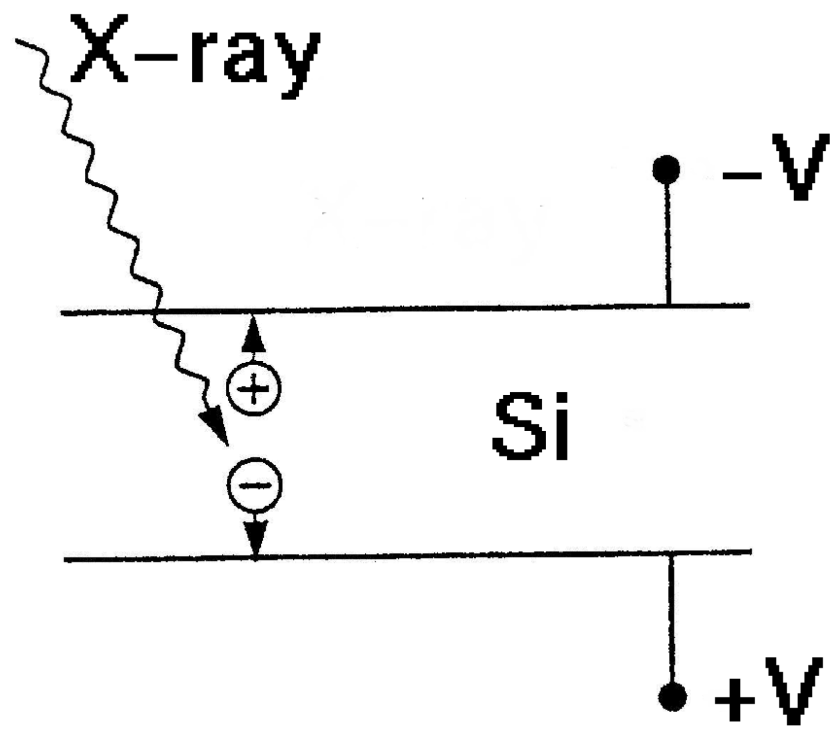
Detection of X-Rays

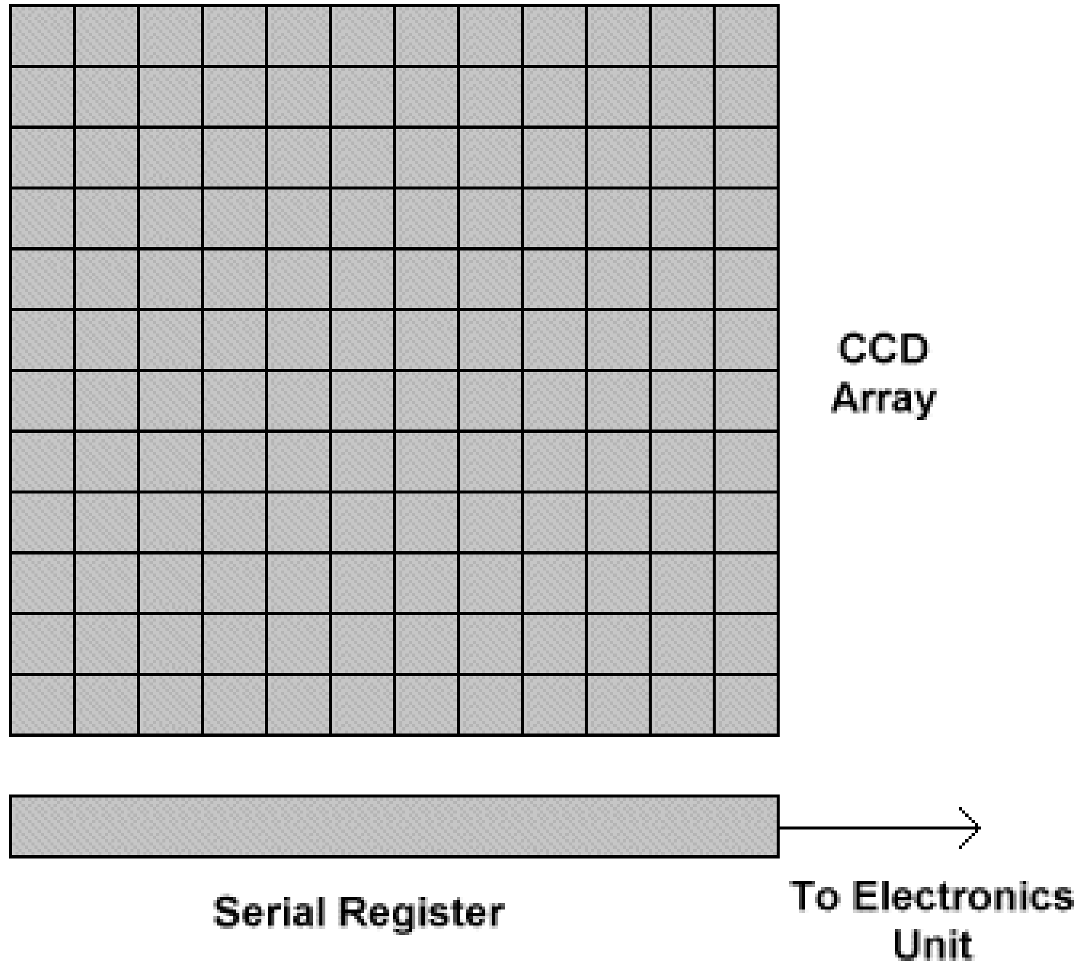
- Solid state detectors
- Proportional counters
- Microcalorimeters
- Detector characteristics

Solid State X-ray Detectors

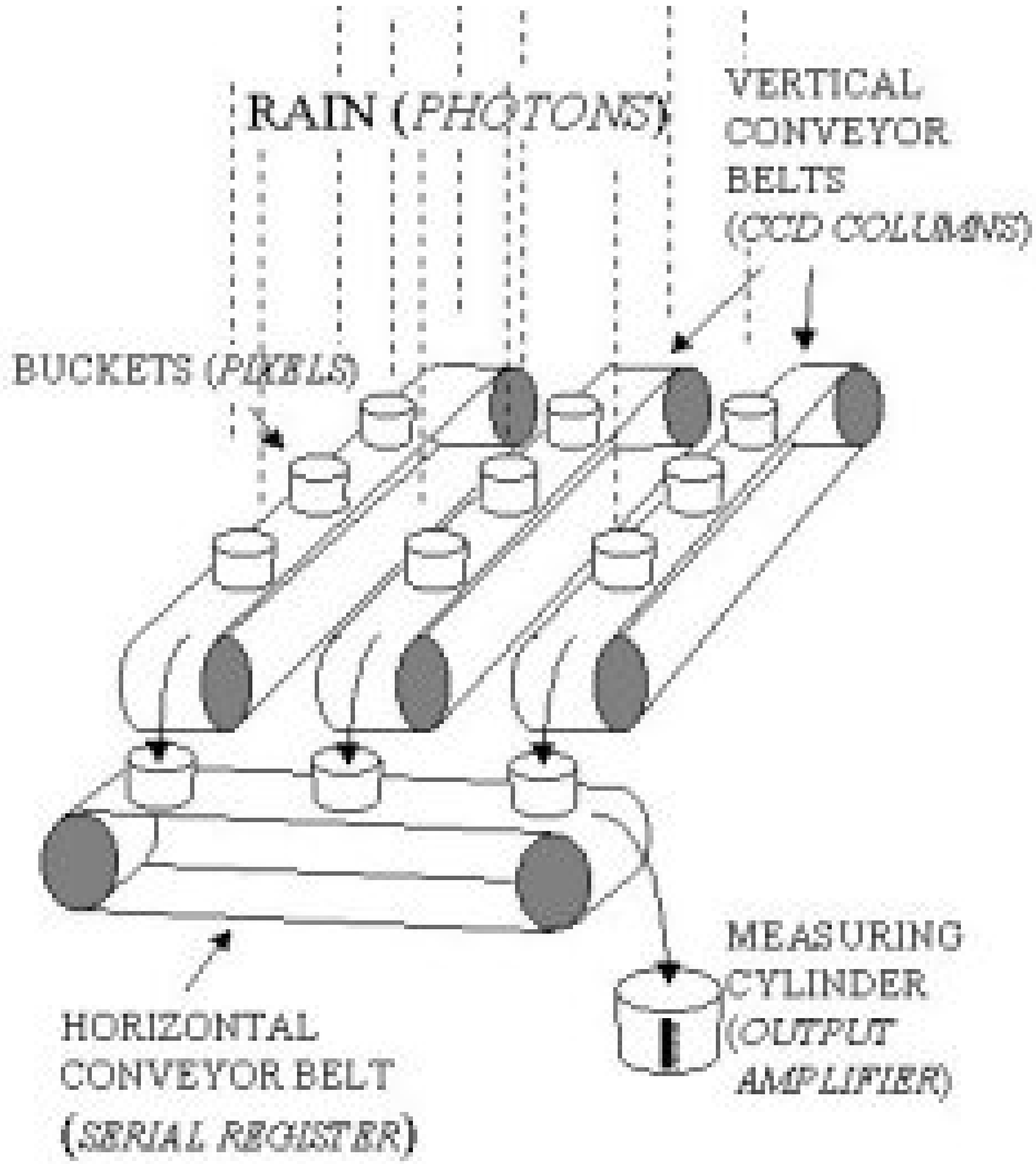


X-ray interacts in material to produce photoelectrons which are collected by applying a drift field

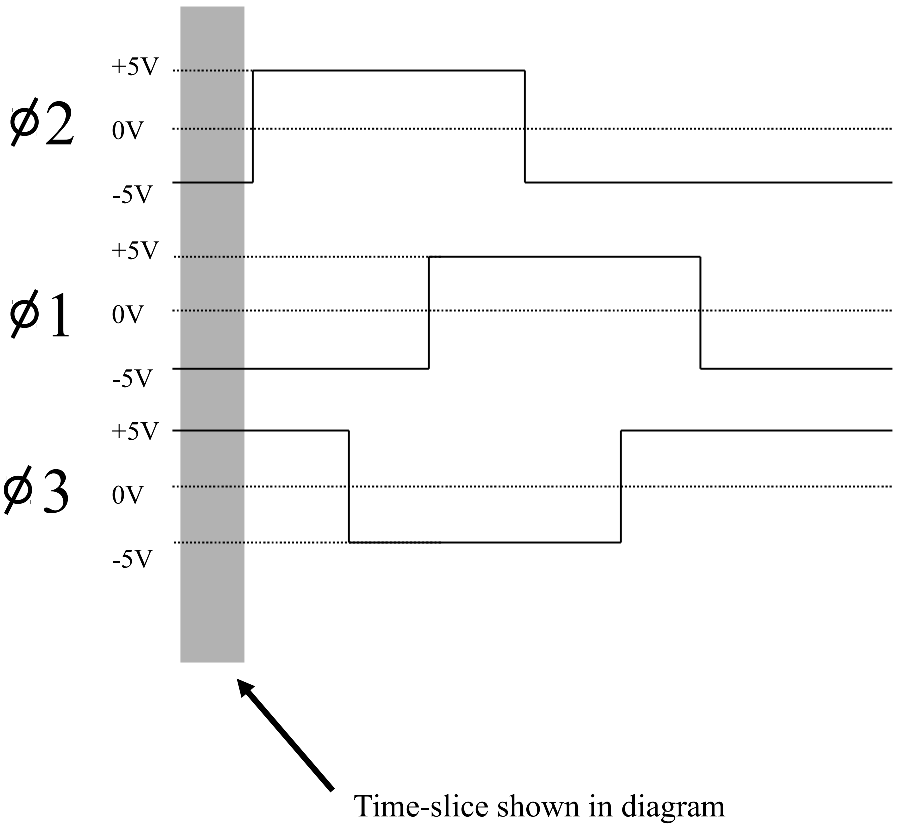
Charge Coupled Devices

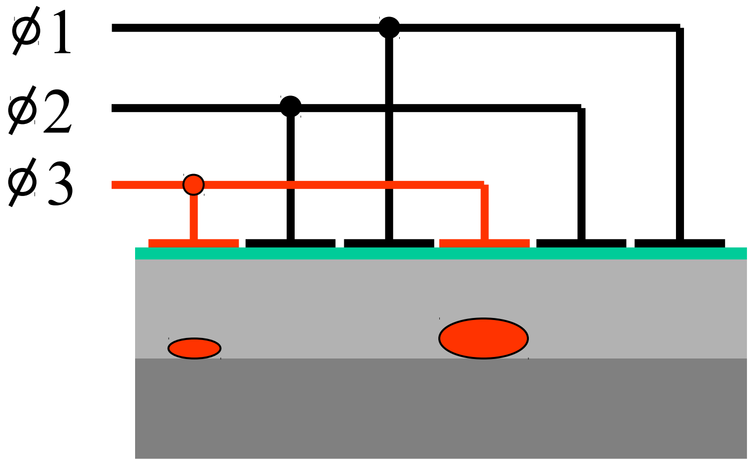


Charge Coupled Devices

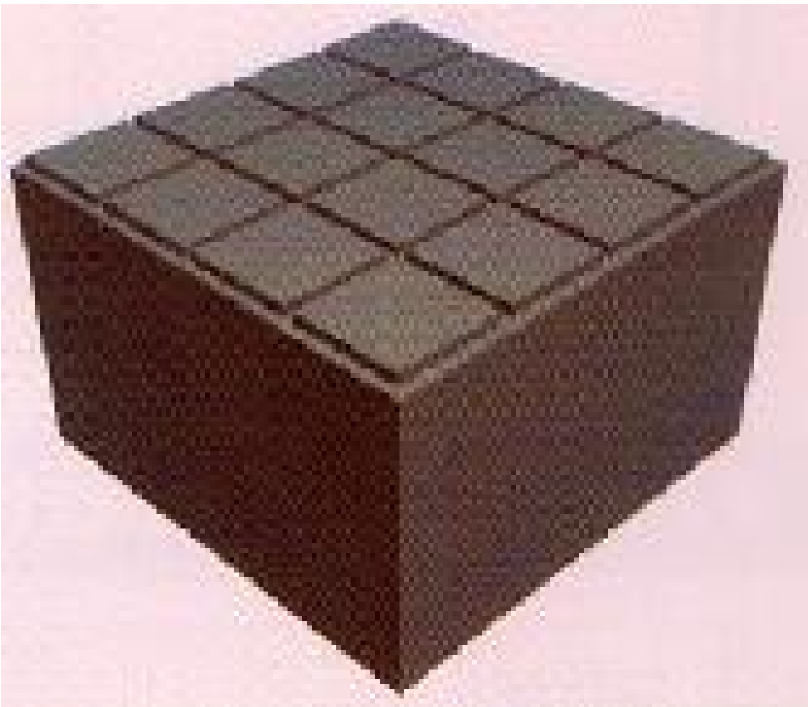


Charge Transfer in CCDs





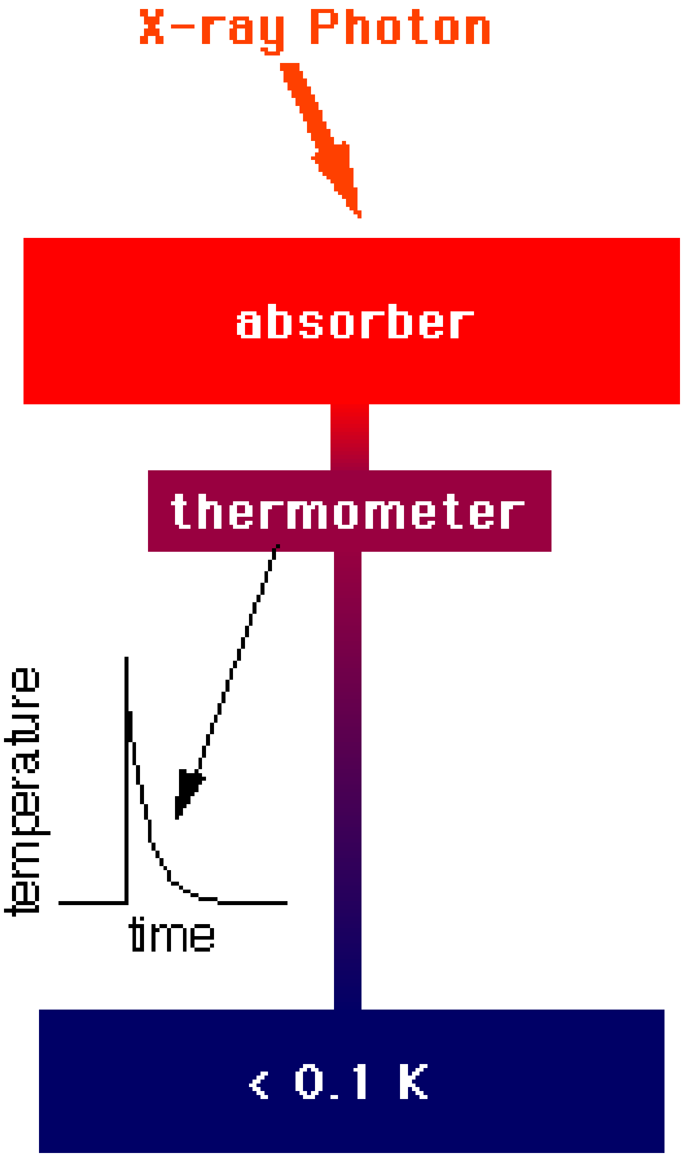
Pixelated Detectors



CCDs have small pixel sizes, good energy resolution, and a single readout electronics channel, but are slow, thin (< 300 microns), and only made in Si.

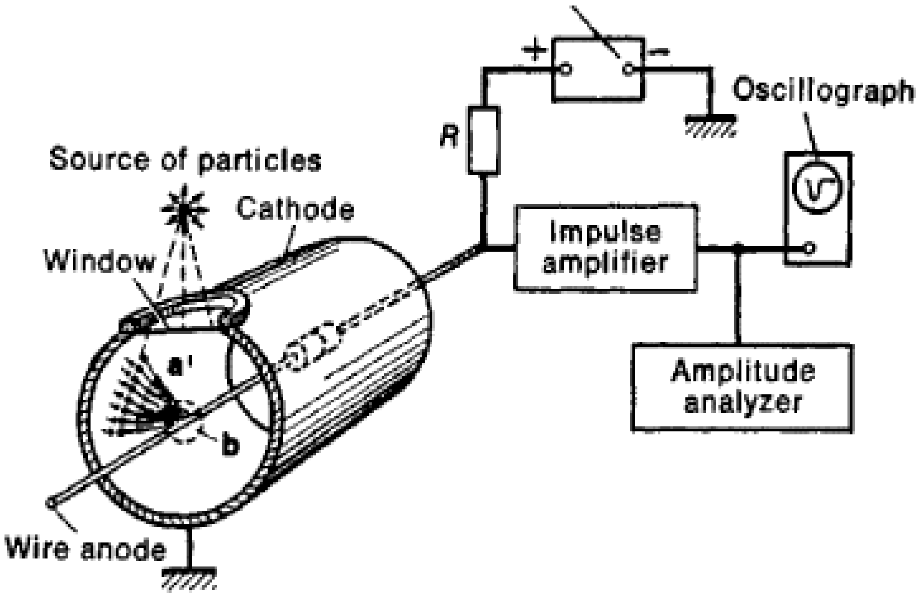
Pixelated detectors have larger pixel sizes, require many electronics channels, but are fast and can be made thick and of various materials – therefore can be efficient up to higher energies

Microcalorimeters

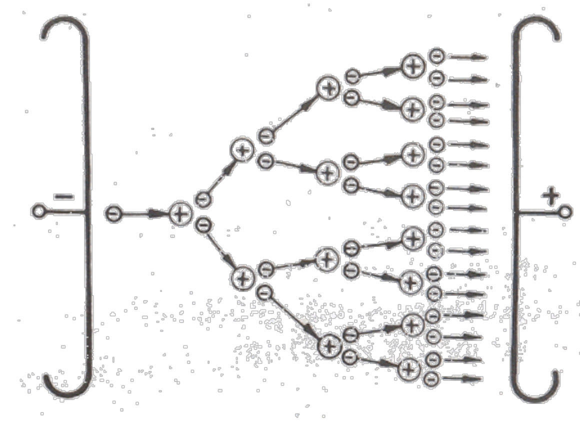


$\Delta E = 6$ eV
@ 6 keV

Proportional Counter

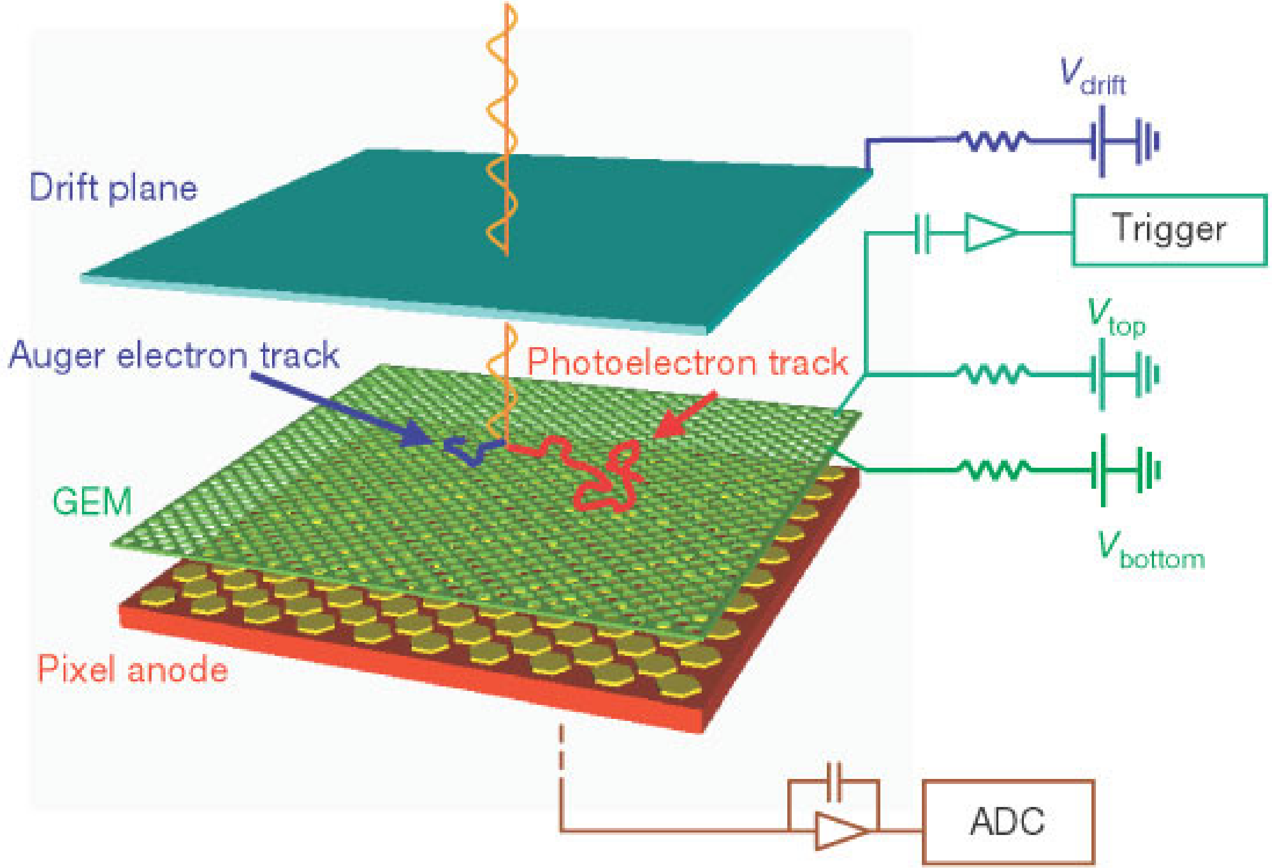


Gas fills volume



- X-ray enters counter, interacts with gas emitting photoelectrons which drift toward anode
- E field near anode is high, electrons are accelerated and ionized additional atoms, original charge is multiplied
- Output is one electrical pulse per interacting X-ray

Position Sensing



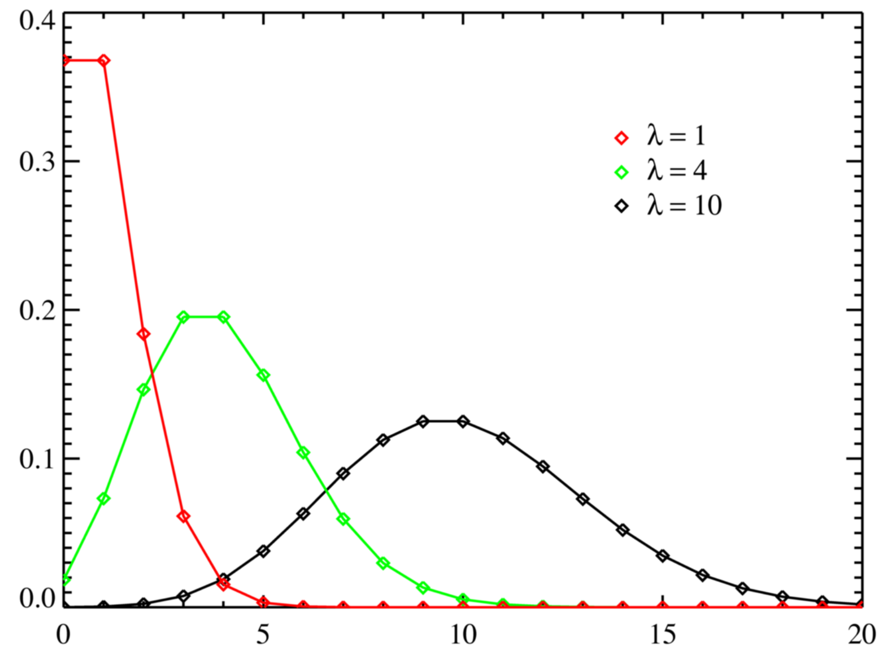
- Need to have drift E field which is parallel.
- Need segmented readout.
- Resolution is limited by diffusion of electron cloud.
- Time resolution is limited by drift time.

Detector Characteristics

- Sensitivity
- Quantum efficiency
- Energy resolution
- Time resolution
- Position resolution

Poisson Process

$$P(k \text{ events in interval}) = \frac{\lambda^k e^{-\lambda}}{k!}$$



- Detection of individual X-rays are random events described by a Poisson process.
- For an expected number of events λ, the Poisson distribution gives the probability of detecting *k* events.
- For large k, the Poisson distribution looks like a Gaussian distribution with mean = λ and standard deviation = sqrt(λ).
- X-ray and gamma-ray detectors are 'photon counting', there are always fluctuations in photon counts.

Source Counts

- Fluctuations in background signal:

$$N = S\,A\,t$$

- t is integration time
- S is source flux (counts cm^{-2} s^{-1})
- A is detector "effective" area

= geometric area × quantum efficiency × window transmission

- Can also measure flux in energy units, multiply photon flux by average photon energy.

Sensitivity

- Fluctuations in background signal:

$$\Delta N = \sqrt{t\left(B_1 + \Omega A B_2\right)}$$

- B_1 is particle background
- Ω is detector solid angle
- A is detector effective area
- $\Omega A B_2$ is rate of X-ray background
- t is integration time
- S is source flux (counts cm^{-2} s^{-1})

Sensitivity

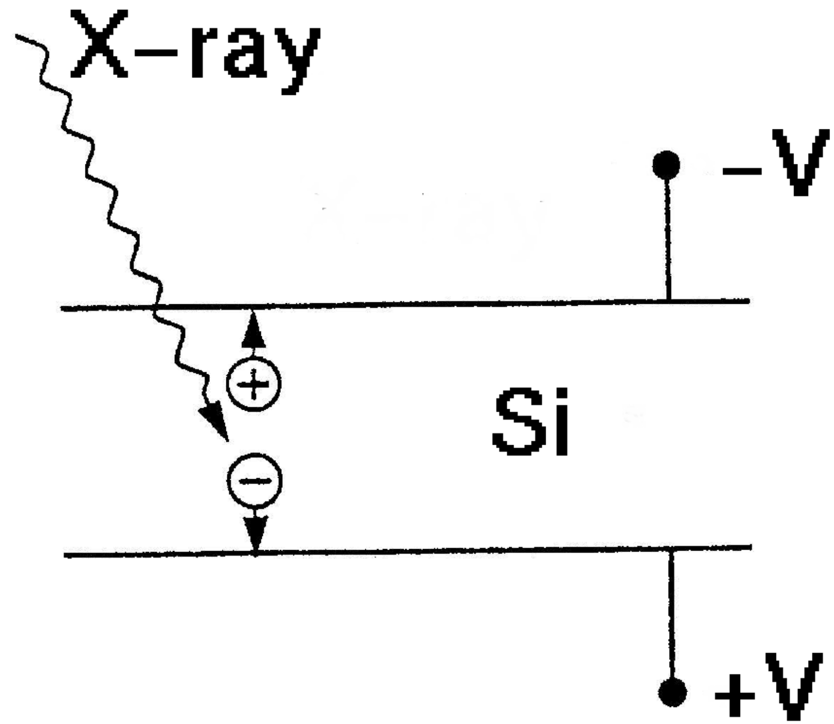
- Signal to noise ratio of source detection

$$\sigma_n = \frac{\text{signal}}{\text{noise}} = \frac{SAt}{\sqrt{B_1 t + \Omega A B_2 t}}$$

- Limiting sensitivity

$$S_{\min} = \sigma_n \sqrt{\frac{B_1 / A + \Omega B_2}{At}}$$

Energy Resolution



Generation of photoelectrons is also a random process and is subject to Poisson fluctuations.

Energy Resolution

Number of initial photoelectrons $N = E/w$, where E = energy of X-ray, w = average ionization energy (3.62 eV for Si, 21.5 eV for Xe)

Creation of photoelectrons is a random process, number fluctuates

Variance of N: $\sigma_N^2 = FN$, where F is the "Fano" factor, fluctuations are lower than expected from Poisson statistics (F = 0.17 for Ar, Xe)

Energy resolution (FWHM) is

$$\frac{\Delta E}{E} = 2.35 \frac{\sigma_N}{N} = 2.35 \sqrt{\frac{wF}{E}}$$

This is a fundamental limit. Energy resolution can be worse due to other factors, e.g. electronic noise, variations in amplification.

Energy Resolution

Energy resolution obeys same equation as for proportional counters, but average ionization energy is much smaller than for gases

Material	w (eV)	Fano factor	ΔE @ 6 keV (eV)
Ar	26.2	0.17	600-1200
Xe	21.5	0.17	600-1200
Si	3.62	0.115	120-250
Ge	2.96	0.13	112
CdTe	4.4	0.11	130-2000

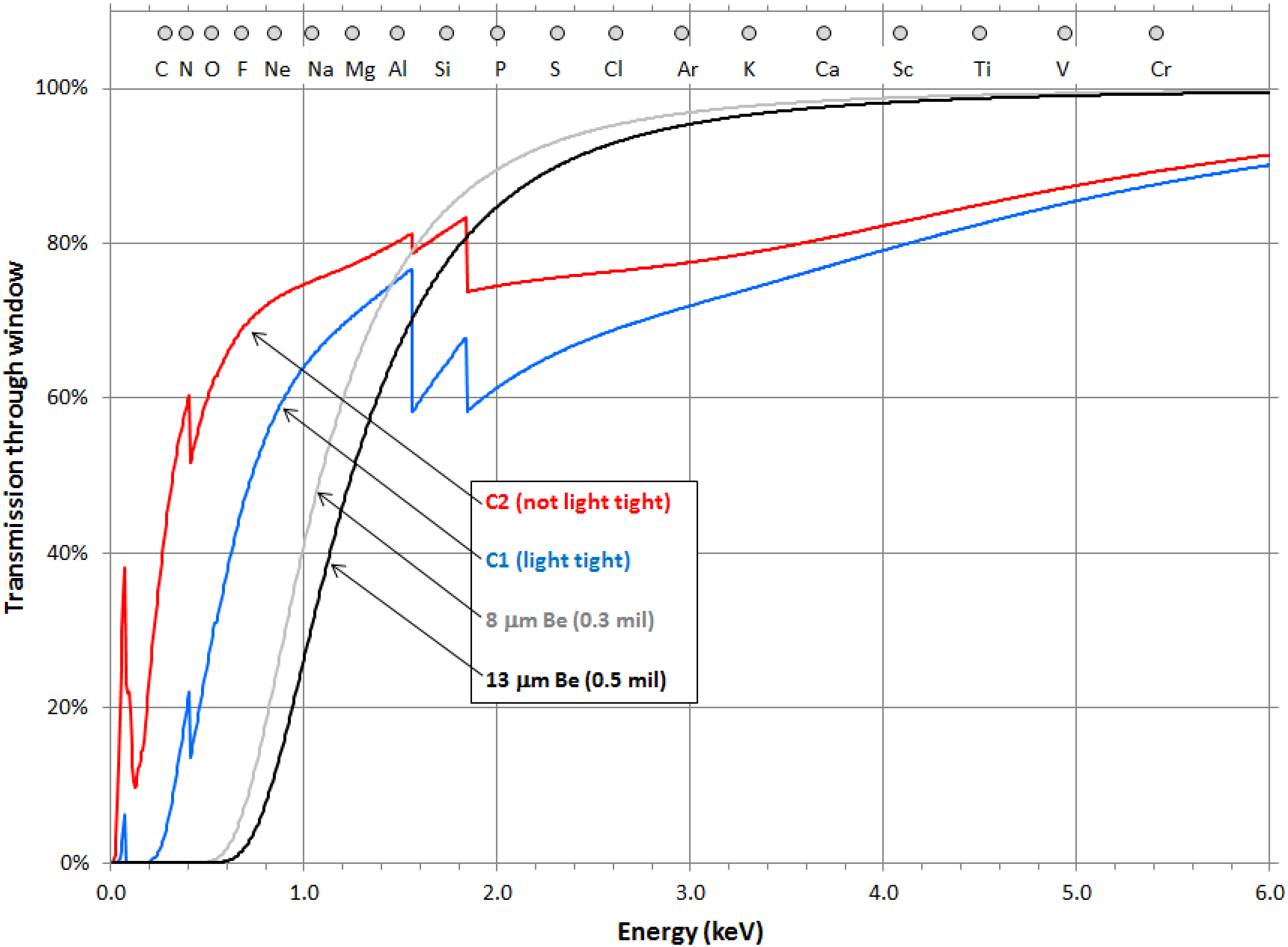
Quantum Efficiency

To be detected, X-ray must pass through window without being absorbed and then be absorbed in gas

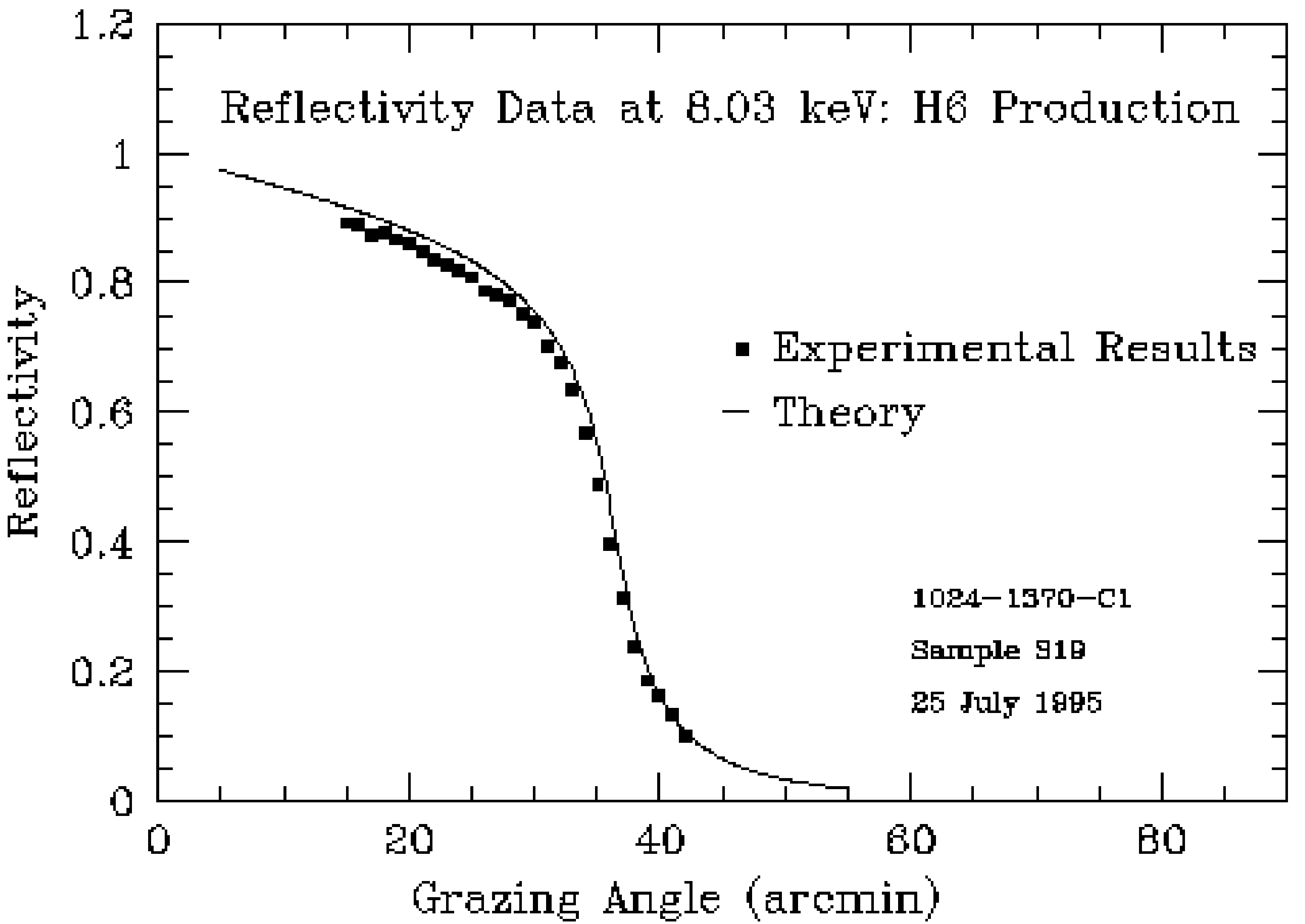
$$Q = T_w \exp\left(-\frac{t}{\lambda_w}\right)\left[1-\exp\left(-\frac{d}{\lambda_g}\right)\right]$$

T_w is geometric open fraction of window, t is window thickness, d is gas depth, λ's are absorption length for window/gas (energy dependent)

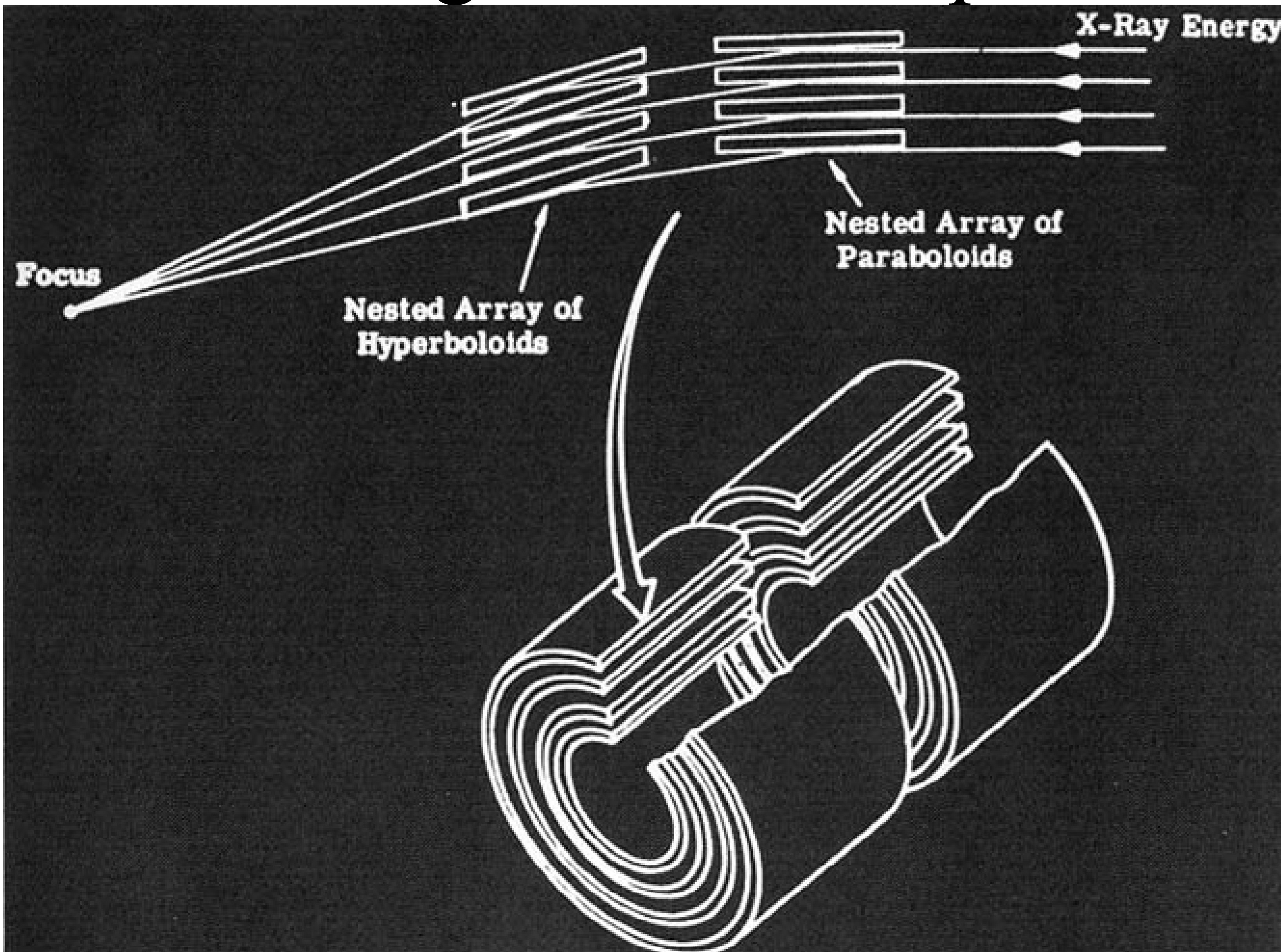
Efficiency versus Energy



X-Ray Reflectivity



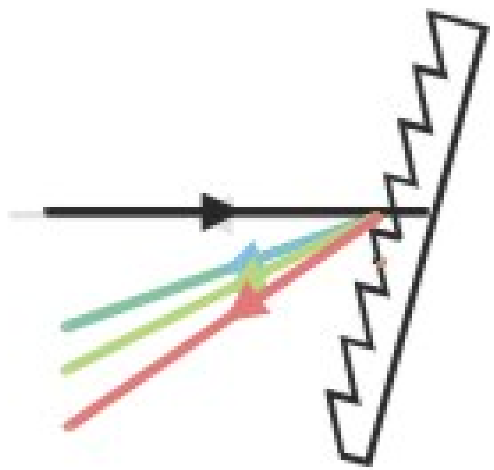
Grazing Incidence Optics

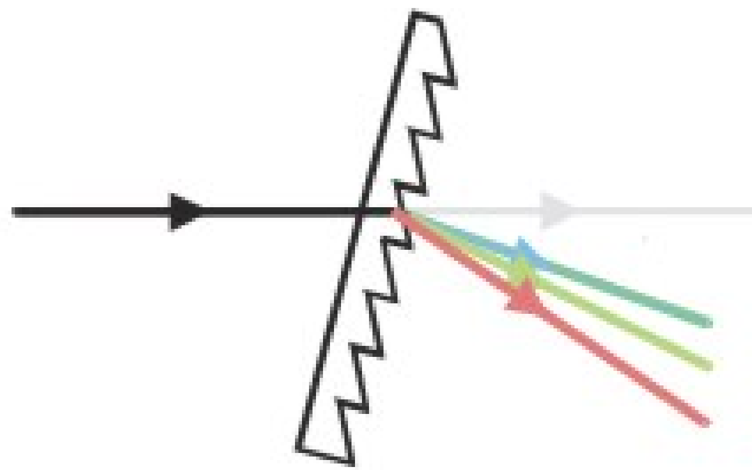


Scientific Gains from Imaging

- Increase S/N and thus sensitivity
  - Reduce source area and thus the associated background
- Allow more accurate background estimation
  - Take background events from the immediate vicinity of a source
- Enable the study of extended objects
  - Structures of SNR, clusters of galaxies, galaxies, diffuse emission, jets, …
- Minimize source confusion
  - E.g., source distribution in galaxies
- Provide precise positions of sources
  - Identify counterparts at other wavelengths

Gratings



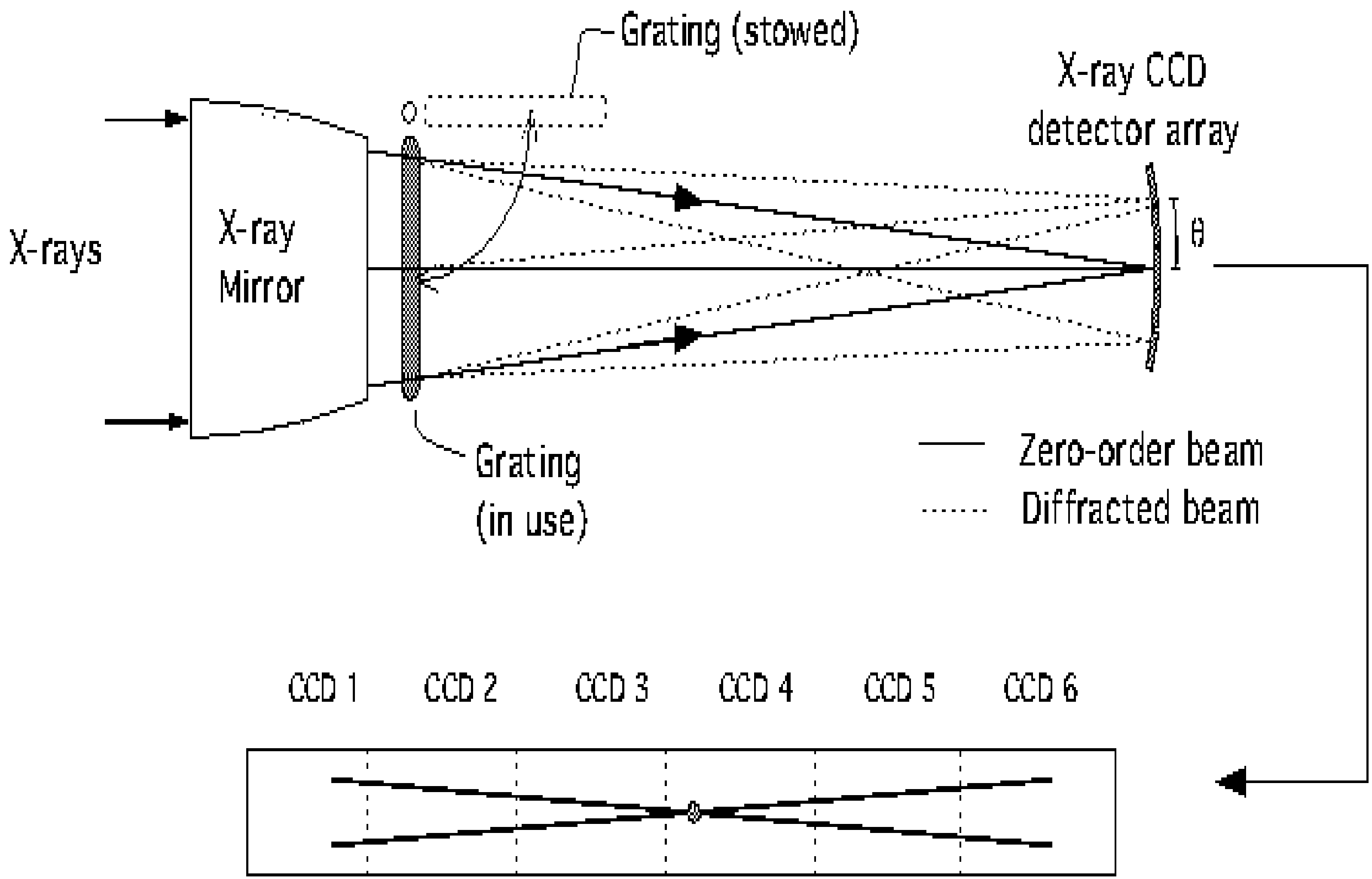


$$\sin\alpha + \sin\beta = -\frac{m\lambda}{d}$$

α = incidence angle, β = diffraction angle, λ = wavelength, m = diffraction order (1, 2, …), *d* = groove spacing

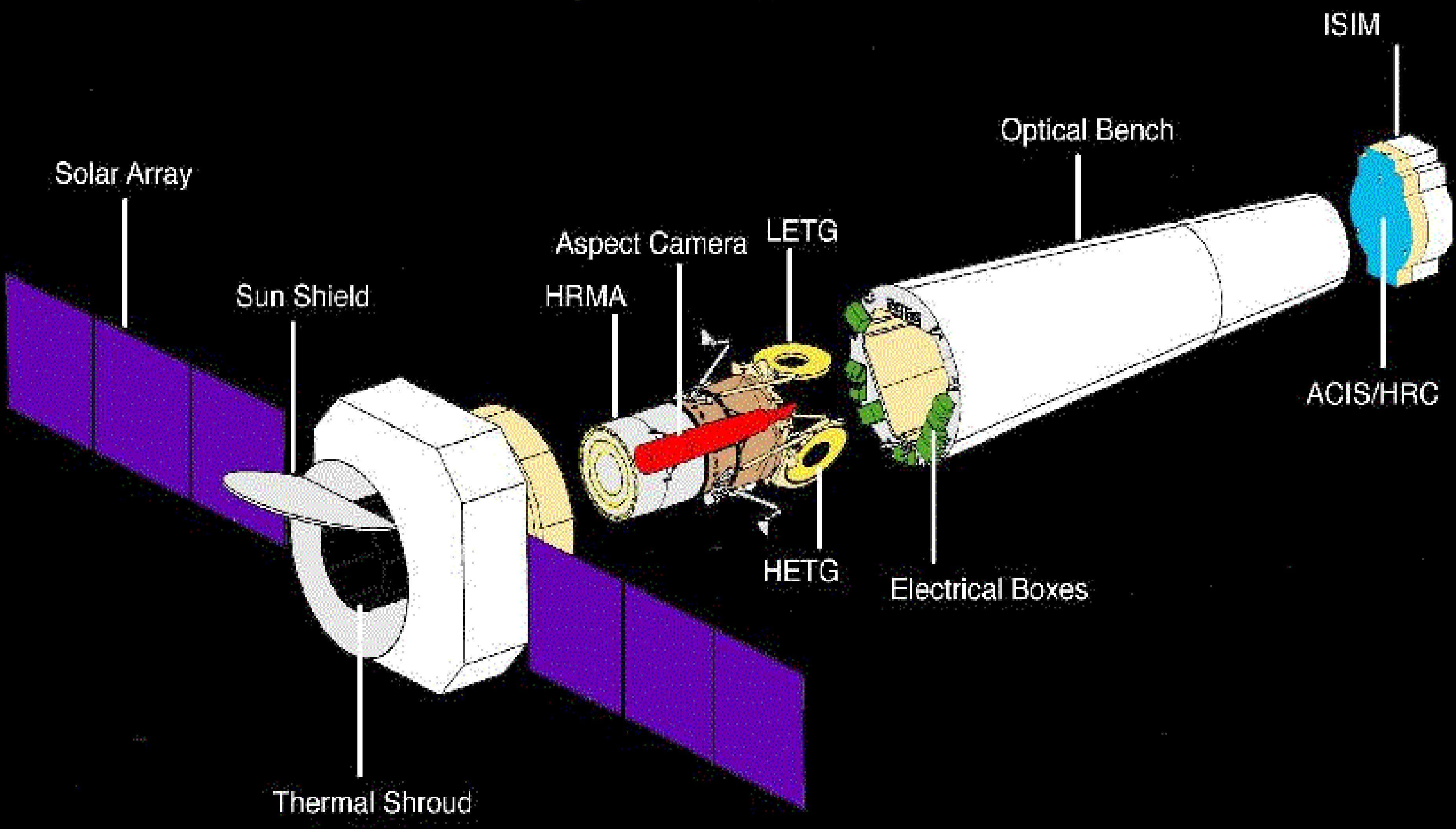
For X-ray diffraction need $d \sim 0.1 - 1$ μm

Gratings



Grating (stowed)
X-ray CCD
detector array
X-rays
X-ray
Mirror
θ
Grating
(in use)
Zero-order beam
Diffracted beam
CCD 1
CCD 2
CCD 3
CCD 4
CCD 5
CCD 6

Chandra


ISIM
Optical Bench
Solar Array
LETG
Aspect Camera
Sun Shield
HRMA
ACIS/HRC
HETG
Electrical Boxes
Thermal Shroud

Hands on Data Analysis

- Next Wednesday, we will do a hands on data analysis exercise.
- Please look at the lecture for 8/31 on "Hands on data analysis" and try downloading and installing the software over the next few days.
- Matt will be available in 607 VAN to help.

- Note that home work #1 is on the web site and is due on Wednesday, 8/31.