Plastic and Liquid Scintillators

In practice use ...

solution of organic scintillators
[solved in plastic or liquid]

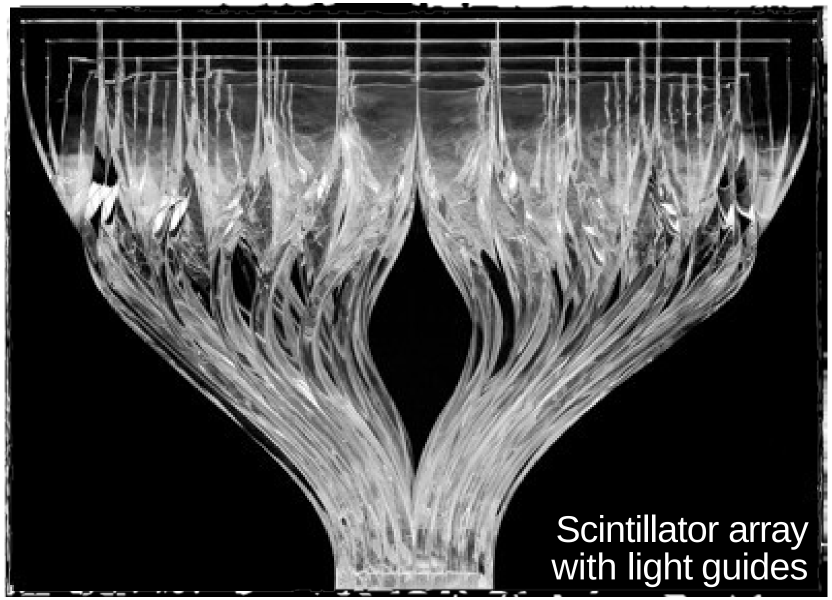
+ large concentration of primary fluor
+ smaller concentration of secondary fluor
+ ...

Scintillator requirements:

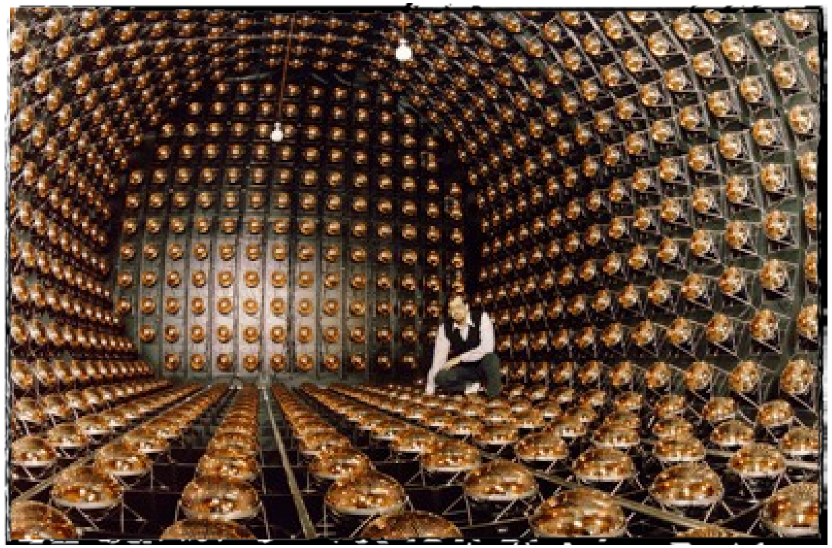
Solvable in base material

High fluorescence yield

Absorption spectrum must overlap
with emission spectrum of base material



Scintillator array
with light guides



LSND experiment

Plastic and Liquid Scintillators

A

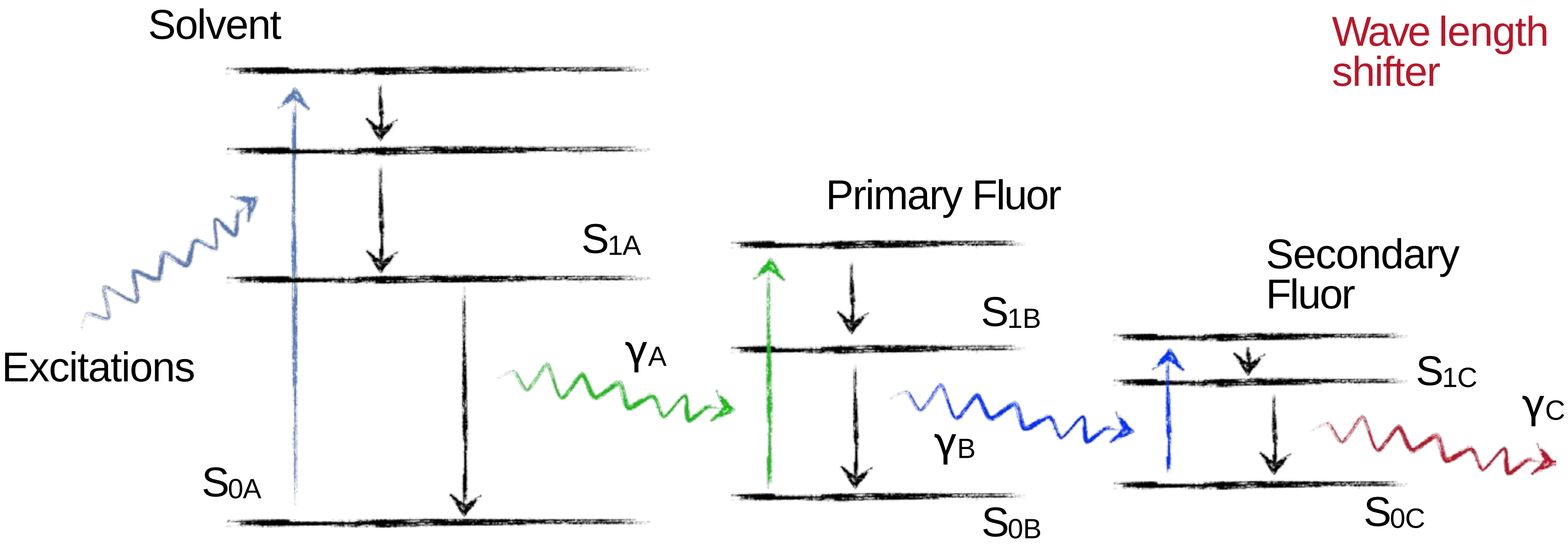
Energy deposit in base material ➛ excitation

Primary fluorescent B

- Good light yield ...
- Absorption spectrum matched to excited states in base material ...

Secondary fluorescent C

Wave length shifter

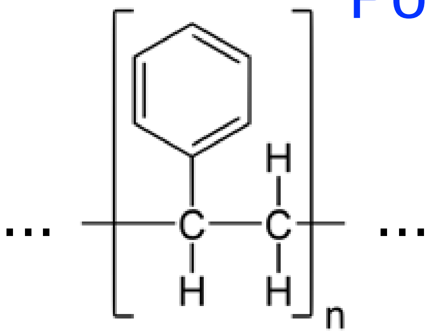


Plastic and Liquid Scintillators

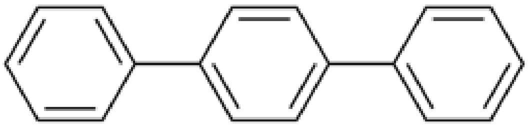
Some widely used solvents and solutes

	solvent	secondary fluor	tertiary fluor
Liquid scintillators	Benzene Toluene Xylene	p-terphenyl DPO PBD	POPOP BBO BPO
Plastic scintillators	Polyvinylbenzene Polyvinyltoluene Polystyrene	p-terphenyl DPO PBD	POPOP TBP BBO DPS

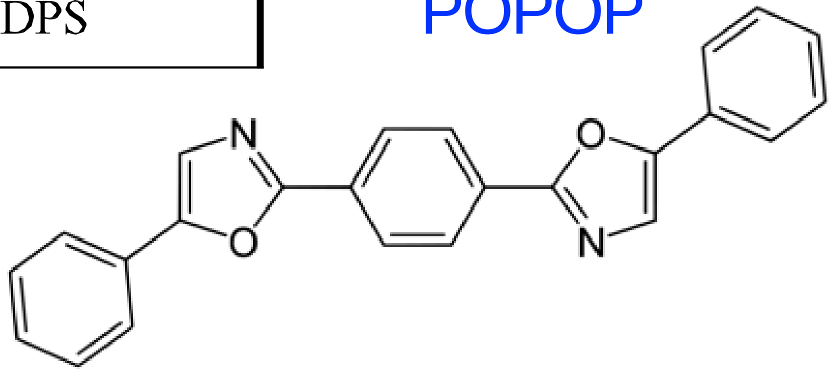
Polystyrene



p-Terphenyl



POPOP



Wavelength Shifting

Principle:

Absorption of primary scintillation light

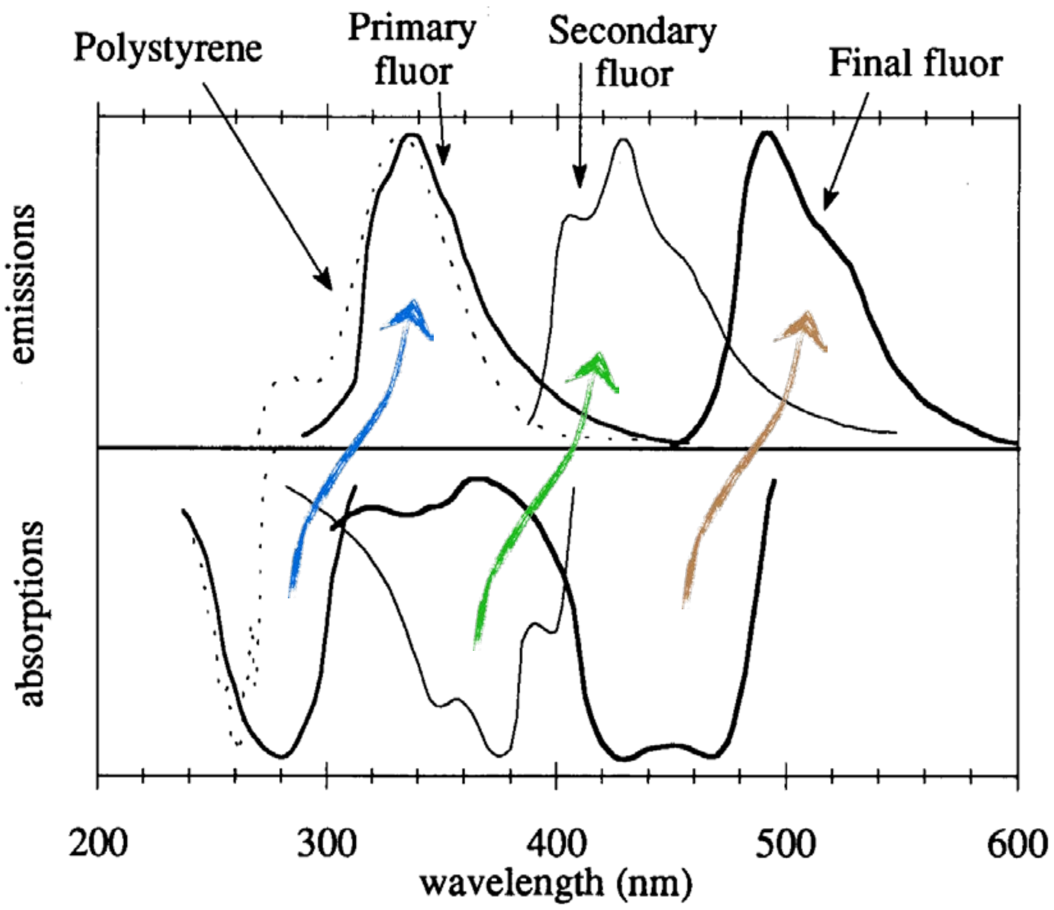
Re-emission at longer wavelength

Adapts light to spectral sensitivity of photosensor

Requirement:

Good transparency for emitted light

Schematics of wavelength shifting principle



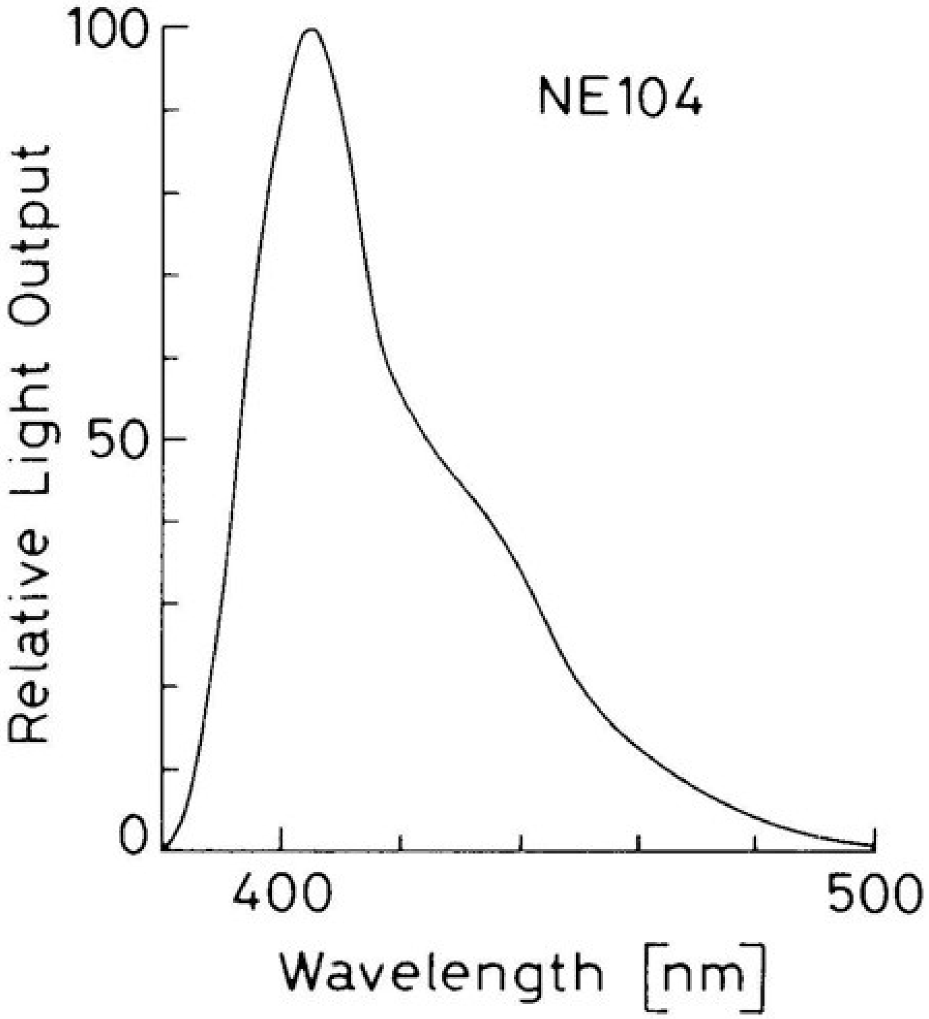
Organic Scintillators – Properties

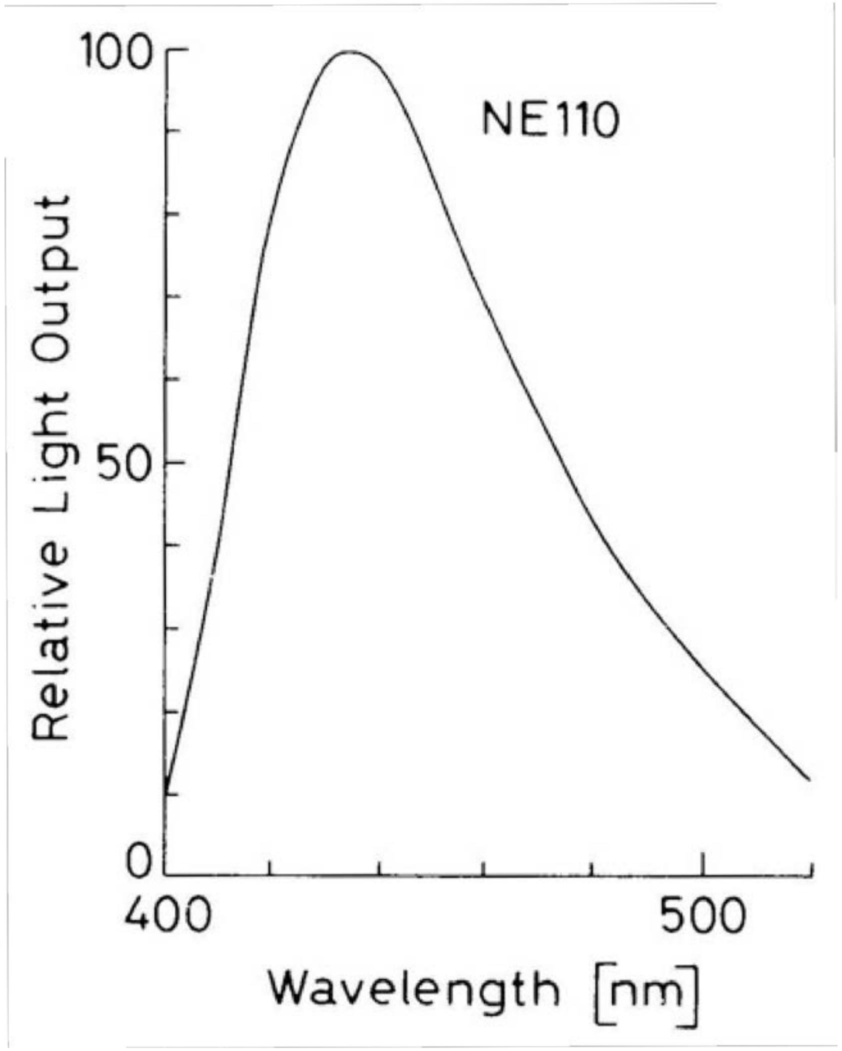
Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4\cdot10^3$
Antracene	1.25	1.59	448	30	$4\cdot10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2\cdot10^4$
NE102*	1.03	1.58	425	2.5	$2.5\cdot10^4$
NE104*	1.03	1.58	405	1.8	$2.4\cdot10^4$
NE110*	1.03	1.58	437	3.3	$2.4\cdot10^4$
NE111*	1.03	1.58	370	1.7	$2.3\cdot10^4$
BC400**	1.03	1.58	423	2.4	$2.5\cdot10^2$
BC428**	1.03	1.58	480	12.5	$2.2\cdot10^4$
BC443**	1.05	1.58	425	2.2	$2.4\cdot10^4$

* Nuclear Enterprises, U.K.

** Bicron Corporation, USA

Organic Scintillators – Properties





Organic Scintillators – Properties

Light yield:
[without quenching]

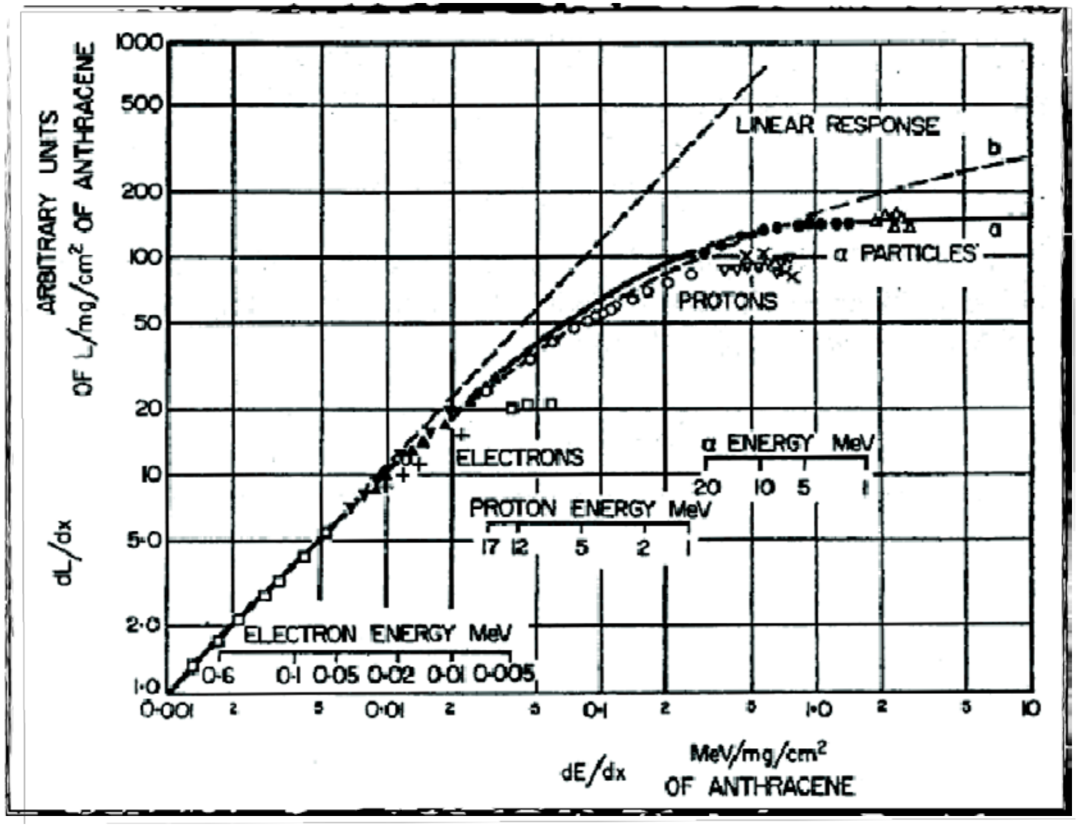
$$\frac{dL}{dx} = L_0 \frac{dE}{dx}$$

Quenching:
non-linear response due to
saturation of available states

Birk's law:

$$\frac{dL}{dx} = L_0 \frac{\frac{dE}{dx}}{1 + kB\,\frac{dE}{dx}}$$

[kB needs to be determined experimentally]



Also other
parameterizations ...

Response different
for different particle types ...

Scintillators – Comparison

Inorganic Scintillators

Advantages	high light yield [typical; $\varepsilon_{sc} \approx 0.13$] high density [e.g. $PBWO_4$: 8.3 g/cm^3] good energy resolution	
Disadvantages	complicated crystal growth large temperature dependence	Expensive

Organic Scintillators

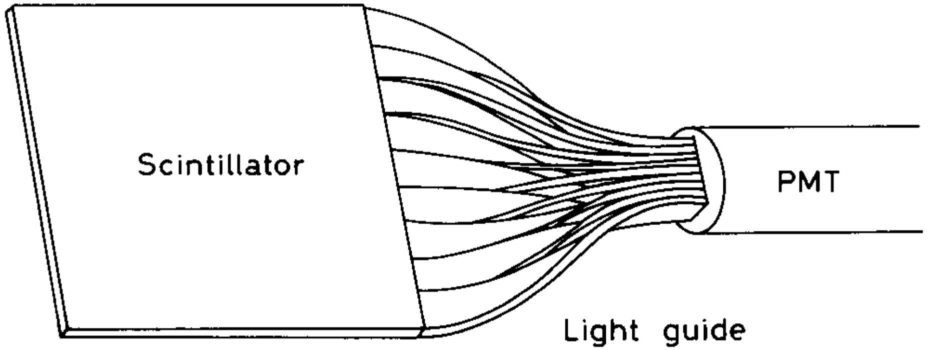
Advantages	very fast easily shaped small temperature dependence pulse shape discrimination possible	
Disadvantages	lower light yield [typical; $\varepsilon_{sc} \approx 0.03$] radiation damage	Cheap

Scintillation Counters – Setup

Scintillator light to be guided to photosensor

➛ Light guide
[Plexiglas; optical fibers]

Light transfer by
total internal reflection
[maybe combined with wavelength shifting]

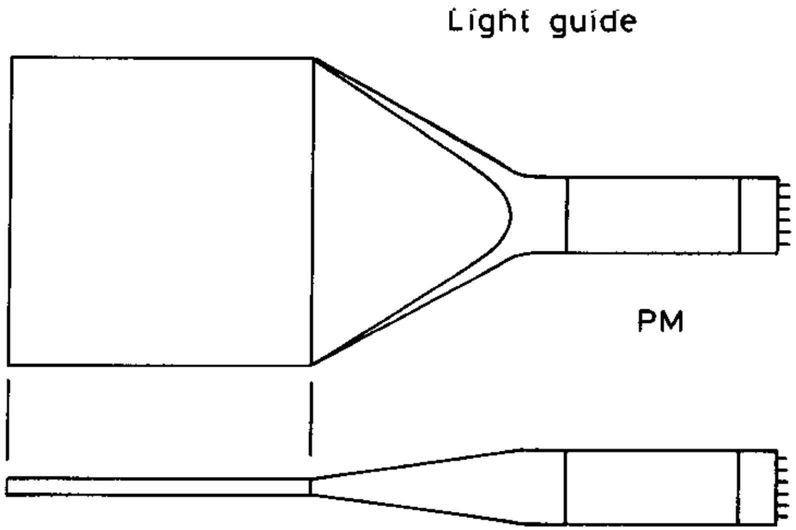


Liouville's Theorem:

Complete light transfer
impossible as $\Delta x \, \Delta\theta = \text{const.}$
[limits acceptance angle]

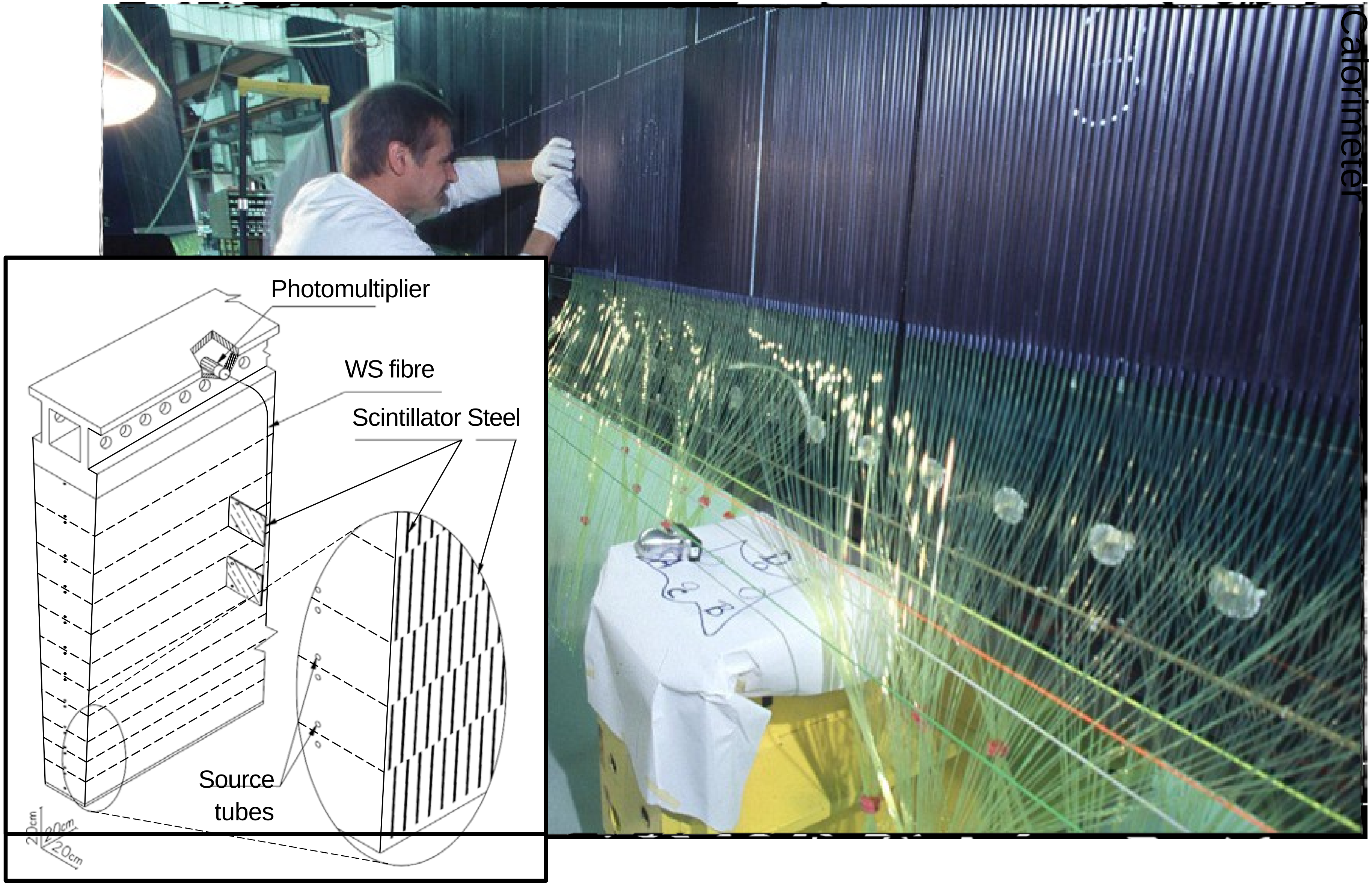
Use adiabatic light guide
like 'fish tail';

➛ appreciable energy loss



'fish tail'

Scintillation Counters – Setup



ATLAS Tile Calorimeter

Photon Detection

Purpose : Convert light into a detectable electronic signal
Principle : Use photo-electric effect to convert photons to photo-electrons (p.e.)

Requirement :

High Photon Detection Efficiency (PDE) or
Quantum Efficiency; Q.E. = $N_{p.e.}/N_{photons}$

Available devices [Examples]:

- Photomultipliers [PMT]
- Micro Channel Plates [MCP]
- Photo Diodes [PD]
- HybridPhoto Diodes [HPD]
- Visible Light Photon Counters [VLPC]
- Silicon Photomultipliers [SiPM]

Photomultipliers

Principle:

Electron emission

from photo cathode

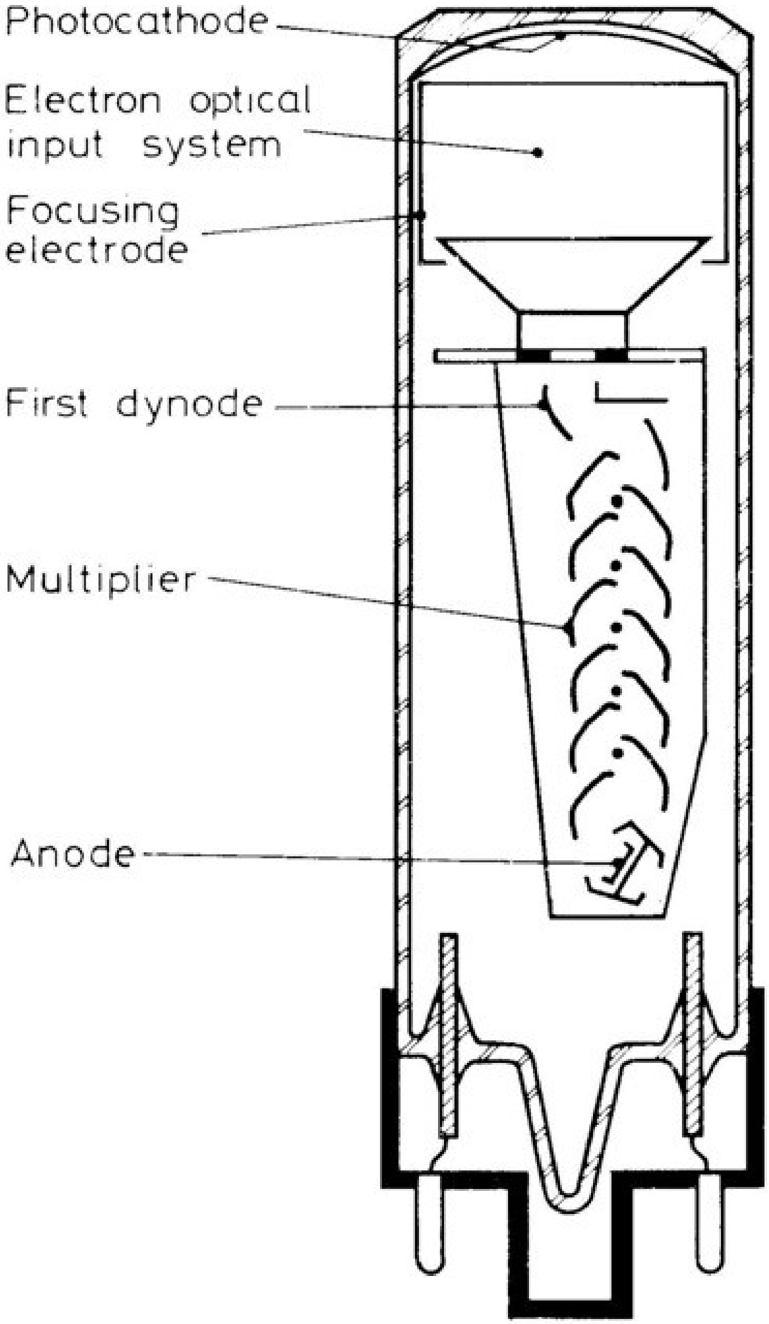
Secondary emission

from dynodes; dynode gain: 3-50 [f(E)]

Typical PMT Gain: > 10^6

[PMT can see single photons ...]

PMT Collection

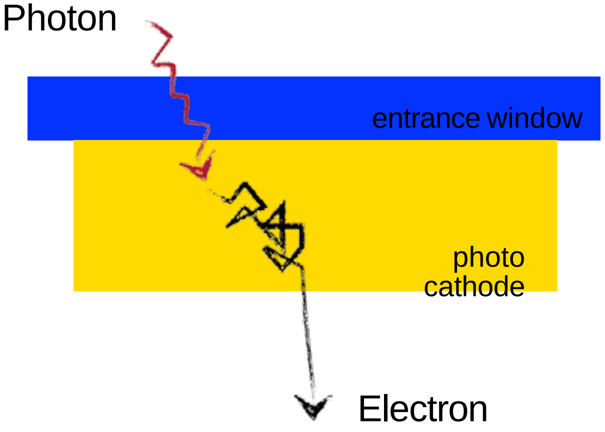


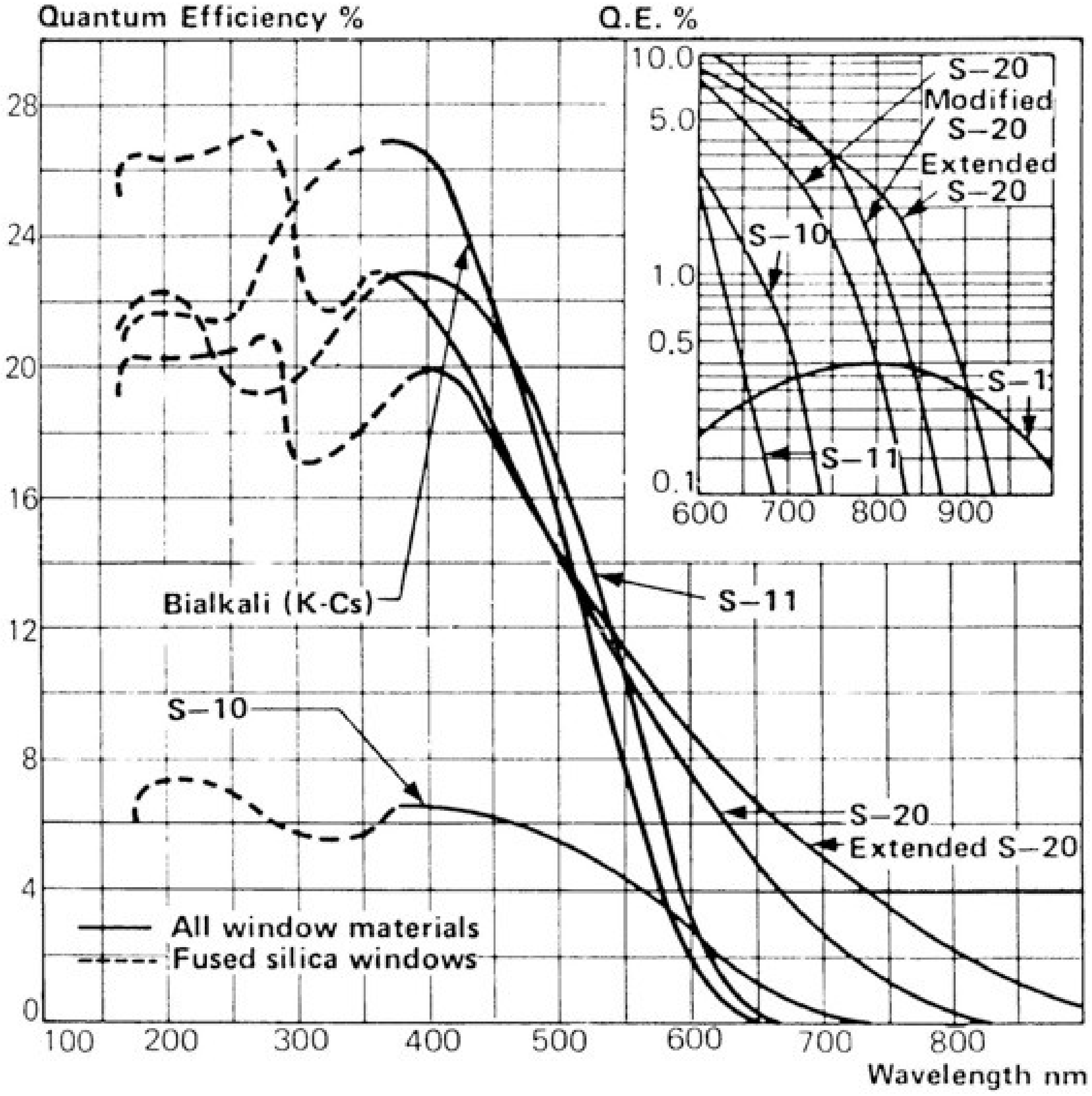
Photomultipliers – Photocathode

Bialkali: SbRbCs; SbK_2Cs

γ-conversion

via photo effect ...





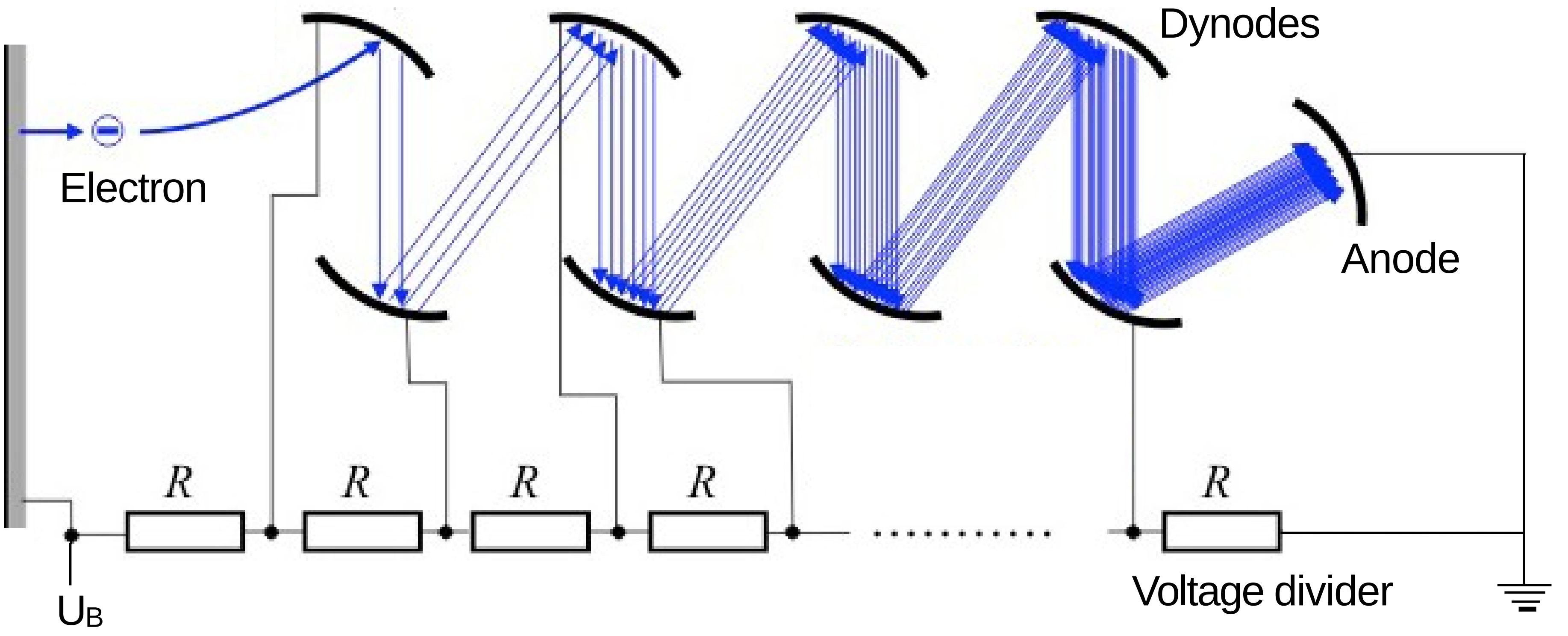
4-step process:

Electron generation via ionization
Propagation through cathode
Escape of electron into vacuum

Q.E. ≈ 10-30%

[need specifically developed alloys]

Photomultipliers – Dynode Chain



Multiplication process:

Electrons accelerated toward dynode
Further electrons produced ➛ avalanche

Secondary emission coefficient:
$\delta = \#(e^- \text{produced})/\#(e^- \text{incoming})$

Typical: $\left.\begin{array}{l} \delta = 2 - 10 \\ n = 8 - 15 \end{array}\right]$ ➛ $G = \delta^n = 10^6 - 10^8$

Gain fluctuation: $\delta = kU_D$; $G = a_0(kU_D)^n$

$dG/G = n\, dU_D/U_D = n dU_B/U_B$

Photomultipliers – Dynode Chain

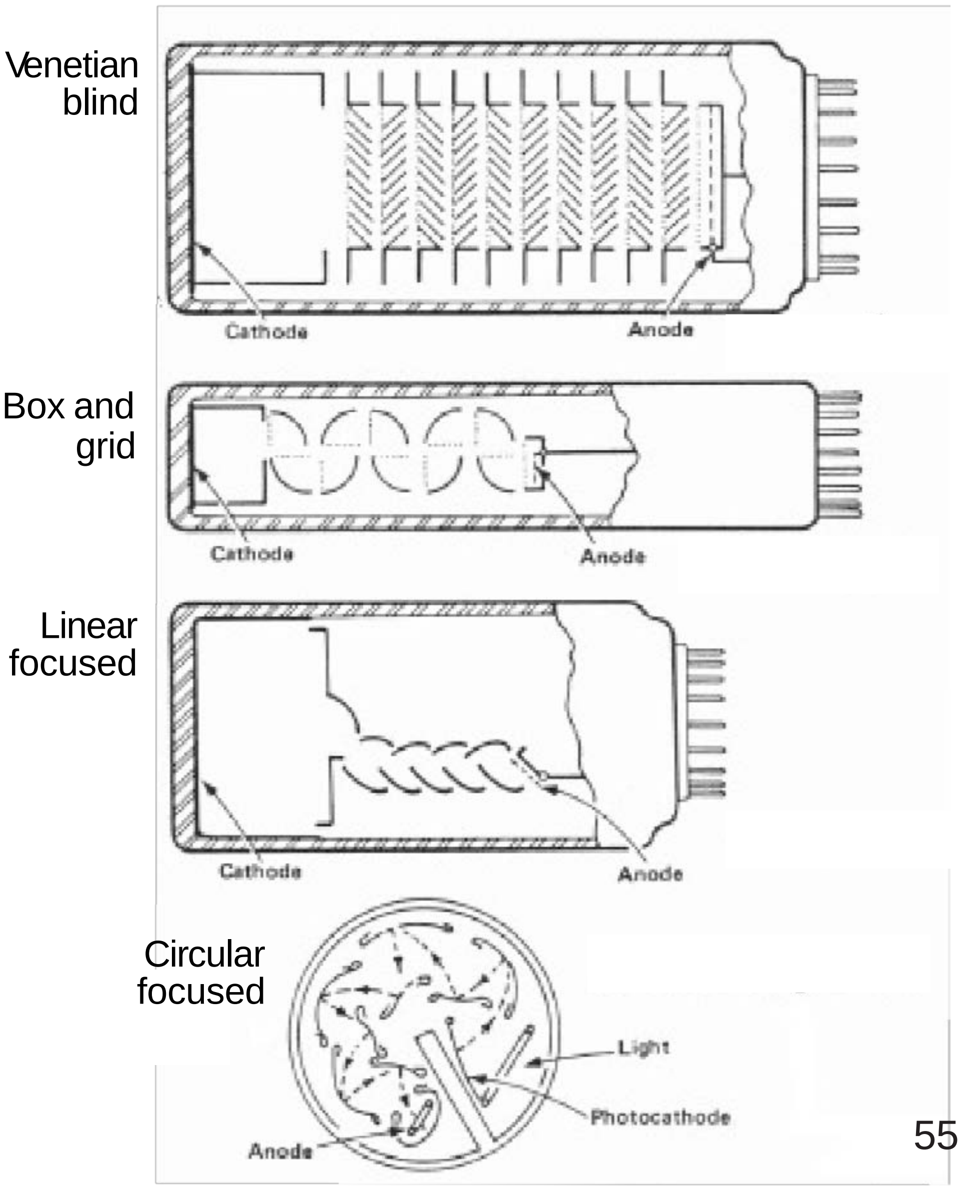
Optimization of

PMT gain
Anode isolation
Linearity
Transit time

B-field dependence

PM’s are in general
very sensitive to B-fields !

Even to earth field (30-60 μT).
μ-metal shielding required.



Photomultipliers – Energy Resolution

Energy resolution influenced by:

Linearity of PMT: at high dynode current possibly saturation by space charge effects; $I_A \propto n_\gamma$ for 3 orders of magnitude possible ...

Photoelectron statistics: given by poisson statistics.

$$P_n(n_e) = \frac{n_e^n \, e^{-n_e}}{n!}$$

with n_e given by dE/dx ...

$$\sigma_n / \langle n \rangle = 1/\sqrt{n_e}$$

light collection efficiency

$$n_e = \frac{dE}{dx} \times \frac{\text{Photons}}{\text{MeV}} \times \eta \times \text{Q.E.}$$

For NaI(Tl) and 10 MeV photon;
photons/MeV = 40000;
η = 0.2; Q.E. =0.25

$$n_e = 20000$$

$$\sigma_n / \langle n \rangle = 0.7\%$$

Secondary electron fluctuations:

$$P_n(\delta) = \frac{\delta^n \, e^{-\delta}}{n!}$$

$$\sigma_n / \langle n \rangle = 1/\sqrt{\delta}$$

with dynode gain δ;
and with N dynodes ...

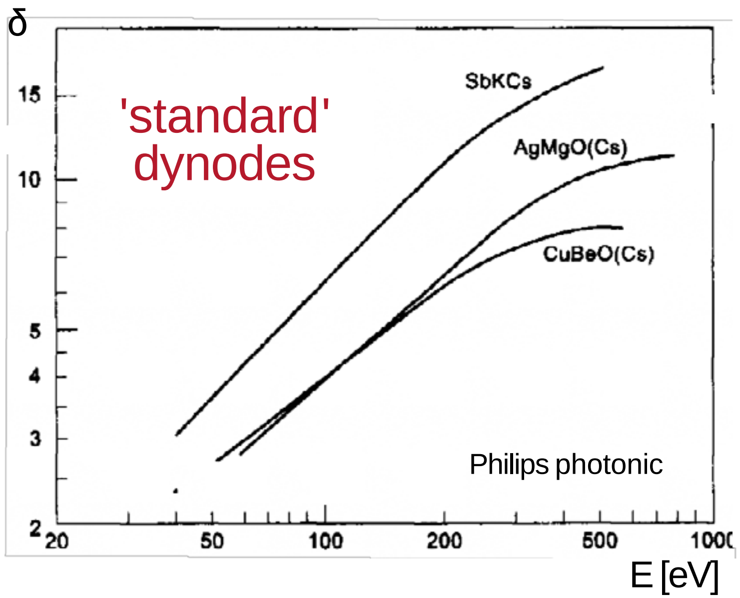
$$\left(\frac{\sigma_n}{\langle n \rangle}\right)^2 = \frac{1}{\delta} + \ldots + \frac{1}{\delta^N} \approx \frac{1}{\delta - 1}$$

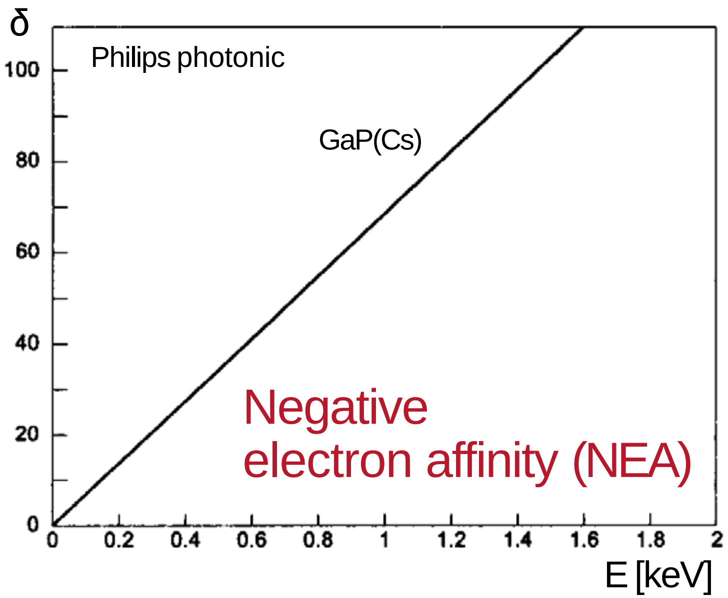
σ_n/<n> dominated by first dynode stage ...

... important for single photon detection

Photomultipliers – Energy Resolution

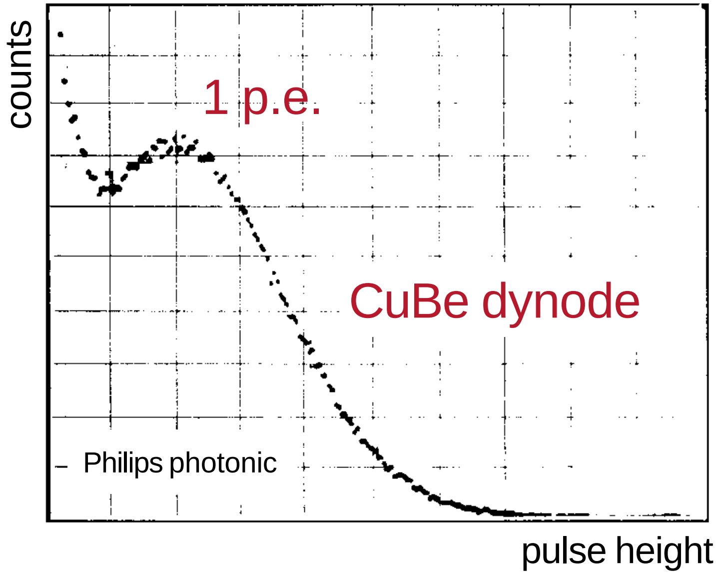
For
detection of
single photons

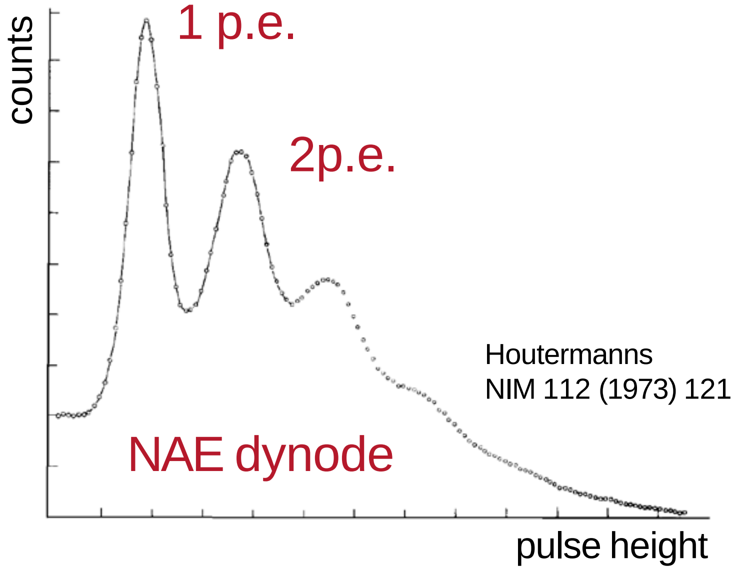




Large δ !

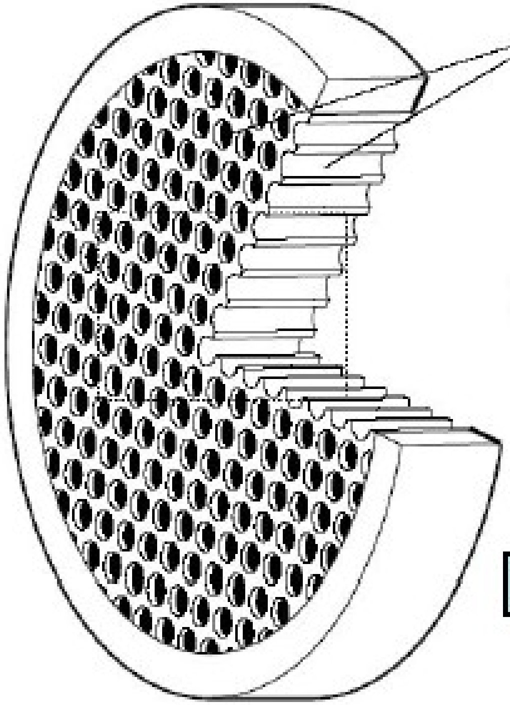
... yields better
energy resolution

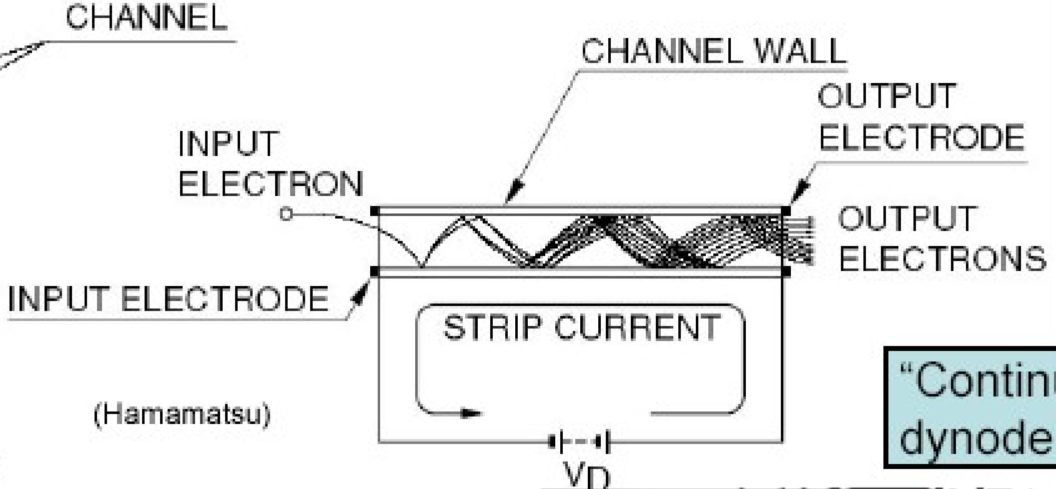




Houtermanns
NIM 112 (1973) 121

Micro Channel Plate

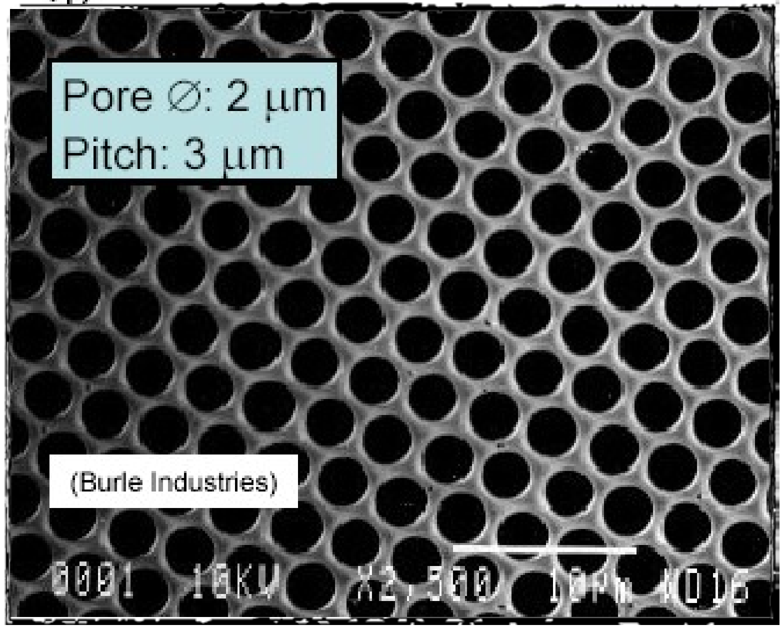




(Hamamatsu)

Pb-glass

“Continuous” dynode chain



Pore ∅: 2 μm
Pitch: 3 μm

(Burle Industries)

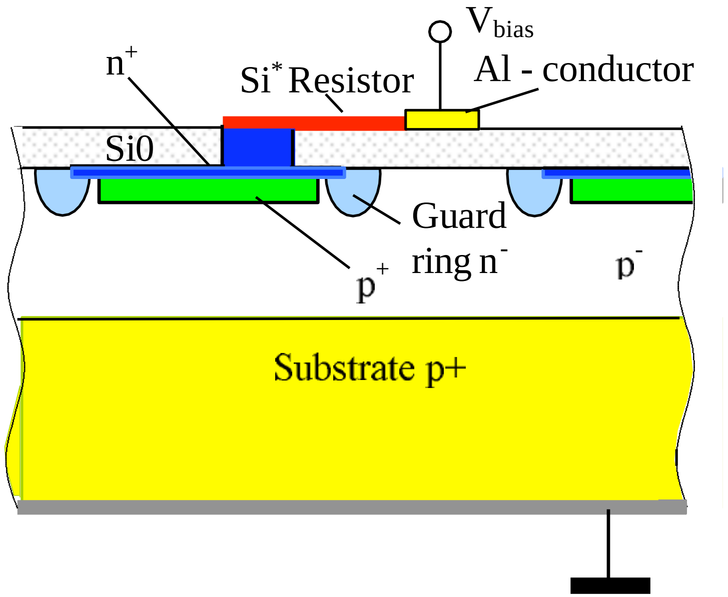
"2D Photomultiplier"

Gain: $5 \cdot 10^4$

Fast signal [time spread ~ 50 ps]
B-Field tolerant [up to 0.1T]

But: limited life time/rate capability

Silicon Photomultipliers



Principle:

Pixelized photo diodes
operated in Geiger Mode

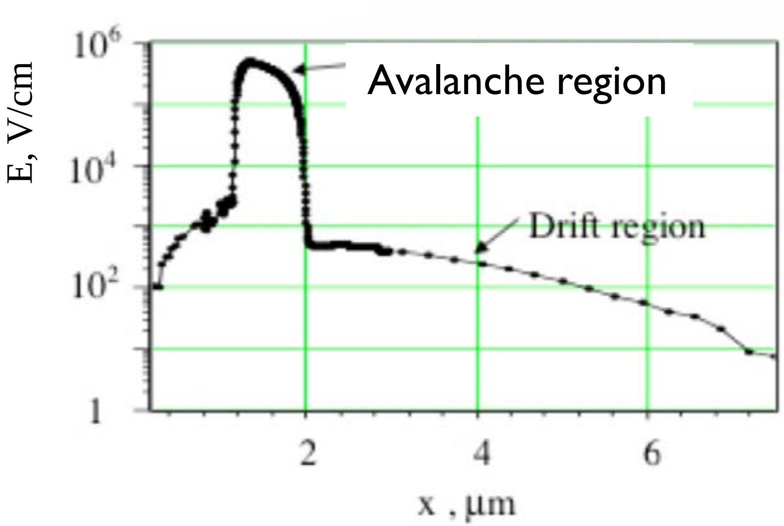
Single pixel works as a binary device

Energy = #photons seen by
summing over all pixels

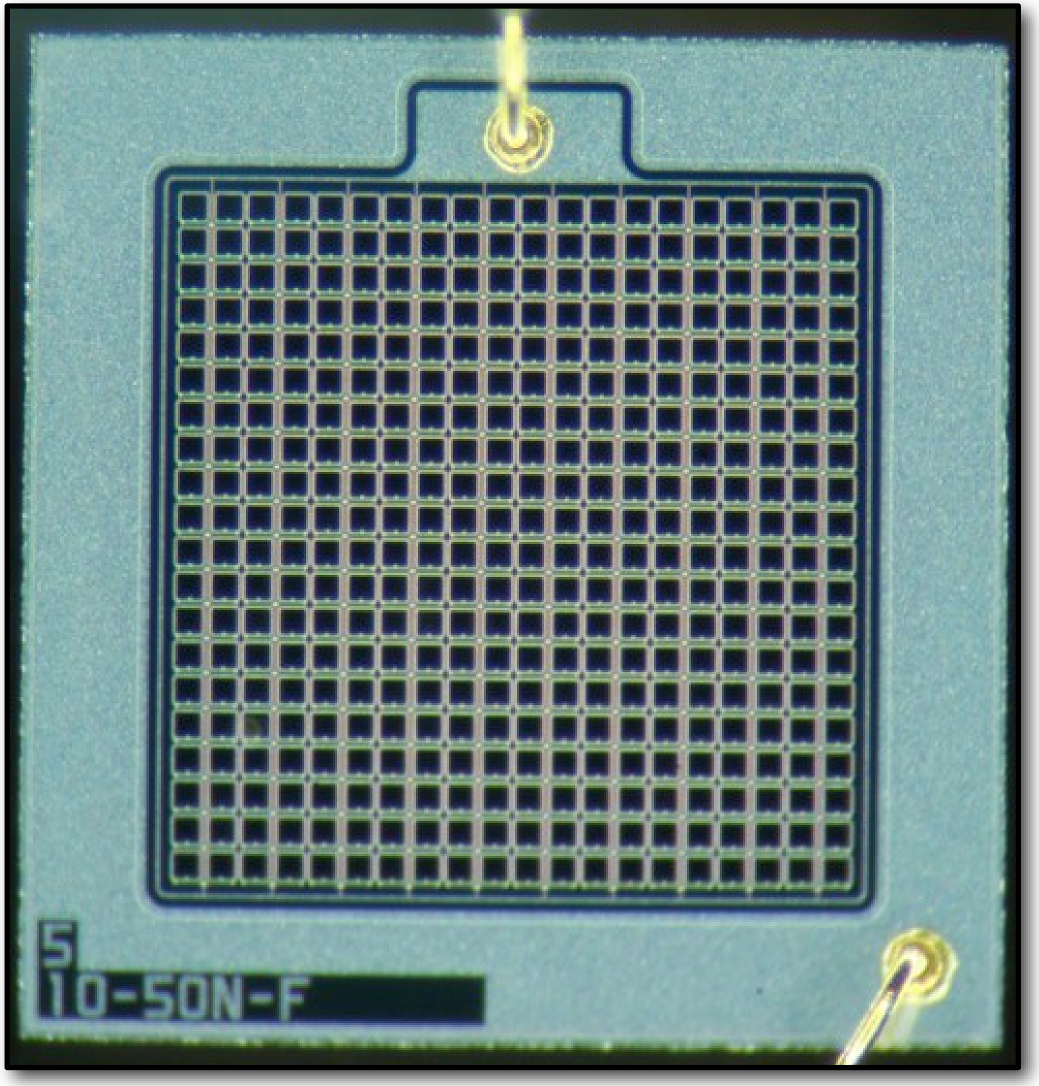
Features:

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

Works at room temperature!
Insensitive to magnetic fields

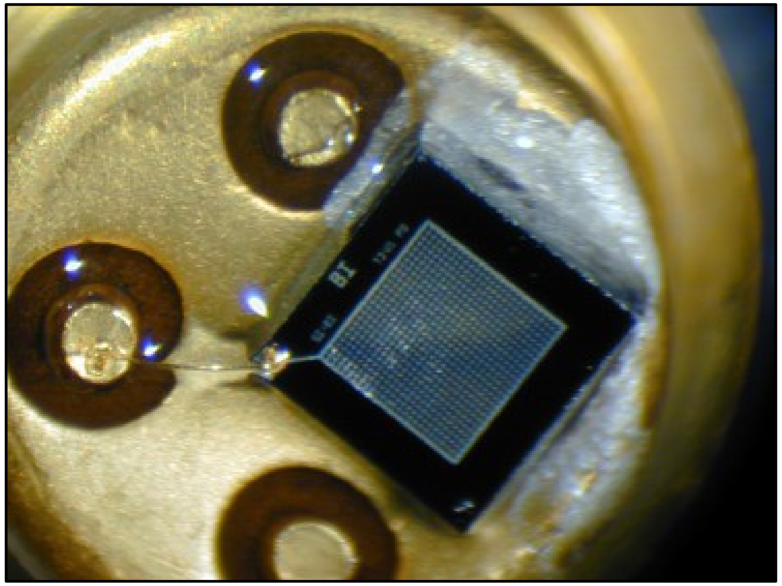


Silicon Photomultipliers

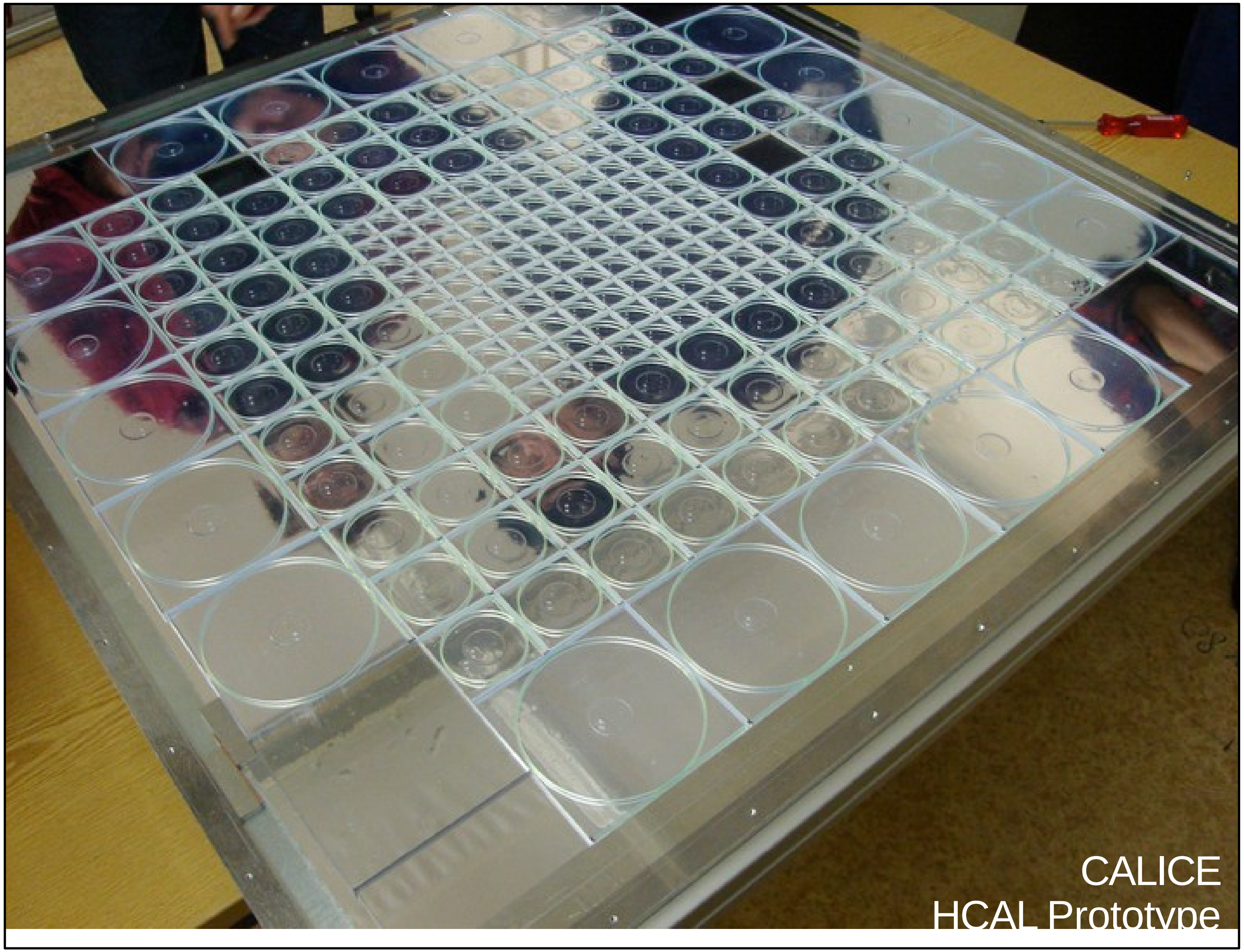


HAMAMATSU
MPPC 400Pixels

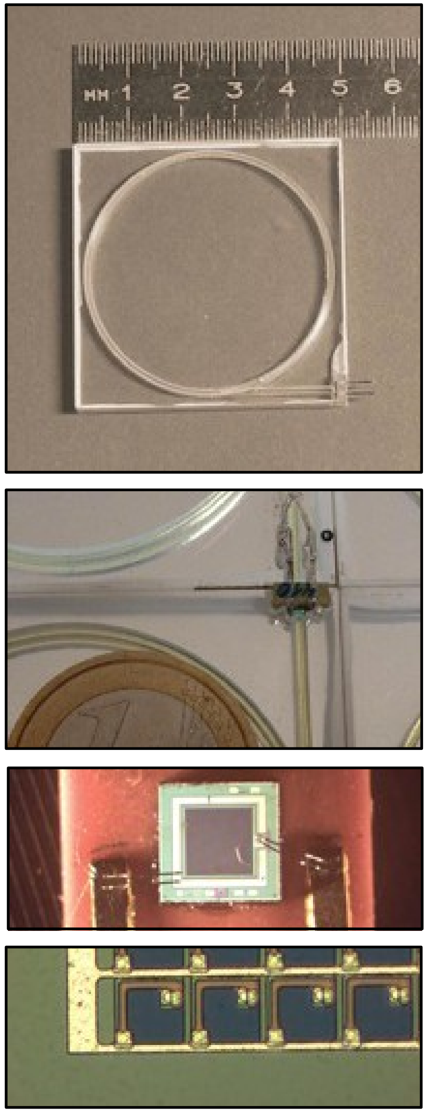
One of the first SiPM
Pulsar, Moscow



Silicon Photomultipliers



CALICE
HCAL Prototype



Scintillation Counters – Applications

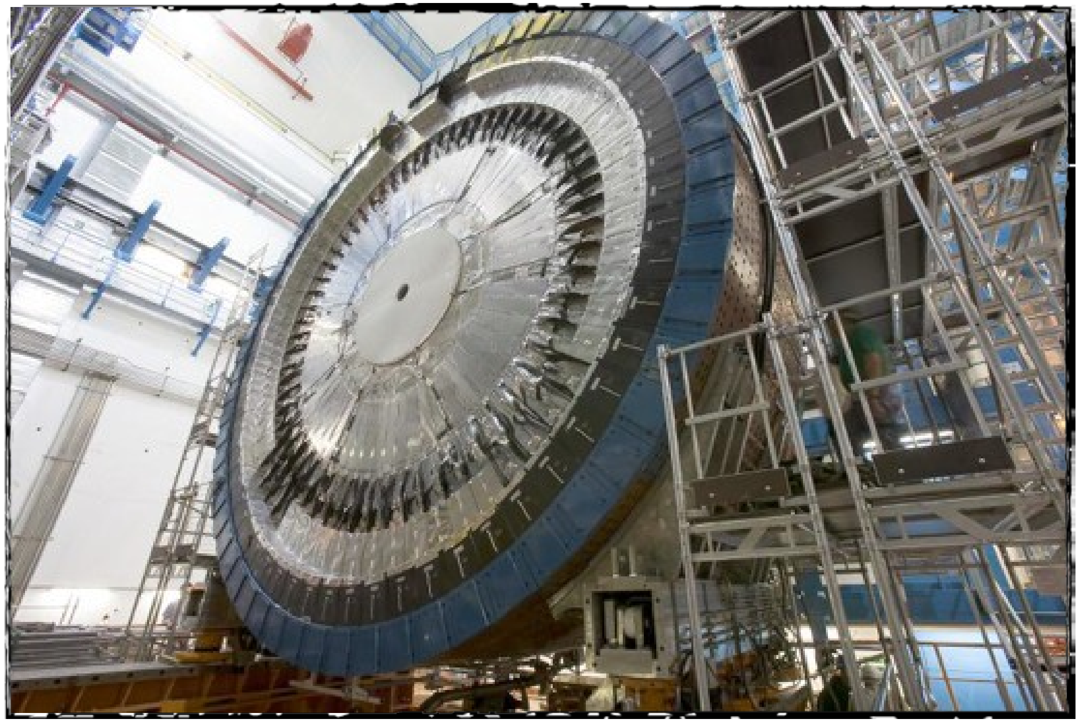
Time of flight (ToF) counters

Energy measurement (calorimeters)

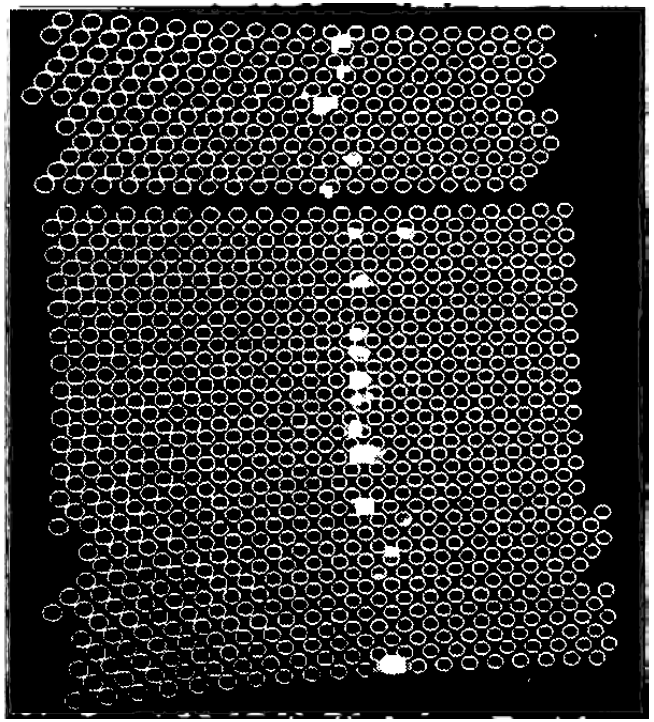
Hodoscopes; fibre trackers

Trigger systems

ATLAS
Minimum Bias Trigger Scintillators

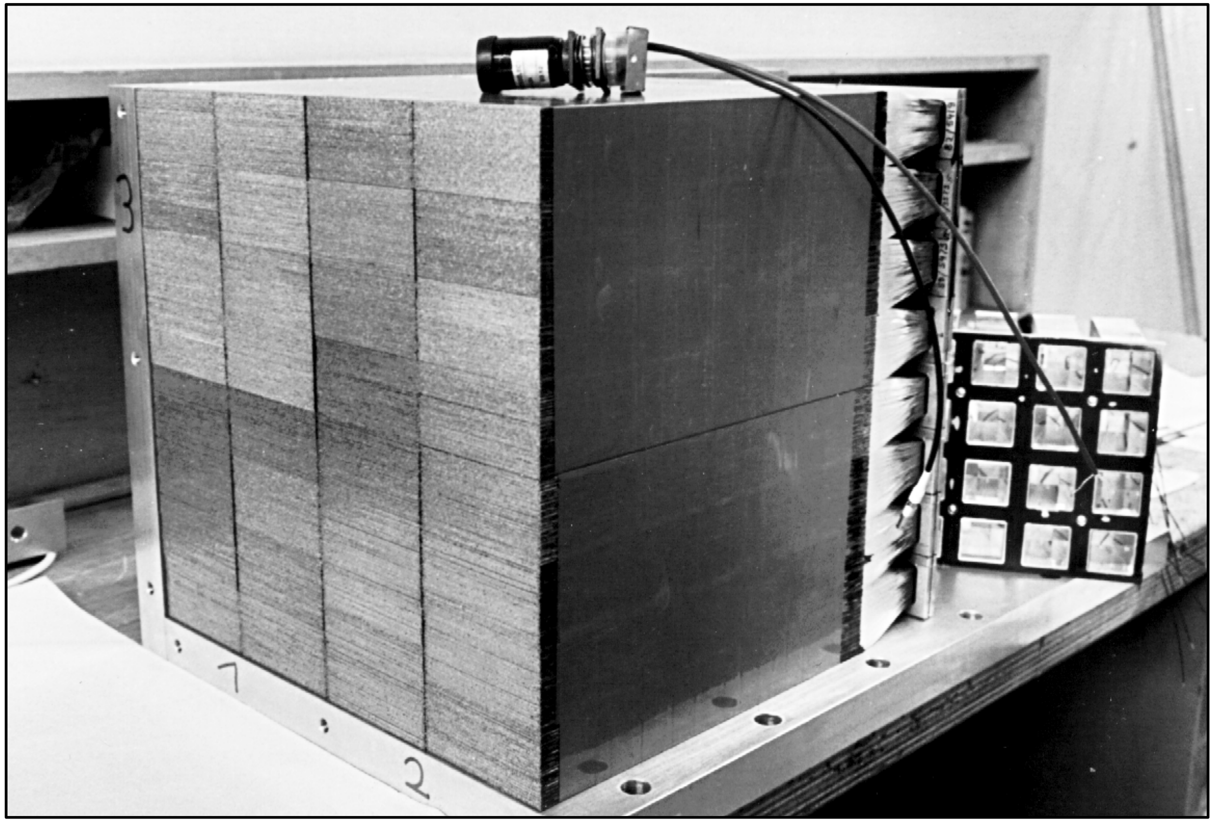


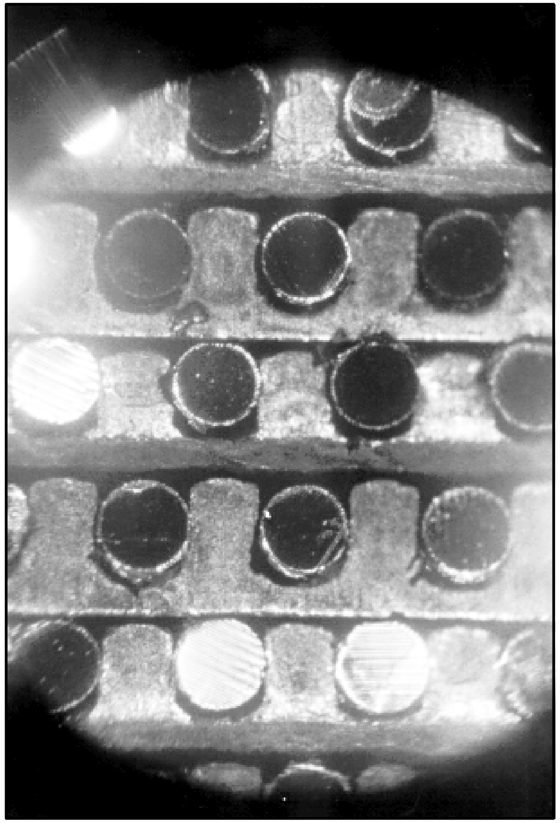
Particle track in
scintillating fibre hodoscope



H1 – Spaghetti Calorimeter

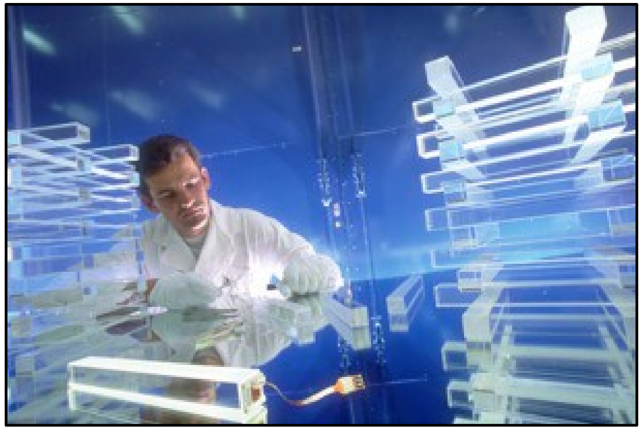
Scintillator : BICRON BCF-12
Photosensor : Photomultipliers





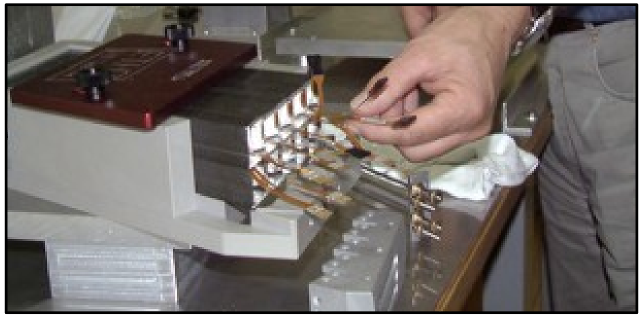
CMS – Crystal Calorimeter (ECAL)

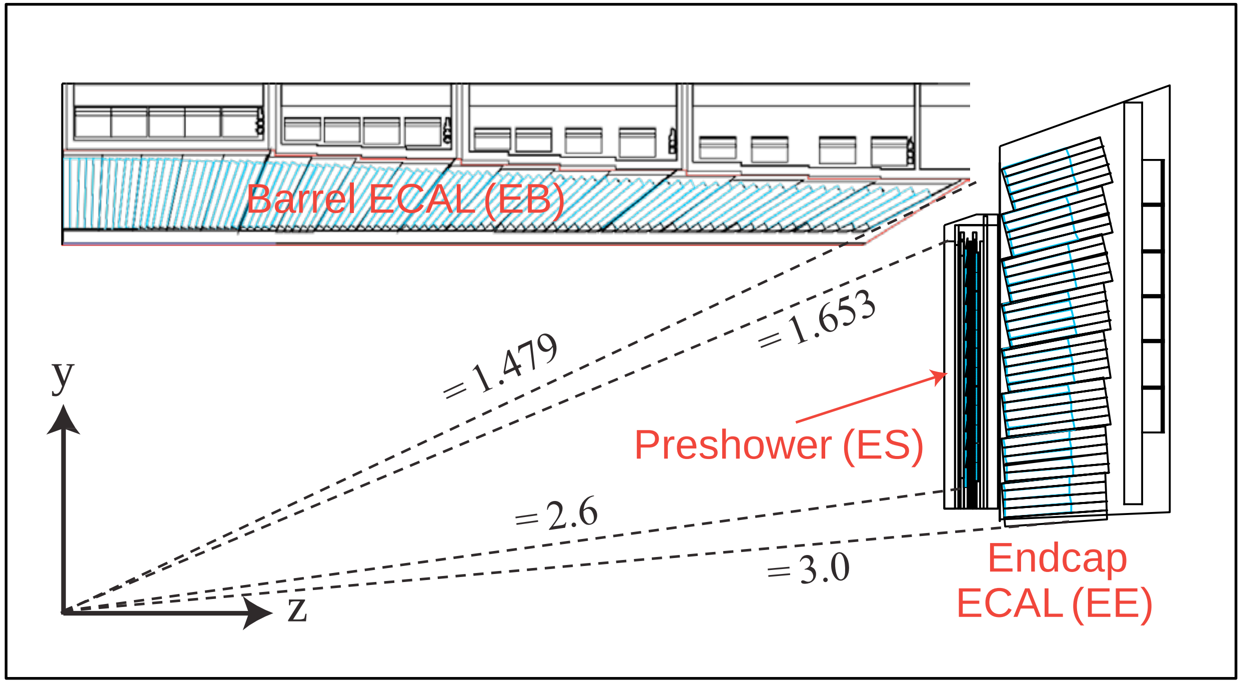
CMS – Crystal Calorimeter (ECAL)



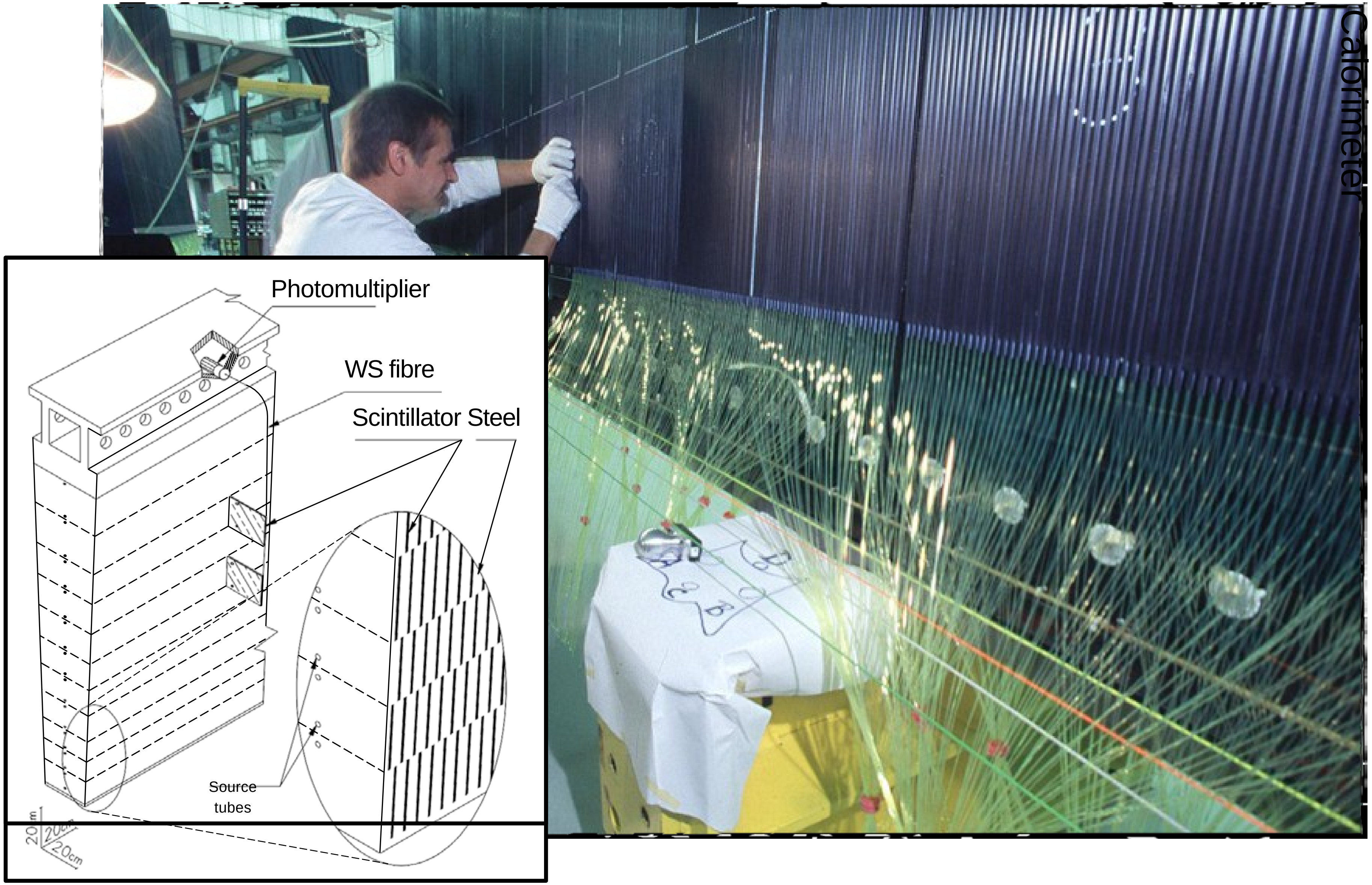
Scintillator : $\mathrm{PBW0}_4$ [Lead Tungsten]
Photosensor : APDs [Avalanche Photodiodes]

Number of crystals: ~ 70000
Light output: 4.5 photons/MeV





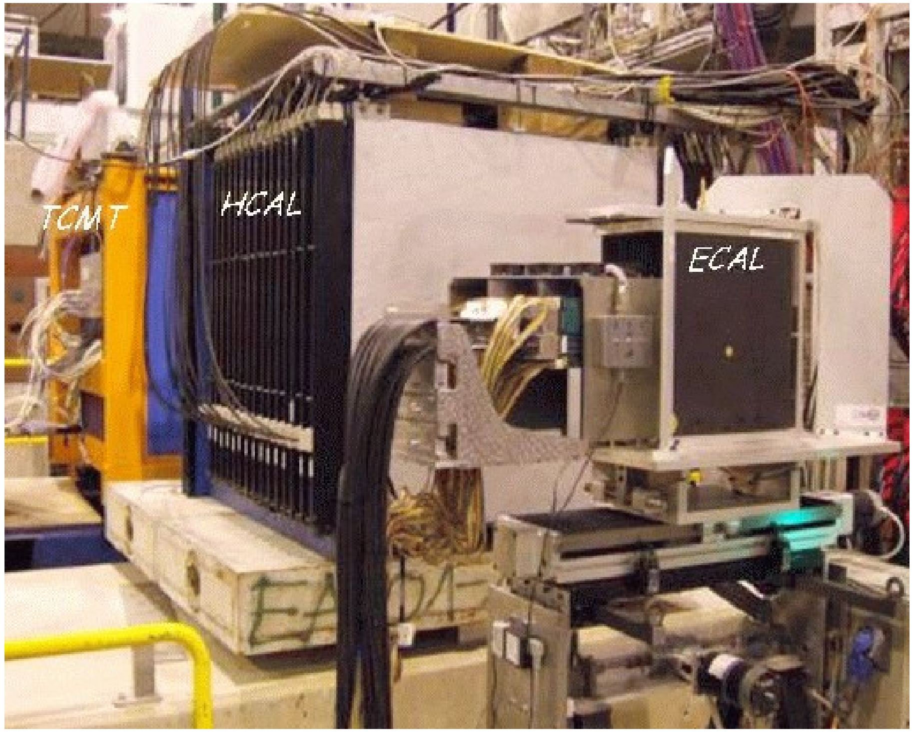
ATLAS – Tile Calorimeter



ATLAS Tile Calorimeter

CALICE – Analogue HCAL

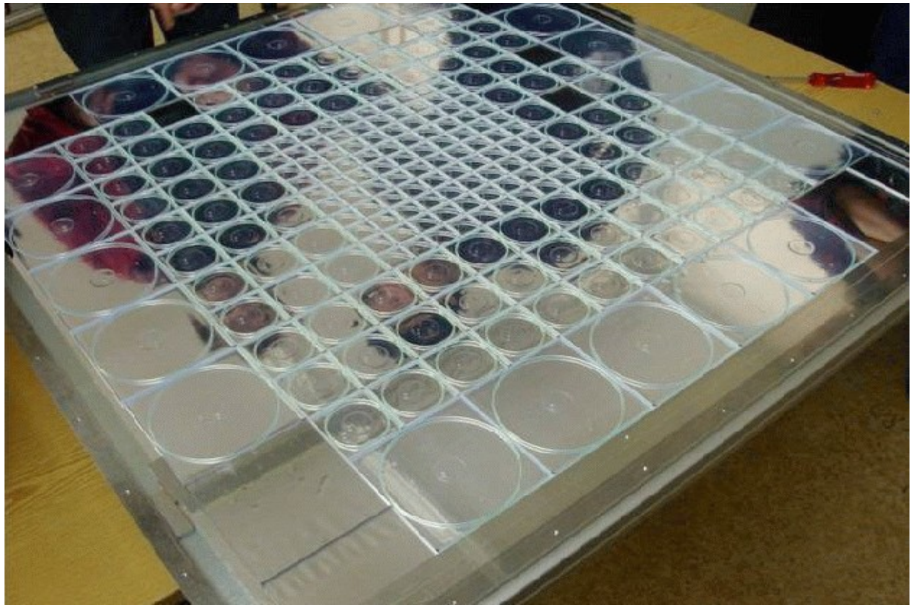
1m^3-Prototype
38 layers



2006/2007 CERN Testbeam
[2008/09, Fermilab]

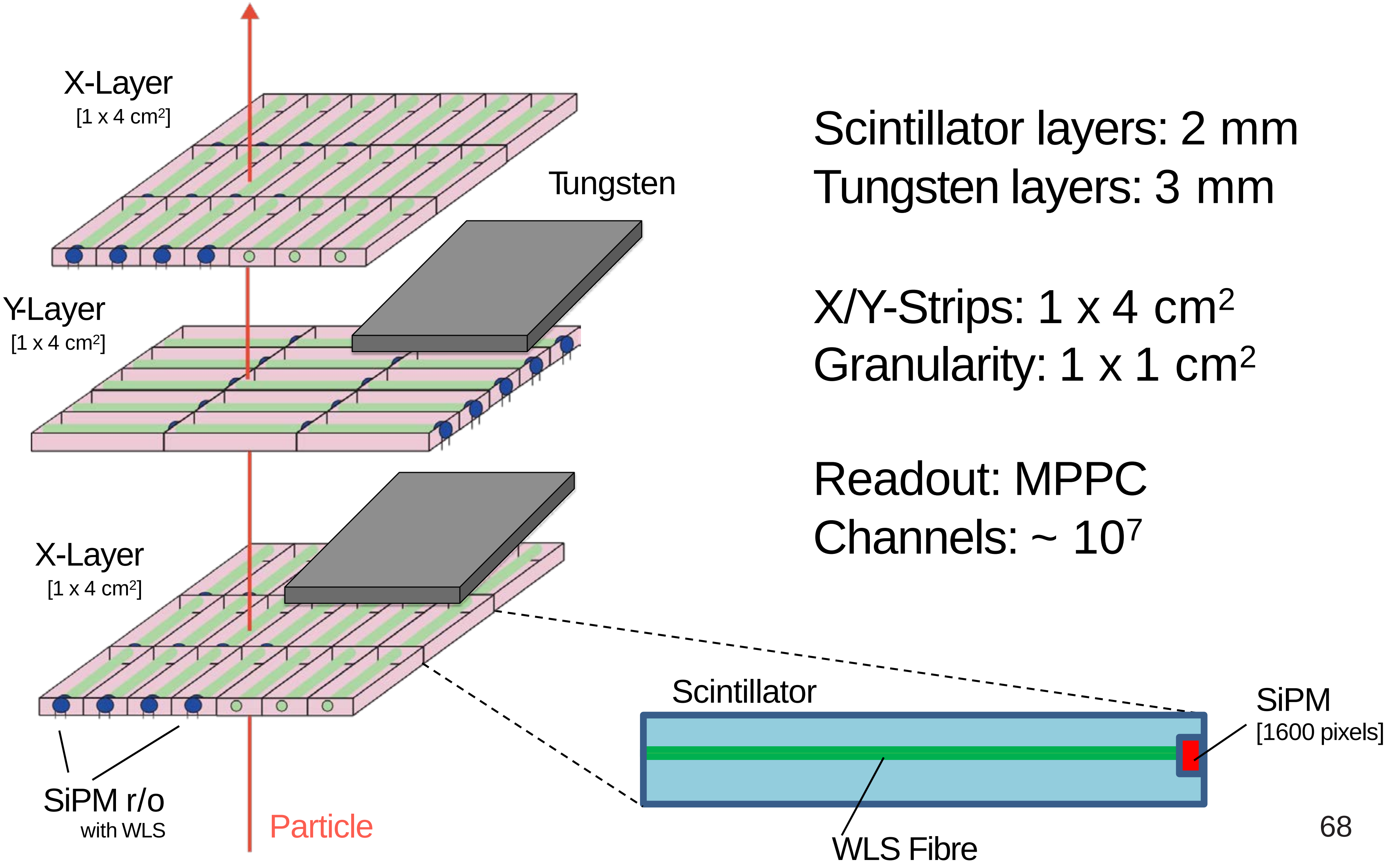
Sandwich structure:

- Scintillator Tiles+WLS+SiPMs (.5 cm)
- Stainless steel absorber (1.6 cm)



Scintillator : Plastic
Photosensor : SiPMs

CALICE – Scintillator ECAL



Scintillator layers: 2 mm
Tungsten layers: 3 mm

X/Y-Strips: 1 x 4 cm^2
Granularity: 1 x 1 cm^2

Readout: MPPC
Channels: ~ 10^7

Some examples of liquid scintillator based detectors

Borexino (low energy solar neutrino detector and geo-neutrino)

KamLAND (reactor neutrino detector and geo-neutrino)

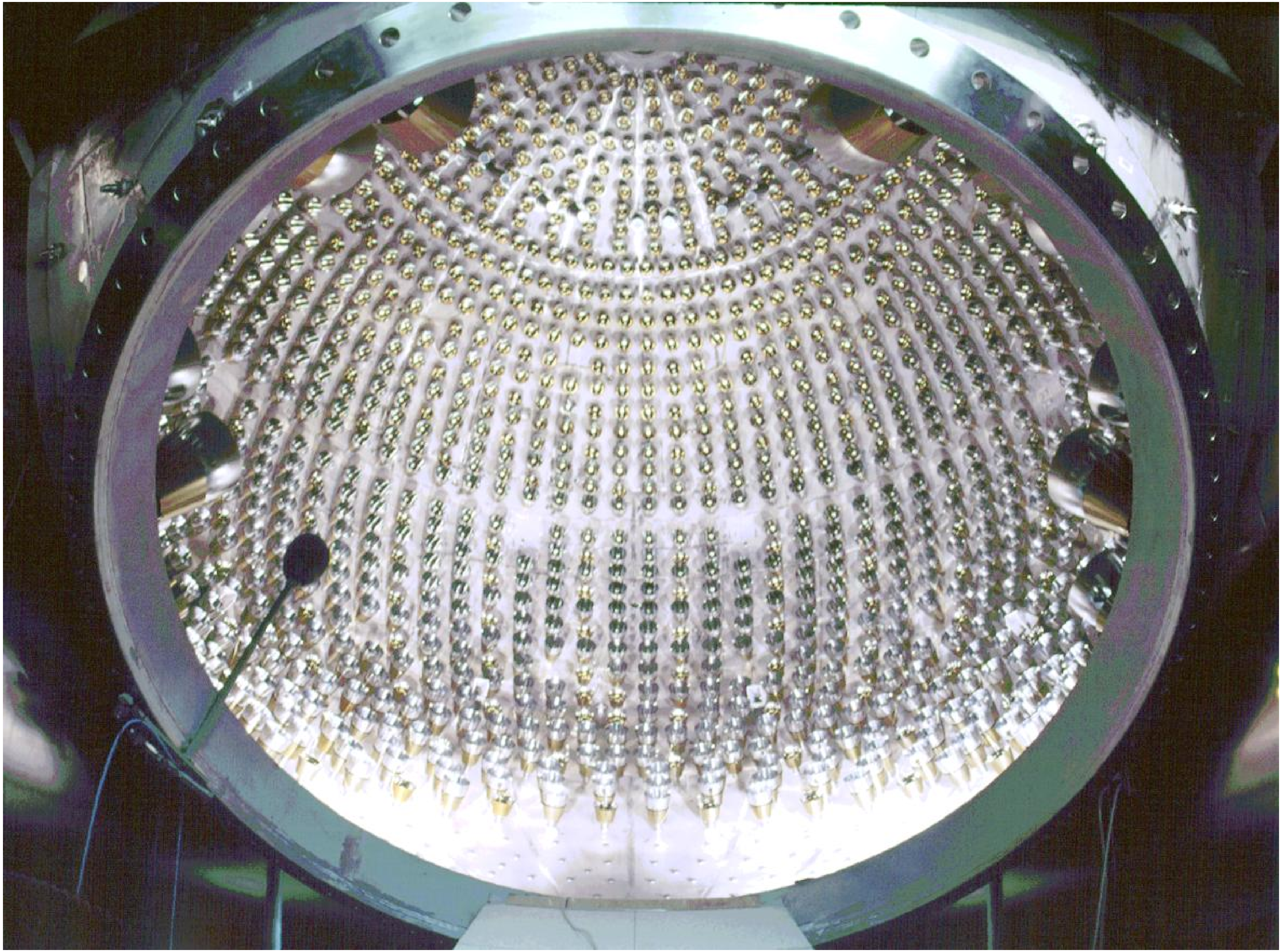
Double Chooz (reactor neutrino detector)

Daya Bay (reactor neutrino detector)

Reno (reactor neutrino detector)

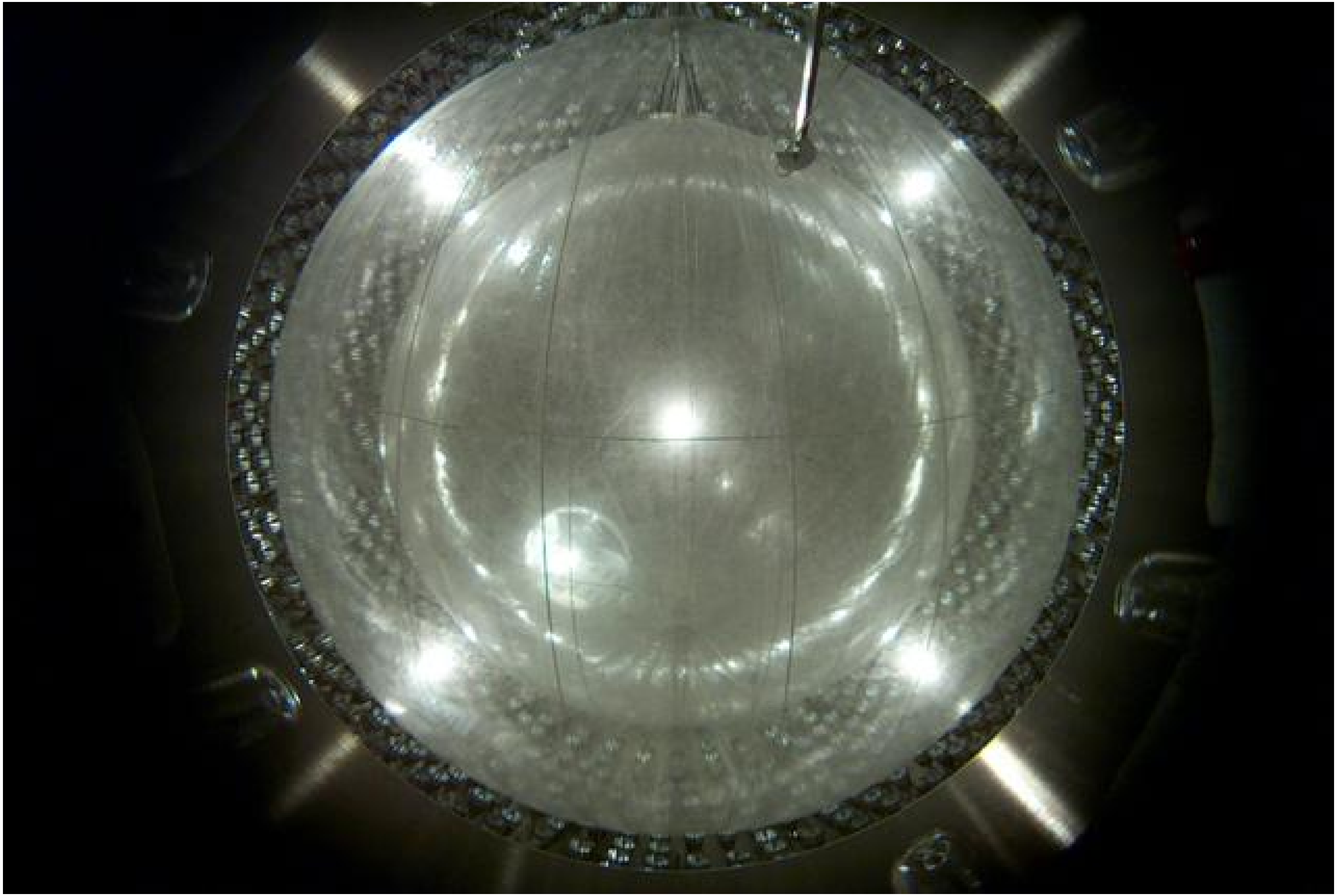
Planned: SNO+ and JUNO

PMT’s on the sphere surface



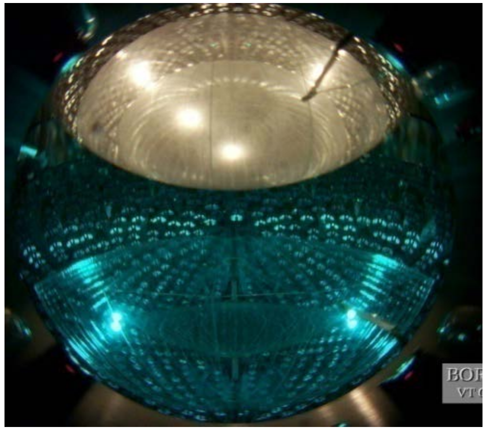
Vessel before inflation (viewed by CCD cameras)

Vessel after inflation (viewed by CCD cameras)



Detector fully filled on May 15th, 2007: DAQ starts

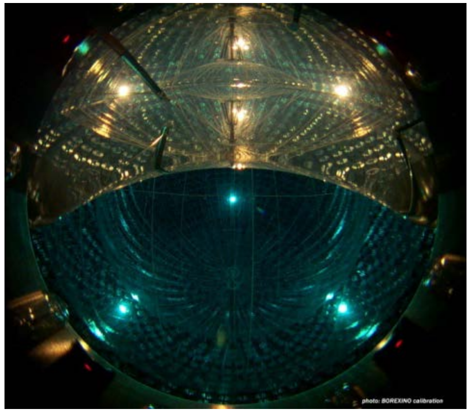
End October 2006



*LAKN –
Low Argon and
Krypton Nitrogen*

Ultra-pure water

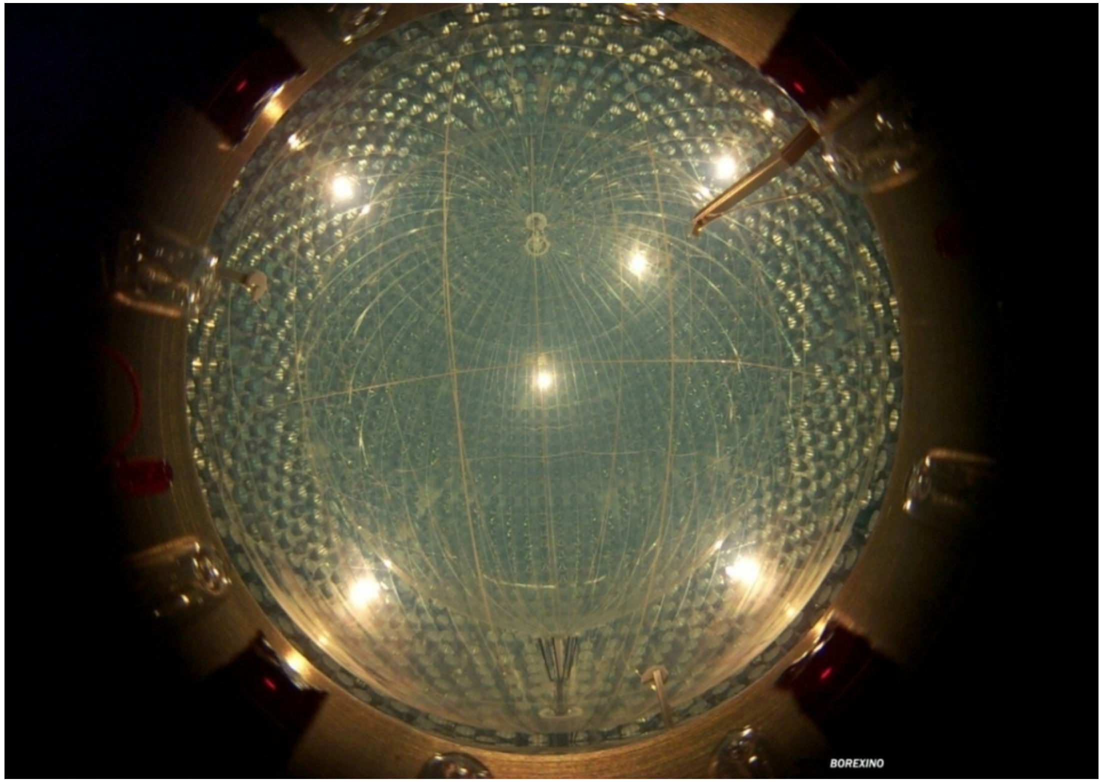
March 2007



Liquid scintillator

Ultra-pure water

May 2007



Photos taken with one of 7 CCD cameras placed inside the detector

Solid State Detectors (SSD)

Ionization chamber medium could be gas, liquid, or solid

- Gas ⇒ electron and ion pairs; Semiconductor ⇒electron and hole pairs

	Gas	Solid
Density	Low	High
Atomic number (Z)	Low	Moderate (Z=14)
Ionization Energy (ε_I)	Moderate (≈ 30 eV)	Low (≈3.6 eV)
Signal Speed	Moderate (10ns-10μs)	Fast (<20 ns)

Solid State Detectors

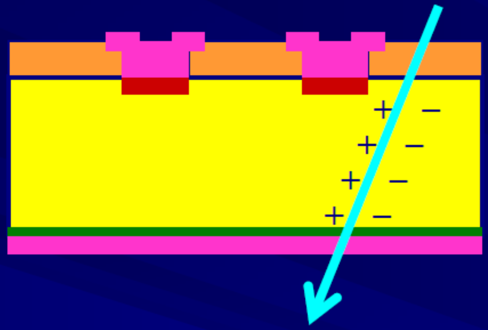
- Energy (E) to create e-h pairs 10 times smaller than gas ionization ⇒ increase charge⇒ good E resolution

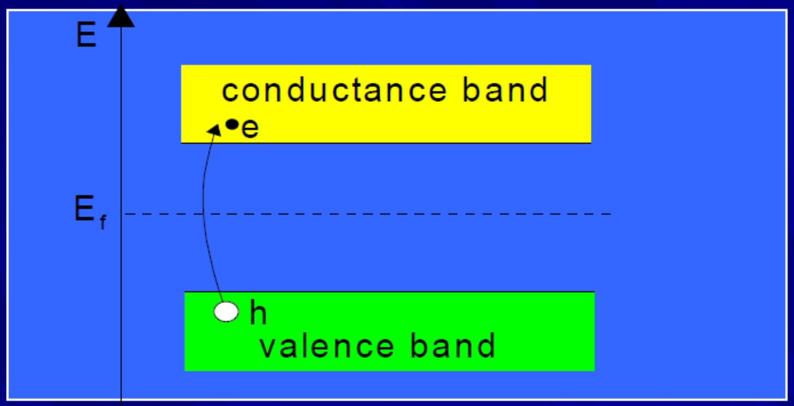
$$\frac{\Delta E}{E} \propto \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{E/\varepsilon_I}} \propto \sqrt{\varepsilon_I}$$

- Greater density
  - Reduced range of secondary electron ⇒ excellent spatial resolution
  - Average E_{loss} ≈390eV/ μm ≈108 e-h/ μm (charge collected is a function of thickness D but no multiplication)
- To minimize multiple scattering D should be small, 300 μm ≈32,000 e-h pairs yields good S/N

Principle of Operation

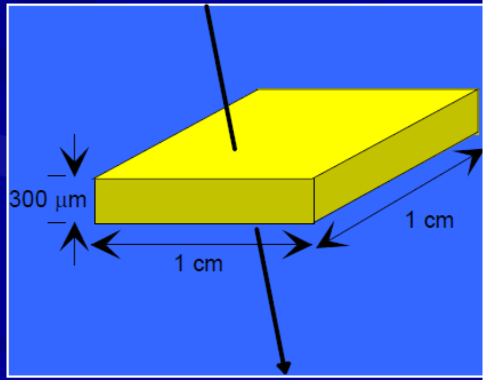
- Goal: precise charged particle position measurement
- Use ionization signal (dE/dx) from charged particle passage





- In a semiconductor, ionization produces electron hole (e-h) pairs
- Use an electric field to drift the e and h to oppositely charged electrodes
- Problem: in pure intrinsic (undoped) silicon, there are more free charge carriers than those produced by a charged particle.

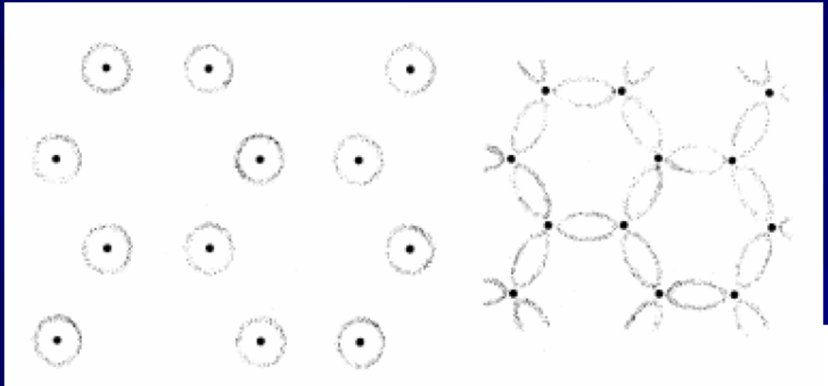
  Ex.: in this volume have 4.5×10^8 free charge carriers
  and only 3.2×10^4 produced by MIP particle



- Problem: electron–hole pairs quickly re-combine
- Solution: Deplete the free charge carriers and collect e (or h) quickly by exploiting the properties of a p-n junction (diode)

Semiconductor: Band Gap

- When isolated atoms are brought together to form a lattice, the discrete atomic states shift to form energy bands



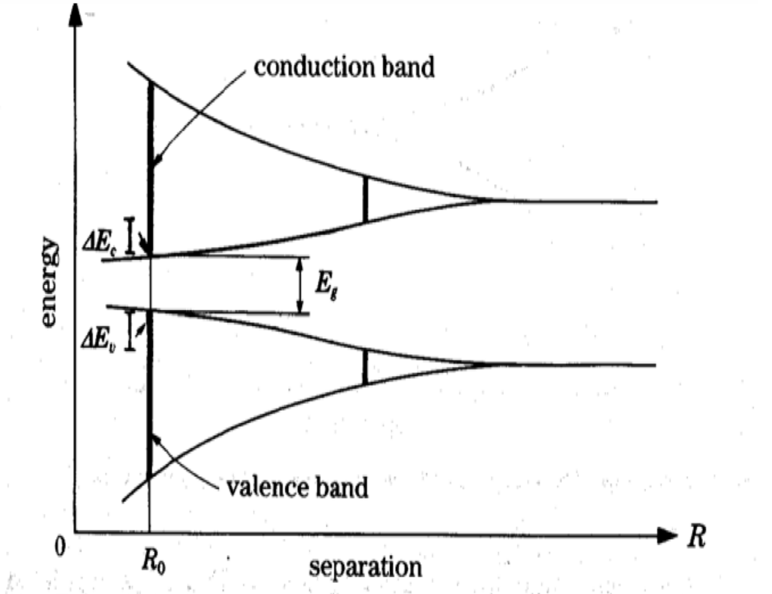
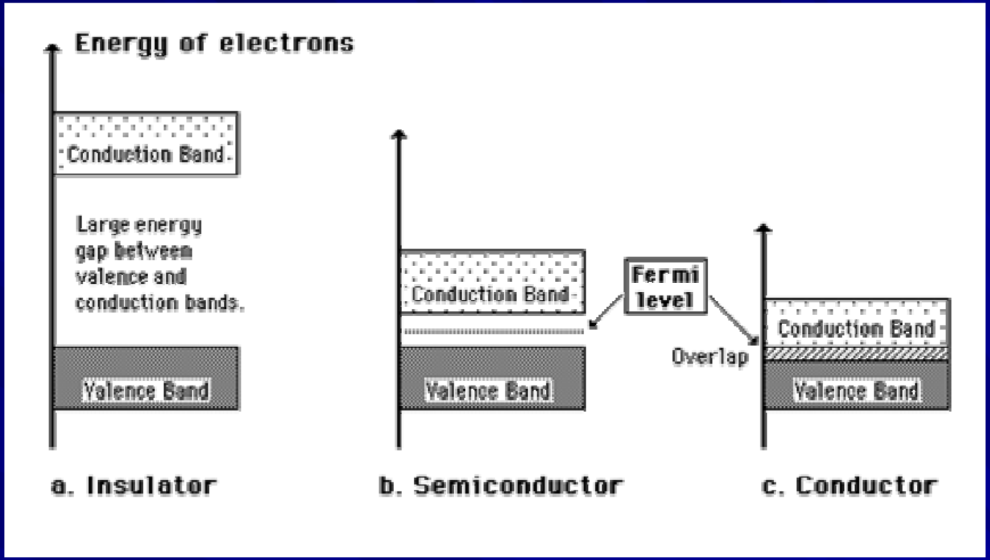


Fig. 1.2. Energy levels in a system of N atoms as a function of the separation R between the atoms. The equilibrium atomic separation is R_0.

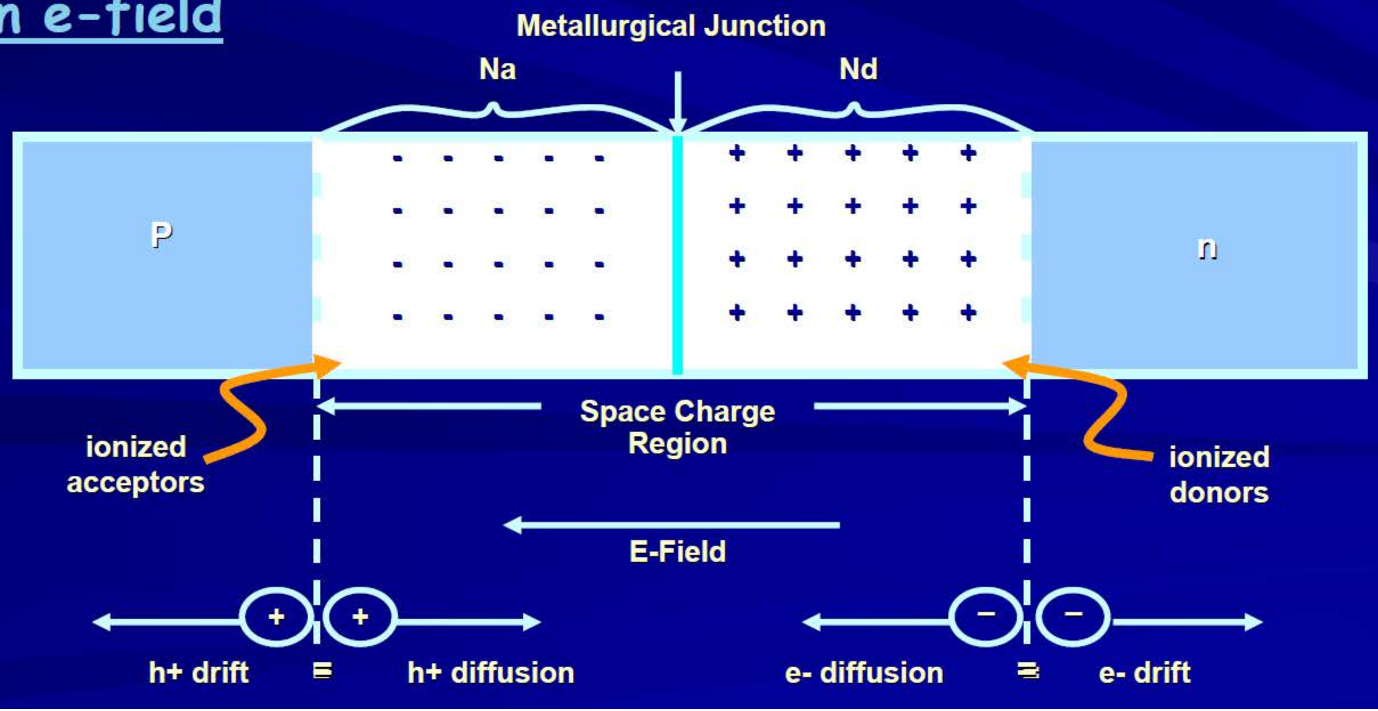


- If the gap is large, the solid is an insulator. If there is no gap, it is a conductor. A semiconductor results when the gap is small.

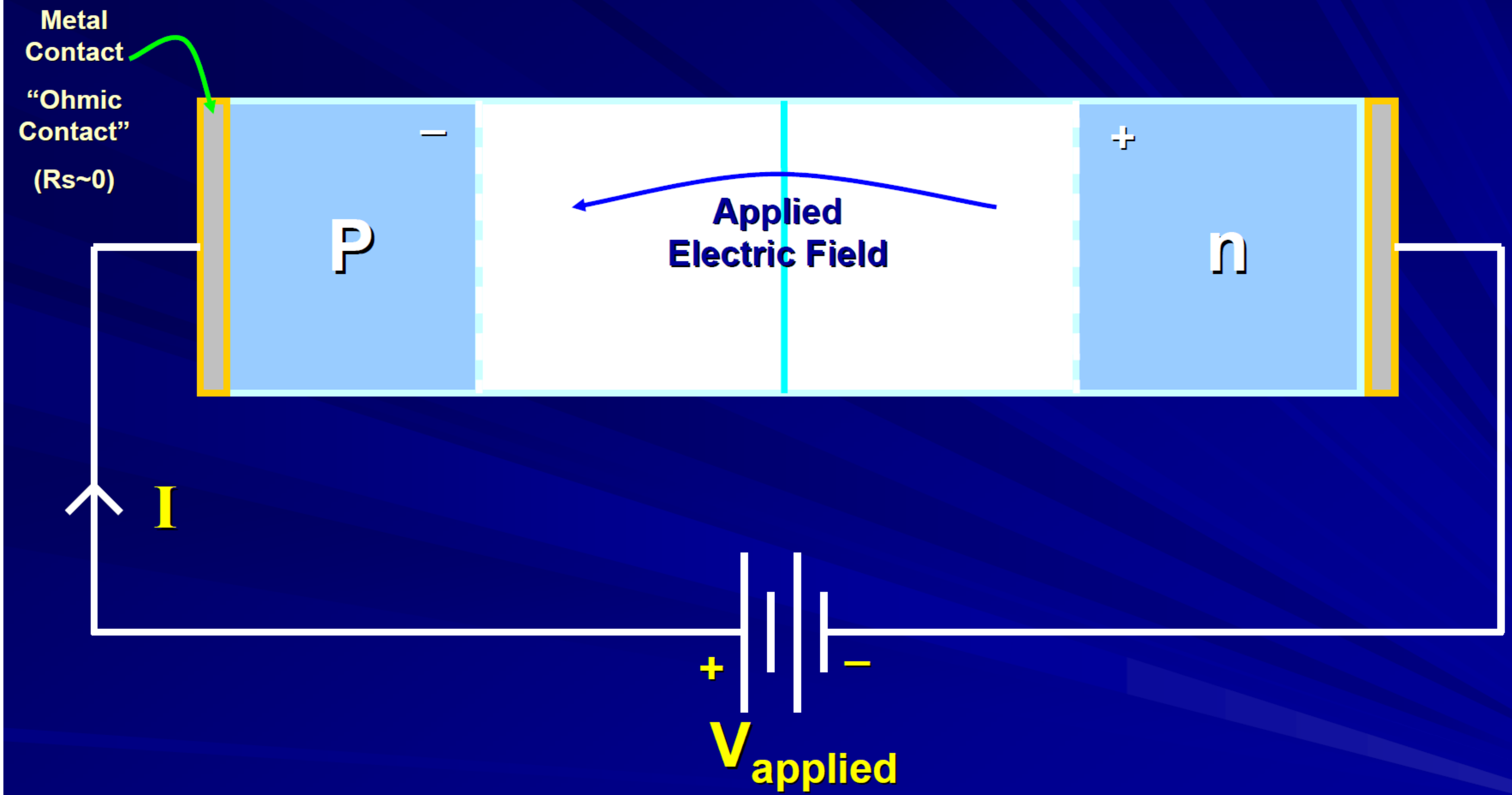
Ge	0.7 eV	GaAs	1.4 eV
Si	1.1 eV	Diamond	4.5 eV

The PN Junction

- **Space Charge Region:** When n and p type silicon are brought together $\Rightarrow$ gradient of electron and hole densities $\Rightarrow$ migration of majority carriers across the junction which leaves a region of net charge of opposite sign on each side, called the space-charge region or depletion region (depleted of free charge carriers). The electric field in the region prevents further migration of carriers $\Rightarrow$ potential difference $\Phi=V_{bi}$ (built in potential).
- **Junction:** Interface where the p- and n-type materials meet.
- **N_A & N_D:** Negative and positive doping (n/cm^3), usually ≈ 10^{15}–10^{20}/cm^3.
- p-n e-field



The Biased PN Junction



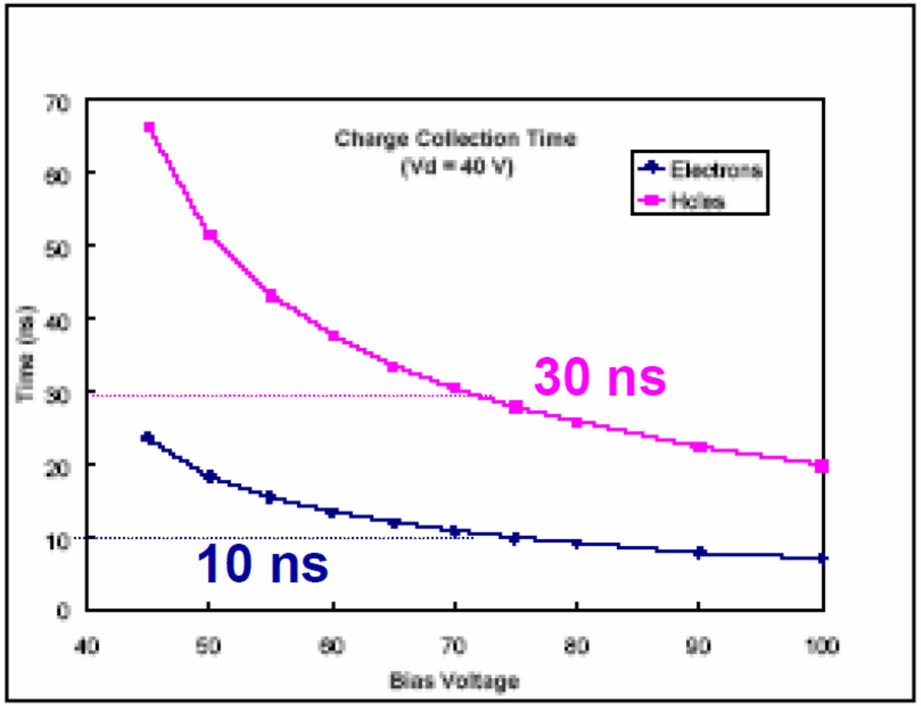
The pn junction is considered biased when an external voltage is applied. There are two types of biasing: Forward bias and Reverse bias. biased p-n junction

Charge collection

- Electron and hole pairs created in the depletion region move under the E field

$$v_{e,h}(x) = \mu_{e,h} E(x)$$

$$\mu_e = 1500 cm^2 / Vs, \mu_h = 450 cm^2 / Vs$$



- The time required for a carrier to traverse the sensitive volume is the collection time.
- The collection time can be reduced by over-biasing the sensor

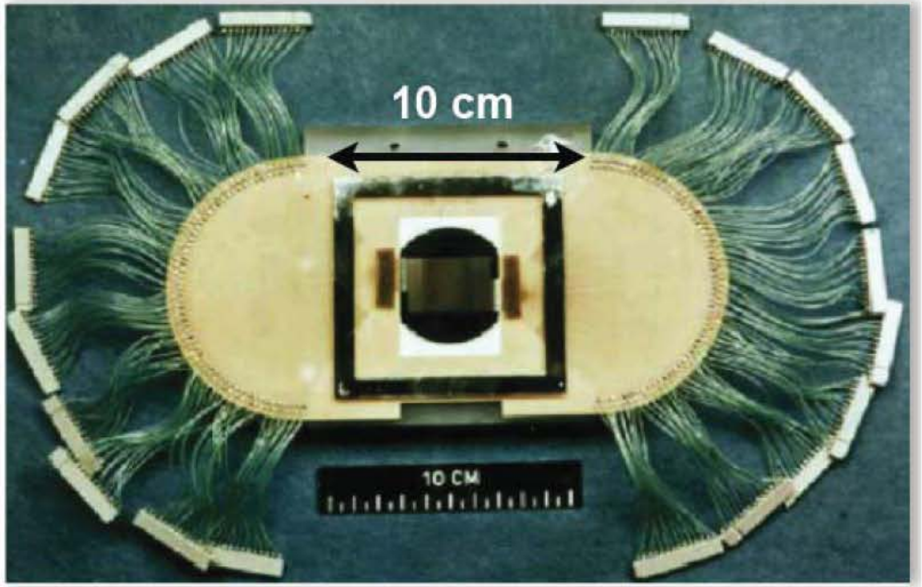
$$t(x) = \frac{D^2}{2\mu_p V_d} \ln\left(\frac{V_{bias} - V_{fd}}{V_{bias} - V_{fd} + 2V_{fd}\left(1 - \frac{x}{D}\right)} \right)$$

Historical developments

> NA11 at CERN

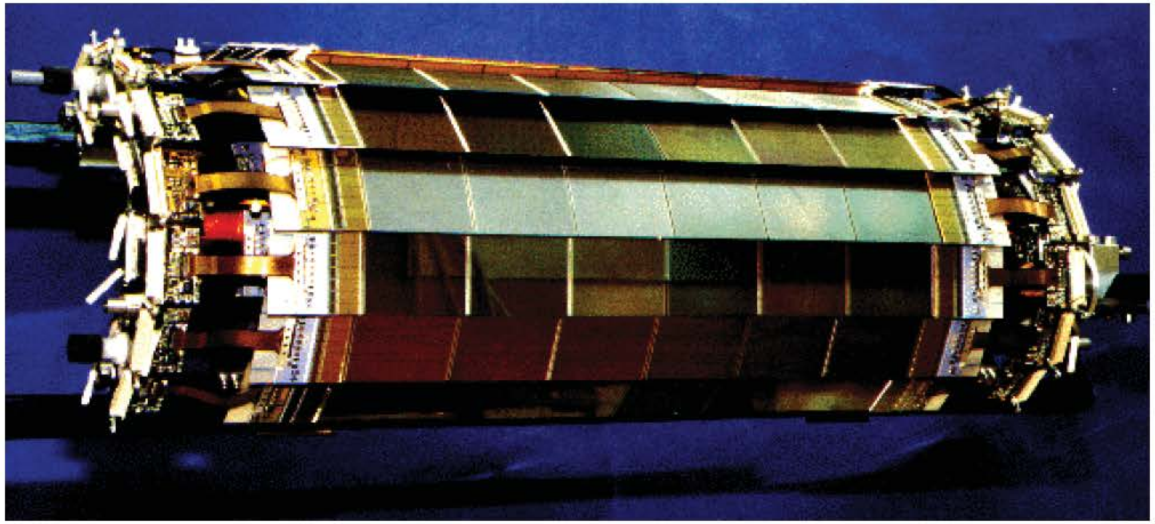
First use of a position-sensitive silicon detector in HEP experiment

- Measurement of charm-quark lifetime
- 1200 diode strips on 24 x 36mm^2 active area
- 250-500 µm thick bulk material
- 4.5 µm resolution



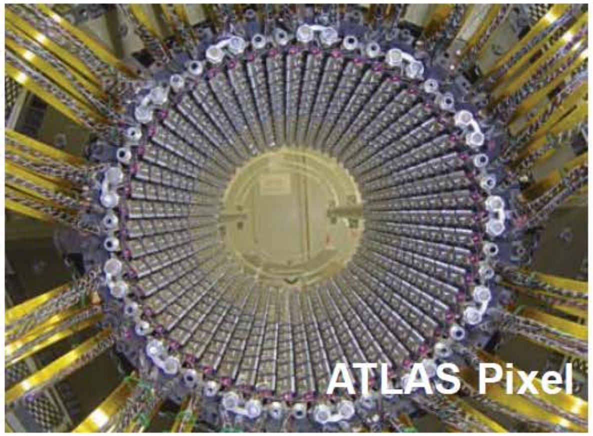
Historical developments

- **LEP and SLAC**
  - ASIC's at end of ladders
  - Minimise the mass inside tracking volume
  - Minimise the mass between interaction point and detectors
  - Minimise the distance between interaction point and the detectors
- Enabled heavy flavour physics i.e. short lived particles



- 2 silicon layers, 40cm long, inner radius 6.3cm, outer radius 11cm
- 300μm Silicon wafers giving thickness of only $0.015X_0$
- S/N rΦ = 28:1; z = 17:1
- $\sigma_{r\phi} = 12\mu m$; $\sigma_z = 14\mu m$

Currently at the LHC



Elemental Semiconductor

- **Germanium:**
  - Used in nuclear physics
  - Needs cooling due to small band gap of 0.66 eV (usually done with liquid nitrogen at 77 K)
- **Silicon:**
  - Can be operated at room temperature
  - Synergies with micro electronics industry
  - Standard material for vertex and tracking detectors in high energy physics
- **Diamond (CVD or single crystal):**
  - Allotrope of carbon
  - Large band gap (requires no depletion zone)
  - very radiation hard
  - Disadvantages: low signal and high cost

Why Silicon

- Semiconductor with moderate bandgap (1.12eV)
- Energy to create e/h pair (signal quanta)= 3.6eV

plus phonon excitation

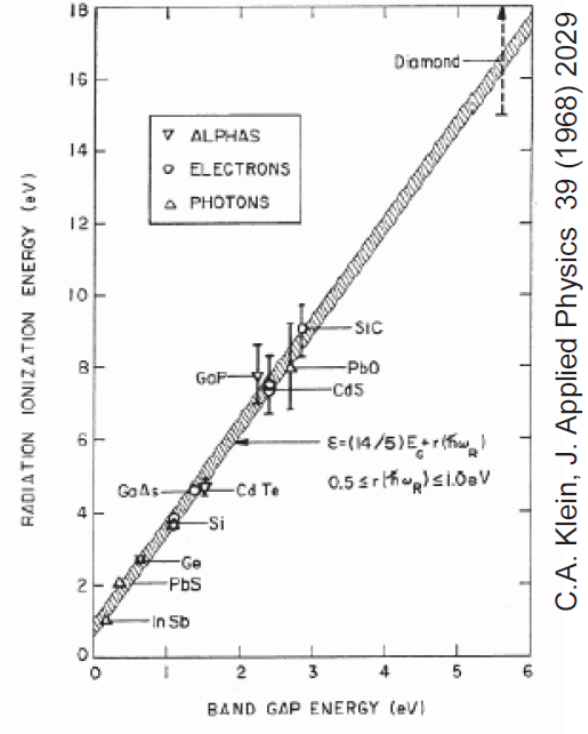
  - (c.f Argon gas = 15eV)
  - High carrier yield
  - Better energy resolution and high signal

  ⇒no gain stage required
- High density and atomic number
  - Higher specific energy loss

  ⇒Thinner detectors

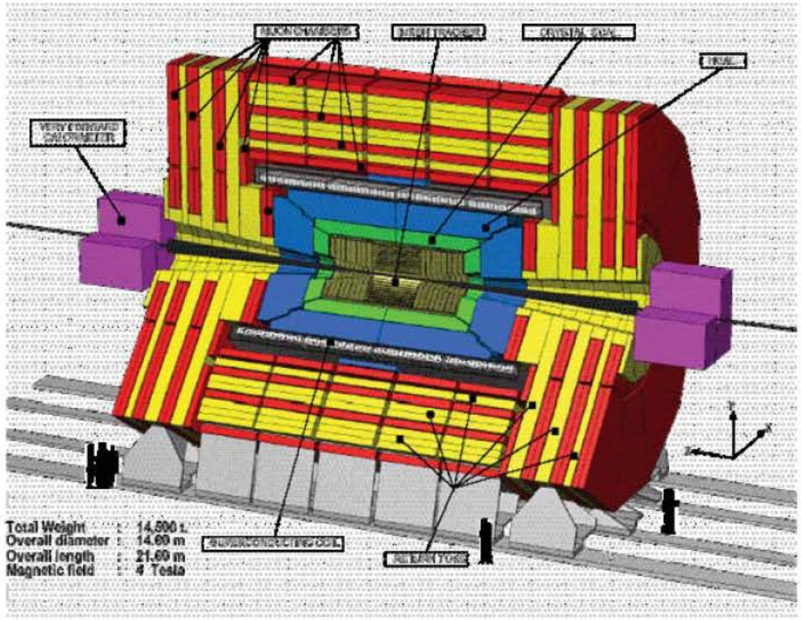
  ⇒Reduced range of secondary particles

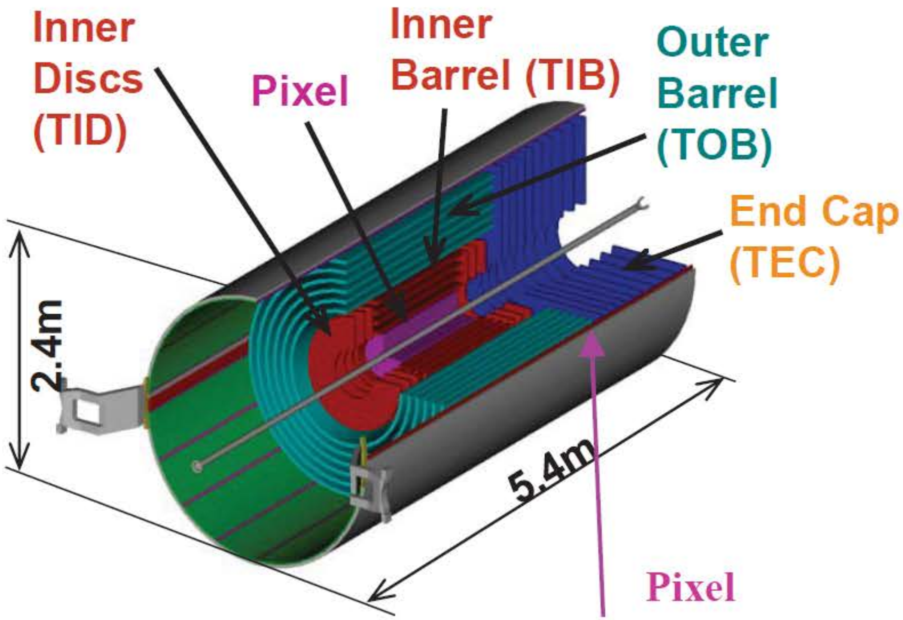
  ⇒better spatial resolution
- High carrier mobility ⇒ Fast!
  - Less than 30ns to collect entire signal
- **Large experience in industry** with micro-chip technology
- High intrinsic radiation hardness



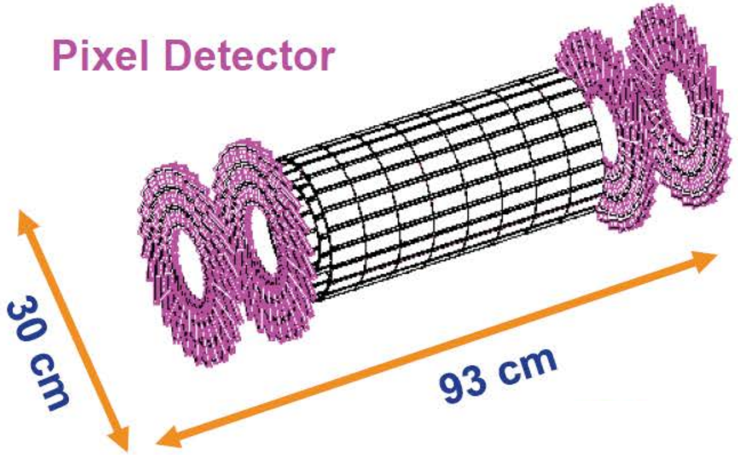
C.A. Klein, J. Applied Physics 39 (1968) 2029

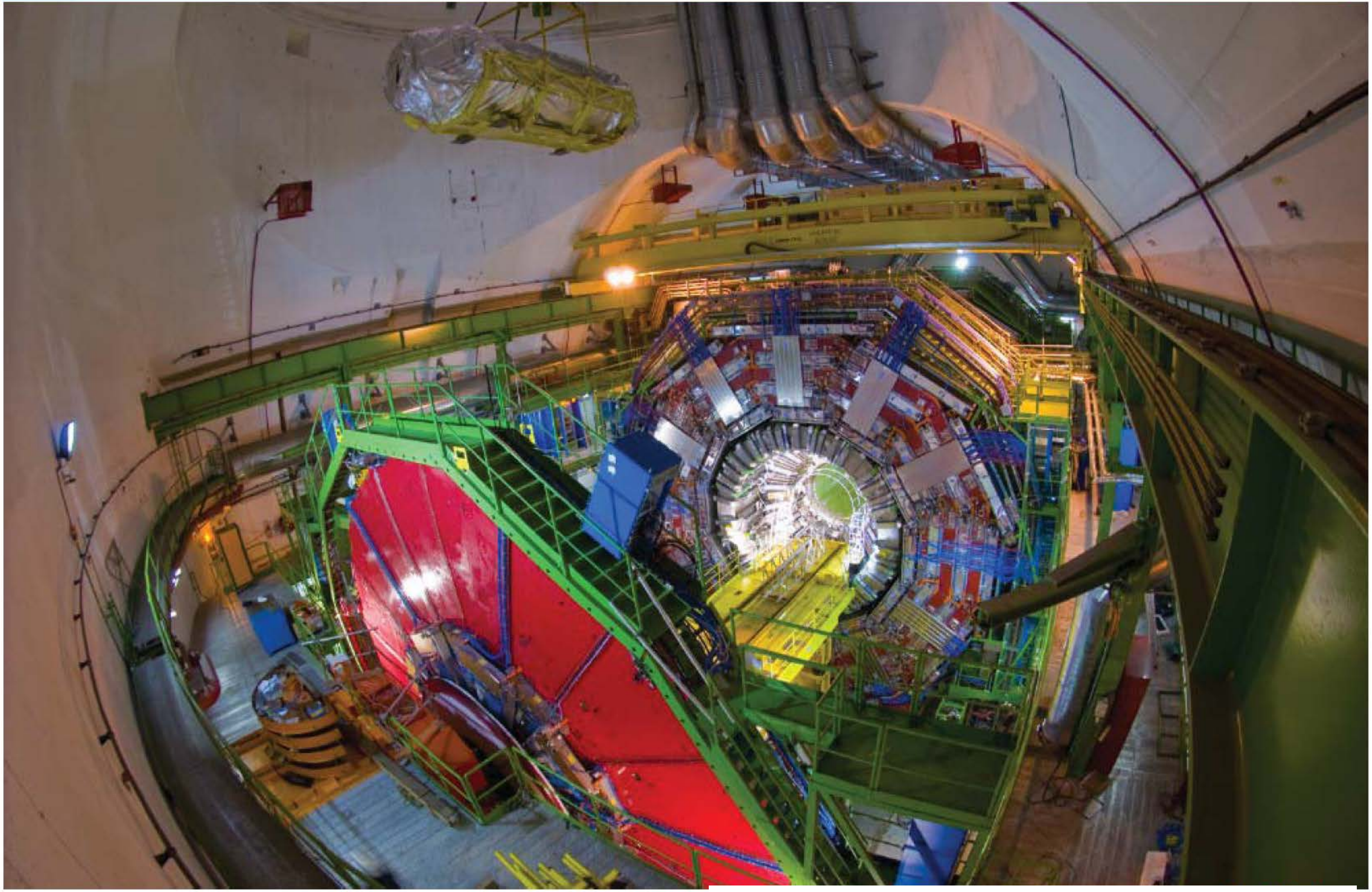
Example – CMS Tracker





- **Largest silicon tracker**
  - **Micro Strip Tracker:**
  - ~ 214 m^2 of silicon strip sensors, 11.4 million strips
  - **Pixel:**
  - Inner 3 layers: silicon pixels (~ $1m^2$)
  - 66 million pixels (100x150μm)
  - Precision: σ(rφ) ~ σ(z) ~ 15μm
  - Most challenging operating environments (LHC)





Summary

- More than 100 years of particle physics & discoveries possible thanks to a large variety of instruments and techniques
- Imaging devices are unbeatable in precision but slow & cannot be triggered
- Logic devices still largely in use (Geiger counters, scintillators, Cherenkov detectors)
- Todays particle detectors merge all possible techniques to create “electronic images” of particles

- In order to detect a particle, it has to interact - and deposit energy

  → all means are good = use all types of interaction