Experimental gamma-ray astronomy (10 keV – 10 MeV)

F. Lebrun

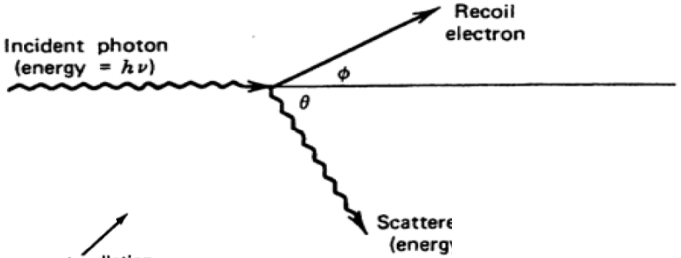
- Detectors
  - Gamma-ray
  - X-ray
  - Anticoincidence systems
- Wide field Imaging techniques
  - 2D Coded mask
  - 2 x 1D Coded mask
  - Compton telescope

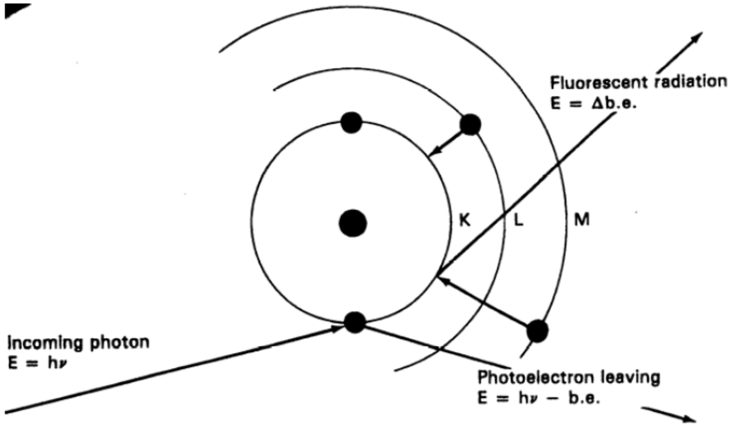
What it is all about

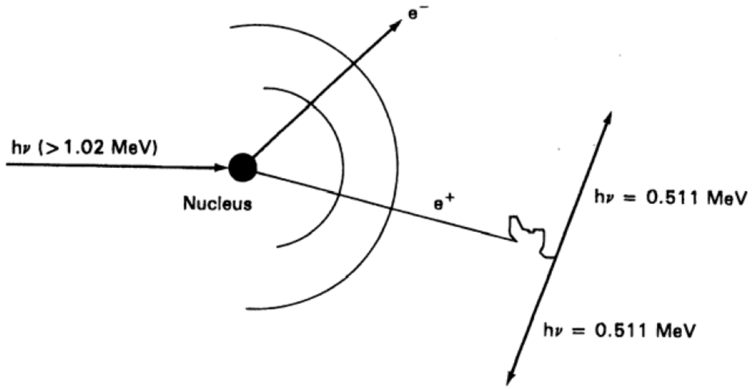
– Detecting gamma-ray photons (10 keV – 10 MeV) from a source of interest (sensitivity)
  - Counting them (photometry)
  - Measuring their energies (spectrometry)
  - Measuring individually or collectively their direction (imaging)
  - Recording their arrival time (timing)
  - Measuring their polarity (polarimetry)

Detecting photons or electrons ?

- In all the inelastic interactions of photons in matter, electrons get part or all the photon energy

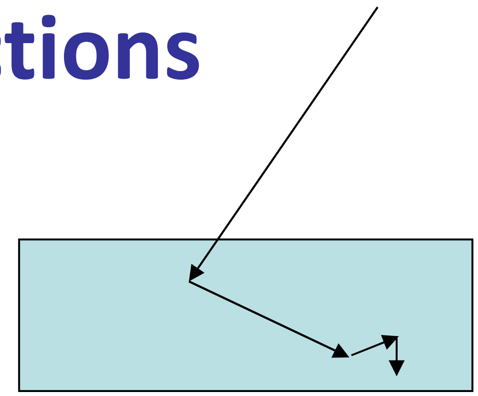




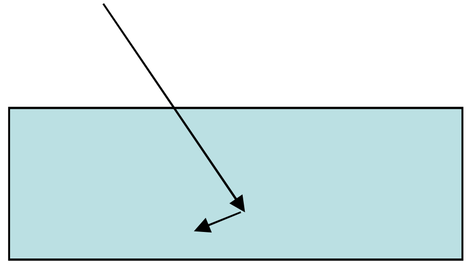


- These electrons lose subsequently their energy via Coulomb collisions, ionization and bremsstrahlung emission

Multiple interactions



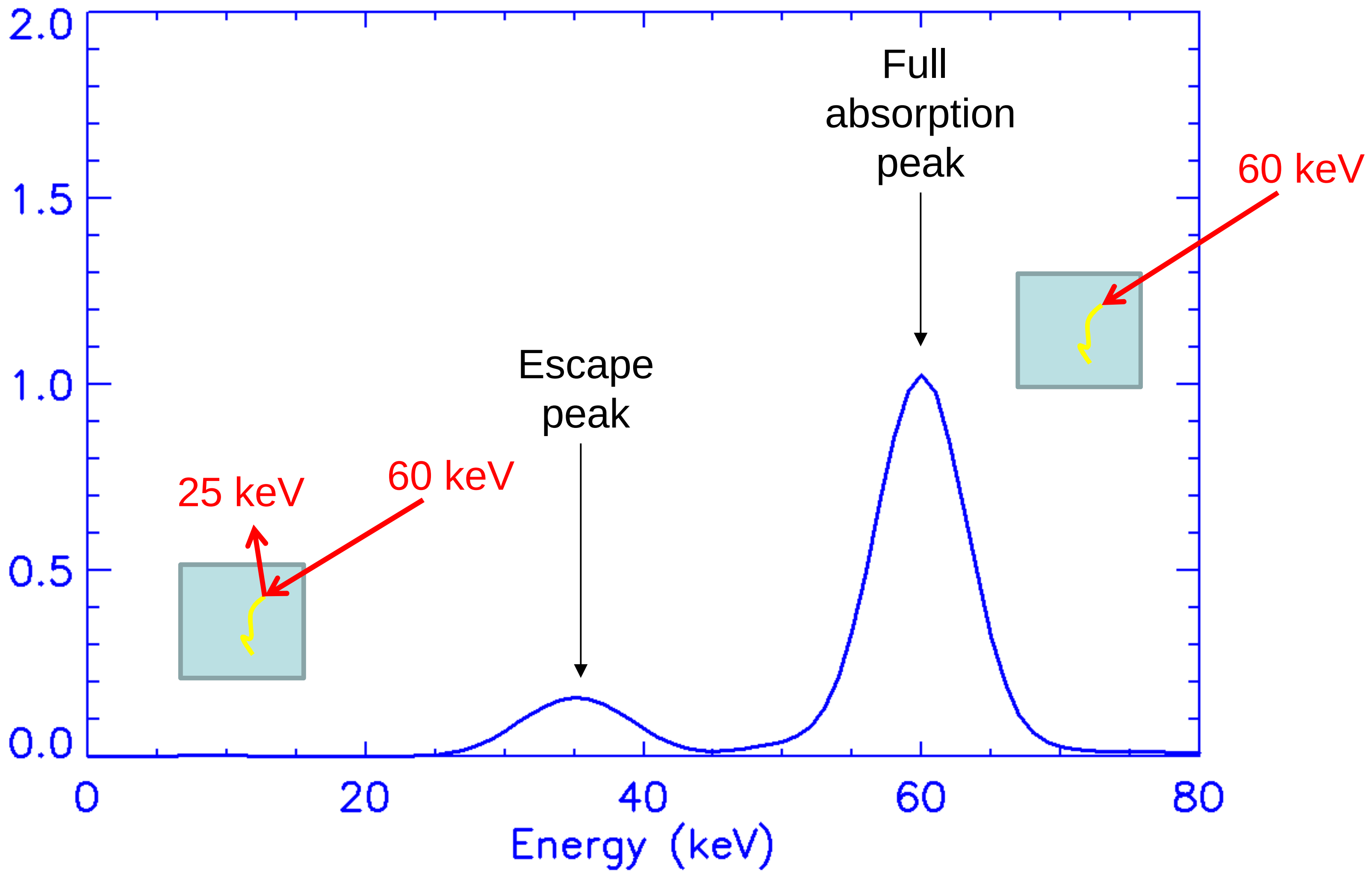
In a thick target, a series of scatters may occur ending with a photoelectric absorption when the energy of the scattered photon is low enough.



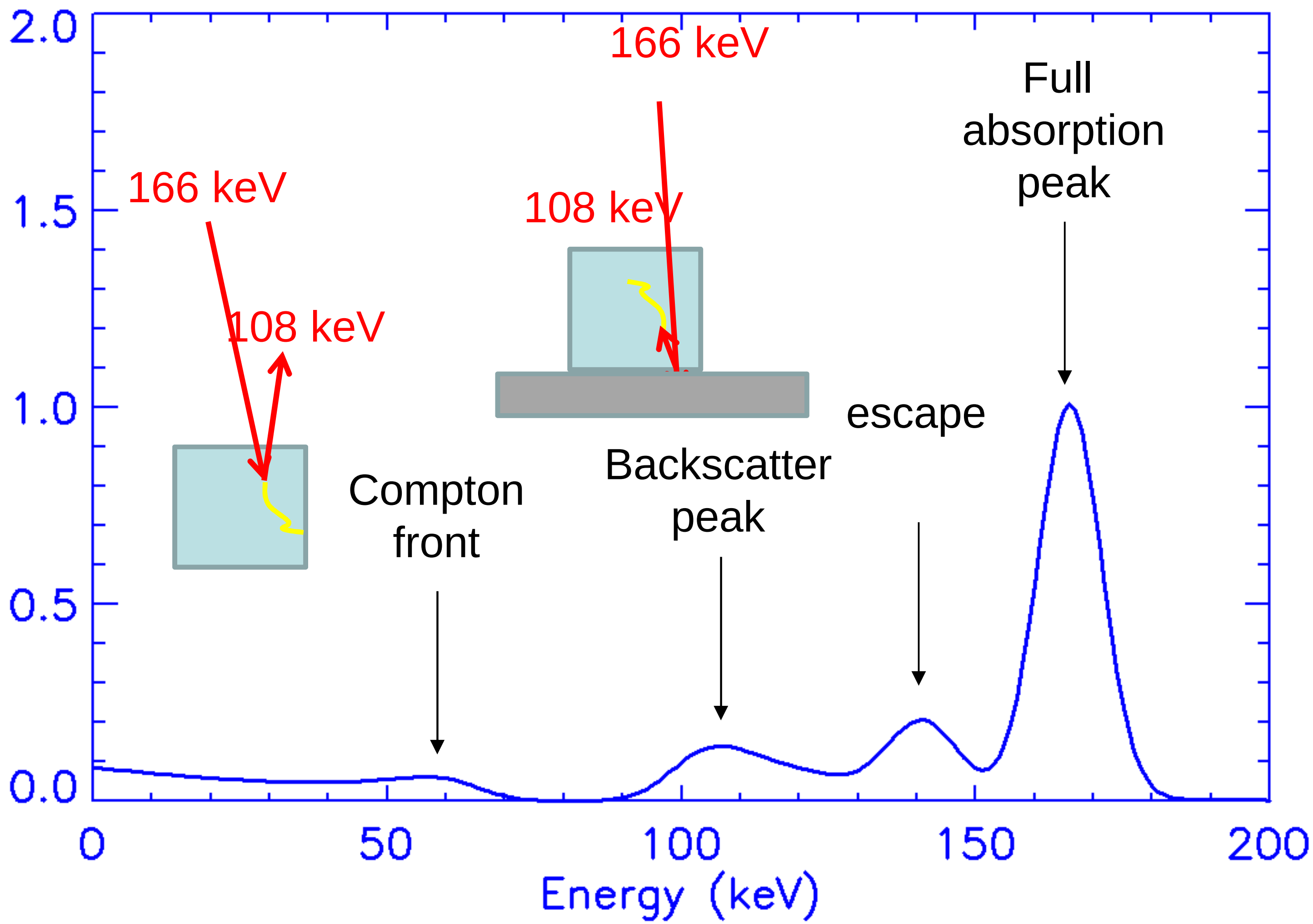
Photoelectric absorption may be followed by fluorescent emission but the fluorescent photon may subsequently be absorbed in the detector

In both cases, if the target is a single detector, the total energy deposited is the energy of the incoming photon exactly as if a single photoelectric absorption had occurred

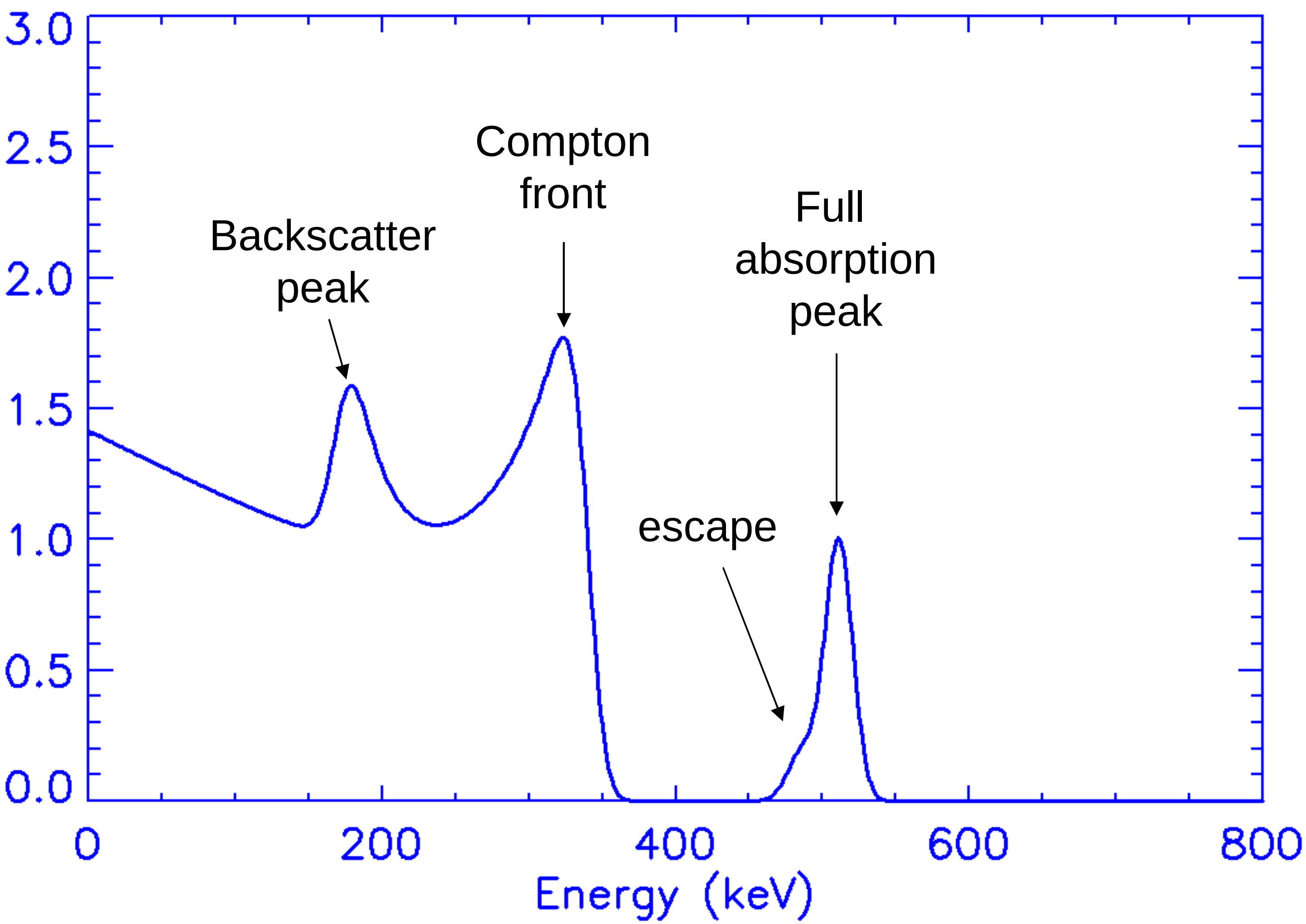
Example of spectral response thin CdTe at 60 keV



Example of spectral response thin CdTe at 166 keV



Example of spectral response thin CdTe at 511 keV

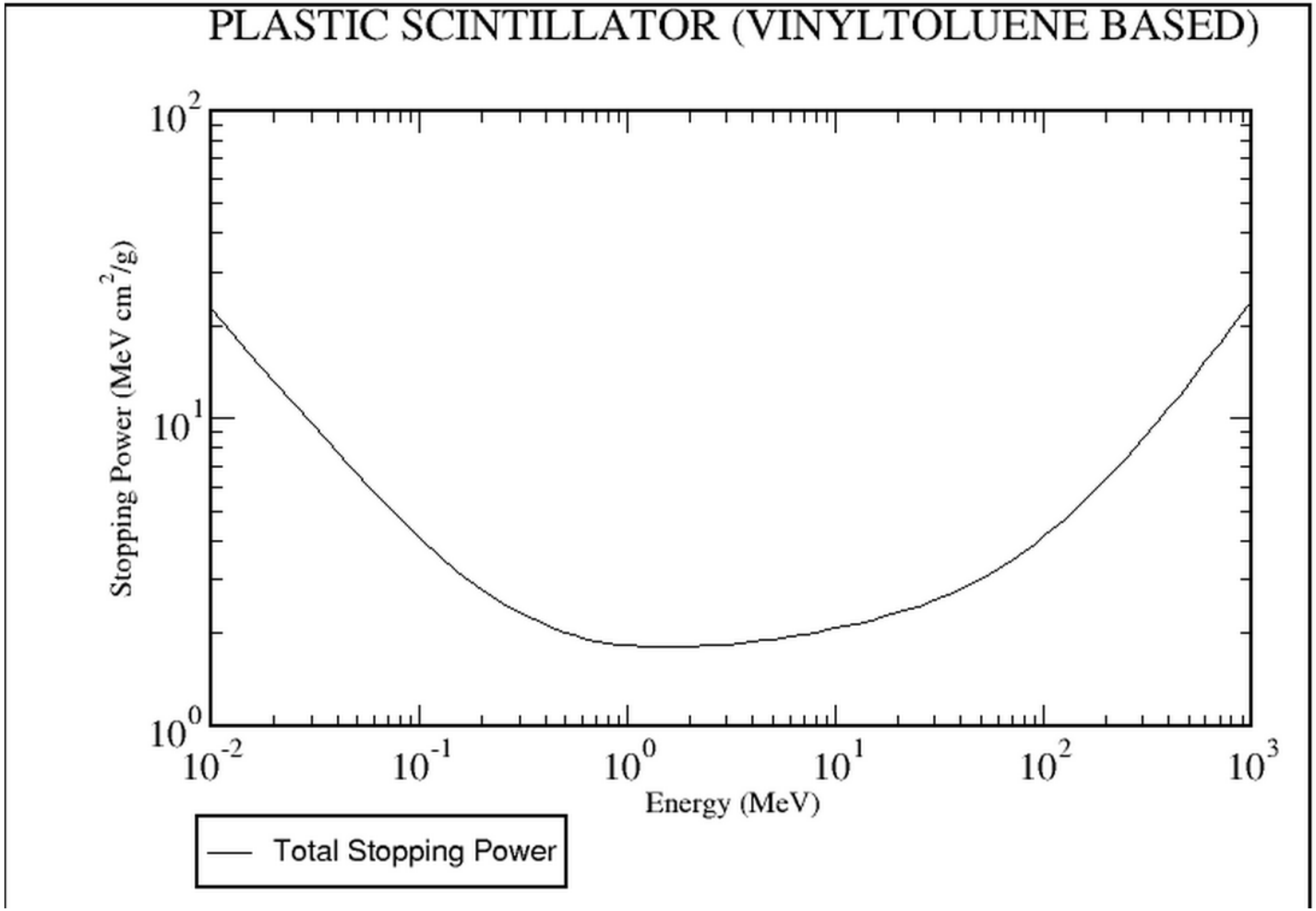


Polarimetry

Linear polarization affects all the interaction processes, i.e. the azimuthal distribution of the interaction products is not flat

- Photoelectric absorption: the K shell electron escape direction follows a sine squared azimuth distribution peaking along the polarization direction
- Compton scatter: the directions of the scattered photon and electron are preferentially ($\sin^2 \phi$) in a plane orthogonal to the polarization direction
- Pair production: the electronic pair is formed preferentially in the plane of polarization

Electron energy losses



Electron avalanche

- An **electron avalanche** is a process in which a number of free electrons in a medium (usually a gas) are subjected to strong acceleration by an electric field, and subsequently collide with other atoms of the medium and thereby ionize them in a process called impact ionization. This releases additional electrons which are themselves accelerated and collide with further atoms, releasing more electrons, in a chain reaction.

  From Wikipedia, the free encyclopedia

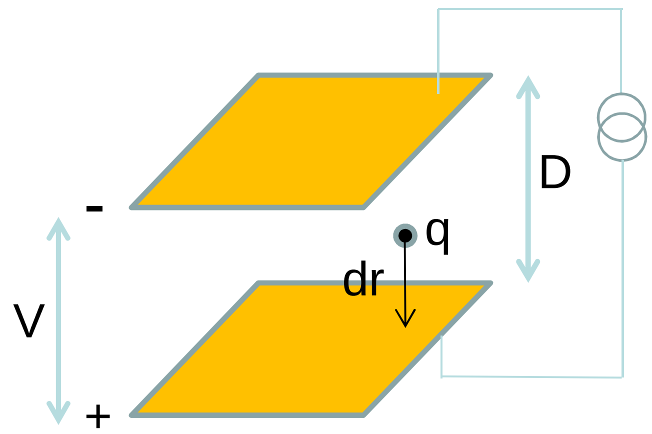
- The avalanche process is a very important one, at work in gamma-ray sources (e.g. TGFs) and in detection techniques (proportional counters, PMTs, APDs, SiPMs etc.)

Where are we ?

- Photons interact with matter and produce photoelectrons
- Photoelectrons lose their energy in ionizing atoms
- Let's see now what are the detector types able to measure this ionization:
  - Gaseous ionization chambers
  - Solid state ionization chambers (semiconductors)
  - Scintillators

Ionization chamber

- The move dr of the charge q in the electric field *E=V/D* parallel to dr, it produces a work *dW = q*E*dr*,
- This induces a drop *dV = q/C dr/D* of the difference of potential between the electrodes. The energy produced by the moving charge is replenished by the external circuit, which supplies a charge *dQ = q dr/D* to the anode to keep the applied voltage constant.
- If n charges q are created at the same time in the chamber, the transient voltage-drop, or pulse, due to their drift up to the electrodes will be *nq/C*, i.e. is a measure of the number of charges created within the chamber.



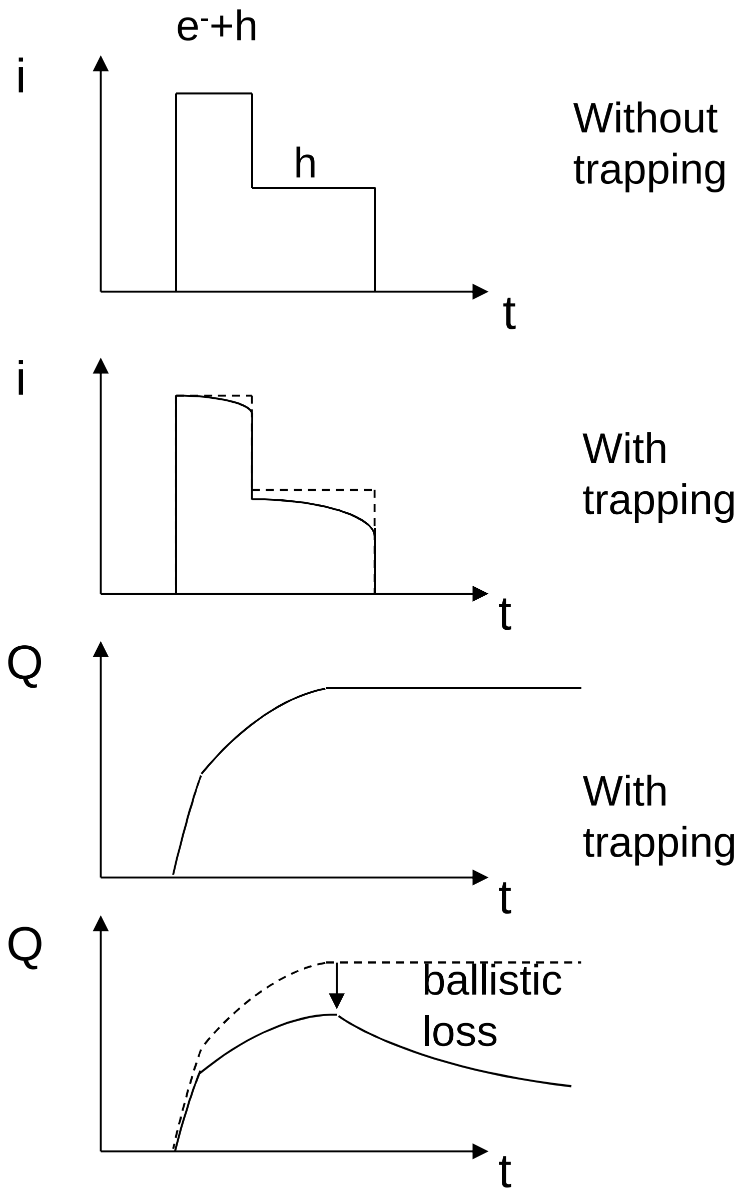
The pulse is not produced by the arrival of the charges to the electrodes but by their transit between the electrodes. If a charge is trapped before arriving to the electrodes, its displacement before trapping contributes to the signal.

Charge carrier properties

- Electrons (and holes) subject to a given electric field acquire a velocity proportional to the E field: $v = \mu E$
- The constant of proportionality μ is called mobility.
- Electrons (and holes) drifting under the effect of an electric field may be trapped.
- Their number decrease exponentially during the transit towards the electrodes so that a lifetime (τ) can be defined.
- μ and τ depends on the detector material, the temperature and may be affected by irradiation. The loss of charge carrier depends on the product $\mu\tau$

Charge losses

- The term charge refers to the charge of a capacitance during the transit of the charge carriers.
- Loss means that this charge is lower than that expected from the transit of all charges that have been created.
- This results from
  - Charge trapping
  - Ballistic losses (discharge of the capacitance during the charge drift time)



Gaseous Detectors

- When a charged particle passes through a gas, free electrons and positive ions are produced along its track. If no electric field is applied, ion pairs will recombine, and no signal is produced. By applying different strength fields, different types of detector can be realized.

- If a small field is applied, the electrons drift towards the electrodes. This regime is exploited in an ionization chamber.

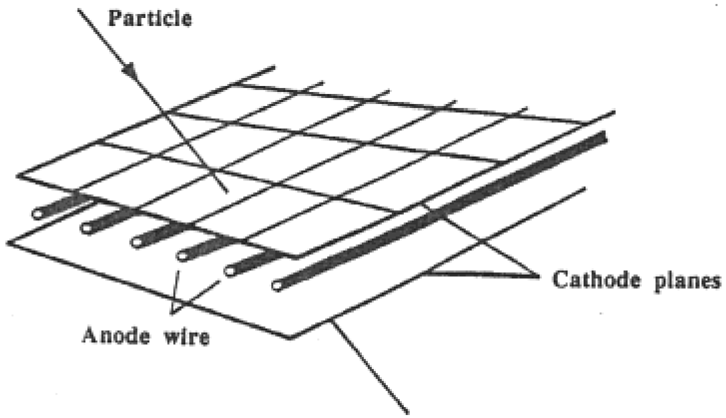
- When a larger field is present, the electrons are soon accelerated until they become ionizing themselves. In this way amplification is produced due to secondary ionization. At low gain, the resultant signal remains proportional to the original ionization, and this is known as operation in "proportional mode".

Proportional Chambers

- In an increased electric field, the electrons are accelerated and produce secondary ionization in an avalanche process.
- A gain, or gas multiplication, of 10^3 to 10^5 is then possible with a produced signal proportional to the original ionization. A detector using this technique is known as a proportional counter.
- The simplest way of producing a local region of high electrical field is to use a cylindrical geometry with a very fine central "sense" wire acting as anode. In this way, the amplification region is surrounded by a lower field, and there is no danger of a direct breakdown between the electrodes.
- The maximum of the avalanche occurs very close to the wire. The electrons therefore have a very short drift distance before being collected at the anode, and so contribute little to the induced signal. The ions, however, even though they are more slowly moving (lower mobility), produce a significant signal as they travel through the region of large *E*.
- Used gas: Argon or Xenon

Multiwire Proportional Chambers (MWPCs)

- A development of proportional chambers was to place many detectors in the same gas volume.
- This is done by positioning parallel fine anode wires about 2 mm apart between planar walls which form the cathode.
- If each wire is about 20 microns in diameter, an intense field will be produced in its vicinity, and each will act as an independent detector, if equipped with amplifier and readout electronics.
- The position resolution (perpendicular to the wires) will then be of the order of the wire spacing, though this can be improved to ~0.7 mm if the centroid of the wire pulses is used.



- Resolution in the perpendicular direction can be achieved by two means.
  - The cathode planes can be divided into independent strips. The centroid of the induced pulses can then provide a measurement to about 0.1 mm.
  - If the anode wires are made of resistive material, then reading out both ends and using charge division provides a resolution of the order of 0.1% of their length.

Problems with Proportional Chambers

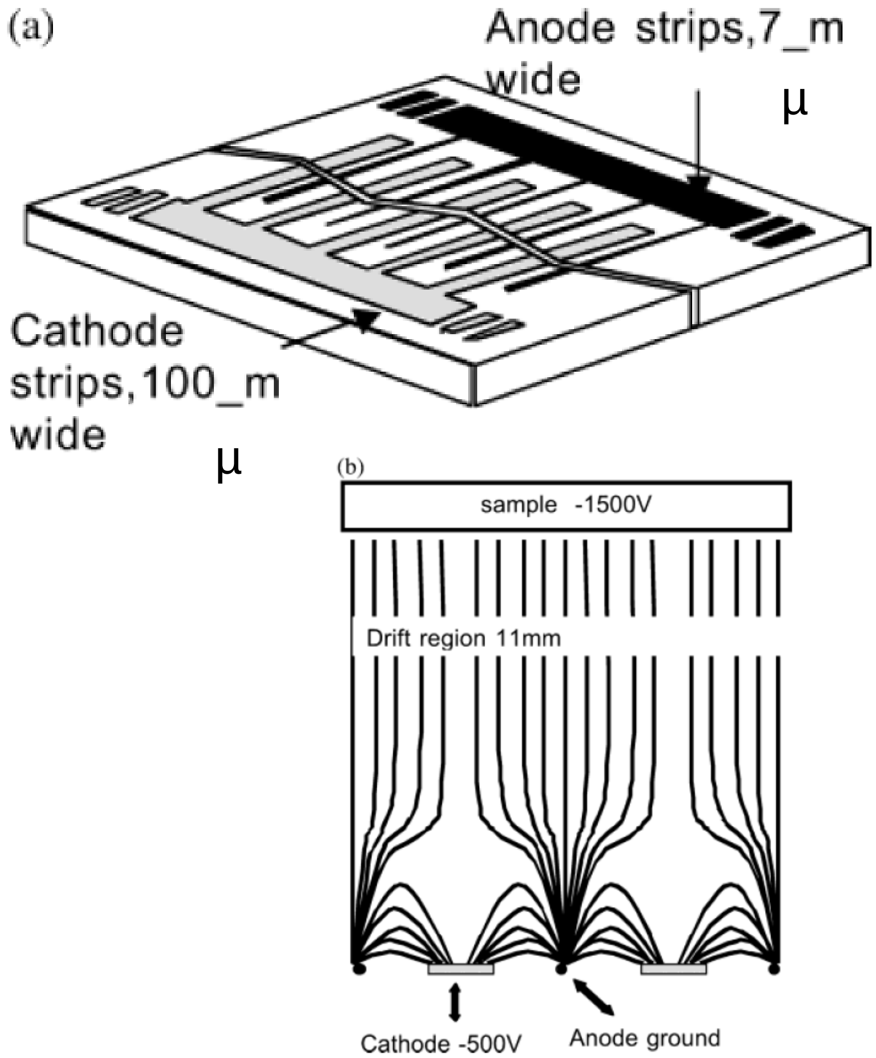
Proportional chambers are used very successfully in a large number of experiments. They do, however, suffer from three potential problems:

- Mechanical - very fine wires are strung under high mechanical tension and significant electrostatic forces, and should be kept in their nominal position with a tolerance of the order of 50 microns.
- Physical and chemical breakdown of gases can lead to deposits on the cathode, which in turn can cause electrical discharge within the chamber.
- There are overall rate limitations, due to the buildup of space-charge (mainly due to the slowly drifting positive ions).

An example of a proportional counter: INTEGRAL/JEM-X

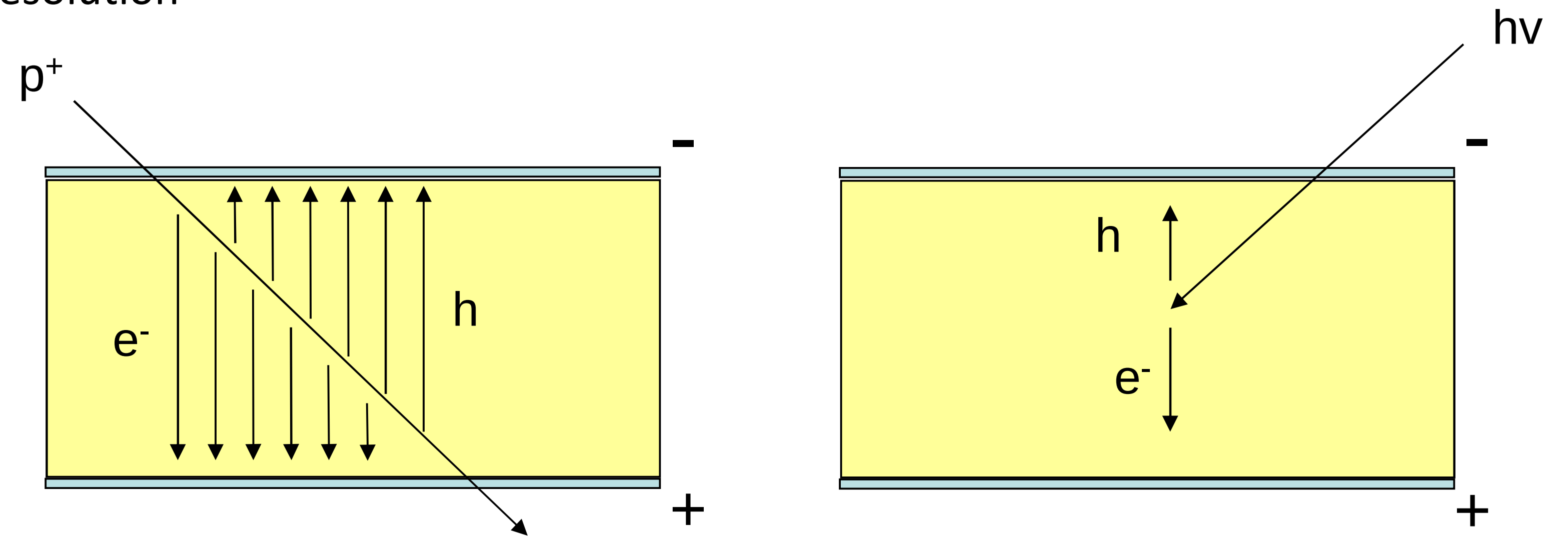
- The photon detection system consists of two identical imaging Micro-Strip Gas Chambers (MSGC). Each detector unit views the sky through its coded aperture mask located at a distance of 3.4 m above the focal plane. In the MSGC detectors the wire electrodes of conventional multi-wire proportional counters are replaced by a thin metal stripe pattern. In the JEM-X the anode strips are only 0.01 mm wide.

- The JEM-X detector has a sensitive area of 500 cm^2 .The detector gas is Xenon at 1.5 bar pressure. A part of the detector electronics, like the front-end amplifiers, is placed inside the gas chamber.



Semiconductor detectors

- They act as solid state ionization chambers
- Crossing charged particles or photoelectrons ionize atoms along their path
- Since a voltage is applied to the electrodes, the charge carriers (electrons and holes) drift towards the electrodes
- This drift induce a pulse of current
- Semiconductor detectors with a low band gap require cooling (e.g. Ge should be operated at 80 K)
- The lower is the charge carrier pair creation energy, the better is the energy resolution



Semiconductor detectors

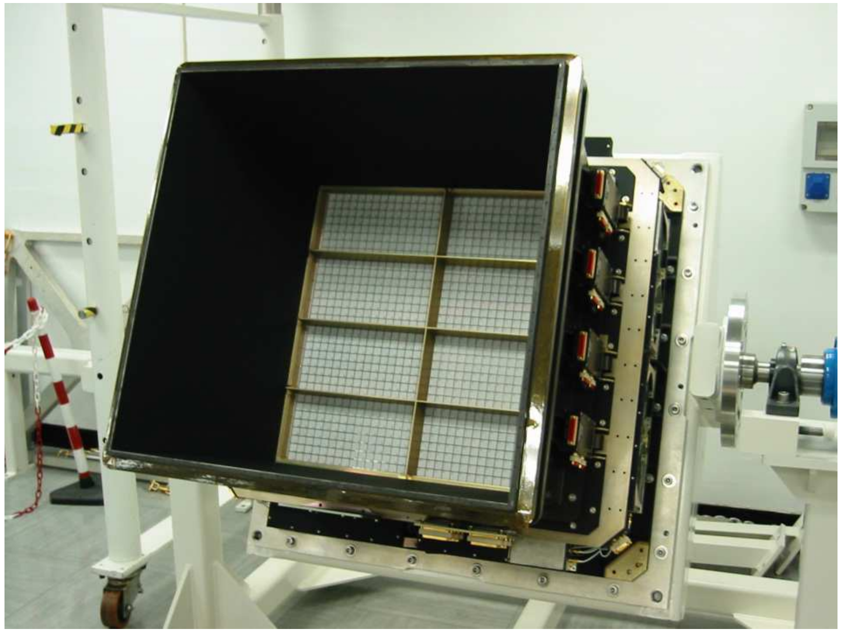
	Si	Ge	CdTe	HgI2	GaAs
Z	14	32	48-52	80-53	31-33
TRL	9	9	9	3	5?
λ (cm) @ 100 keV	2.33	0.34	0.10	0.05	0.34
ρ (cm^{-3})	2.33	5.32	5.8	6.36	5.31
μ/ ρ (cm^2 g^{-1}) @ 100 keV	0.18	0.56	1.67	3.41	0.56
T_{dec} (ns)		5000 ?	5000		
Electron Mobility (cm^2 V^{-1} s^{-1})	1350	3900	950	70	8500
Electron life time (μs)	1000	1000	1.2	2.8	0.01
Hole mobility (cm^2 V^{-1} s^{-1})	480	1900	73	2.5	400
Hole life time (μs)	2000	1000	5	20	0.01
Band gap	1.12	0.66	1.51	2.1	1.22
e-h pair creation energy	3.62	2.96	4.42	4.2	4.2
Maximum thickness (cm)		10	0.6		

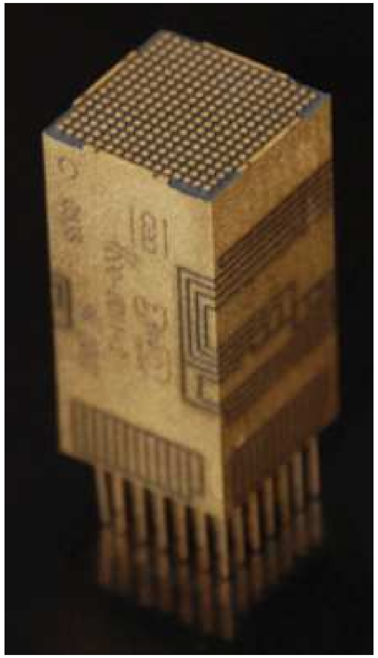
Imaging detectors (N^2 pixels)

- CDDs
  - Very large number of small pixels (e.g. <50µm)
  - Number of readout channels = 1
  - Inconvenient: reading time (~ 10^{-4} s)
  - Example: XMM/EPIC
- Double Side Stripped detectors (DSSD)
  - Number of readout channels = 2N
  - Inconvenient: Capacitance → noise
  - Example: Fermi (SSD)
- Pixel detectors
  - Number of readout channels = N^2
  - Best energy resolution
  - High power consumption
  - Examples: INTEGRAL/ISGRI, SVOM/Eclairs, SIMBOL-X/HED

Pixel cameras

- Each pixel is independent, i.e. has got its own trigger, FEE and read-out
- e.g. INTEGRAL/ISGRI, SIMBOL-X/HED





Stripped cameras

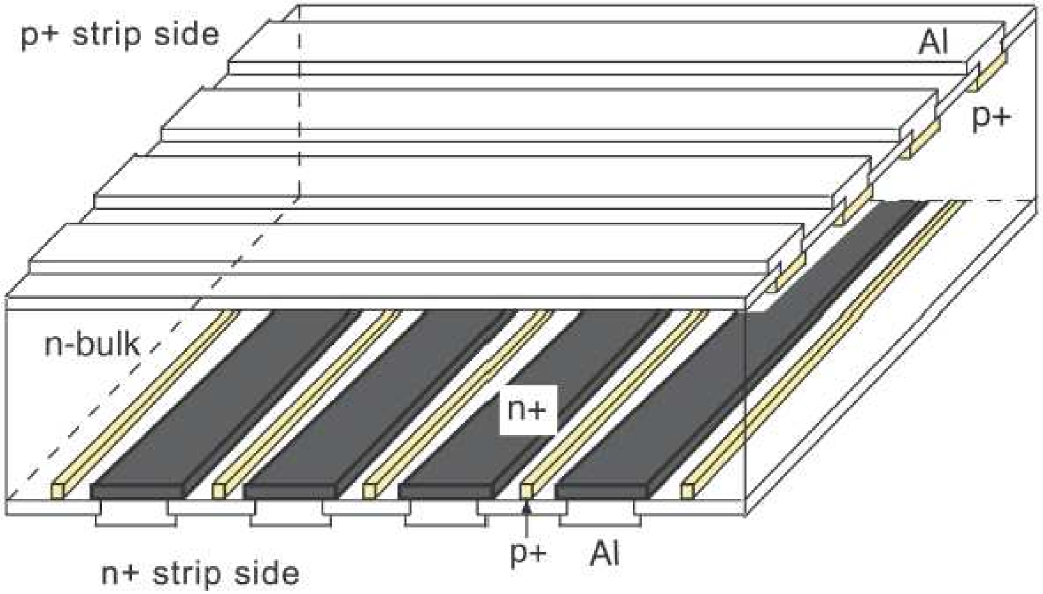
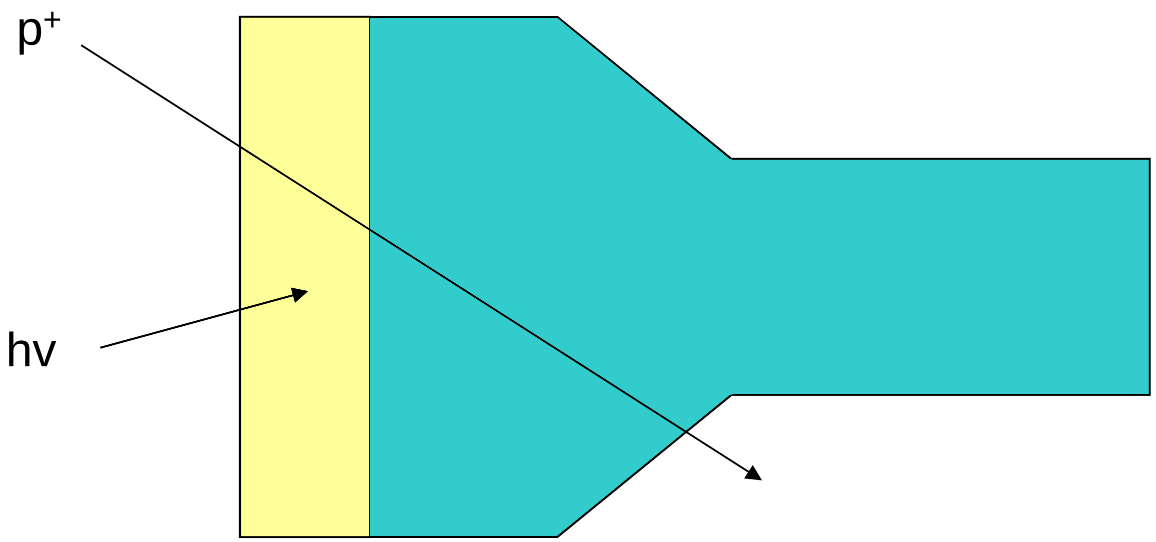


Figure 1. Cross-sectional view of a DSSD. The highly doped positively charged or p-type silicon strips (p+: yellow) and the negatively charged or n-type silicon strips (n+: black) are implanted orthogonally to provide two-dimensional coordinate measurements. Each n+ strip is surrounded by a floating p+-doped implantation to be isolated from any adjacent strips. Aluminum (Al) electrodes are directly coupled on each strip with ohmic contact.

Takeda et al., 2007

scintillators

- In a scintillator, crossing charged particles or photoelectrons ionize atoms along their path
- Recombination takes place and visible fluorescent light (scintillation) is emitted
- A fast visible light detector (PMT, Photodiode) collects the light and produce an electric pulse



Scintillator properties

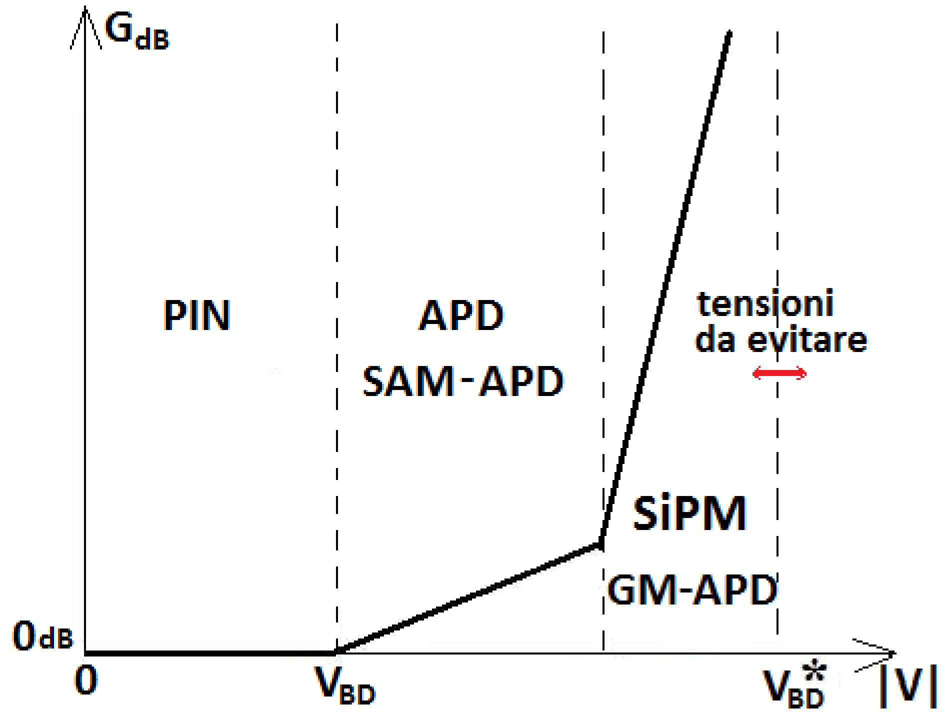
- Stopping power: expressed in terms of mean free path
- Light output: governs the energy resolution
- Decay time: in principle an intrinsic property of the crystals but it may be affected by light collection issues
- Refraction index: affects the light collection and therefore the decay time and the energy resolution
- Some scintillators are highly hygroscopic and require an hermetic envelop

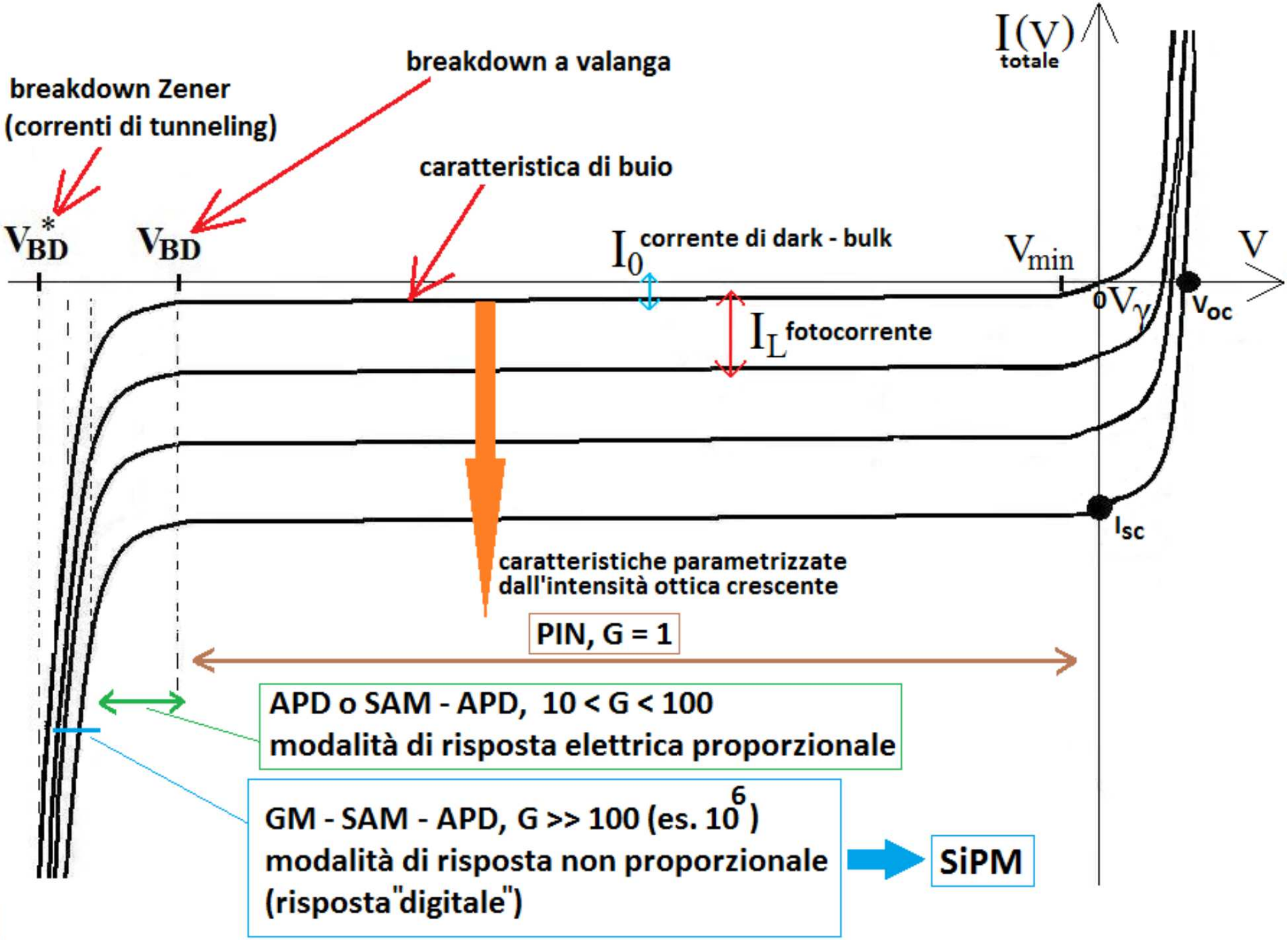
Some available scintillators

	Plastic	LaBr3	NaI	BGO	CsI(Na)	CsI(Tl)
Light coll. (% NaI)	25	165	100	20	85	45
λ_{max} (nm)	425	380	415	480	420	550
λ (cm) @ 100 keV	5.95	0.15	0.16	0.03	0.11	0.11
ρ (cm^{-3})	1.03	5.29	3.67	7.13	4.51	4.51
μ/ρ ($cm^2\ g^{-1}$) @ 100 keV	0.163	1.28	1.67	3.97	2.03	2.03
T_{dec} (ns)	2.1	16	250	300	630	1000
Index of refraction	1.58	1.9	1.85	2.15	1.84	1.79
hygroscopic	no	yes	yes	no	yes	no

Photodetectors

- Since more than 80years, the PMT is the photodetector of choice to convert scintillation photons into electrical signals in most of the applications related to the radiation detection. This is due to its high gain, low noise and fast response.
- Research is now moving to solid state photodetectors that show the following advantages with respect to PMTs:
  - Compactness
  - High quantum efficiency (to provide an energy resolution comparable to PMTs)
  - Insensitivity to magnetic fields (PET/MRI)





I(V)
totale
breakdown a valanga
breakdown Zener
(correnti di tunneling)
caratteristica di buio
V*BD
VBD
I0 corrente di dark - bulk
Vmin
V
0 Vγ
Voc
IL fotocorrente
Isc
caratteristiche parametrizzate
dall'intensità ottica crescente
PIN, G = 1
APD o SAM - APD, 10 < G < 100
modalità di risposta elettrica proporzionale
GM - SAM - APD, G >> 100 (es. 10 6)
modalità di risposta non proporzionale
(risposta "digitale")
SiPM

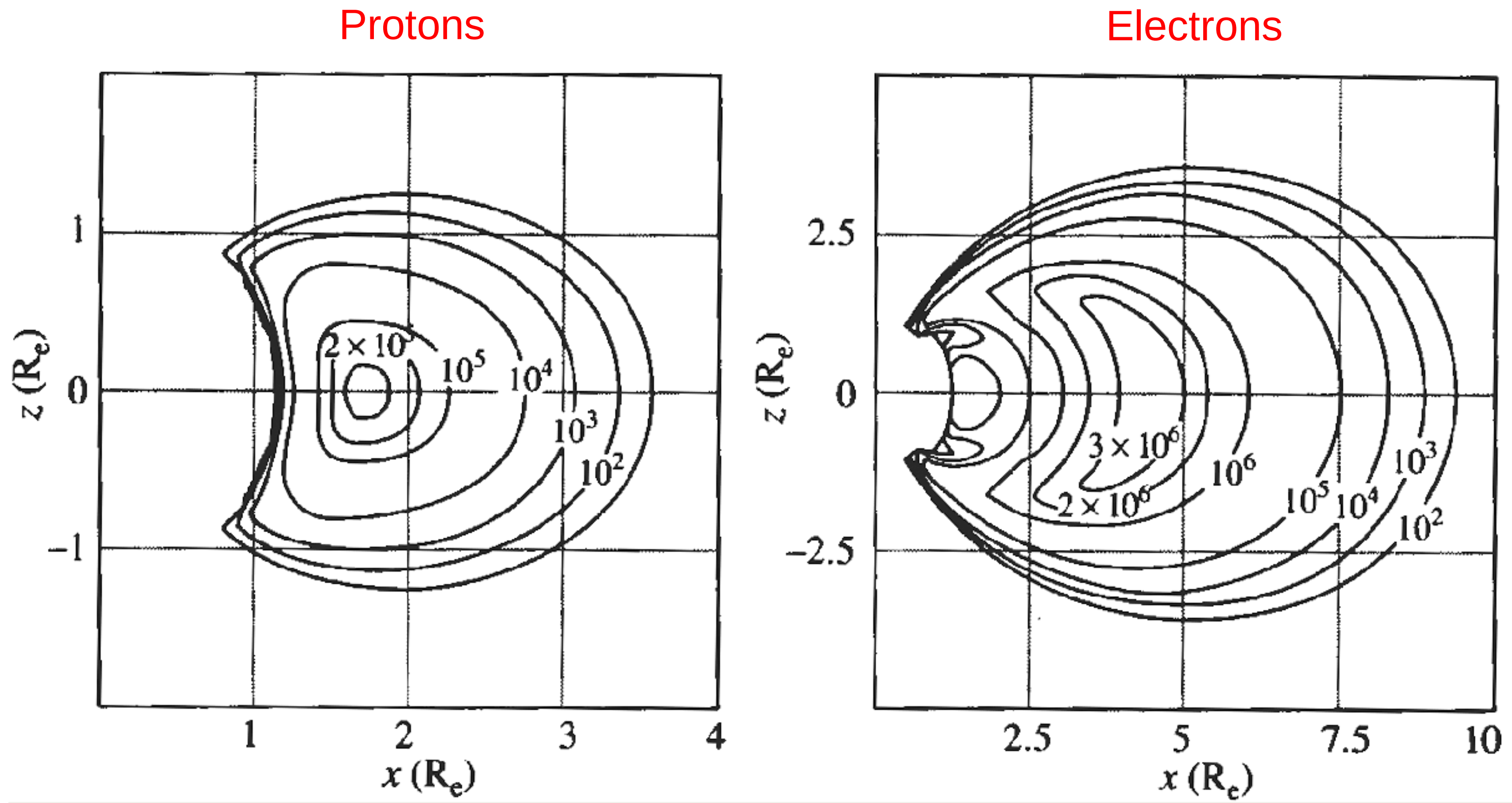
Background

- The notion of background is more tricky than it seems at first sight. What is background for an observer may be signal for another one (e.g. 2 nearby sources, CXB etc.)
- Internal background: it is an effect of the spacecraft high energy particle environment.
  - Prompt:
    - result of the energy loss of electrons, protons or ions through the detectors
    - result of the interactions of secondary particles produced by spallation
  - Delayed: due to the radioactive decay of unstable isotopes produced during spallation interactions

Particle environment

- Radiation belts
- South Atlantic Anomaly
- Cosmic rays
- Solar activity
  - Outbursts
  - Cosmic ray modulation

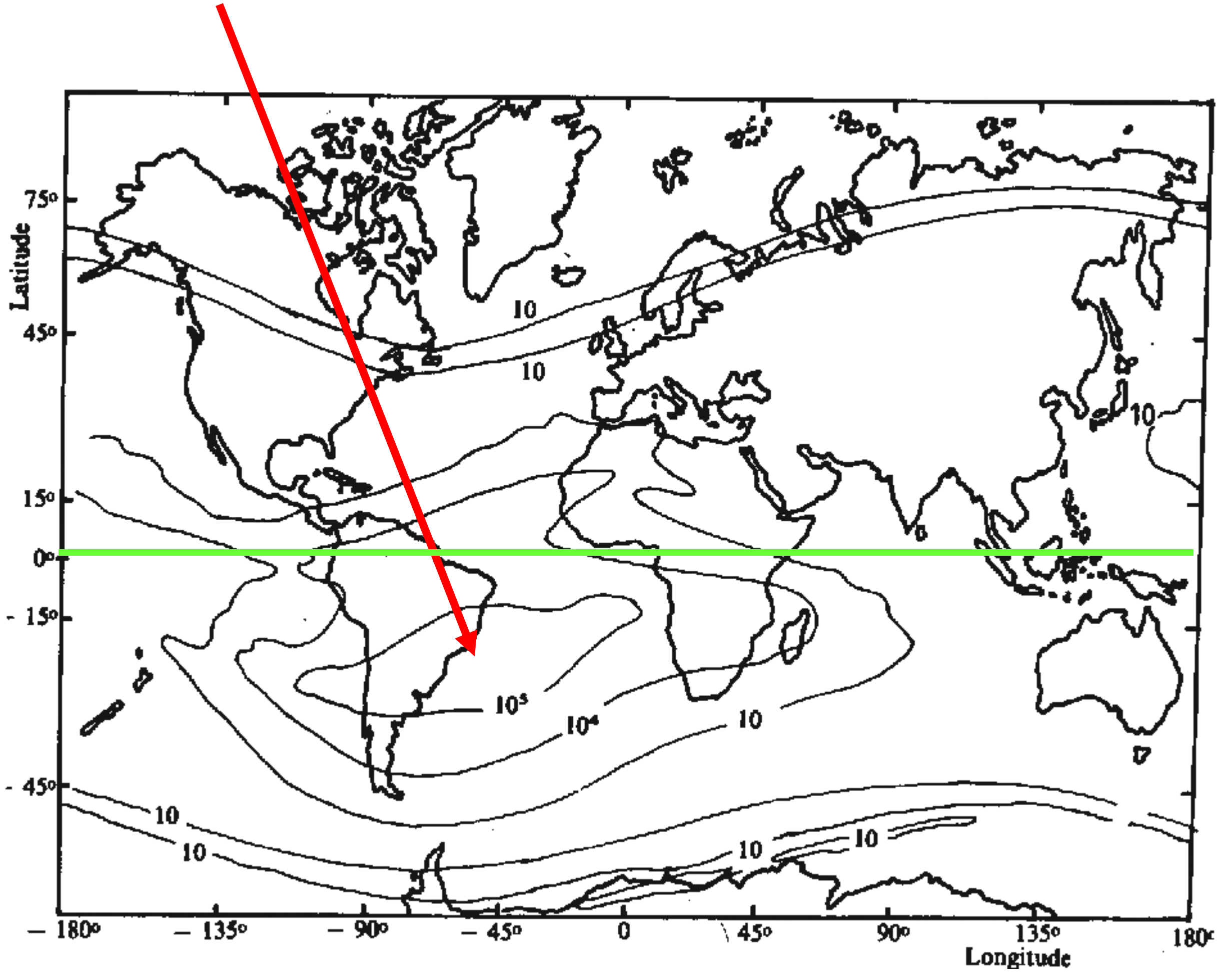
Radiation belts



Units are cm^{-3} s^{-1}. From Daly E.J. (1988)

South Atlantic Anomaly (SAA)

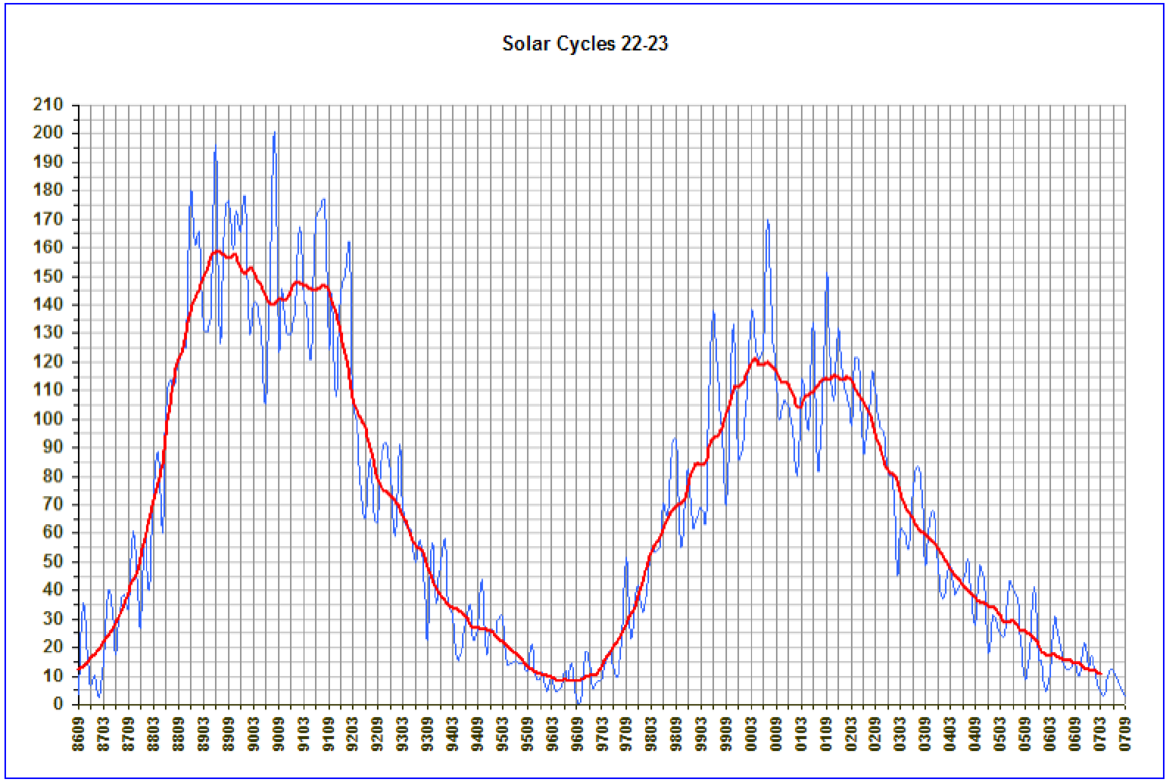
- Affects low earth orbit satellites (CGRO, RXTE, Chandra)
- RXTE: The PCA background is a function of time since SAA. There is radioactivation within the instrument, which decays on various timescales. To get an accurate estimate of the amount of activation, the HEXTE particle monitor is used, which remains on even during SAA passages. The PCA instrument itself is off during SAA passes, but the activation persists for several hours afterward.



Solar activity

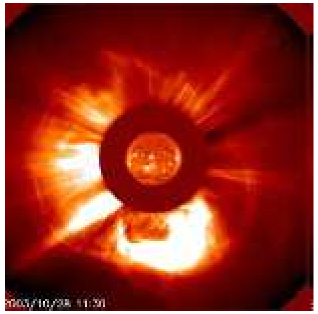
- Cosmic-rays (CR) are “modulated by the solar activity: i.e. the heliosphere expands and recedes during the solar cycle
- This prevent more or less CR to approach the earth (rigidity cutoff modulation)

Number of sun spots



- As a result the detector internal background is inversely linked to the solar activity if the long lived radioisotopes produced by spallation are not dominant

Solar outbursts



- Result of coronal mass ejection (mainly protons)
- Linked directly to solar activity (more frequent at solar maximum)
- Saturates counters of X and gamma-ray detectors (pile-up and dead time effects) and may be dangerous for PMTs
- The heliosphere inflates
- Cosmic-ray density is reduced near the earth
- Internal background of X and gamma-ray detectors may be reduced for a few days !

Background components

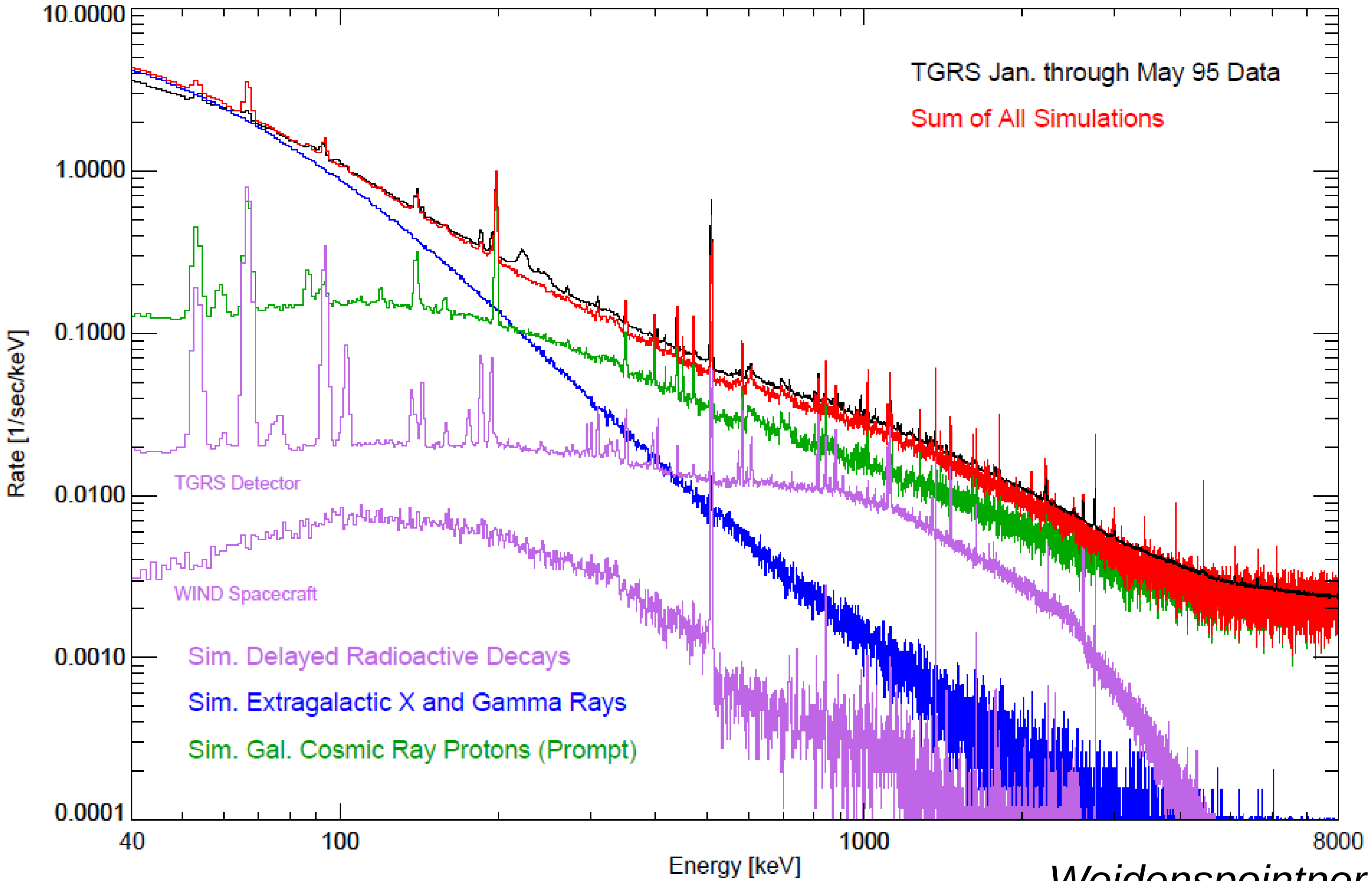
- Low Earth Orbit
  - CDB (FOV)
  - Atmospheric emission
    - CDB albedo
    - CR-induced
  - SAA (inclination > 5°)
    - Prompt
    - delayed

RHESSI, Chandra, SWIFT, Fermi

- High Earth Orbit
  - CDB (FOV)
  - CR-induced (solar modulation)
    - Prompt
    - delayed

XMM-Newton, INTEGRAL

TGRS background (around L1)



Weidenspointner - 2004

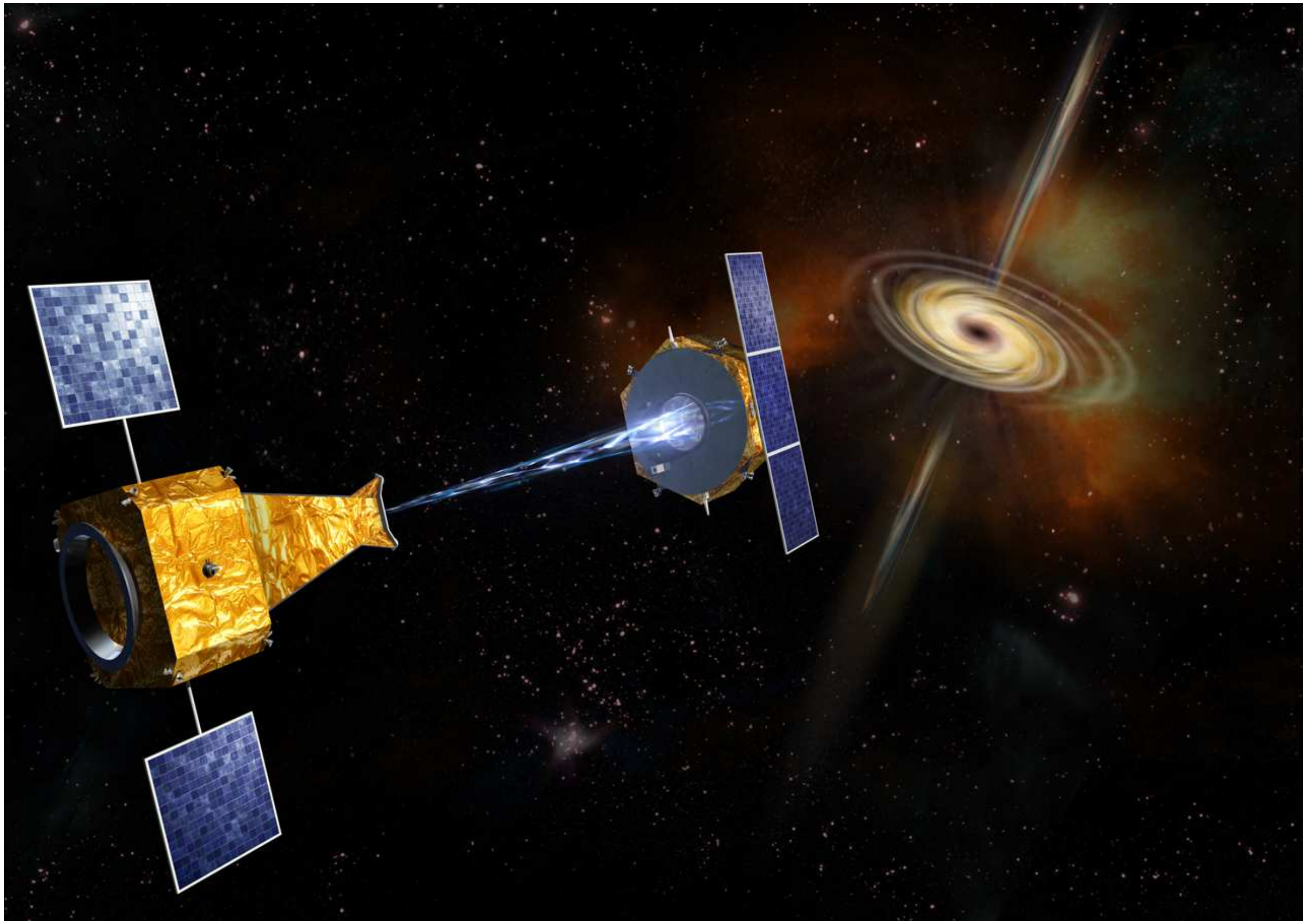
Background reduction

- Passive shields (against CDB and other sources)
- Choice of materials (against delayed instrumental background)
- Choice of orbit: Low Equatorial Orbit (e.g. Bepposax) is best from BKG point of view but
  - Flip/flop or 50% efficiency
  - Available tracking stations
  - Batteries
  - Rare launch opportunities (not commercially interesting)
- Anticoincidence (VETO) systems (against prompt instrumental background)
  - X-rays (Chandra, Simbol-X)
  - Gamma-rays (INTEGRAL)
- Phoswich detectors

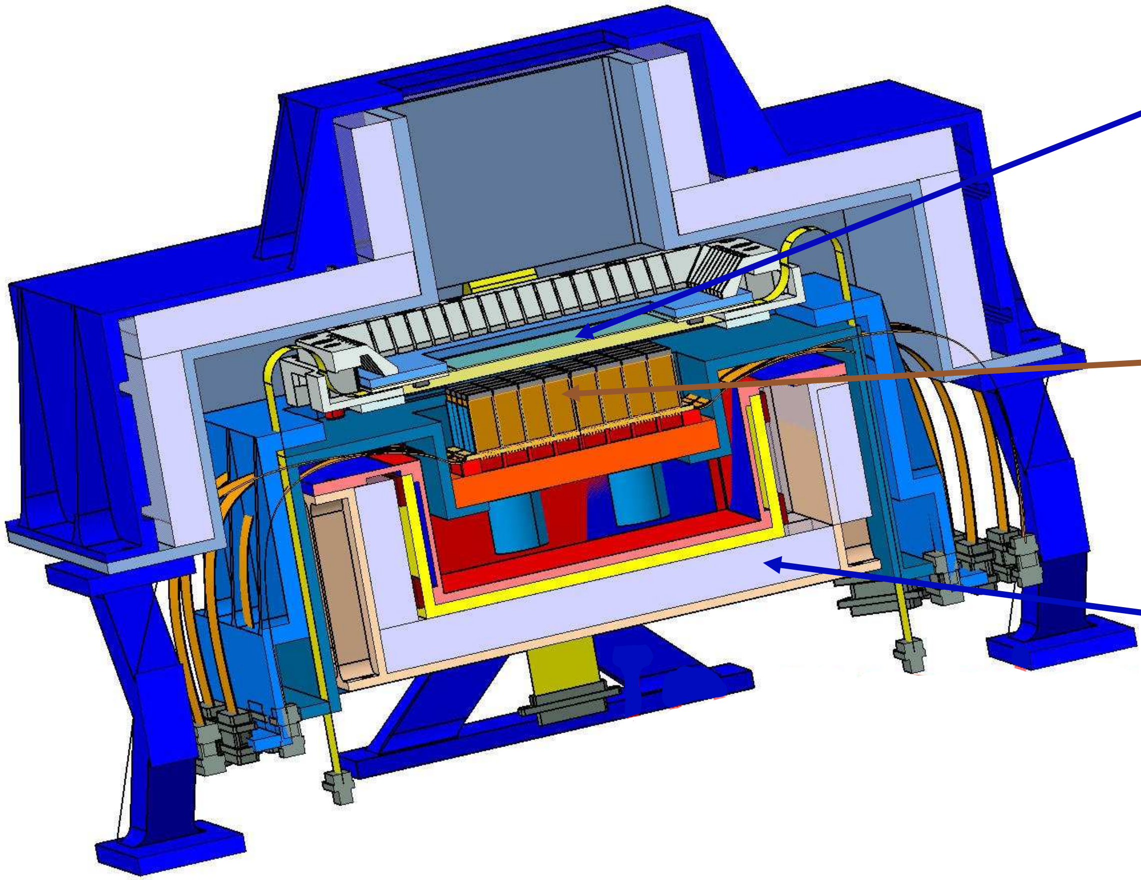
Anticoincidence systems (VETO)

- Most of the internal background is due to protons interactions in the detector and its surrounding material (spacecraft)
- Most CR protons are close to the ionization minimum (1 GeV) and cannot be stopped
- During their material (detector) crossing they leave ample energy deposits that may saturate the electronics (GRANAT/SIGMA, INTEGRAL/PICsIT)
- They can collide with nuclei in the experiment and produce unstable spallation products
- These unstable nuclei decay with gamma-ray emission that can contribute to the background
- If the decay is prompt (less than a few microseconds), the proton passage being easily detected with a simple additional detector, it can provide a VETO signal to prevent the coding of the simultaneous events that triggered the main detector
- Anticoincidence detectors are usually scintillators with relatively poor spectral properties, either plastic (very fast) or high Z (CsI, BGO)

Let's take an example: SIMBOL-X



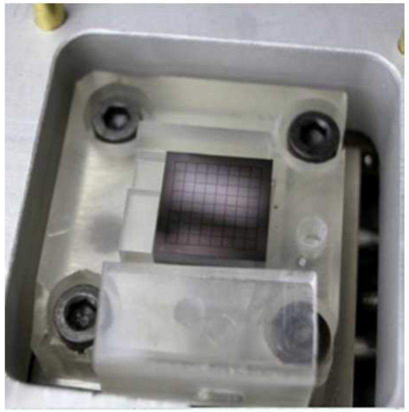
The focal plane assembly

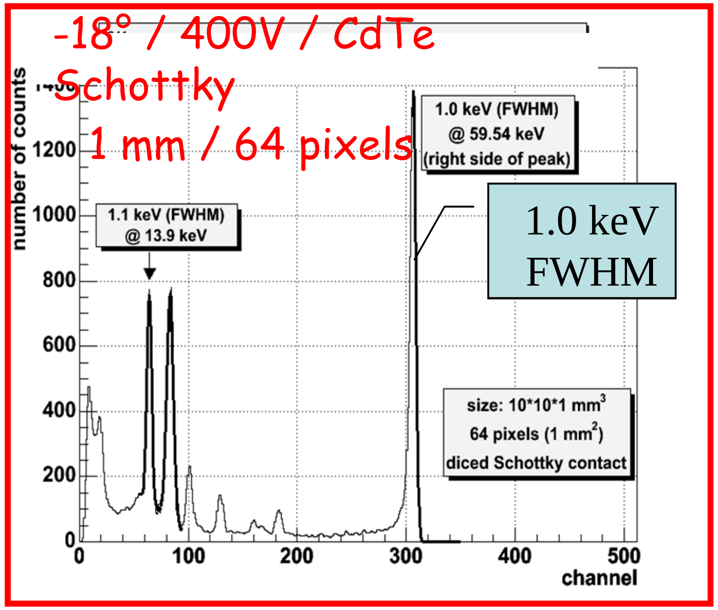


- Spectro-imaging system 0.5-100 keV, fast reading
- Full size : 8x8 cm2, 128x128 pixels of 625 µm
- Operation at ~ -40° C

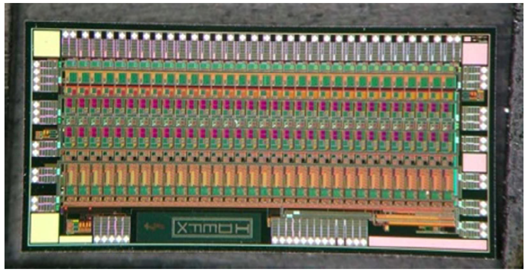
High Energy Detector Basic Brick (CEA/Saclay)

- Detectors : 2 mm thick pixellated CdTe or CdZnTe crystals

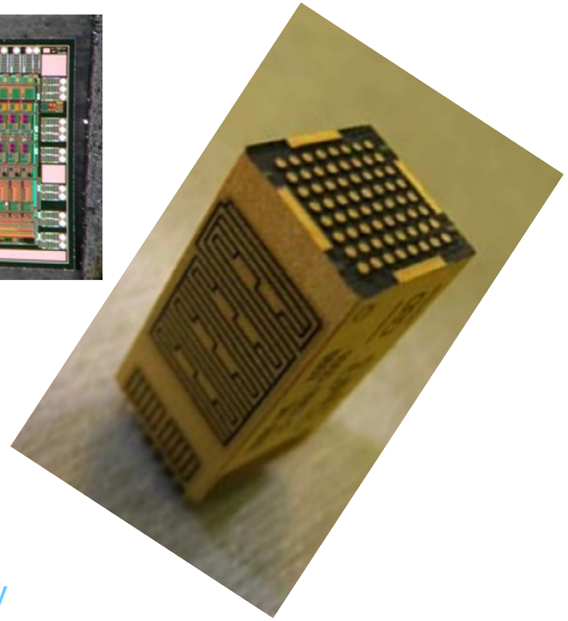




- Electronics : 32 channel front end chip (IdeF-X)



- Hybridization : on going qualification of process, 64 pixels "caliste" modules realized

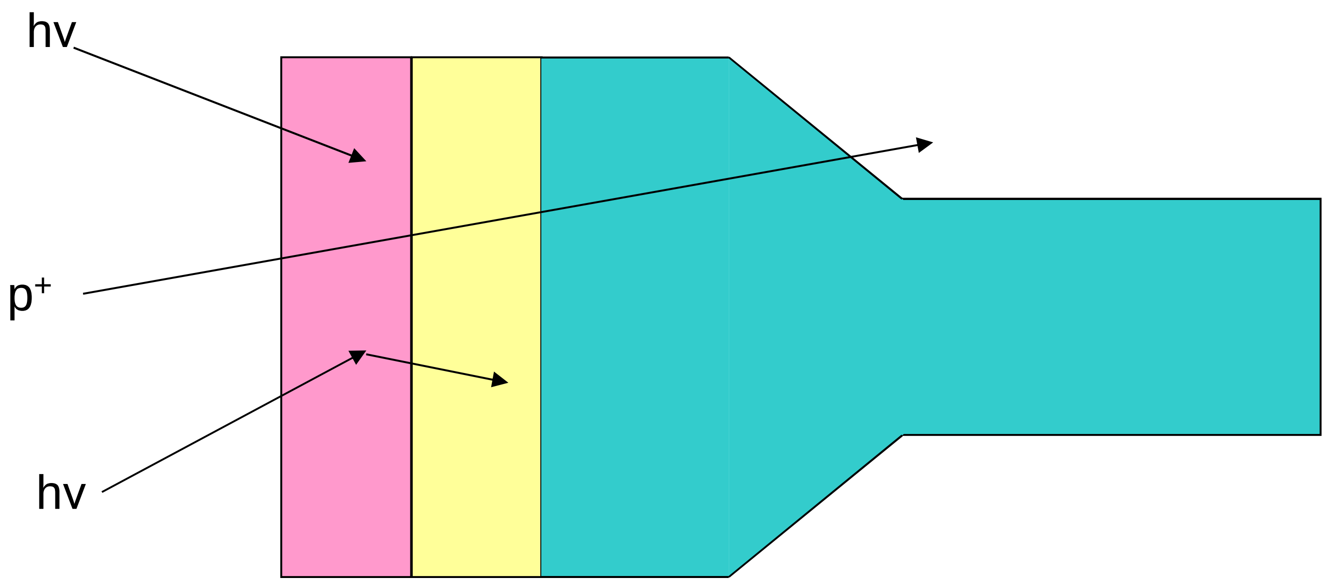


Phoswich detectors

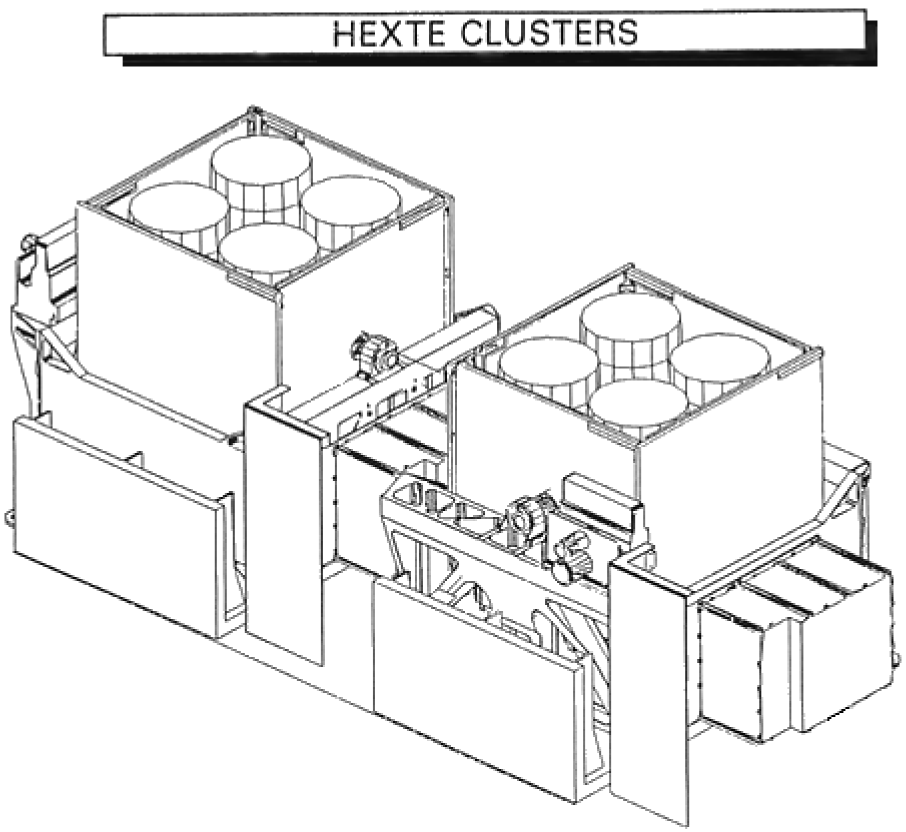
Principle

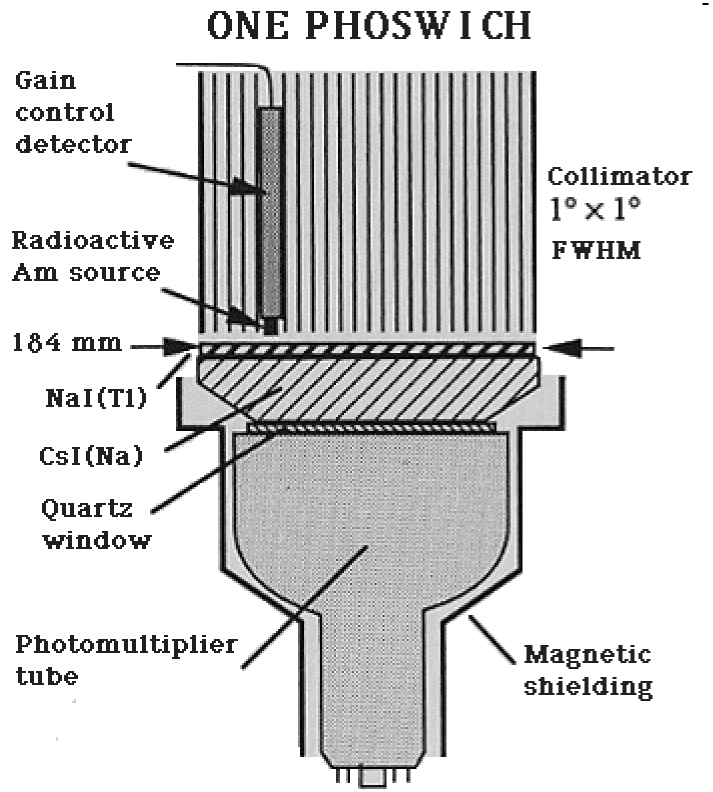
- Use two scintillators with different decay time, e.g. NaI (250 ns) and CsI (1 μs), readout by a single PMT
- Reject all events with pulse duration longer than the decay time of the fastest scintillator (>500 ns)

Phoswich have proven to be very efficient in reducing the background



RXTE/HEXTE





NaI(Tl): 250 ns
CsI(Na): 630 ns

Spectroscopy

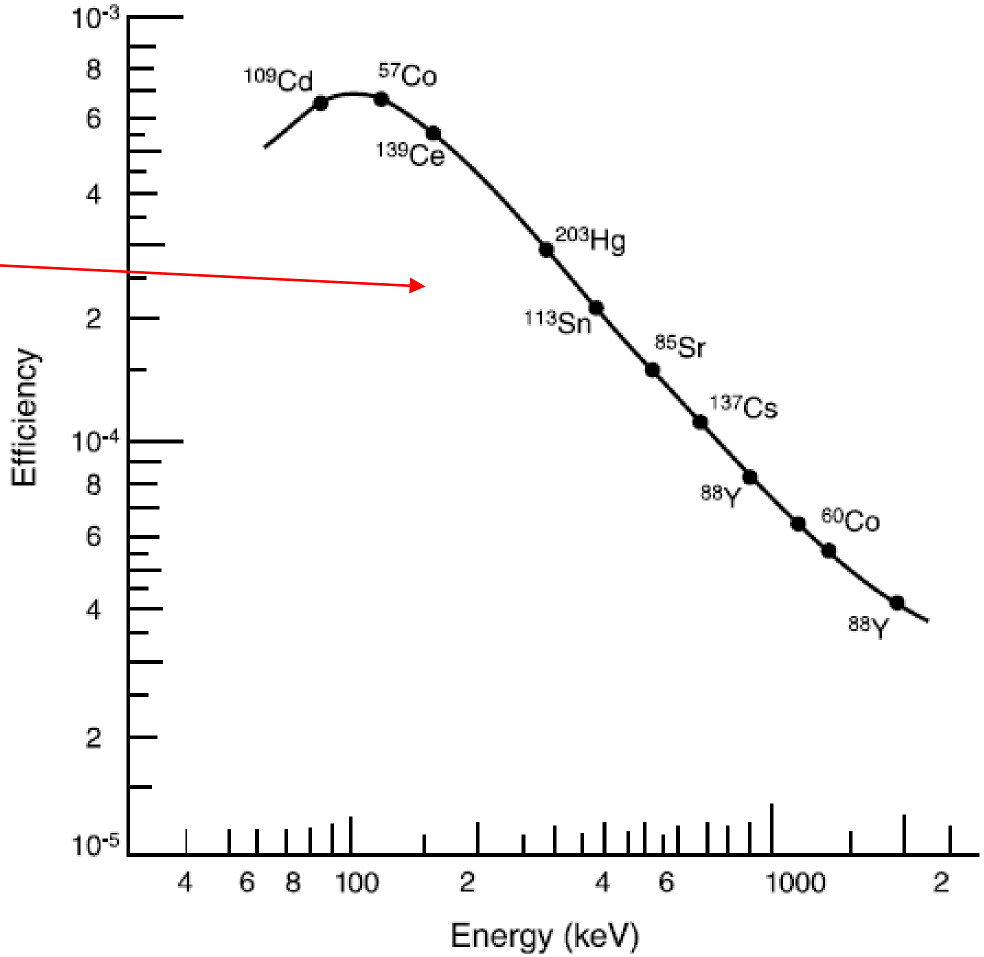
In general semiconductors are better spectrometer than scintillators

- X-rays:
  - Si (CCDs, STJ)
  - Bolometers
- Gamma-rays:
  - Cooled Ge (SPI)
  - CdTe (SIMBOL-X)
  - La Br3 (scintillator !)

Gamma-ray experiment calibration

- Requires
  - X-ray generators (with fluorescence targets)
  - Radioactive sources
  - Particle accelerators
- But
  - Compton scattering in the surrounding materials (e.g. floor, walls etc.)
  - Finite distance of radioactive sources

→ Monte-Carlo simulations



Monte-Carlo simulations

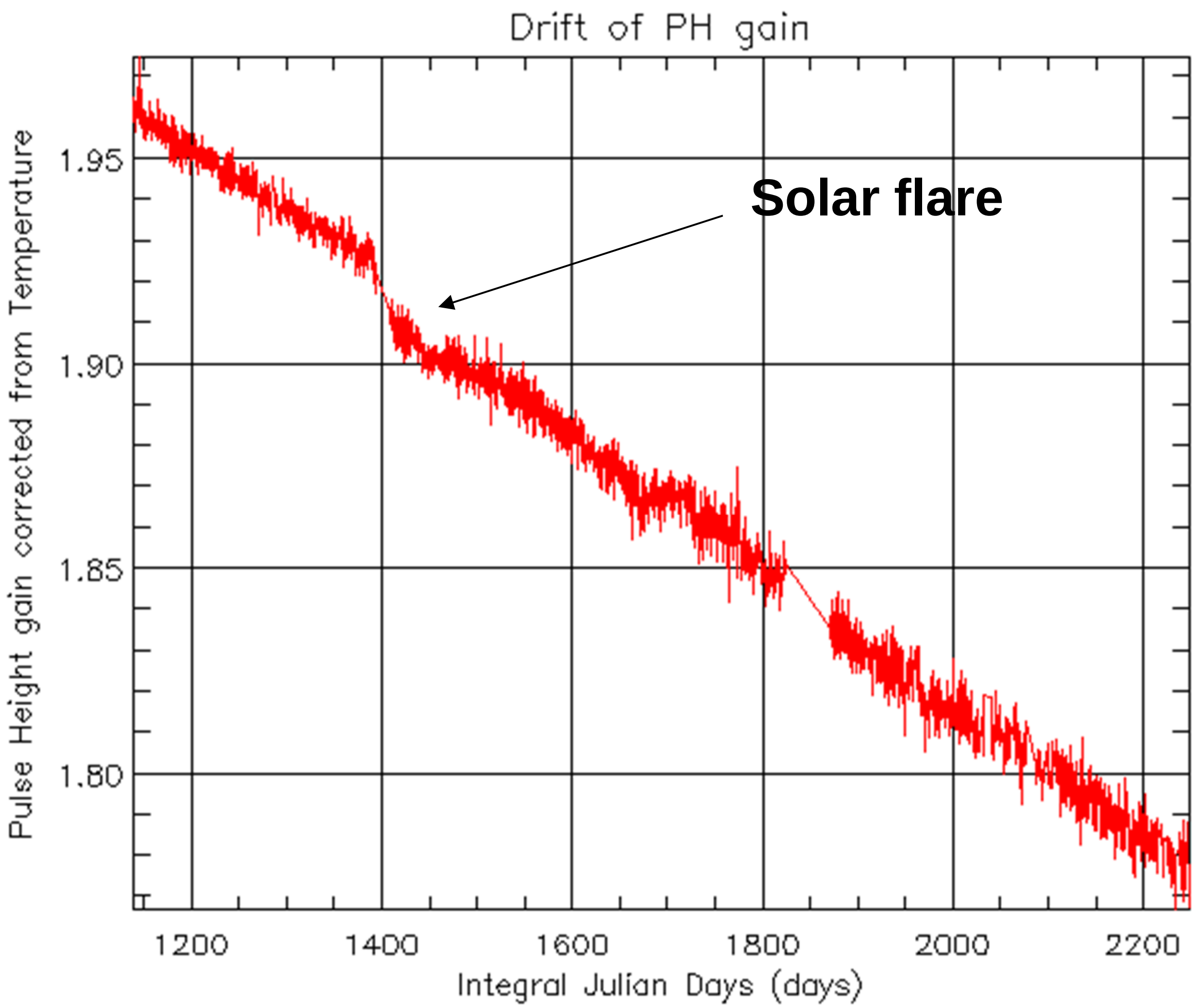
- Allows to compute
  - The sensitive area or ARF (Ancillary Response Function): sensitive area
  - The spectral response or RMF (Redistribution Matrix File)
- Necessary to
  - Interpolate the experiment response
  - Simulate trigger logics
  - Perform tests during flight

In-flight calibration

Needed to account for

- Change in the response due to launch stress or effects of irradiation (on detectors and electronics)
- Thermal gradients (vacuum)
- Thermal variations (sun aspect angle)
- Missing ground measurements
- Detector ageing

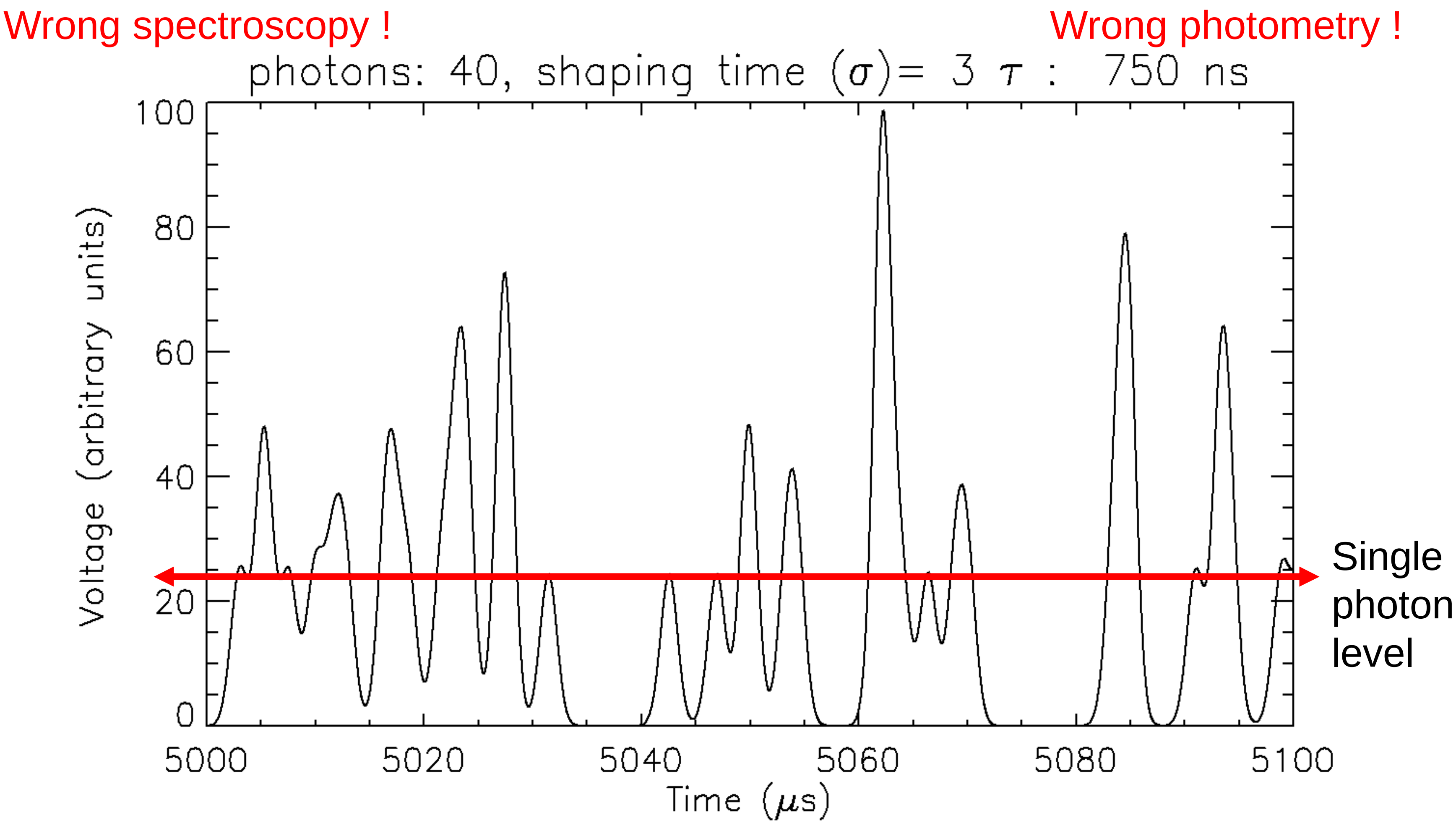
INTEGRAL/IBIS/ISGRI gain drift



Photometry

- The need is the stability of the detector efficiency (dead time, telemetry gaps, spectral drifts) or a constant knowledge of it
- Very high fluxes (e.g. magnetars) require fast detectors <u>and fast electronics</u> or many small independent detectors to avoid pulse pile-up and dead time effects

Pile-up effect



Dead time

It refers usually to the fraction of time (%) during which an instrument cannot make measurements.

- In some cases or circumstances it could be very large
  - Very high gamma-ray flux (e.g. bright magnetar outburst, TGFs)
  - Very high particle flux (radiation belts, SAA, Solar outburst)
- It can be due to
  - a VETO signal triggered by an anticoincidence system. The rapidity requirement is on both the main detector and the VETO detector !
  - The unavailability of the system that is doing something else; in general not in the wait state, accumulating the signal or encoding it for example. For very high gamma-ray flux, one way out (at the expense of power consumption) is to increase the number of detectors and decrease their sizes.

Timing

- High frequency periodic signals (e.g. millisecond pulsars) are usually not a problem for detectors. All you need is:
  - a stable clock
  - an accurate (~10 km) knowledge of the satellite position
  - An accurate knowledge of the detector efficiency (instantaneous photometry)
- However, very fast transient phenomena (e.g. magnetar outbursts, TGFs) requires very fast response of gamma-ray detectors (e.g. LaBr3) to avoid:
  - Pulse pile-up
  - Dead time

Telemetry limitations

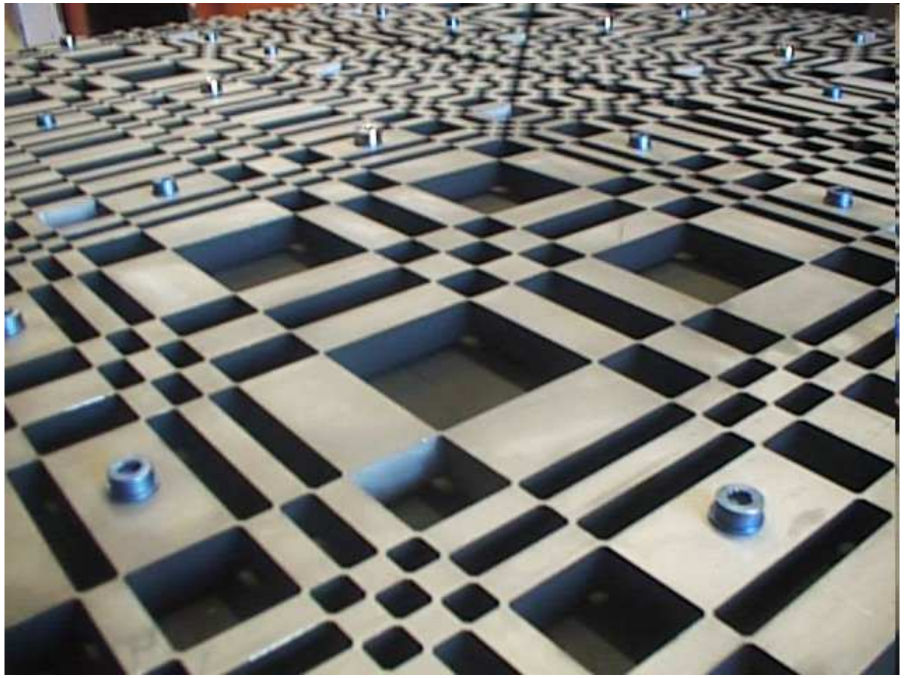
- Telemetry volume depends on the spacecraft distance
- Telemetry slot duration and frequency depends on the orbit
  - LEO: 10 minutes duration every 90 min
  - HEO: ~ 90% of the orbit
- Photon by photon transmission not always feasible
  - Gaps in telemetry (IBIS/ISGRI, SPI)
  - Grey filtering (JEM-X)
  - Histogramming mode (SIGMA, IBIS/PICsIT)

Imaging

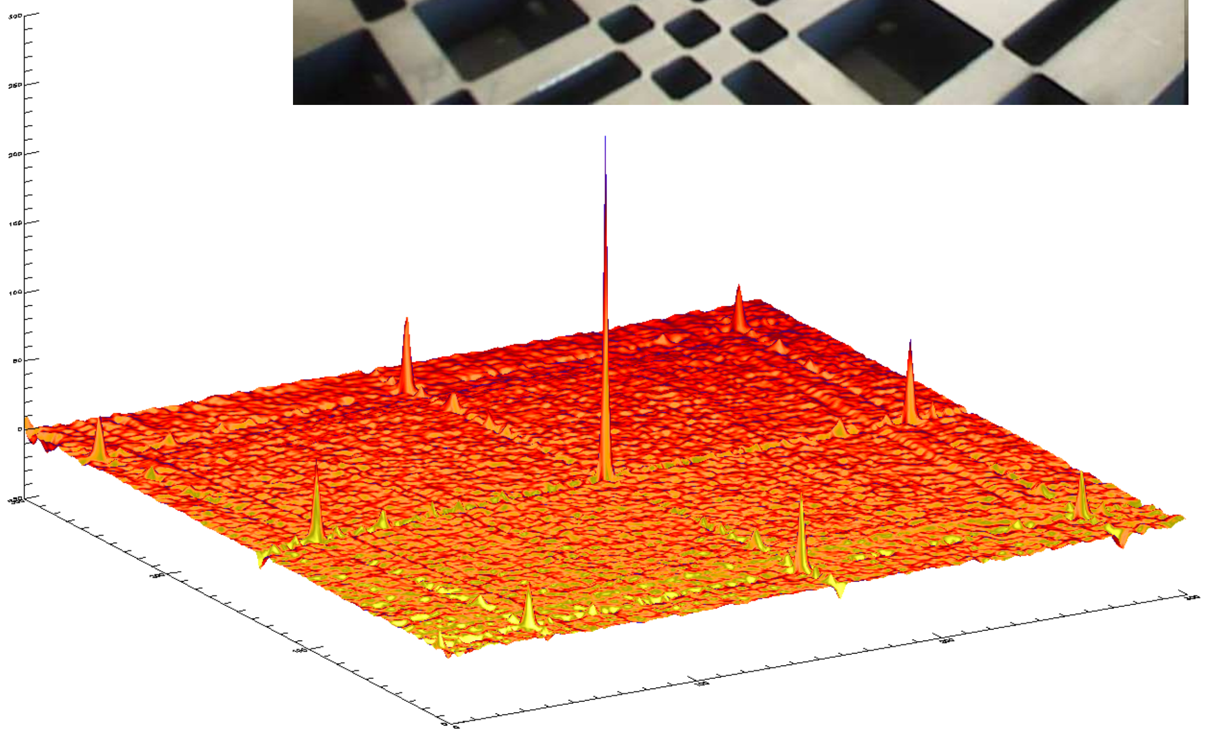
collimators

- Can be
  - passive (HEAO1-A4) or active (Suzaku: BGO)
  - Scanning (HEAO1-A4, MAXI) or pointing (Suzaku)
- Field of view ~ 1°
- No flux concentration

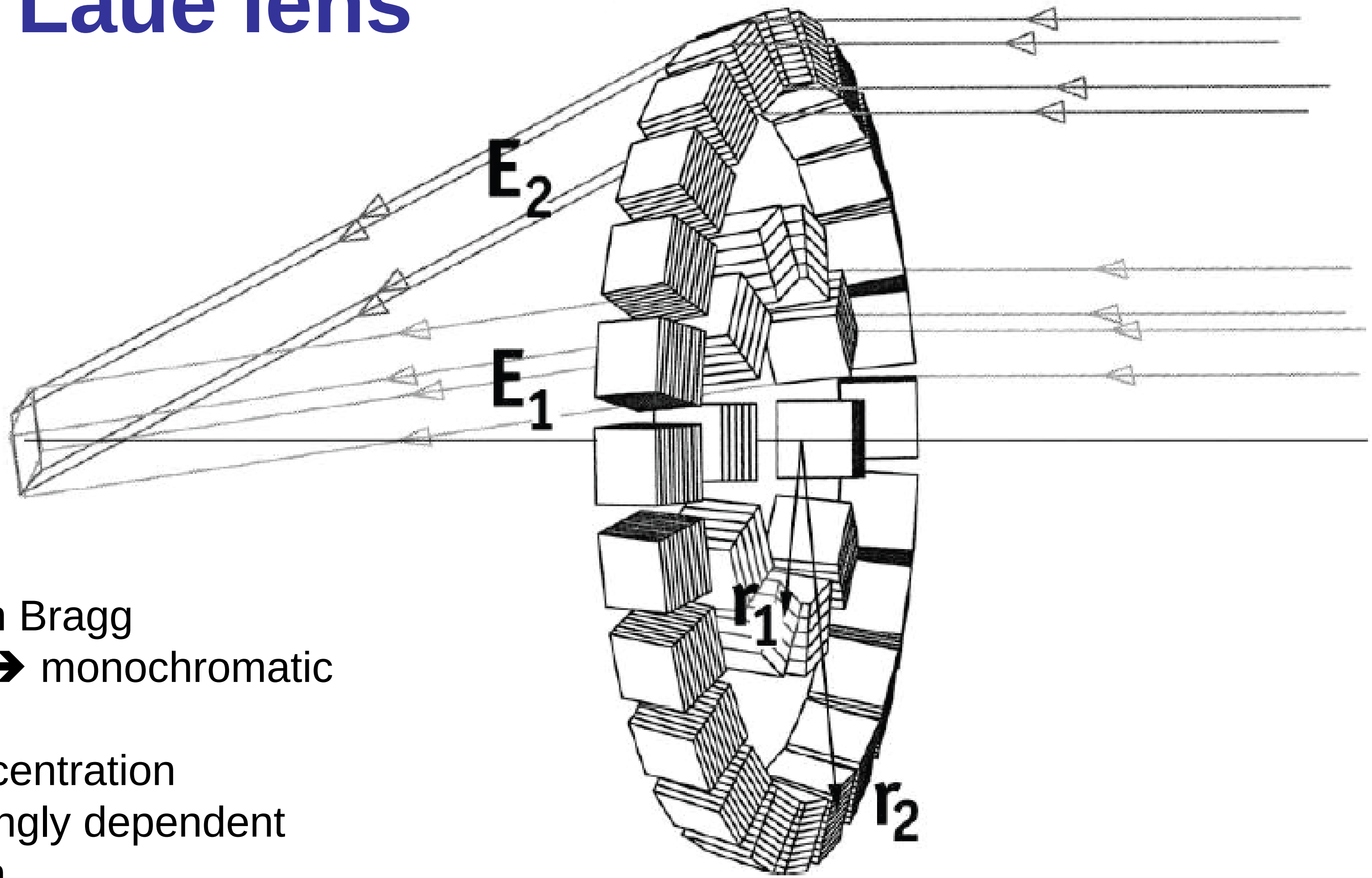
Coded mask imagers



- Wide field of view (20° FWHM for IBIS)
- PSF is energy independent (20 keV - 10 MeV for IBIS). Angular resolution is dictated by the camera spatial resolution and the mask detector distance (12’ for IBIS)
- PSF is multivariate ➔ cleaning algorithm
- No flux concentration
- No BKG reduction

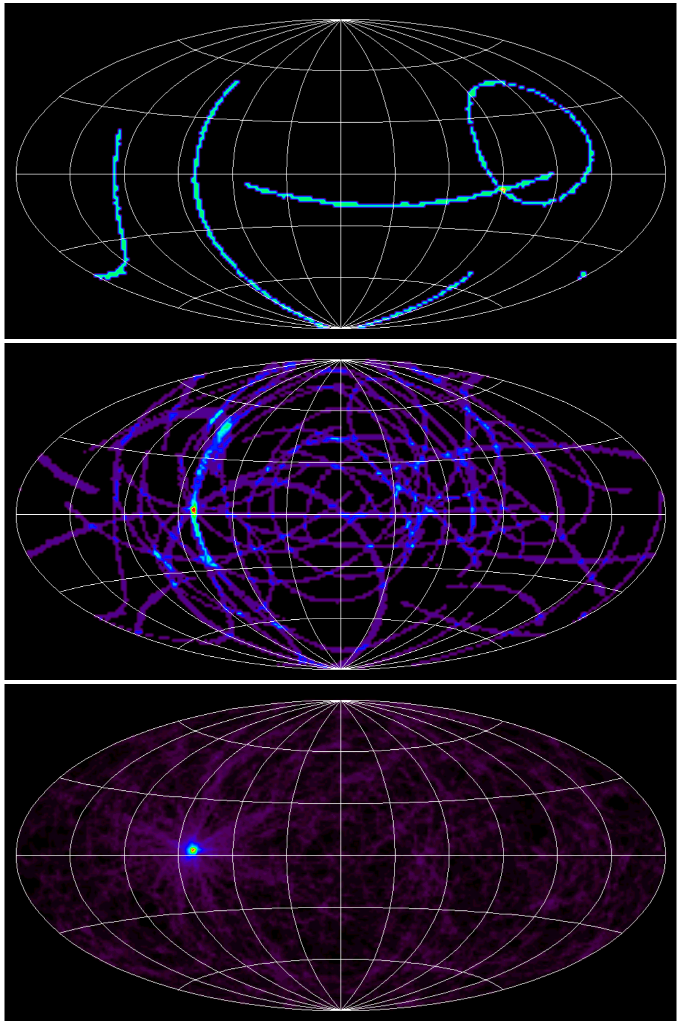


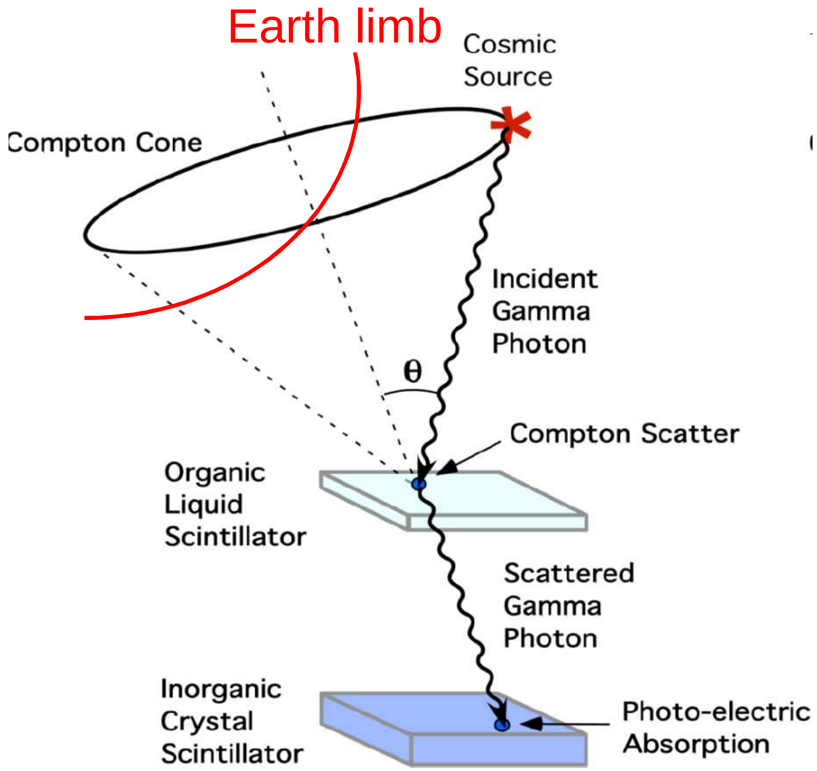
Laue lens



- Based on Bragg condition ➔ monochromatic response
- Flux concentration
- PSF strongly dependent on position
- Very small field of view (~ PSF)

Compton telescope



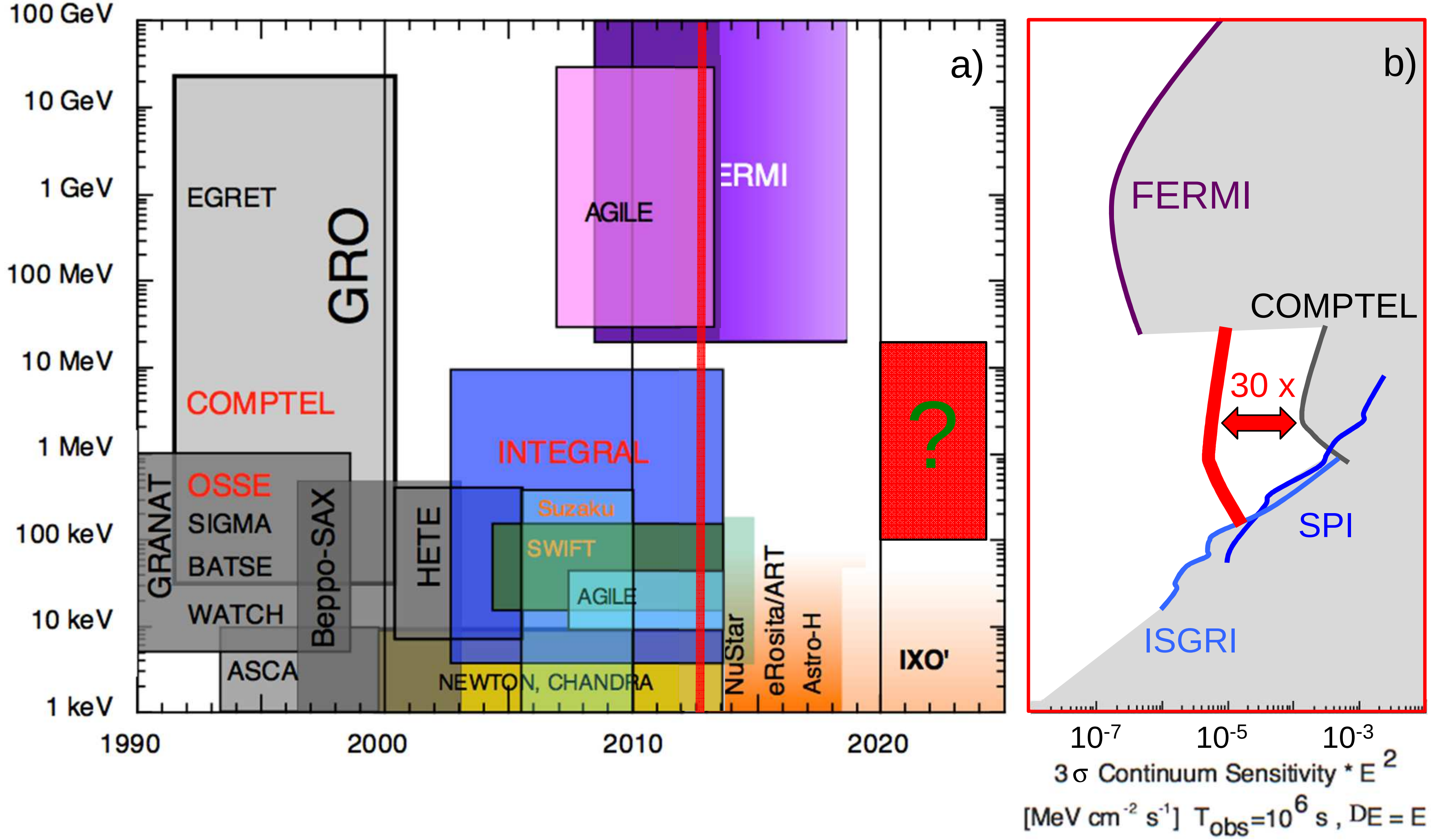


Very wide FOV
Poor angular resolution (>2° at 511 keV)
Good BKG rejection
Excellent polarimeter
Very clean spectral response
Requires <u>good</u> and <u>fast</u> <u>imaging</u> <u>spectrometers</u>

sensitivity

- The sensitivity can be defined as the weakest flux that can be detected by an instrument
- We should distinguish the sensitivities
  - to extended and point sources
  - To continuous or line emission
- It is usually given at a given statistical level (e.g. 3 sigma) and for a given observing time
- In a background limited observation it can be written as: $S = 3*\sigma_B/A$, where σ_B is the fluctuation of C_B the background count rate ($\sigma_B = [C_B/t_{obs}]^{1/2}$) and A is the effective sensitive area
- In the case of a coded mask experiment such as INTEGRAL/(IBIS, SPI, JEM-X) or SWIFT/BAT it can be expressed as: $S = 3 * [C_R/t_{obs}]^{1/2}/A$

roadmap of space-borne high-energy astrophysics



Post-INTEGRAL area : a white spot on the high-energy astrophysics roadmap