Radiation detectors
From past to future

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

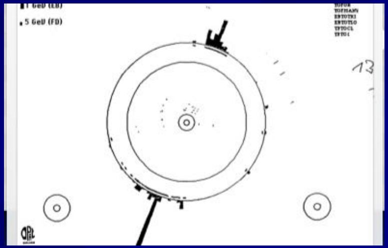
* * *

P. Le Dû

patrickledu@me.com

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**

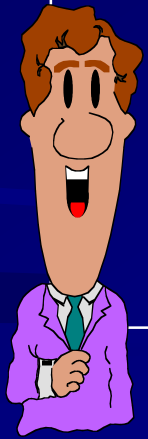


Experimental Physicist
-CEA **Saclay** (1969-2008)
-IN2P3-IPN Lyon (2009 ..)

NPSS ADCOM

Goals of this presentation

- Using my own experience during the last 50 years of working on Radiation detectors and experiments → try to give an introductory flavor of some detector families and their recent evolution and application in various fields



Outlines of the lecture

- Little introduction about radiation detectors
  - A little bit of history over the last 120 years

- Basic sensors families → past, present and future
  - Photons detectors
  - Scintillors and photodetectors

Others like gaseous, silicon , electronics … with be given by my colleagues

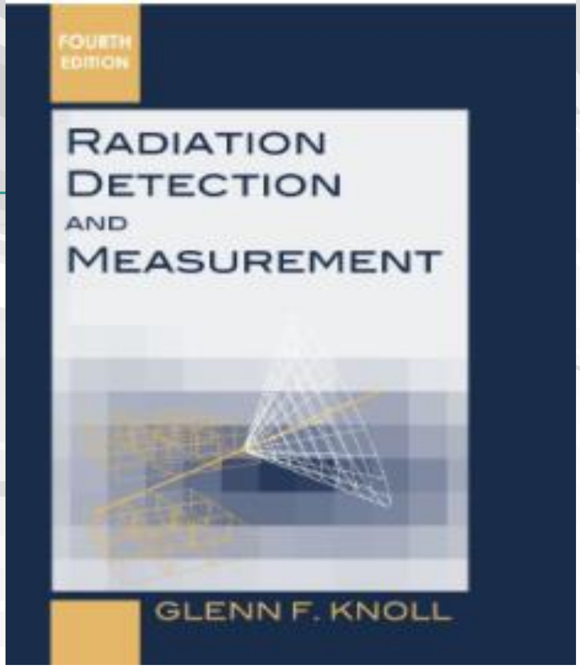
Few words about Radiation Detectors

Radiation

Instrumentation

THE Book

Glenn Knoll



FOURTH EDITION

RADIATION DETECTION AND MEASUREMENT

GLENN F. KNOLL

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

How physics discoveries have impacted our life (1)

1895
W.C. Rontgen
Discovery of X Ray

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

First image of potassium uranyl disulfide

RADIOACTIVITY

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

Marie and Pierre Curie with their daughter Irene

Marie Curie

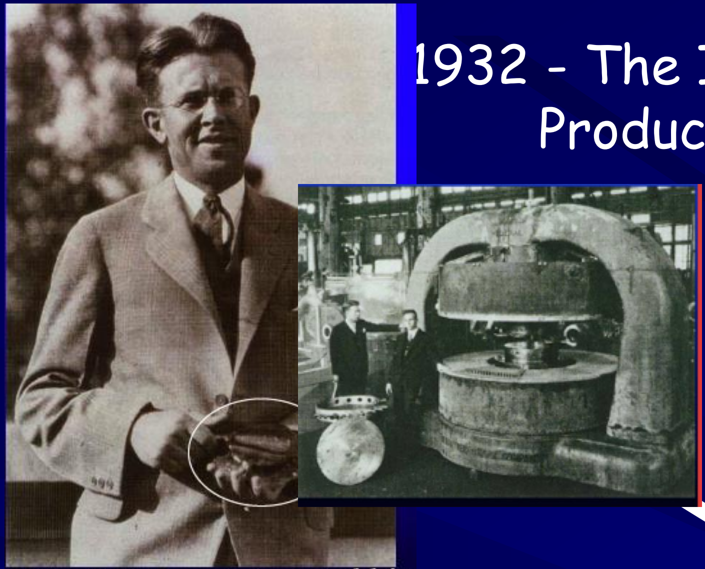
1898
Pierre and Marie Curie
the Radioactivity
Polonium, Radium

1910

X Ray Radiography

1923 - The Tracer principle
`G.V.Hevesy- the father of nuclear medicine

How physics discoveries impact our life (2)

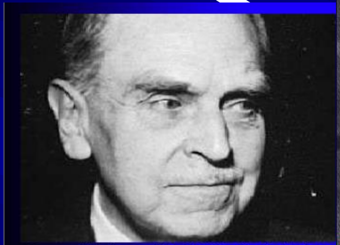


Ernest O. Lawrence and his
First cyclotron 1932

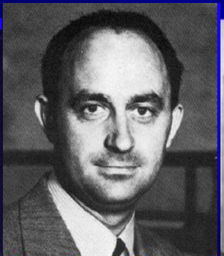
1932 - The Invention of the cyclotron
Production of radioisotopes

1934 - Artificial radioactivity
Irène and Fréderic Jolio Curie
in combination with the cyclotron open the door to the production of useful radio indicators.

1938-1942 Fission of Uranium



Otto Hahn, 1944 Nobel Prize

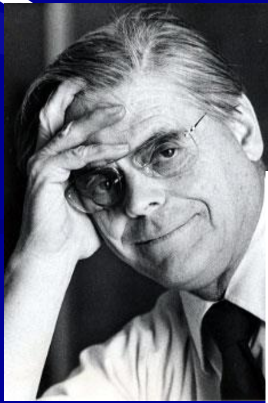


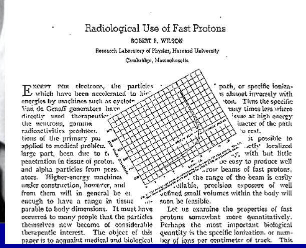
Enrico Fermi

O.Hahn
E. Fermi

From discovery to first graphite miler in Chicago To the Production of long lived radio-isotopes and nuclear energyproduction

1946 – R.R.Wilson The origin of particle therapy Using the Bragg peak discovery (1903)





Radiological Use of Fast Protons

ROBERT R. WILSON

Research Laboratory of Physics, Harvard University
Cambridge, Massachusetts

EXCEPT FOR electrons, the particles
which have been accelerated to hi
energies by machines such as cyclot
Van de Graaff generators have
directly used therapeutic
the neutrons, gamma
radioactivities produced
tions of the primary pa
applied to medical problem
large part, been due to t
penetration in tissue of proto
and alpha particles from pres
ators. Higher-energy machines
under construction, however, and
from them will in general be e
enough to have a range in tissue
parable to body dimensions. It must have occurred to many people that the particles themselves now become of considerable therapeutic interest. The object of this paper is to acquaint medical and biological

path, or specific ioniza-
s almost inversely with
ton. Thus the specific
many times less where
issue at high energy
imeter of the path
o rest.
it possible to
ctly localized
y, with but little
be easy to produce well
row beams of fast protons,
the range of the beam is easily
ollable, precision exposure of well
defined small volumes within the body will soon be feasible.

Let us examine the properties of fast protons somewhat more quantitatively. Perhaps the most important biological quantity is the specific ionization, or number of ions per centimeter of track. This

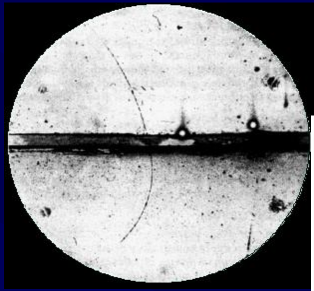
Technologies and Physics discoveries history

History and evolution of radiation detectors tools of discovery

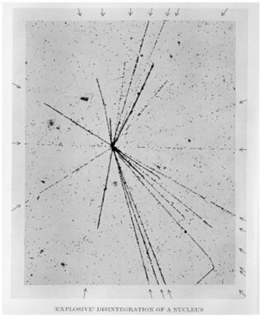
1906	Geiger counter	H.Geiger,E.Rutherford	
1910	Cloud Chamber	C.T.R. Wilson	Positron, Muon
1928	Geiger Muler counter	W. Muller,H.Geiger	
1929	Coincidence method	W. Bethe	
1930	Nuclear Emulsion	M.Blau	Pion, Kaon
1934	Photomultiplier	RCA Corporation	
1947	Scintillator	Kallmann	
1952	Bubble chamber	D.Glaser	Omega moins
1962	Spark chamber	Schwartz,Steinberger, Lederman	Neutrino mu
1968	MWPC	G.Charpak	

In Blue = Nobel price

Evolution over the years

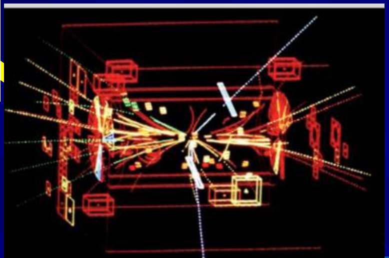


1910



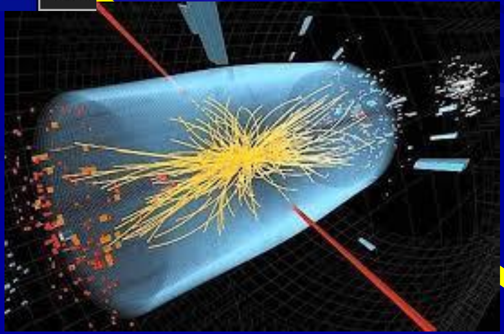
1930

1960



1980

1990



2012

Micron
KeV to TeV
Picosecond
Billion of Pixels

Detector families overview

Detector Technologies & components

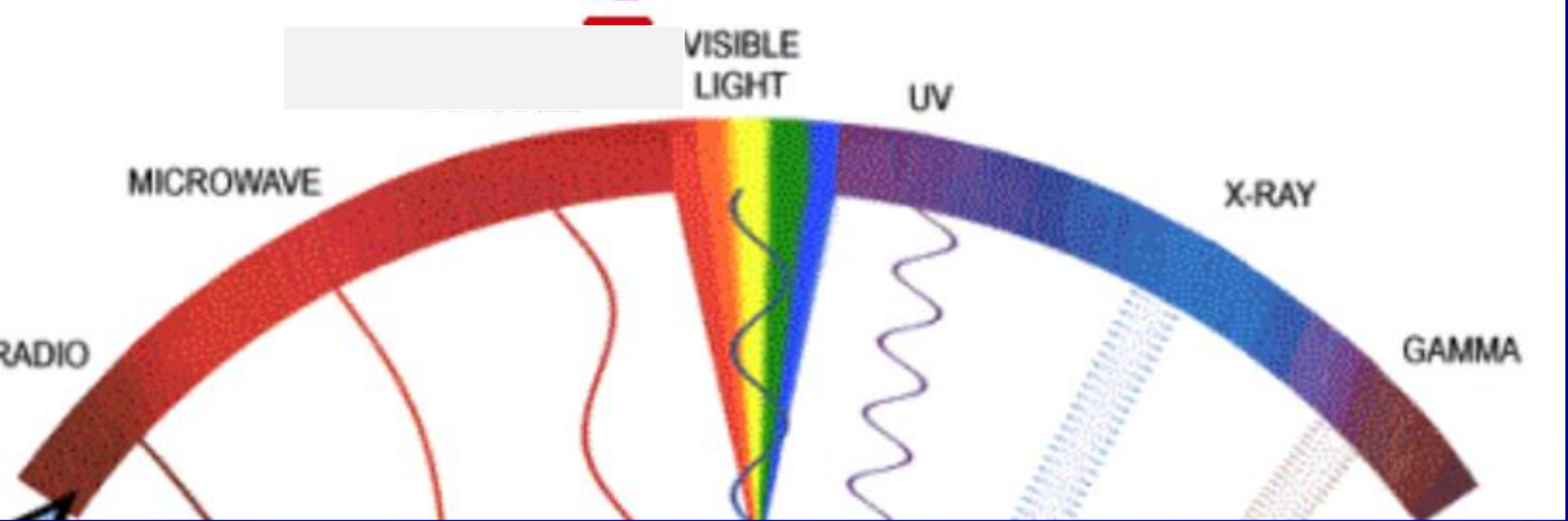
- Scintillators
- Photodetectors
- Gazeous detector
- Silicon/pixel
- Electronics

Associated systems and techniques

- Tracking
- Calorimeters
- Cherenkov
- Time of Flight
- Front End /Read Out
- Event selection /Trigger
- Data Acquisition
- Computing
- Simulation

Photon detectors

From waves to radiations



$5\ 10^6$	Wave Lengh	10^3	500	250	0,5	0,0005	Nanometers
0,000000248	Energy	0,124	2,48	4,96	2480	2480000	EVolts

Purpose of a photodetector is to detect photons

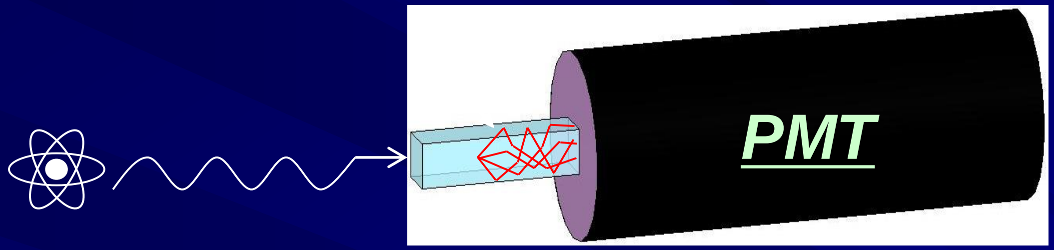
- However, the energy range of photons that we wish to detect is extremely large:→ 0.1 eV ~ > 1014 eV (>100 TeV)
- This requires many different kinds of photodetectors

Photodetectors vs Photon Detectors

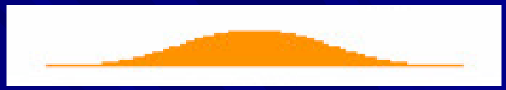
- Define a photon detector as a device that detects photons of an arbitrary energy
- High energy photons (E > 1 MeV) are very penetrating and require high stopping power
- Define a photodetector as a device that detects photons in the eV to few keV range (IR to X-ray). These photons may be detected directly or may be produced by some other type of photon detector

The two scheme to detect photons

Scintillator



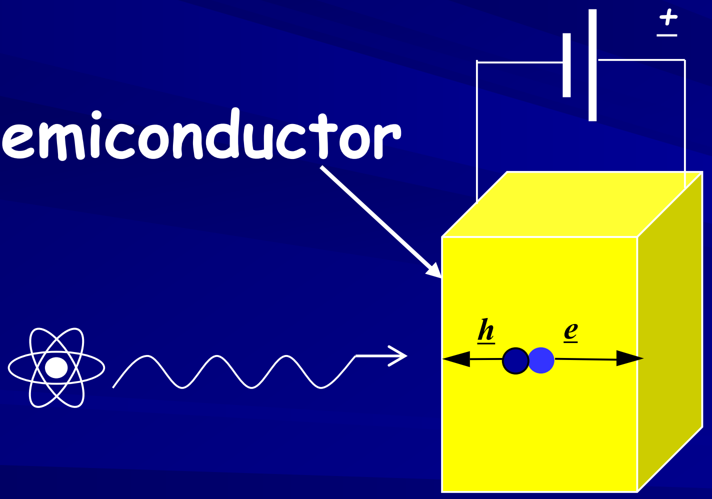
~1,500 e^-
@ 140 keV



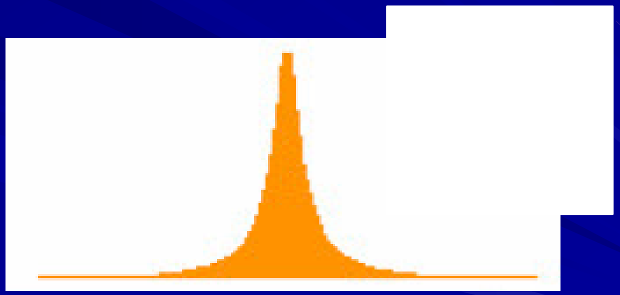
Energy per e^- ~ 10 – 200 eV

Indirect Detection: Gamma Ray --> Visible Light --> Electrical Signal

Semiconductor



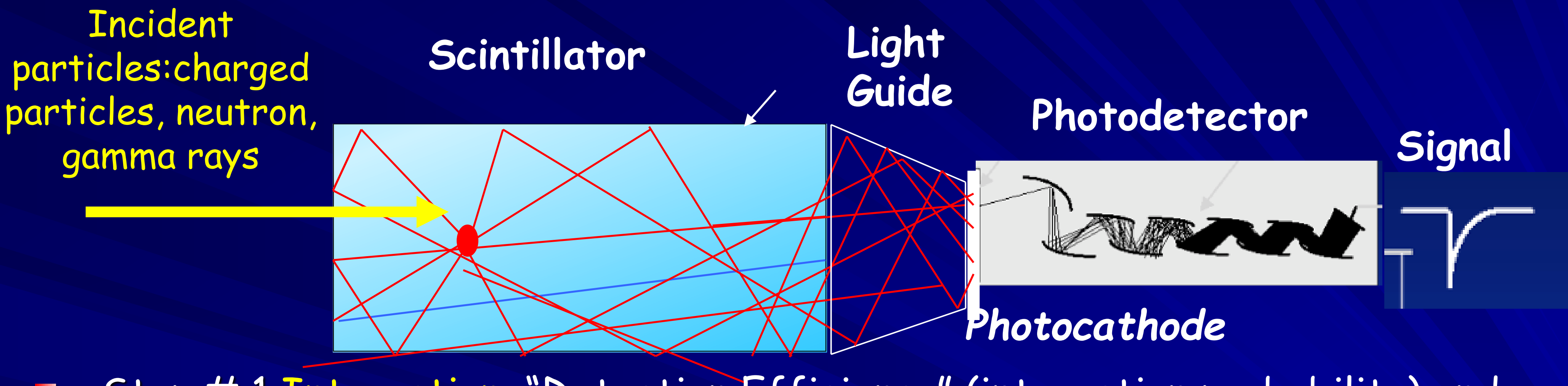
~30,000 e^-
@ 140 keV



Energy per e^- ~ 3 – 5 eV

Direct Detection :Gamma Ray --> Electrical Signal

Basic principle and Factors affecting the performance of a photon detector



- Step # 1 Interaction "Detection Efficiency" (interaction probability) and "Full energy Efficiency" (total absorption probability)
- Step # 2 Scintillation: converts ionization energy into scintillation light (150 to 800 nm) , "Scintillation Efficiency" (photons/MeV)
- Step # 3 "Light Collection Efficiency"
- Step # 4 Photodetection :converts scintillation light into an electrical signal "Quantum Efficiency" (electrons/scintillation photon) (photons/MeV)
- **Step # 5 Electronics: → signal processing, noise, time pick-off**

Scintillators

A scintillator is a material that transforms energy loss due to ionization (dE/dx) into light

Organic

- Plastic (organic fluors in a base polymer)
- Liquids
- crystals (anthacene)
- Low Z / Low density (~ 1 g/cm3)
- Low light yeld (<10 kphotons/Mev)
- n detection by (n,p) interactions
- Fast (ns) decay times
- Relatively inexpensive
- Machinable
- Moderately rad hard (~ 10 kGy/yr)
- Independent on temperature

Inorganic (No C content)

- Crystals (Lyso,NaI,CsI ..)
- Gas (N2 & Noble)
- High Z atoms high density (> 8 g/cm3)
- High Light Yeld (10-100K photon/Mev
- Hygroscopic
- Requires good light collection
- Poor n detection efficiency
- Slow decay time ns to msec
- Expensive (production)
- Fairly radiation hard (~ 100 kGy/yr)
- Temperature dependant

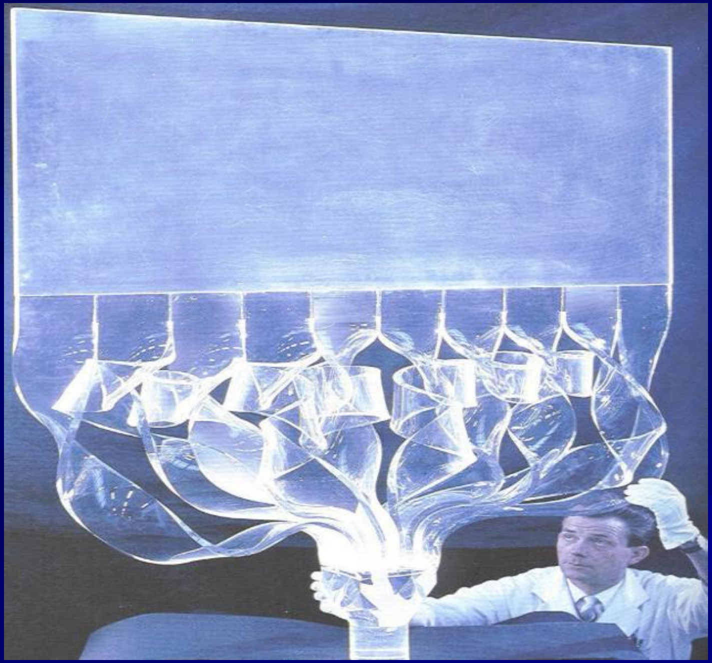
Noble Liquid

- LAr, LKr, Lxe
- Requires working at cryogenic temperatures
- Moderate density and Z(~ 1.4- 3.0 g/cm3)
- Scintillation in UV or VUV
- High Light yield ~ 50,000 photons/MeV
- Produce ionization plus scintillation
- light and collecting charge
- Drift time can give position (TPC)

Organic scintillator

Convert PART of the incident energy

example plastic plates



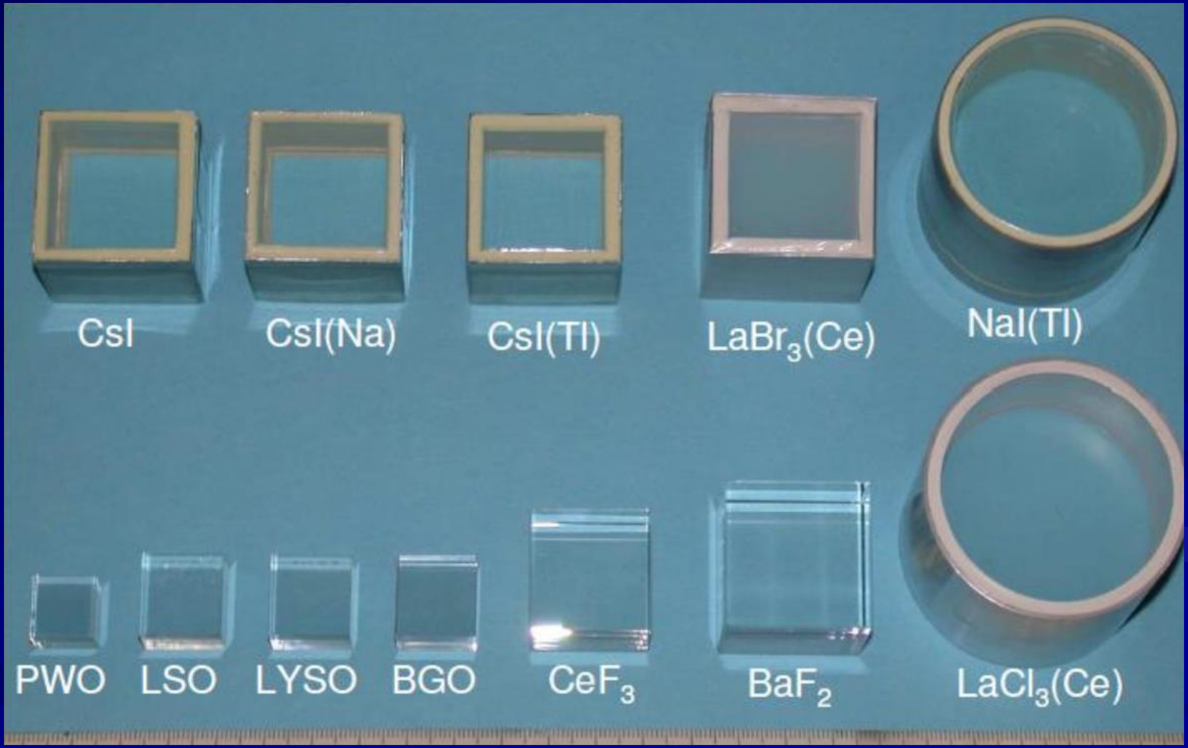
- Easily machined
- Large size available
- Good light transport with wavelength shifting using primary and secondary fluors
- Very fast (ns)
- Cheap
- Not very radiation hard

1 optical photon per 100 eV deposited energy

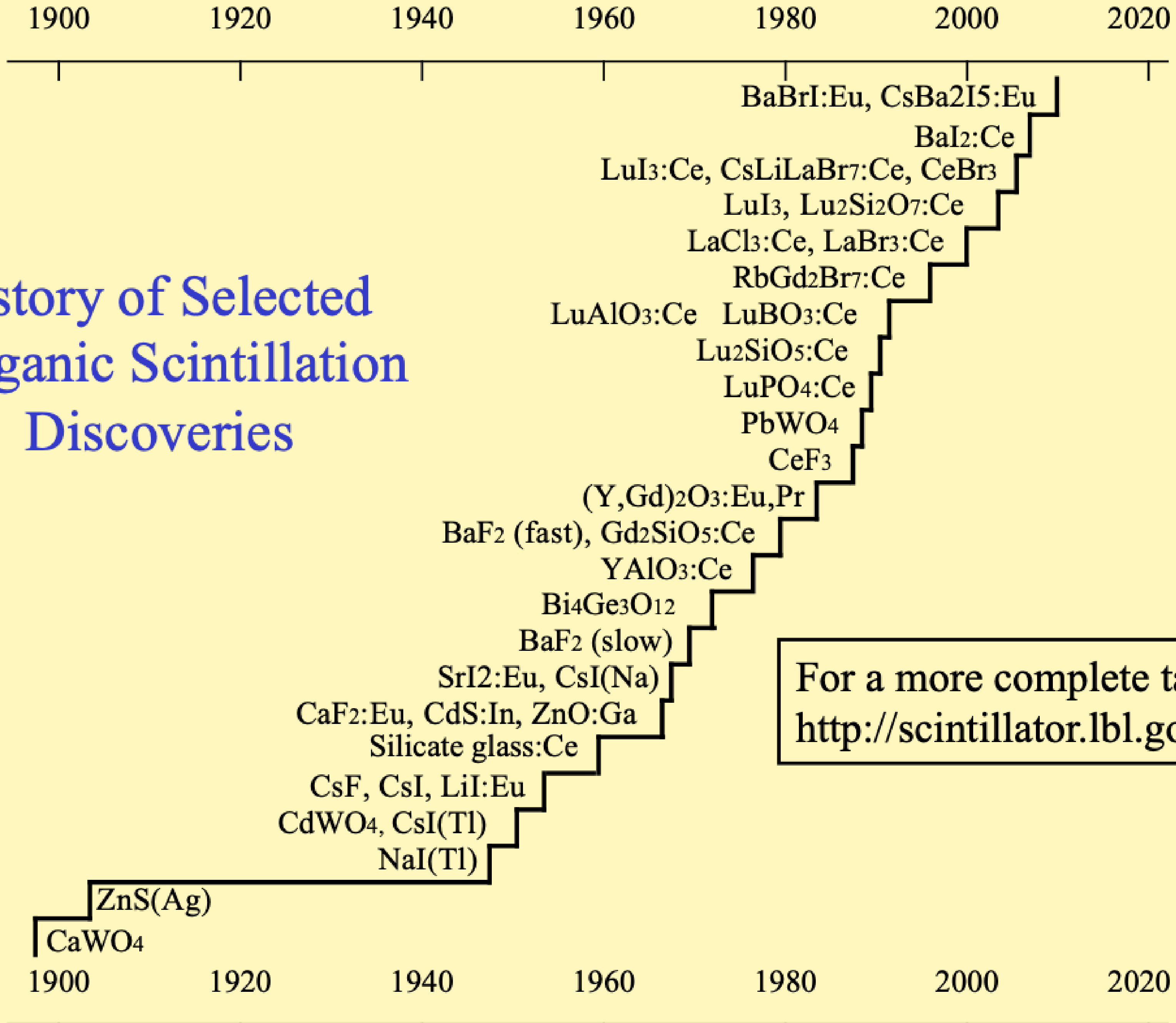
Commonly used in HEP/Nuclear Physics …
counters,hodoscopes and hadronic calorimeters ….

Crystal inorganic scintillator

- Primary ionization excites an electron from the valence band to the conduction band leaving a hole in the valence band



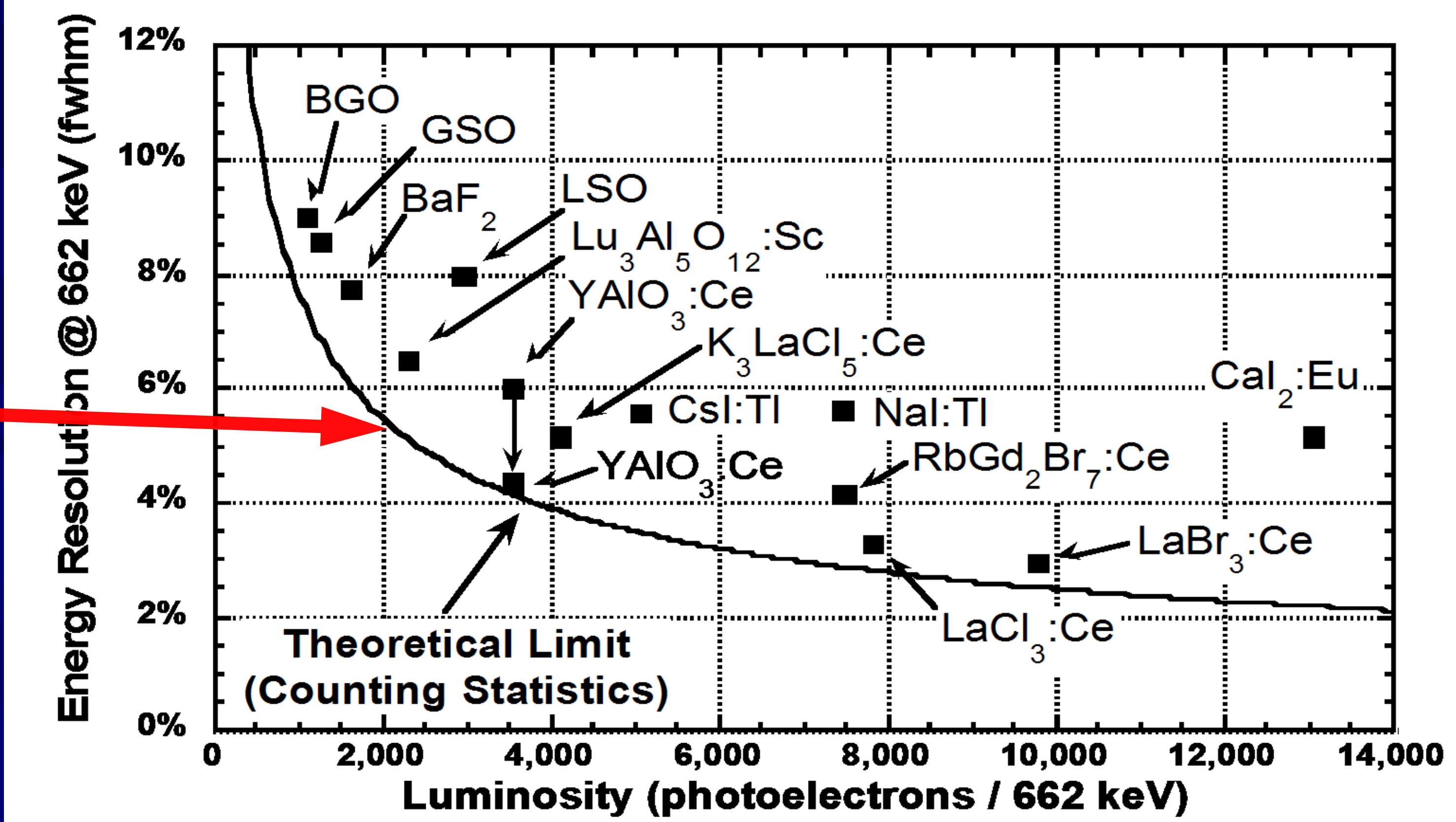
History of Selected Inorganic Scintillation Discoveries



For a more complete table, see http://scintillator.lbl.gov

Energy resolution and non linearity

Poisson limit

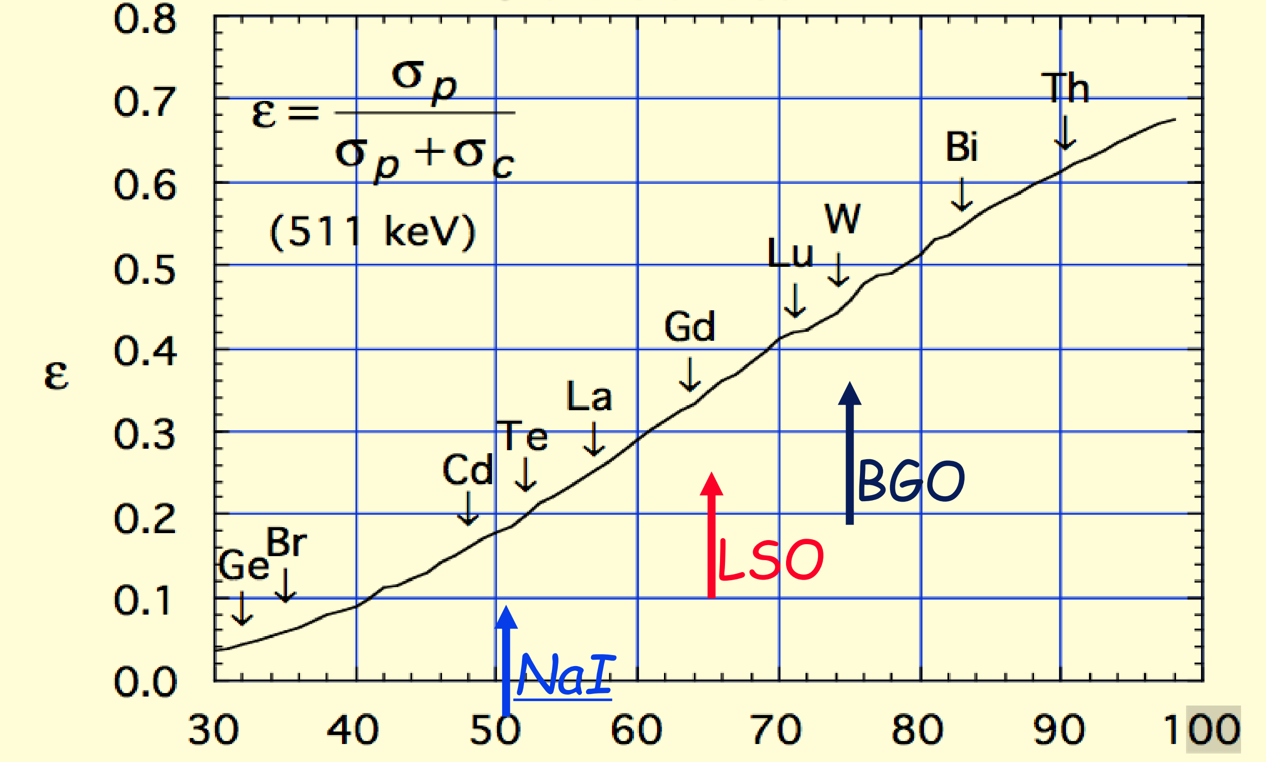


- Light yield non-proportionality is limiting the energy resolution

W. Moses, Nuclear Instruments and Methods in Physics Research A 487 (2002) 123–128

From P. Dorenbos, "Light output and energy resolution of Ce^{3+} doped scintillators," Nucl Instr Meth, A486, pp. 208-213, 2002.

Effective Atomic Number Affect Photoelectric Fraction



Atomic Number (Z)

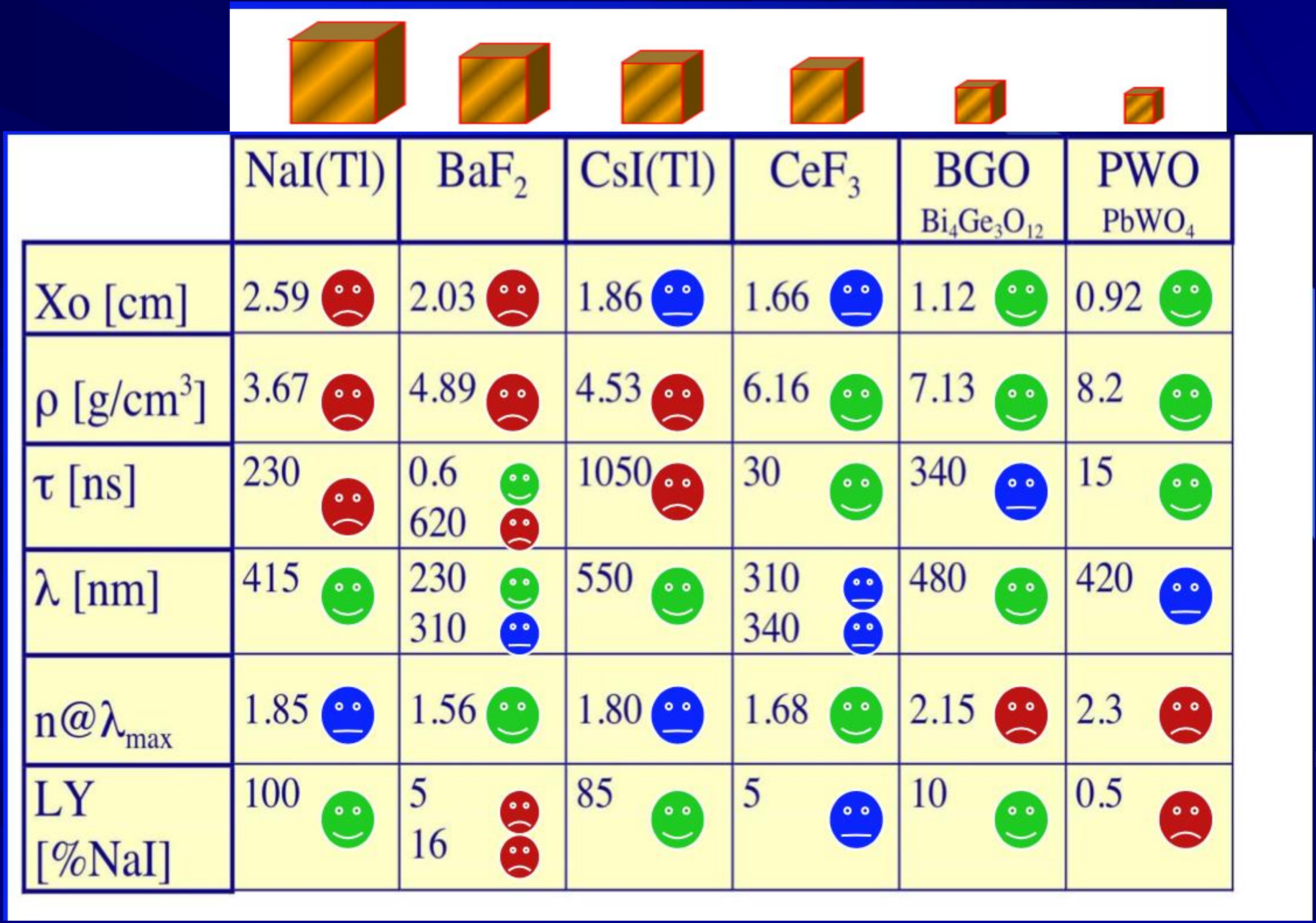
- High effective Z materials => high photoelectric fraction
- High effective Z materials => high attenuation length
- High effective Z materials => higher sensitivity, better spatial resolution

Desirable scintillator properties

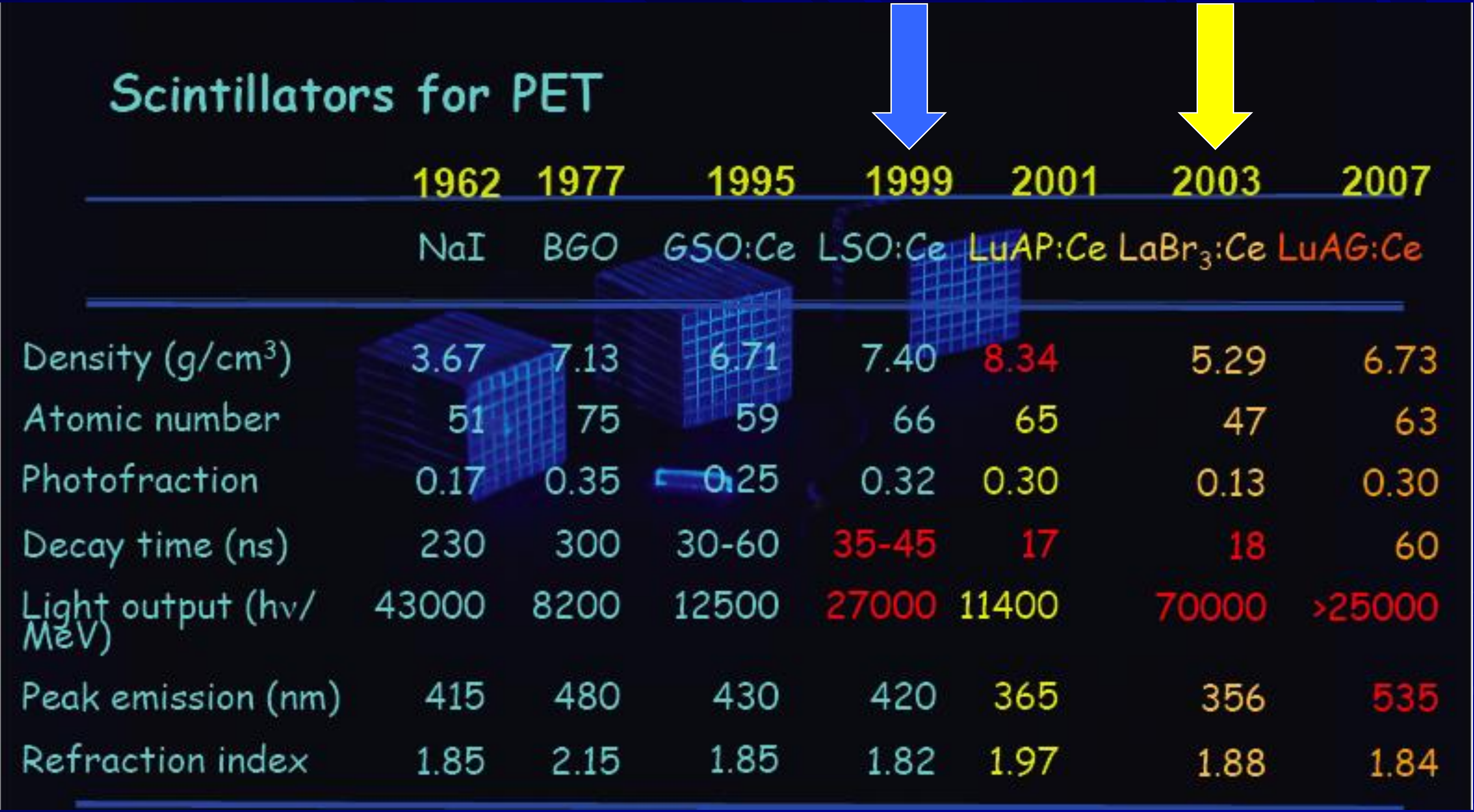
- High density, High Z → Good stopping power fpr gammas (or neutrons)
- Good resolution, all energies → *High photoelectric cross section to total cross section*
- Photon production proportional to energy deposited
- High countrate capability → good signal to noise ratio
- Large detector volumes at low cost
- No Hydroscopic
- Light output (350-450 nm)
- Good high temperature performance
- Excellent uniformity and optical transparency
- Fast response and decay time (ns to µs, depending on application)

NaI
BGO
GSO
LuAp???

Crystal for HEP



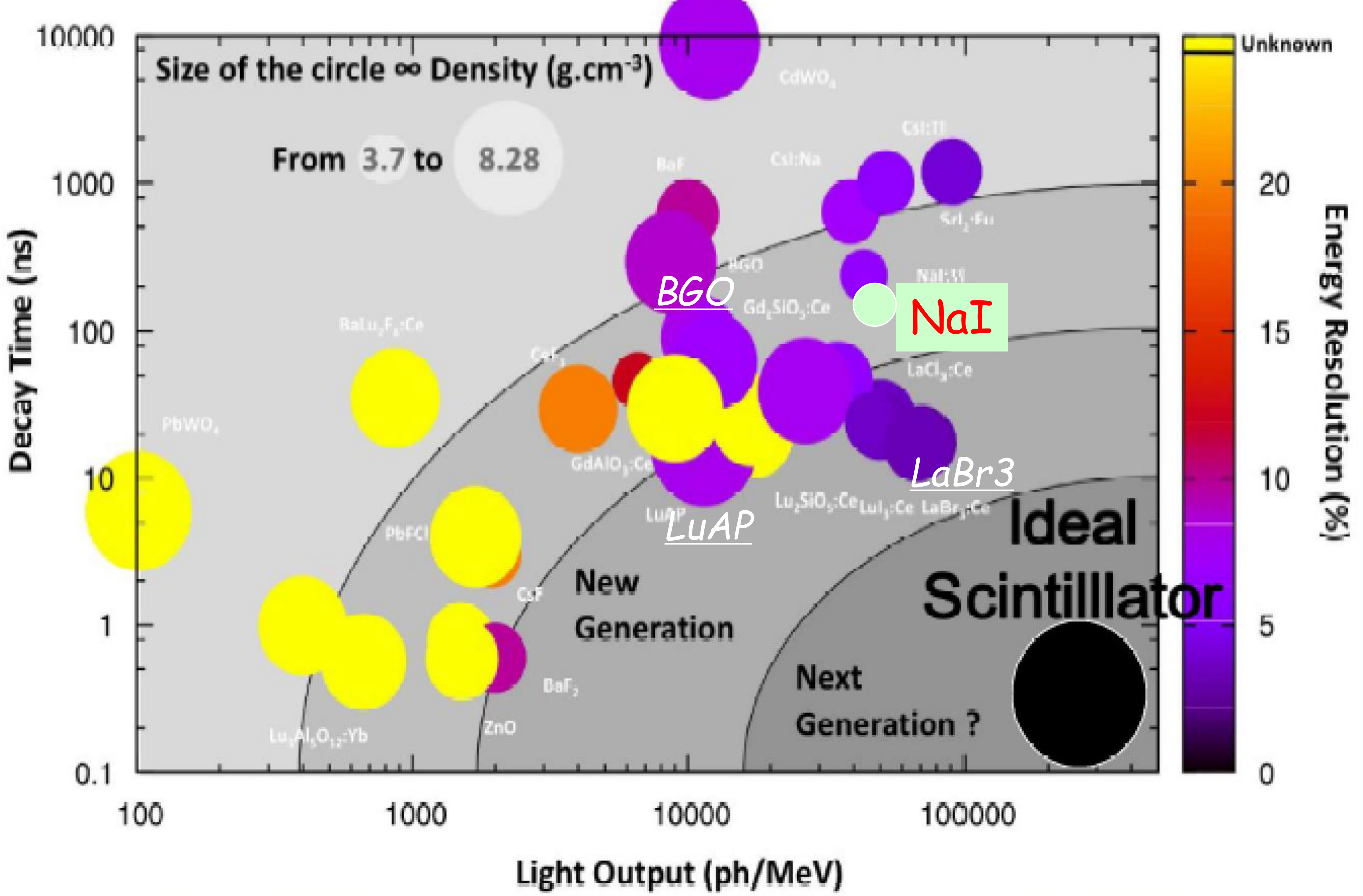
	NaI(Tl)	BaF_2	CsI(Tl)	CeF_3	BGO $Bi_4Ge_3O_{12}$	PWO $PbWO_4$
Xo [cm]	2.59 🙁	2.03 🙁	1.86 😐	1.66 😐	1.12 🙂	0.92 🙂
ρ [g/cm^3]	3.67 🙁	4.89 🙁	4.53 🙁	6.16 🙂	7.13 🙂	8.2 🙂
τ [ns]	230 🙁	0.6 🙂 620 🙁	1050 🙁	30 🙂	340 😐	15 🙂
λ [nm]	415 🙂	230 🙂 310 😐	550 🙂	310 😐 340 😐	480 🙂	420 😐
n@λ_{max}	1.85 😐	1.56 🙂	1.80 😐	1.68 🙂	2.15 🙁	2.3 🙁
LY [%NaI]	100 🙂	5 🙁 16 🙁	85 🙂	5 😐	10 🙂	0.5 🙁



Scintillators for PET

	1962 NaI	1977 BGO	1995 GSO:Ce	1999 LSO:Ce	2001 LuAP:Ce	2003 LaBr$_3$:Ce	2007 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


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

Noble Liquids/Gas

- What type of physics do we do?
  - Neutrino oscillation and properties
  - Dark matter searches
  - Include double beta decay although not “officially” HEP -
- Lots of overlap with other categories & technologies
  - Liquid argon and xenon detectors (single phase and dual phase TPCs, etc)
  - Gas TPCs (high pressure, low pressure)
  - New techniques - for example scintillating bubble chamber for
  - DM/coherent scattering, or liquid helium - (some overlap with Quantum Sensing)

Liquid Xenon drift/scintillation time projection chamber

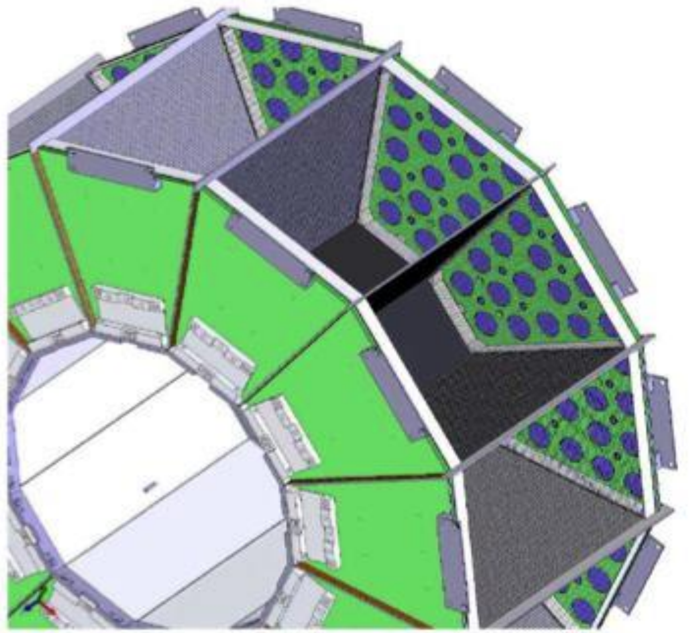


Fig. 1. The LXe PET ring concept. Scintillation light and charge are measured in each of the 12 modules consisting of a LXe time projection chamber viewed by avalanche photodiodes.

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

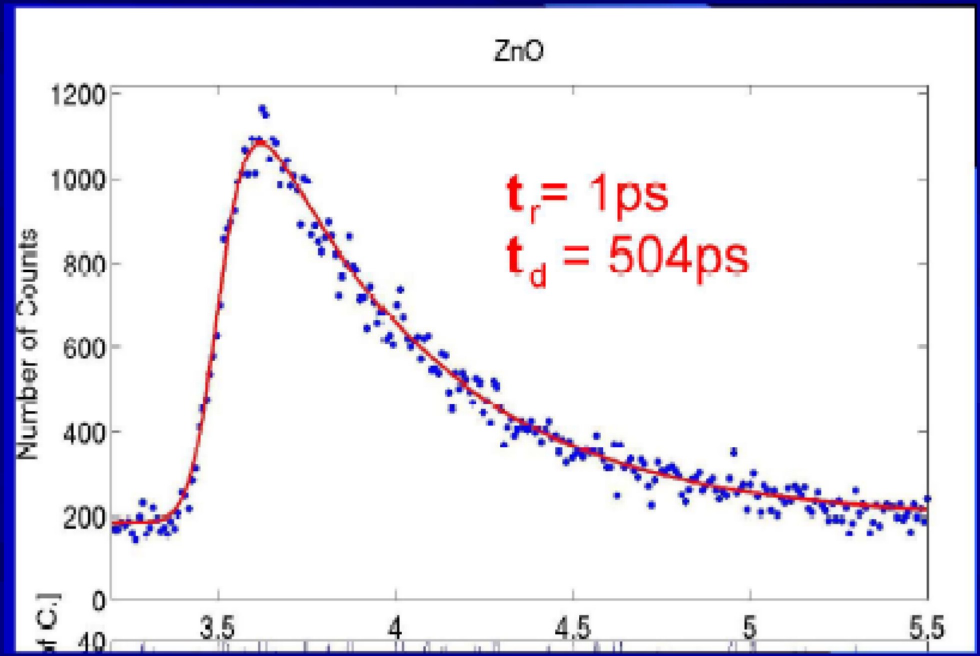
The scintillator world today

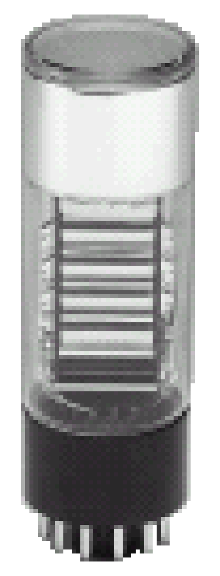
→ re –entering in a development phase (SCINT conference 2017)

- SCINTILLATORS are still widely used in a large number of scientific and industrial domains
- The ideal scintillator does not exist and research should continue on new materials and new production technologies
- Large development effort by the nuclear security community
  - Good energy resolution (LaB3, SrI2)
  - Neutron sensitivity ,
- HEP need material beyond PbWO
  - Radiation hardness compensation
- Medical Imaging (PET) needs material beyond LSO
  - Time of Flight and Energy resolution

FUTURE ?

- Metamaterials based on quantum dots, photonic crystals and photonic crystal fibers can open the way to new detection paradigms with huge design flexibility **(NASA,MIT …)**
  - **Decrease photostatistic jitter**
  - **Redistribute the light in the fastest propagation mode in the crystal**





Photodetectors

From the gazeous world to the silicon world

Photodetectors

- Must convert the light from the scintillator into electrons which can then be amplified and measured
- Photodetectors consist of two basic elements:
  - Photocathode that Converts photons into photoelectrons via the photoelectric effect - Performance determined by the Quantum Efficiency (QE)
- Charge amplification
  - Can involve gain or only direct conversion
  - Performance determined by signal to noise ratio
- Requires appropriate readout electronics

Photodetectors family Type

Vacuum

- Avalanche multiplication
  - Dynodes → PMT,VPT
  - Continuous Dynodes → MCP, Channeltron,
  - Multianodes devices
- Other multiplication process-Hybrid tubes
  - HPD,HAPD,VSIPM
  - ETC …

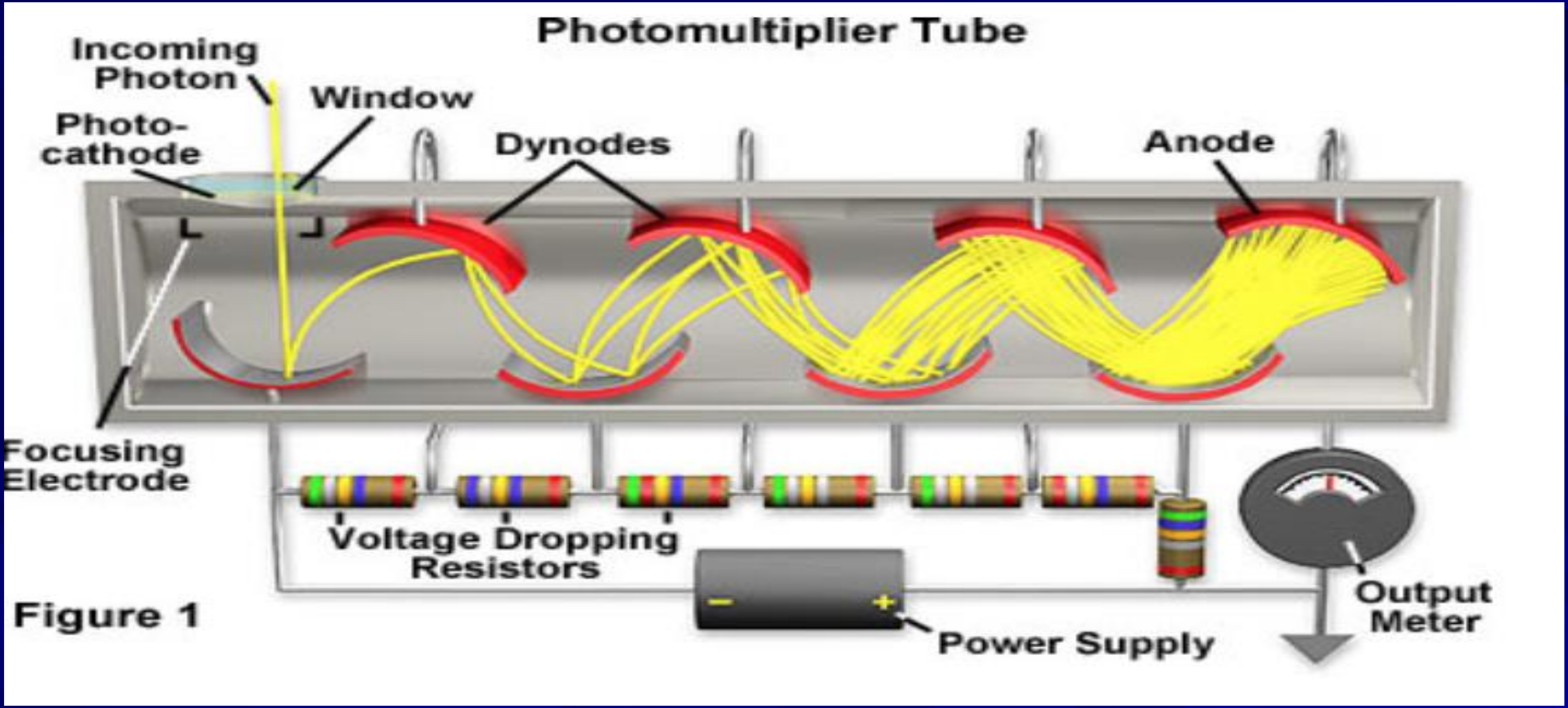
Solid State

- PIN Diode
- APD
- SIPM(MPPC..)
- CCD
- CMOS

Gas

- MWPC
- MGPD

See Maxim Titov presentation



Principle

- Photoelectrode emission
- Acceleration in vacuum
- Collision/SEE emission
- ……
- Collection at the anode

A lot of devices

Each application has to find best devices meeting the requirements

Main Parameters

Advantages

- ❖ Very High gain (10^6 to 10^7)
- ❖ Good sensitivity 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
- ❖ Good Uniformity,Linearity,Stability
- ❖ Low cost per unit

Drawback

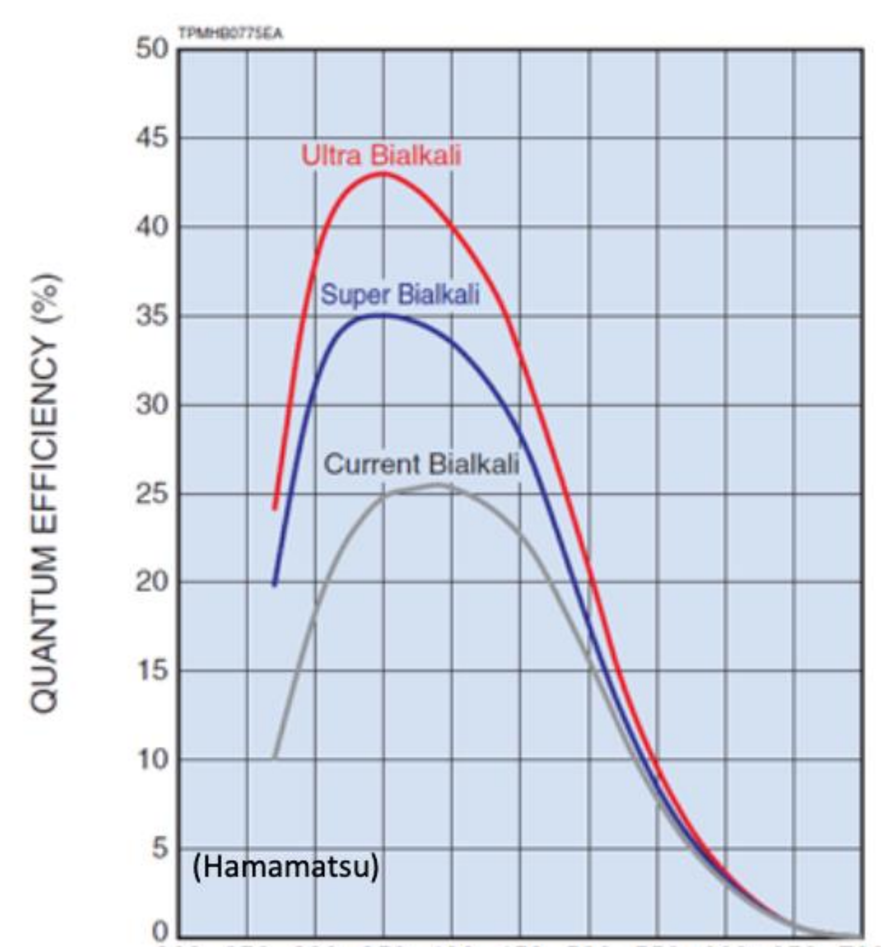
- Bulky
- Vacuum tube technology
- Sensitive to magnetic field

The list of advantages is the reason why PMT is widely used in radionuclide imaging, but the drawbacks are limiting advanced detector concepts.

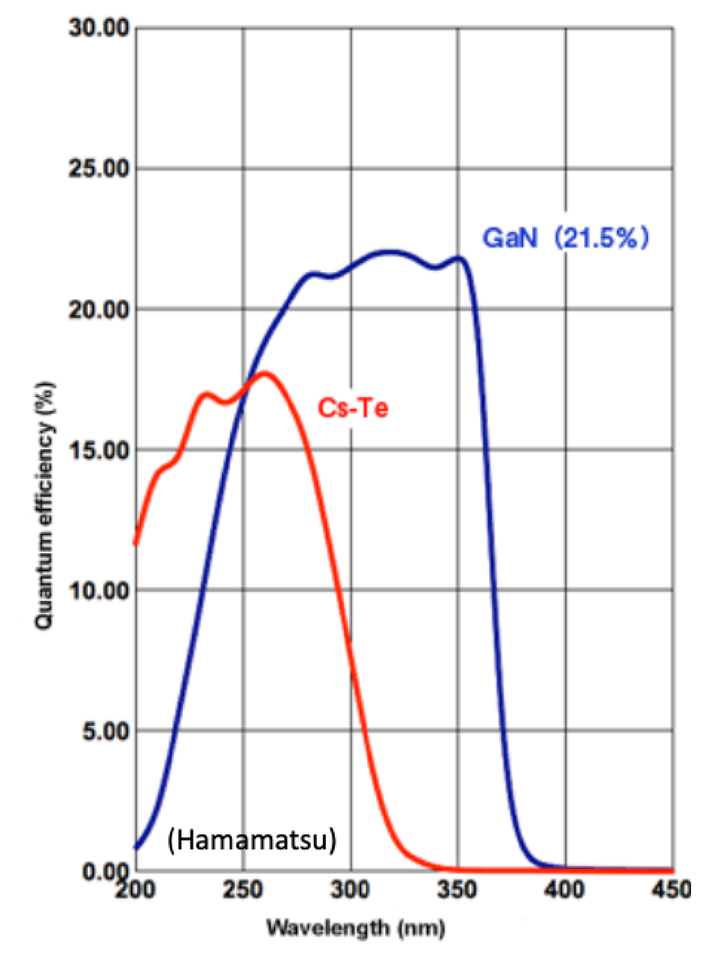
QE of Common Photocathodes

SBA & UBA photocathodes have QE>30% for visible light

Advance in photocathode by the 2 main providers



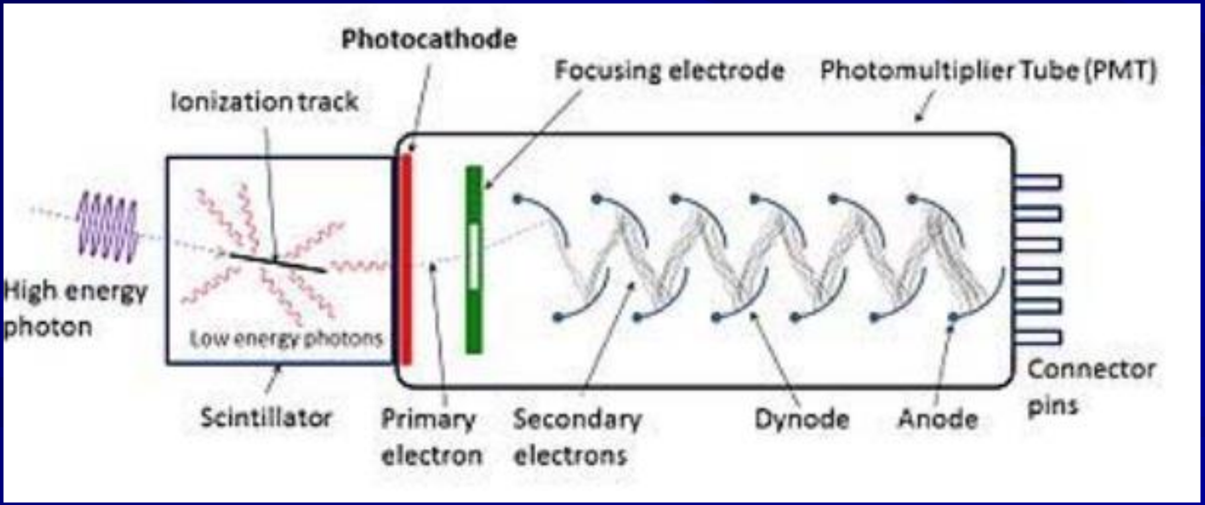
Hammamatsu

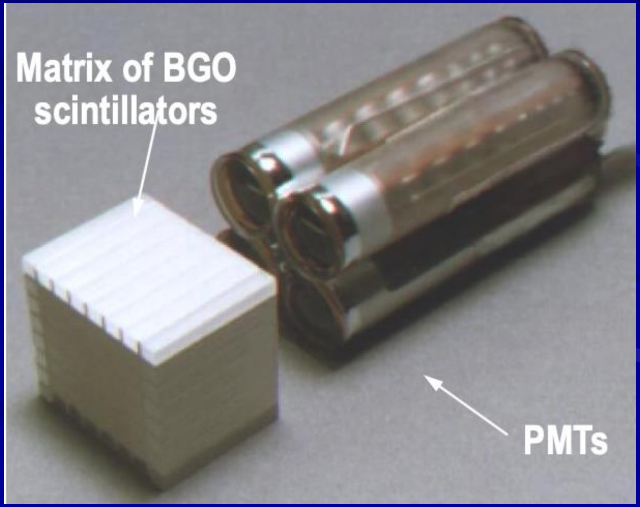


Photonis

Efficiency parameters

- Is determined by the process of photoelectron conversion. Ne/Ni Photocathodes determine the sensitivity range of PMTs.
- For high energy photon often scintillator materials are used to convert high energy photon to a visible /UV light
- Then number of detected photons determine the energy of incident photons …. Then energy resolution of the device





Parameters definition QE, PDE,CE ENF

- QE Quantum Efficiency

$$\frac{\text{Number of Emitted photoelectron}}{\text{Number of incident electron}}$$

- PDE Photon Detection Efficiency

$$\frac{\text{Number of Detected photoelectron}}{\text{Number of Incident photoelectron}}$$

- CE Collection Efficiency

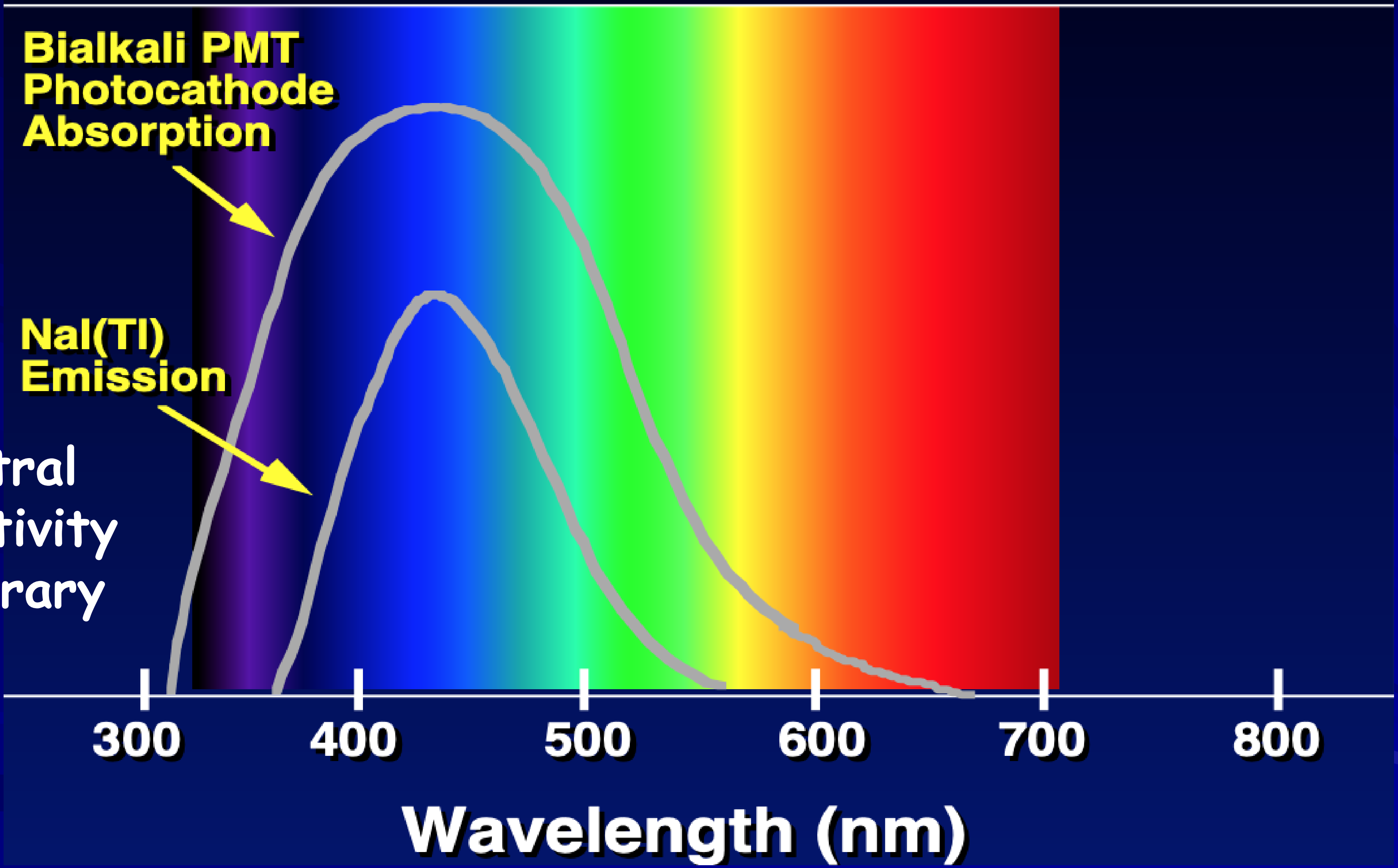
$$\frac{\text{Number of collected photoelectron emitted}}{\text{Number of incident electron}}$$

- ENF Multiplication fluctuations are characterized by the Excess Noise Factor -

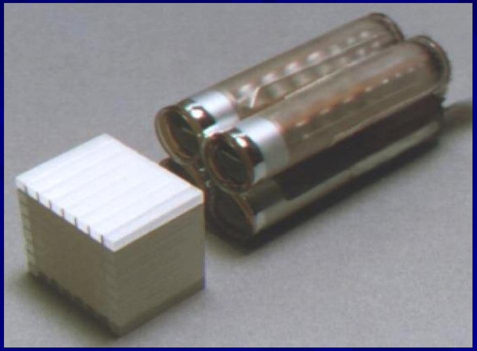
Photo detector	Operating Voltage	QE	CE	ENF	M	Photo Converter
Ideal	-	1.0	1.0	1.0	10_6	-
PMT	> 1 kV	0.3	0.9	~1.2	10_6	Photocathode
MCP	> 1 kV	0.3	~0.7	~1.2	10_6	Photocathode
PD	~ 30 V	0.8	1.0	1.0	1	Silicon
APD	~ 1 kV	0.8	1.0	>2.0	100	Silicon
SiPM	~ 50 V	0.8	~0.6	~1.3	10_6	Silicon

Scintillator-PMT photocathode spectral match

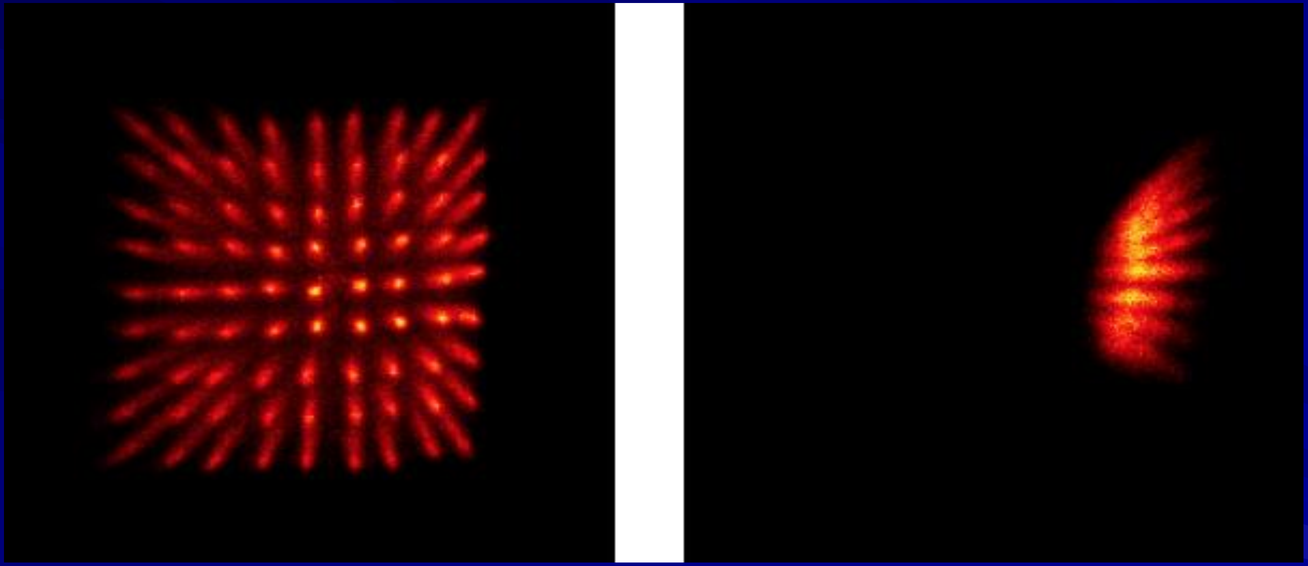
Spectral sensitivity Arbitrary units



Effect of PMT Inside Magnetic Field



Conventional PET Detector Block

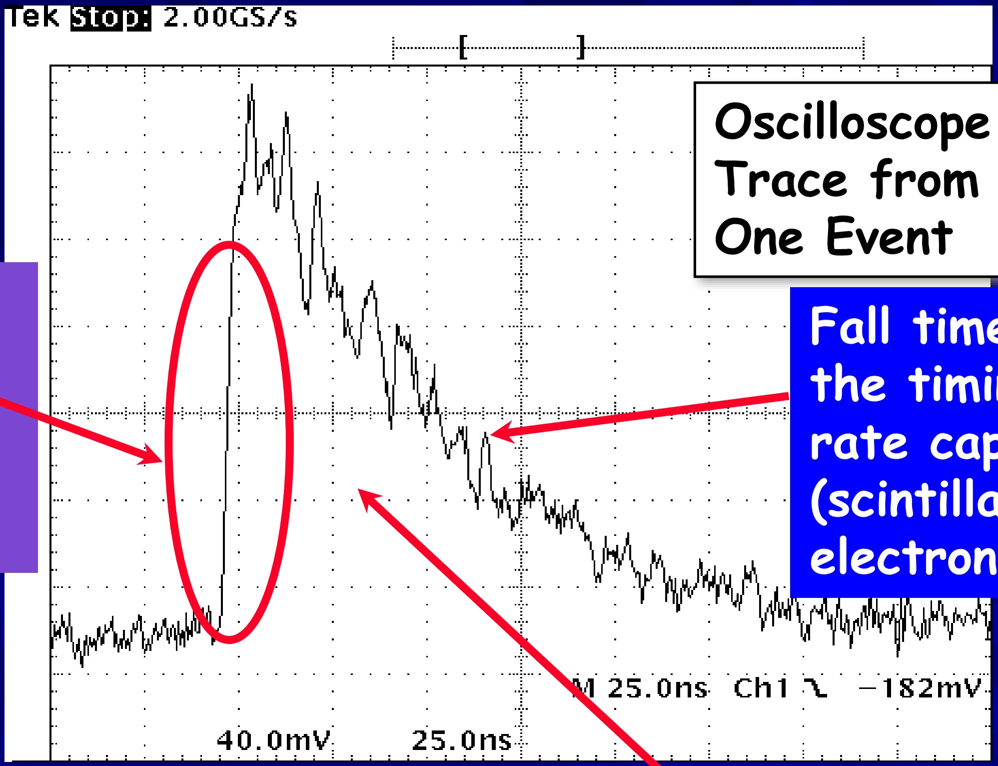


B=0

B≠0

PMT does not work inside magnetic field!!

Typical Raw Signal From Scintillation Detectors



Oscilloscope Trace from One Event

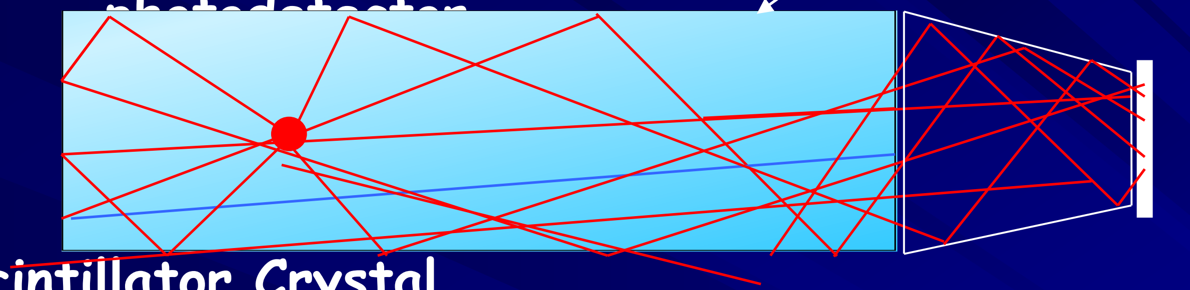
Initial photoelectron rate affect the timing *(scintillator, photodetector, electronics)*

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

The area under the

- Small Signal Level — 0.000000511 TeV
- Small Fraction of Scintillation Light in Leading Edge
- Fundamental Limit Due to Statistical Fluctuations

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)

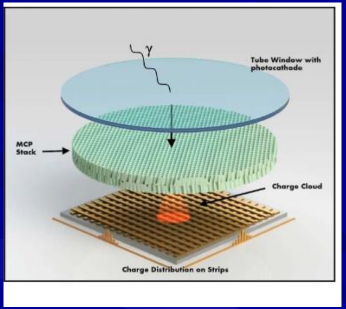
From discret dynodes to continuous amplification

- 1-Single Pixel(1x)
- 2-Multianode PMT (256-1024 x)
- 3-Image intensifier
- 4-Microchannel plate (10^4-10^7)

1

2

3



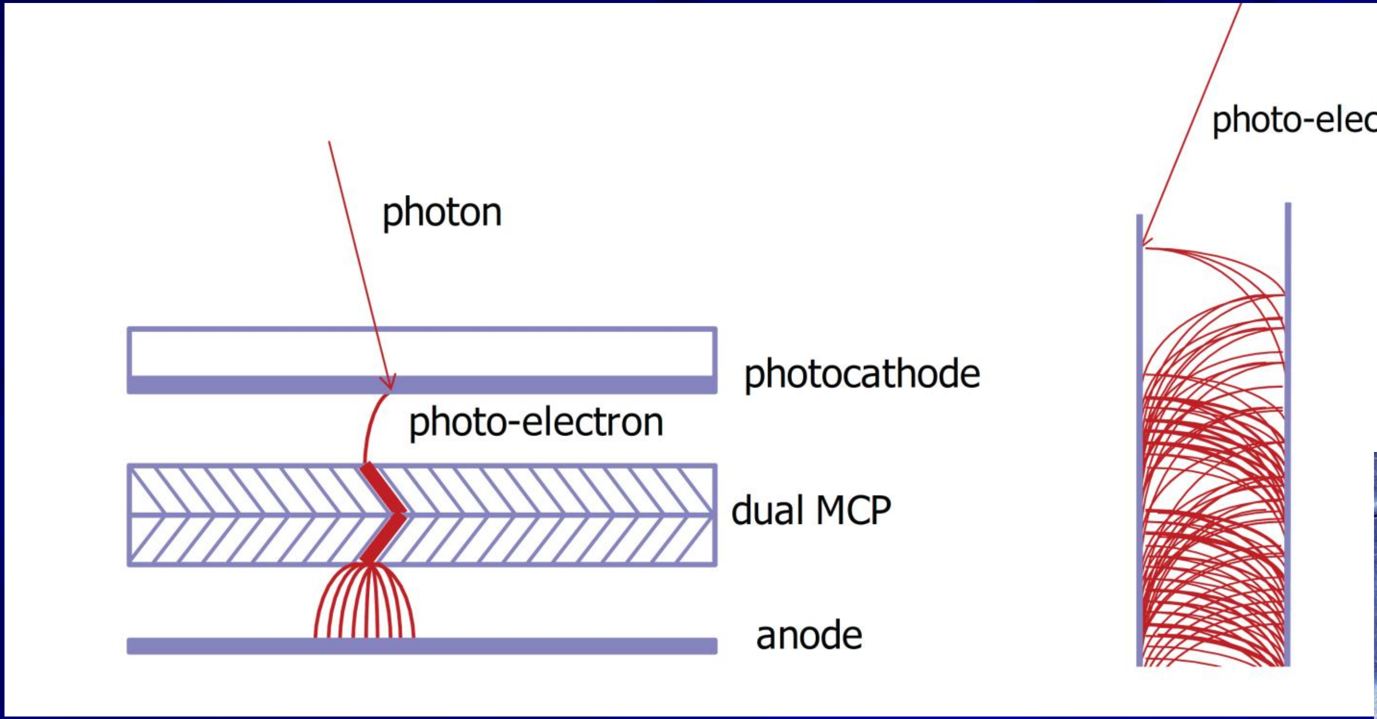
4

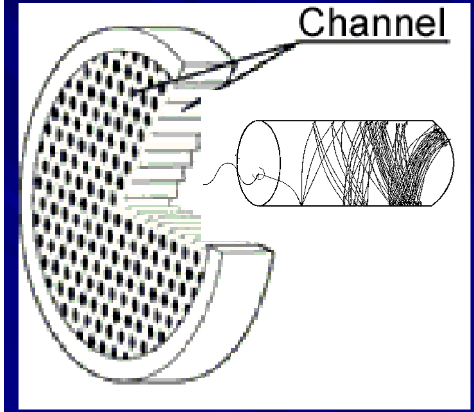
Photomultipliers tubes (PMT)

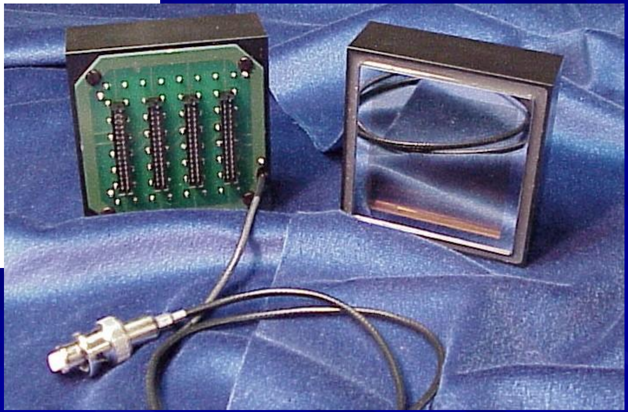
- Standard : PMT → Use since 75 years (RCA 1936)
  - Large gain, high QE,and stability.
  - But bulky, sensitive to magnetic field
- In 70"s → > 10 manufacturers (EMI,RCA ....)
- 2000's → 75% production for medical (Spect/,PET)
- Today only 2 (Hamamatsu & Photonis)
  - **-> closing their main PMT factories**

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

Multi Channel Plate (MCP) principle







Photocathode converts photon to electron

Few μm MCP(s) amplify electron by 10^4 to 10^7

Strip/pixel anode read out

Conventional Photonis MCPs: Drawn/sliced lead-glass fiber bundles.

Micro Channel Plate → LAPPD

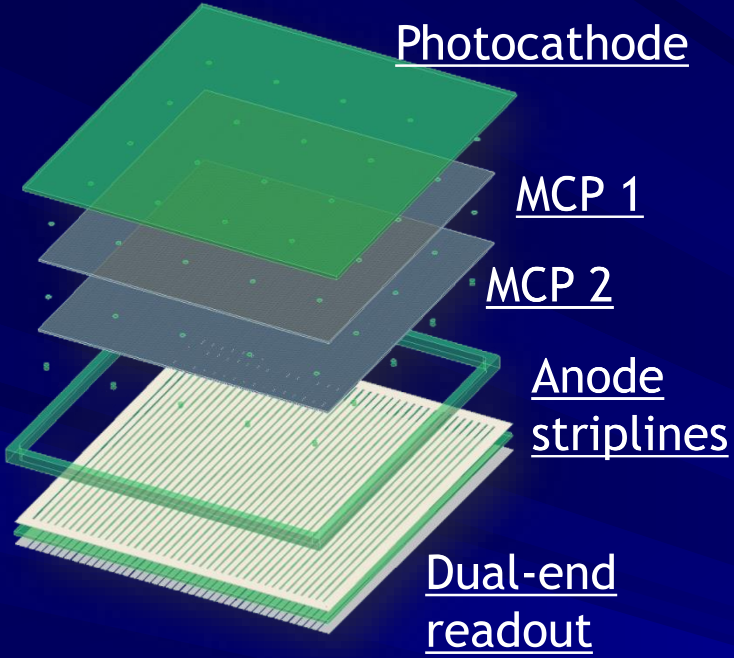
- Goal → large area, low cost: ,long life
- High gain $>10^7$
- low noise, low power,
- Fast timing σ(t)<10 psec,
- Spacial resolution (x)<$1mm

pore sizes
2-20µm

Atomic Layer
deposition (ALD)

http://psec.uchicago.edu/

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

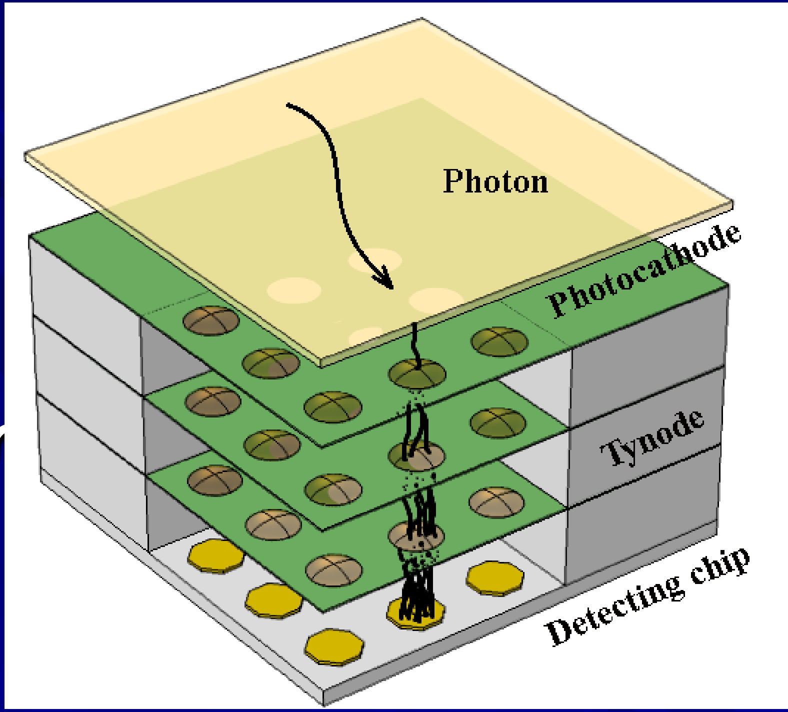
Transmission lines 2D readout:

limits the number of electronic channels compared to pixels

Electronics

- GigaSample/s Waveform Sampling and Digital Processing

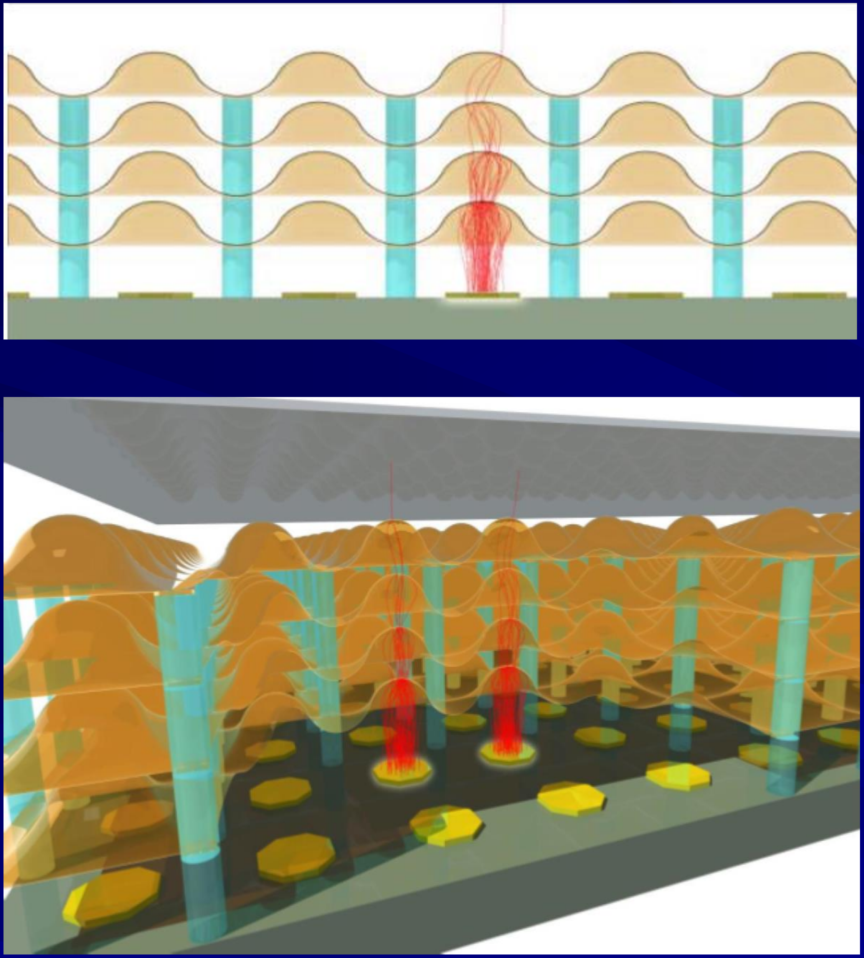
TYNODE:typsi Membrane Project (H.Van Der Graaf) Nikhef-TUDelf-BNL-Photonis



- 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.

Conclusion

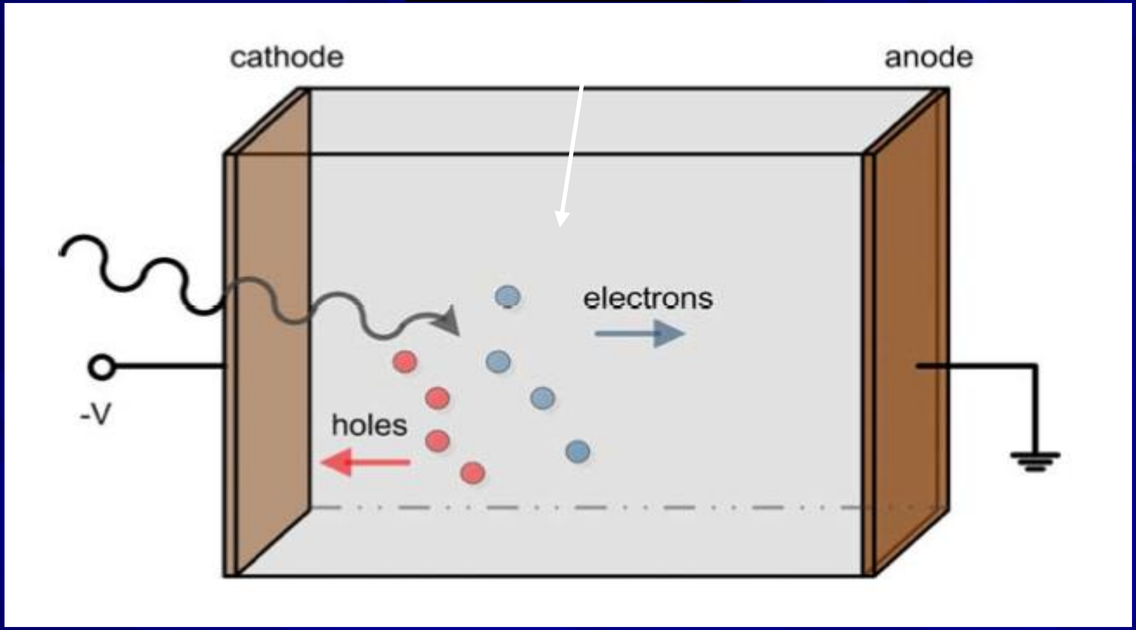


Combine pixel readout with a set of continuous membranes, e.g. made from diamond. Electrons are accelerated between membranes and are amplified upon collision on one side and are emitted on the other side.

The QE of MCP- or Tynode- based detectors is (only) determined by the QE of photocathodes

The sold state world

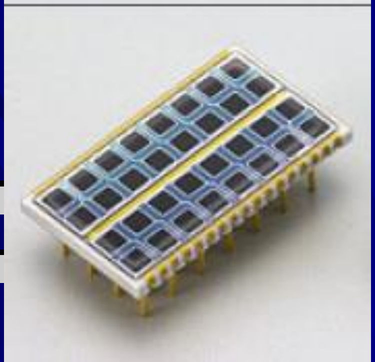
Solid-State Detectors



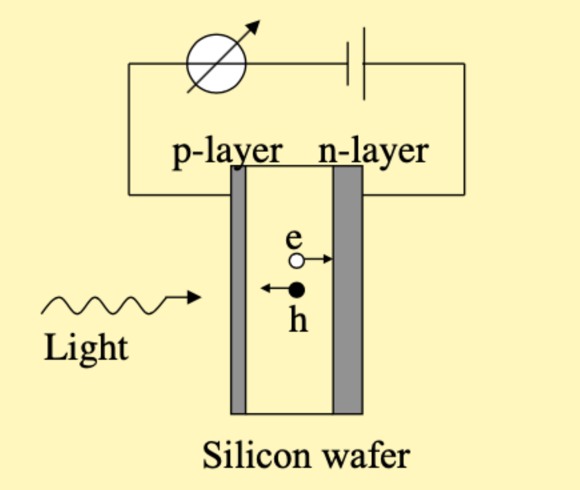
Semiconductor

- 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

Solid State Photodetectors



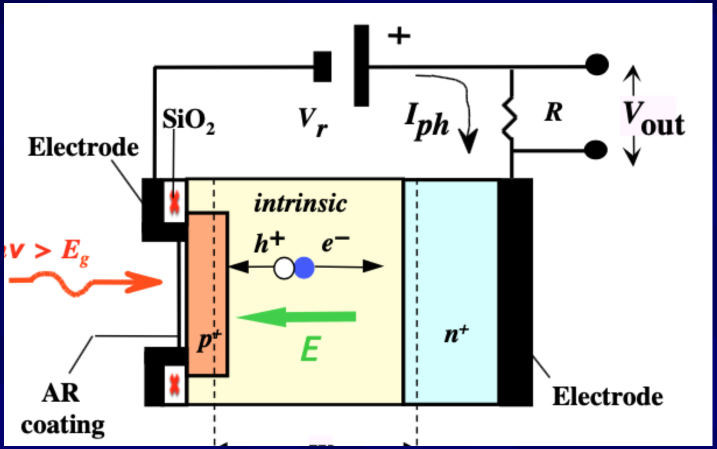
- 1980 → PIN diode for SLAC SLD calorimeter
- 1985 → APD's EGG (McIntyre)
  - First Sherbrooke animal PET (Roger Lecomte)
  - SDC and CMS EM calorimeter read out
- 2000 → SIPM (MPPC ..) arrays in Geiger mode
- 2005 -→ DSIPM (Philips)
- Today → Many providers & development (Philips, Hamamatsu,RMD ….)

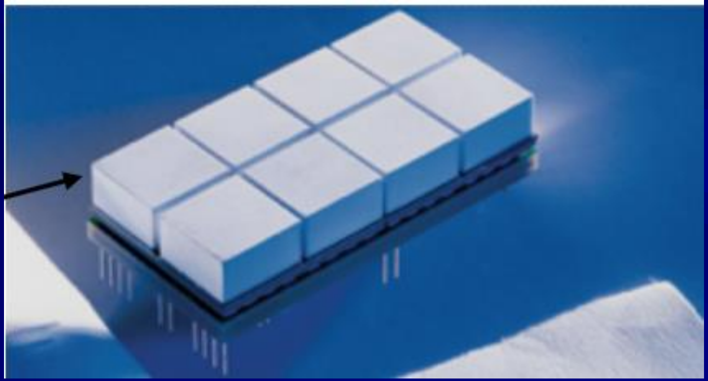


Photodiode

- No gain, G=1
- Linear Output
- Noise level higher than PMT (high leakage current) => can be cooled to lower noise
- SNR is not as good as PMT, cannot be used for single photoelectron detection
- p-layer is very thin (< 1 μm), as visible light is rapidly absorbed by silicon
- High QE (70-90%), can be enhanced with anti-reflective coating
- Insensitive to magnetic field
- Small size

Silicon PIN Diode





PIN photodiode baseddetector module

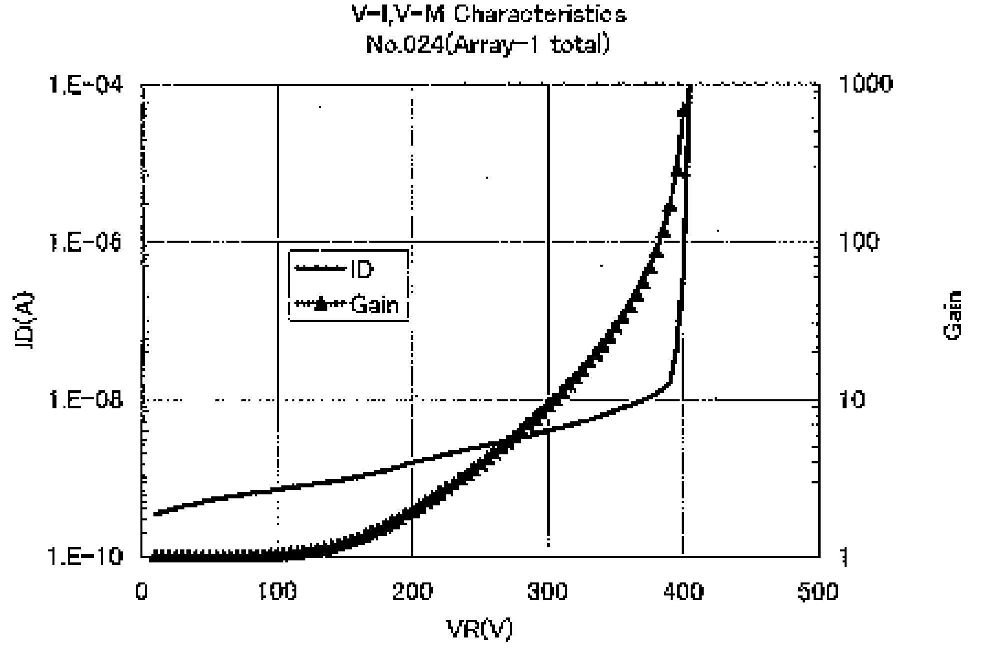
Advantage

- Simple design, robust, compact
- High QE (~80% @ 400 nm)
- Broad spectral response (300 to 900 nm)
- Linear output
- Insensitive to magnetic field
- Low excess noise
- Multi-pixel available

Drawback

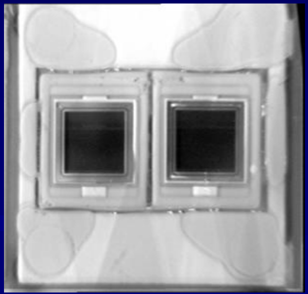
- Gain = 1
- High capacitance
- Slow response
- Minimum detectable pulse ~ 100 photons
- Required low noise preamplifiers to read out

Avalanche Photodiode APD

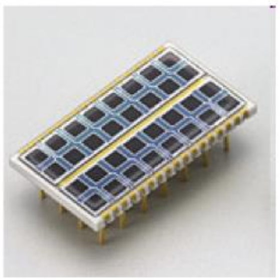


- Gain (50-1000)
- Linear Output
- low noise (~100 electrons for 14x14 mm2 size),
- high QE (~60% at 420 nm),
- fast rise-time (~1 ns)
- compact size,
- insensitive to magnetic fields.

CMS



Hamamatsu single channel APD

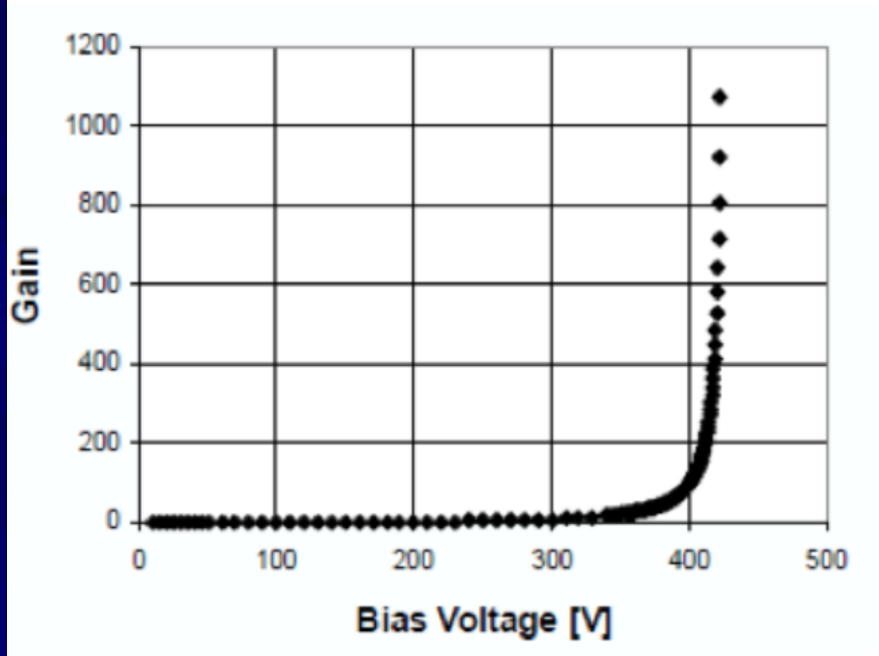


4x8 array
1.6 x 1.6 mm^2
active pixel area
C_T~ 10 pF

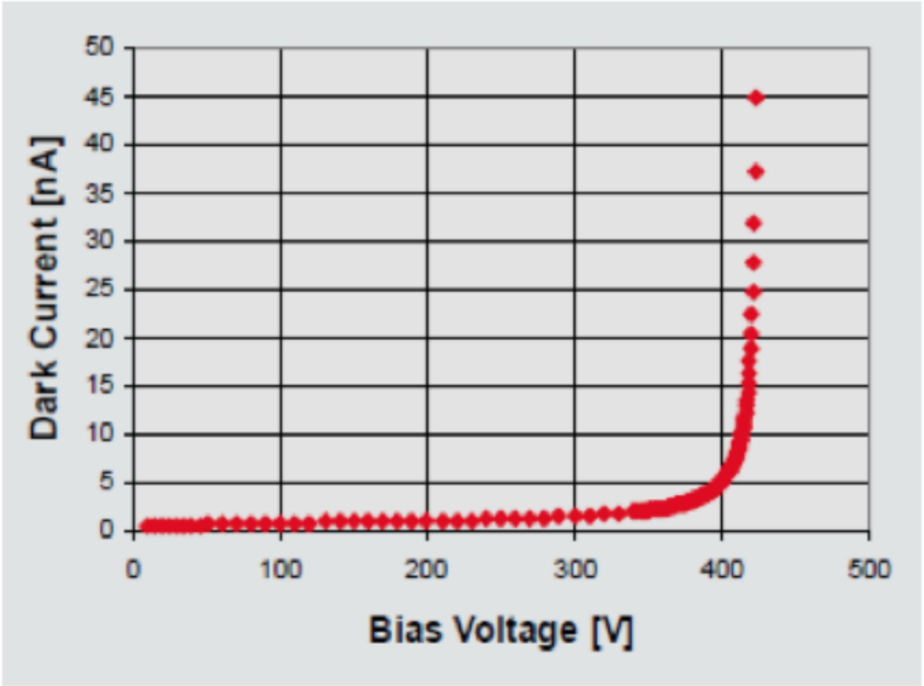
Hamamatsu S8550

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

APD gain and dark current

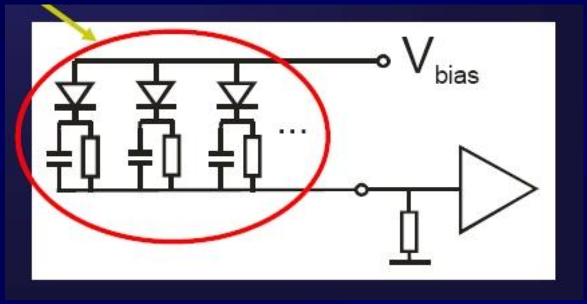


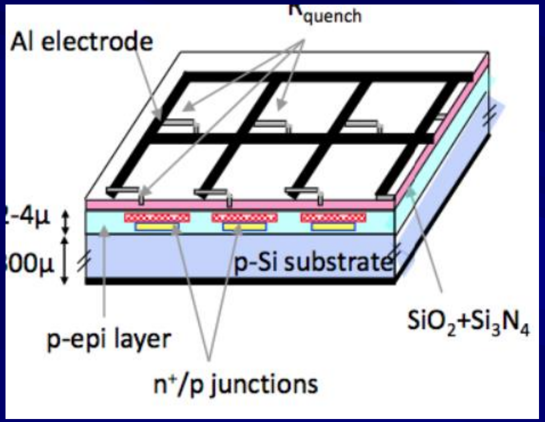
Gain



Dark Current

Geiger Mode APD's (SiPM)





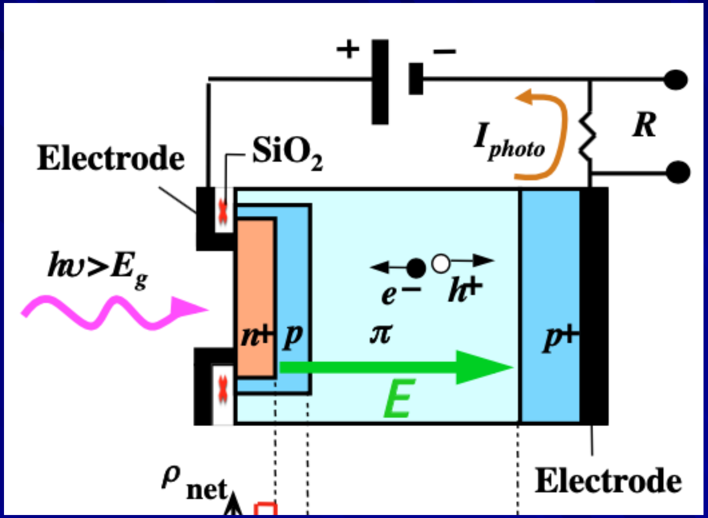
- Matrix of micro APD cells (10-100μm) working in Geiger mode and low bias voltage (100V)
- Each micro cell readout in parallel has a binary response to single photons
- Response to each cell is associated with a large gain => good signal-to-noise ratio
- Each micro-cell is triggered independently (binary) by incoming photons.
- Output current is sum of all triggered micro cells output
- Each micro-cell is passively reset by its own quenching resistor (~100 kΩ).
- Practical (compact reliable, no aging inexpensive)

Show great promise ....

More on Silicon photodetectors : SiPM

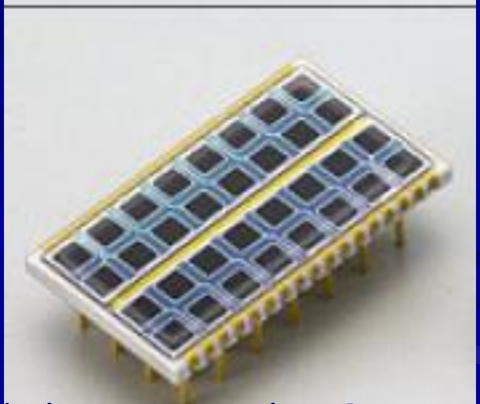
Advantages

- High QE (>70% for 400–600 nm)
- Low Bias voltage (100v)
- High internal gain (10^5 – 10^6)
- Very fast response (~100 ps rise time)
- Compact, rugged,low excess noise factor ~ 1.2
- CMOS (Low cost)
- Capable of detecting single photoelectron
- Insensitive to magnetic field



Drawbacks:

- Trade off between dynamic range and fill factor => modest PDE so far (25-65%)
- Geiger probability => modest PDE (20-40%)
- Limited micro-cell => limited dynamic range
- Sensitive to temperature and voltage fluctuations in analog mode, but not in purely digital mode
- High dark pulsing rate • Optical Cross-talk and after-pulsing issue



hilips Digital SiPM

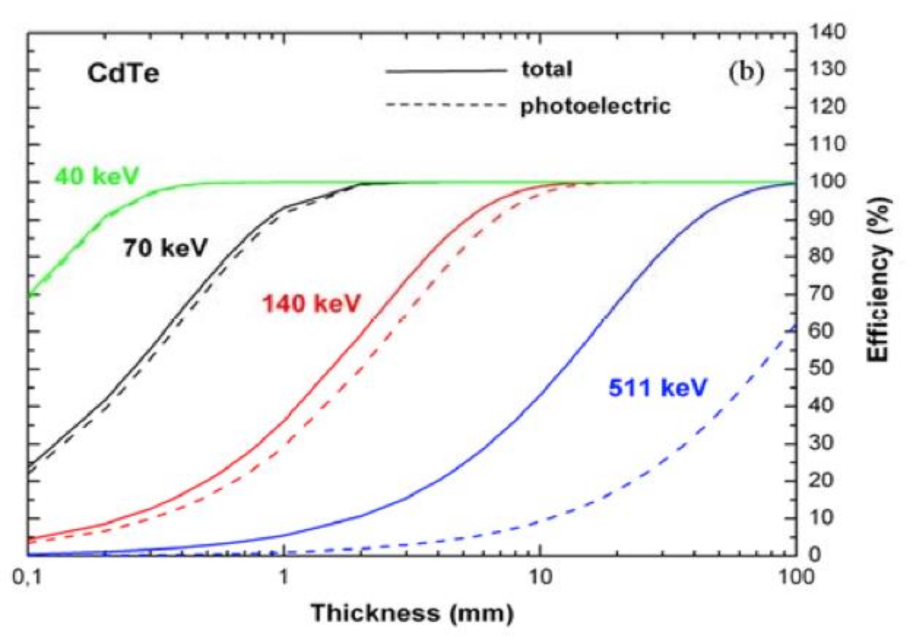
Commonly Used Semiconductors

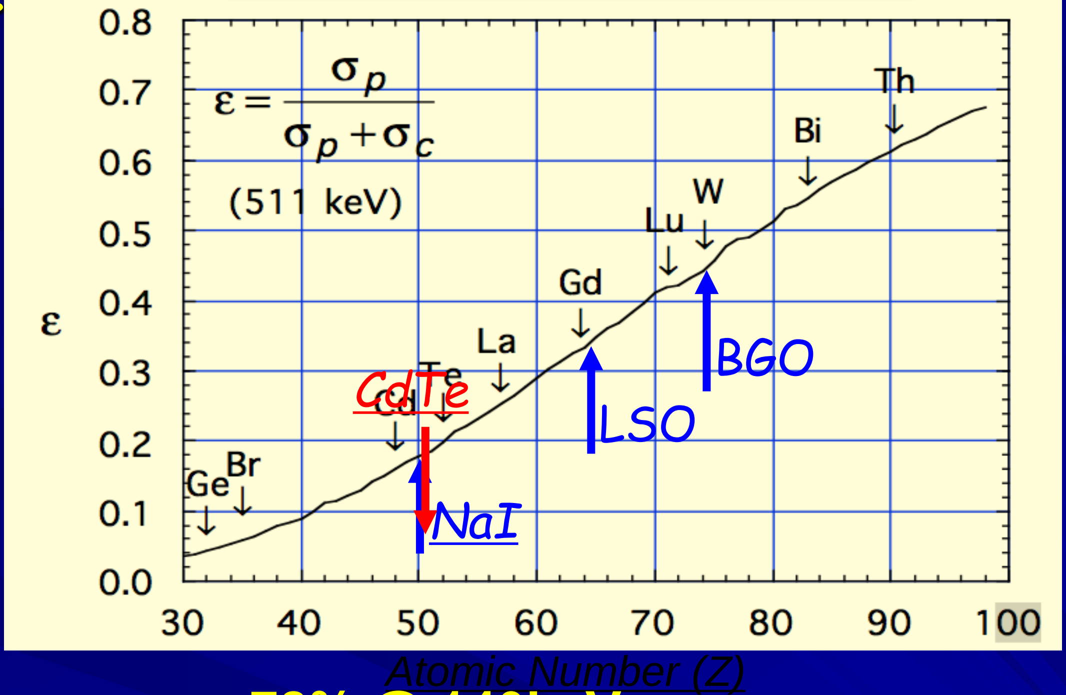
Material	Si	Ge	CdTe	$Cd_{0.9}Zn_{0.1}Te$	HgI_2	TlBr
Atomic #	14	32	48,52	48,30,52	80,53	81,35
Density (g/cm^3)	2.3	5.3	6.2	5.78	6.4	7.56
Band gap (eV)	1.12	0.67	1.44	1.57	2.13	2.68
e-h pair creation energy (eV)	3.62	2.96	4.43	4.6	4.2	6.5
Resistivity (Ω cm)	10^4	50	10^9	10^{10}	10^{13}	10^{12}
$\mu_e l_e$ (cm^2/V)	>1	>1	10^{-3}	10^{-3} - 10^{-2}	10^{-4}	10^{-5}
$\mu_h l_h$ (cm^2/V)	~1	>1	10^{-4}	10^{-5}	10^{-5}	10^{-6}
Fano factor	0.1	0.08	0.11	0.09	0.19	N/A
RT operation?	Y	N	Y	Y	Y	Y

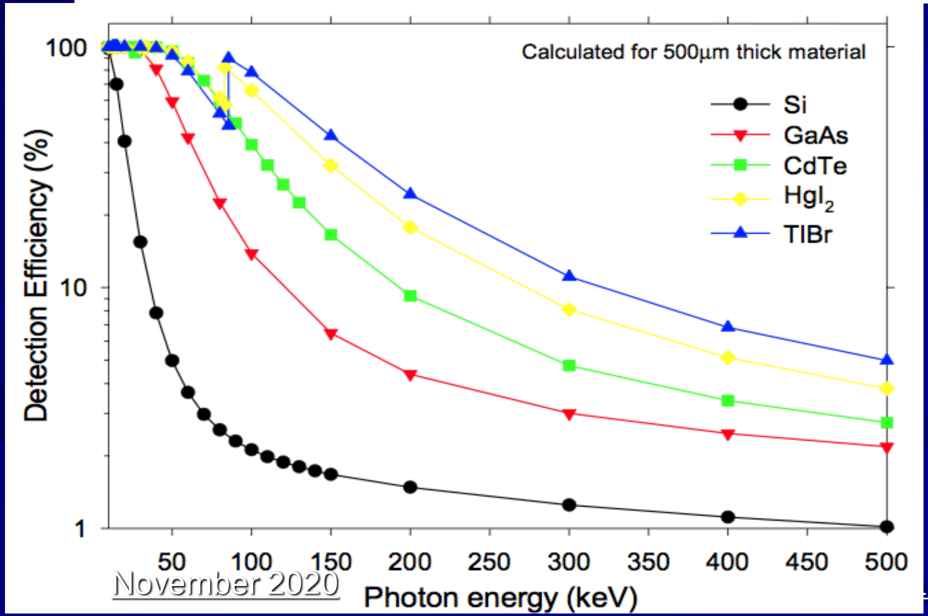
All numbers are for T=25 °C

CdTe and CZT are commonly used in medical imaging

Detection Efficiency and Photoelectric Fraction in Semiconductor





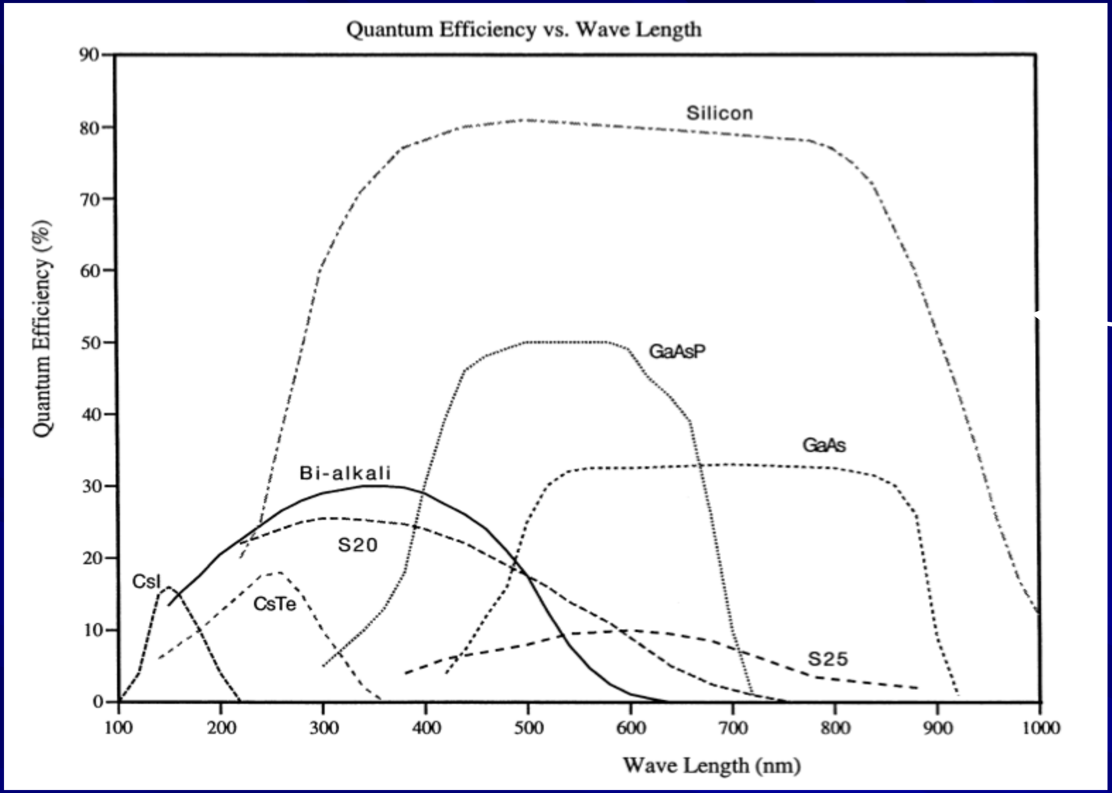


ε=78% @ 140keV

Most commonly used semiconductors (Si, CdTe, CZT) have low effective atomic number

=> low photoelectric fraction for energies > 200 keV

Silicon Photodetector QE



Sufficiently thick Si absorption layer (> 100 μm)

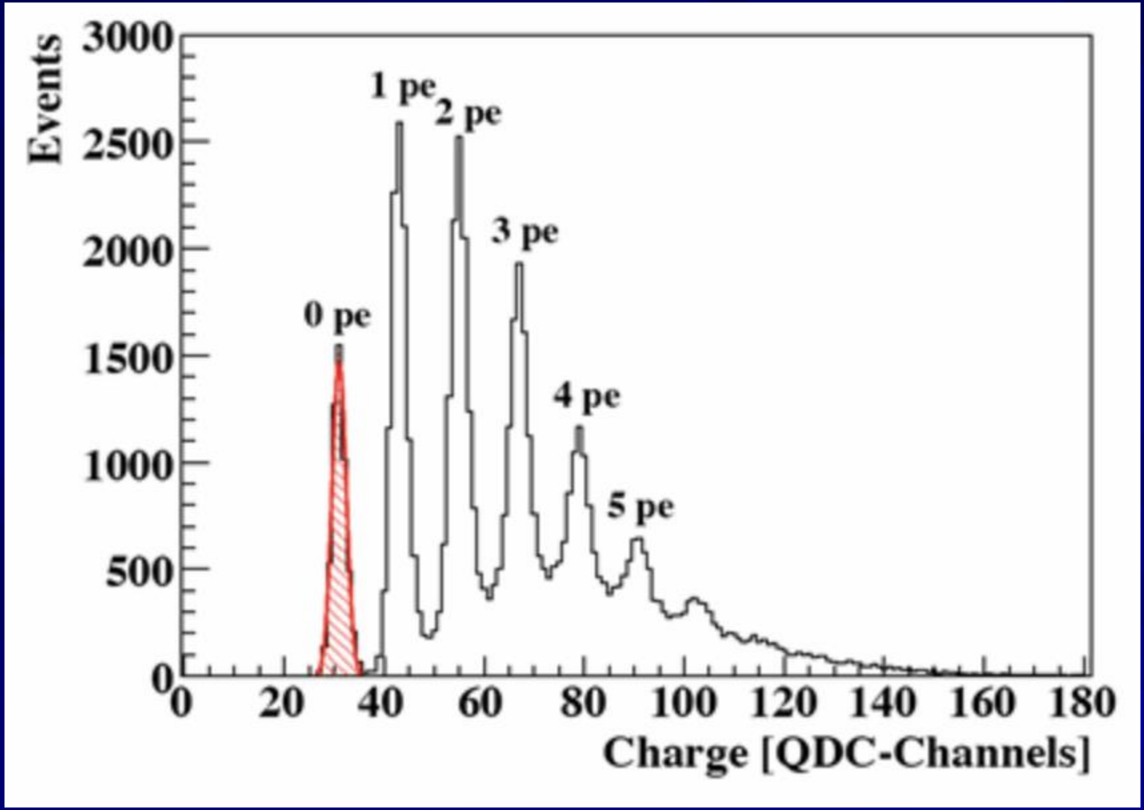
NaI,LSO

CsI

Silicon photodetector gives higher QE than bialkali photocathodes for a broad range wavelength

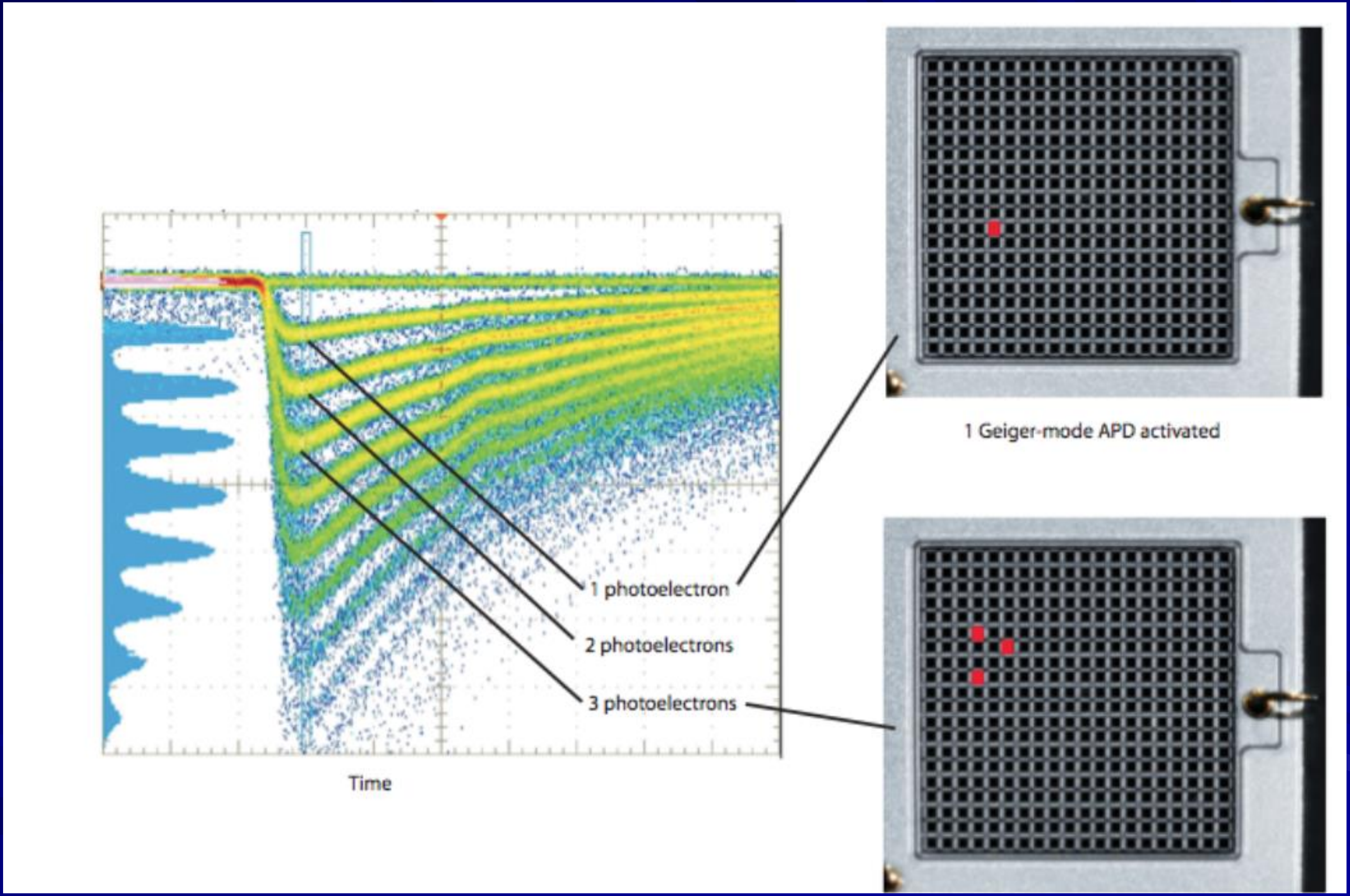
Source: K. Arisaka (NIM A 442, 80, 2000)

Typical SiPM signal

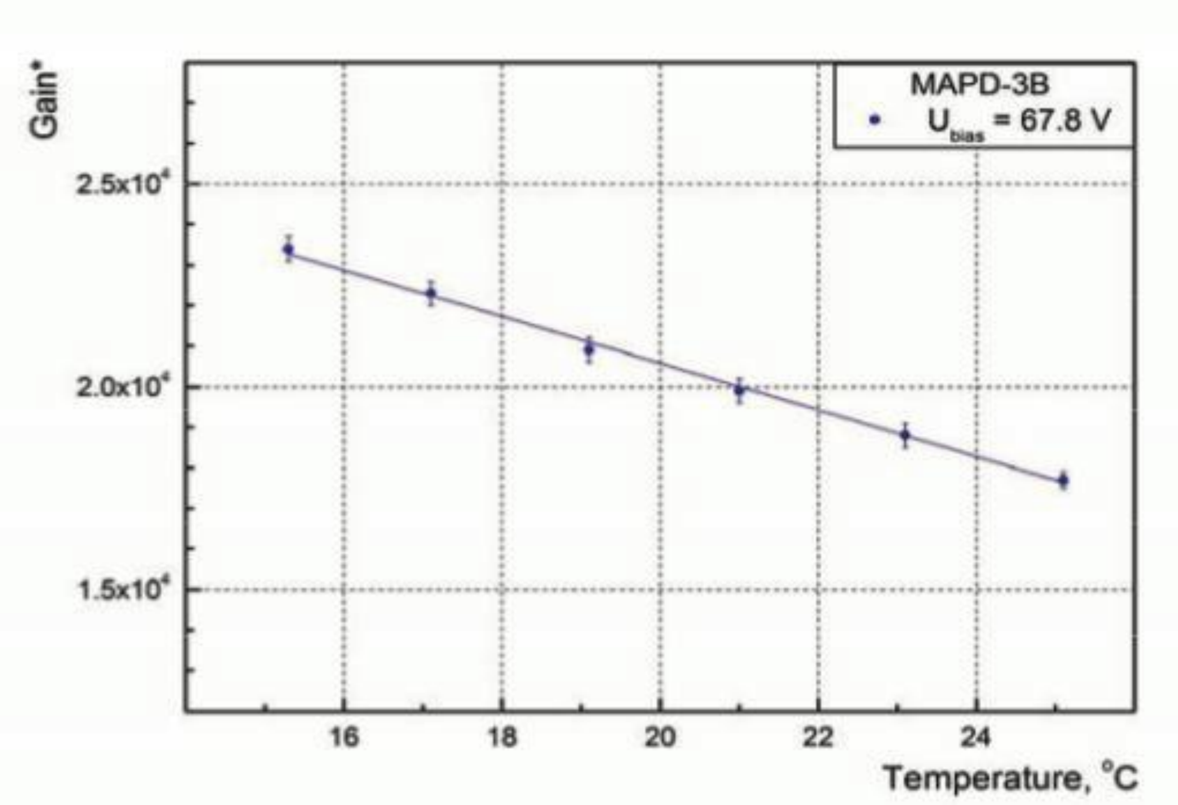


. Example of single photon charge spectrum. A peak in the spectrum corresponds to a certain number of photoelectrons, e.g., 0 pe, 1 pe, etc. Adapted from Eckert et al. (2010).

SiPM Single Photon Detection



Temperature dependence



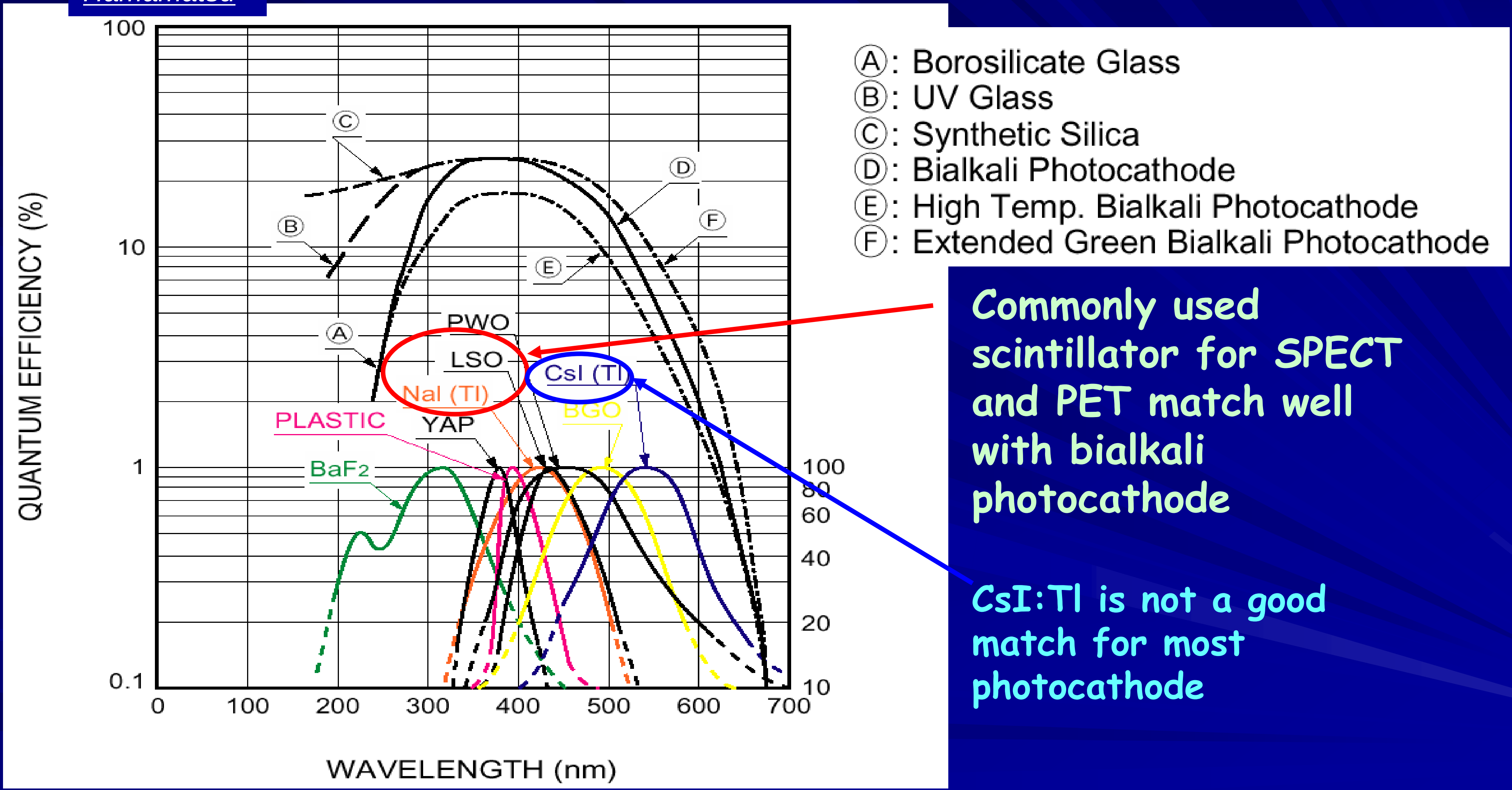
Gain is typically strongly dependent on temperature

Noise is inversely proportional to temperature

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

Matching Emission of Scintillator to PMT Response

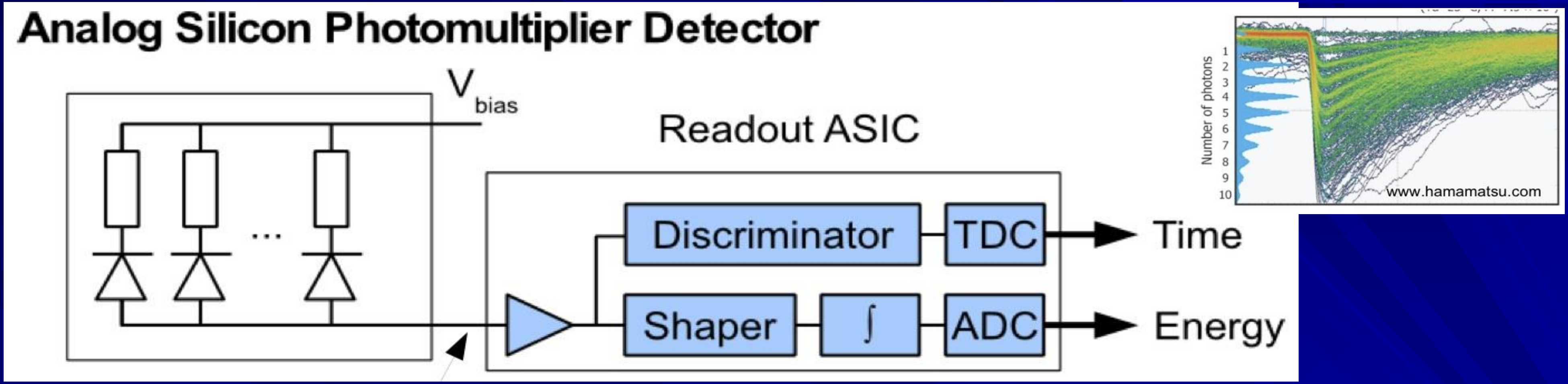
Hamamatsu



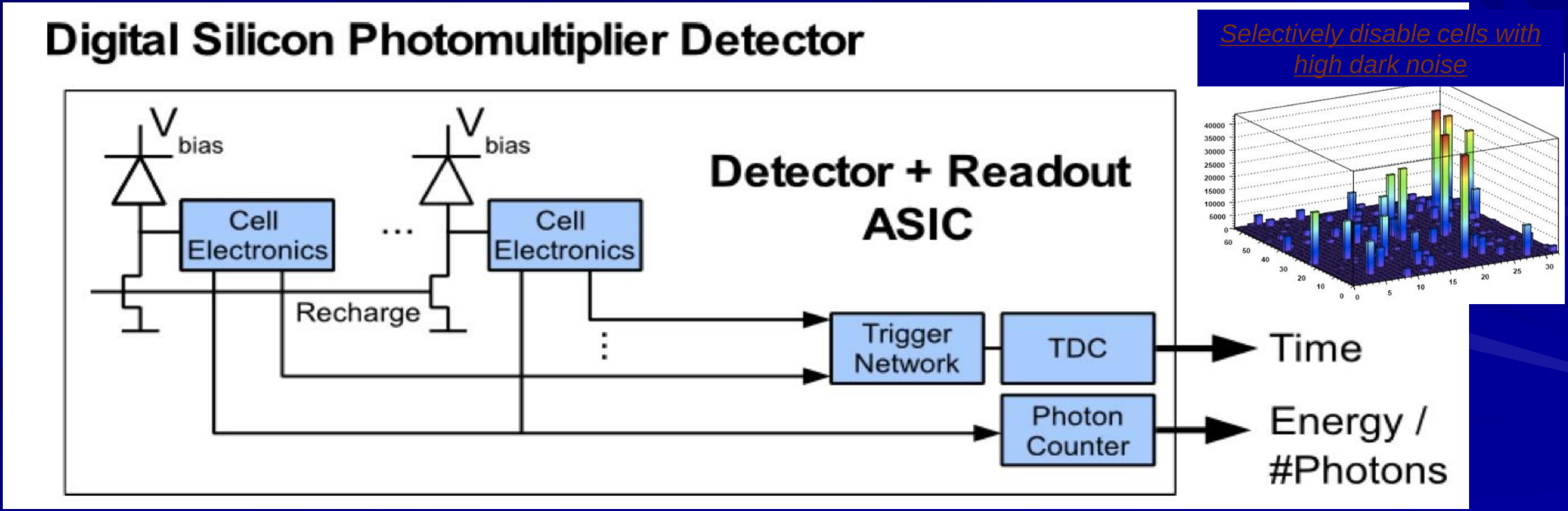
Commonly used scintillator for SPECT and PET match well with bialkali photocathode

CsI:Tl is not a good match for most photocathode

Digital SiPM detectors (PDPC)

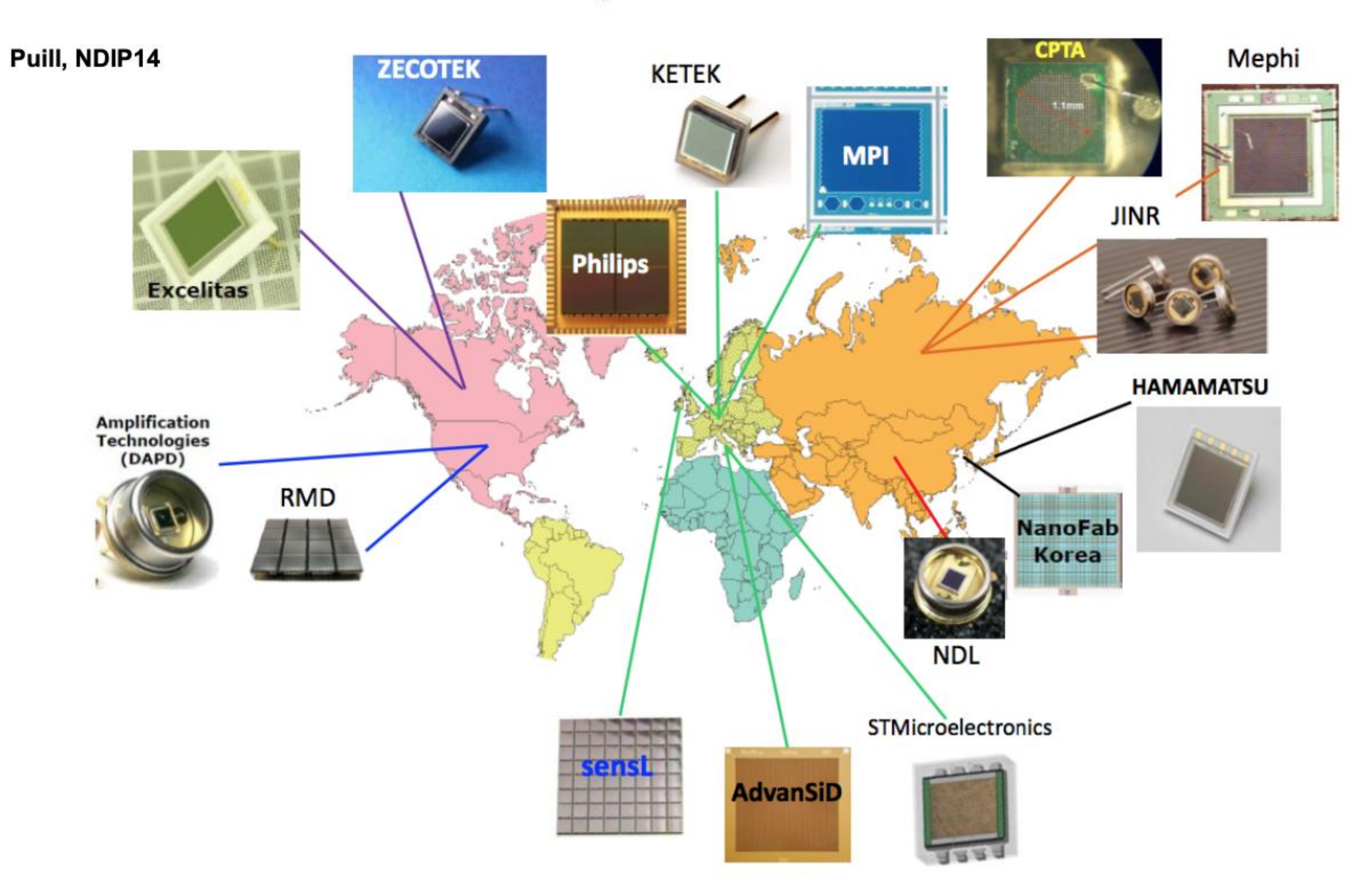


Analog signal sums many photons



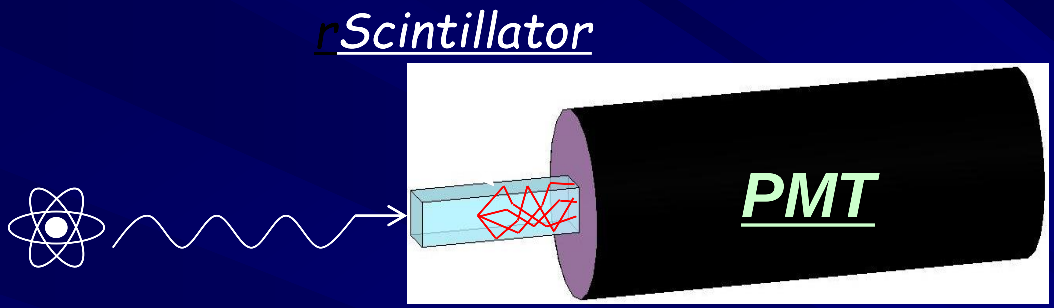
Selectively disable cells with high dark noise

SiPM: Developers and Manufacturers

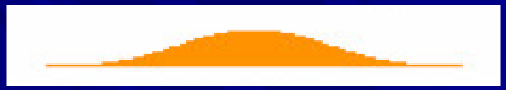


Every manufacturer has its own trademark name for this type of devices: MRS APD, MAPD, SiPM, SSPM, MPPC, dSiPM, ...

Scintillation Detectors vs Solid-State Detectors

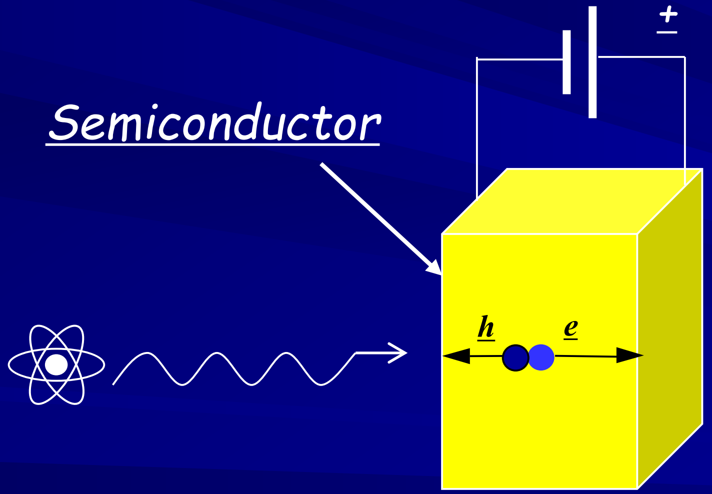


~1,500 e$^-$
@ 140 keV

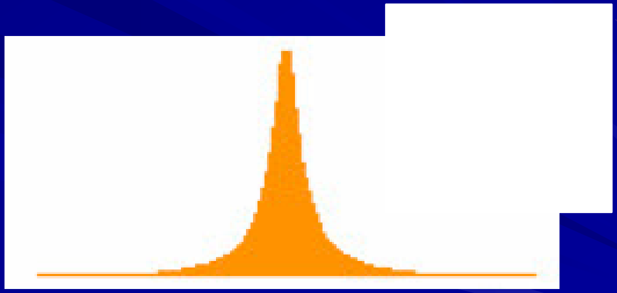


Energy per e$^-$ ~ 10 – 200 eV

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



~30,000 e$^-$
@ 140 keV

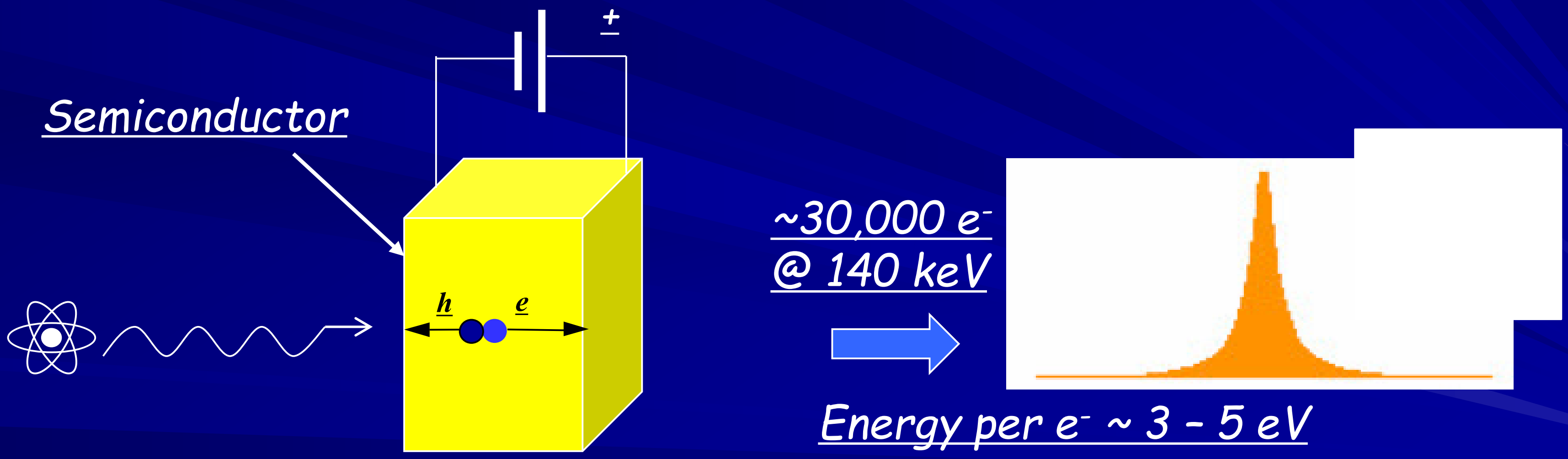


Energy per e$^-$ ~ 3 - 5 eV

Gamma Ray --> Electrical Signal (Direct Detection)

CdTe/CdZnTe Detectors

- Direct conversion photon to signal
- Optimized for Mev photon
- Expensive
- Used in Astrophysics, Satellite,Medical imaging



Semiconductor

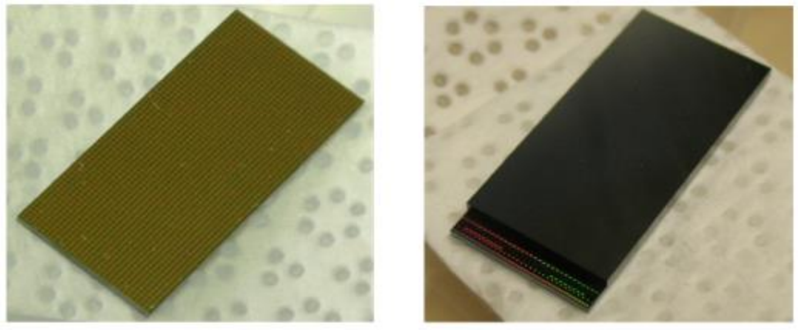
~30,000 e^-
@ 140 keV

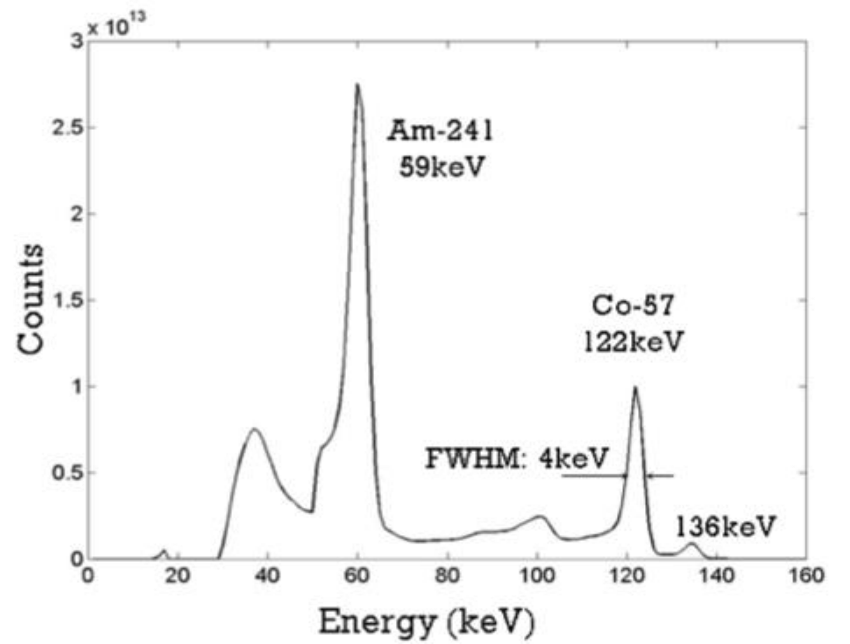
Energy per e^- ~ 3 – 5 eV

Gamma Ray --> Electrical Signal (Direct Detection)

Examples of CdTe/CdZnTe Detectors for SPECT and PET

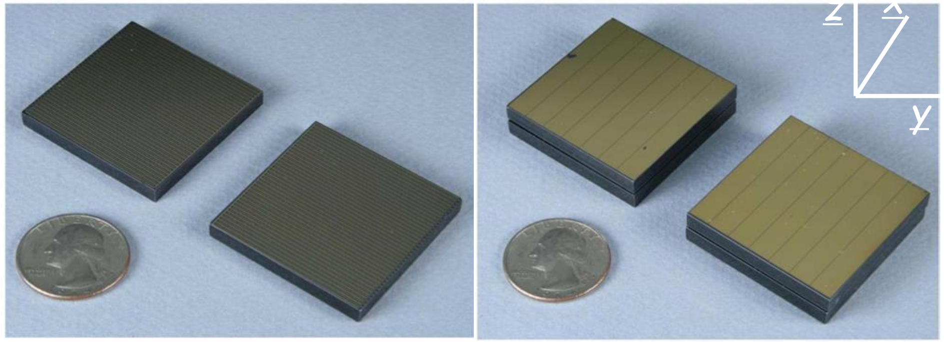
CdTe: 11x22x1 mm^3, 350 μm pixels



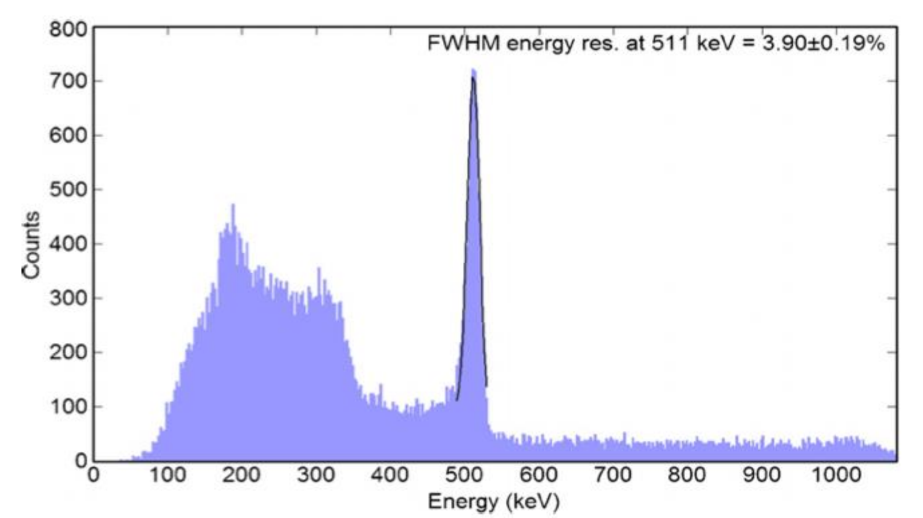


Source: L.J. Meng, et al., Nucl. Instr. Meth., vol. A604, 548 (2009)
Y. Gu, et al., Phys. Med. Biol., vol. 56, 1563 (2011)

CdZnTe: 39x39x5 mm^3, double-sided strip



Edge-on geometry, 3-D positioning
X position: anode strip, 1 mm pitch
Z position: cathode-anode ratio, ~1 mm
Y position: cathode strip, 5 mm pitch



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

Gazeous Silicon
Photodetectors

- No Read Out noise
- Large area possible
- Time tagging every photon with < 20psec resolution
- Single event counting
- Fast gating image intensifier (1ns)
- High spatial resolution with large number of pixels (10kx10k!)
- Radiation hard

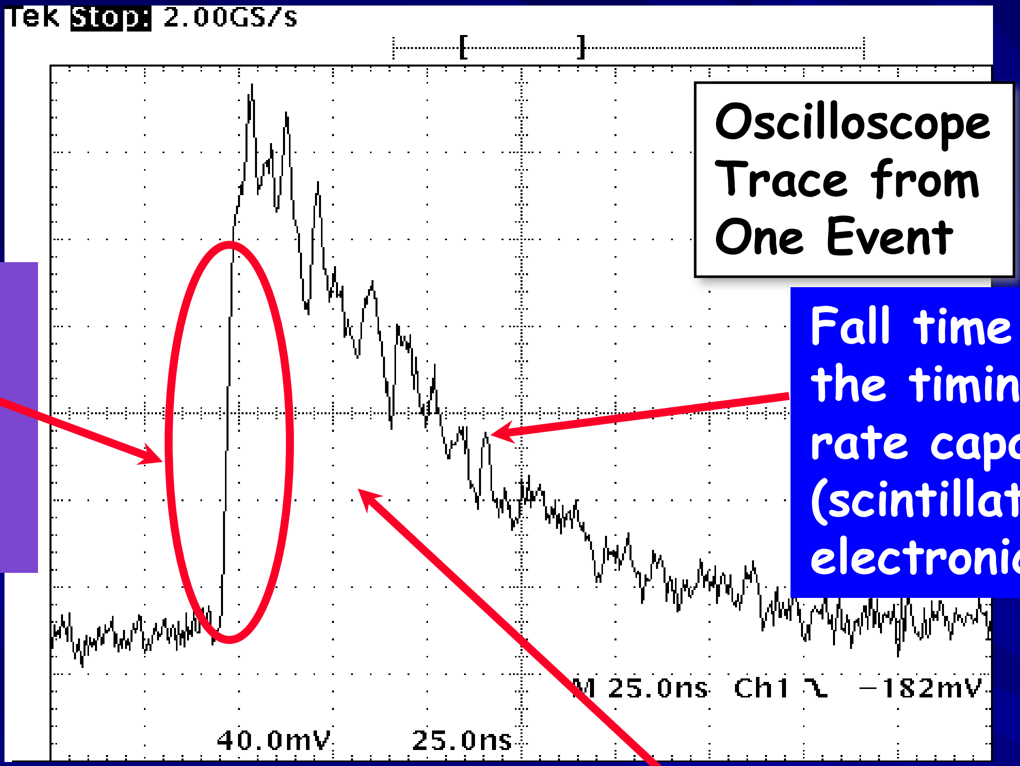
- QE in visible
- Require vacuum
- Require High Voltage
- *Aging in some cases*
- *Sensitivity to magnetic field*

- QE in visible
- Easy to operate
- Reconfigurable active area
- Commercially available sensors
- Well established technology
- No high voltage
- No vacuum
- Large arrays possible for some technologies
- Not sensitive to magnetic field

- Read-Out dark noise
- Smaller area
- Limited time resolution in some devices
- Cooling required
- Radiation dammage

Signal processing
Time of flight

Typical Raw Signal From Scintillation Detectors



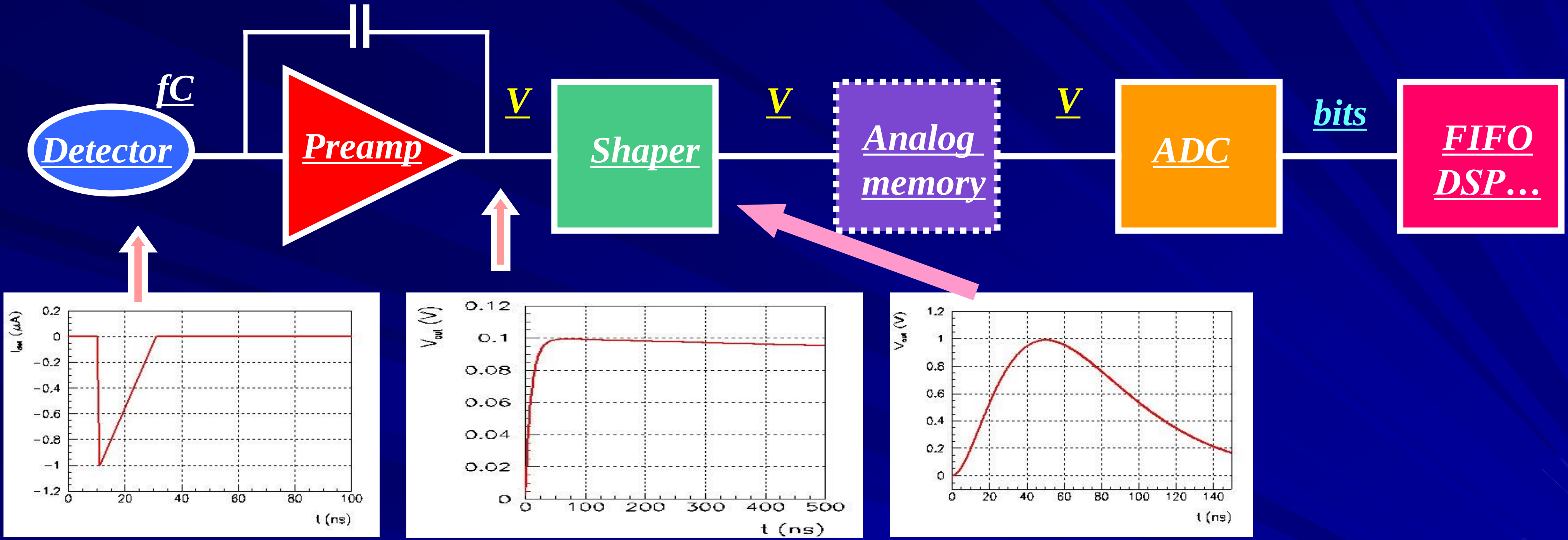
Oscilloscope Trace from One Event

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)*

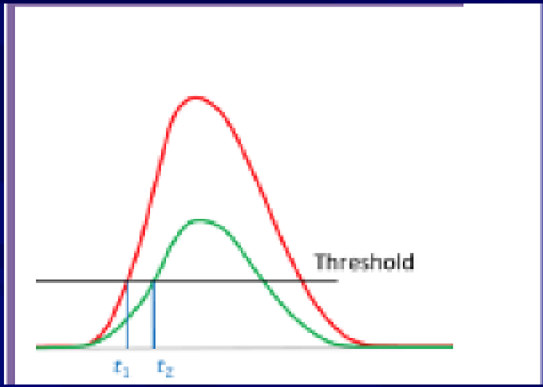
Overview of Front End readout electronics chain



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

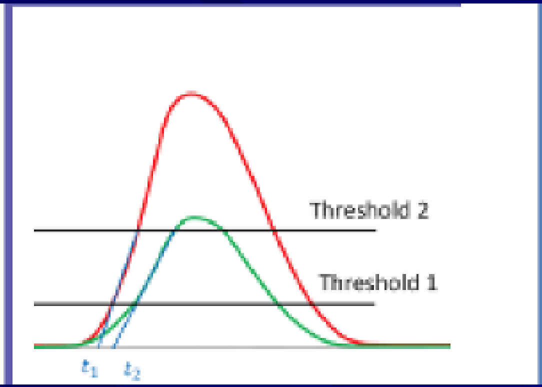
Signal processing first step → THE discriminator

Single threshold



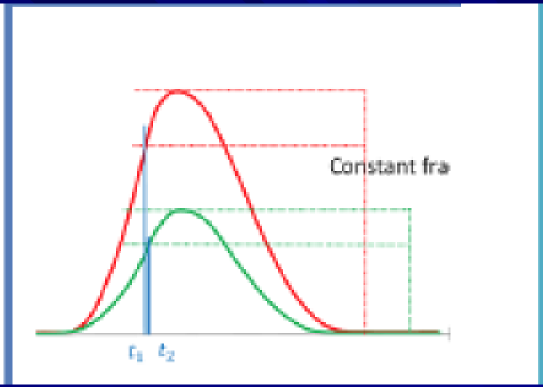
The single threshold is the least precise time extraction measurement. It has the advantage of simplicity

Multiple threshold



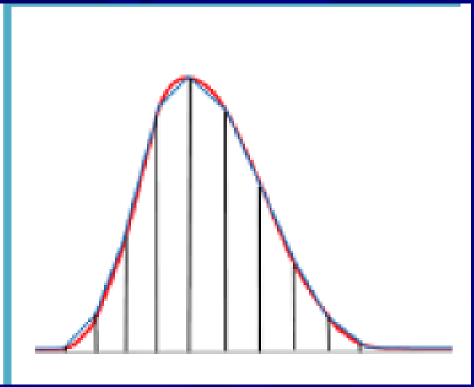
The multiple threshold method take into account the finite slope of the signal. It is still easy to implement

Constant fraction



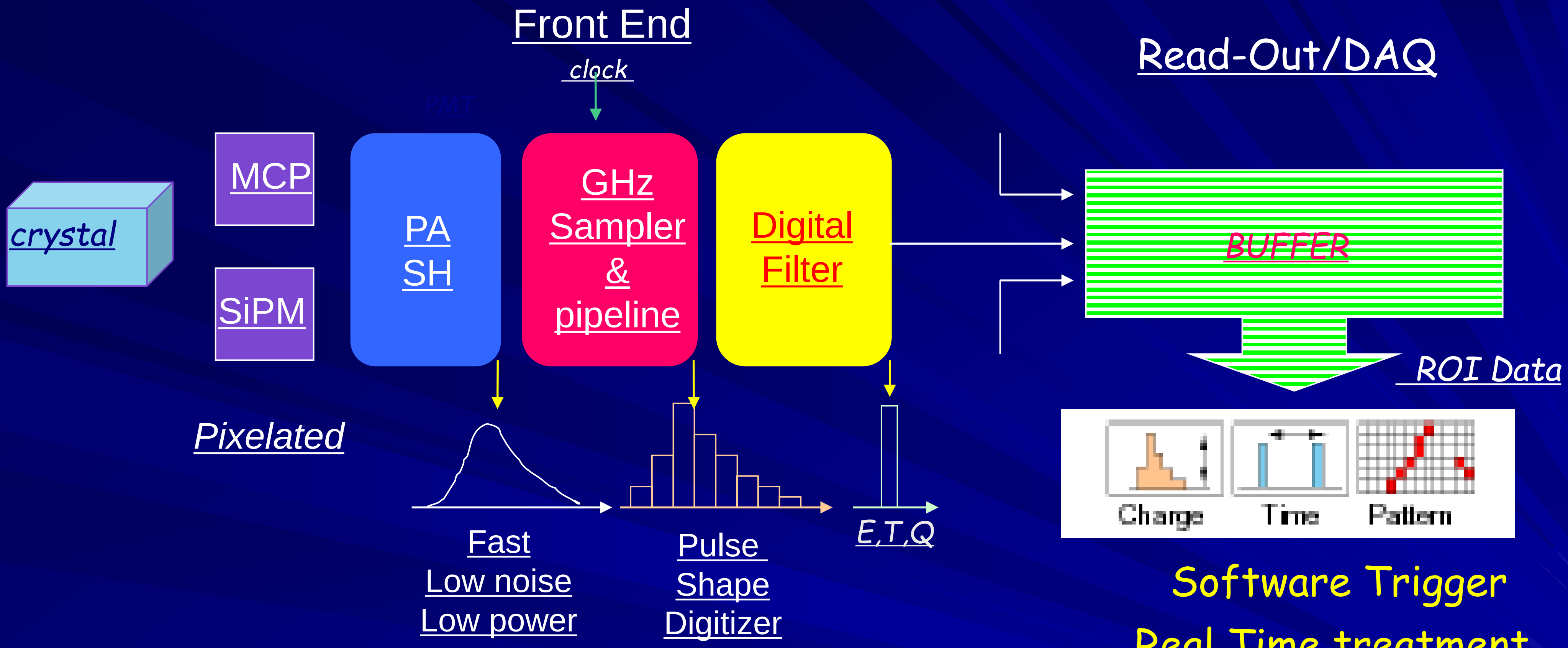
The constant fraction algorithm is very often used due to its relatively good performance and its simplicity for Timing measurement

Waveform sampling



The waveform sampling above the Niquist frequency is the best algorithm since its preserve the signal integrity (time and amplitude)

Exemple of Conceptual TOF-PET architecture model



Front End

clock

PMT

crystal

MCP

SiPM

PA
SH

GHz
Sampler
&
pipeline

Digital
Filter

Read-Out/DAQ

BUFFER

ROI Data

Pixelated

Fast
Low noise
Low power

Pulse
Shape
Digitizer

E,T,Q

Software Trigger

Real Time treatment

- Free-running analog waveform sampling and digitizer (SCA)
- Digital filter used to extract pulse amplitude and high resolution timing (FPGA)
- Pipelined processing architecture to avoid deadtimes (GPU's)
- Parallel digital read out
- Terabit network for communication and processing (xTCA)

Applications

Key Photodetector Parameters vs Application Requirements

- **Photodetector Parameters**
- Photon Detection Efficiency Dark count rate
  Correlated noise
  Timing properties
- Signal shape
  Gain
  Radiation hardness
  Geometry
  Temperature dependence
  Packaging
- Slide adapted from V. Puill

- **Application Requirements**
- ! Largedynamicrange (Calor, Astro, ...)
- ! Time-of-flight (PID, PET, ...)
- ! Energyresolution (Calor, PET, ...)
- ! Largecomplexsystem (HEP, Astro, medical, ...)

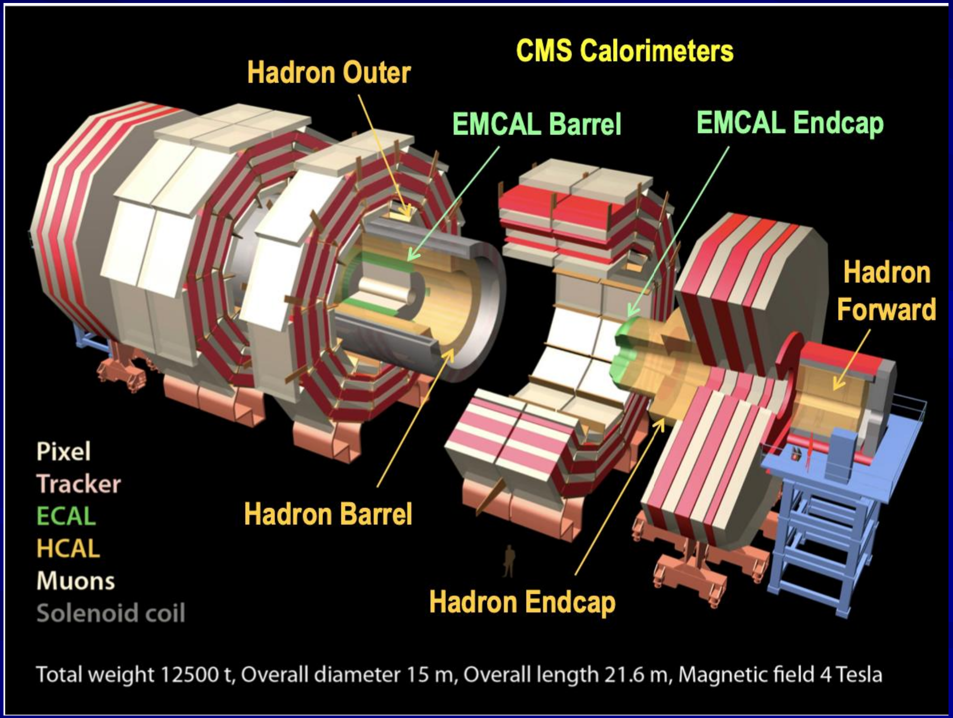
Applications → detection and spectroscopy of energetic photons (and nautrons) in:

- High Energy Particle
- Nuclear Physics
- Positron Emission Tomography
- Security monitoring
- Treaty verification
- Geophysiscal exploration
- Non destructive testing
- Radiation monitoring

Applications

Particle Physics

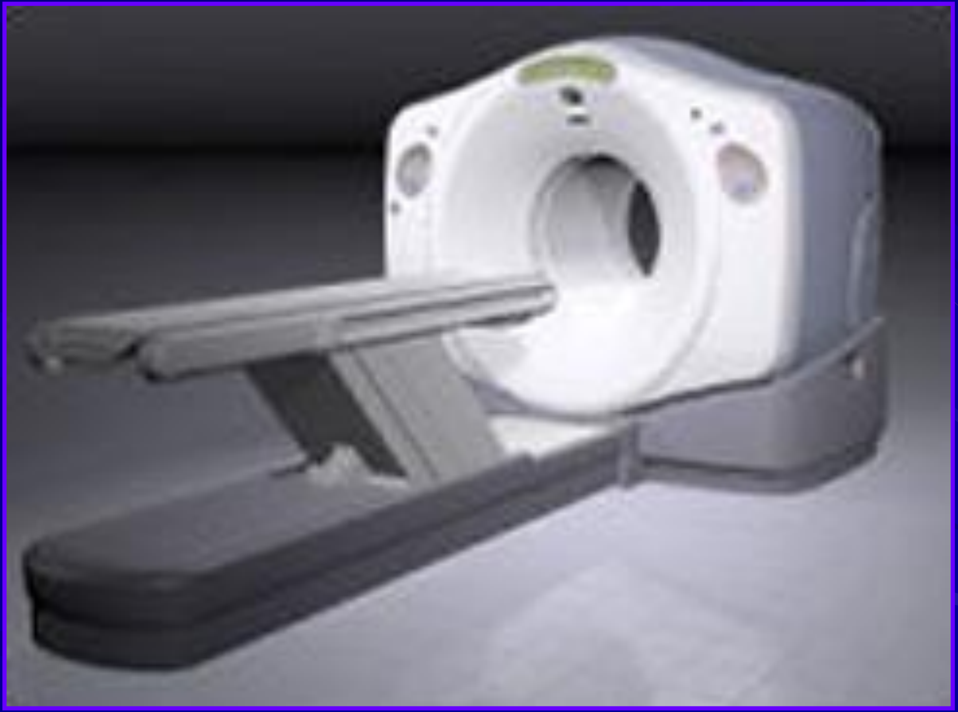
- Calorimetry
- Cherenkov Detectors
- Time of Flight Detectors



Total weight 12500 t, Overall diameter 15 m, Overall length 21.6 m, Magnetic field 4 Tesla

Medical Imaging

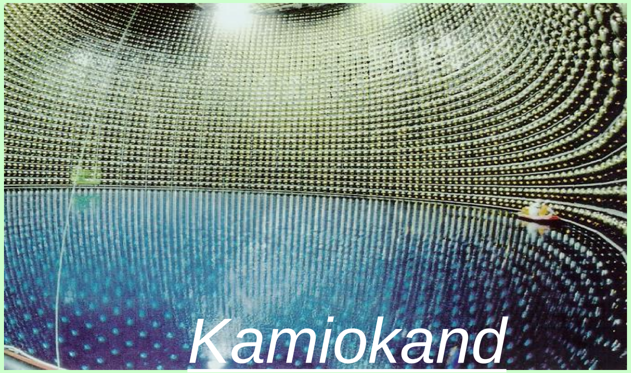
- PET
- SPECT

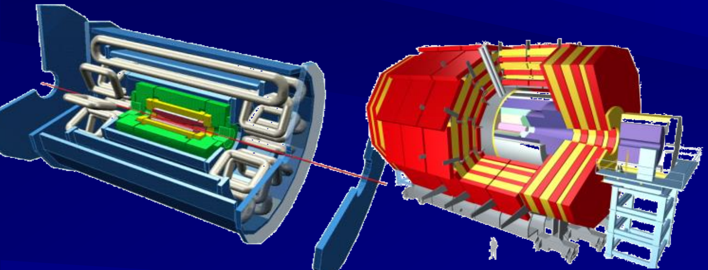


Particle detectors

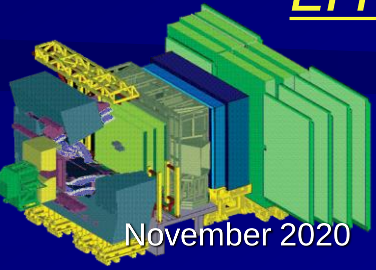
- HEP & Colliders

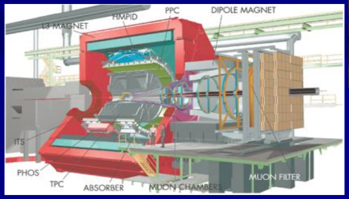
- Fixed target


Kamiokand



LHC






Tevatron-DO

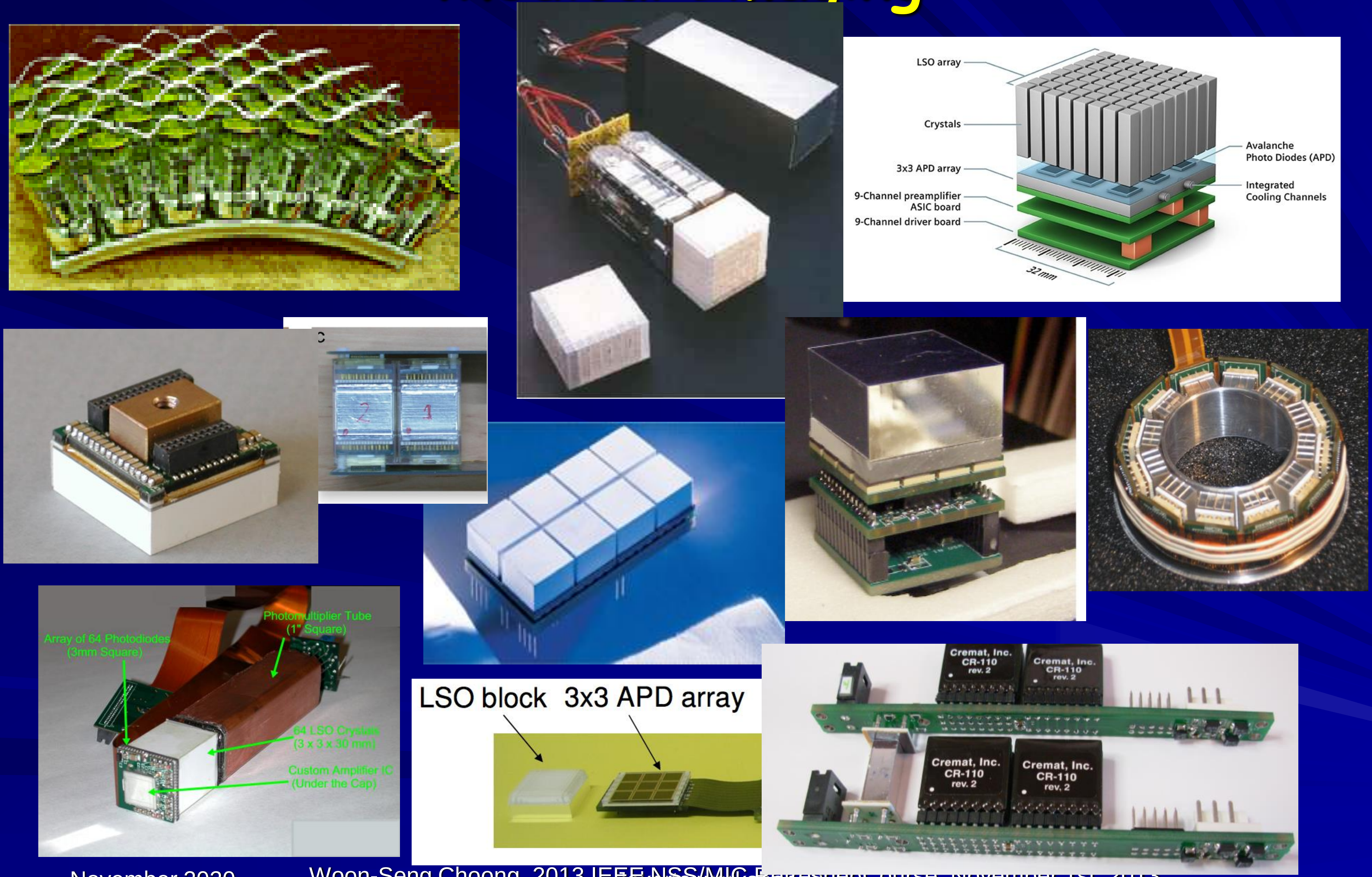

Tevatron-CDF

- Non accelerator


Space


Auger

Scintillation Detectors in Nuclear Medical Imaging



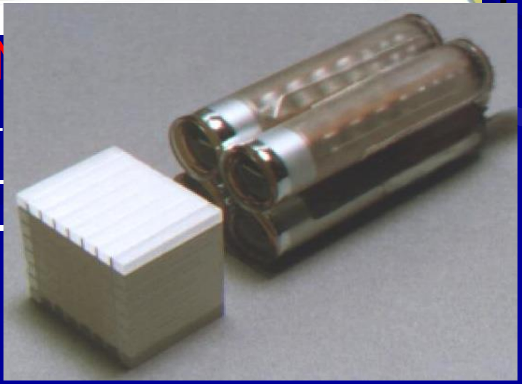
Woon-Seng Choong, 2013 IEEE NSS/MIC Refresher Course, November 1st, 2013, Seoul, South Korea

Photodetector Technologies: A Comparison

Photo detector	PMT		
Technology	Vacuum-Based		
Gain	High		
Detection Efficiency	Low to Moderate		
Noise	Low	Mod	
Timing Response	Moderate to Fast	Sl	
Packaging	Bulky	Con	
Sensitivity to Magnetic Field	Yes	No	N
Bias Voltage	>1kV	~50V	100–

Conventional SPECT & PET detectors has been dominated by the use of PMT.

Courtesy of L. Shao, Philips Medical Systems



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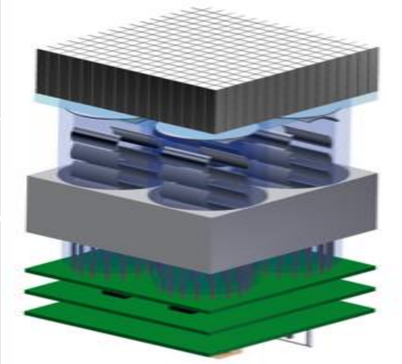
Technology	Vacuum-Based			
Gain	High			
Detection Efficiency	Low to Moderate			
Noise	Low			
Timing Response	Moderate to Fast			
Packaging	Bulky			
Sensitivity to Magnetic Field	Yes	No	No	
Bias Voltage	>1kV	~50V	100–1000V	

Cannot be used in PET/MRI & SPECT/MRI. The timing response is fast, but may be the limiting factor in next generation TOF PET.



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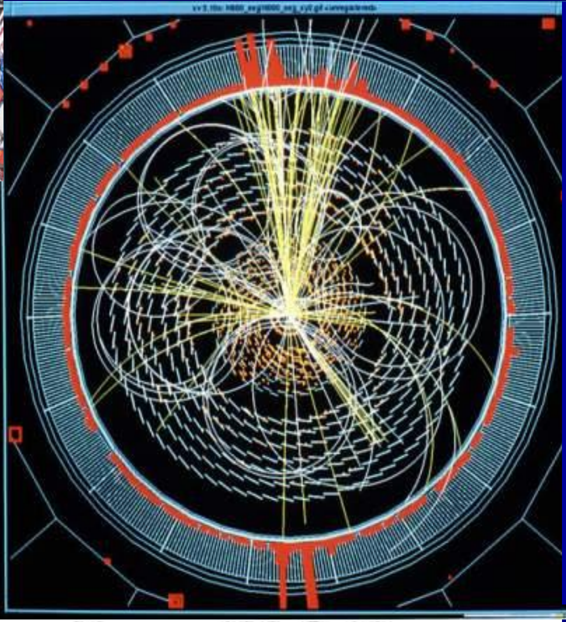
Gain	High	Poor	Moderate	High
Detection Efficiency		h	High	Moderate to High
Noise		ate	Moderate	Moderate
Timing Response		w	Slow	Fast
Packaging	Bulky	Compact	Compact	Compact
Sensitivity to Magnetic Field	Yes	No	No	No
Bias Voltage	>1kV	~50V	100–1000V	~50V

Has low SNR and not suitable for TOF PET.

HEP & PET

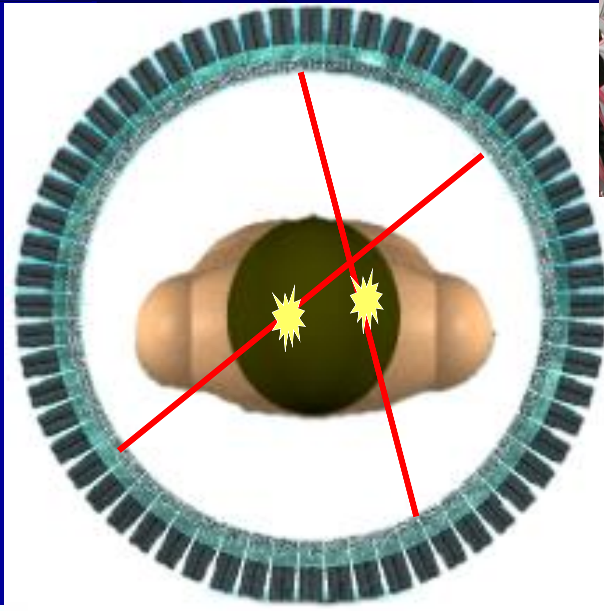
Similarities and differences

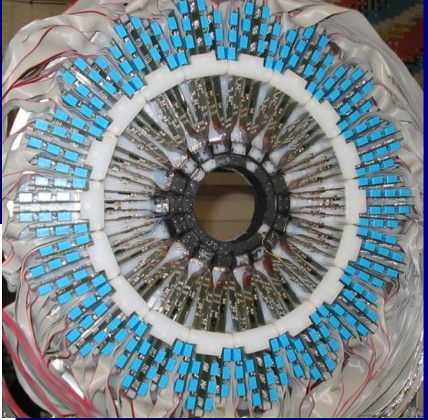


M_{Higgs} = 100 GeV

Calorimeter

HEP



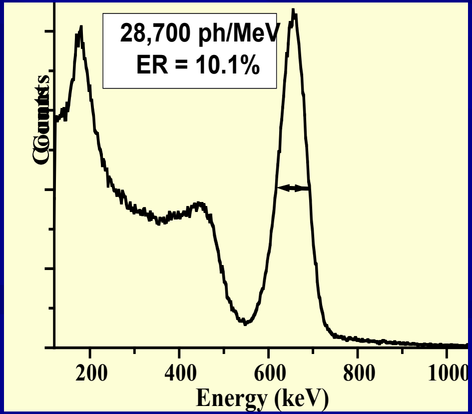


PET
Camera

Biomedical
Imaging

Similarities

Geometry and granularity
Detector (Crystals & scintillator)
Sensor Photodetectors (PMT,APD)
Digitizers: ADC, TDC,
Data volume (Gbytes)



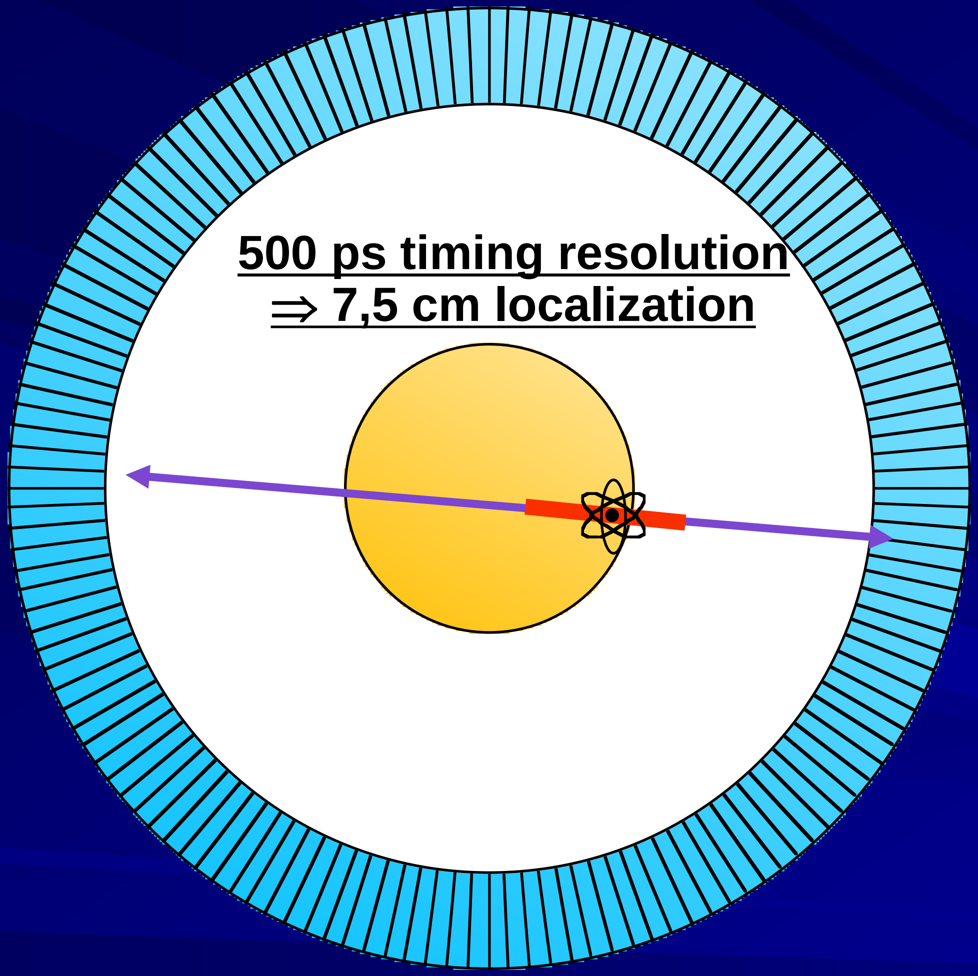
Differences

Energy range
(10GeV → -511keV)
Event Rate 40 → 10 MHz

No synchronization
Self triggered elrctronics
Multiple vertices

Time-of-Flight in medical PET

- Can localize source along line of flight.
- Time of flight information reduces **noise** in images.
- **Line Of Response ---> list mode**



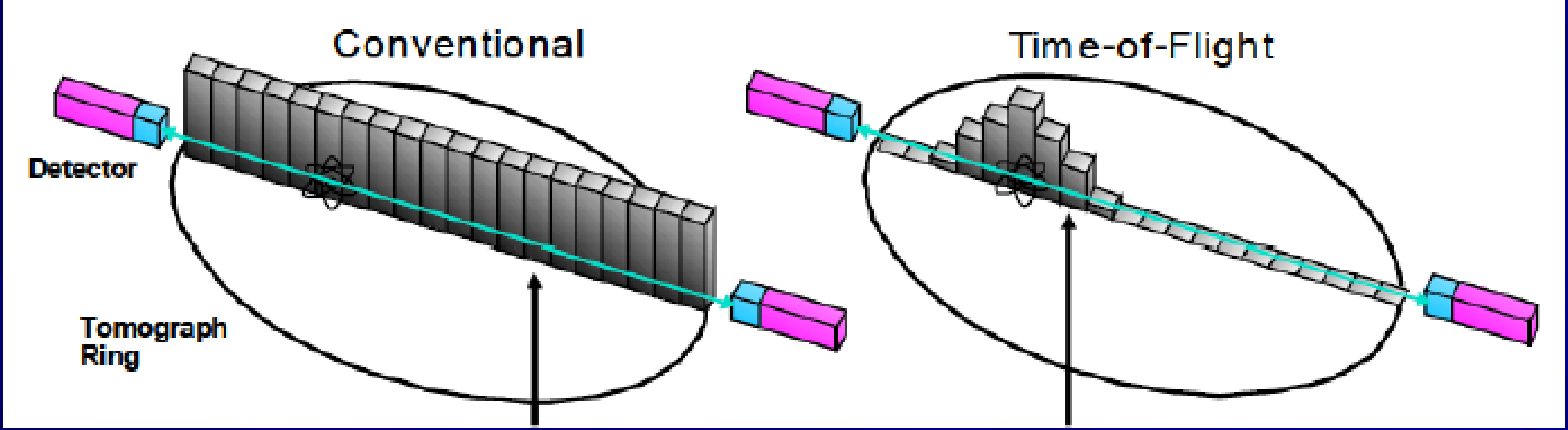
500 ps timing resolution
⇒ 7,5 cm localization

<QE>	PMT	APD
BGO	8.0%	82%
LSO	13.6%	75%

<Npe>	PMT	APD
BGO	275	2816
LSO	1668	9198

W.Moses courtesy

TOF technique (Con't)

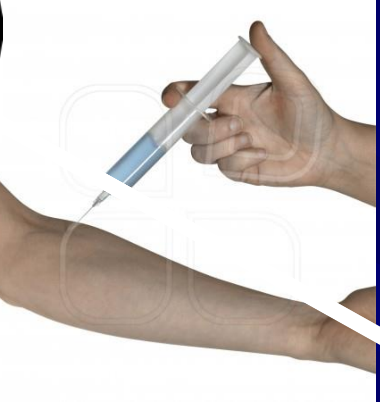


- But need to use list mode data
- More complex data analysis and computing power

The PET sequence

Produce radio-active sugar (FDG

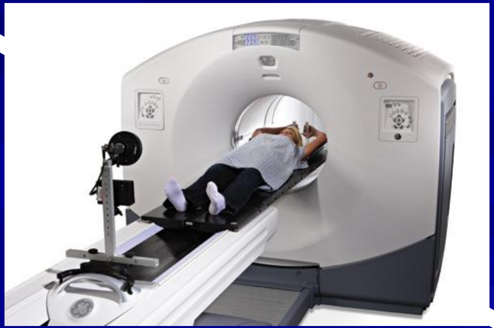
Cyclotron



Intravenous injection

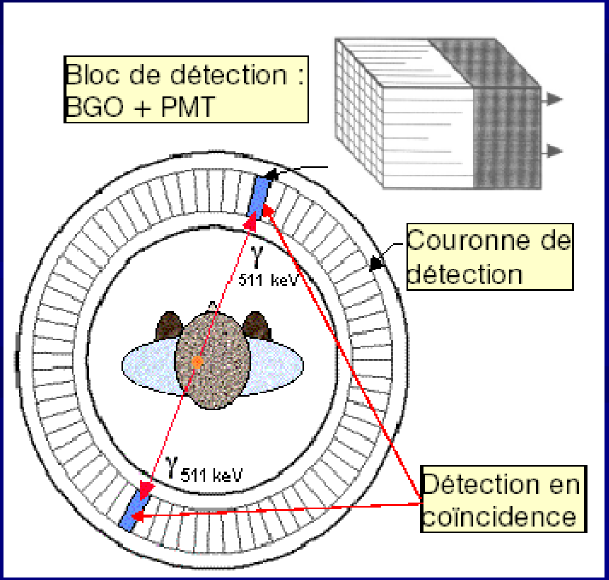
10mC

Wait for accumulation in target site



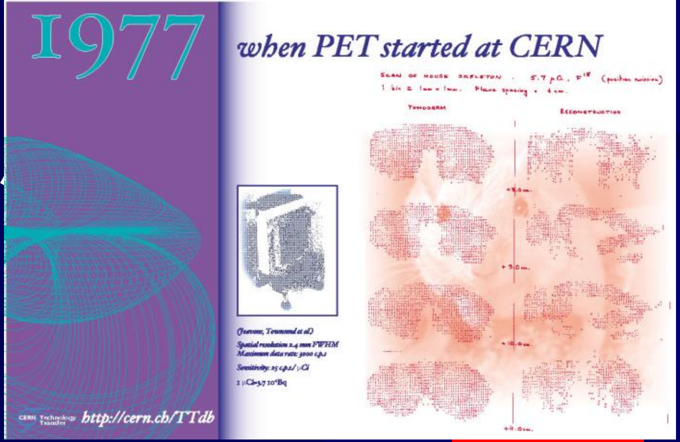
Get 2 gamma events

Reconstruct image coincidence events



Detect coincidence events

Historical Evolution of PET



1977

when PET started at CERN

Scan of mouse skeleton. 5.7 μC, F^{18} (positron emission)
1 bin ≡ 1mm × 1mm. Plane spacing = 4 cm.

(Jeavons, Townsend et al)

Spatial resolution 2.4 mm FWHM
Maximum data rate: 3000 c.p.s

Sensitivity: 25 c.p.s/ μCi

1 μCi=3.7 10^4 Bq

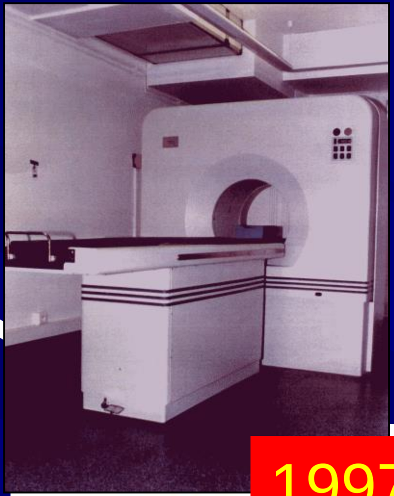
CERN Technology Transfer http://cern.ch/TTdb

1977

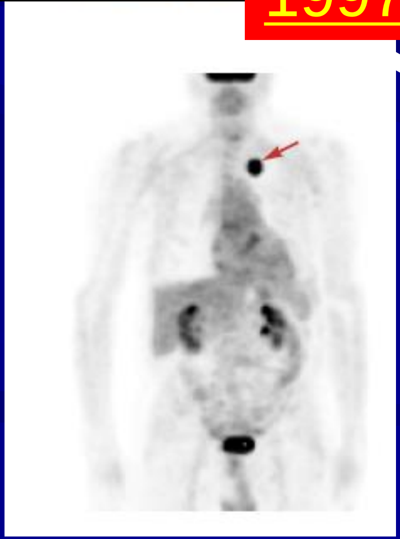
First Steps
Townsend & Jeavons

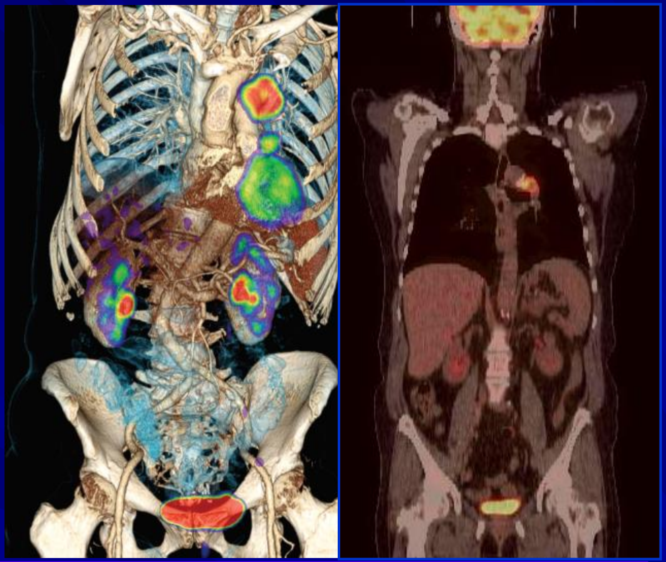
First mouse imaging with ^{18}F

C-PET Philips



1997





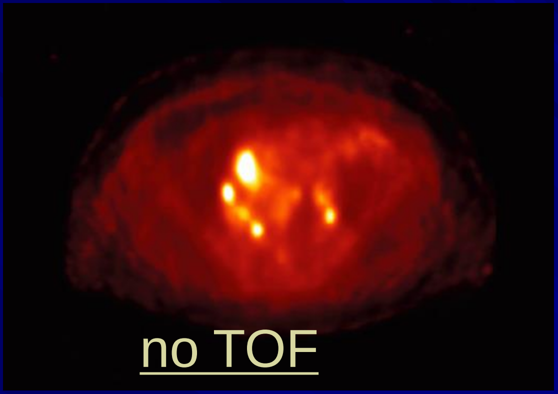
2007

Biograph PET + X ray-CT

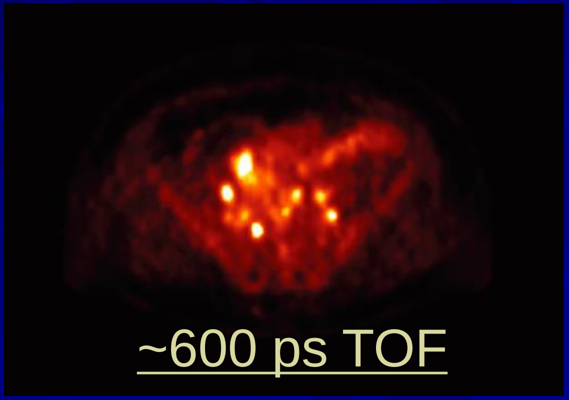
From Today ---> Tomorrow Challenge

2017

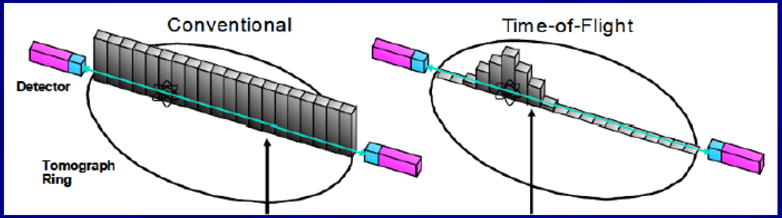
TDM/PET-TOF (250 psec)



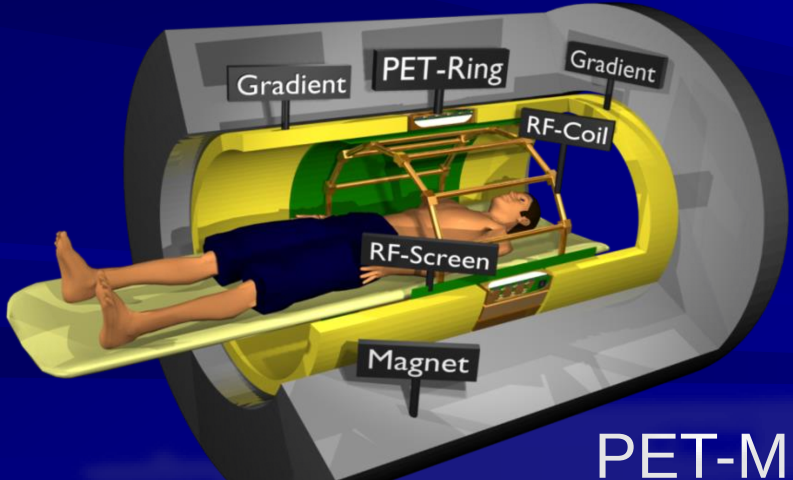
no TOF



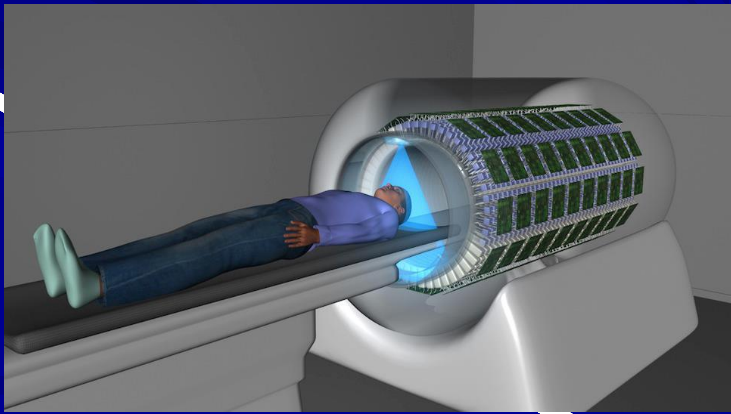
~600 ps TOF



2027 ?



PET-MRI



Explorer total body project

Summary of PET evolution

- Began with Scintillators - one crystal per photosensor (PMTs for most systems to date)
- As we moved to smaller crystals, started doing many on one (crystals to photosensors) designs to reduce cost and allow for physical size of the photosensors
- Added time-of-flight to the mix in the 2000's
- Looked at alternatives, including plastic Scintillators and fibers, various solid state devices
- Recent advances in photosensors, crystals, and solid state materials have opened up the field for many new designs to move the capabilities of PET scanners forward.

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

Final Conclusions

Scientific sessions | Industrial exhibition | Special focus workshops | Short courses

2019 IEEE Nuclear Science Symposium and Medical Imaging Conference

26th International Symposium on Room-Temperature X-Ray and Gamma-ray Detectors

Manchester Central Convention Centre
26 October - 2 November, 2019
Manchester, UK

A forum for physicists, engineers, mathematicians & computer scientists working on Radiation Detectors, Related Technologies and their applications

- ☐ Astrophysics: Synchrotron Radiation
- ☐ Nuclear and High Energy Physics
- ☐ Homeland Security
- ☐ Energy: Environmental Sciences
- ☐ Medical Imaging Systems
- ☐ Image Reconstruction & Data Analysis
- ☐ Radiation Therapy and Dosimetry

General Chair: Paul Marsden
Deputy General Chair: Patrick Le Dû

Scientific Program Chairs
NSS: Cinzia Da Via and Yoshinobu Unno
MIC: Dimitra Darambara and Suleman Surti
RTSD: Paul Sellin and Michael Fiederle

www.nss-mic.org/2019 | nssmic2019@ieee.org
Abstract Submission Deadline 8 May 2019

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

Instrumentation schools References

Thank you
for your attention

- IRSTS 14 Osaka

http://rt2014.rcnp.osaka-u.ac.jp/rt2014-school/index.html

- IRTS 16 HoChiMinh City

http://ntlab.hcmus.edu.vn/en/rt2016-school/

- Le Cap South Africa.18
  https://indico.cern.ch/event/661919/overview
- ICISE July 19
  https://indico.in2p3.fr/event/19513/
- IRSTS Kuala Lumpur (Malaysia) Nov 2019
  https://indico.cern.ch/event/854879/surveys/1178
- IEEE NPSS Workshop on Radiation Instrumentation – Dec 2021

  Dakar Senegal

https://indico.cern.ch/event/954194/

- IEEE NPSS Workshop on Radiation Instrumentation – Nov 2020

  Jakarta Indonesia

https://indico.cern.ch/event/954199/

Lecture-Review references

- CERN SiPM Workshop 2011, State of the art in SiPM's, Y. Musienko
- RICH 2013, Status and Perspectives of Solid State Photo-Detectors, G. Collazuol
- New Developments in Photodetection 2014, Tutorial SiPMs, V. Puill
- https://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_ v3aE.pdf
- PHOTOMULTIPLIER TUBES. Principles & applications. S-O Flyckt* and Carole Marmonier**,Photonis, Brive, France
- Large Area Picosecond Photo-Detectors Project http://psec.uchicago.edu/Papers

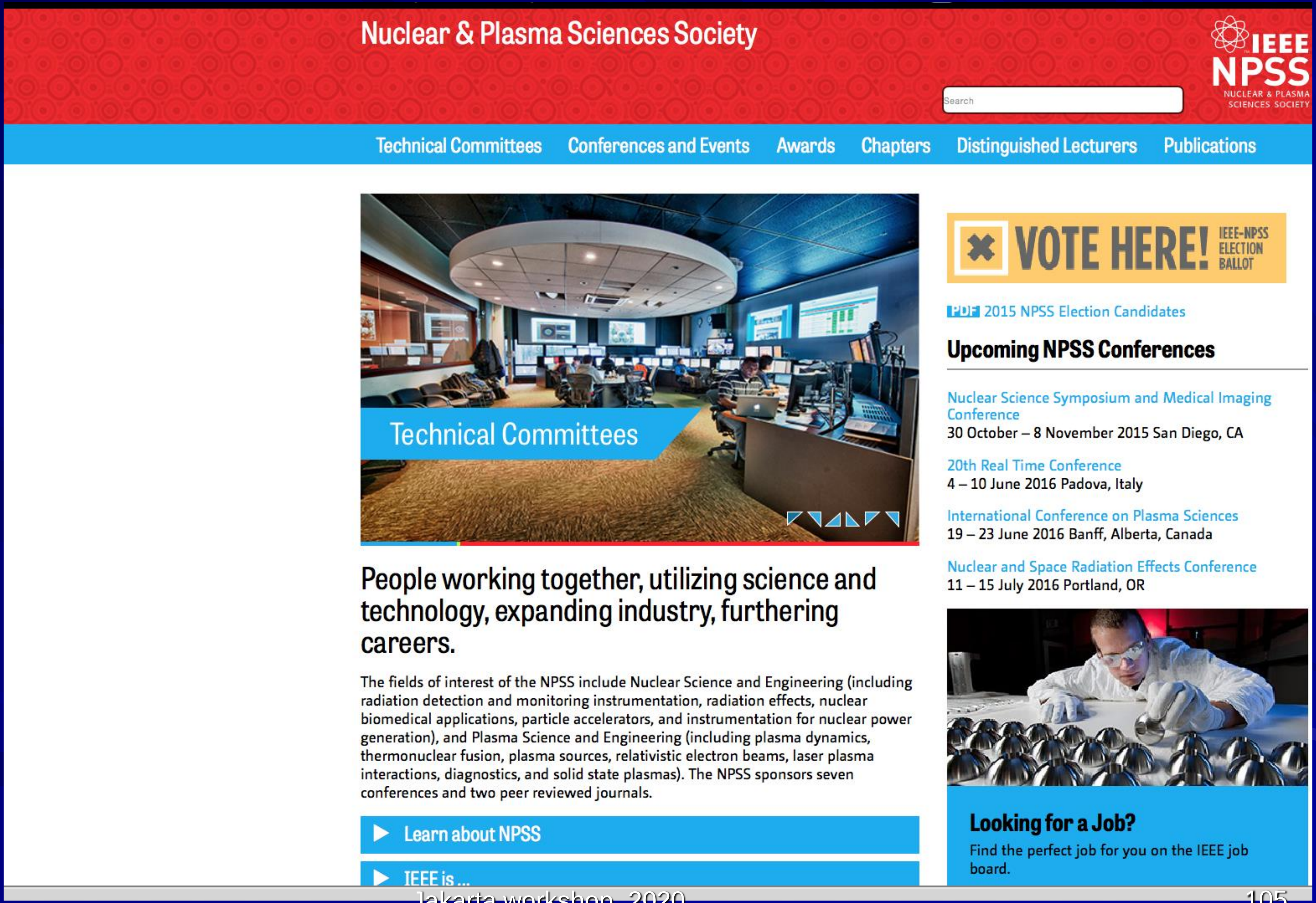
Acknowledgements and References

- **Slides**
  - ,Bill Moses, Steve.Derenzo, P.Lecoq, Veronique Puill, Dieter Renker, Kanai Shah, and many others

- **Books/References**
  - G. F. Knoll, ☐Radiation Detection and Measurement, 3rd Edition, New York, Wiley, 2000
  - Hamamatsu Photonics K. K., “Opto-Semiconductor Handbook”

IEEE Nuclear and Plasma Science Society

http://ieee-npss.org



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IEEE NPSS NUCLEAR & PLASMA SCIENCES SOCIETY

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The fields of interest of the NPSS include Nuclear Science and Engineering (including radiation detection and monitoring instrumentation, radiation effects, nuclear biomedical applications, particle accelerators, and instrumentation for nuclear power generation), and Plasma Science and Engineering (including plasma dynamics, thermonuclear fusion, plasma sources, relativistic electron beams, laser plasma interactions, diagnostics, and solid state plasmas). The NPSS sponsors seven conferences and two peer reviewed journals.

PDF 2015 NPSS Election Candidates

Upcoming NPSS Conferences

Nuclear Science Symposium and Medical Imaging Conference
30 October – 8 November 2015 San Diego, CA

20th Real Time Conference
4 – 10 June 2016 Padova, Italy

International Conference on Plasma Sciences
19 – 23 June 2016 Banff, Alberta, Canada

Nuclear and Space Radiation Effects Conference
11 – 15 July 2016 Portland, OR

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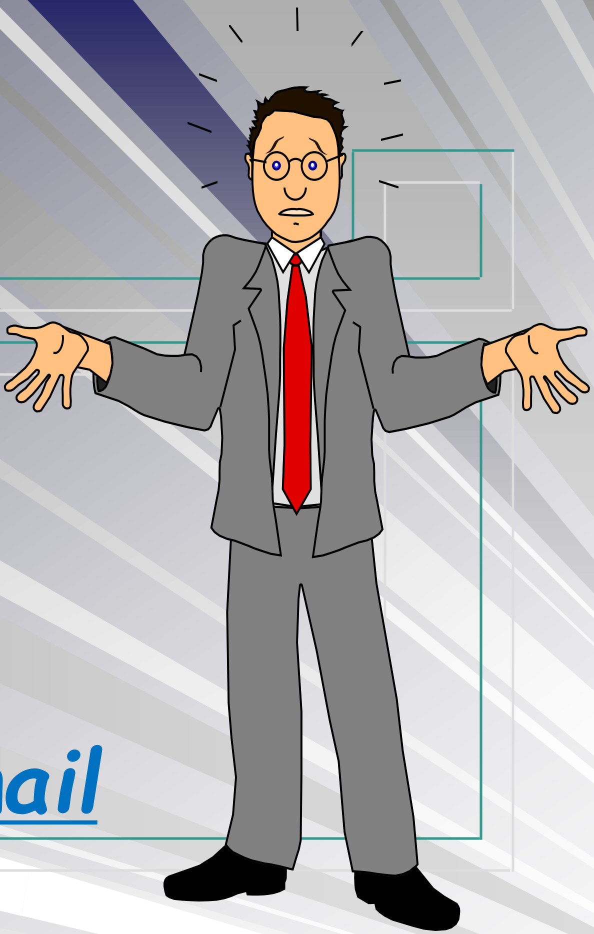
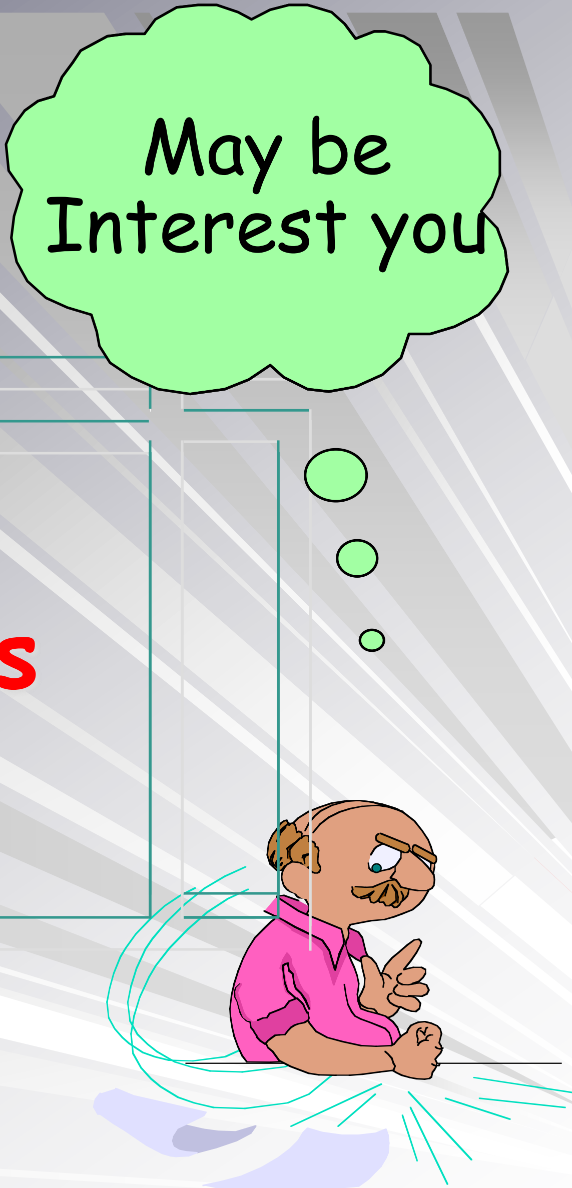


Questions?

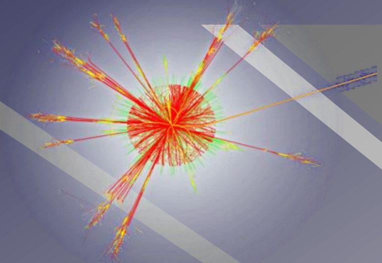
Or send me an email

patrickledu@me.com

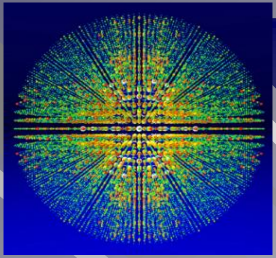
Back up & extra slides



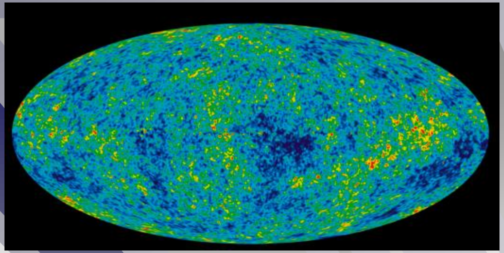
Medical imaging



HEP



x-ray crystallography



cosmology

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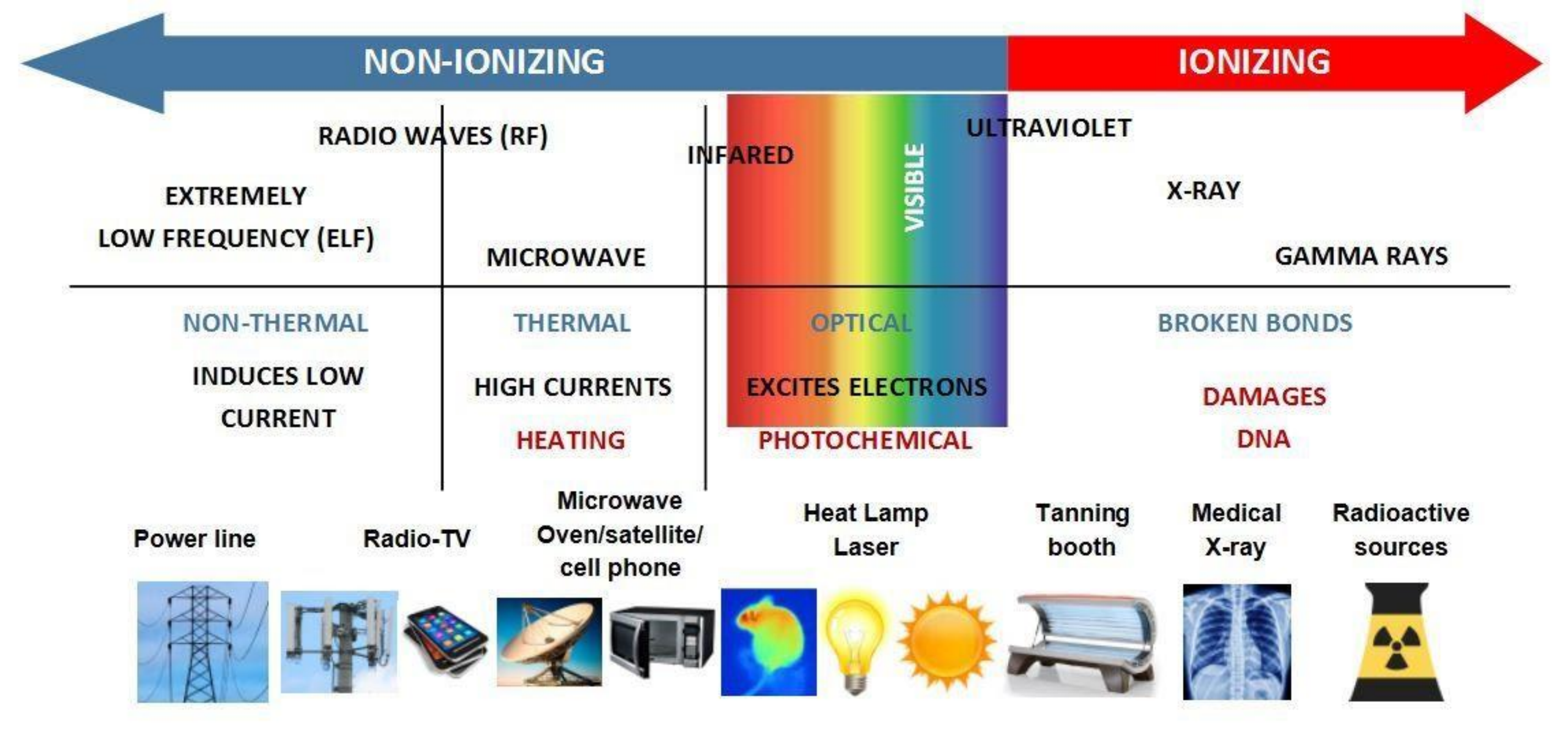
Radiation detectors → Imaging what you cannot see

When radiation interacts with matter

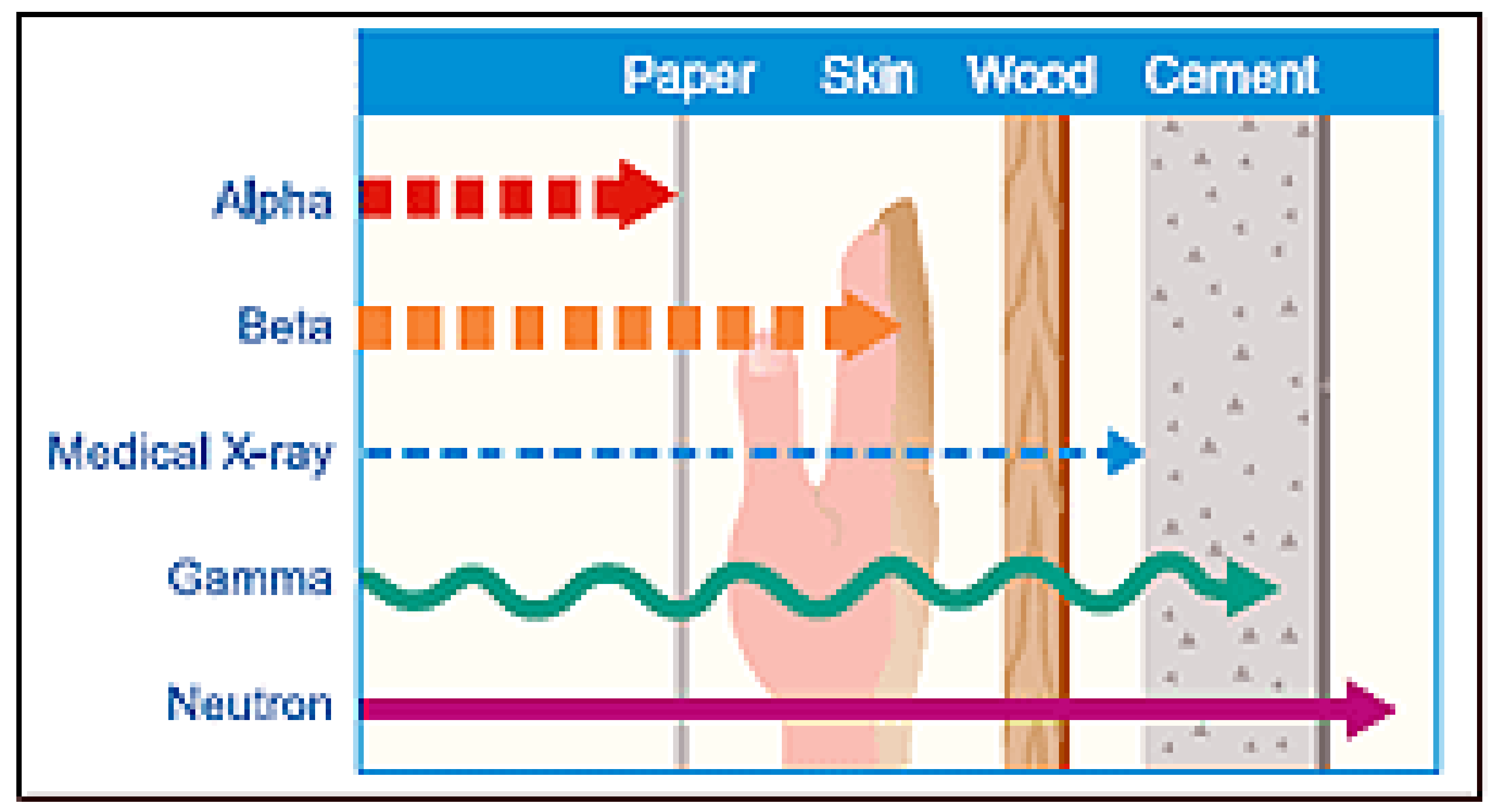
- Non ionizing → not have enough energy to ionize atoms At high energy it becomes ionizing



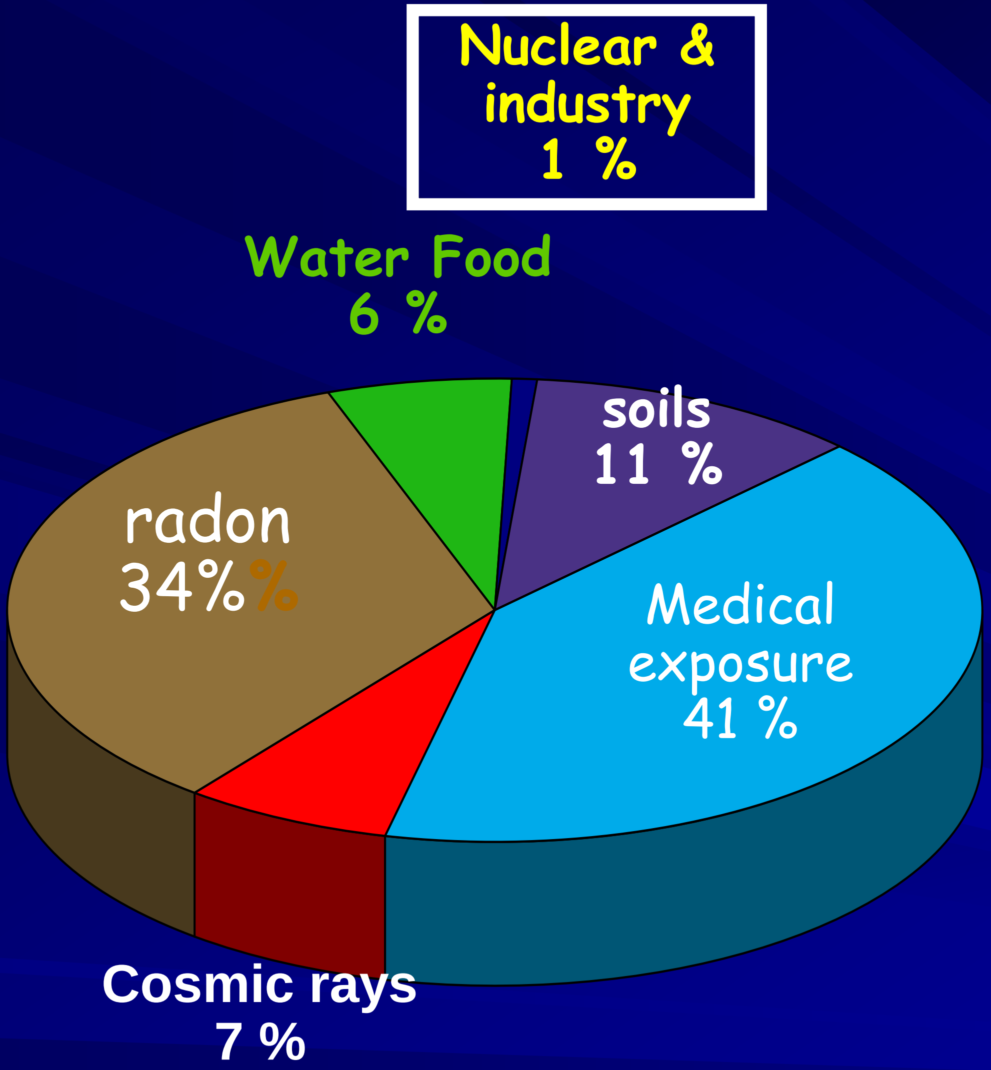
When radiation interacts with matter

Ionizing

has the ability to knock an electron



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...