Radiation Instrumentation detectors Introduction

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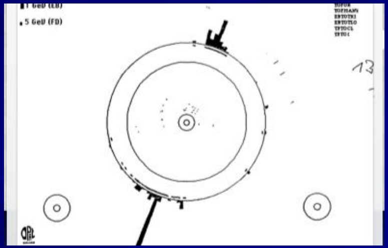
(In collaboration with
Cinzia Da Via
Manchester University)

Vietnam International School on Real Time Systems

Who I am ? -

- NA3 @ CERN (Di-Muon Drell Yan) : 1974-1980
  - Large MWPC (4x4 m2)
  - **Trigger & DAQ**
- LEP - OPAL @ CERN (1980-1990)
  - TOF system
  - **Trigger & DAQ → First Z^0**



- SSC- SDC @ Dallas/LBL Berkeley (1990-1994)
  - **Trigger L2**
  - Shower Max Detector electronics (APD & SCA)
- LHC- ATLAS @ CERN (1994-2000)
  - **L2 trigger** & LARG calorimeter Read Out electronics (SCA)
- D0 @ FNAL (1996-2005)
  - **L1 Calormeter trigger and L2 trigger**.
- ILC study group (1996-2008)
  - **Trigger & DAQ convener → Software triigeer**
- **2000→Technology transfer advisor for medical application (PET & Particle therapy)**
- **Ultra fast (picosecond) timing**

Experimental Physicist

-CEA Saclay (1969-2008)

-IN2P3-IPN Lyon (2009 ..

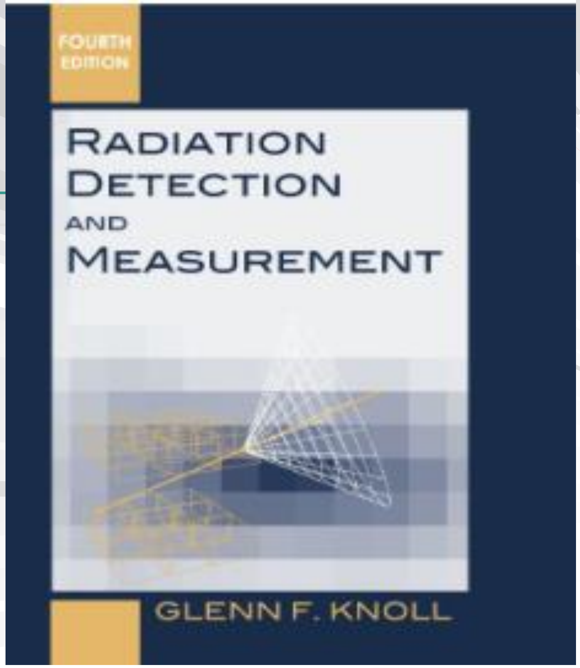
IEEE NPSS NUCLEAR & PLASMA SCIENCES SOCIETY

NPSS ADCOM

-RITC Chair

Few words about Detectors

Radiation Instrumentation
The Bible
Glenn Knoll



Goals of these lectures

- A very simple basic introduction of Radiation Instrumentation detectors seen from a HEP experimental physicist.
- I will present mainly the basics of instrumentation aspect
- Explain why this domain has strong relationship with our field of interest (HEP) and might interest your future

Outlines of the lecture

- What is radiation ?
- A little bit of history
- Basic sensors families
  - Photodetectors
  - Gazeous detectors
  - Silicon detectors
- Interaction particle- matter
- Examples of implementation in small and large detectors

Radiation detectors → Imaging what you cannot see

.. or how the development of radiation instrumentation has been crucial for fundamental scientific discoveries and for the improvement of human life...

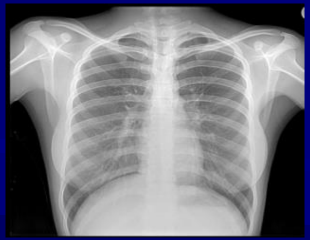
Introduction: Imaging radiation ..

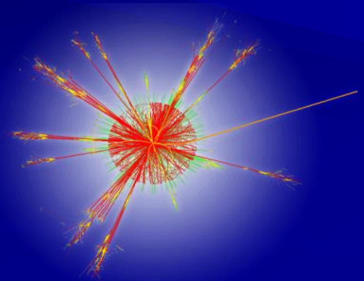

Web cams

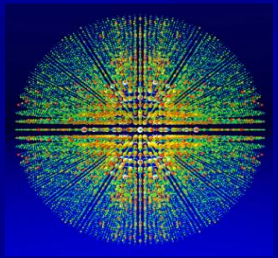

Smart phones

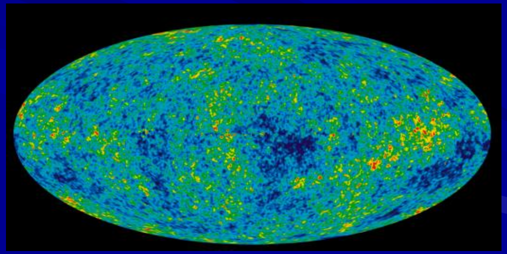
photo cameras

machine vision, automotive, security etc…


Medical imaging


HEP


x-ray crystallography


cosmology

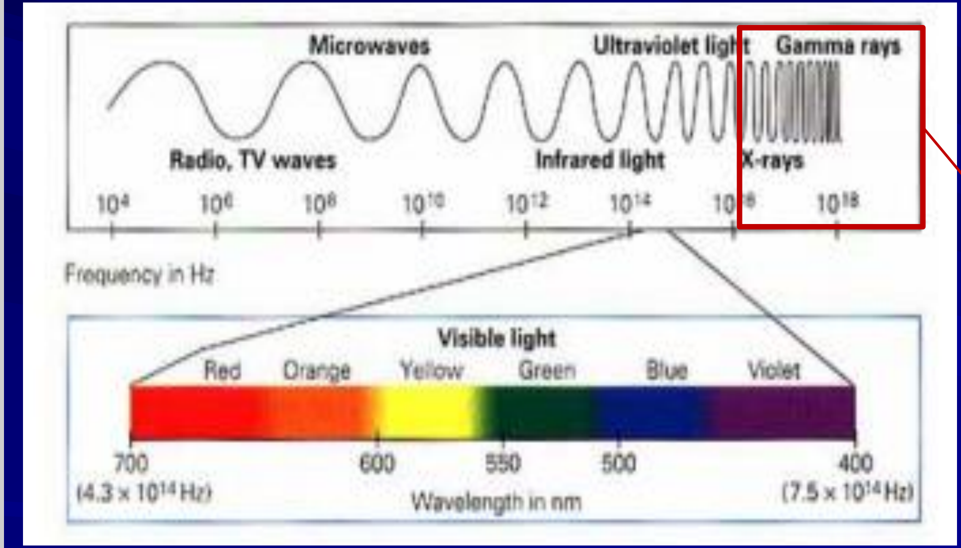
……

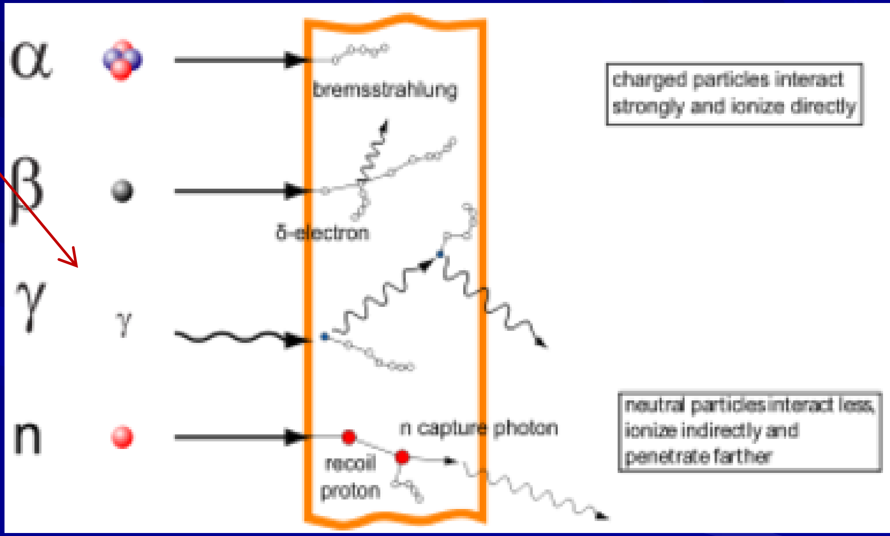
mass spectroscopy, optical tweezers, neutrons, electrons, TOF, SEM/TEM etc…

What is radiation ?

- **Radiation** can be defined as the propagation of energy through space or matter in the form of electromagnetic waves or energetic particles.

When radiation interacts with matter:





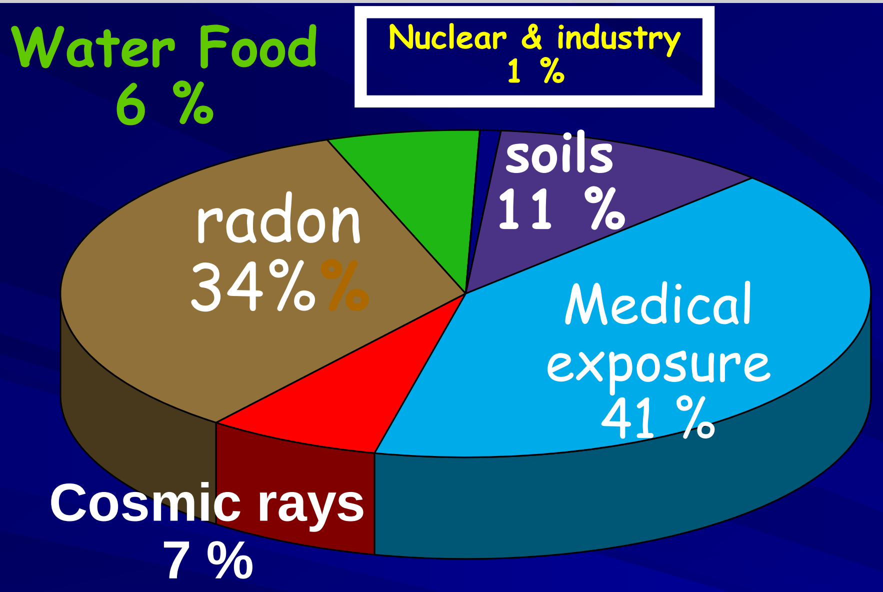
Non-ionizing

does not have enough energy to ionize atoms but in the material it interacts with. At high energy it becomes ionizing

Ionizing

has the ability to knock an electron from an atom, i.e. to ionize..

Main sources of ionizing radiation



- Earth has been radioactive ever since its formation into a solid mass over 4½ billion years ago. However, we have only known about radiation and radioactivity **for just over one hundred years...**


A Cockcroft-Walton

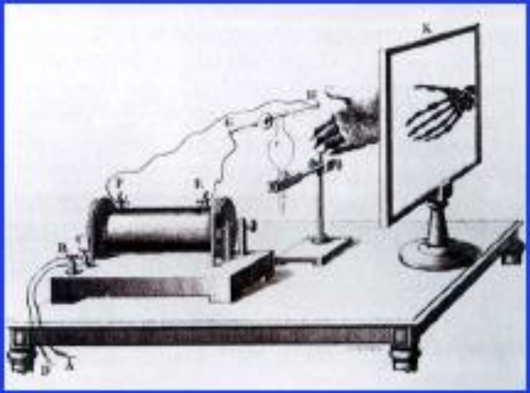

Accelerators


X-ray tubes

Some history

How physics discoveries have impacted our life

18 Nov, 1895 W.C. Rontgen discovers Xrays



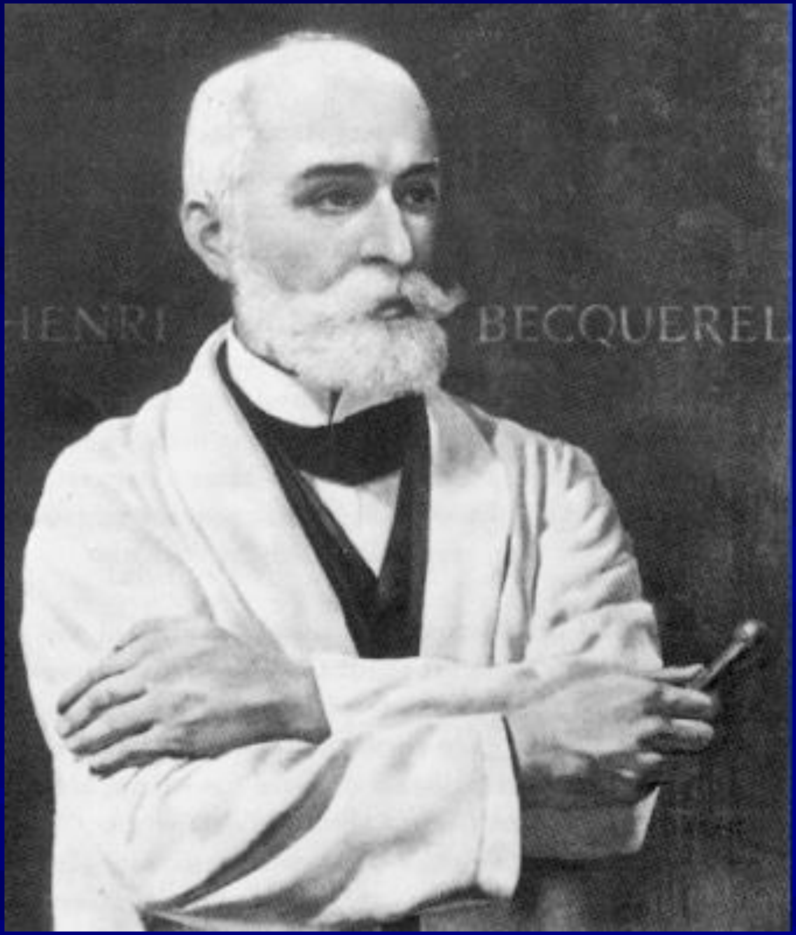
W.C.Röntgens experiment
in Würzburg

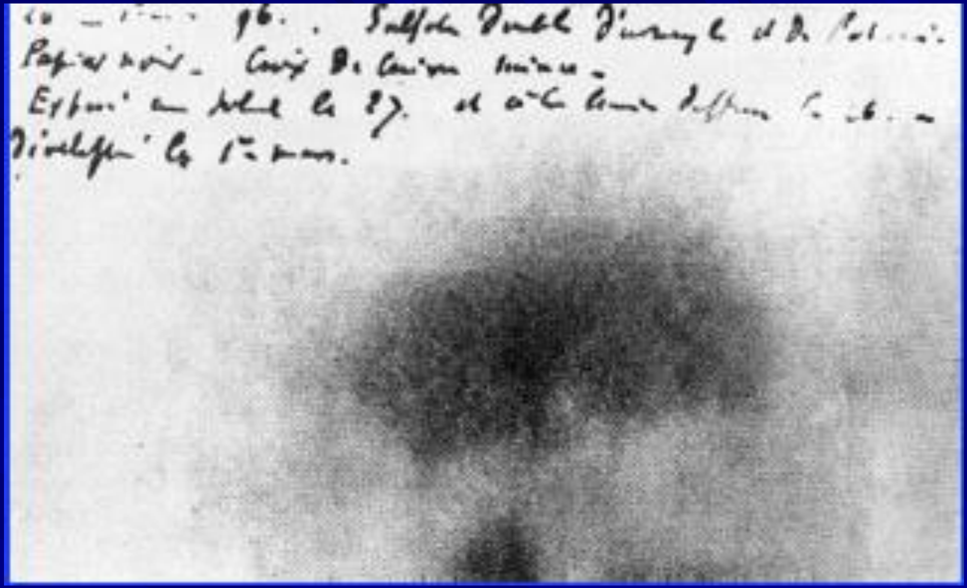
An early XXth century

X-ray tube

Radiograph of
Mrs.Röntgens hand,
the first x-ray image
ever taken,
22.Dec.1895, published in
The New York Times
January 16, 1896

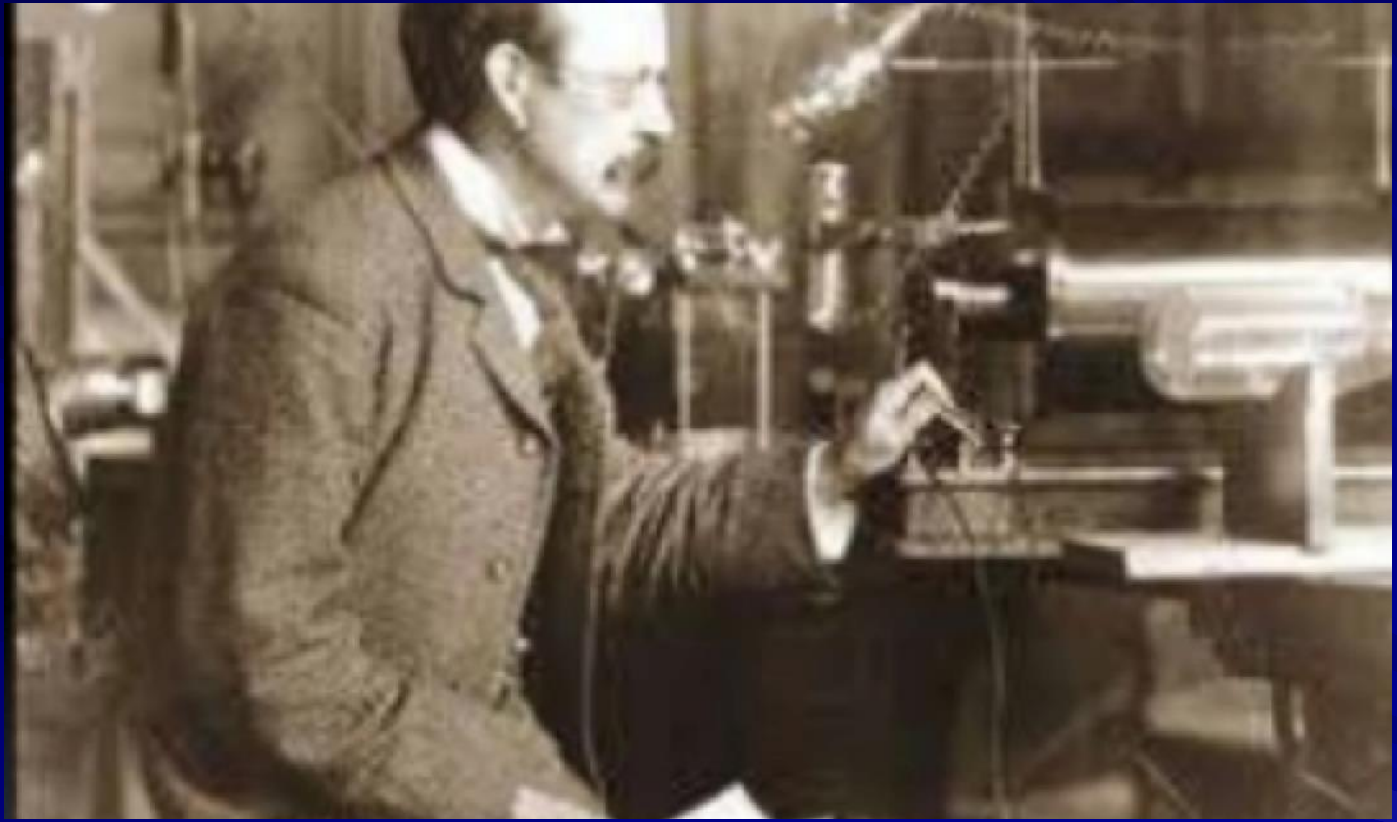
1996 - Discovery of the natural radioactivity by Henri Becquerel



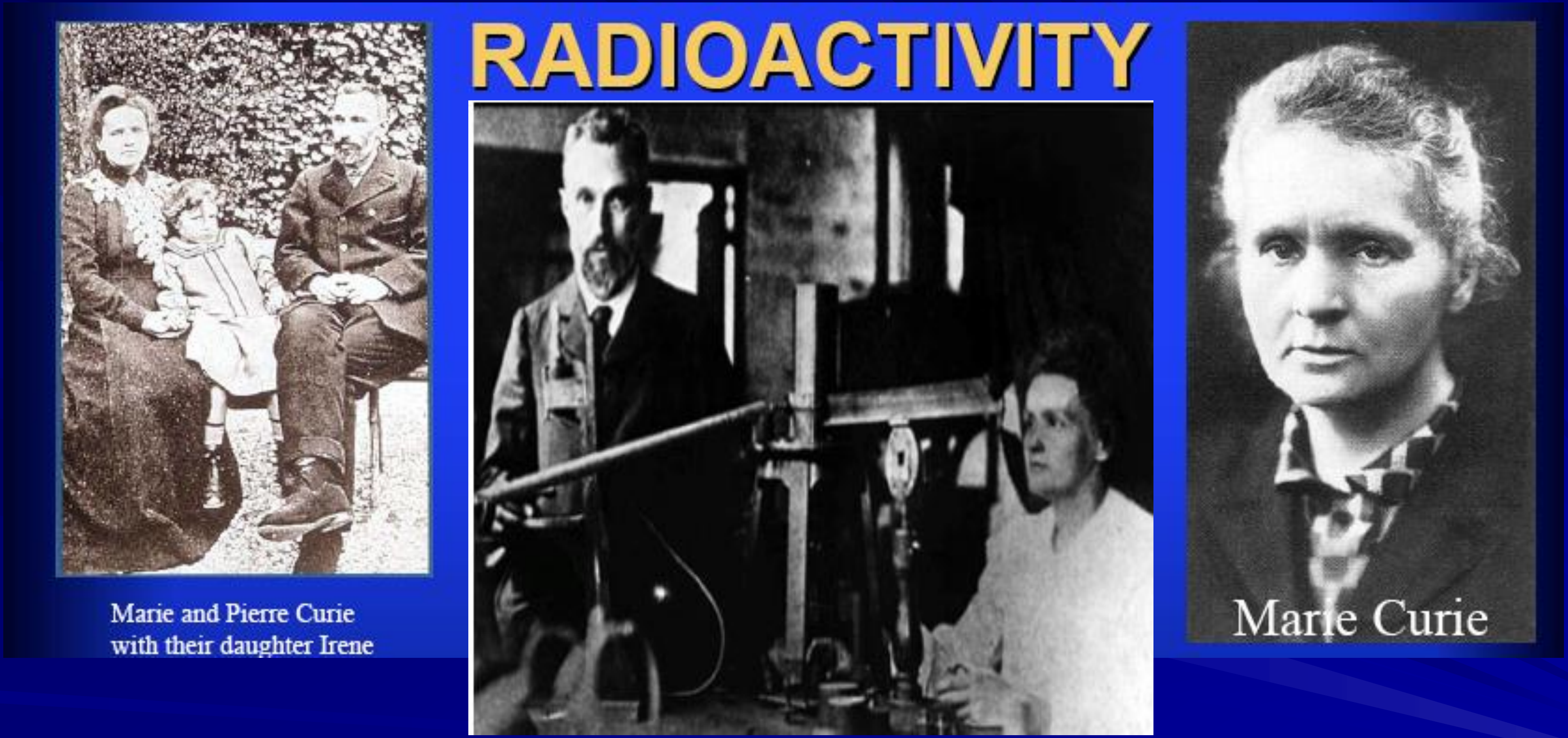


- First image of potassium uranyl disulfide

1897 Discovery of the electron by J.J. Thompson



1898 Pierre & Marie Curie discoversthe:radium and polonium



They share the 1903 Nobel prize of Physics with H. Bequerel

1899 – Discovery of Alfa and Beta particle by E. Rutherford

- 1900 proposal of Radioactive decay and half time.

1900 – Discovery of the GAMMA Ray

- Paul Ulrich Vilars discovers the gamma ray radiation while studying the radiation emitted from Radium
- Vilars's radiation was named 'gamma radiation' by Ernest Rutherford in 1903.

1932 - The Invention of the cyclotron

Ernest O. Lawrence and his First cyclotron 1932

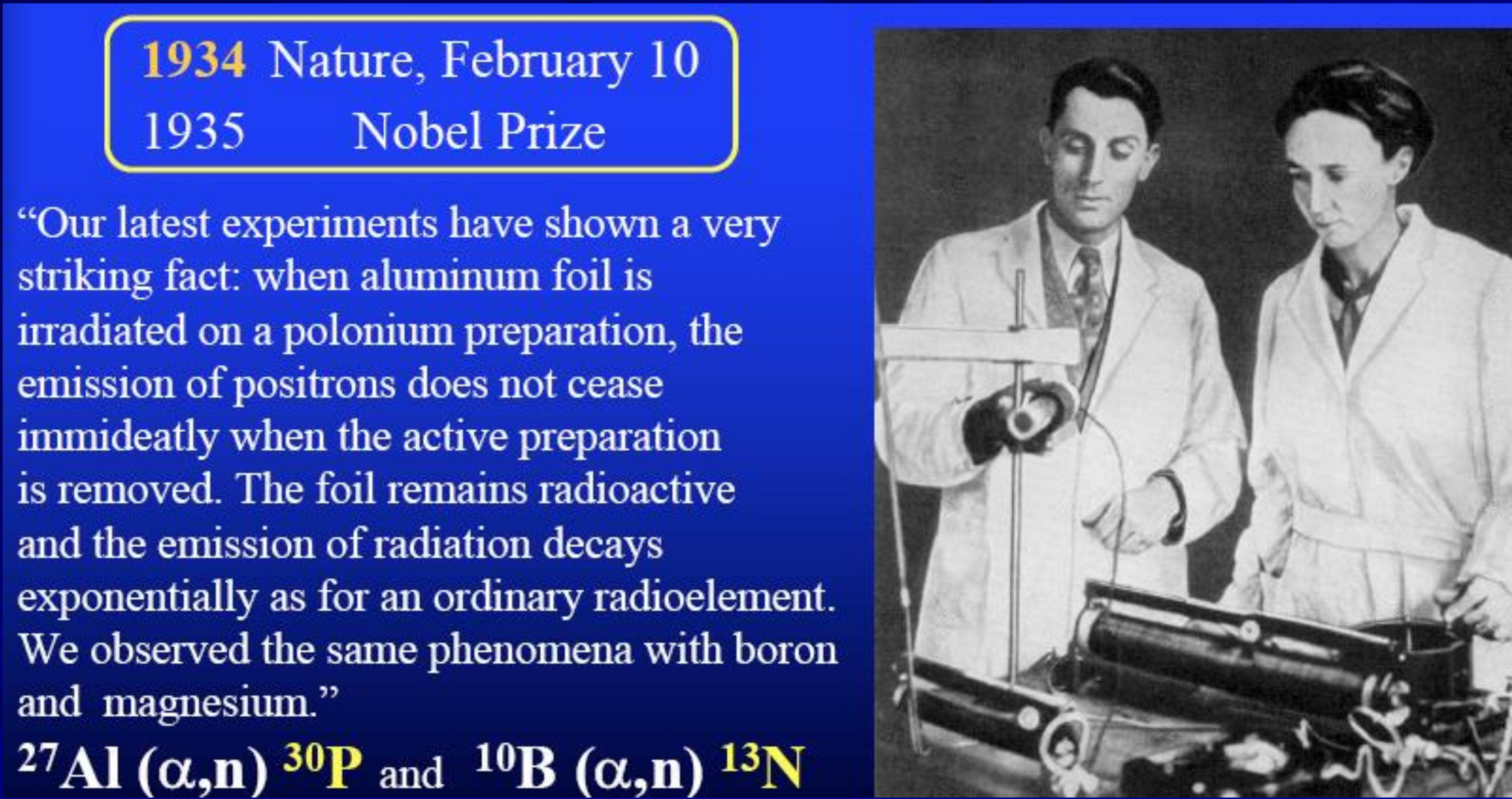
E.O.Lawrence and M.S. Livingston "The production of high speed Light ions without the use of high voltages",

A milestone in the production of usable quantities of radionuclides.

E.O Lawrence and M.S.Livingston with the 27-inch cyclotron at Berkeley 1933, the first cyclotron that produced radioisotopes

1934 - Artificial radioactivity

Irène & Frederic Joliot-Curie



1934 Nature, February 10
1935 Nobel Prize

“Our latest experiments have shown a very striking fact: when aluminum foil is irradiated on a polonium preparation, the emission of positrons does not cease immideatly when the active preparation is removed. The foil remains radioactive and the emission of radiation decays exponentially as for an ordinary radioelement. We observed the same phenomena with boron and magnesium.”

$^{27}\mathrm{Al}\ (\alpha,n)\ ^{30}\mathrm{P}$ and $^{10}\mathrm{B}\ (\alpha,n)\ ^{13}\mathrm{N}$

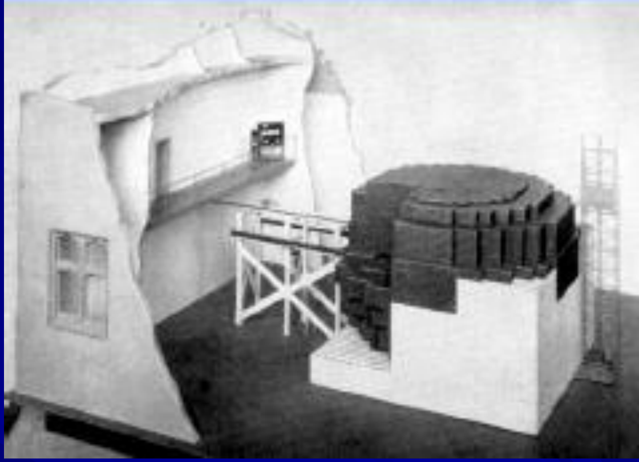
The discovery of artificial radioactivity in combination with the cyclotron open the door to the production of useful radio indicators. Practically any element could be bombarded in the cyclotron to generate radioactive isotopes.

1938-1942 Fission of Uranium

$$^{235}U + n = [^{236}U] \longrightarrow {}^{140}Ba + {}^{94}Kr + 2\,n + \gamma + \text{Energy}$$

Otto Hahn, 1944 Nobel Prize

Enrico Fermi



- From discovery to first *graphite miler in Chicago*
- *Production of long lived radio-isotopes*

The detectors story

History and evolution of radiation detectors tools of discovery

- 1906: Geiger Counter, H. Geiger, E. Rutherford
- 1910: Cloud Chamber, C.T.R. Wilson
- 1928: Geiger-Muller Counter, W. Muller
- 1929: Coincidence Method, W. Bothe
- 1930: Emulsion, M. Blau
- 1940-1950: Scintillator, Photomultiplier
- 1952: Bubble Chamber, D. Glaser
- 1962: Spark Chamber
- 1968: Multi Wire Proportional Chamber, C. Charpak
- 1970es: Silicon era
- Etc. etc. etc.

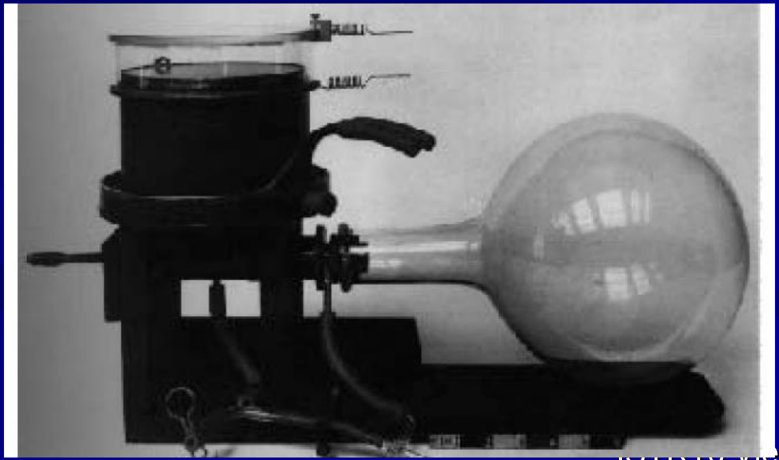
Cloud Chamber C.T.(R. Wilson)

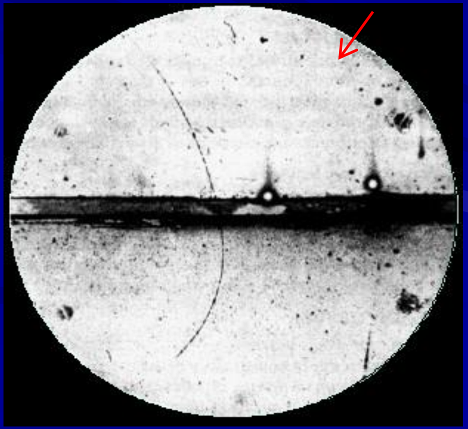
- Combined with the invention of fast photography, one could record particle tracks in the cloud chamber
- used for the discovery of the positron

predicted by Paul Dirac 1928 (Nobel Prize 1933)

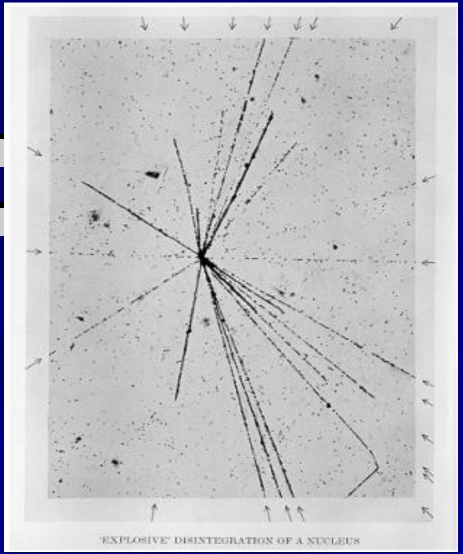
found in cosmic rays by Carl D. Anderson 1932

(Nobel Prize 1936). Also found muon in 1936





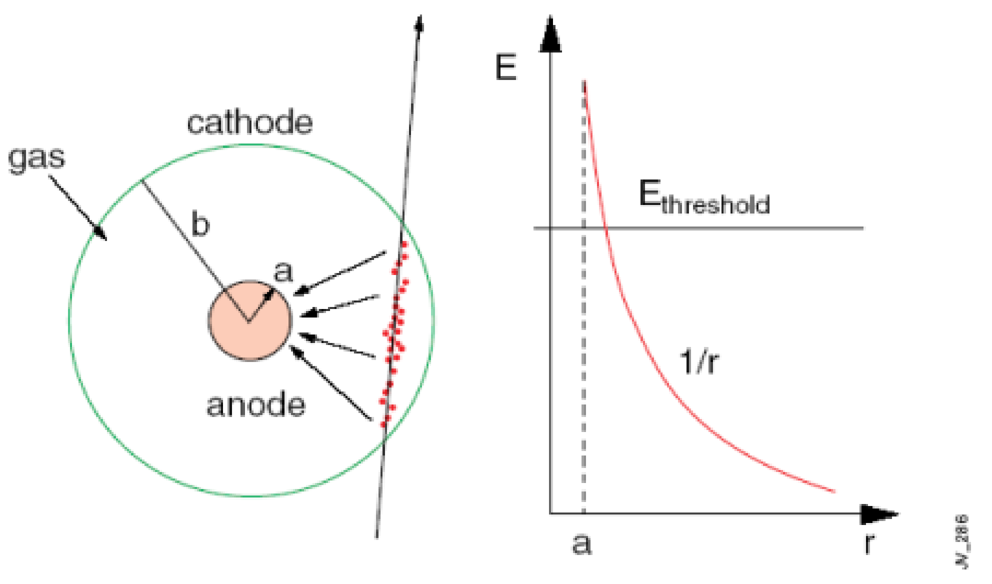
Nuclear Emulsion



'EXPLOSIVE' DISINTEGRATION OF A NUCLEUS

- Nuclear Emulsions pioneered by Marietta Blau between 1923 – 1938
- -photographic emulsion layer, 10 – 200 µm thick,
- -uniform grains of 0.1 – 0.3 µm size
- -very high resolution for particle tracks
- -Discovery of the Pion in cosmic rays (C. Powell 1947 Nobel Prize 1950)
- Discovery of the kaon 1949 (G. Rochester)

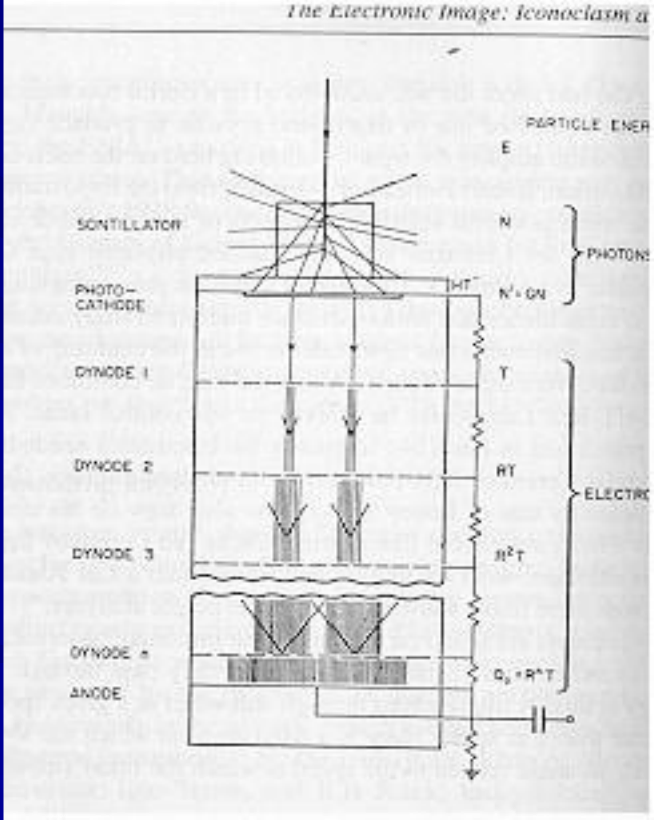
Geiger –Mueller counter



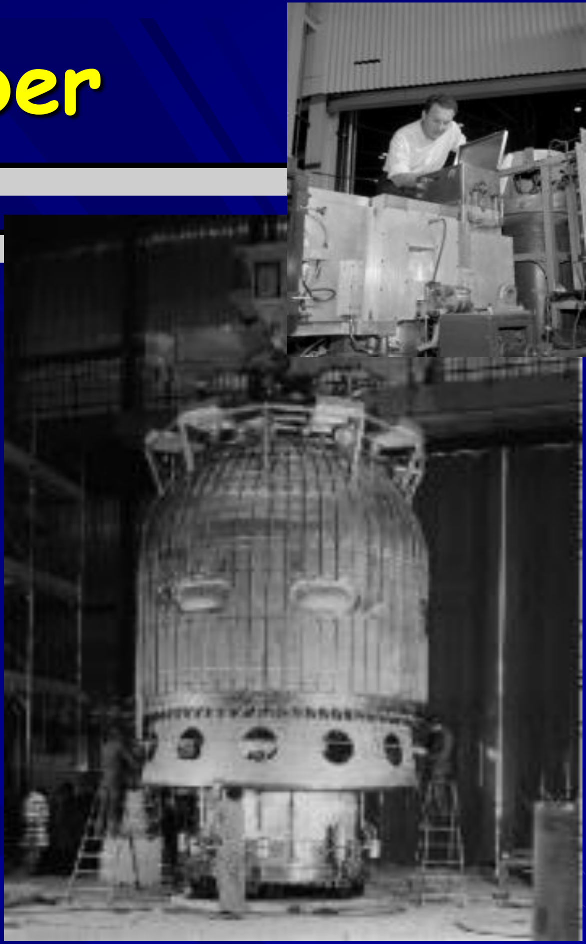
- The Geiger-Müller tube (1928 by Hans Geiger and Walther Müller)
- Tube filled with inert gas (He, Ne, Ar) + organic vapour
- Central thin wire (20 - 50 μm diameter) , high voltage (several 100 Volts)
- between wire and tube
- Avalanche effect close to the wire due to large e-field

The Photopultiplier tube

- Invented 1934 by Harley Iams and Bernard Salzberg (RCA Coorperation)
- -based on photo electric effect and secondary electron emission
- -sensitive to single photons,

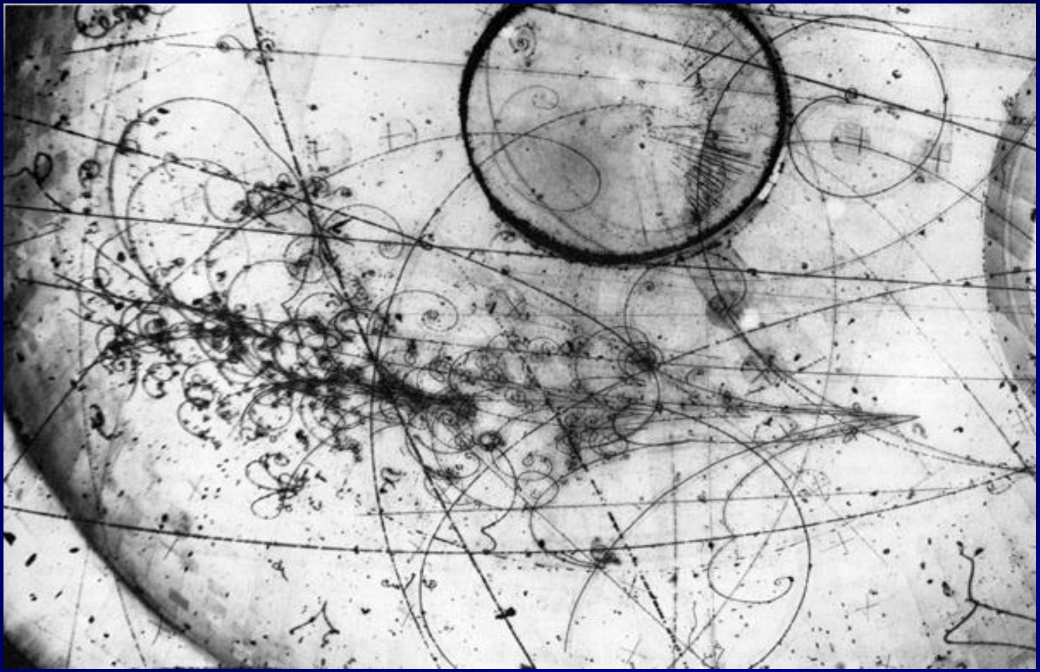


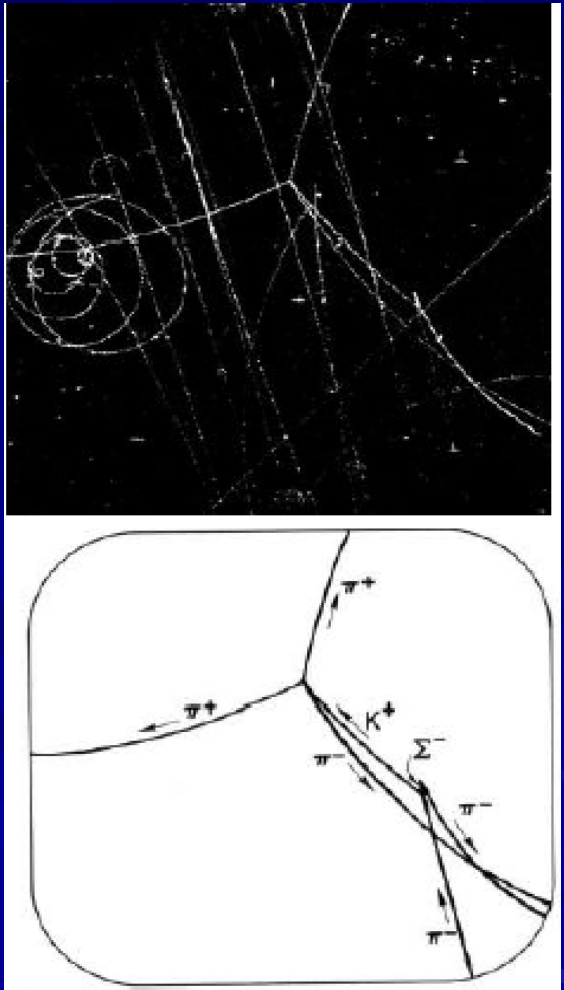
The Bubble Chamber



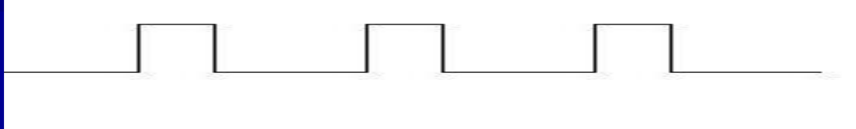
- Bubble chambers. Invented 1952 by Donald Glaser (Noble Prize 1960)
- -similar to could chamber with liquid (e.g. H2) at
- boiling point ("superheated")
- -charged particles leave trails of ions
- formation of small gas bubbles around ions
- 1973 CERN (Gargamelle, BEBC) ,Serpukov (Mirabelle)

The prehistoric world
the Bubble Chamber -1955-1975



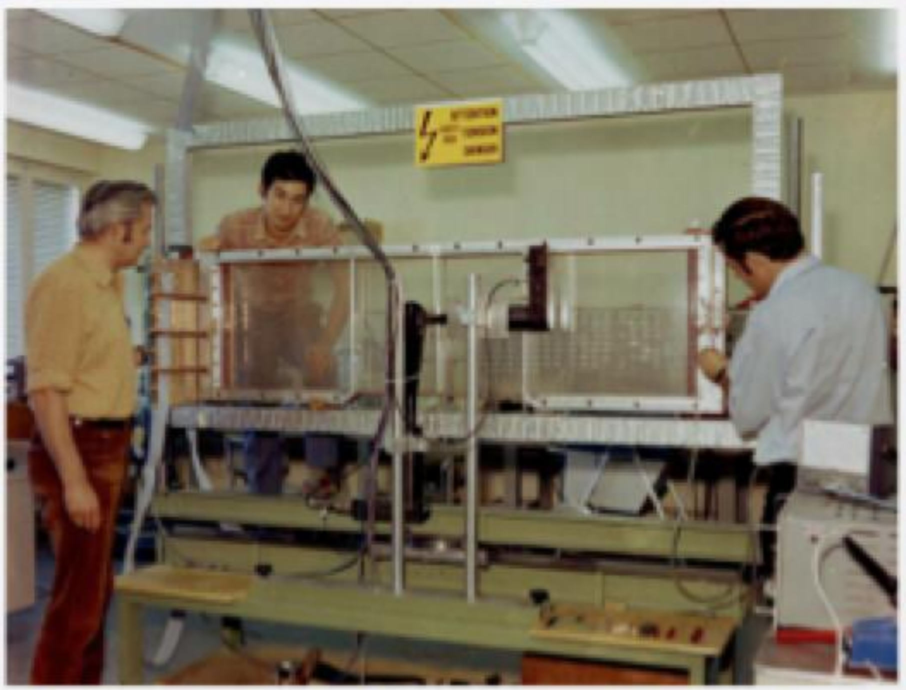


- Our Roots back to ‘triggerless DAQ ’



MWPC

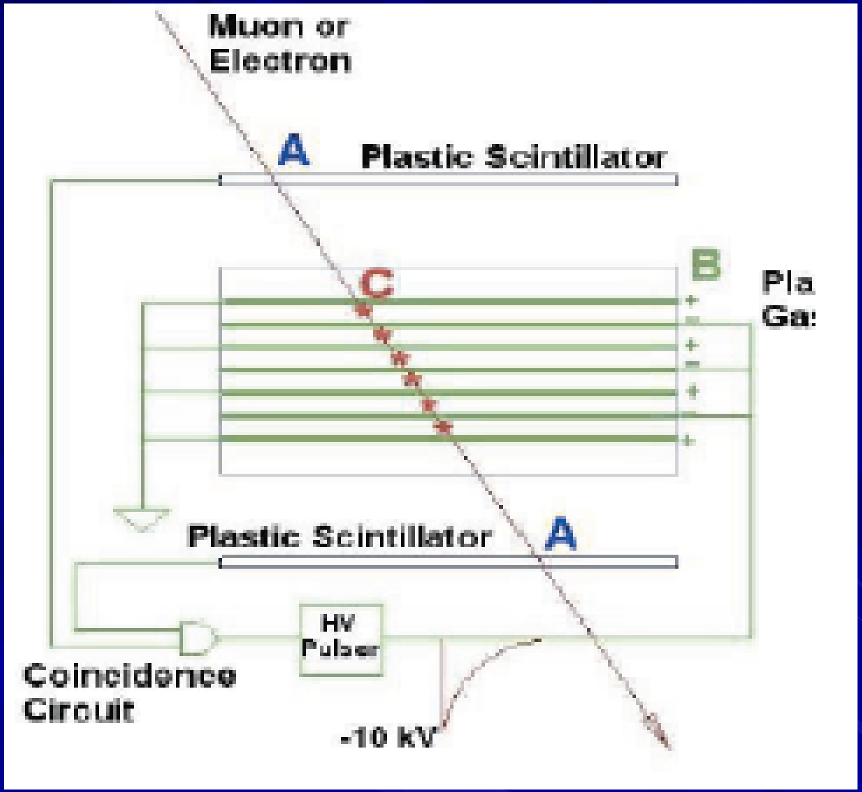
- **Multi Wire Proportional Chamber (MWPC)(1968 by Georges Charpak, Nobel Prize 1992)**
- Extends the concept of the Geiger-Muller to many wires with short distance between two parallel plates



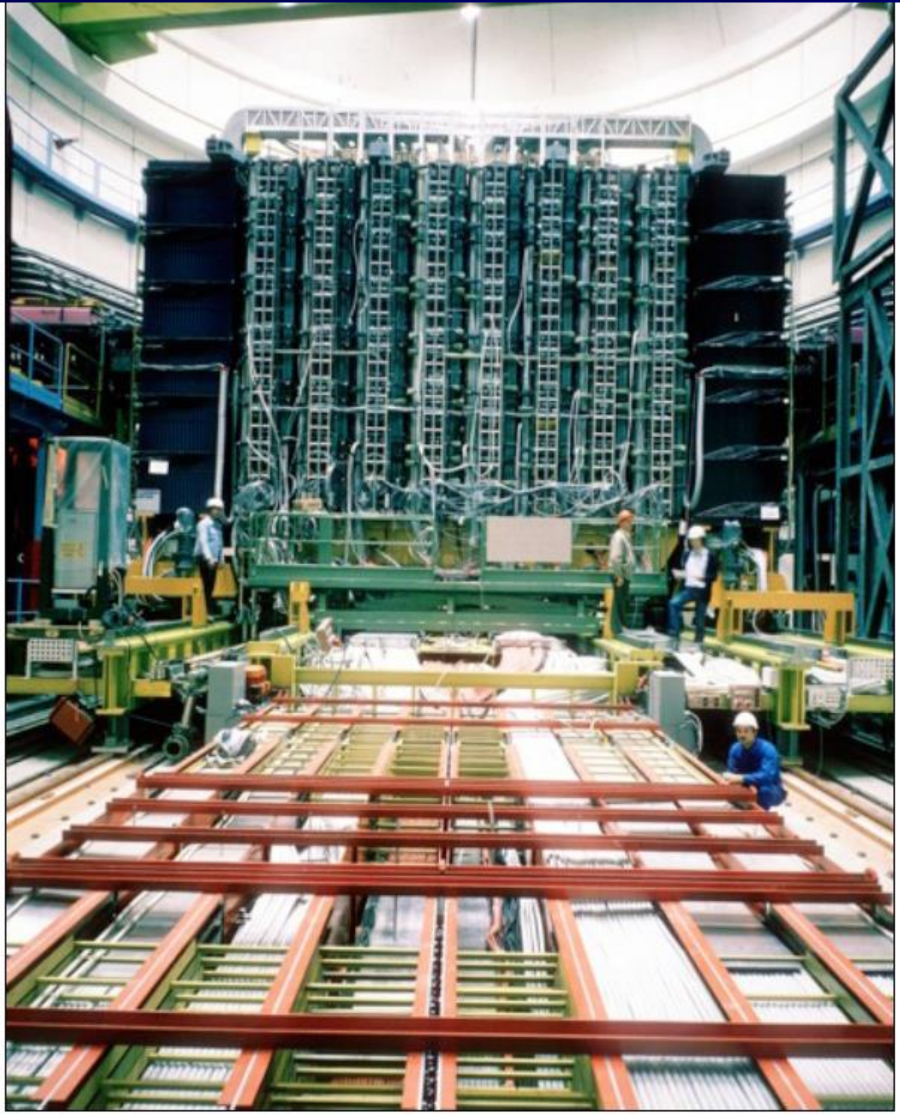
G. Charpak, F. Sauli and J.C. Santiard

Spark Chamber

- Developed early 60's
- Swartz,Steiberger and Lederman using it in discovery of the muon neutrino
- A charged particle traverse the detectro and leaves an ionization trail.
- The scintillator trigger and HV pulse between the metal plates and sparks form in the place where ionization took place



the early Electronics image



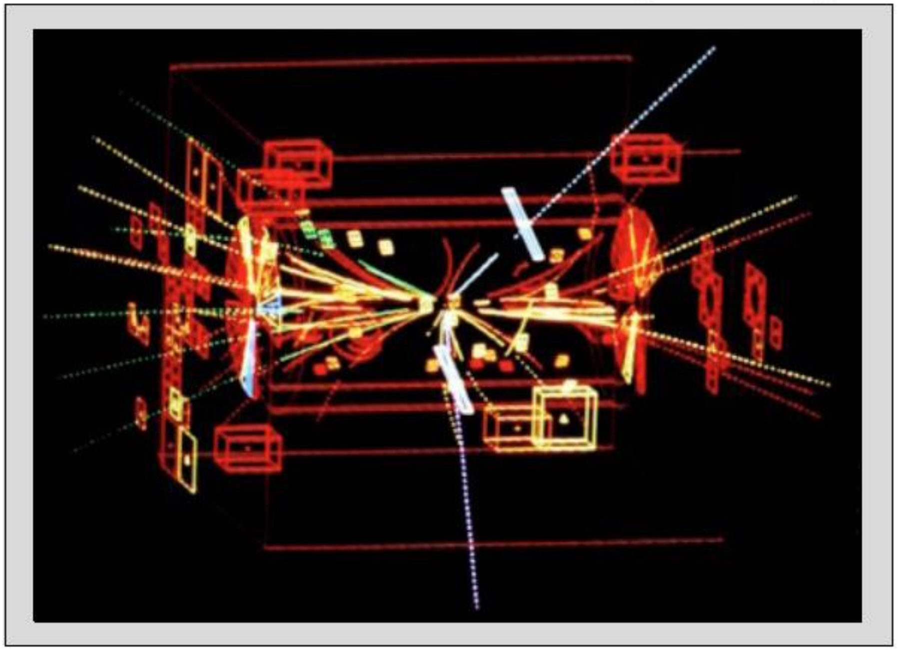
UA1
Detector

Discovery of the W/Z boson (1983)

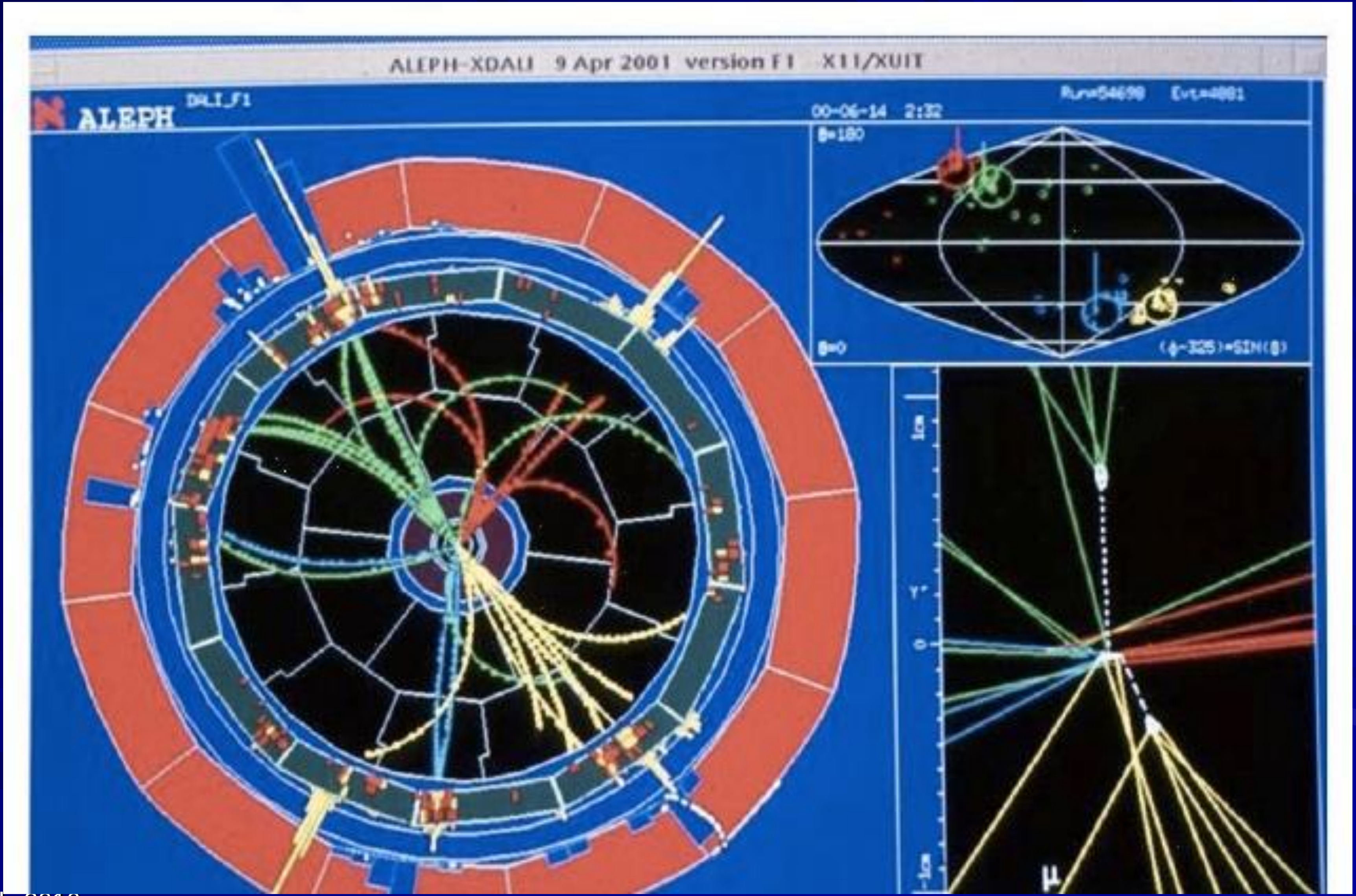
Carlo Rubbia
Simon Van der Meer

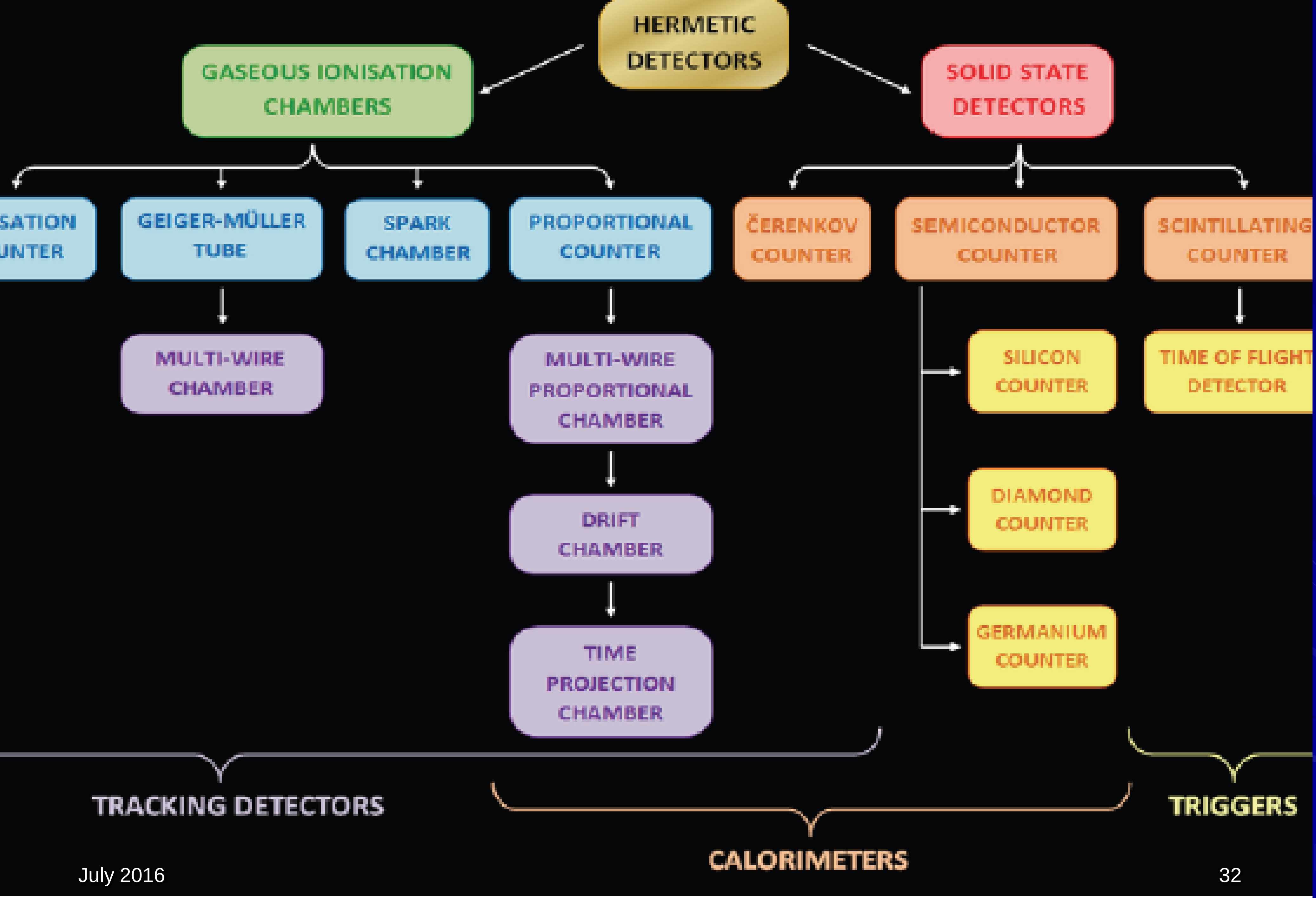
[Nobel prize 1984]

First Z^0 particle seen by UA1



Aleph HZ → bb g candidate





HERMETIC DETECTORS

GASEOUS IONISATION CHAMBERS

SOLID STATE DETECTORS

SATION UNTER

GEIGER-MÜLLER TUBE

SPARK CHAMBER

PROPORTIONAL COUNTER

ČERENKOV COUNTER

SEMICONDUCTOR COUNTER

SCINTILLATING COUNTER

MULTI-WIRE CHAMBER

MULTI-WIRE PROPORTIONAL CHAMBER

DRIFT CHAMBER

TIME PROJECTION CHAMBER

SILICON COUNTER

DIAMOND COUNTER

GERMANIUM COUNTER

TIME OF FLIGHT DETECTOR

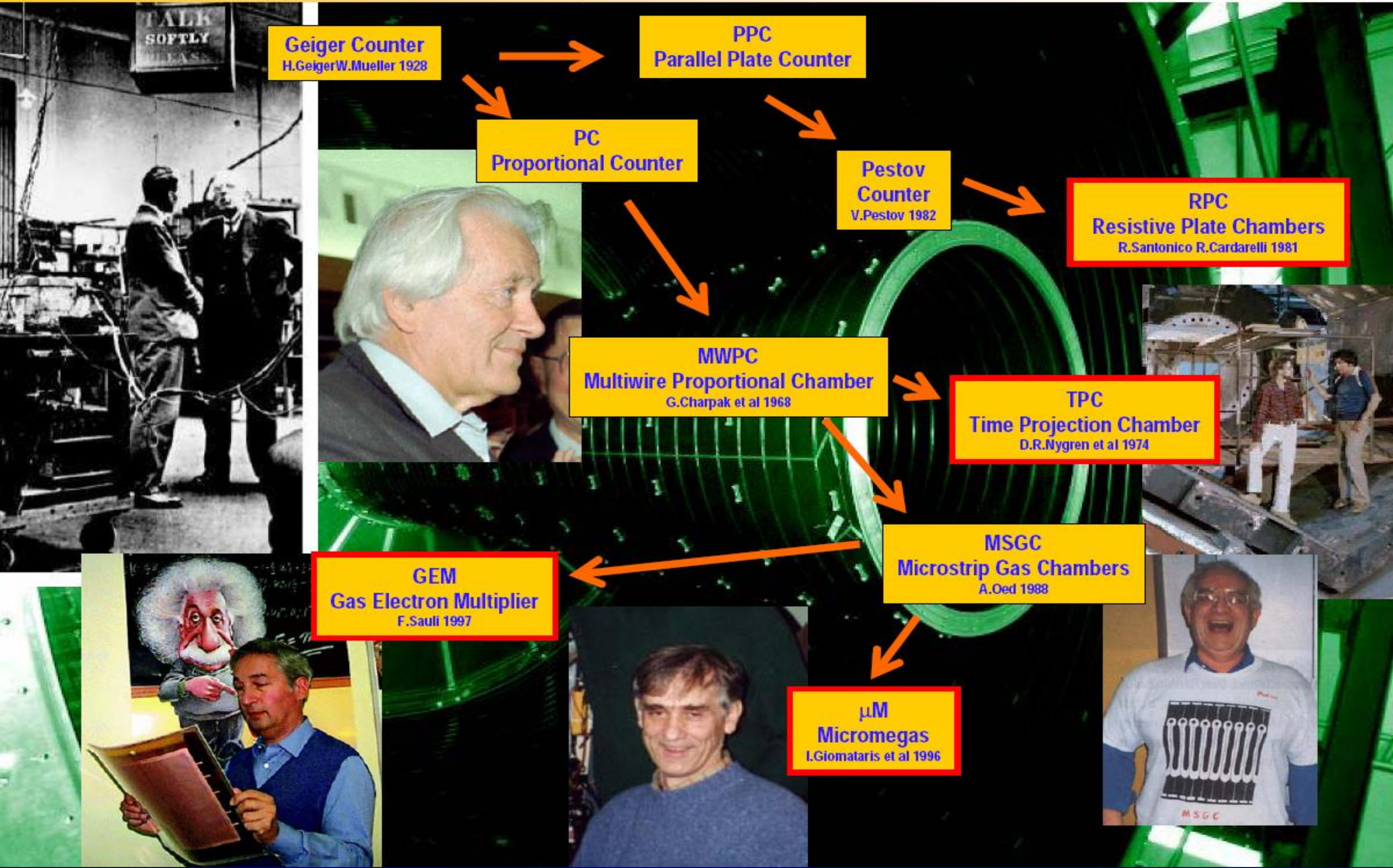
TRACKING DETECTORS

CALORIMETERS

TRIGGERS

Gazeous detector

Gas Detector History



Geiger Counter
H.GeigerW.Mueller 1928

PPC
Parallel Plate Counter

PC
Proportional Counter

Pestov Counter
V.Pestov 1982

RPC
Resistive Plate Chambers
R.Santonico R.Cardarelli 1981

MWPC
Multiwire Proportional Chamber
G.Charpak et al 1968

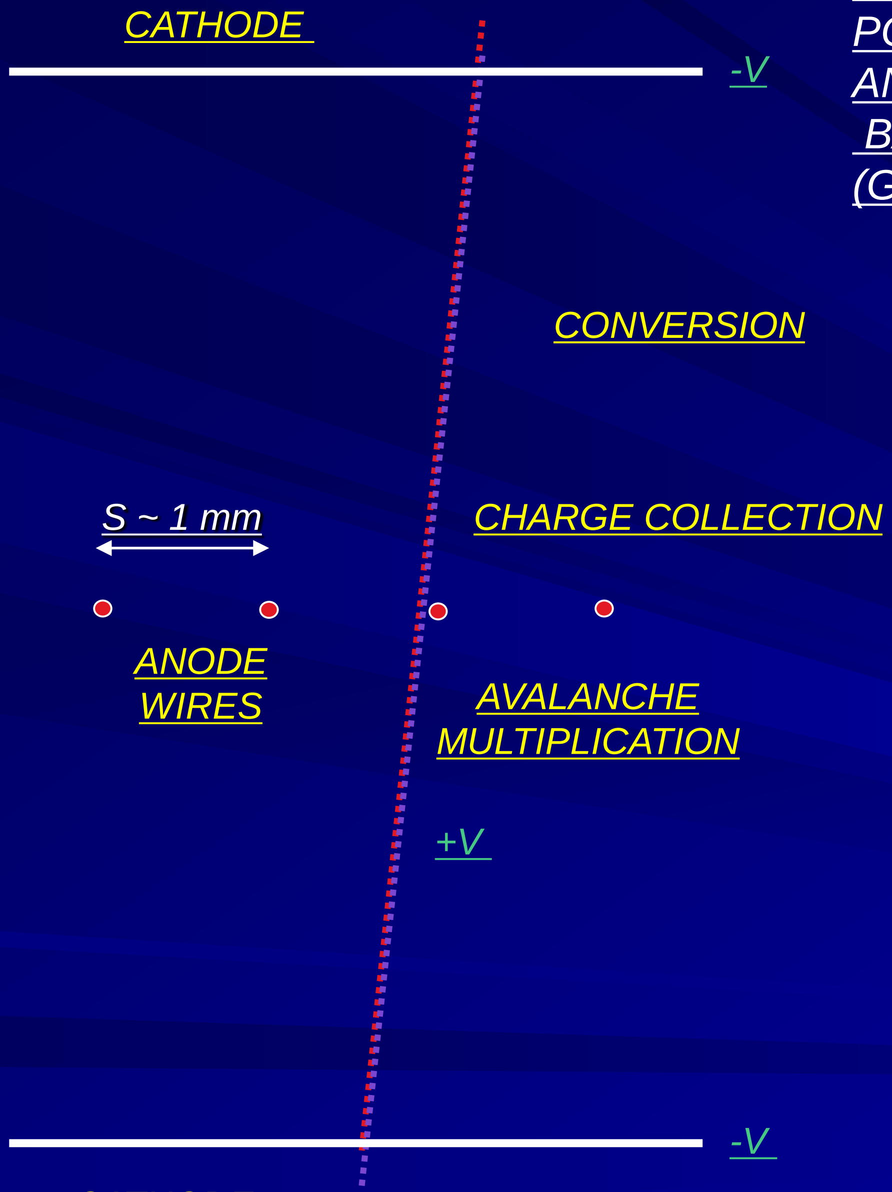
TPC
Time Projection Chamber
D.R.Nygren et al 1974

MSGC
Microstrip Gas Chambers
A.Oed 1988

GEM
Gas Electron Multiplier
F.Sauli 1997

μM
Micromegas
I.Giomataris et al 1996

Multi Wires Proportional chambers MWPC



CATHODE

-V

CONVERSION

S ~ 1 mm

CHARGE COLLECTION

ANODE
WIRES

AVALANCHE
MULTIPLICATION

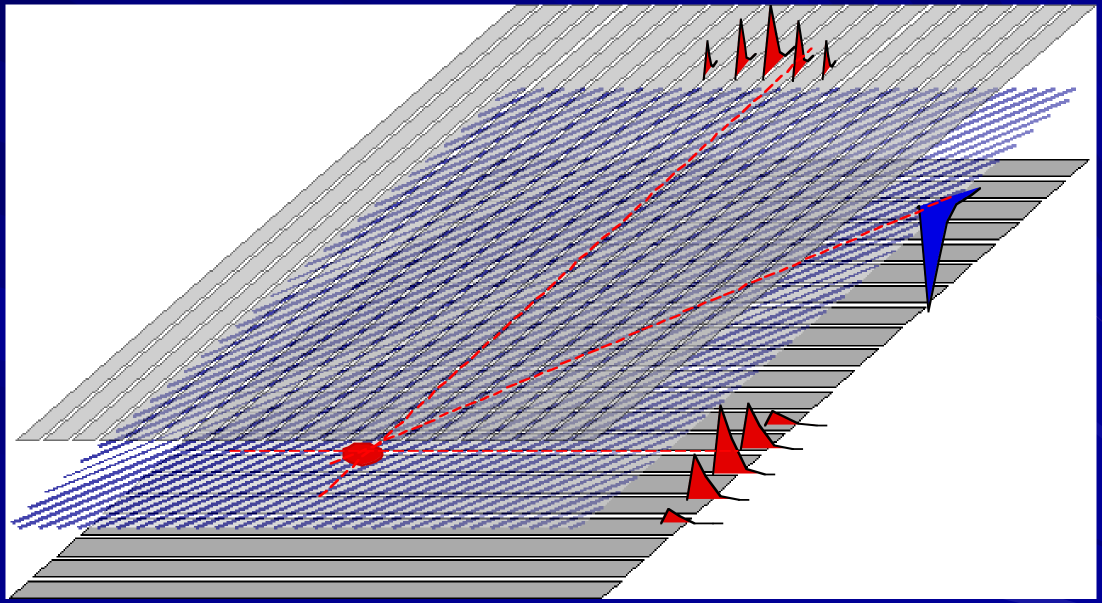
+V

-V

CATHODE

MODERN GASEOUS DETECTORS:
POWERFUL TOOLS FOR RADIATION DETECTION
AND LOCALIZATION IN PARTICLE PHYSICS,
BASED ON THE MULTIWIRE PROPORTIONAL CHAMBER
(Georges Charpak, 1967)

TWO-DIMENSIONAL MWPC READOUT CATHODE INDUCED CHARGE (Charpak and Sauli, 1973)

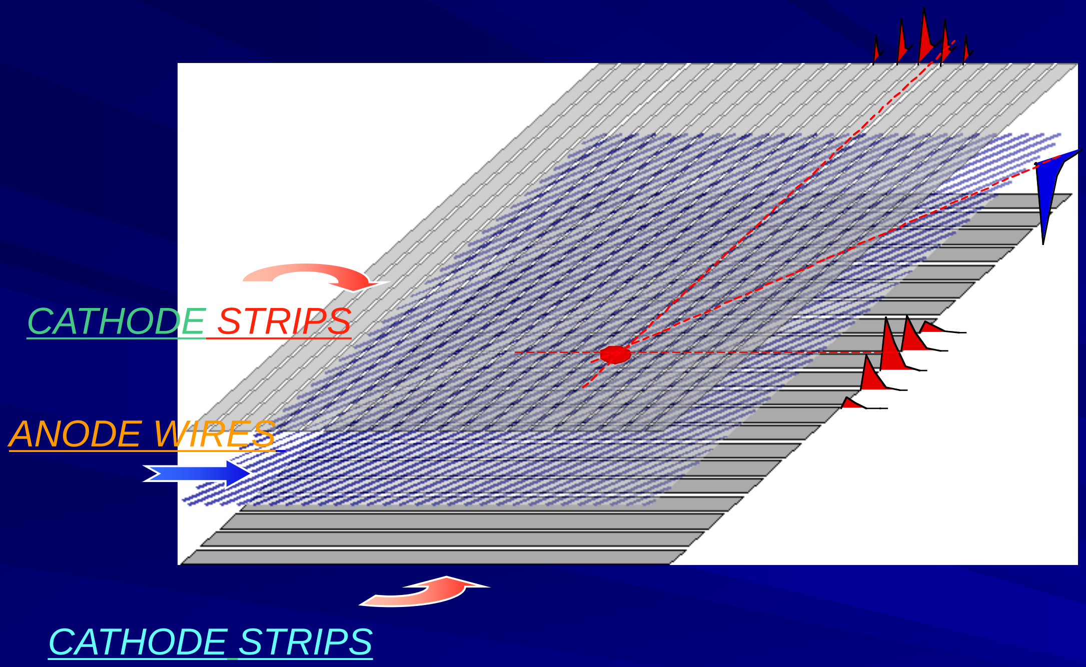


Spatial resolution determined by: Signal / Noise Ratio
Typical (i.e. 'very good') values: S ~ 20000 e: noise ~ 1000e
Space resolution < 100 μm

E. Gatti et al, Optimum geometry for strip cathodes ... , Nucl. Instr. and Meth. 163(1979)83

TWO-DIMENSIONAL LOCALIZATION

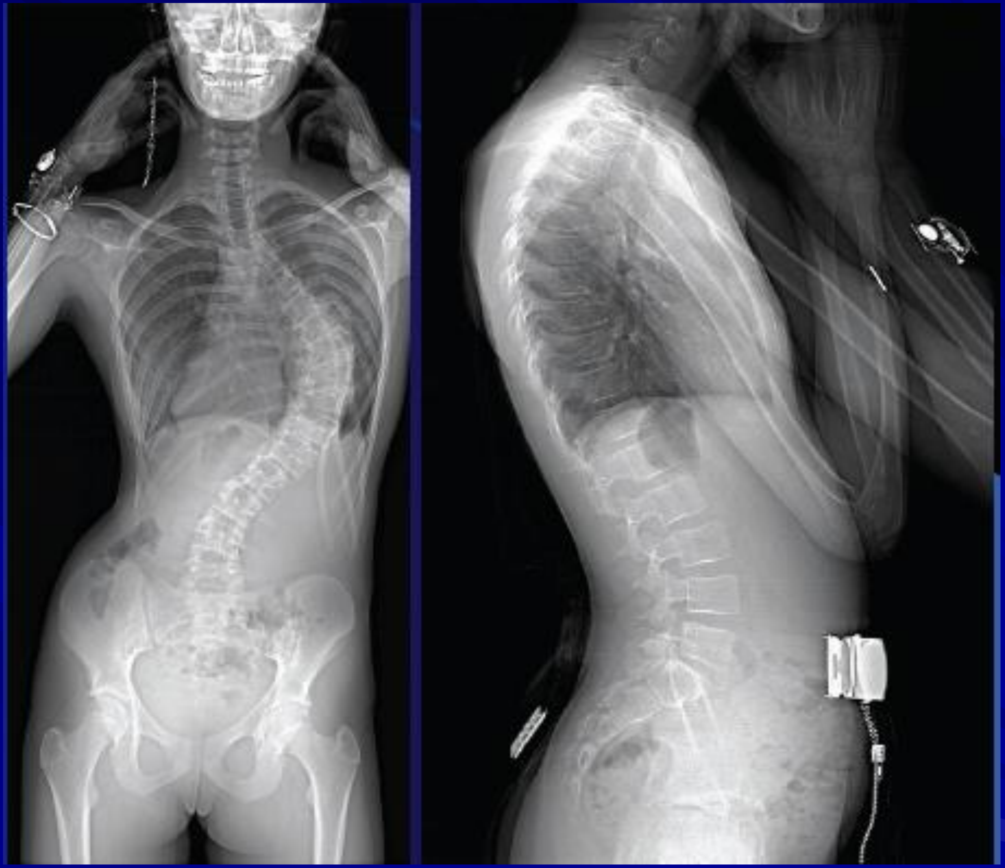
TWO-DIMENSIONAL LOCALIZATION FROM SIGNALS INDUCED ON CATHODE PLANES (Charpak & Fabio Sauli, ~1973)



LOW-DOSE DIGITAL RADIOGRAPHY
WITH MWPC:
CHARPAK’S HAND (2002):

The 1970's dream : Digital radiography with MWPC A tribute to George Charpak

- With 10 time less dose

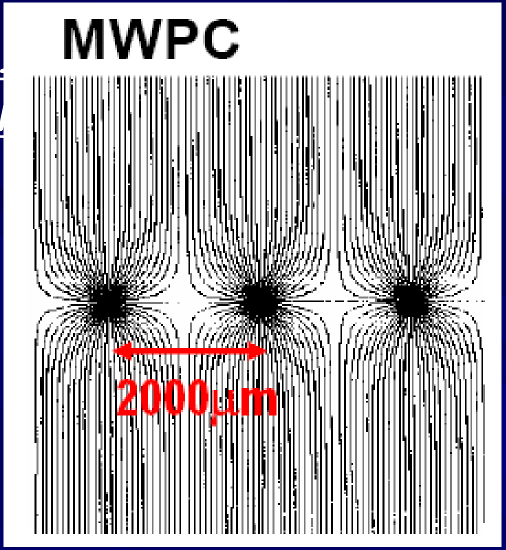


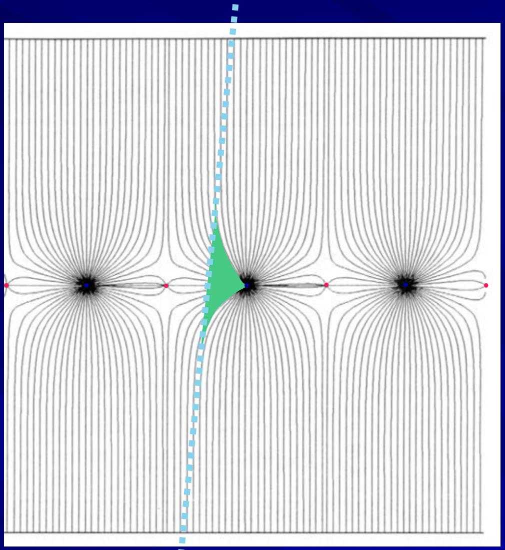
From MWPC's to MGPD's

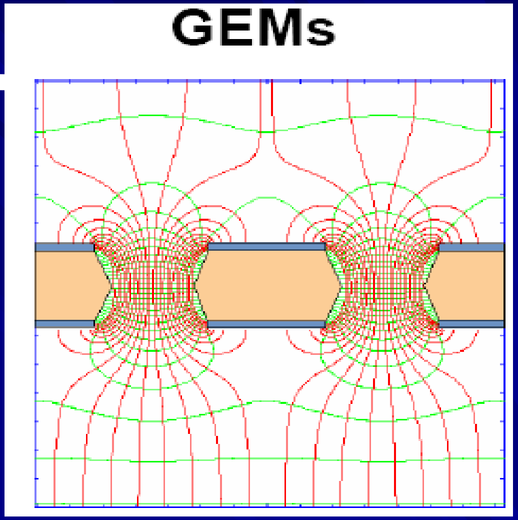
MGPD

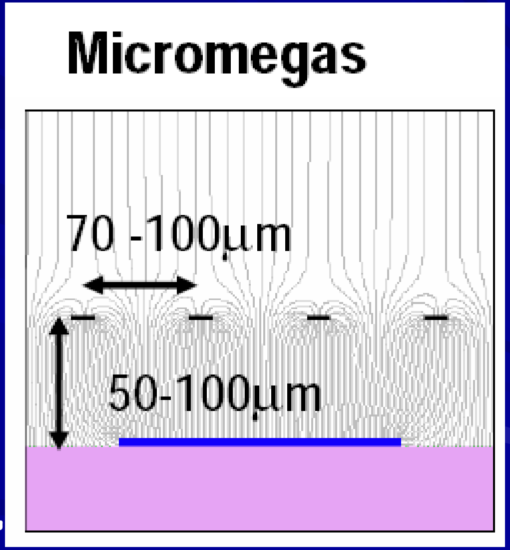
MWPC

Drift Chamber









1975 - 1995
UA2-LEP

1990 -

Multiwire Proportional Chamber

Georges Charpak 1968

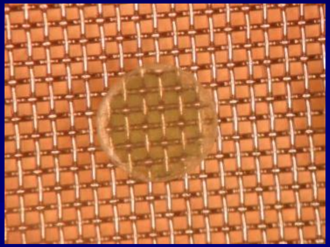
GEM F.Sauli)
Micromegas Y. Giomataris

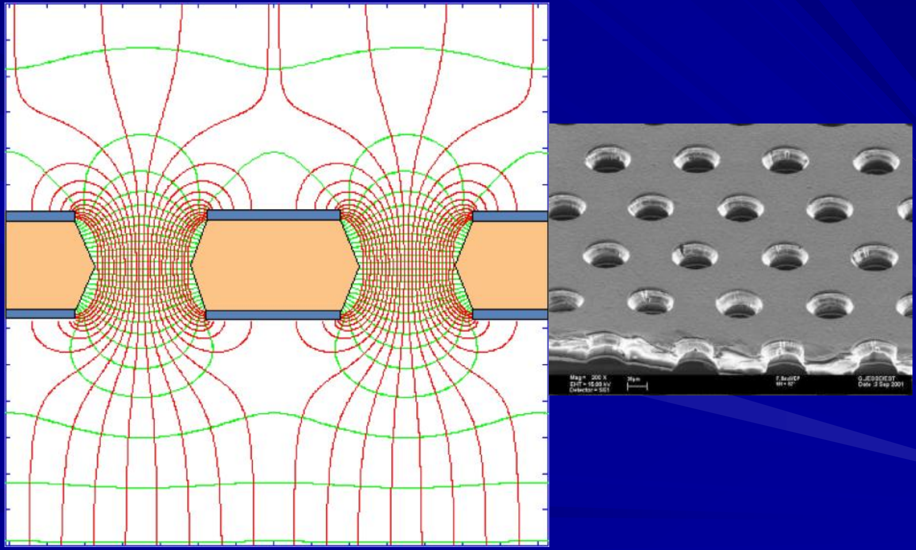
MPGD

- From 1988-1998 Micro-technologies and etching techniques allowed development of Micro Patter Gaseous Detectors

- MICROMEsh GAseous Structure
  - Thin gap Parallel Plate Chamber: micromesh stretched over readout electrode.

- Gas Electron Multiplier
  - Thin, metal-coated polymer foil with high density of holes, each hole acting as an individual proportional counter.

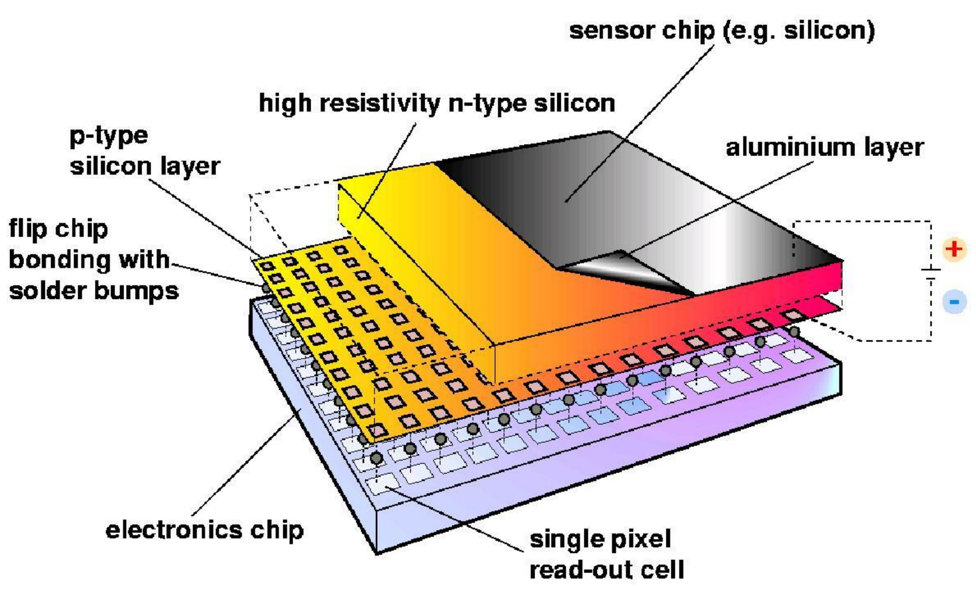


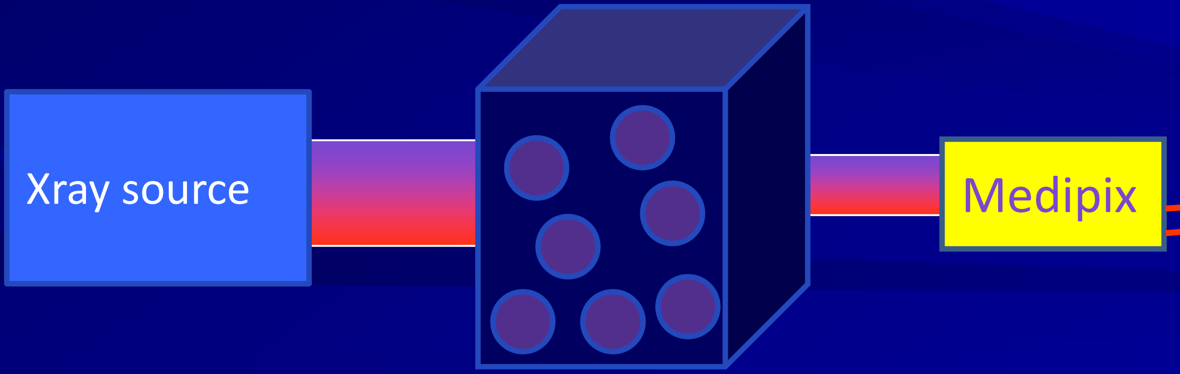


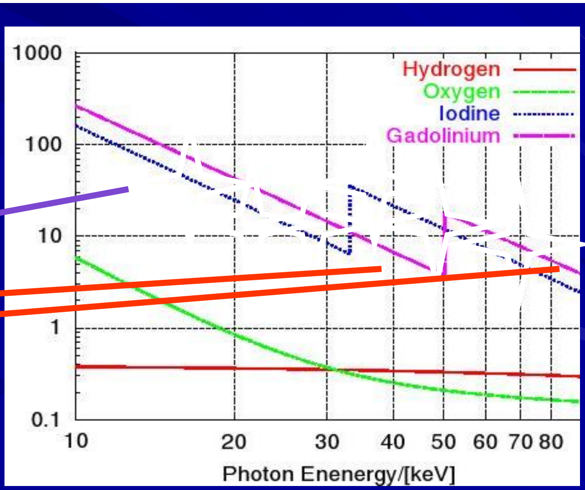
The Future : New Si detector and signal processing
On the way to photon counting?

Medipix3

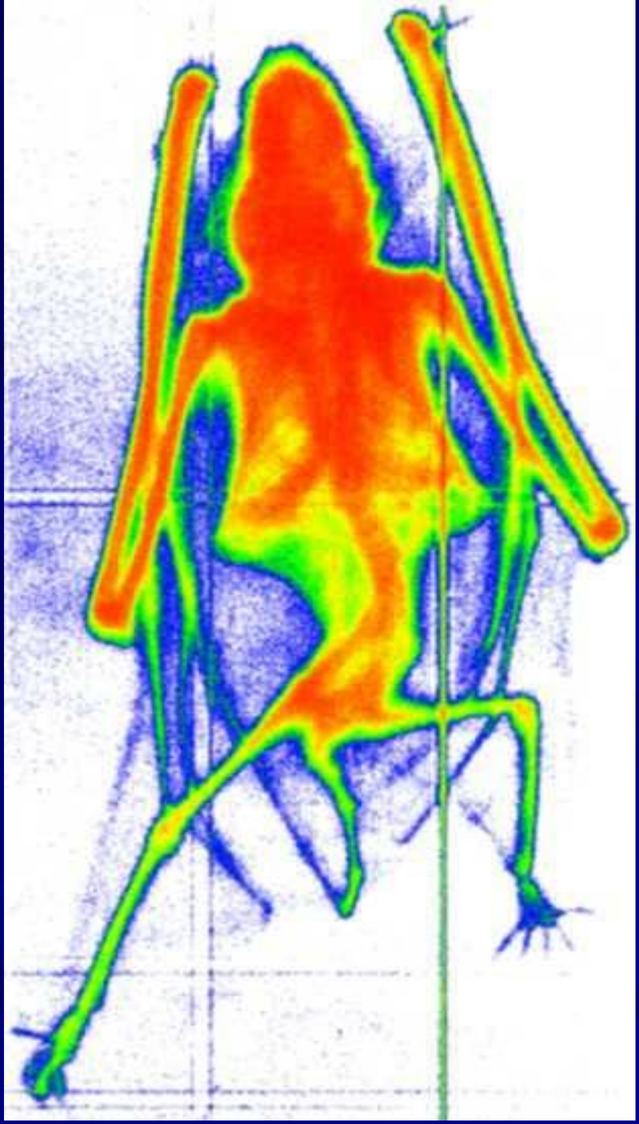
- 8 simultaneous energies
- 55 µm isometric resolution
- Excellent energy resolution
- 10^8 photons per second per mm^2





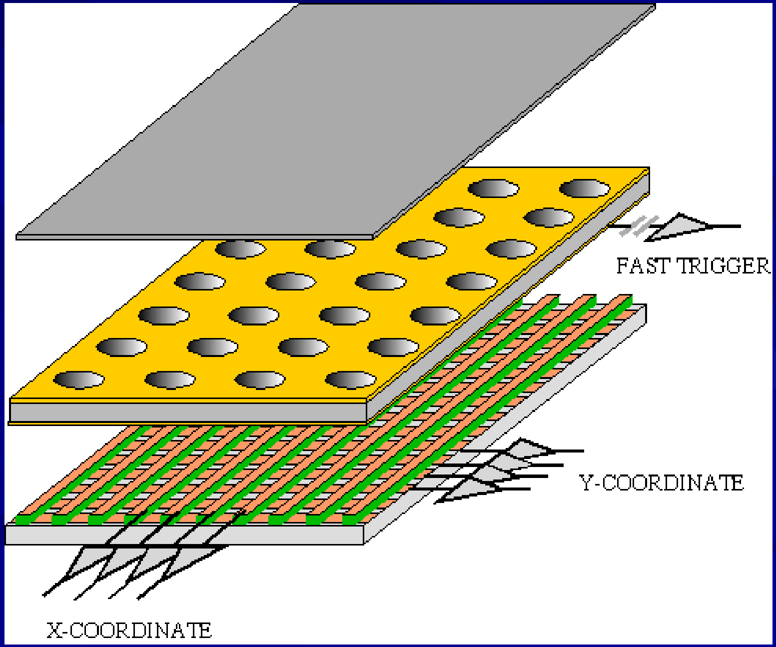


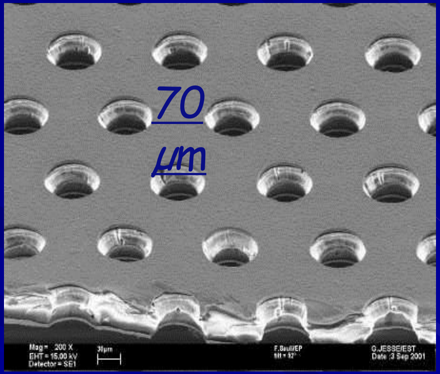
Exemple with GEM Detector



F.Sauli & al.

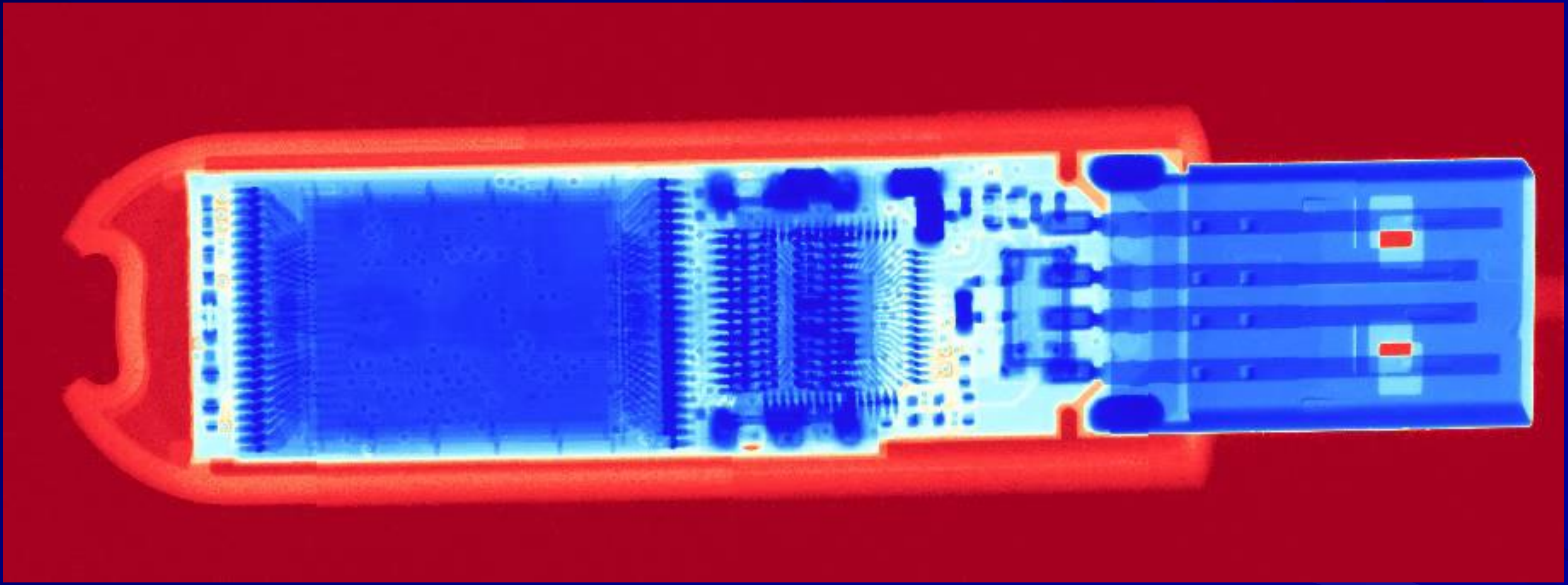
- Thin, metal-clad polymer foil, chemically pierced by a high density of holes (70-80 µm diameter).
- On application of a difference of potential between the two electrodes, electrons released by radiation in the gas on one side of the structure drift into the holes, multiply and transfer to a collection region.
- Cascading several foils results in high multiplication factors.





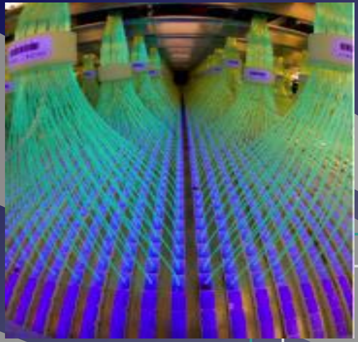
Medipix-CT setup for detector investigations & material analysis

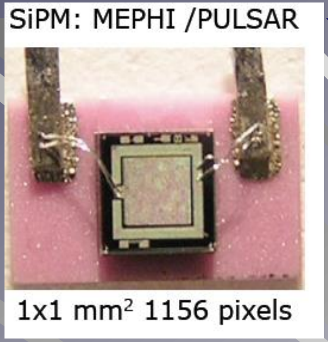
Example → USB flash drive



TPX 110μm + CdTe 2mm
8x2 tiles / mag. 1.5x
65kV / 200μA

Example





T2K
scintillators
WLS fiber
60000 SiPM

Belle2 RICHs
single γ

ILC - CALICE
8×10^6 SiPM

CMS HCAL
2 $\times10^3$ SiPM

Photon detectors

A survey of common areas

LSO

- Material for photon detection
  - Standard : Crystal
    - From L3 BGO , CMS PbO4 --> Crystal Clear Coll.
  - Possible alternatives: LXenon, MG-RPC's … ????

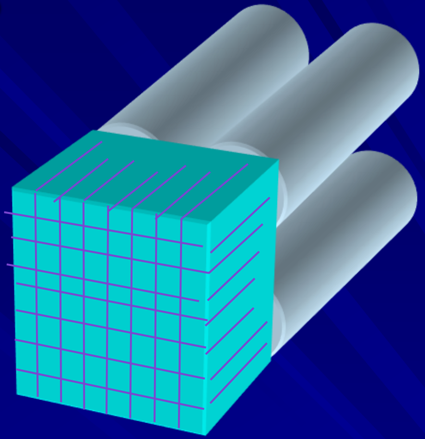
- Photon detectors :

compact, high QE, high gain and stability

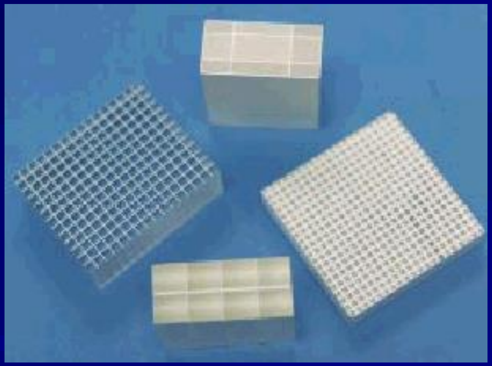
  - Standard : PMT ---> MAPMT --> MCP
  - Semiconductor : APD --> SiPM/MPPC,DSiPM

Detectors → crystals

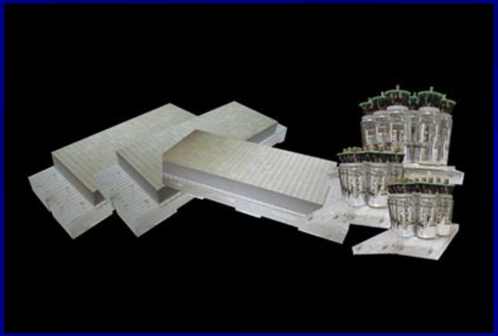
NaI curved
CPET (Philips)



Detection block
Crystals 4x4x20 (or 30) mm^3
Block 8 x 8 crystals , 2 x 2 PM's

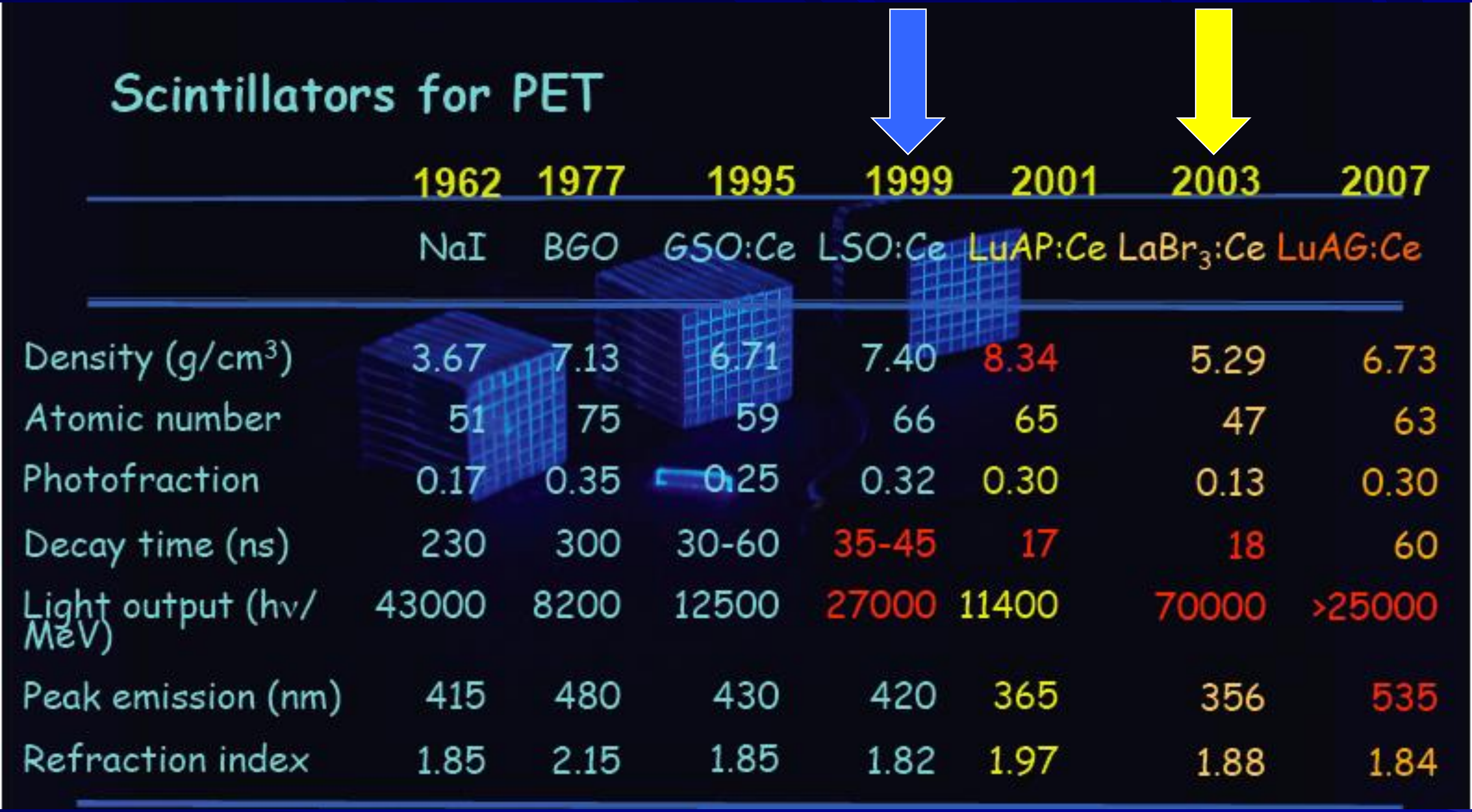


GEMS
BGO (Bicron)



ADAC Philips
GSO

CTI Siemens
LSO



Scintillators for PET

	1962	1977	1995	1999	2001	2003	2007
	NaI	BGO	GSO:Ce	LSO:Ce	LuAP:Ce	$LaBr_3$:Ce	LuAG:Ce
Density (g/cm^3)	3.67	7.13	6.71	7.40	8.34	5.29	6.73
Atomic number	51	75	59	66	65	47	63
Photofraction	0.17	0.35	0.25	0.32	0.30	0.13	0.30
Decay time (ns)	230	300	30-60	35-45	17	18	60
Light output (hν/MeV)	43000	8200	12500	27000	11400	70000	>25000
Peak emission (nm)	415	480	430	420	365	356	535
Refraction index	1.85	2.15	1.85	1.82	1.97	1.88	1.84

No Scintillator with Superior Properties in *All* Aspects

Scintillator Requirements

- *Stopping power*
  - *High Z material*
  - *High density*
- *Photoelectric fraction*
  - *High photoelectric cross section to total cross section*
  - *High Z material*
- *Signal to Noise Ratio*
  - *High luminosity*
- *Fast timing (required for TOF)*
  - *High luminosity*
  - *Short decay time*

Photodetectors

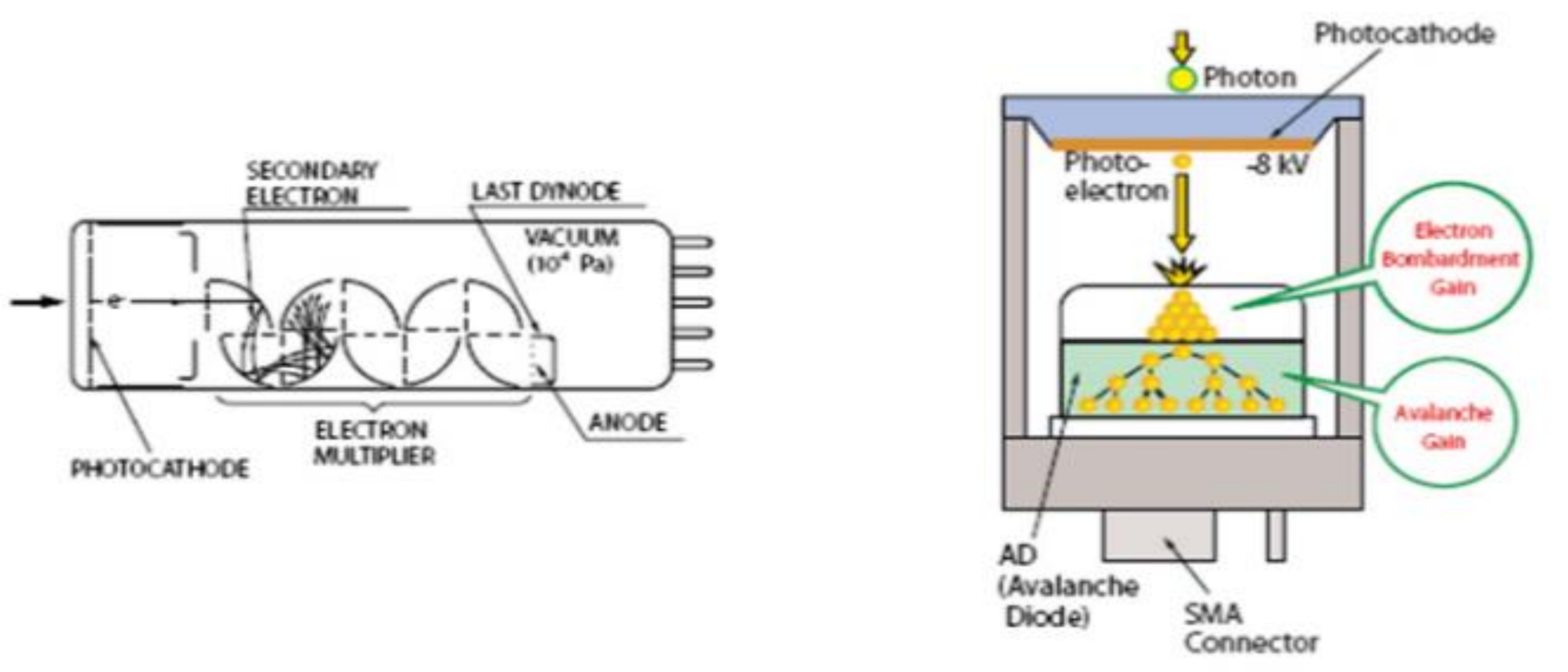
From the gazeous world to the silicon world

Photodetector Requirements

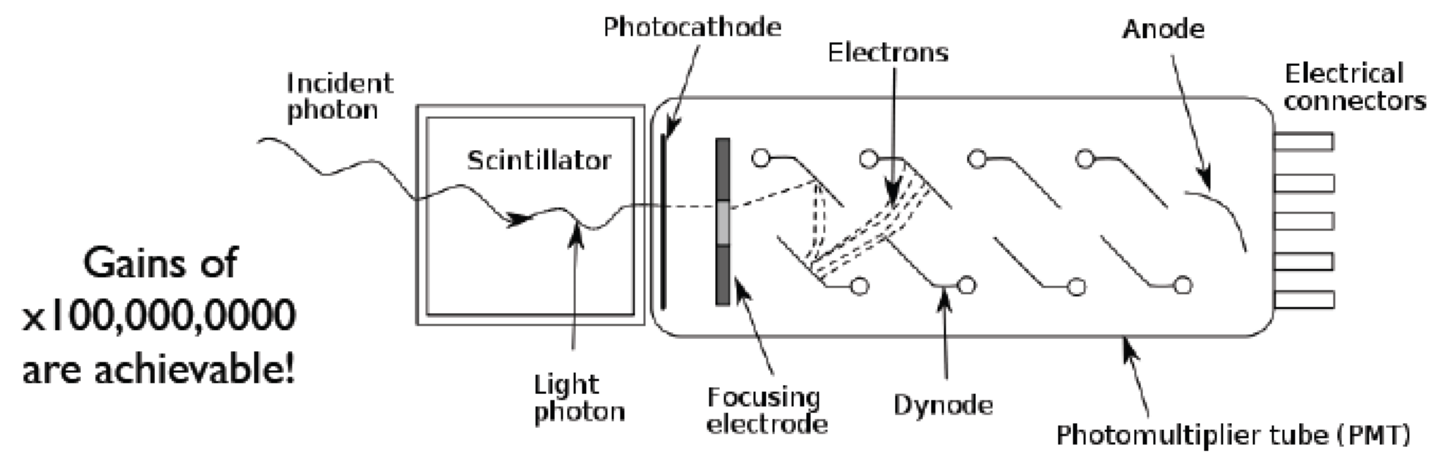
- Required:
  - High gain
  - High photon detection efficiency
  - Low noise
  - Fast response
  - Large detection area
  - Low cost

- Application-Specific:
  - Compact
  - Very fast response
  - Insensitive to magnetic field

Photomultiplier → The Principle



Vacuum Photomultiplier Tubes (2)



Use since 75 years

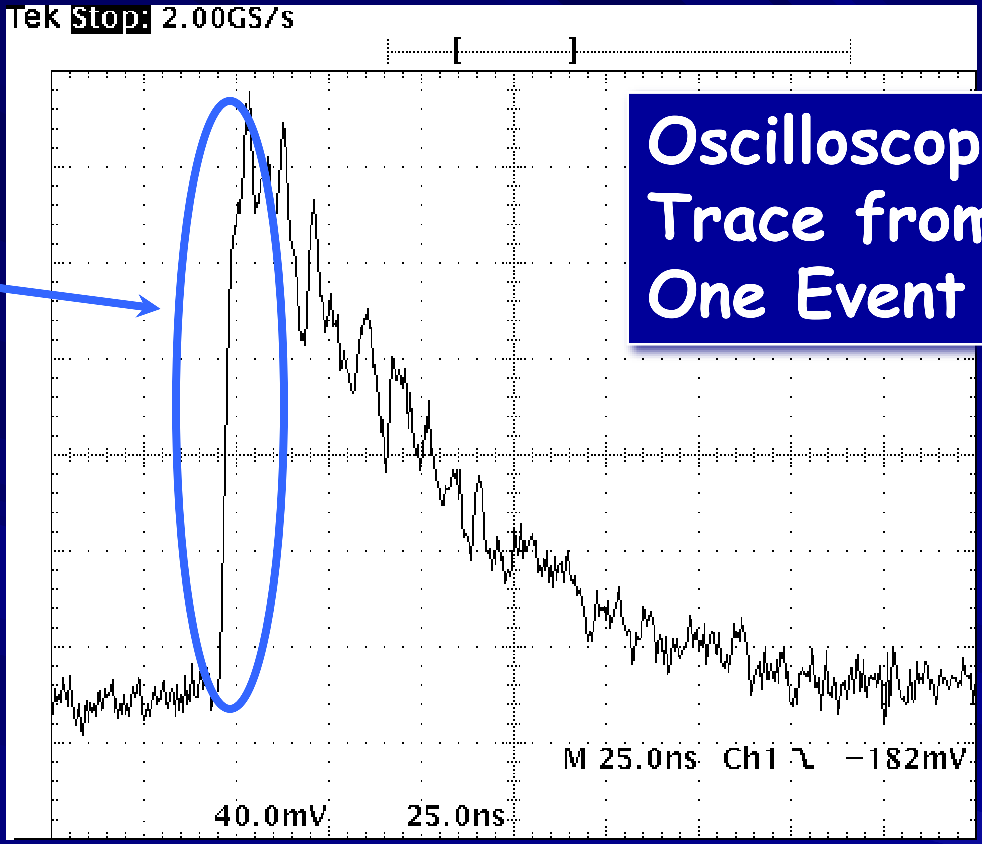
Advantages:

- •High gain (10^6 to 10^7)
- •QE approaching 30−40% with SBA, UBA photocathode (typically ~25%)
- •Low noise, capable of detecting single photoelectron
- •Low excess noise factor (1.05 to 1.5)
- •Fast response (~1 ns rise time)
- •Position-sensitive tubes available
- •Large active area available
- •Low cost per unit area for large sizes

Drawbacks:

- Bulky
- **Vacuum** tube technology
- Sensitive to magnetic field

Raw Signal From Photomultiplier Tube

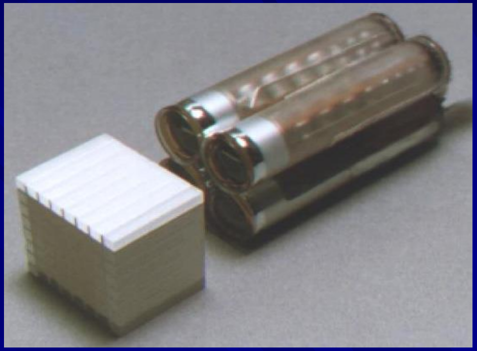


Important Region for Timing

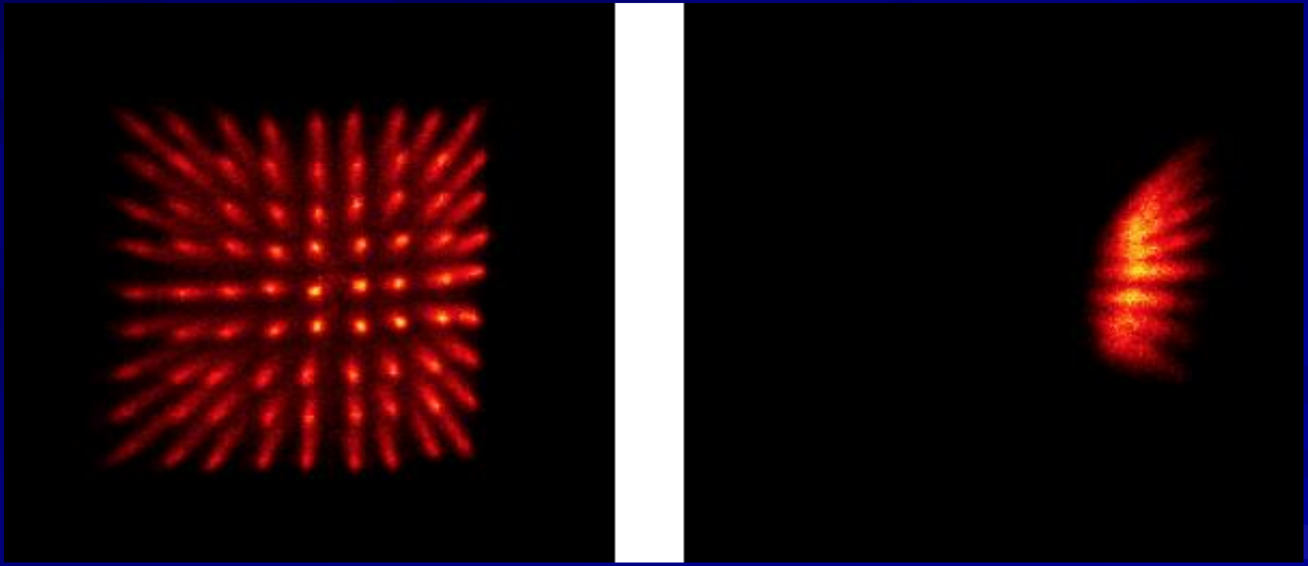
Oscilloscope Trace from One Event

- Small Fraction of Scintillation Light in Leading Edge
- Fundamental Limit Due to Statistical Fluctuations

Effect of PMT Inside Magnetic Field



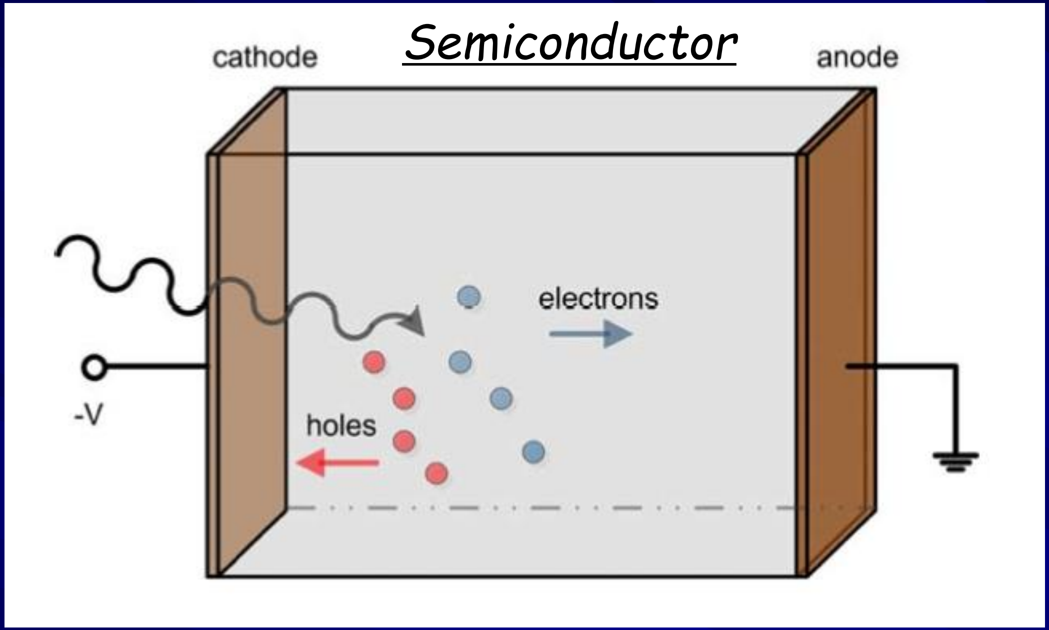
Conventional PET Detector Block

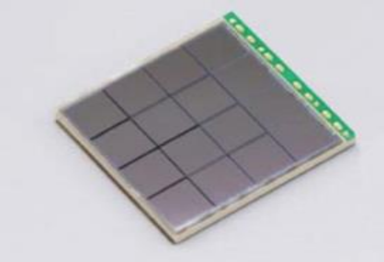


B=0 B≠0

PMT does not work inside magnetic field!!

The solid state photodetector





- *Electric field is created by an applied bias voltage*
- *e-h pairs are created by incoming radiation*
- *Electrons move to the anode and holes move to the cathode*
- *Electrical signal is induced on the electrodes by the moving charges*

Photodiode (PIN)
Avalanche Photodiode (APD)
Silicon Photomultiplier (SiPM)
CdZnTe
CdTe/

Silicon Photodetectors: APD (1990's)

- Advantages:
  - Internal gain
  - High QE (>70% for 400-600 nm)
  - Low bias voltage
  - Compact and robust
  - Small pixels, individual coupling
  - Insensitive to magnetic field

Invented by. McIntyre (GE)

CMS

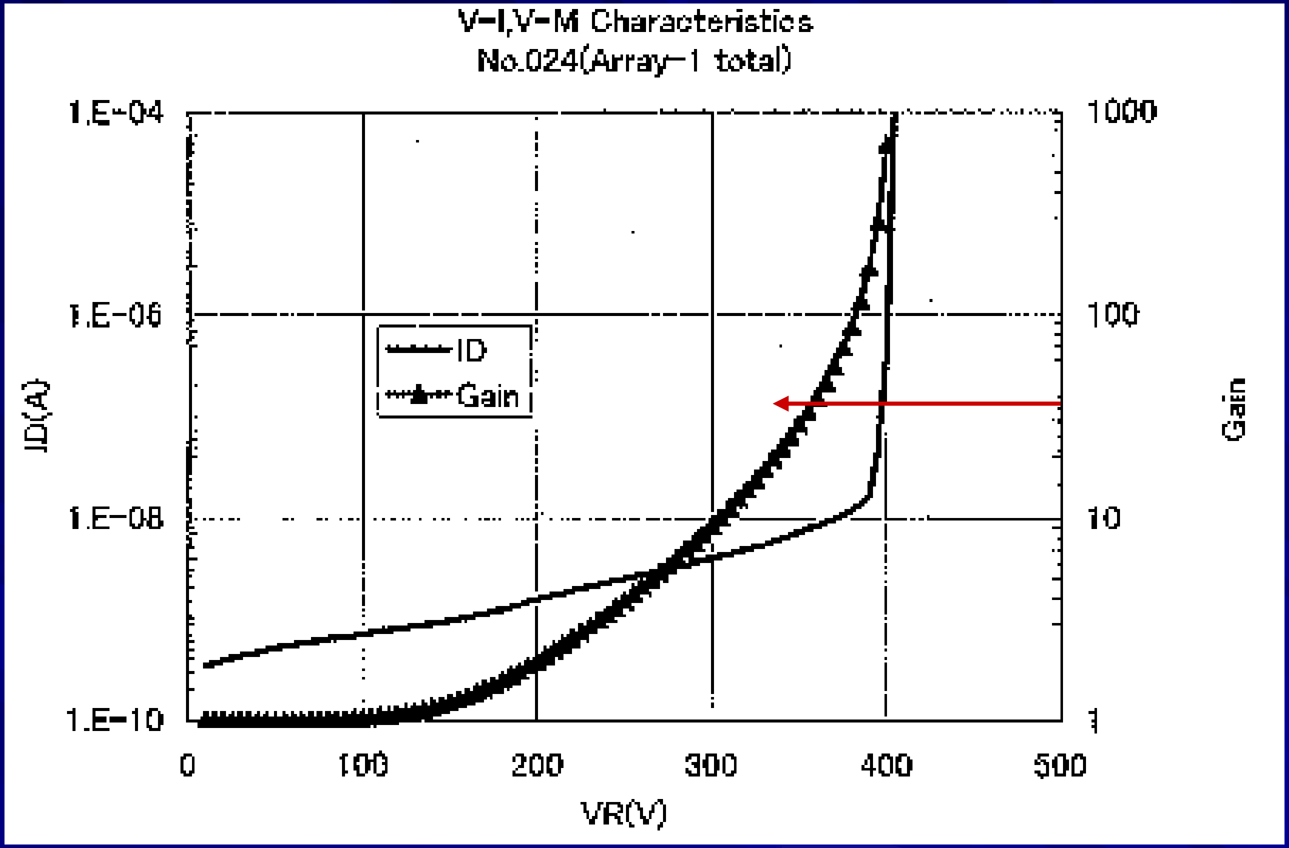
Hamamatsu single channel APD

- Drawbacks
  - Modest gain ($\sim 10^2$ vs 10^6 for PMT)
  - Gain sensitive to temperature and voltage fluctuations
  - Slow response
  - *High excess noise factor*

Need better solid-state photodetector

APD's

Used in CMS 200K Channels



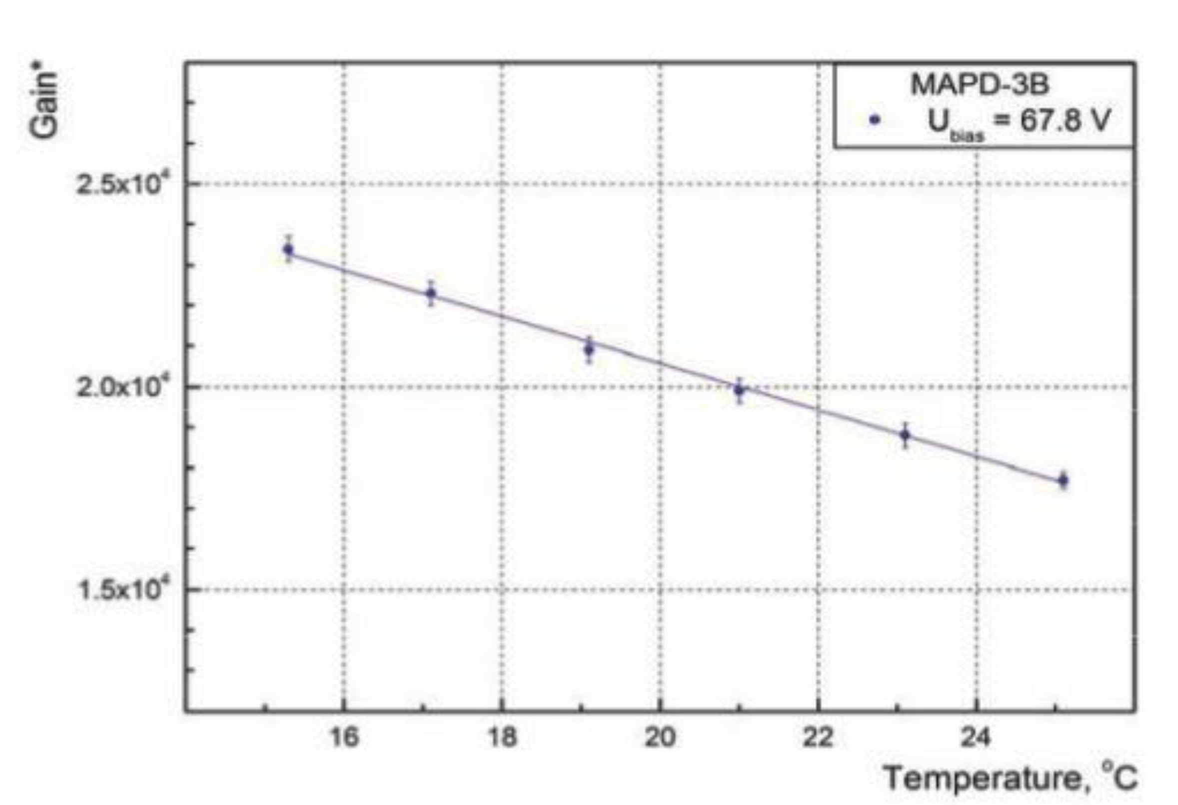
Hamamatsu S8550

4x8 array
1.6×1.6 mm^2
active pixel area
$C_T \sim 10$ pF

Typical G ~ 50
$N_{pe} \sim 1200$
~ 60K signal electrons

Expected noise in final ASIC ~ 500-600 e's

Temperature dependence

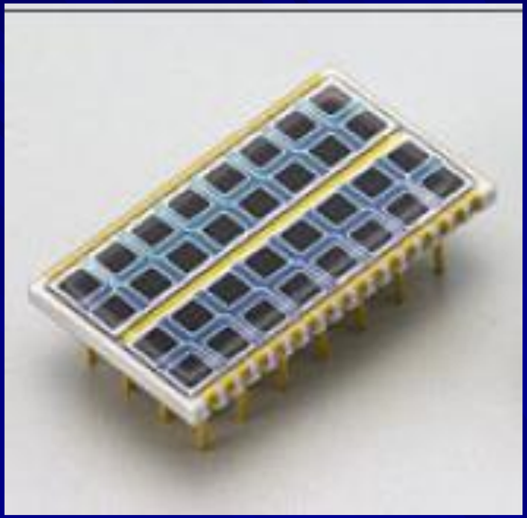


Gain is typically strongly dependent on temperature

Noise is inversely proportional to temperature

Implication is that GM-APDs should be temperature stabilized for most imaging applications (i.e., active cooling system)

Silicon photodetectors : SiPM (2005)



Advantages:

- High QE (>70% for 400−600 nm)
- APD operating in Geiger mode
- High internal gain ($10^5 - 10^6$)
- Very fast response (~100 ps rise time)
- Capable of detecting single photoelectron
- Insensitive to magnetic field

Drawbacks:

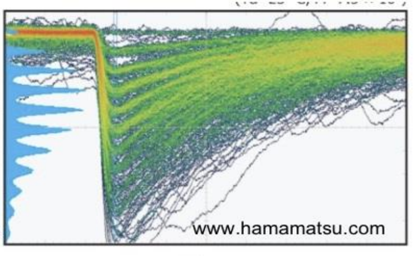
- Modest Geometric fill factor (20-40%)
- Limited micro-cell => limited dynamic range

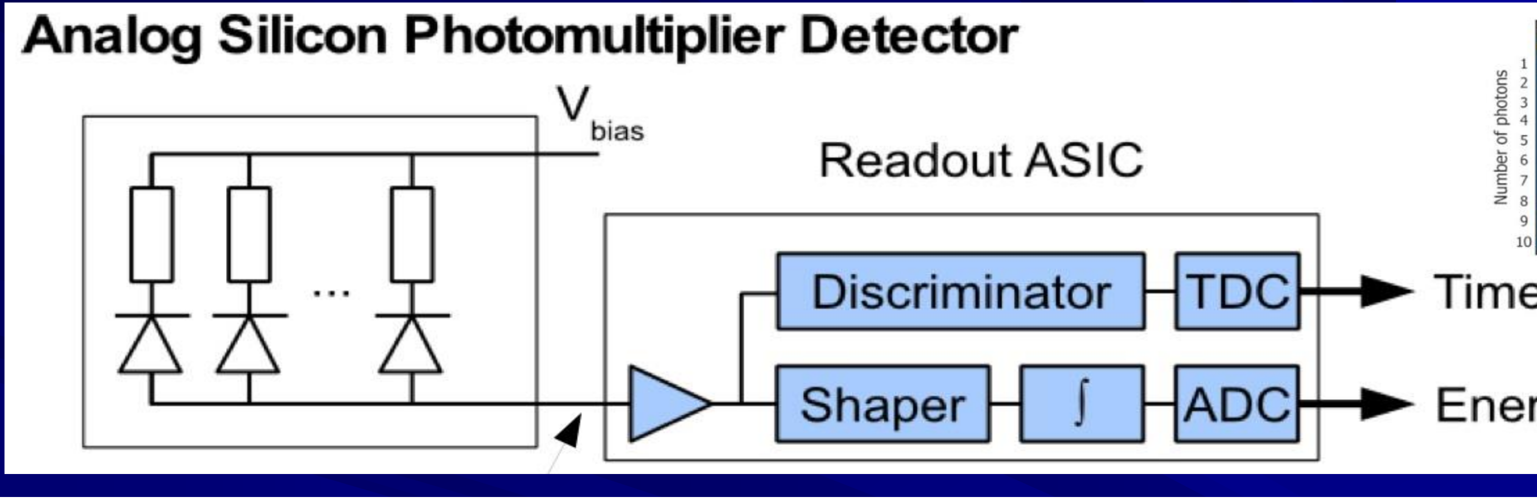
Sensitive to temperature and voltage fluctuations in analog mode, but not in purely digital mode

- Cross-talk and after-pulses issues

Digital SiPM detectors (PDPC)

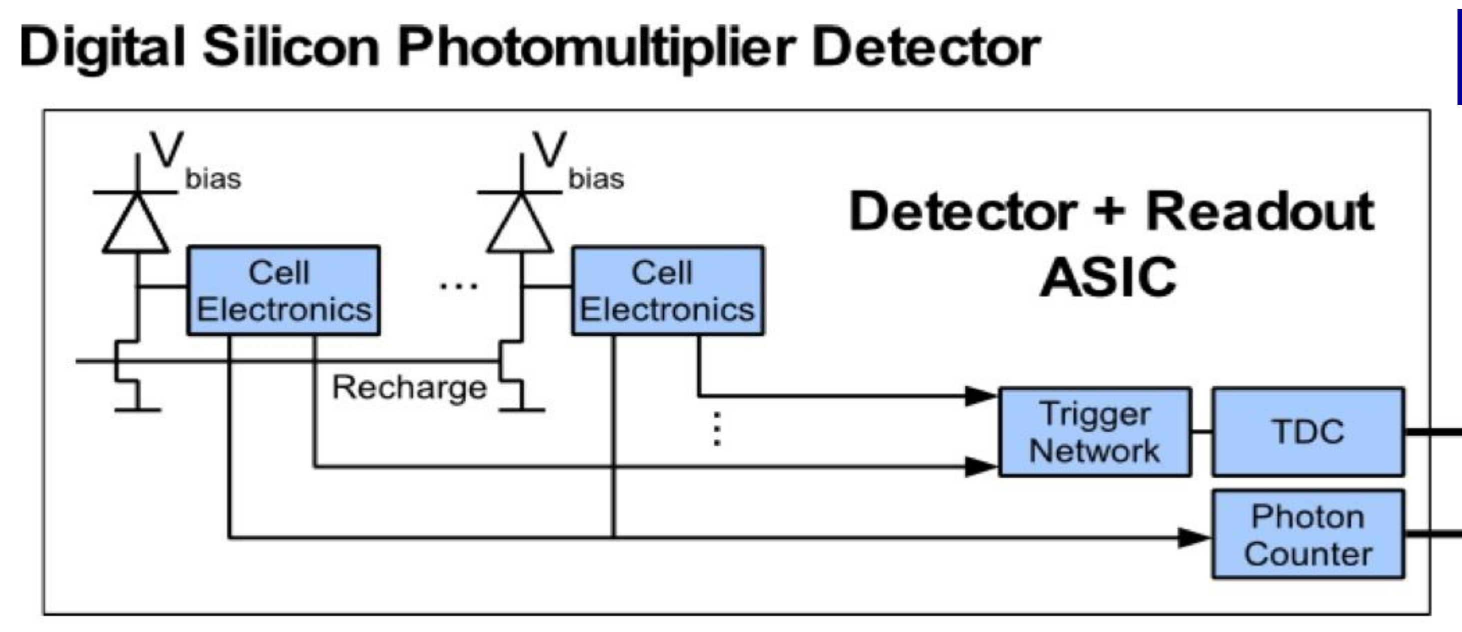
Analog signal sums many photons





Time

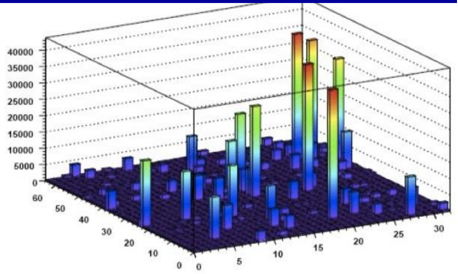
Energy



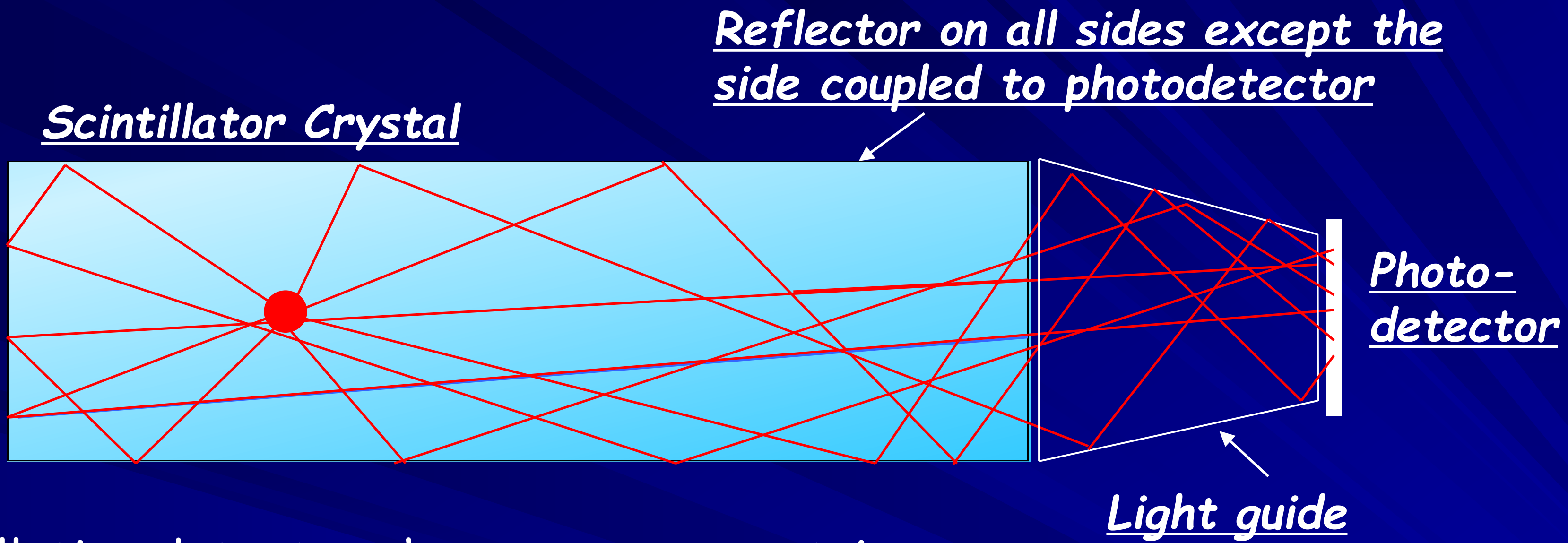
Time

Energy / #Photons

Selectively disable cells with high dark noise



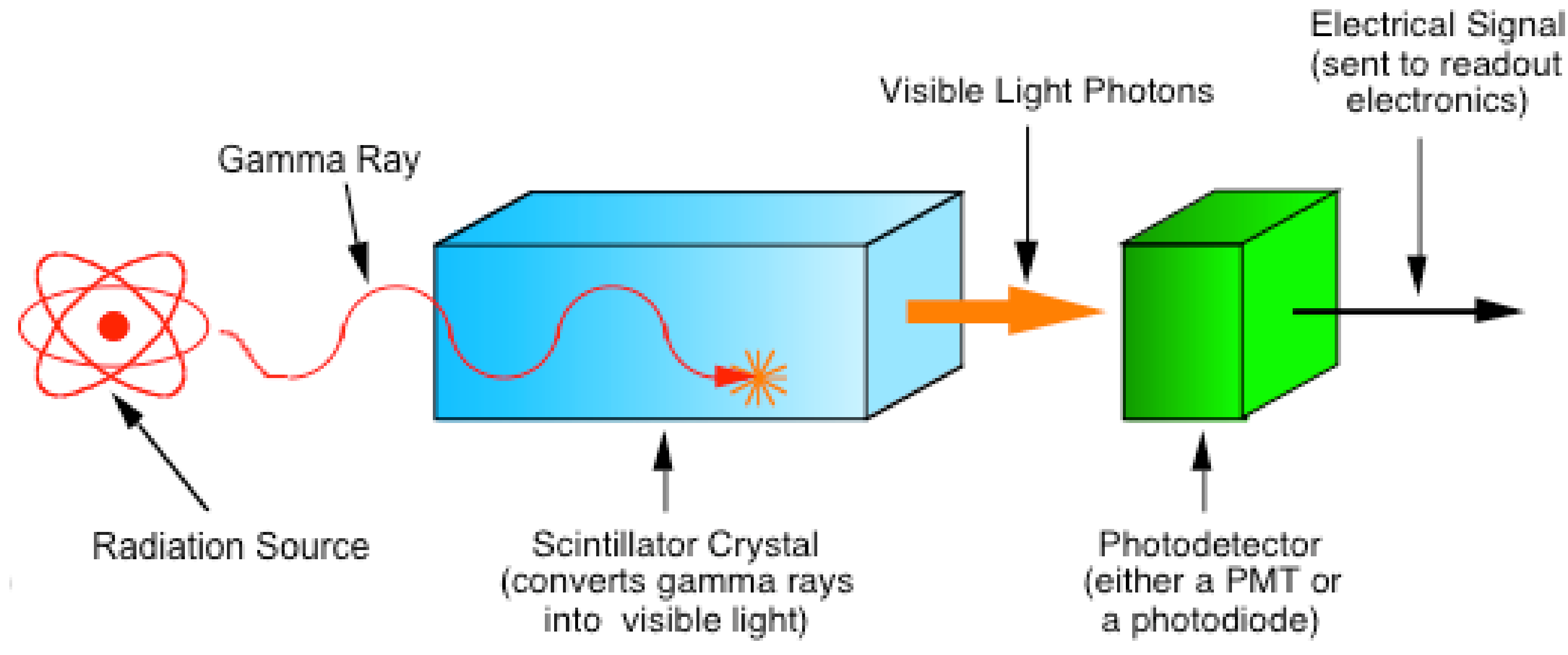
Light Collection



- Scintillation detectors have many geometries
- Scintillator crystal can coupled directly to photodetector
- Use of light guide to match geometry of scintillator to photodetector or to have **scintillator** and photodetector far apart
- Scintillation emission is isotropic
- Light losses: 1) internal absorption (inside crystal)

  2) external absorption (reflection)

Energy Conversion in a Scintillation Detectors



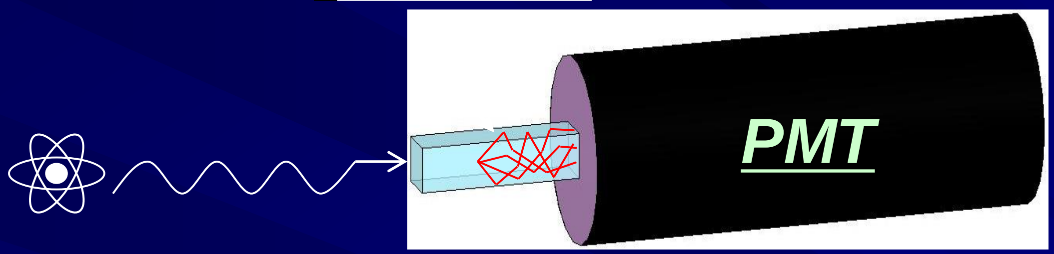
Gamma Ray → Visible Light → Electrical

Factors affecting the performance of a scintillation detectors:

- Scintillator: light yield, rise time, decay time, light transport
- Photodetector: single-electron response, PDE, TTS, noise
- Electronics: signal processing, noise, time pick-off

Scintillation Detectors vs Solid-State Detectors

Scintillator

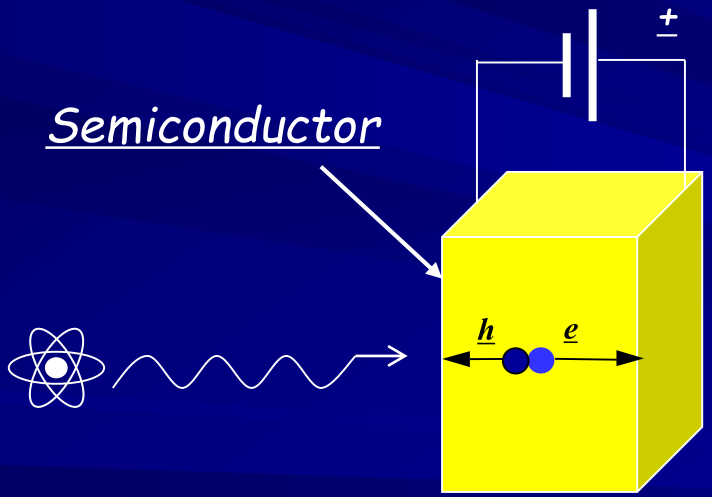


~1,500 e^-
@ 140 keV

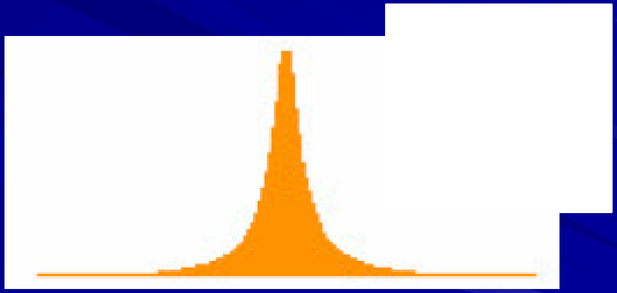
Energy per e^- ~ 10 – 200 eV

Gamma Ray --> Visible Light --> Electrical Signal (Indirect Detection)

Semiconductor



~30,000 e^-
@ 140 keV

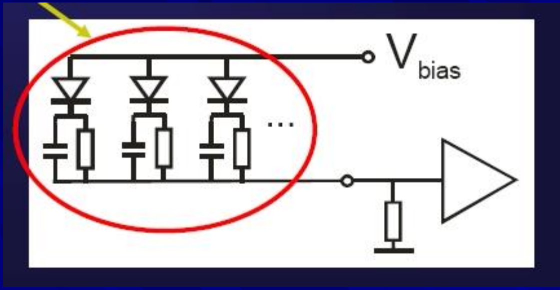


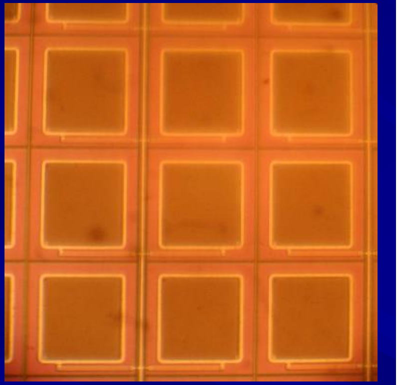
Energy per e^- ~ 3 – 5 eV

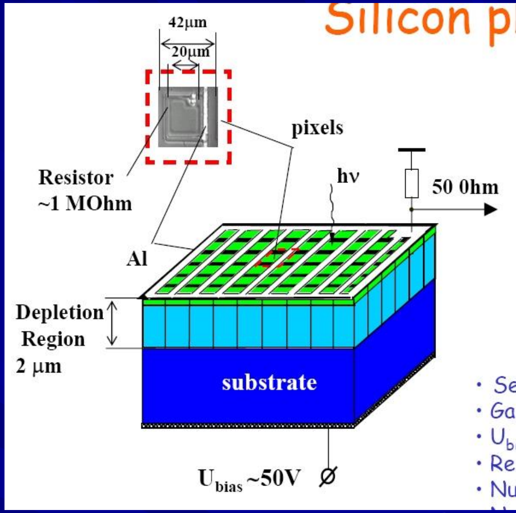
Gamma Ray --> Electrical Signal (Direct Detection)

Next step --> SiPM (Geiger mode APD)

- operating low bias voltage ~ 50 V
- power consumption < 50 μW/mm^2
- single-photon response ~ 105-106e
- optical cross-talk ~ 10%
- peak detection efficiency ~ 25% at 520nm
- timing resolution ~ 100 psec
- typical size ~ few mm2
- dynamic range ~ 1000
- non-sensitivity to magnetic field
- low temperature dependence
- mechanical and electrical robustness
- cheap (CMOS process)
- large dynamic range
- compact, rugged and show no aging,





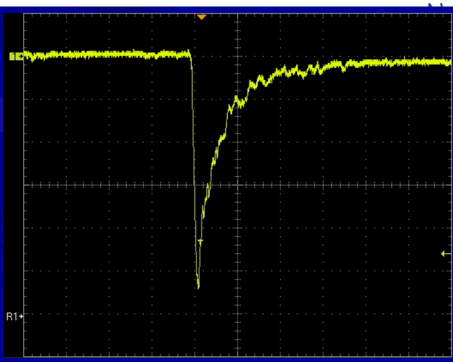


BUT →

Significant dark count rate (~10^5-10^6 Hz / mm^2)

Enhanced optical cross-talk (~10%)

Therefore area is practically limited to few mm^2



511 Kev on LSO

Some 'exotic' technologies

Liquid Xenon drift/scintillation time projection chamber

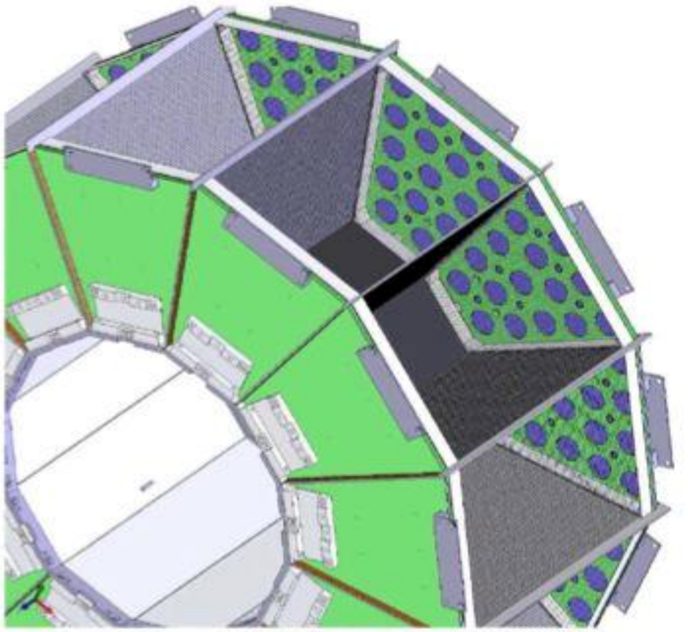


Fig. 1. The LXe PET ring concept. Scintillation light and charge are measured in each of the 12 modules consisting of a LXe time projection chamber viewed by avalanche photodiodes.

Photons entering the LXe produce prompt scintillation light and ionization which drifts under an electric field applied between the cathode and the anode of the TPC.

The multiple interactions of the gamma ray in the chamber can be determined and the point of first interaction estimated

From NIM (2009)
Simultaneous reconstruction of scintillation light and ionization charge produced by 511 keV photons in liquid xenon: Potential application to PET
P. Amaudruz a, D. Bryman b, L. Kurchaninov a, P. Lu b, C. Marshall a, J.P. Martin c, A. Muennich a, F. Retiere a, A. Sher a
a TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, Canada V6T 2A3 b Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC, Canada V6T 1Z1 c University of Montreal, CP 6128 Succursale Centre-Ville, Montreal, Quebec, Canada H3C 3J7

Resistive Plate Chambers

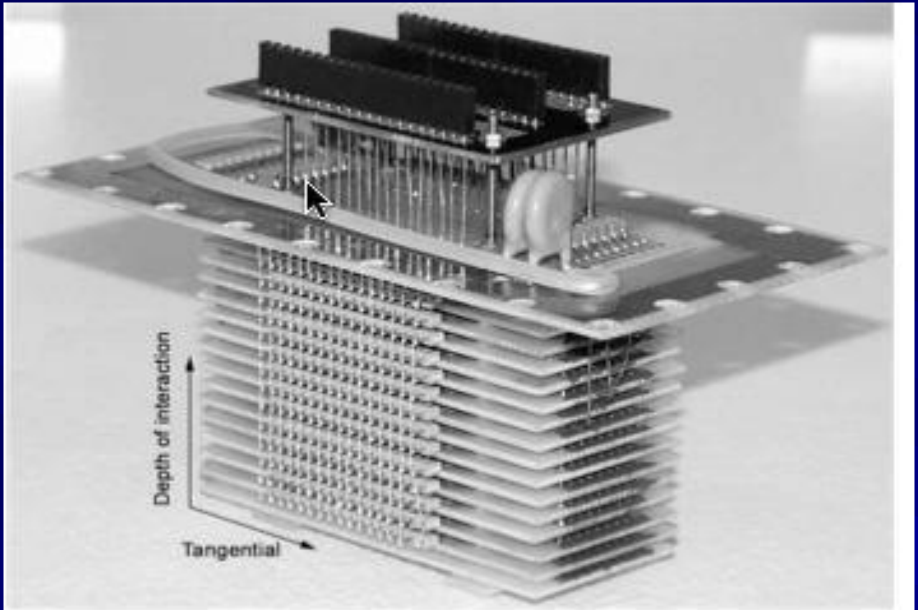


Fig. 2. Detecting element built with 17 identical stacked plates, which define 16 independent sensitive gas gaps, being able to measure the photon interaction point in two dimensions: the tangential dimension and the DOI.

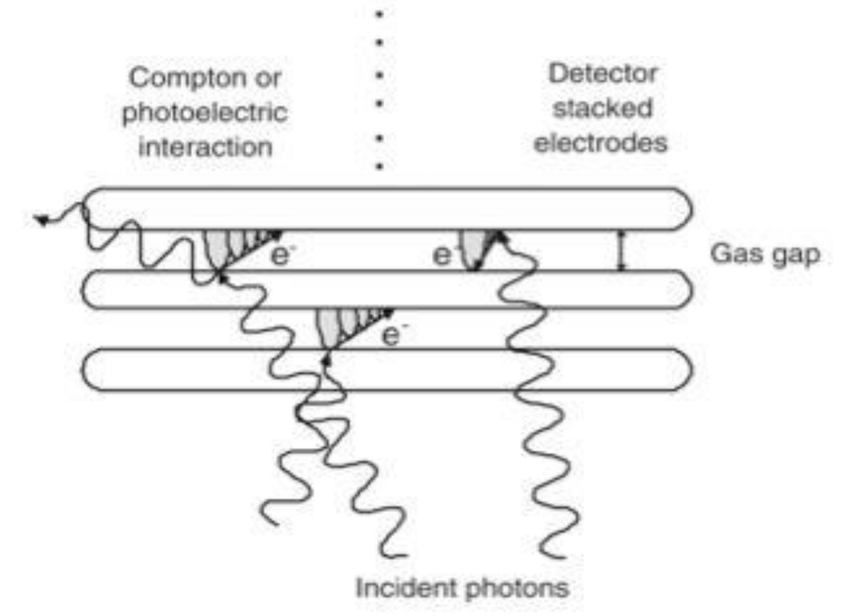


Fig. 1. Schematic view of the detecting element, showing the detection process of the incident gamma photons, which take advantage of the stacked construction of the RPCs.

From TNS 2006

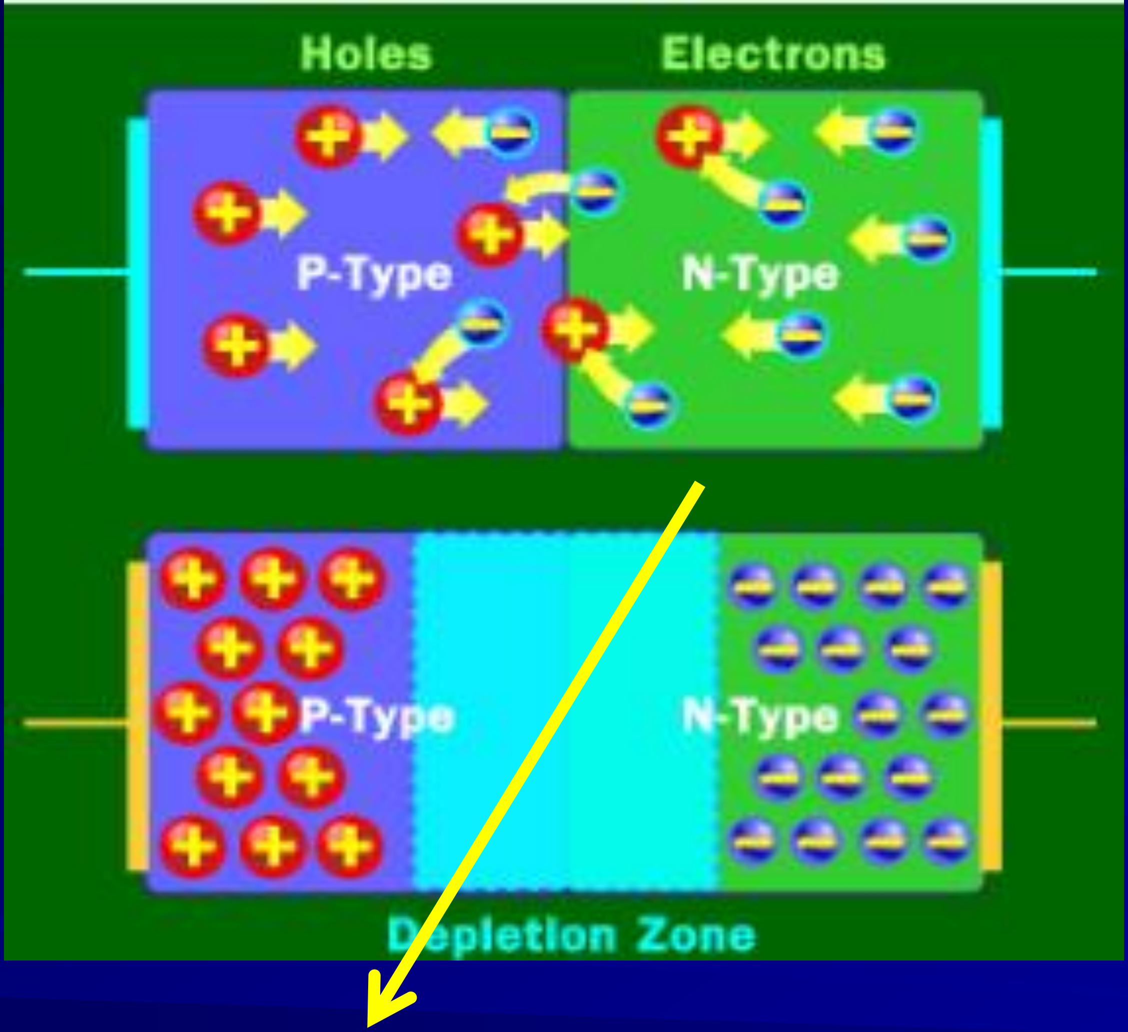
RPC-PET: A New Very HighResolution PET Technology

A. Blanco, N. Carolino, C. M. B. A. Correia, L. Fazendeiro, Nuno C. Ferreira, M. F. Ferreira Marques, R. Ferreira Marques, P. Fonte, C. Gil, and M. P. Macedo

The silicon era

The semiconductors revolution

- First transistor invented 1947 by William B. Shockley, John Bardeen and Walter Brattain (Nobel Prize 1956)
- First semiconductor particle sensor: Pieter Jacobus Van Heerden, The Crystalcounter: A New Instrument in Nuclear Physics. University Math Naturwiss, Fak (1945). CCD Nobel prize Boyle Smith 2009
- Semiconductor a material that has a conductivity between a conductor and an insulator; electricity can pass through it, but not very easily

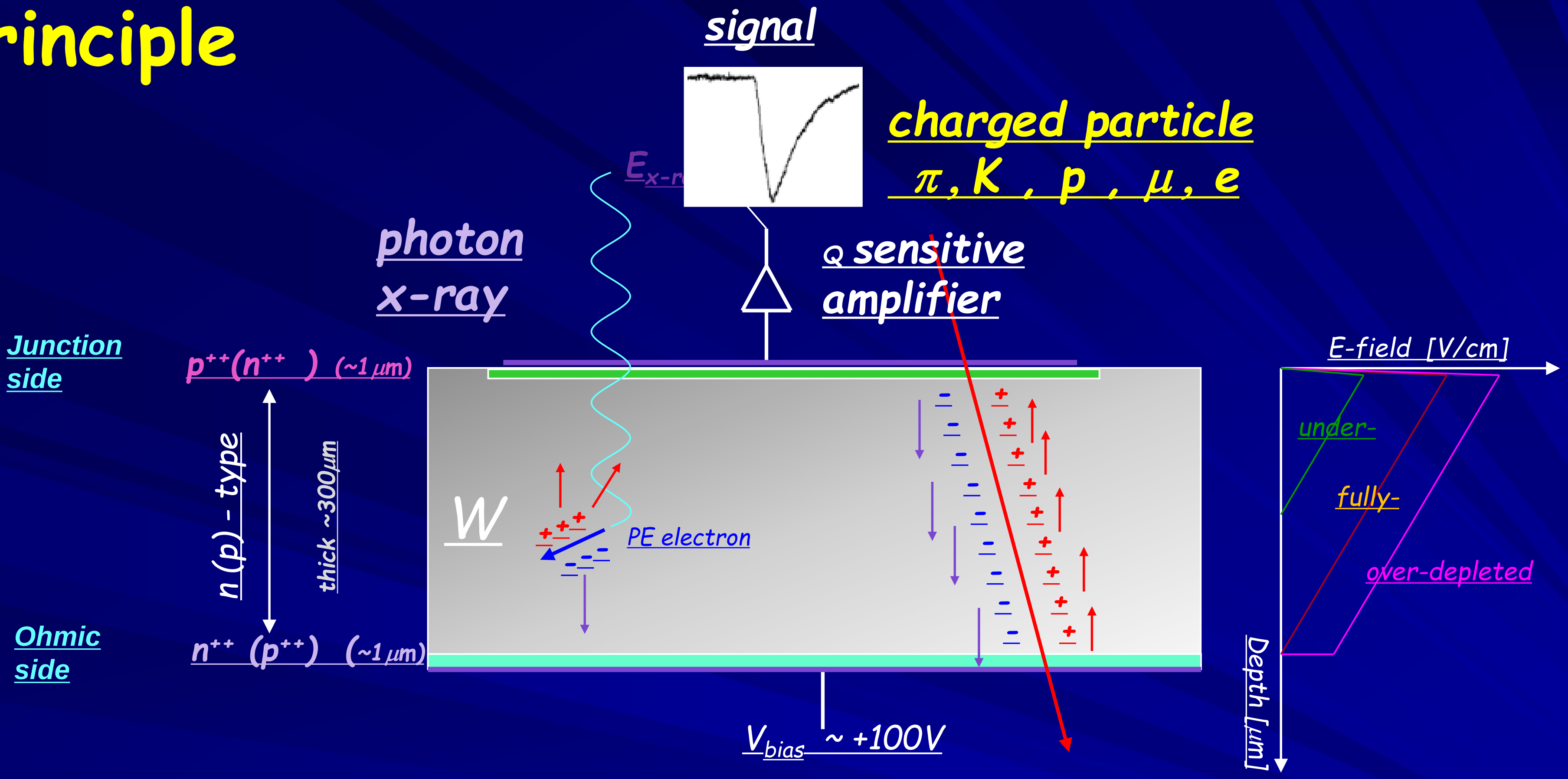


p-n junction

Depleted region
particle yes/no

particle

Semiconductor p-n junction basic working principle

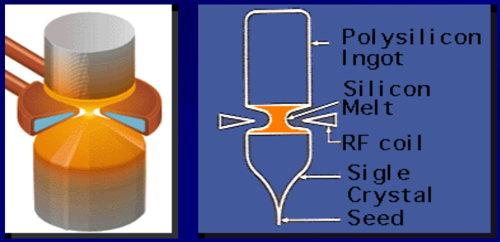


- n+ and p+ electrodes are implanted on the wafer's surfaces to form a p-i-n junction
- V_{bias} is the applied reverse bias voltage, W is the depletion region
- e-h pairs are created by the energy released by the impinging particle
- *e-h drift towards the positive and negative electrode "inducing " a current pulse*
- *Charge collection time depends on the carrier mobility, bias voltage and carrier polarity*

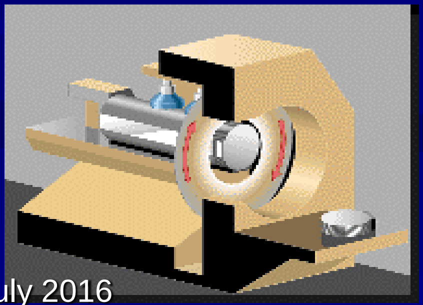
Silicon (atomic number 14) is abundant! It is second after Oxygen in the Earth's crust with 28% .

a) The sand is cleaned and further purified by chemical processes. It is then melted a tiny concentration of phosphorus (boron) dopant is added to make n(p) type poly-crystalline ingots

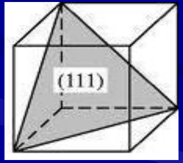
b) Single-crystal silicon is obtained by melting the vertically oriented poly-silicon cylinder onto a single crystal "seed"

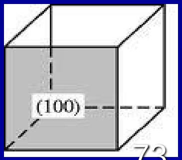


c) Wafers of thickness 200- 500µm are cut with diamond encrusted wire or disc saws.

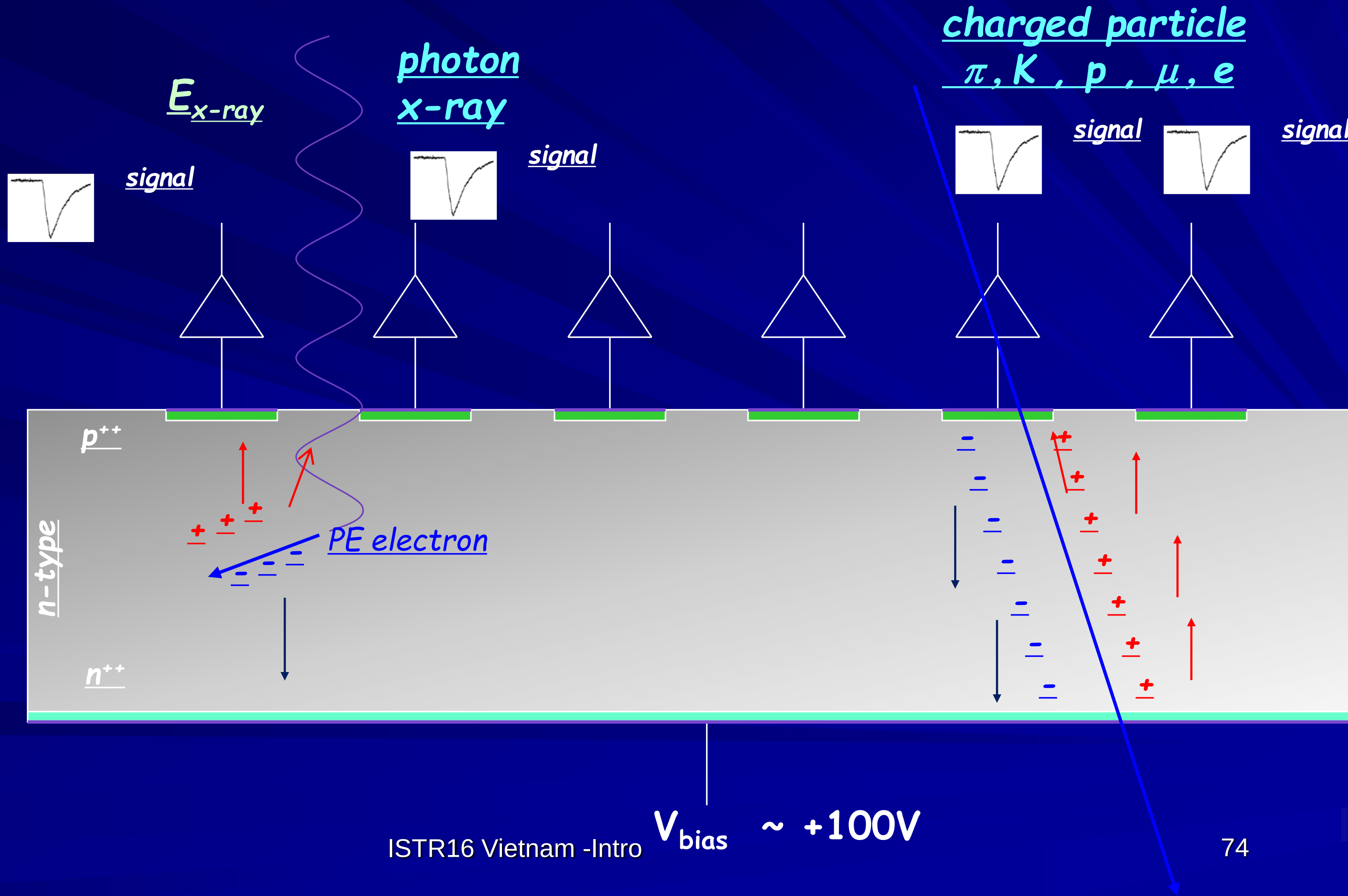


Note: the crystal orientation matters! <111> and <100> crystals can influence the detector properties eg. capacitance

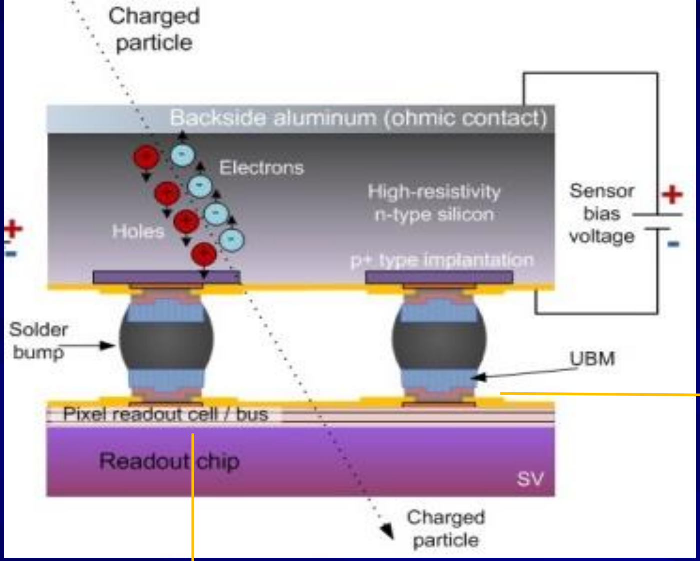




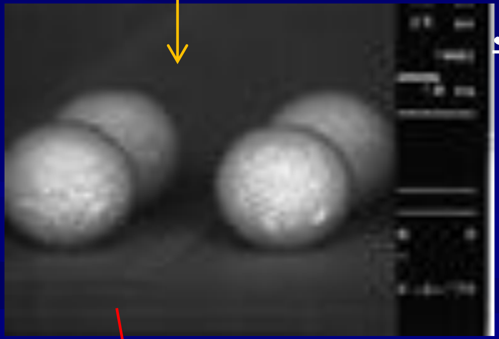
Segmented Silicon Sensors for better Positio Sensitivity



Pixel Detectors "Hybrid"



FE-I4
80x336
=26 880 pixels
125 x 50 um²



solder

50 microns

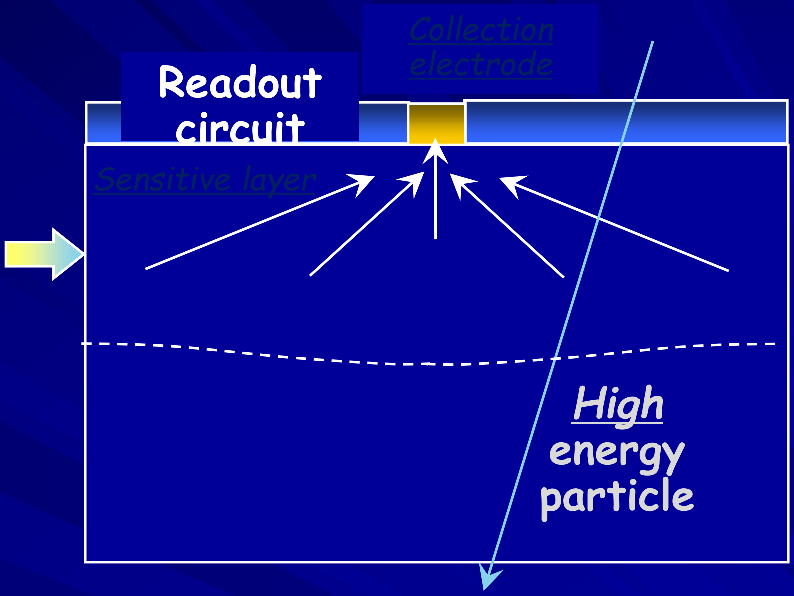
ATLAS FE-I4~4cm²

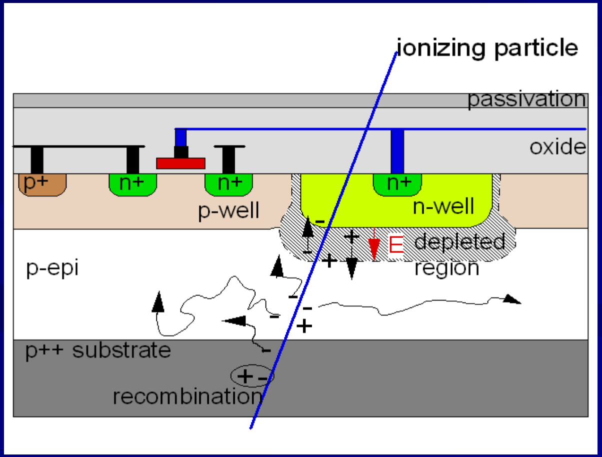
Pixel detectors "Monolithic"

Integrates the readout circuitry together with the detector in 'one piece ' of silicon

The charge generated by a particle is collected on a defined collection electrode either by diffusion or by the application of an E-field

Small pixel size and thin effective detection thickness





IEEE TNS Vol: 56, Issue: 3, 2009

MAPS

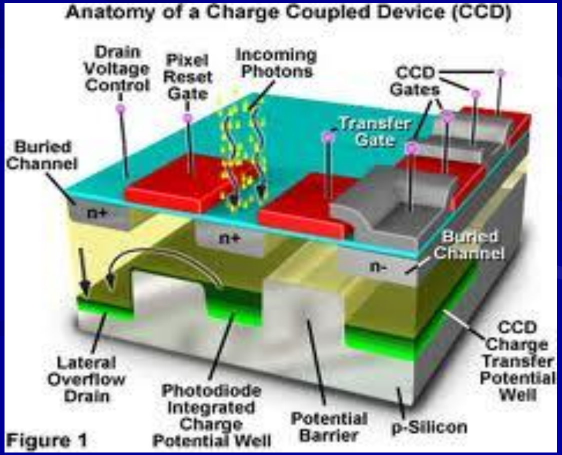
Pixel size :
20 x 20 micron
Thickness
20-50 um

Used in the
EUDET telescope
And at STAR
At RICH

CCD

Charge
coupled
Device
Various
dimensions

Many uses in
Different
fields

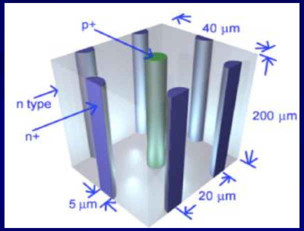


Pixels Sensors in High Energy Physics

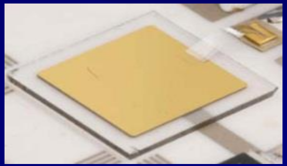
Radiation Hardness
hybrid

Granularity, low mass
monolithic

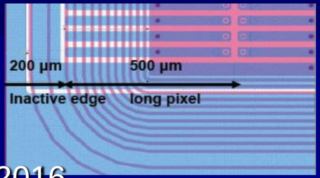
3D sensors



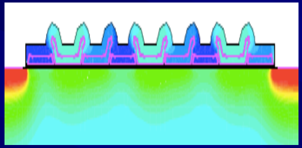
diamond



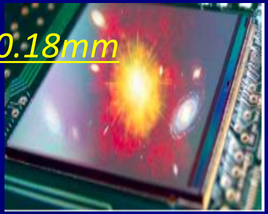
n-in-n, n-in-p-
planar



CCD

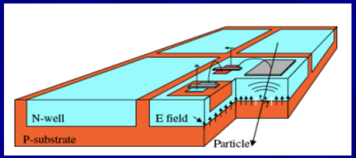


Mimosa

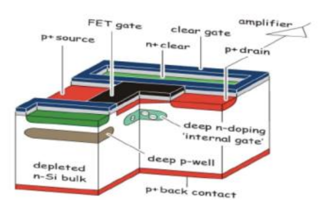


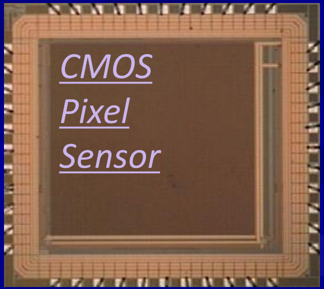
0.18mm

HV-MAPS



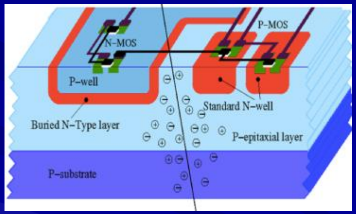
DEPFET



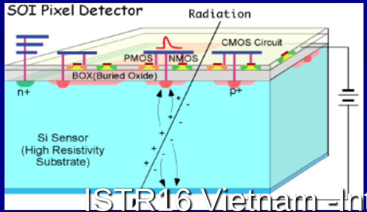


CMOS
Pixel
Sensor

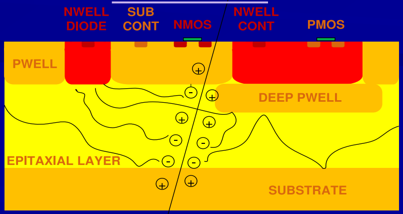
deepNwell



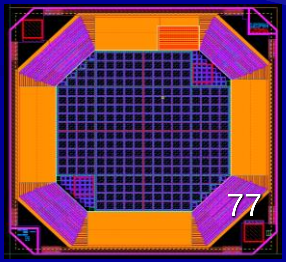
SOI



INMAPS



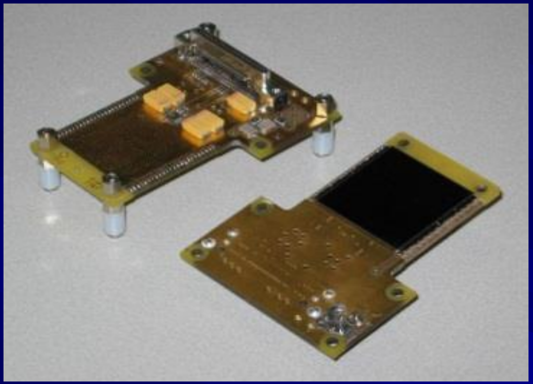
LePiX



Silicon for Synchrotron and low X-ray energy Applications

Single photon Counting ⟷ *Charge Integration*

Medipix



pixellated hybrid detector (Si, GaAs, CdTe, 3D thickness: 300/700/1000mm

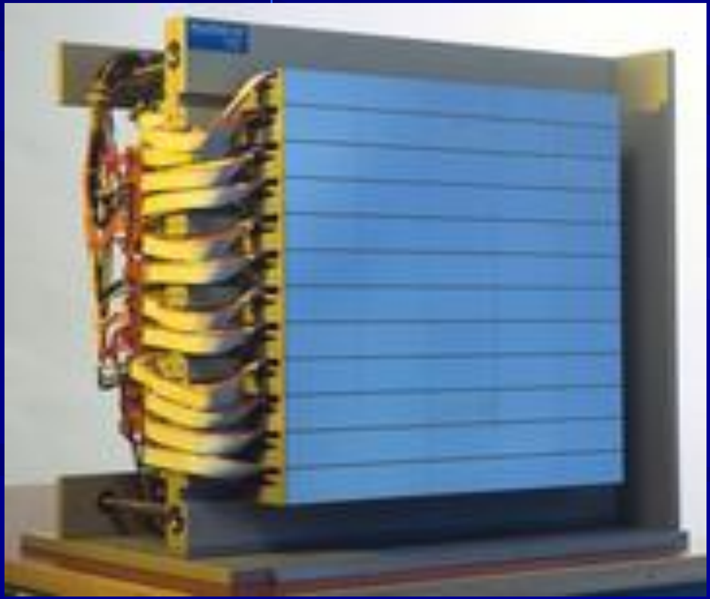
Medipix2 Quad
Pixels: 512 x 512
Pixel size: 55 x 55 mm^2
Area: 3 x 3 cm^2

Gotthard

AGIPD

Mithen II

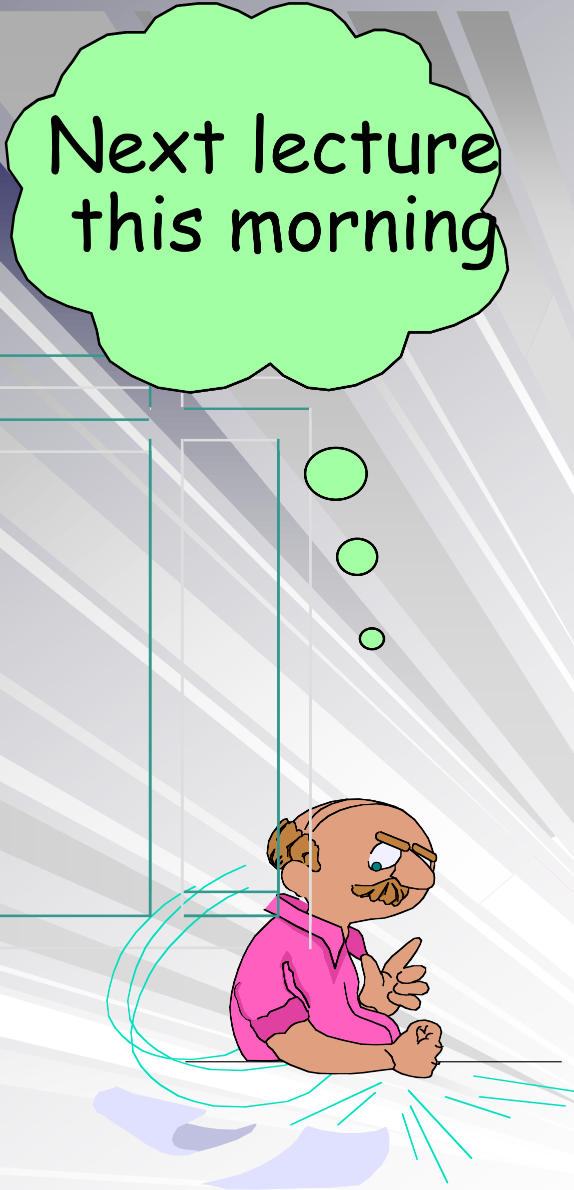
Eiger



The PILATUS 6M,

424 x 435 mm2 with 170 × 170 μm^2 (2463 x 2527) 6 million pixels, has been developed at PSI and commercialized by the company Dectris for synchrotron imaging

End of the first lecture



Questions?