

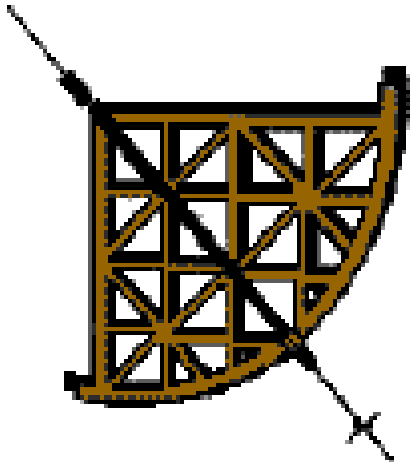
Introduzione alla Cosmologia Fisica Lezione 10

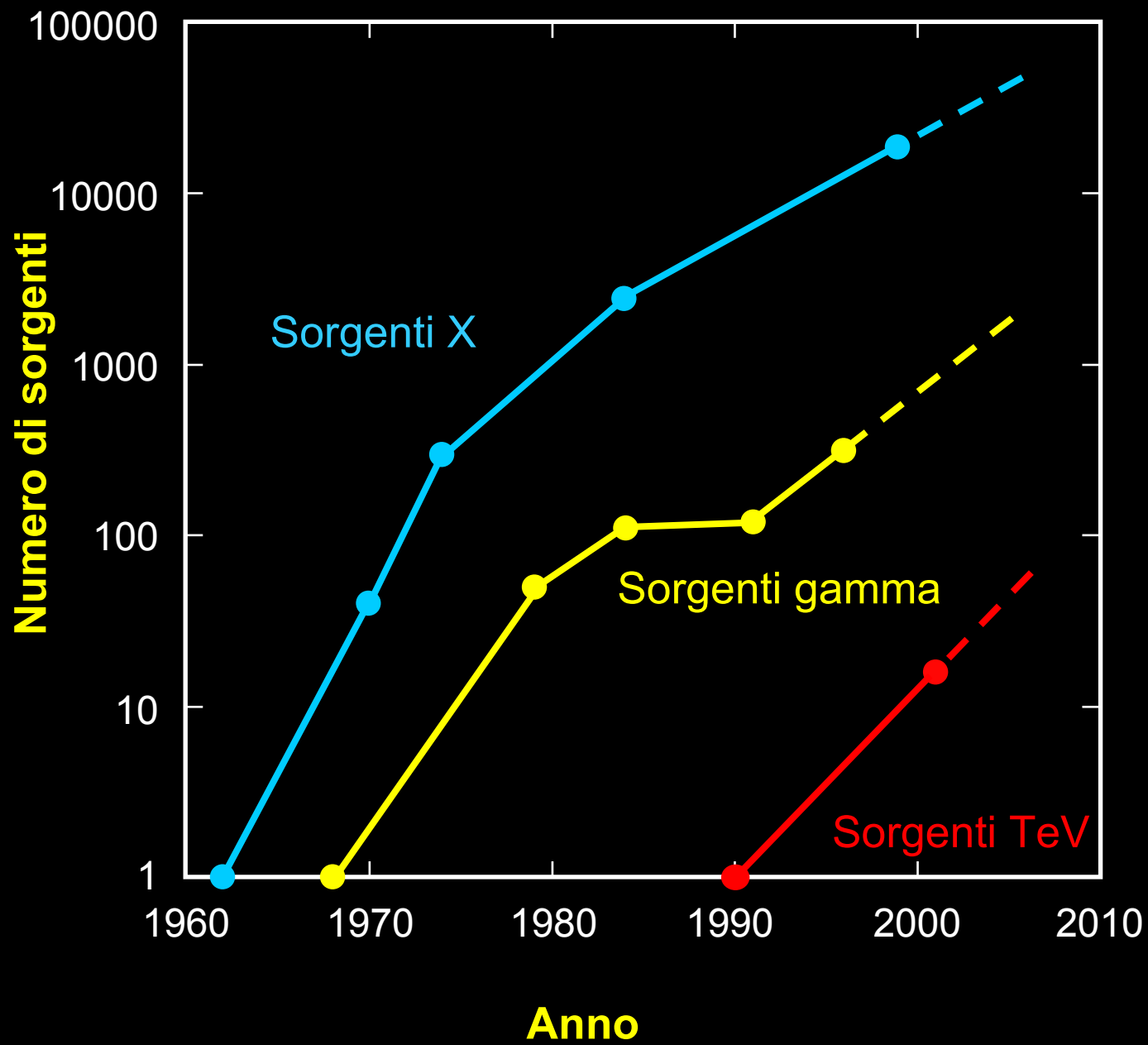
L'Astronomia Gamma, le tecniche

Giorgio G.C. Palumbo

Università degli Studi di Bologna

Dipartimento di Astronomia



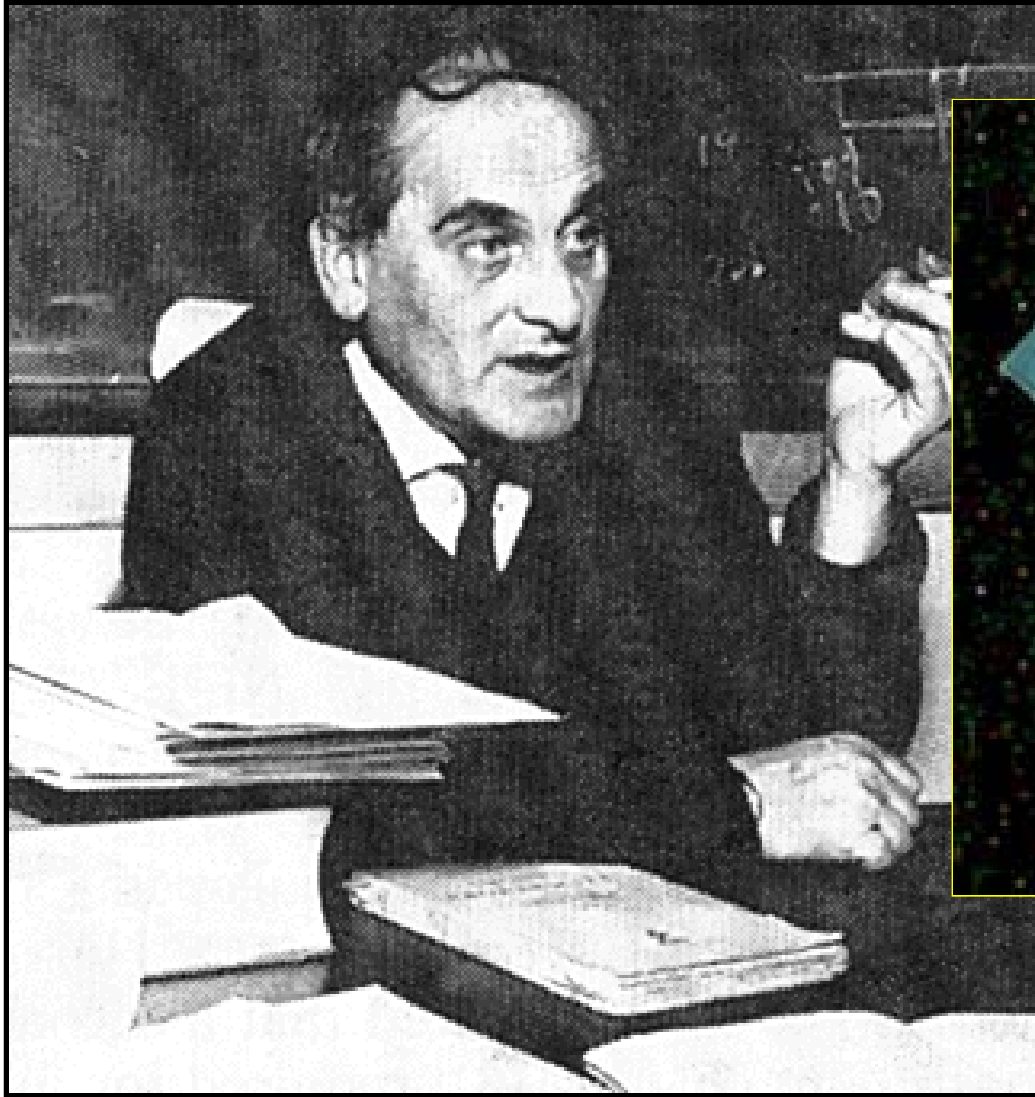


BeppoSAX:

- Scoperta degli afterglows dei GRB
- Scoperta delle distanze extragalattiche dei GRB
- Progenitori:
Associazione con SN e zone di formazione stellare in galassie lontane
- GRB scuri e lampi in raggi X
- Cosmologia con i GRB



Giuseppe “Beppo” Occhialini



MALINDI



BeppoSAX: SEGMENTO DI TERRA

Centro Spaziale Fucino (Telespazio):

- RICEZIONE TELEMETRIA - INVIO TELECOMANDI TRAMITE INTELSAT V

**FUCINO
ROMA**



INTELSAT V

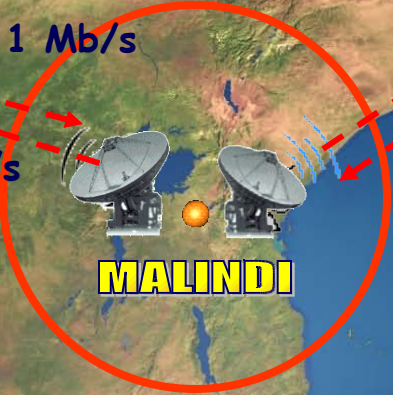
- CENTRO DI CONTROLLO
- CENTRO OPERATIVO SCIENTIFICO
- CENTRO DATI SCIENTIFICI



BeppoSAX

TLM: 1 Mb/s

TLC: 2 Kb/s



MALINDI

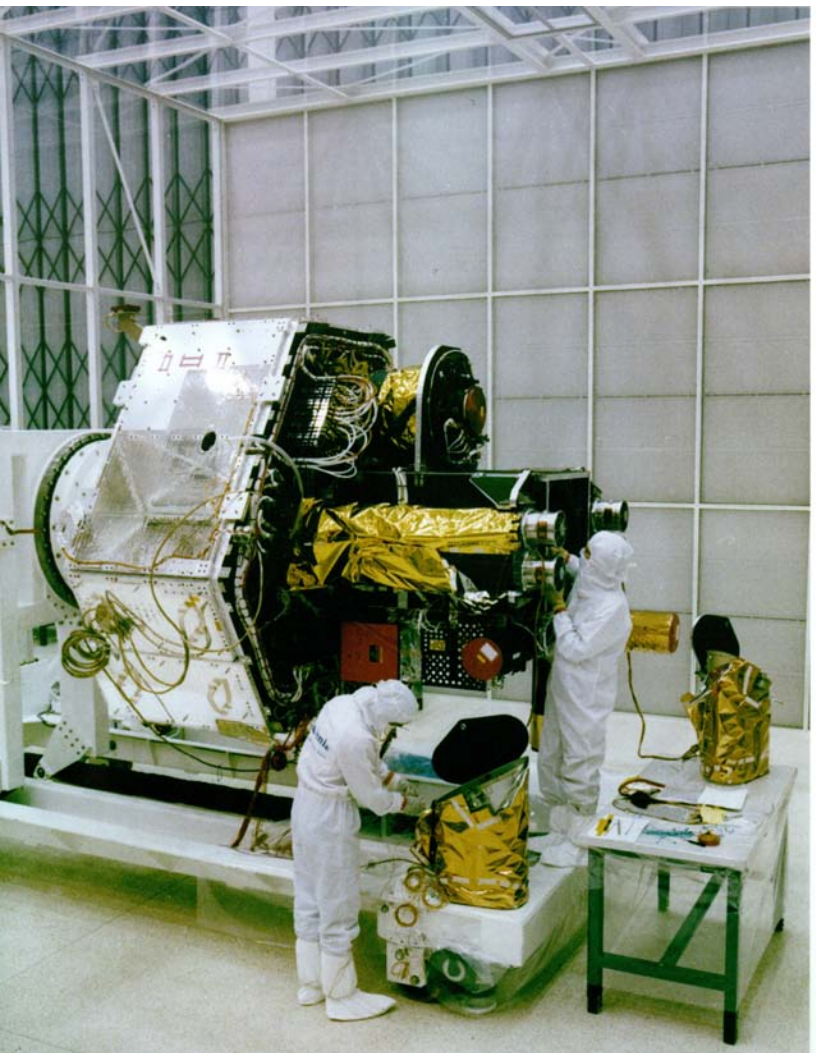
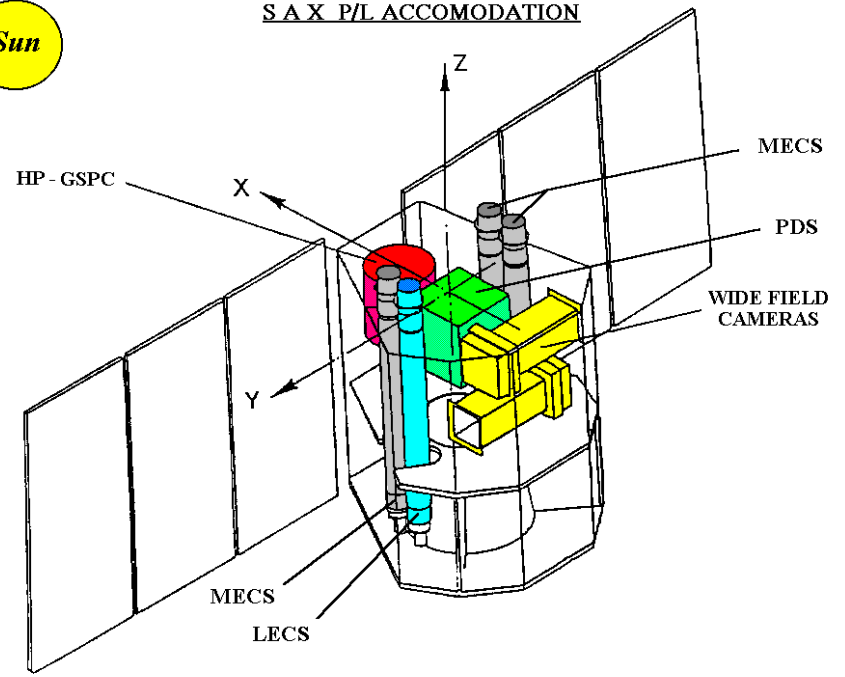
Canali Satellitari:
384 (Prime), 128 Kb/s (Back-up)

- Stazione di Malindi (ASI):
- CONTATTO DIRETTO CON BeppoSAX
- RICEZIONE TELEMETRIA (TLM)
- INVIO TELECOMANDI (TLC)

BeppoSAX strumenti

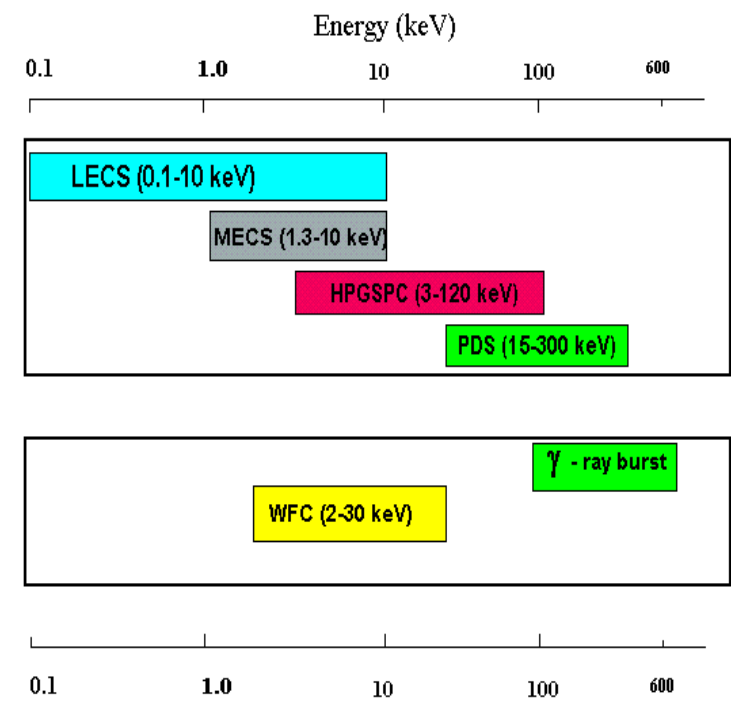


S A X P/L ACCOMODATION



Narrow Field Instruments

Wide Field Instruments
(Perpendicular to NFT)



LECS

MECS

WFC

HPGSPC

PDS

BeppoSAX - PAYLOAD SCIENTIFICO Range Energia (0.1 – 300 keV)

HPGSPC

PDS

MECS 2 e 3

WFCs

UPPER FLOOR

SHEAR PANEL

CONE

LOWER FLOOR

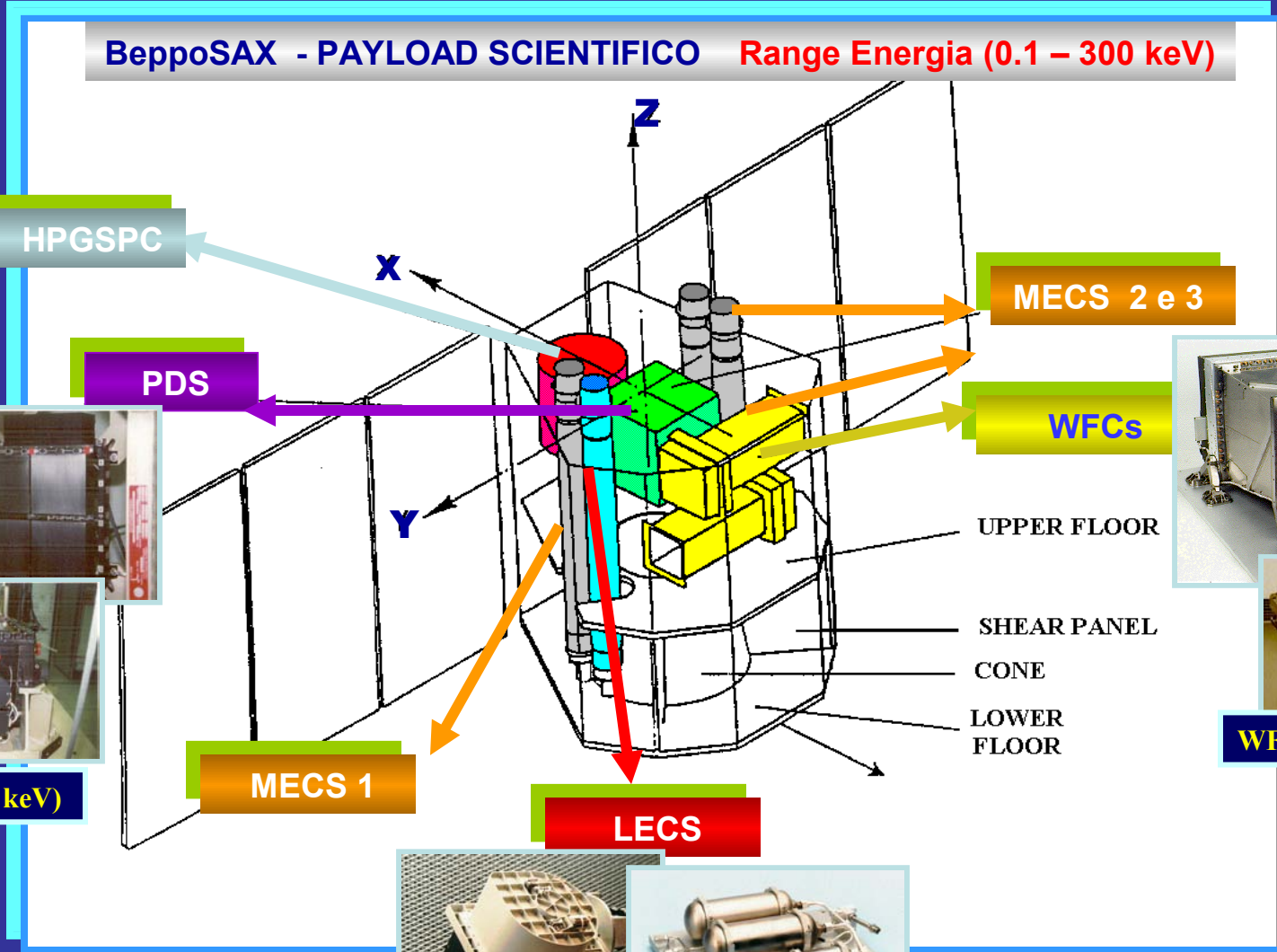
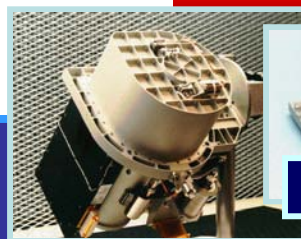
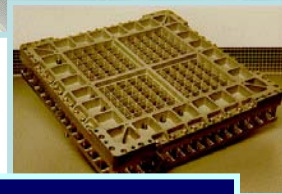
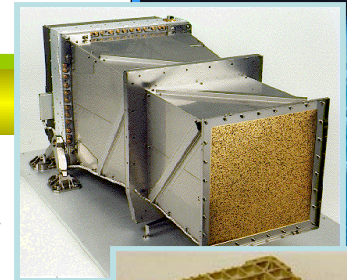
MECS 1

LECS

WFC (2-30 keV)

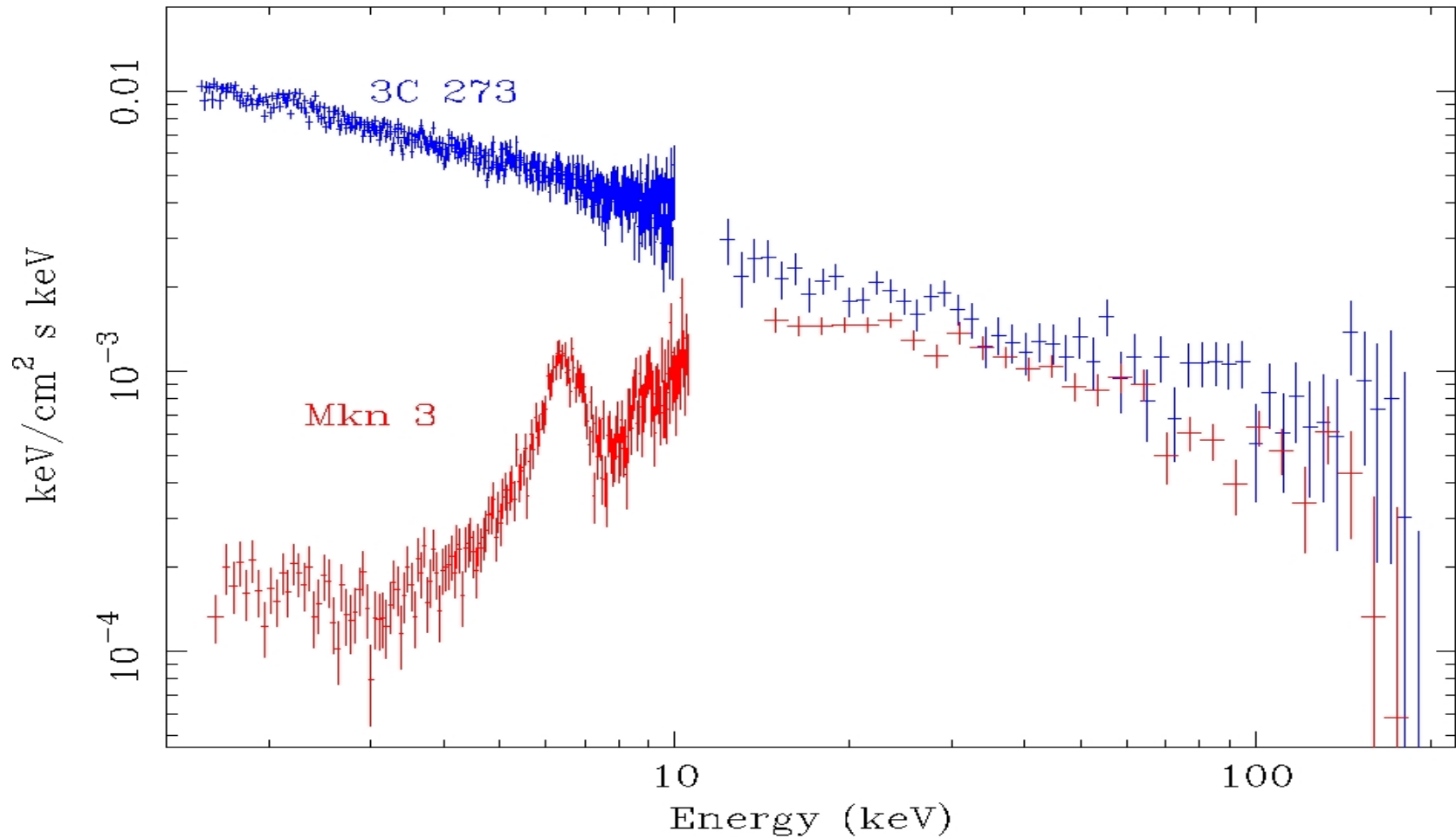
PDS (2-300 keV)

LECS (0.1-10 keV)



Esempio di spettro X di una Seyfert 2 (Mkn3) confrontato con lo spettro del quasar 3c273

BeppoSAX spectra of 3C 273 and Mkn 3

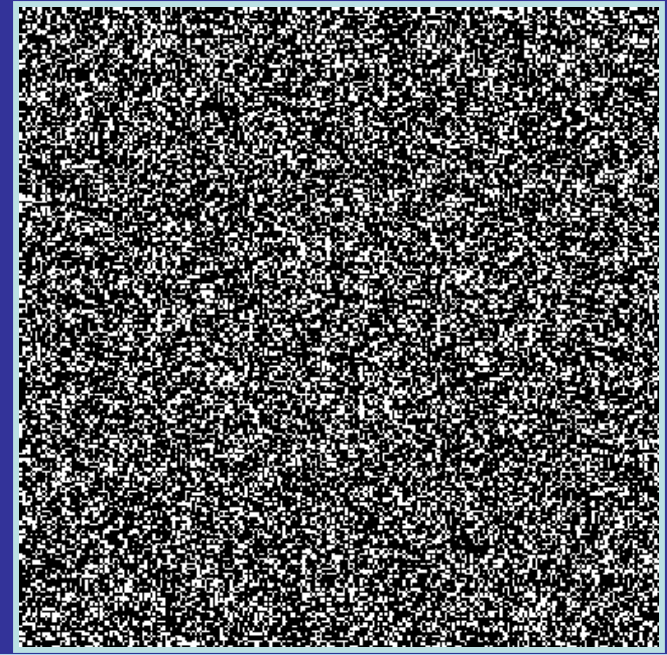
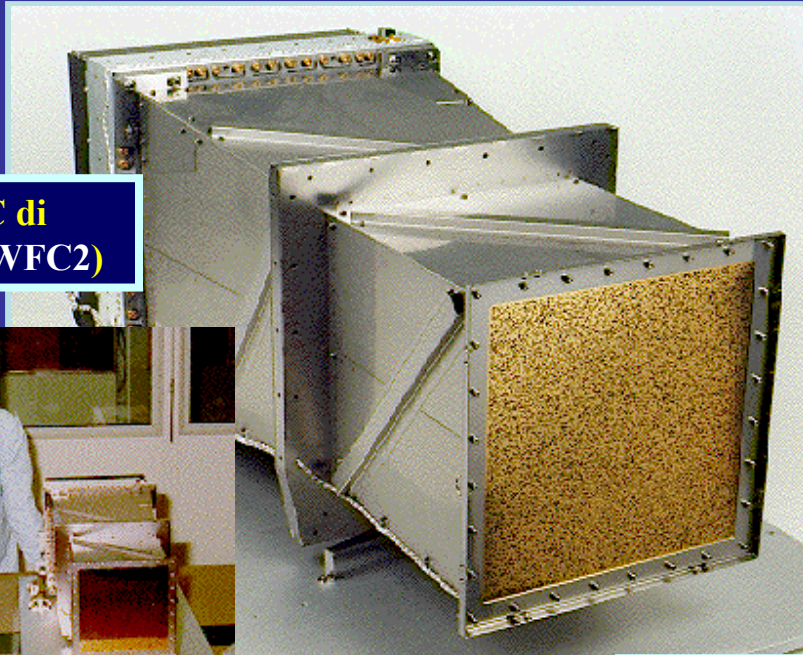
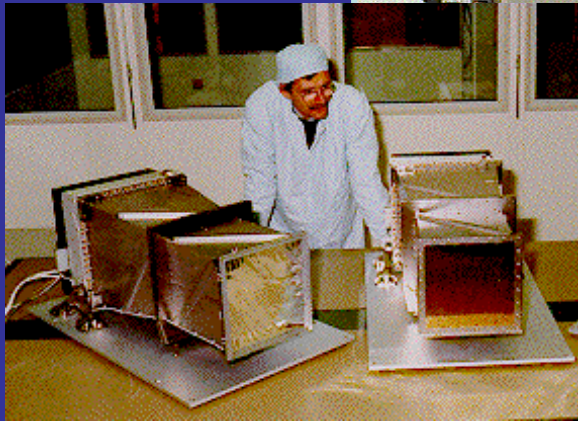


WFC

Wide Field Cameras

Le WFC di BeppoSAX. Sensibilità max per Raggi X di energia intermedia (2-30 keV).

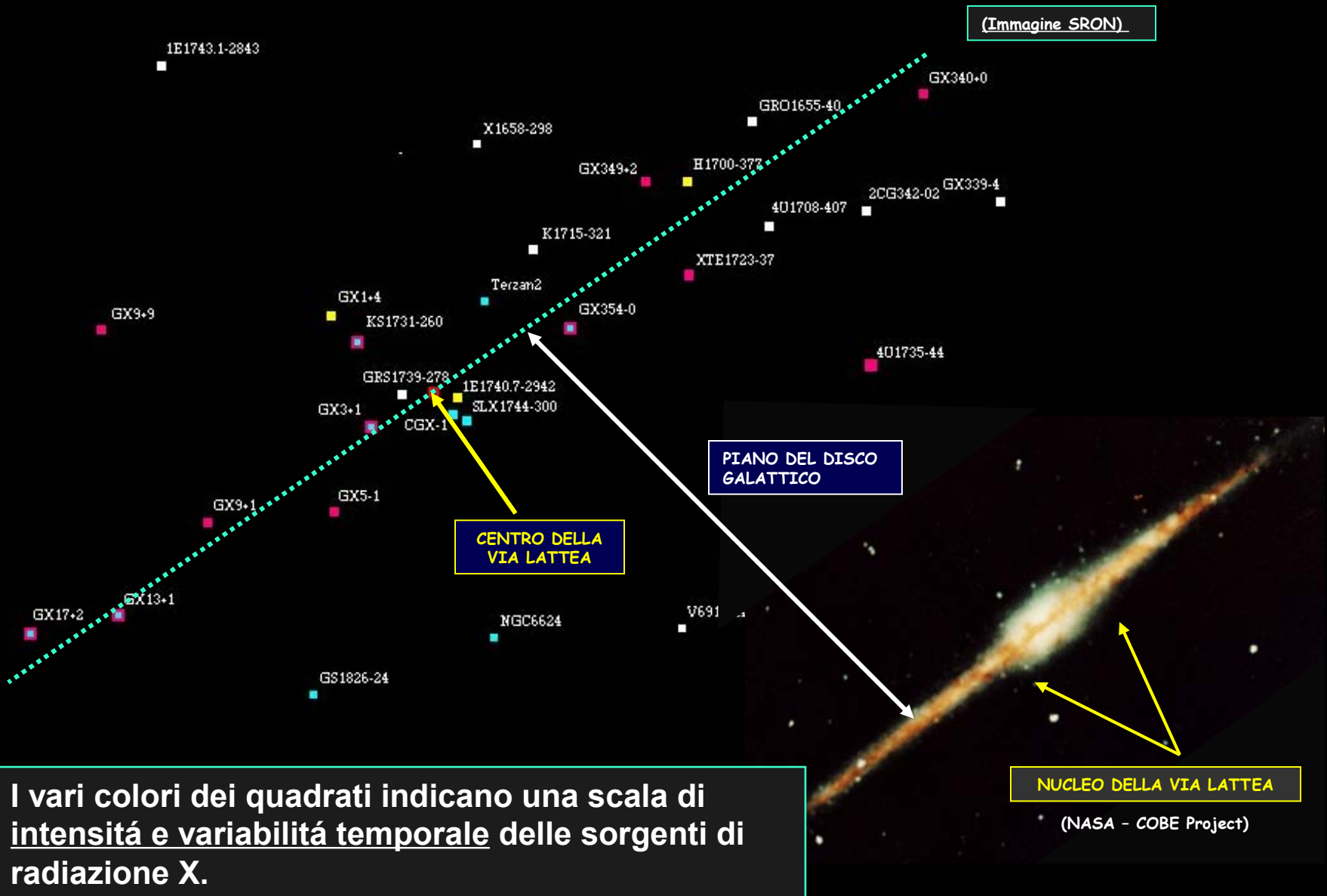
Le due identiche WFC di BeppoSAX (WFC1 e WFC2)



La Maschera Codificata delle WFC di BeppoSAX. È composta da 256 x 256 elementi (pixels).

Le WFC di BeppoSAX sono due, disposte in direzione perpendicolare rispetto alla direzione degli altri strumenti. Con il loro grande campo di vista (circa 40 gradi x 40 gradi di cielo) riescono a controllare simultaneamente un grande numero di sorgenti, per ognuna delle quali forniscono posizione (Immagine), variazione temporale della luminosità (Curva di Luce) e contenuto energetico della radiazione emessa (Spettro).

BeppoSAX OSSERVA IL CENTRO GALATTICO



Telescopi per astronomia gamma: caratteristiche fondamentali

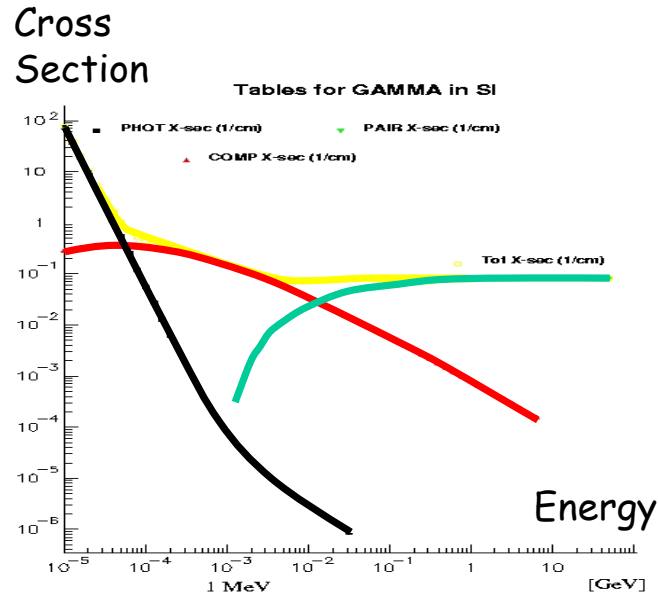
- Elevata efficienza di rivelazione;
- Ampia copertura spettrale;
- Risoluzione energetica;
- Imaging:
 - Ampio campo di vista;
 - Risoluzione angolare;
 - PSLA;
- Risoluzione temporale;
- Sensibilità;

Telescopi / rivelatori gamma

- Spettrometri (fotometri):
 - Contatori di fotoni: scintillatori o rivelatori a stato solido per trasformare i fotoni gamma incidenti in fotoni ottici e/o segnali elettronici;
- Imager:
 - Sistemi complessi (basati su diffusione Compton o produzione di coppie) per calcolare la direzione d'arrivo dei fotoni incidenti
- Combinazioni tra i due....

Telescopi per astronomia gamma

Detection of Gamma Radiation



Photoeffect (< 100 keV)

Photons effectively blocked and stopped

Telescopes:

Collimators
Coded Mask Systems

Pair Creation (> 10 MeV)
Photons completely converted to e^+e^-

Telescope:
Tracking chambers
to visualize the pairs

Compton Scattering (0.2-10 MeV)

Photon Crosssection Minimum
Scattered photons with long range

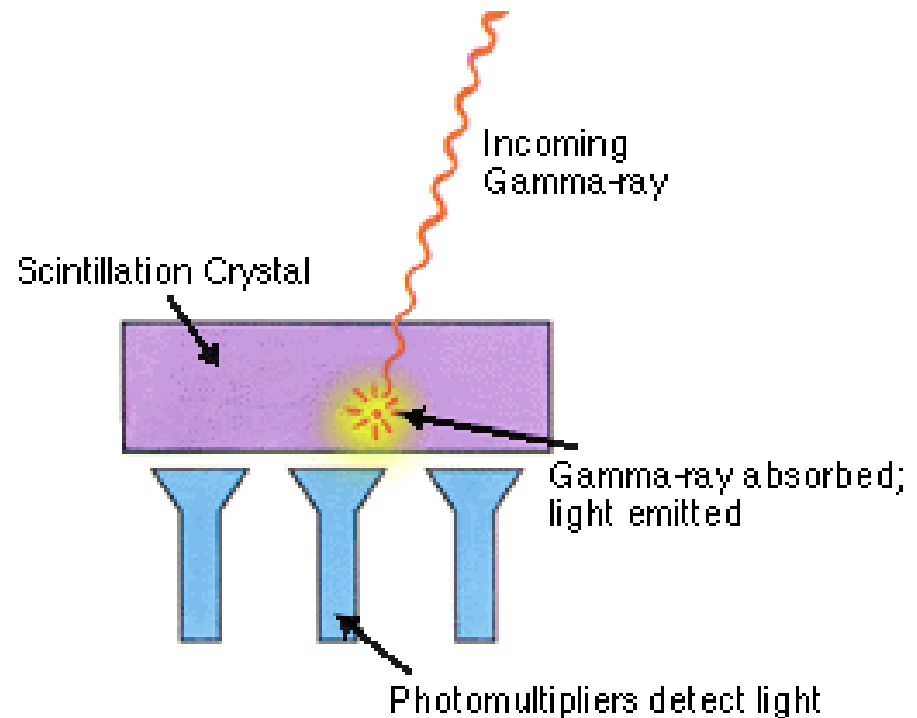
Telescope:

Compton Camera Coincidence System

July 2002

Telescopi per Astronomia gamma

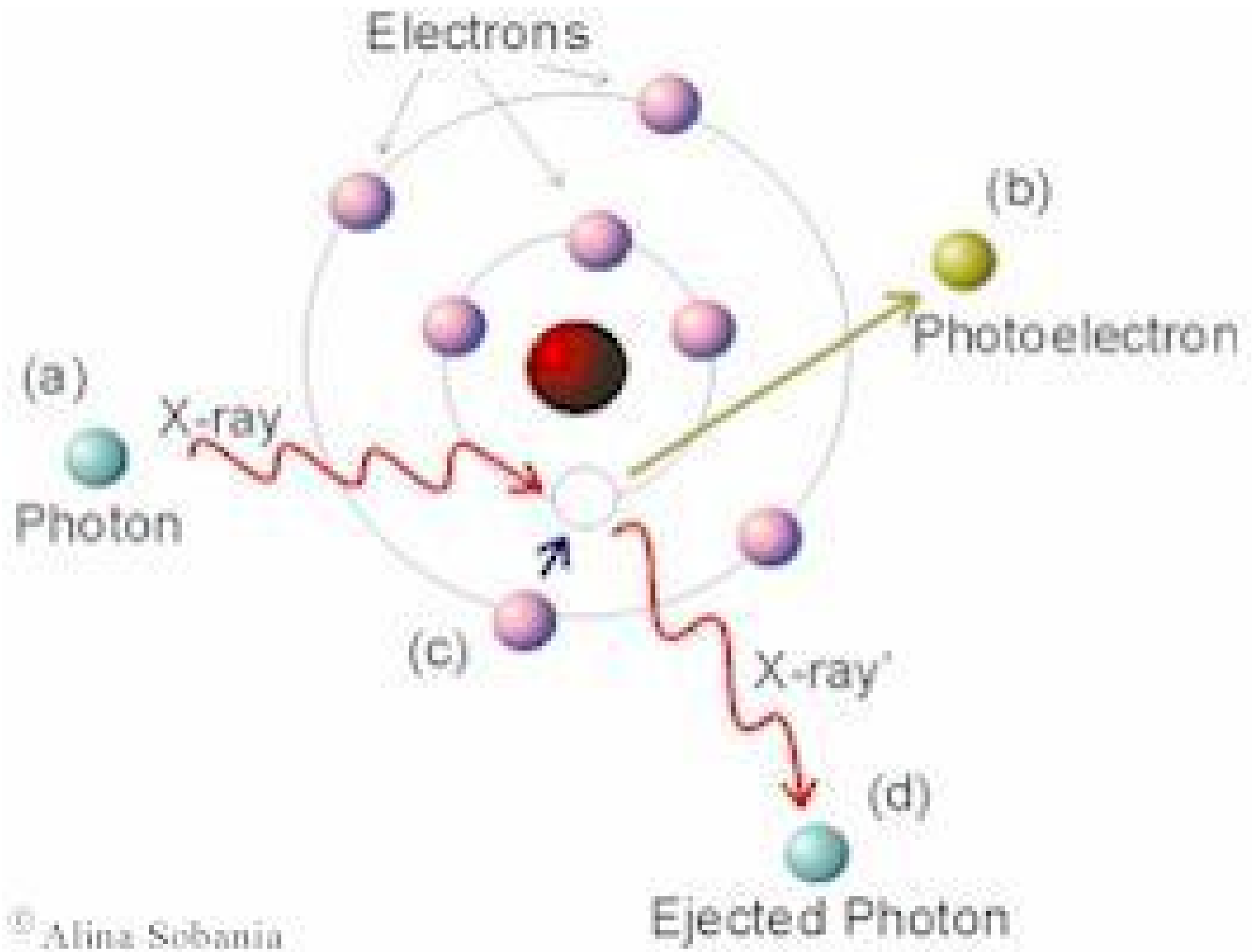
- Assorbimento atmosferico:
 - Astrofisica Spaziale;
- Elevato potere penetrante:
 - Elevati volumi e aree;
- Tecniche indirette per:
 - Spettrometria;
 - Imaging;



Imaging in astronomy gamma

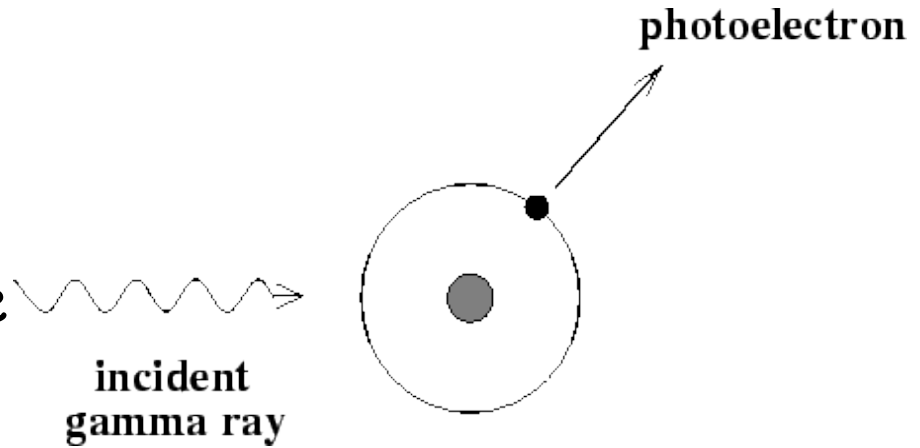
TABLE 5.1 COMPARISON OF GAMMA-RAY IMAGING TECHNIQUES

Imaging Technique	Energy Range	Characteristics
Multi-layer mirrors	below 100 keV	high resolution, narrow field-of-view
Coded-Aperture mask	below 10 MeV	good resolution, wide field-of-view
Compton telescope	~1 MeV– ~100 MeV	good resolution, wide field-of-view
Pair telescope	above 10 MeV	good resolution, wide field-of-view
Atmospheric Cerenkov	above 100 GeV	good resolution, narrow field-of-view

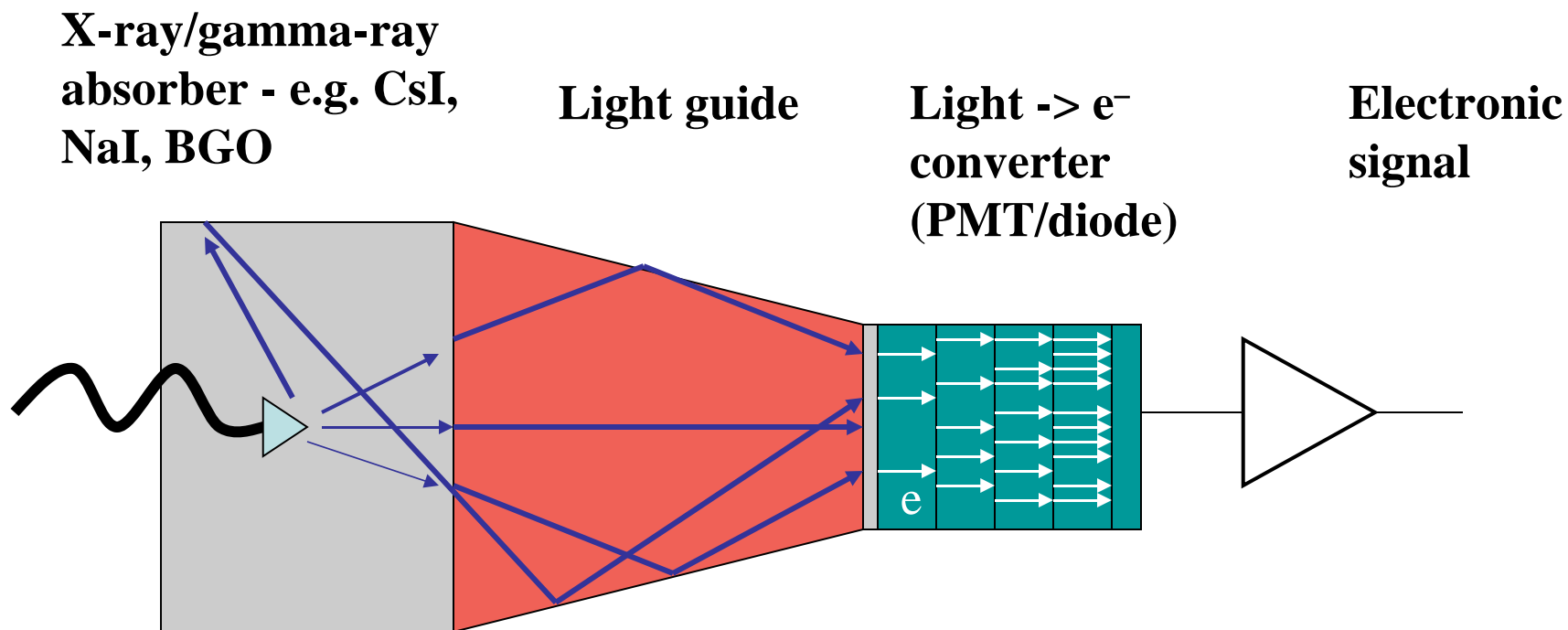


Assorbimento fotoelettrico

- E' l'interazione dominante (i.e. più probabile) tra fotoni X e fotoni gamma di bassa energia, ossia fino a 200-300 keV (o più in funzione del materiale assorbente) con la materia;
- Avviene tra un γ ed un atomo: il primo scompare essendo assorbito completamente nel processo;
- Al suo posto viene emesso un fotoelettrone da parte dell'atomo;



Rivelatori di raggi gamma



Scintillation crystal NaI (Tl)
 0.5 MeV \rightarrow 3 eV γ 's, ~12% efficiency

Light guide
 80% efficient

Bialkali photocath.
 20% efficient

20000 γ

16000 γ

3200 e^-

$\Delta E/E \sim$
 $2.35 \cdot (1/\sqrt{3200})$
 $= 4\% \text{ FWHM}$

Attenuazione dei fotoni gamma

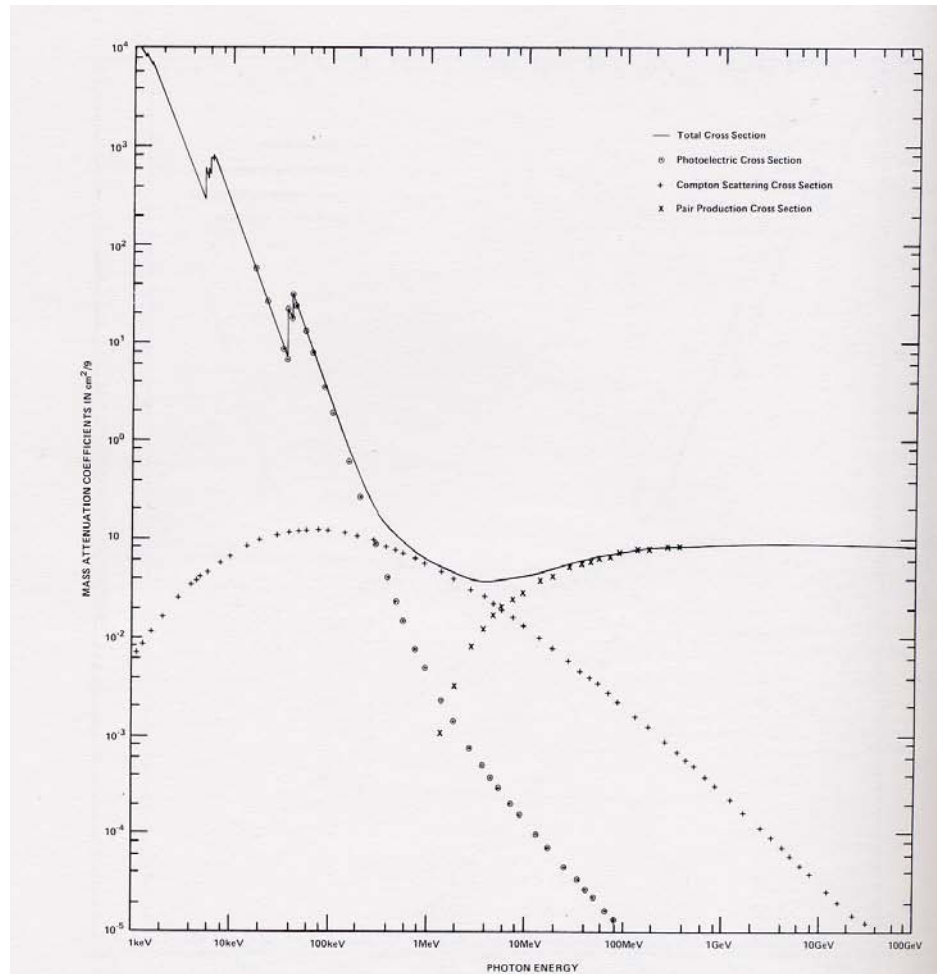
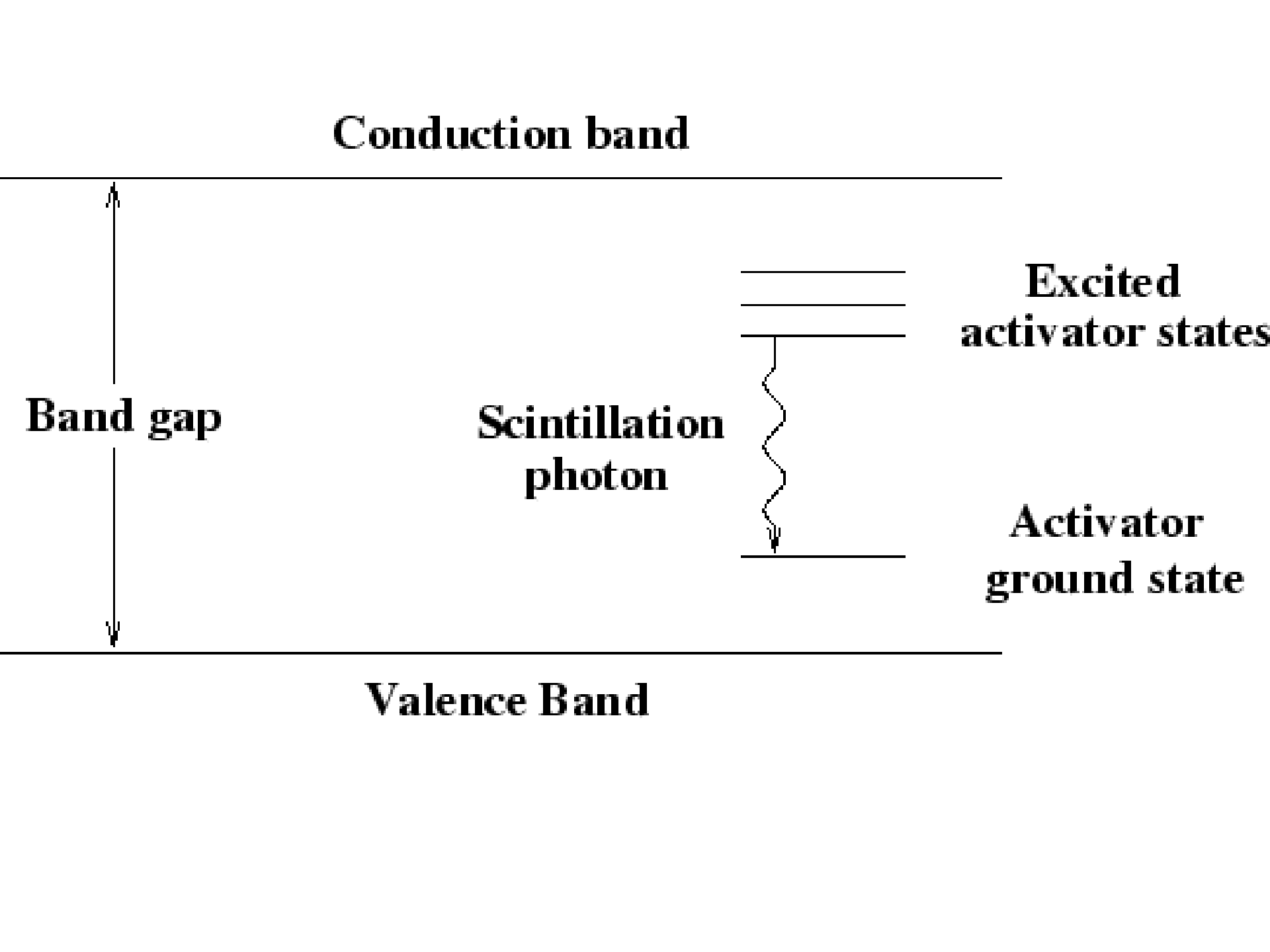


Figure 10-3. The photoelectric, Compton scattering, pair production, and total mass absorption coefficient for Cs I (from Hubbell, 1969, 1977, and Hubbell et al., 1979).

Rivelatori a scintillazione

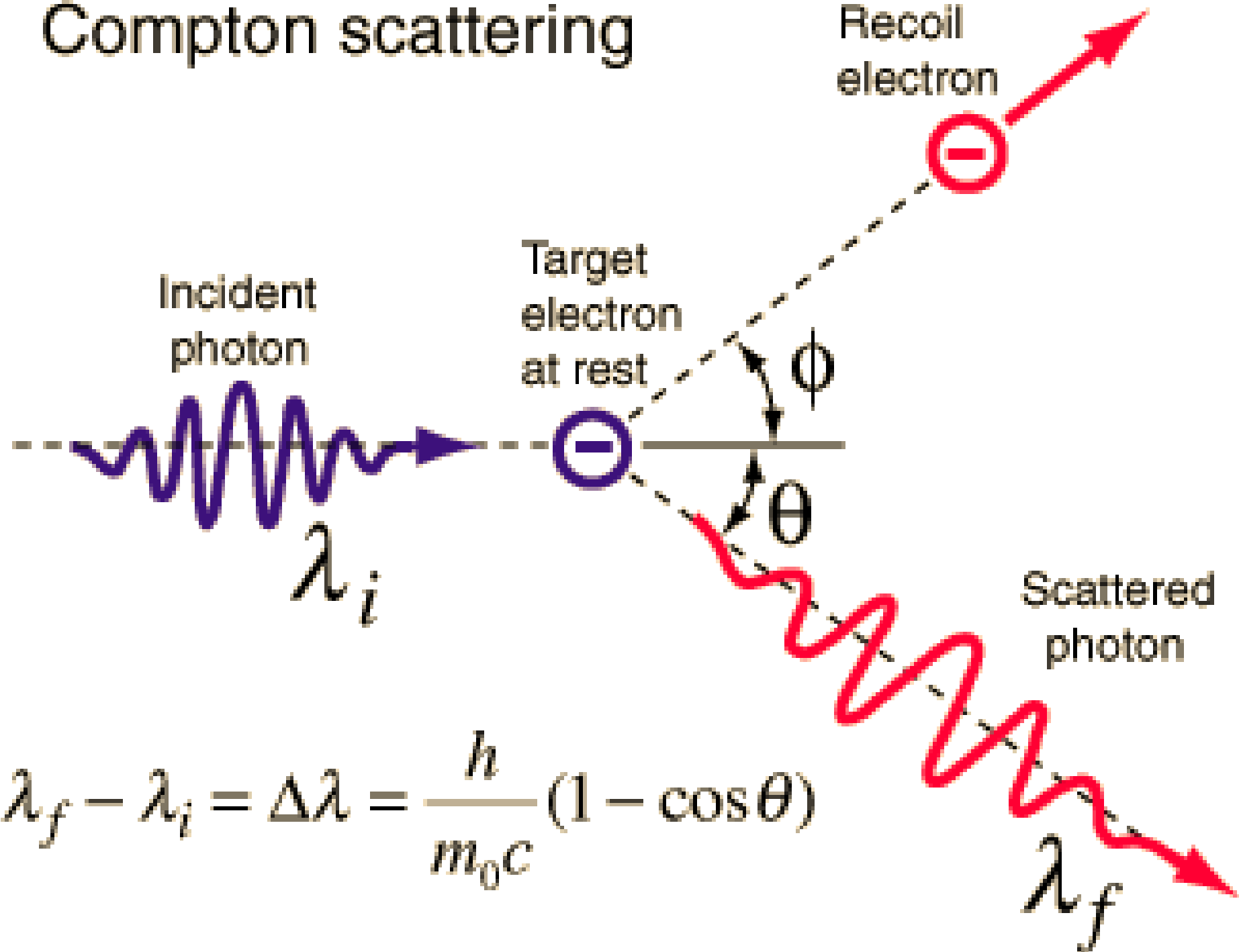
- Il γ incidente interagisce nel cristallo creando un elevato numero di fotoni ottici;
- I livelli energetici sono determinati dalla struttura del reticolo cristallino;
- La band gap separa la banda di valenza dalla banda di conduzione;
- Assorbendo energia, un e^- viene promosso dalla banda di valenza a quella di conduzione;
- Il "drogaggio" del reticolo cristallino con impurità rende più efficiente il processo



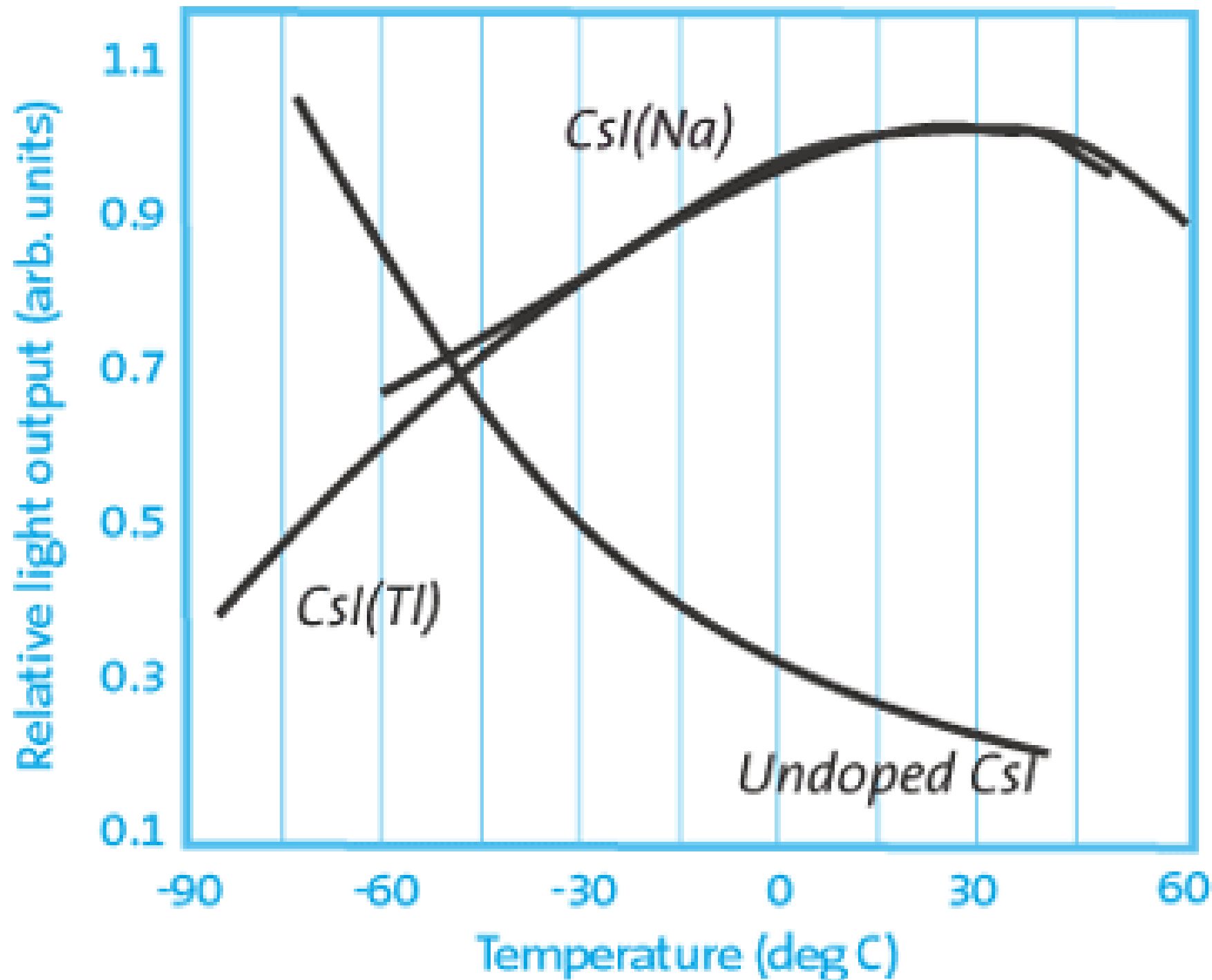
Requisiti

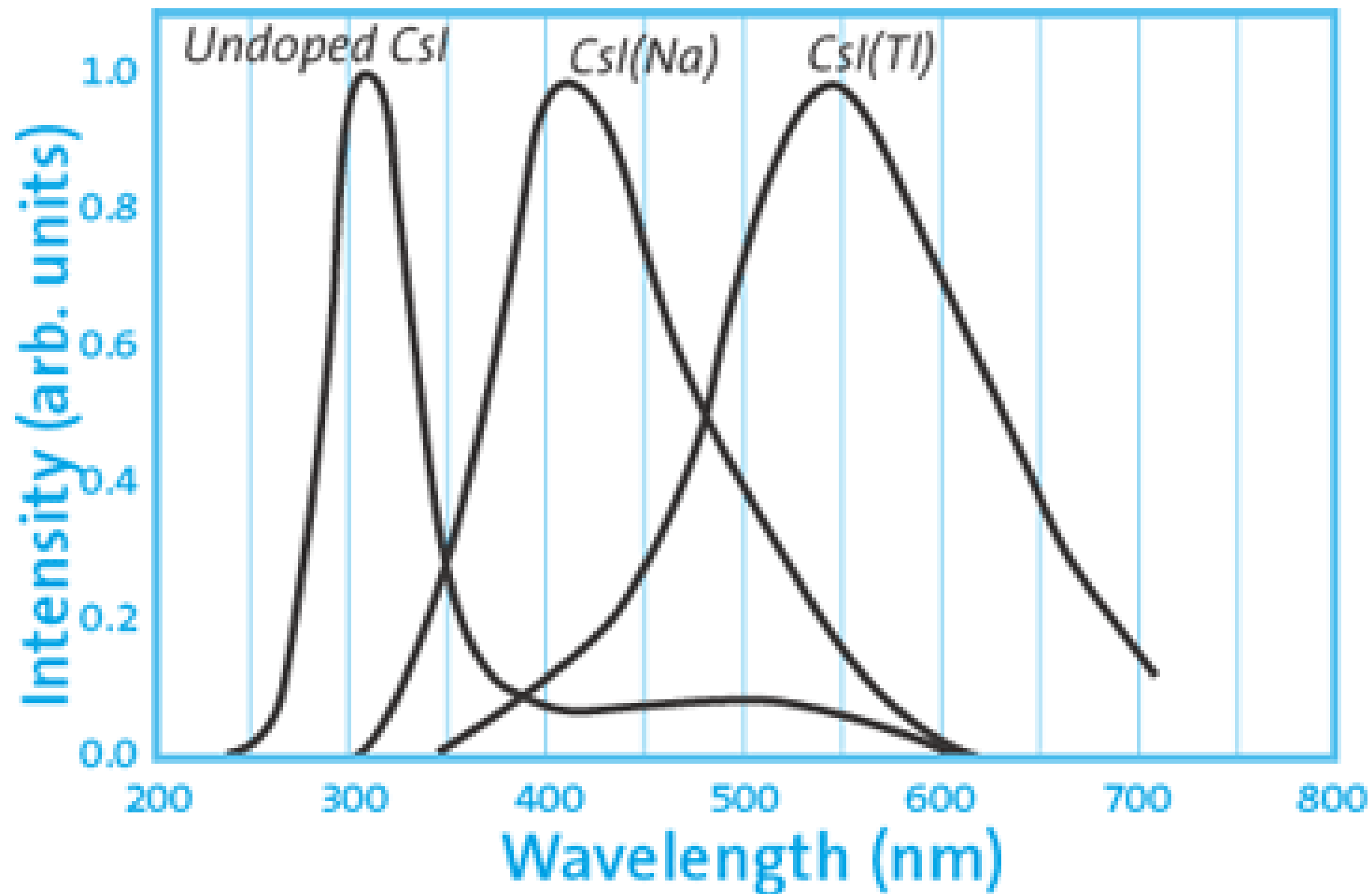
- Elevata efficienza di conversione dell'energia delle particelle cariche in luce di fluorescenza (**efficienza di scintillazione**);
- L'intensità della luce deve essere linearmente proporzionale all'energia delle particelle e quindi all'energia persa dal fotone gamma primario (**linearità**);
- **Trasparenza** alla λ della propria luce di fluorescenza (picco a ~ 550 nm per il CsI(Tl));
- Elevati ρ e $Z \Rightarrow$ elevato $\mu_{pe} \Rightarrow$ elevata ε e potere spettroscopico;
- Indice di rifrazione vicino a quello del vetro per ottimizzare l'accoppiamento ottico con dispositivi per la lettura della luce (PMT, PD);

Compton scattering

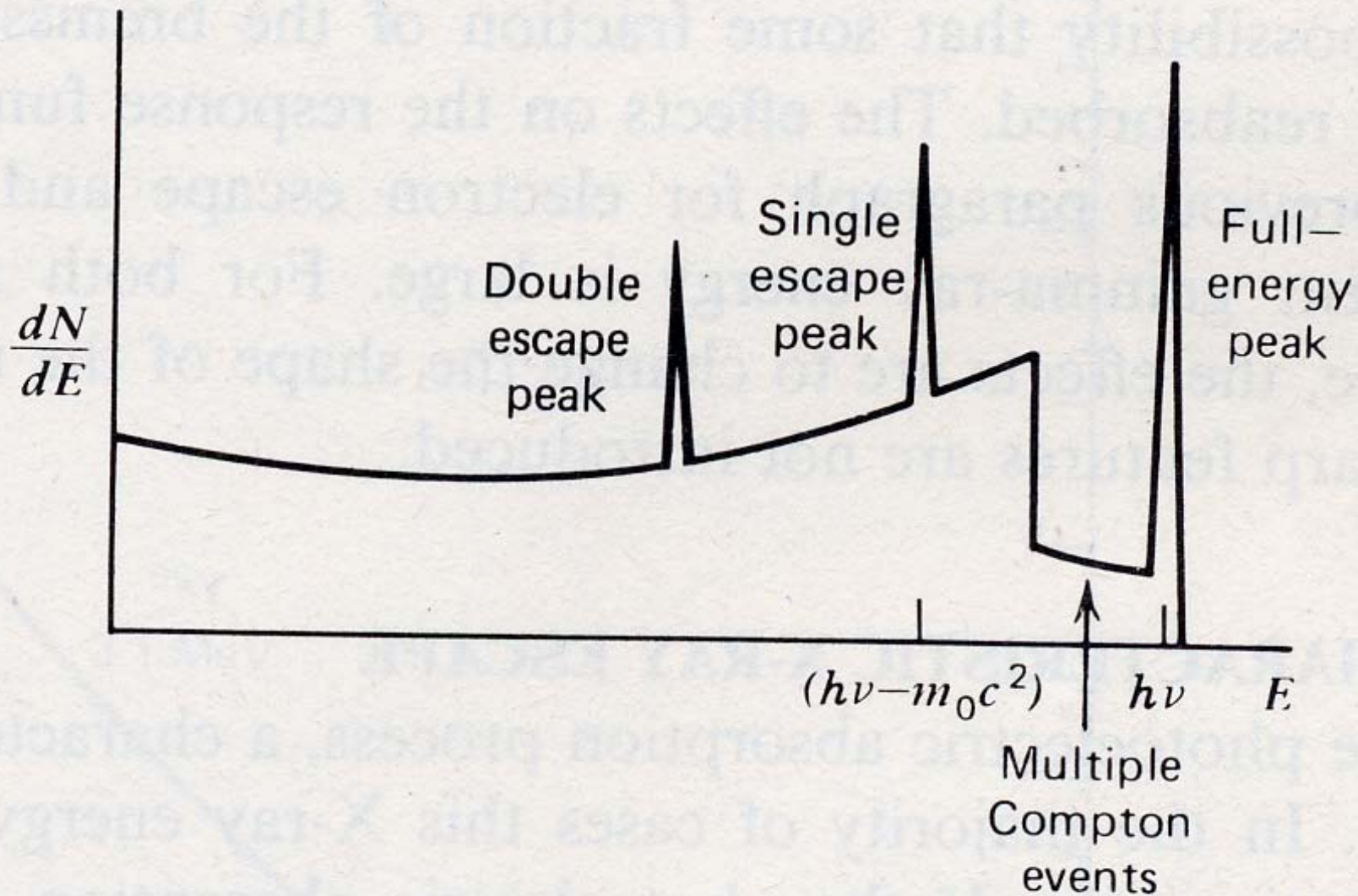


$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c} (1 - \cos \theta)$$





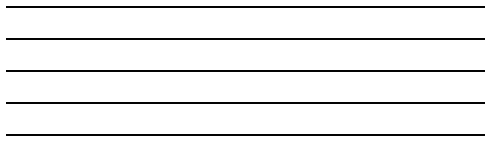
$$h\nu \gg 2m_0c^2$$



Rivelatori a stato solido

Livelli energetici degli e^- nel cristallo:

Banda di
conduzione



Banda di
valenza



Band gap:

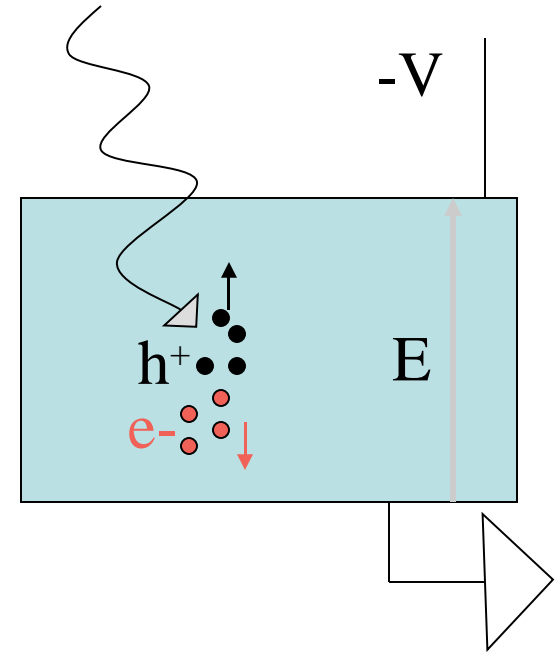
~ 1 eV:

≥ 1.5 eV

Ge, Si (raffreddati, ~ 80 °K)

"room temperature semiconductor"

CdZnTe, CdTe, HgI₂

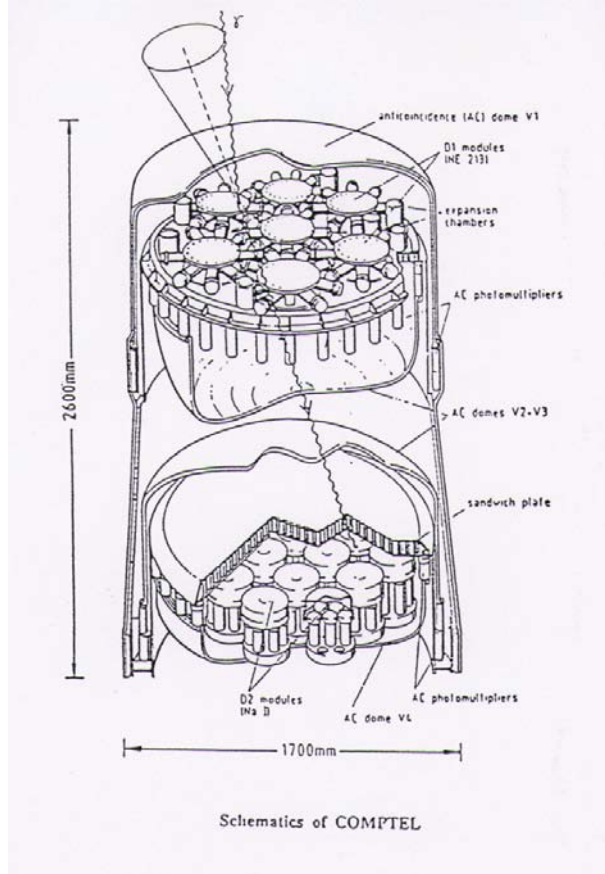
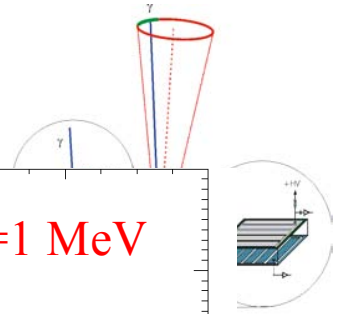


Rivelatori a Cd(Zn)Te

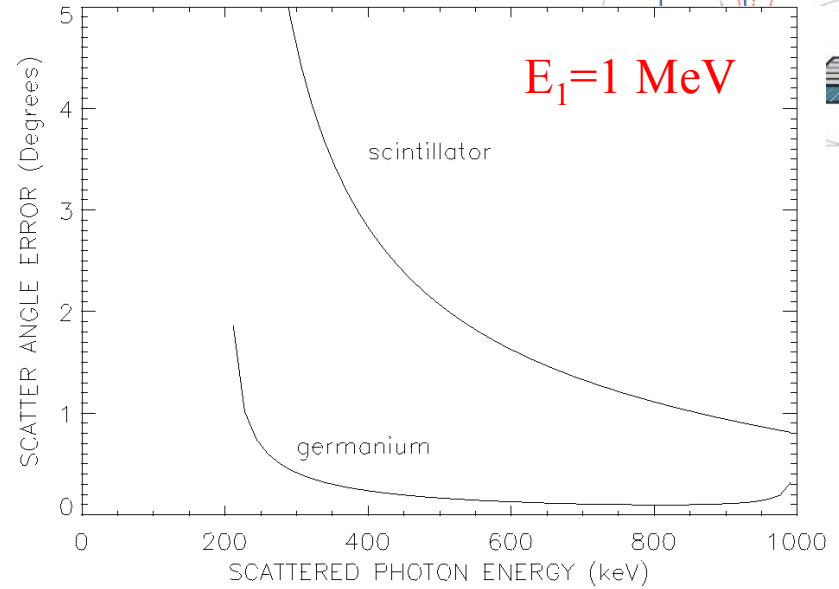
- Energy gap (1.6 eV) permette di non raffreddarli;
 - Alta ρ ($\sim 6 \text{ g cm}^{-3}$) per efficienza;
 - Alto Z (48, 52) per effetto fotoelettrico:
 - 10 volte il μ_{Compt} fino a 110 keV (60 il Ge, 25 il Si);
 - Single site ok per imaging
 - Facilmente segmentabile a piccole dimensioni:
- $\nabla \Rightarrow$ risoluzione spaziale



Compton Scattering



Comptel efficiency ~ 1%



$$\cos \phi = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1} \right)$$

$$\delta \phi = \frac{m_e c^2}{\sin \phi} \left[\frac{\delta E_u^2}{E_1^4} + \delta E_l^2 \left(\frac{1}{E_2^2} - \frac{1}{E_1^2} \right)^2 \right]^{1/2}$$



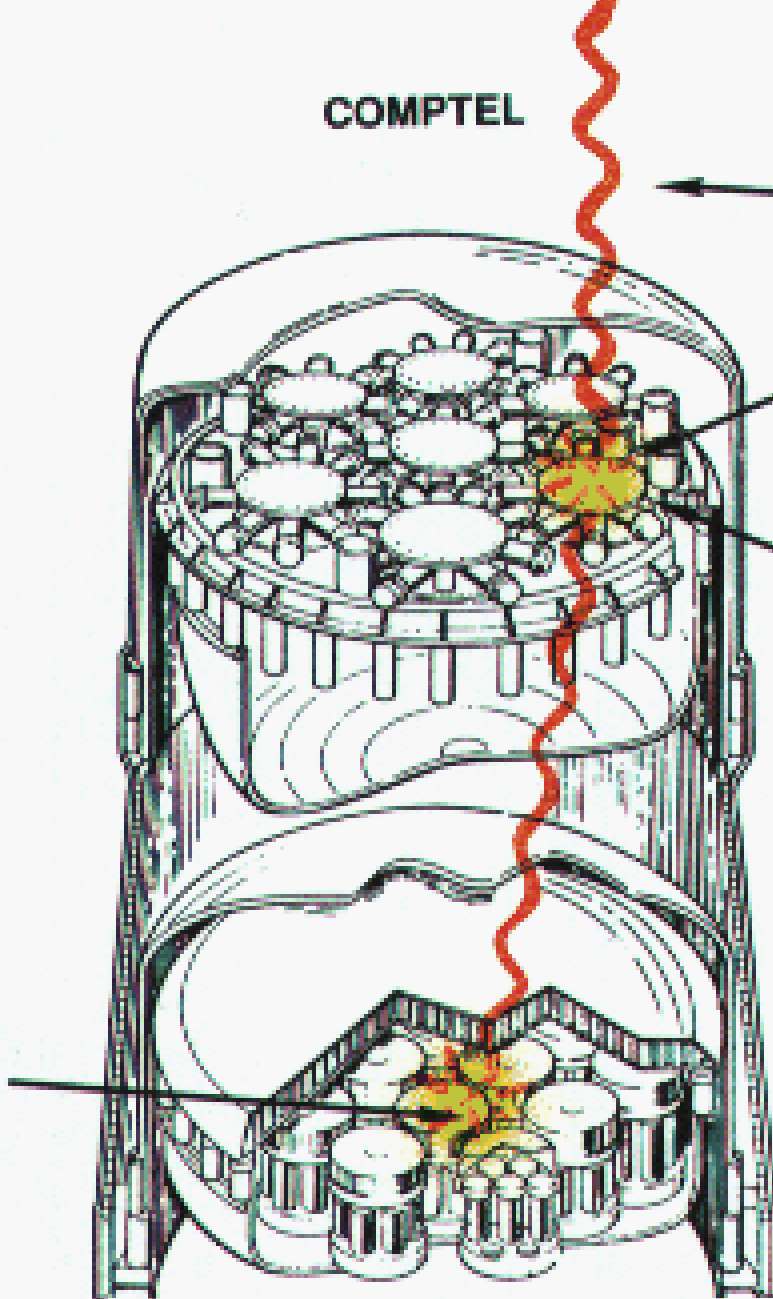
COMPTEL

GAMMA RAY

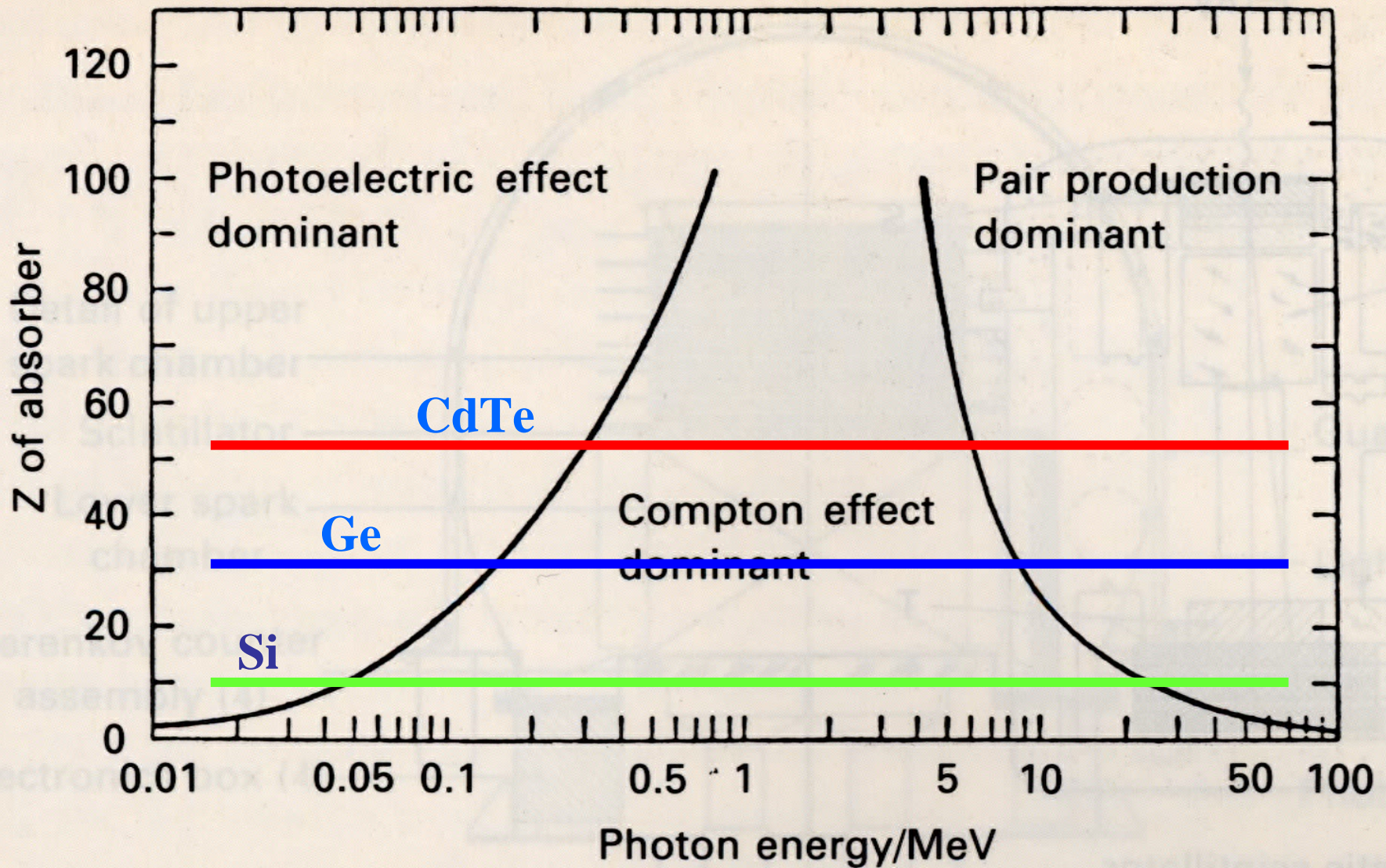
*Gamma Ray scattered;
light emitted.*

Light recorded.

*Gamma Ray absorbed,
light pulse emitted
and recorded.*



Cd(Zn)Te



Germanio

- Buona risposta ad alta energia ($100 \text{ keV} < E < 10 \text{ MeV}$)

Limited electron range - limits total detector thickness to $< 1 \text{ cm}$

Germanium is the best choice for

high-energy ($E > 100 \text{ keV} - 10 \text{ MeV}$) spectroscopy

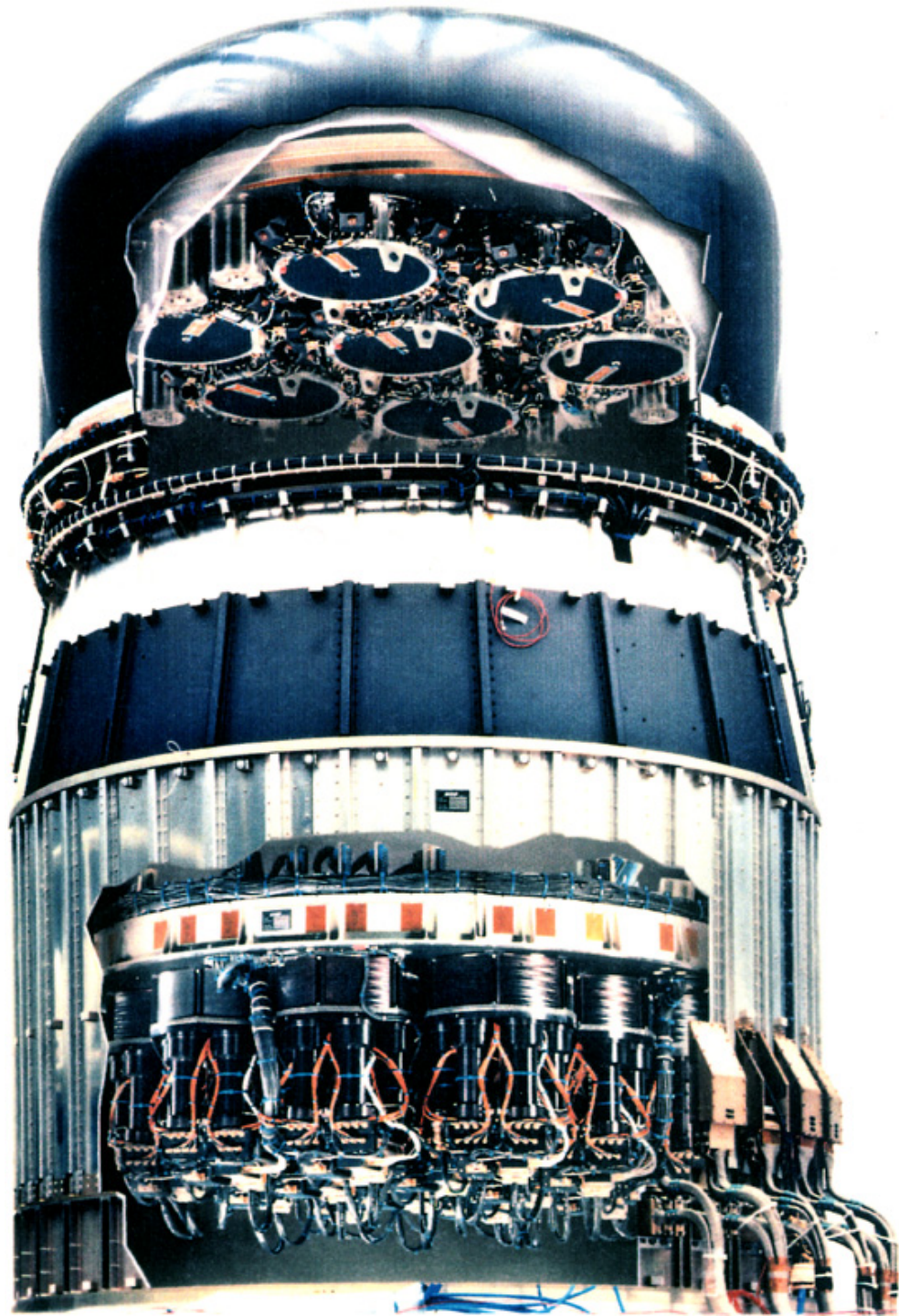
Very thin surface dead layers may give Ge an advantage where response from $1 \text{ keV} - 100\text{'s of keV}$ is desired

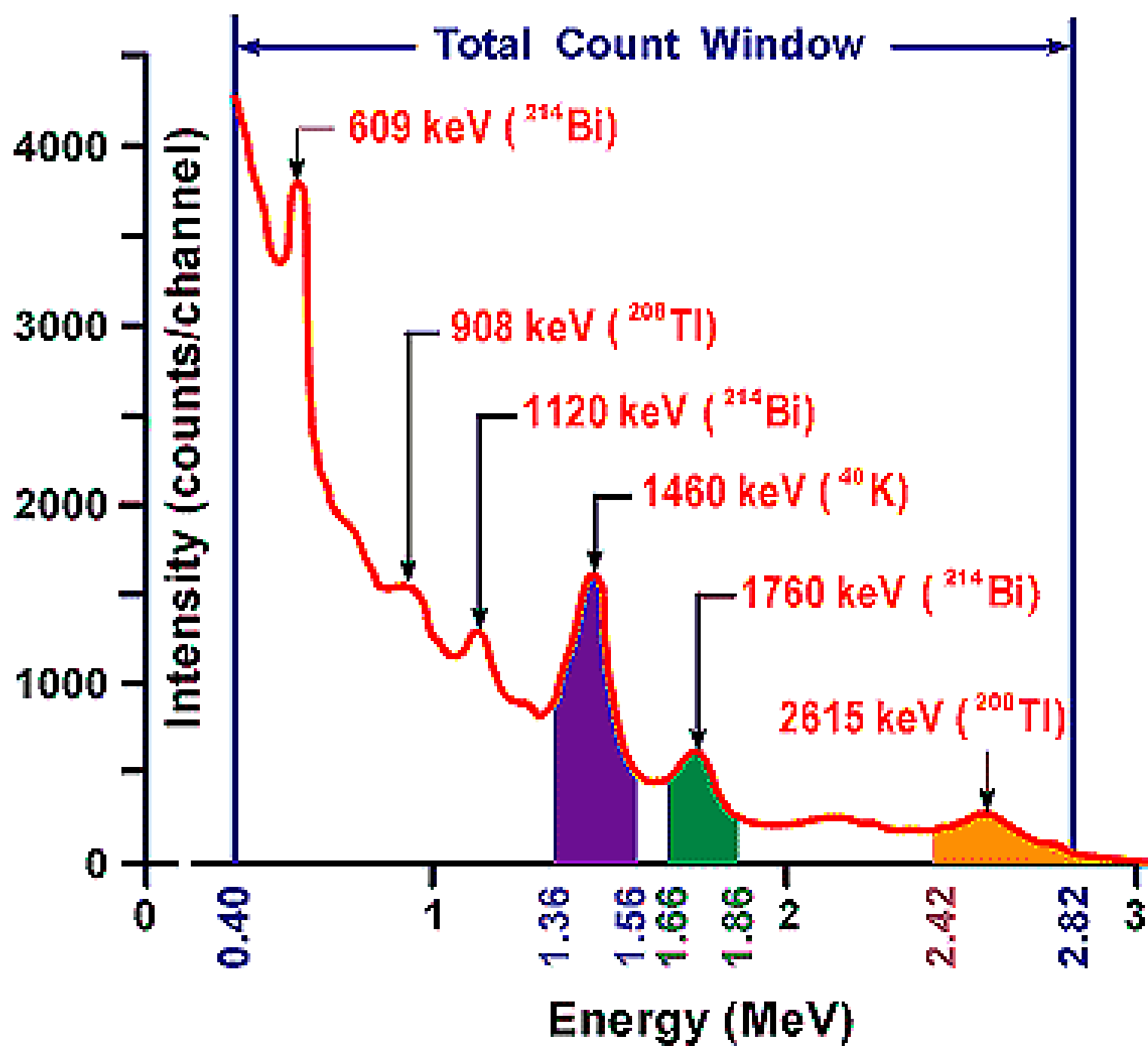
Disadvantages (compared to compound semiconductors or scintillation detectors)

Requires cooling (complexity and cost)

Surfaces sensitive to contamination (handling/packaging more difficult)

For fine ($Dx < 1 \text{ mm}$) position-sensitive detectors, segmented contact technology not well developed.





The Principle of a Double-Scatter Compton Telescope

Measured Event quantities:

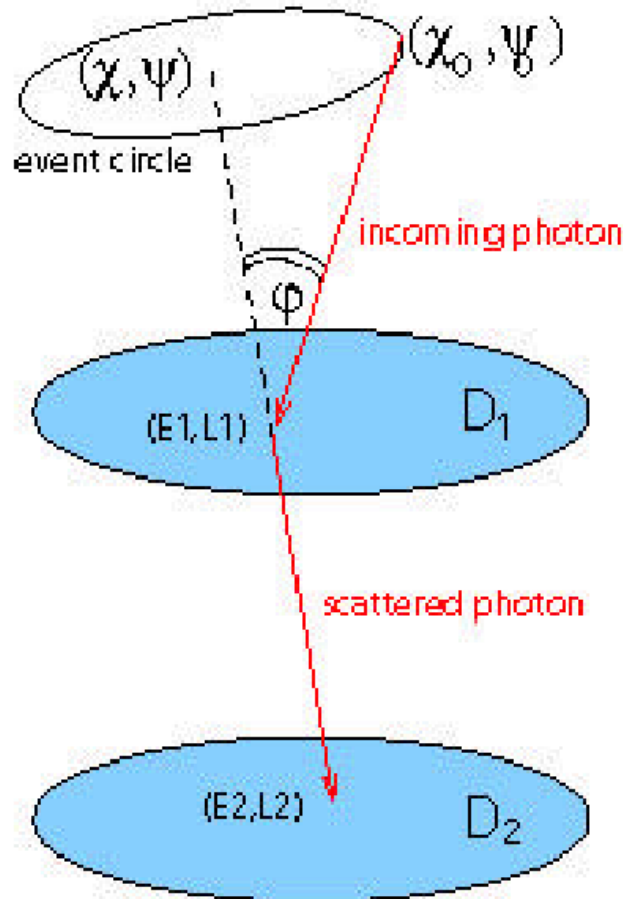
E1 = Energy of the scattered electron deposited in D1

x1,y1 = Interaction Location in D1

E2 = Energy of the scattered photon deposited in D2

X2,y2 = Interaction Location in D2

T, Δt = absolute time, TOF b/w D1-D2



Derived Event quantities:

x1,y1,x2,y2 => scatter direction (χ,ψ)

E1, E2 => total energy of incoming photon, assuming complete absorption in D2

and scatter angle φ from:

$$\cos \varphi = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1} \right)$$



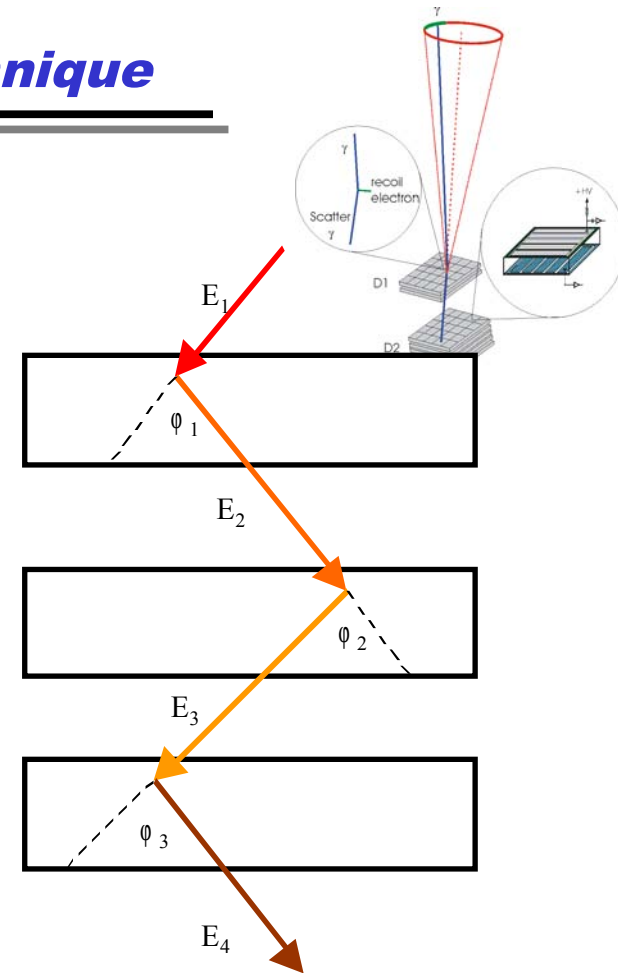
Three Gamma Interaction Technique

$$\cos\phi_1 = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1} \right); \quad L_1 = E_1 - E_2$$

$$\cos\phi_2 = 1 - m_e c^2 \left(\frac{1}{E_3} - \frac{1}{E_2} \right); \quad L_2 = E_2 - E_3$$

$$\cos\phi_3 = 1 - m_e c^2 \left(\frac{1}{E_4} - \frac{1}{E_3} \right); \quad L_3 = E_3 - E_4$$

$$E_1 = L_1 + \frac{L_2 + \left[L_2^2 + \frac{4m_e c^2 L_2}{1 - \cos\phi_2} \right]^{\frac{1}{2}}}{2}$$



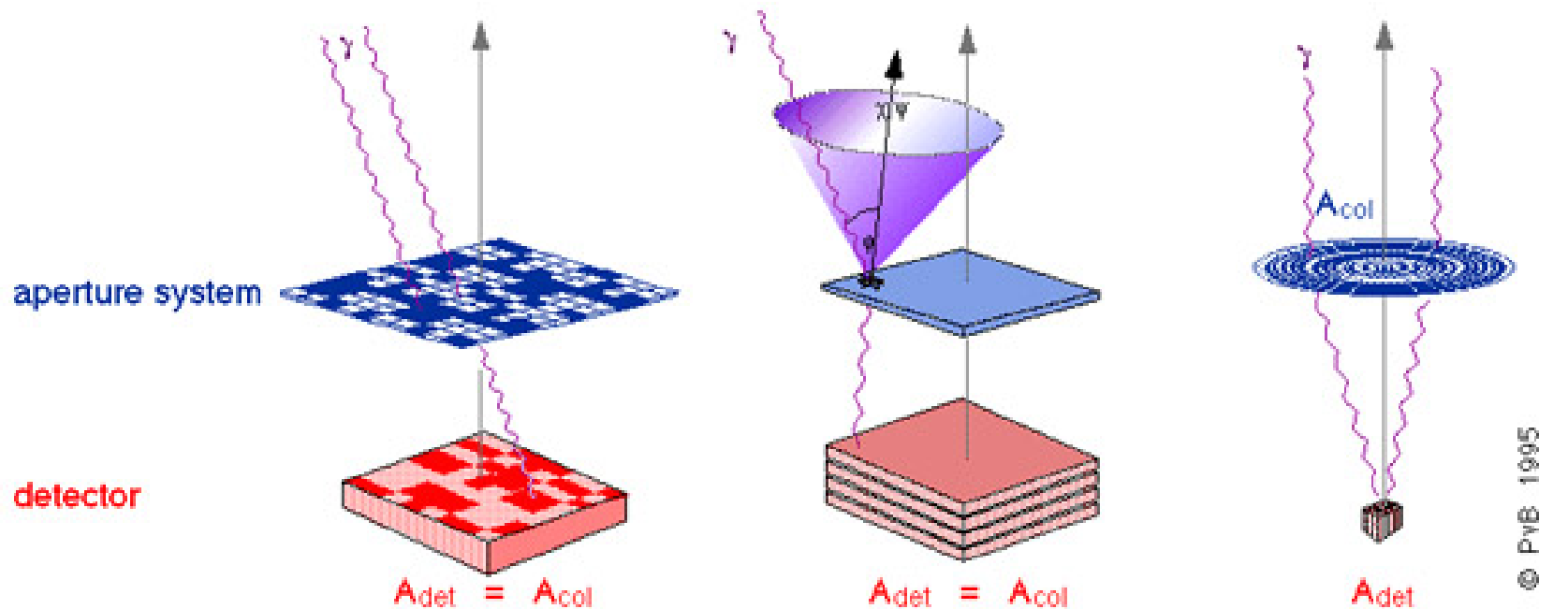
Incident gamma ray energy determined with partial energy loss

- Only three interactions required
- Dramatic improvement in efficiency
- New alternative: Silicon only Compton telescope

Kurfess et al., Proc. 5th Compton Symp. AIP 510 789 (2000)

Imaging in astronomy gamma

	modulating aperture systems	Compton telescopes	crystal lens telescopes
aperture / effect	geometric optics absorption	quantum optics incoherent scattering	wave optics coherent scattering

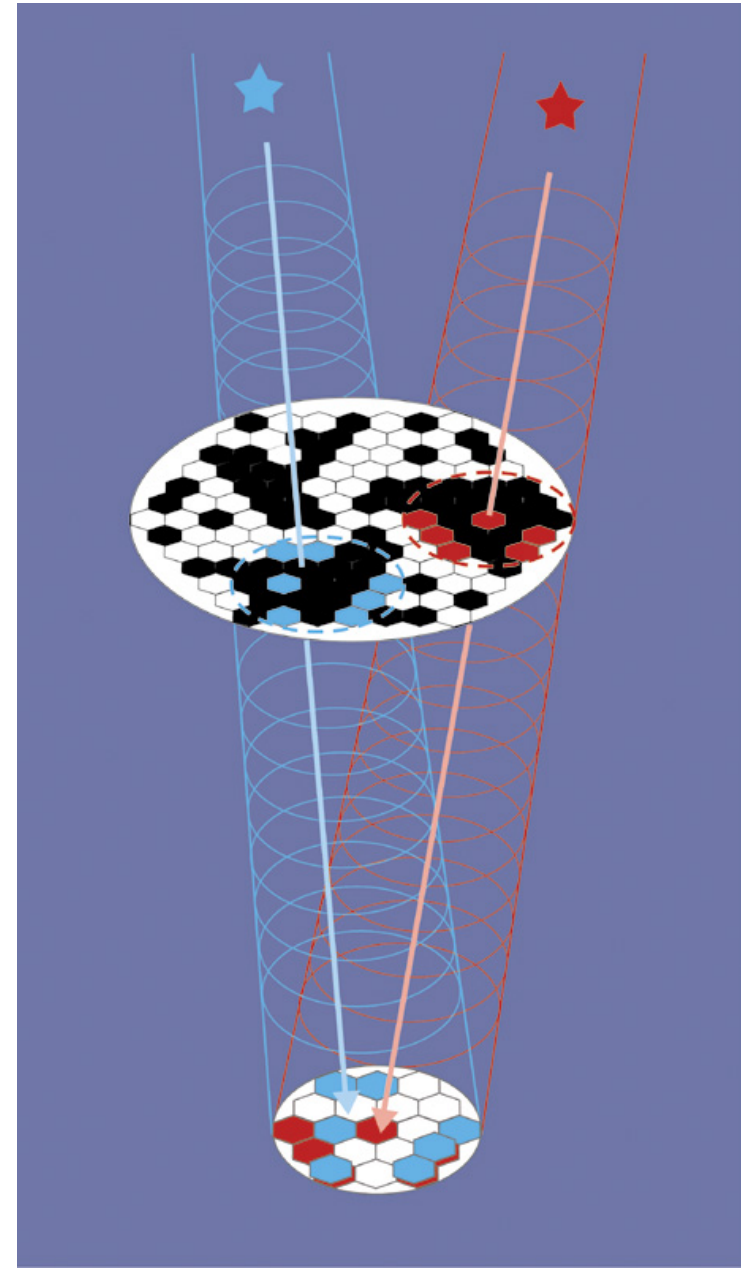


© PyB 1995

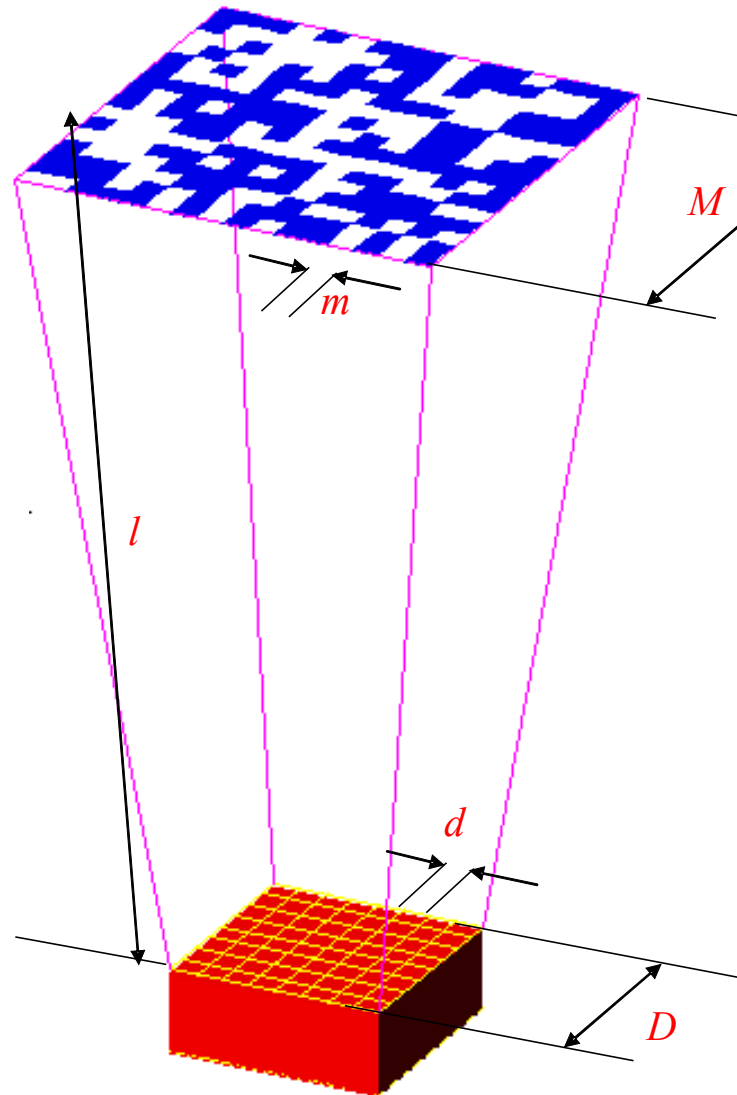
signal S	~	A_{col}	A_{col}	A_{col}
noise N	~	$V_{det} \sim A_{det} = A_{col}$	$V_{det} \sim A_{det} = A_{col}$	$V_{det} \sim A_{det} \ll A_{col}$
S/N	=	const (A)	const(A)	A_{col}/A_{det}

Osservare l'invisibile

- I fotoni gamma possiedono il maggiore potere penetrante;
- $\sim 10^6$ volte più energia del visibile;
- Normali tecniche di foccheggiamento non praticabili;
- Tecniche di rivelazione indiretta:
 - Maschere codificate

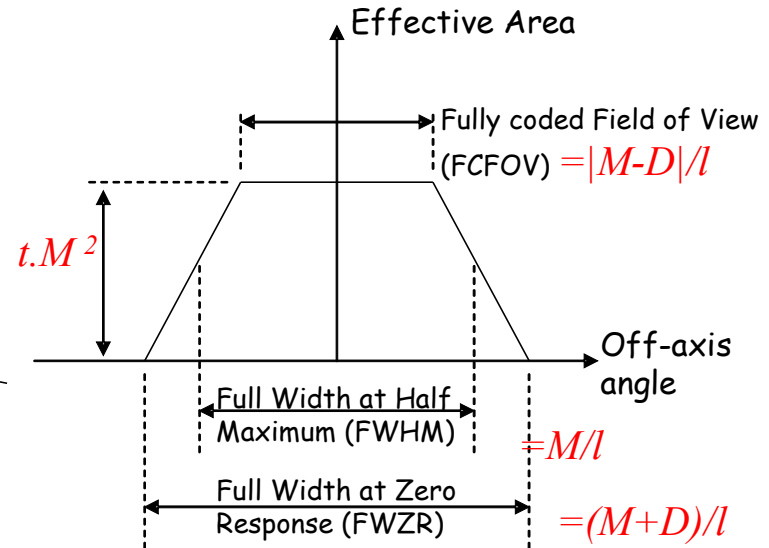


Telescopi a maschera codificata



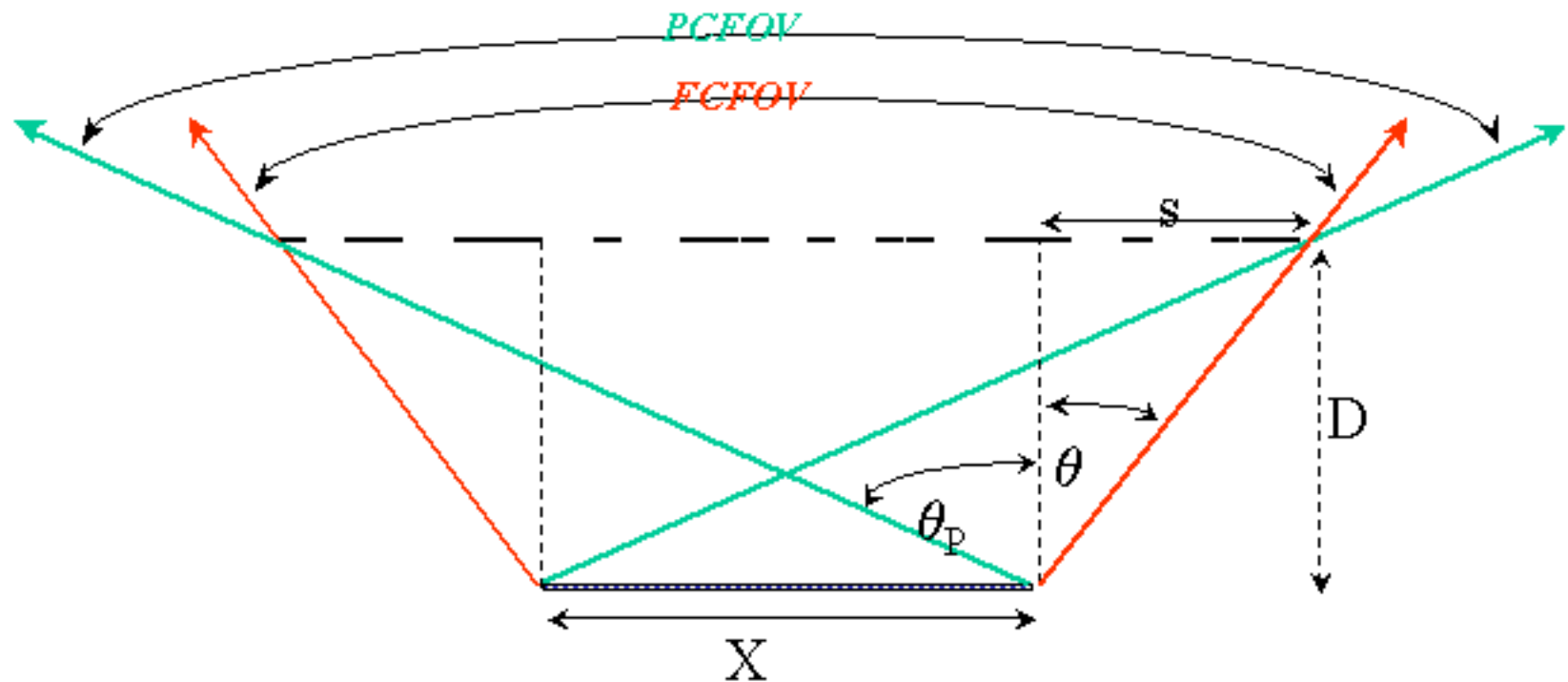
Coded mask telescopes -key parameters

- m Mask Pixel size
- d Detector Pixel size
- M Mask Size
- D Detector Size (assume $D < M$)
- l Mask-Detector Separation
- t Mask open fraction



DEFINITION OF PERFORMANCE PARAMETERS

The Field of View of a Coded Aperture Telescope



The Fully Coded Field of View (FCFOV)

The fully coded field of view has a half angle θ

$$\theta = \text{Tan}^{-1}\left(\frac{s}{D}\right)$$

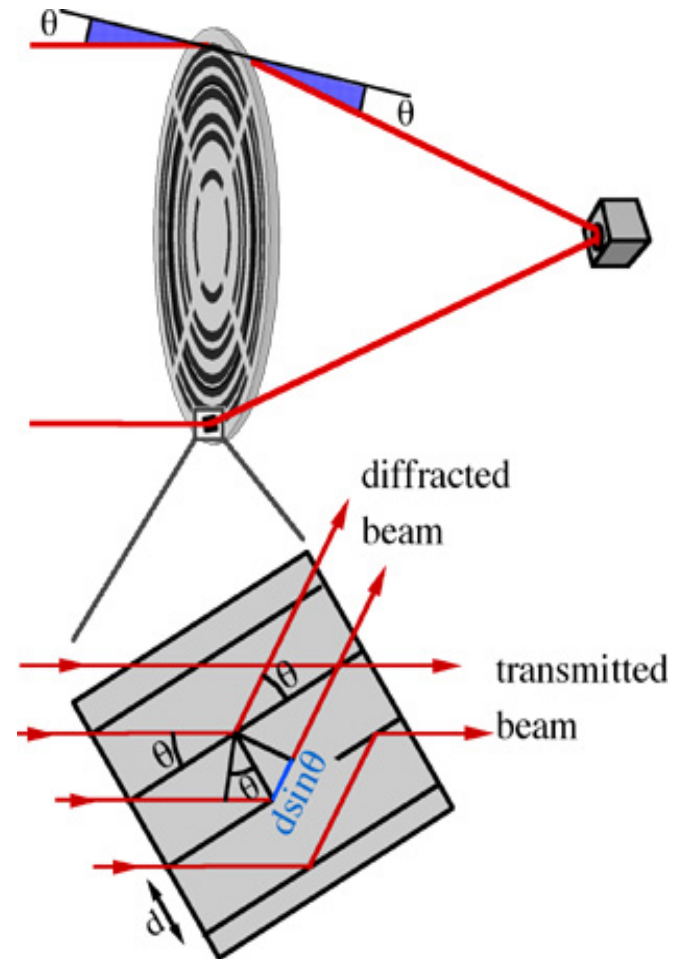
The Partially Coded Field of View (PCFOV)

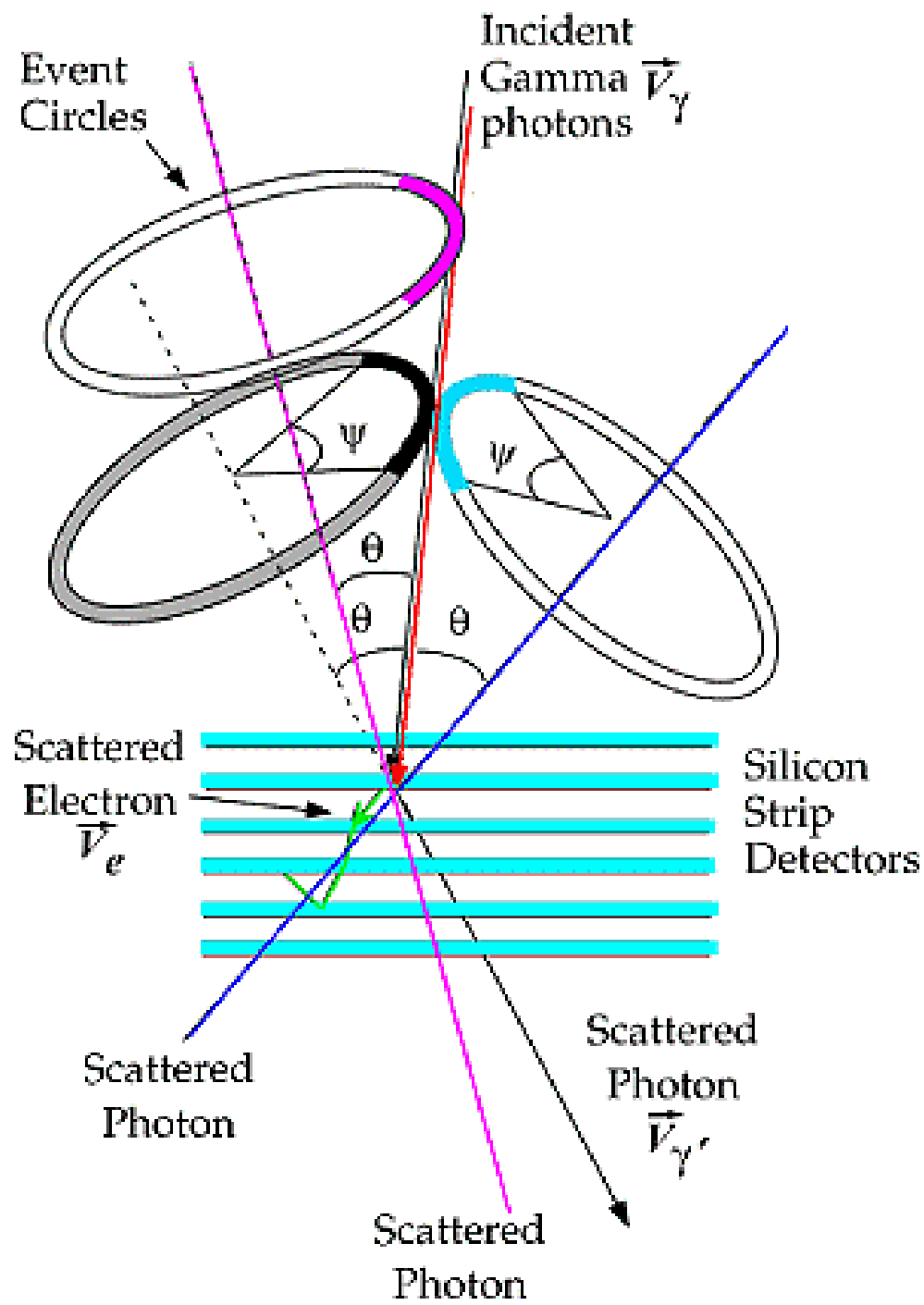
The partially coded field of view has a half angle θ_p

$$\theta_p = \text{Tan}^{-1}\left(\frac{X+s}{D}\right)$$

Lenti (!) per telescopi gamma

- $2 \cdot d \cdot \sin(\theta) = n \cdot \lambda$, dove:
 - d =dist. piani cristallo
 - θ =angolo di Bragg
 - λ =lunghezza d'onda
- Esempio: CLAIRE:
 - diametro lente: 45 cm
 - Ge, $1.5 \times 1.5 \times 4 \text{ cm}^3$
 - distanza focale: 276 cm
 - $E=170 \text{ keV}$ ($\pm 1 \text{ keV}$)
- Bragg: superficie
- von Laue: nel cristallo





A 3D cutaway diagram of a satellite instrument payload. The satellite's structure is shown in a light blue wireframe. Two main instruments are highlighted with red arrows and labels. The 'Imager IBIS' is a white, box-like component with a grid of detector elements on top. The 'Spectrometer SPI' is a large, yellow, cylindrical component with a complex, multi-faceted base. Other components, including various sensors and structural elements, are visible within the payload bay.

Imager IBIS

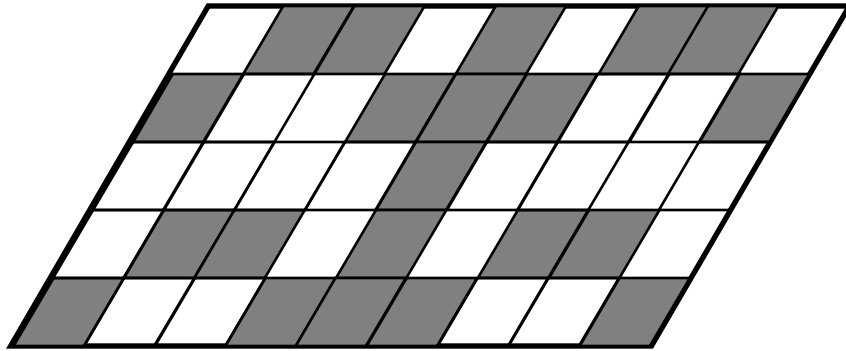
Spectrometer SPI

Imaging and spectroscopy in the 15 keV to 10 MeV band
Source monitoring in the X-ray (2-30 keV) and visible bands

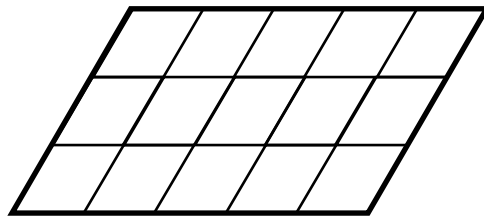
Astronomia con fotoni di alta-energia (1)

Apertura codificata

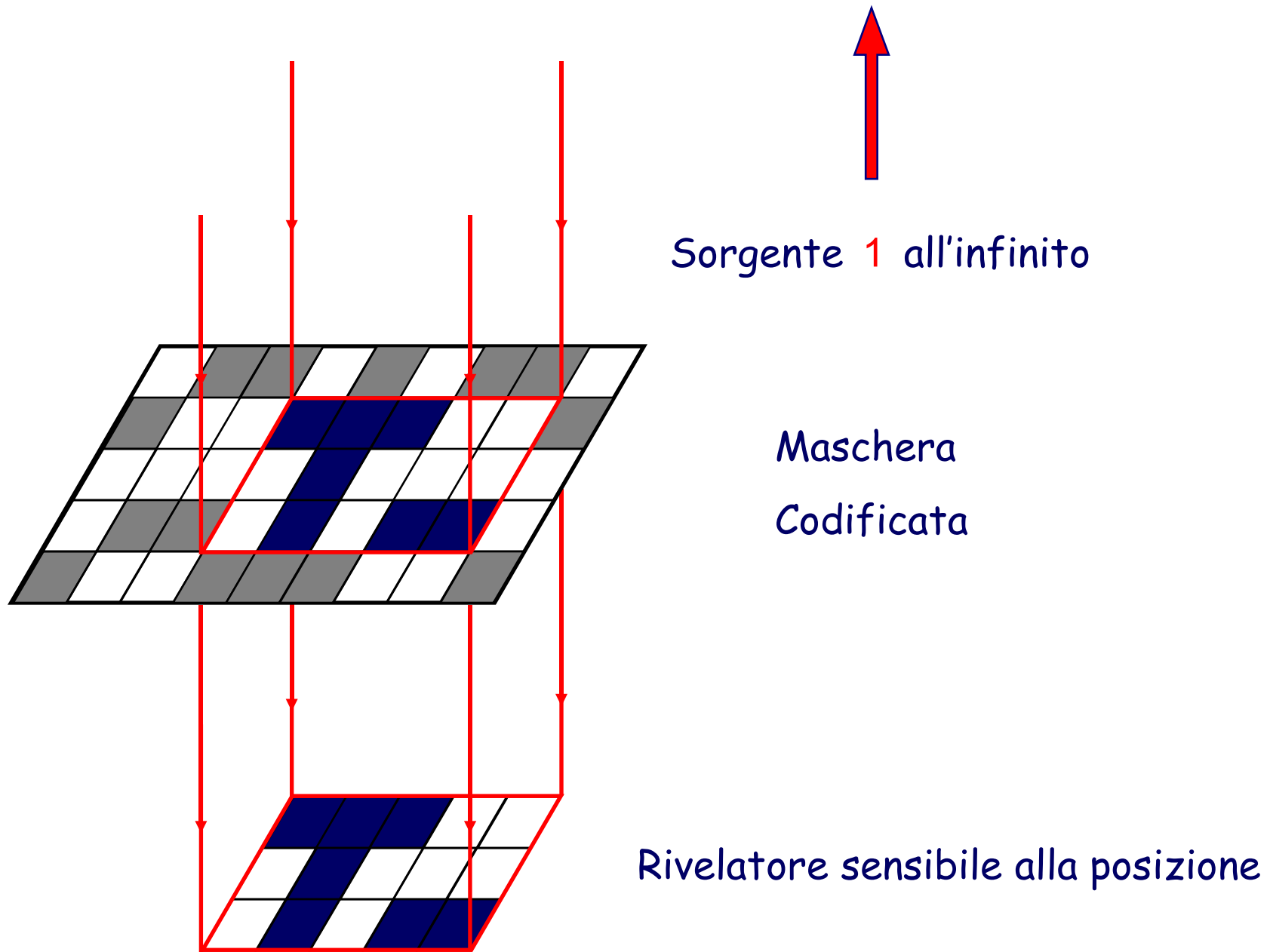
Una maschera codificata (array di blocchi opachi) è messa in modo che una sorgente all'infinito proietta un pattern caratteristico della direzione della sorgente

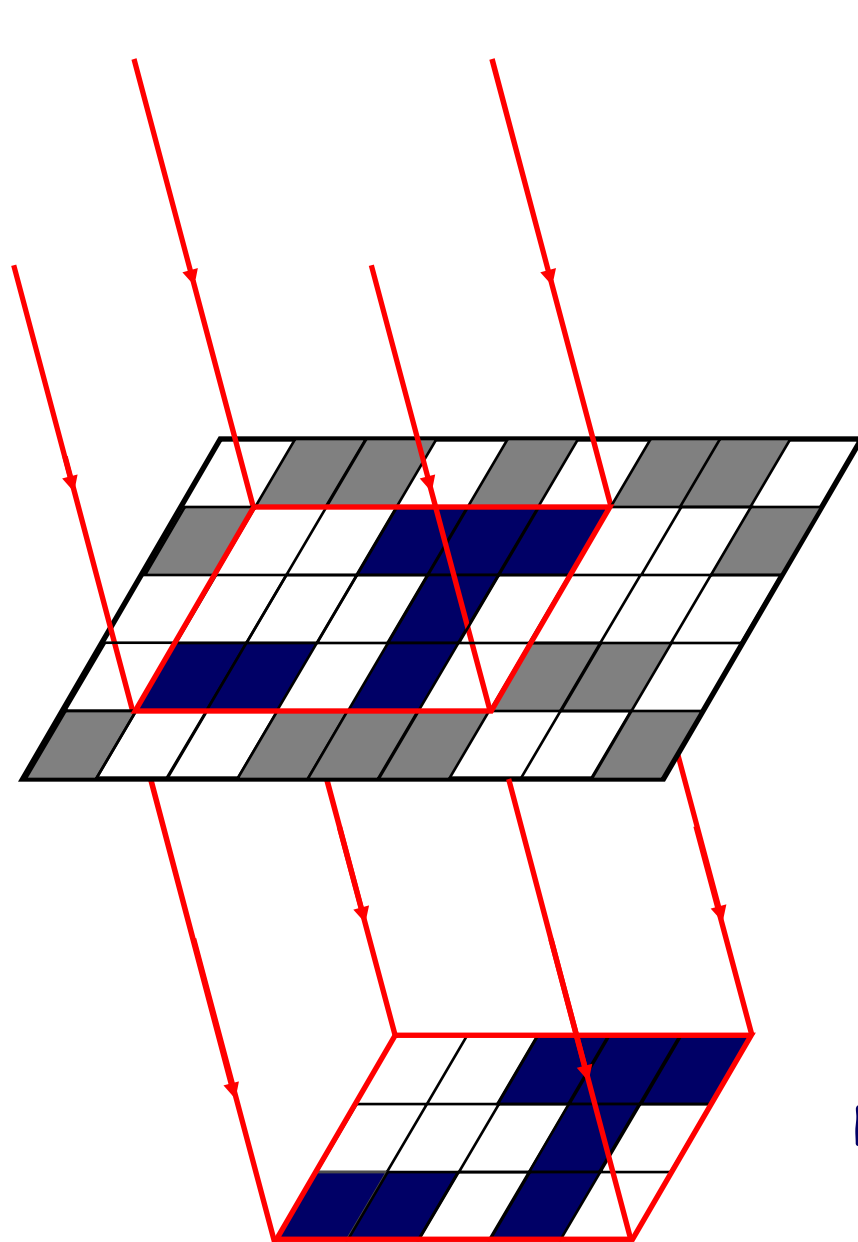


Maschera
Codificata



Rivelatore sensibile alla posizione





Sorgente 2 all'infinito

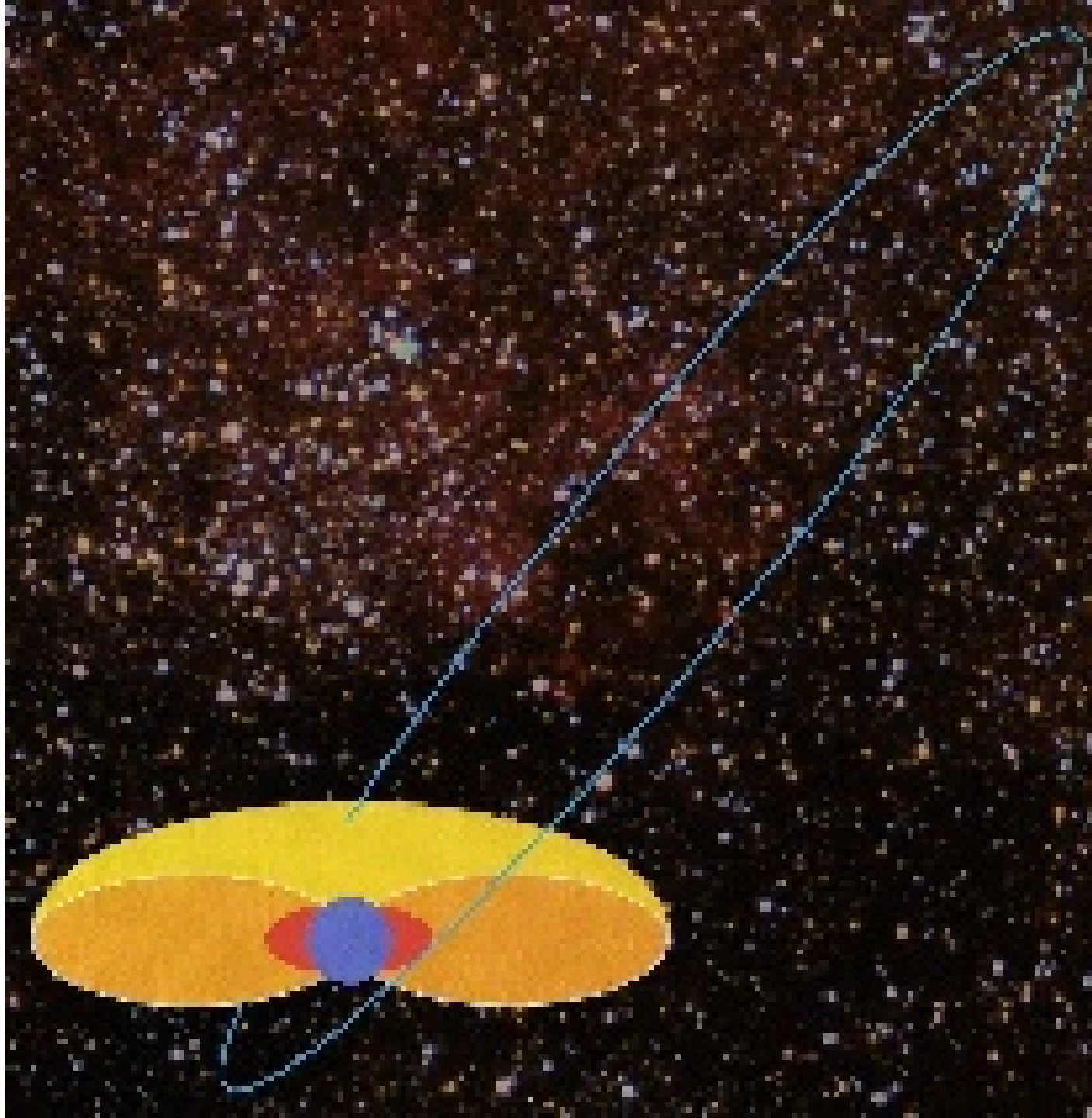
Naschera
Codificata

Rivelatore sensibile alla posizione



Maschera di IBIS

Orbita di INTEGRAL



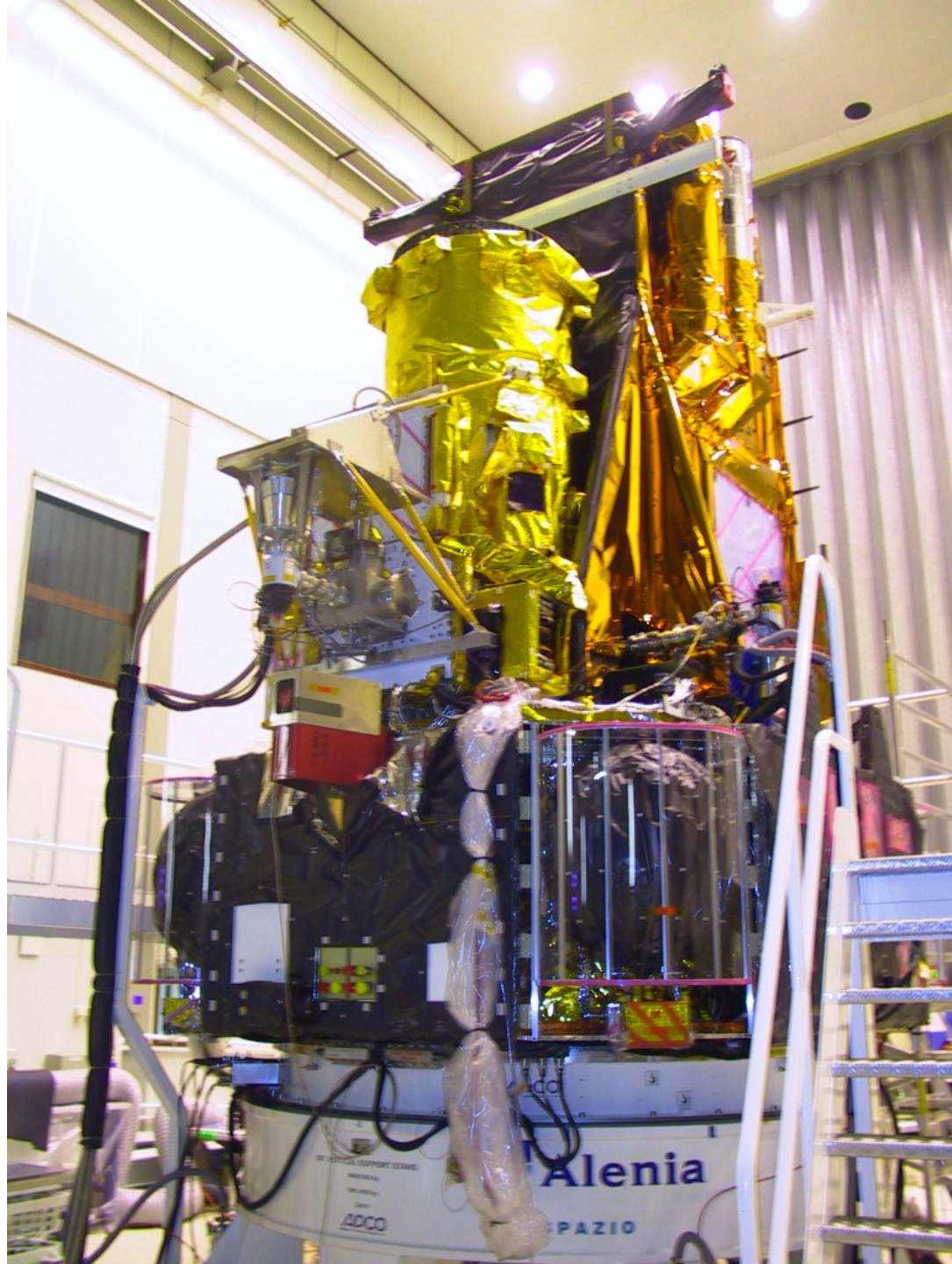


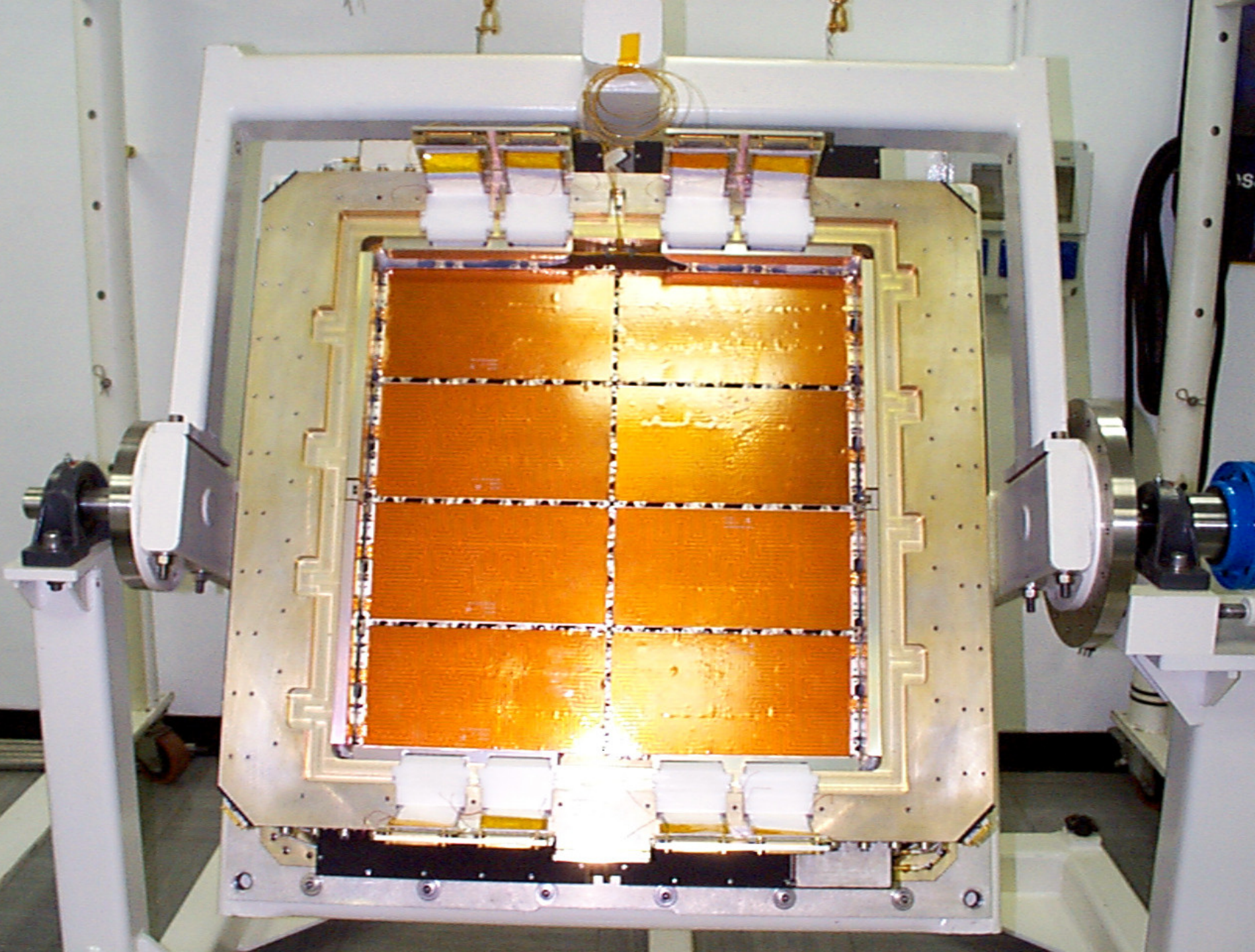


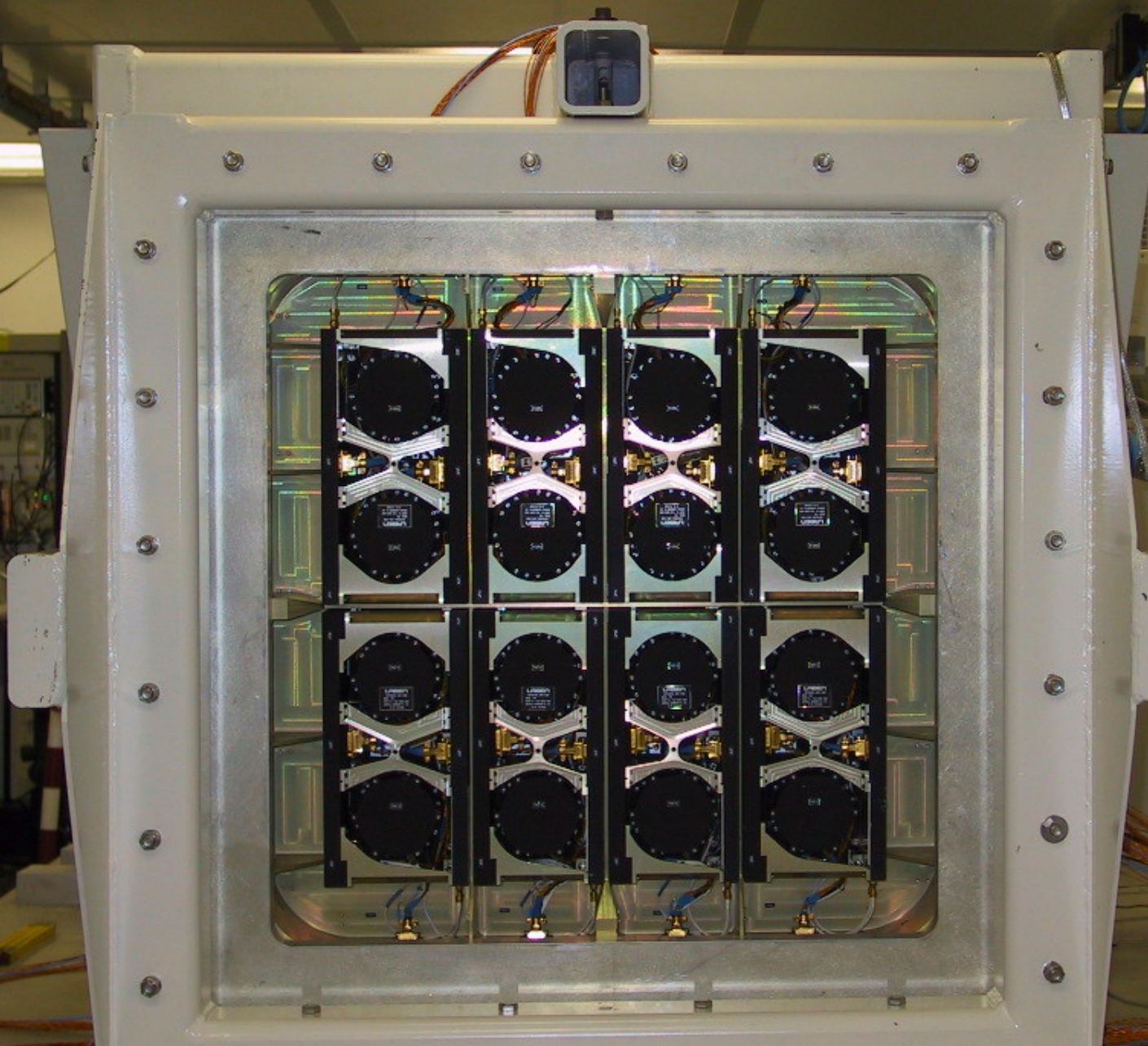


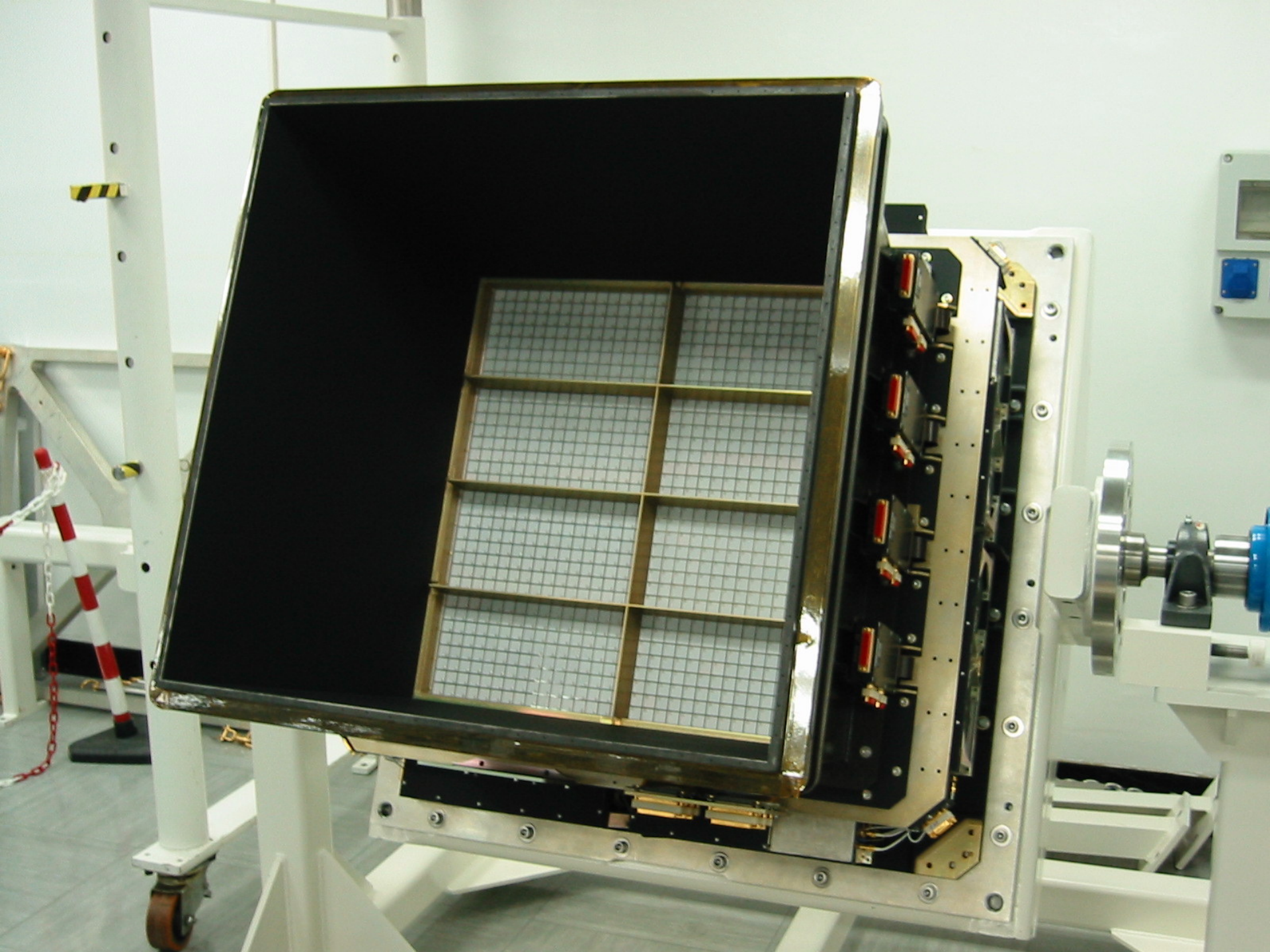




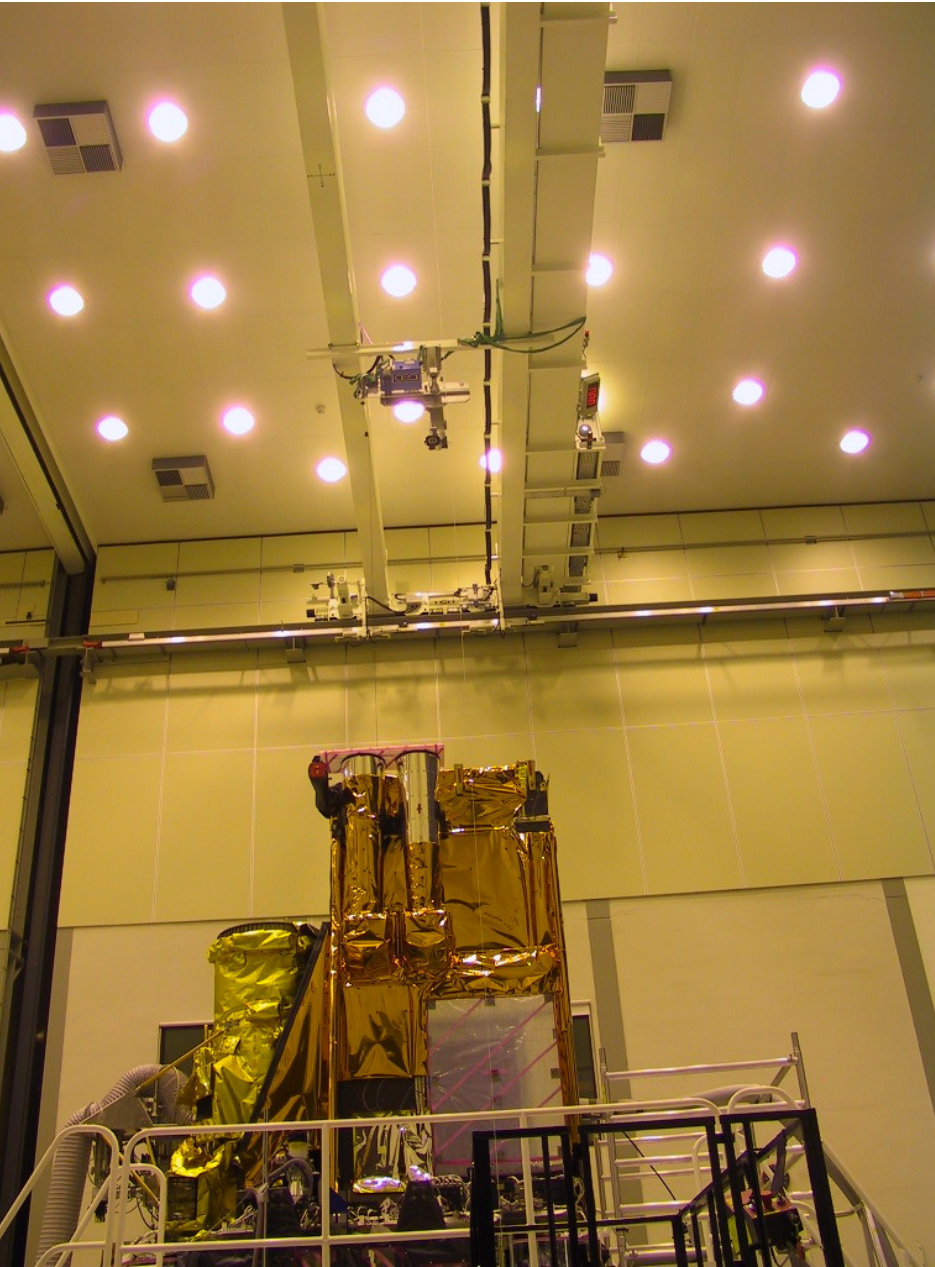








INTEGRAL during Payload Ground Calibration



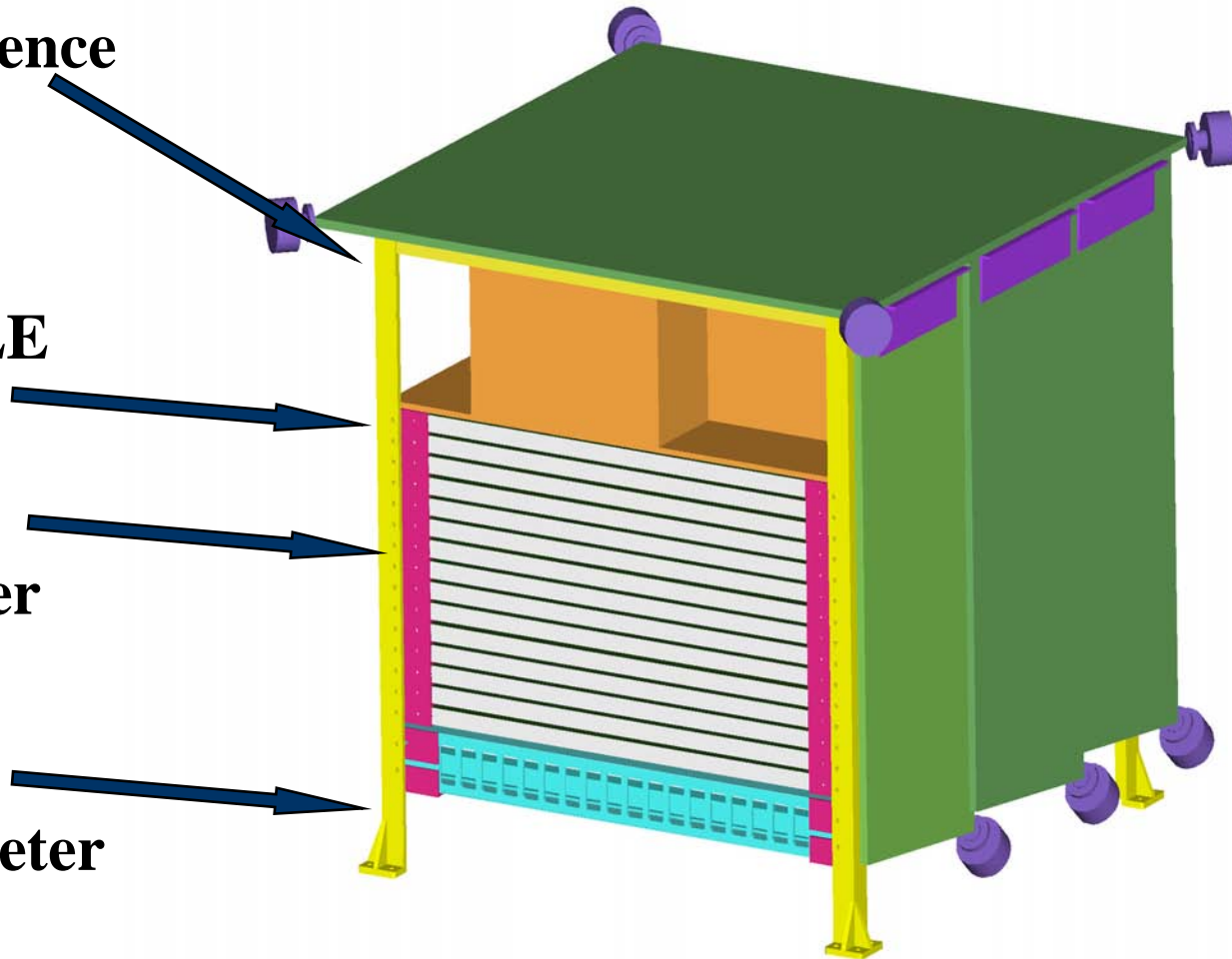
AGILE

Anticoincidence

SuperAGILE

Silicon tracker

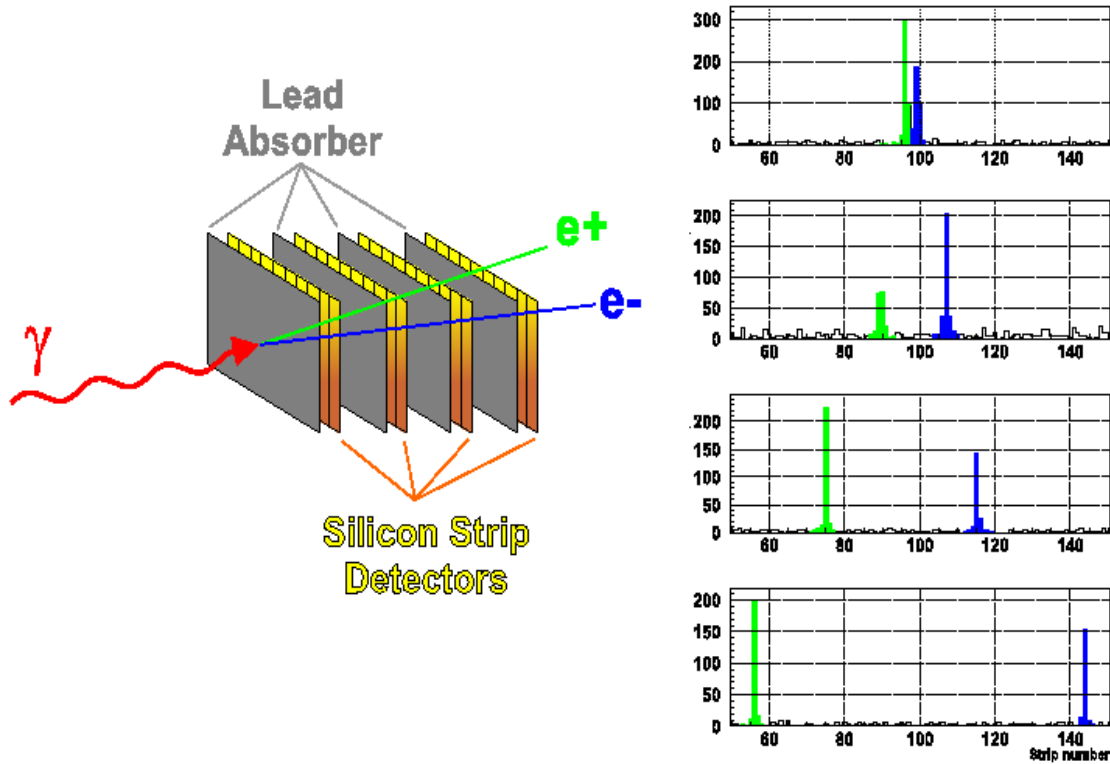
Mini-Calorimeter



AGILE

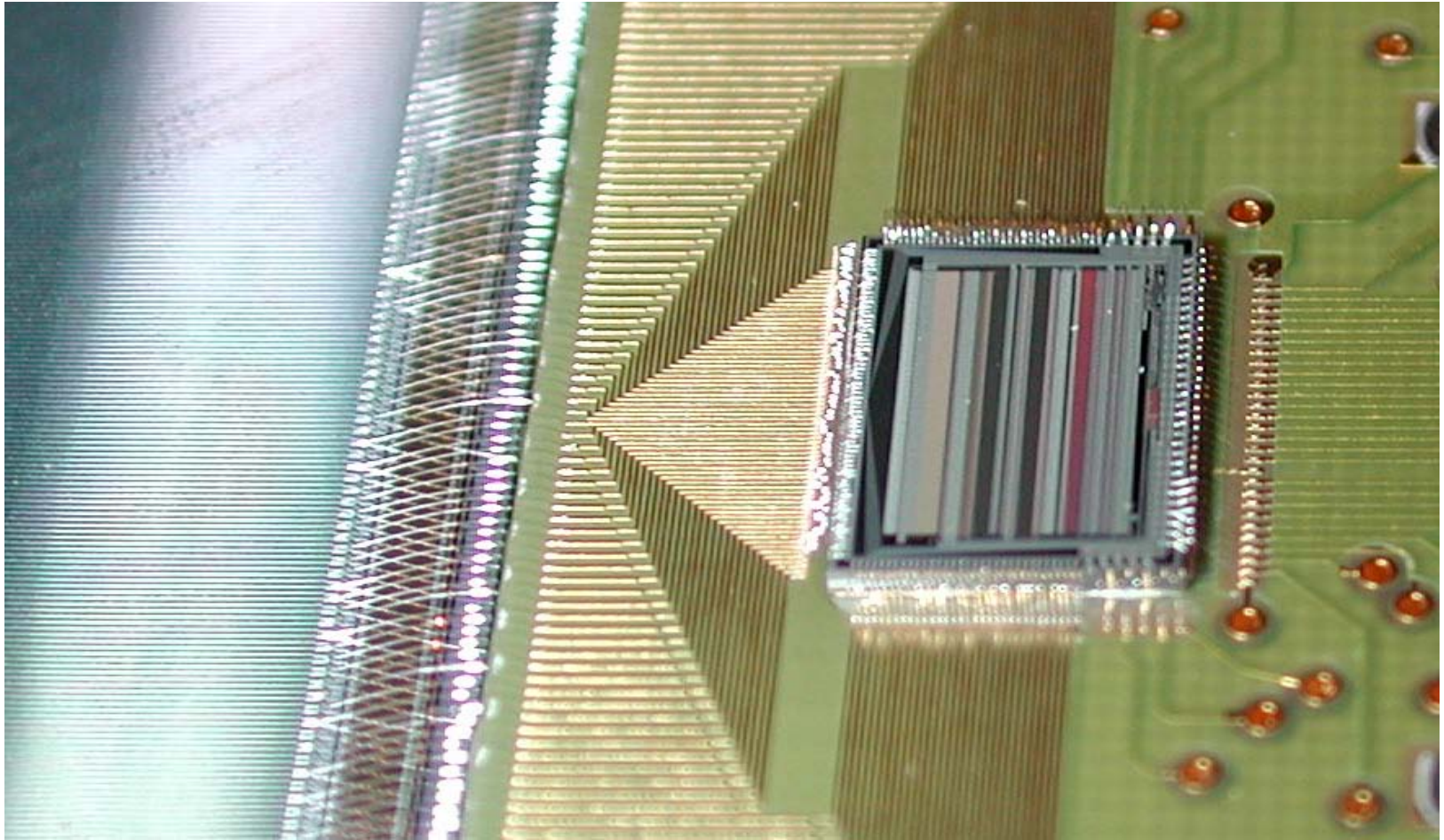
Mini-calorimeter



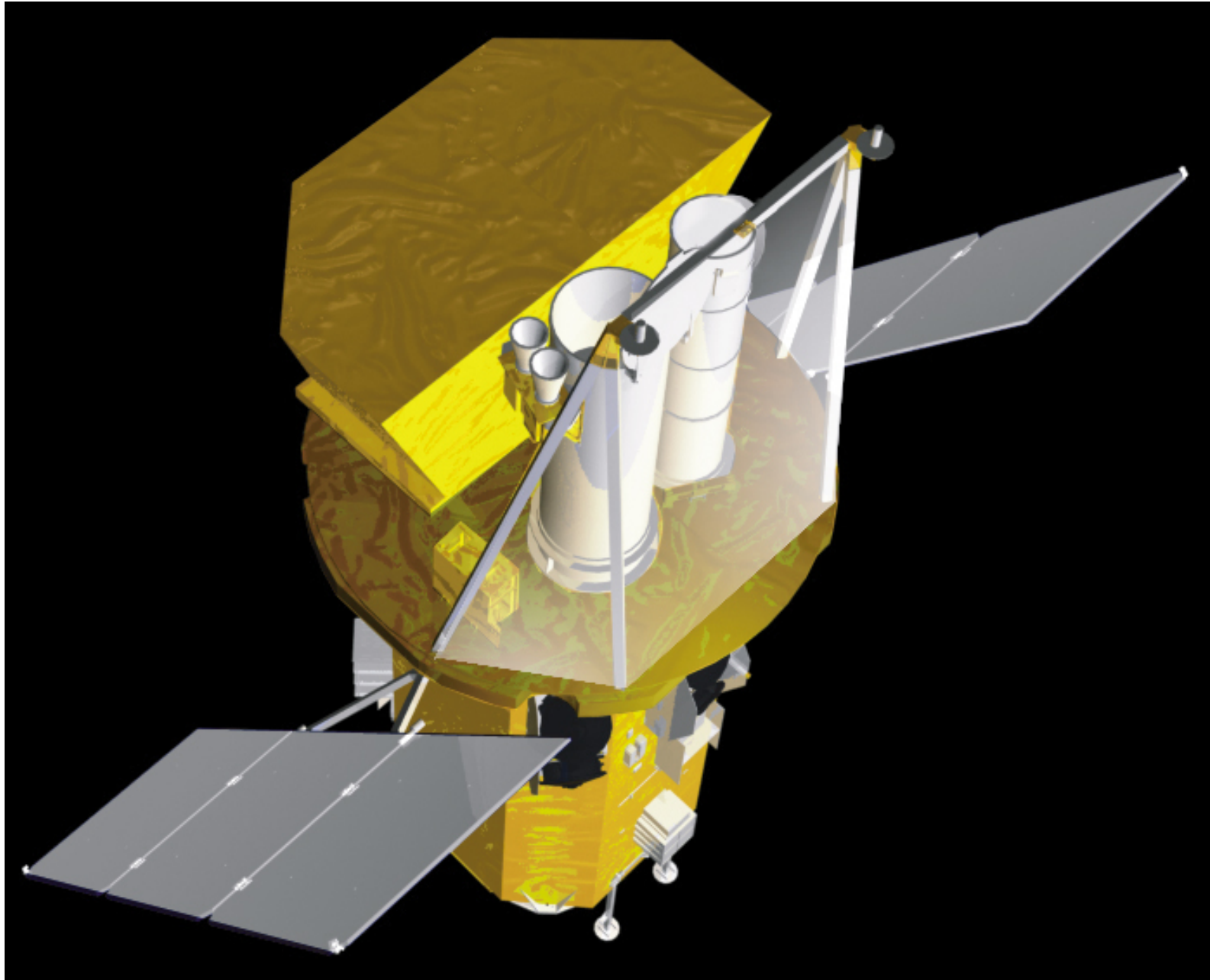


PHOTAG TESTBEAM - INFN TS/IFC MI

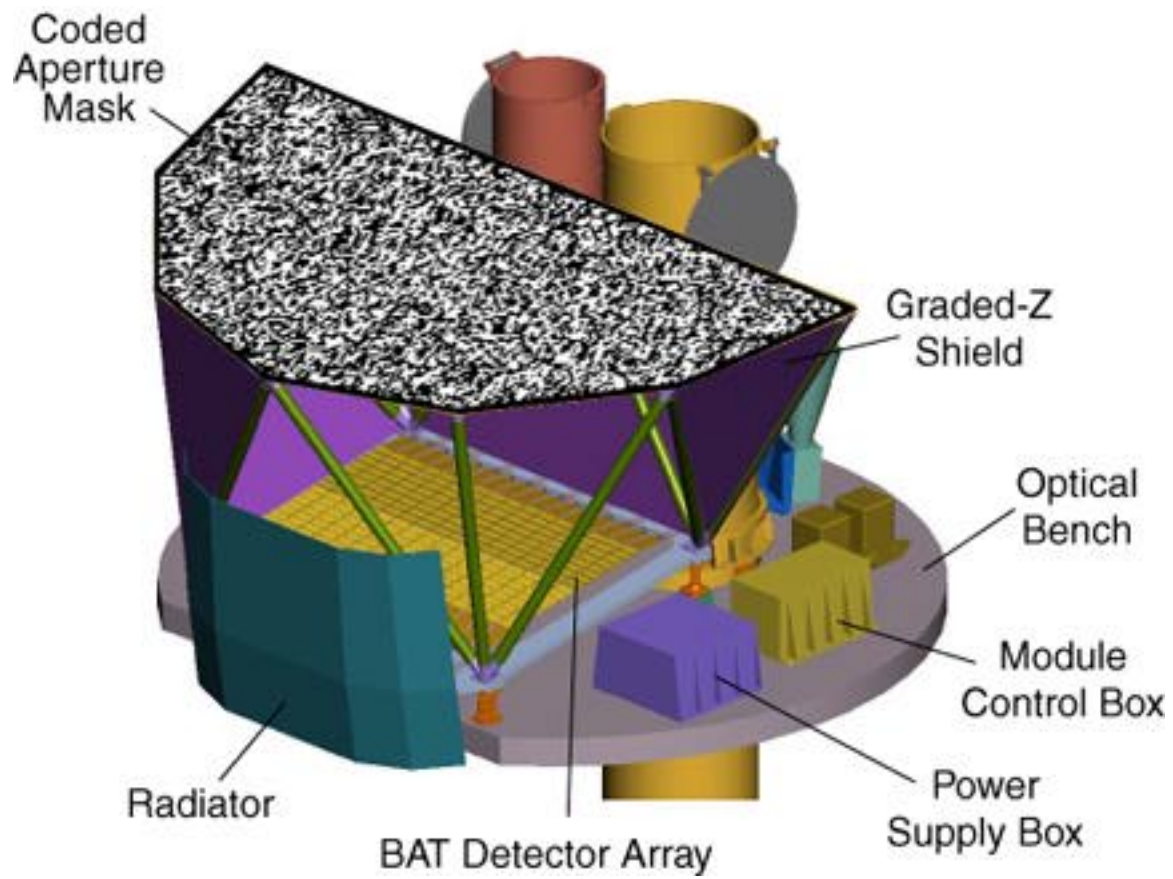
Tracker data from CERN test beam precision $\sim 40 \mu\text{m}$

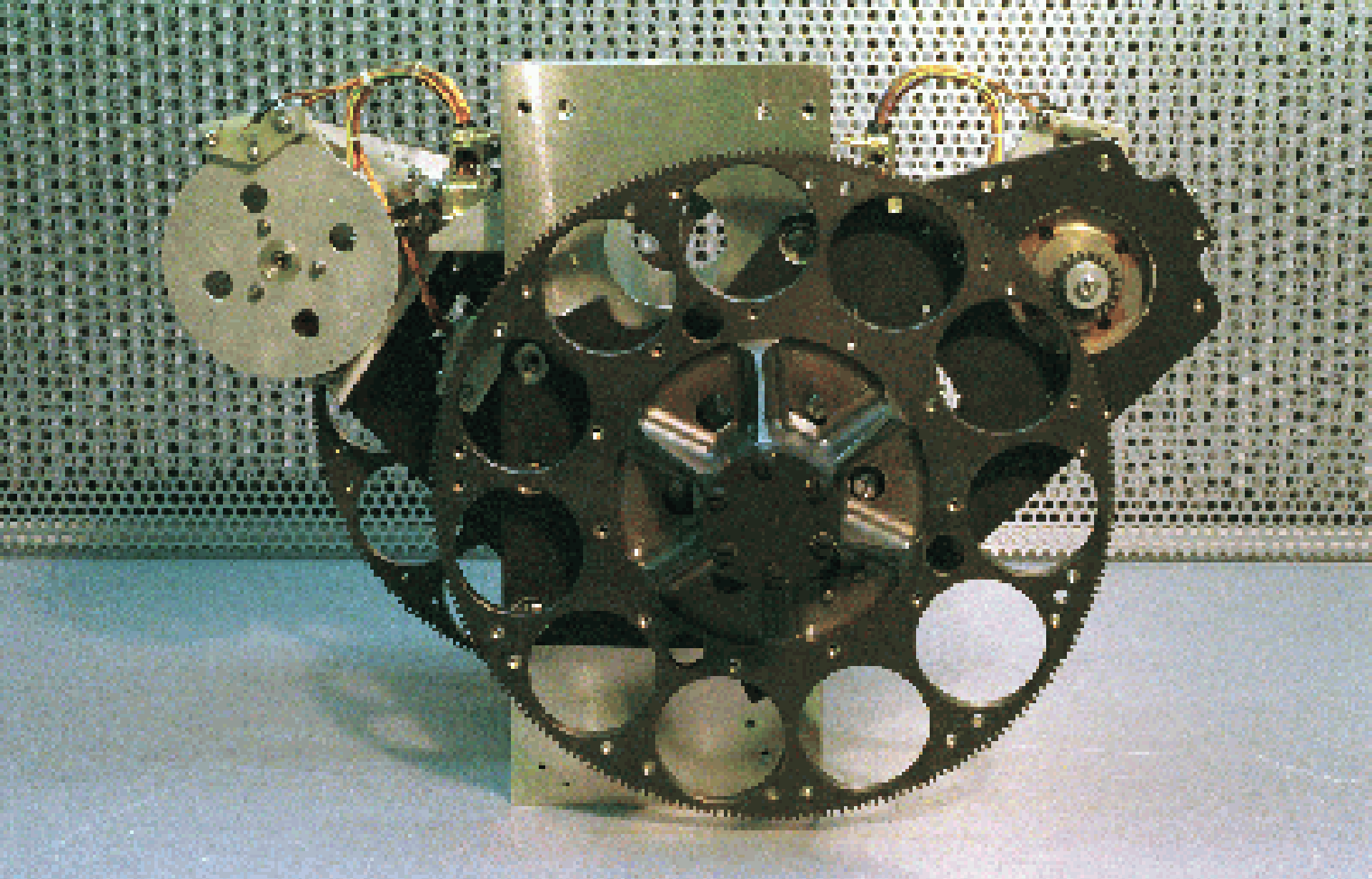


AGILE Silicon microstrip step 121 μm



SWIFT

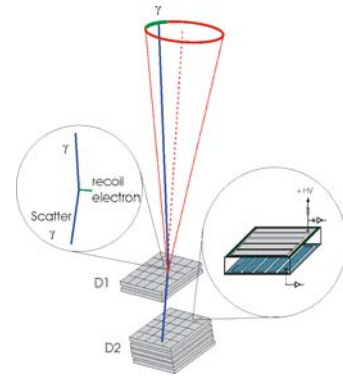




UVOT



Silicon ACT



1 m² frontal area

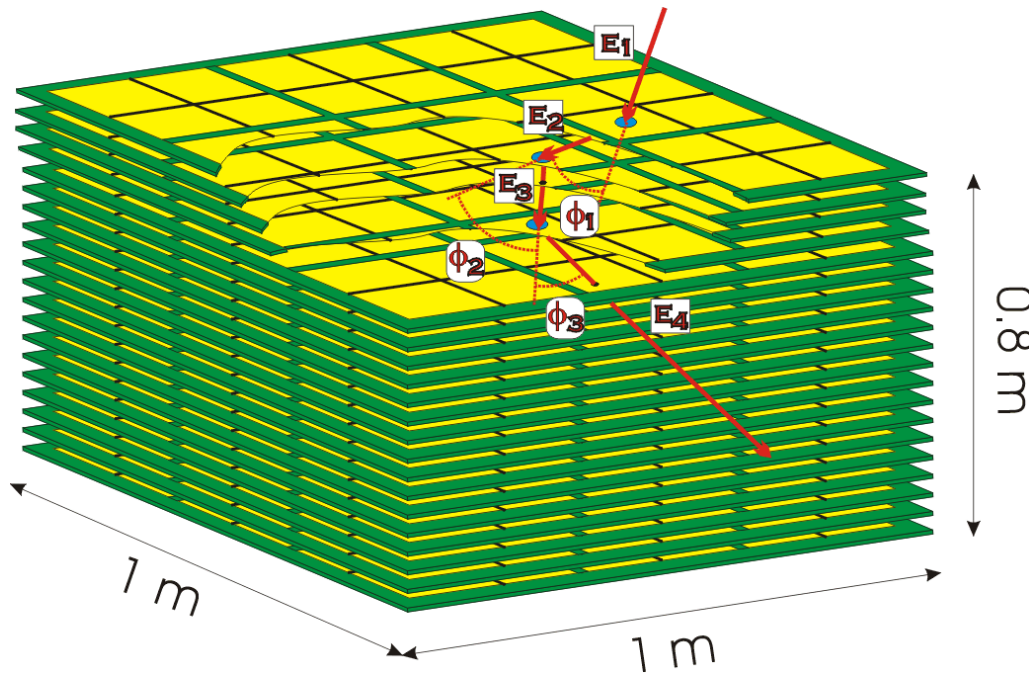
Multiple layers of thick double-sided silicon strip detectors

~ 40 g/cm² thick

430 kg silicon

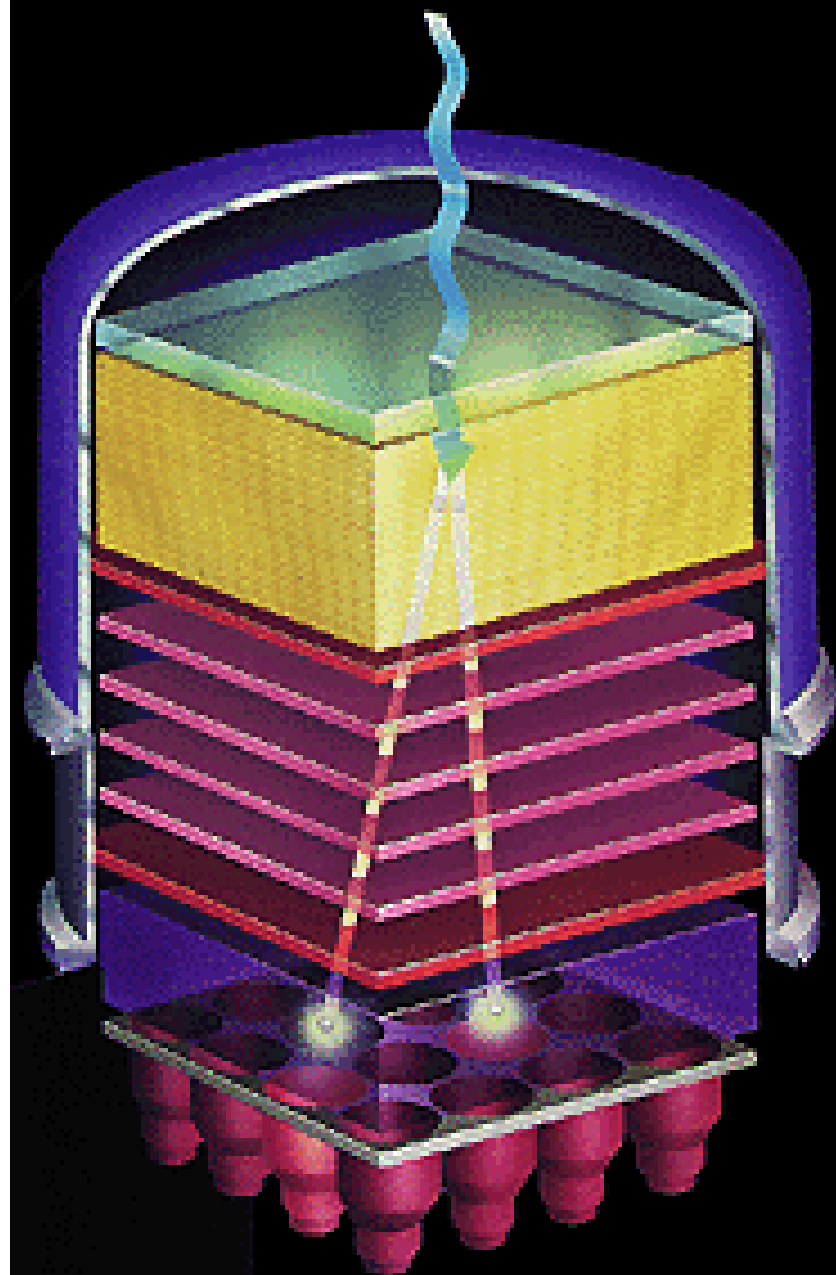
Broad FoV (\pm 75-90 degrees)

Charged particle anti-coincidence

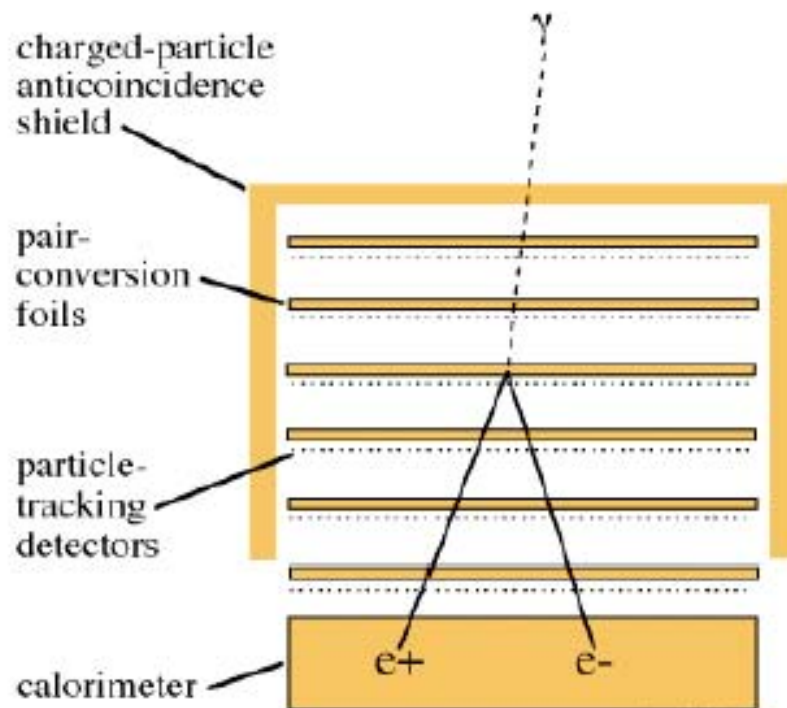


Telescopi gamma per $E > 5-10$ MeV

- Piani di convertitore (e.g. W) si alternano con piani di tracker position sensitive;
- I fotoni gamma incidenti interagiscono nel convertitore via produzione di coppie
- Il tracker rivela le particelle prodotte



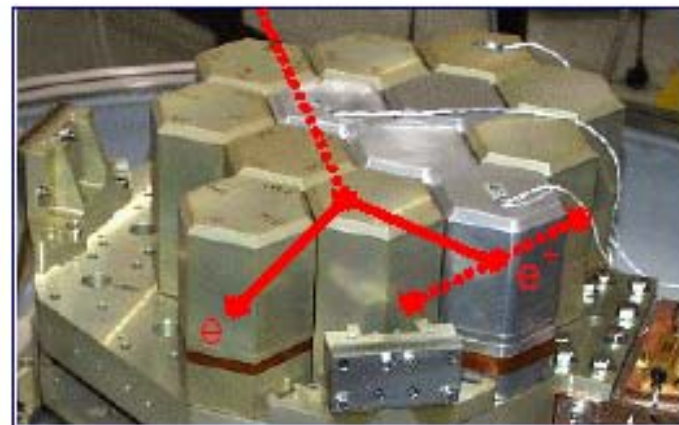
Pair Production Telescopes



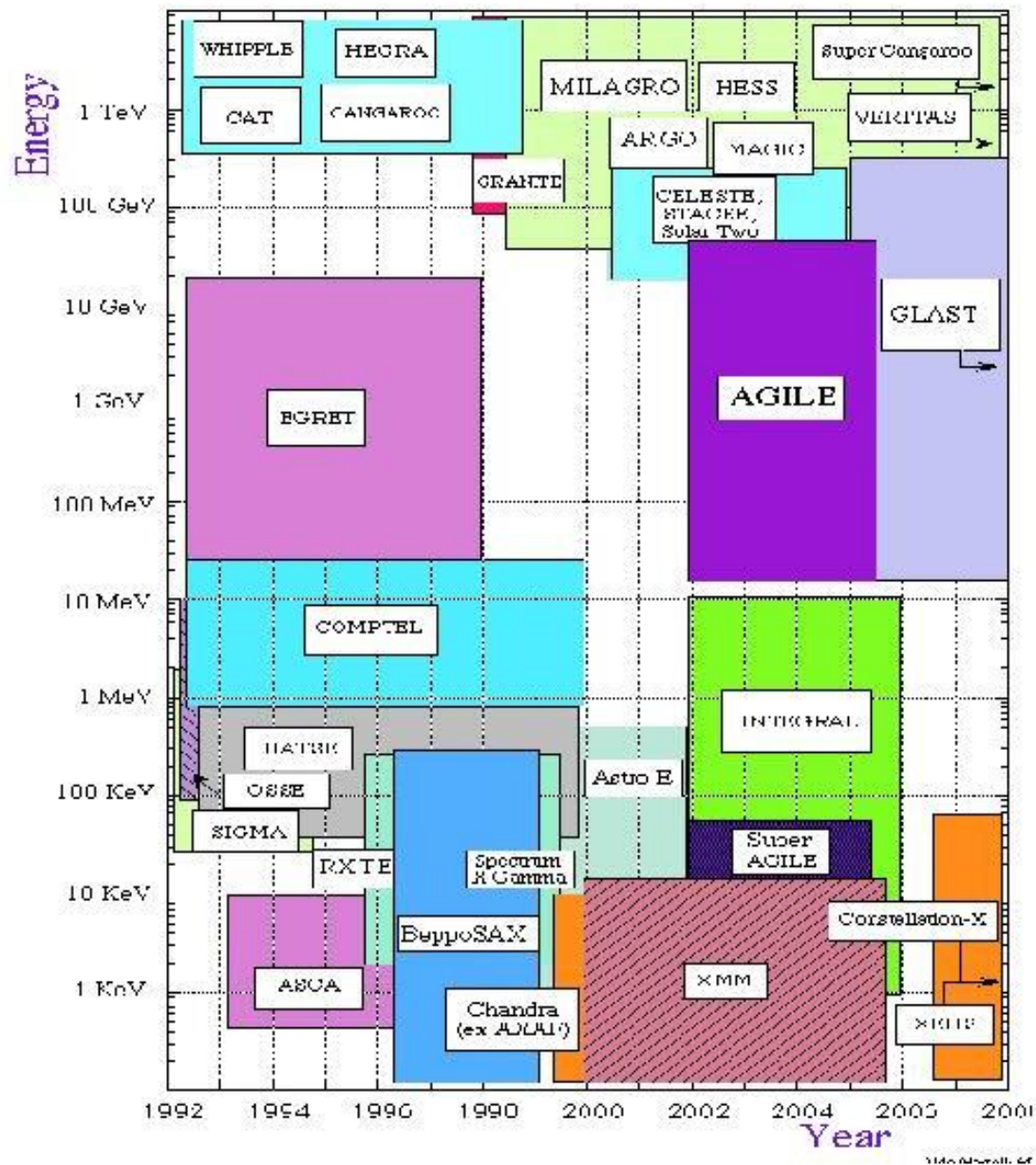
Incident photon whose energy $E_a > 2m_e c^2$ (i.e. $E_a > 1.022$ MeV) is in a position to create an **electron-positron pair** in the intense electric field prevailing close to an atomic nucleus.

Trajectories of the particles does not markedly deviate from the incident photon direction as soon as the photon energy $E_a \gg 2m_e c^2$.

Pair production is also at work in the SPI detector assembly inducing rather complex events.



X-ray and Gamma-ray Projects 1992 - 2008



Credit: AGILE project web pages at:
["http://www.ifctt.mi.cnr.it/Agile/brochure/a-science.ps.gz"](http://www.ifctt.mi.cnr.it/Agile/brochure/a-science.ps.gz)