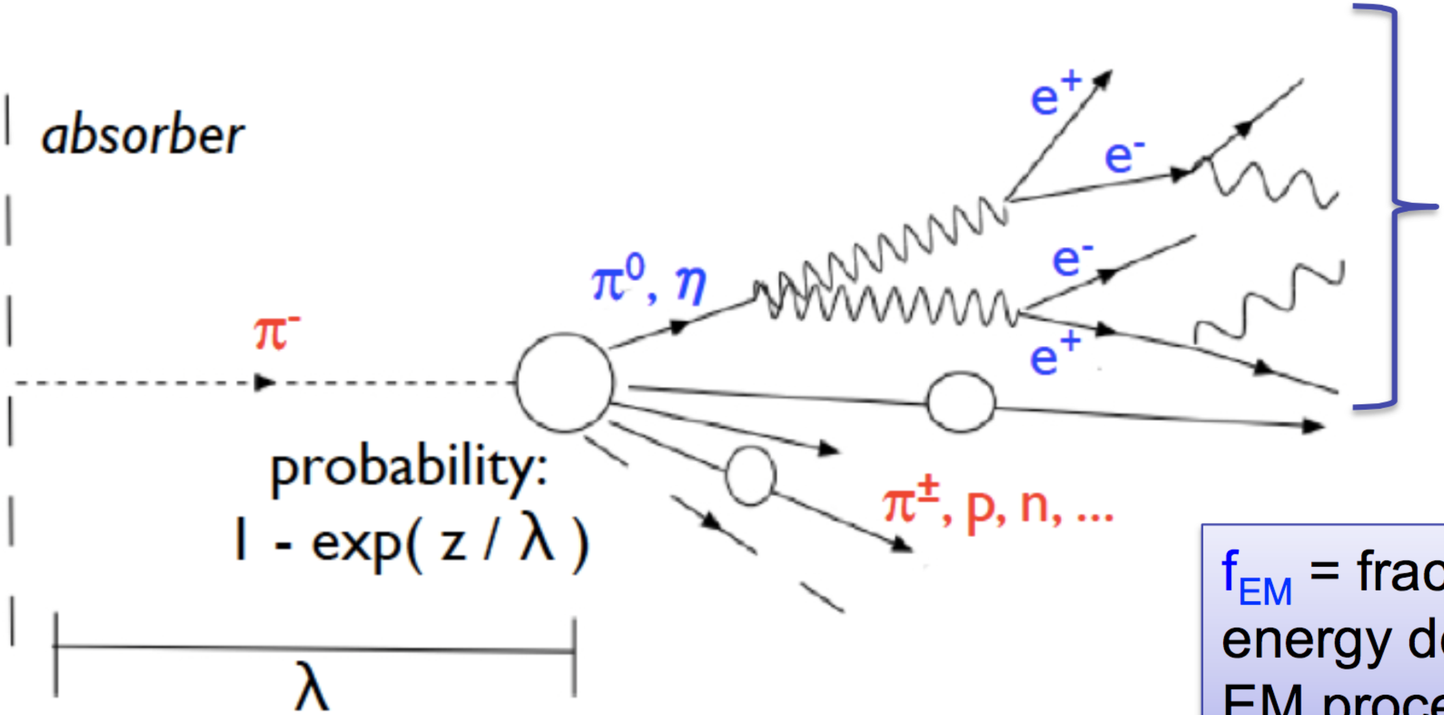
Astrofisica Nucleare e Subnucleare

Interazione Radiazione Materia

Astrofisica Nucleare e Subnucleare

Hadronic interactions

Hadronic showers



π_0 production is a one way street: all energy deposited via EM processes

f_{EM} = fraction of hadron energy deposited via EM processes

Electromagnetic → ionization, excitation (e±)
→ photo effect, scattering (γ)

Hadronic → ionization (π±, p)
→ invisible energy (binding, recoil)

Hadronic shower

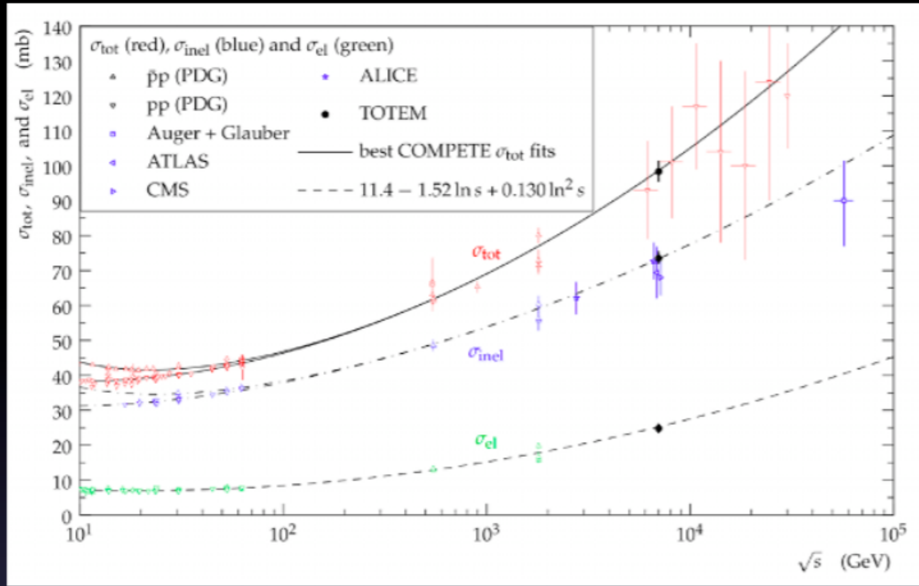
- Hadronic interaction Cross section

$$\sigma_{Tot} = \sigma_{el} + \sigma_{inel}$$

$$\sigma_{el} \approx 10mb \qquad \sigma_{inel} \approx A^{2/3}$$

$$\sigma_{Tot} = \sigma_{tot}(pp)A^{2/3}$$

where: $\sigma_{tot}(pp)$ increases with $\sqrt{s}$



- Hadronic interaction length

$$\lambda_{\text{int}} = \frac{1}{\sigma_{tot} \cdot n} = \frac{A\rho}{\sigma_{pp} A^{2/3} N_A} \approx \left(35g/cm^2\right) A^{1/3}$$

$$N(x) = N(0)\mathrm{e}^{-x/\lambda_{\text{int}}}$$

- λ_{int} characterizes both longitudinal and transverse shower profile

Rule of thumb argument: the geometric cross section goes as the square of the size of the nucleus, a_N^2, and since the nuclear radius scales as $a_N \sim A^{1/3}$, the nuclear mean free path in gm/cm^2 units scales as $A^{1/3}$.

Hadronic shower

Hadronic interaction:

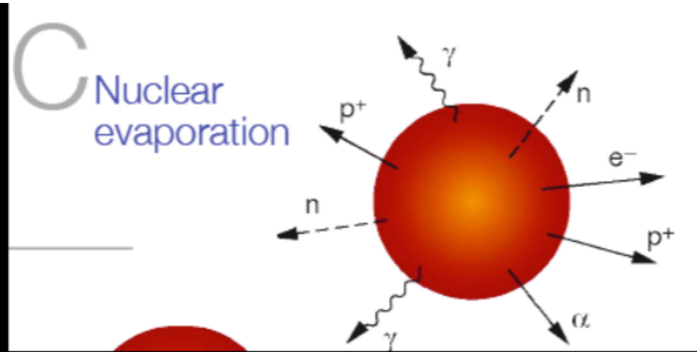
Elastic:

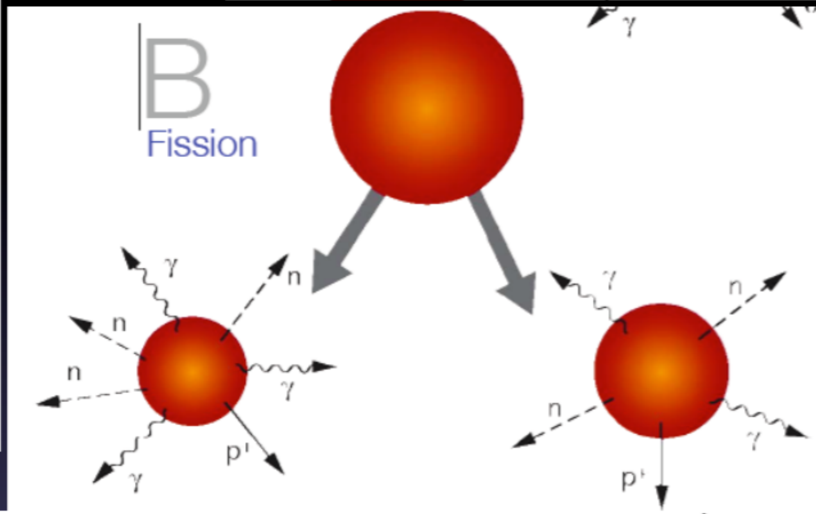
$$p + \text{Nucleus} \rightarrow p + \text{Nucleus}$$

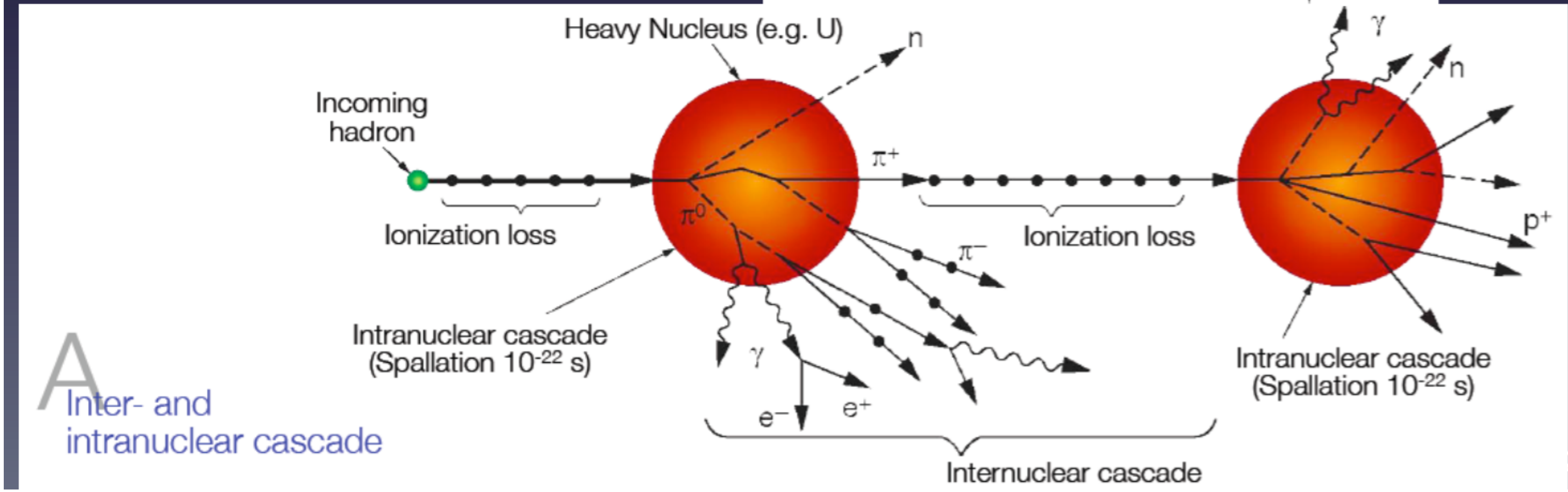
Inelastic:

$$p + \text{Nucleus} \rightarrow$$
$$\pi^+ + \pi^- + \pi^0 + \ldots + \text{Nucleus}^*$$

$$\left[\begin{array}{l} \text{Nucleus}^* \rightarrow \text{Nucleus A} + n, p, \alpha, \ldots \\ \qquad\qquad \rightarrow \text{Nucleus B} + 5p, n, \pi, \ldots \\ \qquad\qquad \rightarrow \text{Nuclear fission} \end{array}\right]$$







Courtesy of H. C. Schoultz Coulon

$$X_{\substack{int\\nucl.}} = \frac{A}{N_a}\frac{1}{\sigma_{\substack{int\\nucl.}}}$$

$$\sigma_{int} \simeq \mathcal{A}^{2/3}\,\sigma_{pp} \qquad\qquad \mathcal{A} = \frac{A}{m_p}$$

$r \propto \mathcal{A}^{1/3}$

$\sigma \propto r^2 \propto \mathcal{A}^{2/3}$

$$X_{int} \simeq \frac{A}{N_a \mathcal{A}^{2/3}\sigma_{pp}}$$

$$\sigma_{pp} \approx 40 \text{ mb}$$

Cu $(\mathcal{A}) \Rightarrow 64$

$\mathcal{A}^{2/3} = 16 \qquad\qquad \mathcal{A}^{0.7} = 18$

$\sigma_{Cu} = 16 \times 40 \text{ mb} = 640 \text{ mb} \simeq 0.6 \text{ b}$

$$E_{c_{\substack{int\\nucl}}} = \frac{\left(-\frac{dE}{dx}\right)_{\substack{ion\\MIN}} \cdot A}{N_a\, \sigma_{\substack{int\\nucl}}} = \underbrace{\frac{3.5\,\frac{Z}{A}\,A}{N_a\,\sigma_{\substack{rad\\(e)}}}}_{E_{c\,(e)}} \frac{\sigma_{\substack{rad\\(e)}}}{\sigma_{\substack{int\\nucl}}}$$

$$E_{c_{\substack{int\\nucl}}} = E_{\substack{c\\(e)}} \frac{\sigma_{rad}}{\sigma_{\substack{int\\nucl}}} \cong E_{\substack{c\\(e)}} \times 10 \quad !!$$

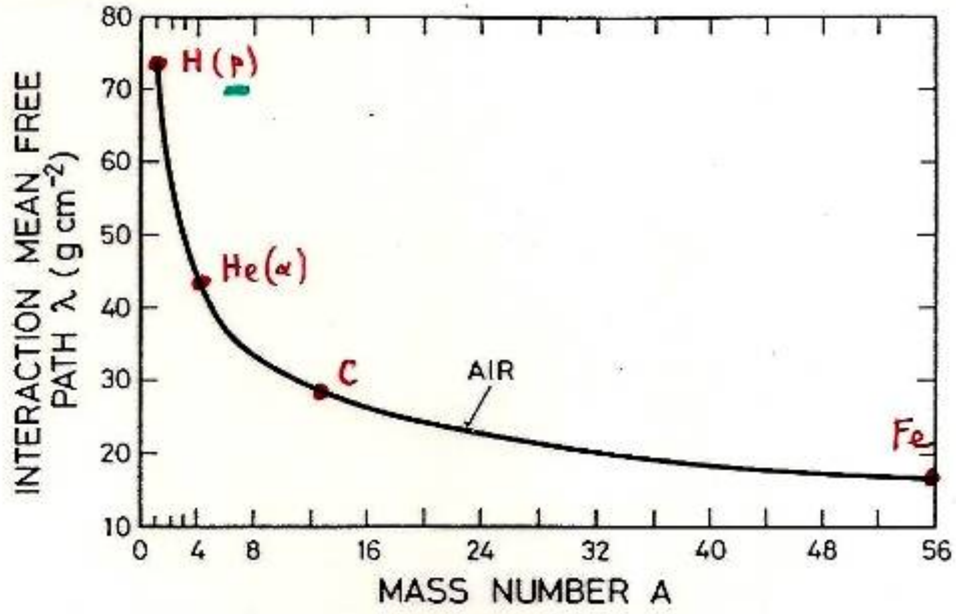


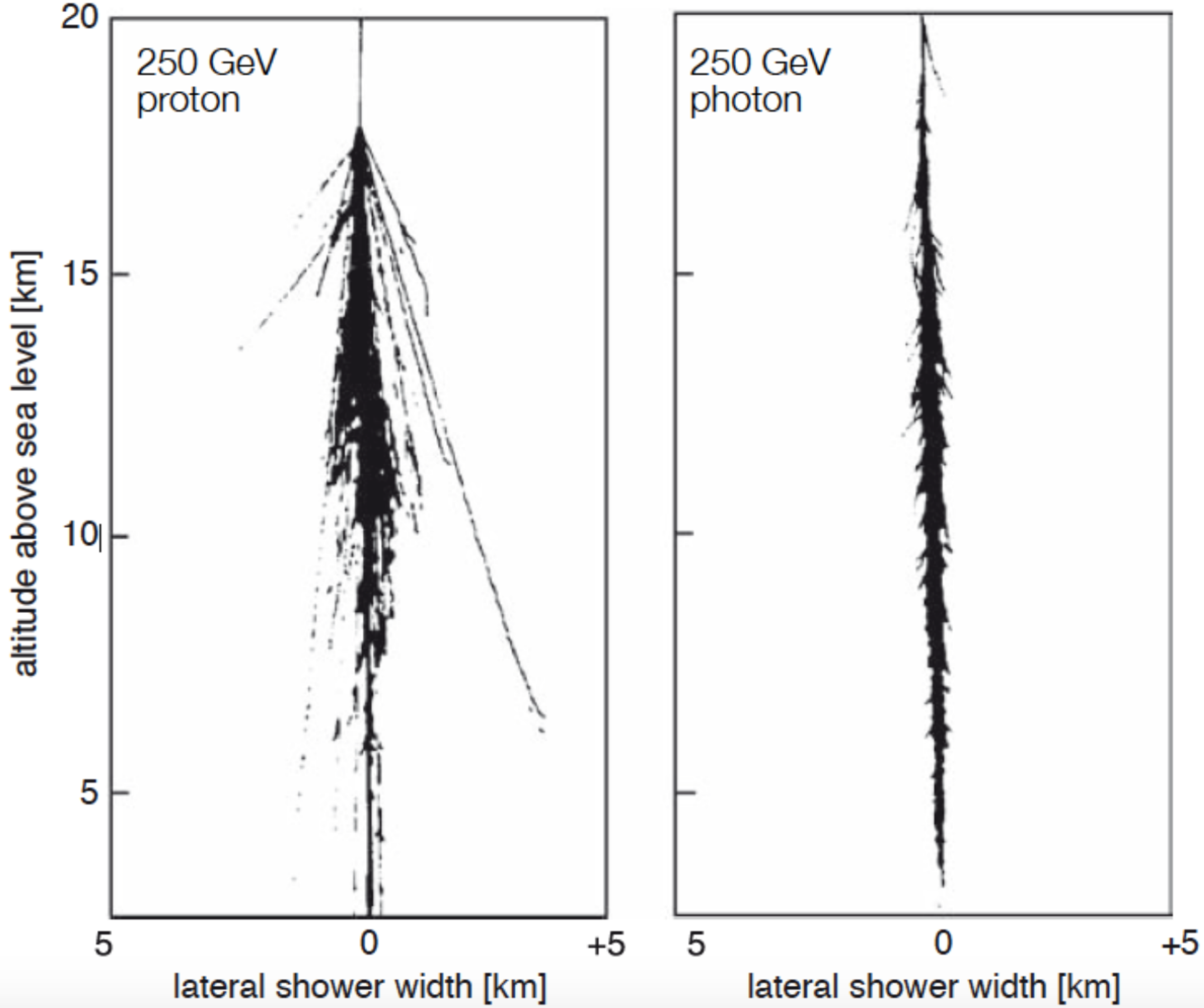
Fig. 1.1.1: Interaction mean free path for high energy nuclear interactions in air versus projectile mass.

$X_{INT.\,NUCL.} \longrightarrow \lambda_I$

Table 5. *Radiation length X_0, critical energy E_c and hadronic absorption length λ_{had}^{int} for some materials*

Material	X_0 (g/cm²)	Kg/m²	E_c (MeV)	λ_{had} (g/cm²)
H_2	63	630	340	52.4
Al	24	240	47	106.4
Ar	20	200	35	119.7
Fe	13.8	138	24	131.9
Pb	6.3	63	6.9	193.7
Lead glass SF 5	9.6	96	~ 11.8	
Plexiglas	40.5	405	80	83.6
H_2O	36	360	93	84.9
NaI(Tl)	9.5	95	12.5	152.0
$Bi_4Ge_3O_{12}$	8.0	80	10.5	164

Comparison hadronic vs EM showers



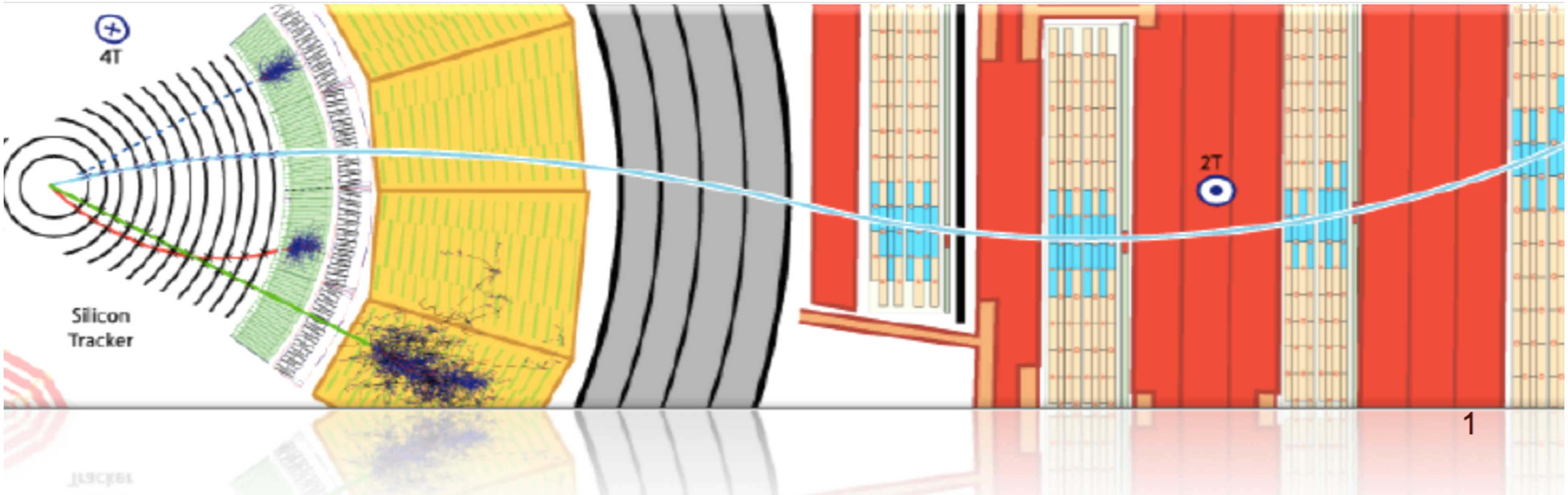
Simulated air showers

Astrofisica Nucleare e Subnucleare

DAQ

Detector Systems

4th July 2012



Trigger

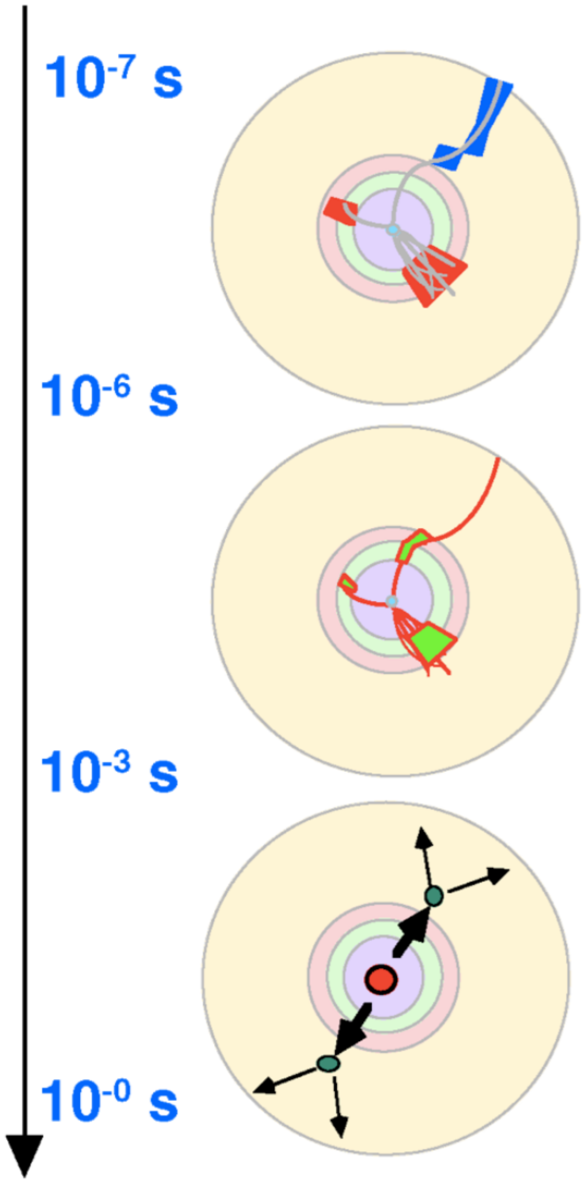
Definition: on-line identification of the most interesting physics events and selection for storage.

At the LHC: Interesting physics: 0.1 ÷ 10 Hz, while event rate: ≈1 GHz,
➔ one "interesting event" every 100 millions!
Impossible to select them all on real time.

Therefore, reduce events to a number that can be stored for offline processing and analysis.

Numbers: keep ≈200 Hz → one every 10 millions
Event size ≈ 1-2MB → need to write up to 25GB/min.
Up to 4 millions GB/yr (≈1 million dvd's/yr !!!).
Moreover: need ≈30s to reconstruct each event offline

LHC Trigger Levels



Collision rate 10^{9} Hz

Channel data sampling at 40 MHz

Level-1 selected events 10^{5} Hz

Particle identification (High p_T e, μ, jets, missing E_T)

- Local pattern recognition
- Energy evaluation on prompt macro-granular information

Level-2 selected events 10^{3} Hz

Clean particle signature (Z, W, ..)

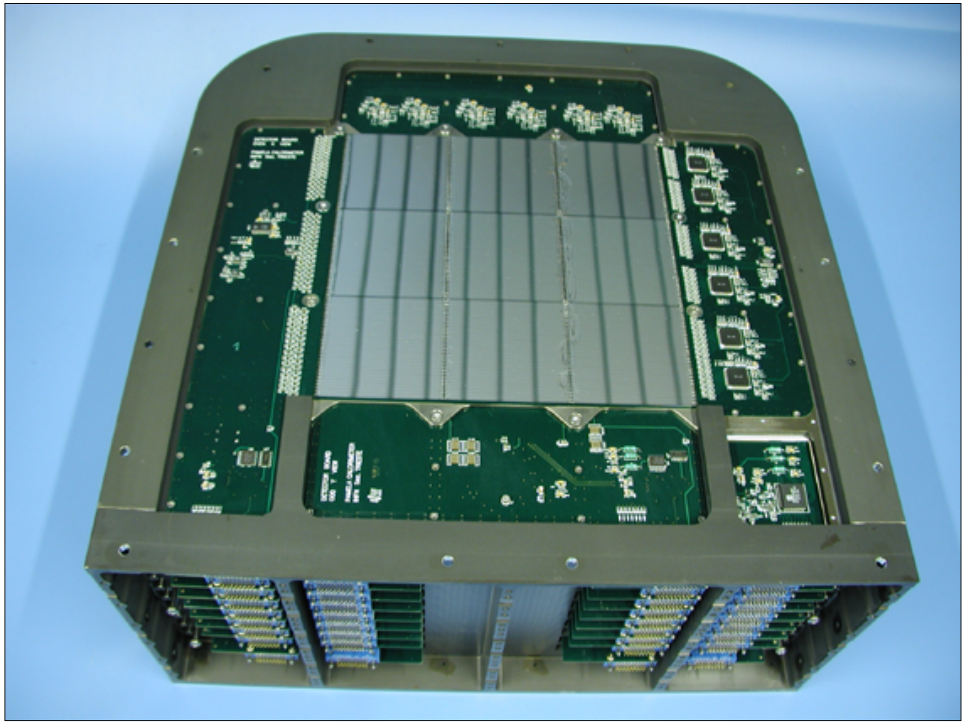
- Finer granularity precise measurement
- Kinematics. effective mass cuts and event topology
- Track reconstruction and detector matching

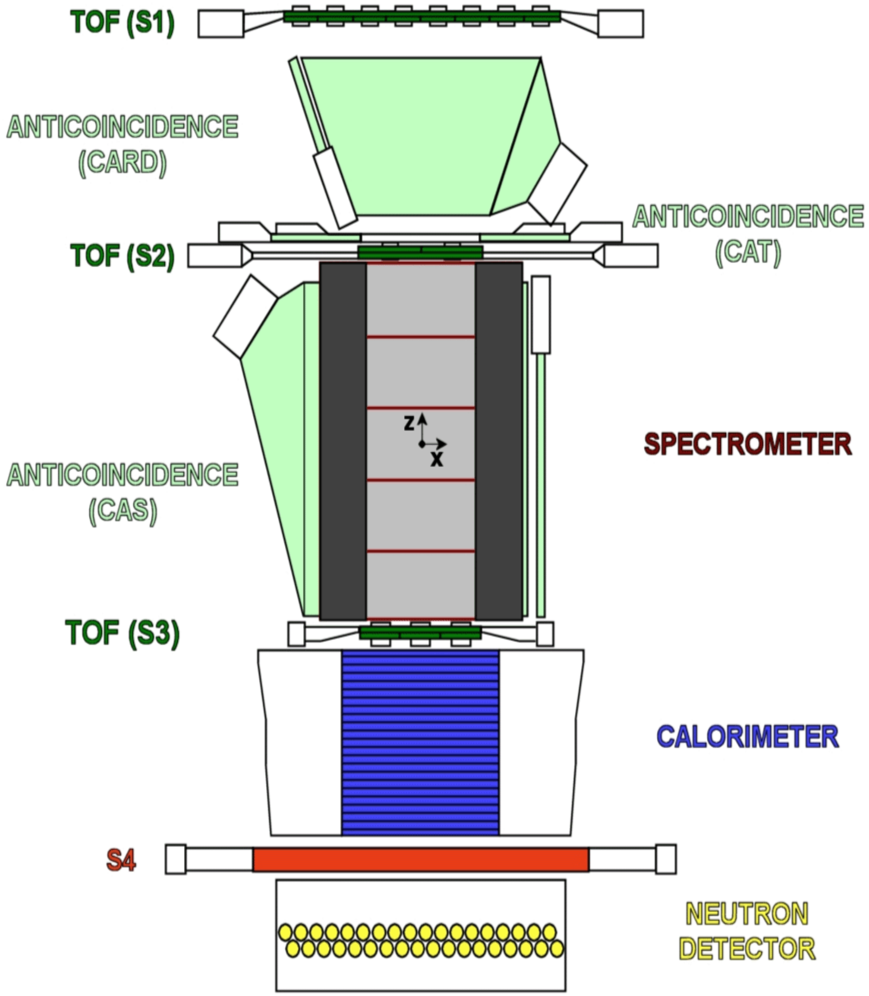
Level-3 events to tape 100- 300 Hz

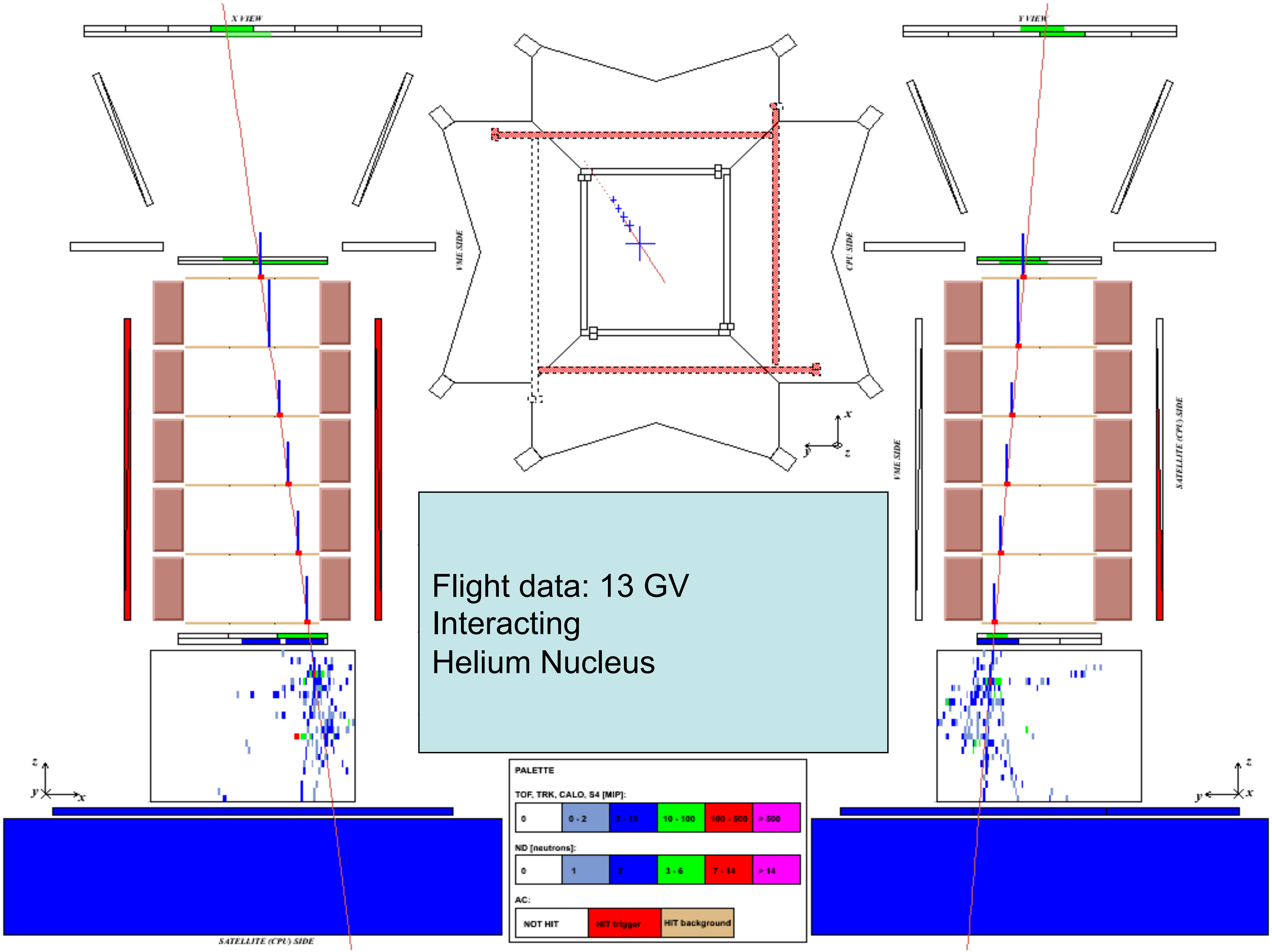
Physics process identification

- Event reconstruction and analysis

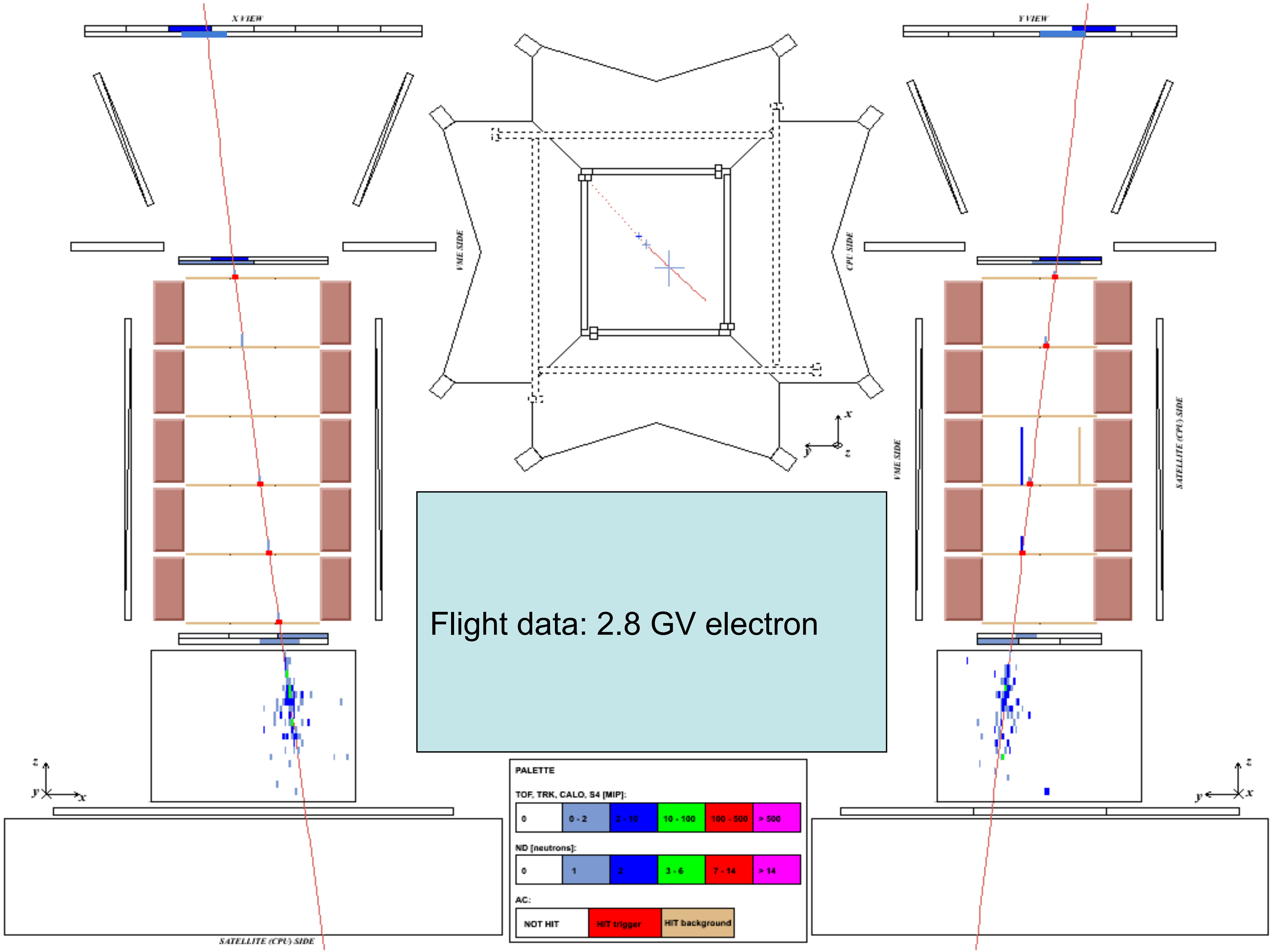
PAMELA




TOF (S1)
ANTICOINCIDENCE (CARD)
ANTICOINCIDENCE (CAT)
TOF (S2)
Z
X
SPECTROMETER
ANTICOINCIDENCE (CAS)
TOF (S3)
CALORIMETER
S4
NEUTRON DETECTOR

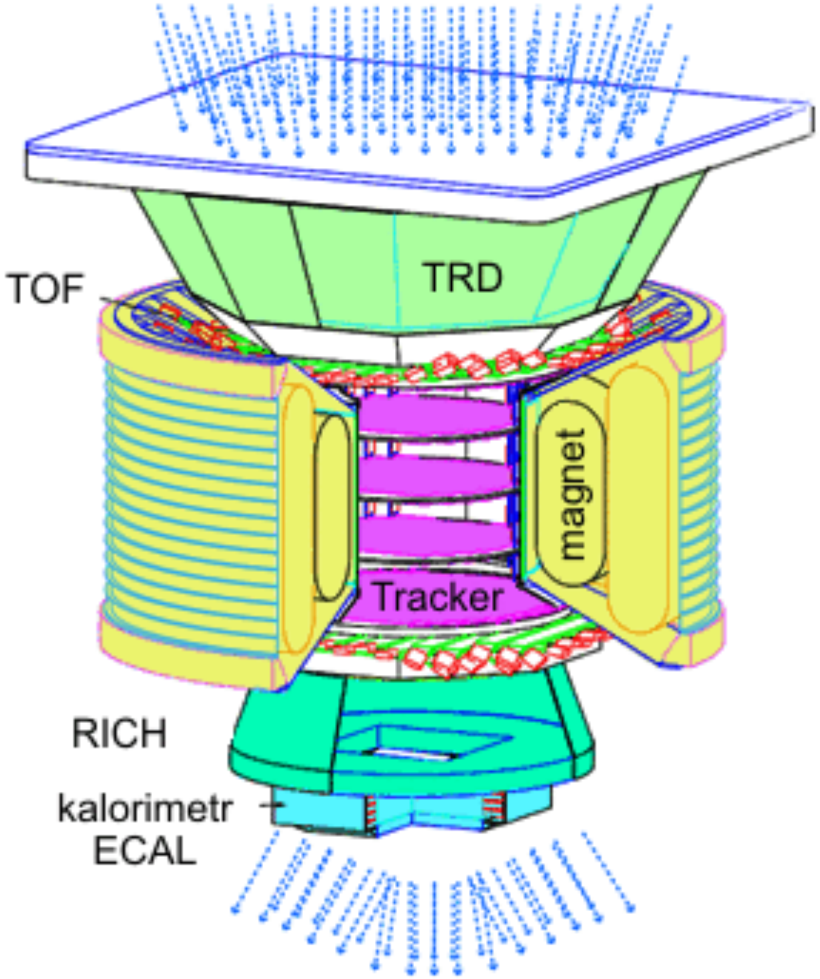


Flight data: 13 GV
Interacting
Helium Nucleus

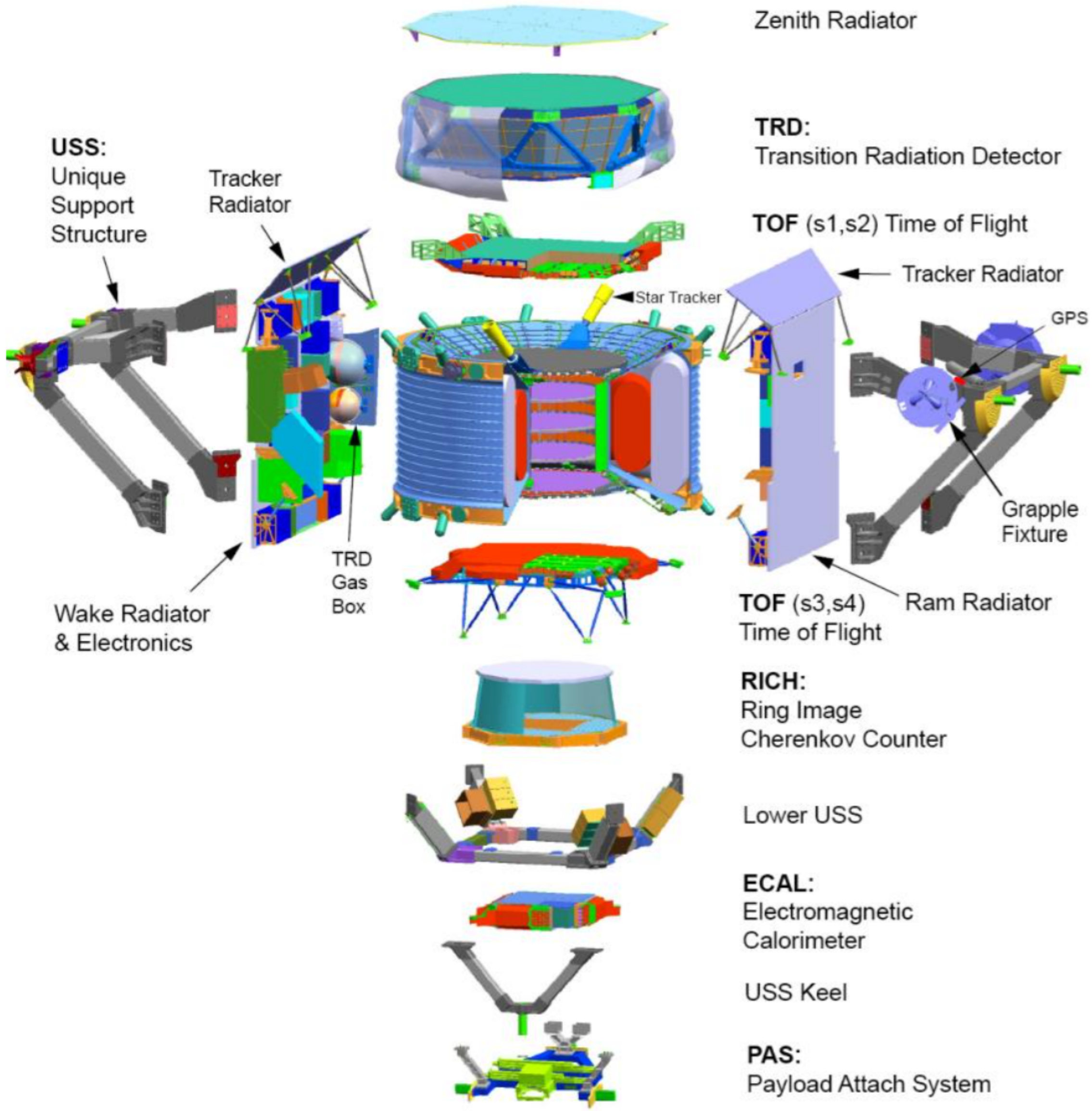


Flight data: 2.8 GV electron

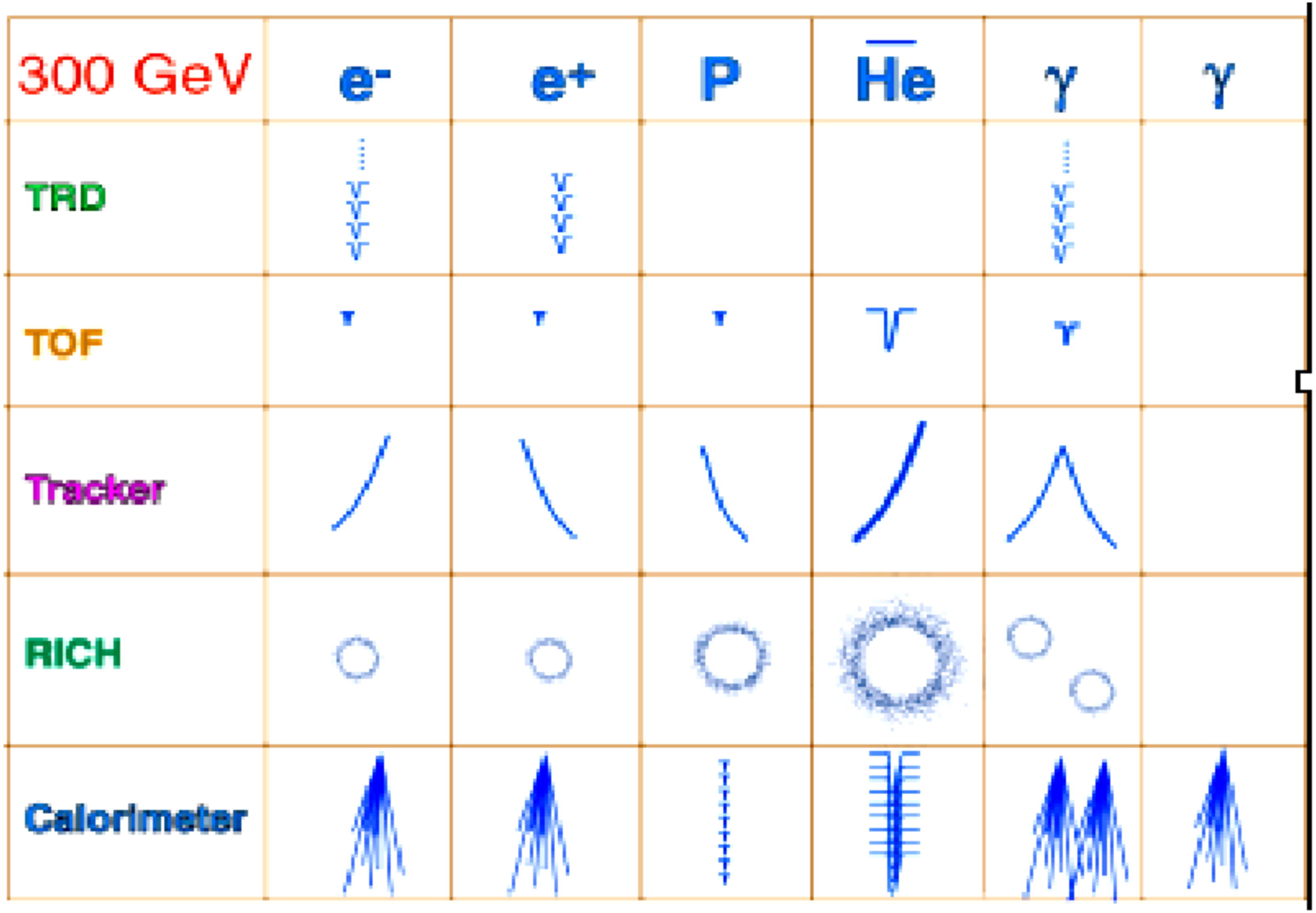
AMS-02



AMS


Zenith Radiator
TRD:
Transition Radiation Detector
USS:
Unique
Support
Structure
Tracker
Radiator
TOF (s1,s2) Time of Flight
Tracker Radiator
Star Tracker
GPS
Grapple
Fixture
TRD
Gas
Box
Wake Radiator
& Electronics
TOF (s3,s4)
Time of Flight
Ram Radiator
RICH:
Ring Image
Cherenkov Counter
Lower USS
ECAL:
Electromagnetic
Calorimeter
USS Keel
PAS:
Payload Attach System

AMS triggers

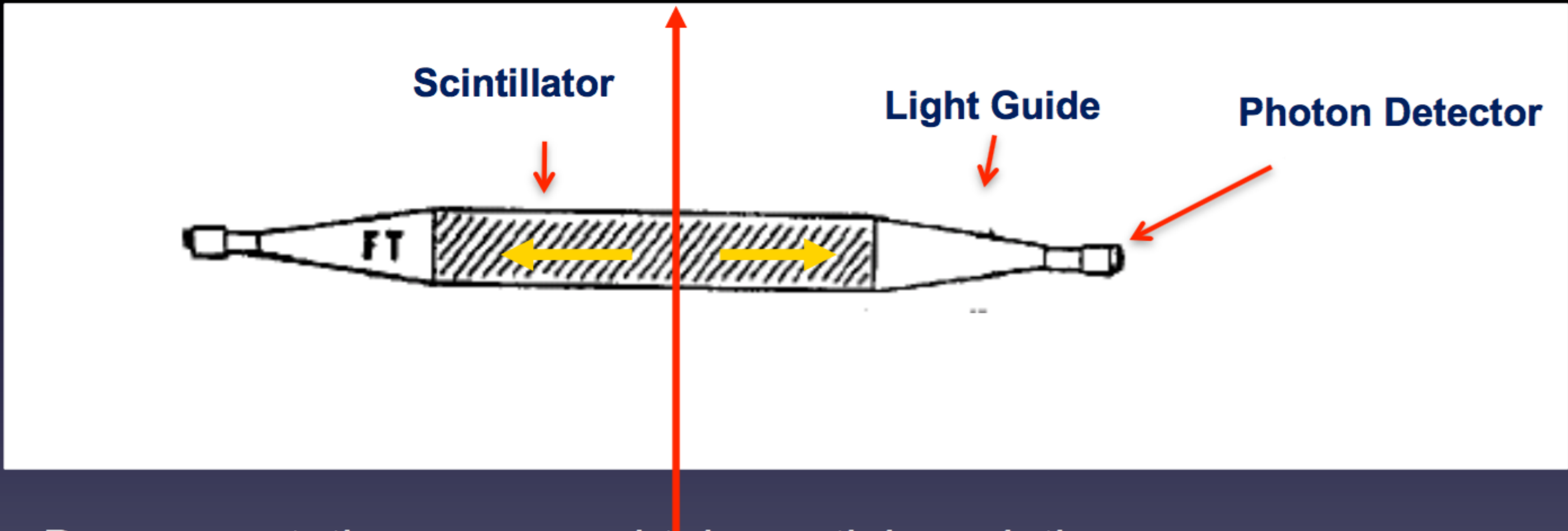


Astrofisica Nucleare e Subnucleare

Scintillation Detectors

Scintillators

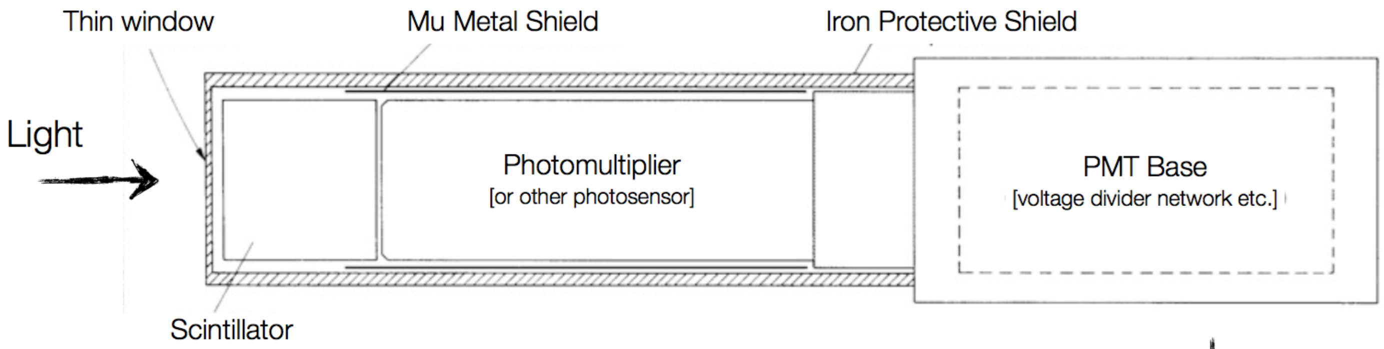
- Photons are being reflected towards the ends of the scintillator.
- A light guide brings the photons to the Photomultipliers where the photons are converted to an electrical signal.



- By segmentation one can obtain spatial resolution.
- Because of the excellent timing properties (<1ns) the arrival time, or time of flight, can be measured very accurately →Trigger, Time of Flight.

Scintillators

Scintillators – Basic Counter Setup

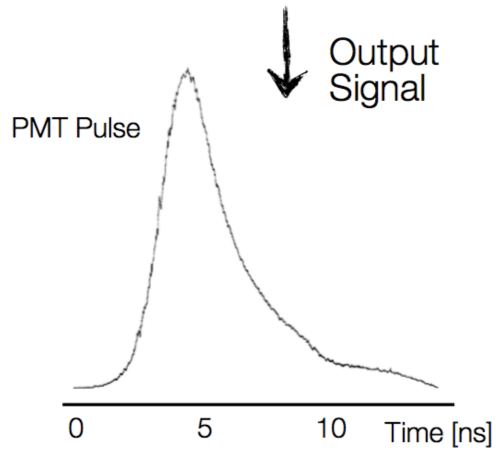


Scintillator Types:

Organic Scintillators
Inorganic Crystals
Gases

Photosensors

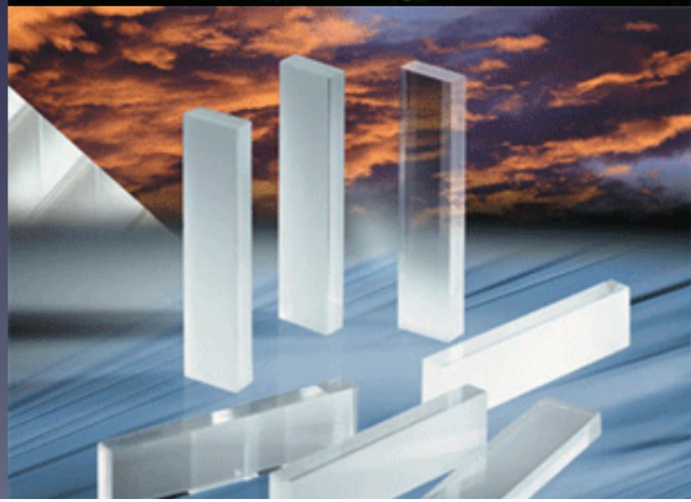
Photomultipliers
Micro-Channel Plates
Hybrid Photo Diodes
Visible Light Photon Counter
Silicon Photo Multipliers



Scintillators

- dE/dx converted into light and then it is detected via photo-sensor (photomultipliers, SiPM,….)
- Main features
  - Sensitivity to energy
  - Fast time response
  - Pulse shape discrimination
- Requirements:
  - High efficiency for conversion of exciting energy to fluorescent radiation
  - Transparency to its fluorescent radiation to allow transmission of light
  - Emission of light in a spectral range detectable for photo-sensors
  - Short decay time to allow fast response

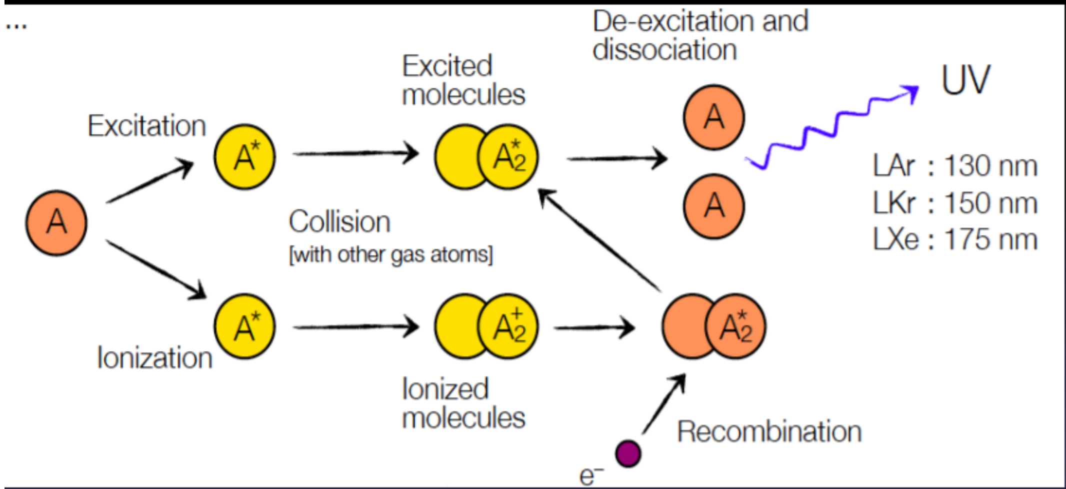
Plastic Scintillator BC412

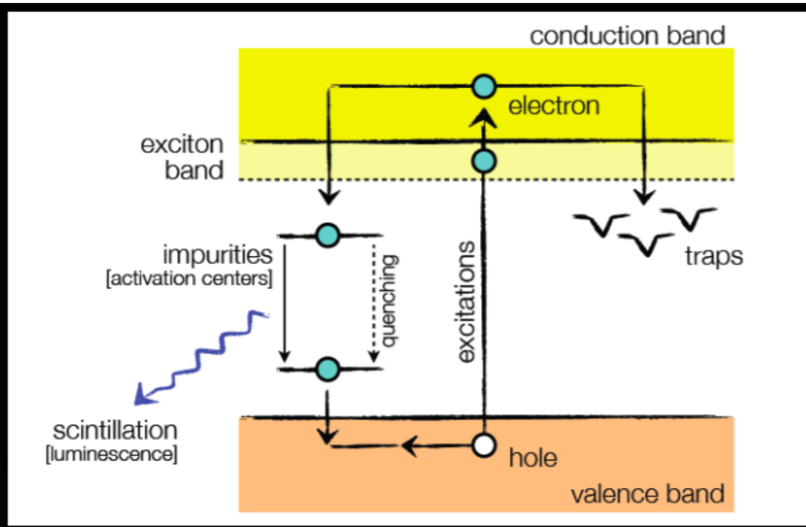


Scintillators

- Inorganic (Sodium iodide (NaI), Cesium iodide (CsI),…)

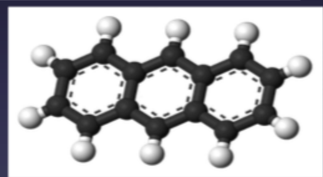
…





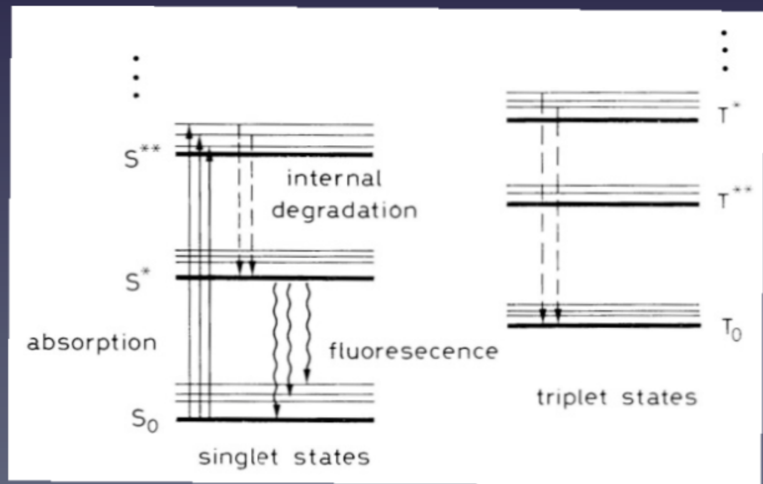
- Noble gasses (Liquid Argon, Liquid Xenon…)

- Organic crystals
  - Aromatic hydrocarbon compounds with benzene rings such as Anthracene (C14H10), etc



- Plastic scintillators
  - Organic scintillators suspended in the aromatic polymer (easy to mold and machine)
- Liquid scintillators

- Molecule structure generates energy levels with transition λ=360-500 nm



Scintillators

Inorganic Scintillators – Properties

Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [μs]	Photons/MeV
NaI	3.7	1.78	303	0.06	$8 \cdot 10^4$
NaI(Tl)	3.7	1.85	410	0.25	$4 \cdot 10^4$
CsI(Tl)	4.5	1.80	565	1.0	$1.1 \cdot 10^4$
$Bi_4Ge_3O_{12}$	7.1	2.15	480	0.30	$2.8 \cdot 10^3$
CsF	4.1	1.48	390	0.003	$2 \cdot 10^3$
LSO	7.4	1.82	420	0.04	$1.4 \cdot 10^4$
$PbWO_4$	8.3	1.82	420	0.006	$2 \cdot 10^2$
LHe	0.1	1.02	390	0.01/1.6	$2 \cdot 10^2$
LAr	1.4	1.29*	150	0.005/0.86	$4 \cdot 10^4$
LXe	3.1	1.60*	150	0.003/0.02	$4 \cdot 10^4$

* at 170 nm

Scintillators

Organic Scintillators – Properties

Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4 \cdot 10^3$
Antracene	1.25	1.59	448	30	$4 \cdot 10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2 \cdot 10^4$
NE102*	1.03	1.58	425	2.5	$2.5 \cdot 10^4$
NE104*	1.03	1.58	405	1.8	$2.4 \cdot 10^4$
NE110*	1.03	1.58	437	3.3	$2.4 \cdot 10^4$
NE111*	1.03	1.58	370	1.7	$2.3 \cdot 10^4$
BC400**	1.03	1.58	423	2.4	$2.5 \cdot 10^2$
BC428**	1.03	1.58	480	12.5	$2.2 \cdot 10^4$
BC443**	1.05	1.58	425	2.2	$2.4 \cdot 10^4$

* Nuclear Enterprises, U.K.
** Bicron Corporation, USA

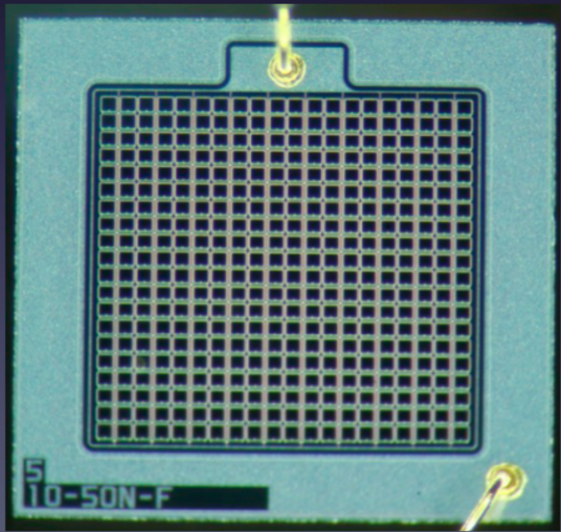
Photo-detectors

- Convert light into an electronic signal by using the photo-electric effect to convert photons into photo-electrons (p.e.)
- Requirement :
  - High Photon Detection Efficiency (PDE) or
  - Quantum Efficiency; Q.E. = $N_{p.e.}/N_{photons}$

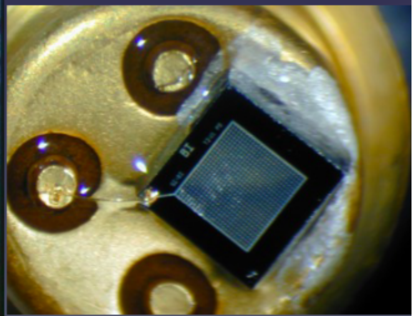
- Photomultipliers

- SiPM

Hamamatsu MPPC



One of the first SiPM Pulsar, Moscow



PMTs

Photomultipliers

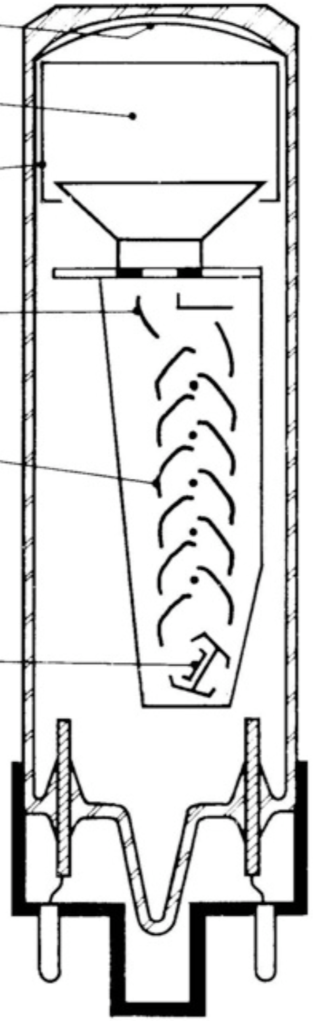
Principle:

Electron emission
from photo cathode

Secondary emission
from dynodes; dynode gain: 3-50 [f(E)]

Typical PMT Gain: > 10^6
[PMT can see single photons ...]

PMT
Collection



Si PMT

Silicon Photomultipliers

Principle:

Pixelized photo diodes
operated in Geiger Mode

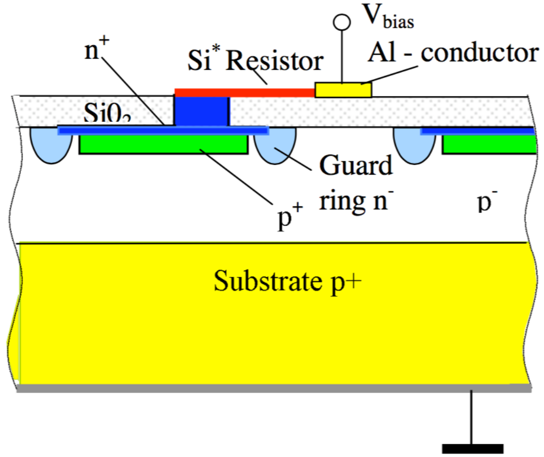
Single pixel works as a binary device

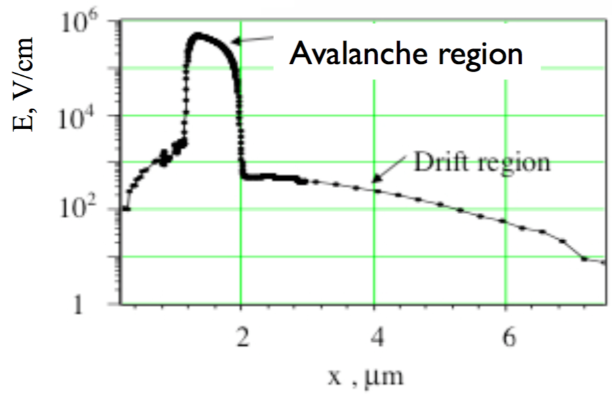
Energy = #photons seen by
summing over all pixels

Features:

Granularity	:	10^3 pixels/mm^2
Gain	:	10^6
Bias Voltage	:	< 100 V
Efficiency	:	ca. 30 %

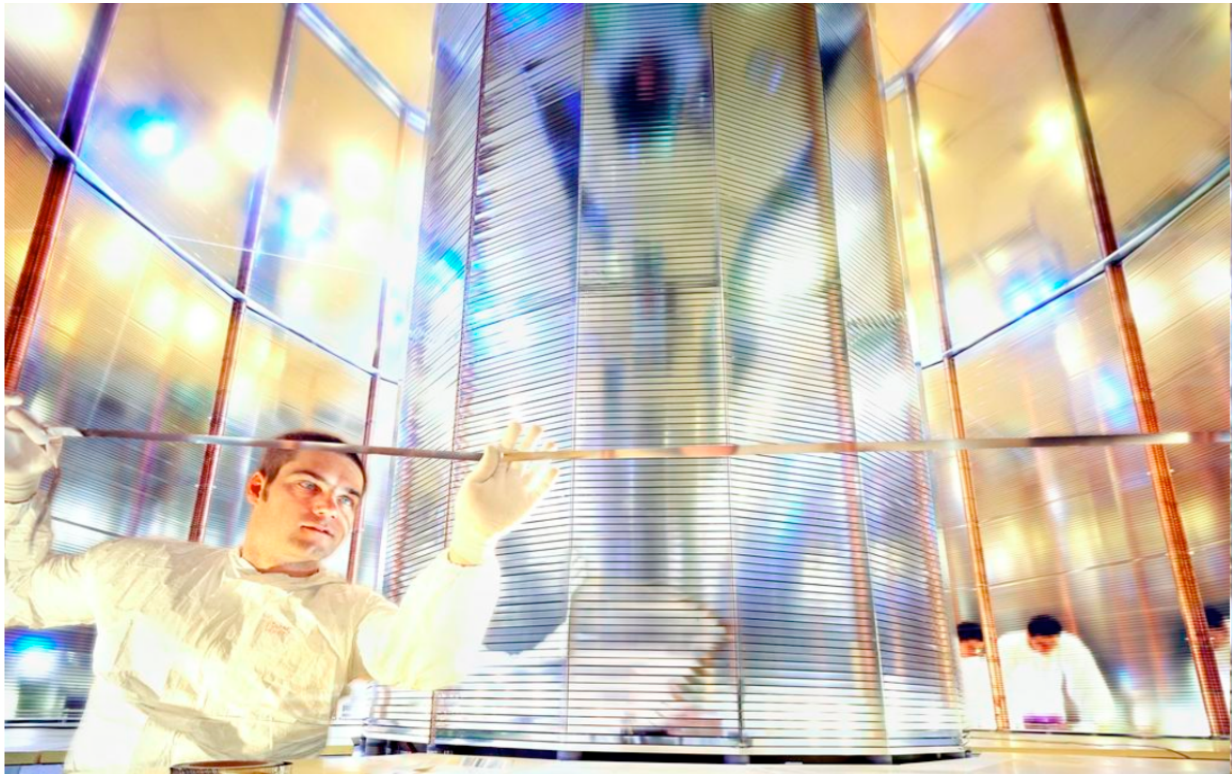
Works at room temperature!
Insensitive to magnetic fields





Astrofisica Nucleare e Subnucleare

Tracker Detectors



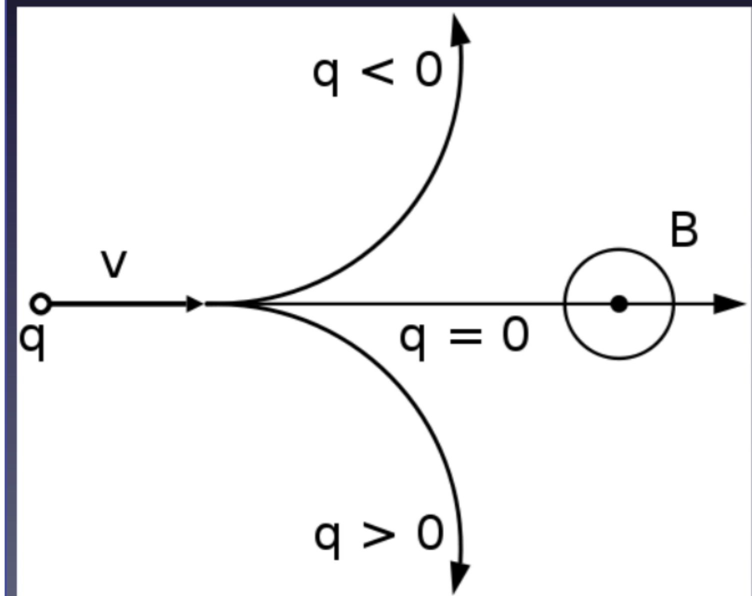
Detectors for Particle Physics

Scintillators and Gaseous detector

D. Bortoletto
University of Oxford & Purdue University

Tracking

- Particle detection has many aspects:
  - Particle counting
  - Particle Identification = measurement of mass and charge of the particle
  - Tracking
- Charged particles are deflected by B fields: $\vec{F} = q\vec{v} \times \vec{B}$

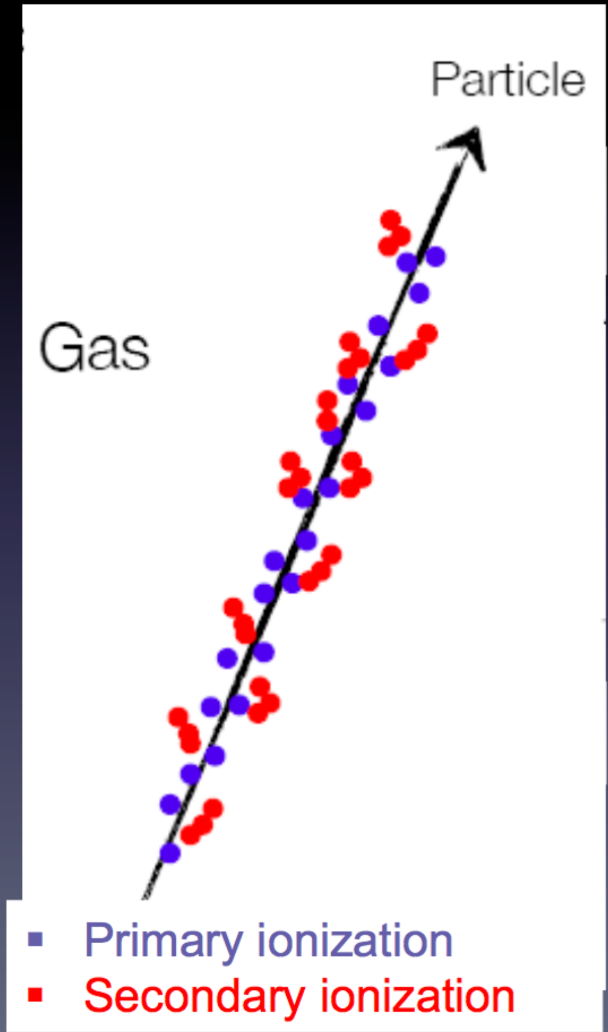


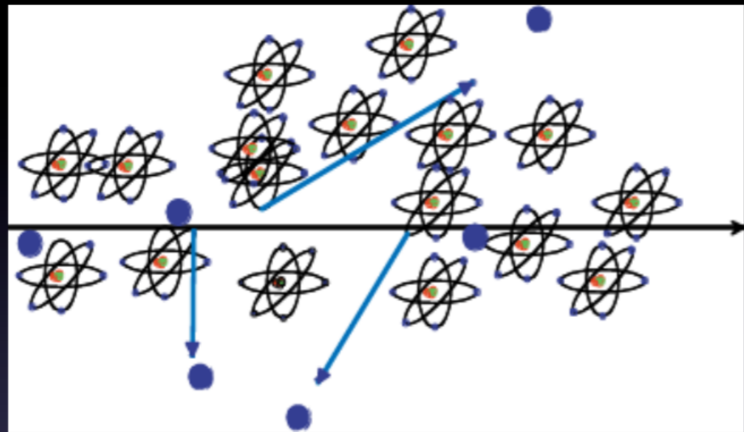
$$\rho = \frac{p_T}{q|B|} = \frac{\gamma m_0 \beta c}{q|B|}$$

- By measuring the radius of curvature we can determine the momentum of a particle
- If we can measure also β independently we can determine the particle mass.

Signal creation

- Charged particle traversing matter leave excited atoms, electron-ion pairs (gases) and electrons-hole pairs (solids)





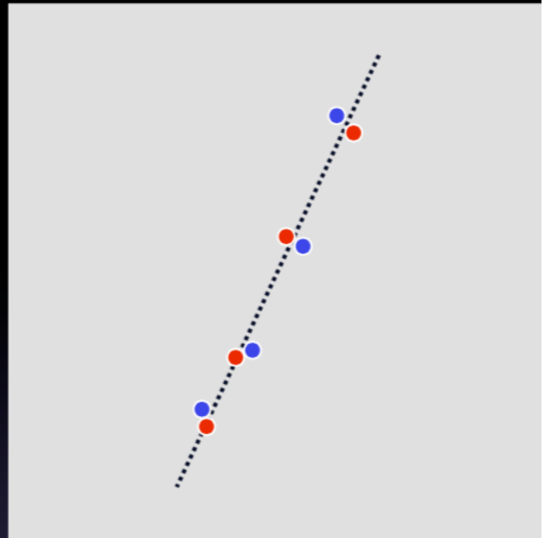
- Excitation: Photons emitted by the excited atoms in transparent materials can be detected with photon detectors
- Ionization: By applying an electric field in the detector volume, the ionization electrons and ions can be collected on electrodes and readout

Astrofisica Nucleare e Subnucleare

Gas Detectors

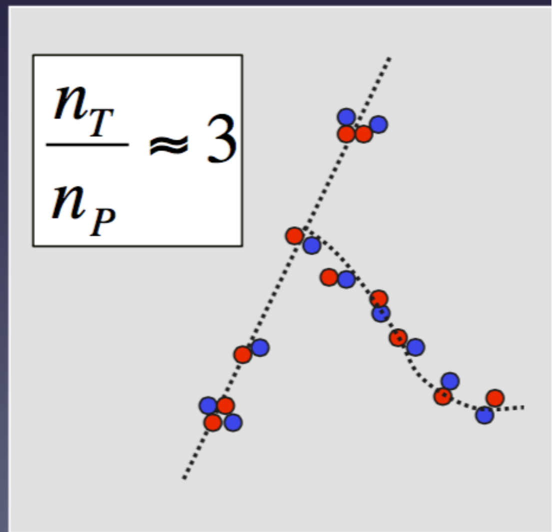
Primary and secondary ionization

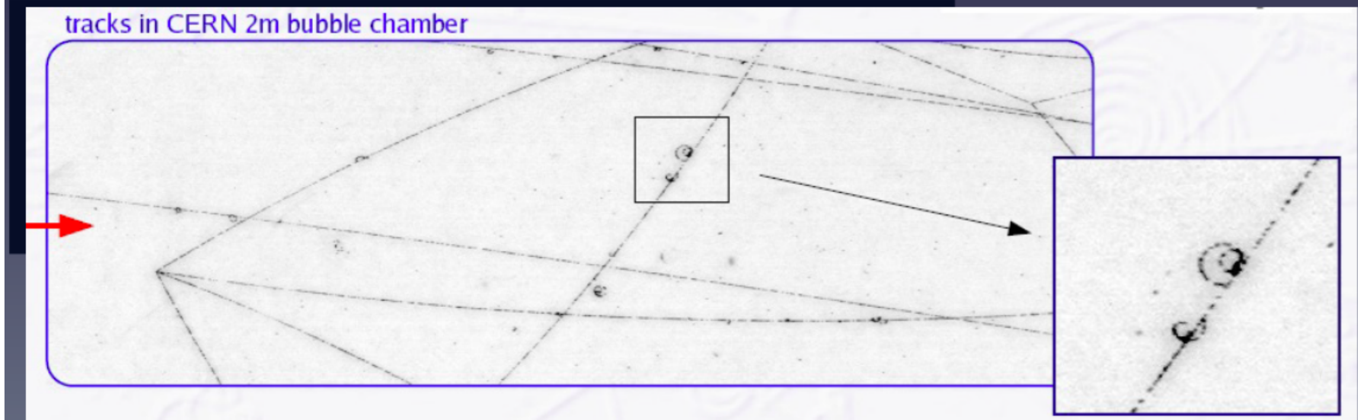
- Coulomb interactions between E field of the particle and of the molecules of the medium produce electron-ion pairs.



- Minimum ionizing particles in argon NTP
  - $\langle n_P \rangle$: 25 cm^{-1}
- Primary electrons can ionize the medium producing local e-ion clusters. Electron can have energy to produce a long trail (delta electron).
- Total number of ion pairs n_T:
  - *E:* energy loss
  - w_i : average energy per ion pair

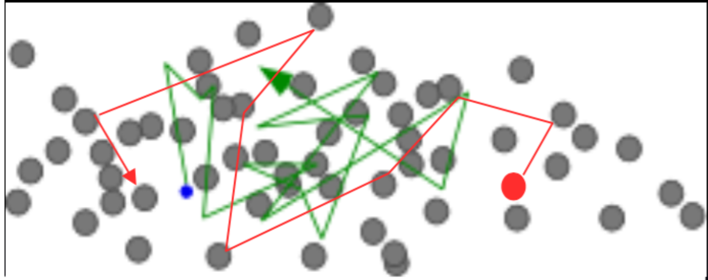
$$n_T = \frac{\Delta E}{w_i}$$





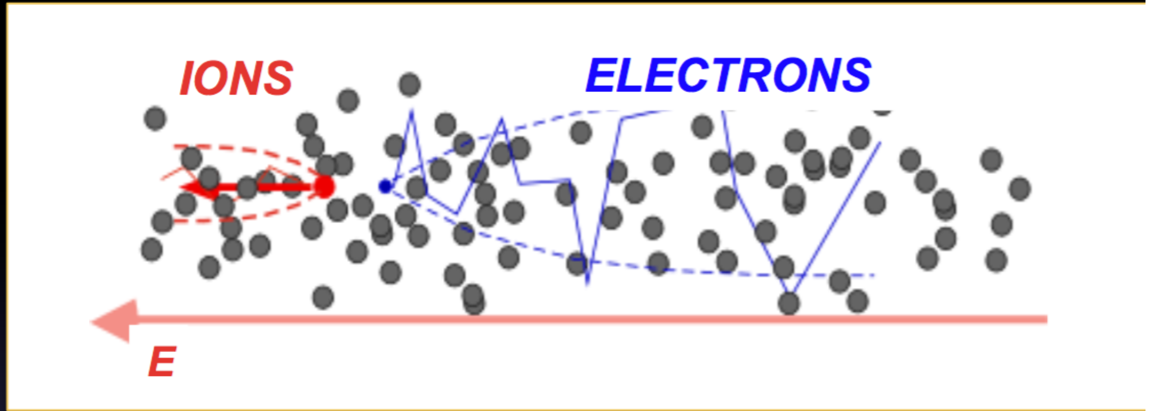
Diffusion & Drift

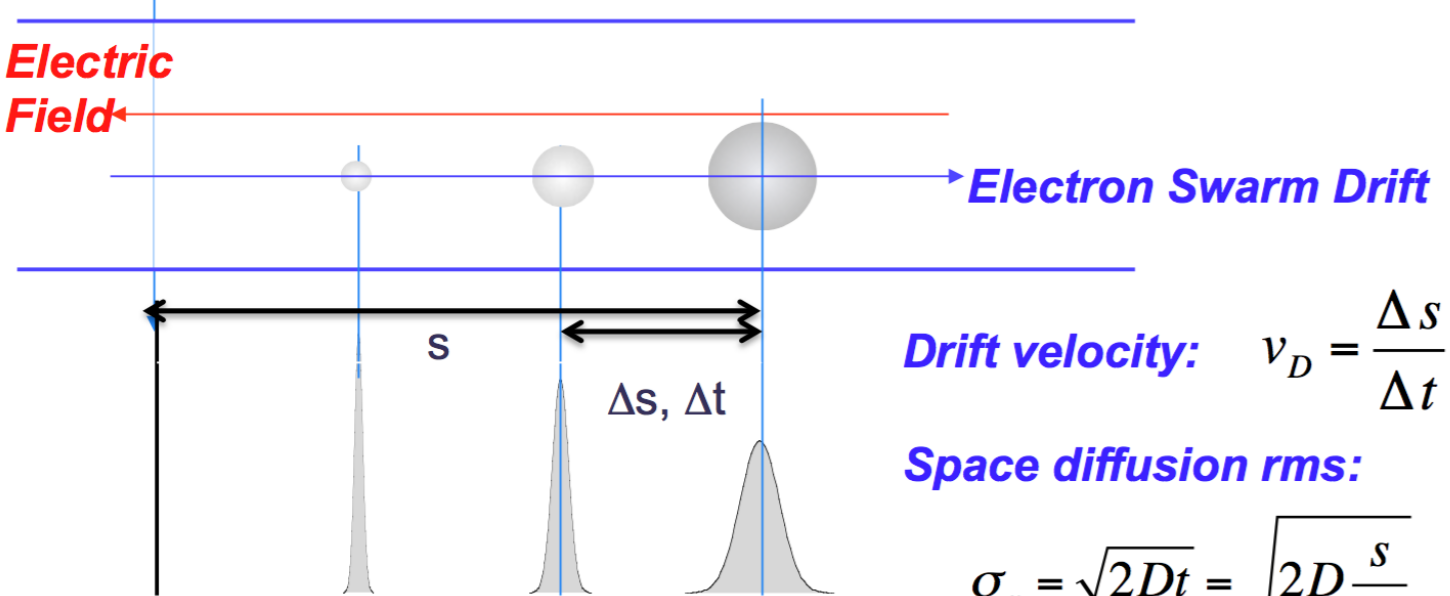
E = 0: Thermal diffusion



$$D = \frac{1}{3} v \lambda = \frac{2}{3\sqrt{\pi}} \frac{1}{P\sigma_0} \sqrt{\frac{(kT)^3}{m}}$$

E >0: Charge Transport and Thermal diffusion





Drift velocity: $v_D = \frac{\Delta s}{\Delta t}$

Space diffusion rms:

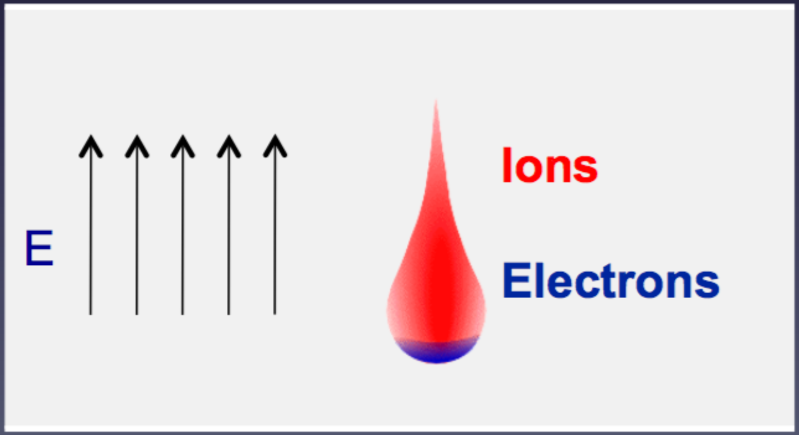
$$\sigma_x = \sqrt{2Dt} = \sqrt{2D \frac{s}{v_D}}$$

Avalanche Multiplication

- The primary ionization signal is very small in a gas layer: in 1 cm of Ar/CO_2 (70:30) at NTP only ~**100** electron–ion pairs are created →use an "internal gas amplification" mechanism to increase signal
- Large E fields →large electron kinetic energy →avalanche formation
  - **$dn = n\,\alpha\,dx$** **α=Townsend Coefficient**
  - **$n(x) = n_0\,e^{\alpha x}$** n(x)=electrons at location x
- Gain or Amplification is:

$$G = \frac{n}{n_0} = e^{\alpha x}$$

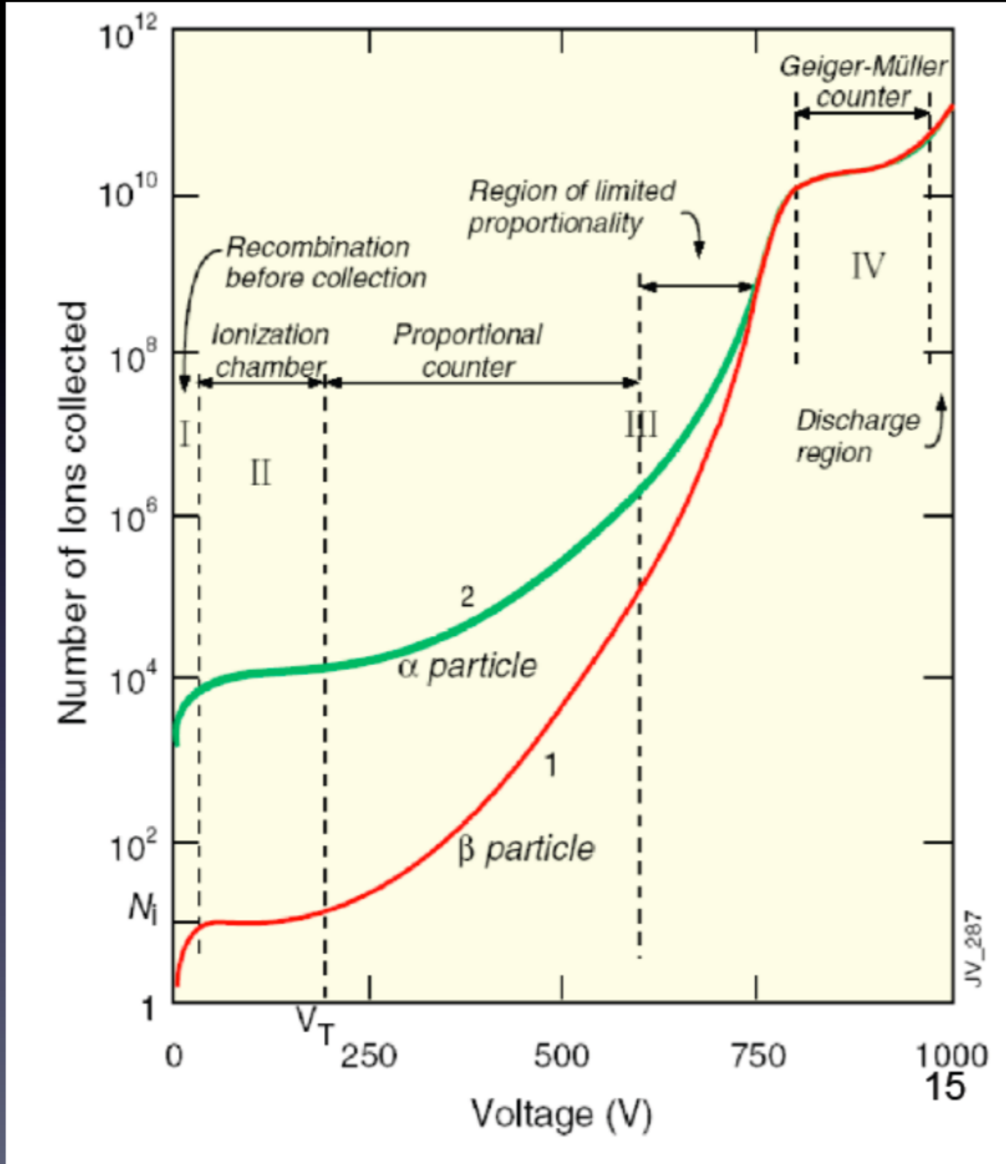
- Raether's limit $G \approx 10^8$, since after that sparking can occur



Drop-like shape of an avalanche

Gas amplification factor

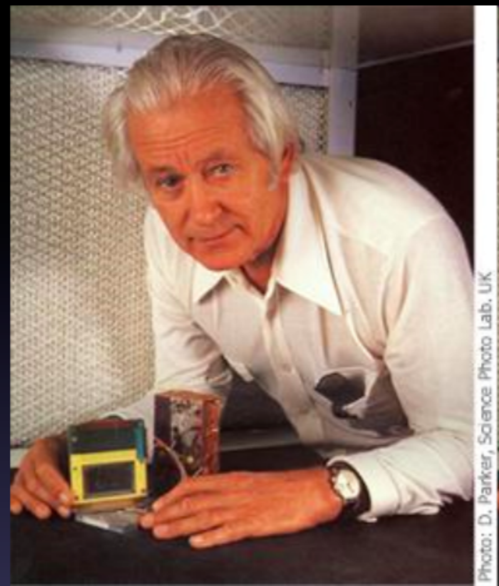
- **Ionization mode:** full charge collection; no amplification; G=1
- **Proportional mode:** multiplication; signal proportional to original ionization ⇒ measurement of dE/dx. Secondary avalanches needs quenching; G ≈10^4-10^5
- **Limited Proportional (**Saturated, Streamer mode): strong photo-emission; Require strong quenchers. High gain 10^{10}⇒ large signal, simple electronics
- **Geiger mode:** Massive photo emission. Full length of anode affected. Discharge stopped by HV cut

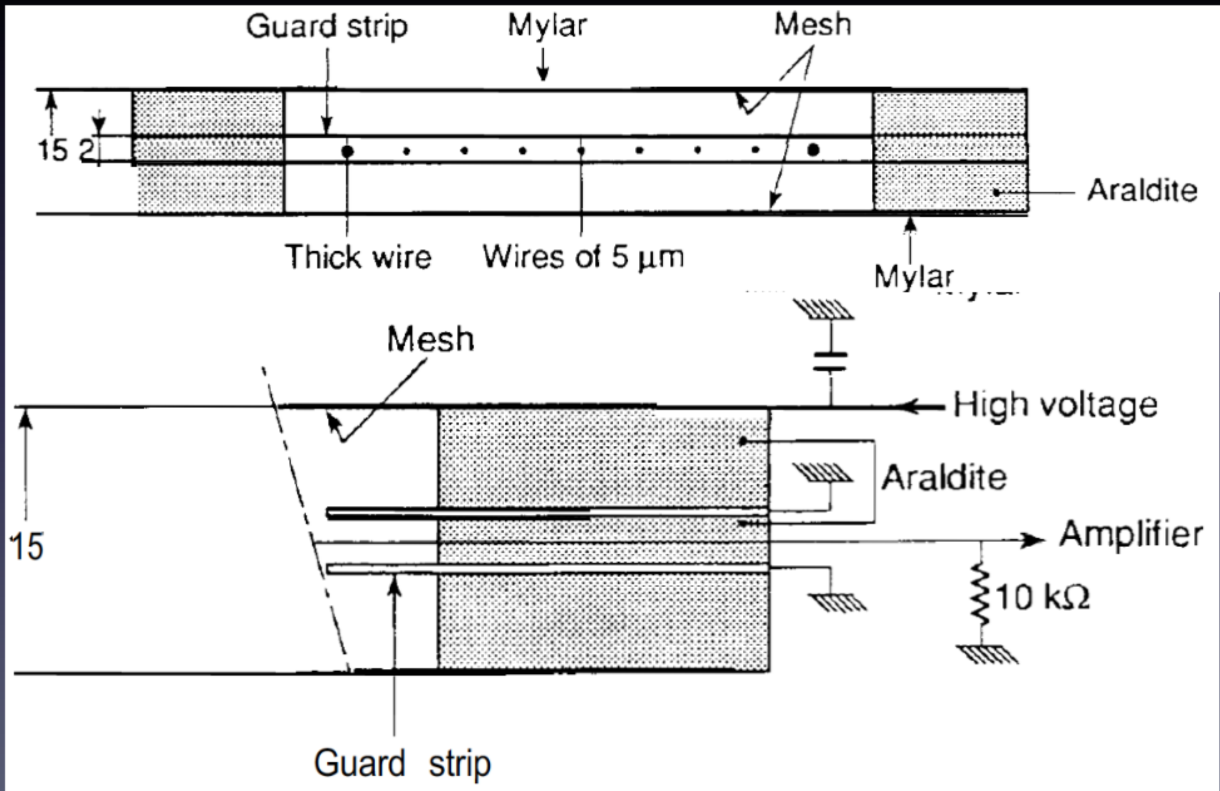


Multiwire proportional chambers

- A proportional counter does not provide the position of the incident particle
- Charpak developed of multi-wire proportional chamber

G. Charpak Nobel price ('92)



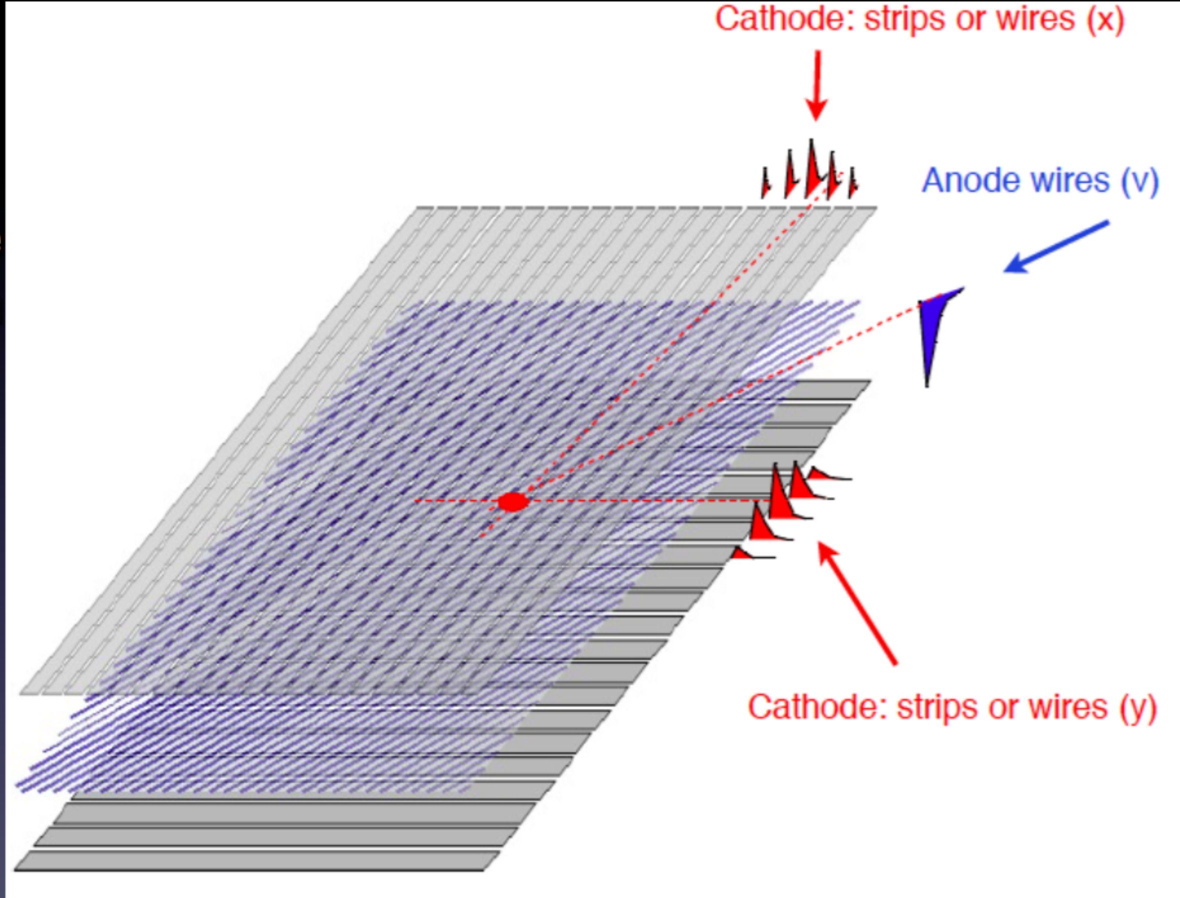


Construction details of the original design of Charpak's multi-wire chambers (from Nobel lecture)

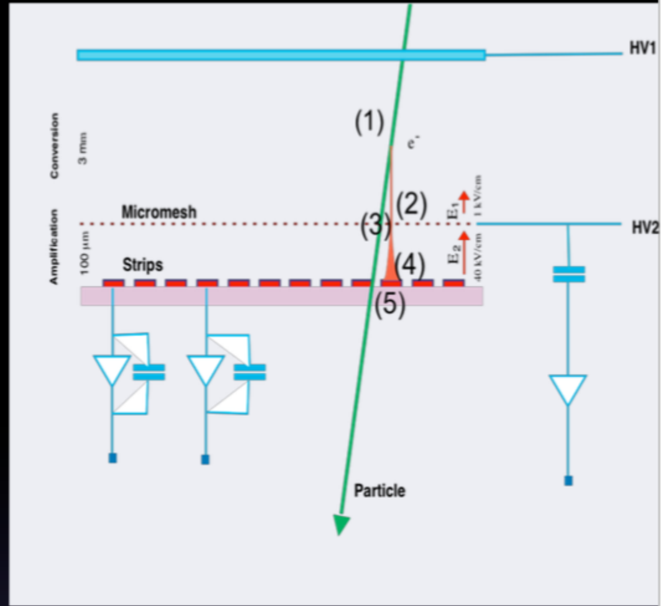
Anode wire =20µ diameter
d=2 mm

2D MWPC

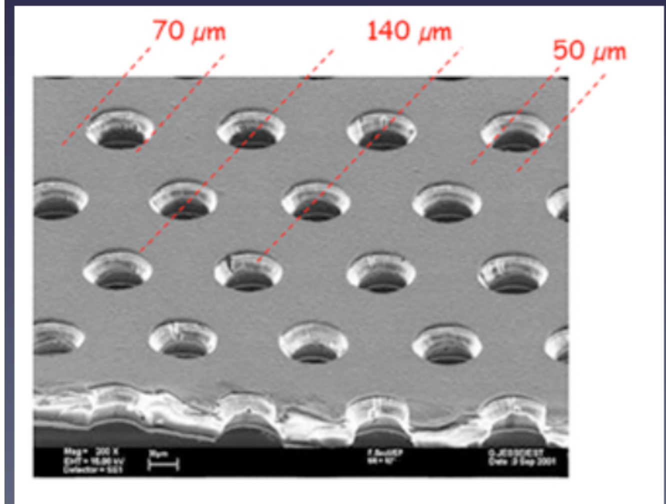
- Two coordinates (x,y) of the track hit can be determined from the position of the anode wire and the signal induced on the cathode strips (or wires)
  - High spatial resolutions due to center of gravity
  - Resolve ambiguities using strip pattern

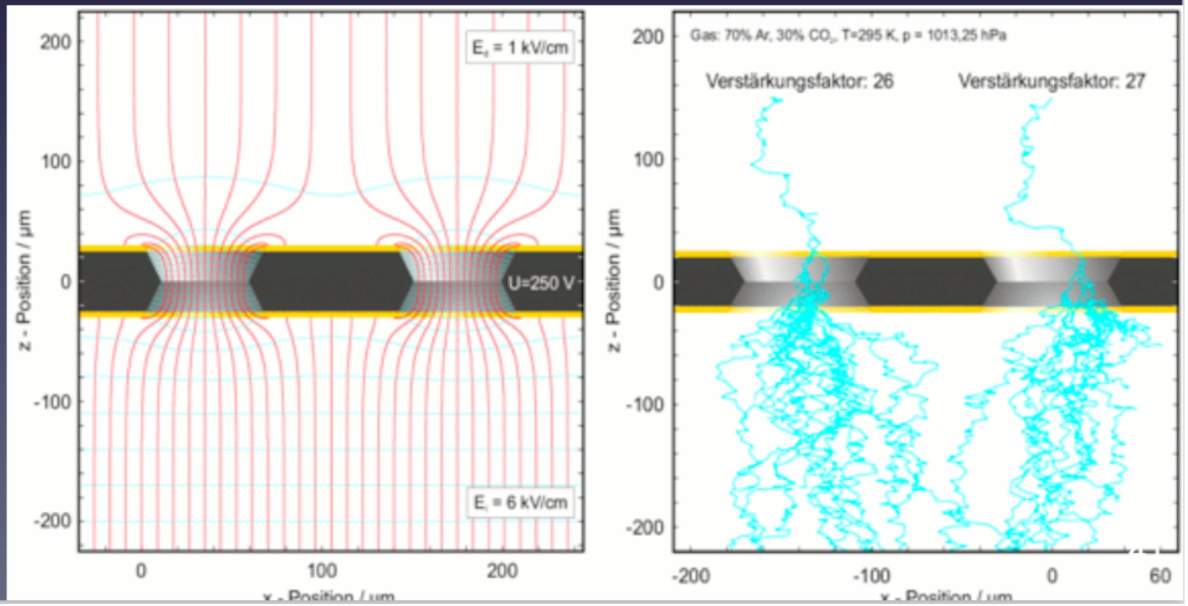


Micromegas and GEM



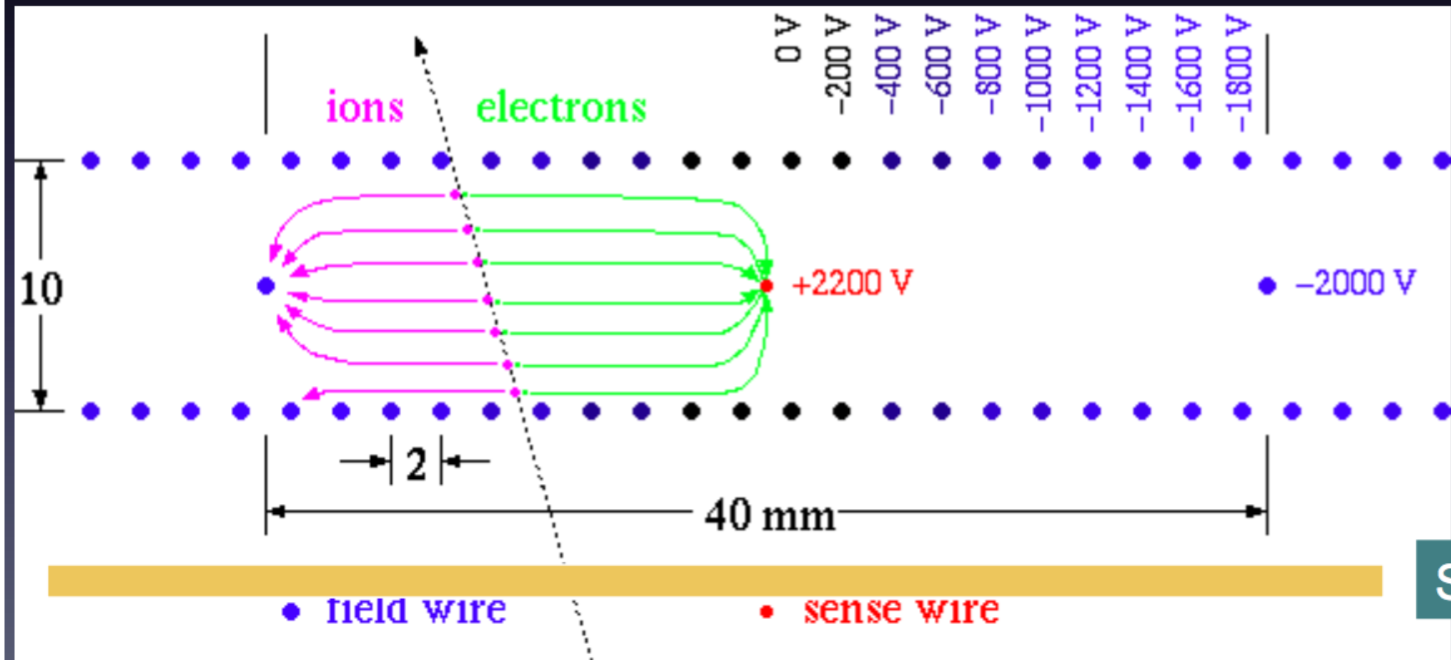
- Micromegas
  - Gas volume divided in two by metallic micro-mesh
  - Gain = 10^4 and a fast signal of 100ns.
- GEM (Gas Electron Multipliers, Sauli 1996)
  - Thin insulating Kapton foil coated with metal film
  - Chemically produced holes pitch ≈100 µm
  - Electrons are guided by high drift field of GEM which generates avalanche
    - Electric field strength is in the order of some 10 kV/cm
    - Avalanche gain of 100 – 1000





Drift chambers

- Obtain spatial information by measuring the electrons drift time
  - time measurement started by an external (fast) detector, i.e. scintillator counter
  - electrons drift to the anode (sense wire), in the field created by the cathodes
  - the electron arrival at the anode stops the time measurement



Scintillator counter

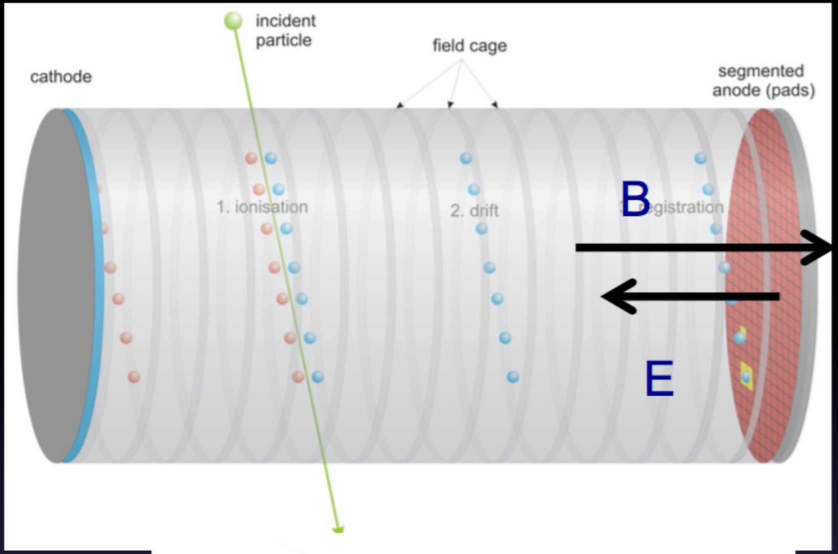
$$x = \int_0^{t_D} v_D \, dt$$

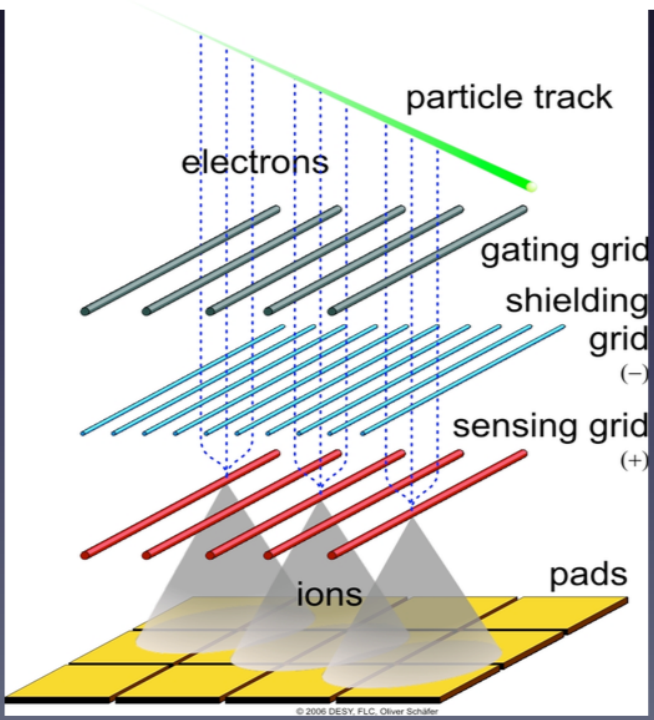
Need well-defined drift field

J. Heintze, 1971

Time Projection chamber (TPC)

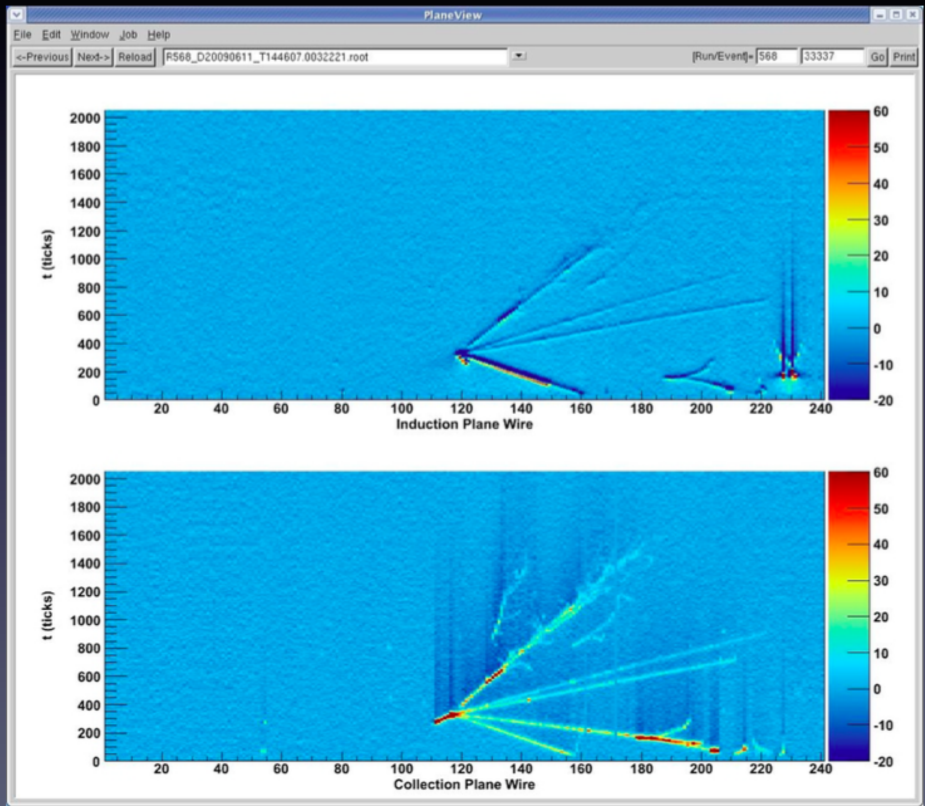
- D.R. Nygren in 1976
- Full 3-D reconstruction
  - XY: MWPC and pads of MWPC at the endcap
  - Z: from drift time measurement (several meters)
    - Field cage for very homogenous electric field
- Typical resolution
  - z and y ≈mm, x=150-300 μm
  - dE/dx ≈5-10%
- Advantages:
  - Complete track information → good momentum resolution
  - Good particle ID by dE/dx
- Challenges
  - Long drift time limited rate
  - Large volume (precision)
  - Large voltages (discharges)
  - Large data volume
  - Difficult operation at high rate





Liquid Argon TPC as a bubble Chamber

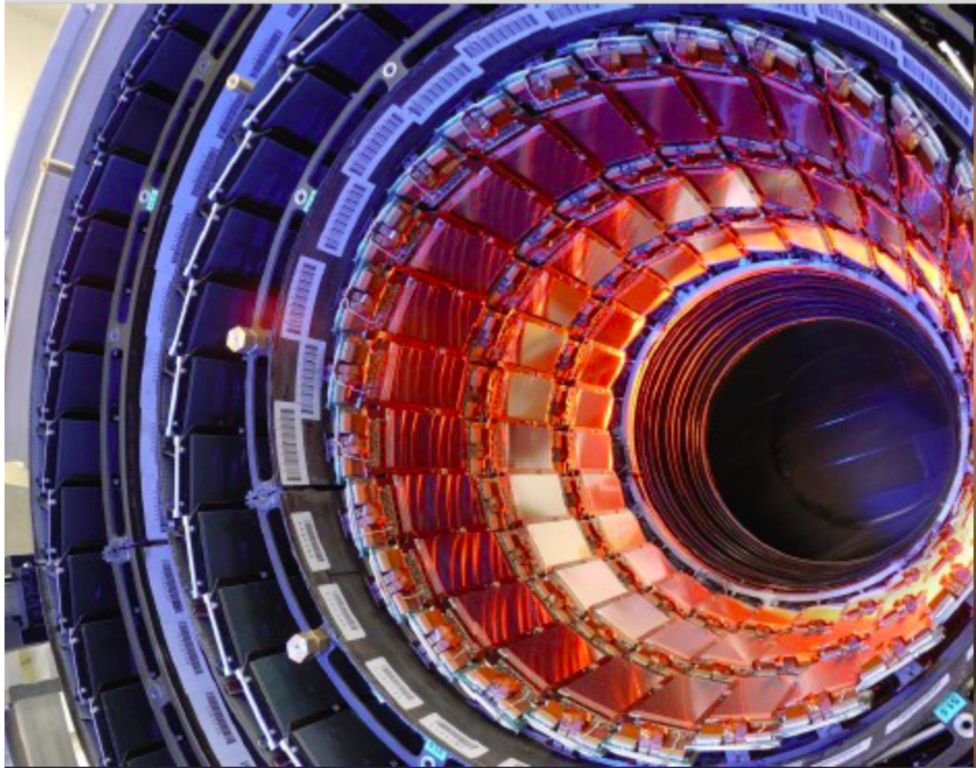
- LAr provides a dense target for neutrinos and for ionization/ Scintillation detection.
- Particle identification comes primarily from dE/dx (energy deposited) along track.
  - Wire spacing ≈ mm and digital sampling provides fine-grained resolution
  - Photons and Electrons can be cleanly separated
- Ideal for neutrino experiments



- Microboone and LBNF neutrino experiments

Astrofisica Nucleare e Subnucleare

Solid State Detectors



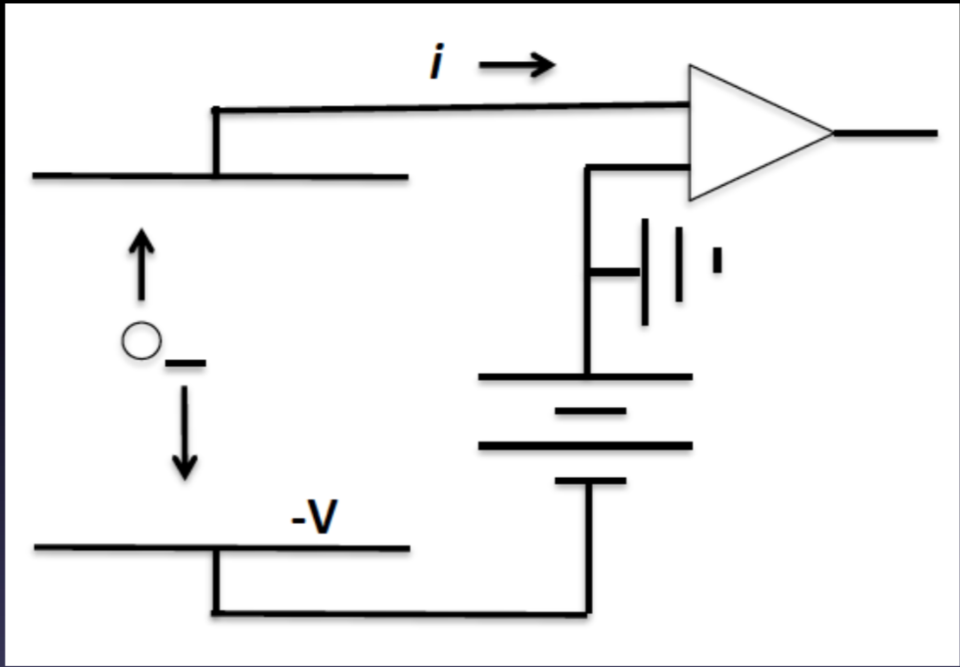
Detectors for Particle Physics

Semiconductor Detectors

D. Bortoletto

Solid State Detector

- A solid state detector is an ionization chamber
  - Ionizing radiation creates electron/hole pairs
  - Charge carriers move in applied E field
  - Motion induces a current in an external circuit, which can be amplified and sensed.



	Gas	Solid
Density	Low	High
Atomic number (Z)	Low	Moderate (Z=14)
Ionization Energy (ε_I)	Moderate ($\approx$ 30 eV)	Low ($\approx$3.6 eV)
Signal Speed	Moderate (10ns-10μs)	Fast (<20 ns)

Comparison solid state versus gas

Ionization chamber medium could be gas, liquid, or solid

- **Gas ⇒ electron and ion pairs; Semiconductor ⇒electron and hole pairs**

	Gas	Solid
Density	Low	High
Atomic number (Z)	Low	Moderate (Z=14)
Ionization Energy (ε_I)	Moderate (≈ 30 eV)	Low (≈3.6 eV)
Signal Speed	Moderate (10ns-10μs)	Fast (<20 ns)

Solid State Detectors

- Energy (E) to create e-h pairs 10 times smaller than gas ionization ⇒ increase charge⇒ good E resolution

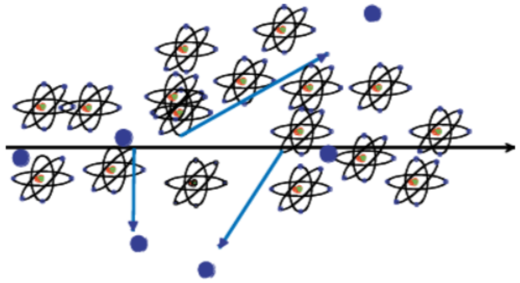
$$\frac{\Delta E}{E} \propto \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{E/\varepsilon_I}} \propto \sqrt{\varepsilon_I}$$

- Greater density:
  - Reduced range of secondary electrons ⇒ excellent spatial resolution
  - Average E_{loss} ≈390eV/ μm ≈108 e-h/ μm (charge collected is a function of thickness d. Up-to-now no multiplication)
- To minimize multiple scattering d is small
  - 300 μm ≈32,000 e-h pairs → good S/N

Solid State Detectors

Gas Detectors

In gaseous detectors, a charged particle is liberating electrons from the atoms, which are freely bouncing between the gas atoms.

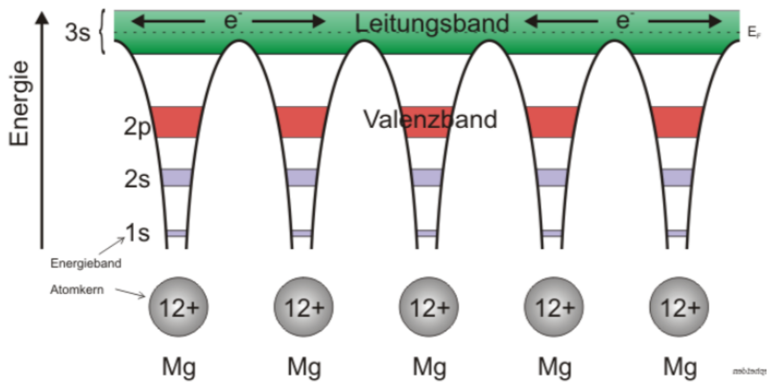


An applied electric field makes the electrons and ions move, which induces signals on the metal readout electrodes.

For individual gas atoms, the electron energy levels are discrete.

Solid State Detectors

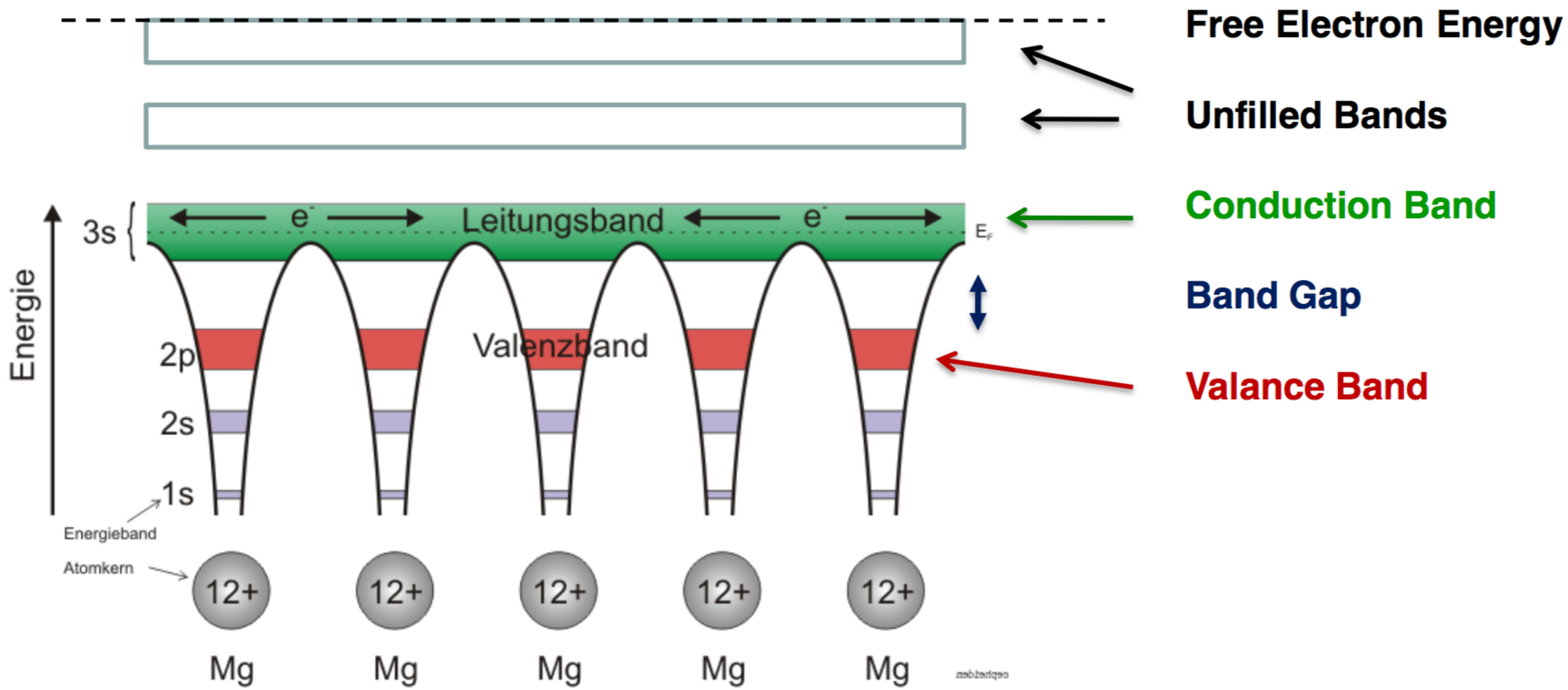
In solids (crystals), the electron energy levels are in 'bands'.



Inner shell electrons, in the lower energy bands, are closely bound to the individual atoms and always stay with 'their' atoms.

In a crystal there are however energy bands that are still bound states of the crystal, but they belong to the entire crystal. Electrons in these bands and the holes in the lower band can freely move around the crystal, if an electric field is applied.

Solid State Detectors



Conductor, Insulator, Semiconductor

In case the conduction band is filled the crystal is a conductor.

In case the conduction band is empty and 'far away' from the valence band, the crystal is an insulator.

In case the conduction band is empty but the distance to the valence band is small, the crystal is a semiconductor.

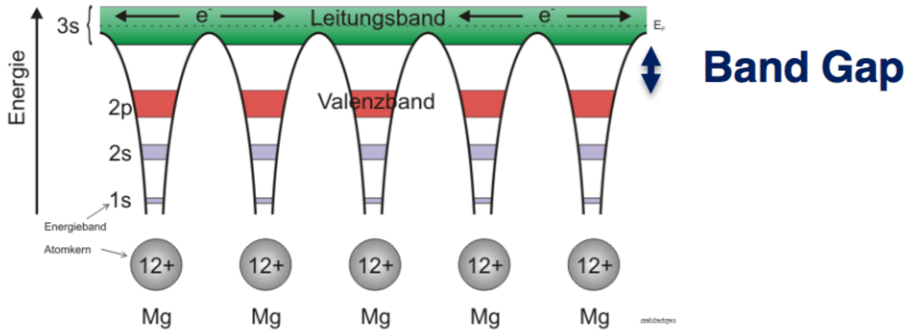
Solid State Detectors

Band Gap, e-h pair Energy

The energy gap between the last filled band – the valence band – and the conduction band is called band gap E_g.

The band gap of Diamond/Silicon/Germanium is 5.5, 1.12, 0.66 eV.

The average energy to produce an electron/hole pair for Diamond/Silicon/Germanium is 13, 3.6, 2.9eV.



Temperature, Charged Particle Detection

In case an electron in the valence band gains energy by some process, it can be excited into the conduction band and a hole in the valence band is left behind.

Such a process can be the passage of a charged particle, but also thermal excitation → probability is proportional $Exp(-E_g/kT)$.

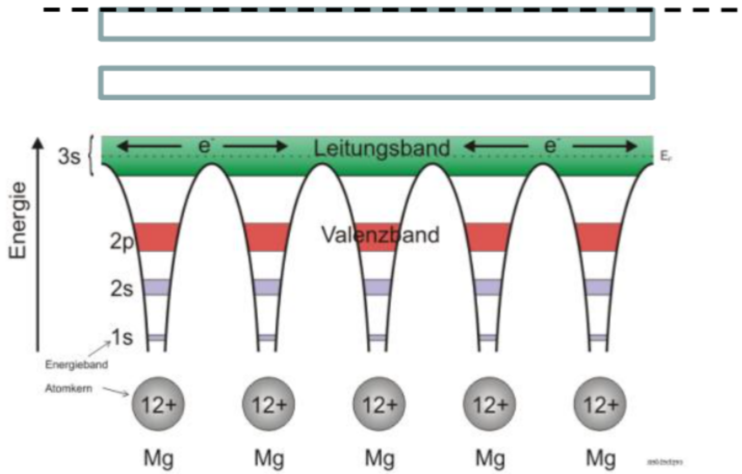
The number of electrons in the conduction band is therefore increasing with temperature i.e. the conductivity of a semiconductor increases with temperature.

Solid State Detectors

Electron, Hole Movement:

It is possible to treat electrons in the conduction band and holes in the valence band similar to free particles, but with an effective mass different from elementary electrons not embedded in the lattice.

This mass is furthermore dependent on other parameters such as the direction of movement with respect to the crystal axis. All this follows from the QM treatment of the crystal (solid state physics).



Cooling:

If we want to use a semiconductor as a detector for charged particles, the number of charge carriers in the conduction band due to thermal excitation must be smaller than the number of charge carriers in the conduction band produced by the passage of a charged particle.

Diamond (E_g=5.5eV) can be used for particle detection at room temperature,
Silicon (E_g=1.12 eV) and Germanium (E_g=0.66eV) must be cooled, or the free charge carriers must be eliminated by other tricks → doping → see later.

Solid State Detectors

Primary 'ionization':

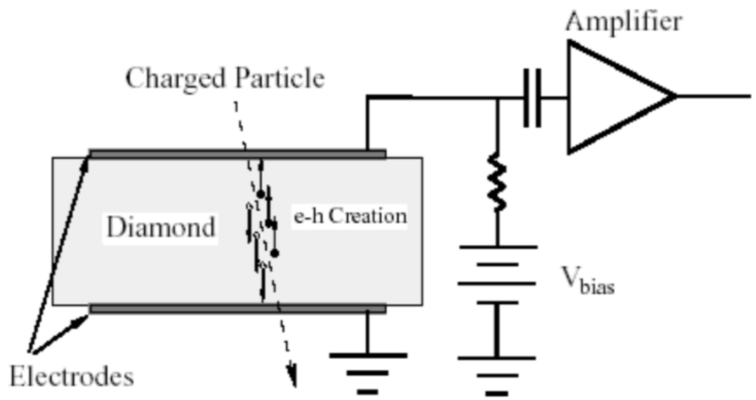
The average energy to produce an electron/hole pair is:
Diamond (13eV), Silicon (3.6eV), Germanium (2.9eV)

Comparing to gas detectors, the density of a solid is about a factor 1000 larger than that of a gas and the energy to produce and electron/hole pair e.g. for Si is a factor 7 smaller than the energy to produce an electron-ion pair in Argon.

Solid State vs. Gas Detector:

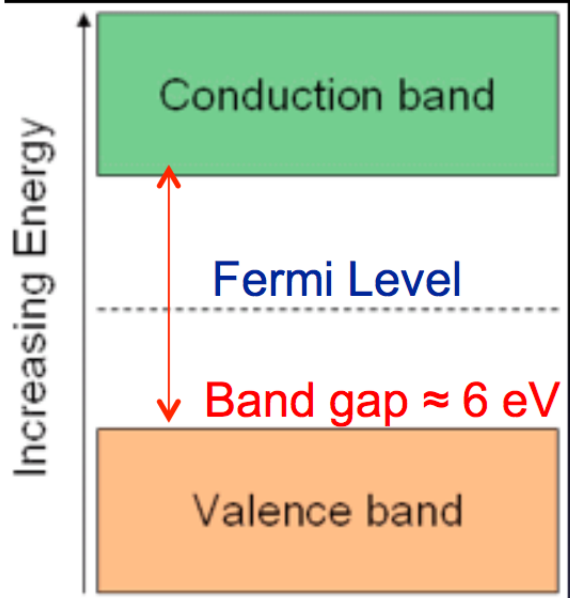
The number of primary charges in a Si detector is therefore about 10^4 times larger than the one in gas → while gas detectors need internal charge amplification, solid state detectors don't need internal amplification.

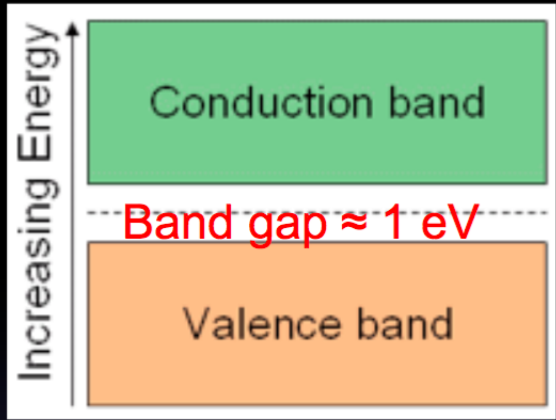
While in gaseous detectors, the velocity of electrons and ions differs by a factor 1000, the velocity of electrons and holes in many semiconductor detectors is quite similar → very short signals.

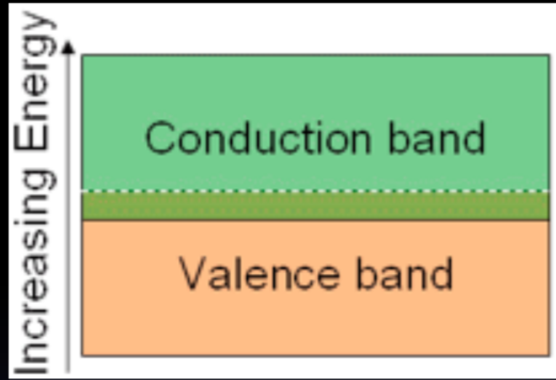


Diamond → A solid state ionization chamber

Semiconductor

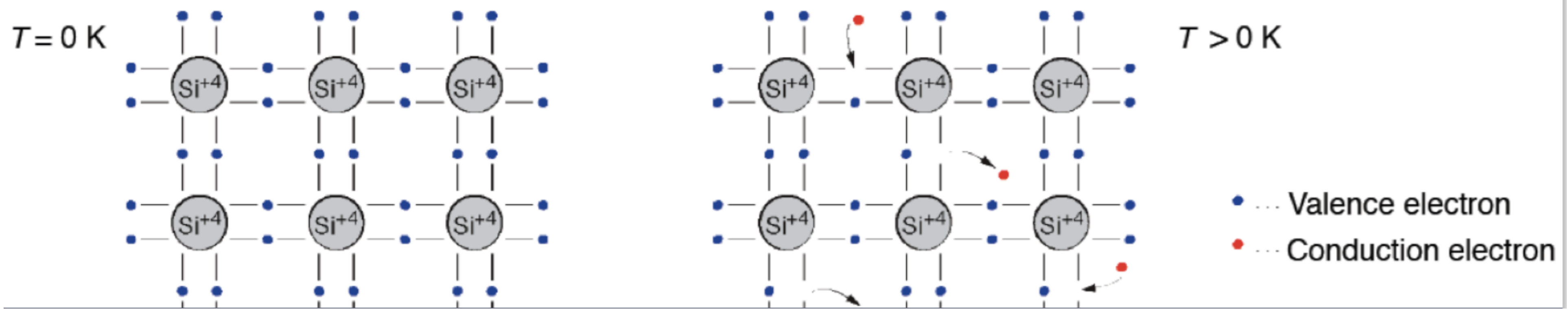






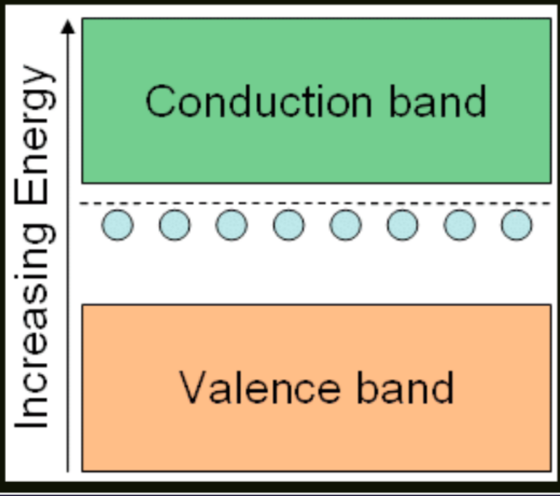
- Fermi level
  - Maximum electron energy at T = 0 K

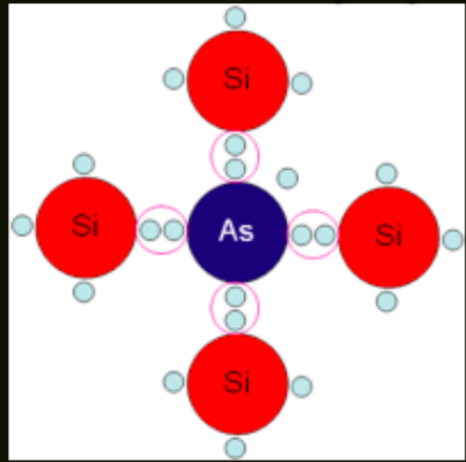
- Semiconductor: at room temperature electrons can already occupy the conduction band and may recombine with holes.
- Thermal equilibrium is reached between excitation and recombination when the charge carrier concentration $n_e = n_h = n_i$= intrinsic carrier concentration≈1.5×10^{10} cm^{-3}

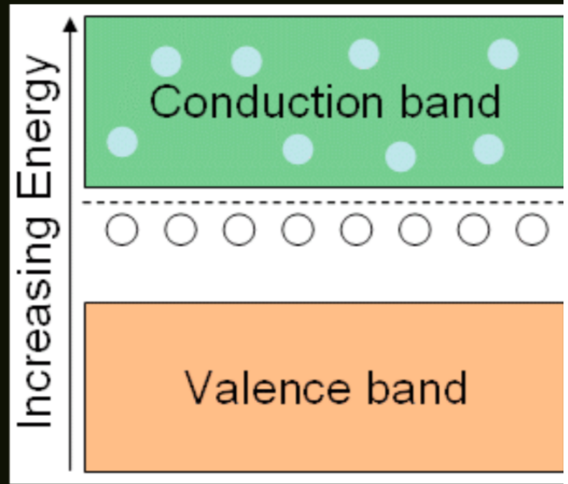


Doped semiconductors

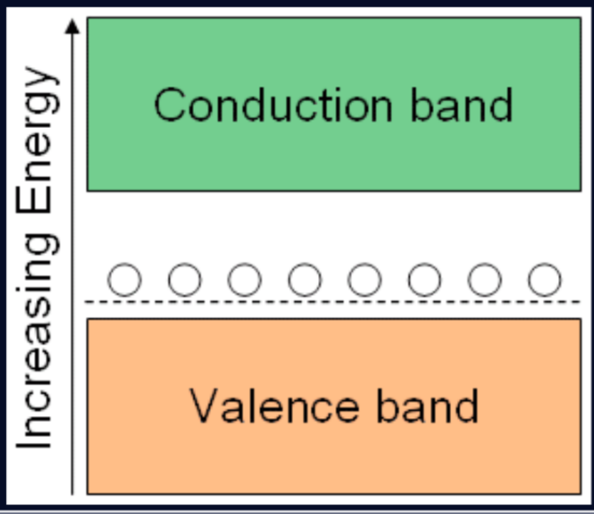
DONOR (N)

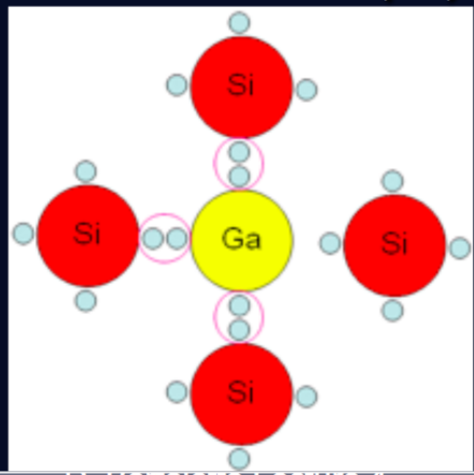


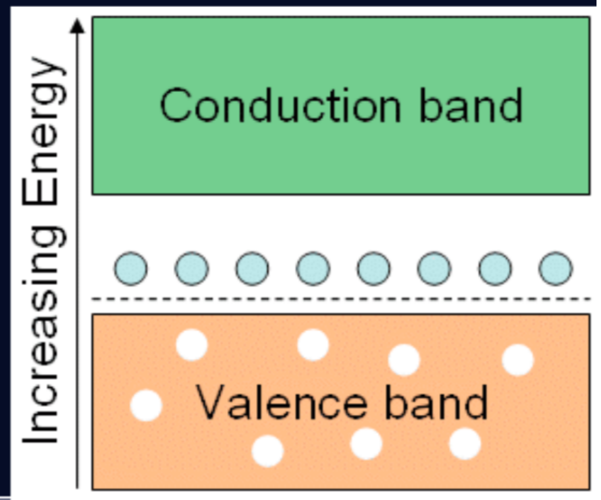




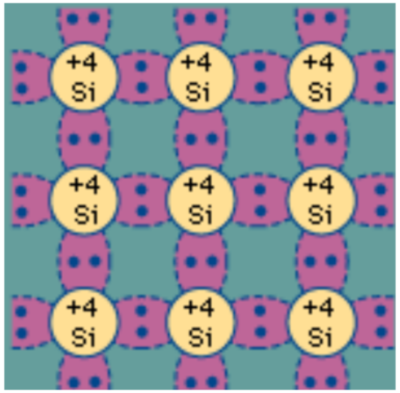
ACCEPTOR (P)



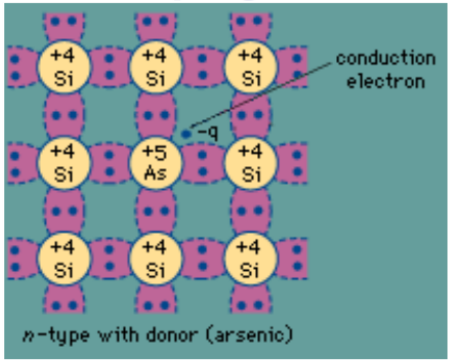


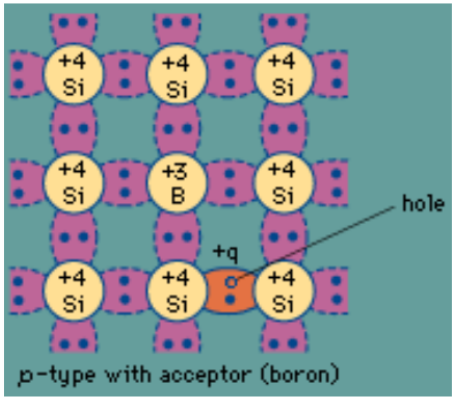


Doping of Silicon



doping



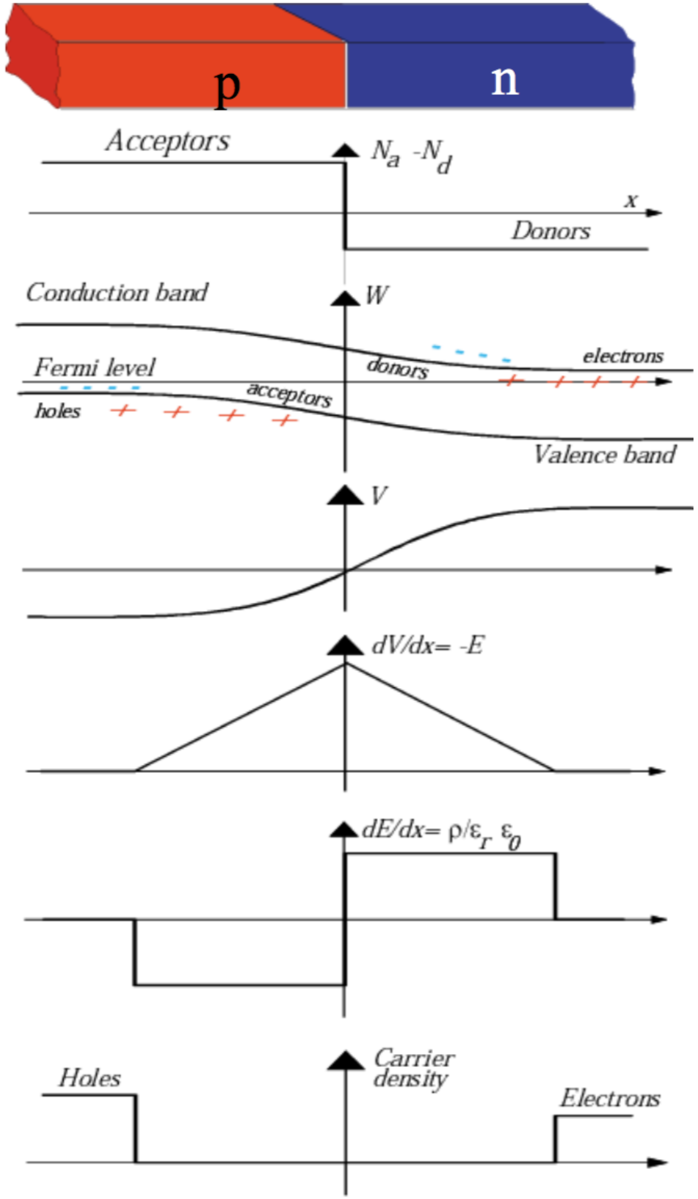


In a silicon crystal at a given temperature the number of electrons in the conduction band is equal to the number of holes in the valence band.

Doping Silicon with Arsen (+5) it becomes and n-type conductor (more electrons than holes).

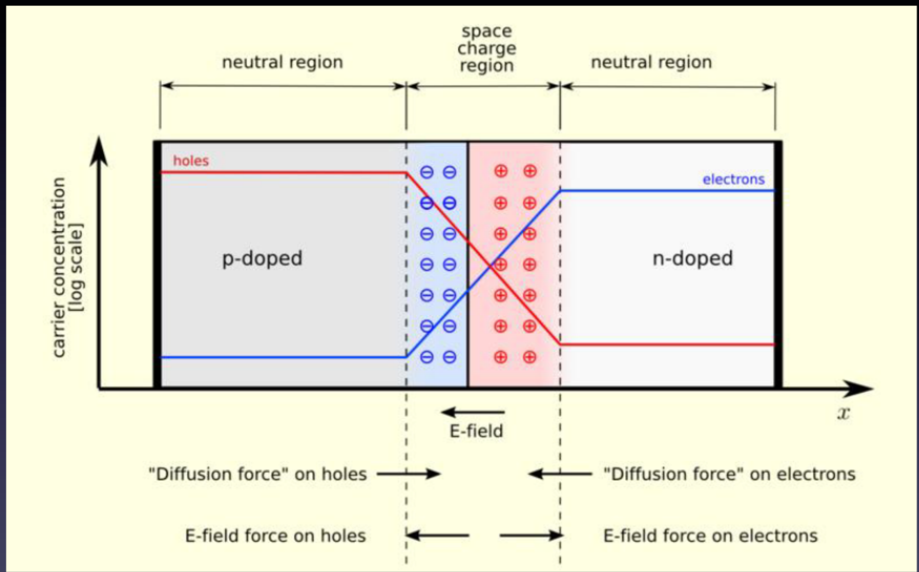
Doping Silicon with Boron (+3) it becomes a p-type conductor (more holes than electrons).

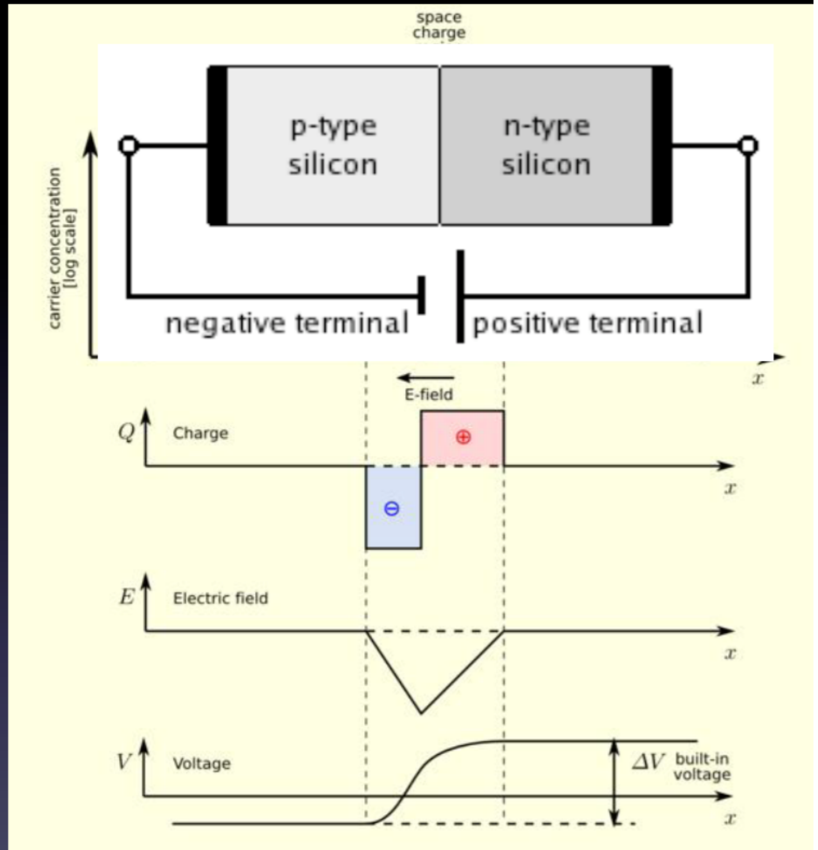
Bringing p and n in contact makes a diode.



PN Junction

- PN junction without external voltage
  - Free charges move until the chemical potential is balanced by an electrical potential called the built-in potential





- The space charge (depletion) region can be made bigger by applying a reverse bias voltage

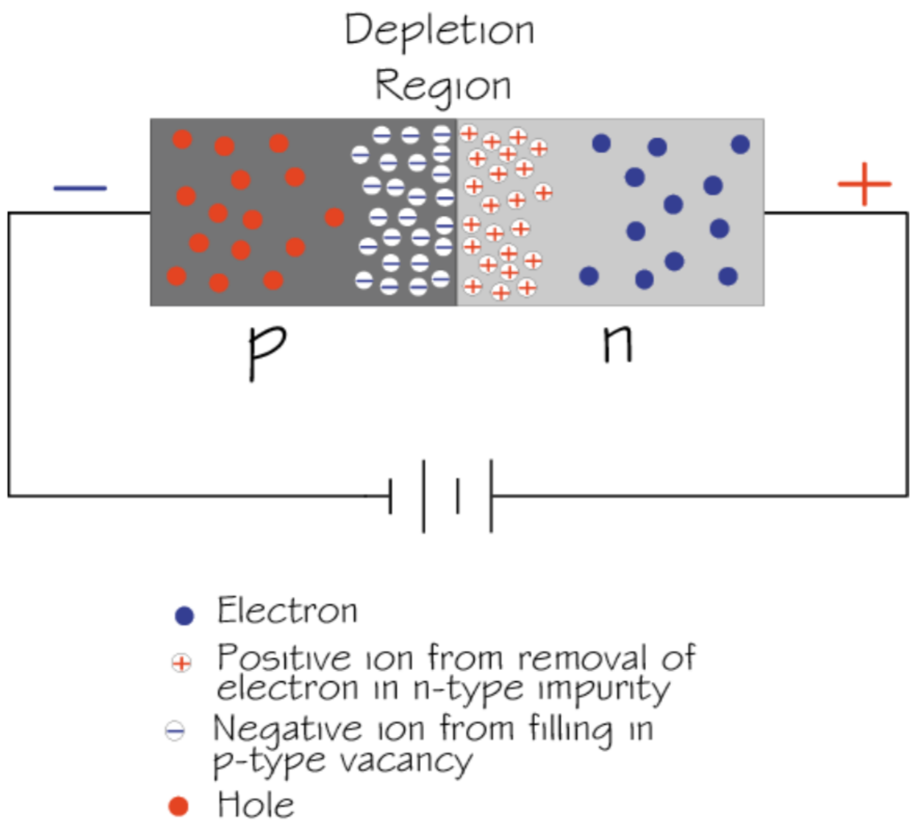
Si-Diode used as a Particle Detector !

At the p-n junction the charges are depleted and a zone free of charge carriers is established.

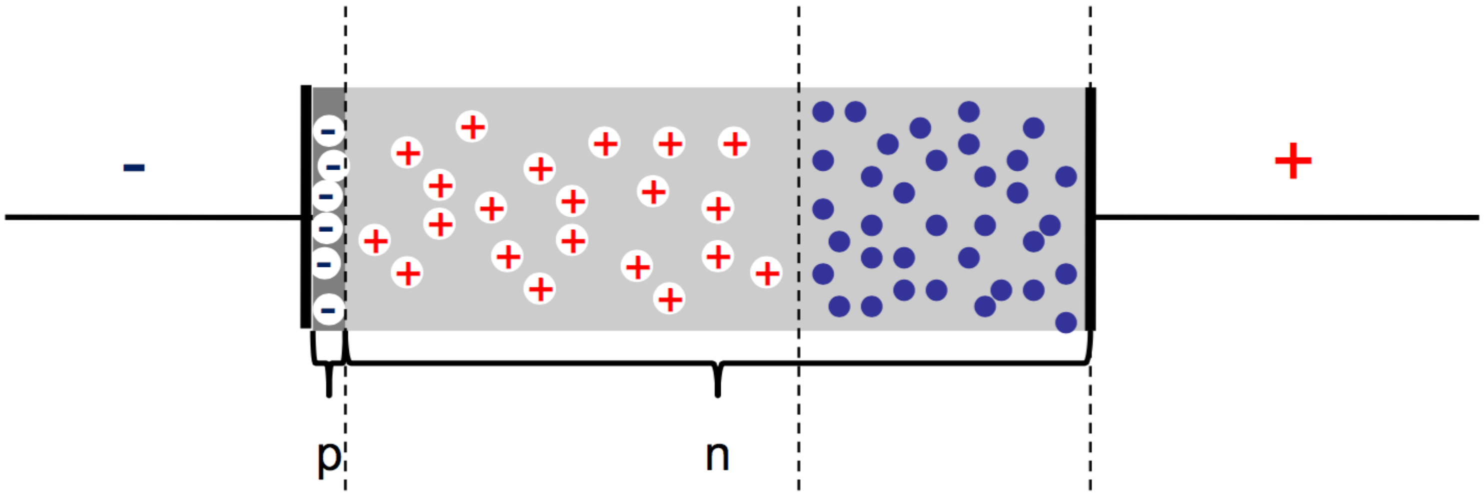
By applying a voltage, the depletion zone can be extended to the entire diode → highly insulating layer.

An ionizing particle produces free charge carriers in the diode, which drift in the electric field and induce an electrical signal on the metal electrodes.

As silicon is the most commonly used material in the electronics industry, it has one big advantage with respect to other materials, namely highly developed technology.



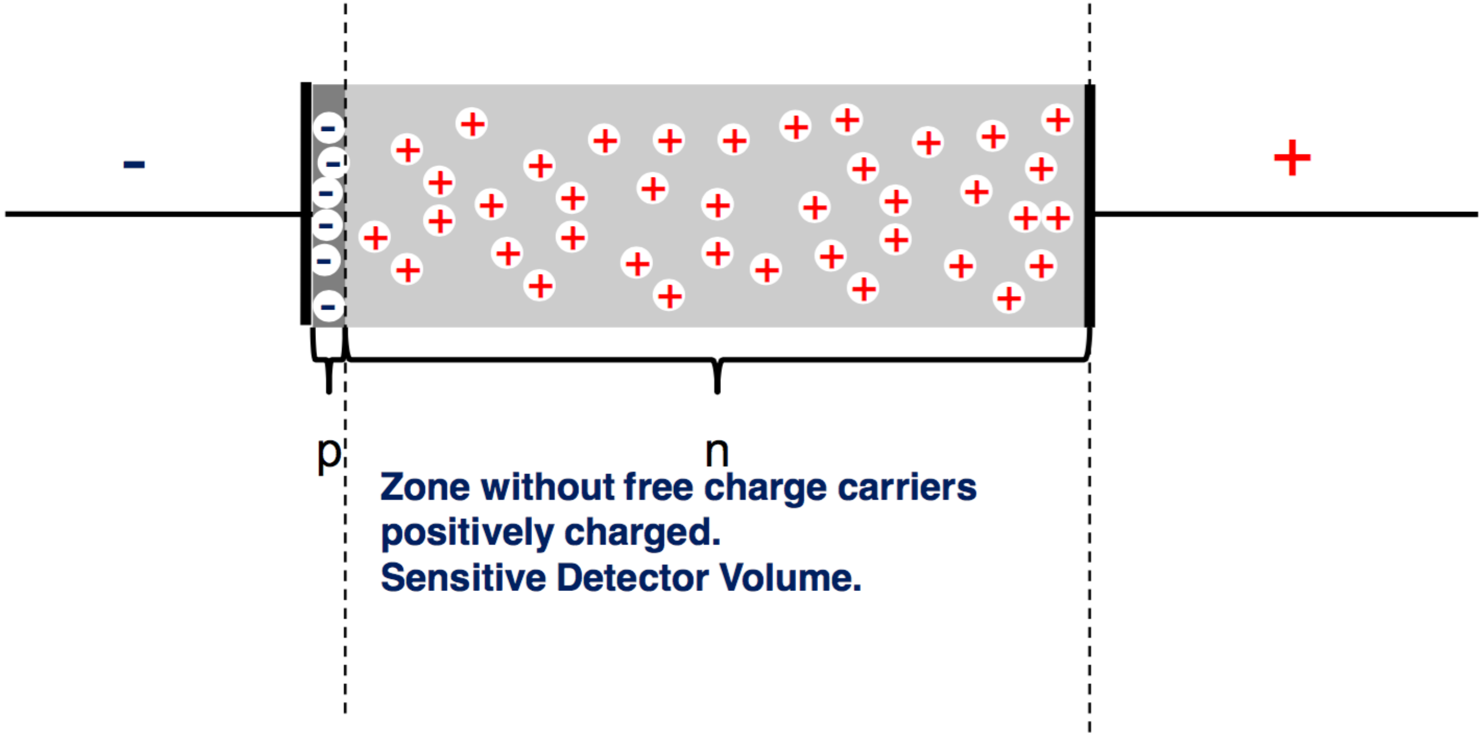
Under-Depleted Silicon Detector



Zone without free charge carriers positively charged. Sensitive Detector Volume.

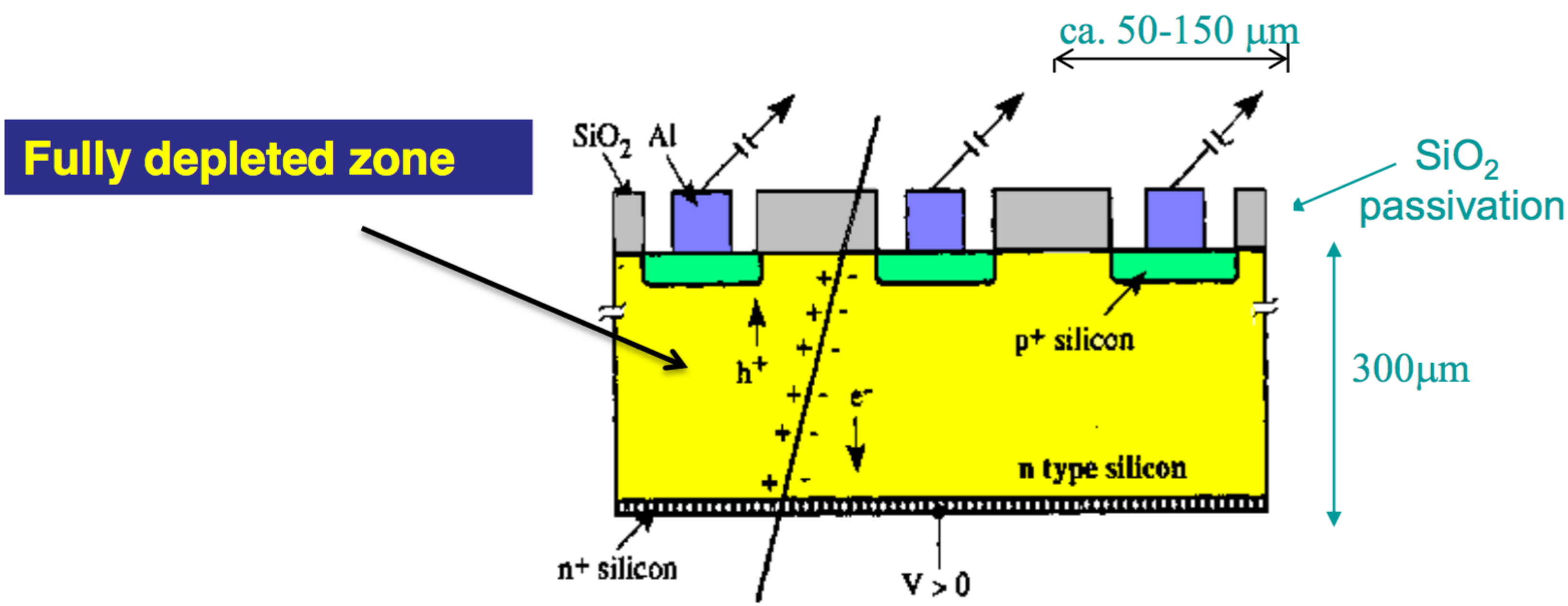
Zone with free electrons. Conductive. Insensitive to particles.

Fully-Depleted Silicon Detector



Zone without free charge carriers positively charged.
Sensitive Detector Volume.

Silicon Detector

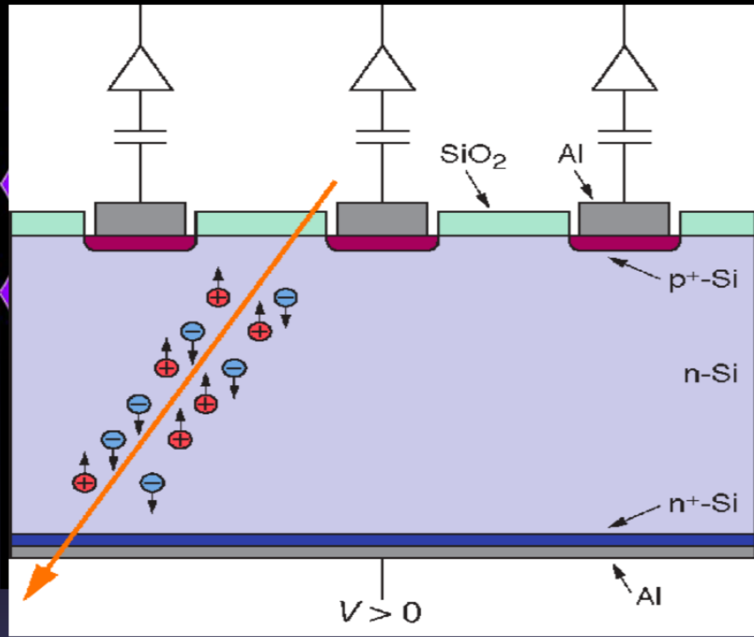


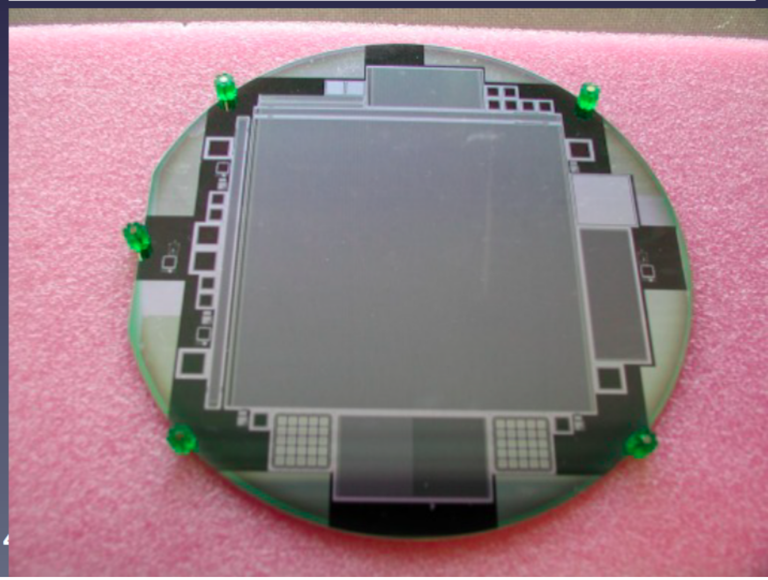
N (e-h) = 11 000/100μm

Position Resolution down to ~ 5μm !

Silicon Strip Detectors (SSD)

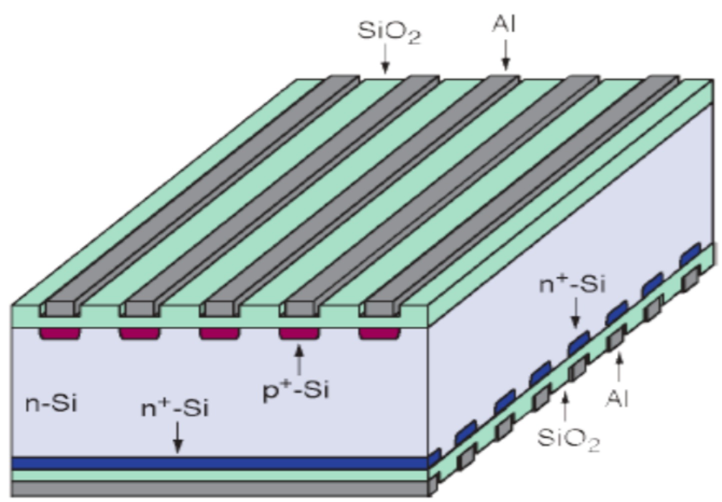
- By segmenting the implant we can reconstruct the position of the traversing particle in one dimension
- DC-coupled strip detector – simplest position sensitive Silicon detector
- Standard configuration:
  - Strips p implants
  - Substrate n doped (~2-10 kΩcm) and ~300μm thick
  - $V_{dep} < 200$ V
  - Backside Phosphorous implant to establish ohmic contact and to prevent early breakdown
- Highest field close to the collecting electrodes (junction side) where most of the signal is induced



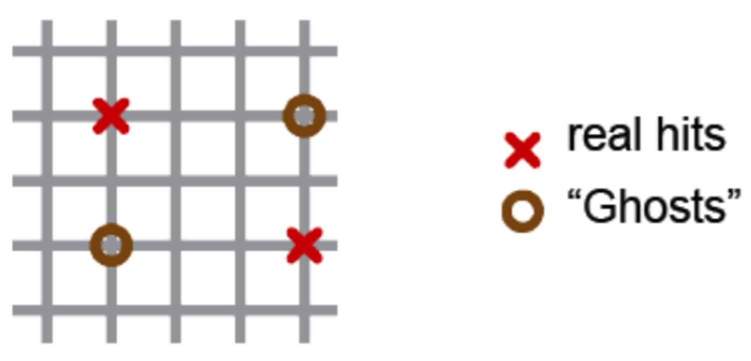


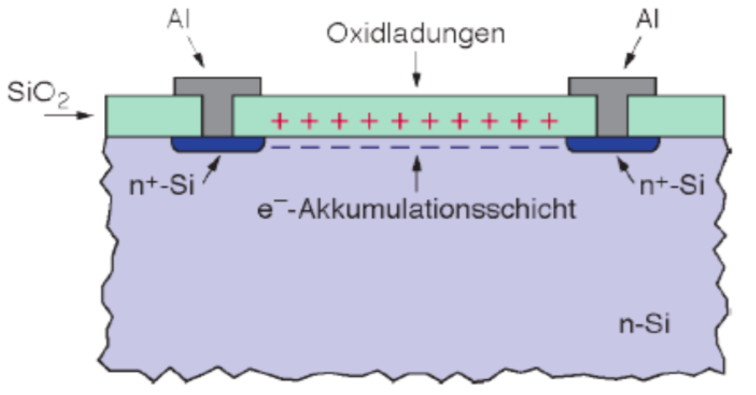
Double Sided Silicon Detectors

- **Advantages:**
  - More elegant for measuring 2 coordinates than using stereo modules
  - Saves material
- **Disadvantages:**
  - Needs special strip insulation of n-side (p-stop, p-spray techniques)
  - Complicated manufacturing and handling procedures
- Expensive
- Ghost hits possible



Scheme of a double sided strip detector (biasing structures not shown)





Positive oxide charges cause electron accumulation layer.

Silicon Drift Detector (like gas TPC !)