DE LA RECHERCHE À L'INDUSTRIE

X and Gamma Ray Detectors

Principles and application

Eric Gros d'Aillon

eric.grosdaillon@cea.fr

02/07/2014

CEA-Leti, MINATEC Campus, Recherche Technologique, F 38054 Grenoble France

Outline

- Introduction
  - Definitions,
  - Interaction with matter (addressed on Monday by T. Patzak)

- Detectors
  - Scintillators / photodetector based sensors. (SiPM addressed on Monday by V. Puill)
  - Gaseous and semiconductor based sensor.
  - Forming an image

- Applications
  - Medical radiography
  - Scintigraphy, emission tomography
  - 1 example per domain : present, SOA

- Conclusion

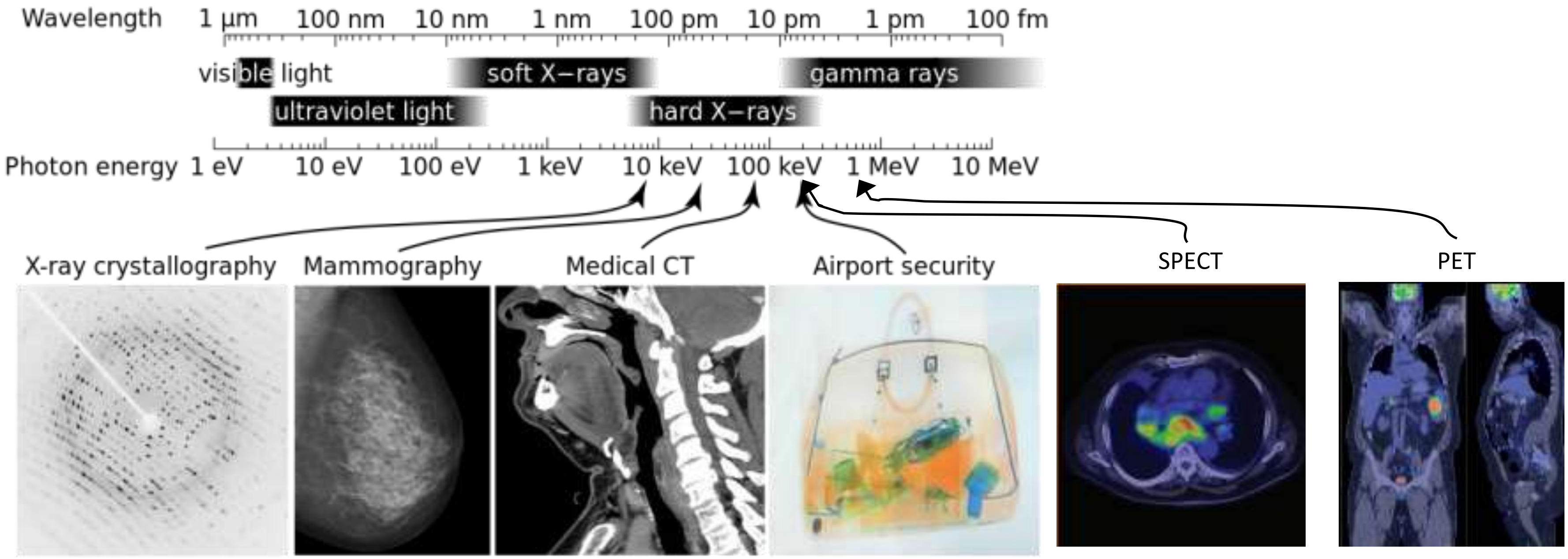
Apologies

- Not all detectors covered. Only imaging detectors
- Electronic non treated
- No all applications covered (unfair choice)
- Not a review

Introduction

X and Gamma ray : definitions

- **Historical** : X-ray energy range from 100eV to 1MeV while gamma rays range from 100keV to 10MeV.
- **Physics** : X-rays are emitted by electrons (either in orbitals outside of the nucleus, or while being accelerated to produce bremsstrahlung-type radiation), while gamma rays are emitted by the atomic nucleus.
- All are ambiguous and convention depends on the community. At the end: high energy electromagnetic ionizing radiation.



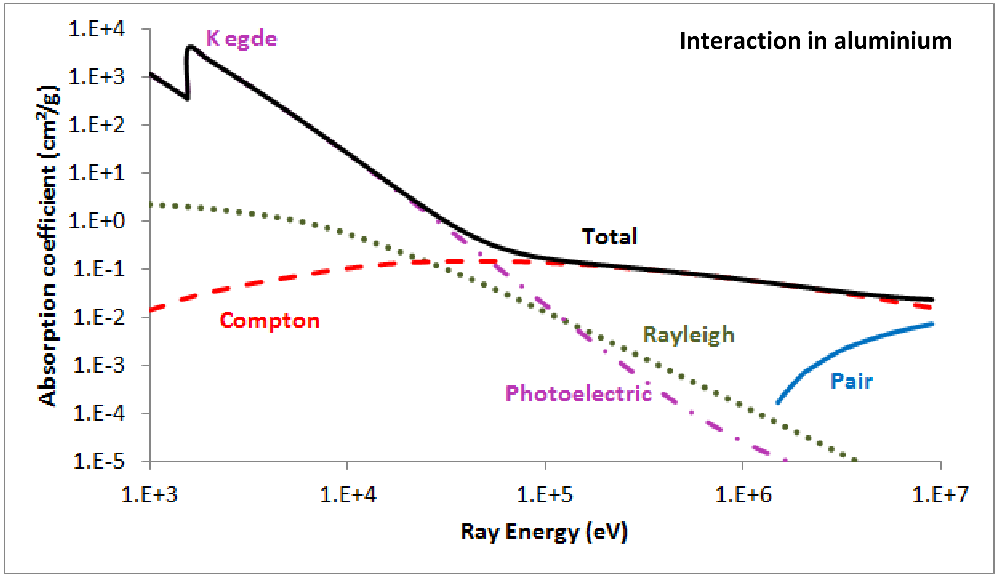
Source : wikipedia

Source : Mediso.hu

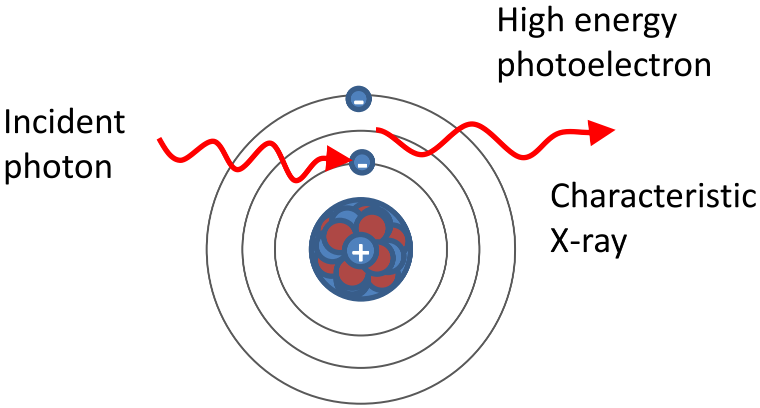
Interaction with matter

Photon absorption is probabilistic and depends on photon energy and material.

- Photoelectric absorption : the photon energy is transferred to an atomic electron, which is ejected at high velocity. Proportional to $Z^{4,5}/E^3$ (except at absorption edges). The atomic relaxation produces either a characteristic X-ray photon or an Auger electron.



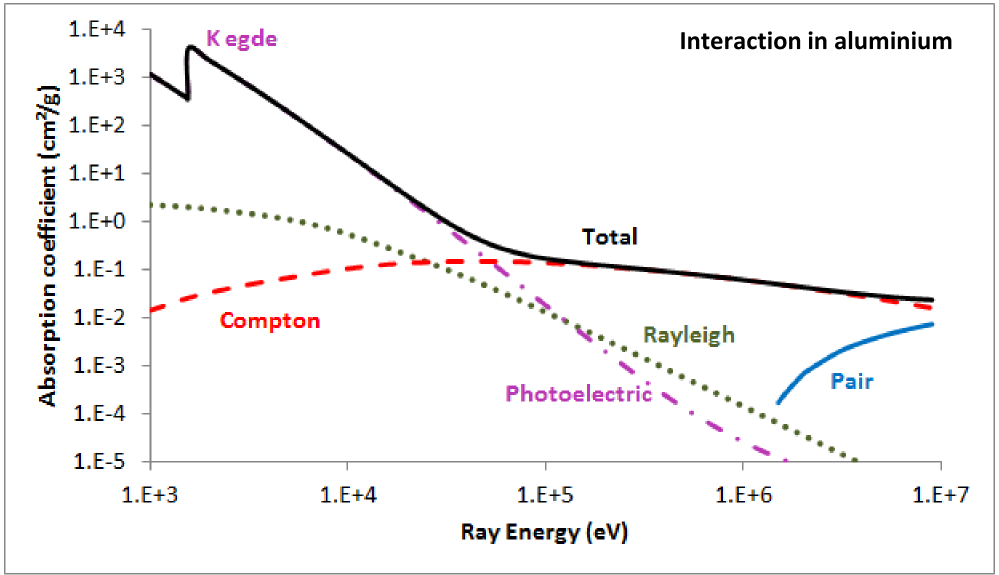
Source : XCOM: Photon Cross Sections Database



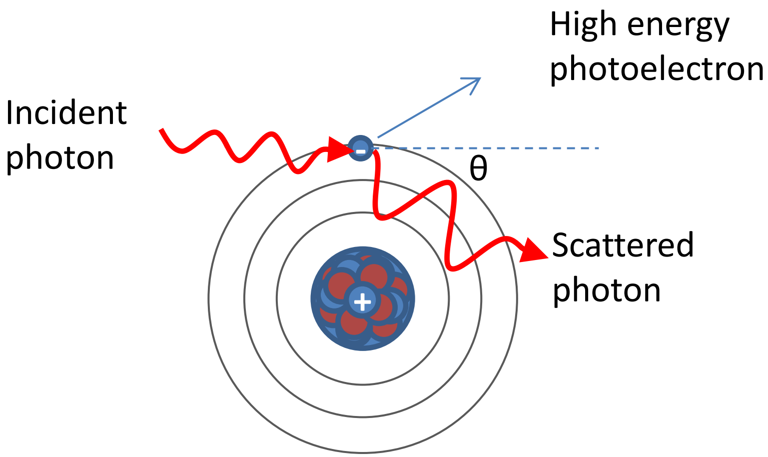
Interaction with matter

Photon absorption is probabilistic and depends on photon energy and material.

- Photoelectric absorption
- Compton scattering : inelastic scattering of the X-ray photon by an outer shell electron with a characteristic angle. Proportional to Z/E. The angle probability is given by the Klein-Nishina formula. (Most probable : 0°)



Source : XCOM: Photon Cross Sections Database

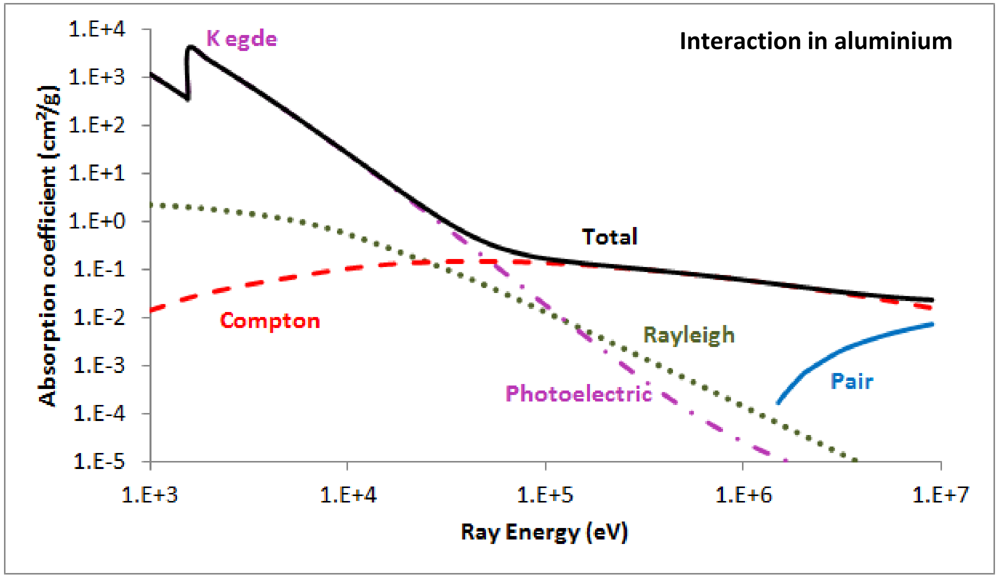


$$\Delta\lambda = \left(\frac{h}{m_e c}\right)(1 - \cos\theta)$$

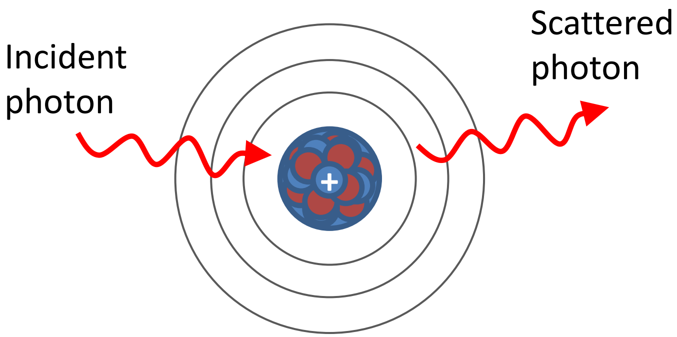
Interaction with matter

Photon absorption is probabilistic and depends on photon energy and material.

- Photoelectric absorption
- Compton scattering
- Rayleigh scattering : elastic scattering by an inner shell electron.



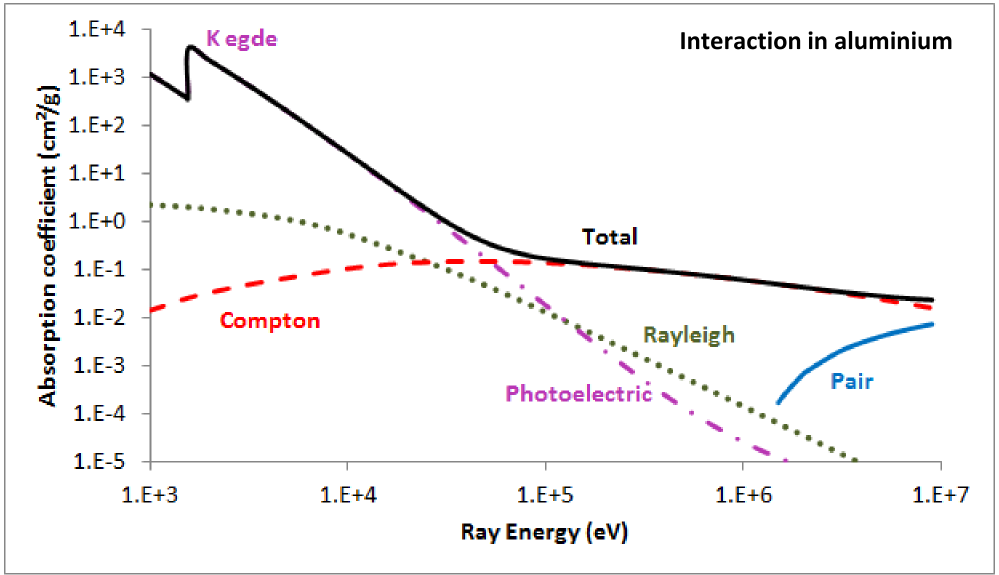
Source : XCOM: Photon Cross Sections Database



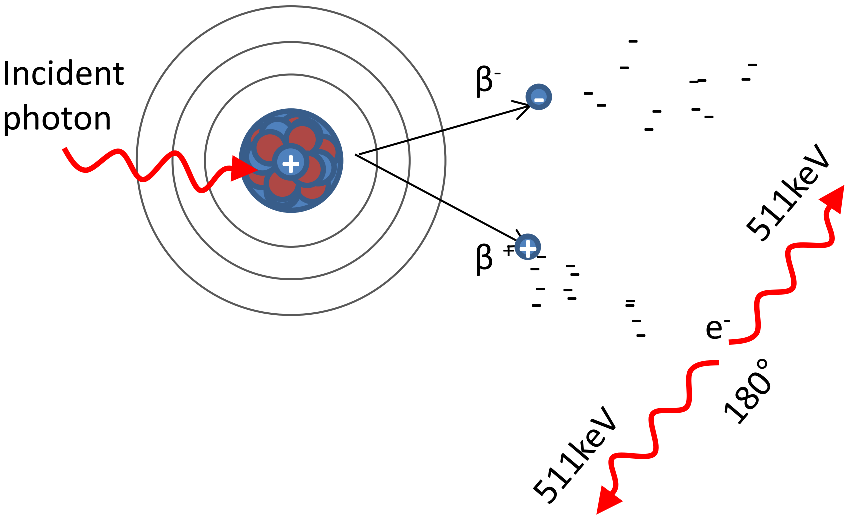
Interaction with matter

Photon absorption is probabilistic and depends on photon energy and material.

- Photoelectric absorption
- Compton scattering
- Rayleigh scattering
- Pair production : Production of an electron-positron pair with kinetic energy which could produce much ionization themselves. The positron annihilate and produces two 511keV gamma photon in coincidence. Proportional to Z^2



Source : XCOM: Photon Cross Sections Database

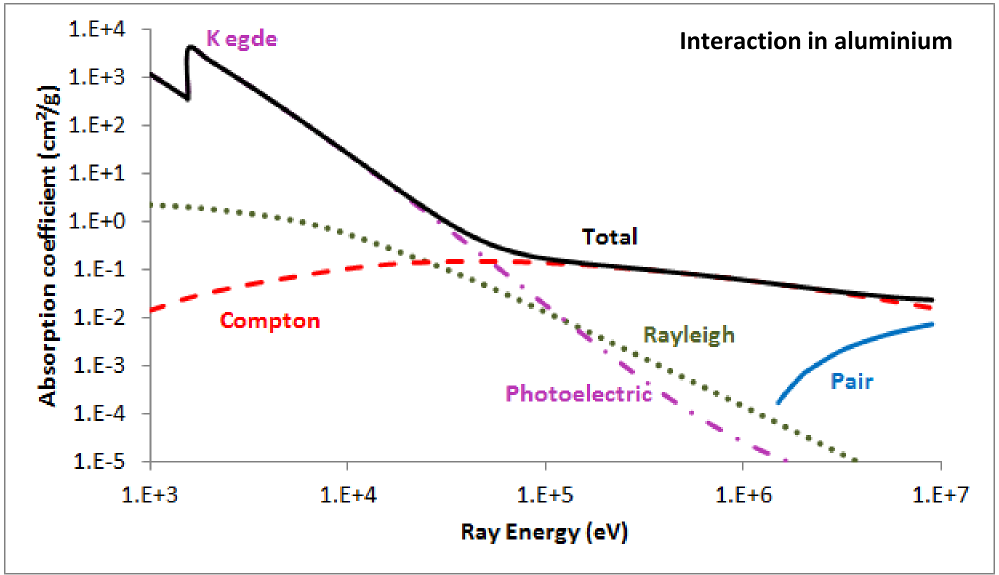


Interaction with matter

Photon absorption is probabilistic and depends on photon energy and material.

- Photoelectric absorption
- Compton scattering
- Rayleigh scattering
- Pair production

➔ Photons interact with matter (multiple interactions) and produce photoelectrons.
Photoelectrons loose their energy in ionizing atoms (i.e. producing electrons) in short distance.

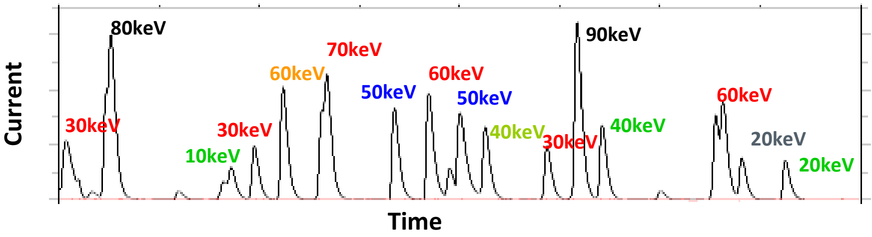


Source : XCOM: Photon Cross Sections Database

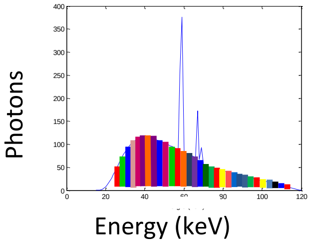
Detector principles

What do we want to measure?

- The photon **direction** (imaging) collectively (integration mode) or individually (counting mode)
- Their individual **energy** (spectroscopy)
- Their **time** of arrival (timing, coincidence, anticoincidence)
- *Their polarity (astrophysics)*
- With a good **sensitivity** for the energies of interest
- Other gain parameters: Noise, gain, linearity, time response



Spectrometric mode



Sensor types

- Sensors families :

1 - Scintillators and photodetector.

Photocathode and vacuum transport of electrons : PMT, MCP, EBCMOS

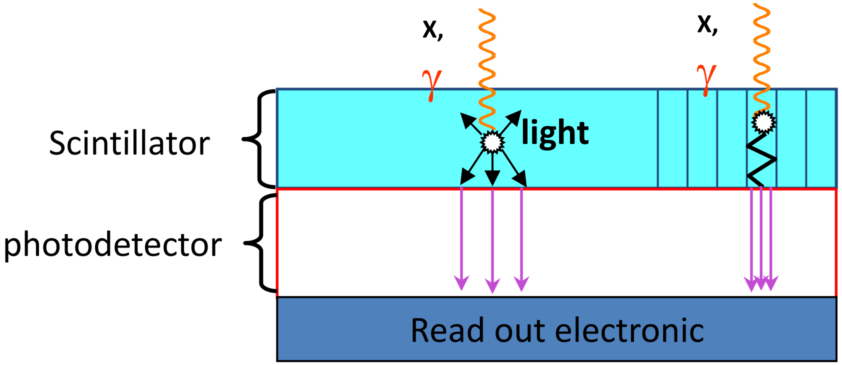
Solid state photo-sensor : PD, CCD, EMCCD, CMOS, APD, SiPM**,** OPD

2 - Drift chambers

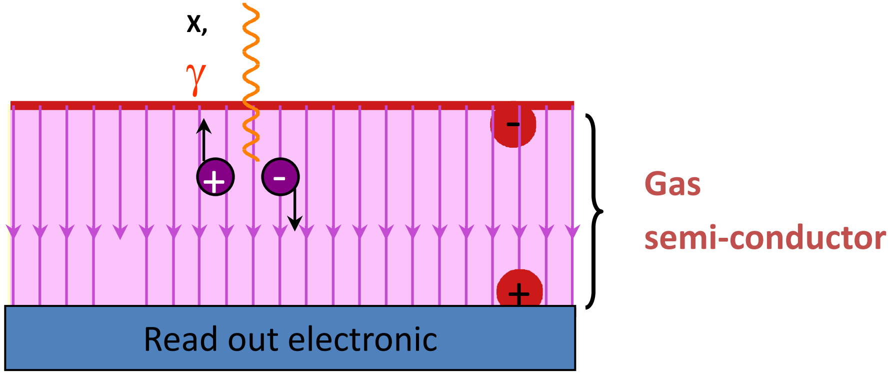
Gaseous ionization chambers (Xe, GEM...)

Solid state sensors : Si, Ge, GaAs, Cd(Zn)Te**,** diamond, SiC

1. Indirect detection



2. Direct detection



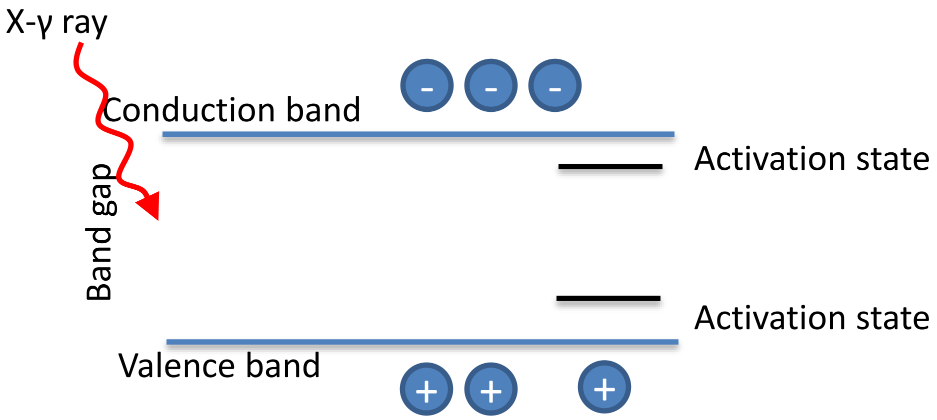
Scintillators
and
photodetectors

Scintillators

- Converts the electrons kinetic energy into detectable light.

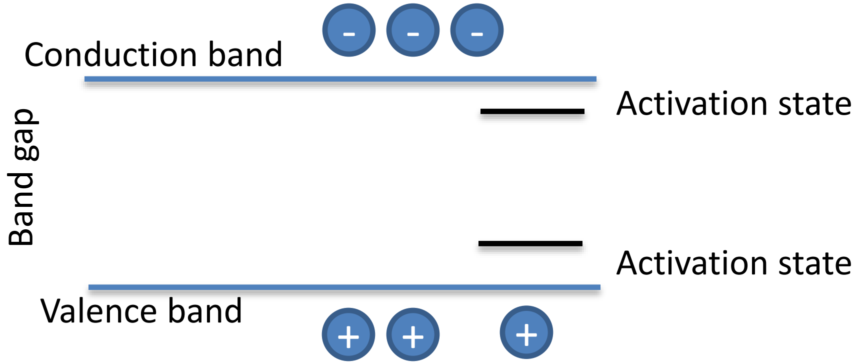
Scintillators

- Converts the electrons kinetic energy into detectable light.



Scintillators

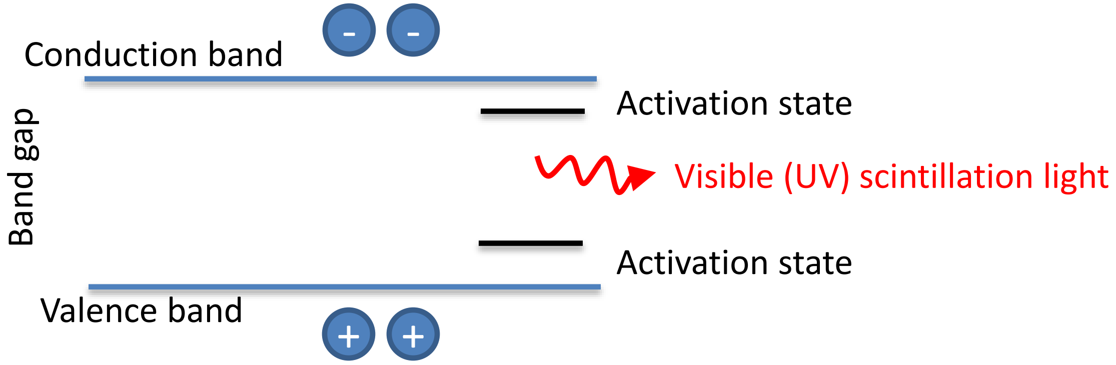
- Converts the electrons kinetic energy into detectable light



Scintillators

- Converts the electrons kinetic energy into detectable light

The number of created photons varies *linearly* with the X-ray energy (noise = $\sqrt{\text{number of photons}}$)



- Criteria of performance :

  <u>X-ray absorption</u>: Stopping power (Z, density)

  <u>Optical</u> : Transparency. **Light yield**, homogeneity, linearity → intrinsic energy resolution

  : wavelength, decay time, refractive index.

  <u>Manufacturing:</u> (size/price)

- Could be organic, inorganic, liquid

Scintillators

- A few examples.

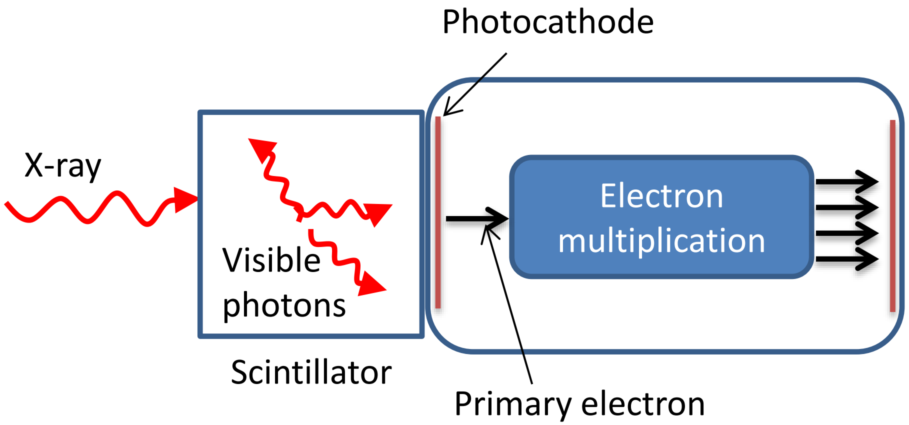
	Light yield Phot/keV	λ nm	Refract. index	Decay time ns	Thick. to stop 50% of 662keV photons cm	Comments
Impact on	Sensitivity Noise	Detector QE (λ)	Reflection	Timing	Detection Efficiency	
NaI:Tl	38	415	1.85	250	2.5	Spectrometry Large volume
CsI:Tl	54	550	1.8	1000	2	Spectrometry. Spatial resolution (needles)
BGO	9	480	2.15	300	1	low afterglow
LYSO	32	420	1.8	40	1.1	Timing
$CdWO_4$	15	470	2.3	14000	1	High Z, low afterglow
$LaBr_3(Ce)$	63	380	1.9	16	1.8	Spectrometry
BC400	11	425	1.6	2	11.5	Very low Z. Large area counter

Source : http://www.crystals.saint-gobain.com/

- The outgoing light must be converted to electrons in second step

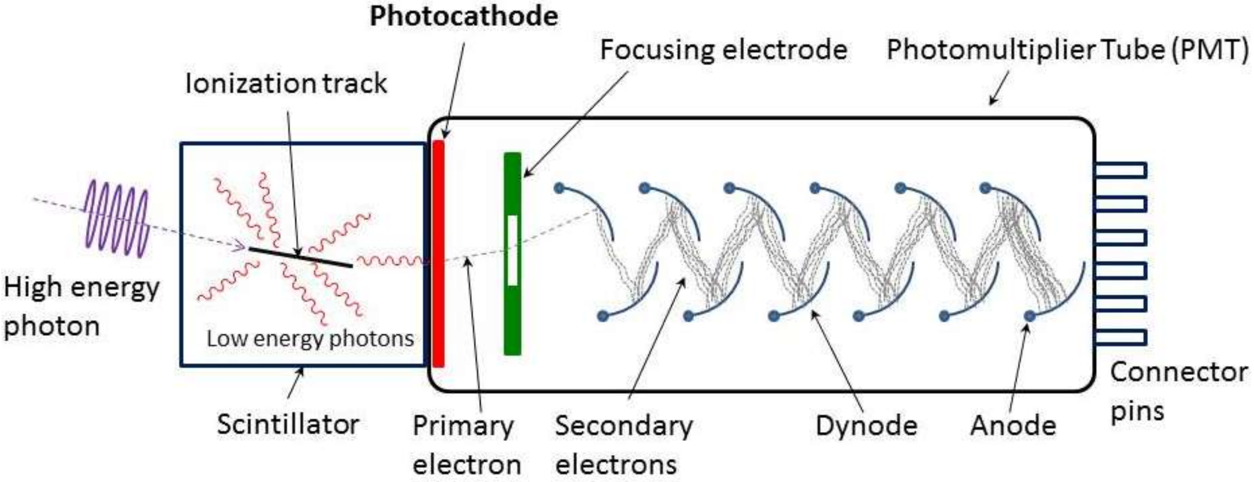
Photocathode and vacuum transport of electrons

- The light produced by the scintillator crystal passes through the entry window.
- The photocathode emits electrons by photoelectric effect (yield 1-20%).
- Photoelectrons are accelerated and multiplied by secondary emission. High applied voltage.
- Photoelectrons are finally collected by the anode(s).



Photocathode and vacuum transport of electrons

- **Photomultiplier Tubes (PMT)**: series of dynodes
- Photoelectrons are focused, accelerated onto dynodes, and multiplied by secondary emission.



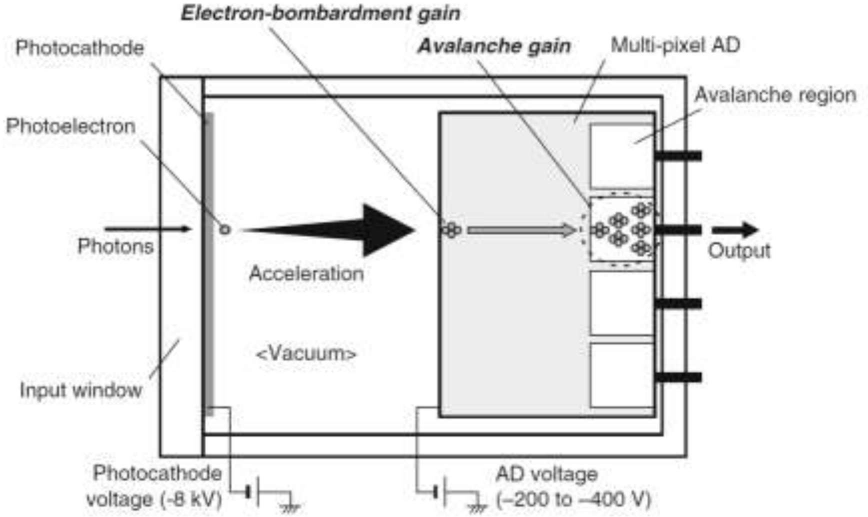
Source : wikipedia

Source : hamamatsu.com

- Pro : Very high Gain (10^6), low noise, sensitive to singe photon, timing perf., high volume production, large wavelength range (110-1100 nm). Could be position sensitive.
- Cons : Bulky, high voltage, fragile, sensitive to magnetic field

Photocathode and vacuum transport of electrons

- **Electron Bombarded image sensor.** Photoelectrons are accelerated onto a semiconductor sensor and multiplied by secondary emission.
- Could be **ebCMOS**, **ebCCD**, array of avalanche photodiodes (**APD**) (multiplied by impact)

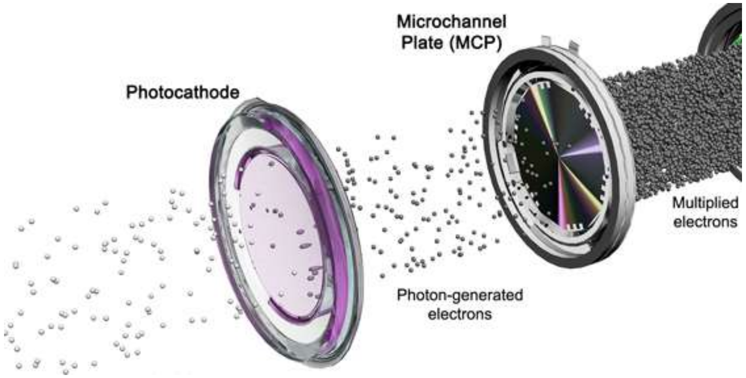


Source : H. Aihara in Single-Photon Imaging, Springer

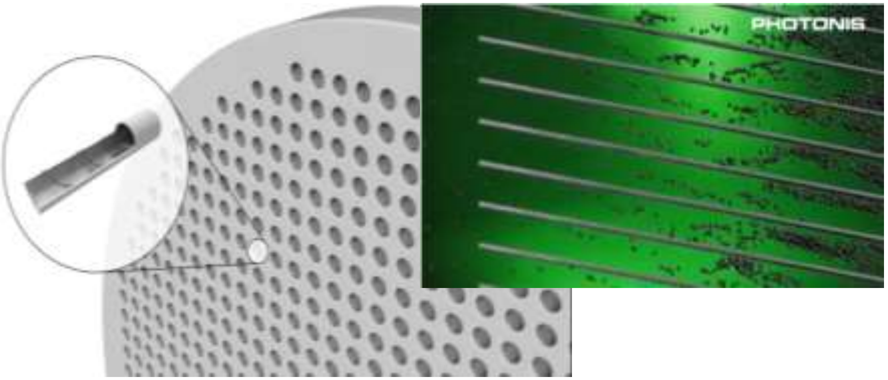
- Pro : imager, spatial resoltuion, High gain (10^{4-5}), no afterpulse, fast
- Cons : dark noise

Photocathode and vacuum transport of electrons

- **Micro Channel Plate (MCP-PMT) :** millions of glass capillaries (2-20µm) bundles in parallel.
- Photoelectrons are accelerated onto the MCP. A primary electron impinges the inner wall and are multiplied by secondary emission
- Inner wall has secondary emission properties : each channel acts as electron multiplier.
- Emitted photoelectron while maintaining spatial information.
- Could be coupled to a **phosphor screen, direct electrical signal, PD array, APD array, CCD camera**



http://www.photonis.com/en/content/88-nightvision-movies

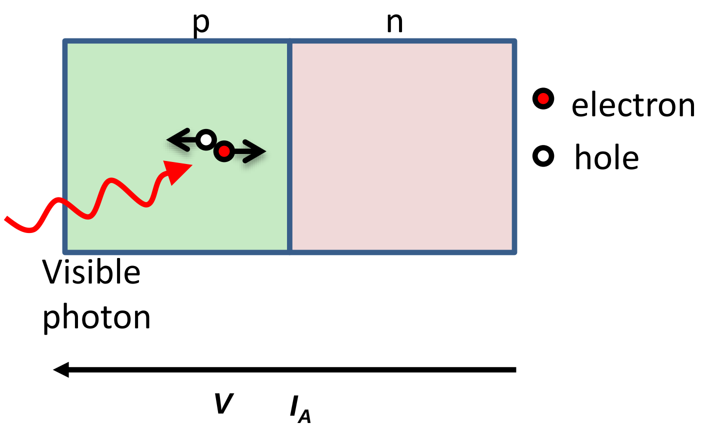


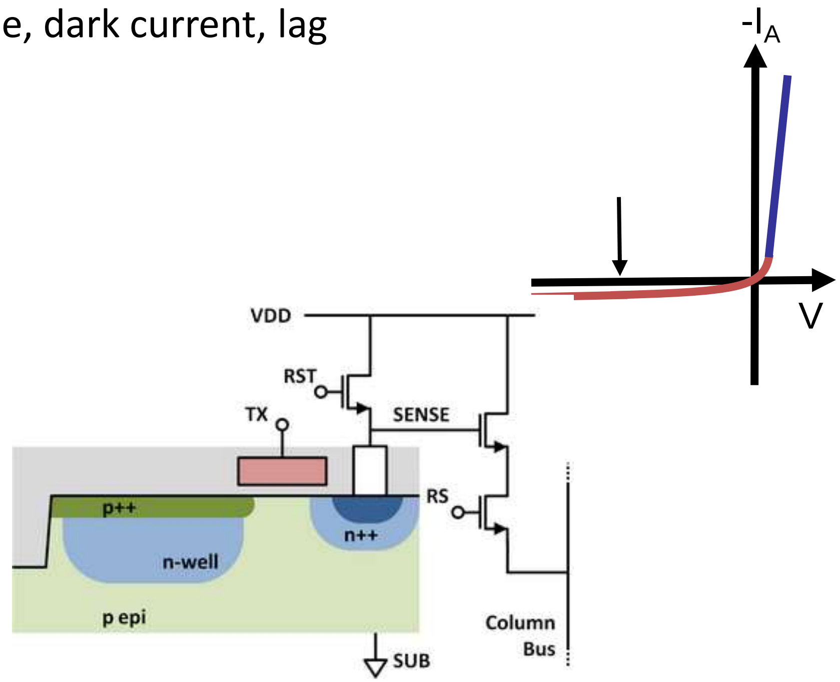
Source : photonis.com

- Pro : High gain (10^4), low noise, fast, spatial resolution, low power consumption.
- Cons : high voltage

Solid state photo-sensor

- **Silicon PhotoDiode (PD).** 1 visible photon = 1 electron hole paire (QE). Charge carriers are collected by drift/diffusion.
- Pinned photodiode : burried PD, lower kTC noise, dark current, lag



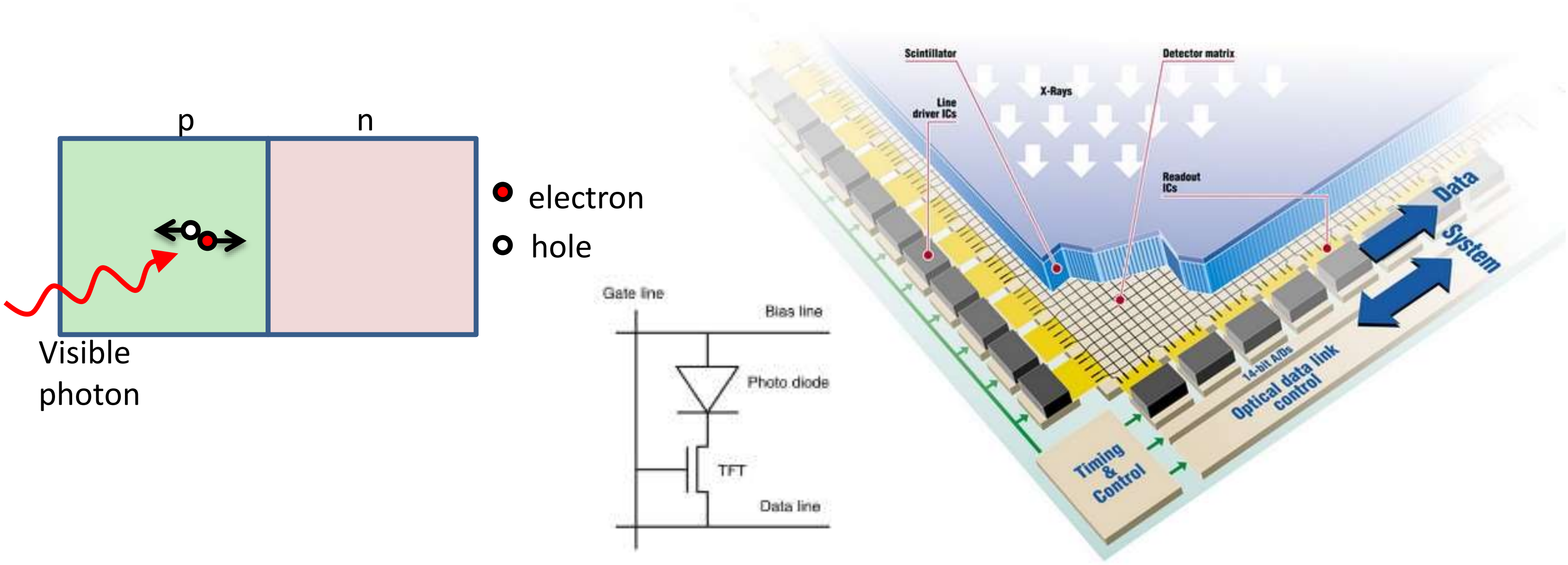


Source : http://docs.lumerical.com/

- Pro : Solid state : robustness, compactness, MRI compatible. Arrays.
- Cons : no gain (no single photon sensitivity), slow

Solid state photo-sensor

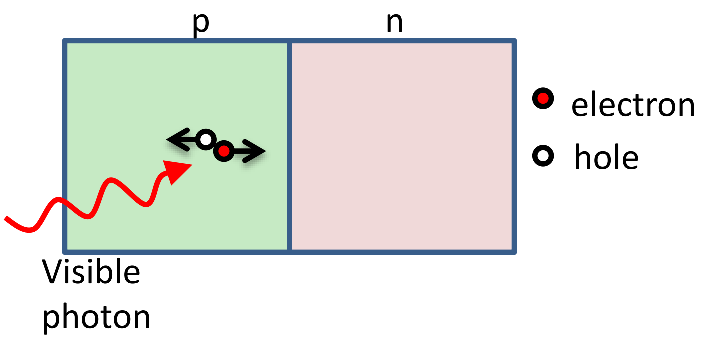
- Silicon PhotoDiode (PD).
- Array of PD : **amorphous silicon-on glass**. One Thin-Film Transistor (TFT) per pixel

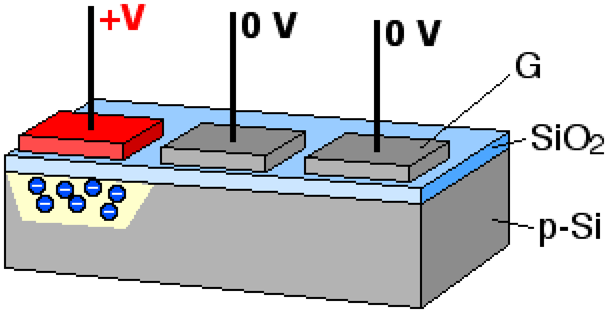


- Pro : Very large surface. Low cost.
- Cons : slow, image lag, no on-chip integration

Solid state photo-sensor

- Silicon PhotoDiode (PD) :
- Array of PD : **(Electron Multiplied) Charge Coupled Devices**

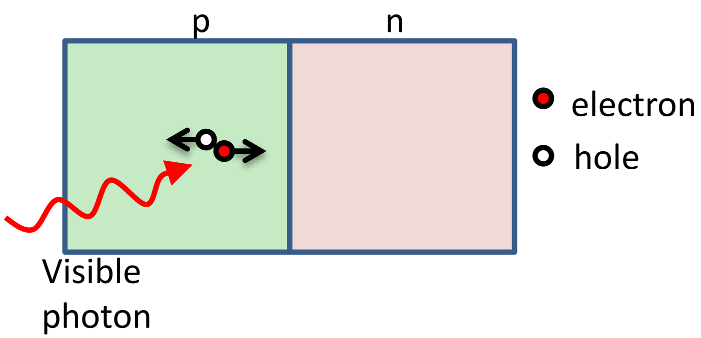


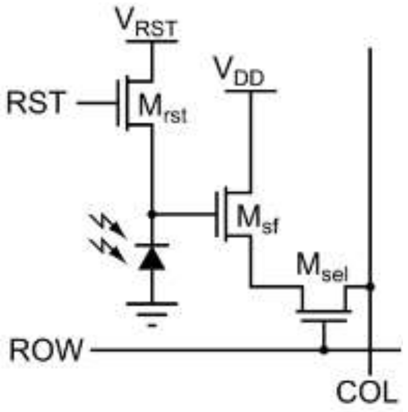


- Pro : Very large number of pixels. Reduction in electronics. Very low noise for EMCCD.
- Cons : Reading time

Solid state photo-sensor

- Silicon PhotoDiode (PD) :
- Array of PD : **Complementary Metal Oxide Semiconductor.** Active pixel : one amplifier in each pixel

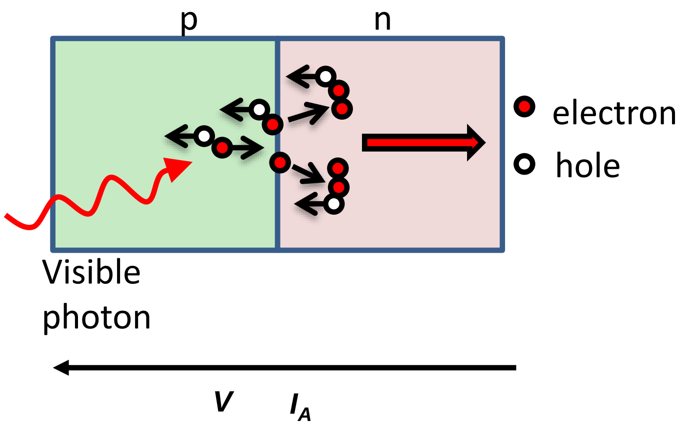


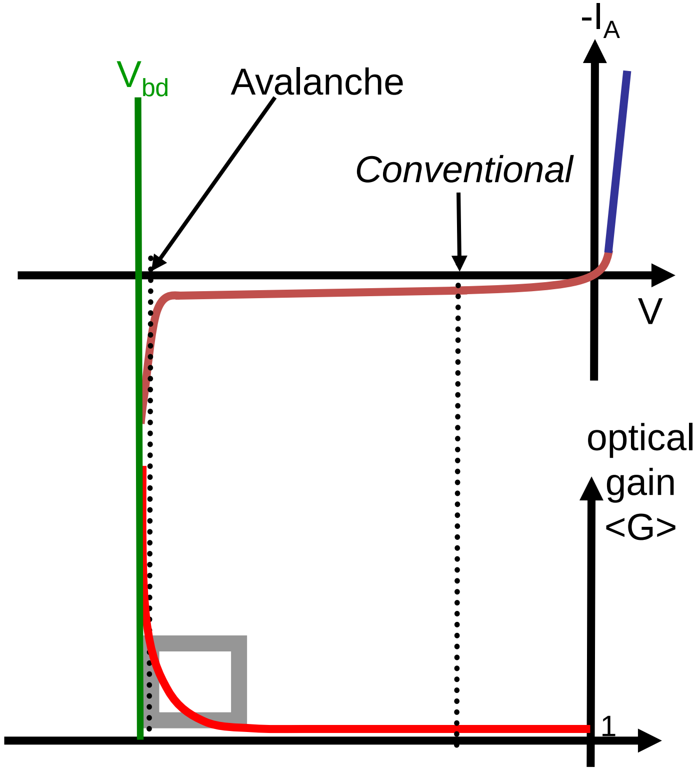


- Pro : Small pixels, high integration. Low noise, high speed. Benefit from consumer market.
- Cons : Small surface (<1cm² most time, limited to 8’’-12’’ wafer size)

Solid state photo-sensor

- Silicon **Avalanche PhotoDiode (APD)**: multiplication of charge carrier by impact ionization
- One can achieve a current gain of 2-10,000



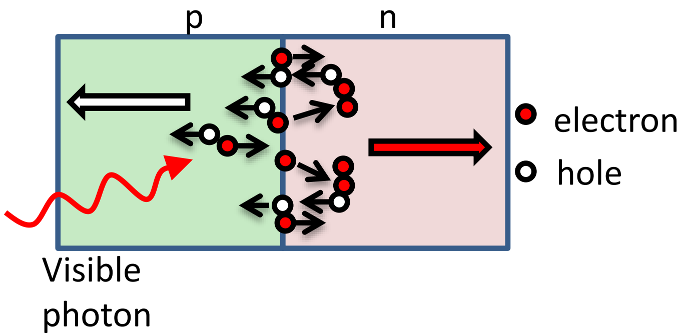


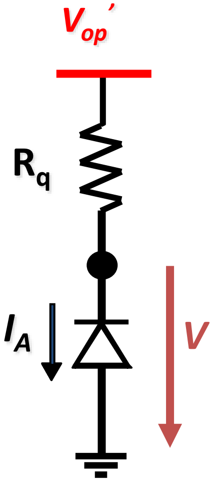
Source : E. Charbon & P. Seitz, http://aqua.epfl.ch

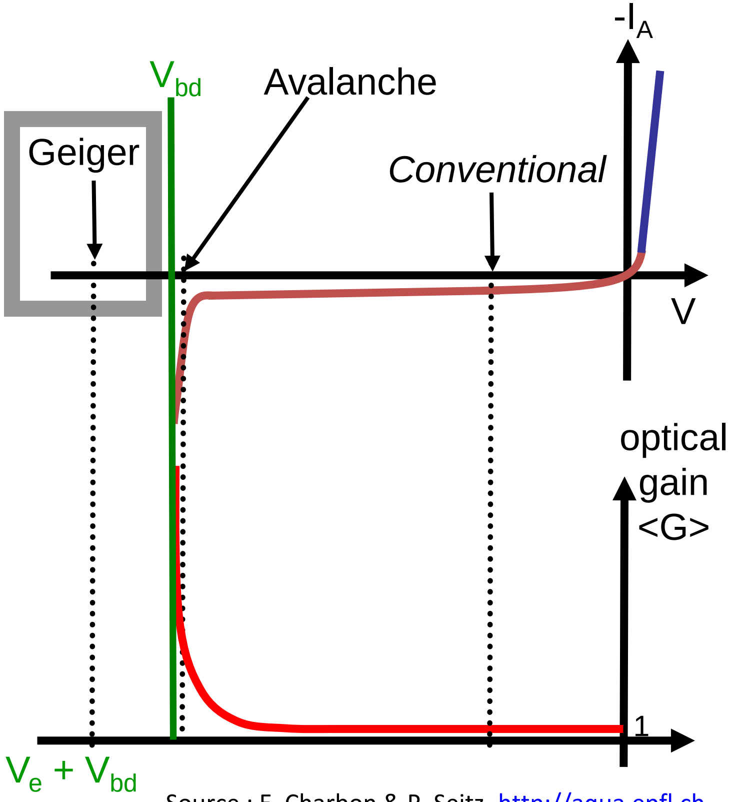
- Pro : gain (10^2), fast, arrays.
- Cons : excess noise factor, gain variation is exponential with bias

Solid state photo-sensor

- Silicon **Avalanche PhotoDiode in Geiger Mode (SPAD)**. self-sustained avalanche : binary component.
- Gain is meaningless
- **Quenching the avalanche**



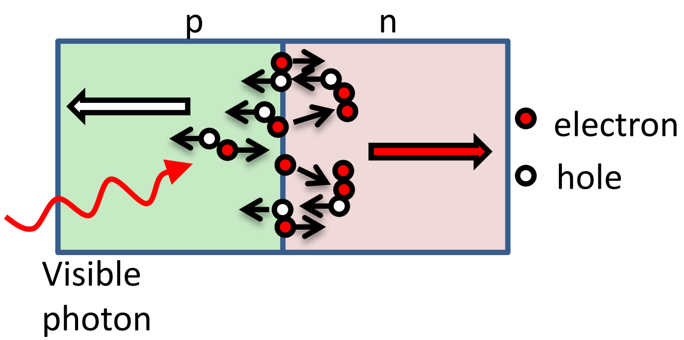


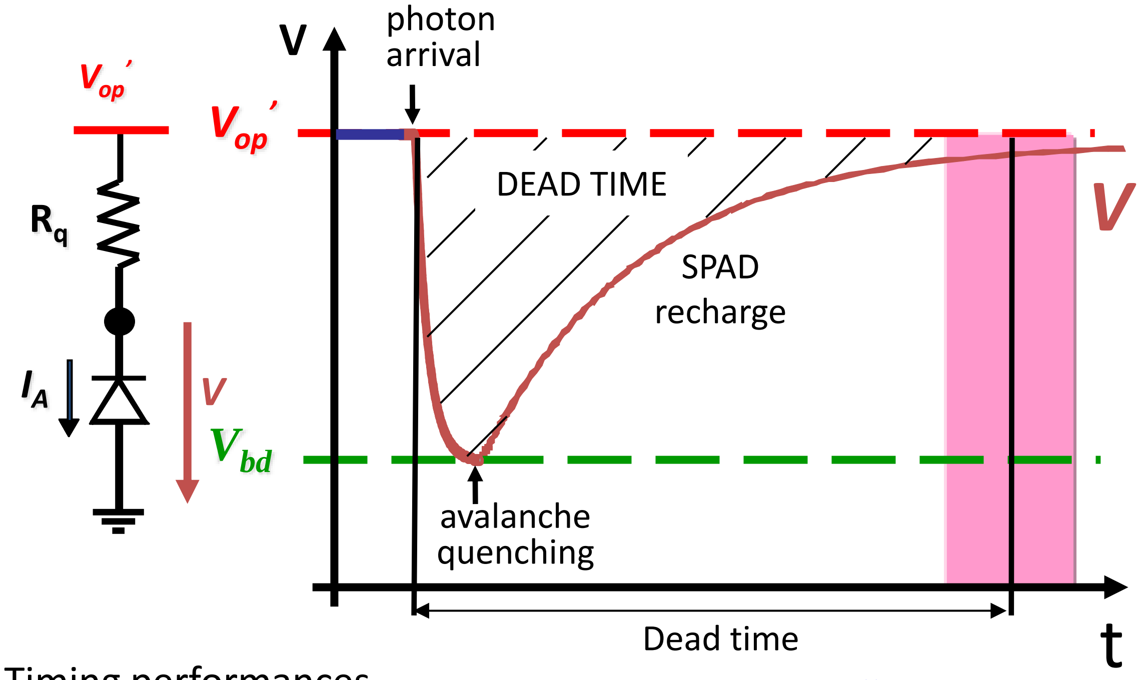


Source : E. Charbon & P. Seitz, http://aqua.epfl.ch

Solid state photo-sensor

- Silicon **Avalanche PhotoDiode in Geiger Mode (SPAD)**. self-sustained avalanche : binary component.
- Virtually “infinite” gain : gain variability is meaningless
- **Quenching the avalanche**



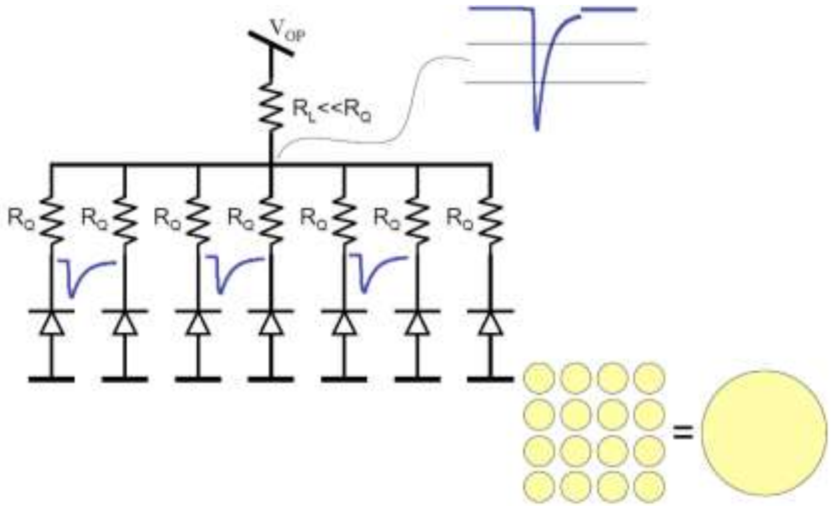


Source : E. Charbon & P. Seitz, http://aqua.epfl.ch

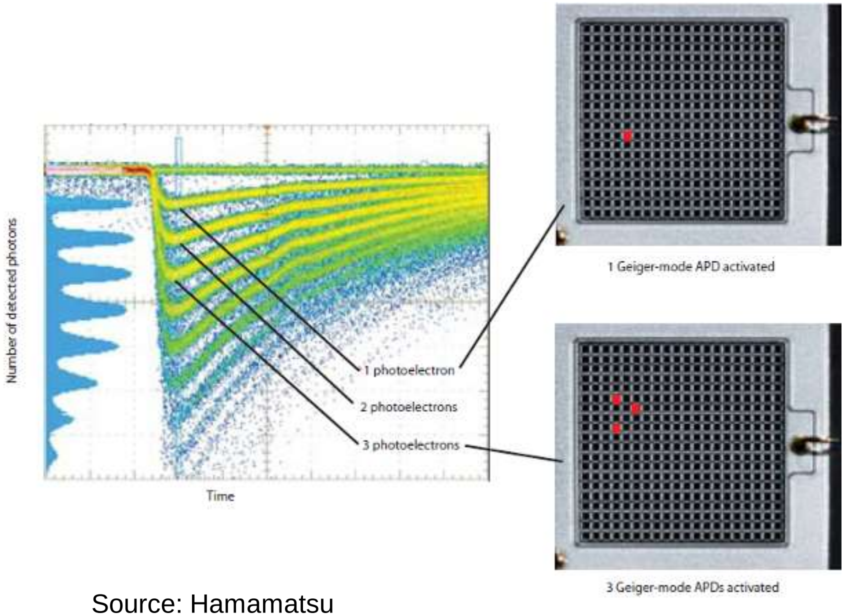
- Pro : Binary component, fast, arrays. Timing performances
- Cons : Dark counts, afterpulse, deadtime

Solid state photo-sensor

- **Silicon PhotoMultiplier (SiPM) :** array of **SPADs** to recover the dependence of output current with input light. Common cathode and anode.



Source : E. Charbon & P. Seitz, http://aqua.epfl.ch

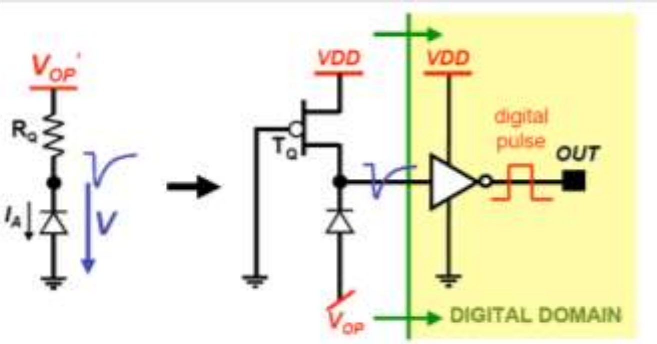


Source: Hamamatsu

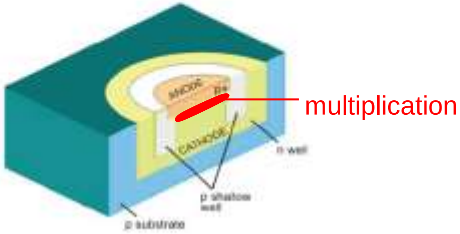
- Pro : Mimick an APD. Timing performances
- Cons : cross talk, afterpulse, deadtime, noise (dark count), light yield non proportionality.

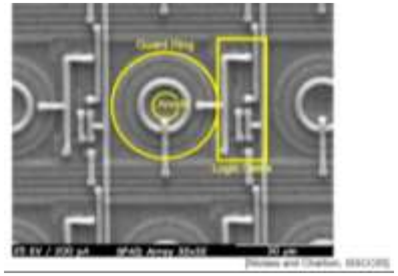
Solid state photo-sensor

- **Digital Silicon PhotoMultiplier :** Implementation of the SiPM concept in conventional CMOS technology : digitalize each counted photon. The SPAD becomes like any other digital device but it is triggered by a photon. Takes benefit of the CMOS dynamics
- Advanced signal treatment can be embedded in the chip
    - Active quenching/recharge to reduce deadtime
    - Gamma event recognition (triggering)
    - Time to Digital Converter
    - Point Of Interaction computation



Source : E. Charbon & P. Seitz, http://aqua.epfl.ch



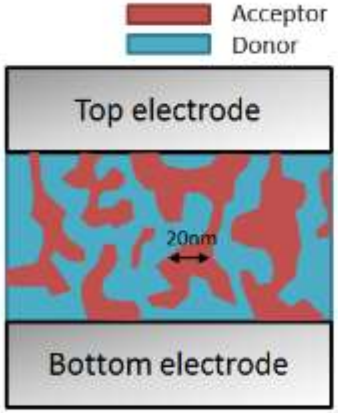


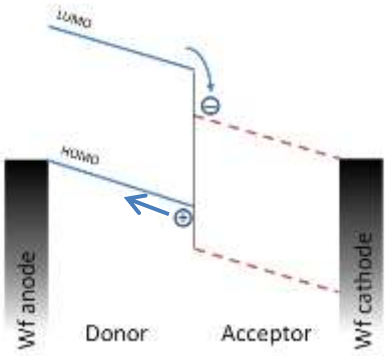
- Pro : scalable, advanced function on chip (TDC, triggering), Timing performances
- Cons : afterpulse, crosstalk, deadtime, noise (dark count), light yield non proportionality

Solid state photo-sensor

- **Organic Photodiodes (OPD):** Bulk heterojunction concept: nanoscale mixing of electron-donor and electron-acceptor organic materials. Deposition by microelectronic or imprint technologies
- a:Si/CMOS/Organic backplane

source: CEA-ISORG



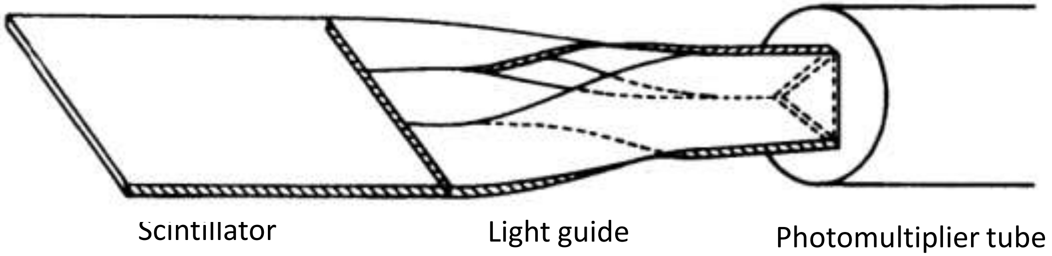


- Pro : large scale, conformable, EQE>70%, low dark reverse current (nA/cm²), ease of exotic integration on flexible and lightweight plastic substrates, large wavelength range (400-1000nm),
- Cons : early R&D development. Low response time, sensitive to temperature (> 130°C), require barrier against oxygen and humidity

→ See next talk by J.M. Verilhac

Light guides

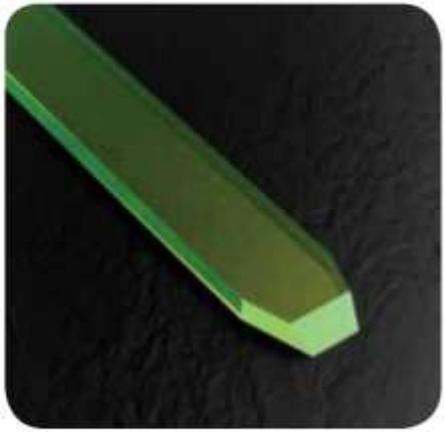
- Match geometry of scintillator to photodetector. Total internal reflection and external reflector. Example : large area square scintillator, a small area round detector (cost, noise). Efficiency limited by space phase conservation (Liouville Theorem).



source: saint-gobain.com

- Spatial separation of scintillator and detector (magnetic field)

- Wavelength Shifter (WLS) plastic bars absorbs light at one wavelength and emit it at a longer wavelength. A portion of this light is guided by TIR along the bar to readout at one end. Useful to build a 1D or 2D readout of a large scintillator plaque.

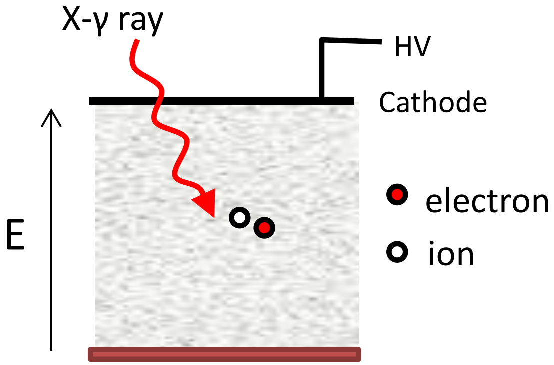


source: saint-gobain.com

Direct detector

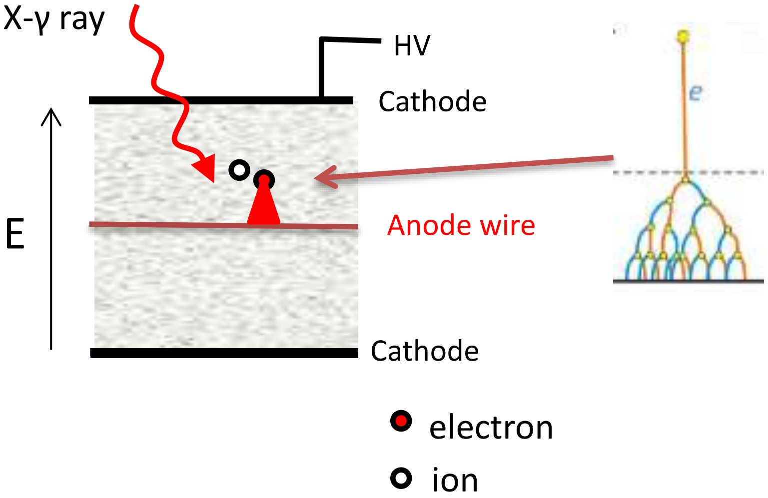
Gaseous detector

- Ionisation of a **gas** by x-rays, directly or by secondary electrons produced in the walls of the tube
- Free electrons and ions drift under an external electric field
- **Ionization chambers**: steady current proportional to the dose rate the gas is exposed to.



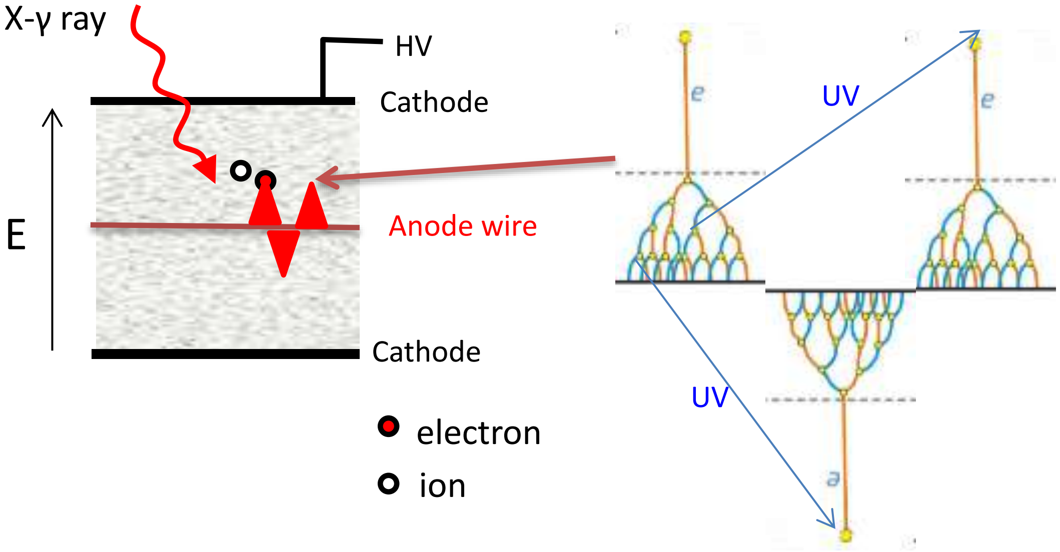
Gaseous detector

- Ionisation of a **gas** by x-rays, directly or by secondary electrons produced in the walls of the tube
- Free electrons and ions drift under an external electric field
- **Ionization chambers**: steady current proportional to the dose rate the gas is exposed to.
- **Proportional counters**: thin positively anode wire in the center of a cylindrical chamber → avalanche effect → spectroscopy



Gaseous detector

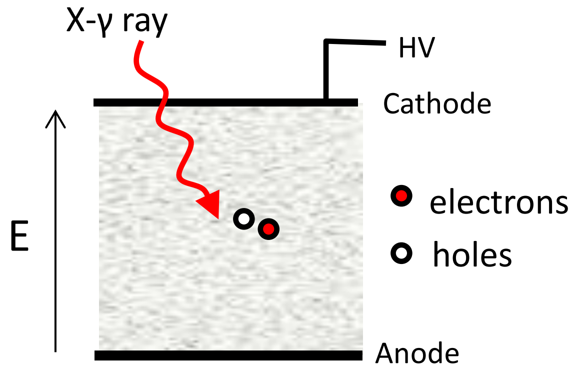
- Ionisation of a **gas** by x-rays, directly or by secondary electrons produced in the walls of the tube
- Free electrons and ions drift under an external electric field
- **Ionization chambers**: steady current proportional to the dose rate the gas is exposed to.
- **Proportional counters**: thin positively anode wire in the center of a cylindrical chamber → avalanche effect → spectroscopy
- **Geiger–Müller counters :** avalanche spread by UV photons. Very strong signal. No spectroscopy.

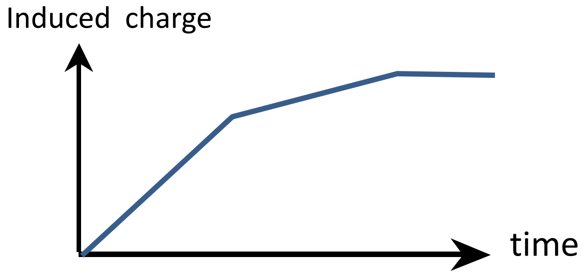


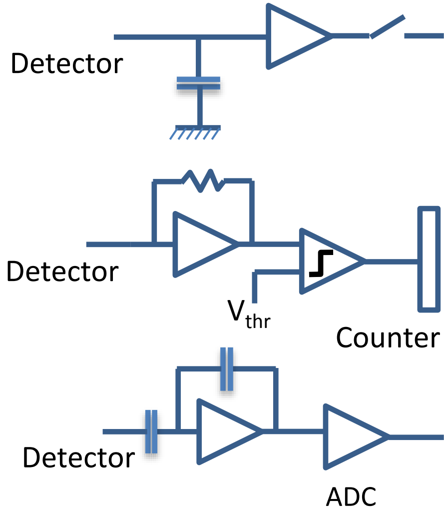
Semiconductor direct detector

- Converts the electrons kinetic energy directly into electron-holes pairs.
- Electron-hole pair creation : 3 × bang gap. Fano Noise $\sqrt{FN_{pair}}$ with F=0.1 → energy resolution
- Charge carriers drift (and diffuse) in a high electric field → spatial resolution
- Currents are induced on each electrodes <u>during</u> the charge carrier drift

Schockley Ramo Theorem : Induced Current = charge × weighting field × velocity







- Non complete charge collection : dependence of the induced charge to the Depth of Interaction
- Measuring drift time can lead to Depth Of Interaction (DOI)

Semiconductor direct detector

- Much less semi-conductors than scintillators for detection

		Si	Ge	Cd(Zn)Te	GaAs
Band Gap	eV	1.12	0.66	1.5	1.2
Z		14	32	48-52	31-33
Absorption coef @100keV	cm	2.33	0.34	0.1	0.34
Electron mobility . lifetime	cm^2/V	1.4	4	1-4 10^{-3}	85 10^{-6}
Hole mobility . lifetime	cm^2/V	0.5	1.9	80.10^{-6}	4 10^{-6}
Max thickness	mm	0.7 - 2	100	5-10	

Temperature

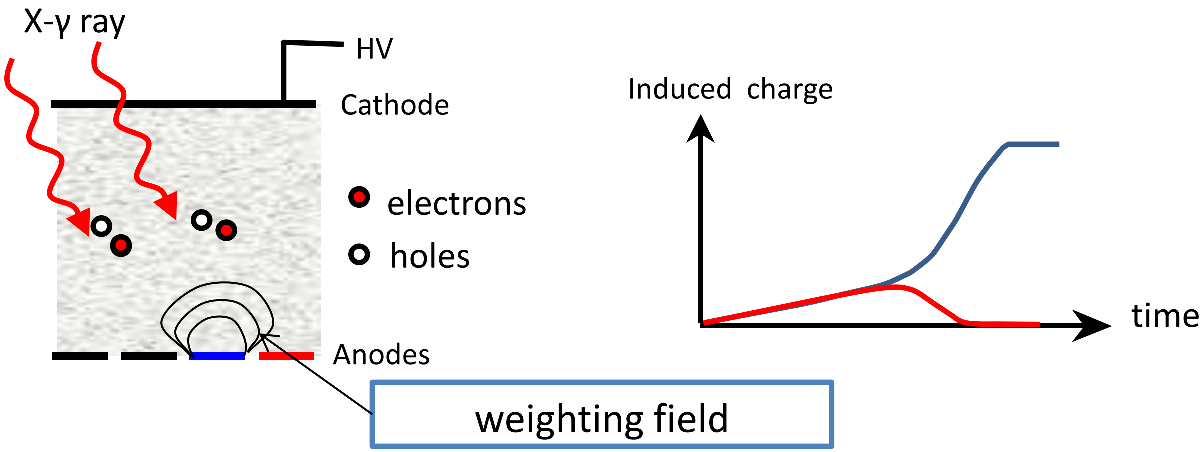
1. X-ray absorption

2. Charge carrier Transport

- **Silicon** : low energy photon (1-12 (20) keV) / high spectroscopic resolution
- Germanium : cryogenic spectrometric detector Very high spectroscopic resolution
- **Cd(Zn)Te** : 20keV-200keV(1MeV), small volumes, single carrier.
- GaAs : outsider. 10-30 keV
- HgI_2, PbI_2 ,TlBr : future material for high energy?

Semiconductor direct detector

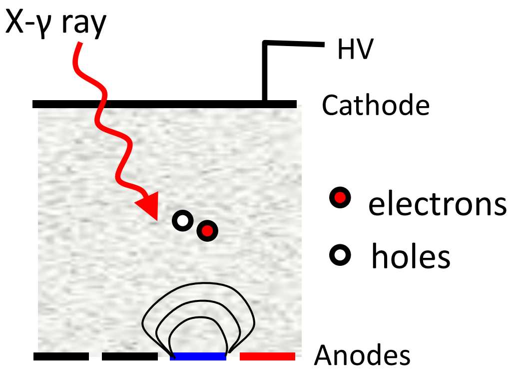
- **Pixelated detectors**.
- Small pixel effect : signal mainly induced close to electrodes
- Silicon, germanium, Cd(Zn)Te

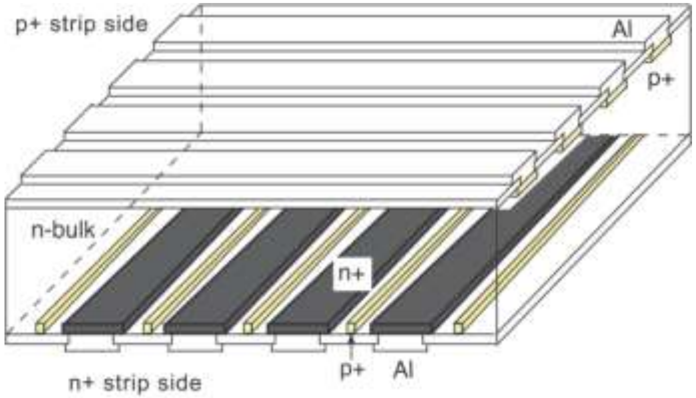


- Weighting field cross talk → noise (or correction)
- Charge sharing : blurring (and false count) if not correct
- Multi-electrode signal treatment. Fine localization (x, y, z). Energy correction. Multi-event recognition (Compton)
- Pro : energy resolution, counting photons at high flux
- Cons : price, surface, hybridization

Semiconductor direct detector

- **Double-sided Drift Detector**
- Reduction of the readout circuit compared to pixelated solution → fine segmentation





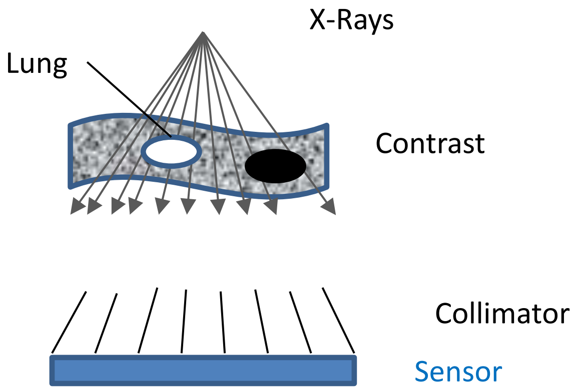
http://spie.org/x20060.xml

- Pro : low cost, reduced electronic, large surface/volume
- Cons : low count rate (multi-hits)

Forming an image

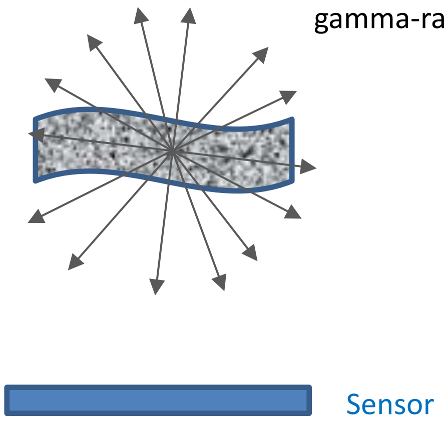
Transmission imaging

- Emission by a source (tube generator, synchroton..)
  - Radiography, CT. Medical imaging : From 20 keV to 160keV. Non Destructive Testing : up to MeV
  - Scientific imaging : from keVto …
- Transmission / absorption in / scattering by the object is responsible of the contrast.
  - Anti-scatter grid



Emission imaging

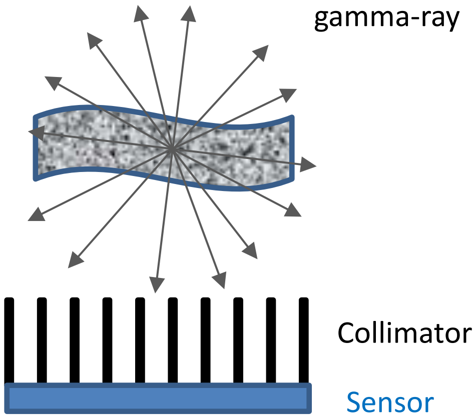
- Emission in the object is responsible to the image.
  - Medical imaging : radiotracer injection. From 50keV to 511keV.
  - Astrophysics : Emission imaging of far light source coming form black body emission (cosmic background, stars), nucleosynthesis (supernovae), bremsstrahlung (black holes). From keV to TeV
- Necessity to form an image : **collimator**



Emission imaging

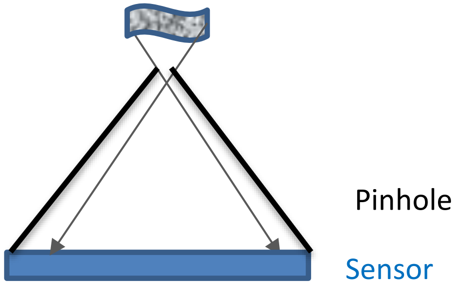
- VOIR FRANCOISE

- Emission in the object is responsible to the image.
- Necessity to form an image : collimator
- Parallel hole collimator : simple, spatial resolution and efficiency uniforms over the entire field of view. Low sensitivity. Can be convergent.



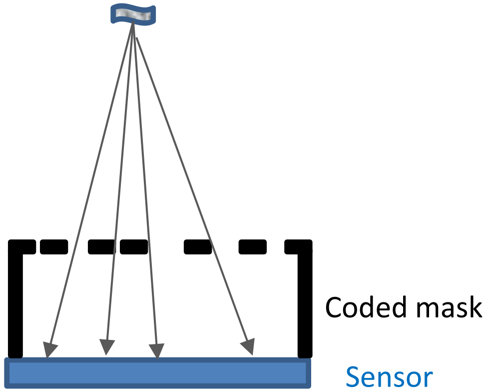
Emission imaging

- Emission in the object is responsible to the image.
- Necessity to form an image : **collimator**
- Parallel hole collimator
- Pinhole : Magnification. Small field of view. High spatial resolution , low sensitivity. Mutlipinhole.



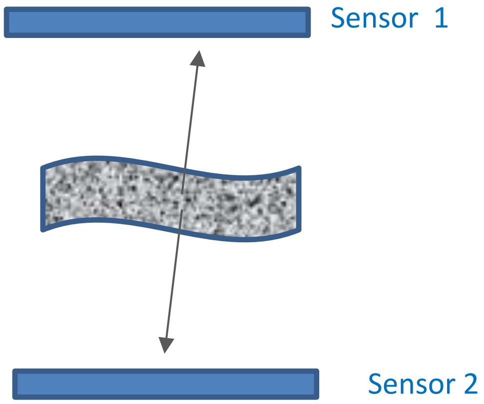
Emission imaging

- Emission in the object is responsible to the image.
- Necessity to form an image : **collimator**
- Parallel hole collimator
- Pinhole
- Coded mask : more efficient. Reconstruction. “punctual sources”



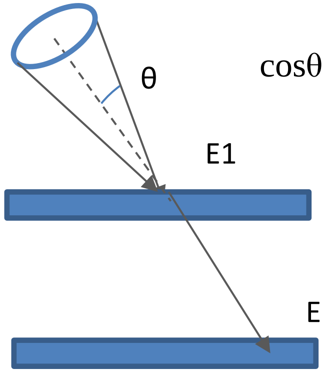
Emission imaging

- Emission in the object is responsible to the image.
- Necessity to form an image : **collimator**
- Parallel hole collimator
- Pinhole
- Coded mask
- Electronic: Positron sources gives, after annihilation with one electron two 511 keV gamma photons in coincidence. High sensitivity.



Emission imaging

- Emission in the object is responsible to the image.
- Necessity to form an image : **collimator**
- Parallel hole collimator
- Pinhole
- Coded mask
- Electronic collimation
- Compton detector : 0.1-1MeV photons. Compton diffusion in the first sensor. Photoelectric effect in the second sensor. Compton formula gives the angle .



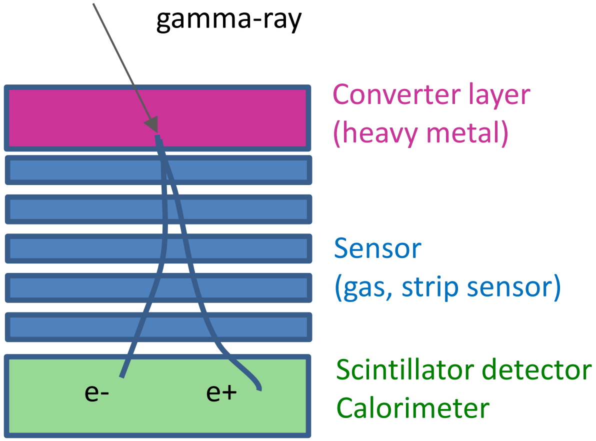
$$\cos\theta = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

Sensor1 : diffuser : Compton scattering

Sensor2 : absorber : photoelectric effect

Emission imaging

- Emission in the object is responsible to the image.
- Necessity to form an image : **collimator**
- Parallel hole collimator
- Pinhole
- Coded mask
- Electronic collimation
- Compton detector
- Pair production : > 10 MeV photons. Conversion in an heavy absorber. Tracking by position sensitive sensors. Energy measurement by a calorimeter



Where are we?

System requirements

Irradiation

- Surface. Tile possible?
- Energy range / Detection Efficiency
- Photon flux

What to measure?

- Individual energy / count
- Image
- Depth of Interaction
- Timing

Environment

- Radiation tolerance
- Magnetic compatibility
- Power consumption
- Compactness

Forming the image

Detector parameters

Detection mode

- Indirect : Scintillator + photodetector
- Direct : Gas, Semiconductor

Interaction type

- Photoelectric
- Compton
- Pair production

Readout mode

- Integration
- Counting
- Spectrometric

Collimator

- Parallel, pinhole, coded mask
- Electronic
- Compton, Pair production

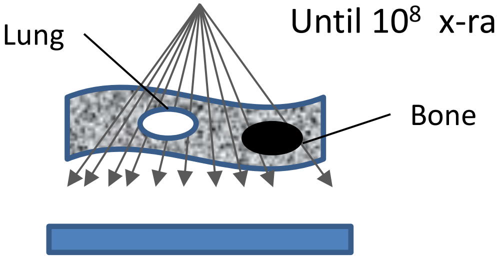
- Lets see some examples, per application

Applications

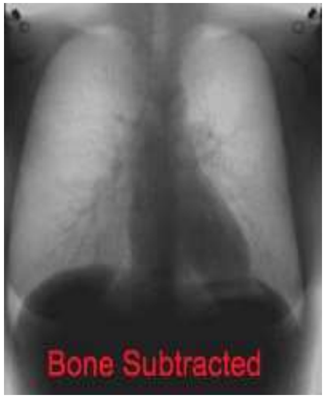
Medical radiography

- Anatomic imaging. Contrast : photoelectric attenuation coefficient higher for bones than for soft tissues. Higher for fat tissues than for water (muscle, liver). Compton scattering dominate for soft tissues.
- Contrast could be enhanced using dual energy imaging (two shots) or using a contrast agent like iodine (Kedge 33.2 keV) : digital subtraction.

X-ray (30Hz) 70-120kV.
(Polychromatic)
Until 10^8 x-ray/mm²/s



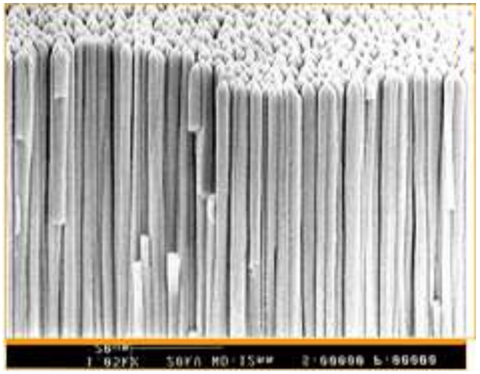
Source : wikipedia

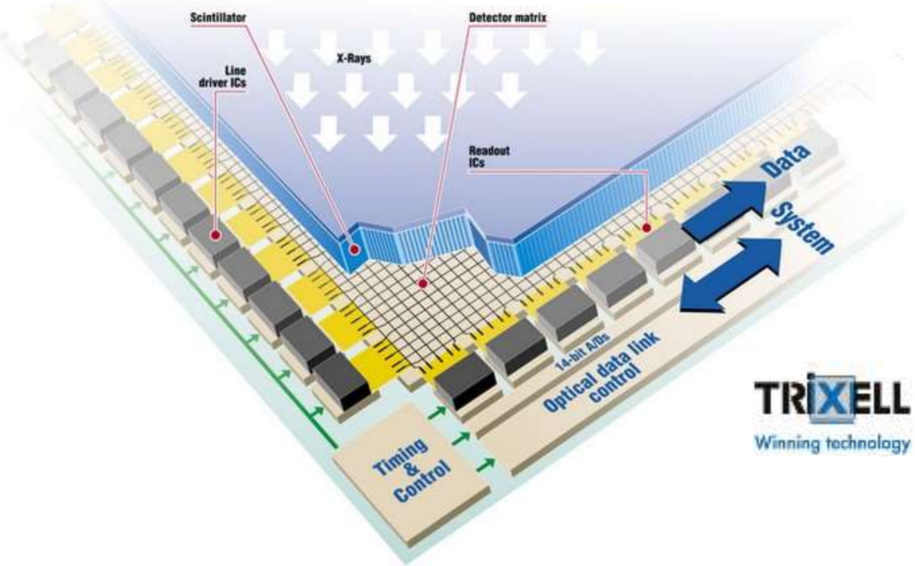


Requirement	Solution
High flux	Integration mode readout
Mean energy 50keV	High Z
Large area (until 42x42cm²), no dead space	Evaporated or ceramic scintillator Amorphous silicon backplane
Spatial resolution 120-200 µm	Scintillator could be structured in needle

Medical radiography

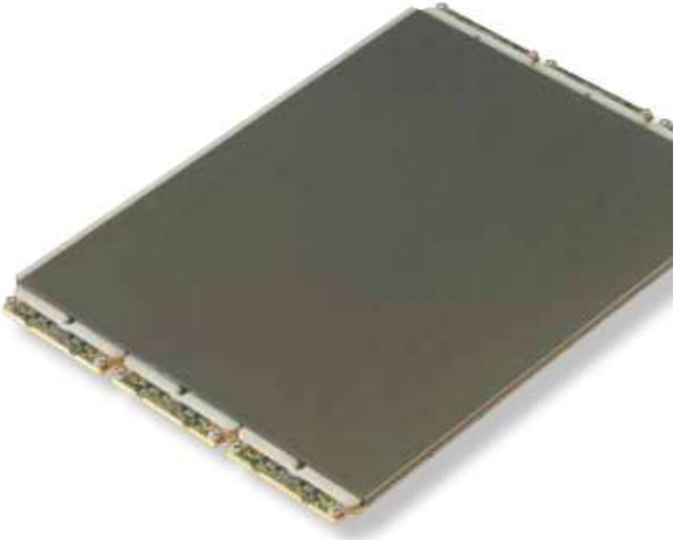
- Current detector: Flat panel. **Scintillator** CsI:Tl (vapor deposition, needle structure, light yield), or Gadolinium Oxides on an amorphous silicon backplane (**PD / TFT**) (large area, small pixels) working in integration mode.
- Compton scattering : antiscatter grid



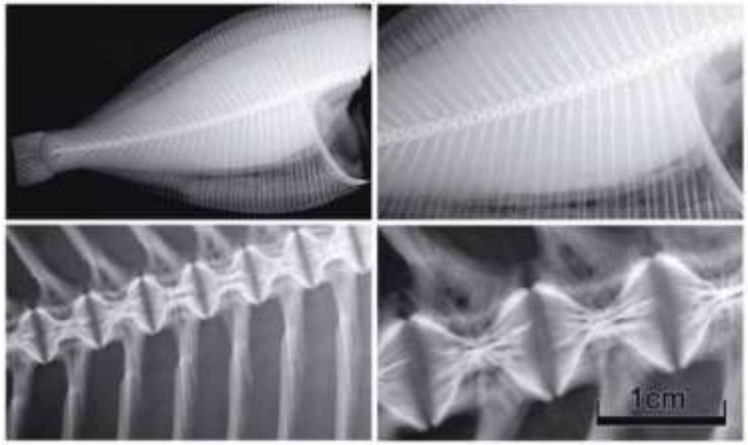


Medical radiography

- Next generation : **Large area CMOS** flat panel sensor and **scintillator**? Example : Teledyne DALSA or Dexela
- Advantage of wafer-scale X-Ray CMOS image sensor designs compared to a-TFT :
  - Smaller pixel pitches (20 to 100 microns), surface up to to 13x13 cm².
  - Claims compared to a-TFT : No image lag, low readout noise levels, superior dynamic ranger, higher speed. Better contrast (Detective Quantum Efficiency (DQE))



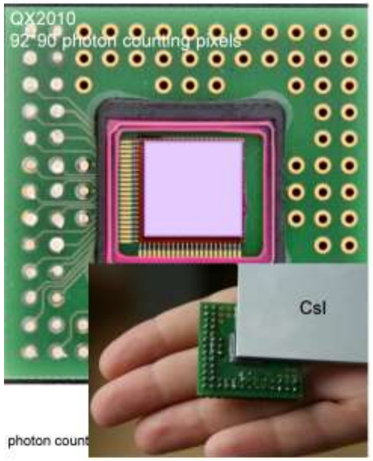
23X28CM Teledyne Dalsa FULL FIELD DIGITAL MAMMOGRAPHY CMOS DETECTOR, FEATURING A 2X3 ARRAY OF CMOS IMAGE SENSOR TILES WITH A 33 MICRON PIXEL PITCH. TOTAL RESOLUTION: 60MP



Source : http://www.teledynedalsa.com/

Medical radiography

- Next generation : **indirect X-ray photon counting** flat panel sensor?
- Advantage of photon counting sensor :
  - Suppression of electronic noise
  - Photon energy discrimination : better use of the dose (1 channel) and physiologic/contrast agent visualization
- Example : Caeleste small prototype. **CMOS counting imager + scintillator** (GdOs or CsI)
  - 92x90 pixel array, 100µm pixel pitch
  - Two channels



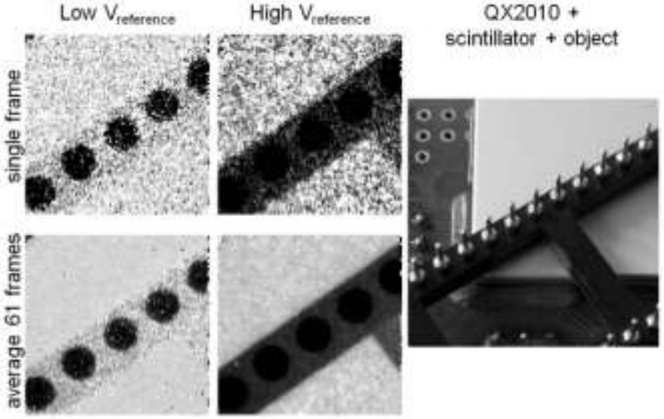


Fig. 5. X-ray image in two channels (left, right) of a DIL socket. Single frame (upper) and averaged over 61 frames (lower). Illumination 40kVp, 25mA, shielding 10mm Al. t_{frame}=180ms, dose=232µGy.

Source : http://www.caeleste.be/

Medical radiography

- **Mammography : 20-50keV X-ray ,** spatial resolution : 50µm, breast compressions
- Philips MicroDose Mammography : two collimators (scatter rejection), **edge on** crystalline **silicon strip** (50 µm pitch) (**direct conversion**), ASIC in **counting mode** (electronic noise rejection). Solution limited to low energy.
- Average dose reduction of 40% claims compared to other digital mammography system

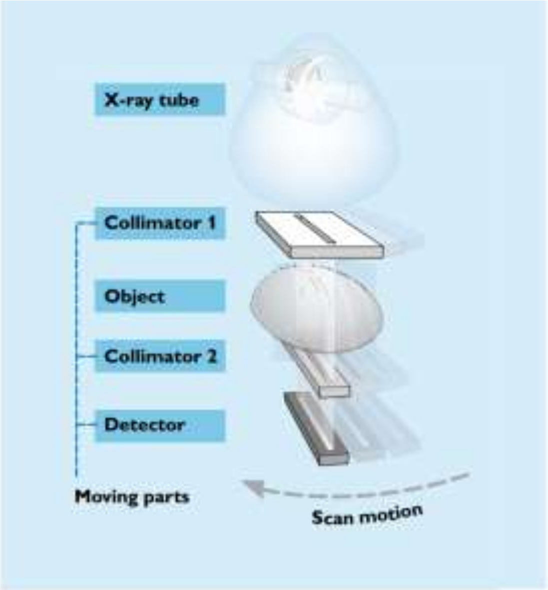


Figure 7 Multi-slit scanning technology used in Philips MicroDose.

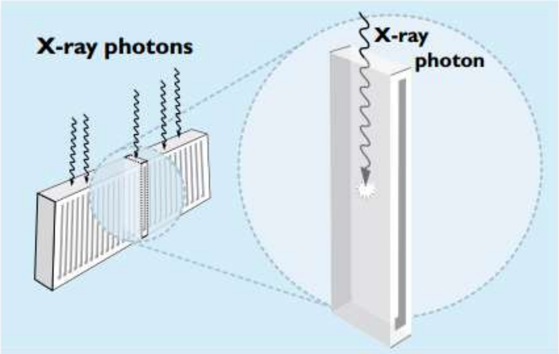


Figure 3 Crystalline Silicon strip detectors with edge-on geometry.

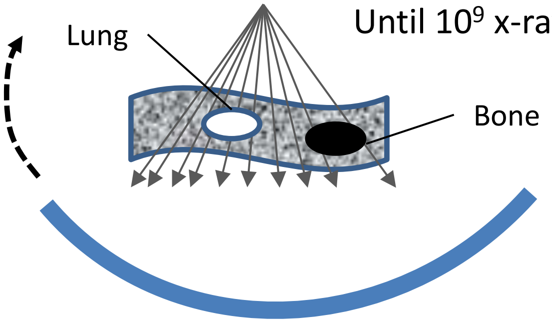
Source : http://www.healthcare.philips.com/

Medical radiography

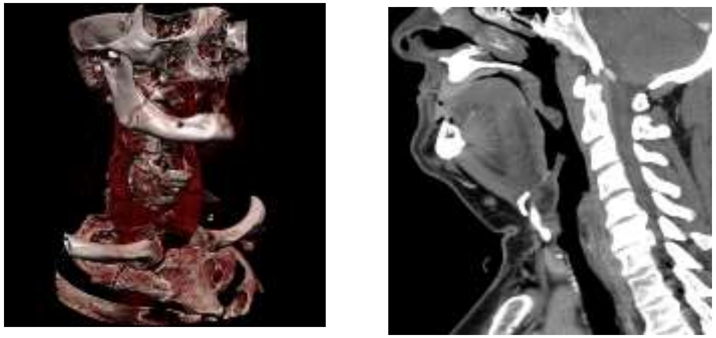
- Example : **medical radiography. Other systems**
- Mammography : Direct detection : better FTM claims compared to scintillator. direct detection (FTM) and **Amorphous selenium** flat panel system with **amorphous silicon TFT** readout integration in integration mode. aSe seems to suffer from image lag and material instability.
- Intraoral dental radiography : small size **CsI** + **CMOS**

Computed Tomography

- 3D anatomic imaging: fast rotation and translation of the x-ray-generator / curved detector around the patient. Helical acquisition.



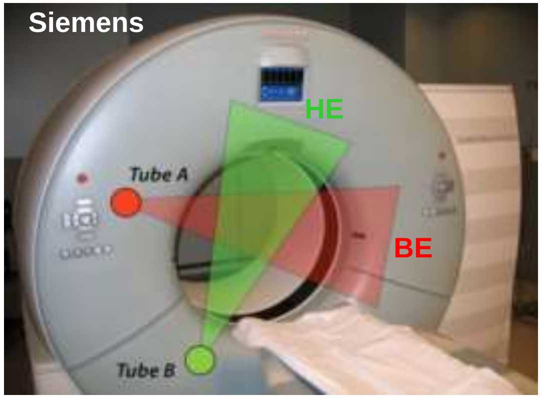
X-ray 160kV.
(Polychromatic)
Until 10^9 x-ray/mm²/s



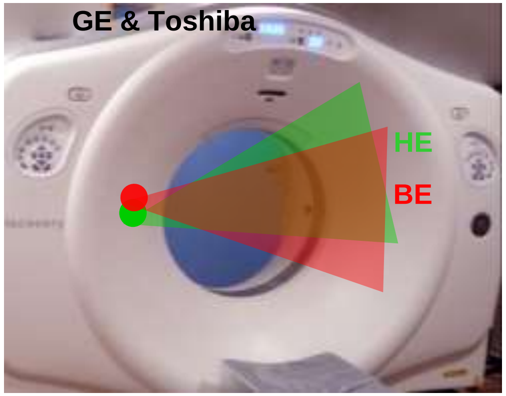
Requirement	Solution
High flux	Integration mode readout
Energy 160 kV (70keV)	High Z
Reconstruction of moving image	Detector without afterglow
Dynamic acquisition (2000-6000 f/s)	Fast scintillator
Surface until 13 x 100 cm² (polygonal)	
Pixel size 1 mm	Silicon photodiodes

Computed Tomography

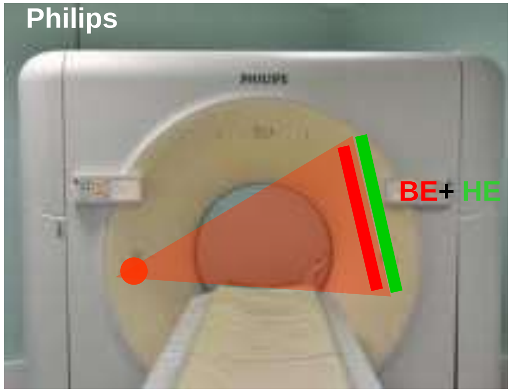
- Fast **scintillator** with low afterglow: GOS (Gd_2O_2S), $CdWO_4$. **Silicon photodiodes.** Antiscatter grid
- State of the art detectors : dual energy for material decomposition, separate imaging of several marked organs, lower reconstruction noise and contrast increasing



2 tubes

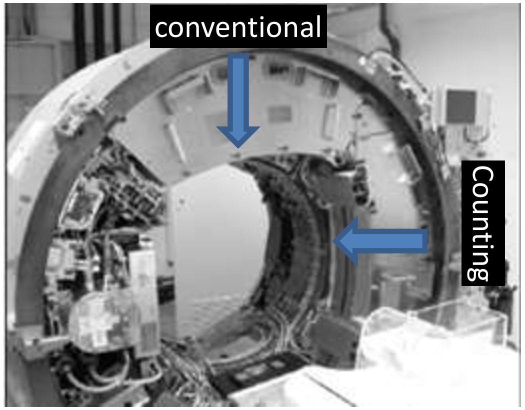


Fast switch



Dual detector

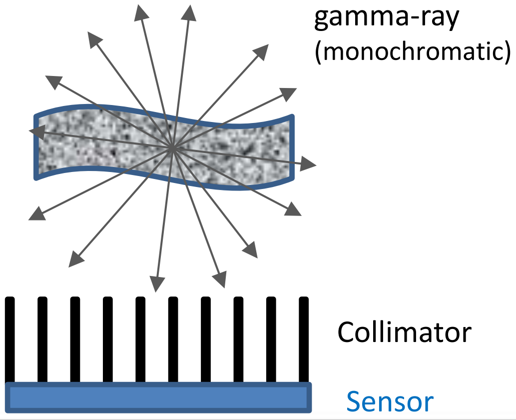
- Next step : **Photon counting** and **direct detection** using **CdTe** sensor ?
- Example : assessment by Siemens (S. Kappler et al., Proc. SPIE, 2012) : compared to conventional CT scanner,   iodine contrast increased by 20%, dose reduction by up to 32%
- Philips and GE have also prototypes



Scintigraphy

- Emission in the object is responsible to the image.
- Metabolic imaging of injected radioisotopes : could be alone, coupled to a molecule, an hormone, antibody.
  - Bones (Technetium-99m : 140keV) : Technetium is attached to a ligand which is taken up by bones. Increased tracer concentration = increased physiological function (fracture).
  - Heart (Thallium 201 : 70, 80keV) : thallium binds the K^+ pumps and is transported into the cells : amount of ^{201}Tl correlates with tissue blood supply. Perfusion study, myocardial viability.
  - Thyroid: (Technetium-99m : 140keV or iodine-131 : 364keV). Morphological and functional info.
  - Lung : (Xenon 133 : 233keV) evaluate the circulation of air within lungs (embolism)

- 2D or 3D images: Single Photon Emission Tomography (SPECT)
  - Necessity to form an image : collimator
    - Parallel hole. Pinhole. Coded mask. Electronic



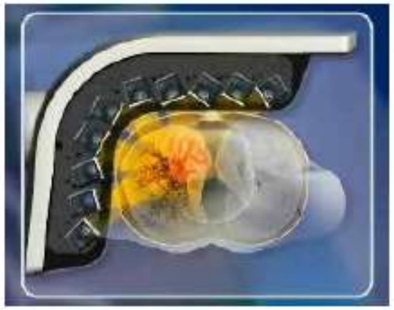
Requirement	Solution
Energy 80-350 keV	High Z
Large surface (40x40cm²)	Scintillator
Distinguish radioisotopes	Energy resolution
Pixel size 1 mm	Photomultiplier

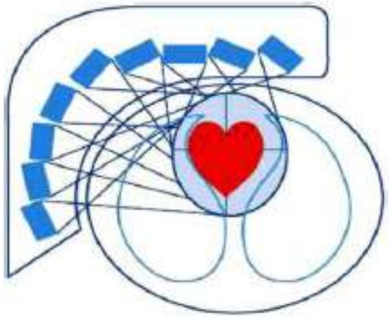
Scintigraphy

- Gamma camera. Example : Mediso Nucline. Luminous and large volume **scintillator** : NaI(Tl) (585 x 470 x 9.5 mm) and **Photomultiplier**

Source : http://www.mediso.com/

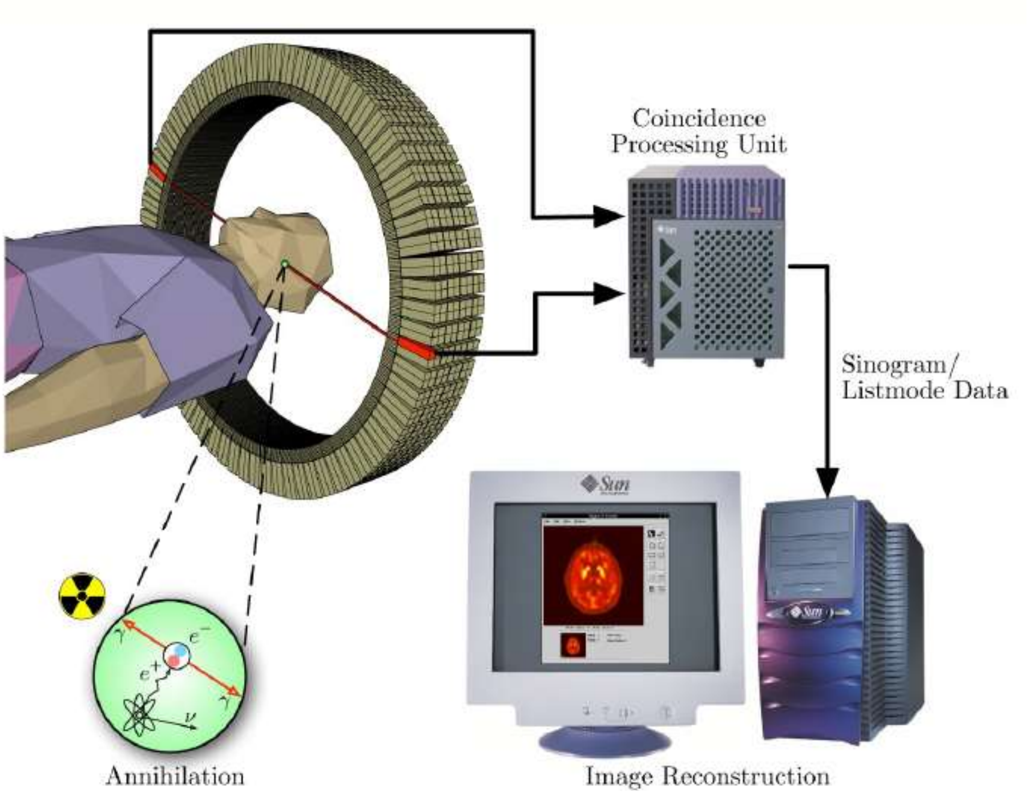
- State of the art new gamma camera for cardiac imaging : **Direct detection** using **CdTe** sensor and **dynamic collimation** (spectrum Dynamics: D-SPECT, GE: Discovery) : Better **energy resolution**, new **geometry**





Positron Emission Tomography

- The radioisotope (18-Fluor) emits a positron. The positron annihilates with an electron, giving two 511 keV photons emitted back to back. Electronic collimation.
- Coupled to CT images for reconstruction and attenuation correction
- Oncology: diagnosis and monitoring of tumors. High sensitivity (electronic collimation).



Source : wikipedia

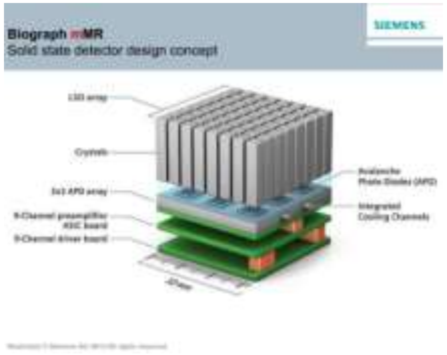
Requirement	Solution
Energy 511 keV	Very High Z
Large surface (x*ycm²)	Scintillator
Scattered discrimination	Energy resolution
Coincidence	Timing resolution
Pixel size 1 mm	Photomultiplier

Positron Emission Tomography

- Example : Mediso Anyscan. Fast **scintillator** : arrays of 4x4x20mm **LYSO** crystals (decay : 40ns) and **Time of Flight** - **Photomultiplier**

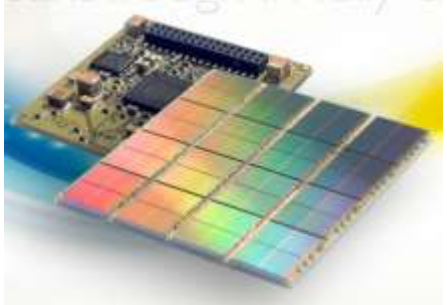
Source : mediso.com

- **Siemens** : Biograph mMR : simultaneous acquisition of whole-body **MR** (3T) and **TOF-PET**. Detectors: **APD**.
- **Philips** : Vereos PET/CT. « Digital PET » : Detectors: **d-SiPM** 1:1 coupling to crystals. Claims : 2x improved volumetric resolution, sensitivity gain, quantitative accuracy (compared to analog)



Biograph mMR
Solid state detector design concept

Source : www.healthcare.siemens.com

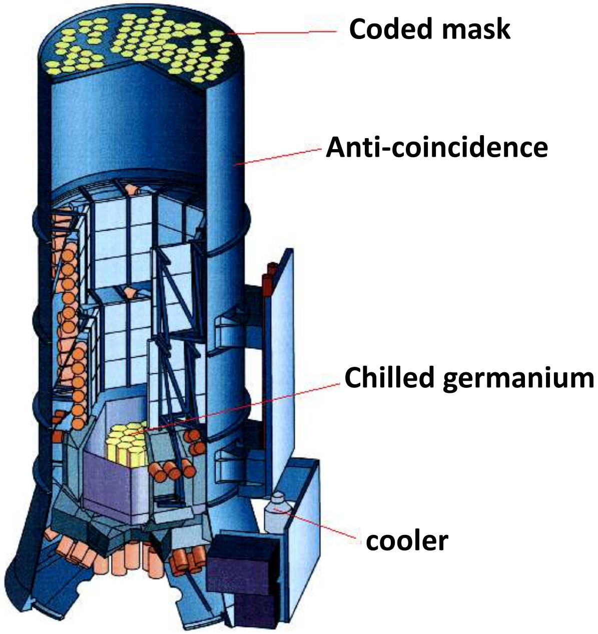


Source : www.healthcare.philips.com

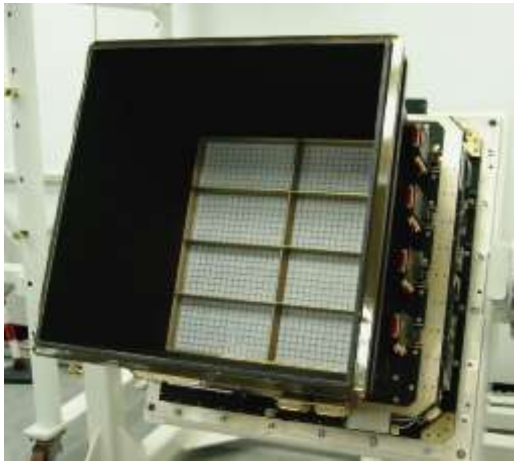
Astrophysics

- INTErnational Gamma-Ray Laboratory mission : exploration of celestial sites that emit gamma radiation in the spectral range from 20 keV to 8 MeV.
- Coded mask.
- Background radiation : anticoincidence system. Mask shield : plastic scintillator behind the tungsten tiles. Detector shield : BGO scintillator around the sides and back of the SPI.

SPI : energy resolution



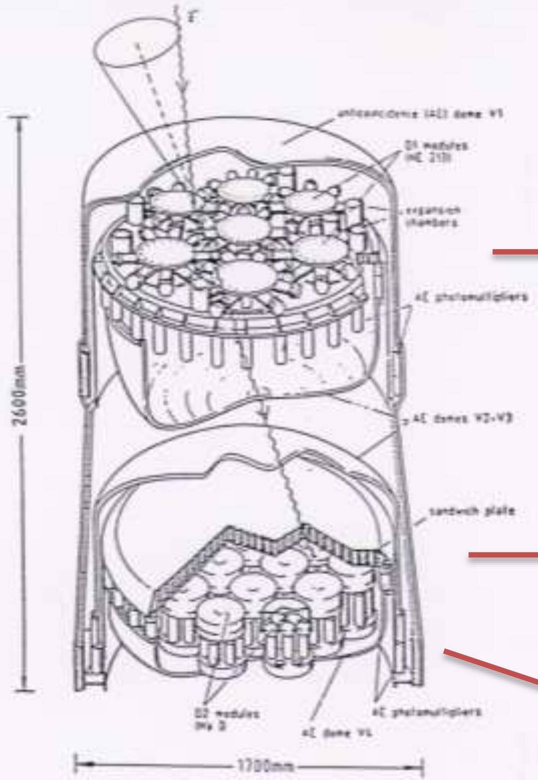
IBIS : angular resolution



ISGRI : CdTe (20keV-1MeV)
PICsiT : CsI (150keV-10MeV)

Astrophysics

- The COMPton TELescope: exploration of celestial sites that emit gamma radiation in the spectral range from 0.75-30 MeV



Diffuser : cylindrical modules of liquid scintillator viewed by eight PMTs.

Absorber : cylindrical NaI (Tl) viewed by eight PMTs.

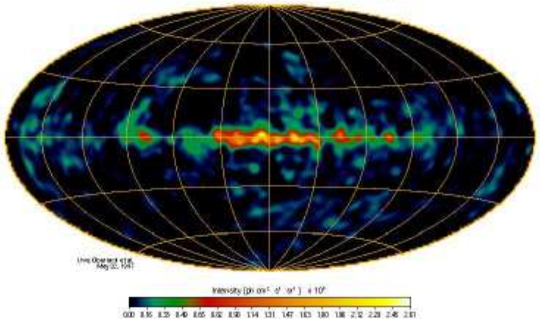
Anticoincidence shield : plastic scintillator

Schematics of COMPTEL

$$E_\gamma = E_1 + E_2$$

$$\cos\bar{\varphi} = 1 - \frac{m_e c^2}{E_2} + \frac{m_e c^2}{E_1 + E_2}$$

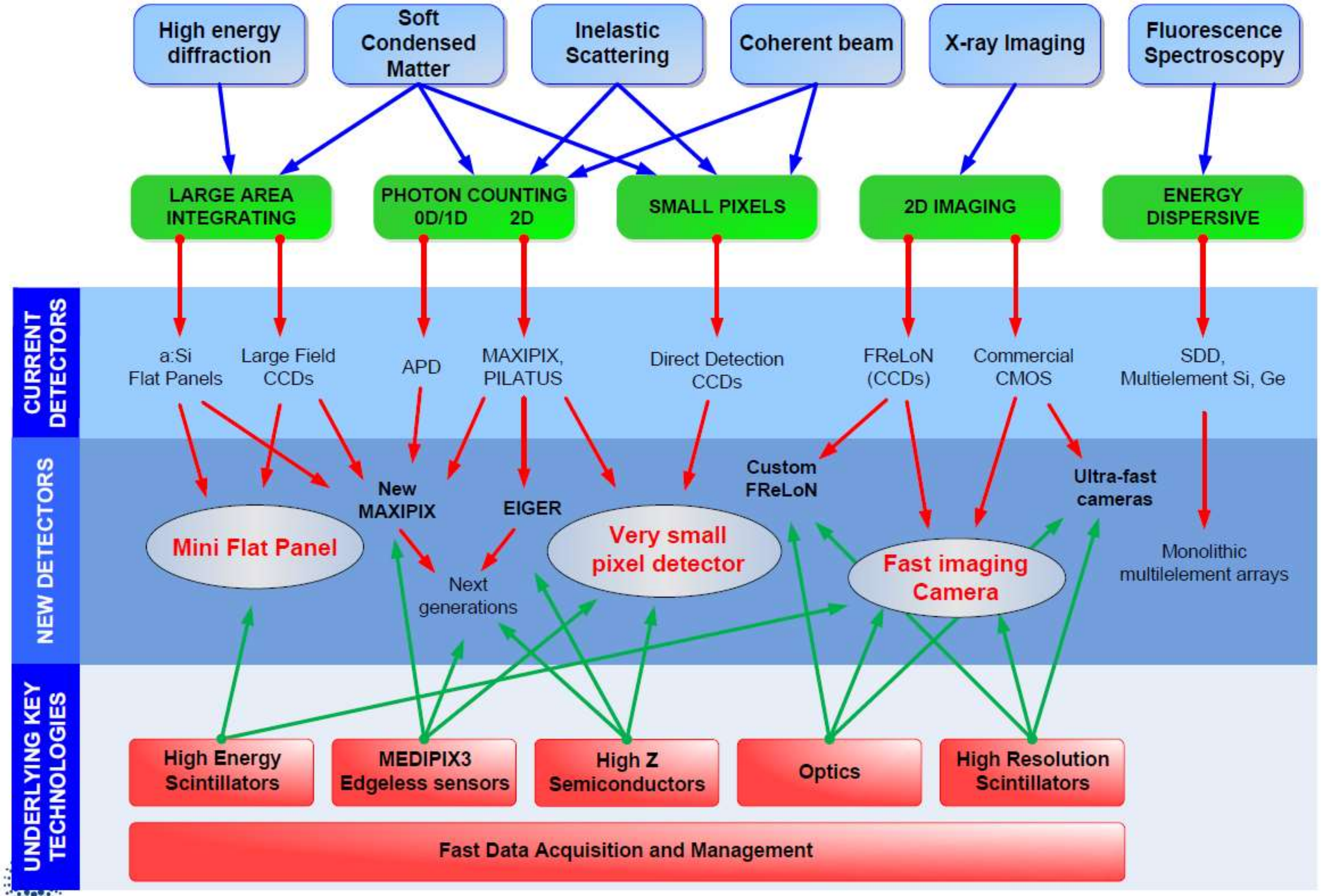
CGRO / COMPTEL 1.8 MeV, 5 Years Observing Time



http://heasarc.gsfc.nasa.gov/

Synchrotron

Detectors @ ESRF: overall picture and foreseen evolution



High energy diffraction

Soft Condensed Matter

Inelastic Scattering

Coherent beam

X-ray Imaging

Fluorescence Spectroscopy

LARGE AREA INTEGRATING

PHOTON COUNTING 0D/1D 2D

SMALL PIXELS

2D IMAGING

ENERGY DISPERSIVE

CURRENT DETECTORS

a:Si Flat Panels

Large Field CCDs

APD

MAXIPIX, PILATUS

Direct Detection CCDs

FReLoN (CCDs)

Commercial CMOS

SDD, Multielement Si, Ge

NEW DETECTORS

Mini Flat Panel

New MAXIPIX

EIGER

Next generations

Very small pixel detector

Custom FReLoN

Fast imaging Camera

Ultra-fast cameras

Monolithic multilelement arrays

UNDERLYING KEY TECHNOLOGIES

High Energy Scintillators

MEDIPIX3 Edgeless sensors

High Z Semiconductors

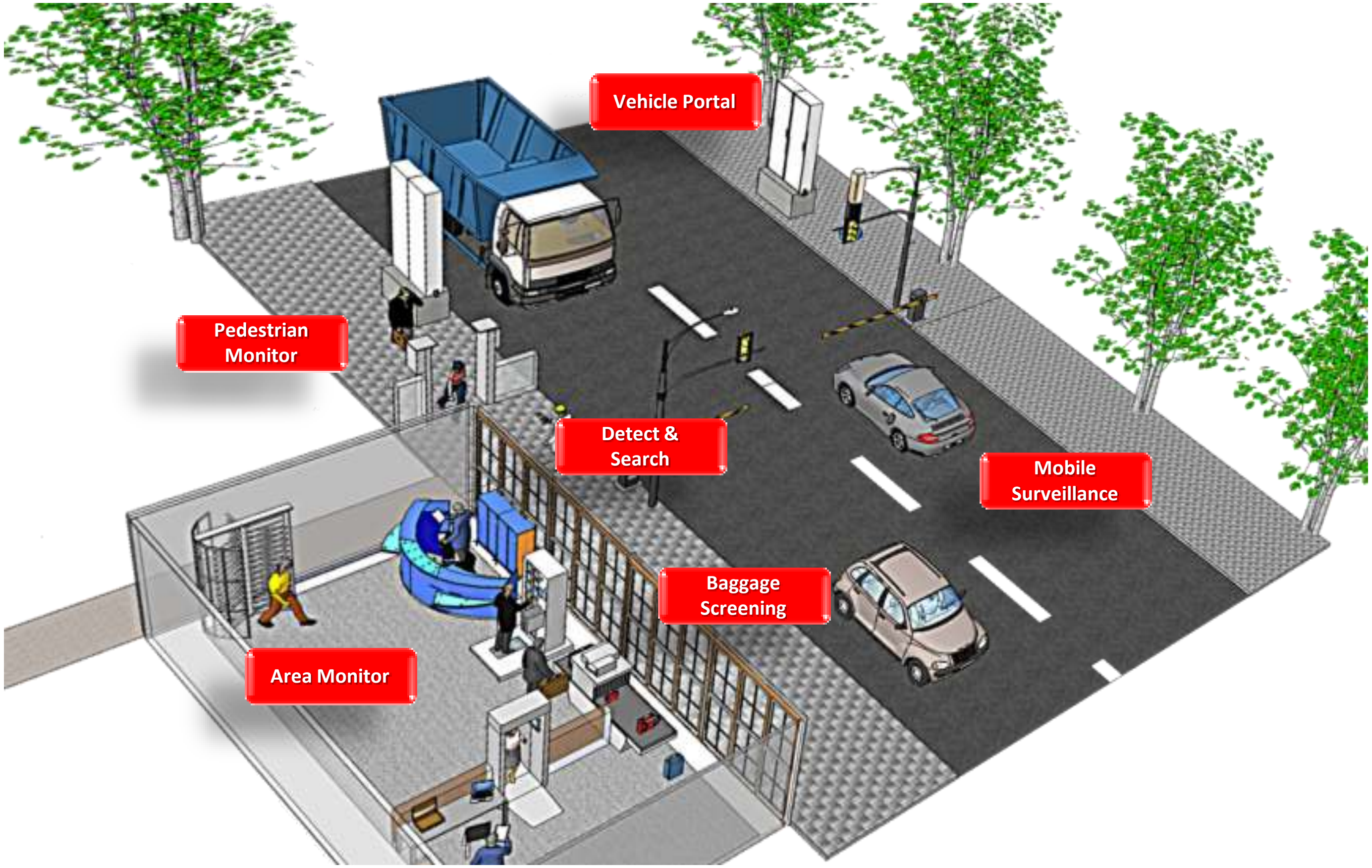
Optics

High Resolution Scintillators

Fast Data Acquisition and Management

Homeland Security

- Detect radioactive materials : large volume plastic scintillators + PMT
- Identify radioactive materials : crystalline scintillator (NaI:Tl) + PMT



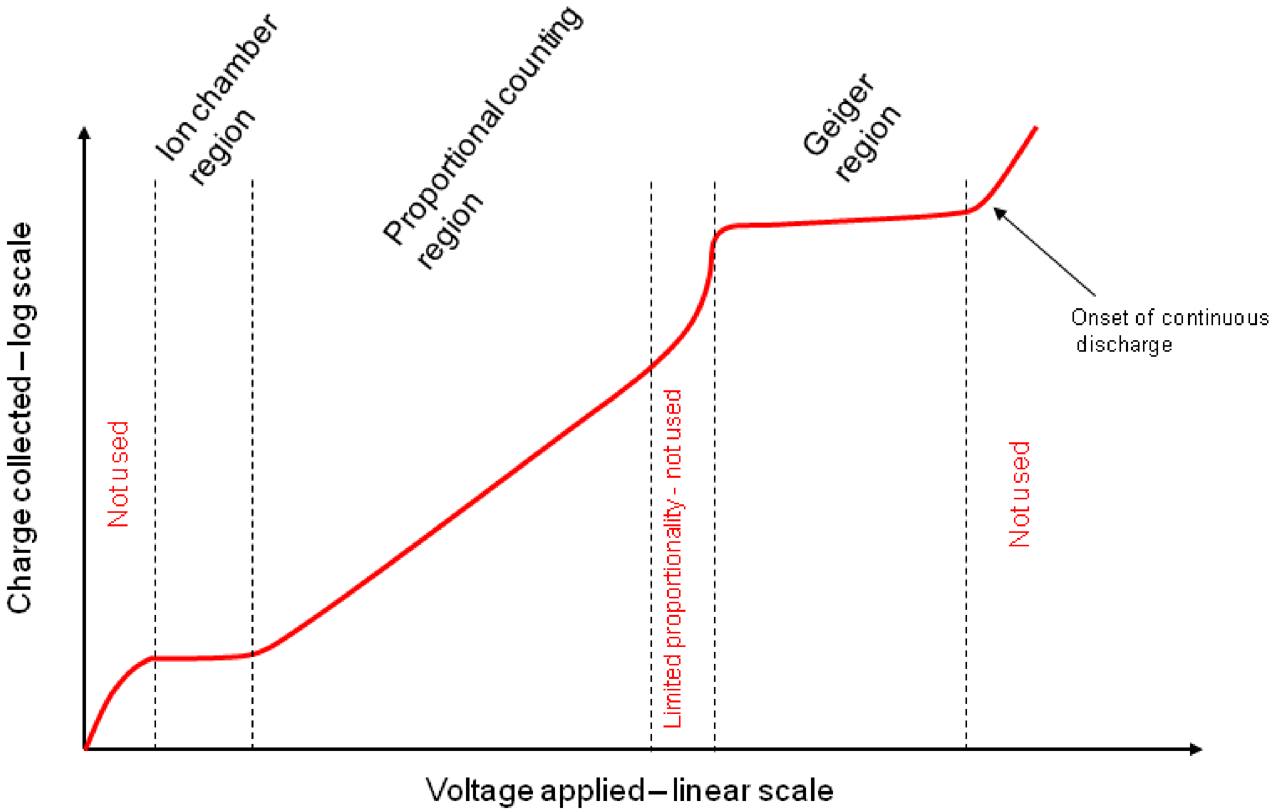
Conclusion

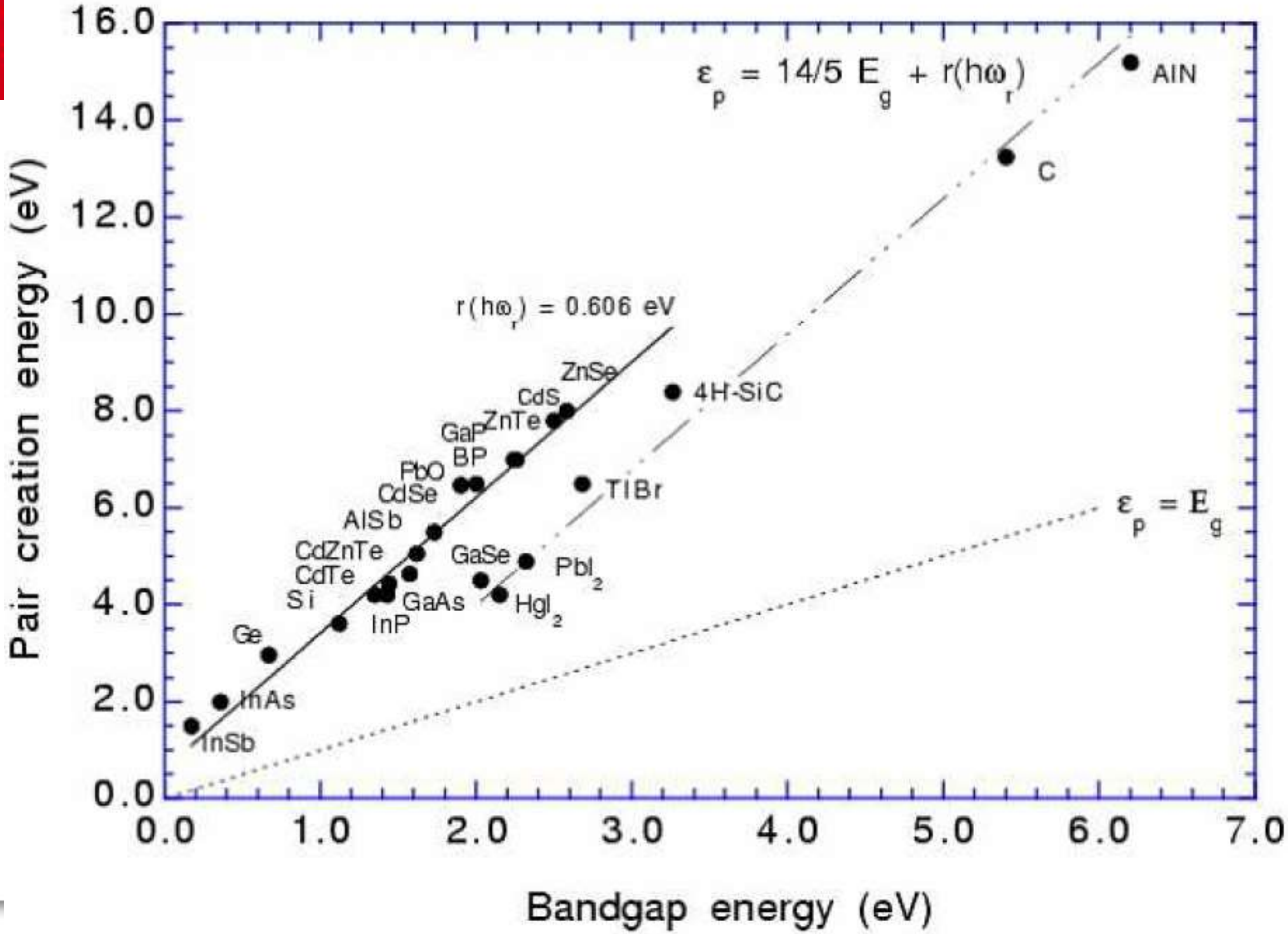
Questions ?

Backup slides

Practical Gaseous Ionisation Detector Regions

Variation of ion pair charge with applied voltage in a wire cylinder system with constant incident radiation.




$\varepsilon_p = 14/5\ E_g + r(\hbar\omega_r)$
$r(\hbar\omega_r) = 0.606$ eV
$\varepsilon_p = E_g$
AlN
C
4H-SiC
ZnSe
CdS
ZnTe
GaP
BP
PbO
CdSe
TlBr
AlSb
CdZnTe
CdTe
GaSe
PbI_2
Si
GaAs
HgI_2
InP
Ge
InAs
InSb
Pair creation energy (eV)
Bandgap energy (eV)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0