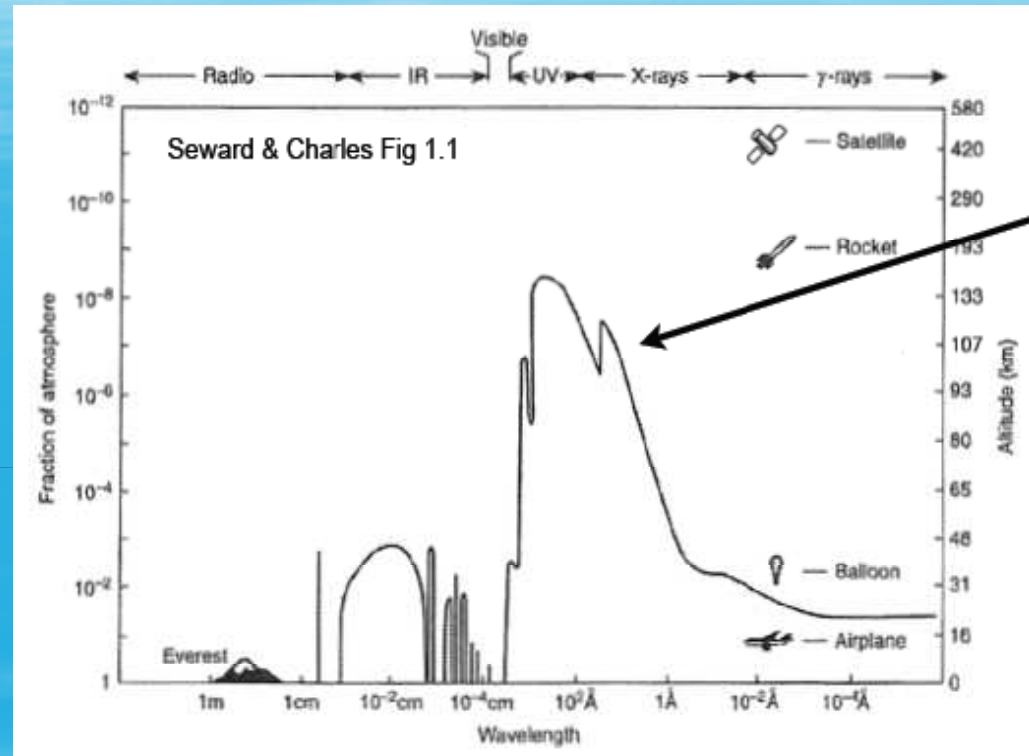
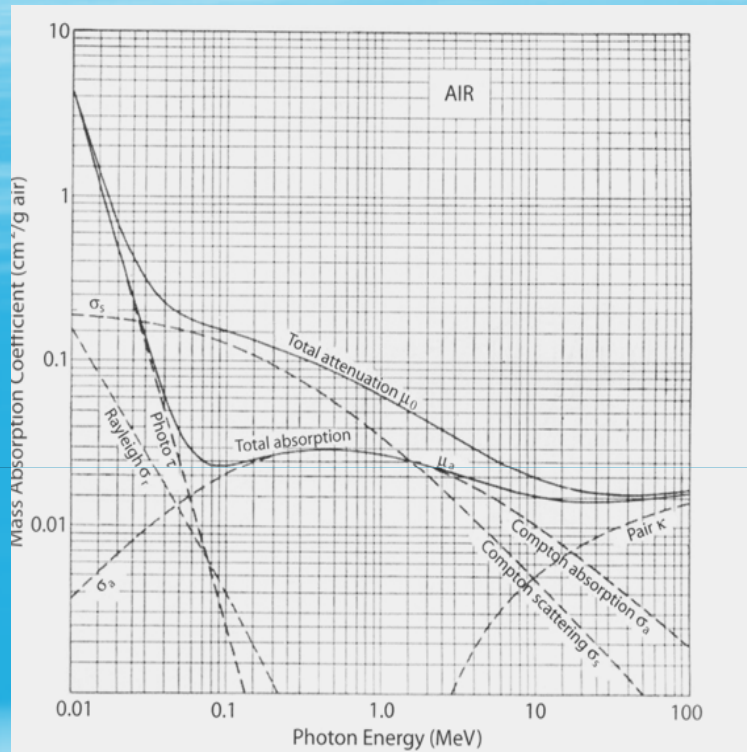


Instruments for X-ray and γ -ray Astrophysics

- X and γ -ray detectors: CCD, proportional and Geiger counters, scintillators, photomultipliers
- X and γ -ray telescopes:
 - Grazing incidence mirrors
 - Temporal and spatial modulators, coded masks
 - Compton telescopes
- Background discrimination: event grades, anti-coincidence shields, pulse shape discrimination

X-ray Absorption in the Atmosphere



- Photoelectric absorption, Compton effect, pair production
- Height for 50% of attenuation changes with E
- 10 cm of air stops 90% of 3 keV photons

γ -ray line sources

F. von Ballmoos

Table 1. Inventory of observed gamma-ray line sources

Physical Process	Energy [keV]	Source	Flux [ph cm ⁻² s ⁻¹]	Instrument (detector type)	Ref.
Nuclear deexcitation					
⁵⁶ Fe(p,p', γ)	847	Solar flares	up to ≈ 0.05	SMM (NaI scintillator)	[16]
²⁴ Mg(p,p', γ)	1369	Solar flares	up to ≈ 0.08	SMM (NaI scintillator)	[16]
²⁰ Ne(p,p', γ)	1634	Solar flares	up to ≈ 0.1	SMM (NaI scintillator)	[16]
²⁸ Si(p,p', γ)	1779	Solar flares	up to ≈ 0.09	SMM (NaI scintillator)	[16]
¹² C(p,p', γ)	4439	Solar flares	up to ≈ 0.1	SMM (NaI scintillator)	[16]
¹⁶ O(p,p', γ)	6129	Solar flares	up to ≈ 0.1	SMM (NaI scintillator)	[16]
Radioactive decay					
⁵⁶ Co(EC, γ) ⁵⁶ Fe	847, 1238, 2598	SN 1987A	$\approx 10^{-3b}$	various scintillators and Ge detectors	[38]
	847, 1238	SN 1991T	$\approx 10^{-3b}$	COMPTEL (scintillators)	[46]
⁵⁷ Co(EC, γ) ⁵⁷ Fe	122, 136	SN 1987A	$\approx 10^{-4}$	OSSE (NaI-CsI phoswich)	[31]
⁴⁴ Ti(EC) ⁴⁴ Sc(β^+ , γ)	1157	Cas A SNR	$7 \cdot 10^{-5}$	COMPTEL (scintillators)	[47]
	1157	RX J0852.0-4622 ^c	$3.8 \pm 0.7 \cdot 10^{-5}$	COMPTEL (scintillators)	[48]
²⁶ Al(β^+ , γ) ²⁶ Mg	1809	structured galactic plane	$4 \cdot 10^{-4}/\text{rad}$	COMPTEL (scintillators)	[32-37]
	1809	Cygnus region	$7.9 \pm 2.4 \cdot 10^{-5}$	COMPTEL (scintillators)	[39]
	1809	Vela region	$1-6 \cdot 10^{-5}$	COMPTEL (scintillators)	[32-37]
e⁺ - e⁻ Annihilation					
	511	galactic bulge	$1.7 \cdot 10^{-3}$	OSSE (NaI-CsI phoswich), Ge detectors	[19-25]
	511	galactic disk	$4.5 \cdot 10^{-4}$	OSSE (NaI-CsI phoswich), Ge detectors	[19-25]
	$480 \pm 120^{a,c}$	1E 1740-29	$1.3 \cdot 10^{-2}$	SIGMA/NaI scintillator	[27]
	511	Solar Flares	up to ≈ 0.1	SMM (NaI scintillator)	[15, 16]
	479 ± 18^a	Nova Muscae	$6.3 \cdot 10^{-3}$	SIGMA (NaI scintillator)	[40]
	400-500 ^a	Gamma Ray Bursts ^c	up to ≈ 70	various scintillators	e.g. [41]
	73 ... 500 ^a	Crab Pulsar ^c	$3 \cdot 10^{-4}$	various scintillators	see [42]
Neutron Capture					
¹ H(n, γ) ² H	2223	Solar flares	up to ≈ 1	SMM (NaI scintillator)	[16]
	2223	White dwarf? RE J0317-853 ^c		COMPTEL (scintillators)	[17]
⁵⁶ Fe(n, γ) ⁵⁷ Fe	5947 ^a	June 10 1974 Transient	$1.5 \cdot 10^{-2}$	balloon borne Ge detector	[43]
Cyclotron Lines					
	10-70	Gamma Ray Bursts ^c	up to ≈ 3	various scintillators	[43]
	20-58	various pulsars (9, eg Her X-1)	$3 \cdot 10^{-3}$	scintillators	[49, 50]
	73-79	Crab Pulsar	$4 \cdot 10^{-3}$	scintillator	[44]

a) Redshifted line

b) Maximum emission

c) single and/or marginal detection, feature has yet to be confirmed by other instruments

γ - ray interaction processes

Table 3. Gamma-Ray interaction processes (from C.M. Davisson, 1966 [67])

Process	kind of Interaction	Name	Approximate Energy Range of Maximum Importance	* Notation	Approximate Variation (Z)	Remarks
I photoelectric absorption	a with bound atomic e^-	photoelectric effect	dominates at low E (1–500 keV) decreases as E increases	τ	Z^5	
II scattering from electrons	a with bound atomic e^-	Rayleigh scattering coherent or elastic scattering	<1 MeV and greatest at small scattering angles	σ or $\sigma(R)$	Z^2 small θ Z^3 large θ	Combines coherently with IVb, IVc, and Vc
coherent	b with free e^-	Thomson scattering	independent of energy	σ_{et}	Z	low frequency limit of Compton scattering
	c with bound atomic e^-		<1 MeV, least at small scattering angles	σ	Z	
incoherent	d with free e^-	Compton scattering	dominates in region of 1 MeV, decreases as energy increases	σ	Z	
III nuclear photoeffect	a with nucleus as a whole	particle production (γ, γ), (γ, n), (γ, p) etc	above threshold has broad maximum between 10–30 MeV			
IV nuclear scattering	a with material as a whole (dep. on nuc E-levels)	Mössbauer effect	important only in very narrow resonance range			Combines coherently with IIa, IVc, and Vc
coherent	b with nucleus as a whole (dep. on nuc E-levels)	nuclear resonance scattering	narrow reson. maxima at low E, broad maxima at 10–30 MeV	σ or $\sigma(T)$	Z^2/A^2	Combines coherently with IIa, IVc, and Vc
	c with nucleus as a whole (indep. of nuc. E-levels)	nuclear Thomson scattering		σ or $\sigma(NR)$	Z^4/A^2	Combines coherently with IIa, IVb, and Vc
incoherent	d with individual nucleons	nuclear Compton scattering	$\lambda \leq$ nuclear radius, i.e. > 100 MeV			
V interact. w. Coulomb field pair production	a in Coulomb field of nucleus	elastic pair production	threshold $\sim$ 1 MeV, dominant at HE, ϕ increases with E	κ or κ_{pair}	Z^2	
	b in Coulomb field of electron	triplet production	threshold at 2 MeV increases as E increases	κ_e or $\kappa_{triplet}$	Z	
Delbrück scattering	c in Coulomb field of nucleus	nuclear potential scattering	real part > imaginary (below 3 MeV) < imaginary (above 15 MeV), real and imaginary both increase as energy increases	σ or $\sigma(D)$	Z^4	Combines coherently with IIa, IVb, and IVc

History of High Energy astrophysics

High Energy astrophysics started late in the history of modern astronomy, compared to other wavelength ranges.

Table 2. Principal cornerstones in the development of high energy astronomy

1895	G. Roentgen	discovery of X-rays
1896	H. Becquerel	discovery of radioactivity
1899	E. Rutherford	discovery of atomic nucleus
1900	P. Villard	discovery of gamma-rays
1911	V. Hess	discovery of Cosmic Rays (balloons, growth curves)
1932	C. Anderson	discovery of positron (balloon borne Wilson-chamber)
1948	Hulsizer & Rossi	high energy γ 's < 1% of CR (counters, balloon/B29)
1948	Perlow & Kissinger	marginal measurement of cosmic γ -rays (counters, V2 rocket)
1958	EXPLORER 1	discovery of radiation belts (J. Van Allen)
1958	Peterson & Winckler	first gamma-rays from solar flare (balloon, counters)
1958	Ph. Morrison	Vatican conference (nouvo cimento): predictions ...
1960's	RANGER 3 & 5	cosmic diffuse flux: $dn(E) \sim E^{-2.2}$
1961	EXPLORER 11	22 cosmic HE γ -rays detected, BG of 22000 CR events
1962	ASE-MIT rocket	first cosmic X-ray source: Sco X-1
1967/68	OSO-3	HE γ -rays from the Galaxy
1967	VELA satellites	discovery of γ -ray bursts (nuclear test ban treaty)
1970	UHURU	first X-ray sky survey
1972 ff	balloons	detection of cosmic 511 keV annihilation line
1972,75	SAS-2, COS-B	HE γ -rays from galactic plane, Vela, Geminga
1979	HEAO-3	discovery of galactic ^{26}Al (Ge spectrometer)
1987	SMM, balloons	SN1987A: ^{56}Co line, SN ν detection
1989-98	GRANAT/SIGMA	variable galactic center sources
1991-99	Compton-GRO	^{26}Al sky map, ^{44}Ti from Cas A, compact source spectra
1997	Beppo-SAX et al.	γ -ray burst afterglow/identification of hosts galaxies

92 P. von Ballmoos

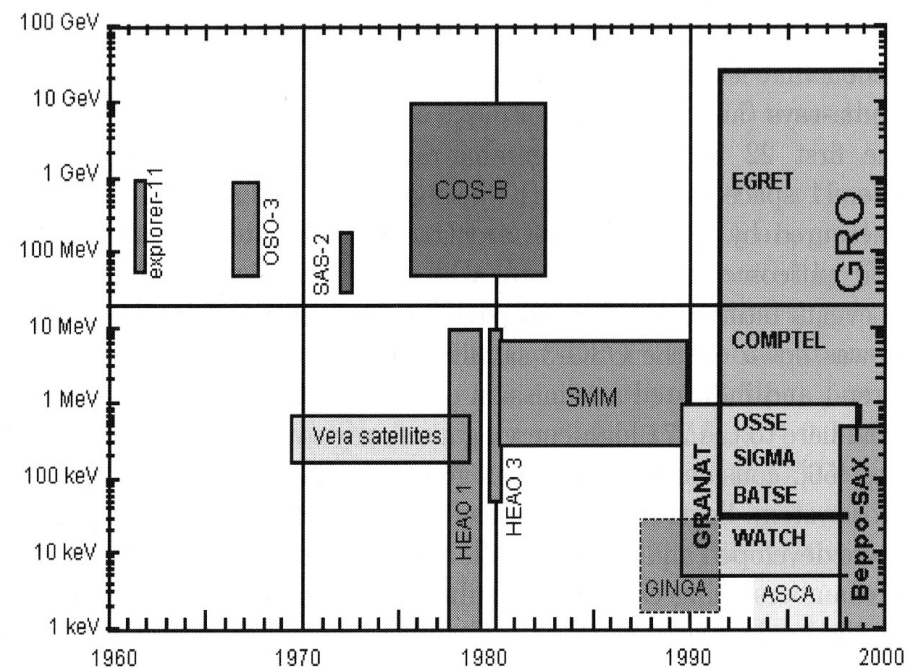
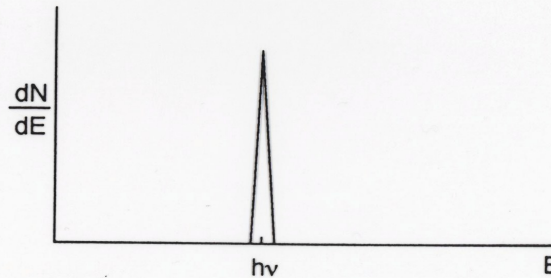
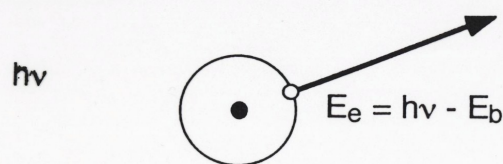


Fig. 1. The “golden age of gamma-ray astronomy”? Never before the high-energy sky has been examined so thoroughly and over such a broad energy range

Spectral signature of high-energy photons

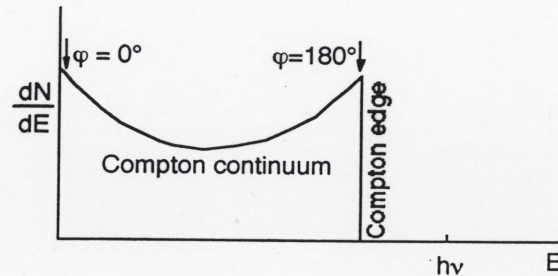
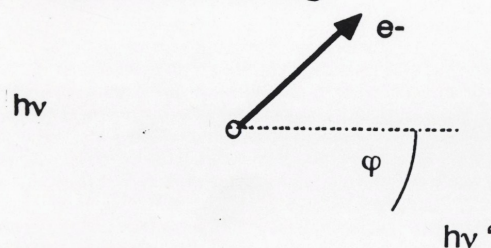
principal energy-loss processes

1. photoelectric absorption



photopeak

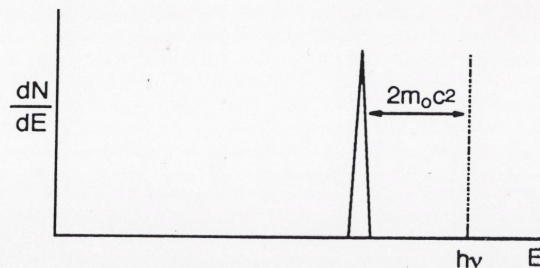
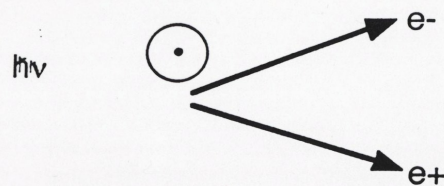
2. Compton scattering



Compton edge

$$h\nu' = \frac{h\nu}{1 + \frac{2 h\nu}{m_0 c^2}}$$

3. Pair production



double escape peak

Spectral signatures of γ -ray detectors: ideal and real detectors

very large detectors

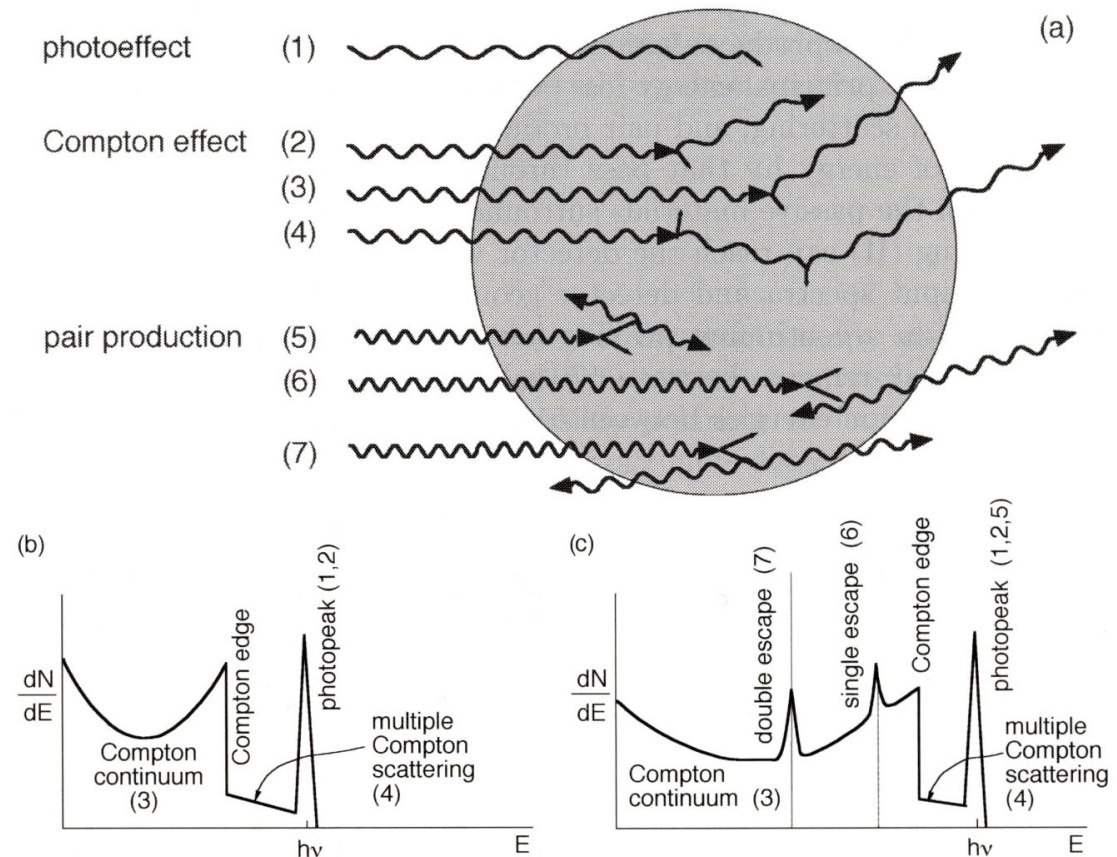
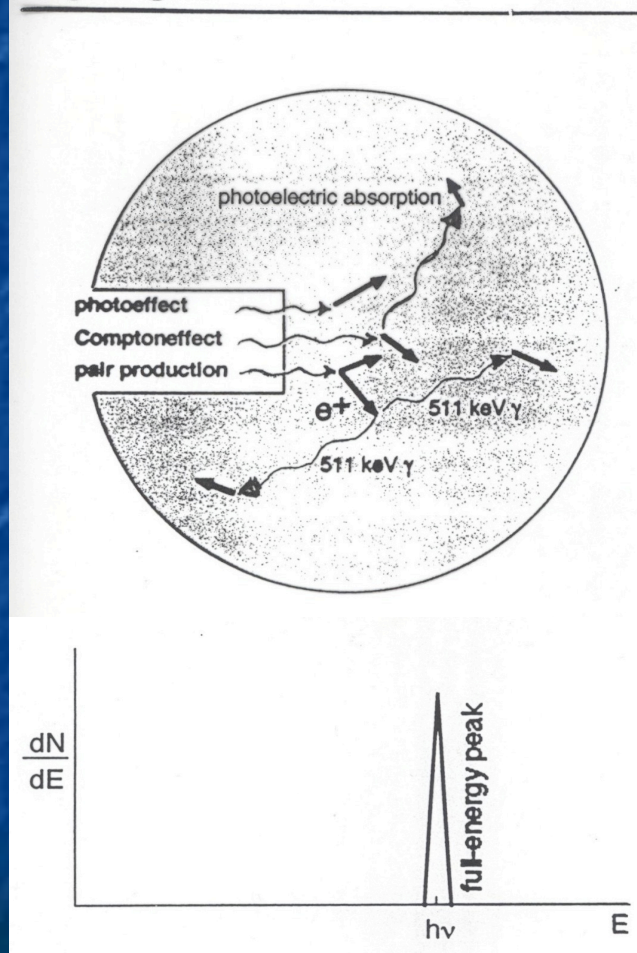


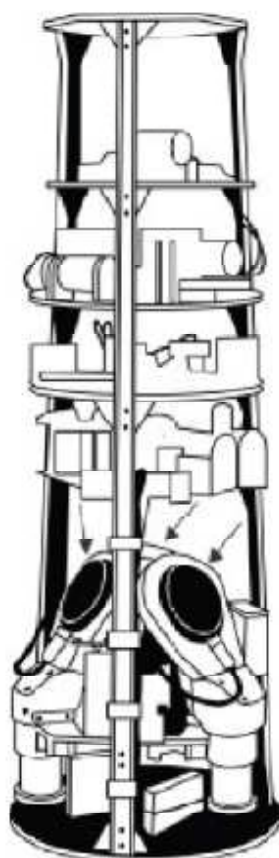
Fig. 13. The spectral signatures of energy loss processes resulting from monochromatic photons ($h\nu$) impinging on a gamma-ray detector (see text)

Pioneering Rocket Observations

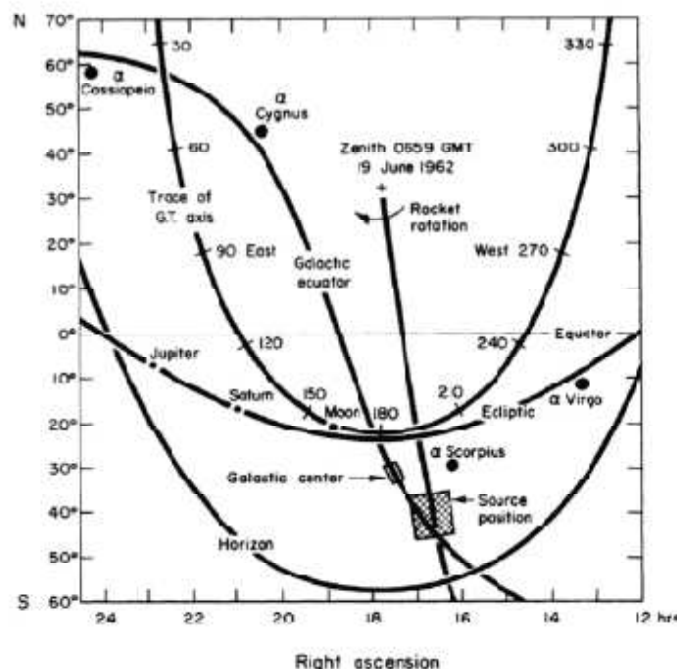
Nobel prize 2002: Riccardo Giacconi



"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"

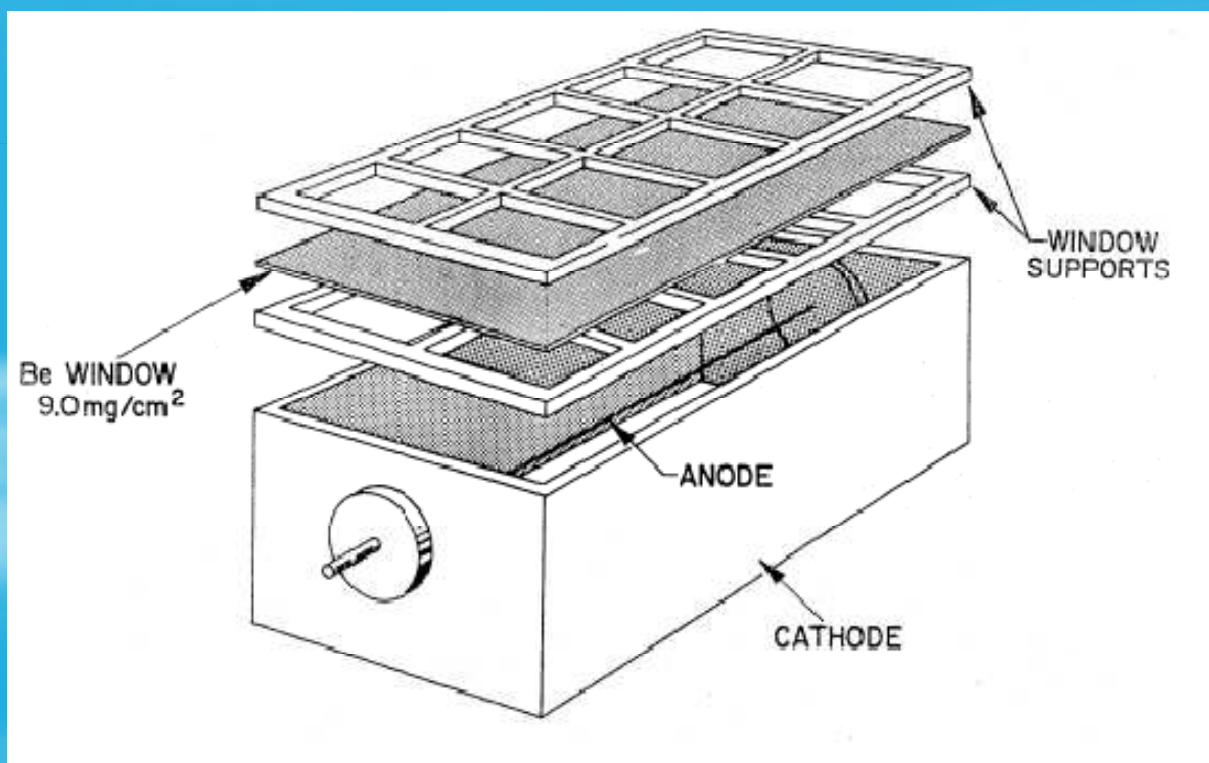


1962: experiment to search for X-rays from the lunar surface: three Geiger counters on a Aerobee rocket



X-ray Detection

- First detectors were proportional counters
- Based on photoionization of a noble gas (e.g. Ar)
- Gain of $10^3 - 10^5$
- Single photon events are detected (need to be!)



26 May 2012

Observational X-ray Astronomy: NASSP Masters 2012

Gas filled detectors

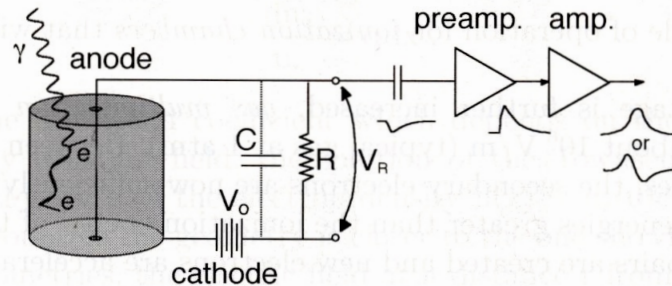


Fig. 16. The components and simplified circuitry of a gas-filled detector. C represents the capacitance of the chamber and any additional capacity. V_R is the output pulse

Gas filled detectors work through photoionization of filling gas. Ionization potential is 10~30 eV (compared to 1~5 eV of solid state devices).

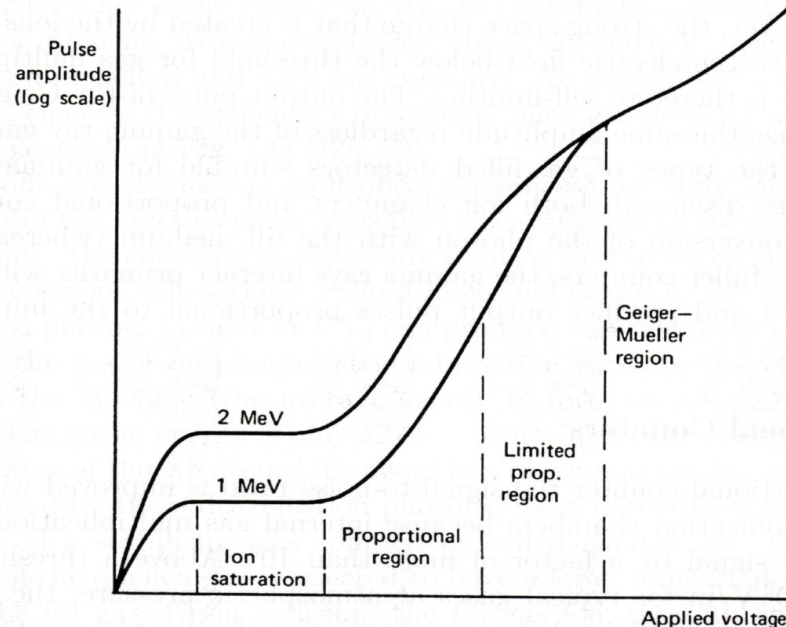


Fig. 17. The regions of operation for gas-filled detectors, explanations see text (from Knoll [81])

Depending on the applied voltage they work in different regimes (linear, saturated) and take different names (proportional counters, Geiger counters).

The First X-ray Astronomy Satellites

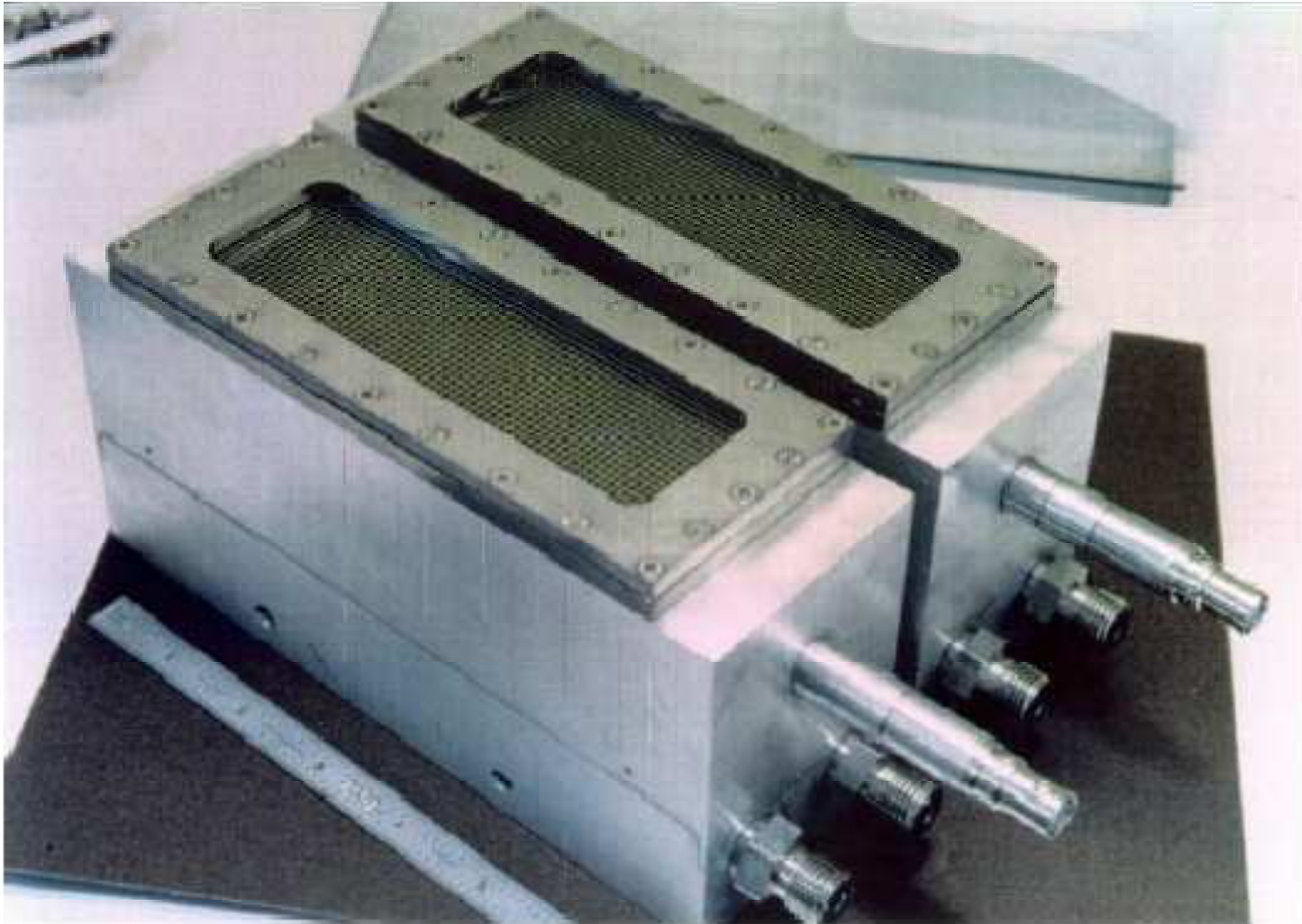
first survey at 2-20 keV
proportional counters



339 X-ray
sources detected

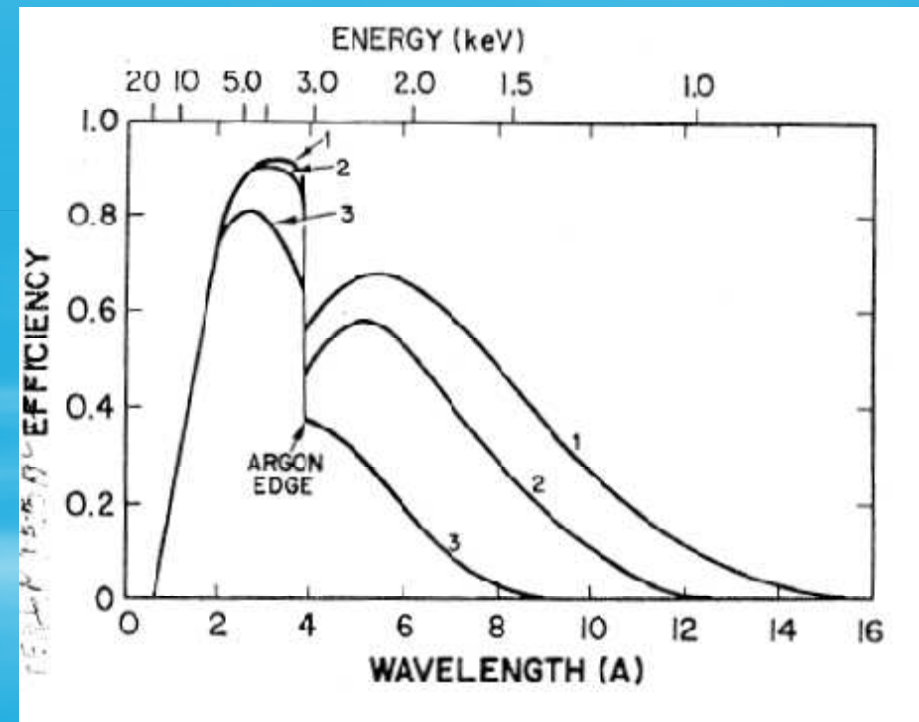
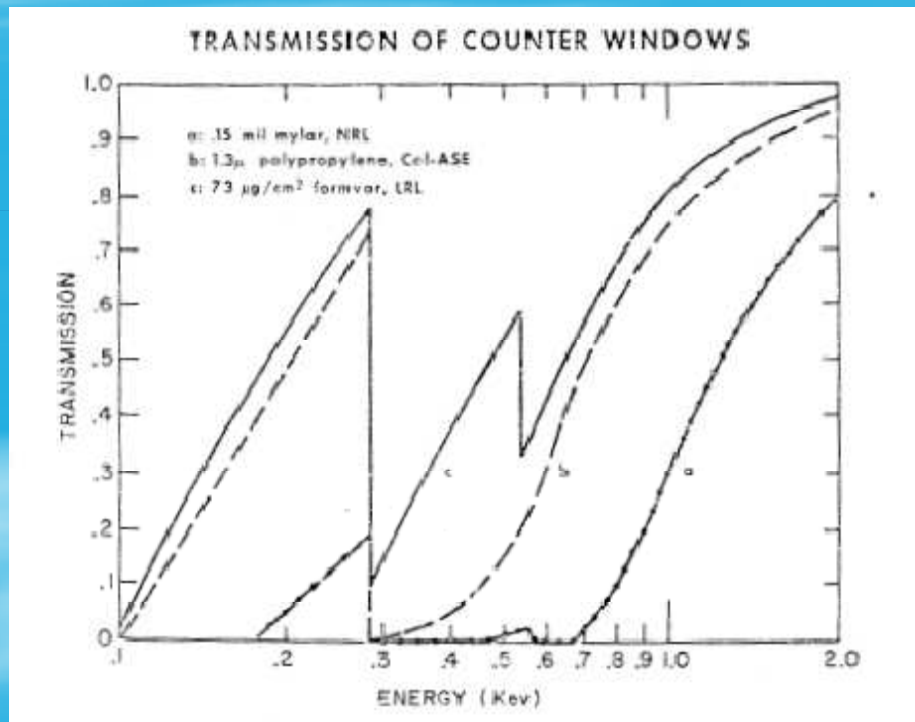
#1: Uhuru 1970 (NASA)

Proportional Counter



Proportional Counters

- Need transparent window
- Need absorptive gas



Solid state detectors

Semiconductor Detectors

probability P that electron-hole pair is thermally generated

$$P(T) \sim T^{3/2} e^{(-E_g/2kT)}$$

T temperature
E_g bandgap energy
k Boltzmann const

Intrinsic semiconductors (pure material) : $n_i = p_i \approx 2.4 \cdot 10^{13} \text{ cm}^{-3}$ in Ge
 $\approx 1.5 \cdot 10^{10} \text{ cm}^{-3}$ in Si

n : concentration of e⁻ in conduction band
 p : concentration of holes in valence band

Impurities / doping

eg. in Si $n_i \approx 10^{10} \text{ cm}^{-3}$, with 2 ppm of impurities, this is $10^{17} \text{ atoms cm}^{-3}$

$$np = n_i p_i$$

$$\Rightarrow n \approx 10^{17} \text{ cm}^{-3}, p \approx 10^3 \text{ cm}^{-3}$$

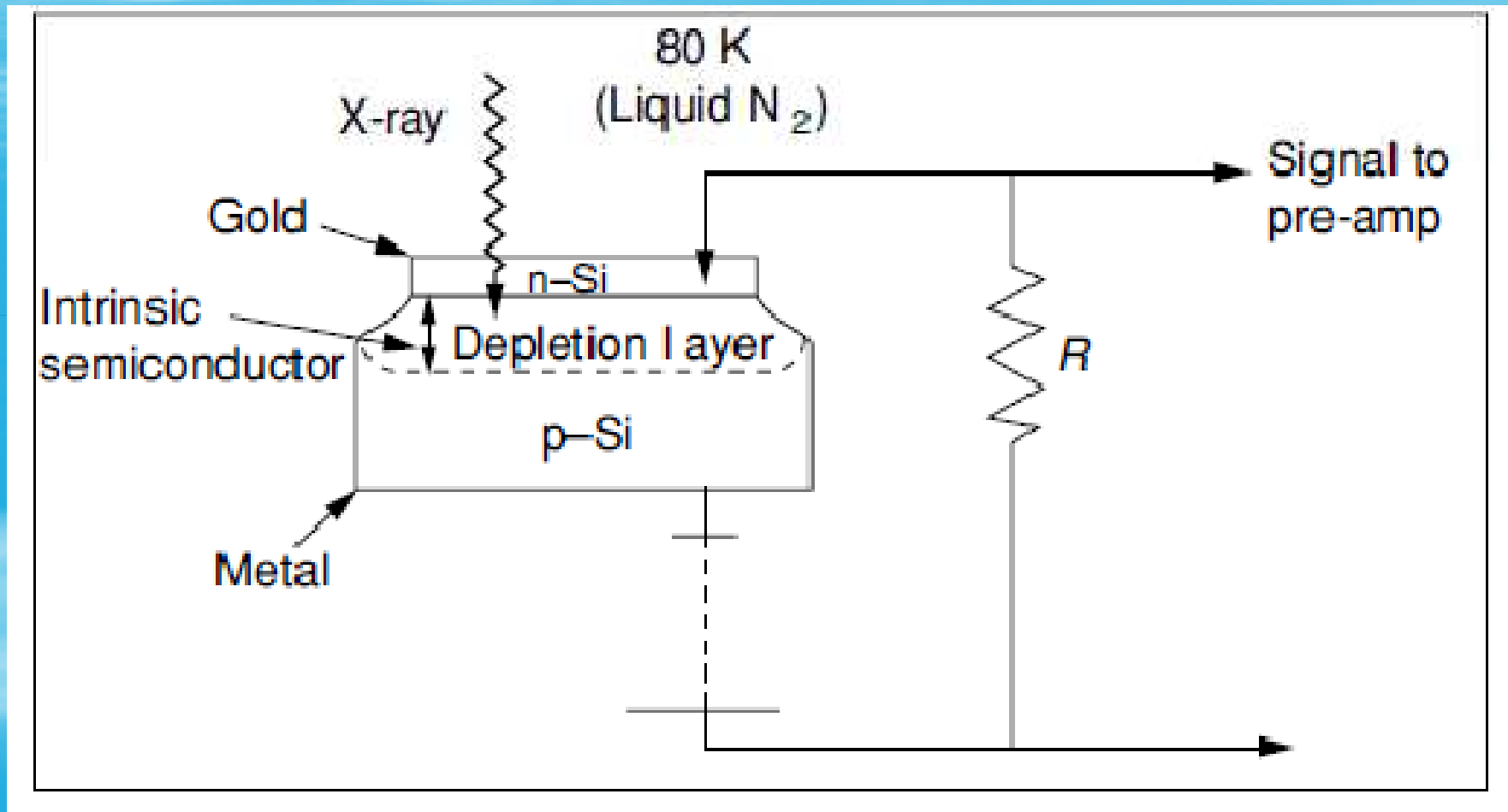
Ionization energy : energy needed to form a e⁻/hole pair $\varepsilon \sim 3 \text{ eV}$ (Ge) , 30 eV (NaI)

Narrow bandgap semiconductor detector materials

Composition	Density [g/cm ³]	Mean Z	Bandgap [eV]	energy e-hole pair [eV]
Si (300 K)	2.33	14	1.12	3.61
Ge (77 K)	5.32	32	0.74	2.98

Einstein Observatory

- New types of detectors
 - Solid State Spectrometer (CCD principle)



Solid state detectors: CCDs

They work as seen for optical astronomy (cf. lecture of Prof. Brescia) but with some differences:

- CCD work in single photon detection mode, through fast reading of pixel array (e.g. every 3.2s in Chandra);
- Cosmic rays are removed based on the 'grade' of each event, I.e. the configuration of activated pixels;
- Electrons deposited in pixels are proportional to the energy of the incident photon, allowing to measure the energy even though with low ($R \sim 10-50$) resolution;

CCD in X-ray band thus give 4-dimensional arrays containing X,Y (or Ra,Dec), energy and time.

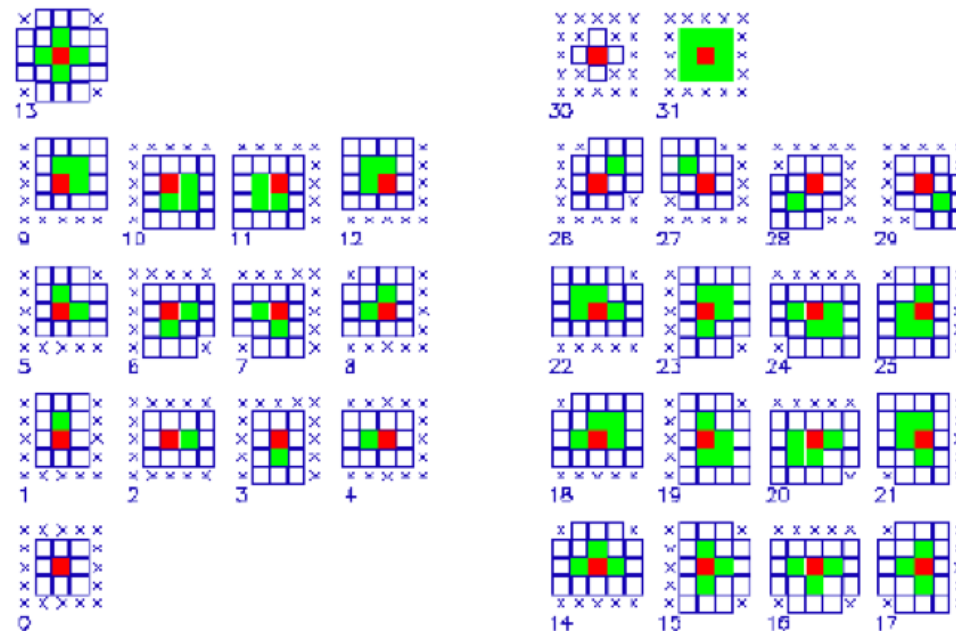
X-ray CCDs

- Energy of single X-ray sufficient to release many electrons in pixel
- Charge on a pixel when read out gives energy of photon
 - Providing only one photon detected by pixel
- Even brightest X-ray sources emit few photons per unit time compared to optical sources
- In a short exposure (~ 1 s), each CCD pixel receives 0 or maybe 1 photon
- Long exposure built up from many short exposures and readouts
- Record position, energy and time of each photon

Pattern selection

Grade selections allows to optimize the Signal to Noise ratio of an observations retaining only "significant" events: direct removal of cosmic rays and lateral photons.

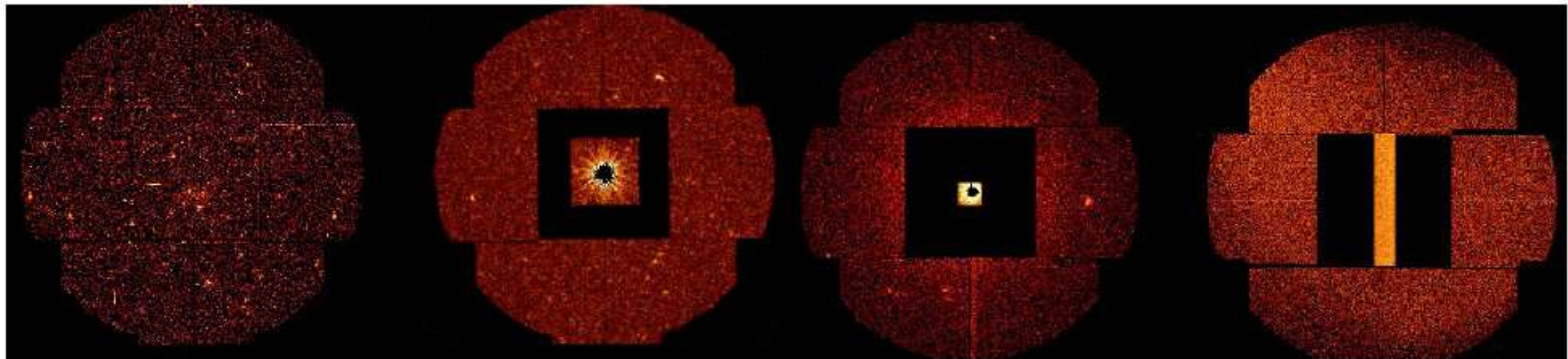
Imaging pattern table used in ground calibration and in flight



(b) EPIC-MOS Pattern

Time Resolution

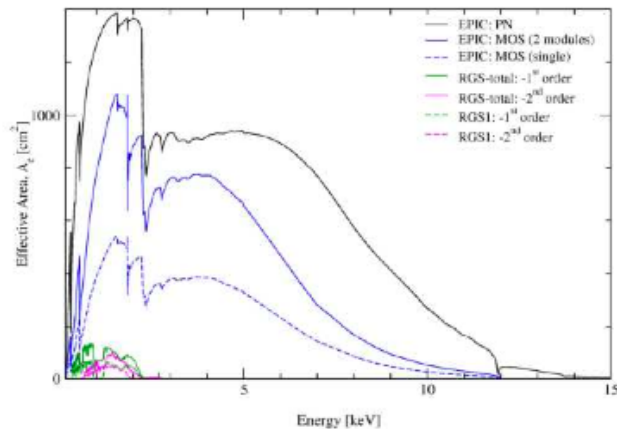
- Time of arrival of photon determined from which short exposure & readout it was detected in
- The time taken to shuffle the charges between pixels to read out CCD places limit on time resolution
- Improve by only activating small part of CCD
 - reduces readout time
 - e.g. different timing modes of EPIC MOS camera on XMM-Newton



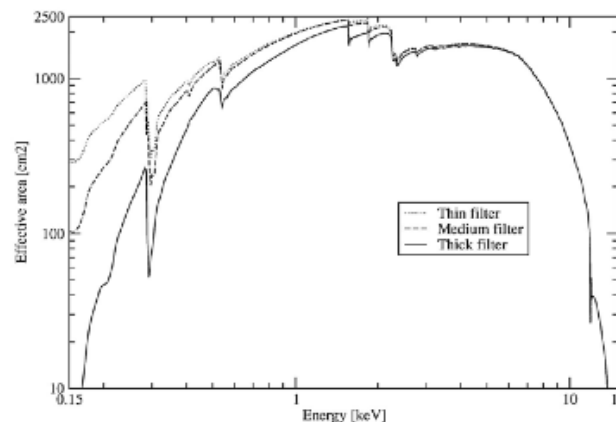
Effective area

CCD rely on photoelectric absorption of incident X-ray photons. Thus the probability of detecting a photon is approximately given by:

$\sigma \propto e^{-(\text{det})} \cdot (1 - e^{-\tau(\text{mirr})})$. The resulting efficiency, expressed in terms of effective area, shows the edges typical of photoelectric absorption.



(a) Effective Area



(b) Logarithmic Effective Area

Figure 4.6: (a) The net effective area of all XMM-Newton X-ray telescopes, EPIC and RGS (linear scale) and (b) Combined effective area of all telescopes assuming that the EPIC cameras operate with the same filters, either thin, medium or thick. (logarithmic scale by XMM-Newton User's Handbook).

In designing a telescope you often want to place absorption edges of the detector within your energy range to increase the detection efficiency, while avoiding those of the mirrors. This is done through a proper choice of the building materials.

Scintillators and Photomultipliers

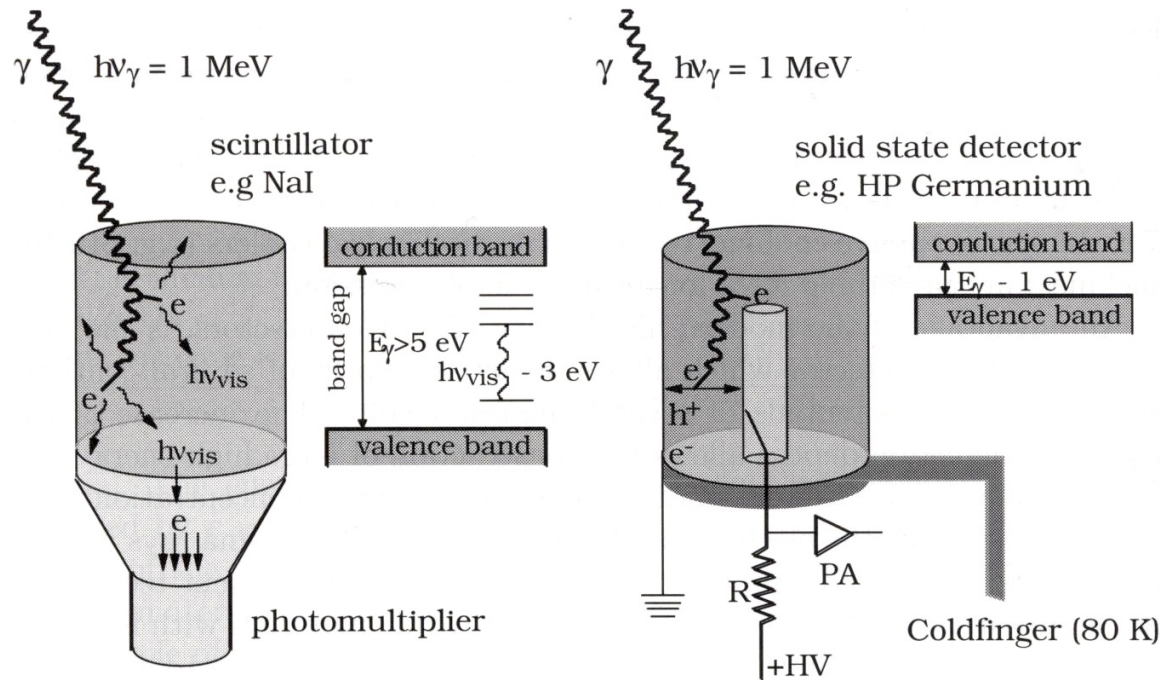


Fig. 31. Scintillator vs. semiconductor detector: comparison of 1 MeV photons interacting in either one of the two detector types

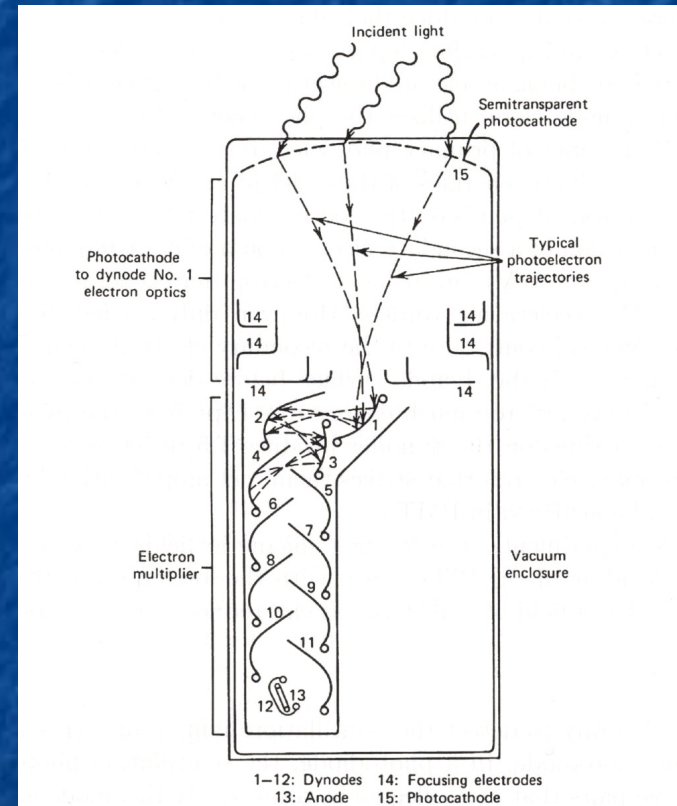
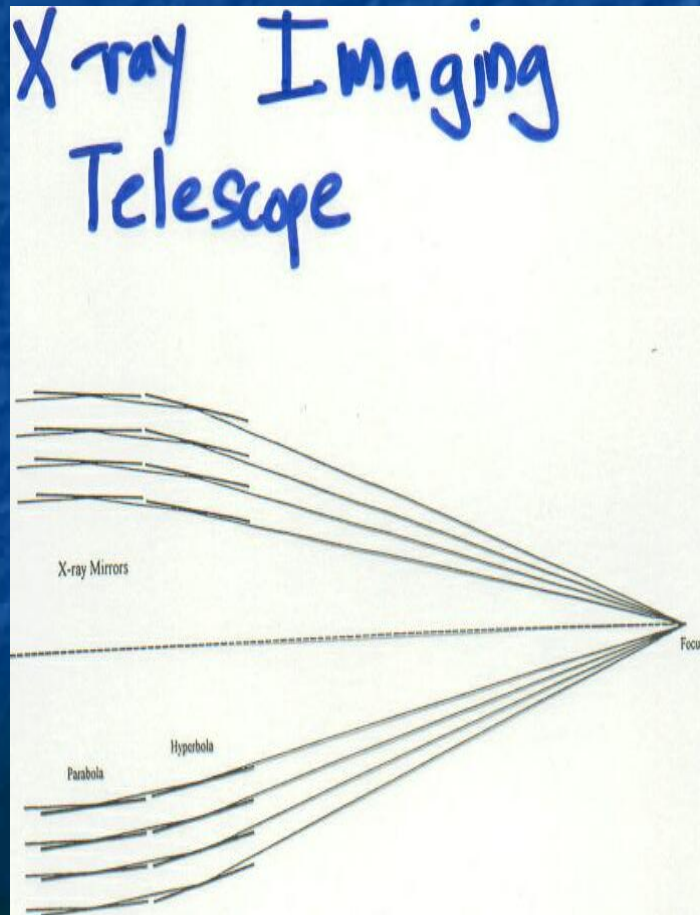


Fig. 30. The elements of a photomultiplier tube [102]

Imaging techniques

High energy photons cannot be focused as their low energy counterparts due to their large penetrating power. Different approaches are thus needed: Grazing-incidence mirrors, Modulators, Compton telescopes



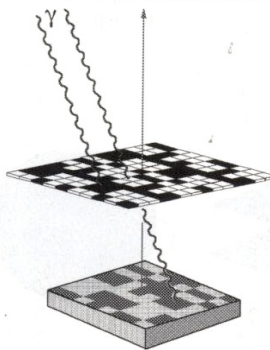
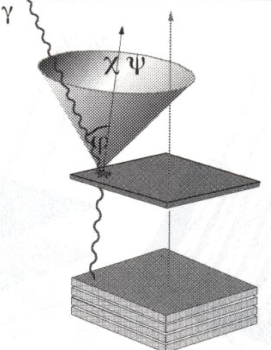
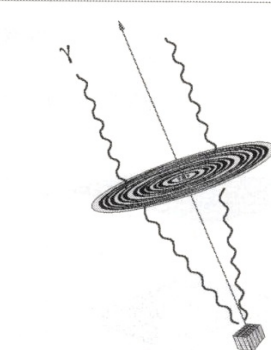
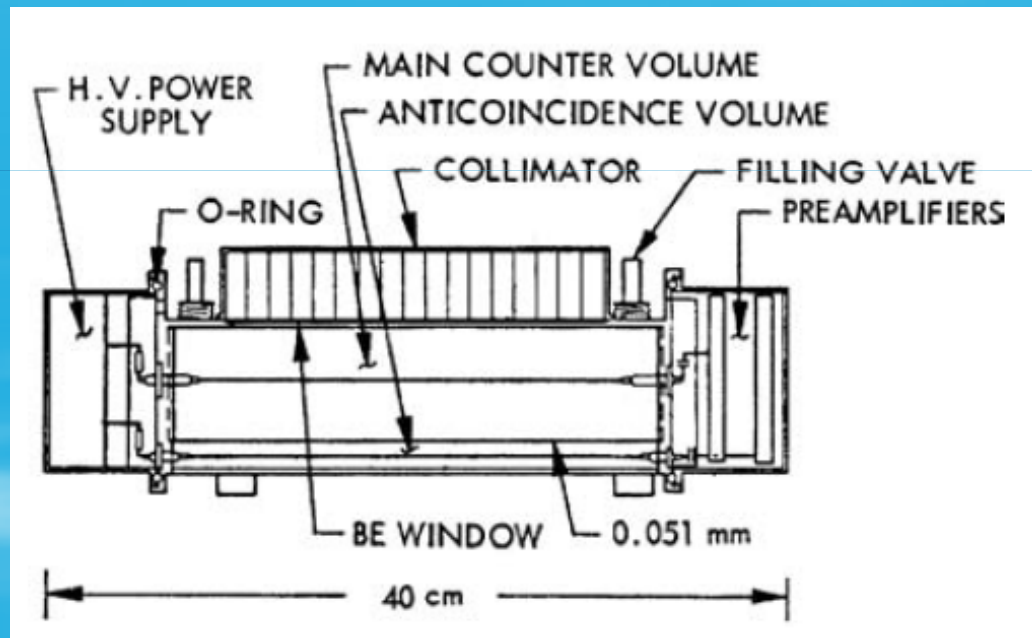
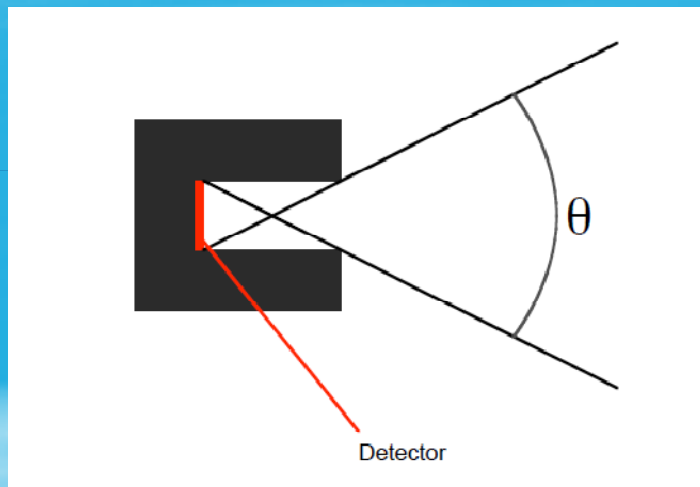
	geometric optics absorption	quantum optics incoherent scattering	wave optics coherent scattering
detector aperture			
aperture	- collimator - "anticollimator" - rotating mod. collimator - coded mask	- scintillator - semiconductor - tracking detector	- total external reflection - crystal diffraction - Fresnel zone plate
detector		- scintillator - semiconductor - tracking detector	

Fig. 34. The three instrumental principles in nuclear gamma-ray astronomy

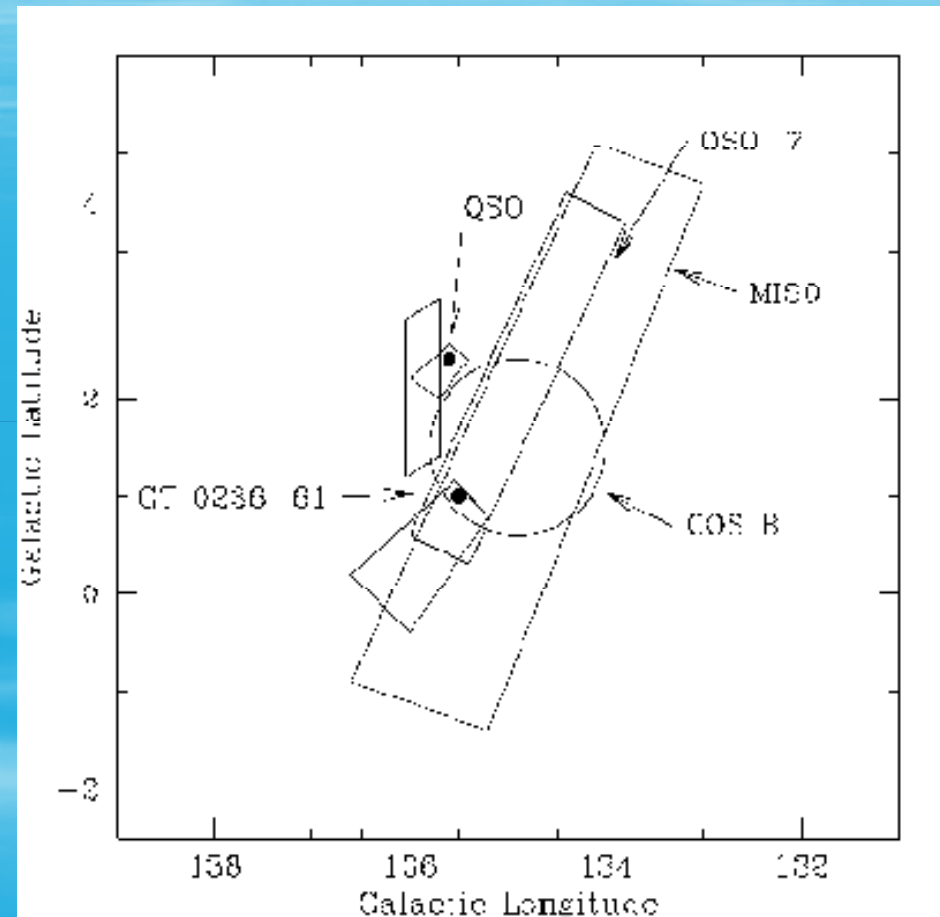
X-ray Source Location

- Crude collimation by means of mechanical obstructions (slats or “egg crate” collimators)



X-ray Source Location

- Non-imaging proportional counter only gave crude source positions
- Source confusion issues



Modulators

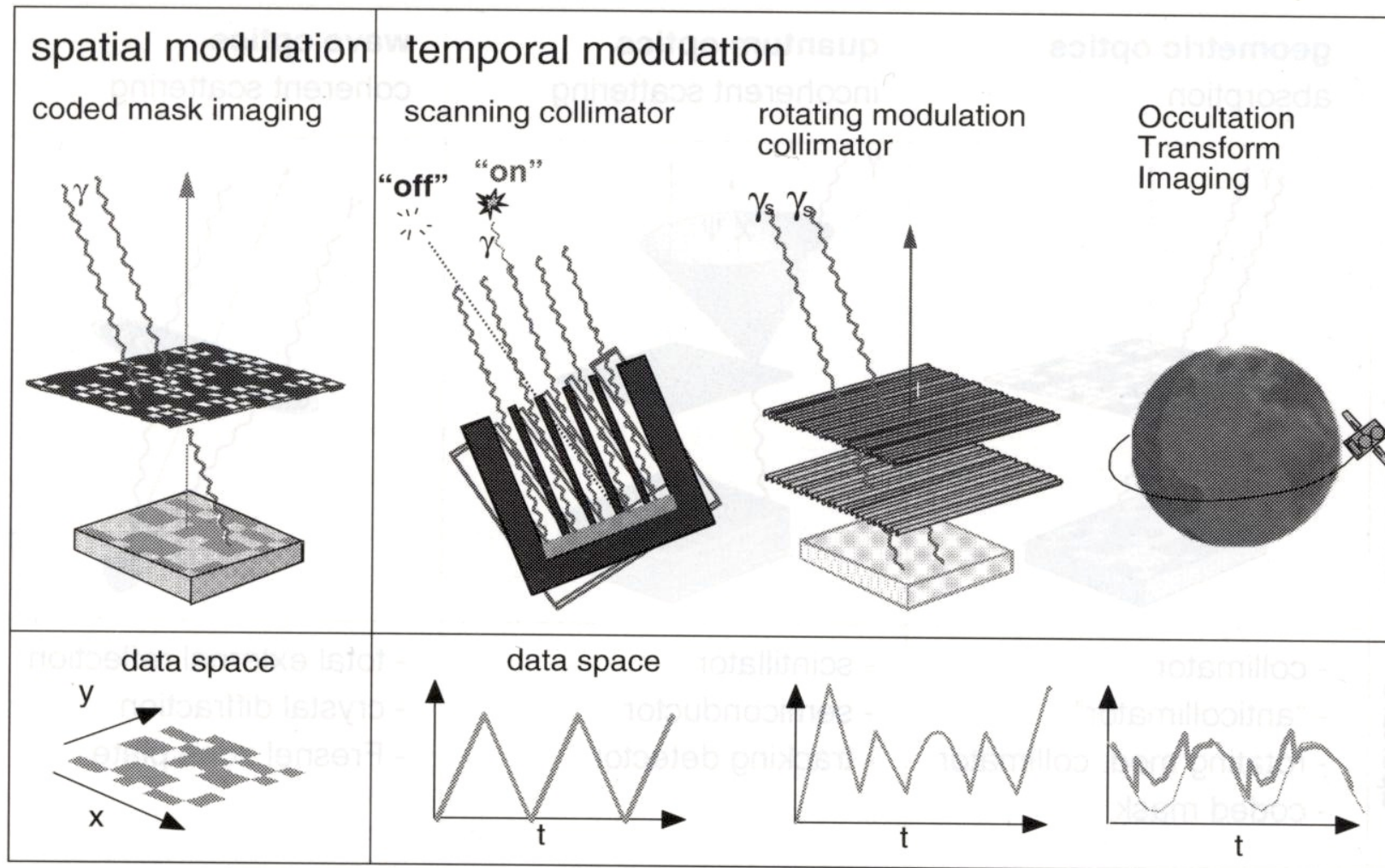
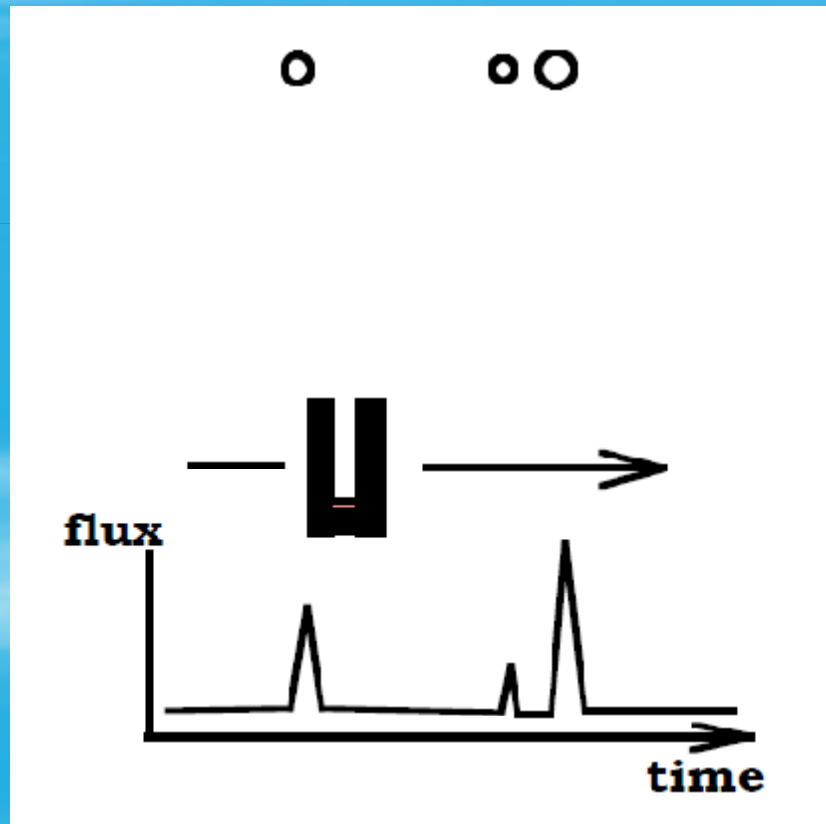


Fig. 35. The categories of modulating aperture systems – spatial and temporal modulation

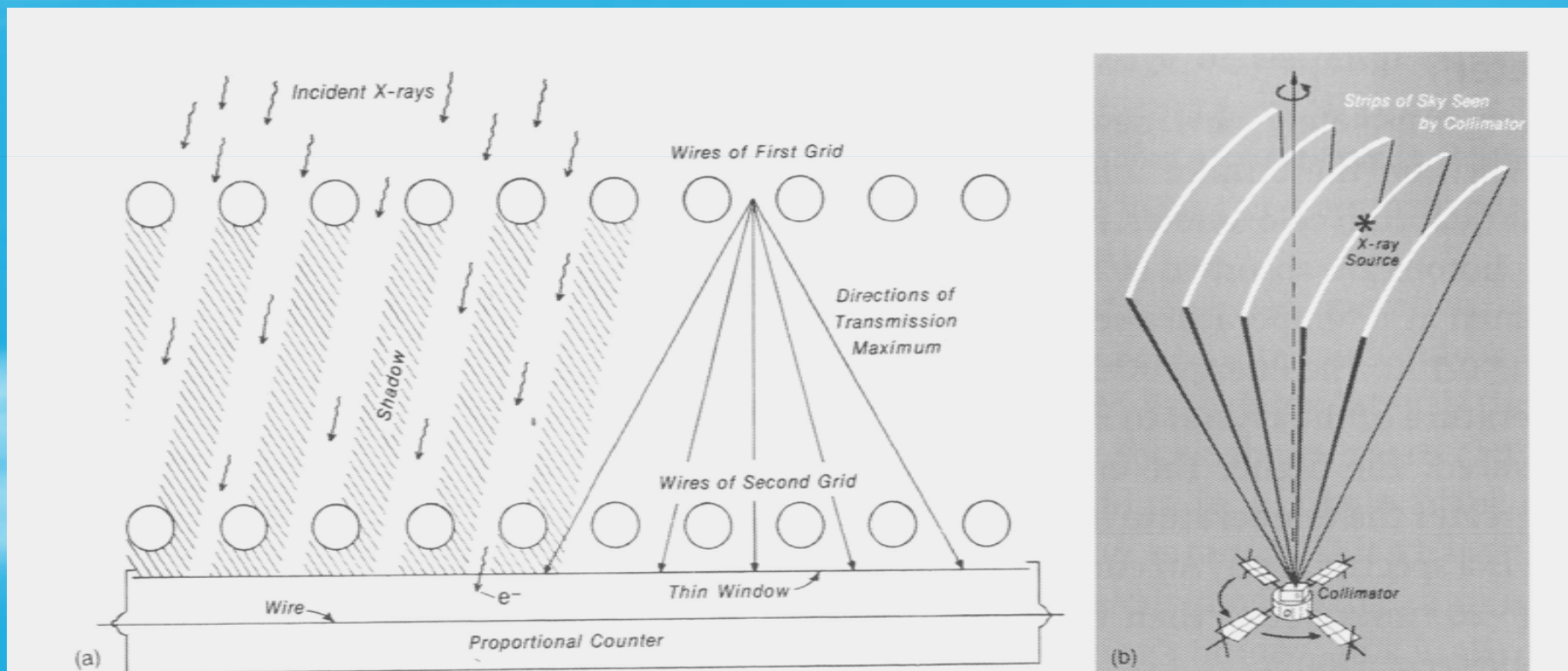
X-ray Source Location

- Improvements from using *modulation* collimators
- Rotate the satellite and periodically occult the X-ray source



X-ray Source Location

- *Scanning Modulation Collimator*
- *Rotating Modulation Collimator*



The First X-ray Astronomy Satellites

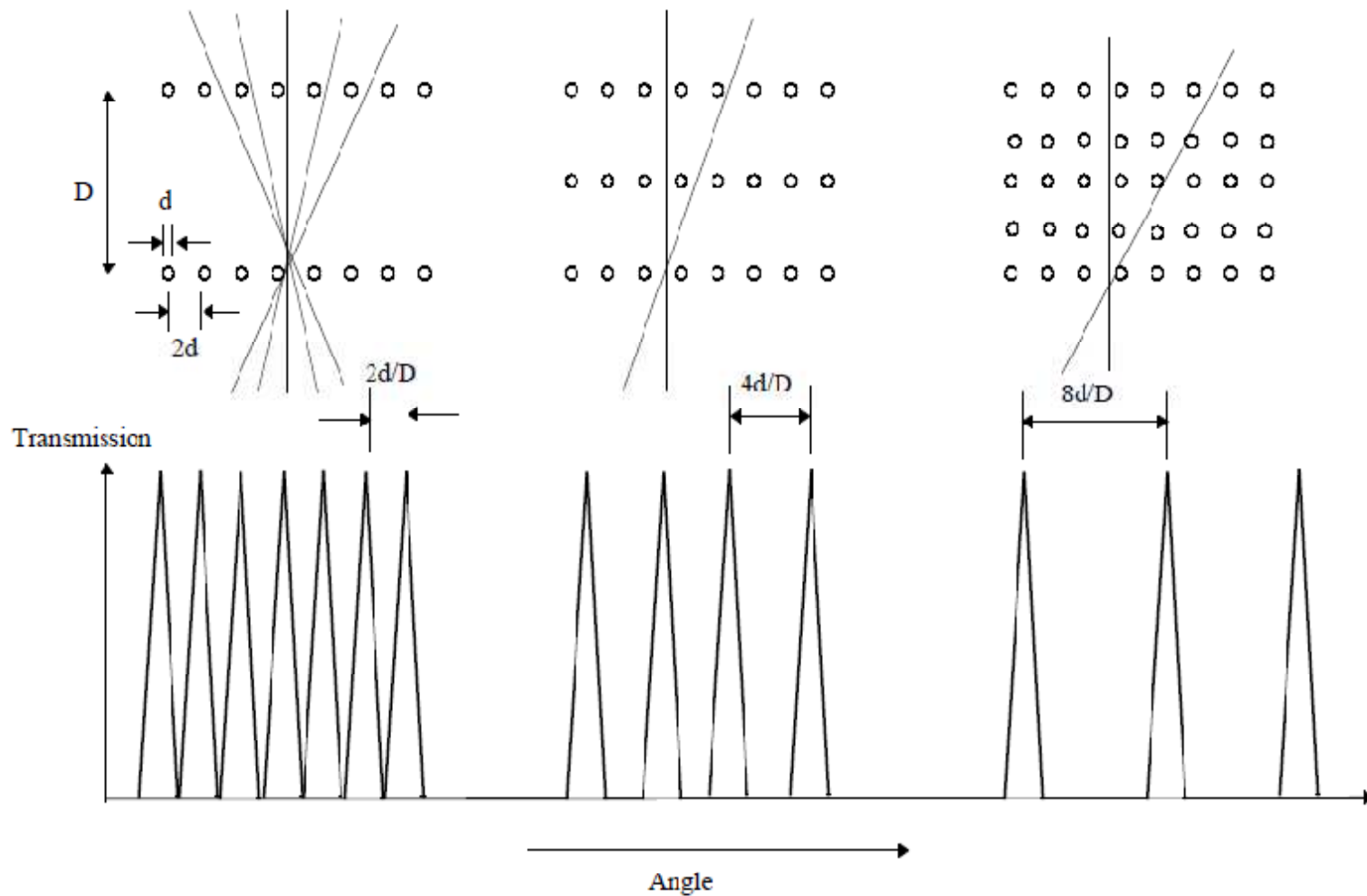
- A number of smaller X-ray satellite missions (Ariel, SAS, OAO)
- All using PCs, some with modulation collimators
- Culminating eventually in the NASA *High Energy Astronomy Observatory* missions:
 - HEAO-1 (scanning collimation; first hard X-ray all-sky survey)
 - HEAO-2 (renamed *Einstein Observatory*; first imaging X-ray telescope)
 - HEAO-3 (cosmic rays)

The First X-ray Astronomy Satellites

- A number of smaller X-ray satellite missions (Ariel, SAS, OAO)
- All using PCs, some with modulation collimators
- Culminating eventually in the NASA *High Energy Astronomy Observatory* missions:
 - HEAO-1 (scanning collimation; first hard X-ray all-sky survey)
 - HEAO-2 (renamed *Einstein Observatory*; first imaging X-ray telescope)
 - HEAO-3 (cosmic rays)

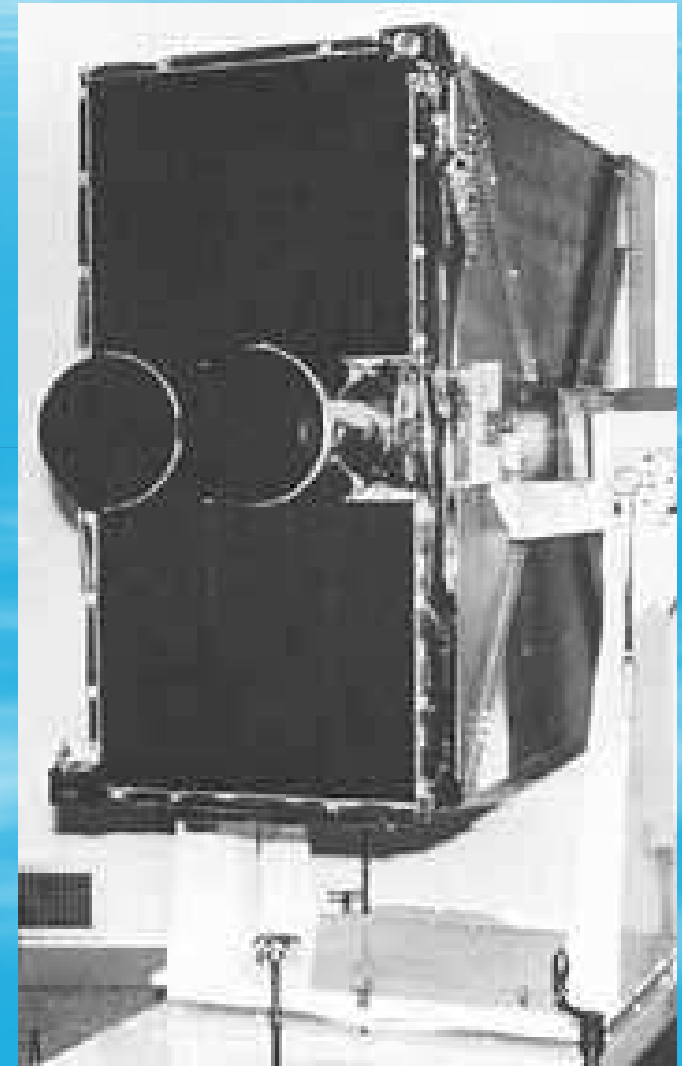
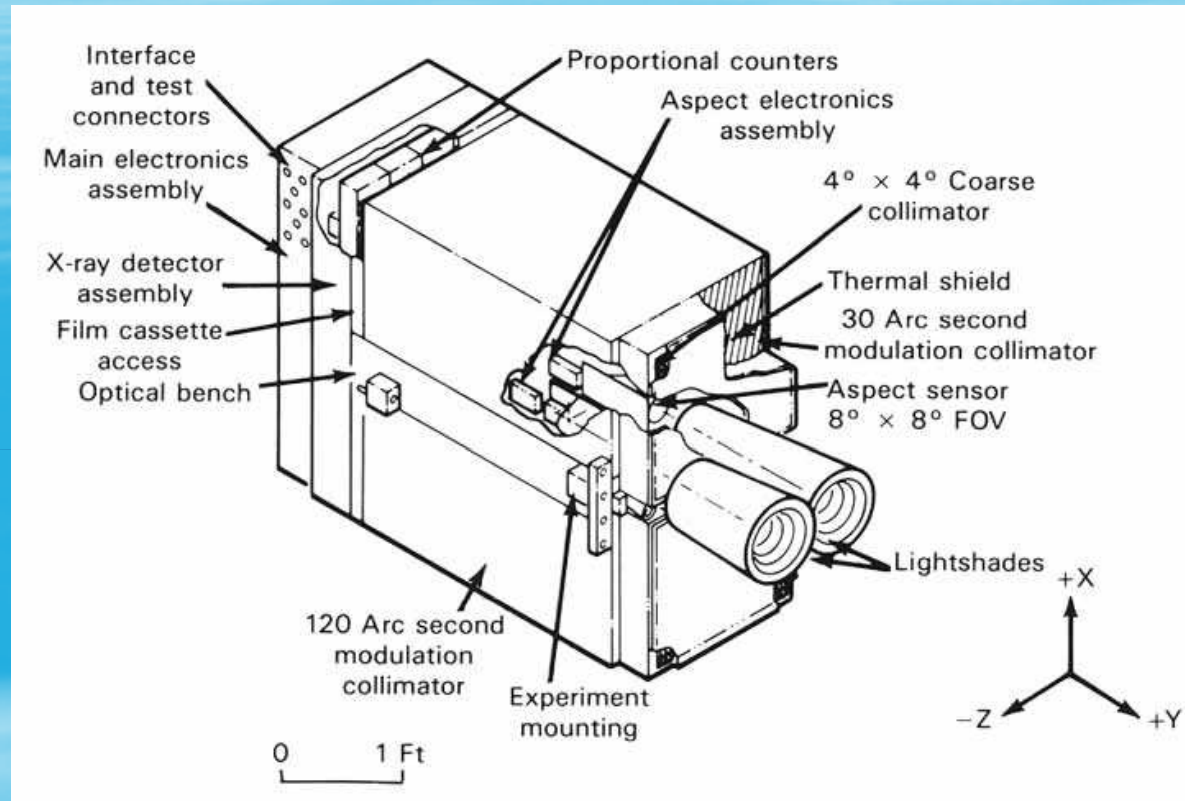
HEAO-1

- *Scanning Modulation Collimator (A3)*



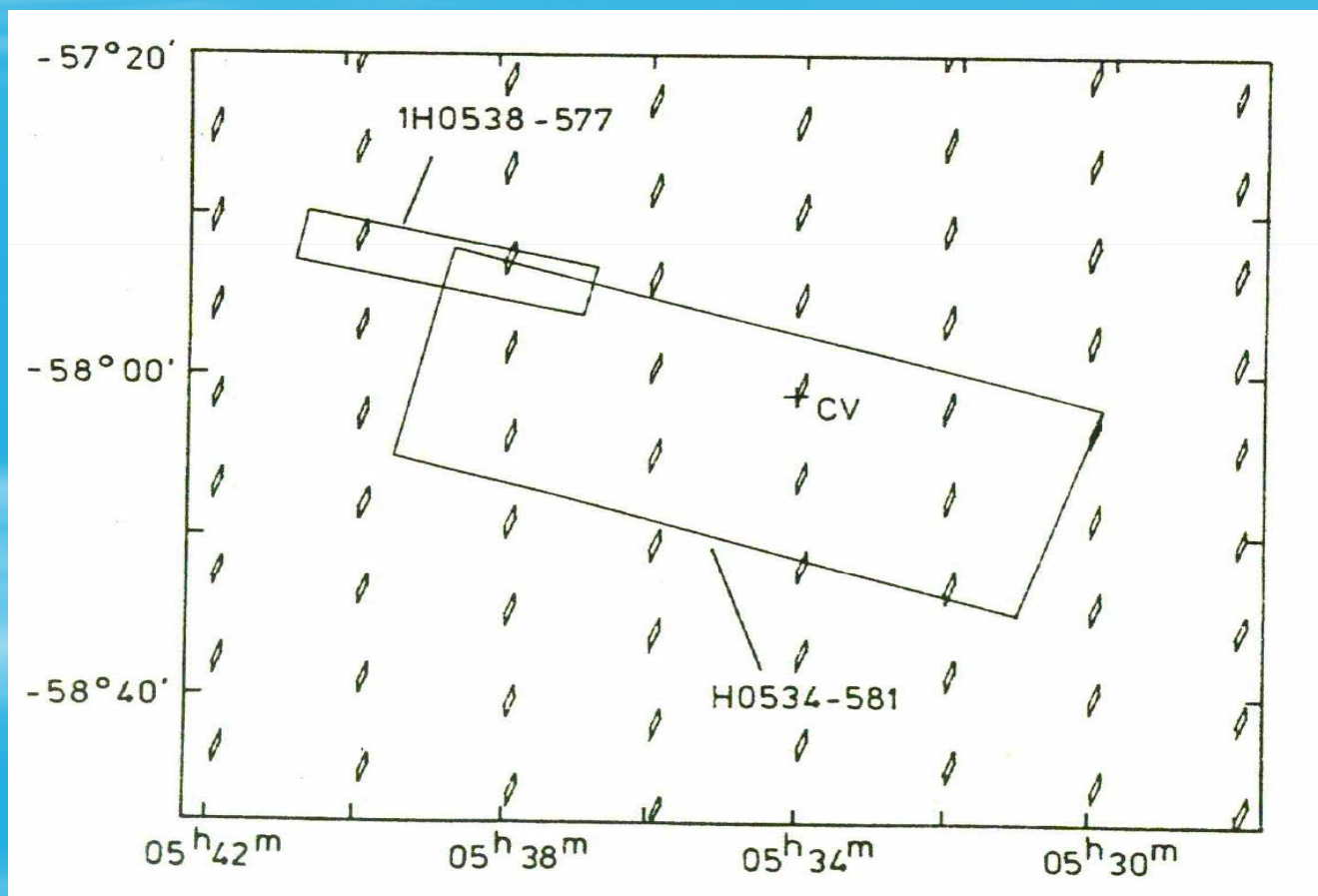
HEAO-1

■ *Scanning Modulation Collimator (A3)*



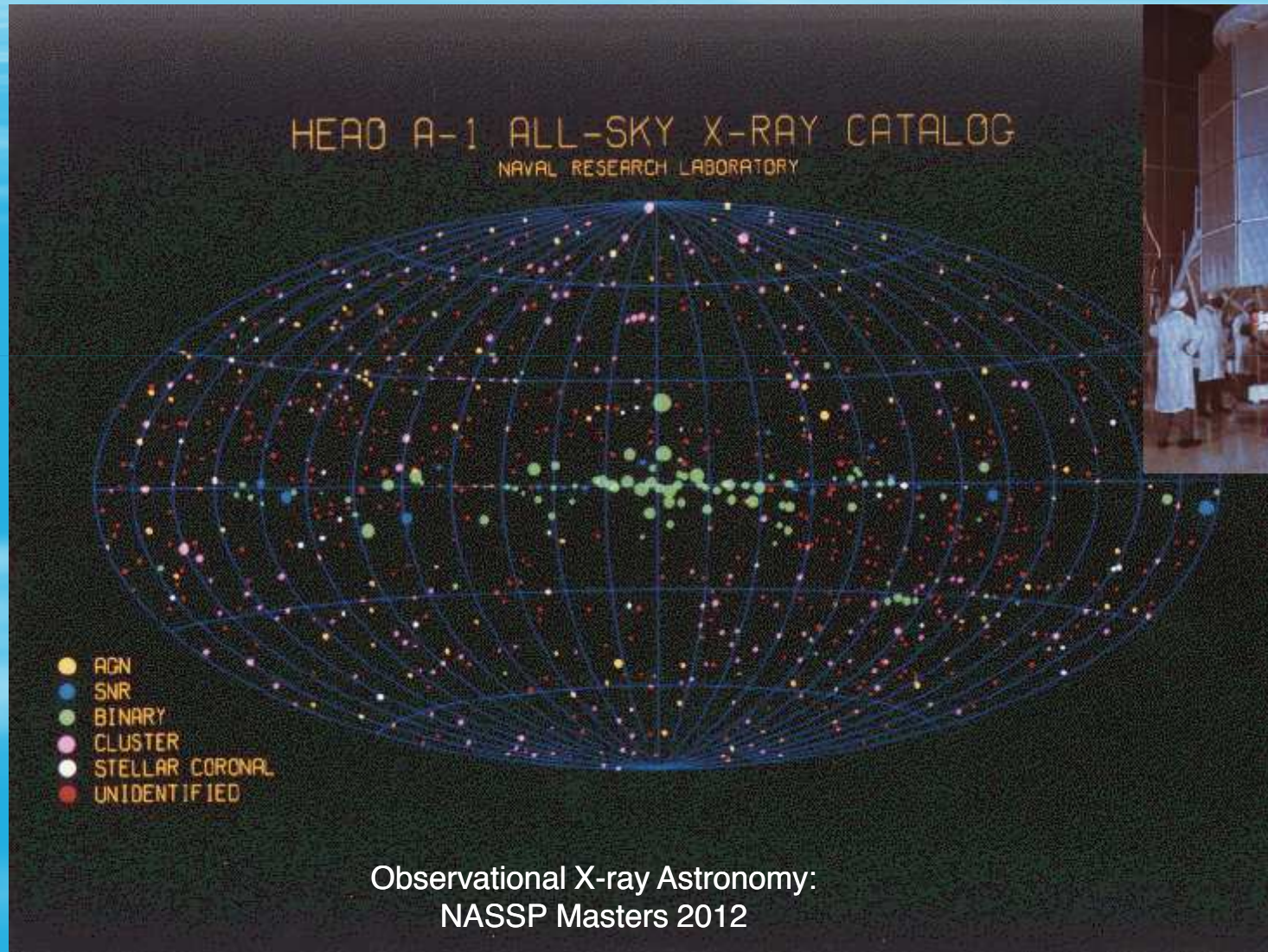
HEAO-1

- *Produced a regular grid of possible non-unique error boxes*
- *~1 x 2 arcmin over 4 x 4 degrees*
- *Any one of them could contain the source*



HEAO-1

- *Total of ~1000 sources detected*

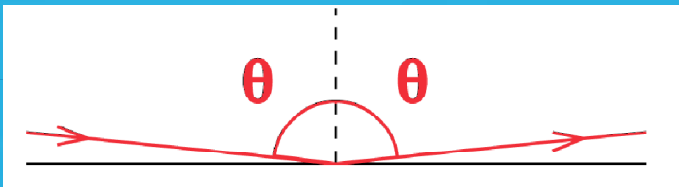


26 May 2012

32

First X-ray Telescope: *Einstein Observatory (HEAO-2)*

- First use of mirrors to focus X-ray
- Grazing incidence optics

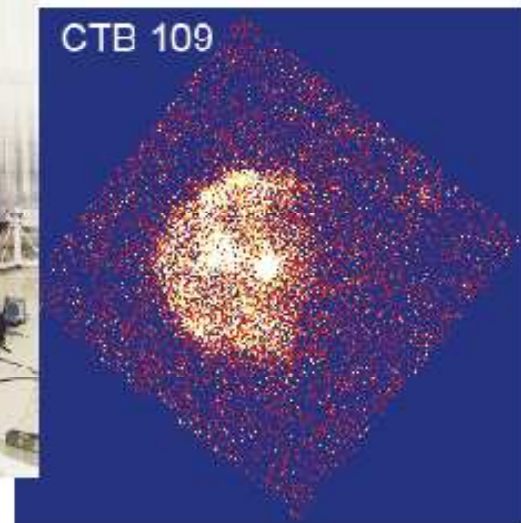


- Pointed observations rather than all-sky survey
- Softer energies

first imaging at 2-20 keV
several instruments (5-200 cm²)

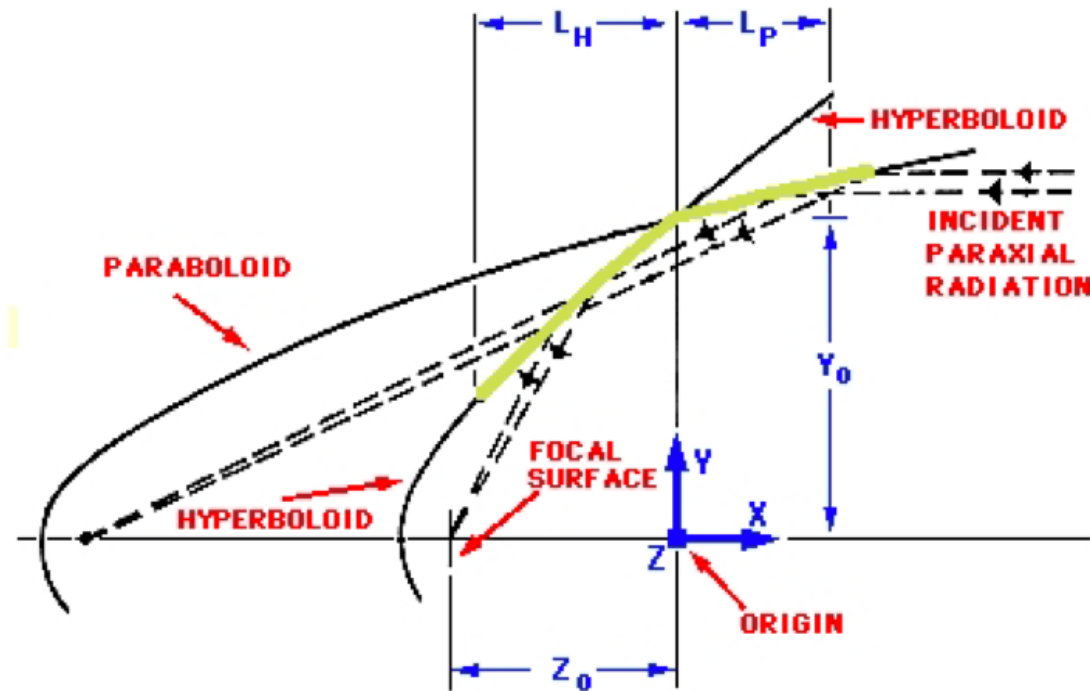


1000s of X-ray sources, discovery of jets (M87), spectroscopy



Incidence grating mirrors

- Using the Snell law, we can use high incidence angles to reflect X-ray photons: $\sin(\theta_1)/\sin(\theta_2) = n_2/n_1$ $\theta_{\text{crit}} = \arcsin(n_2/n_1)$

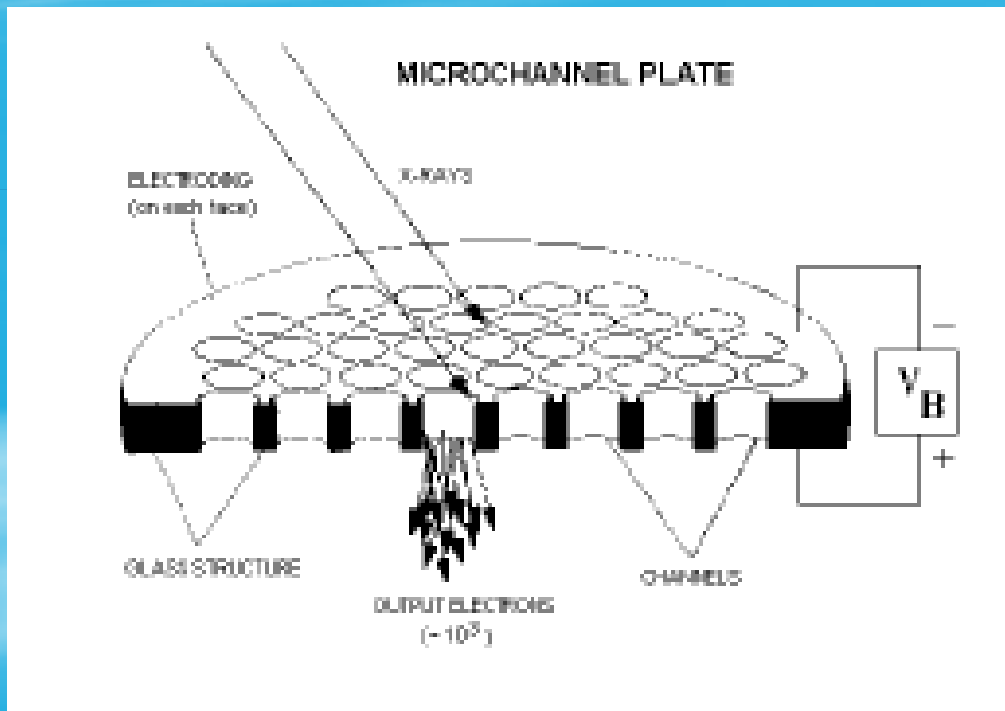


(b) XMM-Newton Scheme

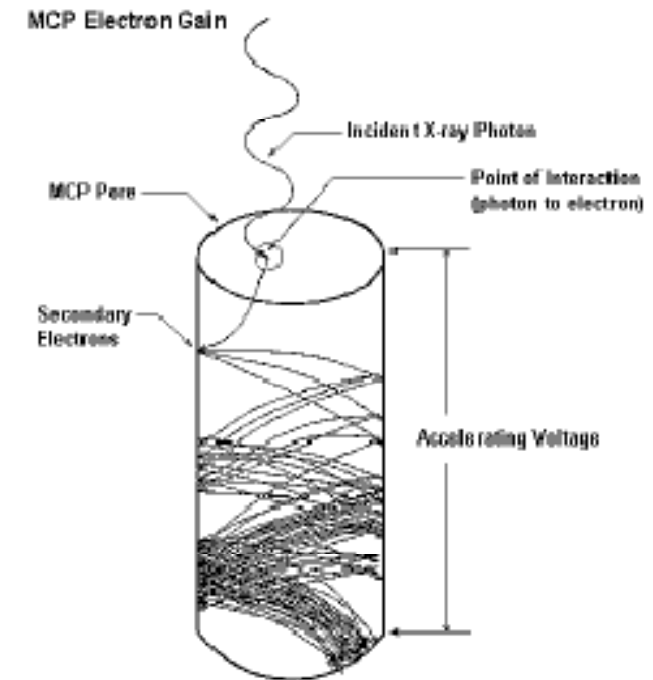
Figure 3.3: Panel(a): 3D View of the X-ray ba e (from de Chambure et al.1999).
Panel(b): Mirrors scheme of XMM-Newton.

Einstein Observatory

- New types of detectors
 - Micro-Channel Plate
 - Solid State Spectrometer

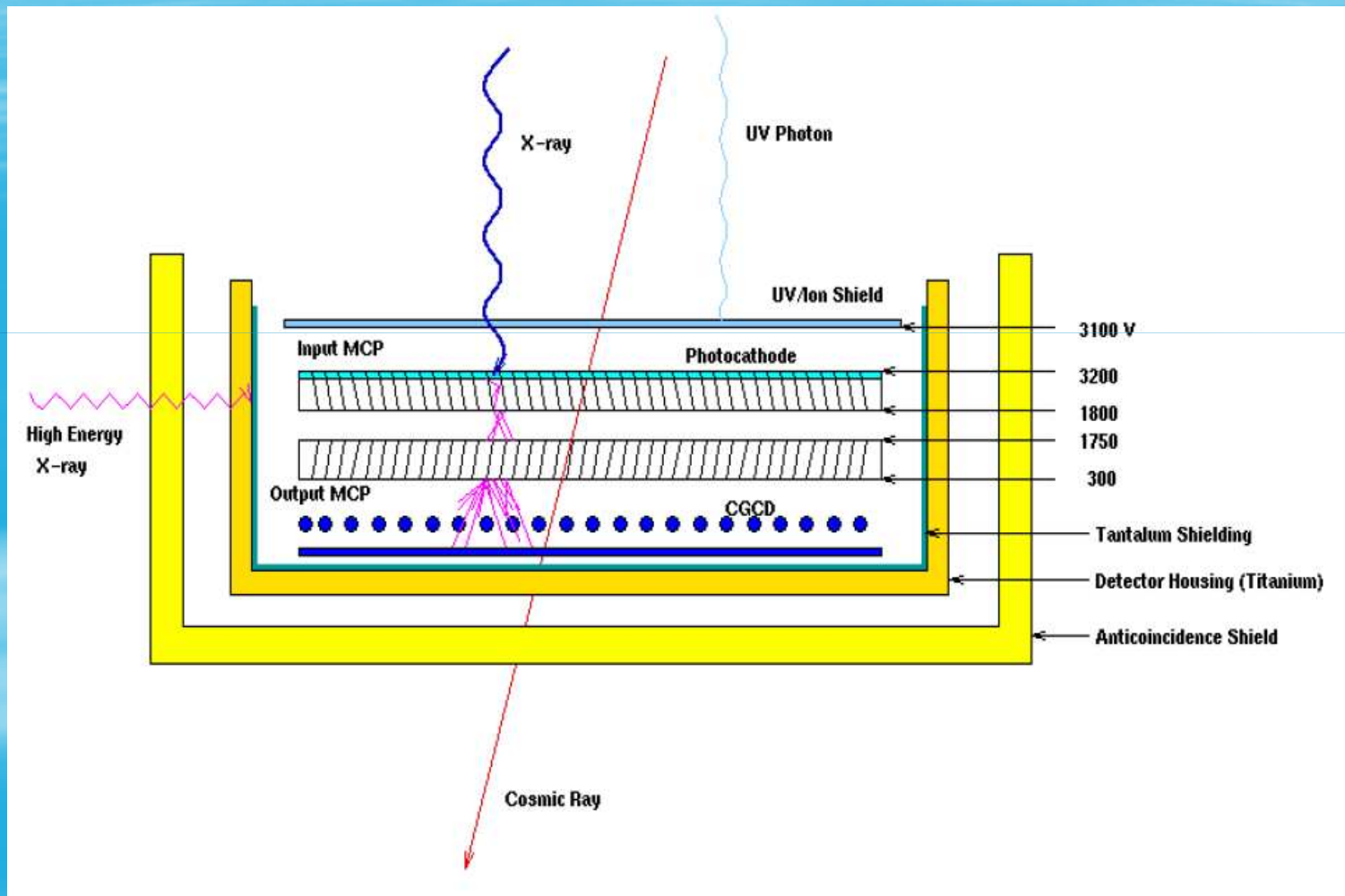


Charge Multiplication: MCP



Einstein Observatory

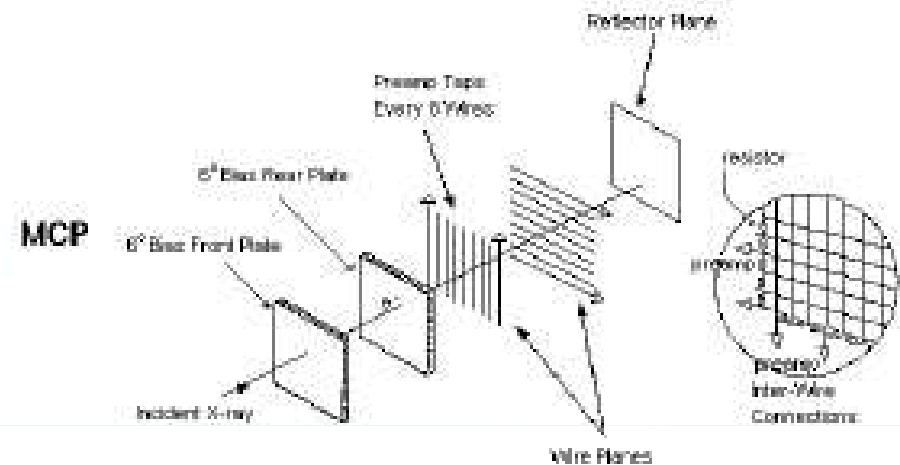
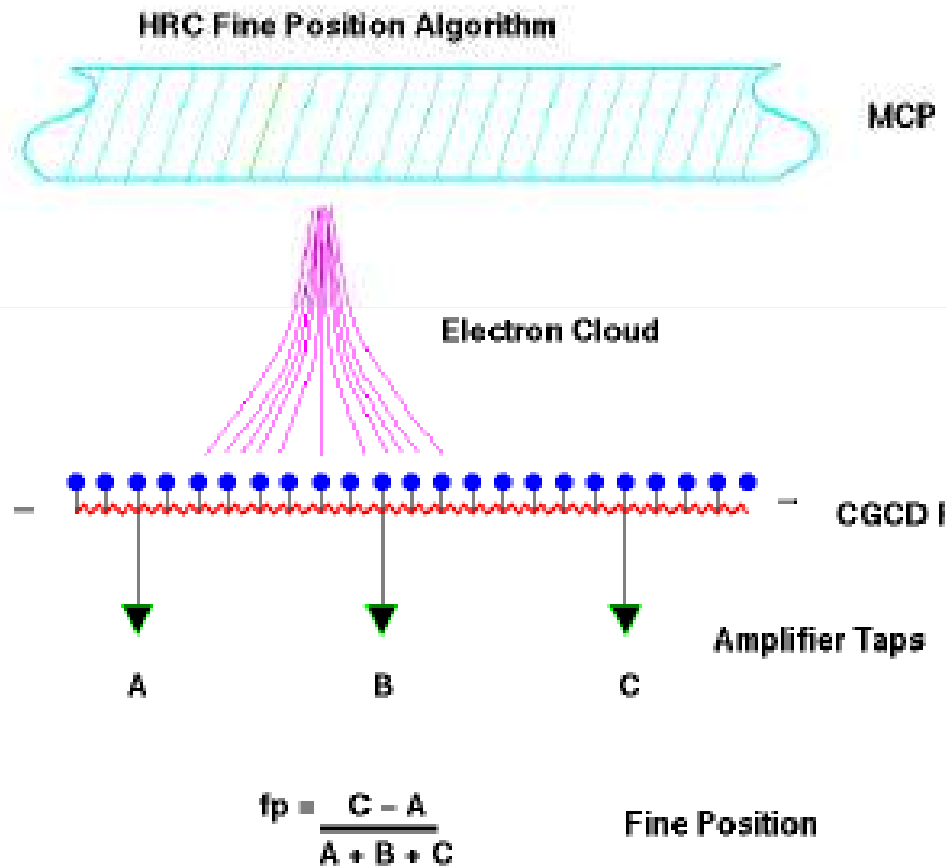
- New types of detectors
 - Micro-Channel Plate



Einstein Observatory

- Micro-Channel Plates (MCP)

Position Readout: MCP



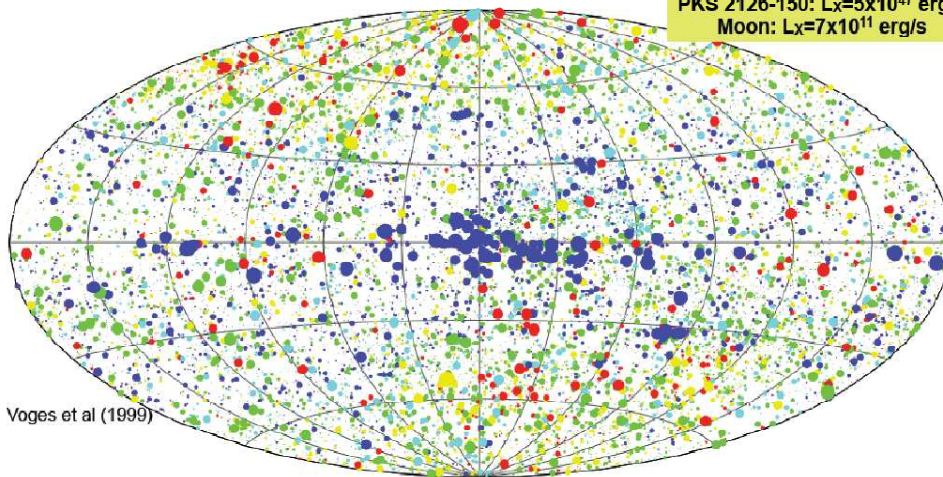
Position algorithm necessarily leaves “gaps”

Has non-linearities

ROSAT: The next imaging X-ray satellite (1990)

- German-UK-US collaboration
- Soft X-ray survey (0.2 – 2.5KeV)
- Greatly improved sensitivity
- ~80,000 sources

ROSAT all-sky survey (0.1-2.4 keV)



Voges et al (1999)

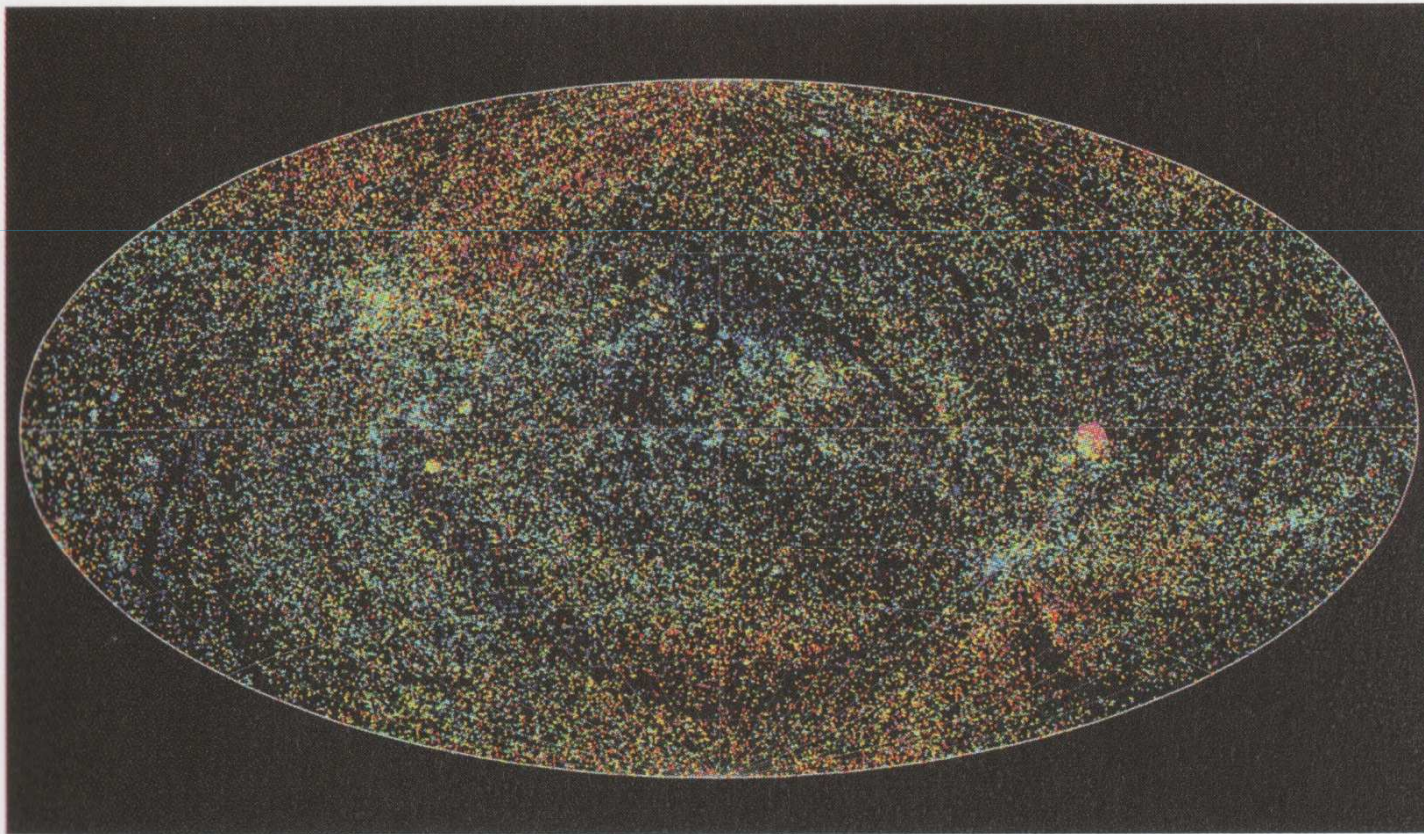
Fig. 5. Aitoff projection of the distribution of all RBSC sources obtained in the ROSAT All-Sky Survey observations until August 13, 1991 in galactic coordinates. The size of the symbols scales with the logarithm of the count-rate and the colours represent 5 intervals of the hardness ratio HR1: red ($-1 \leq \text{HR1} < -0.6$); yellow ($-0.6 \leq \text{HR1} < -0.2$); green ($-0.2 \leq \text{HR1} < 0.2$); blue ($0.2 \leq \text{HR1} < 0.6$) and violet ($0.6 \leq \text{HR1} \leq 1.0$).

0.2-10 keV: 36 orders of
magnitude in luminosity
PKS 2126-150: $L_x = 5 \times 10^{47}$ erg/s
Moon: $L_x = 7 \times 10^{11}$ erg/s



ROSAT

- Greatly improved sensitivity
- Also did first Extreme UV (EUV) survey
- Lots of source IDs and optical follow-up done at SAAO



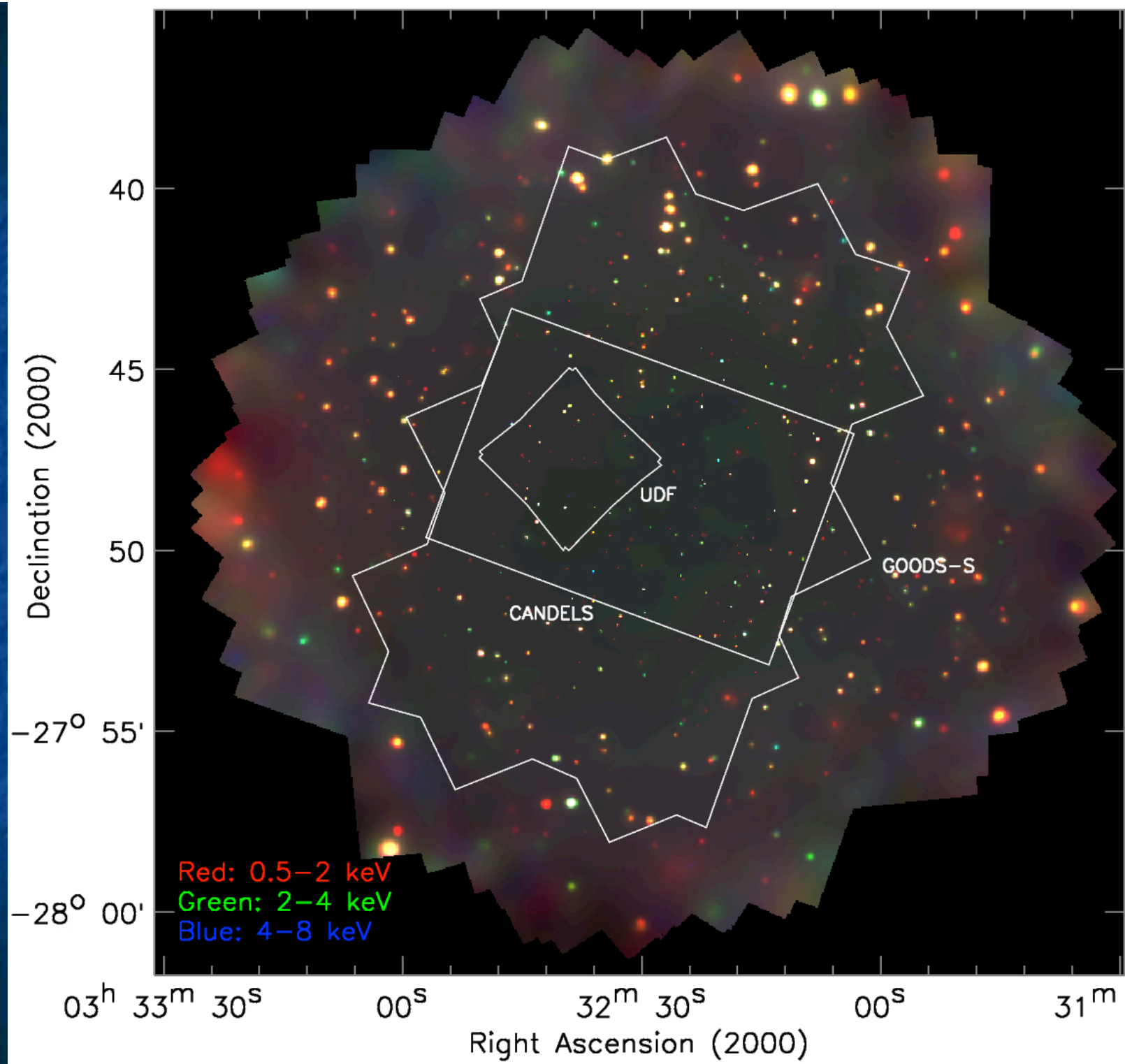
New Millennium

- 1999 saw launch of Chandra and XMM-Newton
 - NASA's Chandra high spatial resolution
 - ESA's XMM high sensitivity
- 2005: Japan's Suzaku mission launched
 - High resolution X-ray spectrometer failed after launch, imager still performing useful science



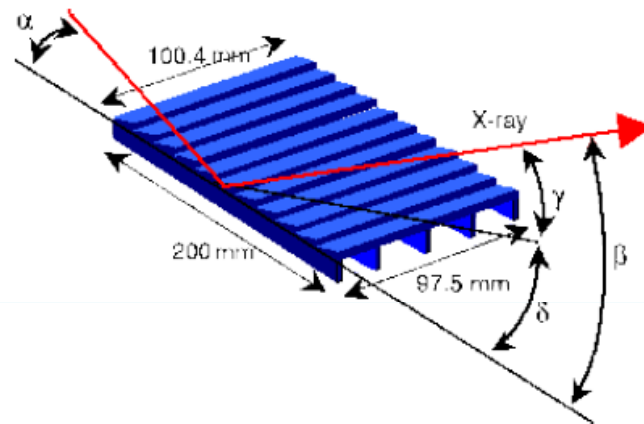
Chandra



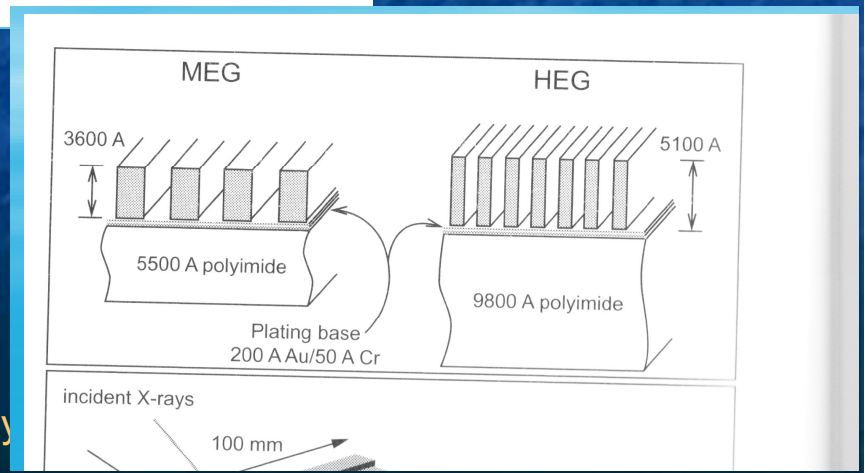


X-ray Gratings

- While CCDs provide good energy resolution, high energy resolution requires grating spectrometers
- Transmission or reflection gratings diffract X-rays

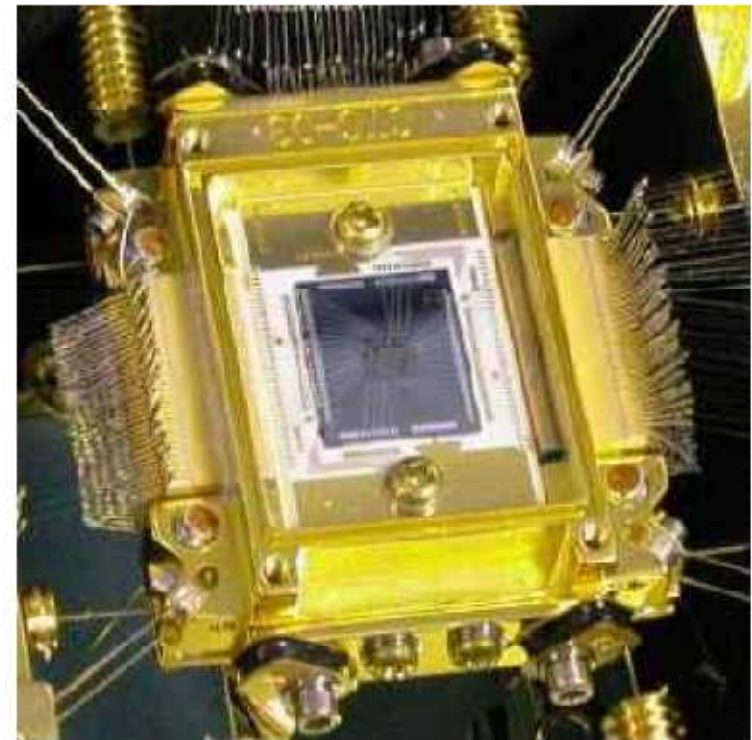


- Reflection gratings on XMM have ~ 650 lines/mm



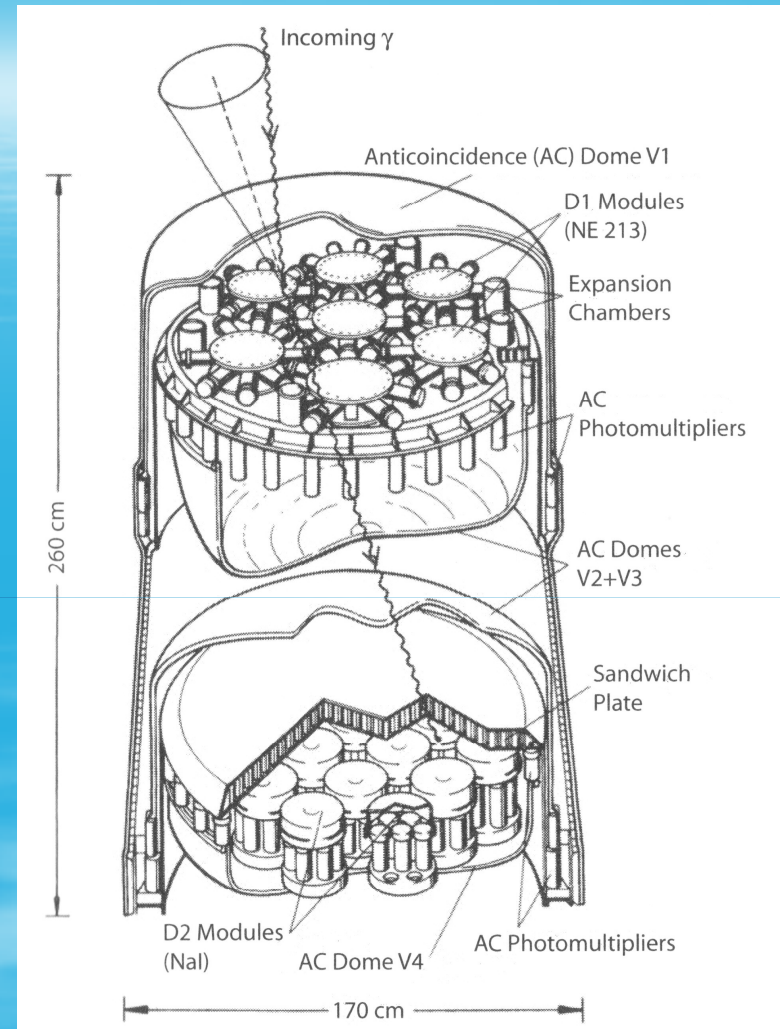
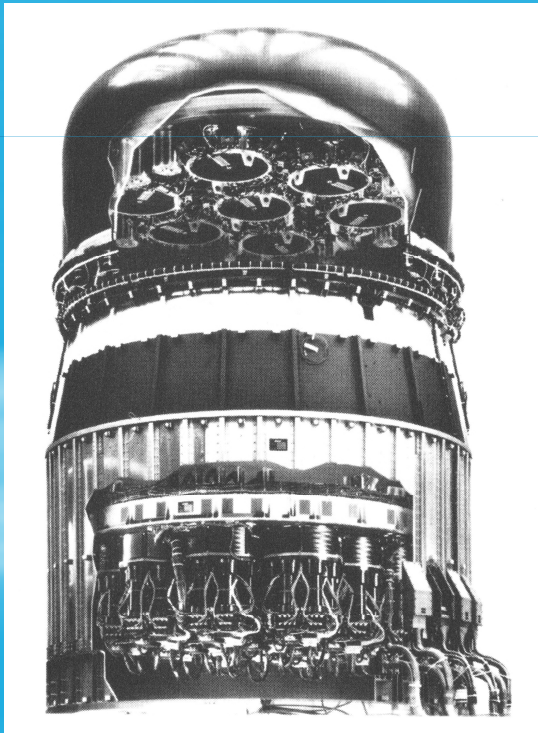
X-ray Calorimeter

- First space-based calorimeter on Suzaku failed, but a calorimeter will be flown in the (near?!) future
- Detects the change in temperature due to the arrival of a single X-ray photon
- Uses Transition-Edge Sensors
 - resistance changes rapidly near critical temperature at which pixel becomes superconductor
- Excellent energy resolution
 - few eV or better



Higher Energy Missions

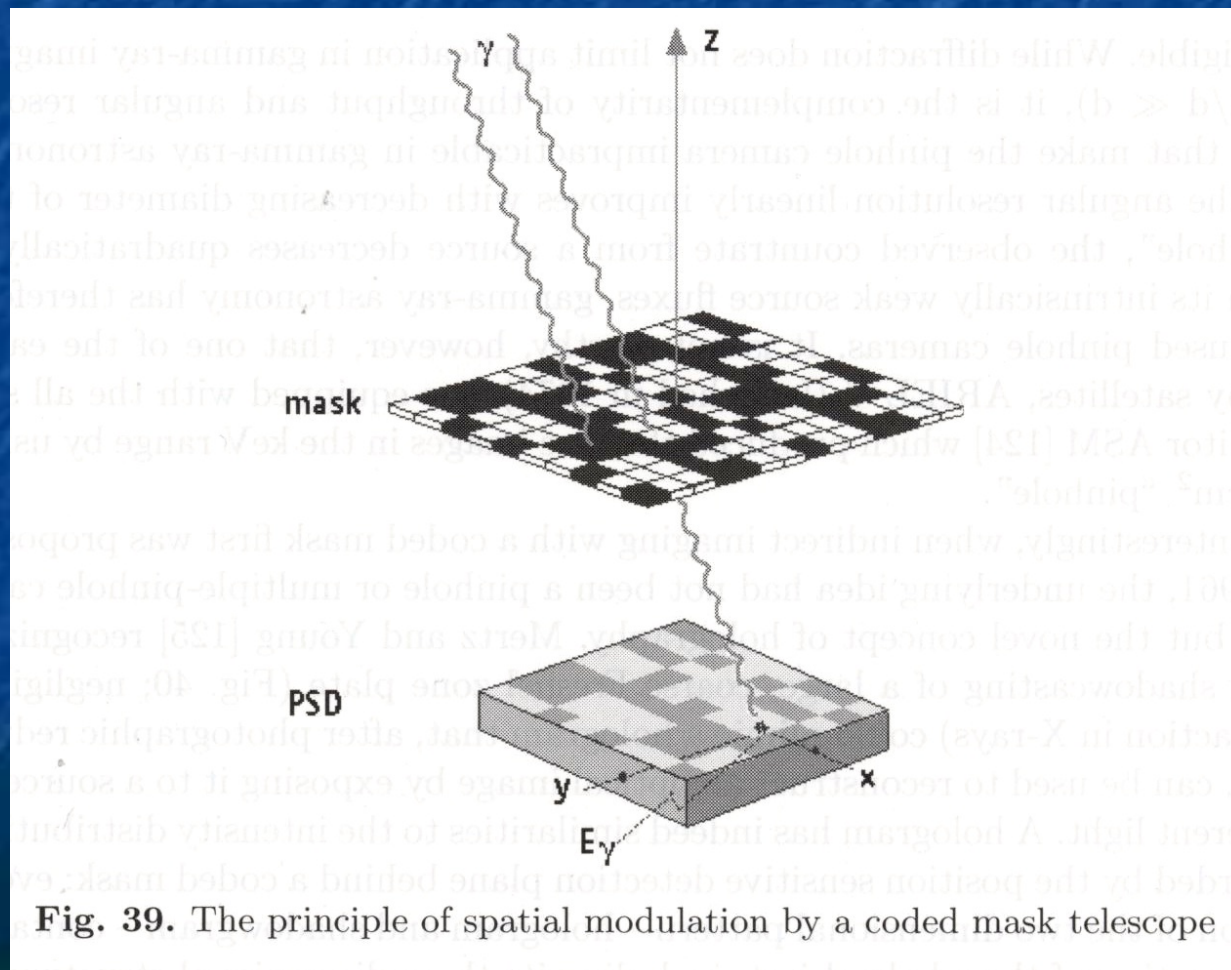
- Gamma Ray satellites
- More energetic photons
- Can't "focus"
- Clever techniques to derive source positions (e.g. partial & nuclear physics)
- Coded aperture masks (INTEGRAL)



The *Compton Gamma Ray Observatory (CGRO)* was the first big NASA mission

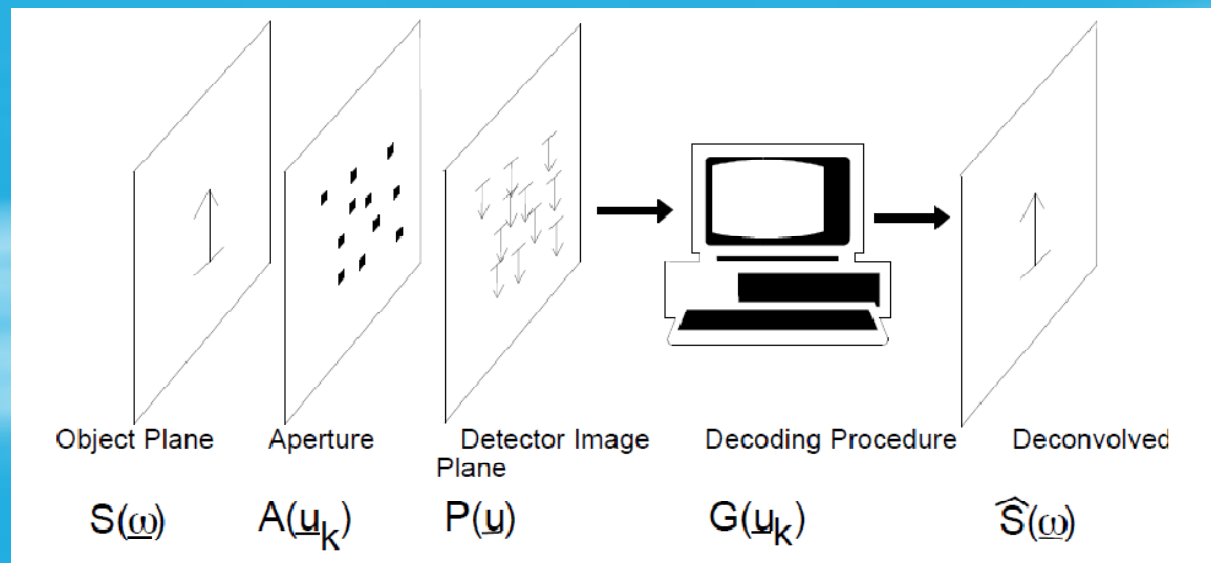
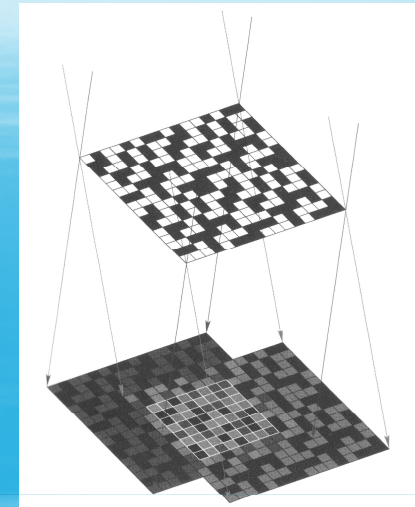
Coded masks

- Coded masks telescopes are based on the idea of imaging through a 'pinhole' but with larger collecting area to increase the efficiency.



Coded Aperture Masks

- Block out photons
- Look at shadow patterns
- Remove source confusion
- Locate to $\sim$ degrees
- Deconvolve multiple source positions



Coded masks imaging

coded mask imaging

Encoding

The intensity measured by the PSD can be expressed as a two-dimensional matrix $D_{i,j}$ (the shadowgram) presenting the number of interactions registered in the detector element i,j .

$$D_{k,l} = \sum_{i,j} S_{i,j} \cdot A_{i+k,j+l} + B_{k,l}$$

$S_{i,j}$: matrix of the source distribution,

$A_{i,j}$: aperture transmission function (1 for transparent mask elements, 0 for opaque elements)

$B_{i,j}$: background noise matrix (all contributions not modulated by the aperture)

Decoding

direct deconvolution : correlate the encoded matrix D with decoding array G (postprocessing array)

$$S'_{i,j} = \sum_{k,l} D_{k,l} \cdot G_{i+k,j+l}$$

Substituting the encoded matrix D results in

$$S' = (S * A) * G + B * G$$

$A * G$ is the point spread function (PSF). Optimal mask patterns produce delta function $A * G = \delta$

$$S' = S + B * G$$

$\Rightarrow$ source is perfectly reconstructed with the exception of a background term.

Coded masks: field of view

The ability to reconstruct the image of the sky depends on the ratio between the size of the mask and the size of the detector. Often a limited detector size or resolution can be associated with dithering techniques.

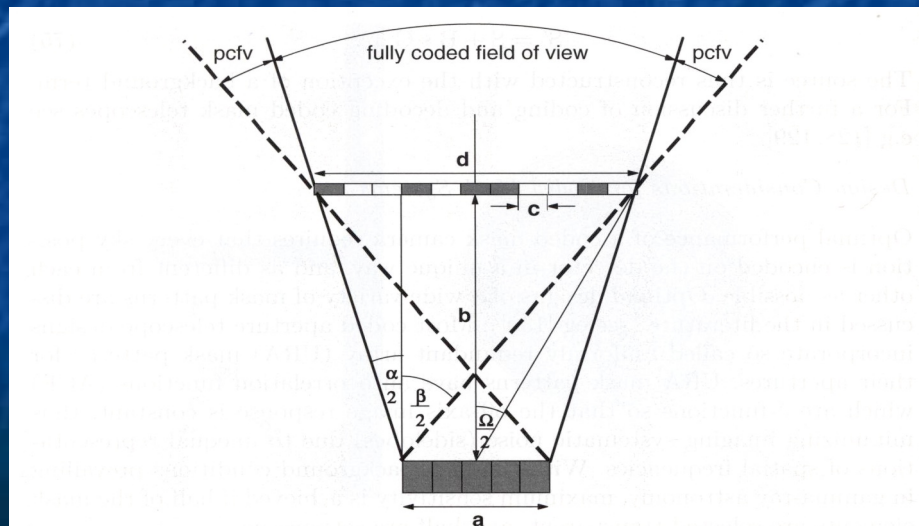
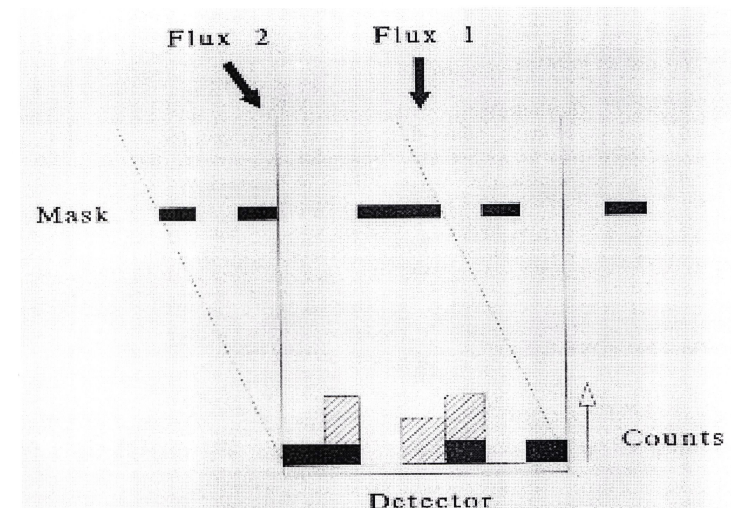
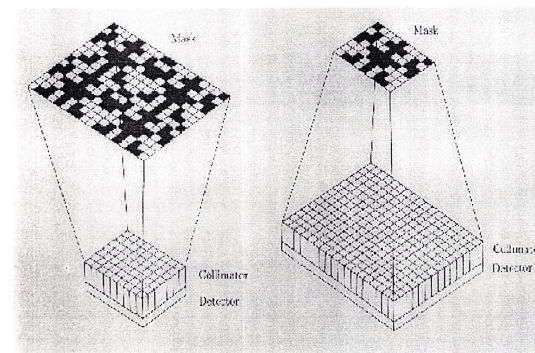


Fig. 42. Schematic side view of a coded mask telescope (pcfv: partially coded field of view)

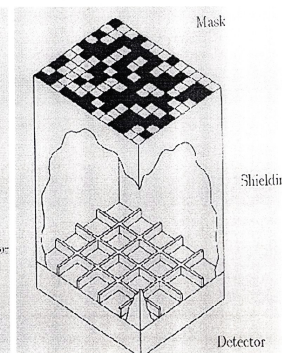
Coded Masks



Optimum configuration



Simple

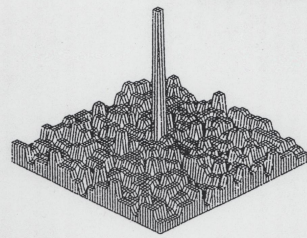


Coded masks: mask patterns

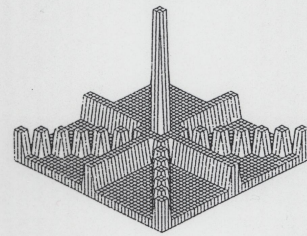
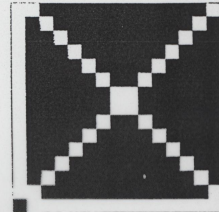
(c)



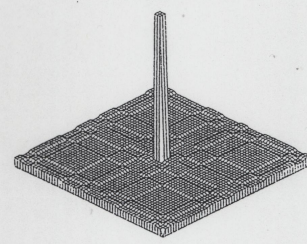
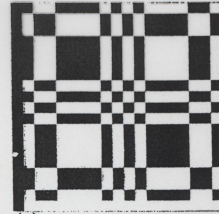
Skinner and Rideout 1995



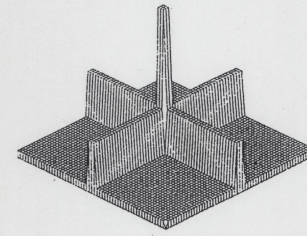
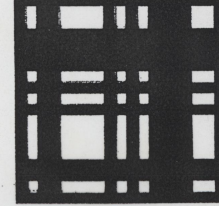
(d)



(e)

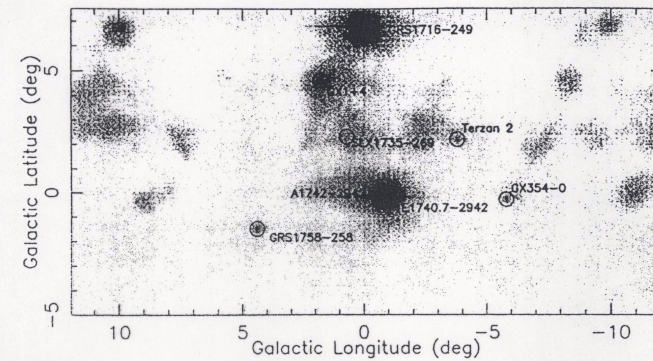


(f)

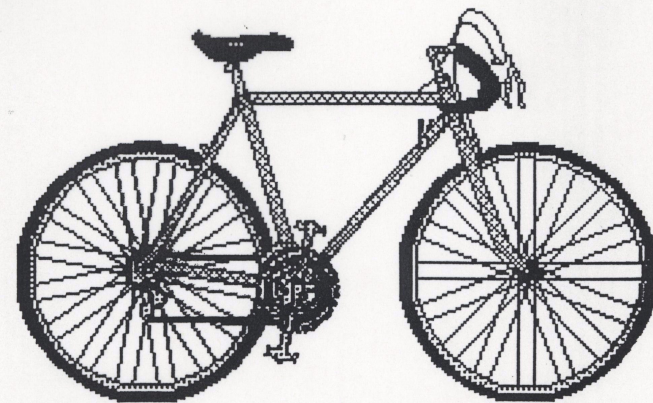


coding / decoding

Skinner 1995



The above image was obtained by correlating the the recorded data pattern with the mask pattern.



Temporal modulators

- The first X-ray satellites had no focusing capabilities and relied on temporal modulation to infer the source of the incoming radiation: e.g. Uhuru

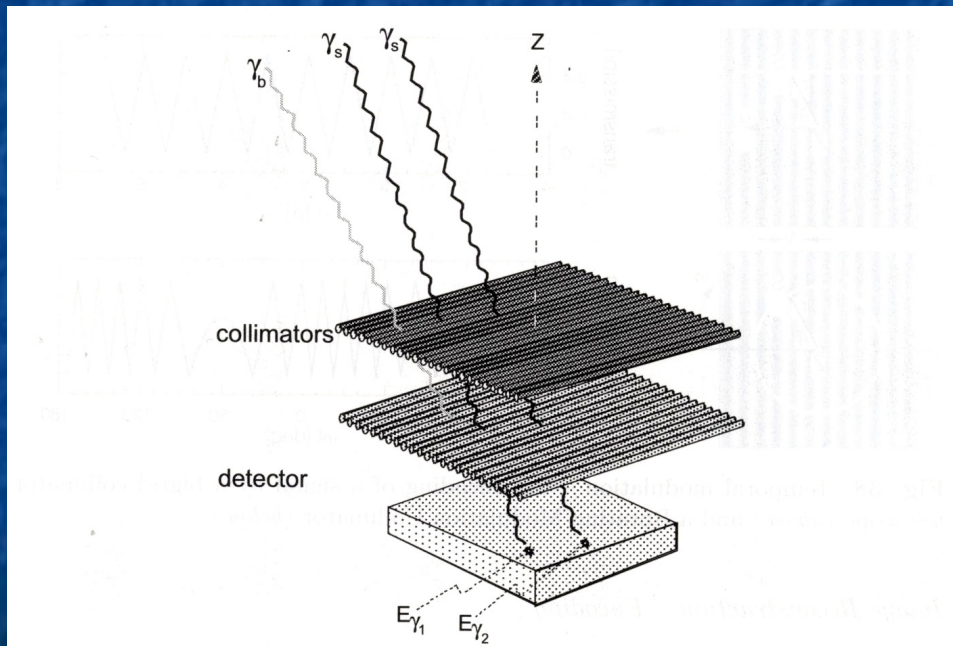


Fig. 37. Temporal modulation – the principle of a bigrid collimator telescope

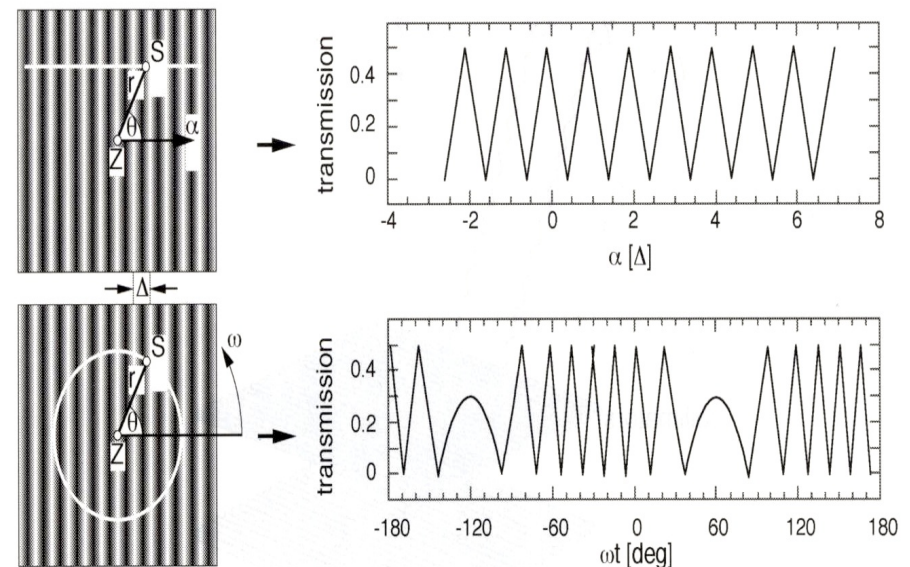


Fig. 38. Temporal modulation – the encoding of a signal by a bigrid collimator telescope (*above*) and a Rotating Modulation Collimator (*below*)

Compton telescopes

- Compton scattering, followed by photoelectric absorption allows to infer the incidence angle of the incoming photons. The sky image reconstruction requires data deconvolution with the scattering pattern.

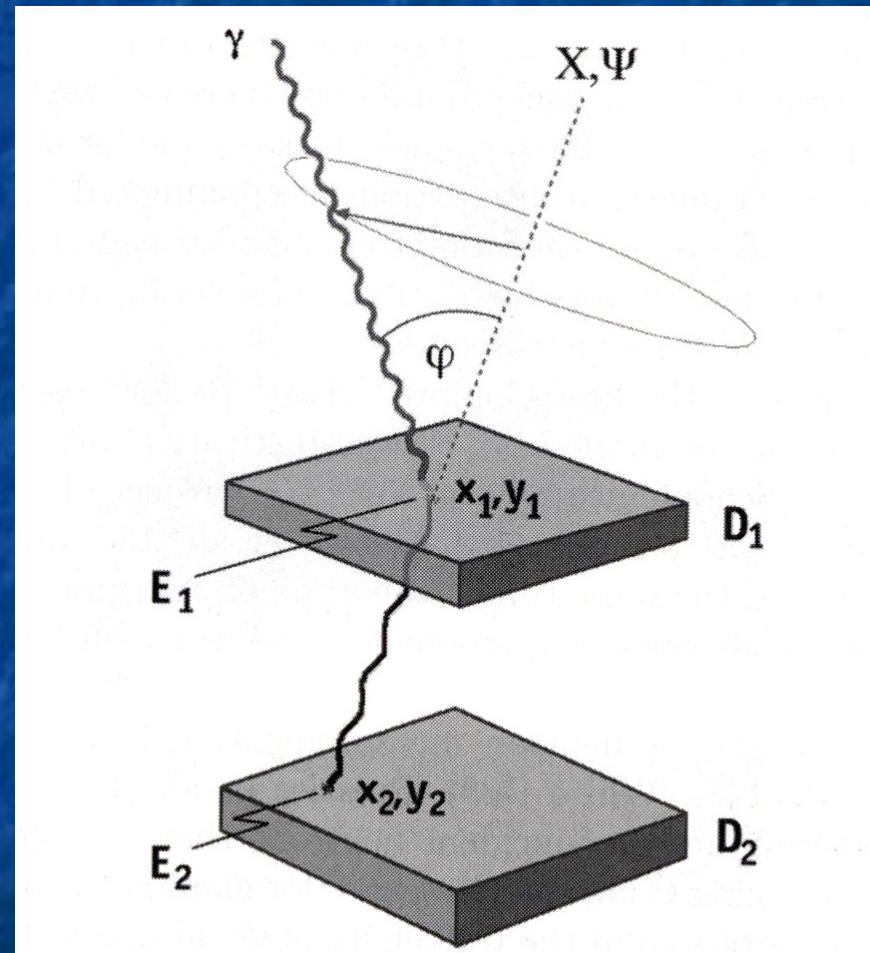
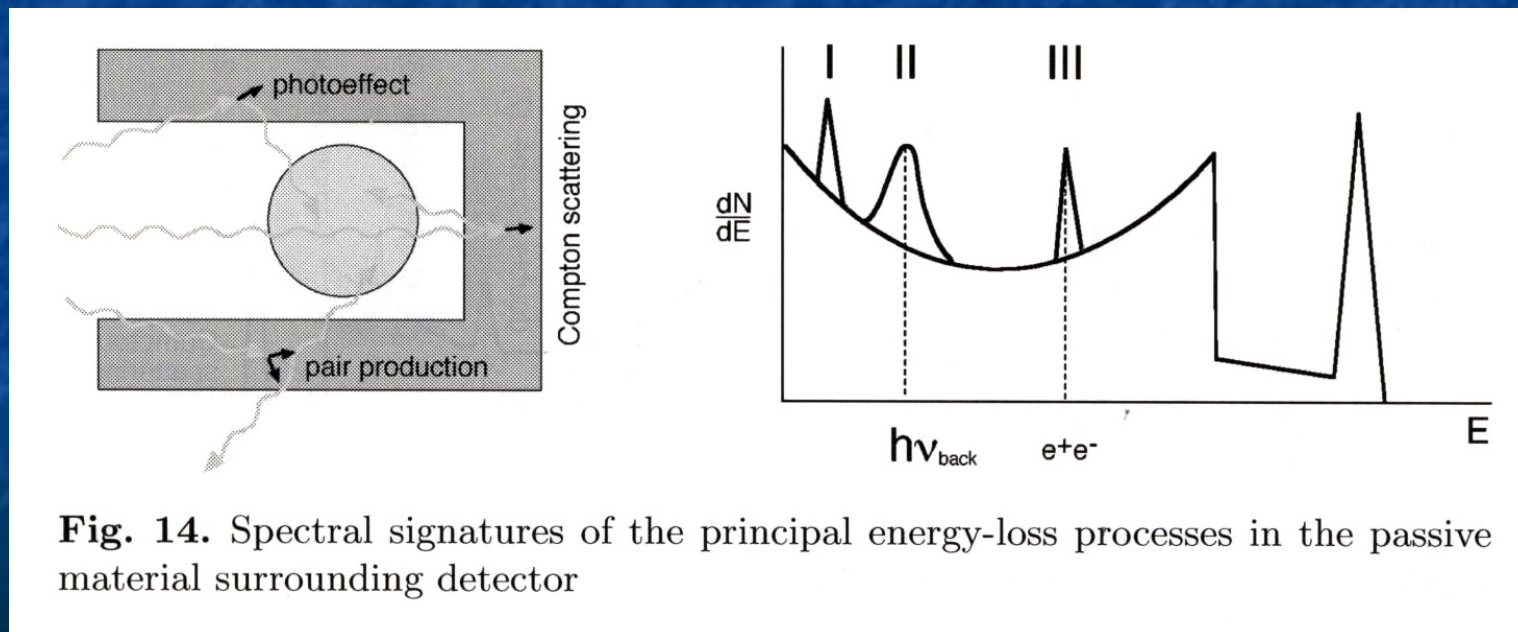


Fig. 45. The principle of a Compton telescope

Background suppression: Anti-coincidence shielding

- Energy-loss processes in the passive material can alter the spectral signature of the incoming radiation and significantly contribute to the detector background.



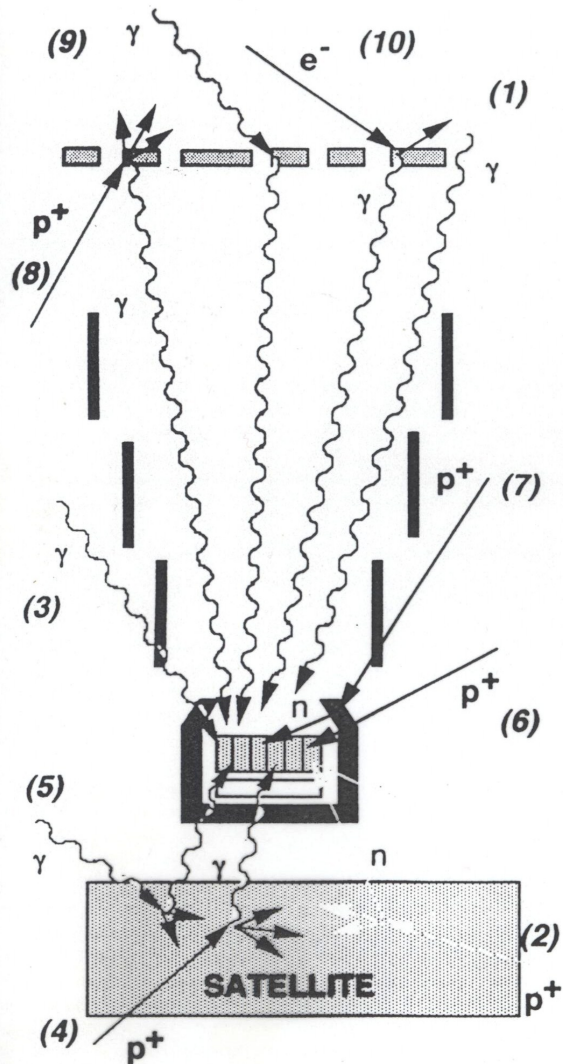
Background suppression: Anti-coincidence shielding

Anticoincidence Shields

- ⊕ background reduction, shields against
 - prompt CR interactions
 - cosmic diffuse gamma-ray component
 - γ -rays generated in the atmosphere / spacecraft
- ⊕ defines a field of view
- ⊕ improves spectral response function
 - "Anti-Compton" rejection of source events not in full energy peak
 - Rejection of source events $> m_e c^2$ in the escape peaks
- ⊖ background generator
 - converts CR p
- ⊖ reduces lifetime
- ⊖ implicitly reduces effective area : with limited mass budgets in balloon and satellite experiments, a shield is most likely the heaviest part of the instrument

(*INTEGRAL SPI* *shield* *ACS* : 856 kg ; *BGO alone* : 504 kg
 detector *camera* : 141 kg ; *Ge alone* : 19 kg)

Background suppression: Anti-coincidence shielding



- (1) - aperture flux (photon, "cosmic diffuse")
- (2) - elastic n interaction (neutron, spacecraft, had. cascade)
- (3) - shield leakage (photon, "cosmic diffuse")
- (4) - shield leakage (photon, spacecraft, hadronic cascade)
- (5) - shield leakage (photon, spacecraft, electrom. cascade)
- (6) - internal β decay (e^- or e^+ , p interacts with detector)
- (7) - internal β decay (e^- or e^+ , secondary n, had. cascade)
- (8) - passive material (photon, hadronic cascade)
- (9) - passive material (photon, electromagnetic cascade)
- (10) - passive material (photon, electromagnetic cascade)

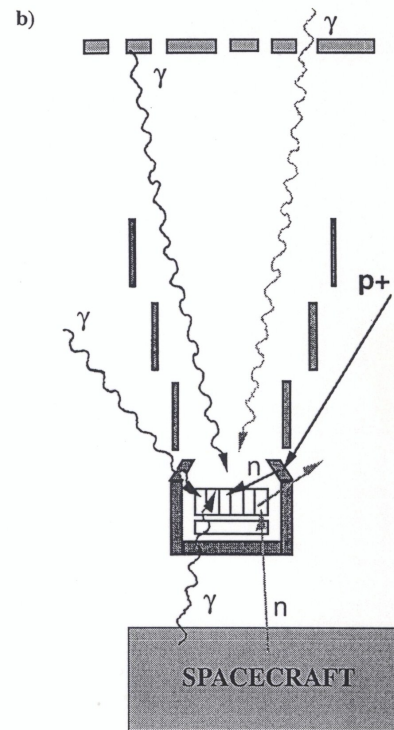
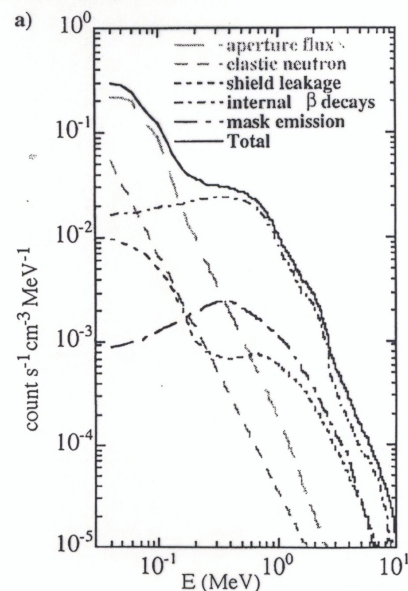
4. The coded aperture mask

The mask is made of 3 cm thick hexagonal tungsten blocks mounted on a graphite-epoxy honeycomb plate with a high transparency to gamma rays (80 % at 20 keV and 90 % at 50 keV). The tungsten blocks are > 90 % opaque over the entire SPI energy range. The opaque mask elements (63) have the same size as the detector modules (6 cm). The distance mask-detector is 1.7 m. These values lead to an angular resolution for point sources of $\approx 2^\circ - 3^\circ$ FWHM, and for the long axis a fully coded field-of-view of 16° , with a zero sensitivity at $\approx 34^\circ$. The mask development is under the responsibility of the University of Valencia (Spain).

It is planned to add to this mask a very thin plastic scintillator which will be delivered by the IFCTR (Italy). Indeed, Monte Carlo simulations have shown that a significant background reduction can be achieved, especially at 511 keV [9], by placing this plastic scintillator as close as possible to the lower side of the passive mask.

5. Background and sensitivity

Extensive simulations of the SPI background have been performed using the GEANT code developed for analysing particle interactions. The estimations have been performed at CESR-Toulouse by P. Jean and P. von Ballmoos, at CEN-Saclay by B. Cordier and N. Diallo, and at GSFC-Washington by J. Naya and B. Teegarden. The possibility to cross-check these calculations, but also to estimate the background from balloon experiments (Hexagone and Hiregs) and from TGRS on the Wind satellite, gives confidence in the results. Extensive analyses of the background have been published [9]. The different background components are detailed in Fig. 3a/b.



The total background is understood as the sum of several components

- **Aperture flux:** cosmic diffuse γ -ray emission
- **Internal β decays:** radioactive nuclei induced in Ge by primary and secondary p^+ , n
 - β^- localized e.g. $^{75}\text{Ge}(\beta^-)^{75}\text{As}(\text{gs})$
 - β^- non-localized e.g. $^{75}\text{Ge}(\beta^-)^{75}\text{As}^* \rightarrow ^{75}\text{As} + \gamma(265 \text{ keV})$
 - β^+ e.g. $^{68}\text{Ga}(\beta^+)^{68}\text{Zn} \rightarrow \text{Two } 511 \text{ keV photons}$
- **Shield leakage:** γ go through the shield without depositing energy in it or are not rejected because of electronic leakage.
 - cosmic diffuse γ -ray emission
 - photons from the spacecraft
- **Elastic neutron scattering:** n from the spacecraft, and dead masses
- **Mask emission:** γ from the mask induced by cosmic-ray particles

Fig. 3a/b. The continuum background components.

Moreover, taking into account the possible background reductions due to the PSD technique, and using the capability with the Ge array to separate (between ≈ 1 to 3 MeV) the gamma rays and the β^+ events, the SPI sensitivity has been calculated for narrow lines and for the continuum (Fig. 4.1 et 4.2.).

New Missions of the Millenia

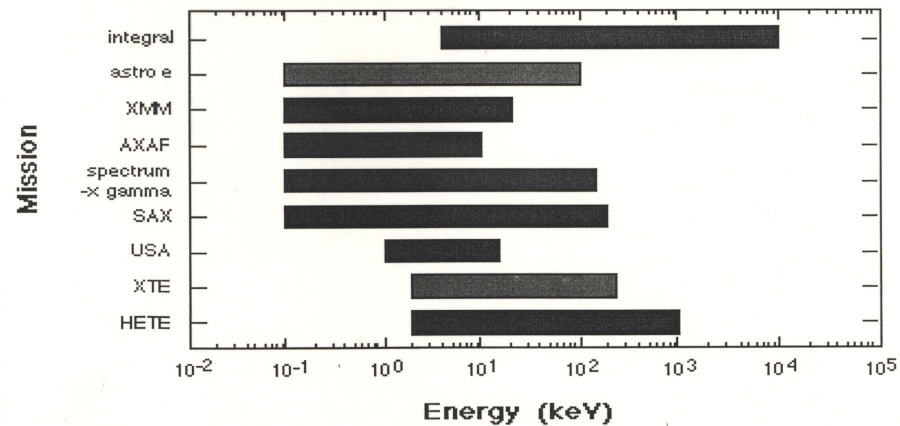
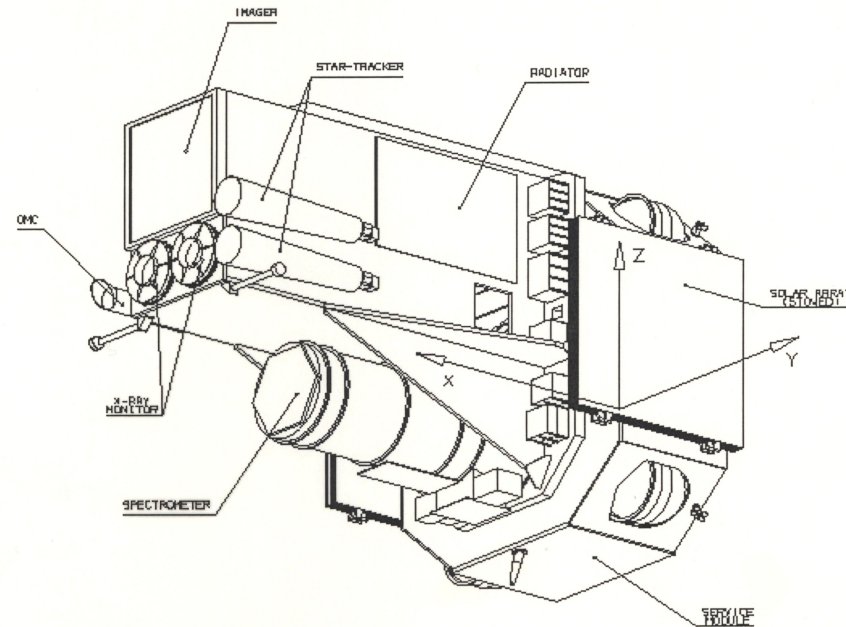
X-ray Astronomy today - Golden Age



Observational X-ray Astronomy:

Integral ray telescope

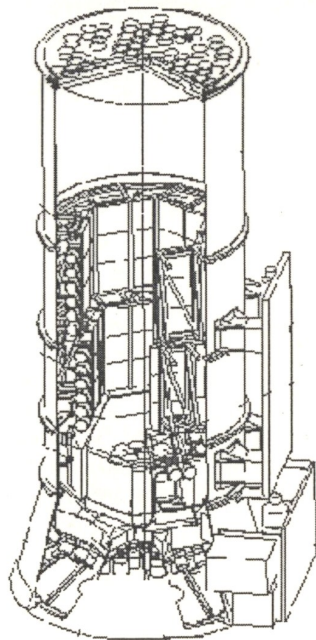
International Gamma-Ray Astrophysics Laboratory (INTEGRAL)



Integral detectors

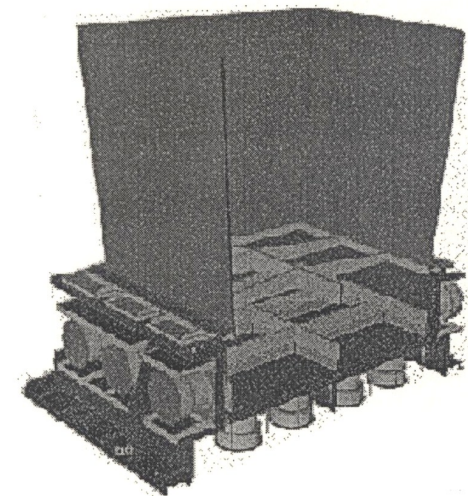
✈ INTEGRAL - Experiments & Instruments

INTEGRAL will carry two main γ -ray instruments:



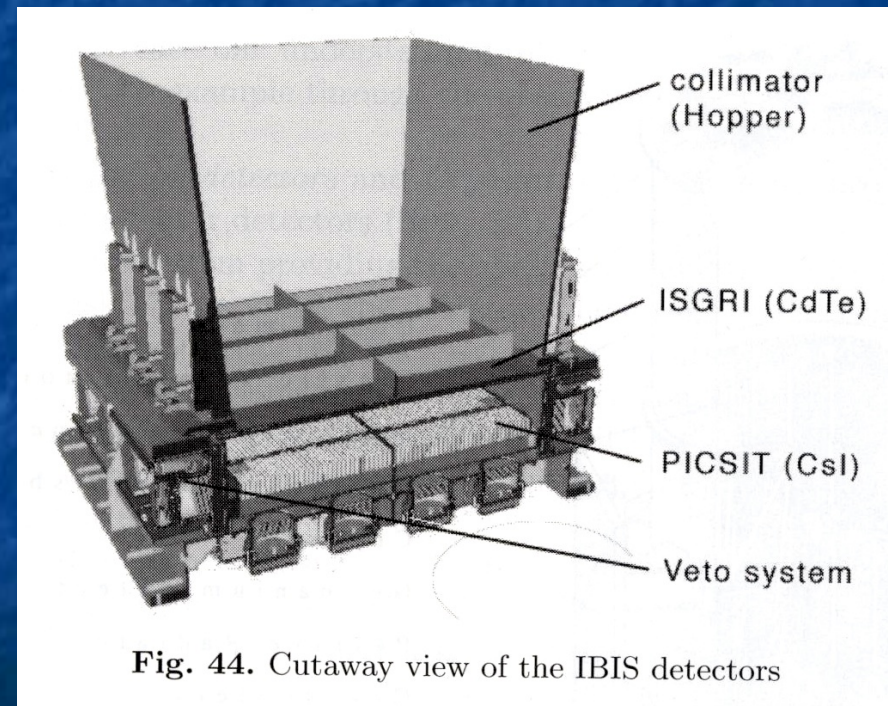
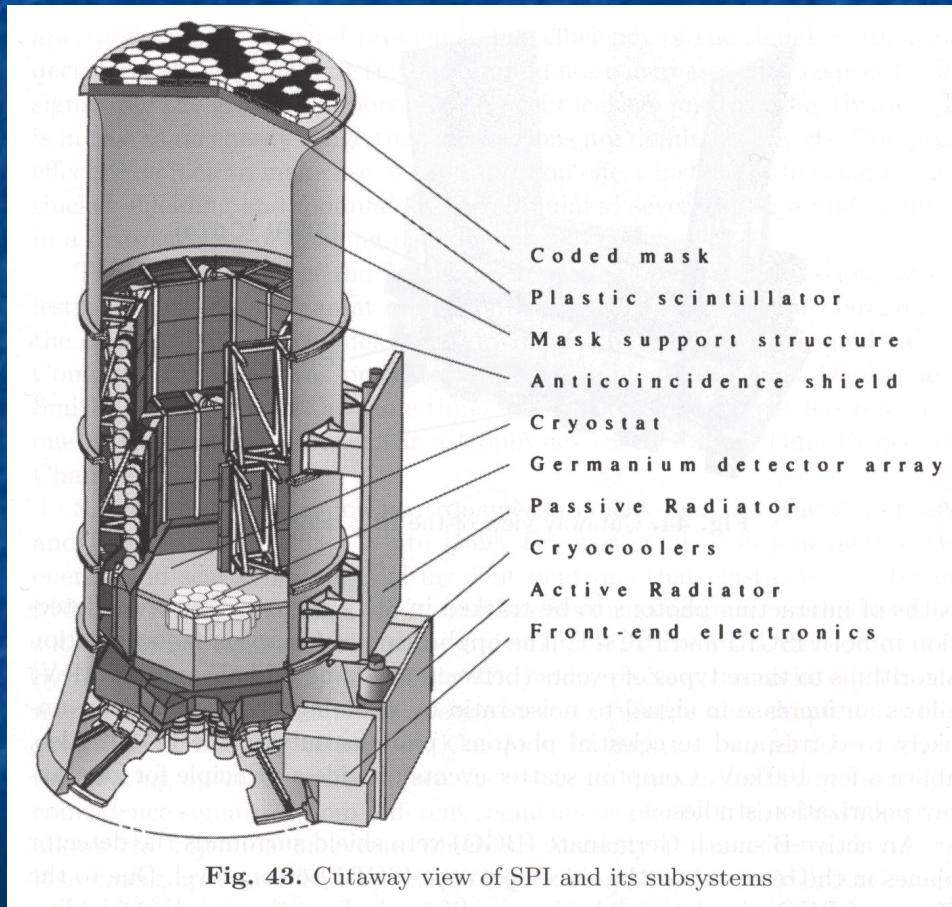
◀ SPI Spectrometer : spectral analysis of γ -ray point sources in 20 keV - 8 MeV energy range. CESR (Toulouse) and MPI (Garching), plus others. $E/\Delta E=500$

Imager IBIS: continuum and broad-line emission imaging of all classes of object in the energy range 15 keV - 10 MeV. IAS/Rome, CE-Saclay and ITESRE (Bologna), plus others. Angular resolution 12' ▶



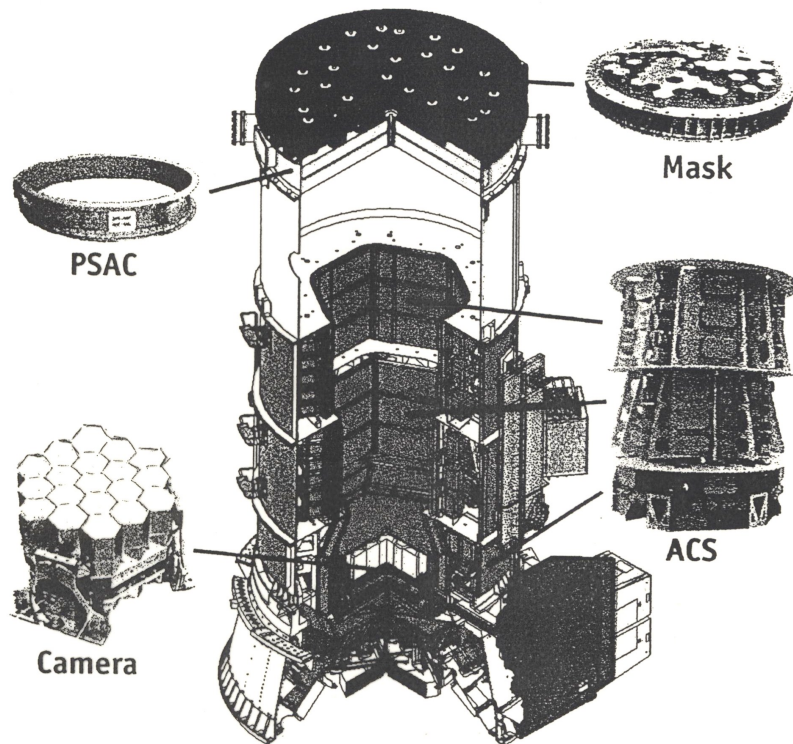
Two other instruments complement the γ -ray detectors: the OMC (optical monitoring camera) and the JEM-X X-ray monitor

Integral main γ -ray detectors



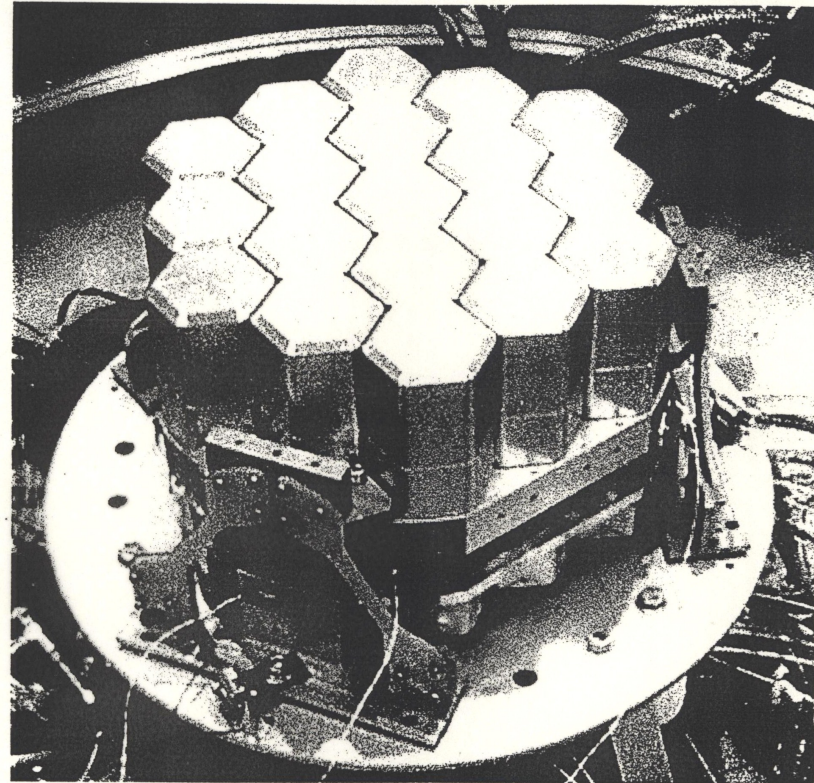
Integral: SPI

SPI - overview



height : 238 cm
diameter : 88 - 110 cm
weight : 1300 kg

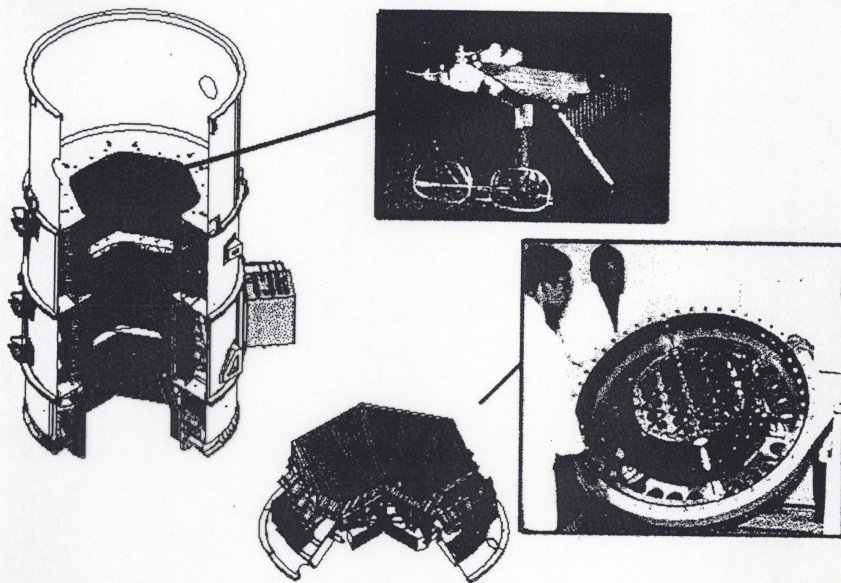
Camera



- 19 high purity n-type Germanium detectors
- Hexagonal shape (6 cm side-side, 7 cm depth)
- Total geometric detection area : 500 cm²
- Operating temperature : 85 K
- Beryllium base plate (passive BG reduction)
- 19 individual pre-amplifiers

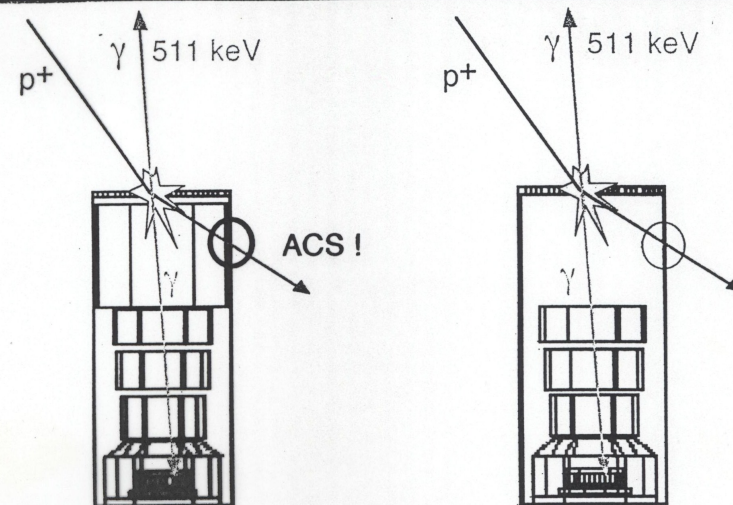
SPI anti-coincidence system

Anitcoincidence Subsystem (ACS)

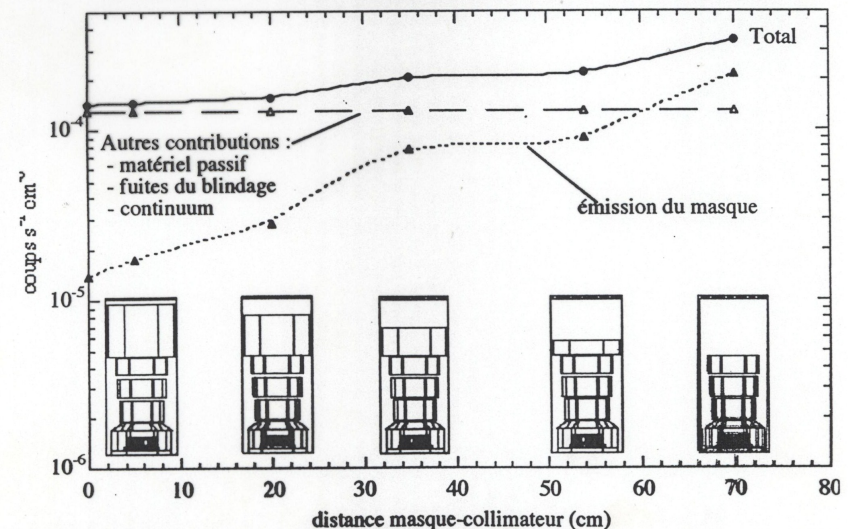


- Passive and active collimator and shield (photons & charged particles)
- Defines aperture of 25° FWHM
- 91 BGO scintillator crystal blocks effective thickness : 5 cm
- 182 photomultiplier tubes
- 91 Front End Electronics (FEE)
- Veto control unit (VCU)

Annihilation from prompt CR interactions



511 keV e^+e^- BG in differnt collimator configurations



=> SPI uses short collimator (mass consideration), yet addition of plastic scintillator underneath W mask