The Universe in X-rays: Lecture 3: CCD type detectors

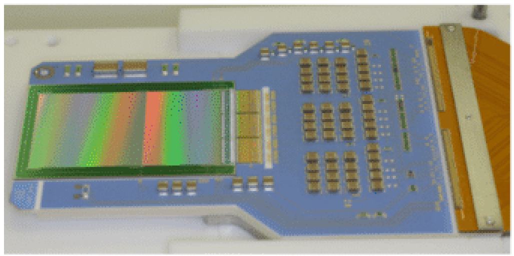
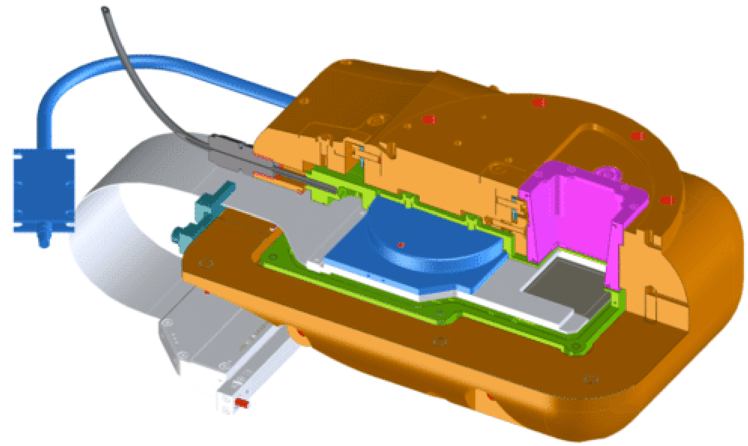
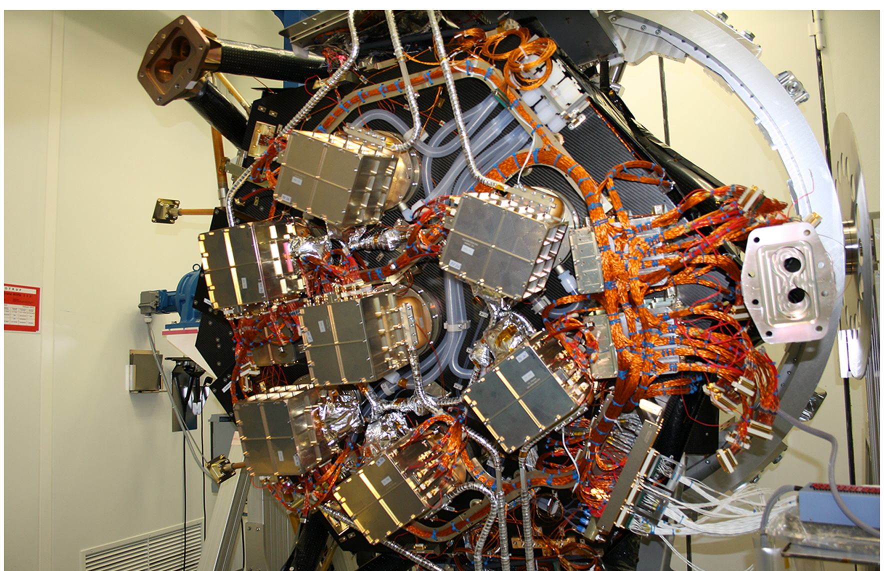
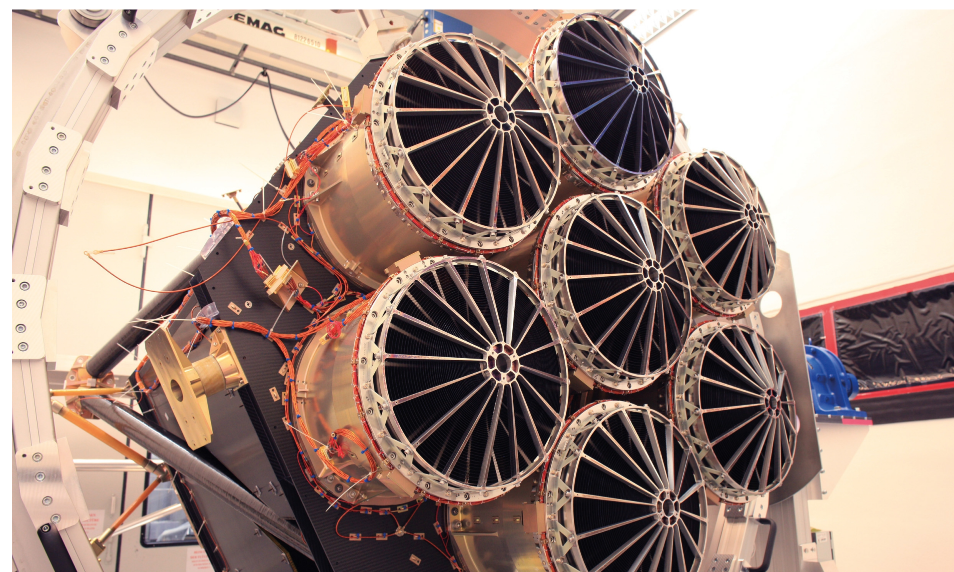


Figure 2.2.1: eROSITA CCD-Module. The CCD with its image area (3×3 cm²) and the slightly smaller frame store area (right) is connected via 384 bond wires with three CAMEX read out chips. They are mounted, together with the (passive) front end electronics, on a ceramic printed circuit board







Agata Różańska, fall semester, 2022/23

Doodle results:

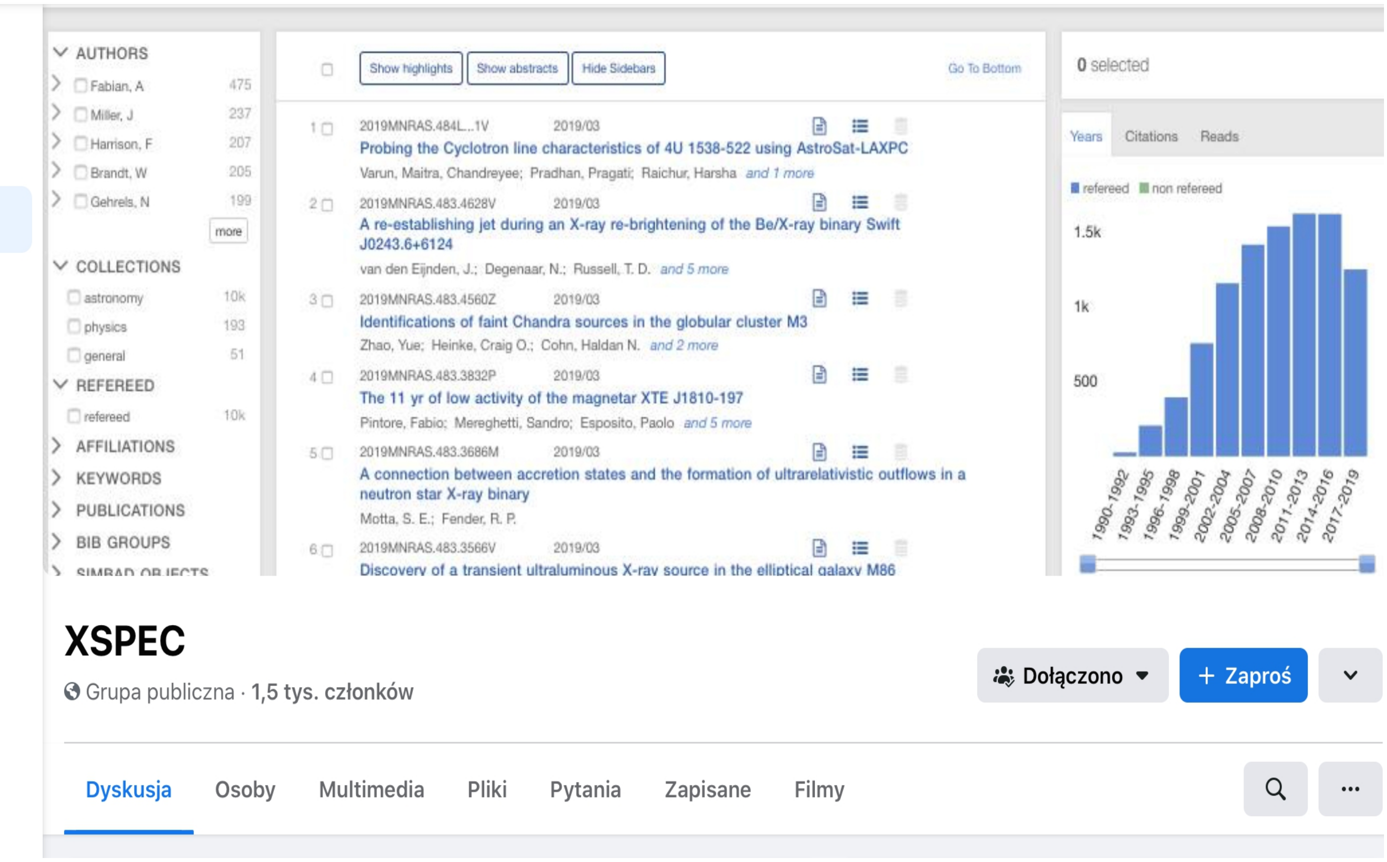
- Thursday at 10:00 is official time for lecture.
- If somebody cannot attend we can make the second group.
- But when?
- The doodle result contains all of us or only those who cannot attend the basic term?

Homework #1

- Satellites are build over many years ~ 8-15 yrs
- Typically first driving science of the mission is accepted
- Short
- Essential
- Rich
- Clear
- Smart

Homework #2

- Instal HEASOFT – xspec fitting package



Summary after 1st and 2nd lecture:

1st Detectors:

PC → Gas

SPC → Gas, Crystal

Gas (+quench gas)

Crystal

$$\frac{\Delta E}{E} \qquad 0.4 \qquad 0.15$$

FANO number
better UV photon statistic

Bkgr. rejection, time res., det. liftime.

Collimator, anticoincidence system.

2nd Imaging and X-ray optics:

MWPC, MWSPC (MultiWire)

-position on A_{det}
-"crude" image

Mechanical collimators, MC:

-to restrict FOV
-position on A_{det}
-scanning – slat collimators

Coded Masks:

-spatial information
-image convolved with the mask pattern
-numerical technique to deconvolve the observed pattern

X-rays – reflection:

- total external reflection depends on E
- and on polarization (Fresnel's Eq.)

X-rays – imaging:

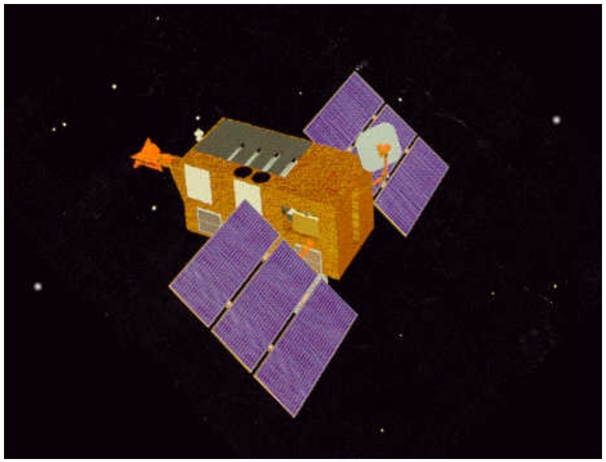
- scattering
- Wolter's Mirrors
Abbe's sine condition works only for on-axis source
- off-axis source are always blurred

Point Spread Function:

- light gets blurred as it passes through the instrument
- image cannot be better than the PSF.

Two types of X-ray satellites:

Type I - detector arrays:



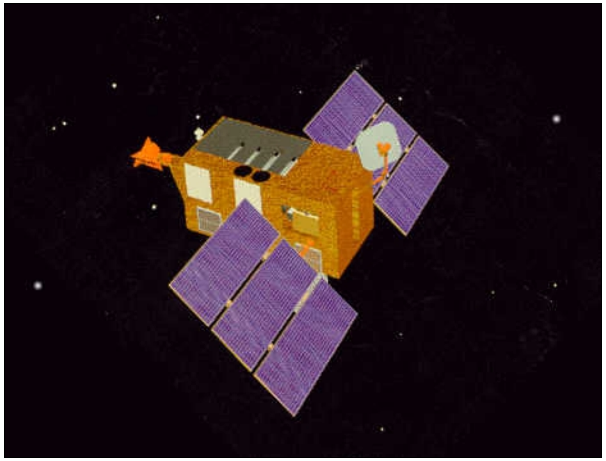
Eff. Area is large:

RXTE
0.65 m^2

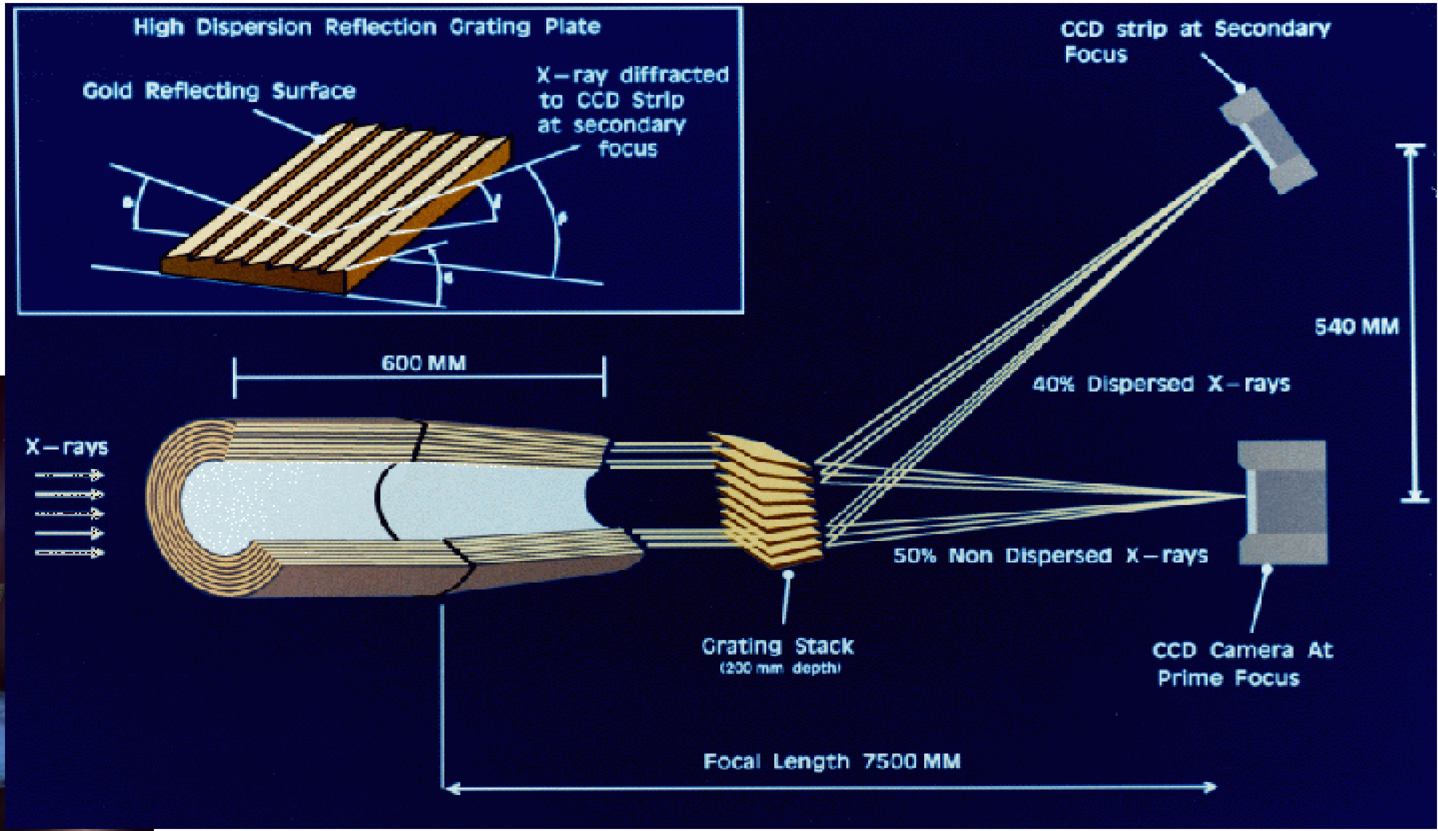
LOFT
8.5 m^2

Two types of X-ray satellites:

Type I - detector arrays:

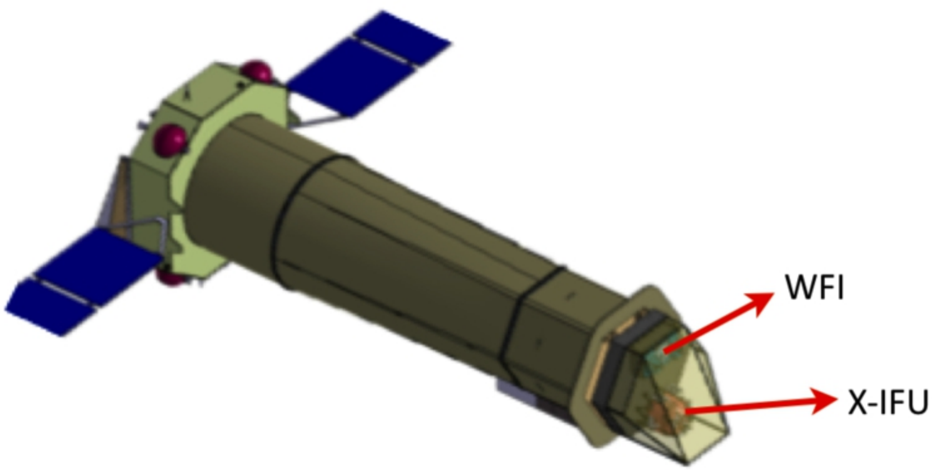


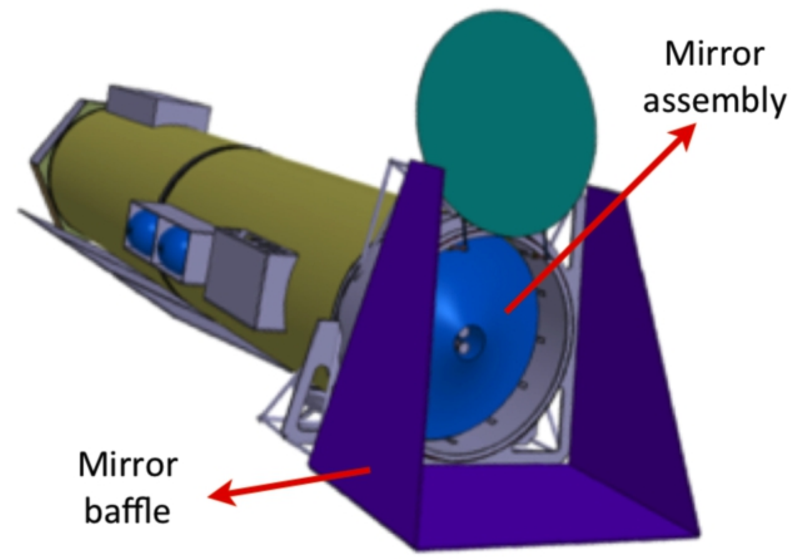
Type II – X-ray telescopes



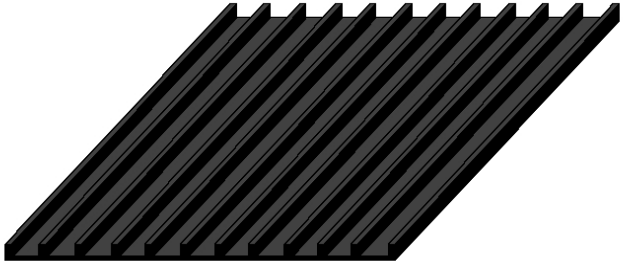
Angular resolution depends on focusing mirrors (if we have them)

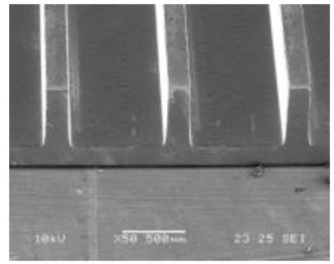
- ATHENA (**A**dvanced **T**elescope for **H**ight **EN**ergy **A**strophysics) future mission will have only one Mirror Assembly and two detectors



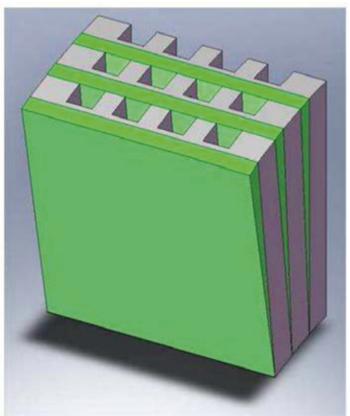


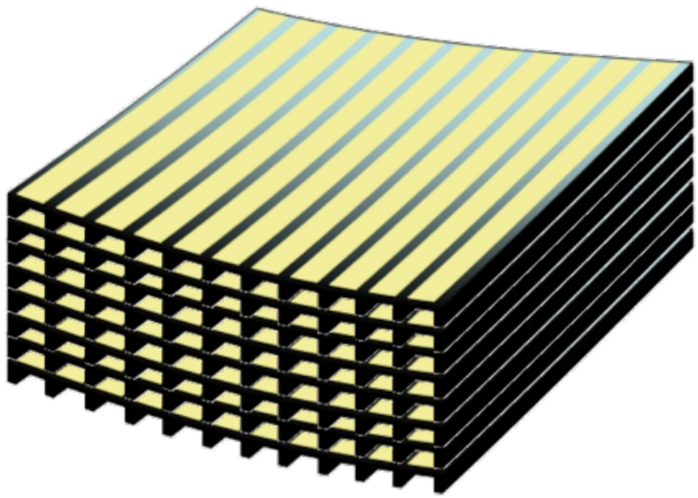
Silicon Pore Optic – SPO Mirrors on ATHENA –

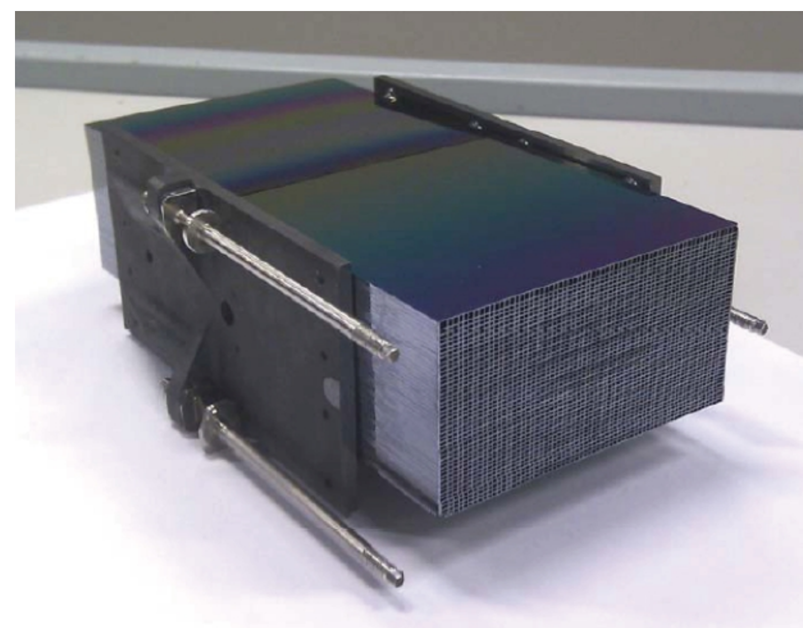




Diameter- 2,4 m

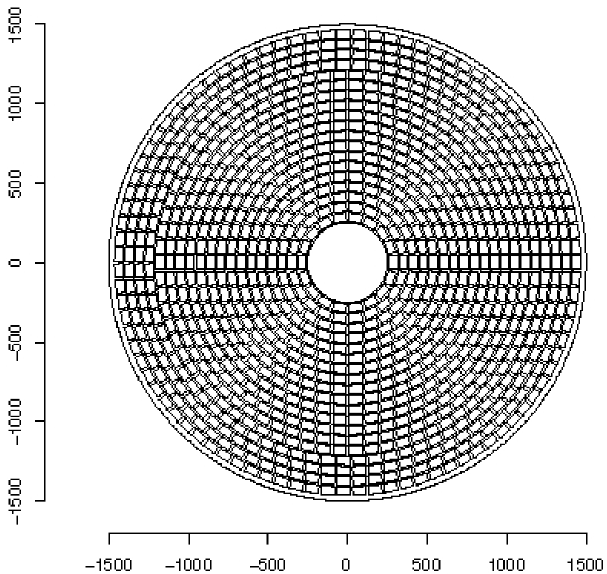


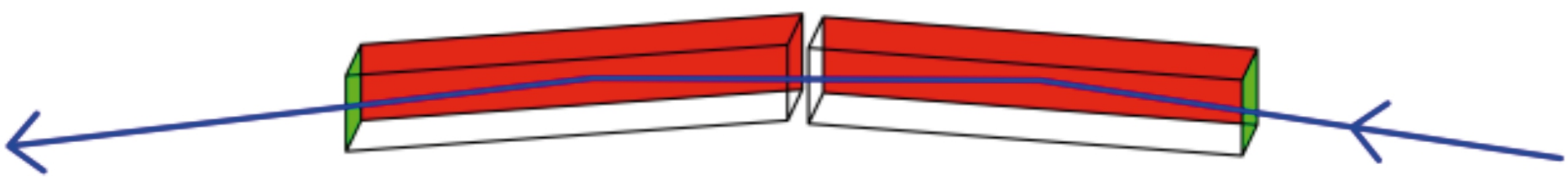




- The large collecting area is achieved using the combination of millions of pores in hundreds of modules.
- The angular resolution is achieved by precise control of the figure and alignment of the reflecting surfaces during the manufacture of the stacks.

Silicon **P**ore **O**ptic – **SPO** Mirrors on ATHENA



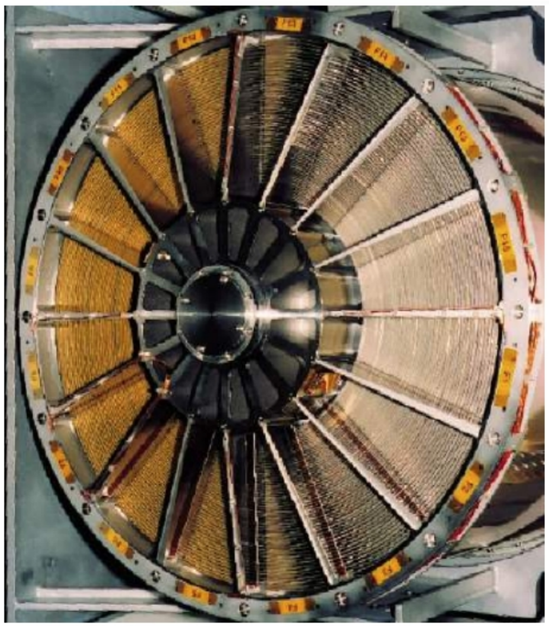


The wide field of view is possible because the rib spacing can be optimized and it is easy to arrange the modules so they approximate the optimum Wolter-Schwartzschild geometry.

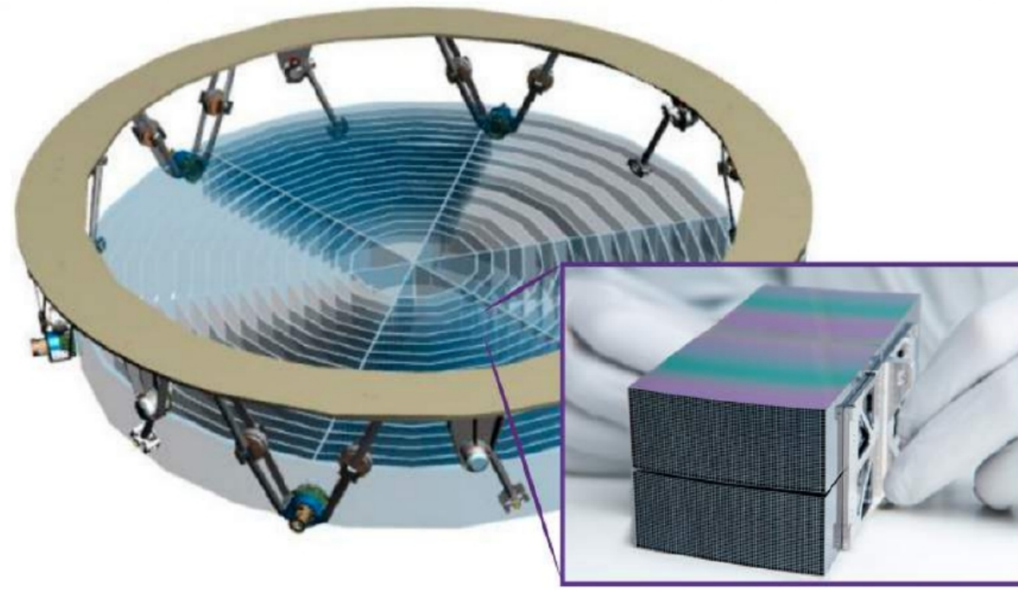
Angular resolution problem with ATHENA mirrors

cosine

From XMM to Athena: New Technology for Largest Optic



XMM-Newton
- 0.35 m radius
- Ni shell replication
  - Concentric shells



Credit: ESA. Cosine and ACO Team

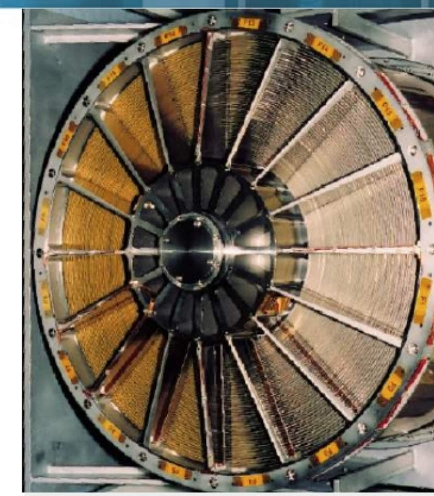
Athena
- 1.2 m radius
- Silicon Pore Optics
  - Stacks of mirrors form mirror modules
  - Mirrors diced from Si wafers from semiconductor industry
  - Combines into the largest X-ray mirror ever flown

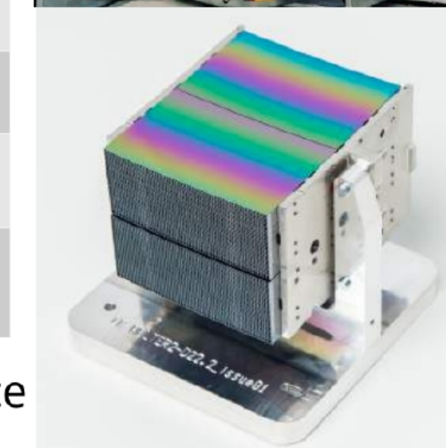
Angular resolution problem with ATHENA mirrors

cosine

Silicon Pore Optics: Cost-Effective Increase of Mirror Area

	XMM-Newton	Athena
Technology	Ni shell replication	Silicon Pore Optics
Outer radius	0.35 m	1.2 m
Mirror thickness	0.47 - 1.07 mm	0.17 mm (0.11)
Number of mirrors	58 shells * 3 telescopes = **174**	1080 shells in 606 modules = **87,000**
Performance:		
Effective area (1 keV)	0.14 m^2	1.9 m^2
PSF HEW (1 keV; on axis)	13 arcsec	5 arcsec





- Modular design decouples the problem of large area and high performance

Angular resolution problem with ATHENA mirrors

The improvement is made with time:

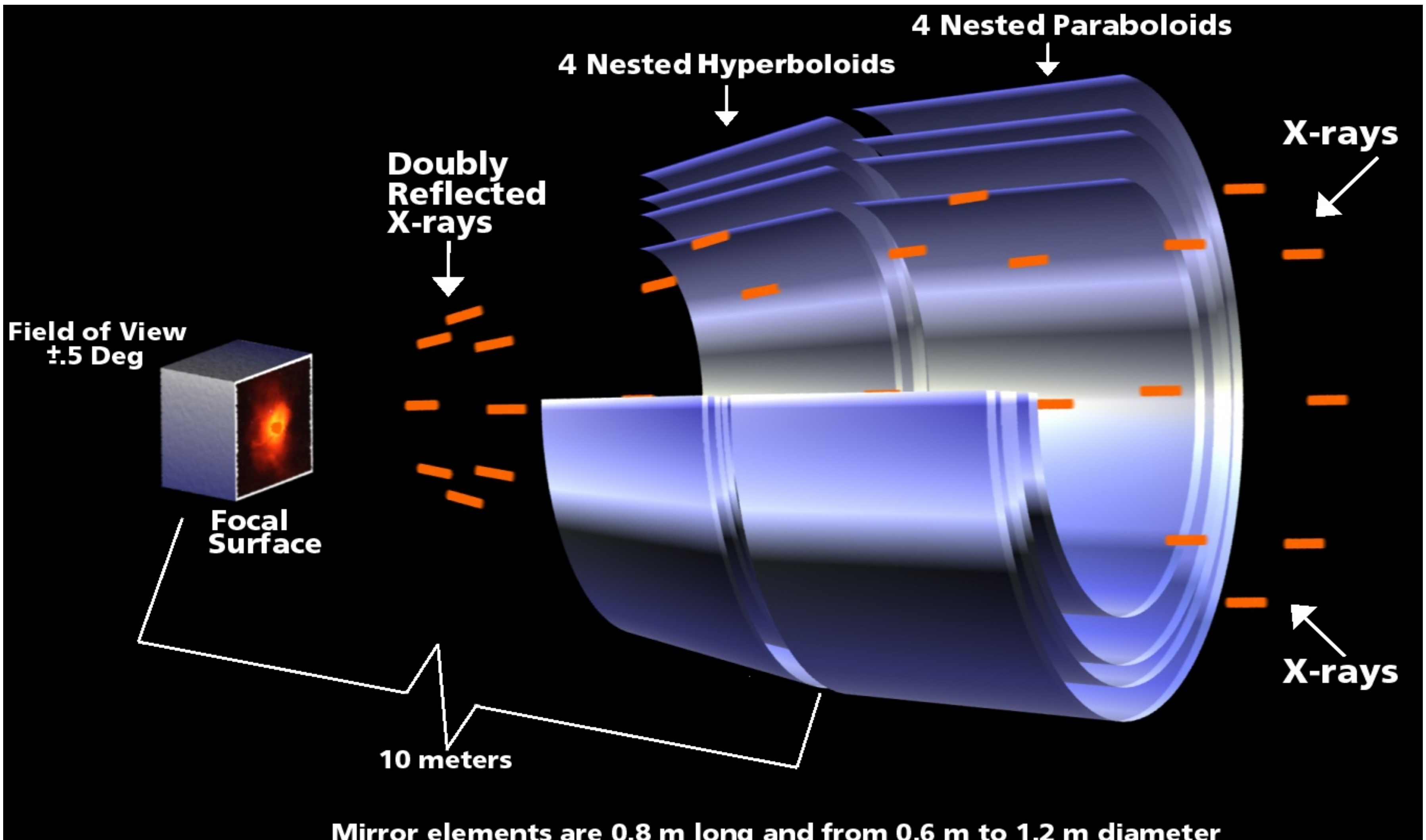
cosine

Robotic Manufacturing: Consistent High Quality Optics

	XOU-066 2019	XOU-067 2019	XOU-92 2020
Half-energy width (arcsec)	17.5	13.2	9.9

This number has to be at lease 5” to meet ATHENA requirements

Angular resolution depends on the whole instrument, but it is directly limited by PSF of the mirror. Detector can only increase angular resolution of the whole system.

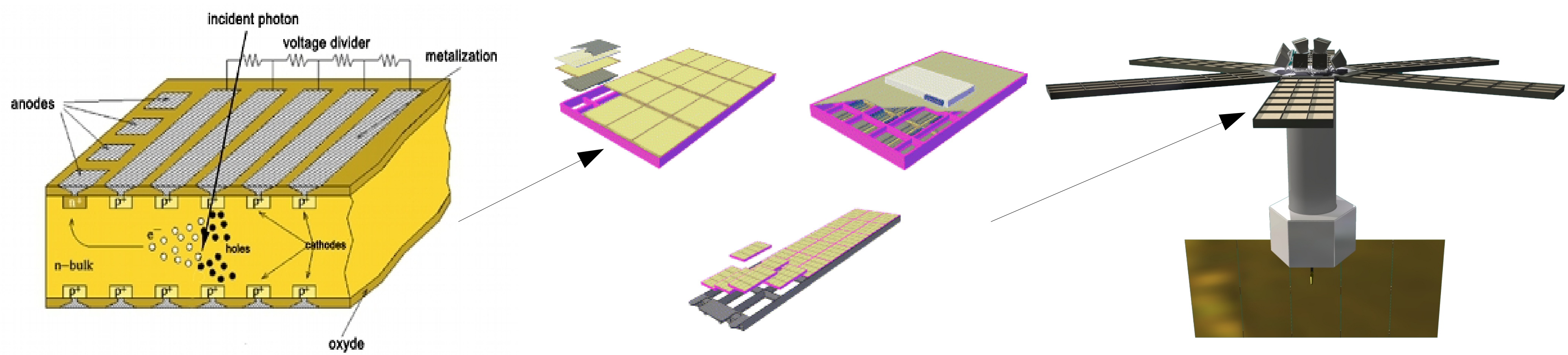


Lecture 4: CCD Detectors:

Charge Couple Device type detectors in the focus of imaging optics.

ASCA – the first used CCDs as a focal plane detector in 1993.
CHANDRA, XMM-Newton – larger detector arrays in 1999.

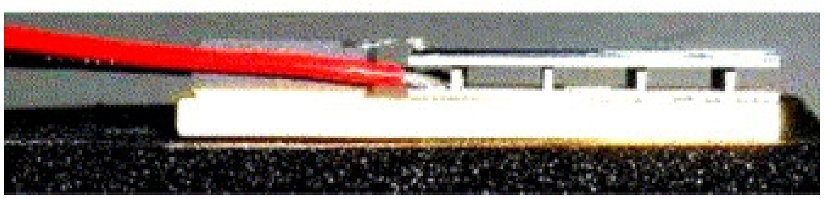
Single photon counting mode - images through the largest X-ray telescopes ever build. Concept of LOFT mission:



MOS XMM-Newton:
6x6 cm2 large pn CCD is working more than 20 years:

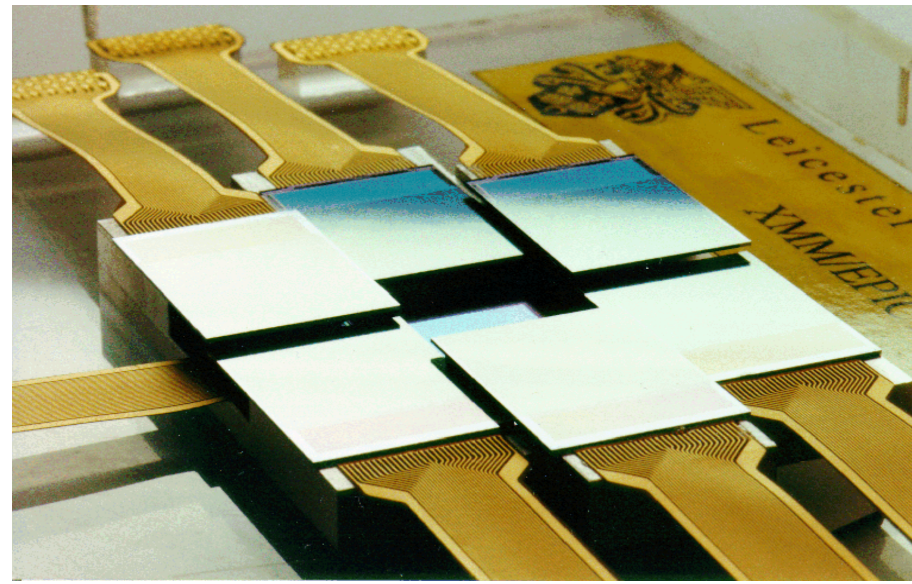
ASCA

Advanced Satellite for Cosmology and Astrophysics



XMM-Newton

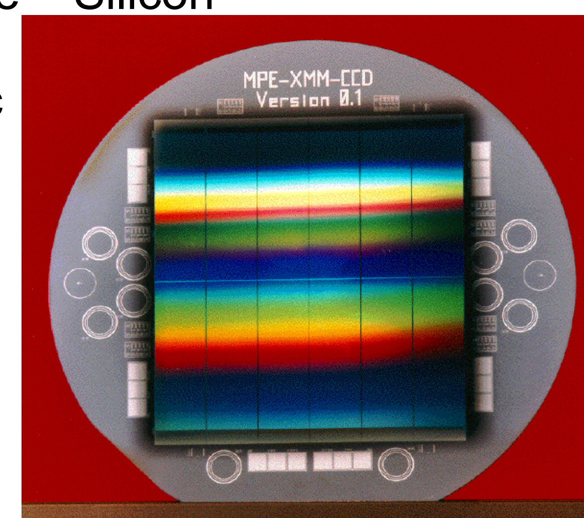
EPIC- European Photon Imaging Camera



MOS: Metal – Oxide – Silicon

1 pixel ~ 1.1 arcsec

PN

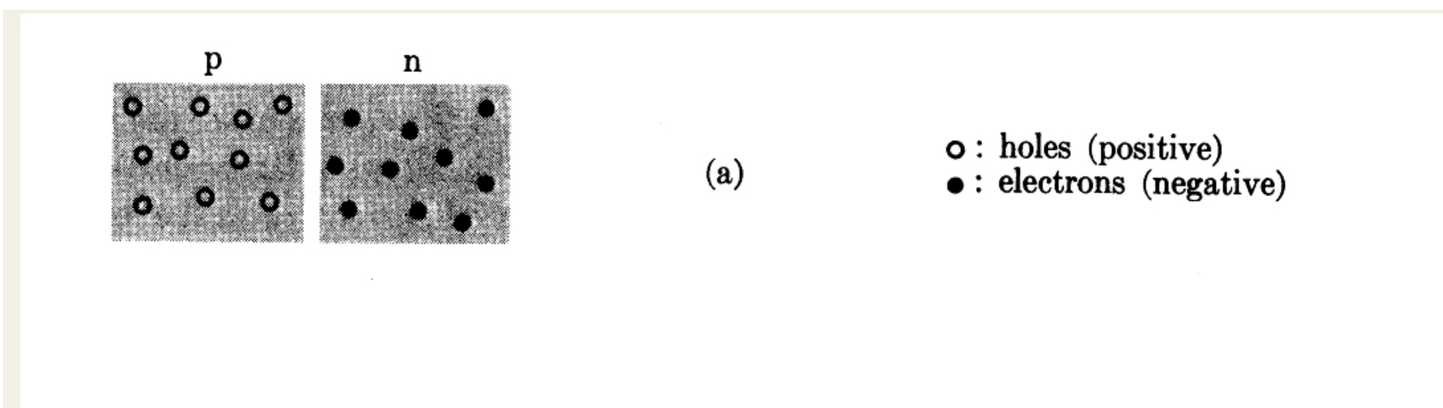


Fully Depleted, Back – illuminated pn CCDs:

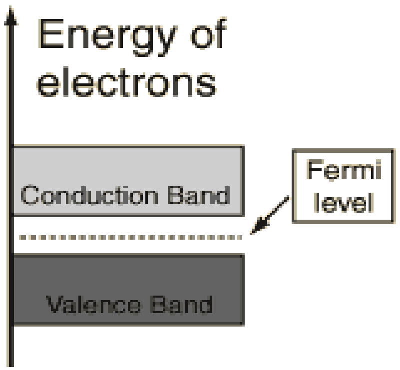
Silicon – as a detector material since 50-ties

Si – 3.7 eV is needed to create electron-hole pair
Z=14

pn CCD – silicon drift detector



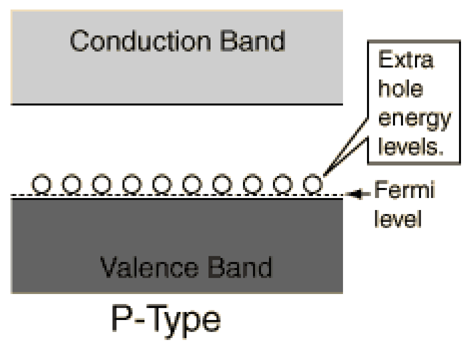
sensor – detector in combination with on-chip electronic.....

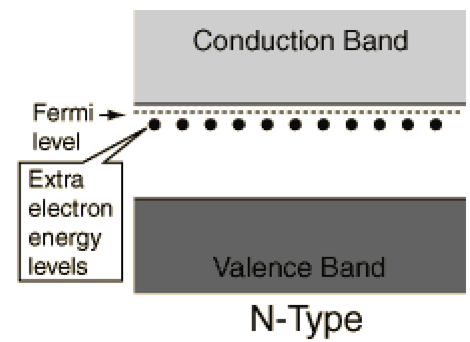


Semiconductors have gap between conduction and valence band:

0.1eV<Bg<3 eV

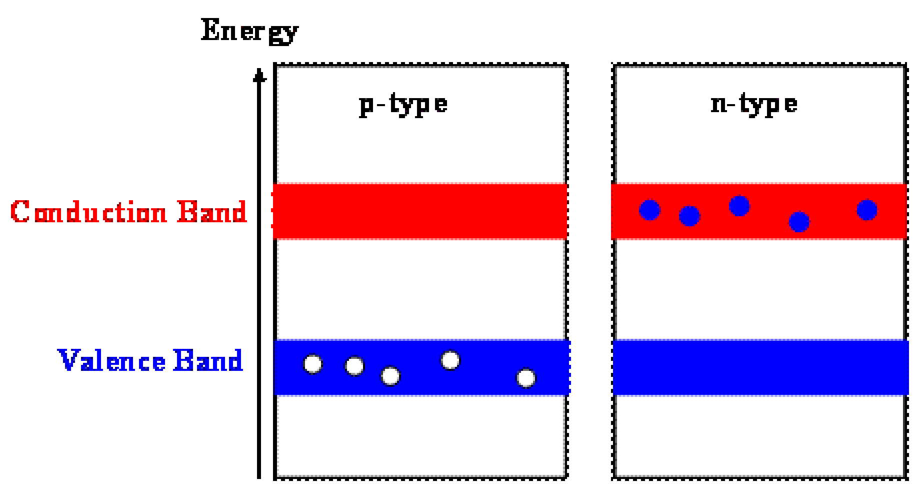
Acceptors – Borium,





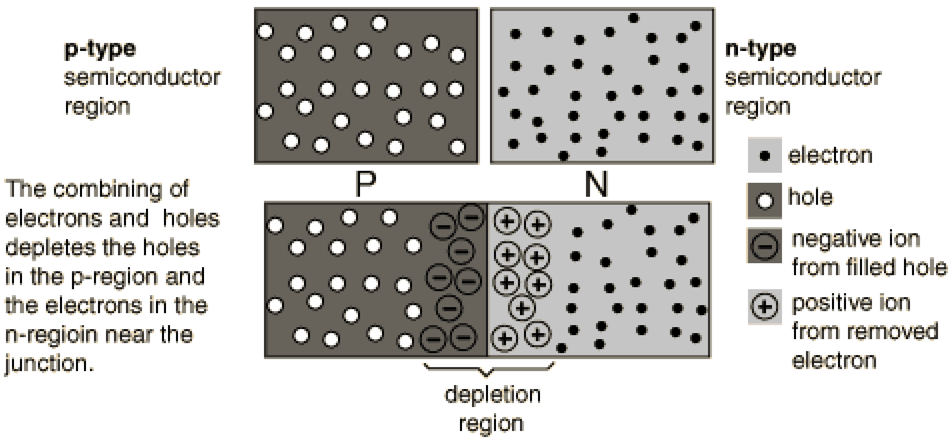
Donors – Phosphor

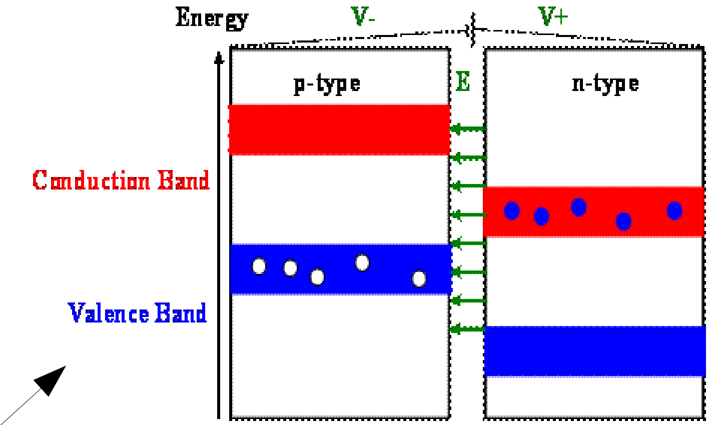
simply accept electrons
from valence band.

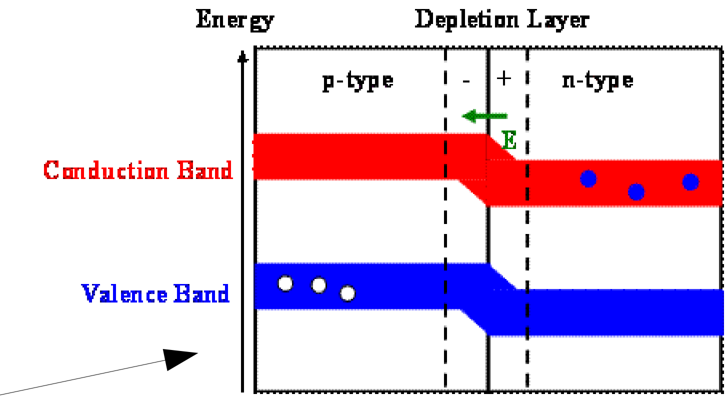


simply give electrons
to conduction band

p-n junction:

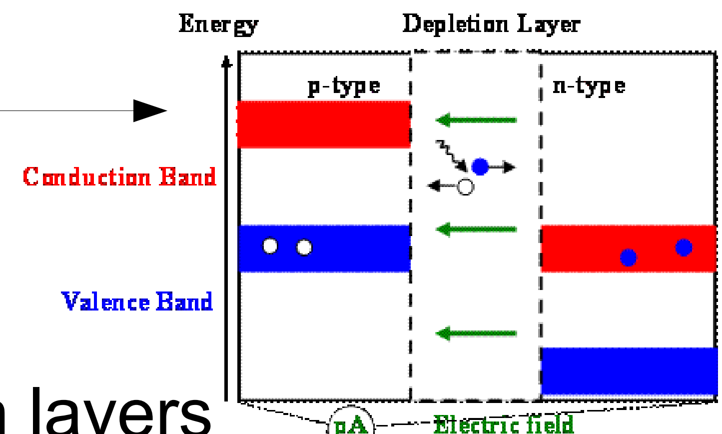






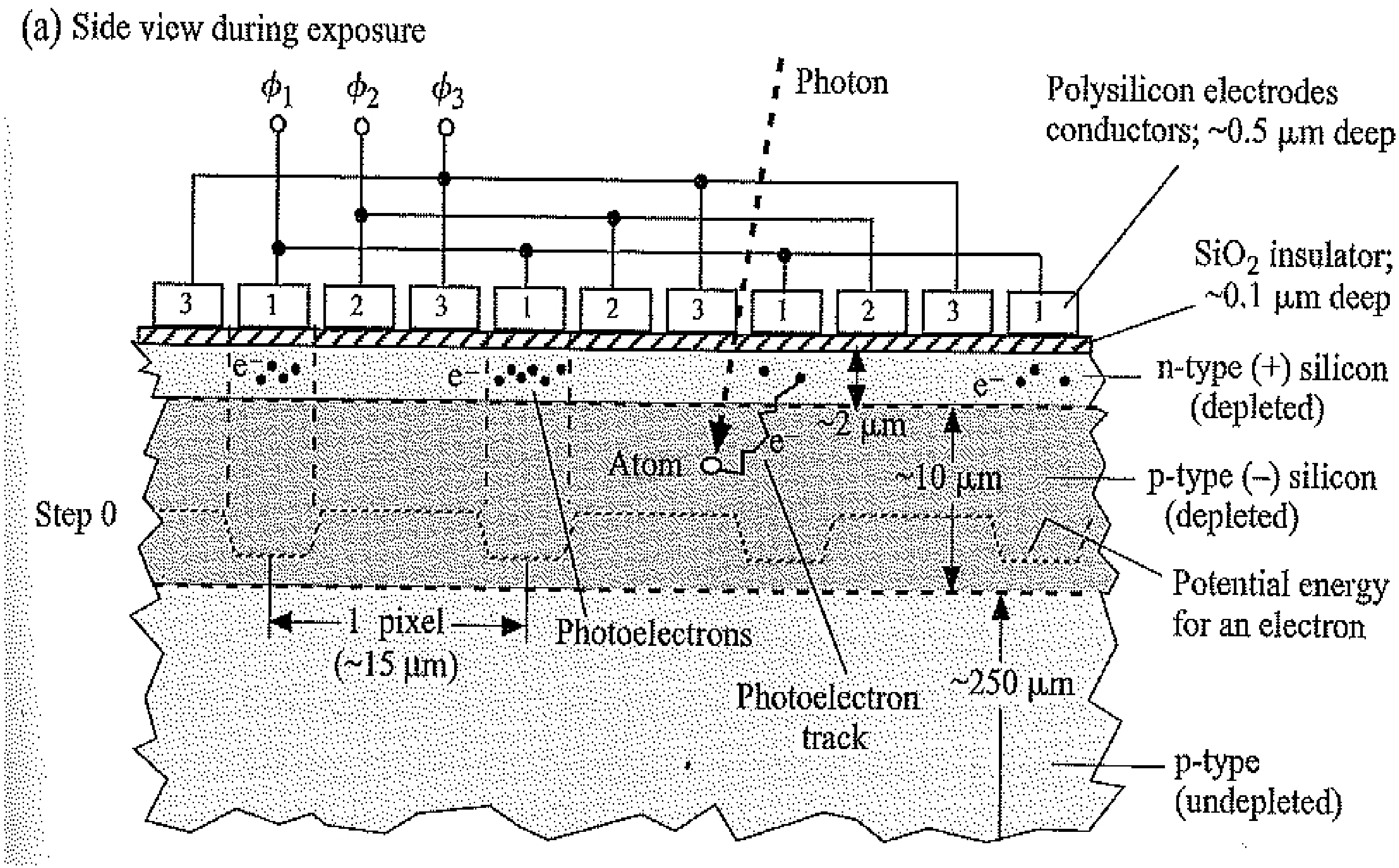
Three steps:

1) established electric field,
2) electron-hole recombination,
3) depletion layer, when any photon can create new electron-hole pair,

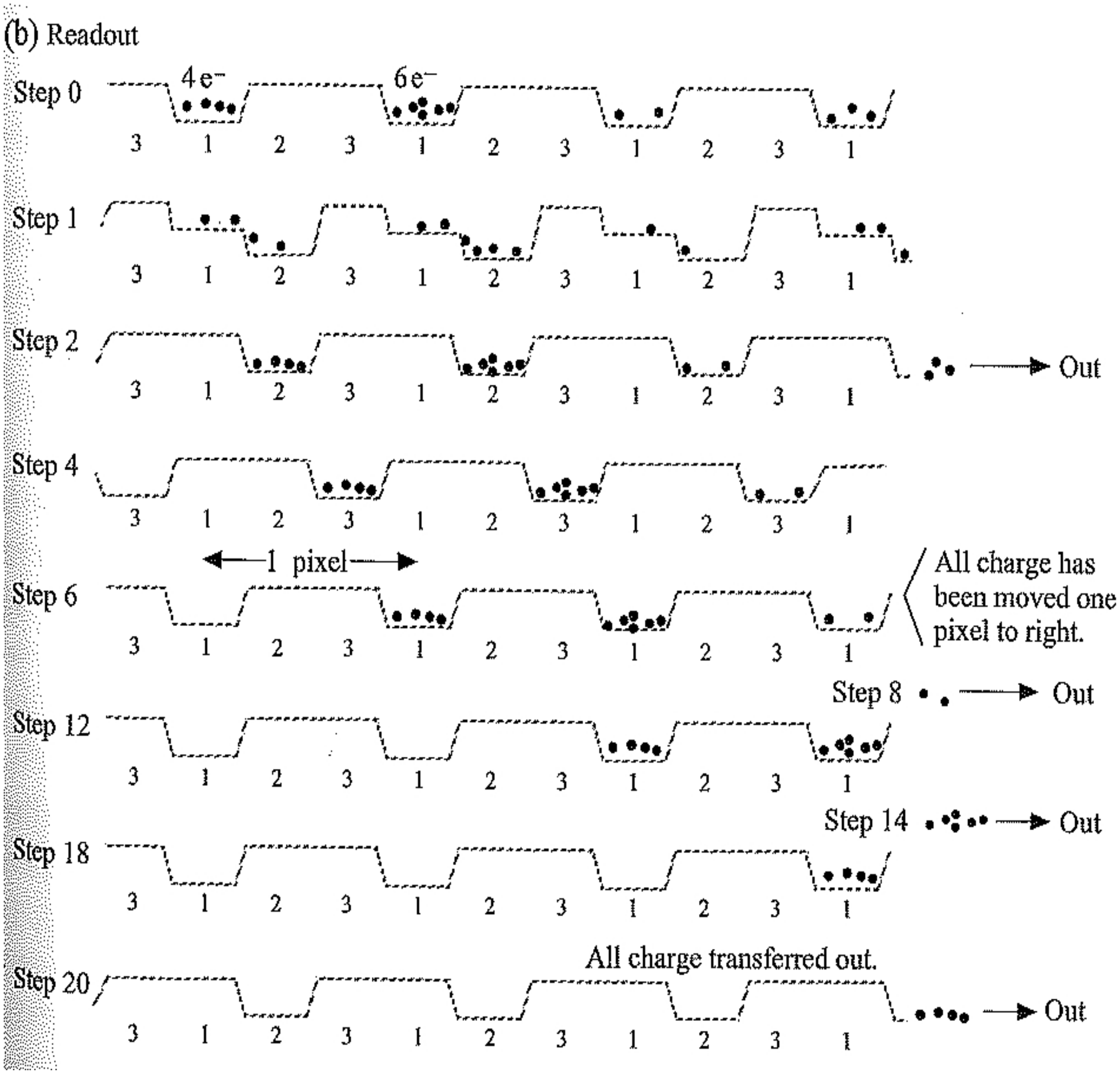


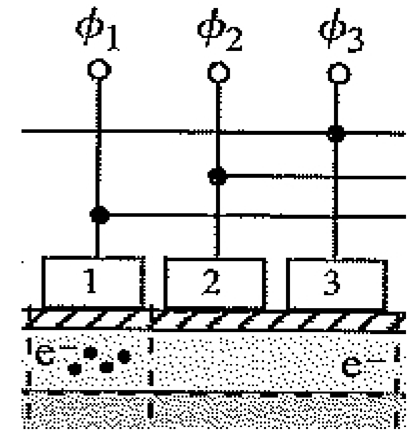
The size of depletion zone depends on the amount of donors and acceptors.
It is useful to create asymmetrical depletion layers

CCD for visible ligh:

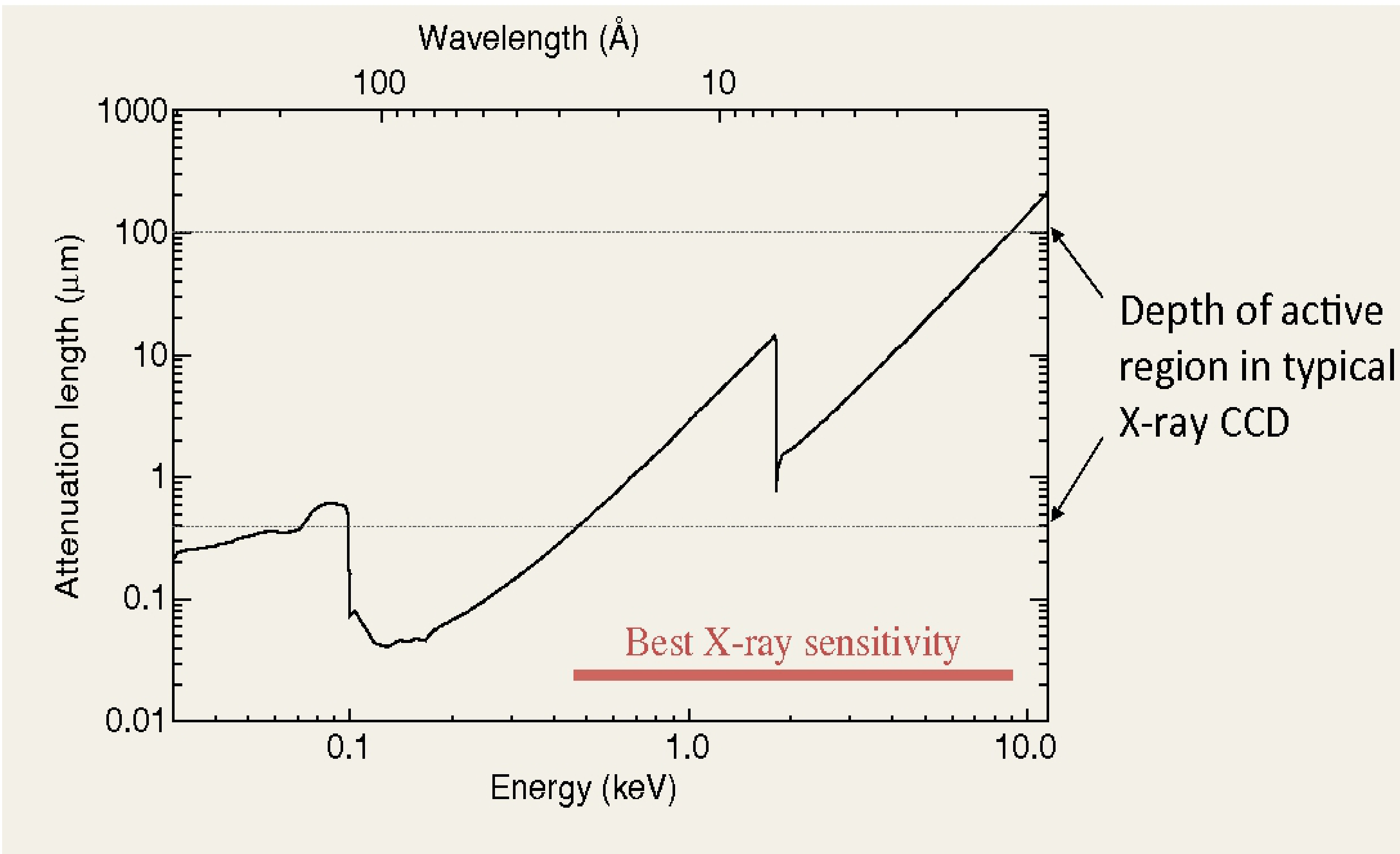


Pixelization: Si easy to make pixels:





Photoelectric Absorption in Silicon, Mean absorption depth.



Visible light   many photons with low energy,
each photon gives one electron.

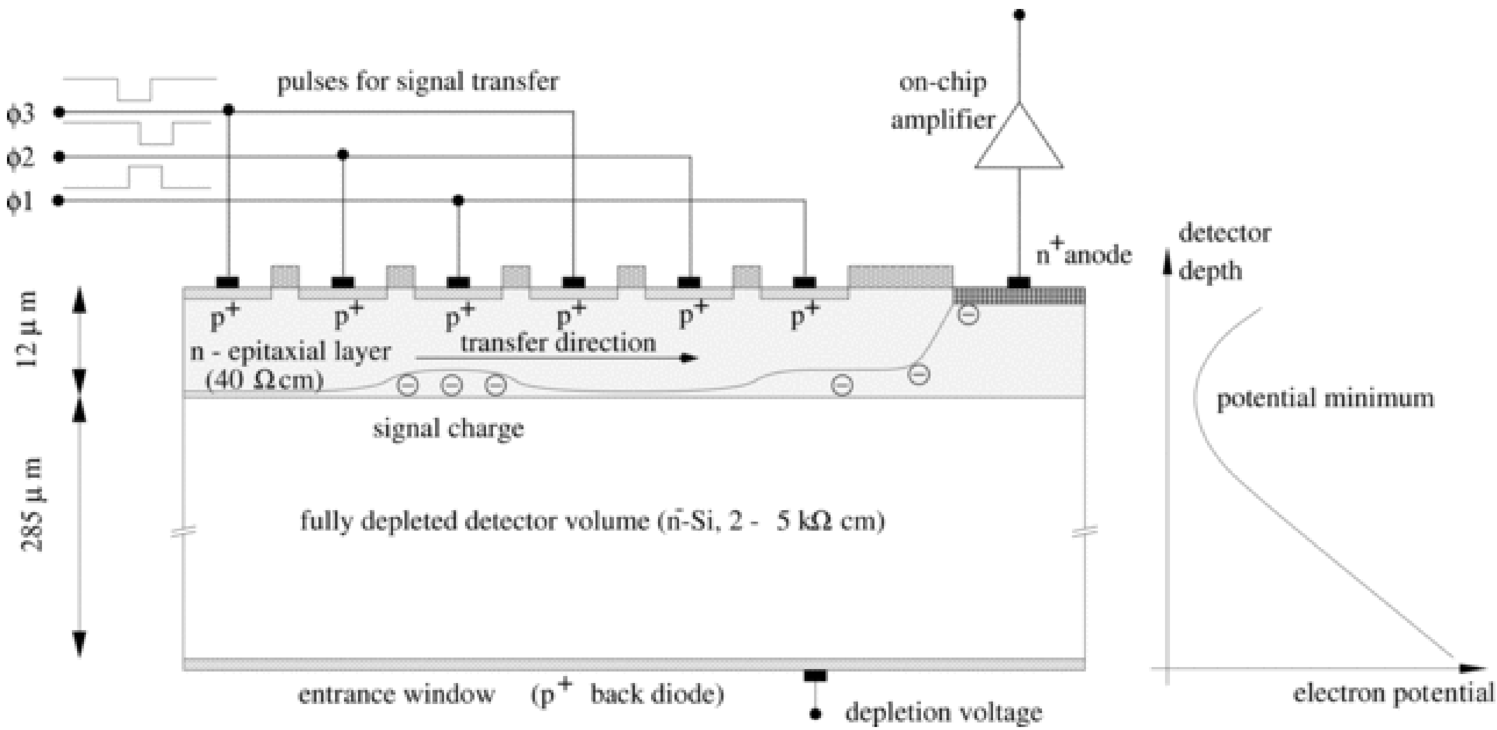
Depletion zone: < 10 μm

X-rays – 1 photon at 4 keV – about 1000 electrons,
it requires wide depletion zone > 50 μm

For X-ray event more electrons are concentrated in the pixel, which gives better energy resolution, than for visible light.

CCD – developed for X-rays:

50 μm and up for X-rays .... back illuminated CCDs



An additional negative voltage ~ 150 V, on the p+ back diode shifts the potential minimum for electrons out from the center towards the surface containing the pixel structure.

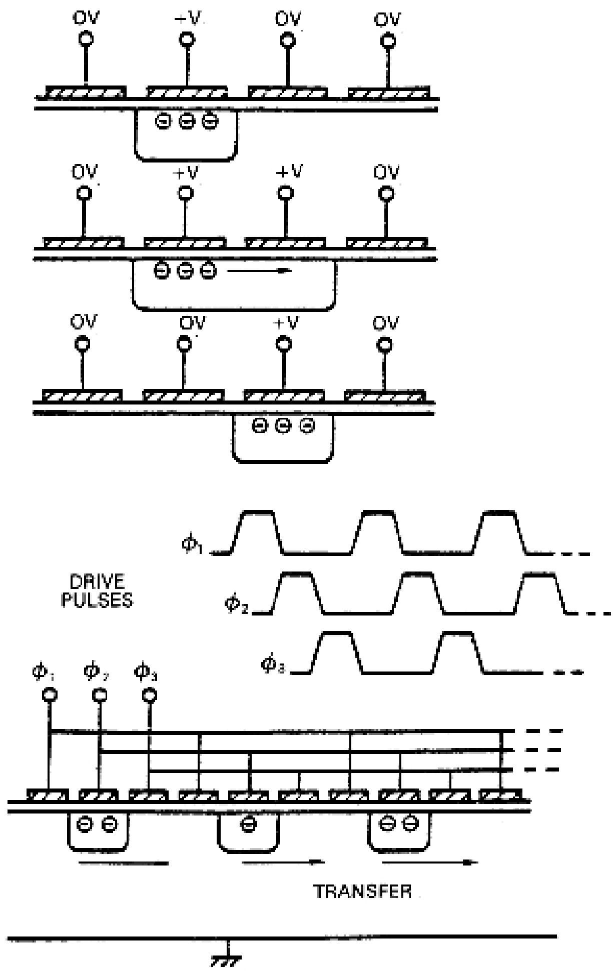


Fig. 6.9. Charge-coupling in a three-phase CCD and the associated timing waveform or clock pattern. In practice the degree of overlap between one electrode and the next depends on the CCD design.

Charge Transfer:

- Charge collected under the gate.
- Adjoining gates are "coupled", charge is transferred.
- Repeat to continue transferring charge.
- Three-phase CCD; three gates define one pixel dimension.

Metal Oxide Semiconductor MOS, XMM-Newton

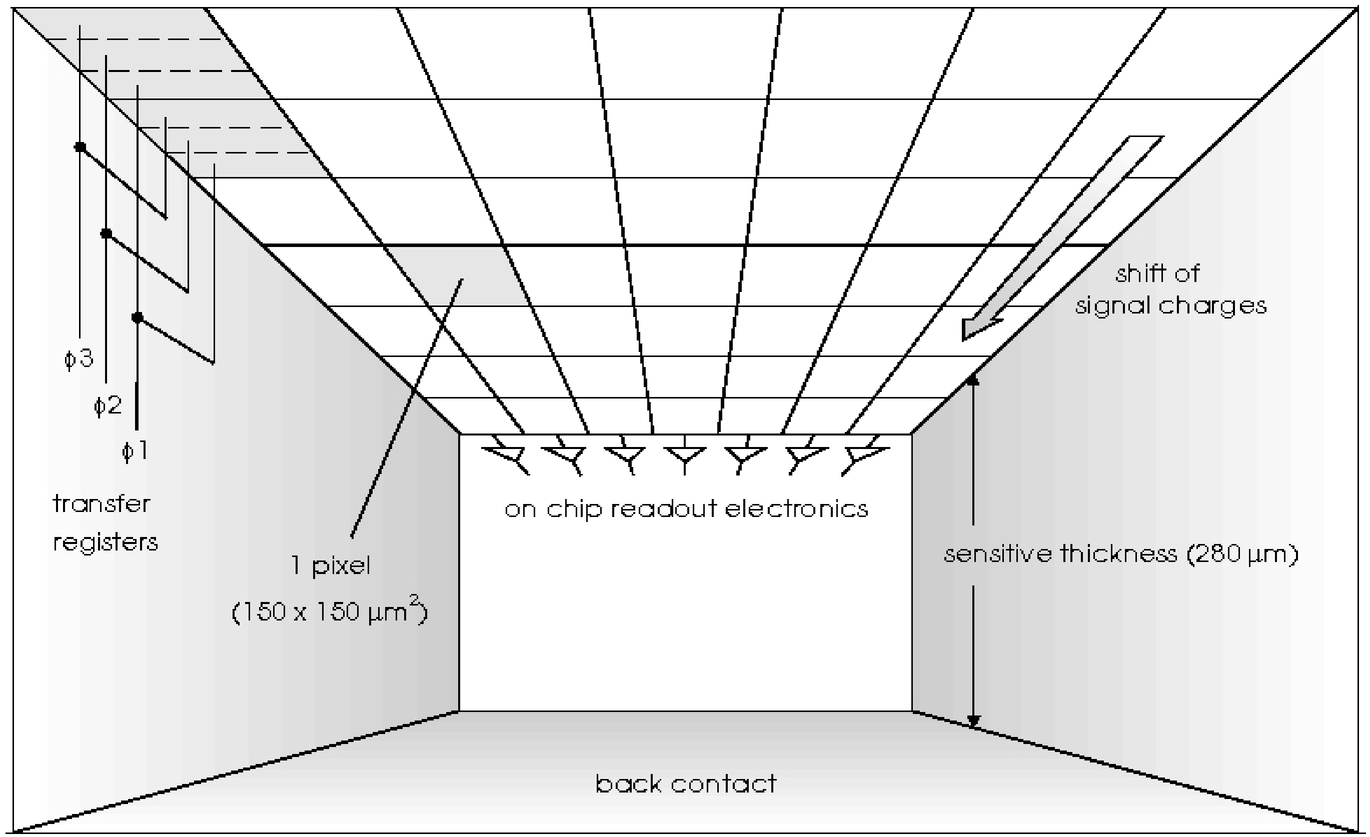


Fig. 1. Inside the pn-CCD. The X-rays hit the device from the backside (bottom). The charges are collected in the electron potential minimum 10 μm from the surface having the pixel structure. After integration, they are transferred to the on-chip amplifier. Each CCD column is terminated by an on-chip JFET amplifier

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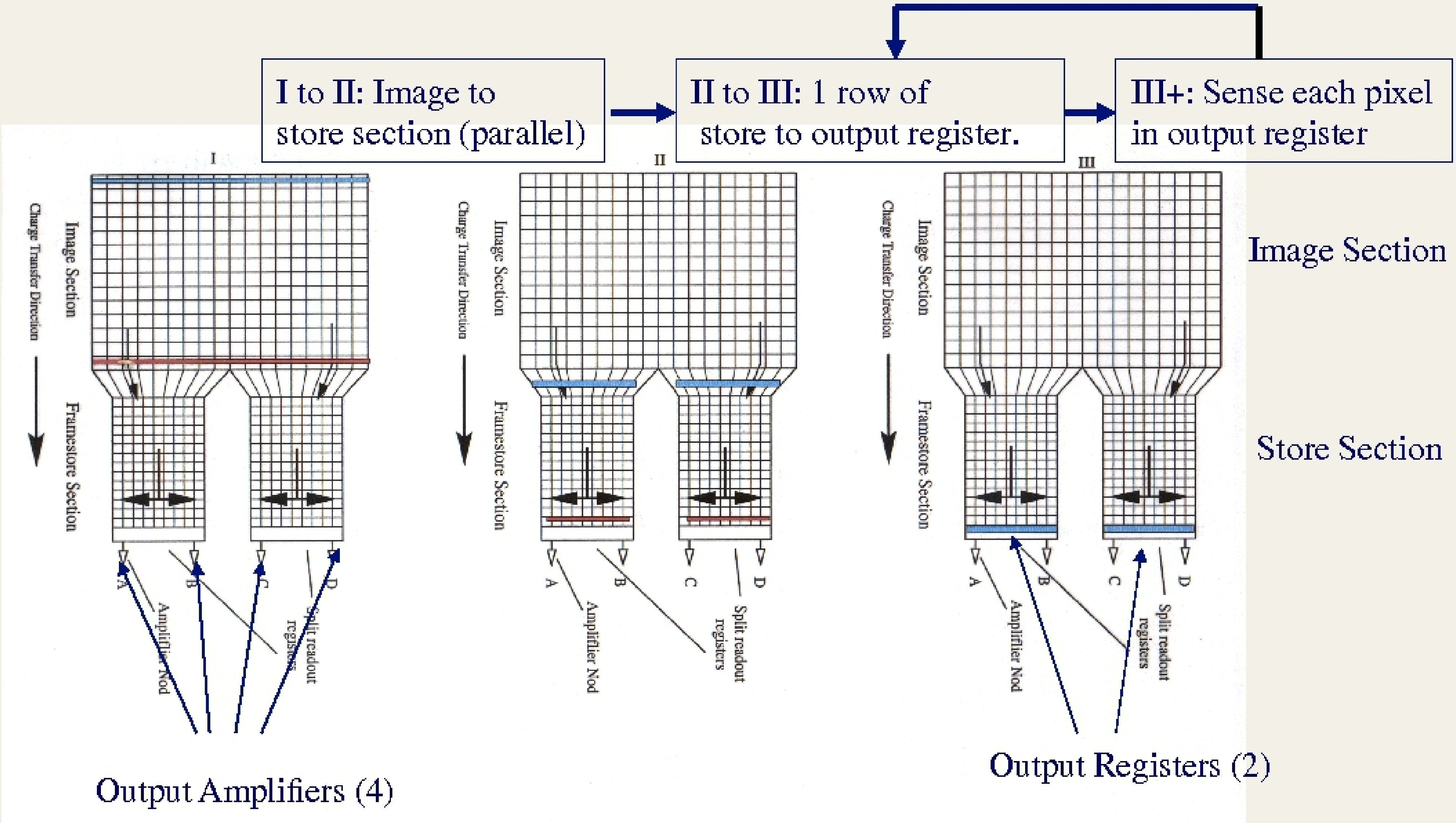
CCD Readout Sequence



Frame transfer CCD

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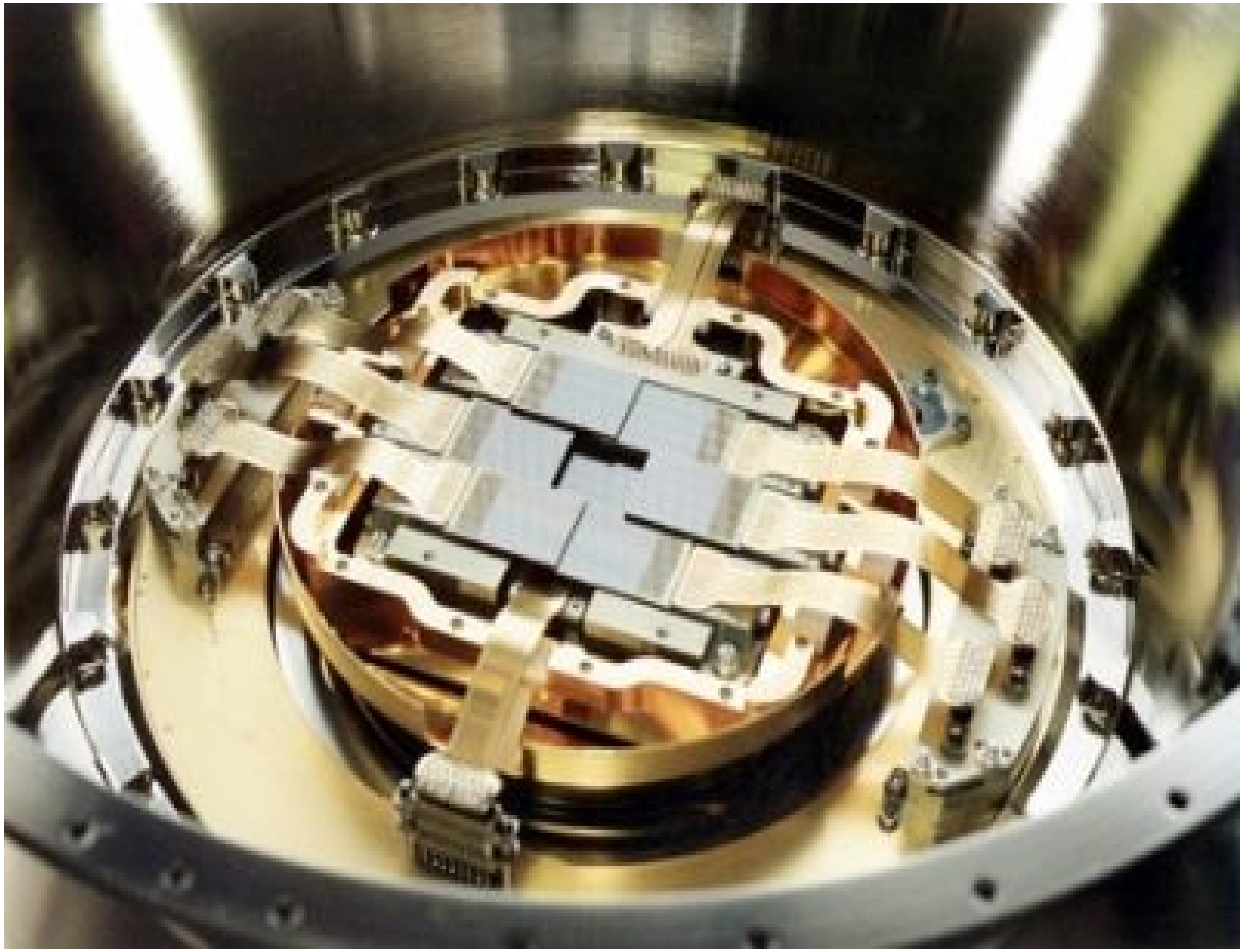
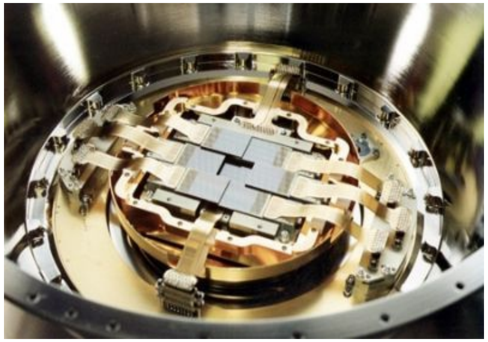
CCD Focal Planes

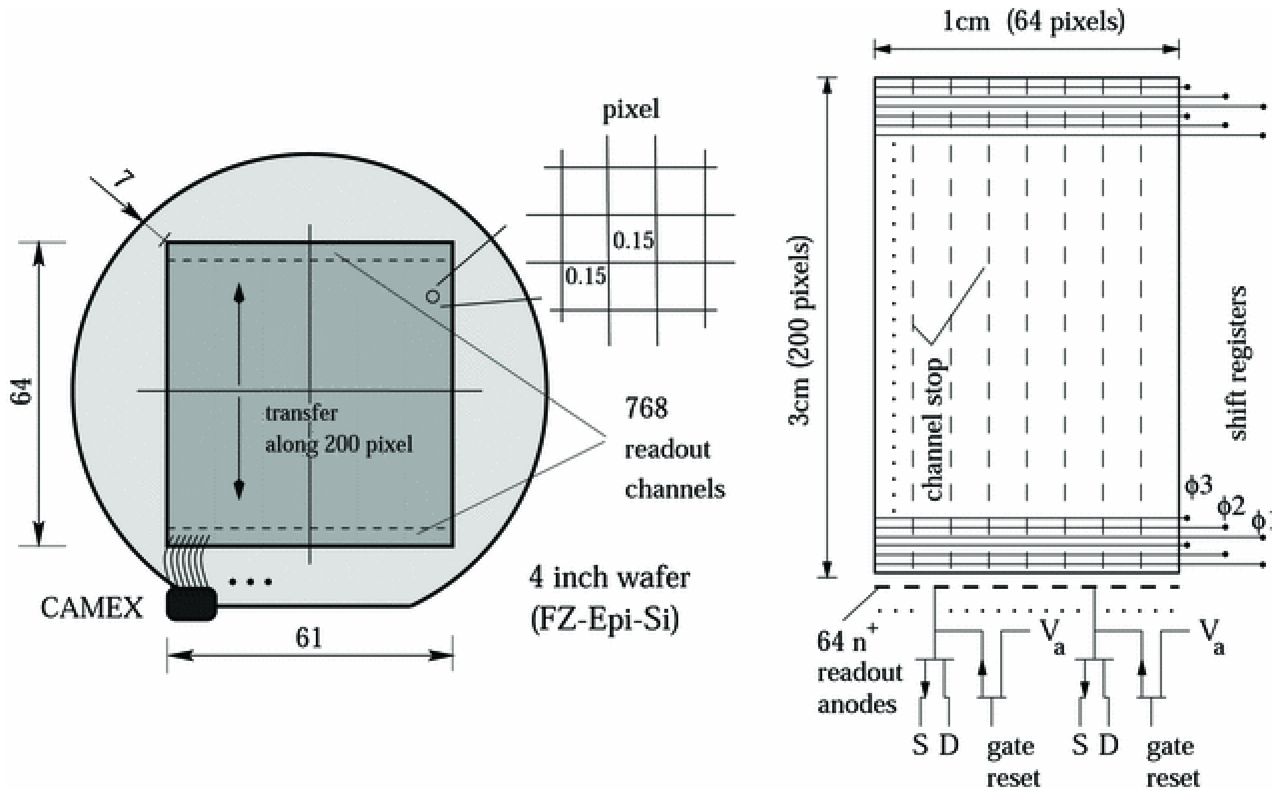
- Typical X-ray CCD is at most a few cm square
- Depending on plate scale of optics, single CCD may be insufficient for desired FOV
- Multiple CCDs can be tiled for larger focal planes
- Multi-CCD focal planes
  - Chandra ACIS, XMM EPIC & RGS, MAXI SSC
- Single CCD focal planes
  - Swift XRT, Suzaku XIS

EPIC MOS 7 CCDs 600 x 600 pixel each:



EPIC MOS 7 CCDs 600 x 600 pixel each:





64 x 61 mm2, 768 on-chip amplifiers process the signals.

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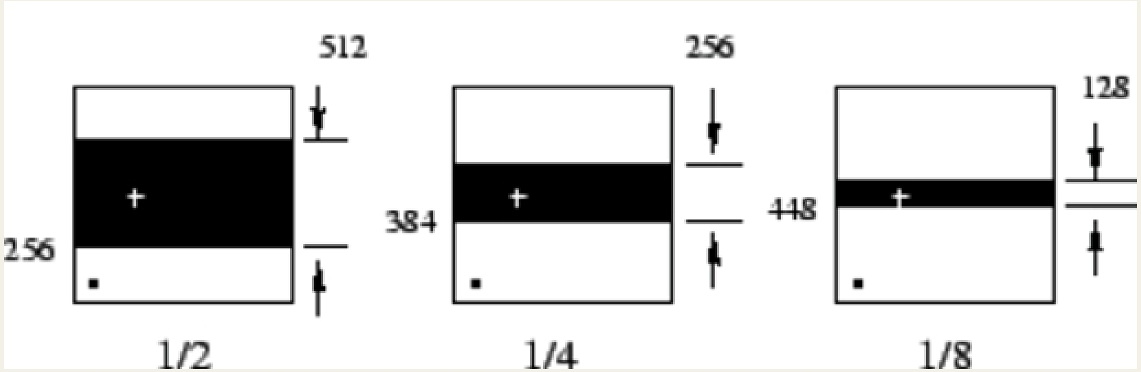
CCD Operation

- X-ray CCDs operated in photon-counting mode
- Spectroscopy requires ≤ 1 photon interaction per pixel per frametime
- Minimum frame time limited by readout rate
  - Tradeoff between increasing readout rate and noise
- For ACIS, 100 kHz readout (10 μs/pix) ⇒ 3.2 s frametime
- Frame time can be reduced by reading out subarrays or by continuous parallel clocking (1D imaging)

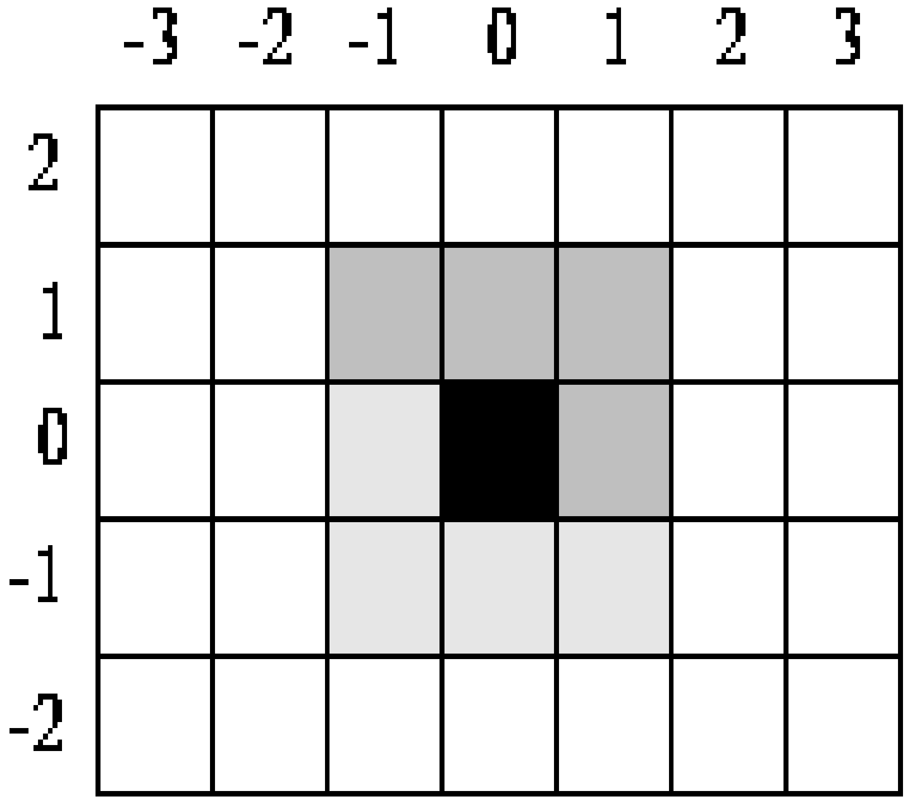


1.5 s   0.8 s   0.4 s

(CXC Proposer's Observatory Guide)

Pulse Height Amplitude, PHA, of the pixel:

Integrated charge per pixel:



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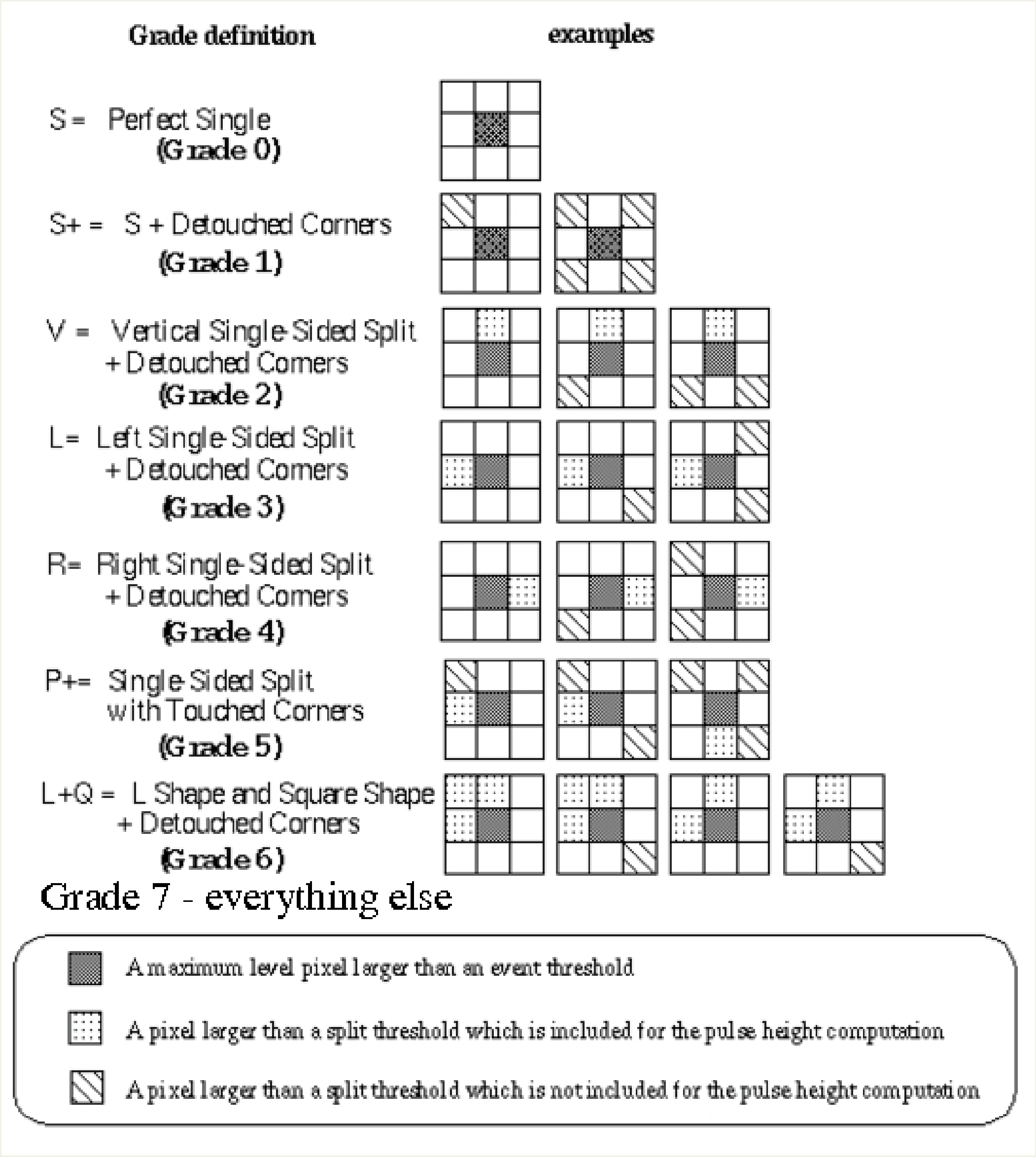
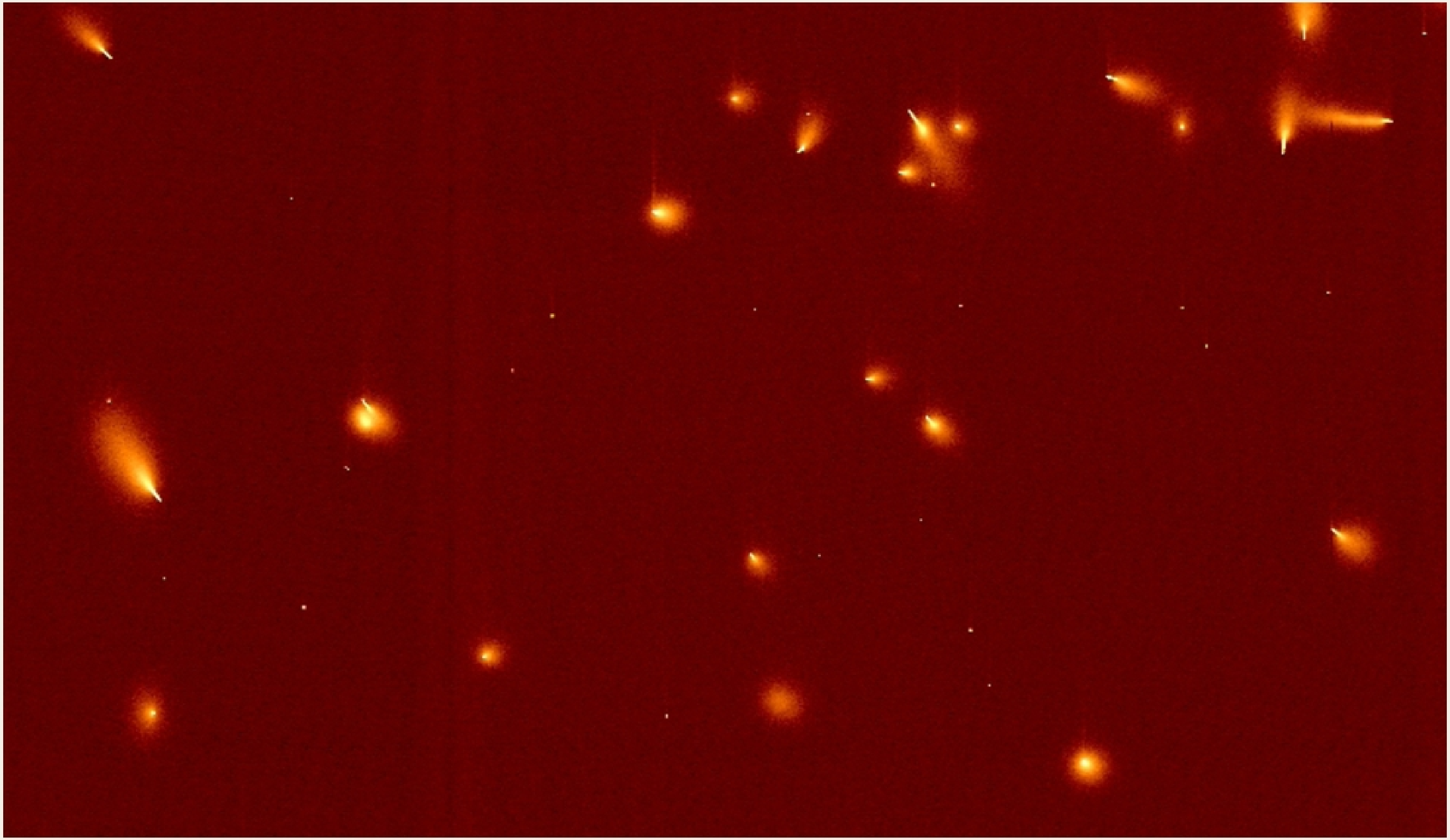
Grading events

ASCA Grade Codes



- Event grade can be used to discriminate between X-ray and cosmic ray events
- X-ray events split into simpler/ smaller shapes (single, singly-split)
- Cosmic ray events are more complex
- Onboard grade filtering can further reduce telemetry
- Grade filtering can improve spectral resolution - split events are noisier than singles

X-ray/Particle Discrimination



Blobs/streaks - charged particles.   Small dots - X-ray events.

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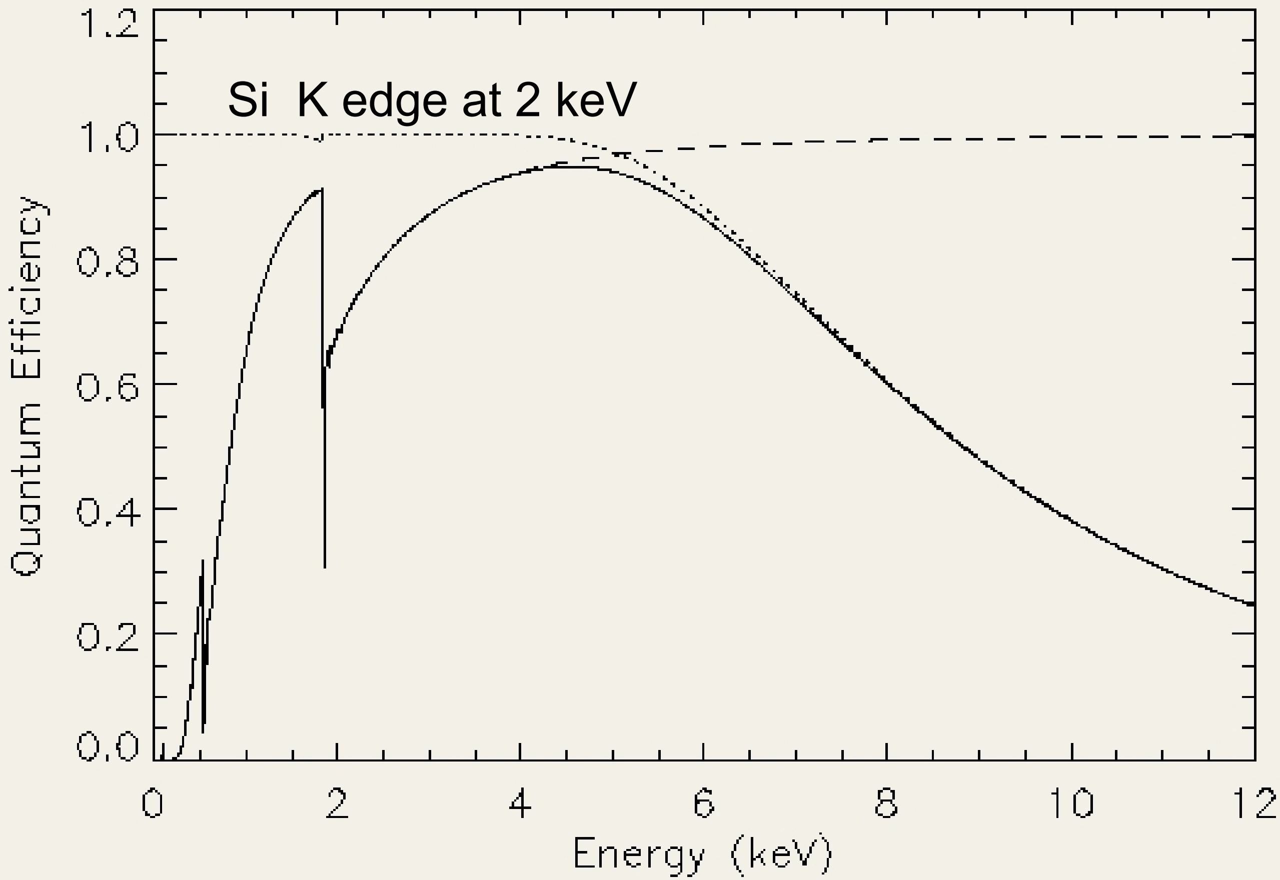
CCD Quantum Efficiency



Transmission through deadlayers (channel stops, gates, oxide layers)

$T = \prod_i e^{-\mu_i t_i}$

Absorption in depleted region

$A = 1 - e^{-\mu_{Si} d}$

μ = linear absorption coefficient

t = thickness of deadlayer

d = depletion depth

$$QE = (1 - e^{-\mu_{Si} d}) \prod_i e^{-\mu_i t_i}$$

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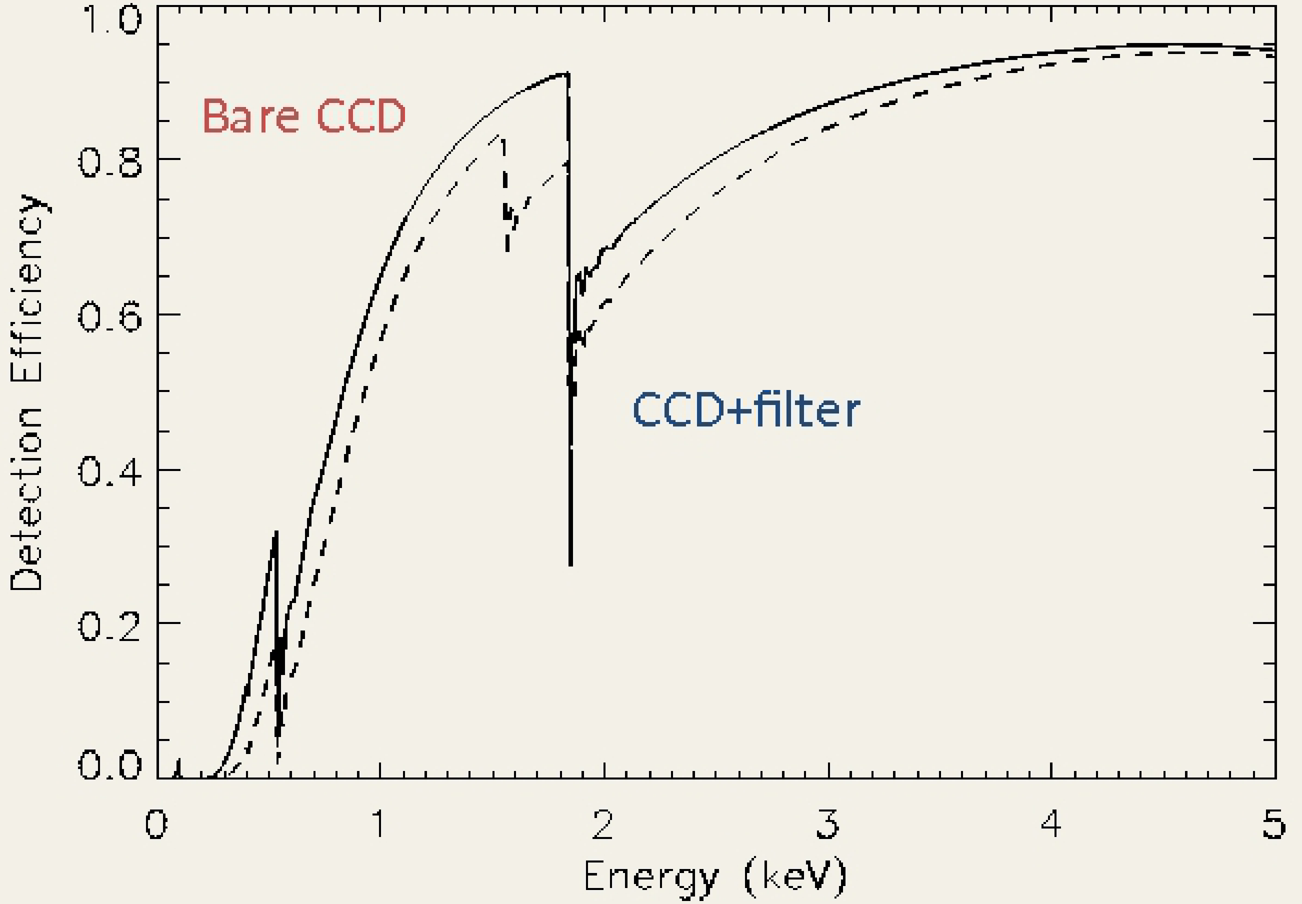
Filter Transmission



At low energies (< 0.5 keV), > 50% reduction in efficiency

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CCD X-ray Spectroscopy: The Basic Idea

- Photoelectric interaction of a single X-ray photon with a Si atom produces free electrons:

$$N_e = E_X / w \ \ (w \approx 3.7 \text{ eV}/e^-)$$

$$\sigma_e^2 = F \times N_e \ (F \approx 0.12; \text{not a Poisson process})$$

- Spectral resolution depends on CCD readout noise and physics of secondary ionization:

$$\text{FWHM (eV)} = 2.35 \times w \times \sqrt{\sigma_e^2 + \sigma_{read}^2}$$

- CCD characteristics that maximize spectral resolution:
  - Good charge collection and transfer efficiencies at very low signal levels
  - Low readout and dark-current noise (low operating temperature)
  - High readout rate (requires tradeoff vs. noise)

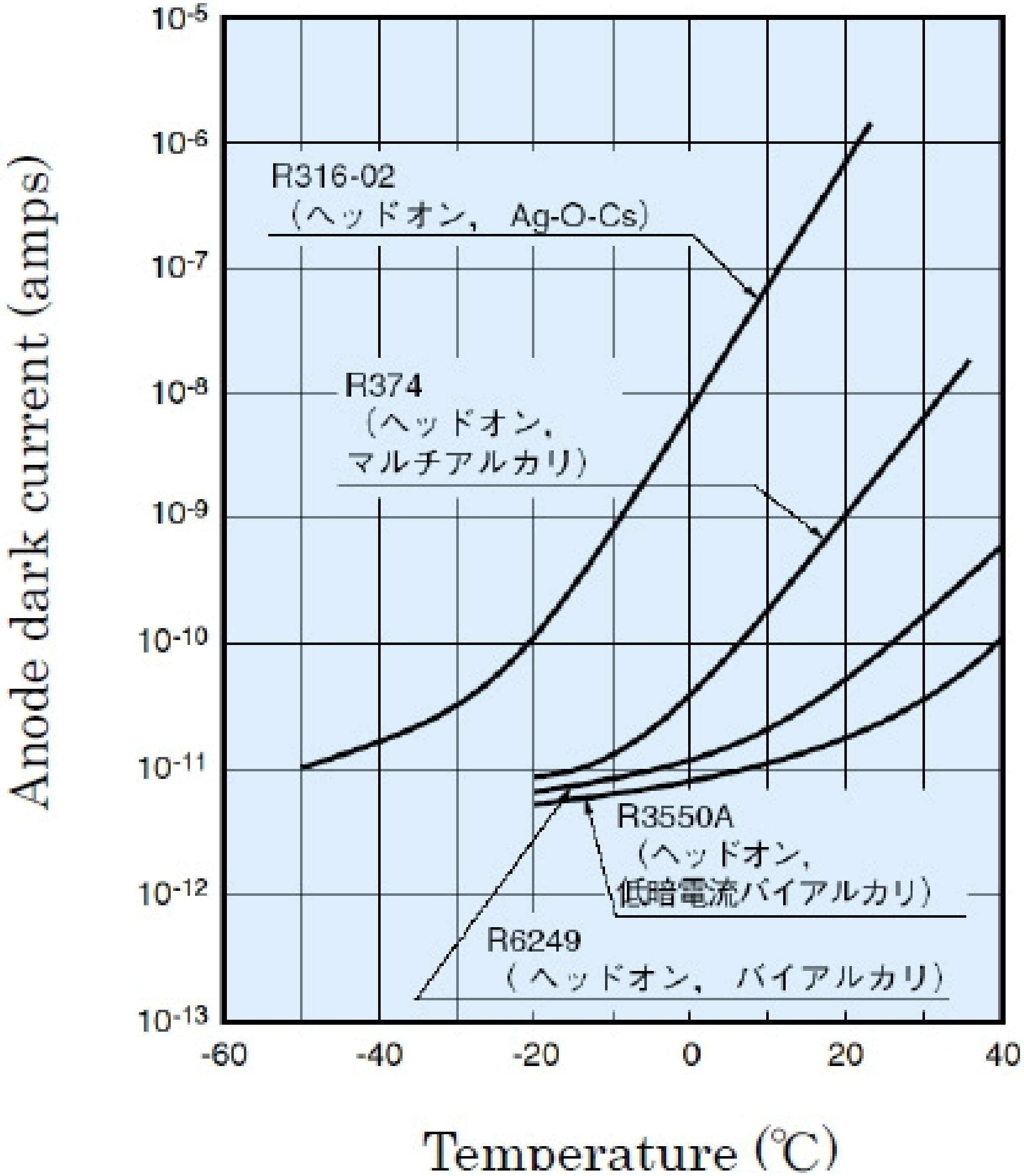

Fig 10 Relation between anode dark current and temperature (Hamamatsu)

Operating Temperature:

T-60° C

MOS XMM-Newton

-120° C

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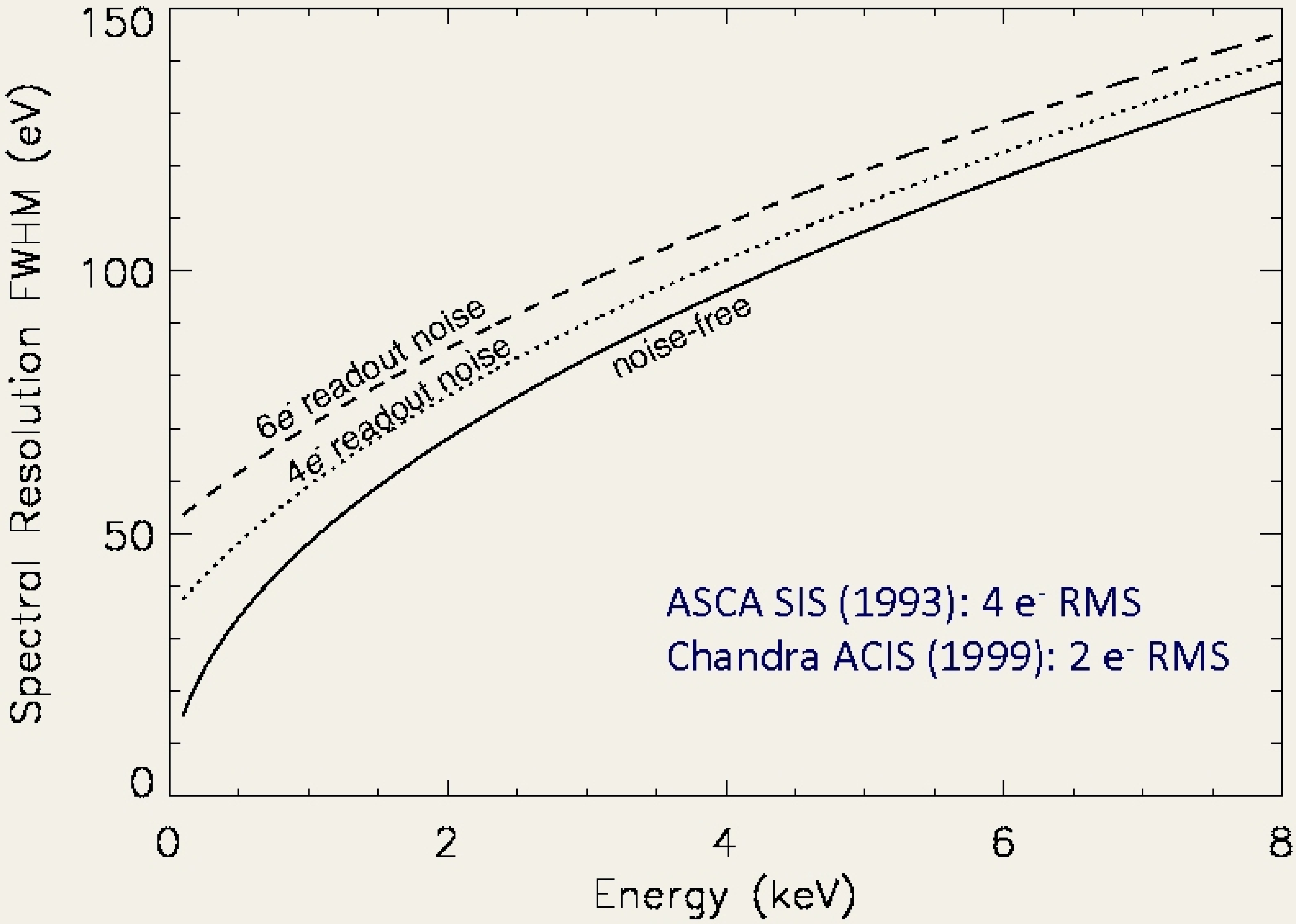
Spectral Resolution



ASCA SIS (1993): 4 e^- RMS

Chandra ACIS (1999): 2 e^- RMS

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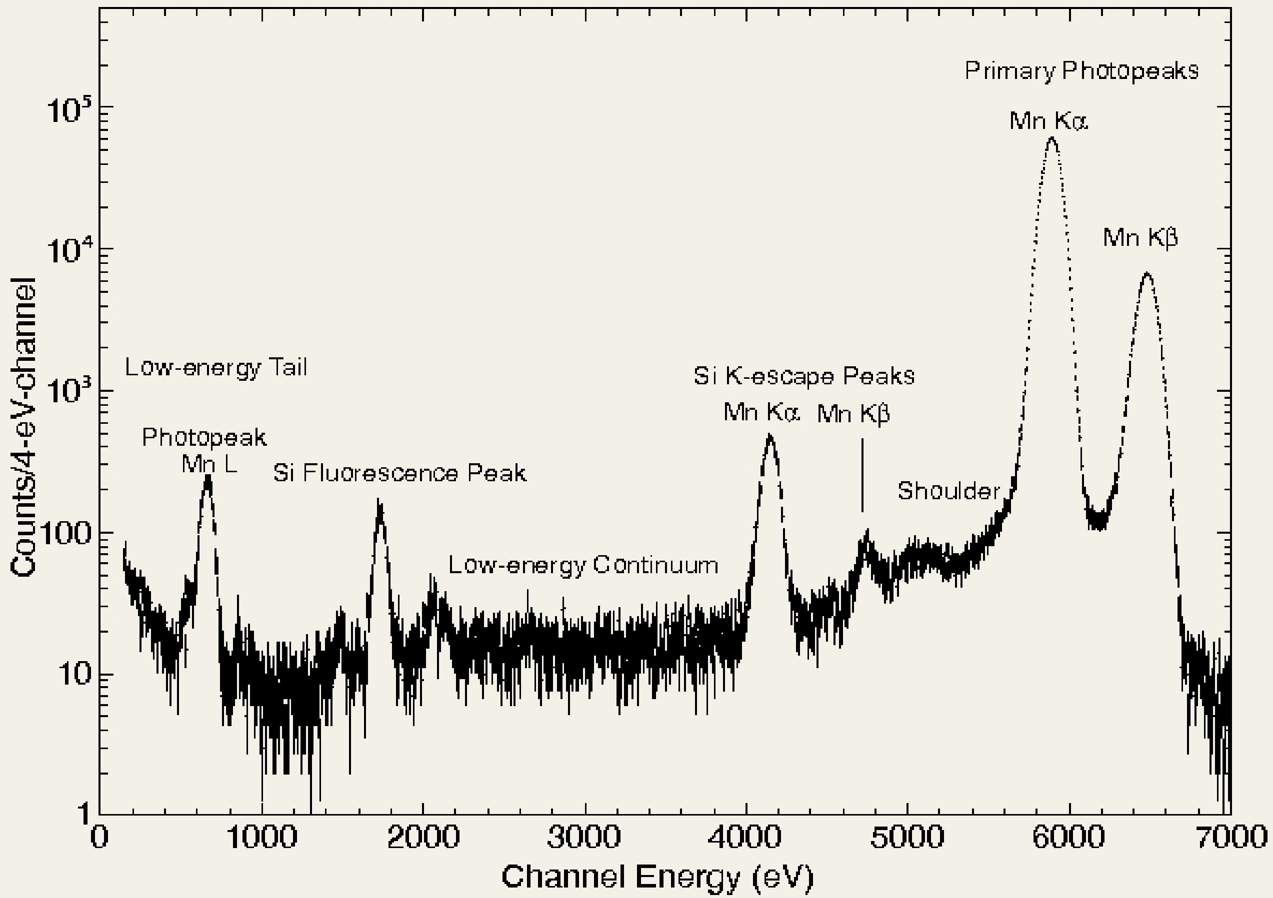
Spectral Redistribution Function

SRF



- X-ray source has three spectral lines: Mn-Kα (5.9 keV), Mn-Kβ (6.4 keV), Mn-L (0.67 keV)
- Instrument produces Si-K fluorescence and escape peaks, low-energy features
- Off nominal features ~2% of total

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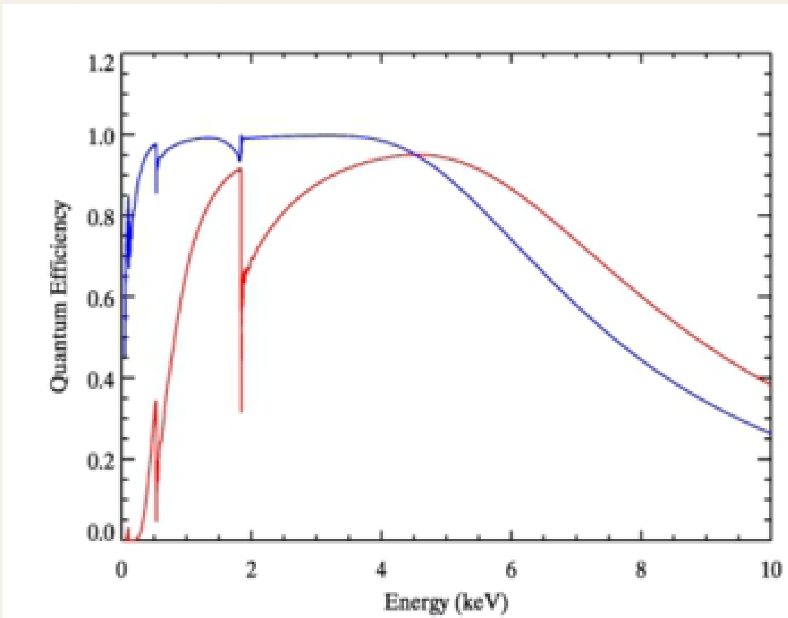
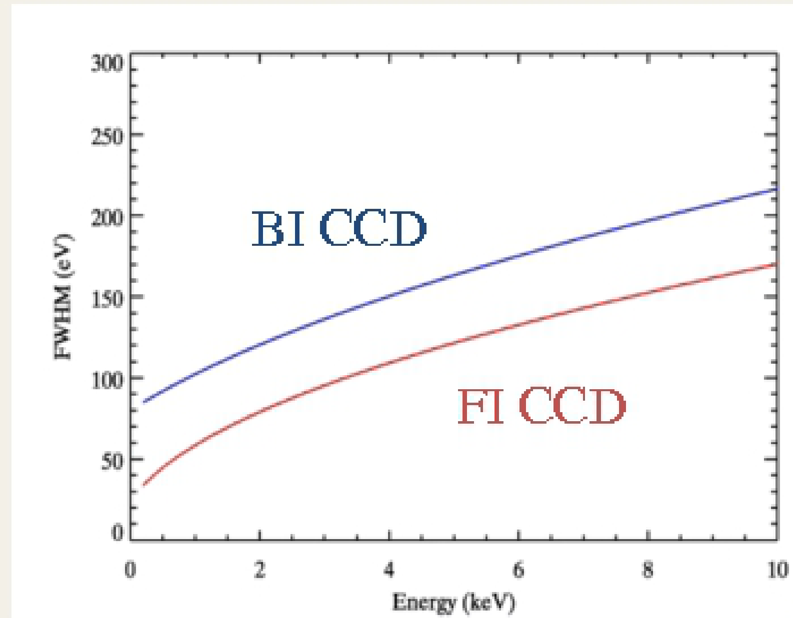
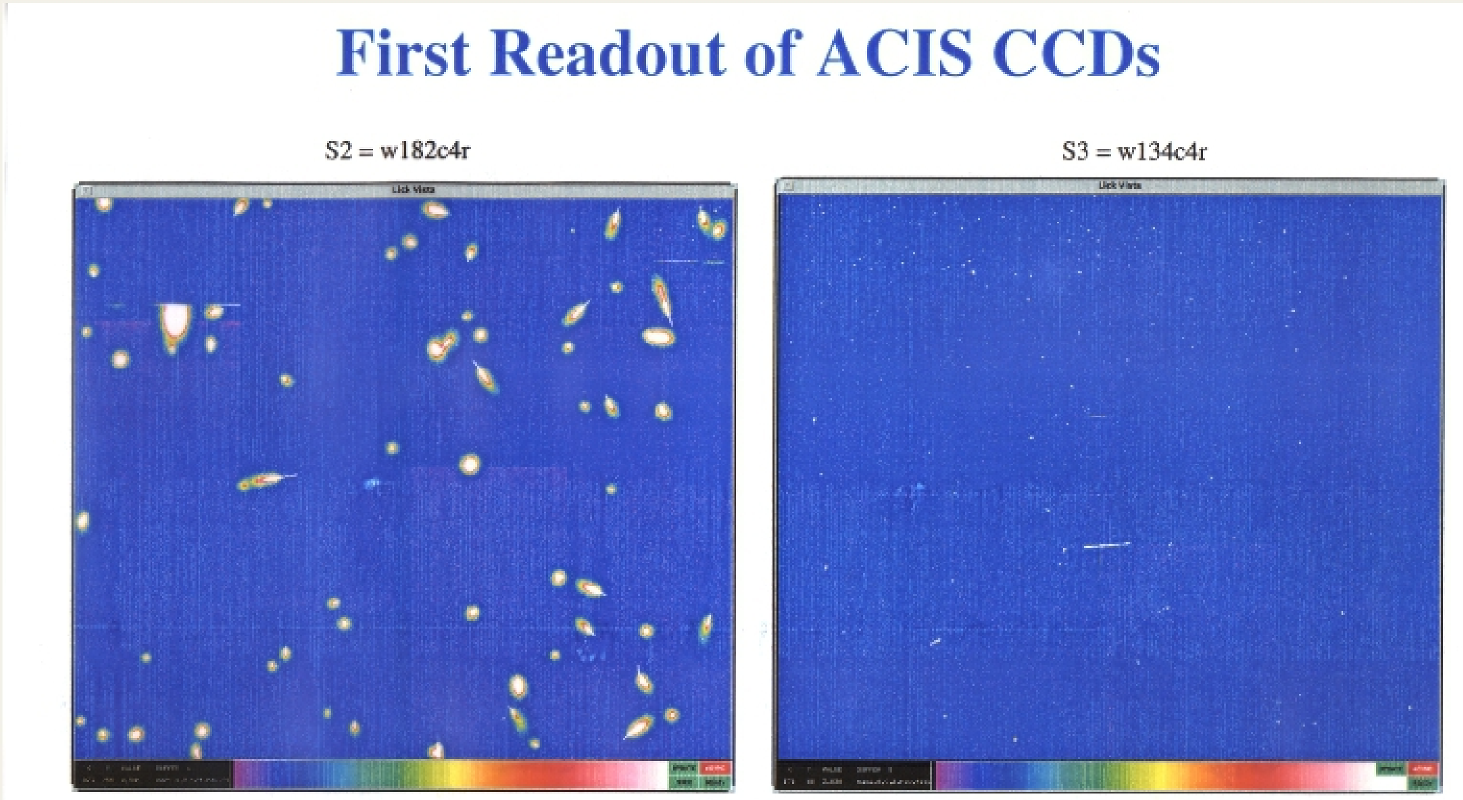
QE Back-illuminated CCDs





- Front-illuminated CCD, reversed and thinned
- Gate structures and channel stops are not dead layers
- Thinner dead layers ⇒ higher low-E QE
- Thinner active region ⇒ lower high-E QE
  - Not always true, XMM EPIC-pn has excellent high-E QE
- Increased noise, charge transfer inefficiency ⇒ higher FWHM
  - Technology is maturing, Suzaku XIS BI quite good FWHM



Front-illuminated CCD | Back-illuminated CCD

- Particle events produce large blooms on FI CCD, not on fully-depleted BI CCD
- Background rejection efficiency much higher for FI CCD

ACIS -Advanced CCD Imaging Spectrometer
Credit by: Catherine Grant, MIT.

ATHENA future mission

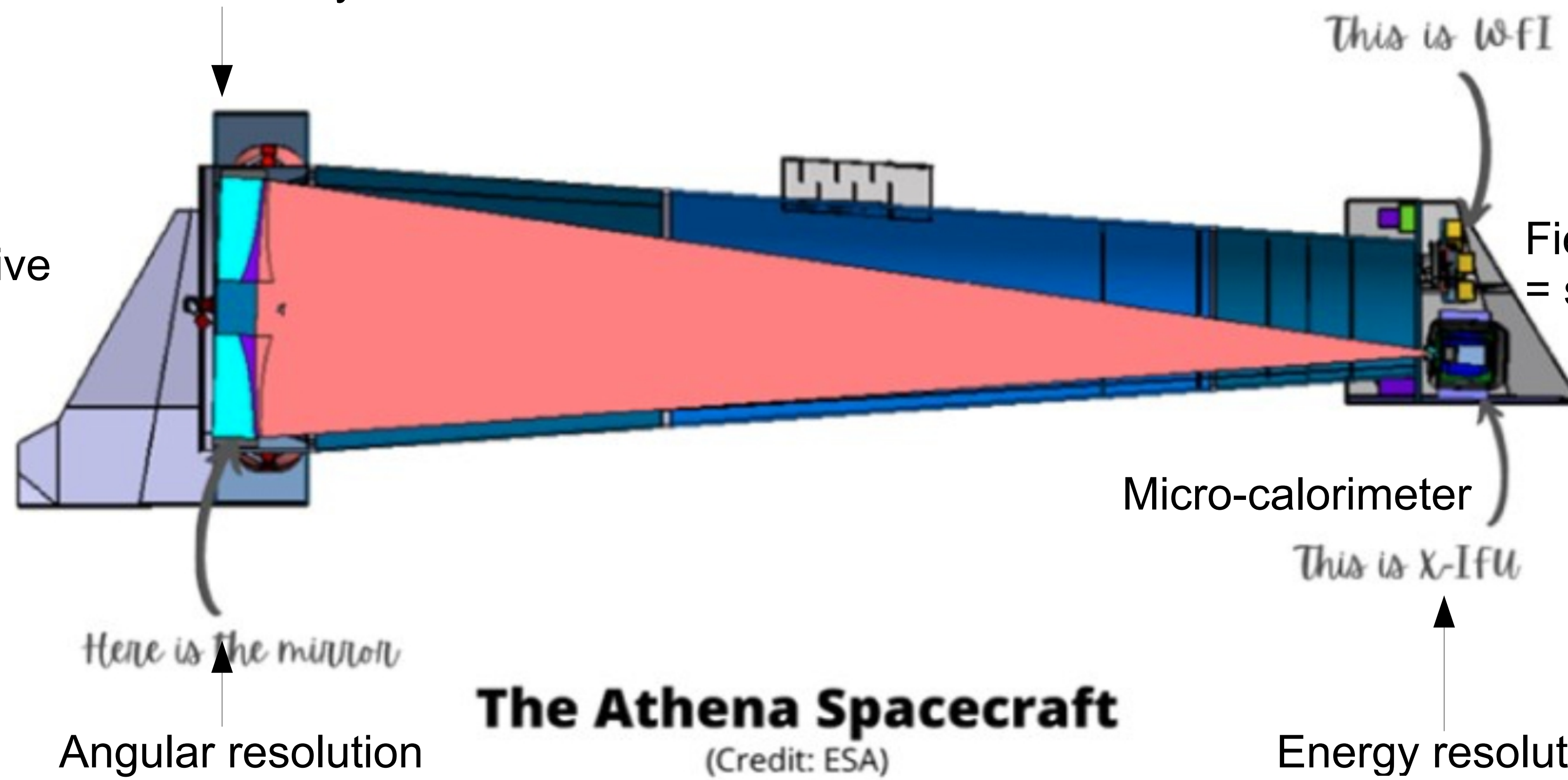
SPO 2,4 m diameter
Mirror Asembly

Active Pixel CCD - DEPFET

Effective
Area

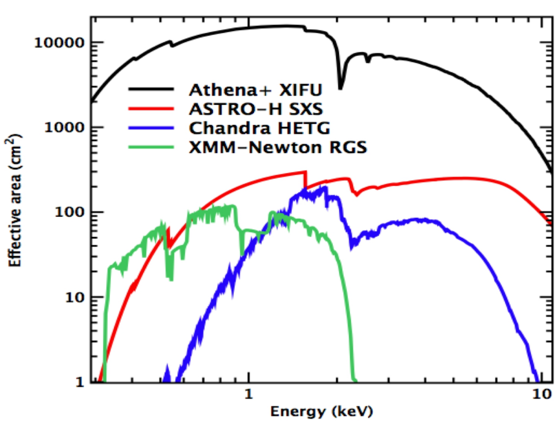
Field of view
= sensor size

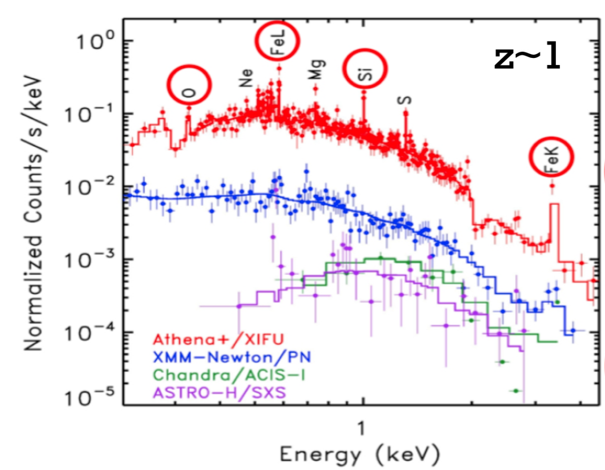
Micro-calorimeter



Angular resolution

Energy resolution





Next steps:

- Lecture #4 will be the last lecture about detectors,
Overview of HW#1

- Lecture #5 – observations and hands-on sessions

HOMEWORK #3:
FITS (flexible Image Transfer System) file format –
Explore what is it? Look at HEASOFT fv – FITS viewer

NEXT LECTURE Nov. 17th 2022
On Nov. 24th 2022 – NO LECTURE

wi-fi password: a w sercu maj
We have eduroam as well