Detecting high energy photons

- Interactions of photons with matter
- Properties of detectors (with examples)

Interactions of high energy photons with matter

- Cross section/attenution length/optical depth
- Photoelectric absorption
- Compton scattering
- Electron-positron pair production

Cross section

Cross-section per atom (or per electron) = σ

Attenuation length $l = 1/n\sigma$, where n is density of atoms

Attenuation of beam $I = I_0 \exp(-x/l)$

For materials, we often use the attenuation coefficient, μ, which is the cross second per mass (cm^2/g)

Then attenuation length $l = 1/n\sigma = 1/\mu\rho$, where ρ is density

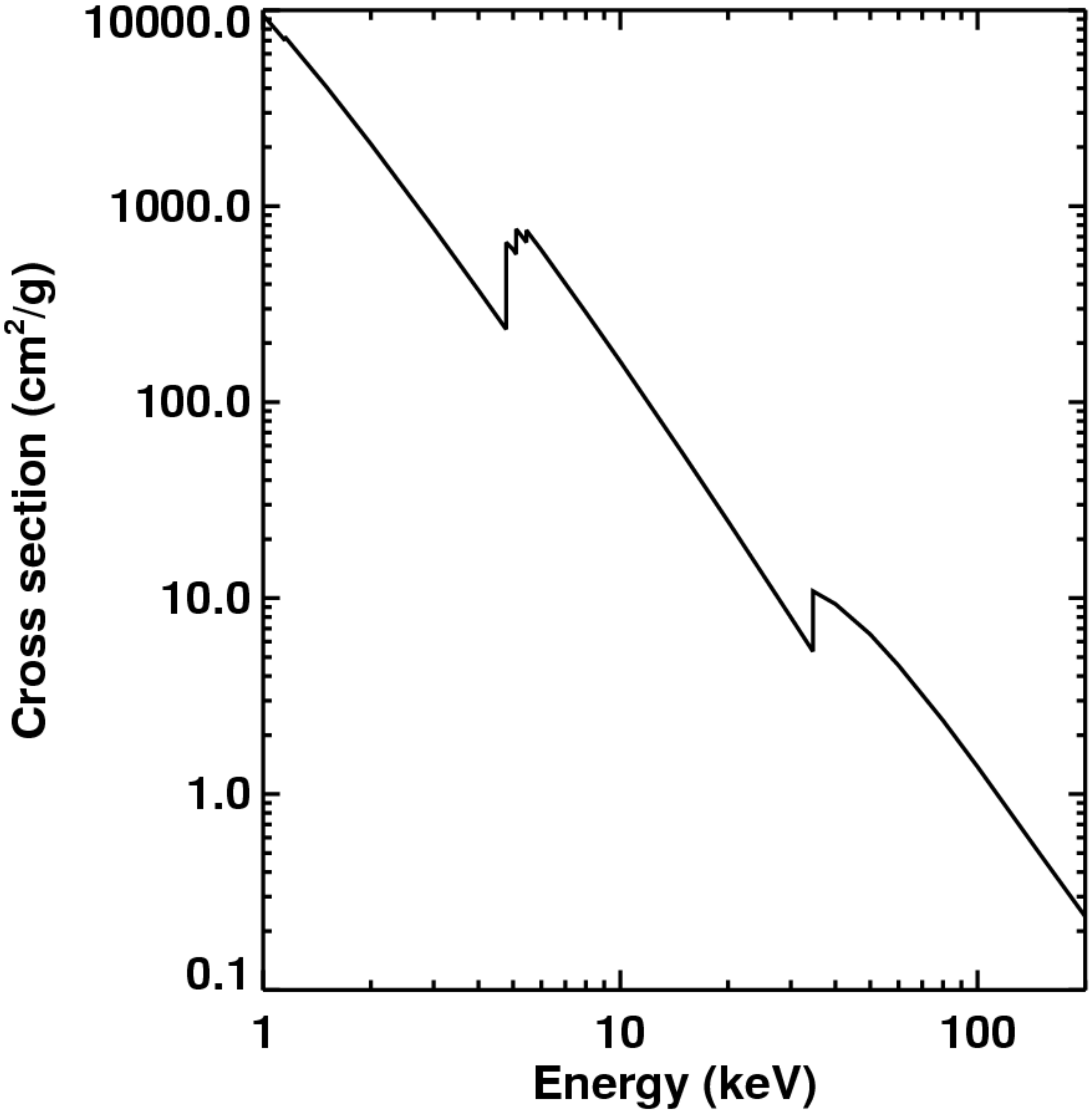
Useful web site for photon cross sections is:

http://physics.nist.gov/PhysRefData/Xcom/Text/XCOM.html

Three interactions

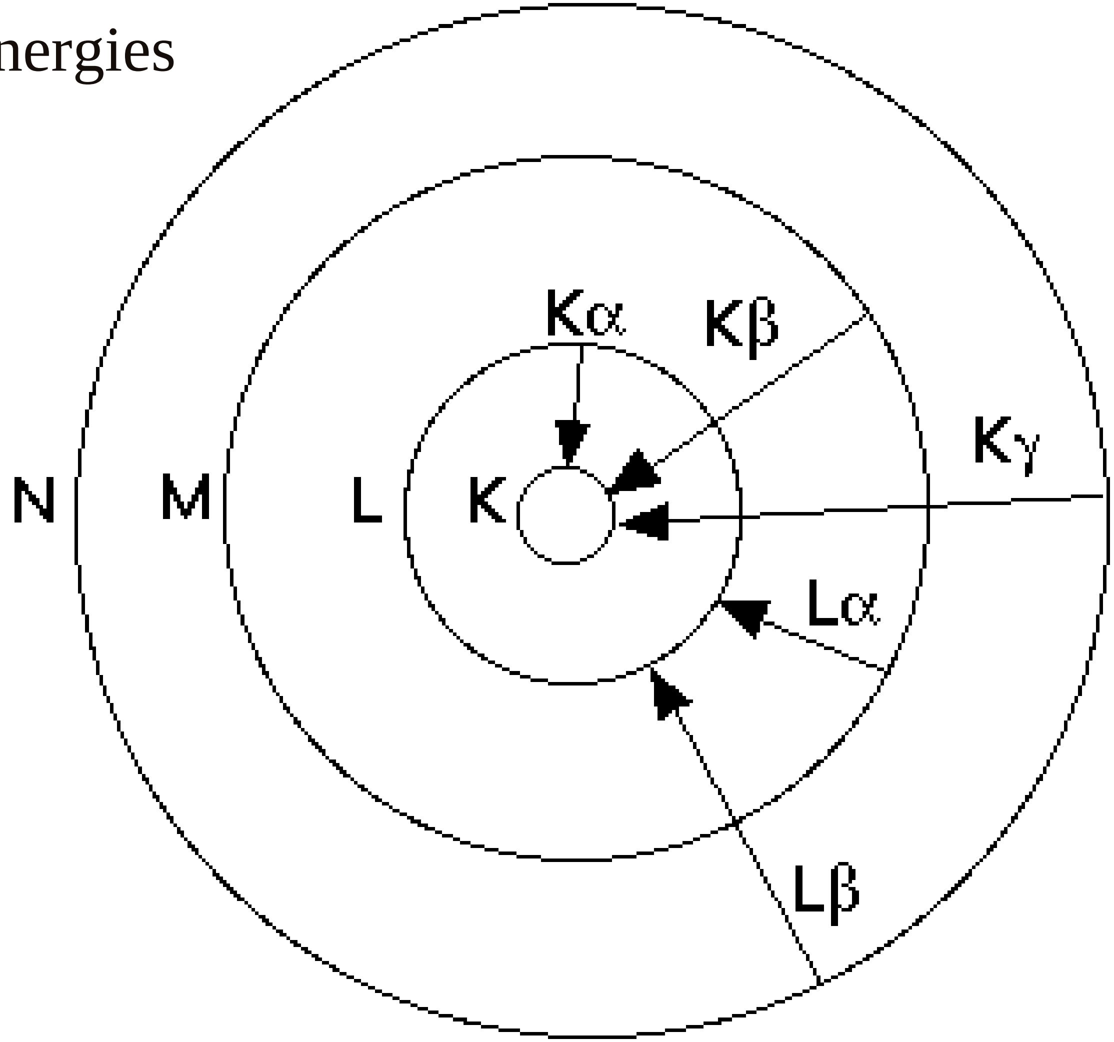
- Photoelectric absorption
  - Photon is absorbed by atom
  - Electron is excited or ejected
- Compton scattering
  - Photon scatters off an electron
- Pair production
  - Photon interacts in electric field of nucleus and produces an e^+ e^- pair

Photoelectric cross section in Xe



Photoelectric absorption

"Edges" occur at the characteristic electronic transition energies



When in emission, elements produce characteristic lines at these energies

Photoelectric absorption

The photon electric cross-section scales with Z^5

This means that high-Z detectors are more efficient at high energies.

Above the highest edge, the cross-section scales roughly as $(\text{energy})^{-3}$.

This means that photo-absorption detectors rapidly become inefficient at high energies.

Interstellar absorption

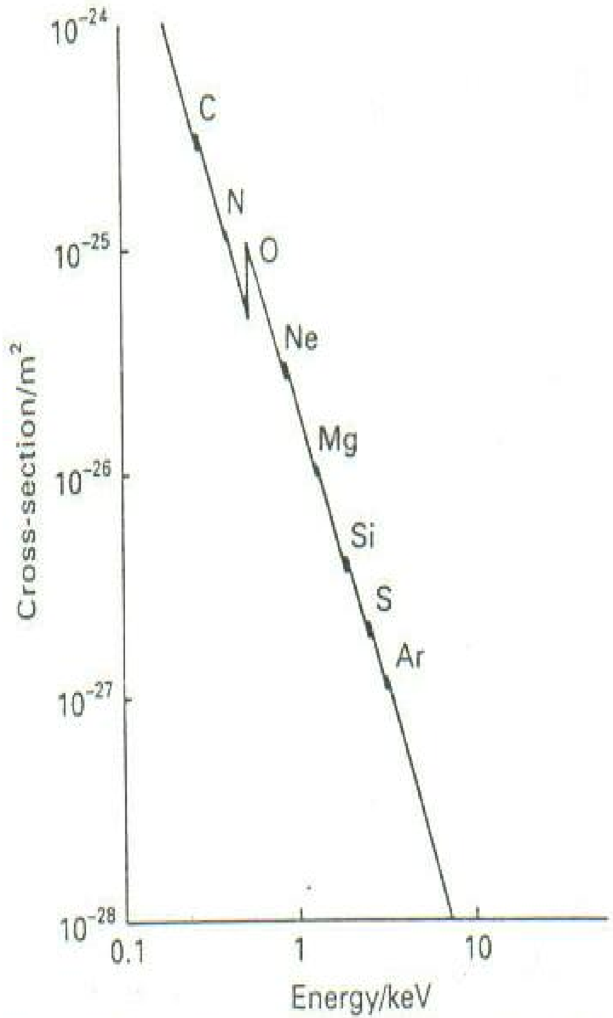
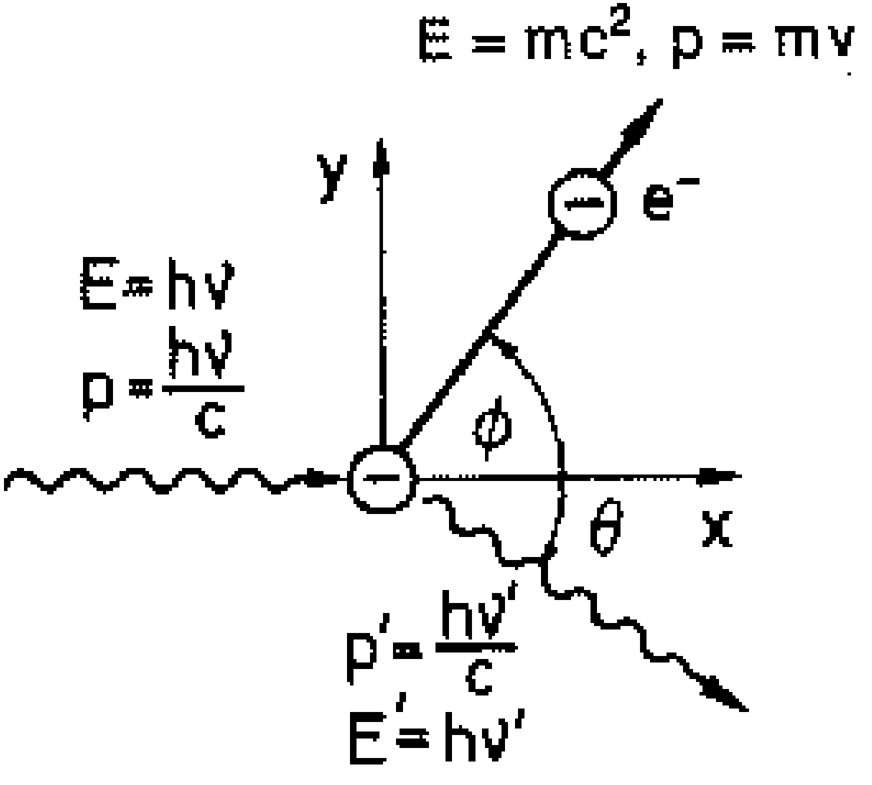


Figure 4.2. The absorption cross-section for interstellar gas with typical cosmic abundances of the chemical elements (see Section 9.2.1). The discontinuities in the absorption cross-section as a function of energy are associated with the K-shell absorption edges of the elements indicated. The optical depth of the medium is given $\tau = \int \sigma_X(E) N_H \, dl$ where N_H is the number density of hydrogen atoms. (After R. H. Brown and R. J. Gould (1970). *Phys. Rev.*, **D1**, 2252.)

Compton scattering



$$E' = E\left[1 + \frac{E}{mc^2}\left(1 - \cos\theta\right)\right]^{-1}$$

Compton scattering

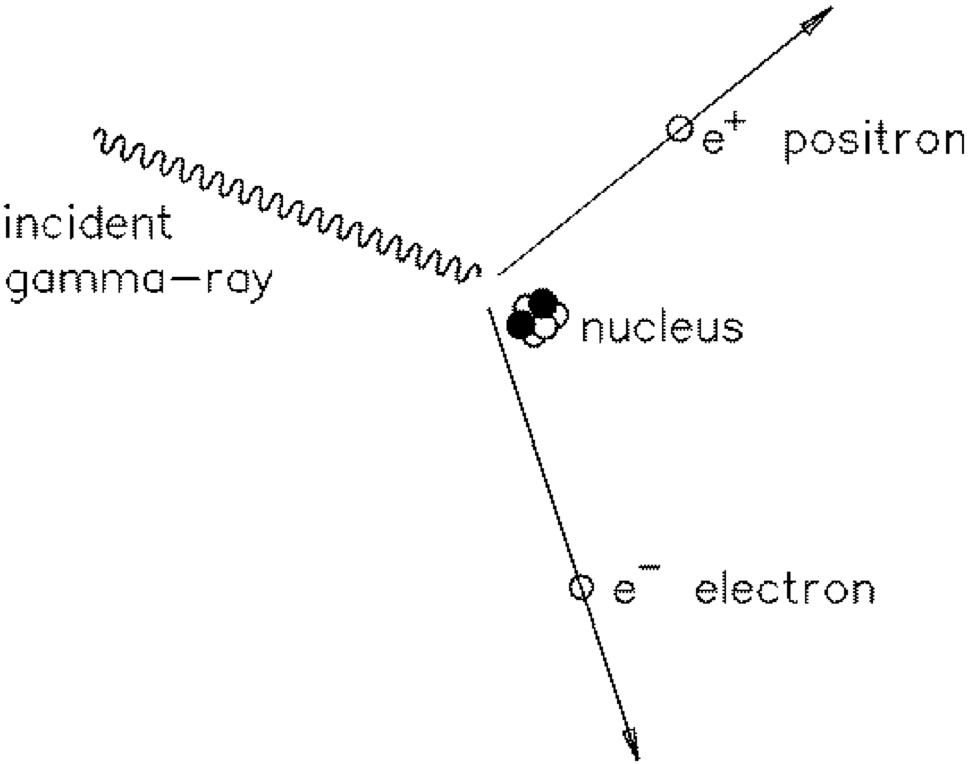
$$E \ll mc^2 \Rightarrow \sigma = \sigma_T = 6.653 \times 10^{-29} m^2$$

$$E \gg mc^2 \Rightarrow \sigma = \frac{3}{8} \sigma_T \frac{E}{mc^2} \ln\left(\frac{2E}{mc^2} + \frac{1}{2} \right)$$

For an electron at rest, the photon loses energy.

A moving electron can increase the photon energy. This is "inverse-Compton" scattering.

Pair Production

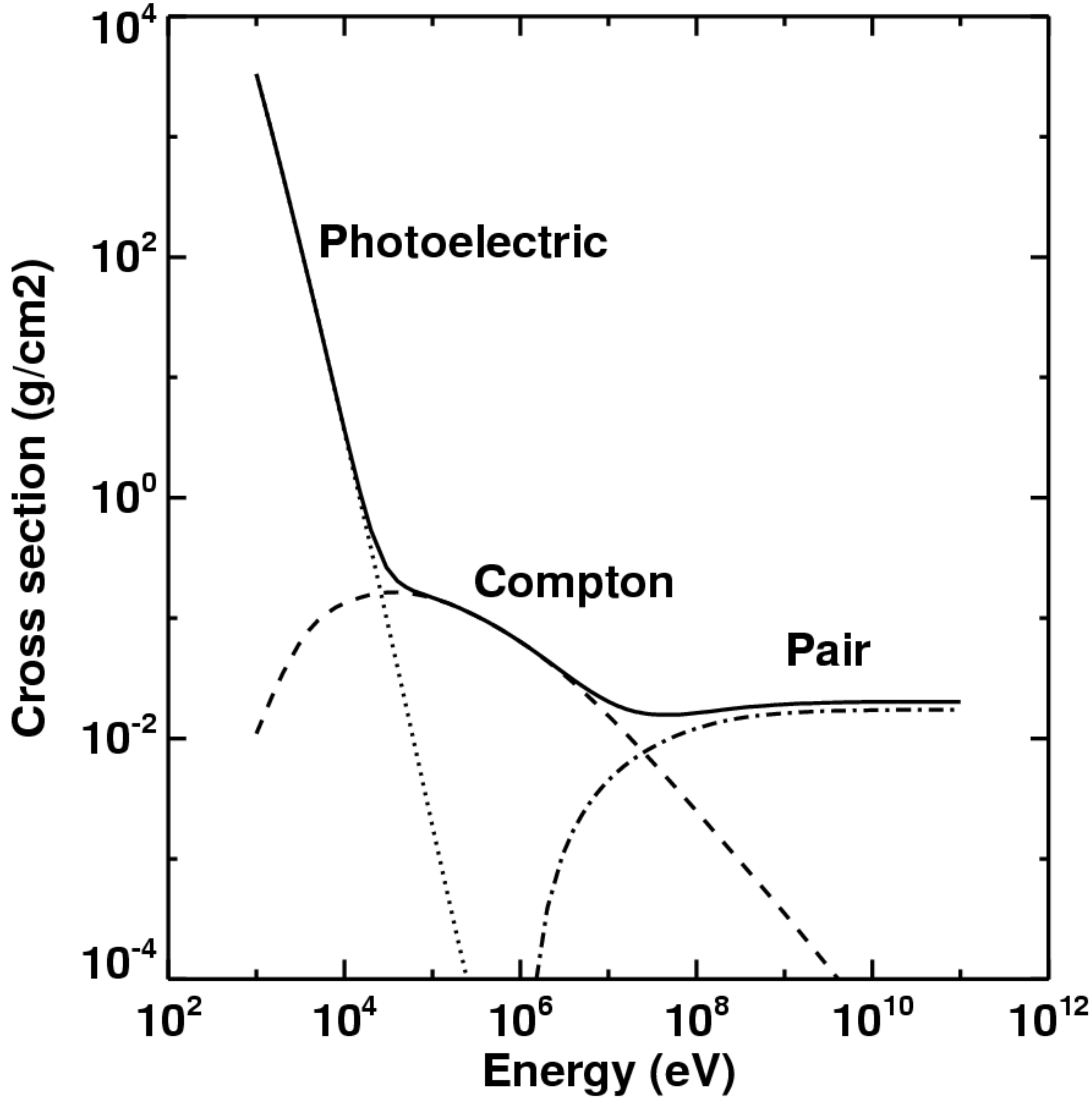


Nucleus is needed for process to converse momentum and energy

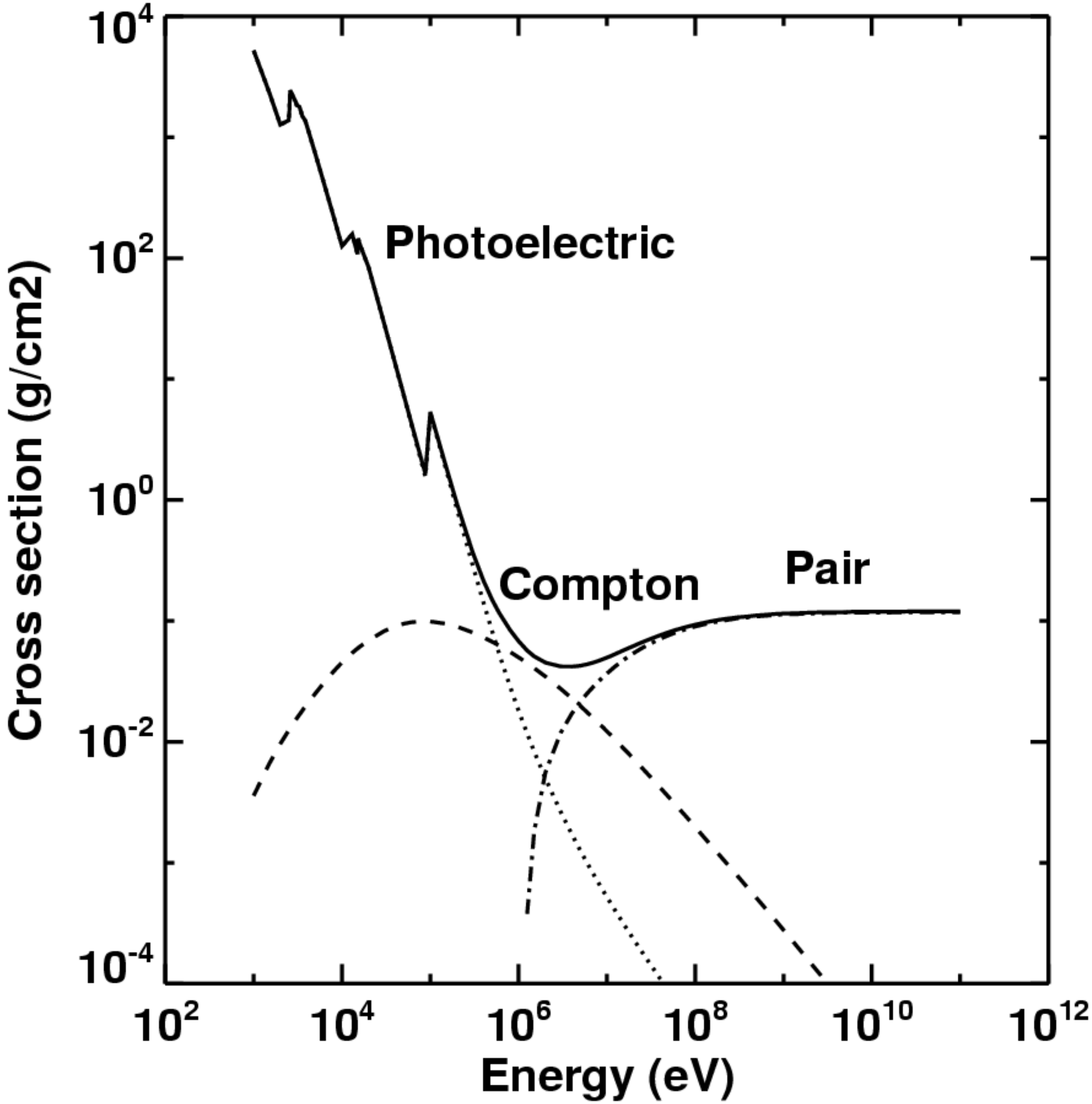
$$\sigma \propto Z^2$$

Only process with cross section which never decreases with energy, dominates at high energies

Photon Cross Sections in Nitrogen



Photon Cross Sections in Lead



Detection of X-Rays

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

Detector Characteristics

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

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

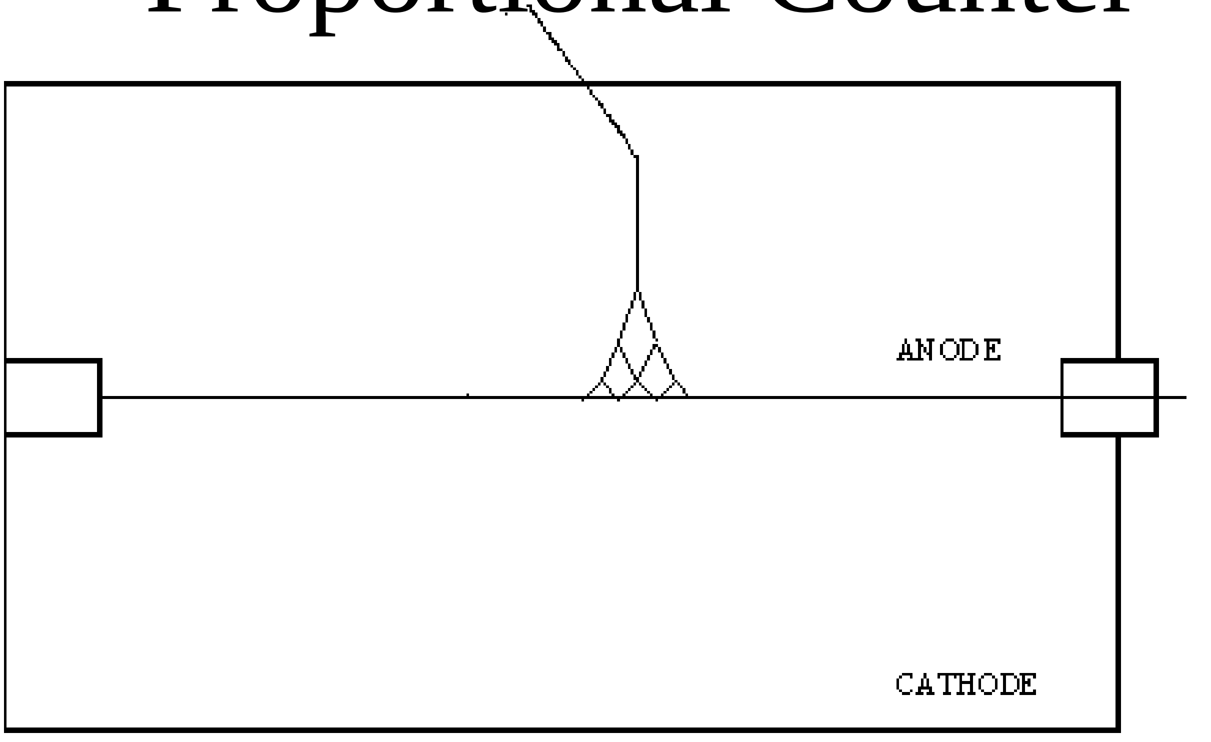
- Signal to noise ratio of source detection

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

- Limiting sensitivity

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

Proportional Counter



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

Energy Resolution

Number of initial photoelectrons $N = E/w$, where E = energy of X-ray, w = average ionization energy (26.2 eV for Ar, 21.5 eV for Xe)

Creation of photoelectrons is a random process, number fluctuates

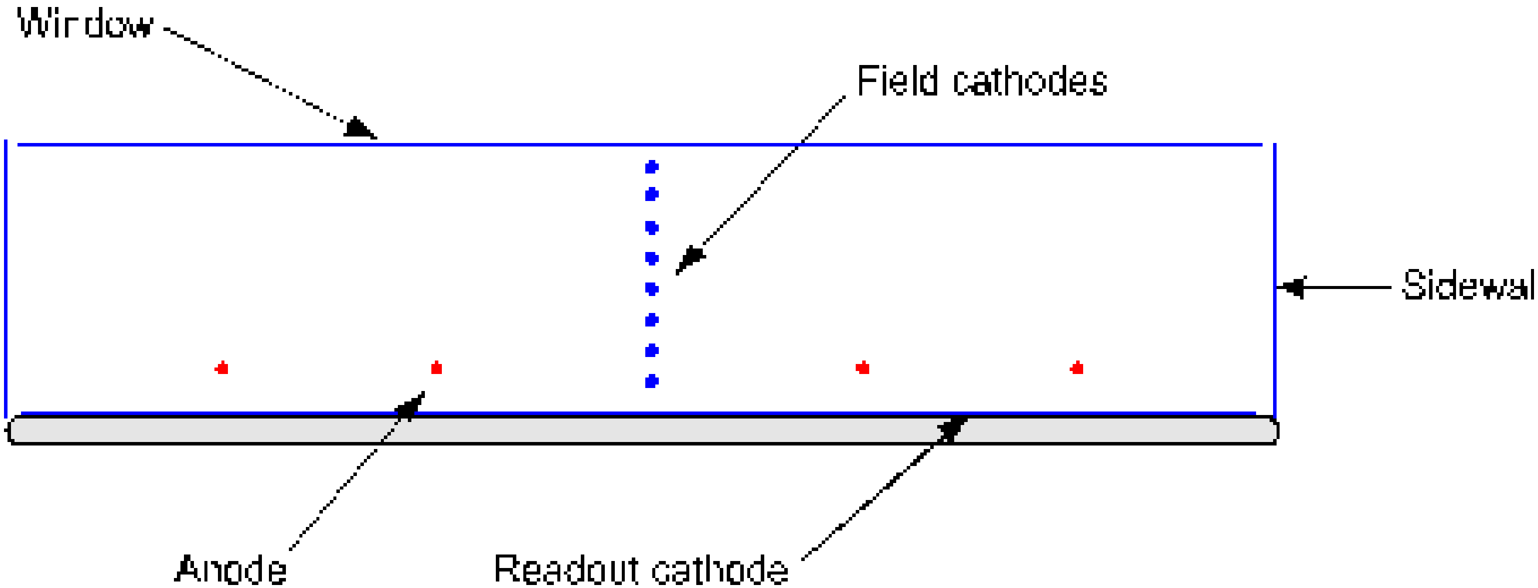
Variance of N: $\sigma_N^2 = FN$, where F is the “Fano” factor, fluctuations are lower than expected from Poisson statistics (F = 0.17 for Ar, Xe)

Energy resolution (FWHM) is

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

Energy resolution is usually worse because of fluctuations in multiplication

Position Sensing



Need to have drift E field which is parallel

Readout anodes or cathodes are segmemted or crossed wires are used

Resolution is limited by diffusion of electron cloud

Time resolution is limited by drift time

SXRP Proportional Counter

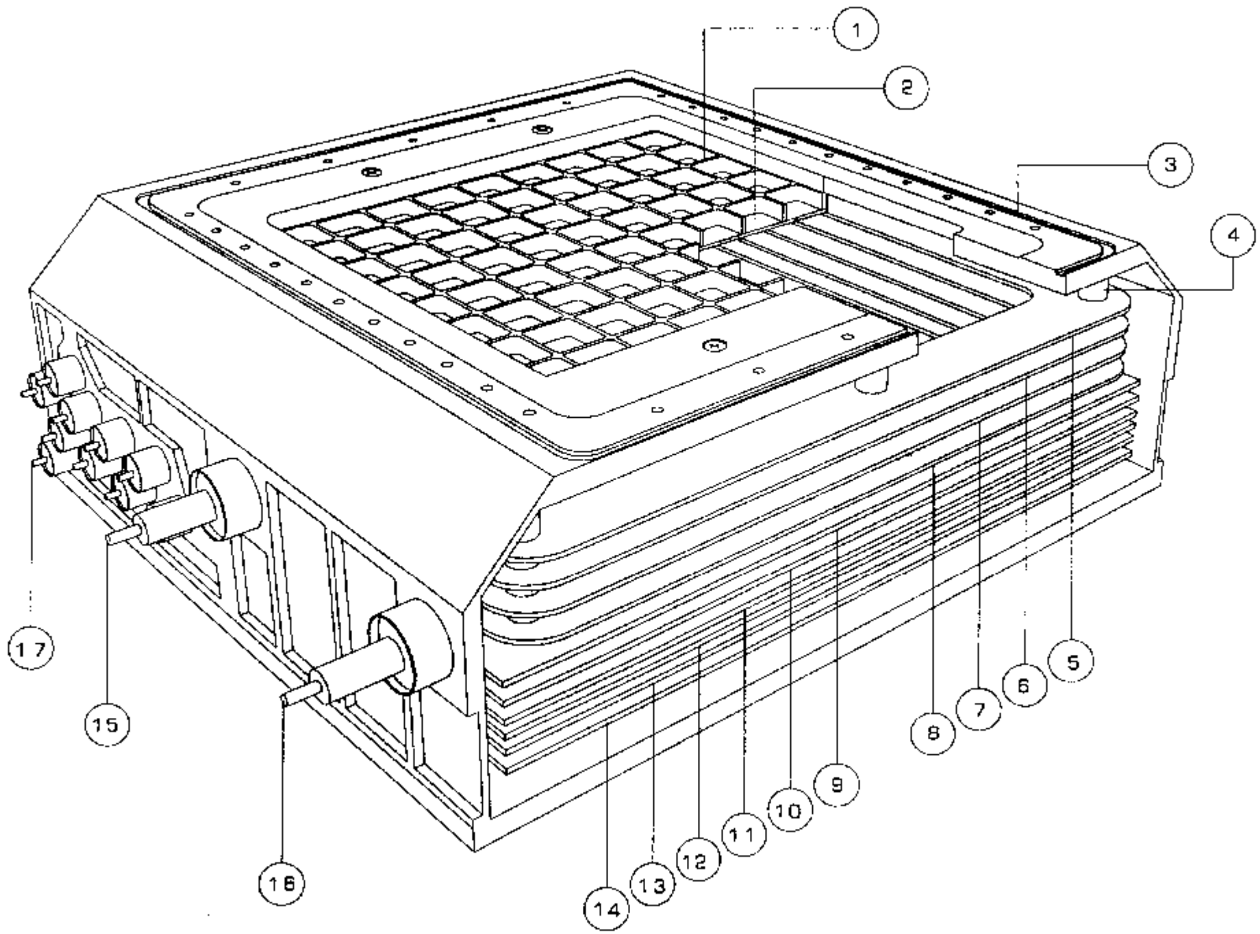


Fig. 2. Drawing of one of the two high-energy proportional counters. The numbers label the following components: (1) Titanium support structure; (2) 150 μm Beryllium window; (3) O-ring groove to allow evacuation of the front part of the detector for calibration purposes; (4) Vespel frame spacers; (5–8) Aluminium field forming rings; (9) cathode alumina wire frame (50 μm diameter gold plated tungsten wire having a pitch of 0.85 mm); (10) anode alumina wire frame (20 μm diameter gold plated tungsten wire having a pitch of 2.54 mm); (11) Plane W&S cathode frame (electroplated copper on kapton); (12) cathode alumina wire frame to prevent charge build-up on the anticoincidence region; (13) anti-anode alumina wire frame (as the anode one); (14) bottom alumina cathode wire frame; (15–16) high-voltage feedthroughs; (17) low-voltage feedthroughs (for the cathode).

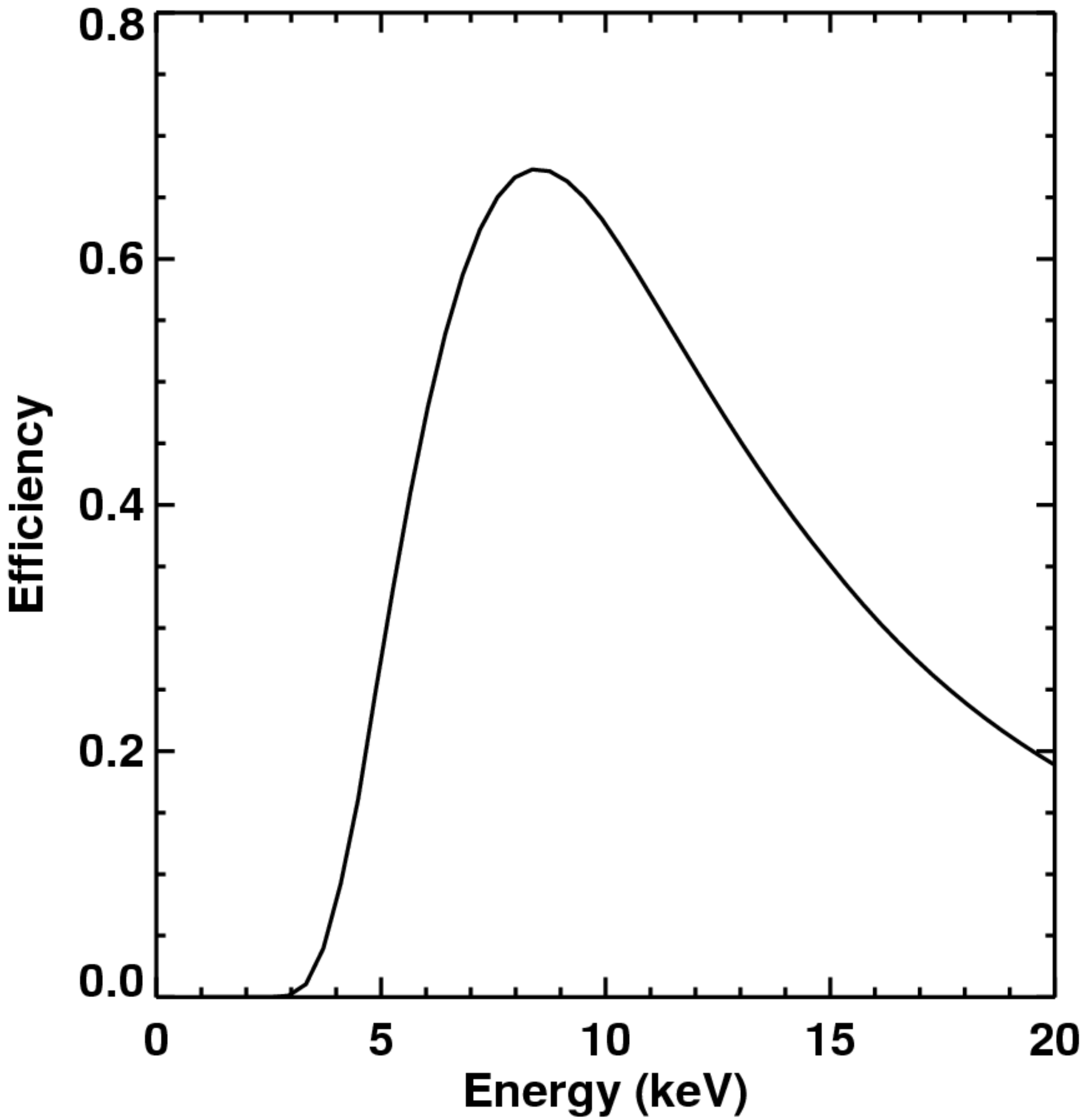
Quantum Efficiency

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

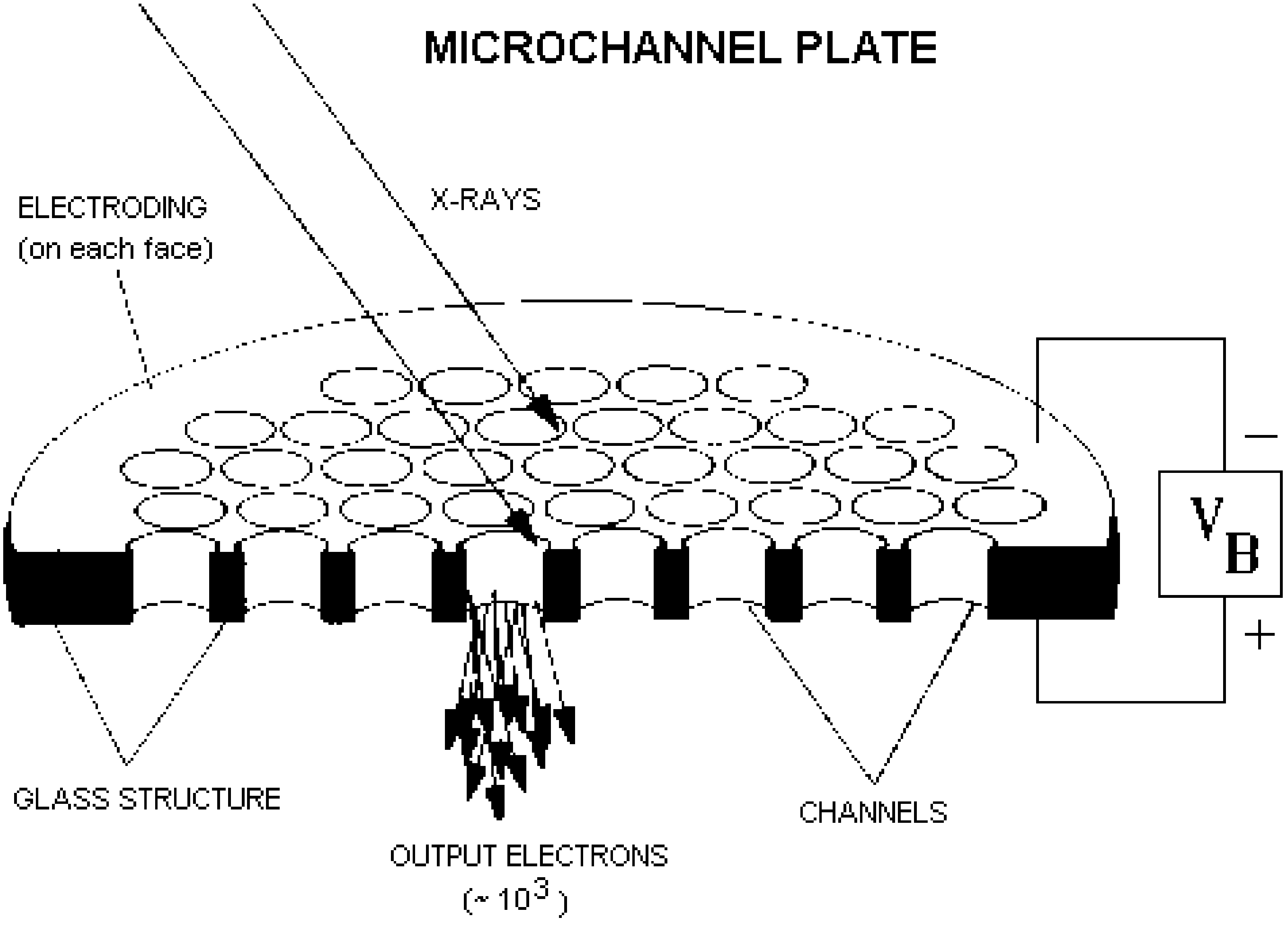
$$Q = T_w \exp\left(-\frac{t}{\lambda_w}\right)\left[1 - \exp\left(-\frac{d}{\lambda_g}\right)\right]$$

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)

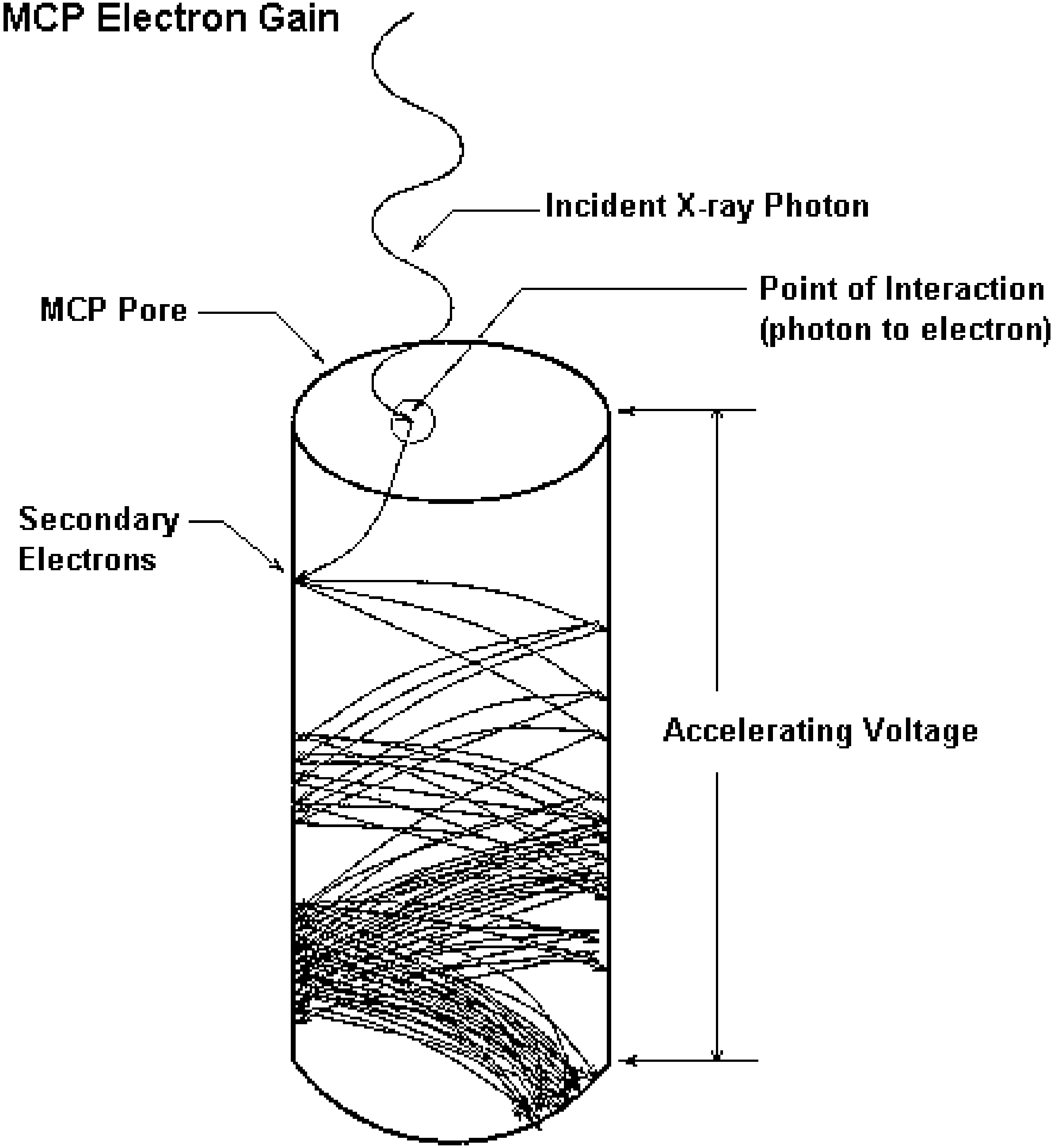
Efficiency versus Energy



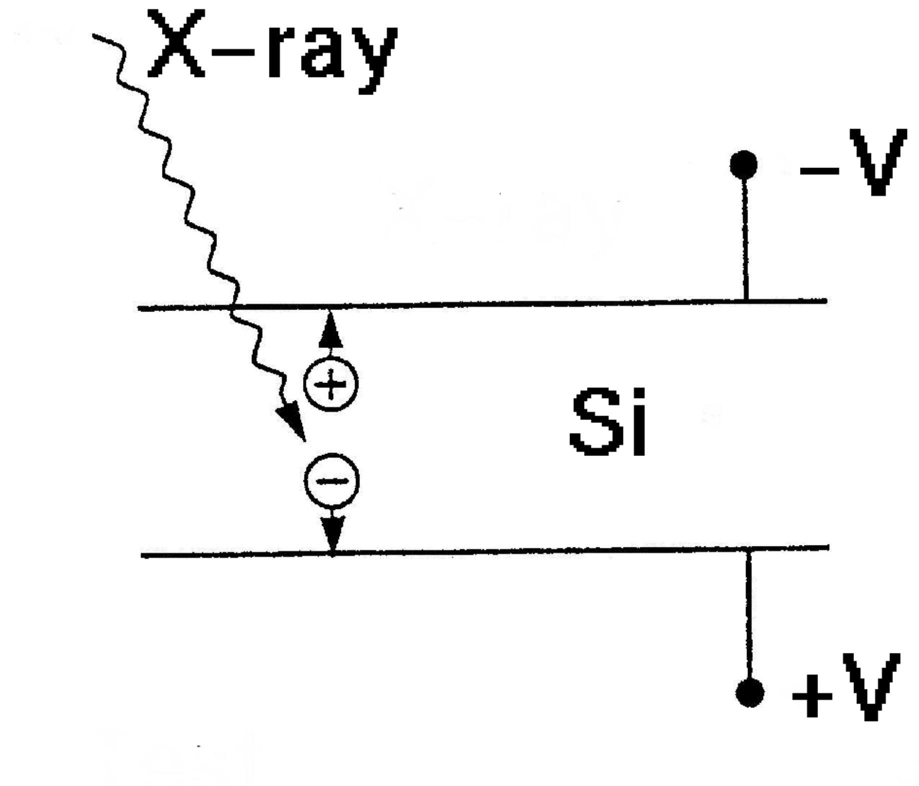
Microchannel Plates



MCP Electron Gain

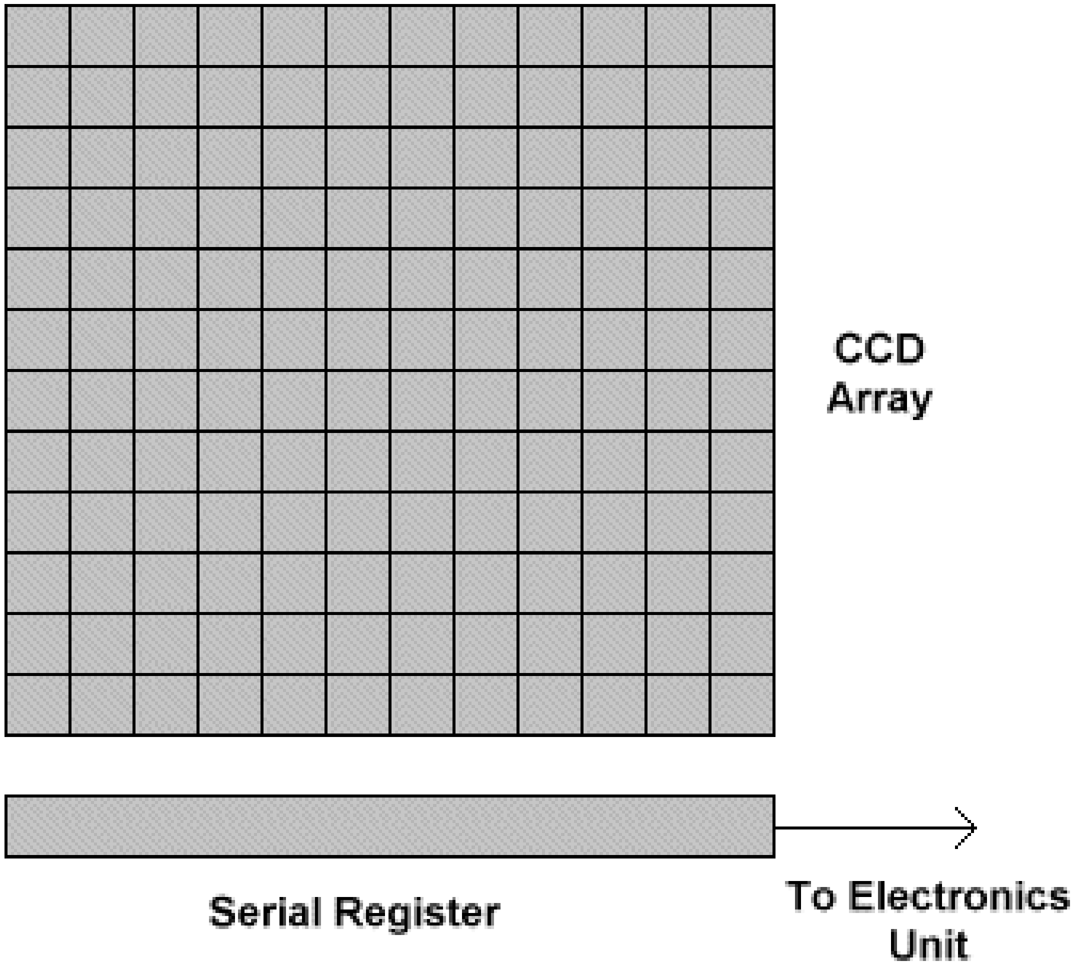


Solid State X-ray Detectors

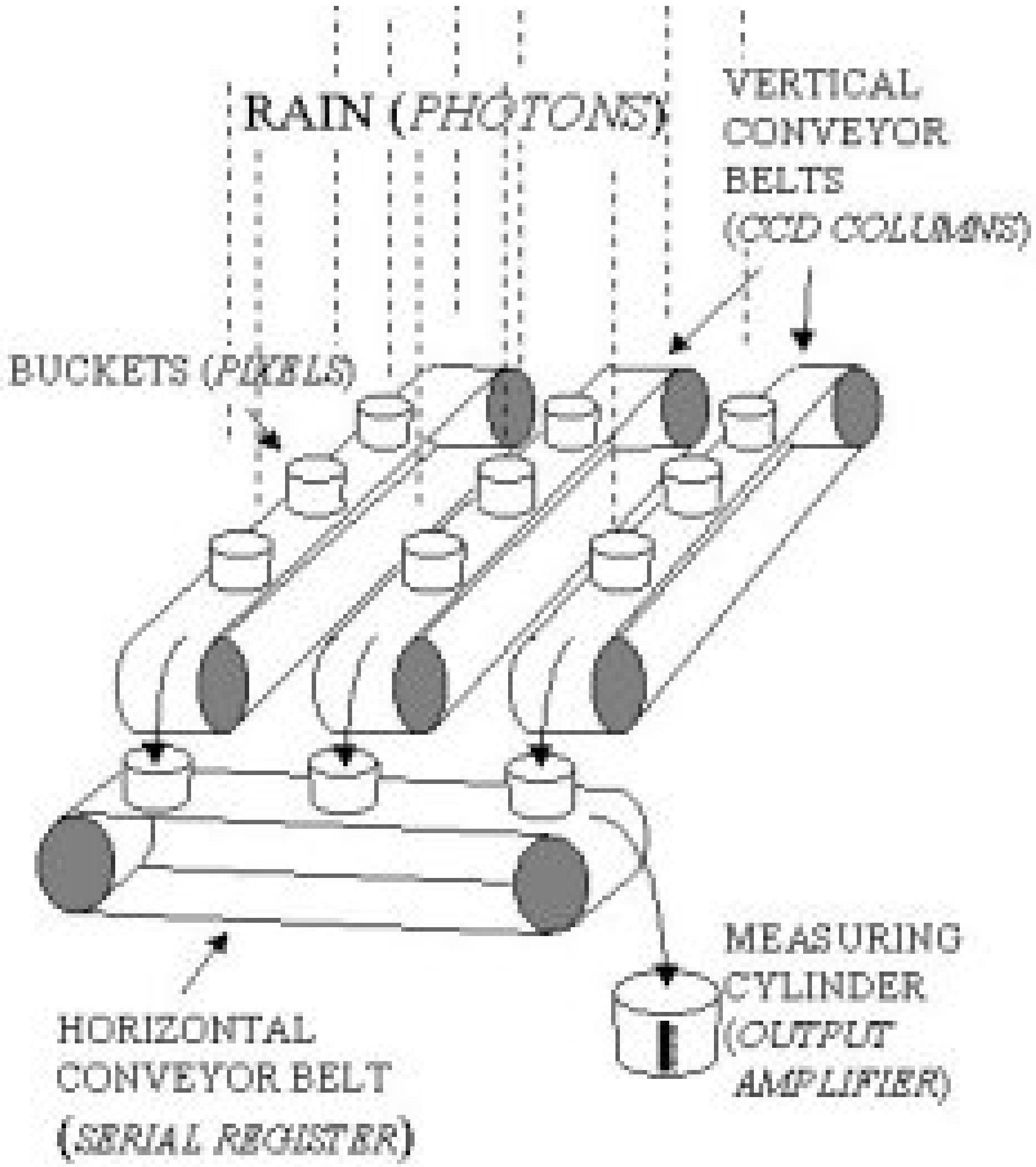


X-ray interacts in material to produce photoelectrons which are collected by applying a drift field

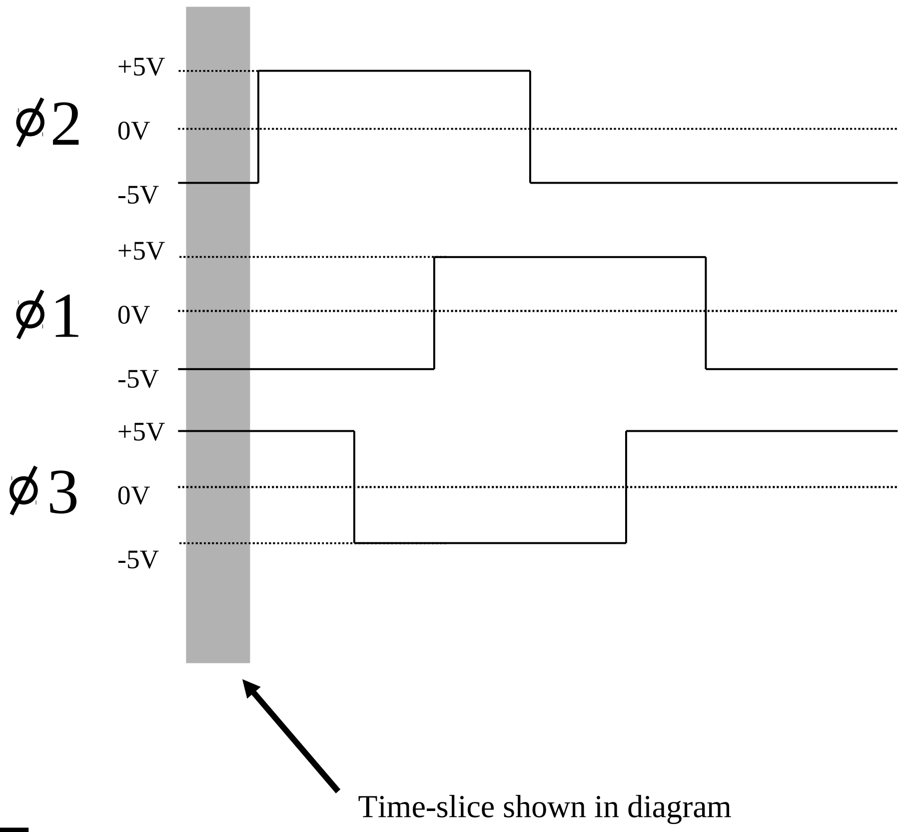
Charge Coupled Devices

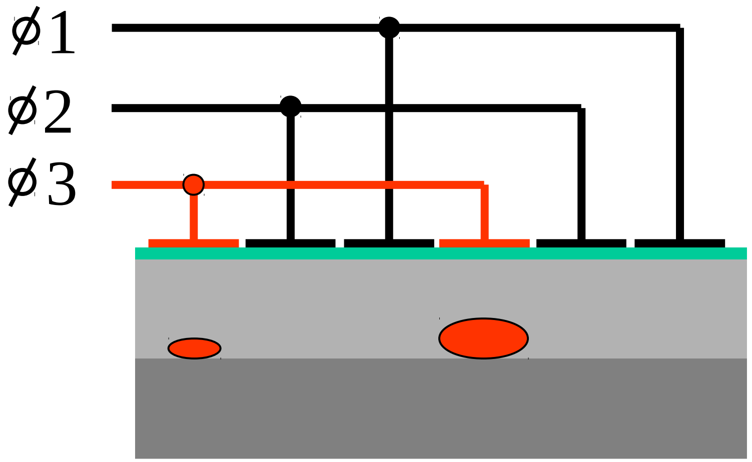


Charge Coupled Devices

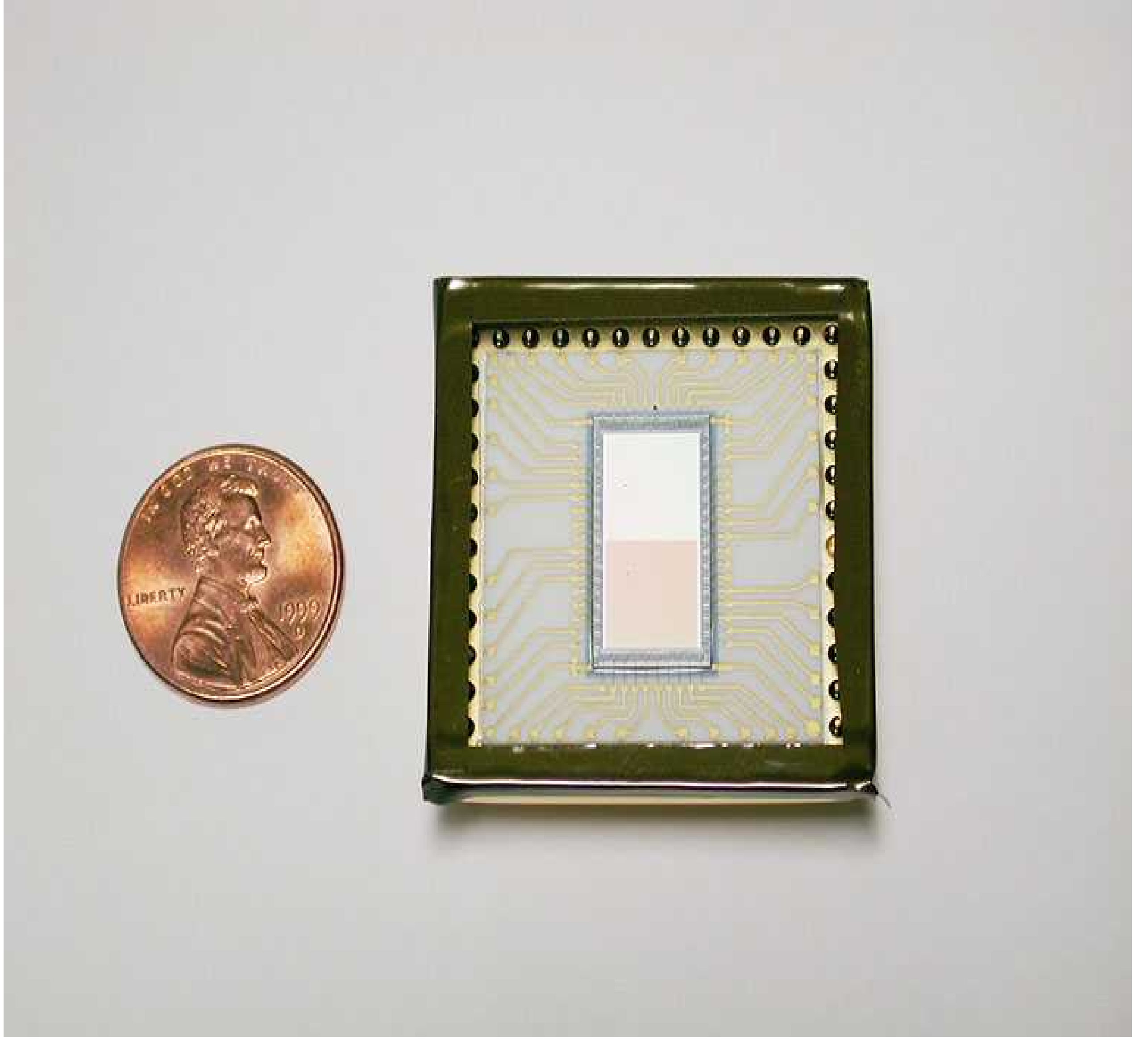


Charge Transfer in CCDs

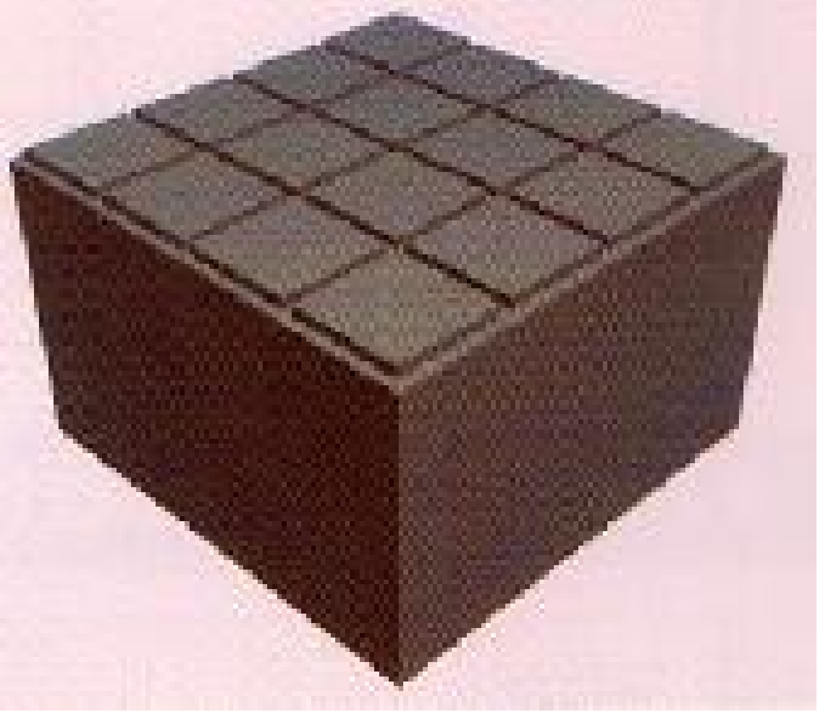




Frame Store CCD



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.

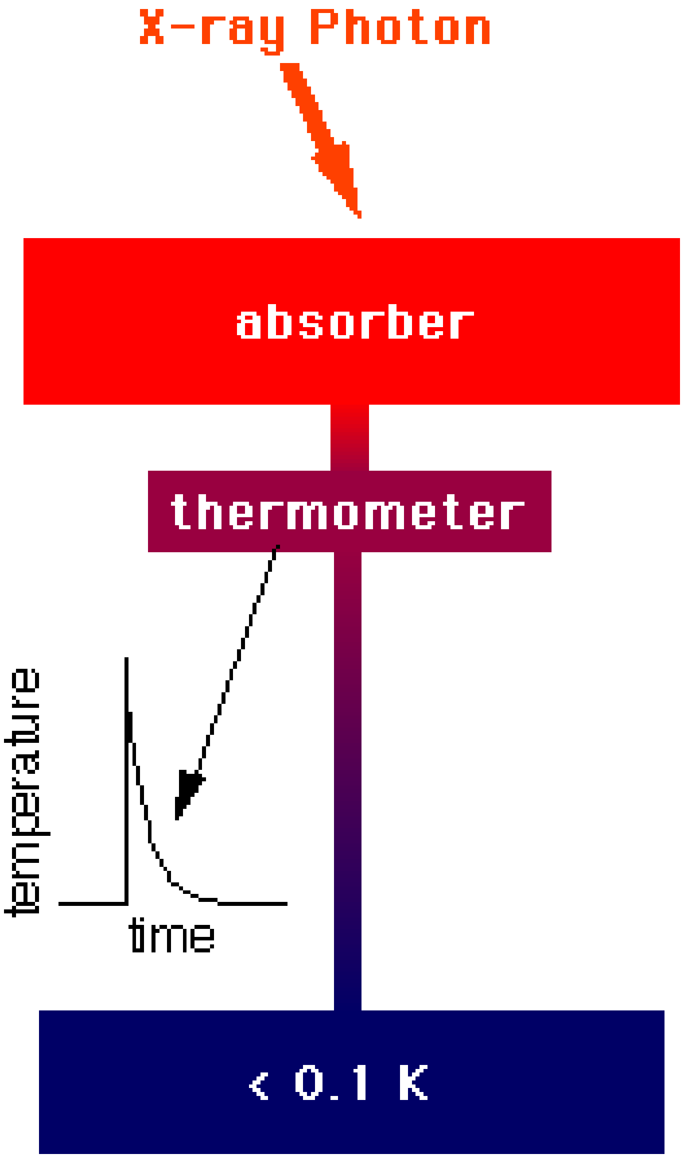
Pixelated detectors have larger pixel sizes, require many electronics channels, but are fast and can be made thick and of various materials – therefore can be efficient up to higher energies

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

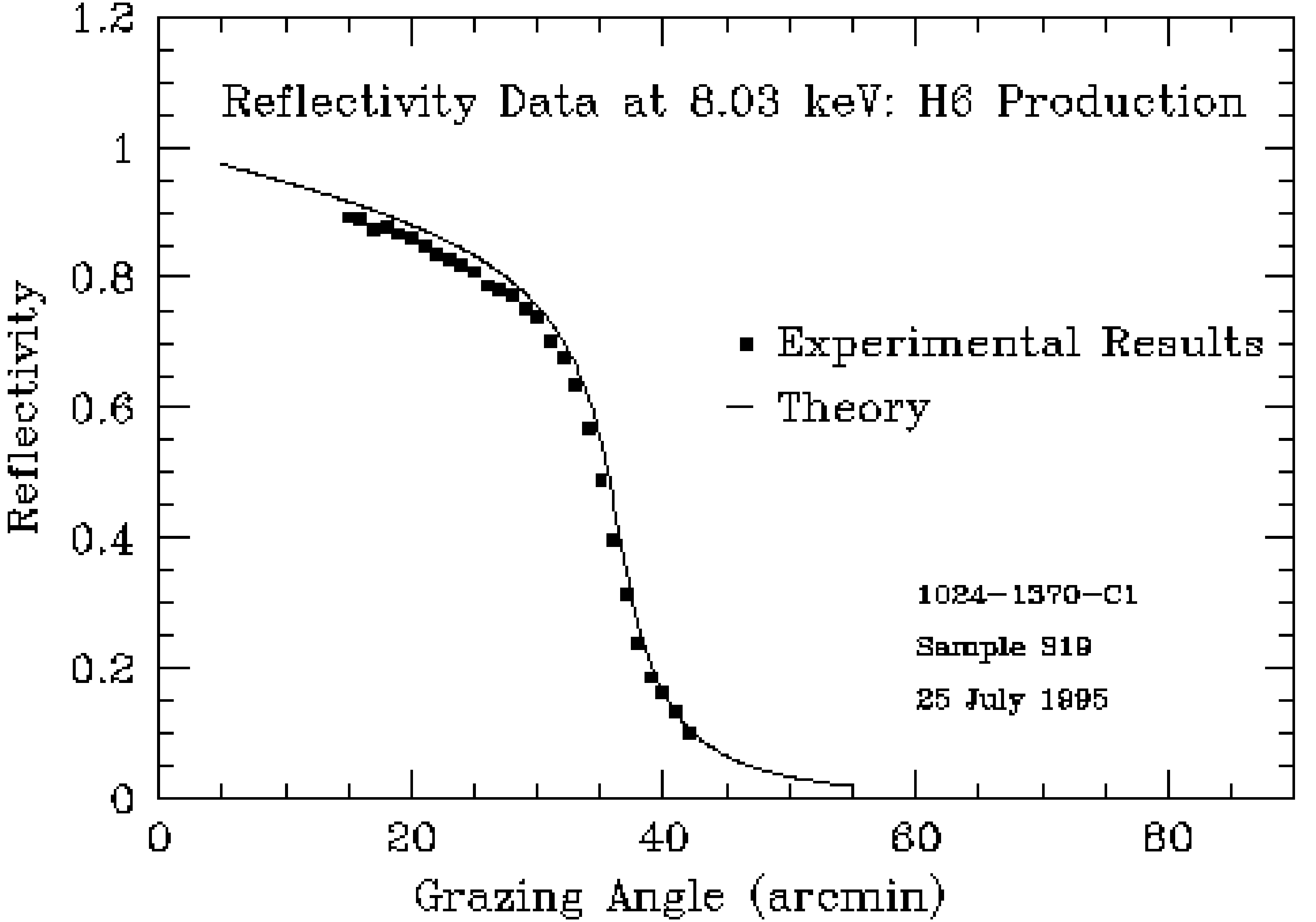
Microcalorimeters



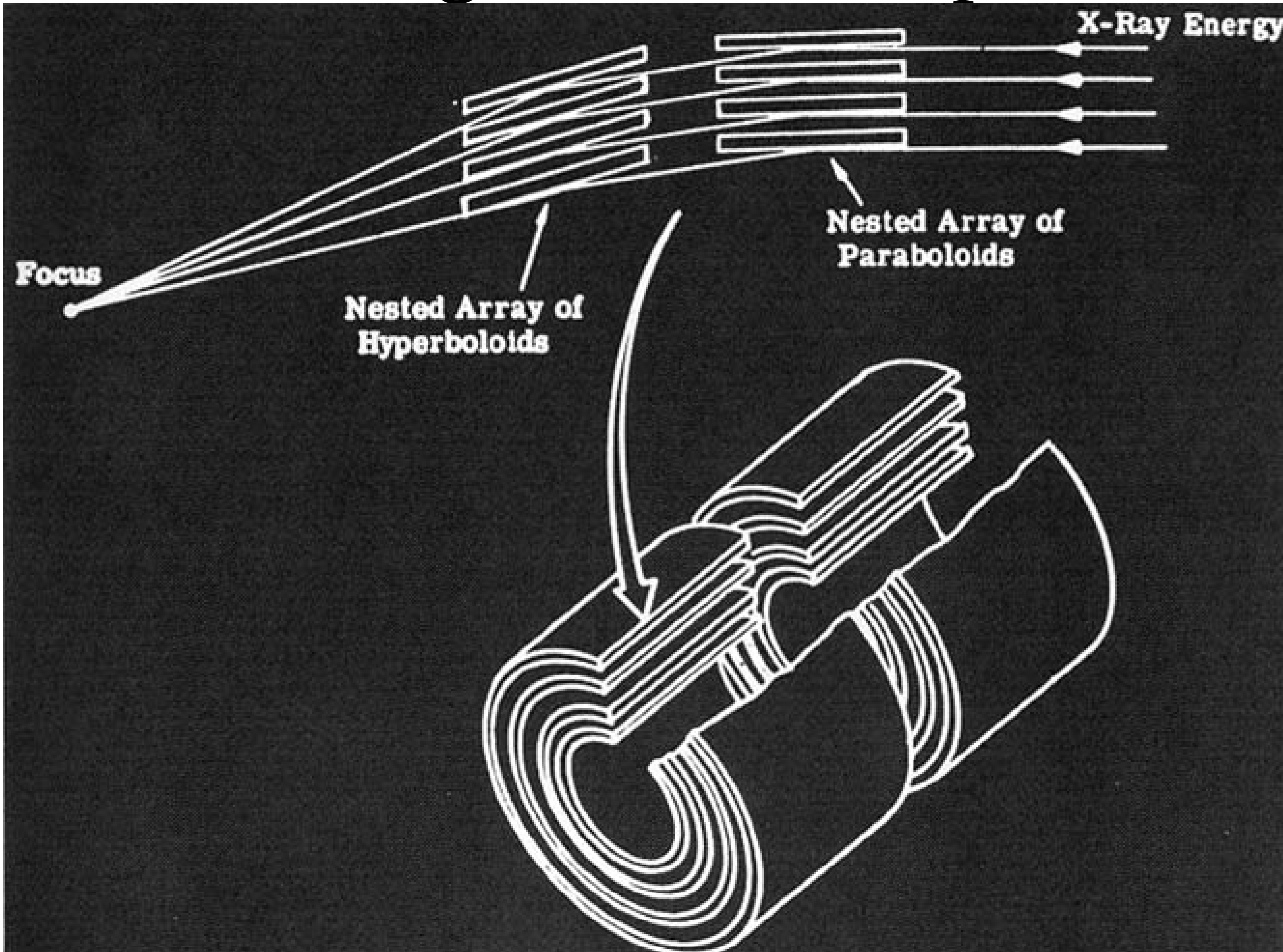
$\Delta E = 6$ eV

@ 6 keV

X-Ray Reflectivity



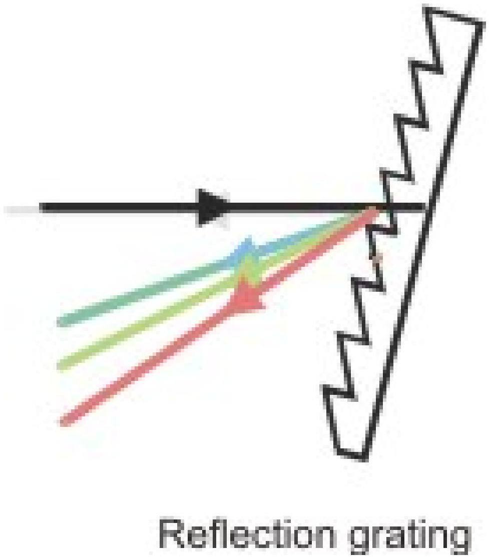
Grazing Incidence Optics

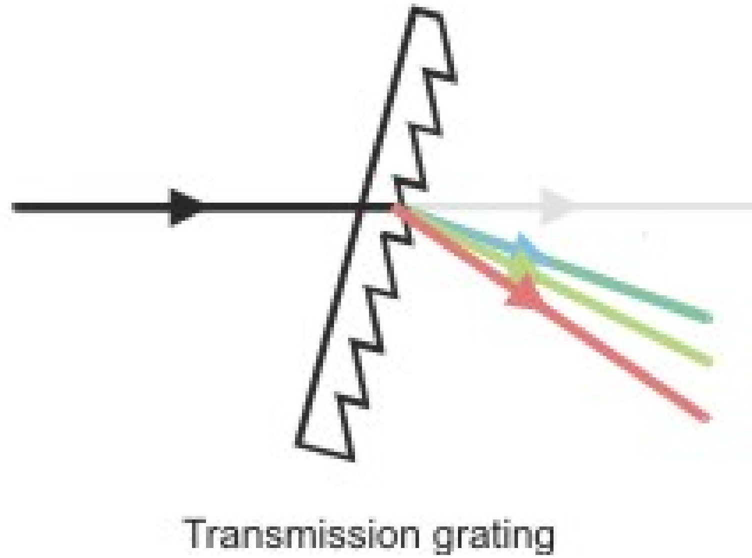


Scientific Gains from Imaging

- 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



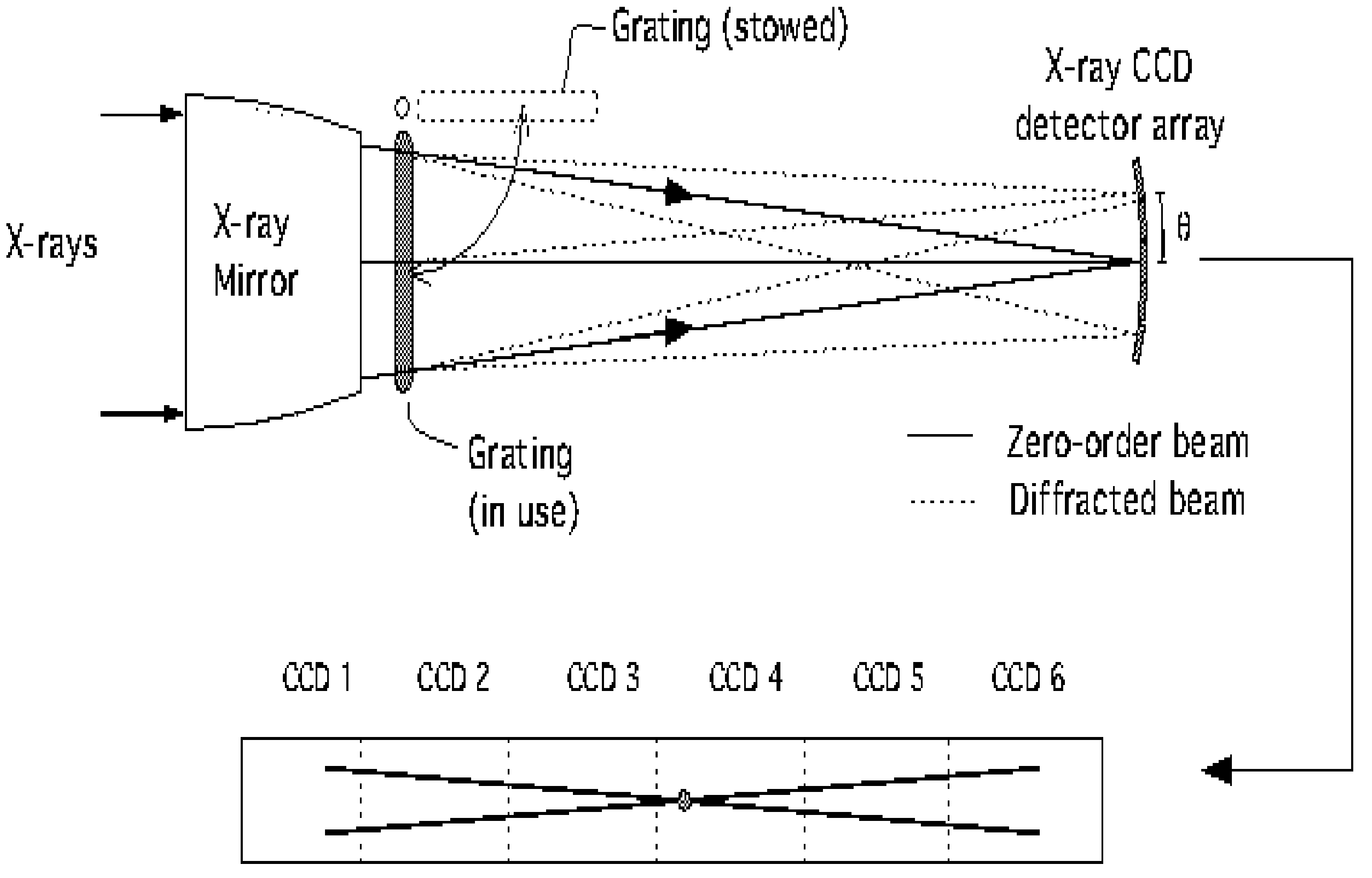


$$\sin\alpha + \sin\beta = -\frac{m\lambda}{d}$$

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

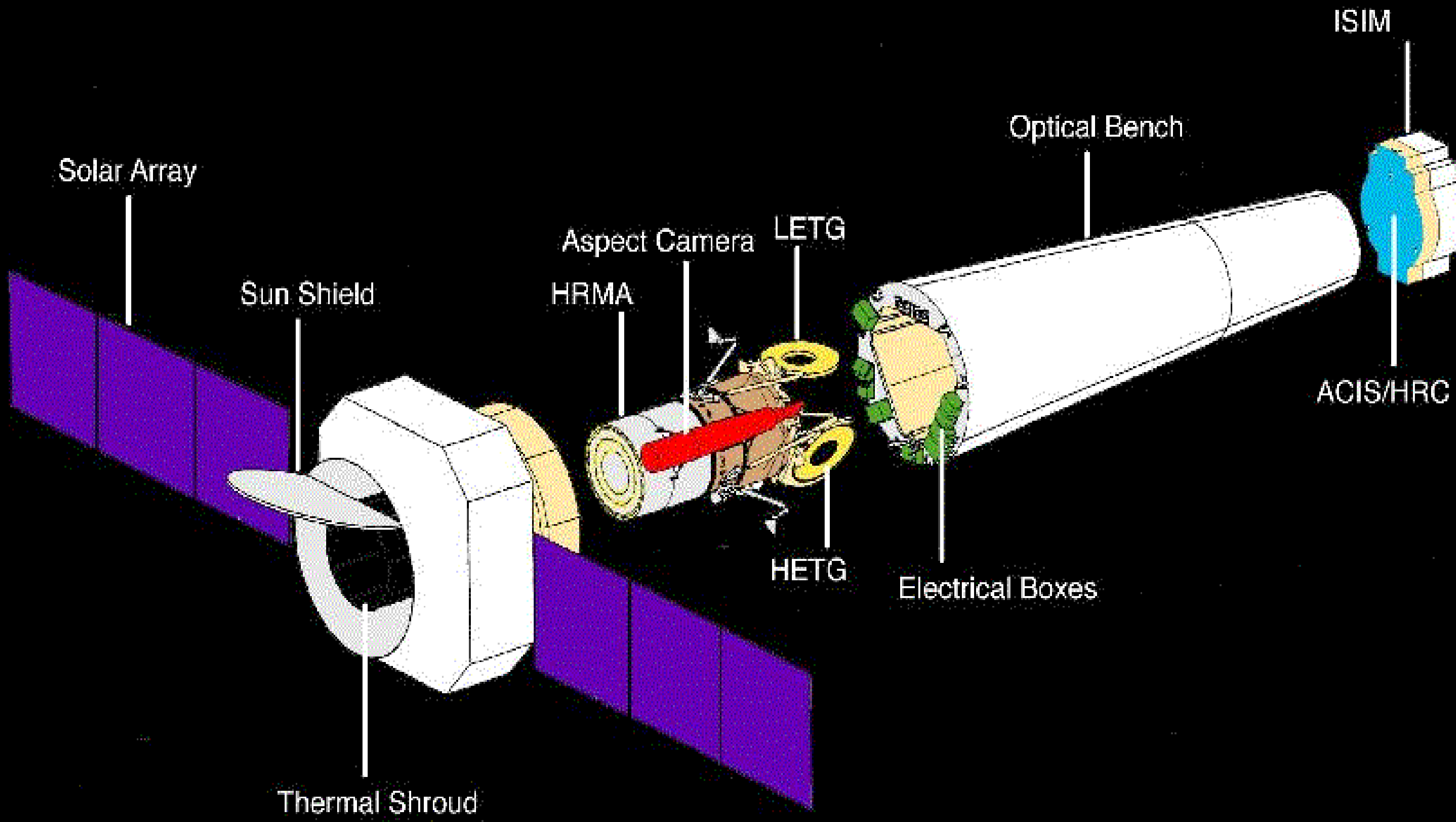
For X-ray diffraction need *d* ~ 0.1 – 1 μm

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
Aspect Camera
LETG
Sun Shield
HRMA
ACIS/HRC
HETG
Electrical Boxes
Thermal Shroud