Development of X-ray silicon detectors for space observatories: XRISM and beyond

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Outline

1. Silicon detectors in X-ray astronomy
2. Xtend, X-ray detector onboard XRISM
3. XRPIX, beyond X-ray CCD

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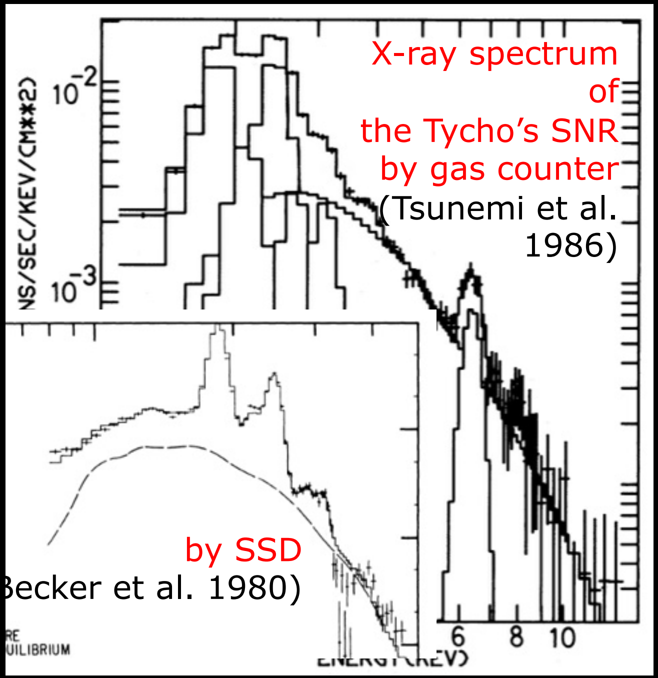
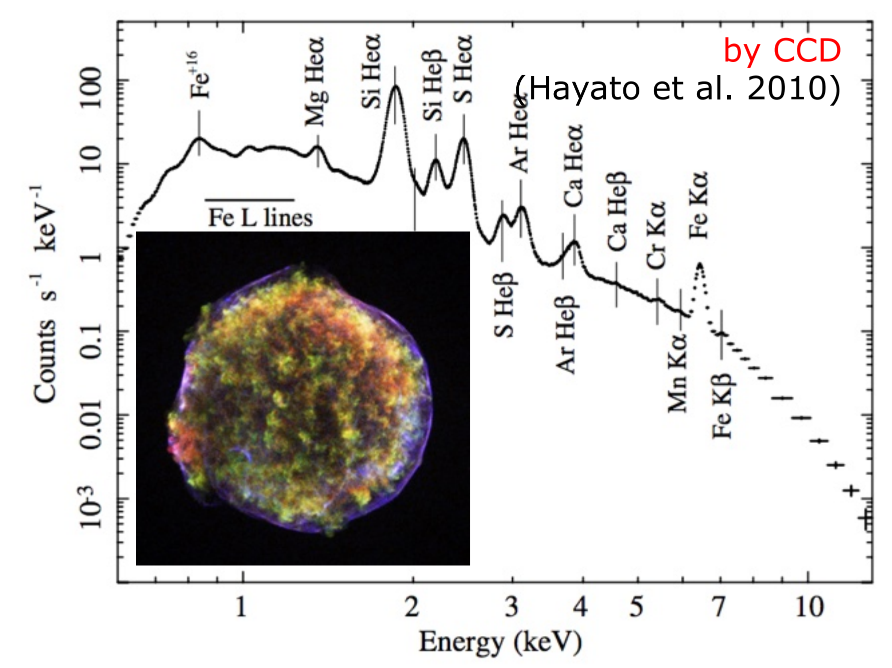
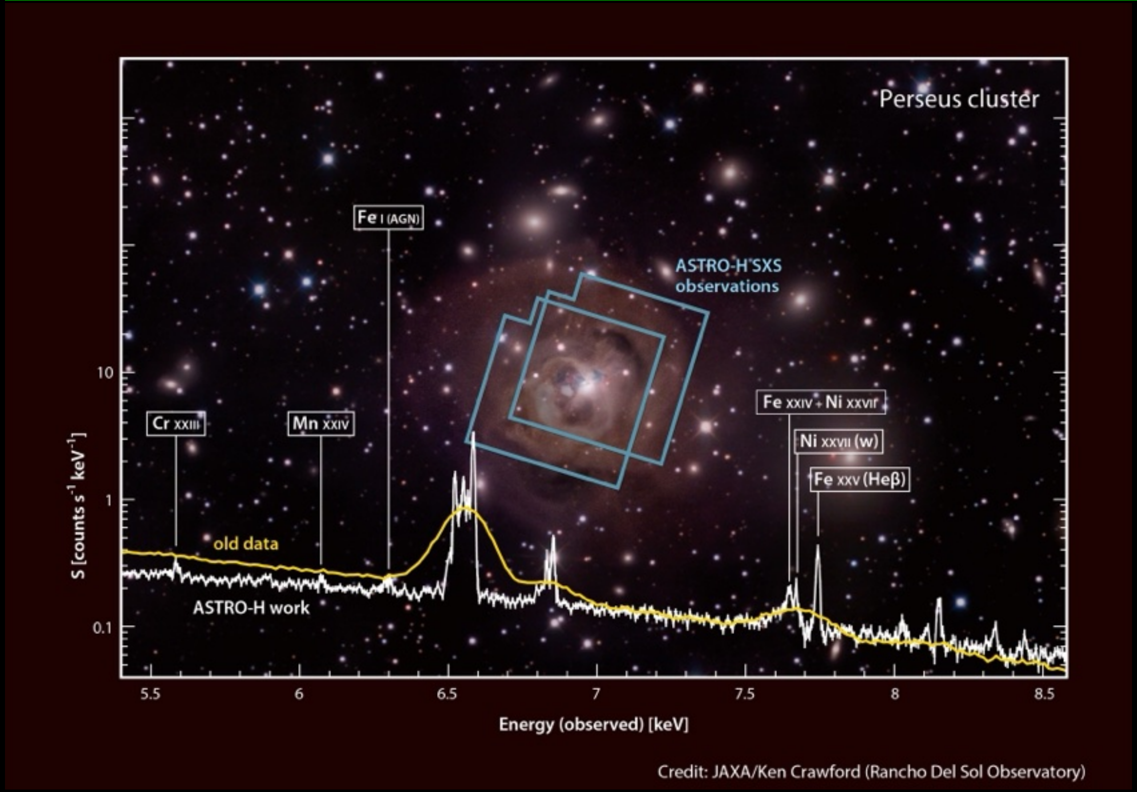
Silicon detectors in X-ray astronomy

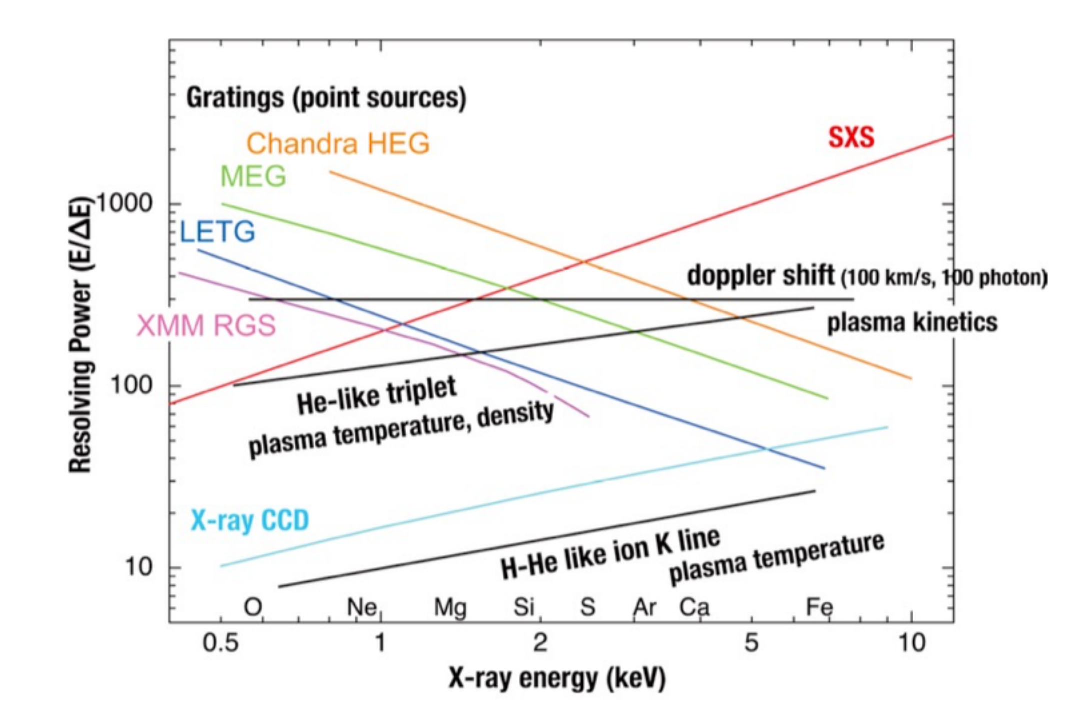




- Introduced as a spectrometer
  - Higher energy resolution compared with conventional gaseous detectors
  - Interesting contrast to that fine spatial resolution is primarily expected as a vertex detector in particle physics
  - The imaging spectroscopy with ``CCD'' has been a main driver of X-ray astronomy in recent decades

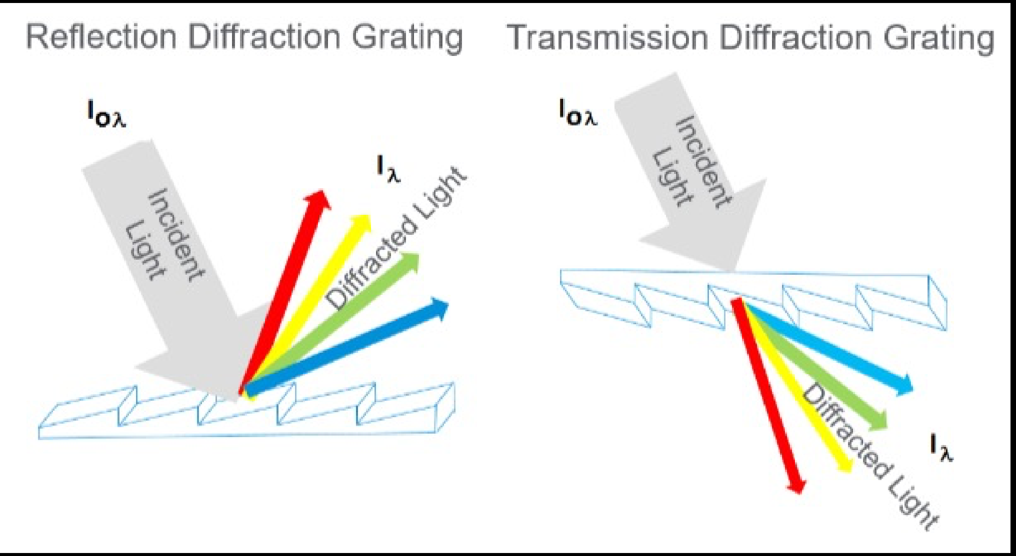
X-ray micro calorimeter



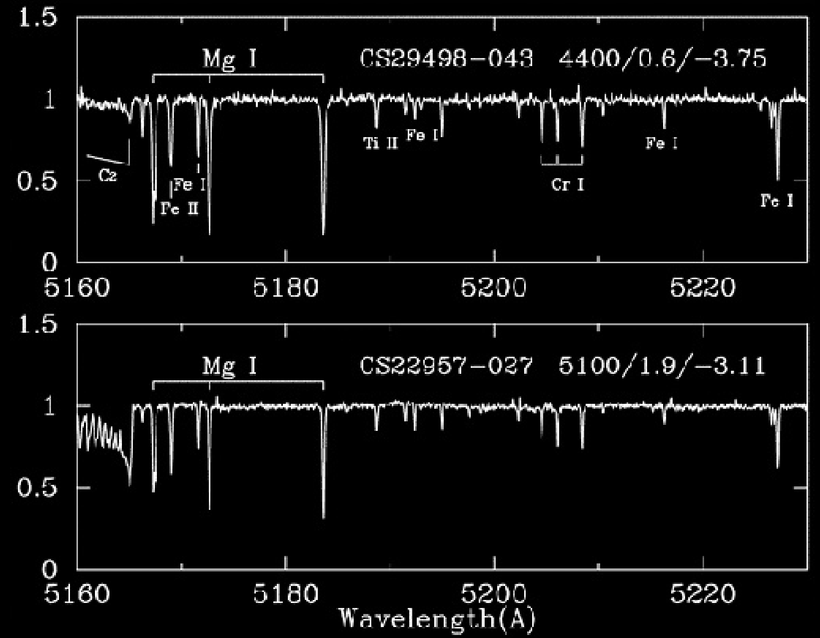


- Unprecedented spectrometer onboard XRISM
  - Non-dispersed and thus large effective area
  - Highest resolving power above 2 keV
  - A number of outstanding results provided by iron line diagnostics

Spectroscopy in Optical and X-ray



Mark Fisher and Travis Burt, Agilent Technologies, Inc.



https://subarutelescope.org/jp/about/instrument/hds/index.html

- Spectroscopy in astronomy usually utilizes the wave-nature of light and its resolving power, defined as λ/Δλ, reaches as high as 100,000 (cf. XRISM microcalorimeter's 1500)
- Spectroscopy in X-ray astronomy also utilizes the particle-nature of light, allowing imaging spectroscopy without slit

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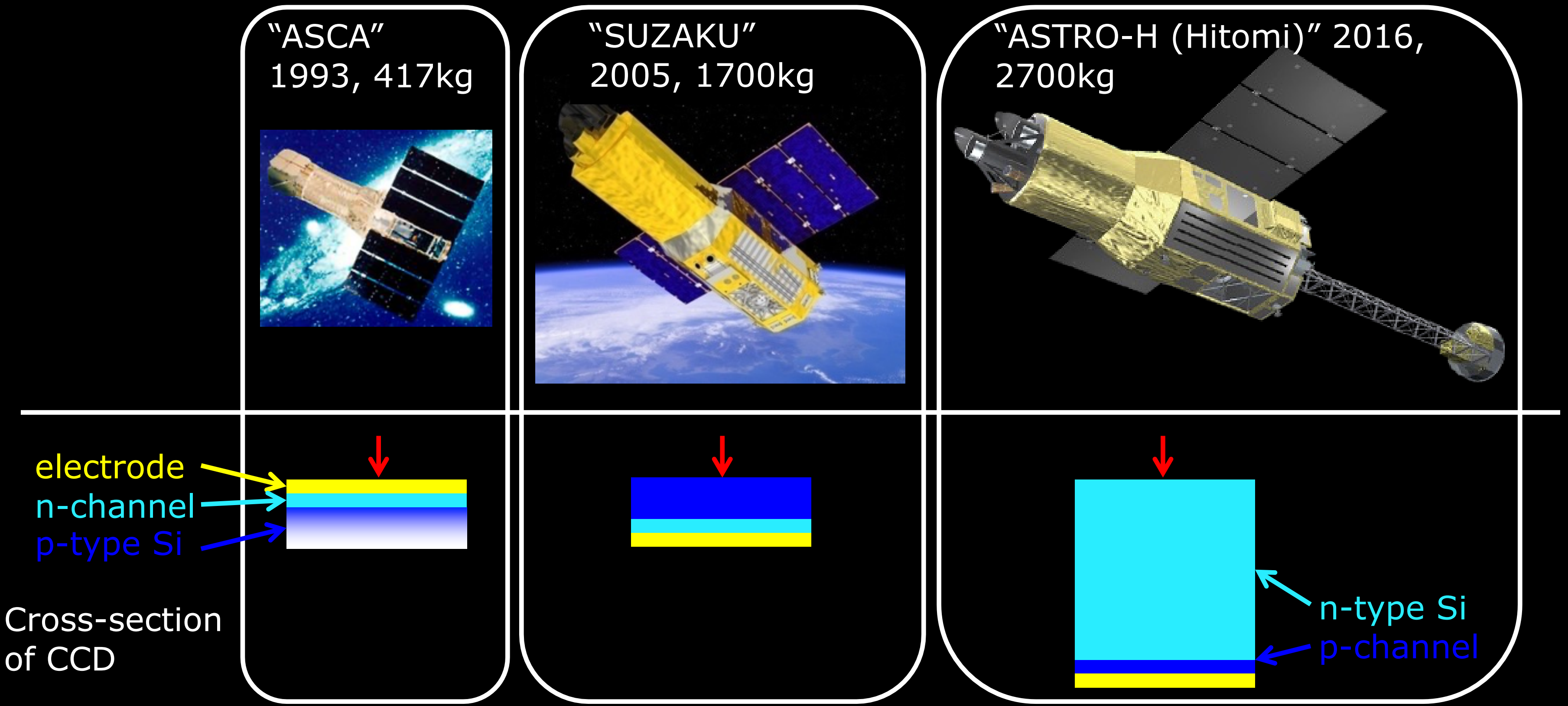
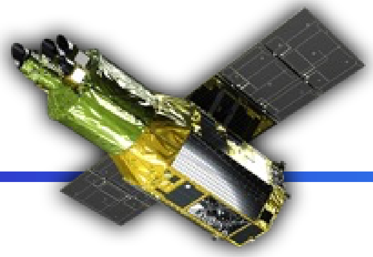
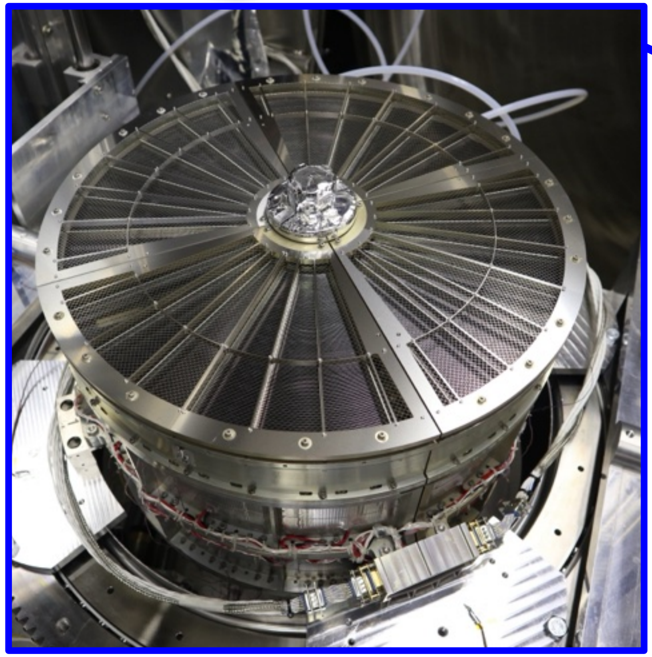
History of X-ray CCDs for astronomical use

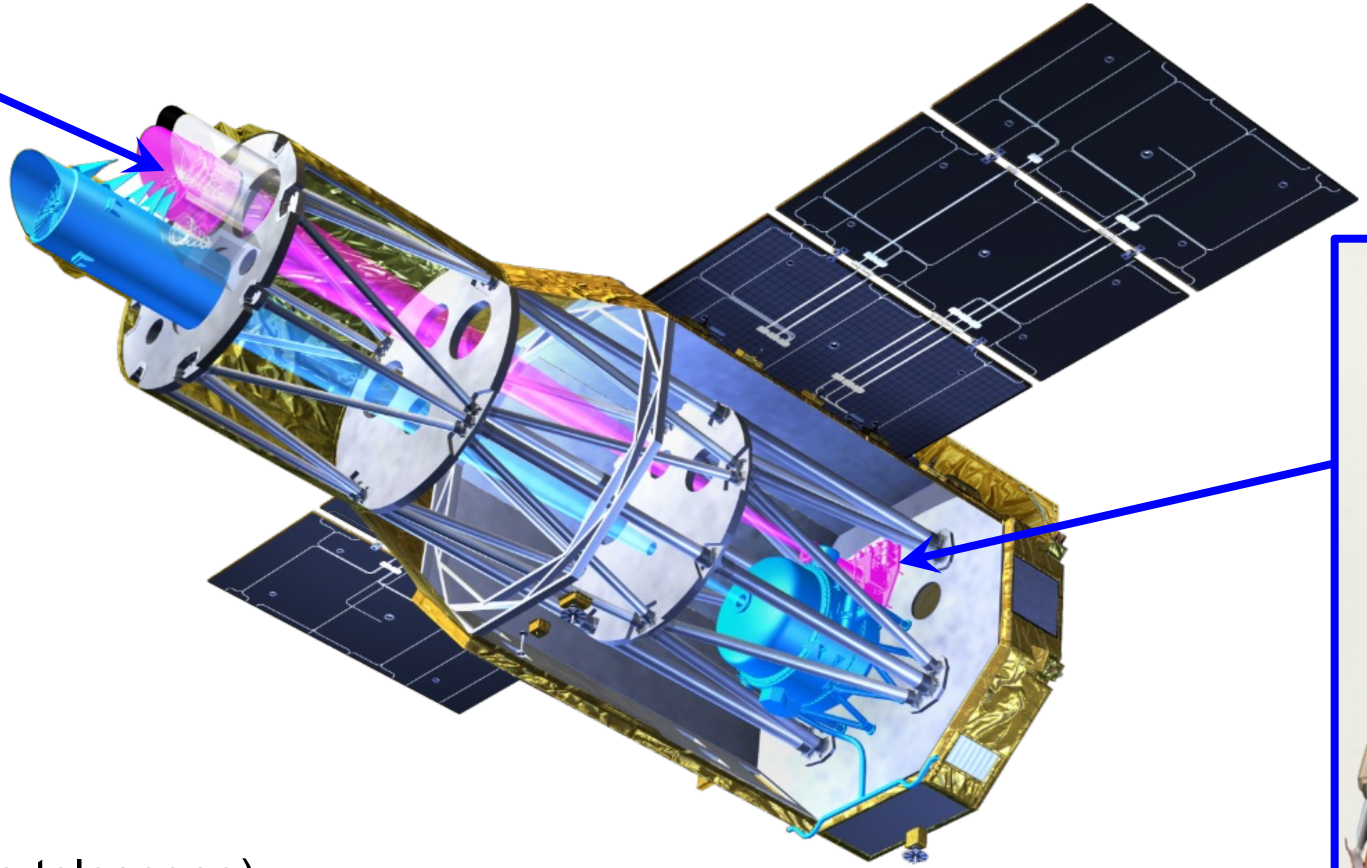


- A standard focal-plane detector with a 20-year history
  - ASCA (1993-2001): N-channel Front-Illuminated CCD
  - Suzaku (2005-2015): N-channel Back-Illuminated CCD
  - Astro-H (Hitomi) (2016), XRISM (2023-): P-channel Back-Illuminated CCD



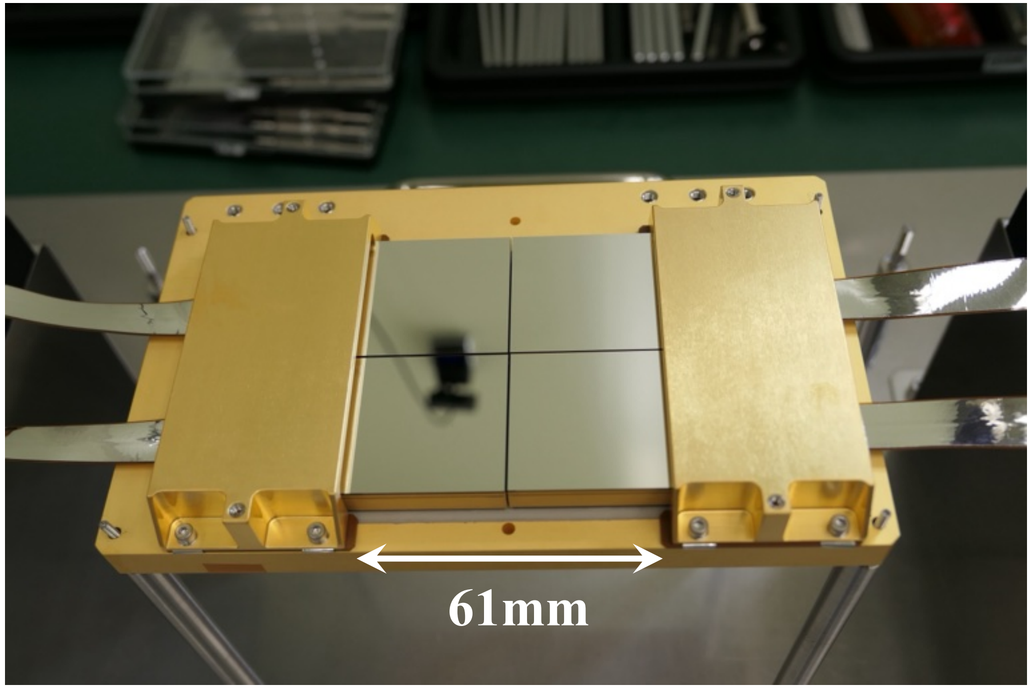
Xtend on XRISM





- Xtend (soft X-ray imaging telescope)
  = XMA (X-ray Mirror Assembly) + SXI (Soft X-ray Imager; CCD camera)
- XMA is an Aluminum thin-foil-nested conically approximated Wolter-I optics. Both Xtend and Resolve have an XMA with identical design.
- Xtend and Resolve observe the same sky and covering almost the same energy band

CCDs for Xtend



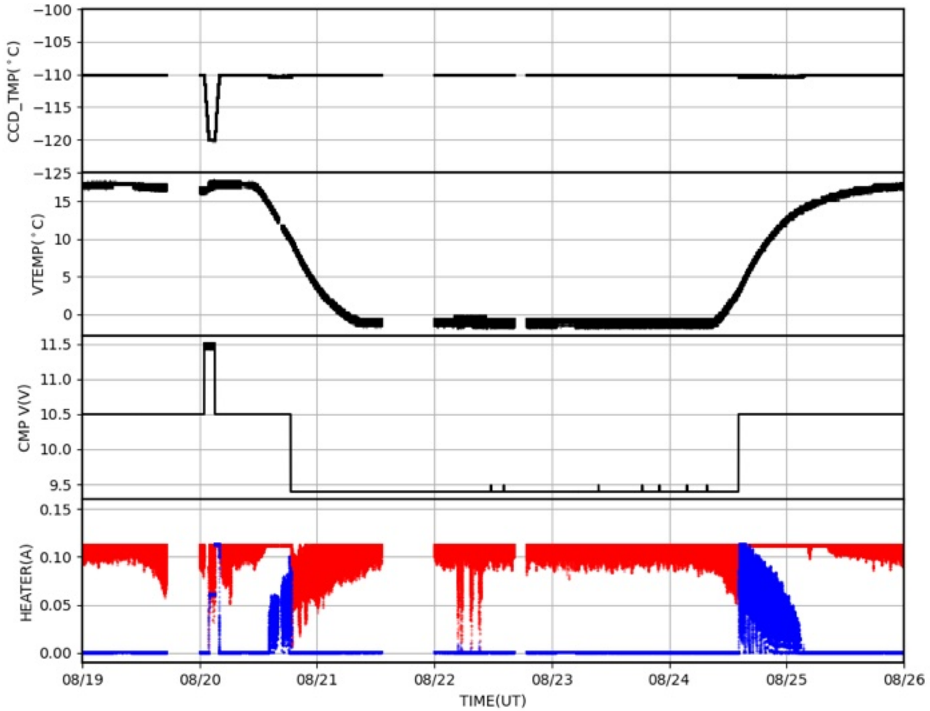
Specifications and nominal operation parameters of the SXI CCD

CCD Specification	Architecture Imaging area size Pixel format (physical/logical) Pixel size (physical/logical) Depletion layer thickness Incident surface layer (back side) Readout nodes (equipped/used)	Frame transfer 30.720 mm × 30.720 mm 1280 × 1280 / 640 × 640 $24\mu m \times 24\mu m$ / $48\mu m \times 48\mu m$ 200 μm 100 nm + 100 nm thick Aluminum coat 4 / 2
Operation parameters	Frame cycle On-chip binning Charge injection	4 seconds 2×2 every 160 physical rows

- We have developed large-size back side illumination type CCD with Hamamatsu Photonics. K.K.
- Four CCDs abutted in 2×2 array form an effective imaging area of 61mm square.
- Two important updates from ASTRO-H CCDs
  - Adoption of a notch implant in the charge transfer path as a measure against the increase of the CTI in orbit
  - Doubling aluminum layers (100nm + 100nm) on the incident surface to reduce the number of pinholes found in ASTRO-H CCD and introducing an extra aluminum layer above the depletion layer to decrease the flux of light leaks from the physical edges

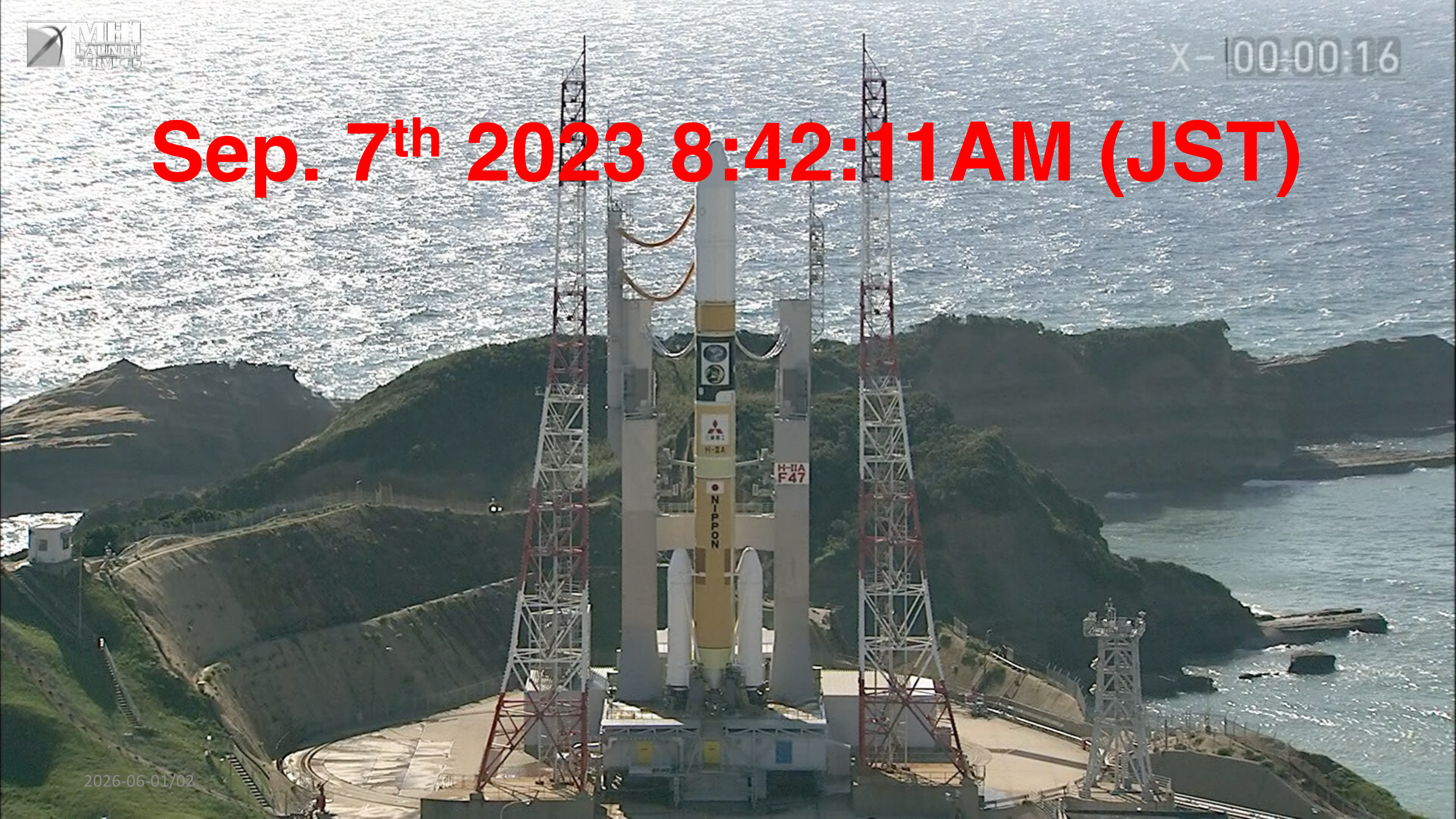
Spacecraft thermal vacuum test

XRISM
X-Ray Imaging and Spectroscopy Mission



- A month-long spacecraft thermal vacuum test was conducted in **August 2022**
- The performance verification of the SXI was successfully carried out in a course of multiple thermal cycles of the spacecraft
  - The SXI system successfully kept the CCD temperature constant at −110 ℃ and demonstrated a cooling performance to make the CCD temperature down to −120 ℃
  - The spectroscopic performance was consistent with those in the sub-system tests


Sep. 6th 2023
before the sun sets (JST)
Vehicle assembly building
© JAXA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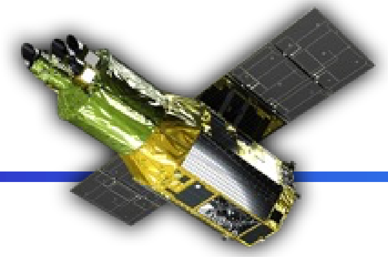
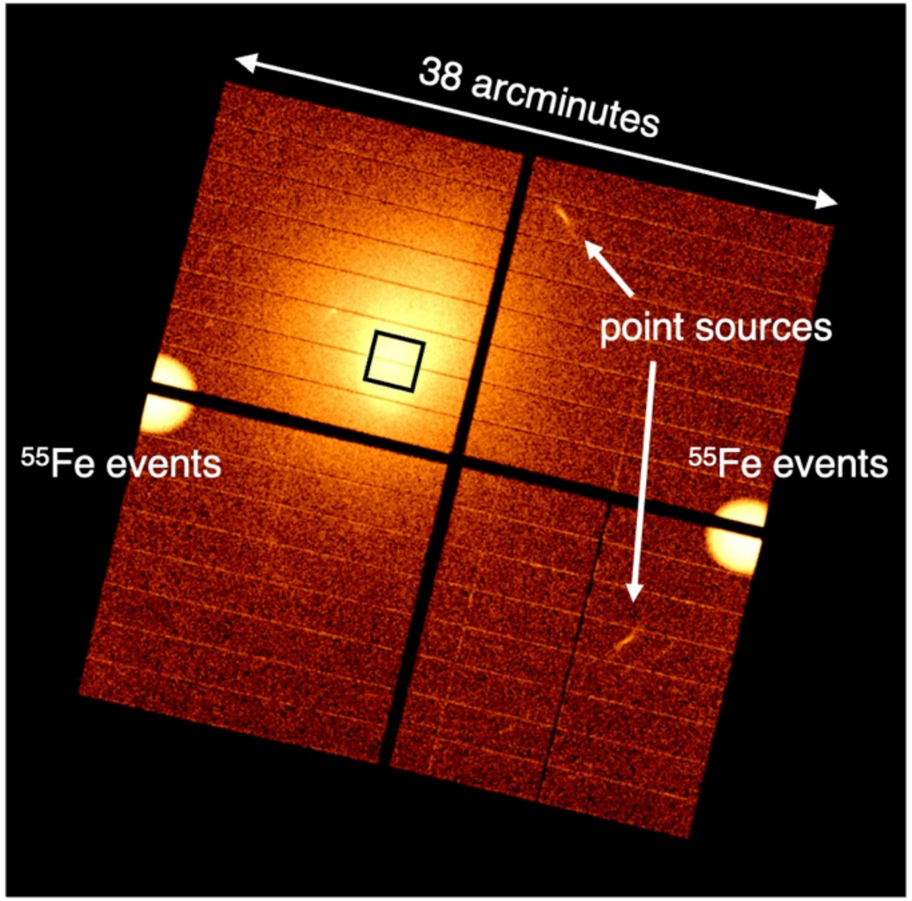
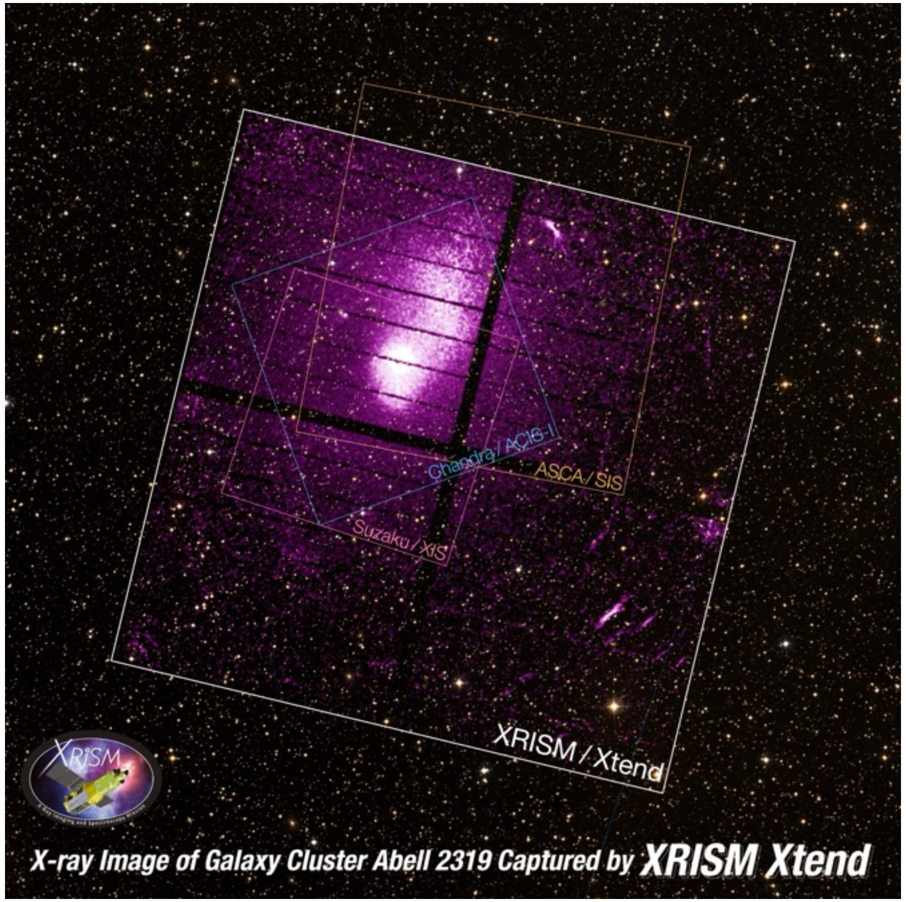


SXI initial operation

- **Start-up operation**
  - 2023 Oct. 17th (Y+40) ‘ SXI-PE & DE Power-up and Initialization
  - 2023 Oct. 18th (Y+41) ‘ SXI-FE Power-up
  - 2023 Oct. 19th (Y+42) ‘ CCD frame data taking before cooling
  - 2023 Oct. 20th (Y+43) ‘ SXI-CD Power-up and CCD cooling
  - 2023 Oct. 21st (Y+44) ‘ CCD frame data taking with -110 ℃ and Event mode (nominal observation) started
- **1/8 window position adjustment**
  - 2023 Nov. 1st (Y+55) ‘ 1/8 win + no bst
  - 2023 Nov. 2nd (Y+56) ‘ 1/8 win + bst
- **Charge-Injection row position adjustment**
  - 2024 Mar. 10th (Y+185) ‘ full window

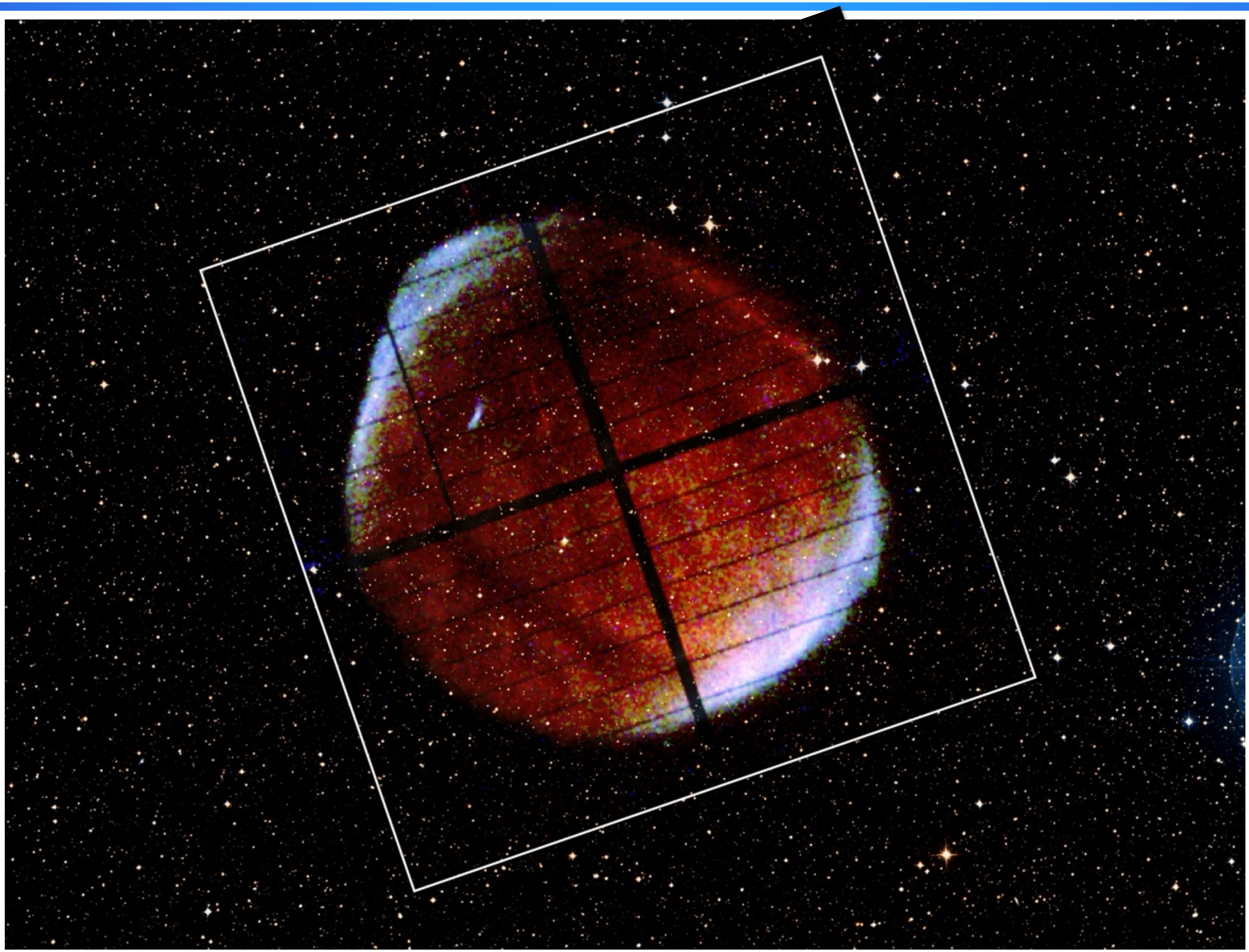
First light image

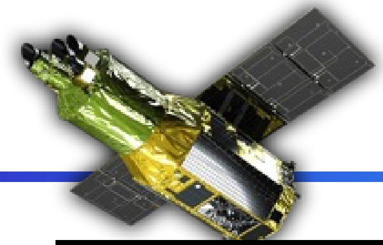




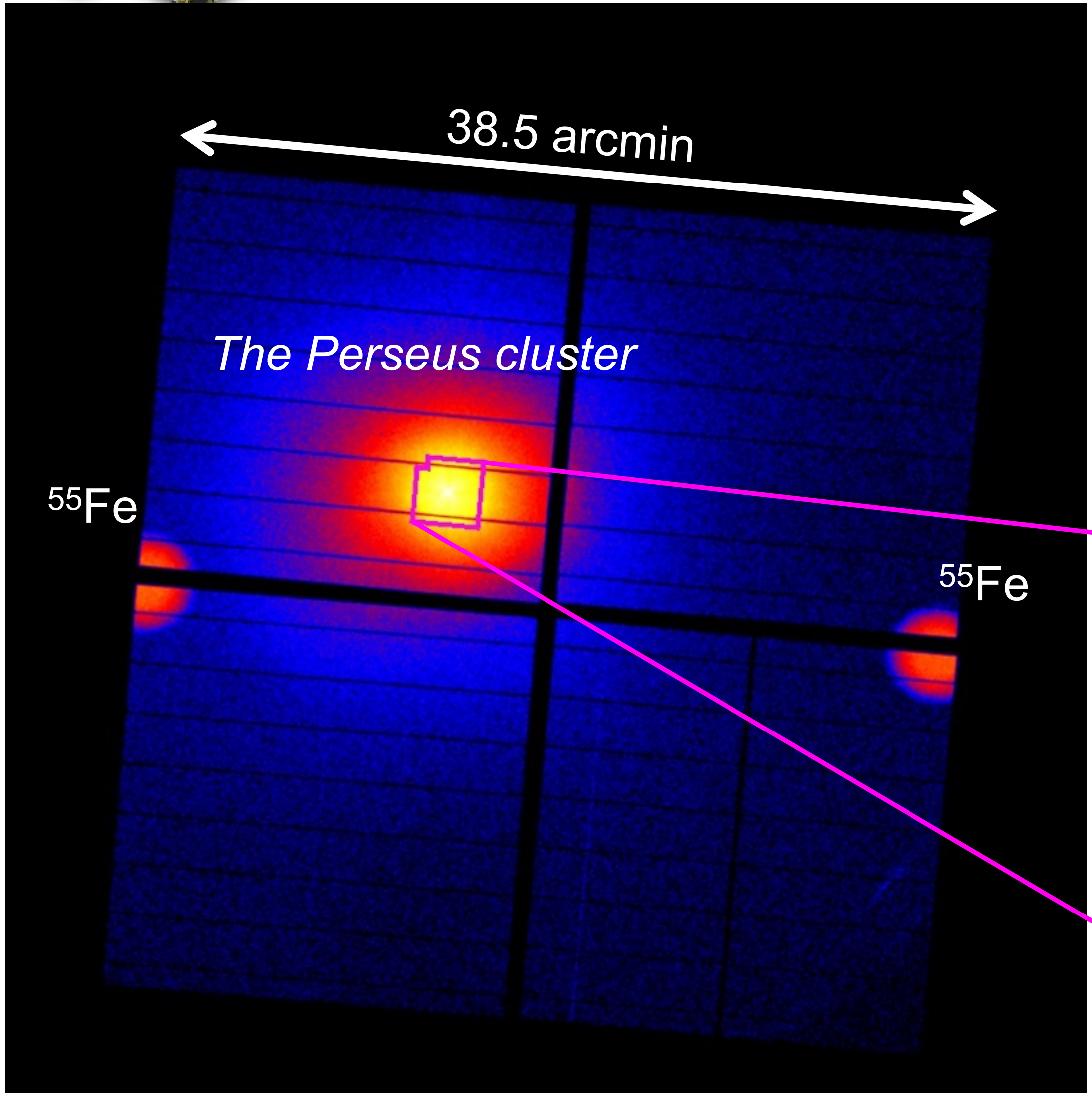
- ➢ Entire regions are fully functional except for bad columns known from ground tests
- ➢ The large FoV would allow us to detect serendipitous sources

Field of View

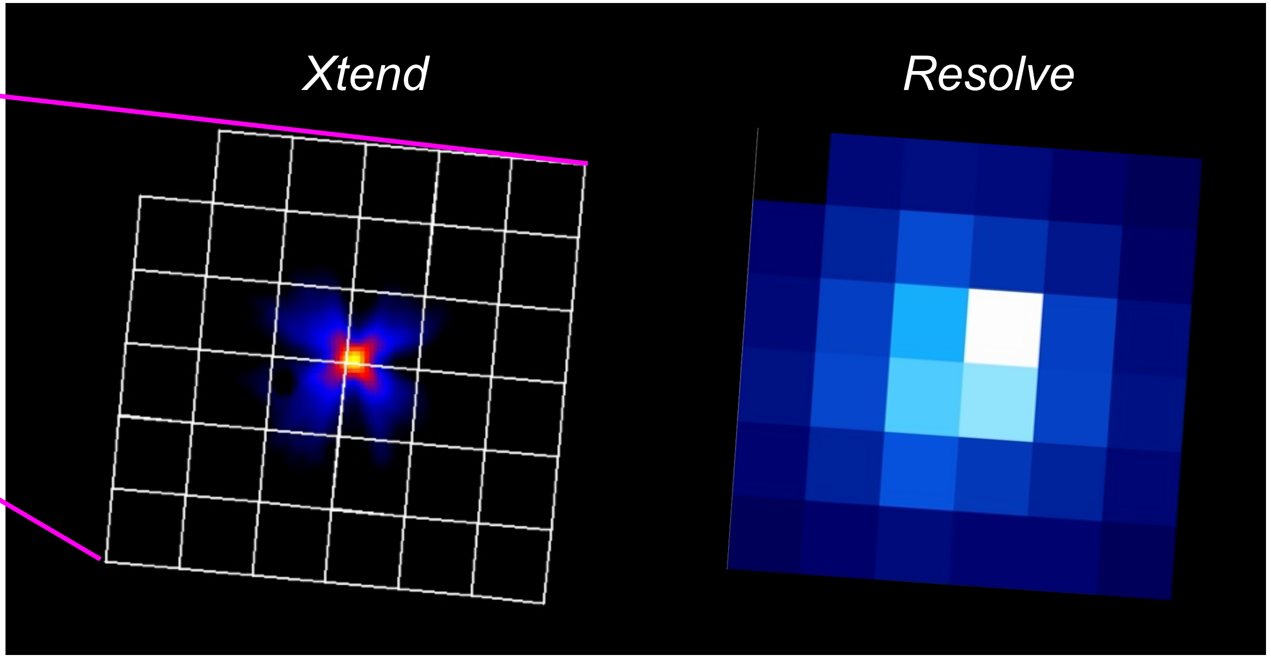




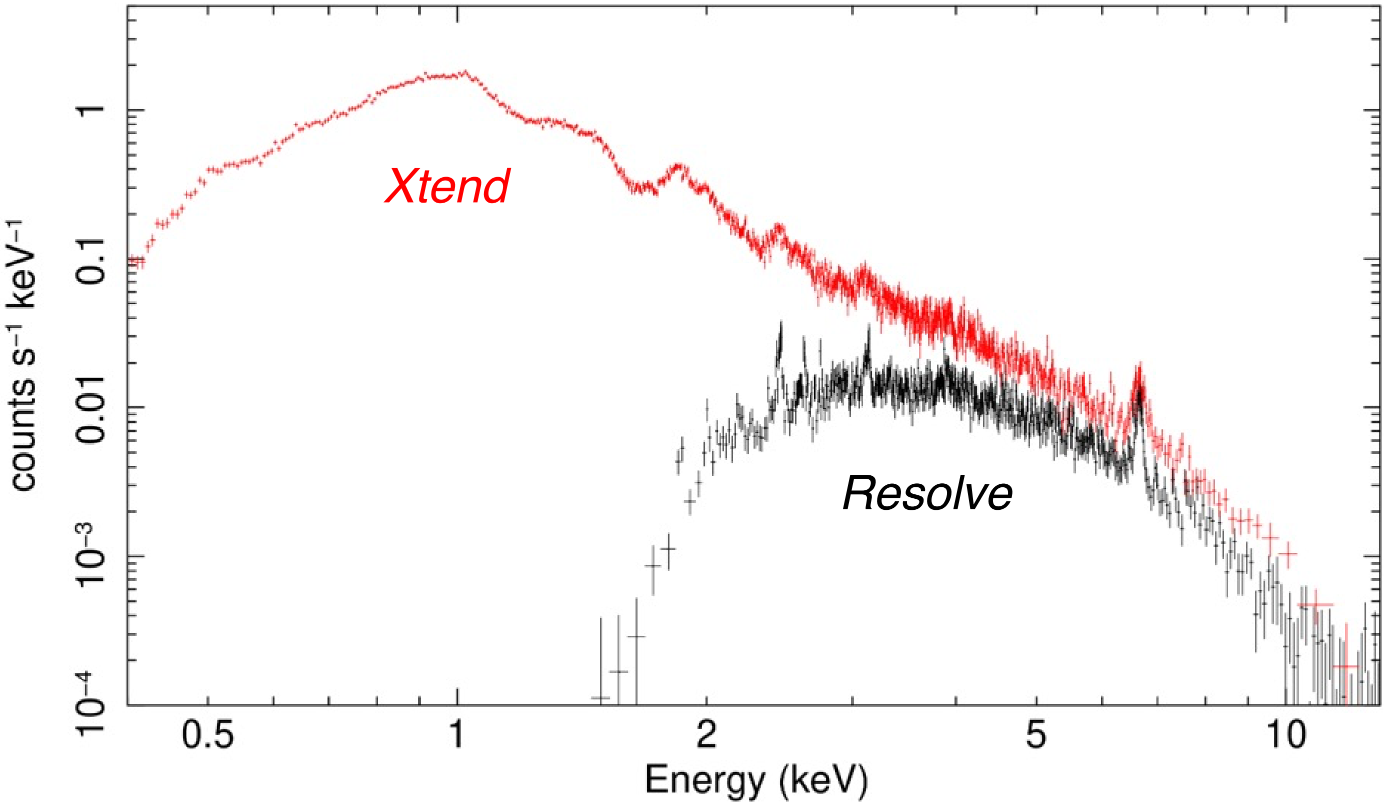
Characteristics of Xtend: image



- Large FoV of 38'5 × 38'5 encompasses the 3'x3' FoV of Resolve in its center, and the finer pixel size of 1.74" (cf. 30" in Resolve) well over-samples the PSF of XMA
- Xtend provides more detailed spatial information within the Resolve FoV and allows possible contamination from X-ray sources outside of the Resolve FoV



Characteristics of Xtend: spectrum



- Broader energy coverage with larger effective area, especially below 2 keV
- Xtend and Resolve have their own characteristics in imaging and spectroscopy, respectively, and play complementary roles in XRISM.

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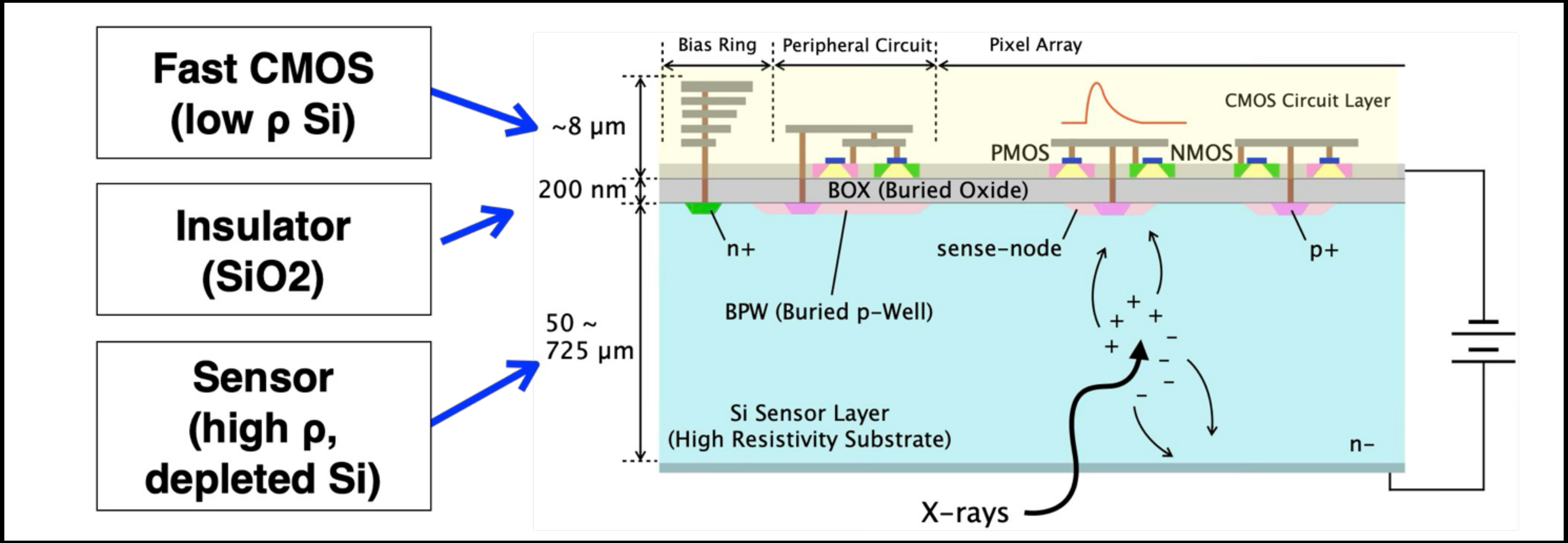
X-ray SOI pixel detector, XRPIX



- XRPIX is a SOI pixel detector for X-ray application, satisfying all the requirements below
  - fine imaging (small pixel ～20μm, large size > 20mm)
  - low noise (< 10e rms),
  - wide-band, high QE (thick depletion > 200μm, backside < 1μm)
  - trigger output function (time resolution < 10μs)
  - on-chip signal processing (CMOS circuit)

Spec of XRPIX

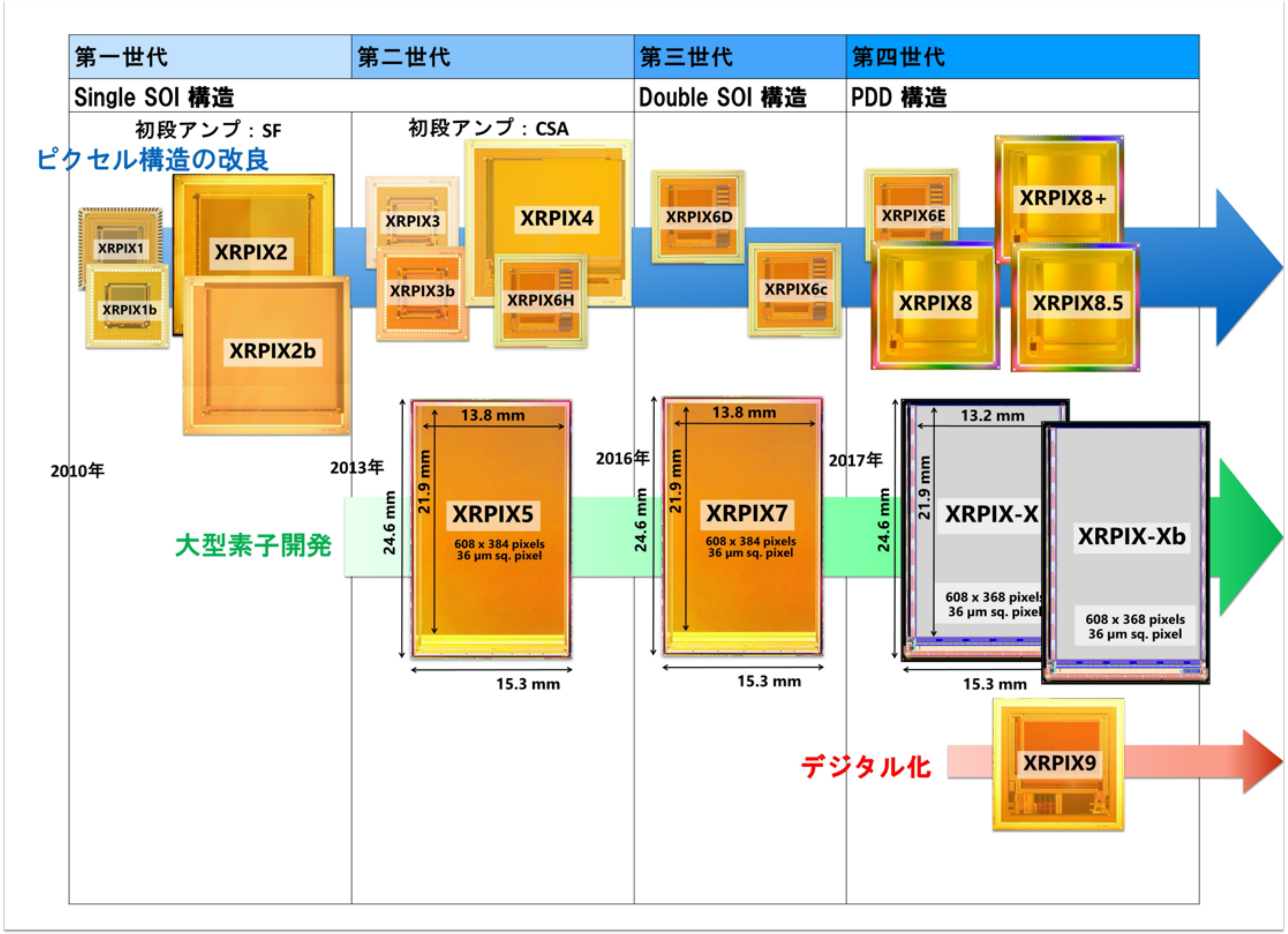
same performance as CCD

Imaging	pixel ~ 36μm□ area: Req. ~15x15mm^2 mosaic with 3side-buttable
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
Max Count Rate	> 2kHz / sensor for observation of bright X-ray sources

new features with X-ray SOIPIX

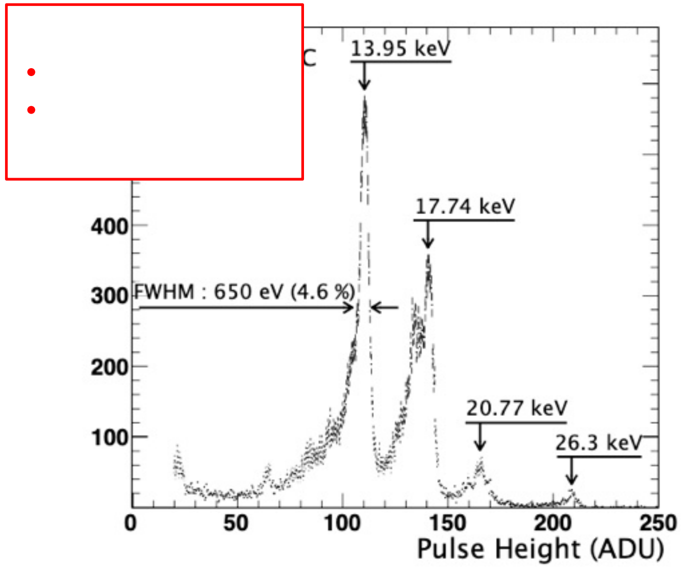
- Ultra low background using the anti-coincidence technique with veto contours
- Pile-up free
- Extremely wide dynamic range
- *with CCD-level spectroscopy*

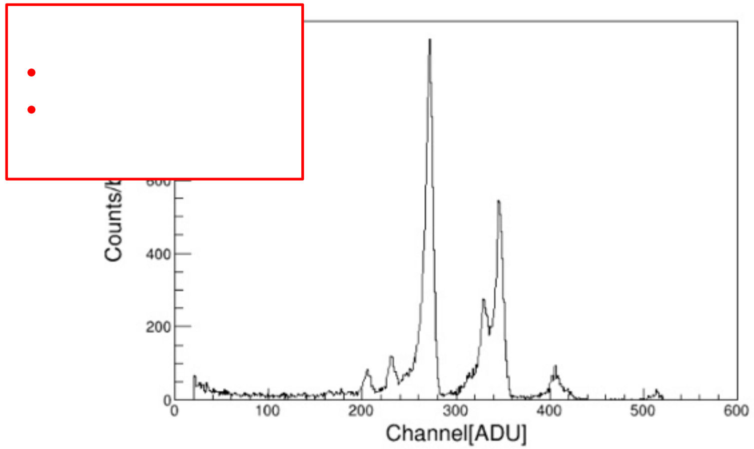
History of XRPIX development

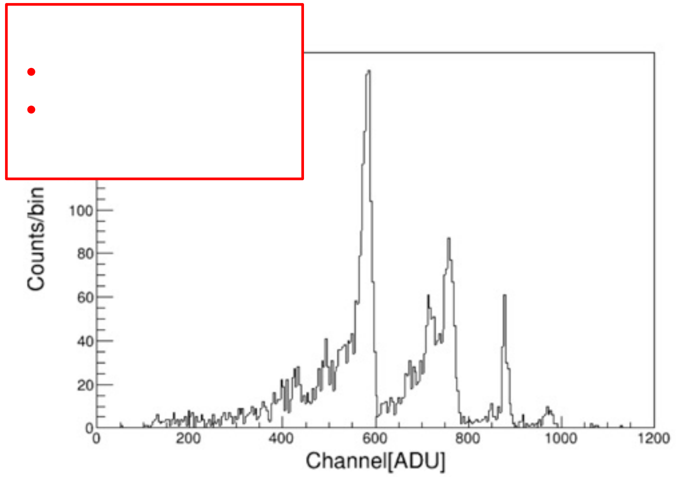


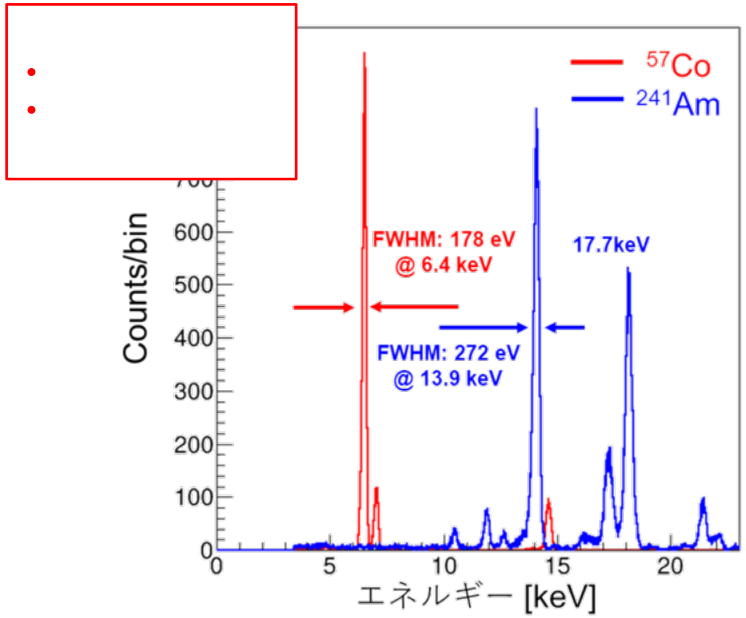
- The history of XRPIX is almost a history of its spectroscopic performance
  - Enlargement and Digitization do not make sense without spectroscopic performance

History of XRPIX development



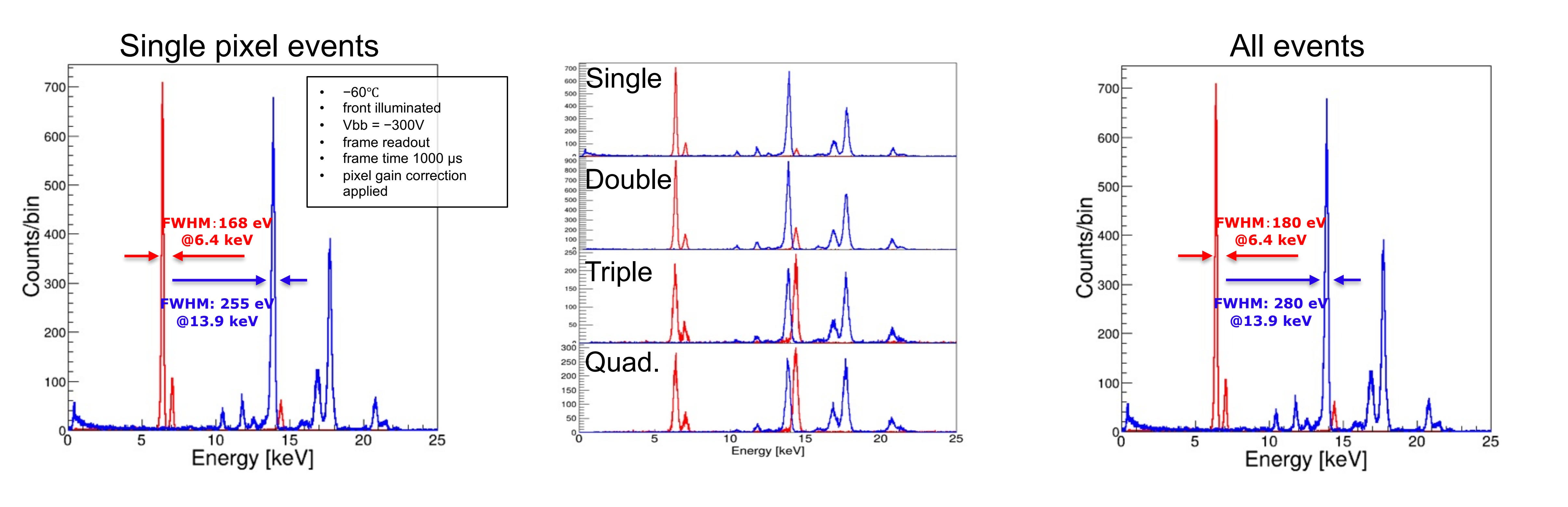






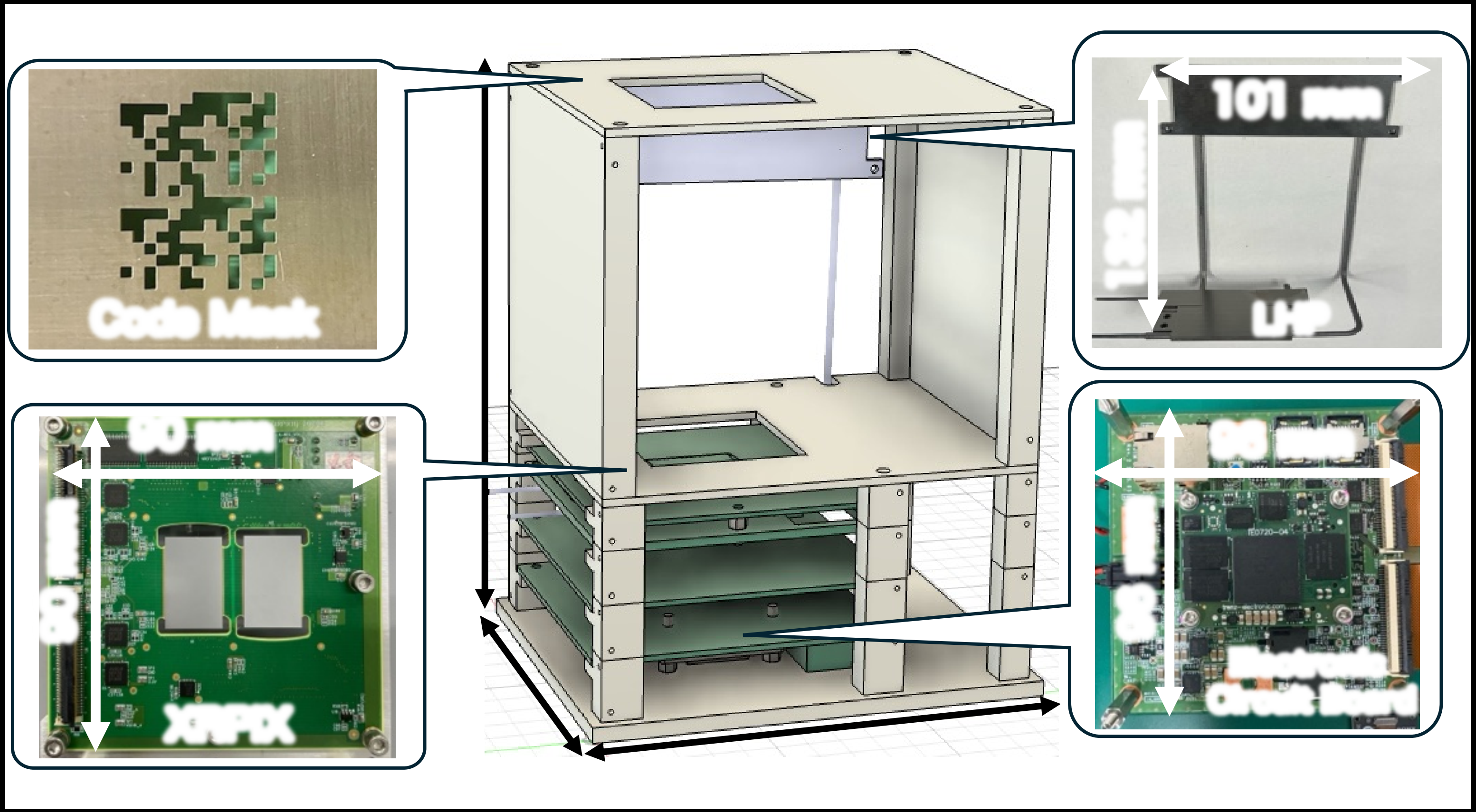
- The history of XRPIX is almost a history of its spectroscopic performance
  - Enlargement and Digitization do not make sense without spectroscopic performance
  - XRPIX has the frame and event-driven readout modes, and the spectroscopic performance of the latter is more important
  - The PDD structure developed in the 4th generation is a milestone in this history, and CCD-comparable-performance has been achieved

Current best performance, XRPIX11



- Truly CCD-comparable-spectrum with all events, not with single-pixel events alone
- Satisfactory spatial uniformity with three-side buttable

2U Camera system : next XRPIX-installed space mission



- A compact X-ray SOI camera, a CubeSat-compatible 2U module
  - coded mask, XRPIX, electronic circuit boards, and a loop heat pipe (LHP)
- SUIM architecture-based system
  - Simplified power-supply boards optimized for small-satellite applications

Summary

- Silicon detectors have been a workhorse instrument of X-ray astronomy for decades as an imaging spectrometer
- The state-of-the-art CCD detector, Xtend onboard XRISM, was developed based on lessons learned from the past and is working pretty much well in space
- Our silicon detector development focus is now shifted to the SOI-CMOS pixel detector, XRPIX, carrying on our legacy of CCD development and bringing it to the next-generation X-ray astronomy. Now it is ``mission ready”!

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