# Instruments for High-Energy Astrophysics (part I)

partly adapted from V. Fioretti's and A. Bulgarelli's presentations

# The ideal detector for satellite-born X-ray astronomy

*It would possess high spatial resolution, with a large useful area, excellent temporal resolution with the ability to handle large count rates, good energy resolution with unit quantum efficiency over a large bandwidth.*

*Its output would be stable on timescales of years and its internal background of spurious signals would be negligibly low.*

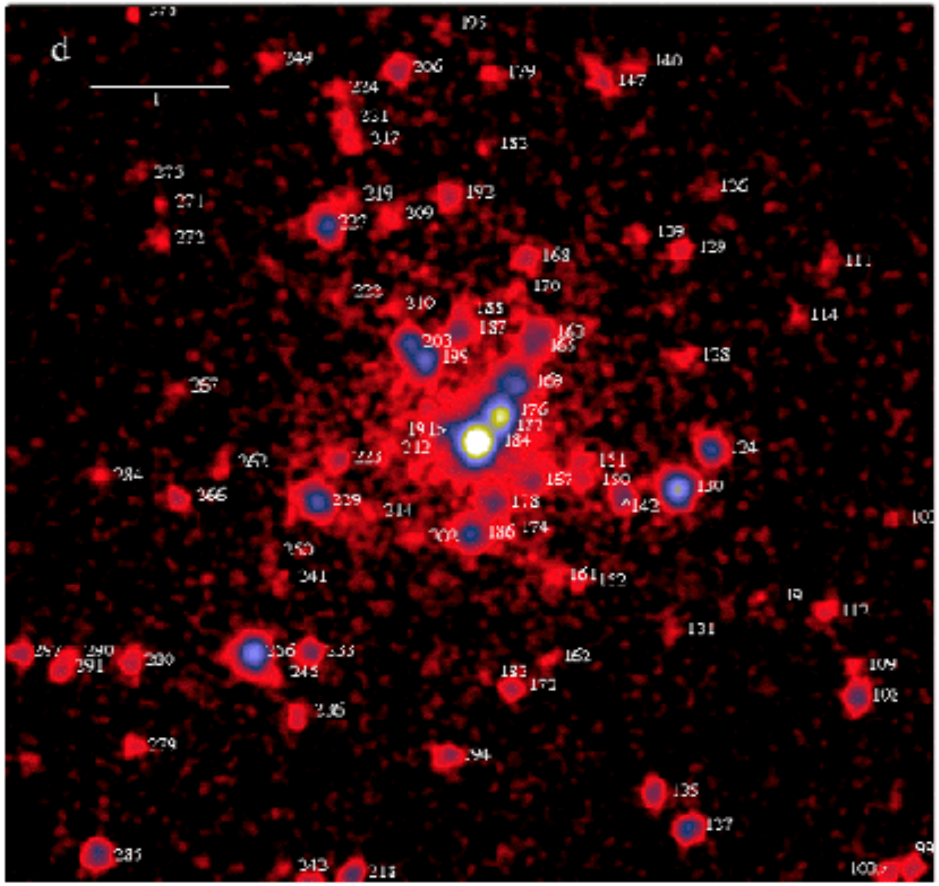
*It would be immune to damage by the in-orbit radiation environment and would require no consumables.*

*It would be simple, rugged, and cheap to construct, light in weight and have a minimal power consumption.*

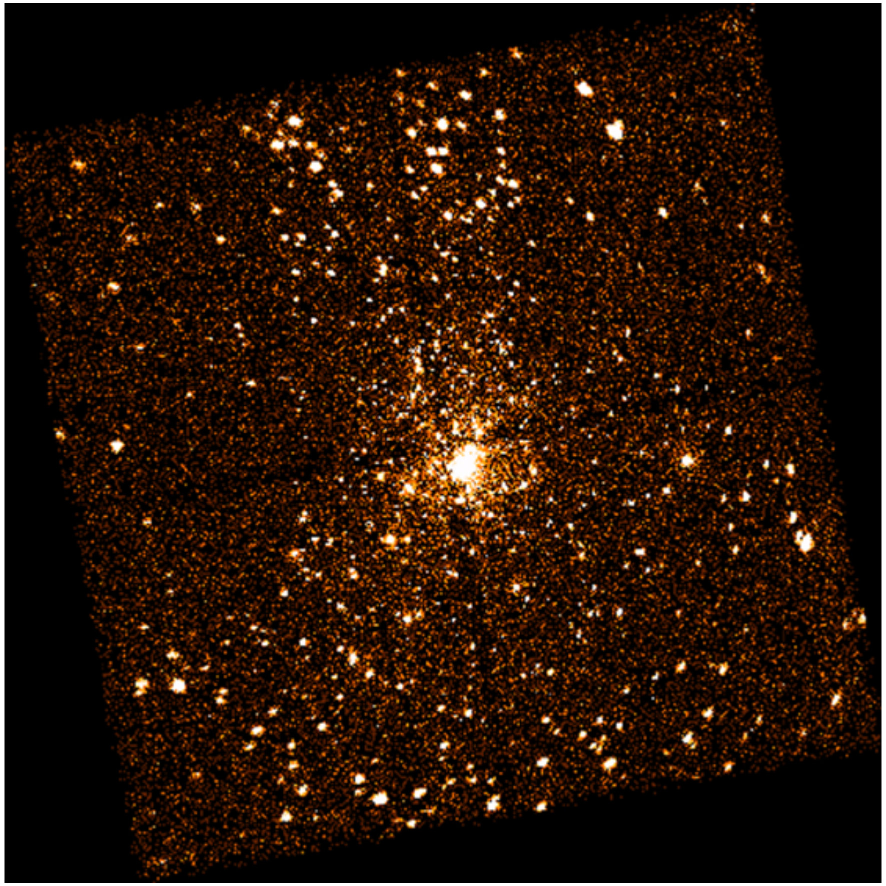
*It would have no moving parts and a low output data rate.*

(*X-ray Detectors in Astronomy* by G. W. Fraser)

# Angular resolution

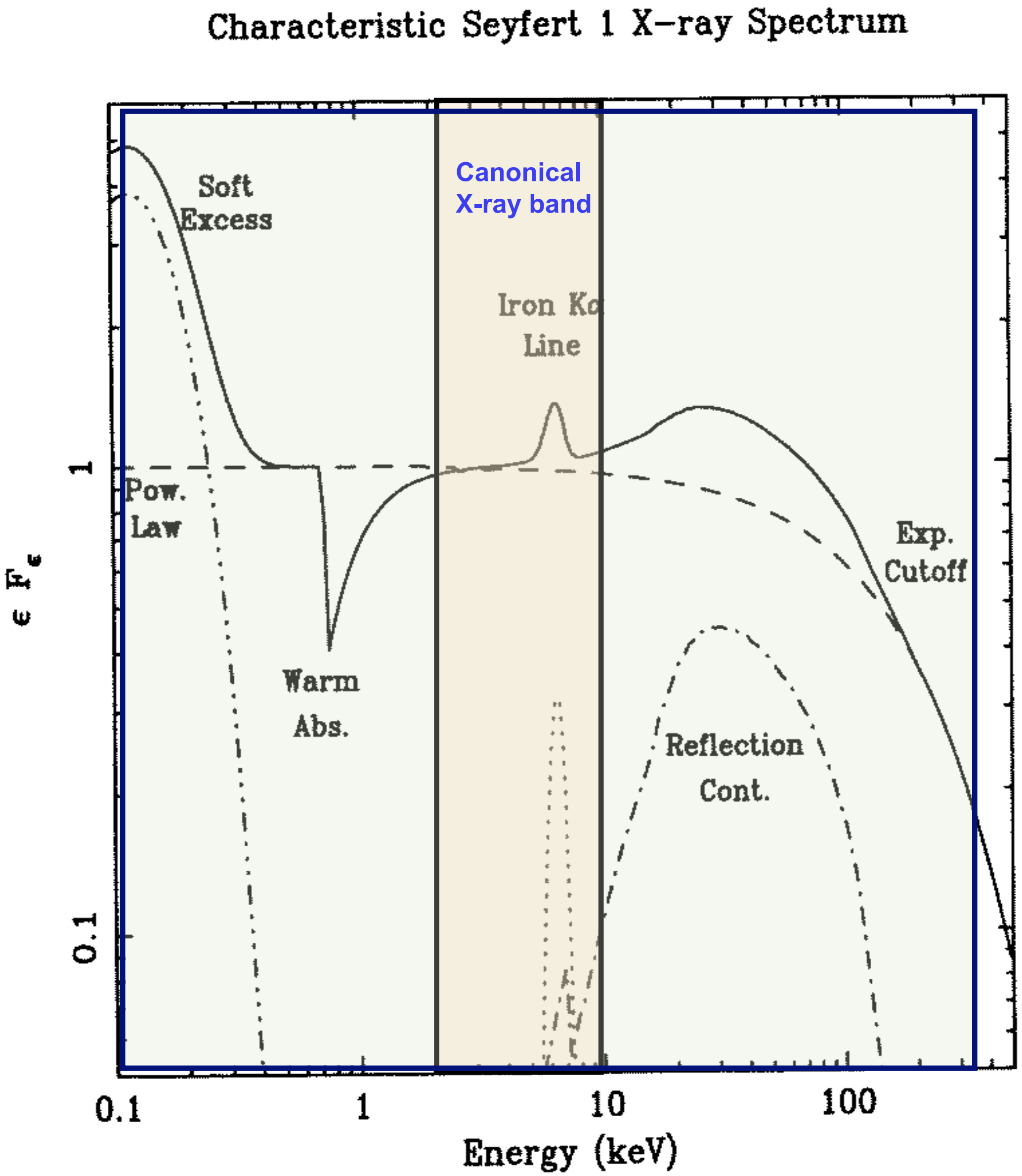


**Orion: *ROSAT* HRI (47 ks)**



**Orion: *Chandra* ACIS (13.7 ks)**

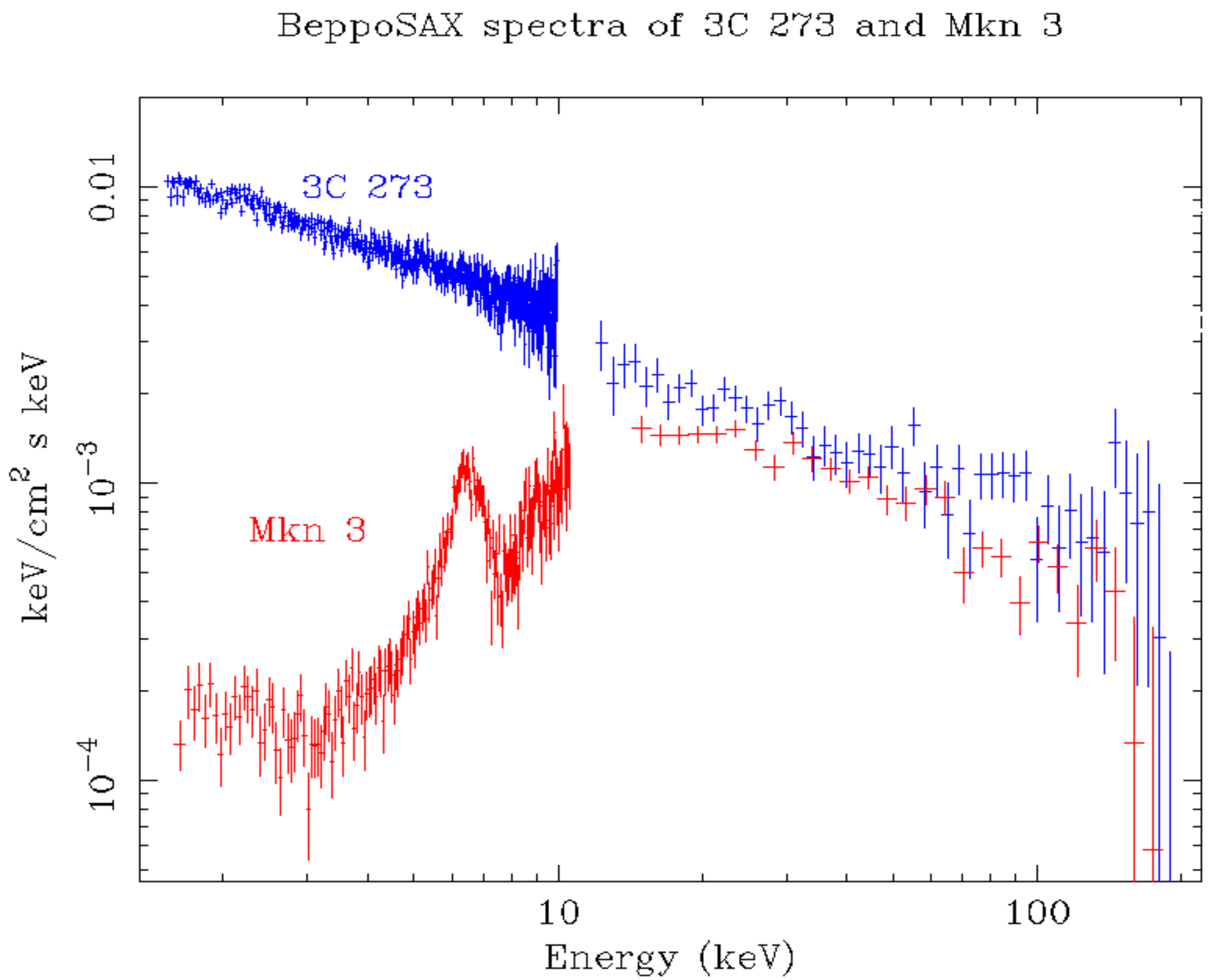
# Bandwidth




- Observations in the "canonical" 2-10 keV band is not optimal to provide a complete characterization of the source properties and emission mechanisms at work

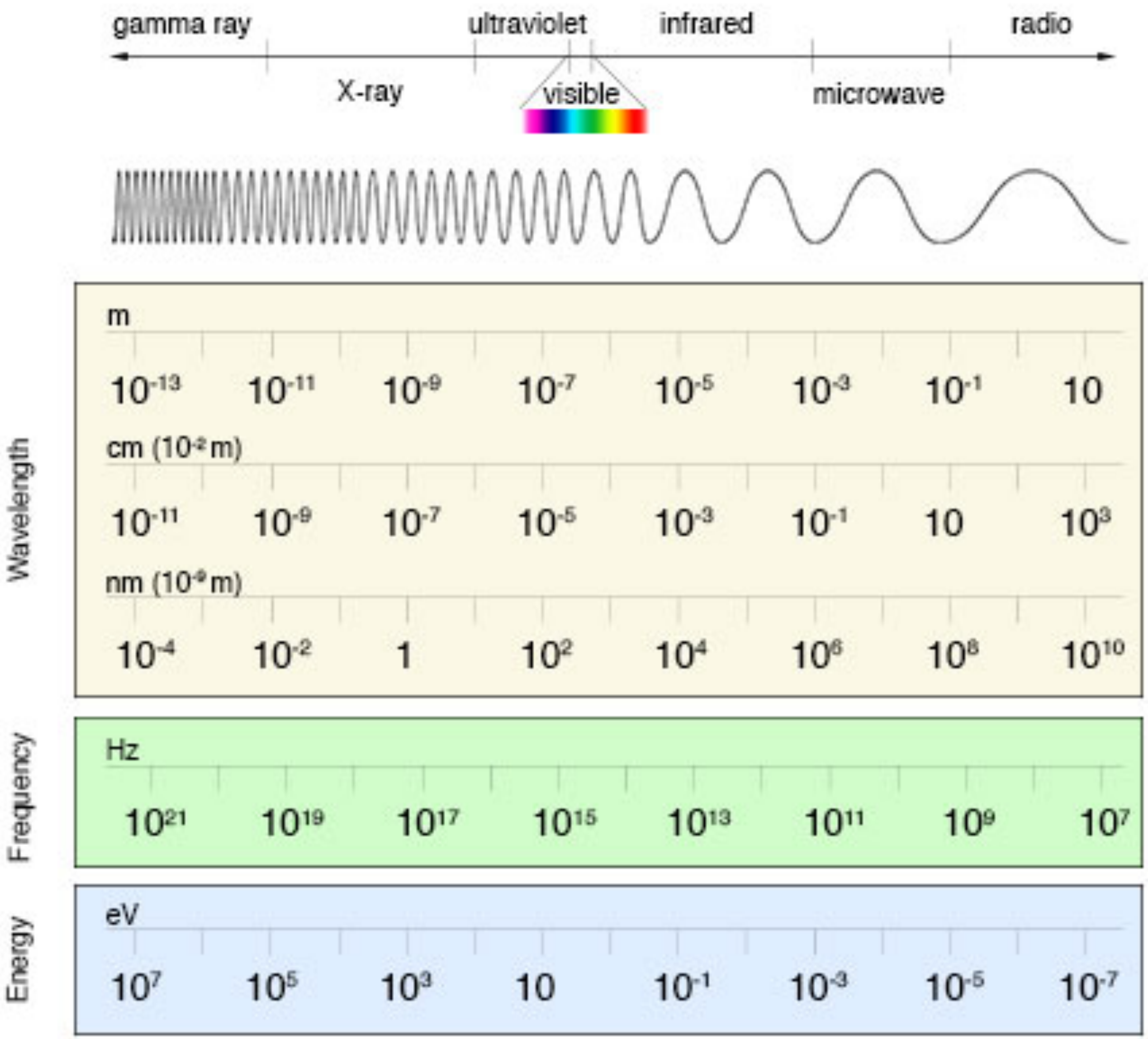
- The 0.1-300 keV band provided by Beppo*SAX* has been unique to provide a broad-band view of the sources

# Bandwidth + high photon statistics




Mkn 3 (Sey 2): ≈ 3C 273 a E > 10 keV ($N_H$ ~$10^{24}$ atoms cm$^{-2}$)

# The electromagnetic spectrum. I.




E=energy

h-=Planck constant

$$E = h\nu$$

frequency

$$E(\text{eV}) = hc/\lambda(\mu\text{m}) \approx 1.24/\lambda(\mu\text{m})$$

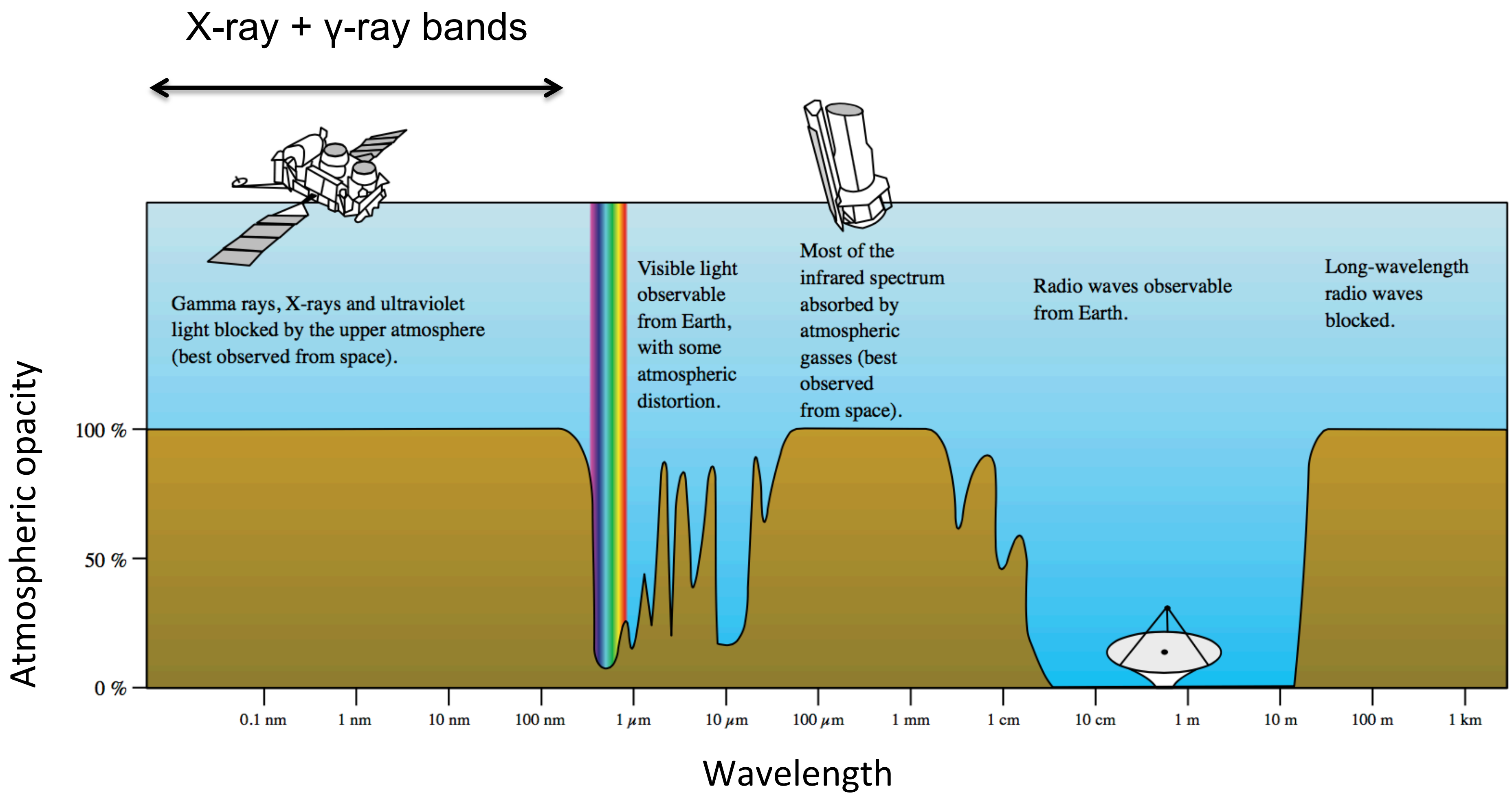
1000 eV = 1 keV

1000 keV = 1 MeV

1000 MeV = 1 GeV

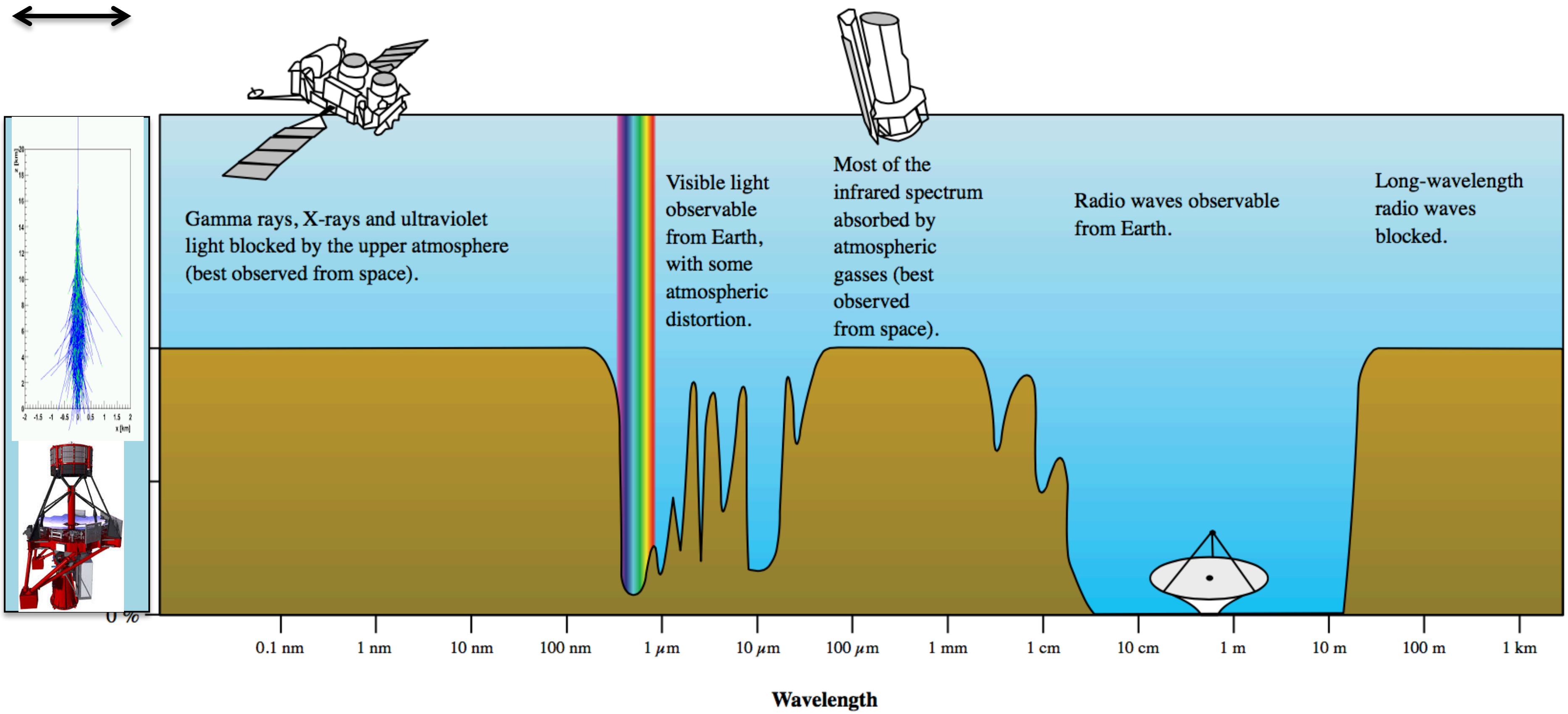
# The electromagnetic spectrum. II.

- Atmospheric absorption → Astrophysics from the space
- First detection of cosmic γ-rays: Explorer XI, 1961, ~100 photons



# The electromagnetic spectrum. III.

E > 10 GeV (Very High Energy γ-rays): interaction of with the atmosphere producing Cherenkov radiation (observable from the ground)



# X-ray/γ-ray telescopes

- Collimation systems/coded-masks/focusing photons with current X-ray optics

- Detectors: primary photons interact with the detector and originate an electric signal

- Shielding the background: active vs. passive systems

- Different materials/layouts depeding on the scientific objectives of a mission: spectral/spatial resolution, energy coverage, satellite orbit, etc.

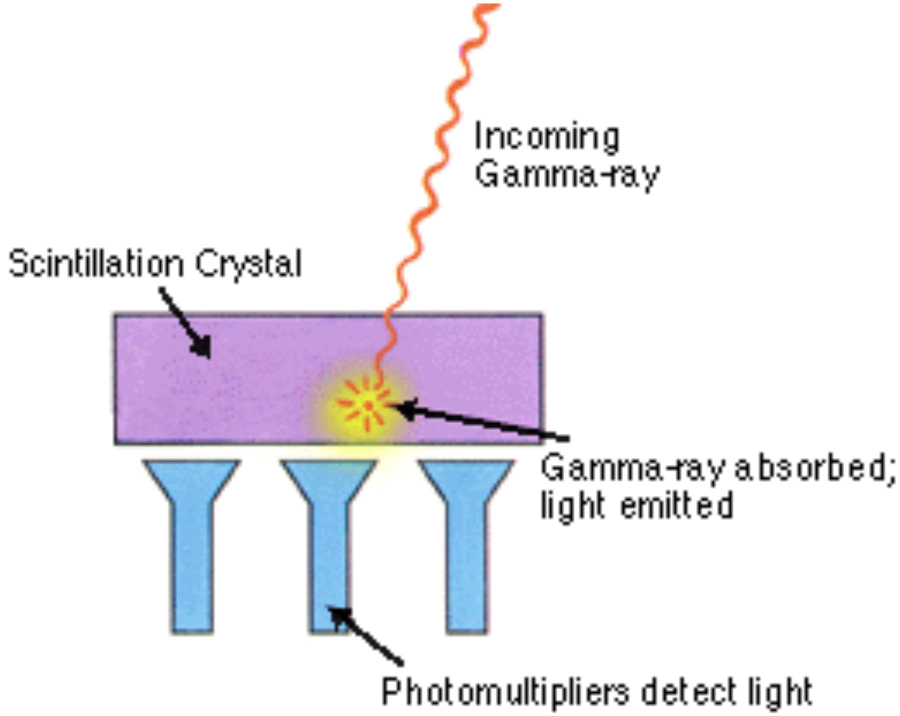
# X-ray/γ-ray detectors

Interaction of the primary photon with the detector

Production of secondary particles (photons, $e^-$, $e^+$, etc.), then conversion into an electric signal

Amplitude of the signal: spectroscopy

Position of the interaction: imaging



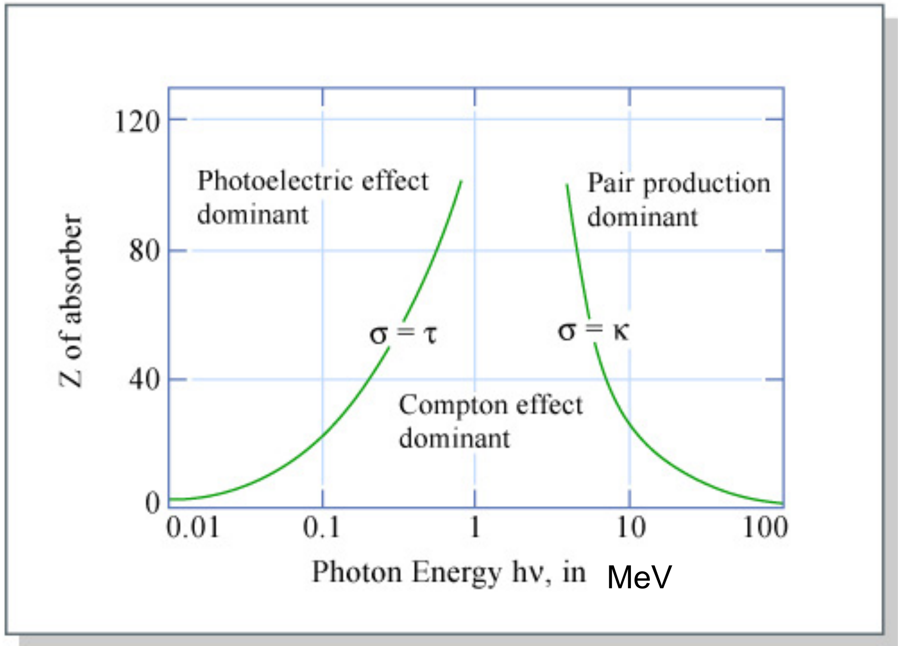
# Radiation-matter interaction at high energies: basic notions

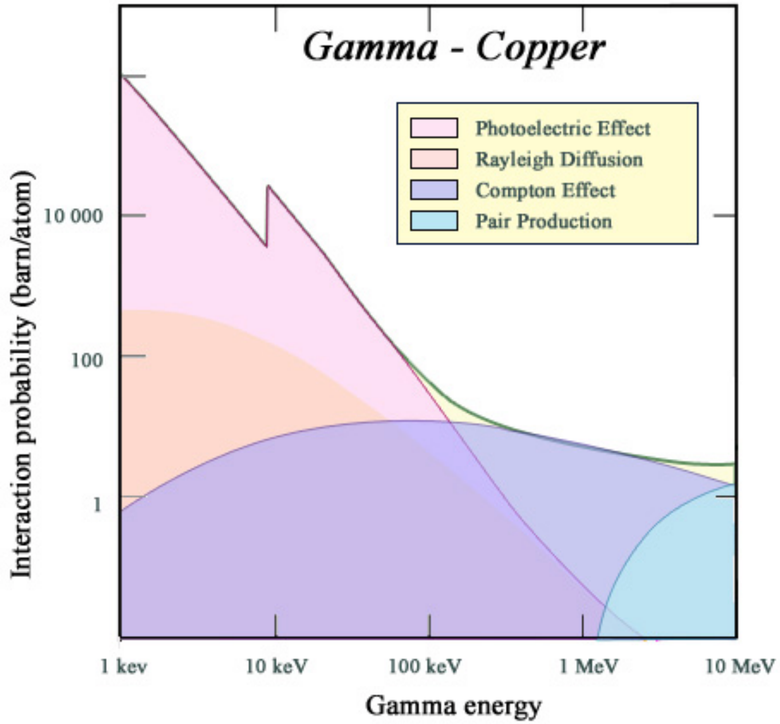
# Radiation-matter interaction. I

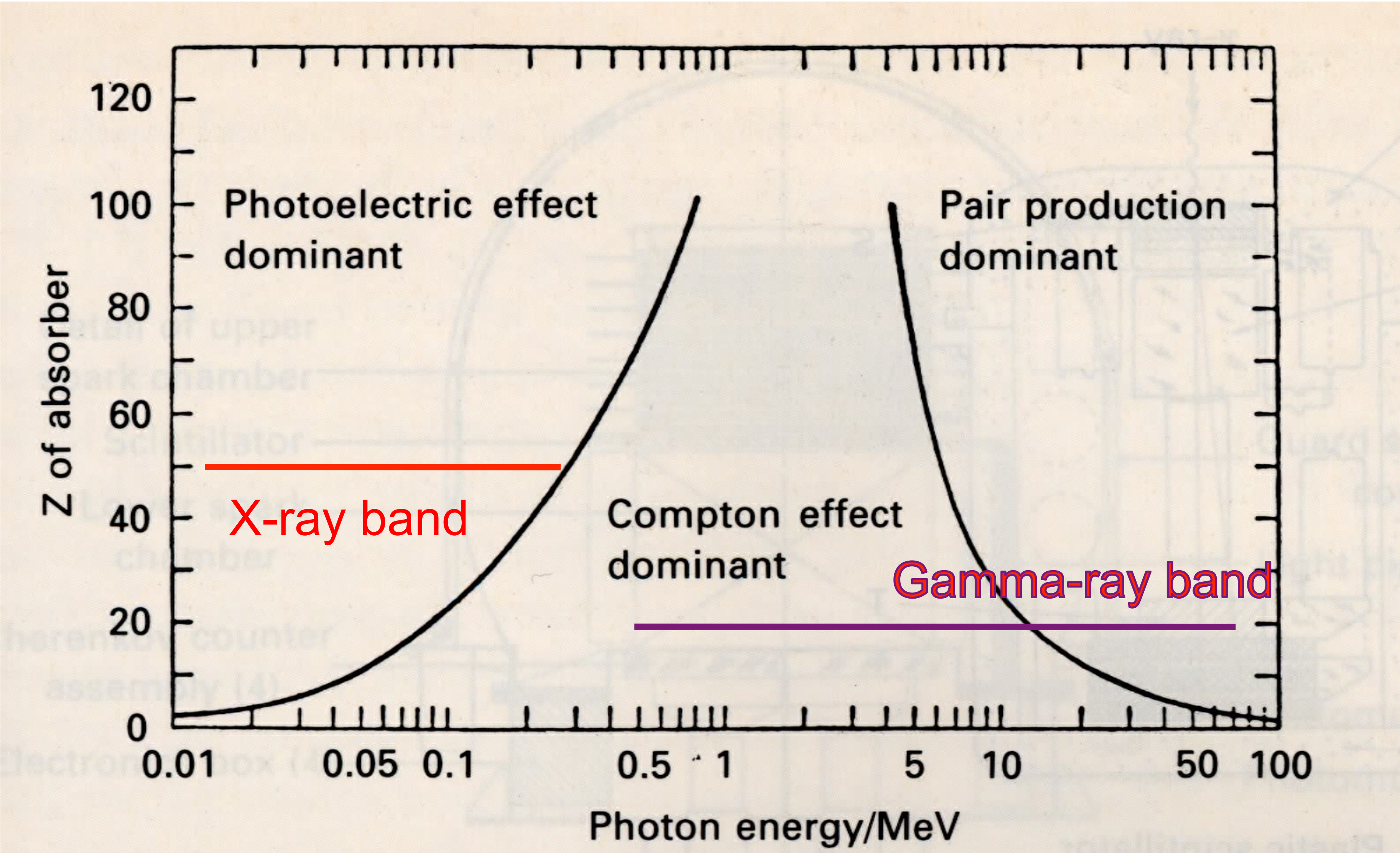
**MAIN PROCESSES:**

- Photoelectric absorption
- Elastic scattering (Thomson, Rayleigh) and inelastic scattering (Compton)
- Pair production

At *different energies* and for *different materials*, the probability of a particular process of interaction changes. This probability is given by the **cross section**



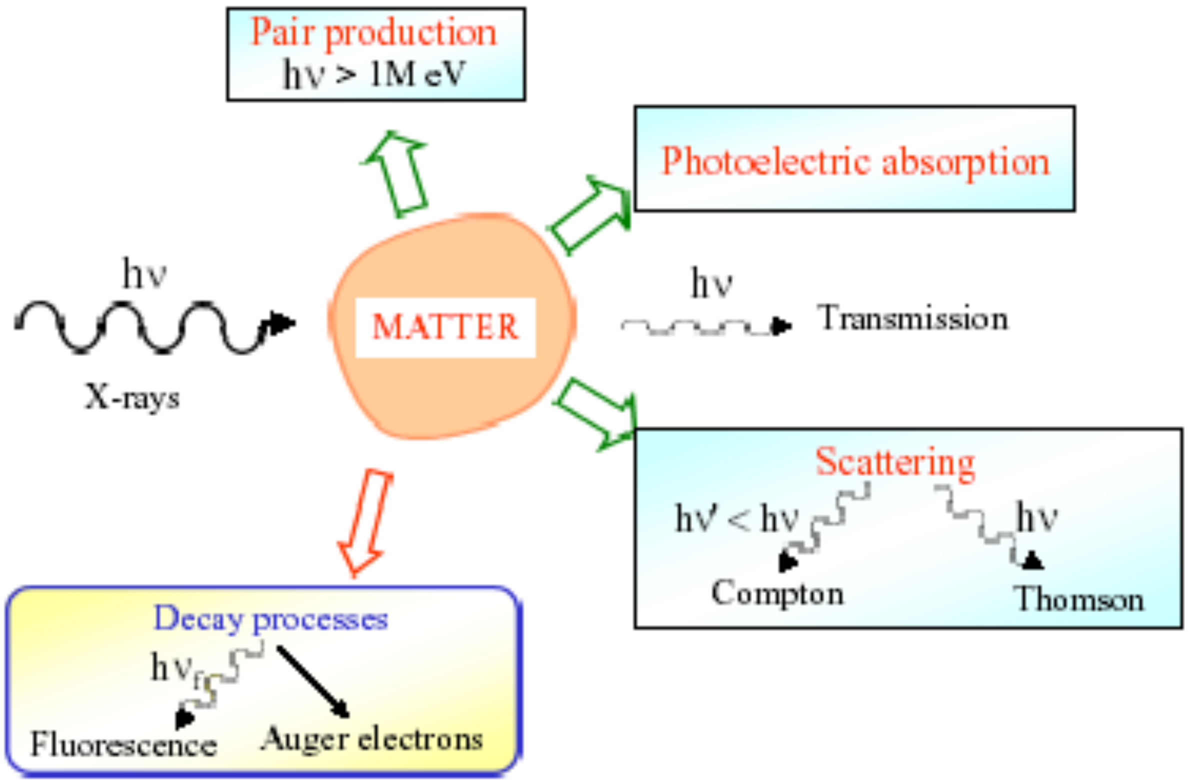





120
100
80
60
40
20
0
Z of absorber
Photoelectric effect dominant
Pair production dominant
Compton effect dominant
X-ray band
Gamma-ray band
0.01
0.05
0.1
0.5
1
5
10
50
100
Photon energy/MeV

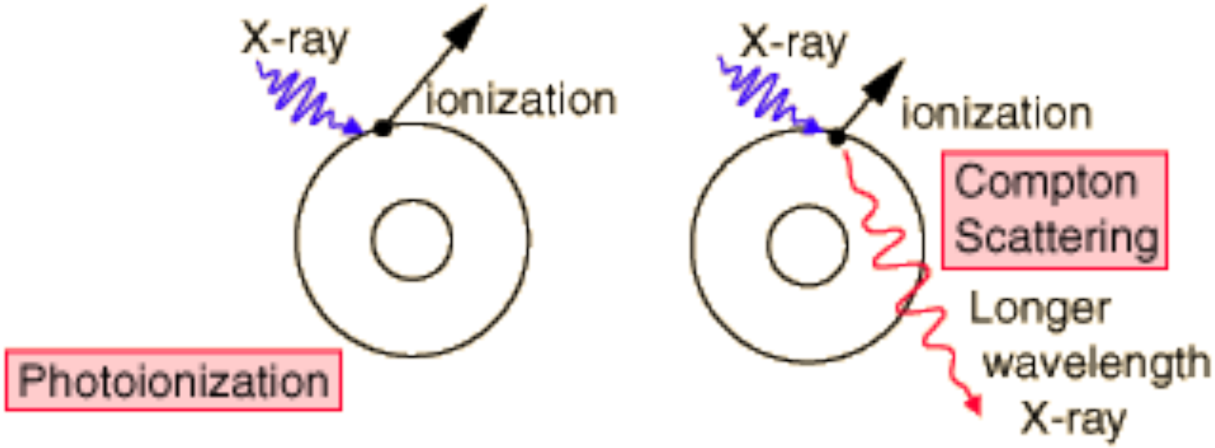
## Radiation-matter interaction through three main processes

Interaction X-rays - Matter




Primary competing processes and some radiative and non-radiative decay processes

# Radiation-matter interaction. II
## Absorption processes




**Photoelectric absorption or photoionization:**
Atomic electrons are removed from their nuclei.
Dominant below 100 keV

**Compton scattering:**
Electrons are hit by photons and absorb part of the energy.
Dominant in the 0.1 - 4 MeV region

**Pair creation:**
In the presence of nuclei, gamma rays can produce pairs of particles and antiparticles

# Radiation-matter interaction. III

The interaction between the radiation (photons) and the material of the detector may provide the following information:

- Energy of the incoming radiation
- Sky position
- Arrival time
- Polarization

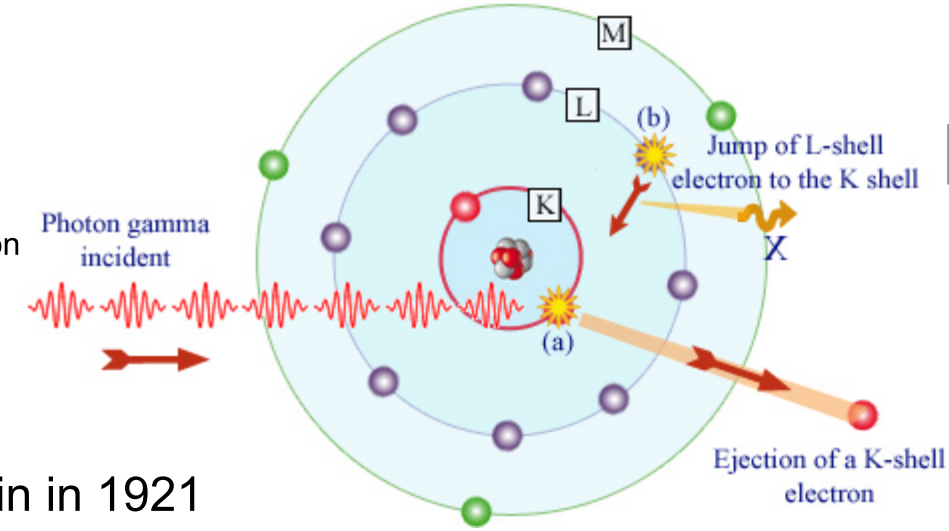
These are needed to provide spectra, imaging, light curves for source variability, …

# Radiation-matter interaction. IV
## The photoelectric effect

**Photon-atom interaction**: a photon is completely absorbed and its energy is transferred to one of the electrons of the atom. This electron becomes free and is emitted by the atom (the so-called photo-electron) or, alternatively, can go to a more external shell.
The kinetic energy of the electron is given by the difference between the energy of the incoming photon and the bounding energy of the electron.

About 80% of the absorptions in the X-ray band happen in the innermost K shell, with the emission of an electron of that shell.

High-energy photon




origin of the iron Kα line

photo-electron

Nobel prize to Einstein in 1921

# Radiation-matter interaction. V
## The photoelectric effect

**Photon-atom interaction**: a photon is completely absorbed and its energy is transferred to one of the electrons of the atom. This electron becomes free and is emitted by the atom (the so-called photo-electron) or, alternatively, can go to a more external shell.
The kinetic energy of the electron is given by the difference between the energy of the incoming photon and the bounding energy of the electron.

About 80% of the absorptions in the X-ray band happens in the innermost K shell, with the emission of an electron of that shell.

photoelectric cross section

$$\mu_{ph} \propto Z^{4.5} E^{-3.5}$$

higher Z elements are preferred to maximize this effect

$$E_{e^-} = h\nu - E_b$$

- $E_{e^-}$: kinetic energy of the photo-electron
- $h\nu$: energy of the incoming (absorbed) photon
- $E_b$: binding energy of the electron

# Radiation-matter interaction. VI
## The photoelectric effect

As a consequence of the interaction, the atom is an excited state → electrons rearrange from the external shells and ***either***

- an X-ray photon (**fluorescence**), typically corresponding to Kα emission, is emitted. Its energy is the difference in energy between the two involved shells, ***or***
- an electron from an external shell (**Auger electron**) is emitted. Its energy is equal to the difference between the energy of the two shells and the ionization energy of the Auger electron.

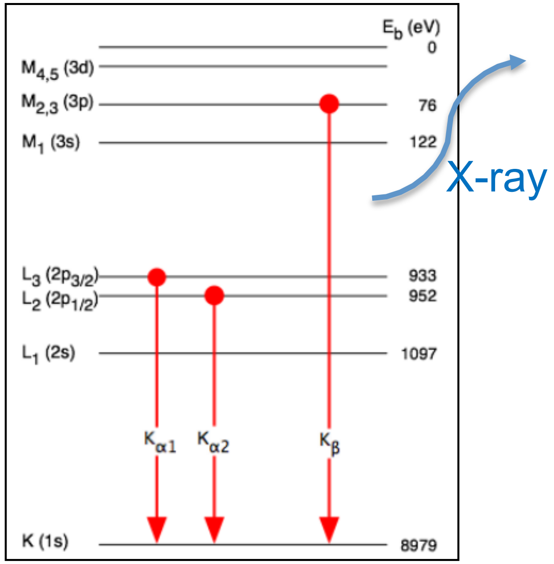
The probability is given by the ***fluorescence yield***:

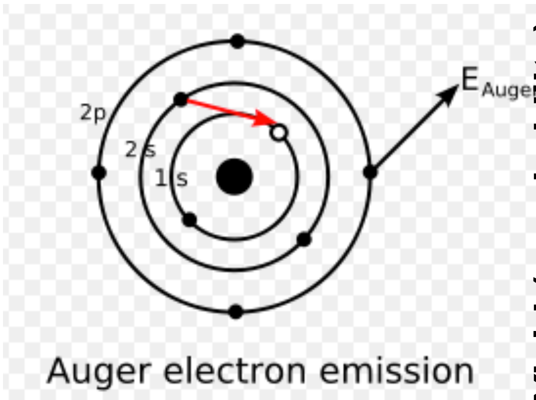
$$Y_Z^K \approx \frac{N_K}{n_{vK}}$$

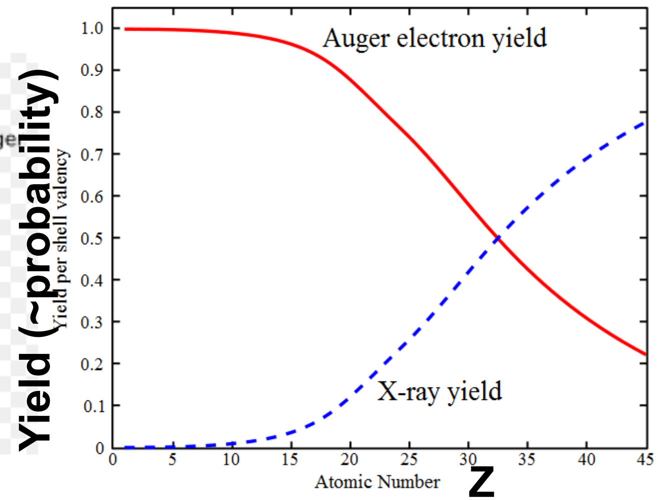
← number of K-shell X-ray photons emitted

← number of primary vacancies

$$Y \approx \frac{Z^4}{Z^4 + 33^4}$$



# Radiation-matter interaction. VII
## Electron scattering

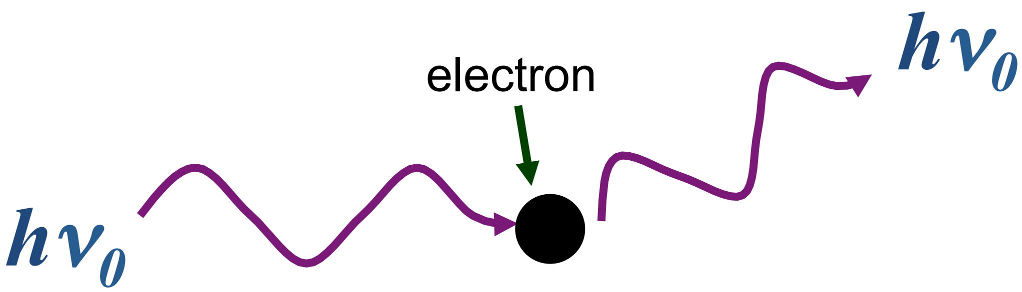
**Thomson scattering:** $h\nu << m_e c^2$

- Elastic scattering
- The photon energy is preserved
- It happens when $h\nu << m_e c^2$

**Compton scattering:** $h\nu \approx m_e c^2$

- Anelastic scattering
- The photon loses energy, which is transferred to the $e^-$
- It happens when $h\nu \approx m_e c^2$

# Radiation-matter interaction. VIII
## Thomson scattering



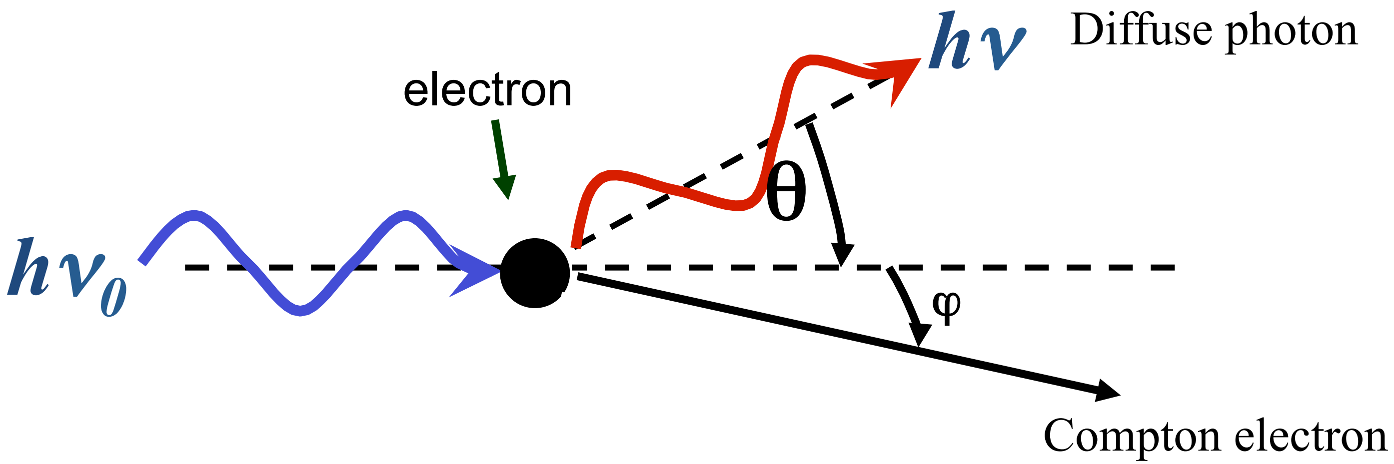

The process is "regulated" by the **Thomson cross section**:

$$\sigma_T = (8/3)\pi\, r_e^2 = (8/3)\pi\, (e^2/m_e c^2)^2 = 6.65\ 10^{-25} cm^2$$

radius of the electron

# Radiation-matter interaction. IX
## Compton scattering (diffusion)

Here the photon after the interaction has a longer wavelength (i.e., lower frequency, hence energy) wrt. the incident photon




Compton wavelength: $h/(m_e c)$

**Frequency change**

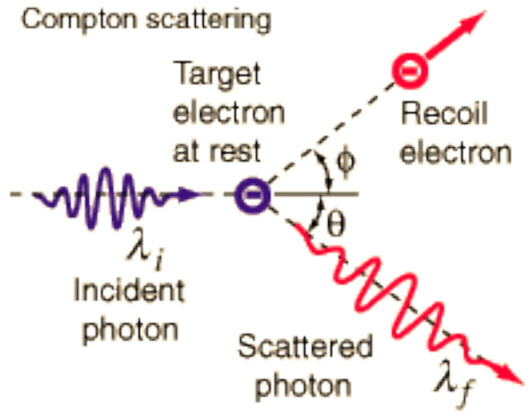
$$\frac{1}{\nu} - \frac{1}{\nu_0} = \frac{h}{m_e c^2}(1 - cos\theta)$$

Energy of the photon before interaction: hv

Energy of the photon after interaction: hv'

Rest energy of the electron: $m_e c^2$ (511 keV)

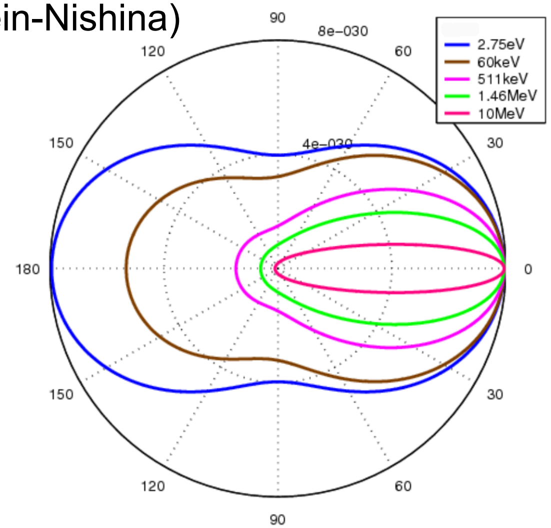
$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0 c^2}(1-\cos\theta)}$$




Energy transmitted to the electron (recoil):

$$E_{e-} = h\nu - h\nu' = h\nu\left(\frac{\frac{h\nu}{m_0 c^2}(1-\cos\theta)}{1 + \frac{h\nu}{m_0 c^2}(1-\cos\theta)}\right)$$

Cross section
(Klein-Nishina)




higher energy → more "directional" radiation

The angular distribution of the diffuse high-energy photons is given by the Klein-Nishina differential cross section

$$\frac{d\sigma}{d\Omega} = Zr_0^2\left(\frac{1}{1+\alpha(1-\cos\theta)}\right)^2\left(\frac{1+\cos^2\theta}{2}\right)\left(1+\frac{\alpha^2(1-\cos\theta)^2}{(1+\cos^2\theta)[1+\alpha(1-\cos\theta)]}\right)$$

where $\alpha = h\nu/m_0c^2$. $\sigma_{K\text{-}N} = \sigma_T$ when $E_\gamma << m_ec^2$

Decreasing cross section at increasing energies as ≈(1/E)

Low-energy (e.g., visible) light will scatter over all angles
X-rays will scatter preferentially forward (but back-scattering may occur)
Higher energy (≈MeV) photons will rarely back-scatter

INTERACTION OF GAMMA RAYS

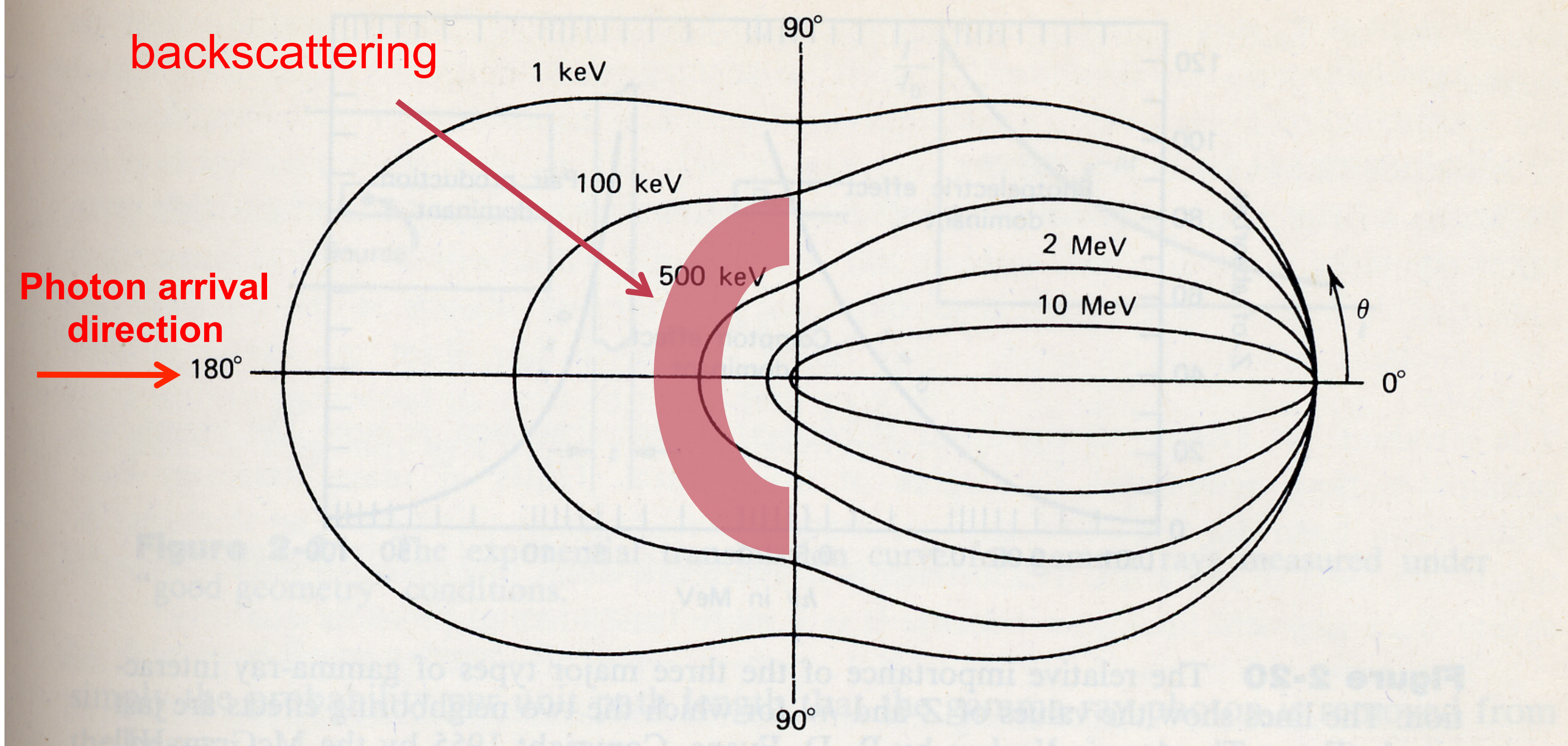



**Figure 2-19** A polar plot of the number of photons (incident from the left) Compton scattered into a unit solid angle at the scattering angle $\theta$. The curves are shown for the indicated initial energies.

# Radiation-matter interaction. X
## Compton backscattering

- θ=0° → hv'=hv, $E_{e-}$=0
- θ=180° → maximum energy transferred to the electron (hence, deposited on the detector) − Backscattering

$$E_{e-}\Big|_{\theta=\pi} = h\nu\left(\frac{2h\nu/m_0c^2}{1+2h\nu/m_0c^2}\right)$$

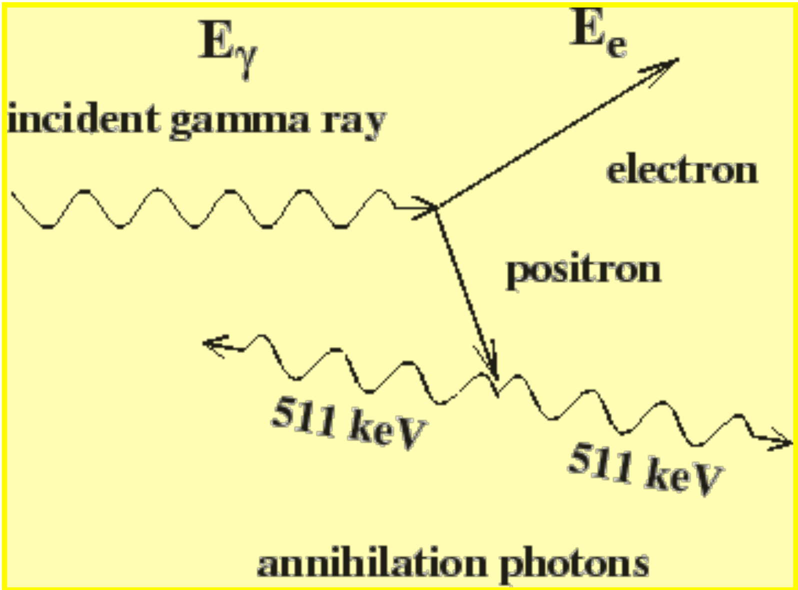
Energy of the backscattered photon:

$$h\nu'\Big|_{\theta=\pi} = \frac{h\nu}{1+2h\nu/m_0c^2}$$

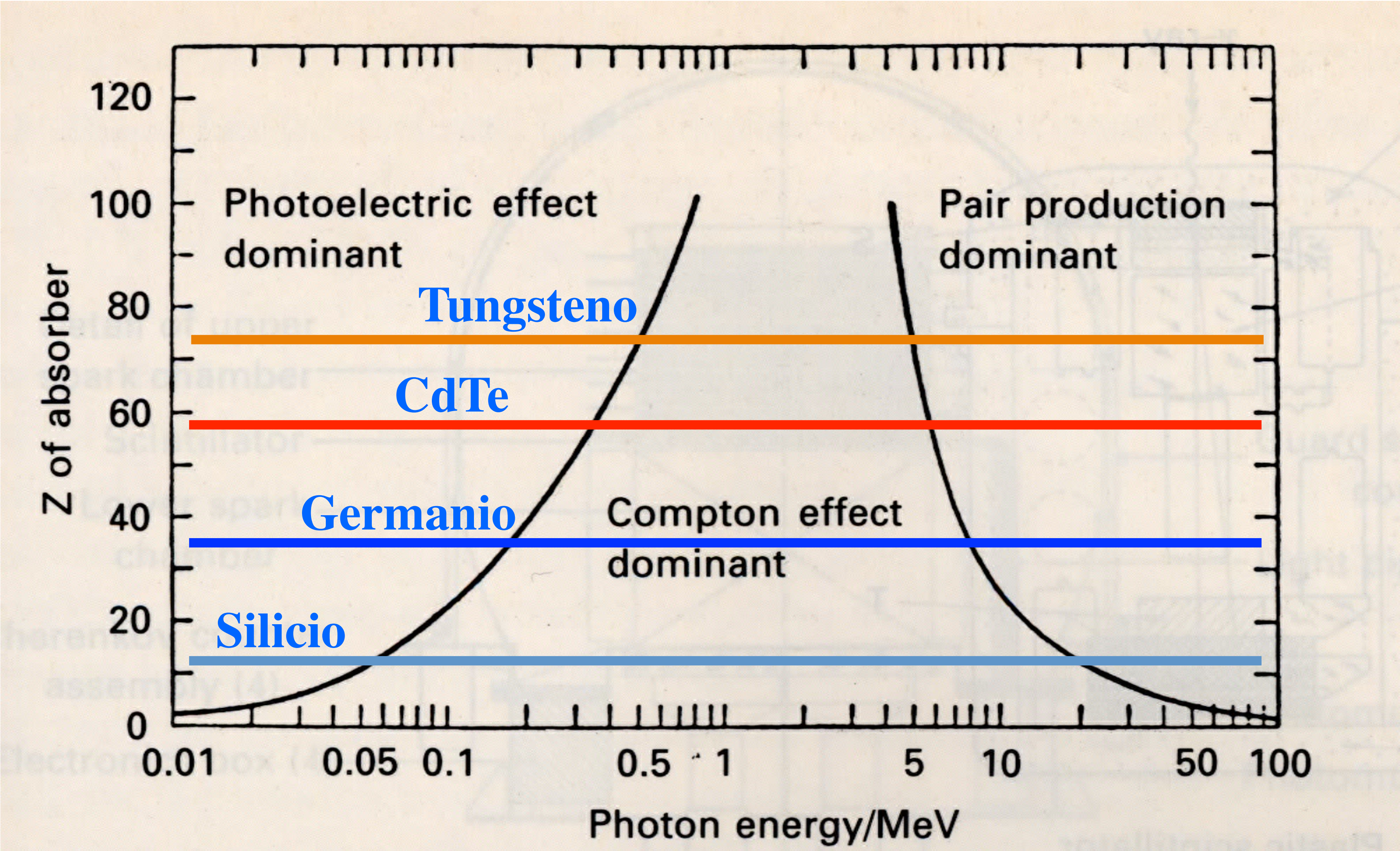
# Radiation-matter interaction. XI
## Pair production

- Energetically possible when $E_\gamma$>1.02 MeV
- The photon interacts with the electric field of the atomic nucleus and produces (is 'converted') into an *electron-positron pair*, which takes all the 'excess' energy
- The $e^+$ annihilates with an $e^-$ of the absorber and two γ-ray photons of 511 keV each are emitted in opposite directions
- Dominant process above 10 MeV (depending on the Z of the material)

$$E_{e-} + E_{e+} = h\nu - 2m_0c^2$$



Probability of interaction



# Radiation-matter interaction. XII
## Cross section and attenuation coefficient

The **cross section σ** is the area which is “offered” by the material to the photon for the interaction, and represents the probability of occurrence of a given interaction

$$\mathbf{I = I_0 \, e^{-\mu x}}$$

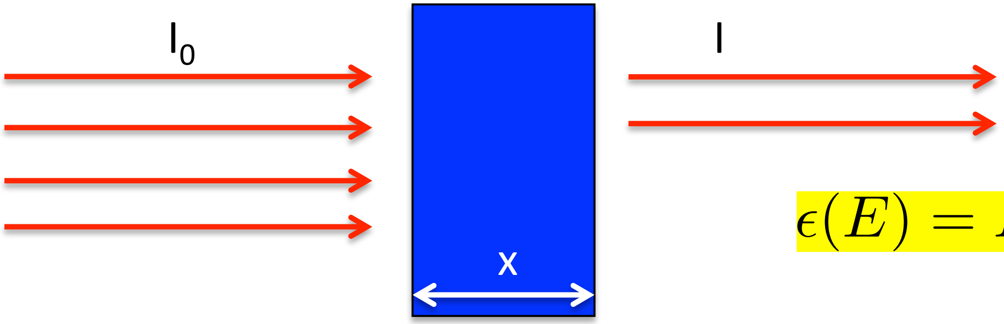
Beer-Lambert law

$I_0$=incident flux
I=output flux
x: thickness of the material

**μ=linear attenuation coefficient [$cm^{-1}$]**
**=σ×n** (n: density of the material [$cm^{-3}$])

probability of interaction of the photon with the material

**Free mean path**: **λ=1/μ=**mean path of the photon before interaction




Efficiency of detection

$$\epsilon(E) = N_{\rm det}/N_{\rm inc} = 1 - I/I_0 = 1 - e^{-\mu x}$$

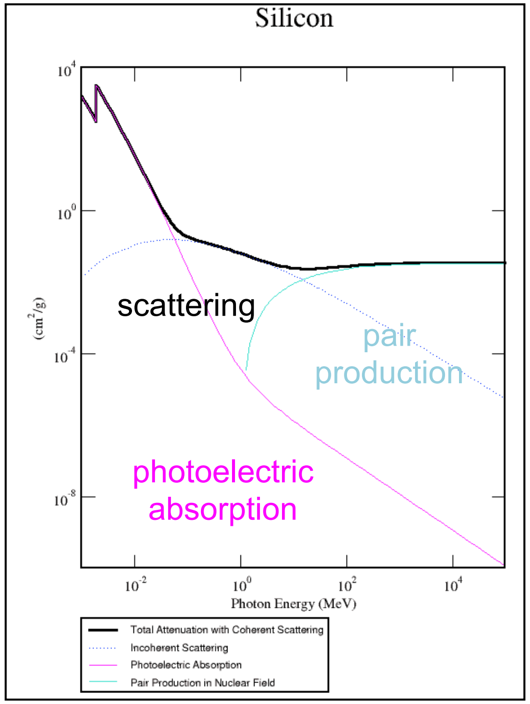
# Radiation-matter interaction. XIII
## Cross section and attenuation coefficient

- **μ/ρ=mass attenuation coefficient [cm²/g]:** capability of a material of absorbing/scattering photons of a given energy per mass unit

$$\mu = \mu_{\mathbf{ph}} + \mu_{\mathbf{compt}} + \mu_{\mathbf{pair}}$$

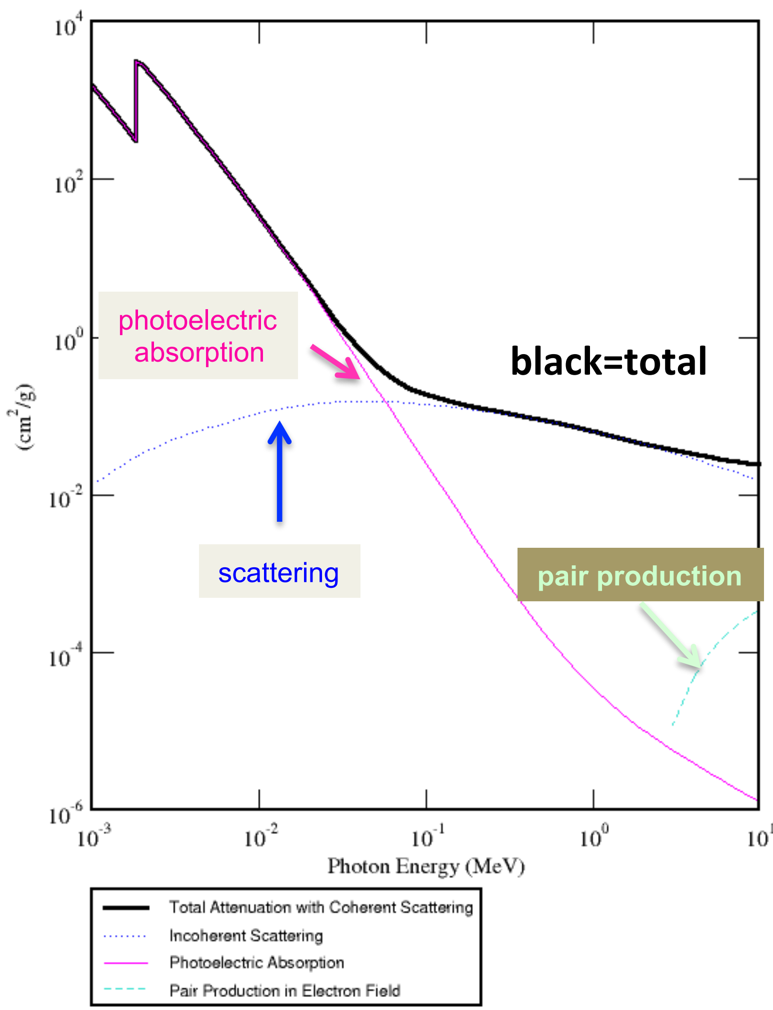
**The attenuation coefficient (linear, mass) of a material is the sum of the probabilities of the attenuation coefficients of the three possible mechanisms of interaction (each contributing mostly in a given energy range)**

(see http://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html)

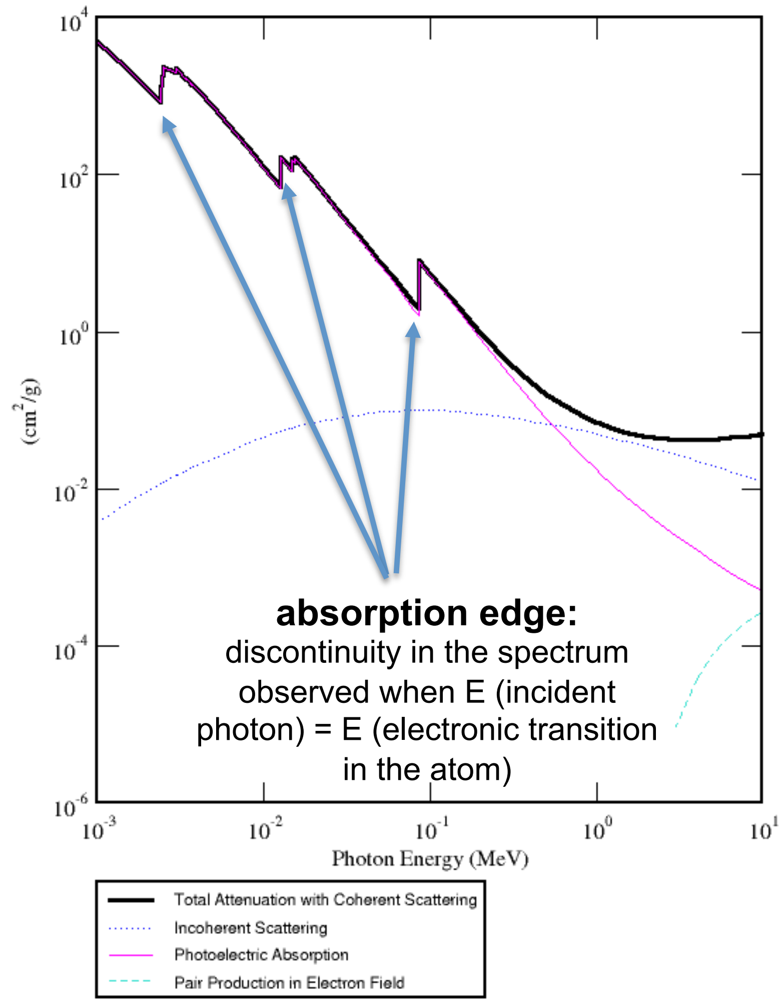


# Radiation-matter interaction. XIV
## Cross section and attenuation coefficient

Silicon Z=14




Thallium Z=81



# Radiation-matter interaction. XV
## Parameter determination of the incoming photon

**Determination of energy and position**

**DIRECT**

The X-ray photon interacts directly with the material of the detector via ionization (or photoionization)

↓

The electrons thus produced collide with the atoms producing further electrons

↓

The final outcome is an electric signal whose voltage is **proportional** to the energy deposited by the incoming photon

Esamples: proportional counters, solid-state semiconductors, scintillators…

**INDIRECT**

The γ-ray photon interacts with a tracker which produces electrons/positrons via pair production and Compton scattering

↓

The secondary particles are traced and absorbed

↓

The study of the traces left by e-/e+ and of their energy allows the *indirect* reconstruction of energy, arrival time and position of the original photon

Esamples: Si tracker + calorimeter

# Radiation-matter interaction. XVI
## How detectors work

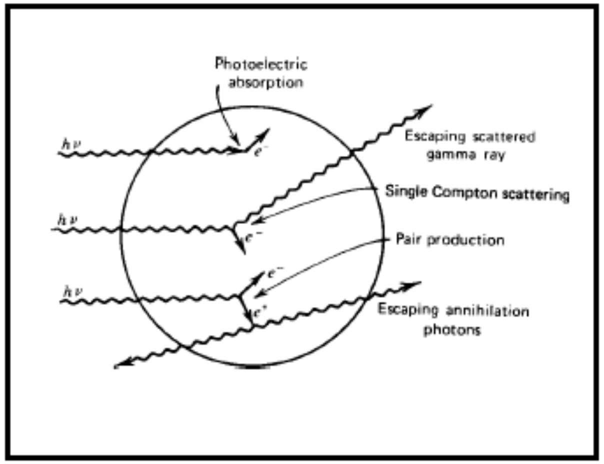



**Figure 9: "Small" detector**

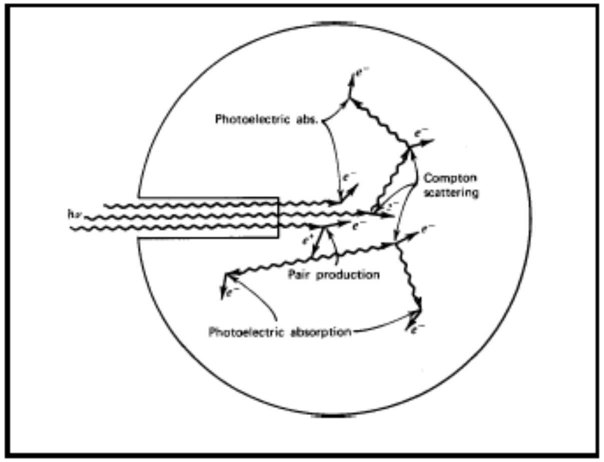



**Figure 10: "Large" detector**

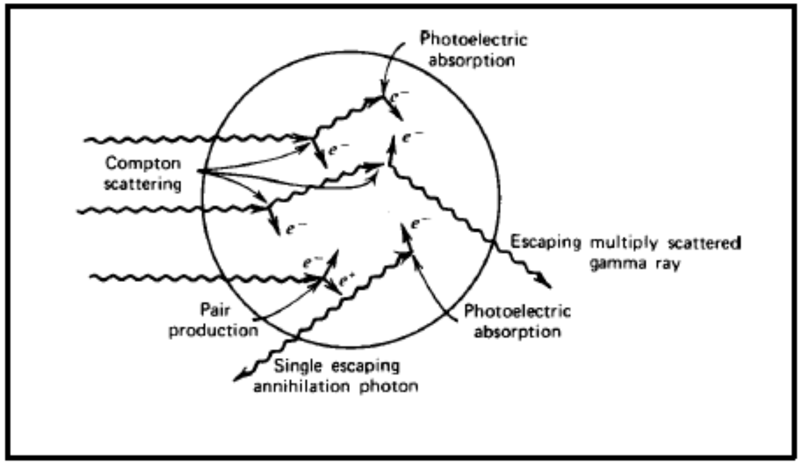



**Figure 11: Intermediately sized detector**

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# Radiation-matter interaction. XVII
## Ideal detector

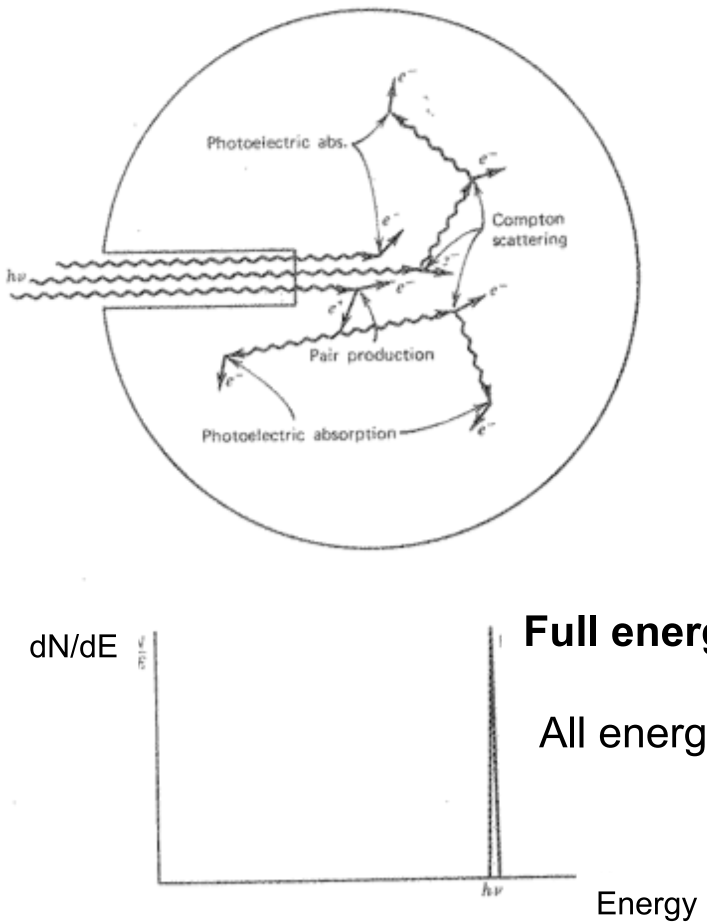



Figure 10.3 The "large detector" extreme in gamma-ray spectroscopy. All gamma-ray photons, no matter how complex their mode of interaction, ultimately deposit all their energy in the detector. Some representative histories are shown at the top.

The ideal detector is the one in which all of the incoming photons are absorbed and release their energy in the detector

In the source spectrum there is a peak (full-energy peak) at the energy of the incident photon

**Full energy peak=photopeak**
(at E=hv)
All energy is deposited in the detector

F. Knoll

# Radiation-matter interaction. XVIII
## 'Real-life' detector

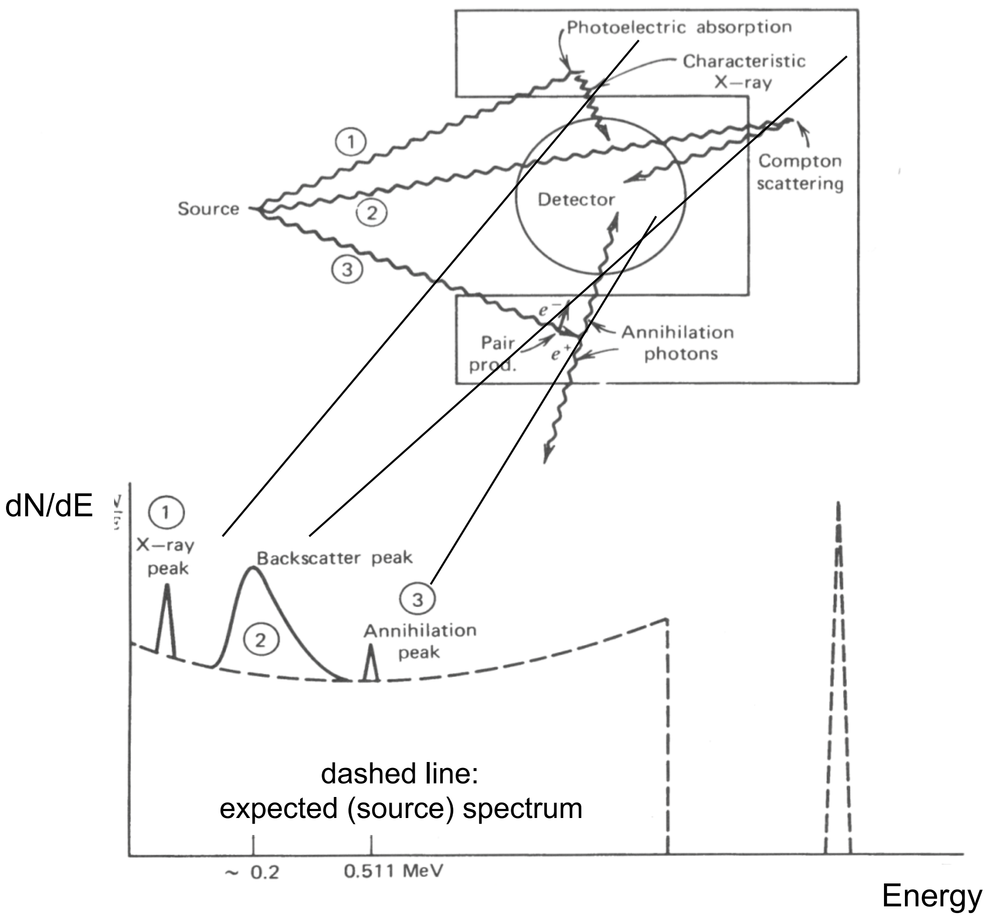


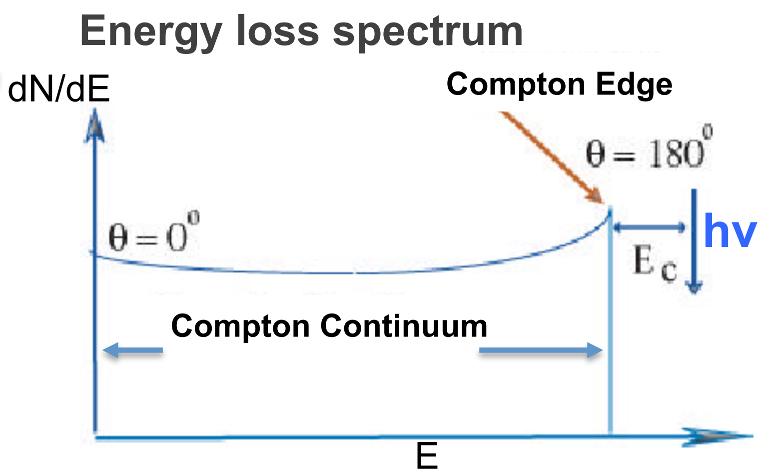

**Figure 10.6** Influence of surrounding materials on detector response. In addition to the expected spectrum (shown as a dashed line), the representative histories shown at the top lead to the indicated corresponding features in the response function.

The photon interacts also with the detector but also with the surrounding material. Fluorescence photons from it can significantly limit the detection of the source signal

F. Knoll

# Radiation-matter interaction. XIX
## Continuum and Compton shoulder

Differential distribution of electron kinetic energy




Ec≈256 keV if θ=π

**Compton continuum** (CC): a continuum of energy can be transferrred to electrons, hence to the detector. The CC is 'averaged' over all angles
The energy deposited in the detector (Ee-) is the difference between the incident and the scattered photon energy:
Ee-=hv-hv', where Ee- can take any value between 0 and $E|_{\theta=\pi}$

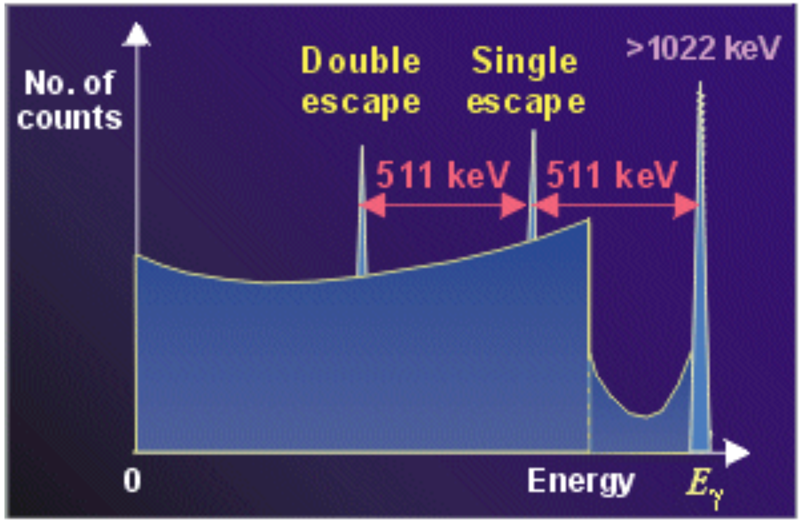
$E_C$=separation between the energy of the incident photon (photopeak) and the energy of the **Compton edge (θ=π)**, related to the Compton shoulder:

$$E_C \equiv h\nu' = h\nu - E_{e-}\Big|_{\theta=\pi} = \frac{h\nu}{1+2h\nu/m_0c^2}$$

$h\nu \gg m_0c^2/2$

$$E_C = \frac{m_0c^2 h\nu}{m_0c^2+2h\nu} \rightarrow \frac{m_0c^2 h\nu}{2h\nu} = \frac{m_0c^2}{2} \quad (\cong 256\,keV)\text{ if }(2h\nu \rangle\rangle m_0c^2)$$

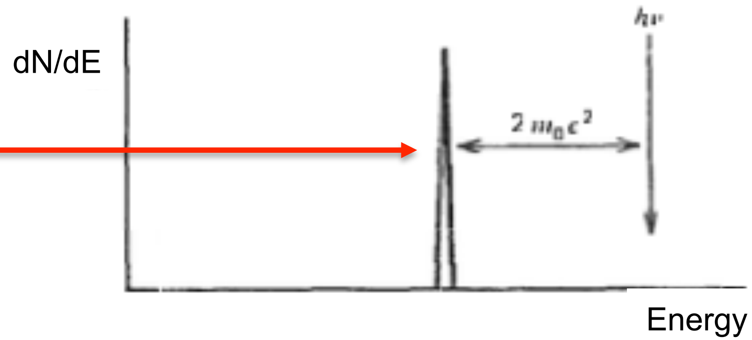
# Radiation-matter interaction. XX
## Single- and double-escape peaks




In case of pair production and following photon annihilation, one or both photons (511 keV) may escape the detector: single- and double-escape peaks at an energy equal to the energy of the primary photon minus either 511 keV or 1.02 MeV

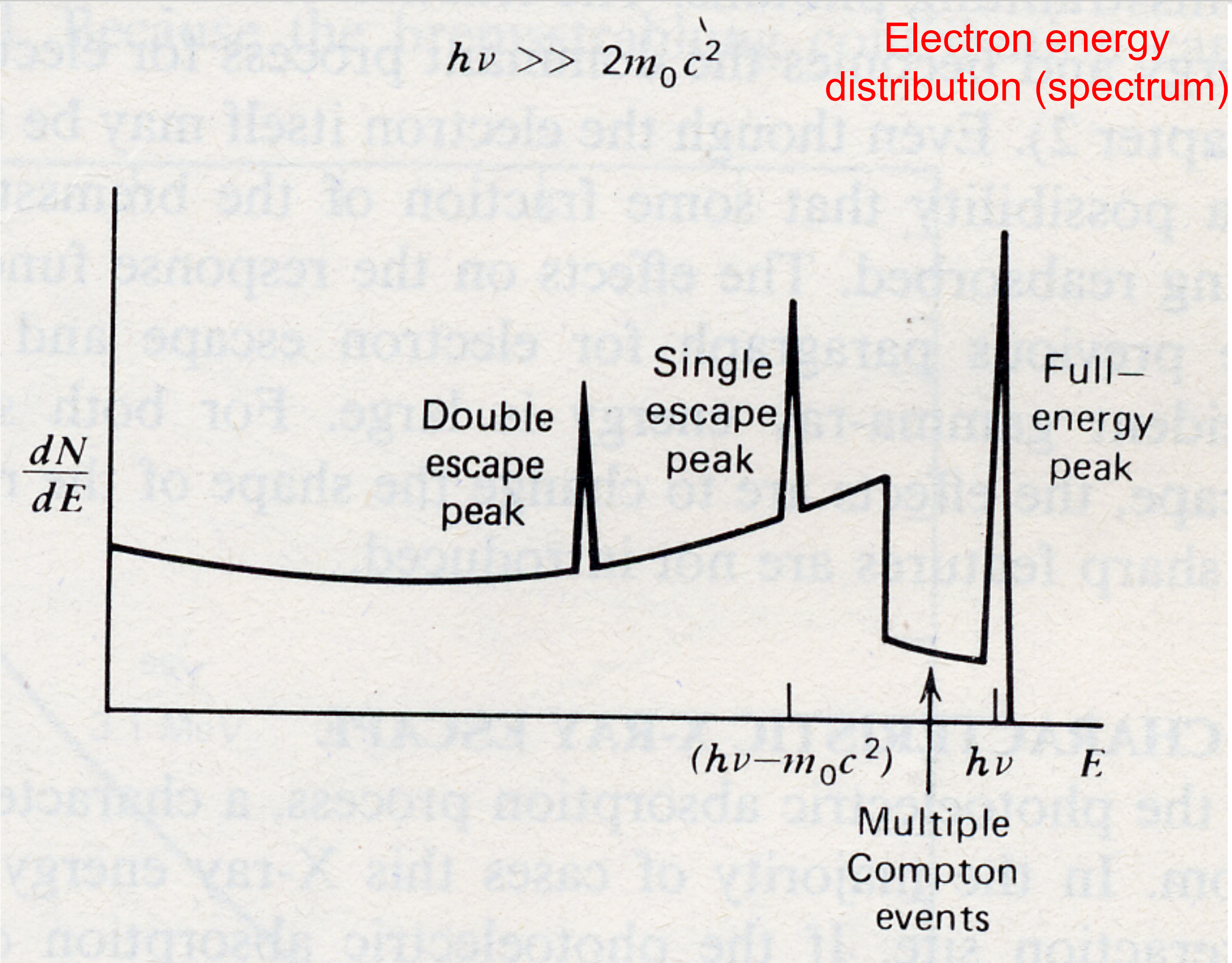
kinetic energy E incident photon E pair creation

$$E_{e-} + E_{e+} = h\nu - 2m_0c^2$$




The kinetic energy of e-/e+ is transferred to the detector *medium*, while the two 511 keV photons produced by positron annihilation are supposed to escape from the detector (double-escape peak)
Probability scales as $Z^2$

# Radiation-matter interaction. XXI
## Single- and double-escape peaks



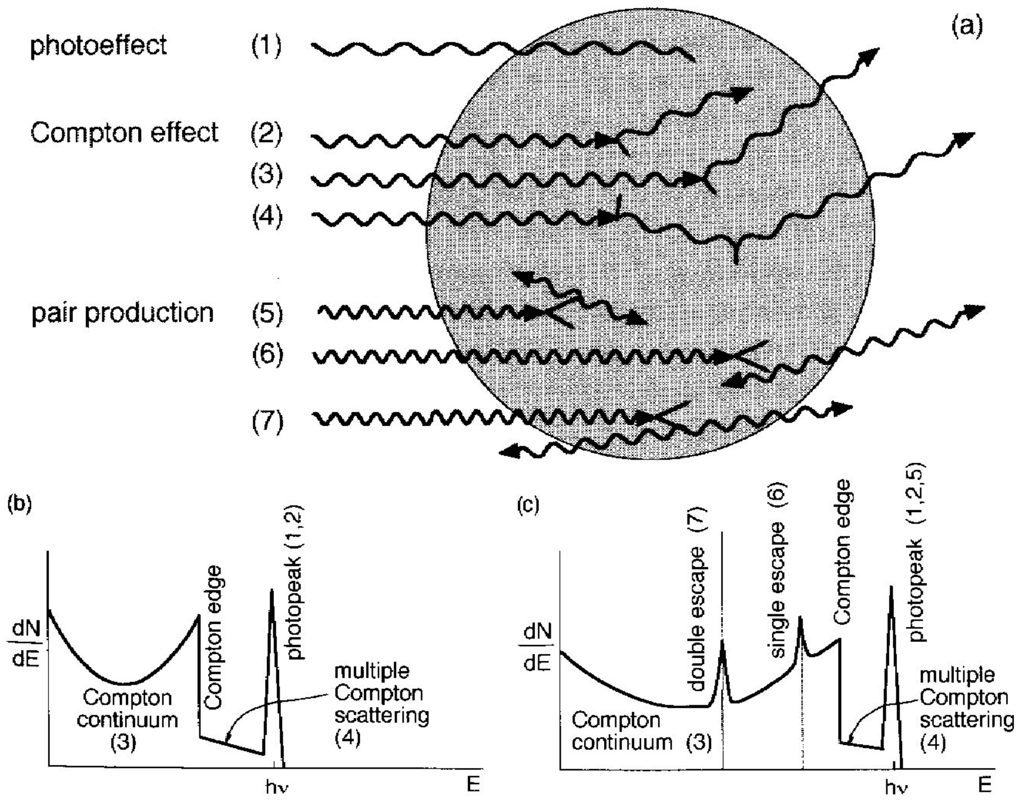

Case of intermediate-size detector (Knoll)

**Photo-peak (full-energy peak)**: all photoelectric events remain in the detector and produce an energy deposit at the energy of the incoming photon

**Single-escape peak**: one annihilation photon (i.e., produced by positron annihilation) leaves the detector without further interaction

**Double-escape peak**: both annihilation photons leave the detector (escape)

# Radiation-matter interaction. XXII
## Final spectrum




High-Energy Spectroscopic Astrophysics, SAAS-Fee Adv. Course 30, 2000

Detecting signals in the X-ray and γ-ray band. Some parameters of interest: angular and spectral resolution, sensitivity, SNR

# Effective area. I

Mirrors — Detector

$$A_{effective}(E,\theta,x,y) = A_{geometric} \times R(E) \times V(E,\vartheta) \times QE(E,x,y)$$

**Effective area** — Geometric area — Reflectivity — Vignetting — Quantum Efficiency

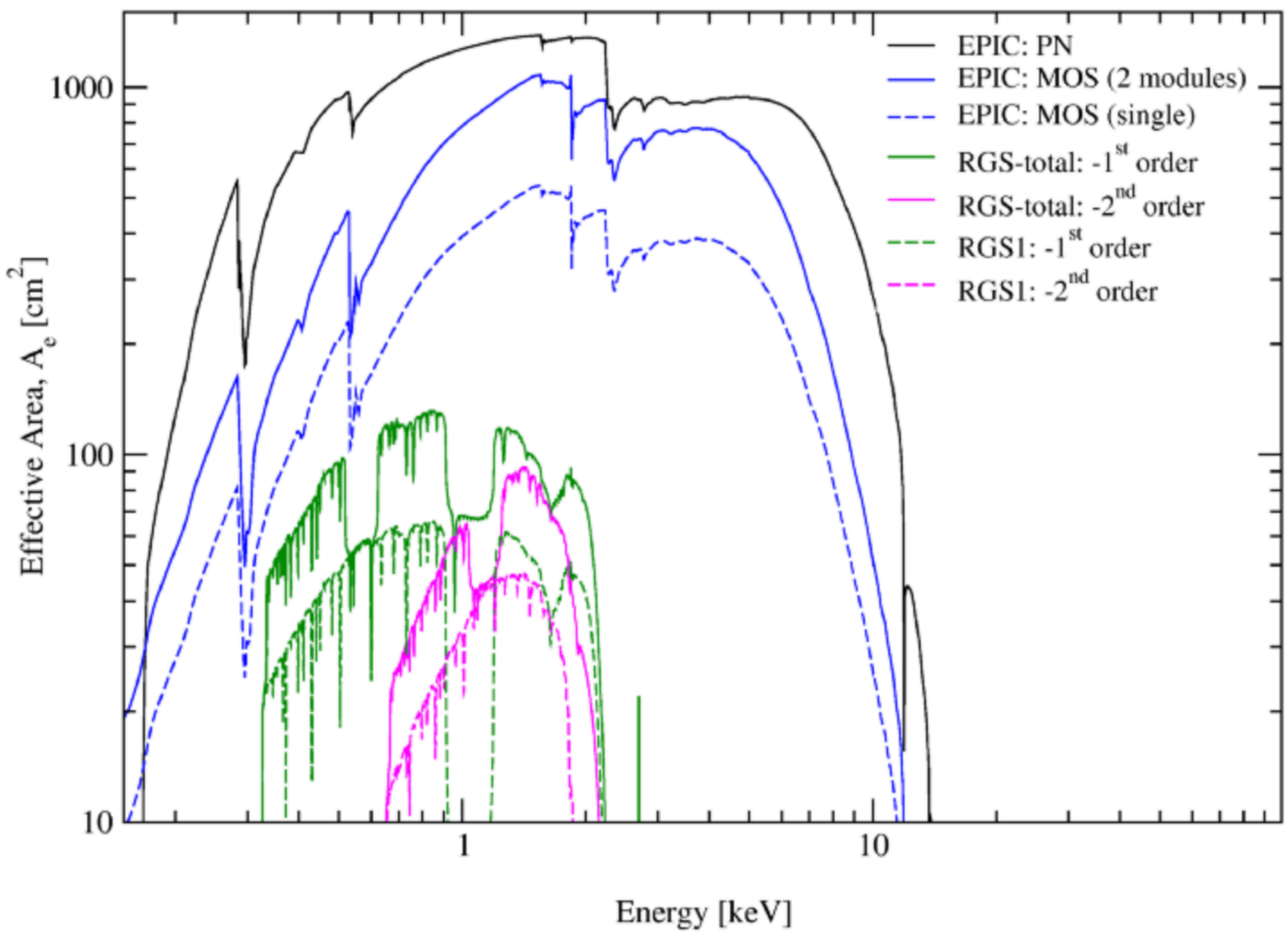
**Most quantities depend on the energy of the photons**

- **Effective area** – in $cm^2$
- **Geometric area** – 'cross section' of the telescope
- **Reflectivity** – fraction of photons reflected by the mirrors
- **Vignetting** – fraction of photons lost as a function of the distance wrt. the optical axis ($\vartheta$)
- **Quantum Efficiency** – fraction of incident photons registered by the detector. (x,y) represents the position on the detector

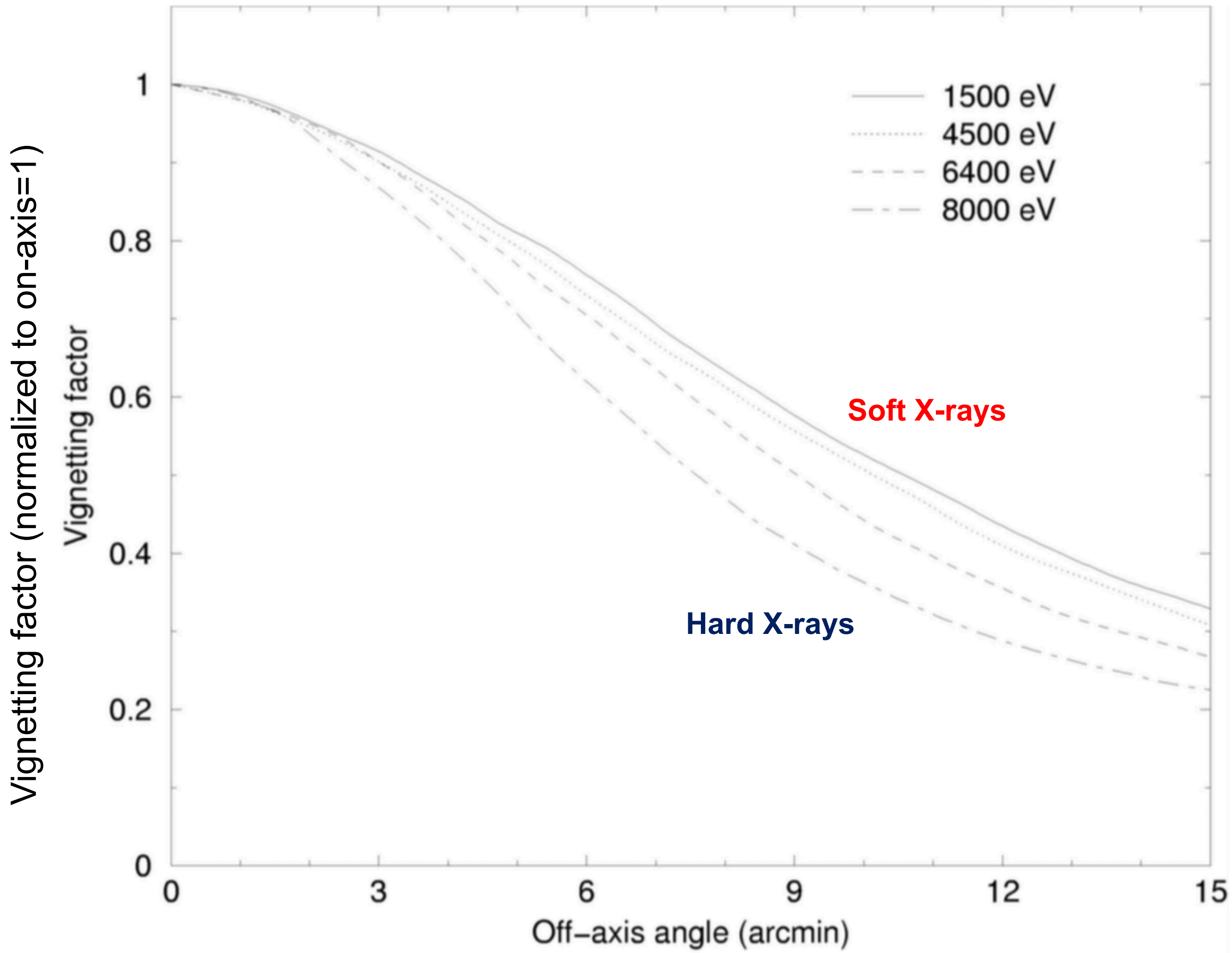
**The effective area represents the capability of the telescope+detector to collect photons**

# Effective area. II

**XMM-*Newton* on-axis effective area** (all instruments)



# Vignetting

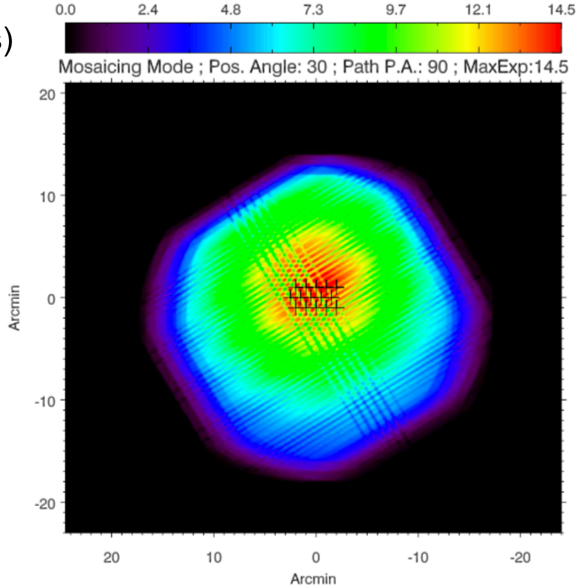



More challenging to focus hard X-ray photons

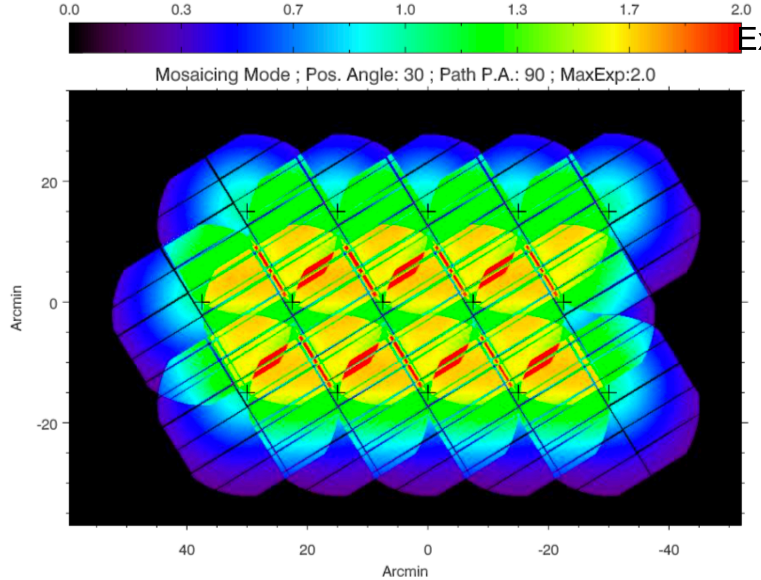
# Vignetting and offset

1 arcmin offset

ExpTime (ks)

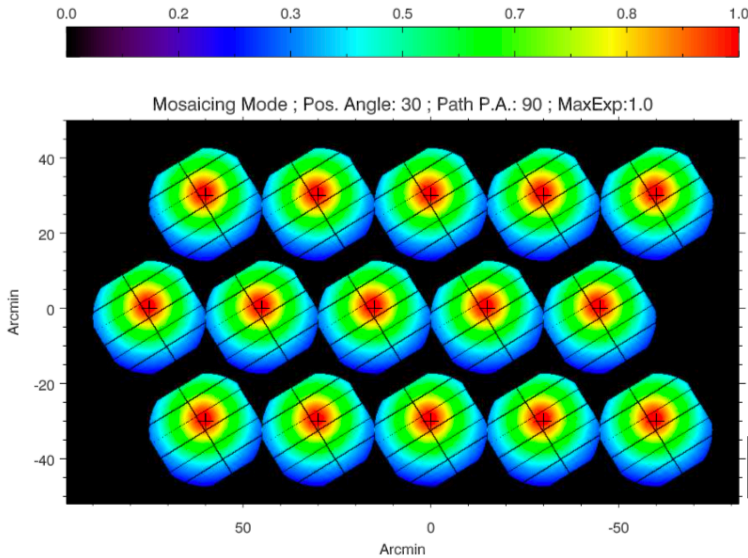



15 arcmin offset




ExpTime (ks)

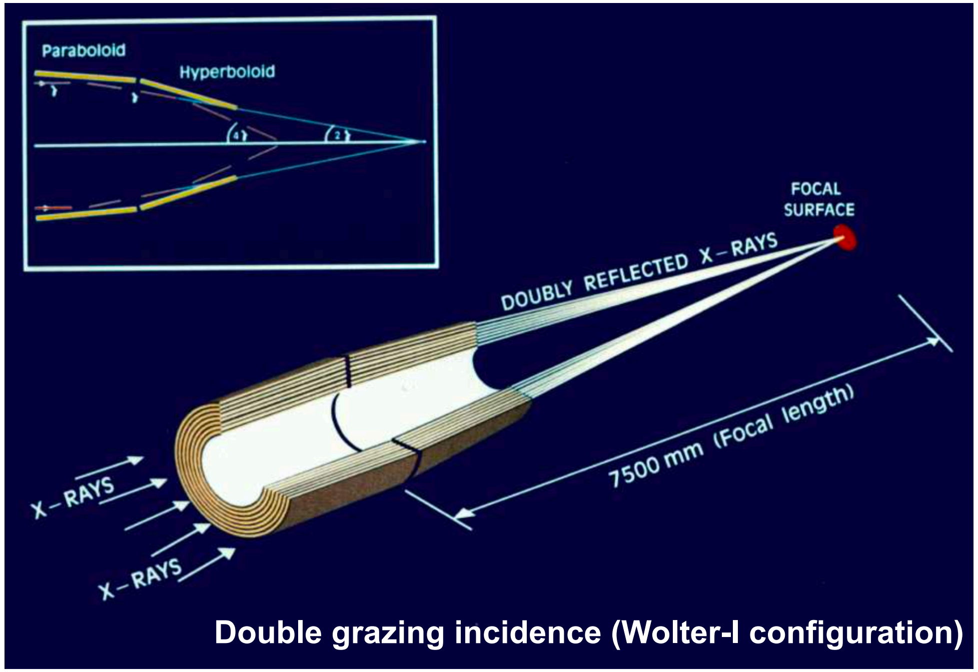
XMM-*Newton* mosaic mode observations (simulations)



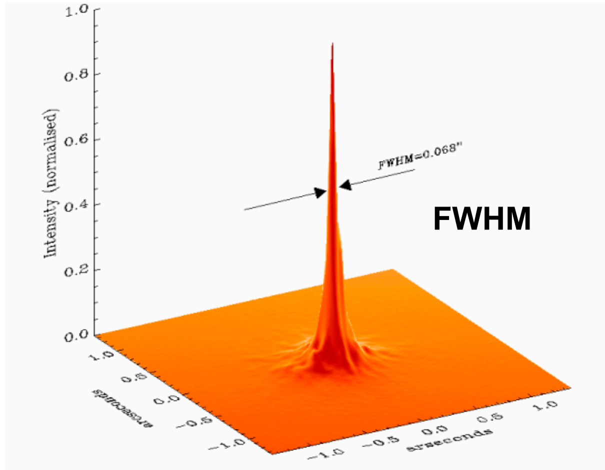

ExpTime (ks)

30 arcmin offset

# Mirrors and PSF (angular resolution). I



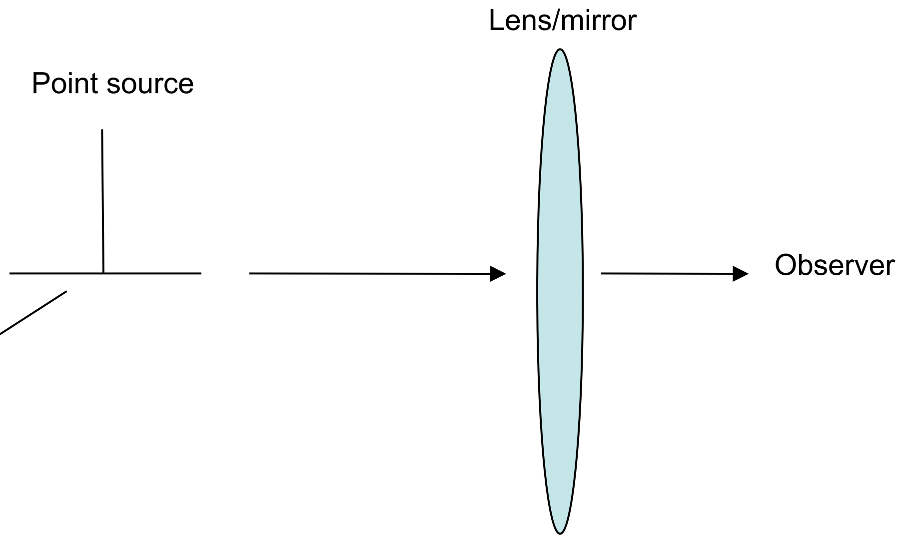

**Double grazing incidence (Wolter-I configuration)**




PSF: describes the shape of a point-like source in the detector and is a measure of the angular resolution

**PSF in X-rays is a function of the energy and off-axis angle**

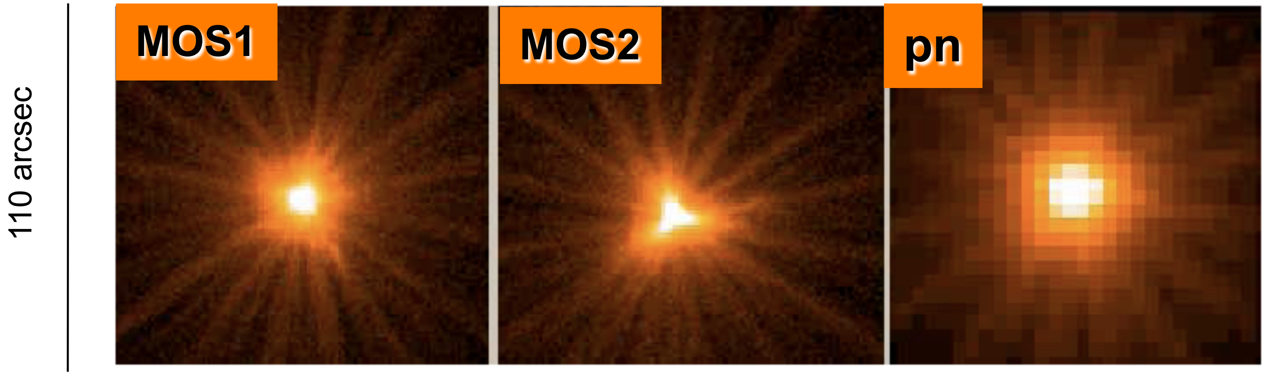
FWHM, HEW: the latter is a more useful measure when the PSF is not Gaussian



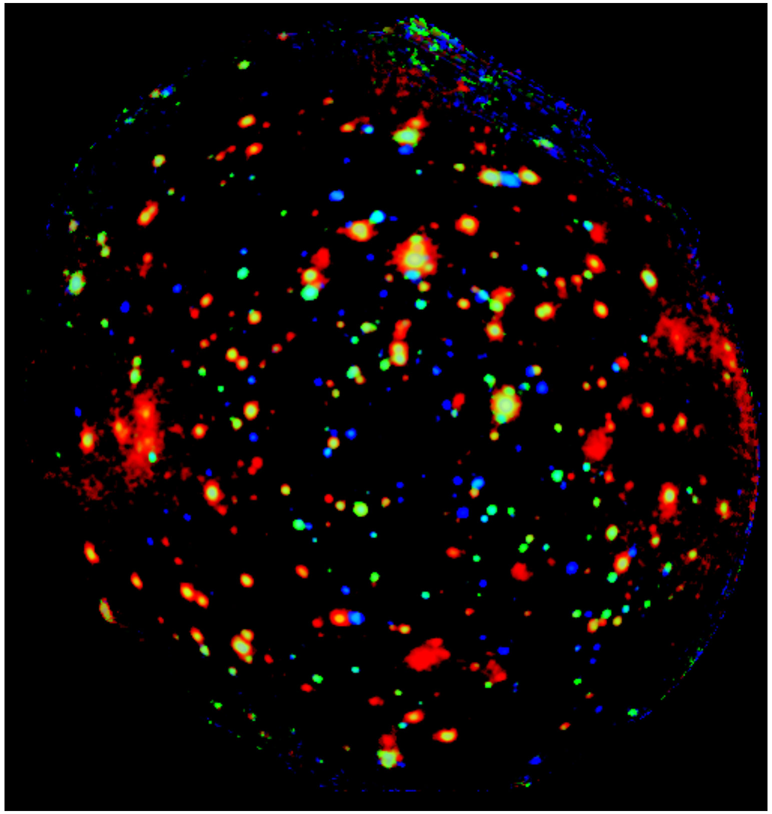

Intrinsic (diffraction) limit: $\theta=1.22\ \lambda/D$ (Rayleigh criterion) BUT not in X-rays

Main limitation in the optical: seeing
Main limitation in X-rays: mirrors (and detector pixel size)

# Mirrors and PSF (angular resolution). II

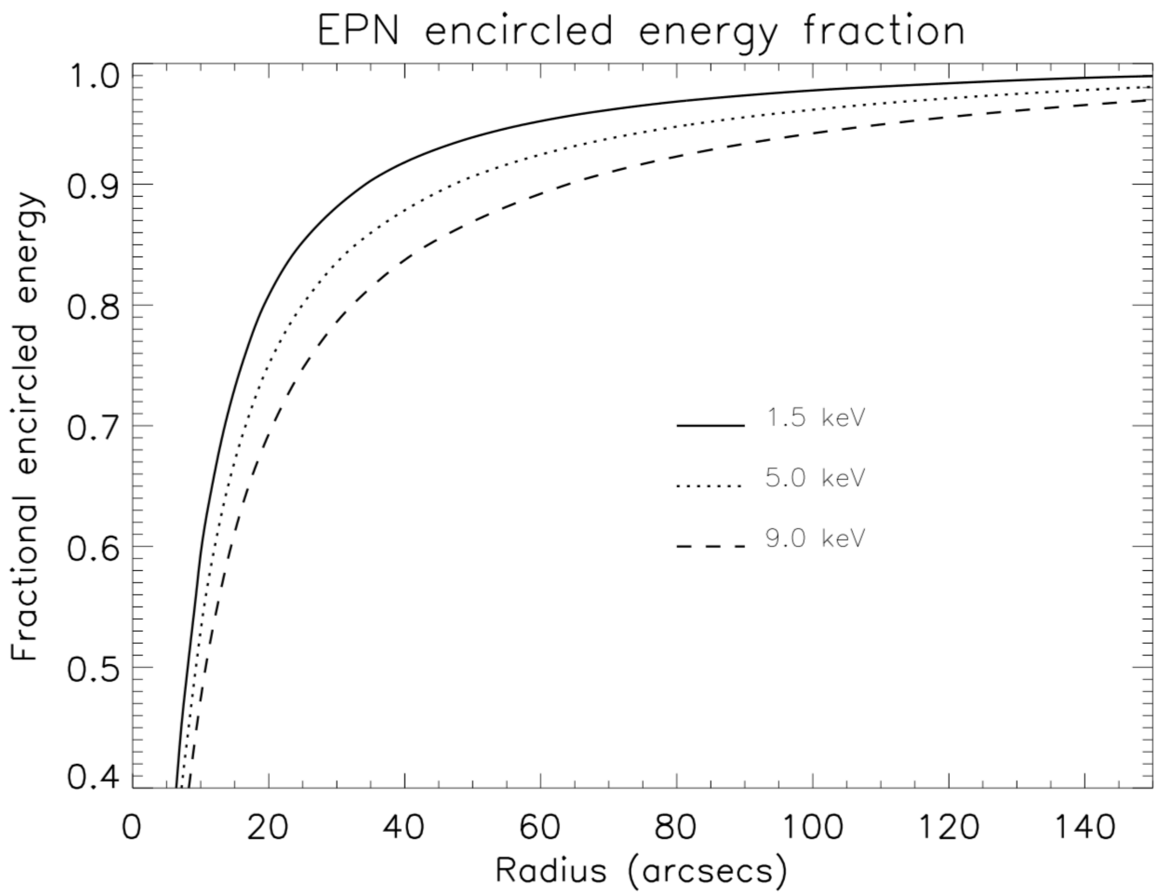



XMM-*Newton* EPIC camera (pn, MOS1, MOS2) on-axis PSF
MOS2 in particular is far from being Gaussian



XMM-*Newton* pn+MOS1+MOS2 3Ms exposure in the CDF-S
Sources at large off-axis (far from the center) appear larger because of the PSF degradation as a function of θ

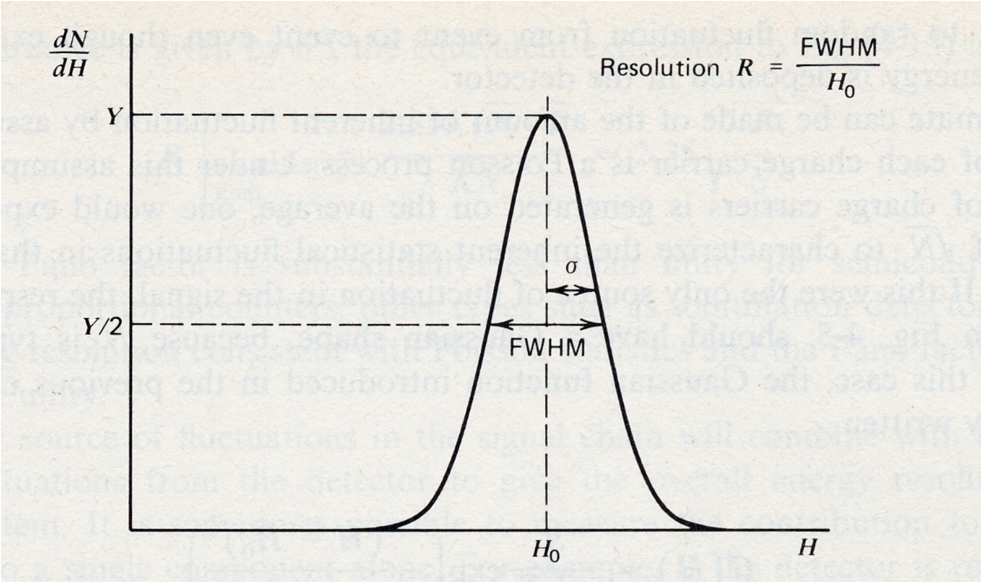
# Mirrors and PSF (angular resolution). III




Angular resolution is often 'replaced' by the **encircled energy fraction**, i.e. the fraction of photons collected within a given aperture (extraction radius). It depends on the energy and the position (x,y, θ) in the detector. It is also referred to as the bi-dimensional PSF

# Spectral (energy) resolution. I

Capability of discriminating photons at at different energies (i.e., features at close energies)



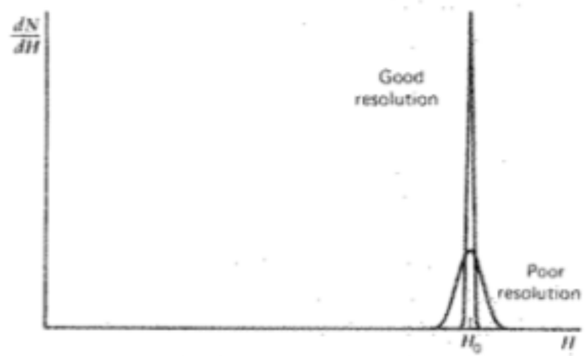




**Figure 4.4** Examples of response functions for detectors with relatively good resolution and relatively poor resolution.

$H_0$=pulse proportional to the number of charge carriers (photons)=KN

$$R_{Poisson} = \Delta\lambda/\lambda = \frac{FWHM}{H_0} = \frac{2.35\sigma}{KN} = \frac{2.35K\sqrt{N}}{KN} = 2.35/\sqrt{N}$$

$$\Rightarrow \quad R_{Stat.Limit} = 2.35\sqrt{\frac{F}{N}}$$

F=Fano factor: not a purely Poissonian distribution

Energy (spectral) resolution depends on the inverse square root of the number of charge carriers

# Spectral (energy) resolution. II

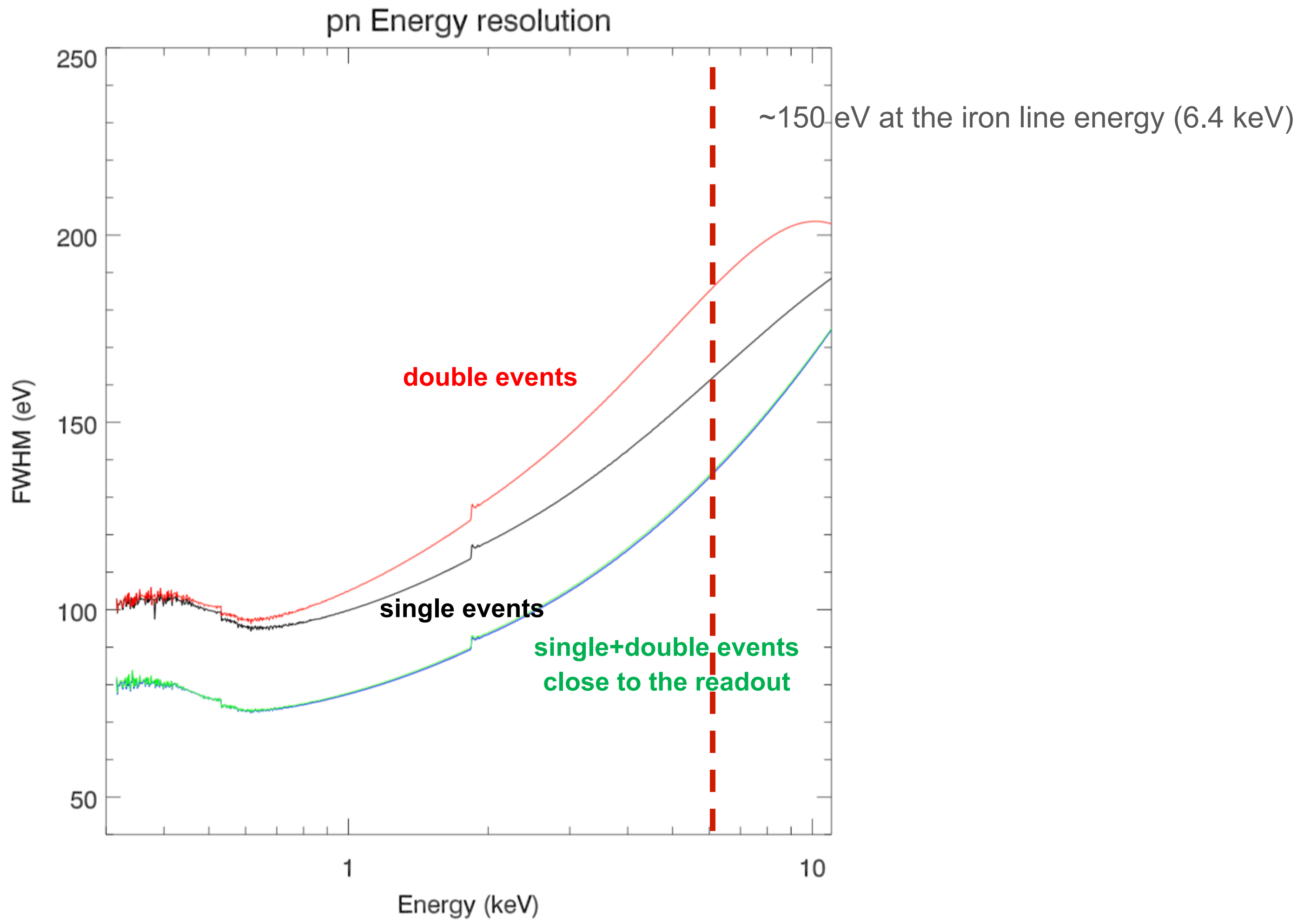
Situation can be more complex when all the relevant terms concurring to the energy resolution are properly considered

$$R^2 = R_{np}^2 + R_{inh}^2 + R_{tr}^2 + R_{\lim}^2$$

- $R_{np}$ = in some scintillators, the number of emitted photons can be not proportional to the deposited energy
- $R_{inh}$ = crystal inhomogeneity inducing local light efficiency variations
- $R_{tr}$ = light collection efficiency
- $R_{lim}$ = 2.35*[(1+$\sigma_{PM}$)/$N_{phe}$]$^{1/2}$, where:
  - $\sigma_{PM}$= PMT gain variance
  - $N_{phe}$= no of photo-e- emitted by PMT

# Spectral (energy) resolution. III

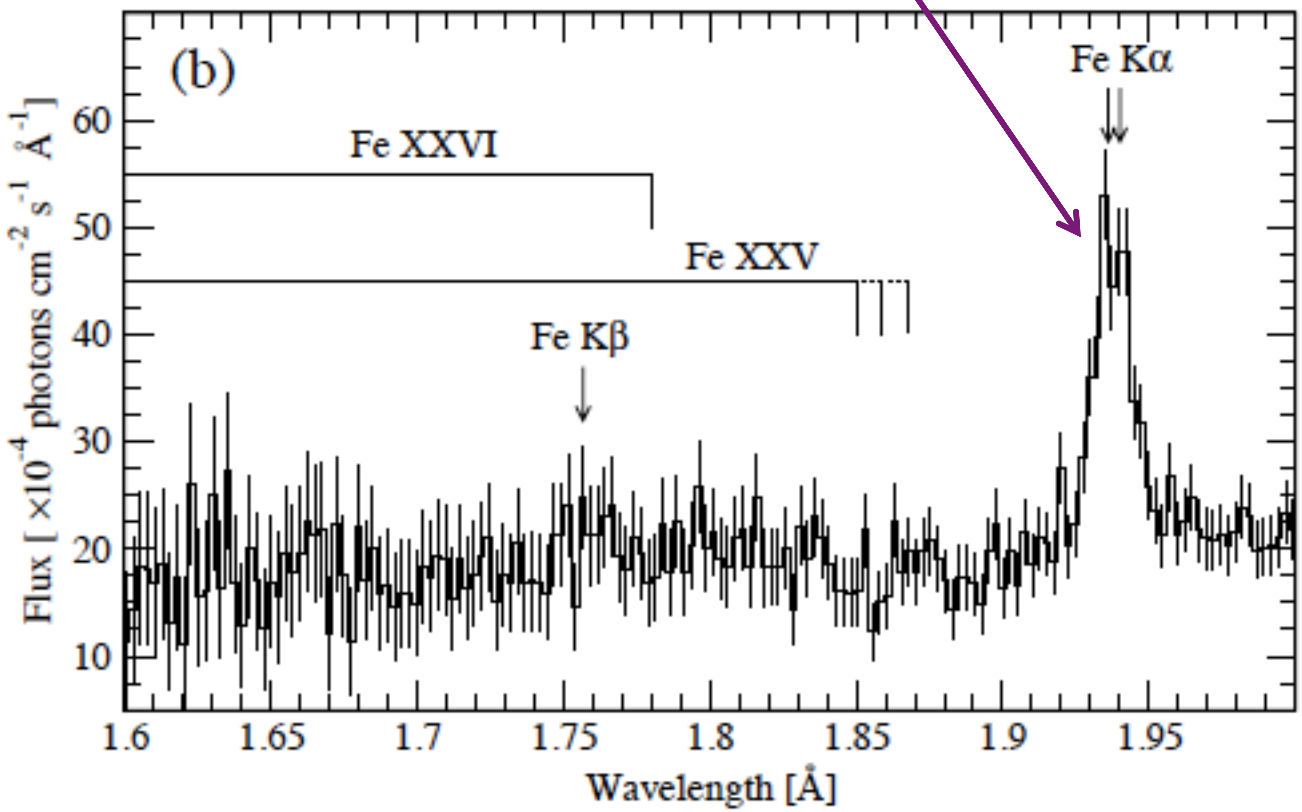
Energy resolution depends on the energy of the photons and on other stuff



# Spectral (energy) resolution. IV

Energy resolution depends on the energy of the photons and on other stuff

Neutral iron 6.4 keV fluorescence line – unresolved doublet




Kaspi et al. 2002 – NGC 3783 - Sey 1
*Chandra*, grating observation

# Sensitivity and signal-to-noise ratio. I

**Sensitivity: minimum detectable flux**

(continuum emission: photons/cm$^2$/s/keV; line emission: photons/cm$^2$/s)

- $\mathbf{C_S}$= source counts
- $\mathbf{C_{bkg}}$= background counts

$$SNR = n_\sigma = \frac{C_S}{\sqrt{C_S + C_{Bkg}}}$$

$$S = (S + B) - B \longrightarrow \sigma_S^2 = \sigma_{S+B}^2 + \sigma_B^2 =$$

$$= (\sqrt{(S + B)})^2 + (\sqrt{B})^2 = S + B + B = S + 2B$$

$$SNR = S / \sigma_S = S / \sqrt{(S + 2B)}$$

# Sensitivity and signal-to-noise ratio. II

$S = \varepsilon \; A \; T \; \Delta E \; F_{src}$
$B = \; A \; T \; \Delta E \; F_{bkg}$

$\varepsilon$=efficiency in source count detection
A=effective area
T=exposure time
$\Delta E$=observing band
$F_{src}$=source flux
$F_{bkg}$=background flux

$B \ll \varepsilon \; F_{src}$
source dominates the signal

$$SNR = \frac{S}{\sqrt{S+2B}} \approx \sqrt{S} \propto \sqrt{F_{src} T}$$

$B \gg \varepsilon \; F_{src}$
back dominates the signal

$$SNR = \frac{S}{\sqrt{S+2B}} \approx S/\sqrt{2B} \propto \sqrt{T}(F_{src}/\sqrt{2F_{bkg}})$$

Signal-to-noise ratio and sensitivity

$$\mathrm{SNR} = n_\sigma \approx \frac{\varepsilon \cdot \mathrm{A} \cdot \mathrm{T} \cdot \Delta\mathrm{E} \cdot \mathrm{F}}{\sqrt{\mathrm{A} \cdot \mathrm{T} \cdot \Delta\mathrm{E} \cdot \mathrm{B}}} \rightarrow F_{Min} = \frac{n_\sigma}{\varepsilon} \sqrt{\frac{B}{\mathrm{A} \cdot \mathrm{T} \cdot \Delta\mathrm{E}}}$$

# Sensitivity and signal-to-noise ratio. III

In the "real world", background comprises instrumental background + cosmic background

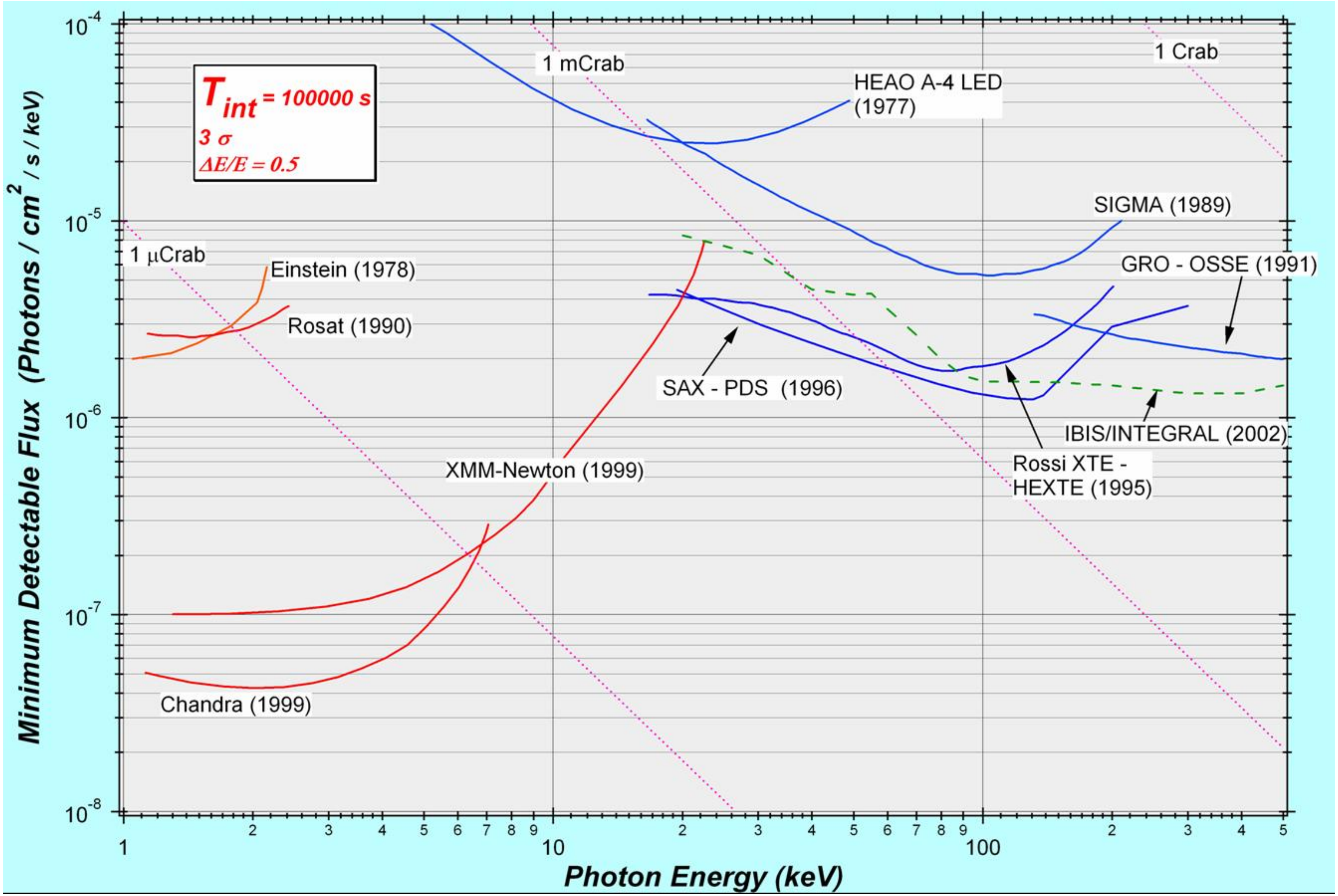
S=source flux density [counts/$m^2$ s]
A=area of the detector
Ω=solid angle subtended by the beam of the telescope on the sky
$B_1$=instrumental (particle) background [counts/s]
$B_2$=cosmic background (XRB) [phot/$m^2$ s ster]
T=exposure time
**SOURCE**=S×A×T (photons related to the source)
**BACKGROUND**=$B_1$×T + $B_2$×A×Ω×T (photons related to the backgrounds)

$$N = \sqrt{(B_1 + B_2 A\Omega) \times T}$$

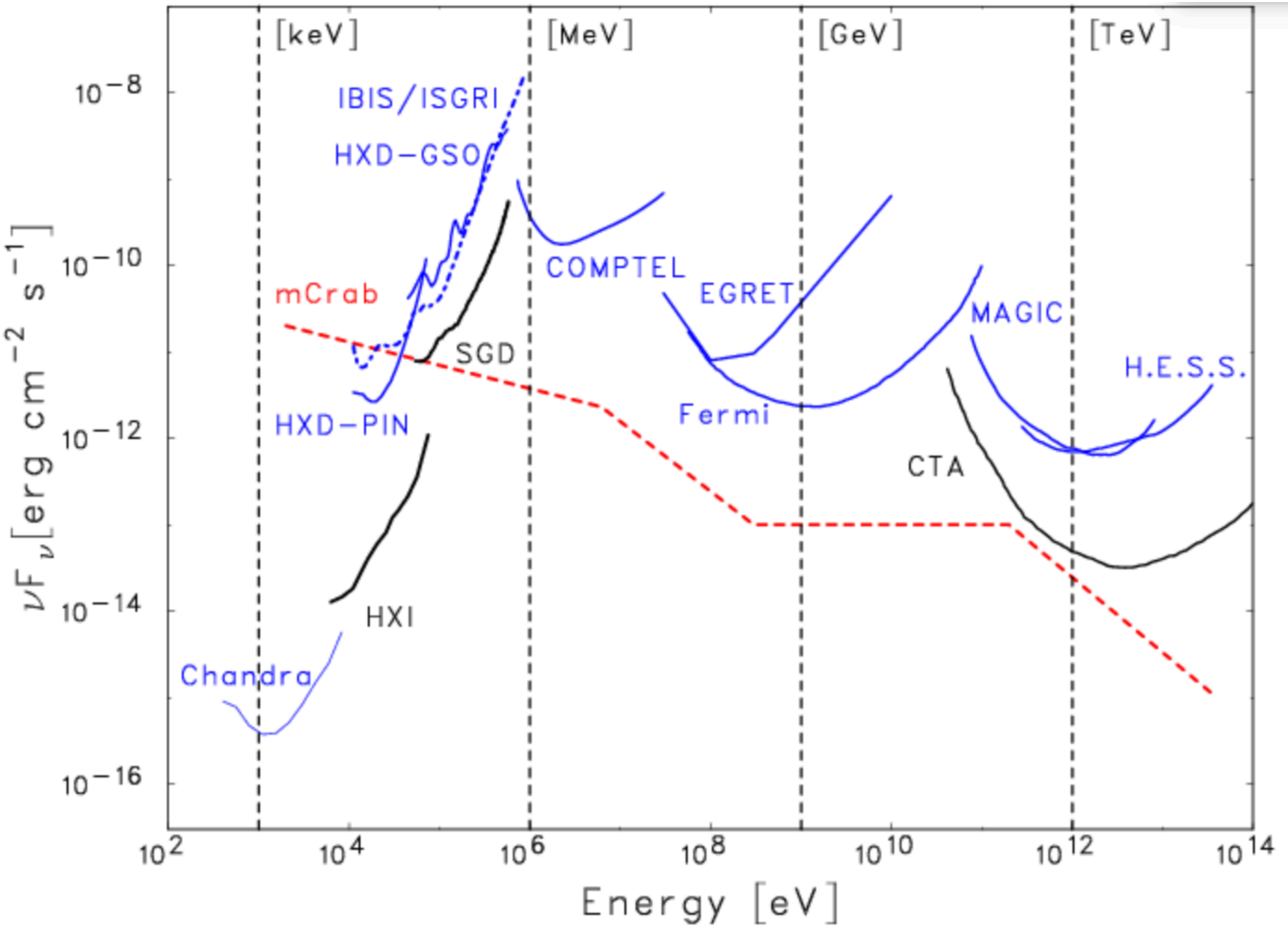
$$S/N = \frac{SAT}{\sqrt{(B_1 + B_2 A\Omega) \times T}} = \frac{SA^{1/2}T^{1/2}}{\sqrt{\left(\frac{B_1}{A}\right) + \Omega B_2}}$$

$$S/N = 5 \Rightarrow S_{\min} = 5\sqrt{\frac{B_1/A + \Omega B_2}{AT}}$$

# Sensitivity and signal-to-noise ratio. IV



# Sensitivity and signal-to-noise ratio. V




Credits: V. Fioretti, A. Bulgarelli

# Source confusion

# Source confusion. I

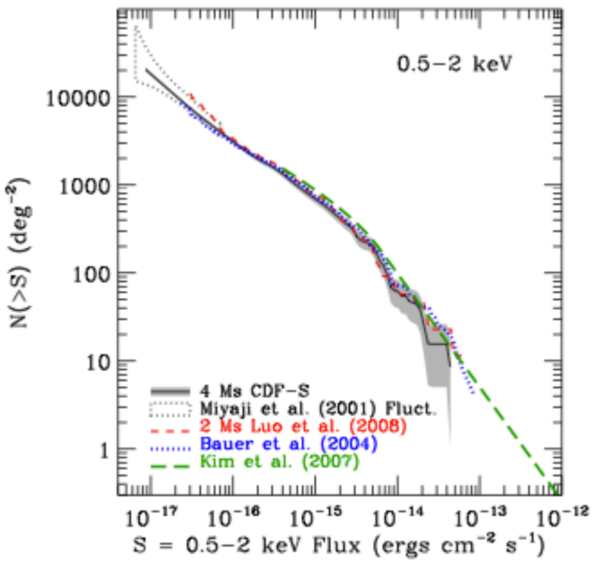
**Confusion:** the "sea" of undetected sources fainter than the detection limit creates a noise in the sky. This "creates" a limit to the depth of the observations (i.e., longer observations do not imply going deeper) = function (#src, PSF)

Standard rule-of-thumb: confusion is important at 30(40) beams per source (a sort of area of avoidance)

Beam=1-σ radius of circle of the Gaussian PSF: $\Omega_{beam}=\pi\sigma^2$

s/b=number of sources per beam at a given flux level S= number of sources N(>S)/number of beams in the solid angle of the image ($\Omega_{image}/\Omega_{beam}$)

LogN-LogS Chandra Deep Field South

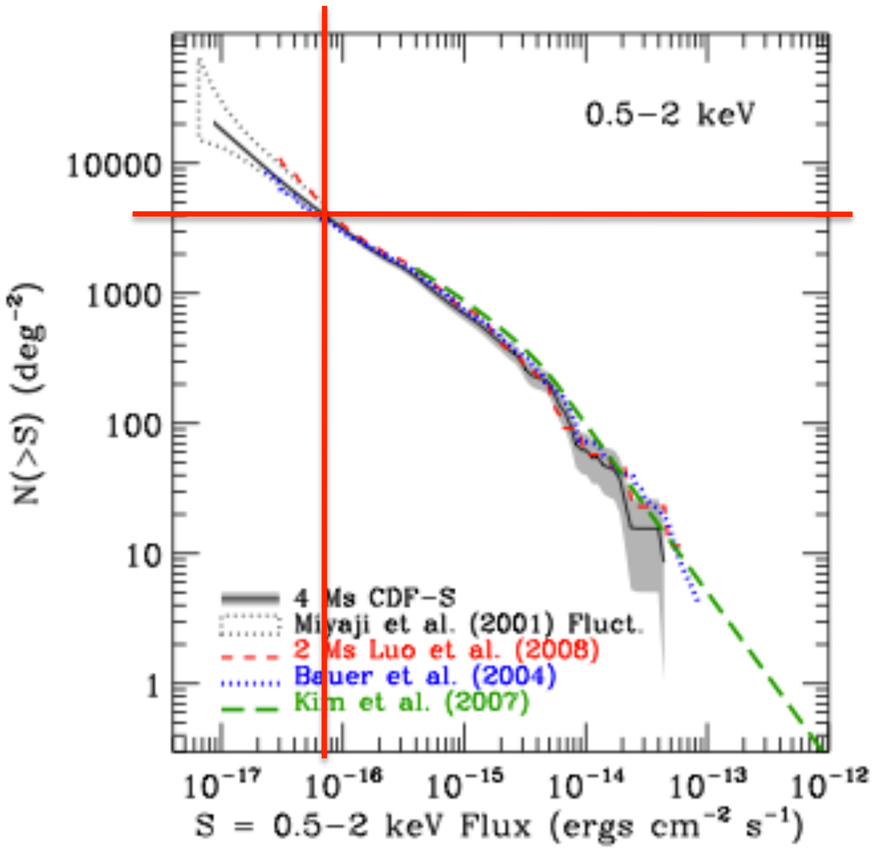



**Example**

$\Omega_{image}$=512×512 pix=262144 pix$^2$
FWHM=4 pix ➔ σ=4/2.34=1.7 pix
➔ $\Omega_{beam}$=9.1 pix$^2$

➔$\Omega_{image}/\Omega_{beam}=2.88\times10^4$ "independent" beams / 30(40) beams/src vs. N(>S) to check/quantify the flux limit below which it becomes being relevant

# Source confusion. II




Example

$\Omega_{image}$=Field-of-View=1 deg$^2$

PSF HPD=10” ➔ σ=5”

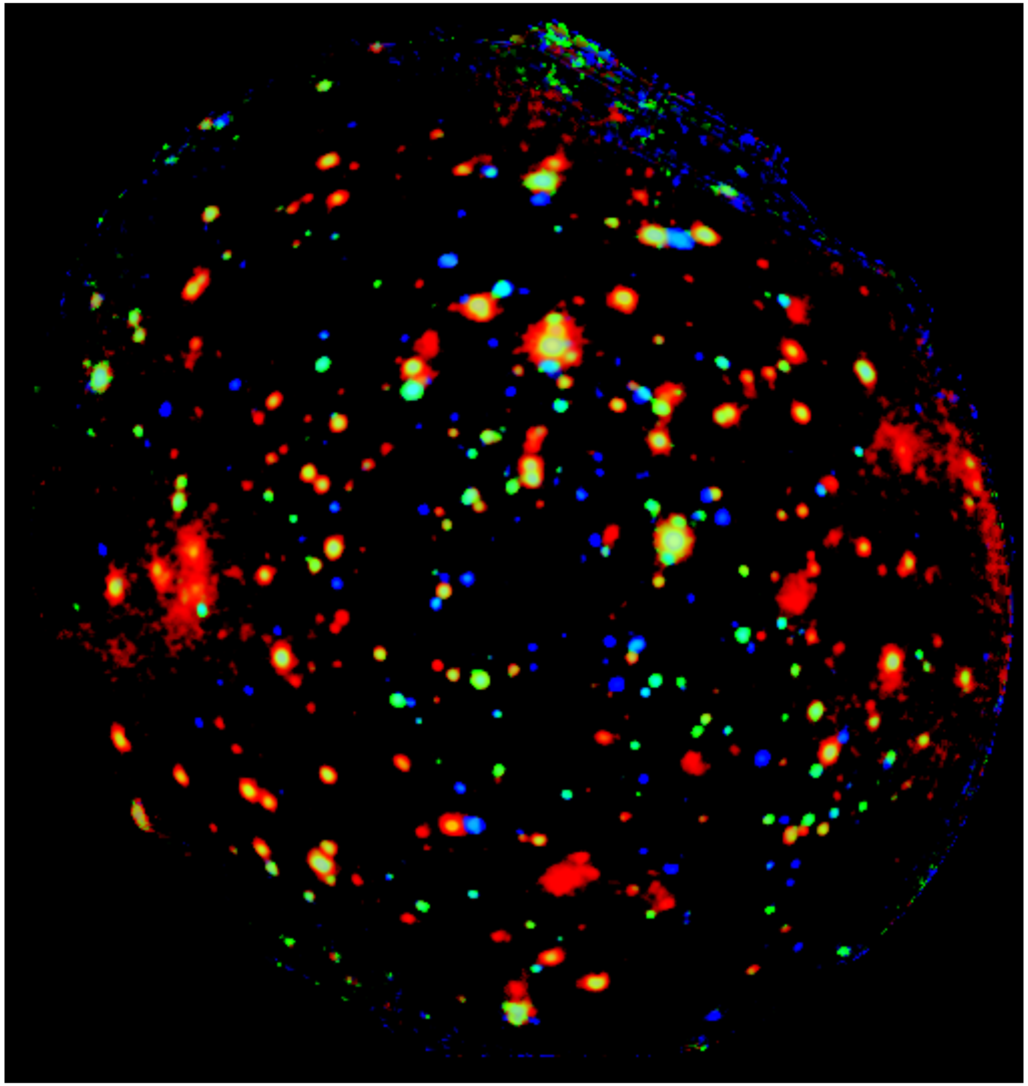
➔ $\Omega_{beam}=\pi\sigma^2$=78.3 arcsec$^2$

➔$\Omega_{image}/\Omega_{beam}$=165096 “independent” beams

➔ρ(sc)=165096/40≈4130 src/deg$^2$

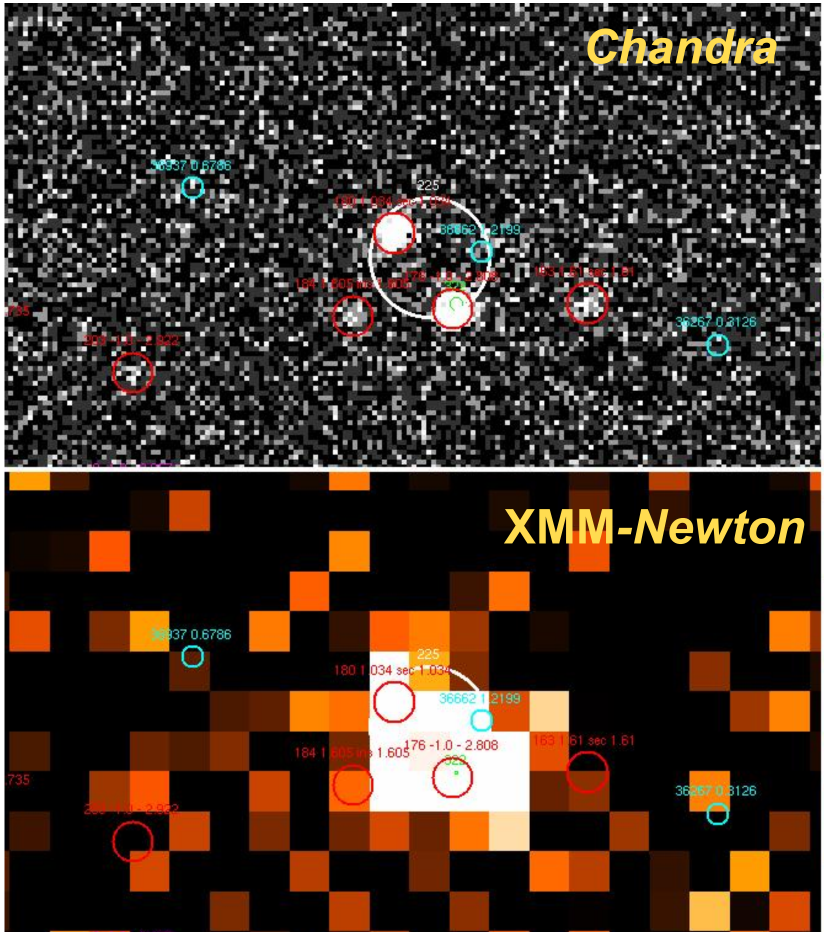
This source density is matched in the 0.5-2 keV LogN-LogS at a flux of ≈(6−7)×10$^{-16}$ cgs

# Source confusion (and source blending). III
## XMM-*Newton* vs. Chandra



Case of confused (but still detectable) sources

Consider all the cases where sources are below the X-ray flux limit



# Source confusion. IV
## Sensitivity vs. confusion