Instruments for High-Energy Astrophysics (part II)

partly adapted from G. Malaguti's presentation

Detectors for X-ray and γ-ray astronomy

Low-Medium energies (E≈1−20 keV)

•Proportional counters (mostly adopted in the past, 'evolution' of Geiger counters)
•Micro-channel plates (MCP; provide very good imaging; ex: *Chandra*)
•Micro-calorimeters (for high spectral resolution; ex: *Hitomi*, *XRISM*, *Athena*)
•CCDs (widely used, valid for both imaging and moderate-quality spectroscopy, low background; ex: *Chandra*, XMM-*Newton*)

Intermediate energies (E≈15 keV − MeV)

•Scintillators (high efficiency, moderate spectral resolution)
•Solid-state detectors (high efficiency, good spectral resolution, cooling problem; ex: *NuSTAR*)

High energies (E≈MeV − GeV)

•Spark chambers and converters/trackers (ex: *Fermi*, *AGILE*)

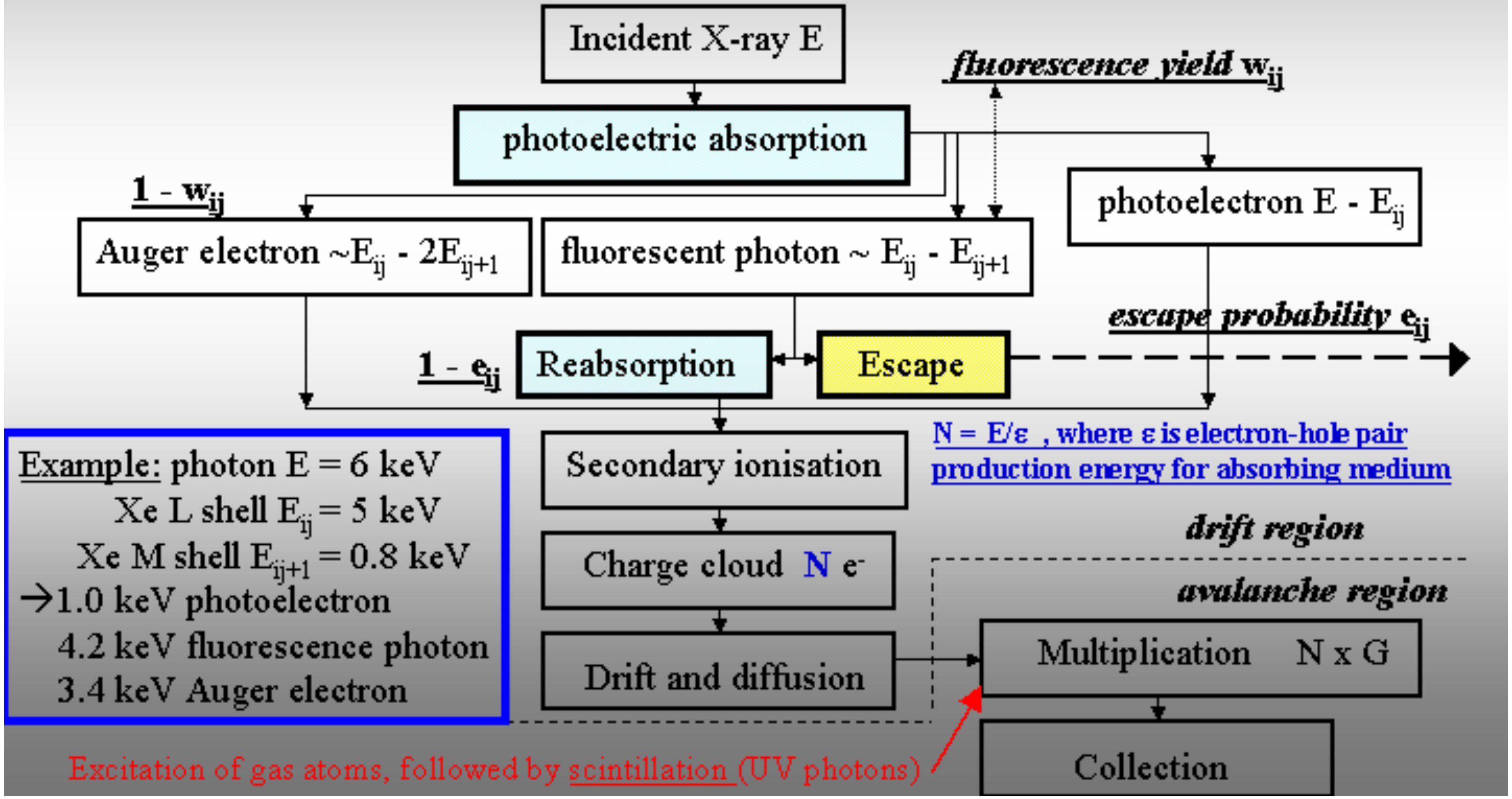
Choice of the detector motivated by the science goals

Proportional counters

Proportional counters. I

Detectors – detection processes/2

Photoelectric absorption is the major process used for various counter applications in astronomy. The flow of the process for a gas proportional counter below is descriptive for a general case.

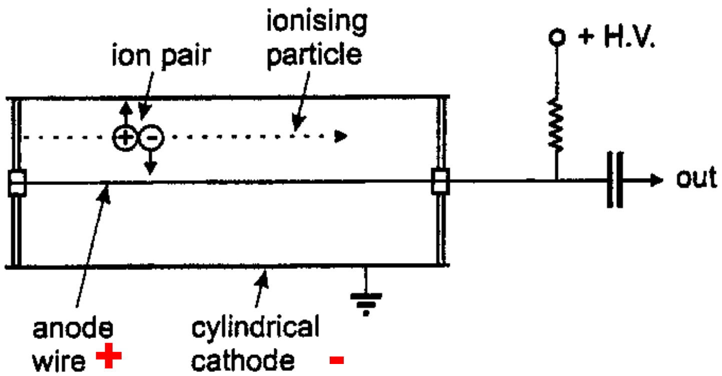


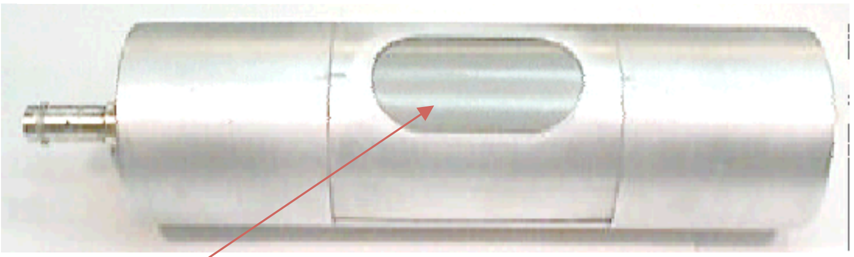
Proportional counters. II

Cylinder Proportional Counter

developed over a century ago it consists of a thin wire anode coaxially positioned in a gas-filled cylindrical cathode tube

First proportional instrument used for X-ray astronomy



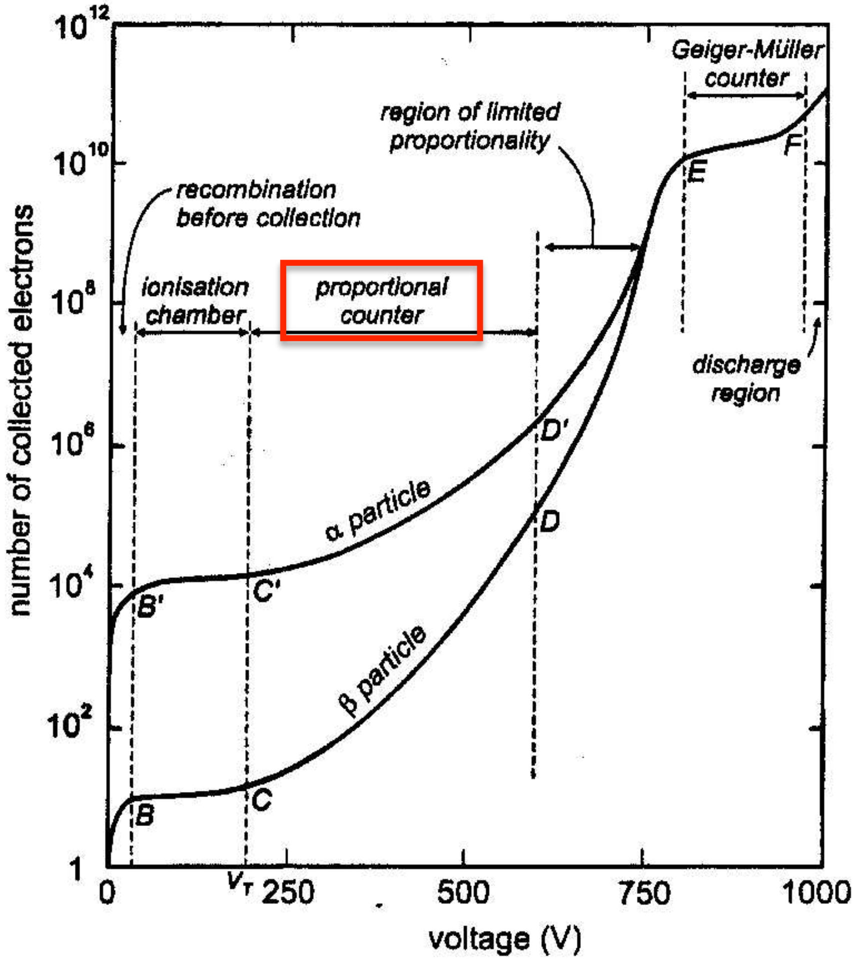


entrance window

In a proportional counter, X-rays are detected by photo-ionization of the counter gas

When a photon interacts in the gas, some gas atoms are ionized, and the electrons are attracted to the positive anode wire. Near the anode wire, the **electrons are accelerated** by the high electric field, producing a **cascade of electrons** that result in a large electric pulse

Proportional counters. III



Depending on the voltage applied on the wire different mode of operation are possible:

- ionization
- proportional
- limited proportionality
- Geiger-Müller (e.g. original AS&S experiment, ΔE/E unconstrained)

Low voltage implies high possibility of electron and ion recombination

Proportional counters. IV

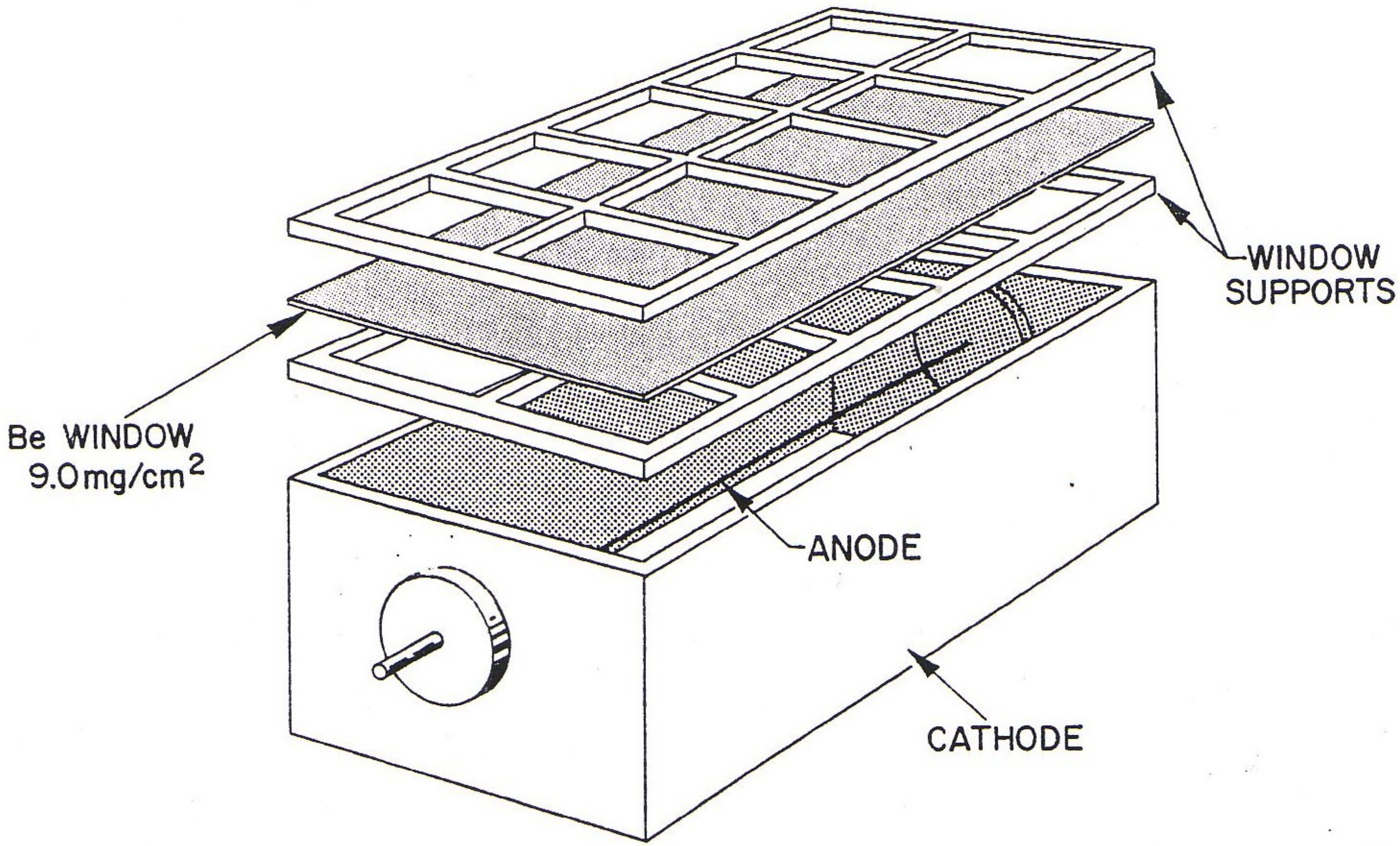


Fig. 2.10. Schematic layout of a thin window gas proportional counter. The Be window is cemented between a supporting 'sandwich' which in turn is hermetically sealed to the cathode to preserve the gas integrity. The anode is usually kept under tension by a spring. The charge sensitive preamp and high voltage power supply are ideally mounted as close as possible to the anode feed-through.

Proportional counters. V

Gas-filled detectors (Argon, Xenon), energy range≈1−20 (30) keV

•The incident X-ray produces a number of ion-electron pairs proportional to its energy

•A high bias voltage is applied and the liberated electrons acquire sufficient energy to produce new ion-electron pairs (strong field **drift region**, amplification takes place). Townsend avalanche

•The voltage is such that the number of ion-electron pairs reaching the anode is **proportional** to the number of ion-electron produced by the incident X-ray

Quantum efficiency

$$\epsilon(E) = e^{-\sigma_W t_W}\left(1 - e^{-\sigma_g t_g}\right)$$

transmission (window, low-Z) Be

absorption (gas, high-Z) Ar, Xe

The energy resolution is limited by statistical fluctuations in the number of electrons liberated (mean energy to form a pair ~30 eV).

Example: a 10 keV photon produces ~300 electron-ion pairs → ~5% energy accuracy

Proportional counters. VI

The induced charge is proportional to the energy deposited in the detector

$$P = (E/W)\times G$$

P: pulse height (amplitude)

E: energy released in the detector

G: gain in the avalanche process ($\propto$V)

W: energy required to create one electron-ion pair (eV)

N=E/W

f= factor to account for variance in the gas gain

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

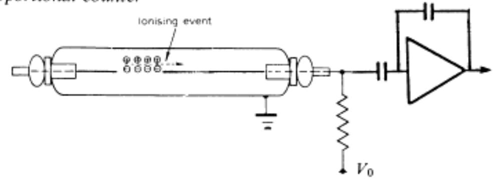
$$\mathbf{R = 2.35\sqrt{\frac{(F+f)}{N}} = 2.35\sqrt{\frac{(F+f)W}{E}}}$$

- Esempio: Ar
  - W=26.2 eV/pair
  - F=0.17
  - f=0.50
  - R (at ≈5 keV) = 12-13%

Gas impurities, loss of electrons at the entrance window may deteriorate the energy resolution

360

Gas proportional counter



Since a proportional counter has internal gain, the system noise can be neglected and the energy resolution is:

$$(\Delta E)_{FWHM} = 2.35[(F+f)WE]^{1/2} \quad \text{eV},$$

where

E = energy deposited in counter (eV),

F = Fano factor,

f = a factor to account for variance in the gas gain,

W = mean energy to form an ion pair (eV).

As an example, for methane gas:

$F = 0.26$

$f = 0.75$

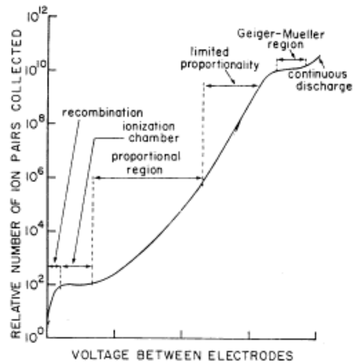
$W = 27$ eV,

so that for a proportional counter:

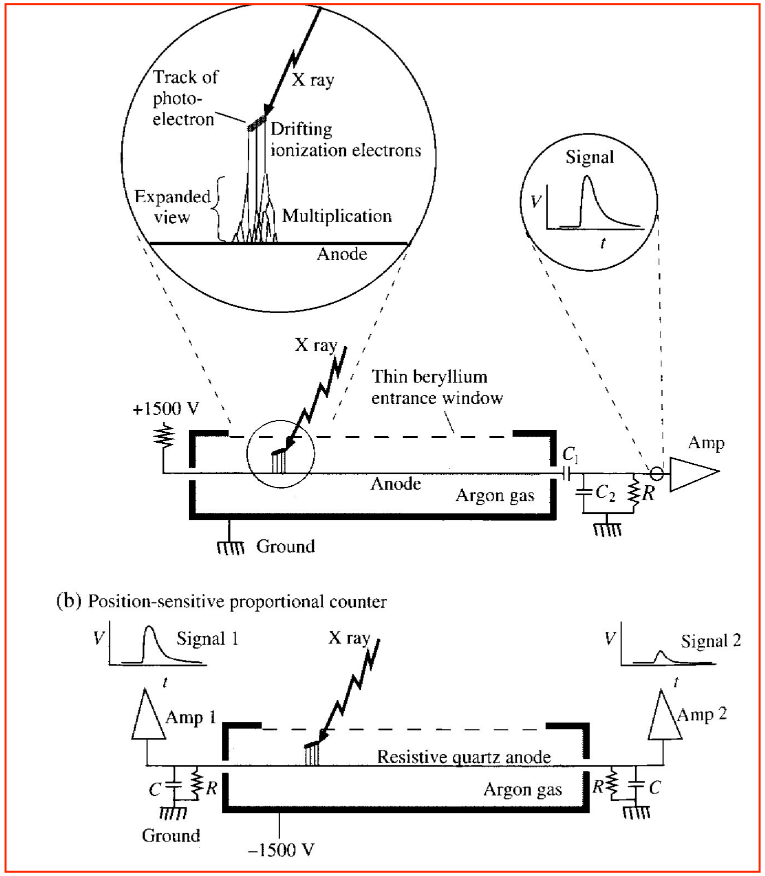
$$\frac{E}{(\Delta E)_{FWHM}} = 2.6E^{1/2} \quad \text{(with } E \text{ in keV)}.$$

Energy resolution

Total number of ion pairs collected in a gas-filled chamber as a function of the voltage across electrodes of the chamber.



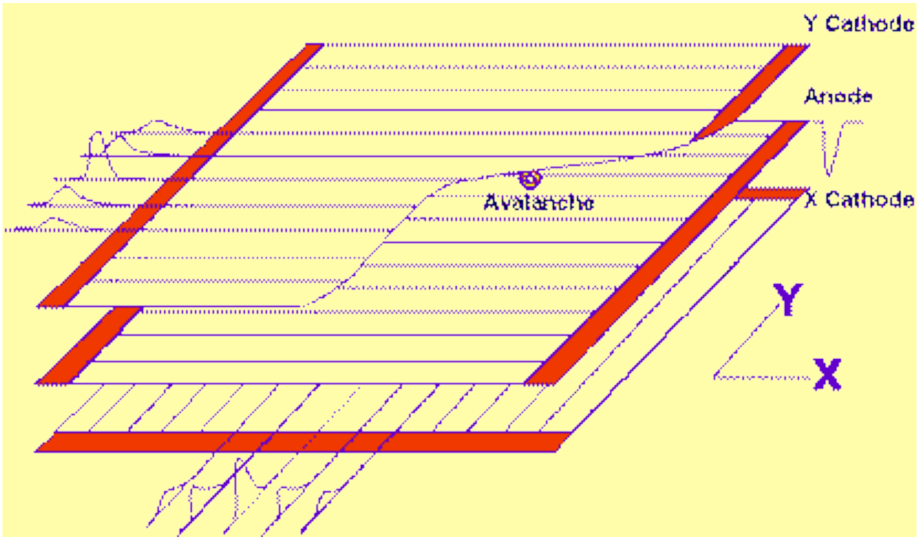
Position-sensitive proportional counters.I



Using ***resistive anodes*** and measuring the charge reaching each end of the anode, it is possible to reconstruct the position of the incoming photons

Position-sensitive proportional counters. II
Multi-Wire proportional chamber (MWPC)

(G. Charpak, 1968)



an array of many anode wires, 1×2 mm apart, in a single gas volume enclosed between two metalized cathode planes.
Each wire acts as an independent proportional counter with a position resolution of 0.2÷1.0 mm.

2D information on the interaction point is derived from the barycentres of the induced charge distribution on the cathode planes.

Typical performances:
- Spatial resolution 0.25 mm (FWHM) at 1 keV
- Energy resolution $\Delta E(FWHM)/E \approx 0.45 \times E^{-1/2}$ (E in keV)

Examples of use:
ROSAT/PSPC
Einstein/IPC

Position-sensitive proportional counters.III

The location of arrival of each X-ray photon is measured

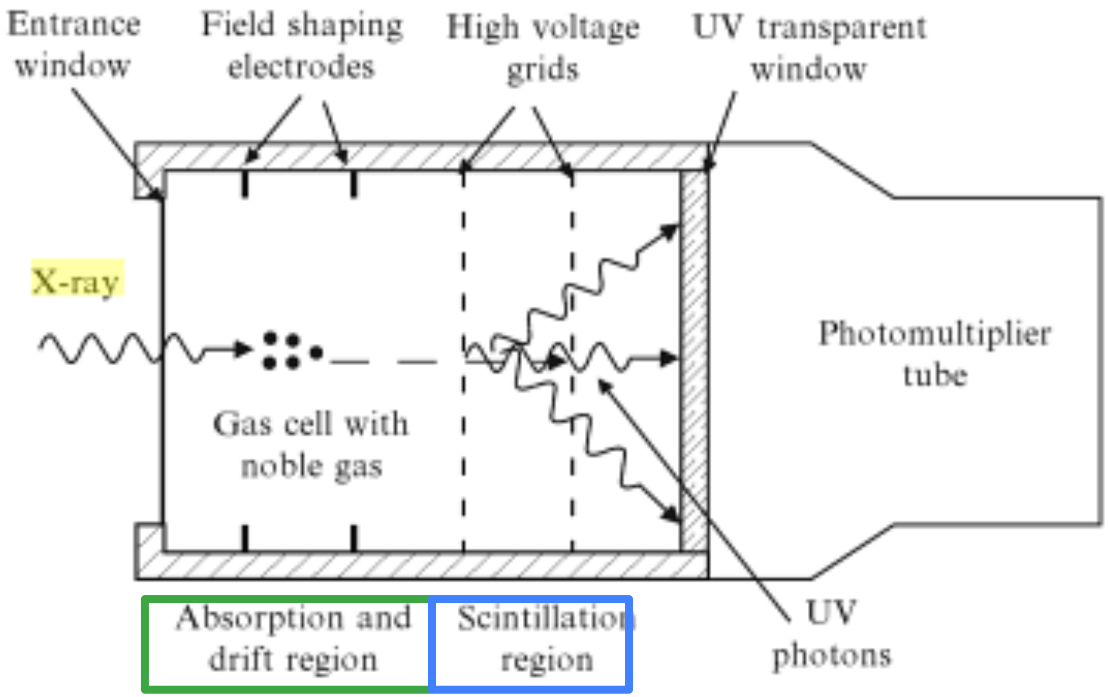
- Ratio of the charge collected at each end of the anode determines the X location (the charge is inversely proportional to the distance from the collection point)
- The location in the Y direction is determined by means of a second orthogonal anode wires system

from proportional counters to gas scintillation proportional counters

Gas Scintillation Proportional Counters (GSPC)

- The incident X-ray photon produces a number of ion-electron pairs proportional to its energy
- The bias voltage is applied and the liberated electrons acquire energy only sufficient to **excite** the other atoms of the gas (**drift region**, amplification takes place)
- **UV photons** are then produced (**scintillation region**) and detected by a photomultiplier
- Better energy resolution than in classical proportional counters

Gas scintillation proportional counters. I

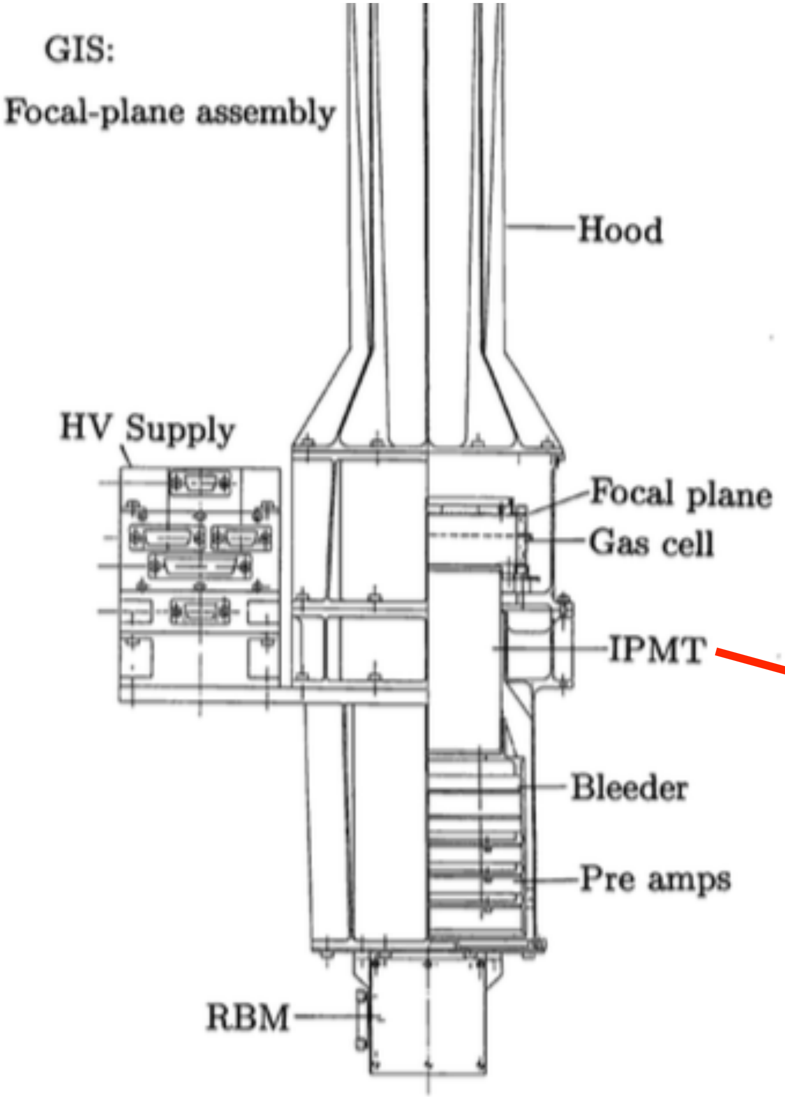


X-rays are absorbed by noble gas or a mixture of noble gases in an **absorption and drift region**. Then the produced electrons pass to a high-field **scintillation region** where they acquire sufficient energy to excite the gas without producing ionization. The de-excitation produces UV (scintillation) photons

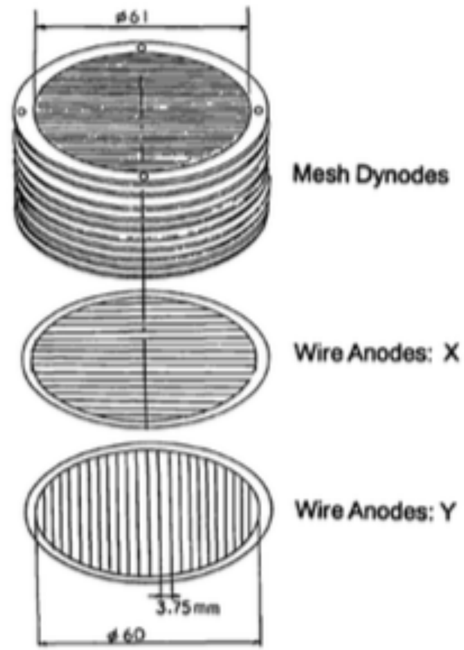
The final signal (PMT) is proportional to the number of collisions.
Advantage: many scintillation photons are produced, hence good energy resolution

Gas scintillation proportional counters. II

Gas scintillation proportional counter (GIS) onboard *ASCA*

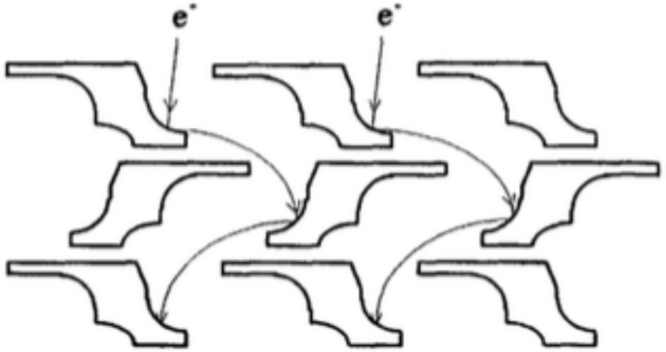


UV photons from scintillations produce a photoelectron in the IPMT (**position-sensitive phototube**), then 'multiplication' via dynodes. The size of the electron cloud during this process is fairly confined. This feature enables the position determination using the cross-wire anodes



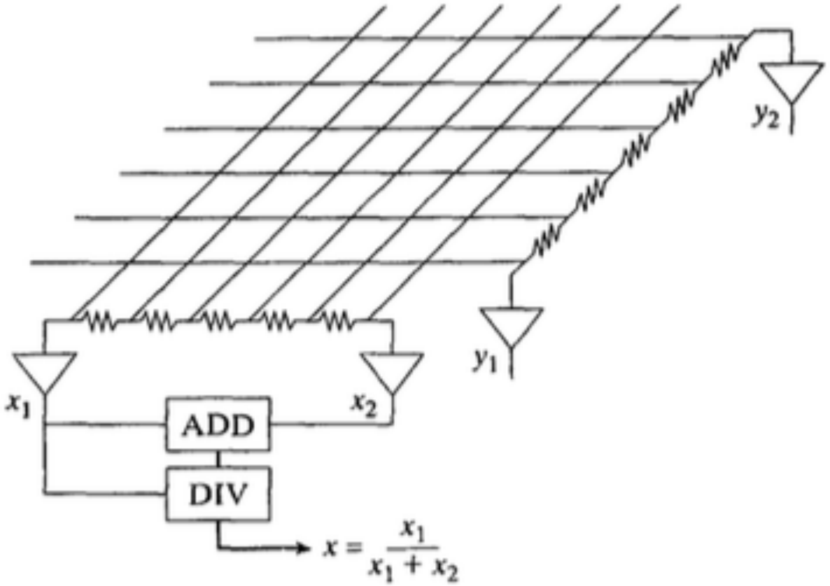
Ohashi+96

Gas scintillation proportional counters. III



Metal channel dynode structure (or fine meshes) – layering metal dynodes to limit the charge from spreading in the PMT (thus focusing it in a narrow spot)

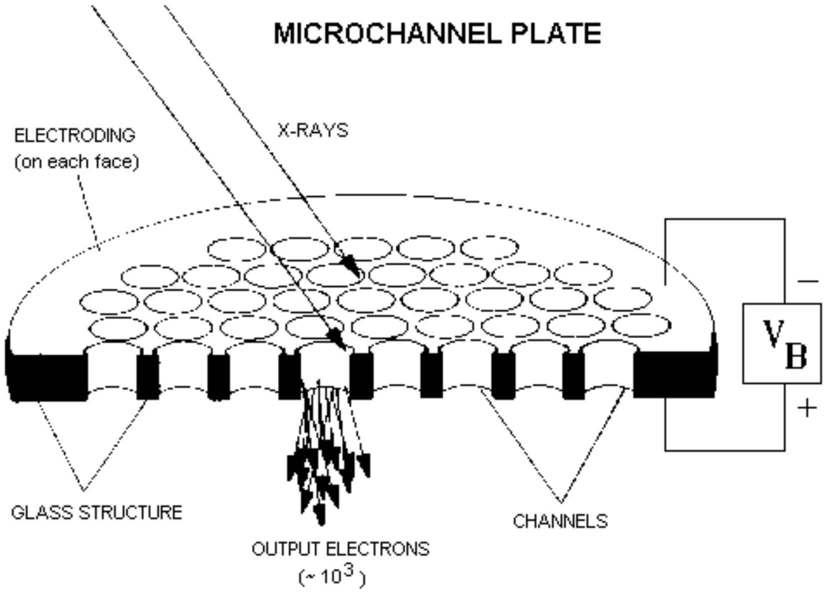
A possible problem is the non-uniformity of response to light across the entrance area of the photocatode



Crossed anode wire – two layers of node wires, each layer consisting of multiple parallel wires – separate *x* and *y* position coding

Micro-channel Plates (MCP)

Micro-channel plate. I



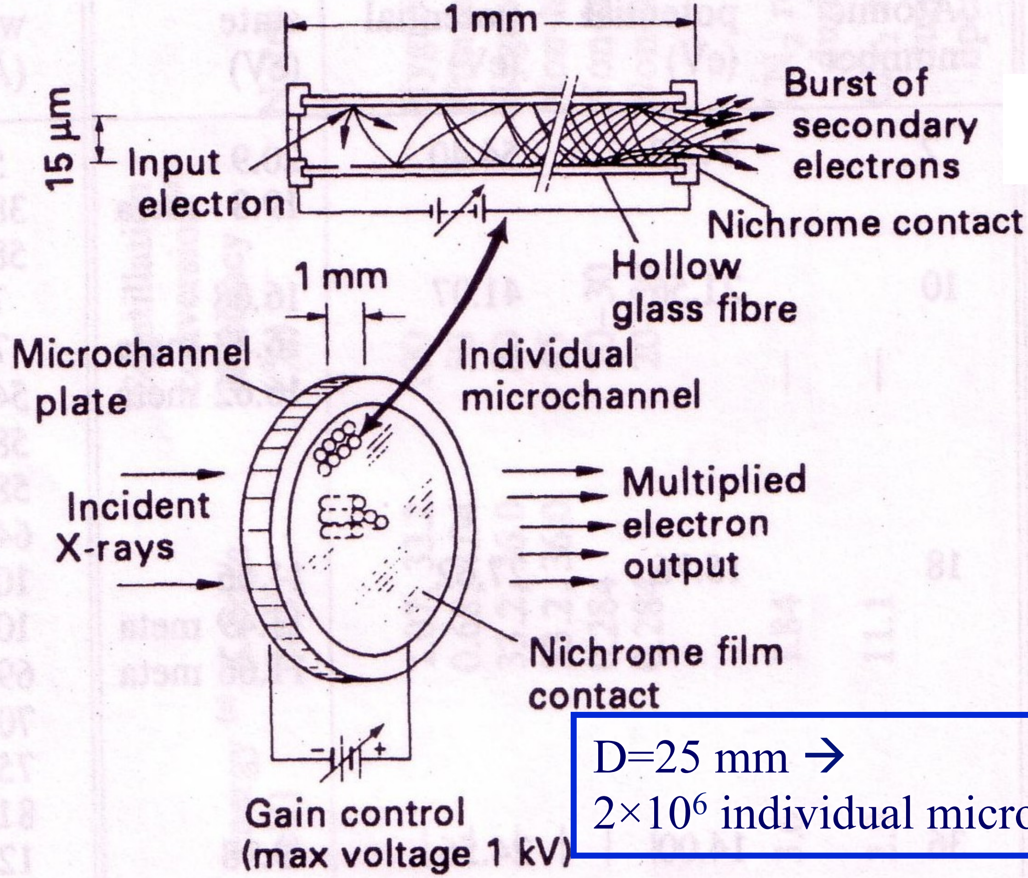
How they work

A photon enters in one of the channel of the MCP structure at a given impact angle, impacting the walls of the channel.
The impact produces an *avalanche of electrons* which propagate through the channel, thus *amplifying the original signal* by several orders of magnitude (gain up to several $\times 10^7$ in *Chandra*/ HRC-I), depending on the geometry of the MCP and the intensity of the applied electric field.
The electron flux out the bottom of the MCP impinges onto the cross grid detector. The location of charges on the grid is processed to build a good-quality image of the X-ray source

Micro-channel plate. II

Schematic diagram of a microchannel plate detector. (Adapted from Behr, A. in Landolt–Bornstein, subvol. 2a, Springer-Verlag, 1981.)

Compact electron multipliers of high gain
Acts similarly to a photo-multiplier tube



The secondary electrons are the main charge carriers

D=25 mm →
2×10^6 individual micro-channels

Micro-channel plate. III

Example of *Chandra* HRC-I (the most recent one)

•Quantum efficiency ~20−50% (~25% at 1.5 keV for CsI photocathode)

•Gain ~6.9×10^7

•Pore diameter=10 μm

•Spatial resolution <0.5 arcsec

•FoV=30×30 $arcmin^2$

•Effective area ~10 cm^2

•Previously used in *Einstein*/HRI and *ROSAT*/HRI

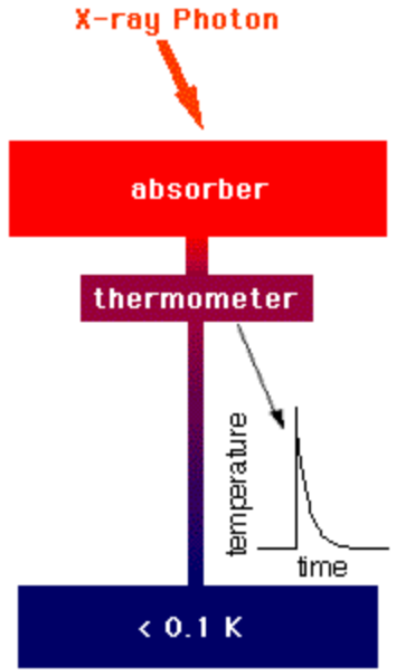
X-ray micro-calorimeters

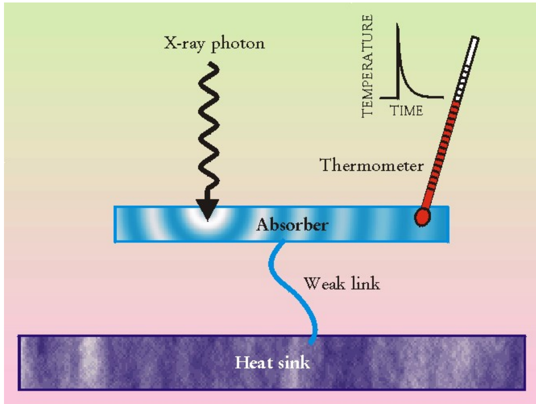
Micro-calorimeter. I

- Individual X-ray photons are absorbed by a crystal which is maintained at a very low temperature (<0.1 K), hence the life time of about 2-3 years
- Material with low thermal capacity and high absorption efficiency (absorber), coupled with a thermistor (*highly sensible to low T changes*) and a *cooling system* (heat sink, to maintain the thermal capacity low)
- The increase of T is measured: it is proportional to the energy of the X-ray photon: $\Delta T \approx E/C$ (t.c.)
- An energy resolution down to few eV can be achieved

Past: *Suzaku* (calorimeter failed); *Hitomi* (mission failed)

Next: *XRISM* (*XARM*), *Athena* (2.5 eV in the inner part)

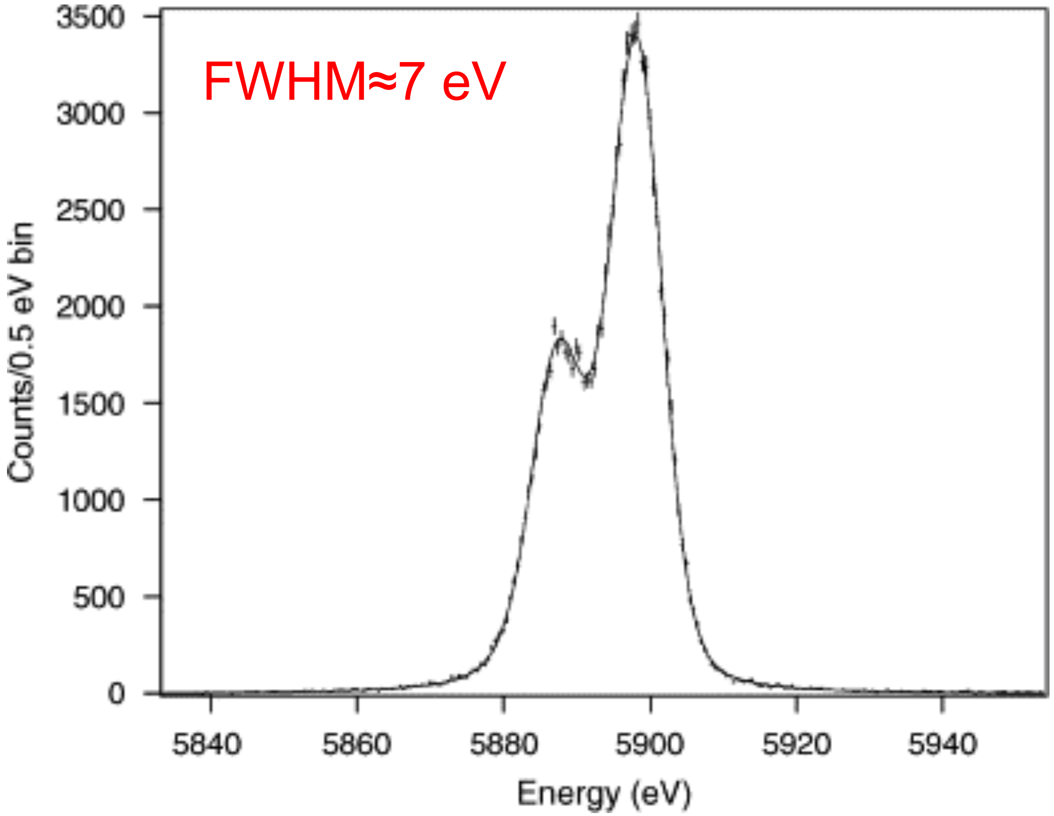




The best spectral resolution of any non-dispersive (grating) spectrometer (but limited field of view) + needs cooling

Micro-calorimeter. II

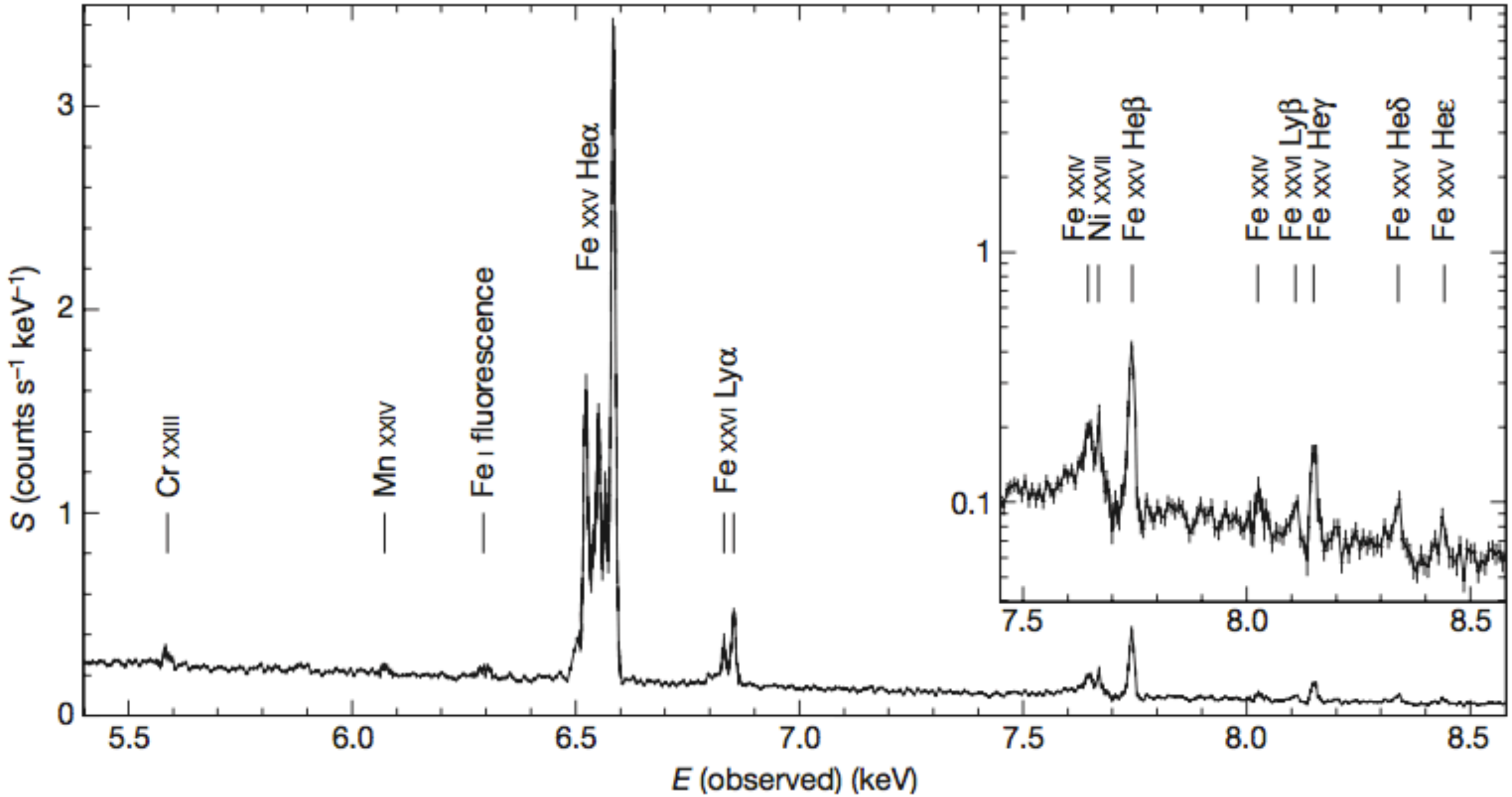
Onboard *Suzaku* – calibration source (^{55}Fe)



Failed at the beginning of the operations

Micro-calorimeter. III

Hitomi, Perseus cluster (Hitomi collaboration, Nature, 2016)

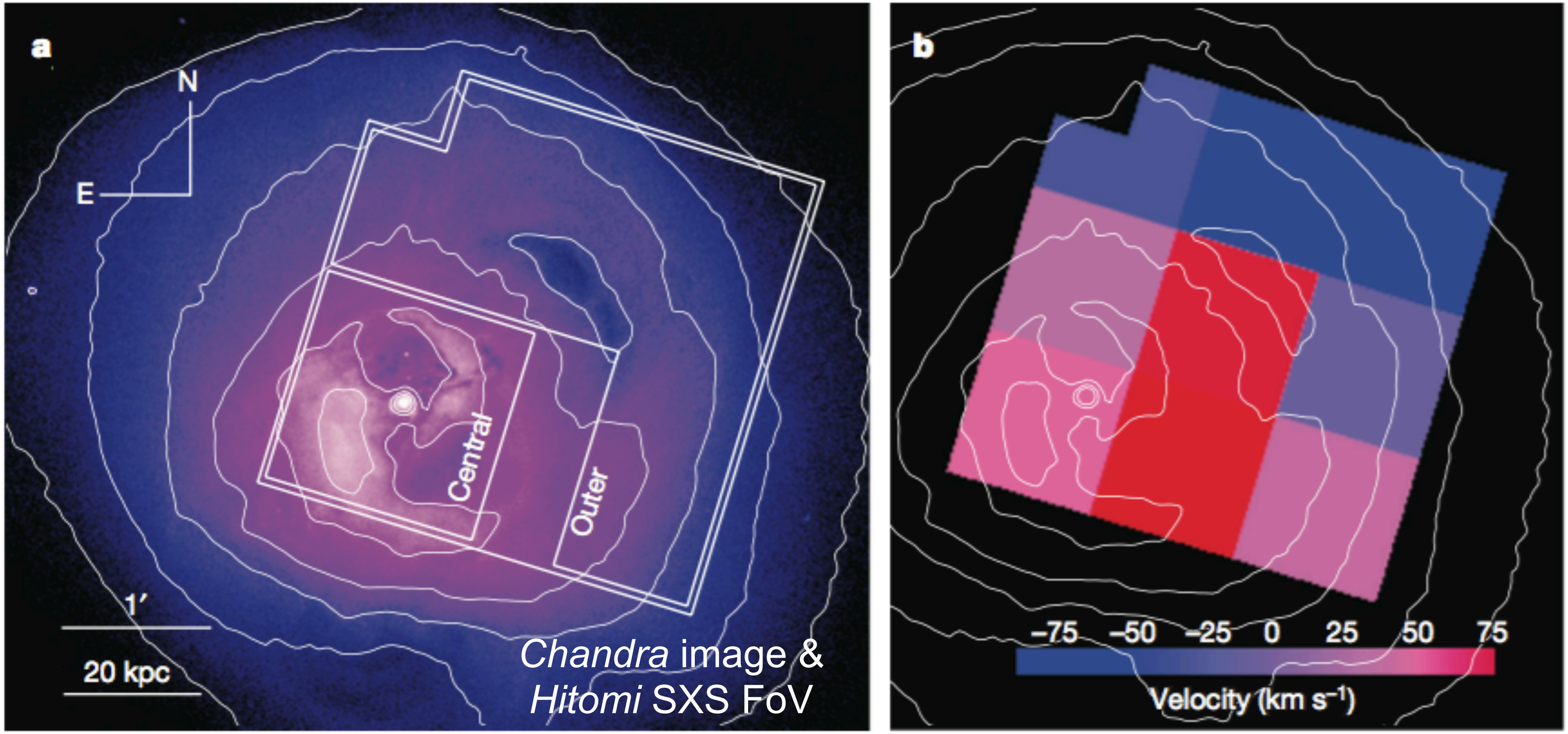


3×3 arcmin^2 inner region

Failed after few measurements

Micro-calorimeter. IV

Hitomi, Perseus cluster (Hitomi collaboration, Nature, 2016)



Velocity map

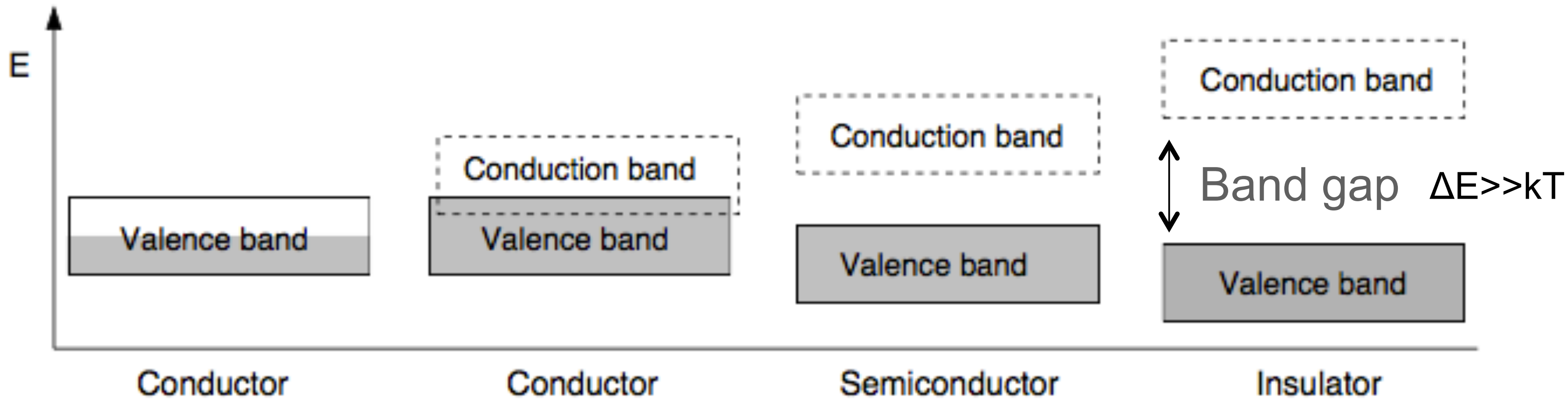
Next step: avoid the limitations of the poor angular resolution (5” for *Athena*, ~2031 launch)

Signal detection and materials
Charge-coupled device (CCD)

Signal detection. Materials. I

Photodetector: the detection process begins when a photon entering a crystal of a semiconductor is absorbed by freeing an electron from its bonds, allowing it to move freely through the detector volume

Electrons ➔ electric current

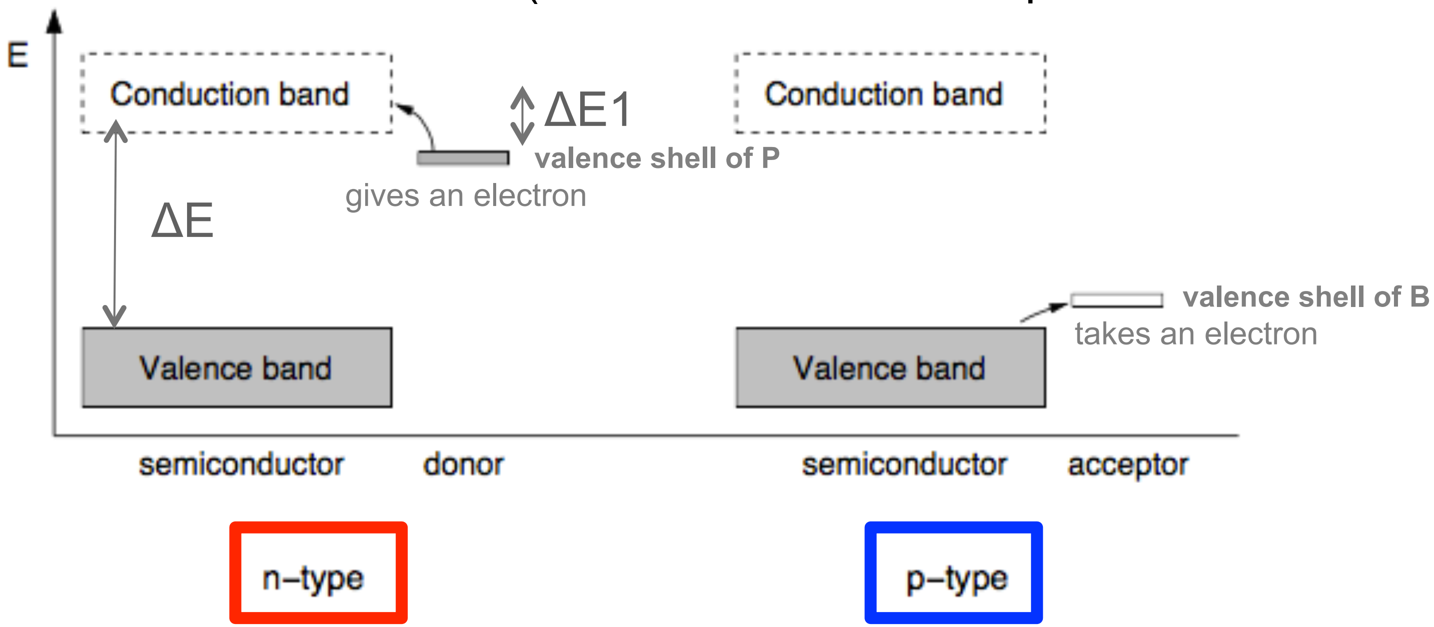


Valence band: low-lying band representing the bound energy states
Conduction band: high-lying band where the electrons are unbound and their motions (under external electric field) are responsible for conducting *currents*
Both electrons and holes contribute to the conduction

Signal detection. Materials. II

Doped (extrinsic) semiconductors

(these materials are helped to "conduct" current)

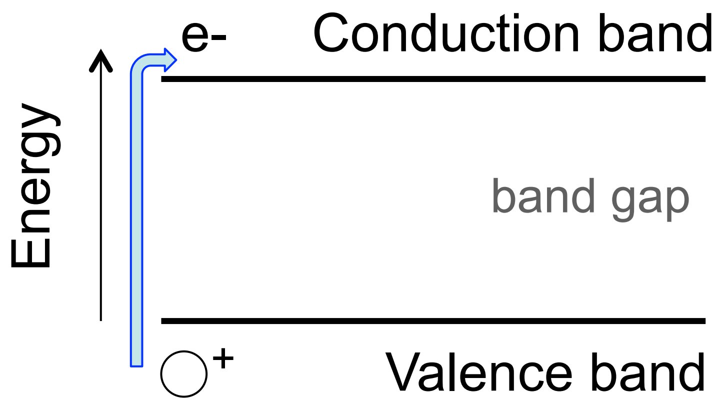


Phosphourus (*P*) injected in a silicon crystal ($1/10^6$) − doping. Phosphorous has a valence shell energy very close to the lower energy of the conduction band of silicon. $\Delta E1 \ll \Delta E$, so at room temperature *P* valence electrons can easily get excited to the conduction band of silicon ➔ free **electrons** (carriers of the current, holes stuck in the *P* atom), **the dopant acts as a donor of electrons (*n-type* semiconductor)**

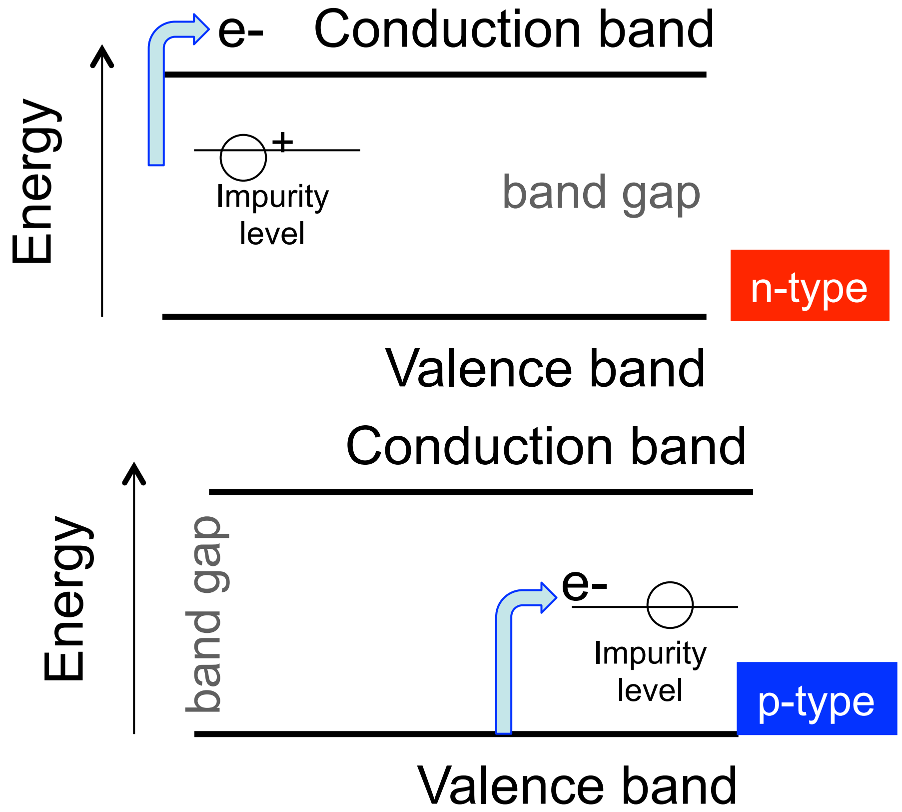
Boron injected into silicon. B has valence shell energy slightly above the upper bound of the valence band of silicon. Thermal fluctuations can now easily inject a silicon valence band electron into this shell. Dopant acts as an acceptor of an electron. Negative charge fixed to boron, **main current carriers are holes in the valence band of the silicon (*p-type* semiconductor)**

Signal detection. Materials. III

Intrinsic photoconductors



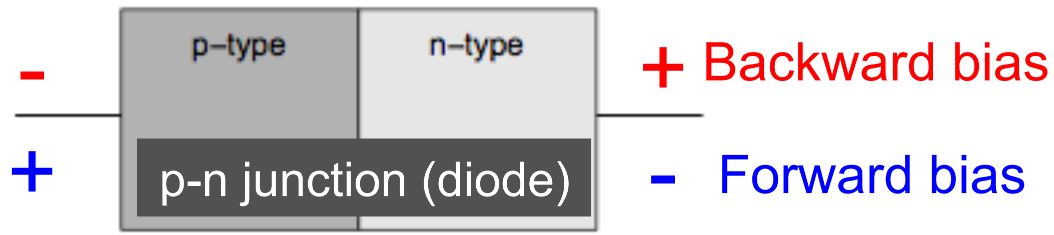
Extrinsic photoconductors



The material is ”forced” to act in a particular way with the doping (extrinsic photoconductors)

p-n junction

Building block of modern electronics



p “contains” mostly holes, n “contains” electrons

Backward bias: holes and electrons kept away from the junction, creating a *depletion region* ➔ no current can flow

Forward bias: holes and electrons pushed towards the junction ➔ recombination at the junction, flow of current

In case of no external potential: thermal diffusive motion of holes and electrons (recombination up to equilibrium)

In case of photons: *photoelectric effect*, free electrons to the n-type and holes to the p-type. These mobile charges produce a *potential difference* that can lead to a *current*, *proportional to the amounts of incoming photons*

Charge Coupled Devices (CCDs). I

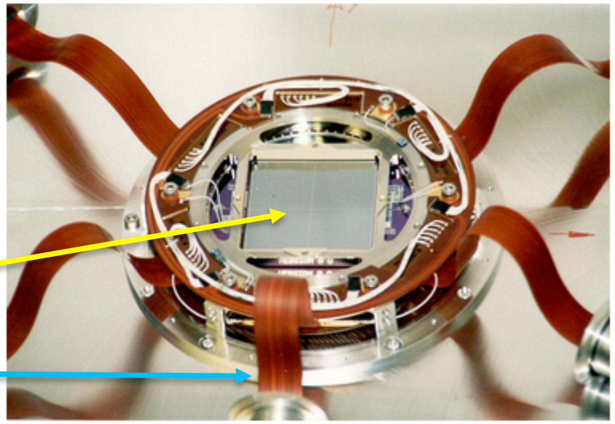
The CCD is a series of semiconductor elements which accumulate the electric charge produced by the interaction between the incident photon and the silicon detector (*photoelectric effect*). The registered charge is *proportional* to the energy of the photon.

Each *pixel* is coupled with the adjacent ones, so the charge can be transferred to the reading register.

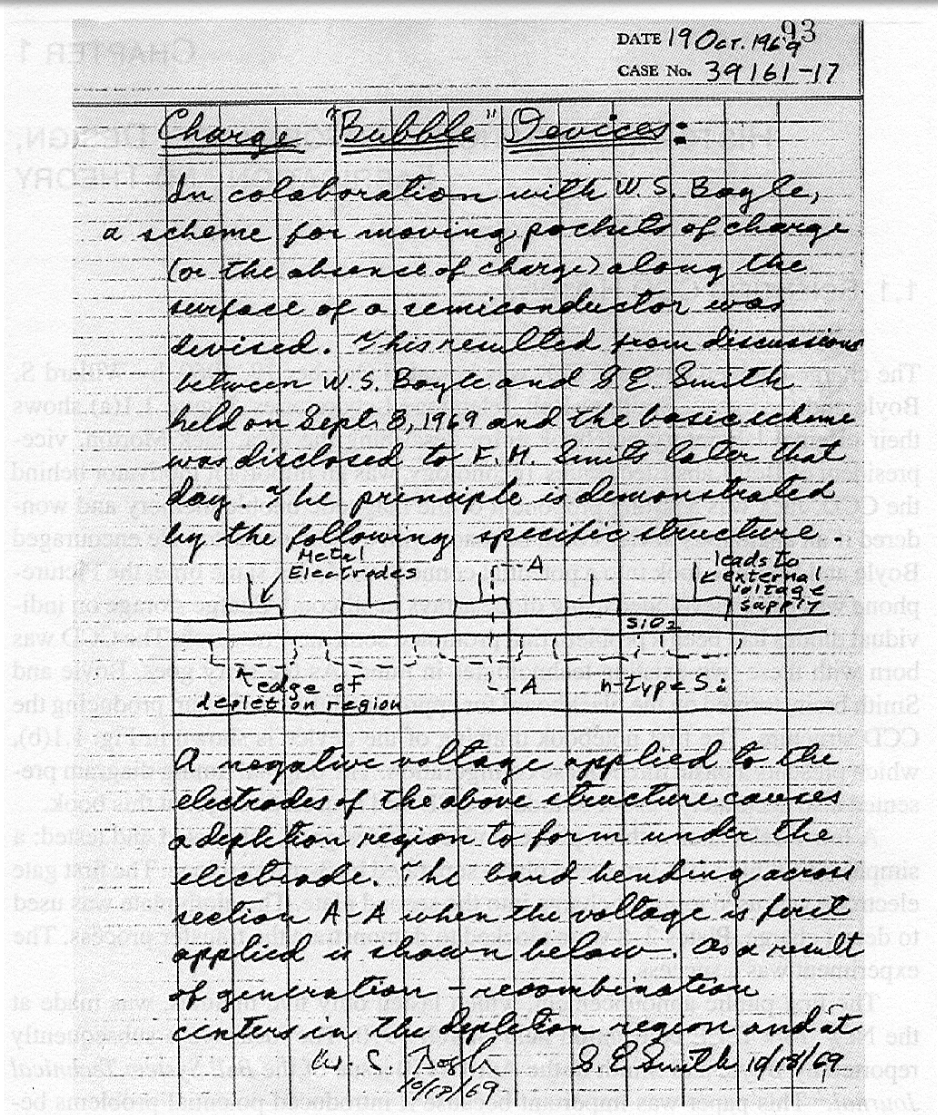
Main properties:

- Good imaging resolution, but usually limited FoV
- Small pixels
- Good energy resolution
- Poor timing resolution (due to slow readout time)
- Photon pileup in case of bright sources

XMM-*Newton*
EPIC/pn CCD (mosaic of 12)
Connections to the preamplifiers



CCDs. II
The concept



DATE 19 Oct. 1969 93
CASE No. 39161-17

Charge "Bubble" Devices:

In colaboration with W.S. Boyle, a scheme for moving pockets of charge (or the absence of charge) along the surface of a semiconductor was devised. This resulted from discussions between W.S. Boyle and G.E. Smith held on Sept. 8, 1969 and the basic scheme was disclosed to E.H. Smith later that day. The principle is demonstrated by the following specific structure.

A negative voltage applied to the electrodes of the above structure causes a depletion region to form under the electrode. The band bending across section A-A when the voltage is first applied is shown below. As a result of generation-recombination centers in the depletion region and at

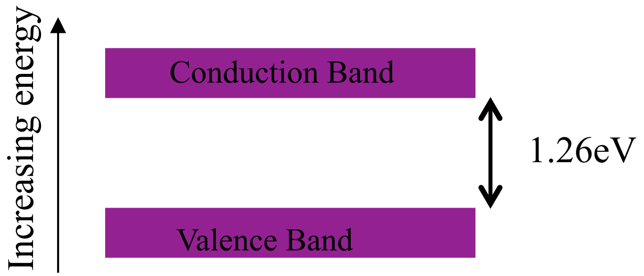
W.S. Boyle 10/19/69 G.E. Smith 10/19/69

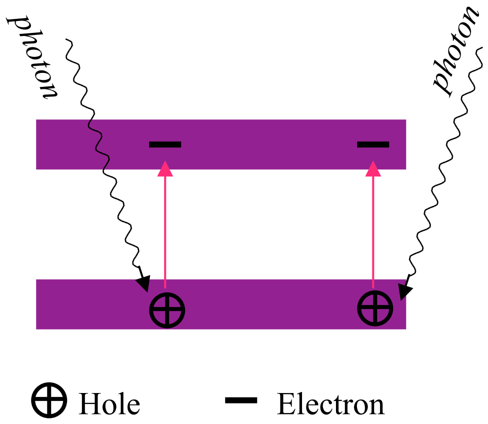
Boyle and Smiths' original notebook entry describing the CCD concept (1969)

Charged 'Bubble' Devices

CCDs. III

The effect is fundamental to the operation of a CCD. Atoms in a silicon crystal have electrons arranged in discrete energy bands. The lower energy band is called the *Valence Band*, the upper band is the *Conduction Band*. Most of the electrons occupy the Valence band but can be excited into the conduction band by heating or by the absorption of a photon. The energy required for this transition is 1.26 electron volts. Once in this conduction band the electron is free to move about in the lattice of the silicon crystal. It leaves behind a 'hole' in the valence band which acts like a positively charged carrier. In the absence of an external electric field the hole and electron will quickly re-combine and be lost**. In a CCD an electric field is introduced to sweep these charge carriers apart and prevent recombination.**





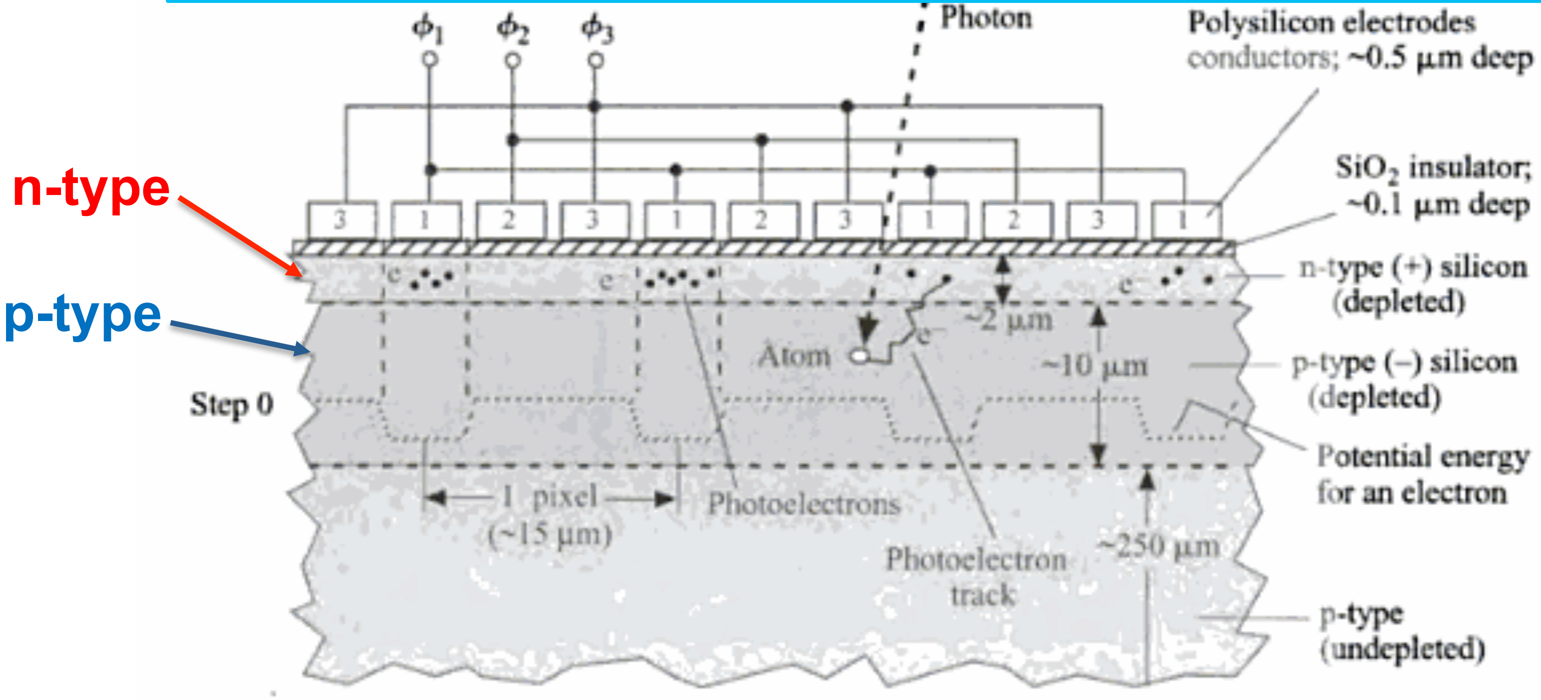
Thermally generated electrons are indistinguishable from photo-generated electrons . They constitute a noise source known as '*Dark Current*' and it is important that CCDs are kept cold to reduce their number.

1.26 eV corresponds to the energy of light with a wavelength of 1μm. Beyond this wavelength silicon becomes transparent and CCDs constructed from silicon become insensitive.

(Credits: S. Tulloch)

CCDs. IV

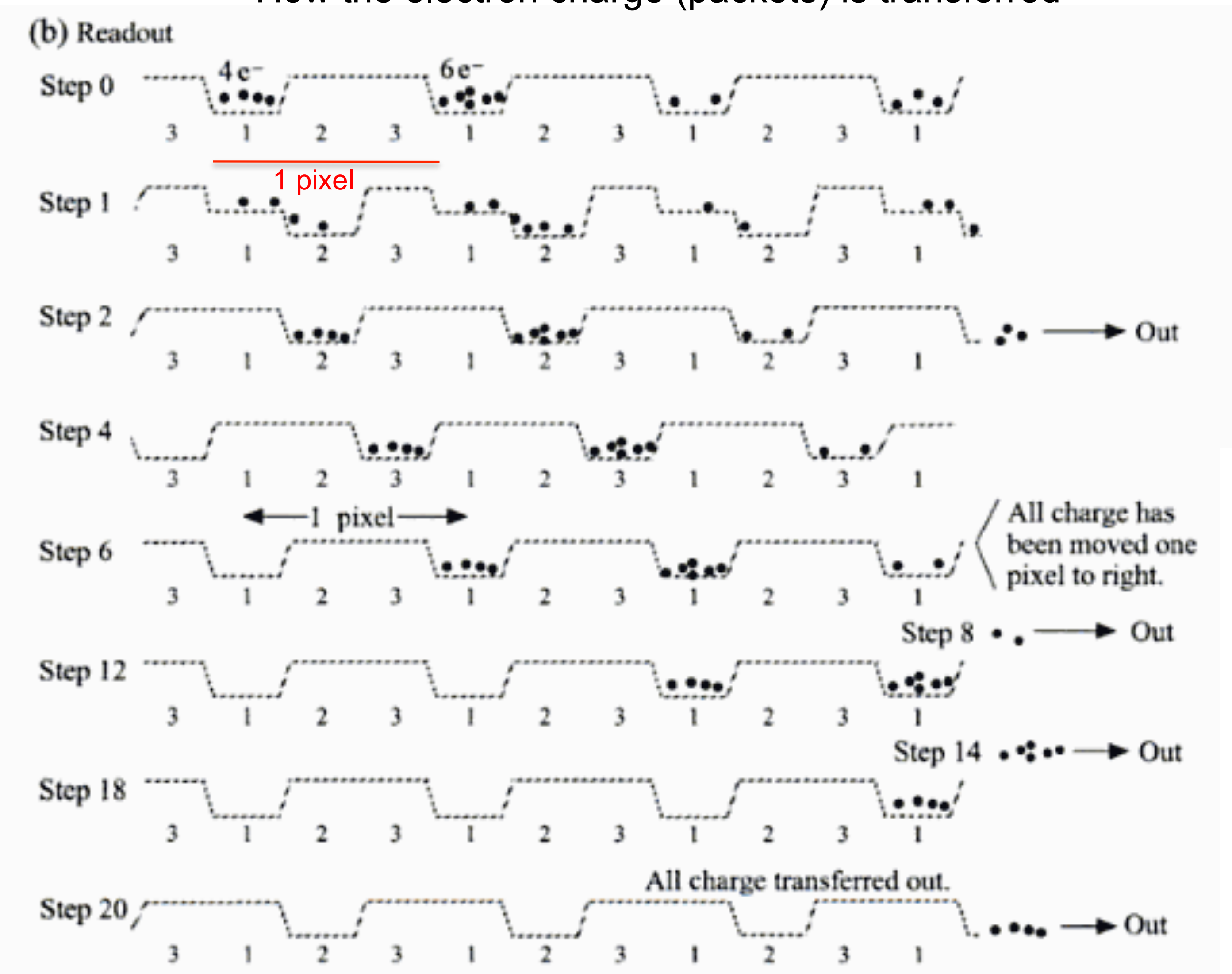
Case of optical CCD: the size of the depletion region is smaller

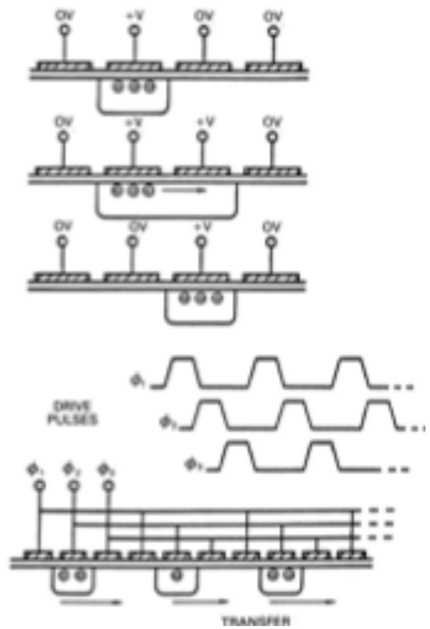


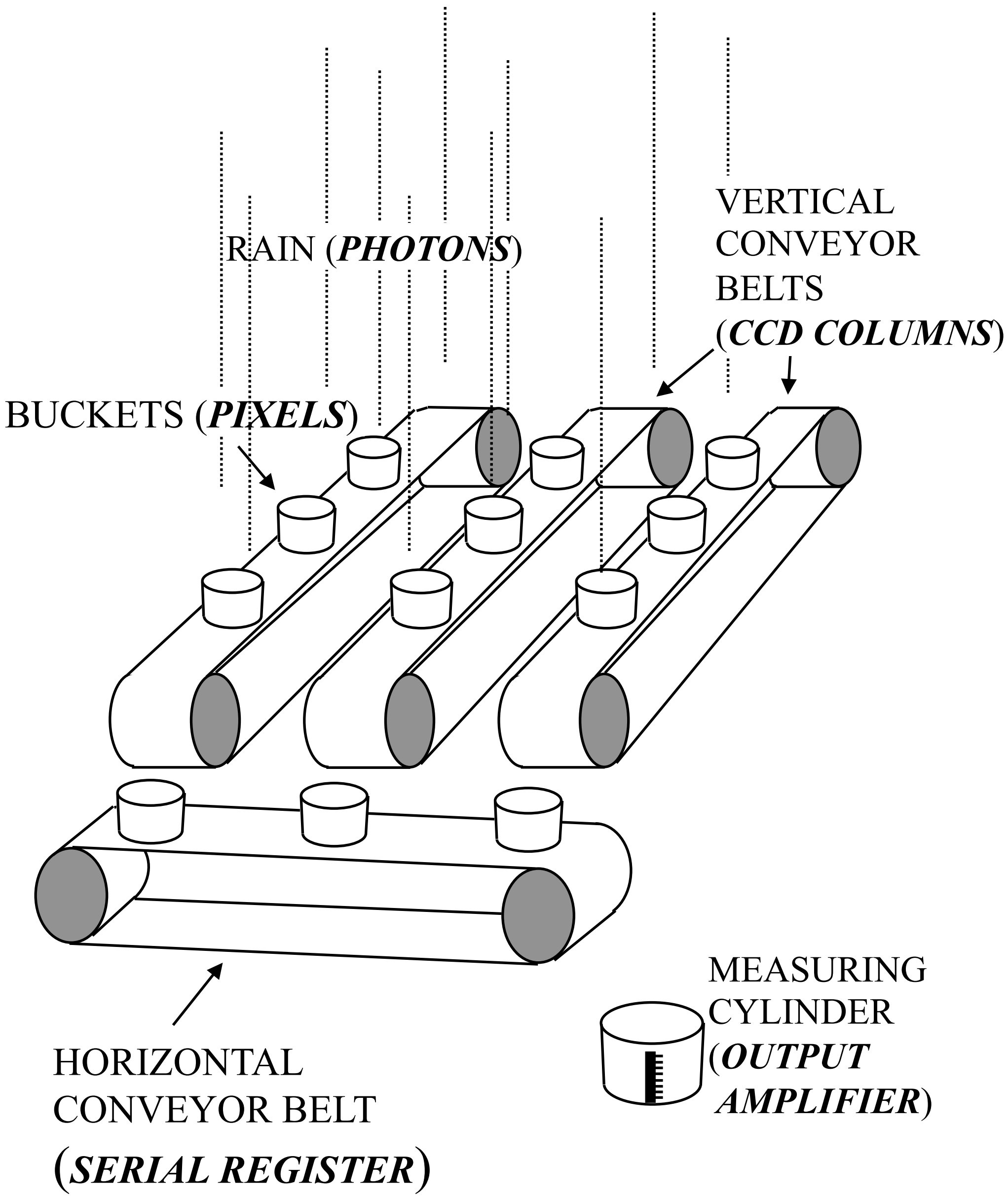
- **n-type semiconductor**: electrons are the main charge carrier
- **p-type semiconductor**: holes are the main charge carrier
- **p-n junction**: if n-type connected to + (via electrodes) and p-type to -, there is the formation of a depletion layer (region), where no free charges are present
- Photon interaction: creation of a hole-electron pair via photoelectric effect (if E>3.65 eV) and, for energies above 1.1 eV (for Silicon), the electron is in the conduction band
- Electrons are subject to positive potentials; opportunately tuned, these potentials force the electrons to move to the read-out facility

CCDs. V

How the electron charge (packets) is transferred

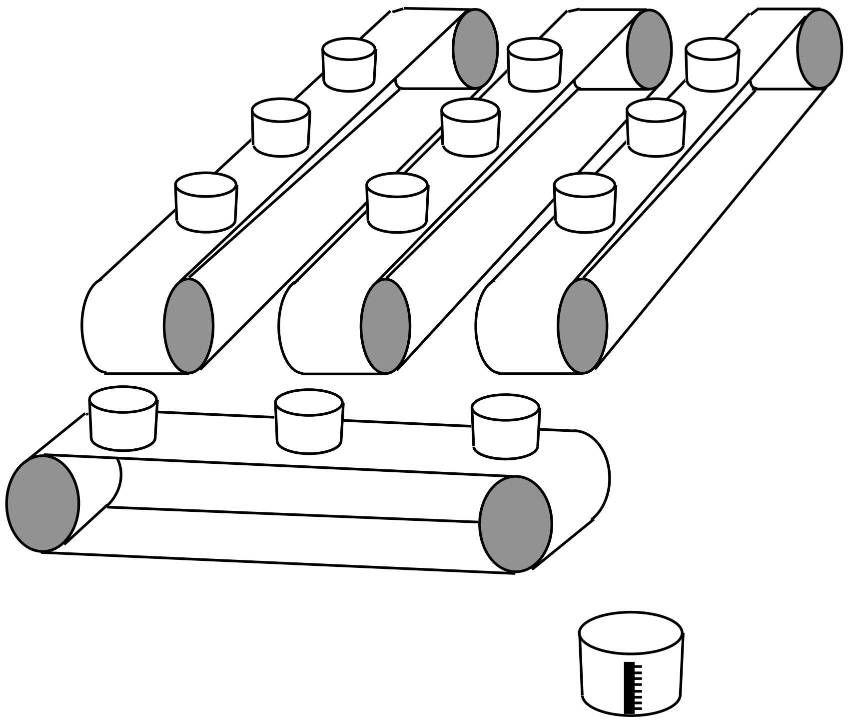




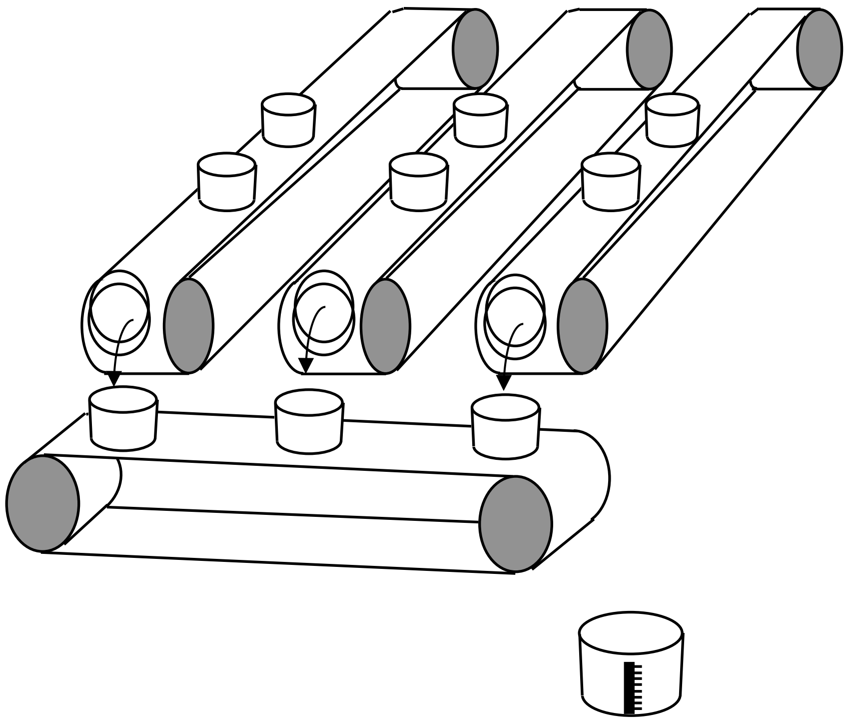


(Credits: S. Tulloch)

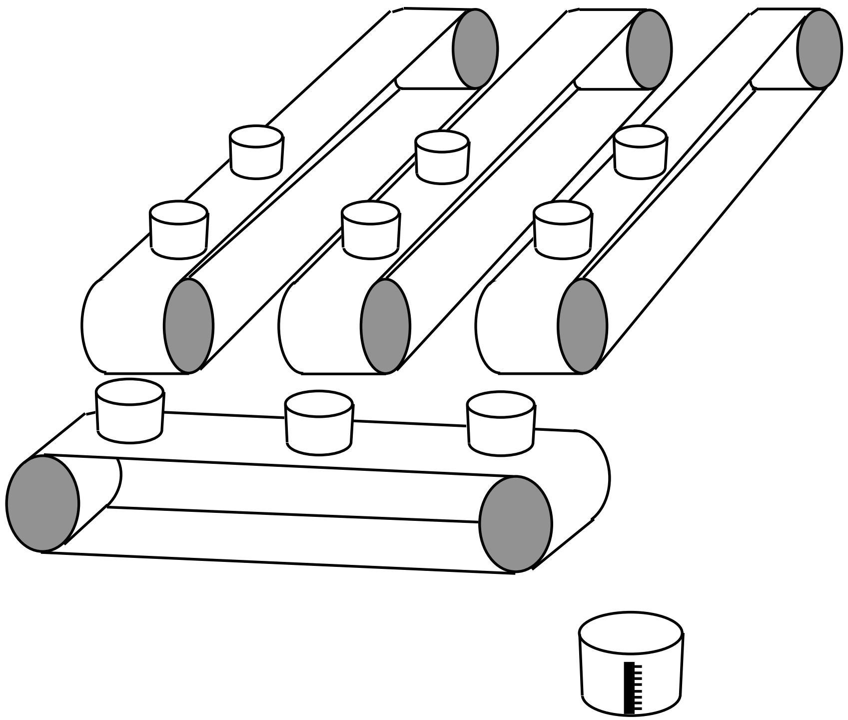
Exposure finished, buckets now contain samples of rain.



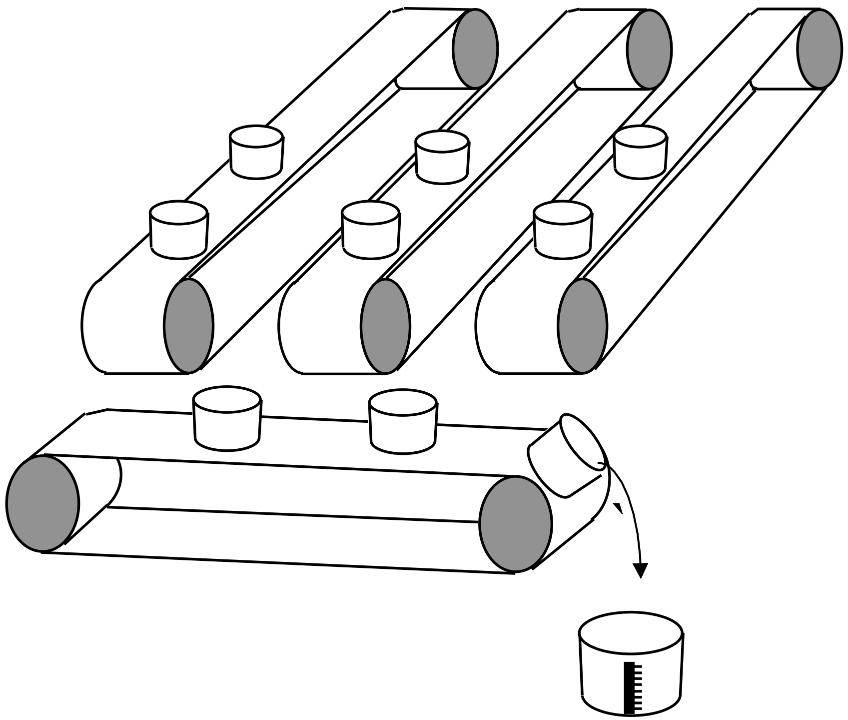
Conveyor belt starts turning and transfers buckets. Rain collected on the vertical conveyor is tipped into buckets on the horizontal conveyor.

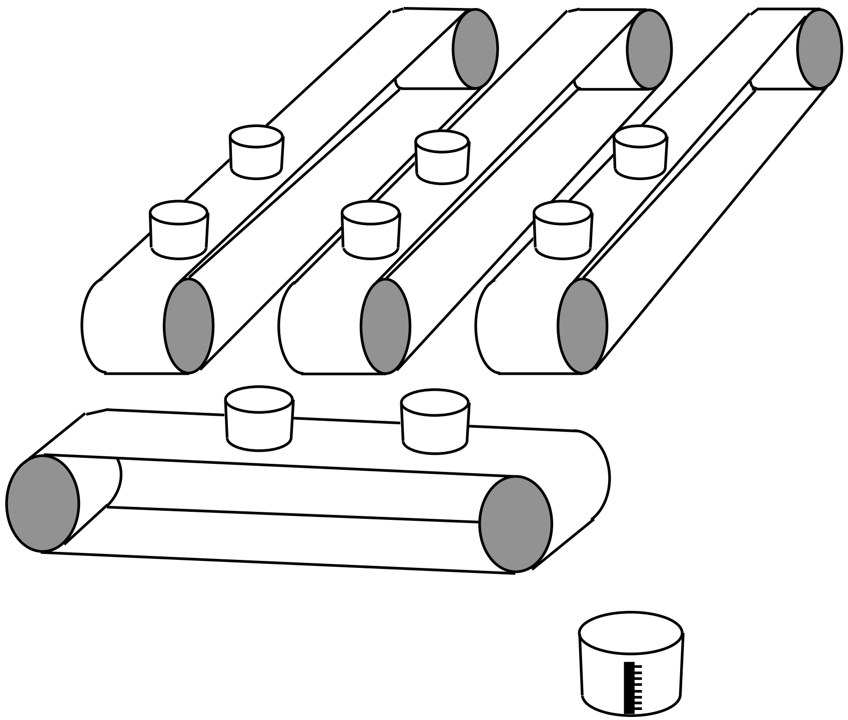


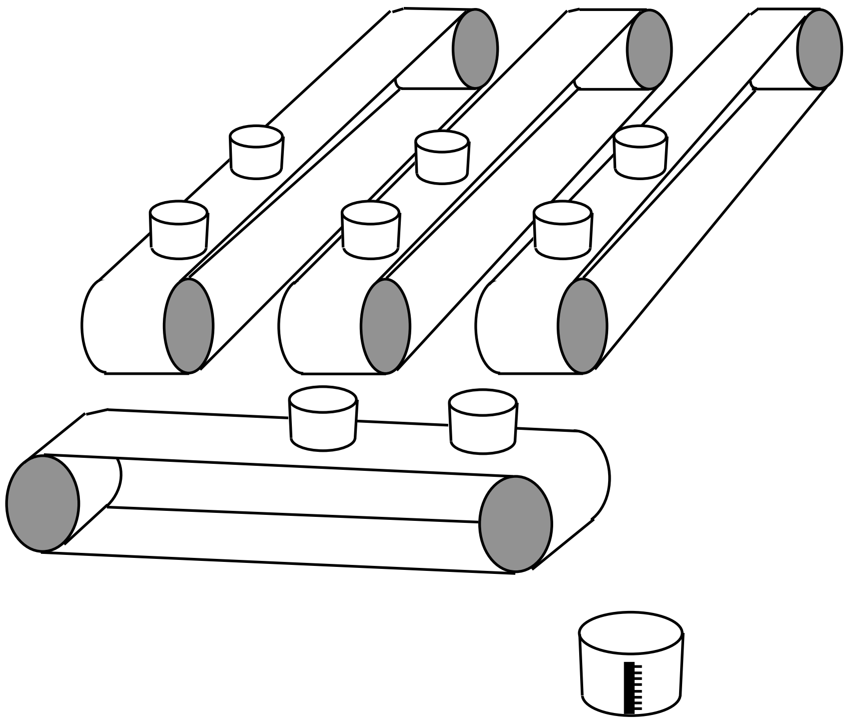
Vertical conveyor stops. Horizontal conveyor starts up and tips each bucket in turn into the measuring cylinder .

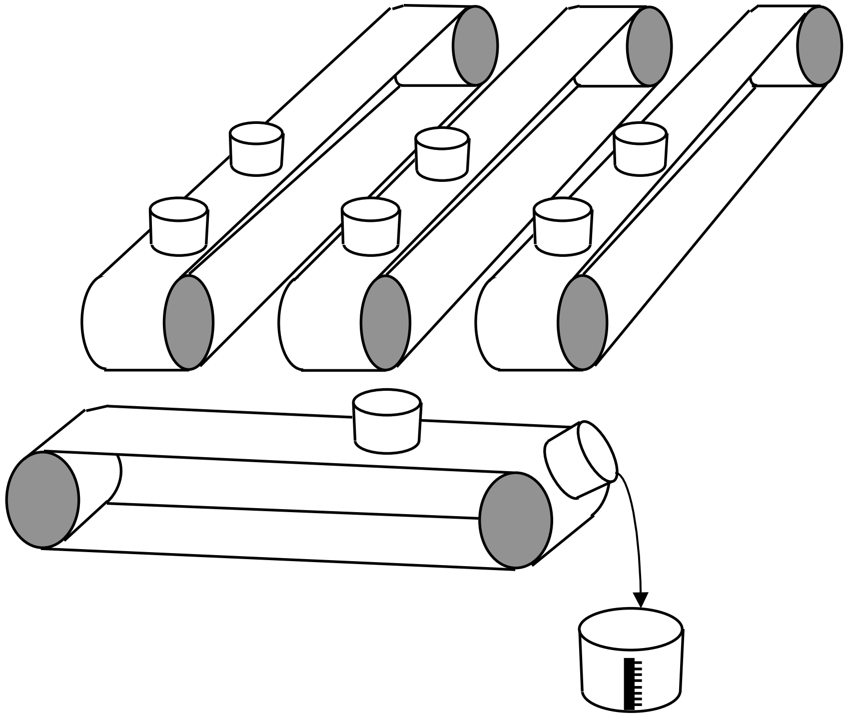


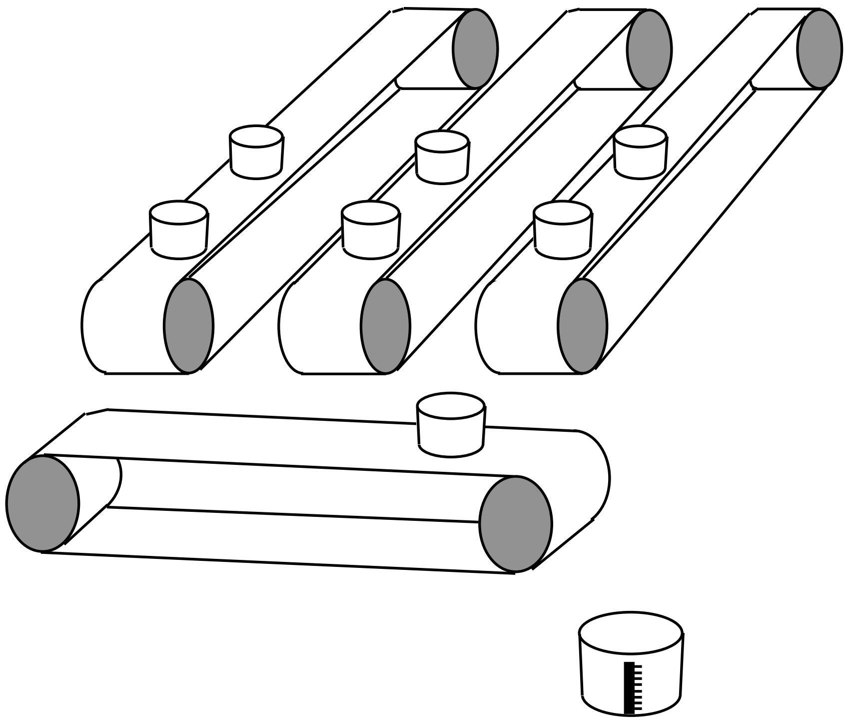
After each bucket has been measured, the measuring cylinder is emptied , ready for the next bucket load.

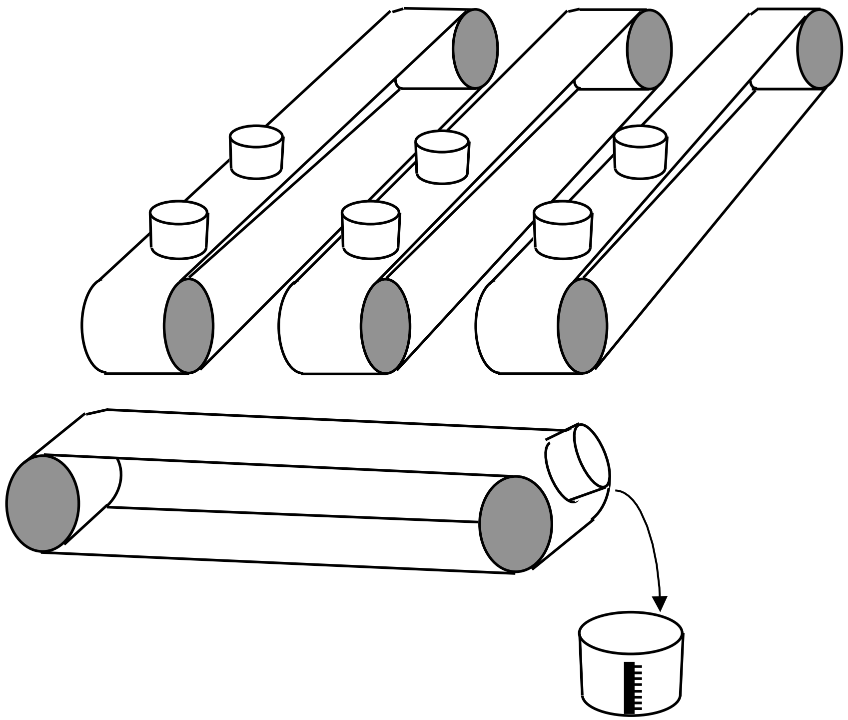


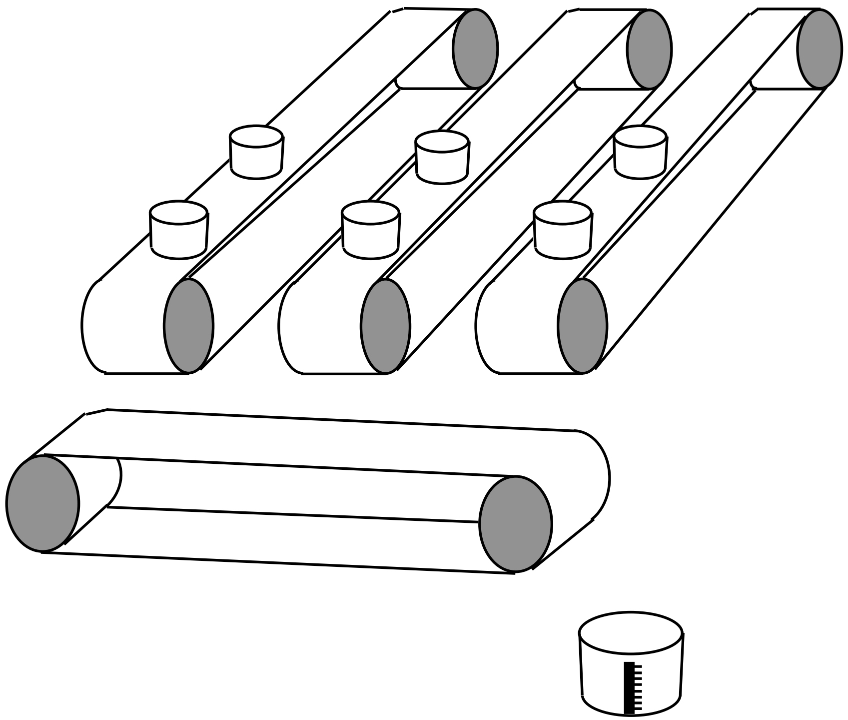




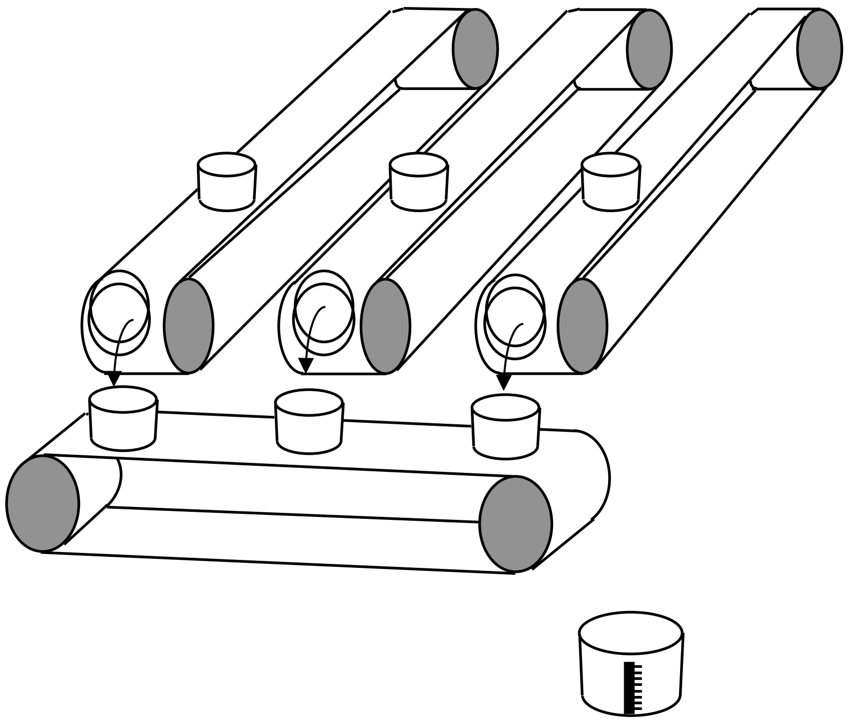


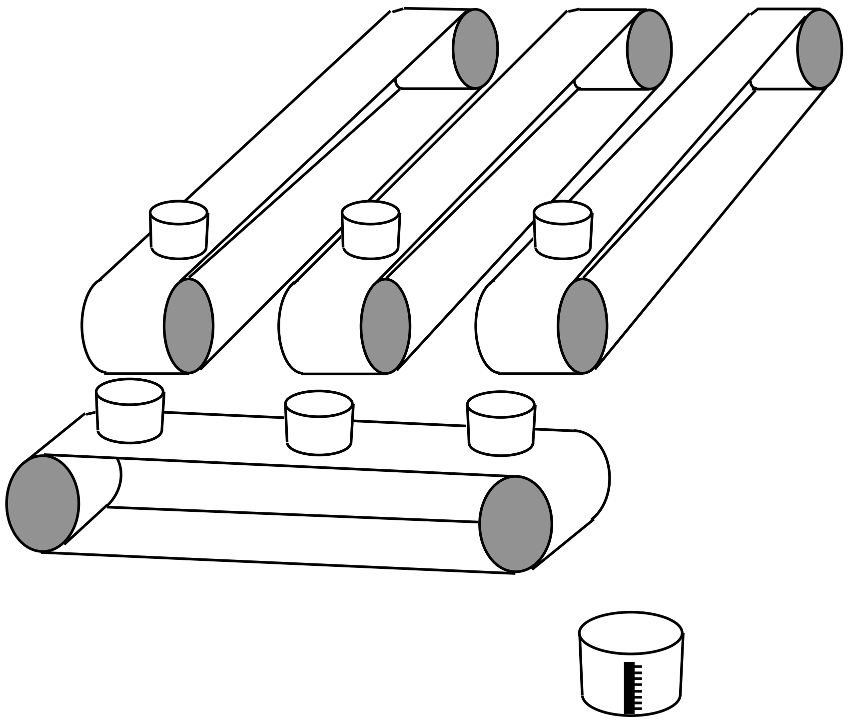


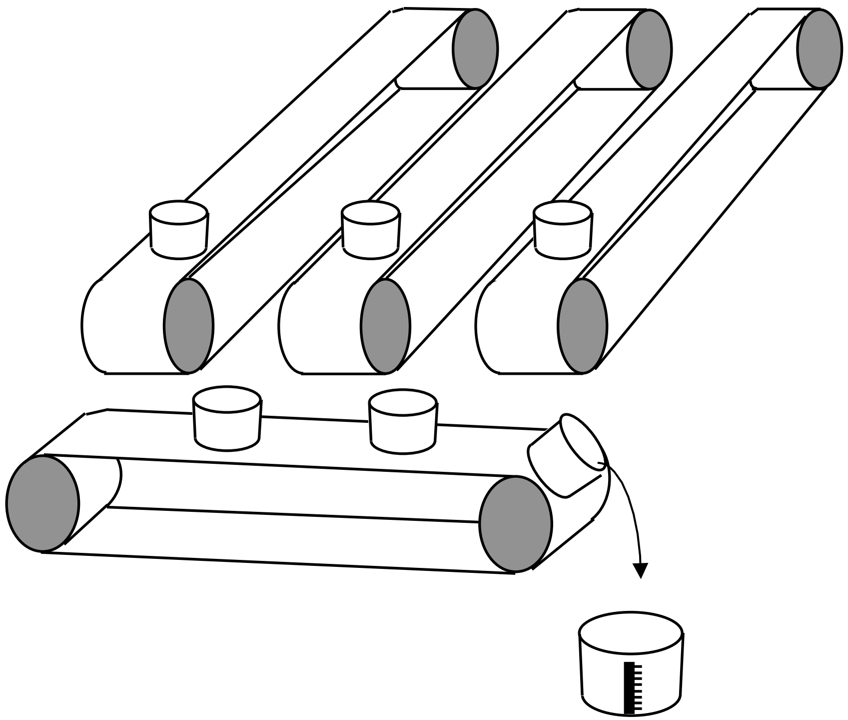


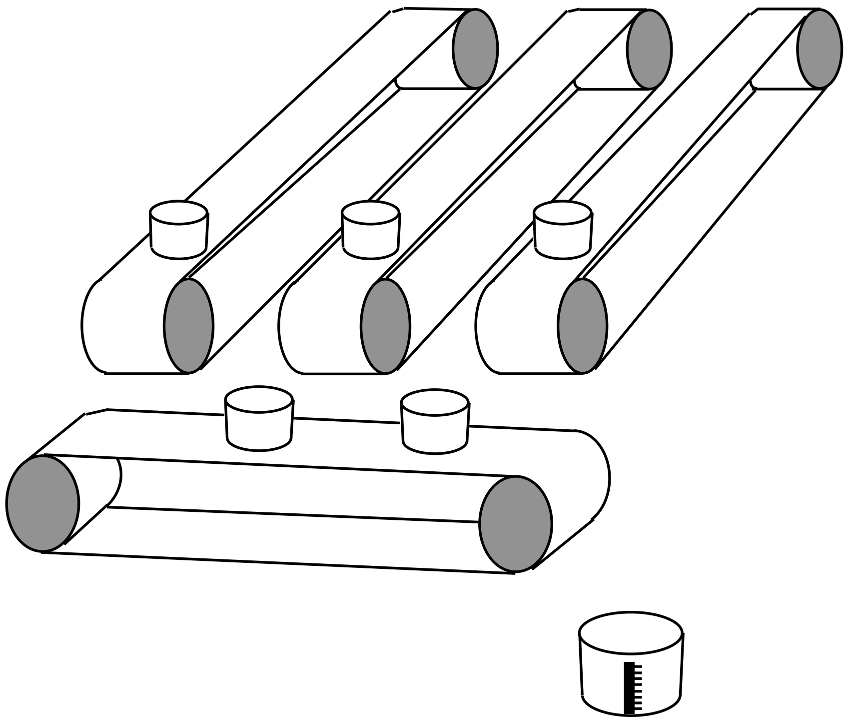


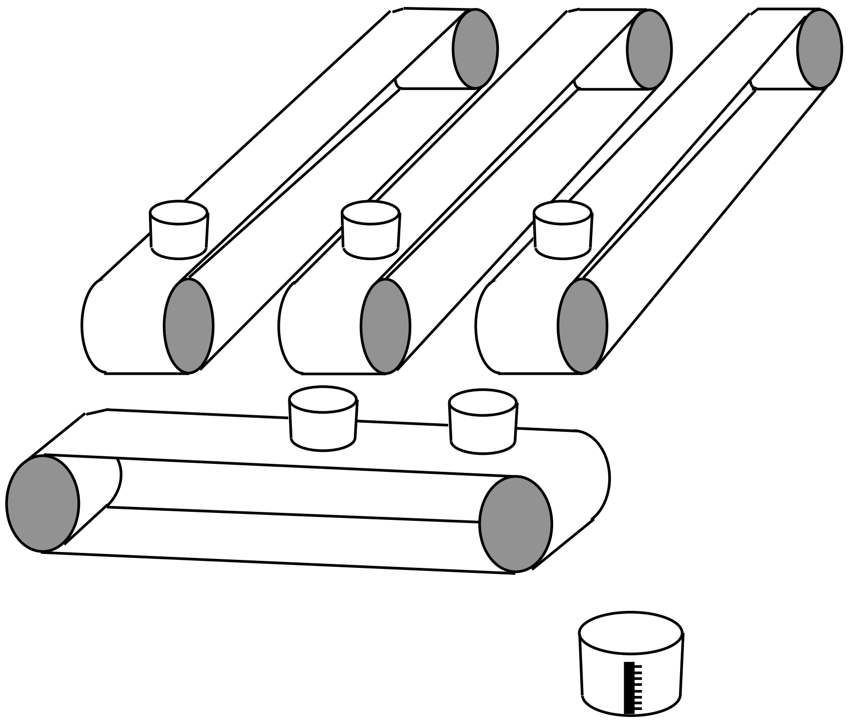
A new set of empty buckets is set up on the horizontal conveyor and the process is repeated.

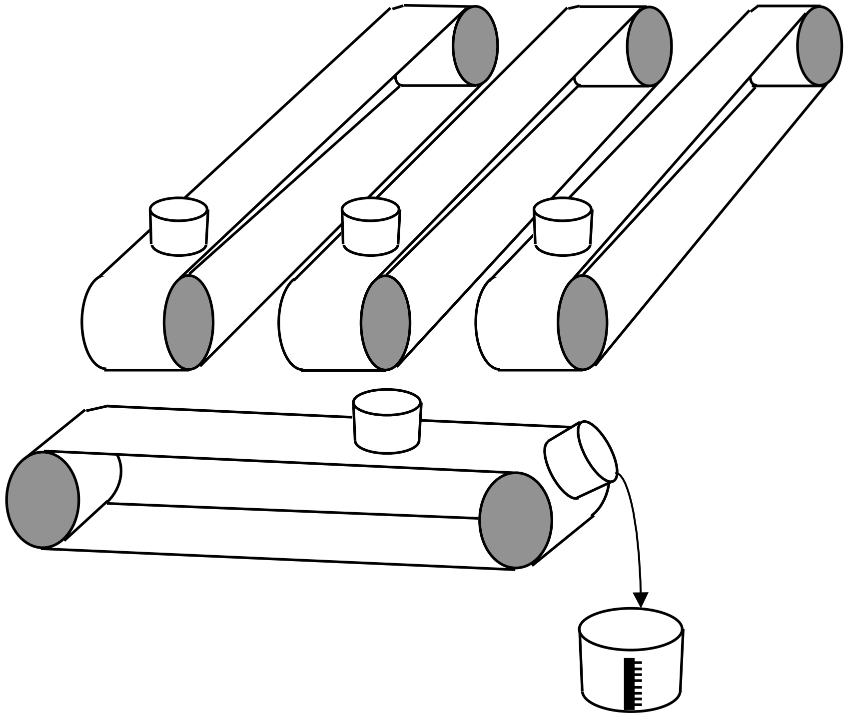


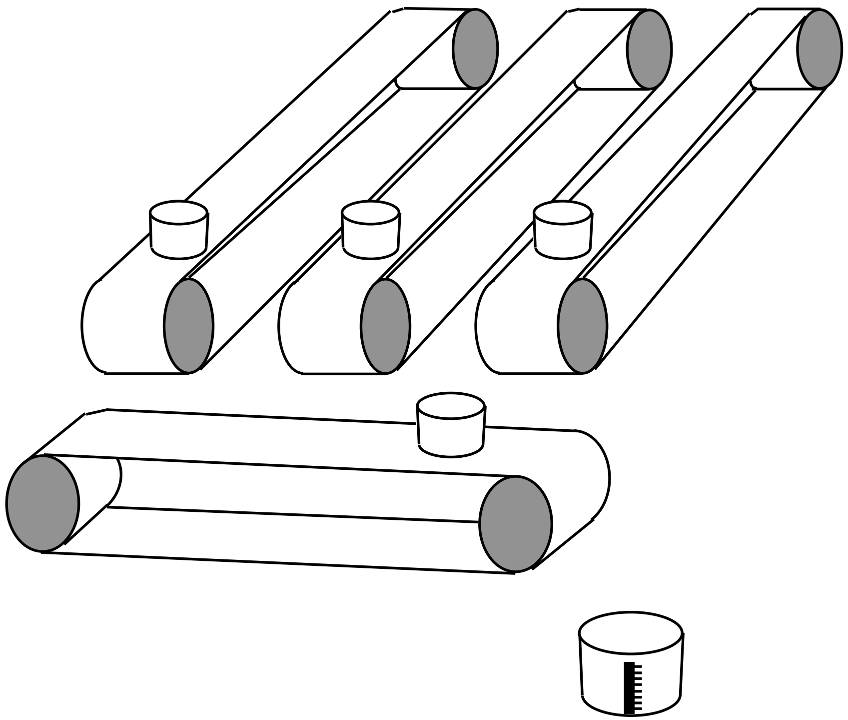


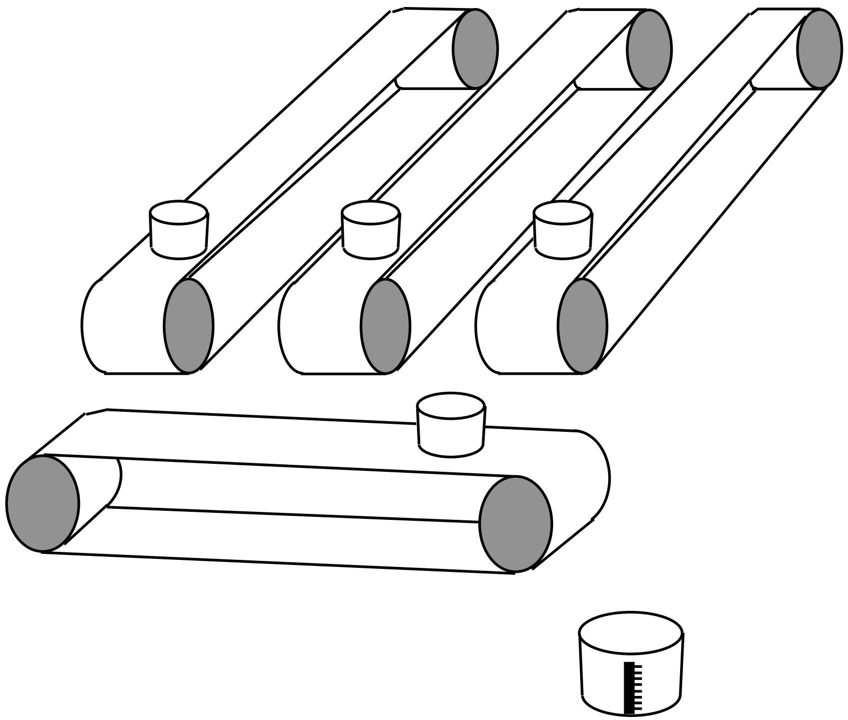


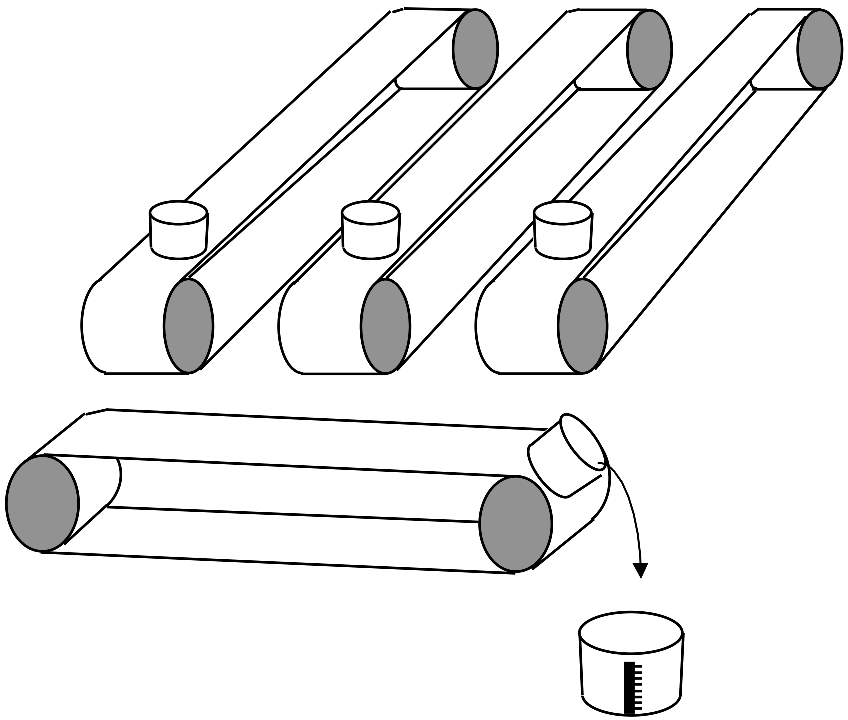


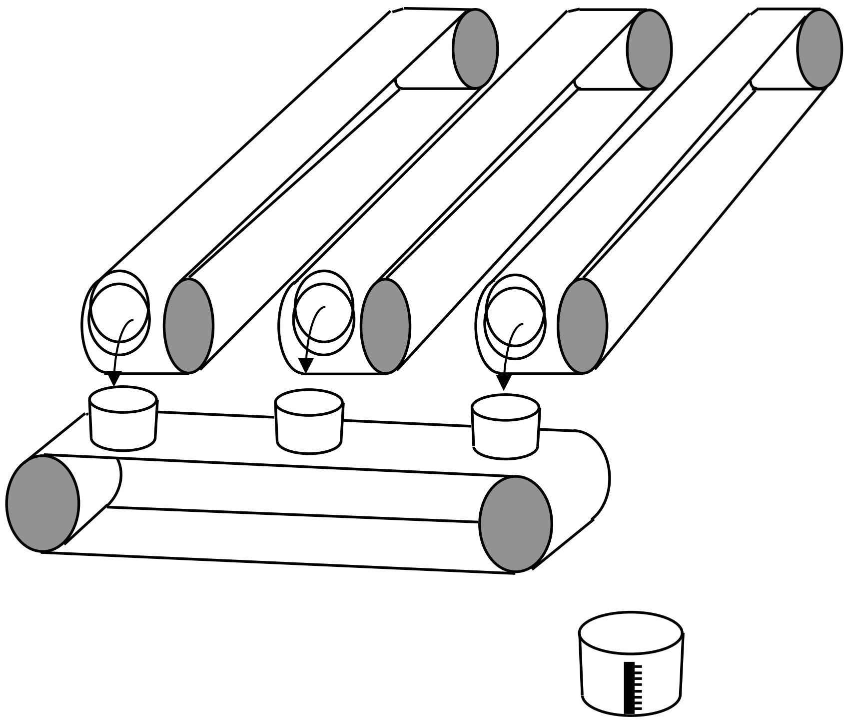


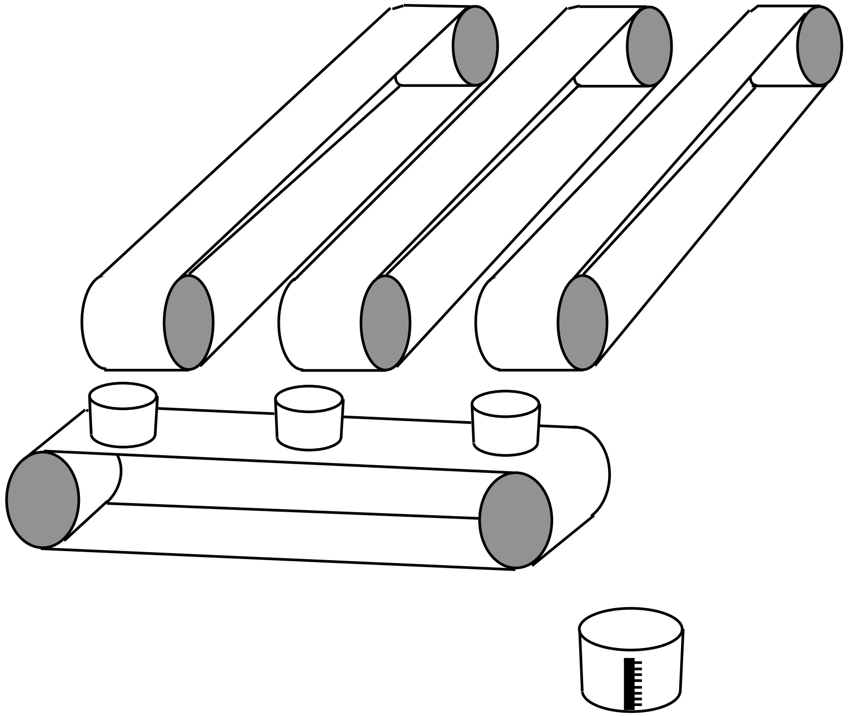


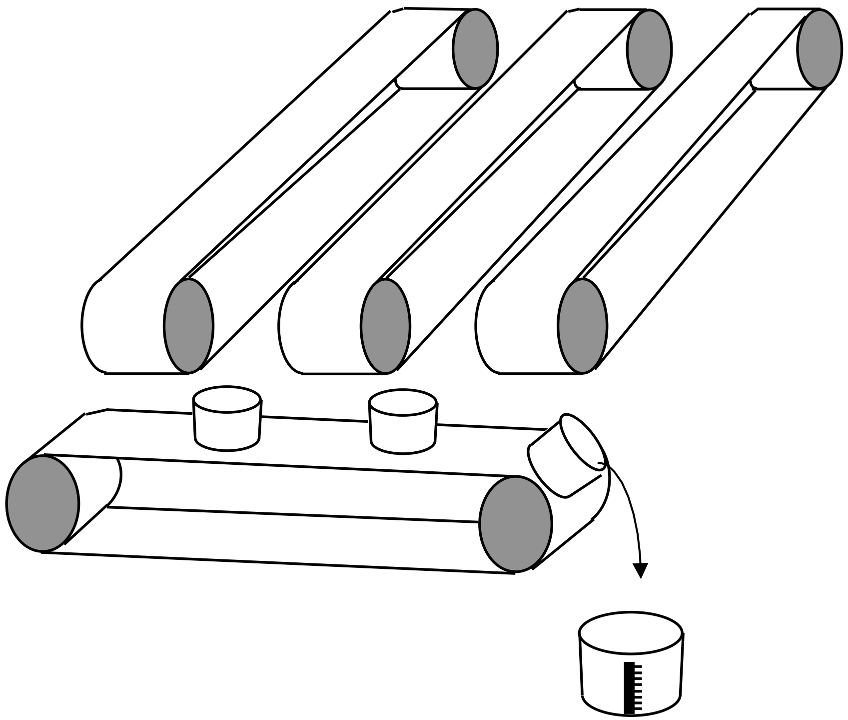


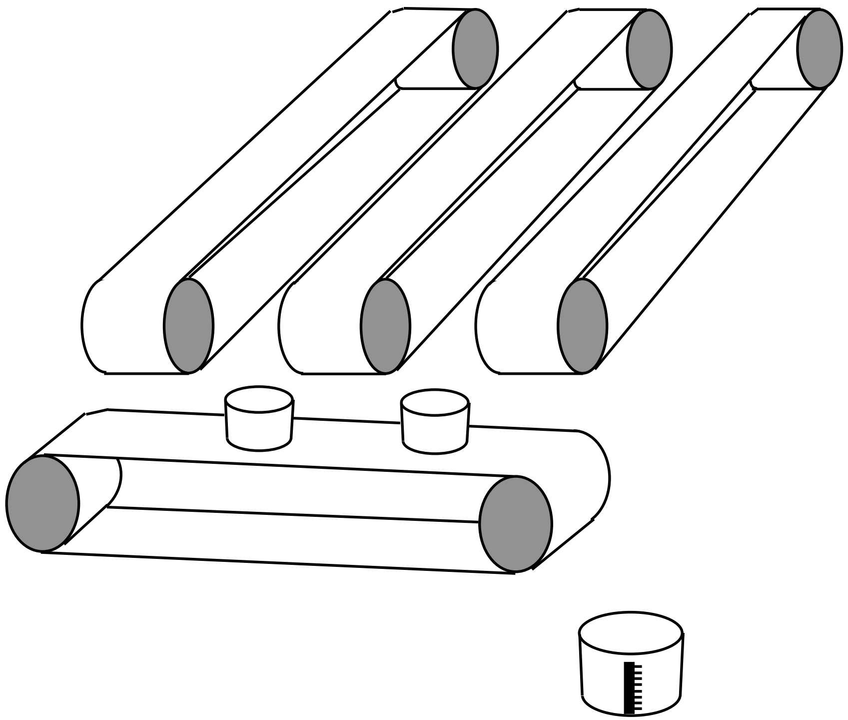


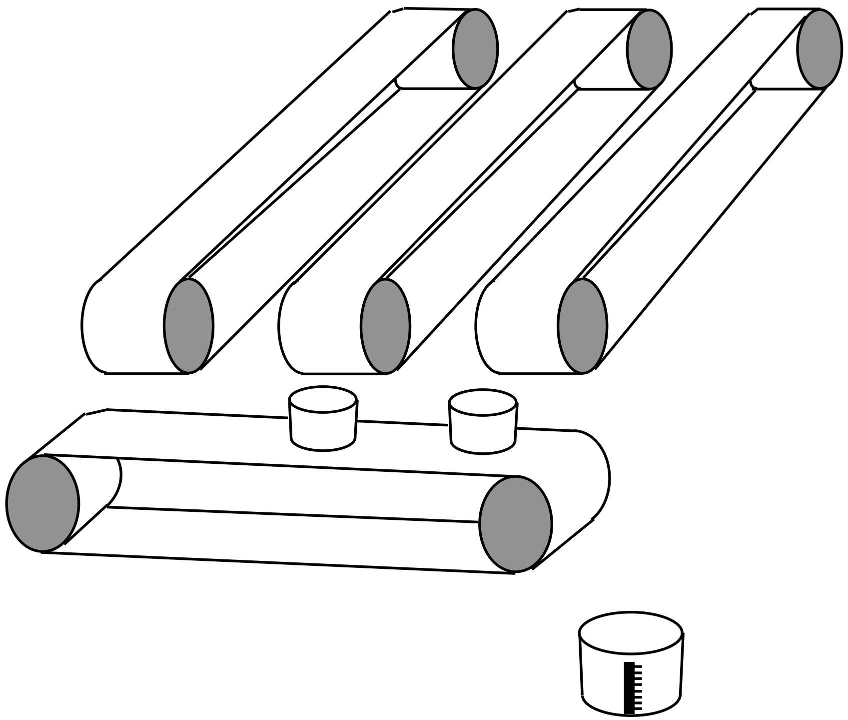


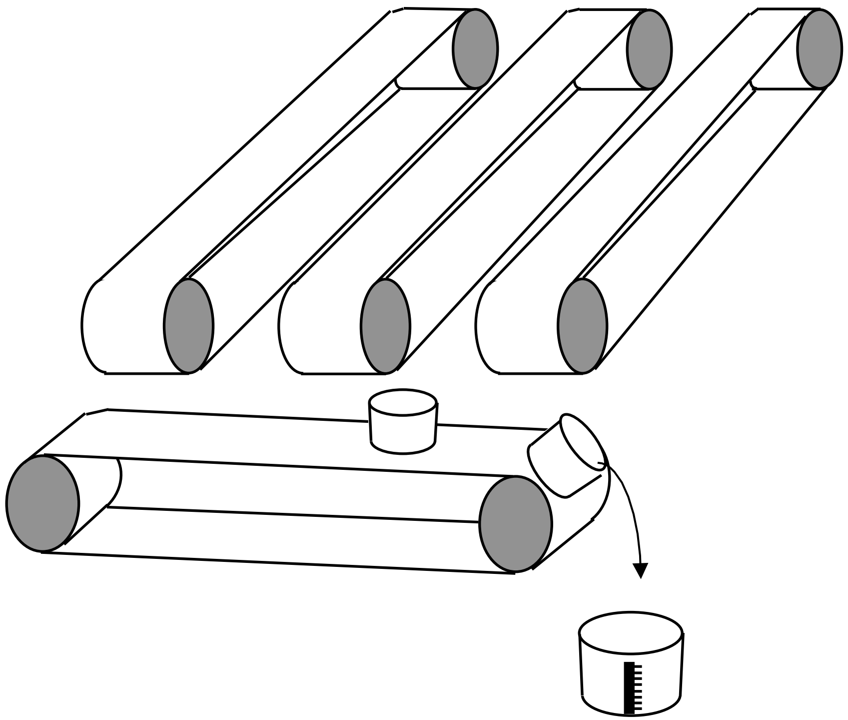


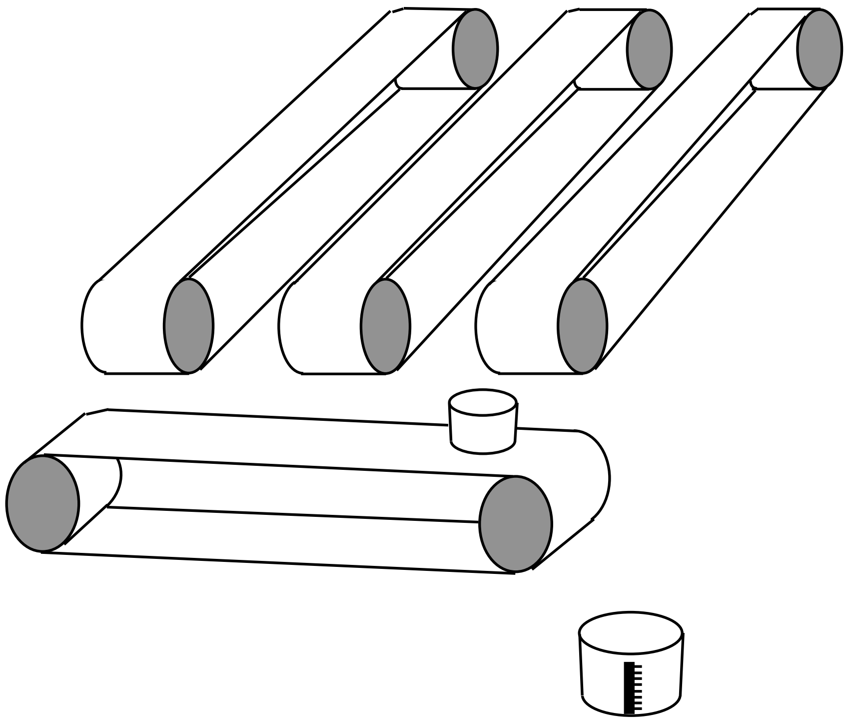


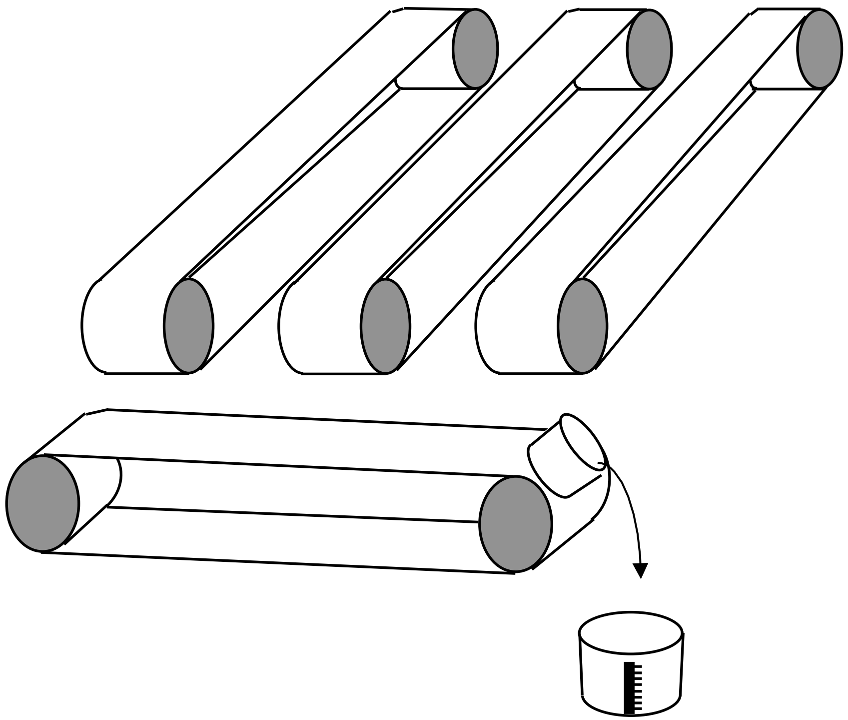




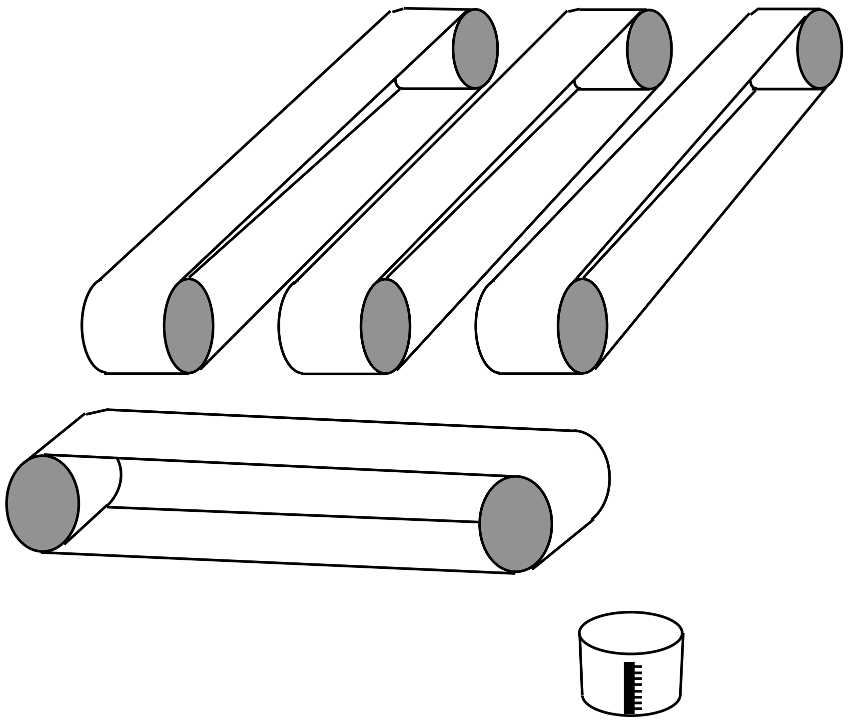








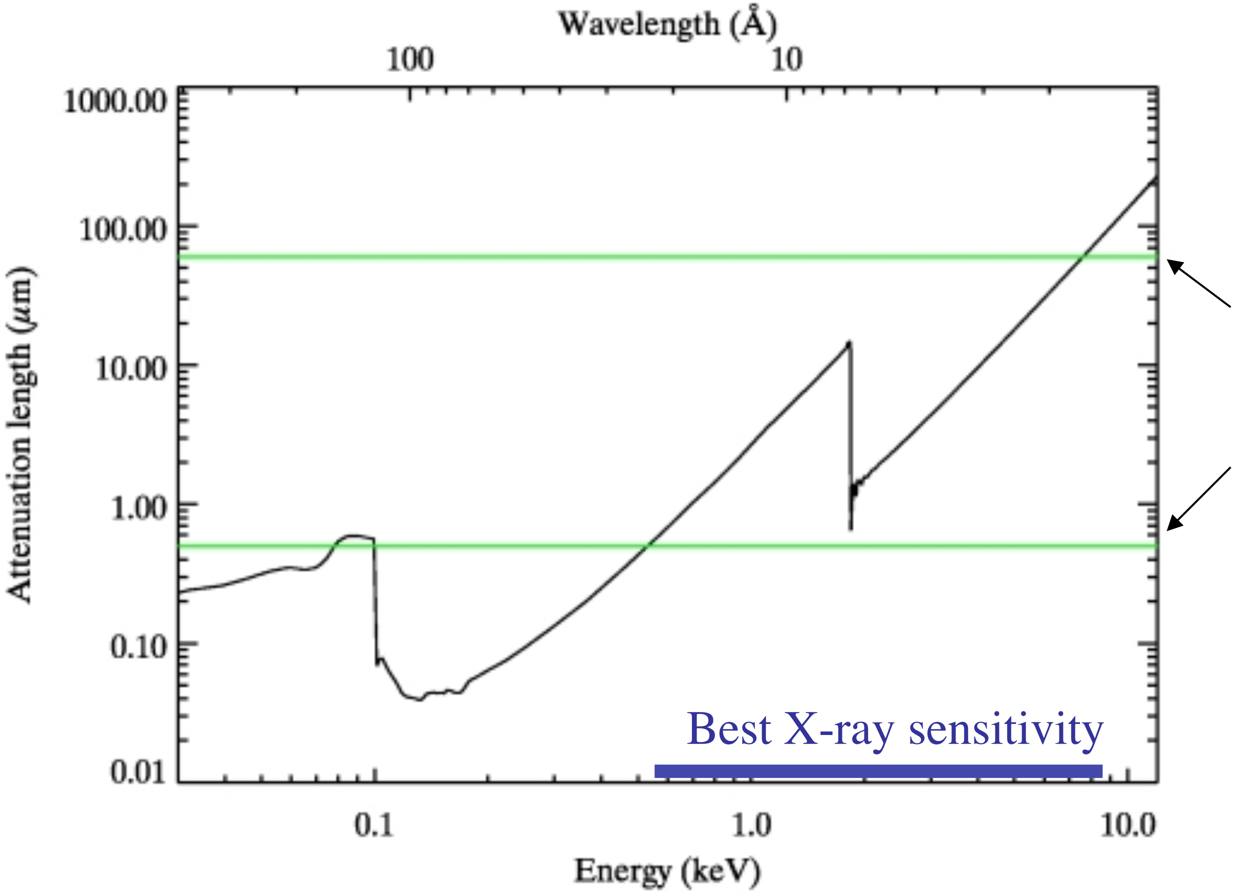
Eventually all the buckets have been measured, the CCD has been read out.



CCDs for X-ray Astronomy

(from C. Grant, MIT)

Photoelectric Absorption in Silicon



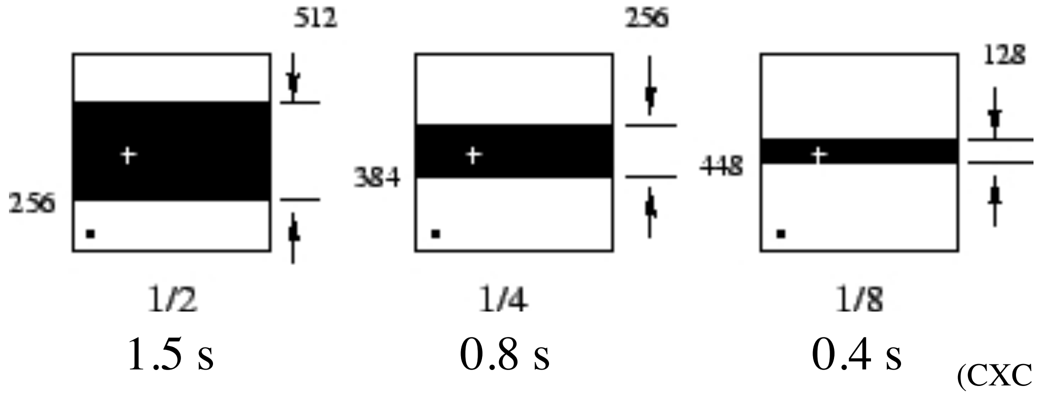
Depth of active region in typical X-ray CCD

Photoelectric Absorption

- Photoelectric interaction of X-ray with Si atoms generates electron-hole pairs.
- On average: $N_e = E_x/w$
  - N_e = number of electrons
  - E_x = energy of X-ray photon
  - w ~ 3.7 eV/e^- (temperature dependent)
- X-ray creates a charge cloud which can diffuse and/or move under influence of an electric field

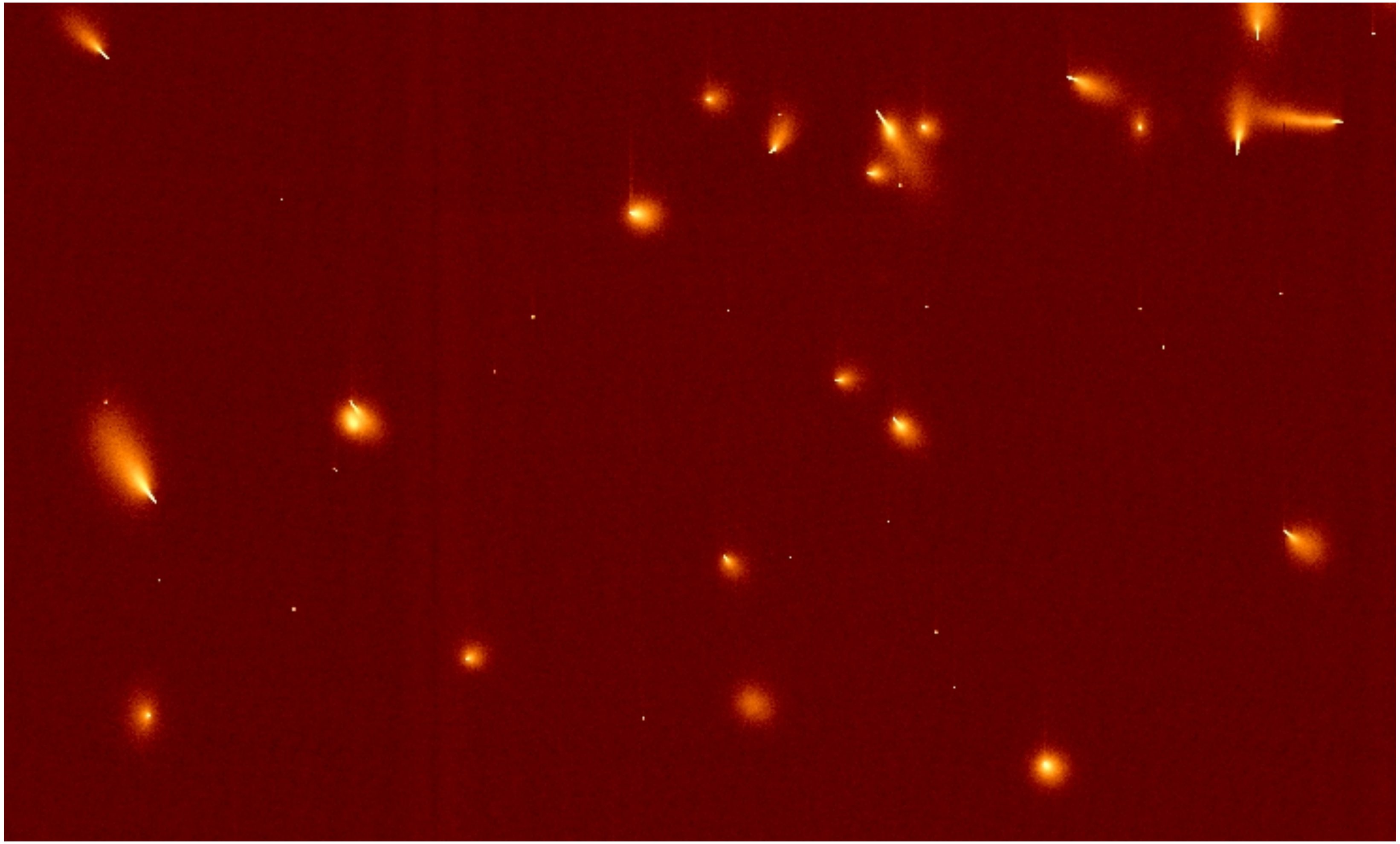
CCD Operating Modes

- X-ray CCDs operated in photon-counting mode
- Spectroscopy requires ≤ 1 photon interaction per pixel per frametime
- Minimum frametime limited by readout rate
- Tradeoff between increasing readout rate and noise
- For ACIS, 100 kHz readout ⇒ 3.2 s frametime
- Frametime can be reduced by reading out subarrays or by continuous parallel clocking (1D imaging)



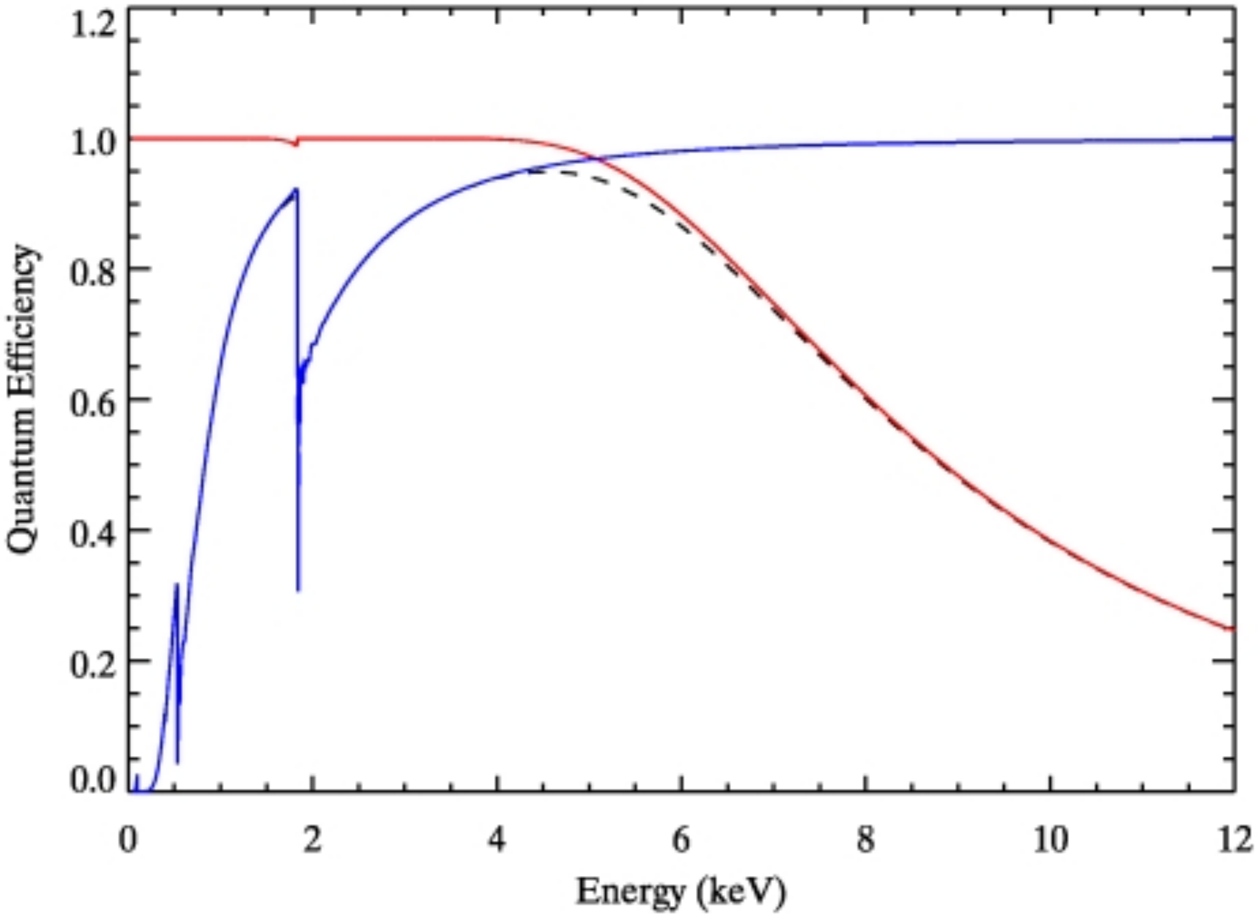
(CXC Proposer's Observatory Guide)

ACIS X-ray/Particle Discrimination



Blobs/streaks - charged particles. Small dots - X-ray events.

CCD Quantum Efficiency



Transmission through deadlayers (channel stops, gates, oxide layers)

$$T = \Pi_i \, e^{-\mu_i t_i}$$

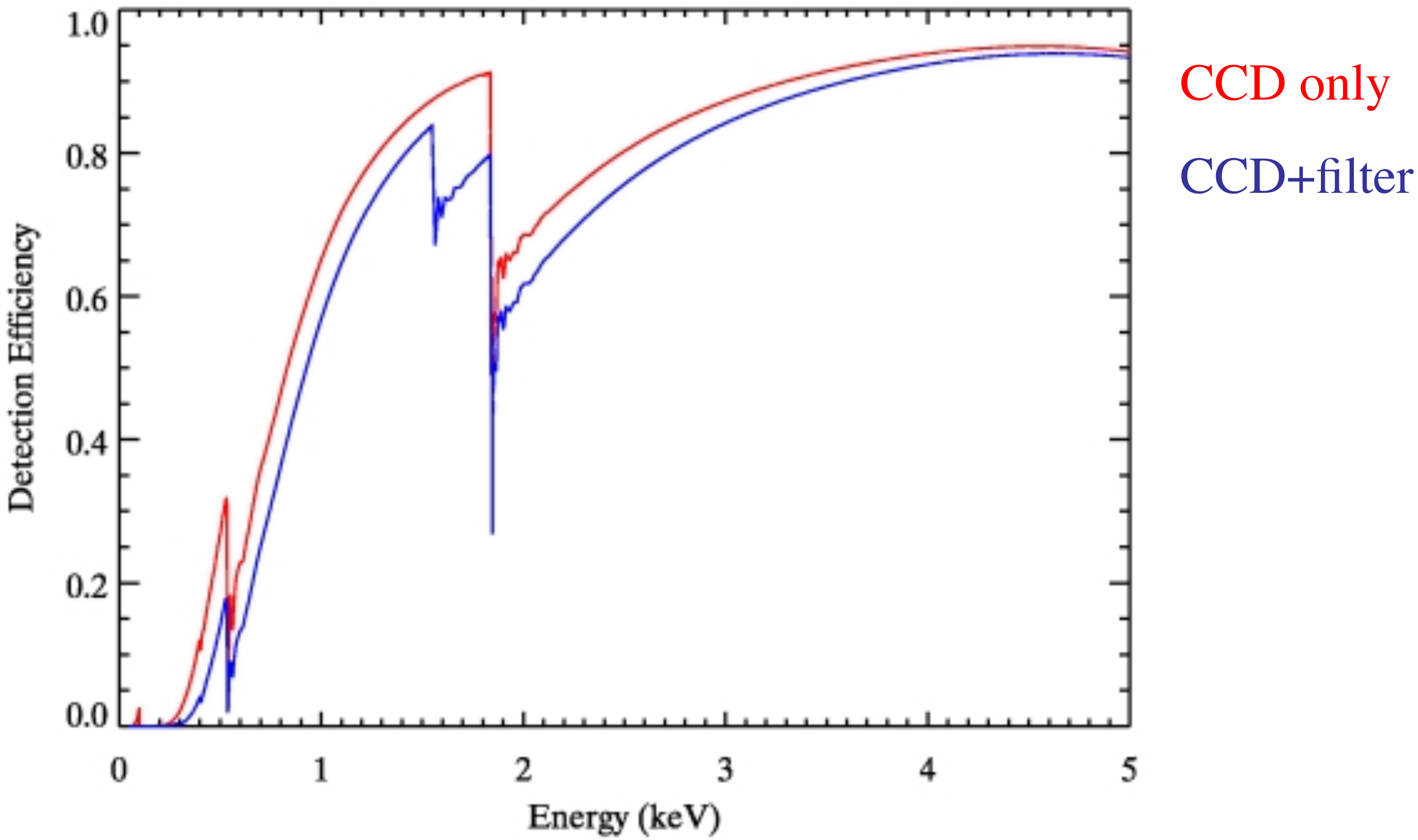
Absorption in depleted region

$$A = 1 - e^{-\mu_{Si} d}$$

μ is linear absorption coefficient
t thickness of deadlayer
d depletion depth

$$QE = (1 - e^{-\mu_{Si} d}) \;\; \Pi_i \, e^{-\mu_i t_i}$$

Filter Transmission



At low energies (< 0.5 keV), > 50% reduction in efficiency

CCD X-ray Spectroscopy: The Basic Idea

- Photoelectric interaction of a single X-ray photon with a Si atom produces "free" electrons:

$$N_e = E_X / w \ (w \approx 3.7 \text{ eV}/e^-)$$

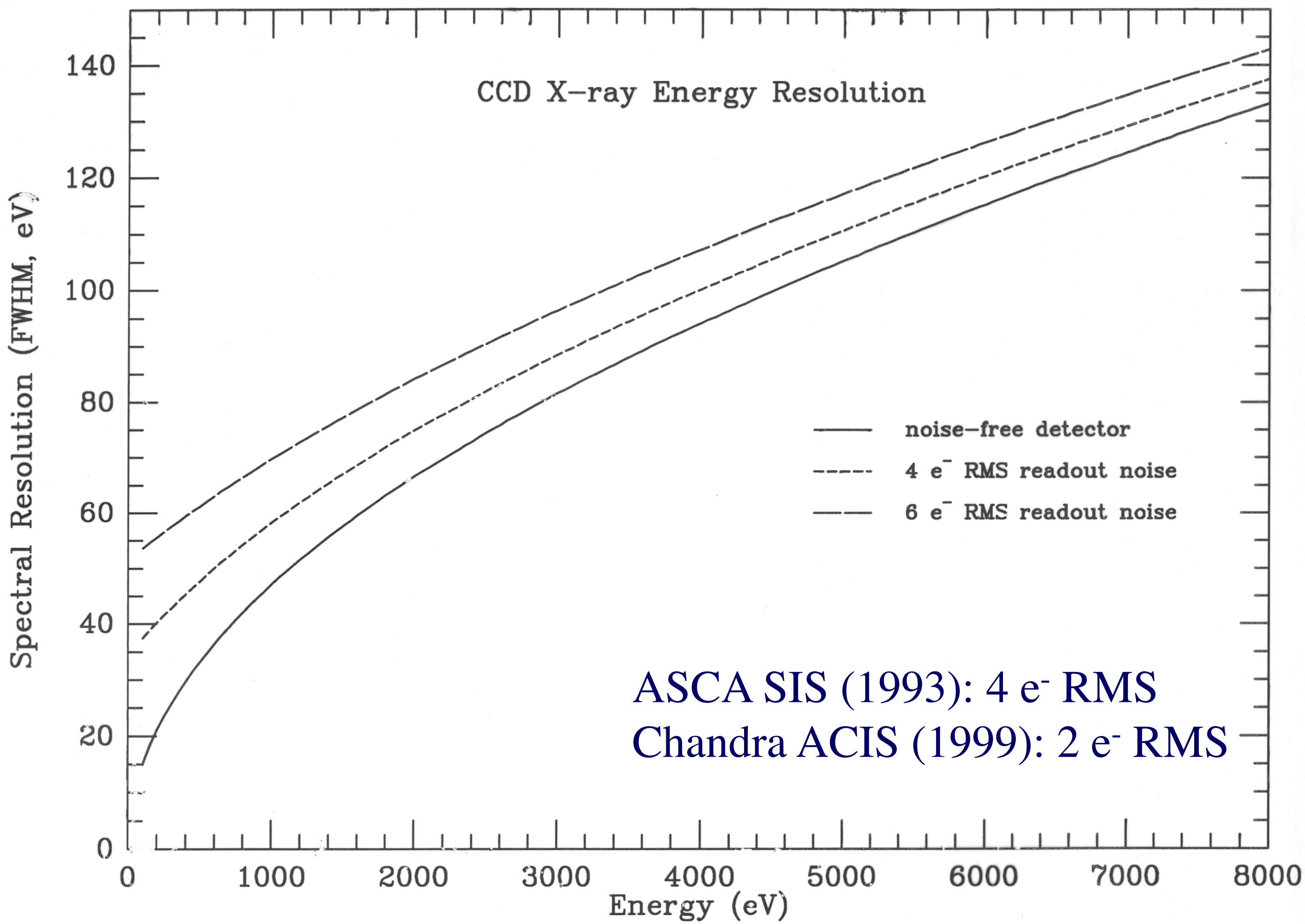
w: gain

$$\sigma_e^2 = F \times N_e \ (F \approx 0.12; \text{ not a Poisson proc})$$

- Spectral resolution depends on CCD readout noise and physics of secondary ionization:

$$\text{FWHM (eV)} = 2.35 \times w \times \sqrt{\sigma_e^2 + \sigma_{read}^2}$$

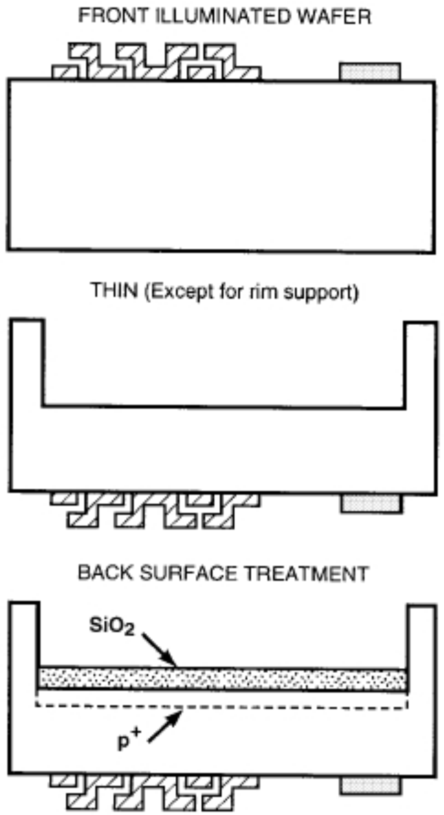
- CCD characteristics that maximize spectral resolution:
  - Good charge collection and transfer efficiencies at very low signal levels
  - Low readout and dark-current noise (low operating temperature)
  - High readout rate (requires tradeoff vs. noise)

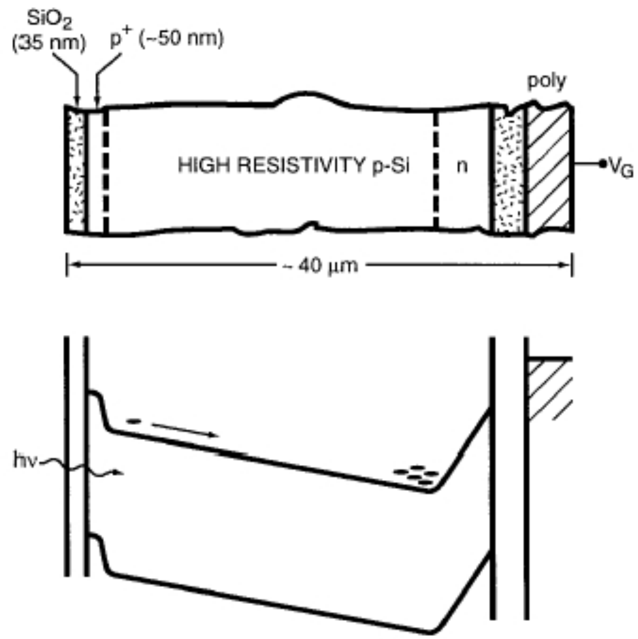

CCD X-ray Energy Resolution
Spectral Resolution (FWHM, eV)
Energy (eV)
0
20
40
60
80
100
120
140
0
1000
2000
3000
4000
5000
6000
7000
8000
noise–free detector
4 e⁻ RMS readout noise
6 e⁻ RMS readout noise
ASCA SIS (1993): 4 e⁻ RMS
Chandra ACIS (1999): 2 e⁻ RMS

Low-Energy Detection Efficiency

- Many astrophysically interesting problems require good low-energy (< 1 keV) efficiency (pulsars, ISM absorption, SNR, …)
- Low energy X-rays are lost to absorption in gate structures and filter
- Solutions:
  - Thinned gates, open gates (XMM EPIC-MOS, Swift)
  - Back-illumination (Chandra ACIS, XMM EPIC-PN, Suzaku XIS)

Back-illuminated CCDs

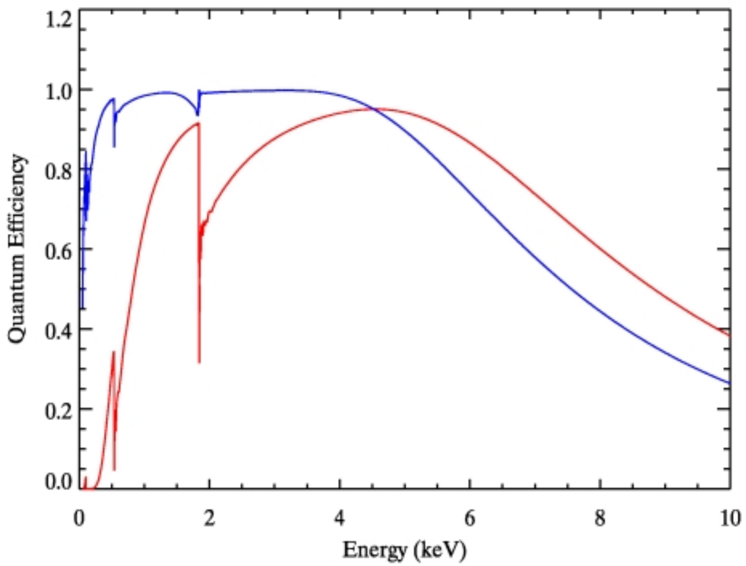


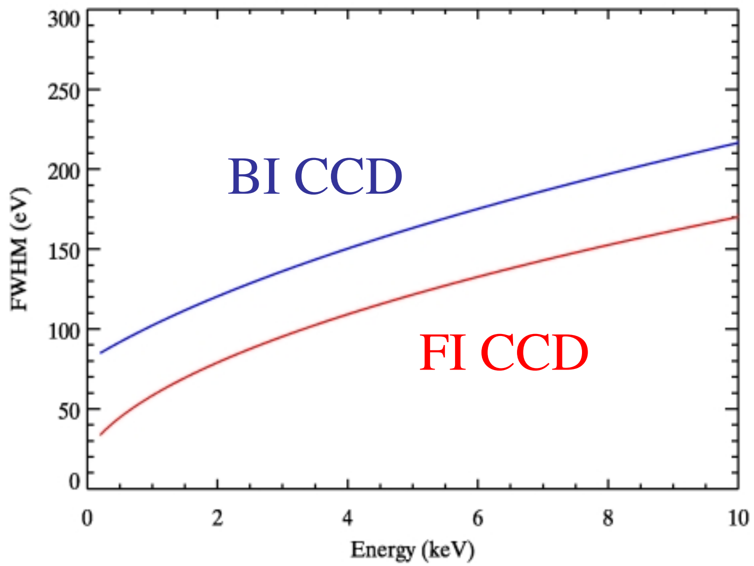


Burke et al., 1997, IEEE Trans. on EE, 44, 1633

- Front-illuminated CCD, reversed and thinned
- Gates structures and channel stops are not deadlayers

Back-illuminated CCDs





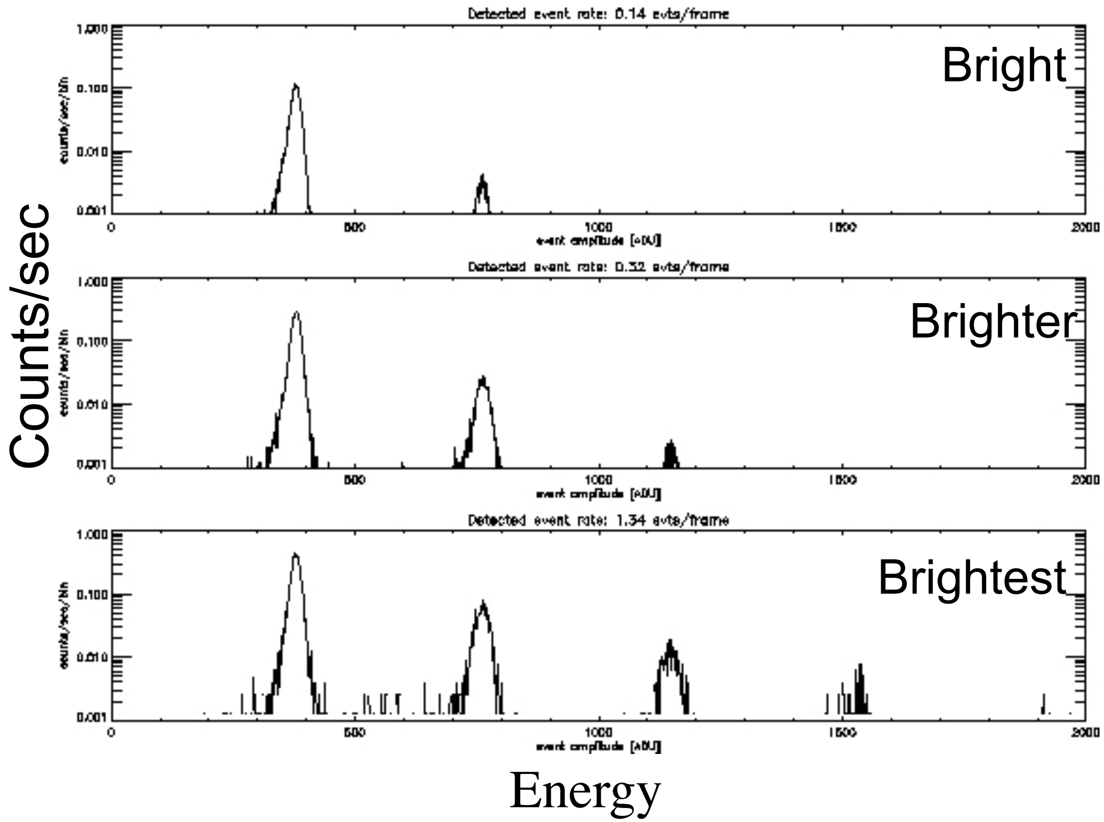
- Thinner deadlayers ⇒ higher low-E QE
- Thinner active region ⇒ lower high-E QE
- Increased noise, charge transfer inefficiency ⇒ higher FWHM

Photon Pileup

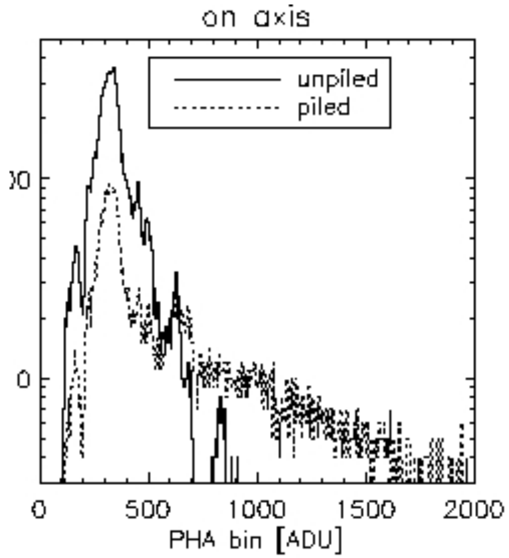
- If two or more photons interact within a few pixels of each other before the image is readout, the event finding algorithm may regard them as a single event
  - Increased amplitude
  - Reduction of detected events
  - Spectral hardening of continuum
  - Distortion of PSF
- Correcting for pile-up is complicated
- Best to set up observation to minimize pileup

Photon Pileup

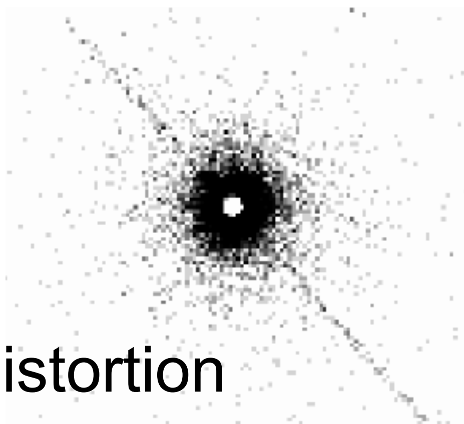
Monochromatic Source



Thermal Spectrum

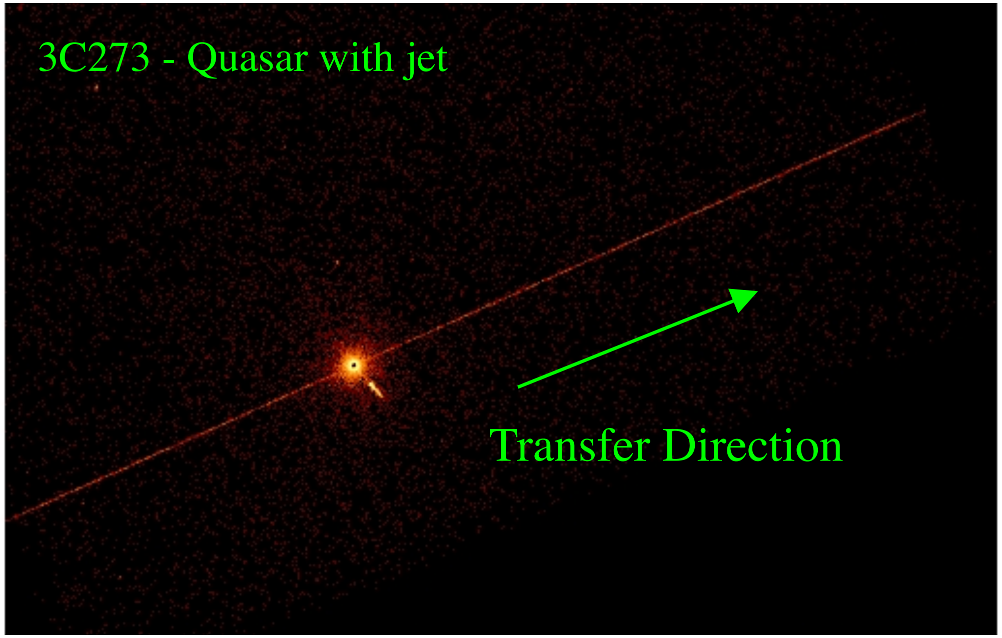


(From Chandra Proposers Observatory Guide)



PSF Distortion

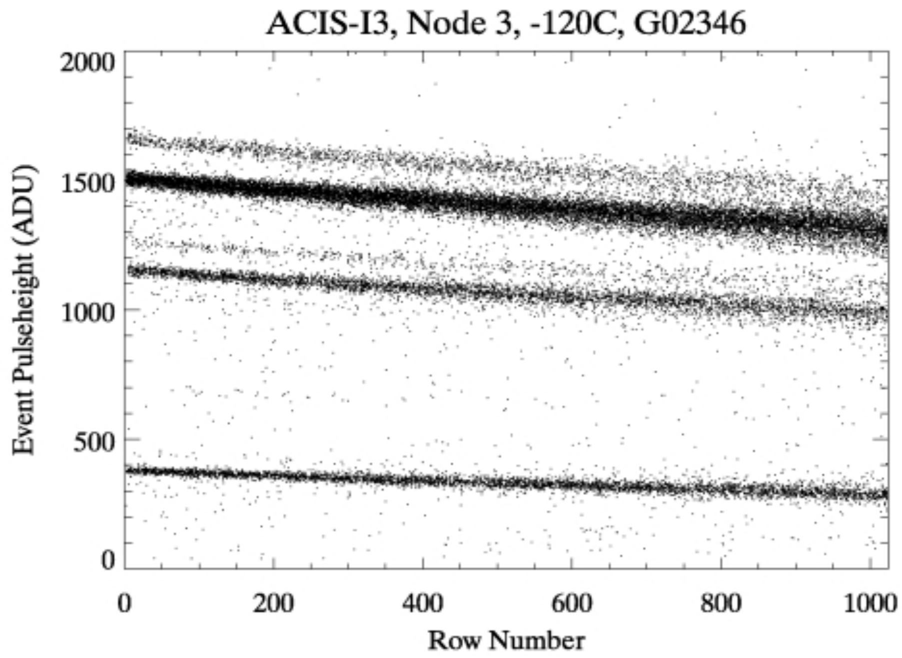
Readout Streak/Out-of-time Events



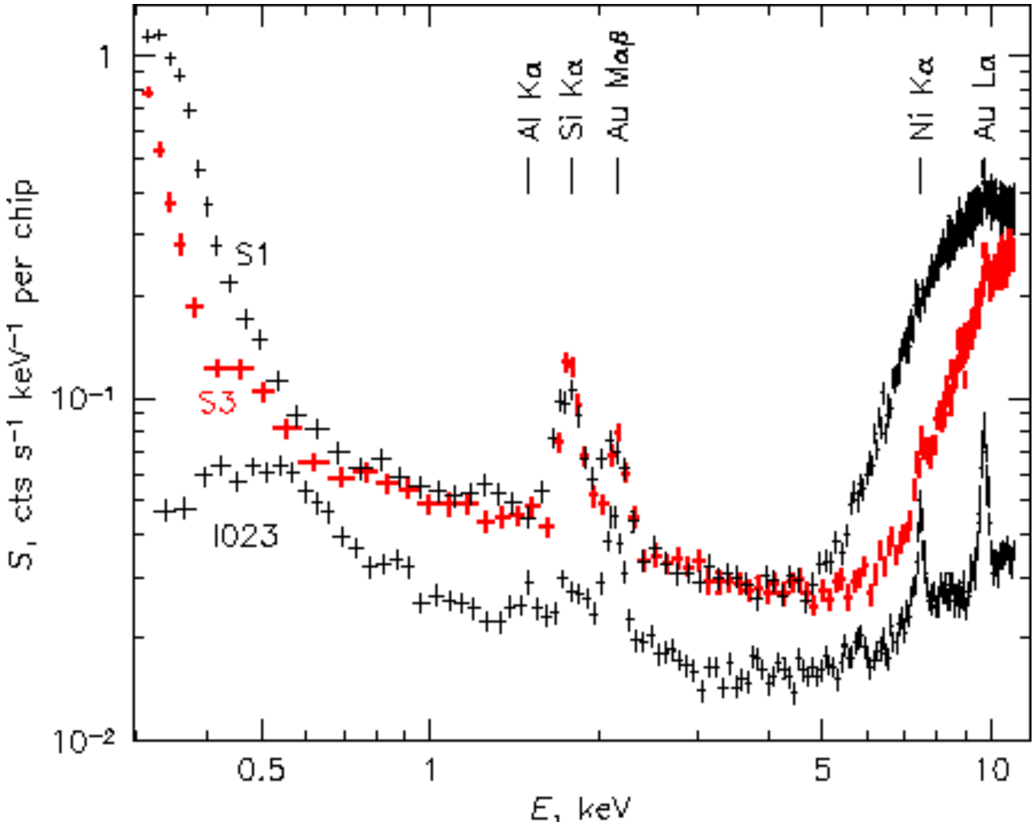
- Photons that interact while imaging array is transferring
- Assigned incorrect row/chip y value
  - Events may have poor initial calibration
- Can be modeled & removed
- Streak events have higher time resolution, no pileup

Charge Transfer Inefficiency

- X-ray events lose charge to charge trapping sites.
- Leads to:
  - Position dependent gain
  - Spectral resolution degradation
  - Position dependent QE
- Caused by radiation damage or manufacturing defects
- Depends on:
  - Density of charge trapping sites
  - Charge trap capture and re-emission properties (temperature)
  - Occupancy of charge traps (particle background)



Spectrum of the Quiescent Background



Spectra of the charged particle ACIS background with ACIS in the stowed position. Line features are due to *fluorescence of material in the telescope and focal plane*.
S1 and S3 are BI CCDs
I023 are FI CCDs

(CXC, Proposer's Observatory Guide)

- Cosmic-ray induced events plus soft diffuse cosmic X-ray background
- Background can be reduced by grade filtering
    - Less effective for back-illuminated CCDs
- Otherwise, background can be modeled or estimated and subtracted

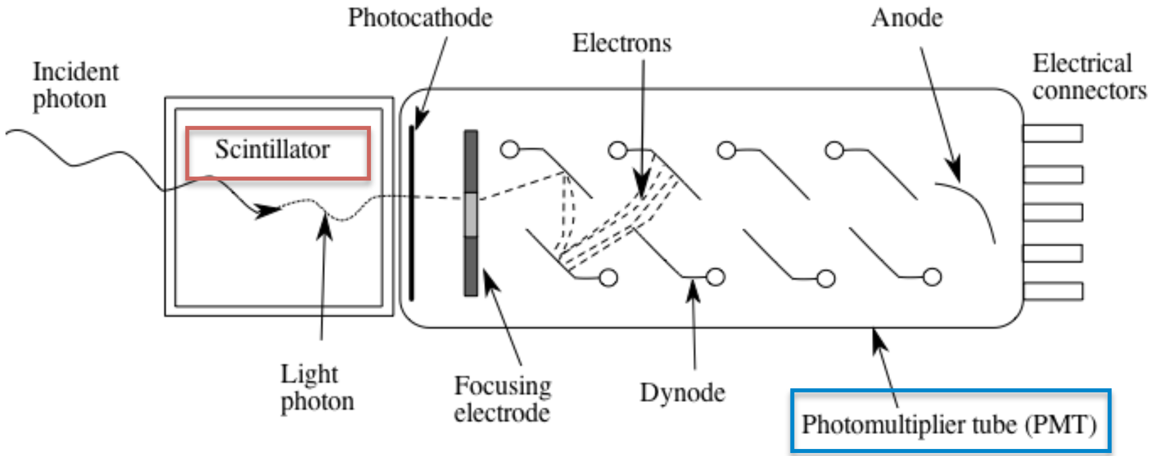
Hot Pixels, Flickering Pixels

- Radiation damage or manufacturing defects can cause pixels to have anomalously high dark current
- Can regularly exceed event threshold and cause spurious events
- Extreme cases may be removed onboard, otherwise filtered in data analysis
- Strongly correlated with temperature
  - More important for ASCA (–60C) and Suzaku (–90C) than ACIS (–120C)
- Unstable defects cause flickering pixels
  - Lower frequency, more difficult to detect and remove

Scintillators

Scintillators. I

- High efficiency in converting the energy of the charged particles into fluorescence light (**scintillation efficiency**)
- The light intensity should be linearly proportional to the energy of the particles, hence the energy of the primary high-energy photon (**linearity**)
- Transparency to the wavelength of the fluorescence light (peak at ~550 nm for the CsI(TI))
- High density and Z → high μ_{pe} → high efficiency and spectroscopic power
- Rifraction index close to that of the glass to optimize che optical coupling with devices 'reading' the resulting light (e.g., PMT)
- Decay time of the fluorescence light should be short

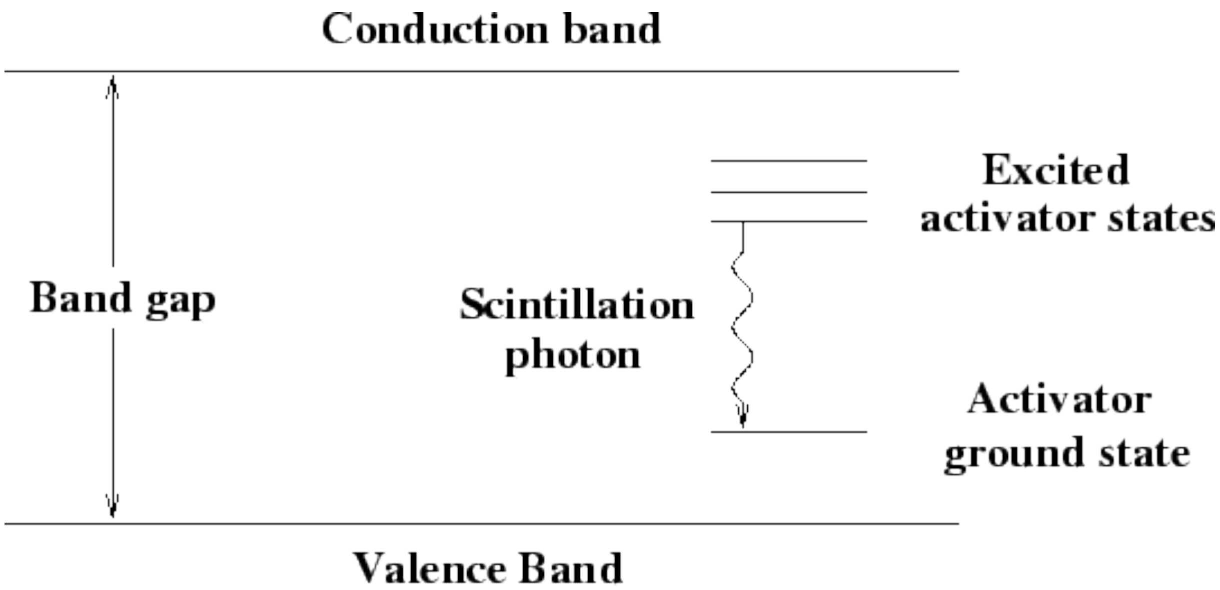


Scintillators. II

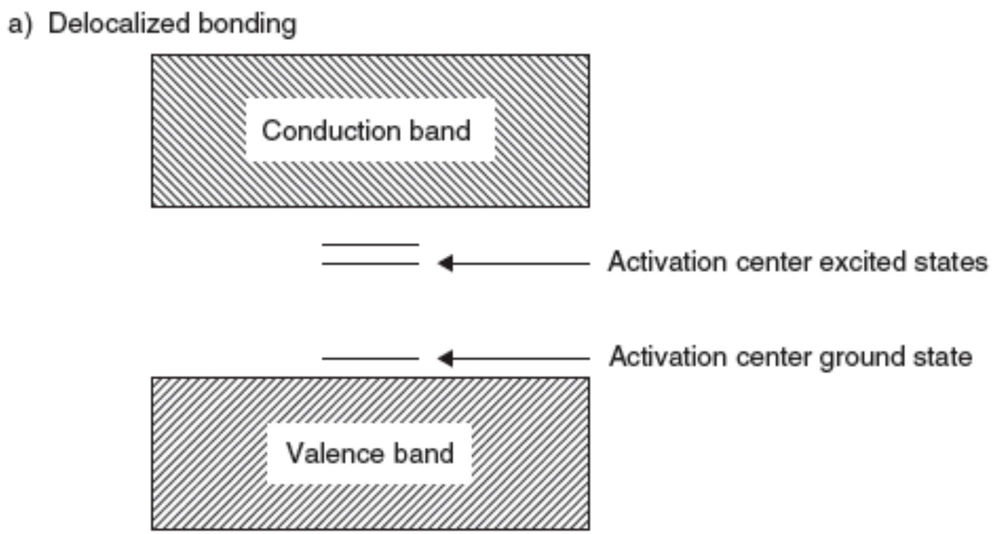
- The incident photon interacts within the crystal, producing a large number of optical photons
- The energetic levels are defined by the structure of the crystal lattice
- The band gap separates the valence from the conduction band
- When the energy is absorbed, an electron passes from the valence band to the conduction band
- The doping of the crystal lattice using impurities makes the process more efficient

In the crystal, electrons can occupy two levels: the **valence band** and the **conduction band**.

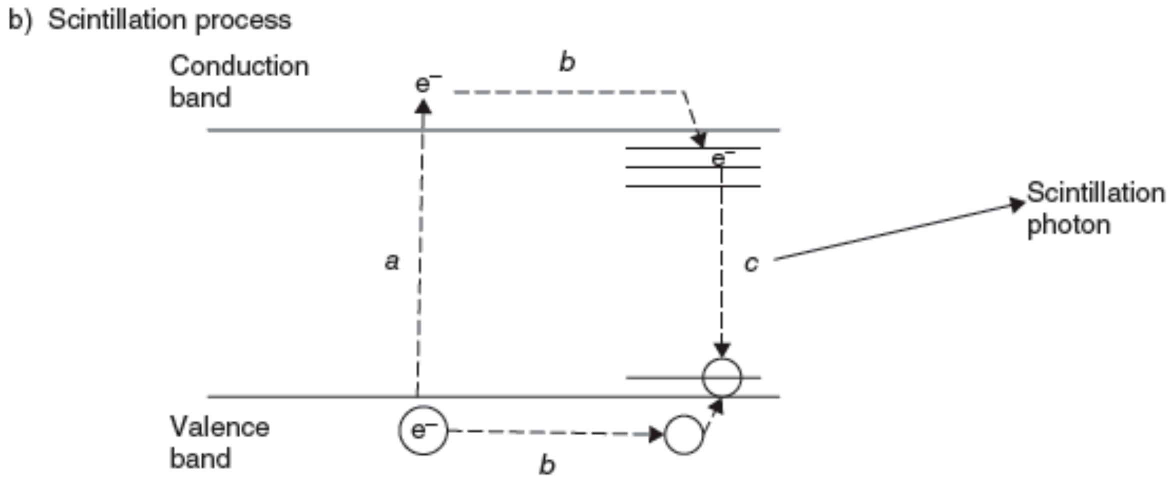
Impurities allow the creation of meta-states that are particularly efficient for the de-excitation from the conduction band



Scintillators. III



created by impurity, electron orbitals, sort of traps.
Make the process more efficient reducing the band gap

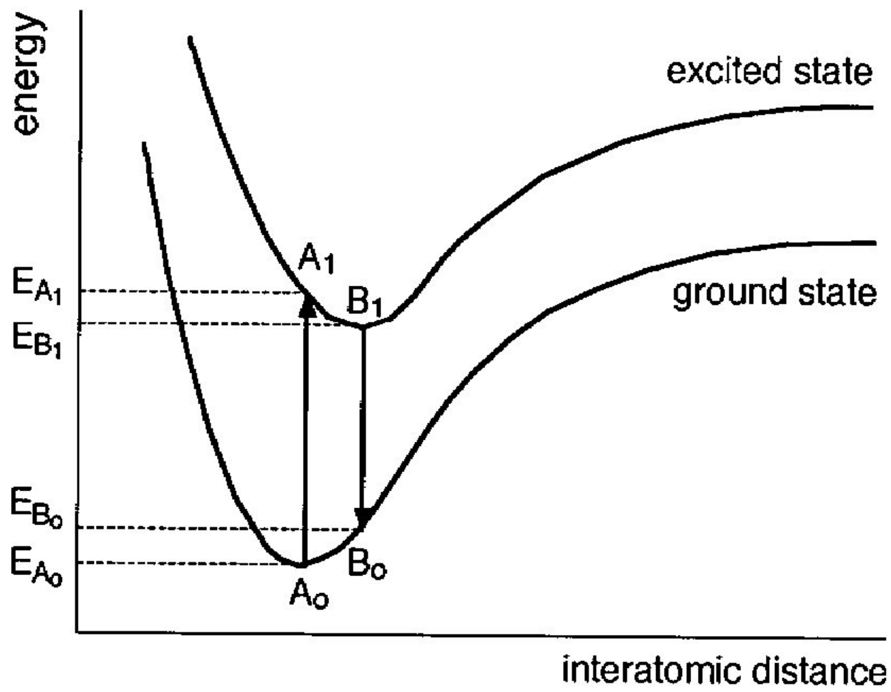


Energy gap ∝ λ photon

Intensity final signal (mV)
∝ I(signal visible light)
∝ # visible photons
∝ E(incoming X/γ-ray)

Not all incoming energy converted into scintillation photons (≈15 %), but proportionality is preserved
De-excitation via heat ("quenching" processes)

Scintillators. IV

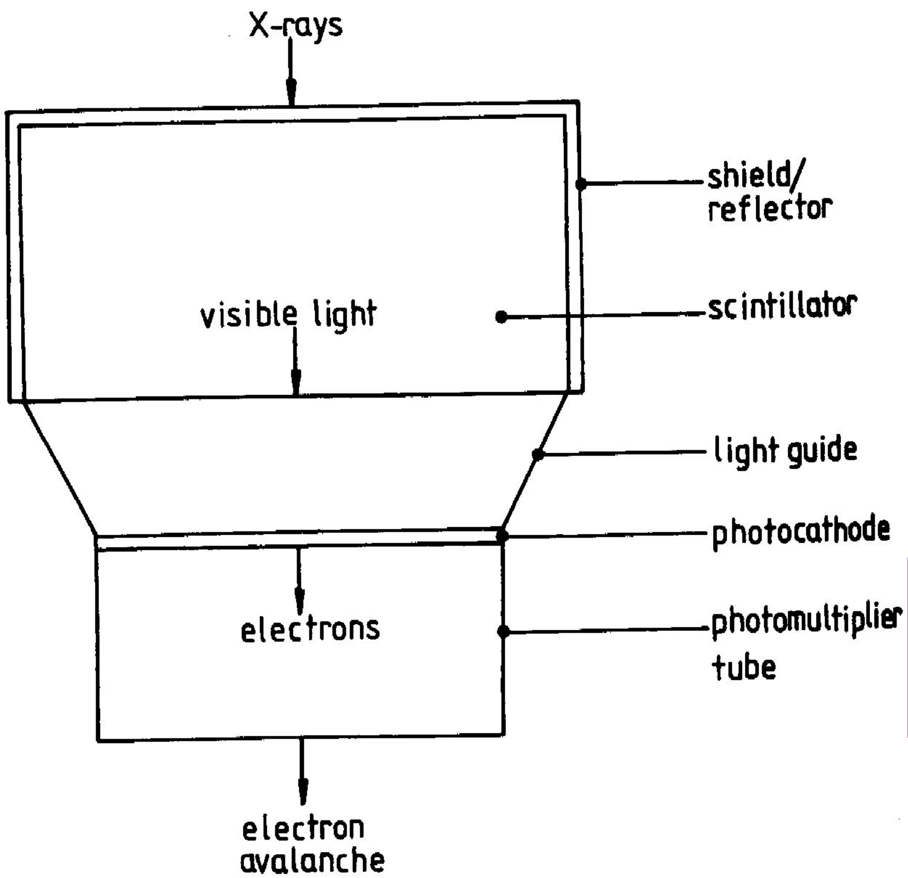


The energy deposited in the detector raises the molecule from the ground-state A_0 to A_1 ($E_e=E_{A1}-E_{A0}$) in a time of ~0.1 ps which is short compared to the vibration time. Since a state with excess vibrational energy is no longer in thermal equilibrium with its neighbors, vibrational energy is quickly lost moving the molecule to B_1. After a time (~10ns) long compared to the vibrational time, the excited state decays to the ground level B_0.

The excess energy $E_p=E_{B1}-E_{B0}$ is carried away from the **scintillation photons**.

$E_e>E_p$ means different absorption- and emission-spectra; this translates into negligible re-absorption, making the scintillator transparent to the scintillation photons.

Scintillators. V

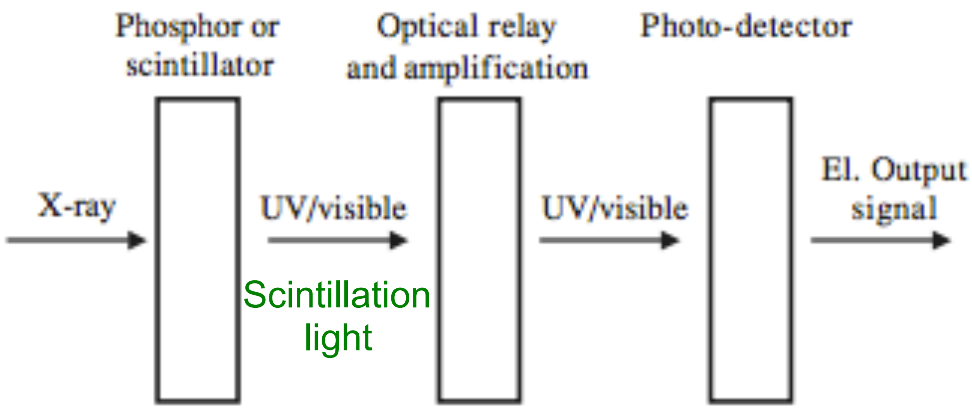


UV-optical photons, depending an the material and the activator

"Amplification" of the signal (higher in PMT than in photo-diodes, although QE is lower)

Fraser "*X-ray detectors in astronomy*"

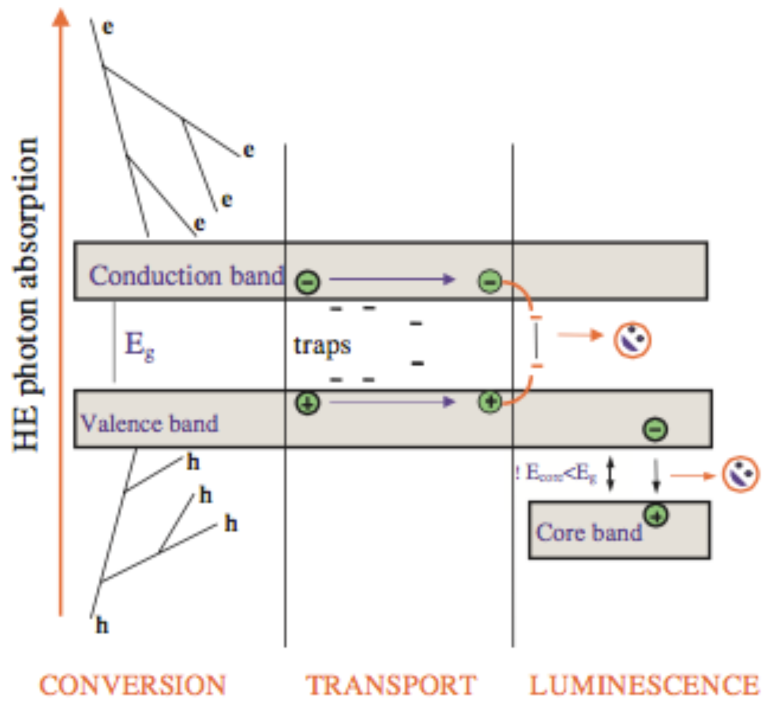
Scintillators. VI



Photon in the scintillator
→ (visible) light production → signal amplification through photodiodes or photomultiplier tubes (PMT), which absorb the light
emitted by the scintillator and reemit it in form of electrons via the photoelectric effect → electric signal

Main characteristics:

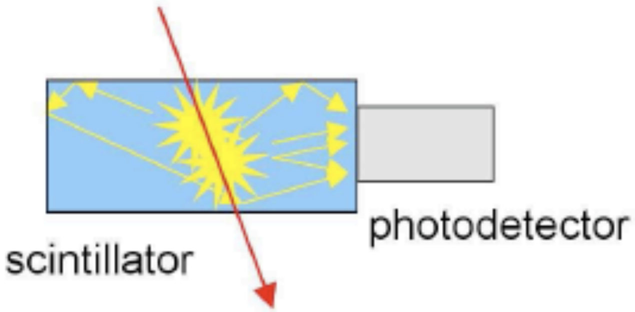
- light yield
- X-ray stopping power
- scintillation response – decay time
- spectral matching between the scintillator emission spectrum and photo-detector
- chemical stability and radiation resistance
- linearity of light response with the incident high-energy photon



Scintillators. VII
Anorganic vs. organic

Cosmic rays (typically not neutral) leave a signature in both instruments (primary and anti-coincidence), while gamma rays do NOT interact with the plastic anti-coincidence system

Scintillators



Scintillation detectors: ionizing particle deposits energy
$\Longrightarrow$ generates scintillation light
$\Longrightarrow$ light scatters in detector
$\Longrightarrow$ is detected and amplified

Two types of scintillation detectors:

anorganic scintillators **(e.g., NaI, CsI)** : up to 40000 photons/MeV, high Z, ns to μs pulse durations, radiation hard **Best response and linearity but slow**

organic scintillators **(plastics [and liquids)]**: up to 10000 photons/MeV, low Z, low ρ, ns pulse durations, medium radiation hard **Faster but yield less light**

For space applications: typically use anorganic scintillators

Plastic scintillators are used in anticoincidence setups.

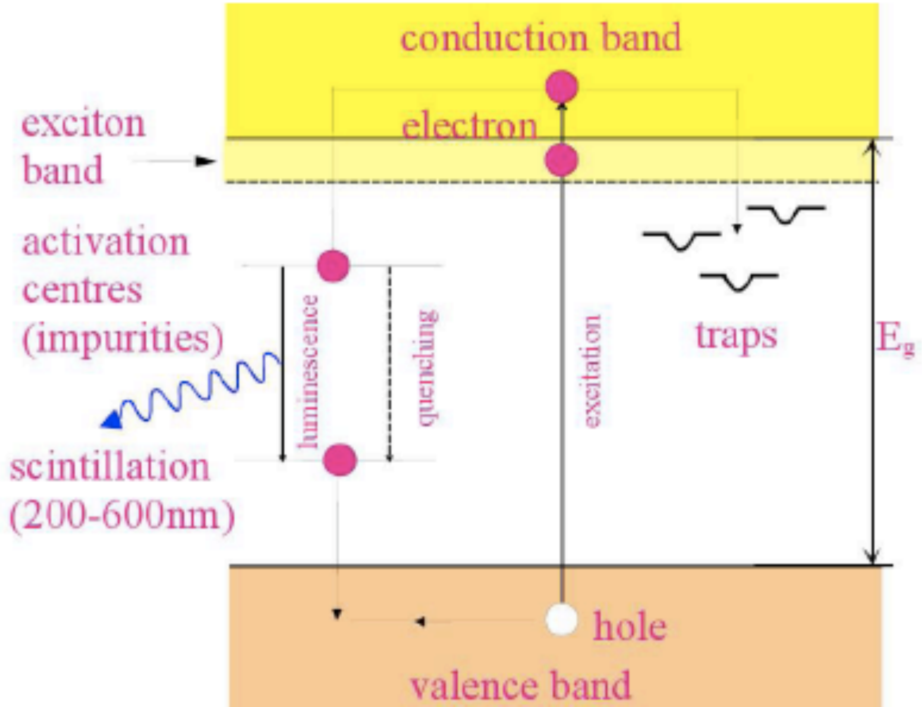
Used for anti-coincidence systems

- **Anorganic scintillators:** best response and linearity but slow
- **Organic (plastic) scintillators:** fast but yield less light, fine for anti-coincidence systems

Scintillators. VIII

Anorganic scintillators

Anorganic Scintillators



Credit: CERN

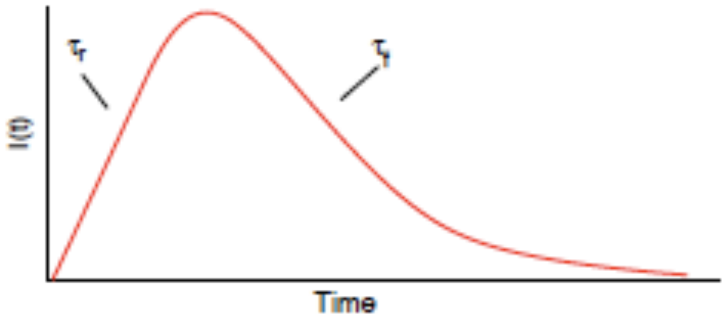
Generation of scintillation light:

- ionizing particle excites electron (and phonons)
- partial de-excitation to an activation center
- de-excitation by emission of scintillation light

Internal degradation, no radiation emission

Scintillators. IX
Anorganic scintillators

Anorganic Scintillators



Typical pulse shape:

$$I(t) = I_0 \left(e^{-t/\tau_f} - e^{-t/\tau_r}\right)$$

where τ_r, τ_f are the time constants

"Rise" and "fall" time

Properties of typical scintillators:

Material	ρ g cm^{-3}	λ_{max} Å	τ_f [μs]
NaI(Tl)	3.67	4100	0.25
CsI	4.51	3100	0.01
CsI(Tl)	4.51	5650	1.00
BGO	4.88	4800	0.30

BGO: Bismuth-Germanate; note that there are many more scintillator materials available, the above are the ones typically used in space applications.

Credit: CERN

Scintillators. X
Scintillator properties

Number of produced optical photons given a registered energy

Material	Density (g/cm^3)	Max emission (nm)	Decay Constant (μs)	Light Yield (ph/MeV)
NaI(Tl)	3.67	415	0.23	38000
CsI(Tl)	4.51	565	1	52000
BGO	7.13	505	0.3	8200
CeF_3	6.16	340	0.027	4200
NE102 (plastic)	1.032	423	0.002	10800

Thallium-activated Sodium iodide

Thallium activated Cesium iodide

Bismute germinate (Bi_4 Ge_3 O_{12})

Density needed to stop gamma-rays

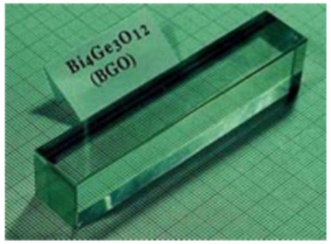
Dictates how the scintillation light should be detected

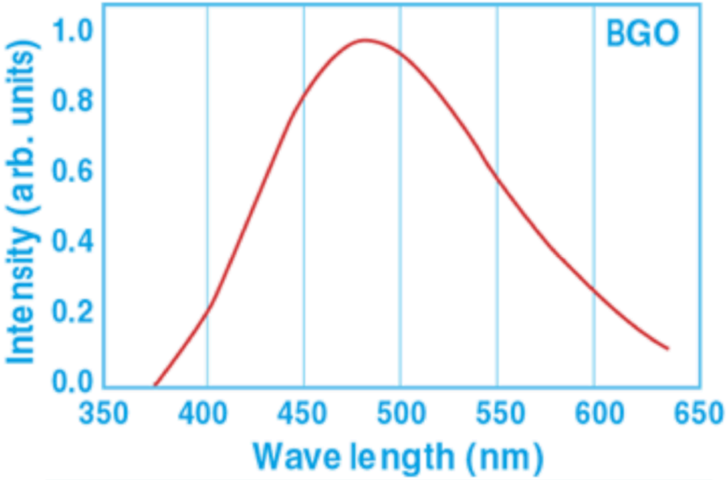
Can be important to have a fast light pulse

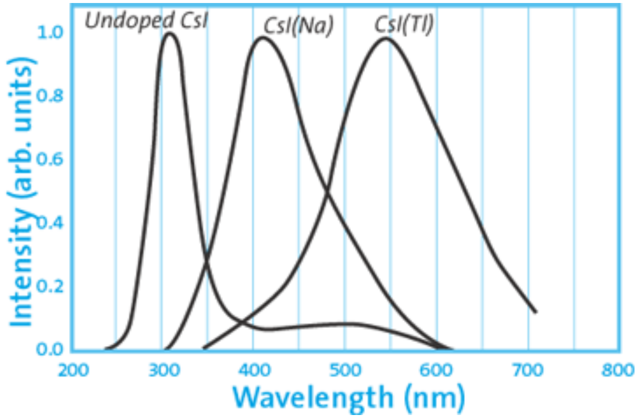
More signal always a good thing !

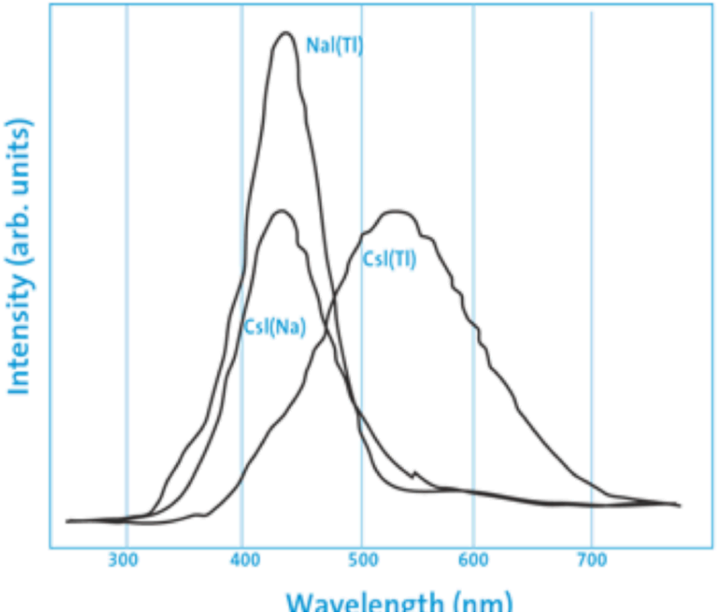
Scintillators. XI
Scintillator properties

UV light produced in the scintillators





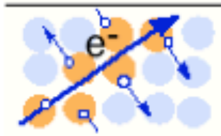




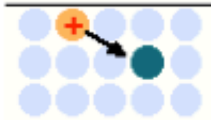
Scintillators. XII
Possible interactions in the scintillator

inorganic scintillators *Scenario of an interaction*

γ-ray interaction with matter produces a secondary e^-
photoeffect, Compton, pair-production

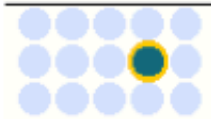


ionization : fast e^- traversing crystal gen. a large number of e^-/hole pairs
e^- are raised from the valence-band to the conduction-band

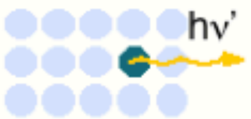


holes quickly drift to an activator site
$E_{ionization}$ of impurity < $E_{ionization}$ of typical lattice site

e^- are free (conduction)
until they encounter an ionize impurity ...



excitation : e^- fall into impurity => neutral, excited atom
(possibly with allowed transition to ground state)



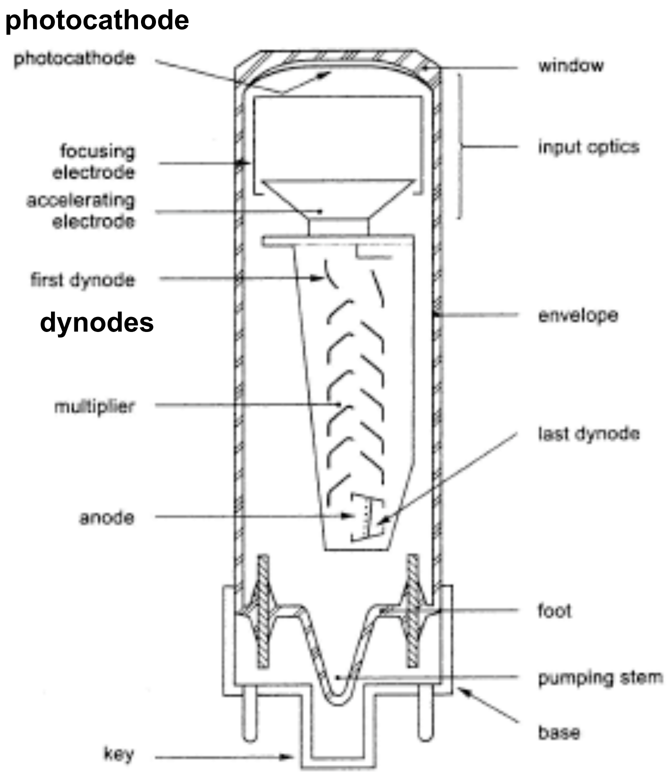
deexcitation : transition in visible domain (for appropriate activators)
(excited states $t_{1/2}$ ~10^{-7}s)

visible photons interact with matter e.g on the photocathode of a PMT
(who transforms em-radiation back into electrons ...)

Photomultipliers.I

Scintillation photons produce electron-hole pairs → Emission of electrons at the photocathode, due to the incoming scintillation light → *Electron "multiplier"* due to collisions with dynodes and acceleration by a potential drop

Photomultiplier



Primary scintillation signal is amplified with a photo-multiplier tube (PMT).

Technical considerations:

- Match PMT to scintillator crystal

  light losses at contact point between scintillator and PMT [scattering!], sensitivity of photocathode must be matched to peak of scintillation light,. . .

- Magnetic shielding

  Typical numbers: 25% decrease in efficiency if a PMT is operated in a 1 mT field!

Alternatives to PMTs: e.g., microchannel plates

Philips Photonics after H. Spieler

QE=number of photo-electrons emitted (photo-cathode)/number of incident photons≈20-50%

Photo-diodes are more efficient (up to 90%) in terms of QE but the signal enhancement is low (lower voltage, noise is large, need pre-amplifier)

Photomultipliers.II

Typical numbers

Typical numbers for a scintillator / PMT system for a 511 keV gamma-ray (after Spieler):

- 25000 photons at scintillator
- 15000 photons hit photocathode
- 3000 electrons at first dynode
- 3×10^9 electrons at anode

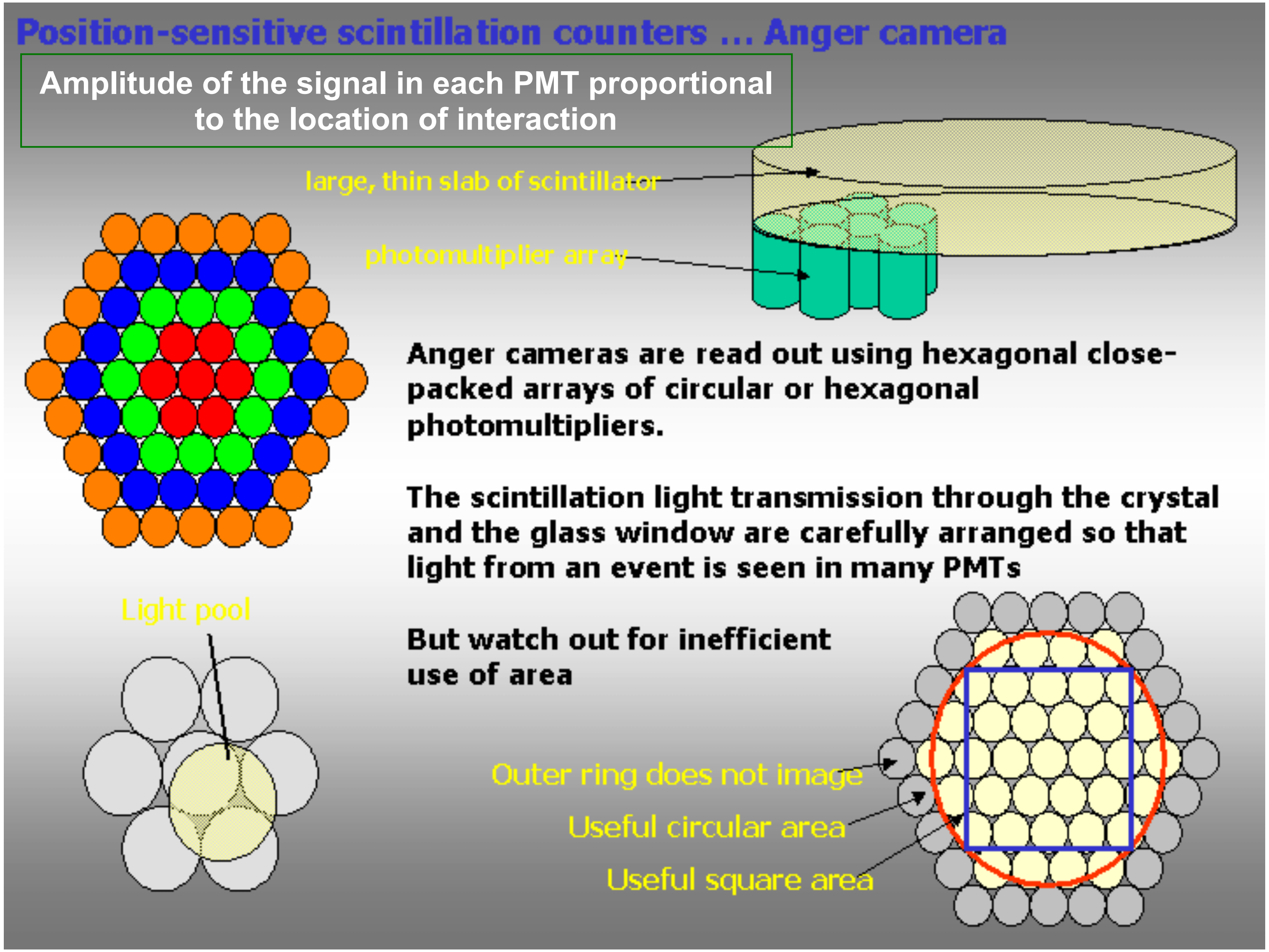
giving 2 mA peak current.

Energy resolution determined from smallest "quanta", i.e., here the number of electrons at the first dynode. Therefore for this example

$$\frac{\Delta E}{E} \sim \frac{2.35}{\sqrt{3000}} = 5\% \text{ at } 511\,\text{keV}$$

Typically scintillators are a factor 1.5 worse because of nonuniformities.

Scintillators. XIII
Applications: the Anger camera

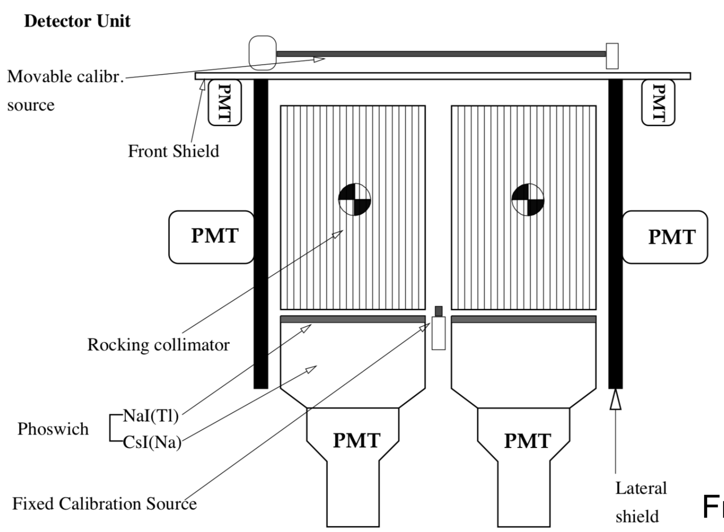


Anger, 1958

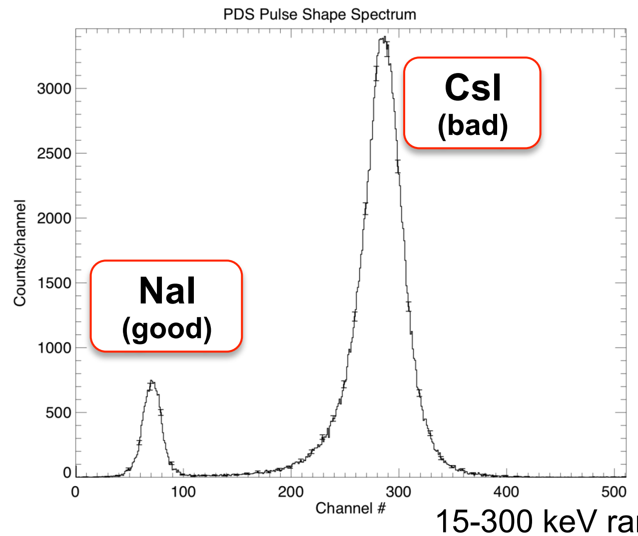
Scintillators. XIV
Applications: the Phoswich

Phoswich=phosphor sandwitch (Example: SAX/PDS)
Two (or more) scintillators are 'sandwiched' together and viewed by the same photomultiplier

• Scintillators are chosen to have different decay times, so that the shape of the output pulse from the photomultiplier tube is dependent on the relative contribution of scintillation light from the two scintillators
• The analysis of the differences in the pulse shapes allows distinguishing events occurring in only one scintillator from those occurring in both
• More penetrating particles can produced signal in both scintillators
• Different materials have different pulse shapes (different decay time) and are used to discriminate different events



Frontera et al. (1997)

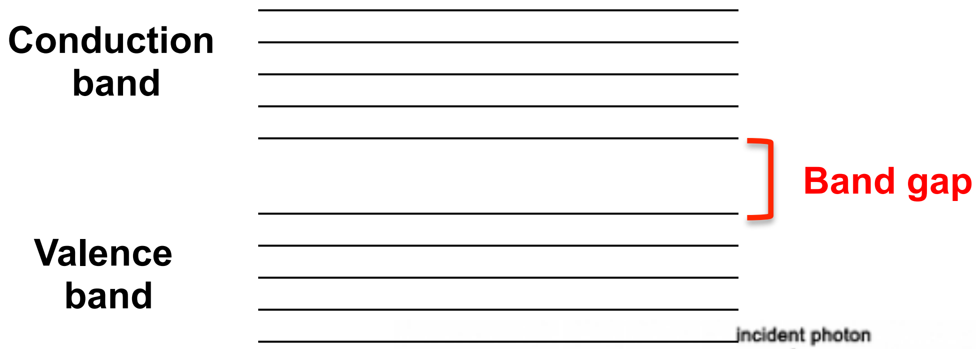


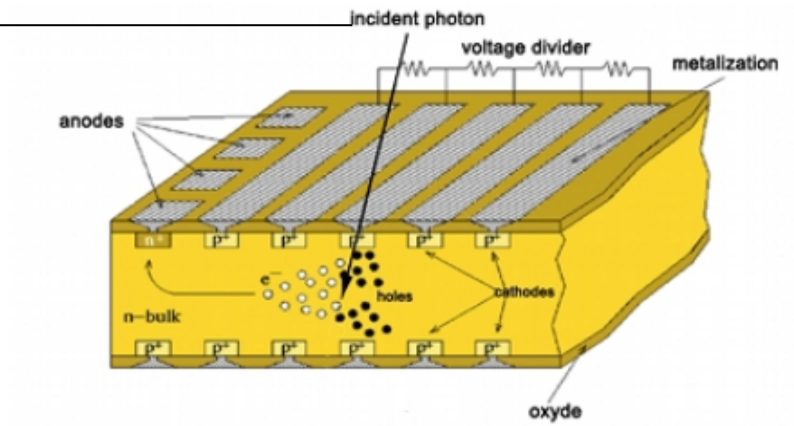
15-300 keV range

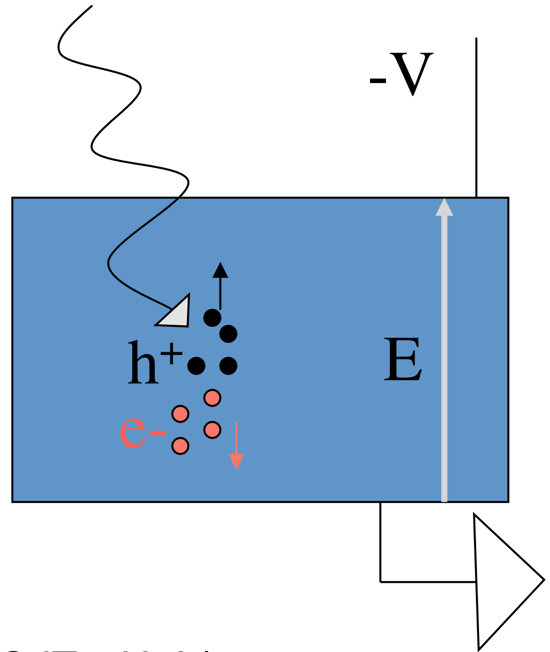
Solid-state detectors:
CZT And Germanium

Solid-state detectors. I

- Solid-state detectors (SDDs) are semiconductor materials and to work take advantage of the properties of the band structure of crystals [valence band, conduction band (i.e., energetic levels of e- in the material), band gap]
- Electrons from the valence band can migrate to the conduction band under the influence of thermal stirring and/or radiation
- The detection of the charge is direct







Band gap:

~1 eV: Ge, Si (need cooling, ~80 K)

≥1.5 eV: "room temperature semiconductor" (CdZnTe, CdTe, HgI_2)

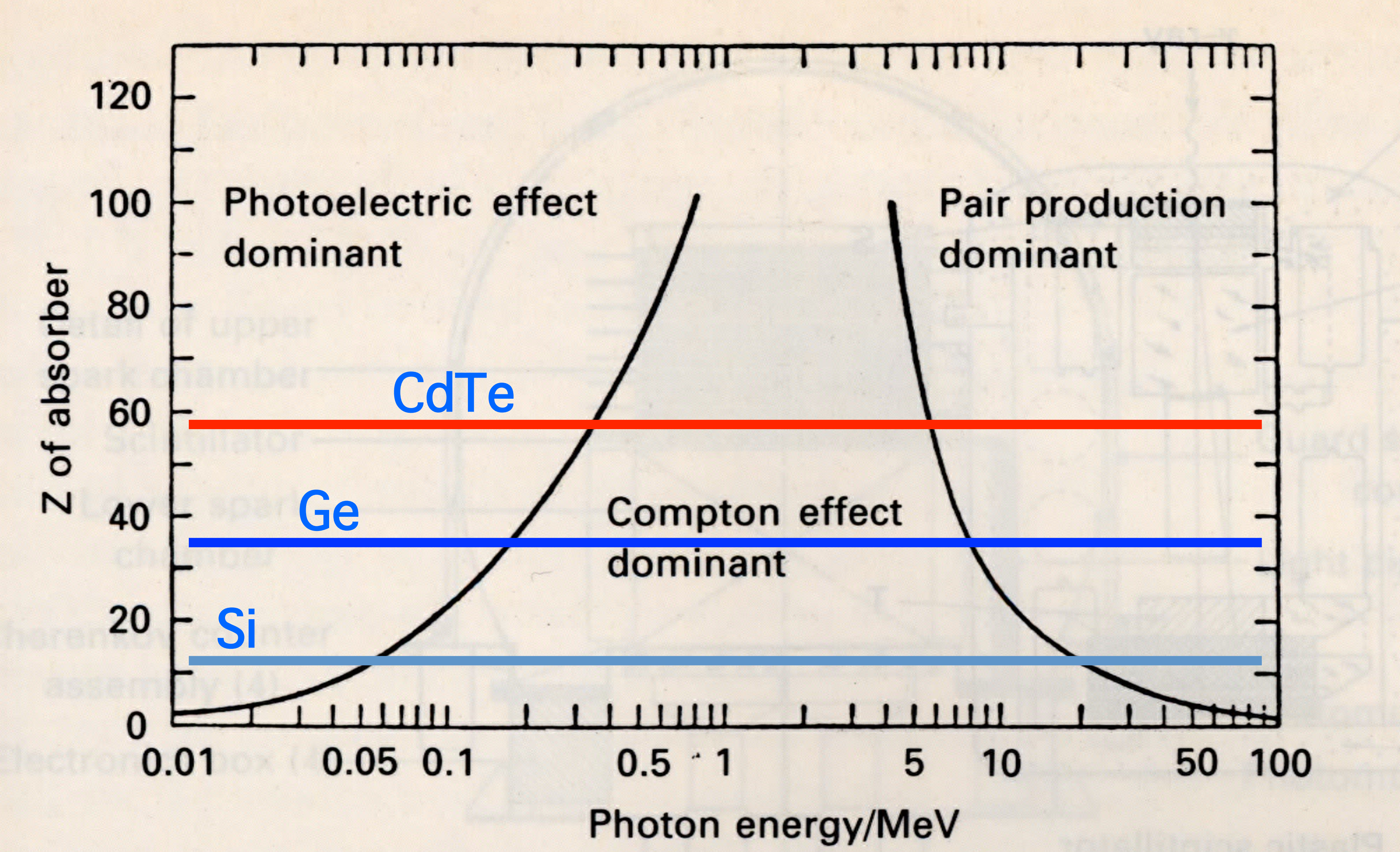
Solid-state detectors. II

Principle: SSDs collect the charge generated by ionizing radiation in a solid.
These detectors are semiconductors operating similarly to a solid-state diode with a reverse bias.
The applied high voltage generates a thick ‘depletion layer, thus any charge created by the radiation in this layer is collected at an electrode

The charge is proportional to the energy deposited in the detector, therefore these devices can also yield information about the energy of individual particles or photons.
Silicon and germanium are among the most common materials used in SSDs.

Electrons drift toward the anode, and holes to the cathode due to the applied strong electric fields. Recombination is inhibited. The current pulse is proportional to the total charge generated by the incident particle (i.e., to the energy deposited in the detector)

Solid-state detectors. III
Cd(Zn)Te



Solid-state detectors. IV

Properties of semiconductor materials

Composition	Density $[g/cm^3]$	Mean Z	Bandgap [eV]	Energy per e^--hole pair [eV]
Ge	5.32	32	0.74	2.98
Si	2.33	14	1.12	3.61
CdTe cadmium telluride	6.2	50	1.6	4.43
Cd(Zn)Te	6.0	48	1.6	
HgI_2 mercuric iodide	6.36	62	2.15	4.22

- Probability that an electron-hole pair is thermally generated: $P \propto T^{3/2}\ e^{-Eg/2kT}$
- The larger the energy gap E_g, the lower the probability
- Higher temperatures imply higher probability for thermally-induced "transitions"

It must be avoided that electrons get free (thus producing signal) because of the environment temperature and not because of the interaction of the incoming photon with the material

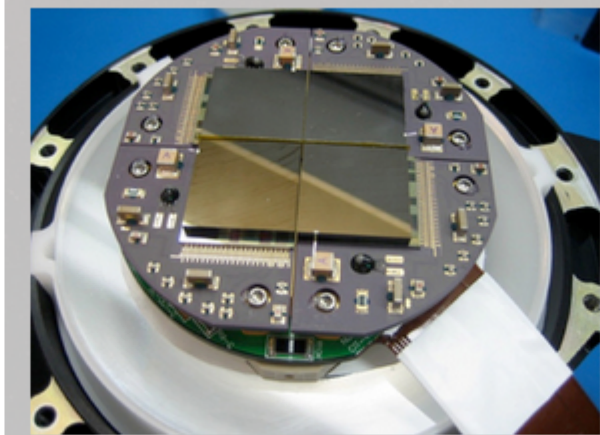
Solid-state detectors. V

CdTe detectors

- E (gap)=1.52 eV, cryogenics non required (Ge: ~1 eV)
- High ρ (~6 g cm^{-3}) to maximize the efficiency
- High Z (48, 52) for the photoelectric absorption, can work up to high energies
- Can be segmented easily into small sizes, fine for spatial resolution
- Lower efficiency than Si and Ge (lower efficiency in the charge collection), hence lower spectral resolution

CdZnTe=CZT detectors

- Lower dark current than CdTe (slightly higher E_{gap}), so stronger electric fields can be applied, and the charge collection can be quicker



NuSTAR focal plane.

NuSTAR CZT detector

Solid-state detectors. VI

Germanium

- Good response to high-energy photons
- Best choice for E>100 keV − 10 MeV spectroscopy (very thin surface dead layers may allow a good response from few to 100's keV)
- Disadvantages: requires cooling

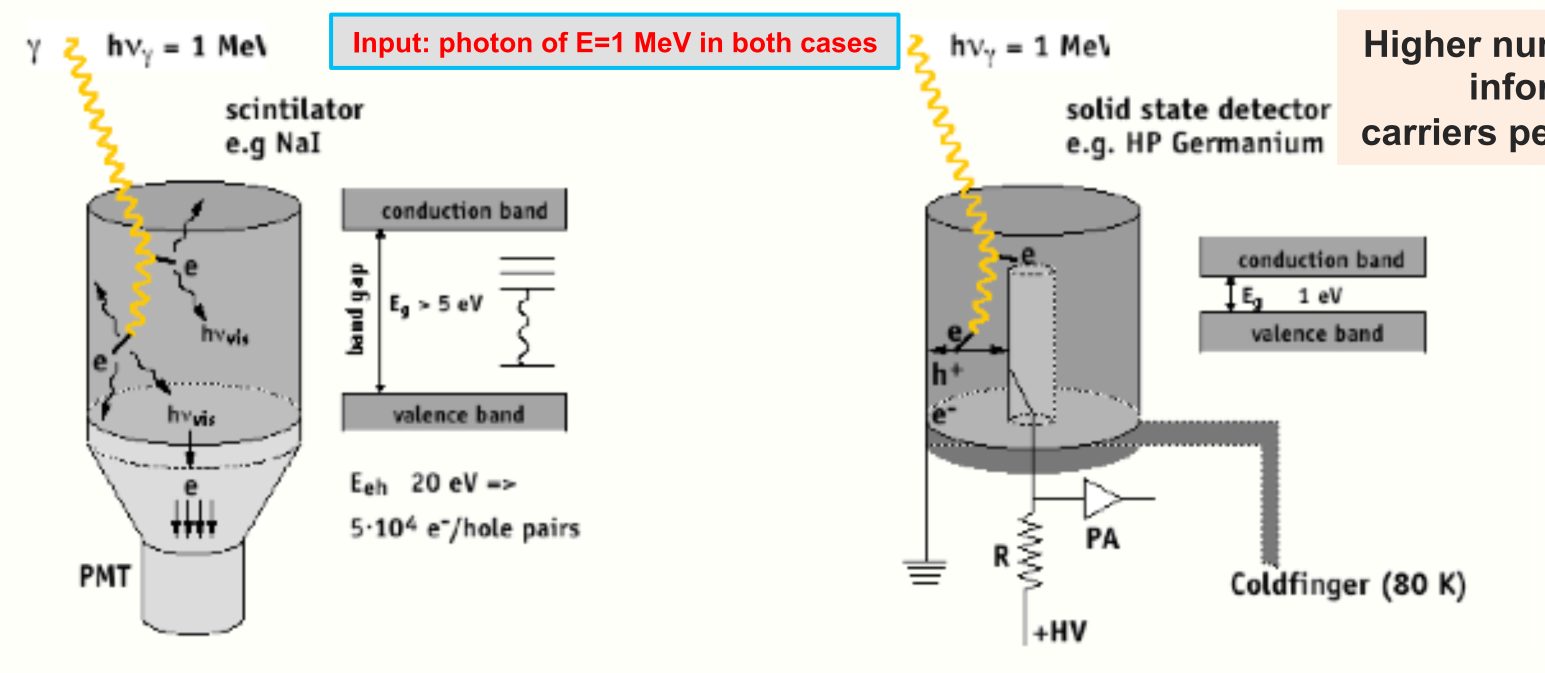
  surface sensitive to contamination

  for fine position-sensitive detectors, segmented contact technology not well developed
- Example: *Integral*/IBIS (SPI instrument)

Scintillators	Semiconductors

Input: photon of E=1 MeV in both cases

Higher number of information carriers per pulse



Scintillation eff. ~ 12% => 120 keV (V/UV)
Vis. photon energy ~ 3eV => 40'000 V/UV ph
on photocathode => 20'000 photons
quantum eff. QE ≈ 20% => 4'000 photo-e^- (N_{sci})

Energy to form e-/hole pair : $E_{eh} \approx 3$ eV
$N_{sem} \approx 10^6/3\text{eV} \approx$ 300'000 charge carriers
$F_{sem} \approx$ 0.06-0.14 (Fano factor)

$$R = \frac{1}{2.35}\sqrt{\frac{N}{F}}$$

$R = 0.42\,(N_{sc}/F_{sci})^{1/2} \approx 25$

F_{sci}= Fano factor for the scintillators

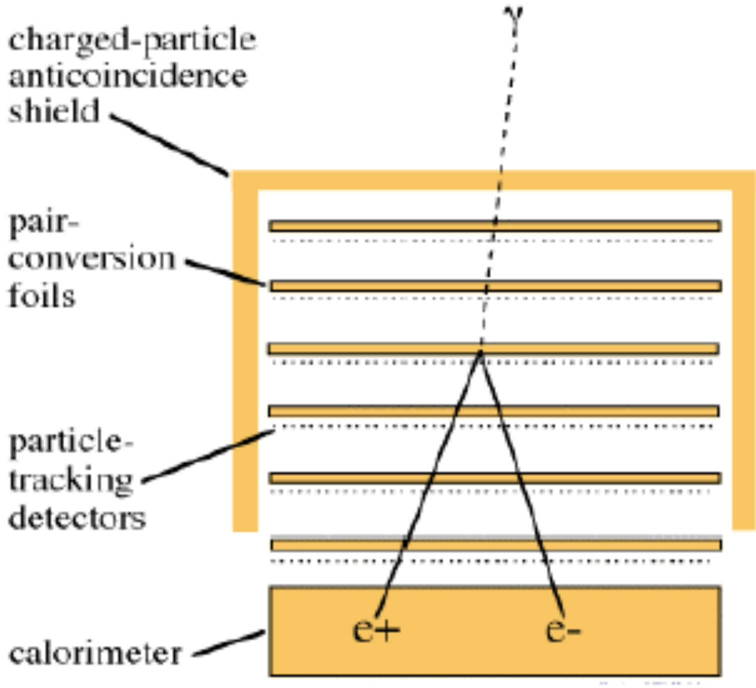
$R = 0.42\,(N_{sem}/F_{sem})^{1/2} \approx 500$

F_{sem}= Fano factor for the semiconductors

Tens of keV of energy resolution in scintillators vs. few keV in semiconductors detectors

Pair-production detectors
Converters/trackers

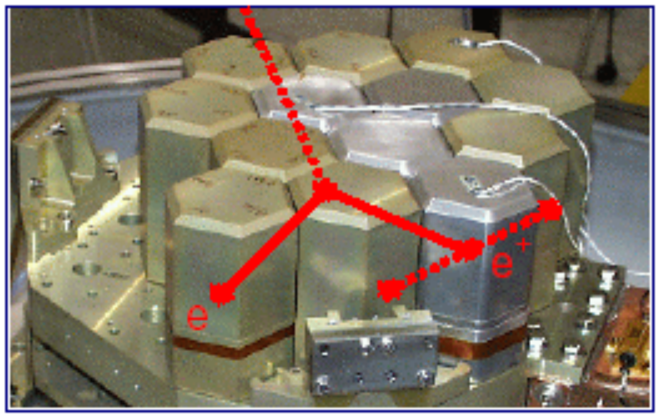
Pair production Telescopes. I



Incident photon whose energy $E_{ã} > 2m_ec^2$ (i.e. $E_{ã} >$ 1.022 MeV) is in a position to create an electron-positron pair in the intense electric field prevailing close to an atomic nucleus.

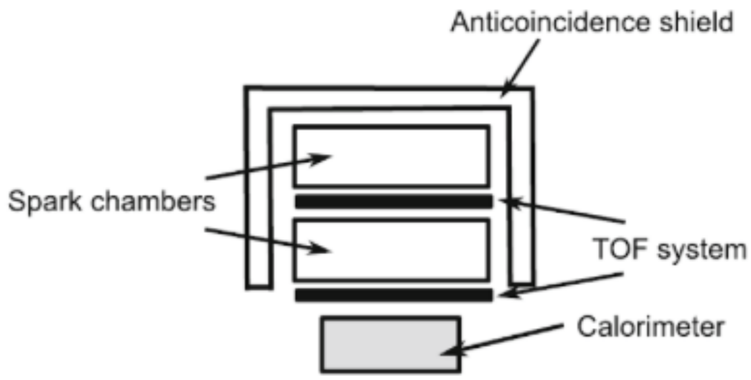
Trajectories of the particles does not markedly deviate from the incident photon direction as soon as the photon energy $E_{ã} >> 2m_ec^2$.

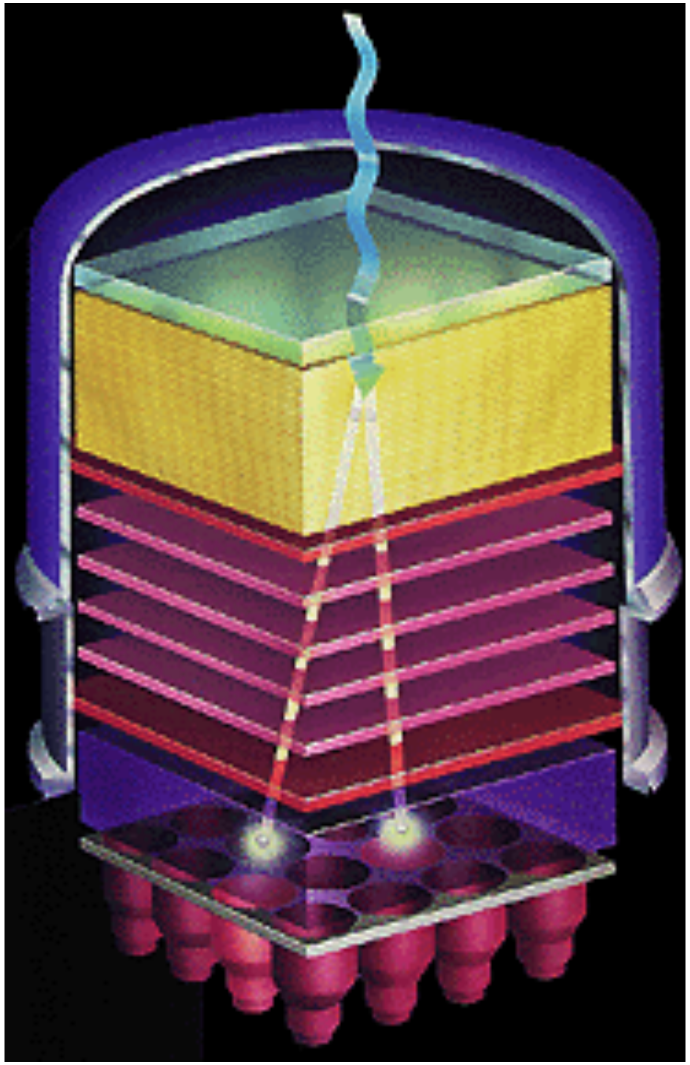
Pair production is also at work in the SPI detector assembly inducing rather complex events.



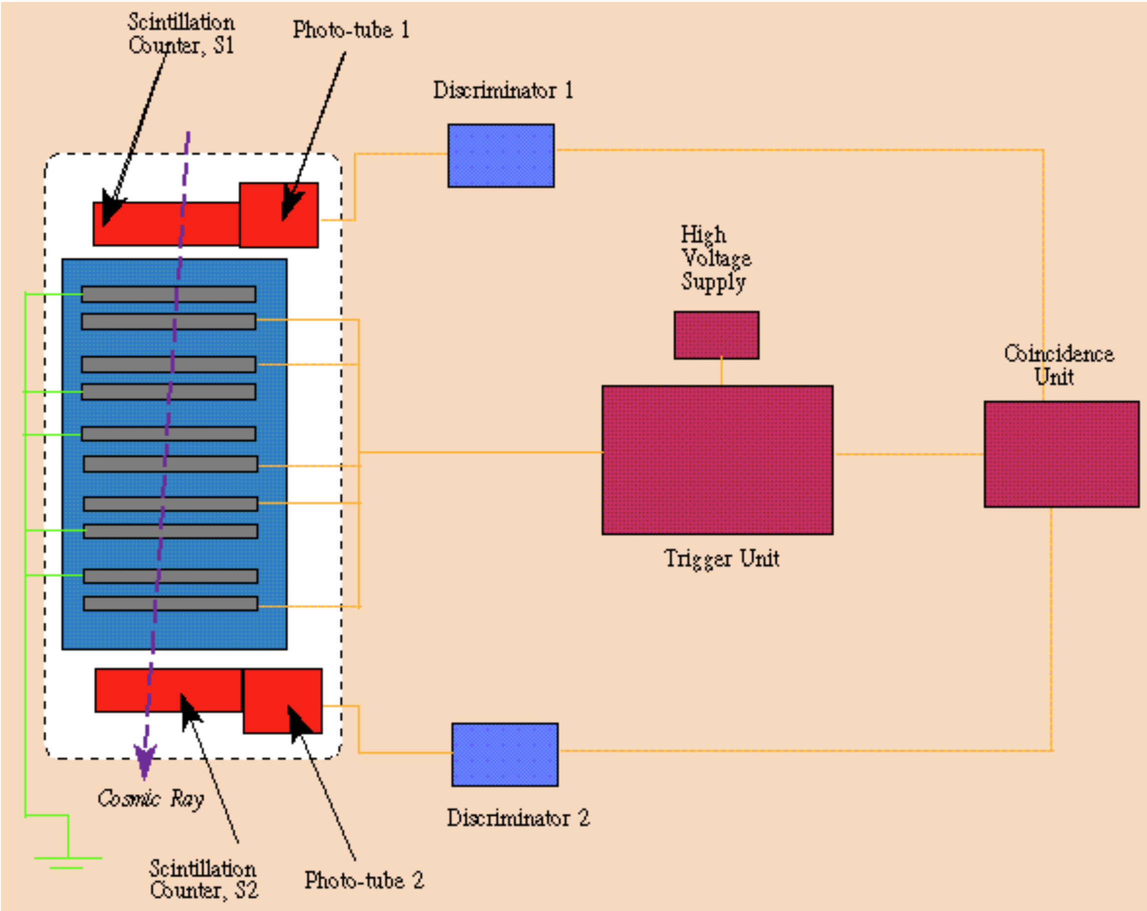
Pair production Telescopes. II

- Converter foils (made of e.g. W) + planes of position-sensitive trackers
- The incident photons interact in the converter producing pairs
- The tracker detect the resulting particles
- Calorimeters at the bottom





Spark Chambers. I



The e-/e+ pass across the chamber and ionize the gas.

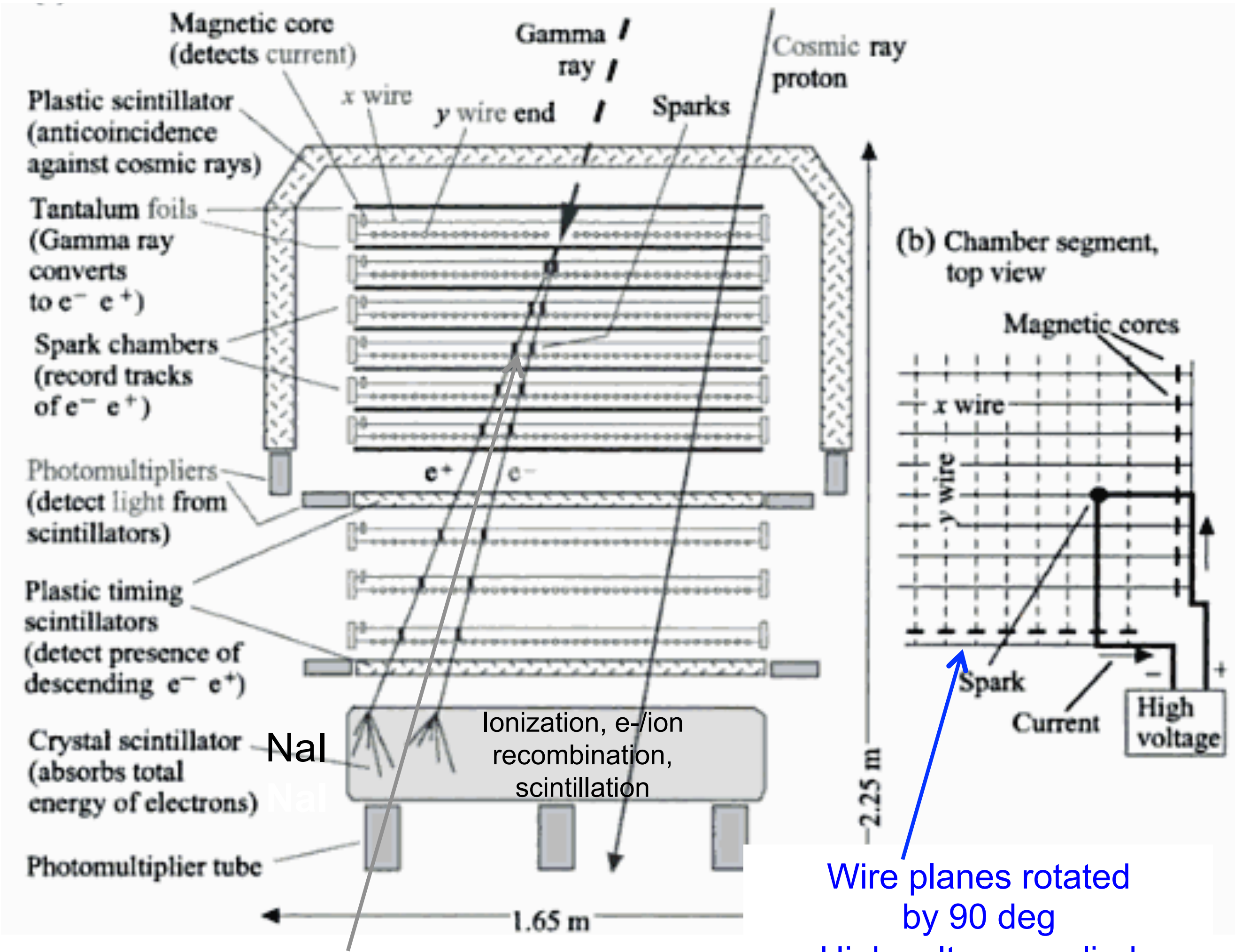
Triggering the detector electrifies the wires, attracting the free electrons and providing the detected signal.

The trail of sparks provides a three-dimensional picture of the the e+/e- paths.

Widely used detectors in the 1970s, consist of metal plates placed in a sealed box filled with a gas (He, Ne, or mixture).
The charged particles ionized the gas, producing **sparks**, "recorded" by the camera. High-voltage pulses applied

Spark Chambers. II

Charged particles (CRs) interact with the plastic anti-coincidence scintillator producing light at the end. Gamma-rays will be absorbed after interaction with high-Z material



Tracks of ionization in the gas of each chamber

Wire planes rotated by 90 deg
High voltage applied and the signal associated to a specific couple of wires

Simplified view of EGRET onboard CGRO

Tantalum (Z=73) has a high cross section for pair production

Electron+positron have substantial kinetic energy and tend to travel in the same direction of the original photon

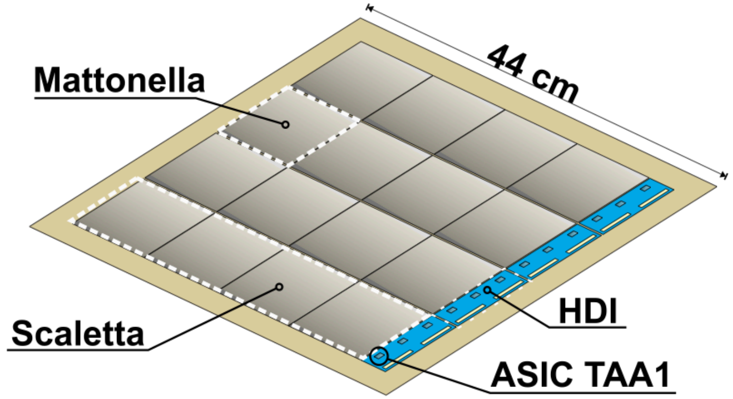
Spark chambers record the tracks of the particles

Anticoincidence system reject cosmic rays, interacting with the plastic scintillator (producing ionization and scintillation)

Measurement of the tracks and total energy of e^-/e^+ pairs yield energy and arrival direction of γ-rays

Silicon trackers

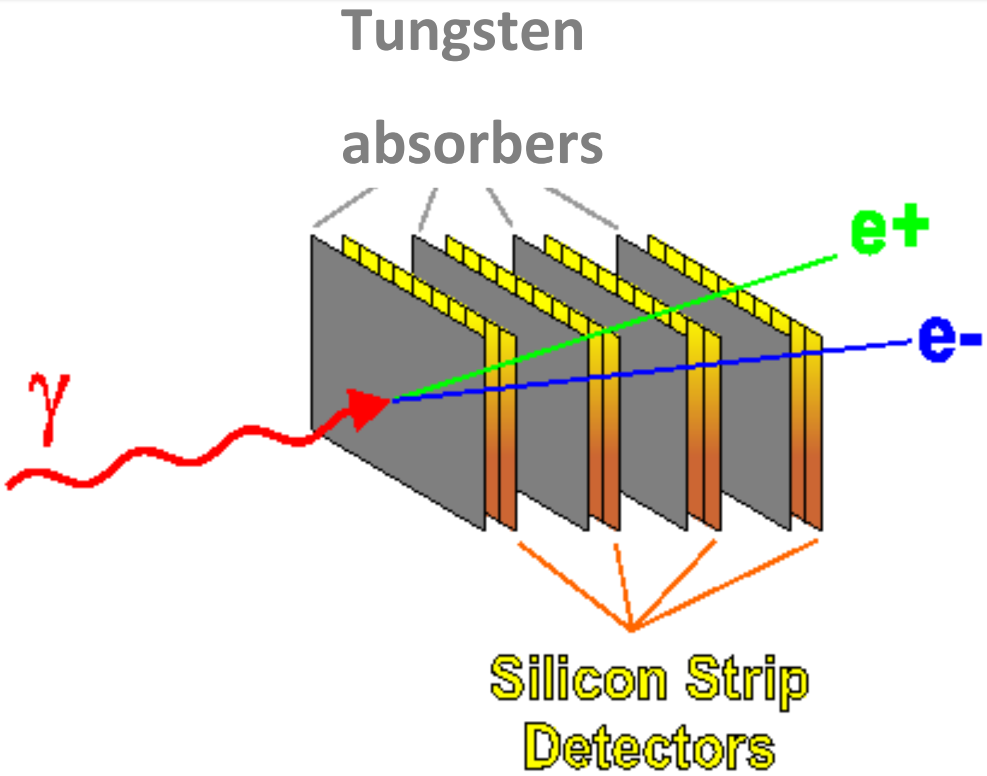
- The main purpose of a **Silicon Tracker** is to provide a compact **imager** for gamma-ray photons of energy **above 10 MeV**.
- The tracker plays two roles at the same time:
  - it **converts the gamma-rays** in heavy-Z material layers (245 um of Tungsten), where the photon interacts producing an electron/positron pair in the detector,
  - and **records the electron/positron** tracks by a sophisticated combination of **Silicon microstrip detectors** and associated readout.



In one plane, strips are oriented in the "x"-direction, while the other plane has strips in the "y"-direction. The position of a particle passing through these two silicon planes can be determined more precisely than in a spark chamber

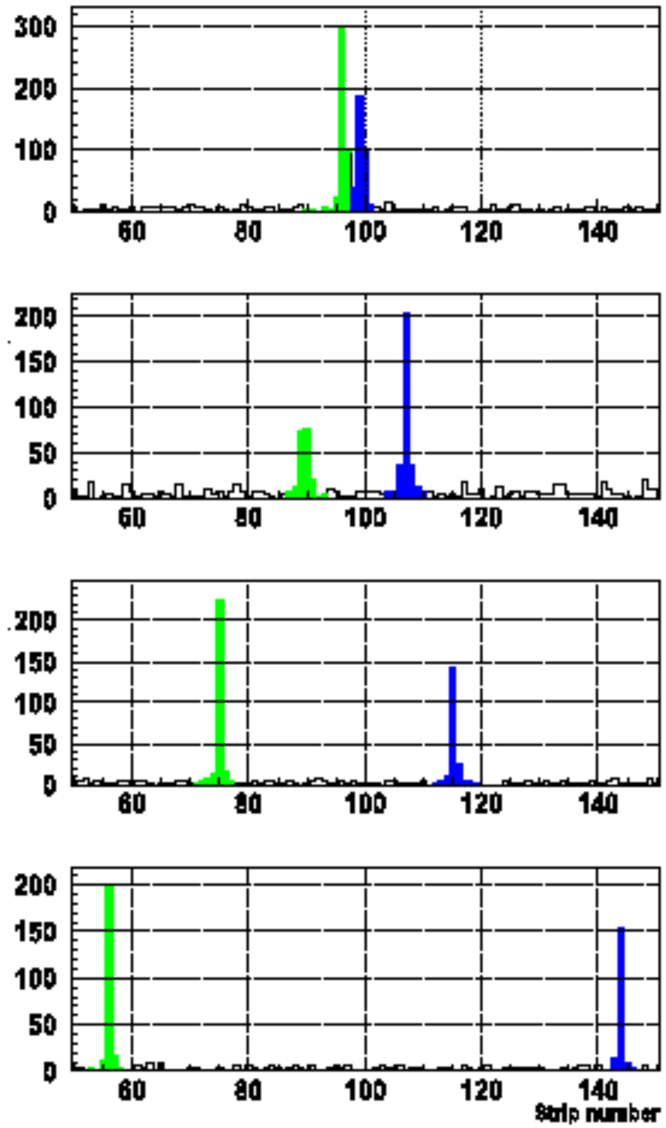
Credits: A. Bulgarelli

Silicon strip detectors



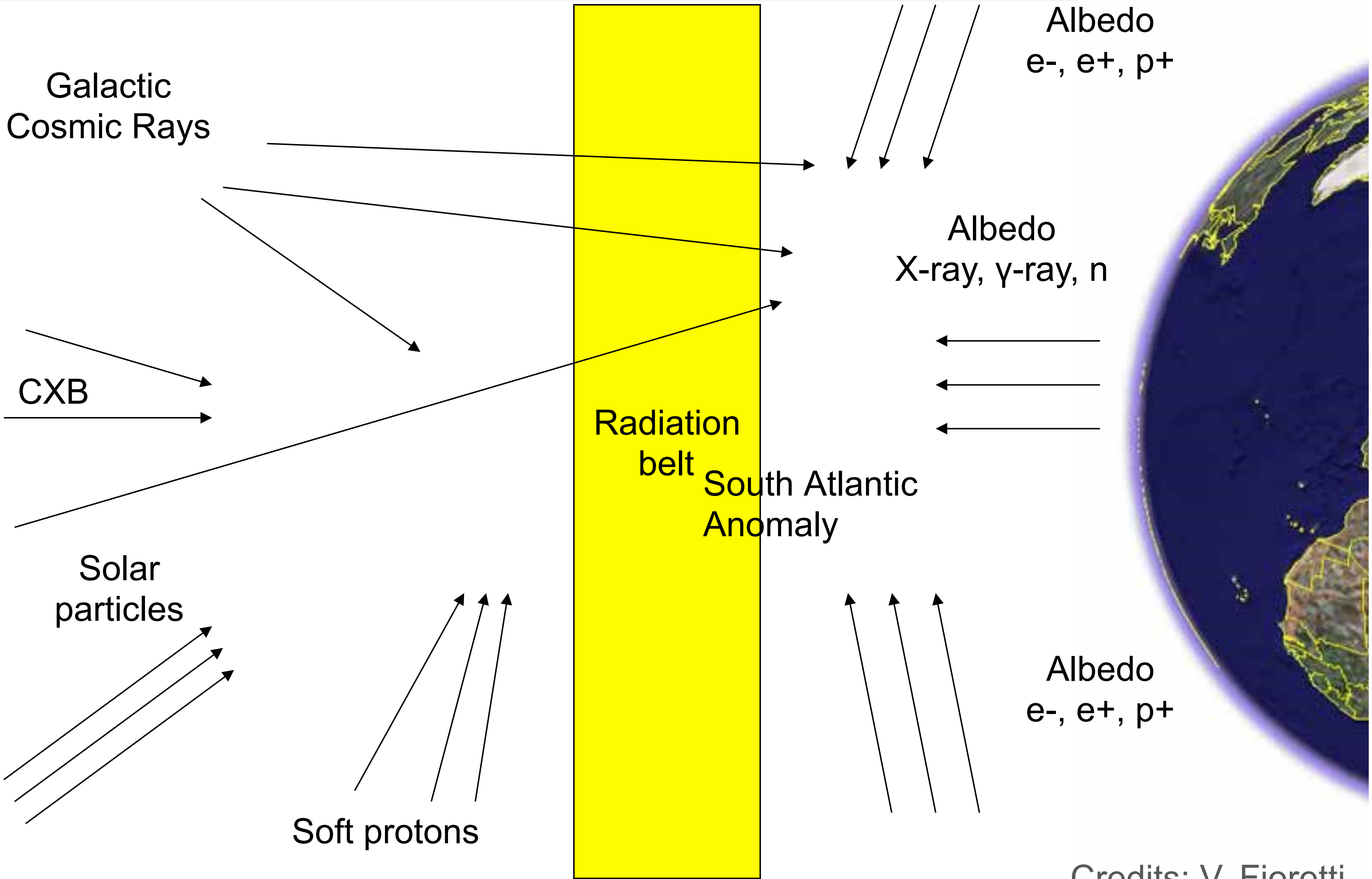
An event is a collection of all the electron/positron interactions into the microstrips of the silicon detector (each interaction generates a cluster that is a group of neighboring strips collecting the charge deposited by the particle)

A complete representation of the event topology allows the **reconstruction of the incoming direction and energy of the gamma-ray**



Background

Background. I



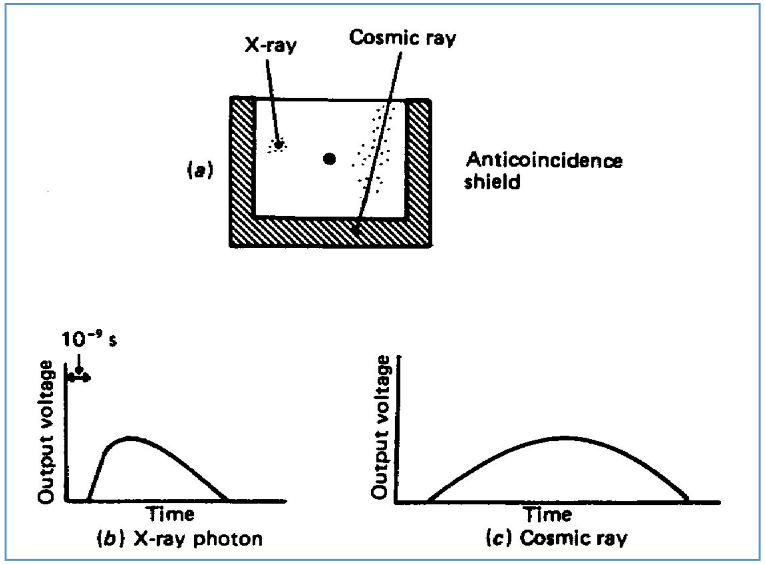
Credits: V. Fioretti

Background. II

- The background of an X-ray/Gamma-ray telescope consists of signals measured in the detector and unrelated to the source
- It is a fundamental parameter to compute the sensitivity
- It is challenging to compute it precisely before the telescope is operating in the final orbit through:
  - Montecarlo simulations
  - Geometry of the spacecraft (telescope, instrument)
  - Environment
  - Orbit
  - Solar activity

COMPONENTS:
Hadron component: prompt cosmic rays/delayed cosmic rays (induces radioactivity)/solar flares/trapped particles (magnetosphere)
Photons: diffuse cosmic background/atmospheric albedo

Shielding techniques. I



From M.S. Longair, "High Energy Astrophysics" (Vol. 1)

1. Anti-coincidence detectors: any event triggering both the counter and the scintillating material can be safely rejected as cosmic ray (CR)
2. Rise-time or pulse-shape discrimination: a fast particle (CR) or electron produces a tail of ionization and, consequently, results in a broad pulse, whereas an X-ray photon produces a sharper pulse
3. Technique using a phoswich detector: the detector consists of alternate layers of material having different responses as scintillator detectors for photons and CR. While the first material is sensitive to photons, the following is not. A photon produces only a pulse, while a CR results in a double pulse in a certain time interval

Shielding techniques. II

Need to block or to signal the unwanted particles

Active shielding through anti-coincidence

Plastic scintillators
to reject charged particles

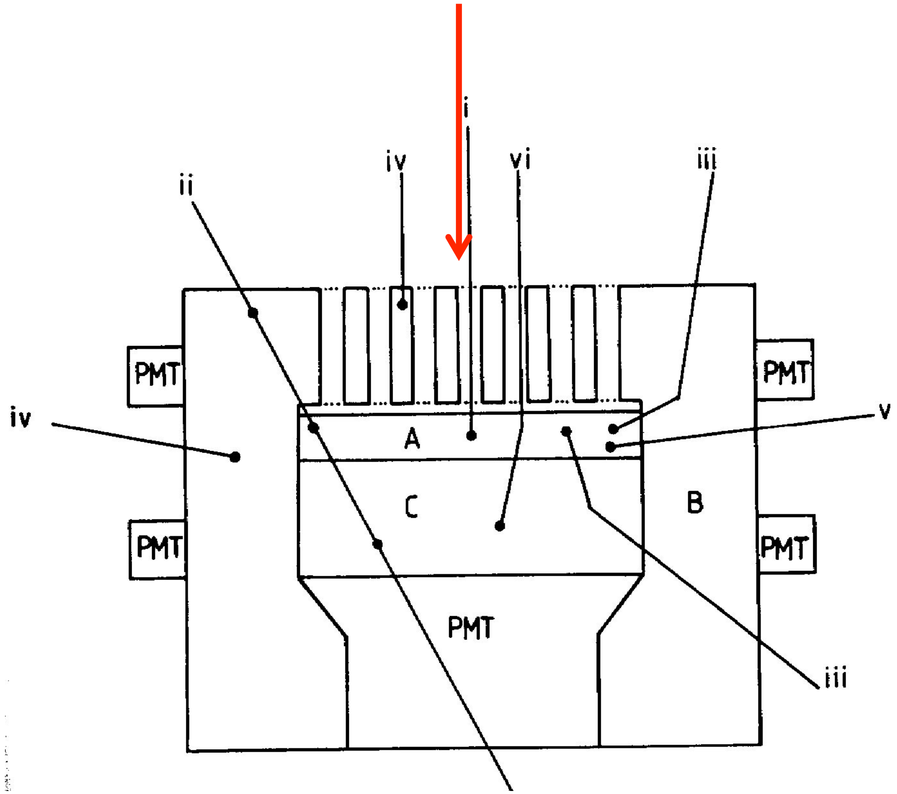
Thick CsI, bismuth germanate ("BGO”)
adopted to detect and veto gamma-ray events
of non-cosmic origin

Detection in both main, typically small, detector and large suppression detector implies γ-ray has scattered out of the main detector before depositing all of its energy, and the data are ignored. The much larger suppression detector has much more stopping power than the main detector, and it is highly unlikely that the γ-ray will scatter out of both devices

Shielding techniques. III

Passive + active shielding

collimator (passive shield)



A & C: phoswich system
B: anti-coincidence system
(active shield)

Shielding techniques. IV

Passive & active shielding