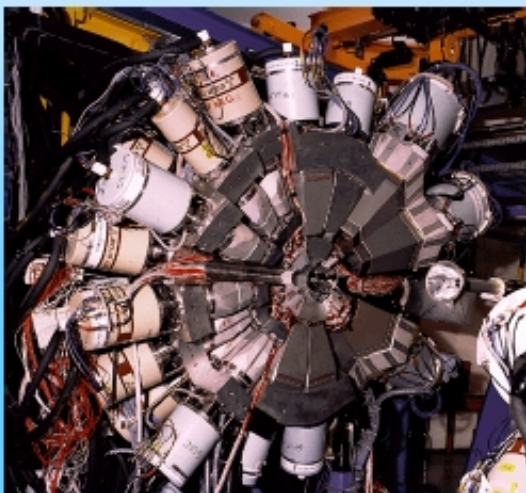


# *Détecteurs à semi-conducteurs*

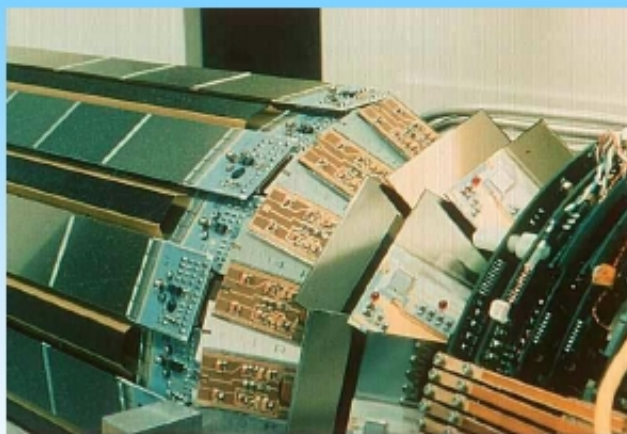
## *et leurs applications dans :*



*La Physique Nucléaire*



*L 'Astrophysique*



*La Physique des Particules*



*L 'Imagerie médicale*

# Détecteurs à semi-conducteurs

## Sommaire

- **Bibliographie**
- **Motivations expérimentales**
- **Détecteur à semi-conducteur générique**
- **Physique des semi-conducteurs**
- **Détecteurs à germanium**
- **Détecteurs à micropistes et pixels**
- **Effets de radiation: silicium-3D, diamant**
- **Électronique de lecture (notion)**
- **Autre types de détecteurs (SDD, CCD, DEPFET, a-Si)**
- **Développement: Ge segmenté, capteurs CMOS (MAPS), SiPM (SPAD)**

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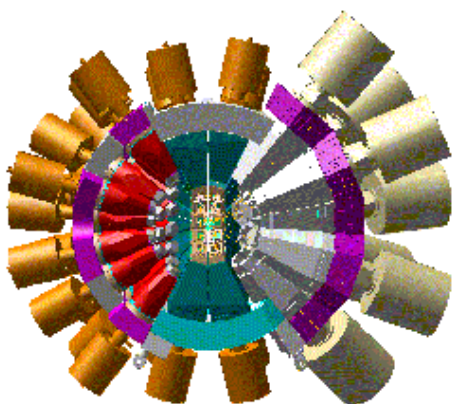
## Remerciement

Je remercie tous mes collègues et collaborateurs qui m'ont inspiré pendant la préparation de ce cours. Vous trouvez ci-après leurs nom et adresse électronique (la liste certainement non exhaustive) pouvant être, aussi pour vous, une source inestimable d'informations:

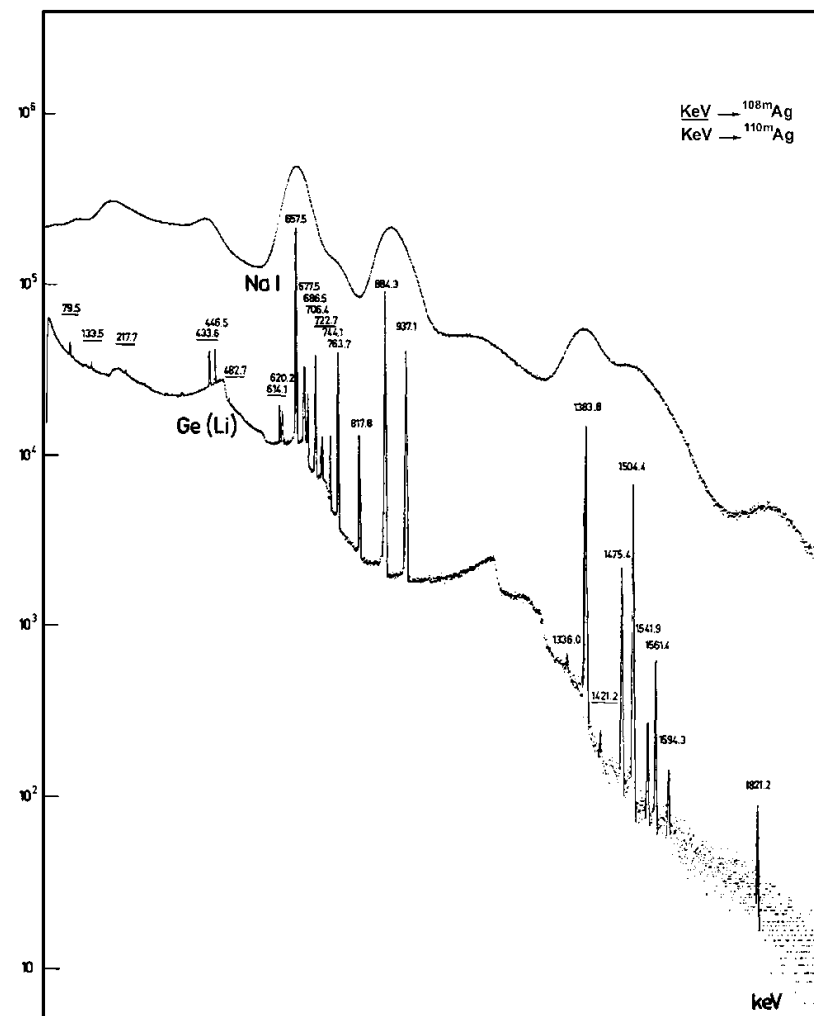
*Pierre Delpierre (delpierre@c ppm.in2p3.fr), Grzegorz Deptuch (deptuch@fnal.gov), Pierre Jarron (Pierre.Jarron@cern.ch), Harris Kagan (Harris.Kagan@cern.ch), Patrice Medina (patrice.medina@IREs.in2p3.fr), Michael Moll (Michael.Moll@cern.ch), Malgorzata Sowinska (m.sowinska@eurorad.com), Renato Turchetta (R.Turchetta@rl.ac.uk), Peter Weilhammer (Peter.Weilhammer@cern.ch)*

# Physics motivation in nuclear physics experiments: $\gamma$ spectroscopy

The great superiority of a germanium detectors in energy resolution, in connection with reasonably good efficiency, allows the separation of many closely spaced gamma-ray energies. Consequently, virtually all gamma-ray spectroscopy that involves complex energy spectra is now carried out with germanium systems.



Example of modern experience in nuclear physics: EUROBALL



Comparative pulse height spectra recorded using a sodium iodide scintillator and a Ge(Li) detector (gamma radiation from  $^{108}\text{Ag}$  and  $^{110}\text{Ag}$ ).

# Physics motivation in particle physics experiments: tracking

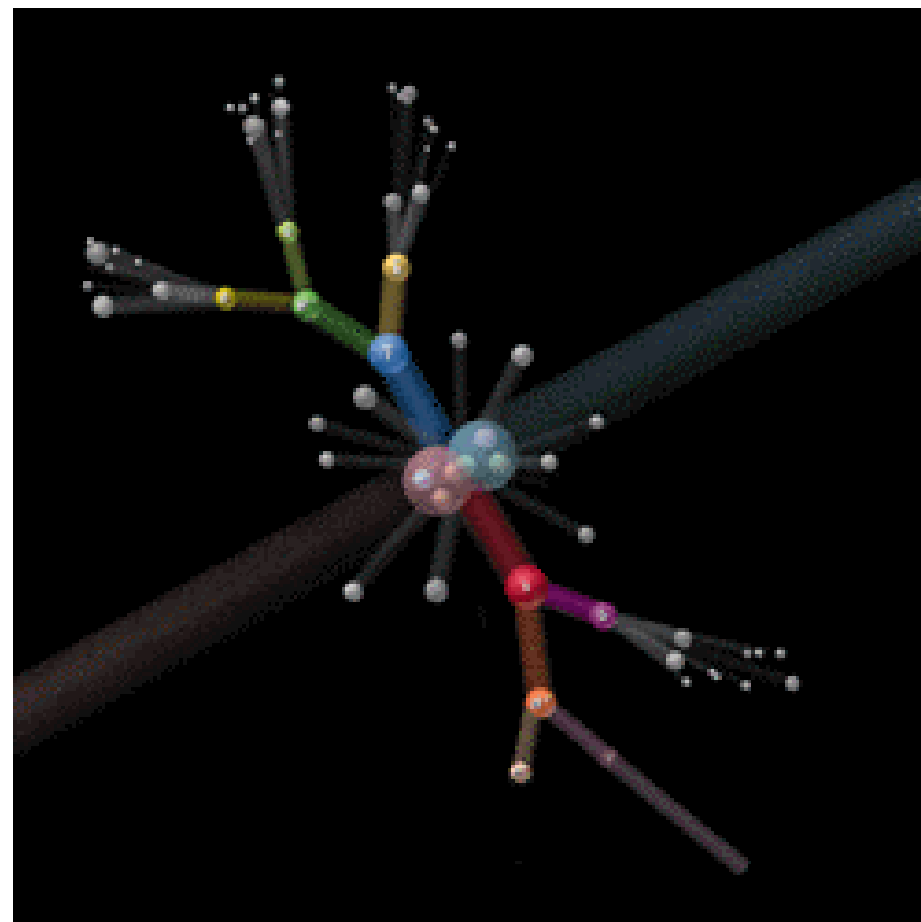
**Vertex reconstruction is used for the following:**

- lifetime
- quark mixing
- B-tagging
- top physics
- background suppression

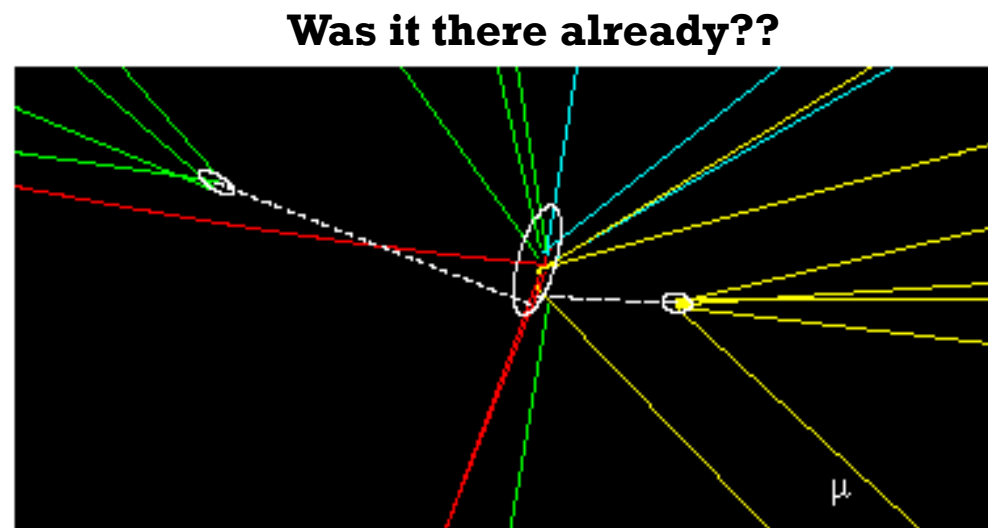
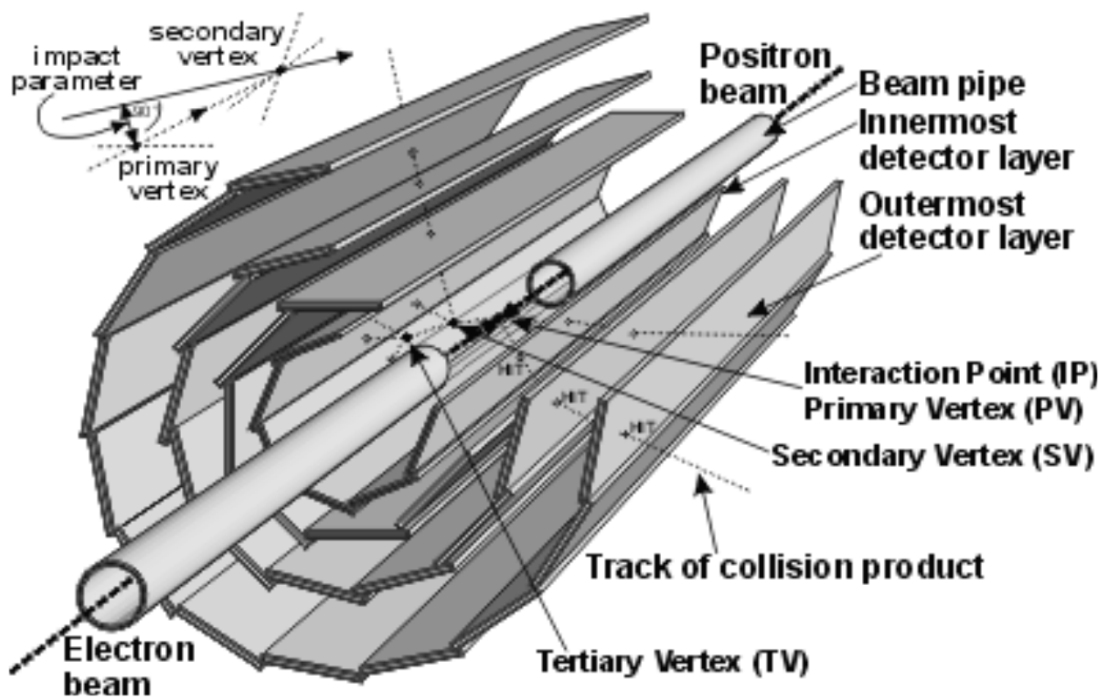
**For this application, the spatial resolution is THE factor of merit!**

## Typical Tracking Detector Characteristics

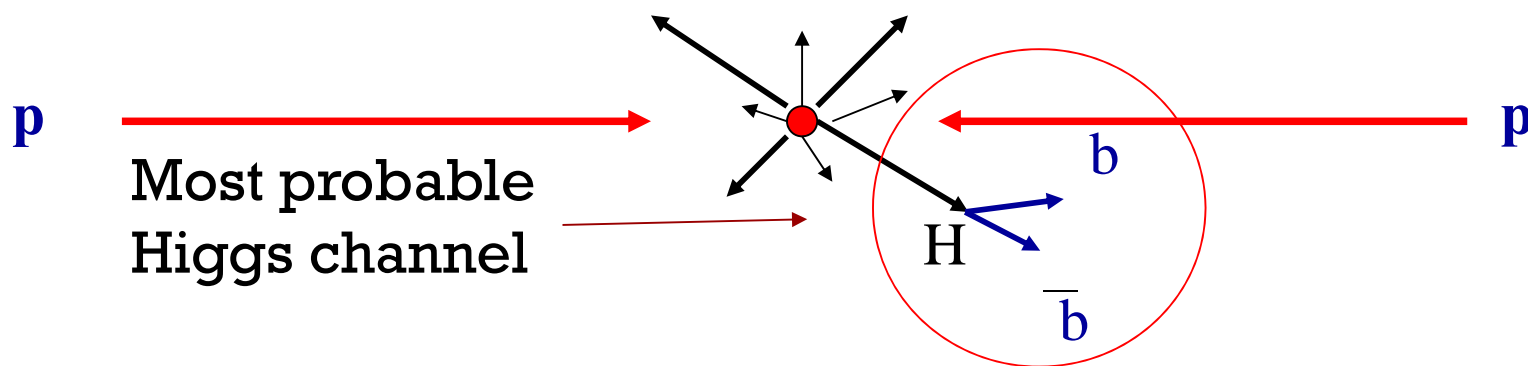
<u>Detector Type</u>	<u>Spatial Resolution</u>
Drift Chambers	~100 $\mu\text{m}$
MSGC	~30 $\mu\text{m}$
Silicon Detectors	2-15 $\mu\text{m}$
Nuclear Emulsion	1 $\mu\text{m}$



## Vertex detector based on silicon detectors

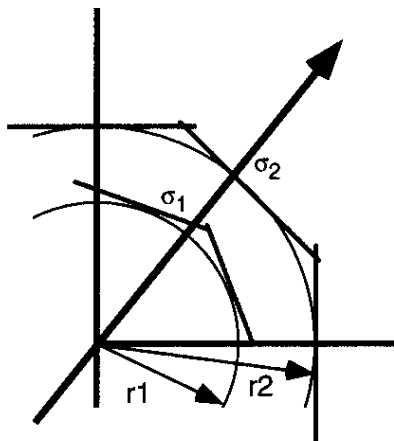


Event display shows a b candidate reconstructed in the ALEPH vertex detector.



## Impact Parameter Resolution

### Without Multiple Scattering



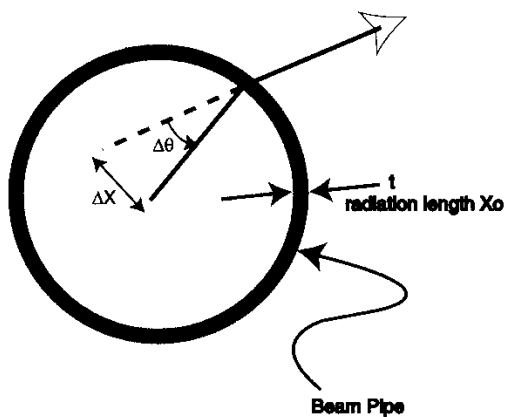
$$\sigma_I^2 = \sigma_1^2 + \frac{r_1^2}{(r_2^2 - r_1^2)} \sigma_2^2$$

So we want:

-small  $r_1$ , large  $r_2$

-small  $\sigma_1, \sigma_2$

### With Multiple Scattering

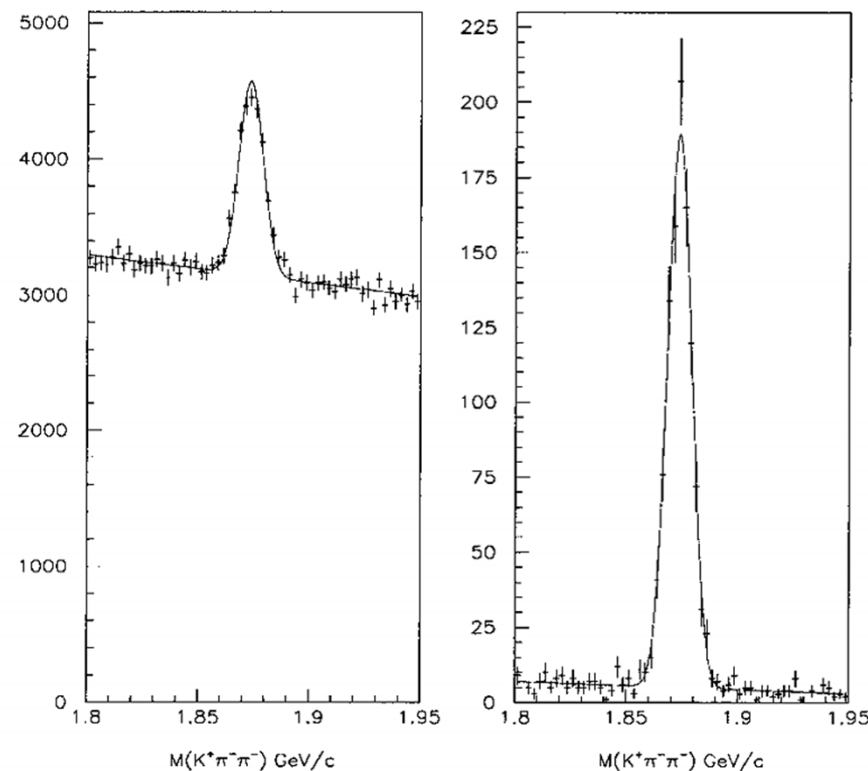


$$\Delta\theta \propto \frac{15}{P\beta} \sqrt{\frac{t}{X_0}}$$

$$\Delta X \propto \frac{r}{P\beta} \sqrt{\frac{t}{X_0}} \approx \frac{r}{P\beta} \sqrt{tZ^2\rho}$$

## Background suppression

### Before and After Vertex Cuts



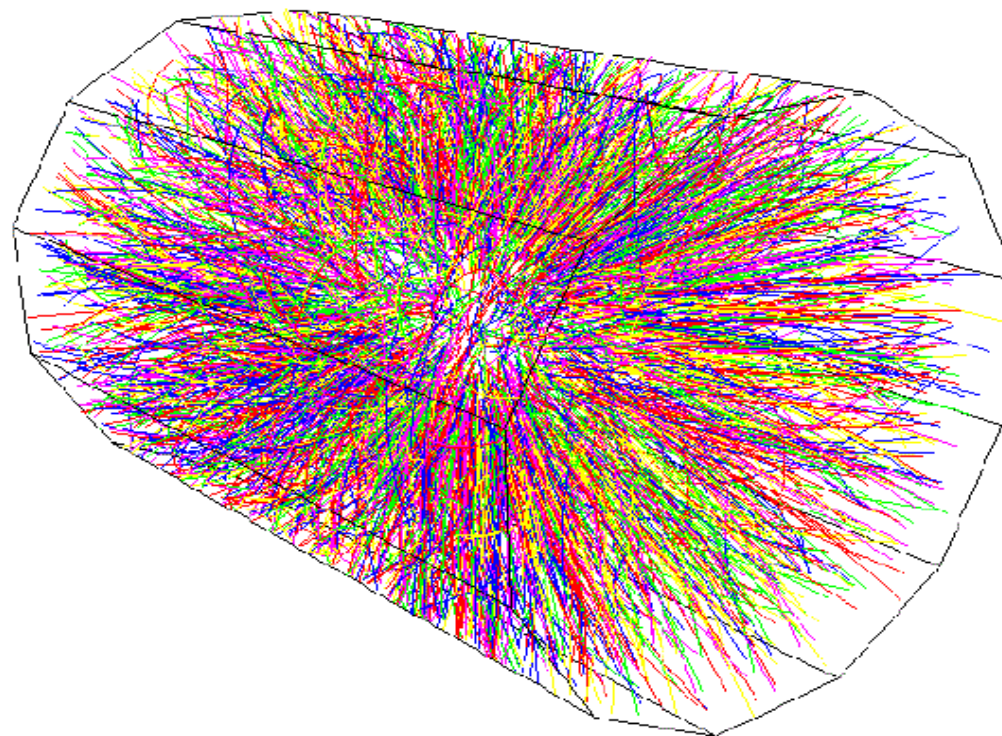
7 $\sigma$  vertex cut from beam spot.

## Extreme complexity of HE (Particle&Nuclear) Physics events

### Requirements:

- high granularity
- Reliability
- Cost!

**Silicon detectors are the only choice!**

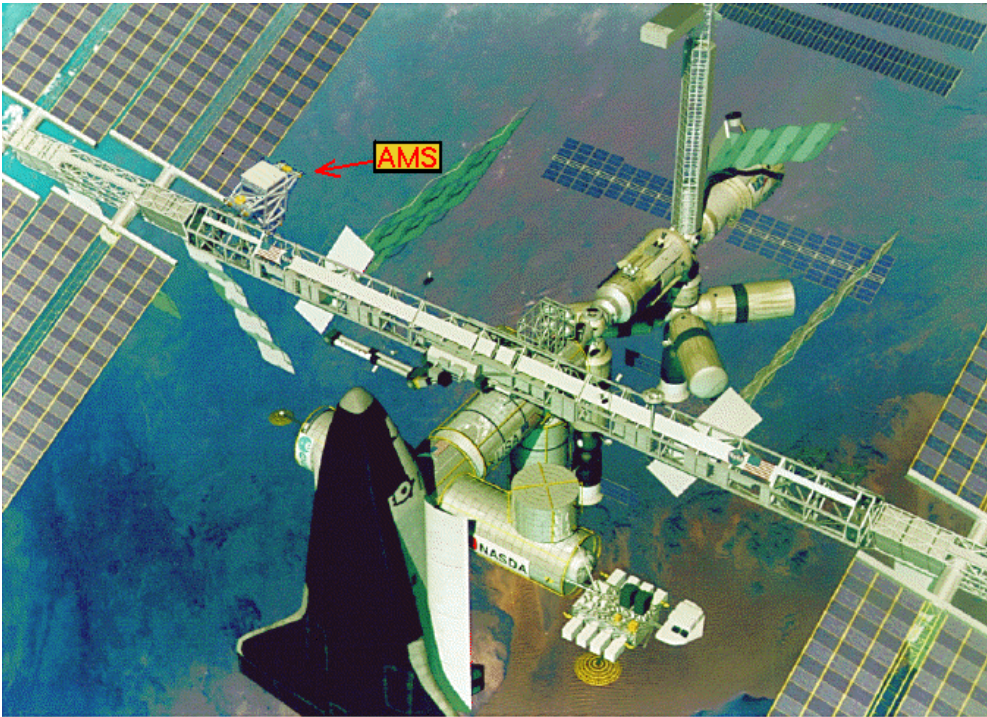


Geant-simulated Au - Au event (STAR)



## Physics motivation in astrophysics: space experiments

In space experiments, reliability and large system integration plays an essential role. Excellent performance (energy and spatial resolution, quantum efficiency) of new generation of silicon detectors allows exploration of new observation windows in astronomy and astrophysics.



International Space Station hosting AMS experiment:  
Dark Matter?



XMM-Newton: X-ray astronomy

# Physics motivation in medicine: radiography, X-ray tomography, SPECT and PET scanners.

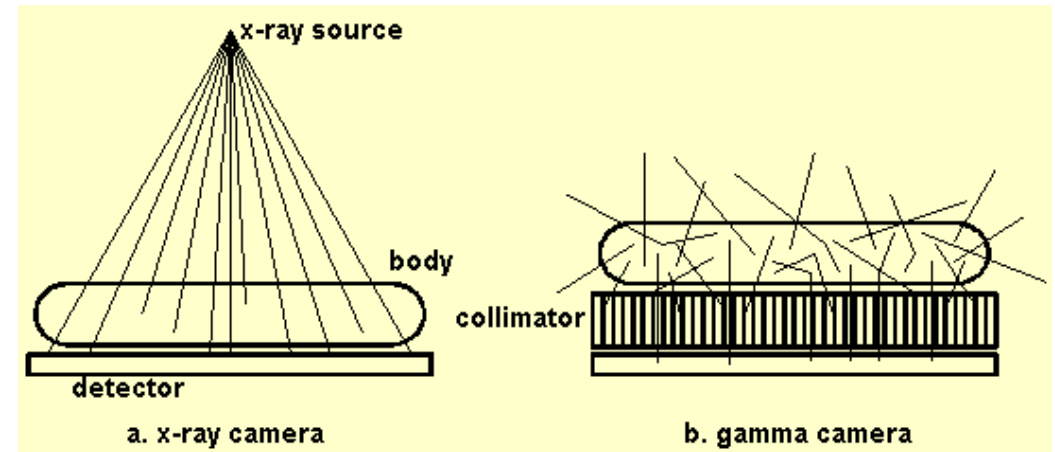
## High quality, fast&safe imaging, portable instruments

The x-ray camera images a projection of the body's density distribution and the pixel size is in the sub millimeter range.

Semiconductor x-ray imaging detectors step up the image quality and its content of information, or equivalently, they reduce the required radiation dose per image. The detectors can absorb and utilize most of the radiation without significant reduction of resolution.

The gamma camera images radioactive isotope distribution within the body. The effective pixel size is above 3 mm. The allowed radiation level and photon statistics determine the spatial resolution of the image.

Application of semiconductor detectors to gamma imaging enables design of portable systems. The detectors may somewhat improve the resolution and reduce blurring of scattered radiation. However, they need to be cost competitive with scintillator detectors in order to be widely used in gamma cameras.

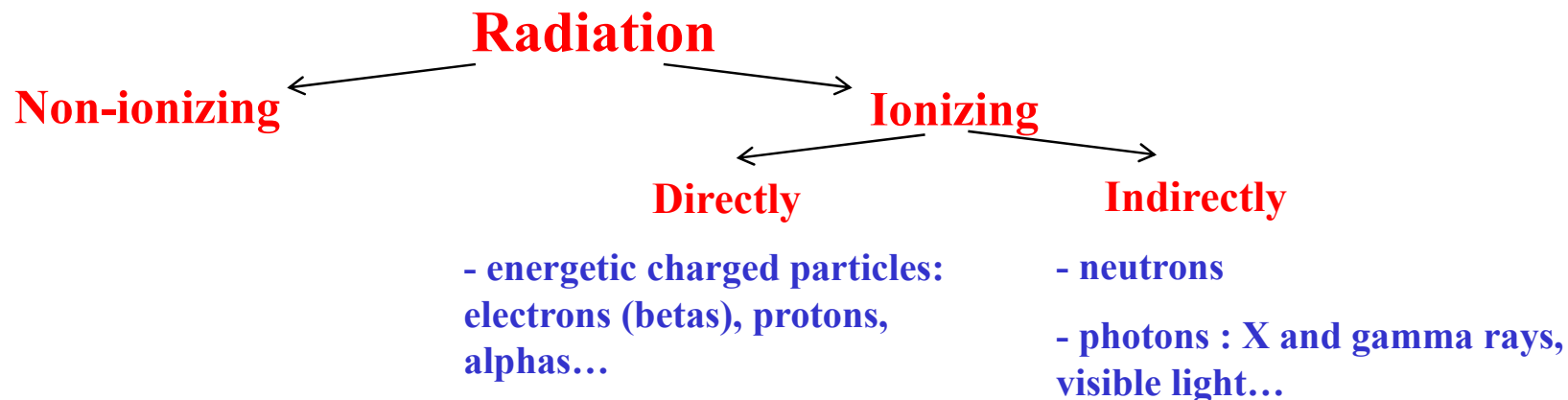


## The Generic Semiconductor Radiation Detector

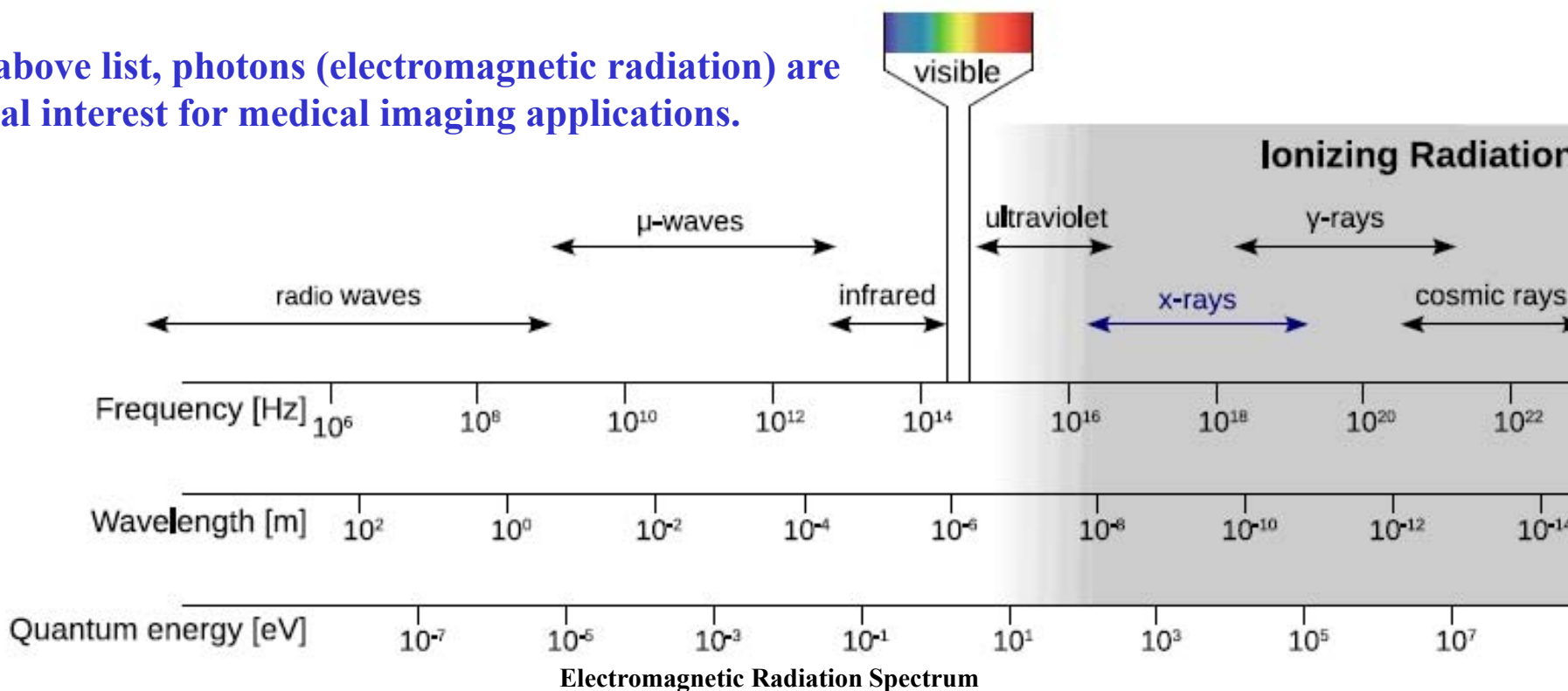
In general, the following steps must take place in the process of **Ionising Radiation** detection :

- **Radiation Interaction** with the detector active medium : transfer of a part of initial radiation energy to the detector (OR total absorption with total energy transfer).
- **Charge Carriers Creation** inside detector : effective use of absorbed energy.
- Efficient **Charge Carriers Transport** across detector volume using internal electric field : useful signal (electric current pulse) generation.
- **Amplification and processing** of a primary signal with the help of an (external) electronic circuits : interface with data acquisition/storage system.

In consequence, good ionising radiation detector should optimise all above steps...



Out of above list, photons (electromagnetic radiation) are of special interest for medical imaging applications.



## Radiation Interaction

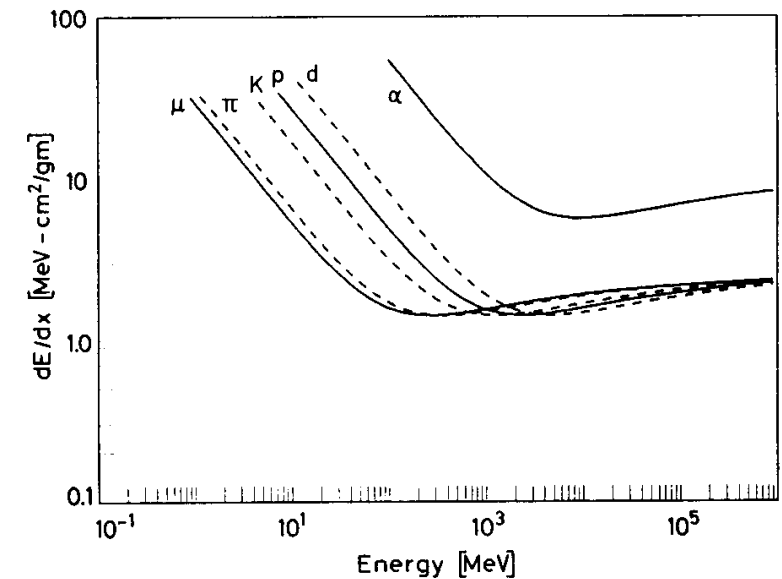
Charged particles : inelastic collisions with the atomic electrons of the material : the Bethe-Bloch Formula. The stopping power

$dE/dx \sim z^2 \rho(Z/A)/\beta^2$  where  $z$  is a particle charge;  $\rho$ ,  $Z$ ,  $A$  are a density, atomic number and atomic weight of absorbing material,  $\beta=v/c$  is the particle velocity

Neutrons : nuclear reaction with the production of charged secondary particles

Photons : Photoelectric Effect, Compton Scattering, Pair Production

In the case of photons, the most ‘wanted’ is a Photoelectric Effect, because in this case totality of incoming energy is transferred to detector medium in a relatively small volume ( $\sim 10 \mu\text{m}$  diameter)



The stopping power  $dE/dx$  as function of energy for different particles

## The Interaction of Photons

The probability of gamma or x-ray photon interaction with a detector material of atomic number  $Z$  is proportional to  $Z^n$  ( $4 < n < 5$ ) for photoelectric interaction,  $Z$  for Compton scattering and  $Z^2$  for pair production.

$$I(x) = I_0 e^{-\mu x}$$

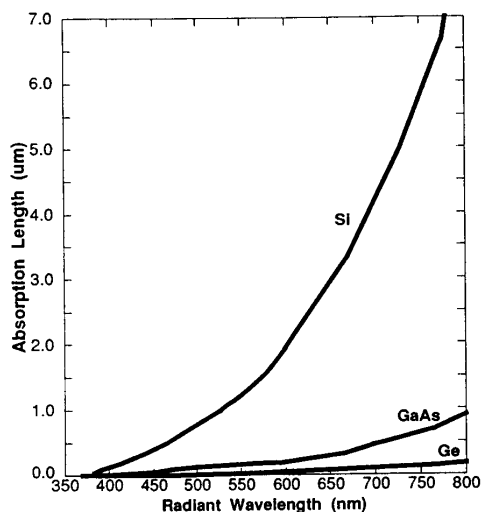
Where :

$I$  : photon flux

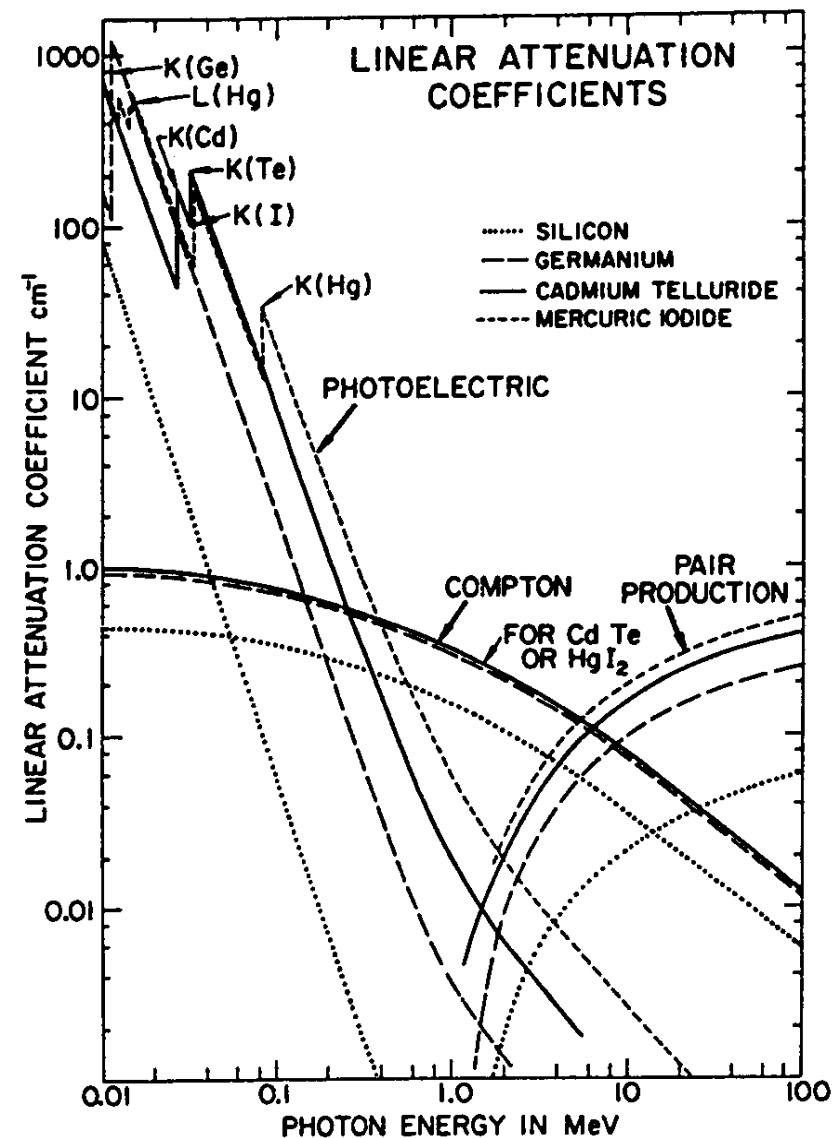
$x$  : absorber thickness

$\mu$  : linear attenuation coefficient

$l = 1/\mu$  : absorption length



Absorption length in Si, GaAs and Ge for visible light range.



Linear attenuation coefficient in silicon, germanium, cadmium telluride and mercuric iodide

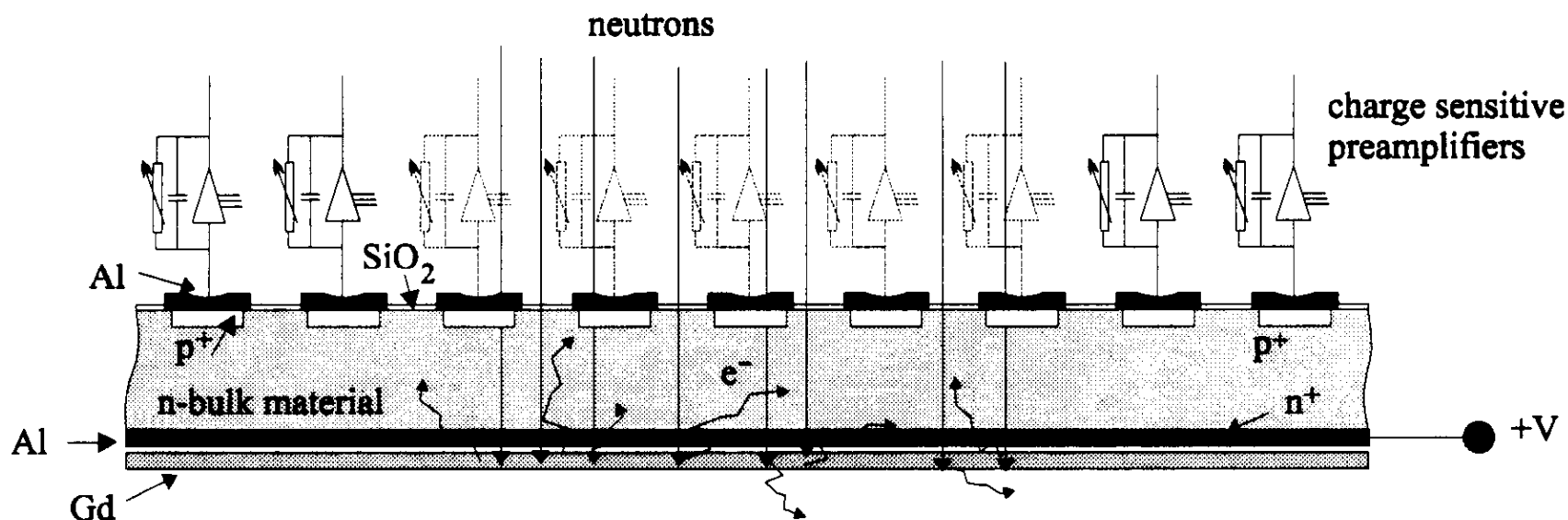
## The Interaction of (slow) Neutrons

Neutrons are detected through nuclear reactions which result in energetic particles as protons, alpha particles, recoil nucleus, fission fragments. The most popular reaction for the conversion of slow neutrons into directly detectable particle is the  $^{10}\text{B}(n,\alpha)$  reaction:



Another method is to use neutron capture reaction (by gadolinium, vanadium, rhodium...), leading to a beta-active isotope.

**Neutron elastic scattering on (light) nuclei in case of fast neutrons (e.g. scattering on polyethylene foil):**



## Charge Carriers Creation

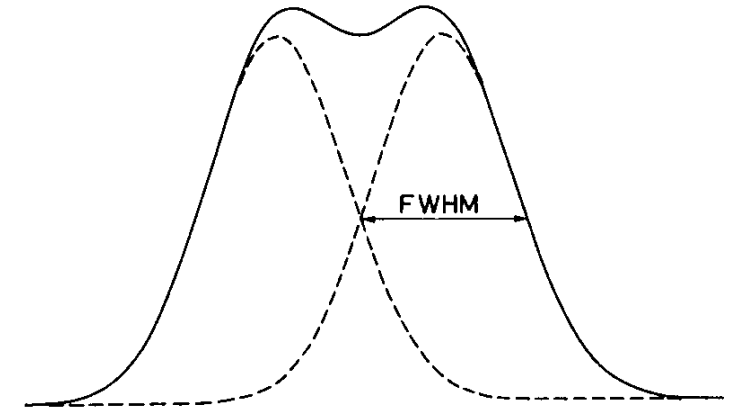
The number of charge carriers created inside detector active volume after absorption of energy  $E$  depends on the material parameter  $w$ , which is an average energy needed for creation of one pair of charge carriers.

$$N = E/w$$

The intrinsic energy resolution:

$$R = 2.35 \frac{\Delta N}{N} = 2.35 \sqrt{\frac{Fw}{E}}$$

where  $F$  is the **Fano Factor** (on the order of 0.12 in silicon)



Definition of energy resolution



## Charge Carriers Transport

Free charge carriers in semiconductor are mobile. **Drift** is movement of carriers due to an electric field :

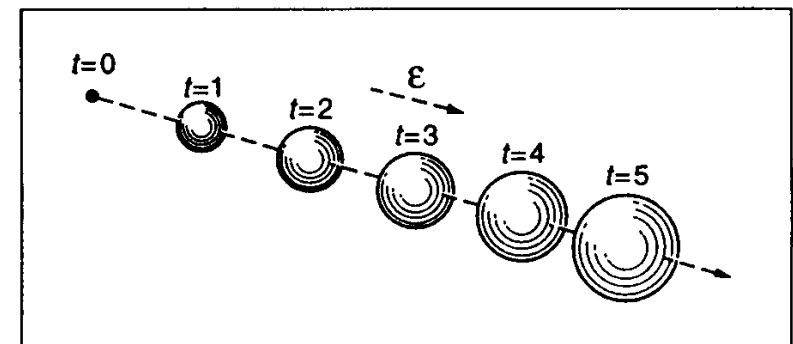
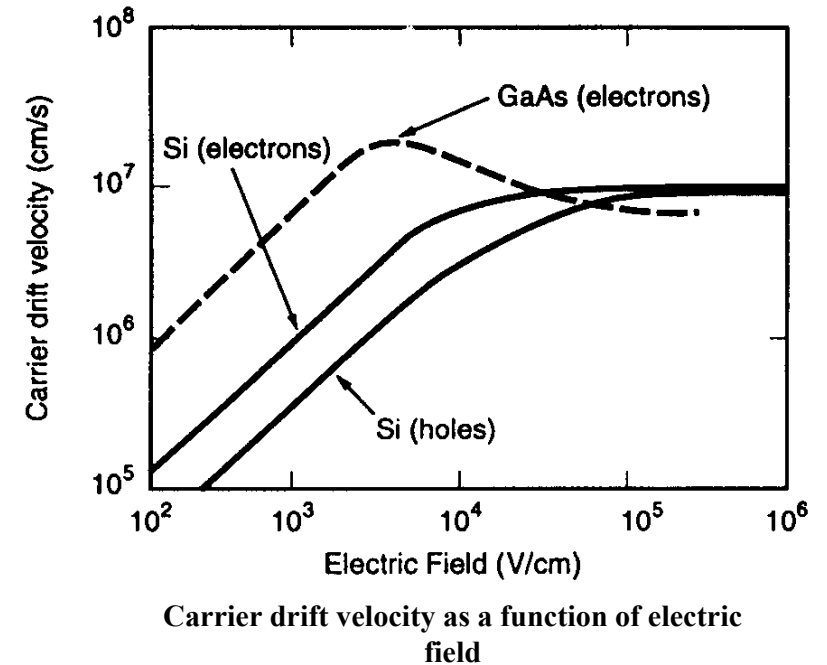
$$\vec{V}_d = \vec{E}\mu$$

where  $\mu$  is mobility. Mobility depends on temperature, impurity concentration and (for higher E values) on E.

**Diffusion** is random thermal motion : the RMS radius of charge distribution increases as the square root of a drift time :

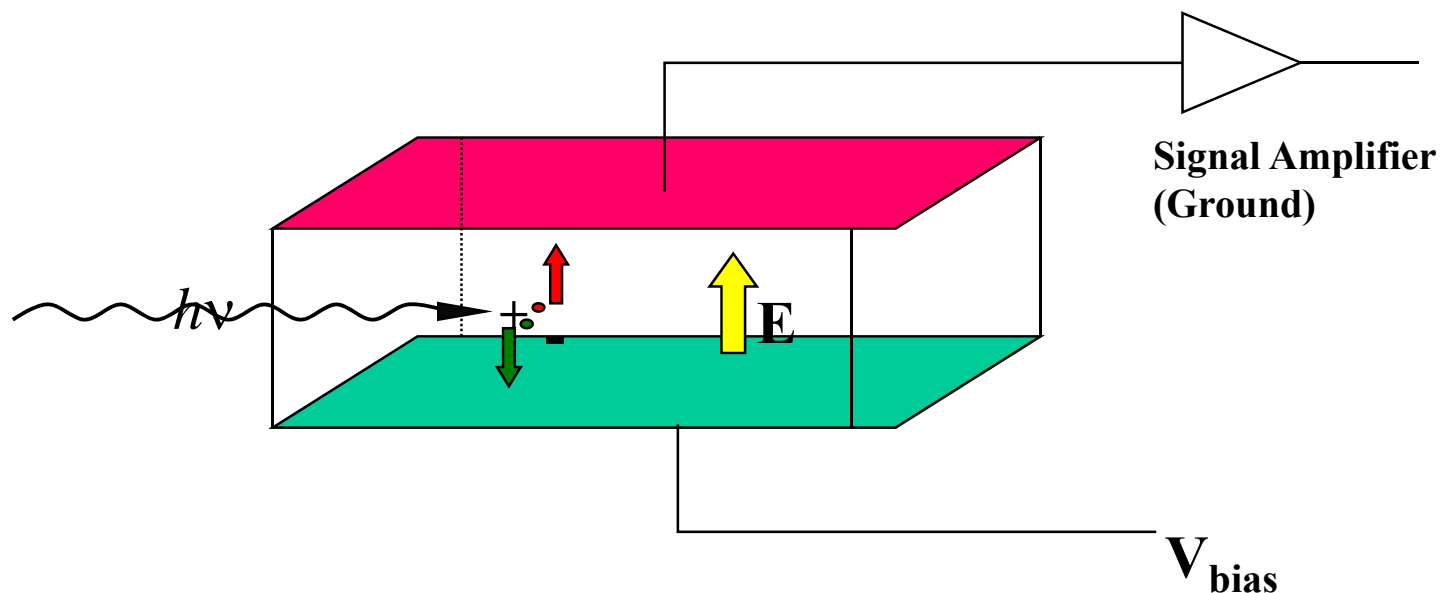
$$\sigma = \sqrt{2Dt}$$

where  $D = kT\mu/q_e$ .



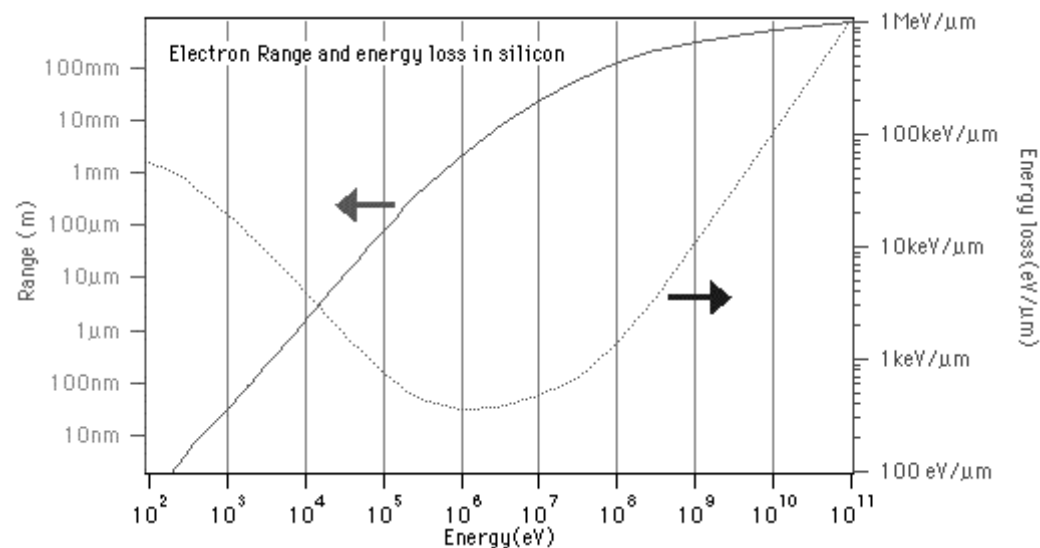
Combined drift and diffusion of initially compact charge cluster

## The Generic Semiconductor Radiation Detector

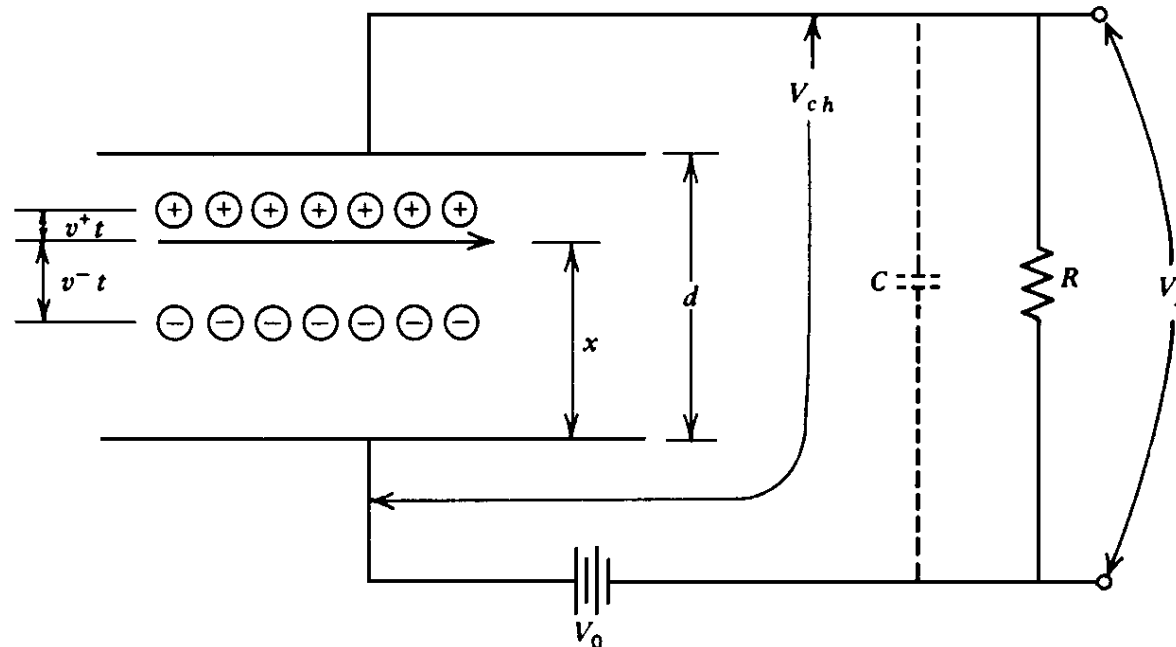


### Shape of a Radiation-Generated Cloud

- Visible and UV light: single e-h pair
- X-Rays: “point” interaction,  $N_{e-h} = E_X / 3.6 \text{ eV}$
- $\alpha$  particle: short, dense track (Bragg curve)
- $\beta$  radiation: low density (close to MIP), scattered path
- High-energy particles: uniform low density track (MIP)
- Non-relativistic charged particle:  $dE/dX \sim z^2/E$



## Derivation of a pulse shape from an ion chamber (1)



**Original stored energy = Energy absorbed by ions + Energy absorbed by electrons + Remaining stored energy**

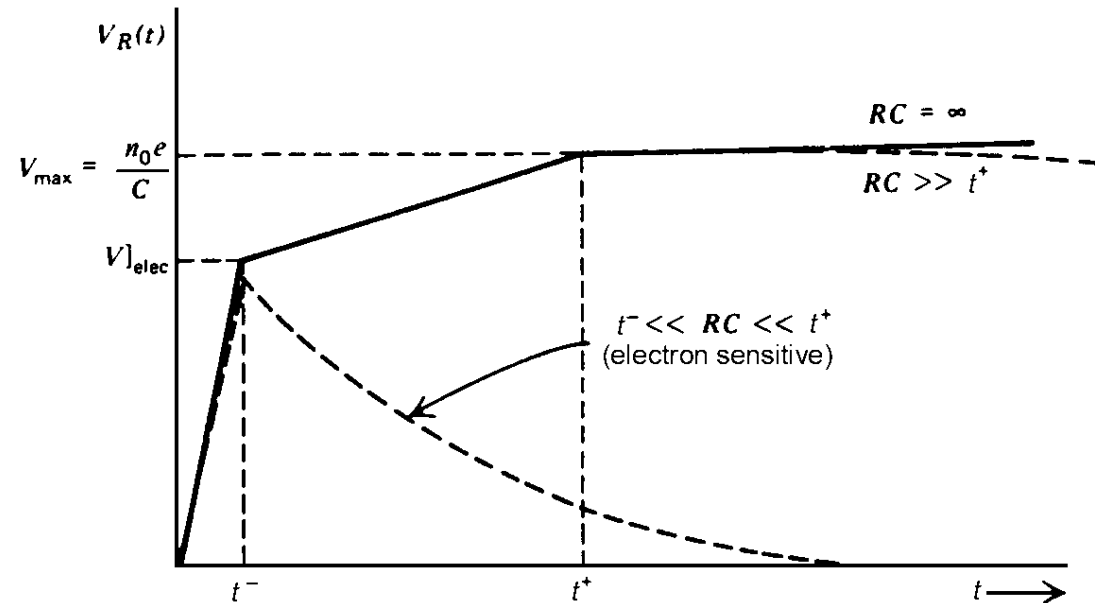
$$(1/2) CV_0^2 = n_0eEv^+t + n_0eEv^-t + (1/2) CV_{ch}^2 \quad (E \text{ is an electric field})$$

$$(1/2) C(V_0^2 - V_{ch}^2) = n_0eE(v^+ + v^-)t$$

$$(1/2) C(V_0 + V_{ch})(V_0 - V_{ch}) = n_0e(V_{ch}/d)(v^+ + v^-)t$$

**Approximations:**  $(V_0 - V_{ch}) = V_R$ ,  $(V_0 + V_{ch}) = 2V_0$ ,  $(V_{ch}/d) = (V_0/d)$

## Derivation of a pulse shape from an ion chamber (2)



$$(1/2) C(2V_0)V_R = n_0e(V_0/d)(v^+ + v^-)t$$

$$V_R = (n_0e/dC)(v^+ + v^-)t$$

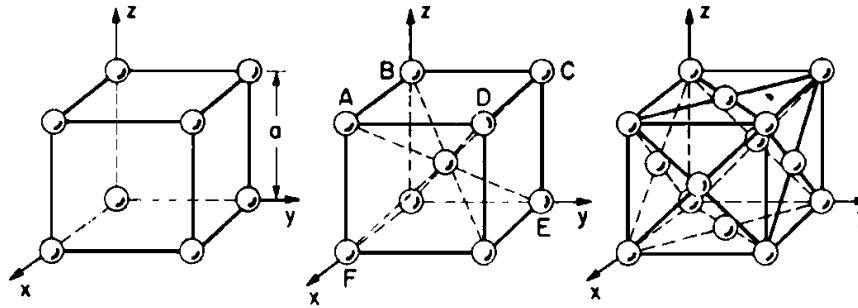
After a time of  $t^- = x/v^-$ , the electrons reach the anode  $\implies V_R = (n_0e/dC)(v^+t + x)$

After a time of  $t^+ = (d - x)/v^+$ , the ions reach the anode  $\implies V_R = (n_0e/dC)[(d - x) + x]$

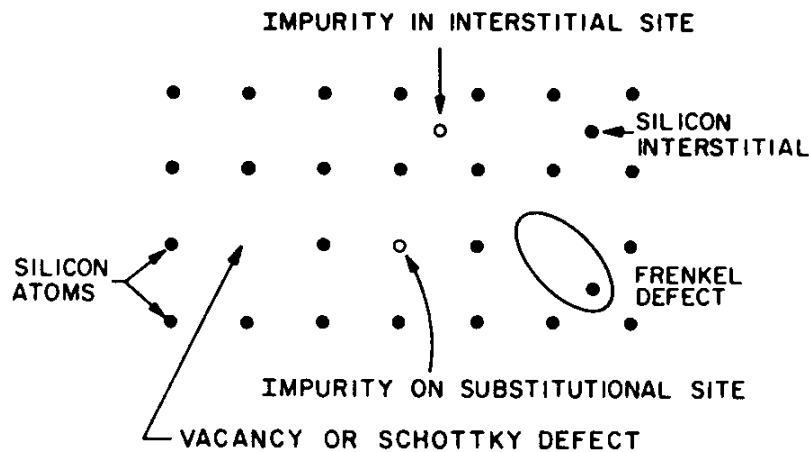
Or: 
$$V_R = n_0e/C = Q/C$$

General case of a current induced in segmented detector : **Ramo's Theorem** (see later)

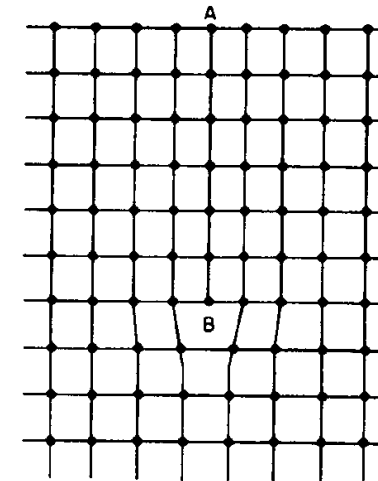
## Physics and Properties of Semiconductors: **crystal structure**



Three cubic-crystal unit cells. (a) Simple cubic.  
(b) Body-centered cubic. (c) Face-centered cubic

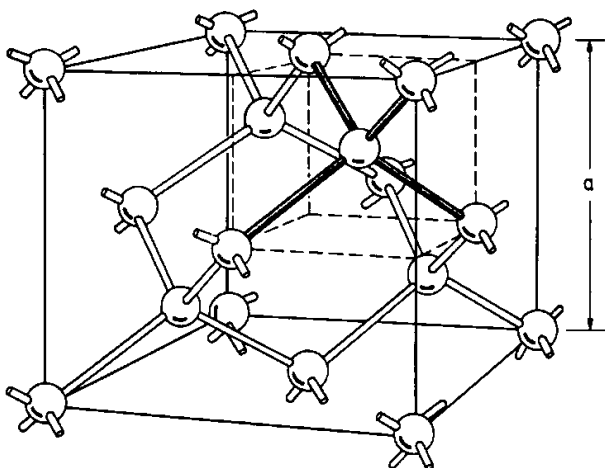


The location and types of point defects in a simple lattice

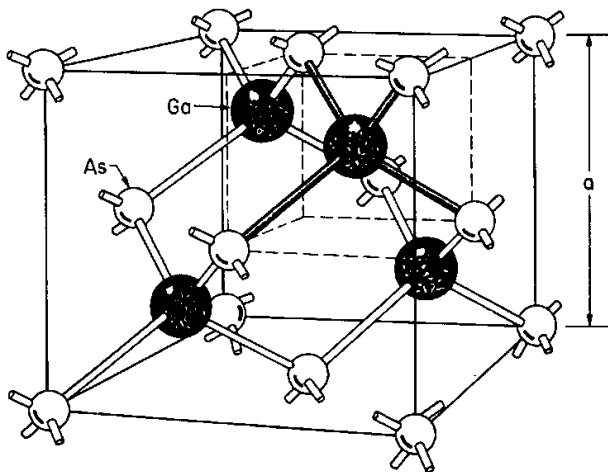


An edge dislocation in a cubic lattice  
created by an extra plane of atoms

## Physics and Properties of Semiconductors: **valence bonds**



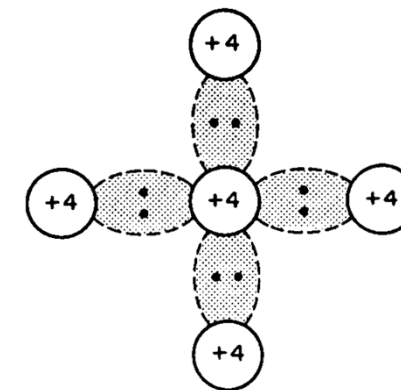
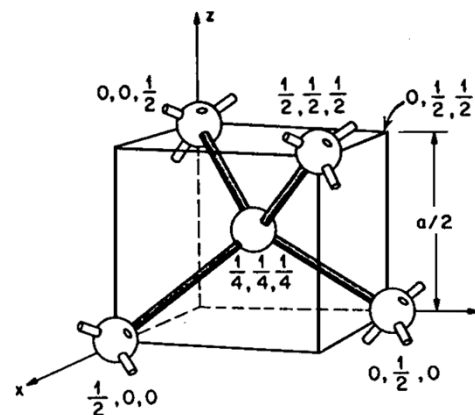
(a)



(b)

a). Diamond lattice (germanium, silicon)

b). Zincblende lattice (GaAs) (a is the lattice constant)



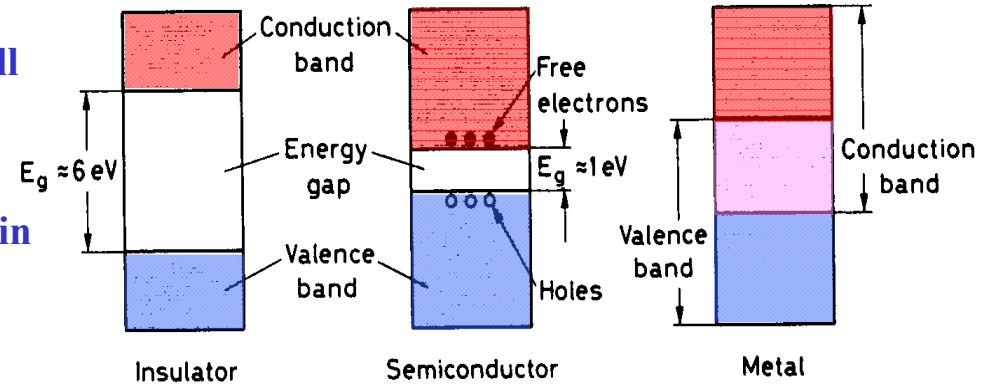
(a) A tetrahedron bond. (b) Schematic two-dimensional representation of a tetrahedron bond.

## Physics and Properties of Semiconductors: **energy bands**

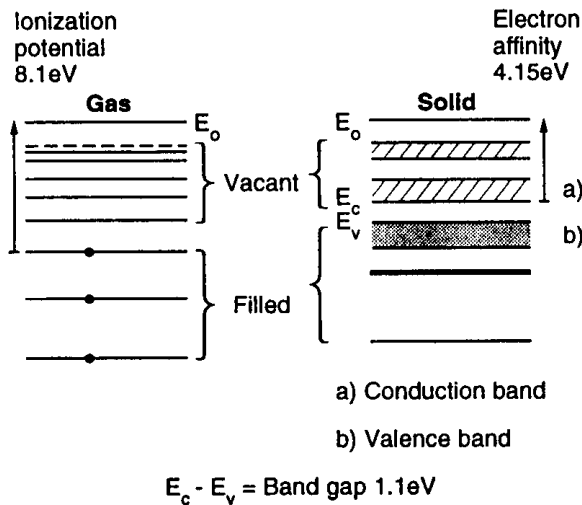
Semiconductors are crystalline materials whose outer shell atomic levels exhibit an **energy band structure**: a **valence band**, a “forbidden” **energy gap** and **conduction band**.

Electrons in the valence band are tightly bound and remain associated to their respective lattice atoms.

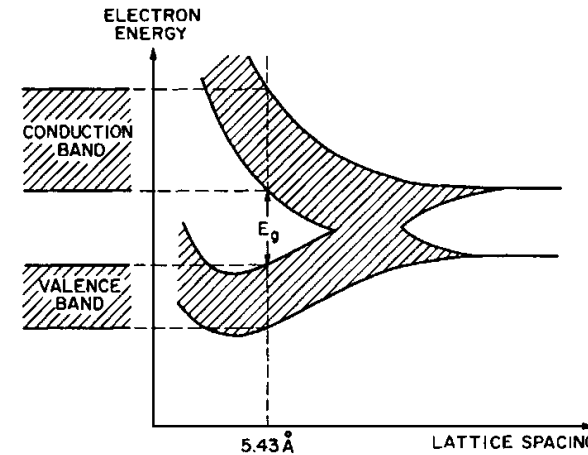
Electrons in the conduction band are detached from their parent atoms and are free to move across the crystal.



Energy band structure of conductors, insulators and semiconductors



Allowed energy levels in gaseous silicon which become energy bands in the solid material]



Formation of energy bands as a diamond lattice crystal is formed by bringing together isolated silicon atoms

## Charge Carriers in Semiconductor : **Intrinsic Material**

Probability of occupation by an electron of a given state is given by Fermi-Dirac statistics :

$$f(E) = 1/(1+\exp(E-E_f)/kT)$$

**Fermi level**  $E_f$  is the energy at which the probability is one-half. For energy levels which are at least a few  $kT$  units above or below the Fermi level ( $kT=0.026$  eV at room temperature) :

$$f(E) = \exp(-(E-E_f)/kT) ; \text{ for } E > E_f$$

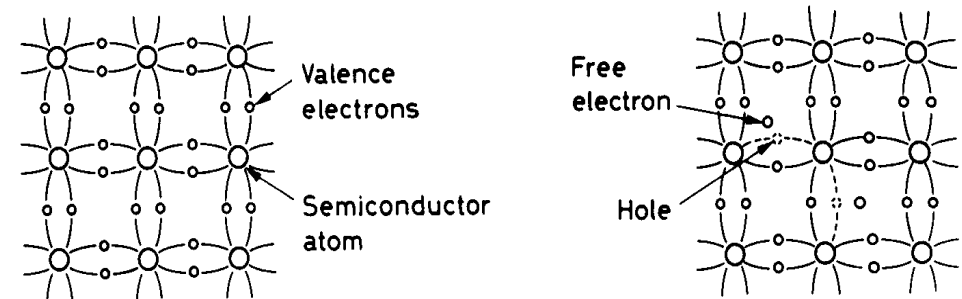
$$f(E) = 1 - \exp(-(E_f-E)/kT) ; \text{ for } E < E_f$$

The charge carriers concentration :

$$n = N_C \exp(-(E-E_f)/kT) \text{ (electrons)}$$

$$p = N_V \exp(-(E_f-E)/kT) \text{ (holes)}$$

where  $N_C$  and  $N_V$  (both  $\sim T^{3/2}$ ) are effective density of states



Covalent bonding of silicon : at 0 K, all electrons participate in bonding (left), at higher temperature some bonds are broken by thermal energy leaving a hole in the valence band (right)



## Charge Carriers in Semiconductor : **Intrinsic Material**

For intrinsic semiconductors :  $n=p=n_i$  and

$$E_f = E_i = (E_c + E_v)/2 + kT/2 \ln(N_v/N_c)$$

(Fermi level close to middle of the gap)

Also :

$$pn = N_v N_c \exp(-E_g/kT) ; \text{ where } E_g = E_c - E_v$$

and :

$$n_i \sim T^{3/2} \exp(-E_g/2kT)$$

The current density :

$$\mathbf{J} = d_c \mathbf{v} = en_i(\mu_e + \mu_h)\mathbf{E} ; \text{ where } d_c \text{ is charge density,}$$

$\mathbf{v}$  velocity and  $\mu$  mobility

**intrinsic material resistivity :  $\rho = 1 / en_i(\mu_e + \mu_h)$**

**For silicon in room temperature :**

$$n_i \sim 1.5 \cdot 10^{10}$$

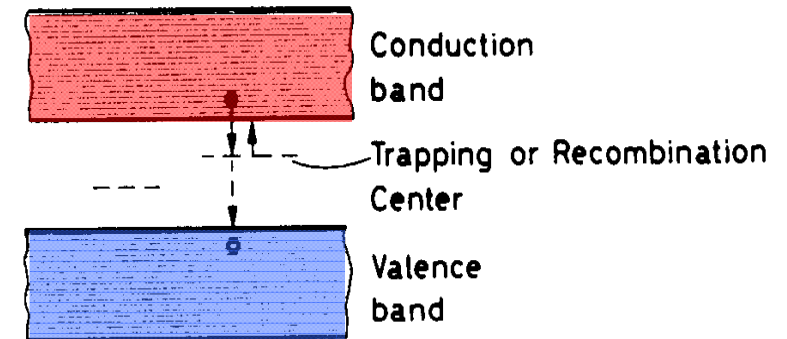
**Only 1 in  $10^{12}$  atoms is ionised!**

**For silicon in room temperature :**

$$\rho = 230 \text{ k}\Omega \text{ cm}$$

## Recombination and Trapping

An electron may recombine with a hole by dropping from the conduction band into an open level in the valence band. Direct recombination is very rare : the most important mechanism is through **recombination centers** resulting from **impurities** in crystals. A second effect which arises from impurities is **trapping**. In both cases the **lifetime** of charge carriers is degraded. In principle, this lifetime should be much longer comparing to collection time. In addition to impurities, crystal structural defects in the lattice like point effects (vacancies, interstitials) or dislocation may also give rise to similar states in the forbidden band. Unlike wanted impurities (dopants), recombination and trapping centers produce deep levels (far from conduction or valence band).



Recombination and trapping sites in the forbidden energy gap

**Semiconductor detectors require relatively pure crystals. For large volume detectors, in particular, impurity concentration cannot be more than  $\sim 10^{10}$  per  $\text{cm}^3$**

## Doped Semiconductors

**Doping** : introduction of small amount of impurity atoms having one more (or one less) electron in their outer atomic shell. These impurities integrate themselves into crystal lattice to create so called **extrinsic** semiconductors. The energy levels created by an extra (missing) electron are extremely close to conduction (valence) band. Therefore, at normal temperature, all this levels are excited (filled) creating a free electron (hole).

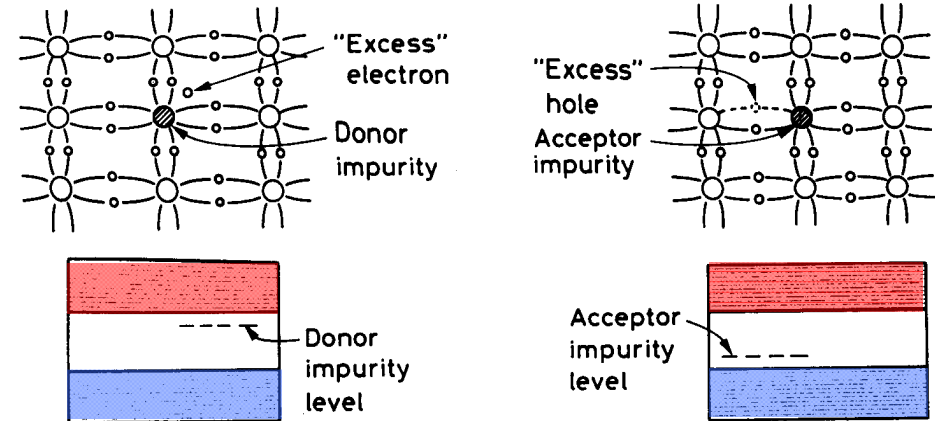
Low off mass action when in thermal equilibrium :  
 $np = n_i^2 = AT^3 \exp(-E_g/kT)$

Also :  $N_D + p = N_A + n$  ; where  $N_D$  and  $N_A$  are donor and acceptor concentration

In n-type material where  $N_A=0$  and  $n \gg p$  :

$n = N_D$  and  $p = n_i^2 / N_D$  (also  $\rho = 1 / e N_D \mu_e$ )

where  $n$  and  $p$  is majority and minority carrier concentration



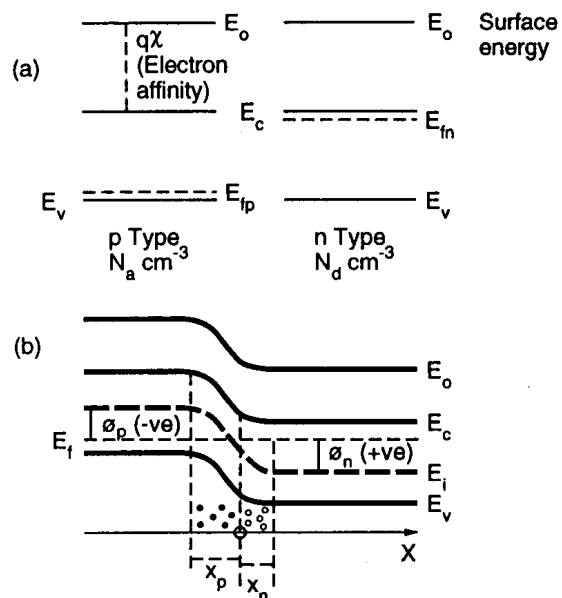
Donor impurities (to form n-type semiconductor) add excess electrons. Acceptor impurities (to form p-type semiconductor) add excess of holes

	Li	Sb	P	As	Bi
Energy level (eV)	0.033	0.039	0.044	0.049	0.069
Energy level (eV)	0.045	0.057	0.065	0.16	0.26
	B	Al	Ga	In	Tl

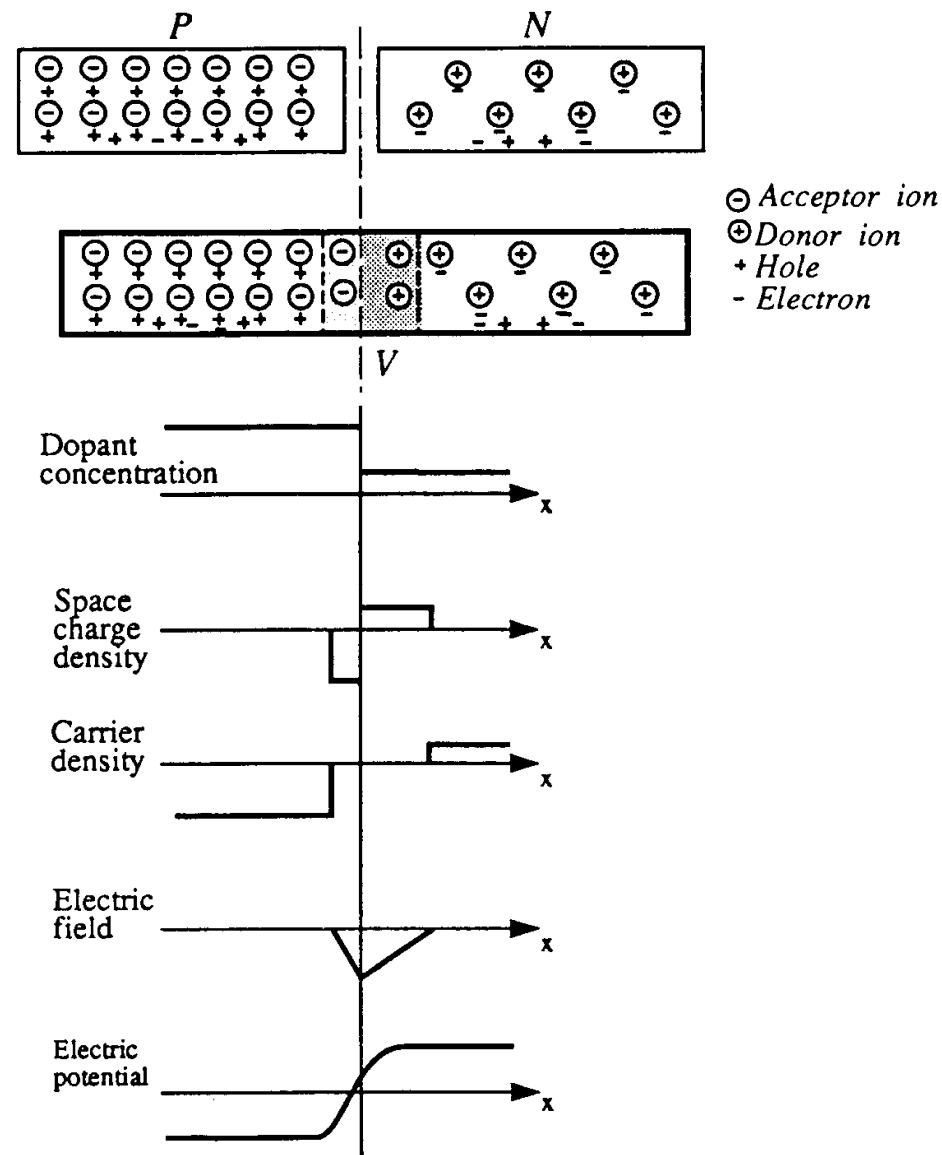
Energy levels within the band gap corresponding to various n- and p-type dopants

## The p-n Junction

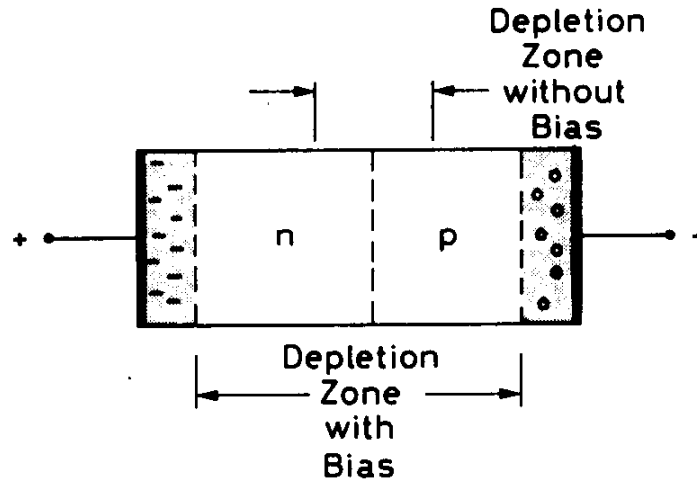
Two crystals of opposite type are brought together : a **depletion layer** is formed on either side of junction.



(a) Energy levels in two electrically isolated silicon samples (of p- and n-type). (b) When in contact, the Fermi level is constant throughout the material. The band edges bend in accordance with the space charge generated



## Reversed Bias Junction

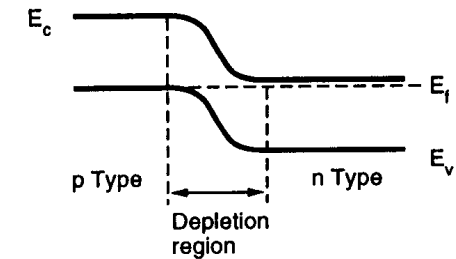


If one side of a p-n junction is more heavily doped than the other, which is usually the case, than the **depletion zone** will extend farther into lighter-doped side. For example, if  $N_A \gg N_D$ , then the depletion zone is almost entirely on the n-side of the junction. The total width of depletion zone in that case is :

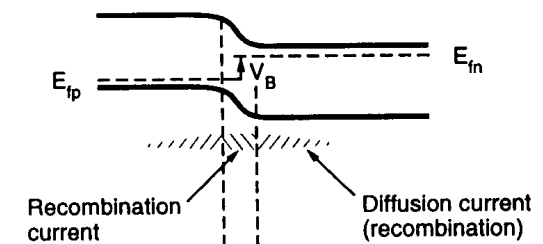
$$d \cong \sqrt{\frac{2\epsilon(V_0 + V_{bias})}{eN_D}} \cong \sqrt{2\epsilon\rho_n\mu_e V_{bias}}$$

Also Junction Capacity  $\sim (\rho_n V_{bias})^{-1/2}$

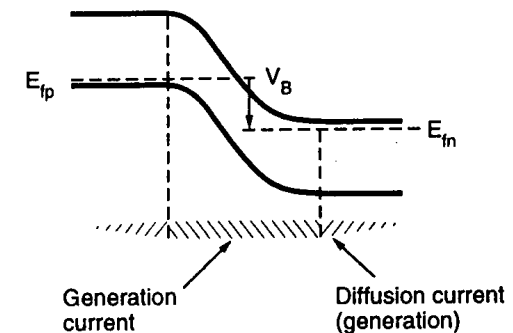
(a)  $V_B = 0$



(b)  $V_B = 0.6 \text{ V}$



(c)  $V_B = -1.2 \text{ V}$



Effect of an applied voltage across the semiconductor junction

## Choice of detector material

Many parameters should be taken into account :

- **type of ionising radiation** to be detected, in particular **energy range** in the case of photons
- **type of work to be done** : spectroscopy, imaging, both ...
- **in the case of imaging** : simple counting or also energy measurements
- **total area/volume/segmentation (number of channels)**
- **system aspects** : room or cryogenic temperature
- **radiation damage**
- **availability and price of the material**

## Choice of detector material

Material	Z	$E_g$ [eV]	w [eV]	$\mu_c$ [cm <sup>2</sup> /Vs]	$\mu_h$ [cm <sup>2</sup> /Vs]	$\tau_c$ [s]	$\tau_h$ [s]	$\epsilon$	$\rho$ [g/cm <sup>3</sup> ]
C (diamond)	6	5.4	13.2	1800	1200	10 <sup>-8</sup>	<10 <sup>-8</sup>	5.5	3.51
Si	12	1.12	3.61	1350	480	>10 <sup>-3</sup>	2 10 <sup>-3</sup>	11.7	2.33
Ge	32	0.67	2.98	3900	1900	>10 <sup>-3</sup>	10 <sup>-3</sup>	16	5.33
GaAs	32	1.42	4.70	8500	450	10 <sup>-8</sup>	10 <sup>-7</sup>	12.8	5.32
CdTe	50	1.56	4.43	1050	100	3 10 <sup>-6</sup>	2 10 <sup>-6</sup>	11	6.2
CdZnTe		1.5-2.2	5	1350	120	10 <sup>-6</sup>	5 10 <sup>-8</sup>		6
HgI <sub>2</sub>	54	2.13	4.20	100	4	10 <sup>-6</sup>	10 <sup>-5</sup>	8.8	6.4
a-Si	12	1.8	4	1	0.005	7 10 <sup>-9</sup>	4 10 <sup>-6</sup>	11.7	2.3
a-Se	34	2.3	7	0.005	0.14	10 <sup>-6</sup>	10 <sup>-6</sup>	6.6	4.3

There are many others: SiC, TlBr, InP...

## Semiconductor choice for radiation detectors in practice:

- **Silicon:** tracking in particle physics, soft X-ray spectroscopy and imaging in astronomy (space) and in material science, medical imaging
- **Germanium:**  $\gamma$  spectroscopy in nuclear physics
- **CdTe (room temperature):** hard X-ray spectroscopy in space, medical imaging
- **Diamond (polycrystalline CVD):** extreme radiation hardness (Beam Condition Monitor at LHC)
- **AsGa, HgI<sub>2</sub>:** ???

### Choice of detector material for tracker : **silicon!**

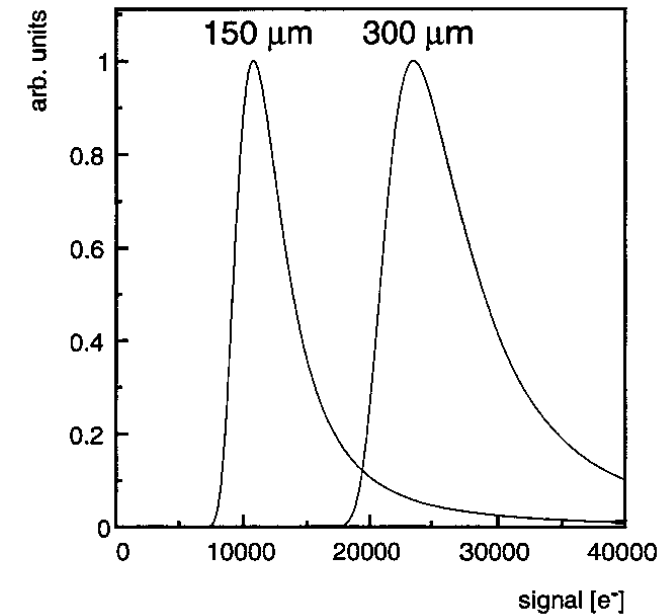
Bethe-Bloch equation applied for silicon and for minimum-ionising particles ( $\gamma \sim 3.5$ ) gives:

$$dE/dx = 39 \text{ keV}/100\mu\text{m}$$

-an energy deposition of  $\sim 3.6 \text{ eV}$  will produce an e-h pair in silicon

-minimum-ionising particle will produce  $\sim 10\,000$  e-h pairs traversing  $100 \mu\text{m}$  of silicon

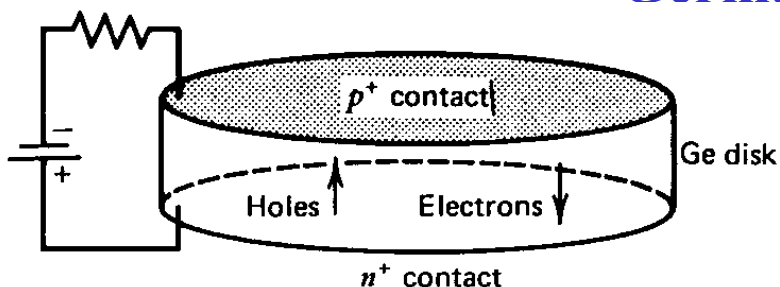
- because of Landau fluctuation :  $E_{\text{peak}} \sim 7300$  e-h pairs per  $100 \mu\text{m}$  of silicon



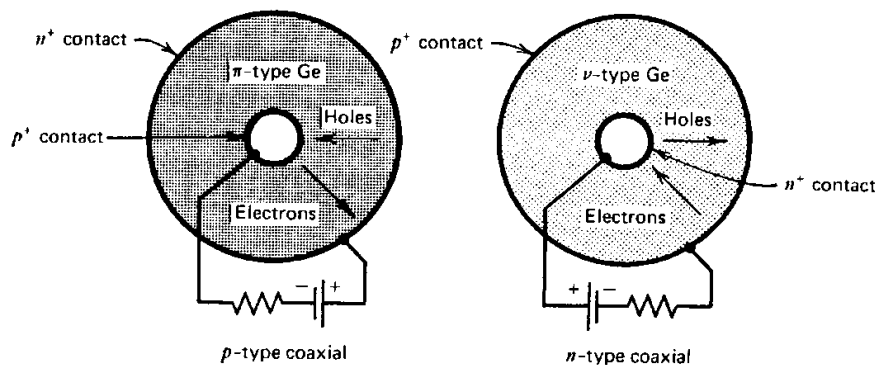
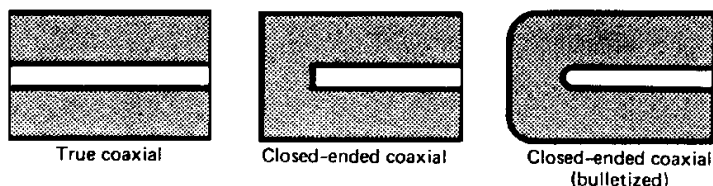
Landau distribution (calculated) for a  $300\mu\text{m}$  and a  $150\mu\text{m}$  thick silicon detector.



## Germanium Gamma-Ray Detectors



Configuration of a planar HPGe detector. The Ge semiconductor may be  $\nu$  type ( $p^+$  contact is rectifying),  $\pi$  type ( $n^+$  contact is rectifying), or lithium drifted.



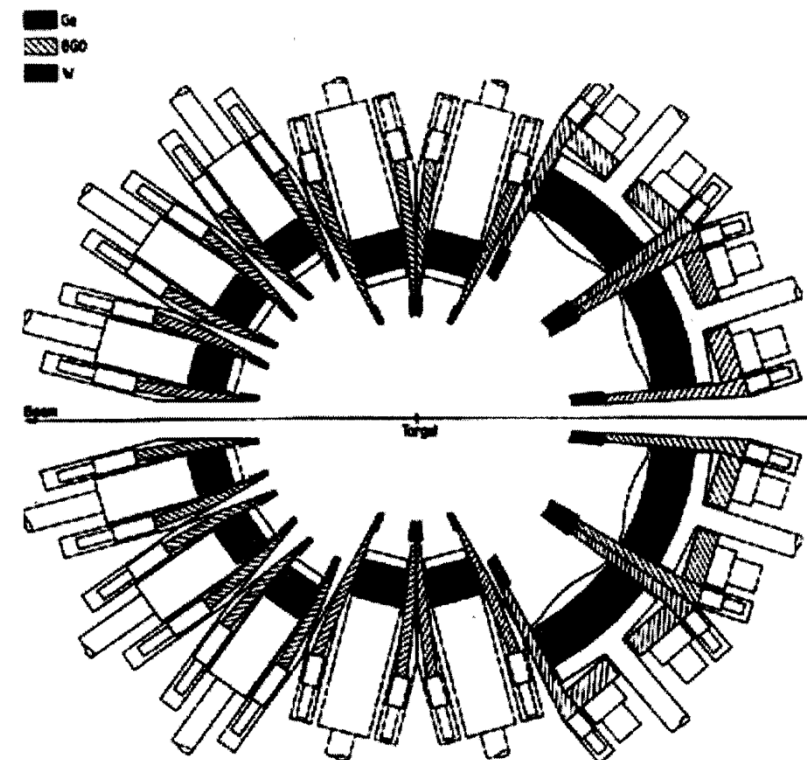
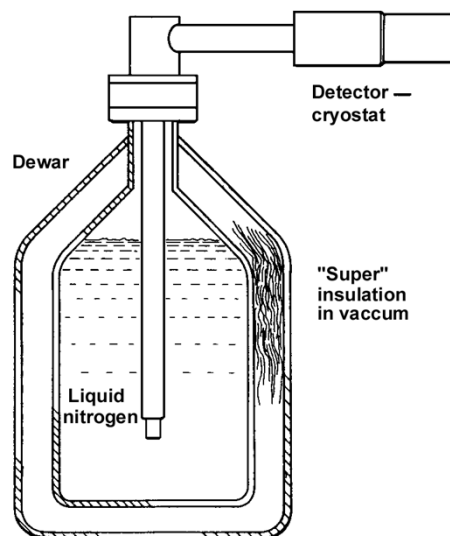
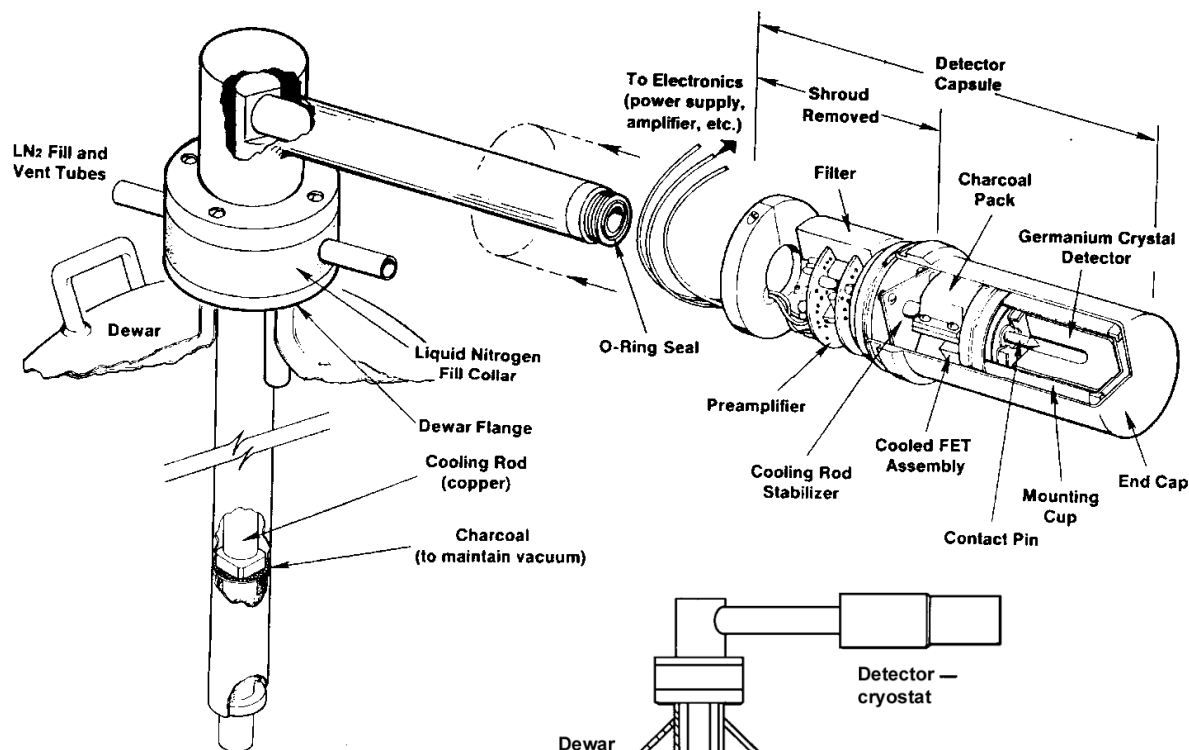
The three common shapes of a large-volume coaxial detectors..



HP-Ge crystal diameter ~10 cm (2000)

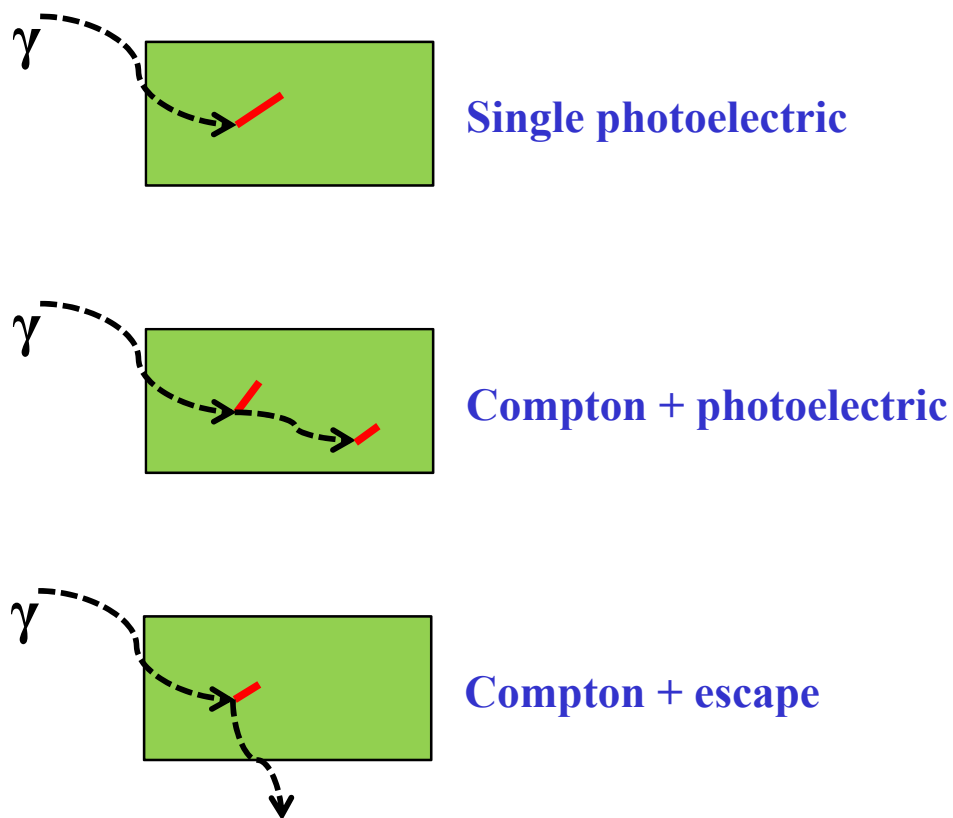
# HPGe detector within its vacuum capsule and liquid nitrogen cooling system

**Impurity concentration:  $10^9 < N_d [cm^{-3}] < 5 \cdot 10^9$**

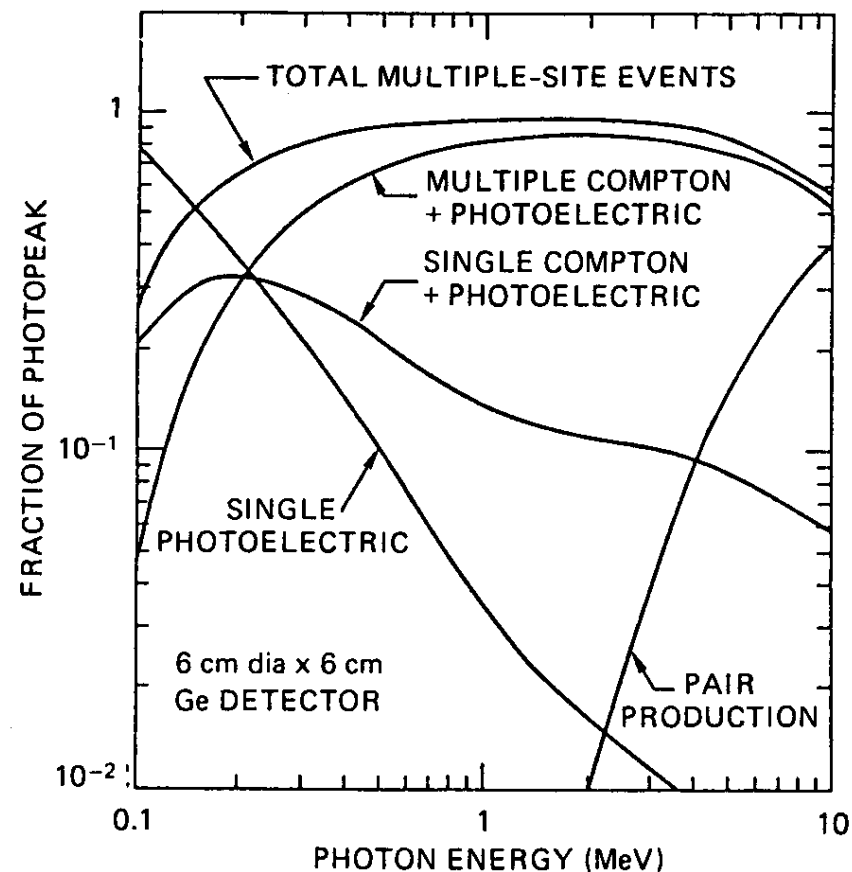


**$\gamma$ -detector array EUROBALL (239 Ge detectors):  
solution for complicated multi-photon  
spectroscopy**

## Gamma-ray spectroscopy with germanium detectors



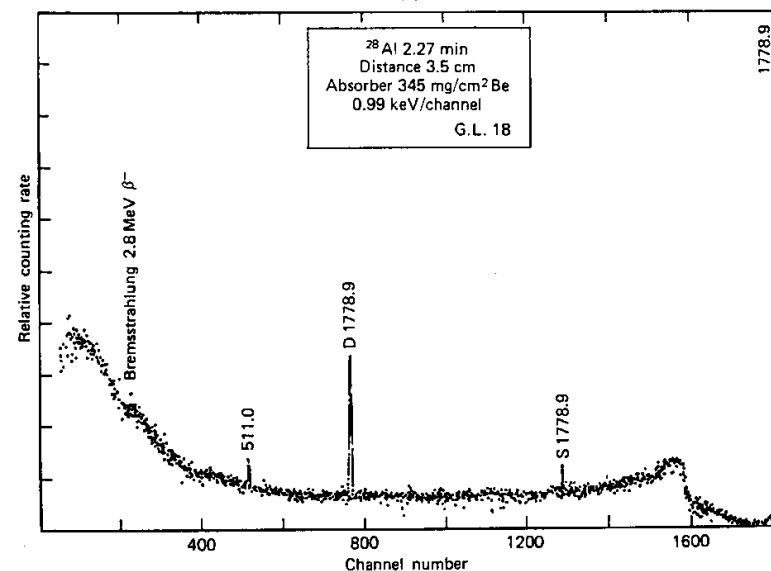
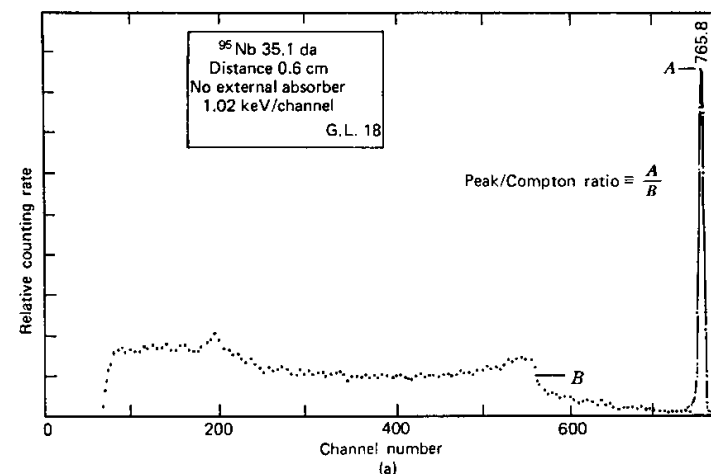
### Possible gamma-ray absorption ways



Predicted fraction of the full-energy peak contributed by different energy loss mechanisms in a 6cm x 6cm coaxial HPGe detector.

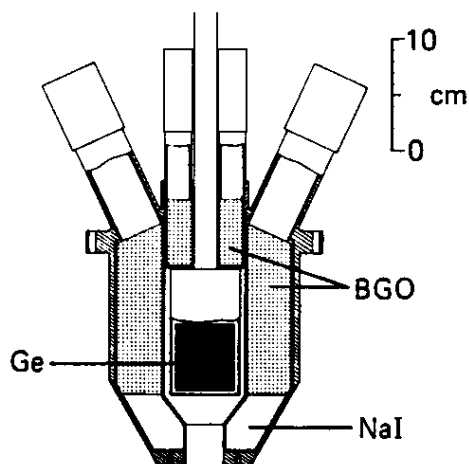
## Detector factors of merit for gamma-ray spectroscopy

- energy resolution  
( $\Delta E/E$ , FWHM,  $\sigma_E$ )
- peak/Compton ratio

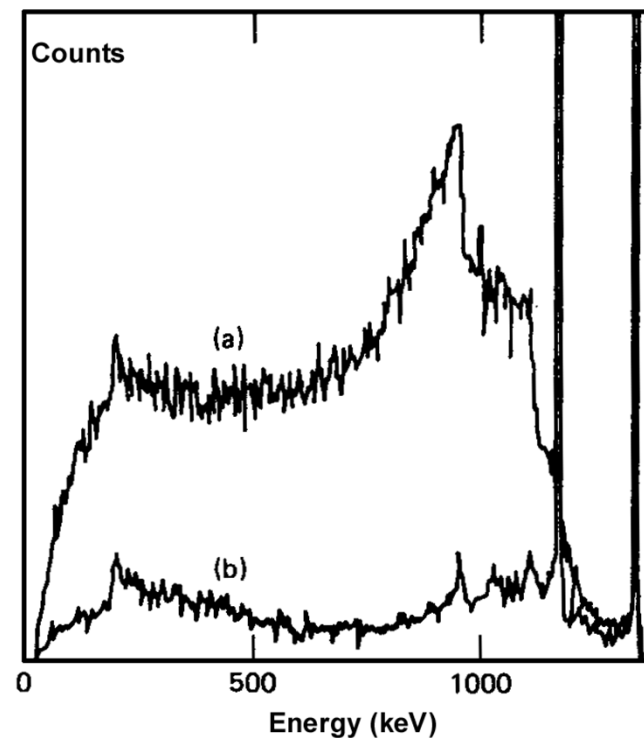


Measured pulse height spectra for monoenergetic gamma rays from a  $18 \text{ cm}^3$  Ge(Li) detector. The full-energy peak, Compton continuum, single and double escape peak as well as a 511 keV peak from annihilation photons in surrounding materials are visible.

## Compton rejection by anticoincidence

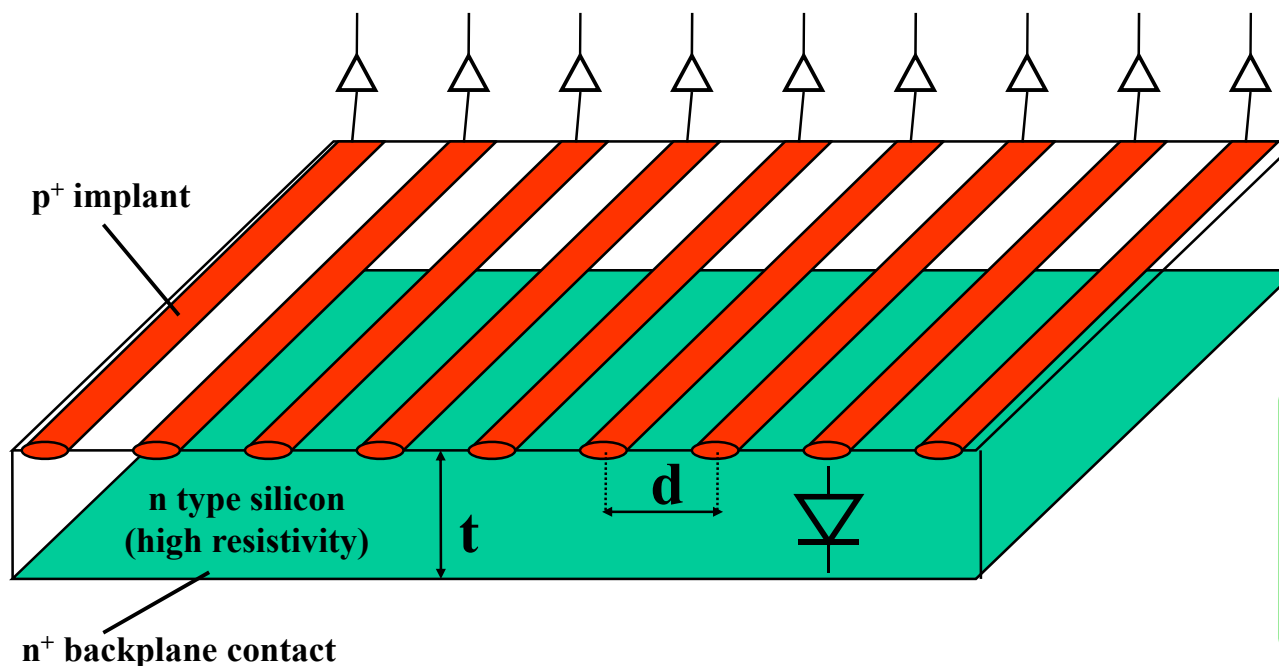


An example of a germanium detector surrounded by a Compton suppression system made up of NaI(Tl) and BGO scintillators.



Pulse height spectra from a  $^{60}\text{Co}$  gamma-source using the system shown at the left. (a) Normal spectrum. (b) Spectrum recorded in anticoincidence with the scintillation detectors, showing the suppression of the Compton continuum.

## Semiconductor Position Sensitive Detectors: Single Sided Microstrip Detector



**To be measured:**  
- hit position  
- signal amplitude

### Single sided microstrip detector

Typical parameters :  $t \sim 300 \mu\text{m}$ ,  $d \sim 50 \mu\text{m}$ , size  $\sim 10 \times 10 \text{ cm}$

**Spatial Resolution is the Factor of Merit :**

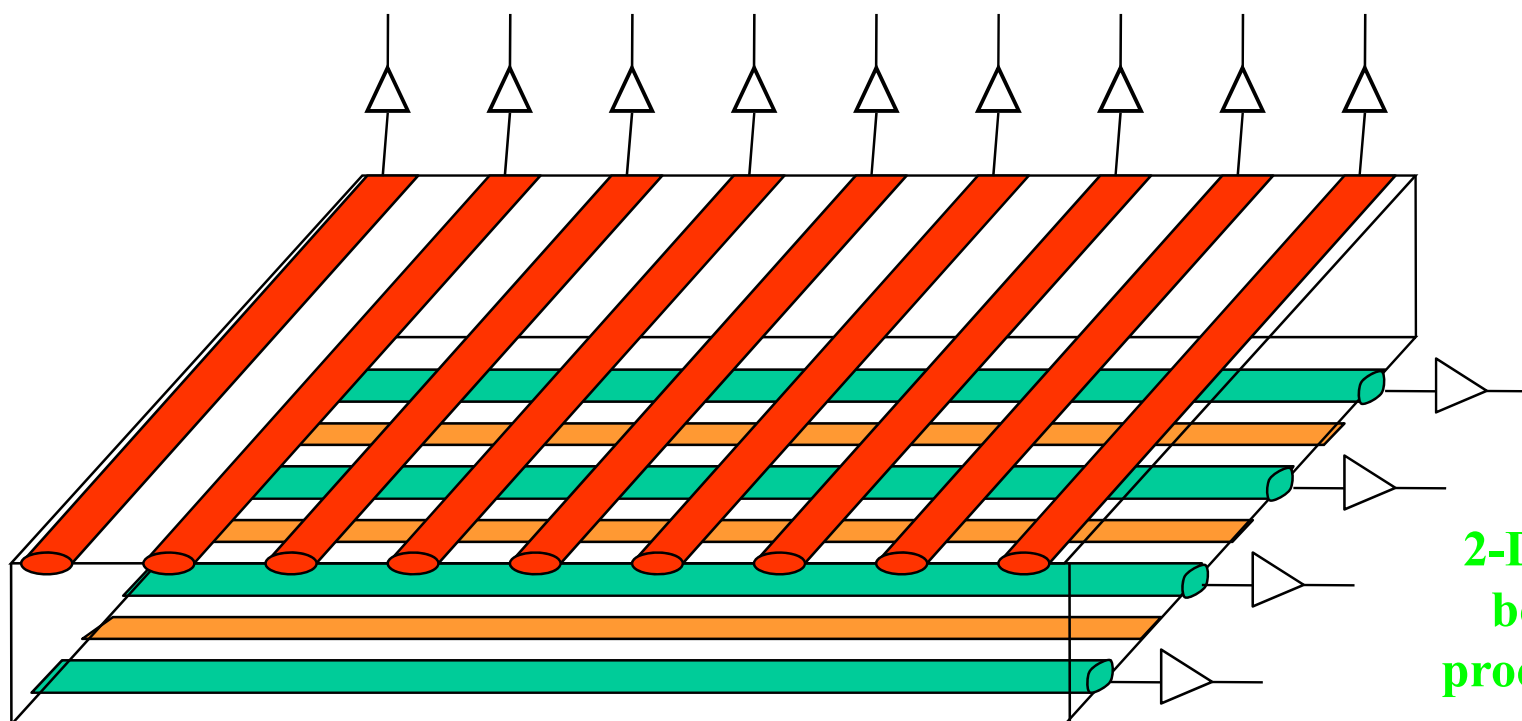
**$\sigma = 1.3 \mu\text{m}$  has been demonstrated**

$$\sigma \approx d / \sqrt{12}$$

$$\sigma \sim d/2 (S/N)^{-1}$$

If analog readout

## Semiconductor Position Sensitive Detectors: Double Sided Microstrip Detector



**2-D Information, but  
both sides must be  
processed and read out**

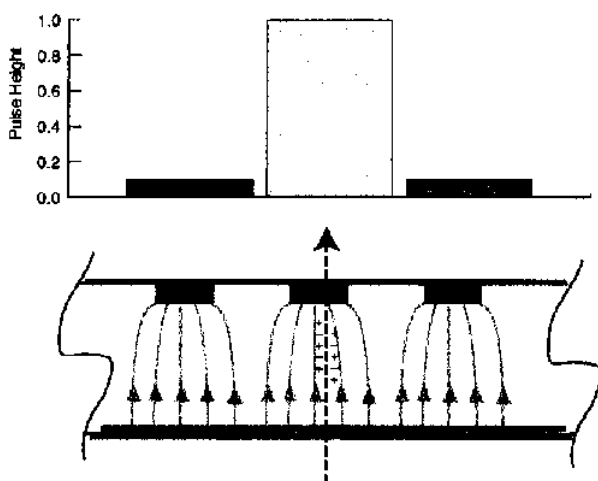
**Problem of n-strips  
isolation!**

**Problem with multihits!**

## Hit resolution

The position resolution will depend on how many strips the charge is deposited on

One Strip Clusters

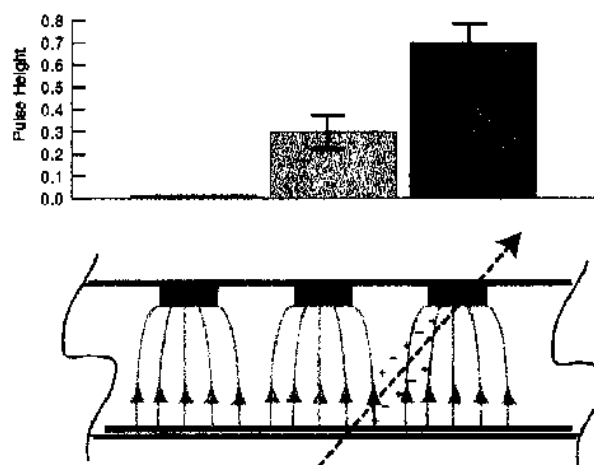


For 1 strip clusters the resolution is simply:

$$\sigma_{hit} = \frac{\Delta}{\sqrt{12}}$$

Where  $\Delta$  is the strip pitch

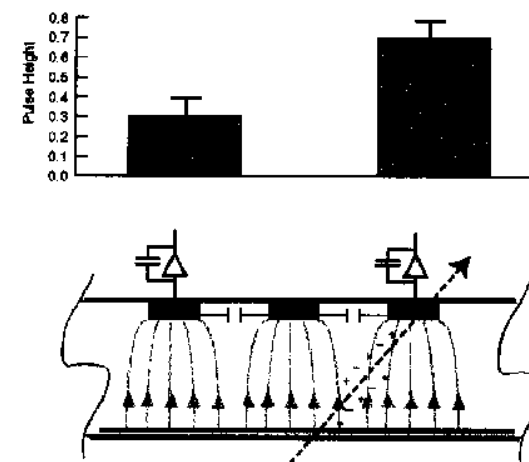
Two Strip Clusters



For 2 strip clusters the centroid calculation gives the resolution of :

$$\sigma_{hit} \propto \frac{\Delta \text{ Noise}}{2 \text{ Signal}}$$

Floating Strips



Because of capacitive coupling between strips, we don't need to readout every strip to maintain good position resolution, BUT, because of stray capacitance to the back plane, some charge from the floating strip can be lost, causing problems.



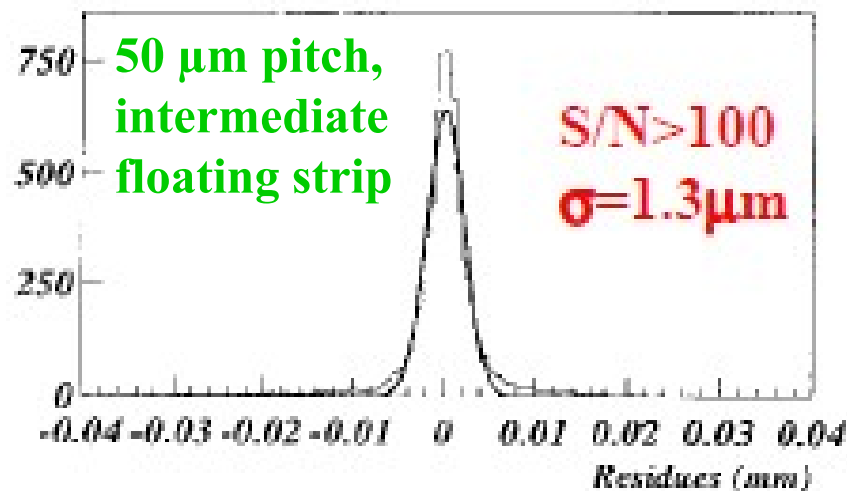
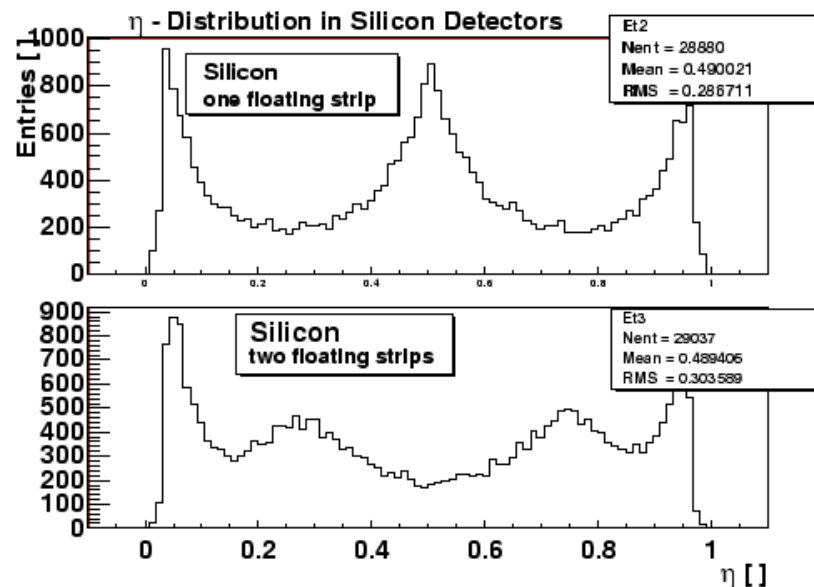
## Hit spatial resolution : signal processing (interpolation)

“ $\eta$ ” algorithm  
(two strip clusters)

$$\eta = \frac{Q_l}{Q_l + Q_r}$$

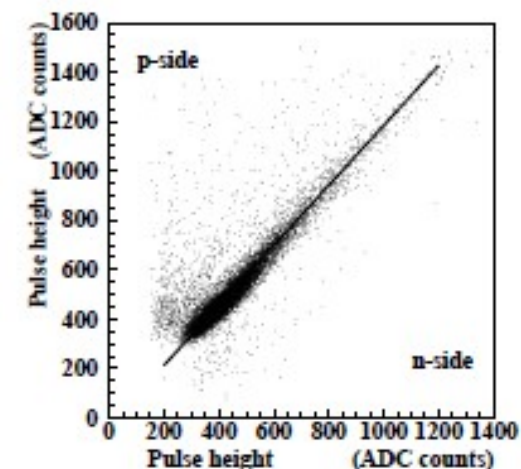
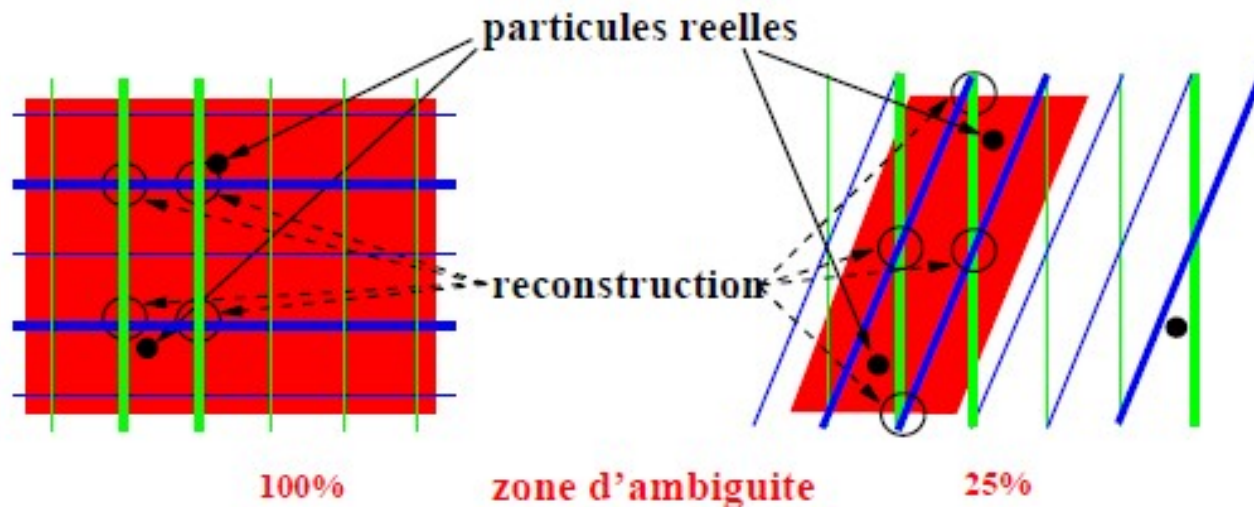
Hit position:

$$x_0 = \frac{1}{N_{tot}} \int_0^{\eta_0} \frac{dN}{d\eta} d\eta$$



Single plane resolution

## Track reconstruction with strip detectors - problem of ambiguities



Example of ALICE detector  
(4.2x7.6 cm) : 15 tracks/detector.  
Even with stereo angle of  $2^\circ$   
(pretty poor resolution in one  
direction) there is still 26%  
remaining ambiguous tracks

Some of ambiguities can be  
resolved by charge matching  
(double-sided detectors)

**The only radical solution :  
pixels!**

## Semiconductor Position Sensitive Detectors: Hybrid Pixel Detector

A pixel detector is a single sided detector segmented in both directions.

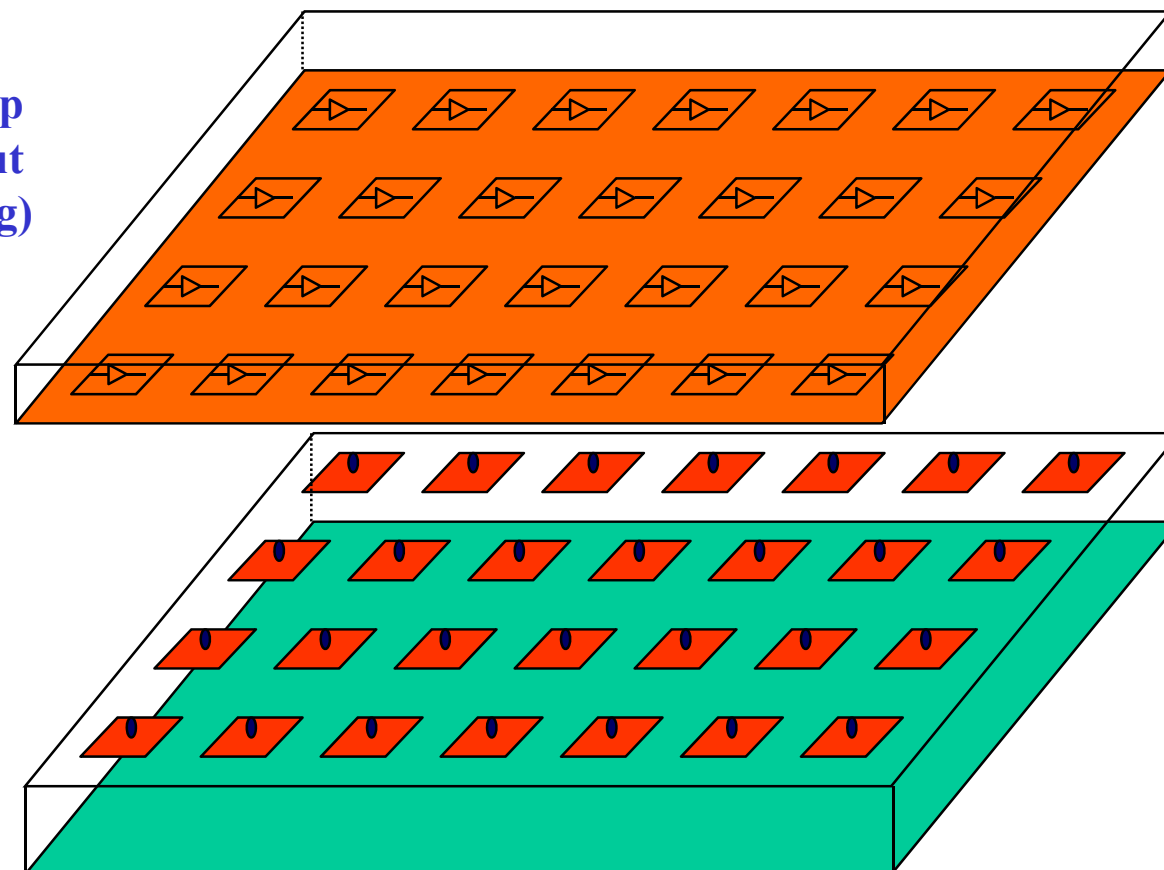
The readout chip is mounted directly on top of the pixels, each pixel has it's own readout amplifier. Metal micro balls (Bump bonding) are used to provide electrical connection between two wafers. This is relatively complicated and expensive procedure!

To be measured:

-hit position

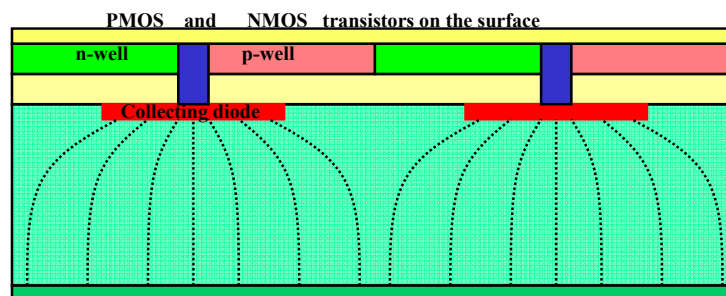
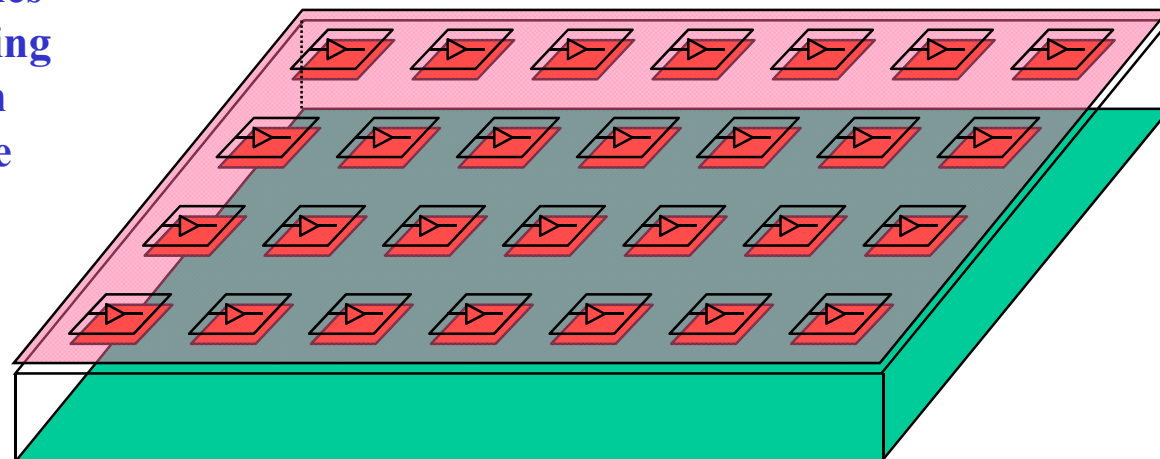
-hit arrival time

- signal amplitude



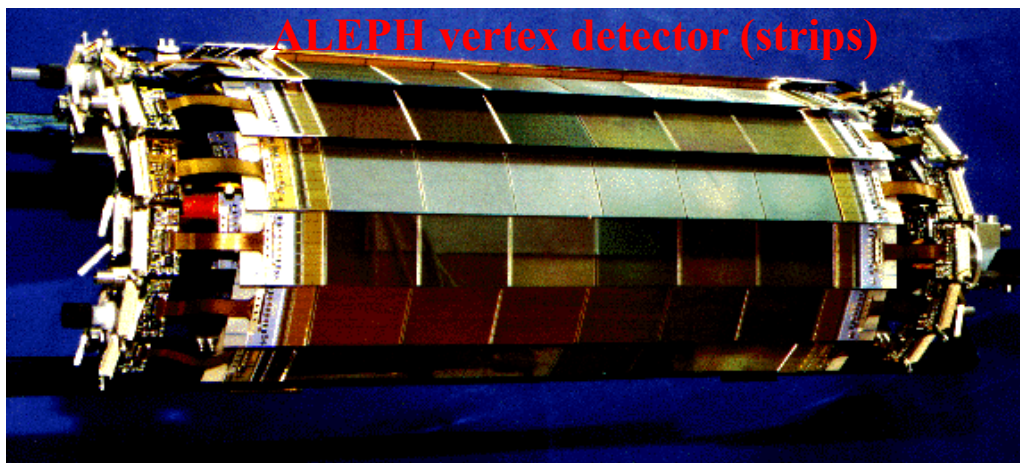
## Semiconductor Position Sensitive Detectors: Monolithic Pixel Detector

Both detector elements and readout electronics are integrated on the same (silicon) wafer, using slightly (?) more complicated process. High granularity, low noise, thin detectors can be fabricated this way.

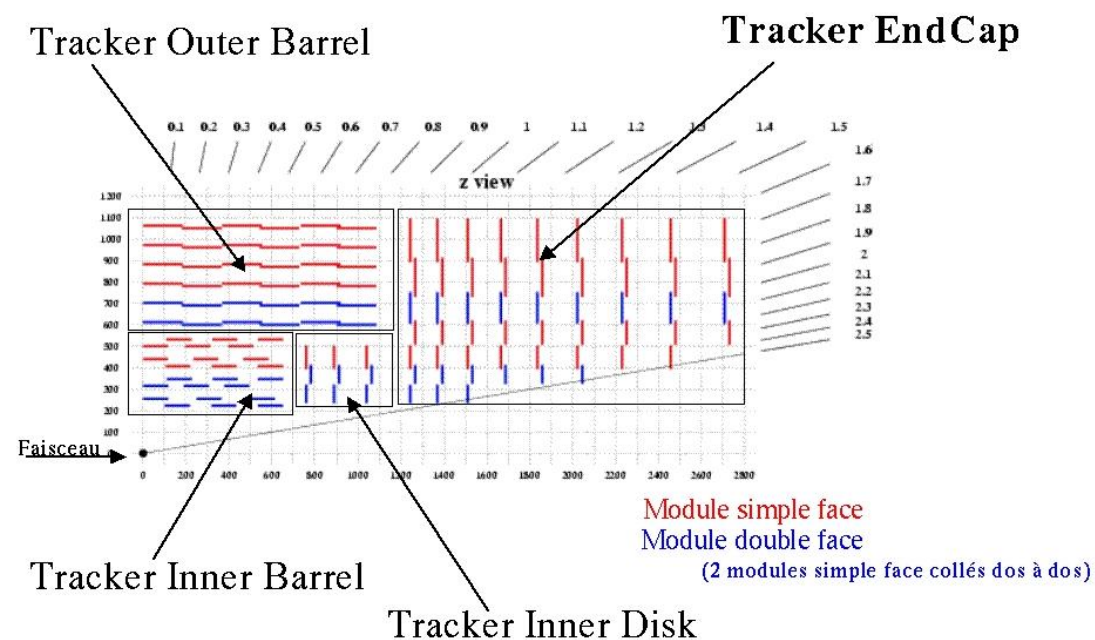


**Example of possible monolithic detector implementation:  
SOI CMOS + High Resistively handling wafer**

## Past and .....



## present of silicon trackers!

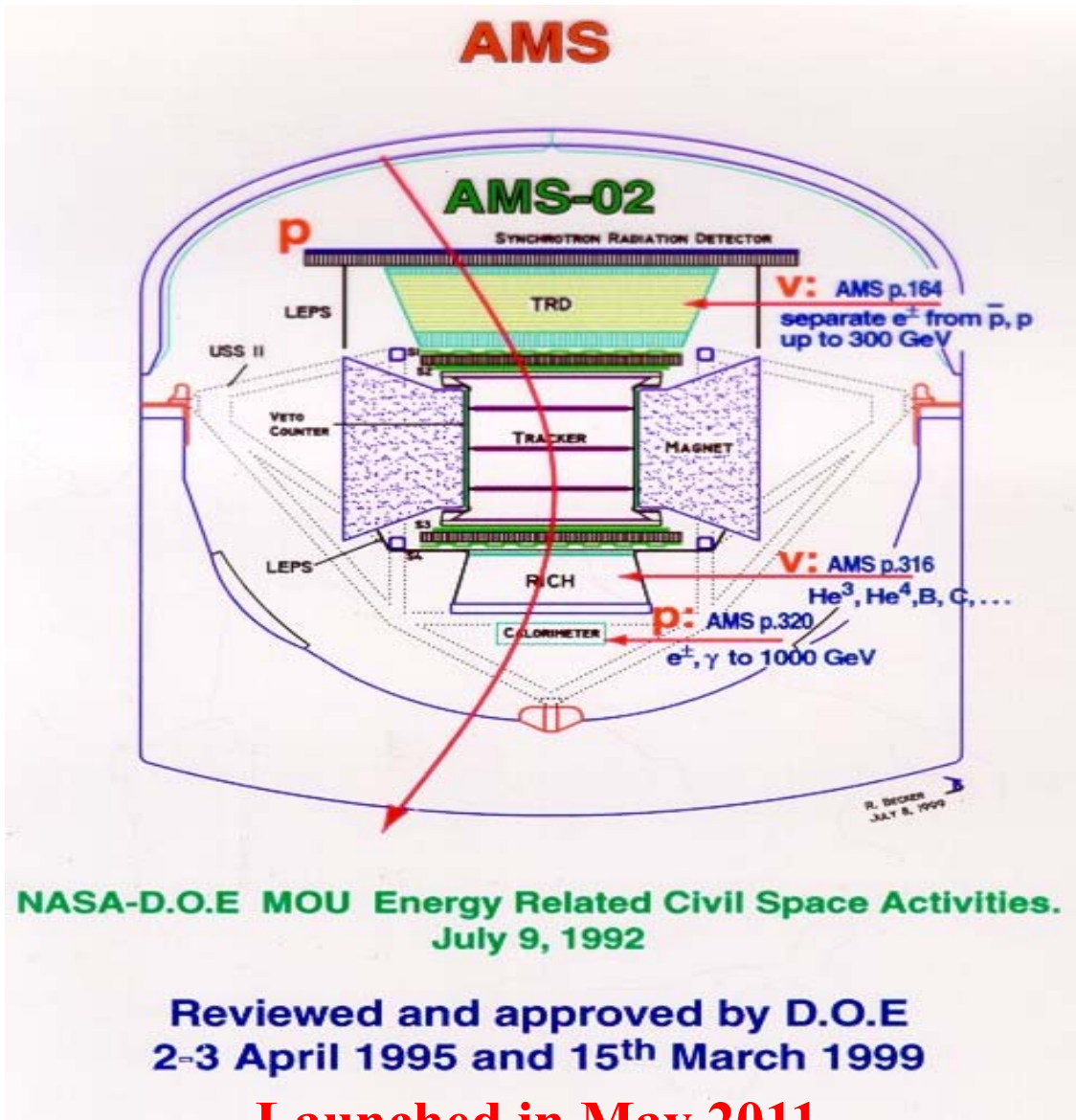


**CMS tracker & vertex detector:  
>200 m<sup>2</sup> of silicon!**

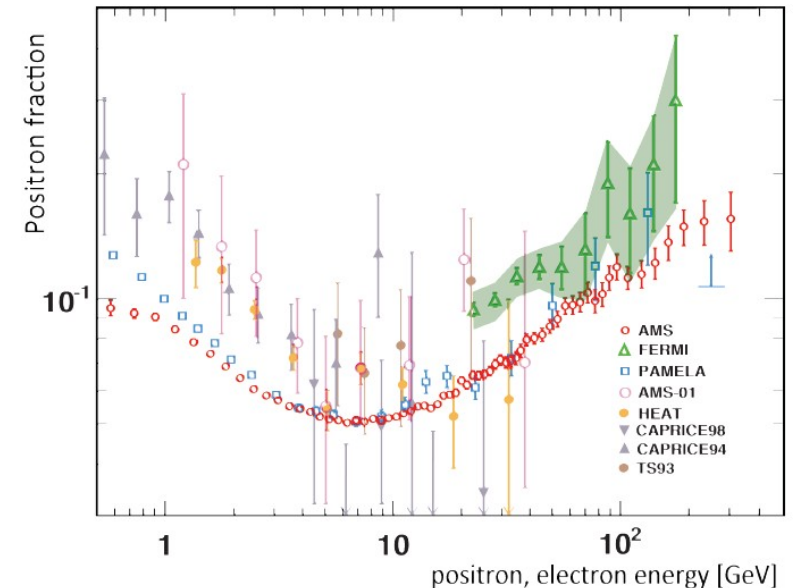
# Alpha Magnetic Spectrometer on International Space Station (ISS)

## Silicon Tracker (~6 m<sup>2</sup>)

- Aim:
  - Rigidity (P/Z<sub>e</sub>) measurements
  - Sign of Charge
  - Absolute Charge (dE/dX, in addition to ToF system)
- Tracker detector based on 8 thin layers of double-sided silicon microstrips, with a spatial resolution better than 10 μm, ≈ 200.000 of electronics channel and ≈ 800 W of power.



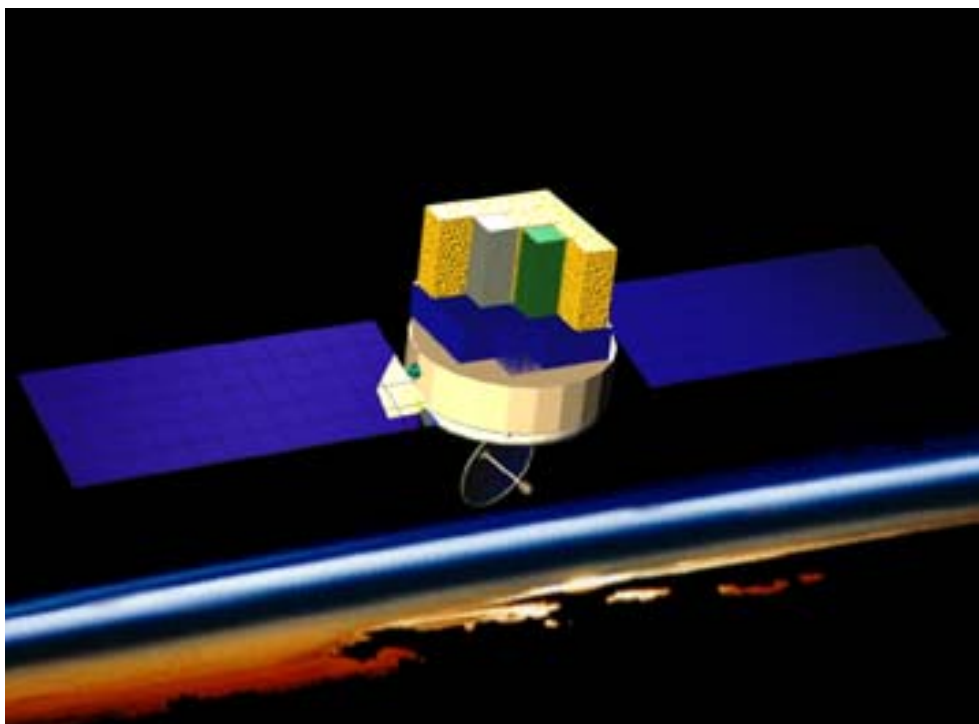
**Launched in May 2011**



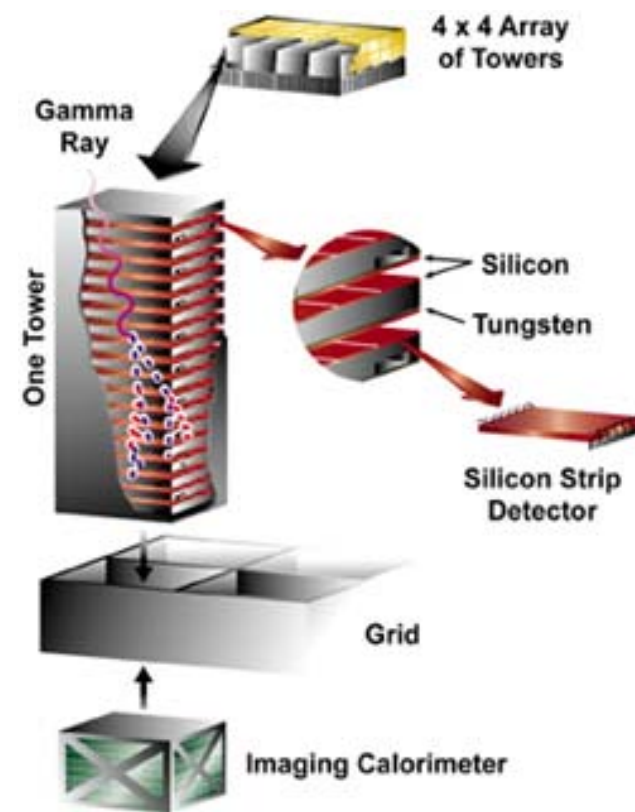
Positron fraction as measured by AMS and previous experiments

## Gamma-Ray Large Area Space Telescope (GLAST → FERMI)

Pair conversion  $\gamma$  telescope using silicon tracker ( $\sim 80\text{m}^2$ ) in space!



**Launched in June 2008**



Large Area Telescope

## Bulk Radiation Damage in Silicon Detectors: **Primary Damage**

**Motivation:** promising new physics is related to some very rarely produced particles, high event rate is necessary in many modern experiments. It means that detectors and electronics will be harshly irradiated!

**Example:** Vertex Detectors at ATLAS and CMS will receive  $>10^{15} n_{1\text{MeVeq}}/\text{cm}^2$  over the lifetime!

### **PKA : Primary Knock on Atom**

-average recoil energy for PKA produced by 1 MeV neutrons is 50 keV

### **Displacement threshold in Silicon**

-Single lattice atom (Frenkel pair):  $E_d \sim 25\text{eV}$

-Defect Cluster:  $E_c \sim 5\text{keV}$

### **Neutrons (elastic scattering)**

- $E_n > 185\text{ eV}$  for single displacement

- $E_n > 35\text{ keV}$  for cluster

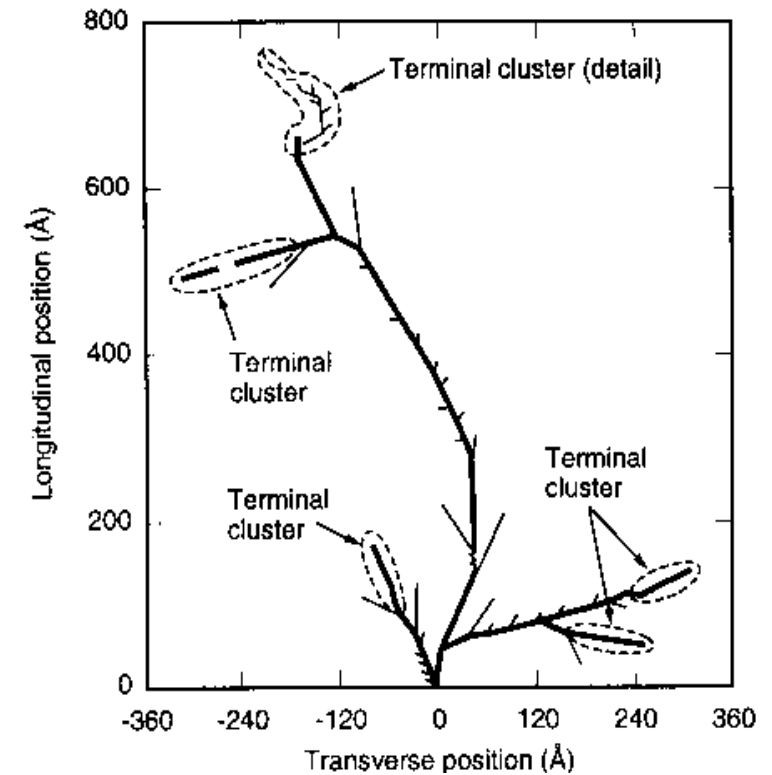
### **Electrons**

- $E_e > 255\text{ keV}$  for single displacement

- $E_e > 8\text{ MeV}$  for cluster

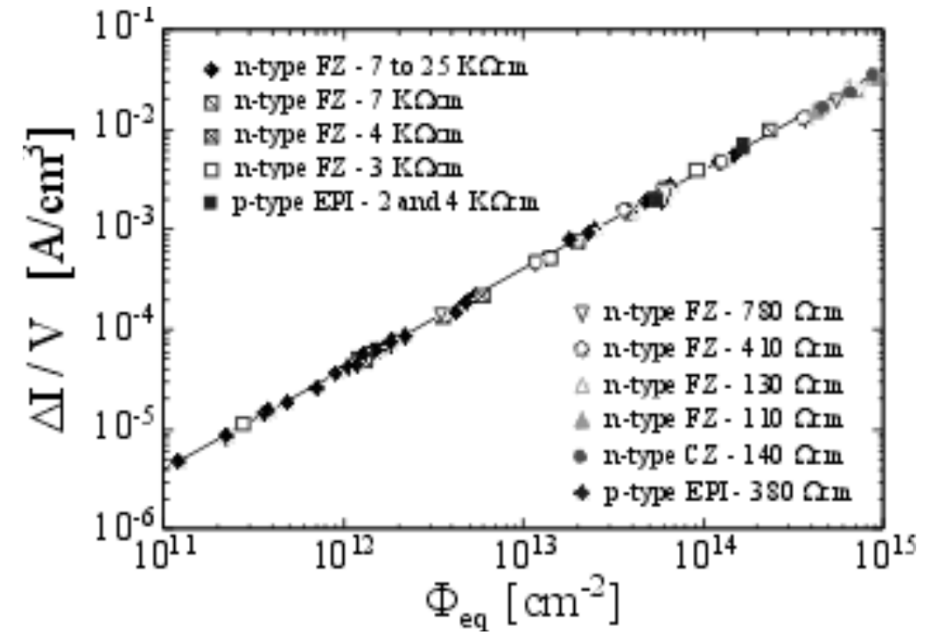
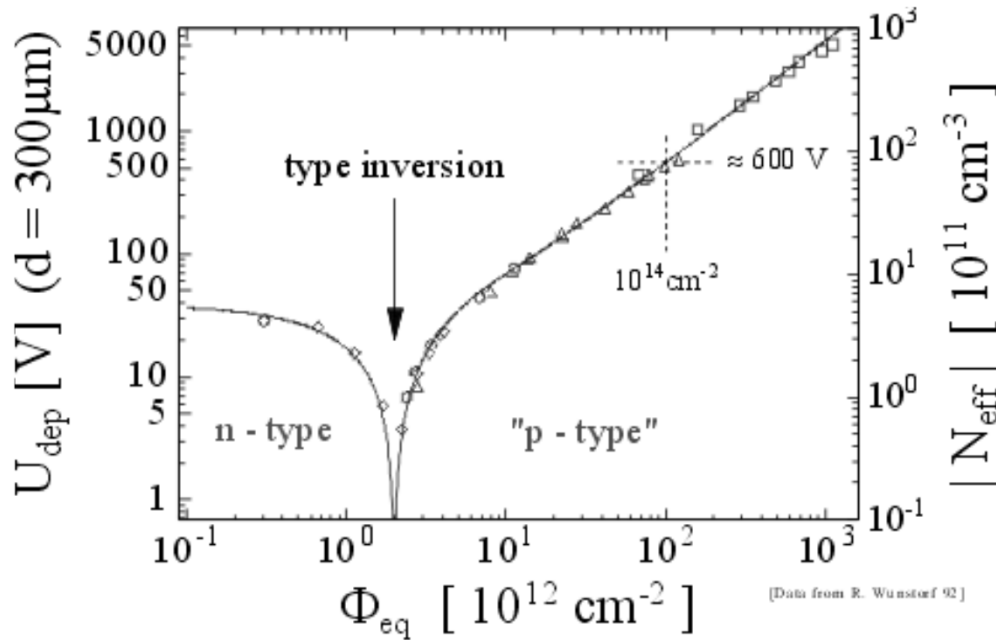
### **$^{60}\text{Co}$ -gammas**

-Compton electrons with max.  $E \sim 1\text{MeV}$  (no cluster production)





## Effect of damage in Silicon



Changes in  $N_{\text{eff}}$  (effective doping concentration) and in full depletion voltage

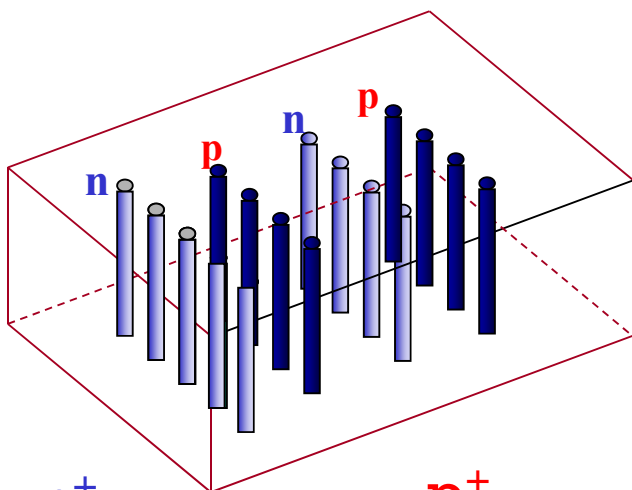
$$N_{\text{eff}} \sim V_{\text{dep}}/d^2$$

Increase of a **leakage current**:

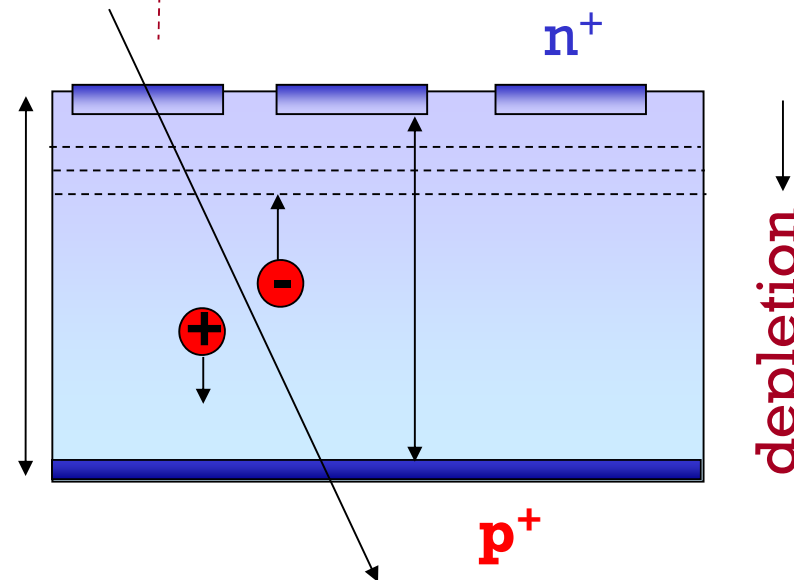
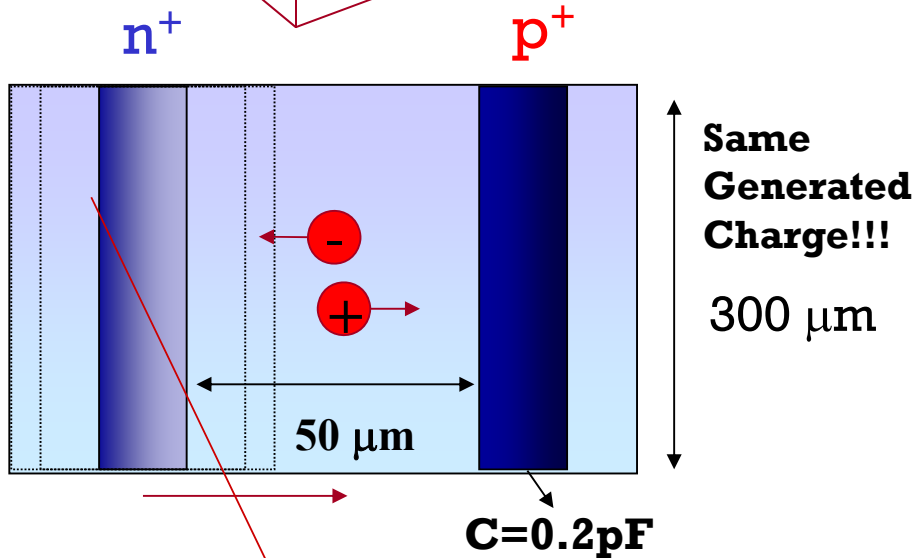
$$\Delta I = \alpha \Phi_{\text{eq}}$$

where  $\alpha$  is a (universal) **damage parameter**

## Another solution for extreme irradiation: Silicon Radiation Sensor with Three Dimensional Electrode Arrays



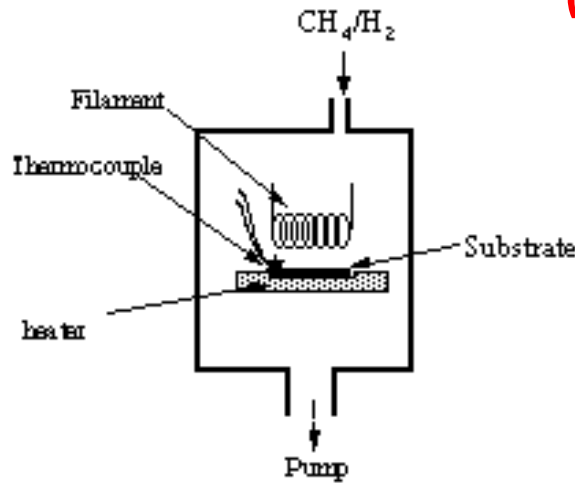
- ❖ SHORT COLLECTION PATHS      50  $\mu\text{m}$  (300 $\mu\text{m}$ )
- ❖ LOW DEPLETION VOLTAGES      <10V (60V)
- ❖ RAPID CHARGE COLLECTION      1-2n (25 ns)
- ❖ EDGELESS CAPABILITY      active edges
- ❖ LARGE AREA COVERAGE      active edges
- ❖ SUBSTRATE THICKNESS INDEPENDENT :
  - ❖ BIG SIGNALS
  - ❖ X-RAY DETECTION EFFICIENCY for low Z materials



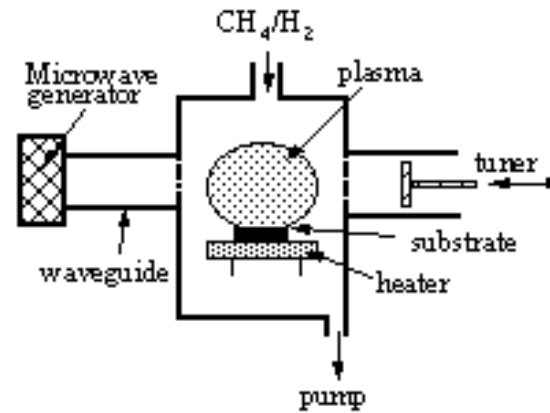
S. Parker, C. Kenney, 1995

## Still another solution for extreme irradiation: CVD diamond detectors

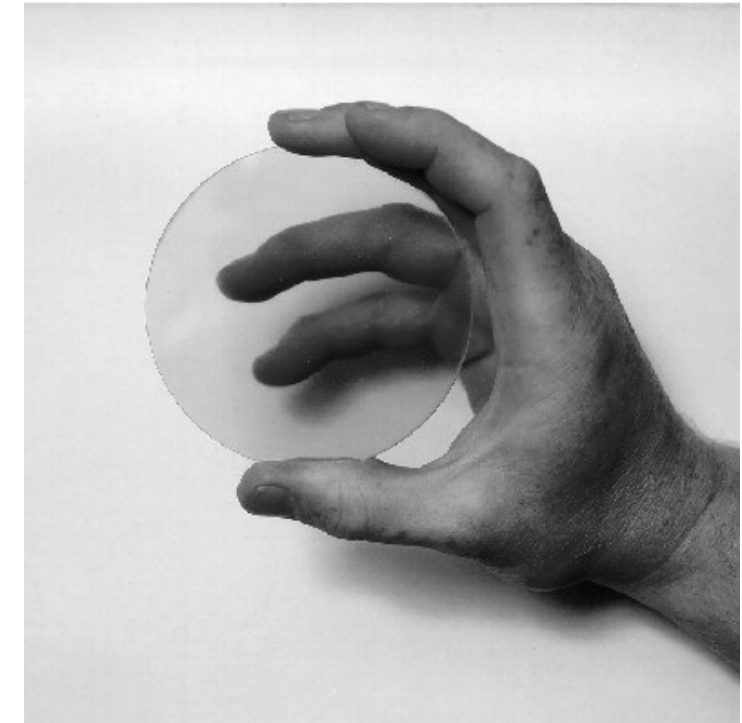
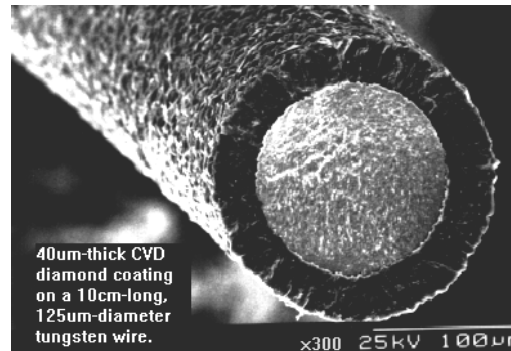
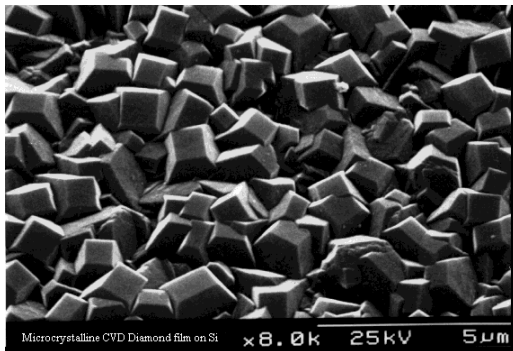
**$(CH_4, 1\%) + H_2(99\%) + \text{energy (plasma)} \Rightarrow \text{CVD diamond layer}$**   
 **$(T < 1000^\circ\text{C}, p < 100 \text{ mbar})$**



a) Hot Filament



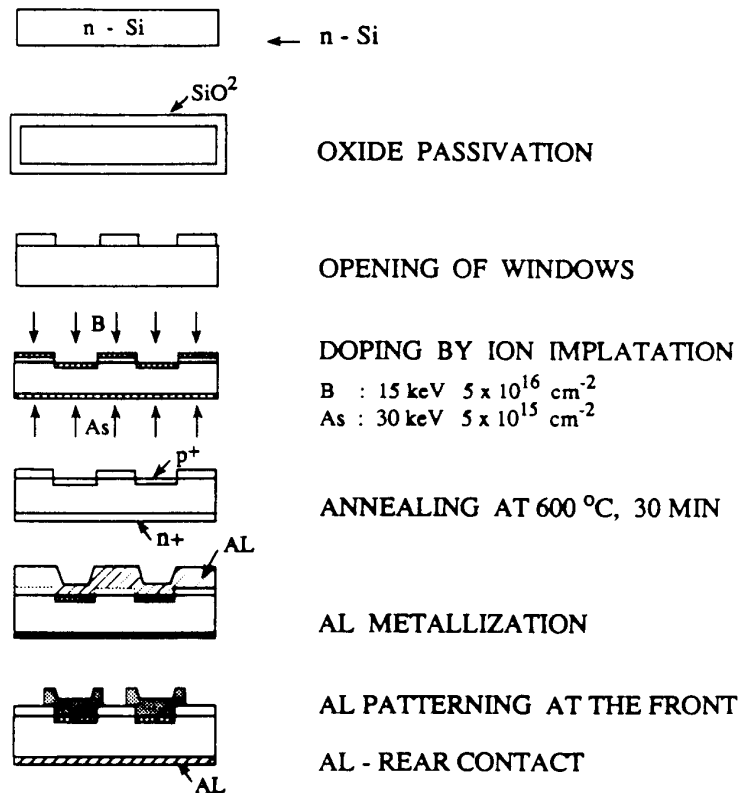
b) Microwave Plasma



CVD diamond 4" wafer

Couche du diamant : structure polycristalline

Microstrip Silicon Detectors has been introduced in 1980, following introduction of the **Planar Technology** for detector fabrication.

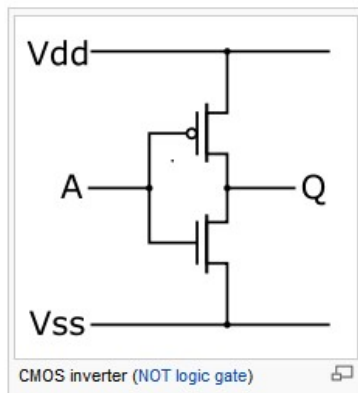
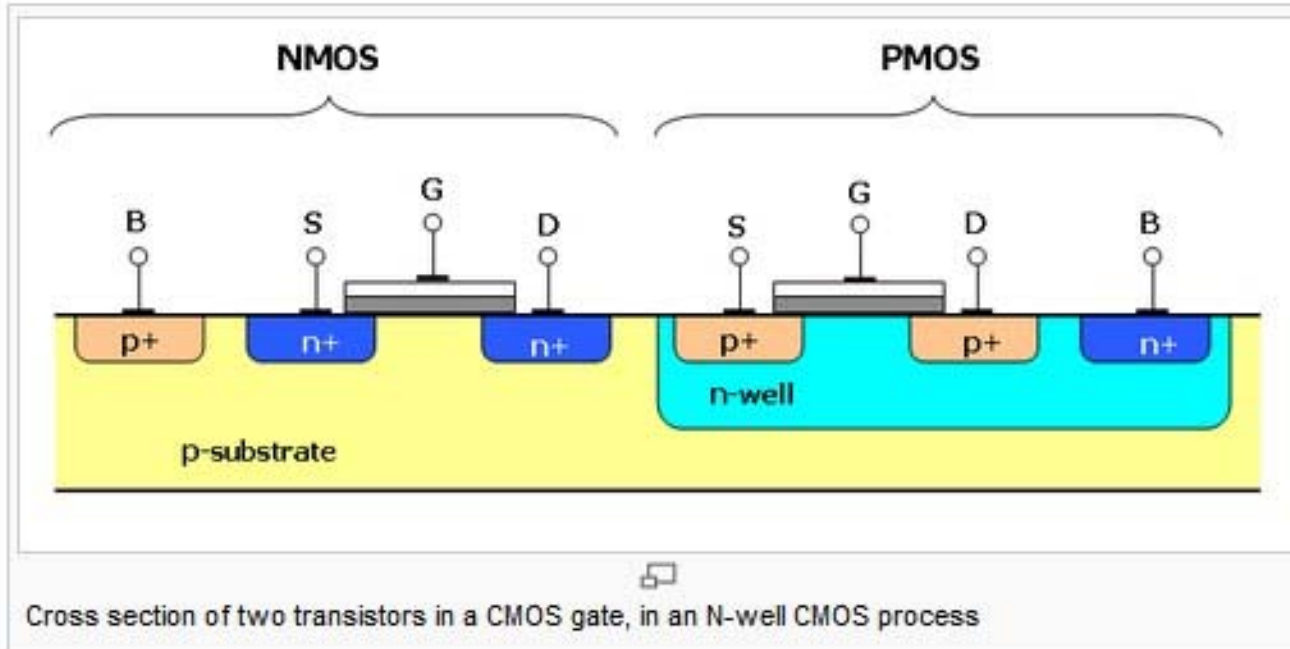


Today this technology is mature, systems having total sensor area of  $\sim \text{m}^2$  ( $10^5$  readout channels) has been built for High Energy Physics (LEP) Experiments. Next generation of experiments will require both area and number of channels increased by factor of 100.

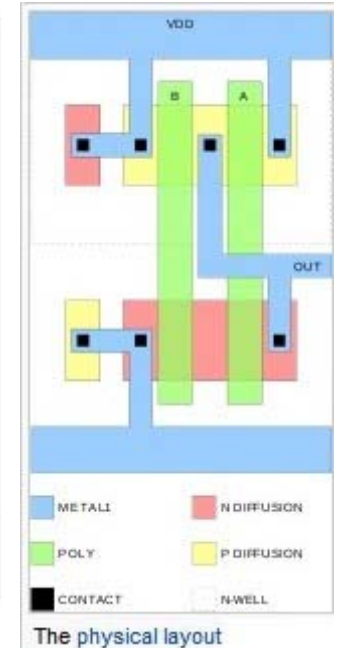
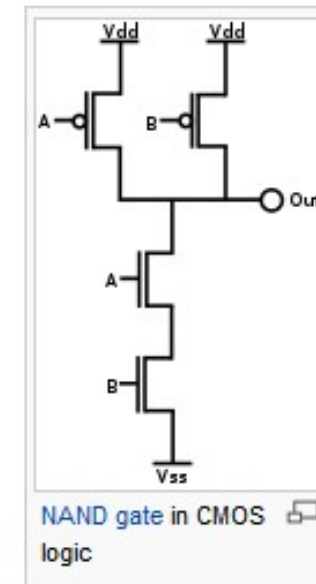
The planar process for detector fabrication. From:  
Kemmer, NIM 226 (1984) 89

# CMOS Process: Complementary Metal-Oxide-Semiconductor (transistors)

The technology for constructing majority of today's electronics: microprocessors, memories, image sensors...



**Inverter (buffer):  
2 CMOS transistors**



**Logic gate (NAND):  
4 CMOS transistors**

## Current induced in segmented detector : Ramo's Theorem

$$i(t) = q\vec{v} \bullet \vec{P}_k$$

Where  $\vec{P}_k$  is a pseudo-field (weighting field):  $\vec{P}_k = -\vec{\nabla}V_k$

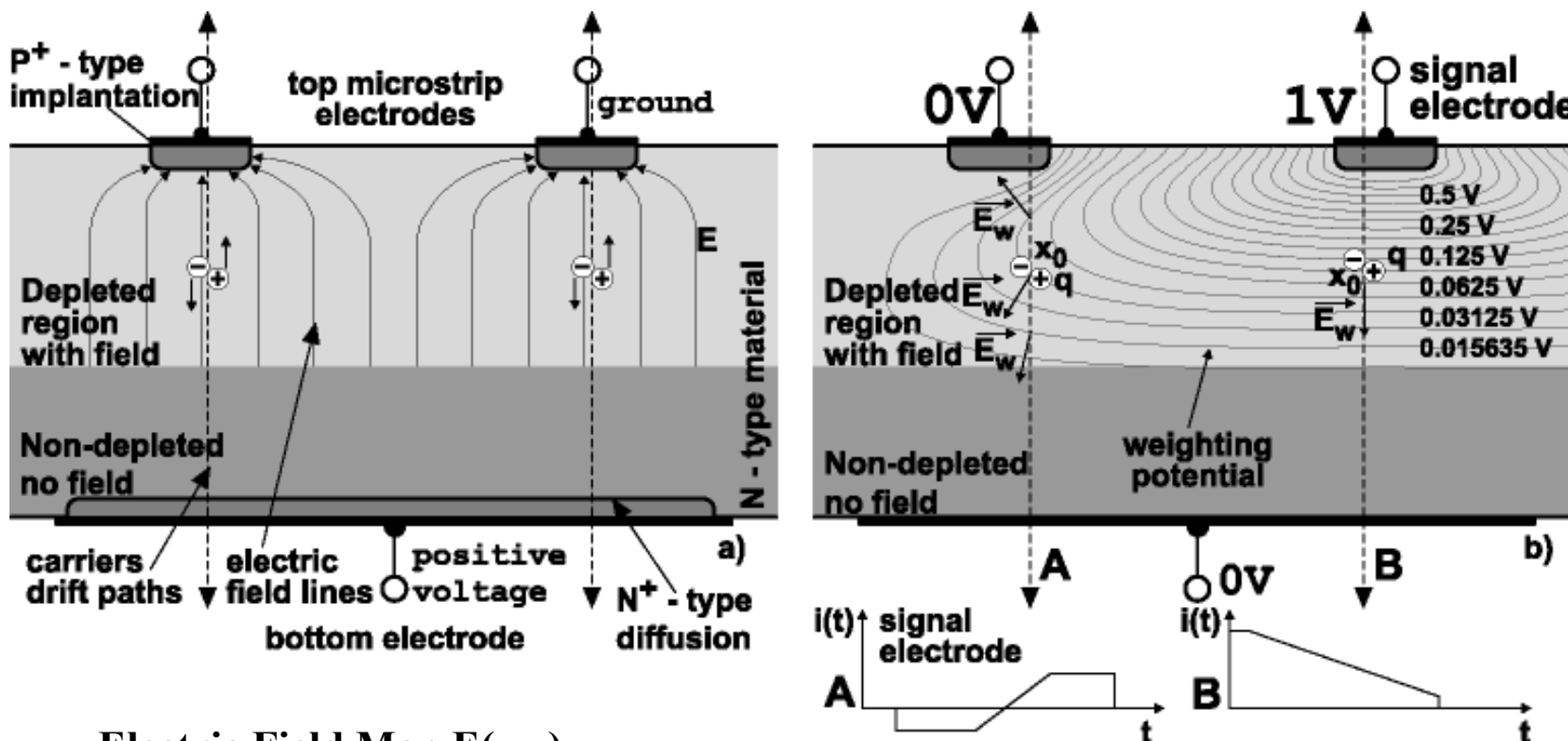
and  $V_k$  is a pseudo-potential calculated using following assumption:

- 1).  $V_k = 1$  on the segment of interest
- 2).  $V_k = 0$  elsewhere

$\vec{v}$  is a charge carrier velocity  
(mobility and local physical electric field product)

# Strip detector: signal shape calculated using Ramo's Theorem

Powerful software packages: SILVACO, ISE-TCAD (Synopsis)



Electric Field Map  $E(x,y)$



Drift velocity  $V(x,y)$



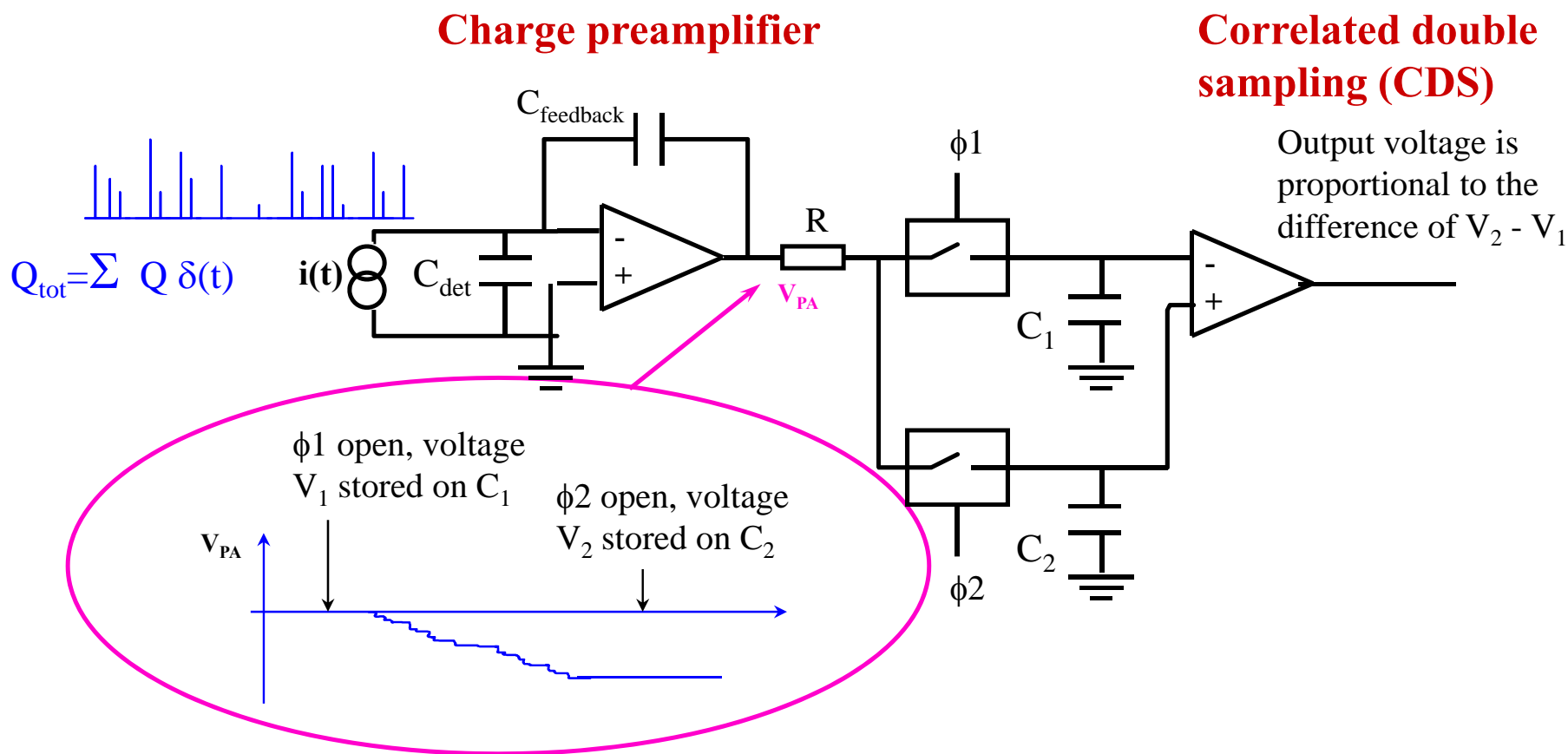
Pseudo-field  $P_k(x,y)$



Current  $I(t)$

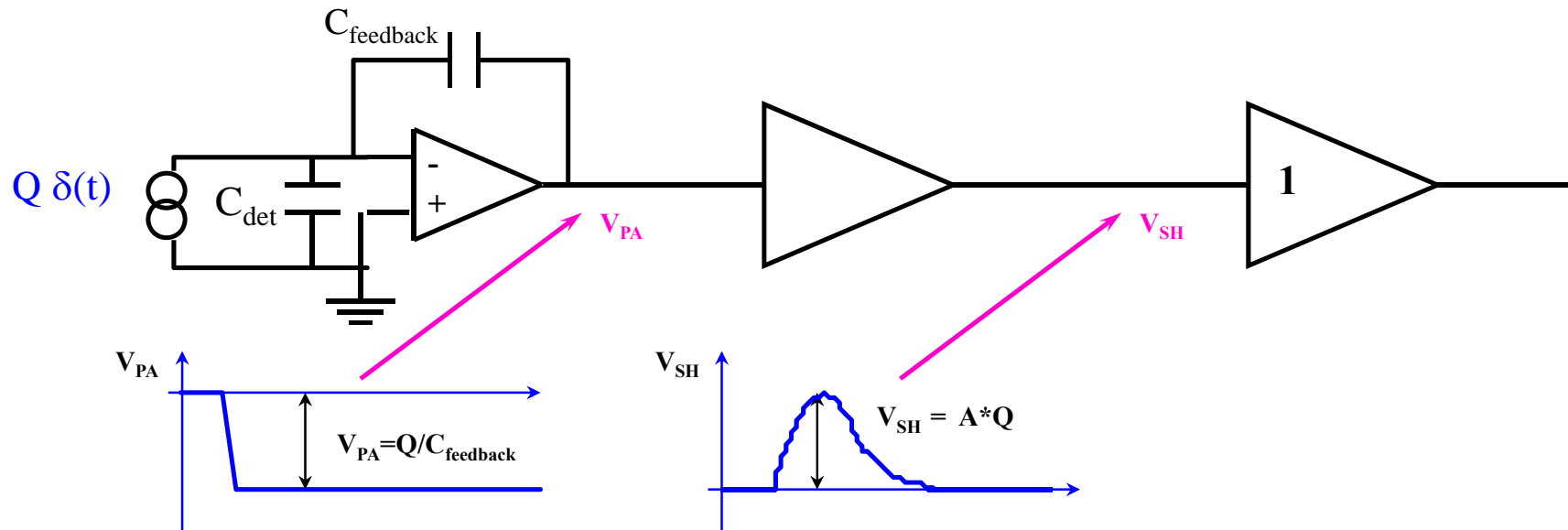
# Basic signal processing: integrating mode

What is used for amorphous-Silicon arrays (the detector is an amorphous silicon photodiode).





# Basic signal processing: single particle detection mode



## Charge preamplifier

Output signal proportional to the charge created by the radiation.

Charge proportional to the energy lost by the particle.

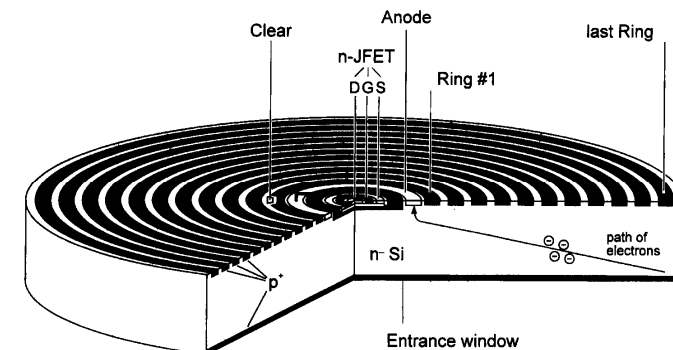
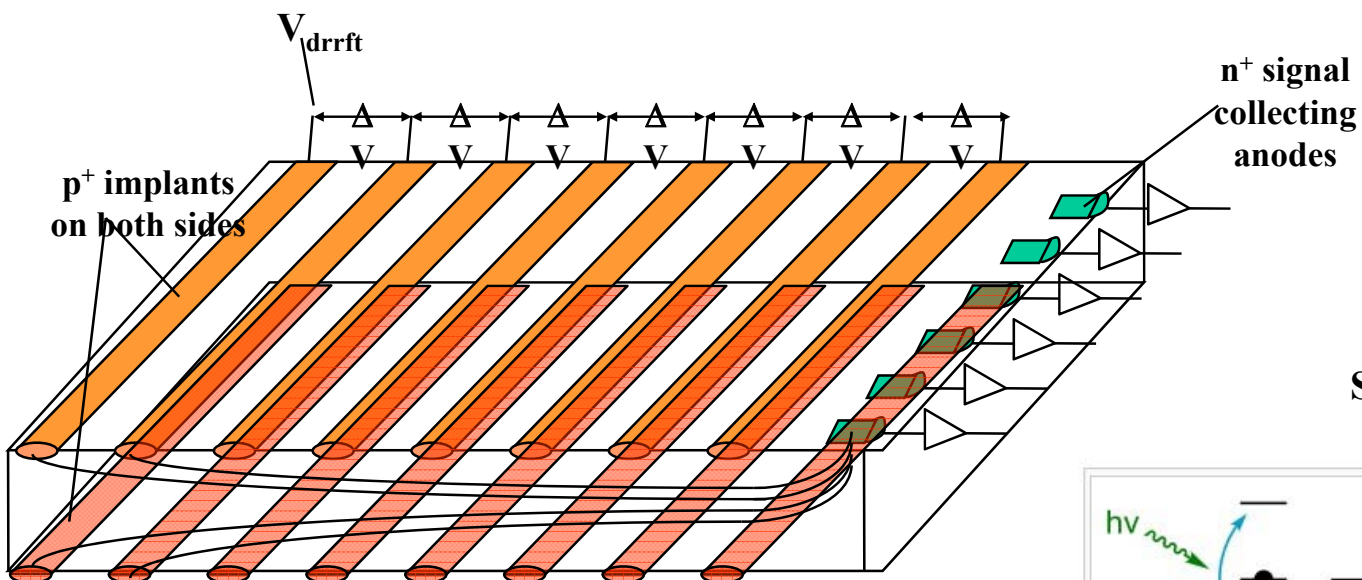
## Shaper

The infinite step at the output of the charge preamplifier is transformed in a short pulse with amplitude proportional to  $Q$ . It also filters the noise.

## Buffer

It transforms impedances and optimises the power transfert.

# Semiconductor Position Sensitive Detectors: Silicon Drift Detector (SDD)

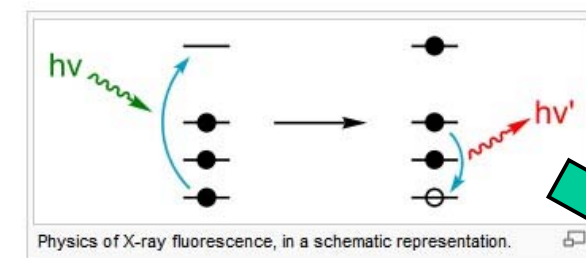


Silicon Drift Chamber used as photodetector

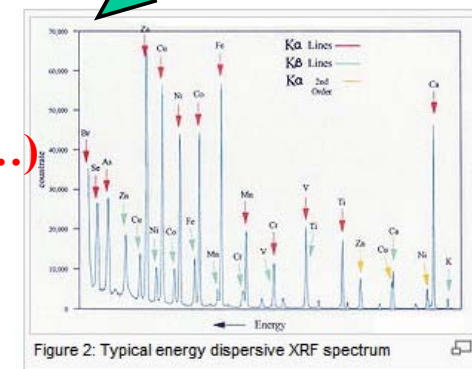
**To be measured:**  
hit position, arrival time, signal amplitude

**4 modes of operation: no time, external/  
internal start, controlled drift**

**Tracking in particle physics:**  
**STAR (disaster!), ALICE (seems OK)**



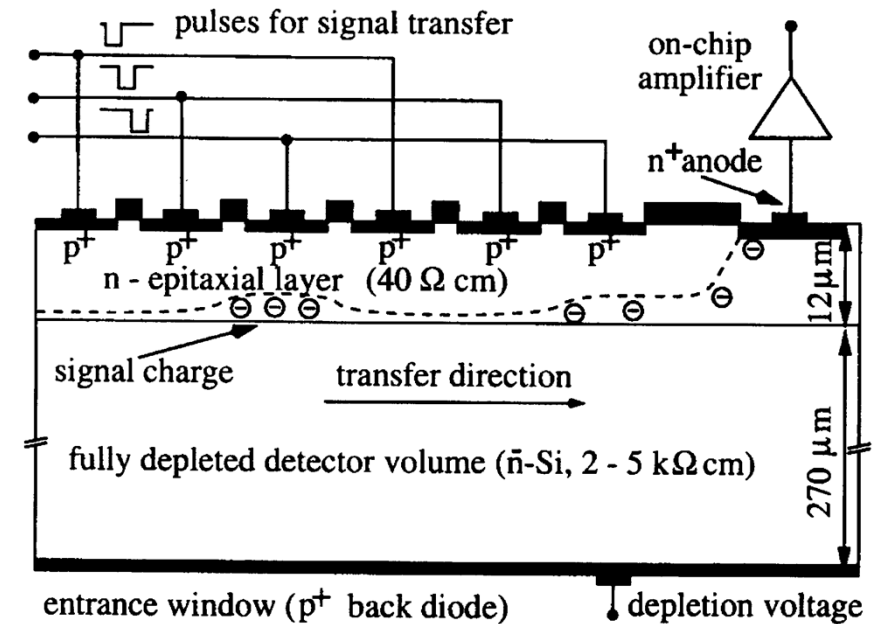
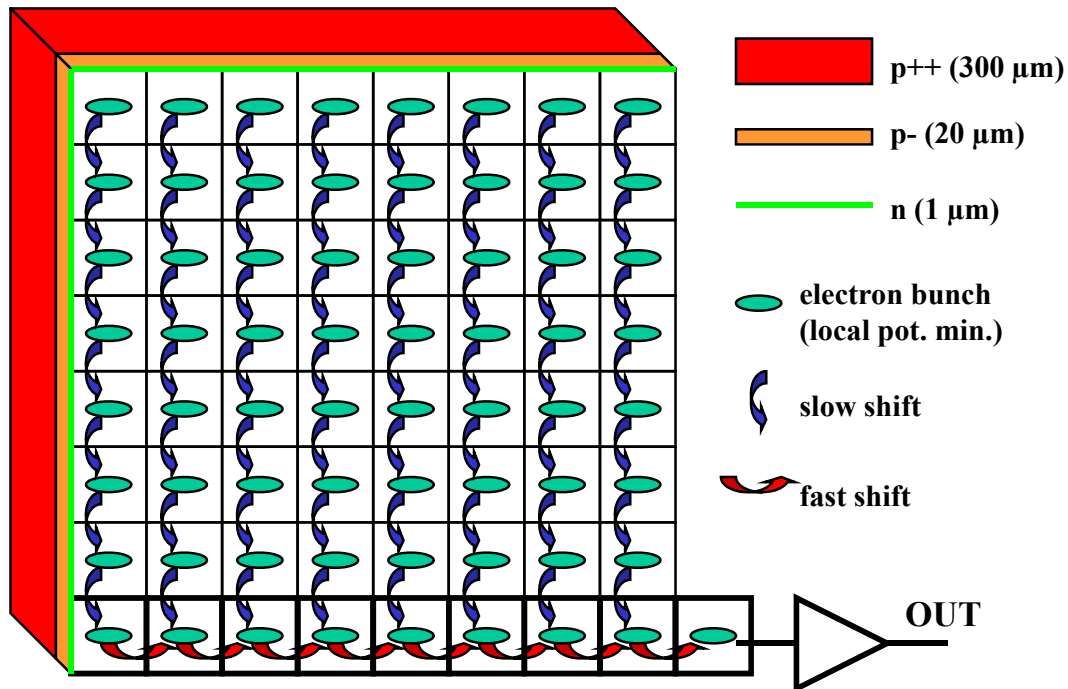
**Soft X-ray spectroscopy  
(fluorescence analysis, PIXE...)**



**Excellent candidate for (space) Compton telescope???**

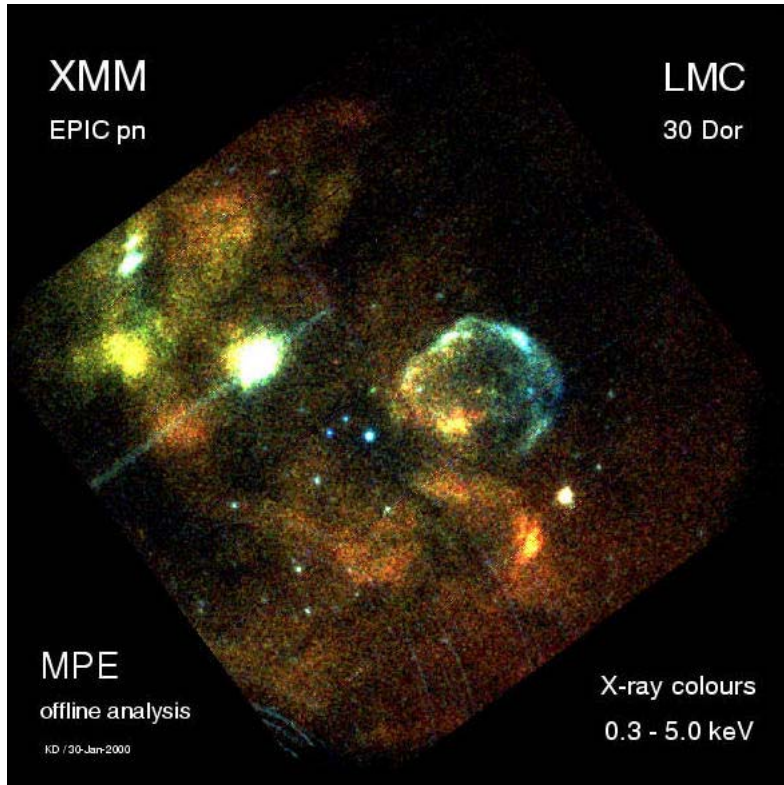
## Semiconductor Position Sensitive Detectors: Charge Coupled Device (CCD)

An imaging CCD consist firstly of a square matrix of potential wells, so the charge signal generated below the silicon surface can be accumulated, building up an image. Secondly, by manipulating clock voltages in the parallel register charge can be transferred in parallel from one row to the next and into linear register in the bottom of the matrix. Then the linear register is read out, cell after cell. Thus the CCD image is converted from a 2-D charge pattern to a serial train of pulses.



**Fully depleted pn-CCD with integrated on-chip first amplification stage**

## The EPIC/XMM camera based on pn-CCD



The large Magellanic Cloud in X-rays (0.3-5.0 keV).  
First Light Image of the pn-CCD camera.

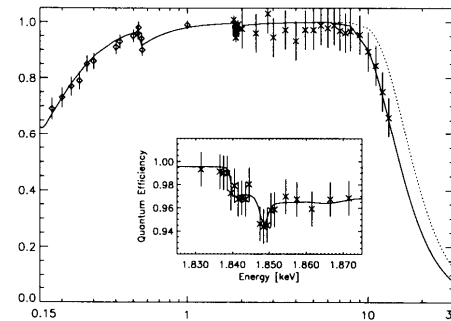
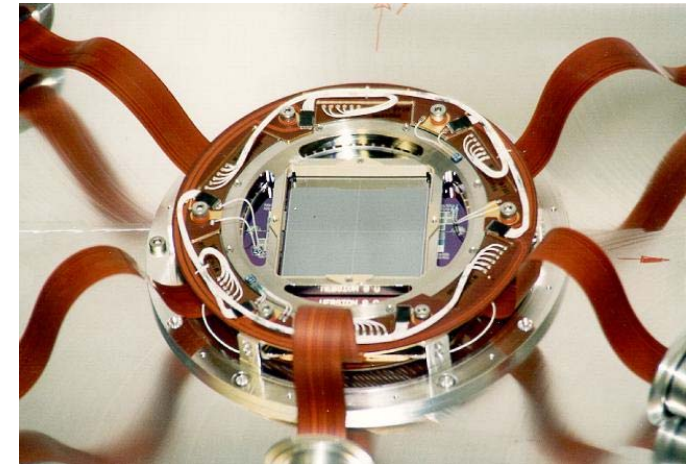


Figure 5. Quantum efficiency of the pn-CCD. The solid line represents a 300µm thick sensitive volume, the dotted line 500µm.

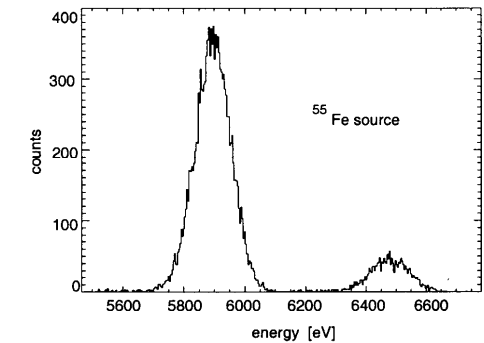


Figure 6. Mn  $K_{\alpha}$  spectrum of an  $^{55}\text{Fe}$  source. The measured FWHM is 130 eV at  $-120^{\circ}\text{C}$ .

The 6 cm×6 cm large pn-CCD will be the heart of the EPIC/XMM camera. The picture shows the twelve chips mounted and the connections to the integrated preamplifiers. The quantum efficiency is greater than 80% over the whole XMM energy range of 200 eV to 12 keV. It is extremely radiation-resistant, has a good energy resolution, and owns an excellent time resolution.

## DEPFET Pixel Sensor for X-rays

- can be back illuminated, can have a fill factor of 1, can be made very large (all pros of CCD)
- does not need a charge transfer, no out-of-time events, every pixel is xy-addressable (all pros of APS)
- in addition, can have a non destructive multiple readout to reach very low noise figures

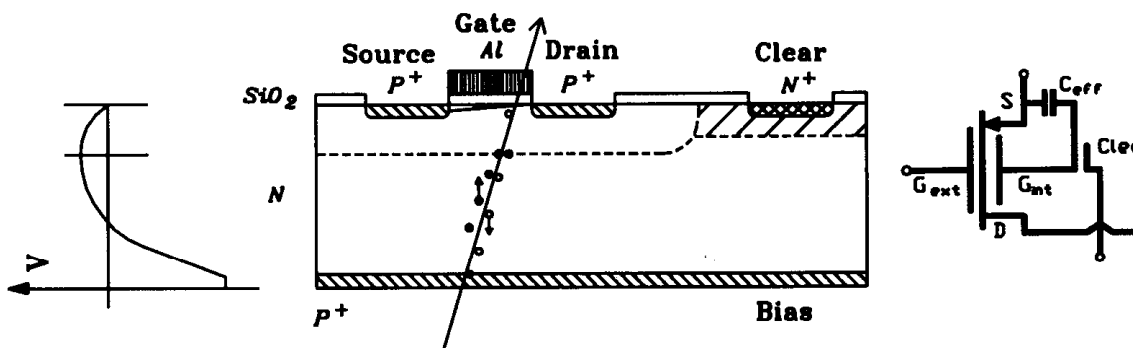
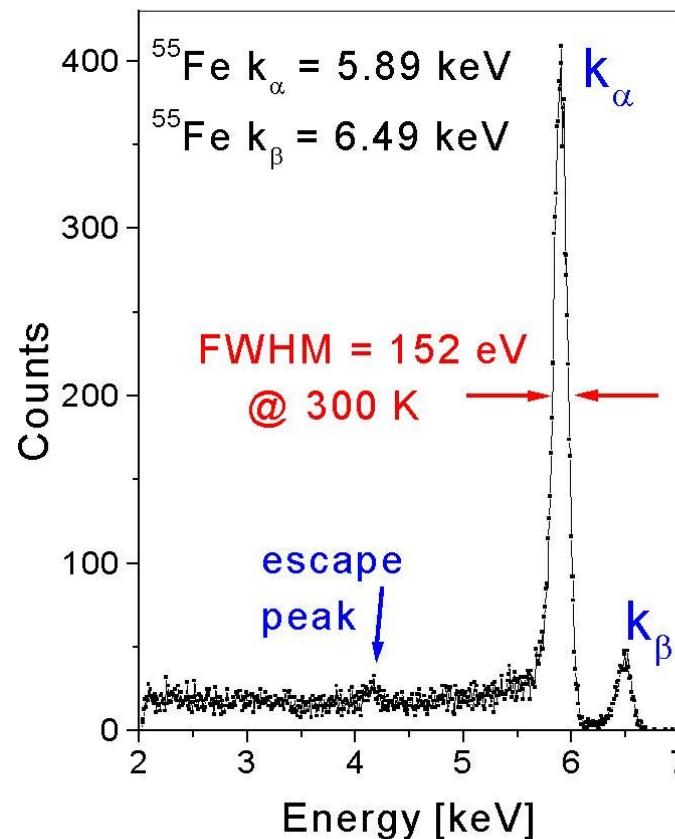


Figure 1. The DEPFET structure and device symbol

J.Kemmer, G.Lutz et al. NIM A 288 (1990) 92

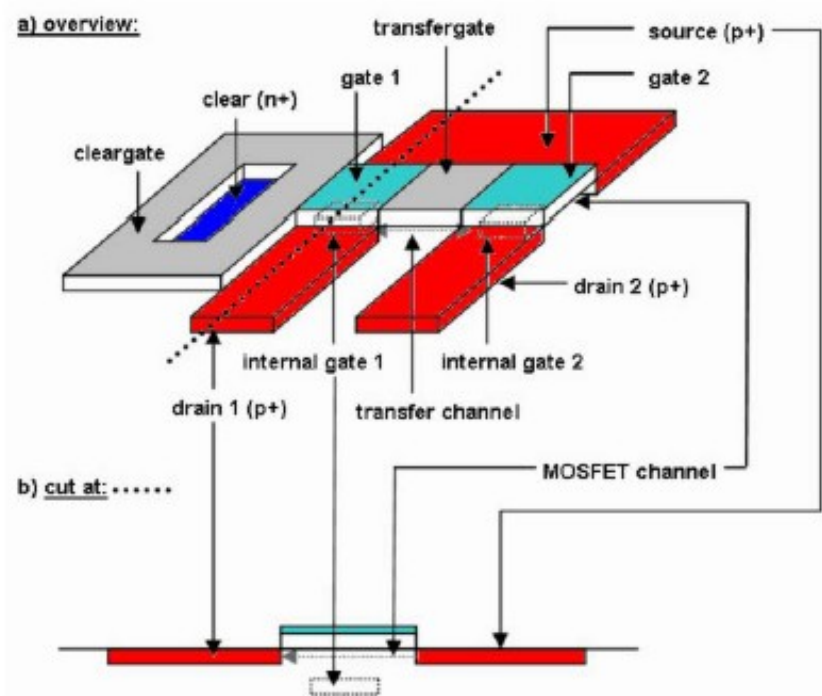
Device concept:  
combination of FET transistor with  
sideward depletion (drift chamber)



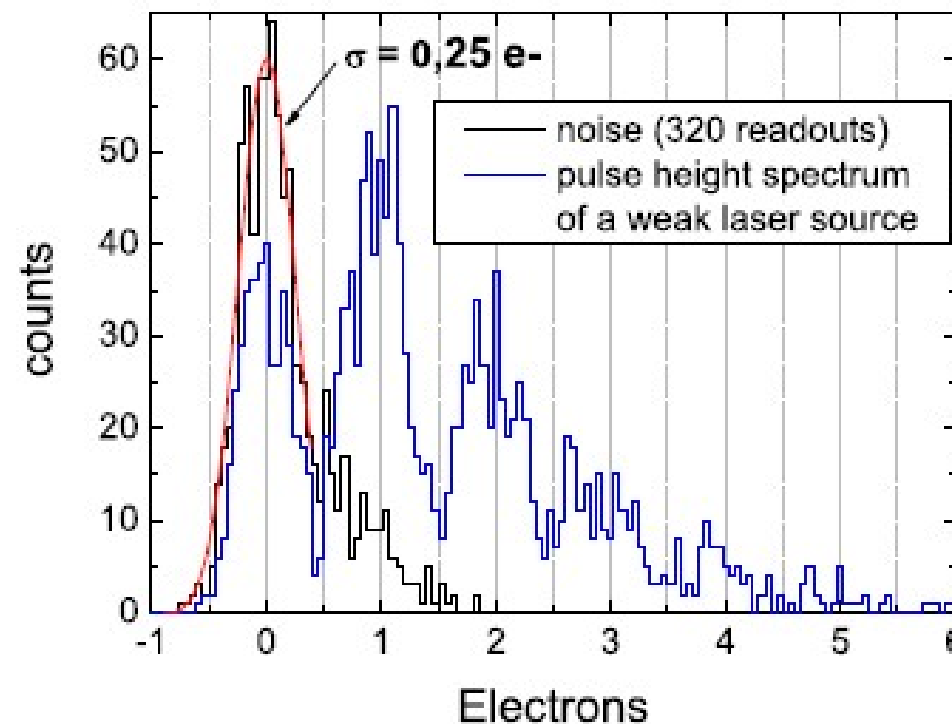
**DEPFET : excellent noise figures (9 electrons rms.)  
at room temperature!**

# DEPFET: non-destructive readout!

## Sub-Electron noise measurements on RNDR Devices (Repetitive, Non-Destructive Readout)



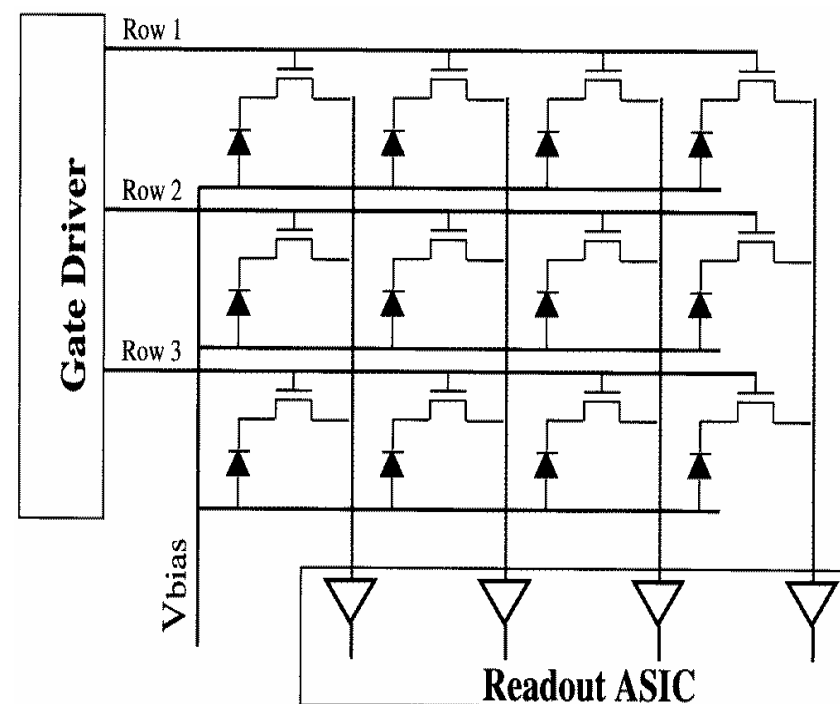
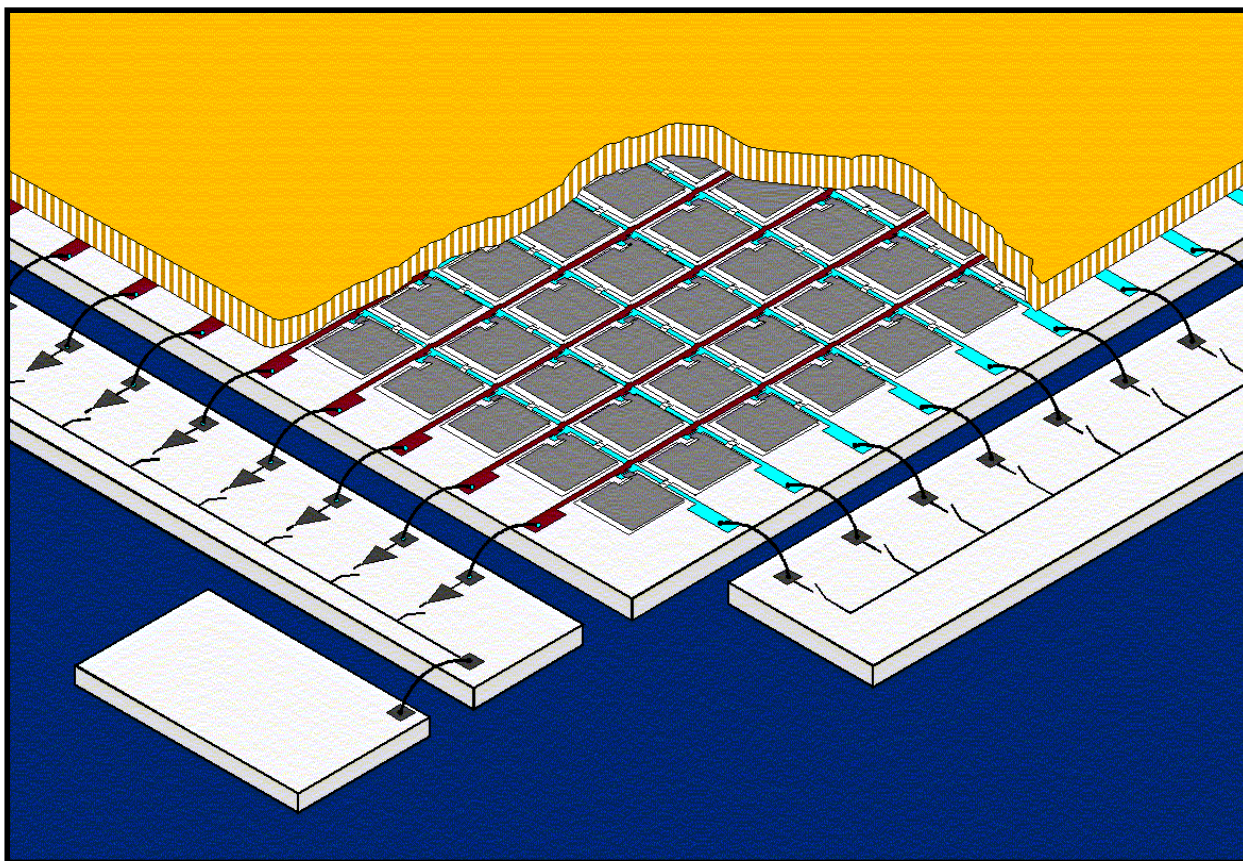
Twin-DEPFET with a CCD-like charge transfer



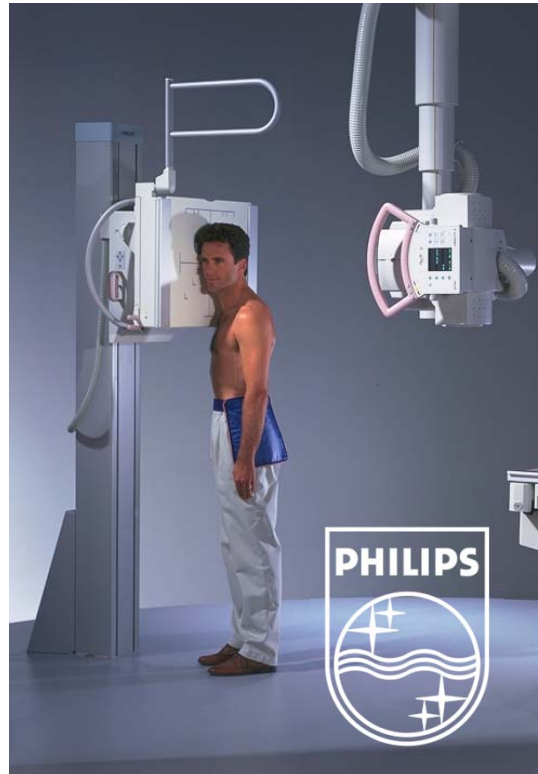
$$\sigma_{ENC} = 0.25 e^- = 4.6 e^- / \sqrt{360}$$

## Amorphous silicon array

Based on Flat Panel display technology. First theoretical studies in 1989. Pixel size down to 127  $\mu\text{m}$ . Size up to about 43\*43  $\text{cm}^2$ , 14-bit data. Number of pixel up to 9 millions. Many manufacturers are close (or ready) to commercialisation for digital radiology.



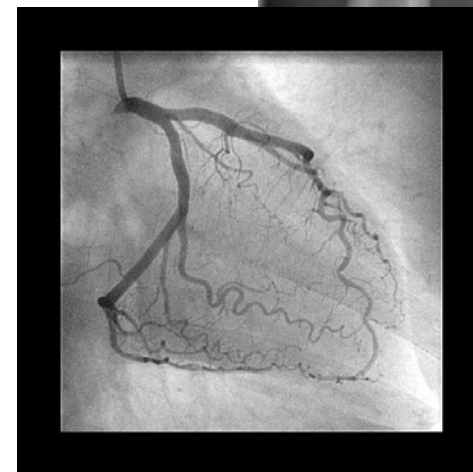
Sensor structure



## Static AND dynamic detectors



Shoulder



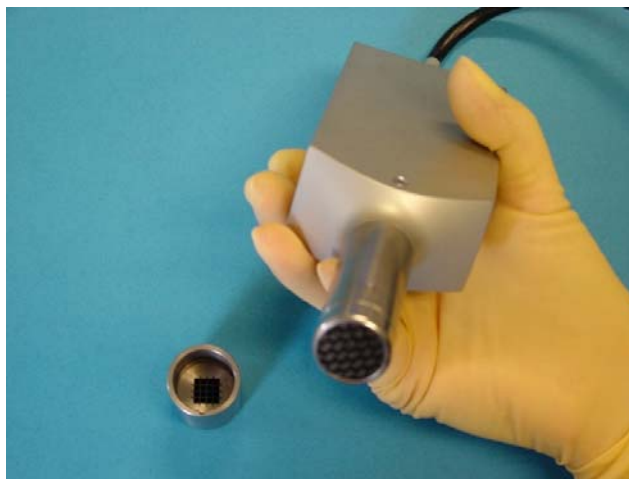
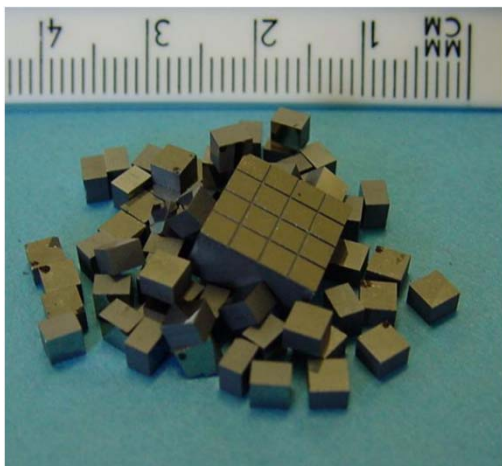
Heart arteries with  
contrast agent

	<i>Digital Diagnost</i>	<i>Integris Allura FD</i>
Detection	static	static + dynamic (up to 30 frames/s)
Field of view	43 cm x 43 cm	18 cm x 18 cm
Number of pixels	3k x 3k	1k x 1k
Pixel size	143 $\mu\text{m}$ x 143 $\mu\text{m}$	184 $\mu\text{m}$ x 184 $\mu\text{m}$
DQE(0)	$\approx 60 \%$	$\approx 75 \%$



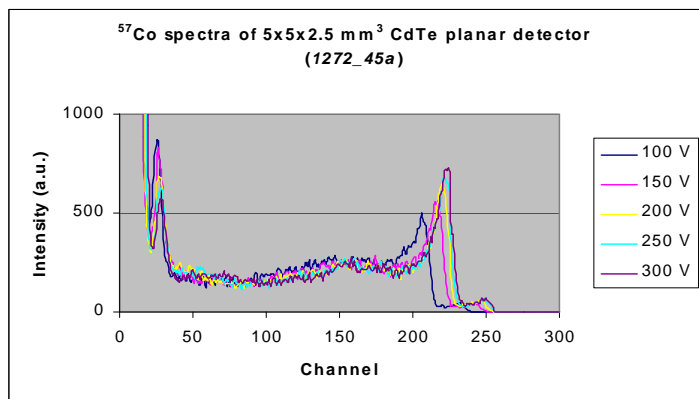
# CdTe/CdZnTe detectors: high Z, high band-gap (room temperature) semiconductor

## Detectors



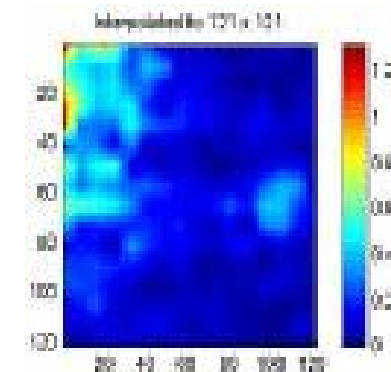
**CdTe 4x4 array**  
**2.23x2.23x5mm<sup>3</sup>**  
**(pitch 2.4 mm)**

Weight = 500 g



**57Co spectroscopy with a small size planar detectors**

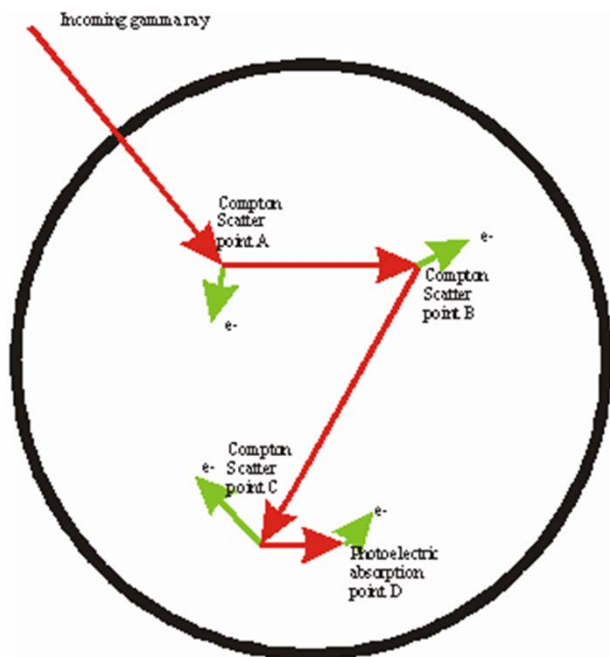
Standard and mini-probes from:



**Mini-Gamma camera:**  
**Sentinel node image**

# Perspectives: **Gamma-Ray Tracking Arrays**

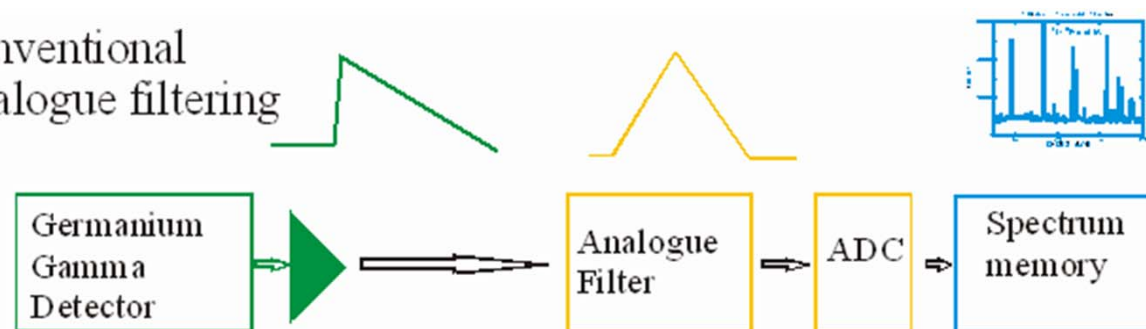
a way to construct a  $4\pi$  Germanium shell detector



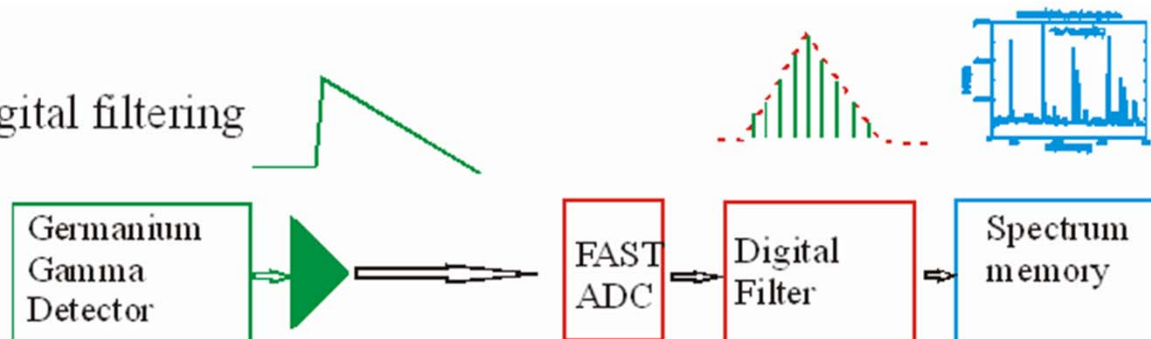
## Several development items:

- segmented Ge detectors
- digital signal-processing electronics
  - pulse shape analysis methods
  - tracking algorithms
- simulation of tracking arrays

Conventional  
Analogue filtering

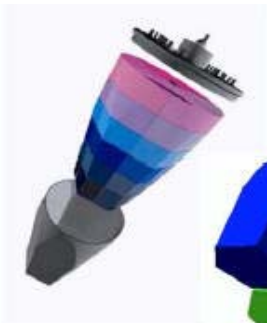


Digital filtering



# AGATA: Advanced Gamma-Ray Tracking Array

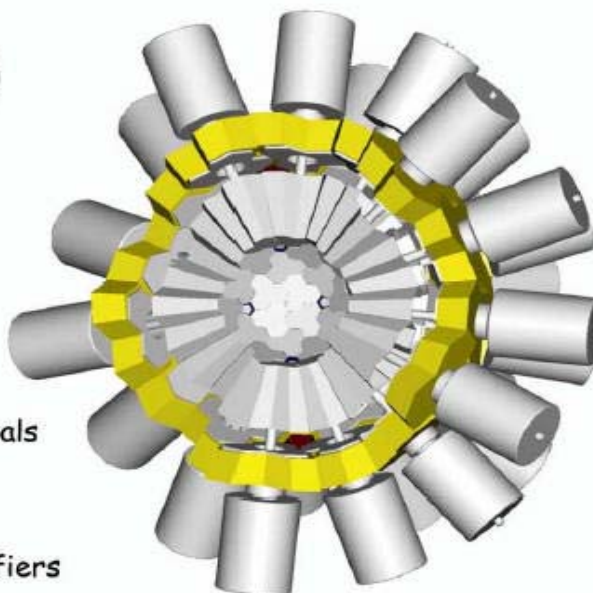
## Detectors



Ge crystals:  
Hexaconical shape  
90-100 mm long  
80 mm max diameter  
36 segments  
Al encapsulation:  
0.6 mm spacing  
0.8 mm thickness

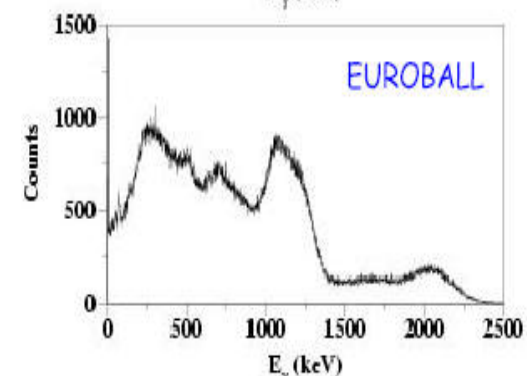
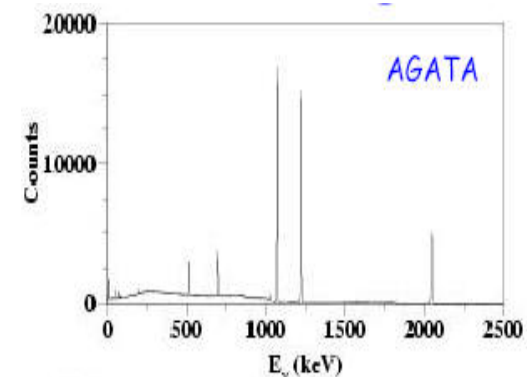


Triple clusters:  
3 encapsulated crystals  
Al end-cap:  
1.5 mm spacing  
1.5 mm thickness  
111 cold FET preamplifiers



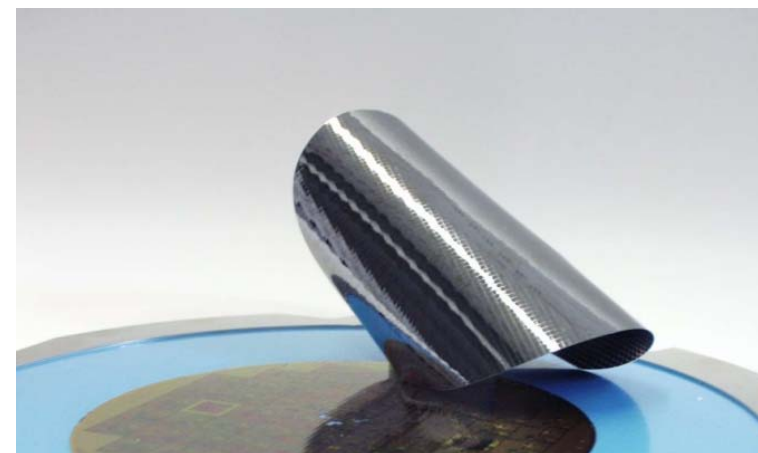
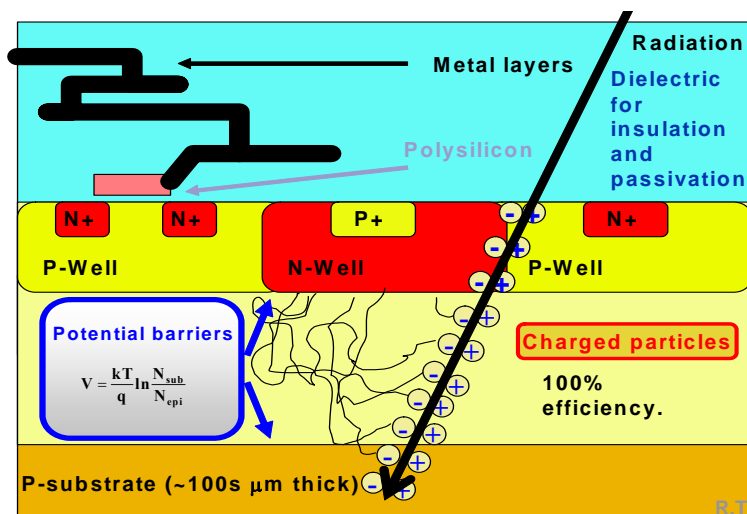
Distance between faces of crystals:  
in same cluster ~3 mm  
in adjacent clusters ~9 mm

Total weight of the 60 clusters of the  
AGATA-180 configuration ~2.5 tons  
Mounted on a self-supporting structure

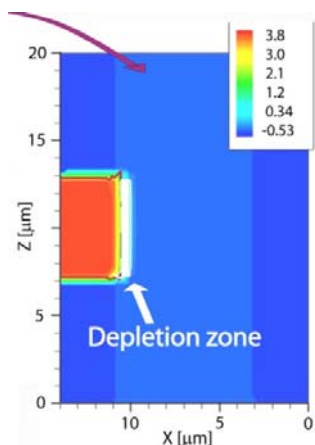


*Simulated g-ray spectra comparing the response of AGATA (top) with that of a conventional Ge-array (bottom) assuming a fragmentation reaction at 100 MeV/A.*

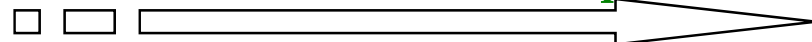
# Monolithic Active Pixel Sensor: use of thin epitaxial layer (10 – 20 μm) for MIP tracking. Industrial CMOS process for fabrication!



May be extremely thin (~25 μm of silicon in total, ~0.027 %  $X_0$ ), flexible (!) and still fully efficient for MIP tracking!

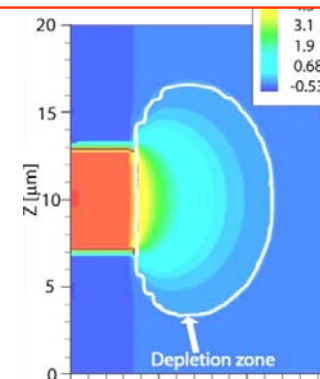


*past*



*present*

Industrial availability of high resistivity substrate (epi) in a standard process



Fast and more efficient charge collection  
→ more radiation tolerant

# Present status of MAPS: just one example of mature design

## Binary sparsified readout sensor for EUDET beam telescope:

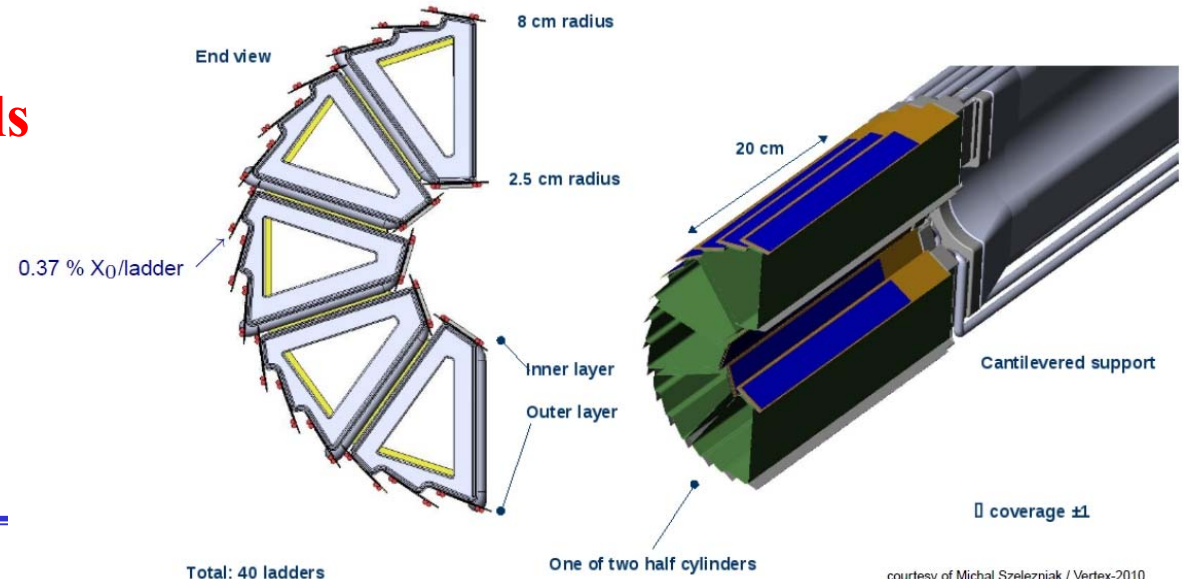
> 2 cm<sup>2</sup> active area, 0.7 Mpixel tracker

- Medium speed readout (100 μm integration → 10 kFrame/s)
- Spatial resolution < 4 μm for a pitch of 18.4 μm
- Efficiency for MIP > 99.5 %
- Fake hit rate < 10<sup>-6</sup>
- Radiation hardness > 10<sup>13</sup> n/cm<sup>2</sup> (high resistivity epi substrate)
- Easy to use, “off-shell” product: used already in several application



## First real scale exercise of large system based on MAPS: new STAR Microvertex Detector: AMS 0.35 μm OPTO CMOS

400 sensors (2x2 cm<sup>2</sup>), 300 Mpixels

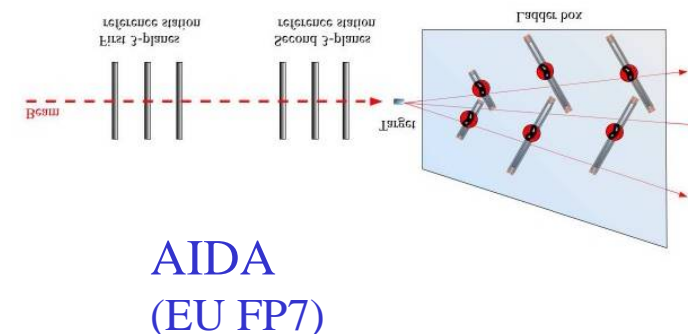
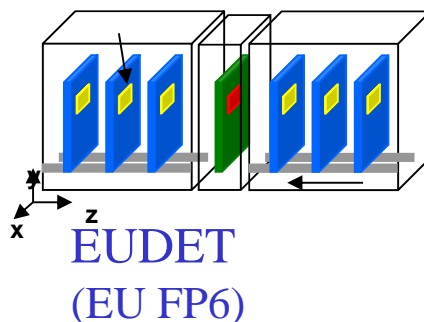


## Recent news (May 2013): 4 (out of 10) full sectors of ST AR Microvertex installed!

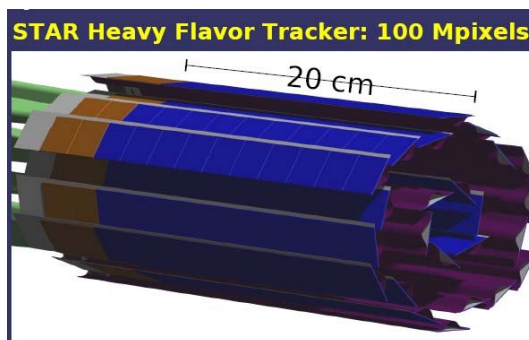


# Applications of CMOS sensors in physics experiments

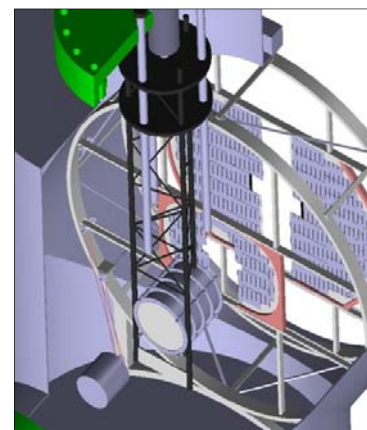
Generic beam telescope →  
internationale tests infrastructure



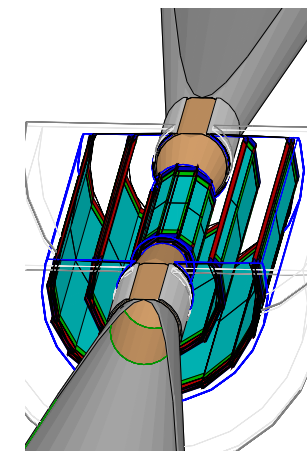
Vertex detectors →  
subatomic physics  
experiments



**STAR**  
(RHIC, Brookhaven)



**CBM**  
(SIS, Darmstadt)



**ILC**  
(?)

**In discussion: vertex detector for ALICE and SuperB, electromagnetic calorimeter (FoCal) for ALICE/LHC → 50 m<sup>2</sup> of CMOS sensors (~5 M€)**

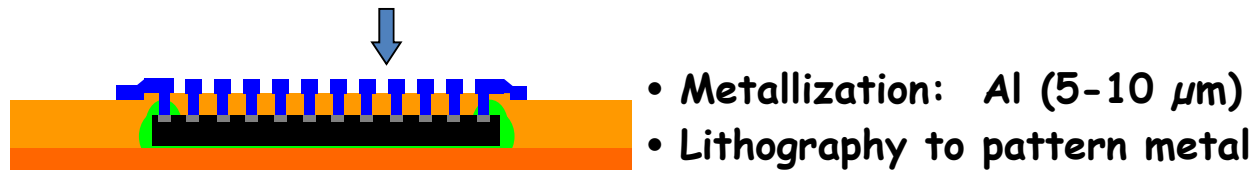
## Novel approach for ultra thin sensor packaging:

use of a “standard” flex PCB process for chip embedding in plastic foils

(IPHC/CERN CERNVIETTE Project, Rui de Oliveira, Serge Ferry)

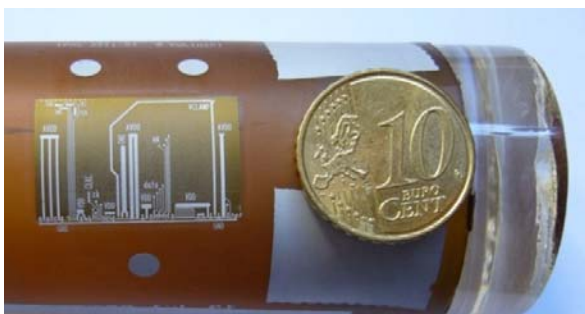
**The goal: < 0.1 % of  $X_0$  per sensor layer (all included)**

### Embedding principle

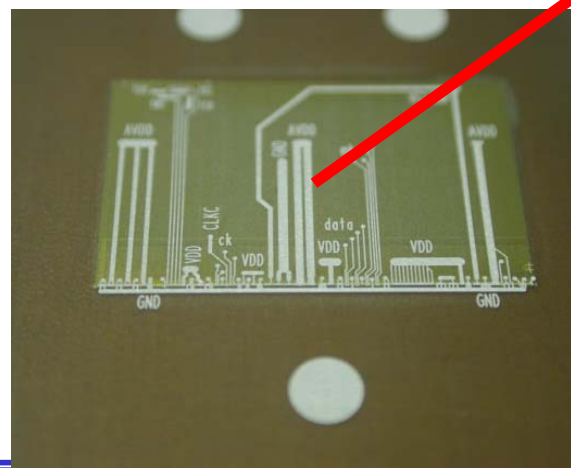
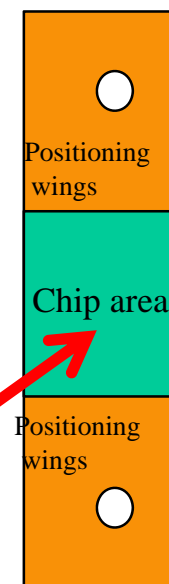
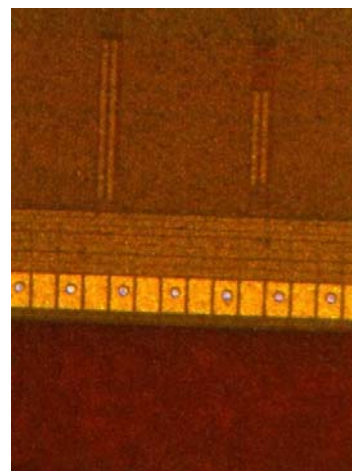




# First redistribution layer on top of M-26 (EUDET) CMOS pixel sensor, thinned down to 50 $\mu\text{m}$



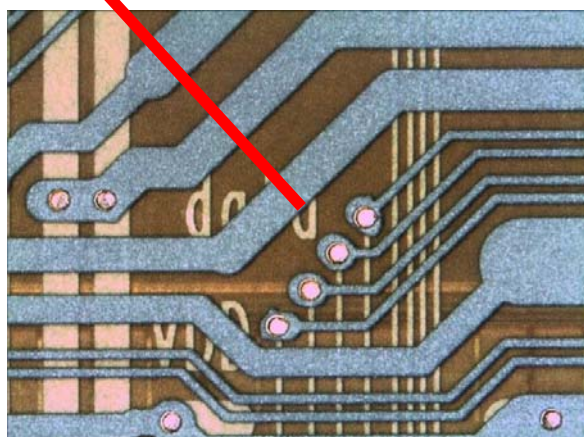
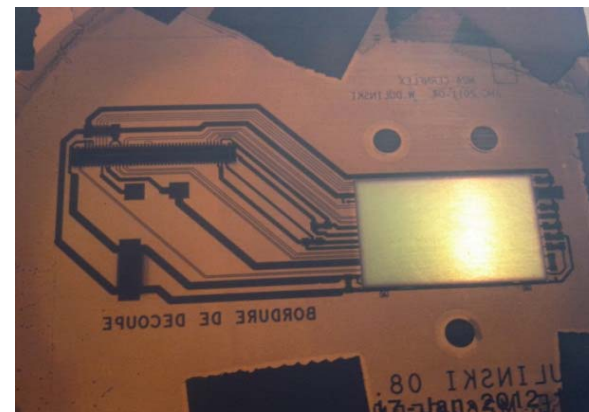
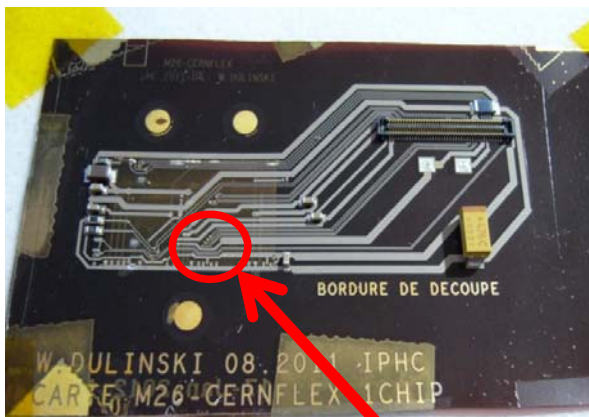
Solid state flexible sensor wrapped over cylindrical shape (R=20 mm)



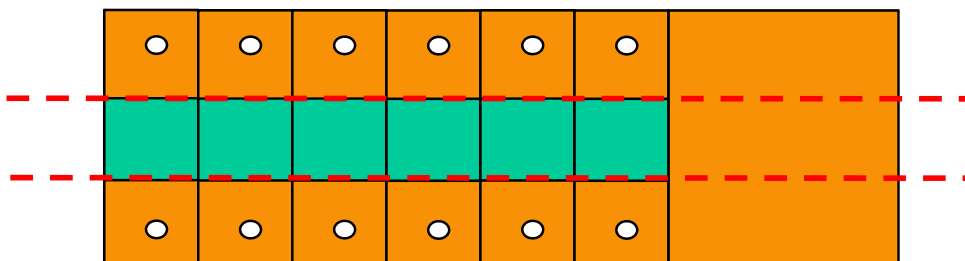
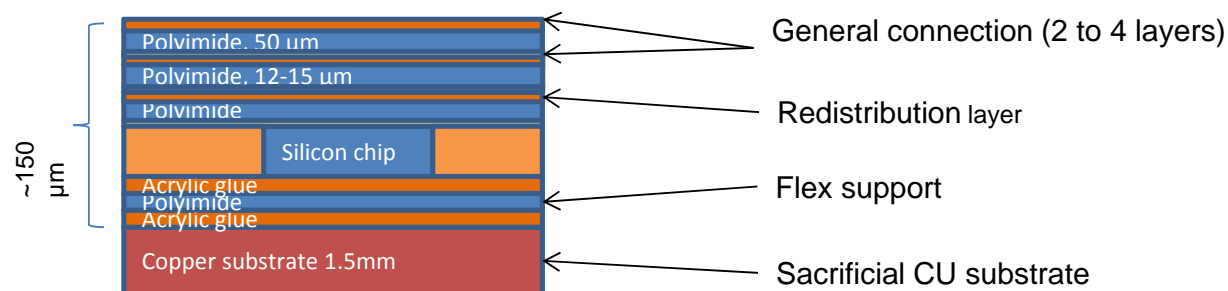
Laser flex cutting  
keeping  
positioning wings.

50um accuracy

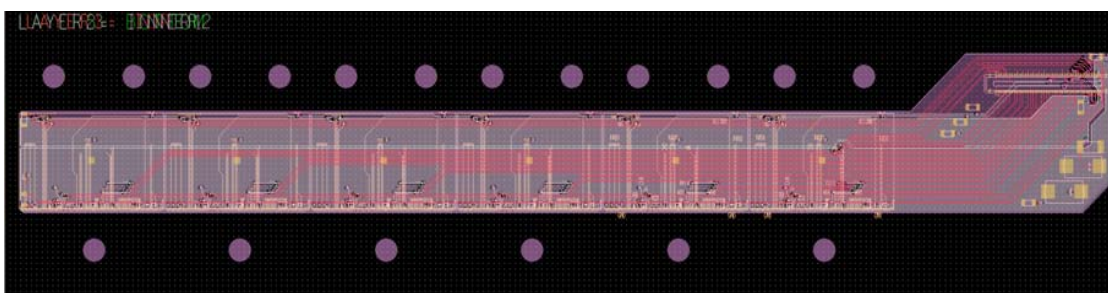
# Second layer just for preliminary check



# Multi chip embedding principle

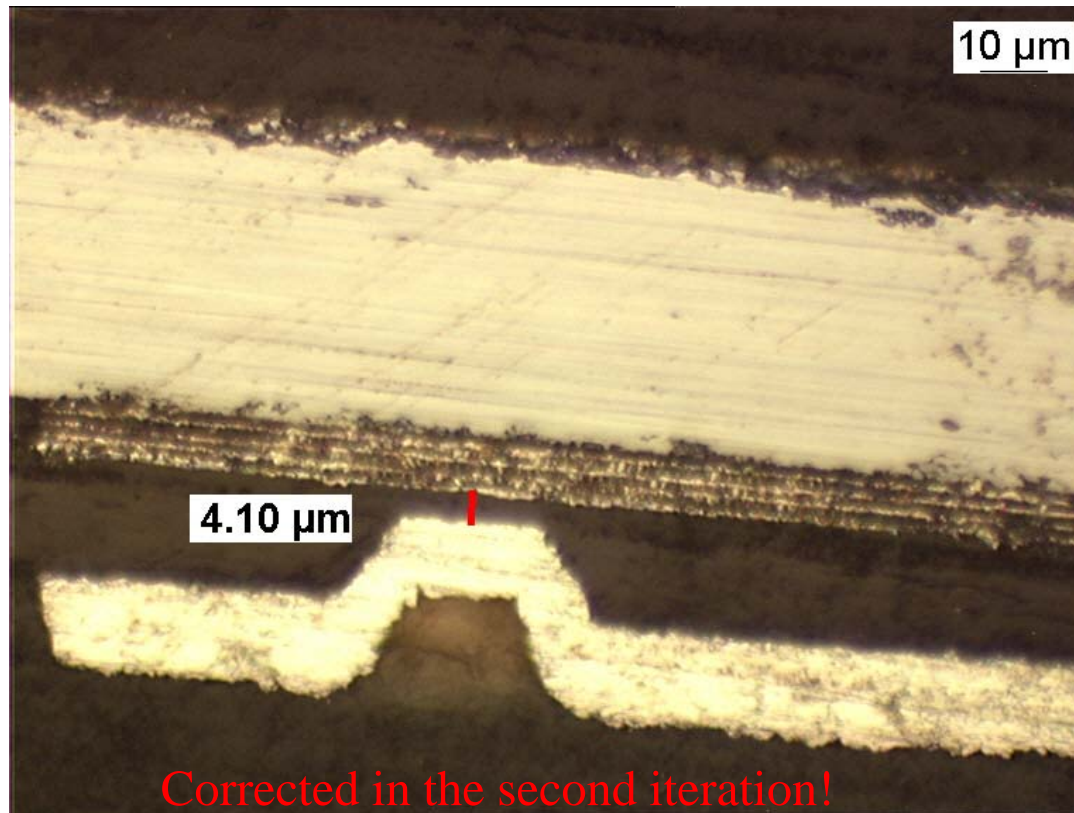


Redistribution layer  
is made on single  
chips



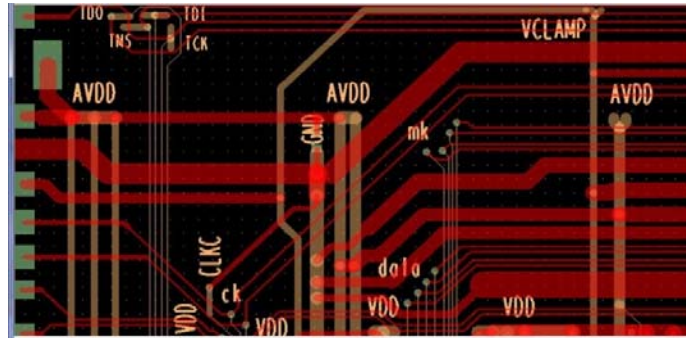
General  
connection are  
made on the full  
module (ladder)

**Some problems in the first iteration: too short plasma etching of glue layer, no electrical contacts... But excellent metal adhesion and thickness uniformity!**

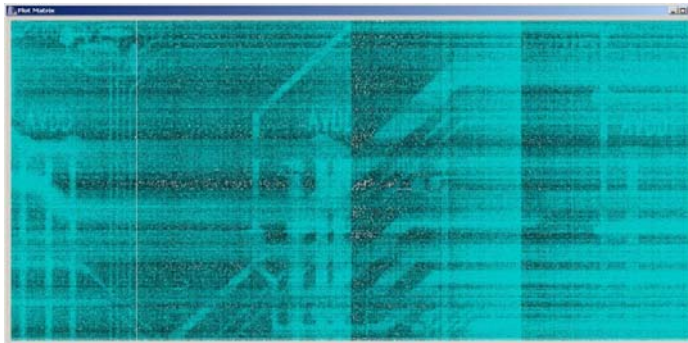


**Processing would be far easier if the first redistribution metal layer implemented already in the CMOS foundry (top metal)!**

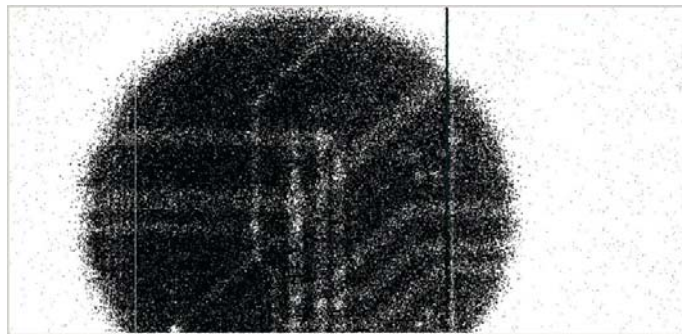
## Second iteration: one chip (2 metals) module works!



Lithography details of interconnecting metal (two layers of  $\sim 10 \mu\text{m}$  thick Al) deposited on top of the pixel sensor



“Shadow” of metal measured by pixel sensor in visible light



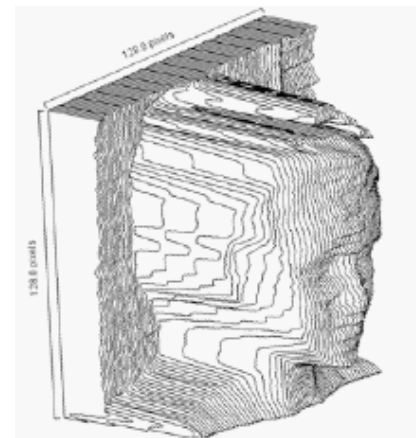
Auto-radiography of metal measured by pixel sensor using 5.9 keV Xrays ( $^{55}\text{Fe}$ )

**Next steps: two-chip ladder (June 2013) and then full ladder built with six M26 sensors (4 kapton/aluminum layers)...**

# Avalanche diodes for low light level, 3D-imaging

(credit to Iouri.Musienko@cern.ch for some slides)

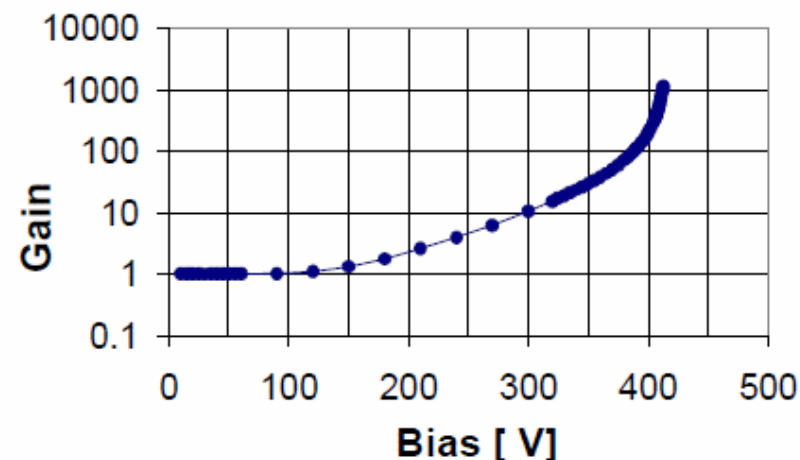
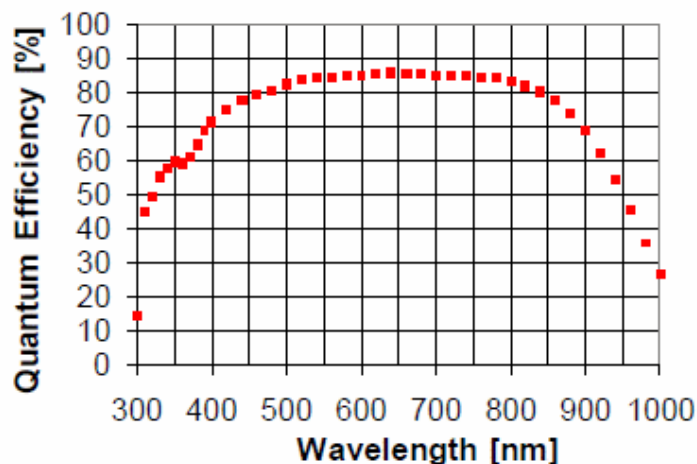
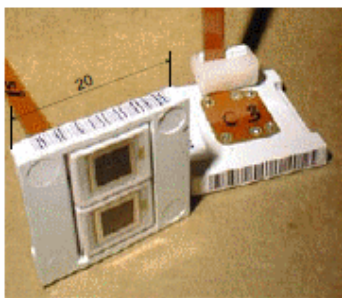
Applying high electric field in uniform p-n junction may cause an avalanche multiplication of electrons and holes created by absorbed light...



E. Charbon, DELFT

3D image recorded with TOF pixel sensor

## Linear APD parameters (CMS APD)

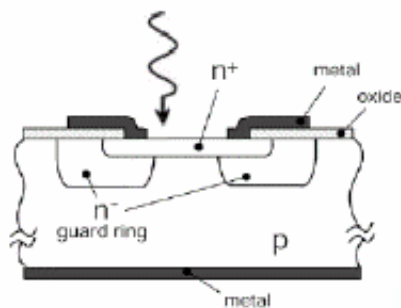


# APDs operated in Geiger mode

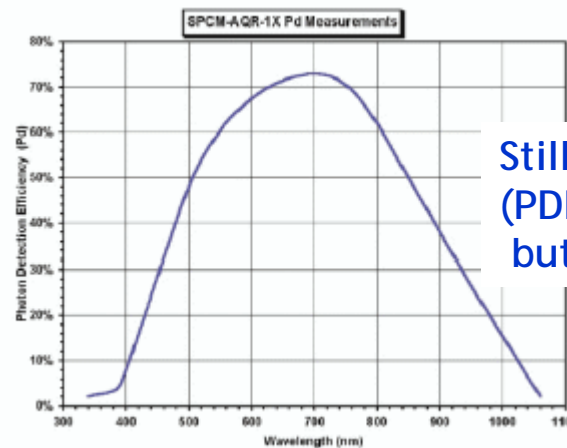
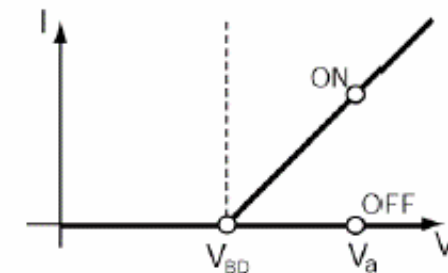
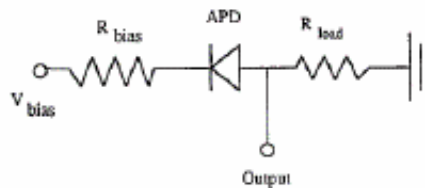
Photon counting with high efficiency → operate APDs over breakdown →  
Geiger mode APDs

Single pixel Geiger mode APDs were developed a long time ago  
( see for example: *R. Haitz et al, J.Appl.Phys. (1963-1965)*  
*R. McIntyre, J.Appl.Phys. v. 32 (1961)*)

## Planar APD structure

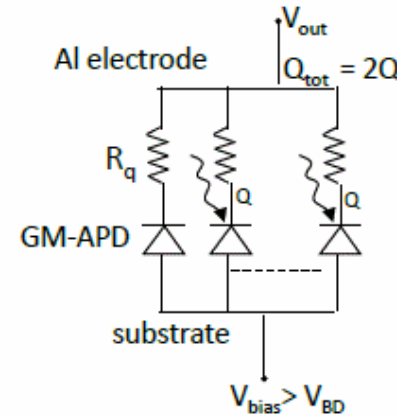
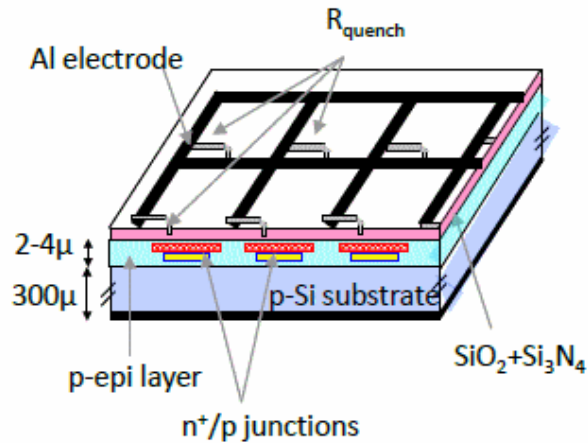


## Passive quenching circuit



Still excellent Single Photon Detection Eff.  
(PDE up to 70%) and timing (FWHM ~350 ps)  
but low temperature operation, **linearity**...

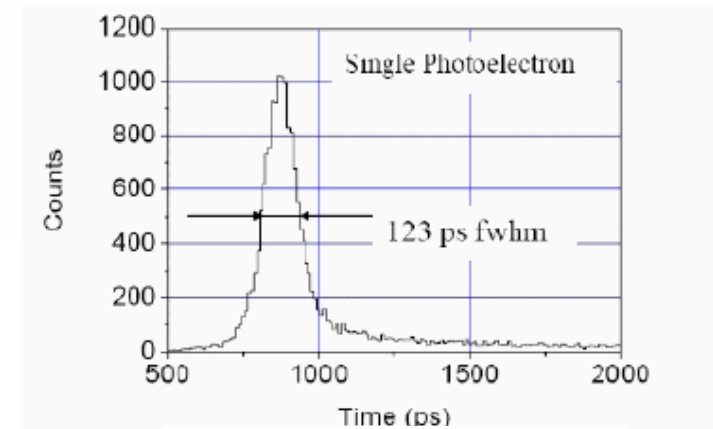
# SiPM structure and principles of operation



(EDIT-2011, CERN)

- SiPM is an array of small cells (SPADs) connected in parallel on a common substrate
- Each cell has its own quenching resistor (from 100kΩ to several MΩ)
- Common bias is applied to all cells (~10-20% over breakdown voltage)
- Cells fire independently
- The output signal is a sum of signals produced by individual cells

For small light pulses ( $N_\gamma \ll N_{\text{pixels}}$ ) SiPM works as an analog photon detector



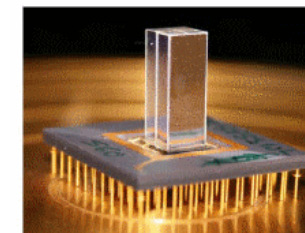
SiPM time resolution



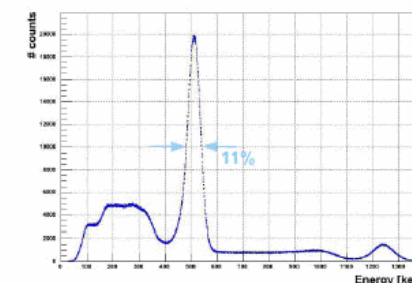
# Avalanche diodes (SPADs) in CMOS?

## dSiPM (Philips)

dSiPM - array of SPADs integrated in a standard CMOS process. Photons are detected and counted as digital signals using a dedicated cell electronics block next to each diode. This block also contains active quenching and recharge circuits, one bit memory for the selective inhibit of detector cells. A trigger network is used to propagate the trigger signal from all cells to the TDC.

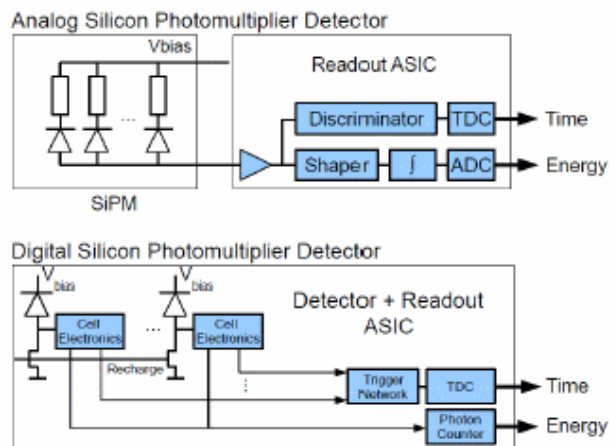


- 2x2 Array of 3x3x15mm<sup>3</sup> LYSO
- 1:1 coupling using MeltMount
- Illuminated by <sup>22</sup>Na source
- Corrected only for saturation
- dE/E = 11% (combined)

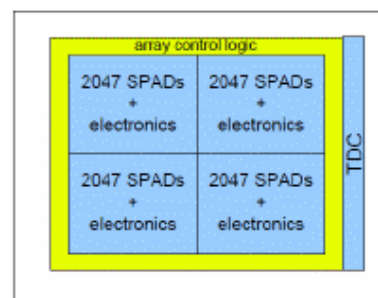
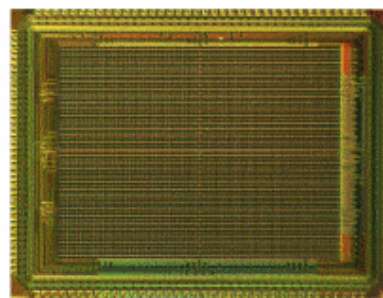


511 keV photon spectrum measured with dSiPM

### Digital SiPM – The Concept



### Digital SiPM – Test Chip Architecture



- Pixel composed of 4 identical sub-pixels with 2047 microcells each
- Microcell size 30μm x 52μm, 50% fill factor including electronics
- A 1 bit inhibit memory in each microcell to enable/disable faulty diodes
- Active quench & recharge, on-chip memory and array controllers
- Integrated time-to-digital converter with  $\sigma = 8\text{ps}$  time resolution
- Variable trigger (1-4 photons) and energy (1-64 photons) thresholds
- Acquisition controller implemented in FPGA for flexibility and testing

(T. Frach, IEEE-NSS/MIC, Orlando, Oct. 2009)

# *Conclusions*

*Les détecteurs à semi-conducteurs sont devenues les éléments incontournables dans les expériences de la physique subatomique, dans l'astrophysique et dans beaucoup des autres domaines...*

*Merci pour votre attention!*