Overview of the X-ray Astronomical Imaging Detectors - CCD to APS -

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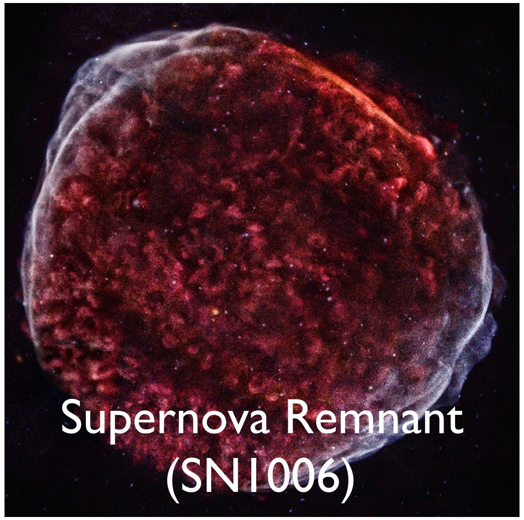
2017 Dec 11 @ SOIPIX2017/HSTD11

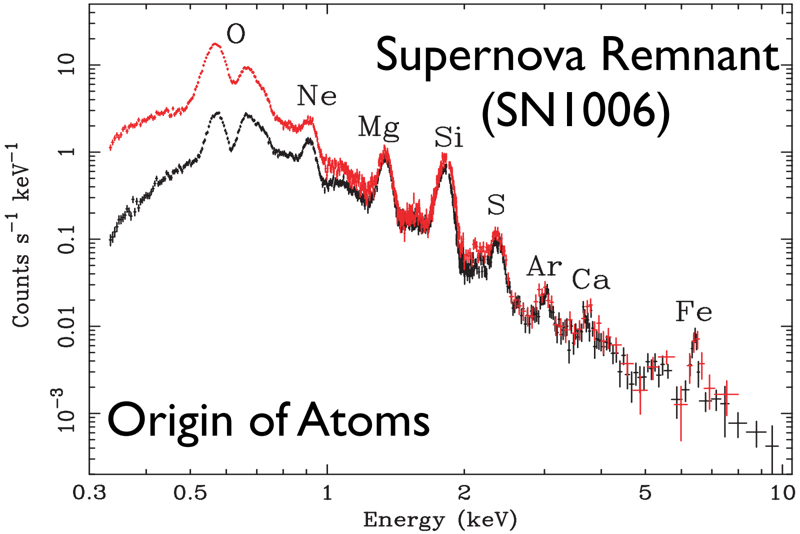
Outline

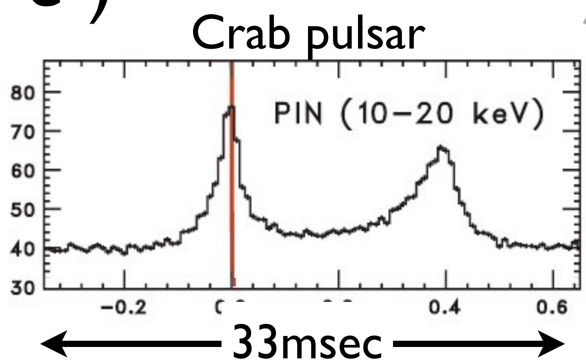
- Some Intro. Overview of Imaging System
- X-ray CCD for < 10 keV band
- CCD with Parallel Readout
- CMOS APS, Hybrid
- CdTe / CdZnTe
- X-ray SOIPIX (our development)

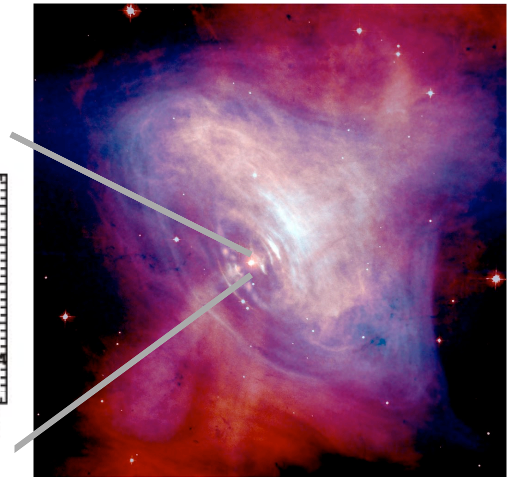
What is necessary for X-ray Astronomy

- Imaging
  - Fine structure of diffuse sources
  - Faint sources
- Spectroscopy
  - Temperature
  - Abundances of Elements
  - Doppler Velocity
- Wide X-ray Energy band
  - Absorbed sources
  - Non-thermal emission (e.g. Synchrotron from TeV e-)
- Timing
  - Pulsation and Burst



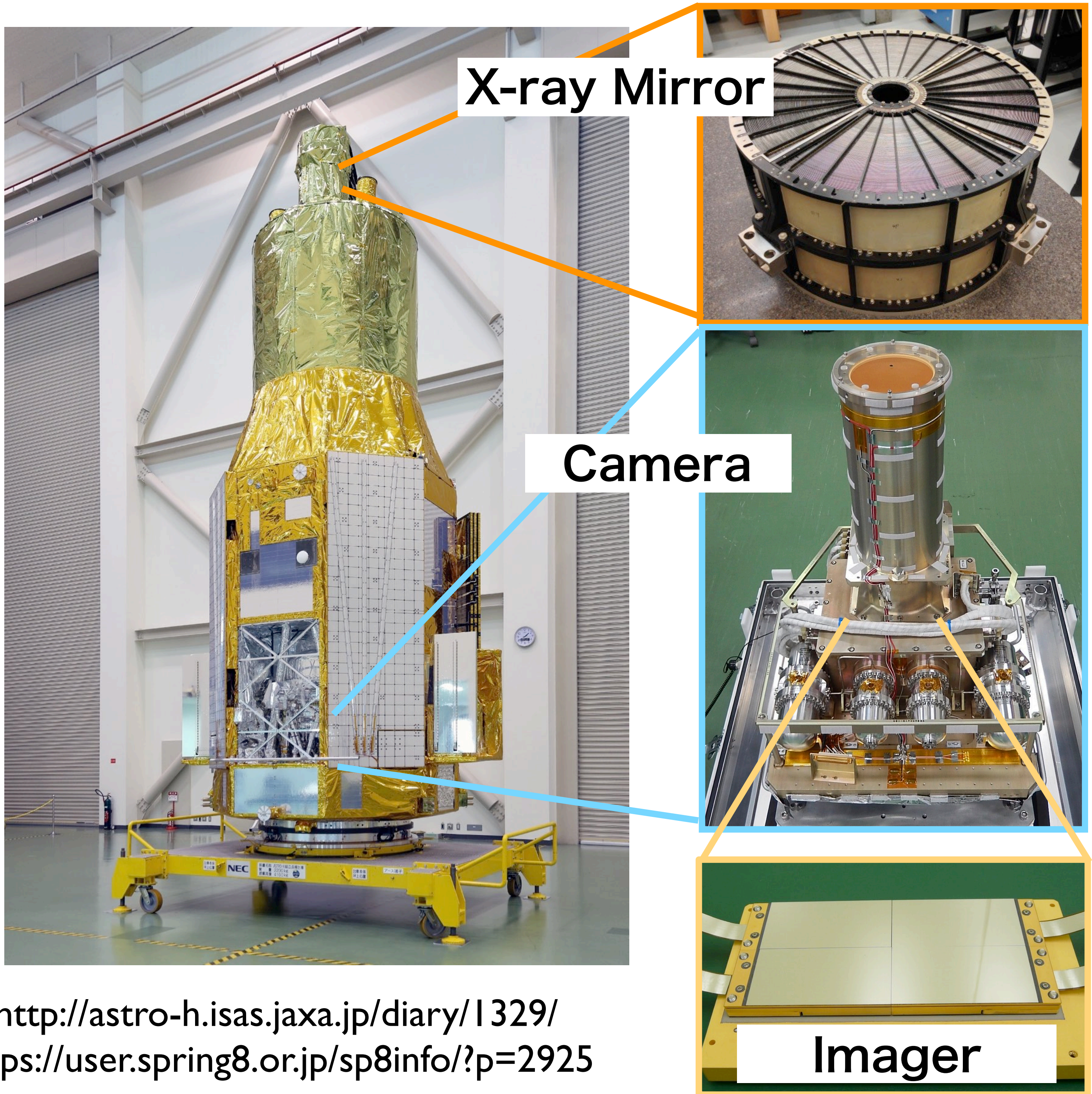


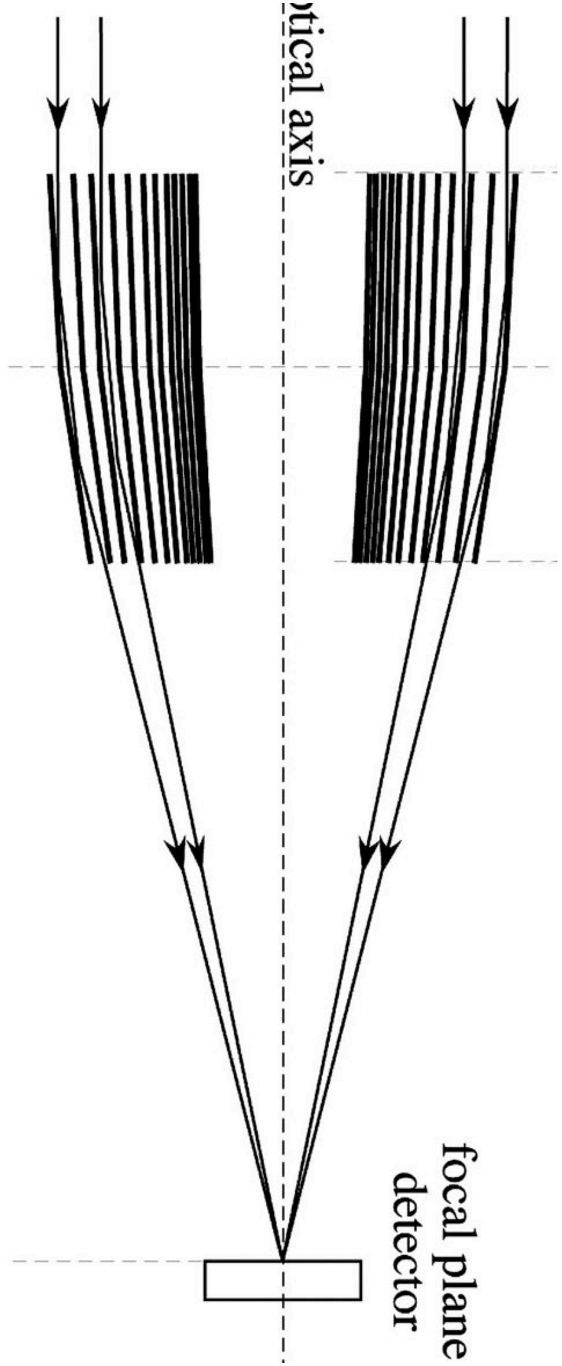




http://chandra.harvard.edu/photo/2013/sn1006/
http://hubblesite.org/image/1248/news_release/2002-24
Yamaguchi+08 PASJ 60, S153

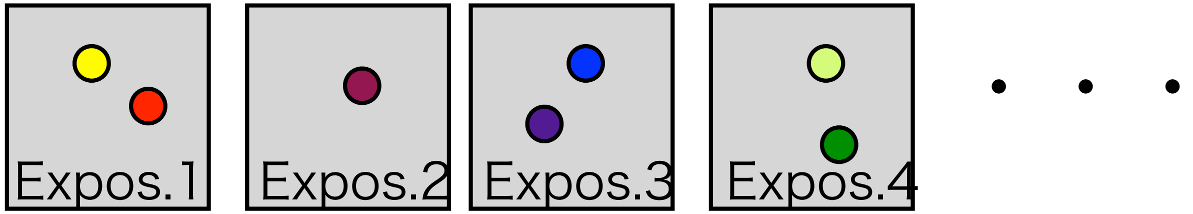
X-ray Imaging System

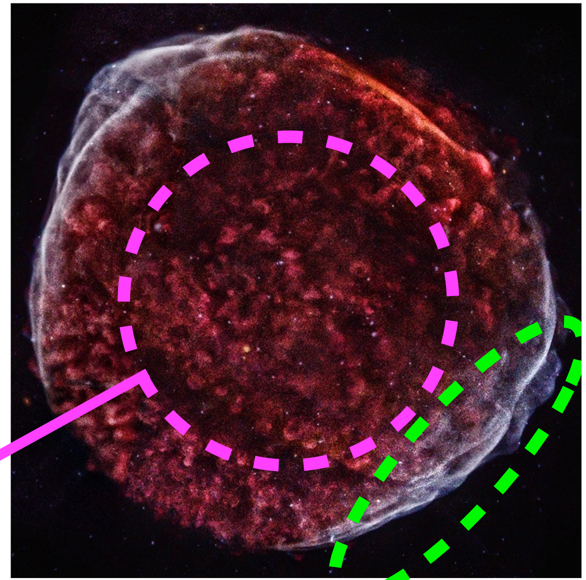




http://astro-h.isas.jaxa.jp/diary/1329/
ttps://user.spring8.or.jp/sp8info/?p=2925

X-ray Photon Counting



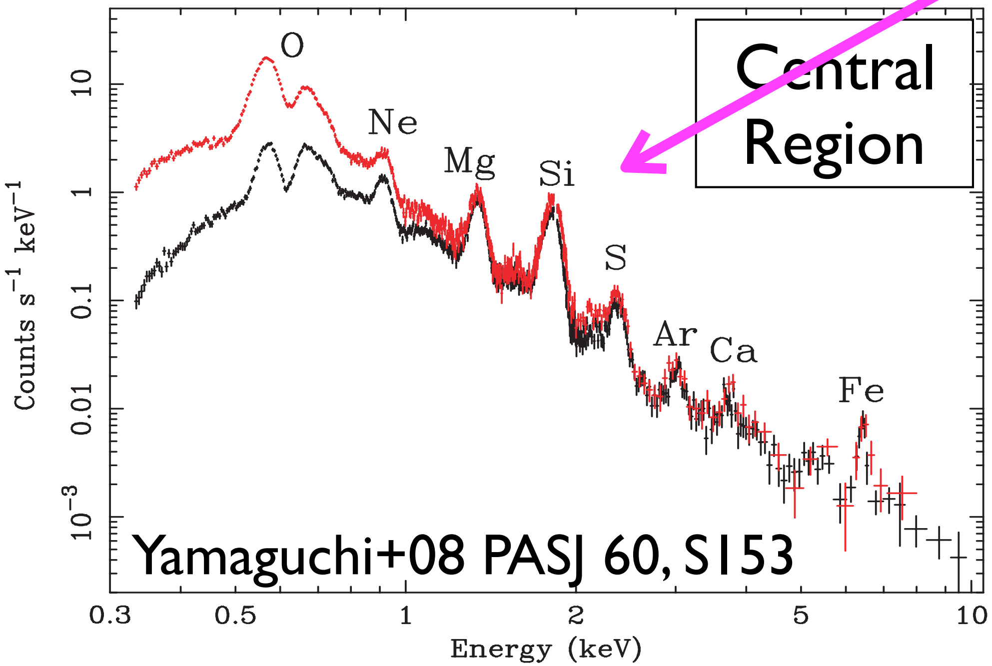


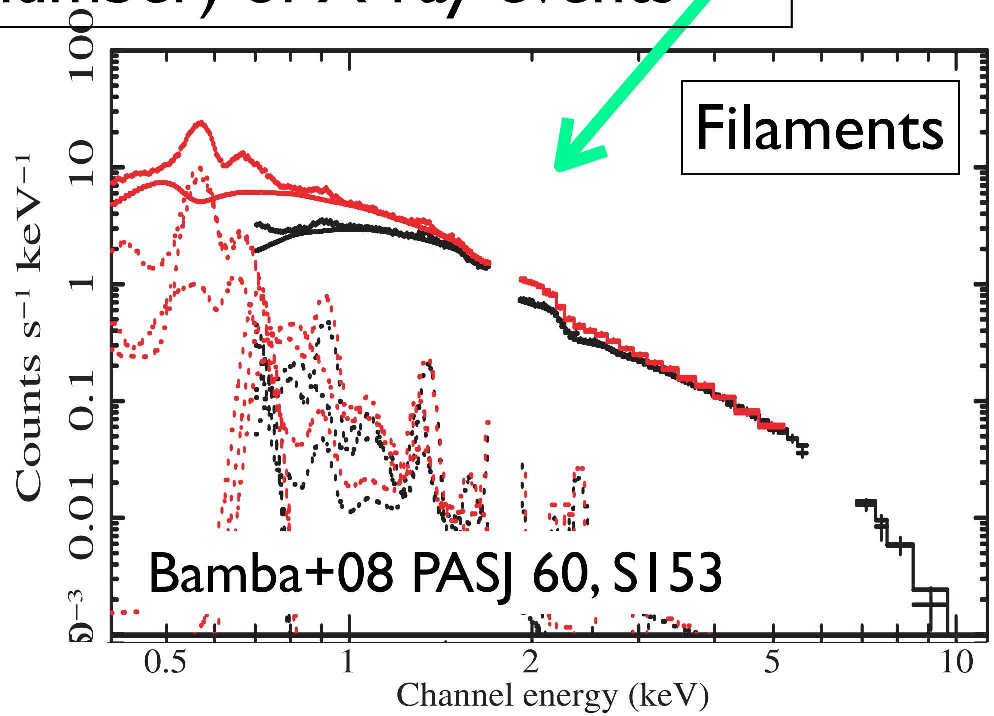
http://chandra.harvard.edu/photo/2013/sn1006/

- 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

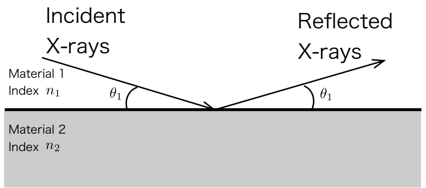
Histogram of energy (electron number) of X-ray events

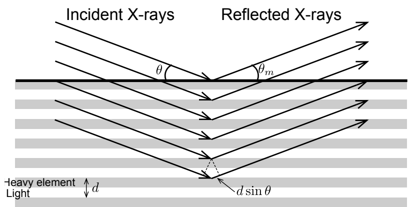


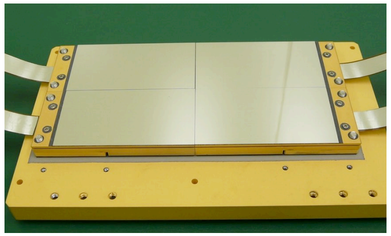


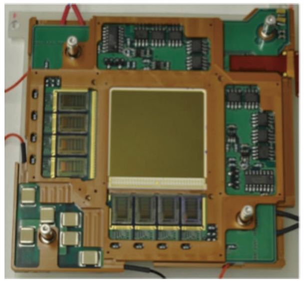
Overview of Imaging System

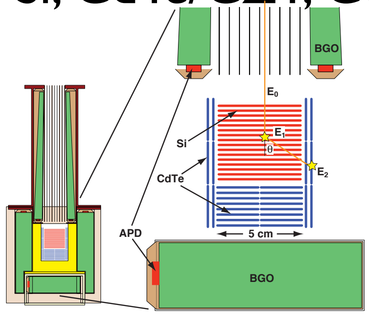
	Soft X-ray	Hard X-ray	Soft Gamma-ray
	1keV – 10keV	10keV – 100keV	100keV –
Optics	Total Reflection Single layer Mirror	Bragg reflection Multilayer Mirror	No Reflection Coded Mask Compton Camera
Semiconductor Imager	Si	CdTe/CZT	Si, CdTe/CZT, Ge









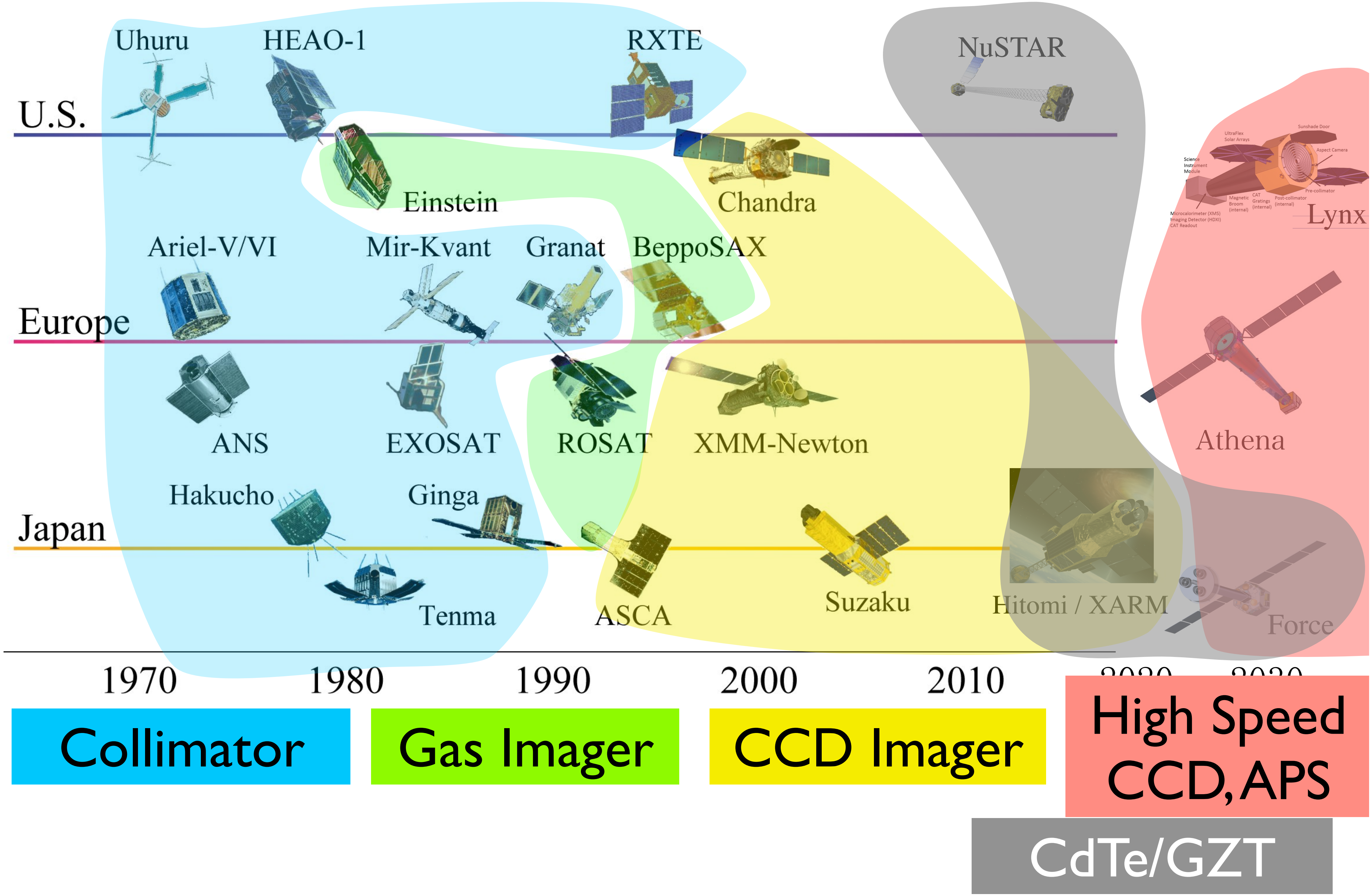


Detection: Photoabsorption (up to ~100keV) → ← Photoabsorption, Compton Scattering (above ~100keV)

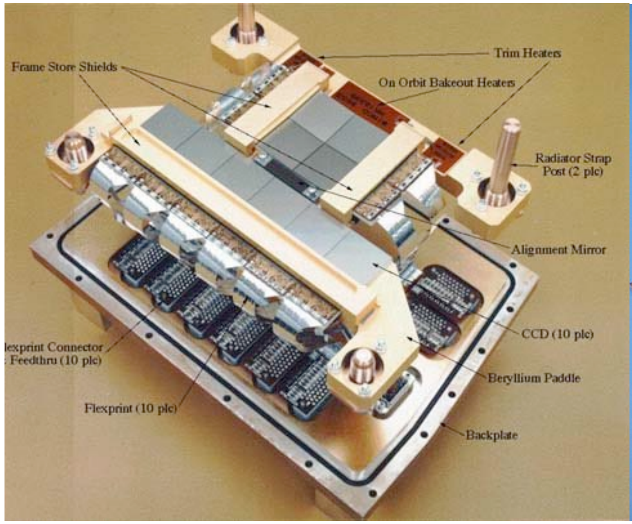
Background: Cosmic X-ray Background (Unresolved Faint Sources) (up to ~10keV) → ← Non X-ray Background (High Energy Particle) (above ~10keV)

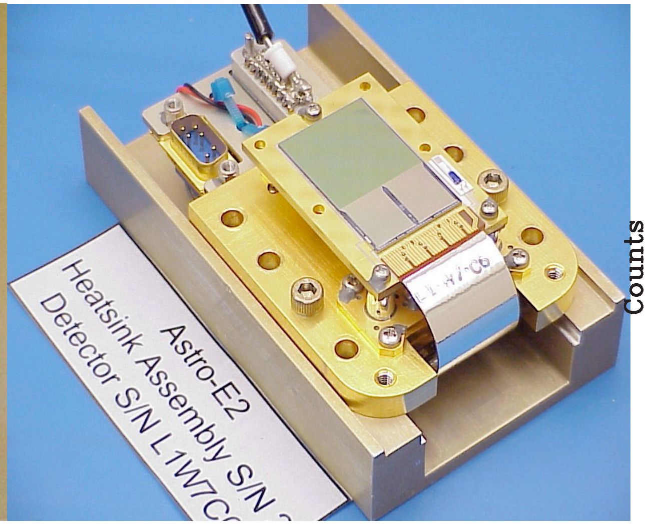
20170116_OIST_Okajima.pdf
2016WatanabeSPIE_The soft gamma-ray detector (SGD) onboard ASTRO-H
2016NakazawaSPIE_The hard x-ray imager (HXI) onboard ASTRO-H
http://www.isdc.unige.ch/integral/outreach/integral

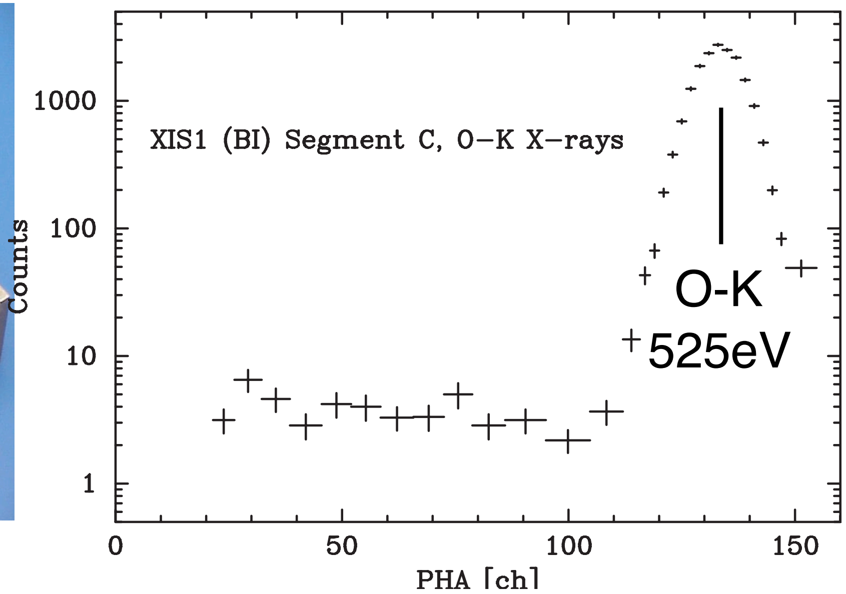
Major X-ray Astronomical Satellites



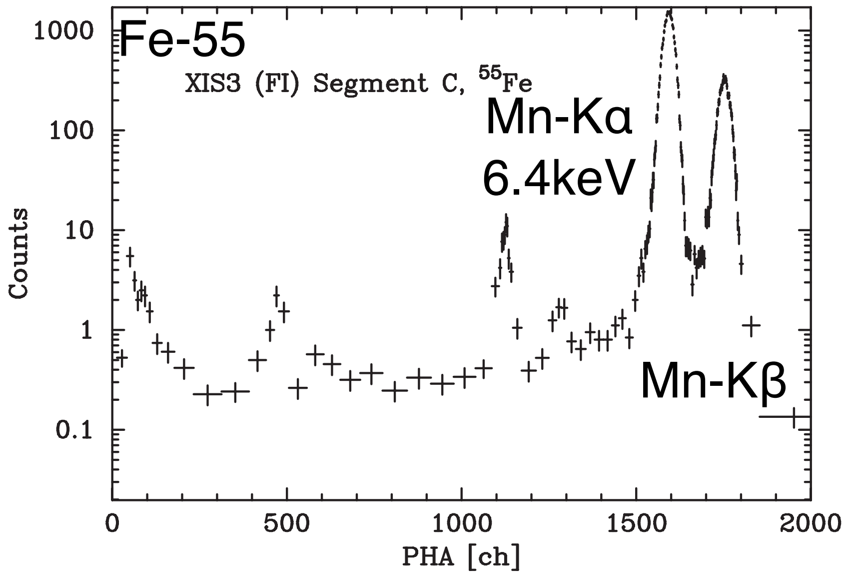
CCD cameras of Chandra (ACIS) & Suzaku (XIS)







- CCDs of MIT Lincoln Lab.
  - Depletion 65um for FI, 42um for BI
  - Pixel size 24μm□, Format 1K×1K
  - ENC ~3e (rms), 135eV (FWHM) at 6keV
- Proton irradiation produces displacement damage in silicon
  - Reduce Charge Transfer Efficiency (CTE)
  - Degrade spectral performance.

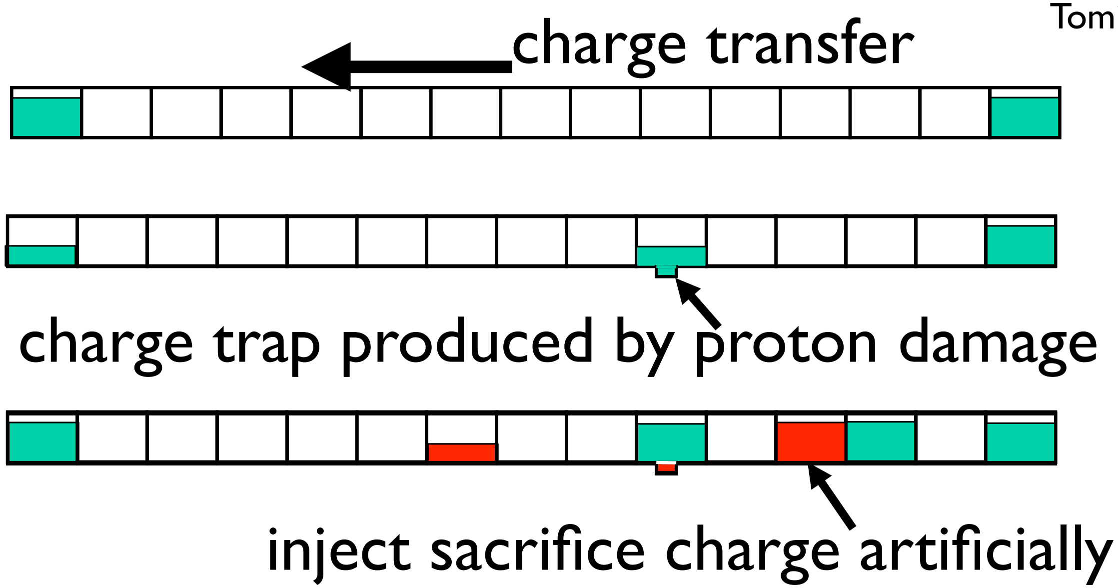


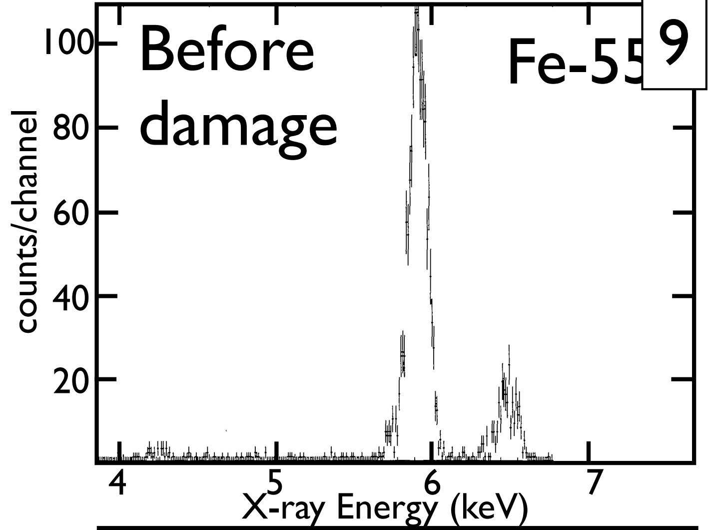
http://chandra.harvard.edu/resources/illustrations/ACIS.html 2007KoyamaPASJ_Suzaku_XIS.pdf

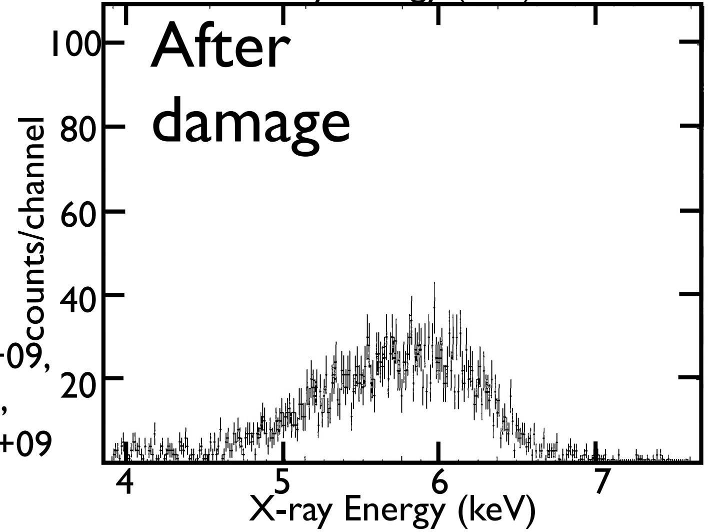
Charge Injection to Recover CTE

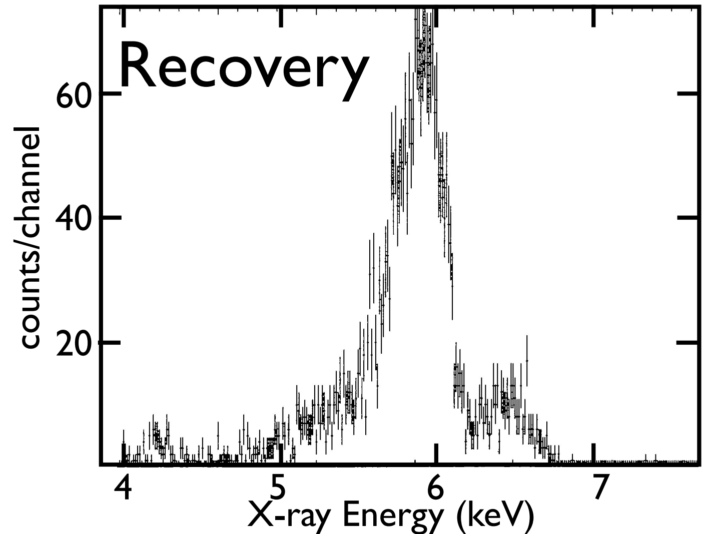
Proton damage and recovery experiment

Tomida, TT+97



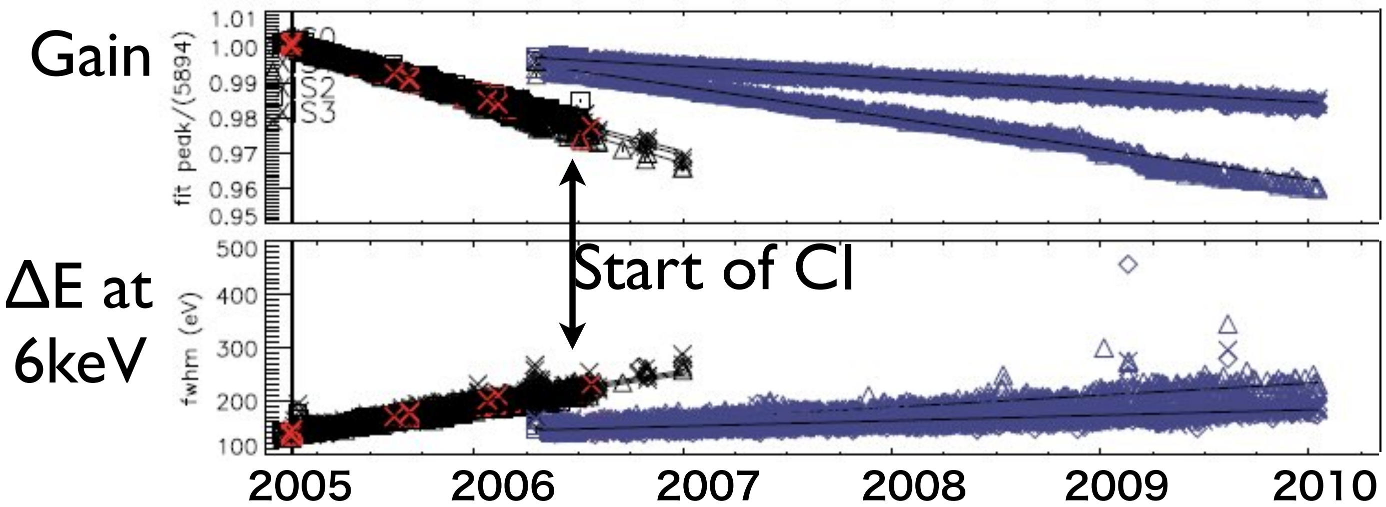




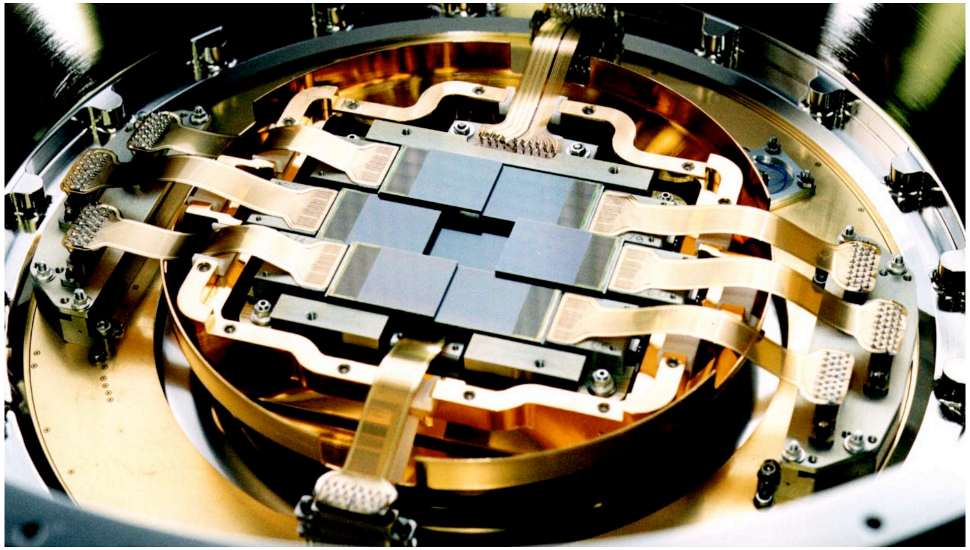


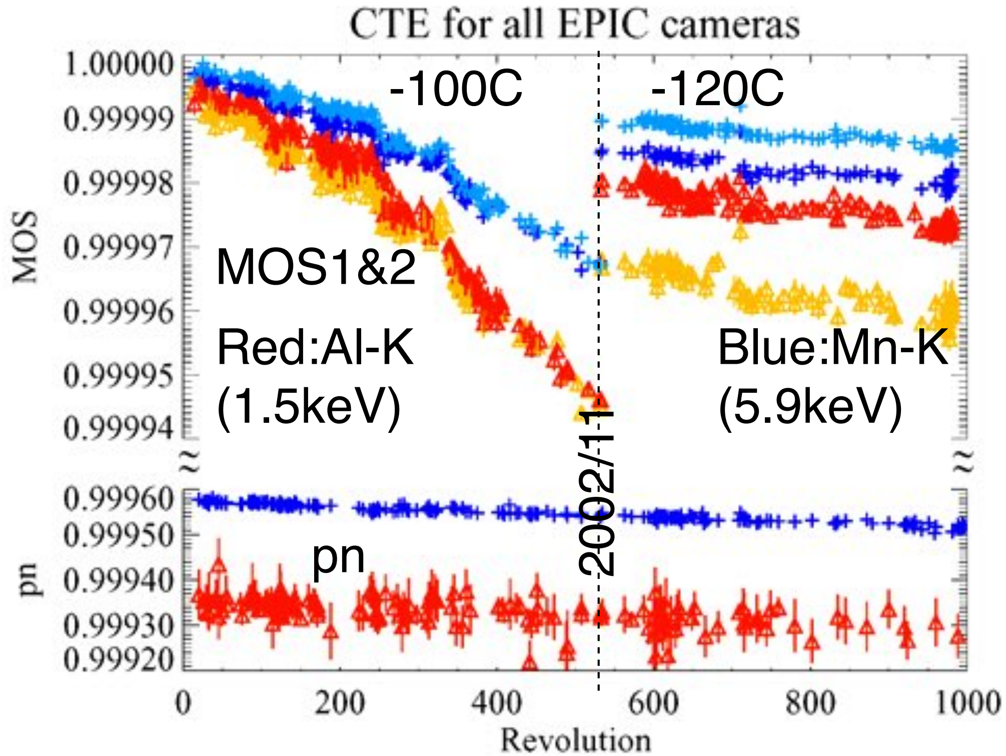
Suzaku realized the charge injection technique in orbit for the first time.

Uchiyama, TT+09, Ozawa, TT+09, Nakasjima, TT+09 etc

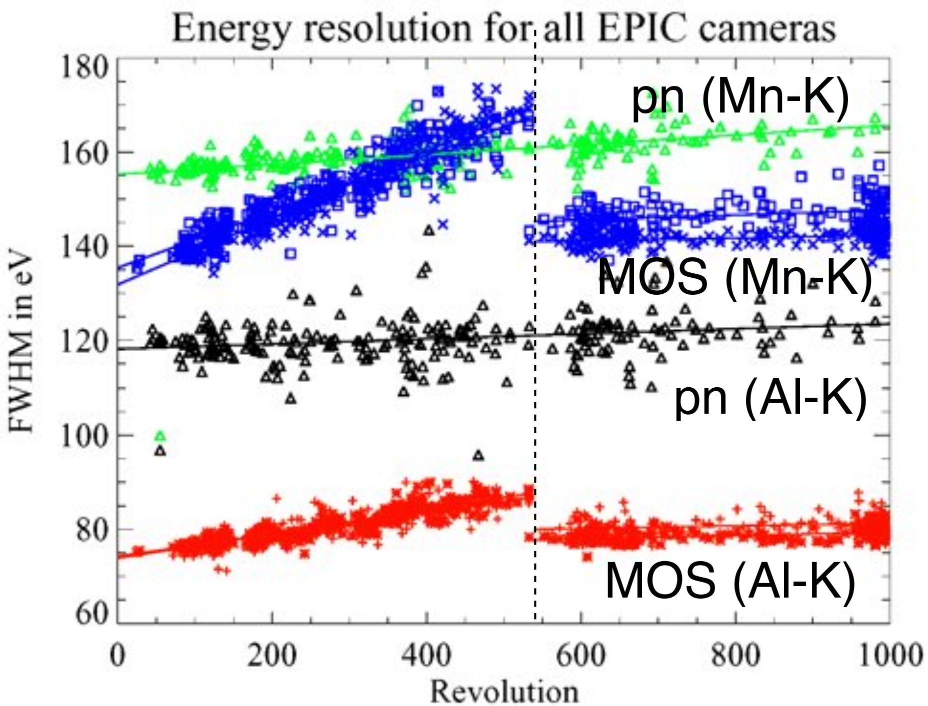


EPIC-MOS of XMM-Newton - Low Temp. to Recover CTE



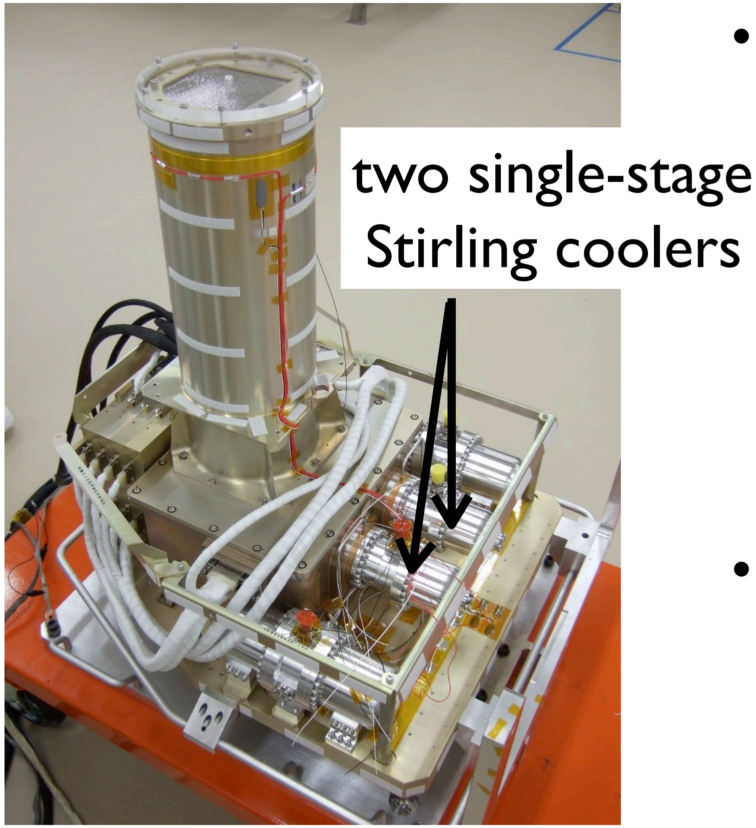


- Leicester U., EEV (Teledyne e2V)
  - Pixel size 40μm□, Format 600×600
  - Depletion 35um. FI with Open-electrode structure for high QE at a low energy band.
  - ENC ~3e (rms), 135eV (FWHM) at 6keV
- Recover CTE by cooling the sensor to -120C.
  - Make de-trapping time longer ⇒ traps stay full for a long time.
  - Once the traps are filled, signal charge can be transferred without loss.

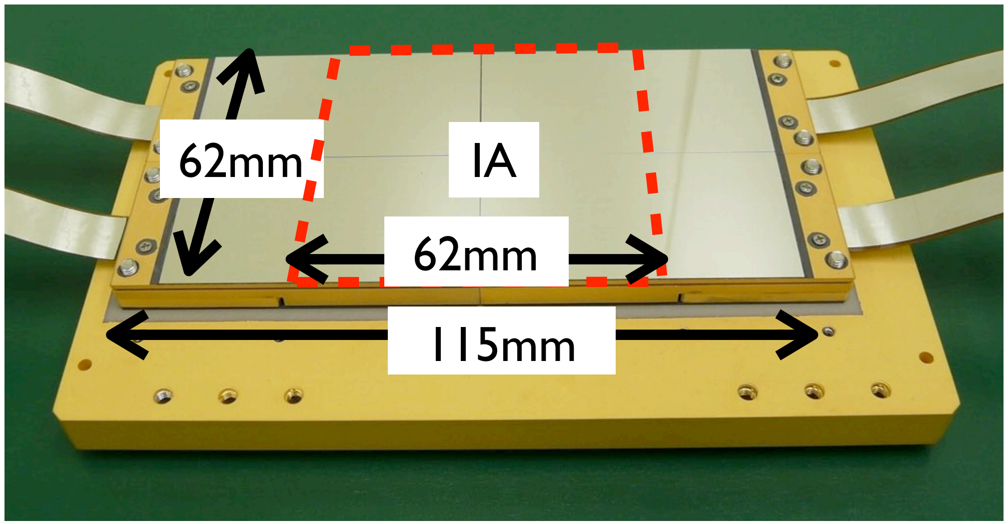


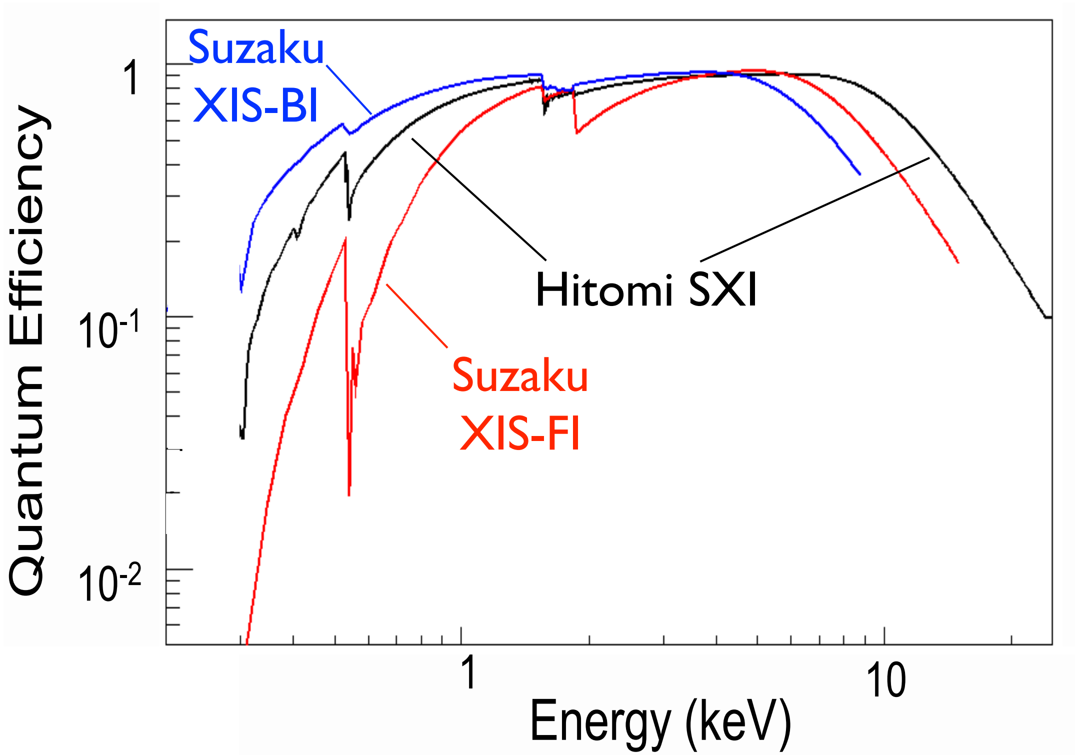
https://www2.le.ac.uk/departments/physics/research/src/Missions/xmm-newto
2005KirschSPIE_Health and cleanliness of the XMM-Newton science payload

CCD of Hitomi (SXI) - BI with a Thick Depletion



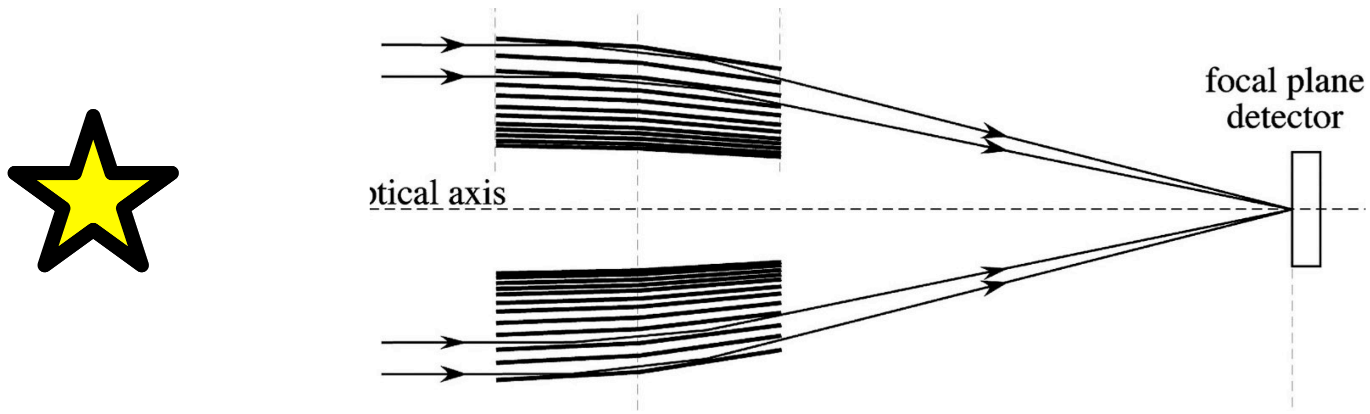
- Osaka U., Kyoto U., ISAS. Hamamatsu
  - Pixel Size 24μm, Format 1280×1280. 2x2 array.
  - BI with 200um depletion by using N-type wafer with >10kΩcm so that we obtain high QE at both of high and low energy bands.
  - On-chip Al coating to block optical light
- Charge Injection and Cool down to -120℃ by using Stirling coolers





Limitation due to low time resolution of CCD (~1sec)

- Unable to make good use of the performance of large collecting area and high angular resolution of the latest mirrors.
  - Event pileup occurs. Photon counting is impossible.

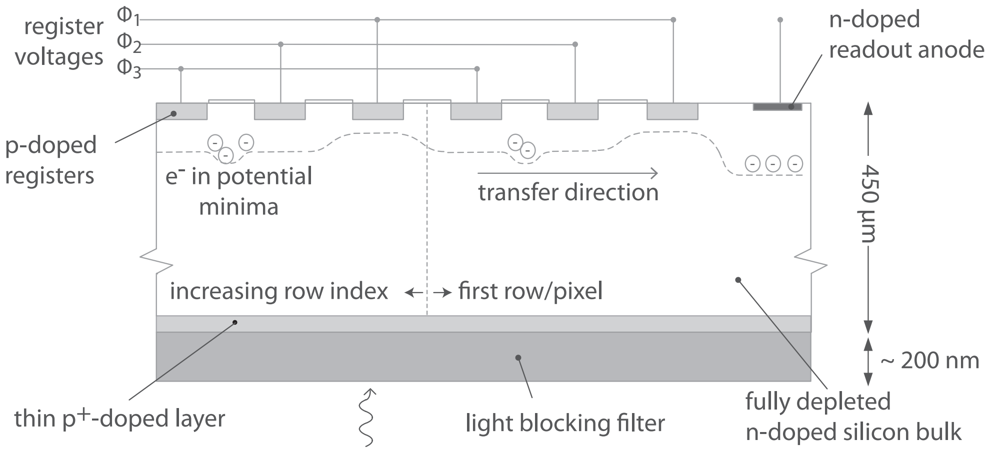


- Unable to resolve fast variability of compact objects such as blackholes and neutron stars.
- Unable to apply anti-coincidence technique
  - Unable to make use of the excellent performance of Si in the band above 10keV due to the high particle background

High Frame Rate and High Time Resolution are Key Issues for Next Generation of X-ray Astronomical Imagers below 10keV

CCD with Parallel Readout

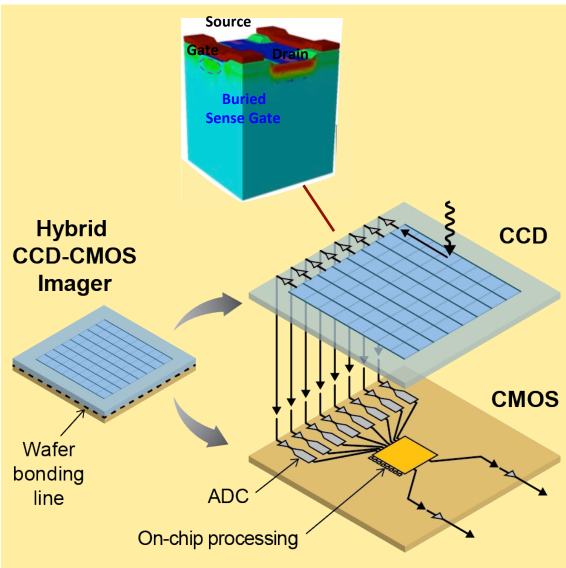
pn-CCD (MPE, PNSensor)



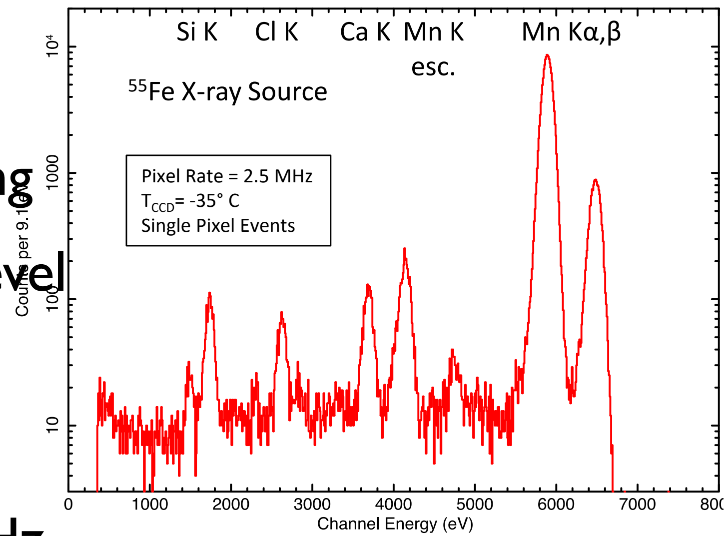
- Transfer registers are formed by pn-junctions.
- XMM-Newton, eROSITA
- Pixel Size 75µm, Depletion 450µm
- Exposuere 50msec, Readout 9.2msec for 384×384 pixels (24µsec/row).
- 140 eV (FWHM) at 6keV

2014MeidingerSPIE_Report on the eROSITA camera system.pdf

Digital CCD (MIT Lincoln Lab.)



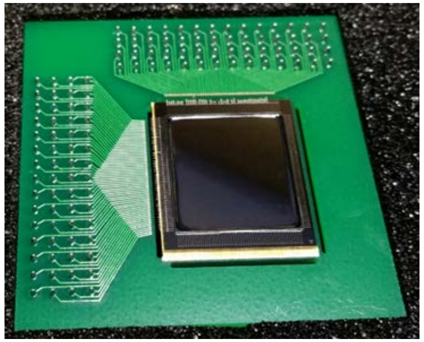
- CCD-to-CMOS integration via tight-pitch wafer-to-wafer bonding
- CMOS-compatible CCD clock level of +1.1 to -0.9V. Low-power
- Low ENC with high pixel rate
  - 6.4e @ 1.25MHz, 10e @ 5MHz
- Pixel Size 8µm



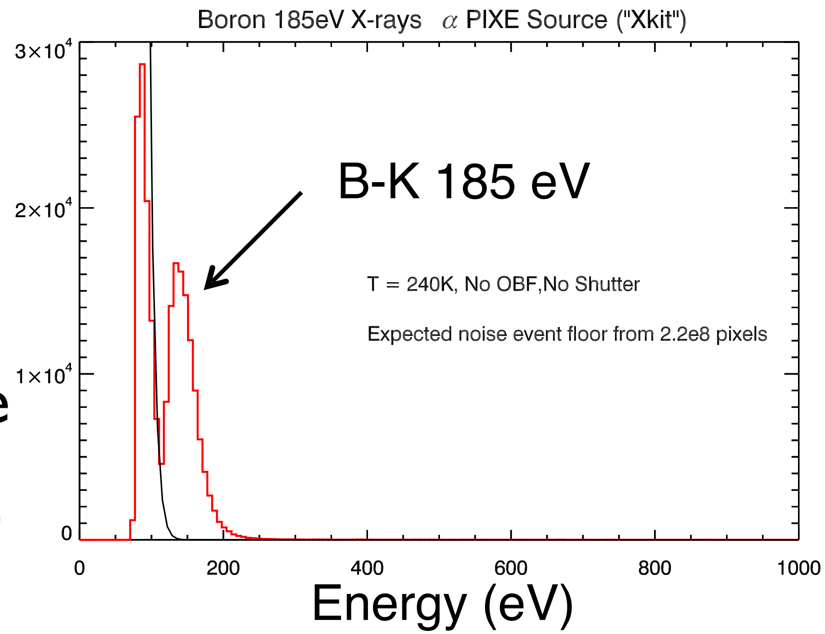
143 eV (RWHM) for 6keV X-ray @ 2.5MHz

No charge transfer. CMOS, APS

Monolithic bulk CMOS (SAO/Sarnoff)

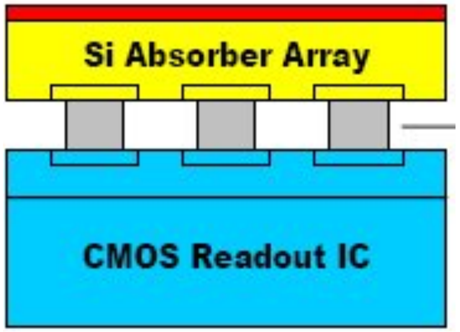


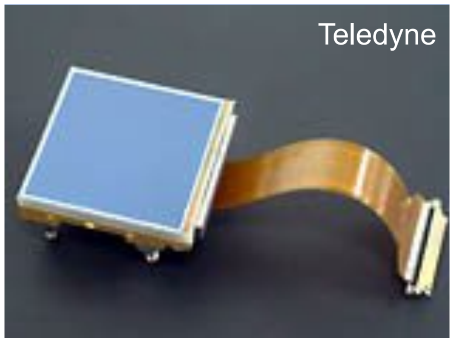
- Pixel Size 16μm, depletion 10~15μm
- 6 Transistor Pinned Photo Diode pixels with ~135μV/e
- Low ENC ~3e (rms), B-K at 185eV is detected



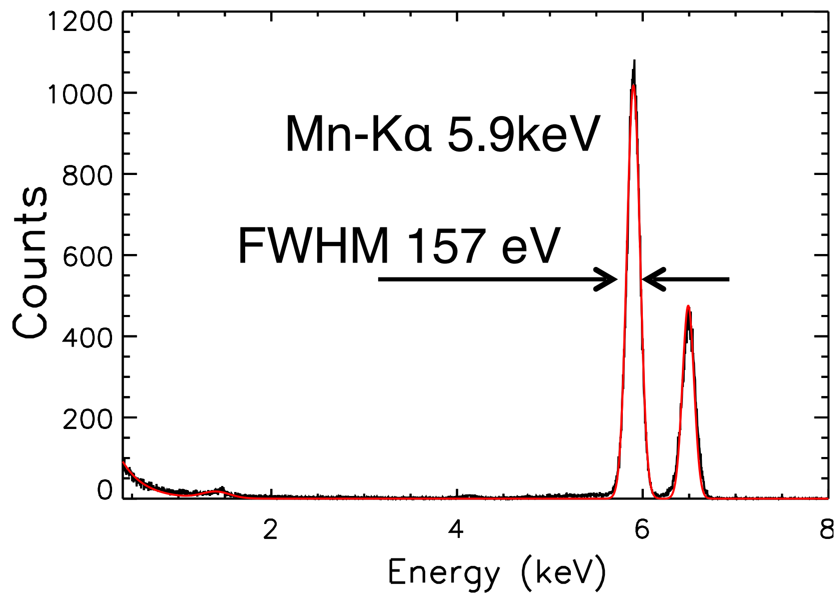
2017KenterSPIE_Advancing the technology of monolithic CMOS detectors for use as x-ray imaging spectrometers

Si Hybrid sensor (PSU/Teledyne)





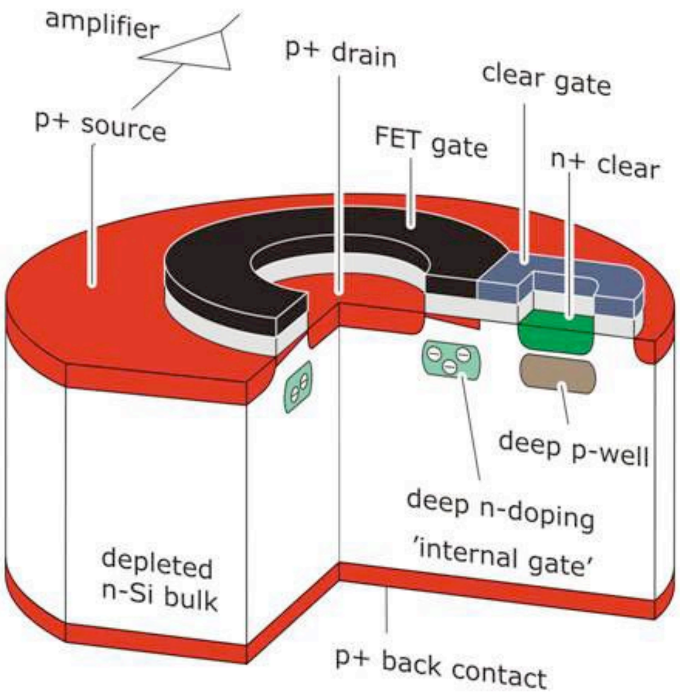
- Si sensor array and readout array bump-bonded together.
- Based on IR detector technology with heritage from JWST
- Pixel Size 12.5 ~ 36μm, depletion 200μm



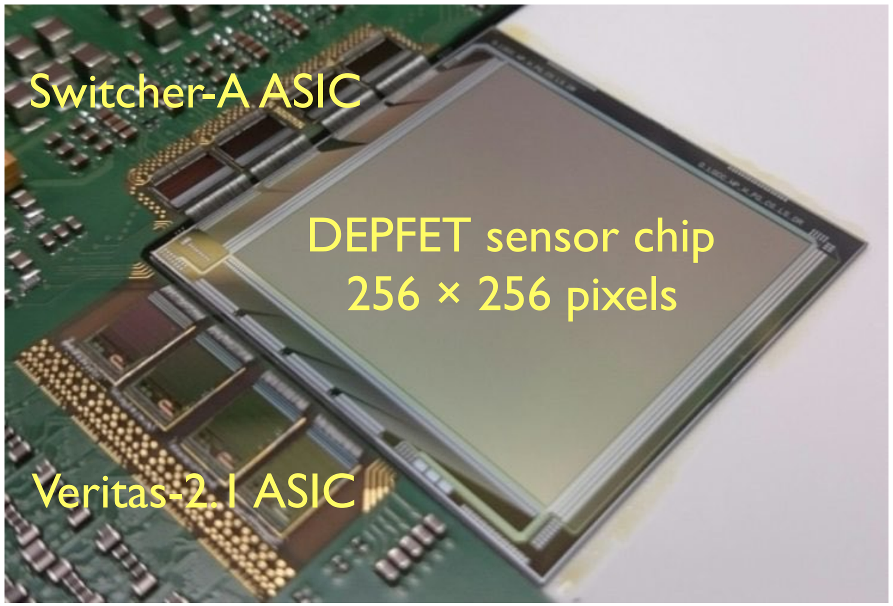
2017HullSPIE_Recent X-ray hybrid CMOS detector developments and measurements

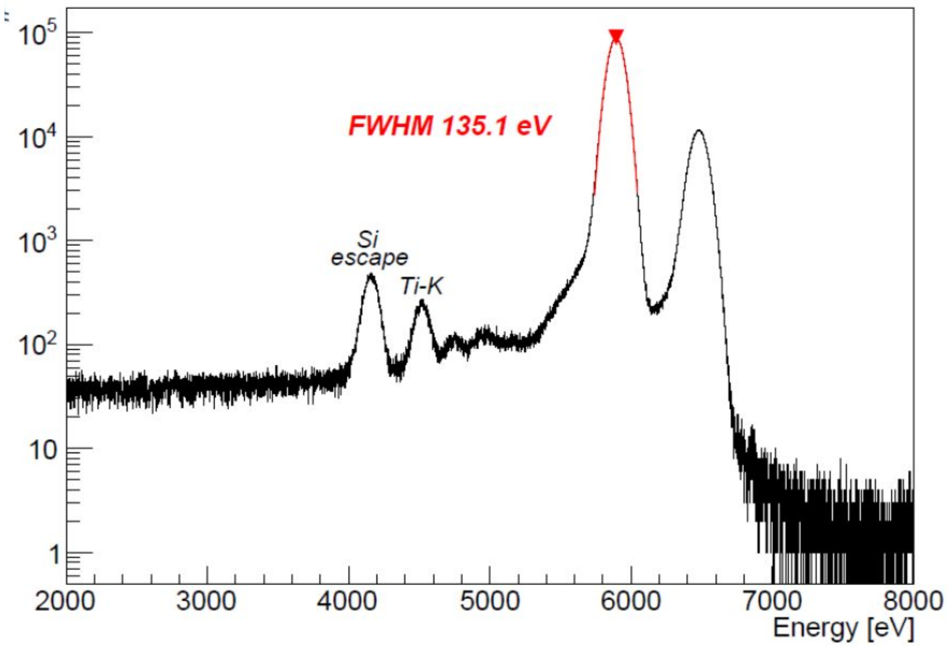
No charge transfer. CMOS, APS

DEPFET (MPE, PNSensor)



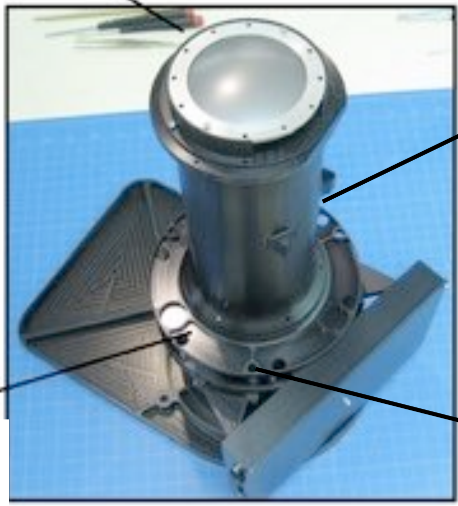
- It consists of a p-channel FET on a n-type bulk that is fully depleted by a reverse biased backside diode.
- WFI of ATHENA
- Pixel Size 130μm, Depletion 450μm
- Parallel readout at 1-5μsec/row, time resolution 5msec for 1K×1K pixels
- ENC ~2-2.5 e (rms)

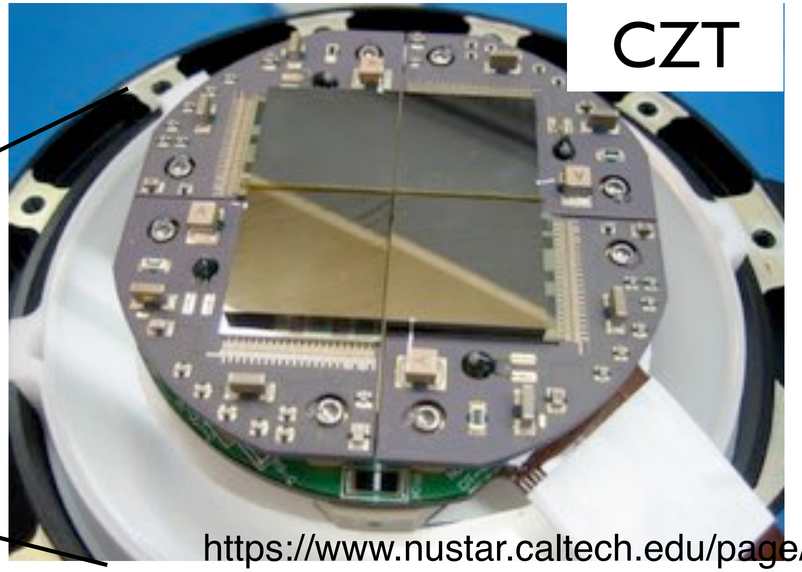




2017MeidingerSPIE_The Wide Field Imager instrument for Athena

CdZnTe pixel of NuSTAR



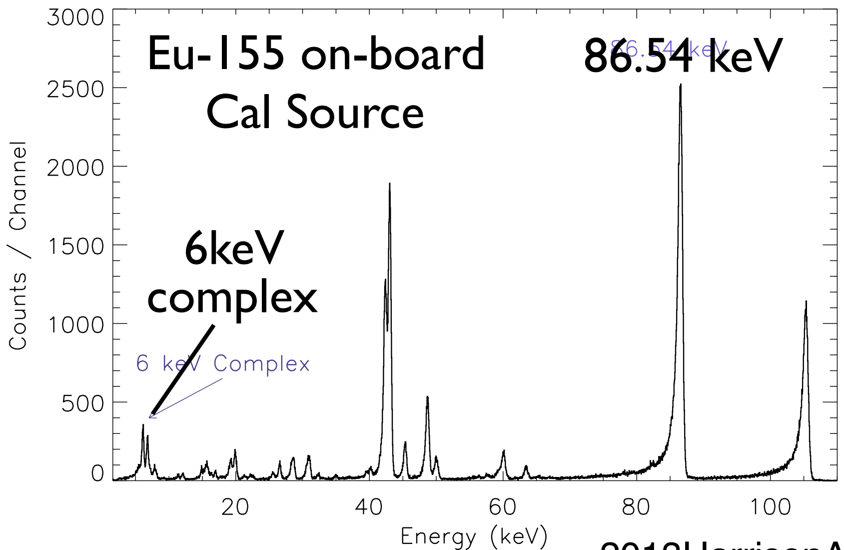


https://www.nustar.caltech.edu/page/detectors

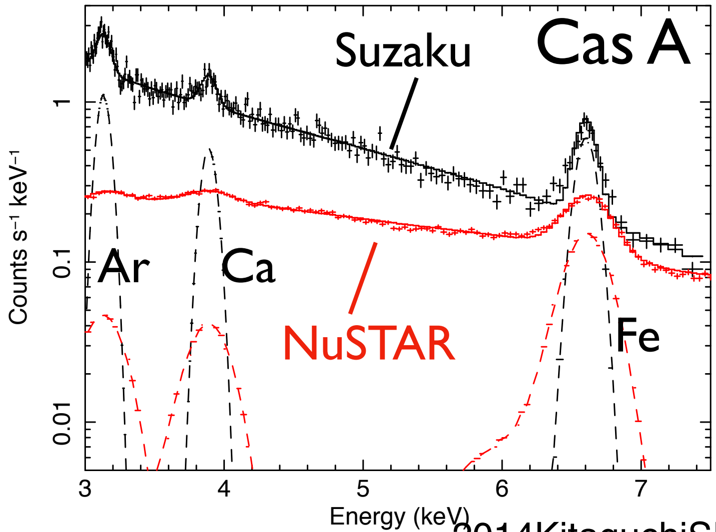
CsI Active Shield

- Thickness 2mm, 20mm×20mm
- 605μm□, 32×32 pixels
- Time resolution of 2μsec

- Low noise by small input capacitance
  - ΔE 600eV at 6keV, 1keV at 60keV
  - Lower E threshold of 2keV

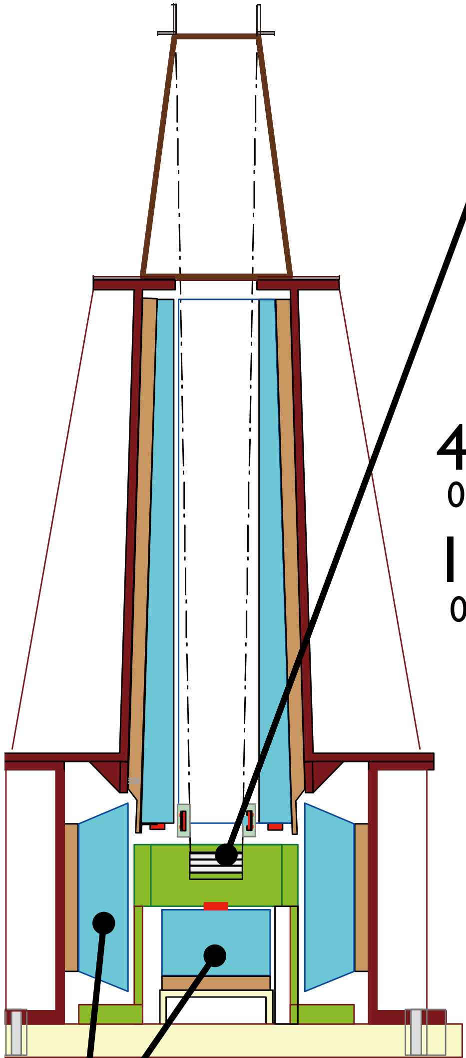


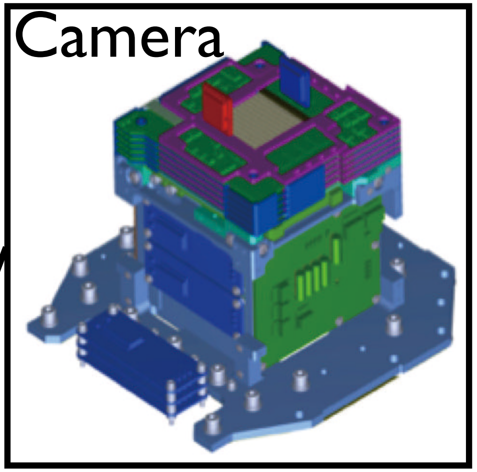
2013HarrisonApJ.pdf

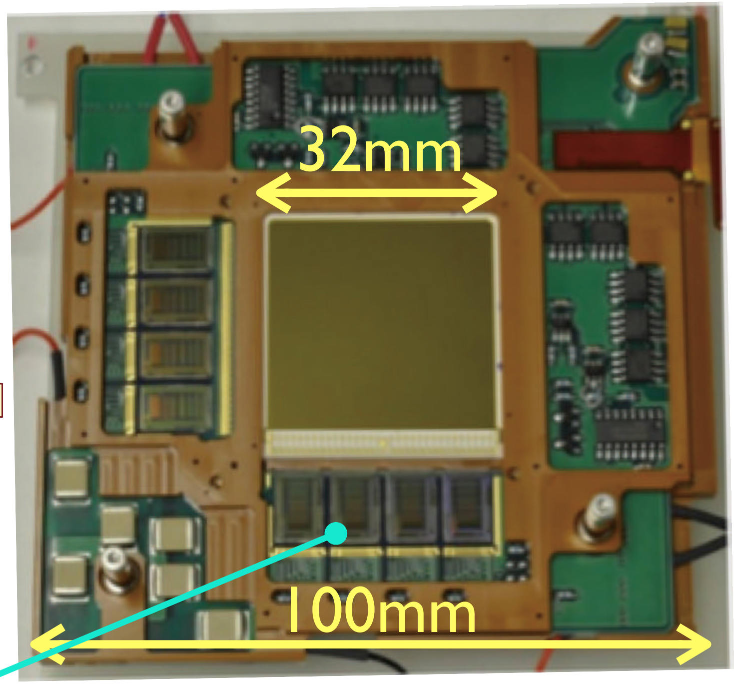


2014KitaguchiSPIE.pdf

HXI (DSSD + CdTe-DSD) of Hitomi

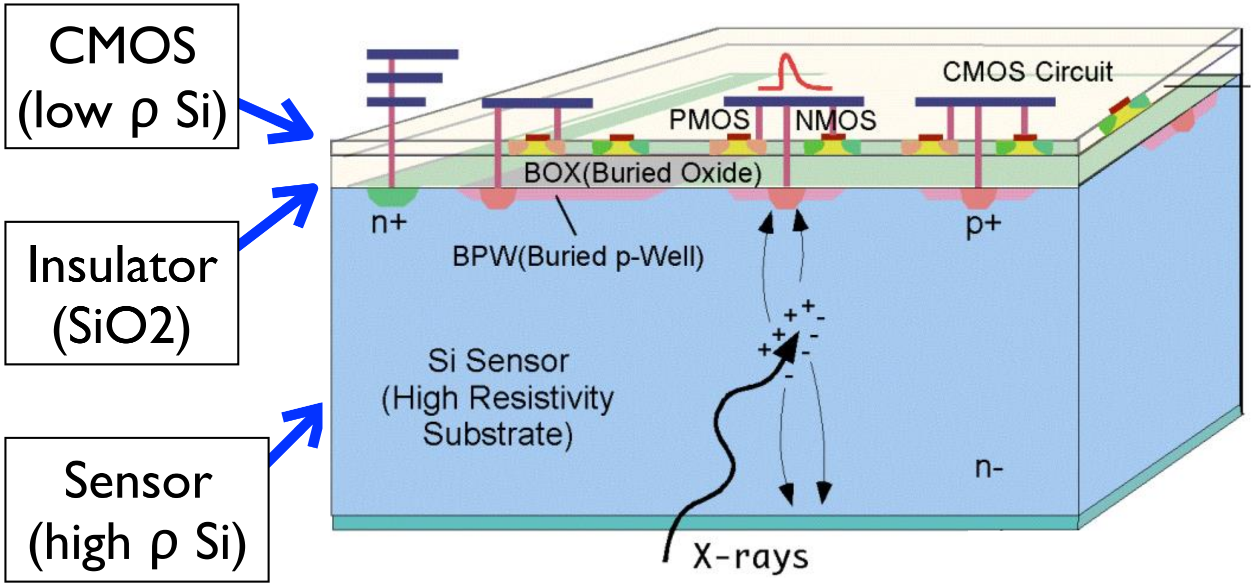






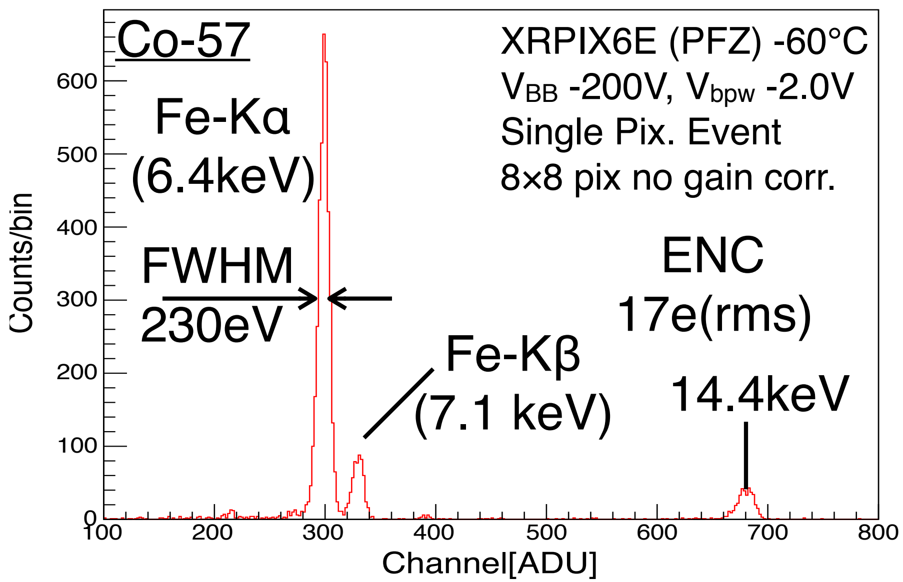
- 5-30keV by 4 DSSDs 0.5mm thick
  - low BGD by no activation
- 20-80keV by CdTe-DSD 0.75mm thick
  - Strip type
  - Larger input capacitance than a pixel type, which is a disadvantage for spectroscopy
  - Fine pitch (small pixel size) with smaller number of channels is available
  - 250µm for CdTe-DSD for Hitomi. 60µm for FOXSI-3 (see talk by Furukawa-san)
  - No dead structure including ASIC below sensor. Compton camera by stacking the sensors.

X-ray SOIPIX (Kyoto/Miyazaki/KEK/Shizuoka/TUS)

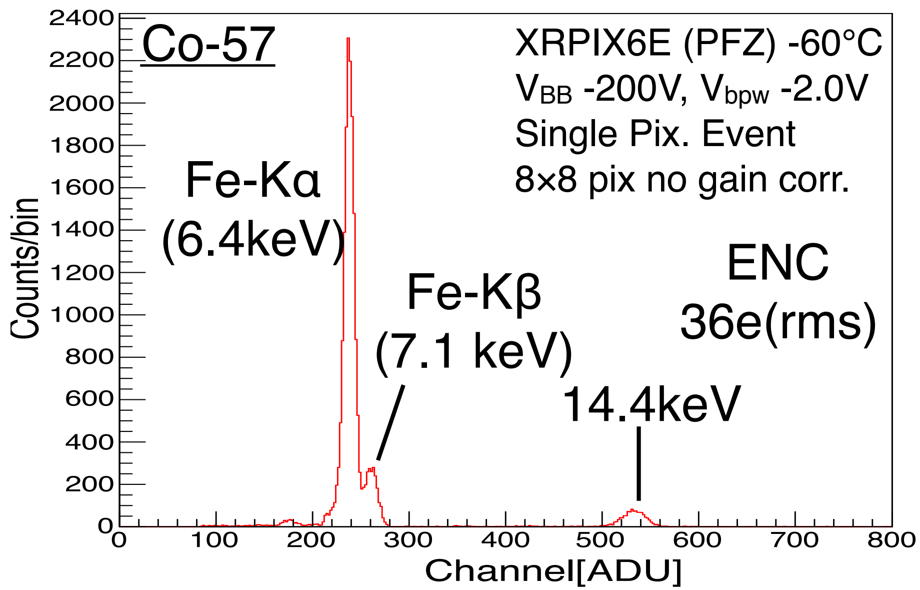


- Each pixel has its own trigger logic and analogue readout CMOS circuit.
- Using trigger function and Readout hit pixel only.
- Time resolution ~1μsec and throughput ~ 1kHz
- BI with depletion >200μm

Frame readout mode



Event-Driven readout mode



See also talks by Kawahito-sensei, Arai-sense, Mori-sani, Onuki-san, Kamiya-san.
posters by Takeda-san, Hayashi-san, Harada-san, Yarita-san, Negishi-san.

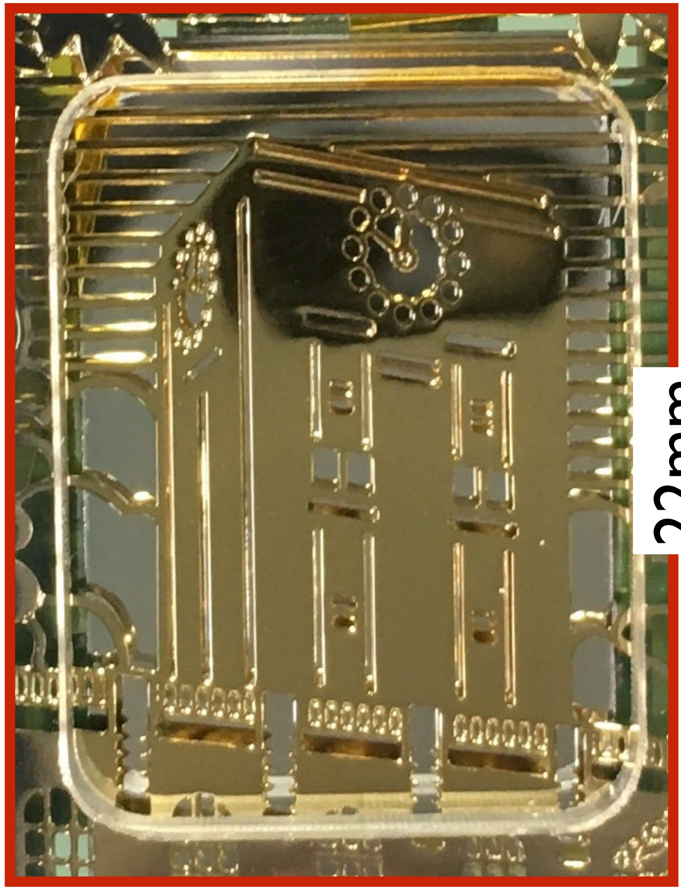
Imaging in Event-Driven Mode

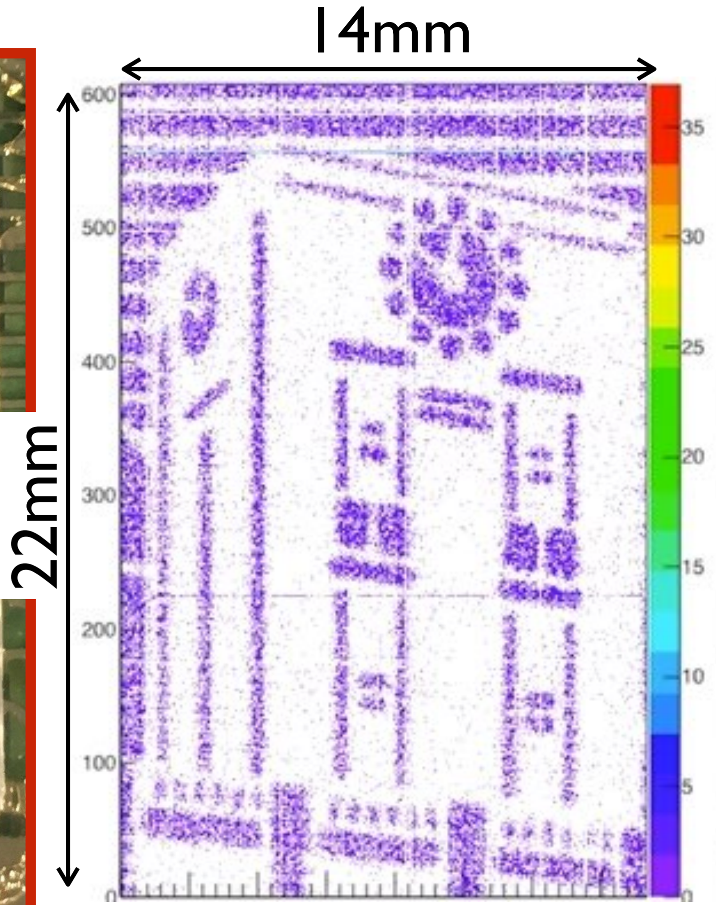
透かし彫り栞/金

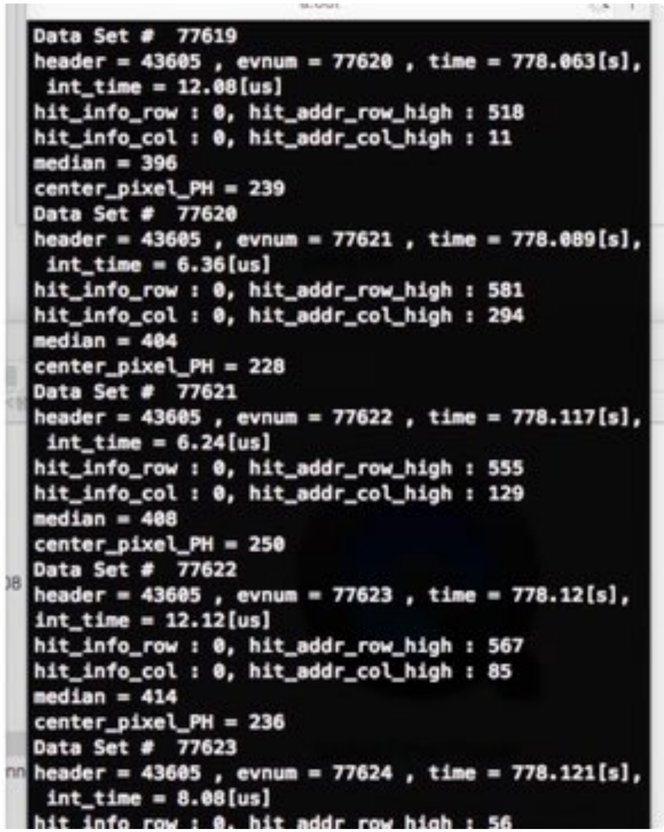
SIZE:W35×H85mm

◆純金表面加工◆時計台を透かし彫りにした実用性の高いアイテムです。 **860** 円

https://www.u-coop.net/kyodai/goods/indicate.php?mode=detail&id=27&category=6







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Data Set #  77619
header = 43605 , evnum = 77620 , time = 778.063[s],
 int_time = 12.08[us]
hit_info_row : 0, hit_addr_row_high : 518
hit_info_col : 0, hit_addr_col_high : 11
median = 396
center_pixel_PH = 239
Data Set #  77620
header = 43605 , evnum = 77621 , time = 778.089[s],
 int_time = 6.36[us]
hit_info_row : 0, hit_addr_row_high : 581
hit_info_col : 0, hit_addr_col_high : 294
median = 404
center_pixel_PH = 228
Data Set #  77621
header = 43605 , evnum = 77622 , time = 778.117[s],
 int_time = 6.24[us]
hit_info_row : 0, hit_addr_row_high : 555
hit_info_col : 0, hit_addr_col_high : 129
median = 408
center_pixel_PH = 250
Data Set #  77622
header = 43605 , evnum = 77623 , time = 778.12[s],
int_time = 12.12[us]
hit_info_row : 0, hit_addr_row_high : 567
hit_info_col : 0, hit_addr_col_high : 85
median = 414
center_pixel_PH = 236
Data Set #  77623
header = 43605 , evnum = 77624 , time = 778.121[s],
 int_time = 8.08[us]
hit_info_row : 0, hit_addr_row_high : 56
```

Cd-109, Vbb=10V, Room Temp. (movie in 10 times speed)

Capability of event rate > 500Hz is Confirmed

Summary

- The conventional type of MOS-CCD is the standard imaging spectrometer in the energy band above 10 keV.
- Fast time resolution and fast readout is the key issues for the next generation of imagers.
  - PNCCD, Digital CCD, Monolithic CMOS, Hybrid, DEPFET, X-ray SOIPIX.
- CdTe/CZT pixel and double-side strip detectors have been developed and used in the energy band above 10 keV.