

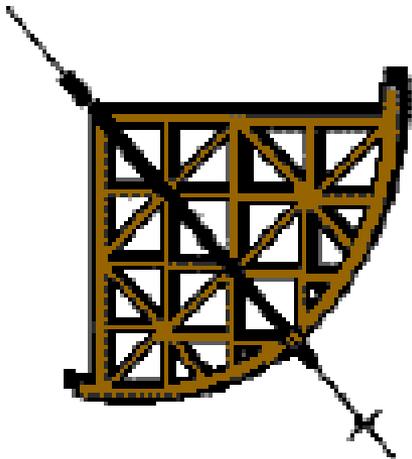
Introduzione alla Cosmologia Fisica Lezione 10

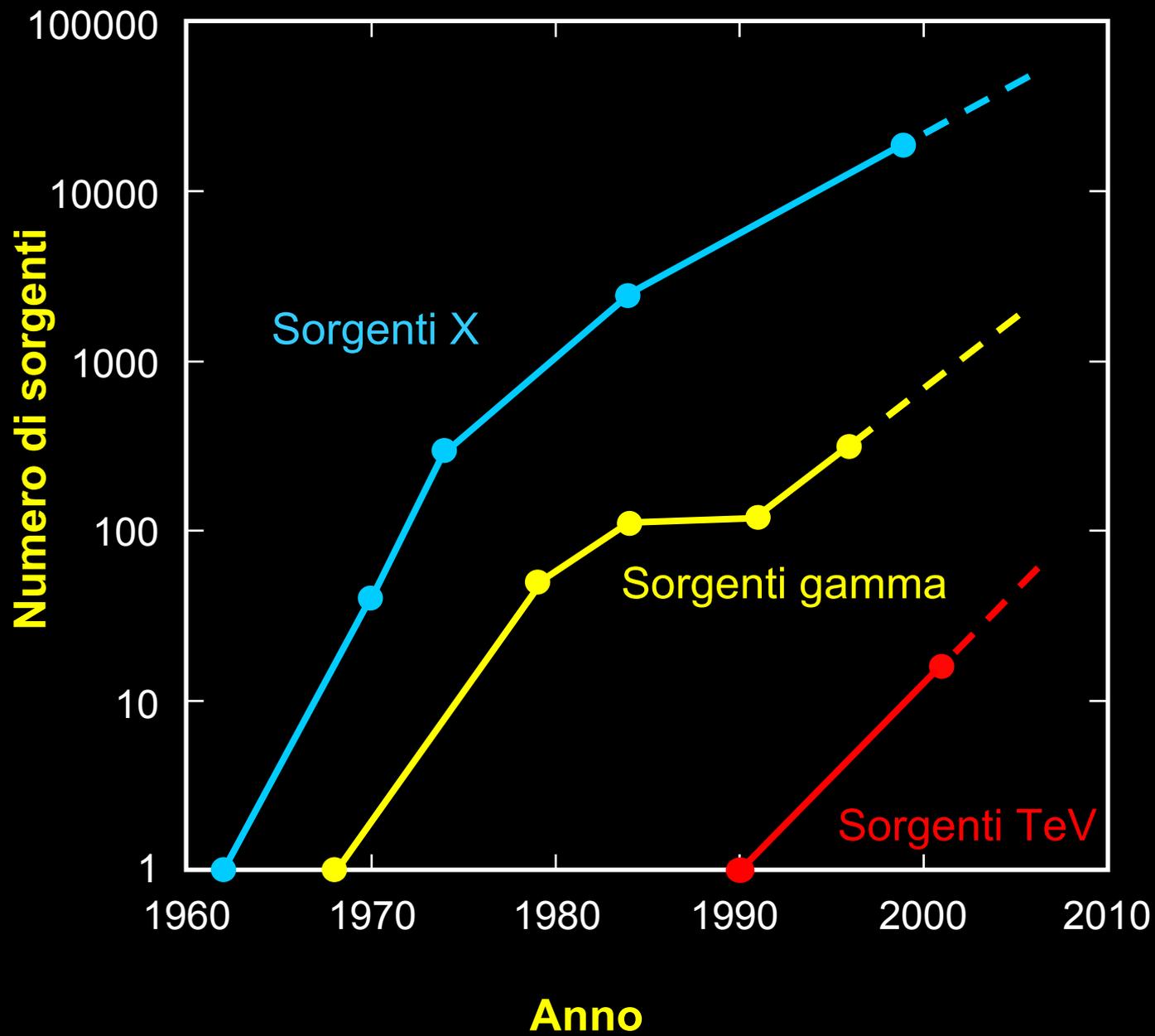
L'Astronomia Gamma, le tecniche

Giorgio G.C. Palumbo

Università degli Studi di Bologna

Dipartimento di Astronomia



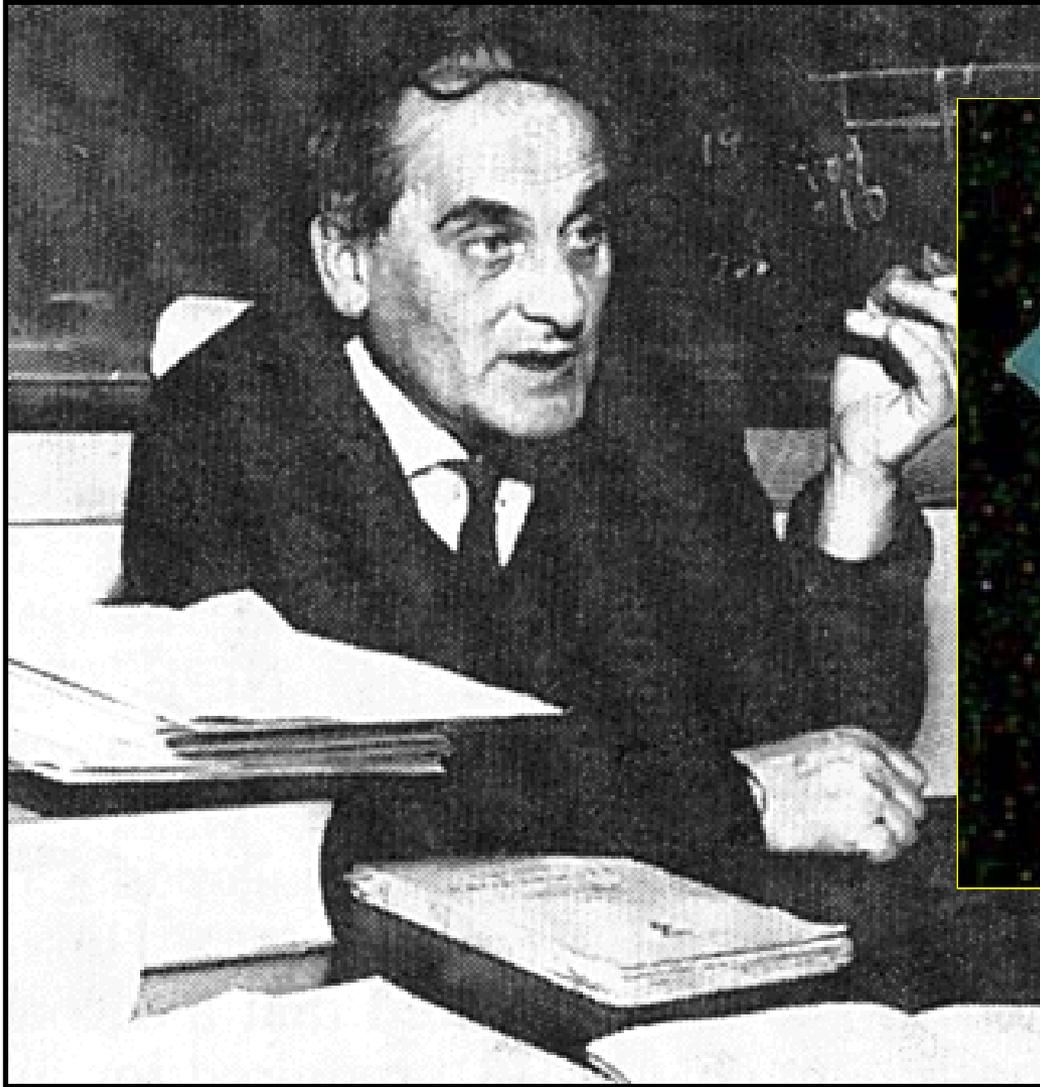


BeppoSAX:

- 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**

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



BeppoSAX

TLM: 1 Mb/s

TLC: 2 Kb/s

MALINDI

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

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

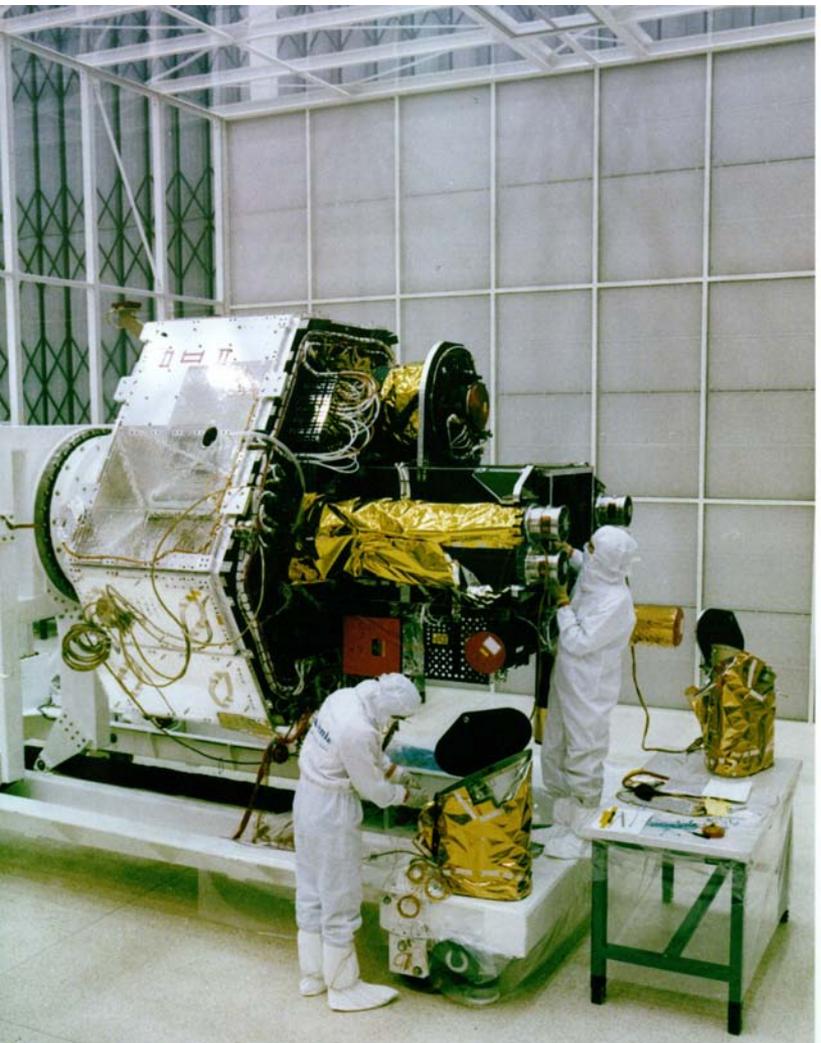
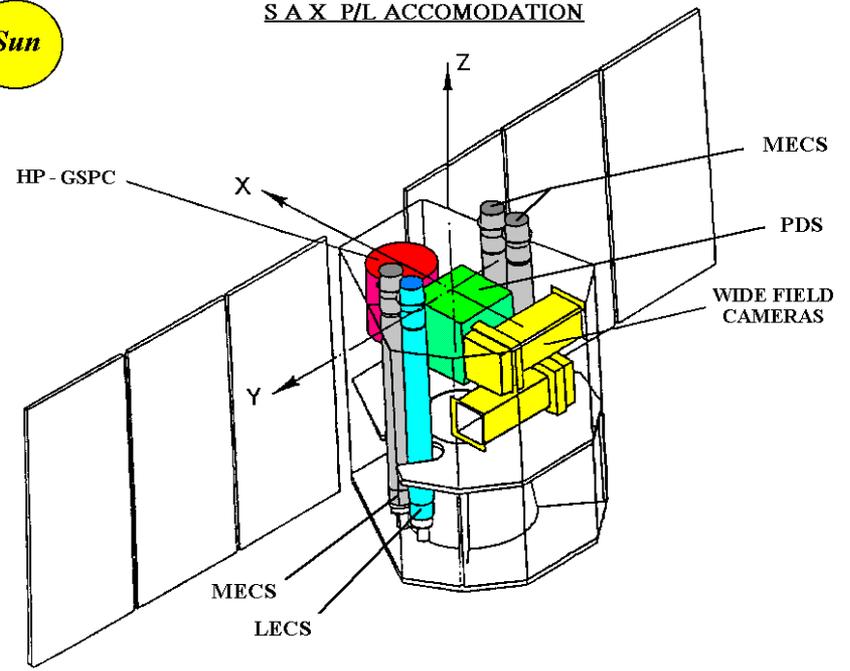
INTELSAT V



BeppoSAX strumenti

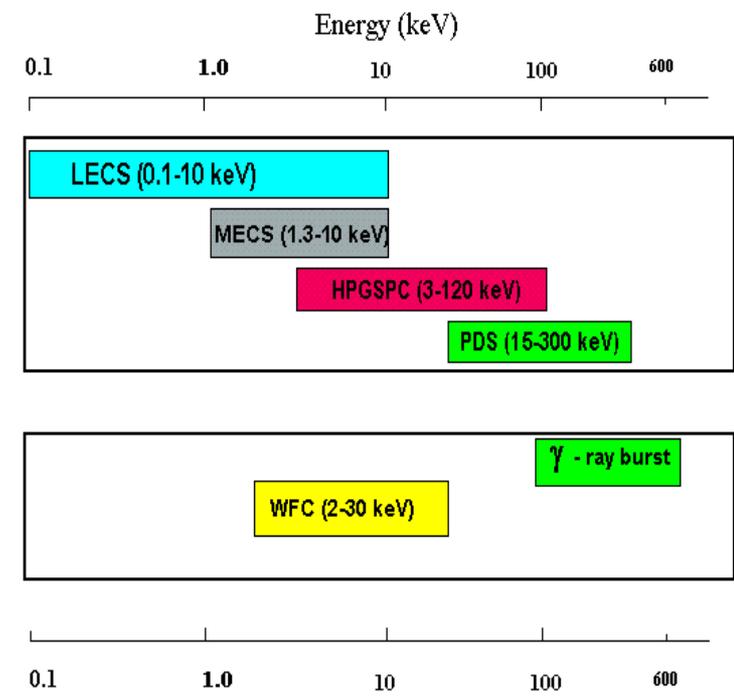


S A X P/L ACCOMODATION



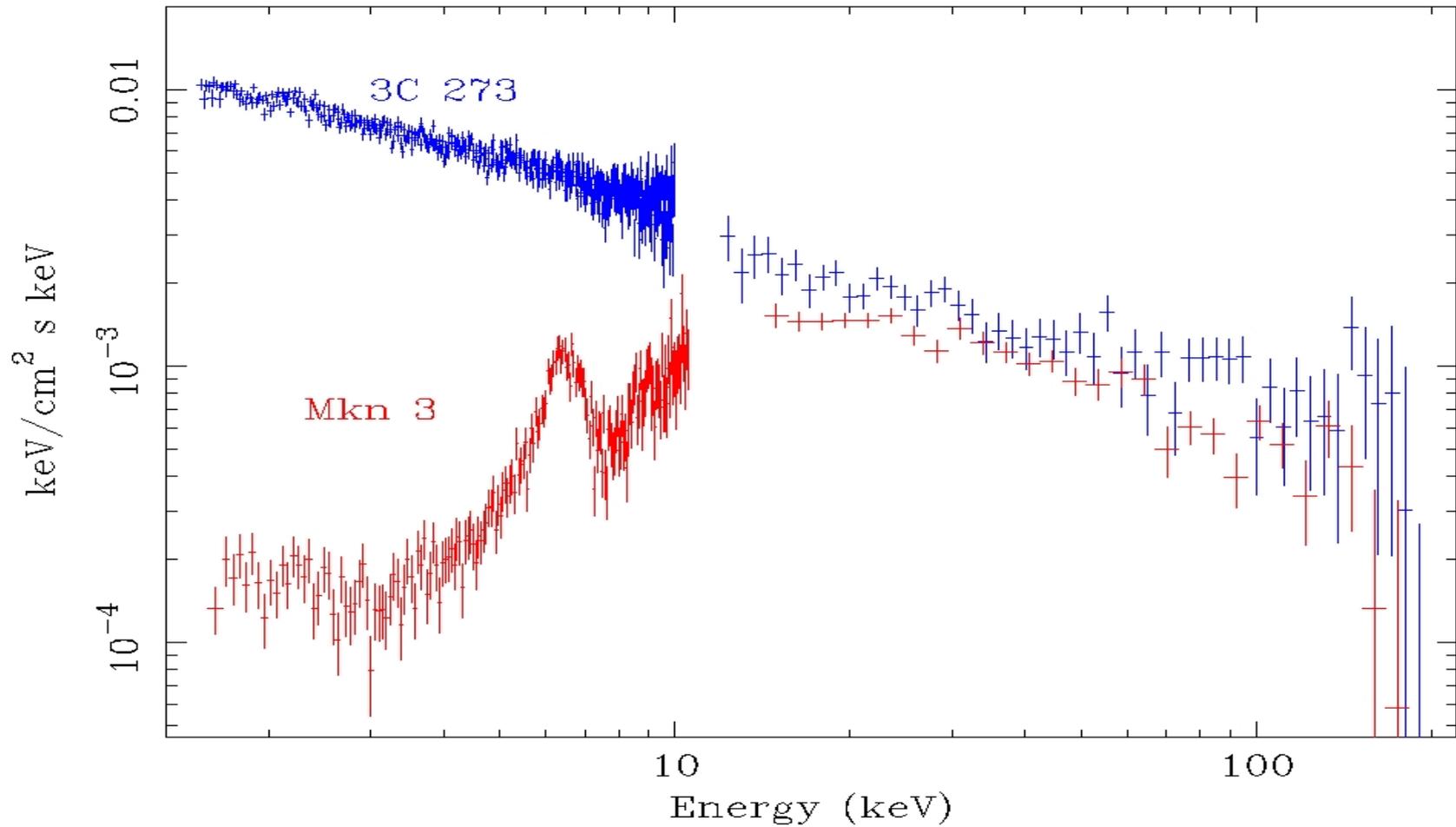
Narrow Field Instruments

Wide Field Instruments
(Perpendicular to NFT)



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

BeppoSAX spectra of 3C 273 and Mkn 3

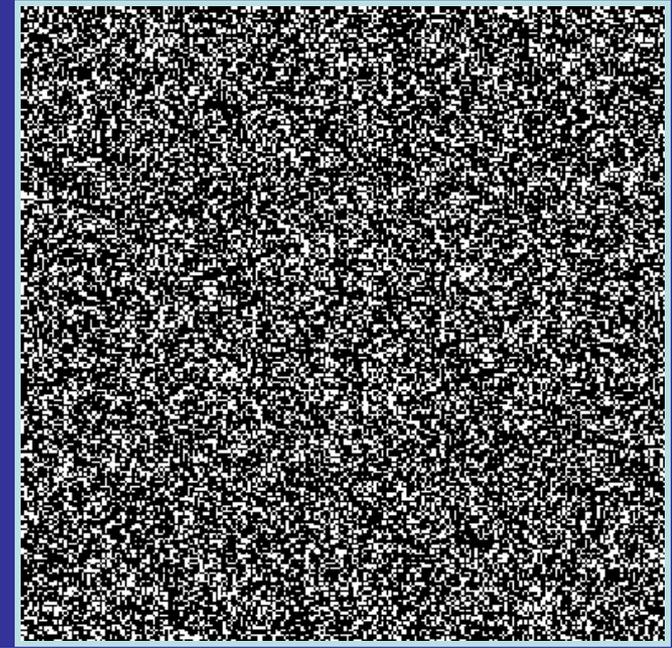
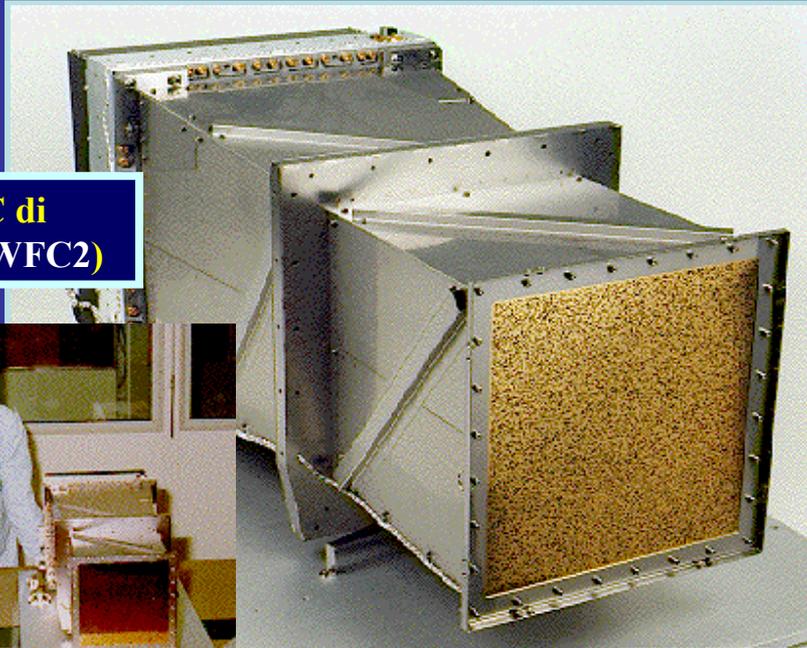


WFC

Wide Field Cameras

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

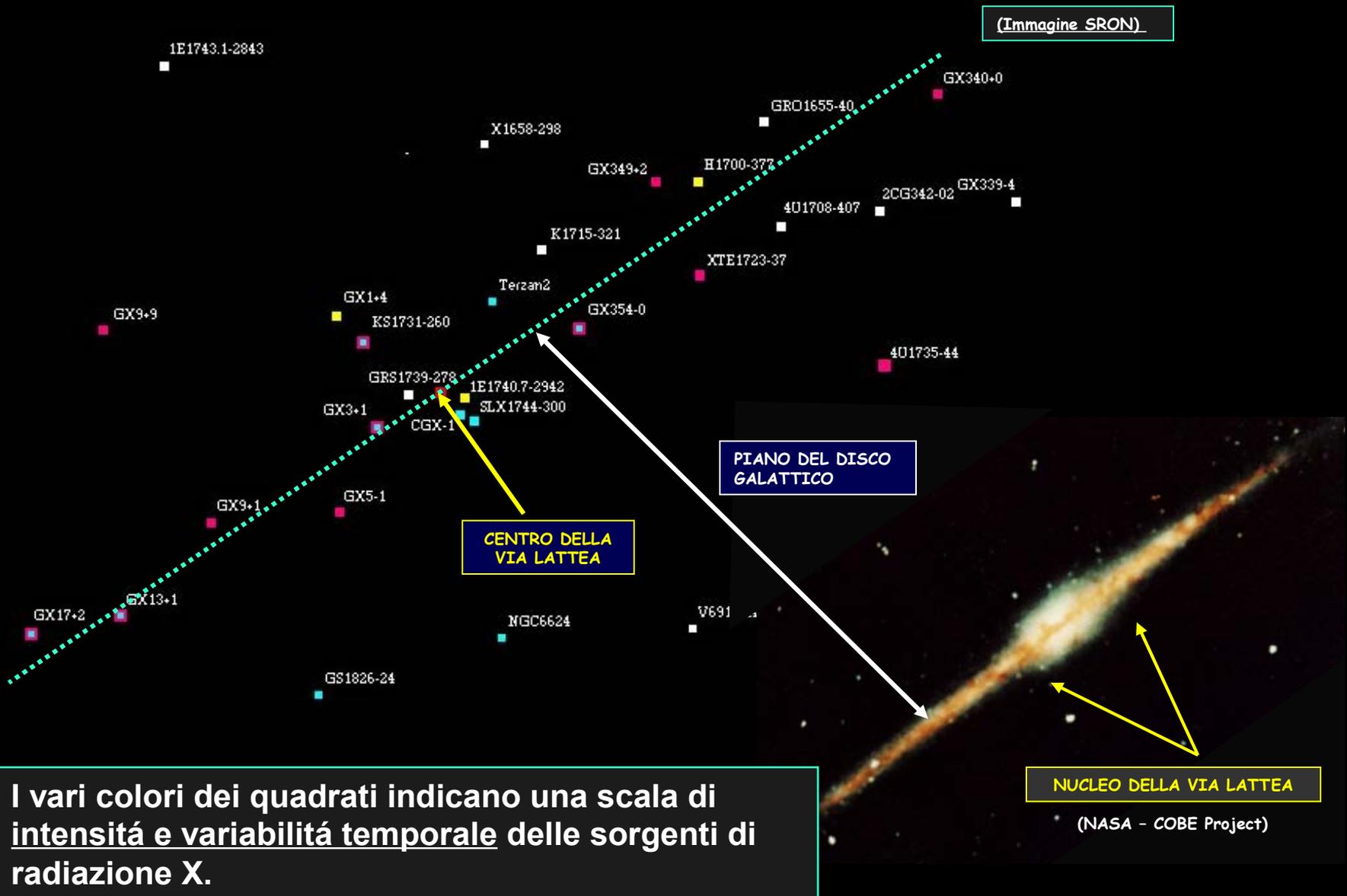
Le due identiche WFC di BeppoSAX (WFC1 e WFC2)



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

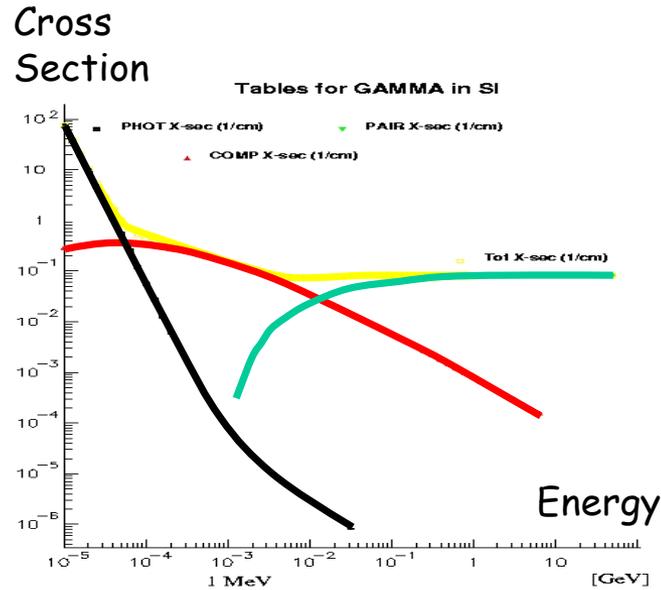
- Elevata efficienza di rivelazione;
- Ampia copertura spettrale;
- Risoluzione energetica;
- Imaging:
 - Ampio campo di vista;
 - Risoluzione angolare;
 - PSLA;
- Risoluzione temporale;
- Sensibilità;

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)

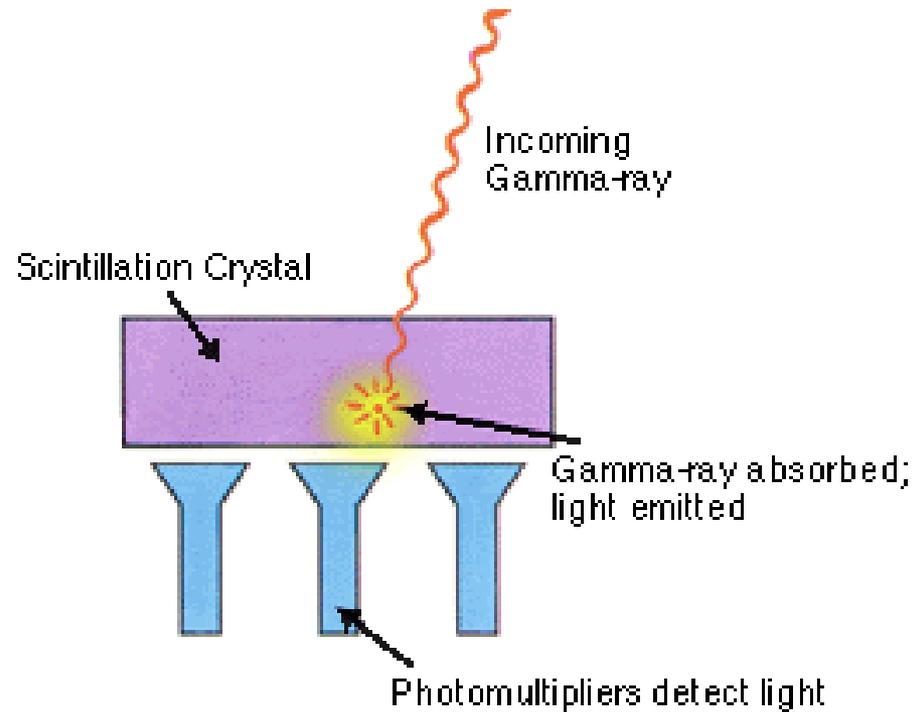
Photon Cross section Minimum
Scattered photons with long range

Telescope:

Compton Camera Coincidence System

Telescopi per Astronomia gamma

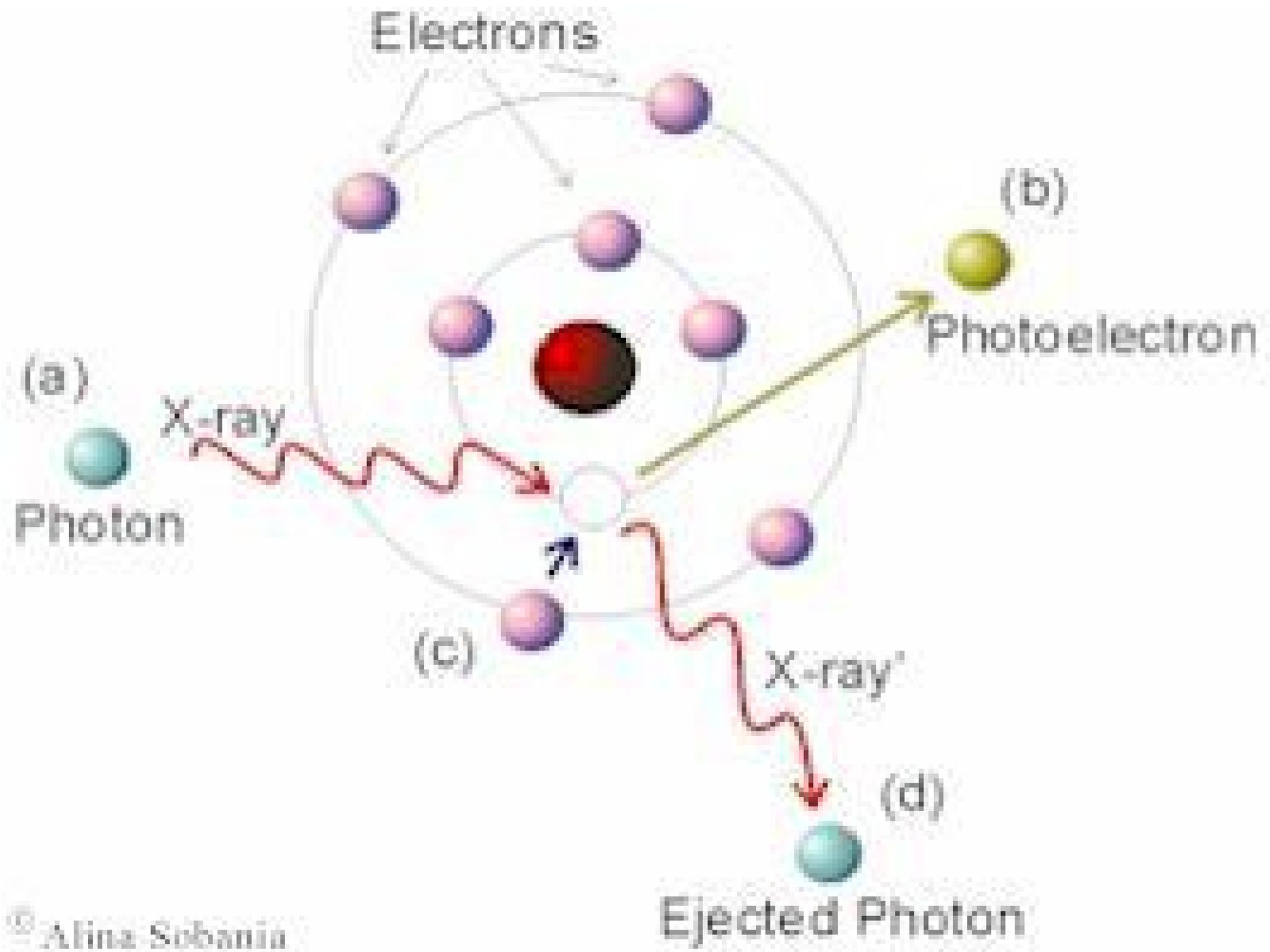
- Assorbimento atmosferico:
 - Astrofisica Spaziale;
- Elevato potere penetrante:
 - Elevati volumi e aree;
- Tecniche indirette per:
 - Spettrometria;
 - Imaging;



Imaging in astronomy gamma

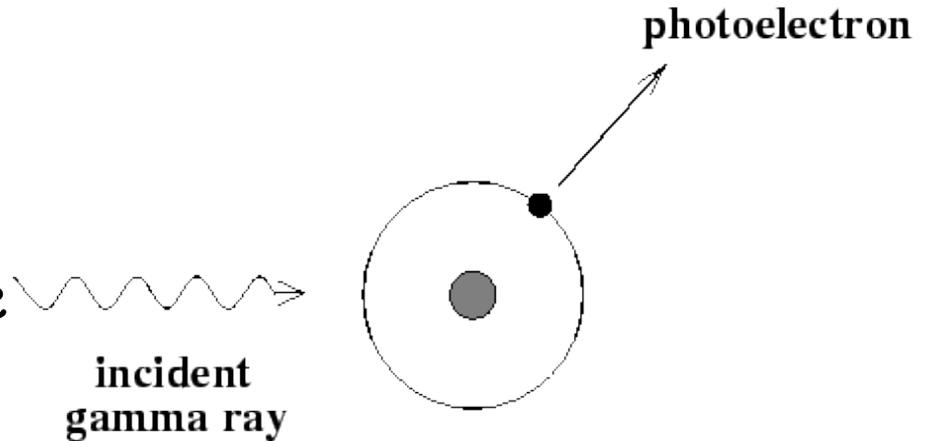
TABLE 5.1 COMPARISON OF GAMMA-RAY IMAGING TECHNIQUES

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

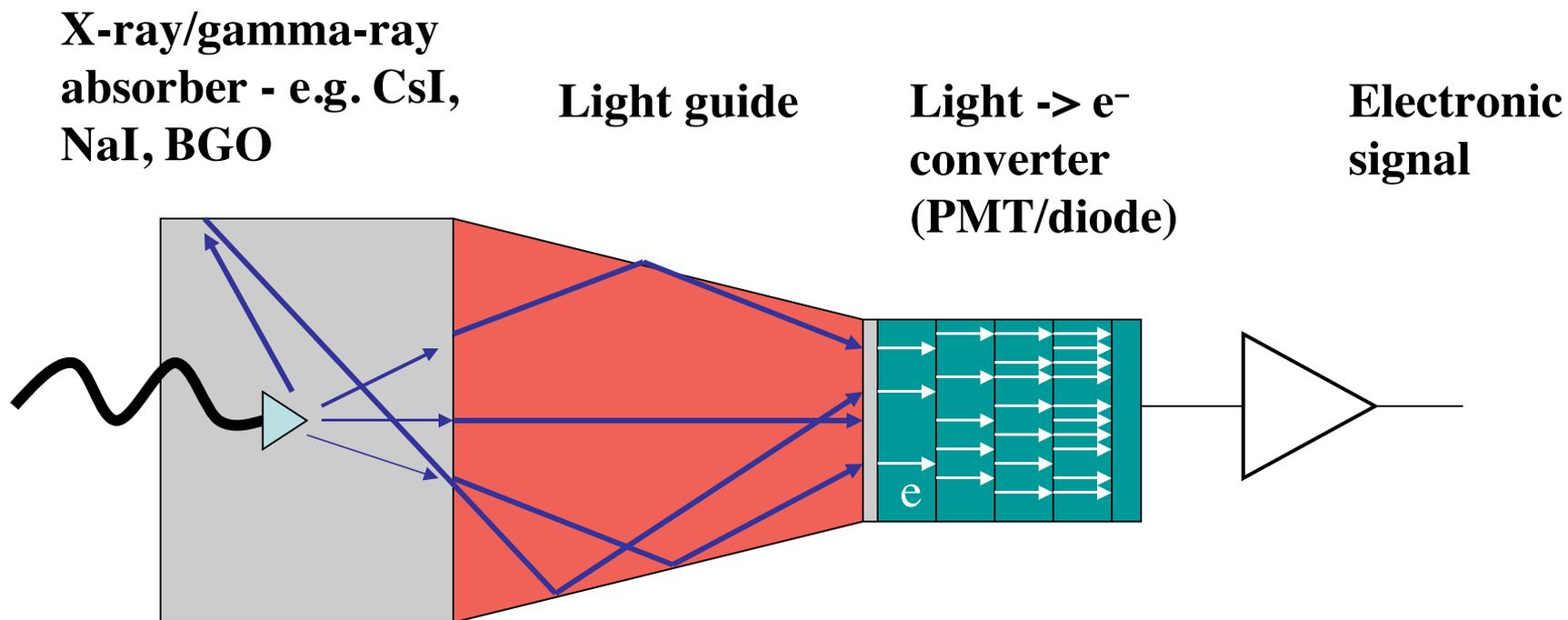


Assorbimento fotoelettrico

- 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, \sim 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

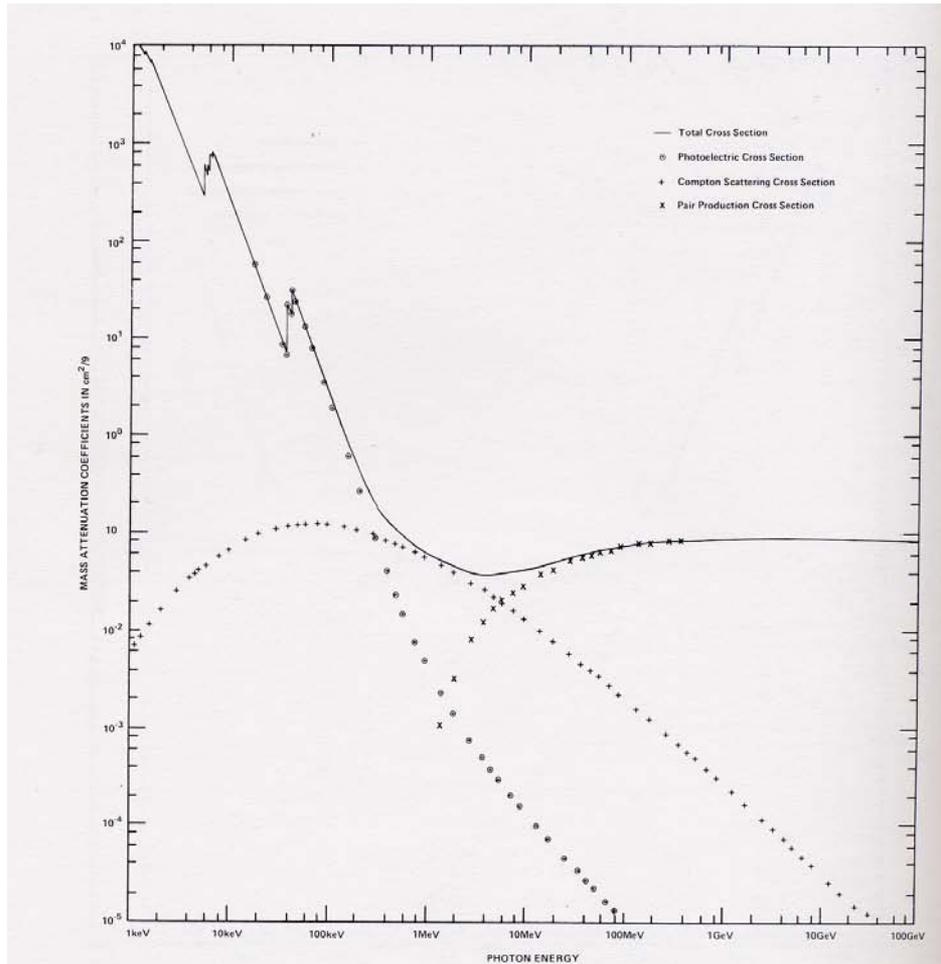
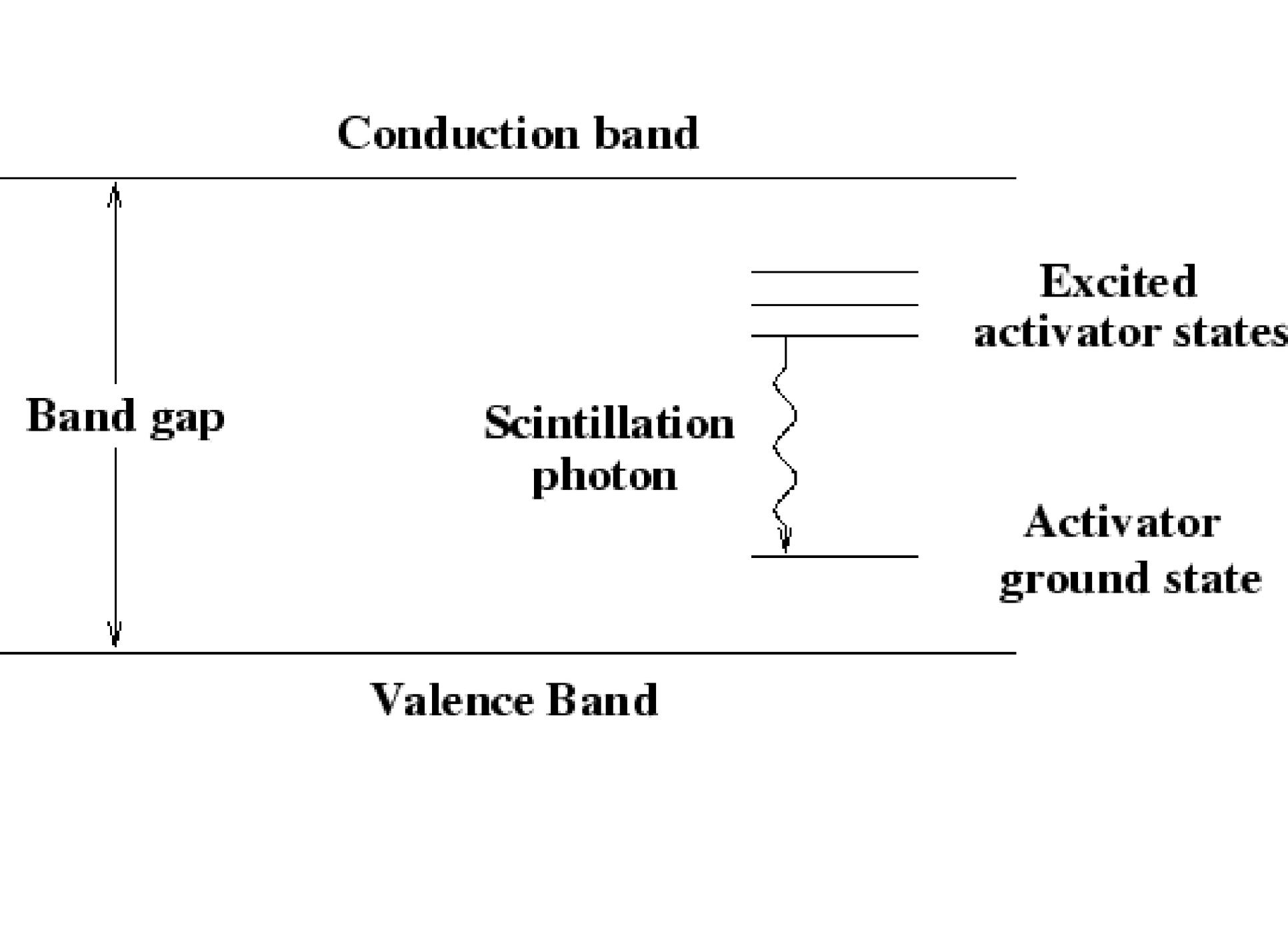


Figure 10-3. The photoelectric, Compton scattering, pair production, and total mass absorption coefficient for Cs I (from Hubbell, 1969, 1977, and Hubbell et al., 1979).

Rivelatori a scintillazione

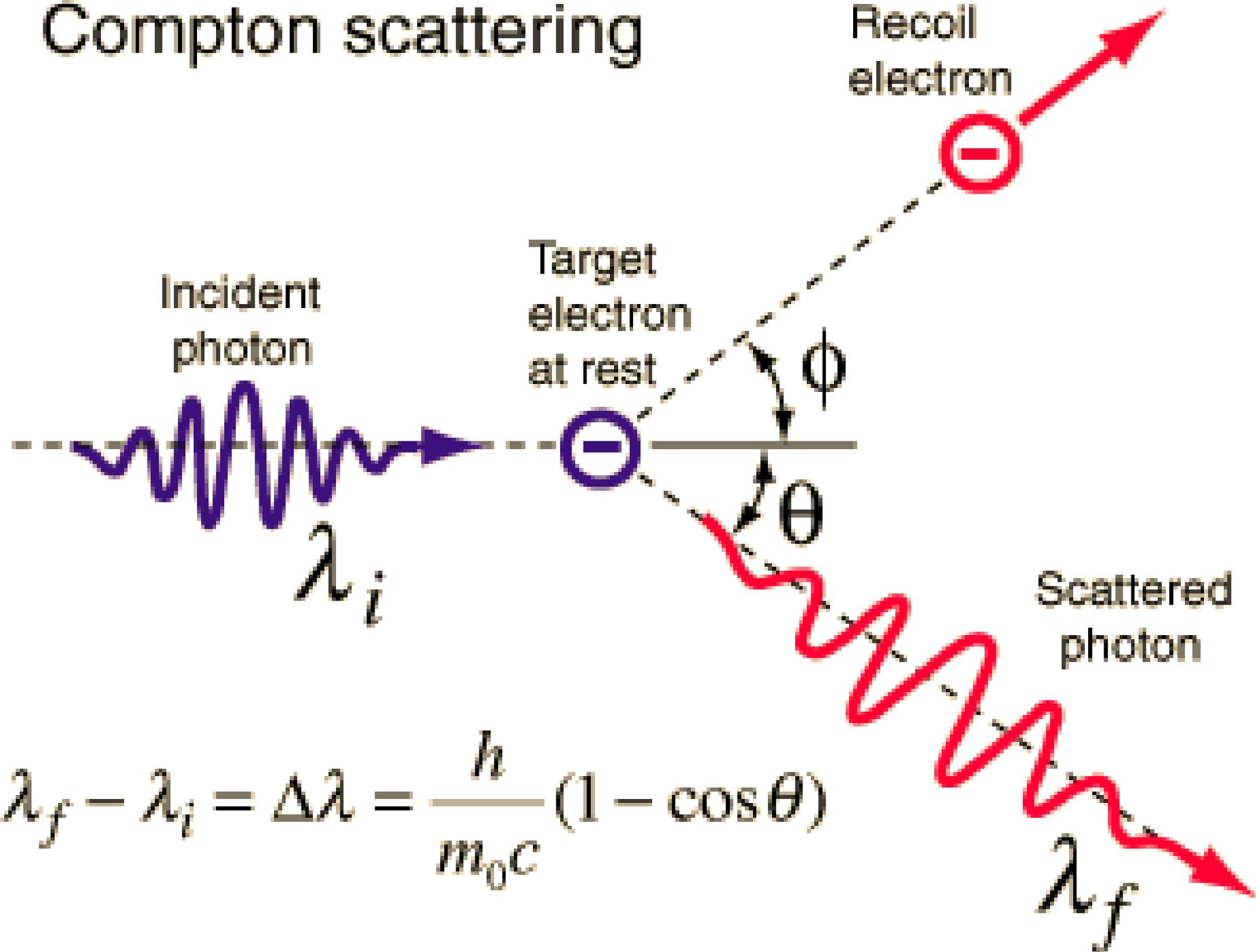
- Il γ incidente interagisce nel cristallo creando un elevato numero di fotoni ottici;
- I livelli energetici sono determinati dalla struttura del reticolo cristallino;
- La band gap separa la banda di valenza dalla banda di conduzione;
- Assorbendo energia, un e^- viene promosso dalla banda di valenza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



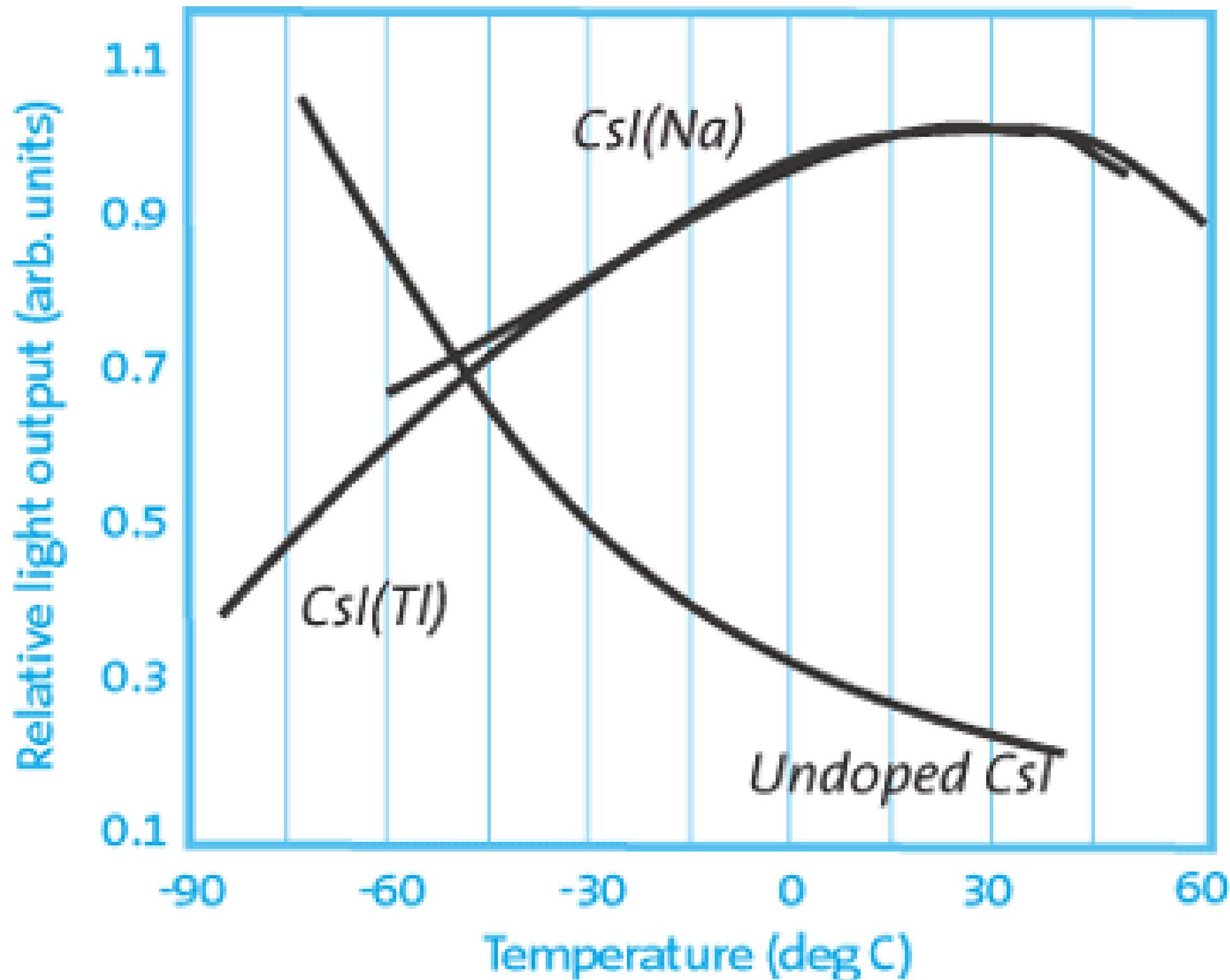
Requisiti

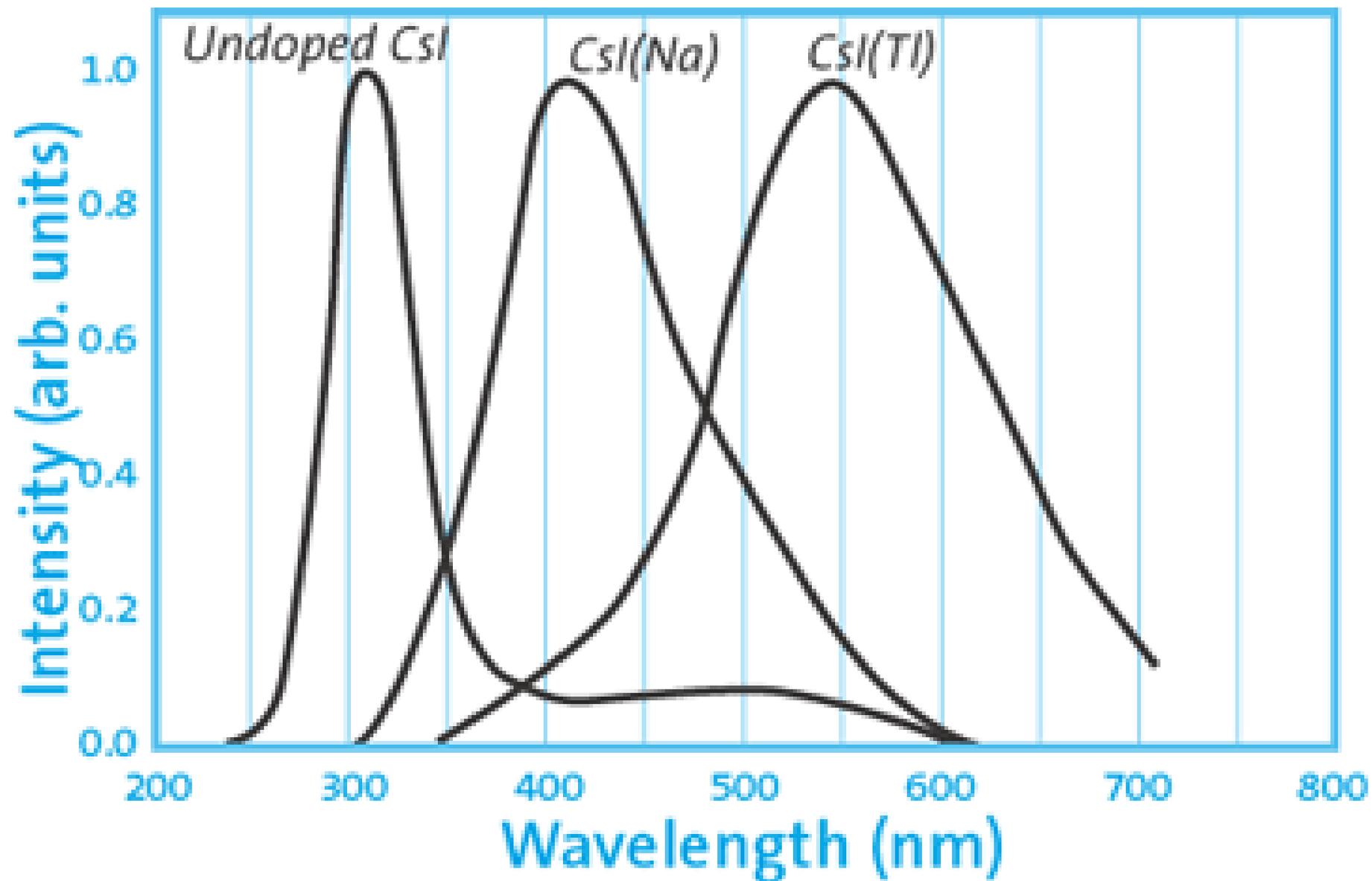
- Elevata efficienza di conversione dell'energia delle particelle cariche in luce di fluorescenza (**efficienza di scintillazione**);
- L'intensità della luce deve essere linearmente proporzionale all'energia delle particelle e quindi all'energia persa dal fotone gamma primario (**linearità**);
- **Trasparenza** 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

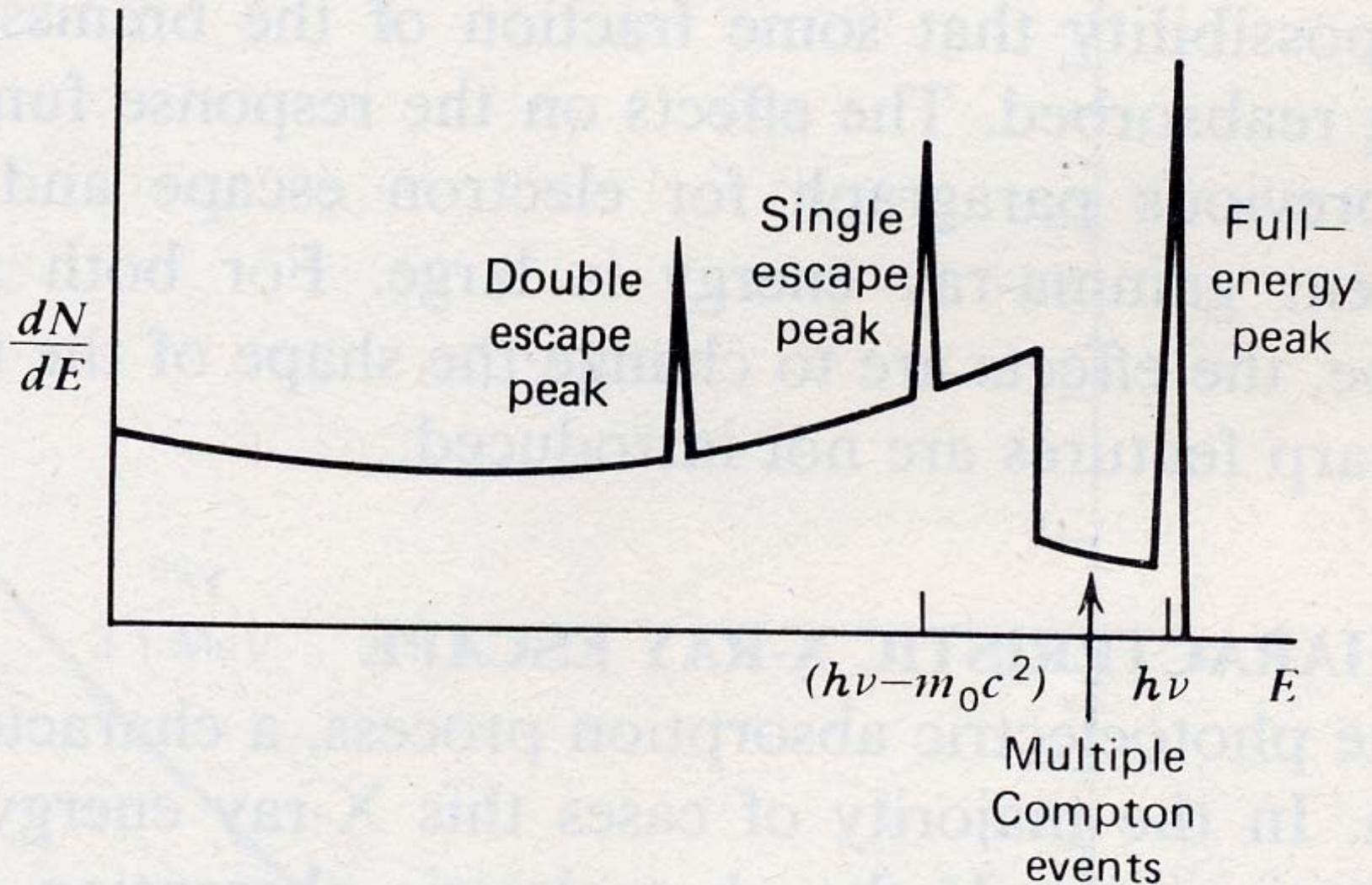


$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c} (1 - \cos \theta)$$





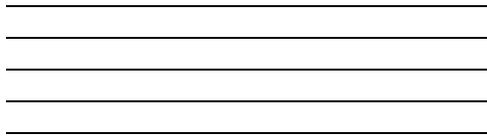
$$h\nu \gg 2m_0c^2$$



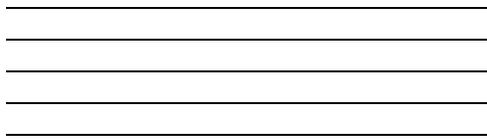
Rivelatori a stato solido

Livelli energetici degli e⁻ nel cristallo:

Banda di
conduzione



Banda di
valenza



Band gap:

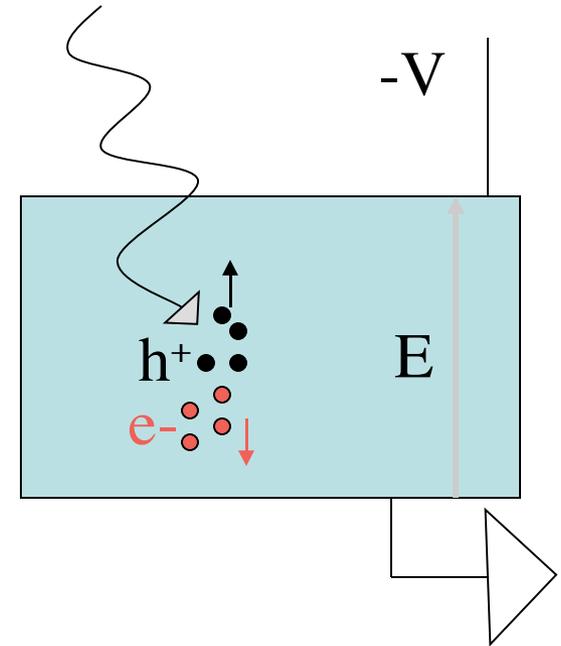
~1 eV:

≥1.5 eV

Ge, Si (raffreddati, ~80 °K)

"room temperature semiconductor"

CdZnTe, CdTe, HgI₂

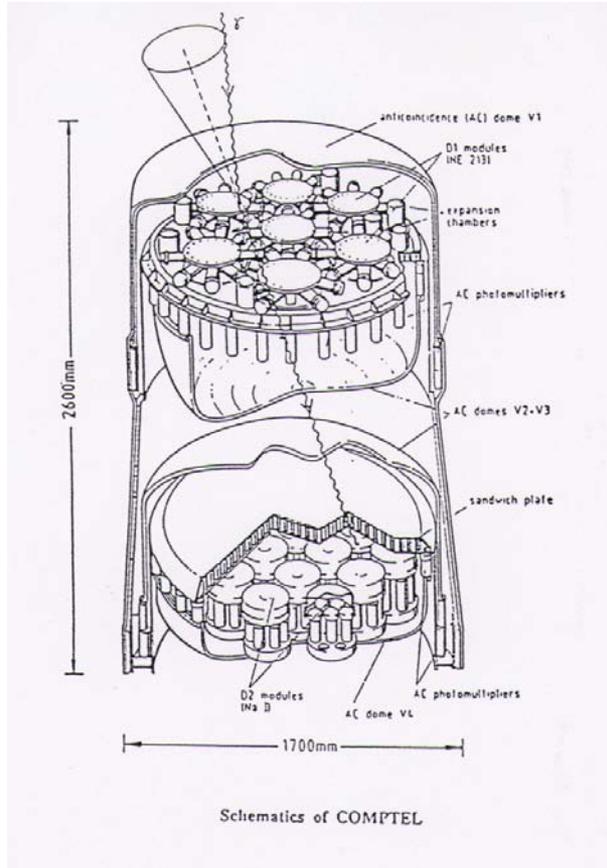
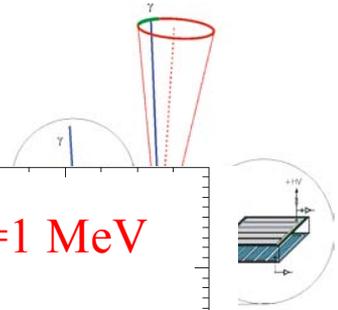


Rivelatori a Cd(Zn)Te

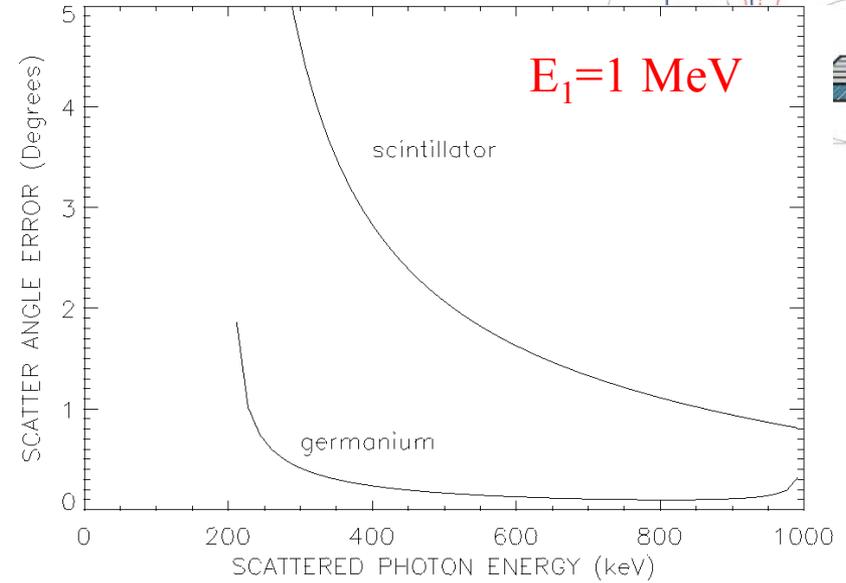
- Energy gap (1.6 eV) permette di non raffreddarli;
 - Alta ρ ($\sim 6 \text{ g cm}^{-3}$) per efficienza;
 - Alto Z (48, 52) per effetto fotoelettrico:
 - 10 volte il μ_{Compt} fino a 110 keV (60 il Ge, 25 il Si);
 - Single site ok per imaging
 - Facilmente segmentabile a piccole dimensioni:
- $\nabla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



Compton Scattering



Comptel efficiency ~ 1%



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

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



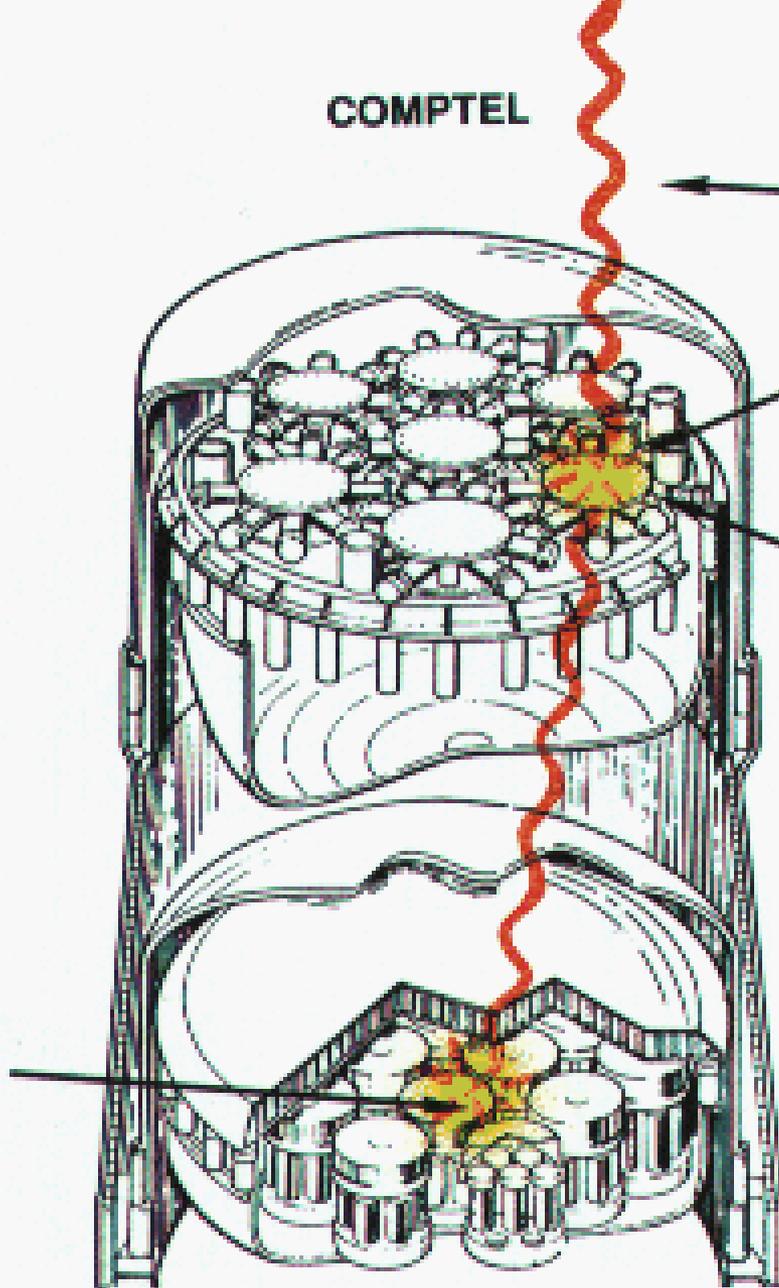
COMPTEL

GAMMA RAY

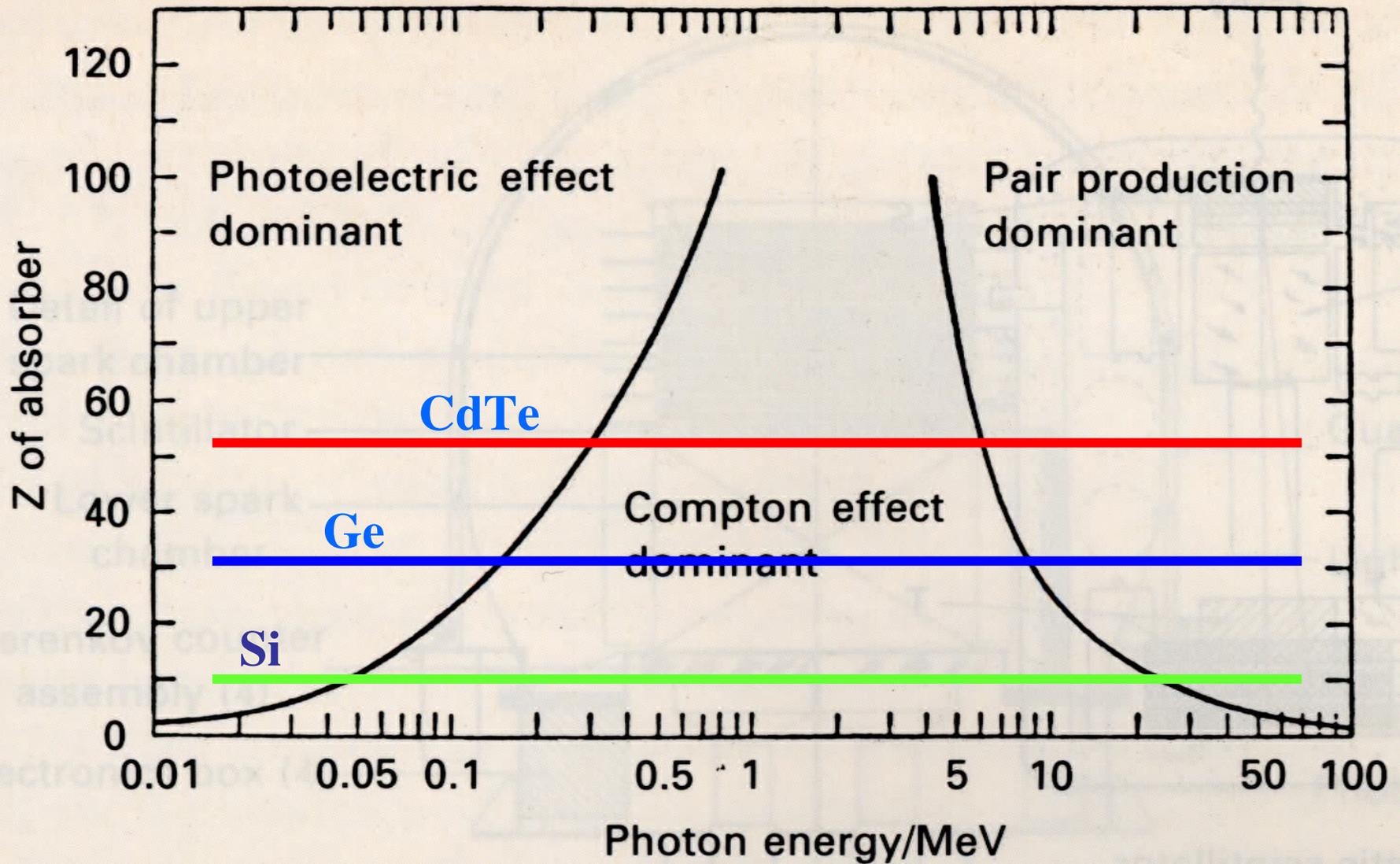
*Gamma Ray scattered;
light emitted.*

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

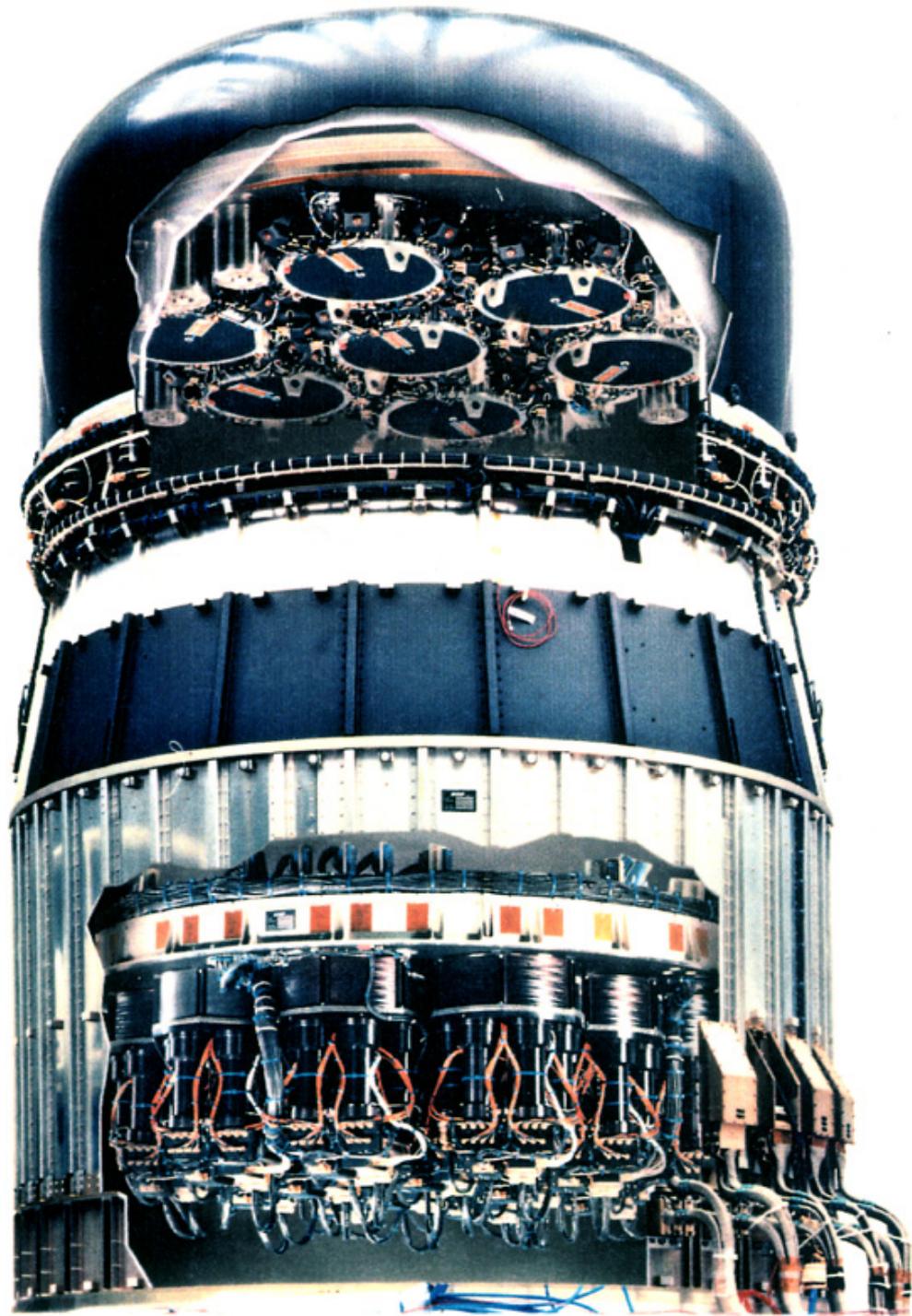
Very thin surface dead layers may give Ge an advantage where response from $1 \text{ keV} - 100\text{'s of keV}$ is desired

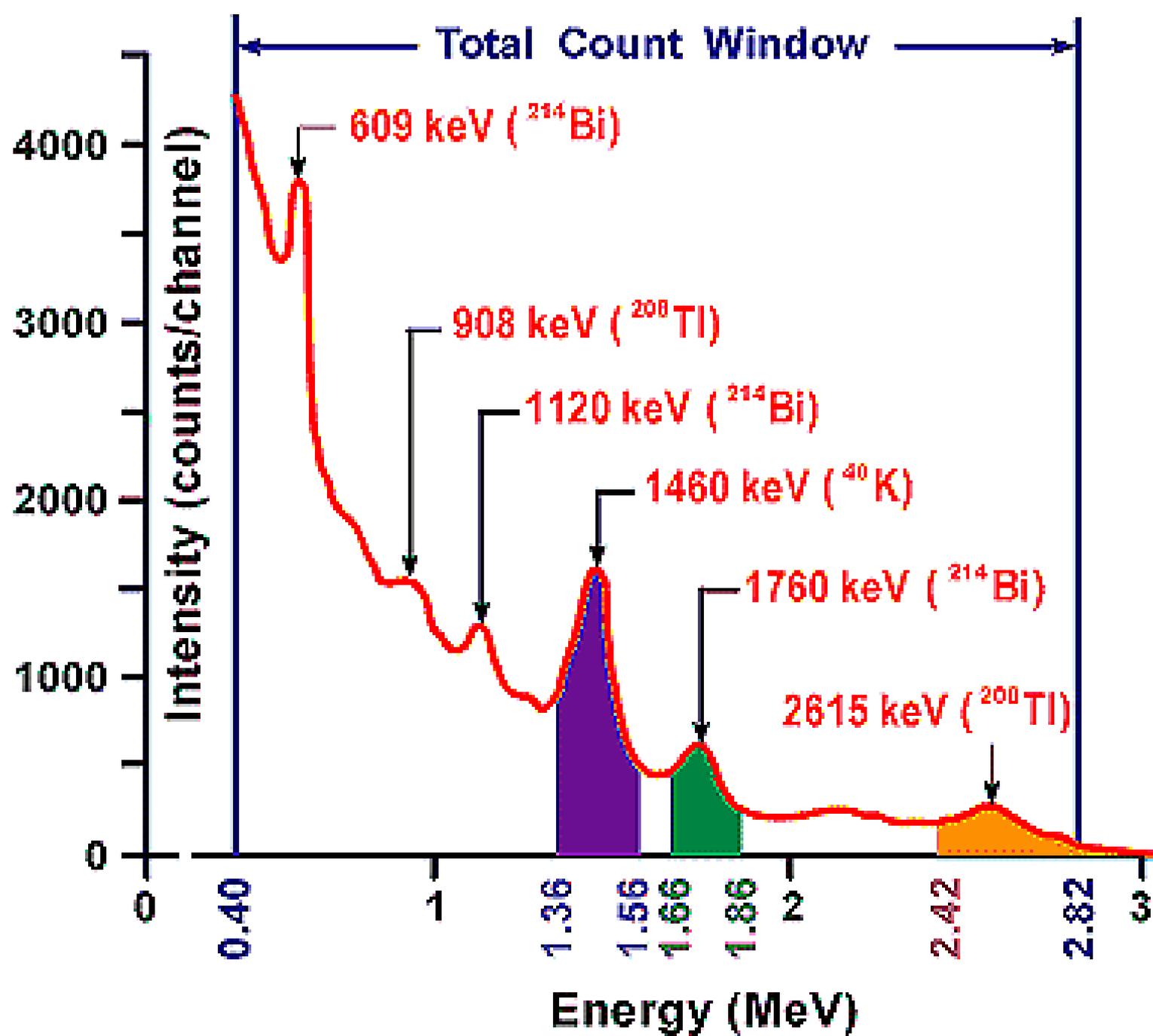
Disadvantages (compared to compound semiconductors or scintillation detectors)

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:

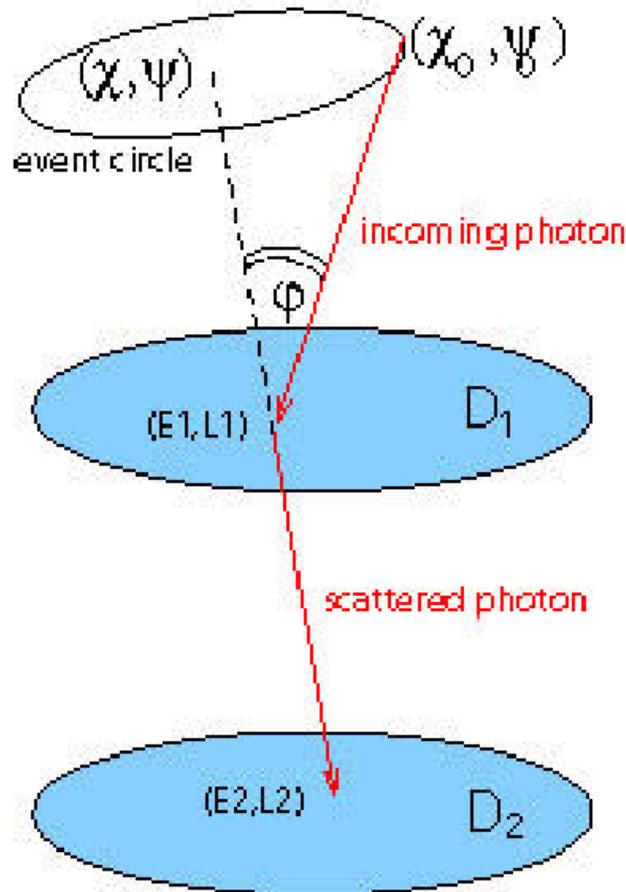
E1 = Energy of the scattered electron deposited in D1

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:

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



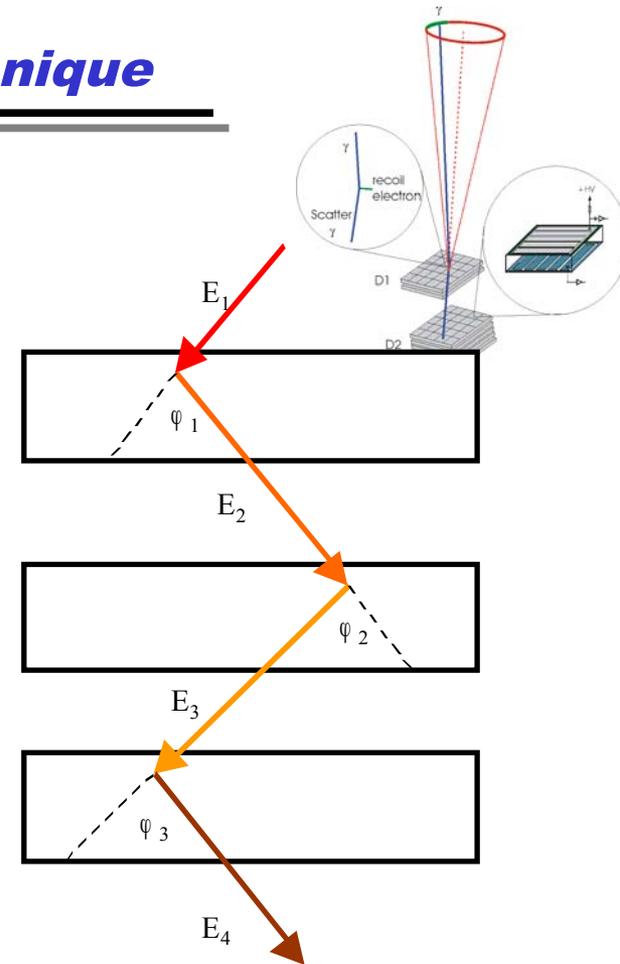
Three Gamma Interaction Technique

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

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

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

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



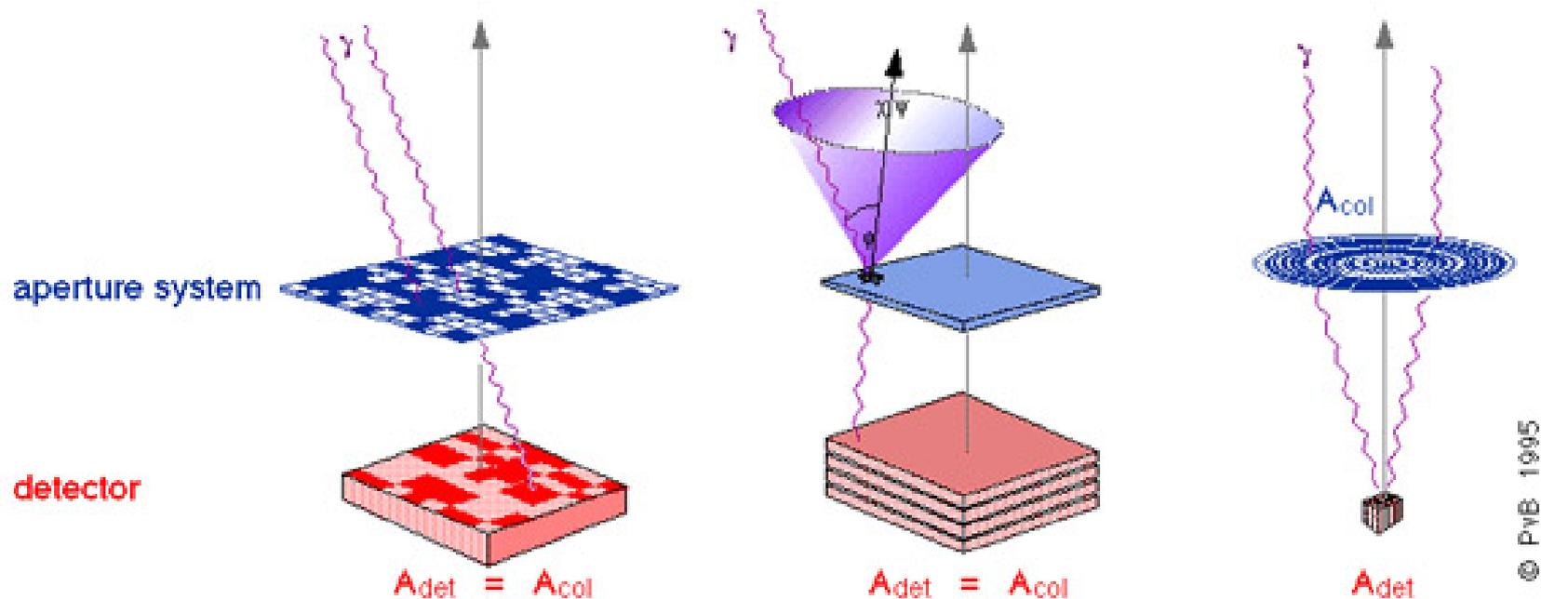
Incident gamma ray energy determined with partial energy loss

- 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

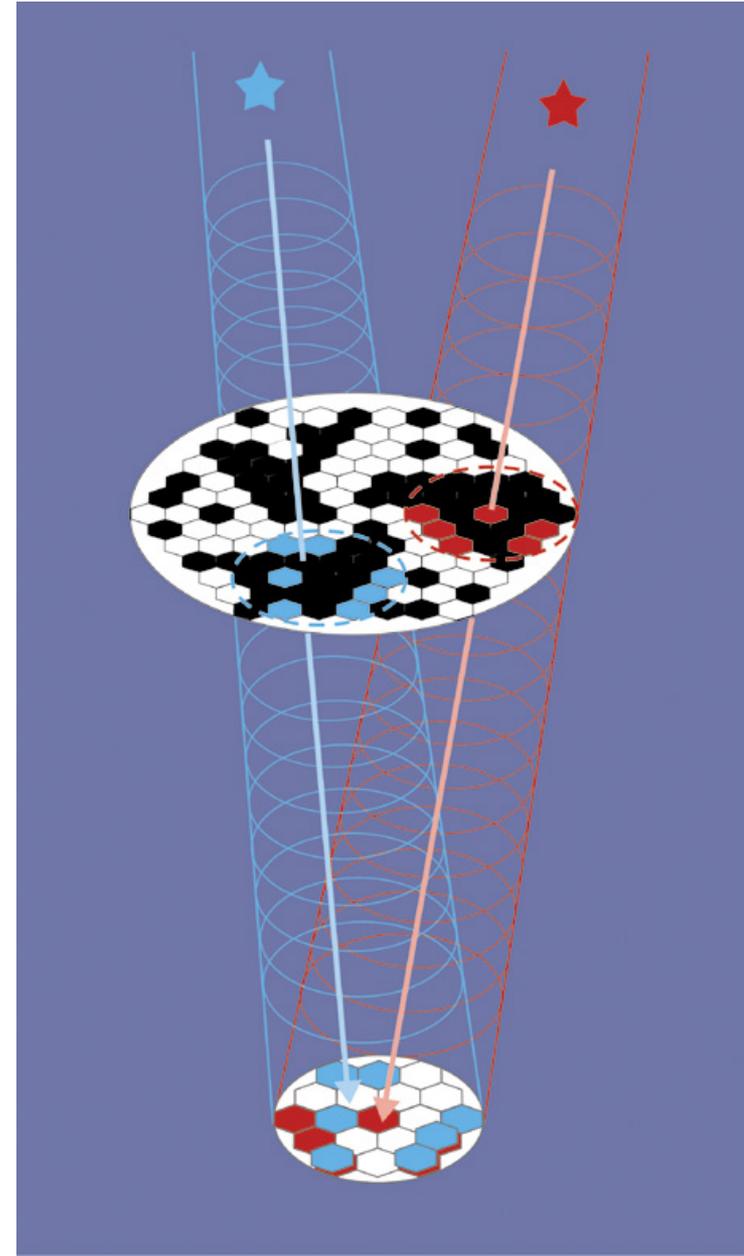


© PyB 1995

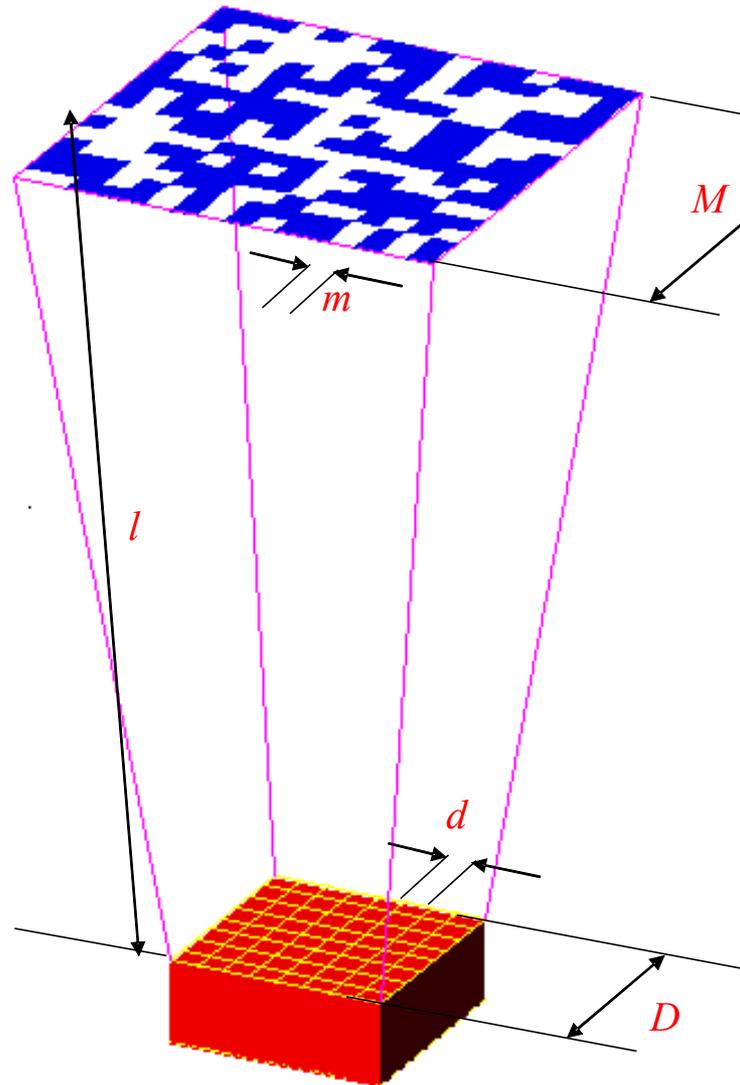
signal S	~	A_{col}	A_{col}	A_{col}
noise N	~	$V_{det} \sim A_{det} = A_{col}$	$V_{det} \sim A_{det} = A_{col}$	$V_{det} \sim A_{det} \ll A_{col}$
S/N	=	const (A)	const(A)	A_{col}/A_{det}

Osservare l'invisibile

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

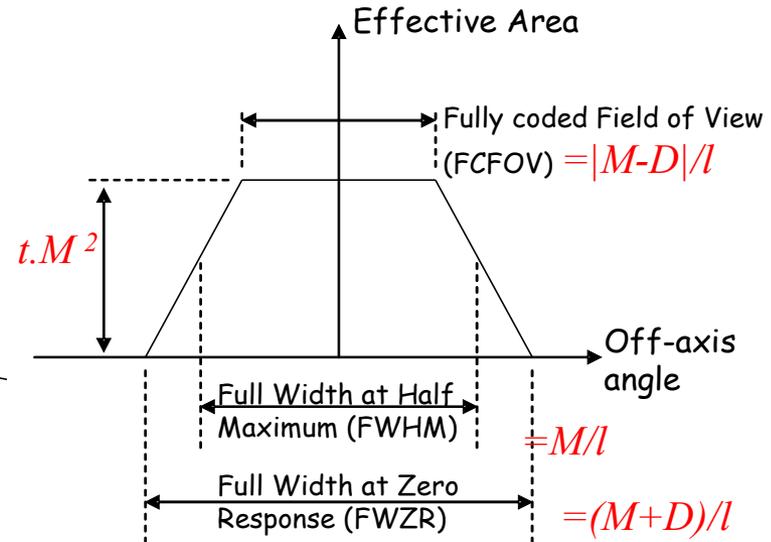


Telescopi a maschera codificata



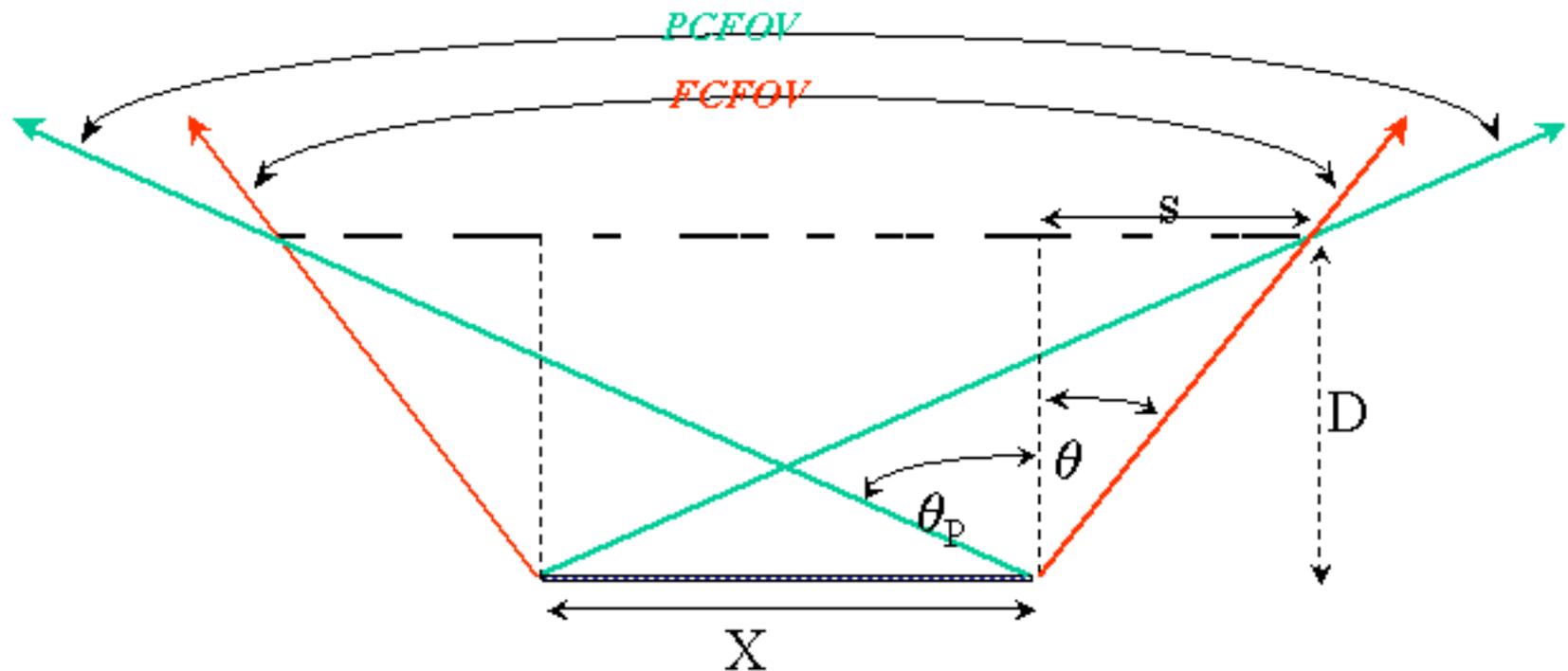
Coded mask telescopes -key parameters

- 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

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

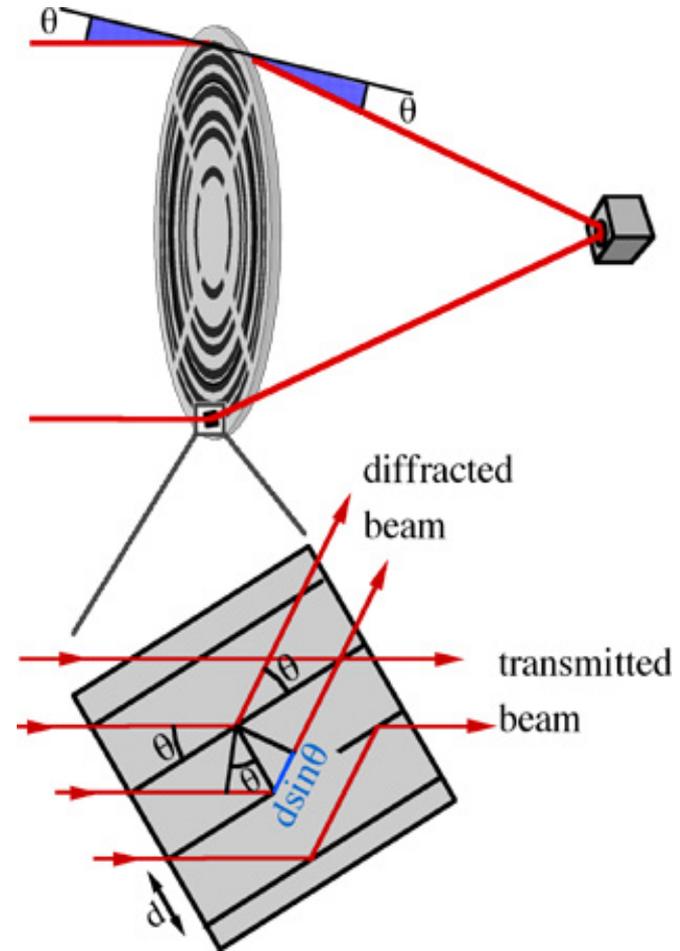
The Partially Coded Field of View (PCFOV)

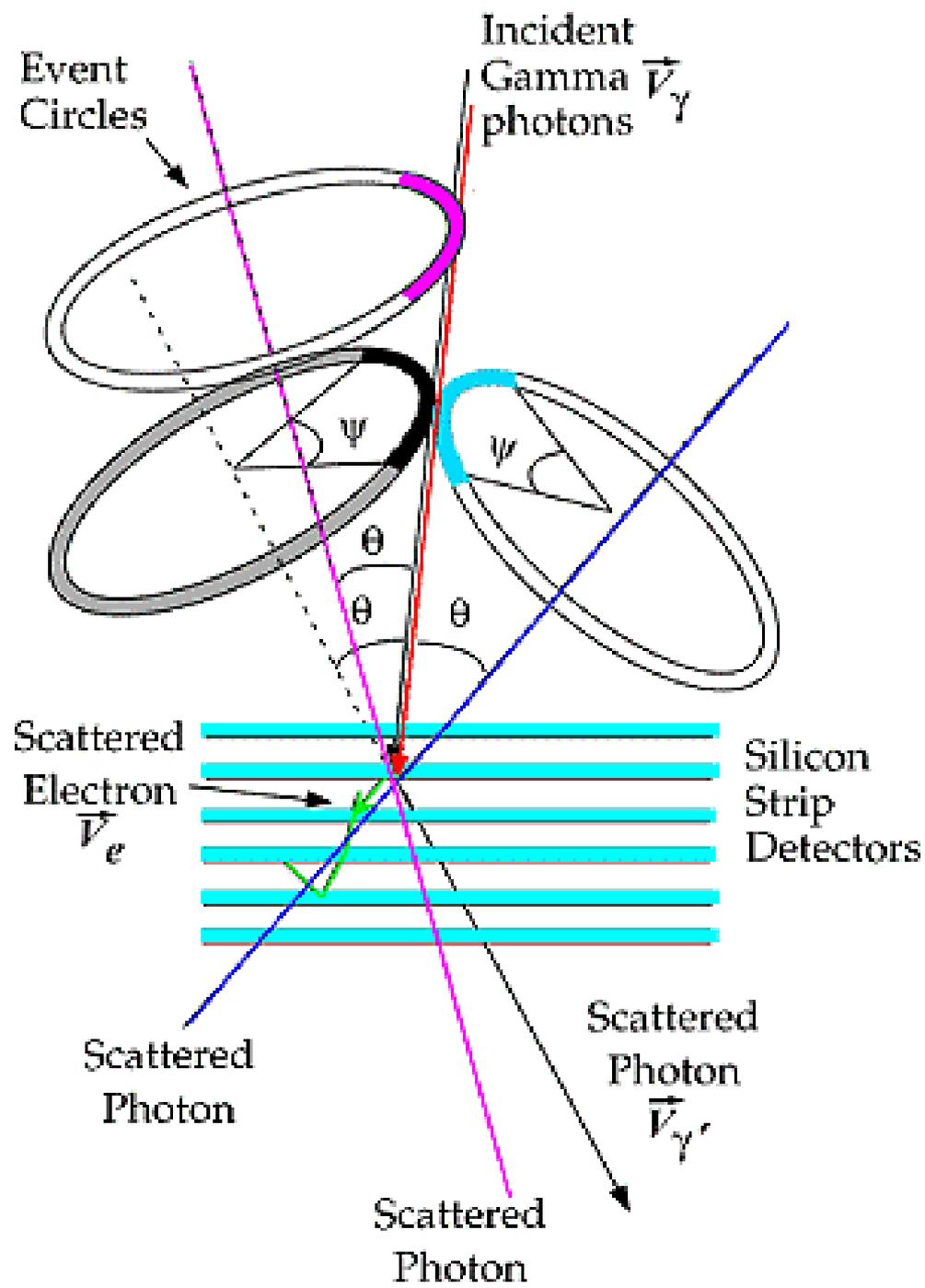
The partially coded field of view has a half angle θ_p

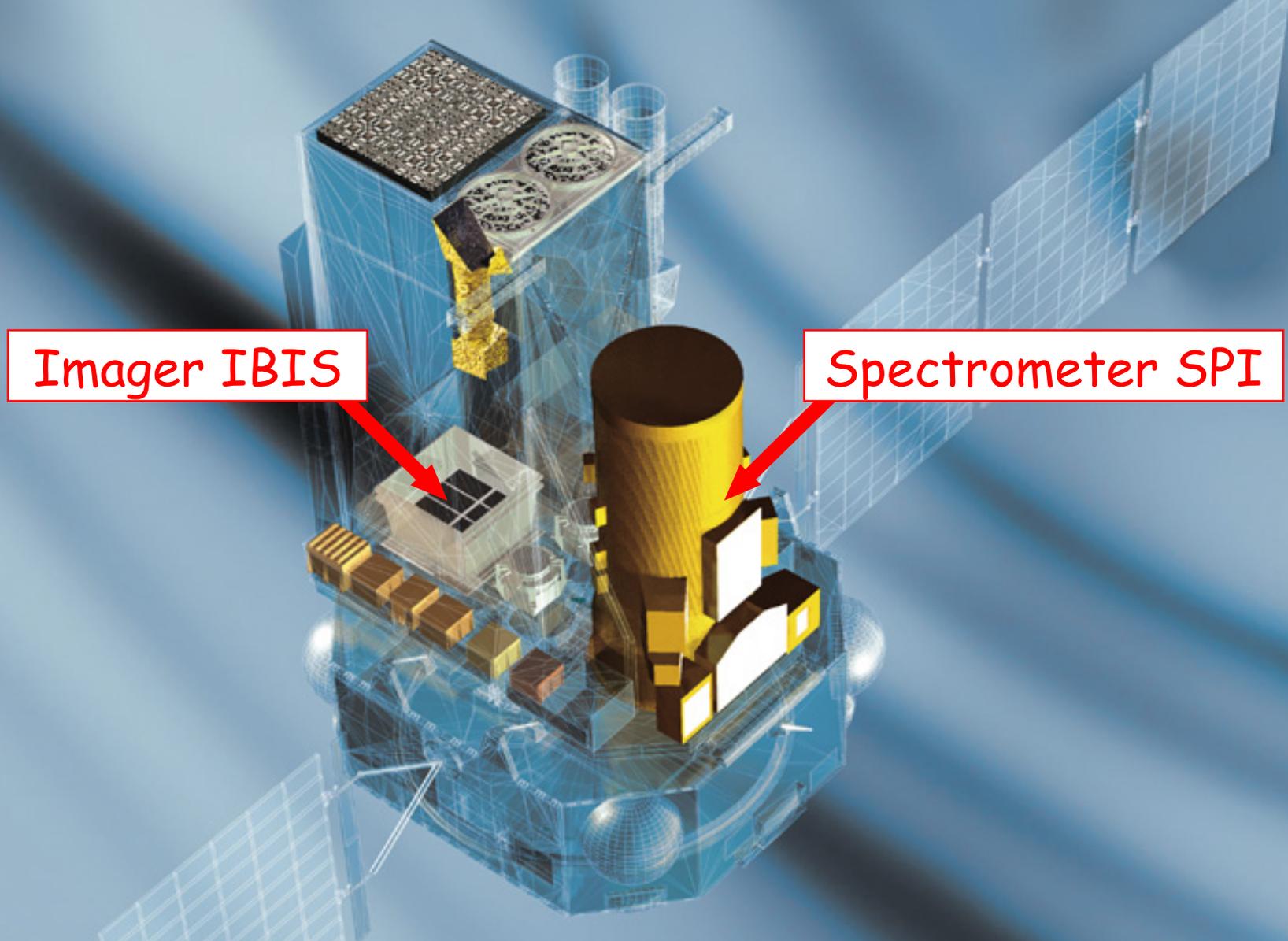
$$\theta_p = \text{Tan}^{-1}\left(\frac{X+s}{D}\right)$$

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







Imager IBIS

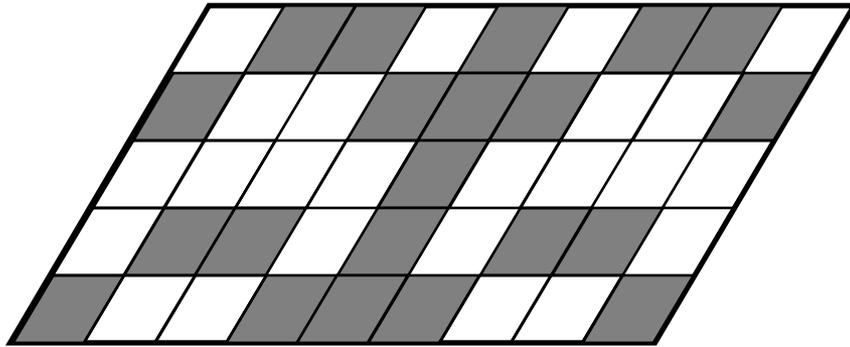
Spectrometer SPI

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

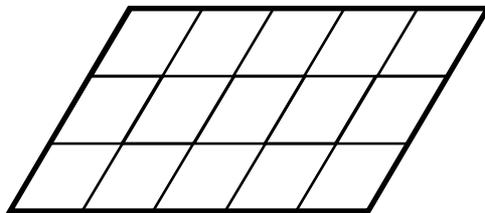
Astronomia con fotoni di alta-energia (1)

Apertura codificata

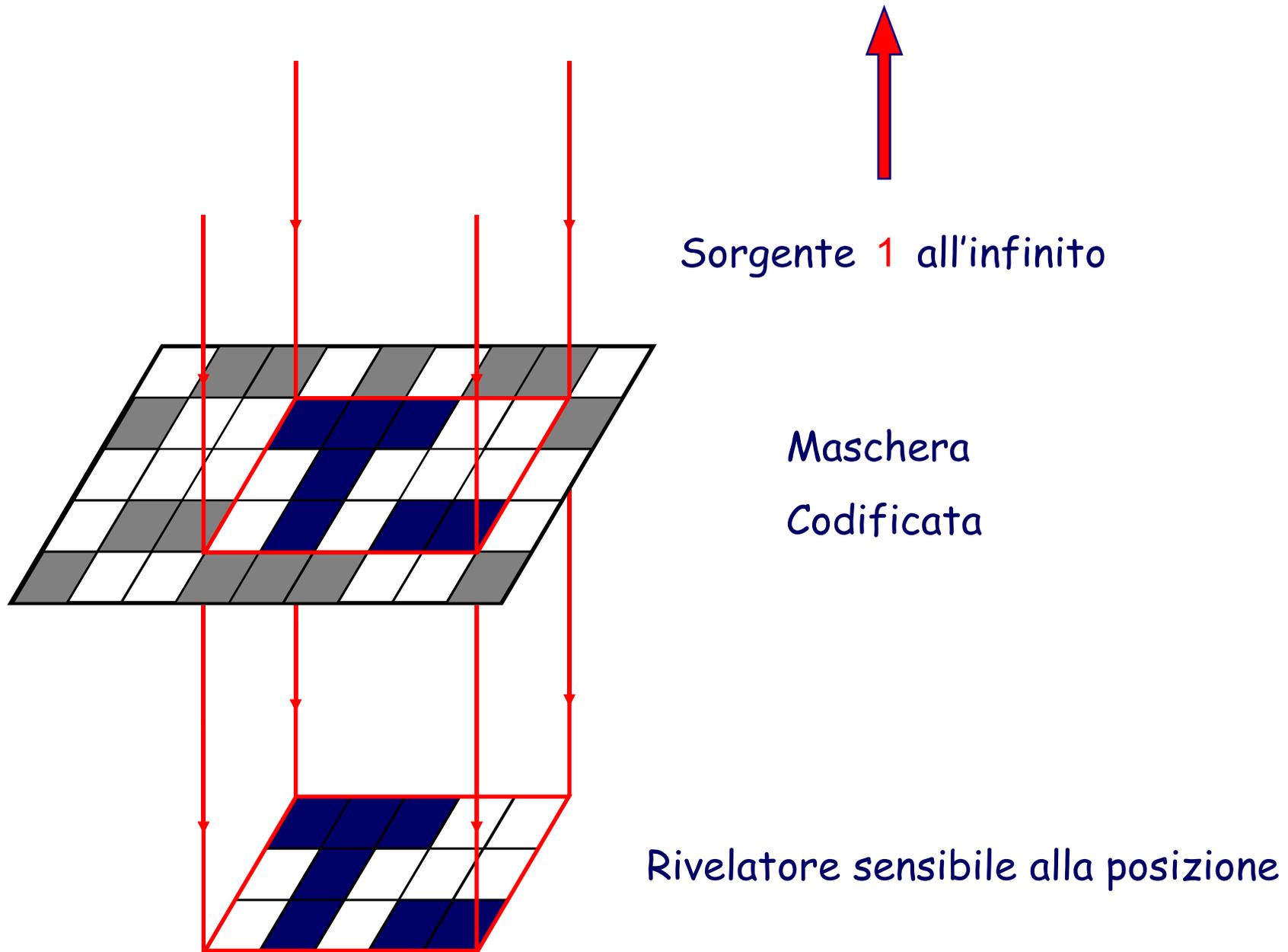
Una maschera codificata (array di blocchi opachi) è messa in modo che una sorgente all'infinito proietta un pattern caratteristico della direzione della sorgente

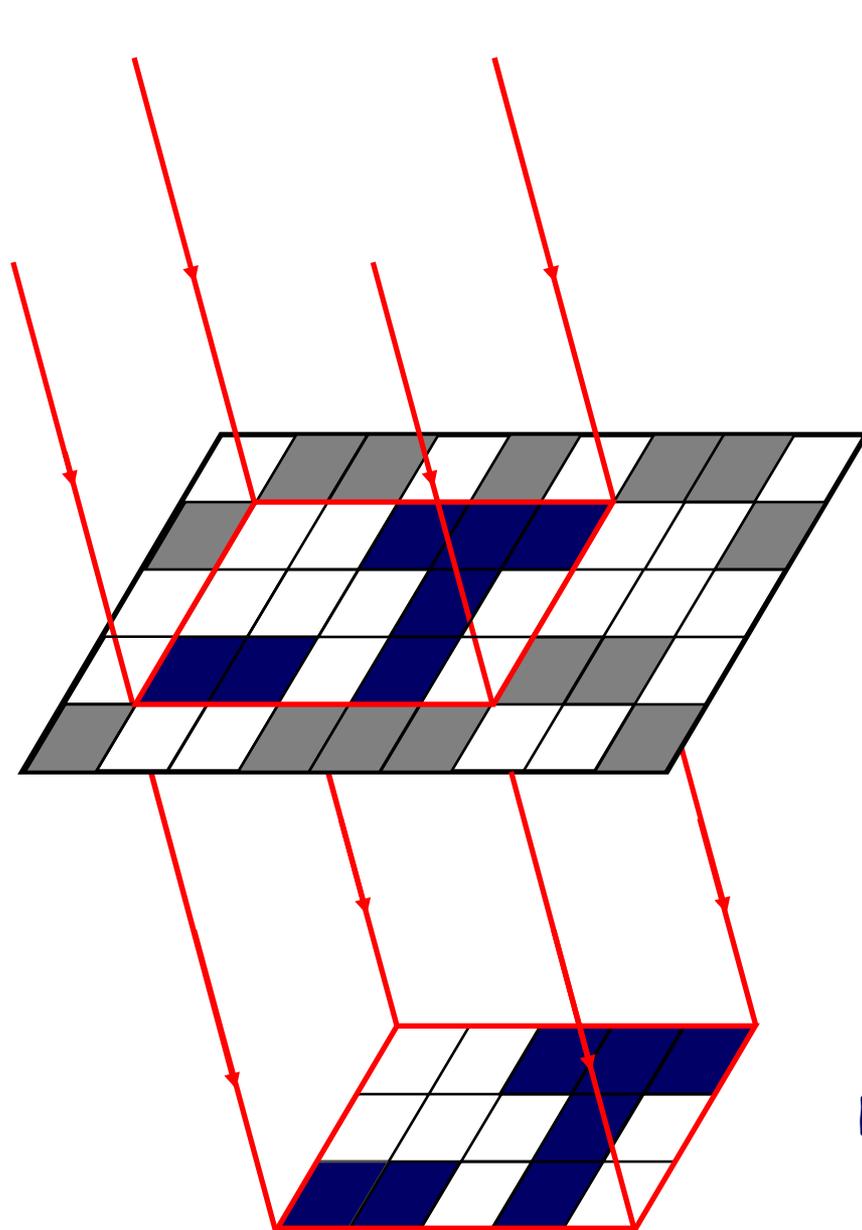


Maschera
Codificata



Rivelatore sensibile alla posizione

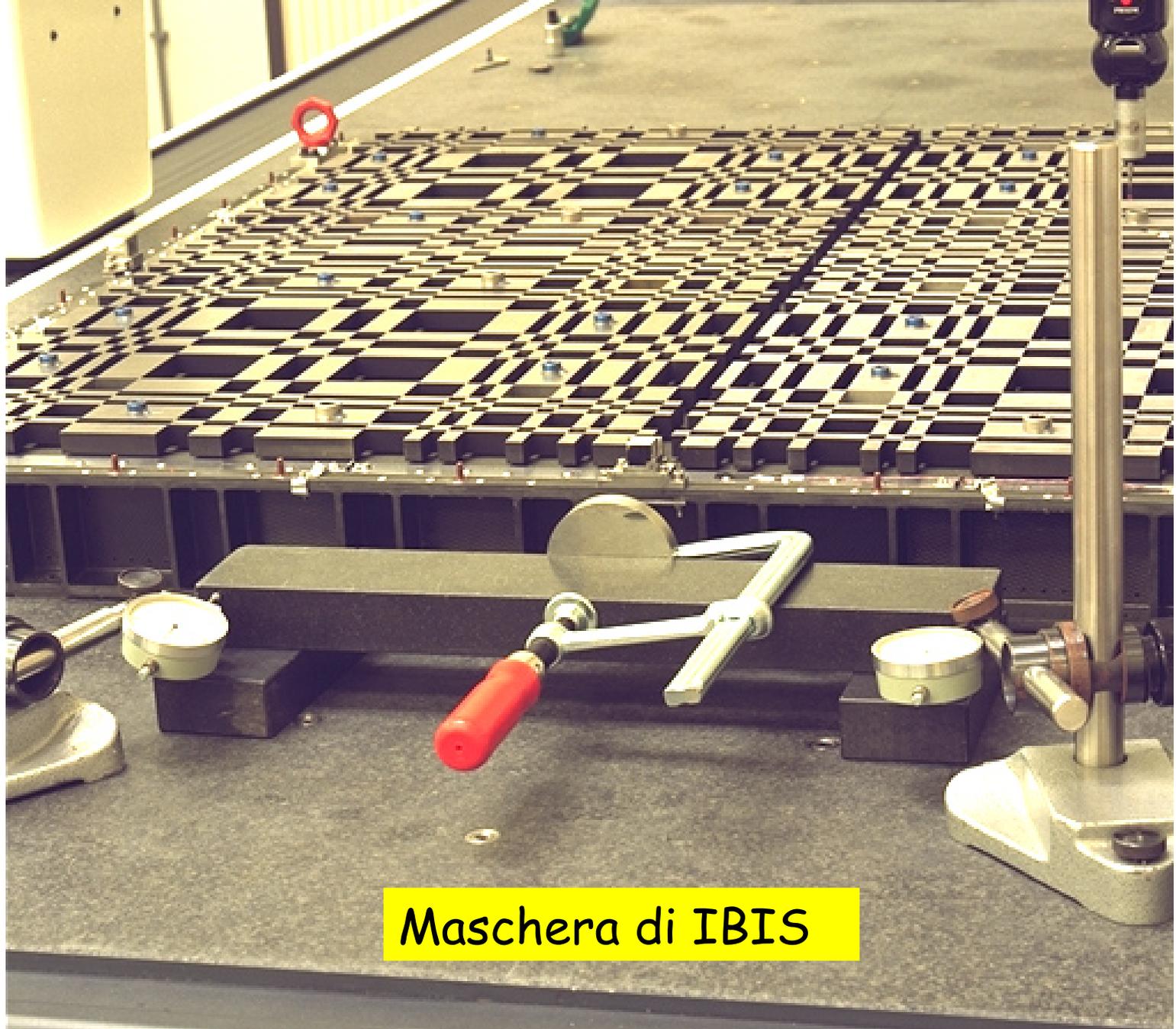




Sorgente 2 all'infinito

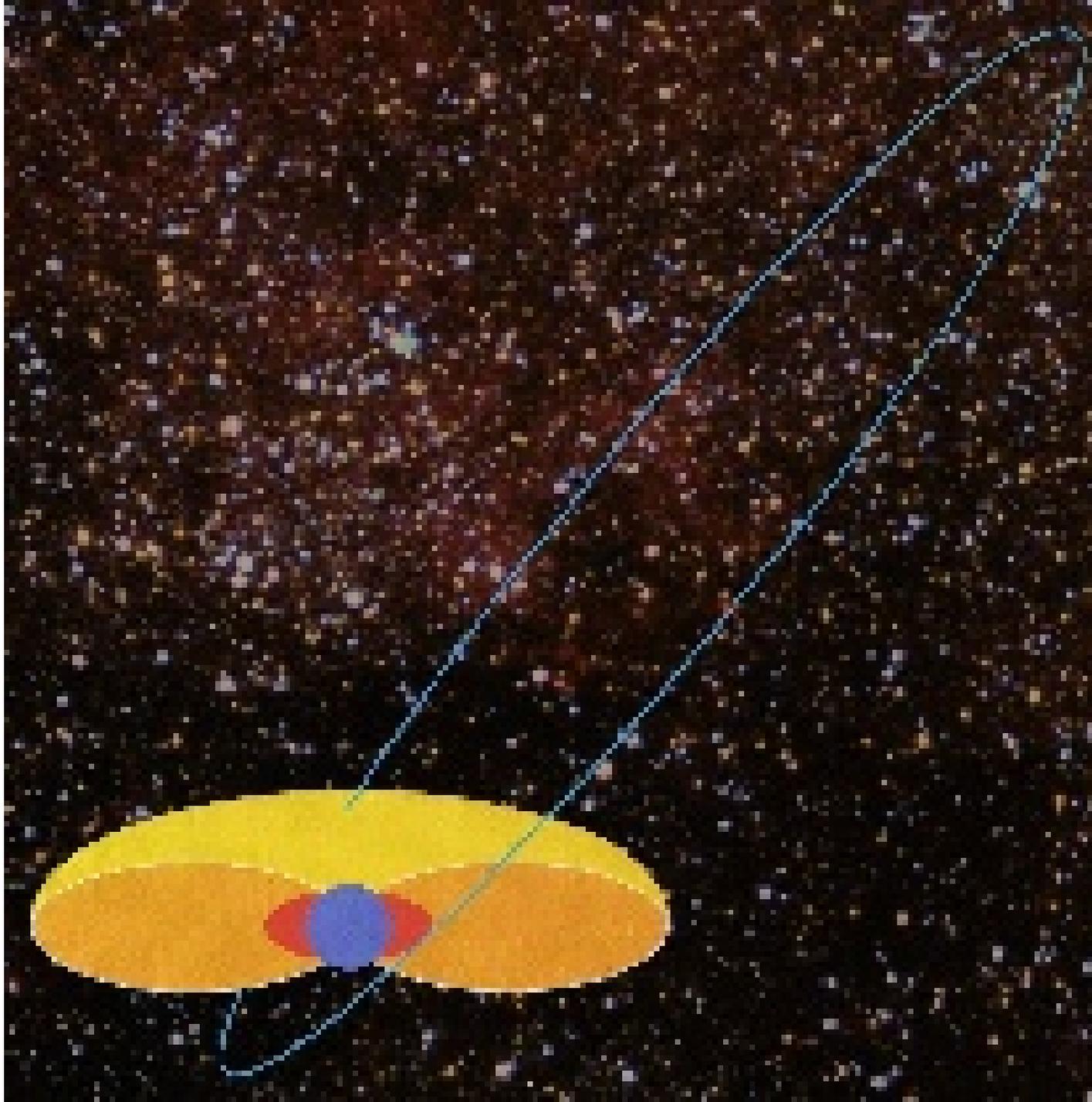
Naschera
Codificata

Rivelatore sensibile alla posizione



Maschera di IBIS

Orbita di INTEGRAL

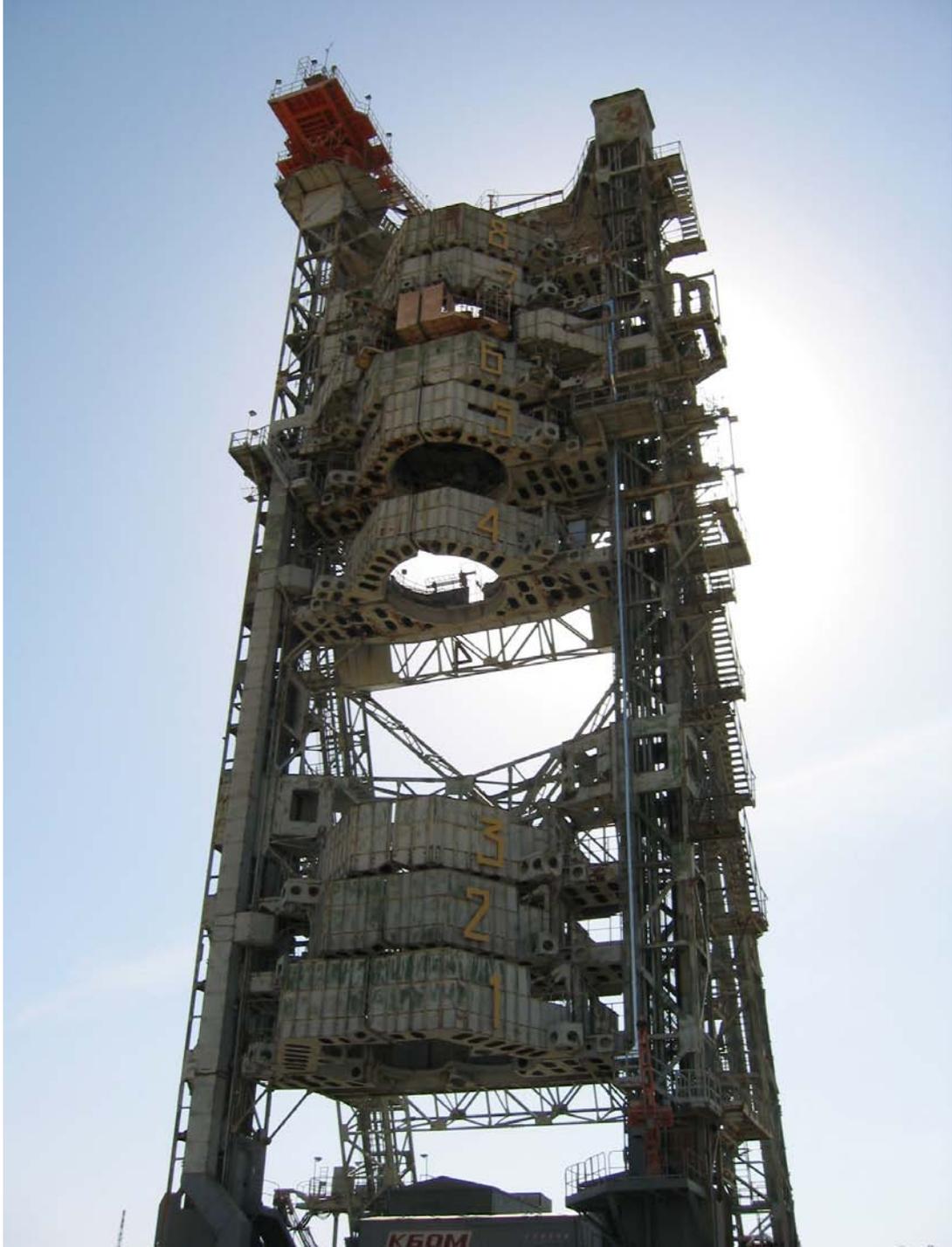








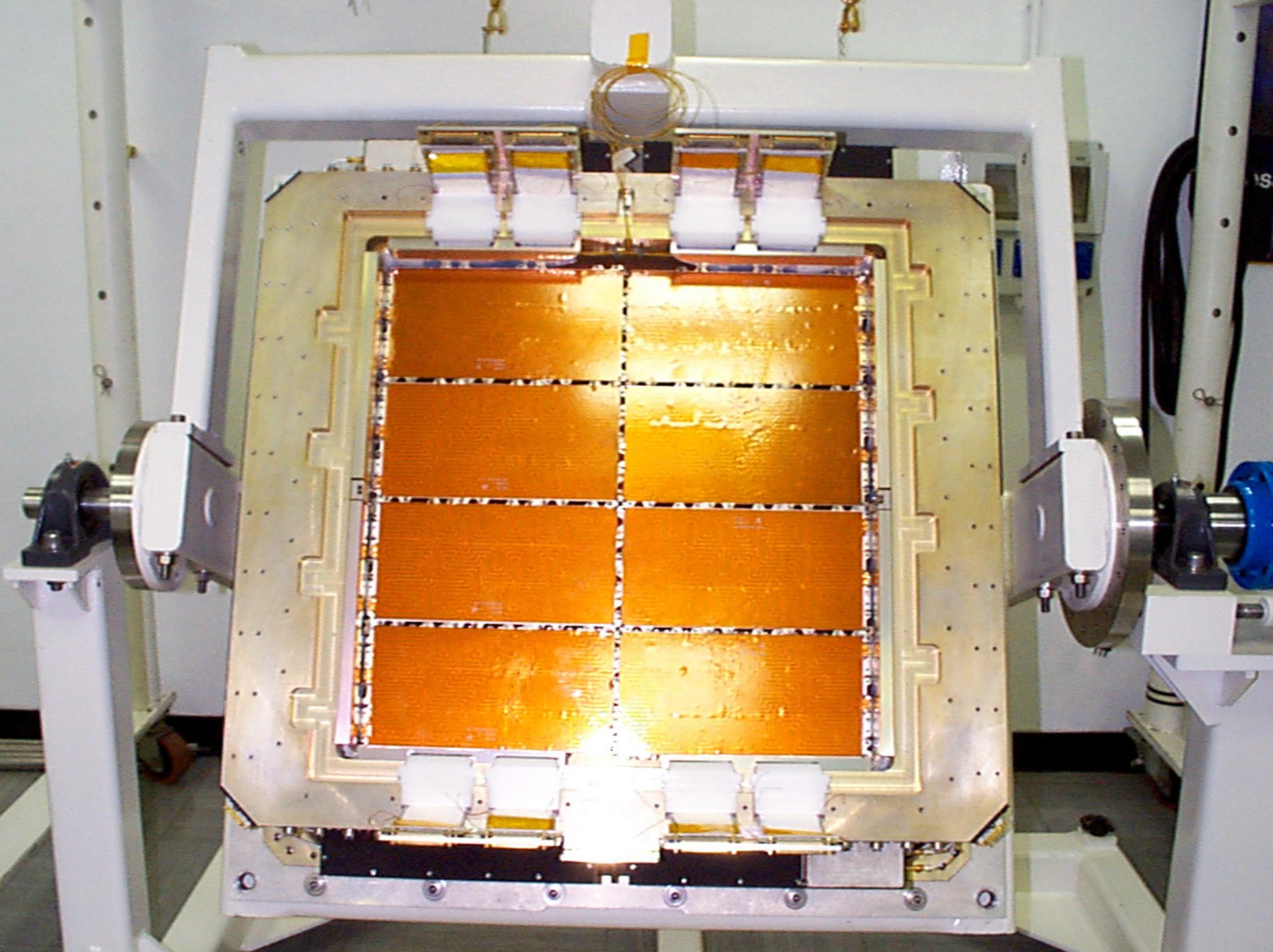
САОТ-01

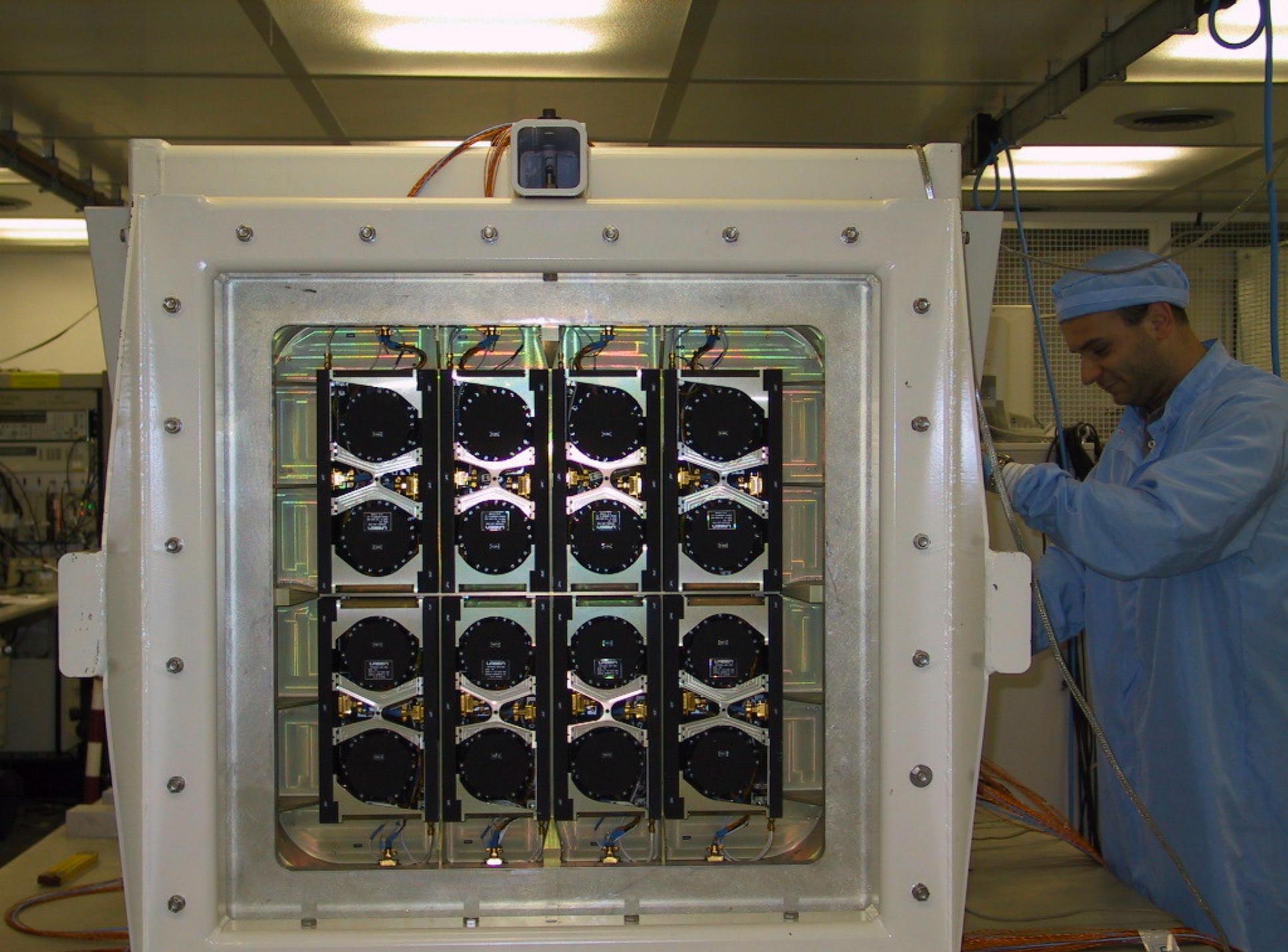


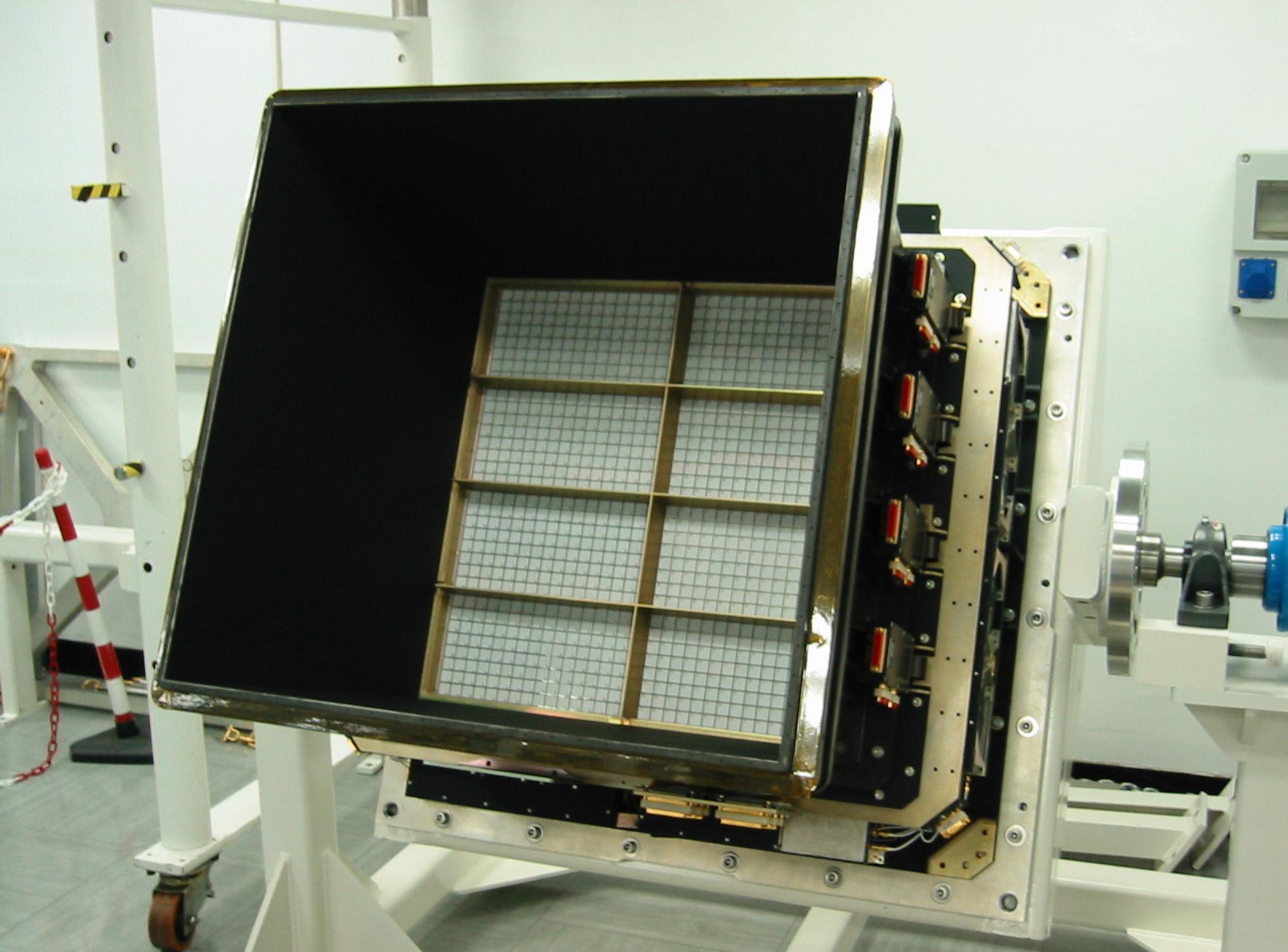
КБ0М



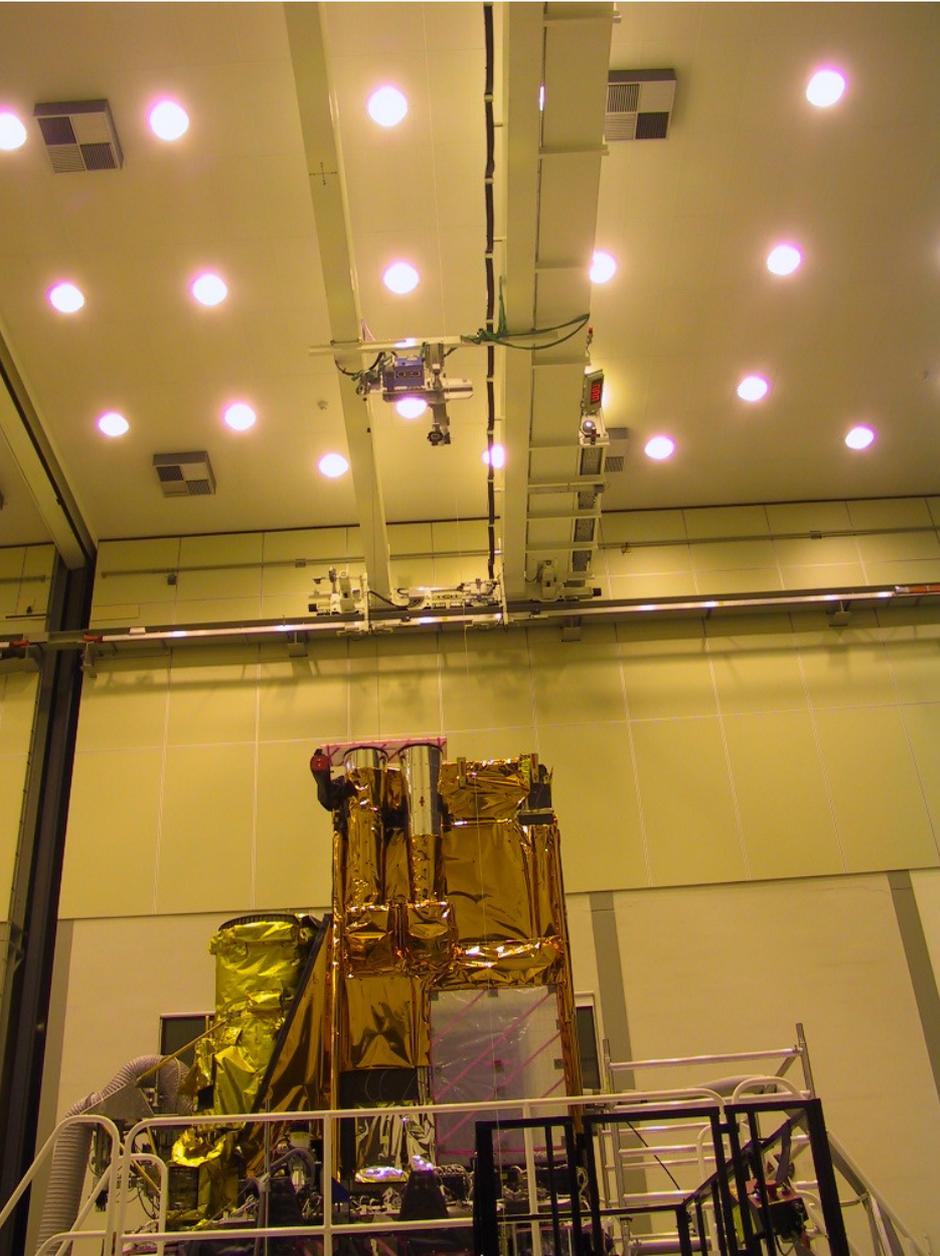








INTEGRAL during Payload Ground Calibration



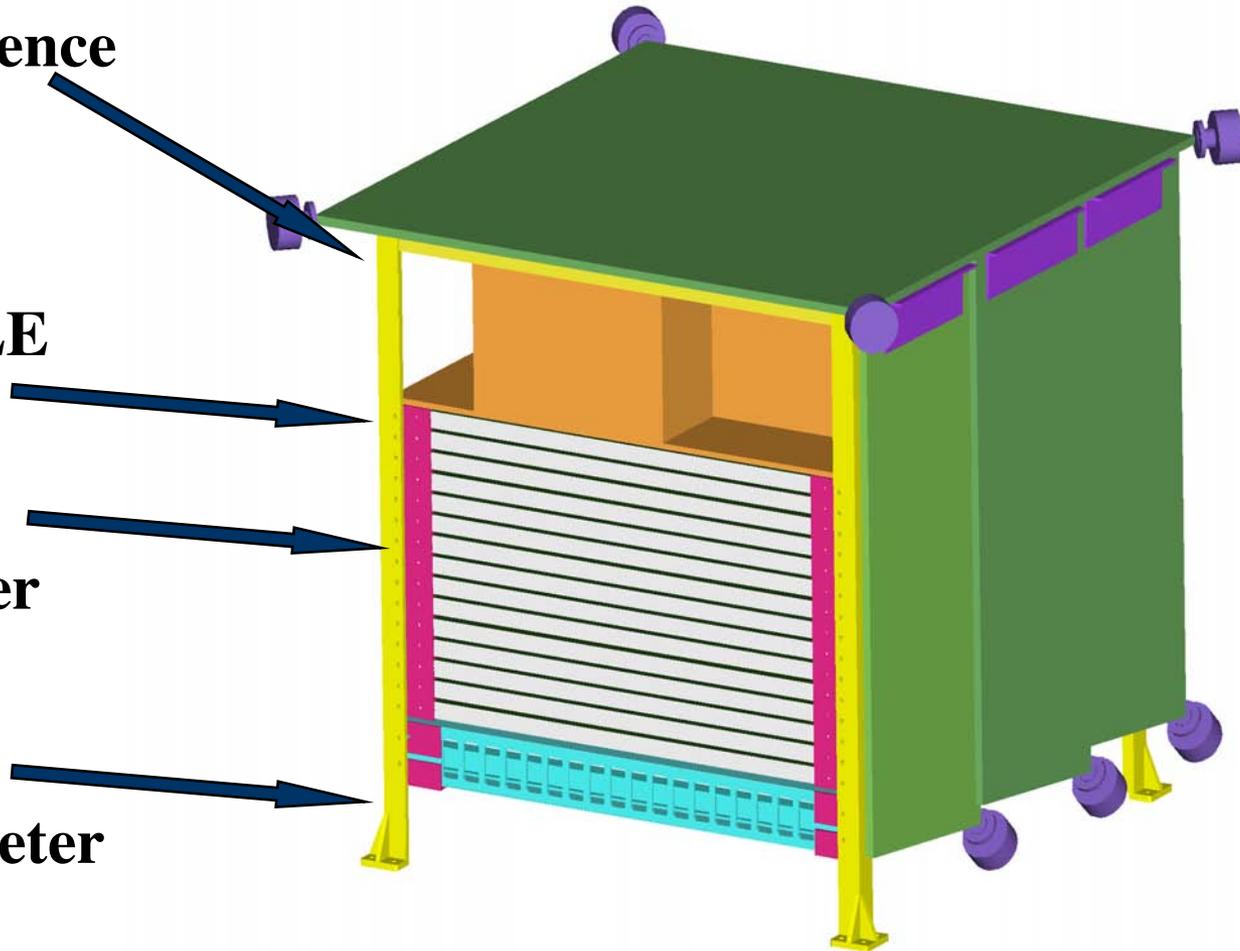
AGILE

Anticoincidence

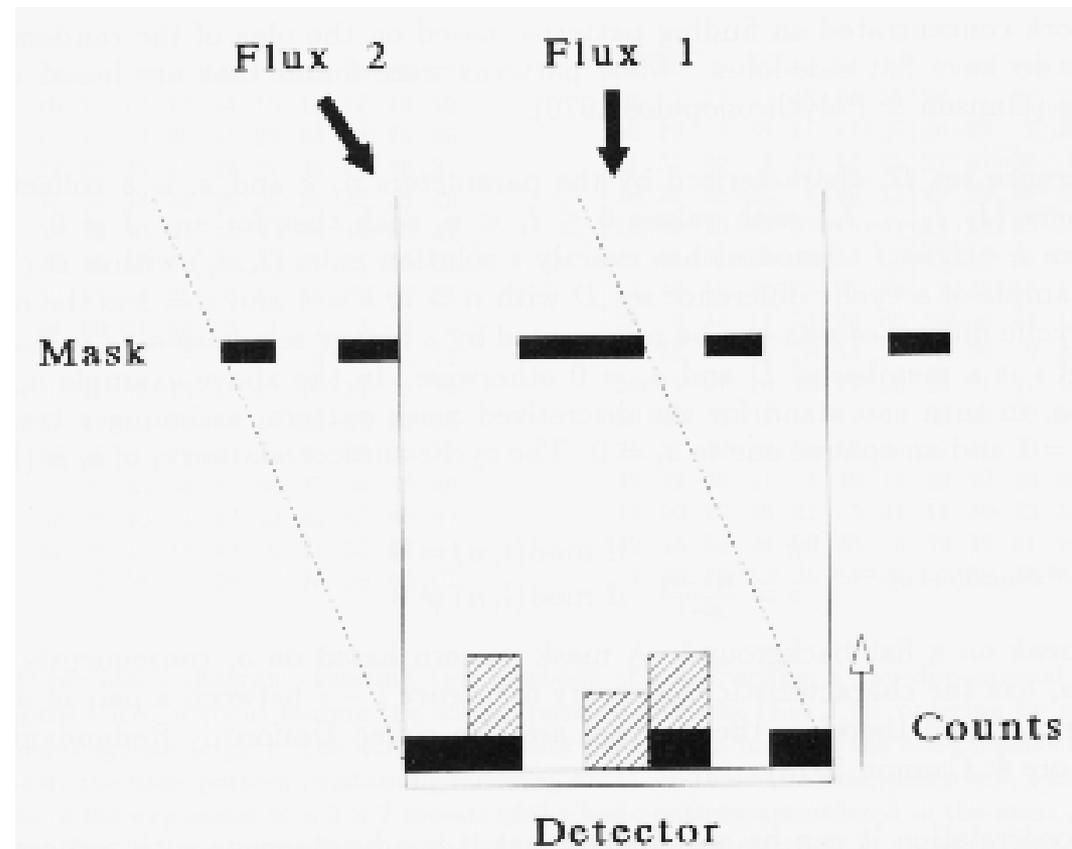
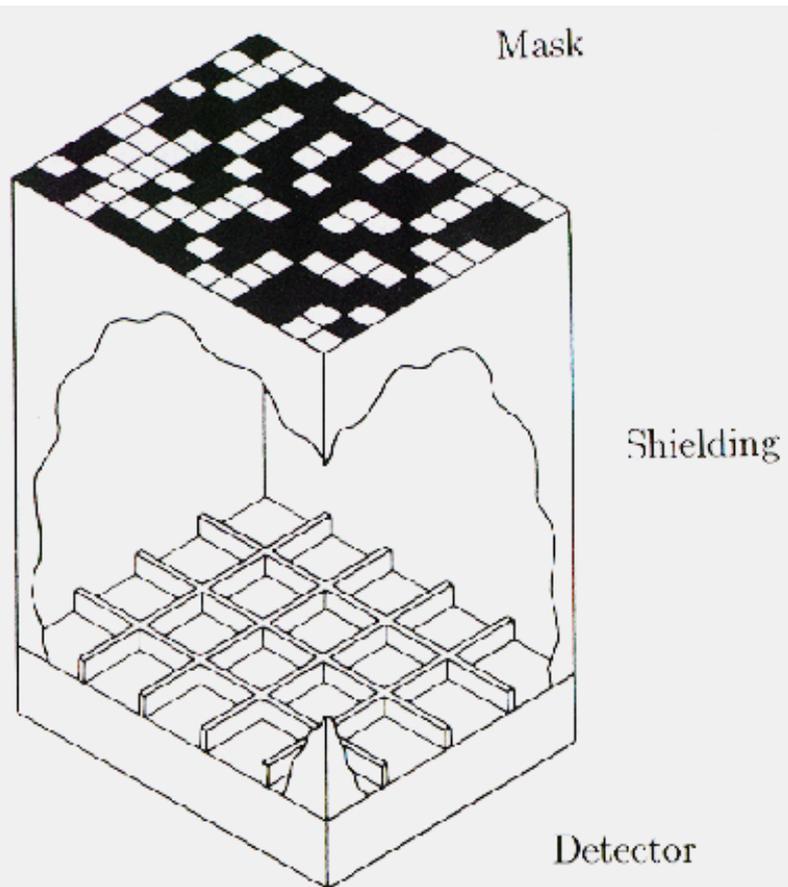
SuperAGILE

Silicon tracker

Mini-Calorimeter



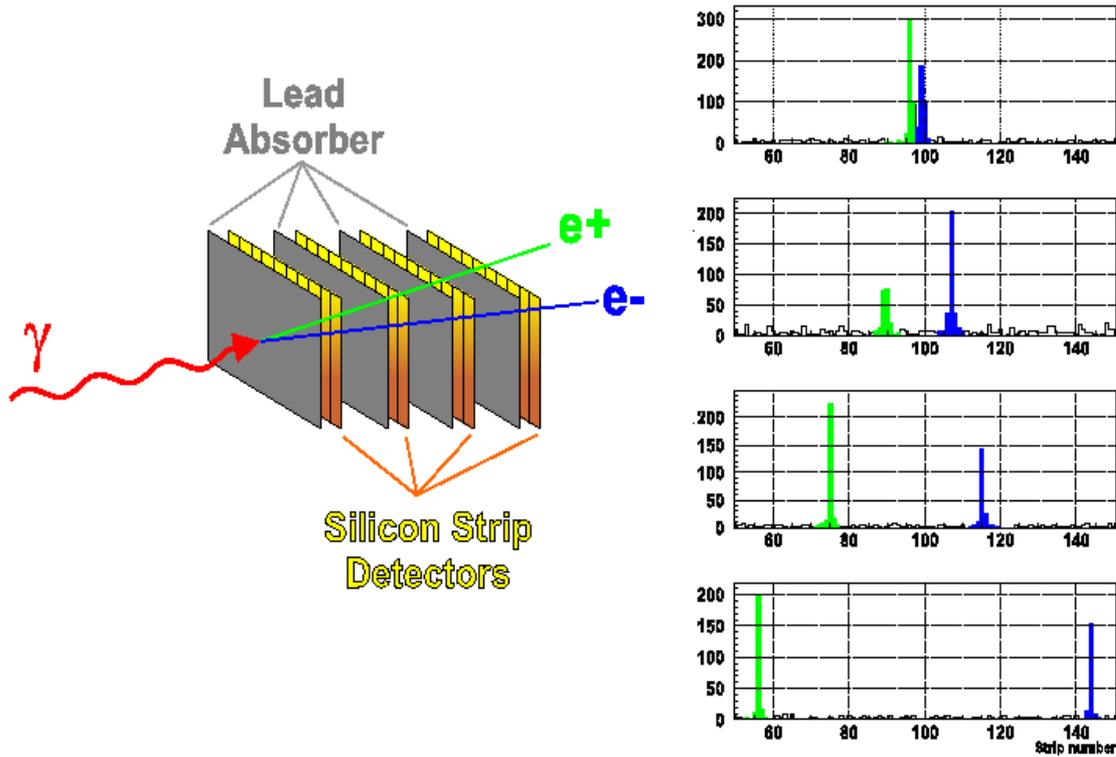
AGILE



AGILE

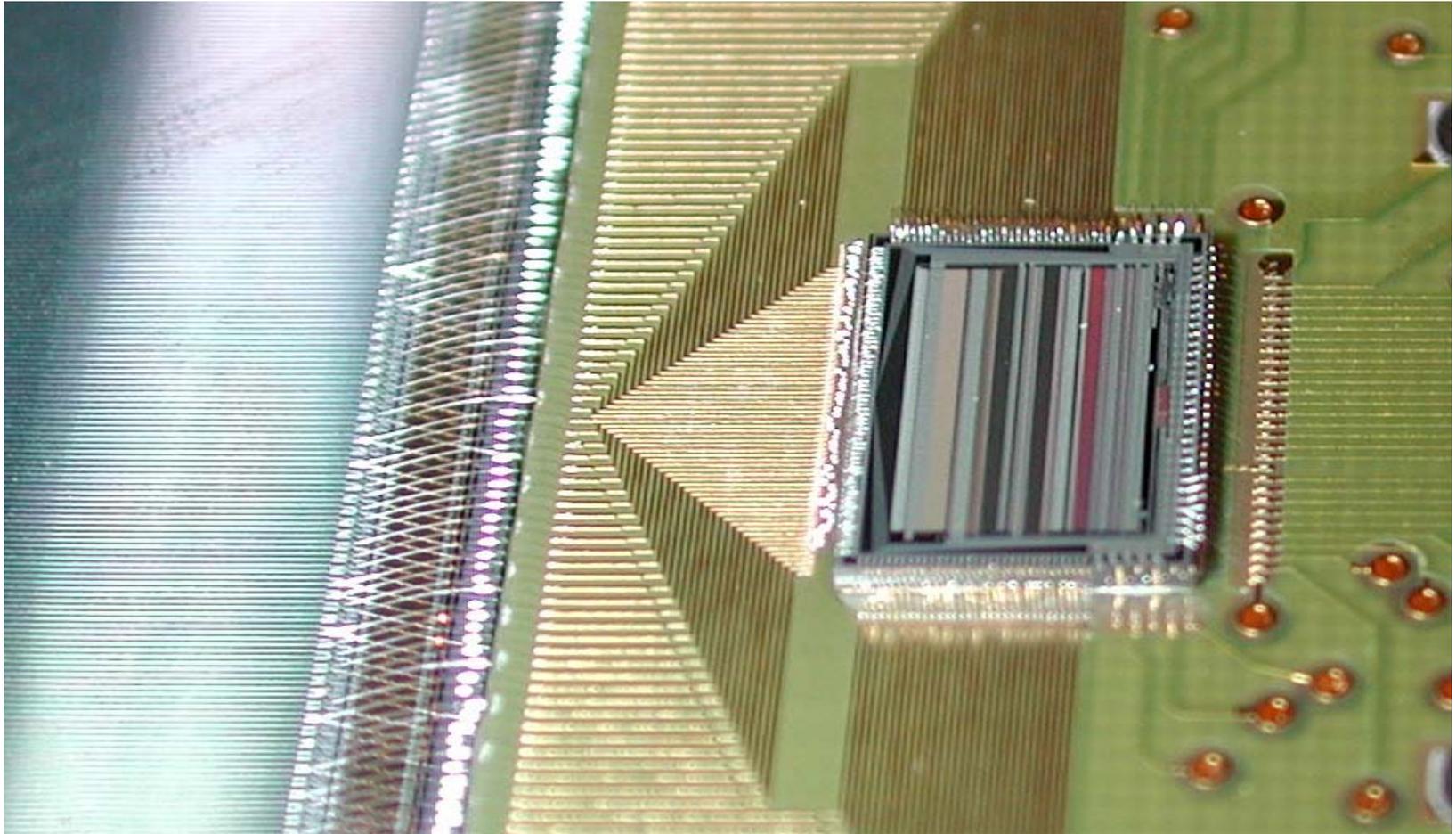
Mini-calorimeter



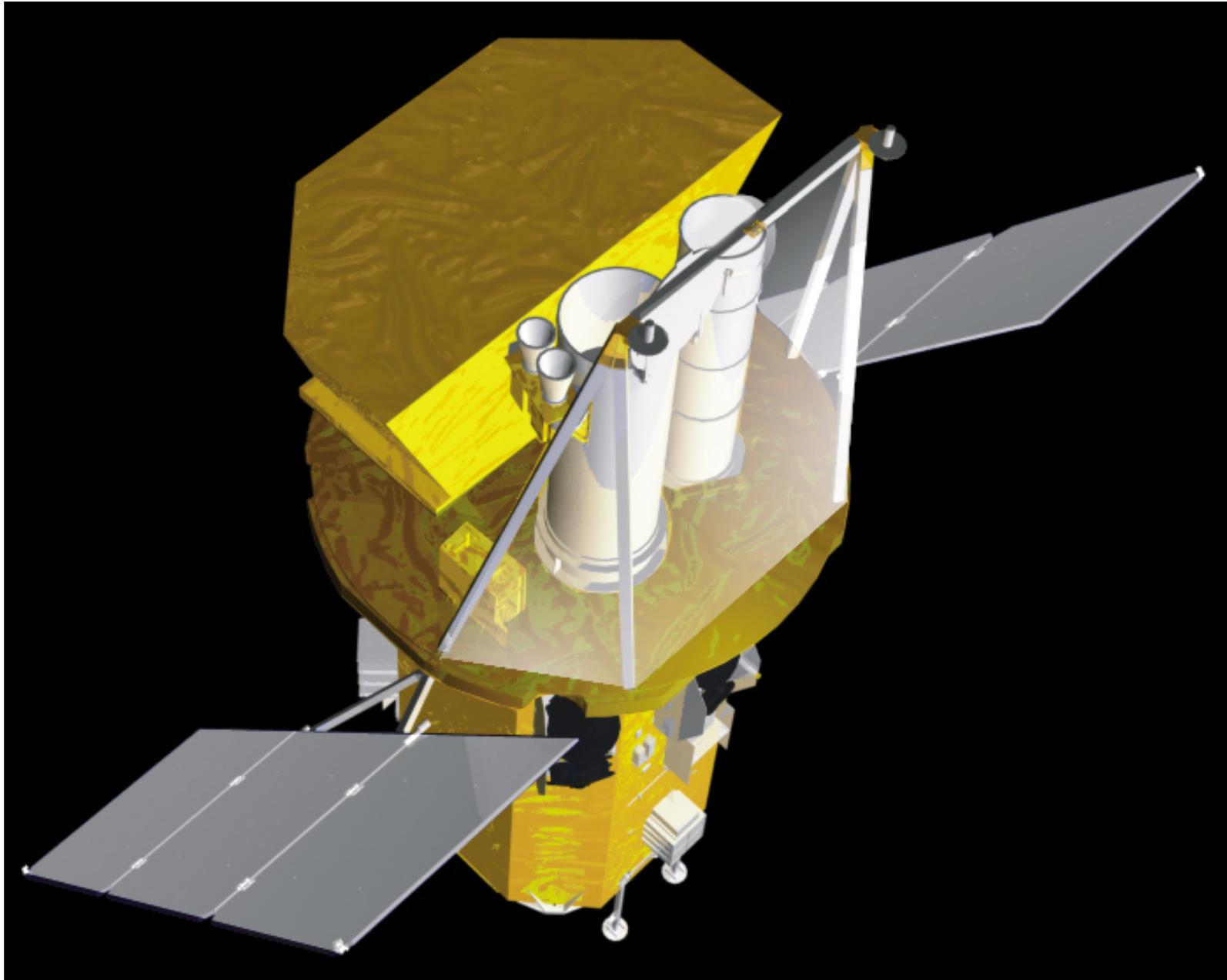


PHOTAG TESTBEAM - INFN TS/IFC MI

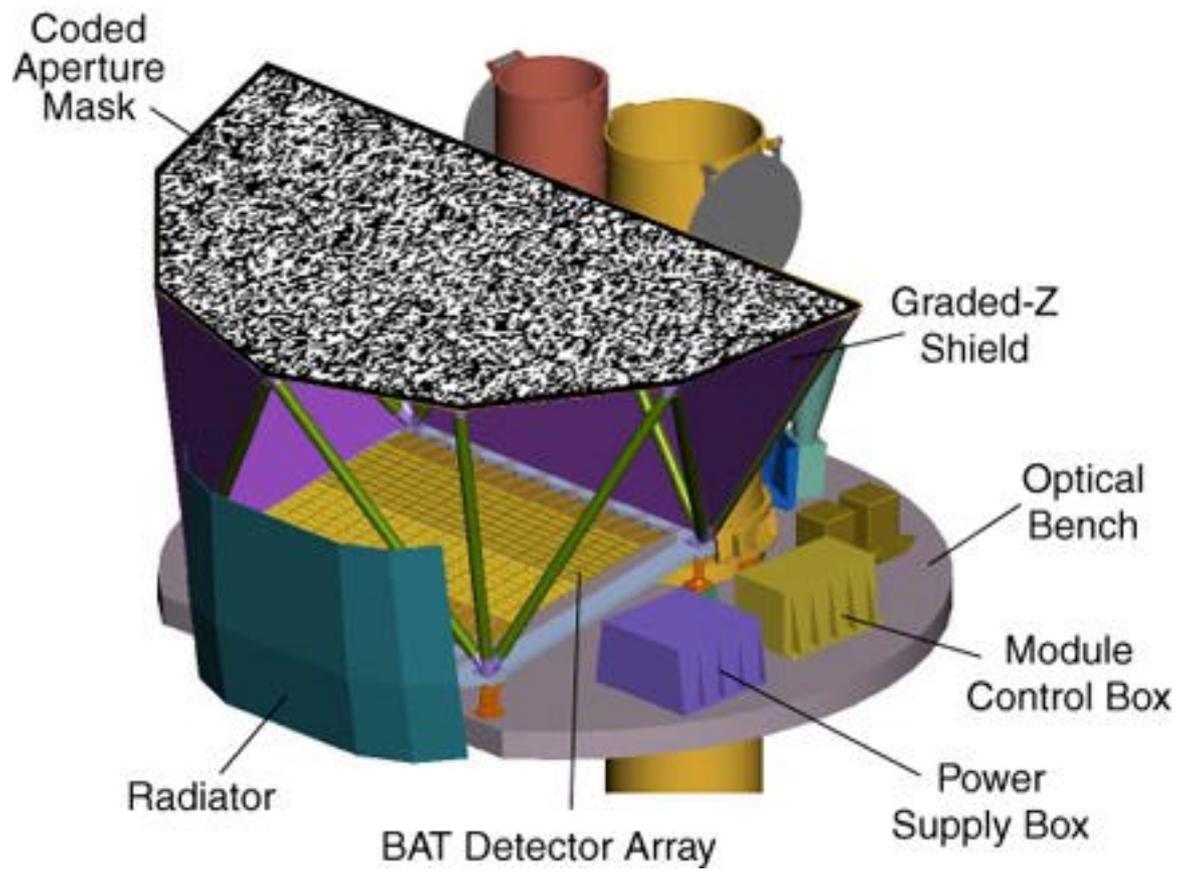
Tracker data from CERN test beam precision $\sim 40 \mu\text{m}$

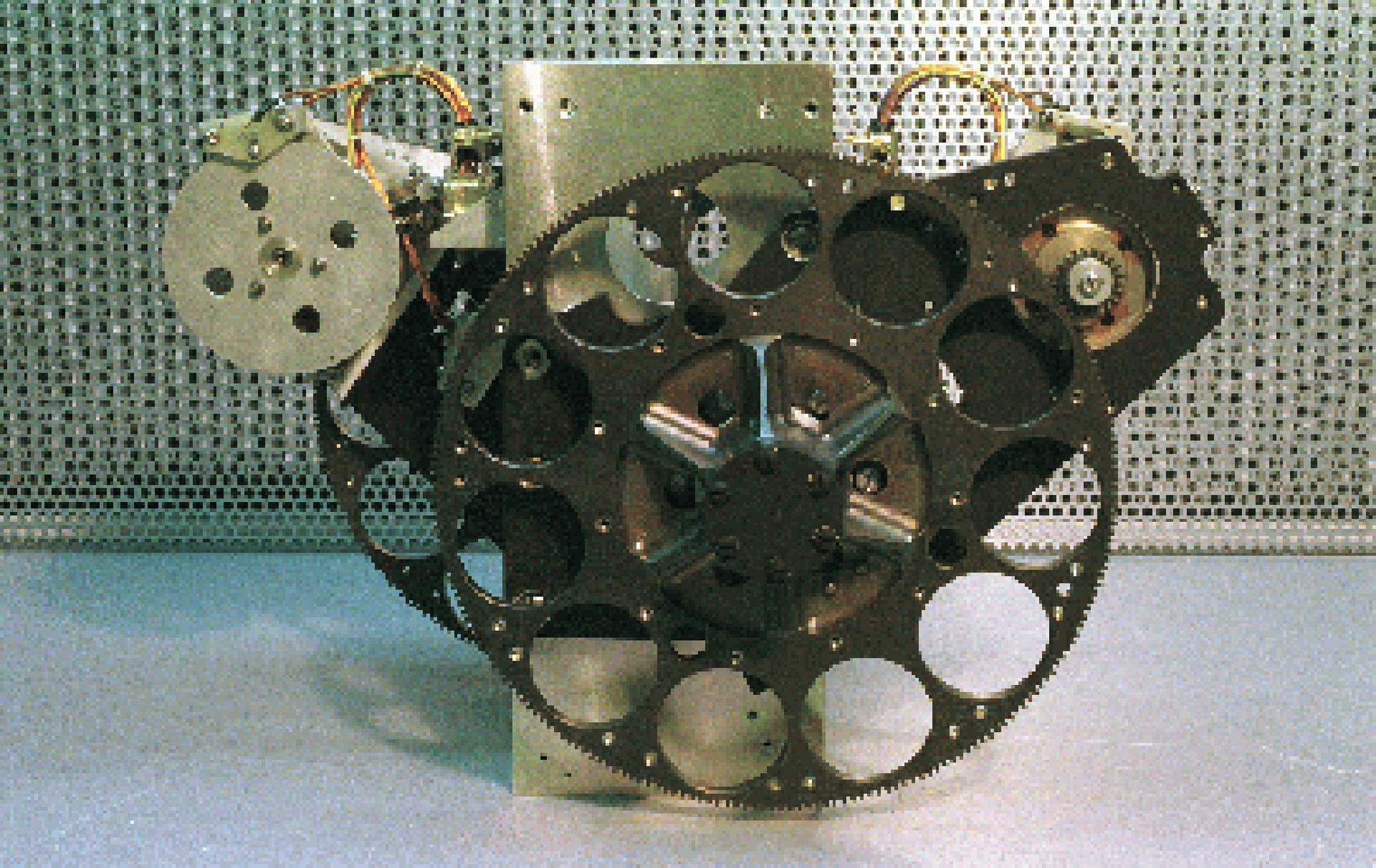


AGILE Silicon microstrip step 121 μm



SWIFT

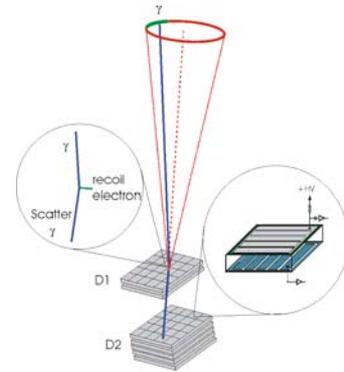




UVOT



Silicon ACT



1 m² frontal area

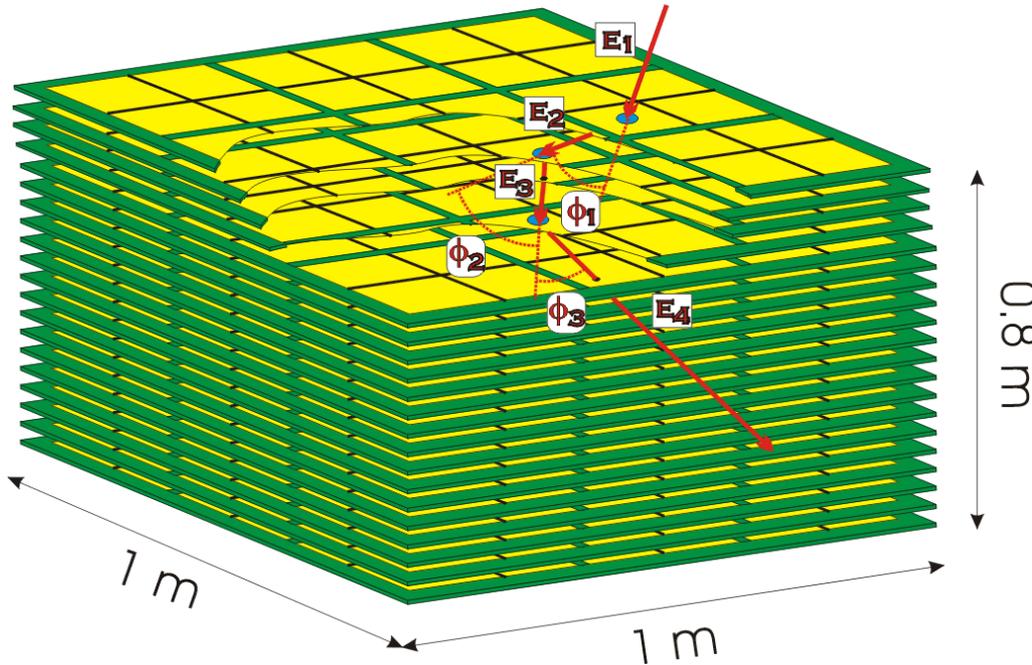
Multiple layers of thick double-sided silicon strip detectors

~ 40 g/cm² thick

430 kg silicon

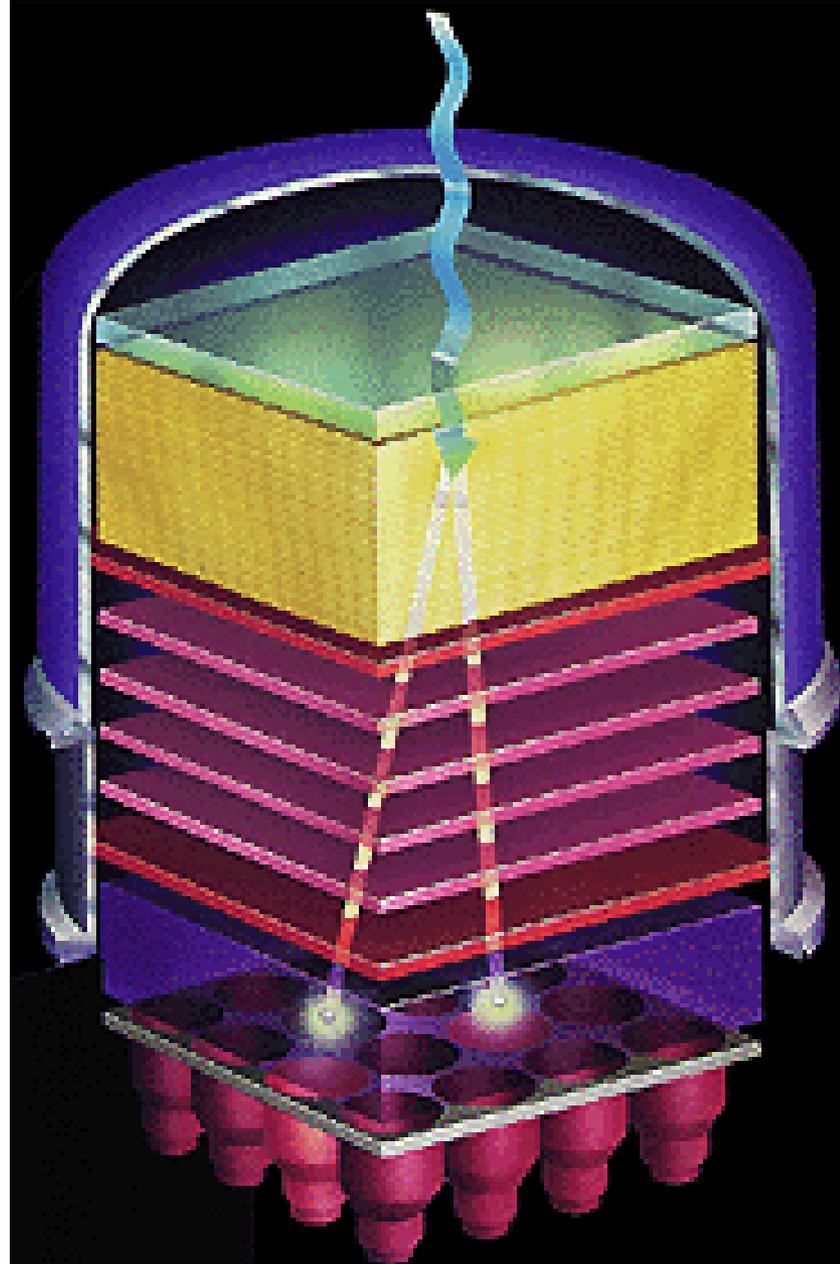
Broad FoV (\pm 75-90 degrees)

Charged particle anti-coincidence

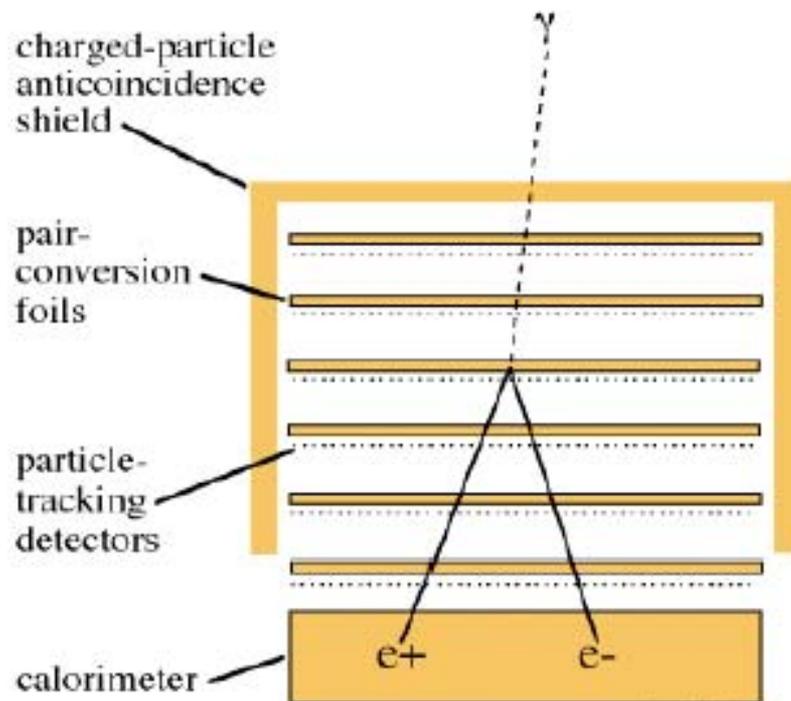


Telescopi gamma per $E > 5-10$ MeV

- 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



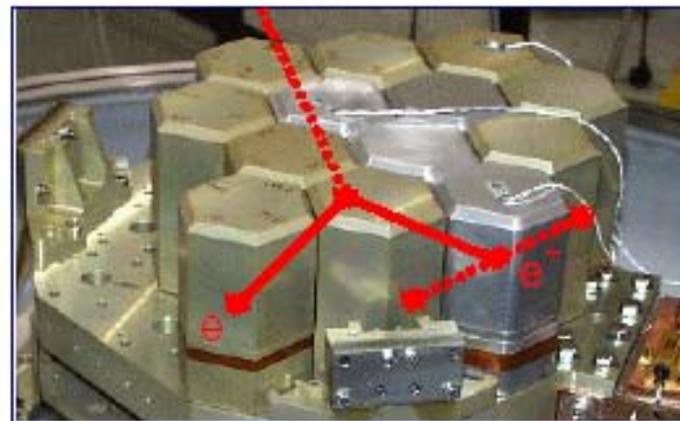
Pair Production Telescopes



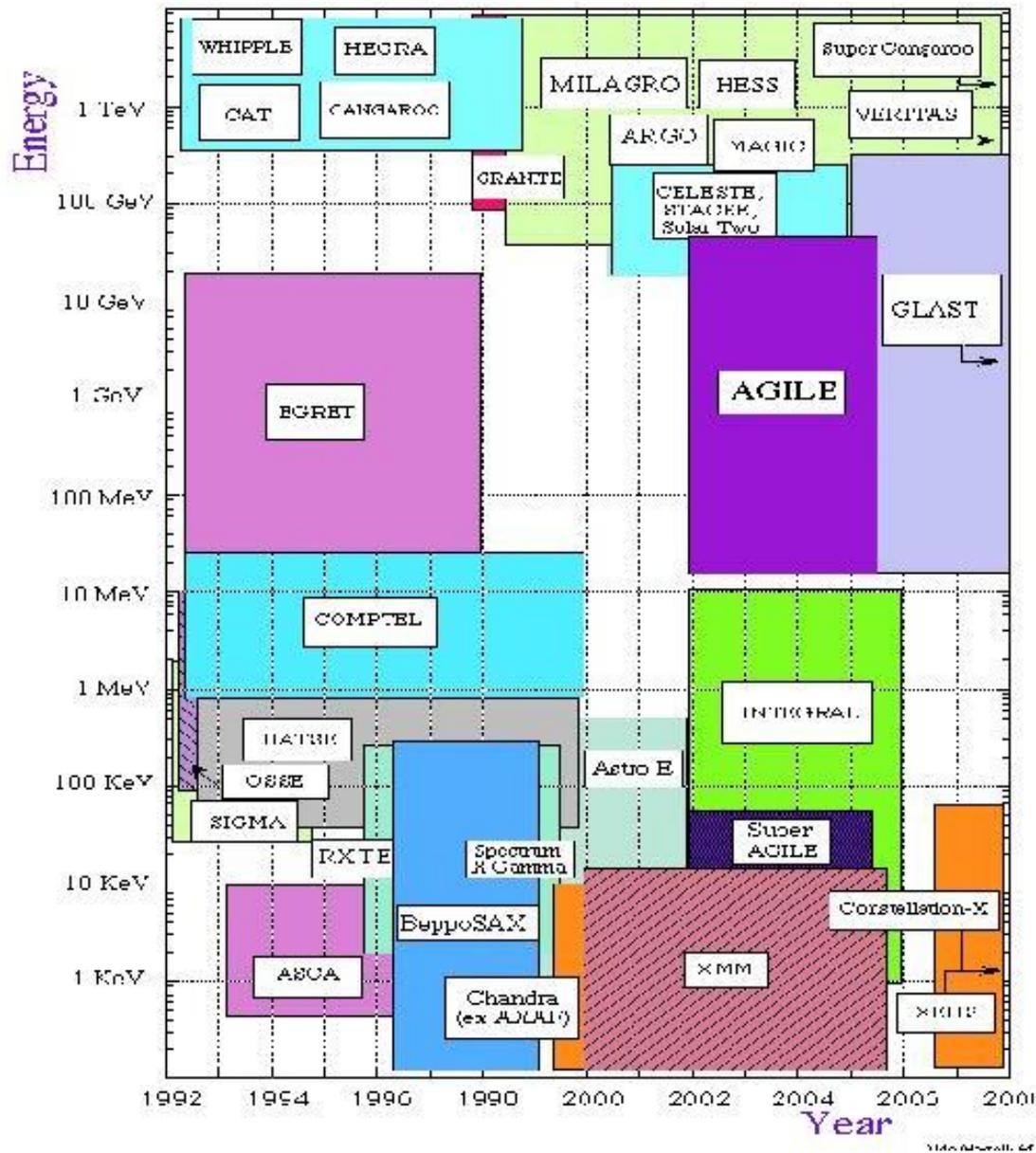
Incident photon whose energy $E_a > 2m_e c^2$ (i.e. $E_a > 1.022$ MeV) is in a position to create an **electron-positron pair** in the intense electric field prevailing close to an atomic nucleus.

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)