Fundamentals of Particle Detectors

Fulvio Tessarotto (CERN and INFN – Trieste)

Introduction

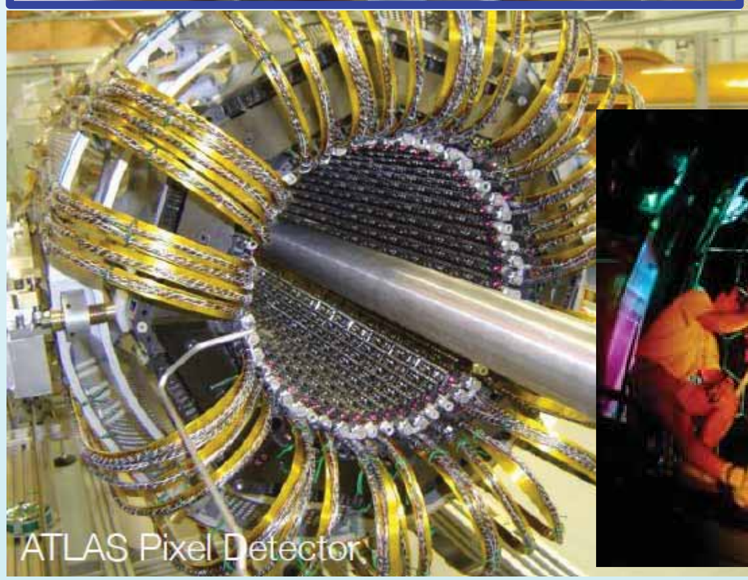
discoveries and detectors

gas detectors

silicon detectors

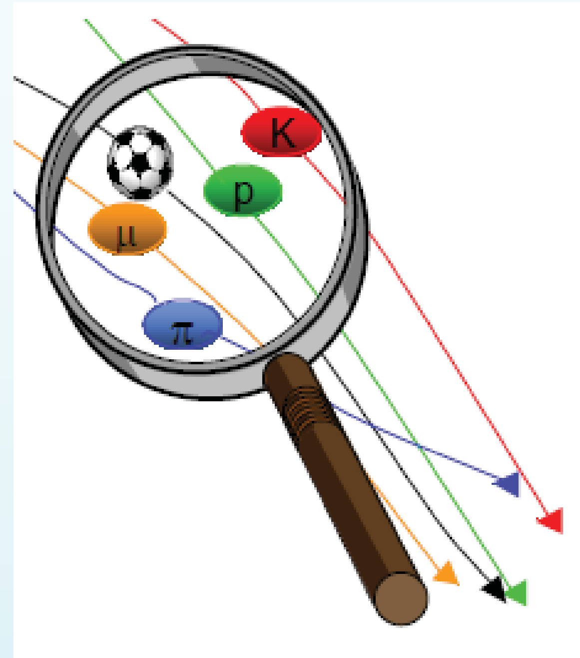
photon detectors

calorimeters



Particle detectors to see the invisible

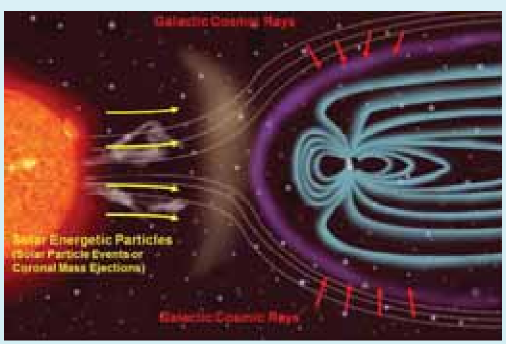
Particle detectors are instruments invented to measure the feeble signals produced by subatomic particles

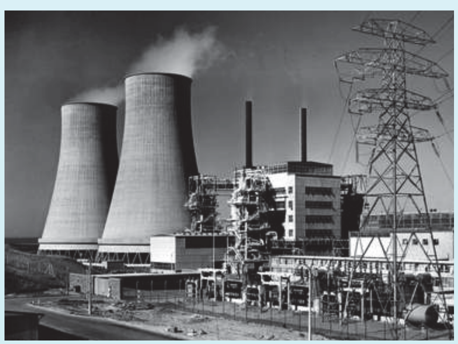


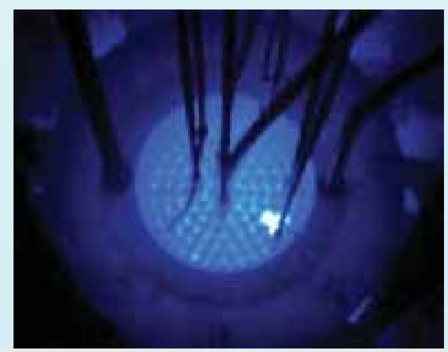
Thanks to particle detectors subatomic particles can be "seen" and their characteristics can be measured

A single particle is "invisible" but many particles at the same time can produce an effect visible to naked eye:

← Polar aurora images



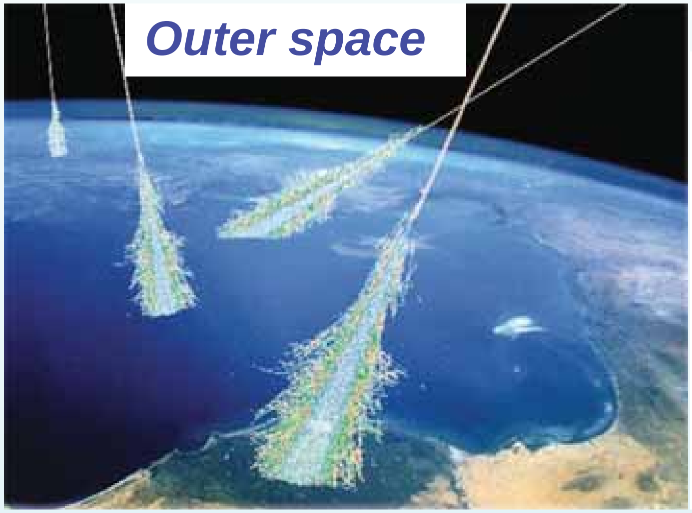




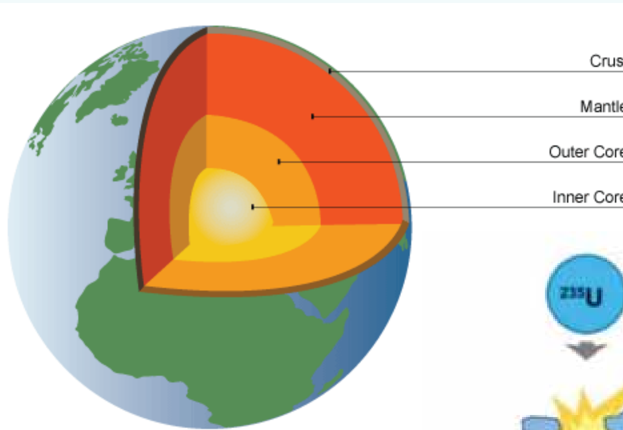
Nuclear reactor cores

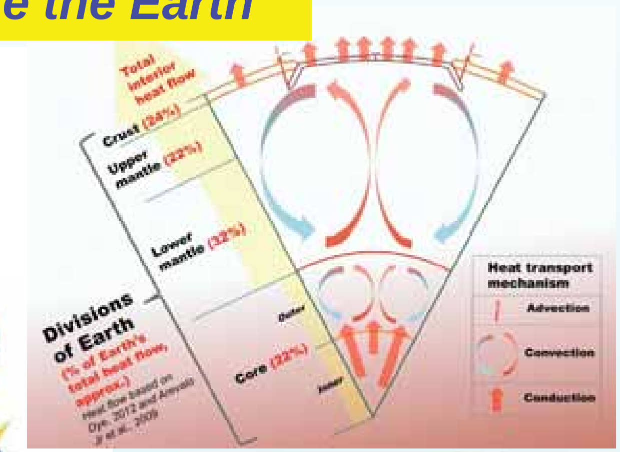
particles come from everywhere

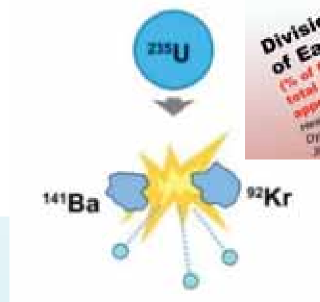
Outer space

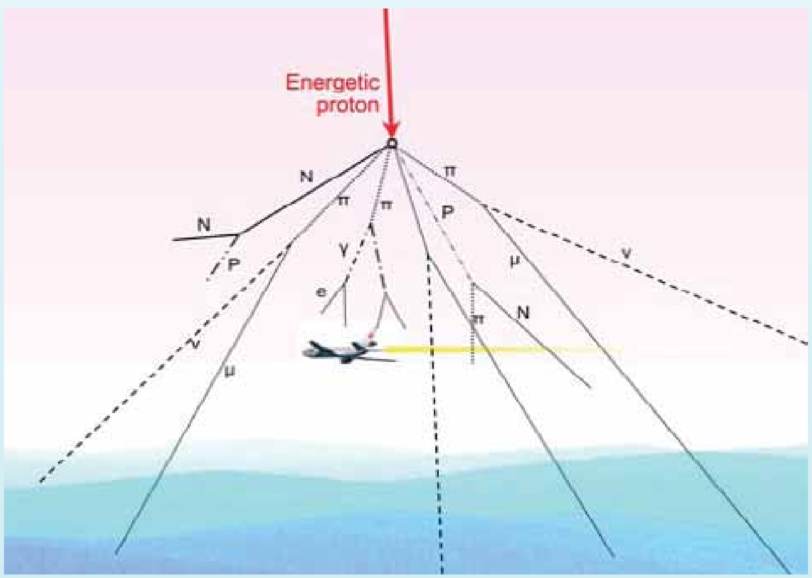


Radioactive decays inside the Earth









Almost every material on the Earth surface too, including our own bodies

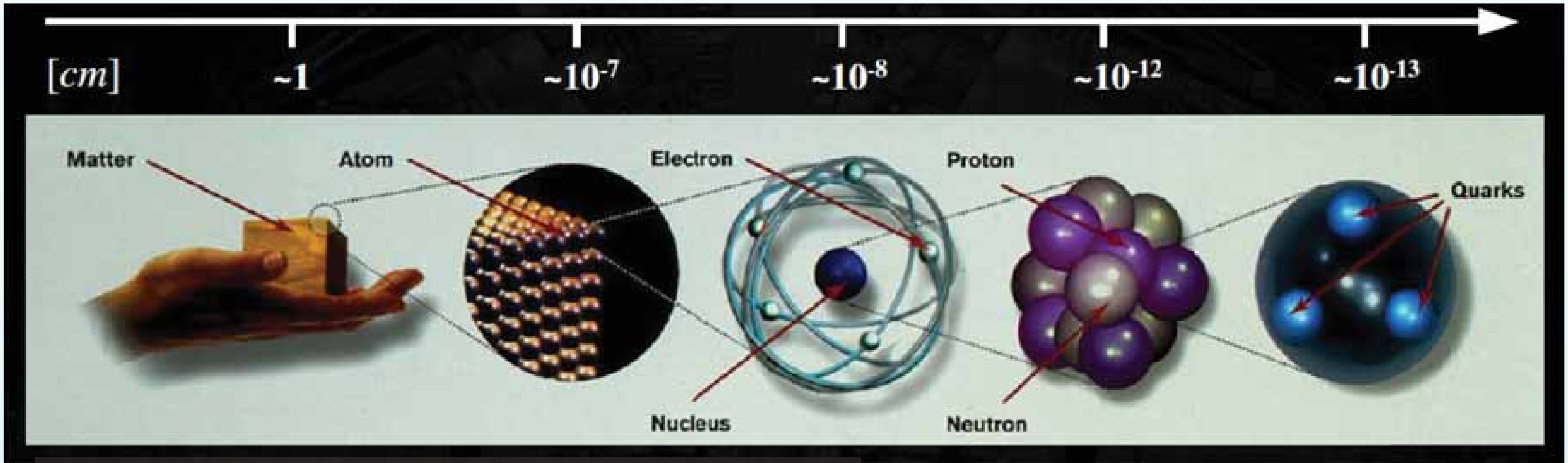
On average a human body has ~30 mg of Potassium 40, corresponding to ~ 4 kBq

and can be produced in a laboratory

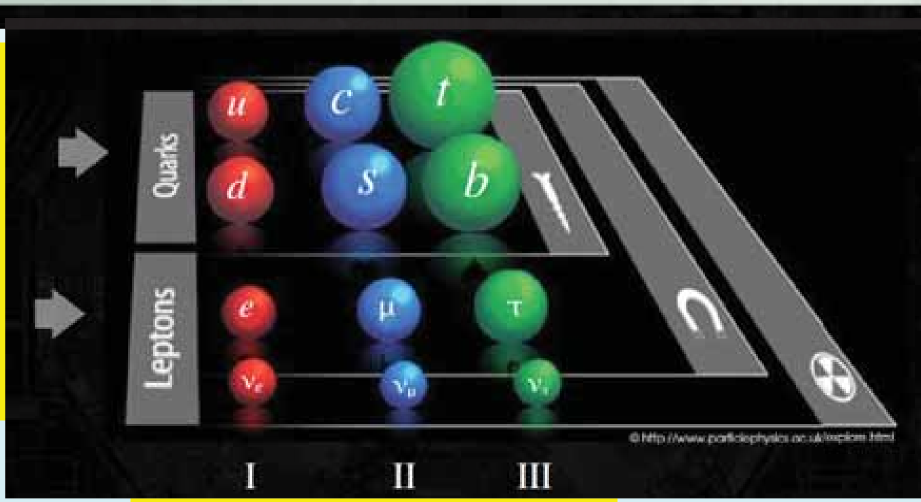
In a high-energy event all kind of particles are produced: many of them immediately decay, others survive long enough to interact with the materials they traverse.

The complete reconstruction of an event requires the detection of the produced particles and the identification of their characteristics: a complex set of particle detectors has to be used to accomplish this task.

The constituents of matter

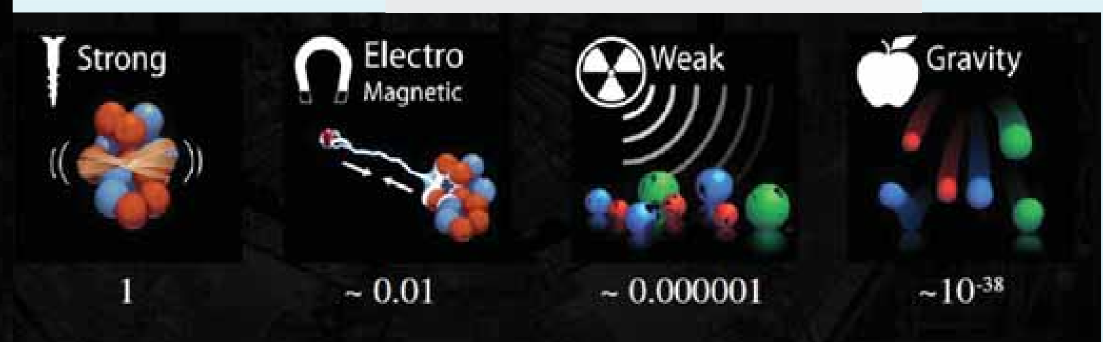


Two families



Three generations

Four interactions



gluon *photon* *W-Z* *graviton*

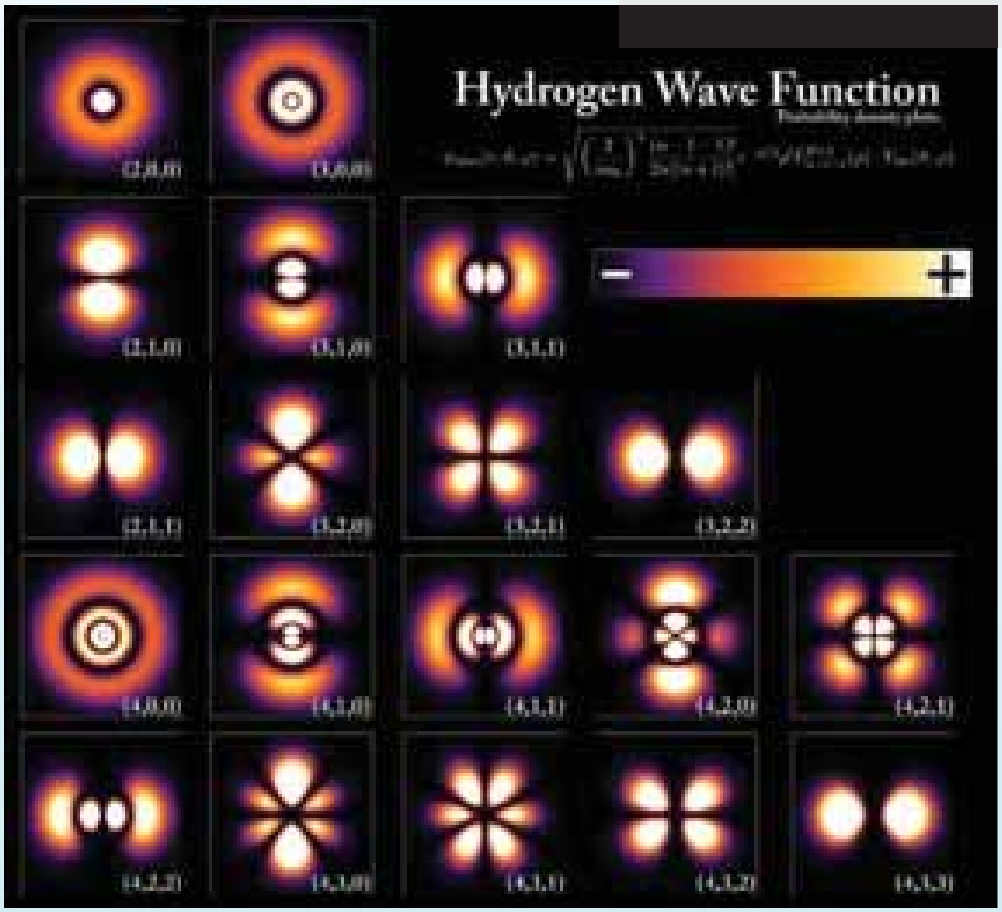
and the Higgs boson

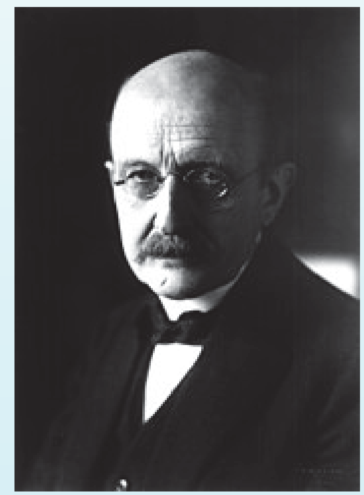
Particles do what we cannot

The laws which hold at the microscopic level are different from ours

A particle or an atom can stay at the same time in two or more different places

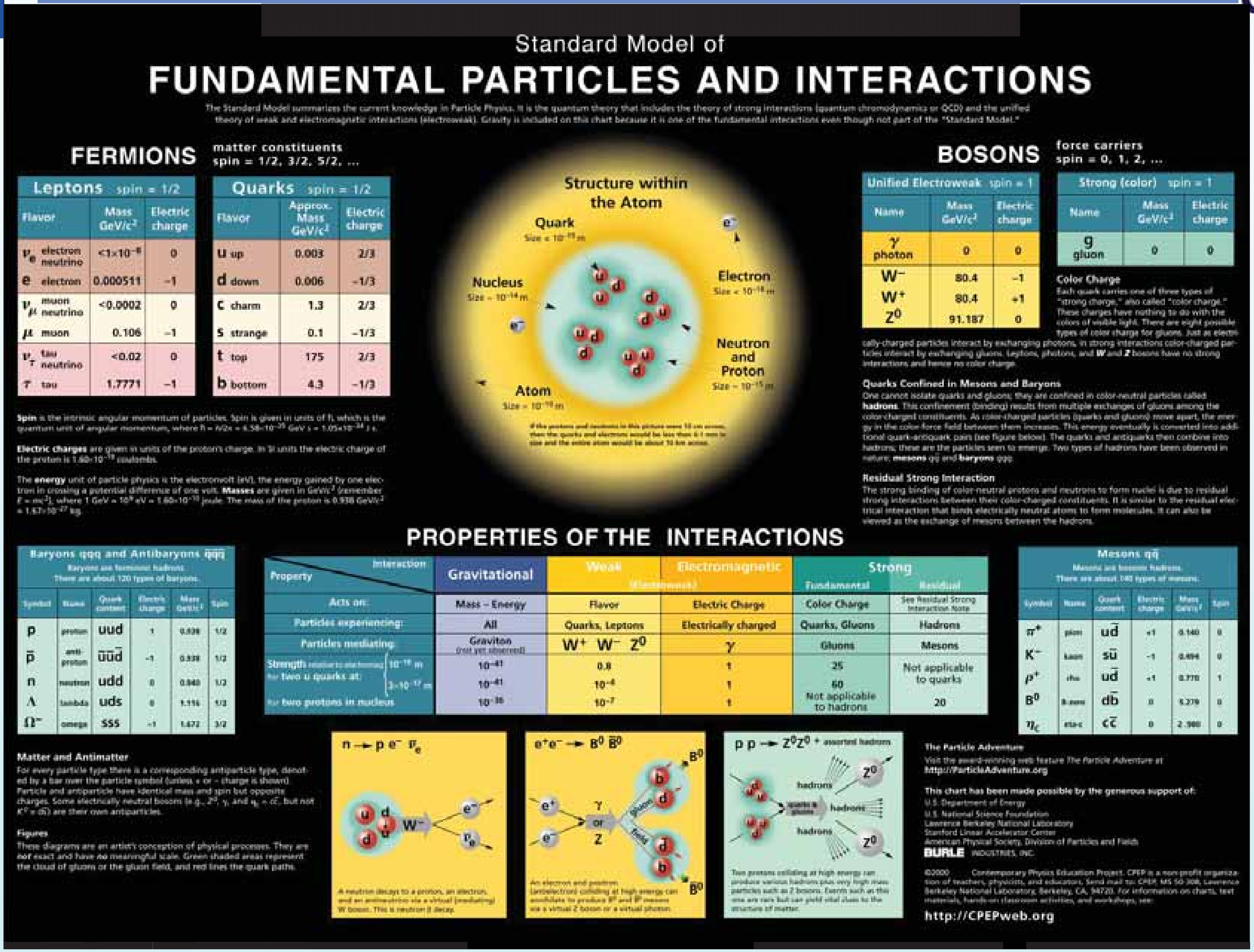
A particle can move from a point to another in space without passing anywhere in between the two points





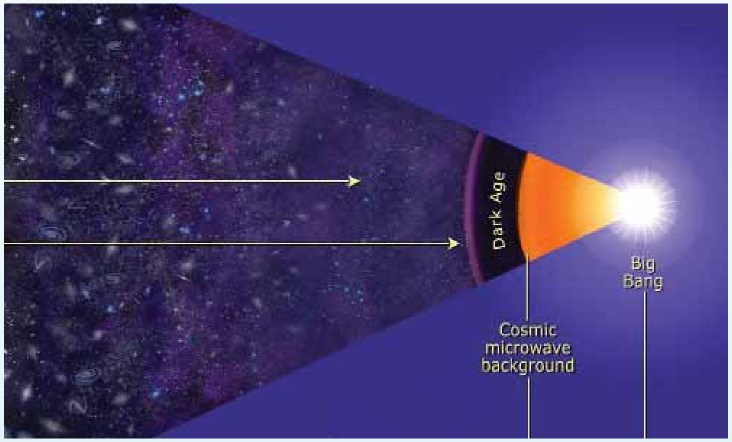
Max Plank is the father of the quantum theory

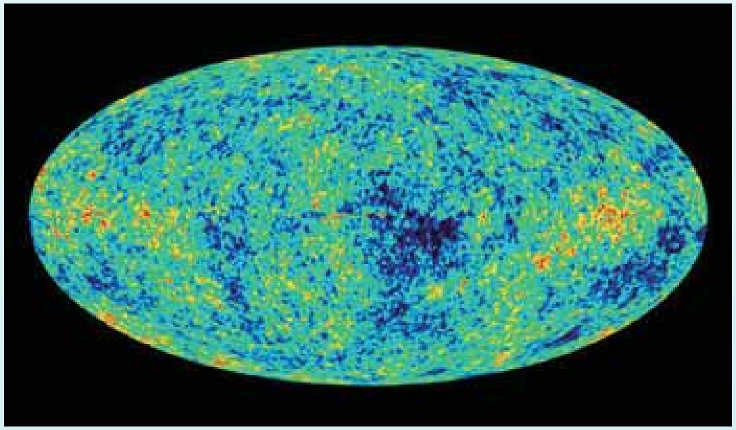
The Standard Model

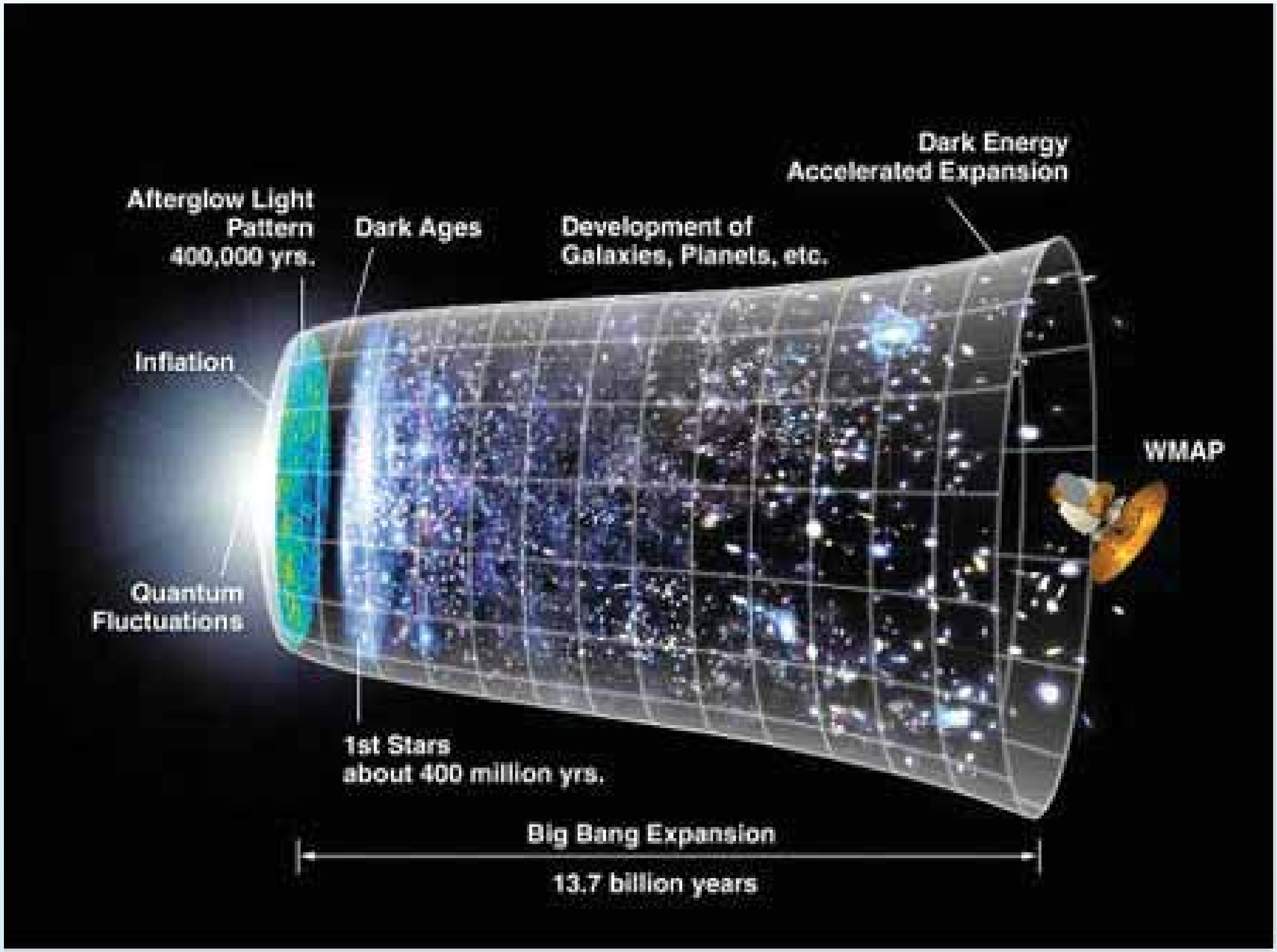


History of the Universe

From Cosmic Microwave Background Radiation and other measurements

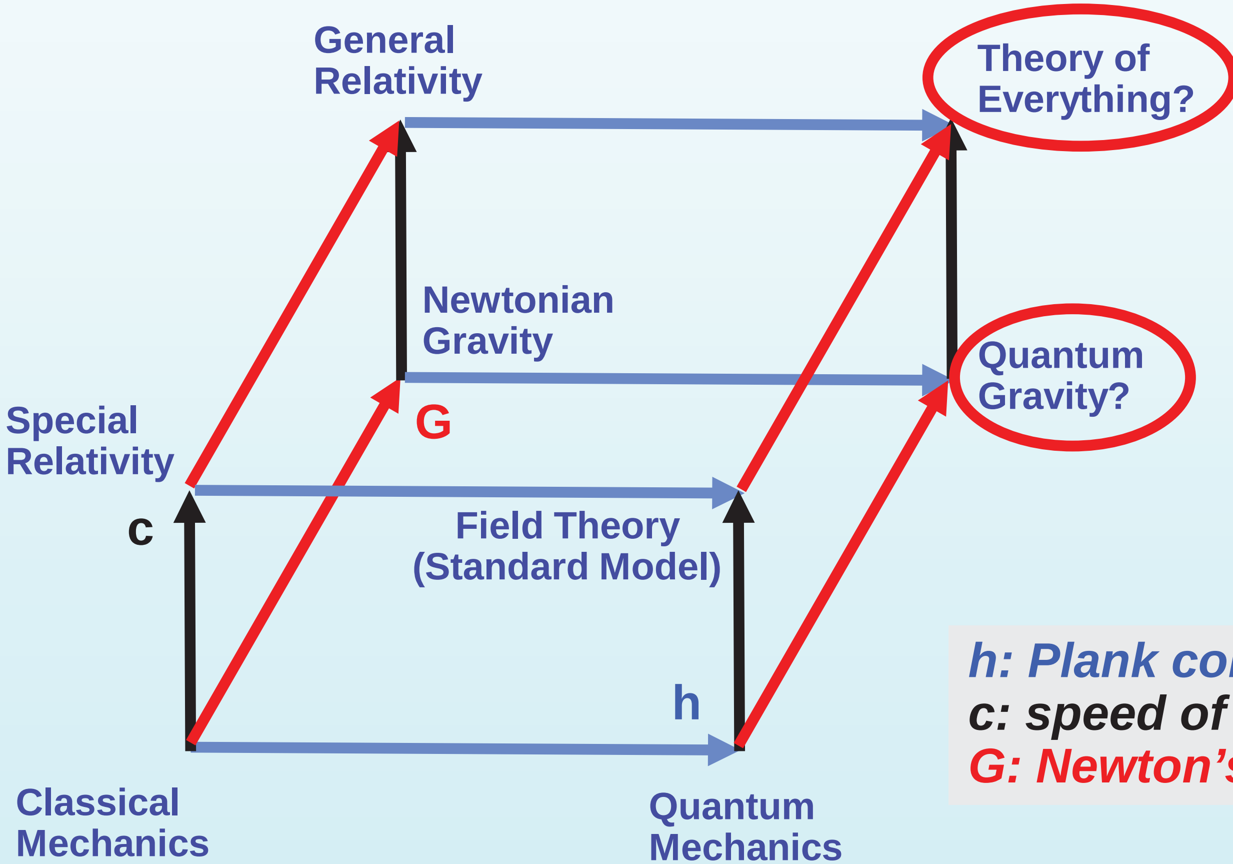


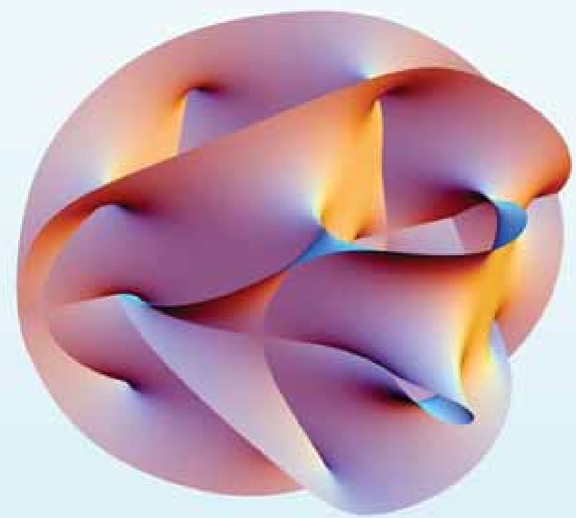




Theoretical panorama

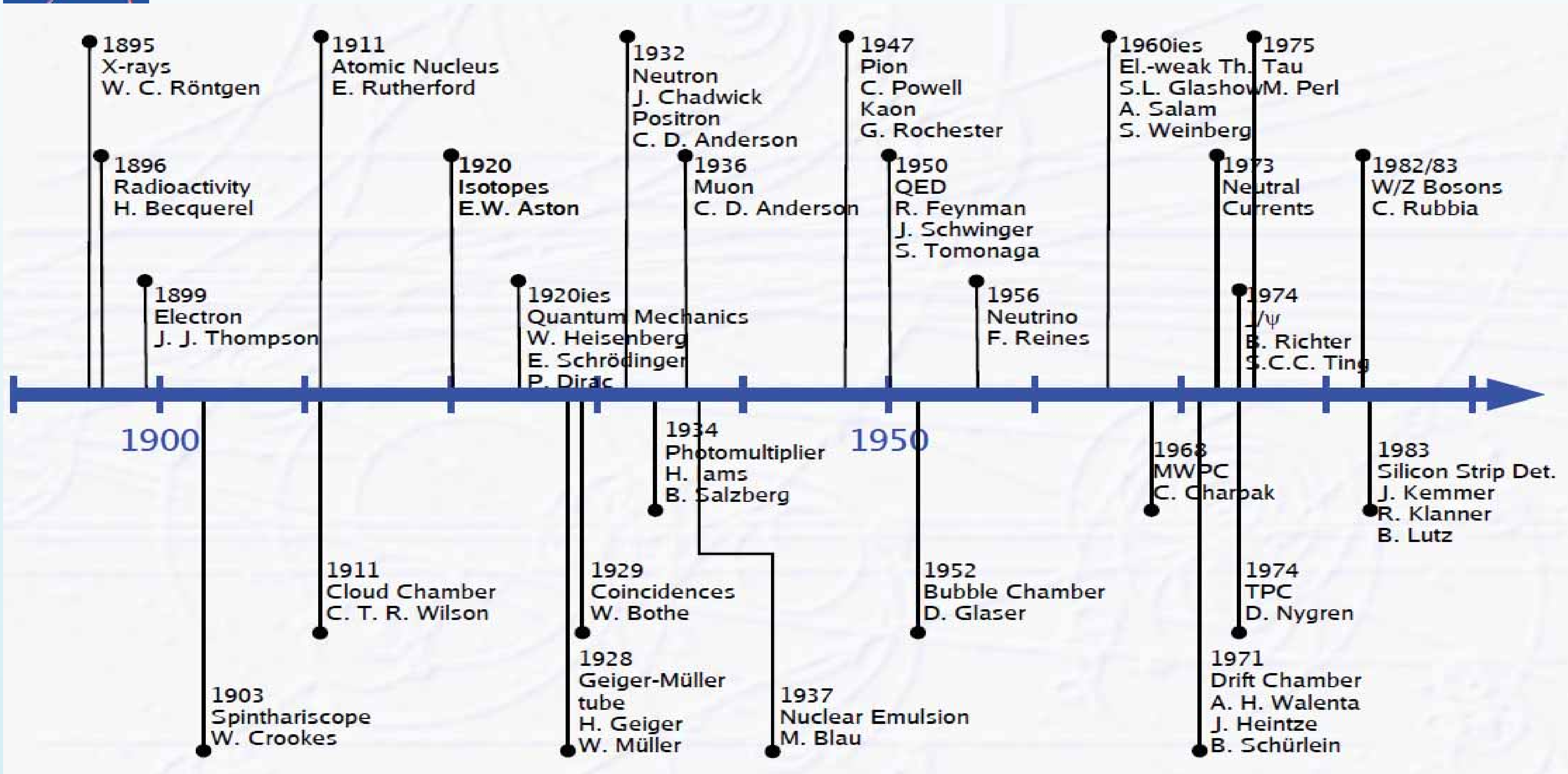
The fundamental constants of nature and unified theories





h: Plank constant
c: speed of light
G: Newton's constant

Discoveries and detector technologies



The history of discoveries and that of particle detectors are intimately interconnected

The discovery of radiation

Photographic plates

First

Detection of
α-, β- and γ-rays

1896

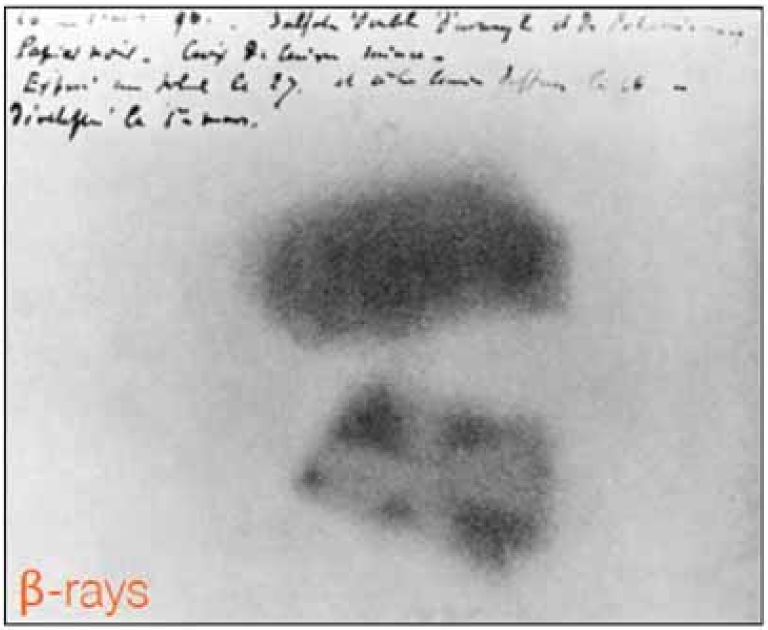
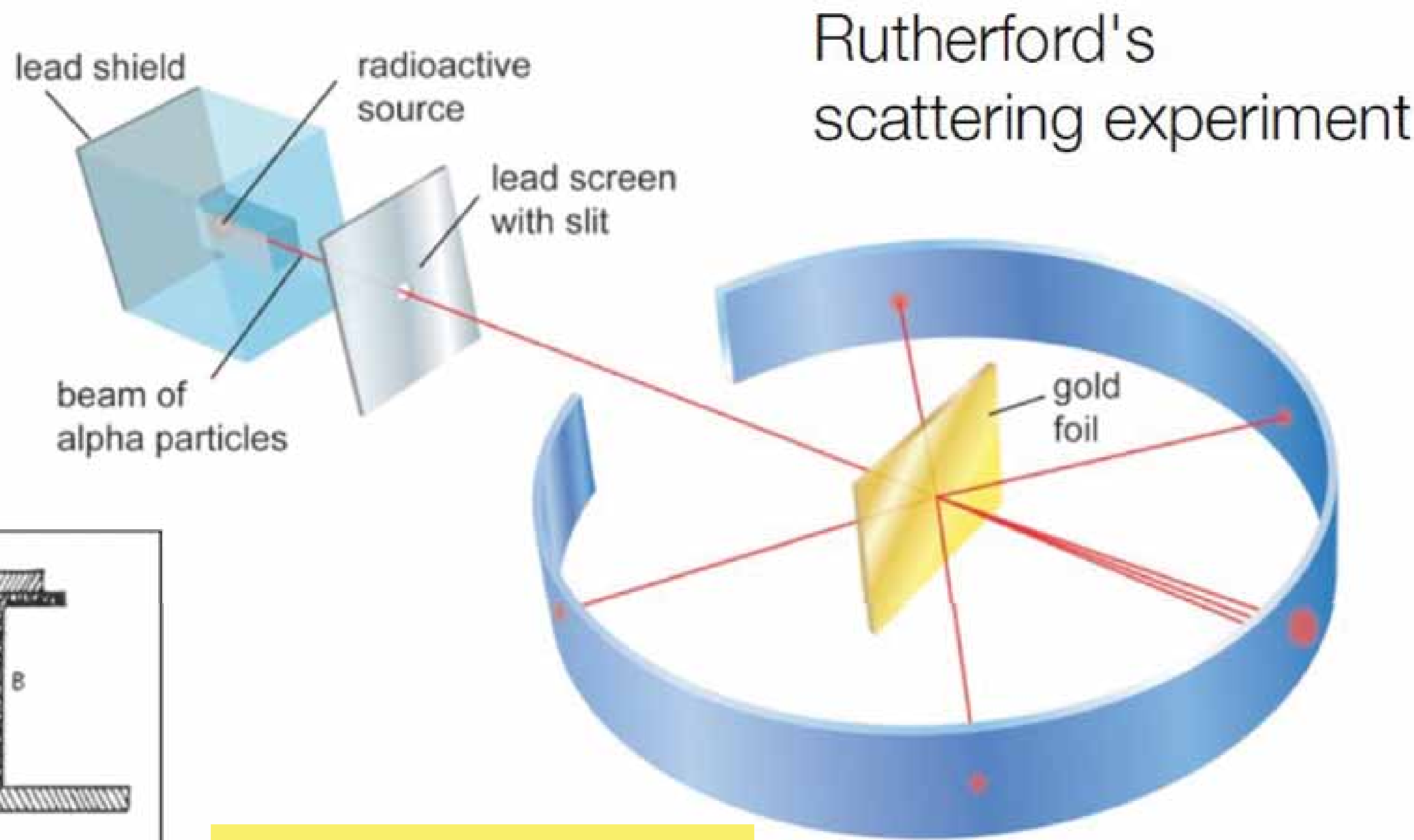


Image of Becquerel's photographic plate which has been fogged by exposure to radiation from a uranium salt.

1896

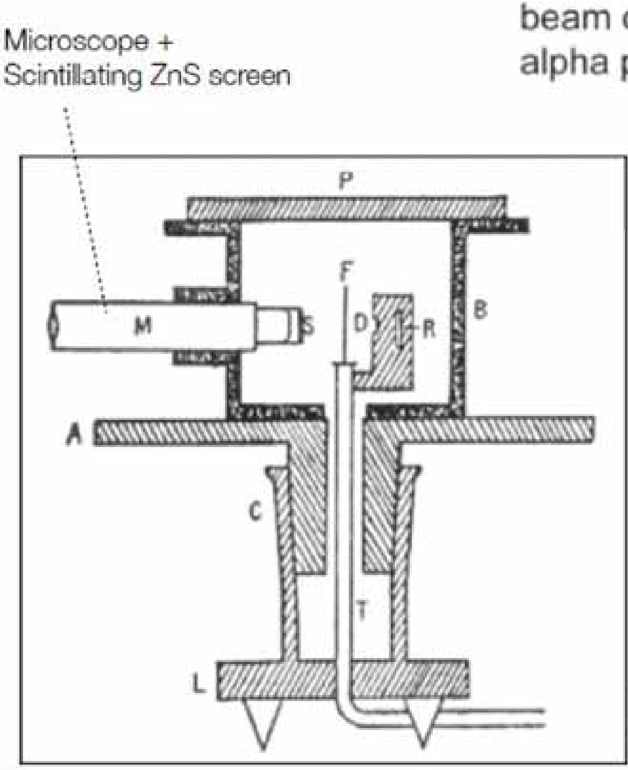
An x-ray picture taken by Wilhelm Röntgen of Albert von Kölliker's hand at a public lecture on 23 January 1896.

The discovery of the atomic nucleus



Schematic view
of Rutherford experiment

1911



Rutherford's original
experimental setup

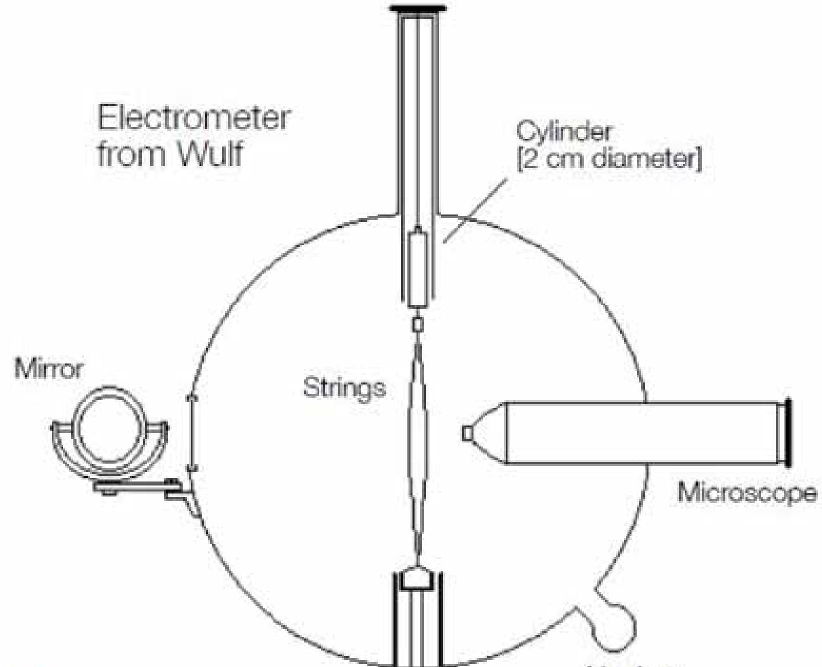
Scintillating screens:
William Crooks, 1903

1912: cosmic rays

Detection of cosmic rays

[Hess 1912; Nobel prize 1936]

Wulf electroscope invented in 1909



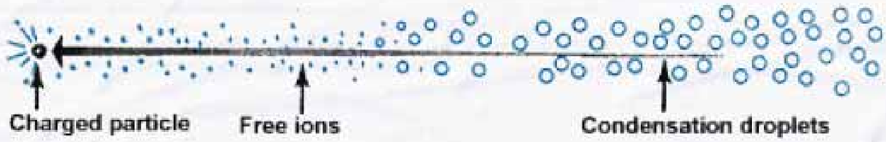
1912

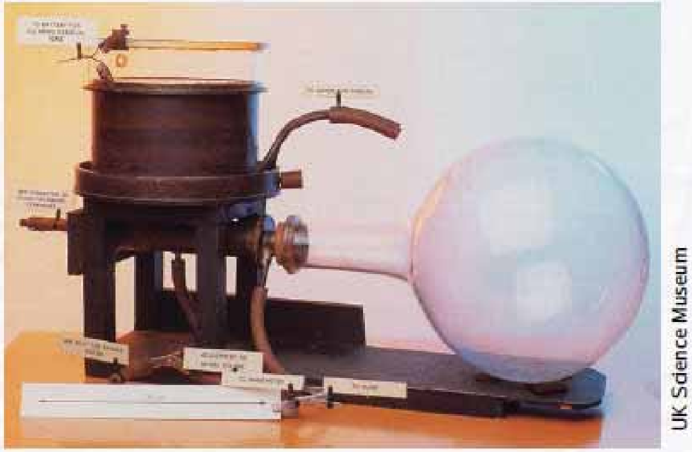
Victor F. Hess before his 1912 balloon flight in Austria during which he discovered cosmic rays.

1911: the cloud chamber

Cloud chamber (1911 by Charles T. R. Wilson, Noble Prize 1927)

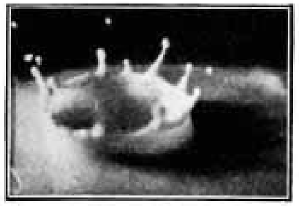
- chamber with saturated water vapour
- charged particles leave trails of ions
  - water is condensing aound ions
- visible track as line of small water droplets





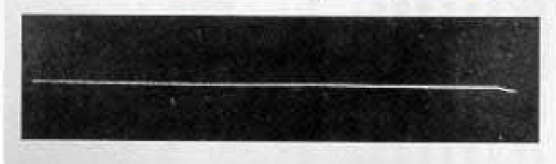
Also required

- high speed photographic methods
  - invented by Arthur M. Worthington 1908 to investigate the splash of a drop
  - ultra short flash light produced by sparks



Charles T. R. Wilson

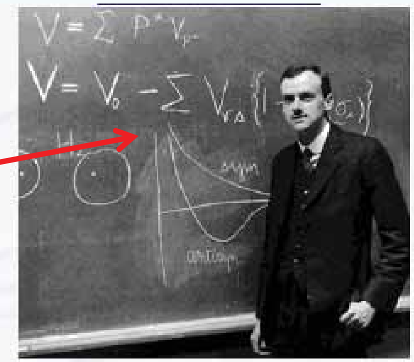
First photographs of α–ray particles 1912



1932: antimatter, 1936: muon

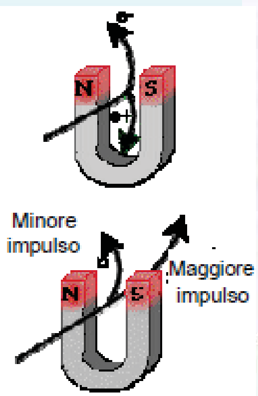
Was also used for the discovery of the positron

- predicted by Paul Dirac 1928 (Nobel Prize 1933)
- found in cosmic rays by Carl D. Anderson 1932 (Nobel Prize 1936)

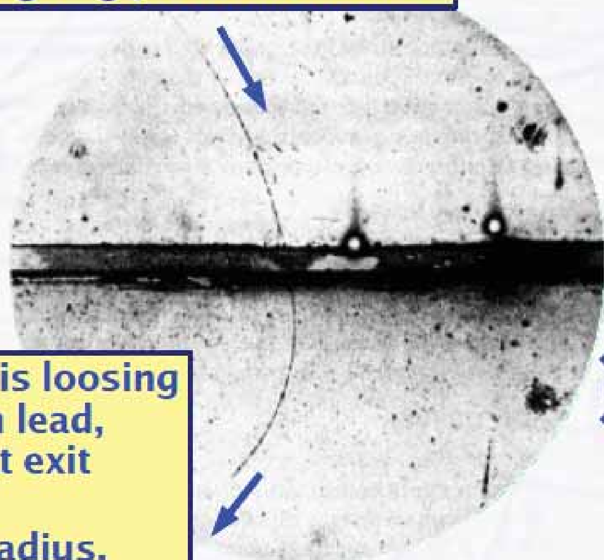


Anderson also found the muon in 1936, the first 2nd generation particle in the Standard Model

Isidor Isaac Rabi said:
"Who ordered that?"



downward going positron, 63 MeV



6 mm lead plate

1.5 T magnetic field

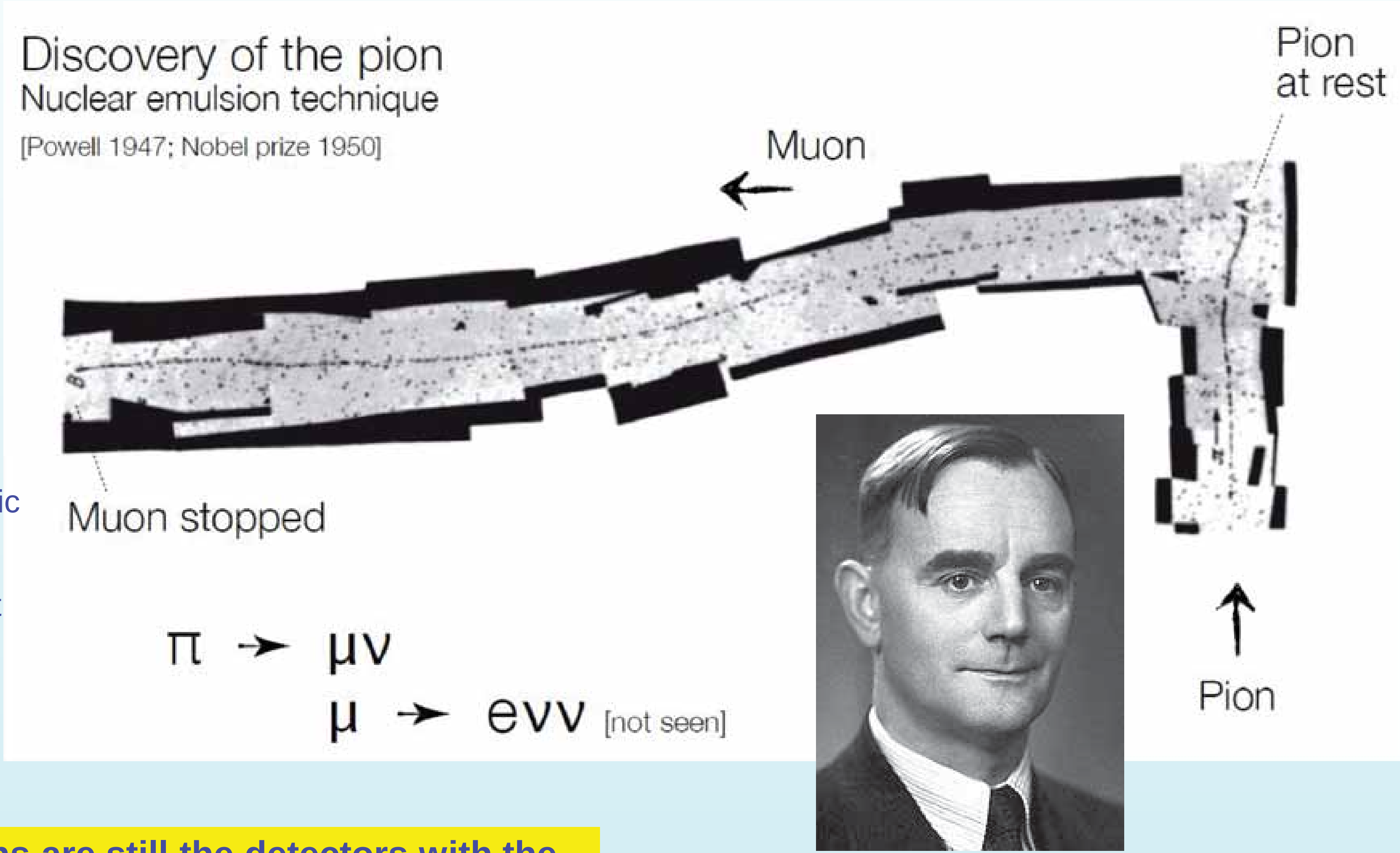
positron is loosing energy in lead, 23 MeV at exit
→
smaller radius, this defines the track direction!

Carl D. Anderson

Nuclear emulsions

Marietta Blau:

she developed in Vienna the photographic nuclear emulsion technology for very accurate measurement of high energy nuclei and discovered the "disintegration stars" of spallation events



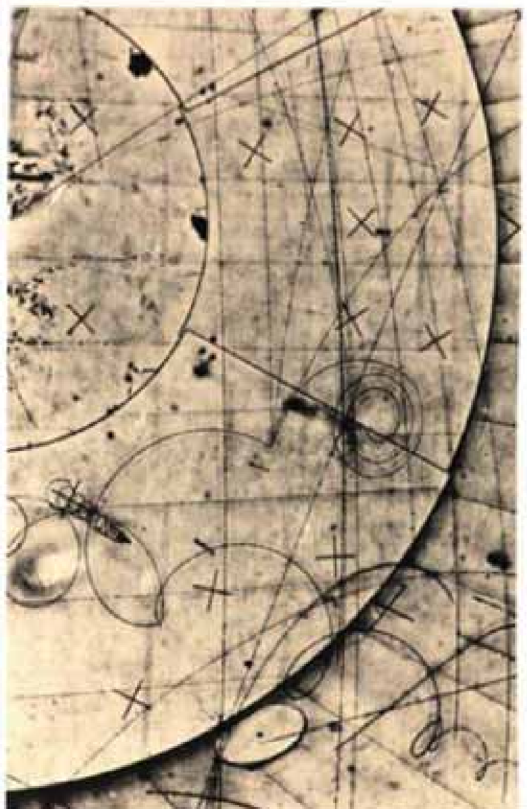
Cecil Frank Powell
Nobel Prizes 1950

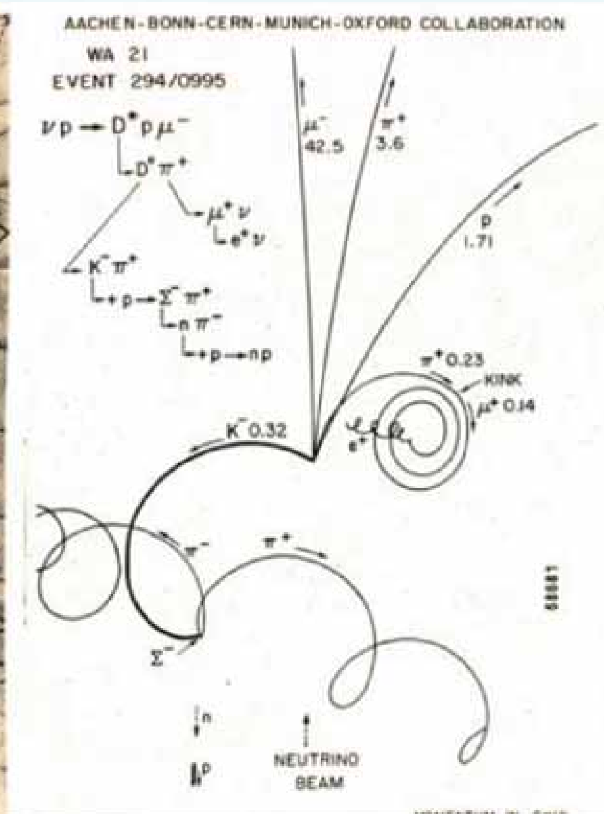
emulsions are still the detectors with the highest intrinsic space resolution: < 1 μm

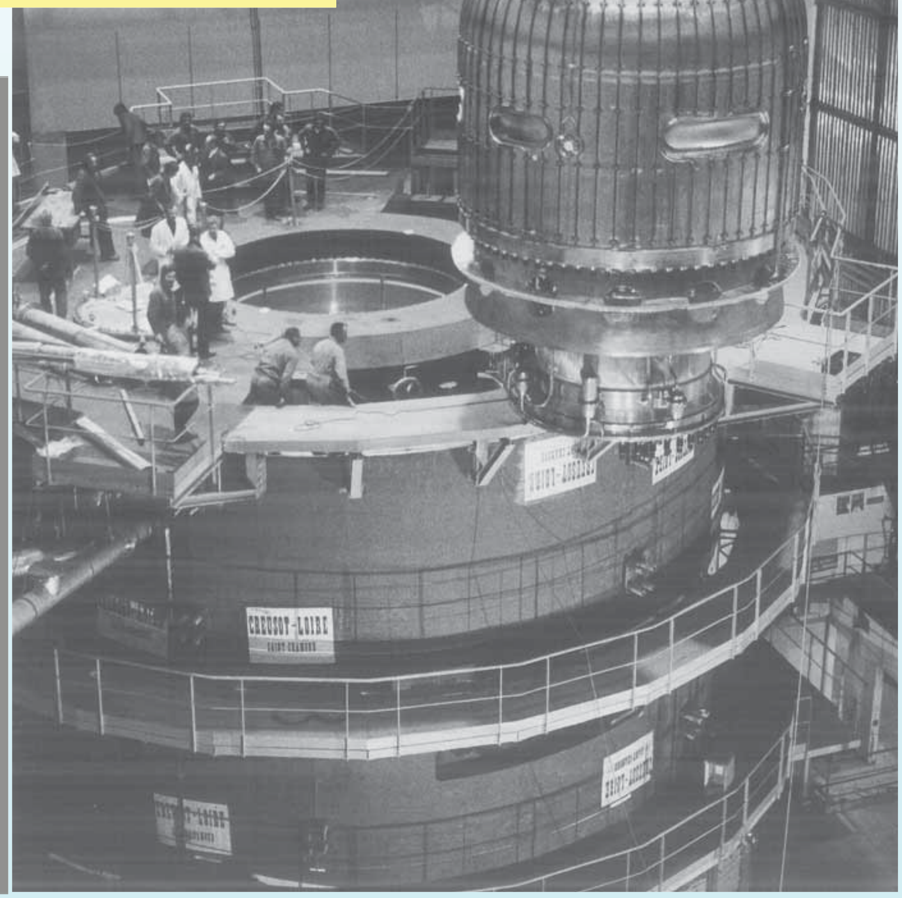
1952: bubble chamber

The bubble chamber, invented by Donald Arthur Glaser in 1952, has been for many years the most powerful instrument of ionizing particles investigation.

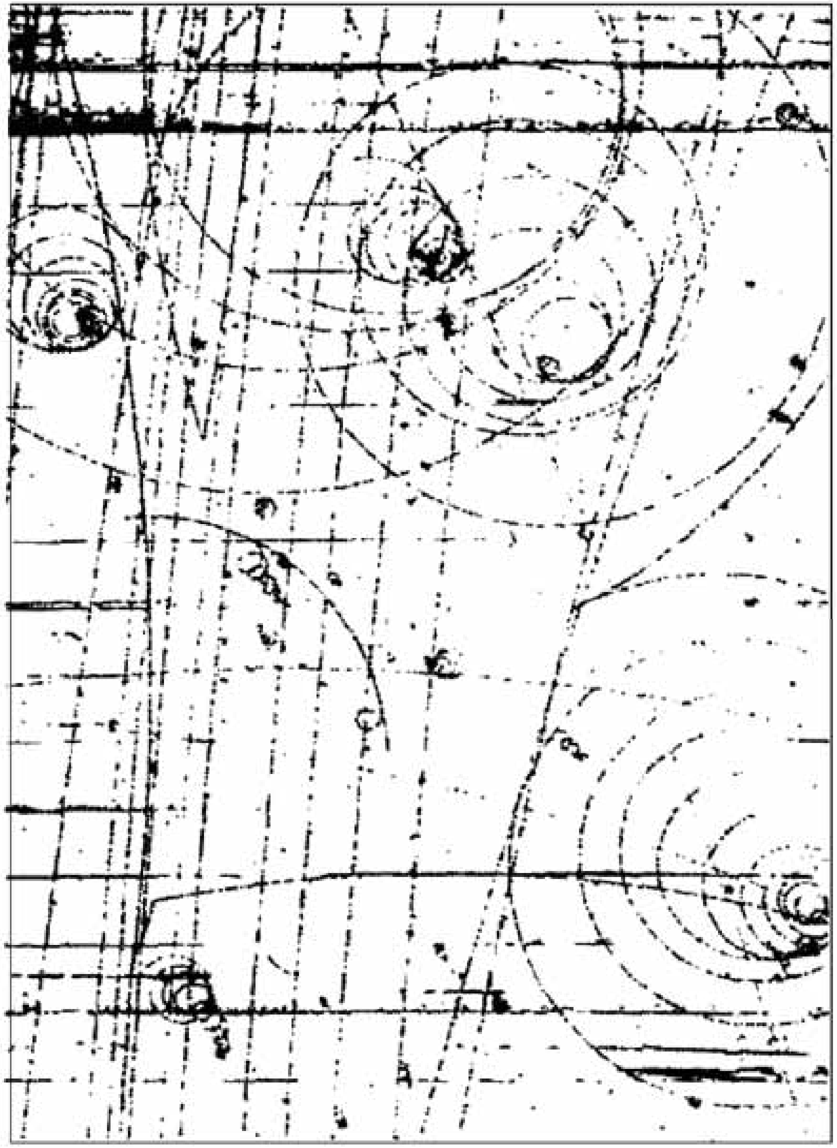
BEBC (Big European Bubble Chamber)

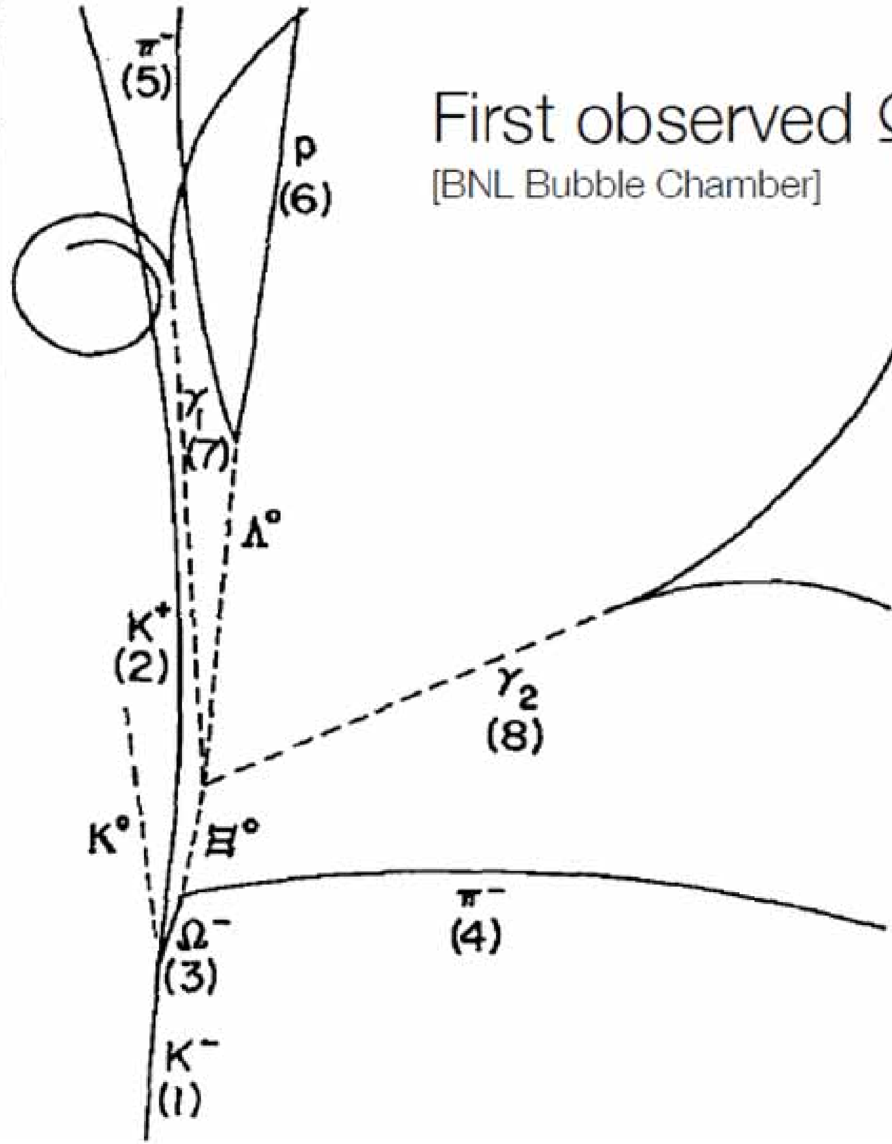






1964: the first predicted particle



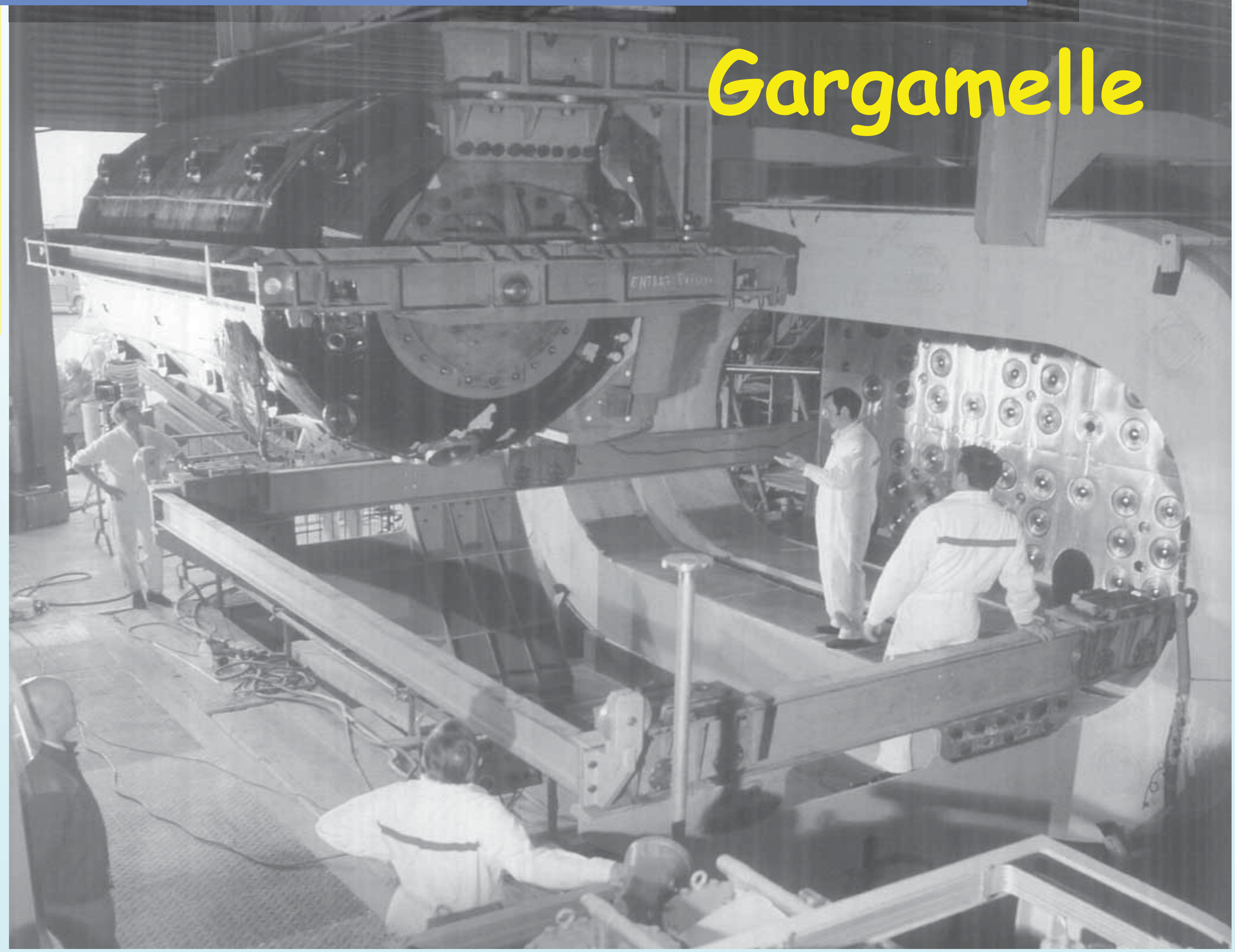


First observed Ω^- event

[BNL Bubble Chamber]

1973: the e.w. theory is confirmed

1973: a big discovery in Europe, at CERN.
Gargamelle detects weak neutral currents
The electroweak theory is confirmed



Salam receives the Nobel prize in 1979 together with Weinberg and Glashow

1983: the weak bosons discovery

Was achieved thanks to complex accelerator and detector systems

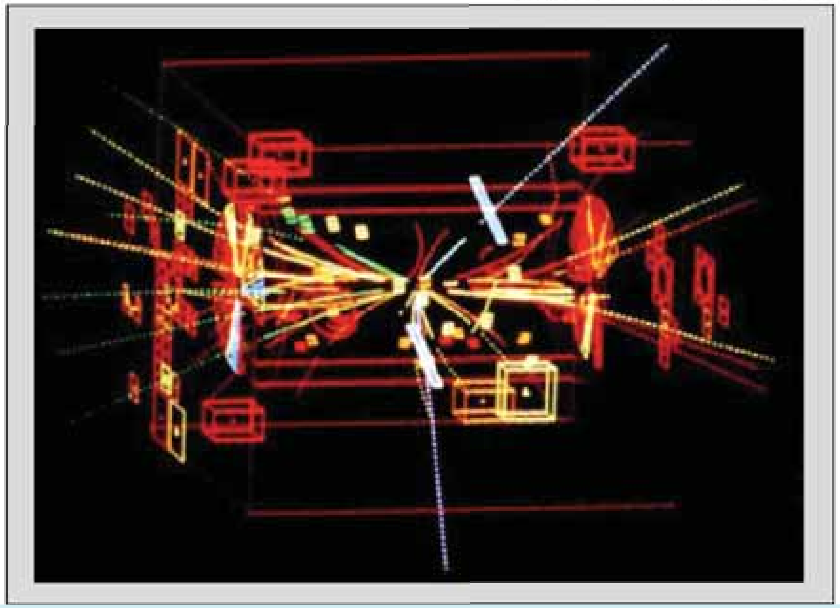
UA1
Detector

Discovery of the W/Z boson (1983)

Carlo Rubbia
Simon Van der Meer

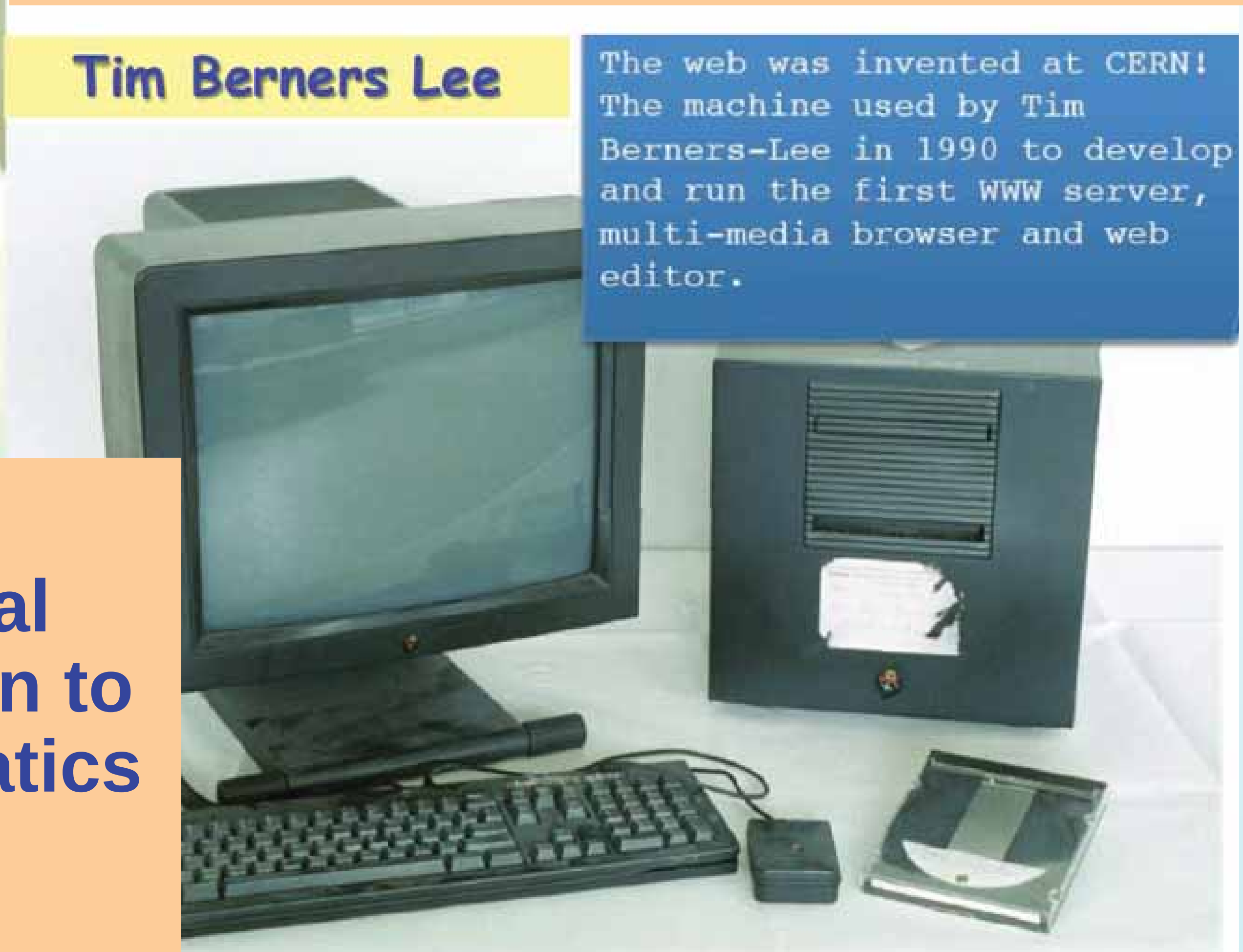
[Nobel prize 1984]

First Z^0 particle seen by UA1



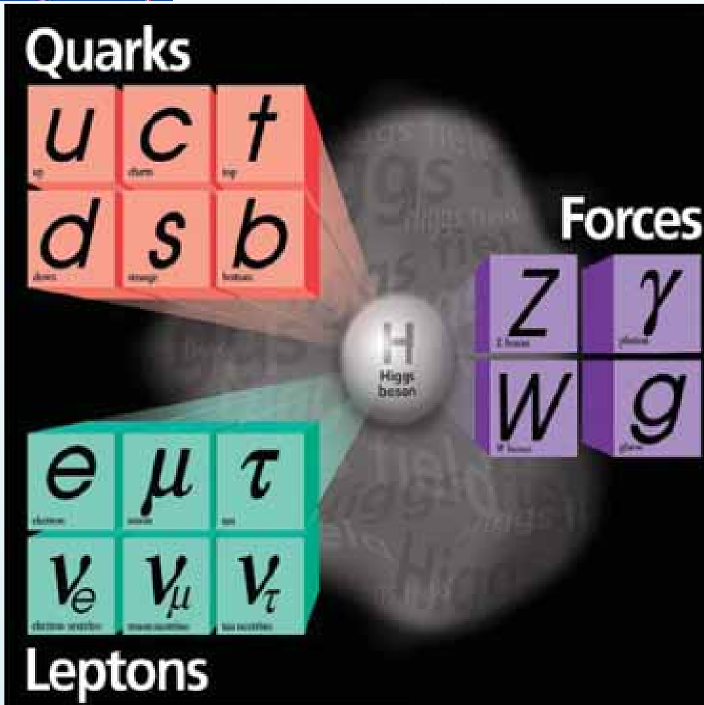
Tim Bernes-Lee invented the www

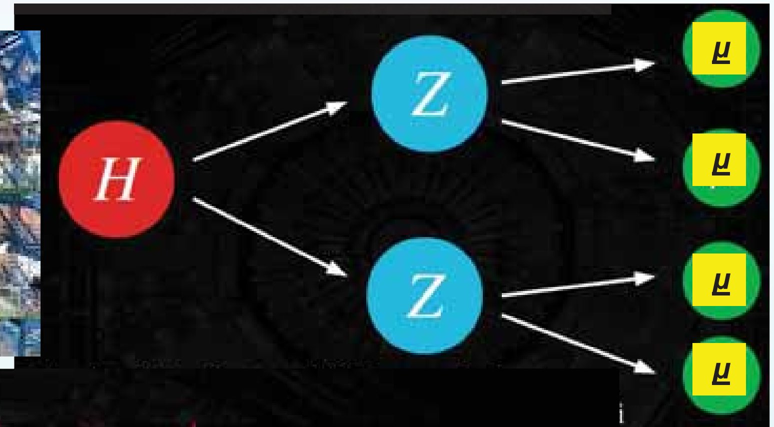
in 1990 at CERN, to allow full exploitation of the data from these particle detectors

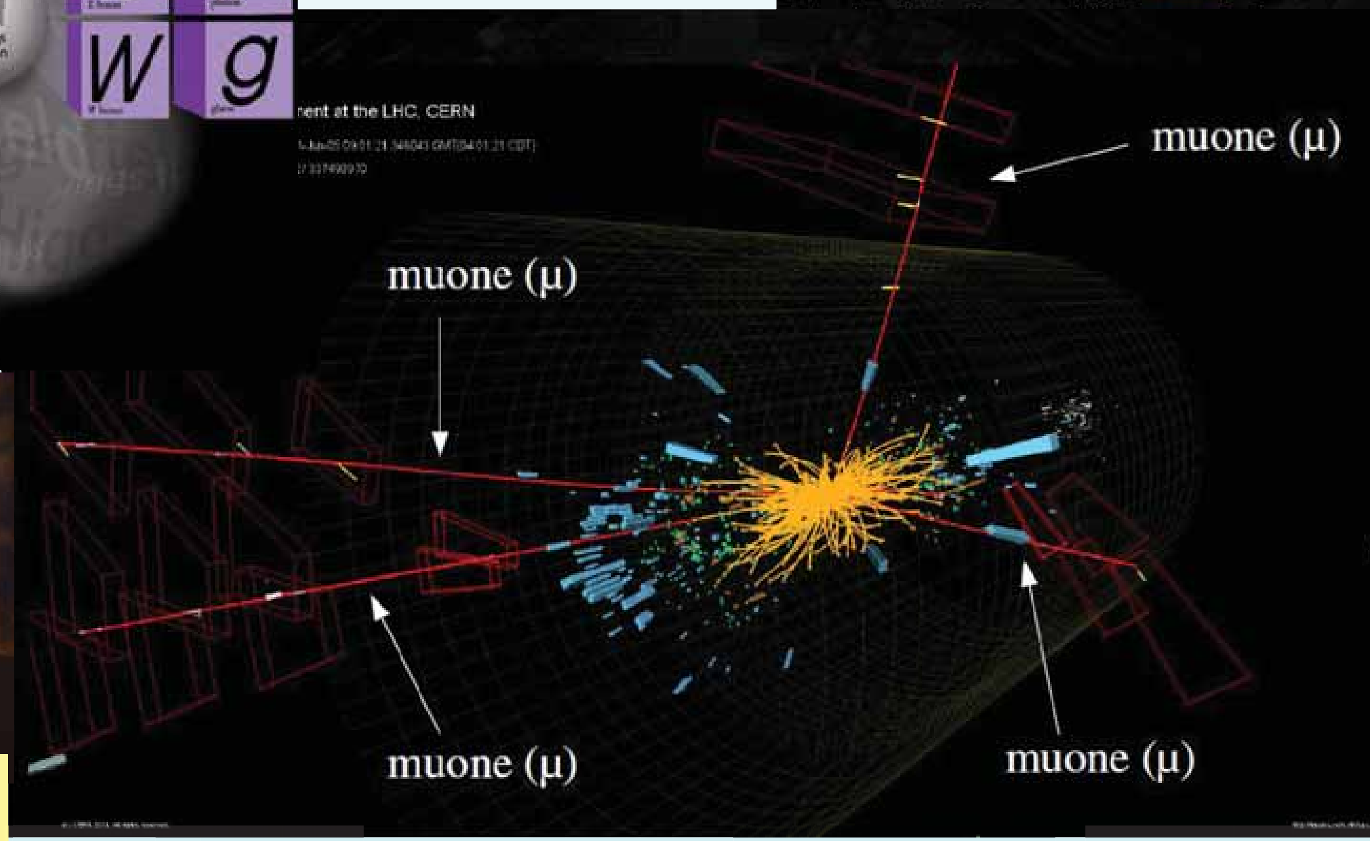


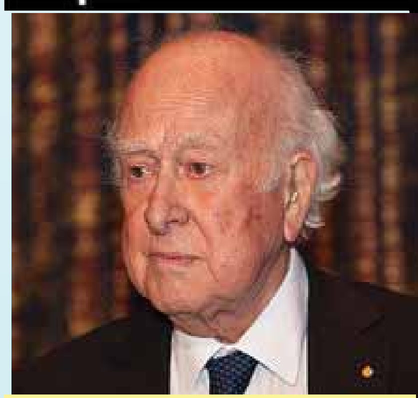
fundamental contribution to the informatics revolution

2012: discovery of the Higgs boson



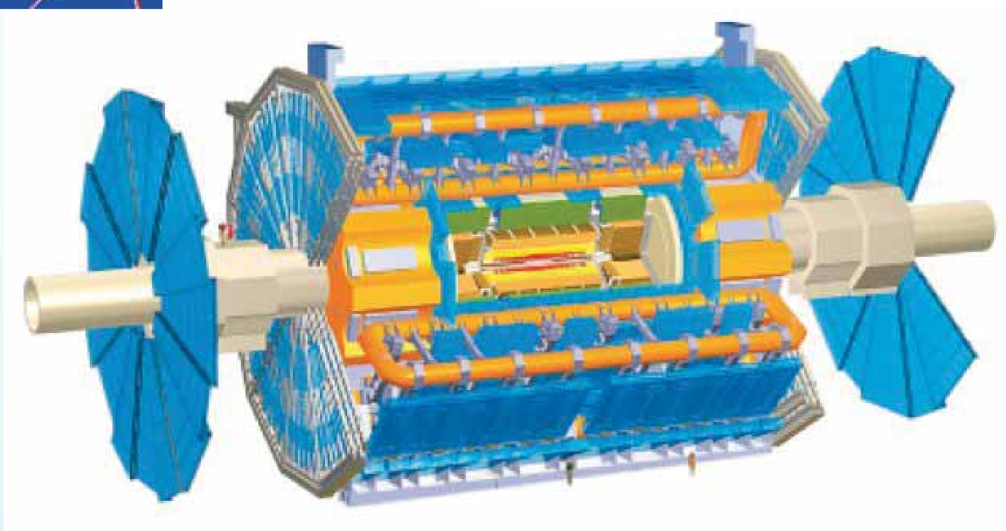


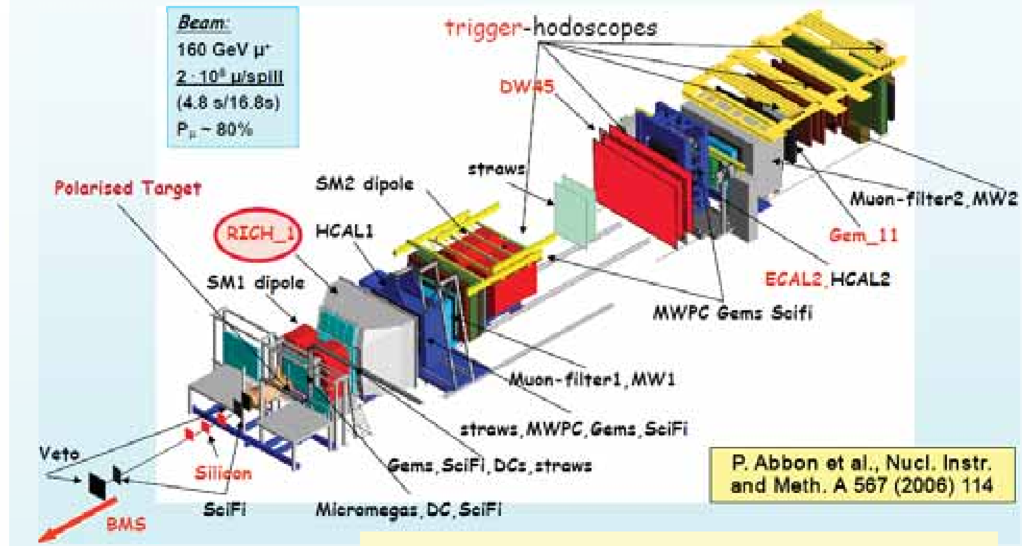


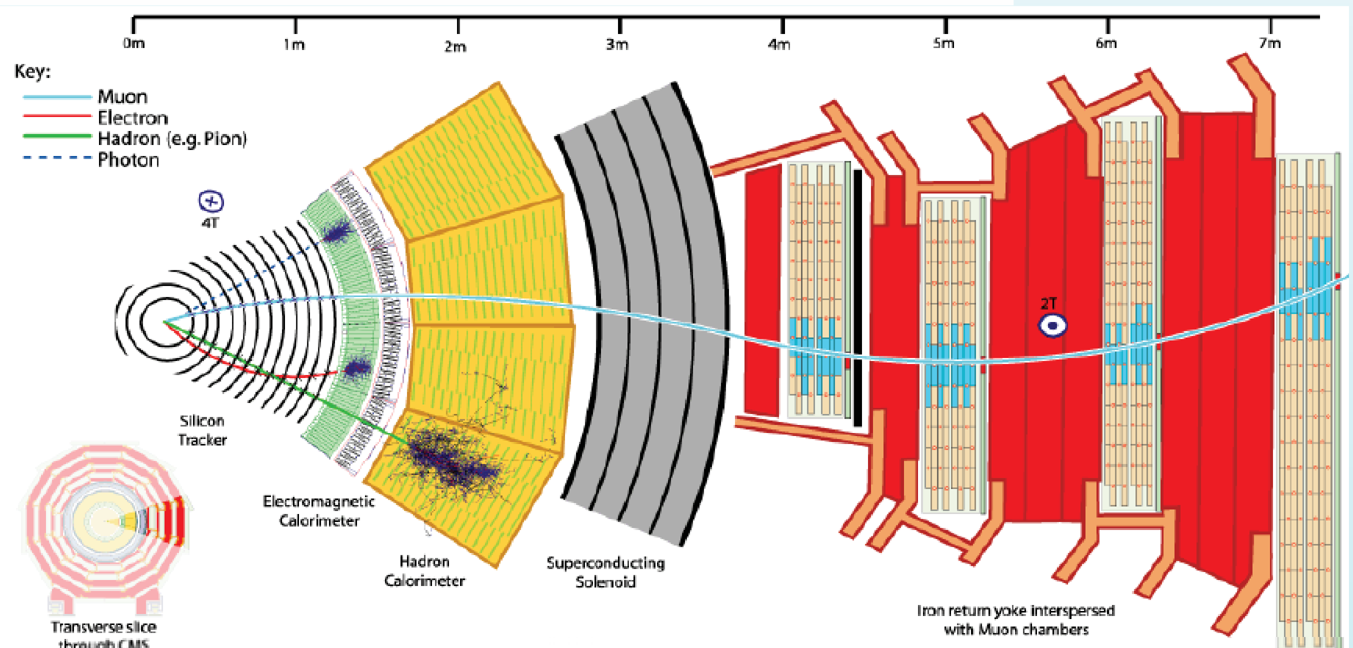


Peter Higgs,
Nobel Prize 2013

A modern experiment

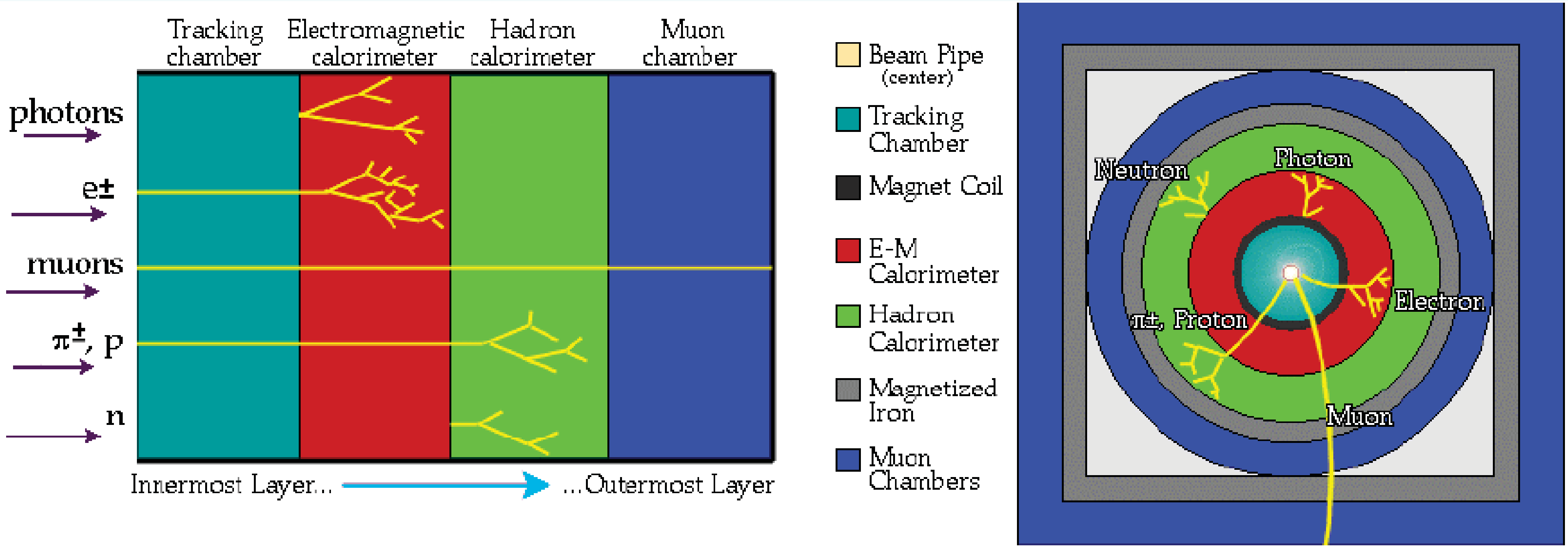






uses a combination of different detectors, combines the information from all of them and fully reconstructs the characteristics of the interesting event which took place

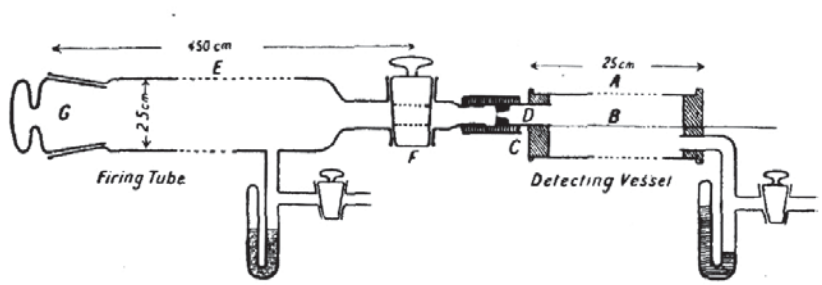
Different particles are seen by different detectors



- Particles are detected via their interaction with matter.
- Many different physical principles are involved (mainly of electromagnetic nature). Finally we will always observe ionization and excitation of matter.

100 years of gaseous detectors: gallery 1

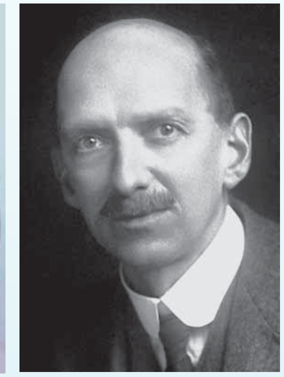
1908: FIRST WIRE COUNTER
USED BY RUTHERFORD IN THE STUDY OF NATURAL RADIOACTIVITY



E. Rutherford and H. Geiger ,
Proc. Royal Soc. A81 (1908) 141

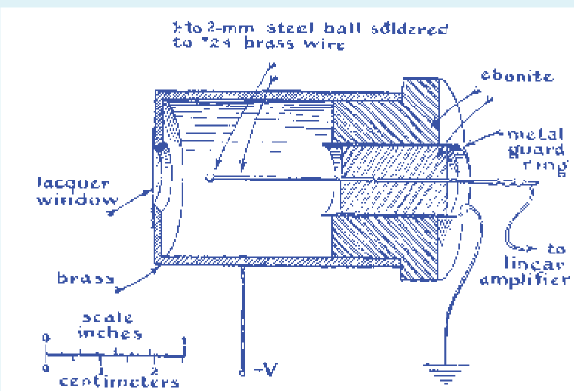
Nobel Prize in Chemistry in 1908

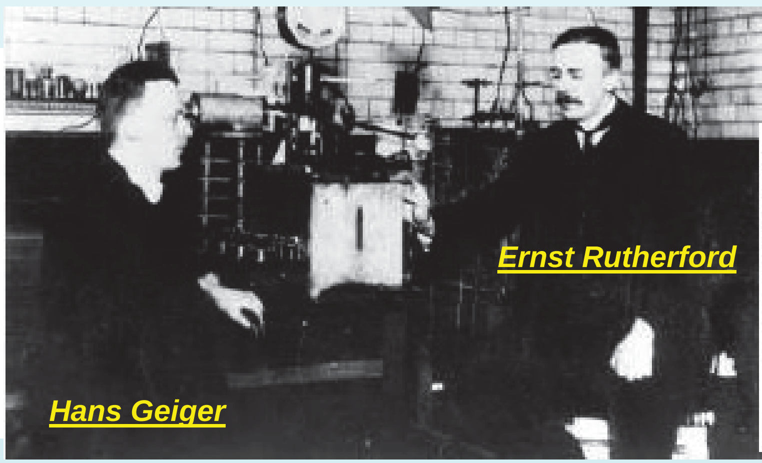
1911: CLOUD CHAMBER



Charles T.R. Wilson
Nobel Prize in 1927

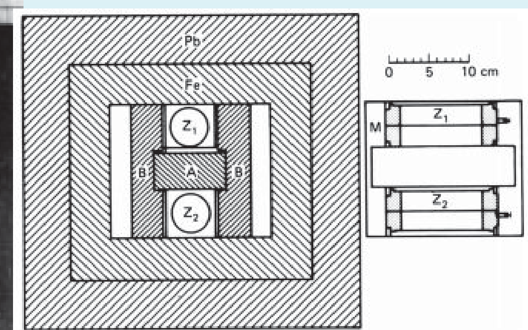
1928: GEIGER COUNTER
SINGLE ELECTRON SENSITIVITY

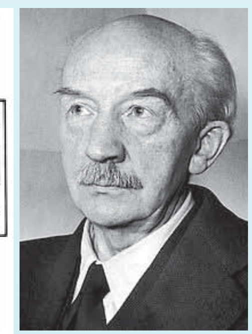




H. Geiger and W. Müller,
Phys. Zeits. 29 (1928) 839

COINCIDENCE METHOD

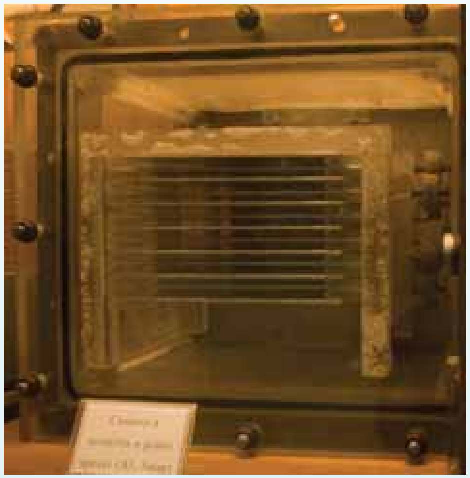




Walther Bothe
Nobel Prize in 1954

100 years of gaseous detectors: gallery 2

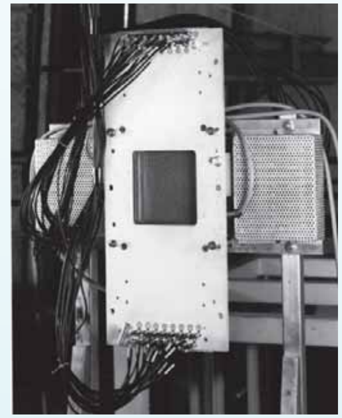
SPARK CHAMBER

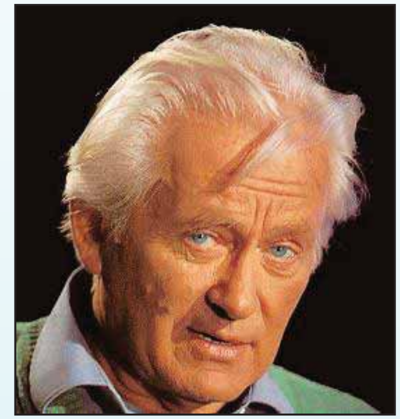


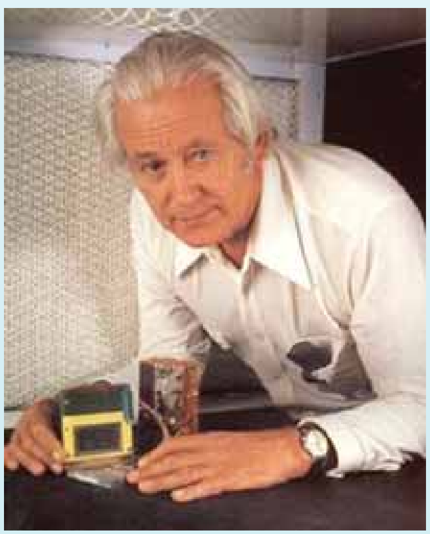
1952: BUBBLE CHAMBER

Donald A. Glaser
Nobel Prize in 1992

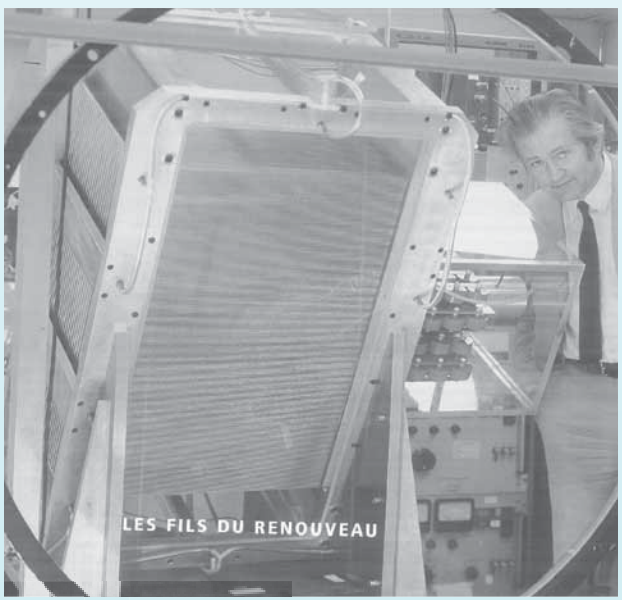
1968: MULTIWIRE PROPORTIONAL CHAMBER

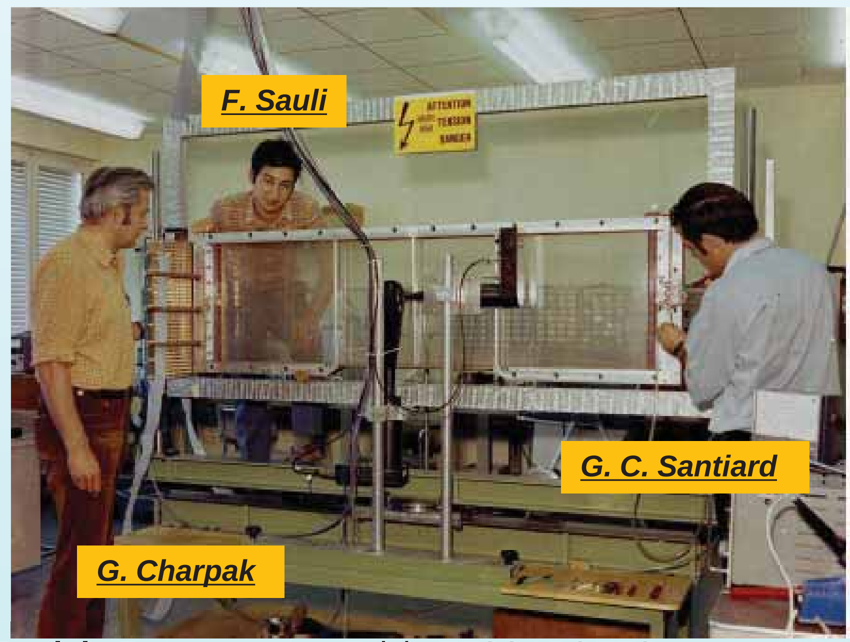




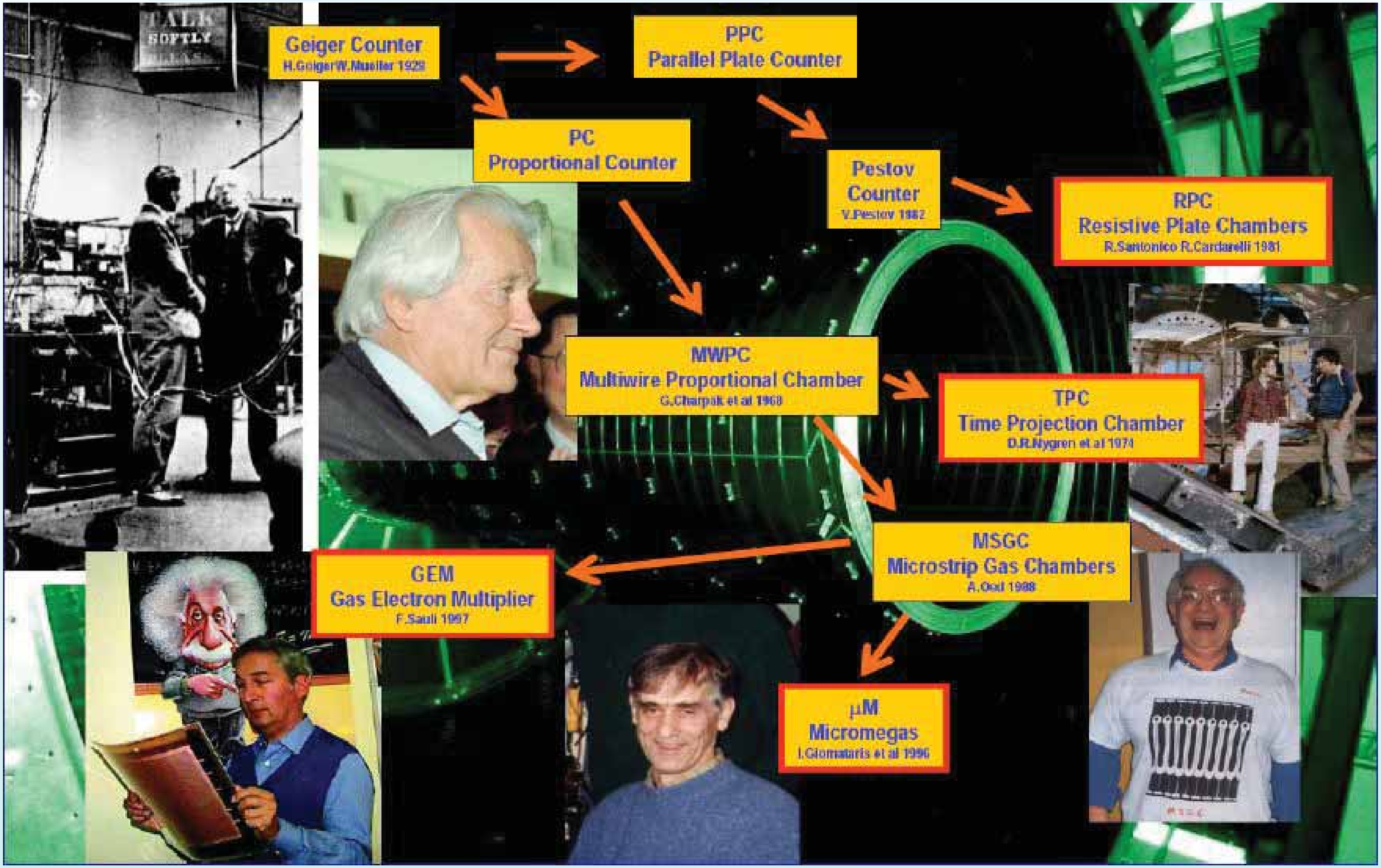


George Charpak
Nobel Prize in 1992

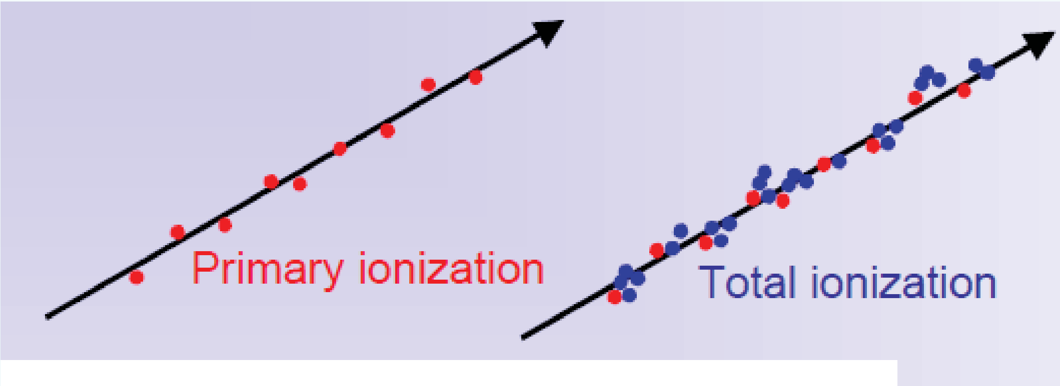


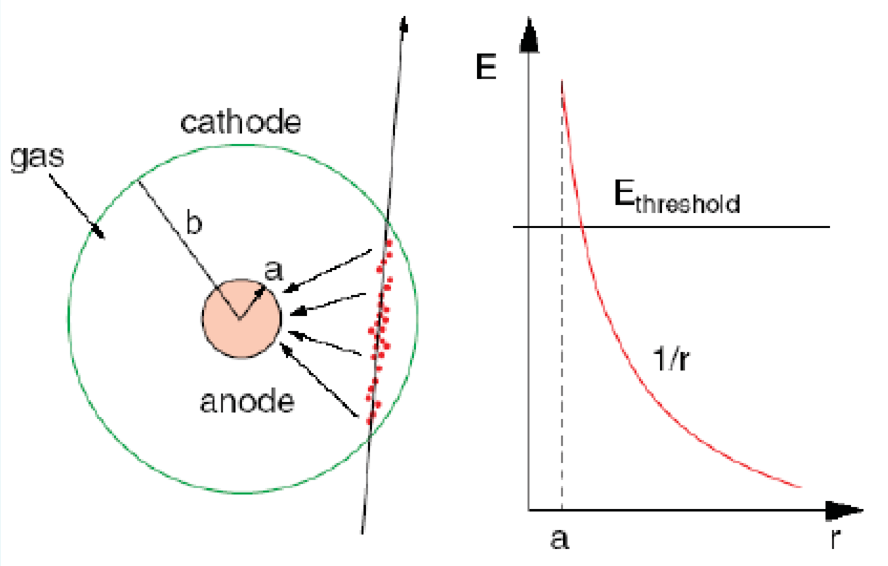


100 years of gaseous detectors: gallery 3

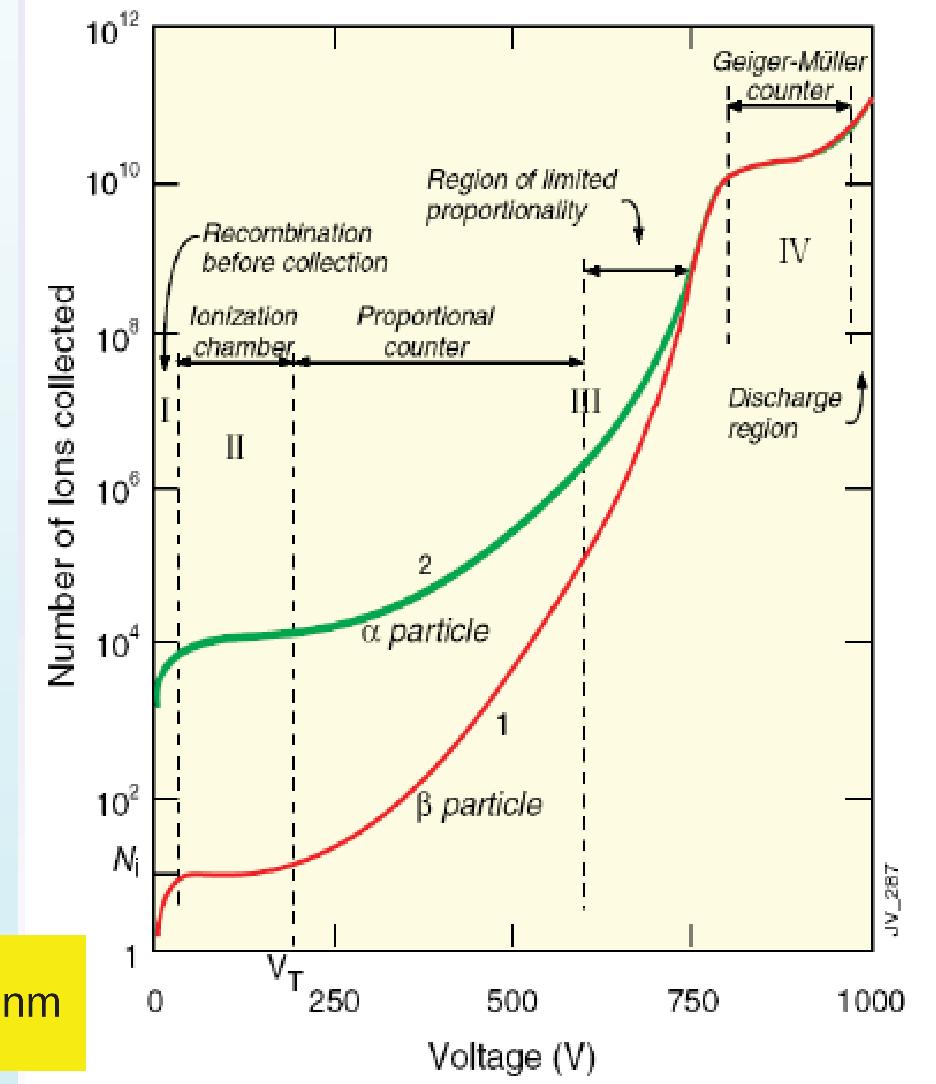


Gas ionization & single wire detector

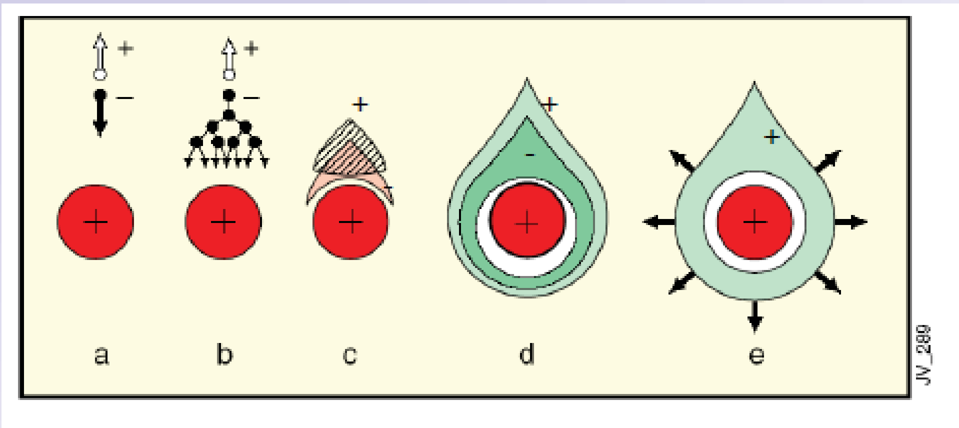




Ar atom radius: ~ 70 pm
distance between Ar atoms: ~ 4 nm
mean free path: ~2 μm



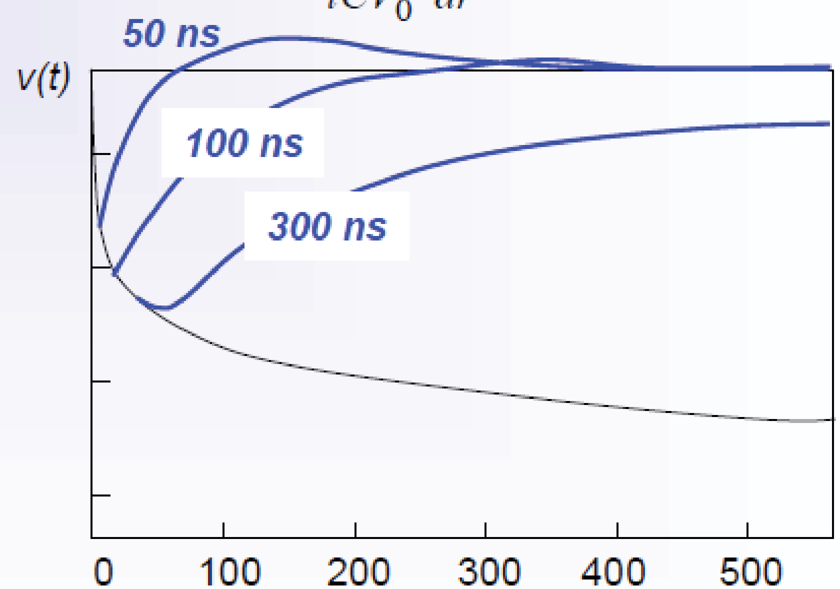
Signal formation



Avalanche formation within a few wire radii and within t < 1 ns.

Signal induction both on anode and cathode due to moving charges (both electrons and ions).

$$dv = \frac{Q}{lCV_0}\frac{dV}{dr}dr$$

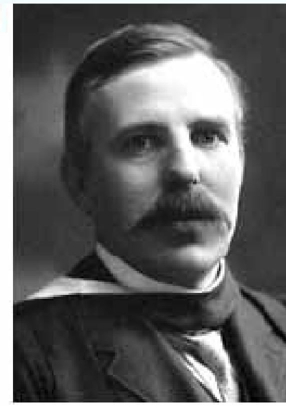


Electrons collected by the anode wire i.e. dr is very small (few μm). Electrons contribute only very little to detected signal (few %).

Ions have to drift back to cathode i.e. dr is large (few mm). Signal duration limited by total ion drift time.

Need electronic signal differentiation to limit dead time.

E(a)rnest Rutherford
(1871-1937)

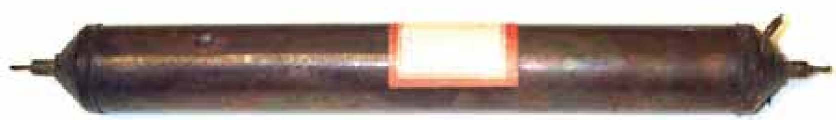


Geiger counter

- Detects radiation by discharge;
- can count α, β and γ particles (at low rates ...);
- no tracking capability.
- 1908: Ernest Rutherford and Hans Geiger
- 1928: Hans Geiger and Walther Müller

Hans Geiger
(1882-1945)

Walt(h)er Müller
(1905-1979)

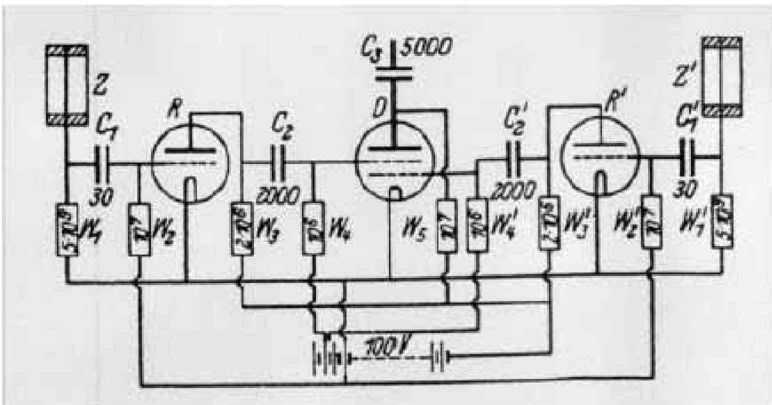


A Geiger-Muller counter built in 1939 and used in the 1947-1950 for cosmic ray studies in balloons and on board B29 aircraft by Robert Millikan et al.

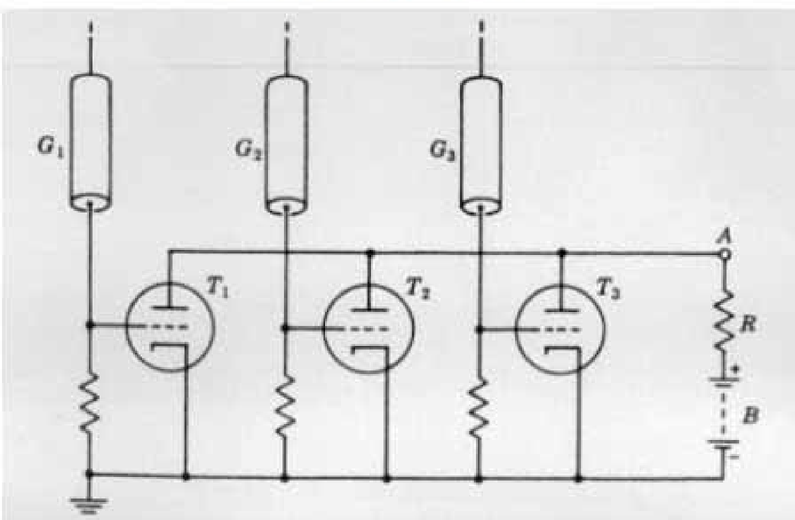
Made of copper, 30 cm long

Electric Registration of Geiger Müller Tube Signals

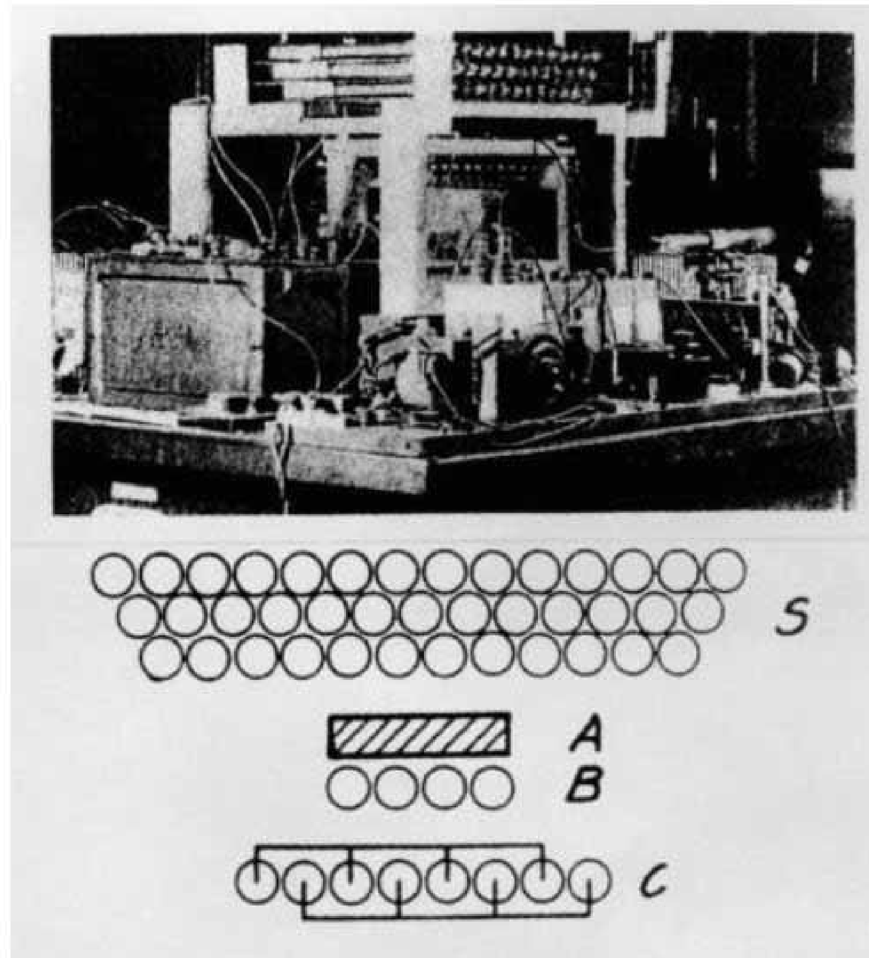
Charges create a discharge in a cylinder with a thin wire set to HV. The charge is measured with a electronics circuit consisting of tubes → electronic signal.



W. Bothe, 1928



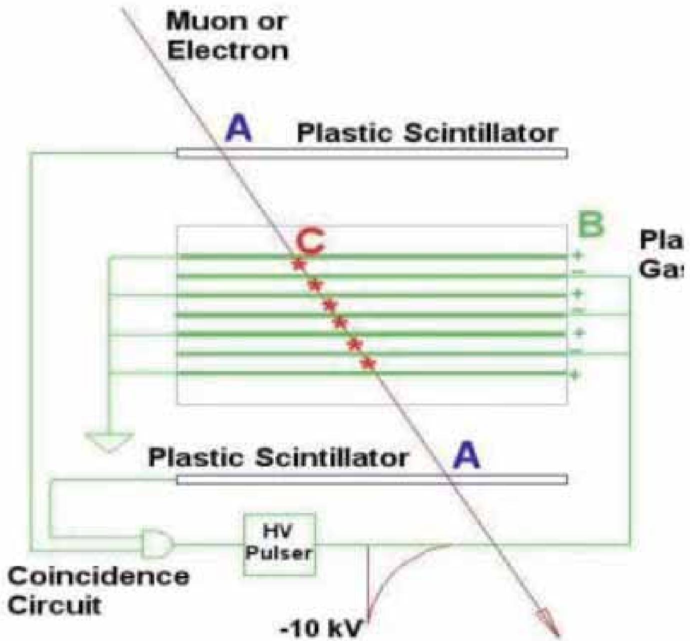
B. Rossi, 1932

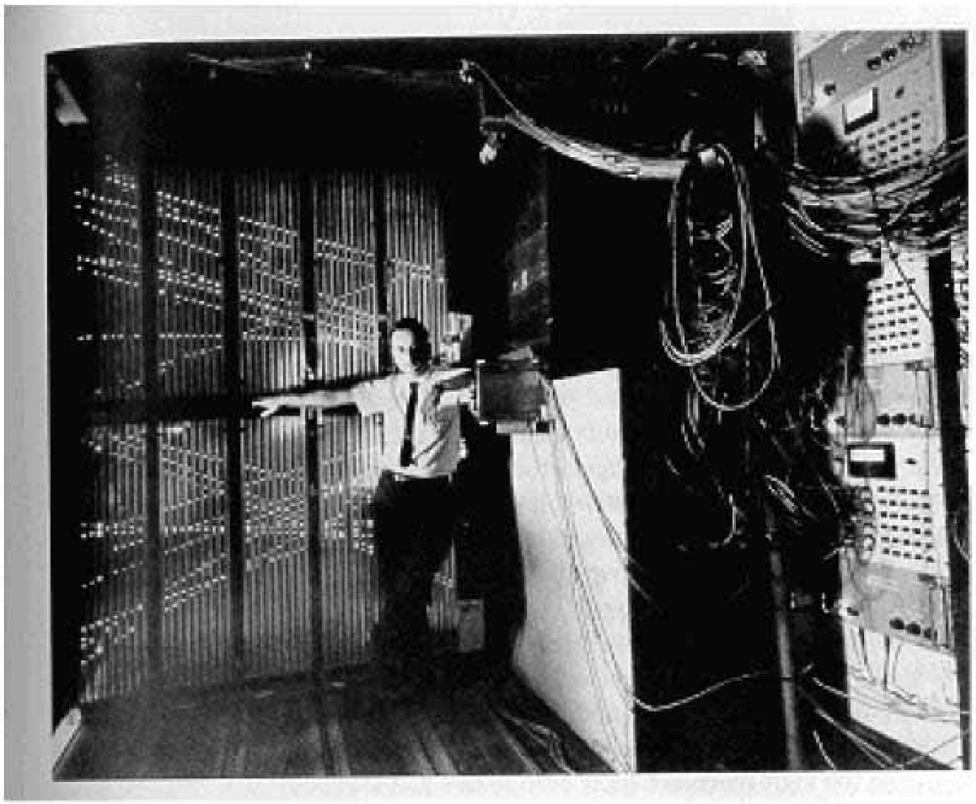


Cosmic Ray Telescope 1930ies

Spark Chamber, 1960ies

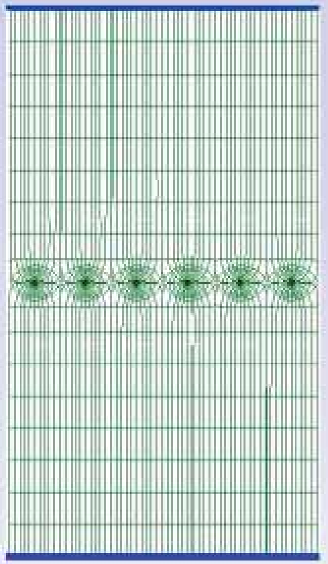
Charges create 'conductive channel' which initiates a spark in case HV is applied.





Discovery of the Muon Neutrino 1960ies

Multi Wire Proportional Chamber



Simple idea to multiply SWPC cell : Nobel Prize 1992

First electronic device allowing high statistics experiments !!

Typical geometry

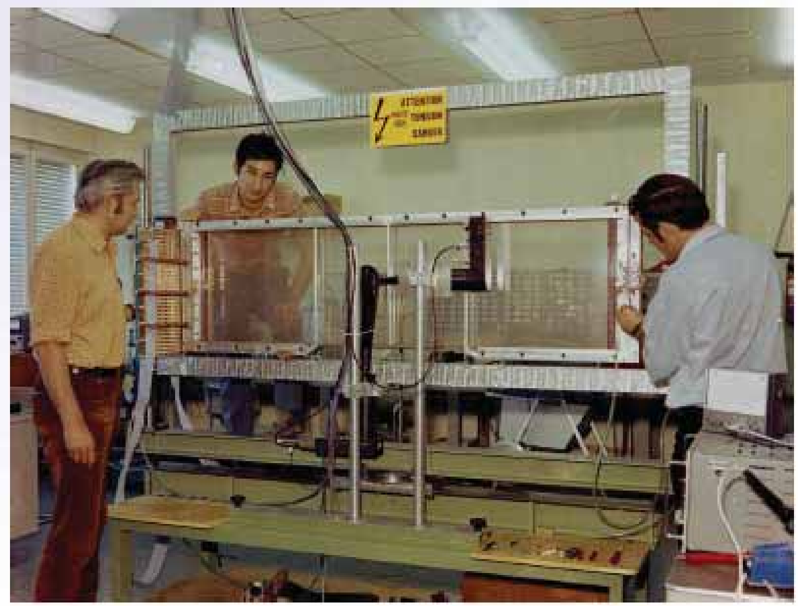
5mm, 1mm, 20 μm

Normally digital readout :

spatial resolution limited to

$$\sigma_x \approx \frac{d}{\sqrt{12}}$$

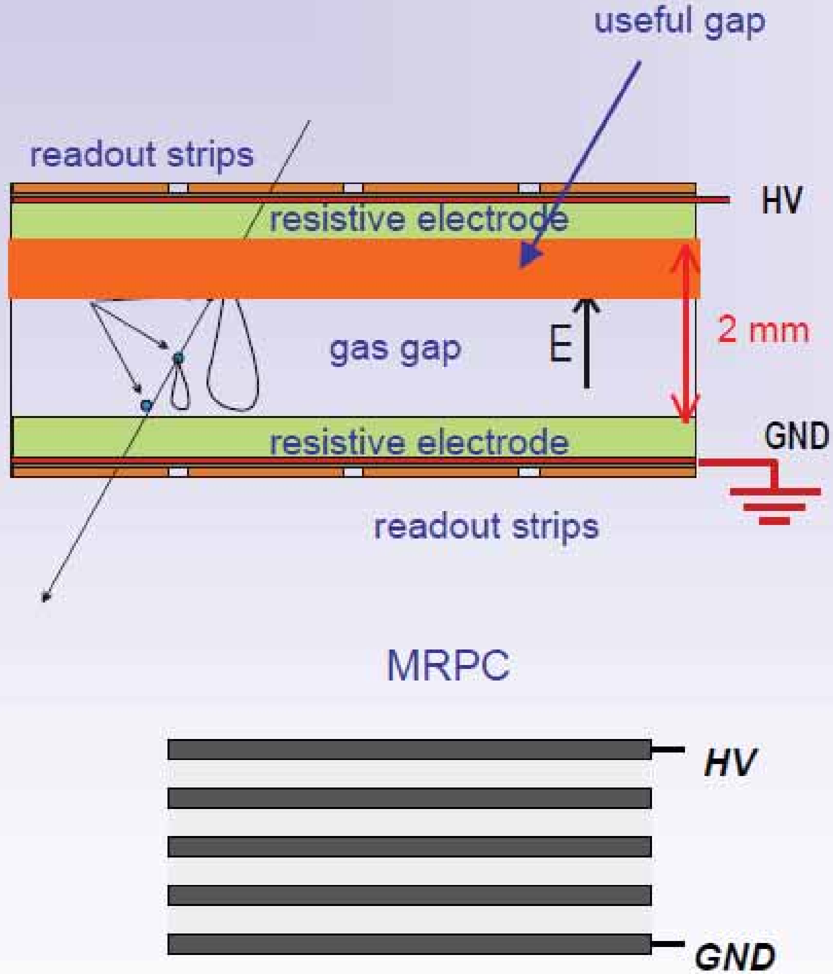
for d = 1 mm σ_x = 300 μm



G. Charpak, F. Sauli and J.C. Santiard

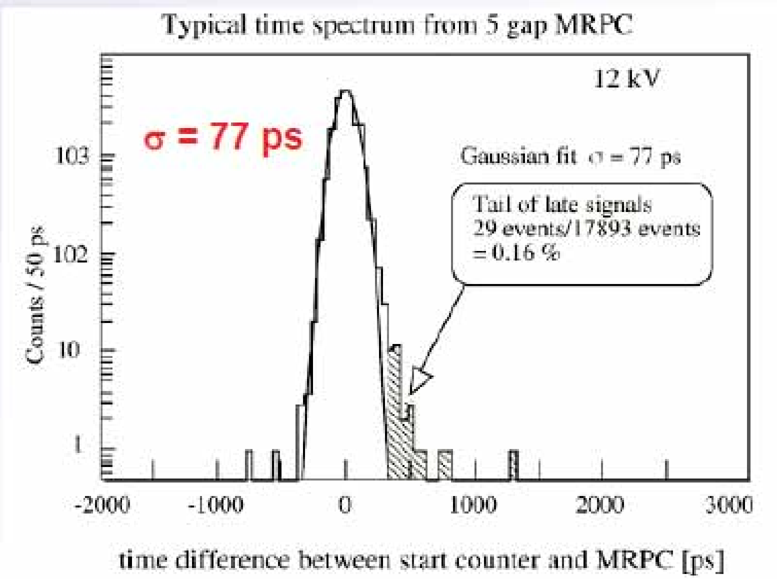
Old ALICE TPC

Resistive plate chambers



Rate capability strong function of the resistivity of electrodes in streamer mode.

A. Akindinov et al., NIM A456(2000)16

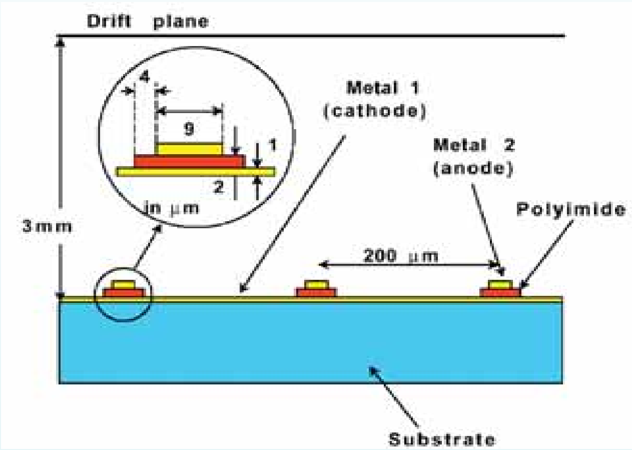


Time resolution

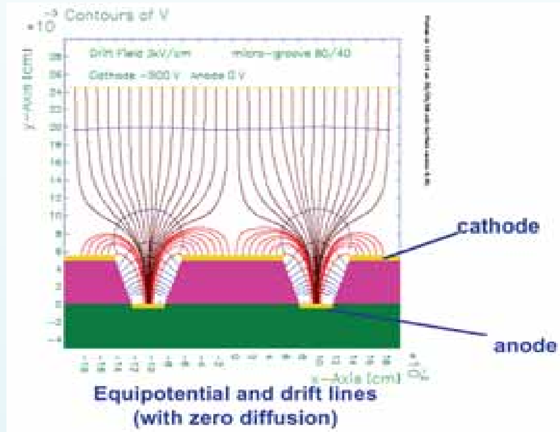
Multigap RPC - exceptional time resolution suited for the trigger applications

Several different MPGDs have been developed

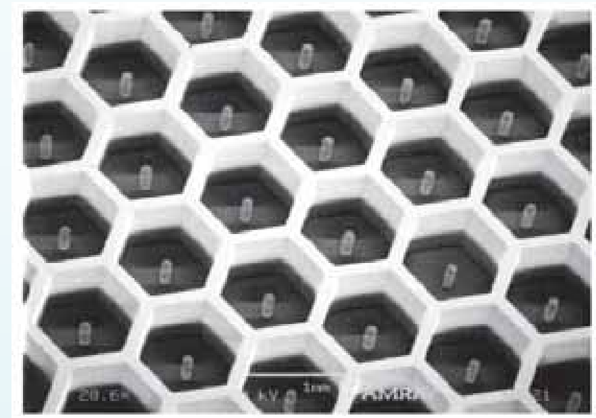
MICRO-GAP CHAMBER



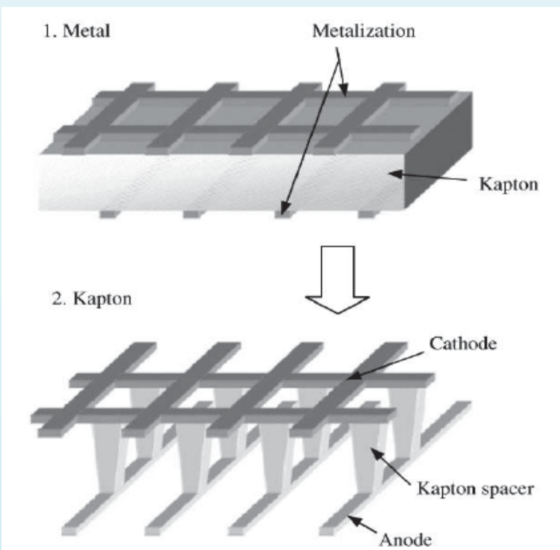
MICRO-GROOVE CHAMBER



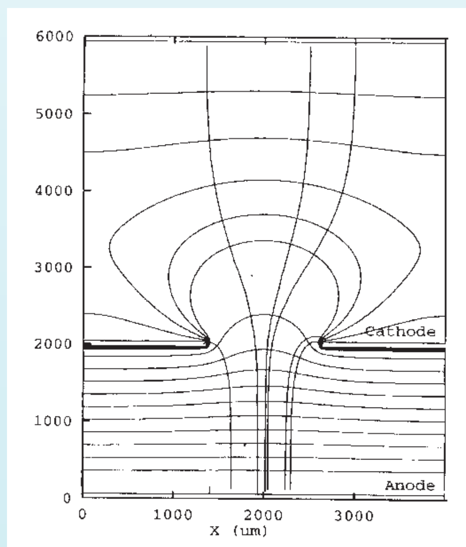
MICRO-PIN ARRAY



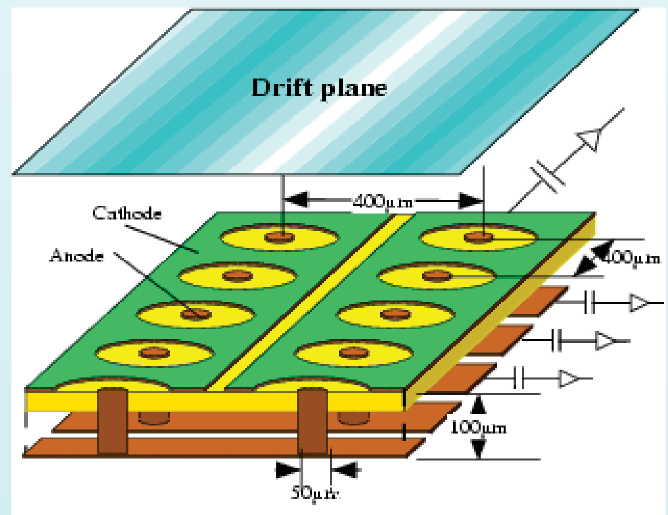
MICRO-WIRE CHAMBER



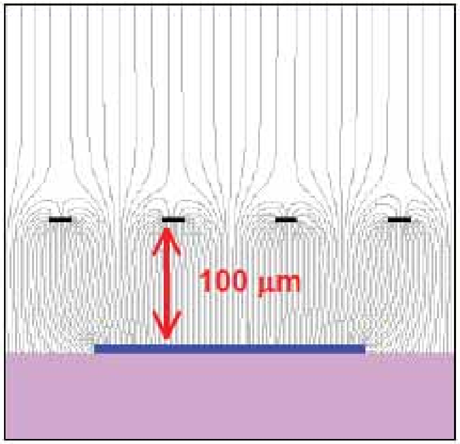
COMPTEUR A TROUS

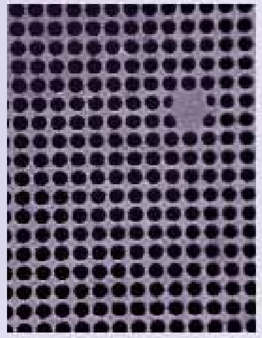


MICRO-PIXEL CHAMBER



Micromegas



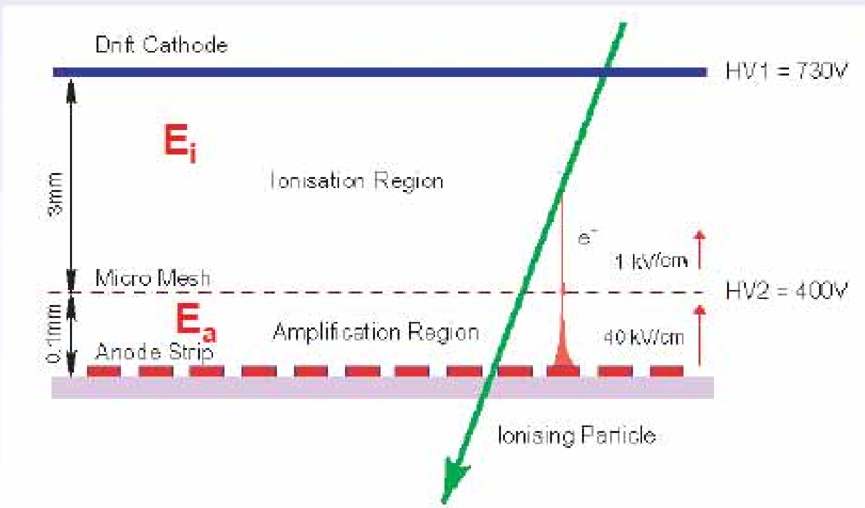


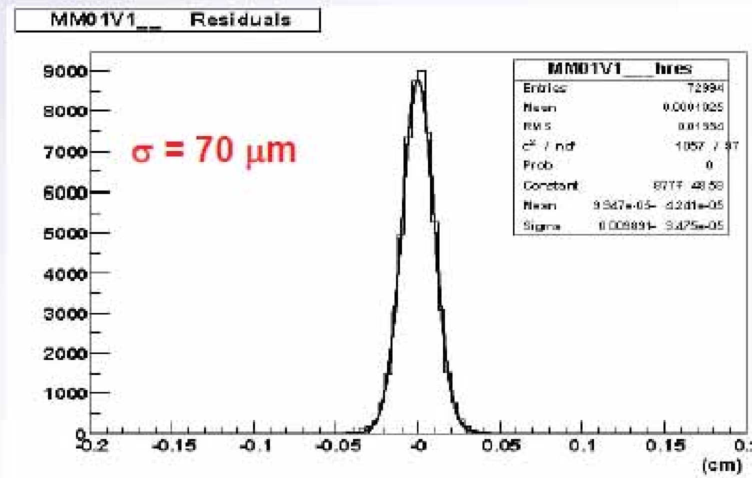
micromesh

Micromesh mounted above readout structure (typically strips).

E field similar to parallel plate detector.

E_a/E_i ~ 50 to secure electron transparency and positive ion flowback supression.





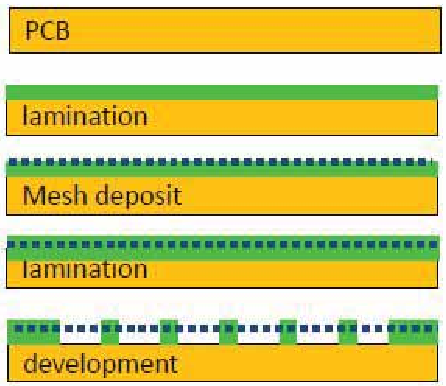
Space resolution

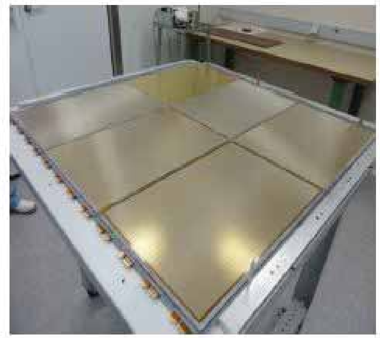
Bulk Micromegas technology

Y. Giomataris
R. de Oliveira

M. Chefdeville

T2K TPC, A. Delbart, M. Zito

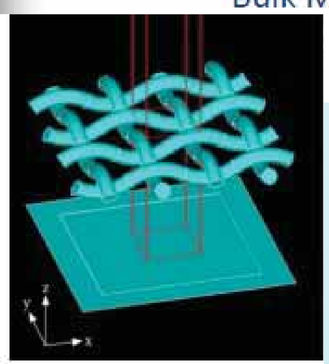




- Fine segmentation 1cm^2, thickness 8mm for ILC Hadronic calorimetry
- Tested in the RD51 1 kHz beam

Bulk Micromegas ILC DHCAL first m^2
LAPP Annecy

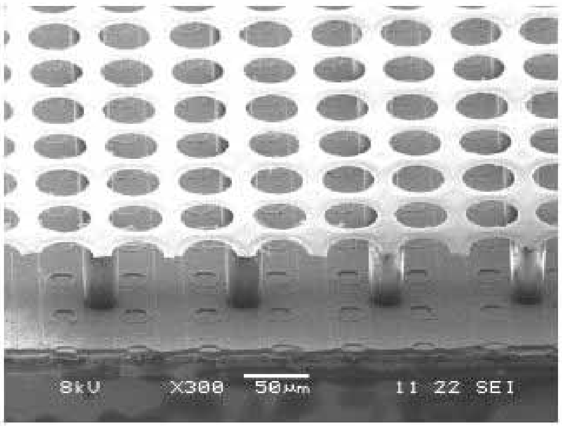
woven mesh

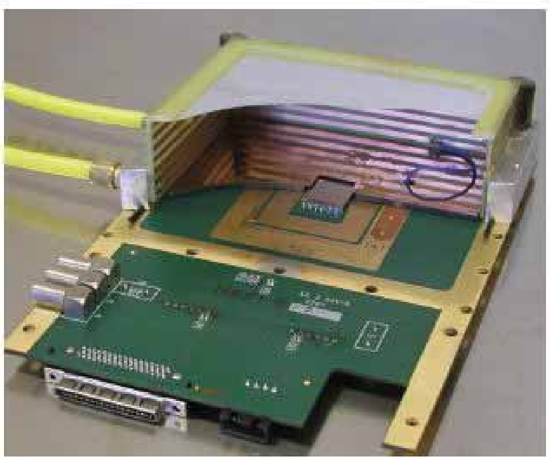


INGRID

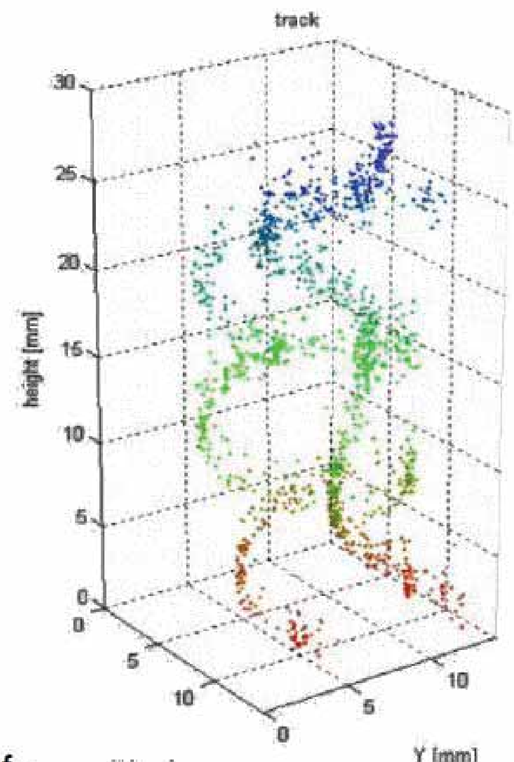
Integrated Micromegas and Pixel Sensor

Postprocessing of the TIMEPIX chip to build a metal mesh on insulating pillars

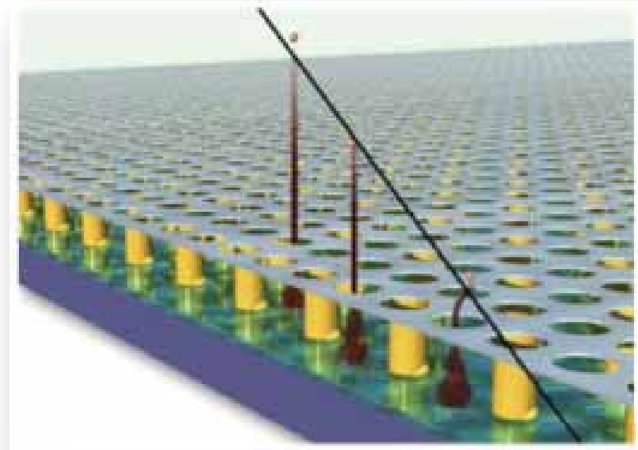


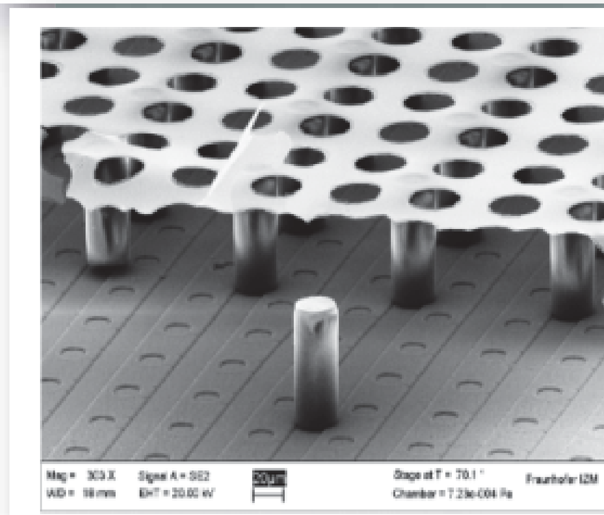


Electron tracks from [90]Sr in magnetic field (0.2 T):



H. Van der Graaf ,
IEEE Nucl. Sci. Symp. Conf. Rec. (Dresden, October 2008)



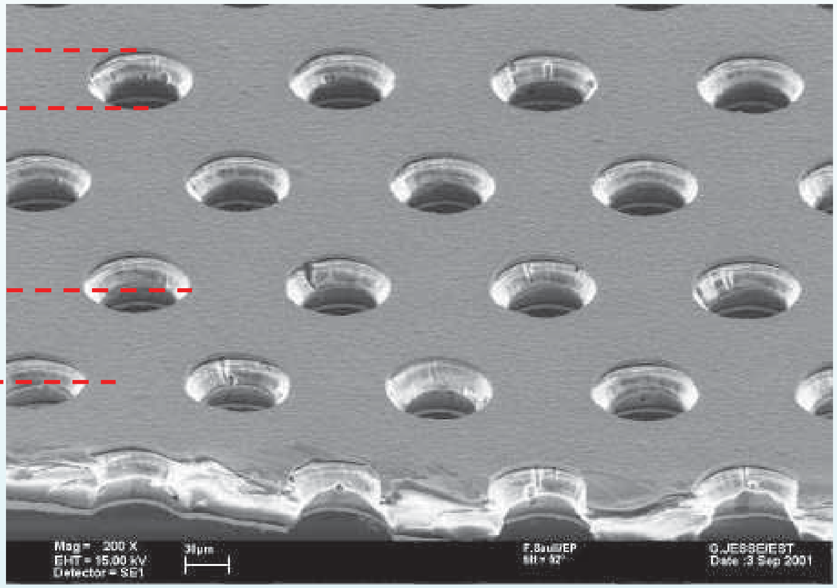


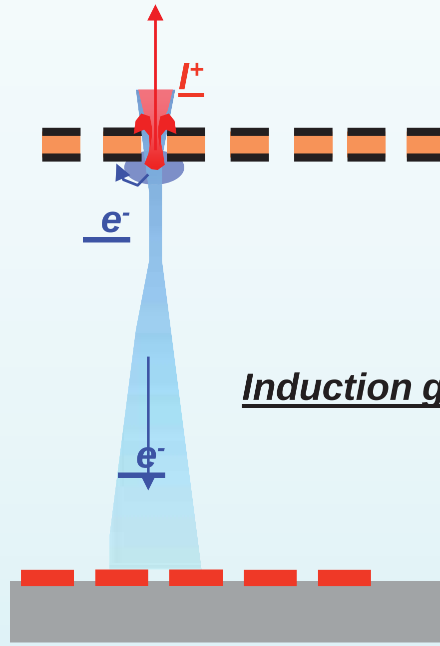
GEM

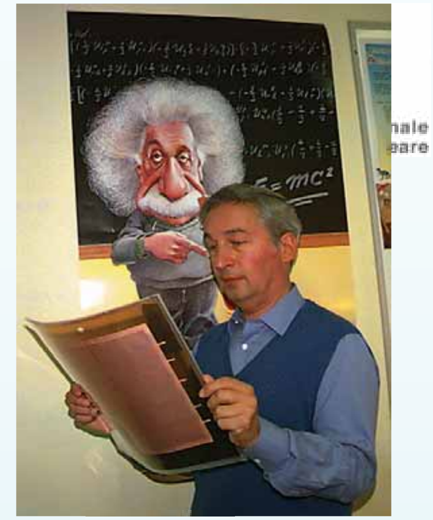
Thin metal-coated polymer foil pierced by a high density of holes (50-100/mm^2)
Typical geometry: 5 μm Cu on 50 μm Kapton, 70 μm holes at 140 μm pitch

70 μm

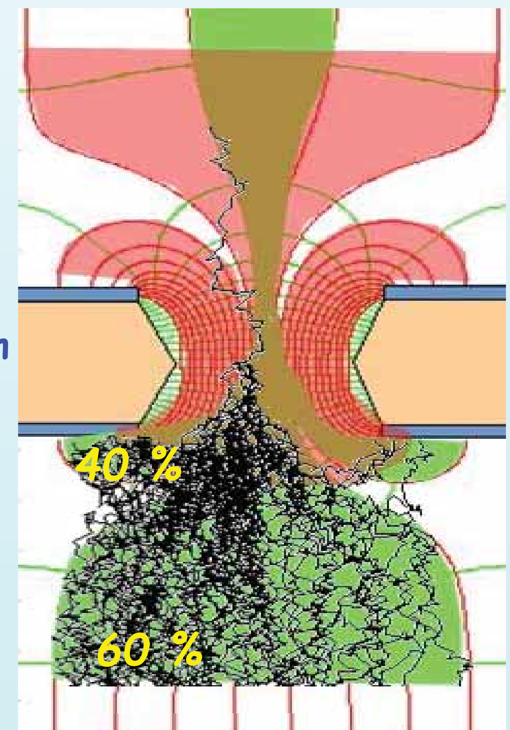
140 μm

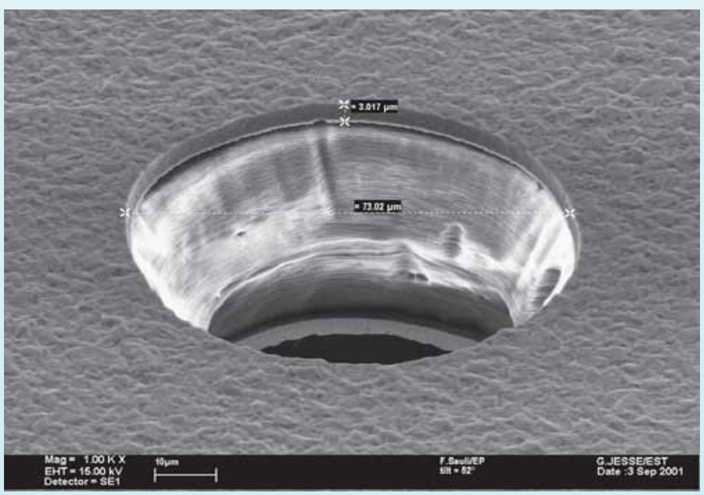


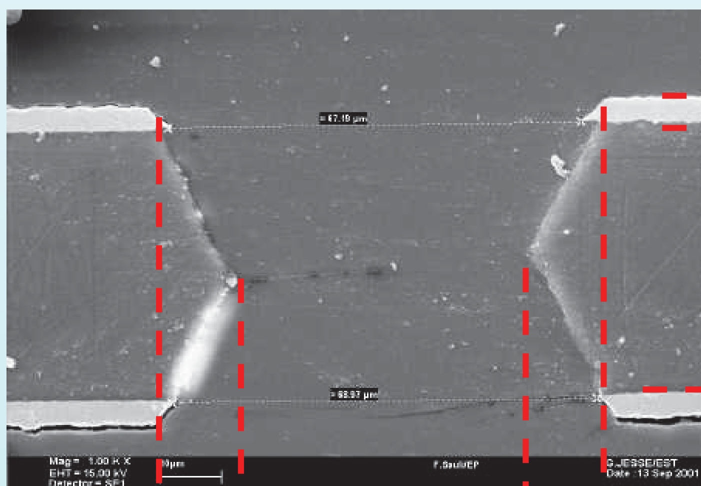




Ions







5 μm

50 μm

55 μm

70 μm

GEM Manufacturing

Rui De Oliveira
CERN-EST-DEM

GEM foils are produced at CERN using proprietary process.

50 μm Kapton
5 μm Cu both sides

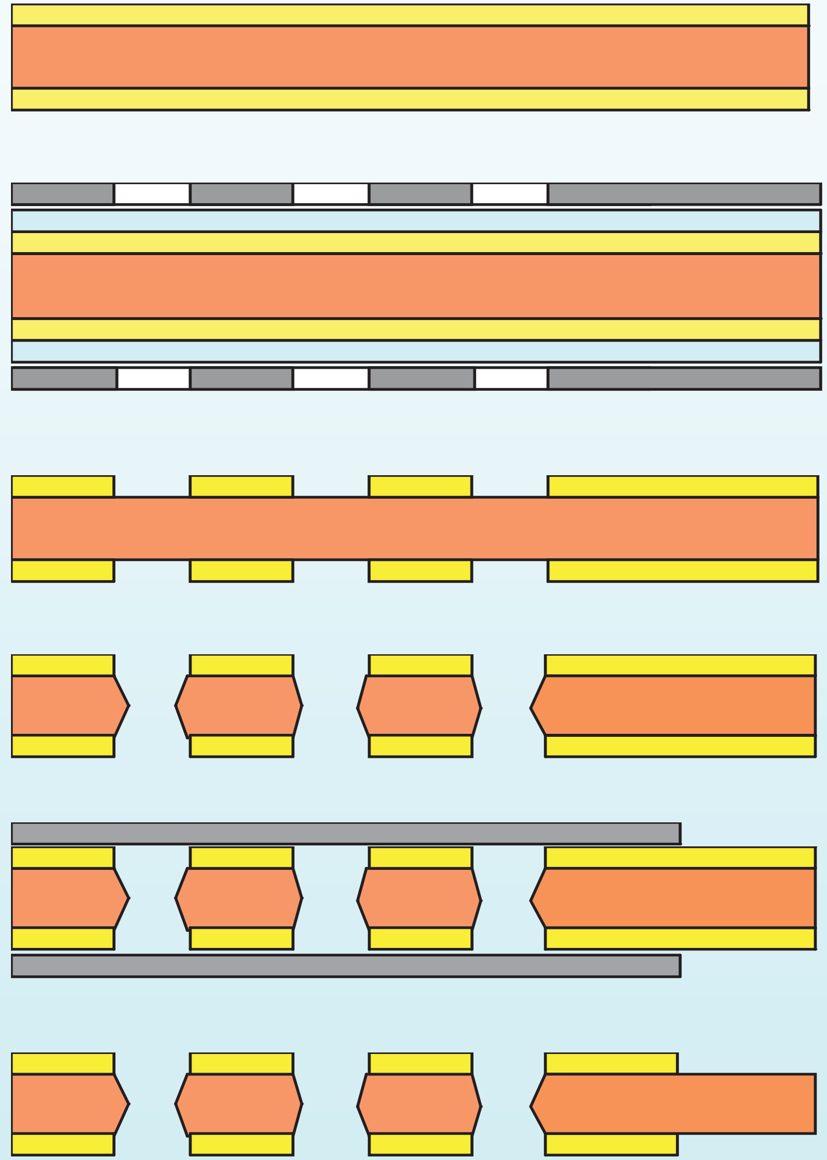
Photoresist coating, masking and exposure to UV light

Metal etching

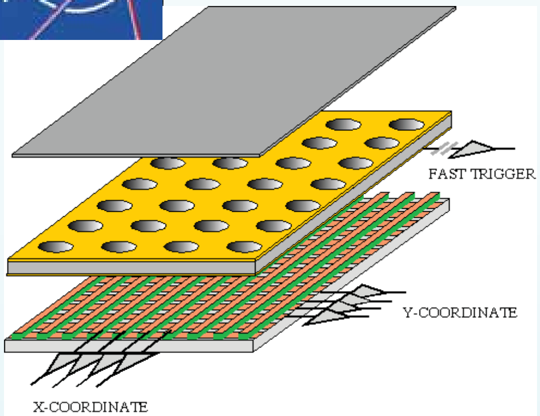
Kapton etching

Second masking

Metal etching and cleaning

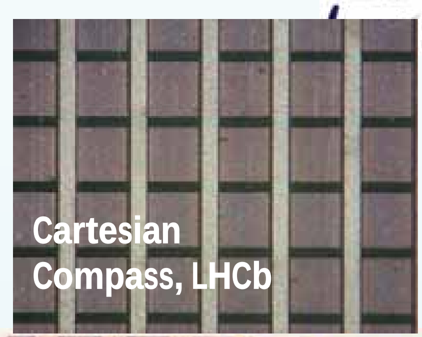


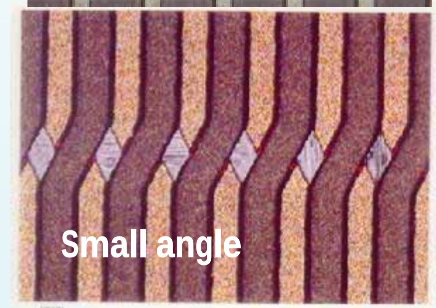
GEM – Gas Electron Multiplier



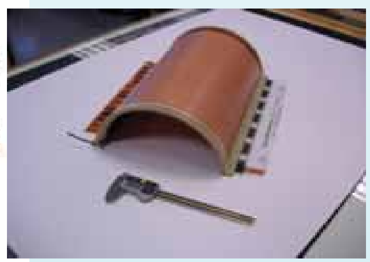
Full decoupling of the charge amplification structure from the charge collection and readout structure.
Both structures can be optimized independently !

A. Bressan et al, Nucl. Instr. and Meth. A425(1999)254





Different flat shapes



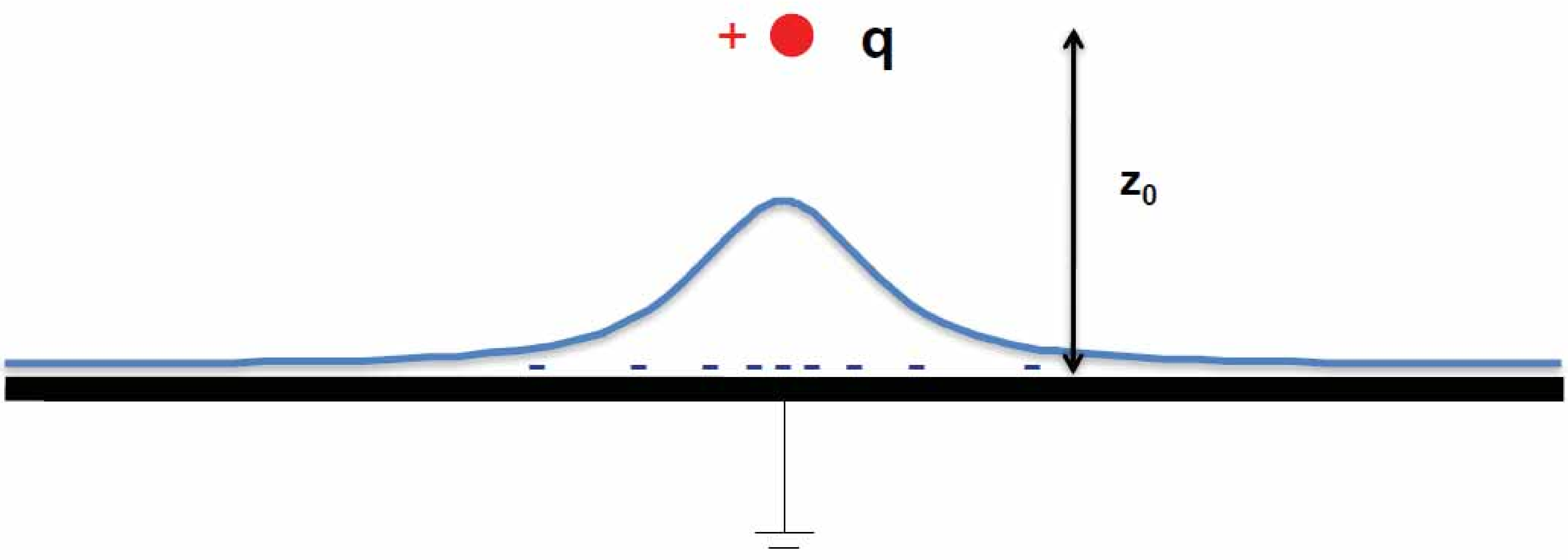
cylindrical

spherical

Most of the detectors use three GEM foils in cascade for amplification to reduce discharge probability by reducing field strength.

Induced charges

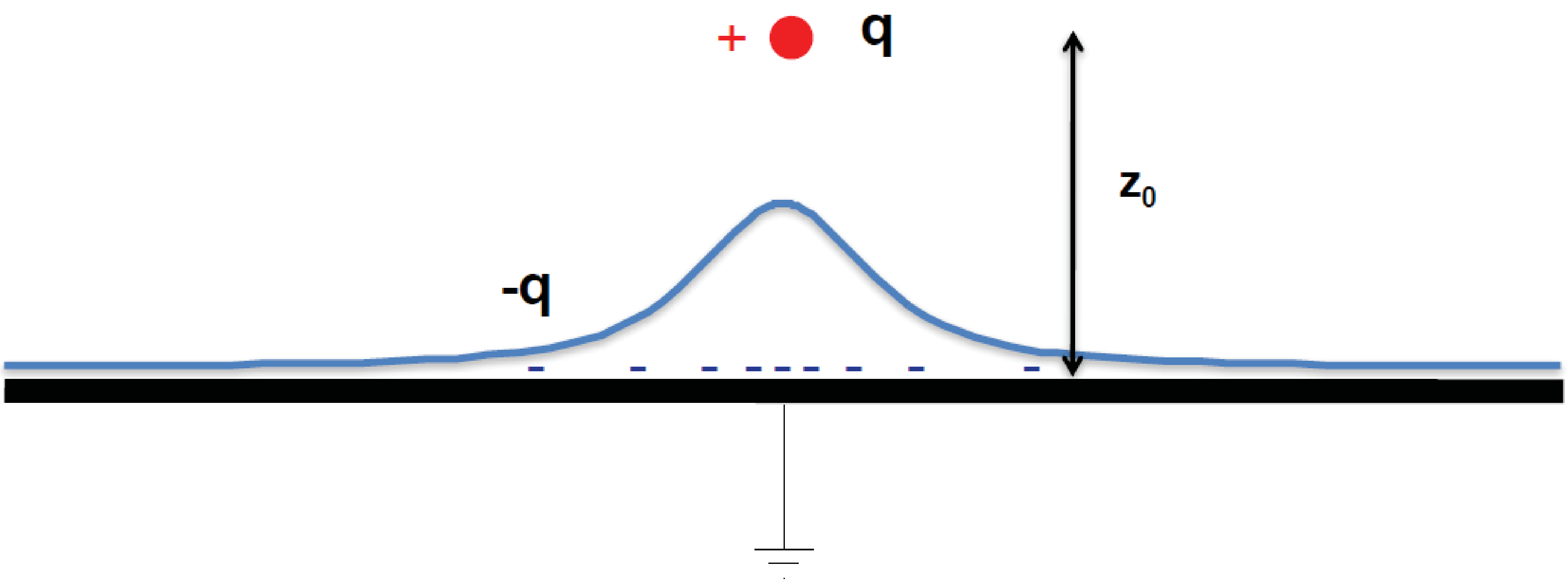
A point charge q at a distance z_0 above a grounded metal plate 'induces' a surface charge.



Induced charges

The total charge induced by a point charge q on an infinitely large grounded metal plate is equal to –q, independent of the distance of the charge from the plate.

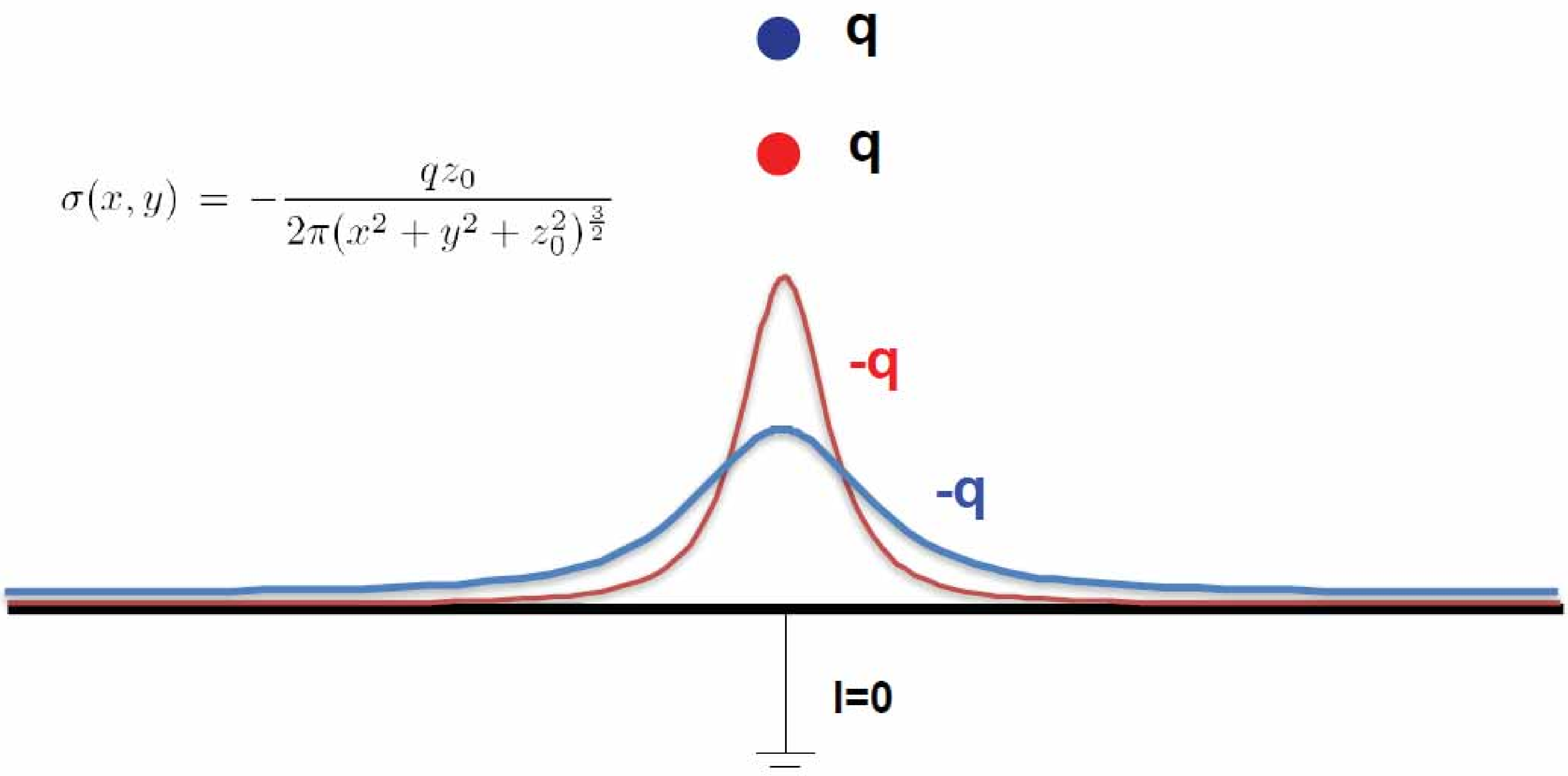
The surface charge distribution is however depending on the distance z_0 of the charge q.



Induced charges

Moving the point charge closer to the metal plate, the surface charge distribution becomes more peaked, the total induced charge is however always equal to –q.

$$\sigma(x,y) = -\frac{q z_0}{2\pi(x^2+y^2+z_0^2)^{\frac{3}{2}}}$$



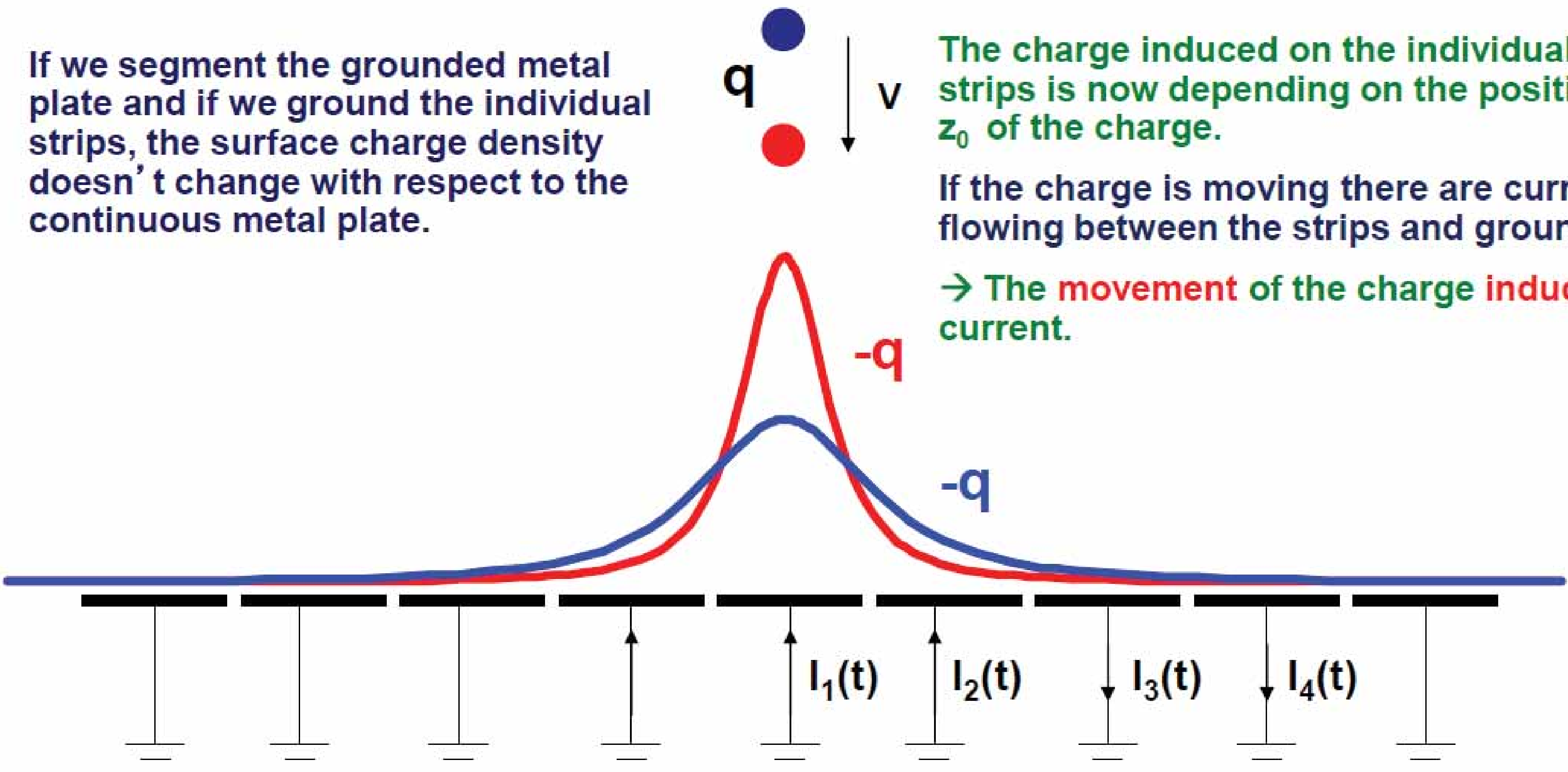
Induced charges

If we segment the grounded metal plate and if we ground the individual strips, the surface charge density doesn't change with respect to the continuous metal plate.

The charge induced on the individual strips is now depending on the position z_0 of the charge.

If the charge is moving there are currents flowing between the strips and ground.

→ The movement of the charge induces a current.



$$Q_1(z_0) = \int_{-\infty}^{\infty}\int_{-w/2}^{w/2} \sigma(x,y)dxdy = -\frac{2q}{\pi}\arctan\left(\frac{w}{2z_0}\right) \qquad z_0(t) = z_0 - vt$$

$$I_1^{ind}(t) = -\frac{d}{dt}Q_1[z_0(t)] = -\frac{\partial Q_1[z_0(t)]}{\partial z_0}\frac{dz_0(t)}{dt} = \frac{4qw}{\pi[4z_0(t)^2 + w^2]}v$$

Solid state detectors: Silicon

Some characteristics of Silicon crystals

- Small band gap — E_g = 1.12 eV ⇒ E(e-h pair) = 3.6 eV (≈ 30 eV for gas detectors)
- High specific density — 2.33 g/cm^3 ; dE/dx (M.I.P.) ≈ 3.8 MeV/cm ≈ 106 e-h/μm (average)
- High carrier mobility — μ_e =1450 cm^2/Vs, μ_h = 450 cm^2/Vs ⇒ fast charge collection (<10 ns)
- Very pure — < 1ppm impurities and < 0.1ppb electrical active impurities
- Rigidity of silicon allows thin self supporting structures
- Detector production by microelectronic techniques

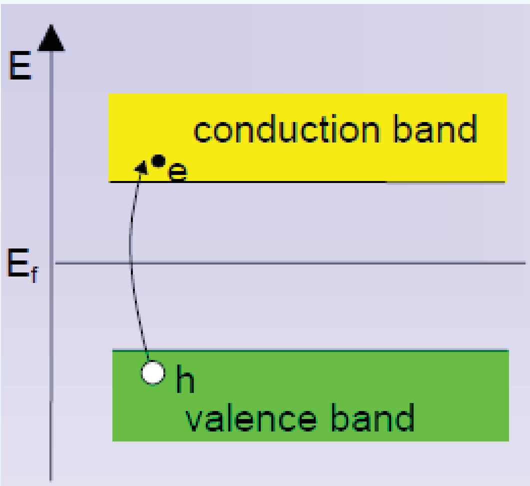
  ⇒ well known industrial technology, relatively low price, small structures easily possible

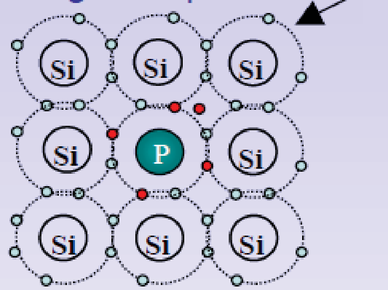
Alternative semiconductors

- Diamond
- GaAs
- Silicon Carbide
- Germanium

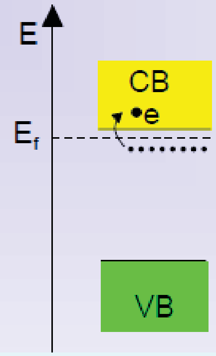
	Diamond	SiC (4H)	GaAs	Si	Ge
Atomic number Z	6	14/6	31/33	14	32
Bandgap E_g [eV]	5.5	3.3	1.42	1.12	0.66
E(e-h pair) [eV]	13	7.6-8.4	4.3	3.6	2.9
density [g/cm^3]	3.515	3.22	5.32	2.33	5.32
e-mobility μ_e [cm^2/Vs]	1800	800	8500	1450	3900
h-mobility μ_h [cm^2/Vs]	1200	115	400	450	1900

Doping and p-n junction

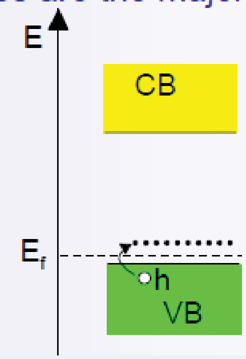




- **Doping: n-type Silicon**
  - add elements from Vth group
    ⇒ **donors** (P, As,..)
  - electrons are majority carriers



- **Doping: p-type Silicon**
  - add elements from IIIrd group
    ⇒ **acceptors** (B,..)
  - holes are the majority carriers



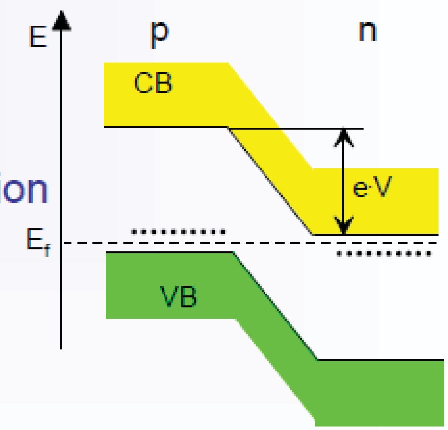
- **p-n junction**

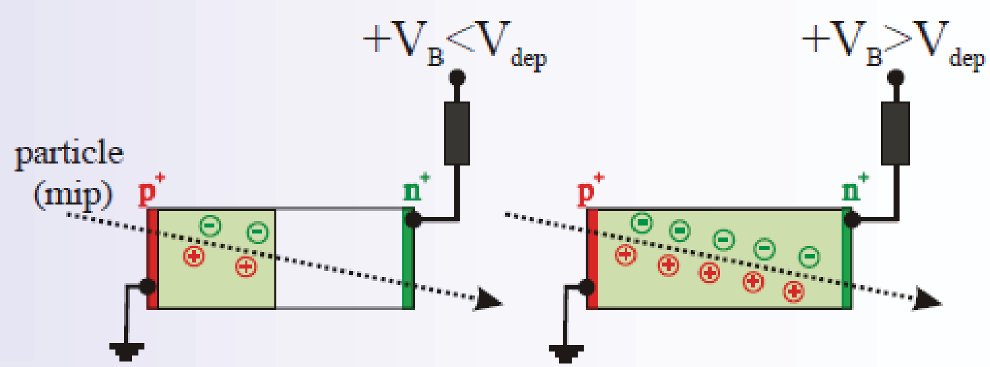
There must be a single Fermi level !

⇒ band structure deformation

⇒ potential difference

⇒ depleted zone





Full charge collection only for $V_B>V_{dep}$!

Wafer production

Produce a polysilicon rod

- Melt very pure sand (SiO_2) together with coke (~1800°C)

$$SiO_2 + 2C \rightarrow Si + 2CO$$

- Grind the "metallurgical grade silicon" (98% Si) and expose it to hydrochloric gas

$$Si + 3HCl\ (gas) \rightarrow SiHCl_3 + H_2$$

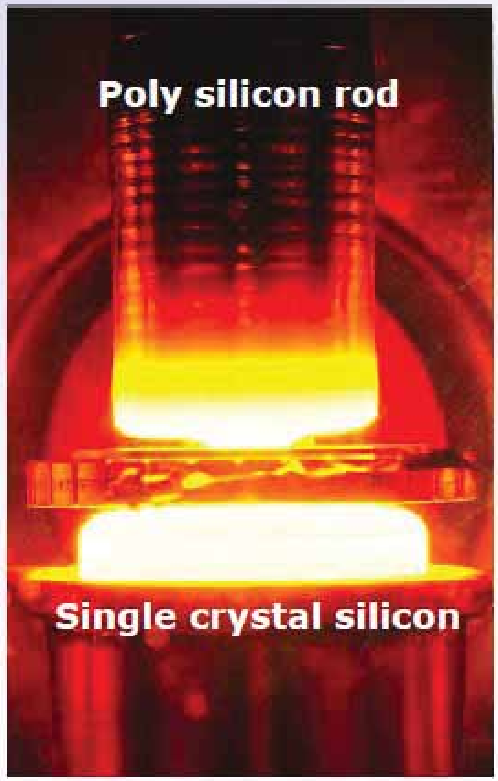
- Trichlorsilane boils at 31.7°C and can thus be distilled and purified
- Deposit silicon in a Chemical Vapour Deposition process

$$SiHCl_3 + H_2 \rightarrow Si + 3HCl$$

- Cast silicon into a polycrystalline silicon rod

Float Zone process

- Using a single Si crystal seed, melt the vertically oriented rod onto the seed using RF power and "pull" the monocrystalline ingot



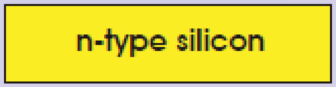
Monocrystalline Ingot

- grind into round shape
- make the flat or a notch

Wafer production

- Slice the ingot into wafers of 300-500 μm (diamond saw)
- lapping of wafers
- etching of wafers
- polishing of wafers

Silicon sensor production

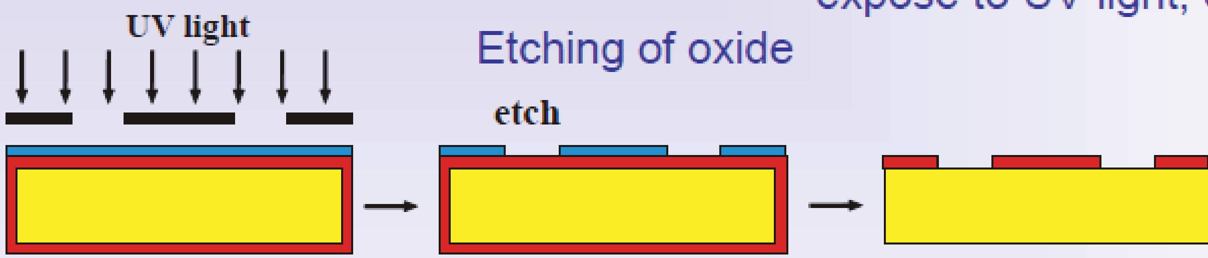


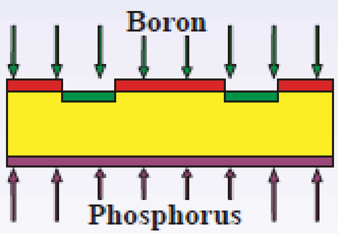
- Polished n-type silicon wafer (typical $\rho \sim$ 1-10 KΩcm)

- Oxidation (800-1200°C)

- Photolithograpy (coat with photo resist; align mask, expose to UV light, develop photoresist);

  Etching of oxide

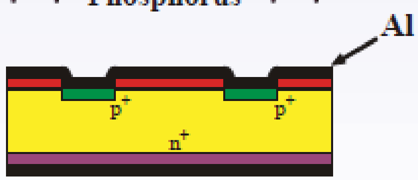




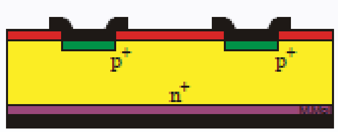
- Doping with boron and phosphorus by implantation (or by diffusion)

  Annealing to cure radiation damage and activate dopants

  - p^+ n junction on front side
  - n n^+ ohmic contact on back side

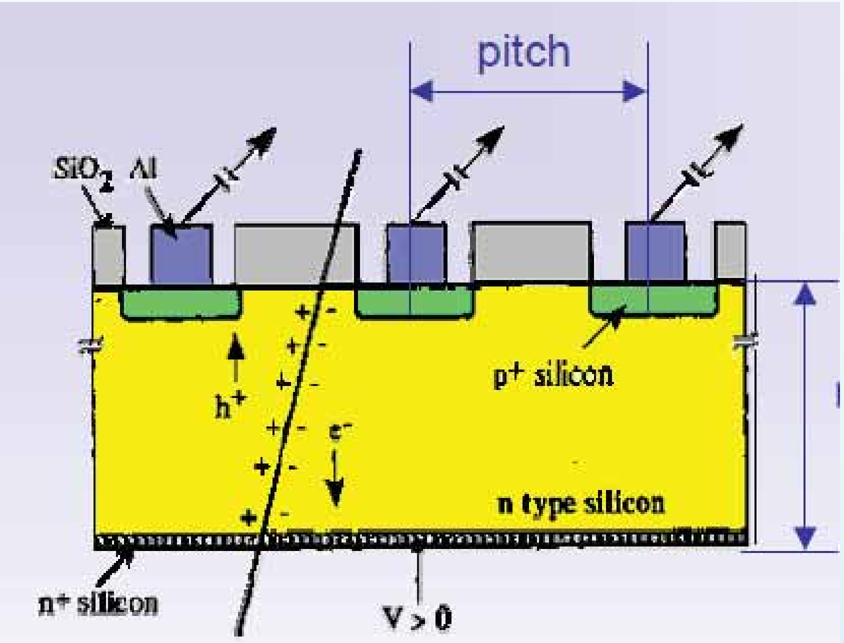


- Aluminize surface (e.g. by evaporation)

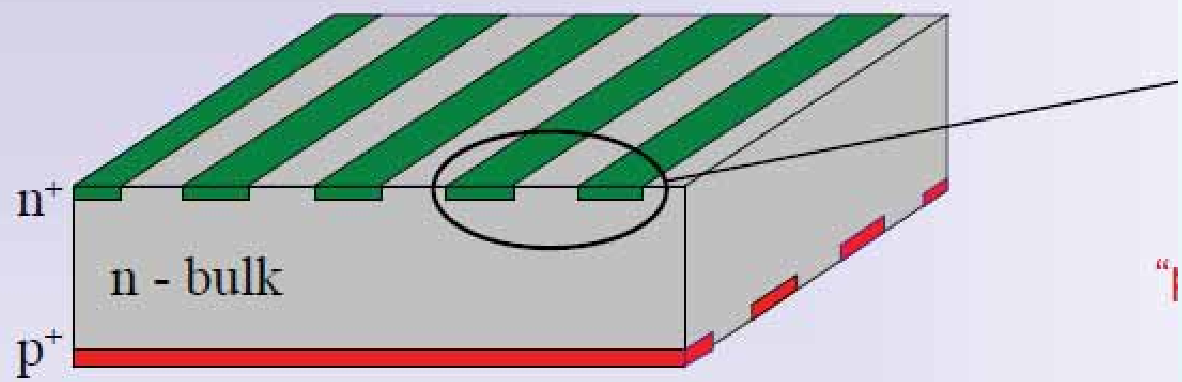


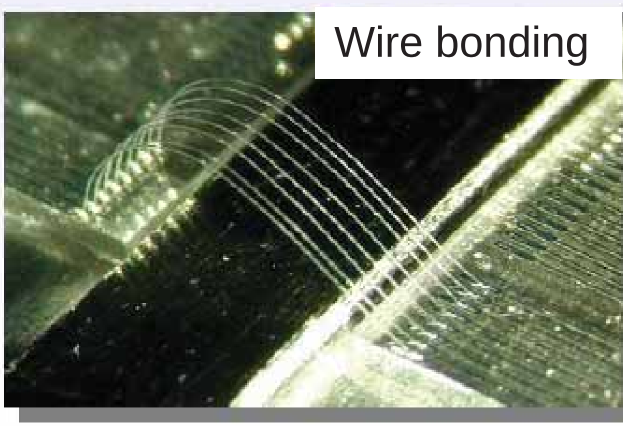
- Pattern metal for diode contacts

Silicon sensor production



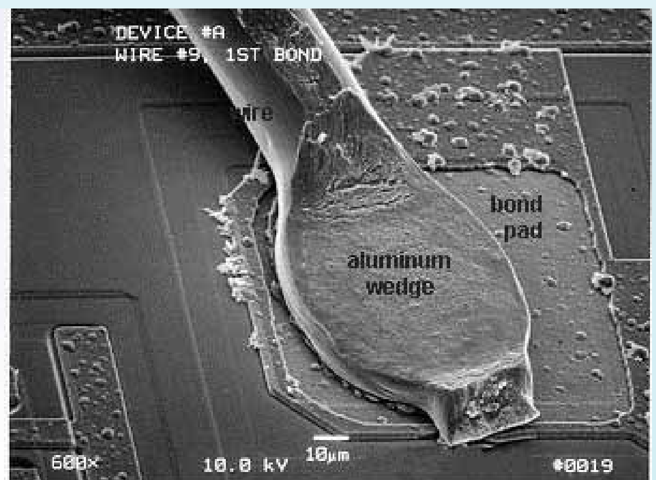
Get a 2nd coordinate
Put n^+ and p^+ strips on opposite sides and read them both





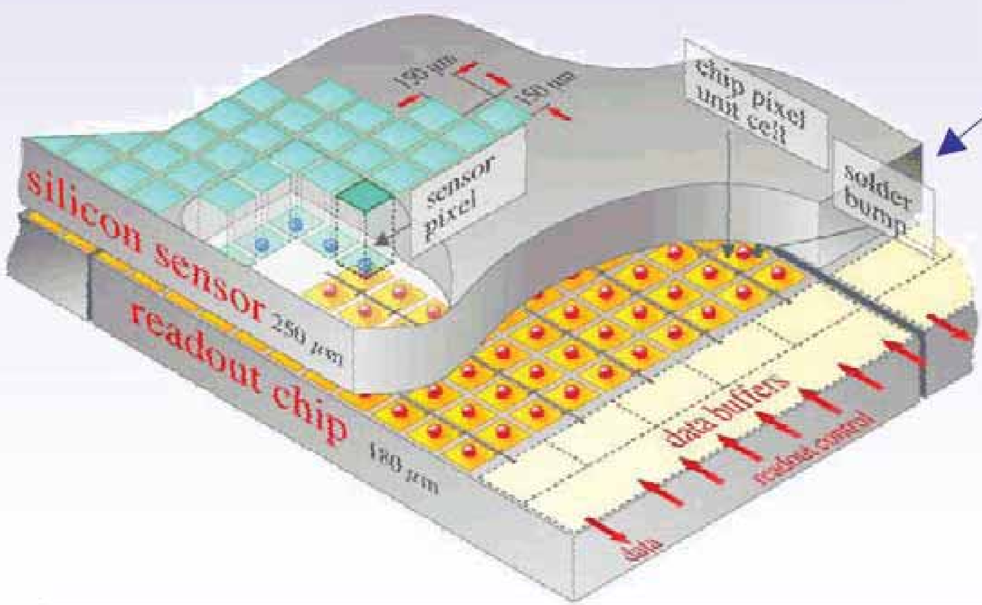
Microscope:
connect sensor to
fan-out circuit

Electron microscope:
bond "foot"

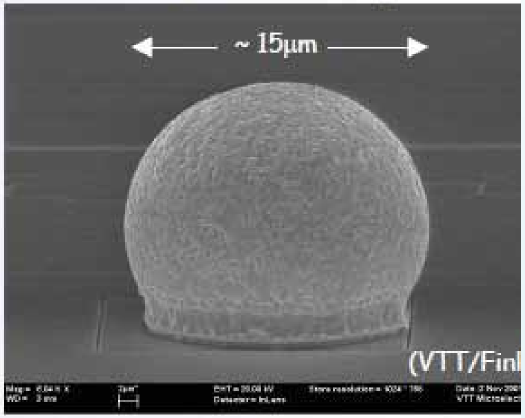


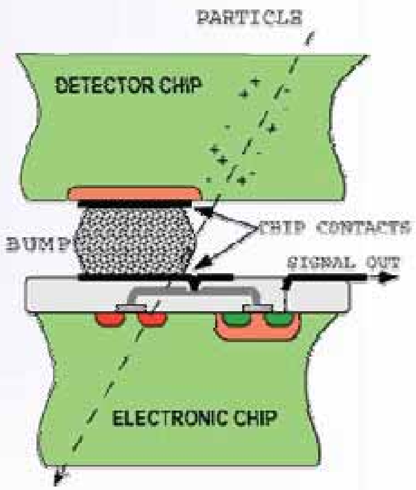
Pixel detector

- **HAPS – Hybrid Active Pixel Sensors**
  - segment silicon to diode matrix with high granularity (⇒ true 2D, no reconstruction ambiguity)
  - readout electronic with same geometry (every cell connected to its own processing electronics)
  - connection by "bump bonding"
  - requires sophisticated readout architecture
  - Hybrid pixel detectors will be used in LHC experiments: ATLAS, ALICE, CMS and LHCb



Solder Bump: Pb-Sn

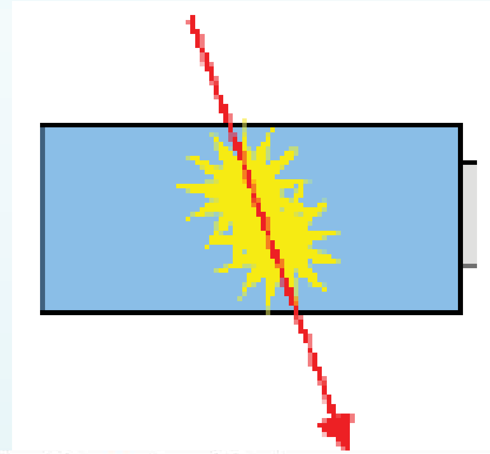




Flip-chip technique

Scintillation detectors

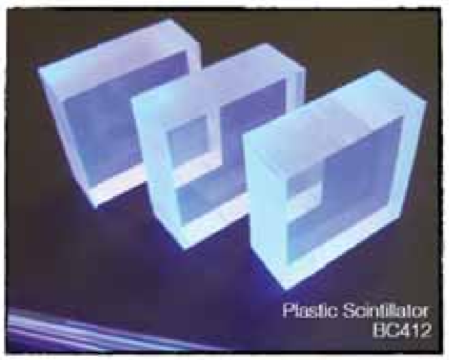
Particle Detection via Luminescence



Scintillators – General Characteristics

Principle:

dE/dx converted into visible light
Detection via photosensor
[e.g. photomultiplier, human eye ...]



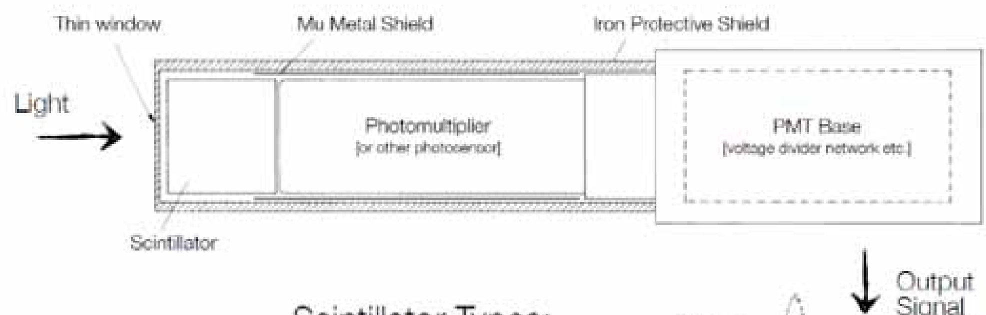
Main Features:

Sensitivity to energy
Fast time response
Pulse shape discrimination

Requirements

High efficiency for conversion of excitation energy to fluorescent radiation
Transparency to its fluorescent radiation to allow transmission of light
Emission of light in a spectral range detectable for photosensors
Short decay time to allow fast response

Scintillators – Basic Counter Setup

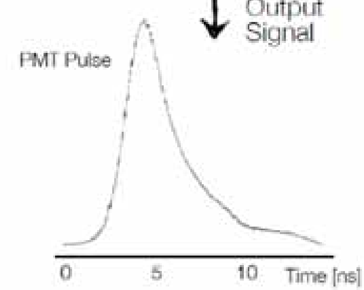


Scintillator Types:

Organic Scintillators
Inorganic Crystals
Gases

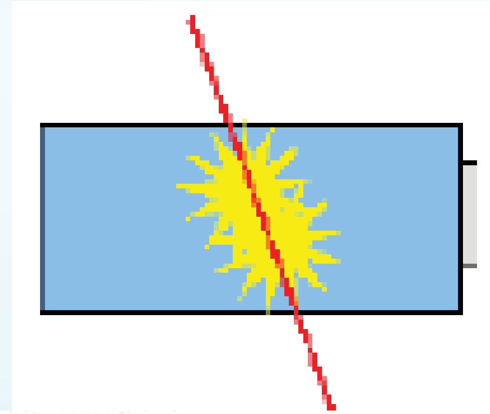
Photosensors

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



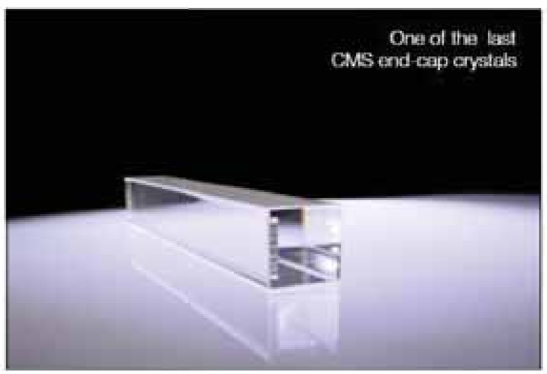
Scintillation detectors

Particle Detection via Luminescence



Inorganic Crystals

Example CMS
Electromagnetic Calorimeter



Large light yield, good energy resolution

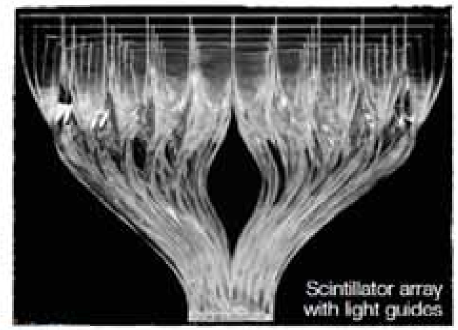
Plastic and Liquid Scintillators

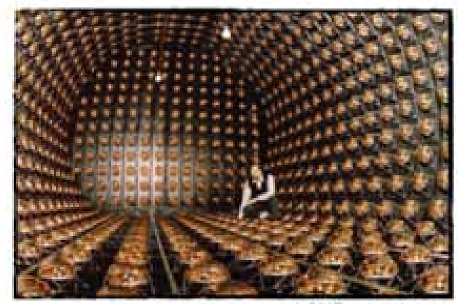
In practice use ...

solution of organic scintillators
[solved in plastic or liquid]
+ large concentration of primary 'fluor'
+ smaller concentration of secondary 'fluor'
+ ...

Scintillator requirements:

Solvable in base material
High fluorescence yield
Absorption spectrum must overlap
with emission spectrum of base material





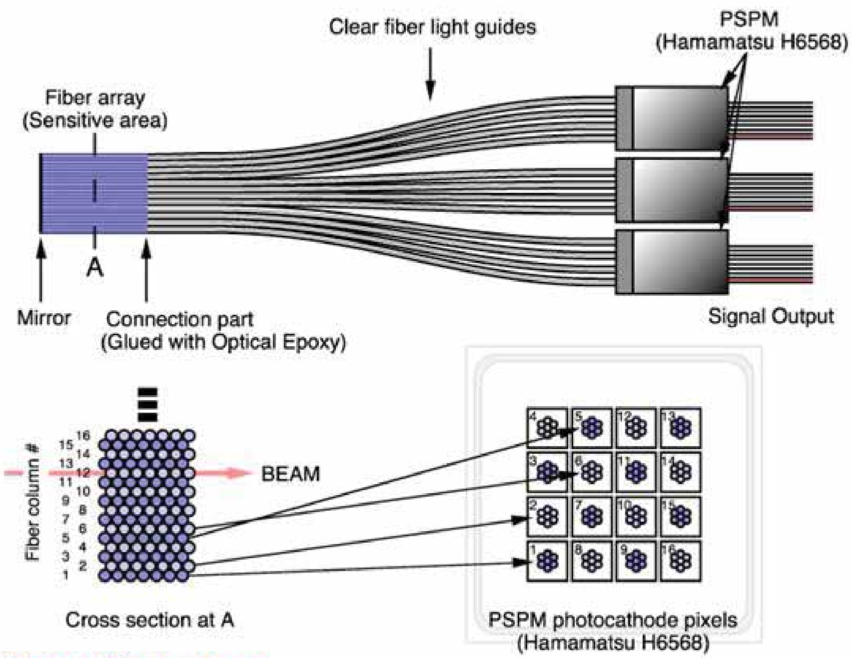
LSND experiment

Fast and cheaper

Scintillating Fibers hodoscopes

Scintillating Fibers Hodoscopes

9 stations: 21 coordinates

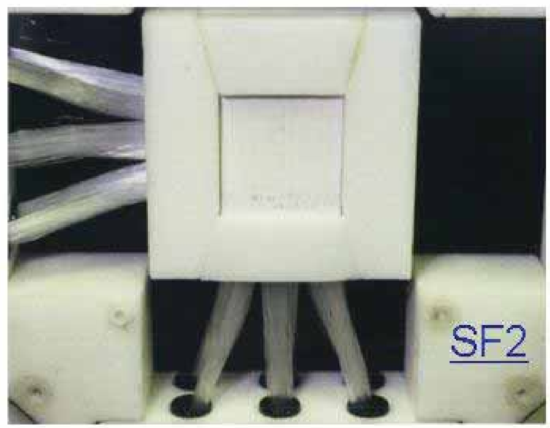


Rate capability > 5 MHz per channel

Efficiency: 99%

Space resol. 130 – 250 μm

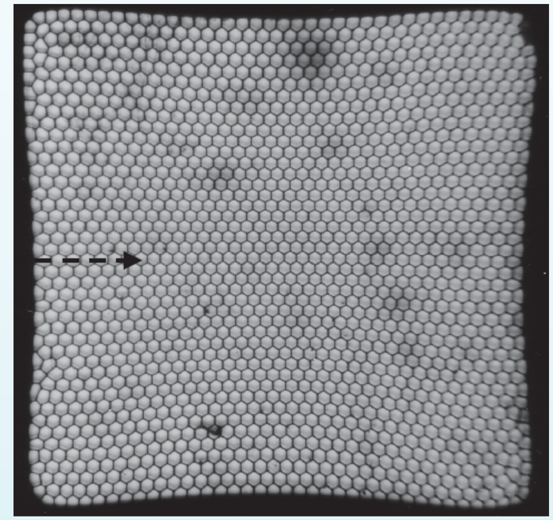
Time resol. < 400 ps

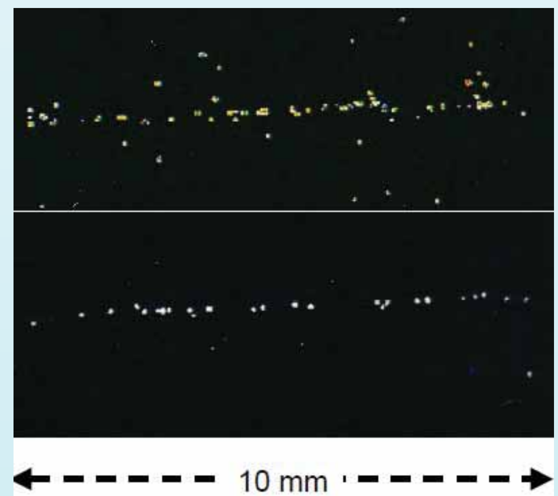


Sensitive area:

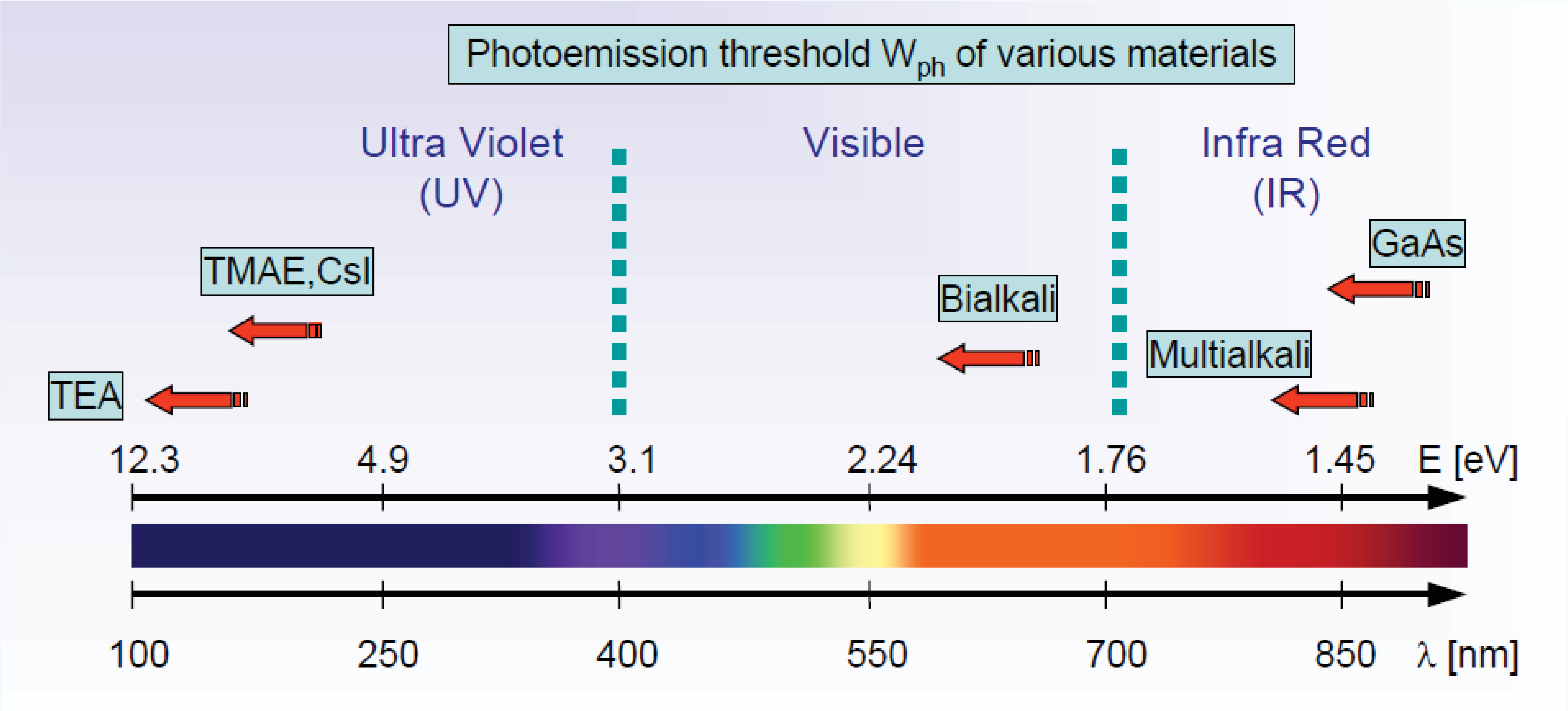
7-layers of Kuraray SCSF-78MJ 0.5 mm Ø

RD7 60μm hexagonal fibers





Photon detection



Photomultipliers

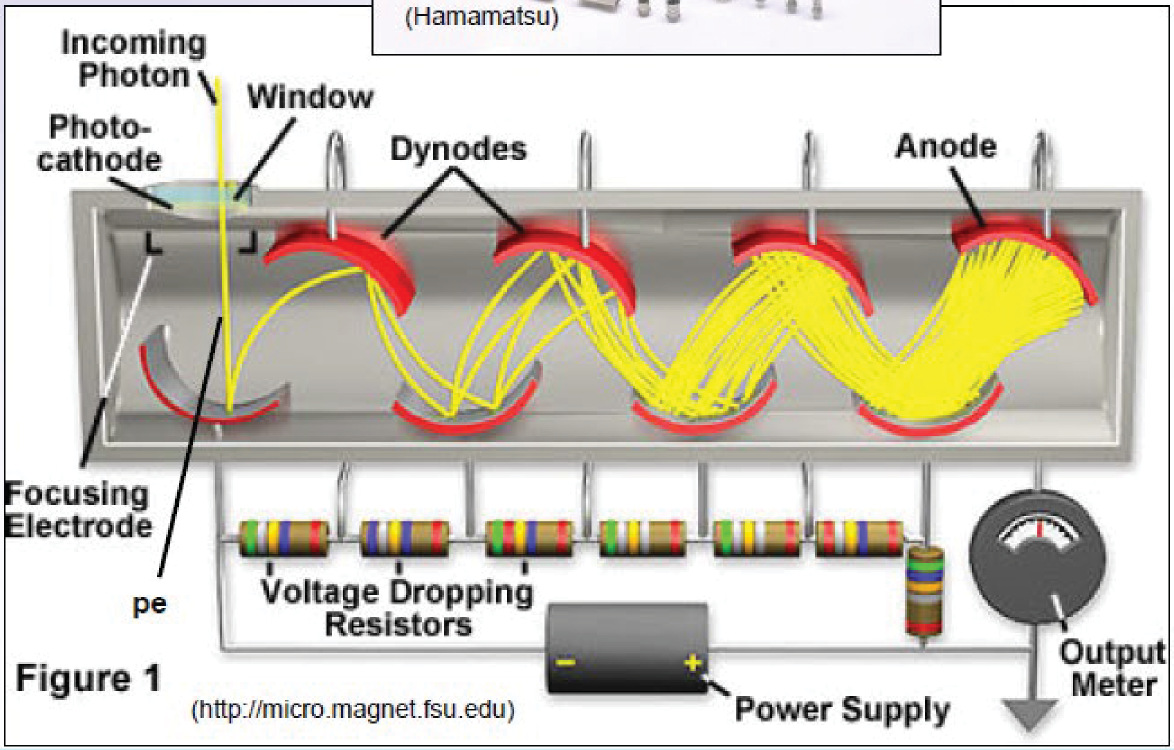
Basic principle:

- Photo-emission from photo-cathode
- Secondary emission (SE) from N dynodes:
  - dynode gain g≈3-50 (function of incoming electron energy E);
  - total gain *M*:

$$M = \prod_{i=1}^{N} g_i$$

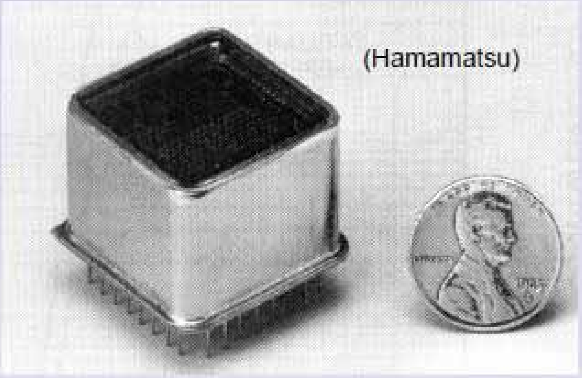
- Example:
  - 10 dynodes with g=4
  - $M = 4^{10} \approx 10^6$

(Hamamatsu)



(http://micro.magnet.fsu.edu)

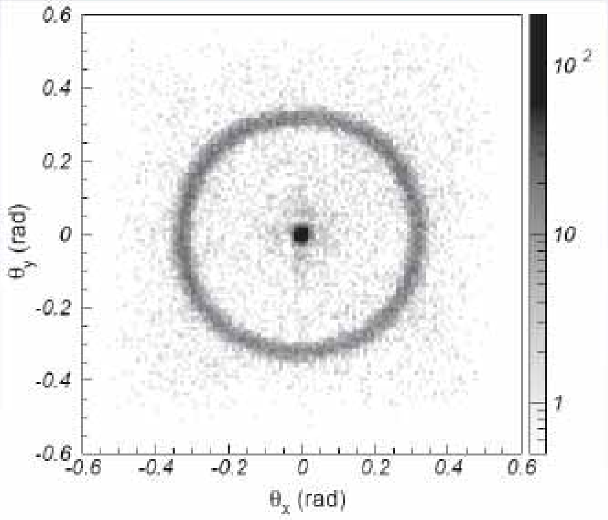
Multianode and flat-panels



Multi-anode (Hamamatsu H7546)

- Up to 8 × 8 channels (2 × 2 mm^2 each);
- Size: 28 × 28 mm^2;
- Active area 18.1 × 18.1 mm^2 (41%);
- Bialkali PC: QE ≈ 20% @ λ_{max} = 400 nm;
- Gain ≈ 3 10^5;
- Gain uniformity typ. 1 : 2.5;
- Cross-talk typ. 2%

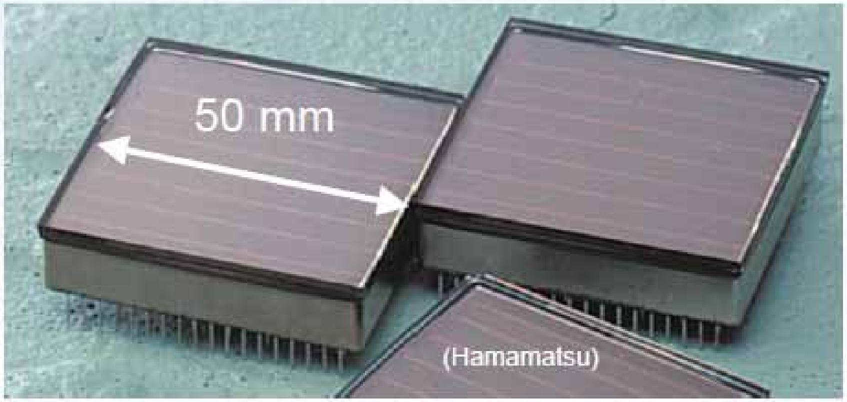
Cherenkov rings from 3 GeV/c π^- through aerogel



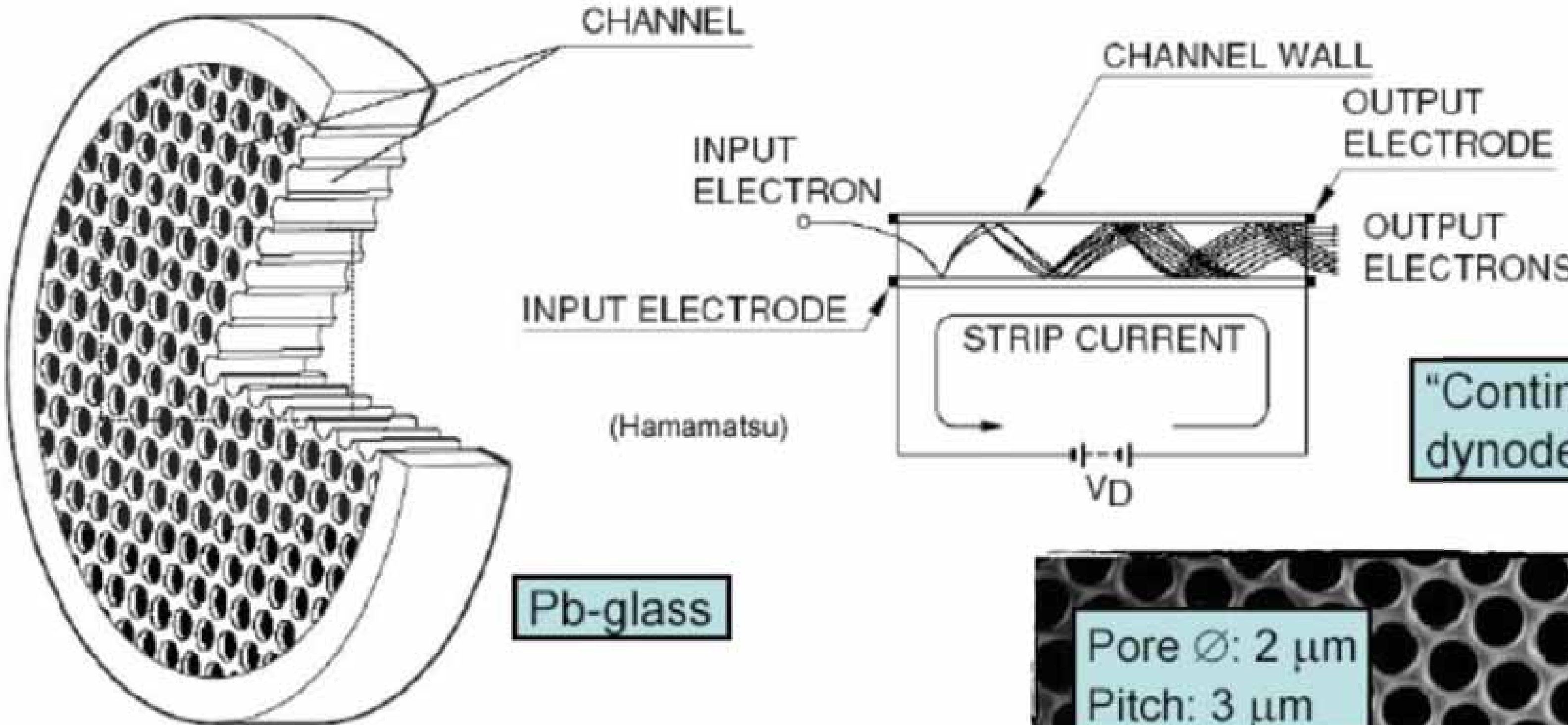
(T. Matsumoto et al., NIMA **521** (2004) 367)

Flat-panel (Hamamatsu H8500):

- 8 x 8 channels (5.8 x 5.8 mm^2 each);
- Excellent surface coverage (89%)

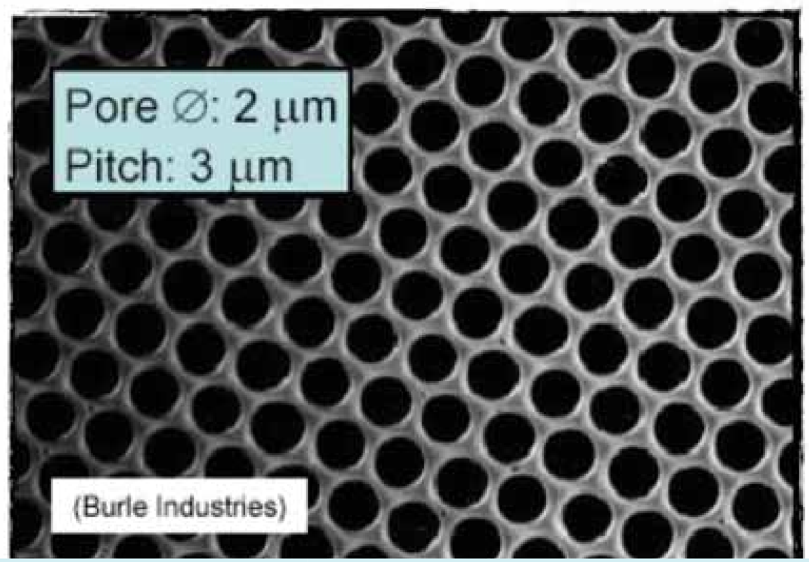


Micro-Channel Plates



"Continuous" dynode chain

Pb-glass



"2D Photomultiplier"

Gain: $5 \cdot 10^4$

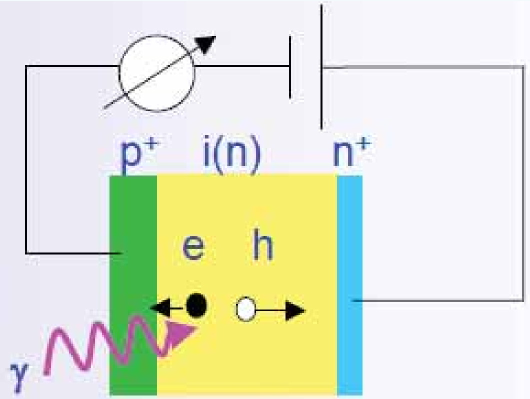
Fast signal [time spread ~ 50 ps]

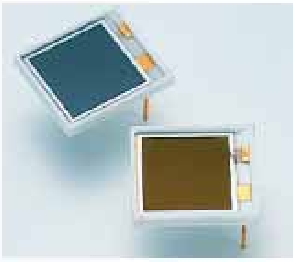
B-Field tolerant [up to 0.1T]

Photodiodes

Photodiodes:

- P(I)N type
- p layer very thin (<1 μm), as visible light is rapidly absorbed by silicon (see next slide);
- High QE (80% @ λ ≈ 700nm);
- No gain: cannot be used for single photon detection;



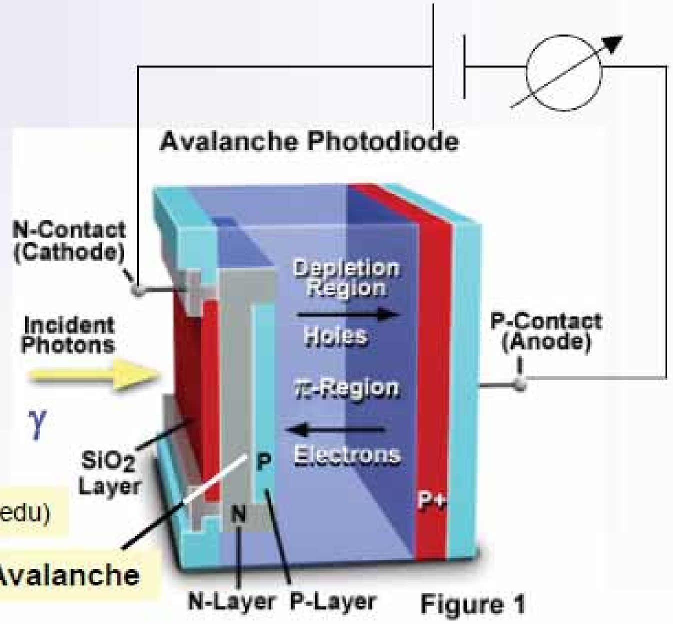


Avalanche photodiode:

- High reverse bias voltage: typ. 100-200 V

⇒ due to doping profile, high internal field and avalanche multiplication;

- High gain: typ. 100-1000;
- Used in CMS ECAL;



(http://micro.magnet.fsu.edu)

Si PMs

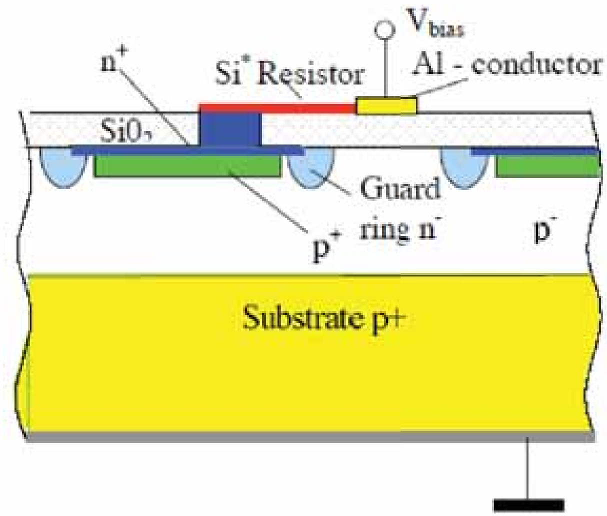
Silicon Photomultipliers

Principle:

Pixelized photo diodes operated in Geiger Mode

Single pixel works as a binary device

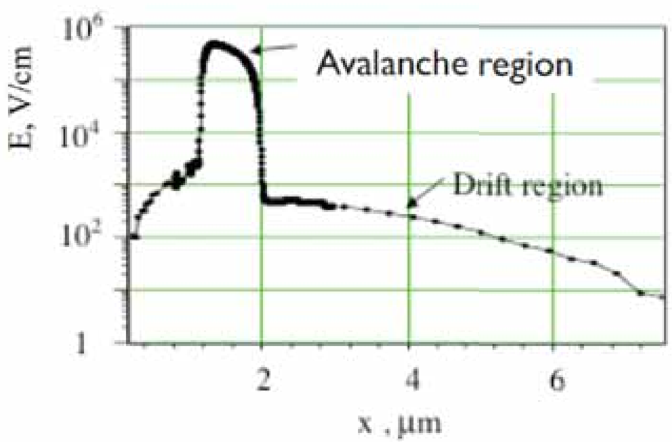
Energy = #photons seen by summing over all pixels



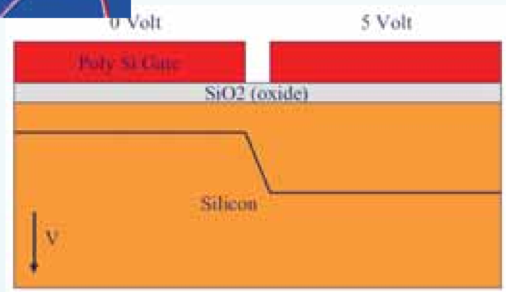
Features:

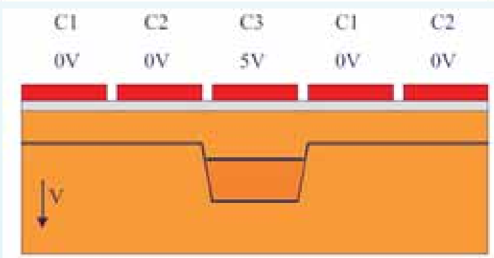
Granularity	:	10^3 pixels/mm^2
Gain	:	10^6
Bias Voltage	:	< 100 V
Efficiency	:	ca. 30 %

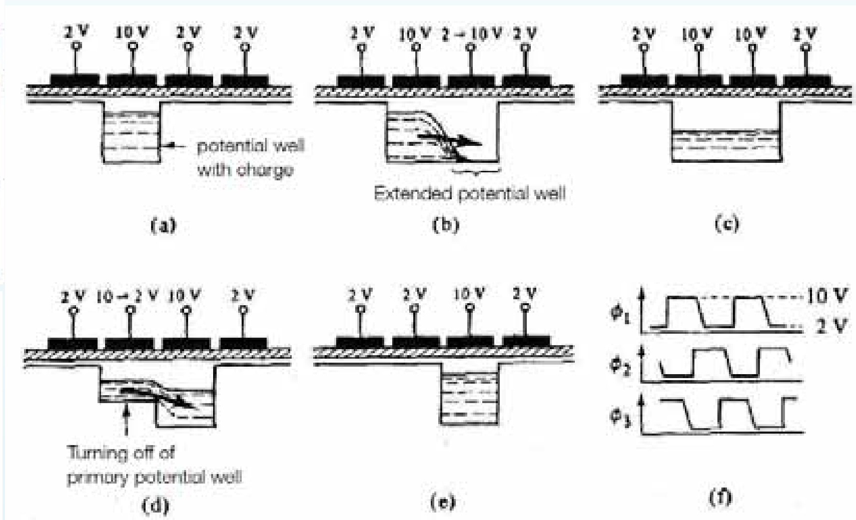
Insensitive to magnetic fields!
Works at room temperature ...



CCD





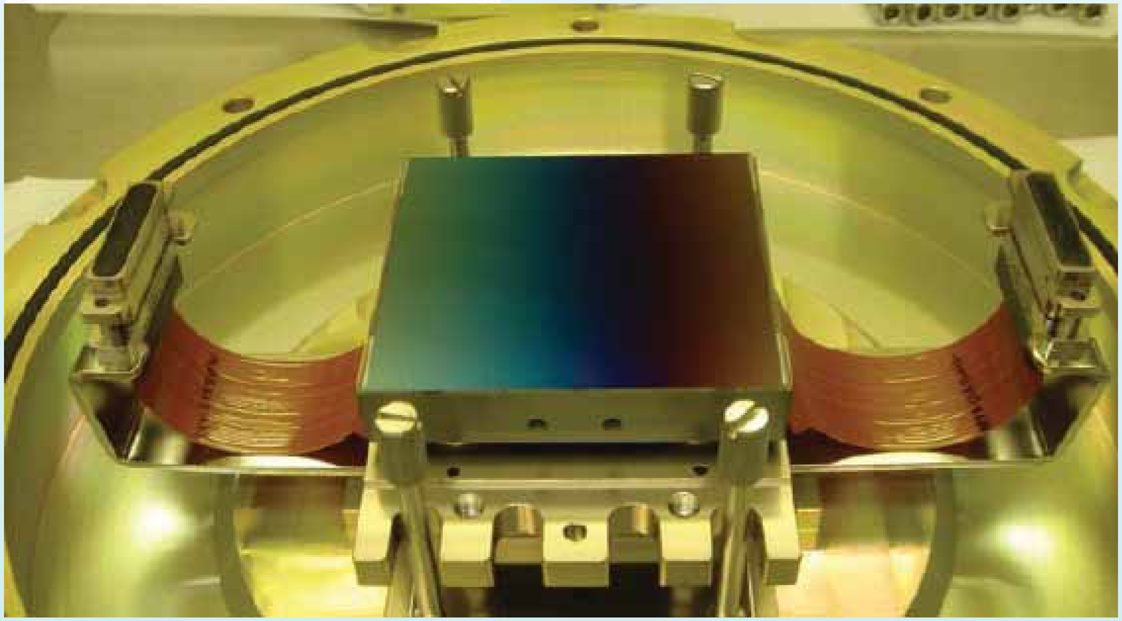


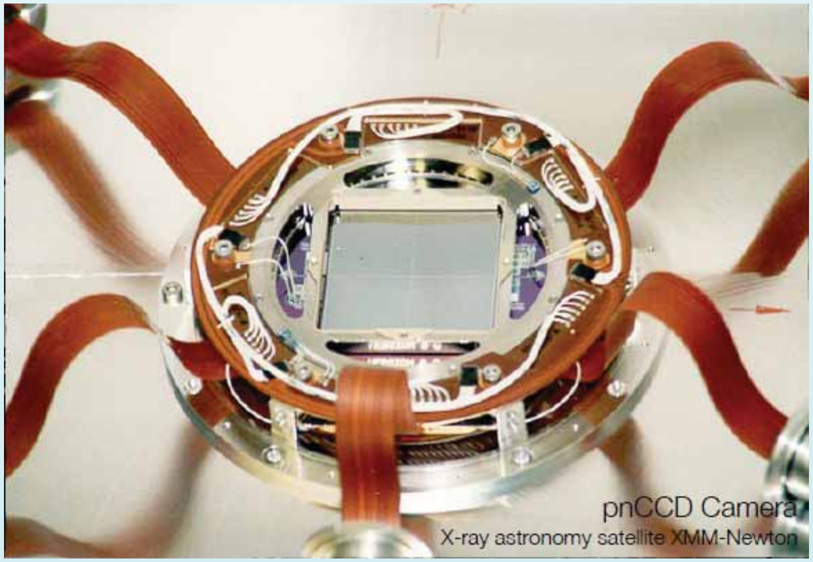
The Nobel Prize in Physics 2009

"for groundbreaking achievements concerning the transmission of light in fibers for optical communication"

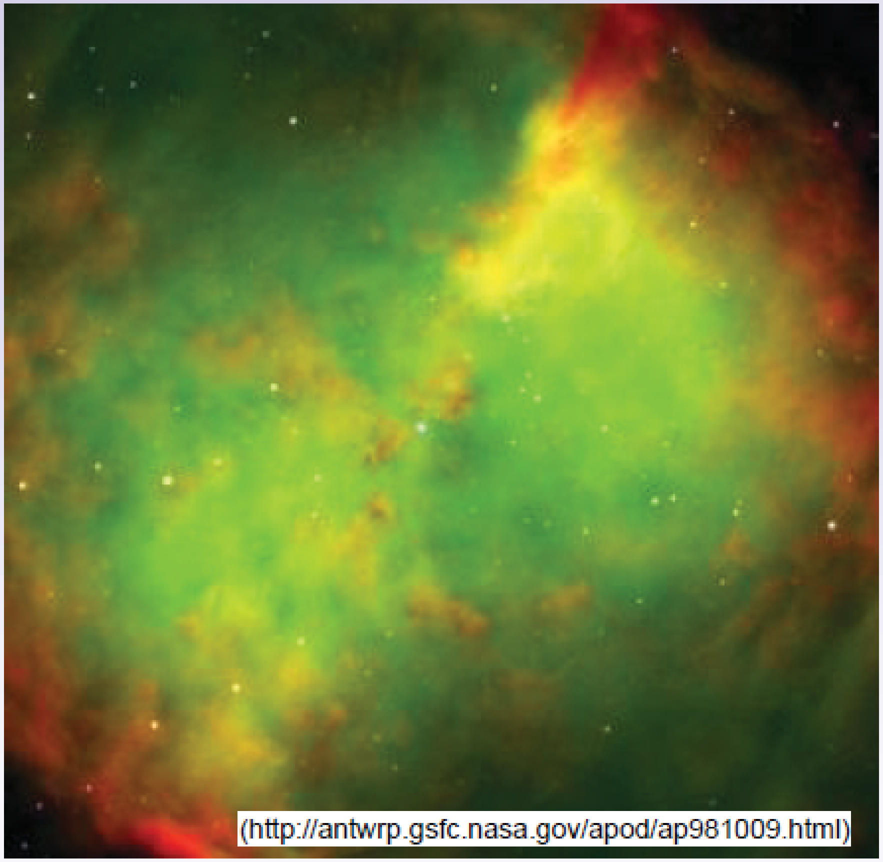
"for the invention of an imaging semiconductor circuit – the CCD sensor"

Charles K. Kao | Willard S. Boyle | George E. Smith

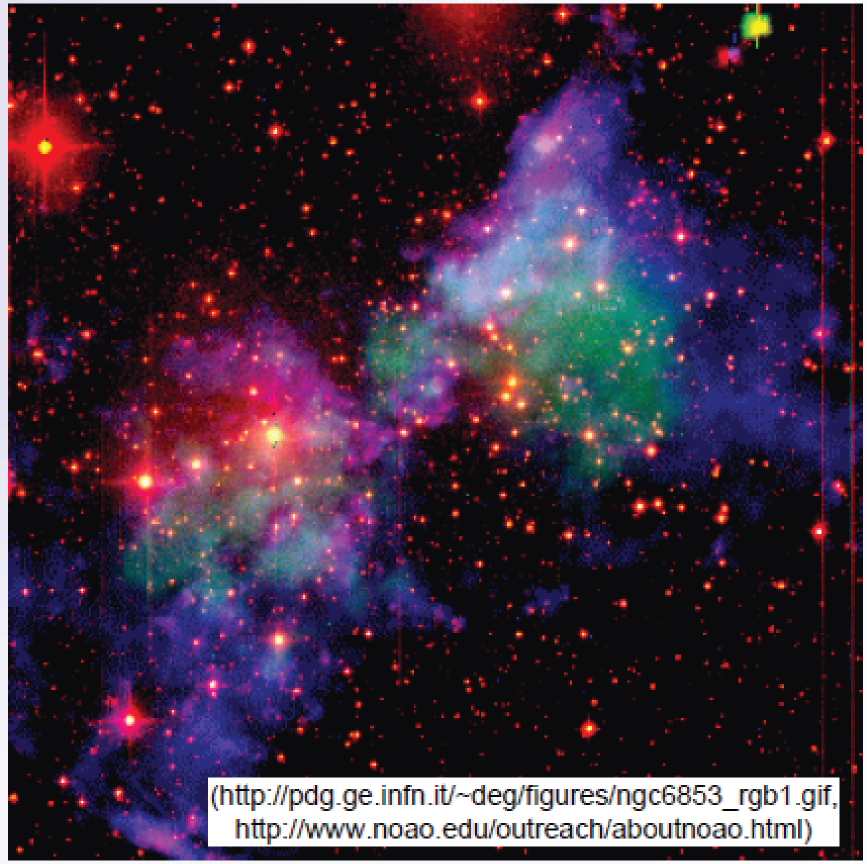




Dumbbell nebula in Vulpecula (M27, NGC 6853)



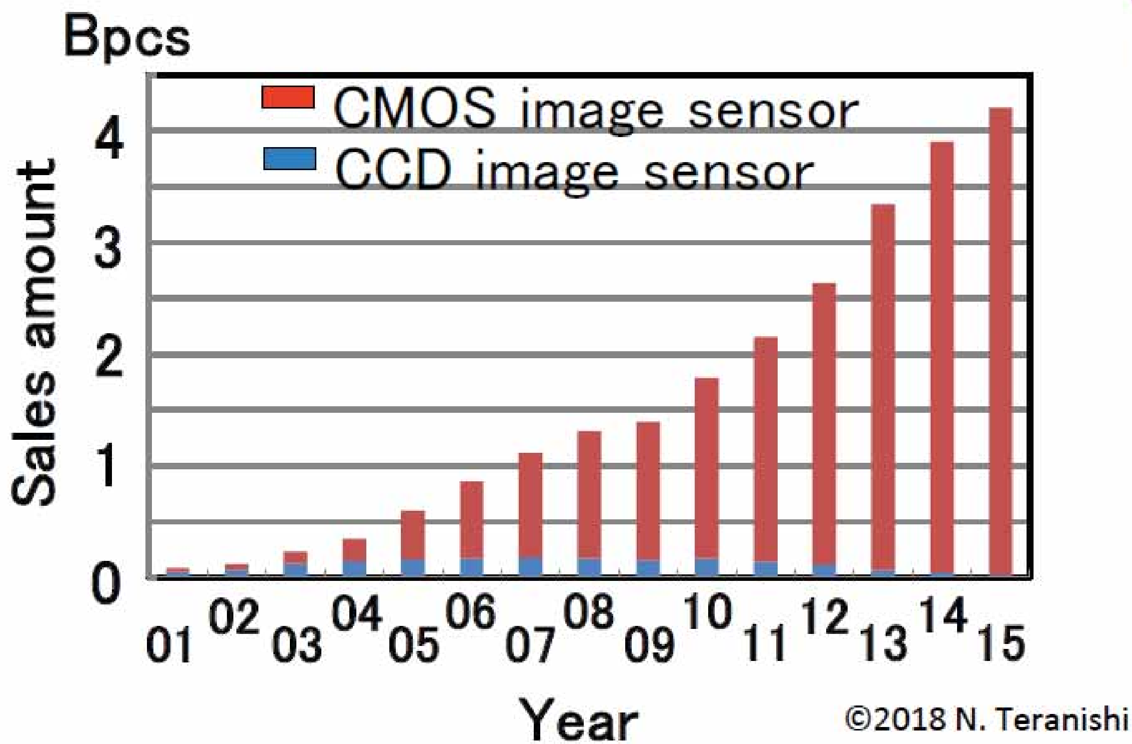
FORS false color image using a Tektronix back-illuminated 2k×2k CCD with 24μm pixels thinned and anti-reflection coated.
This image was obtained on ESO 8.2-m VLT Unit Telescope (UT) 1 on September 28, 1998.



NOAO false color image using a back-illuminated fully depleted 2k×2k CCD with 15μm pixel.
This image was obtained on WIYN 3.5-m Telescope on June 7, 2001.

Image Sensors

- IS sales amount has grown by camera phone.
- IS spreads into various applications,
- "Others" includes scientific, industrial, …



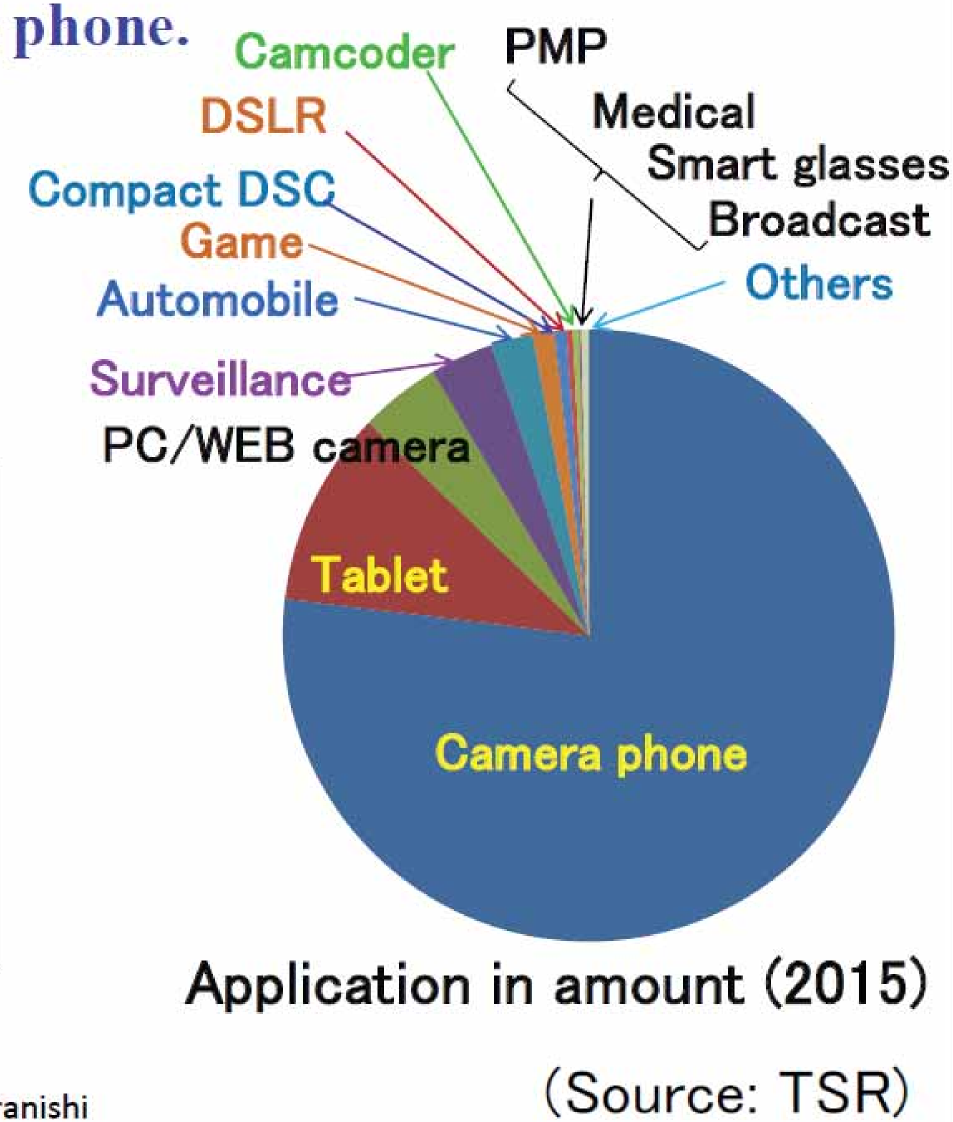


Image Sensors

Examples of applications

Smart-phone

Movie

Automobile

Endoscope

Iris verification

Security

Image Sensor

DSC

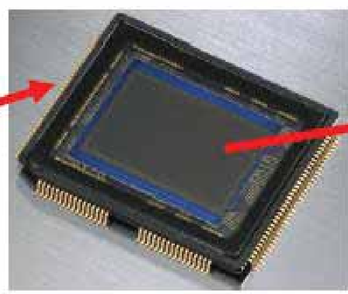
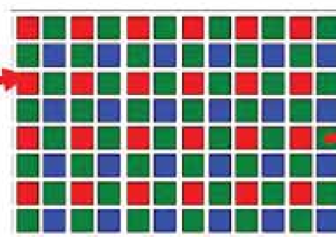
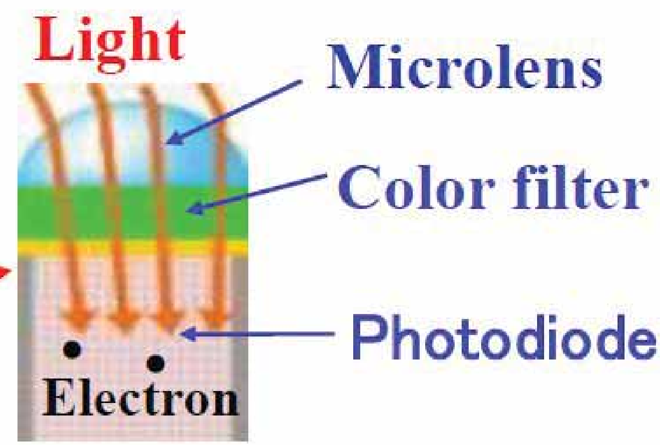


Image sensor



Pixel array

©2018 N. Teranishi

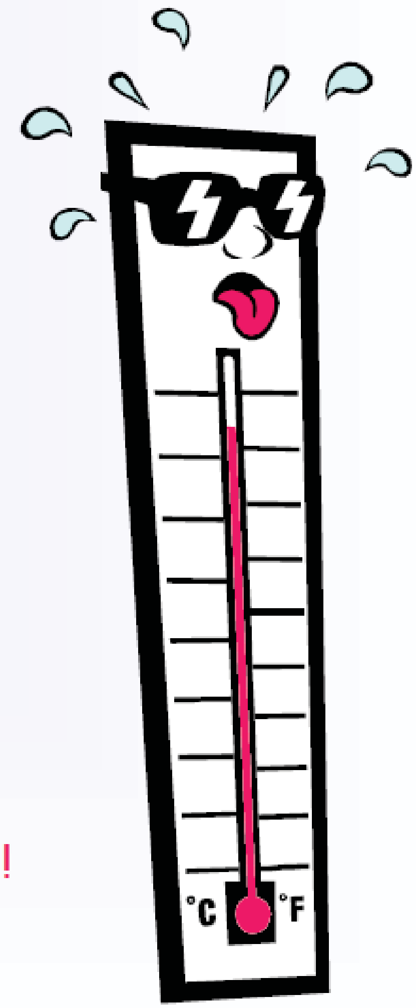


Pixel cross-section

Calorimetry

Calorimetry = Energy measurement by total absorption, usually combined with spatial reconstruction.

latin: cal[illegible] heat



- LHC beam: Total stored beam energy
  $E = 10^{14}$ protons $\times$ $14 \cdot 10^{12}$ eV $\approx 1 \cdot 10^{8}$ J

- Which mass of water M_{water} could one heat up (ΔT = 100 K) with this amount of energy (c_{water} = 4.18 J g^{-1} K^{-1}) ?
  $M_{water} = E / (c \Delta T) =$ 239 kg

- What is the effect of a 1 GeV particle in 1 liter water (at 20° C)?
  $\Delta T = E / (c \cdot M_{water})$ = $3.8 \cdot 10^{-14}$ K !

There must be more sensitive methods than measuring ΔT !

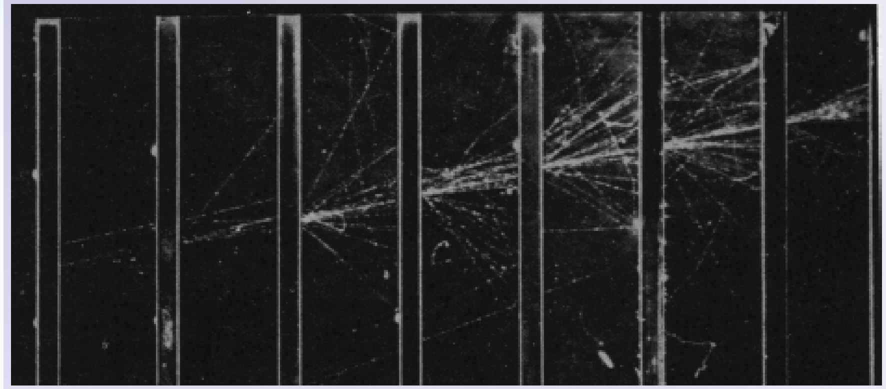
Electromagnetic Calorimeters

Basic mechanism for calorimetry in paricle physics: formation of

- ⇨ electromagnetic
- ⇨ or hadronic showers.

Finally, the energy is converted into ionization or excitation of the matter.

Charge — Cerenkov light — Scintillation light



electron shower in a cloud chamber with Pb

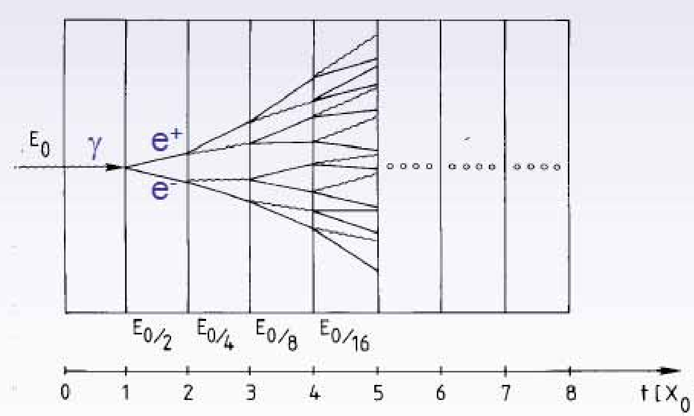
Calorimetry is a "destructive" method. The energy and the particle get absorbed!

Detector response ∝ E

Calorimetry works both for

- ⇨ charged ($e^{\pm}$ and hadrons) → Complementary information to p-measurement
- ⇨ and neutral particles (n,γ) → Only way to get direct kinematical information for neutral particles

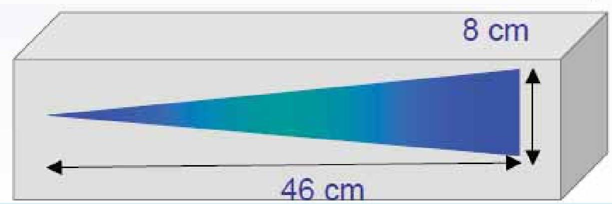
Simple qualitative model



Example: E_0 = 100 GeV in lead glass

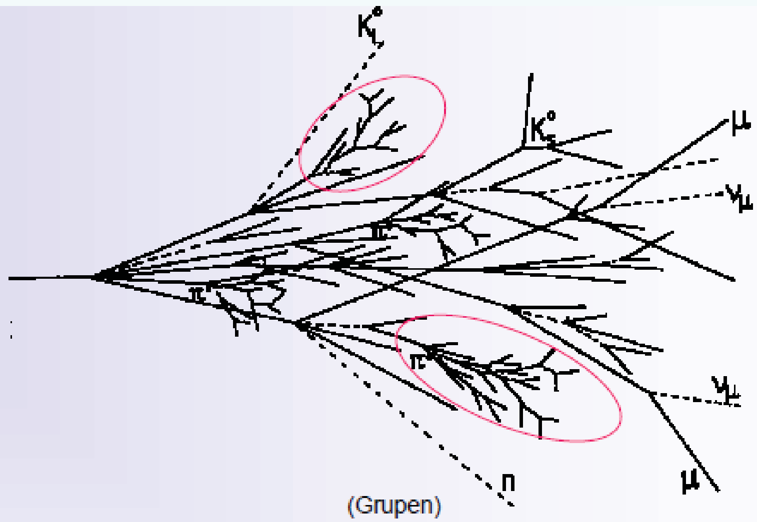
E_c=11.8 MeV → $t_{max} \approx 13$, $t_{95\%} \approx 23$

$X_0 \approx 2$ cm, $R_M = 1.8 \cdot X_0 \approx 3.6$ cm



Hadronic Calorimetry

Various processes involved.
Much more complex than electromagnetic cascades.



(Grupen)

CMS Hadronic Calorimeter: brass and plastic scintillators

A hadronic shower contains two components:

hadronic + **electromagnetic**

hadronic ↓

- charged hadrons p, $\pi^\pm$, $K^\pm$,
- nuclear fragmets ….
- breaking up of nuclei (binding energy)
- neutrons, neutrinos, soft γ's, muons

electromagnetic ↓

neutral pions $\rightarrow 2\gamma$

$\rightarrow$ electromagnetic cascades

$$n(\pi^0) \approx \ln E(GeV) - 4.6$$

example $E = 100$ GeV: $n(\pi^0) \approx 18$

invisible energy $\rightarrow$ large energy fluctuations $\rightarrow$ limited energy resolution