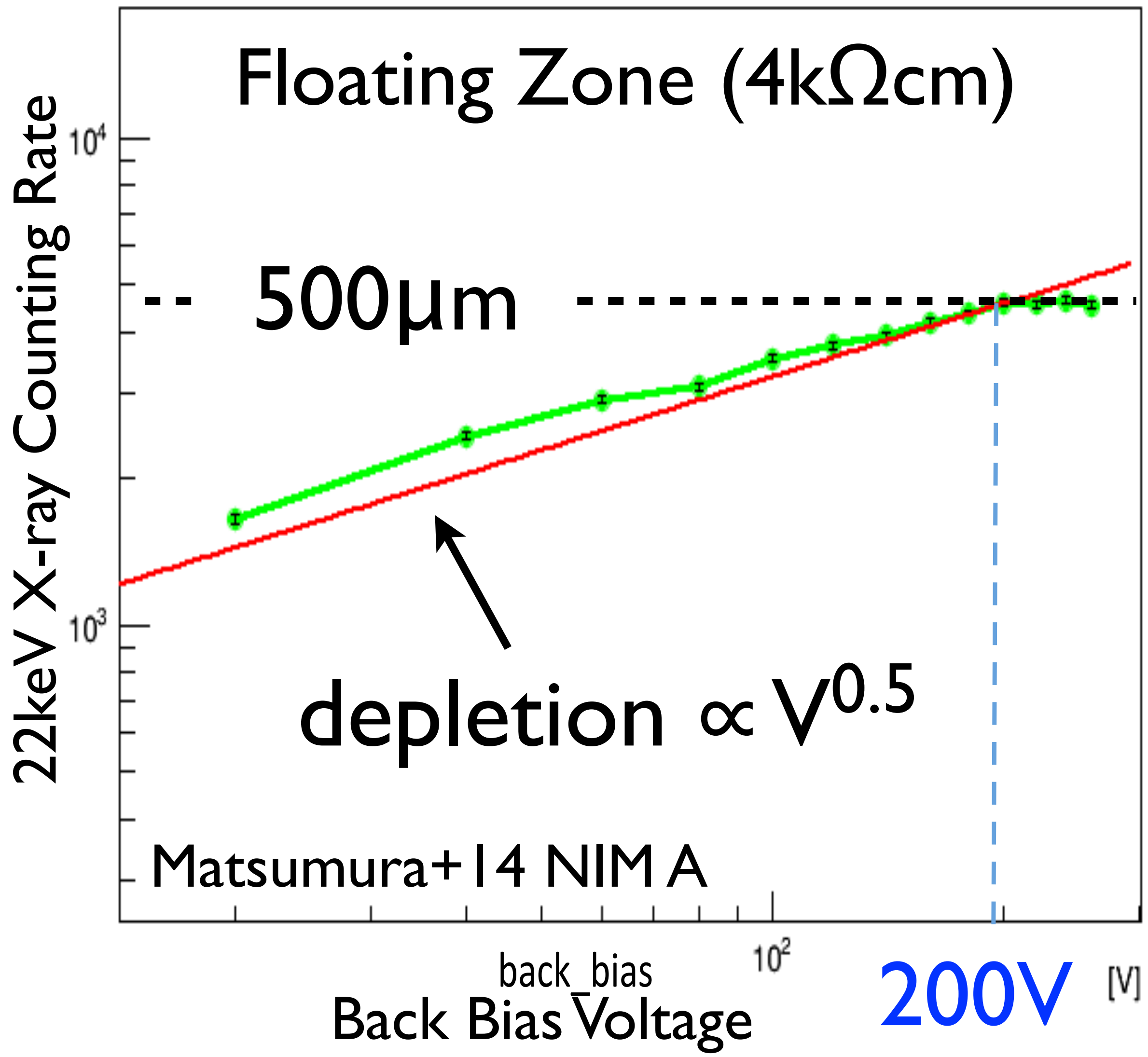
XRPIX5 FZn(N-1-4) 500um

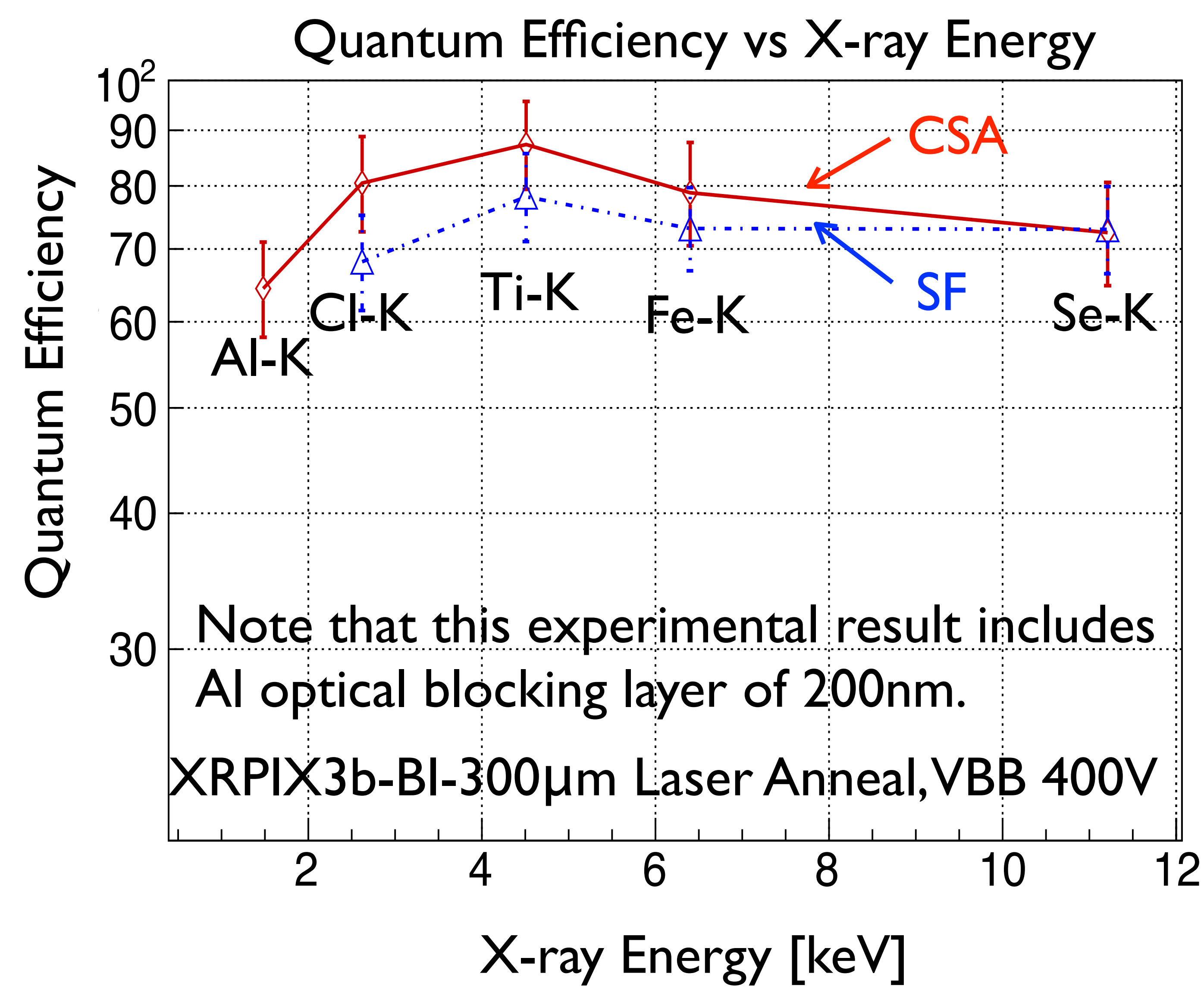
-40℃, Vb=200V, Frame Mode of 8×8 pixels



- Imaging Area of 13.8x21.9mm2. 3-sides Buttable.
- Readout noise ~37e (rms), ΔE ~ 700eV (FWHM) at 13.95keV in the Frame mode. No change from small devices (XRPIX3b).
- There is no difference in the spectral performance by the position.
- We are now preparing readout of the whole region in the Frame and Event-Driven modes.

Thick, fully depleted back-illuminated XRPIX



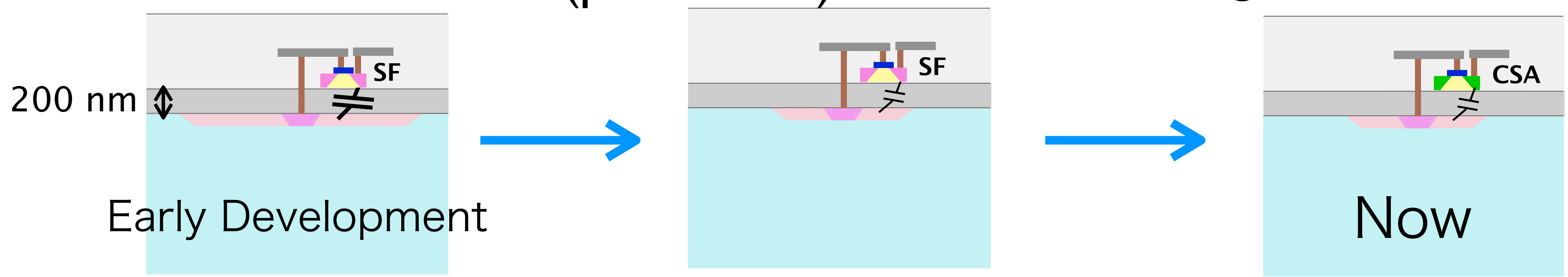


- Depletion Thickness of 500μm is achieved by using a high ρ FZ wafer.
- Thickness of dead layer obtained from the QE ratio between Al-K and Cl-K is 0.66±0.31 μm (including Al OBL 200nm).
- It satisfies the requirement of < 1μm.
- Further improvement by parameter tuning is in progress.

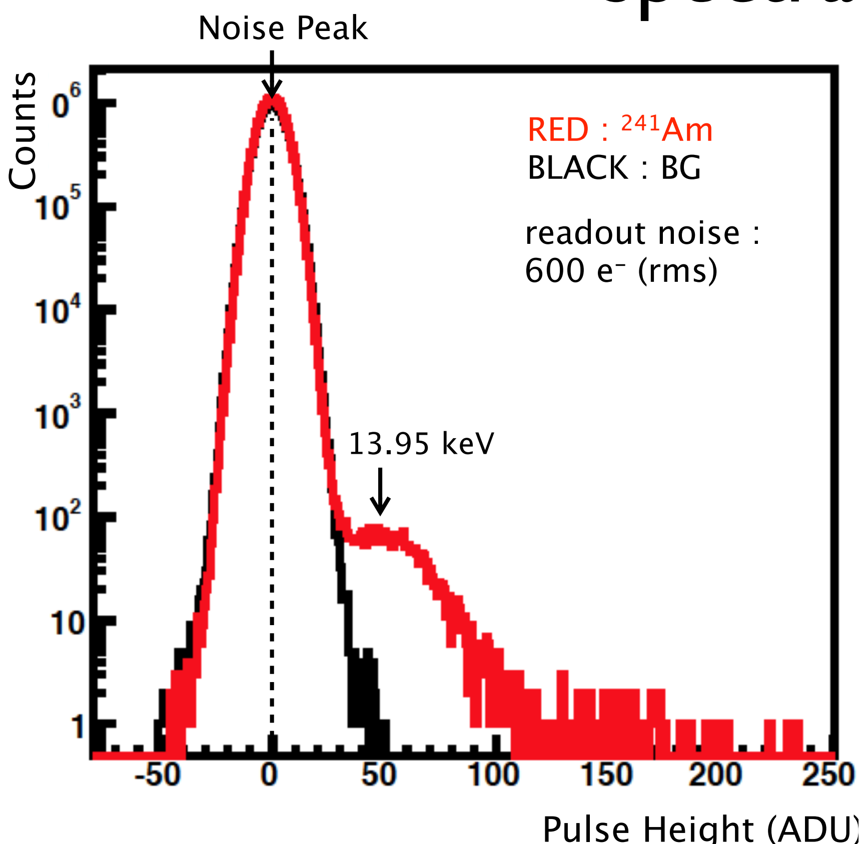
Improvement of Spectral Performance in Frame Mode

increase the node-gain by applying smaller BPW (parasitic C).

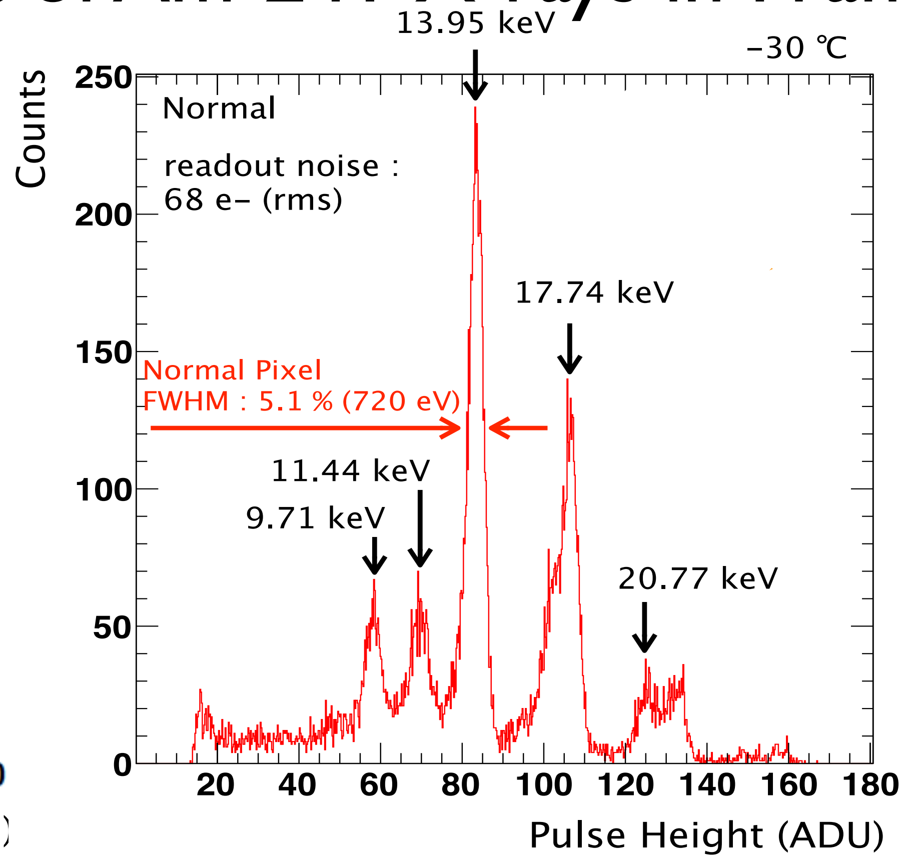
Introduction of charge-sensitive amplifier



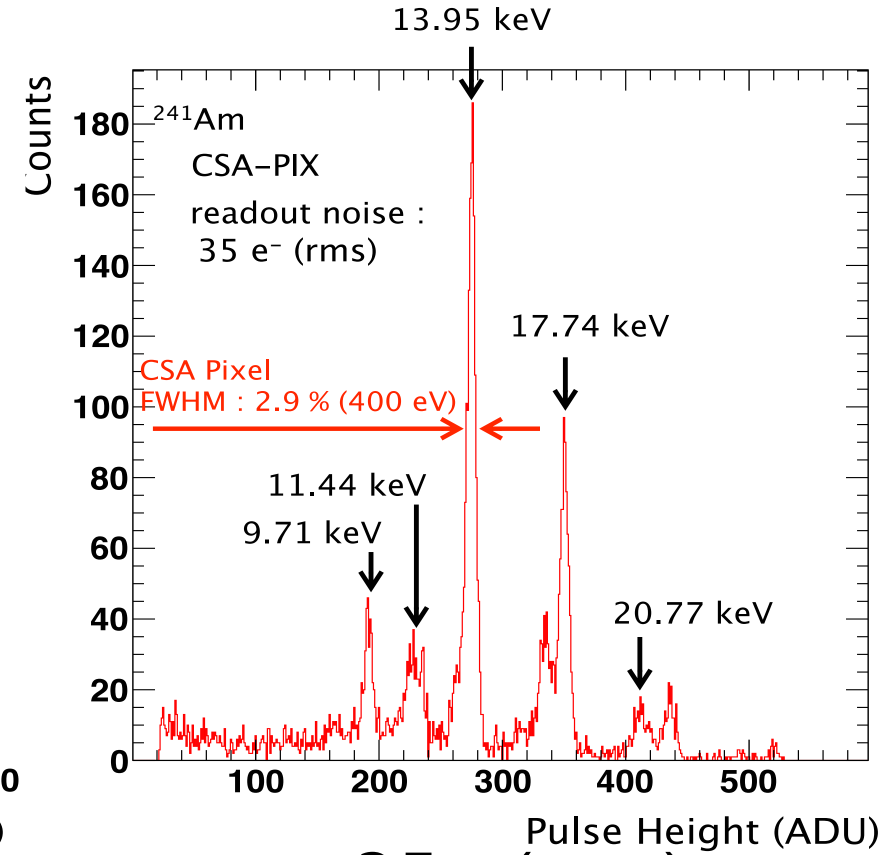
Spectra of Am-241 X-rays in Frame mode



~600e (rms)



~68e (rms)



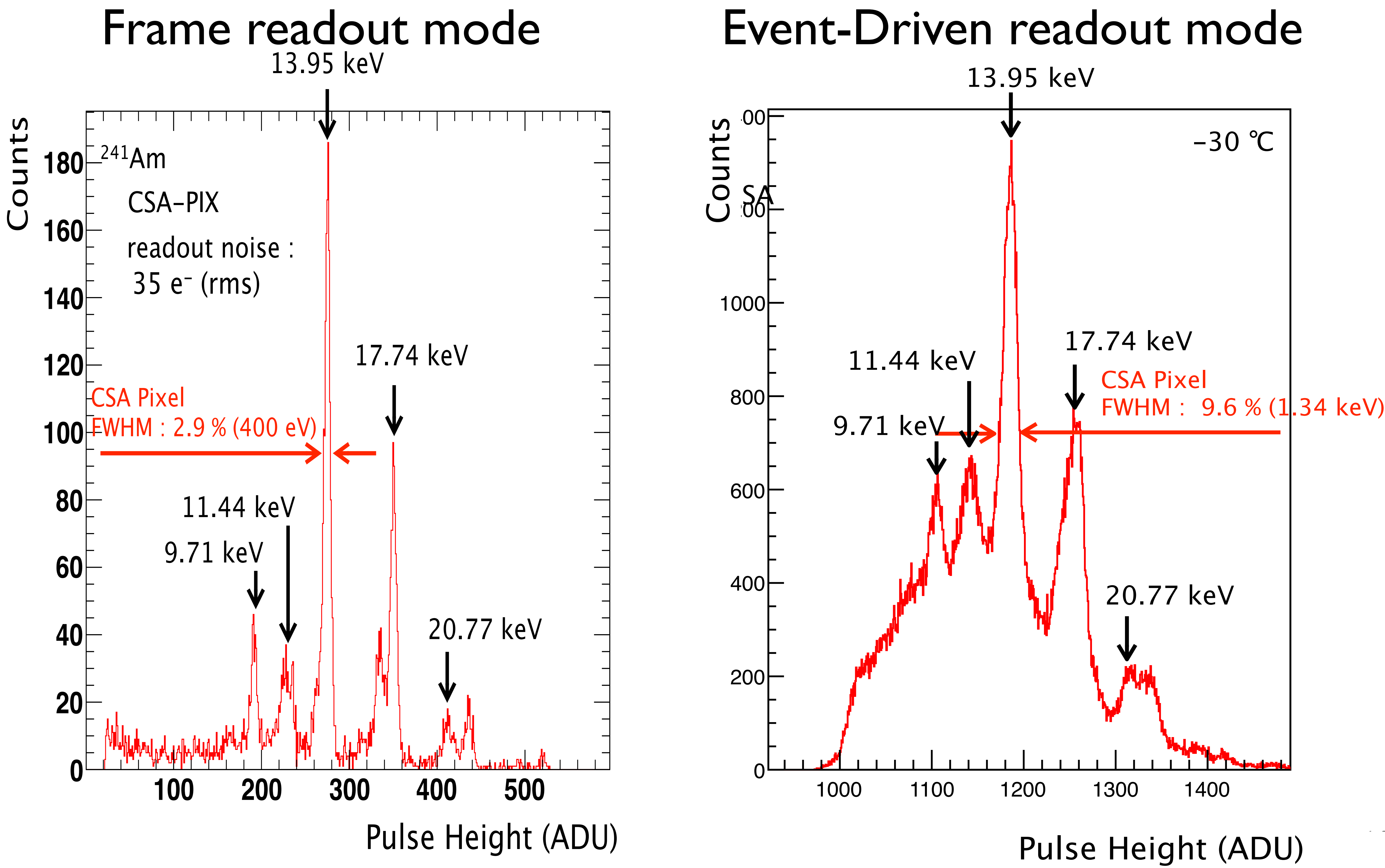
~35e (rms)

Enough area of BPW is necessary to suppress back gate effect.
We were unable to reduce the area of BPW further at this moment.

Takeda+2015 JINST

Comparison of Event-Driven and Frame Modes

Spectra with XRPIX3-CZ w/CSA



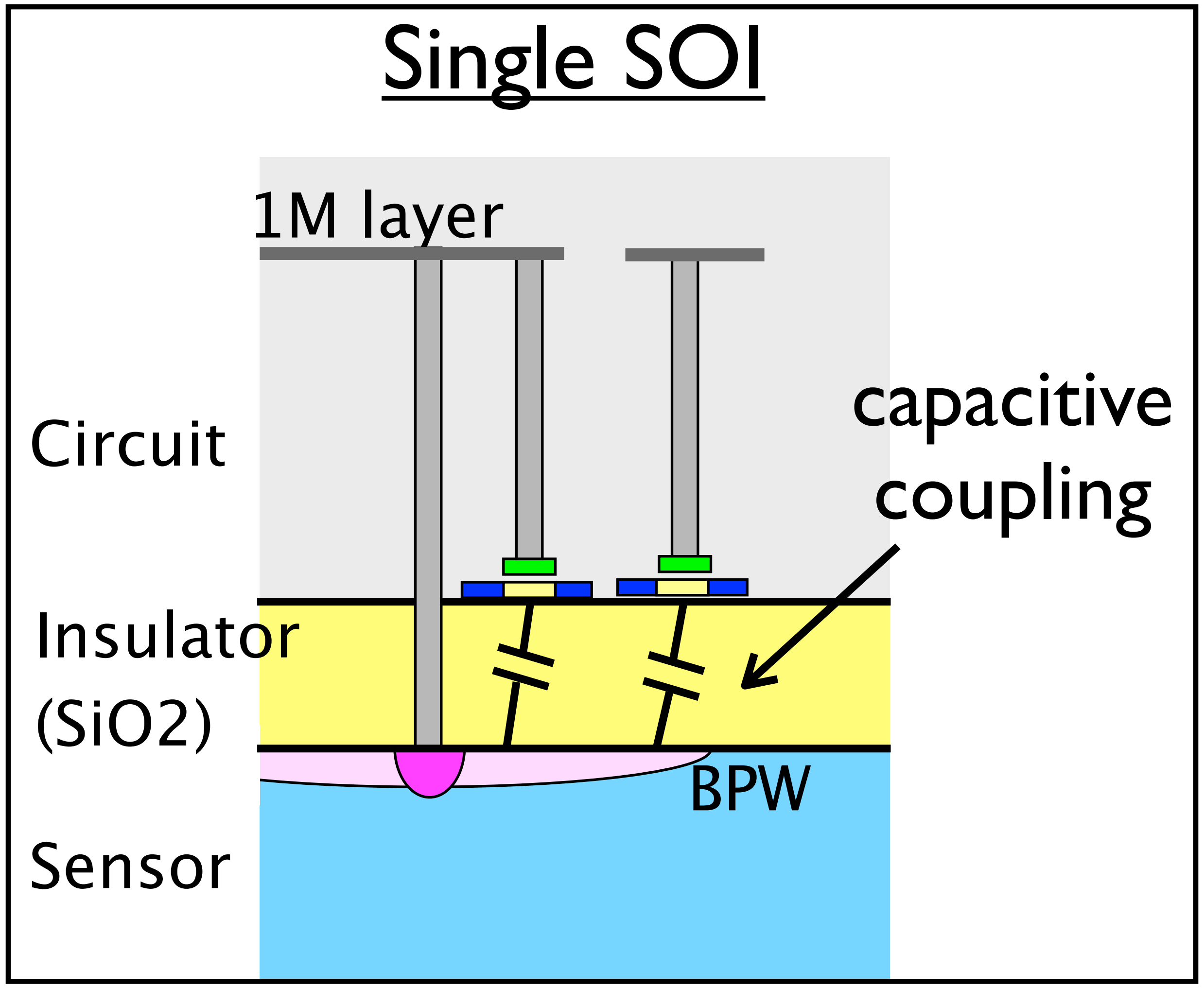
Takeda+2015 JINST, Takeda+2013 IEEE/NSS, Takeda Ph.D Thesis, 20140814_takeda_v0.pdf

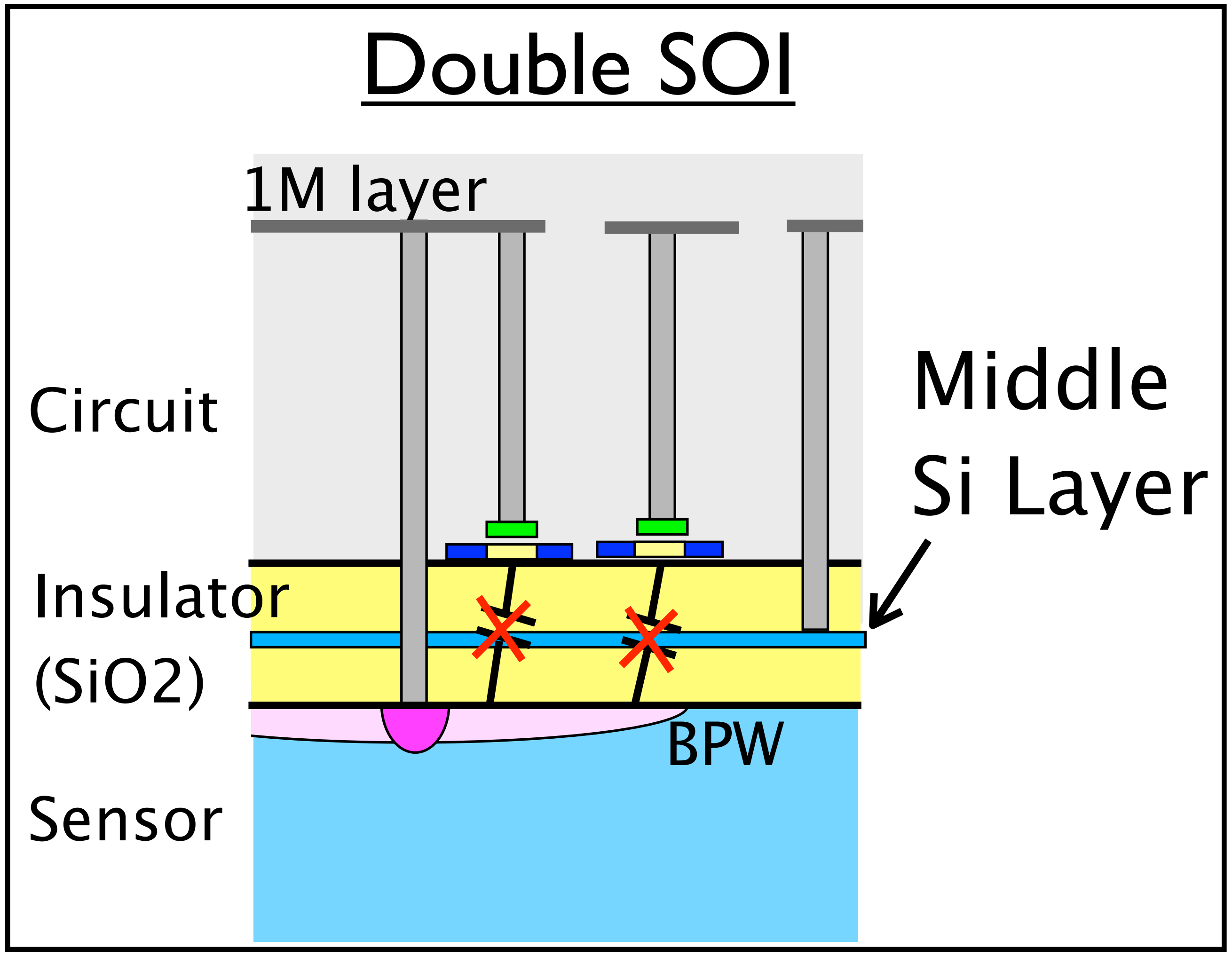
Double SOI Structure

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

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

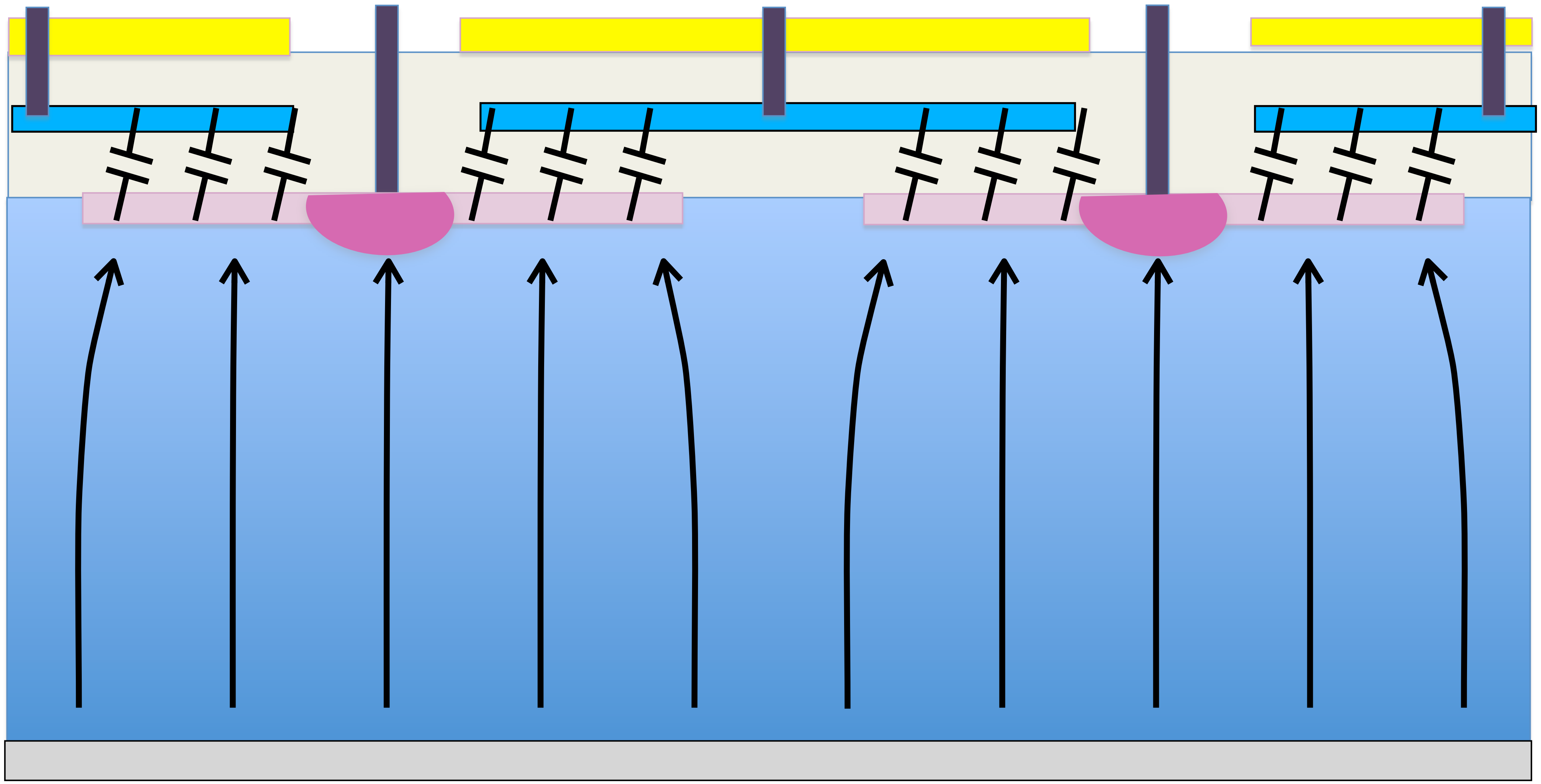
2) crosstalk between digital circuit and BPW (electrically connecting to the sense-node) ⇒ "Double SOI"





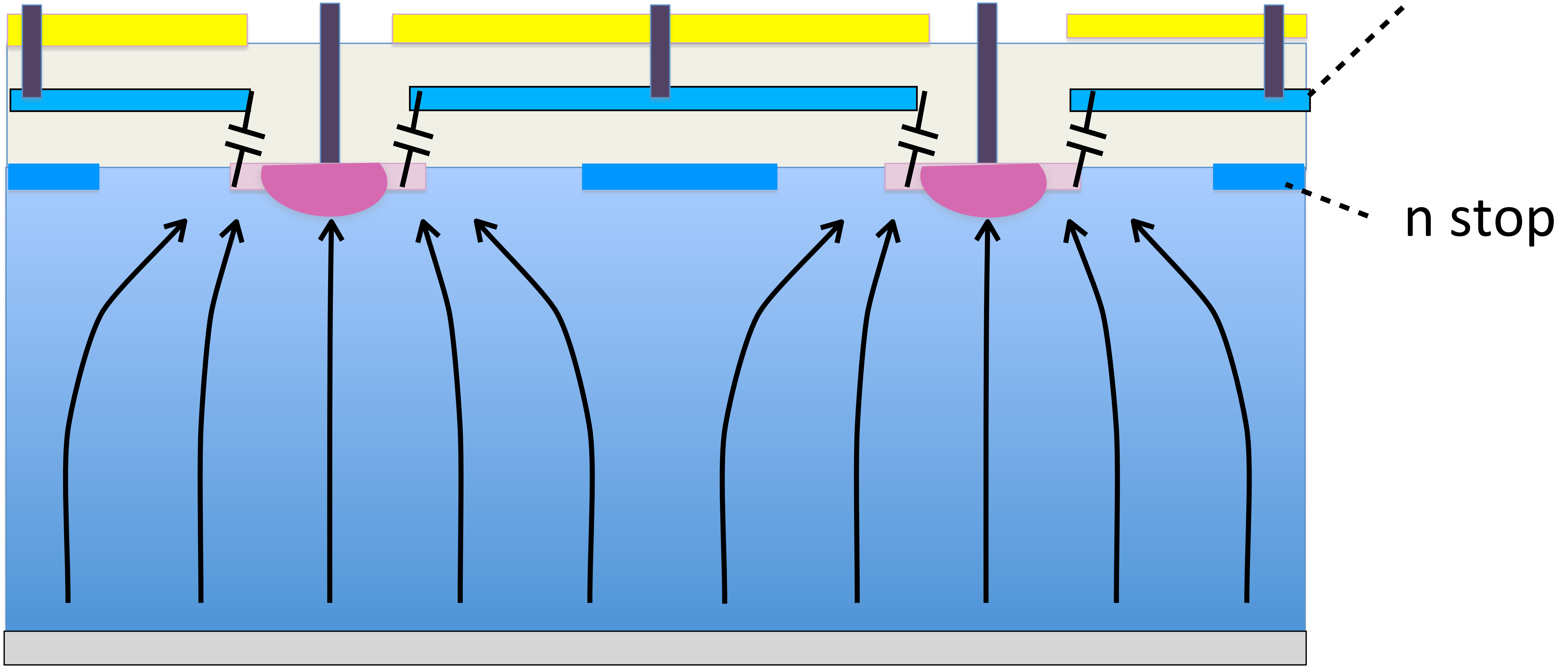
Ohmura+2016 NIM A in press

Large Parasitic between middle Si and BPW



- DSOI successfully suppresses the crosstalk. But...
- DSOI newly introduces a large parasitic capacitance between the BPW and the middle Si, which reduces the node gain.
- DSO can suppress the back gate effect in stead of the BPW.

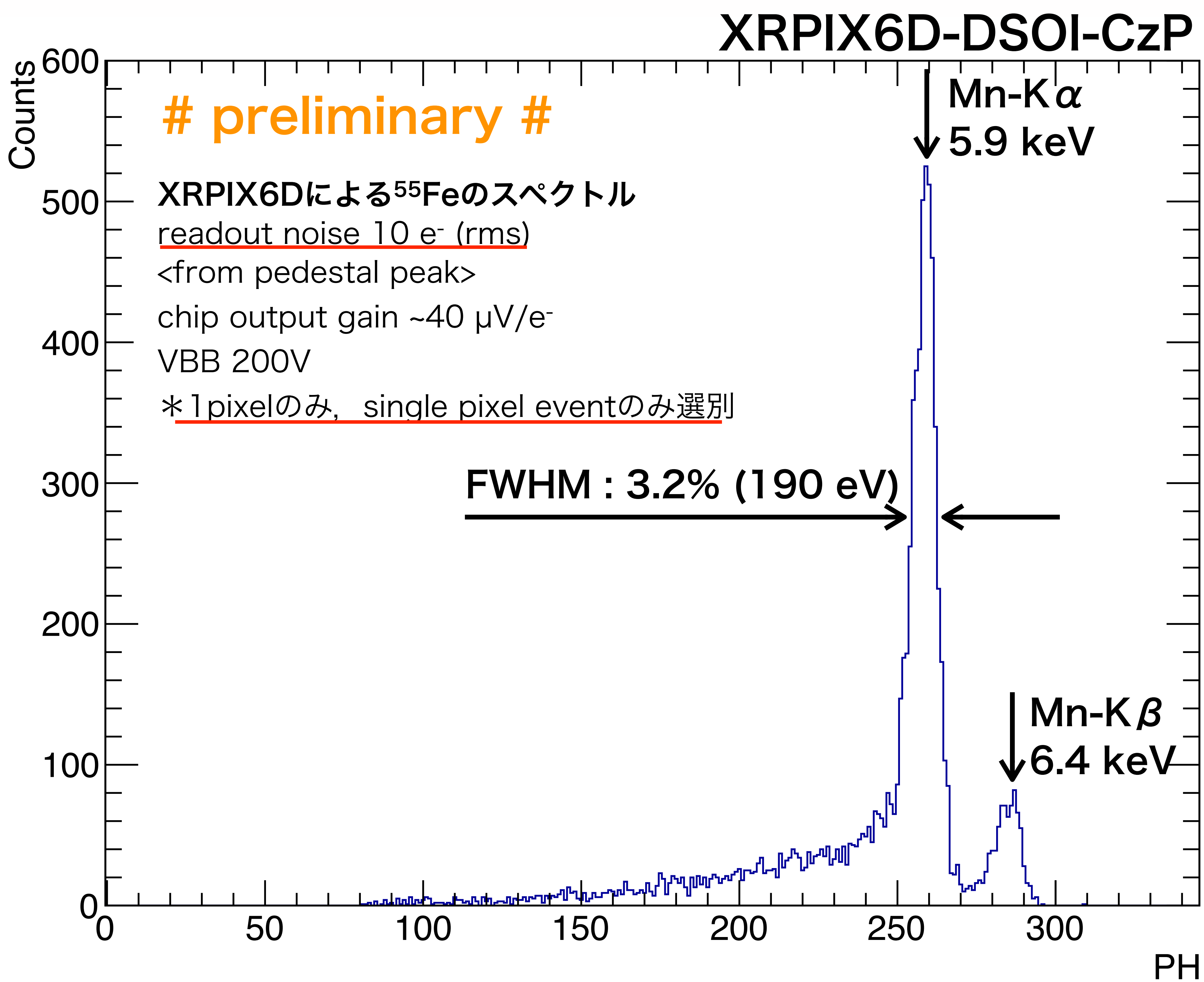
Reduce the size of BPW



(Note: Actual wafer of Double SOI is not N-type but P-type.)

- We can reduce the size of BPW and make the parasitic capacitance low.
  ⇒ increases the node gain.
- We apply a higher voltage to the middle Si than that to BPW and implant n stop in order to converge the electric field toward the BPW and collect signal charge (holes).
  ⇒ New device (XRPIX6D)

New Device - XRPIX6 using Double SOI



- The readout noise in Frame mode almost reached the requirement of ~10e (rms) successfully.
- We are starting evaluation of the readout noise in Event-Driven mode.

Target Specification of the Device

Imaging	area ~ 15x45mm2, (prototype ~2x2mm2) 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**
Time Resolution	< 10μsec for the anti-coincidence with the rate of ~kHz
Max Count Rate	> 2kHz / detector for observation of bright X-ray sources
Non X-ray BGD (anti-coincidence)	1/100 of CCD at 20 keV (5e-5 c/s/keV/10x10mm2)

the same as CCD

~half size

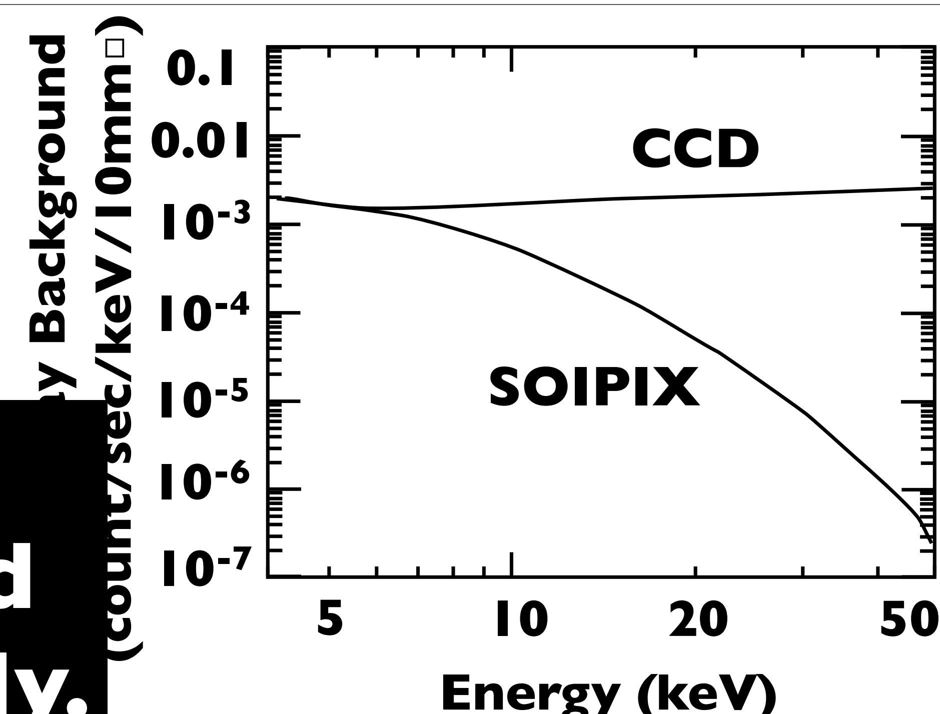
~0.5 μm

>300μm

~10 (rms) in Frame mode

Already achieved in a small device

X-ray SOIPIX



In Frame mode, each performance almost achieved the requirement independently.

Thank you

T.Tsuru, T.Tanaka, H.Uchida, H.Matsumura, M.Itou, S.Ohmura, H.Hayashi, K.Tachibana (Kyoto Univ.), A.Takeda, K.Mori, Y.Nishioka, N.Takebayashi, S.Yokoyama (Miyazaki Univ.), S.Kawahito, K.Kagawa, K.Yasutomi, H.Kamehara, S.Shrestha (Shizuoka Univ.), Y.Arai, I.Kurachi (KEK), T.Kohmura, K.Tamasawa, Y.Ozawa, S.Sato (Tokyo Univ. of Science), S.Nakashima (ISAS)