Scintillation Detectors and Their Applications

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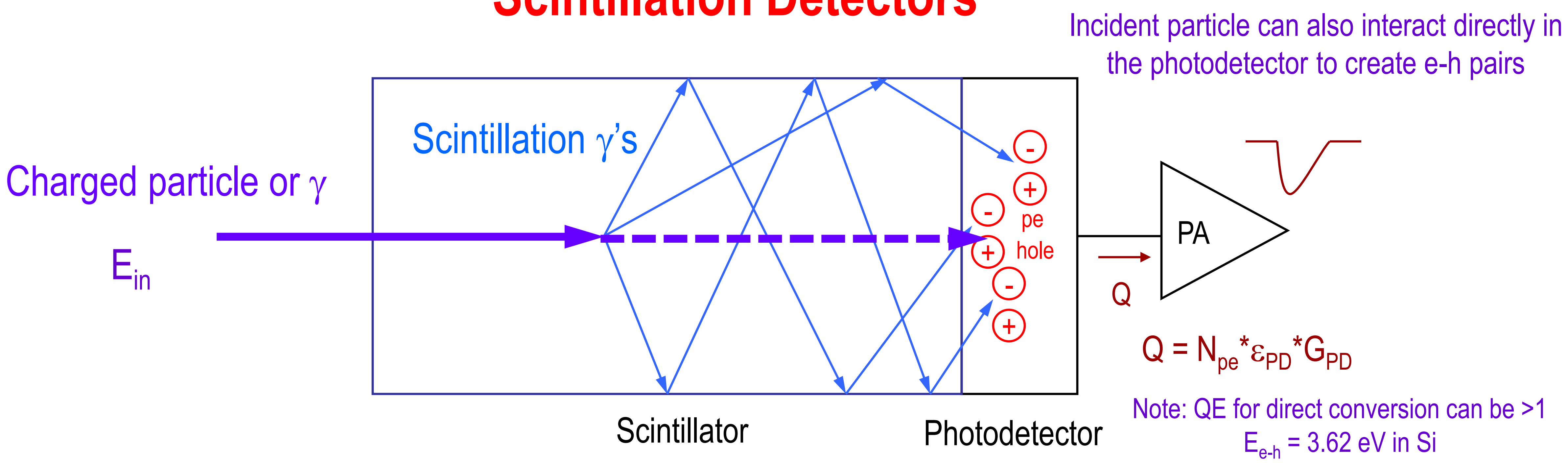
Outline

- Introduction
- Fundamentals of Scintillators
- Photodetectors
- Applications
  - Nuclear and Particle Physics
  - Astrophysics
  - Medical imaging
  - Nuclear Waste Management & Non-Proliferation

Scintillation Detectors

- A scintillation detector is a device that detects the light produced by the deposition of energy via dE/dx in a scintillator. It consists of two basic elements:
  - Scintillator (produces the light)
  - Photodetector (detects the light)
- Can also include other elements such as additional absorbers which absorb part of the energy lost by a particle, light collectors and readout electronics.

Scintillation Detectors



High energy particles deposit energy in the scintillator and produces scintillation photons

$$N_{scint} = E_{in} * \varepsilon_{con}$$

Scintillation photons are collected and detected in the photodetector producing *photoelectrons*

$$N_{pe} = N_{scint} * \varepsilon_{col} * QE$$

Basic Types of Scintillators

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

Organic Scintillators

- Plastics, liquids, organic crystals
- Low density (~ 1 g/cm^3)
- Low Z
  - Requires interspersing high Z absorber material to achieve high stopping power for high energy γ's
  - n detection by (n,p) interactions
- Up to 10,000 γ/MeV
- ns decay times
- Relatively inexpensive
- Moderately rad hard (~ 10 kGy/yr)

Inorganic Scintillators

- Crystals
- Can high density (> 8 g/cm^3)
- Typical have high Z
  - Leads to homogeneous detectors with very good energy resolution
  - Requires good light collection
  - Poor n detection efficiency
- Up to 50,000 γ/MeV
- ns to msec decay times
- Expensive
- Fairly radiation hard (~ 100 kGy/yr)

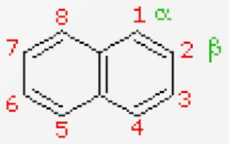
Noble Liquids Scintillators

- LAr, LKr, LXe
- Requires working at cryogenic temperatures
- Moderate density and Z
  - (~ 1.4- 3.0 g/cm^3)
- Scintillation in UV or VUV
- Light yield ~ 50,000 γ/MeV
- Produce ionization plus scintillation

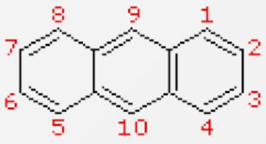
Organic Scintillators

crystals

(very rarely used in HEP)



naphthalene
$C_{10}H_8$
m.p. 81° C

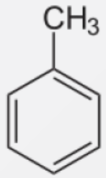


anthracene
$C_{14}H_{10}$
m.p. 217° C

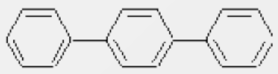
liquids

(solutions)

(rarely used in HEP)



e.g. toluene



e.g. p-terphenyl

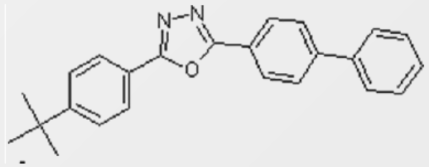
solvent + fluor

plastics

(polymerized solutions)

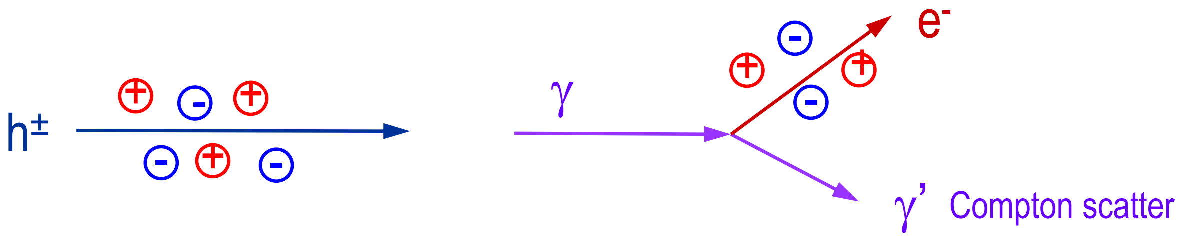
(much used in HEP)

e.g. polyvinlyltoluene

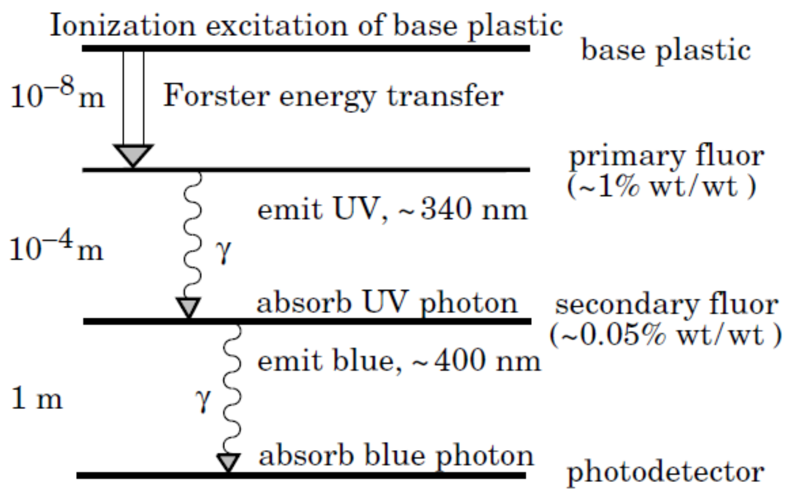


e.g. Butyl-PBD

Plastic Scintillators



- Charged particles produce ionization which causes excitations in the medium
- Gammas interact and produce electrons which cause ionization



Review of Particle Physics
Journal of Physics G, Vol 37, No 7A (2010)

- Primary ionization causes excitation of molecules in the base plastic
- De-excitation of the base plastic produces scintillation photons in the short wavelength UV (~ 300 nm), which are absorbed by a primary fluor, or energy is transferred directly from the base to the fluor in a very short distance.
- Primary fluor emits at a longer wavelength (~ 340 nm), which is absorbed by a secondary fluor that emits in the visible (~ 400 nm)
- Each process involves losses due to the efficiency of energy transfer at each step, resulting in an overall light yield of ~ 1 photon per 100 eV of energy deposit

Wavelength Shifters

Wavelength shifters absorb light at a short wavelength and re-emit at a longer wavelength.

Change in wavelength between absorption and re-emission is called the Stokes Shift

Wavelength shifting can take place in the base plastic scintillator, or can be applied to the light produced by the scintillator using other materials such as wavelength shifting bars or fibers.

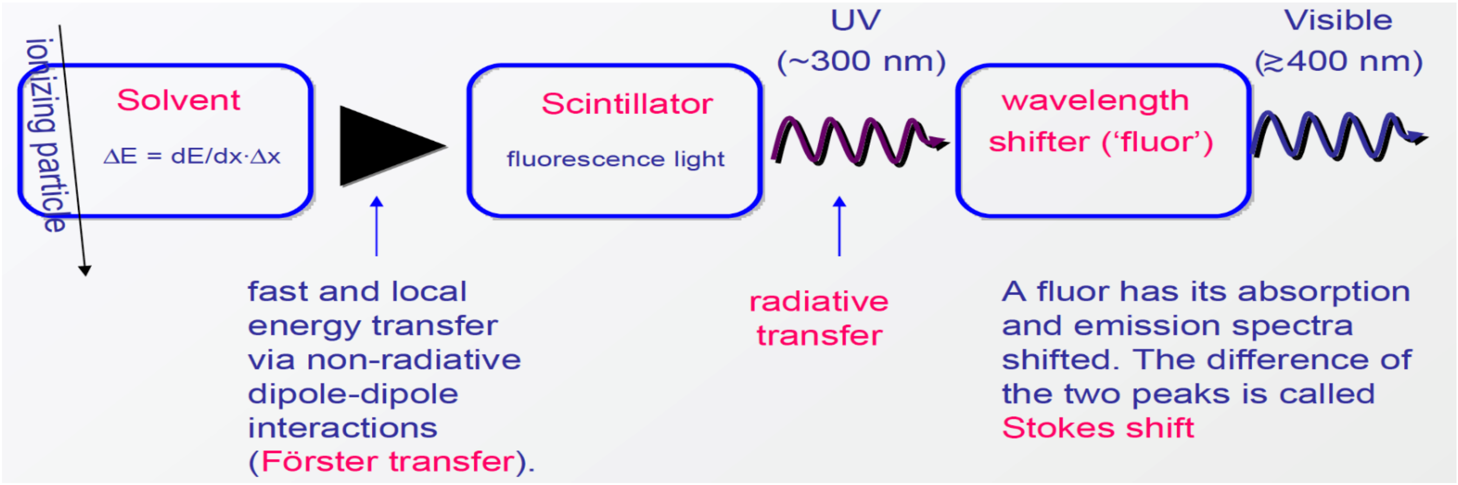
Wavelength shifting can accomplish several goals:

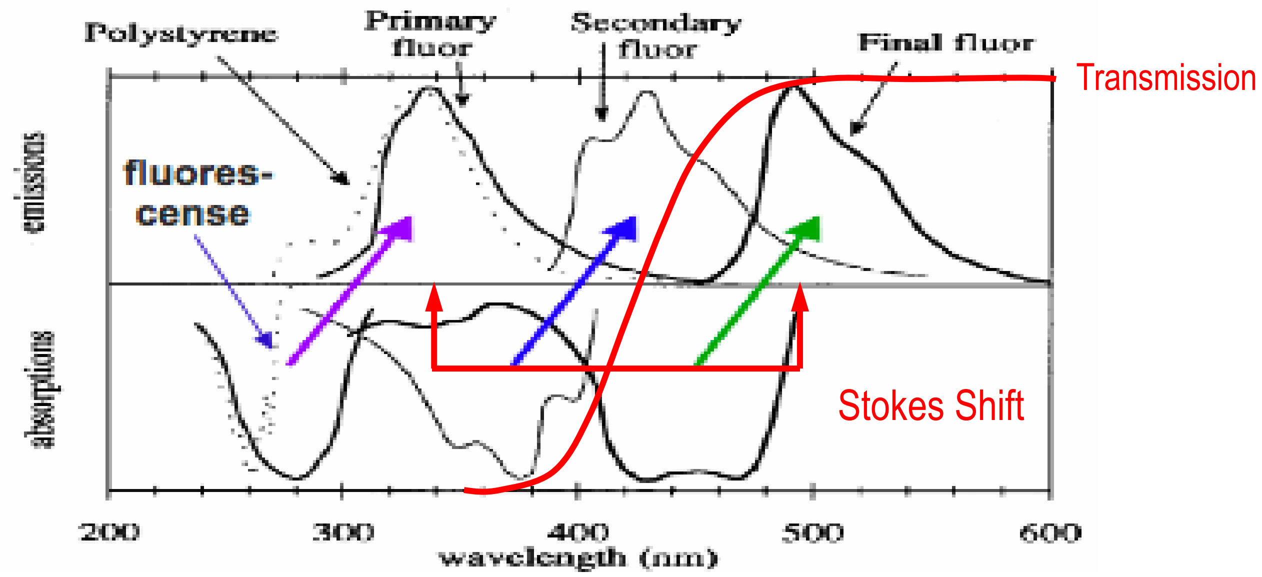
1. Improve light propagation in the material
   - Attenuation length of most base materials is much longer at longer wavelengths
2. Redirect the light for better light collection
3. Provide a better wavelength match to the photodetector

These features come at some cost:

1. Efficiency of wavelength shifting may be low
2. Primary light must be collected by the wavelength shifter
3. Decay time of wavelength shifter may be slower than primary emitter

Wavelength Shifters





Commonly Used Plastic Scintillators

Scintillator	Light output (% Anthracene)	Decay time (ns)	Wavelength of emission max (nm)	Attenuation length (cm)	Application
BC 400	65	2.4	423	250	General purpose
BC 404	68	1.8	408	120	Fast counting
BC 408	64	2.1	425	380	Large area
BC 412	60	3.3	434	400	Large area
BC 418	67	1.4	391	100	Ultrafast timing
BC 428	50	12.0	490	330	Green emitting

Bicron/Saint-Gobain

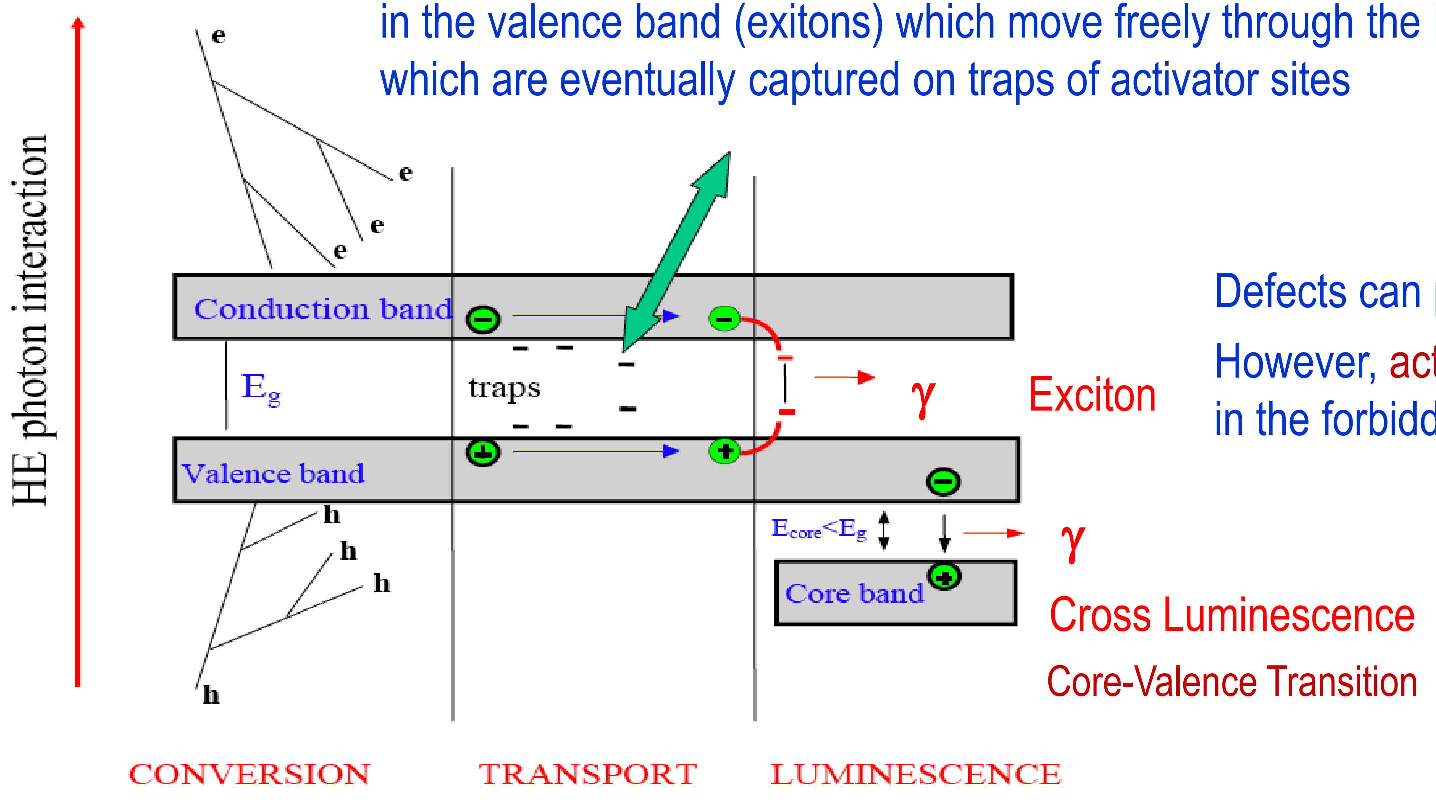
Review of Particle Physics
Journal of Physics G, Vol 37, No 7A (2010)

Light output of Anthracene ~ 40,000 γ/MeV (similar to NaI)

Crystal Scintillators

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

Electrons in the conduction band form loosely bound states with holes in the valence band (exitons) which move freely through the lattice which are eventually captured on traps of activator sites



$$n_{e-h} = \frac{E_\gamma}{\beta E_{gap}}$$

E_γ = incident gamma ray energy
β = efficiency factor for e-h pair formation (β ~ 2-4)

Defects can produce unwanted traps in the forbidden gap

However, activators such as Tl and Ce can create energy levels in the forbidden gap that can produce luminescence

$$N_{photon} = n_{e\text{-}h} \cdot S \cdot Q$$

S = Transfer efficiency to luminescence center
Q = Luminescence efficiency

Note: Activator determines wavelength and decay time of emission

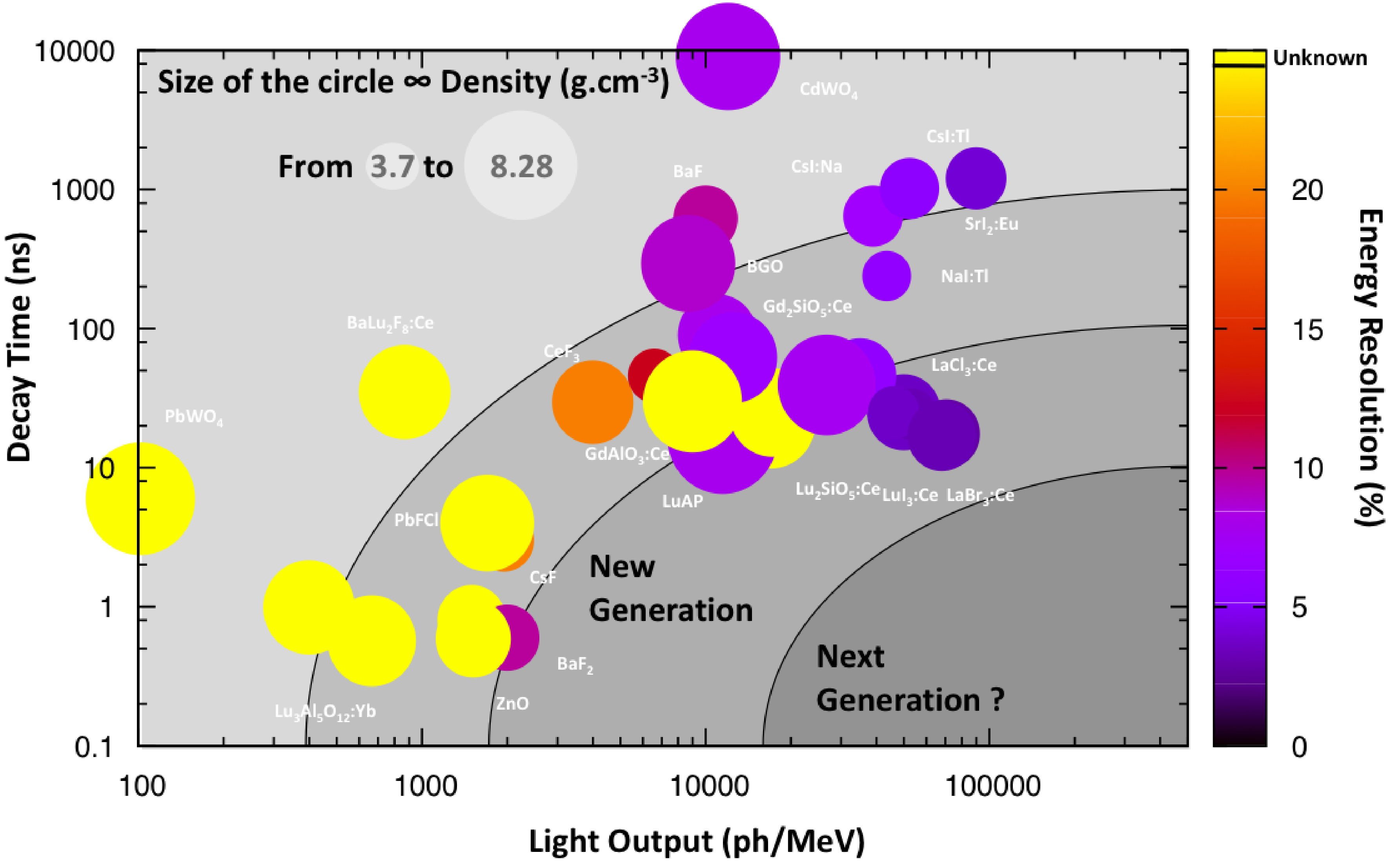
Commonly Used Crystal Scintilators

Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	λ_{max}	$n^\natural$	Relative output†	Hygro-scopic?	$d(LY)/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	230	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	630^s	300^s	1.50	36^s	no	-1.3^s
							0.9^f	220^f		3.4^f		$\sim 0^f$
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1300	560	1.79	165	slight	0.3
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	35^s	420^s	1.95	3.6^s	slight	−1.3
							6^f	310^f		1.1^f		
$PbWO_4$	8.3	1123	0.89	2.00	10.1	20.7	30^s	425^s	2.20	0.083^s	no	−2.7
							10^f	420^f		0.29^f		
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	402	1.82	83	no	−0.2
$LaBr_3$(Ce)	5.29	788	1.88	2.85	6.9	30.4	20	356	1.9	130	yes	0.2

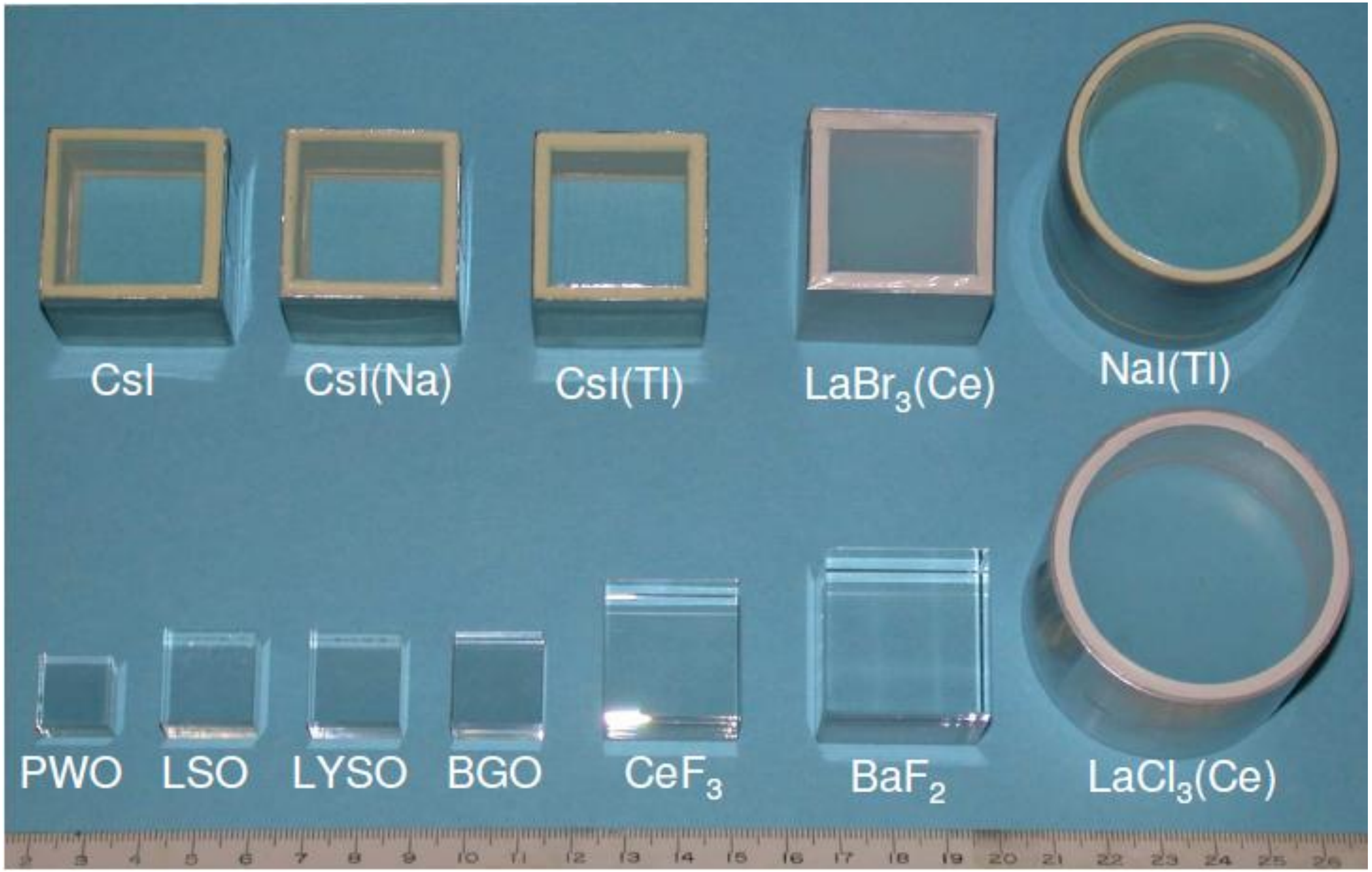
Review of Particle Physics
Journal of Physics G, Vol 37, No 7A (2010)

Light output of NaI(Tl) ~ 40,000 γ/MeV

Characteristicsof Crystal Scintillators



Crystal Scintillators

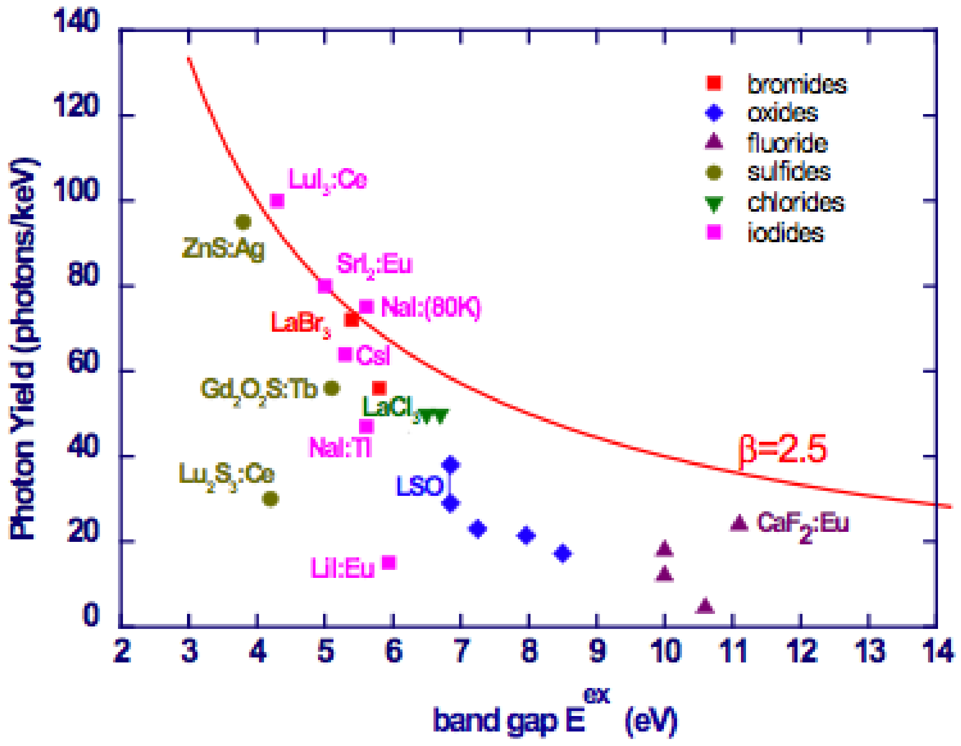


R.Zhu, IEEE Trans. Nucl. Sci., Vol 55, No. 4 (2008) 2425-2431

Crystal scintillators with ~$(1.5\ X_o)^3$ volume

Energy Resolution in Scintillators

$$(\sigma_E/E)^2 = (1/N_{pe}) + (\sigma_{int}/E)^2 + (\sigma_{np}/E)^2$$



$$N_{ph} \le N_{eh} = \frac{E_\gamma}{\beta E_{gap}}$$

σ_{int} = Intrinsic Non-Uniformity

σ_{np} = Non-Proportionality

Scintillator Non-Proportionality

Plastic scintillators do not respond linearly to ionization density

Saturation effects occur due to quenching and recombination

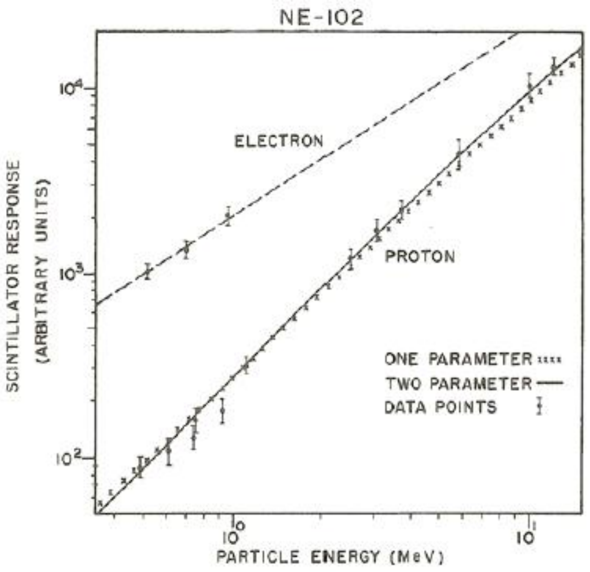
dE/dx ~ 2 MeV/cm for minimum ionizing particles

Semi-emperical formula:

Birks Law

$$\frac{dL}{dx} = L_0 \frac{dE/dx}{1 + k_B dE/dx}$$

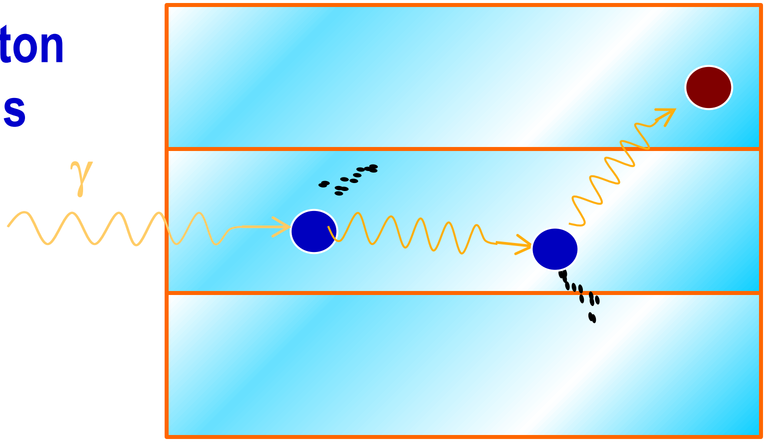
k_B = Birks' constant
determined by measurement

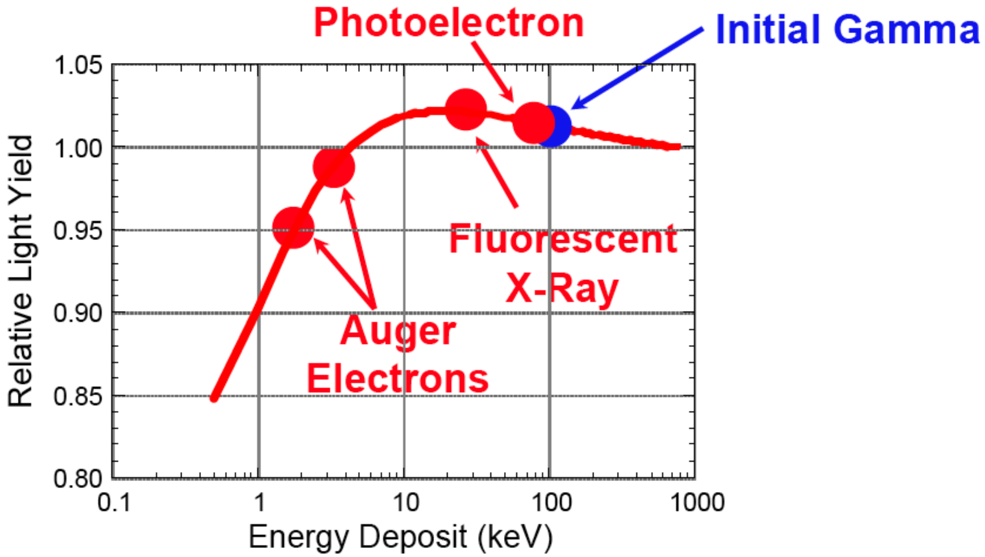


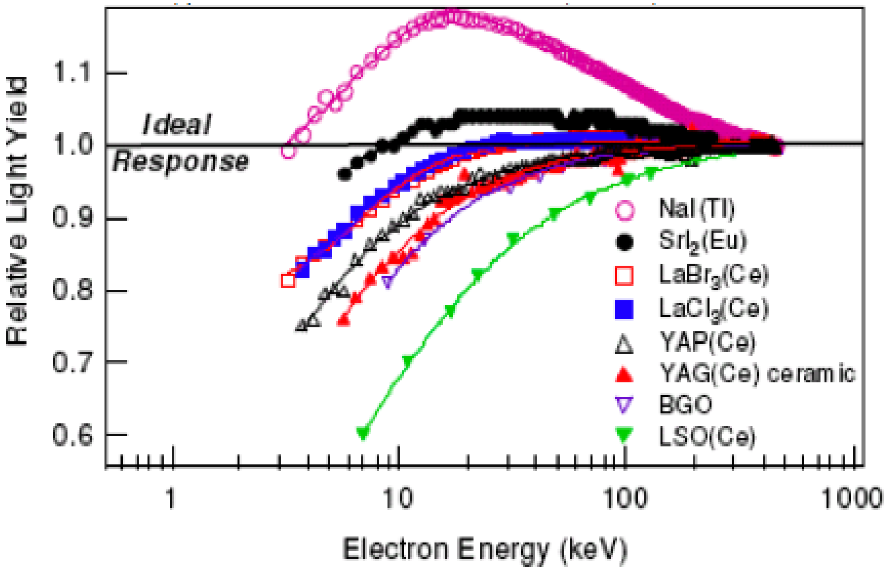
G.Knoll, Radiation Detection and Measurement

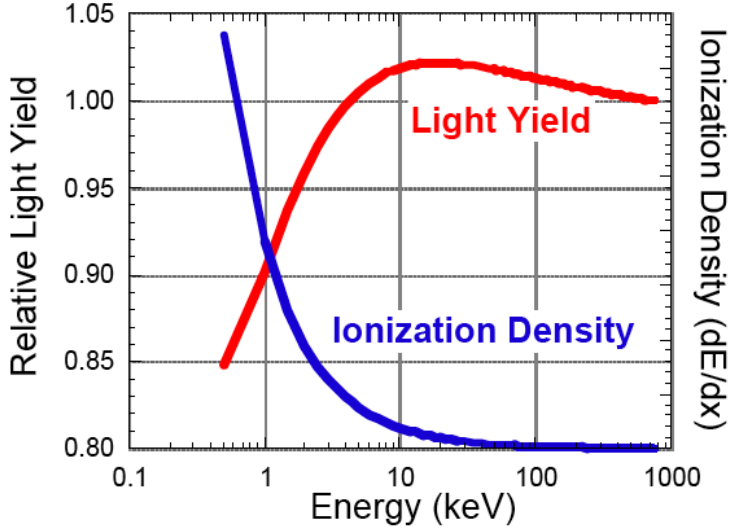
Non-Proportionality in Crystals

Multiple photon interactions







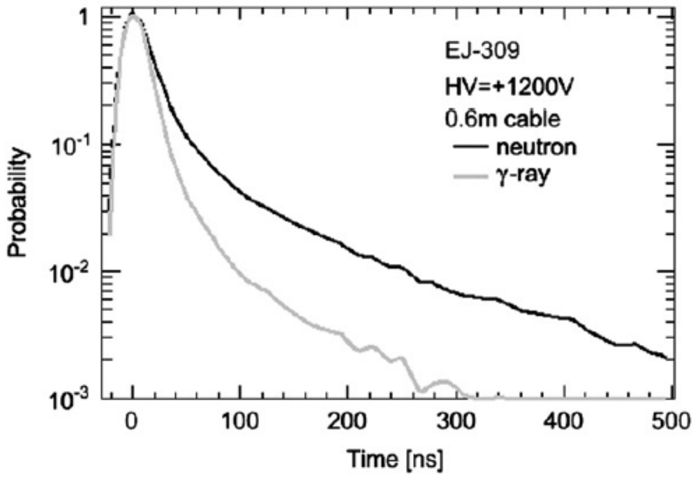


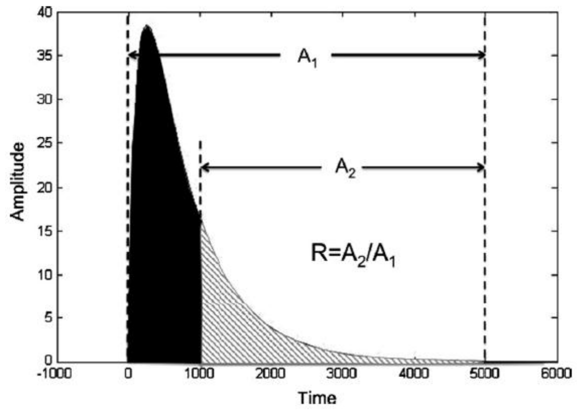
Pulse Shape Discrimination

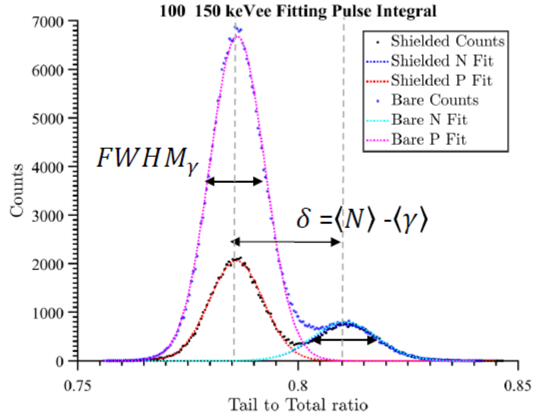
Non-Proportionality in Organic Scintillators can be used for Pulse Shape Discrimination

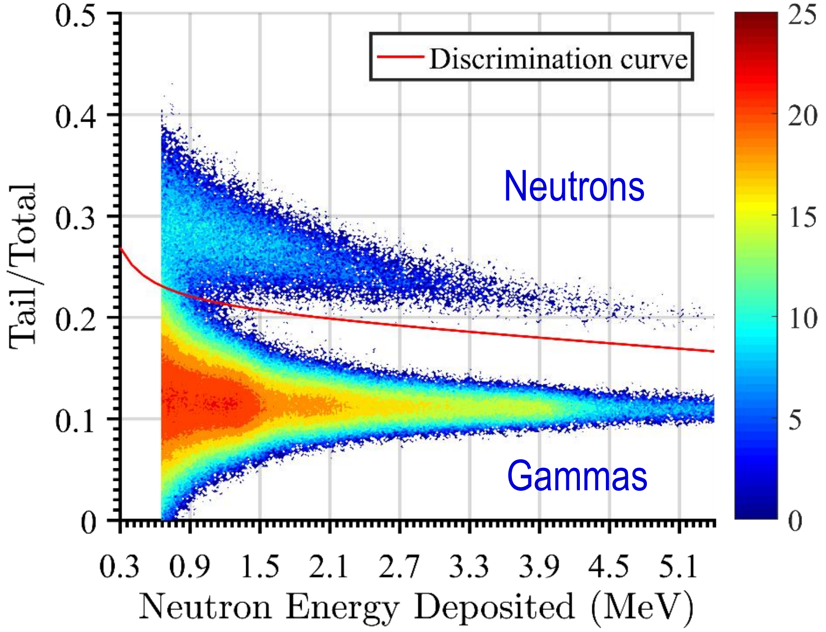
Tail/Total Ratio provides n-γ separation

EJ-309 Liquid Scintillator



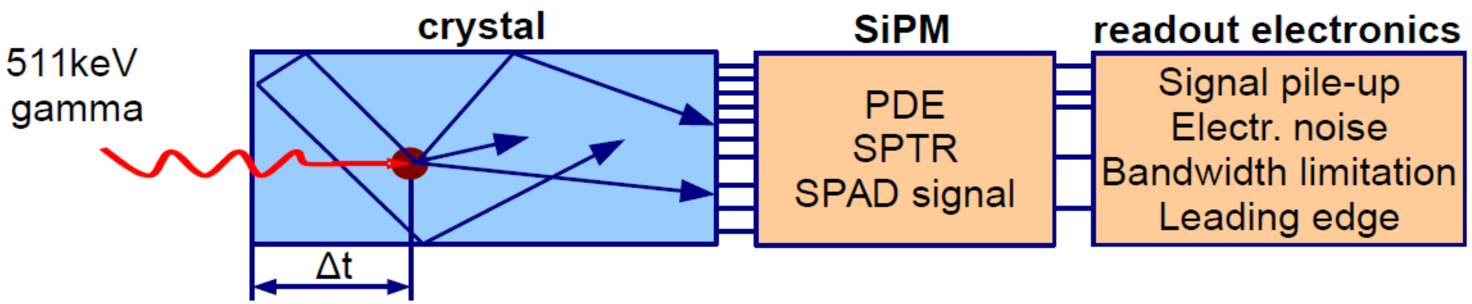






Fast scintillation is quenched
Slow Fluorescence not quenched

Fast Timing with Scintillators



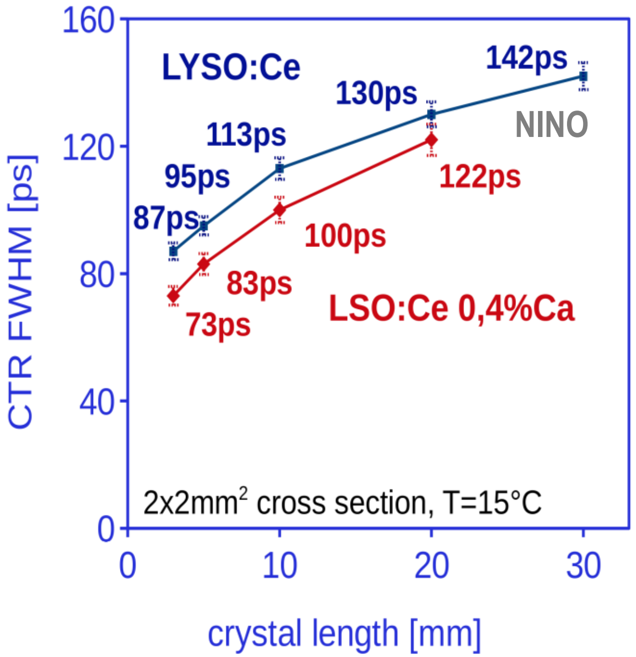
Factors Affecting Time Resolution

- Fluctuations in DOI
- Scintillation mechanism (t_{decay})
- Light transport
- Photodetection efficiency
- Signal processing electronics (SNR)

$$t_{\text{k-th photon}} = \Delta t + t_{\text{Scintillation}}(k) + t_{\text{photon travel}}(k) + t_{\text{SPTR}}$$

PET

511 keV



S. Gundacker et al, 2016 JINST 11 P08008

Applications:

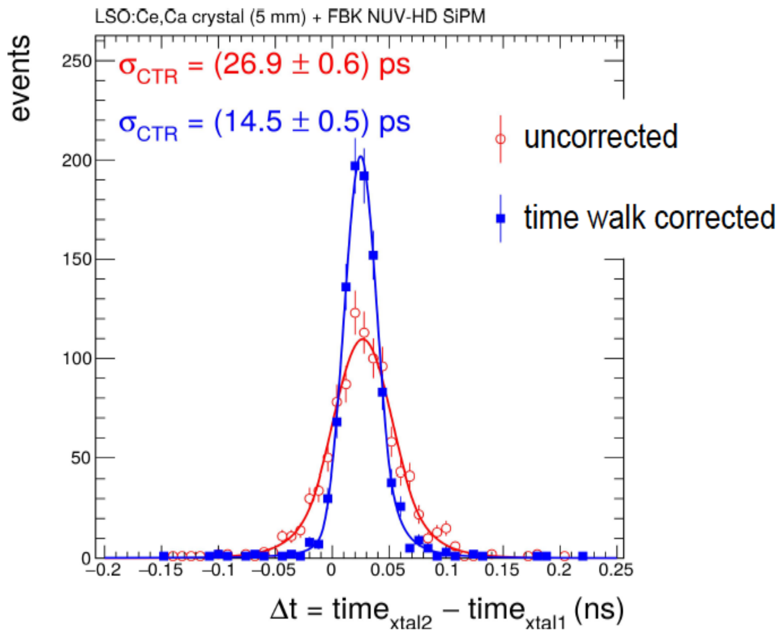
- TOF PET
- Pileup in HEP (LHC)
- Improving calorimeter resolution
  - Dual readout calorimetry – Scint/Č
- Particle ID by TOF
- Particle ID by DIRC
- Fast RICH applications

10 ps Challenge

P.Lecoq, IEEE Trans. Nucl. Sci. Vol. 1-6 (2017) 473-485

HEP

≈ 5 MeV



A.Benaglia, M. Lucchini et al., NIM 830 (2016) 30

Radiation Damage

Radiation can produce defects in a scintillating material resulting in a loss in transmission and/or scintillation light output

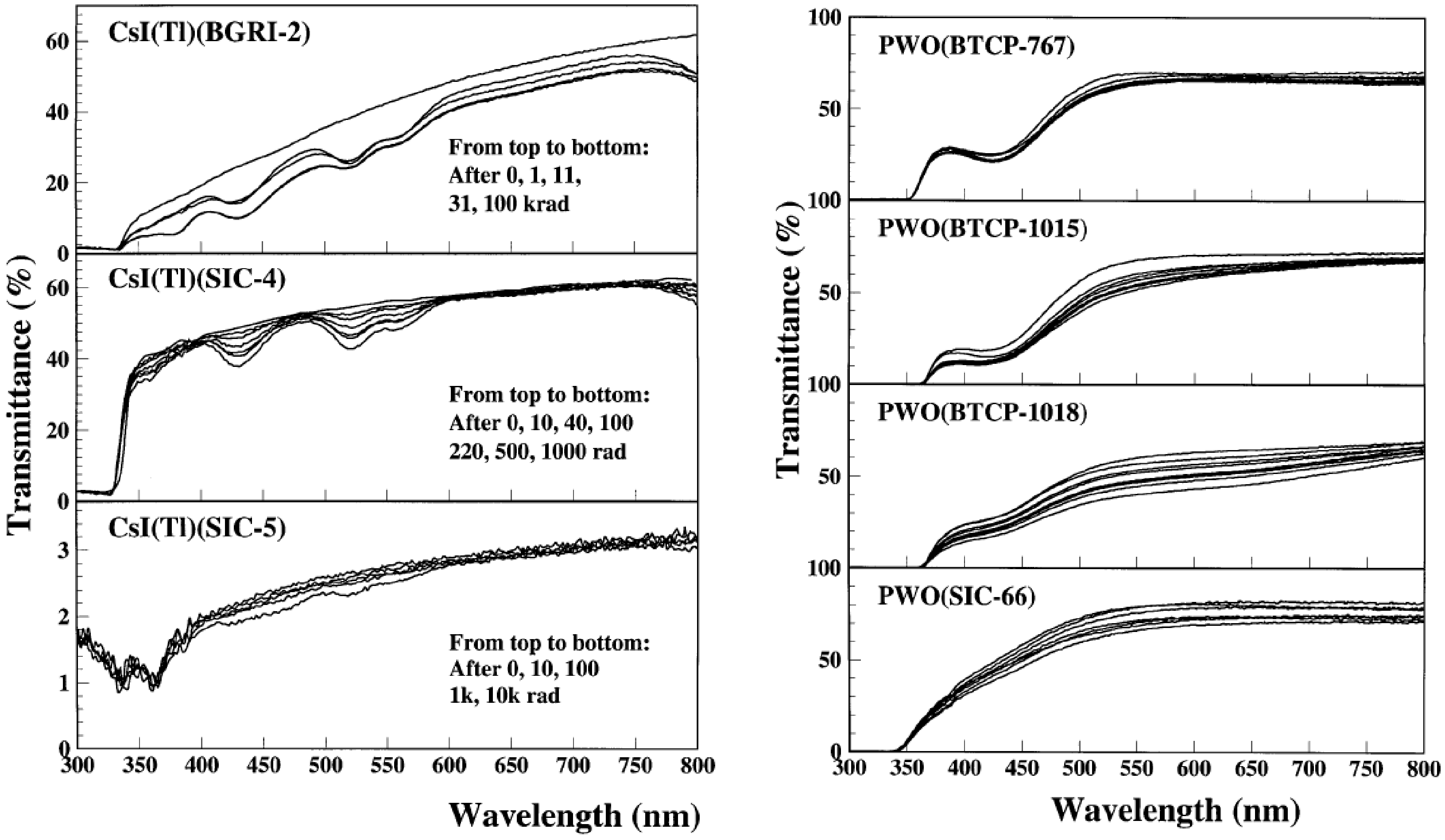
Ionization Damage

- Electrons are liberated and are captured in existing traps in the crystal or plastic
- These traps can then cause resonance absorption centers for the emitted scintillation photons which often appear as optical absorption bands
- Shallow resonance traps can often be annealed away by thermal or optical annealing

Displacement Damage

- Heavy particles (charged hadrons, neutrons, heavy ions, etc..) can cause displacement damage in the material and produce additional defects
- These defects can be permanent (e.g., due to nuclear breakup) or are harder to anneal (interstitial-vacancy recombination)
- However, generally, the scintillation mechanism is not damaged

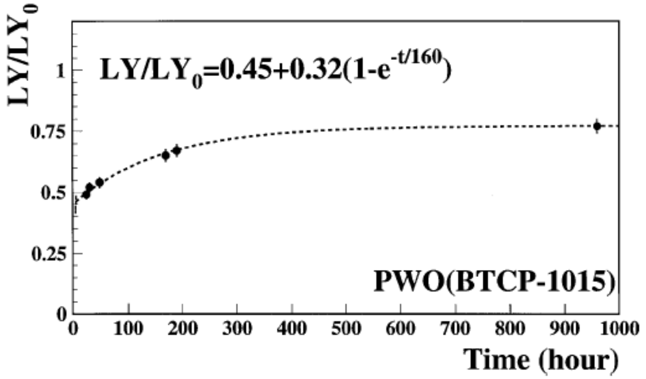
Radiation Damage in Crystals

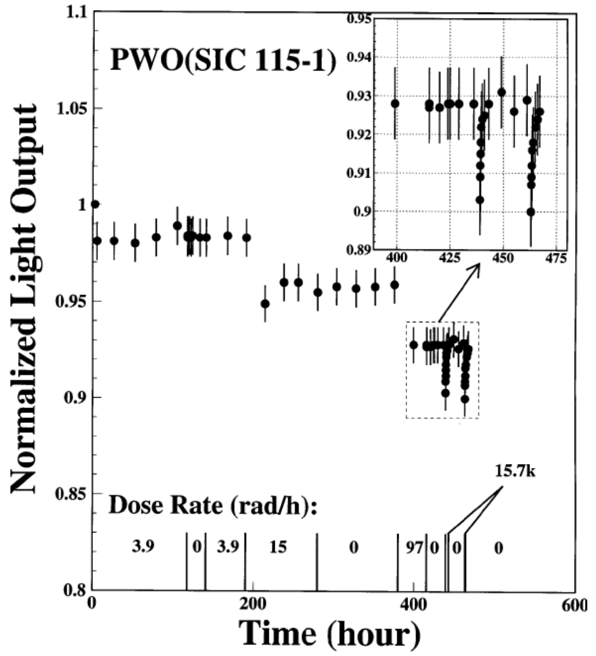


Production of optical absorption bands

R.Y.Zhu, Nucl. Inst. Meth. A413 (1998) 297-311

Recovery





Dose rate dependence

Radiation Damage in Plastics

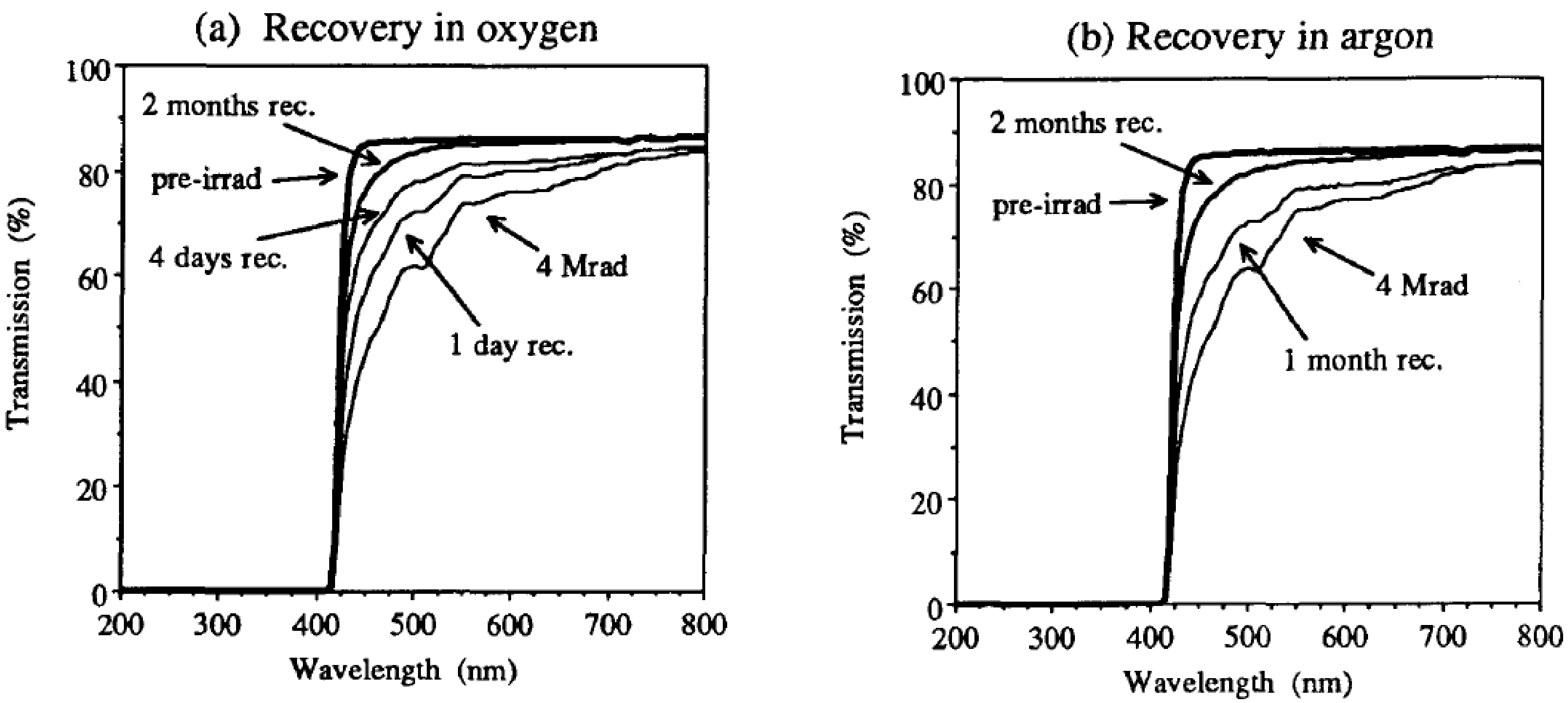
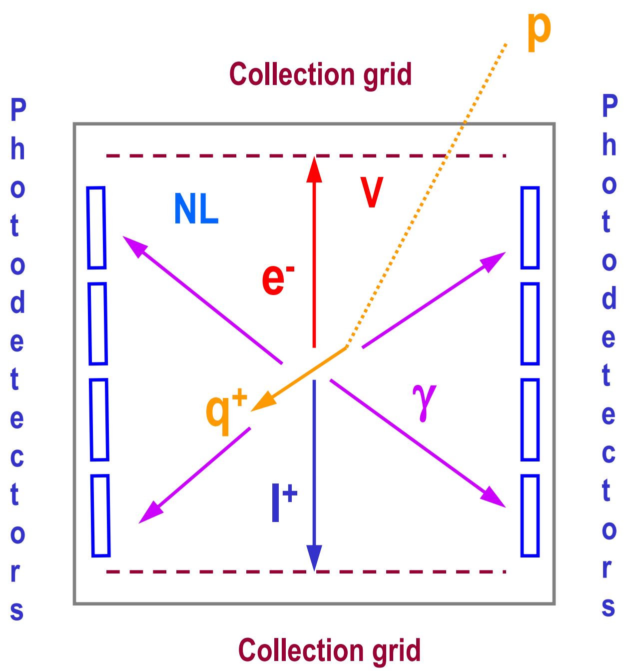


Figure 4: Transmission spectra of cylindrical BC408 samples (15 mm diameter x 10 mm thickness) after being irradiated (in air) to 4 Mrad by a ^{60}Co source (140 krad/hr) and allowed to recover in flowing (a) oxygen and (b) argon atmospheres.

Annealing in oxygen is more effective due to reduction of oxygen vacancies

C.Zorn, IEEE Trans. Nucl. Sci . Vol. 37-2 (1990) 504-512

Noble Liquid Scintillators



- Moderate density
- High scintillation light yield
- Emission in the VUV
- Possibility of measuring scintillation light and collecting charge
- Drift time can give position (TPC)

	LAr	LKr	LXe
Atomic Number (Z)	18	36	54
Density (g/cm3)	1.40	2.41	2.95
Boiling Point (deg C @ 1atm)	87.3	119.8	165.0
Radiation length (cm)	14.0	4.7	2.4
Moliere radius (cm)	8.0	5.5	4.2
Interaction Length (cm)	84	61	57
Luminescence (nm)	128	147	174
Light yield	102	~100	116
Decay time (ns) fast	6.5	2.0	2.2
slow	1100.0	85.0	27.0
* Absolute light yield = 40000 g /MeV			

Some values from R.Wigmans, Calorimetry, Energy Measurement in Particle Physics

Light Collection

Light produced in the gamma converter must be collected and directed onto the photodetector.

Light collection techniques
- Direct reflection or use of reflective materials
- Light guides
- Wavelength shifters

Factors to consider
- Efficiency
- Uniformity
- Geometry
- Matching to readout device

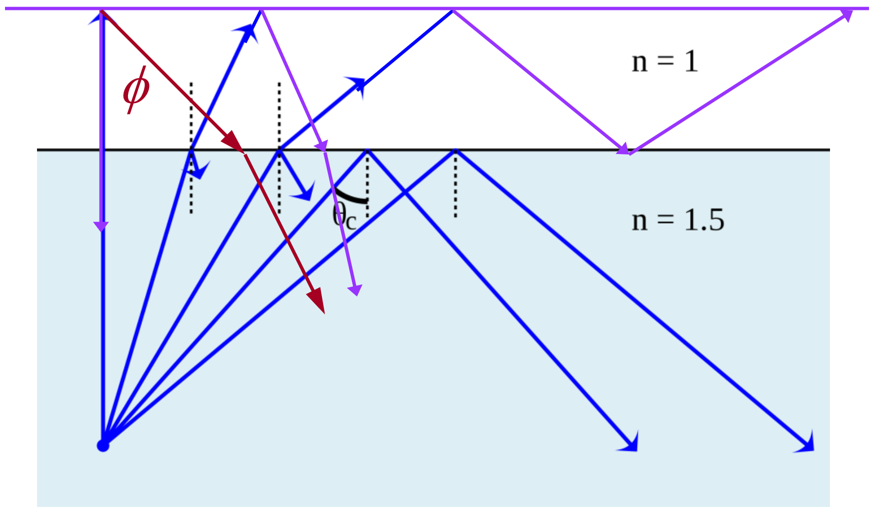
Reflectors

Diffuse reflection
Lamberts Law

$$\frac{dI(\phi)}{dI_0} = \cos(\phi)$$

Critical angle

$$\theta_c = \sin^{-1}\frac{n_1}{n_0}$$



Best reflector is Total Internal Reflection

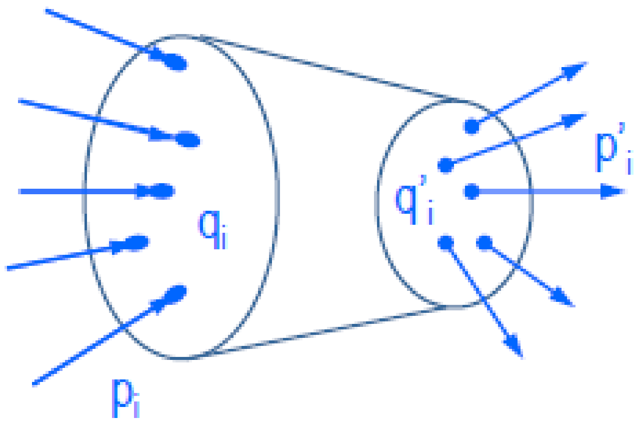
- Scintillation light is produced isotropically
- Some fraction F will be trapped in the scintillator by internal reflection
  - requires good polished surface
  - however, may lead to non-uniformities due to self absorption
- Escaping fraction can be reflected back into scintillator by an external reflector
  - Requires an air gap between scintillator surface and reflector to preserve internal reflection
  - Specular reflector preserves angle
  - Diffuse reflector can change the angle of exiting rays to improve efficiency

Focusing Light Guides

Need to concentrate the light, but Phase Space density $\rho(q,p)$ remains constant with time

Louisville's Theorem

$$\frac{d\rho}{dt} = \sum_{i=1}^{n} \left(\frac{\partial \rho}{\partial q_i} \dot{q}_i + \frac{\partial \rho}{\partial p_i} \dot{p}_i \right) = 0$$

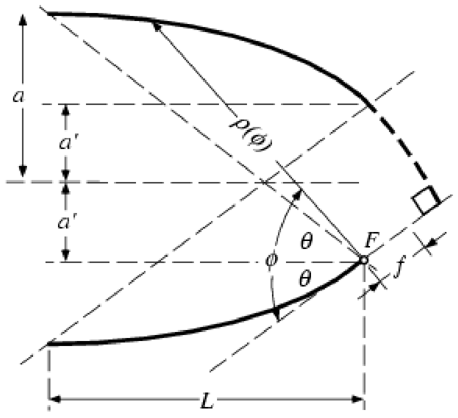


Reducing area increases divergence

Winston Cone

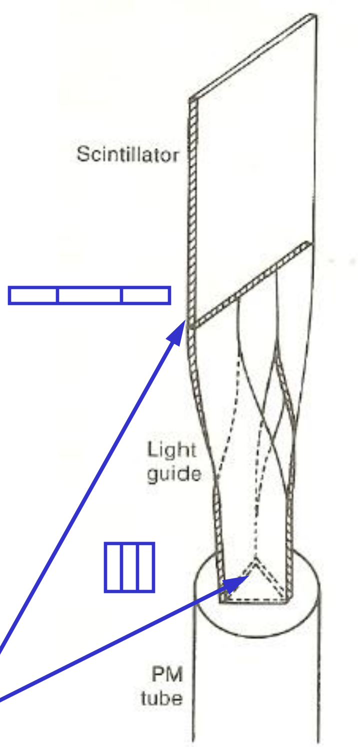
R.Winston, J. Opt. Sci. Amer. 60 (1970) 245-247

Off axis parabola of revolution
Focuses rays on exit aperture

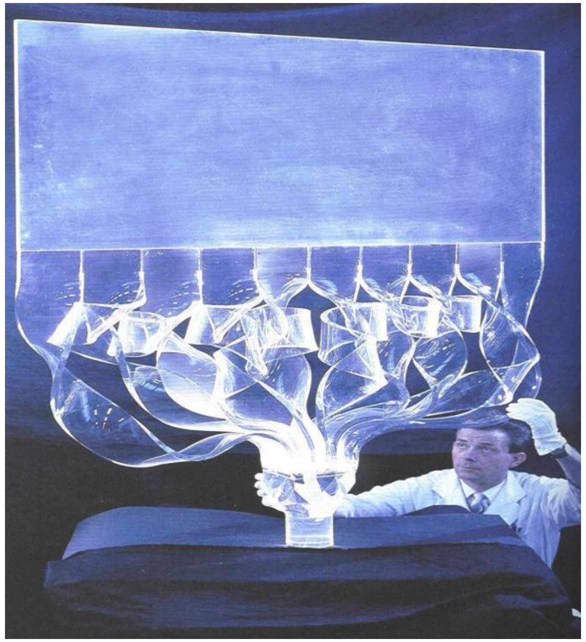


Try to preserve initial area

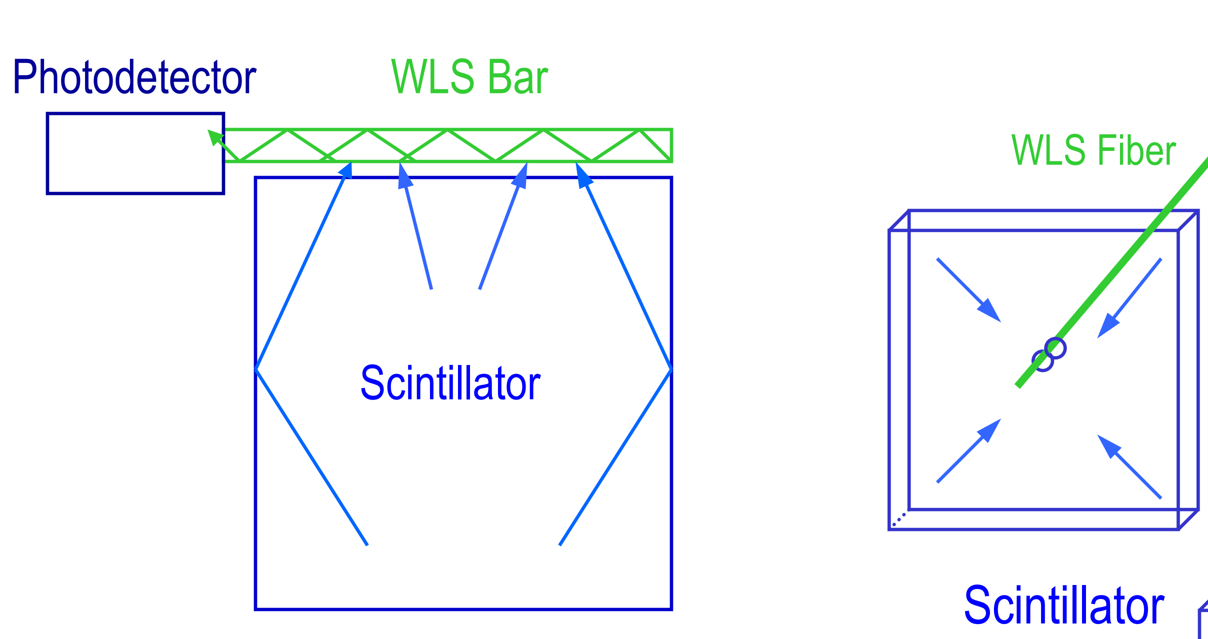
Adiabatic Light Guide

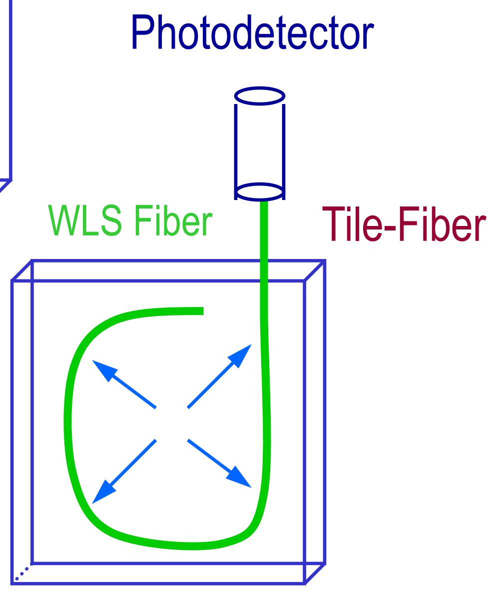


G.Knoll, Radiation Detection and Measurement



Wavelength Shifters as Light Collectors



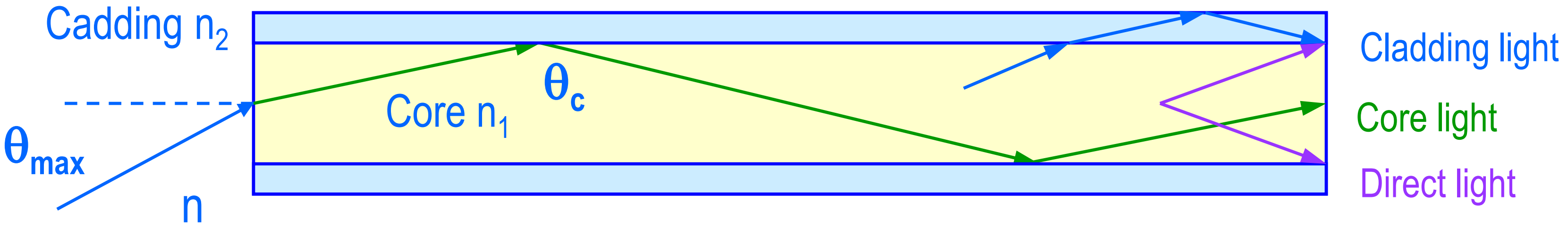


Wavelength shifter absorbs scintillation light and re-emits shifted light at a longer wavelength and in a different direction

Wavelength shifter (bar, fiber,…) acts as its own light guide, bringing the shifted light to the photodetector

Note: Transfer of light from scintillator to wavelength shifter, absorption, re-emission, collection and transfer to photodetector can be very inefficient

Optical Fibers



Fibers are used both as light guides and as active detector material
- Scintillator or Cherenkov

Light is trapped by internal reflection between core and cladding ($n_1 > n_2$)

Numerical Aperture defines the maximum angle that can be trapped

$$N.A. = n \cdot \sin\theta_{max} = \sqrt{n_1^2 - n_2^2}$$

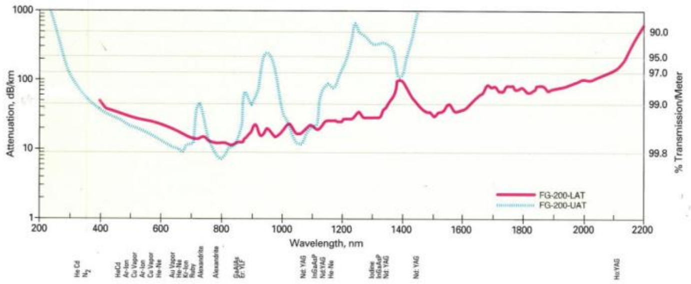
Trapping fraction is small

$$F_{fib} = \frac{1}{2}\left(1 - \frac{n_2}{n_1}\right)$$

G.Knoll, Radiation Detection and Measurement

n_1=1.58 (polystyrene)
n_2=1.49 (PMMA)
F_{fib} ~ 3%
x2 ~ 6% if use reflector or read out both ends

Attenuation length is highly wavelength dependent
Some escaping light is trapped in the cladding
Direct light can also escape



3M Optical Fibers

All can lead to non-uniformities in Sci-Fi applications

Photodetectors

Must convert the light from the scintillator into electrons which can then be amplified and measured

Photodetectors consist of two basic elements:

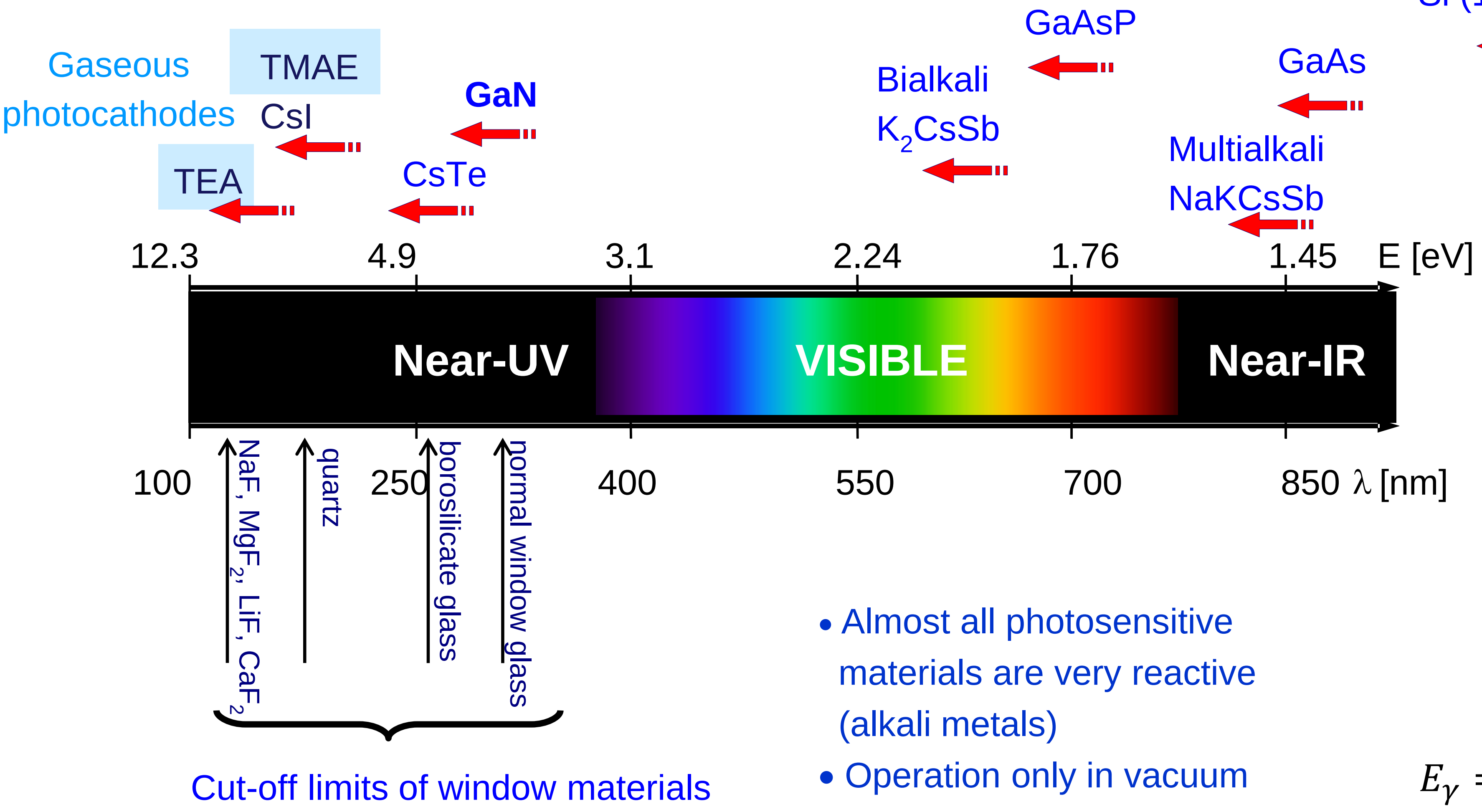
Photocathode

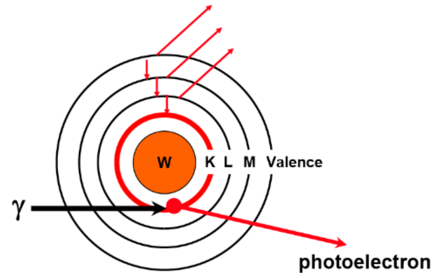
- Converts photons into photoelectrons via the photoelectric effect
- Performance determined by the Quantum Efficiency

Charge amplification

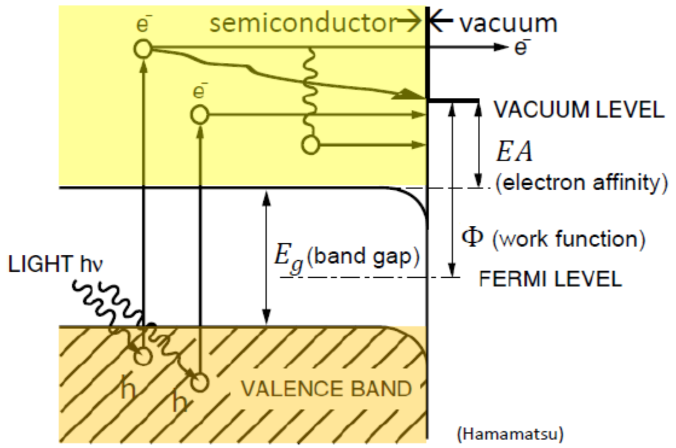
- Can involve gain or only direct conversion
- Performance determined by signal to noise ratio
- Requires appropriate readout electronics

Photocathodes





Photoelectric Effect



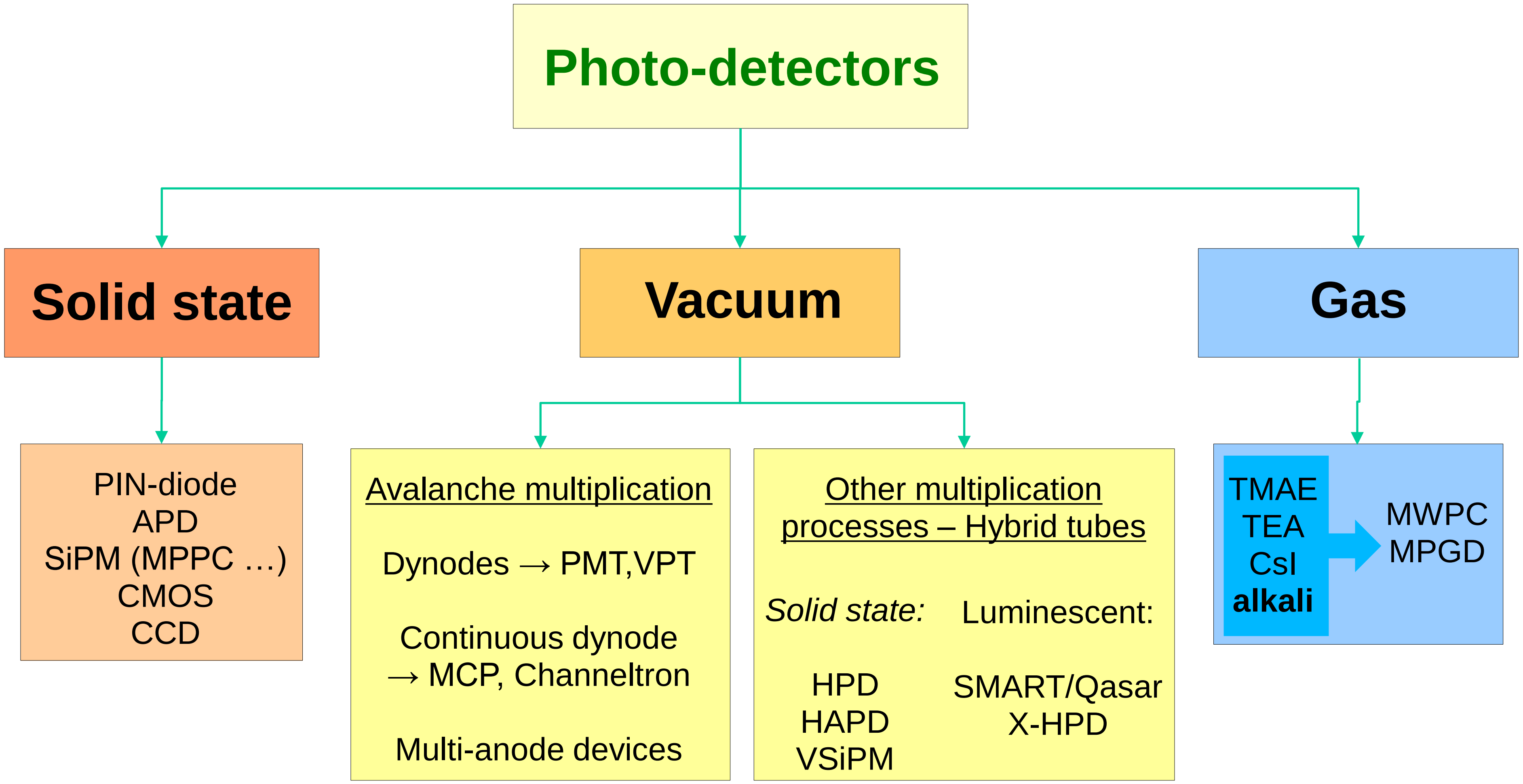
- Almost all photosensitive materials are very reactive (alkali metals)
- Operation only in vacuum or extremely clean gas.
- Exceptions: CsI, Si

Photon energy:

$$E_\gamma = h\nu = \frac{hc}{\lambda} \approx \frac{1239\ \mathrm{eV \cdot nm}}{\lambda}$$

Visible range 400 nm – 780 nm
→ 3.1 - 1.6 eV

Types of Photodetectors



Properties of Various Photodetectors

Type	λ (nm)	$\epsilon_Q\ \epsilon_C$	Gain	Risetime (ns)	Area (mm^2)	1-p.e noise (Hz)	HV (V)	Price (USD)
PMT*	115–1700	0.15–0.25	10^3–10^7	0.7–10	10^2–10^5	10–10^4	500–3000	100–5000
MCP*	100–650	0.01–0.10	10^3–10^7	0.15–0.3	10^2–10^4	0.1–200	500–3500	10–6000
HPD*	115–850	0.1–0.3	10^3–10^4	7	10^2–10^5	10–10^3	$\sim 2 \times 10^4$	~600
GPM*	115–500	0.15–0.3	10^3–10^6	$O(0.1)$	$O(10)$	10–10^3	300–2000	$O(10)$
APD	300–1700	~0.7	10–10^8	$O(1)$	10–10^3	1–10^3	400–1400	$O(100)$
PPD	320–900	0.15–0.3	10^5–10^6	~ 1	1–10	$O(10^6)$	30–60	$O(100)$

Review of Particle Physics
Journal of Physics G, Vol 37, No 7A (2010)

PMT = Photomultiplier tube (workhorse, but doesn't work in magnetic fields)
MCP = Multichannel Plate Detector (dense, small diameter charge amplifiers - fast)
HPD = Hybrid Photodiode Detector (vacuum PMT with silicon sensor)
GPM = Gaseous Photon Detector (solid & gaseous photocathode – can cover large areas)
APD = Avalanche Photodiode (also PIN diode)
PPD = Pixellated Photon Detector (SiPM, GPMT, MPPC,…)

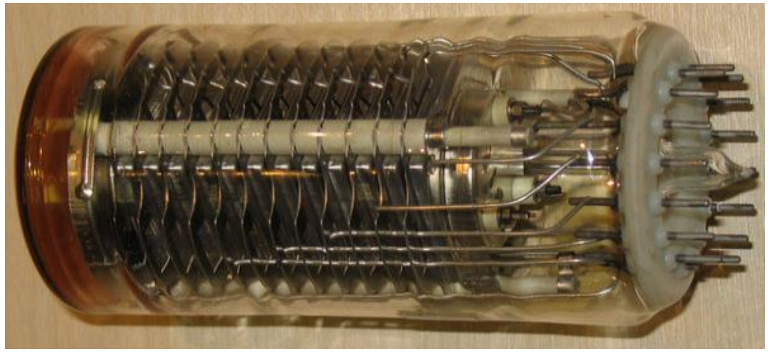
Photomultiplier Tubes

Principle of operation:

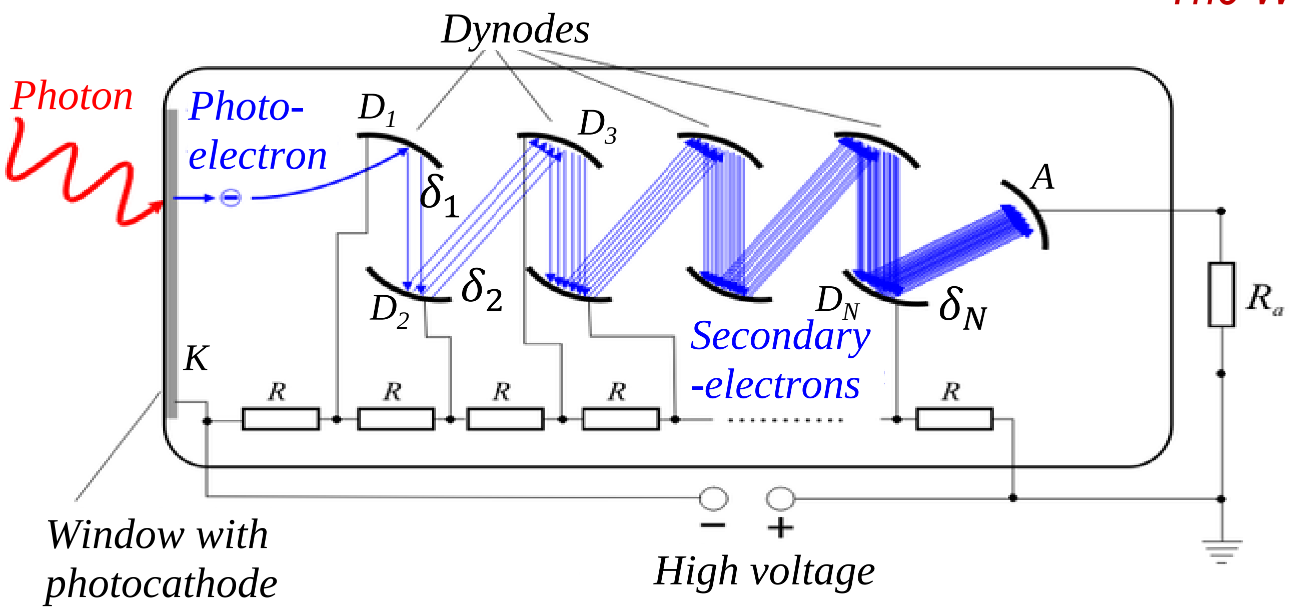
- photo-emission from the photocathode – QE
- collection of photoelectrons by 1st dynode
- Secondary emission (SE) from N dynodes:
  - dynode gain $\delta_i \sim 3 - 50$ (function of incoming electron energy);
  - total gain M:

$$M = \delta_1 \cdot \delta_2 \cdots \delta_N = \prod_{i=1}^{N} \delta_i$$

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

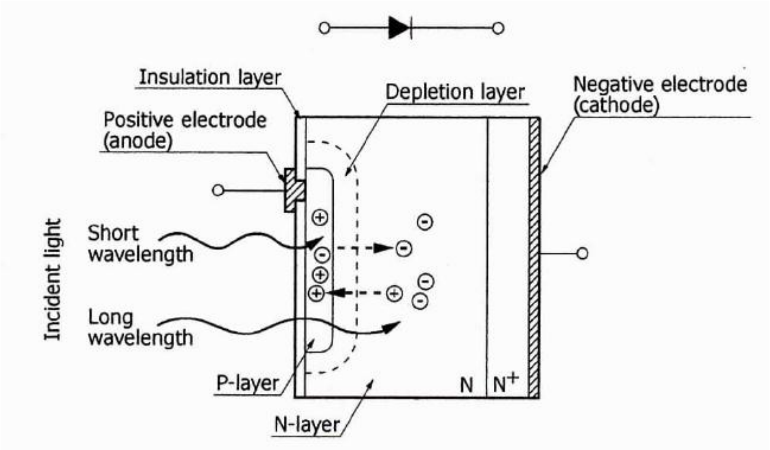


The Workhorse



Silicon Photodetectors

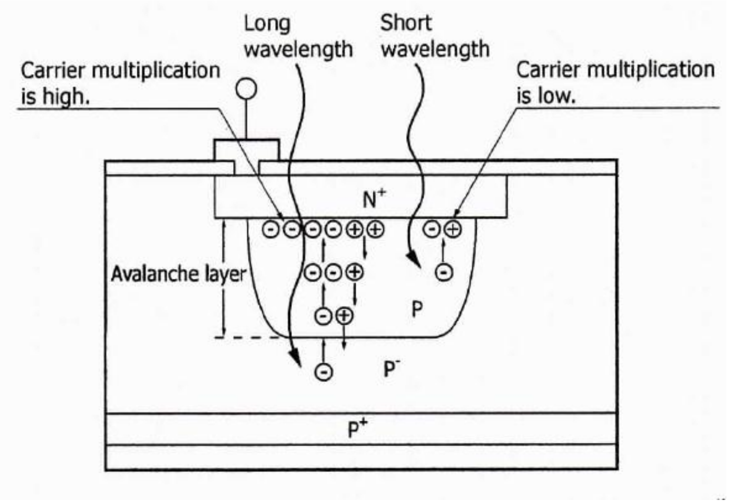
PIN Diodes



Gain = 1

Linear output

Avalanche Photodiodes (APDs)

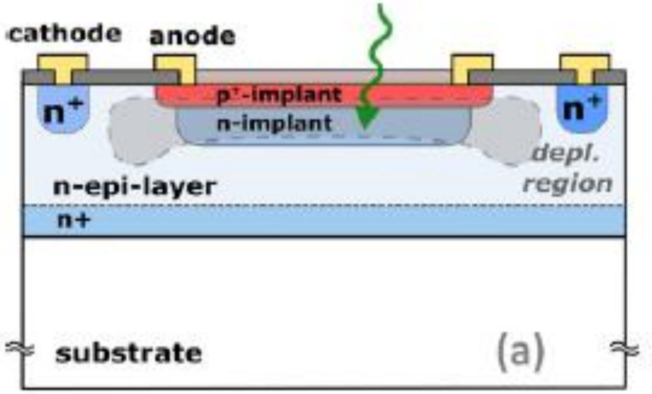


Gain = ~ 50-500

$V_{bias} < V_{breakdown}$

Linear output

Geiger APDs (GAPDs)



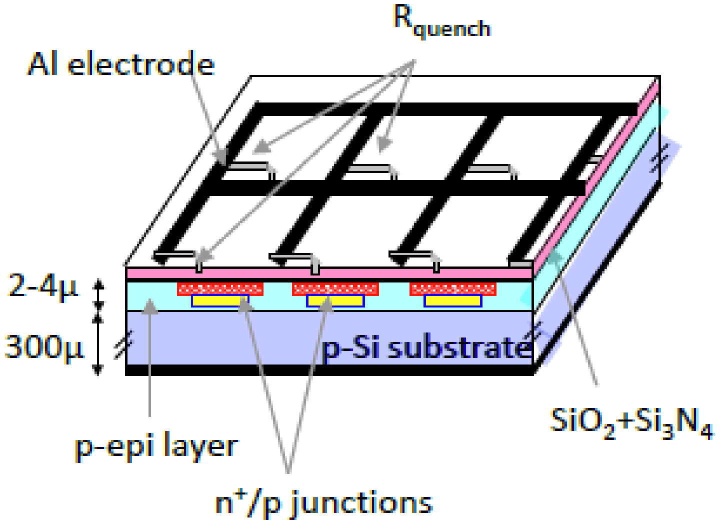
Gain = ~ 50-500

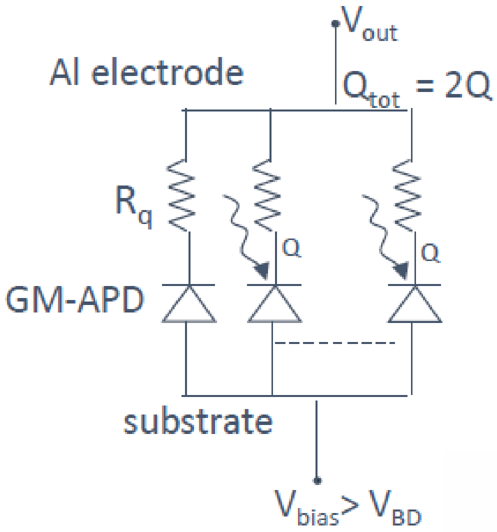
$V_{bias} > V_{breakdown}$

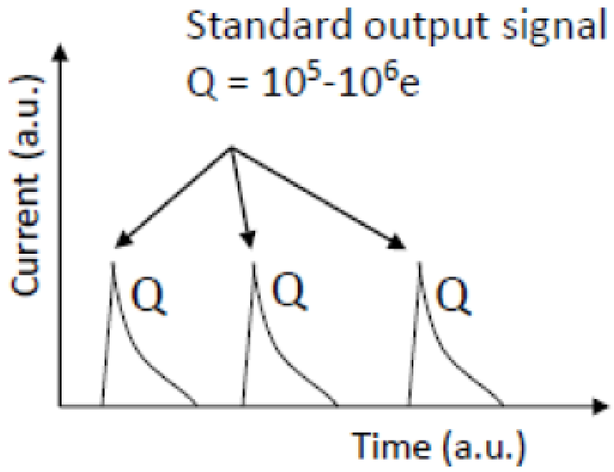
“Quantized” output

Silicon Photomultipliers (SiPMs)

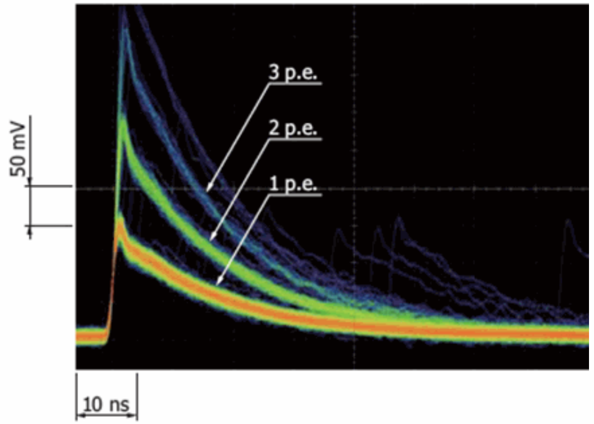
Silicon Photomultipliers are arrays of Single Photon Avalanche Diiodes (SPADs) that are biased slightly above the breakdown voltage such that even a single particle (including a photon) can trigger an avalanche

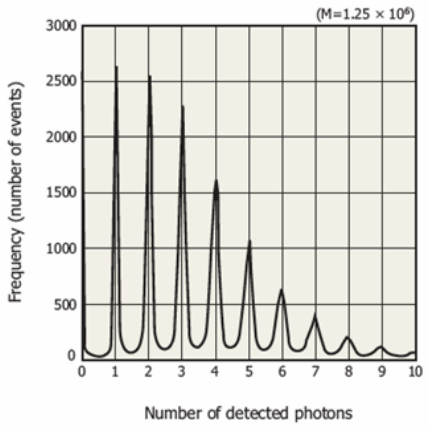






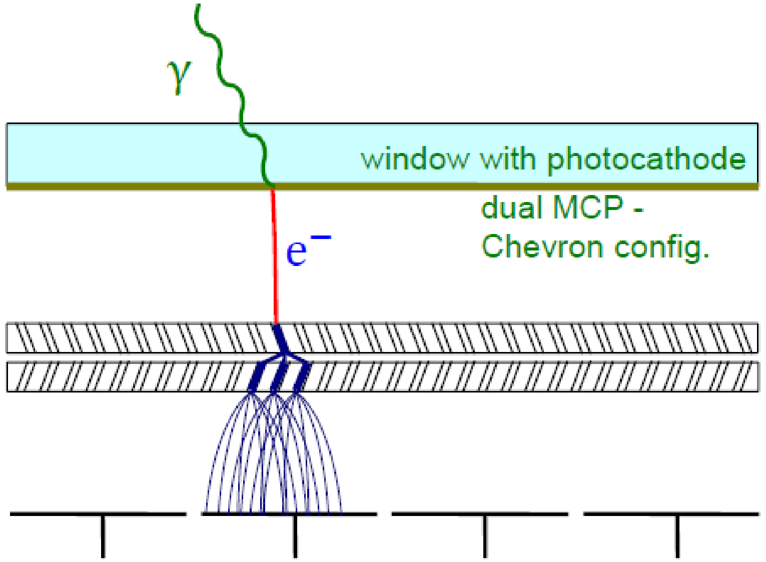
- Provides high gain (similar to PMT)
- Excellent single photon resolution
- Non-linear output at high incident flux (saturation of pixels)
- High noise due to thermal carriers (~ 100 kHz/mm^2)
- Large temperature dependence ($\Delta G/G$ ~ 2%/˚C)
- Insensitive to magnetic fields
- Very susceptible to neutron damage



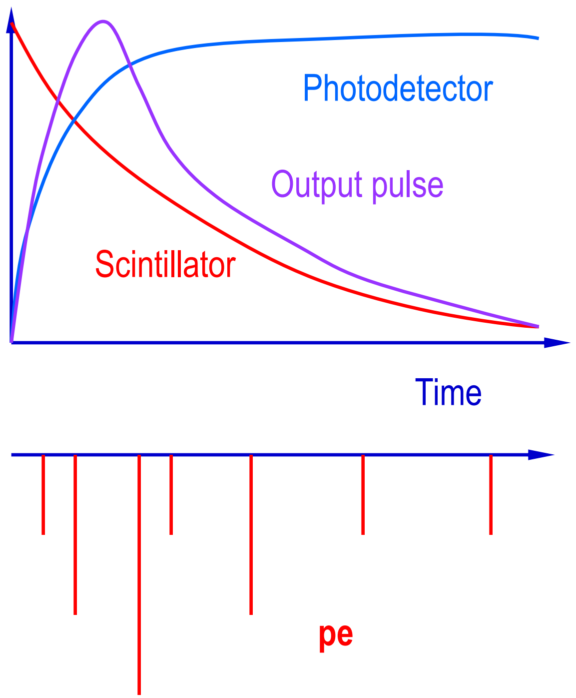


Microchannel Plates (MCP)

A MCP is a thin glass plate with an array of holes forming a continuous dynode structure.
Since the avalanche process is highly contained and the transit time spread is very small, these devices provide very fast timing and excellent time resolution.



Timing Resolution:

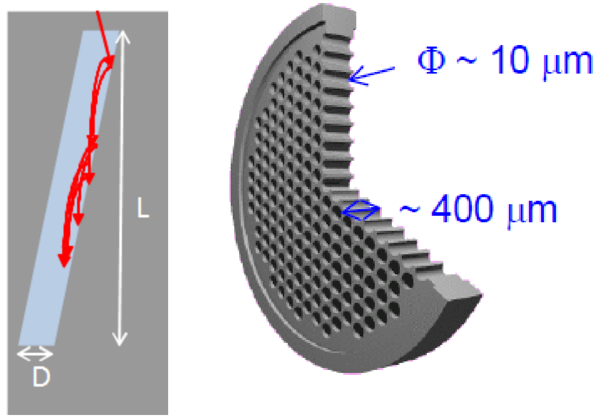


Time resolution determined by:
- Decay time of detector material
- Time response of photodetector
- Light yield of detector material
- Cherenkov materials give fastest time response

Photoelectron arrival time is a statistical process

If light yield is low, individual photoelectron arrival times will be seen

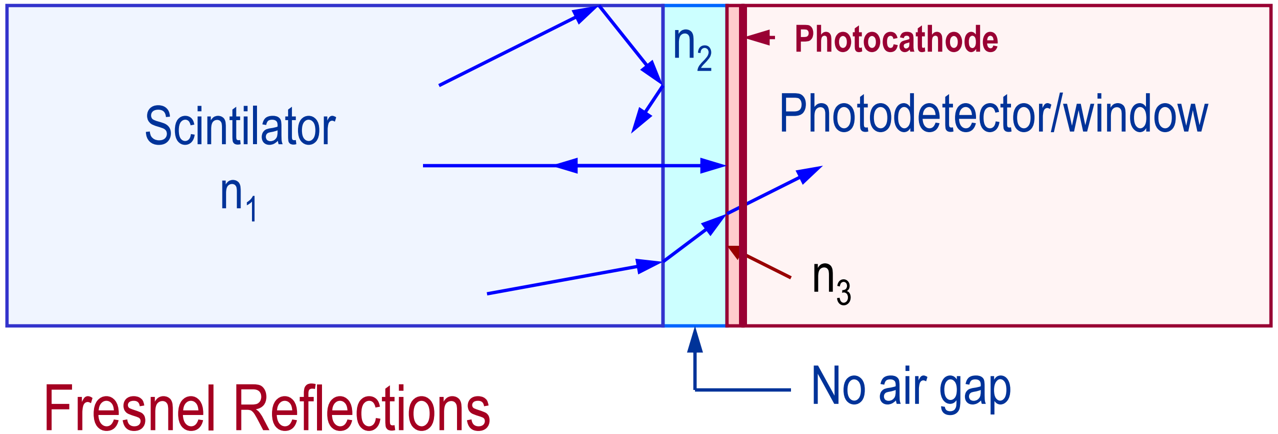
Best timing achieved by detecting first photoelectron



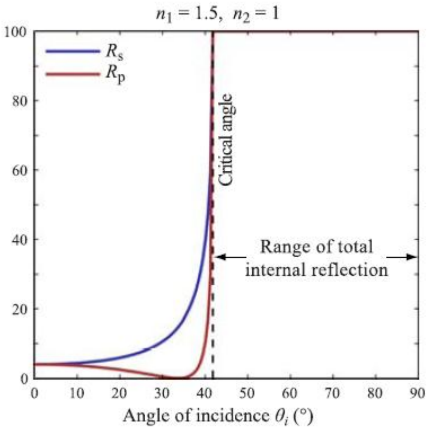
Coupling to Photodetector

Coupling material

Window of photodetector can be limiting in terms of transmission



Fresnel Reflections



Wikipedia

Normal incidence

$$R = \left[\frac{n_2 - n_1}{n_2 + n_1}\right]^2$$

n_1=1.5, n_2=1.0

R ~ 4%

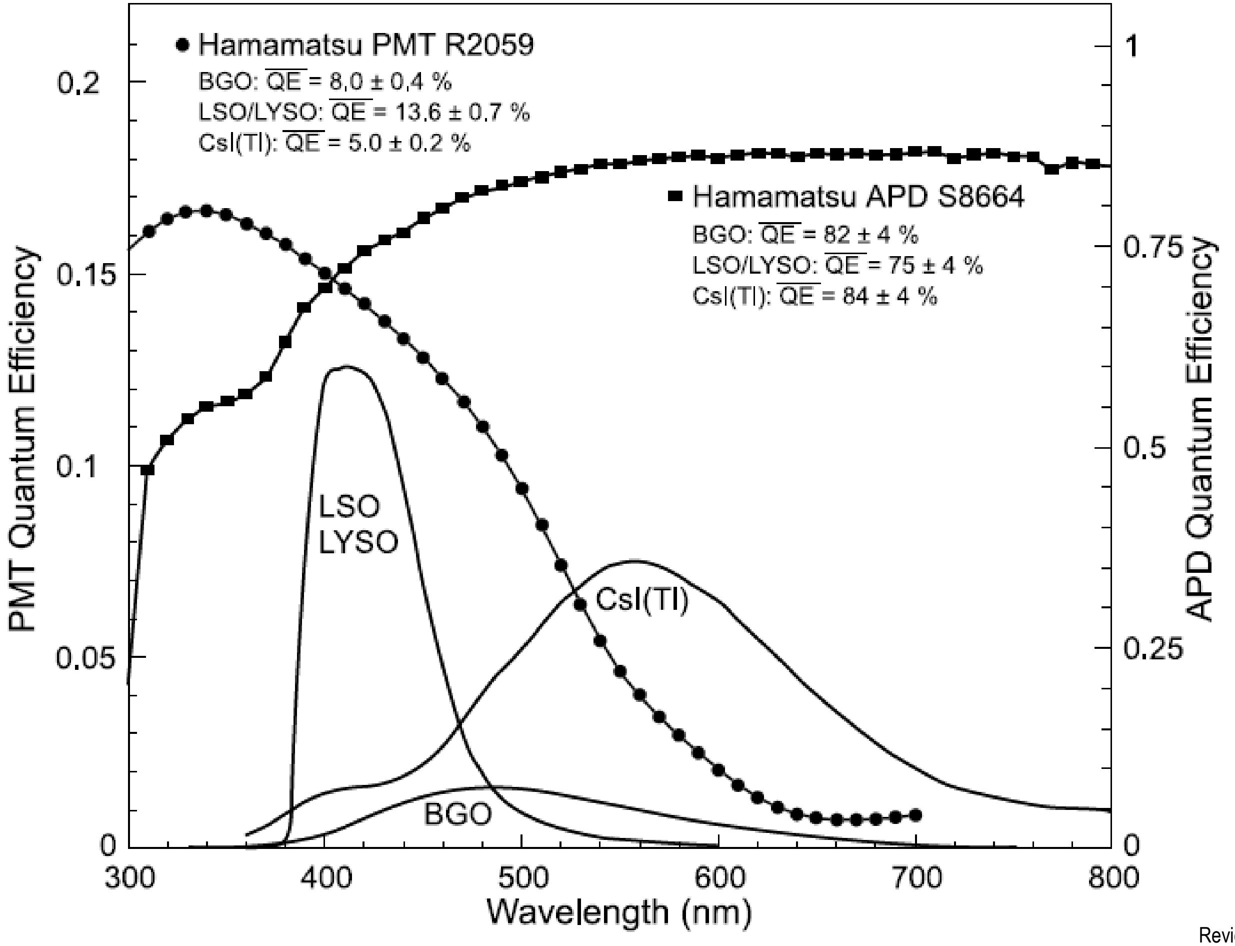
Coupling materials (n~ 1.4):
- Optical grease/glue
- Silicon "cookies"

$\Rightarrow$ n2 ~ n3

However, for heavy crystals n_1>n_2

Matching the Photodetector to the Scintillator

Emission Weighted Quantum Efficiency: $\overline{QE} = \int QE_{PD}(\lambda) \cdot I_{em}(\lambda) d\lambda$



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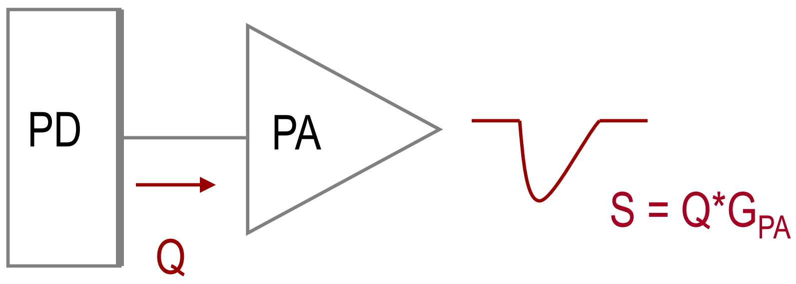
Photoelectrons and Noise



$N_{pe} = N_{\gamma}$*QE $\quad$ Q = N_{pe}*ε_{PD}*G_{PD}

Photoelectrons are the primary signal and can never be recovered at a later stage in signal processing

Figure of Merit : N_{pe}/MeV

Energy Resolution

$$\frac{\sigma(E)}{\langle E \rangle} = \sqrt{\frac{ENF}{N_{pe} \cdot \varepsilon_{PD}} + \left(\frac{ENC}{N_{pe} \cdot \varepsilon_{PD} \cdot G_{PD}}\right)^2}$$

ENF = Excess noise factor from photodetector

ENC = Equivalent Noise Charge in electronic gain stage

Low noise amplification at the early stage of signal processing is crucial for achieving good signal to noise

Excess Noise Factor

Multiplication fluctuations are characterized by the Excess Noise Factor - ENF

- If photons are Poisson distributed so are photoelectrons with average $\overline{n}_{pe} = PDE \cdot \overline{n}_{\gamma}$
- After multiplication with average gain and variance M, σ_M^2 we get average output signal $\overline{n} = M \cdot \overline{n}_{pe}$ and

$$\frac{\sigma_n^2}{\overline{n}^2} = \left(1 + \frac{\sigma_M^2}{M^2}\right) \cdot \frac{\sigma_{pe}^2}{\overline{n}_{pe}^2} = ENF \cdot \frac{1}{\overline{n}_{pe}} = \mathrm{ENF} \cdot \frac{1}{PDE} \cdot \frac{1}{\overline{n}_{\gamma}}$$

- Excess noise factor is

$$ENF = \frac{\sigma_{out}^2/N_{out}^2}{\sigma_{pe}^2/N_{pe}^2} = 1 + \frac{\sigma_M^2}{M^2} = \frac{\langle M^2 \rangle}{\langle M \rangle^2}$$

- Impact on photon counting capability and energy resolution

$$\frac{\sigma_E}{E} = \sqrt{\frac{ENF}{PDE}} \sqrt{\frac{1}{N_{\gamma}}}$$

Sensor	ENF
PMT	1-1.5
APD(Si)	~3 @ gain=50
HPD, HAPD	~1
SiPM	1-1.5
MCP-PMT	1-1.5

Applications of Scintillation Detectors

- Nuclear and Particle Physics
  - Calorimetry
  - Tracking
  - Particle ID (TOF)
- Astrophysics
  - Dark Matter
- Medical Imaging
  - PET
  - SPECT
- Homeland Security
  - Nuclear Non-Proliferation
  - Nuclear Waste Management
- And many more…

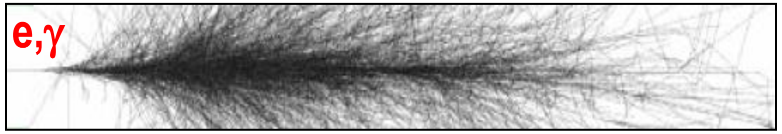
Calorimetry

The purpose of calorimetry in particle physics is to measure the total energy of high energy particles.

Energy comes in two forms: electromagnetic and hadronic

Calorimeters come in two types: sampling and homogenous

Requirements for good energy resolution:
- Detect as much of the total energy as possible (best for homogenous)
- Equalize response for electromagnetic and hadronic energy (e/h→1)
- High light yield (⇒ good photostatistics)
- Good uniformity (both longitudinally and transverse)

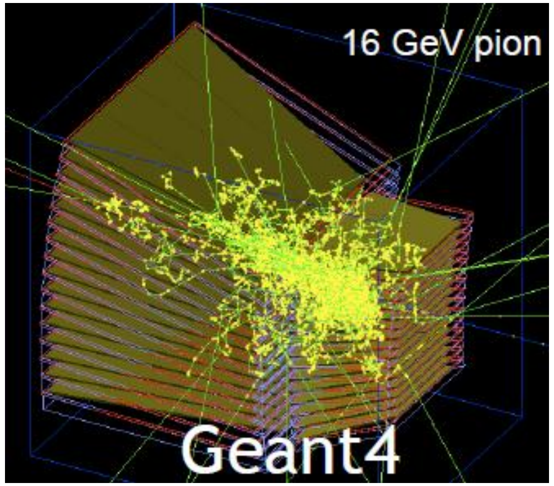


Electromagnetic

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

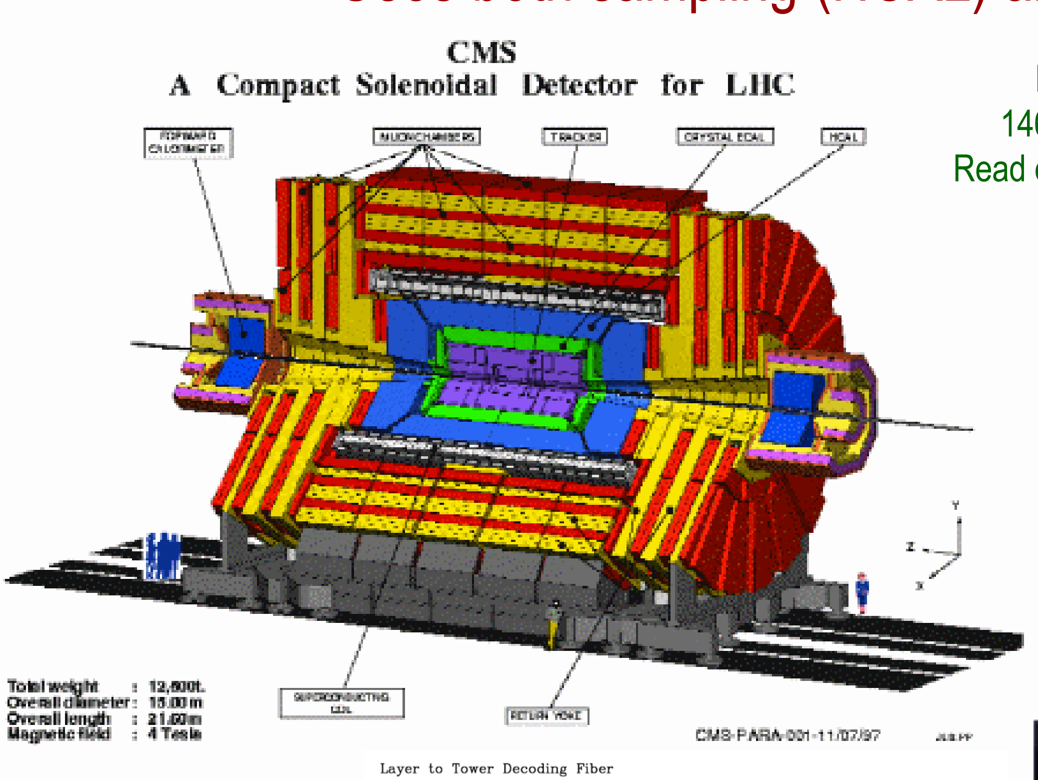
Sampling fluctuations + photostatistics (a), Noise (b), Constant (c)

Hadronic

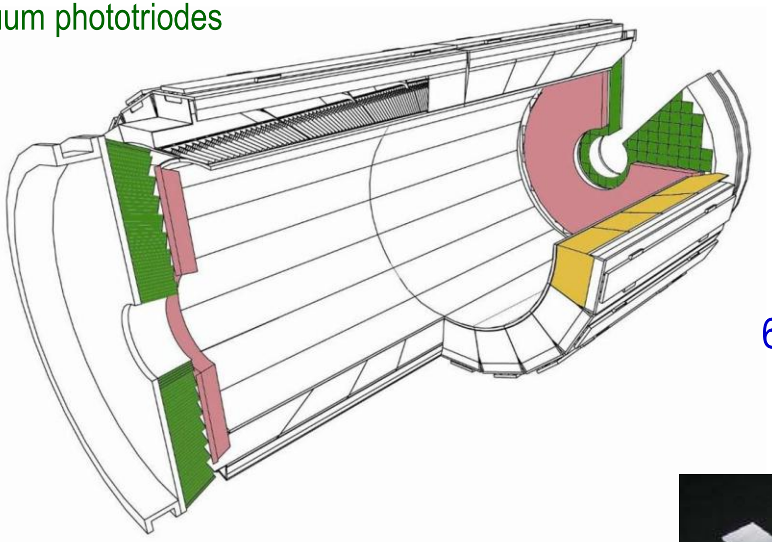


CMS at the CERN LHC

Uses both sampling (HCAL) and homogeneous (EMCAL) calorimeters

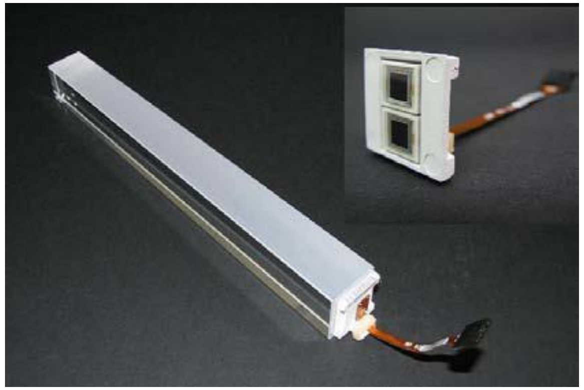


Endcap: $1.48 < \eta < 3.0$
14648 crystals (2x2x22 cm^3)
Read out with vacuum phototriodes



75468 $PbWO_4$ Crystals
X_0 = 0.89 cm
R_M = 2 cm

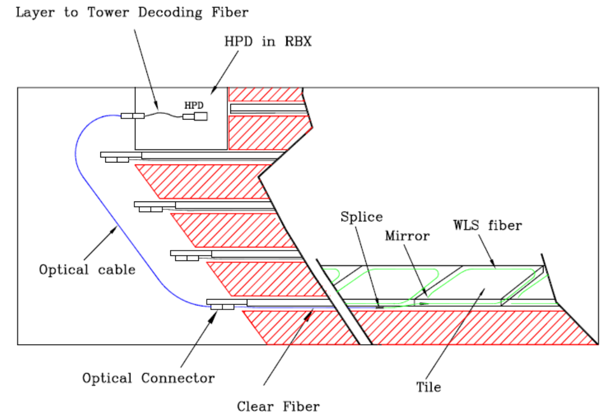
Barrel: $|\eta| < 1.48$
61200 crystals (2x2x23 cm^3)
Read out with APDs

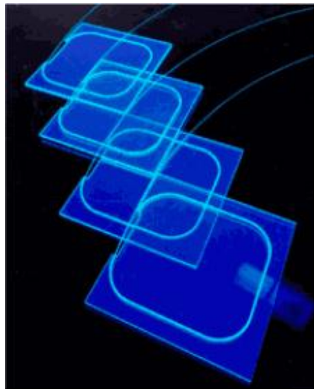


Dual APDs for redundancy
covering ~ 10% of area

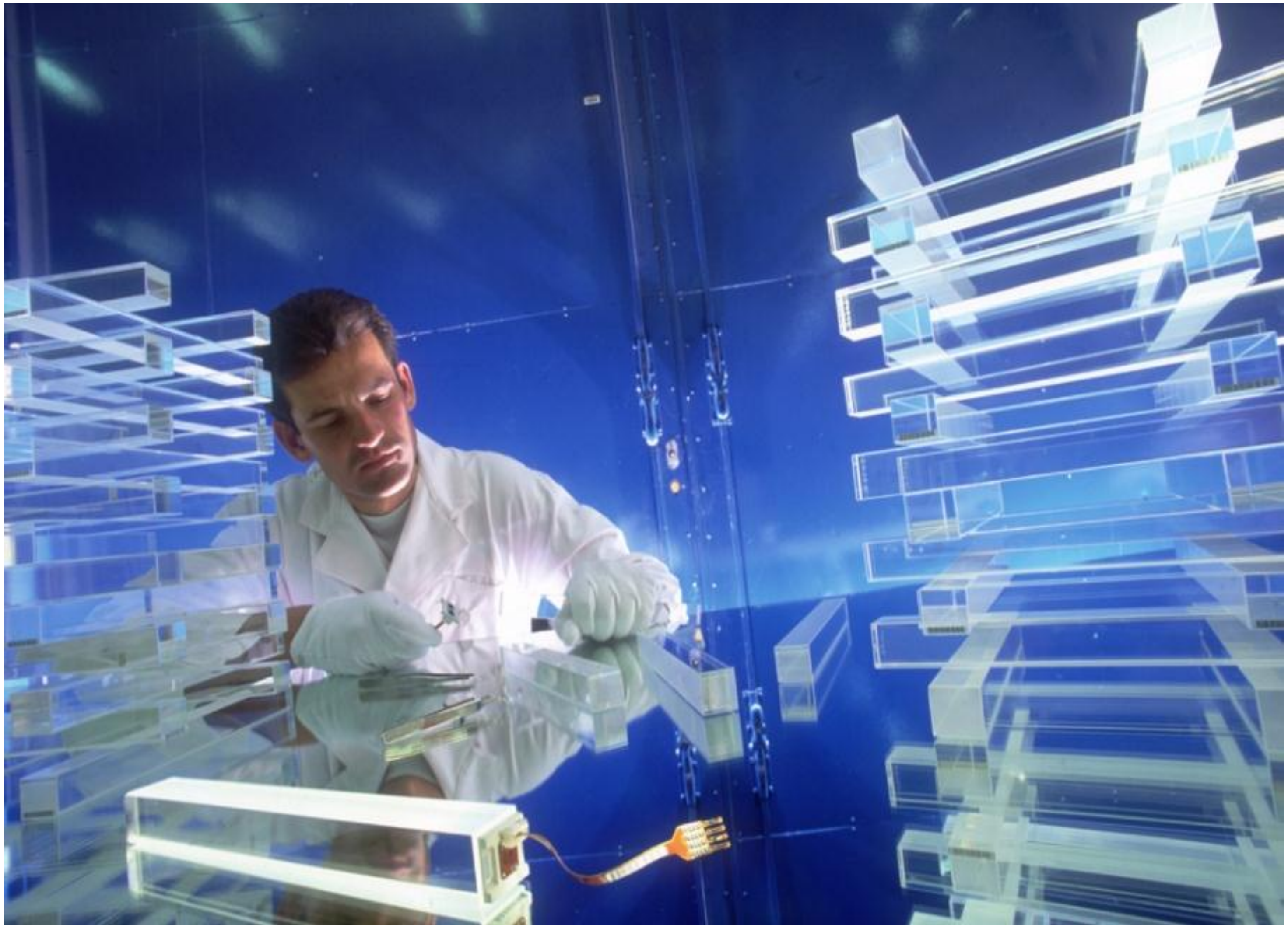
Light Yield ~ 100 γ/MeV
$\Rightarrow$ ~ 4.5 p.e/MeV
Uniformity ~ 0.3%
$|dLY/X_0| < 0.35\%/X_0$

Barrel HCAL
Scintillating Tiles
Read out with
WLS fibers



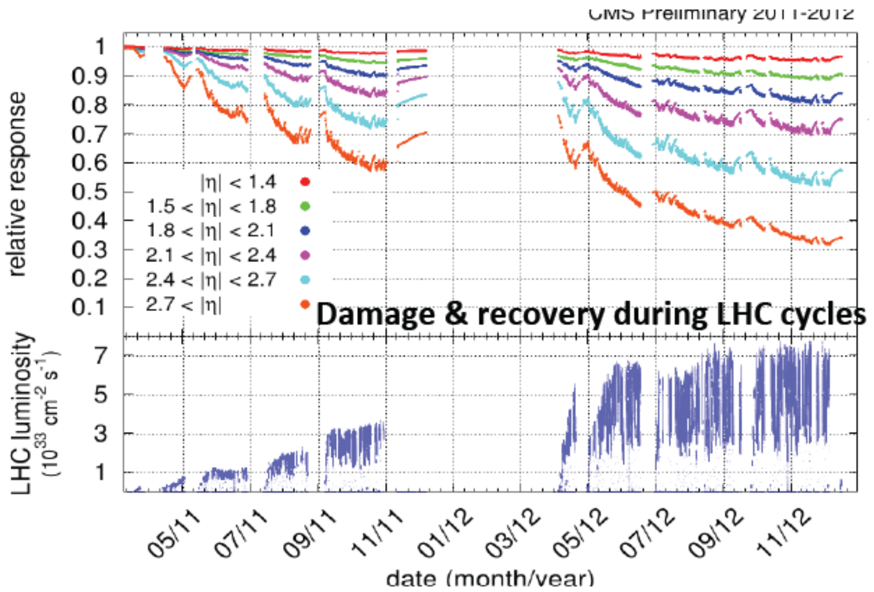


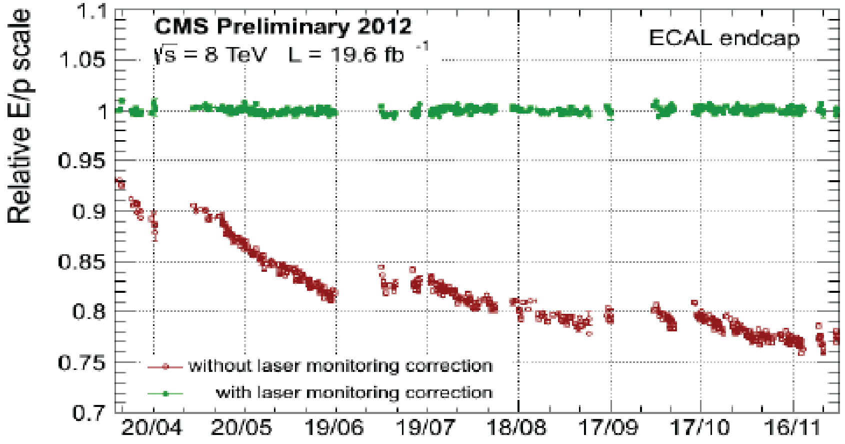
CMS Lead Tungstate Crystals



Crystals produced in Russia and China

Radiation Damage in PWO and Response Monitoring

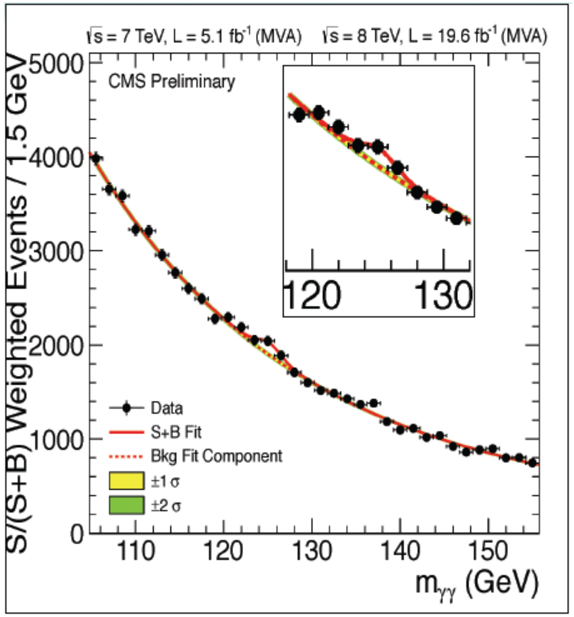




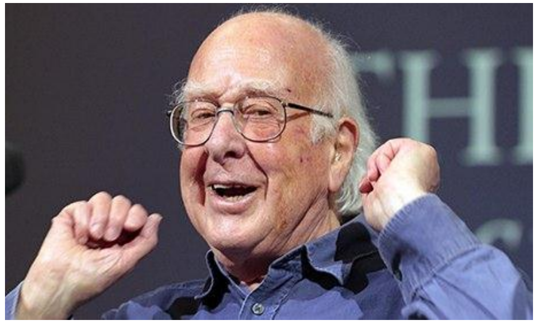
C. Biino, CALOR 2014

2012

Hard Work



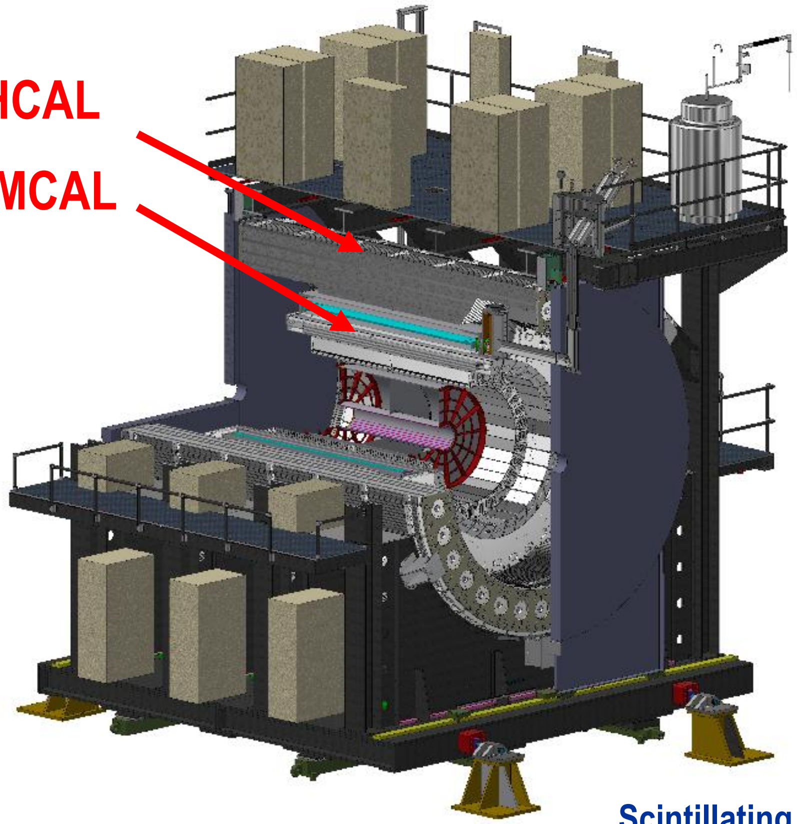
Reward **2013**

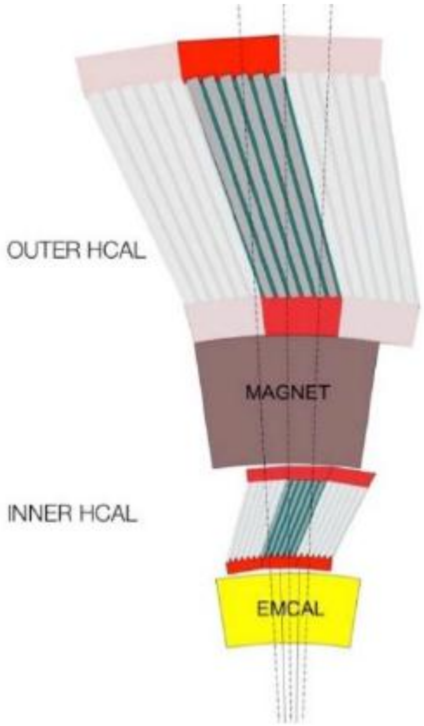


The sPHENIX Calorimeters

HCAL

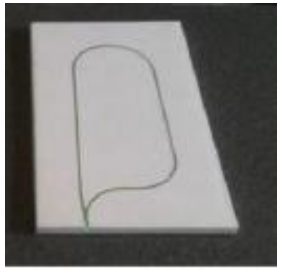
EMCAL

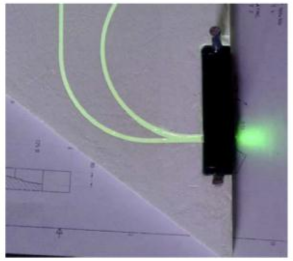




HCAL

Scintillating Tiles Read Out with WLS Fibers

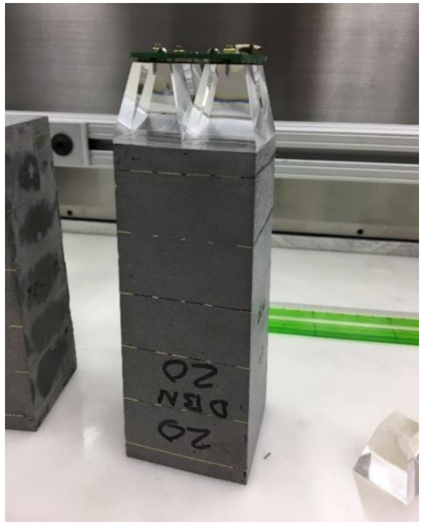




Fibers Ends Read Out With SiPMs

Steel Absorber Plates

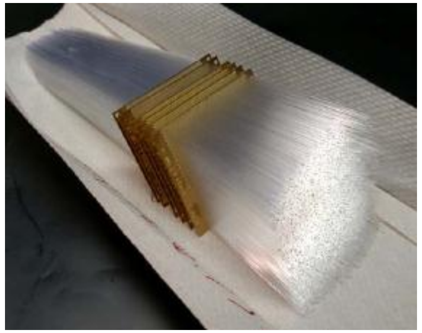
4 Towers Read Out With SiPMs



EMCAL (SPACAL)

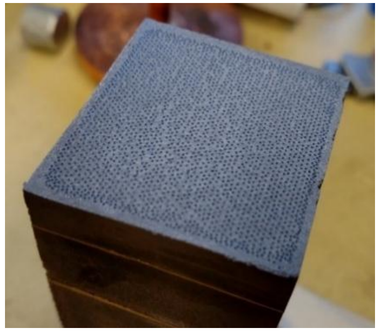
Absorber:
Tungsten Powder/Scintillating Fiber/Epoxy Matrix

Scintillating Fibers



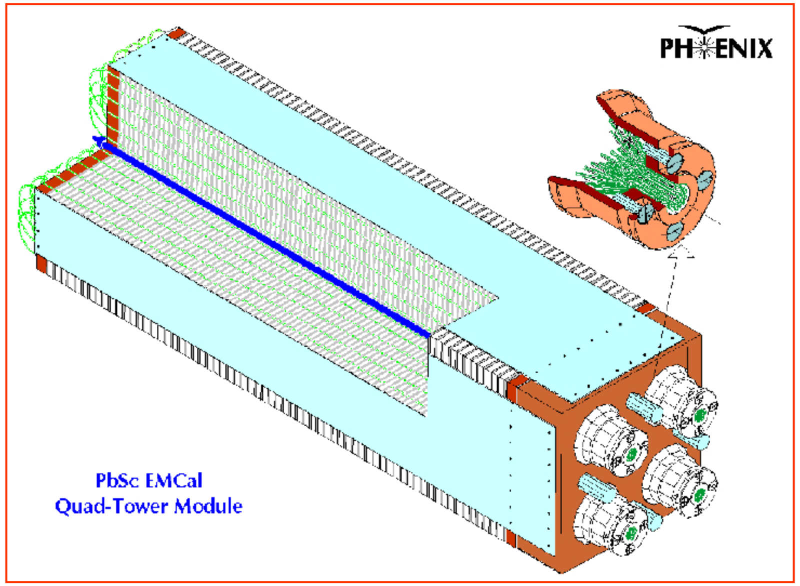
W/SciFi Absorber Block

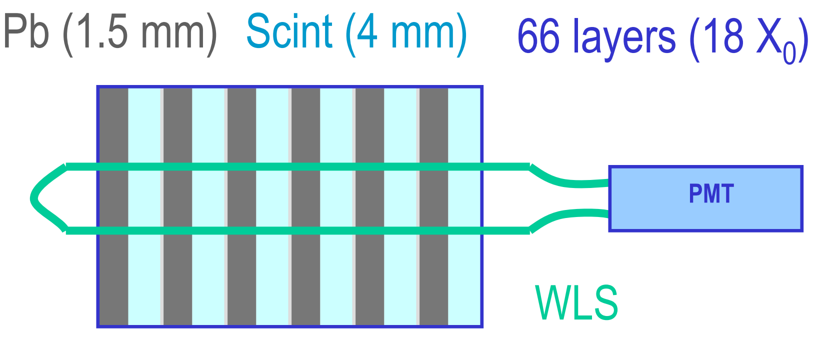
Readout end of Absorber Block



Shashlik (Shish-Kebab) Calorimeters

Alternating stack of lead and scintillator plates
Wavelength shifting fibers pass longitudinally through the stack
Fibers are bundled in the back and read out with PMTs



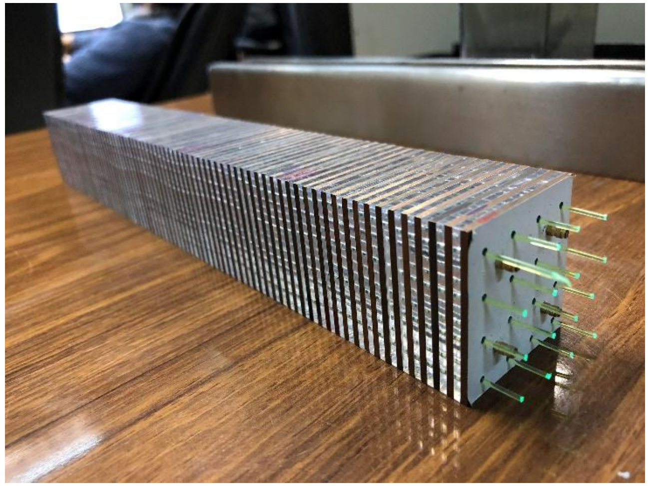


Light Yield ~ 1.5 p.e./MeV

$$\frac{\sigma_E}{E} = \frac{8.1\%}{\sqrt{E}} \oplus 2.1\% \qquad \sigma_t \sim 200\,ps$$

L.Aphecetche et.al., Nucl. Inst Meth. A499 (2003) 521-526

EIC Calorimeter R&D
W/Cu Plate Shashlik



Read out individual WLS fibers with SiPMs

Search for Dark Matter

Possible Candidate: Weakly Interacting Massive Particles (WIMPs)
interact only through weak interaction (like neutrinos)

WIMP interacts with nucleus, producing nuclear recoil
- Large direct scintillation signal (S1) in LXe, small ionization charge

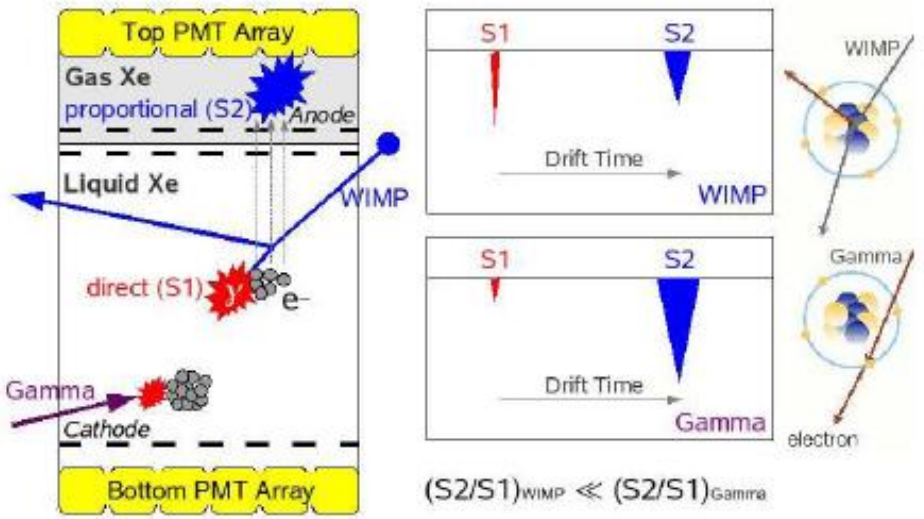
Gammas (background) interact with electrons
- Small direct scintillation signal, large ionization charge

Prompt signal (S1) produced in LXe

Delayed signal (S2) produced in gaseous Xe

Ionization charge drifts to gas phase Xe where it is extracted with a large electric field and amplified in proportional mode giving second delayed scintillation signal (S2)

Dual Phase TPC



Discriminate WIMPs from gammas by measuring ratio S2/S1

E. Aprile, Rev. Mod. Phys, Vol 82 (2010)

XENON 1T Dark Matter Experiment
Underground Experiment at Grand Sasso

XENON 1T Cryostat and Assembly Hall

TPC

PMT Array

Scintillation Detectors for PET
(Positron Emission Tomography)

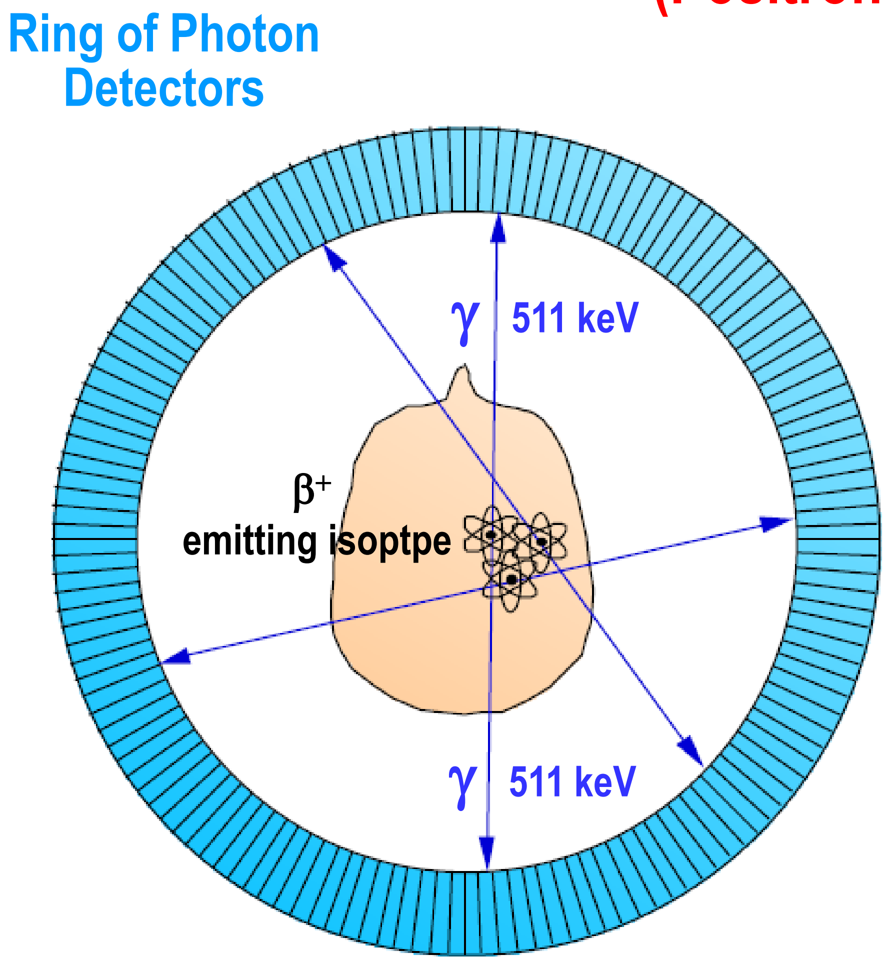
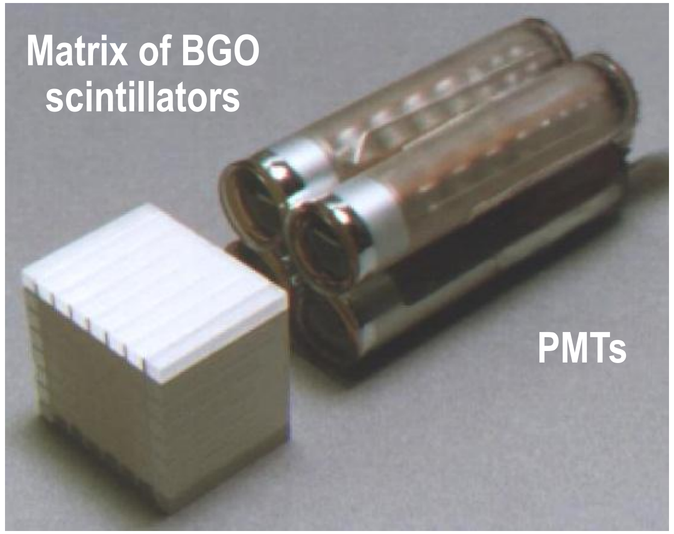


Figure courtesy of W.Moses

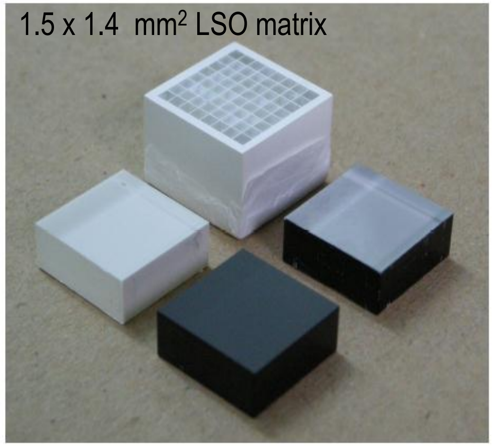
511 keV photons require high stopping power

⇒ Crystals such as BGO, LSO, LYSO
($\rho \sim 7$ g/cm^3, $\mu^{-1} \sim 1.2$ cm)

Light output: BGO ~ 8400 γ/MeV
LSO ~ 30,000 γ/MeV



Light sharing (Anger Logic) PMT readout



Highly pixellated SiPM readout

Time of Flight PET

10 ps Challenge

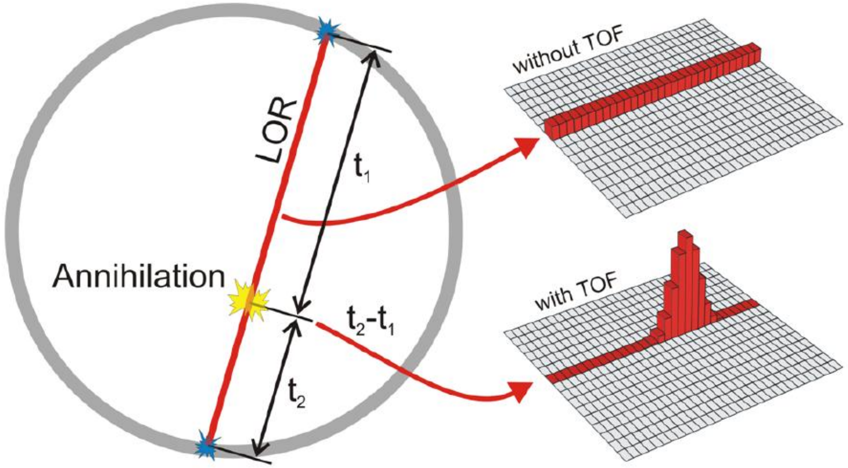
Achieving a Coincidence Time Resolution (CTR) < 10 ps

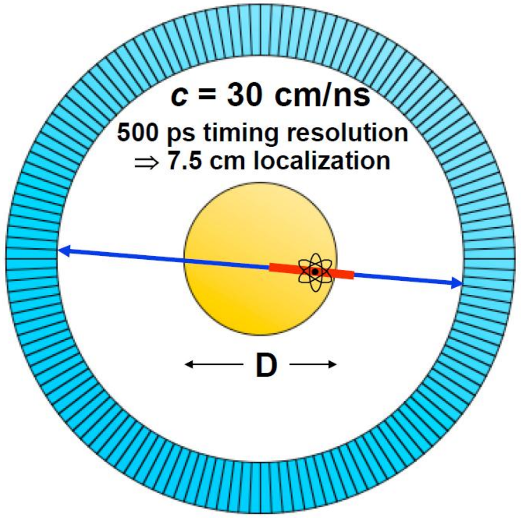
- Improve image quality
- Reduce patient exposure
- Reduce scan time
- Enable easier whole body imaging

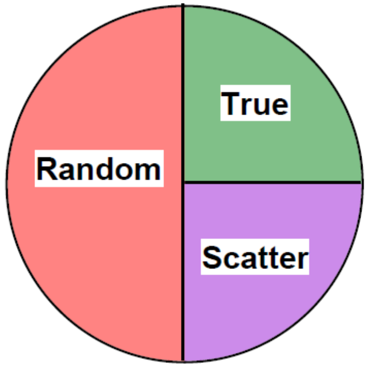
Large randoms background in PET

Use timing information to localize decay point along line

Requires fast, bright crystal such as $LaBr_3$

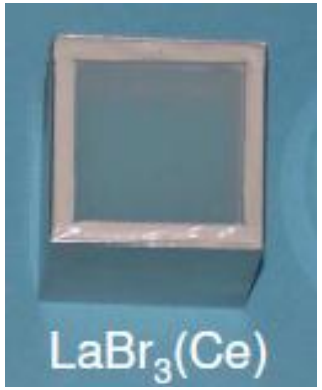






3D PET

Reduces noise in image
Variance reduction ~ $2D/c\Delta t$
Δt 500 ps ⇒ x5 reduction in variance



σ_t < 100 ps
σ_E < 4% @ 511 keV

Also requires high speed CFD and TDC
⇒ ASICs

Figures courtesy of W.Moses

PET/TOF/MR Scanners

GE SIGNA PET/MR Scanner

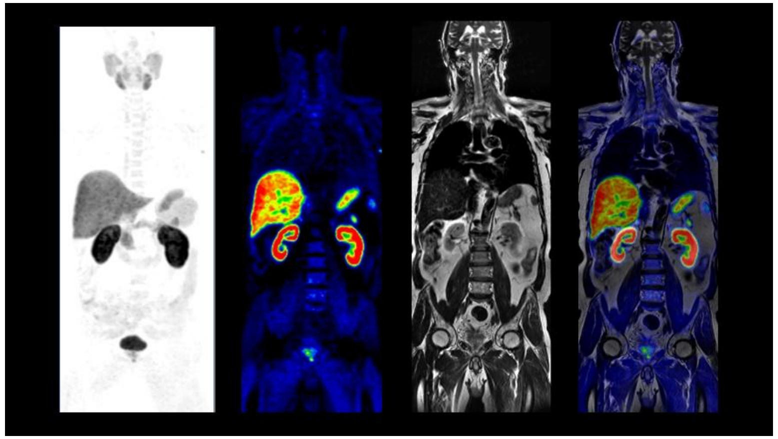
MRI

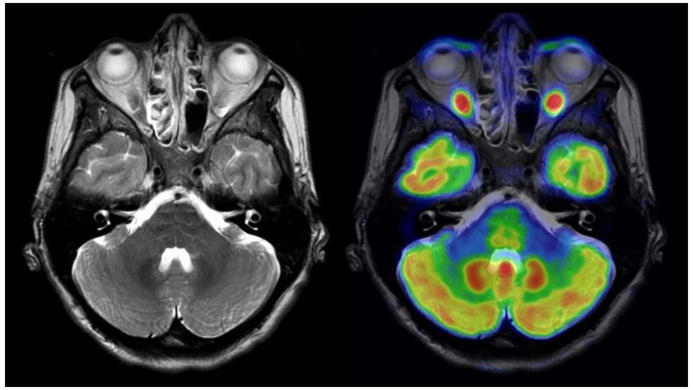
- 3T Magnet
- 50 cm radial MRI FOV

PET

- SiPM readout
- 25 mm LBS(~ LSO) crystals
- < 400ps timing resolution
- 25cm axial FOV
- 21cps/kBq for count rate capability

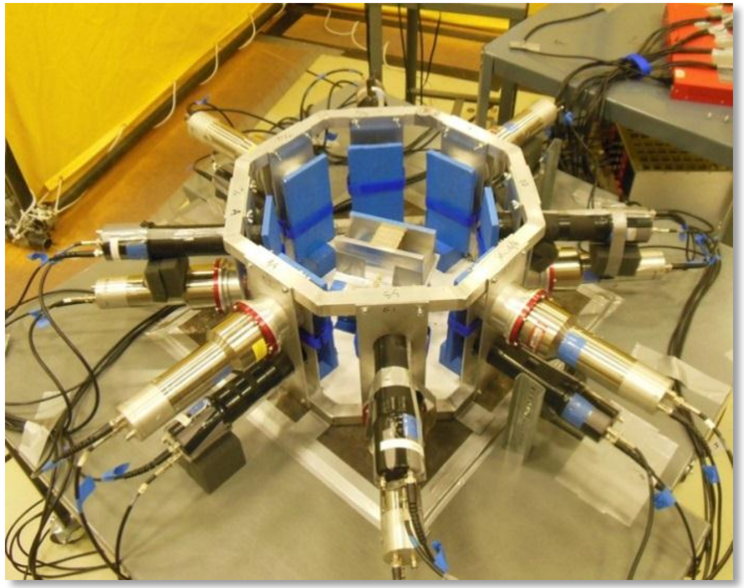
PET Detector Module





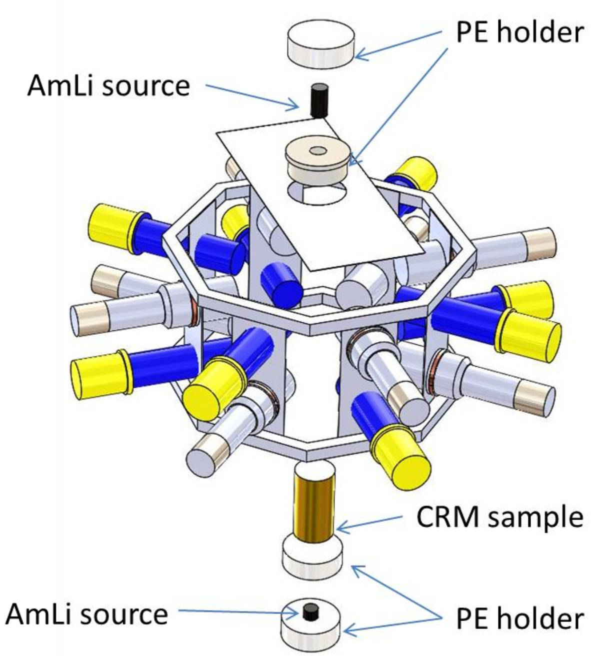
Nuclear Waste Management & Non-Proliferation

Passive Assay Systems



Assay of nuclear fuel measuring n-γ spectra using liquid and crystal organic scintillators

Active Assay Systems



Measure n-γ spectra using neutron activation

Detection of Nuclear Materials

Summary

- Scintillation detectors are widely used in many areas of particle physics, medical imaging, homeland security and many other applications.
- There exists a wide variety of scintillating materials to choose from ranging from inexpensive plastic scintillators for charged particle detection to high density crystals for detecting high energy electrons and gammas.
- There are also a wide variety of photodetectors that can be used in conjunction with many types of scintillators ranging from conventional photomultiplier tubes to many modern solid state detectors.
- A good overall detector design requires looking at all factors affecting performance (choosing the right photodetector, good light collection and matching, and low noise electronics)

References

- Radiation Detection and Measurement, Glenn F. Knoll
- Inorganic Scintillators for Detector Systems, P. Lecoq, A. Gektin, M. Korzhik
- Calorimetry Energy Measurements in Particle Physics, R. Wigmans

Acknowledgements

- Paul Lecoq (CERN)
- Bill Moses (LBNL, Retired)
- Samo Kopar (Josef Stefan Institute Ljubljana and University of Maribor)
- Stefan Gundacker (CERN)
- Ren Yuan Zhu (Caltech)
- Sara Pozzi (University of Michigan) and John Valentine (LBNL)

Backup Slides

Photon Interactions in Matter

Photoelectric

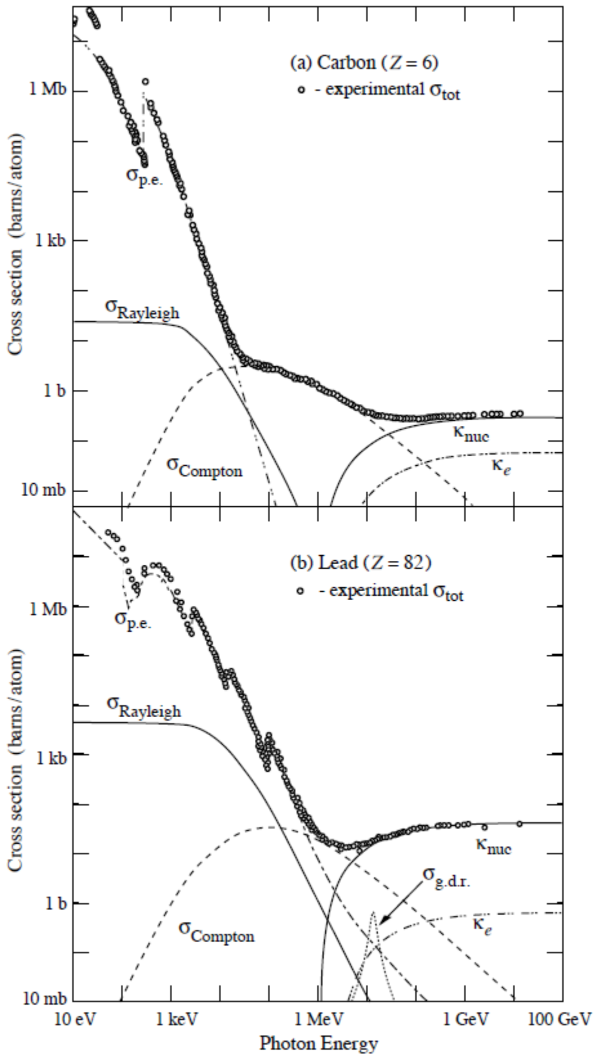
$$\sigma_{ph} \propto \frac{Z^5}{E_\gamma^{7/2}}$$

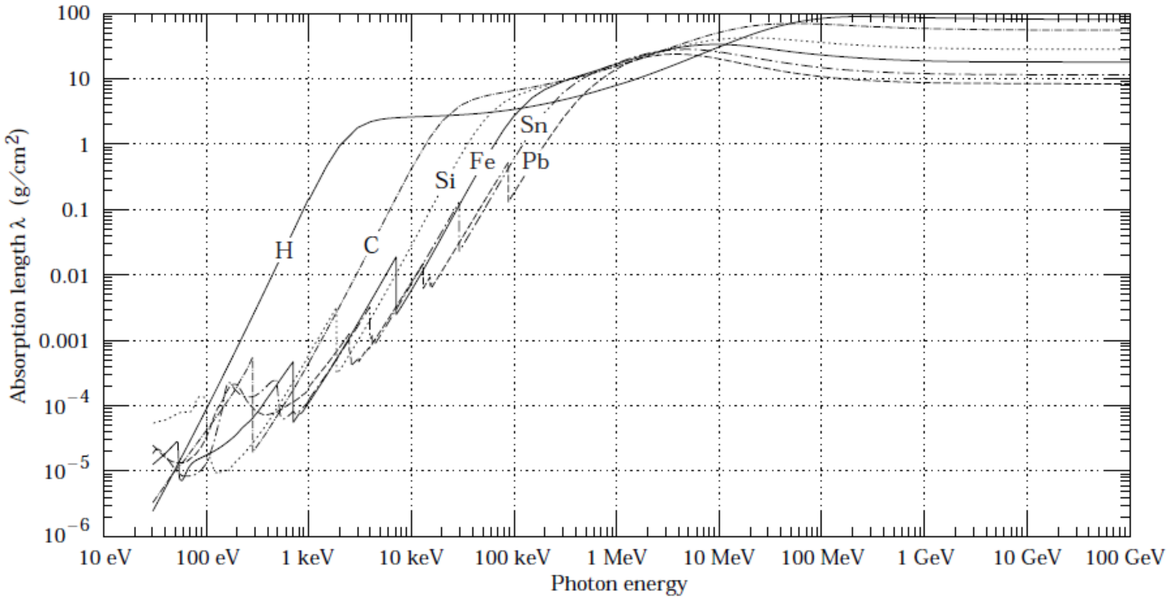
Compton

$$\sigma_c \propto Z$$

Pair Production

$$\sigma_{pair} \propto Z^2 \ln(2E_\gamma)$$

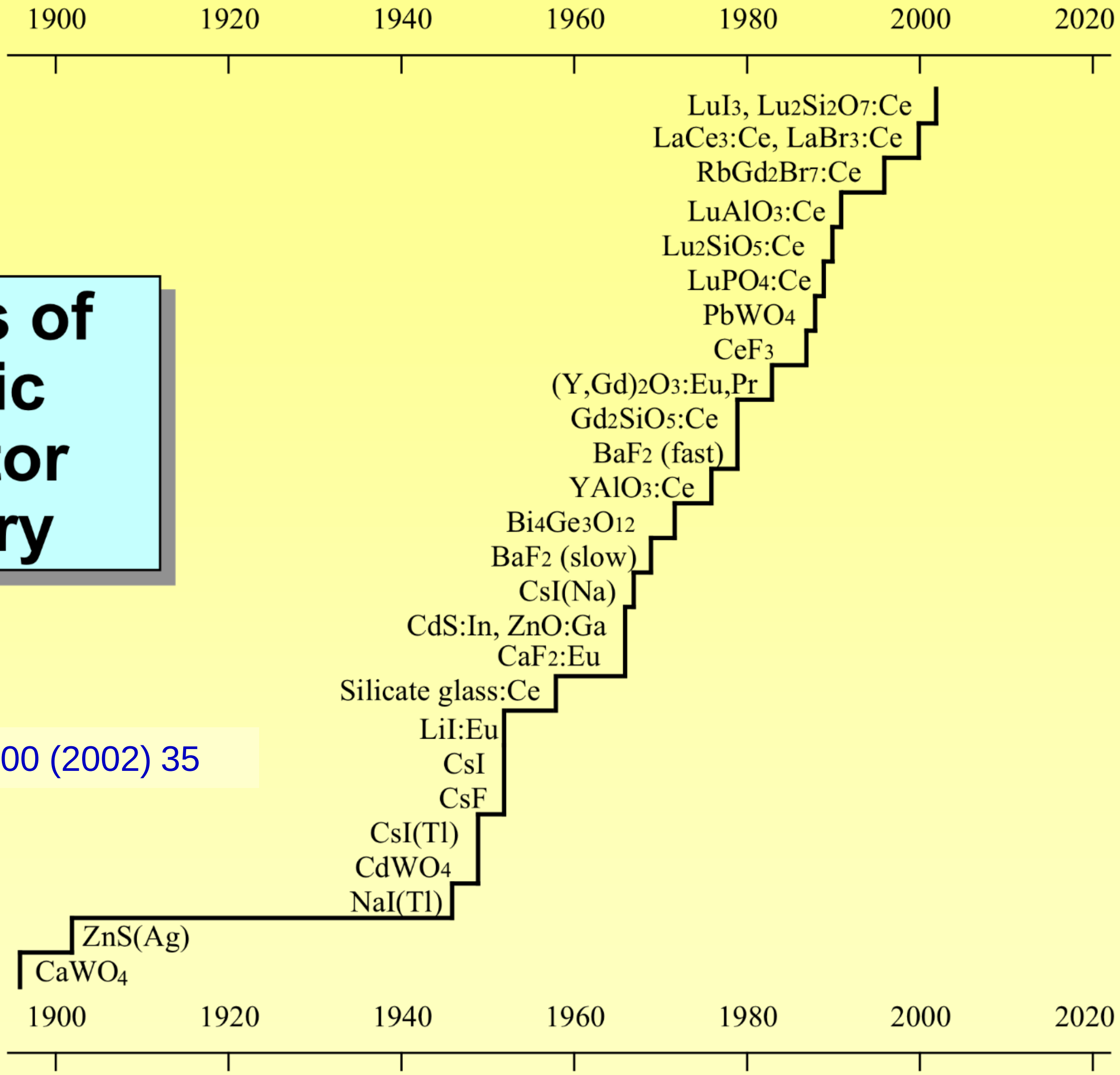




Inverse Attenuation Length $\mu = \rho/\lambda$ (cm^{-1}) $I(x) = I_0 e^{-\mu x}$		
E	Si	Pb
10 keV	93.2	1419
1 MeV	0.15	0.67
1 GeV	.08	1.34

History of Crystal Scintillators

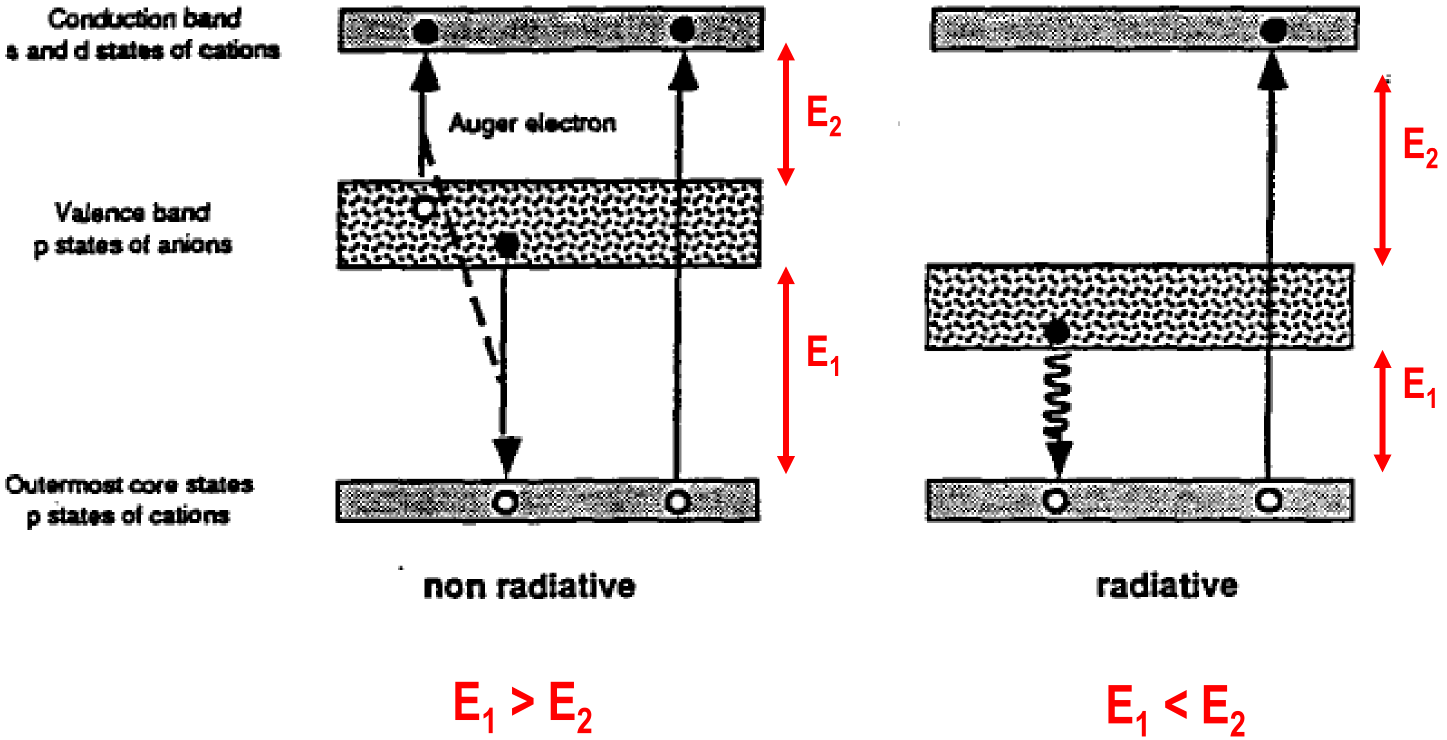
105 Years of Inorganic Scintillator Discovery

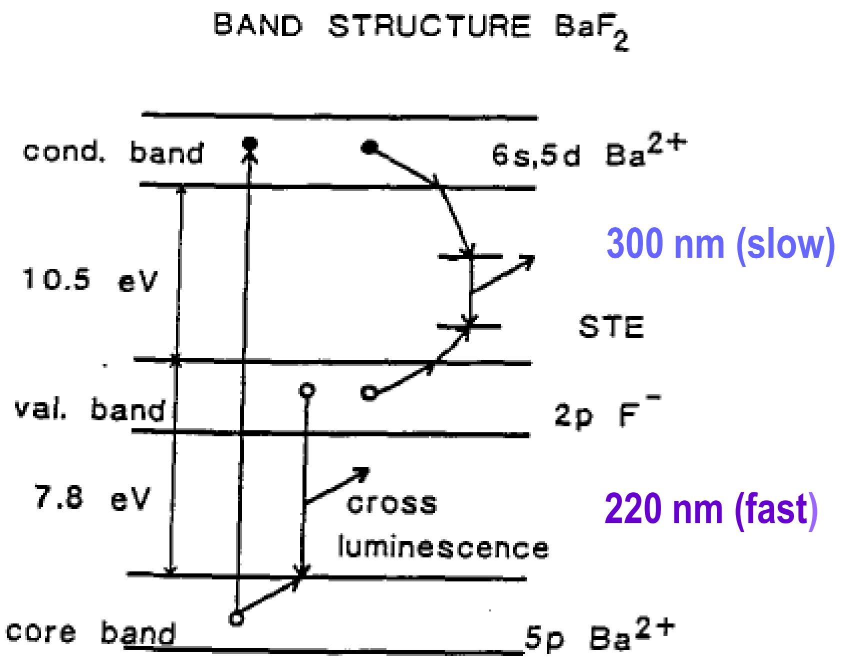


M. J. Weber J. Lumin. 100 (2002) 35

Cross Luminescence

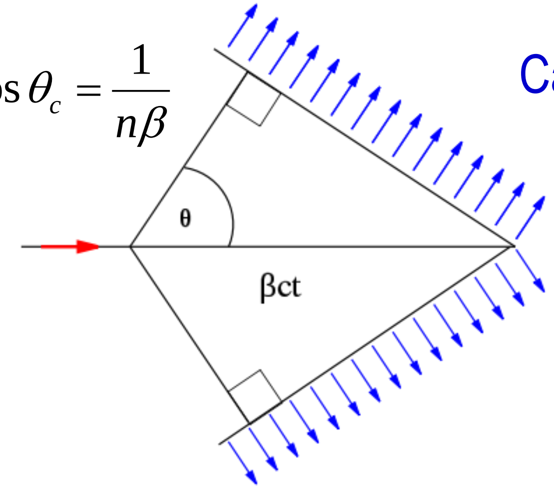
Example : BaF_2 Fast and Slow Components





Cherenkov Radiators

$$\cos\theta_c = \frac{1}{n\beta}$$



Can be used as threshold detectors or Ring Imaging Detectors

Sensitive to most relativistic particles, so for calorimetry, measures electromagnetic component of shower

	Air	Aerogel	Water	Quartz	PbGl	PbF2
Density (g/cm^3)	1.2x10^{-3}	0.2-0.4	1.00	2.2	6.3	7.77
Index of refraction	1.0003	1.01-1.10	1.33	1.46	1.8	1.78
Radiation Length (cm)	3.1x10^4	68-136	36	12.3	1.26	0.93
N_{pe}/cm for N_0=100	0.06	9	43	53	69	68

$$\frac{dN}{d\lambda} = 2\pi\alpha\sin^2\theta_c\frac{1}{\lambda^2} \Rightarrow$$ Spectrum peaks in the deep (V)UV

$$N_{pe} = L\frac{2\pi\alpha}{hc}\int\varepsilon(E)\sin^2\theta_c(E)dE \qquad \varepsilon = \varepsilon_{col}\cdot\varepsilon_{det}$$

n=n(E) for a dispersive medium

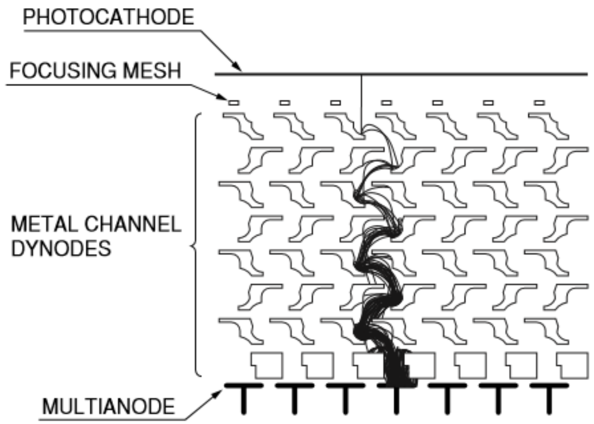
Figure of Merit : $N_0 = 370\,cm^{-1}eV^{-1}\int\varepsilon(E)dE$

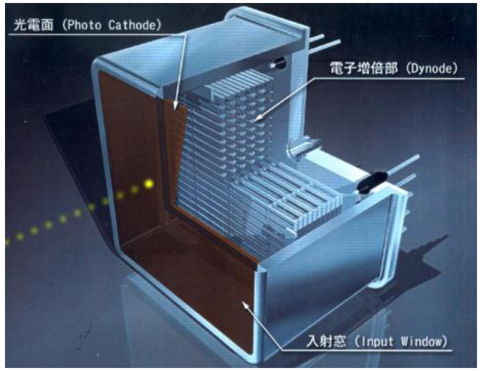
$$N_{pe} = LN_0\langle\sin^2\theta_c\rangle$$

Multianode PMTs

Metal channel dynode (Hamamatsu):

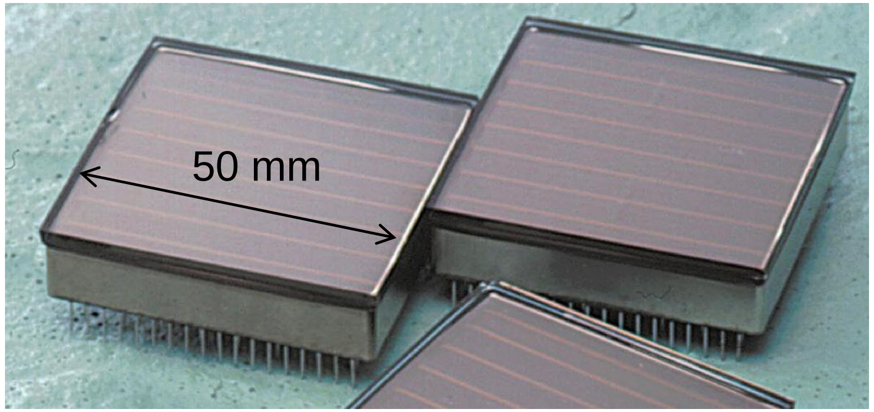
- multiplication is confined in a narrow channel
  → multi-anode designs
  → some tolerance to modest magnetic field
- ~ 30 mm x 30 mm
- gain up to 10^7, excellent single photon detection
- gain uniformity typ. 1 : 2.5;
- cross-talk typ. < 2% (for 2x2 mm^2 pads)
- low DCR, few counts/cm^2/s





Flat-panel (Hamamatsu H8500):

- 8 x 8 channels (5.8 x 5.8 mm^2 each)
- ~ 50 mm x 50 mm
- Excellent active area coverage (89%)



Radiation Damage in SiPMs

Displacement damage

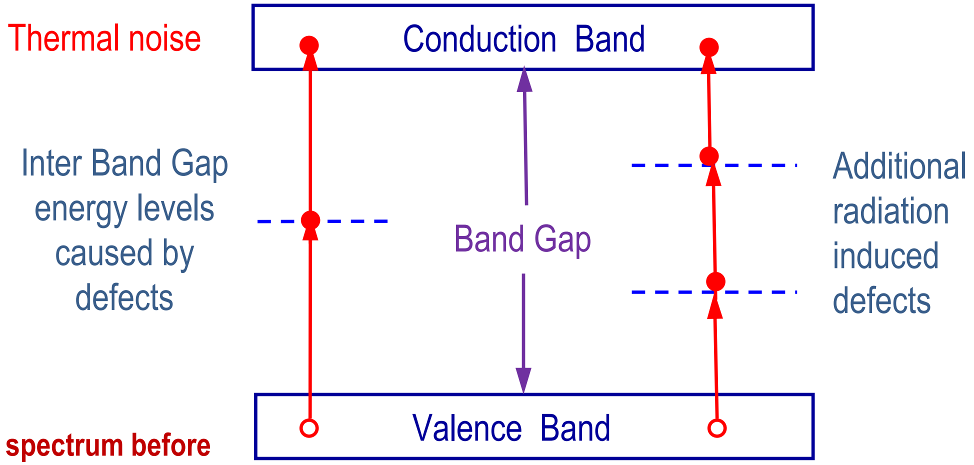
- Caused by neutrons or charged particles with energies ~ 1 MeV or higher interacting in silicon
- Knocks out a Si atom from the lattice leaving behind a vacancy and an interstitial atom, causing a defect
- Defects create energy levels in the band gap, allowing easier thermal excitation of valence band electrons to the conduction band

⇒ Higher thermal noise and increased dark current

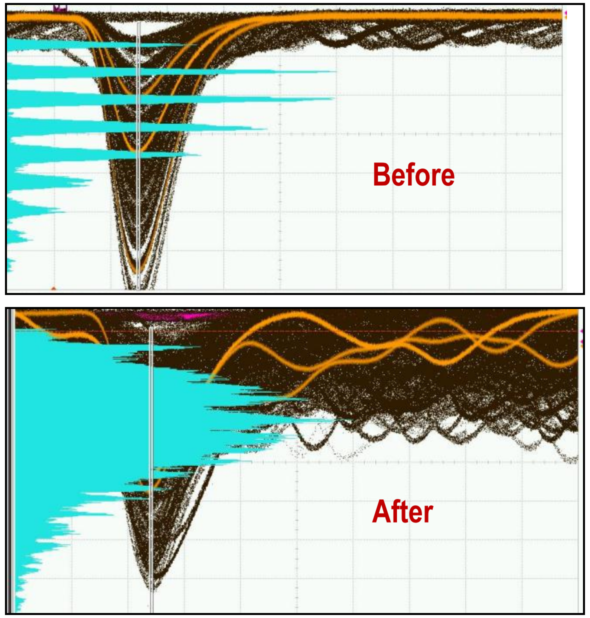
- Noisy pixels can lead to loss in PDE

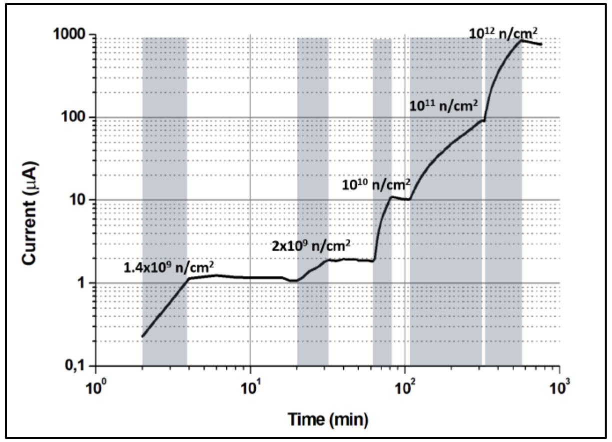
Ionization Damage

- Caused by gammas or charged particles
- Can cause charge buildup in insulating materials (e.g., SiO_2) which can distort the electric field in the device
- Can also cause optical damage in the window leading to transmission loss



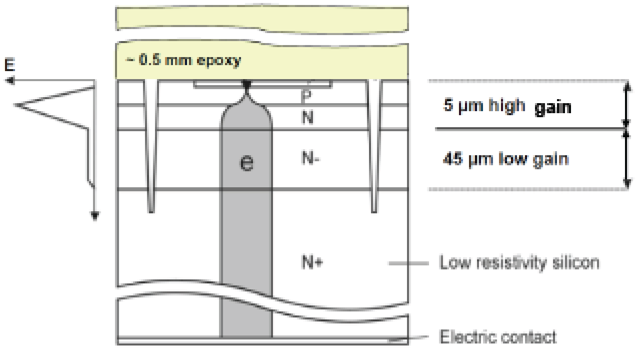
Single photoelectron spectrum before and after exposure to neutrons





Increase in dark current after exposure to neutrons

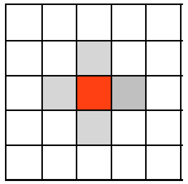
Nuclear Counter Effect in APDs



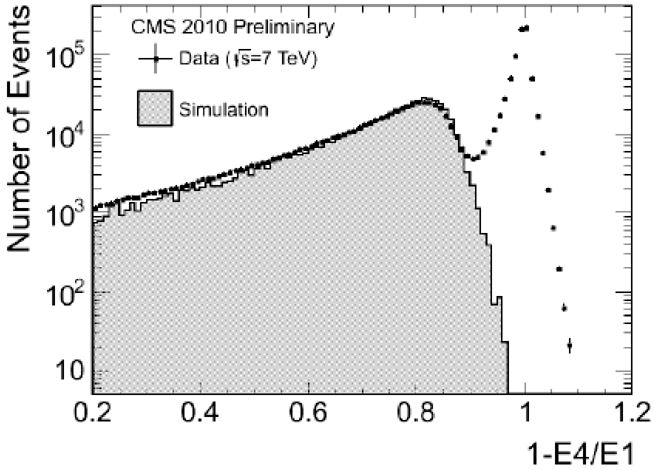
CMS Avalanche Photodiode (APD)

Hamamatsu S8148

- NCE signal produced by direct ionization in silicon by charged particles or neutrons
- Specially developed APD to reduce this effect
- Thin high gain depletion layer (G ~ 50, t_{eff} ~ 5 μm) followed by thicker low gain layer (G~1.4, t_{eff} ~ 45 μm)
- Expect ~ 100 MeV equivalent energy for MIP
- Equivalent neutron energy can be several hundred GeV



Direct ionization hits produces anomalous pattern compared with normal EM shower



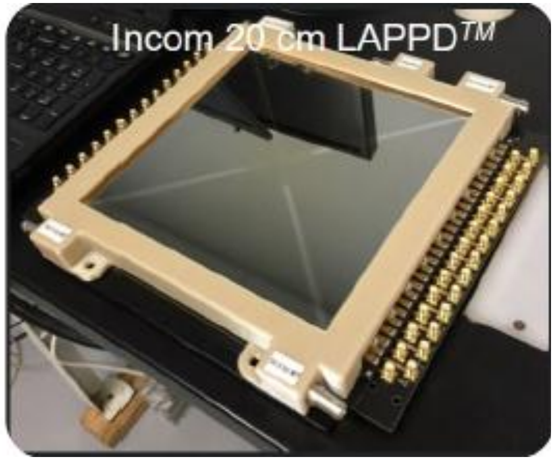
Distribution of "Swiss-cross" variable for Minimum Bias data and MC for signals with E_T>3 GeV.

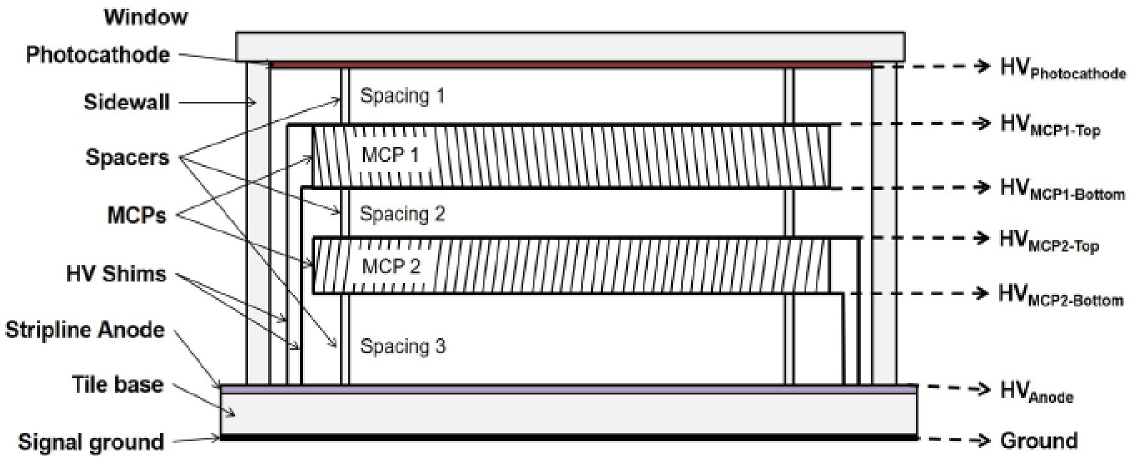
D.A.Petyt, CALOR 2012

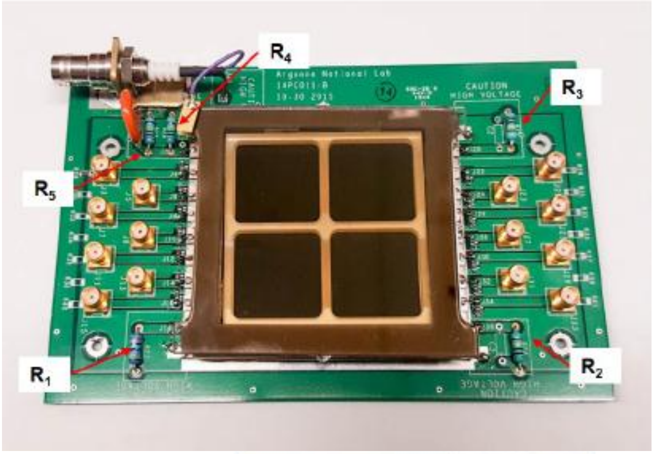
Large Area Picosecond Photodetectors (LAPPDs)

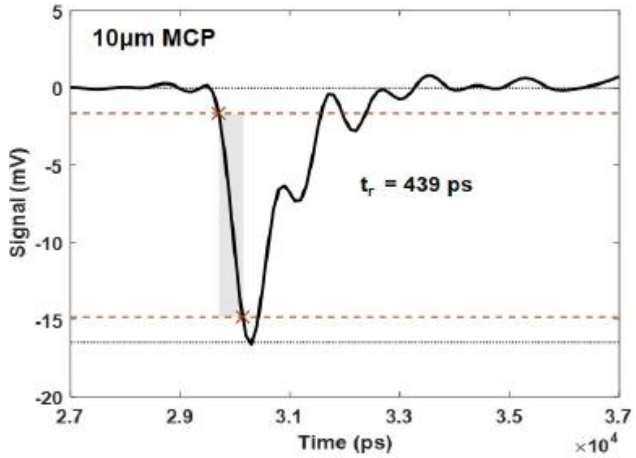
Large Area Pixellated Microchannel Plate detectors

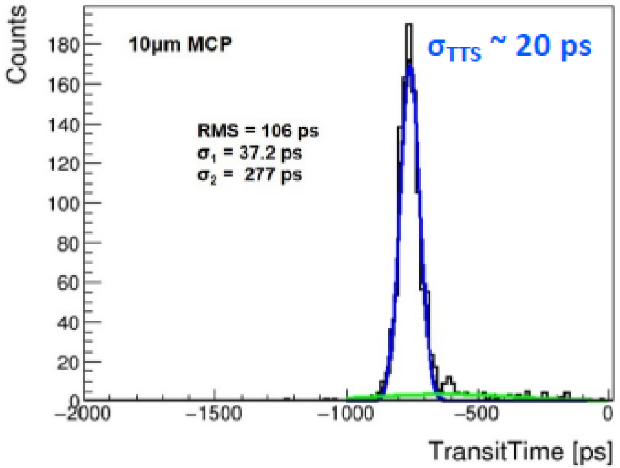
Developed to address the needs of the HEP and NP community











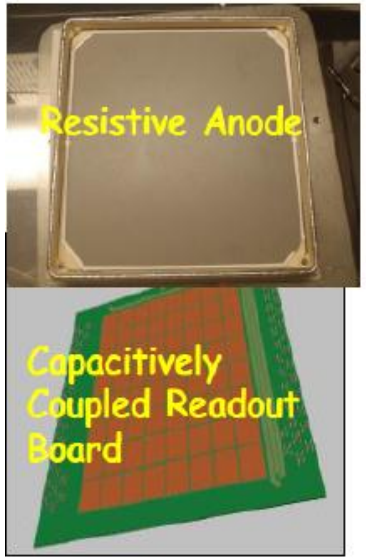
$$\sigma_{MCP-PMT} = \sqrt{\sigma_1^2 - \sigma_{Laser}^2 - \sigma_{Ele.}^2}$$

System: σ_1 = 37.2 ps

Laser jitter: σ_{Laser} = 30 ps

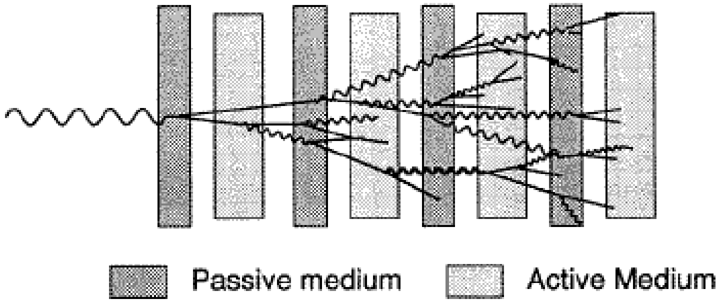
Electronics: $\sigma_{Ele.}$ = 7 ps

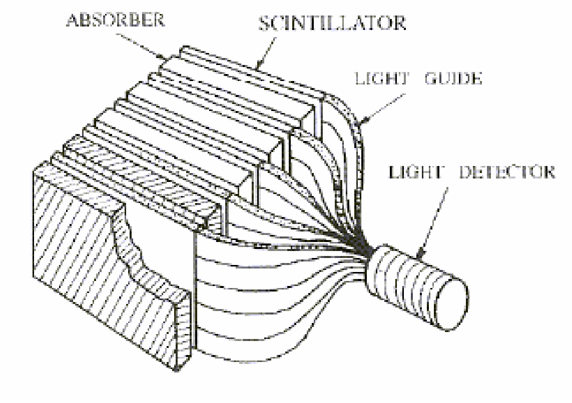
*10 μm MCP-PMT: **σ = 20 ps***



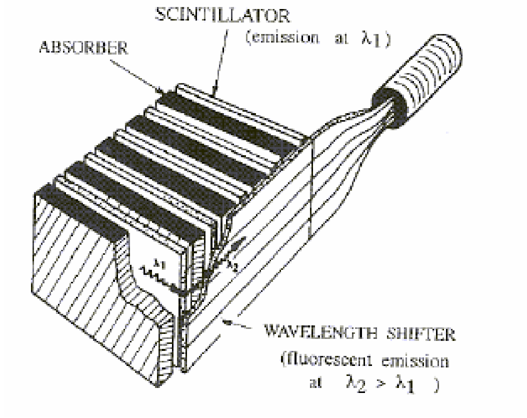
Sampling Calorimetry

R.Wigmans, Calorimetry Energy Measurement in Particle Physics





Direct readout



WLS Bar Readout

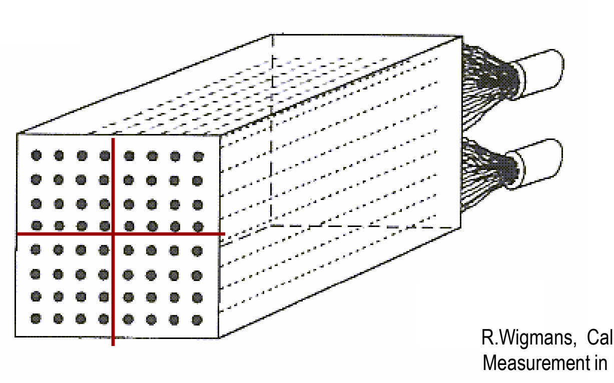
Alternating layers of passive material (absorber) and active medium to measure the energy of high energy particles

With scintillator as the active medium, problem is to collect the light onto the photodetector

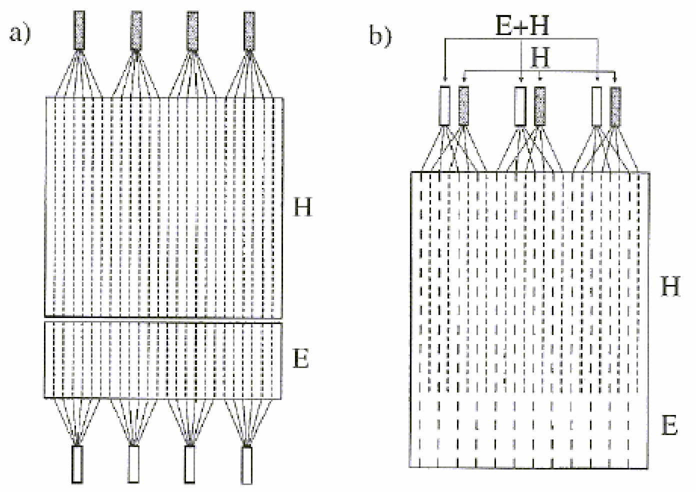
Most direct collection techniques produce unfavorable geometry for stacking modules or creating calorimeters which are hermetic (i.e., without cracks or dead material)

Want good uniformity (longitudinal and transverse) to give good energy resolution

Fiber Calorimeters



R.Wigmans, Calorimetry Energy Measurement in Particle Physics



Fibers form the active medium which are interspersed longitudinally with the absorber material

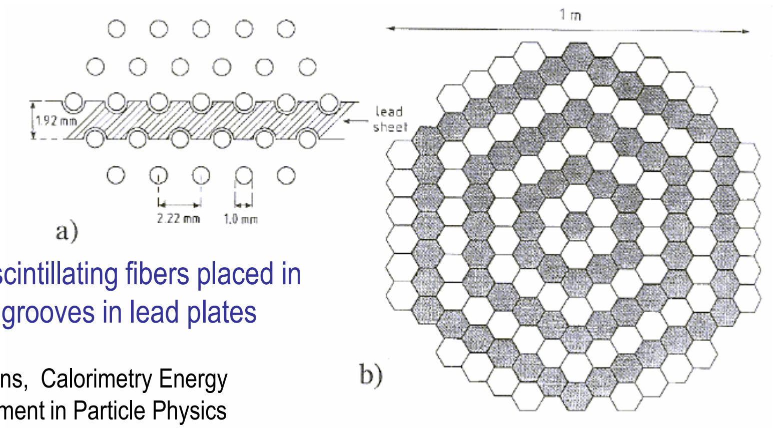
Brings light to the front or back of the calorimeter where photodetector can be attached

Fibers can be plastic scintillator, wavelength shifter or Cherenkov material, or a combination

Electromagnetic (front) and Hadronic (back) sections can be read out separately using different fibers

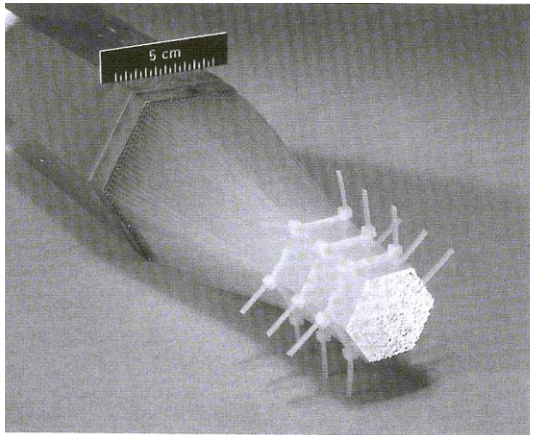
Allows almost any degree of transverse segmentation

The SPACAL "Spaghetti" Calorimeter



1 mm plastic scintillating fibers placed in machined grooves in lead plates

R.Wigmans, Calorimetry Energy Measurement in Particle Physics



Convenient Readout
Fibers brought to back, bundled and read out with 2" PMTs

First calorimeter based on scintillating fibers as the active medium
- very compact (80% absorber)
- small sampling fraction (2.3%)
- could be made hermetic with fine segmentation

Photostatistics → 300 p.e./GeV

⇒ ~ 6%/√E contribution to energy resolution

$$\left(\frac{\sigma_E}{E}\right)_{EM} = \frac{13\%}{\sqrt{E}} \oplus 1\% \qquad \left(\frac{\sigma_E}{E}\right)_{Had} = \frac{33\%}{\sqrt{E}} \oplus 2.2\%$$

Other Sci-Fi Calorimeters
H1
KLOE
JETSET
CHORUS
E864 (BNL)

The ‘Dream Calorimeter’

DREAM = Dual REAout Module

R.Wigmans
Texas Tech University

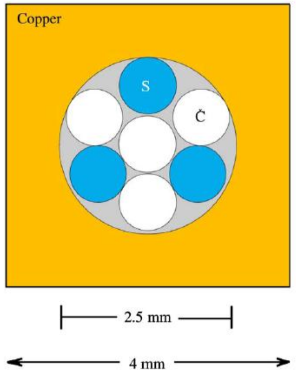
Concept:

Measure electromagnetic fraction (f_{em}) and total hadronic energy of entire shower event by event

$$\left(\frac{\pi}{e}\right) = f_{em} + \left(1 - f_{em}\right)\cdot\left(\frac{h}{e}\right)$$

Use Cherenkov fibers to measure EM component, plastic fibers to measure (total) hadronic component

Energy resolution ultimately limited by fluctuations in nuclear binding energy loss

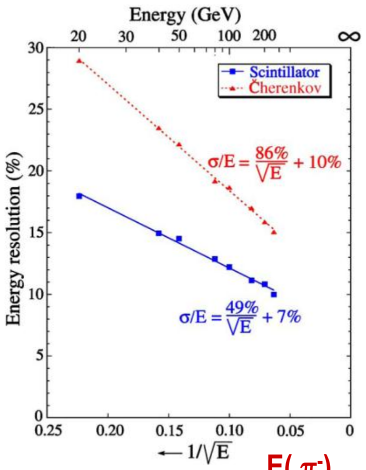


Copper absorber (2 m long)
4 Cherenkov fibers
(quartz + clear plastic)
3 Plastic scintillating fibers

$$\frac{e}{h} \sim 1.3 \rightarrow \frac{h}{e} \sim 0.77$$

~ 18 p.e./GeV plastic,
~ 8 p.e./GeV quartz

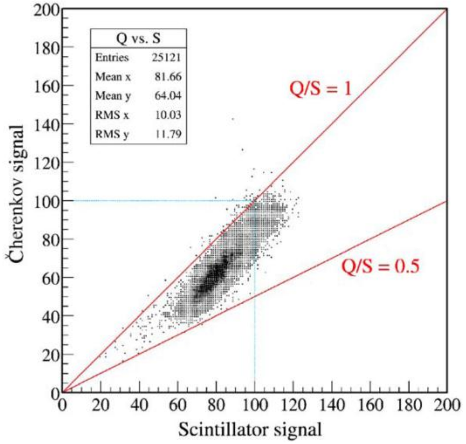
Uncorrected



E(π^-)

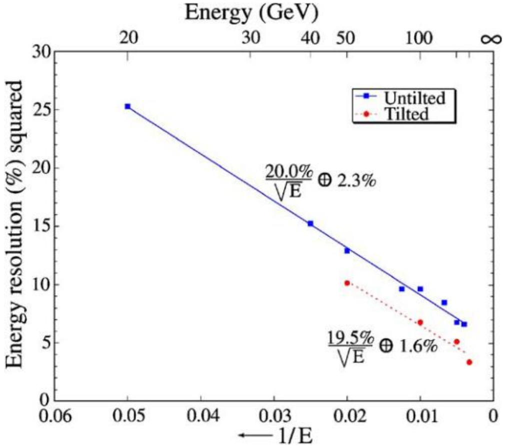
N.Akchurin et.al., NIM A537 (2005) 537-561

Quartz-Scintillator correlation (event-by-event)



100 GeV π^-

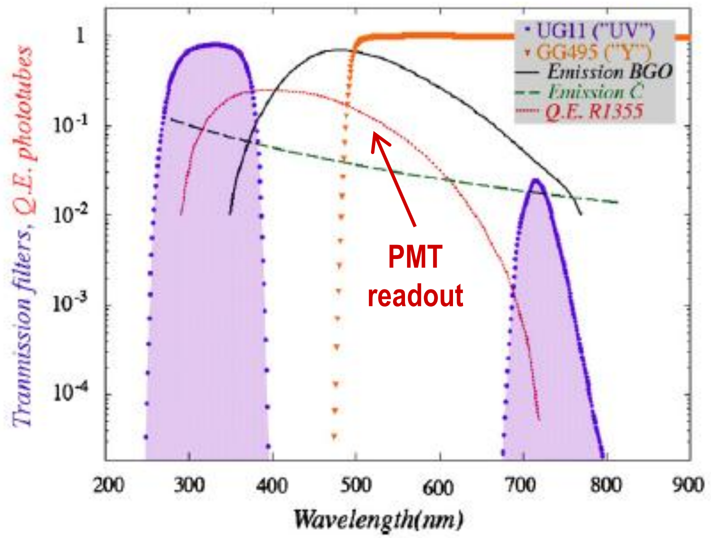
Corrected



E(π^-)

Dual Readout Using Crystals

BGO Example



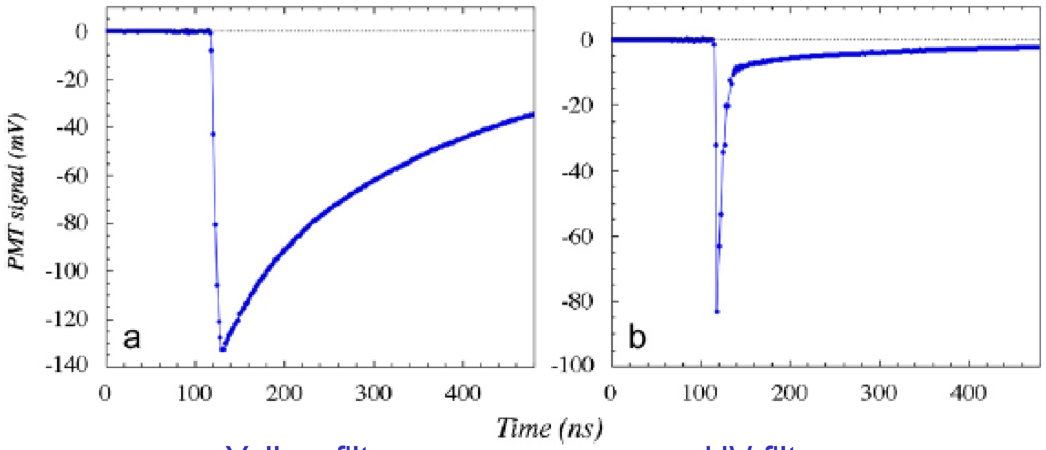
All charged particles produce scintillation light

Highly relativistic particles (EM component of shower) produces additional Cherenkov

Use spectral and time structure differences to separate EM and hadronic components of shower

However, crystals produce large e/h
- large signal for electrons and poor sensitivity to neutrons (not hydrogenous)

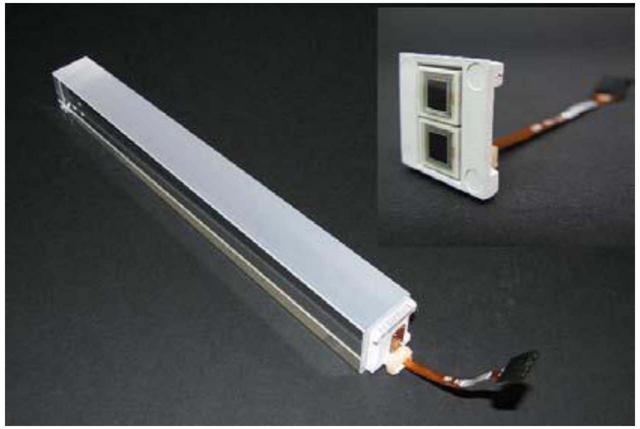
N.Akchurin et.al., NIM A585 (2008) 395-374



Yellow filter UV filter

Property	Cherenkov	Scintillation
Angular Distribution	Forward peaked cone $\cos\theta=1/n\beta$	Isotropic
Time structure	Instantaneous	few to hundreds of ns
Light spectrum	$1/\lambda^2$	~ 400 nm

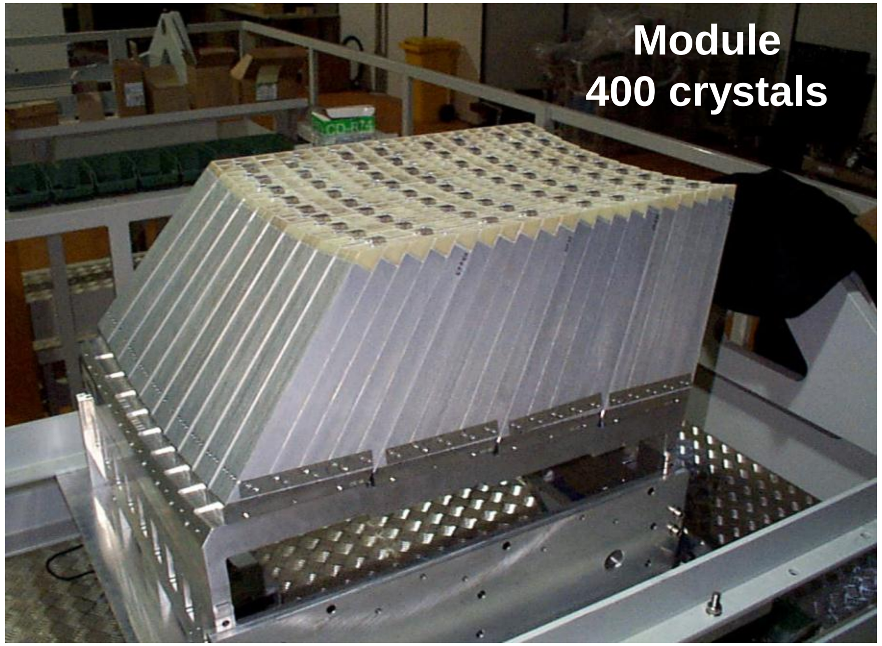
CMS Barrel EMCAL



Dual APDs
for redundency
covering ~ 10% of area

~ 4.5 p.e/MeV

Light Yield ~ 100 γ/MeV
Uniformity ~ 0.3%
$|dLY/X_0| < 0.35\%/X_0$
between 3 and 13 X_0



$PbWO_4$ crystals

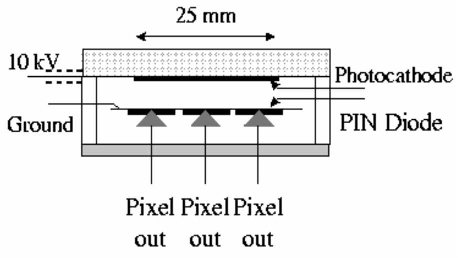
- Must be extremely uniform to obtain design energy resolution
- Must be radiation hard (achieved after extensive R&D program)

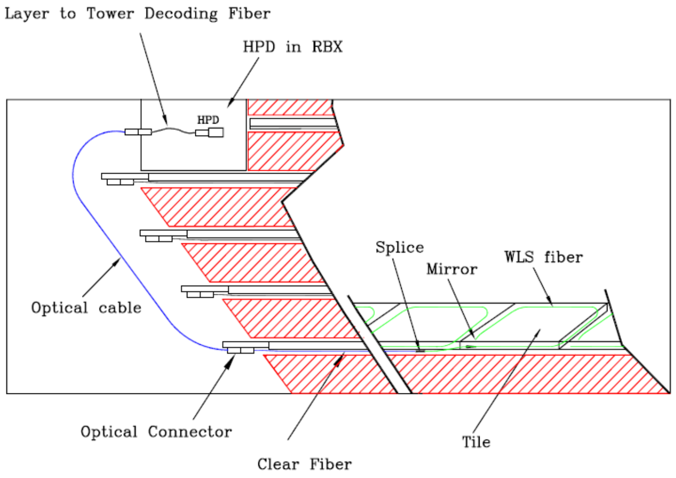
Hammamastu S-8148 (5x5 mm^2)

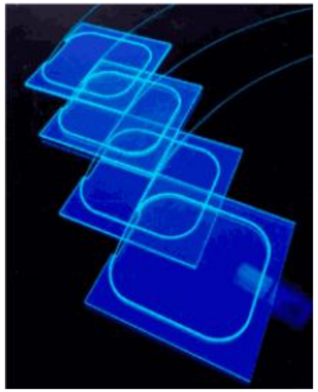
- Insensitive to magnetic field
- Gain: M=50
- dM/dV = 3%/V, dM/dT = -2.3%/°C
  - requires good V and T stability (~.05°C)
- <Q.E.> ~ 70% with $PbWO_4$
- Nuclear counter effect (minimized depletion layer)

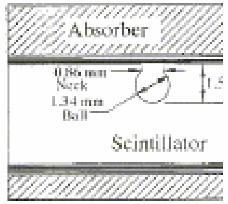
CMS Barrel Hadron Calorimeter

HPD







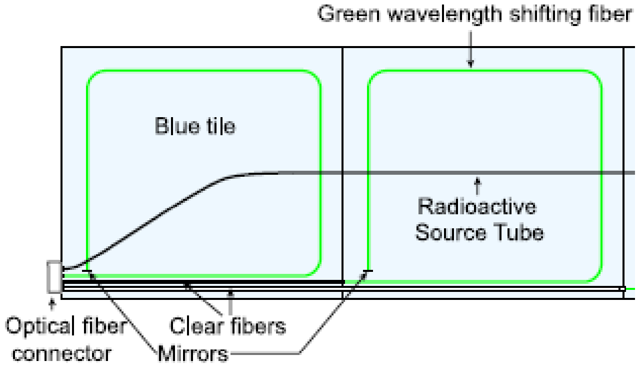


Scintillating tiles read out with WLS fibers placed in groove in the tile

Fibers are read out with Hybrid Photodiodes (HPDs)

- low sensitivity to (axial) magnetic field
- high gain
- low noise
- large dynamic range

$$\left(\frac{\sigma_E}{E}\right)_{Had} \approx \frac{85\%}{\sqrt{E(GeV)}}$$



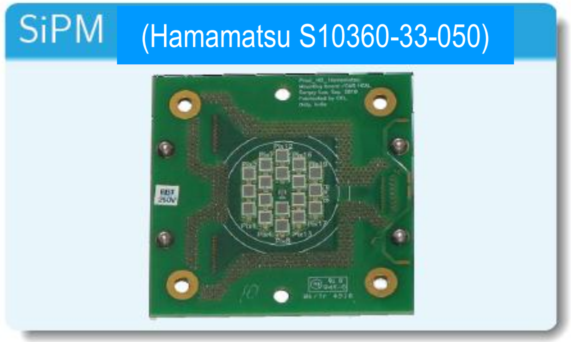
Couple WLS to clear fibers to transport light over long distances (better attn. len.)

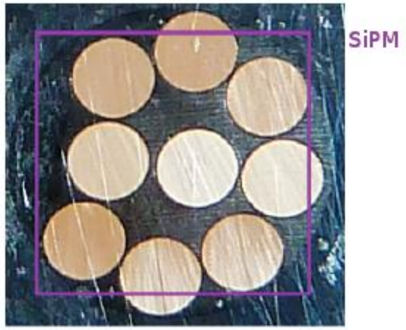
Other Tile-WLS Fiber Calorimeters
ATLAS Hadron
LHBb HCAL
STAR EMCAL
D0
HERA
CALICE (w/SiPMs)

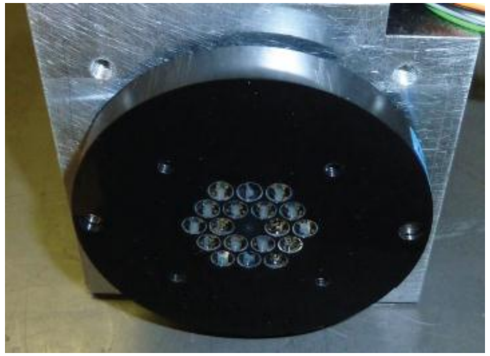
CMS HCAL Upgrade Plans

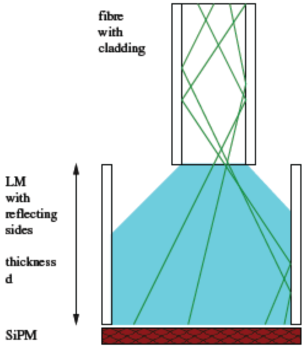
HPDs suffer from gain instability, high noise, discharging, and ion feedback
Plan to replace them with SiPMs to improve performance and increase signal/noise

HO during Long Shutdown 1 (2013-2014)





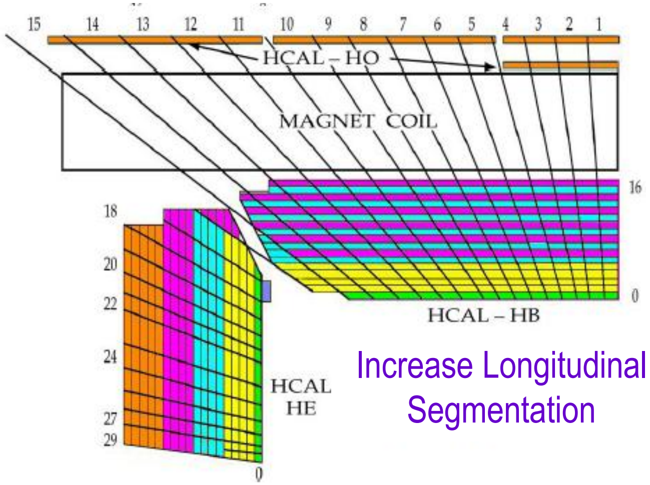




A.Kunsken, CALOR14

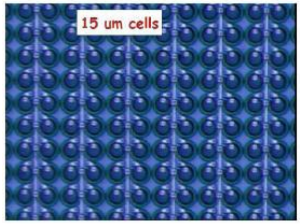
Need mixer to collect and randomize light onto SiPMs

HB and HE during Long Shutdown 2 (2018)



Increase Longitudinal Segmentation

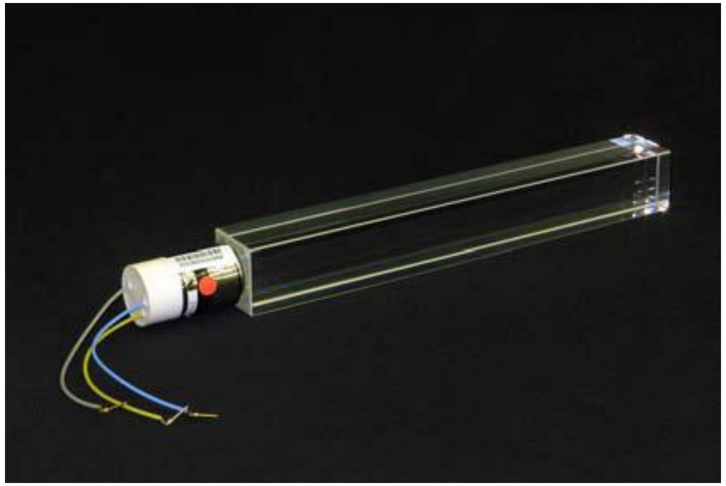
New Hamamatsu MPPCs with 10-15 μm pixels



- 15 μm pixels
  $\Rightarrow$ ~ 4400 pixels/mm^2
- Better linearity
- Larger dynamic range
- Fast recovery time
- More rad hard

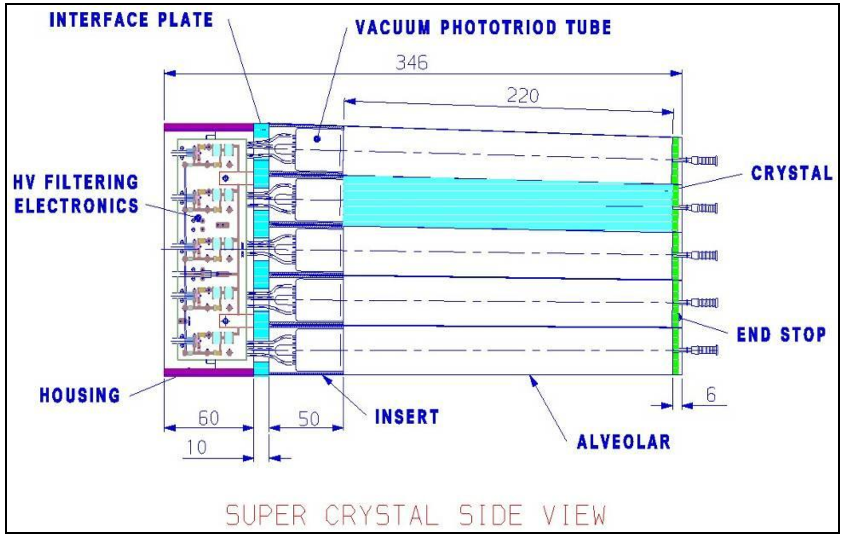
E.Laird, CALOR14

CMS Endcap EMCAL



~ 4.5 p.e/MeV

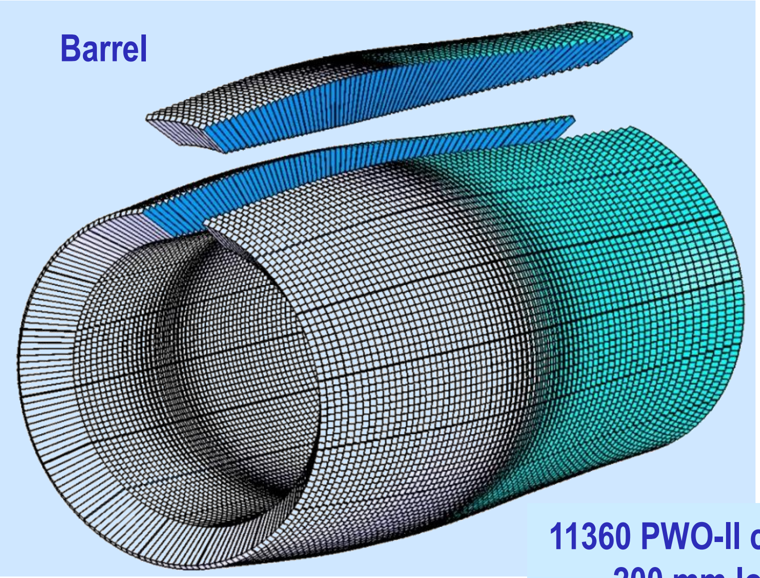
(larger area
lower QE
than APDs)



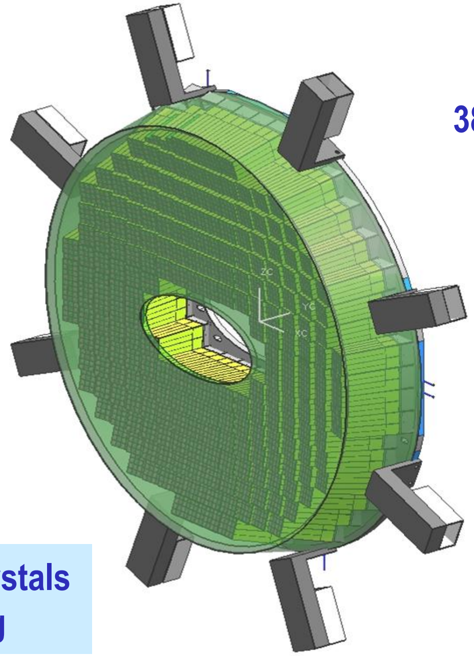
Vacuum Phototriode (Research Institute Electron, St. Petersburg, Russia)

- Single gain stage PMT (1" dia)
- <QE> ~ 22% at 420 nm
- Minimal sensitive to magnetic fields (15% loss at 4T)
- Gain: M=10
- Quartz window
- Rad tolerance < 10% after 20 KGy (could not use APDs due to higher radiation levels)

New Photosensors for PANDA



11360 PWO-II crystals
200 mm long



Endcap
3864 crystals

Hamamatsu R2148MOD
especially made for $\overline{\text{P}}$ANDA, $\varnothing < 24$ mm

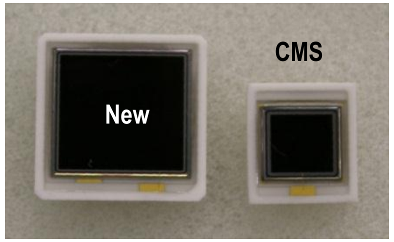
- $\varnothing = 23.7$ mm
  $\ell = 30$ mm
- $U_A = 750$ V
  $U_D = 500$ V
- G = 9.3
- QE = 32 %
  (at 420 nm)

RIE St. Petersburg, Russia
- Tetrode (photo cathode, 2 dynodes, anode)
- G = 24 – 45
- QE = 14 – 20%

- physical goals of PANDA require further development

	PWO-I (CMS)	PWO-II (PANDA)
luminescence maximum, nm	420	420
La, Y concentration level, ppm	100	40
expected energy range of EMC	150MeV - 1TeV	10MeV - 10GeV
light yield, phe/MeV at room temperature	8-12	17-22
EMC operating temperature, °C	+18	-25
energy resolution of EMC at 1GeV, %	3,4	2,0

Barrel Readout
Large Area APDs

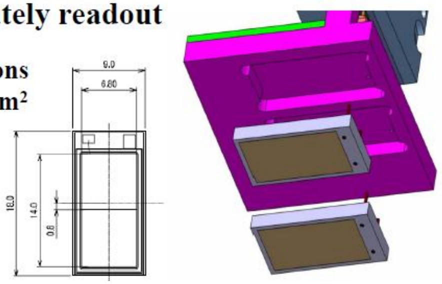


10x10 mm   5x5 mm

Hamamatsu APDs

final concept: 2 LAAPDs/crystal, separately readout

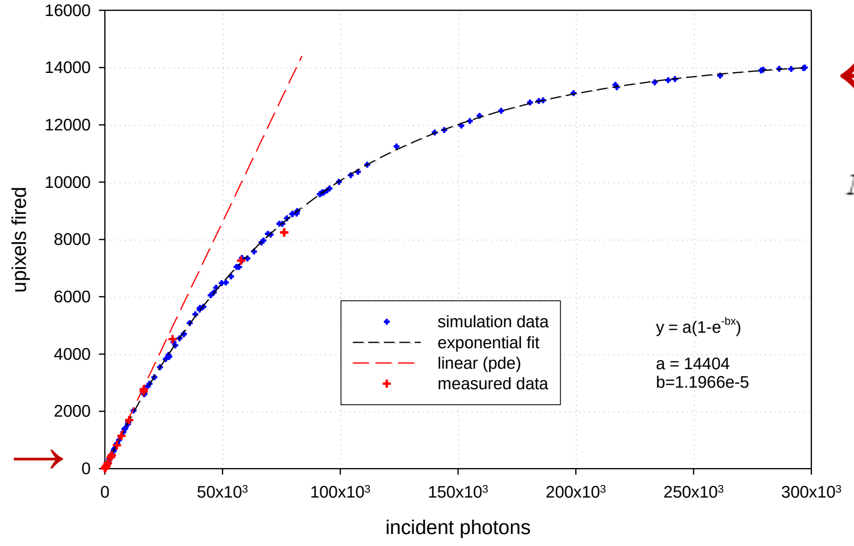
dimensions 7 x 14 mm²



R. Novotny, CALOR12

Use of SiPMs in Calorimetry

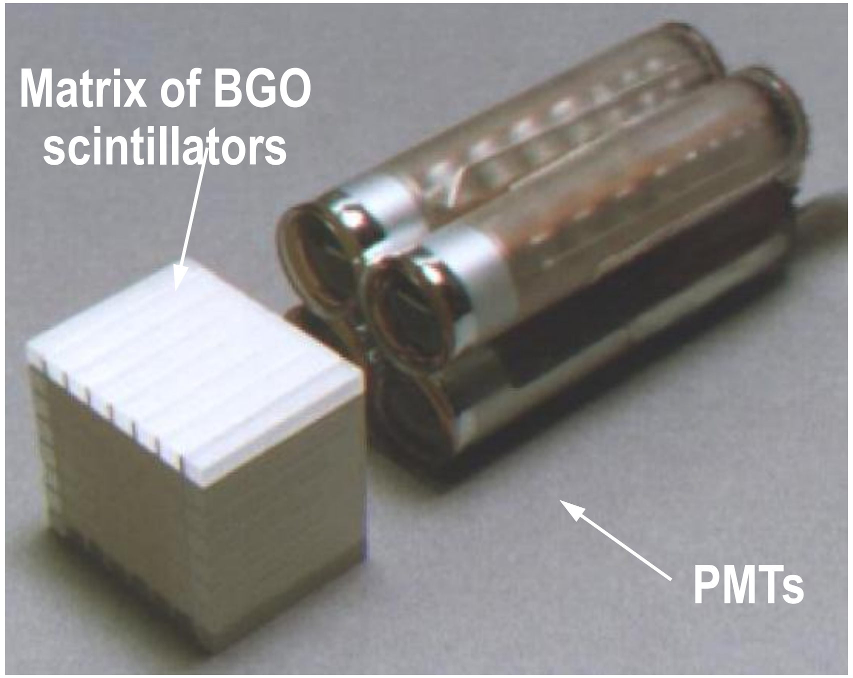
Requirements	
Calorimetry	**PET**
• Large dynamic range (~ 10^3-10^4)	• Small device size (~ 1x1 mm^2 – 3x3 mm^2)
• Good linearity	• Tileable
• Large area coverage	• Fast timing for TOF PET
• Radiation hardness	



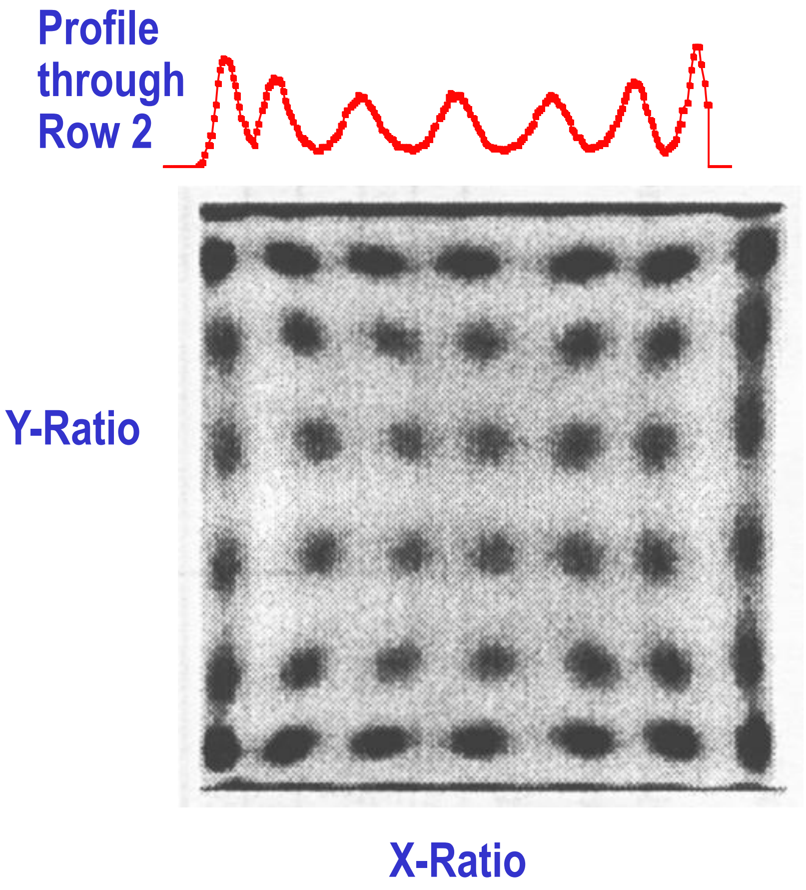
$$N_{firedcells} = N_{total} \cdot (1 - e^{-\frac{N_{photon} \cdot PDE}{N_{total}}})$$

Requires uniform illumination

Standard PET Detector



Figures courtesy of M.Casey (Siemens, formerly CTI)



PMTs and BGO have been the workhorse for PET
- used in most clinical human PET scanners
- new scanners are utilizing LSO/YLSO instead of BGO

Position decoded by Anger Logic

Spatial resolution: ~ 4 mm for human scanners
~ 2 mm for small animal scanners

Image is "blurred" due to decoding of which pixel was hit

Spatial Resolution in PET

$$FWHM = 1.25\sqrt{(d/2)^2 + b^2 + (0.0022D)^2 + r^2 + h^2}$$

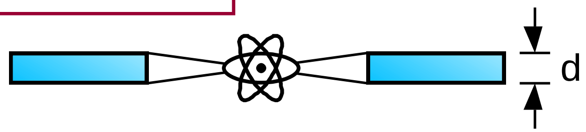
Geometric — Decoding — Non-colinearity — Positron range — DOI

1.25 : degradation due to tomographic reconstruction
d : crystal size
b : uncertainty due to determining block position
D : coincident detector separation
r : effective source size (including positron range)
h : uncertainty in depth of interaction

* Derenzo & Moses, "Critical instrumentation issues for resolution <2mm, high sensitivity brain PET", in *Quantification of Brain Function, Tracer Kinetics & Image Analysis in Brain PET*, ed. Uemura et al, Elsevier, 1993, pp. 25-40.

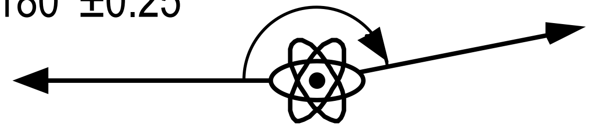
Contributions to the Spatial Resolution

Geometrical:



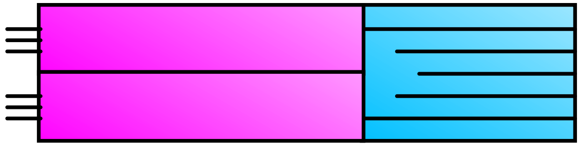
d/2

Non-coplanarity:



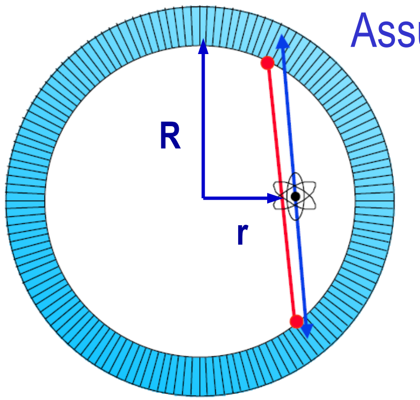
.0044R   R=radius of detector

Decoding:



~ 2 mm for standard block detectors
0 mm for 1-1 coupling

Depth of Interaction:



Assuming 30 mm crystals

$$h = 12.5 \frac{r}{\sqrt{r^2 + R^2}}$$

Positron range:

In tissue

Isotope	E_{max} β^+ (MeV)	Effective FWHM (mm)
^{18}F	0.64	0.55
^{11}C	0.96	1.0
^{14}N	1.20	1.4
^{15}O	1.70	2.4

W.Moses & S.Derenzo

How Well Can One Do ?

Assumptions:
- 1-1 coupling
- ^{18}F (shortest range)
- 30 mm thickness
- 10 cm radial FOV

Center of FOV, as a function of crystal width:

Crystal Width (mm)	1.0	0.5	0.0
Decoding (1-to-1coupling)	0	0	0
Range (^{18}F)	0.55	0.55	0.55
Acollinearity (R=100 mm)	0.44	0.44	0.44
Distance from Center (mm)	0	0	0
DOI (30 mm detector thickness)	0	0	0
Reconstruction (x factor)	1.25	1.25	1.25
Total (mm)	**1.08**	**0.93**	**0.88**

1 mm crystal width, as a function of distance off axis

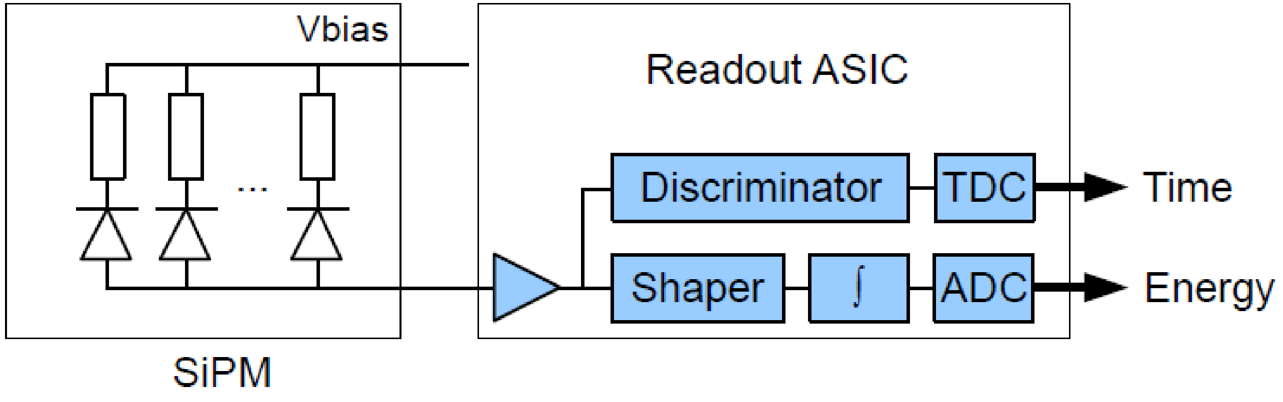
Crystal Width (mm)	1.0	1.0	1.0	1.0
Decoding (1-to-1coupling)	0	0	0	0
Range (^{18}F)	0.55	0.55	0.55	0.55
Acollinearity (R=100 mm)	0.44	0.44	0.44	0.44
Distance from Center (mm)	0	10	20	30
DOI (30 mm detector thickness)	0	1.24	2.45	3.59
Reconstruction (x factor)	1.25	1.25	1.25	1.25
Total (mm)	**1.08**	**1.89**	**3.25**	**4.62**

W.Moses & S.Derenzo

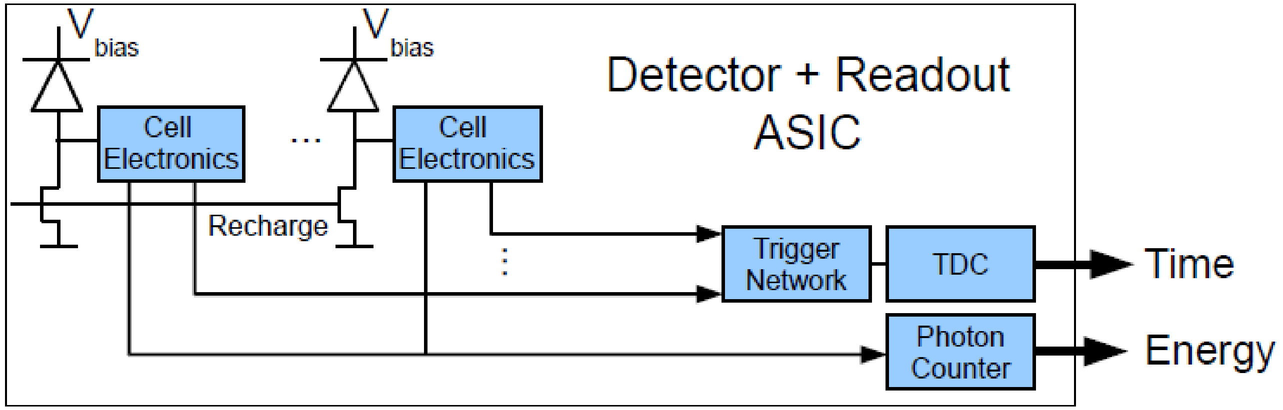
PHILIPS

Digital SiPM – The Concept

Analog Silicon Photomultiplier Detector



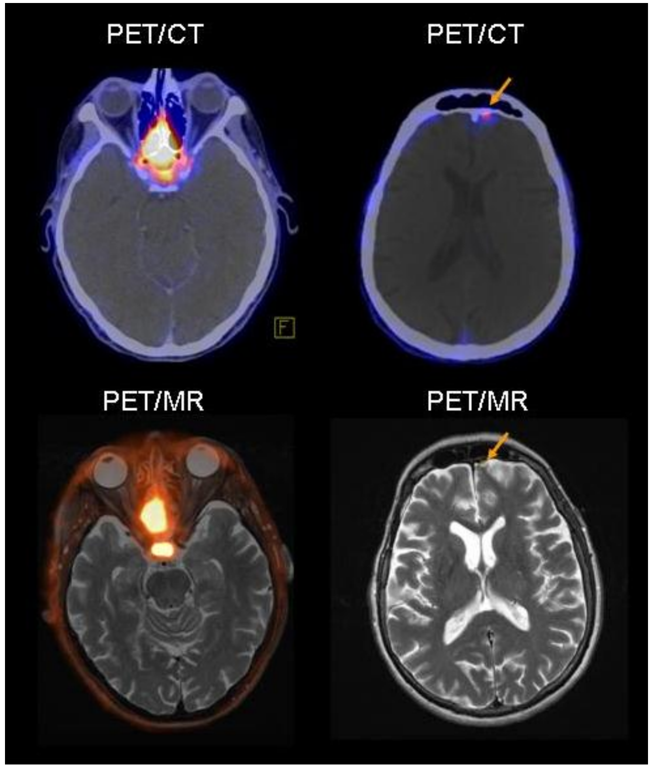
Digital Silicon Photomultiplier Detector



Simultaneous PET-MRI

Advantages of simultaneous PET-MRI

- MRI provides high spatial resolution for excellent anatomical information with good soft tissue contrast.
- PET provides high sensitivity and specificity for studying metabolic activities and radiotracer uptake
- PET/MR delivers ~ ½ the radiation dose of PET/CT
- Simultaneous acquisitions result in perfectly co-registered images with less scan time than sequential imaging, and also allows time correlated studies such as in combination with fMRI



B.Pichler
PSMRI 2012

Technical Challenges with Simultaneous PET-MRI

- PMTs used in conventional PET detectors are very sensitive to to even small magnetic fields
- MRI uses strong RF pulses at frequencies of several hundred MHz and pulsed gradient magnetic fields that can cause interference with the PET readout electronics
- PET detector and readout electronics can cause interference with very sensitive MRI detectors for measuring weak MRI signals
- Any magnetic materials in the PET detector can perturb the very homogeneous magnetic field of the MRI and can cause distortions in the MRI image