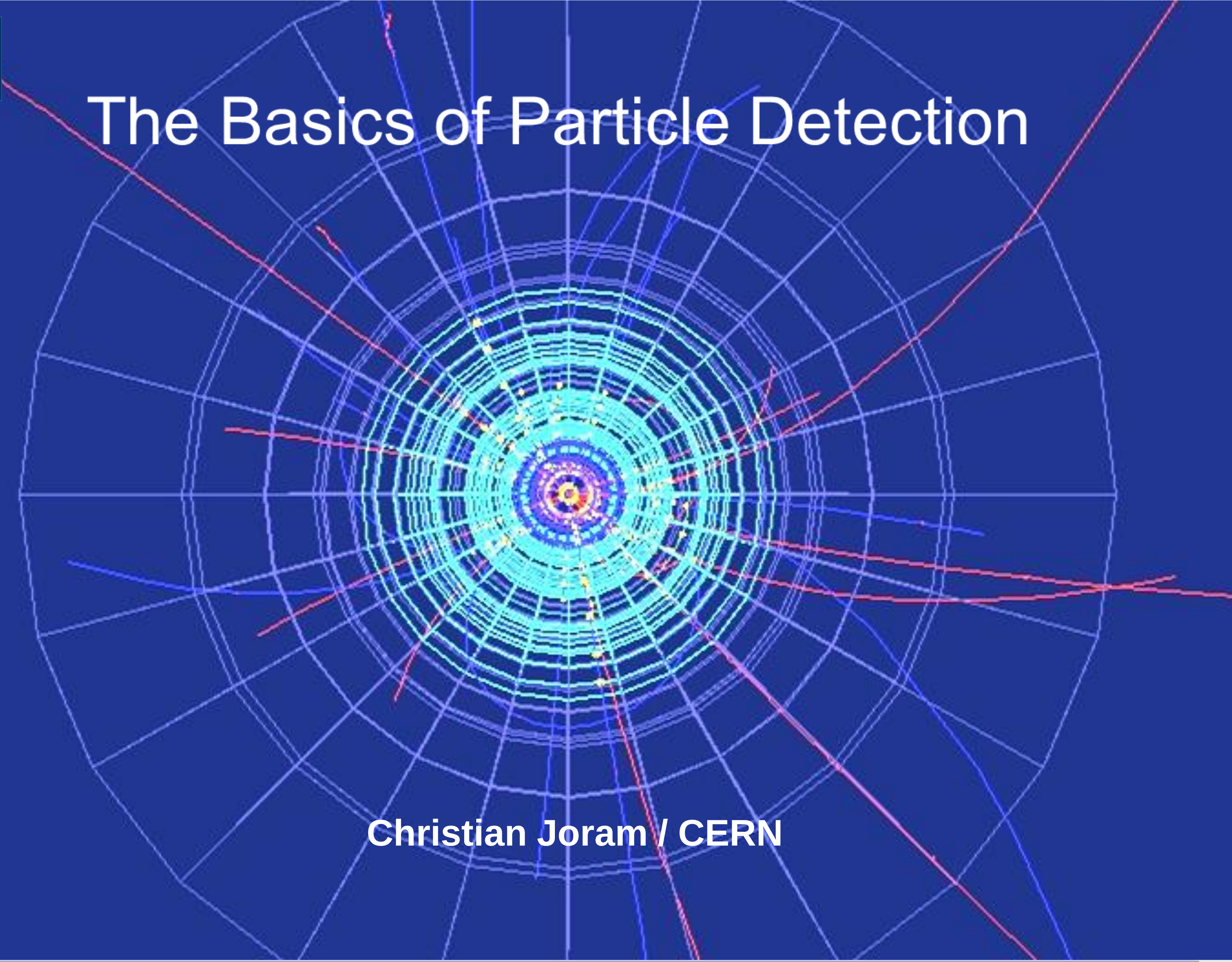
The Basics of Particle Detection



Christian Joram / CERN

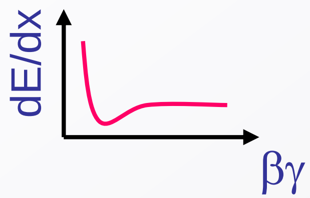
Outline

- Lecture 1 **– Interaction of charged particles**
- Lecture 2 **– Gaseous and solid state tracking detectors**
- Lecture 3 **– Calorimetry, scintillation and photodetection**
  - Calorimetry
    - electromagnetic cascades
    - hadronic interactions
    - neutrons and neutrinos
    - hadronic cascades
  - Scintillation
  - Photodetection

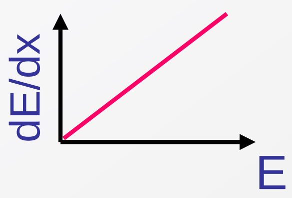
Summary: basic electromagnetic interactions

e⁺ / e⁻

- Ionisation



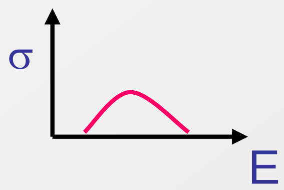
- Bremsstrahlung



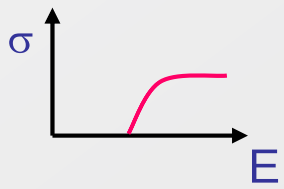
γ

- Photoelectric effect

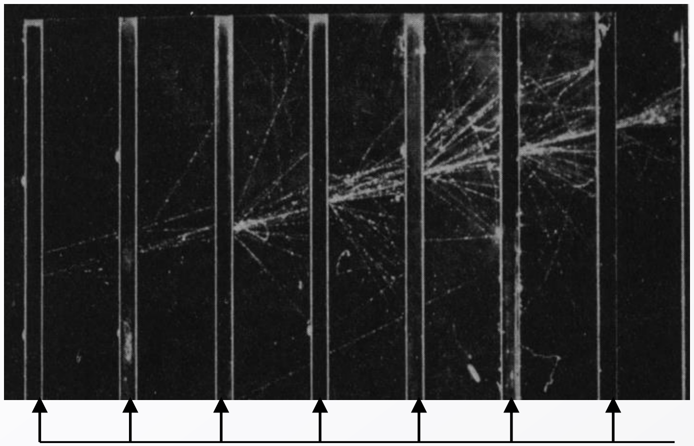
- Compton effect



- Pair production



Electromagnetic cascades (showers)



Pb plates

Electron shower in a cloud chamber with lead absorbers

- Consider only Bremsstrahlung and (symmetric) pair production.
- Assume: $X_0 \sim \lambda_{pair}$

$$N(t) = 2^t \qquad E(t)/\text{particle} = E_0 \cdot 2^{-t}$$

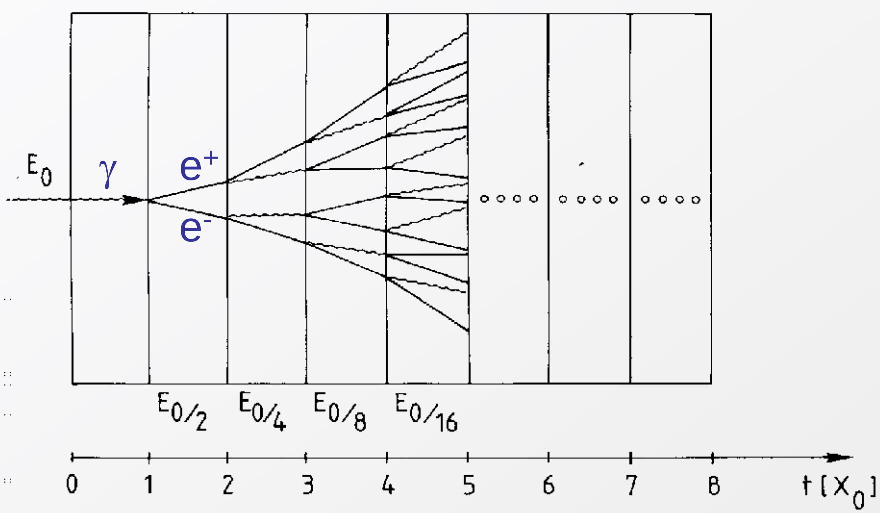
Process continues until $E(t) < E_c$

$$N^{total} = \sum_{t=0}^{t_{\max}} 2^t = 2^{(t_{\max}+1)} - 1 \approx 2 \cdot 2^{t_{\max}} = 2\frac{E_0}{E_c}$$

$$t_{\max} = \frac{\ln E_0/E_c}{\ln 2}$$

After $t = t_{max}$ the dominating processes are ionization, Compton effect and photo effect $\rightarrow$ absorption of energy.

Simple qualitative model



Shower can be initiated by photon **OR** by electron.

Electromagnetic calorimeters

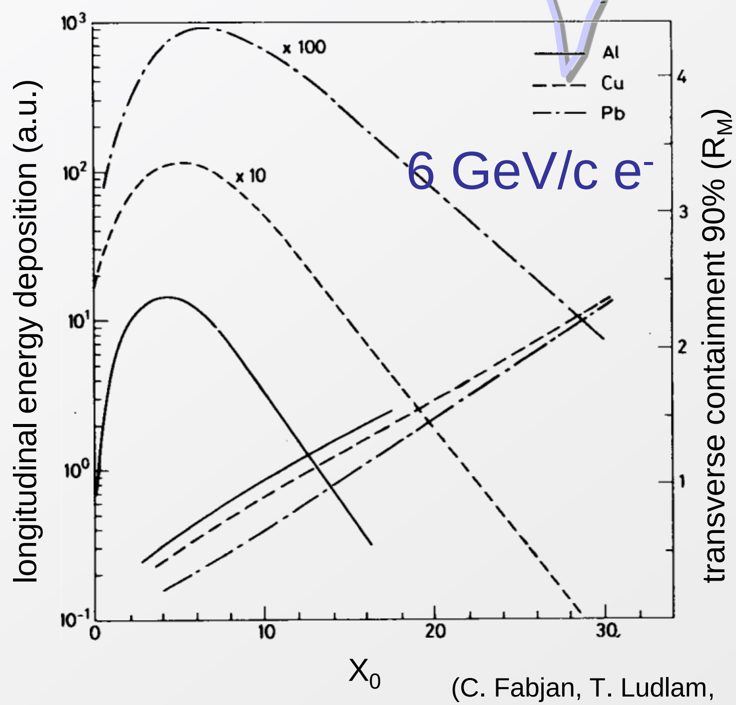
- A detector, which measures the energy of a $e^{+/-}$ or a high energy γ by fully absorbing it → destructive method!

Longitudinal profile $$\frac{dE}{dt} \propto t^{\alpha} e^{-t}$$

Shower maximum at $$t_{\max} = \ln \frac{E_0}{E_c} \frac{1}{\ln 2}$$

95% containment $$t_{95\%} \approx t_{\max} + 0.08Z + 9.6$$

Size of a calorimeter grows only logarithmically with E_0



(C. Fabjan, T. Ludlam, CERN-EP/82-37)

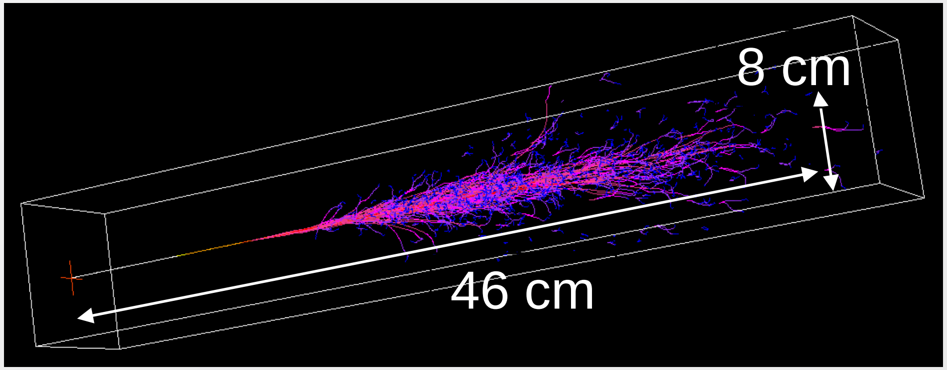
- Transverse shower development: 95% of the shower cone is located in a cylinder with radius 2 R_M

$$R_M = \frac{21\,\mathrm{MeV}}{E_c} X_0 \quad [g/cm^2]$$ Molière radius

Example: E_0 = 100 GeV in lead glass

E_c=11.8 MeV → $t_{max} \approx 13$, $t_{95\%} \approx 23$

$X_0 \approx 2$ cm, $R_M = 1.8 \cdot X_0 \approx 3.6$ cm



Energy resolution of a calorimeter

General expression $\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$

Also true for hadronic showers (see below)

Also spatial and angular resolution scale like $1/\sqrt{E}$

stochastic term

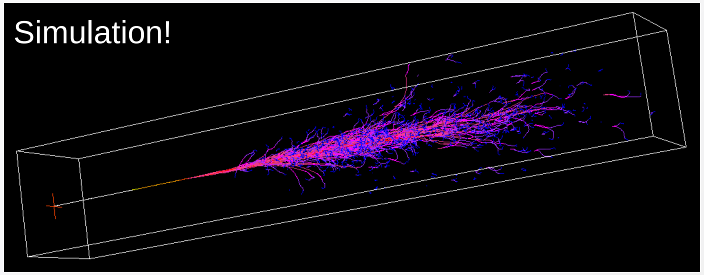
'constant term'
- inhomogenities
- bad cell inter-calibration
- non-linearities

Quality factor !

'noise term'
- Electronic noise
- radioactivity
- pile up

Homogeneous calorimeter

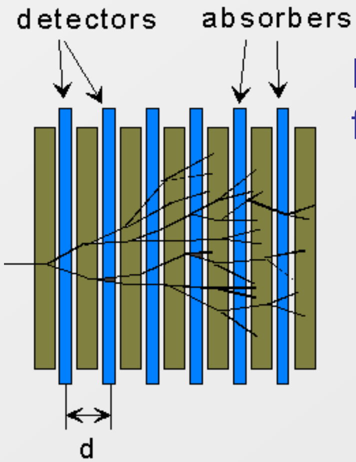
Absorber = active material.



High E-resolution, no longitudinal shower information. High cost.

Sampling calorimeter

Absorber and active detector layers.



Extra sampling fluctuations

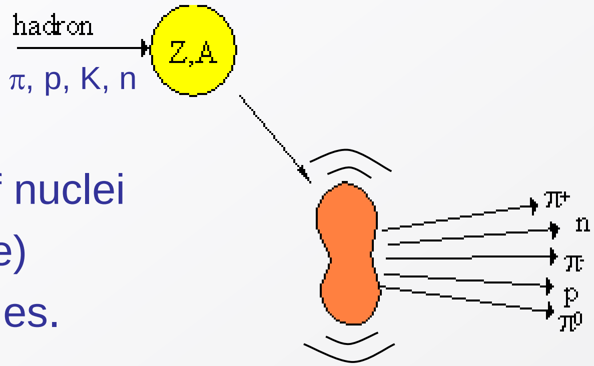
$$\frac{\sigma(E)}{E} \propto \sqrt{\frac{d}{E}}$$

Shower 'image'

Lower cost.

Nuclear Interactions

The interaction of energetic hadrons (charged or neutral) with matter is dominated by inelastic nuclear processes.



multiplicity $\propto \ln(E)$

$p_t \approx 0.35$ GeV/c

Excitation and finally break-up of nuclei
→ nuclear fragments (radioactive)
+ production of secondary particles.

For high energies (>1 GeV) the cross-sections depend only little on the energy and on the type of the incident particle (π, p, K…).

$$\sigma_{inel} \approx \sigma_0 A^{0.7} \quad \sigma_0 \approx 35\, mb$$

In analogy to X_0 a hadronic absorption length can be defined

$$\lambda_a = \frac{A}{N_A \sigma_{inel}} \propto A^{\frac{1}{4}} \quad \text{because} \quad \sigma_{inel} \approx \sigma_0 A^{0.7}$$

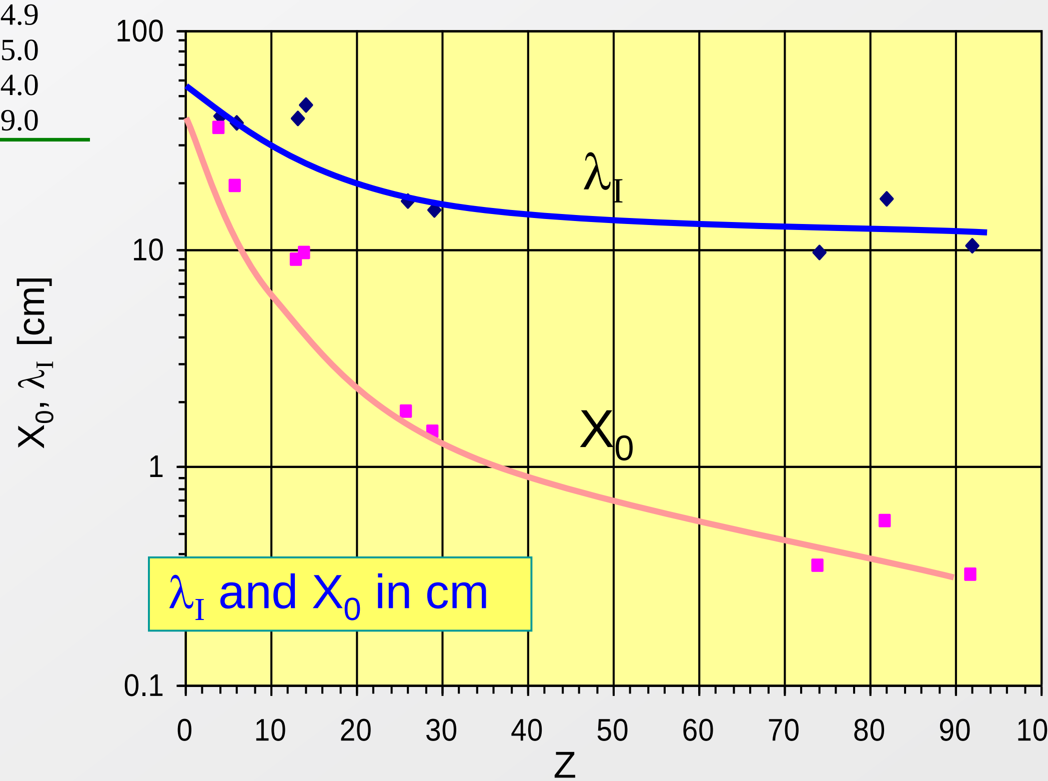
similarly a hadronic interaction length

$$\lambda_I = \frac{A}{N_A \sigma_{total}} \propto A^{\frac{1}{3}} \qquad \lambda_I < \lambda_a$$

Interaction of charged particles

Material	Z	A	ρ [g/cm^3]	X_0 [g/cm^2]	λ_I [g/cm^2]
Hydrogen (gas)	1	1.01	0.0899 (g/l)	63	50.8
Helium (gas)	2	4.00	0.1786 (g/l)	94	65.1
Beryllium	4	9.01	1.848	65.19	75.2
Carbon	6	12.01	2.265	43	86.3
Nitrogen (gas)	7	14.01	1.25 (g/l)	38	87.8
Oxygen (gas)	8	16.00	1.428 (g/l)	34	91.0
Aluminium	13	26.98	2.7	24	106.4
Silicon	14	28.09	2.33	22	106.0
Iron	26	55.85	7.87	13.9	131.9
Copper	29	63.55	8.96	12.9	134.9
Tungsten	74	183.85	19.3	6.8	185.0
Lead	82	207.19	11.35	6.4	194.0
Uranium	92	238.03	18.95	6.0	199.0

For Z > 6: $\lambda_I > X_0$



Interaction of neutrons and neutrinos

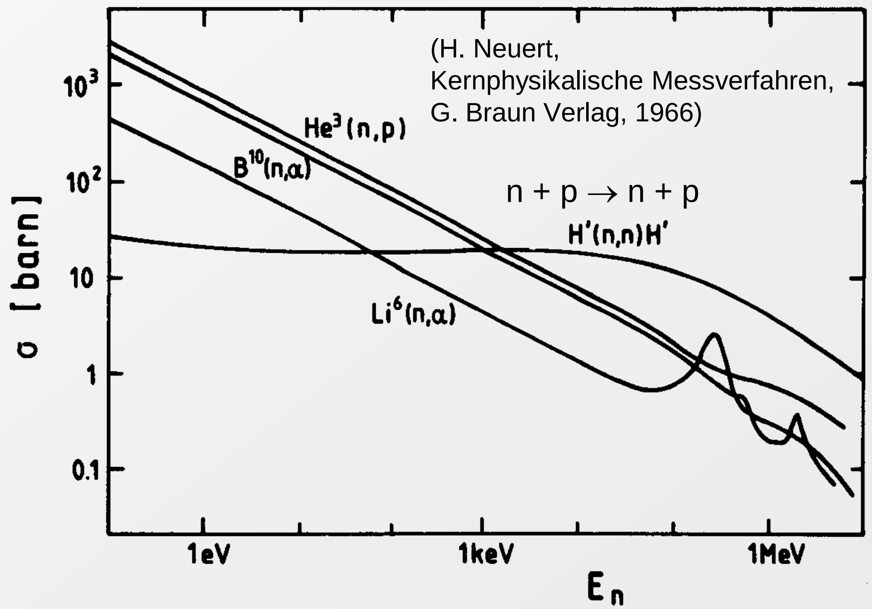
Interaction of neutrons

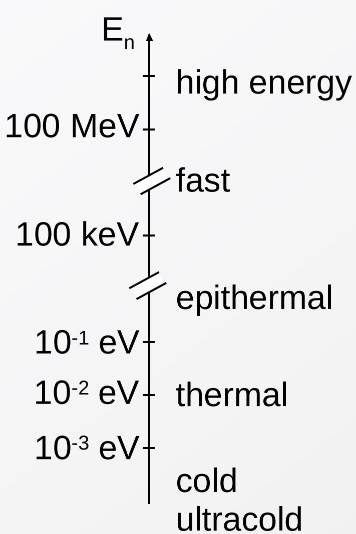
Neutrons have no charge, i.e. their interaction is based only on strong (and weak) nuclear force. To detect neutrons, we have to create charged particles.

Use neutron conversion and elastic reactions …

$$\left.\begin{array}{l} n + {}^{6}Li \rightarrow \alpha + {}^{3}H \\ n + {}^{10}B \rightarrow \alpha + {}^{7}Li \\ n + {}^{3}He \rightarrow p + {}^{3}H \end{array}\right\} \quad E_n < 20\ \text{MeV}$$

$$n + p \rightarrow n + p \qquad E_n < 1\ \text{GeV}$$





In addition there are …

- neutron induced fission $\quad E_n \approx E_{th} \approx 1/40$ eV
- inelastic reactions $\quad E_n > 1$ GeV

Interaction of neutrinos

Neutrinos interact only weakly $\rightarrow$ tiny cross-sections. For their detection we need again first a charged particle. Possible detection reactions:

– $\nu_\ell + n \rightarrow \ell^- + p \qquad \ell = e, \mu, \tau$

$\nu_\ell + p \rightarrow \ell^+ + n \qquad \ell = e, \mu, \tau$

The cross-section for the reaction $\nu_e + n \rightarrow e^- + p$ is of the order of 10^{-43} cm^2 (per nucleon, $E_\nu \approx$ few MeV).

$\rightarrow$ detection efficiency $\varepsilon_{\det} = \sigma \cdot N_a = \sigma \cdot \rho \dfrac{N_A}{A} d$ $\quad$ (N_a : area density $\neq N_A$: Avogadro's number)

1 m Iron: $\varepsilon_{\det} \approx 5 \cdot 10^{-17}$

1 km water: $\varepsilon_{\det} \approx 6 \cdot 10^{-15}$

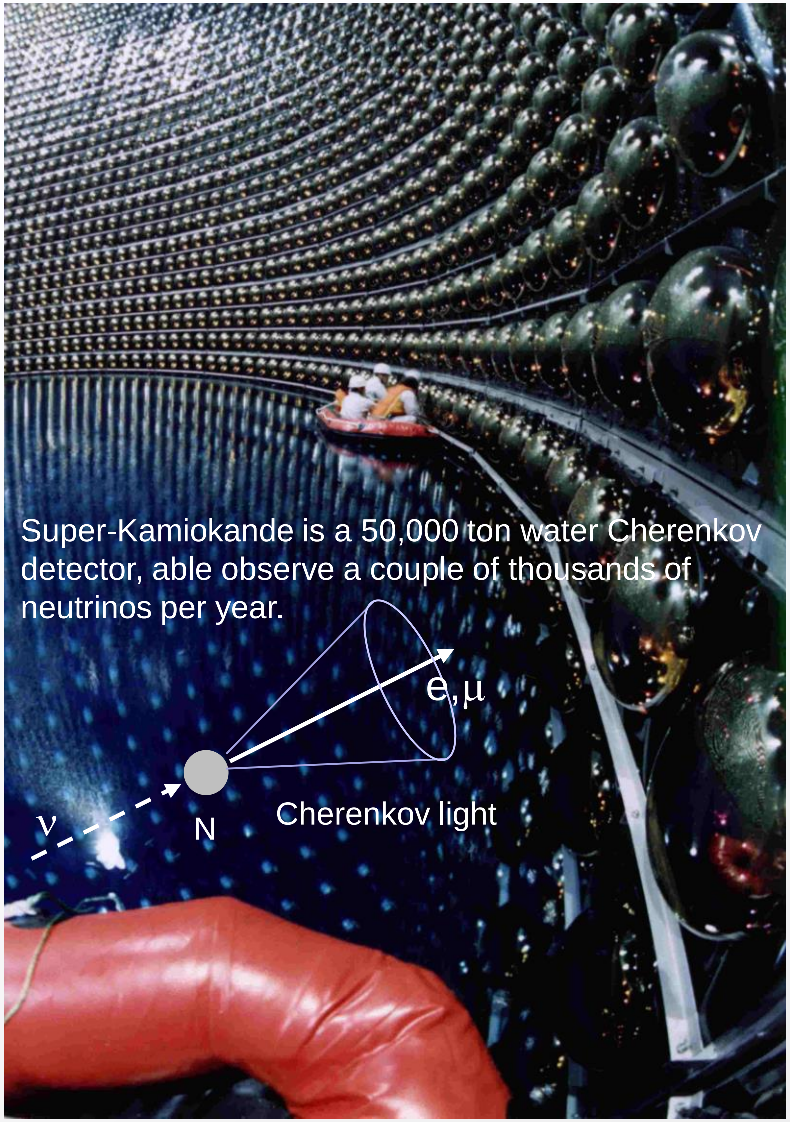
Neutrino detection requires big and massive detectors (ktons - Mtons) and very high neutrino fluxes (e.g. 10^{20} ν / yr).

In collider experiments fully hermetic detectors allow to detect neutrinos indirectly:

- sum up all visible energy and momentum.
- attribute missing energy and momentum to neutrino.

Interaction of neutrons and neutrinos

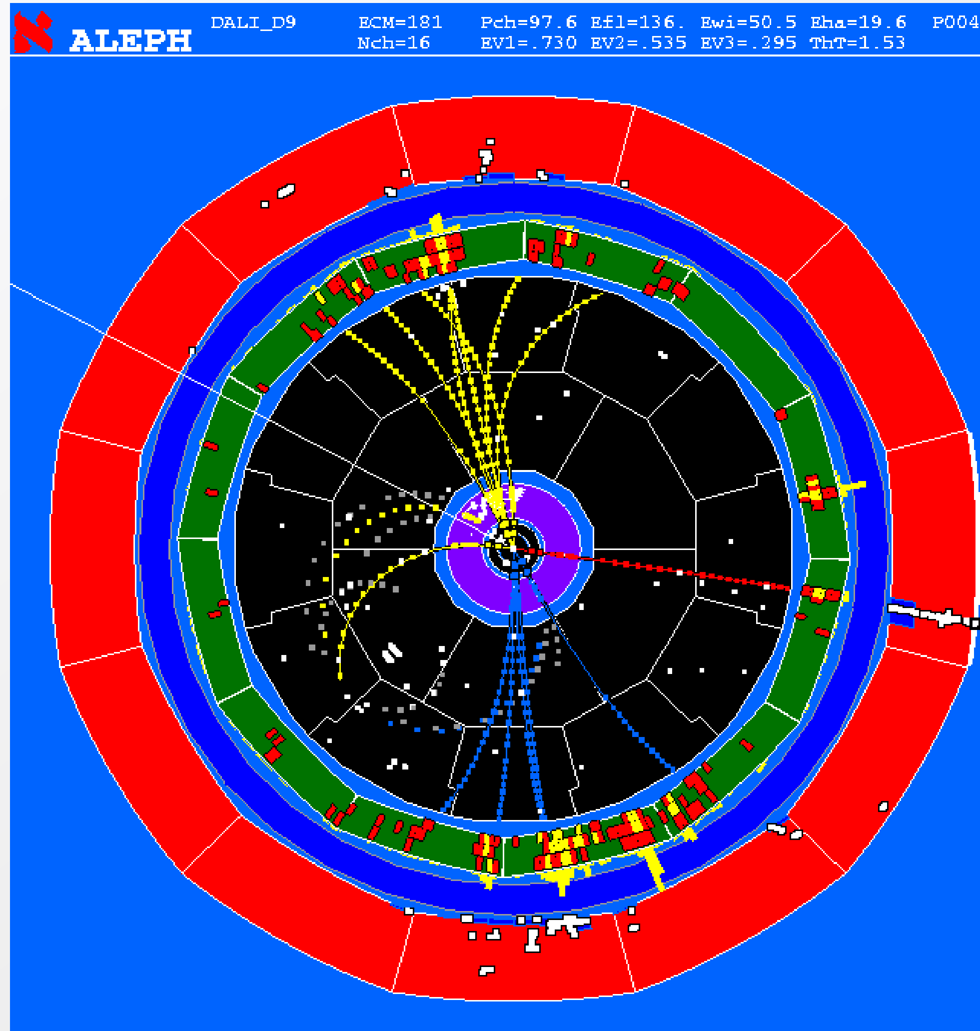
Direct neutrino detection



Indirect neutrino detection

e^+e^- ($\sqrt{s}$=181 GeV) $\rightarrow W^+W^- \rightarrow qq\mu\nu_\mu$

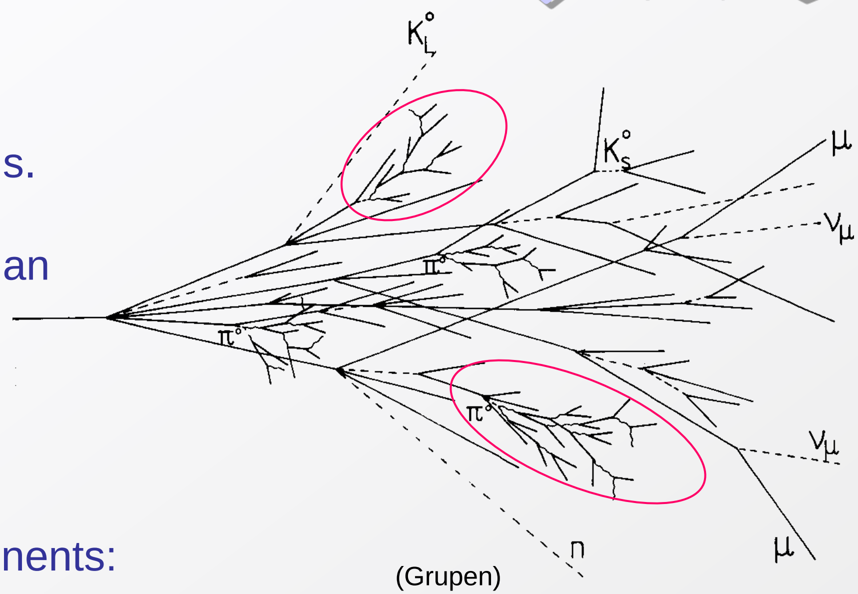
$\rightarrow$ 2 hadronic jets + μ + missing momentum



Hadronic cascades

Lots of processes involved:
Strong, e.m. and weak interactions.

Much more complex and larger than electromagnetic cascades.
($\lambda_I > X_0$)



(Grupen)

A hadronic shower has two components:

hadronic + **electromagnetic**

↓

- charged hadrons p,$\pi^{\pm}$,$K^{\pm}$,
- nuclear fragmets ….
- breaking up of nuclei (binding energy)
- neutrons, neutrinos, soft γ's, muons

↓

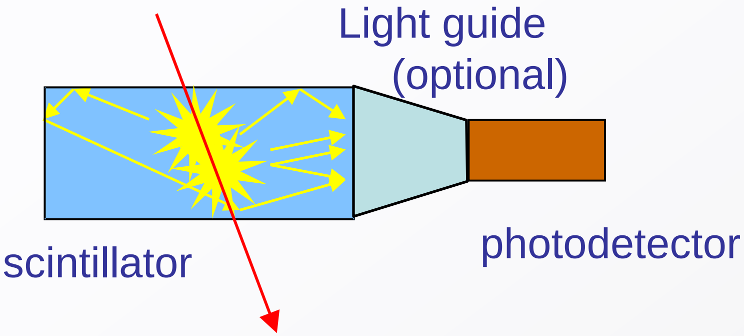
neutral pions $\pi^0 \rightarrow 2\gamma$
$\rightarrow$ electromagnetic cascades

$$n(\pi^0) \approx \ln E(GeV) - 4.6$$

example E = 100 GeV: n(π^0) $\approx$ 18

invisible energy $\rightarrow$ large fluctuations of visible energy
$\rightarrow$ Modest energy resolution of hadronic calorimeters.

Introduction to Scintillators



Energy deposition by an ionizing particle or photon (γ)

$\rightarrow$ generation
$\rightarrow$ transmission
$\rightarrow$ detection

of scintillation light

Two categories

Organic scintillators
(crystals, plastics or liquid solutions)

- Up to 10000 photons per MeV
- Low Z (not good for photoeffect)
- Low density ρ~1g/cm^3
- Doped, large choice of emission wavelength
- ns decay times
- Relatively inexpensive
- Medium Rad. Hard (10 kGy/year)
- Used in hadr./e.m. calorimetry, as trigger counters, for lab tests

Inorganic
(crystalline structure)

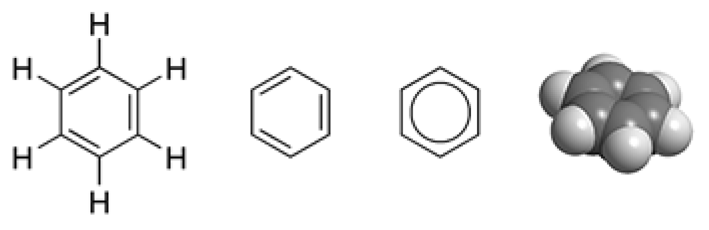
- More light (up to 70000 ph/MeV)
- High Z, high density
- Rel. expensive
- Used in e.m. calorimetry

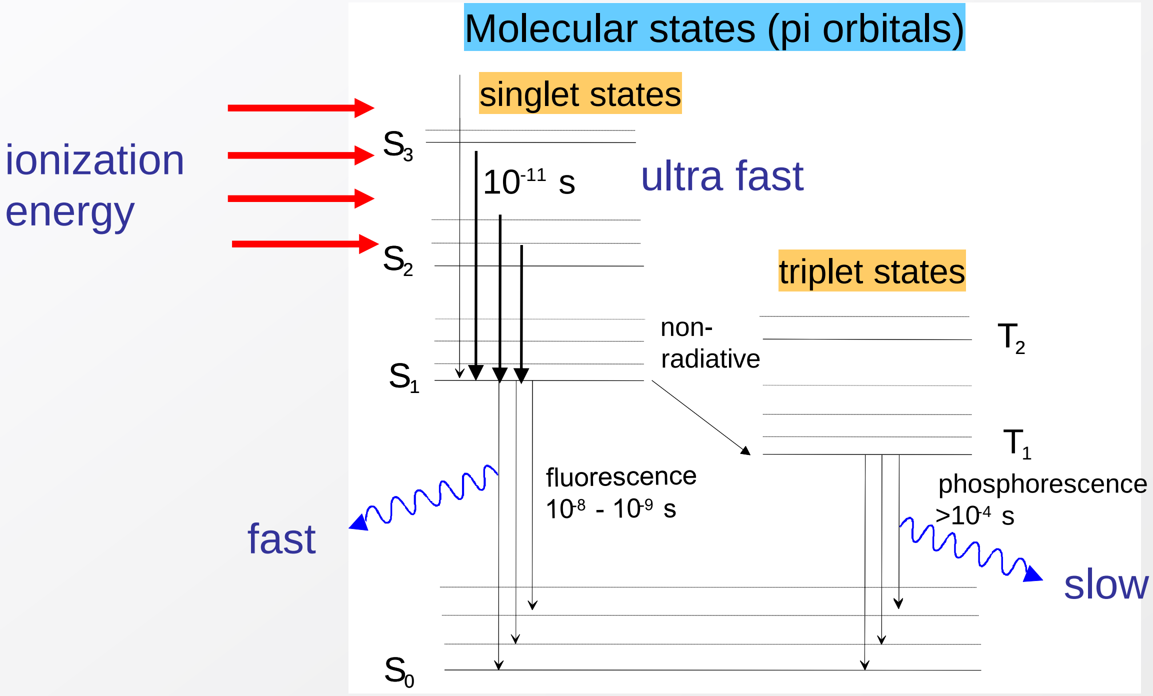
Don’t confuse scintillators with lead glass !

The light generation in lead glass is actually based on the Cherenkov effect. Lead glass is the poor man’s crystal. High density, but little light output.

Organic scintillation mechanism

The organic scintillation mechanism is based on the pi-electrons (molecular orbitals) of the benzene ring (C_6H_6).

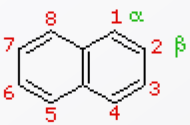




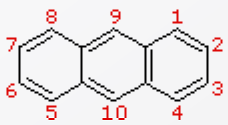
Organic scintillation mechanism

Organic scintillators exist as

crystals
(very rarely used in HEP)

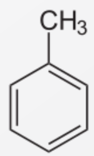


naphthalene
$C_{10}H_8$
m.p. 81° C

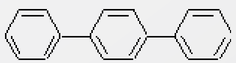


anthracene
$C_{14}H_{10}$
m.p. 217° C

liquids
(solutions)
(rarely used in HEP)



e.g. toluene

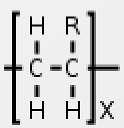


e.g. p-terphenyl

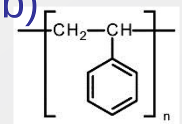
solvent + activator

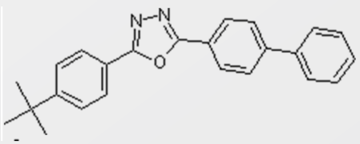
plastics
(polymerized solutions)
(much used in HEP)

a)



b)

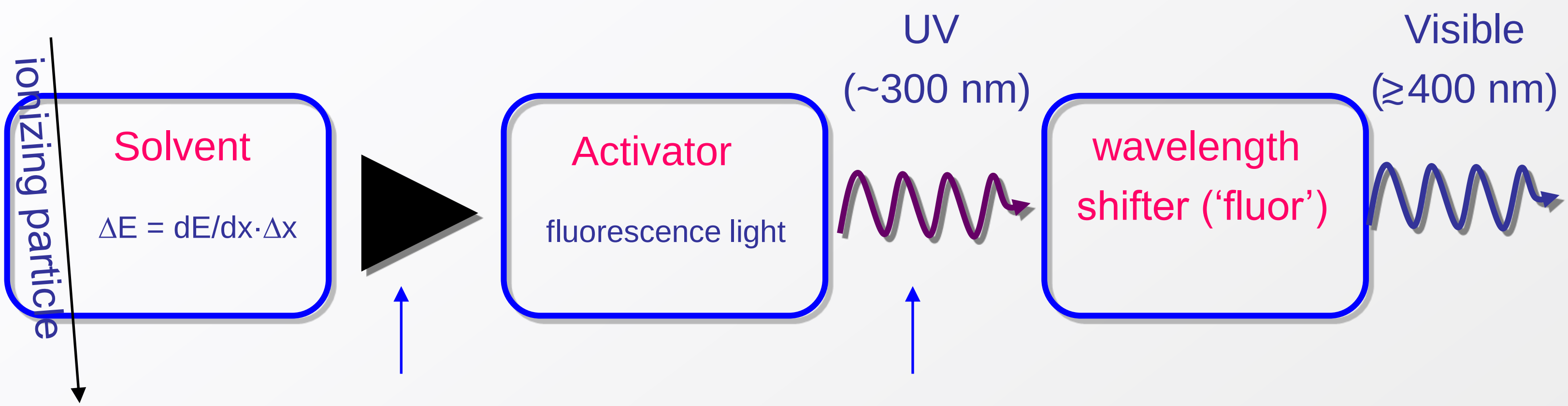




e.g. Butyl-PBD

e.g. polyvinlyltoluene (a) or polystyrene (b)

Often they consist of a solvent + activator and a secondary fluor as wavelength shifter.



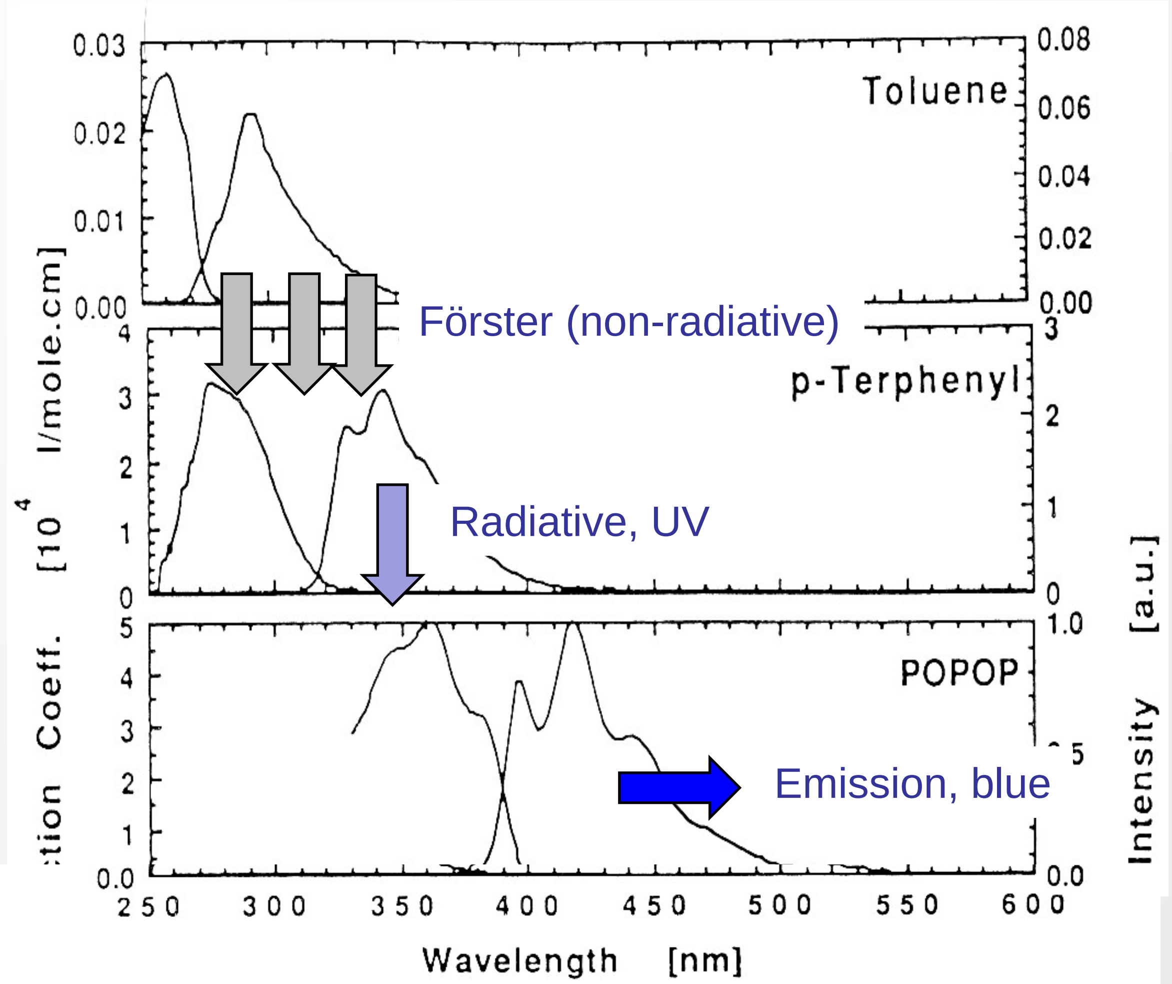
fast and local energy transfer via non-radiative dipole-dipole interactions (Förster transfer).

radiative transfer

A fluor has shifted absorption and emission spectra. The difference of the two peaks is called Stokes shift

Two dopant scheme for plastic scintillators

Abs. and emission spectra



Some examples of commercial plastic scintillators. There are just two main suppliers: (Saint Gobain, FR/US) or ELJEN (US) which deliver rather comparable products.

Physical Constants of SGC Plastic Scintillators

Scintillator	Light Output % Anthracene[1]	Wavelength of Maximum Emission, nm	Decay Constant, Main Component, ns	Bulk Light Attenuation Length, cm	Refractive Index	H:C Ratio	Loading Element % by weight	Density	Softening Point °C
BC-400	65	423	2.4	250	1.58	1.103		1.032	70
BC-404	68	408	1.8	160	1.58	1.107		1.032	70
BC-408	64	425	2.1	380	1.58	1.104		1.032	70
BC-412	60	434	3.3	400	1.58	1.104		1.032	70
BC-414	68	392	1.8	100	1.58	1.110		1.032	70
BC-416	38	434	4.0	400	1.58	1.110		1.032	70
BC-418	67	391	1.4	100	1.58	1.100		1.032	70
BC-420	64	391	1.5	110	1.58	1.102		1.032	70
BC-422	55	370	1.6	8	1.58	1.102		1.032	70
BC-422Q	11	370	0.7	<8	1.58	1.102	Benzephenone,0.5%*	1.032	70
BC-428	36	480	12.5	150	1.58	1.103		1.032	70
BC-430	45	580	16.8	NA	1.58	1.108		1.032	70

blue

UV

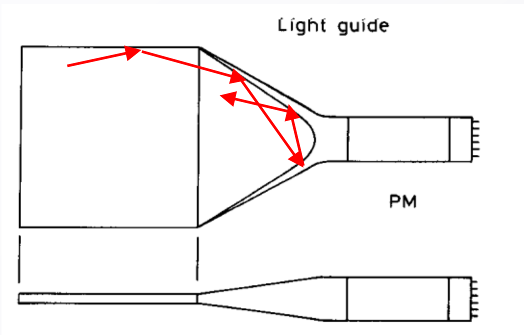
≈8000 photons / MeV

Scintillators readout

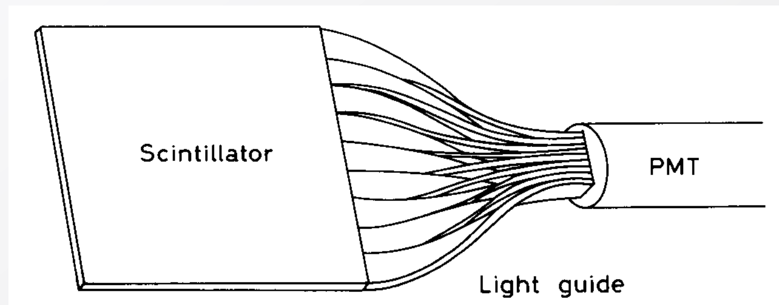
Readout has to be adapted to geometry, granularity and emission spectrum of scintillator.

Geometrical adaptation:

- Light guides: transfer by total internal reflection (+outer reflector)



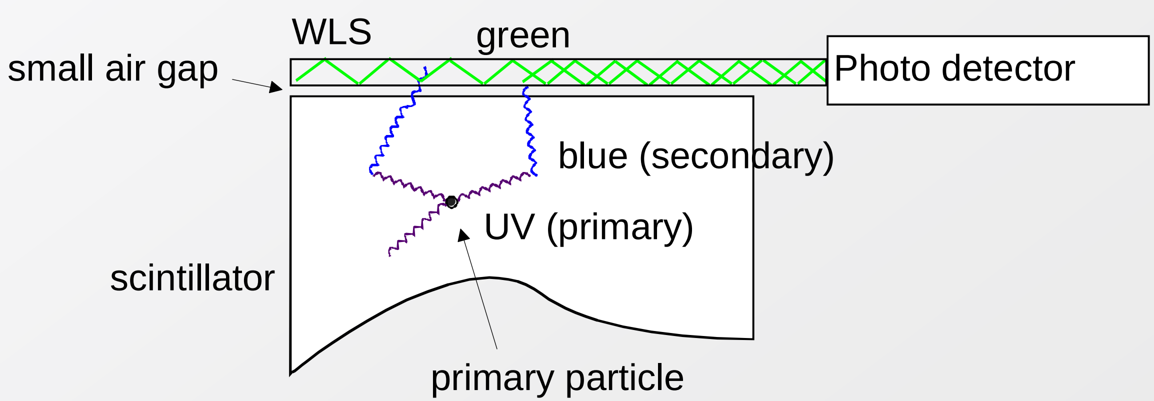
“fish tail”



adiabatic

Watch out: it’s very hard to beat Liouville!

- Wavelength shifter (WLS) bars / fibres

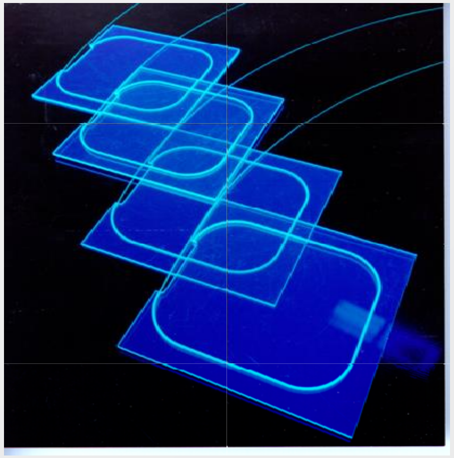


Most common applications of organic scintillators

- Large volume liquid or solid detectors
- neutron detection
- underground experiments
- sampling calorimeters (HCAL in CMS or ATLAS, etc.),
- trigger counters,
- TOF counters,
- Fibre tracking
  (see below)

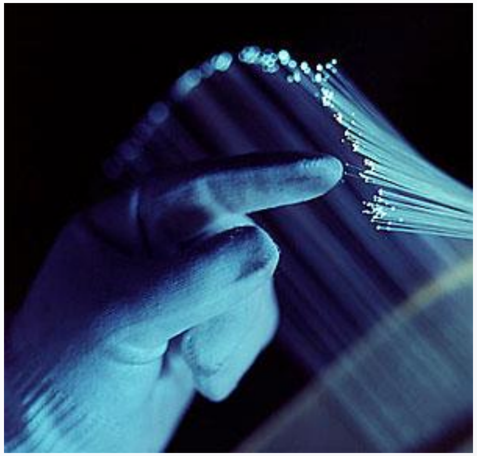
Plastic scintillators in various shapes (Saint Gobain)

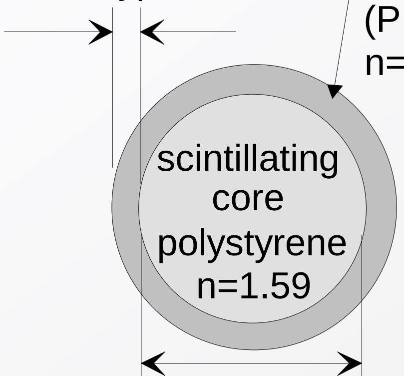
Michigan University: ‘neutron wall’. The flat-sided glass tubes contain liquid scintillator.



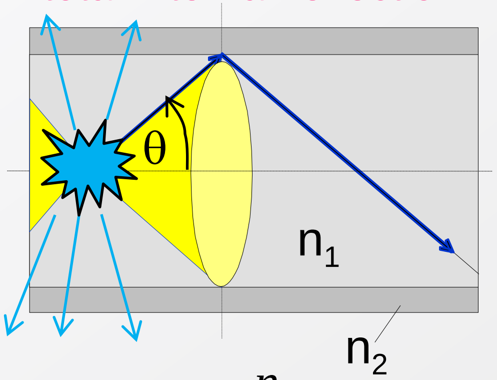
Scintillating tiles of CMS HCAL.

Working principle of scintillating plastic fibres :





light transport by
total internal reflection



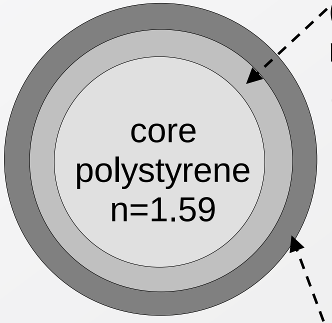
$$\theta \leq \arccos \frac{n_2}{n_1} \approx 20.4^\circ$$

Trapping fraction

$$\frac{d\Omega}{4\pi} = 0.5\,(1 - \cos\theta) \approx 3\%$$

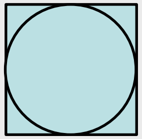
(per side)

Double cladding system
(developed by CERN RD7)



$$\frac{d\Omega}{4\pi} = 0.5\,(1 - \cos\theta) \approx 5.3\%$$

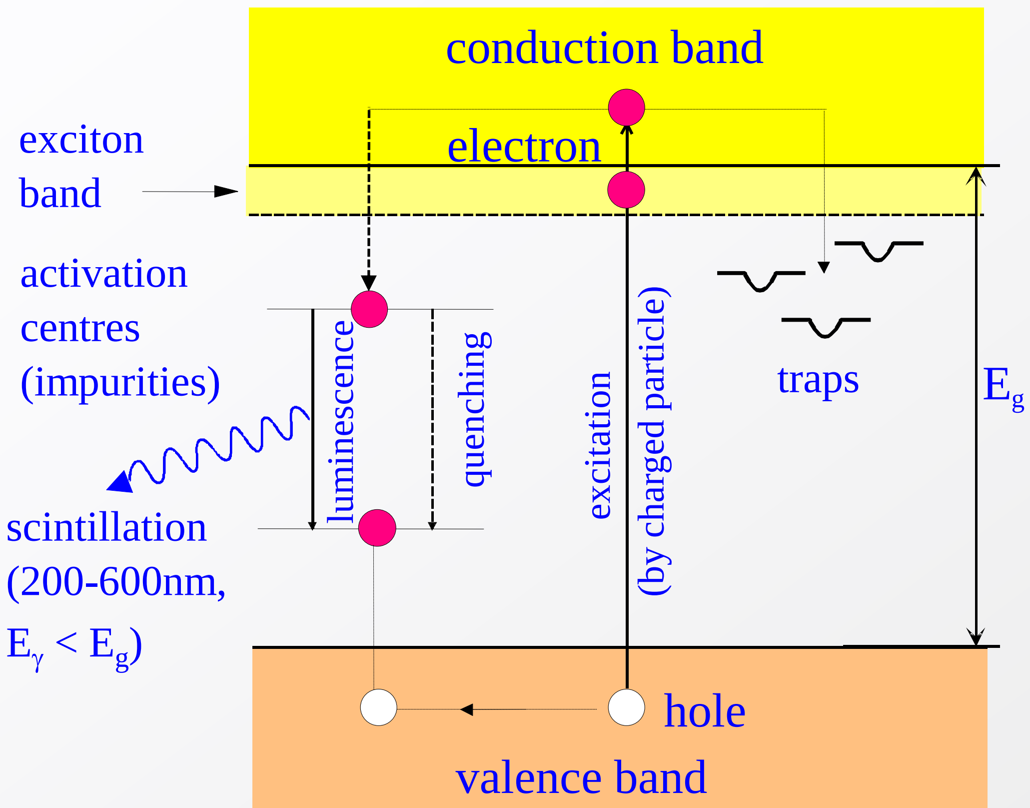
There are also square fibres. Their trapping fraction is slightly higher (additional angular phase space), but corners are problematic for light transport.



Inorganic scintillation mechanism

- Based on band structure of a crystal. Does not work for liquids or gases.

Exception: Liquefied noble gases scintillate, too. Different process. Not treated here.

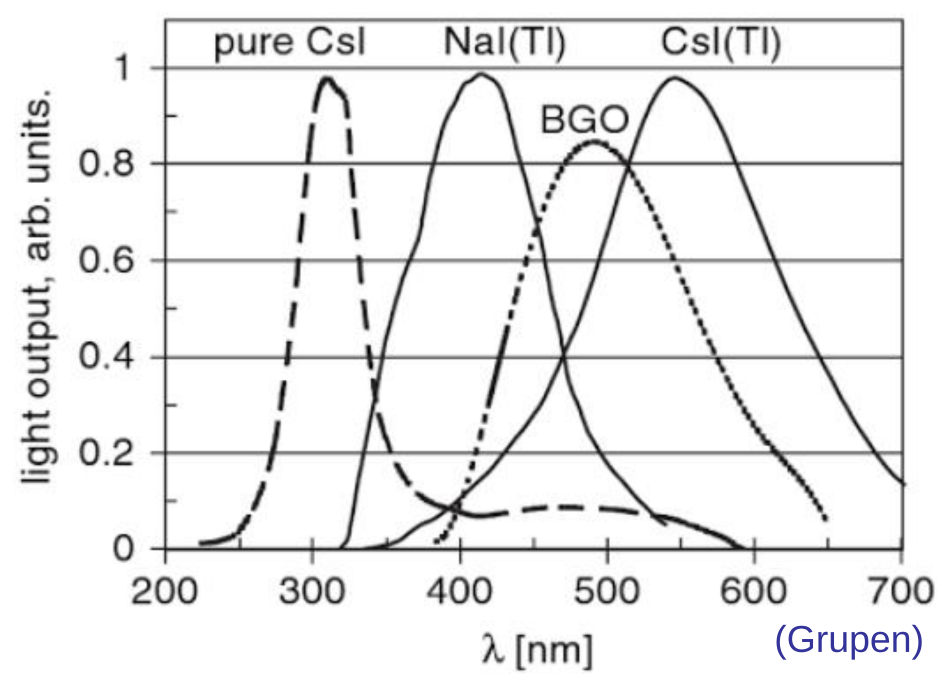


Band gap E_g should be large (>3 eV) to ensure that crystal is transparent.

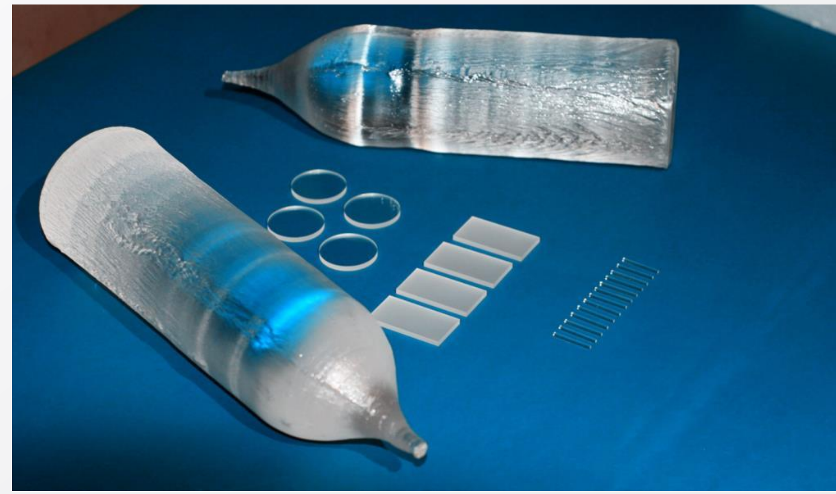
Warning: sometimes ≥ 2 time constants:

- fast recombination (ns-μs) from activation centers
- delayed recombination due to trapping (μs-ms)

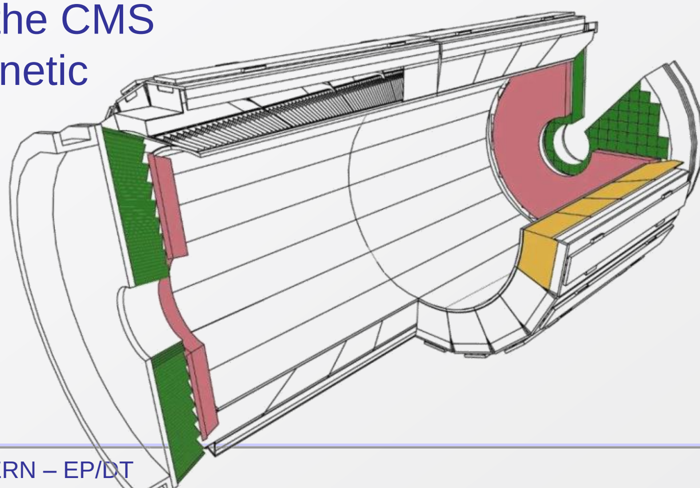
Inorganic scintillators

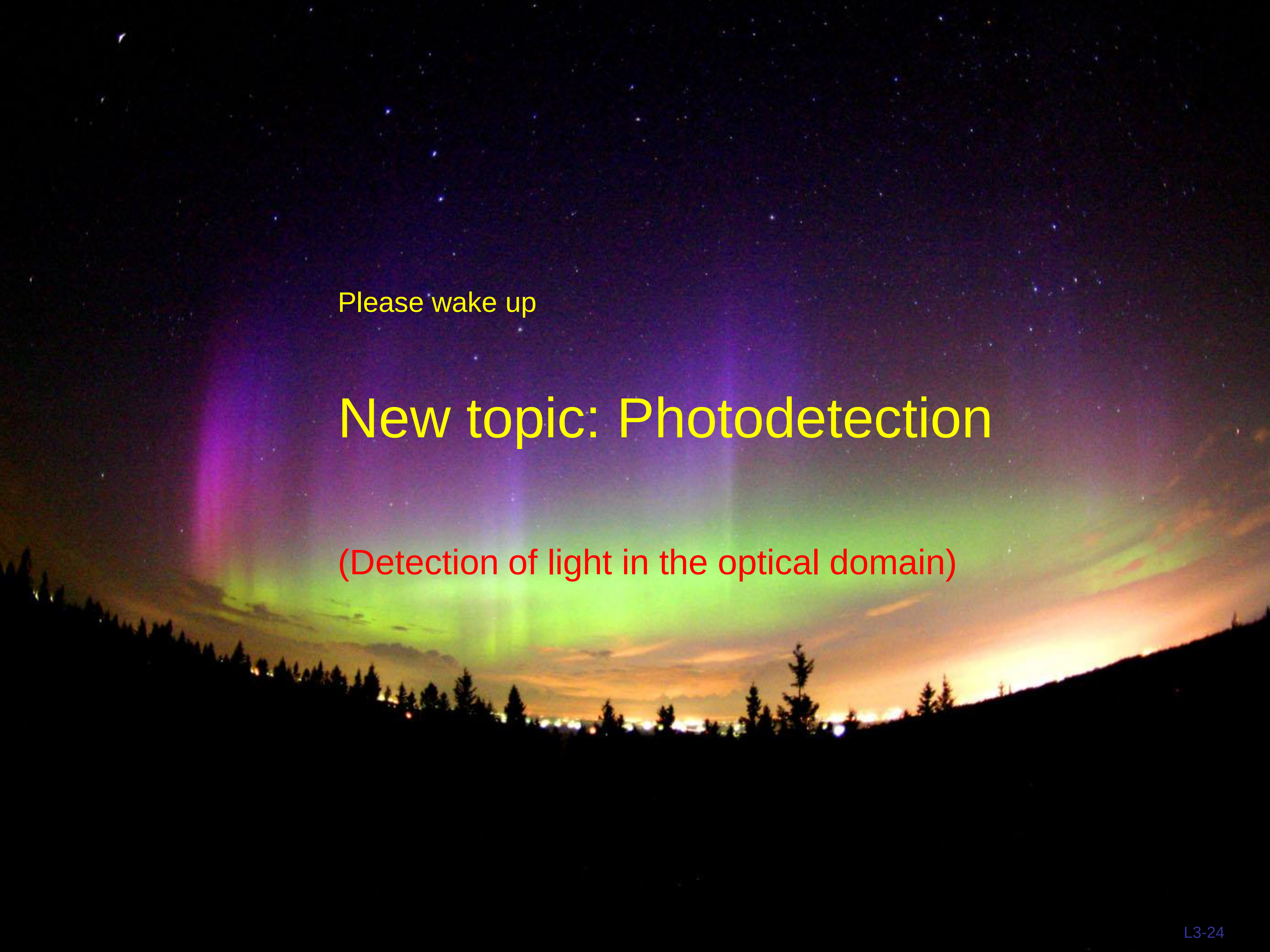


(Grupen)



~75000 $PbWO_4$ crystals in the CMS electromagnetic calorimeter





Please wake up

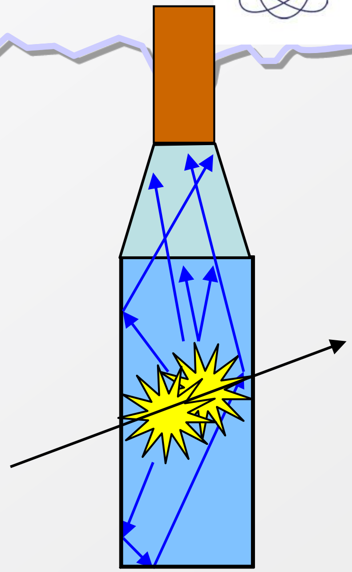
New topic: Photodetection

(Detection of light in the optical domain)

The classical domains of application

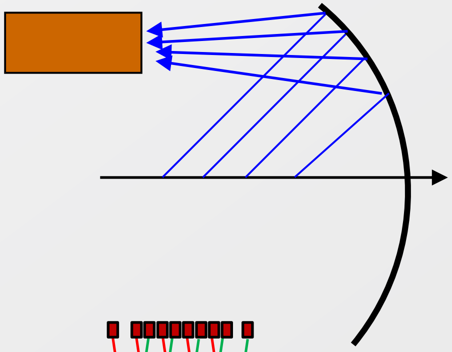
❑ Calorimetry

- Readout of organic and inorganic scintillators, lead glass, scint. or quartz fibres → Blue/VIS, usually 10s – 10000s of photons



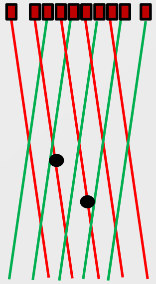
❑ Particle Identification

- Detection of Cherenkov light →UV/blue, single photons
- Time Of Flight → Usually readout of organic scintillators (not competitive at high momenta) or Cherenkov radiators



❑ Tracking

- Readout of scintillating fibres → blue/VIS, few photons



Basics of photon detection

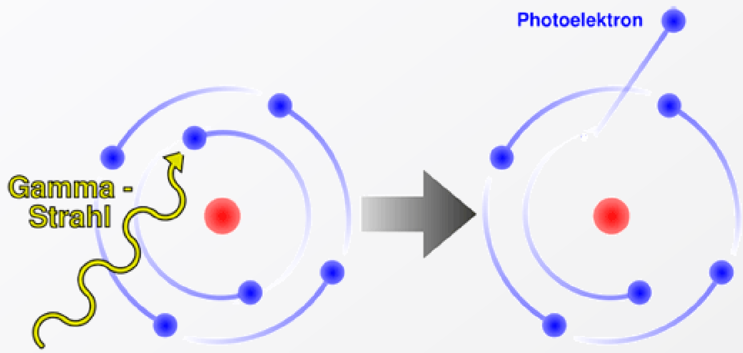
Purpose:

Convert light into detectable electronic signal

(we are not covering photographic emulsions!)

Principle:

Use photoelectric effect to 'convert' photons (γ) to photoelectrons (pe)

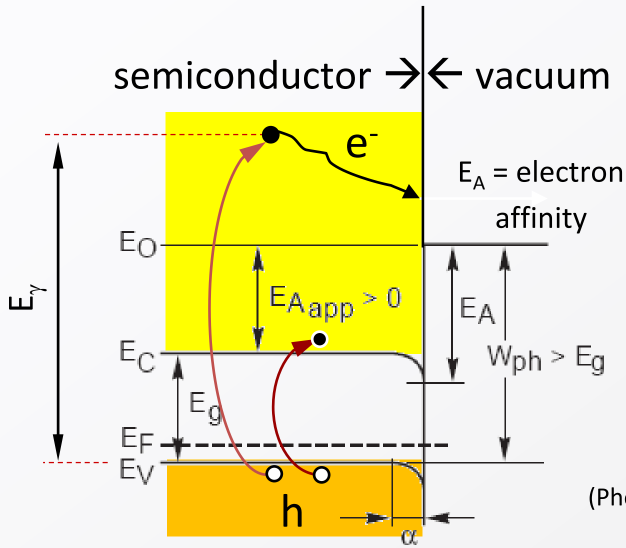


Details depend on the type of the photosensitive material (see below).

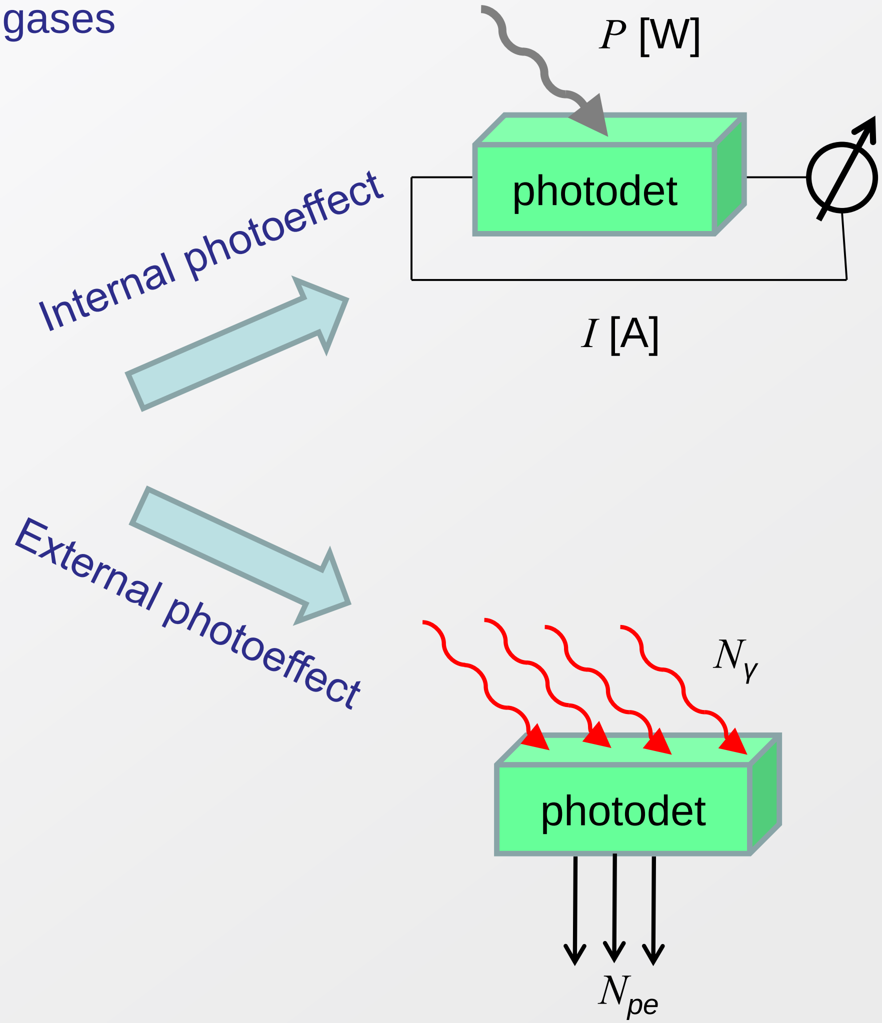
Photon detection involves often materials like K, Na, Rb, Cs (alkali metals) . They have the smallest electronegativity → highest tendency to release electrons.

Basics of photodetection

Many photosensitive materials are semiconductors, but photoeffect can also be observed from gases and liquids.



(Photonis)



Internal photoeffect: $E_\gamma > E_g$

External photoeffect: $E_\gamma > E_g + E_A$

Basics of photon detection

Requirements on photodetectors

- High sensitivity, usually expressed as: quantum efficiency $QE(\%) = \frac{N_{pe}}{N_\gamma}$

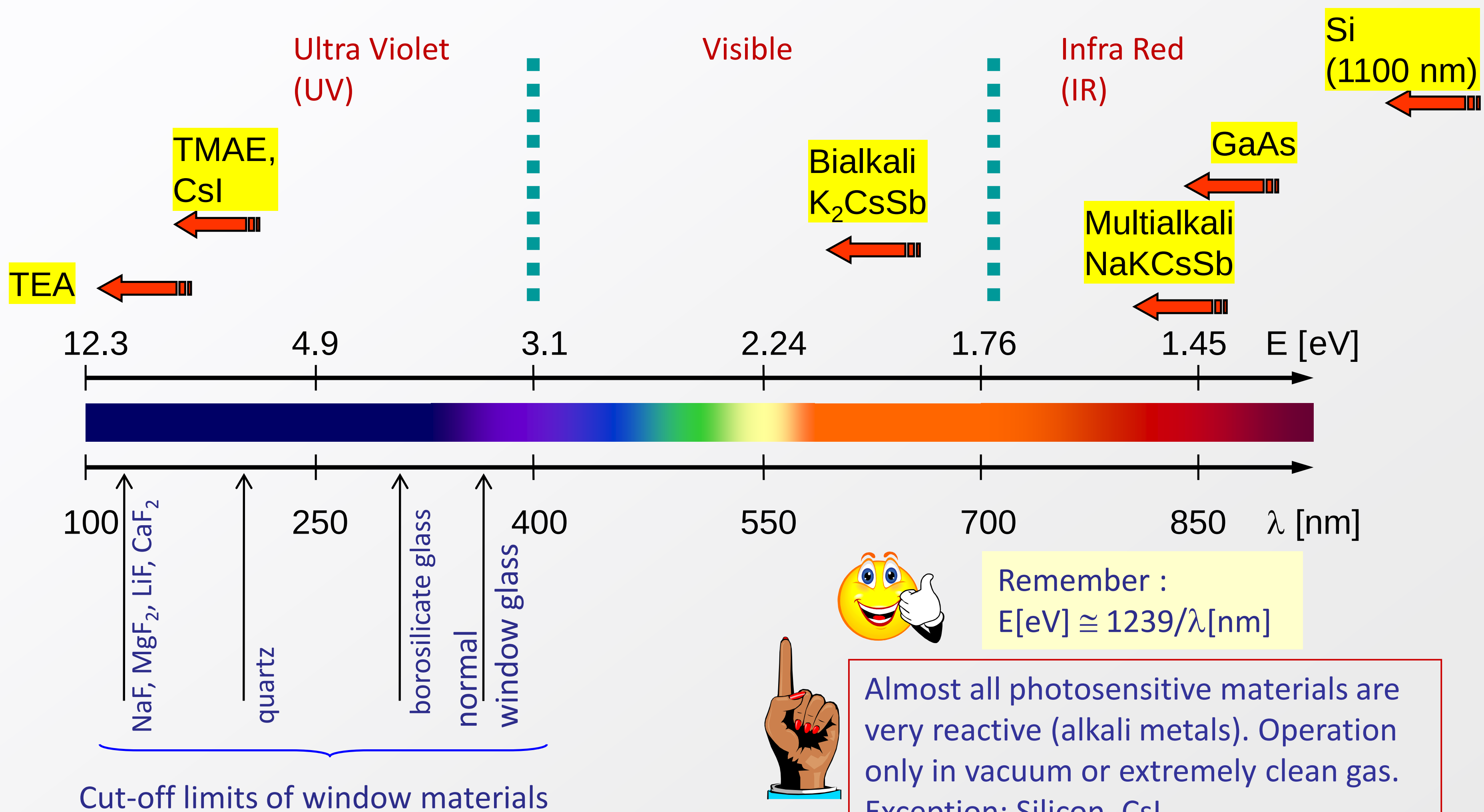
  or radiant sensitivity S (mA/W), with $QE(\%) \approx 124 \cdot \frac{S(mA/W)}{\lambda(nm)}$

QE can be >100% (for high energetic photons) !

- Good Linearity: Output signal ~ light intensity, over a large dynamic range (critical e.g. in calorimetry (energy measurement).
- Fast Time response: Signal is produced instantaneously (within ns), low jitter (<ns), no afterpulses
- Low intrinsic noise. A noise-free detector doesn't exist. Thermally created photoelectrons represent the lower limit for the noise rate ~ $A_o T^2 \exp(-eW_{ph}/kT)$. In many detector types, noise is dominated by other sources.
- + many more (size, fill factor, radiation hardness, cost, tolerance/immunity to B-fields…)

Frequently used photosensitive materials / photocathodes

begin of arrow indicates threshold



Remember :
E[eV] ≅ 1239/λ[nm]

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

Latest generation of high performance photocathodes

QE Comparison of semitransparent bialkali QE

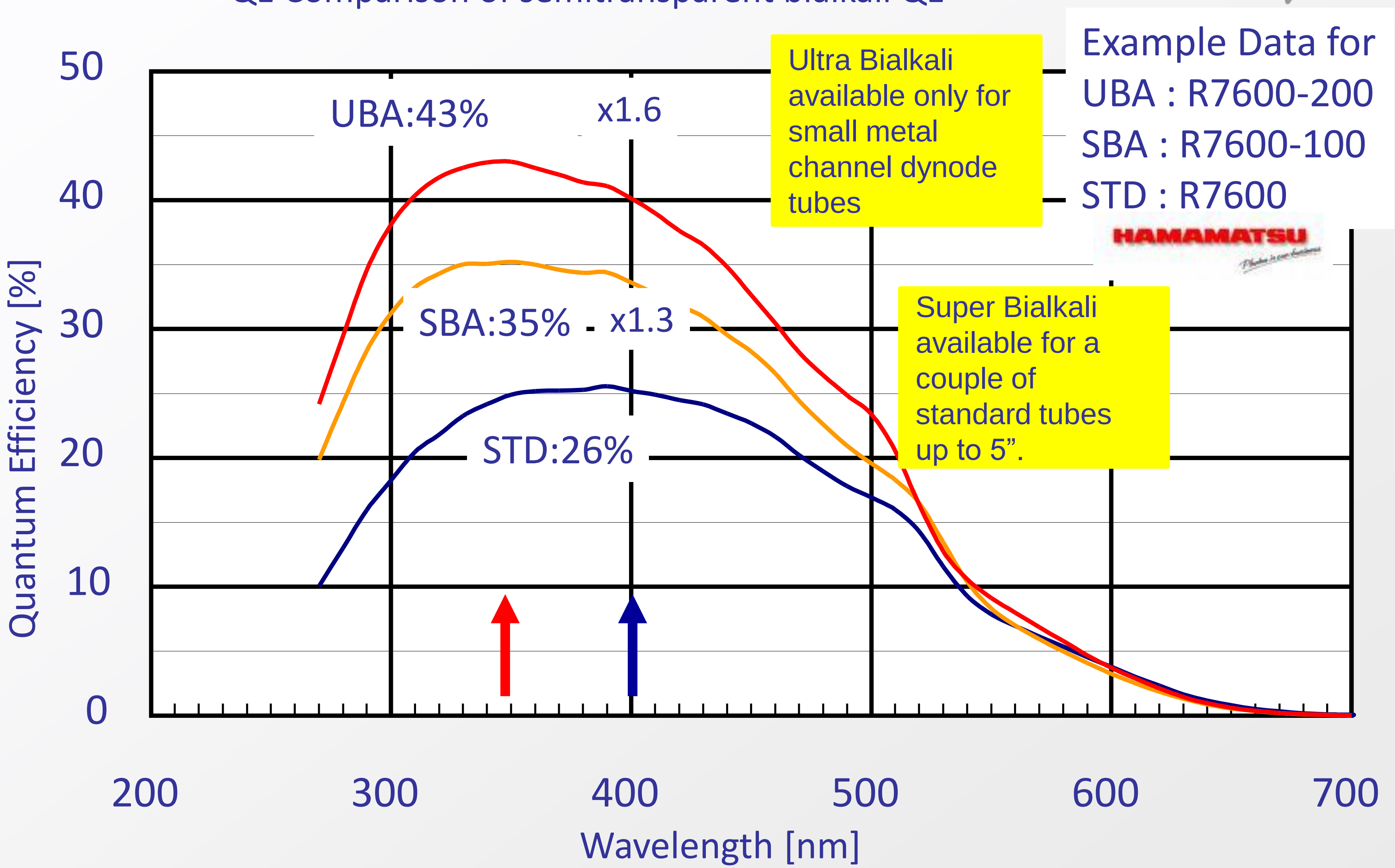


Photo-multiplier tubes (PMT's)

Basic principle:

<u>Photo-emission</u> from photo-cathode

<u>Secondary emission</u> from N dynodes:

- dynode gain $g \approx$ 3-50 (function of incoming electron energy E);
- total gain M:

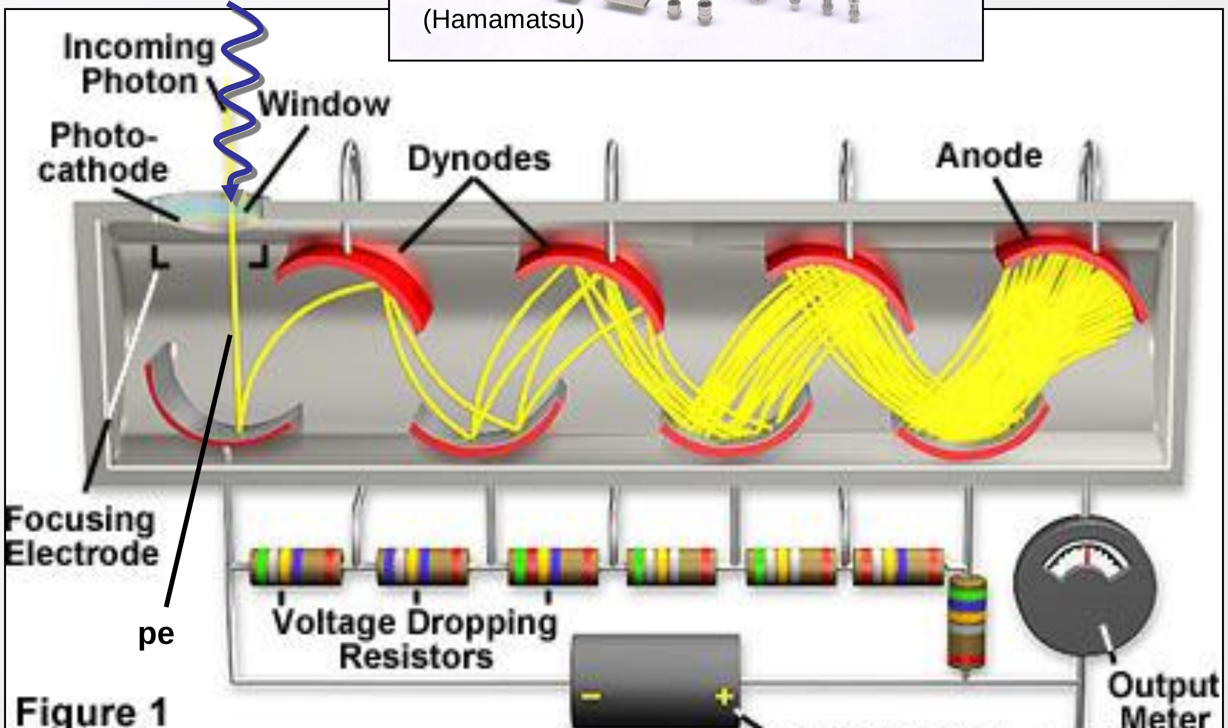
$$M = \prod_{i=1}^{N} g_i$$

Example:

- 10 dynodes with $g = 4$
- $M = 4^{10} \approx 10^6$

Very sensitive to magnetic fields, even to earth magnetic field (30-60 μT = 0.3-0.6 Gauss).
→ Shielding required (mu-metal).

(Hamamatsu)



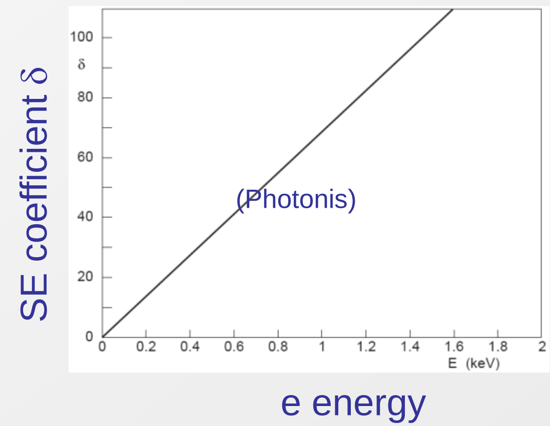
(http://micro.magnet.fsu.edu)

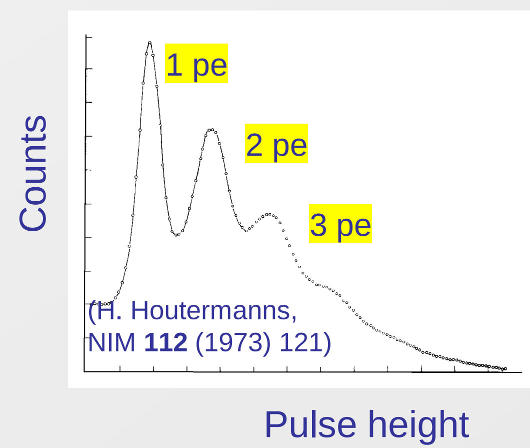
Gain fluctuations of PMT's

- Mainly determined by the fluctuations of the number of secondary electrons m_i emitted from the dynodes;
- Poisson distribution: $$P(n,m_i) = \frac{m_i^n e^{-m_i}}{n!}$$
- Standard deviation: $$\frac{\sigma_n}{m_i} = \frac{\sqrt{m_i}}{m_i} = \frac{1}{\sqrt{m_i}}$$

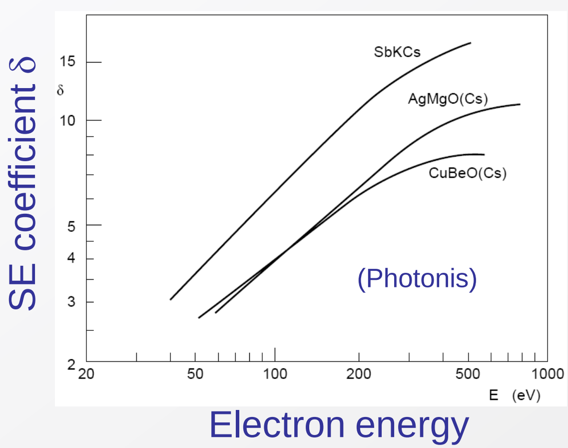
$\Rightarrow$ fluctuations dominated by 1st dynode gain $m_1 = \delta_1$

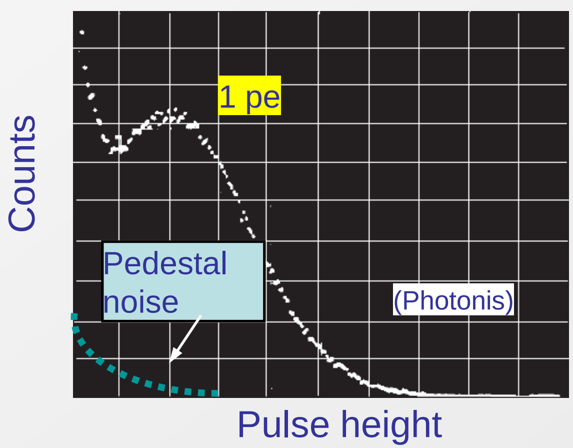
GaP(Cs) dynodes E_A<0



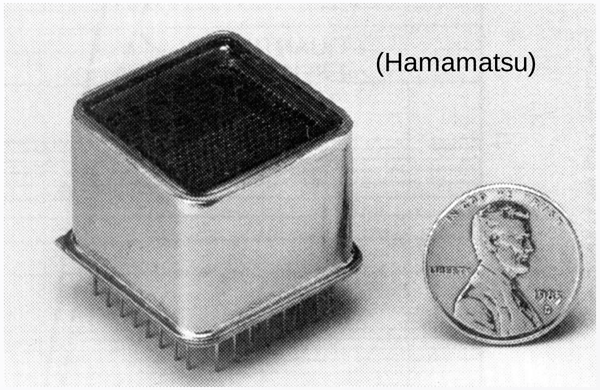


CuBe dynodes E_A>0





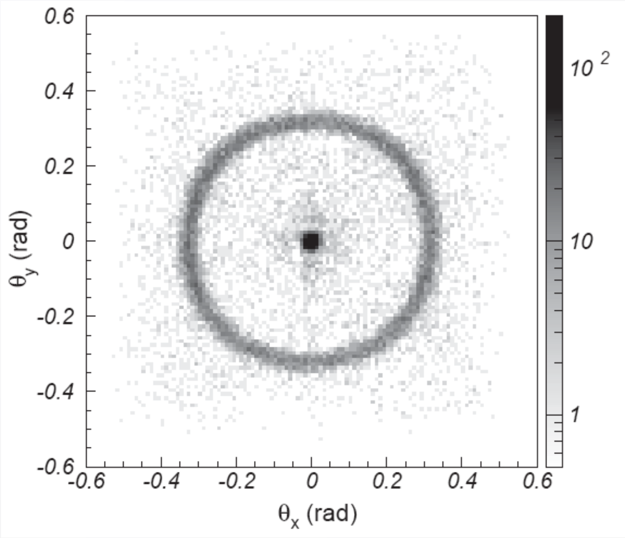
Multi-anode and flat-panel PMT's



Multi-anode PMT (Hamamatsu)

- Up to 8 × 8 channels (2 × 2 mm^2 each);
- Size: 28 × 28 mm^2;
- Bialkali PC: QE ≈ 25 - 45% @ λ_{max} = 400 nm;
- Gain ≈ 3 10^5;
- Gain uniformity typ. 1 : 2.5;
- Cross-talk typ. 2%

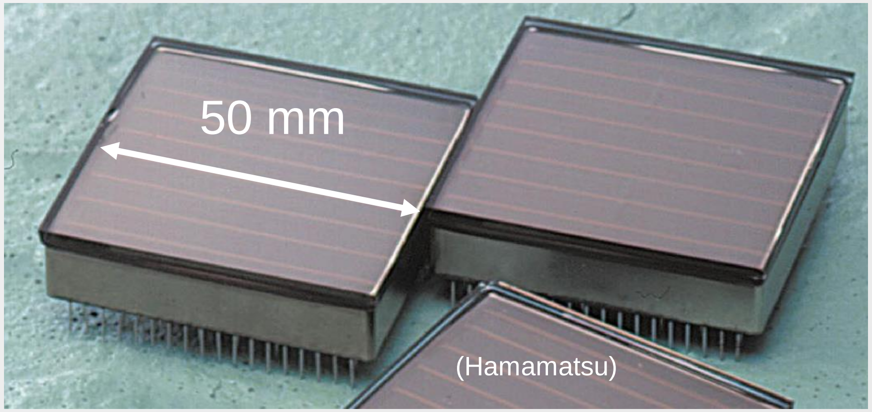
Cherenkov rings from
3 GeV/c π^- through aerogel



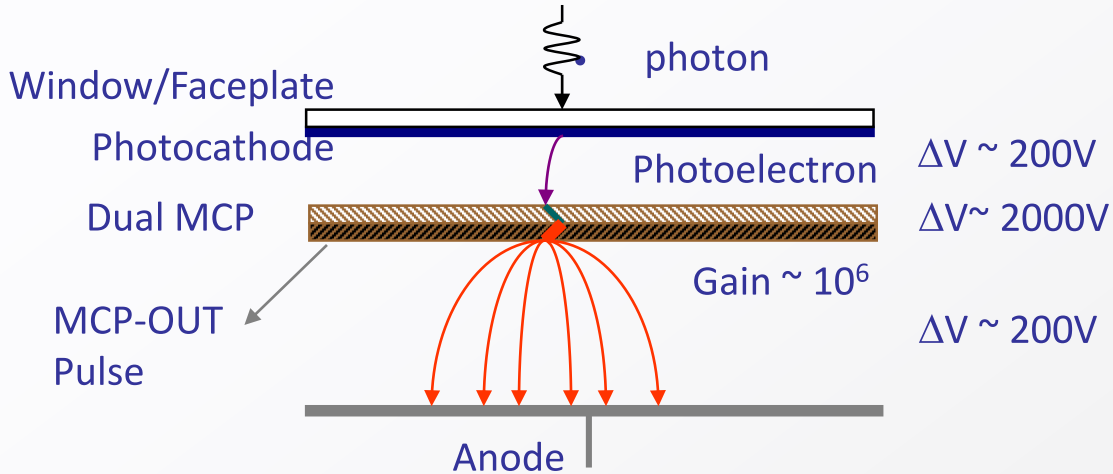
(T. Matsumoto et al., NIMA **521** (2004) 367)

Flat-panel (Hamamatsu H8500):

- 8 x 8 channels (5.8 x 5.8 mm2 each)
- Excellent surface coverage (89%)

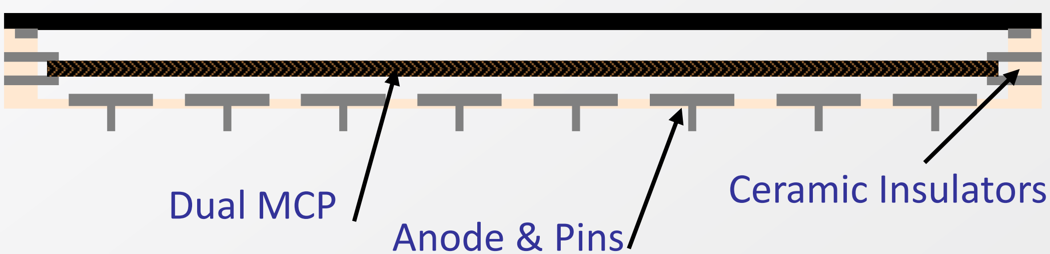


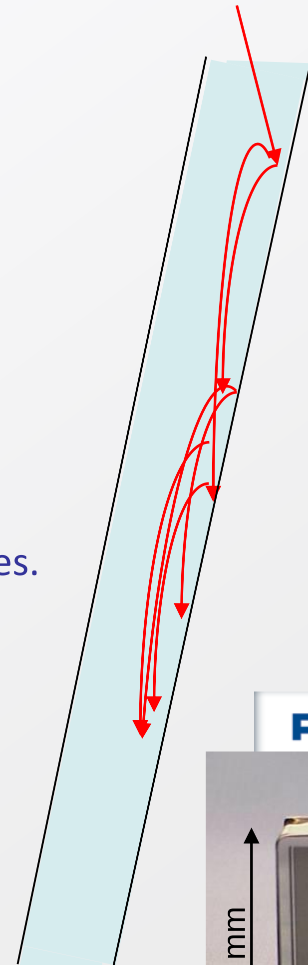
Micro Channel Plate (MCP) based PMTs



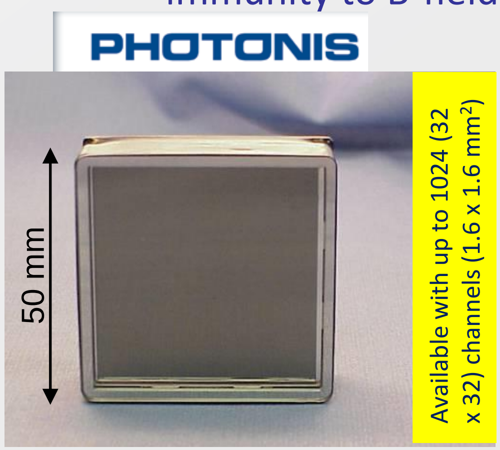
MCPs are usually based on glass disks, with lots of aligned pores. The surface of the pores are metal coated.

Gain stage and detection are decoupled → lots of potential and freedom for MA-PMTs: Anode can be easily segmented in application specific way.

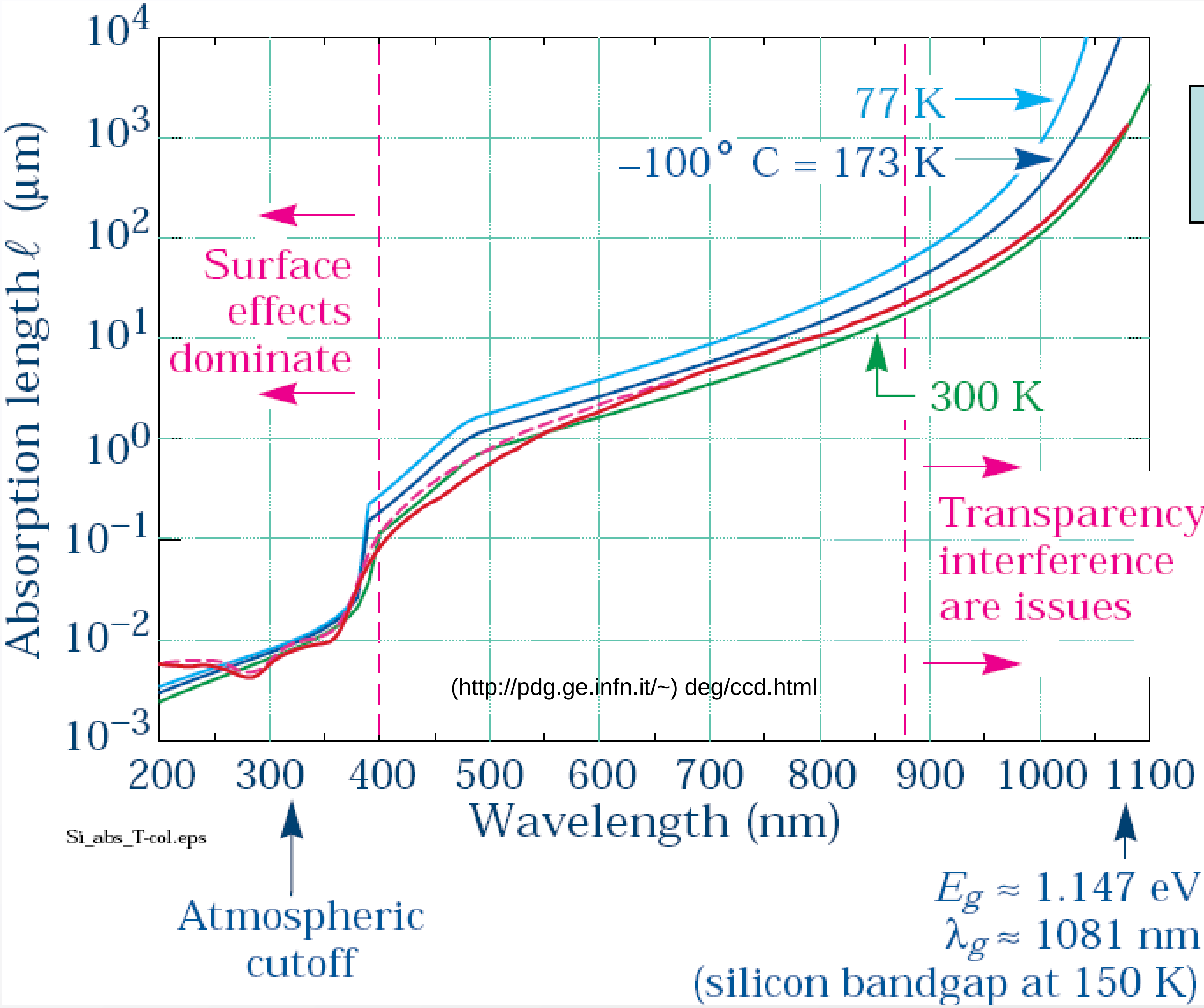




- Typical secondary yield is 2
- For 40:1 L:D there are typically 10 strikes (2^{10} ~ 10^3 gain per single plate)
- Pore sizes range from <10 to 25 μm.
- Small distances → small TTS and good immunity to B-field



Light absorption in Silicon

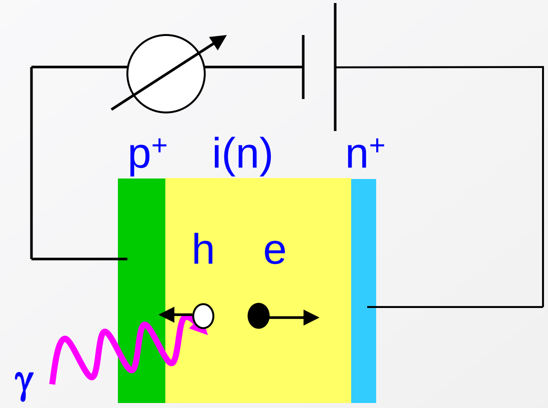


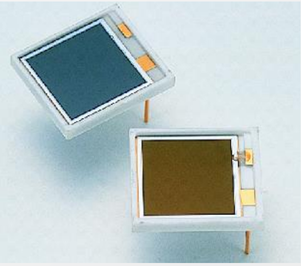
At large λ, temperature effects become important

Solid-state photon detectors

(Si) – Photodiodes (PIN diode)

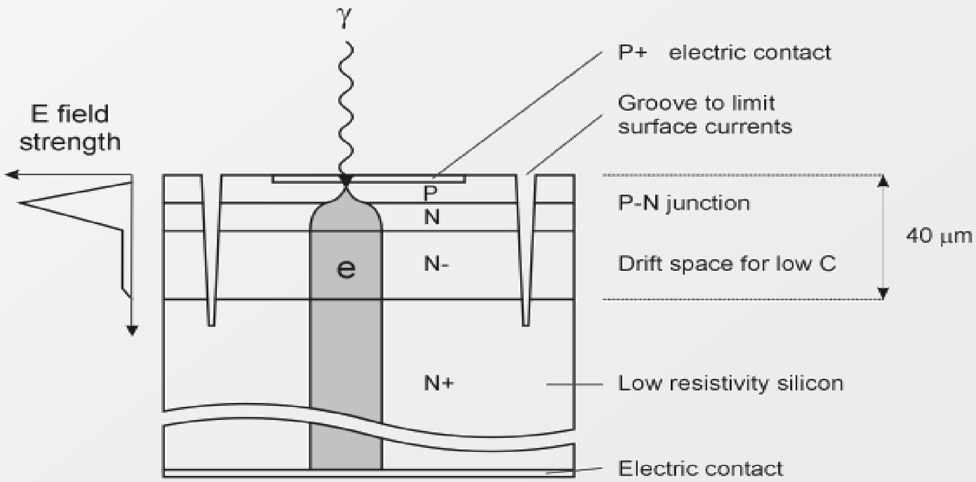
- P(I)N type
- p layer very thin (<1 μm), as visible light is rapidly absorbed by silicon
- High QE (80% @ $\lambda \approx$ 700nm)
- Gain = 1



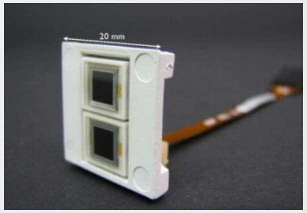


Avalanche photodiode (APD)

- High reverse bias voltage: typ. few 100 V
- Special doping profile → high internal field ($>10^5$ V/cm) → e and h avalanche multiplication
- Avalanche must stop due to statistical fluctuations.
- Gain: typ. O(100)
- Rel. high gain fluctuations (excess noise from the avalanche). CMS ECAL APD: ENF = 2 @G=50.
- Very high sensitivity on temp. and bias voltage ΔG = 3.1%/V and -2.4 %/K



Hamamatsu S8148.
(140.000 pieces used in CMS barrel ECAL).

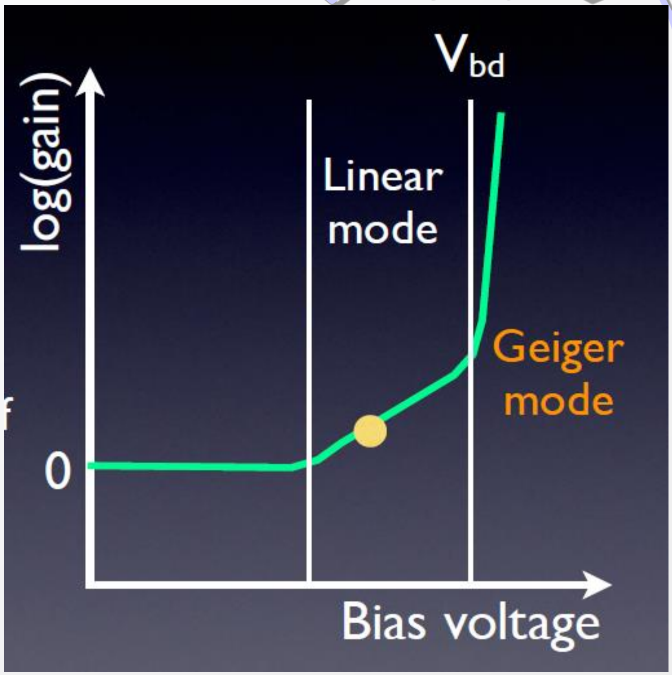


Solid-state … Geiger mode Avalanche Photodiode (G-APD)

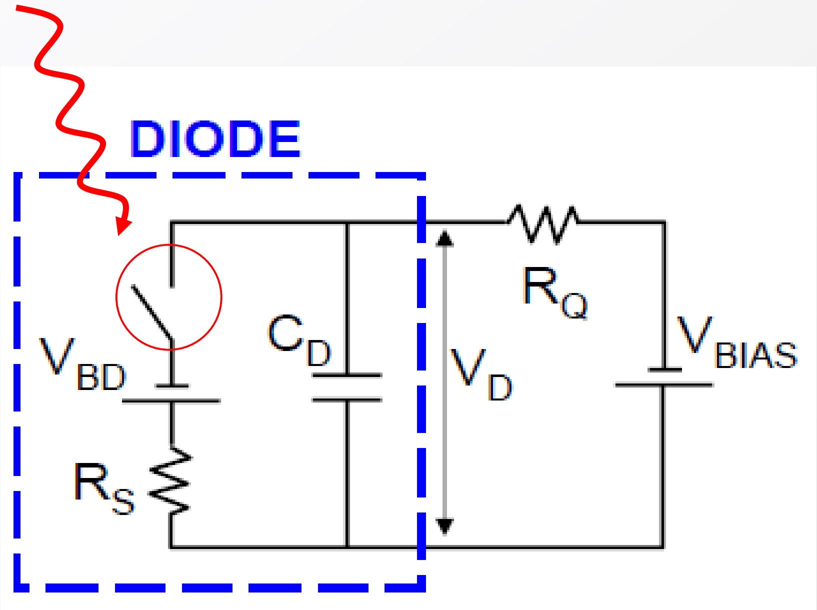
How to obtain higher gain (= single photon detection) without suffering from excessive noise ?

Operate APD cell in Geiger mode (= full discharge), however with (passive) quenching.

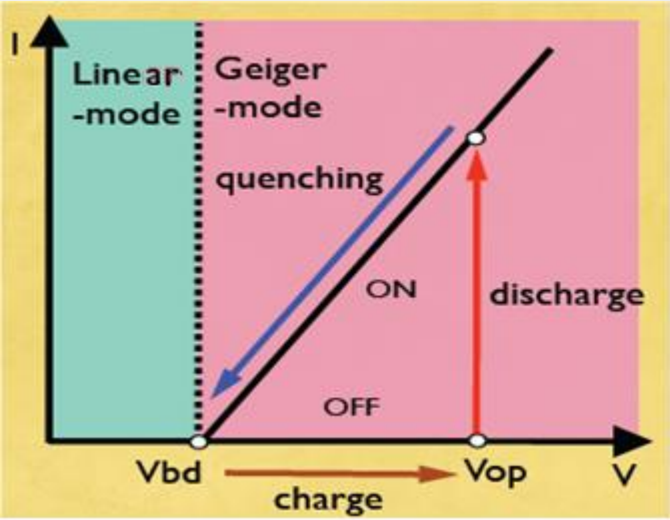
Photon conversion + avalanche short-circuits the diode.



J. Haba, RICH2007

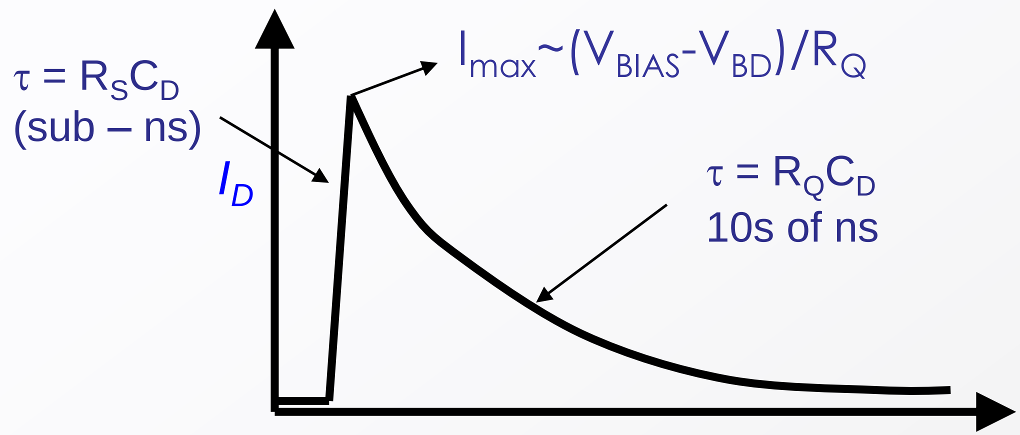


J. Haba, RICH2007



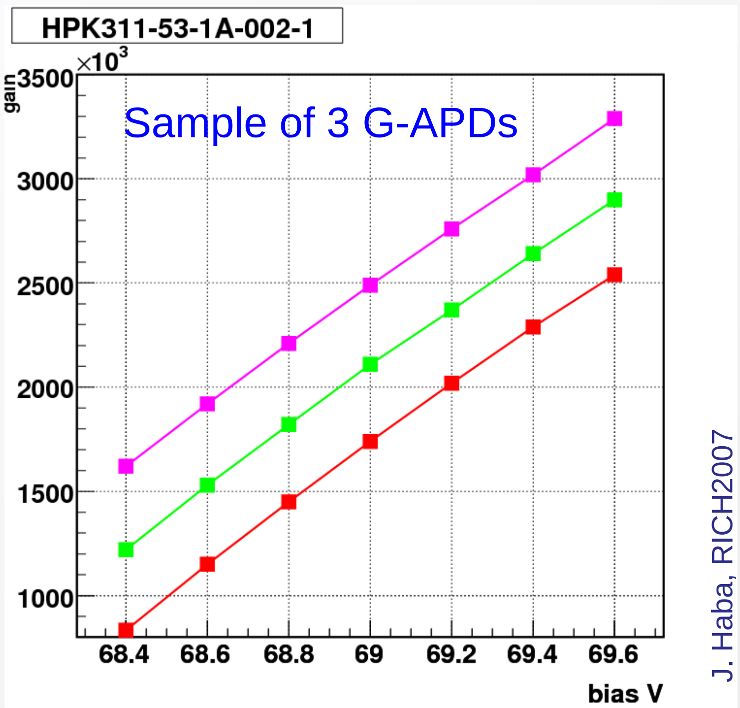
J. Haba, RICH2007

Solid-state … Geiger mode Avalanche Photodiode (G-APD)

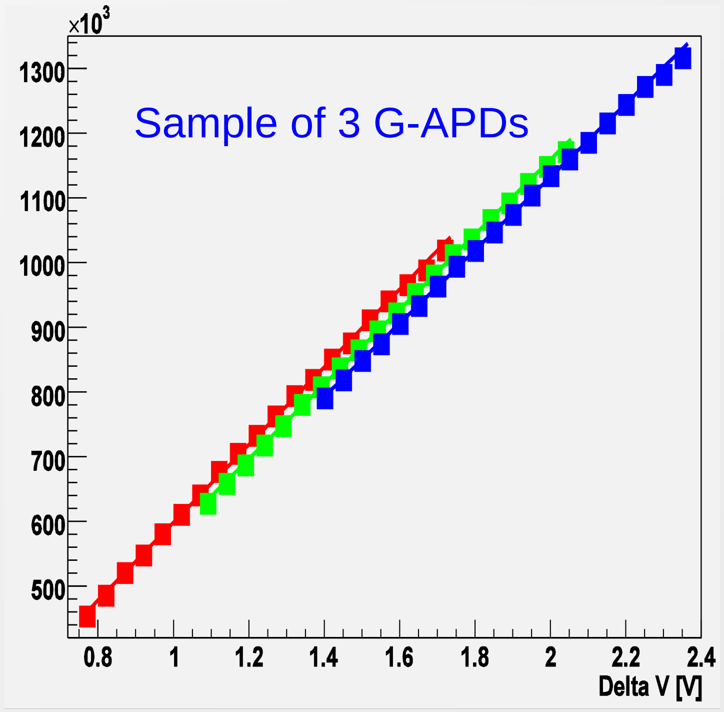


$$Gain = Q/e$$
$$= I_{max} \cdot \tau / e$$
$$= (V_{BIAS}-V_{BD}) C_D / e$$
$$= \Delta V \, C_D / e$$

G ~ 10^5 -10^6 at reasonable bias voltage (<100 V)

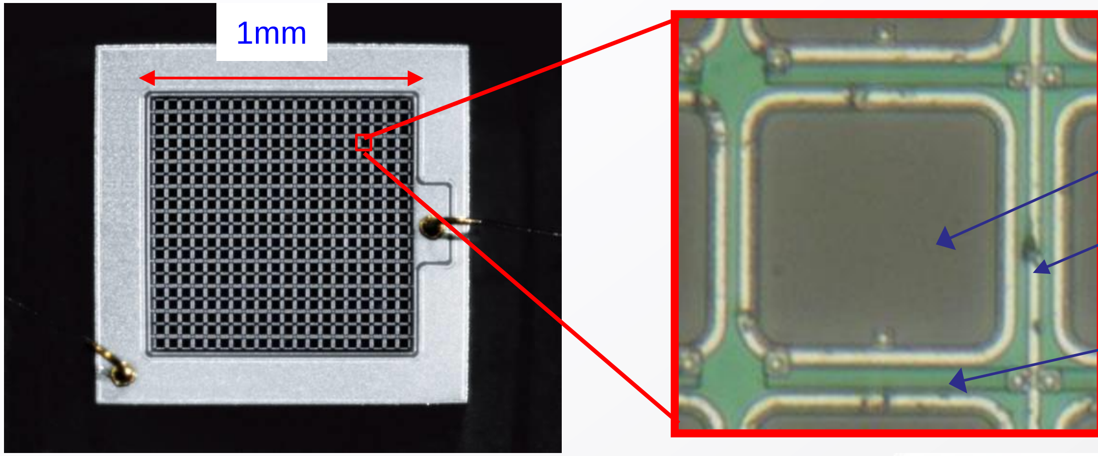


J. Haba, RICH2007



J. Haba, RICH2007

Multi pixel G-APD, called G-APD, MPPC, SiPM, …



100 – several 1000 pix / mm^2

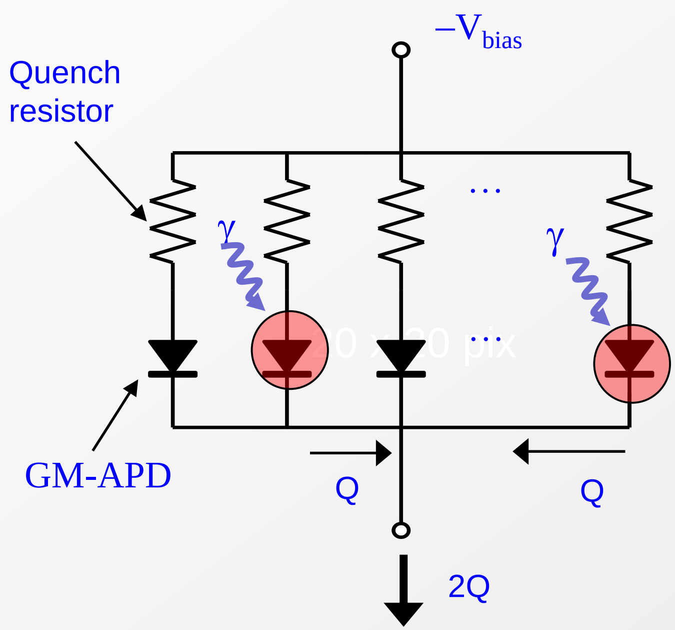
GM-APD

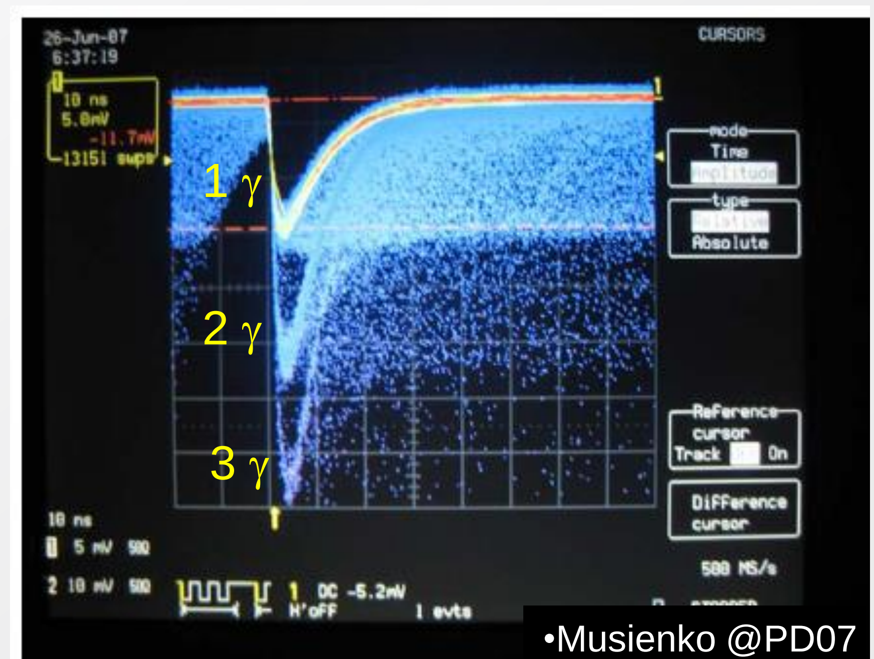
Bias bus

Quench resistor

Only part of surface is photosensitive!

Sizes up to 6×6 mm^2 now standard.





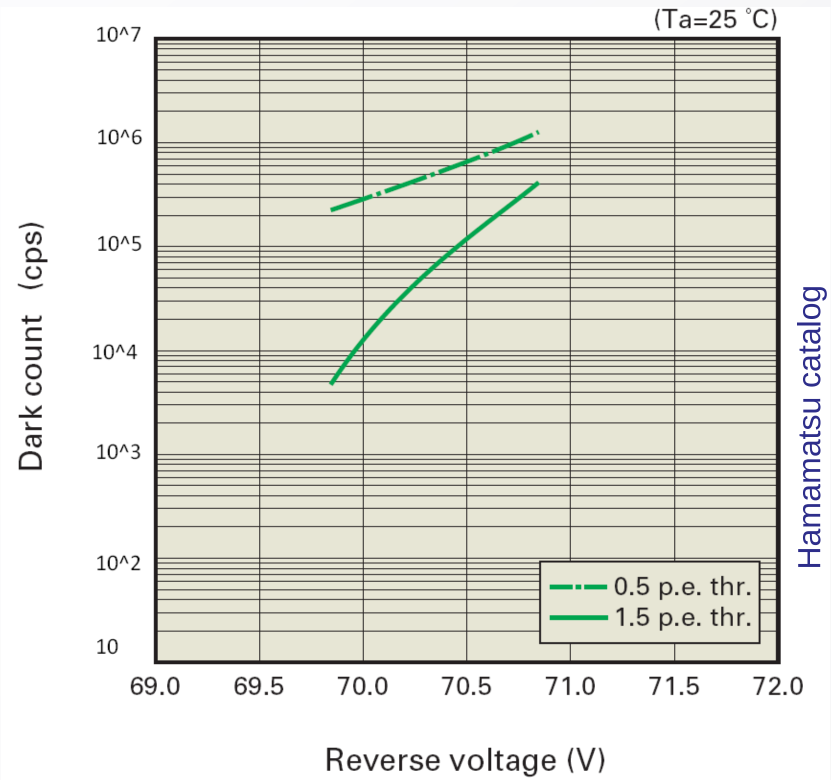
Quasi-analog detector allows photon counting with a clearly quantized signal

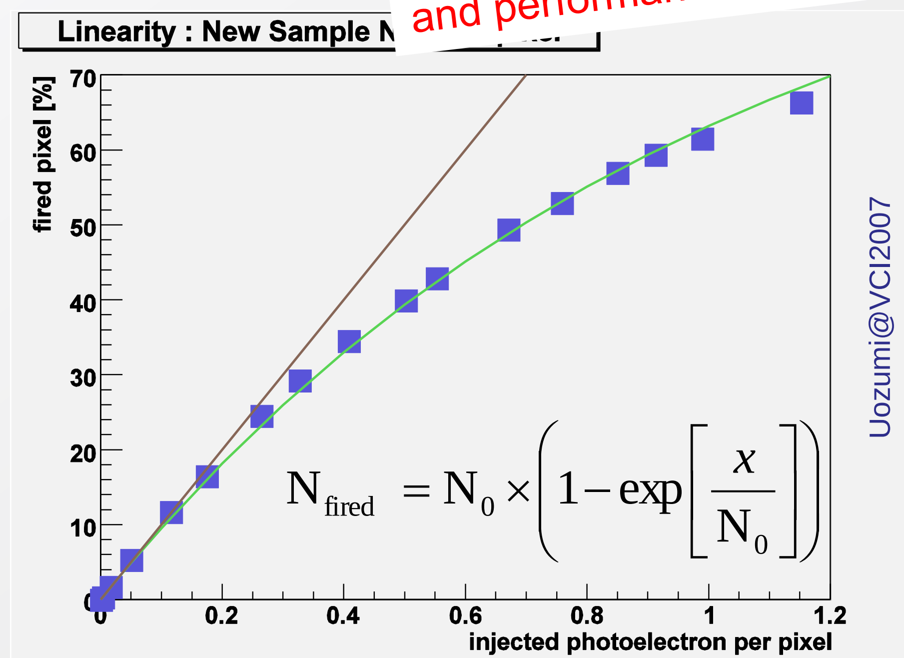
Multi pixel G-APD = G-APD, MPPC, SiPM, …

You cannot get "something for nothing"

- G-APD show dark noise rate in the O(100 kHz – MHz / mm^2) range.
- The gain is temperature dependent O(<5% /°K)
- The signal linearity is limited
- The price is (still too) high

~10 producers are now in the market. Continuous improvement in technology and performance.





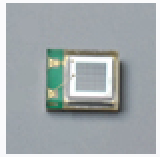
SiPM designs (just examples)

Hamamatsu HPK (http://jp.hamamatsu.com/)

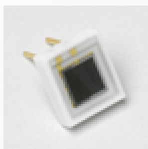
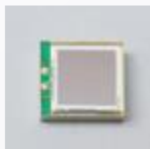
25x25µm², 50x50µm², 100x100µm² pixel size

1x1mm²





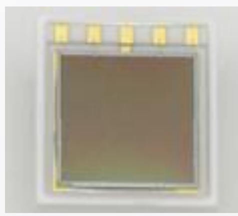
3x3mm²

Arrays

1x4mm²

1x4 channels



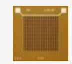
6x6 mm²

2x2 channels

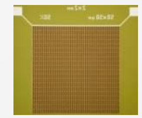
FBK-IRST

50x50µm² pixel size

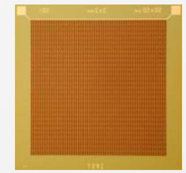
1x1mm²



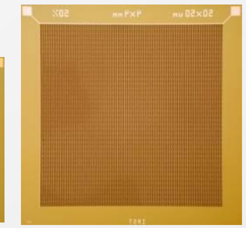
2x2mm²



3x3mm²

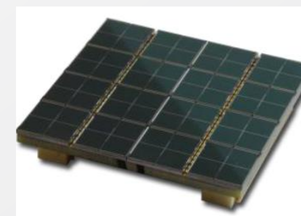


4x4mm²



4x4mm²

2x2 channels



3x3 cm²

8x8 channels

SensL (http://sensl.com/)

20x20µm², 35x35µm², 50x50µm², 100x100µm² pixel size

3.16x3.16mm²

4x4 channels

3.16x3.16mm²

4x4 channels

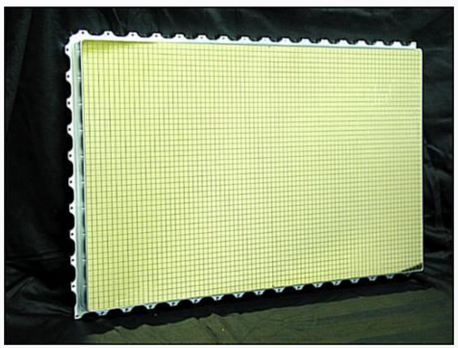
6 x 6 cm²

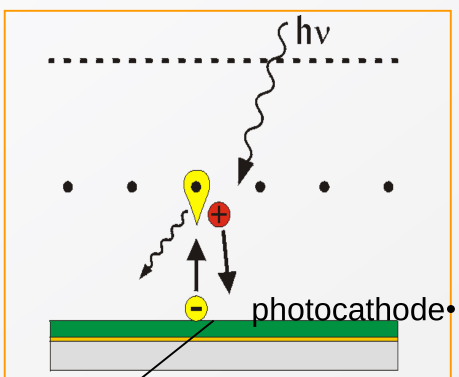
16x16 channels

Gaseous photodetectors: A few implementations...

Proven technology:

Cherenkov detectors in ALICE, HADES, COMPASS, J-LAB…. Many m^2 of CsI photocathodes

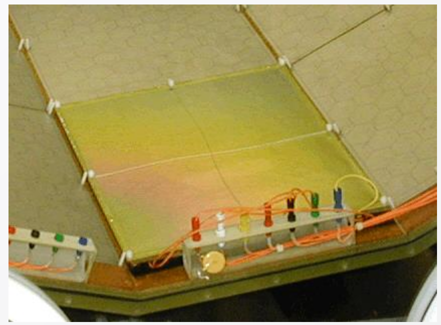


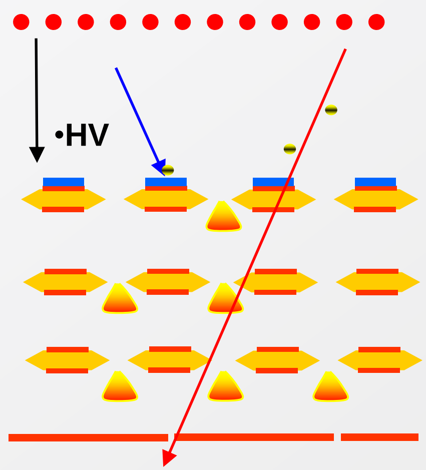


CsI on readout pads

Micro Pattern Structures (GEM) + CsI

HBD (RICH) of PHENIX.





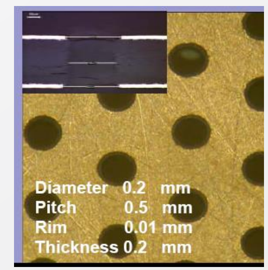
CsI on multi-GEM structure

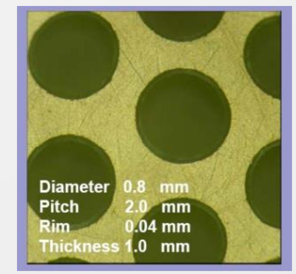
R&D:

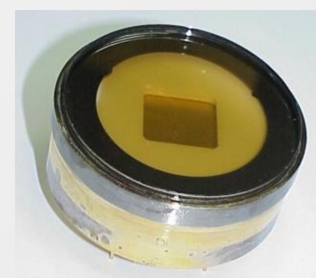
Thick GEM structures

Visible PC (bialkali)

Sealed gaseous devices





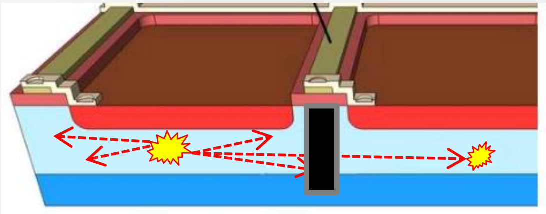


Sealed gaseous photodetector with bialkali PC. (Weizmann Inst., Israel)

BACK-UP SLIDES

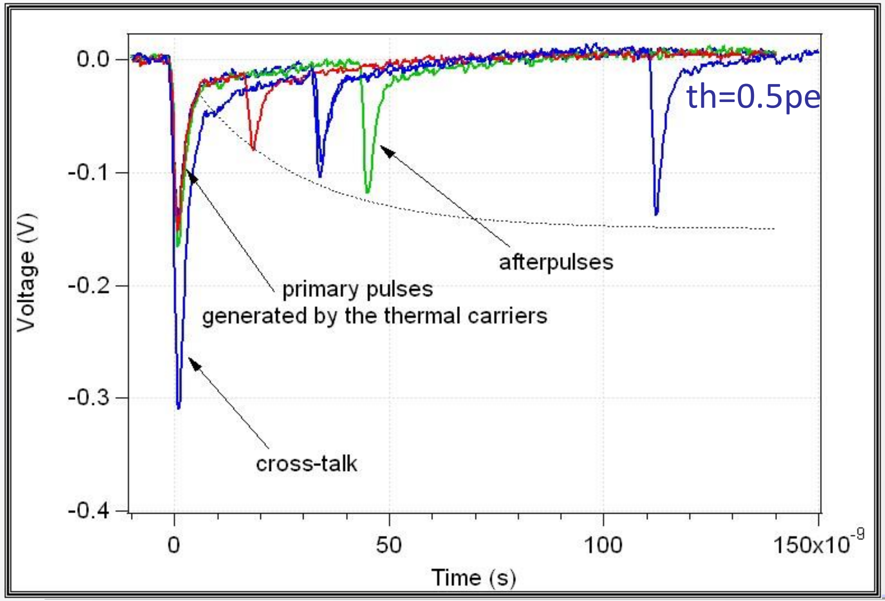
Dark counts due to …

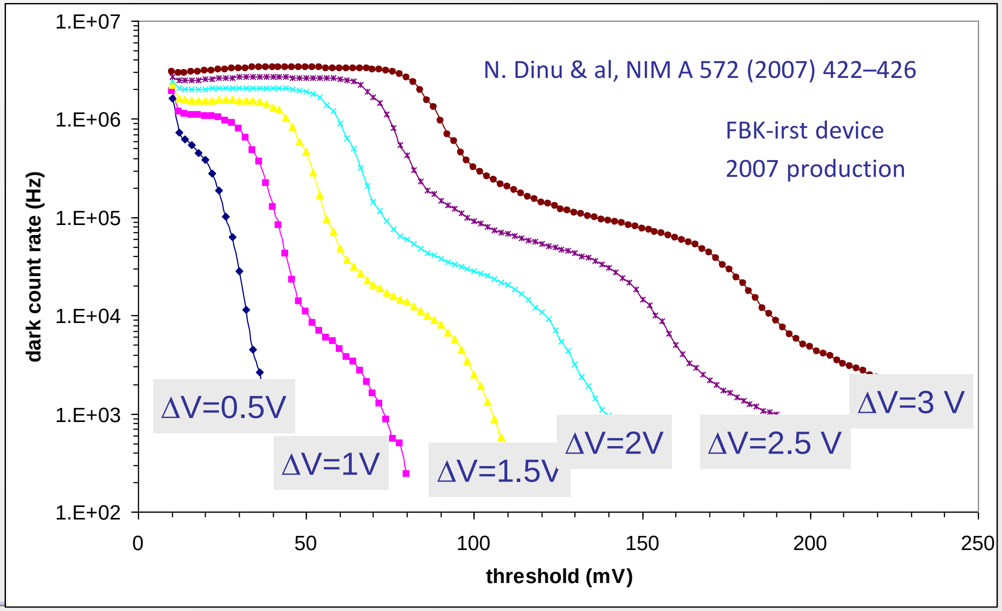
- **Thermal/tunneling** : thermal/ tunneling carrier generation in the bulk or in the surface depleted region around the junction
- **After-pulses :** carriers trapped during the avalanche discharging and then released triggering a new avalanche during a period of several 100 ns after the breakdown
- **Optical cross-talk:** 10^5 carriers in an avalanche plasma emit on average 3 photons with an energy higher than 1.14 eV (A. Lacaita et al. IEEE TED 1993). These photons can trigger an avalanche in an adjacent μcell.



→ Limit gain, increase threshold

→ add trenches btw μcells

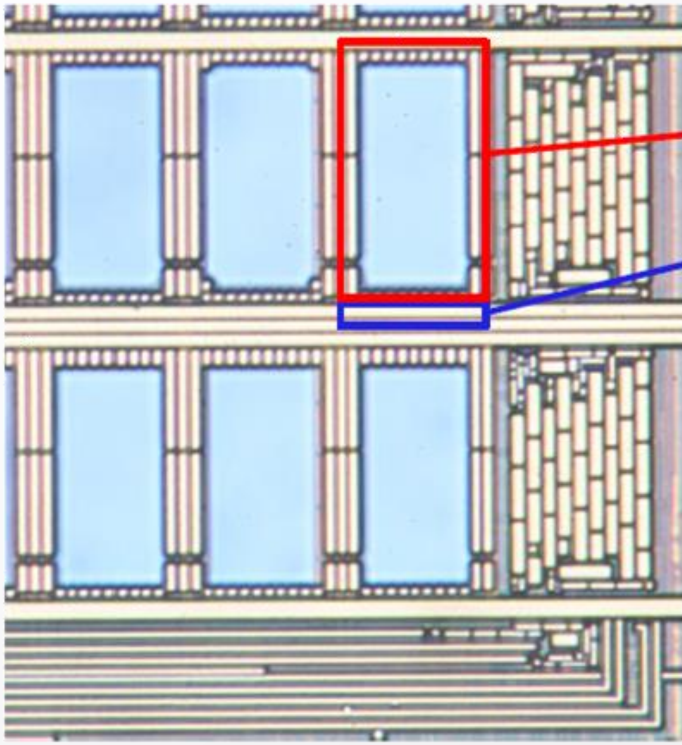




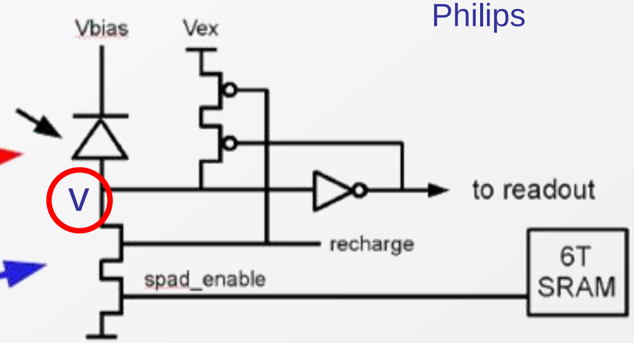
Digital SiPM

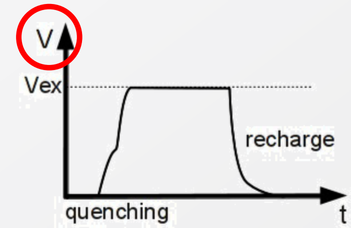
Implementation of SiPMs in a CMOS process allows adding lots of functionality…

1 digital cell (area depends on type, e.g. 30 x 50 μm)



Philips





- Cell electronics area: 120µm²
- 25 transistors including 6T SRAM
- ~6% of total cell area
- Modified 0.18µm 5M CMOS
- Foundry: NXP Nijmegen

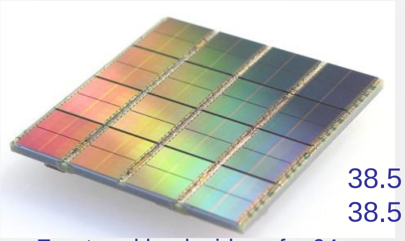
Different from analog SiPMs: Upon the detection of a photon, the avalanche is actively quenched using a dedicated transistor, and a different transistor is used to quickly recharge the diode back to its sensitive state.

Digital SiPM

Compared to the analog technology, the digital one (offered by Philips) has a number of

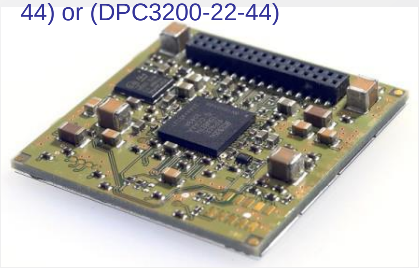
advantages

- \+ Integration of bias supply, amp, TDC, counter…
- \+ Fast active quenching → no afterpulses
- \+ Possibility to de-activate noisy cells → potentially lower dark noise
- \+ Reduced sensitivity to voltage and temperature variations
- \+ Compactness
- \+ Possibility to add local intelligence



38.5 x 38.5 mm^2

Front and back sides of a 64 channel digital tile (DPC6400-22-44) or (DPC3200-22-44)



Philips

… **problems shared with analog**

- ○ High dark noise (a discharging cell doesn't know whether it is digital or analog)
- ○ Signal saturation (limited number of cells)

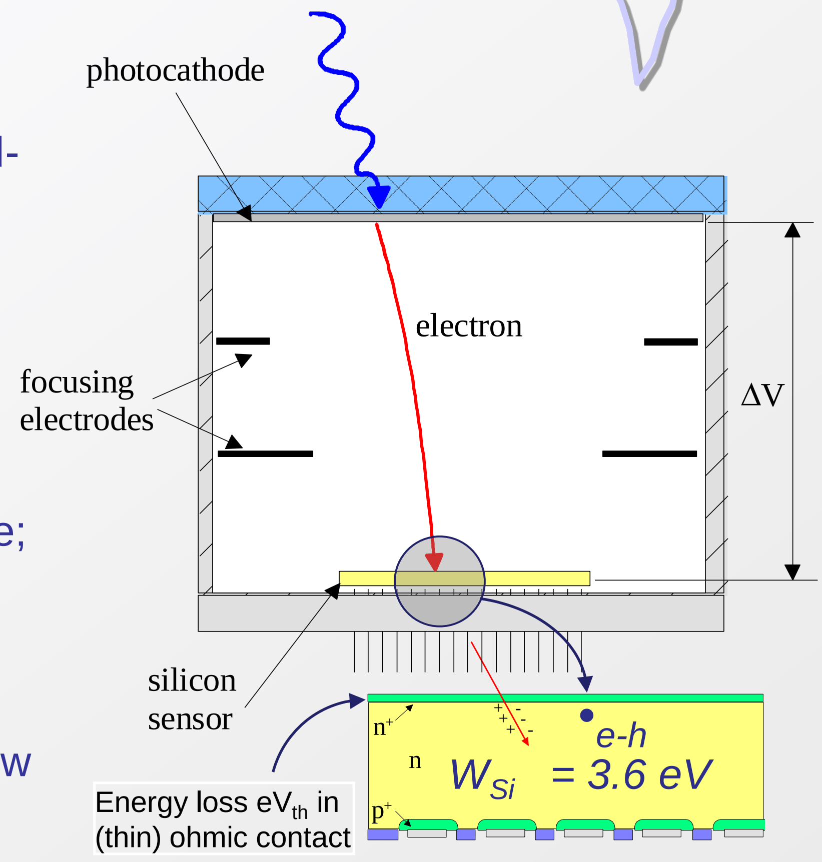
… and also has some **drawbacks**

- \- The local electronics is a source of heat → cooling advisable
- \- The readout functionality is designed into the sensor. In case of mismatch with the needs, relatively expensive modifications of the sensor/FPGA may be required.

Hybrid Photon Detectors (HPD's)

Basic principle:

- Combination of vacuum photon detectors and solid-state technology;
- Optical window, (semitransparent) photo-cathode;
- Electron optics (optional: demagnification)
- Charge Gain: achieved *in one step* by energy dissipation of keV pe's in solid-state detector anode; this results in low gain fluctuations;
- Encapsulation of Si-sensor in the tube implies:
    - compatibility with high vacuum technology (low outgassing, high T° bake-out cycles);
    - internal (for speed and fine segmentation) or external connectivity to read-out electronics;
    - heat dissipation issues;



$$M = \frac{e(\Delta V - Vth)}{W_{Si}}$$

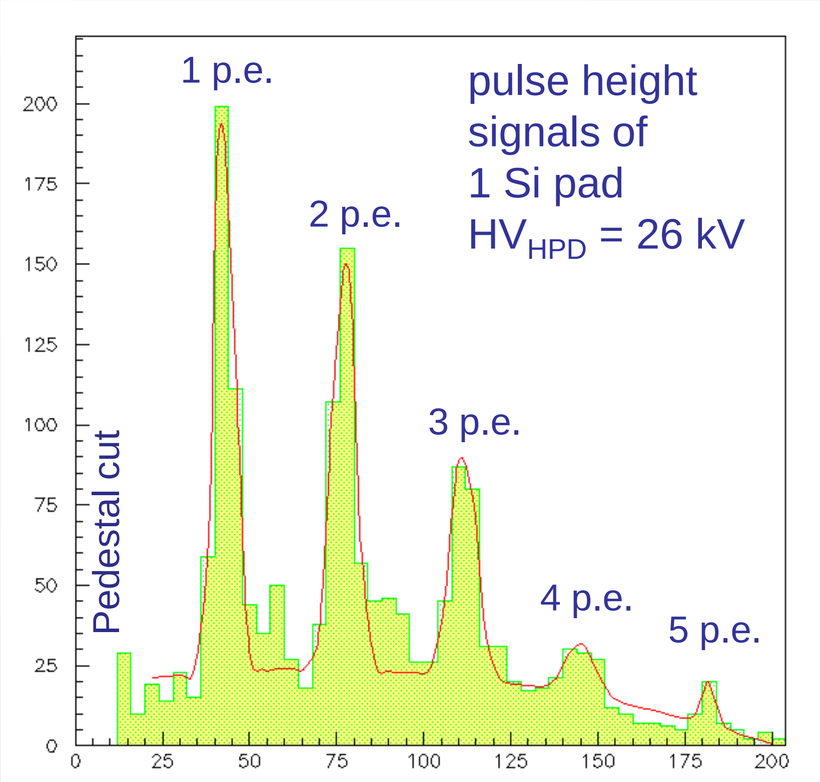
ΔV = 20 kV
→ M ~ 5000

$$\sigma_M = \sqrt{F \times M}$$

F = Fano factor
F_{Si} ~ 0.1

Hybrid Photon Detectors (HPD's)

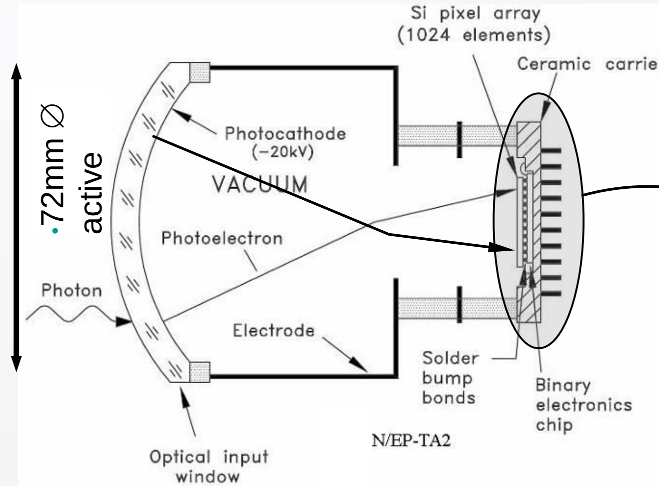
10-inch prototype HPD (CERN)
for Air Shower Telescope CLUE.



pulse height (ADC counts)

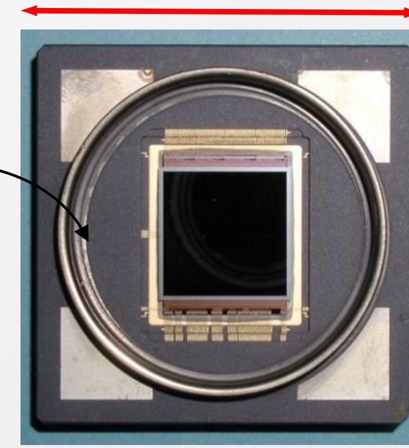
Photon counting. Continuum due to electron back scattering.

Pixel-HPD's for LHCb RICH detectors



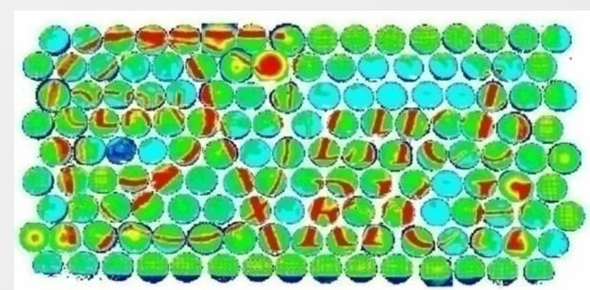
T. Gys, NIM A 567 (2006) 176-179

50mm



Pixel-HPD anode

- Cross-focused electron optics
- pixel array sensor bump-bonded to binary electronic chip, developed at CERN
- 8192 pixels of 50 × 400 μm.
- specially developed high T° bump-bonding;
- Flip-chip assembly, tube encapsulation (multi-alkali PC) performed in industry (VTT, Photonis/DEP)



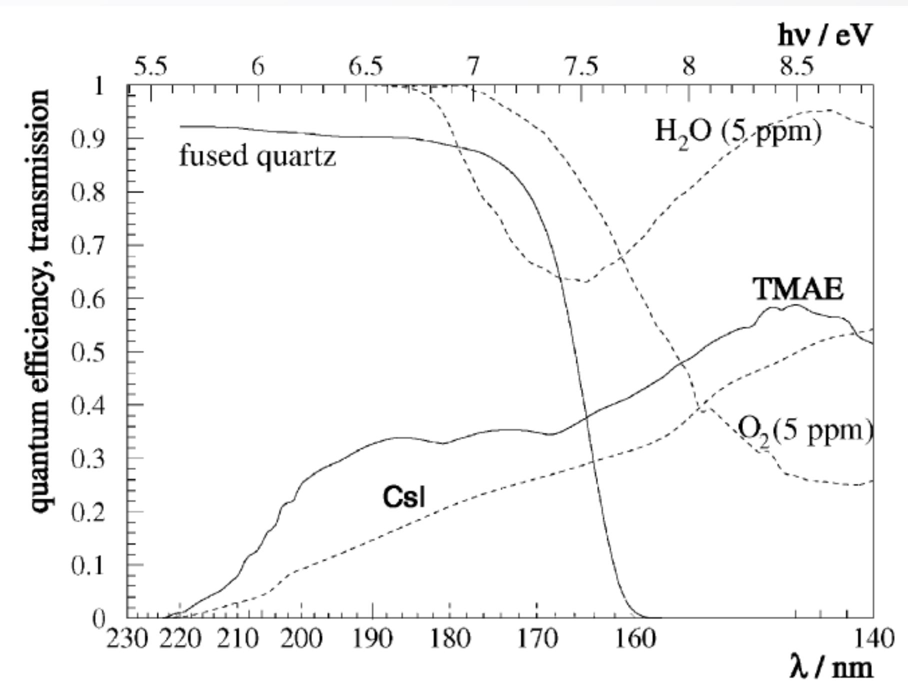
During commissioning: illumination of 144 tubes by beamer. In total : 484 tubes.

Gaseous Photodetectors

Principle: (A) Ionize photosensitive molecules, admixed to the counter gas (TMAE, TEA);

or (B) release photoelectron from a solid photocathode (CsI, bialkali...);

Then use free photoelectron to trigger a Townsend avalanche → Gain

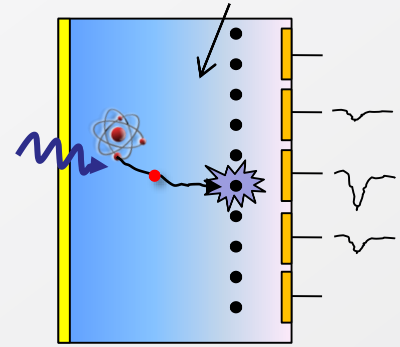


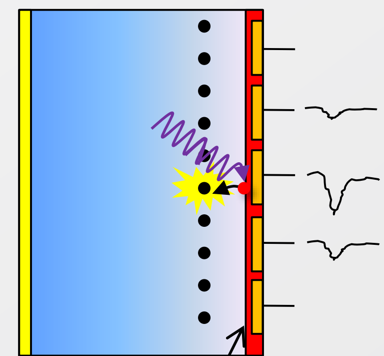
TEA, TMAE, CsI work only in deep UV region.

Bialkali works in visible domain, however requires VERY clean gases.

Long term operation in a real detector not yet demonstrated.

e.g. CH_4 + TEA



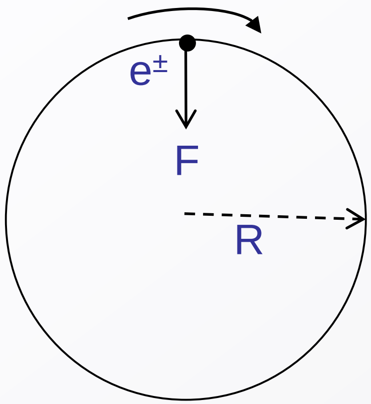


Thin CsI coating on cathode pads

- Usual issues: How to achieve high gain (10^5) ? How to control ion feedback and light emisson from avalanche? How to purify gas and keep it clean? How to control aging ?

Side remark…

Bremsstrahlung plays an important role in accelerators, but essentially only in circular $e^{\pm}$ machines. Here it is called 'Synchrotron radiation'



Magnetic field forces particles on a circle → permanent acceleration towards the centre of the circle.

Radiated power:

$$P_r = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{m^4} \frac{E^4}{R^2}$$

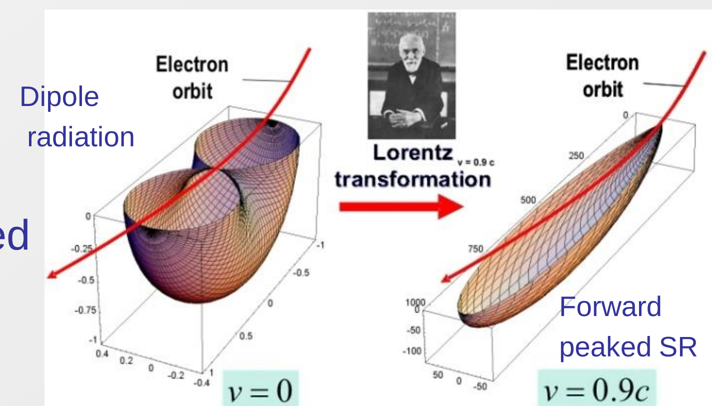
$$\frac{P_{r,e}}{P_{r,p}} = \frac{m_e^4}{m_p^4} \approx 1836^4 = 1.1 \cdot 10^{13}$$

Negative aspect: The radiated energy per turn can eat up the gained energy by acceleration and so limit the achievable energy. Famous example: LEP (e^+e^- collider).

$$\Delta E_{turn} = \oint P_r dt = P_r \frac{2\pi R}{c}$$

E_{LEP} ~100 GeV. R_{LEP} ~4300 m → ΔE_{turn} ~ 2 GeV

Positive aspect: The radiated energy is extremely forward peaked (Lorentz transformed) and can be used as very bright and intense photon source, e.g. for material studies. See e.g. ESRF (www.esrf.eu)

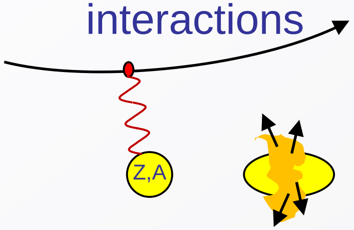


A few more words on muons (at very high energies)

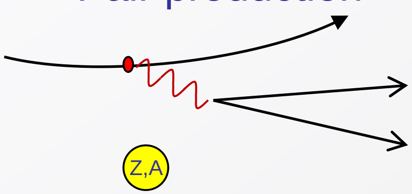
Muons interact electromagnetically (like the e^+,e^-, but due to its high mass, direct Bremsstrahlung ($\sim E/m^2$) is strongly suppressed.

There are other radiative processes

- Photo-nuclear interactions

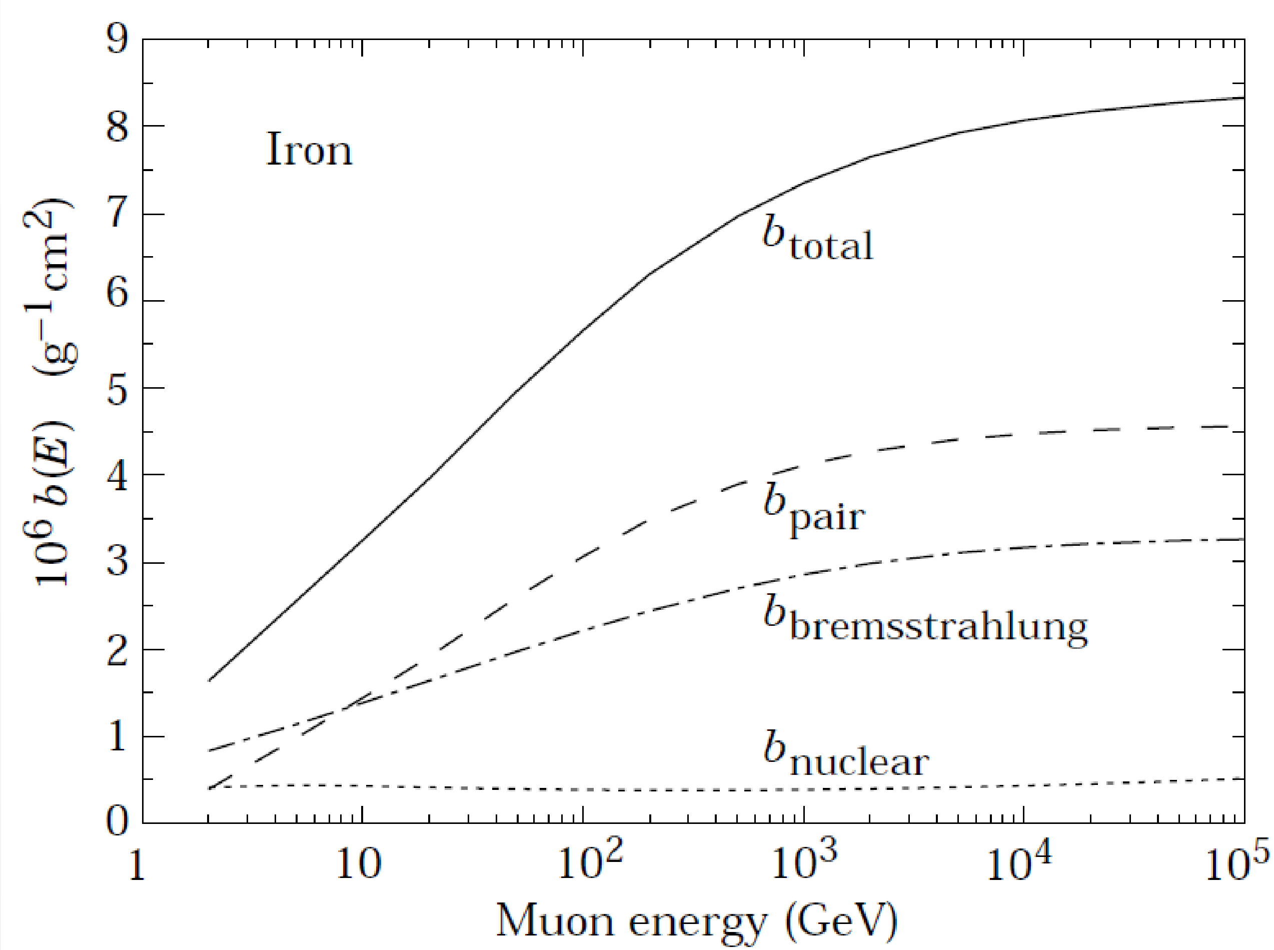


- Pair production



Like for Bremsstrahlung, they scale with E

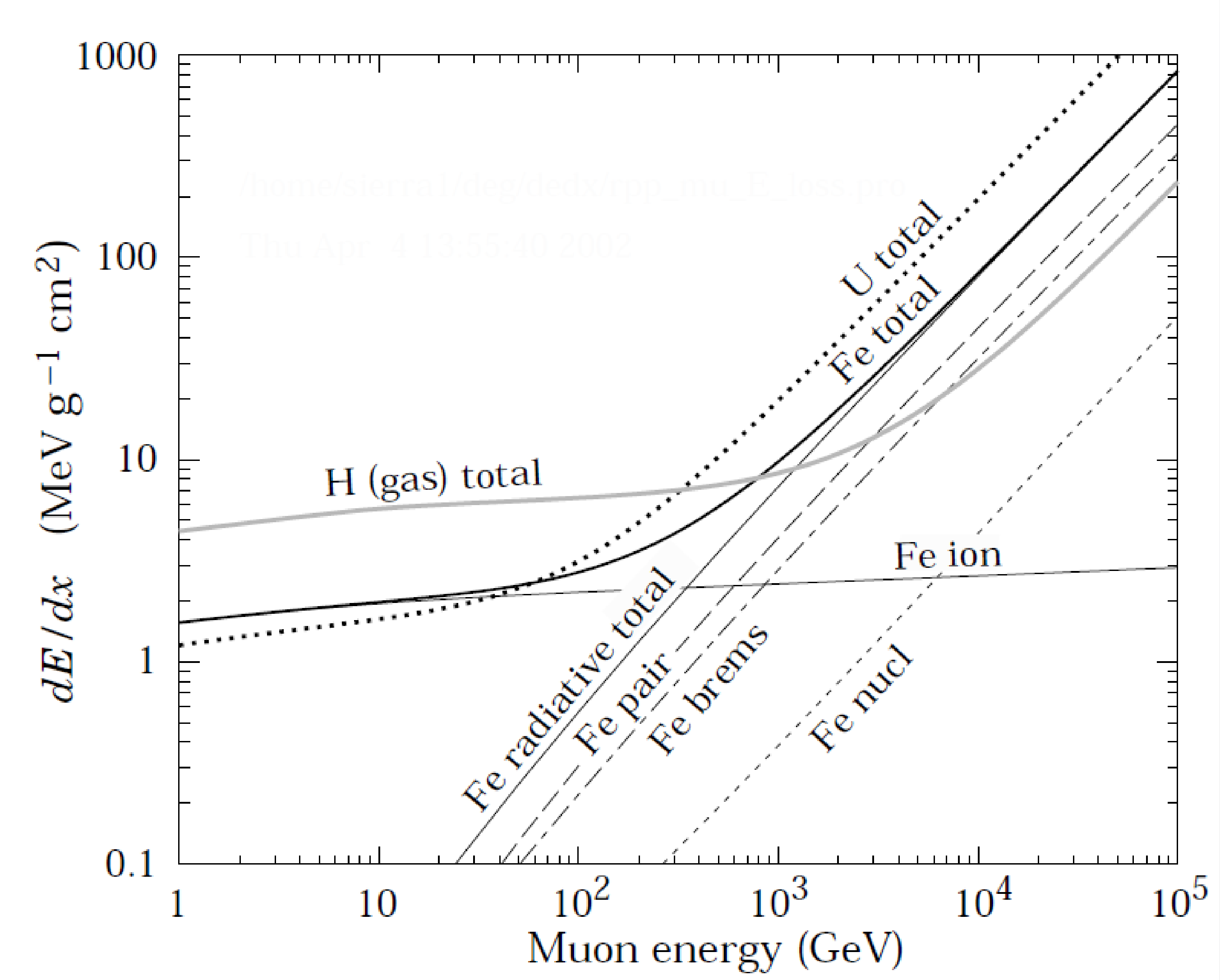
$$\frac{dE}{dx} = b(Z, A, E_\mu) \cdot E_\mu$$



Total energy loss of muons (in different materials)

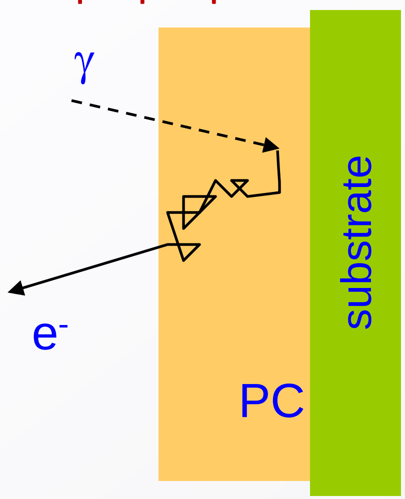
$$\frac{dE}{dx} = a + b \cdot E_{\mu}$$

ionization radiative

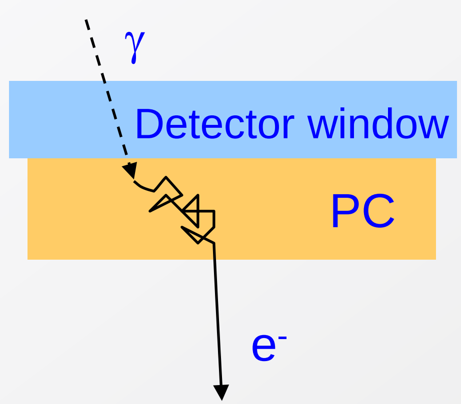


Basics of photon detection

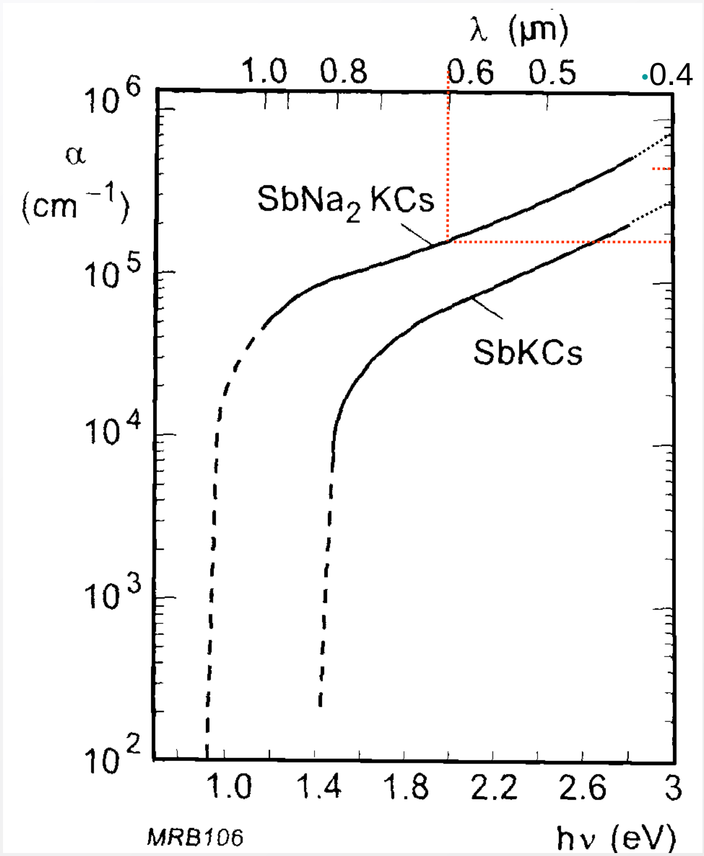
Opaque photocathode



Semitransparent photocathode



Light absorption in photocathode



$\lambda_A = 1/\alpha$

Red light ($\lambda \approx 600$ nm)
$\alpha \approx 1.5 \cdot 10^5$ cm^{-1}
$\lambda_A \approx 60$ nm

Blue light ($\lambda \approx 400$ nm)
$\alpha \approx 4 \cdot 10^5$ cm^{-1}
$\lambda_A \approx 25$ nm

Blue light is stronger absorbed than red light !

→ Make semitransparent photocathode just as thick as necessary!