Radiation detectors
From past to future

A very simple basic introduction of Radiation Instrumentation detectors seen from a HEP experimental physicist

P. Le Dû

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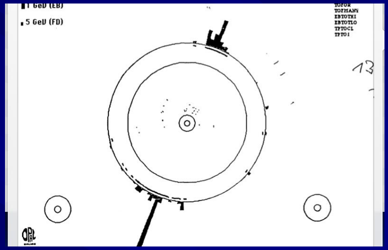
Who I am ? -

- 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 .*

DE LA RECHERCHE À L'INDUSTRIE

cea

IEEE

NPSS

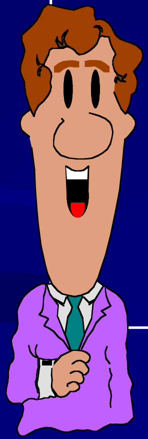
NUCLEAR & PLASMA SCIENCES SOCIETY

NPSS ADCOM

-*RITC Chair*

Goals of this presentation

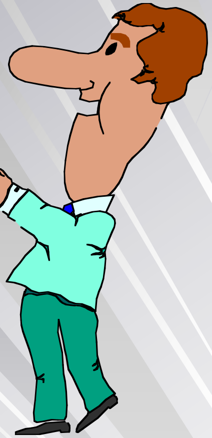
- Using my own experience during the last 49 years of working on Radiation detectors and experiments → try to give a flavor of what could be the application of the recent evolution and developments in various fields



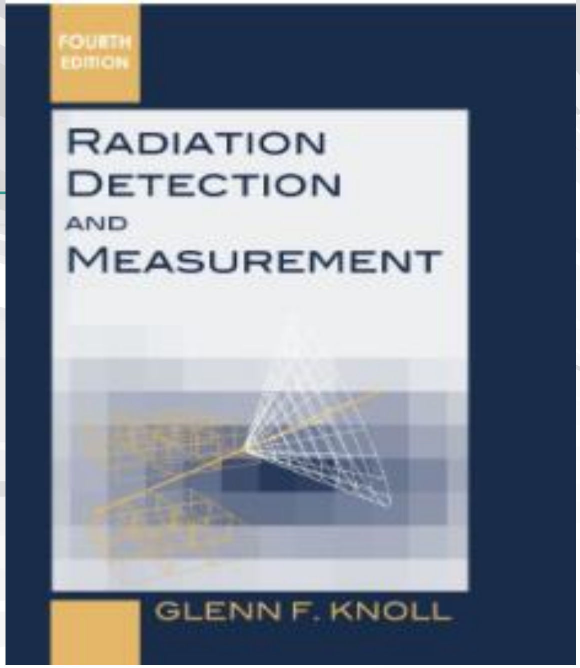
Outlines of the lecture

- Little introduction about radiation detectors
  - Context
  - A little bit of history over the last 120 years
- Basic sensors families → past, present and future
  - Photodetectors
  - Gazeous detectors
  - Silicon detectors
  - Electronics and data collection

Few words about Radiation Detectors



Radiation
Instrumentation
The Bible
Glenn Knoll



FOURTH EDITION

RADIATION DETECTION AND MEASUREMENT

GLENN F. KNOLL

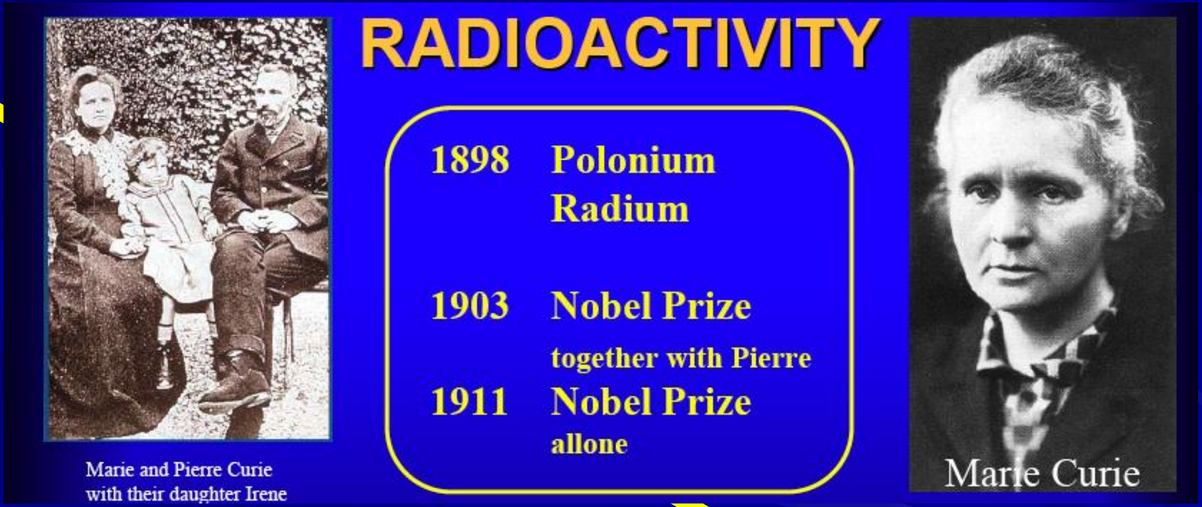
The origin

How physics discoveries have impacted our life (1)

1895
W.C. Rontgen
Discovery of X Ray

First image of potassium uranyl disulfide

1896 - Discovery of natural radioactivity by H. Becquerel
1897 – J.J. Thomson – electron
1899 – E. Rutherford : Alpha & Beta
1900 – U. Vilars – the Gamma



RADIOACTIVITY

1898	**Polonium** **Radium**
1903	**Nobel Prize** **together with Pierre**
1911	**Nobel Prize** **allone**

Marie and Pierre Curie
with their daughter Irene

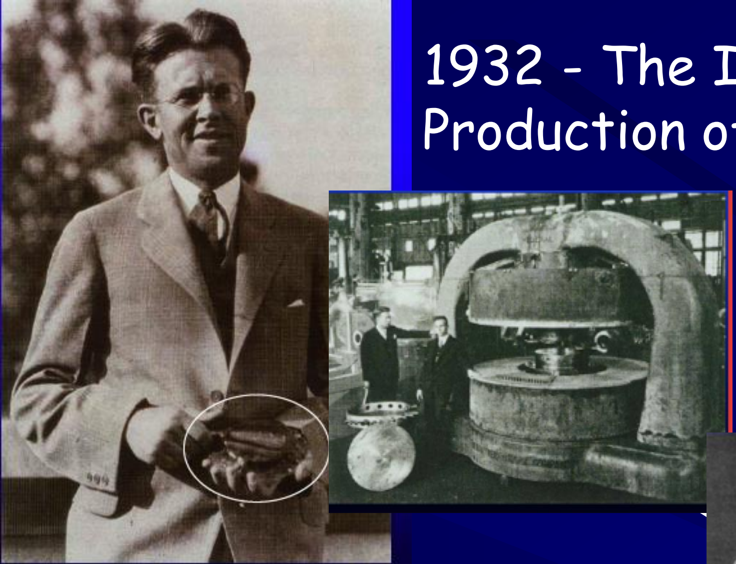
Marie Curie

X Ray
Radiography

1898
Pierre and Marie Curie
the Radioactivity
Polonium,Radium

How physics discoveries impact our life (2)

1932 - The Invention of the cyclotron
Production of radio isotopes→ nuclear medicine



Ernest O. Lawrence and his
First cyclotron 1932

1934 - Artificial radioactivity
Irène and Fréderic Jolio Curie

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

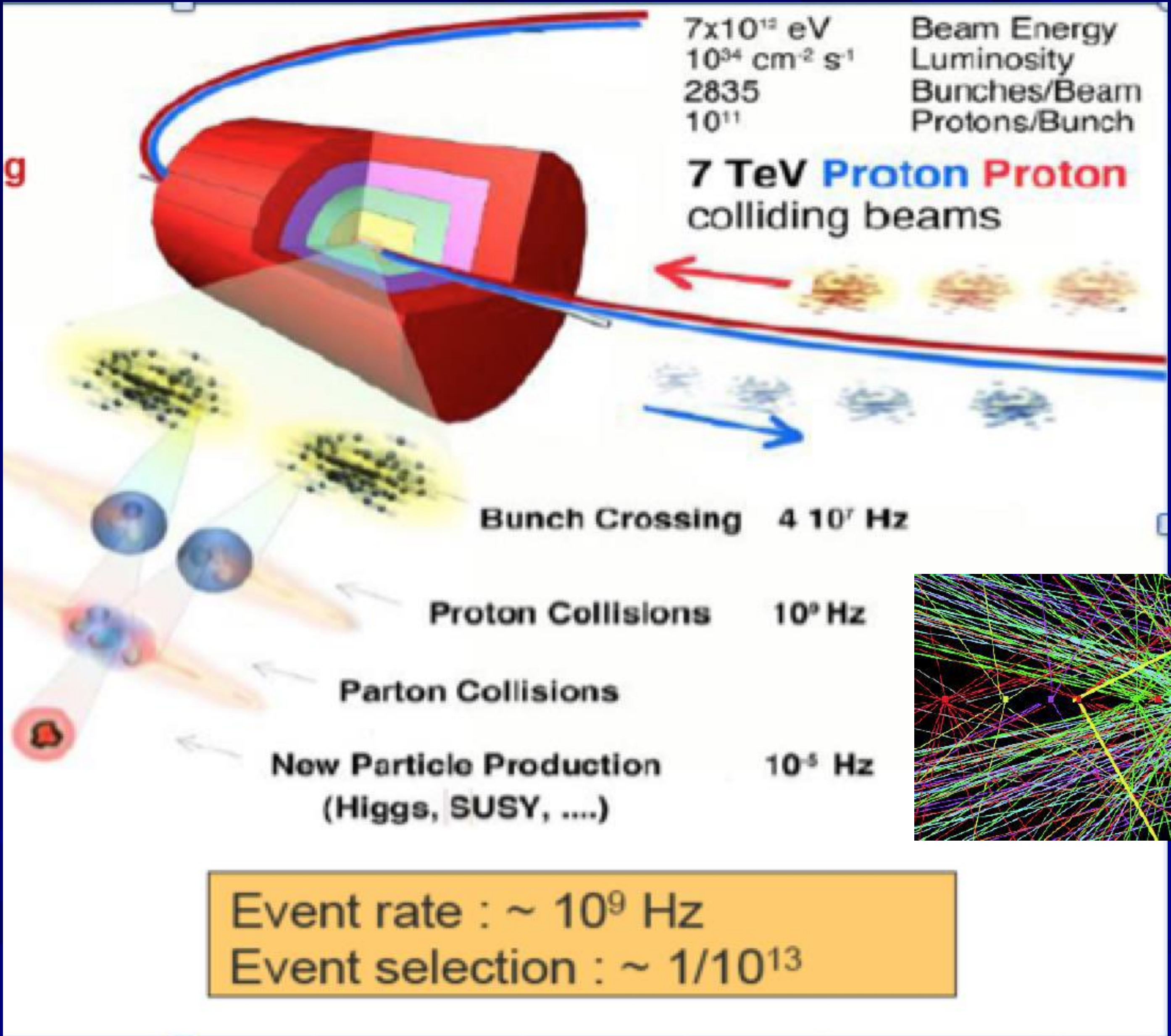
From discovery to first graphite miler in Chicago
To the Production of long lived radio-isotopes
And nuclear enrgy production

Otto Hahn, 1944 Nobel Prize

O.Hahn
E. Fermi

The context

My context → :The challenging LHC



$7x10^{12}$ eV	Beam Energy
10^{34} cm^{-2} s^{-1}	Luminosity
2835	Bunches/Beam
10^{11}	Protons/Bunch

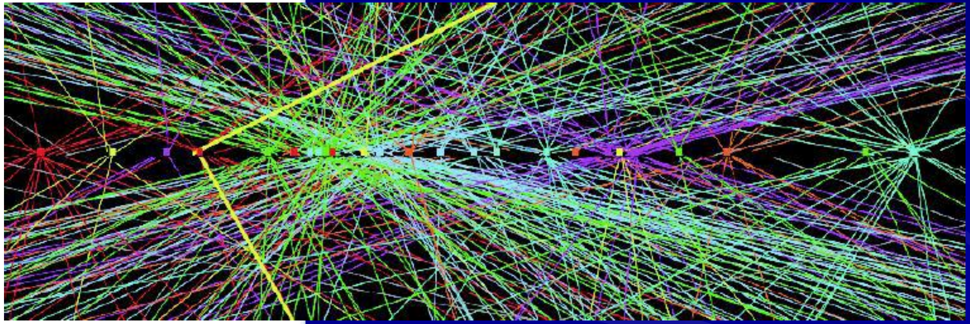
7 TeV Proton Proton
colliding beams

Bunch Crossing	**4 10^7 Hz**
Proton Collisions	**10^9 Hz**
Parton Collisions	
New Particle Production (Higgs, SUSY, ...)	**10^{-5} Hz**

Event rate : ~ 10^9 Hz
Event selection : ~ $1/10^{13}$

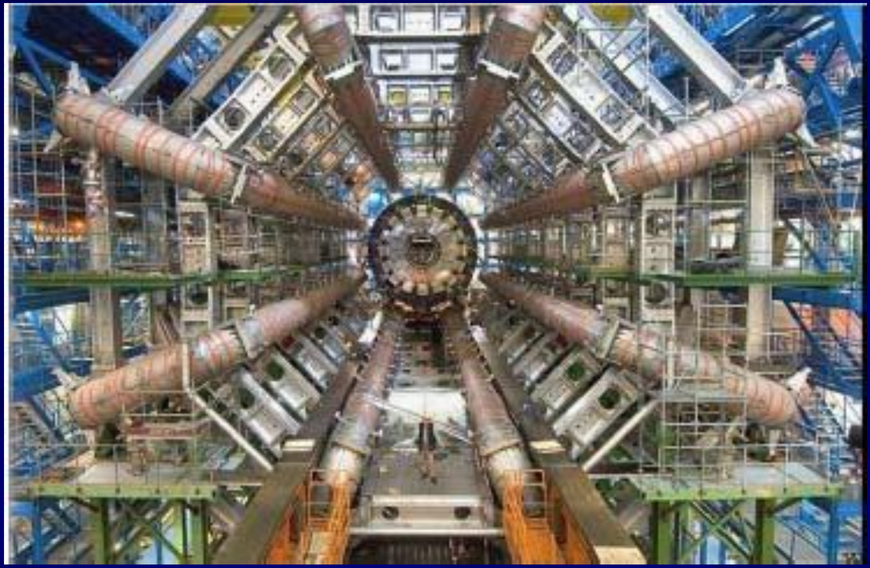
Quark-Quark
collisions@ 7 Tev

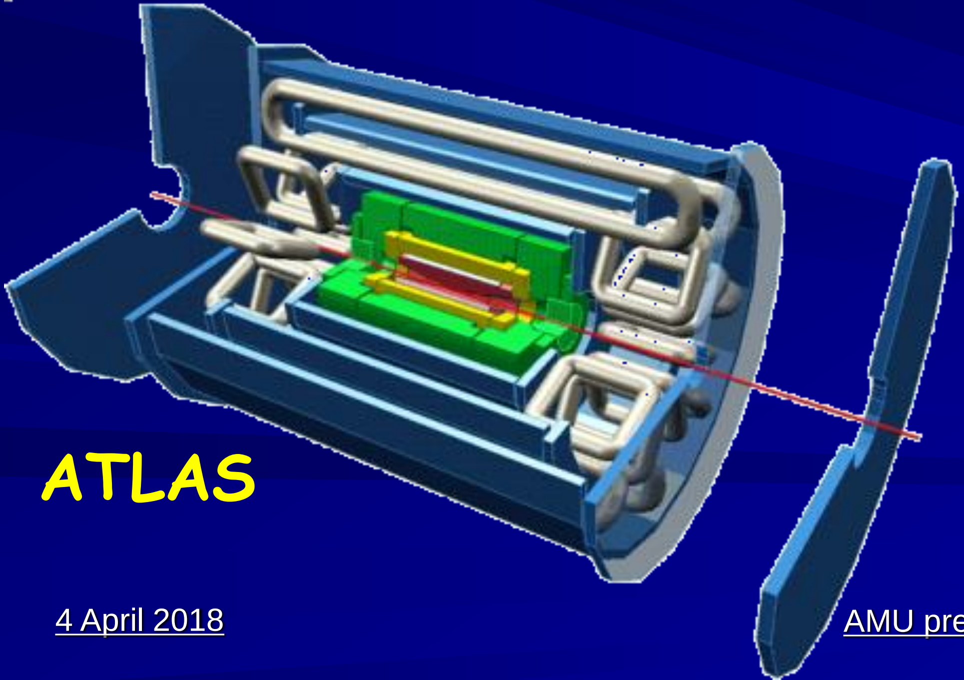
→ *Collision*
Every 25 ns



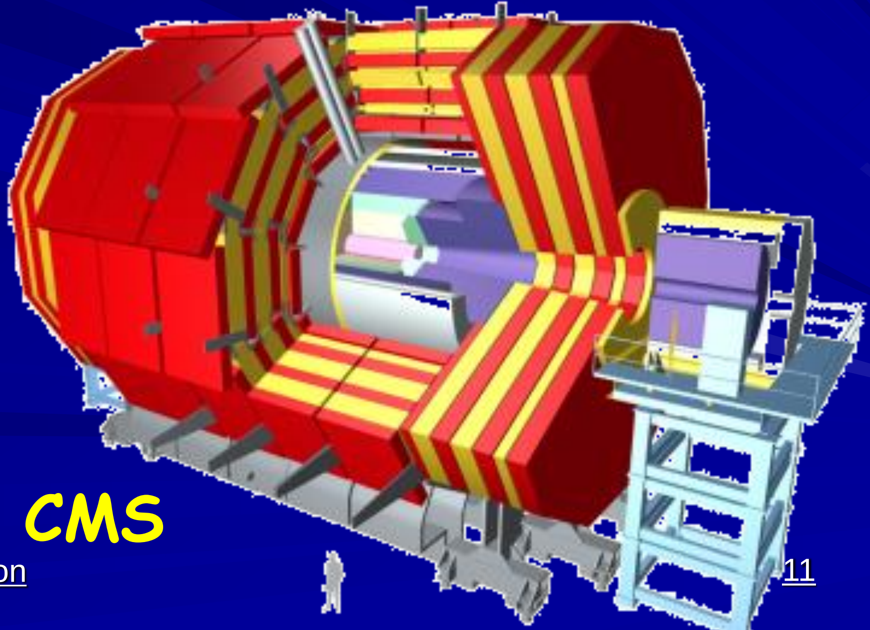
Z -> μμ event
at LHC ATLAS
15 April 2012

LHC Detectors



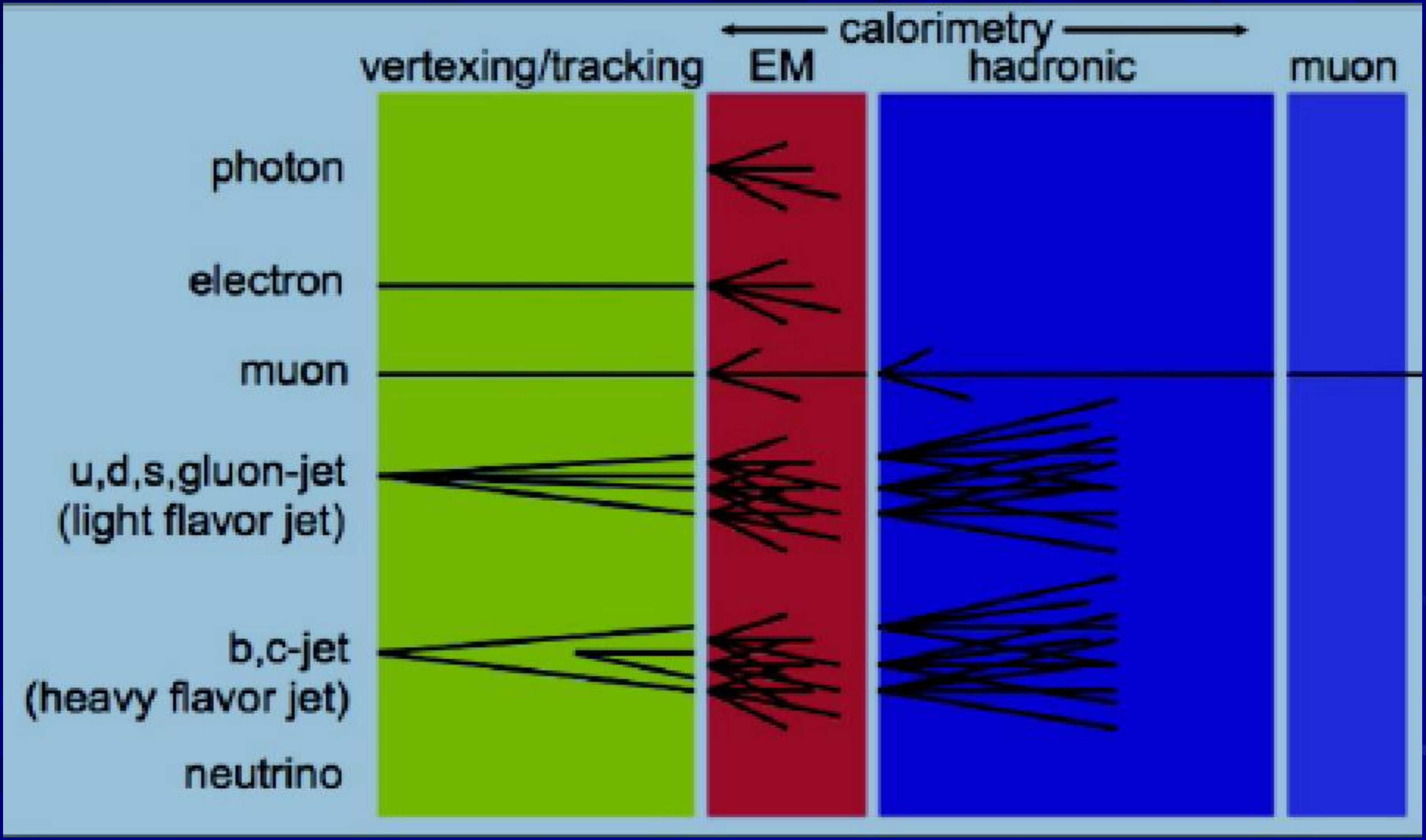


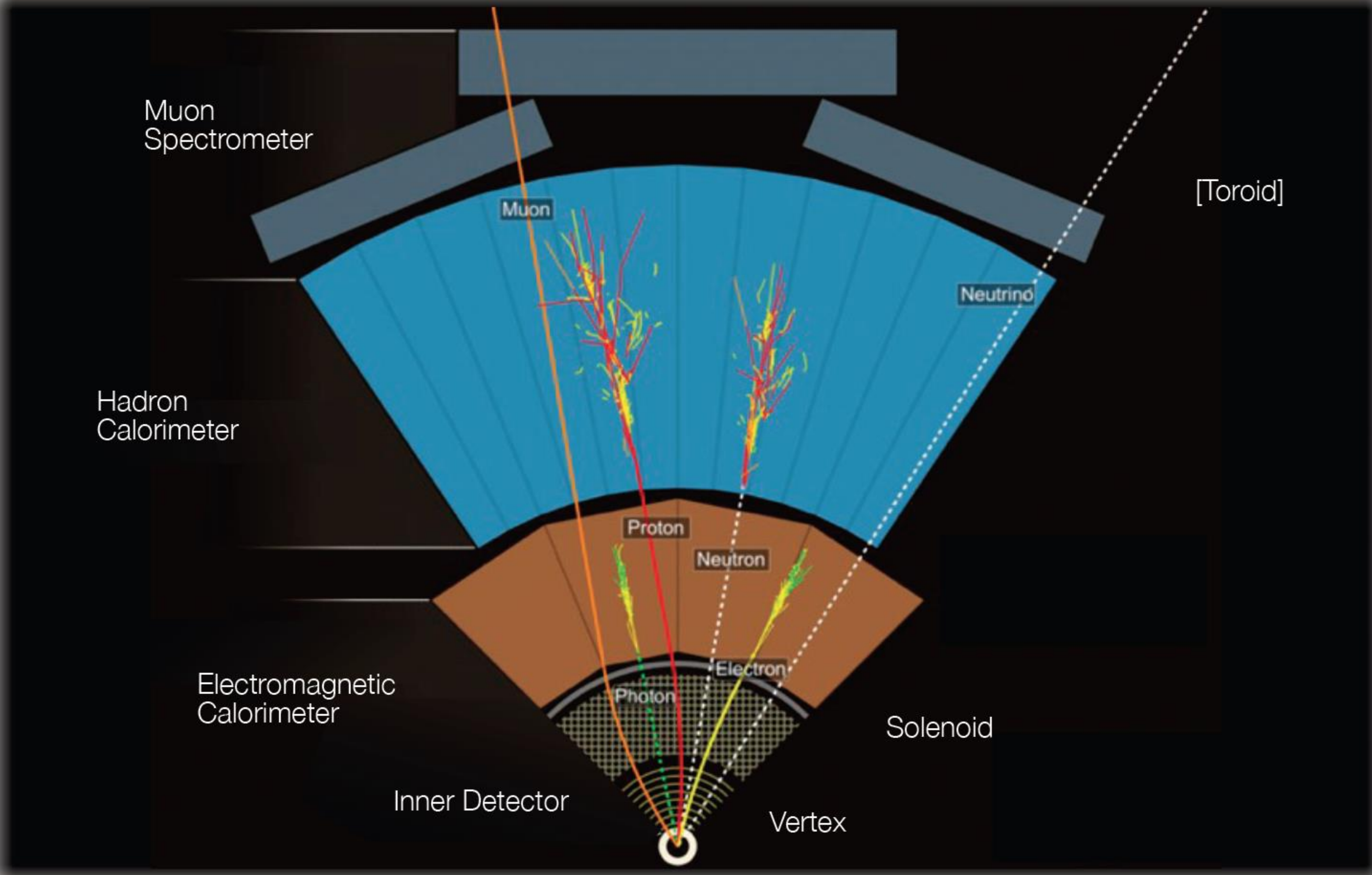
ATLAS



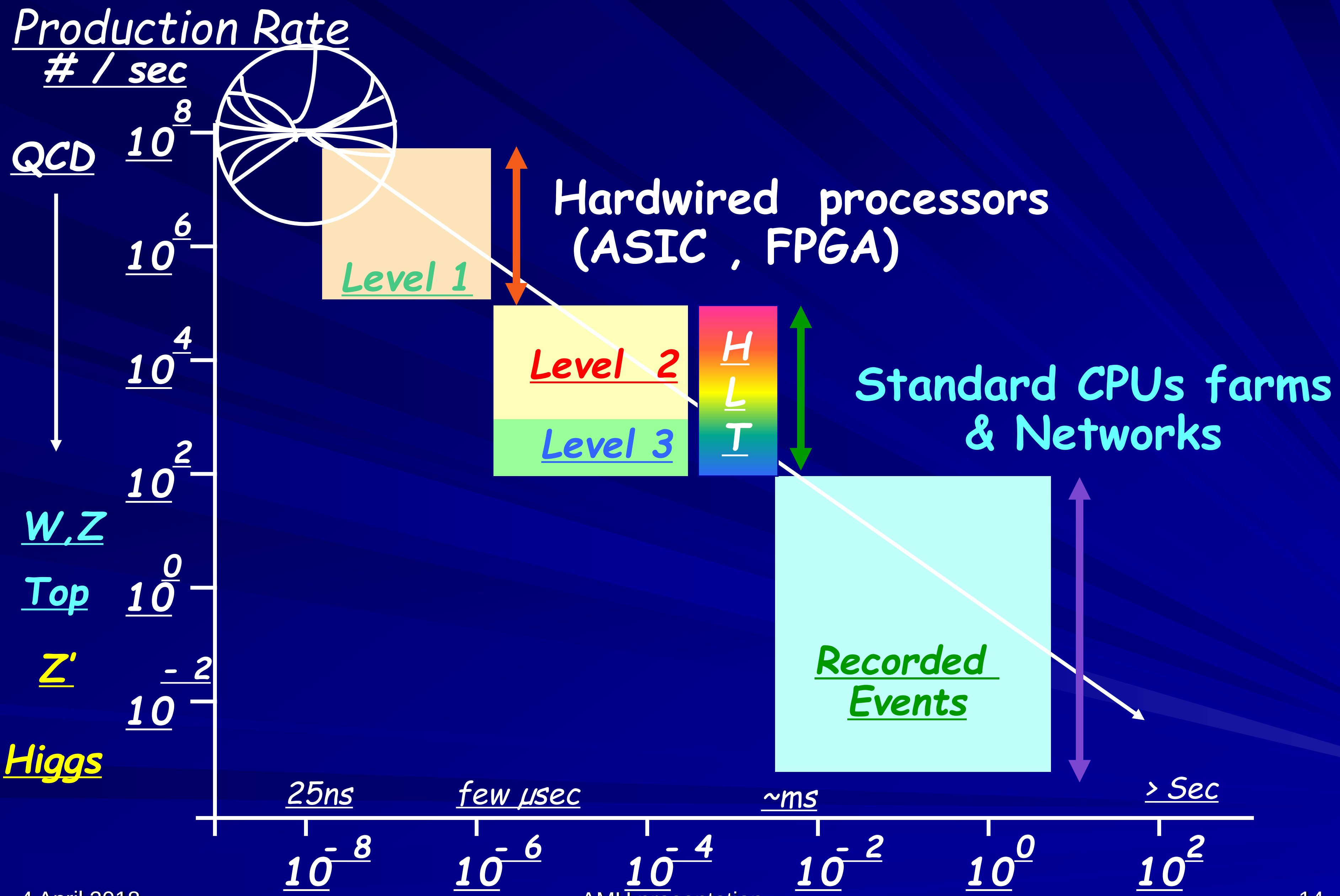
CMS

Physics signals & Trigger signatures




Muon Spectrometer
[Toroid]
Muon
Neutrino
Hadron Calorimeter
Proton
Neutron
Electromagnetic Calorimeter
Electron
Photon
Solenoid
Inner Detector
Vertex

LHC Multilevels Selection scheme



Production Rate

/ sec

QCD

W,Z

Top

Z'

Higgs

10^{8}

10^{6}

10^{4}

10^{2}

10^{0}

10^{-2}

Level 1

Hardwired processors (ASIC , FPGA)

Level 2

Level 3

H L T

Standard CPUs farms & Networks

Recorded Events

25ns

few µsec

~ms

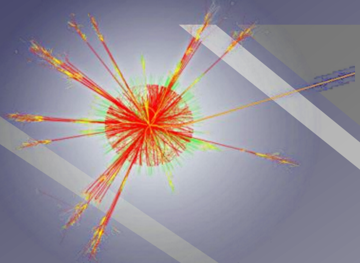
> Sec

10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2}

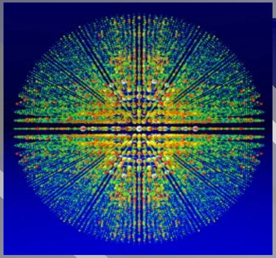
HEP ' state of the art ' parameters

- Beam
  - 230 superimpose events every 25 ns @ SLHC
  - 700 picosecond collision time @ CLIC (future?)
- Tracking and vertexing
  - The Micron or less
- Energy
  - From Kev to Tev with very good resolution
- Timing
  - We are speaking today to achieve the PICOSECOND
- # Channels
  - Billions due to 'pixellated & high granularity detectors
- integration, large scale apparatus in a partly radiation hard environment

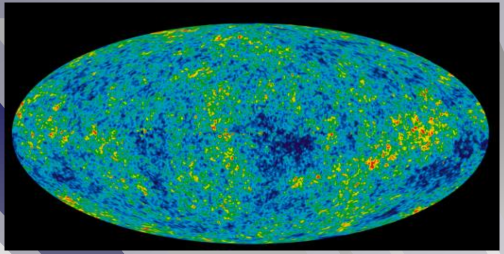
Medical imaging



HEP



x-ray crystallography



cosmology

......

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...

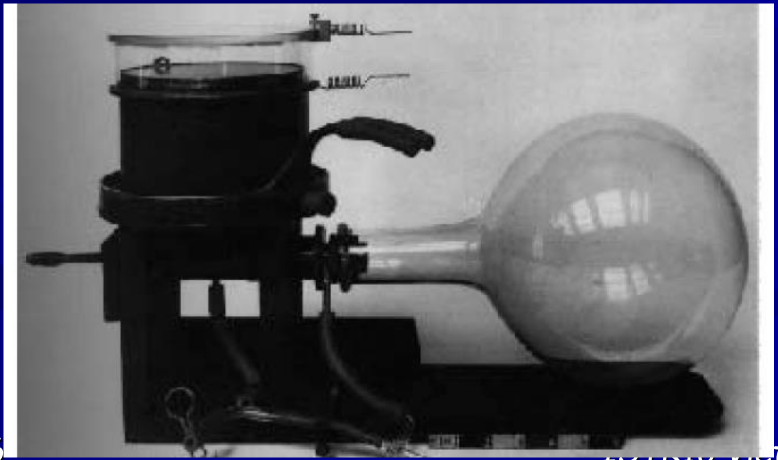
History and evolution of radiation detectors tools of discovery

- 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
- 1970: Silicon era
- Etc. etc. etc. → *In blue = Nobel Prize*

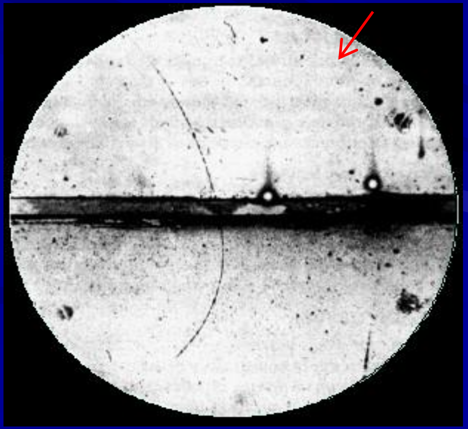
Cloud Chamber C.T.(R. Wilson)

- 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

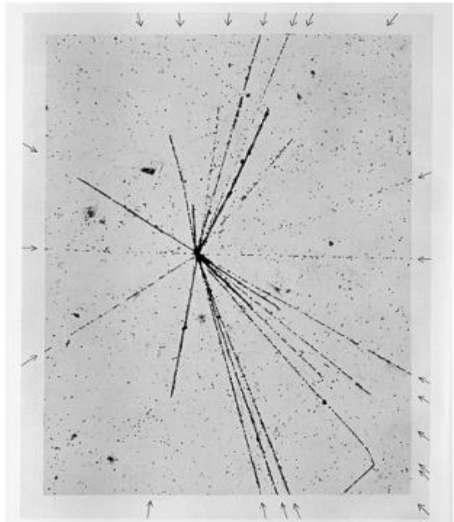


63 MeV e+



Lead foil

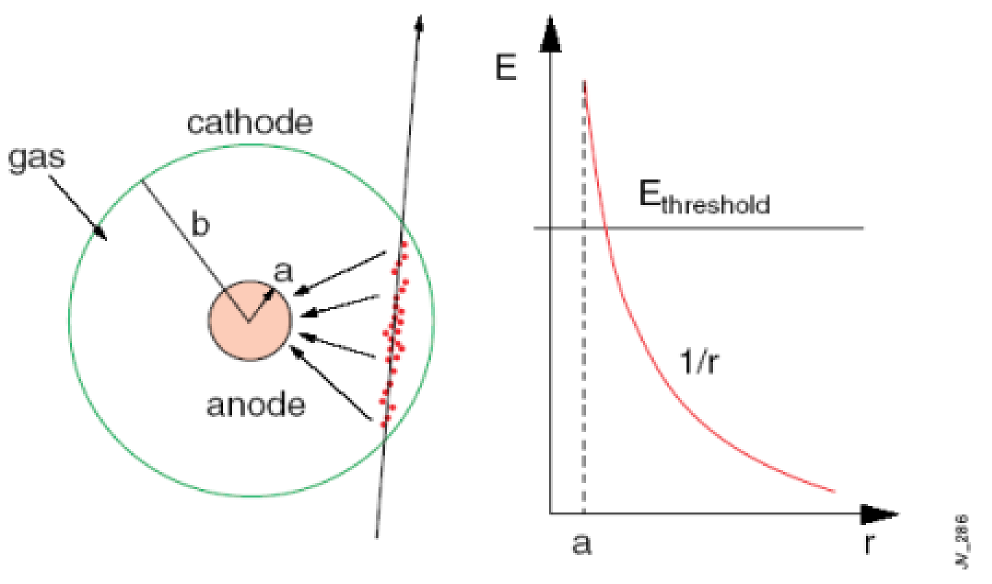
Nuclear Emulsion



'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)

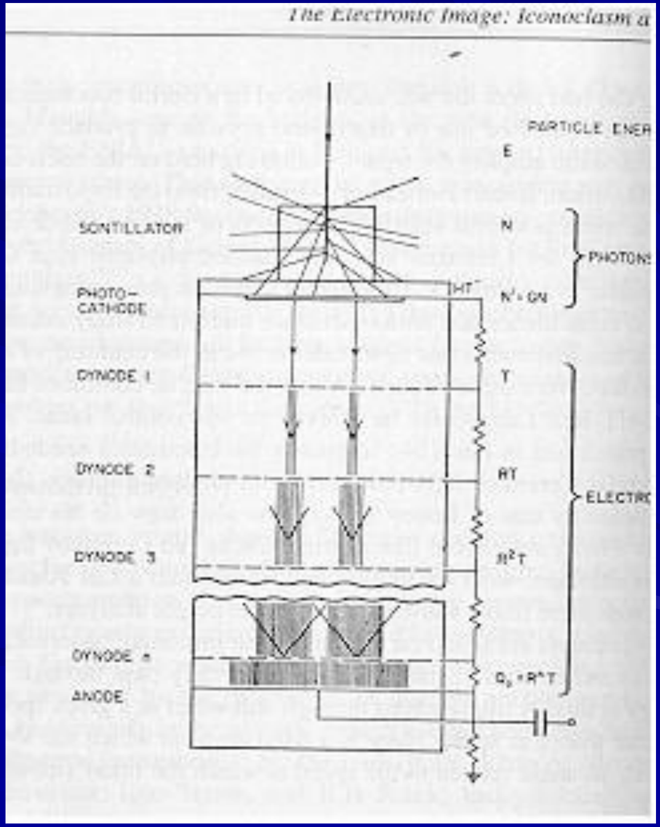
Geiger –Mueller counter



- 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

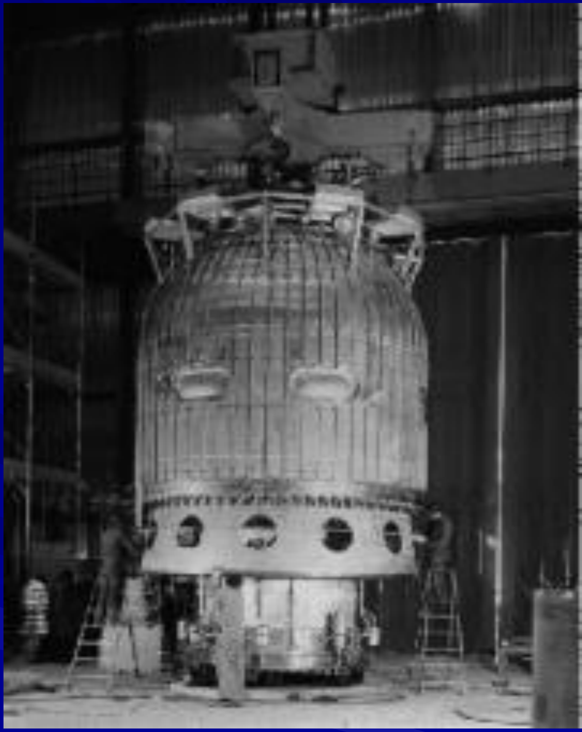
The Photopultiplier tube

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

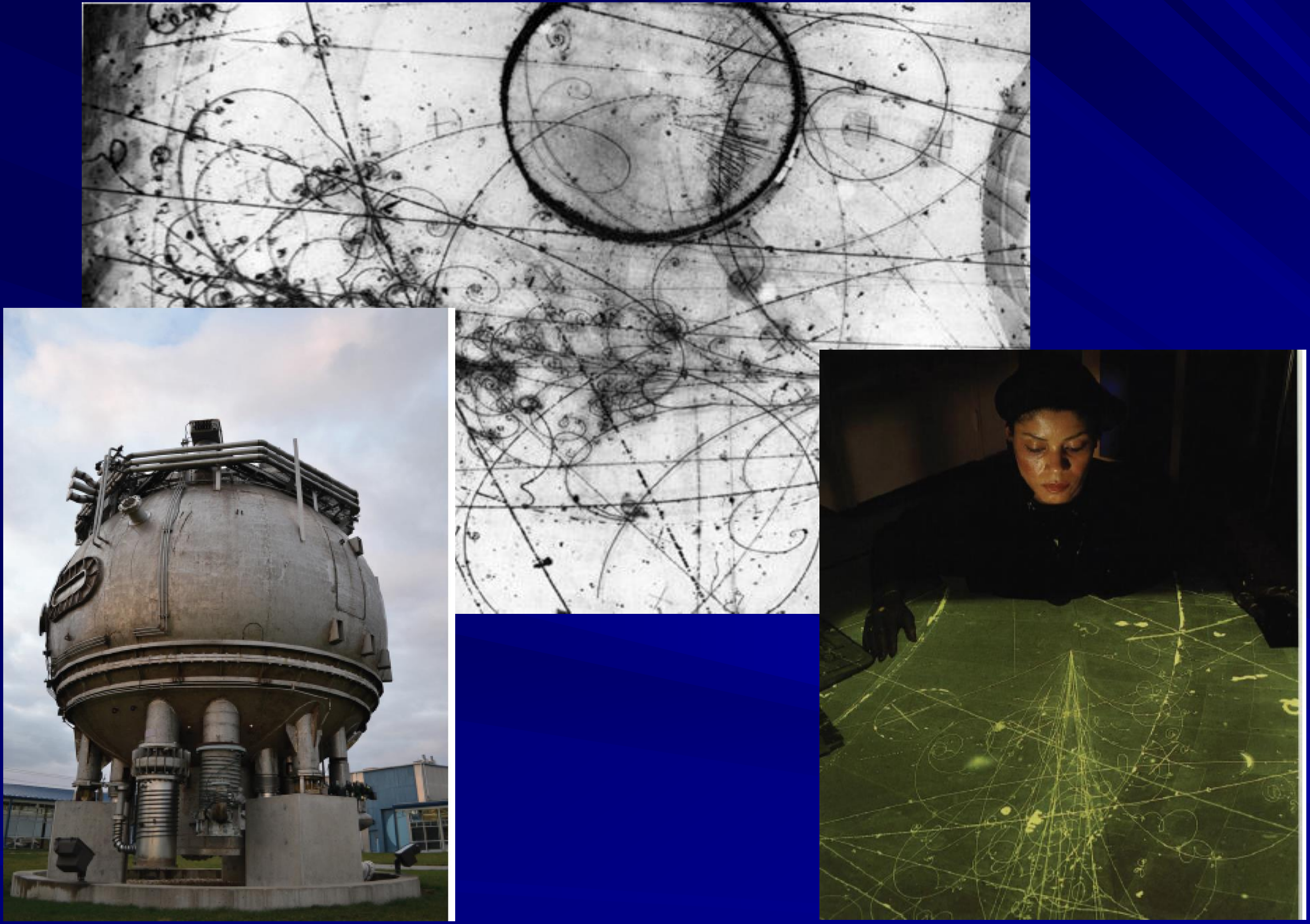


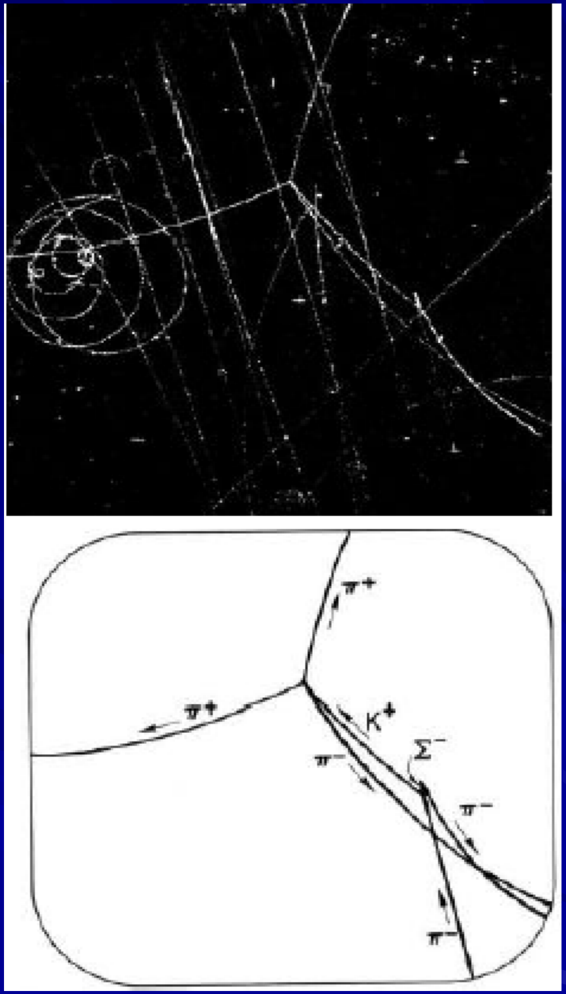
The Bubble Chamber

- 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)

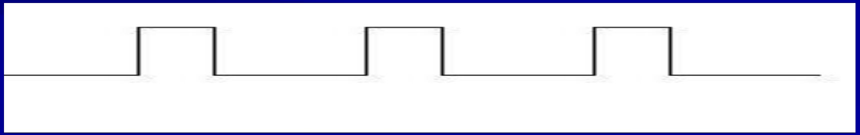


The prehistoric world
the Bubble Chamber -1955-1975





- Our Roots back to ‘triggerless DAQ ’



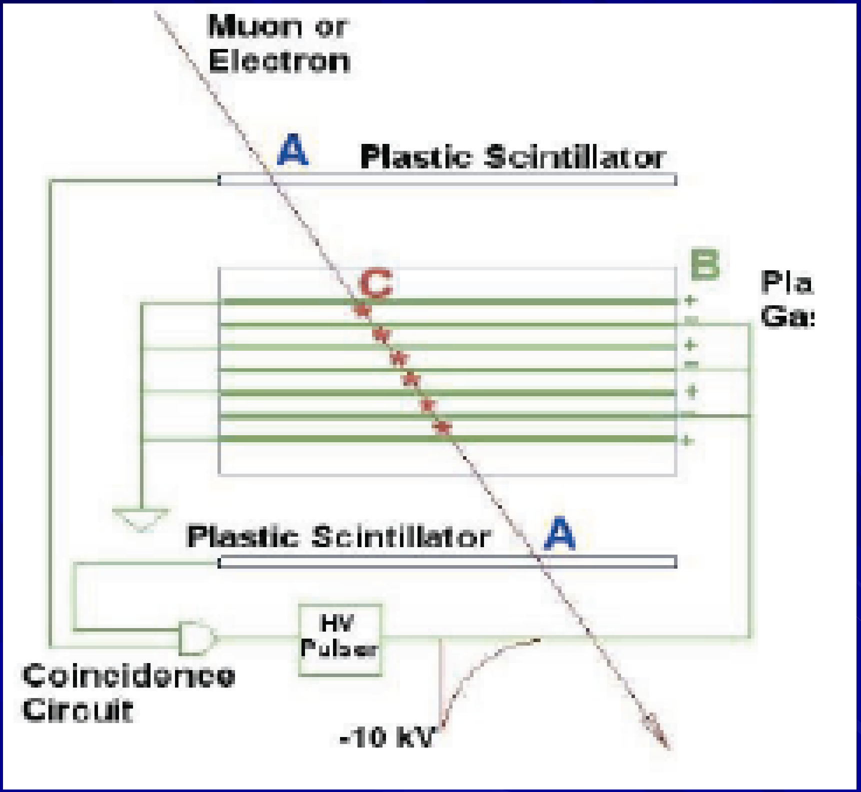
MWPC

- 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

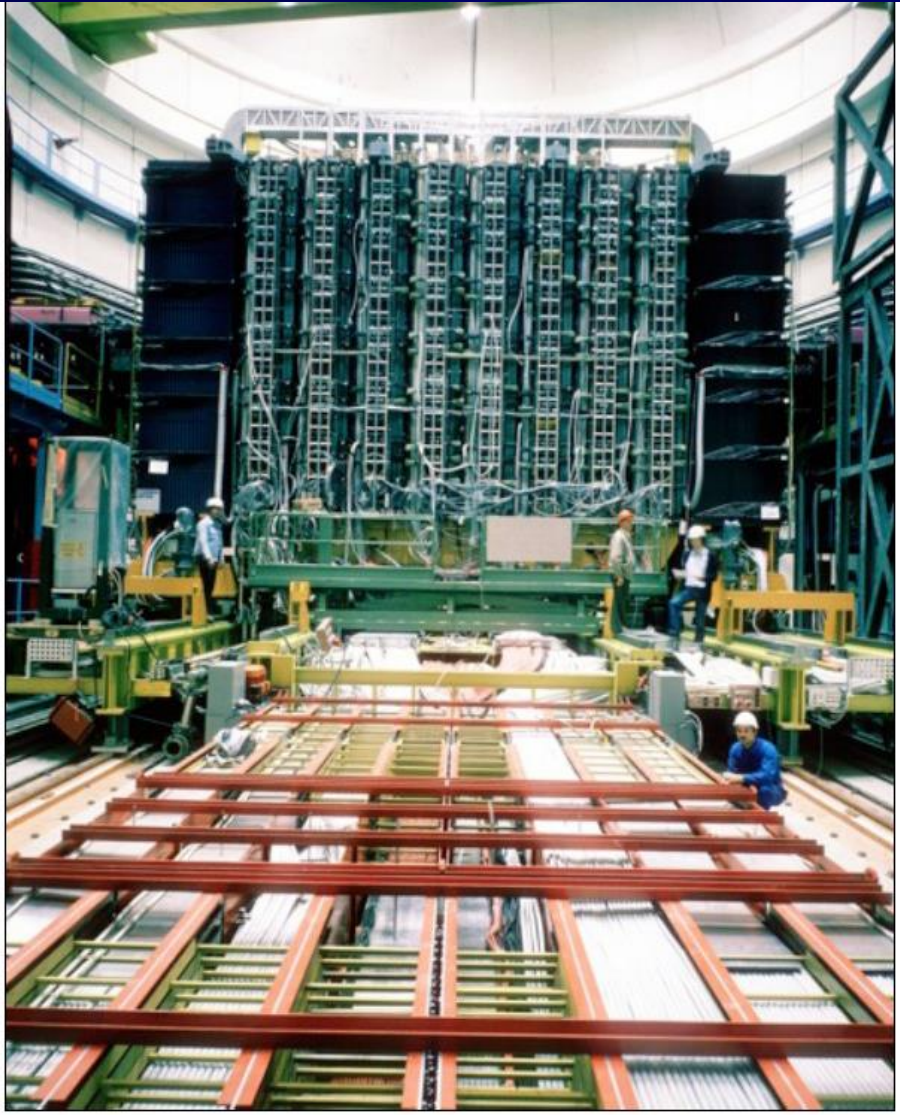
G. Charpak, F. Sauli and J.C. Santiard

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



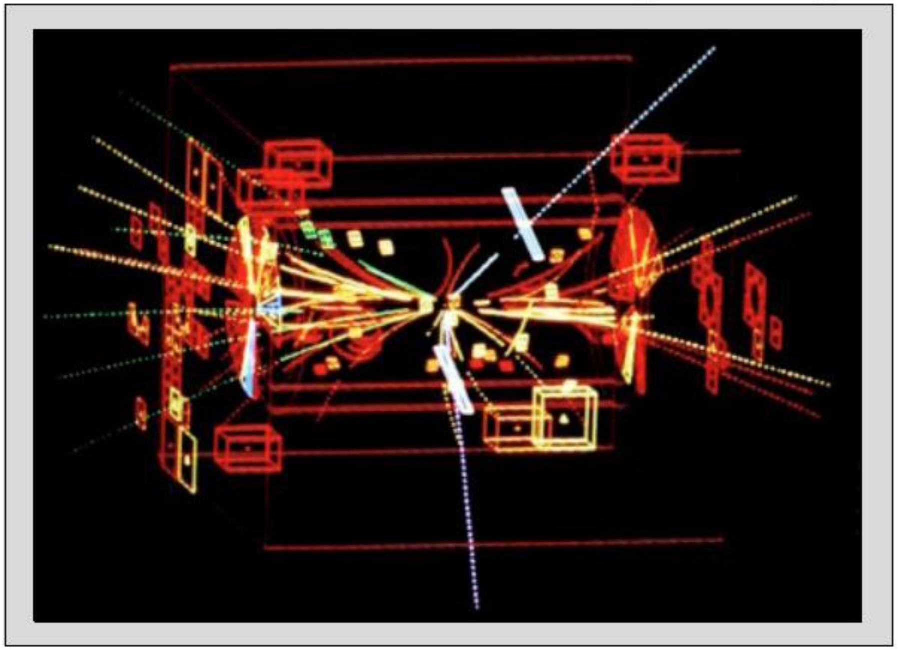
UA1
Detector

Discovery of the W/Z boson (1983)

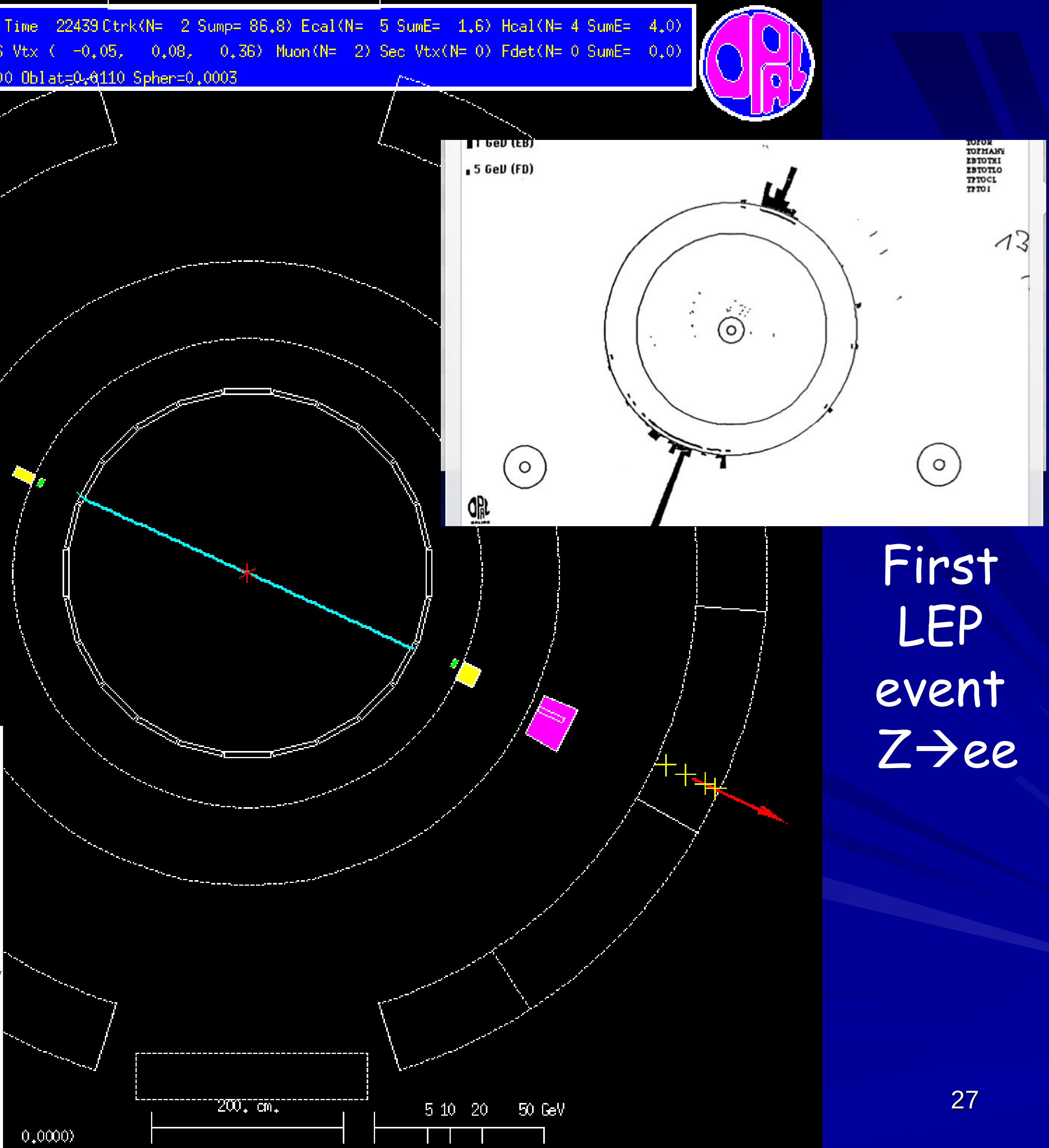
Carlo Rubbia
Simon Van der Meer

[Nobel prize 1984]

First Z^0 particle seen by UA1

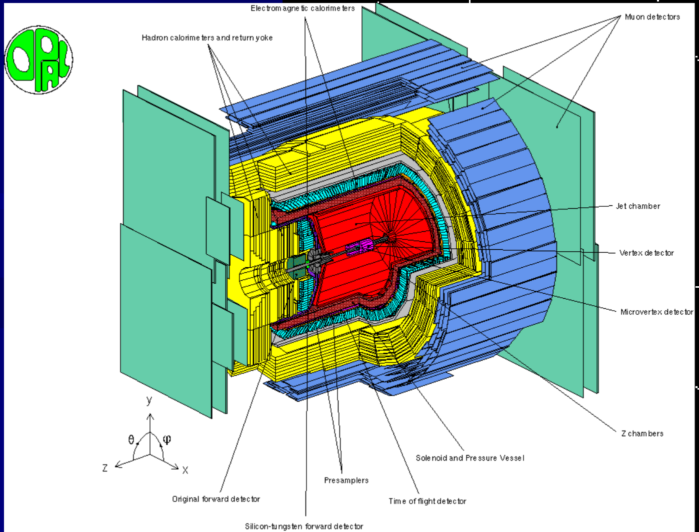


Z →μμ

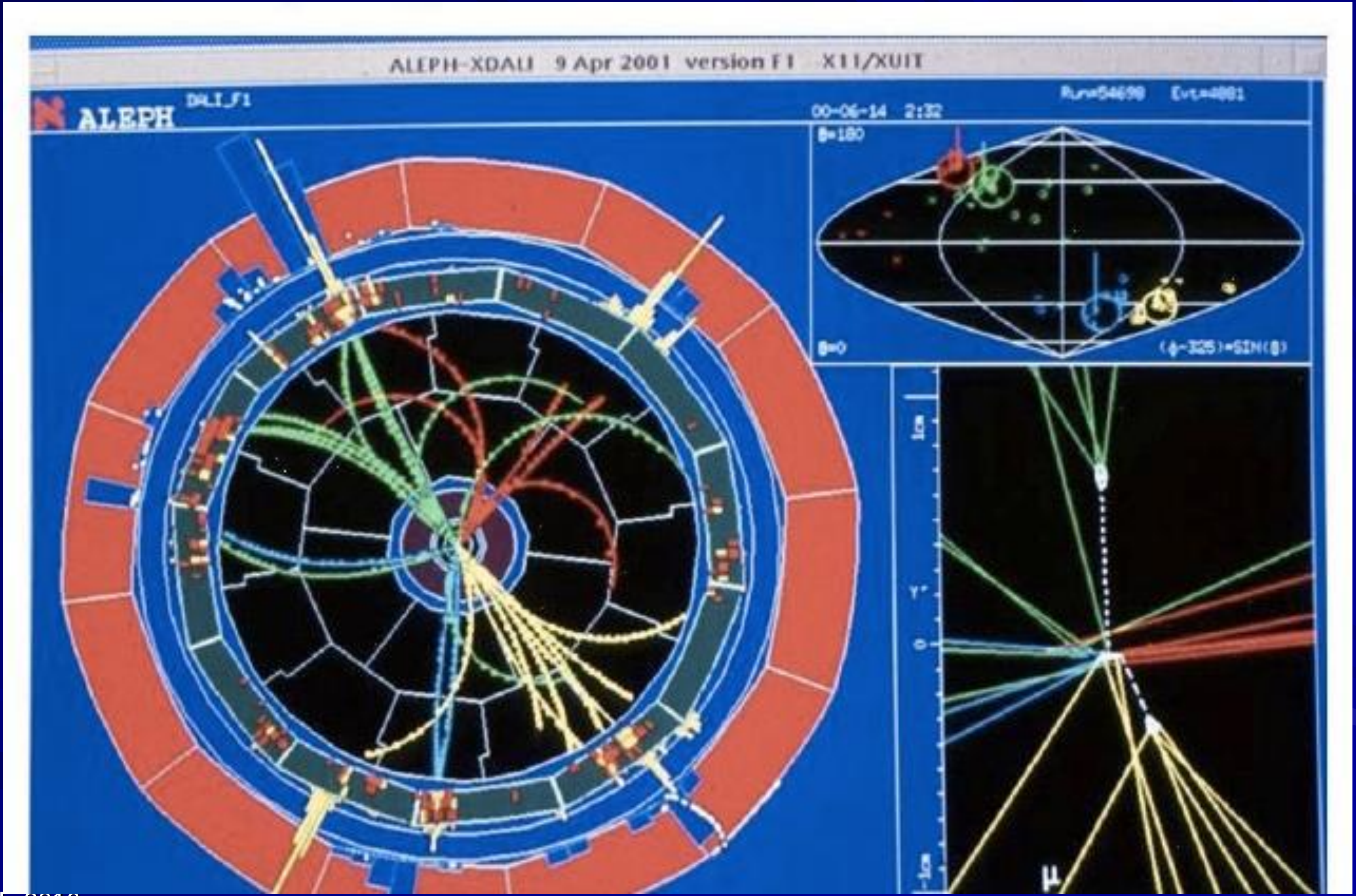


```
Run:event 4093:  4556  Date 930527 Time   22439 Ctrk(N=  2 Sump= 86.8) Ecal(N=  5 SumE=  1.6) Hcal(N= 4 SumE=  4.0)
Ebeam 45.658 Evis  90.8 Emiss   0.6 Vtx (  -0.05,   0.08,   0.36) Muon(N=  2) Sec Vtx(N= 0) Fdet(N= 0 SumE=  0.0)
Bz=4.350  Thrust=0.9999 Aplan=0.0000 Oblat=0.0110 Spher=0.0003
```

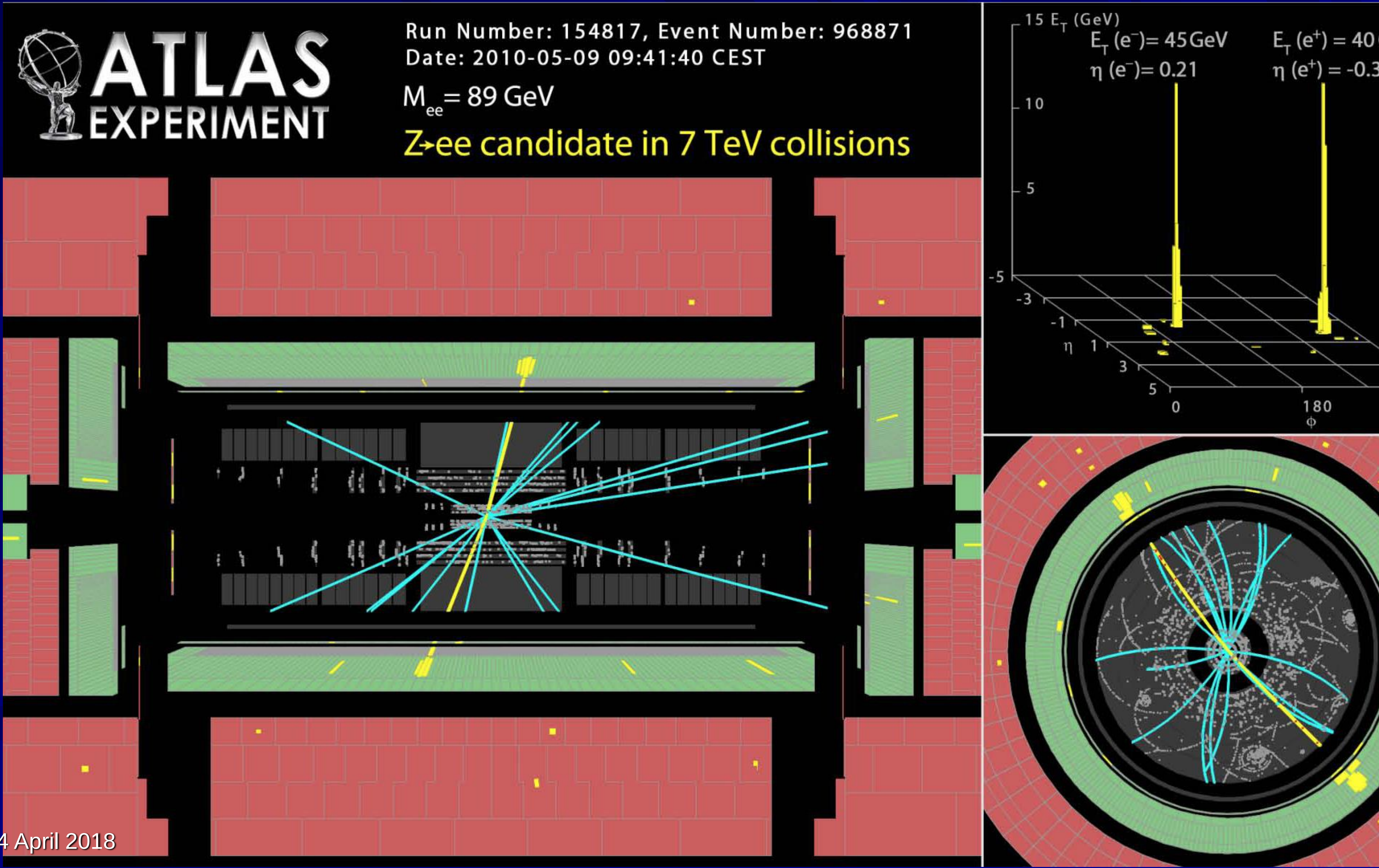
First LEP event Z→ee



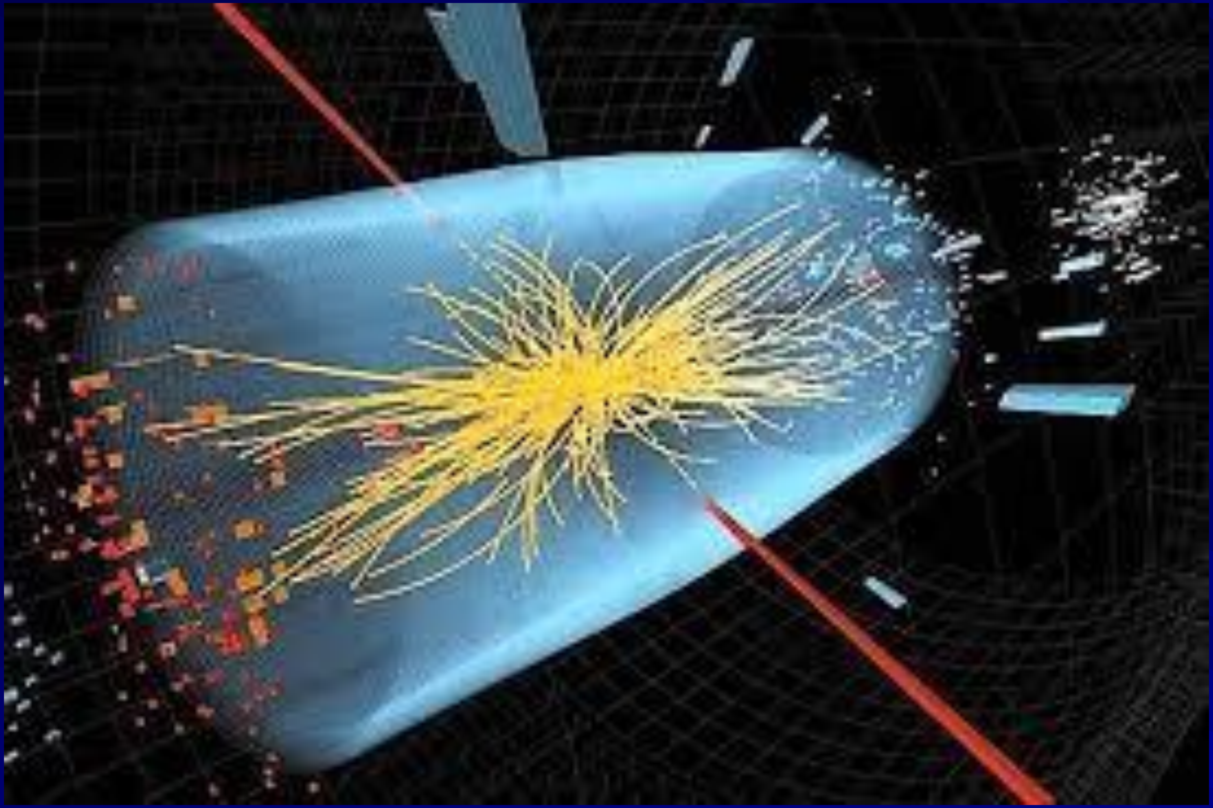
LEP Aleph HZ → bb g candidate (2000)

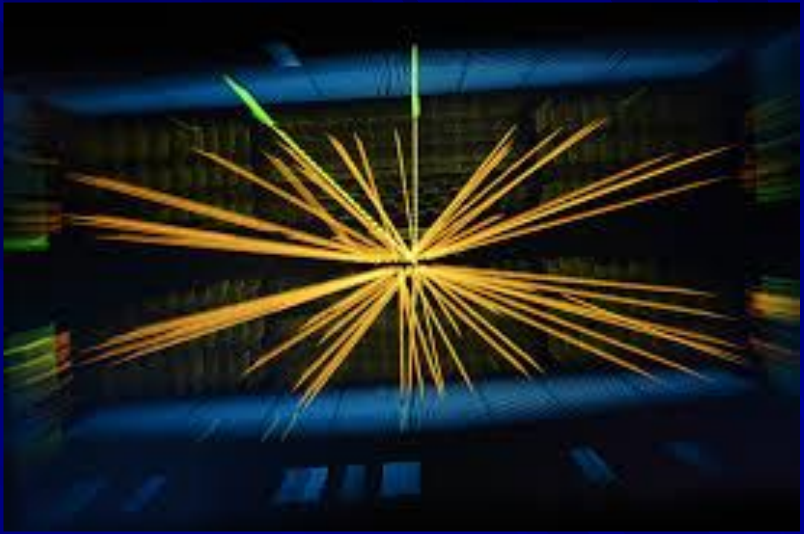


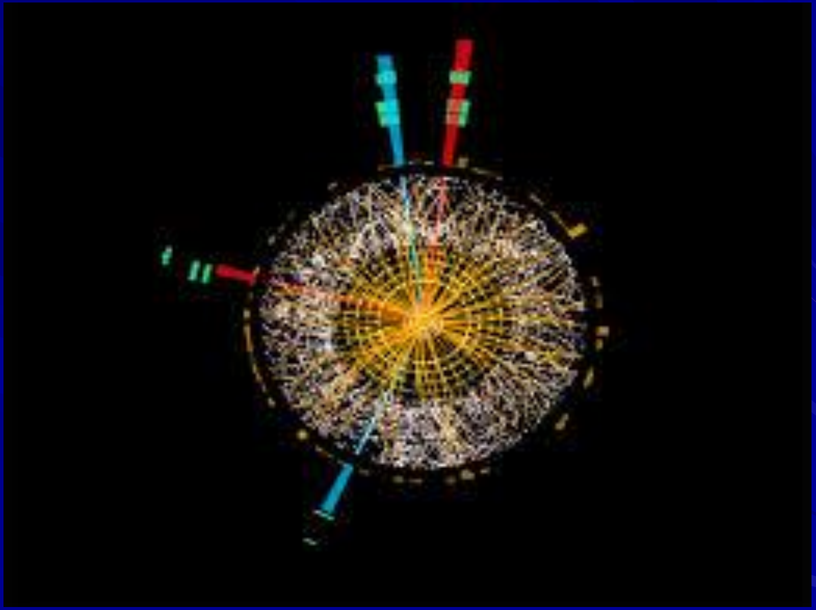
ATLAS (2010)

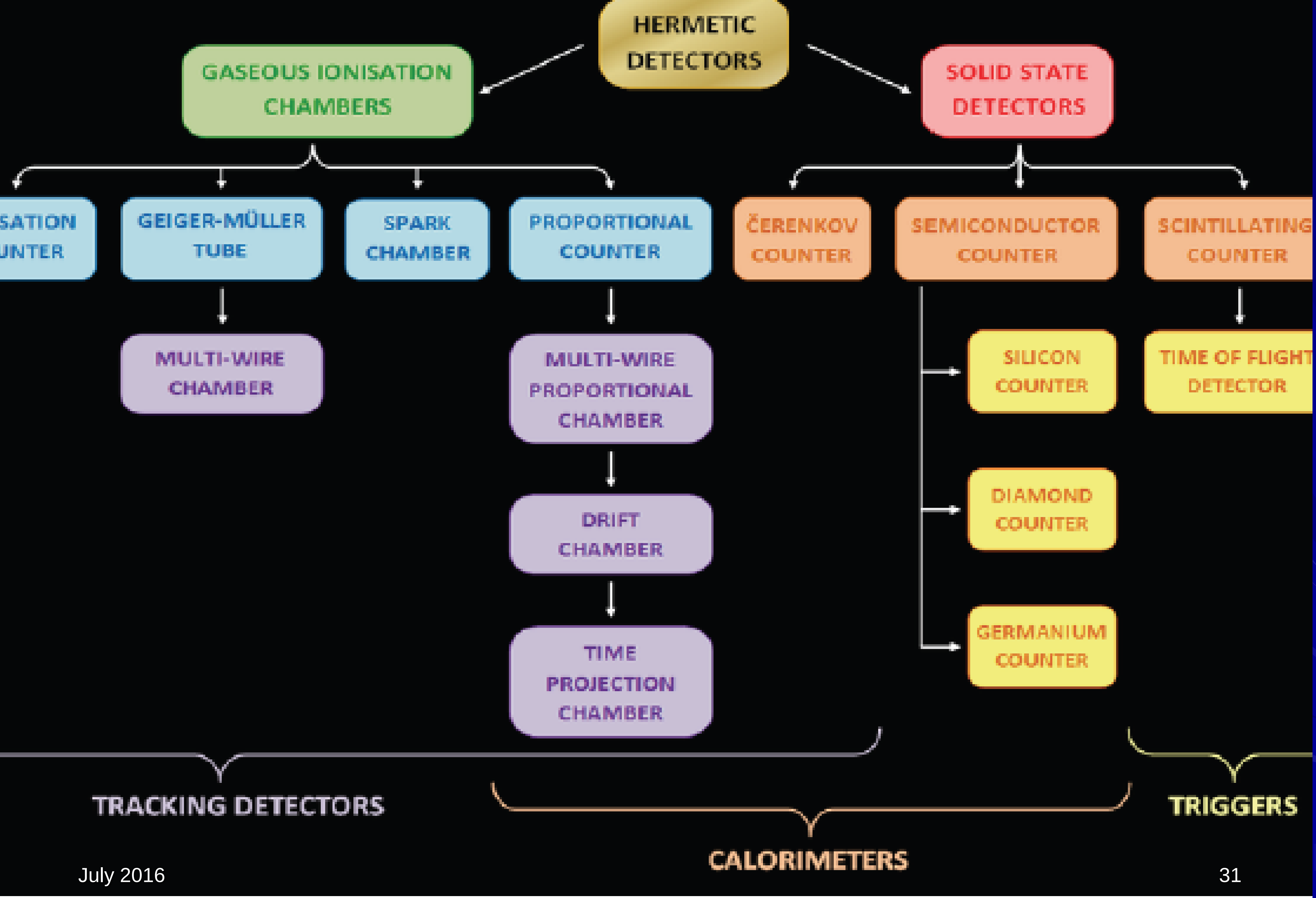

ATLAS EXPERIMENT
Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST
M_ee = 89 GeV
Z→ee candidate in 7 TeV collisions
15 E_T (GeV)
E_T (e⁻)= 45GeV
η (e⁻)= 0.21
E_T (e⁺) = 40
η (e⁺) = -0.3
10
5
-5
-3
-1
η
1
3
5
0
180
φ

A Higgs image









HERMETIC DETECTORS

GASEOUS IONISATION CHAMBERS

SOLID STATE DETECTORS

SATION UNTER

GEIGER-MÜLLER TUBE

MULTI-WIRE CHAMBER

SPARK CHAMBER

PROPORTIONAL COUNTER

MULTI-WIRE PROPORTIONAL CHAMBER

DRIFT CHAMBER

TIME PROJECTION CHAMBER

ČERENKOV COUNTER

SEMICONDUCTOR COUNTER

SILICON COUNTER

DIAMOND COUNTER

GERMANIUM COUNTER

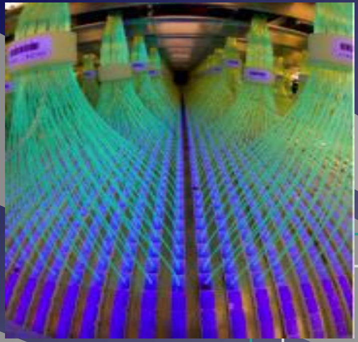
SCINTILLATING COUNTER

TIME OF FLIGHT DETECTOR

TRACKING DETECTORS

CALORIMETERS

TRIGGERS

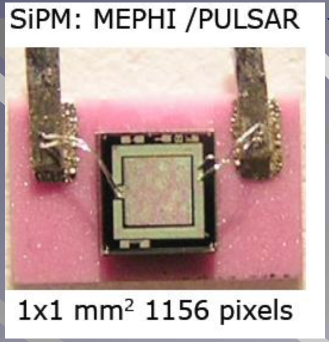


T2K

scintillators

WLS fiber

60000 SiPM



Belle2 RICHs

single γ

ILC - CALICE

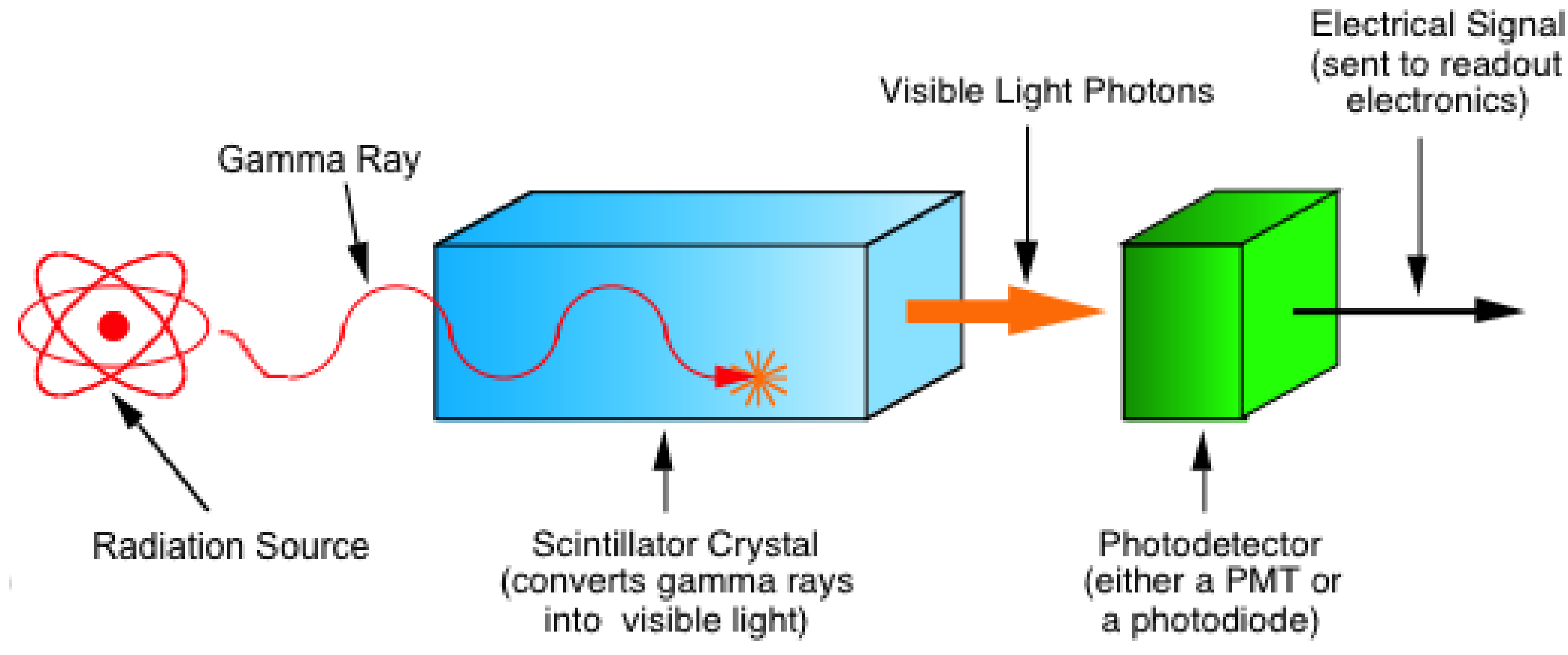
$8x10^6$ SiPM

CMS HCAL

$2\ x10^3$ SiPM

Photon detectors

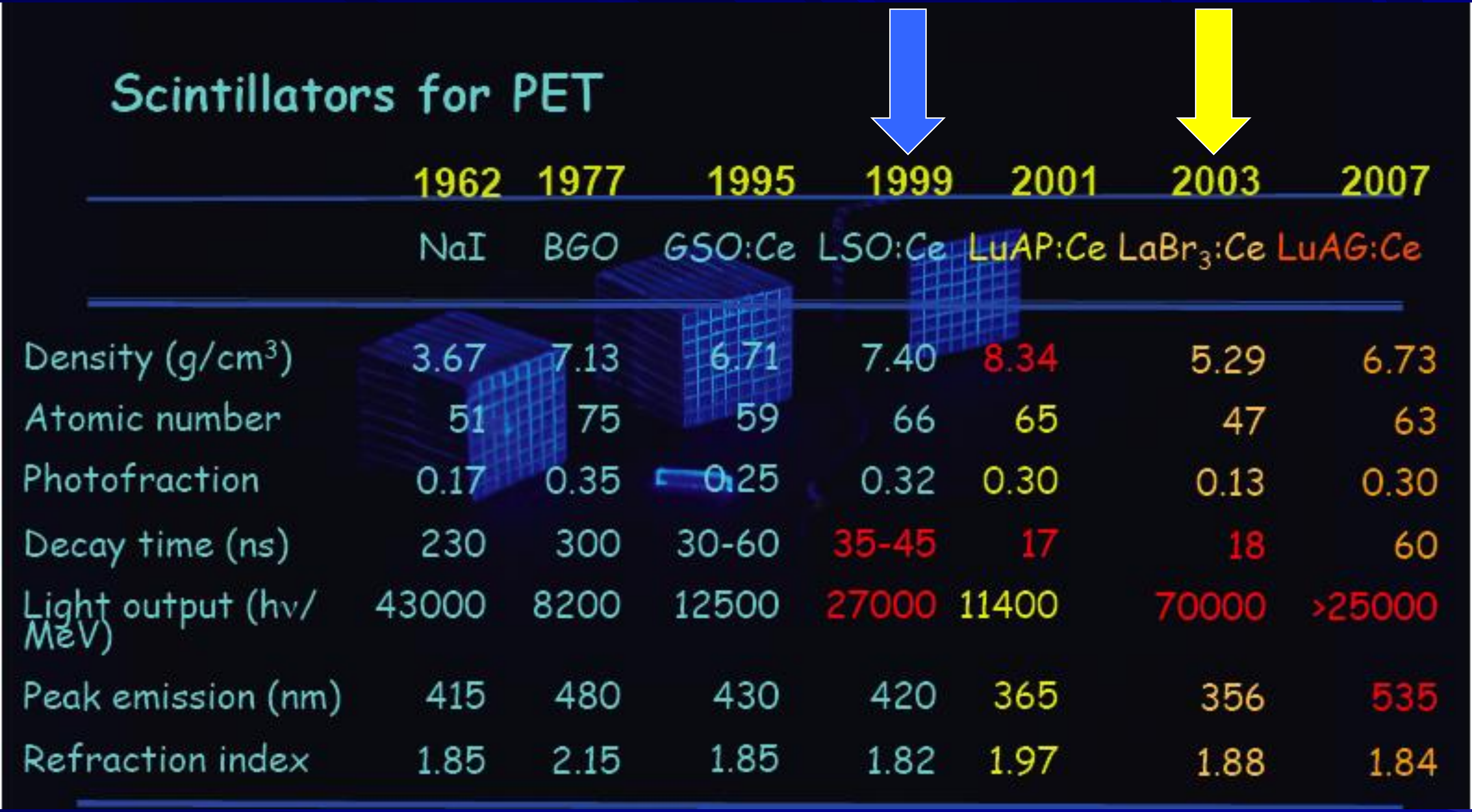
Basic principleEnergy→ Conversion in a Scintillation Detectors



Gamma Ray →> Visible Light → Electrical *Signal*

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**



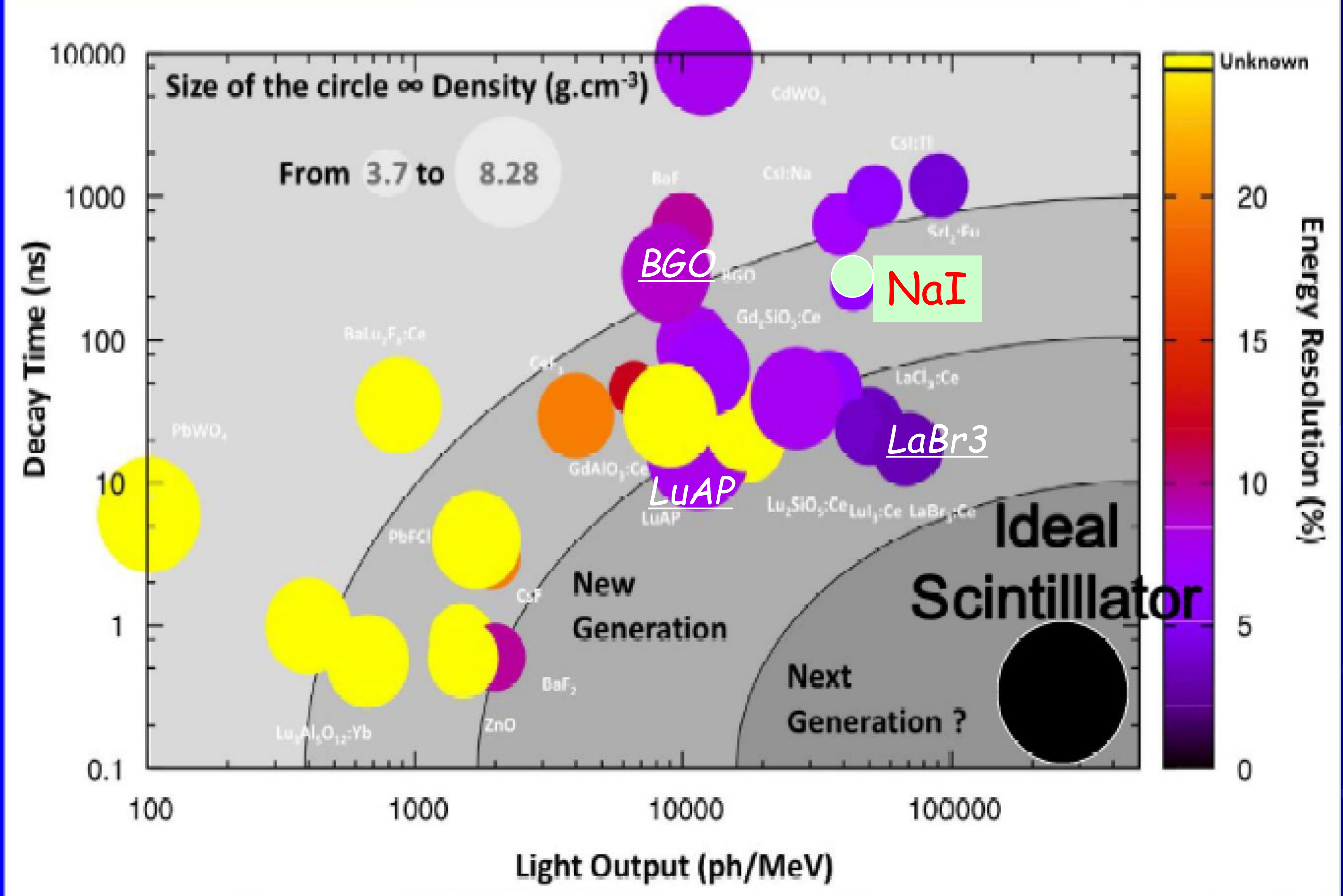
Scintillators for PET

	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

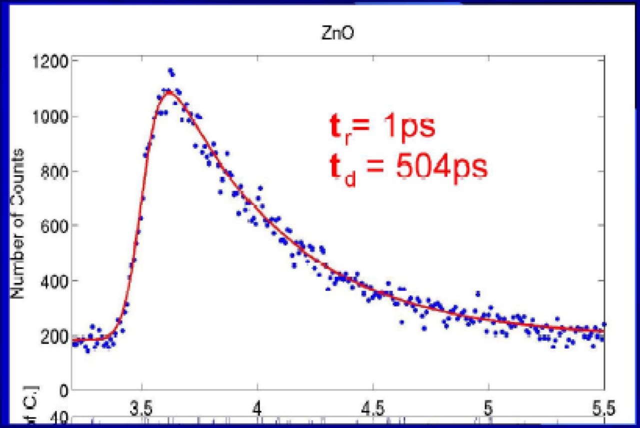
- *Stopping power*
  - *High Z material*
  - *High density*
- *Photoelectric fraction*
  - *High photoelectric cross section to total cross section*
  - *High Z material*
- *Signal to Noise Ratio*
  - *High luminosity*
- *Fast timing (required for TOF)*
  - *High luminosity*
  - *Short decay time*


Size of the circle ∞ Density (g.cm-3)
From 3.7 to 8.28
CdWO4
CsI:Tl
CsI:Na
BaF
SrI2:Eu
BGO
BGO
NaI
Gd2SiO5:Ce
BaLu2F8:Ce
CeF3
LaCl3:Ce
LaBr3
PbWO4
GdAlO3:Ce
LuAP
LuAP
Lu2SiO5:Ce
LuI3:Ce
LaBr3:Ce
Ideal
Scintilllator
PbFCl
CsF
New
Generation
Next
Generation ?
BaF2
ZnO
Lu3Al5O12:Yb
Decay Time (ns)
10000
1000
100
10
1
0.1
100
1000
10000
100000
Light Output (ph/MeV)
Unknown
20
15
10
5
0
Energy Resolution (%)

The scintillator world in 2018

→ re –entering in a development phase (SCINT 2017)

- Large development effort by the nuclear security community
  - Good energy resolution (LaB3, SrI2
  - Neutron sensitivity ,

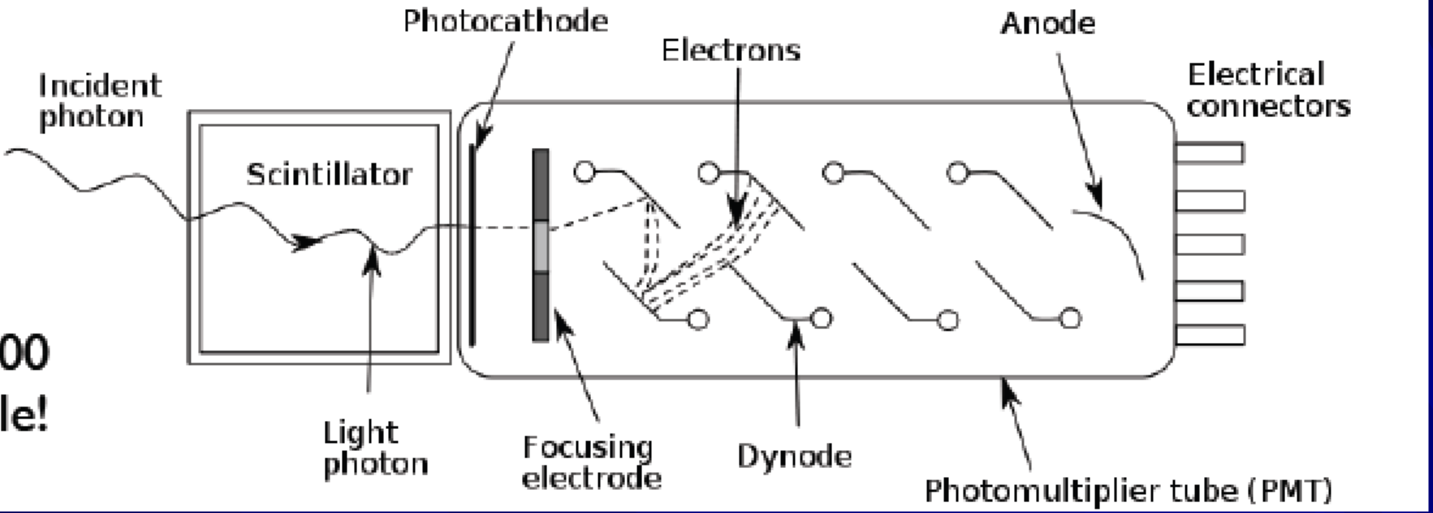


- HEP need material beyond PbWO
  - Radiation hardness compensation
- PETMedical Imaging (PET) needs material beyond LSO
  - Time of Flight and Energy resolution
- **Recent using nanotechnologies → Photonic Crystal (NASA,MIT …)**
  - **Increase light output**
  - **Decrease photostatistic jitter**
  - **Redistribute the light in the fastest propagation mode in the**

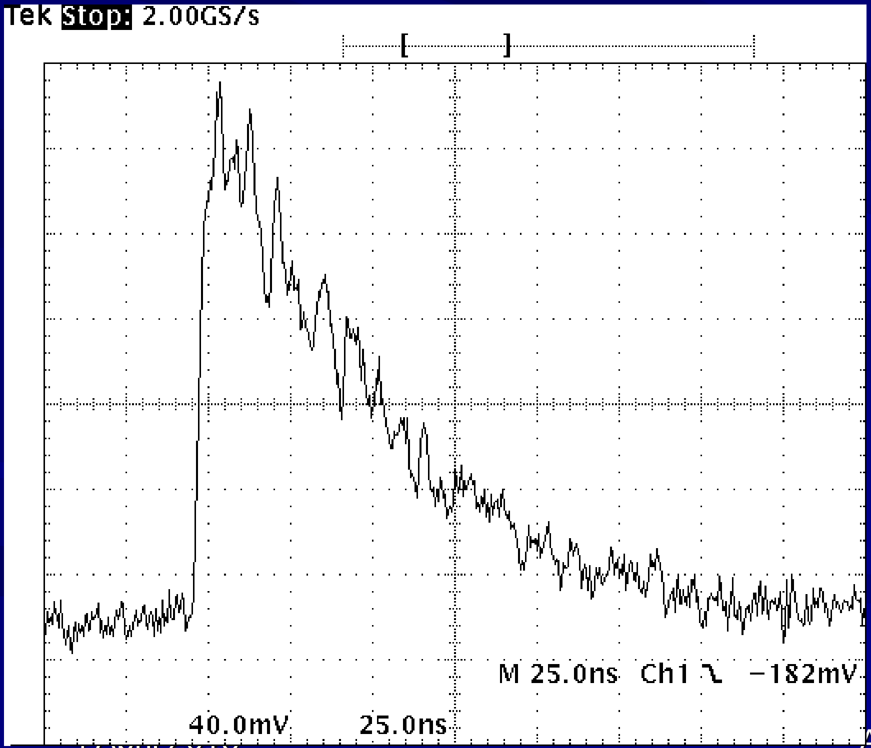
Photodetectors

From the gazeous world to the silicon world

Vacuum Photomultiplier Tubes



Gains of
x100,000,0000
are achievable!



Photomultipliers tubes (PMT)

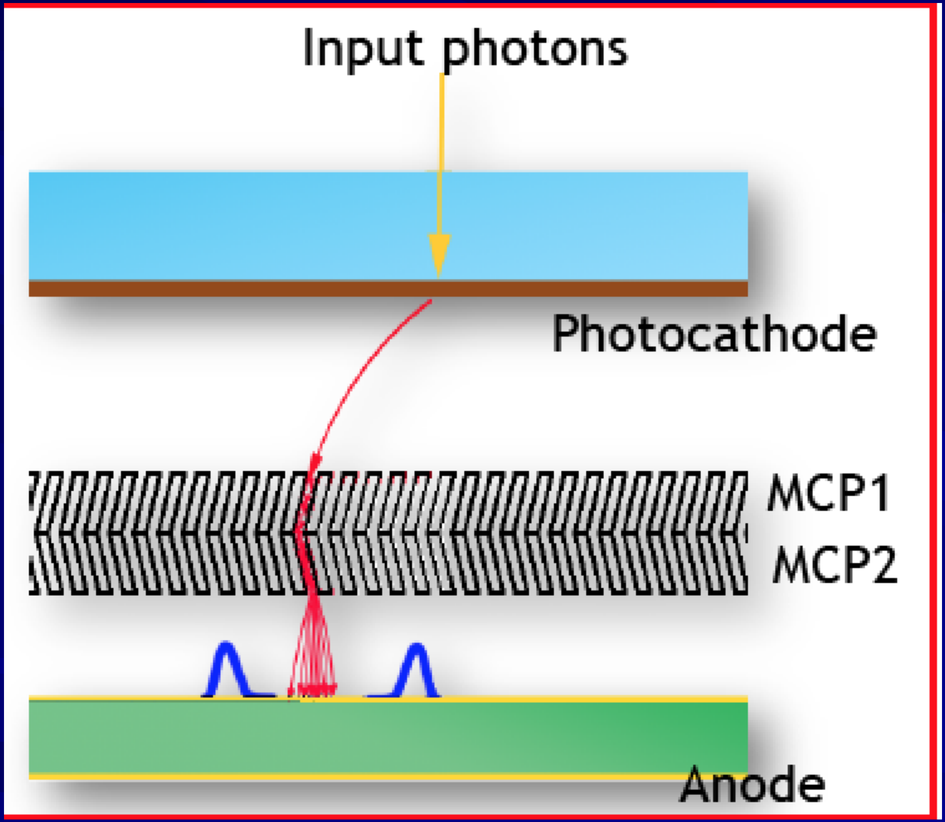
- Standard : PMT → Use since 75 years (RCA 1936)
  - Large gain, high QE,and stability.
  - But bulky, sensitive to magnetic field
- In 70"s → > 10 manufacturers (EMI,RCA ....)
- 2000's → 75% production for medical (Spect/,PET)
- Today only 2 (Hamamatsu & Photonis)
  - -> **closing their main PMT factories**

- However → New technological developments
  - LAPPD (UC Chicago & Argonne)
  - Tynode (H. Van Der Graaf)

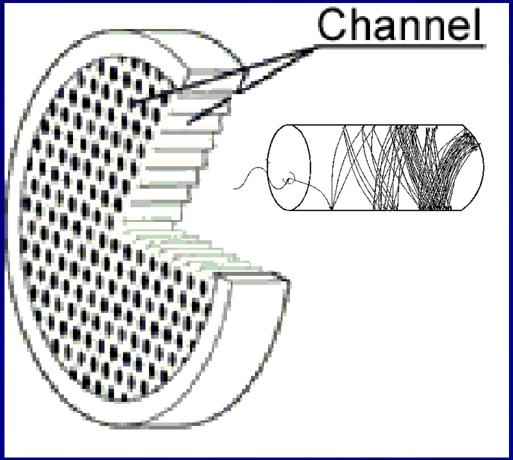
Micro Channel Plate → How does it work ?

- High,gain>10^7,low noise,low power, $\sigma(t)<10$ psec, $\sigma(x)<\$1$mm
- Goal → large area, low cost:

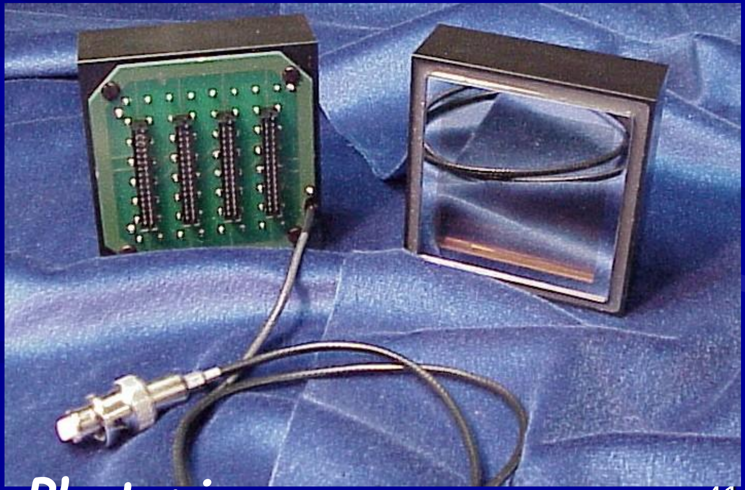
(since intrinsic time and space scales are set by the)



Atomic Layer deposition (ALD)

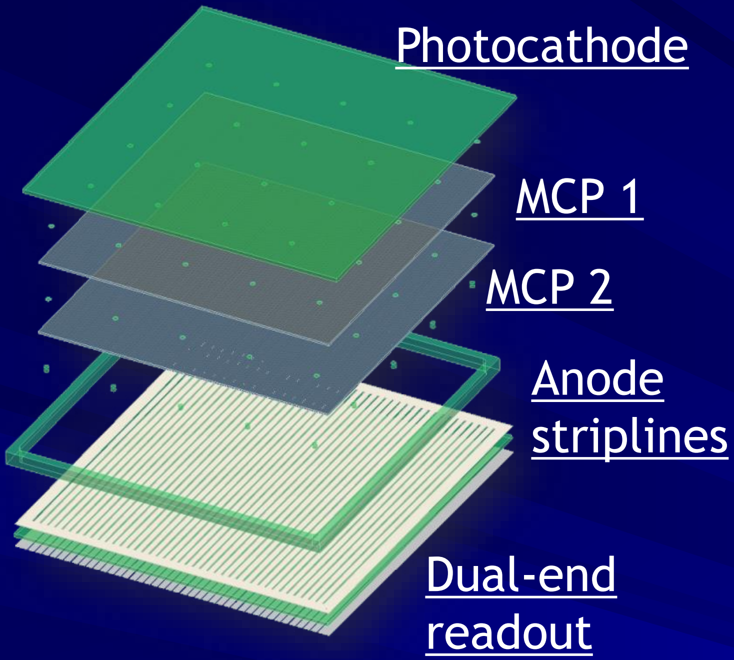


pore sizes 2-20μm



Photonis

Large Area Micro-Channel Plates Devices



LAPPD project : Chicago-ANL-Hawaii

Large Area: 200 x 200 mm2

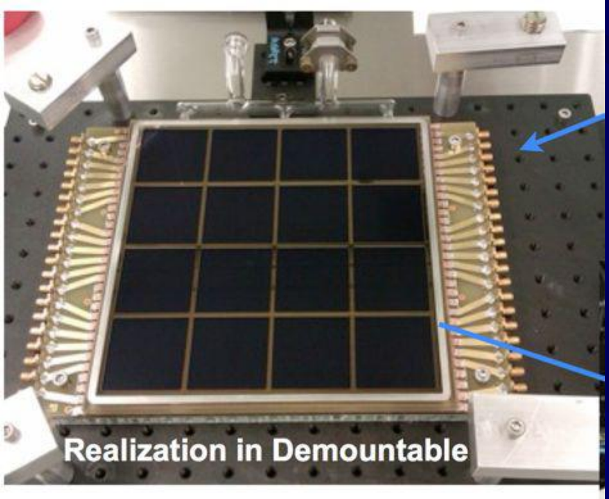
- Flat Geometry
- PMT Sensitivity: QE >20% w/bi-alkali photocathode
- Picosecond Timing: resolution <60 pS,
- Sub-mm spatial resolution
- Lower Cost per Unit Area

Transmission lines 2D readout:

limits the number of electronic channels compared to pixels

Electronics

- GigaSample/s Waveform Sampling and Digital Processing

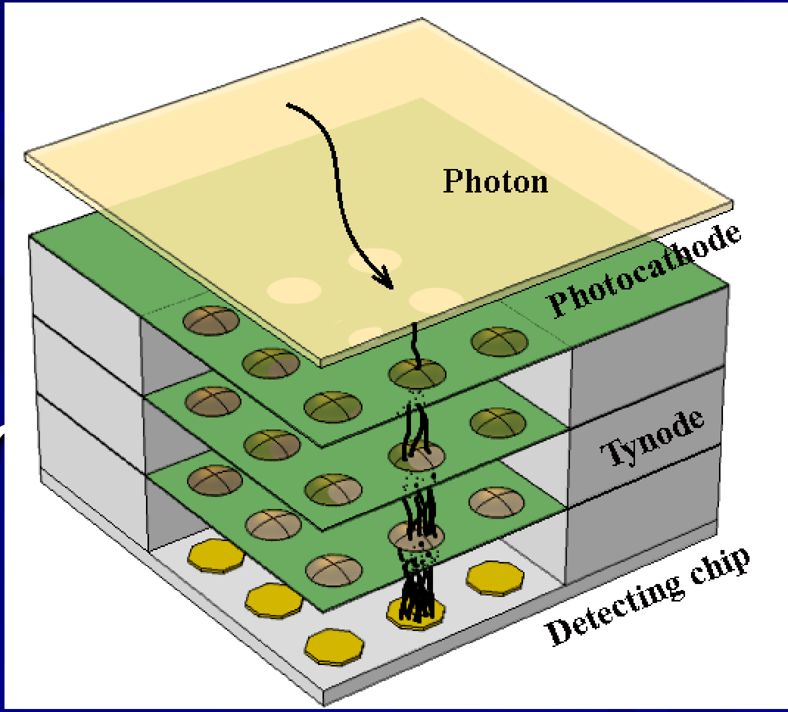


Coming soon

A Super Module holds 12 tiles in 32 rows.15 waveform sampling ASICS on each end of the tray Digitze 90 strips. 2$layers of local Processing (Altera) measuer extract Charge,time,positon,goodnessof fit

http://psec.uchicago.edu/

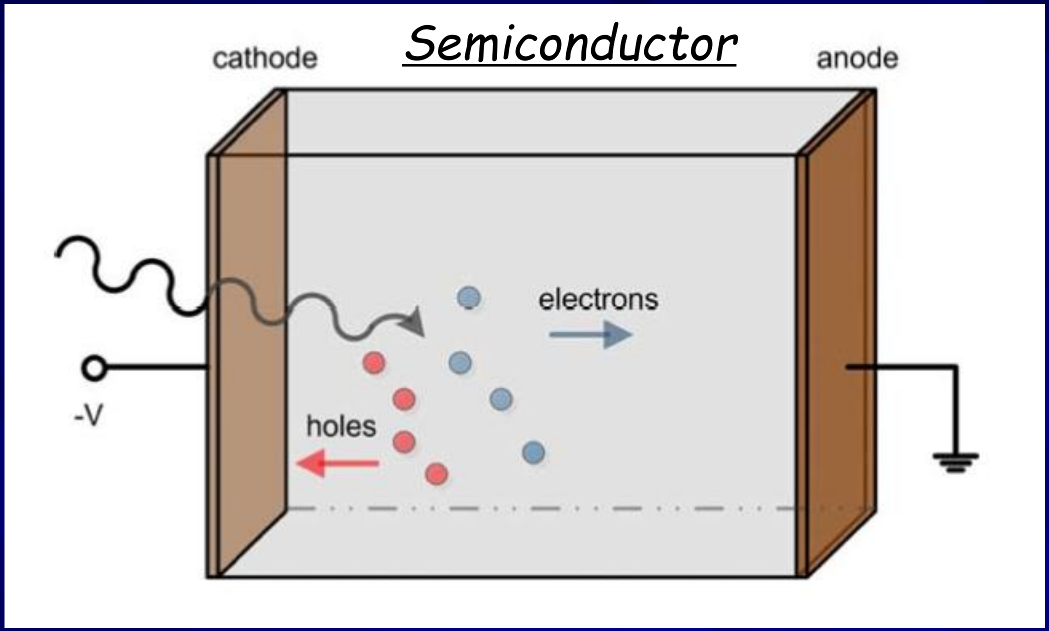
TYNODE:typsi Membrane Project (H.Van Der Graaf) Nikhef-TUDelf-BNL-Photonis



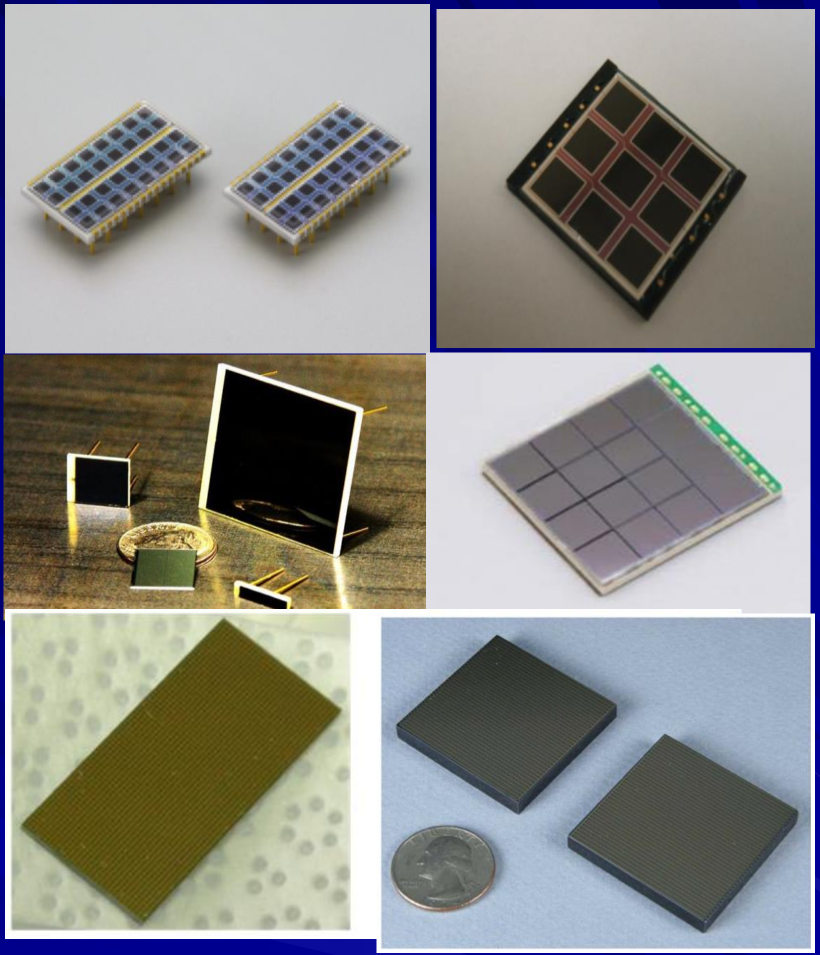
- **detection efficiency: Quantum Efficier**
- **single (digital) soft photon detectors**
- **time resolution**
- **2D spatial resolution**
- **Principle = active photocathode**

- → drift field pushing electrons to emission vacuum surface
- electric field created in between by potential defining graphene planes
- all layers build up individually by *atomic layer deposition* ALD
- electron emission stimulated by negative electron affinity by *termination*
- First designed after *ab initio* simulations of 3D atomic building blocks
- http://dx.doi.org/10.1016/j.nima.2016.11.064.

The'solid state photodetector

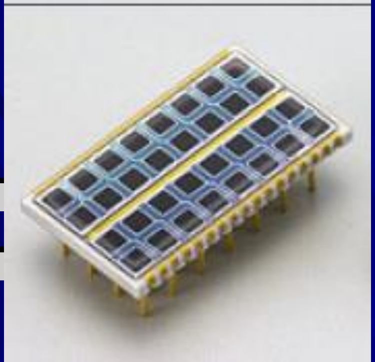


- Electric field is created by an applied bias voltage
- e-h pairs are created by incoming radiation
- Electrons move to the anode and holes move to the cathode
- Electrical signal is induced on the electrodes by the moving charges



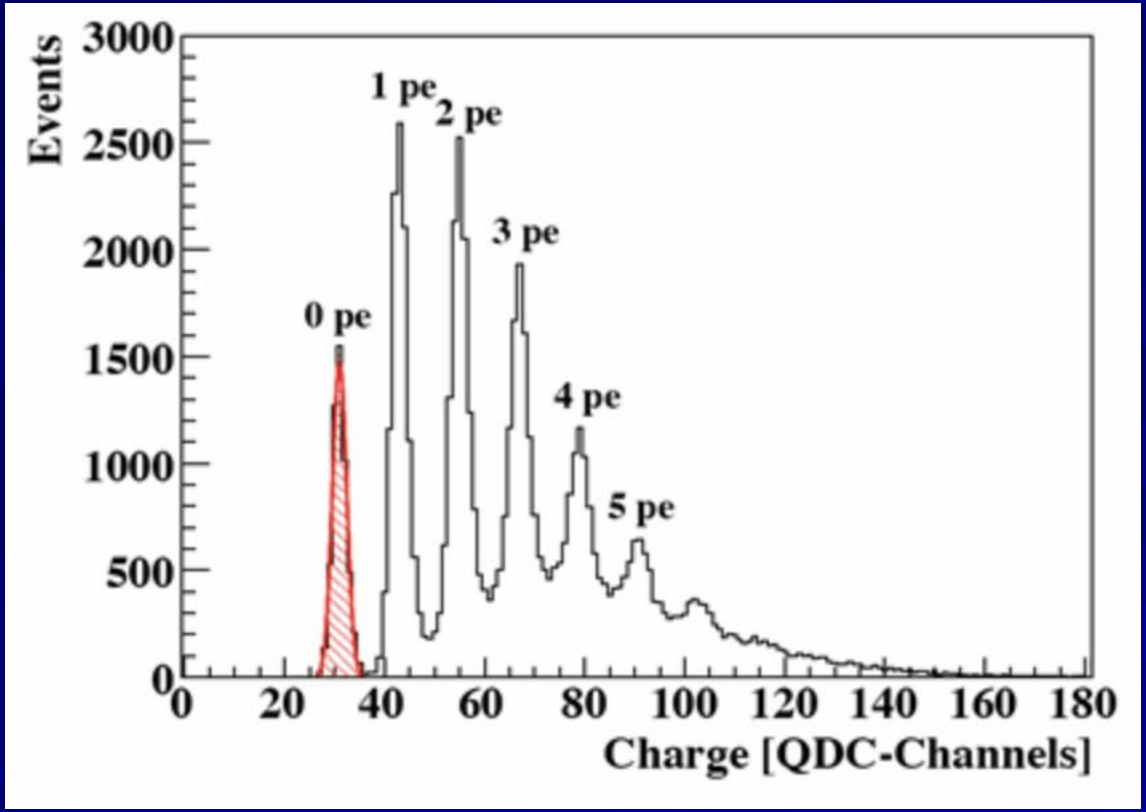
Photodiode (PIN)
Avalanche Photodiode *(APD)*
Silicon Photomultiplier (SiPM)
CdZnTe
CdTe/

Solid State Photodetectors



- 1980 → PIN diode for SLAC SLD calorimeter
- 1985 → APD's EGG (McIntyre)
  - First Sherbrooke animal PET (Roger Lecomte)
  - SDC and CMS EM calorimeter read out
- 2000 → SIPM (MPPC ..) arrays in Geiger mode
- 2005 -→ DSIPM
- Today → Many providers & development (Philips, Hamamatsu,RMD ….)

Typical SiPM signal

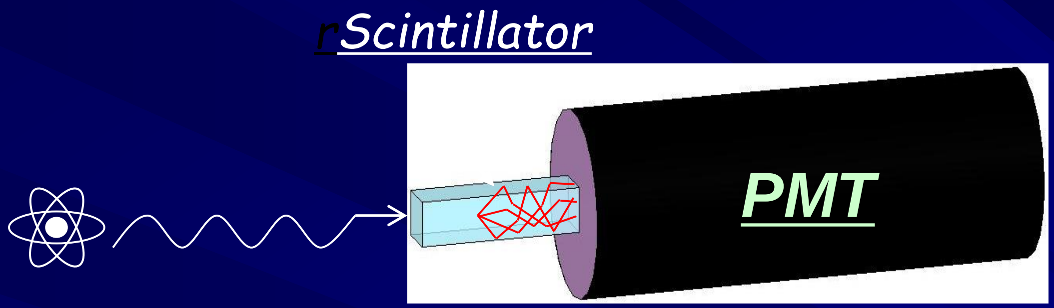


. Example of single photon charge spectrum. A peak in the spectrum corresponds to a certain number of photoelectrons, e.g., 0 pe, 1 pe, etc. Adapted from Eckert et al. (2010).

Photodetector Technologies: A Comparison

Photo detector	PMT	PIN	APD	SiPM
Technology	Vacuum-Based	Solid-State	Solid-State	Solid-State
Gain	High	Poor	Moderate	High
Detection Efficiency	Low to Moderate	High	High	Moderate to High
Noise	Low	Moderate	Moderate	Moderate
Timing Response	Moderate to Fast	Slow	Slow	Fast
Packaging	Bulky	Compact	Compact	Compact
Sensitivity to Magnetic Field	Yes	No	No	No
Bias Voltage	>1kV	~50V	100–1000V	~50V

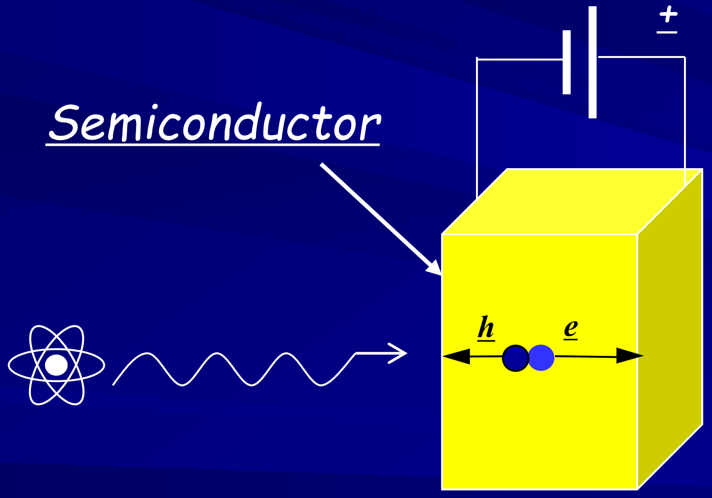
Scintillation Detectors vs Solid-State Detectors



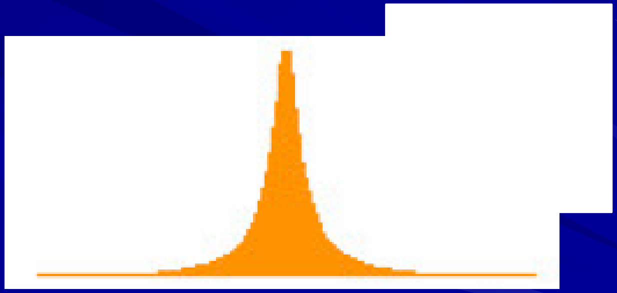
~1,500 e^-
@ 140 keV

Energy per e^- ~ 10 – 200 eV

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



~30,000 e^-
@ 140 keV



Energy per e^- ~ 3 – 5 eV

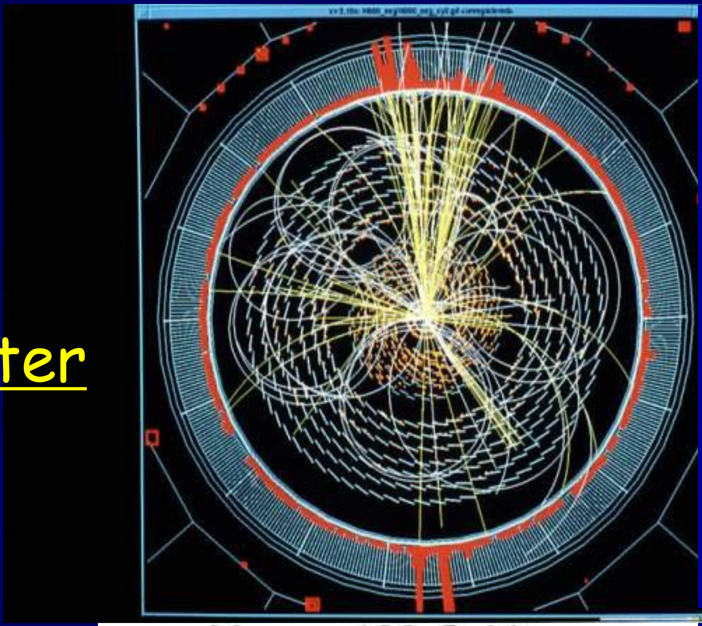
Gamma Ray --> Electrical Signal (Direct Detection)

HEP & PET

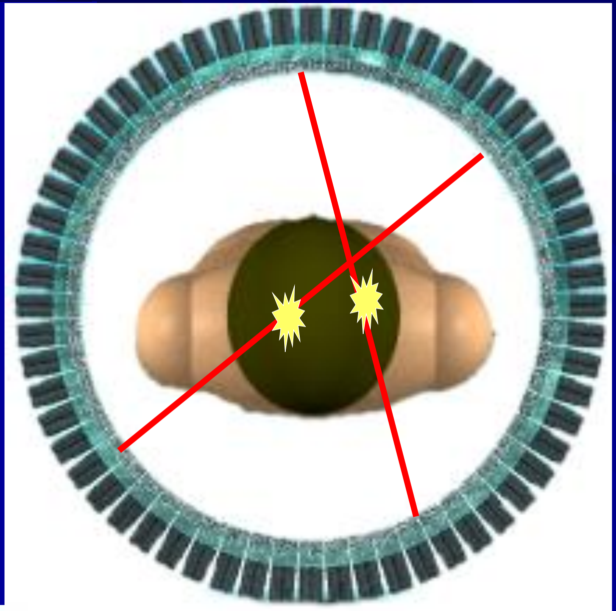
Similarities and differences

Calorimeter

HEP



M_{Higgs} = 100 GeV



PET Camera

Biomedical Imaging

Similarities

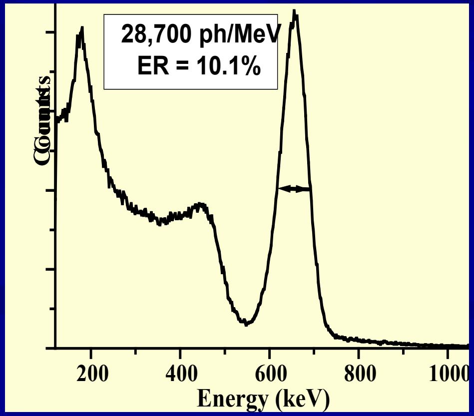
Geometry and granularity

Detector (Crystals & scintillator)

Sensor Photodetectors (PMT,APD)

Digitizers: ADC,TDC,

Data volume (Gbytes)



Differences

Energy range

(10GeV → -511keV)

Event Rate 40 → 10 MHz

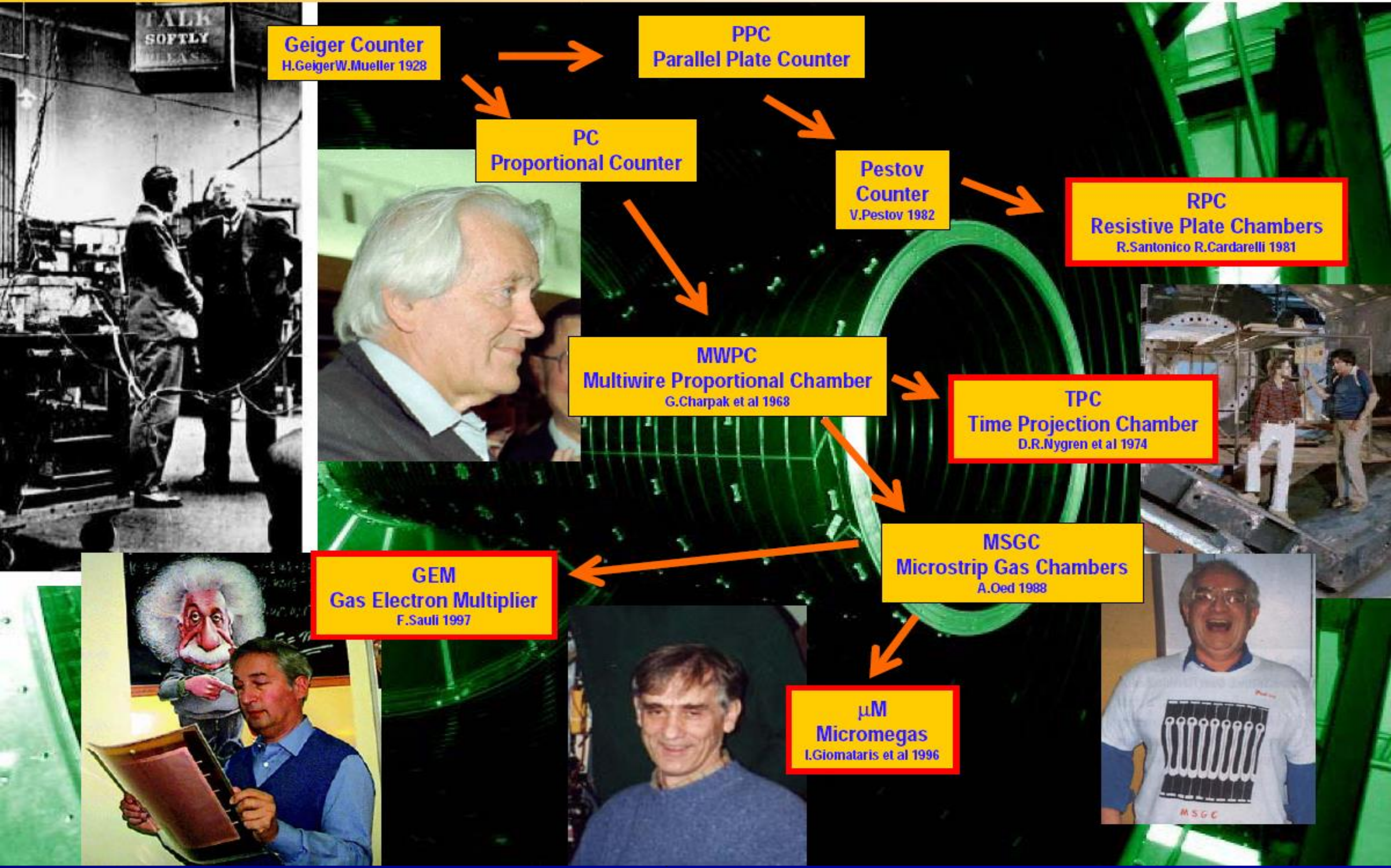
No synchronization

Self triggered elrctronics

Multiple vertices

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

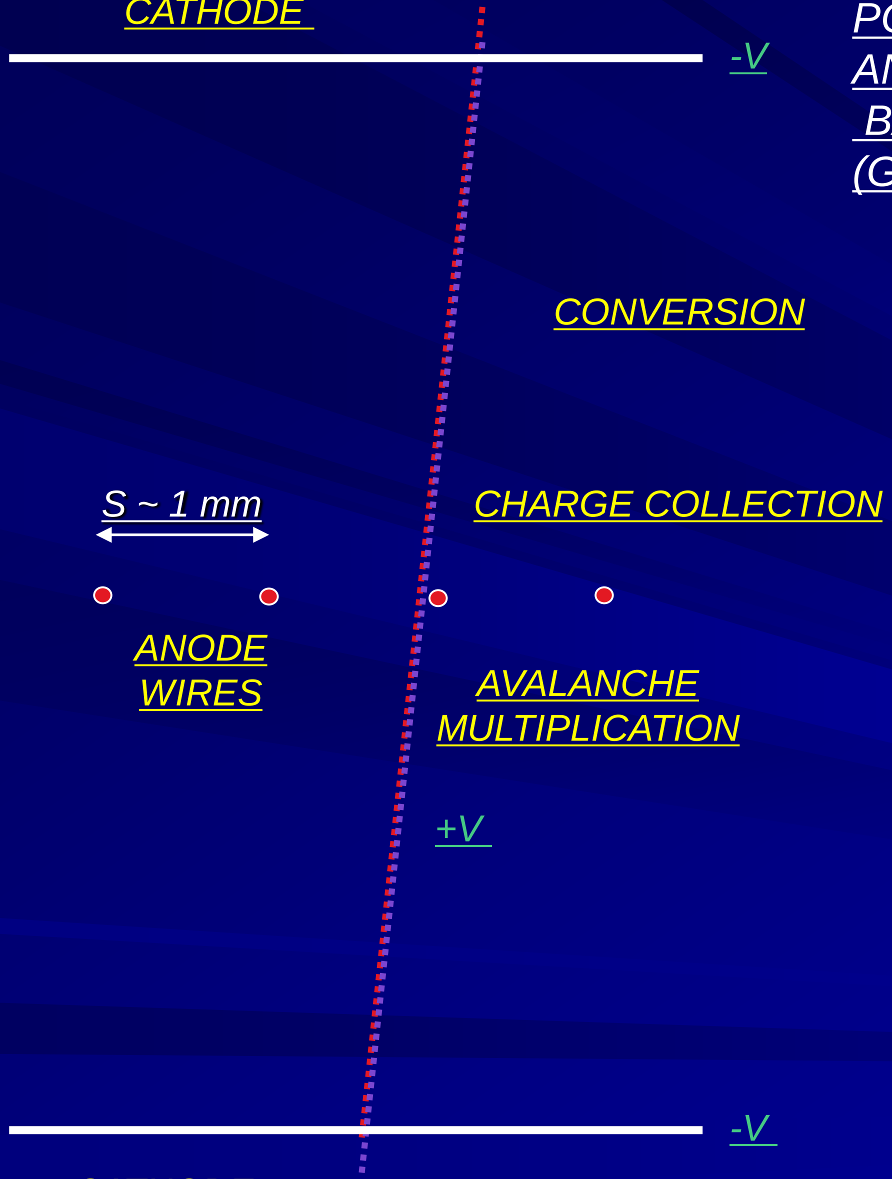
TPC
Time Projection Chamber
D.R.Nygren et al 1974

MSGC
Microstrip Gas Chambers
A.Oed 1988

GEM
Gas Electron Multiplier
F.Sauli 1997

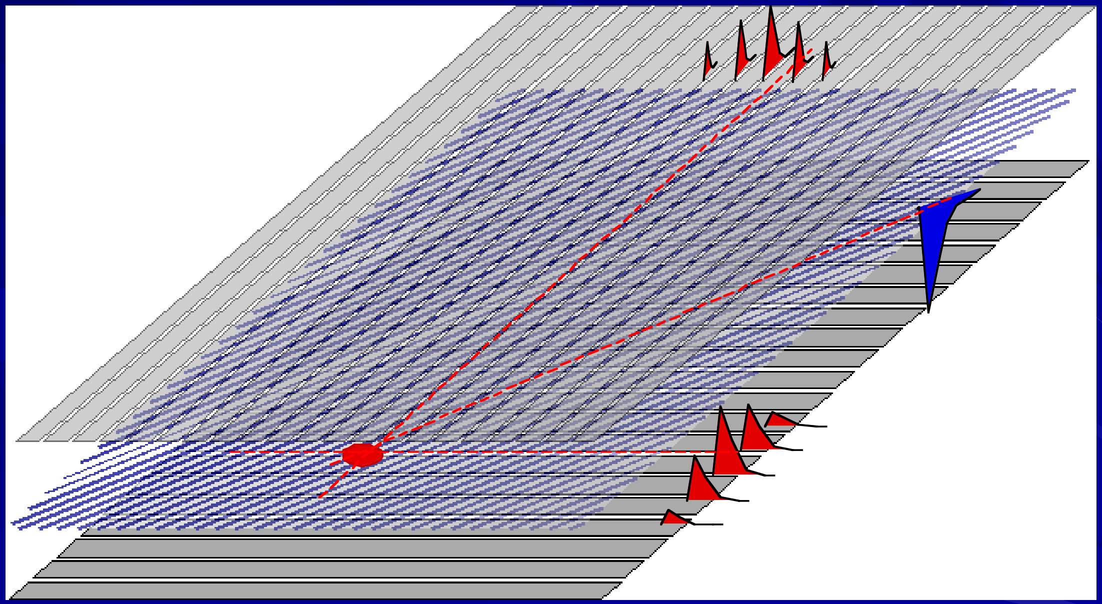
μM
Micromegas
I.Giomataris et al 1996

Multi Wires Proportional chambers MWPC



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)

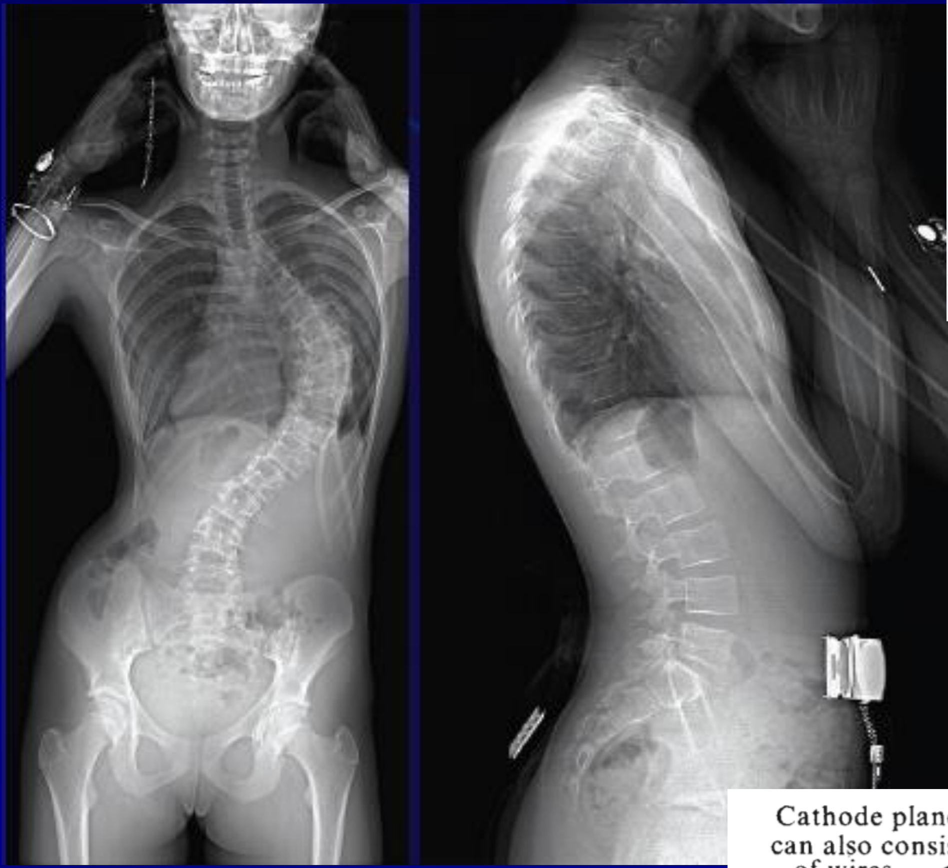


Spatial resolution determined by: Signal / Noise Ratio
Typical (i.e. 'very good') values: S ~ 20000 e: noise ~ 1000e
Space resolution < 100 μm

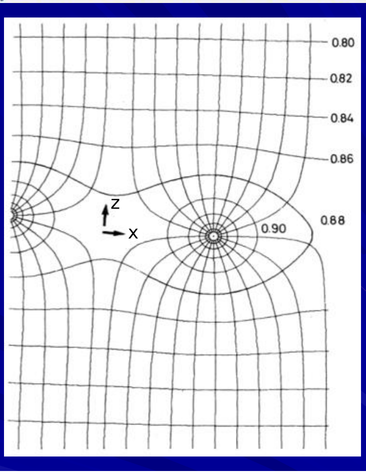
E. Gatti et al, Optimum geometry for strip cathodes ... , Nucl. Instr. and Meth. 163(1979)83

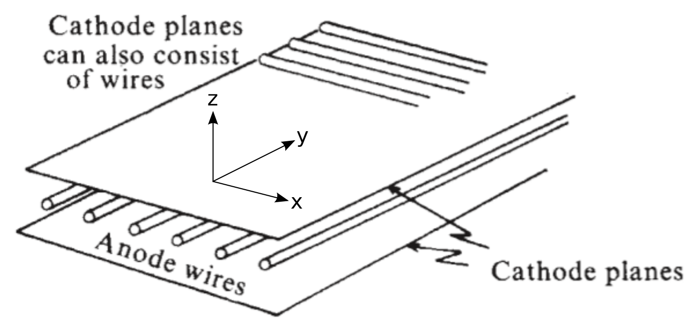
The 1970's dream : Digital radiography with MWPC
A tribute to George Charpak

- With 10 time less dose



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



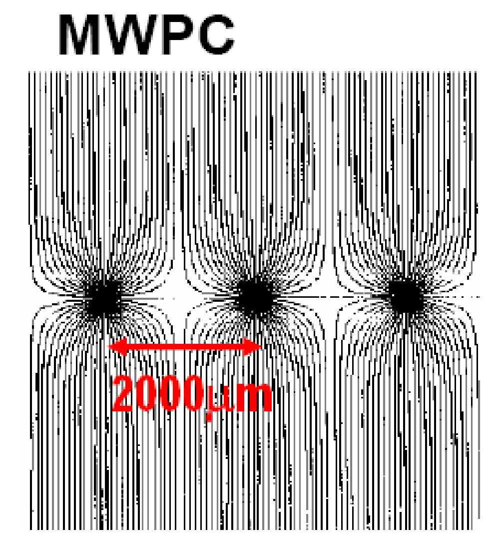


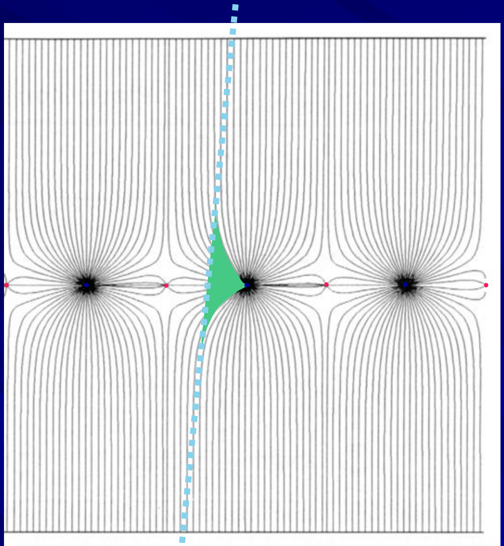
From MWPC's to MGPD's

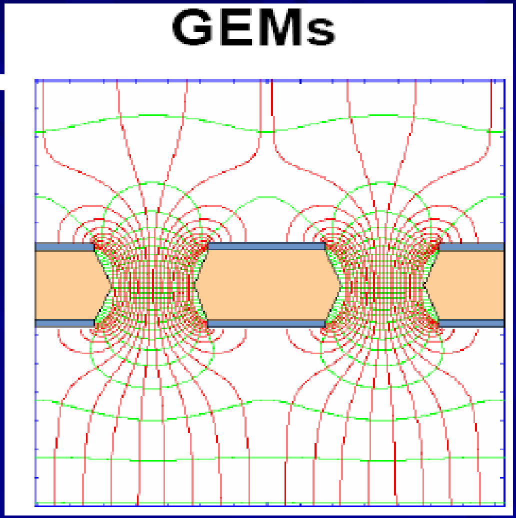
MGPD

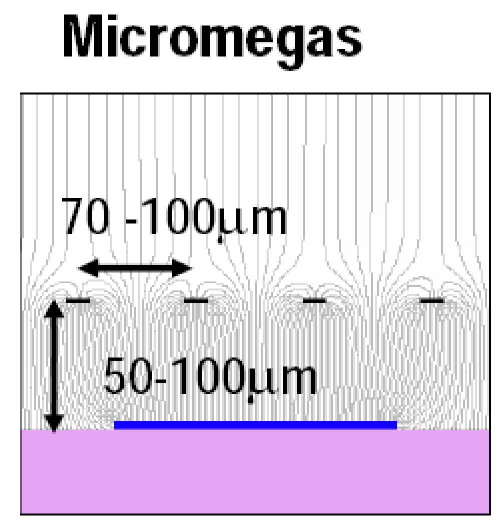
MWPC

Drift Chamber









1975 - 1995
UA2-LEP

1990 -

Multiwire Proportional Chamber

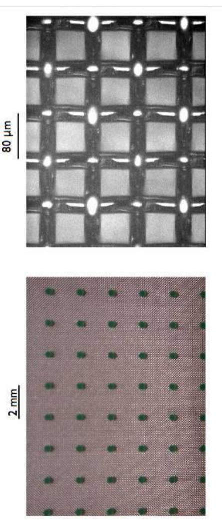
Georges Charpak 1968

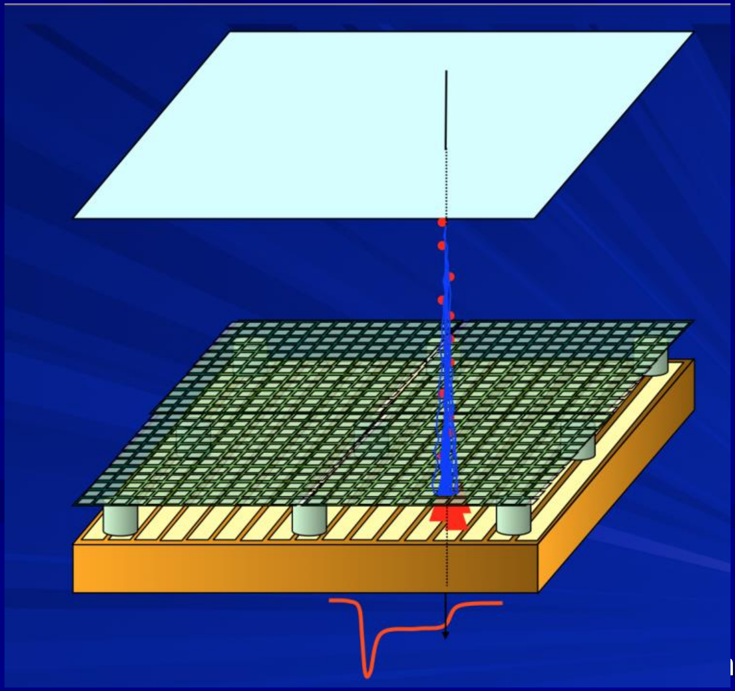
GEM F.Sauli)
Micromegas Y. Giomataris

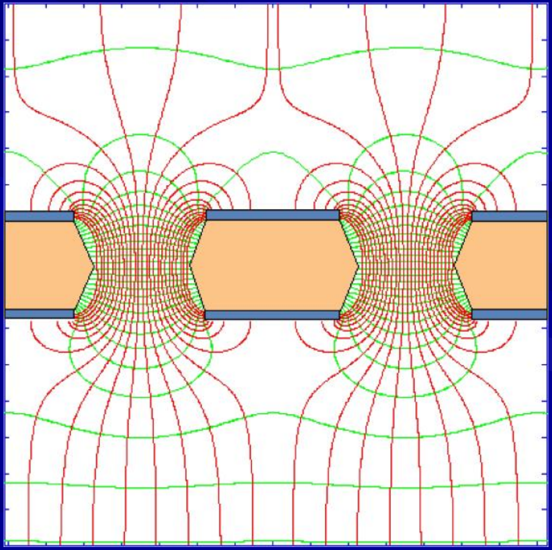
MPGD

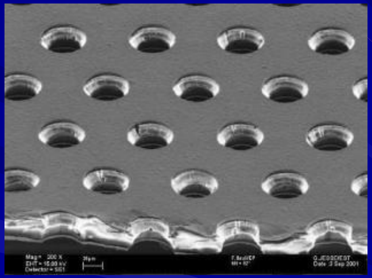
- From 1988-1998 Micro-technologies and etching techniques allowed development of Micro Pattern Gaseous Detectors

- MICROMEsh GASeous Structure (MICROMEGAS)
  - Thin gap Parallel Plate Chamber: micromesh stretched over readout electrode.
- Gas Electron Multiplier (GEM)
  - Thin, metal-coated polymer foil with high density of holes, each hole acting as an individual proportional counter.









To summarize X Ray imaging

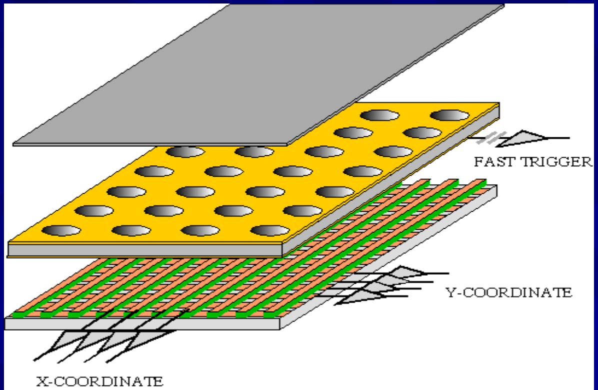
Wire Chamber Radiography:

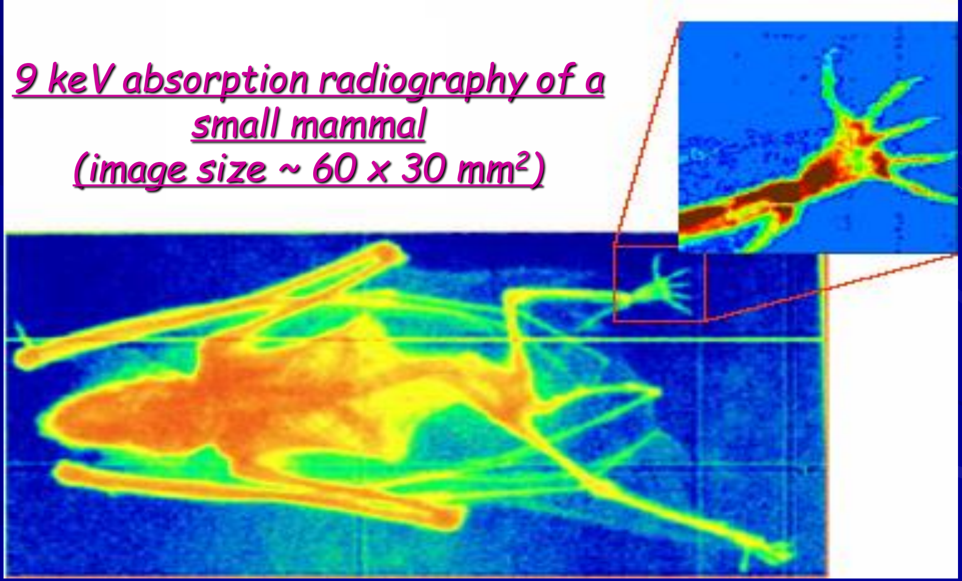
Position resolution ~ 250 μm

A. Bressan et al, Nucl. Instr. and Meth. A 425(1999)254
F. Sauli, Nucl. Instr. and Meth.A 461(2001)47
G. Charpak, Eur. Phys. J. C 34, 77-83 (2004)
F. Sauli, http://www.cern.ch/GDD

GEM for 2D Imaging:

Using the lower GEM signal, the readout can be self-triggered with energy discrimination:





9 keV absorption radiography of a small mammal
(image size ~ 60 x 30 mm^2)

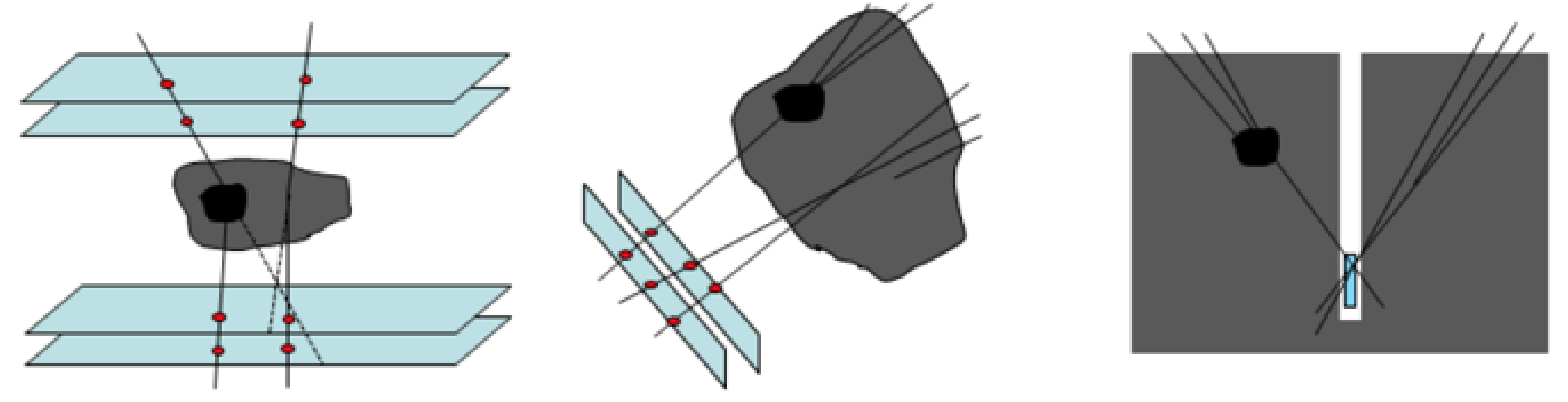
Position resolution ~ 100 μm
(limited by photoelectron range in the gas)

Muon Tomography

- Muon generated by cosmic rays in the upper atmosphere used as a probe (150 events/s/m2)
- o Highly penetrating particles for 'radiography' of dense materials w/o any source
- o Two different operating modes

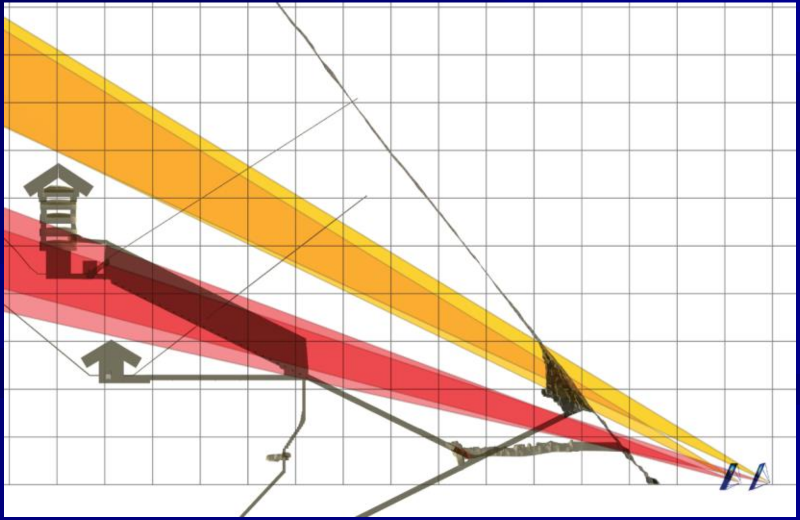
Deviation: *scattering angle used To measure density*

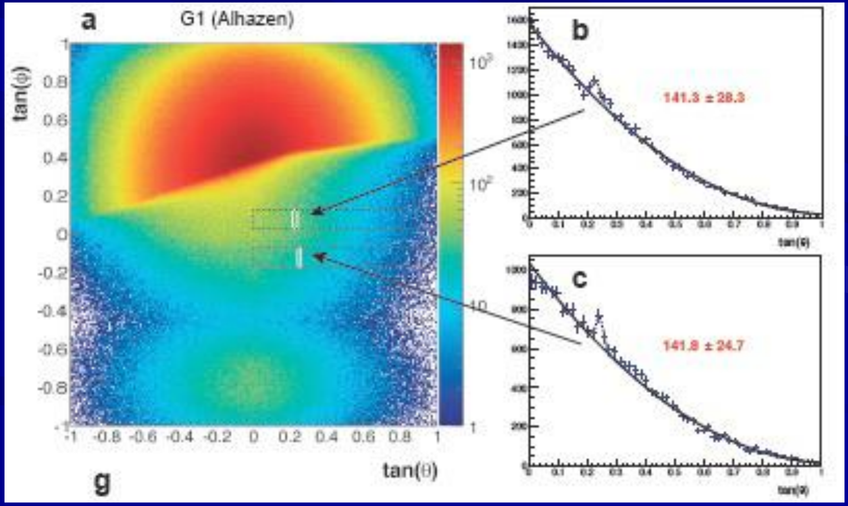
Absorption: *density contrast imaging*



Scan pyramid

- 2 telescopes Pointed from outside to the heart of the pyramid in the same region than the 2 japanese teams (located inside)
- **Nov 2017: publication in NATURE of the evidence of a new XXL VOID above the Grand Gallery.**
- Joint Discovery from the 3 teams
- first time that a so-deep structure is found using muontomography
- Extremely large media coverage (TV news, Front page of
- national newspapers…)

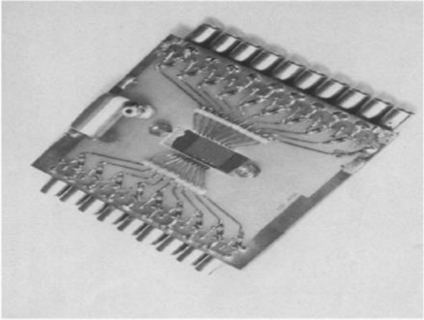




The silicon era

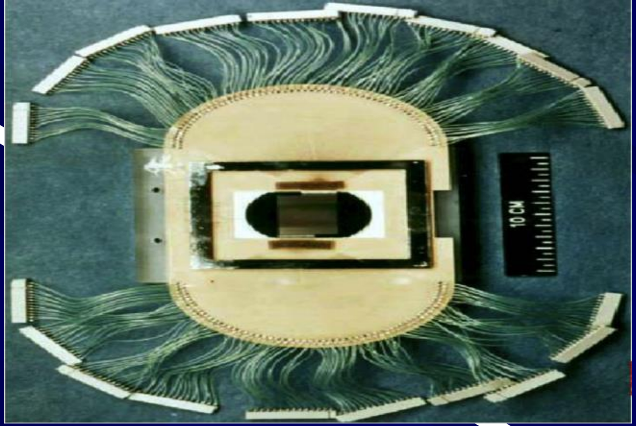
The semiconductors revolution

- First transistor invented 1947 by William B. Shockley, John Bardeen and Walter Brattain (Nobel Prize 1956)
- First Si strip/pixel detector for Particle Physics in the 70's
- Multimillion channels
- Radiation hardness issues
- Move to pixellated devices for vertices detection



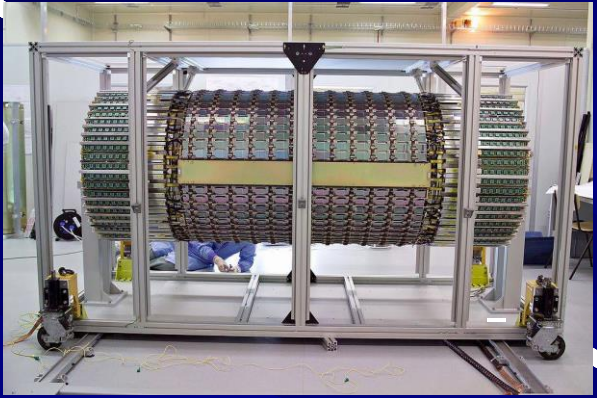
64 Ch. Si-strip sensor with 300 µm pitch

Historical Evolution of SID



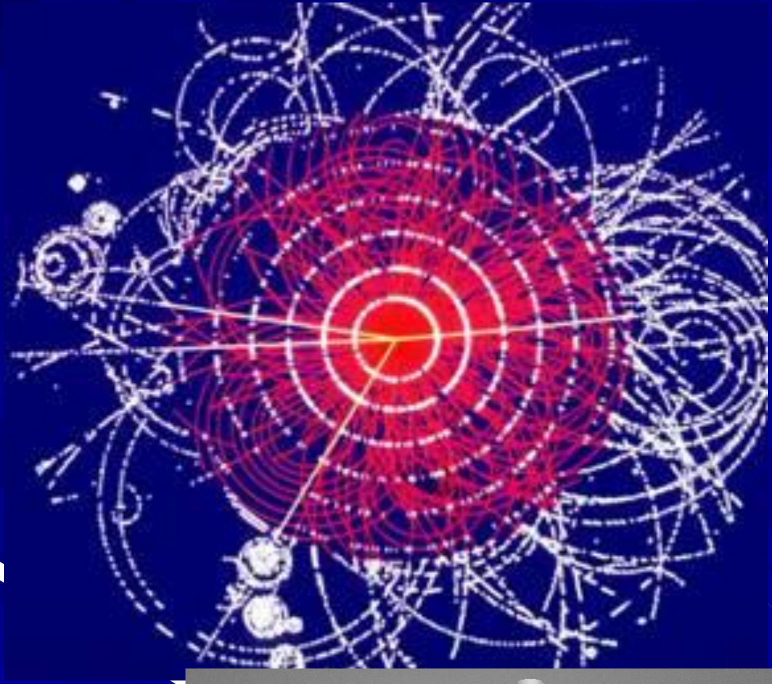
1981: 6 planes Si-strip detectors
- 24x36mm2, 1200 strips/sensor
- strip pitch 20 □m, 280 µm thick
- 60 □m readout □ □□=5.4 □m
- 120 □m readout □ □=7.8 □m
- total <2000 channels
- 100% efficiency

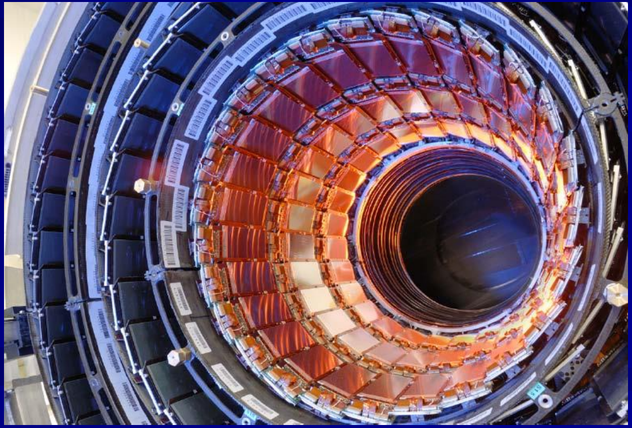
1981



ATLAS SCT 6M Ch.

2007

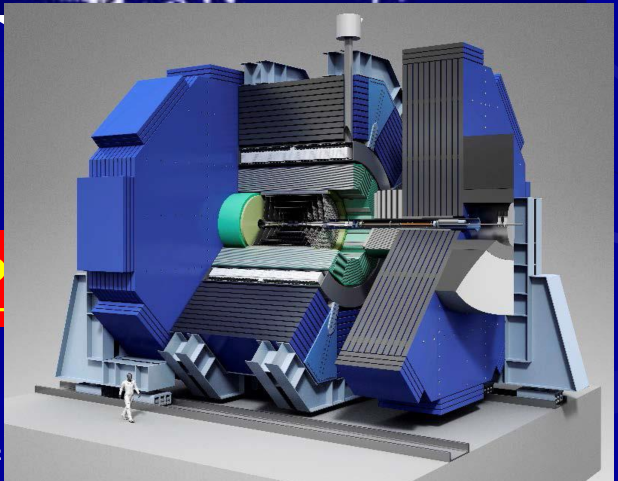




CMS Tracker

C-PET Philips

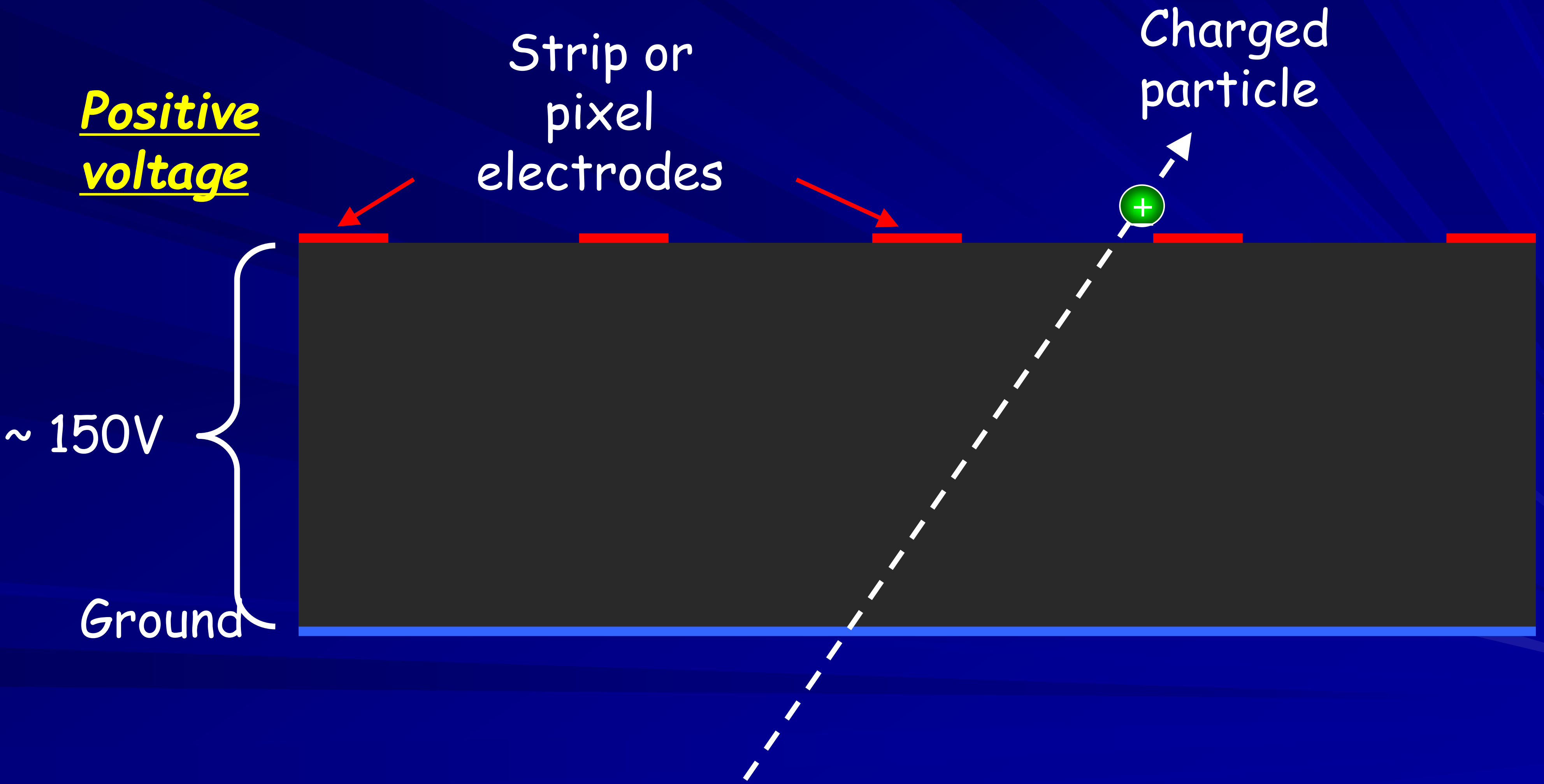
2300 ?



SID
ILC project

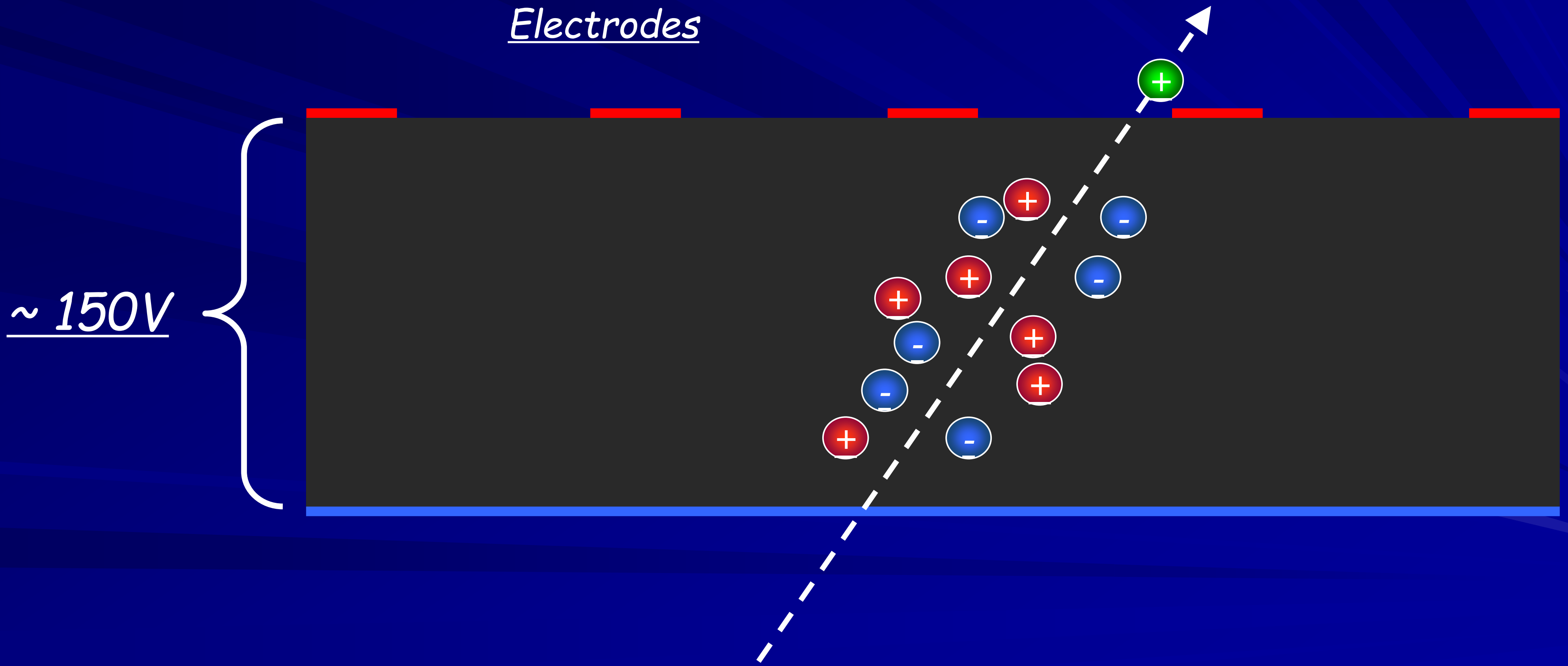
Operation sequence

Charged particle crosses detector



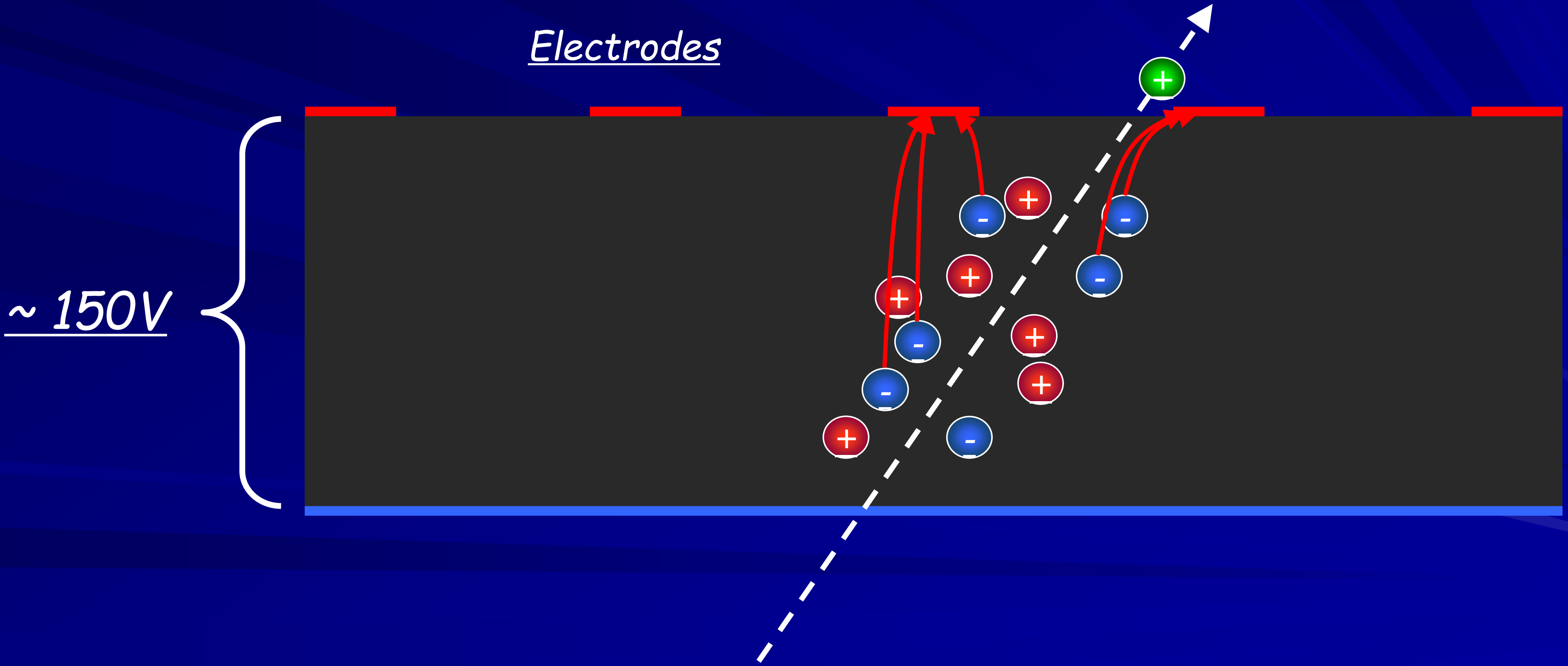
Operation sequence

Creates electron hole pairs

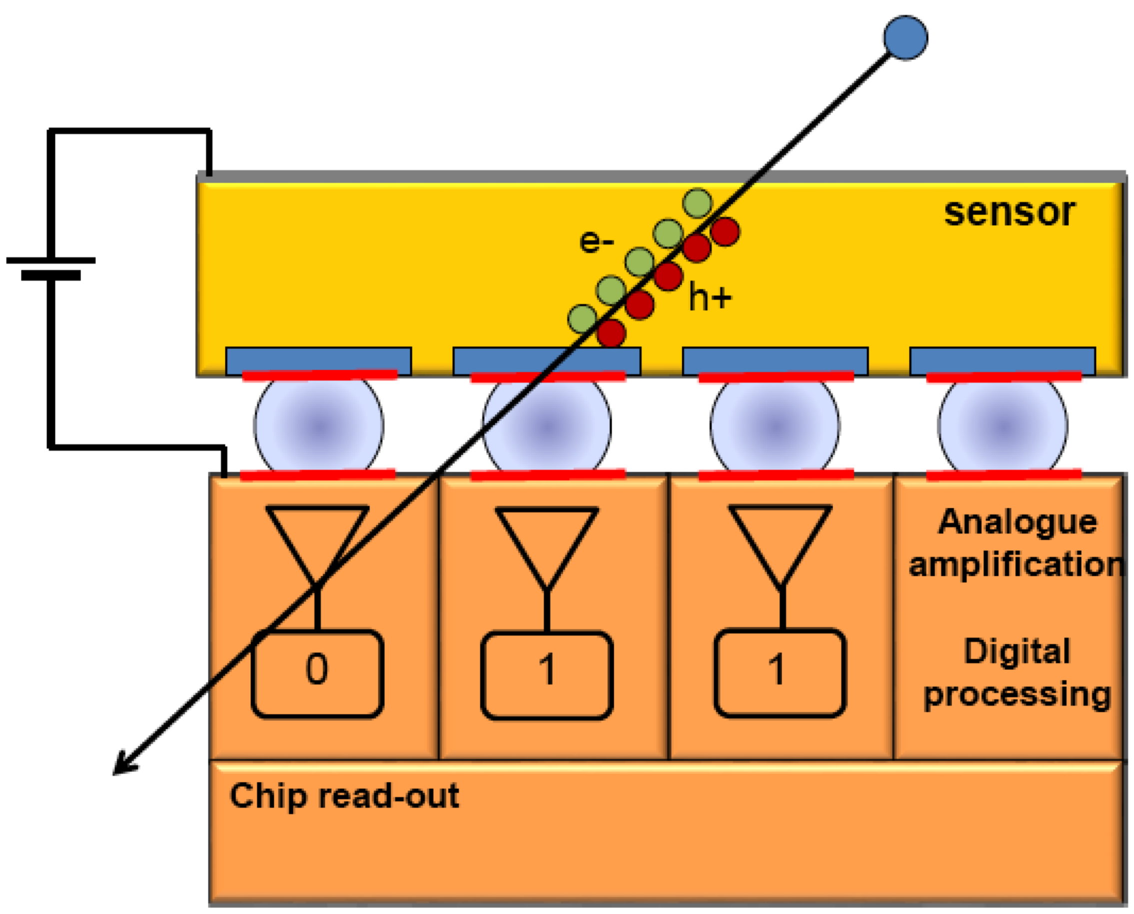


Operation sequence

these drift to nearest electrodes ⇔ position determination

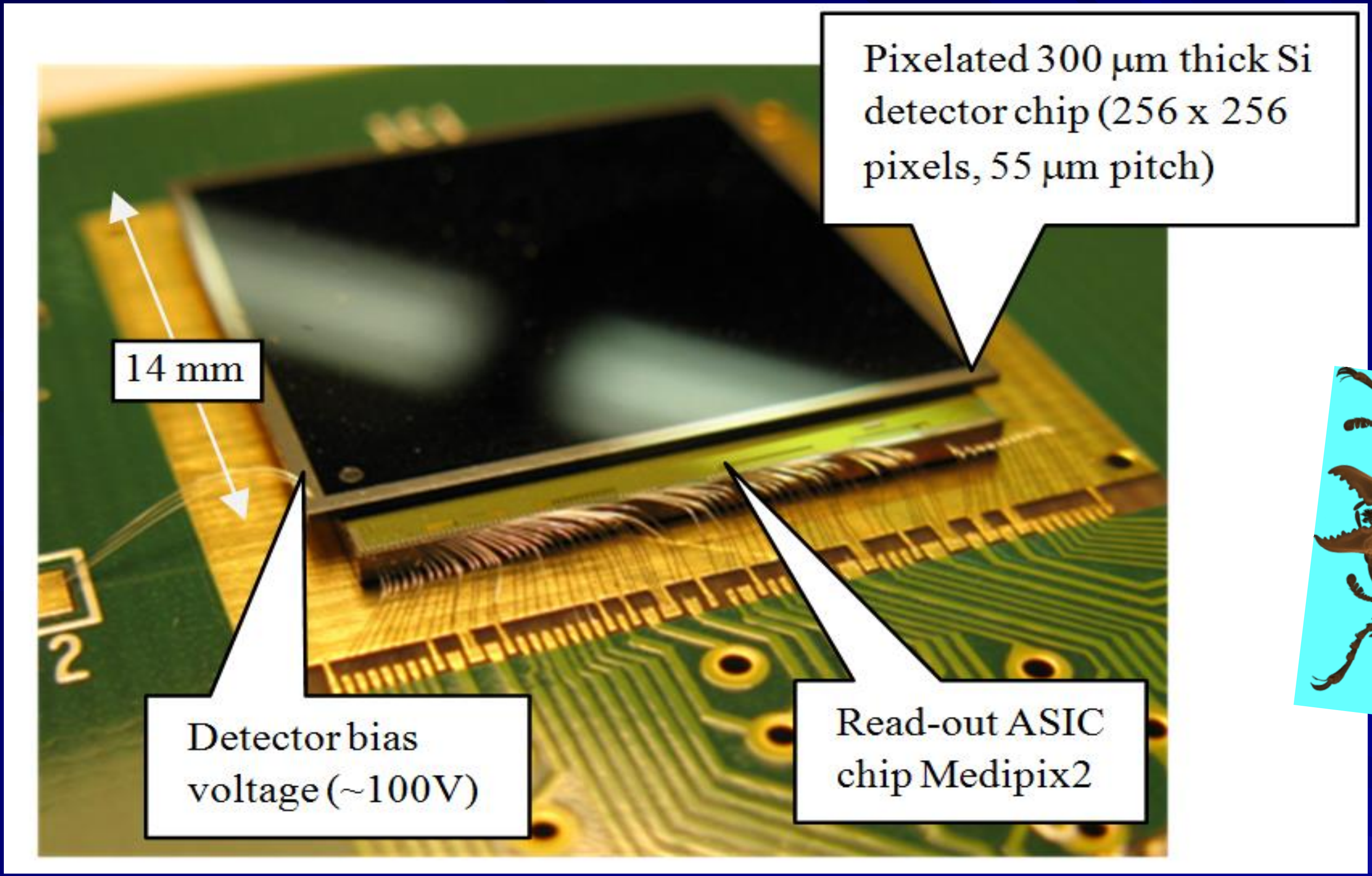


Hybrid Pixel detector principle



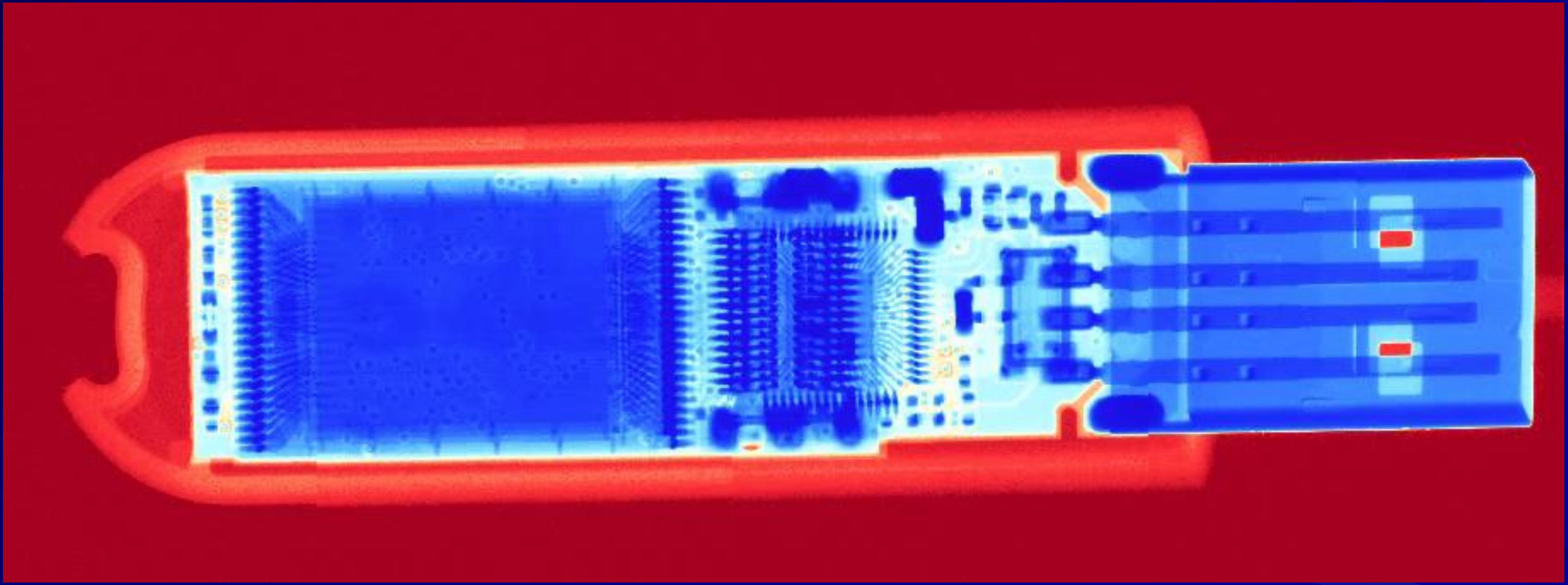
- An ionising particle deposits charge in the silicon sensor
- The reverse biasing of the sensor diode structure drives the charge to the readout chip
- The charge is shaped and a threshold applied
- Digital processing occurs
- The data is read out off the chip

Medipix-Timepix family



Medipix-CT setup for detector investigations & material analysis

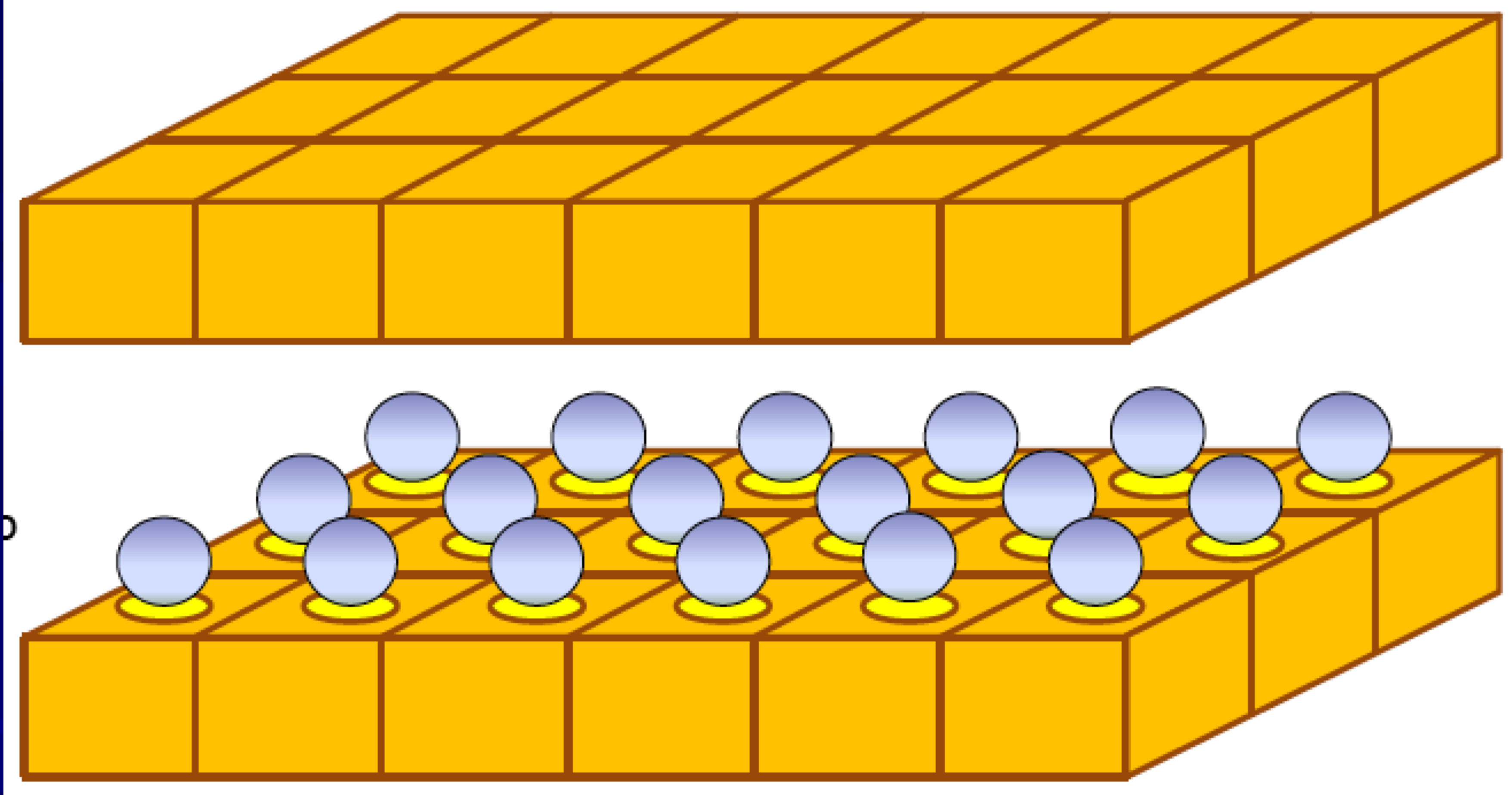
Example → USB flash drive



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

Hybrid Pixel Detectors

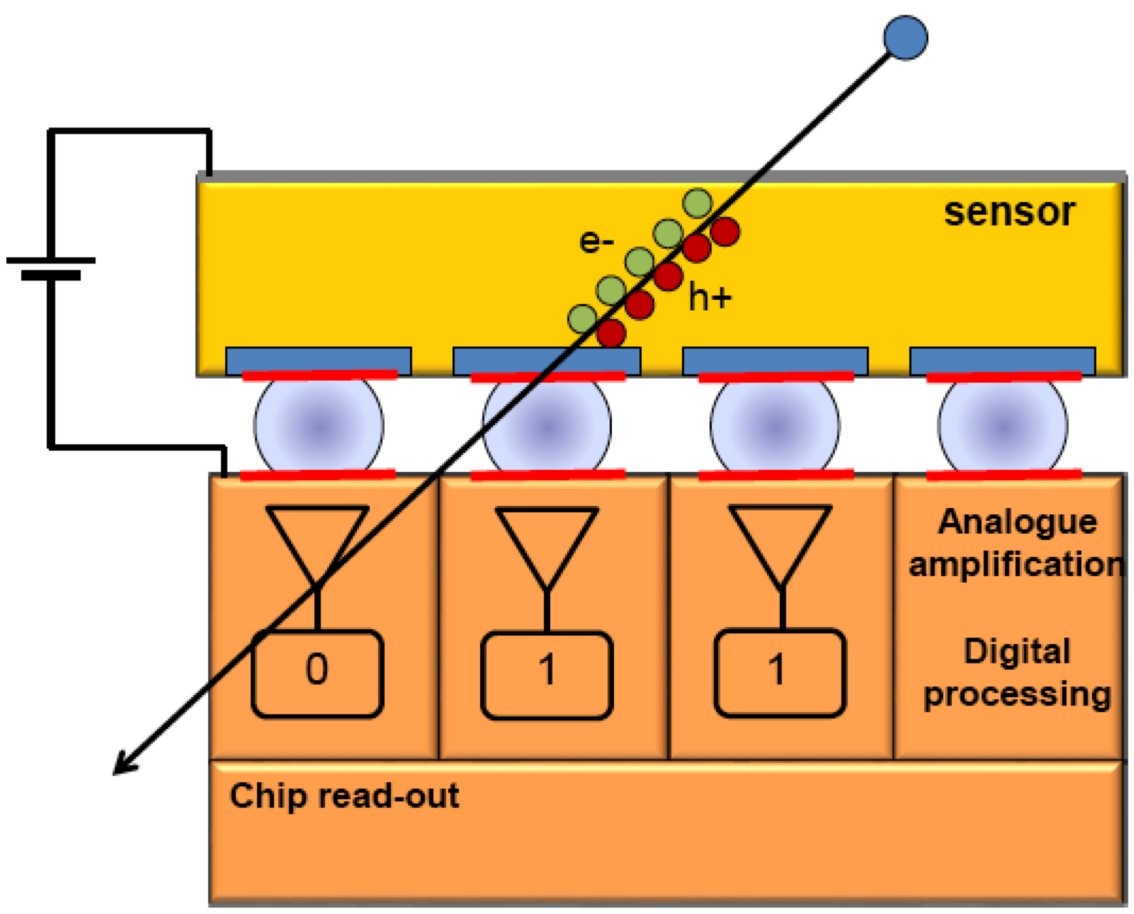
Sensor (Silicon, Pixel, MGPD, GaAs ….



Solder
Bump
Bond

Read Out Asic

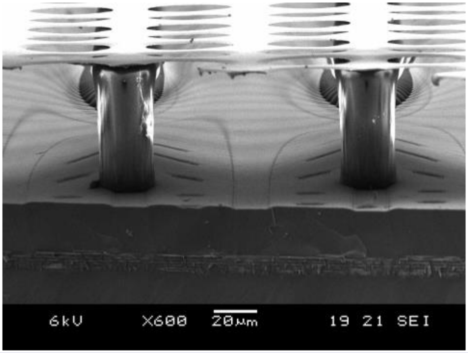
Hybrid Pixel detector principle



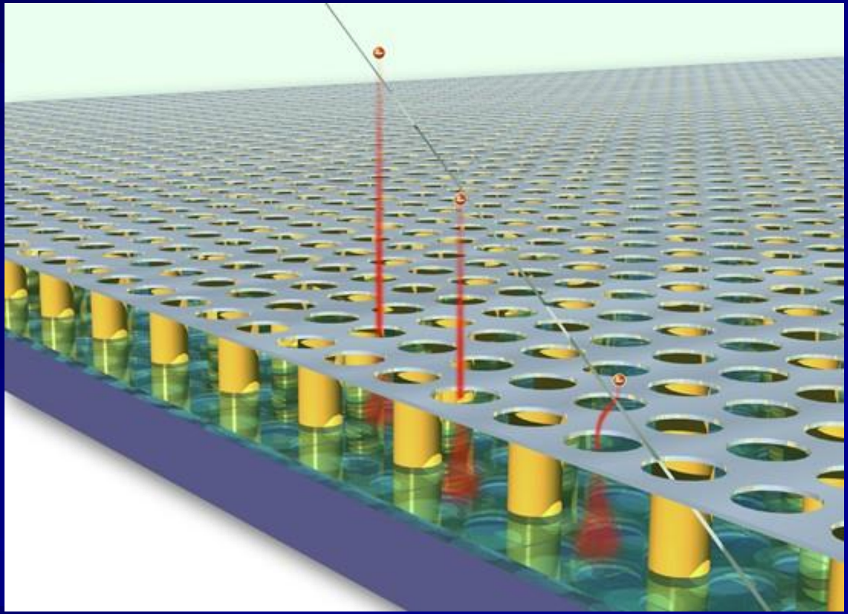
- An ionising particle deposits charge in the silicon sensor
- The reverse biasing of the sensor diode structure drives the charge to the readout chip
- The charge is shaped and a threshold applied
- Digital processing occurs
- The data is read out off the chip

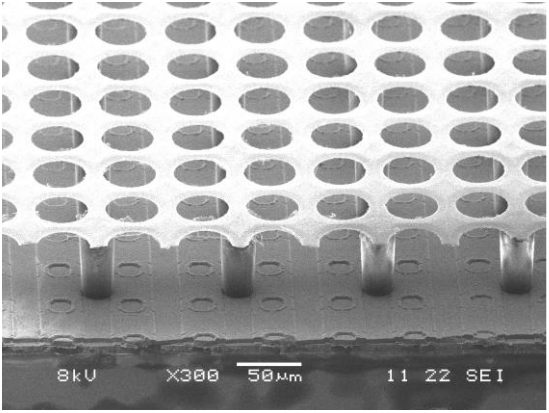
Next → INGRID

- **InGrid** :integrate the Micromegas/GEM concept on top of a MediPix pixel CMOS chip (Timepix)
  - pixel size: 55 x 55 μm^2
  - per pixel: preamp – shaper – 2 discr. –
  - Thresh. DAQ - 14 bit counter



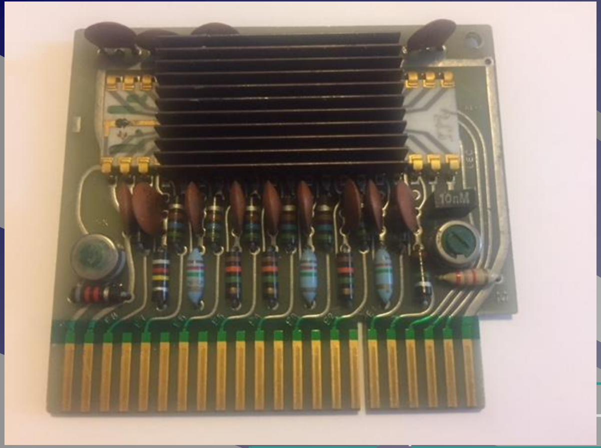
metalized foil
~100 μm ~1mm





71Cmos Medipix chip

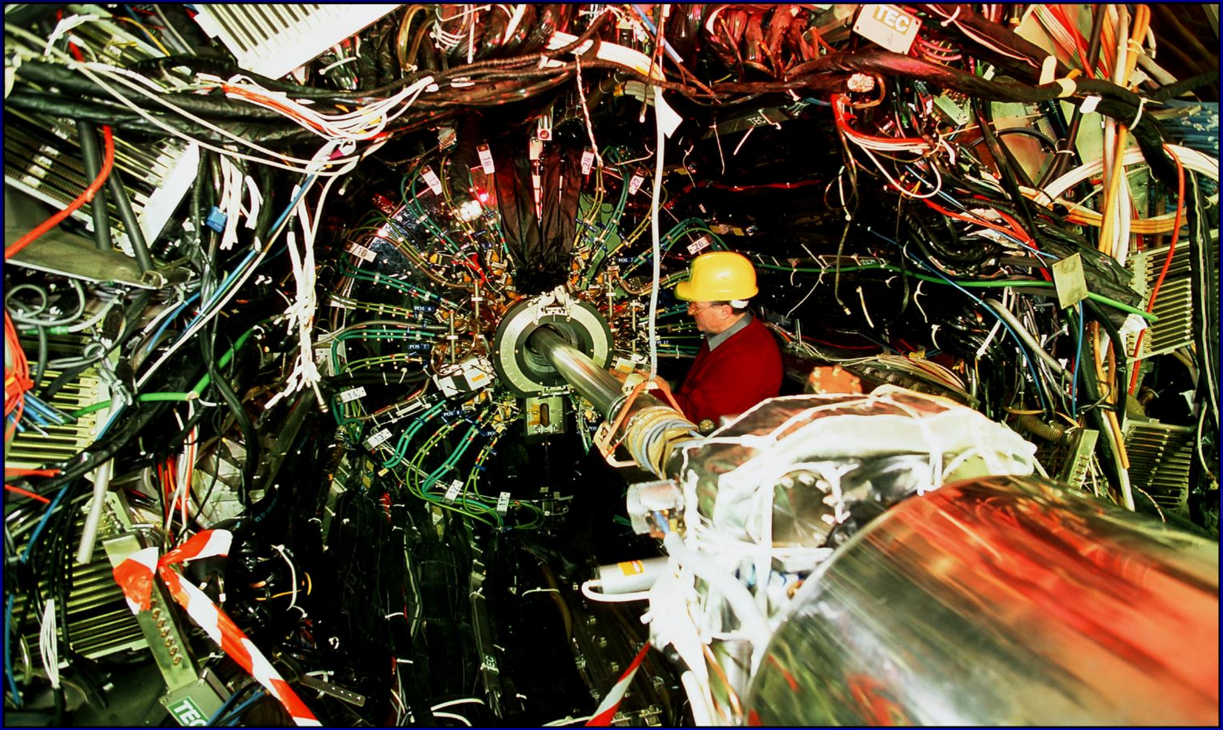
- Use → Large Trackers - Calorimeters @ MI devices



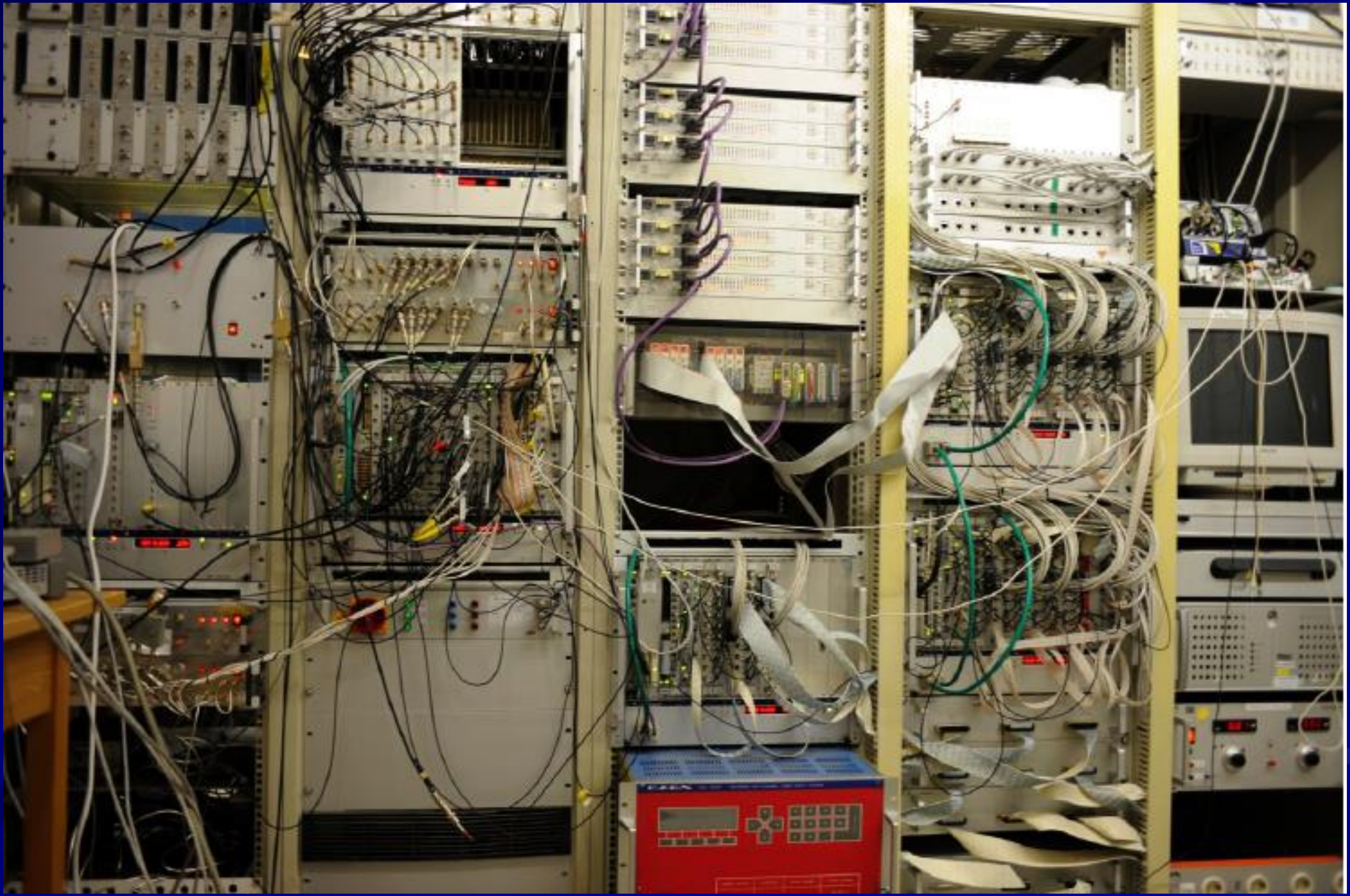
Electronics
Signal processing
Data analysis

Electronics in experiments

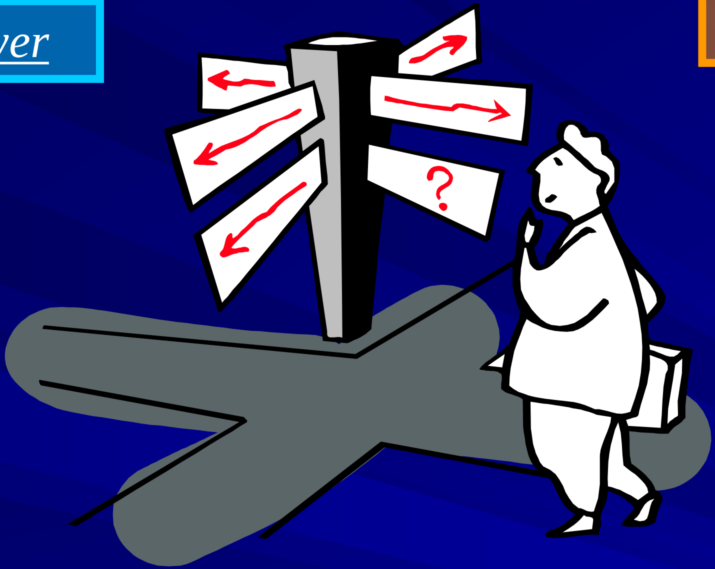
- A lot of electronics in the experiments…
  - Readout electronics :
    - amplification, filtering… : Analog electronics
    - Processing & Trigger electronics : Digital electronics (bits)



But also that !



Readout electronics : requirements



Low noise

Low power

High speed

High reliability

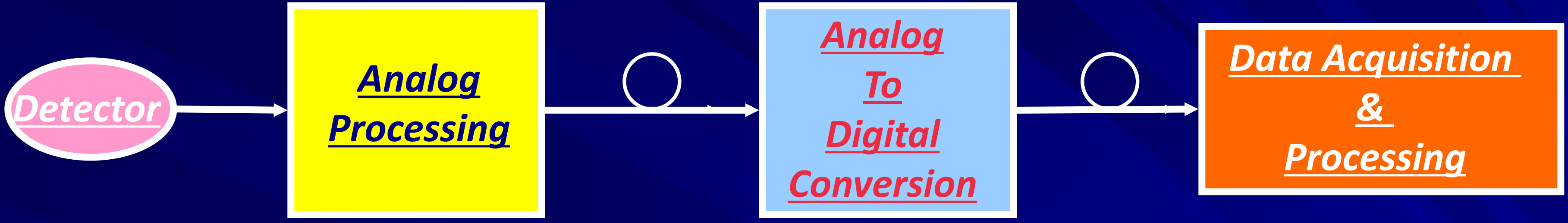
Large dynamic range

Radiation hardness

Low material

Low cost !
(and even less)

The electronics blocks



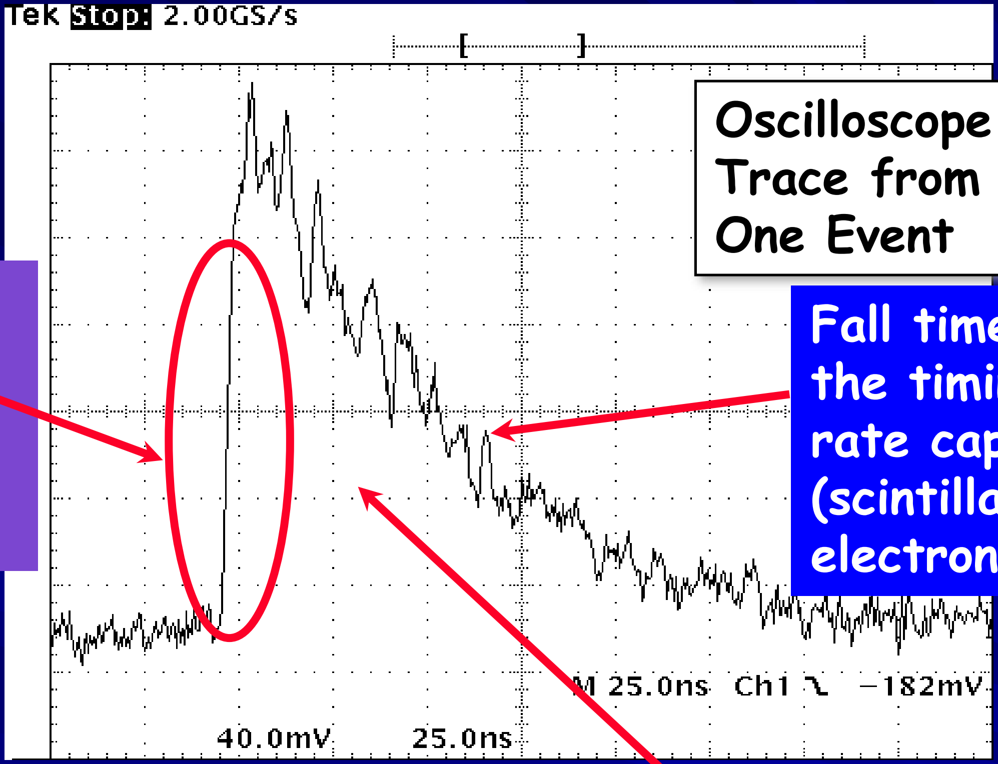
On-detector

On-detector
Or
Off-detector

Off-detector

- Analog processing
- Analog to digital conversion
- Technology evolution
- Off-detector digital electronics

Typical Raw Signal From Scintillation Detectors



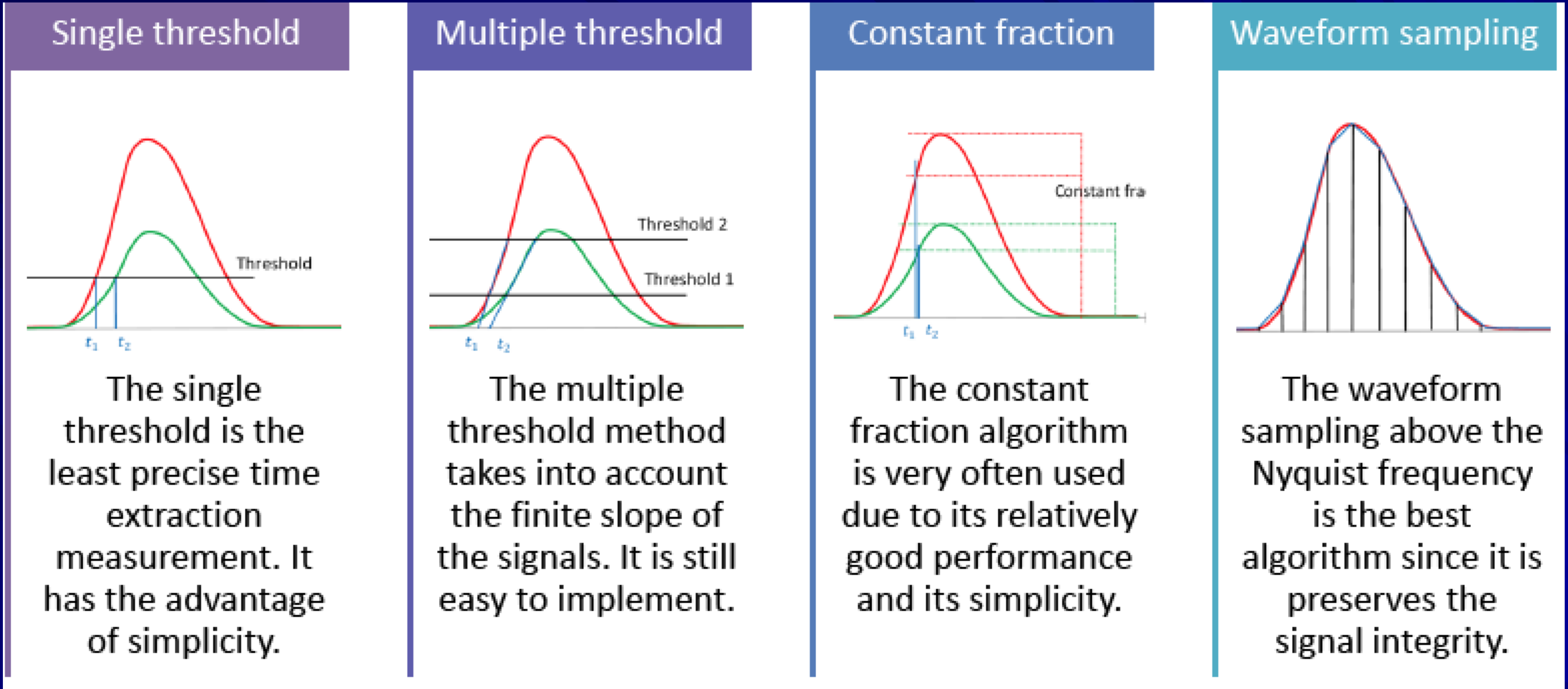
Oscilloscope Trace from One Event

Initial photoelectron rate affect the timing *(scintillator, photodetector, electronics)*

Fall time affect the timing and rate capability (scintillator, electronics)

The area under the curve affect the SNR *(scintillator, photodetector, electronics)*

Timing extraction method



Single threshold

The single threshold is the least precise time extraction measurement. It has the advantage of simplicity.

Multiple threshold

The multiple threshold method takes into account the finite slope of the signals. It is still easy to implement.

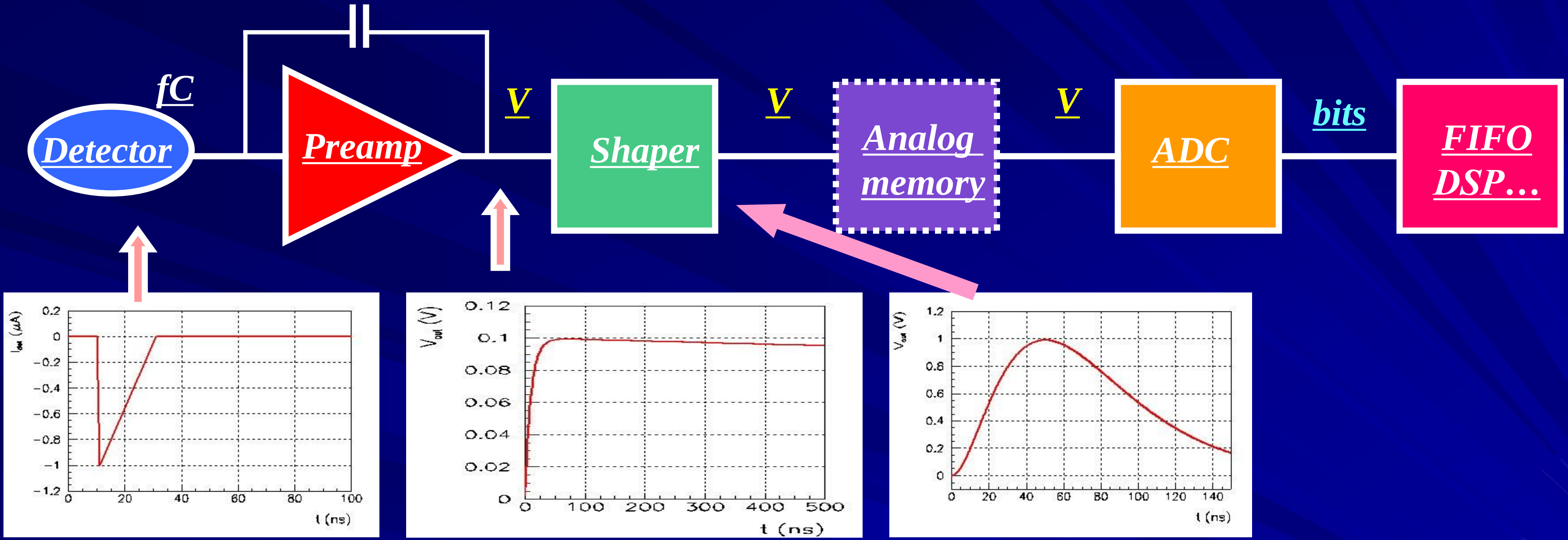
Constant fraction

The constant fraction algorithm is very often used due to its relatively good performance and its simplicity.

Waveform sampling

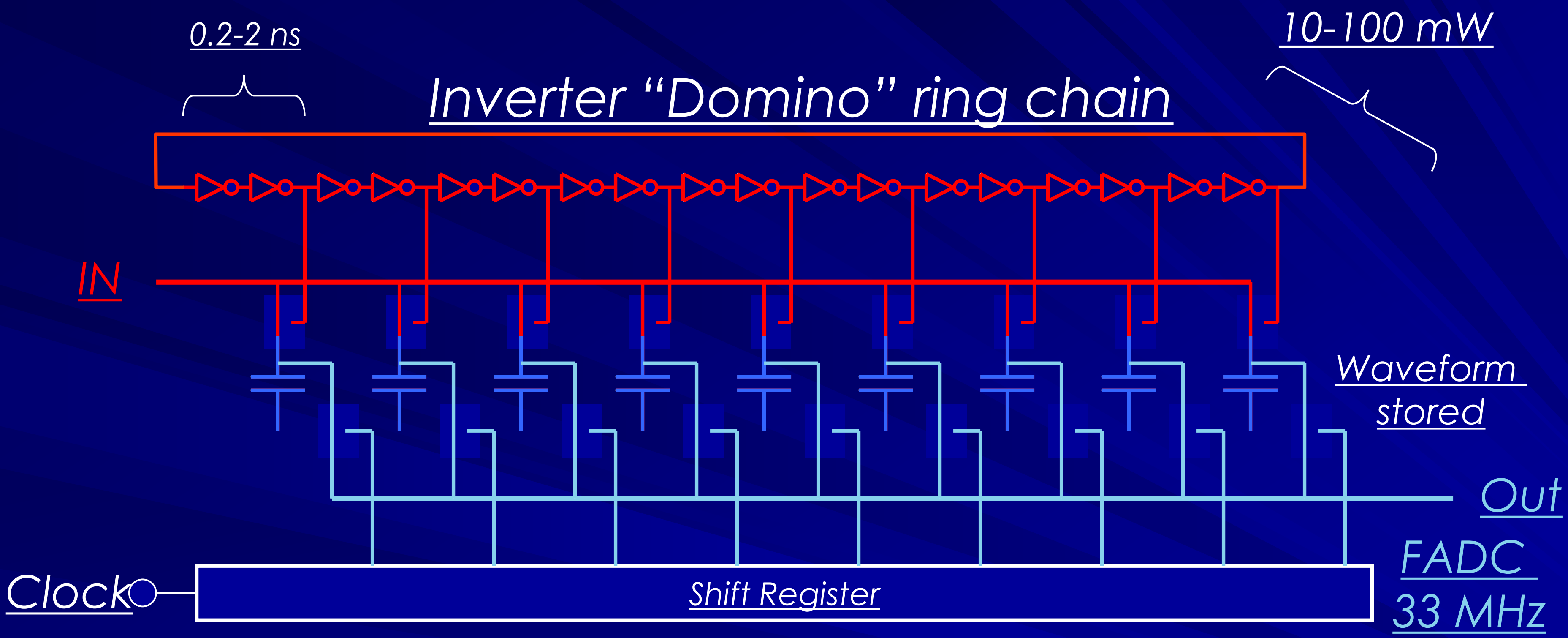
The waveform sampling above the Nyquist frequency is the best algorithm since it is preserves the signal integrity.

Overview of Front End readout electronics chain



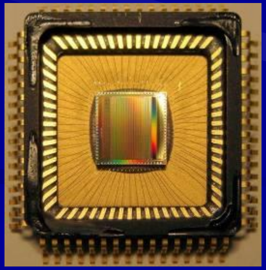
- Very small signals (fC) -> need amplification
- Measurement of amplitude and/or time
  - (ADCs, discris, TDCs)
- Several thousands to millions of channels

Analog memories → Waveform digitizers

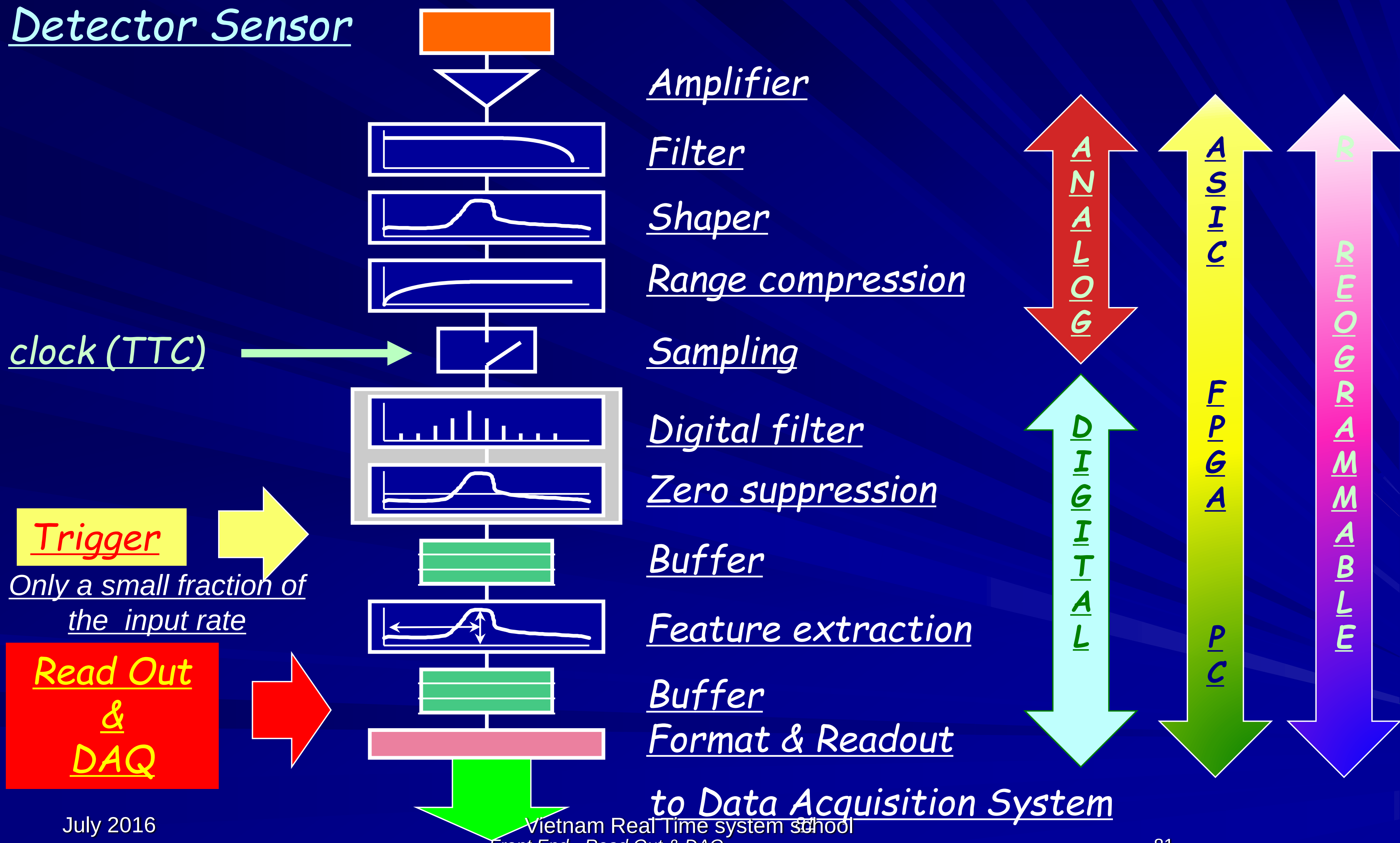


"Time stretcher" GHz → MHz

DRS4 (PSI)



The read-out chain processing flow



Detector Sensor

Amplifier

Filter

Shaper

Range compression

clock (TTC)

Sampling

Digital filter

Zero suppression

Trigger

Only a small fraction of the input rate

Buffer

Feature extraction

Read Out & DAQ

Buffer

Format & Readout

to Data Acquisition System

ANALOG

DIGITAL

ASIC

FPGA

PC

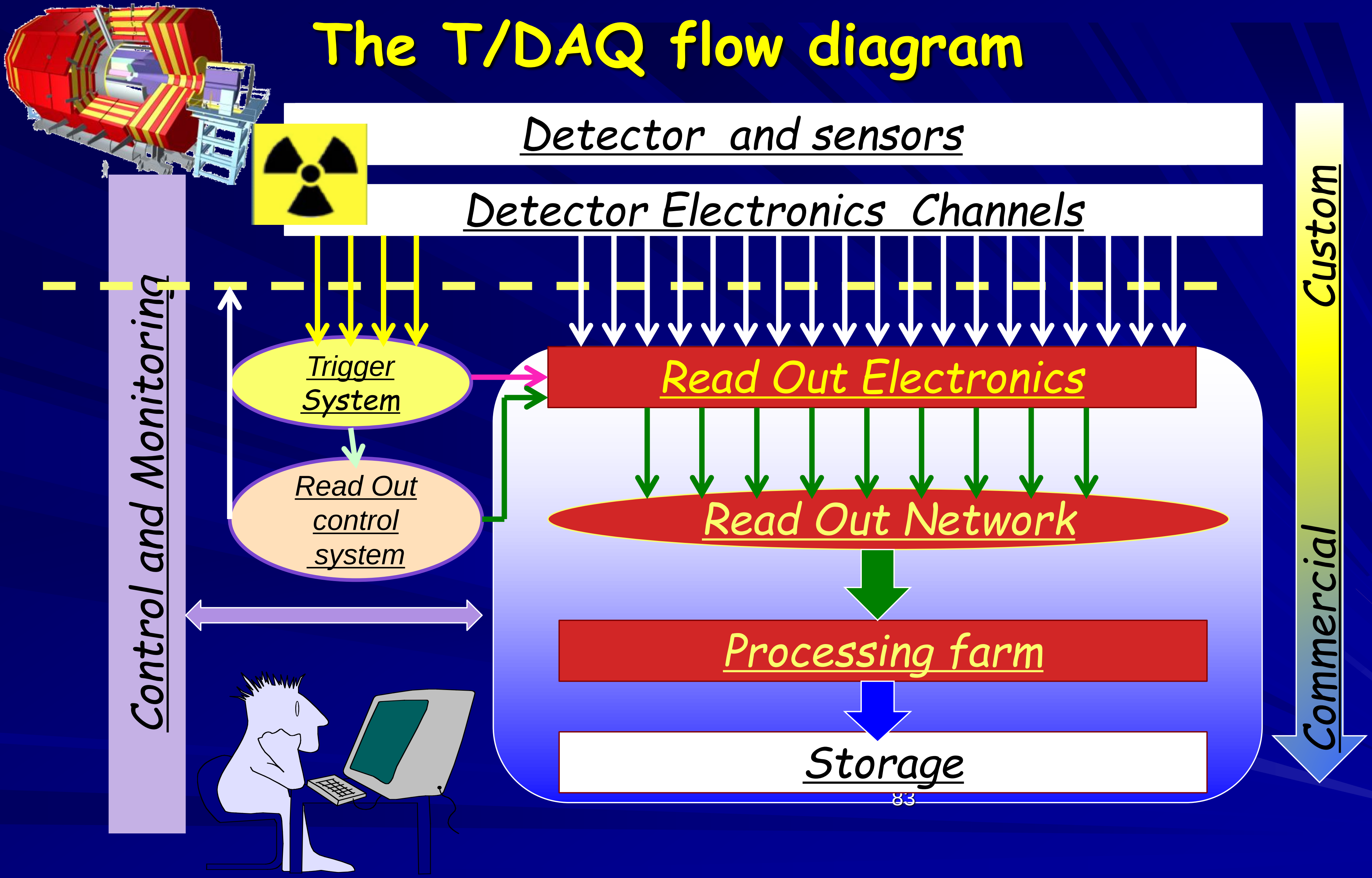
R

REOGRAMMABLE

What Do We Need to Read Out a Detector ?

- A selection mechanism → "TRIGGER"
- Electronic readout of the sensors of the detectors →"front-end electronics"
- A system to keep all those things in sync → "clock"
- A system to collect the selected data →"DAQ"
- A Control System to configure, control and monitor the entire DAQ
- Time, money, students

The T/DAQ flow diagram



Detector and sensors

Detector Electronics Channels

Trigger System

Read Out control system

Read Out Electronics

Read Out Network

Processing farm

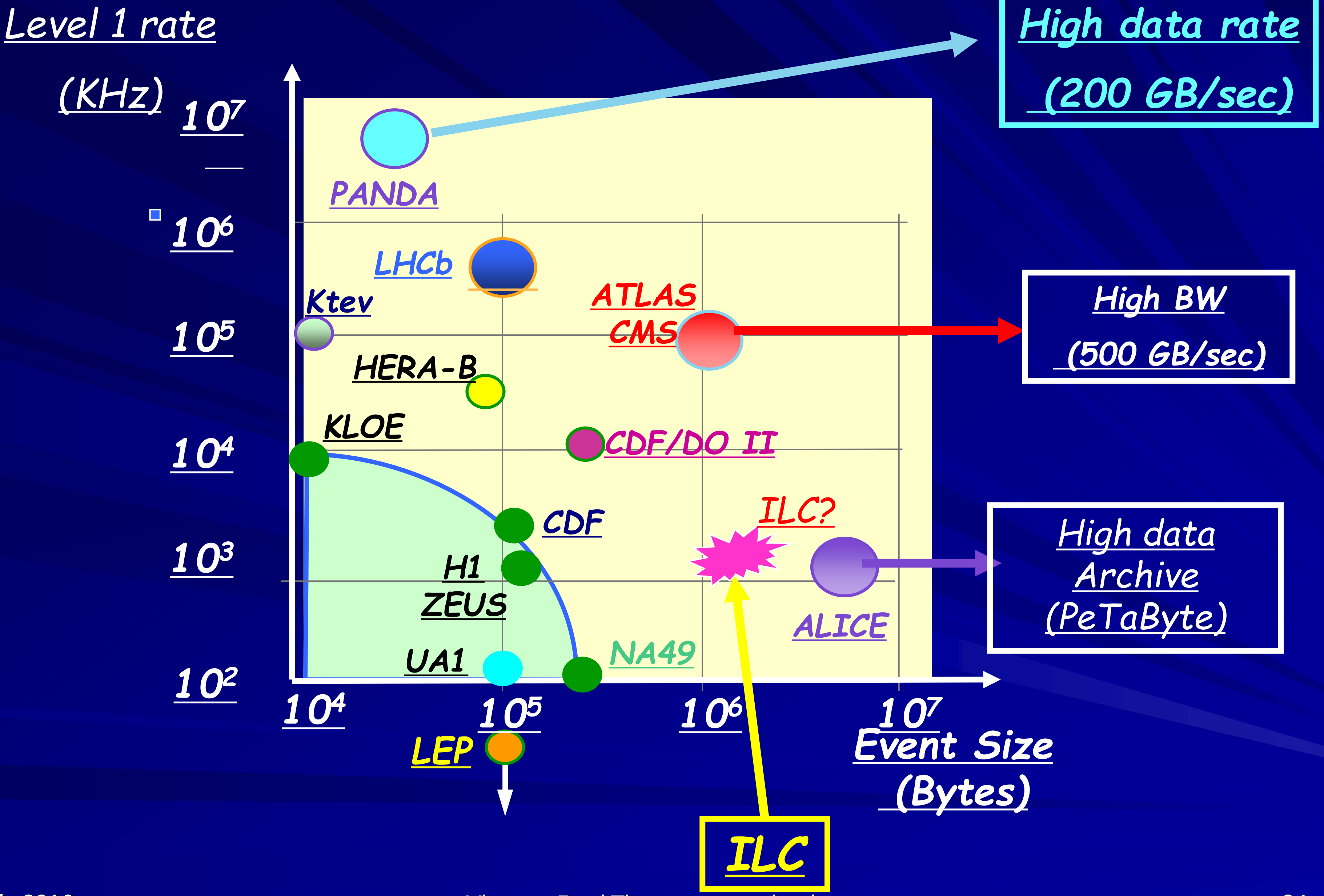
Storage

Control and Monitoring

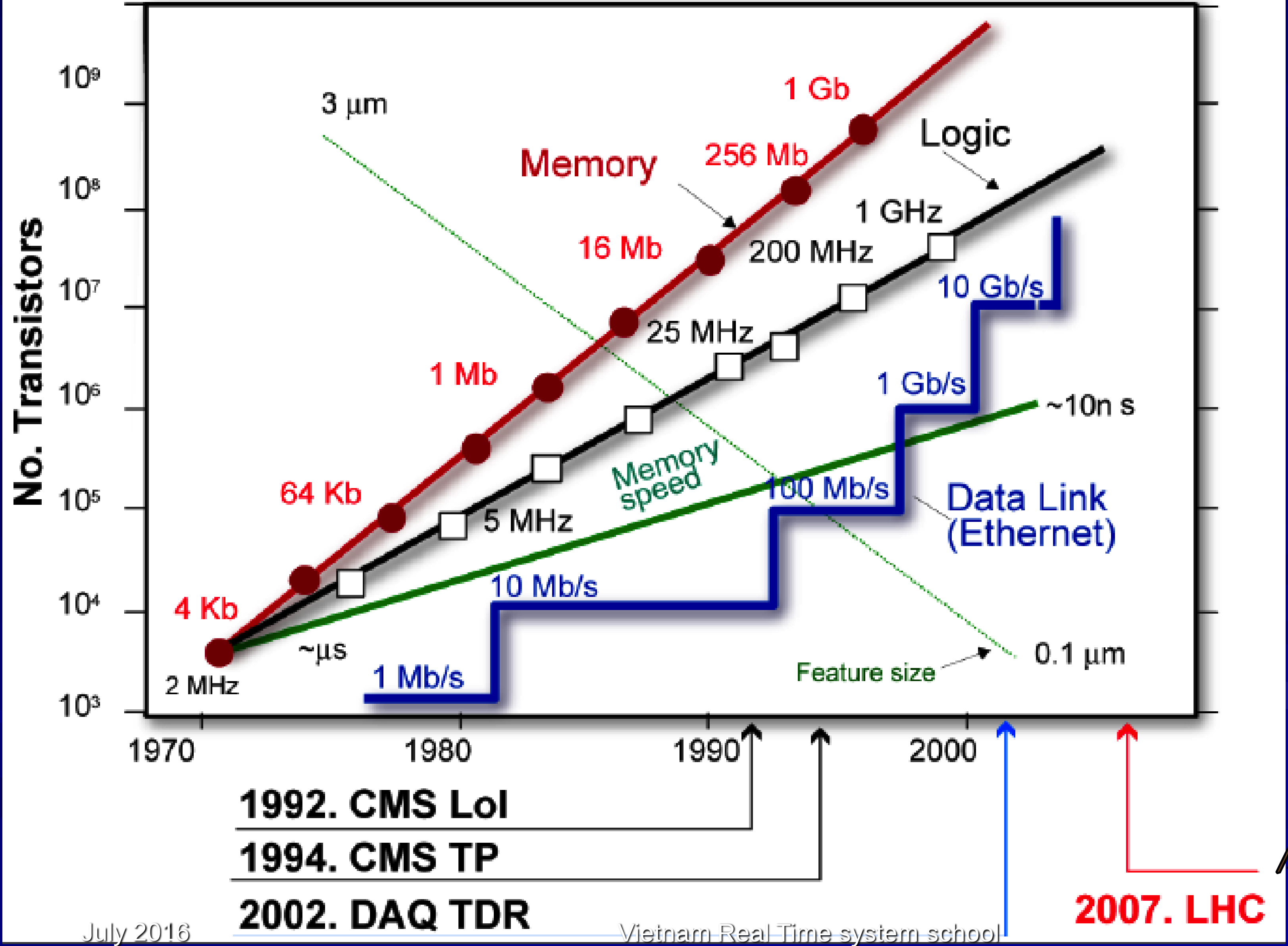
Custom

Commercial

Rates and data volume



The Long Term issue challenge → 15 years of design-20 years of life



Tevatron
CDF/DO
1980-2012

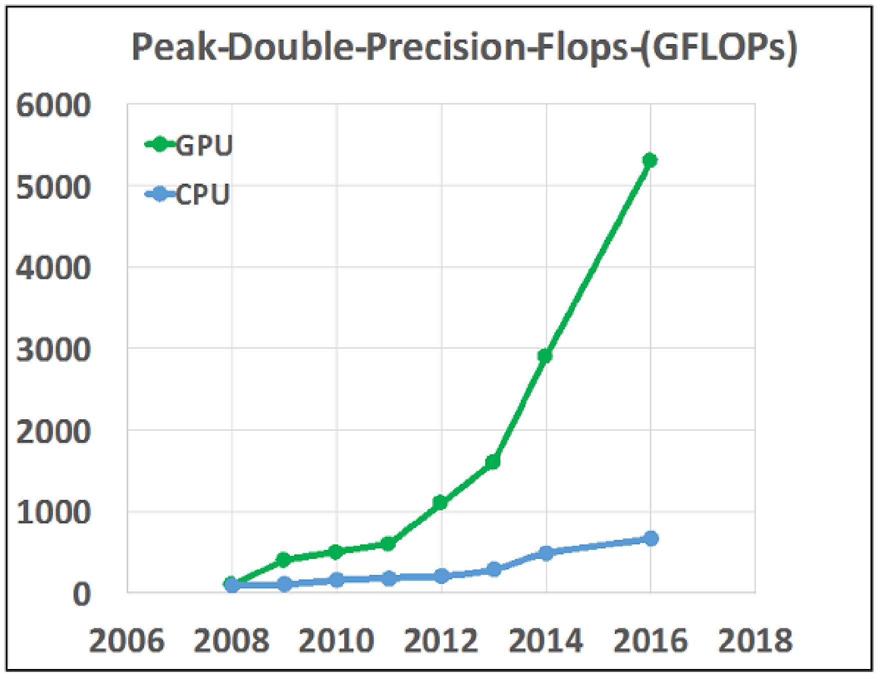
The 'More law'
LHC example

Computer farm evolution → GPU's

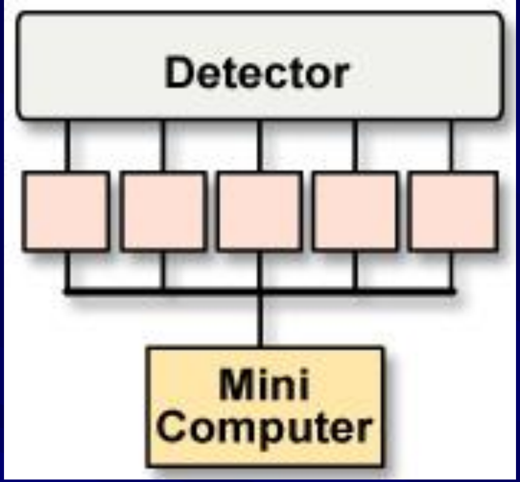
- GPUs: Graphical Processor Units :

highly parallel, multi-threaded, multicore processors with remarkable computational power and high memory bandwidth: promising candidate for fast track fitting at high luminosity

From the video game world



Evolution of DAQ technologies and architectures

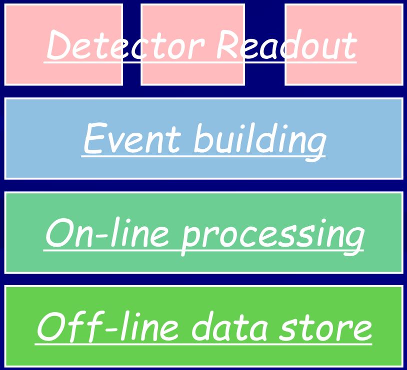


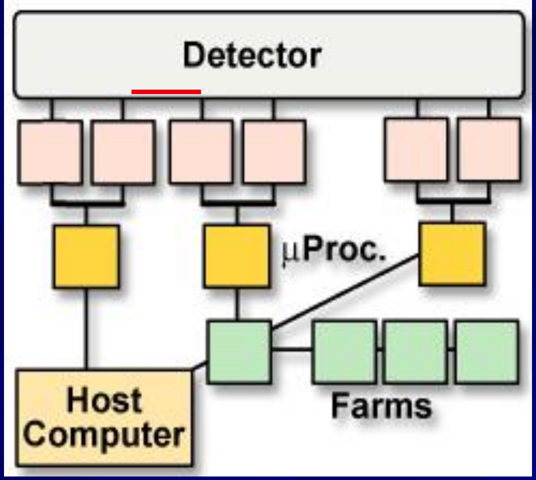
1970-80

CERN PS/SPS

Minicomputers

Readout custom design
First standard: CAMAC
kByte/s


Detector Readout
Event building
On-line processing
Off-line data store

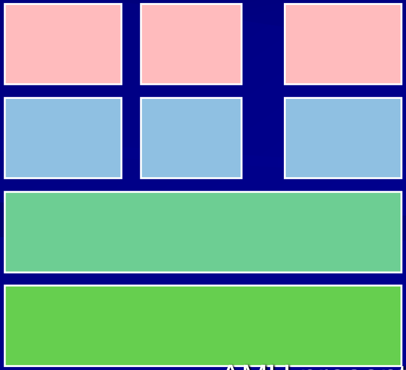


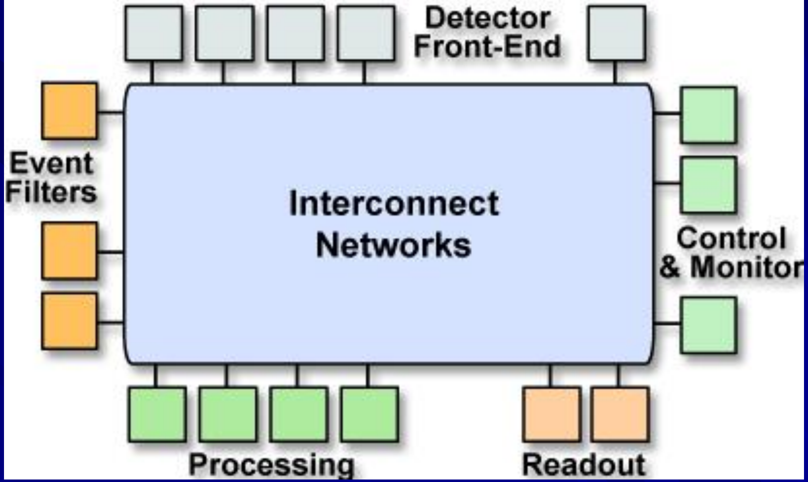
1980-90

LEP

Microprocessors

HEP standards (Fastbus)
Embedded CPU,
Industry standards (VME)
MByte/s



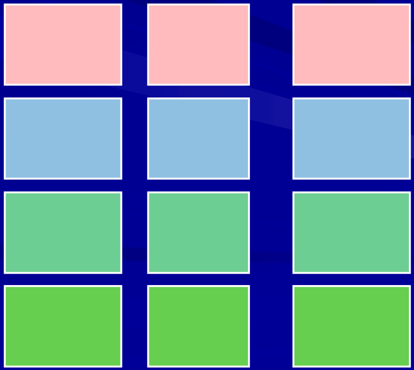


2007 …

LHC (CMS)

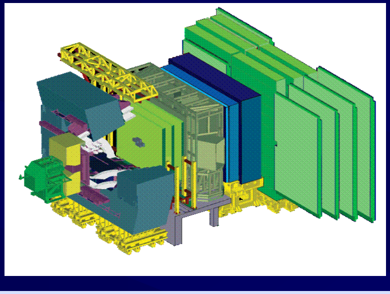
Networks/Grids

IT commodities, PC, Clusters
Internet, Web, etc.
GByte/s

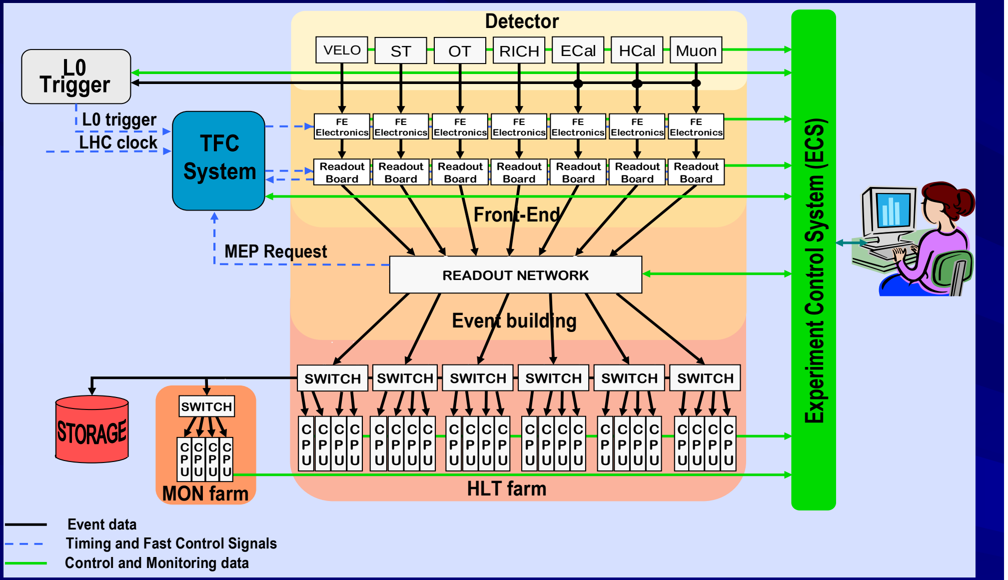


From S. Cittolin

DAQ = The evolution of architecture

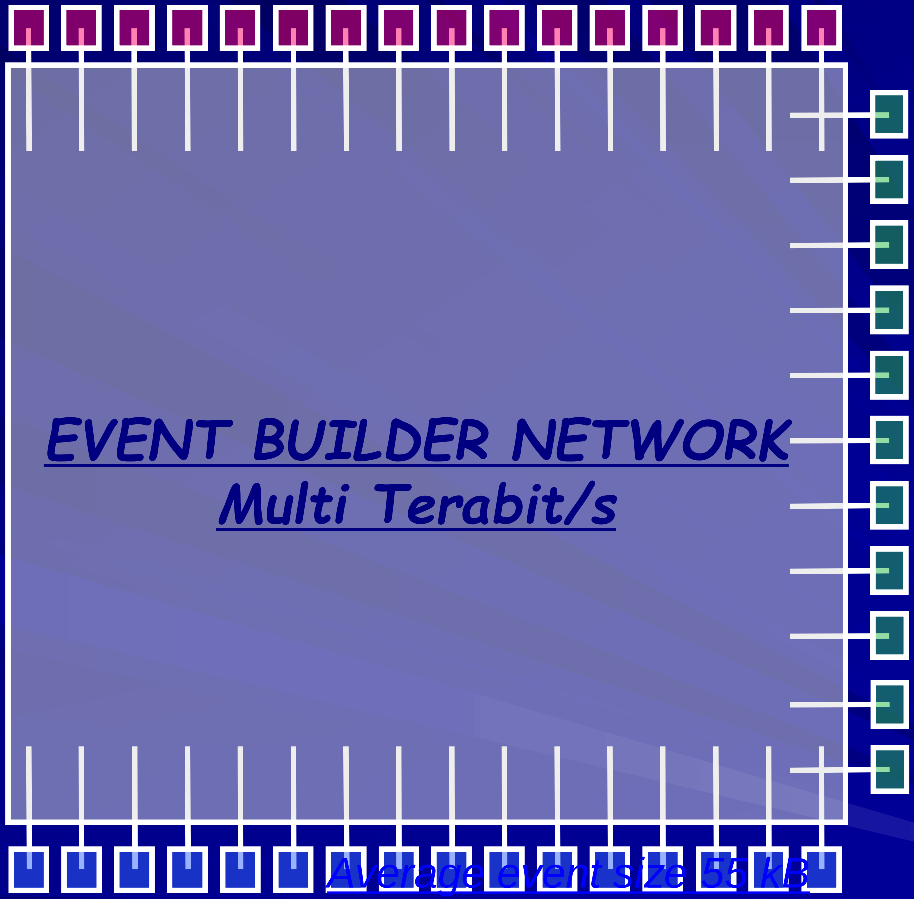


LHCb



Average event size 55 kB
Average rate into farm 1 MHz
Average rate to tape 4 – 5 kHz

Direct network access From Detectors and Machine



EVENT BUILDER NETWORK
Multi Terabit/s

Controls & Storage servers

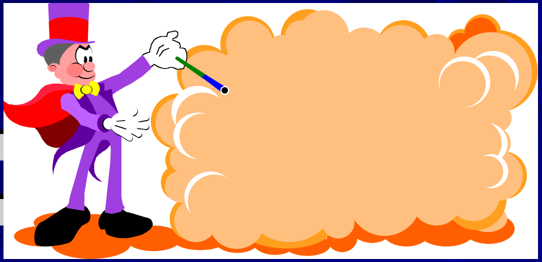
Trigger Farms & Analysis

Average event size 55 kB
Average rate into farm 1 MHz
Average rate to tape 4 – 5 kHz

Technology forecast summary

- End of traditional parallel backplane bus paradigm
  - Announced every year since ~1989
  - VME-PCI still there
    - watch PCI Express, RapidIO, ATCA
- Commercial networking products for T/DAQ
  - Conferences:
    - ATM, DS-Link, Fibre Channel, SCI
  - Today: Gigabit Ethernet (1 → 10 → 30 GB/s)
- The ideal processing / memory / IO BW device
  - The past:
    - Emulators (370E),Transputers, DSP's, RISC processors
  - Today: FPGA's →
    - Integrates receiver links, PPC, DSP's and memory

Technology forecast (Con't)



- ***Point-to-point link technology***
  - The old style: Parallel Copper – Serial Optical
  - The modern style: Serial Copper – Parallel Optics
    - Today 10Gb/s → 30Gb/s
- **Processors** → Moore's law still true until 2015 ..at least!
  - Continuous increasing of the computing power (Clock)
- **Memory size → quasi illimited !**
    - Today : > 100 GBytes
    - 2015: > Tera Bytes …
- **Modern wisdom (about technology)**
  - "People tend to overestimate what can be done in one year, and underestimate what can be done in 10 years."

Historical Evolution of data collection

IBM card

1970

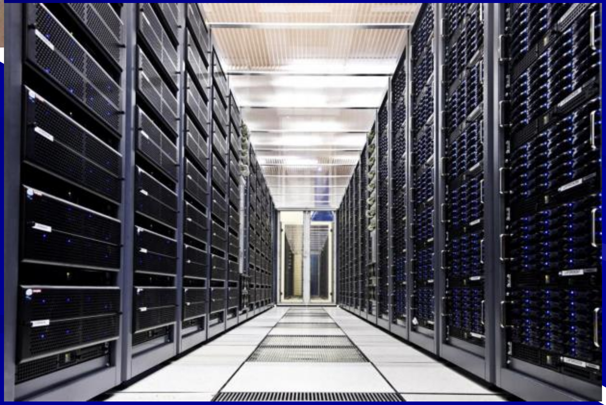
1980

Digital PDP 11/45 mini computer

1990

VME micro processor card

2010

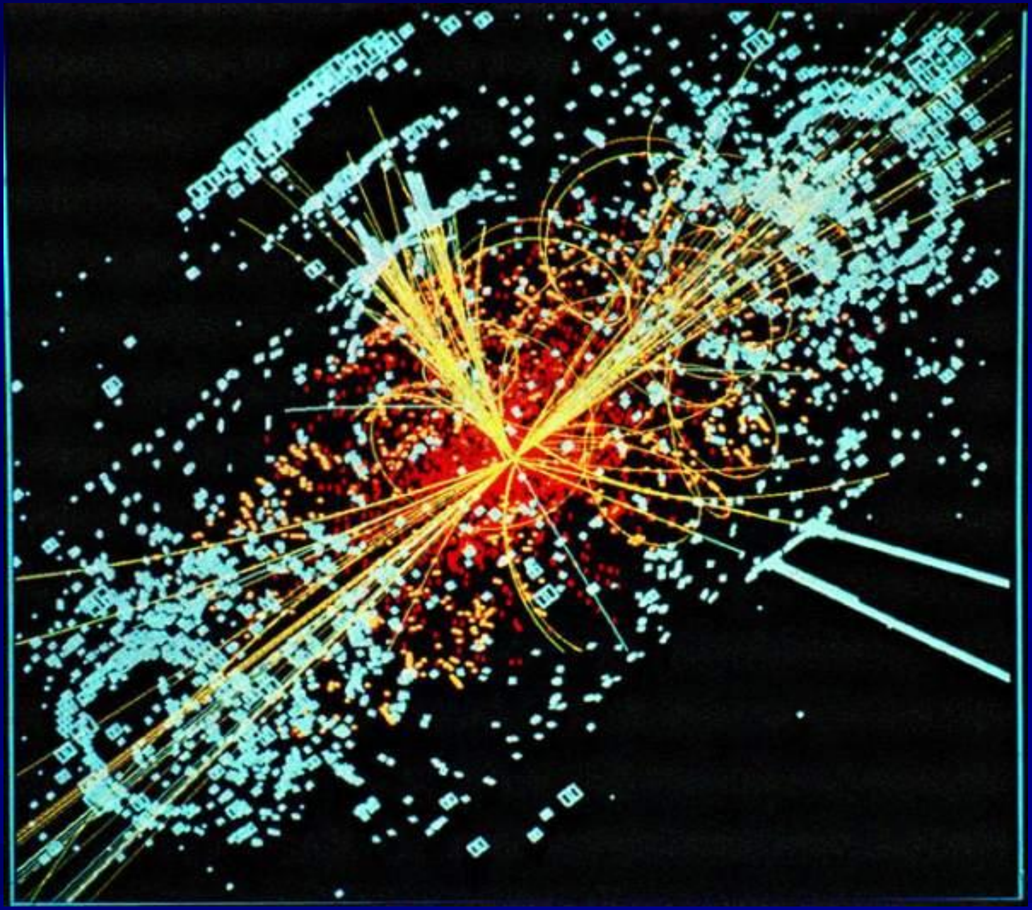


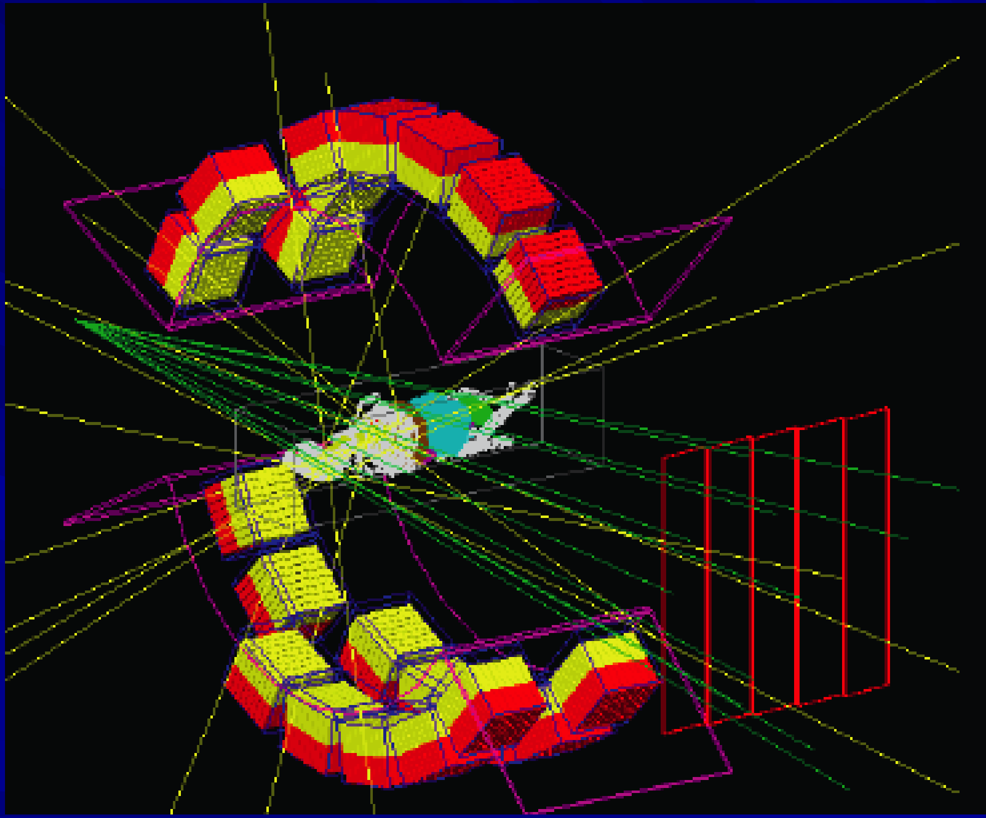
LHC PC farm

Simulation

Higgs event at LHC (CMS) with Geant4

PET with GATE: Geant4 Application for Tomographic Emission

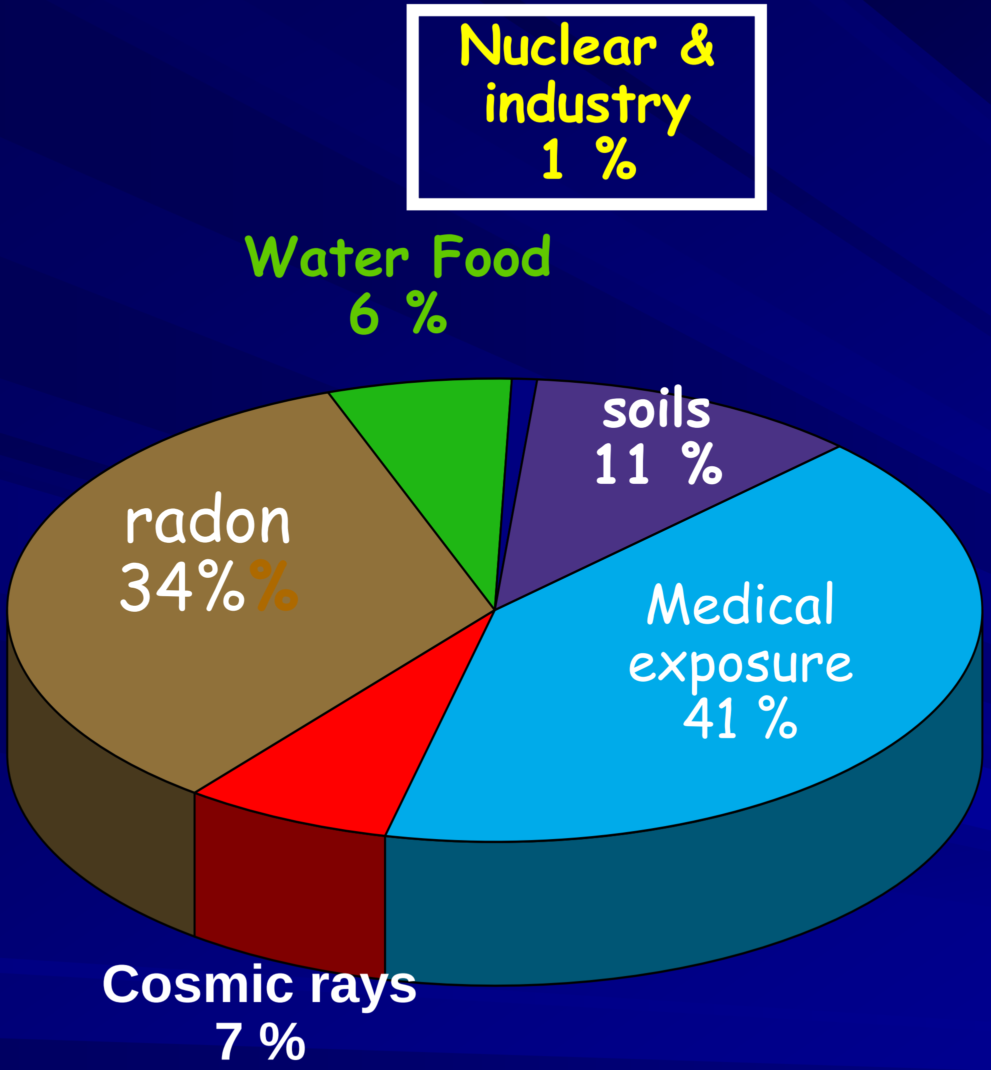




Effects of radiation on human body

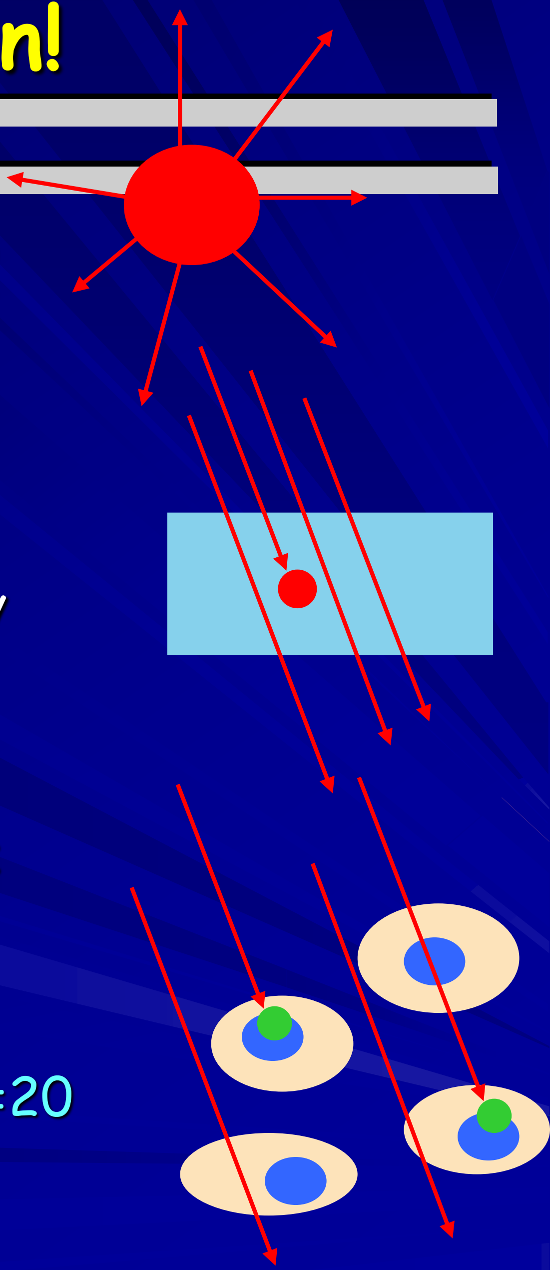
What is a Curie,Bequerel, Seivert?

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...

The Units - a bit of definition!



- Activity = Number of decays per second
  - Becquerel Bq : 1 decay / second
  - Curie Ci : 37 x 10^9 Bq (37 GBq)
- Dose : specificity of radiation effects
    - ionisation,modification of biogical activity
  - absorbed energy / mass unit
  - Gray Gy : 1 joule / kilogram
- Effective dose : indication of global risc
  = absorbed dose x WR* x WT**
  - Sievert Sv
    - WR*= 1 pour RX, beta and gamma, p=5, α=20
    - WT** = 0.05 for thyroïd, 0.01 for skin

Effective dose values

- 10.000 mSv : high irradiation / rapid death
- 1.000 mSv : moderate irradiation / clinical visible signs (burn…)
- 5 mSv : annual irradiation in Clermont-Ferrand (volcanic soil)
- 2,5 mSv : annual irradiation in Paris
- 1 mSv : legal limit irradiation in France
- 1 mSv : average annual medical irradiation in France

A simple exemple

a 'standard' Scintigraphy exam

	W_R	W_T	%
RX : 100 mGy / 50 cm^2 skin	1	0,01	30 %
^{131}I : 10 mGy / thyroïde	1	0,05	100 %

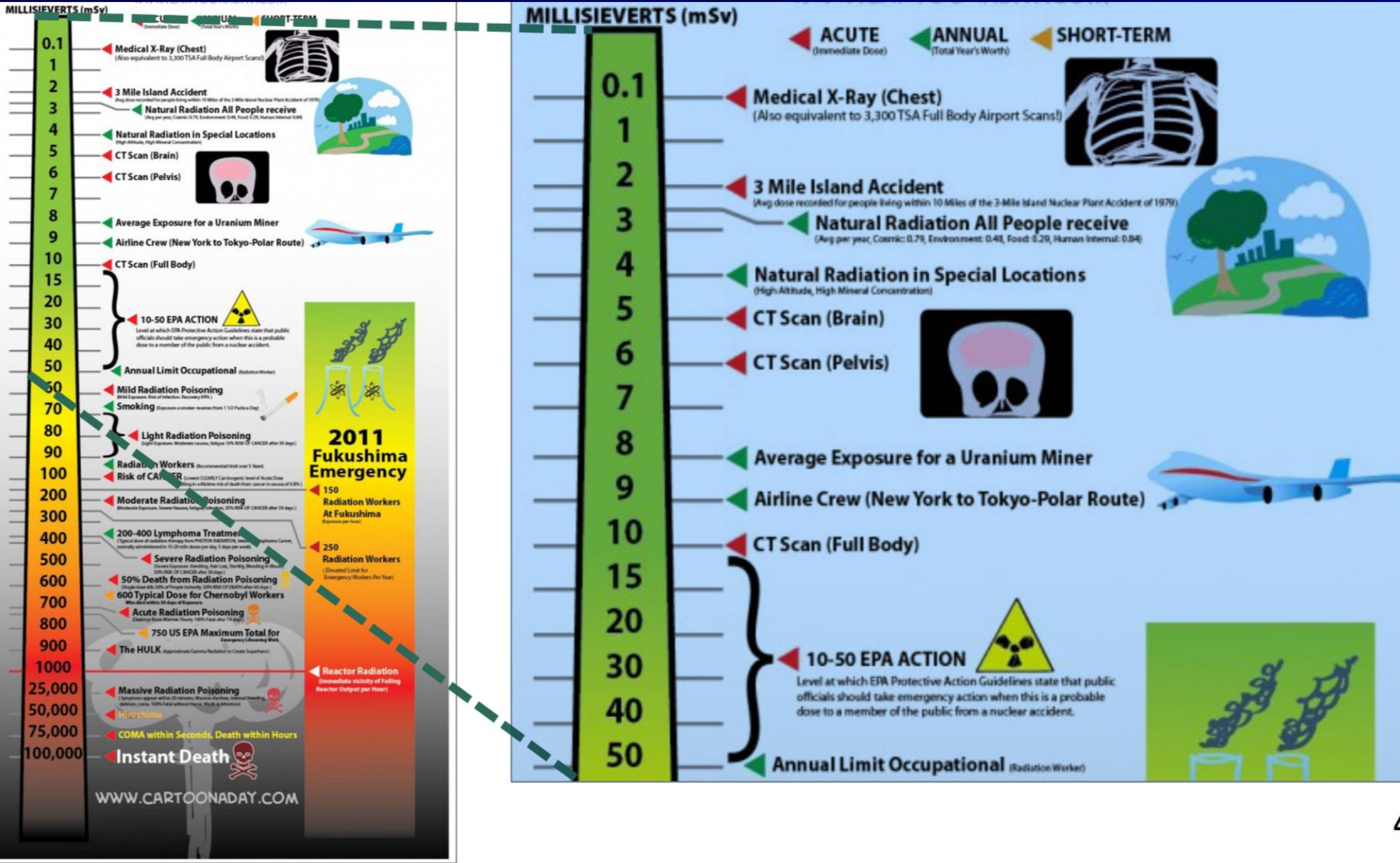
Effect dose = (100 x 1 x 0,01 x 0,30) + (10 x 1 x 0,05 x 1)
= 0,8 mSv

- Sv= Unit well adapted to radioprotection
- However : why this official' limit of 1 mSV/ year is so low ?
  - No sanitary argument : industrial irradiation :10 -15 µSv
  - Interpretation of the 'low' absolute value might be controversial!
- Do not take into account debit and age ..an personal sensitivity

Variation of natural radioactivity

- Cosmic rays
  - sea level 0,25 mSv / year
  - Mexico (2240 m) 0,80 mSv / year
  - La Paz (3900 m) 2,00 mSv / year
- External exposure due to earth exposure
  - average 0,9 mSv / year
  - Espirito Santo (Bresil) 35 mSv / year
  - Maximum (Iran) 250 mSv / year
  - Marseille (France) 0,20 mSv / year
  - Limousin (France) 1,20 mSv / year
- Internal exposure due to water
  - Evian water 0,03 mSv / year
  - St Alban water 1,25 mSv / year

Typical radiation doses



Exposure for radiological exams

- Some examples

organ	dose skin mGy	effective dose mSv
Thorax, face	0r,2 - 0,5	0,015 - 0,15
Lumbar region	4 - 28	1,5
Urography	40 - 60	3
Brain scan	7 - 78	1
Whole Body scan	30 - 60	4 - 10
Mammography	7 - 25	0,5 - 1

Summary & Conclusions (1)

- HEP has considerable acquired knowledge, expertise and resources that can, when transferred properly, significantly impact the practice of medical imaging and therapy
- A lot of exciting ideas and developments!
  - Should attrack young 'experimentalists'
- Activity that need to be 'promoted' actively outside our community for the benefit of us…in these hard time !
  - HEP is not only hunting the Higgs !

Summary & Conclusions (2)

- It take sometime between the discovery and initial ideas.
- But when the technology is mature, it can make a gigantic breakthrough in the development of a technical device or system
- Collaboration between various scientists and expert is fundamental and the key factor for success.
- Building a community (network) about a specific subjects is the way to integrate students and experts

Thanks to

- C. DaVia (Manchester).
- D.Townsend (U. Singuapor)
- H. Frisch (U. Chicago)
- P. Lecoq (CERN)
- R. Lecomte (Sherbrook)
- W. Moses (LBL)
- S. Ritt (PSI)
- K. Parodi (HIT)
- Pr. J.N. Talbot (Hopital Tenon - Paris)
- … and many others

Thank you
for your attention

2016

–

2017

2018

Final Conclusions

There is a lot to do
Particularly
for students

References
Proceedings
of NSS-MIC
conferences
Transaction on Nuclear Sciences (TNS)
http://www.nss-mic.org/2016/NSSMain.asp

Questions?