Particle Detectors

M. Swartz

Particle Detectors

Elementary particles are detected via their interactions with matter. There are 4 different interactions in use:

- Charged particles ionize matter and leave electron-ion pairs in their wake
  - accounts for nearly all particle detection technologies
  - neutral particles are observed only because they produce charged secondaries
- Charged particles traveling faster than the speed of light in a transparent medium emit Cerenkov Radiation
- Charged particles traversing the interface between regions of different dielectric constant emit photons in the opposite direction [Transition Radiation]
  - physics is related to Cerenkov Radiation
- Charged/neutral particles can interact with nuclei to produce phonons [quantized lattice vibrations] in crystals

Useful Definitions

We usually deal with relativistic particles and need to remember some more general definitions of energy and momentum

$$E^2 = p^2c^2 + m^2c^4 \qquad \vec{\beta} = \frac{\vec{v}}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

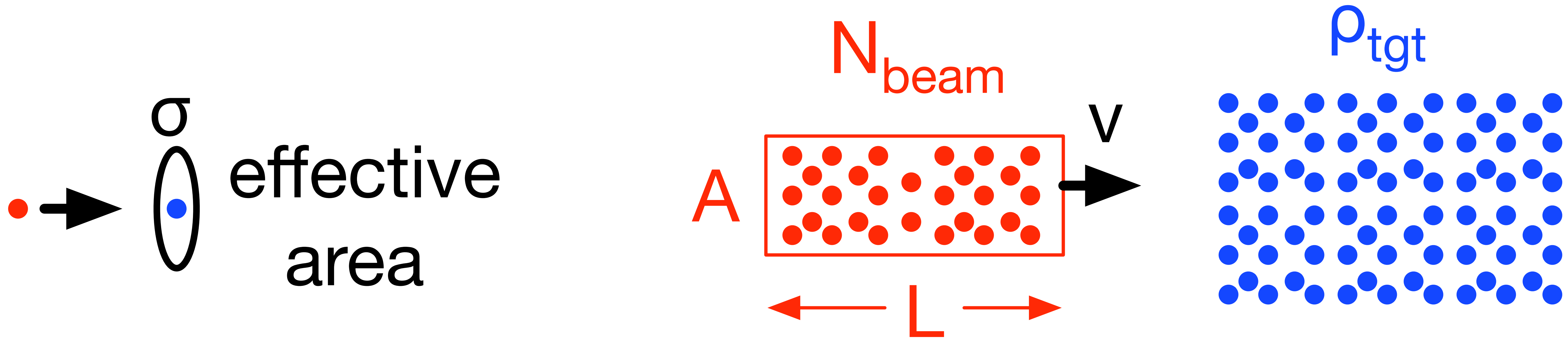
$$E = \gamma mc^2 \qquad \vec{p} = \gamma m\vec{v} = \gamma m\vec{\beta}c$$

$$T = E - mc^2 = mc^2\left[\gamma - 1\right] = mc^2\left[\frac{1}{\sqrt{1-\beta^2}} - 1\right] \simeq \underbrace{mc^2\left[1 + \frac{1}{2}\beta^2 - 1\right] = \frac{1}{2}mv^2}_{\beta \ll 1}$$

- we often measure velocity in units of v/c
- the γ factor varies from 1 [slow particles] to large values [very relativistic particles]
  - E and p scale with γ and become large as β -> 1
- kinetic energy T is the difference between the total energy E and the rest mass energy mc^2

More Useful Definitions

Interactions between particles [elementary ones, or atoms/molecules] can be characterized by an effective area known as a cross section σ



Assume that we have a beam of N_{beam} particles of cross sectional area A and length L moving at a speed v. It impinges on a medium have a number density ρ_{tgt}. The number of interactions per second the we expect would be dN/dt,

$$\frac{dN}{dt} = \frac{N_{\rm beam}}{A} \cdot \frac{v}{L} \cdot \sigma \cdot \underbrace{\rho_{\rm tgt} A L}_{N_{\rm tgt}} = N_{\rm beam} v \sigma \rho_{\rm tgt}$$

If the interactions remove beam particles, then we should include a - sign.

$$\frac{dN_{\rm beam}}{dt} = -N_{\rm beam} v \sigma \rho_{\rm tgt} \quad \rightarrow \quad dN_{\rm beam} = -N_{\rm beam} \sigma \rho_{\rm tgt} v dt$$

As a function of distance traveled dz = vdt, we see that

$$\frac{dN_{\rm beam}}{N_{\rm beam}} = -\sigma\rho_{\rm tgt}dz \quad \rightarrow \quad N_{\rm beam} = N_0 e^{-z/\ell},\ \ell = \frac{1}{\sigma\rho_{\rm tgt}}$$

The beam is exponentially attenuated with a mean free path of 1/(ρσ). This physics can be found in many systems. [Note that all densities are number densities not mass densities.]

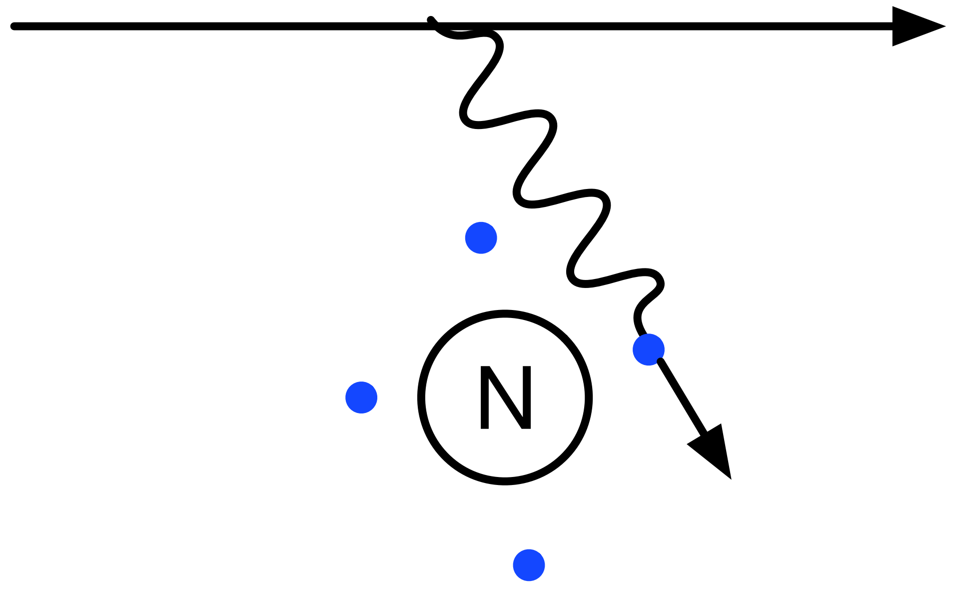
This physics even appears in chemical reactions! Let's consider two chemical species A and B that interact to produce C: A+B->C. Let's assume that A and B are moving thermally and have a cross section σ to produce species C.

$$\frac{dN_C}{dt} = N_A v_{\rm rel}\sigma\rho_B = \rho_A V v_{\rm rel}\sigma\rho_B \ \rightarrow\ \frac{d\rho_C}{dt} = \frac{1}{V}\frac{dN_C}{dt} = \underbrace{k(T)}_{v_{\rm rel}\sigma}\rho_A\rho_B$$

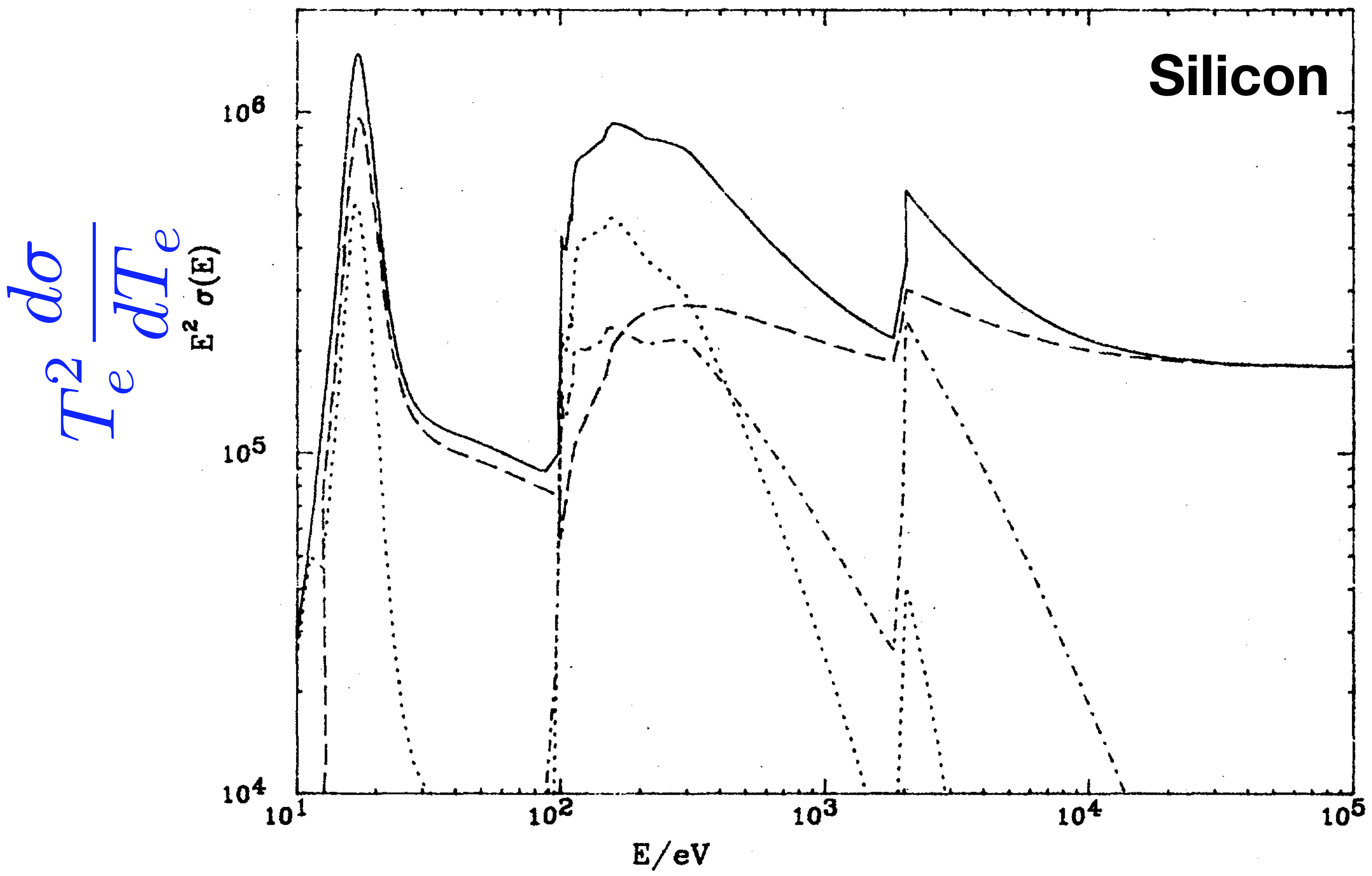
- $v_{\rm rel}$ is the relative thermal velocity of the species [scales as $T^{1/2}$]

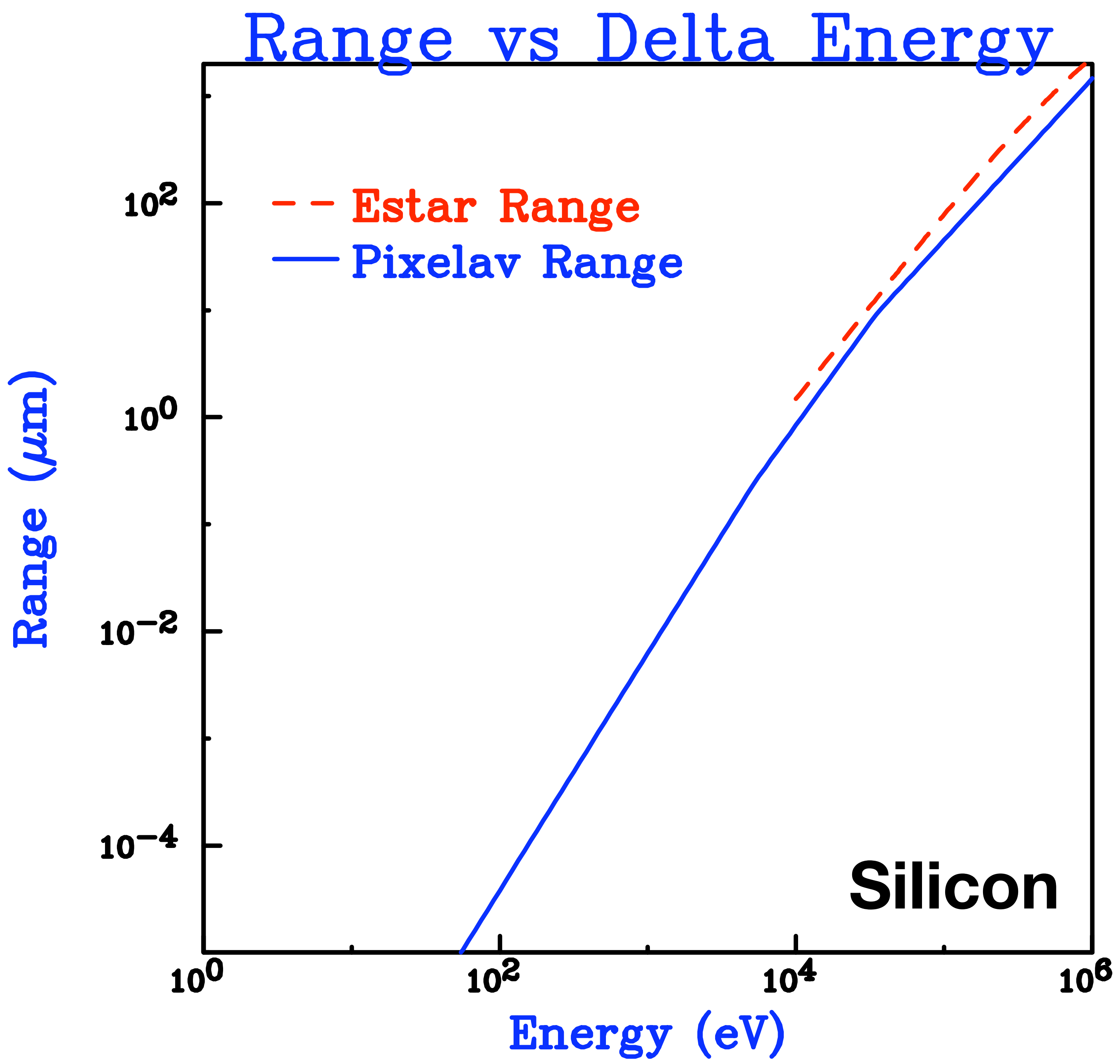
- the reaction constant k includes the cross section which may have a $v_{\rm rel}$ dependence [barriers] making the T dependence more complex.

Ionization

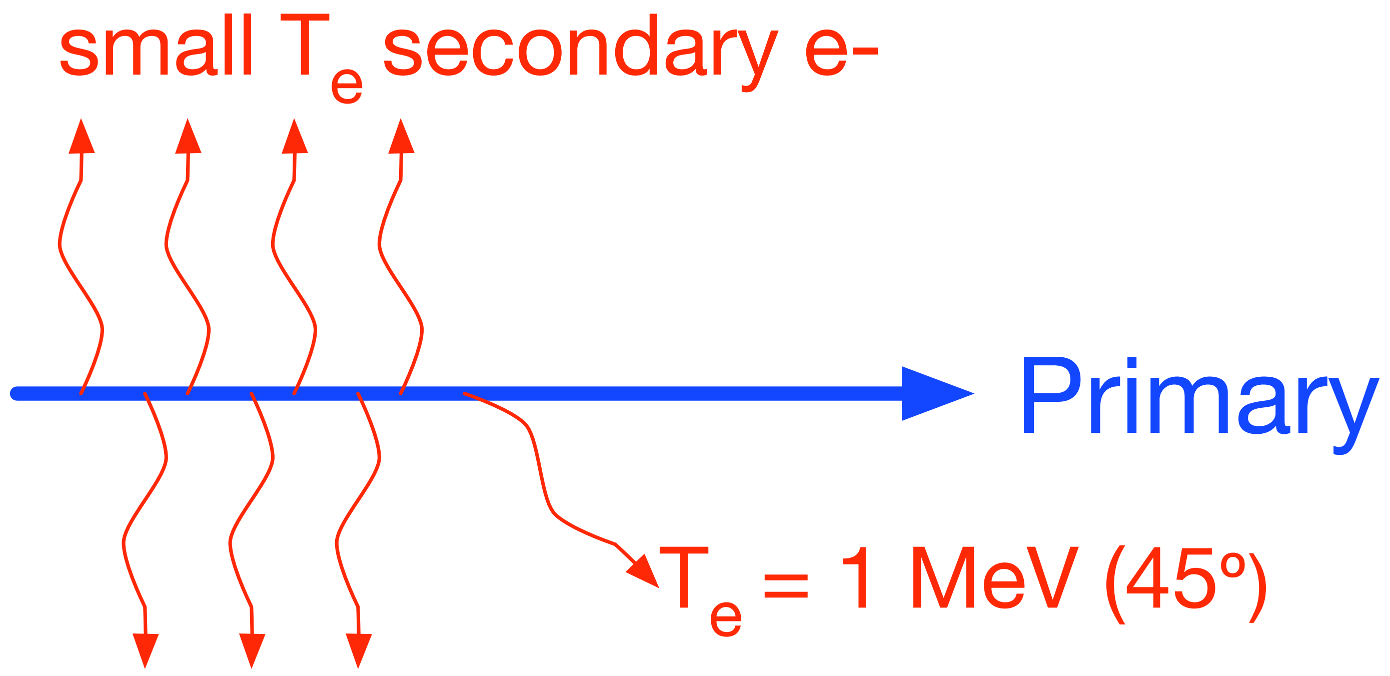


Charged particles interact with electrons bound to atoms and molecules ionizing the atom/molecule and transferring kinetic energy to the electron. The ejected electrons can have kinetic energies from a few eV to MeV.





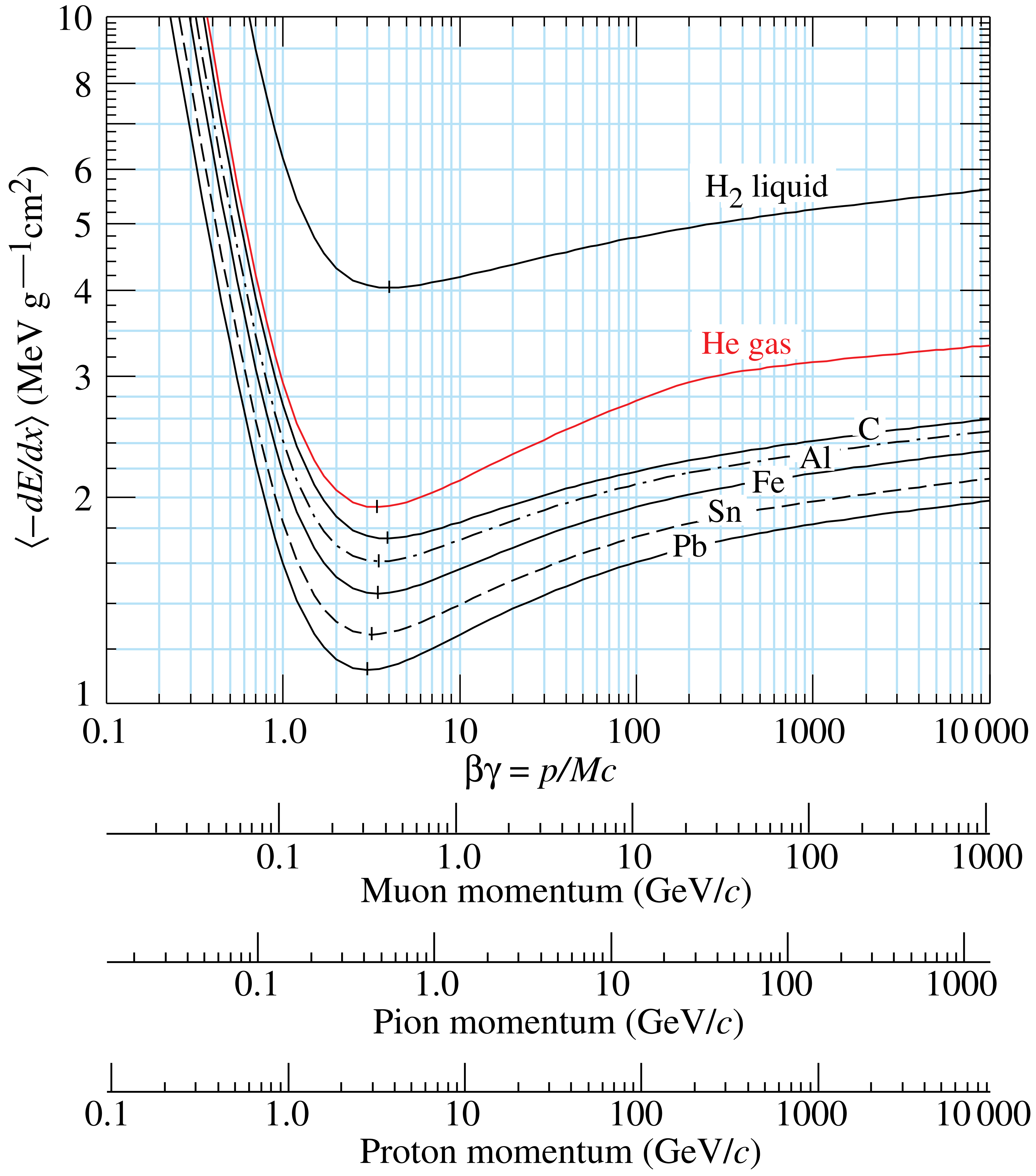
$$\cos\theta_{ep} = \sqrt{\frac{T_e}{T_e + 2m_e c^2}}$$



- secondary electrons have T_e from few eV to MeV [travel up to ~1mm] emitted mostly at 90° wrt the primary
- secondary electrons ionize material to make more e-ion pairs [significant enhancement]

The mean energy lost by a charged particle as it traverses some material is given by the famous Bethe-Bloch equation,

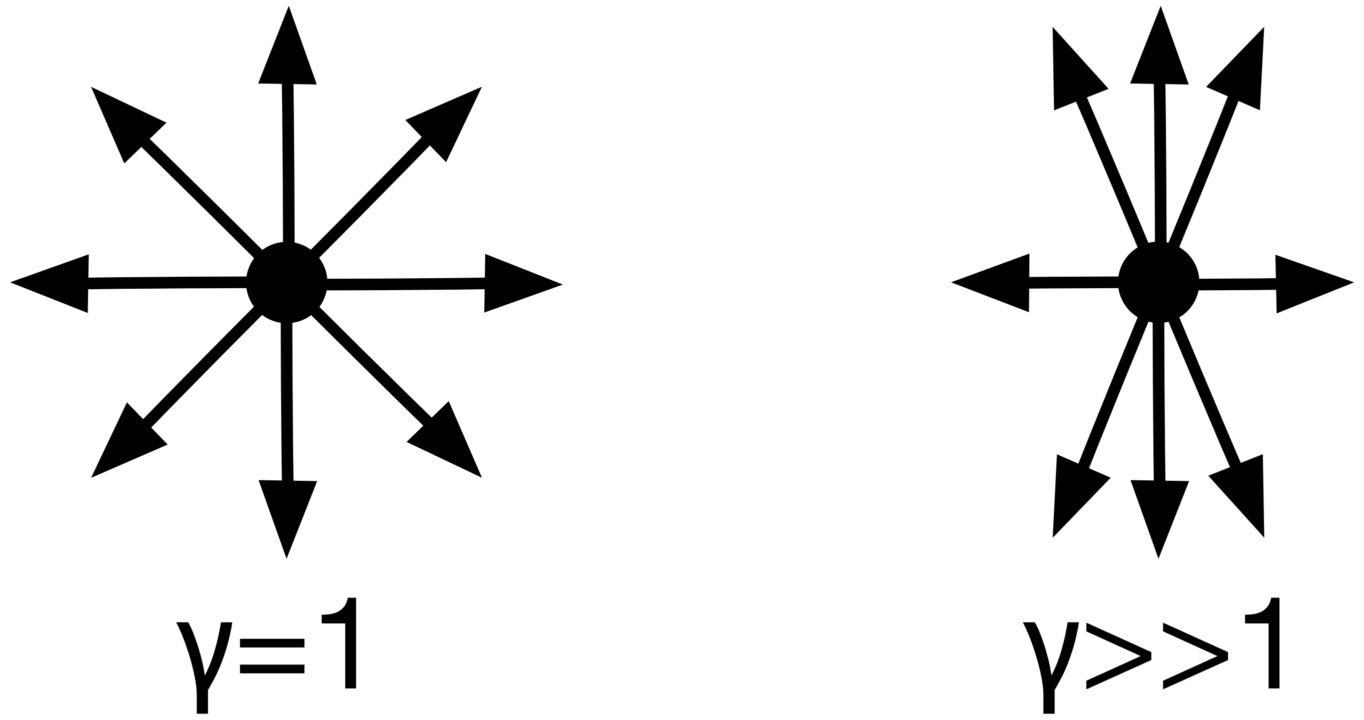
$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I_0^2} - \beta^2 \right]$$

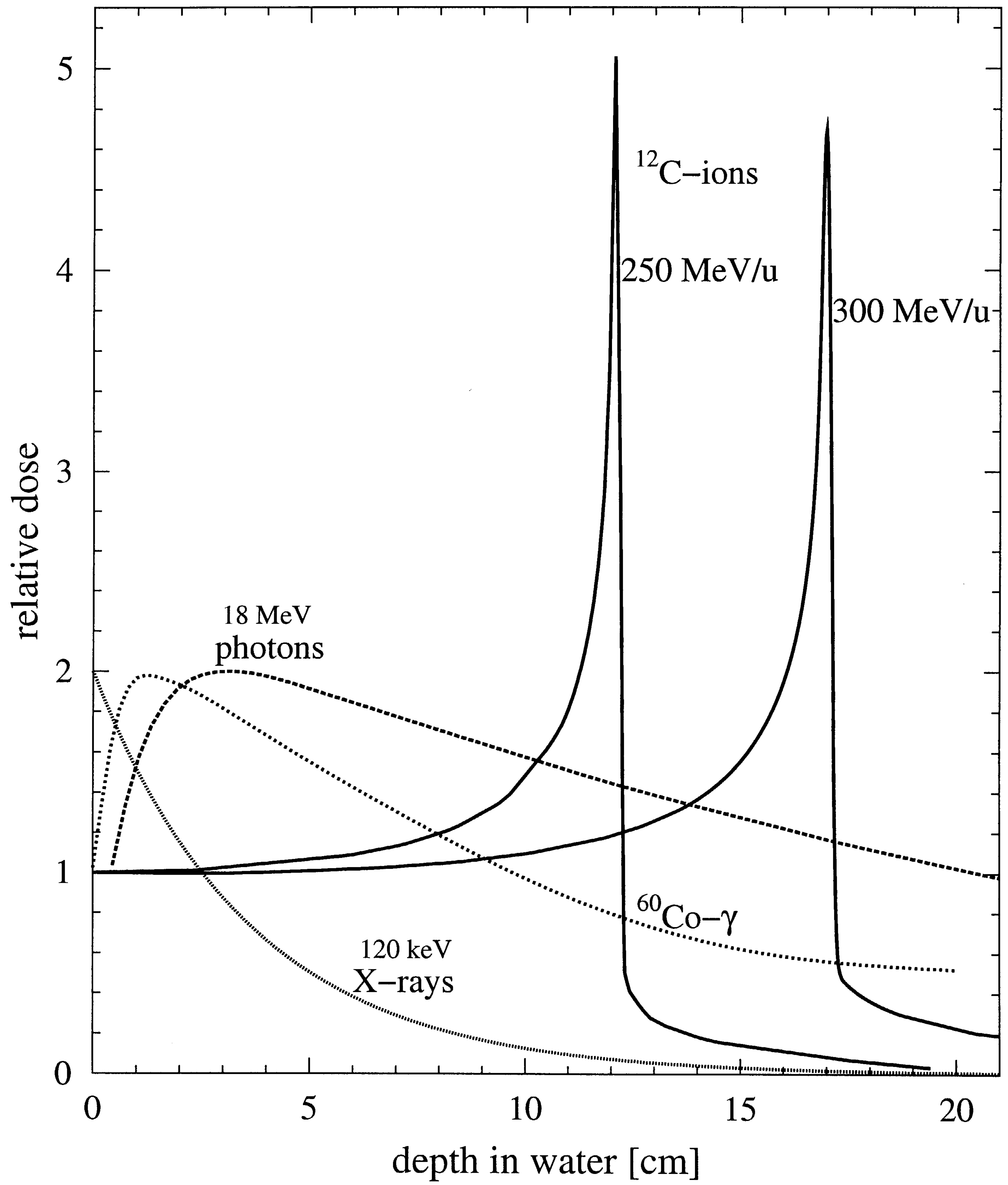


- K = 0.307 MeV g^{-1}cm^2 [multiply by ρ_M to get MeV/cm]
- the minimum energy loss occurs when βγ ~ 3-5
  - [dE/dx]$_{min}$ typically varies from 1-2 in MeV g^{-1}cm^2 units
- the average excitation potential I_0 ~ (10-15 eV) x Z
- energy per e-ion pair W ~ 3.6 eV [Si] - 30 eV [gases]
  - determines the average number of electron-ion pairs
- normal incidence min I particle: in 300um thick Si yields ~22,000 e-ion pairs, in 1 cm of Ar gas ~100 e-ion pairs

The increasing dE/dx for slow particles implies that stopping particles deposit significant ionization/energy in a small distance. This makes protons and ions useful for cancer therapy.

The increasing dE/dx for fast particles is caused by the relativstic increase in the transverse E-field of primary

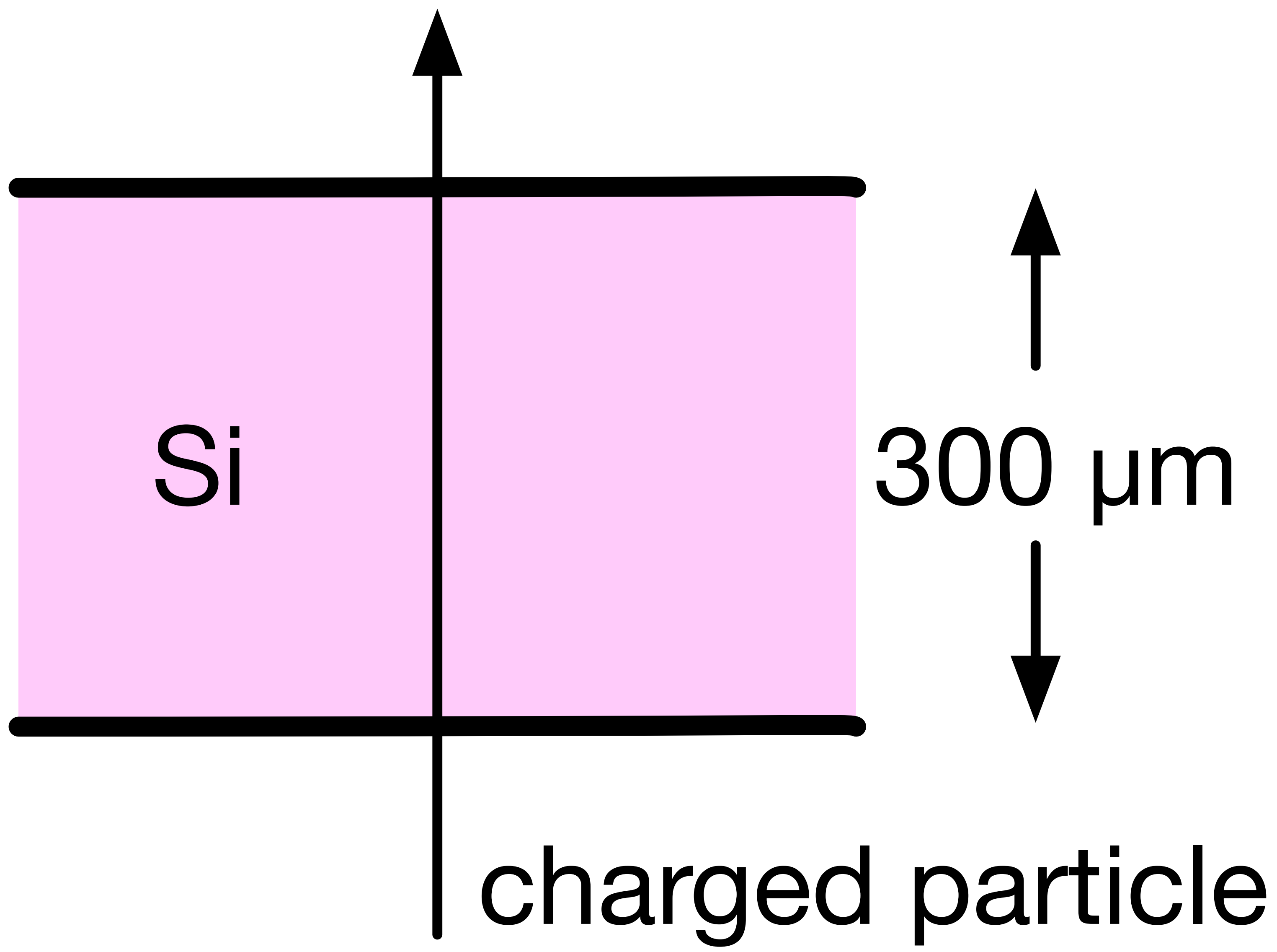




- known as the “relativistic rise”
- increase is limited by the “density effect”
  - polarization of the material

Question 1

A relativistic charged particle passes through 300 μm of silicon. Approximately how much charge does it deposit in the material?



A. 100e

B. 22,000e

C. 0e

Question 1

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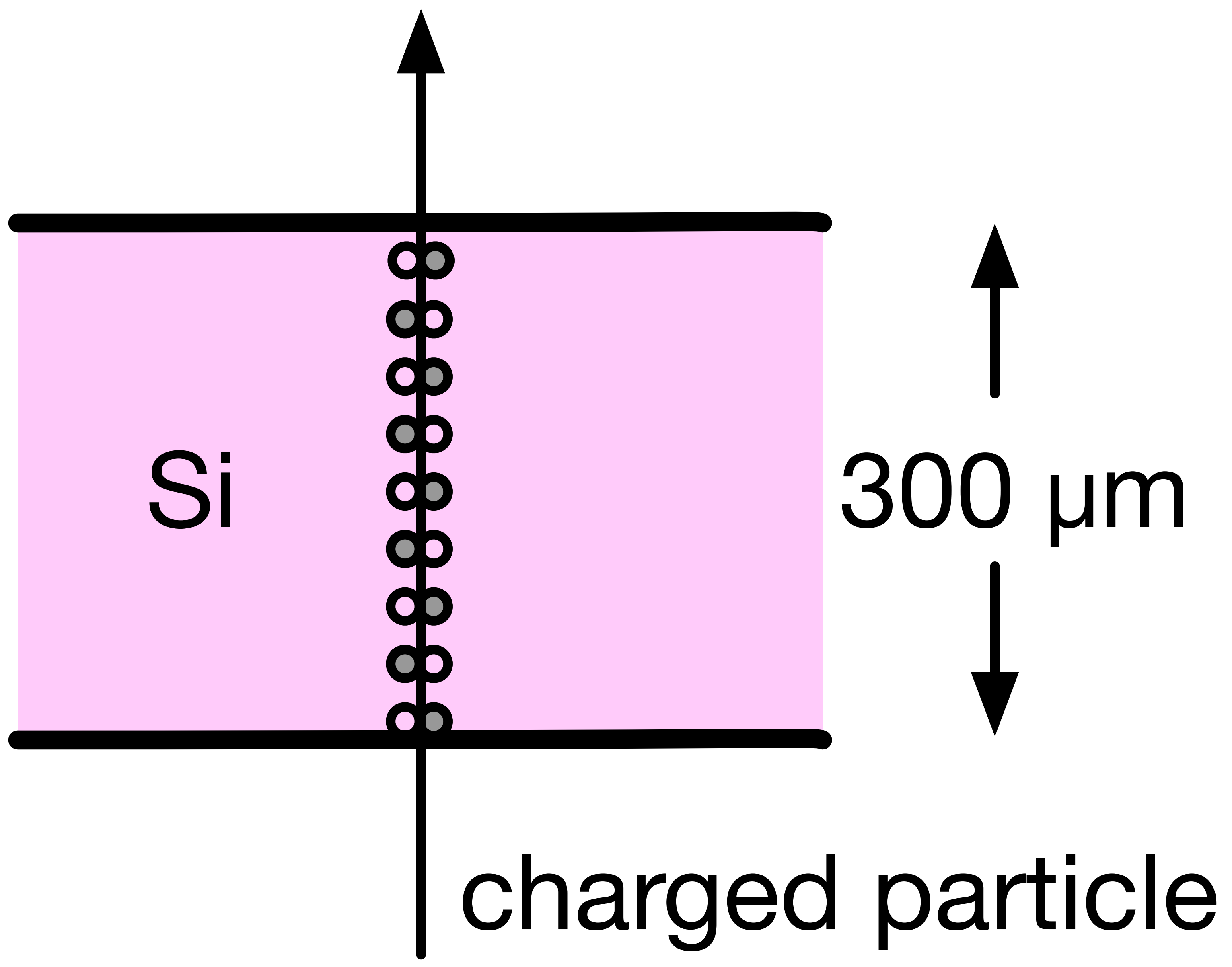


A. 100e

B. 22,000e

C. 0e

The relativistic charged particle makes about 22,000 electron ion pairs but deposits 0 net charge in the material. To detect the particle, we can:

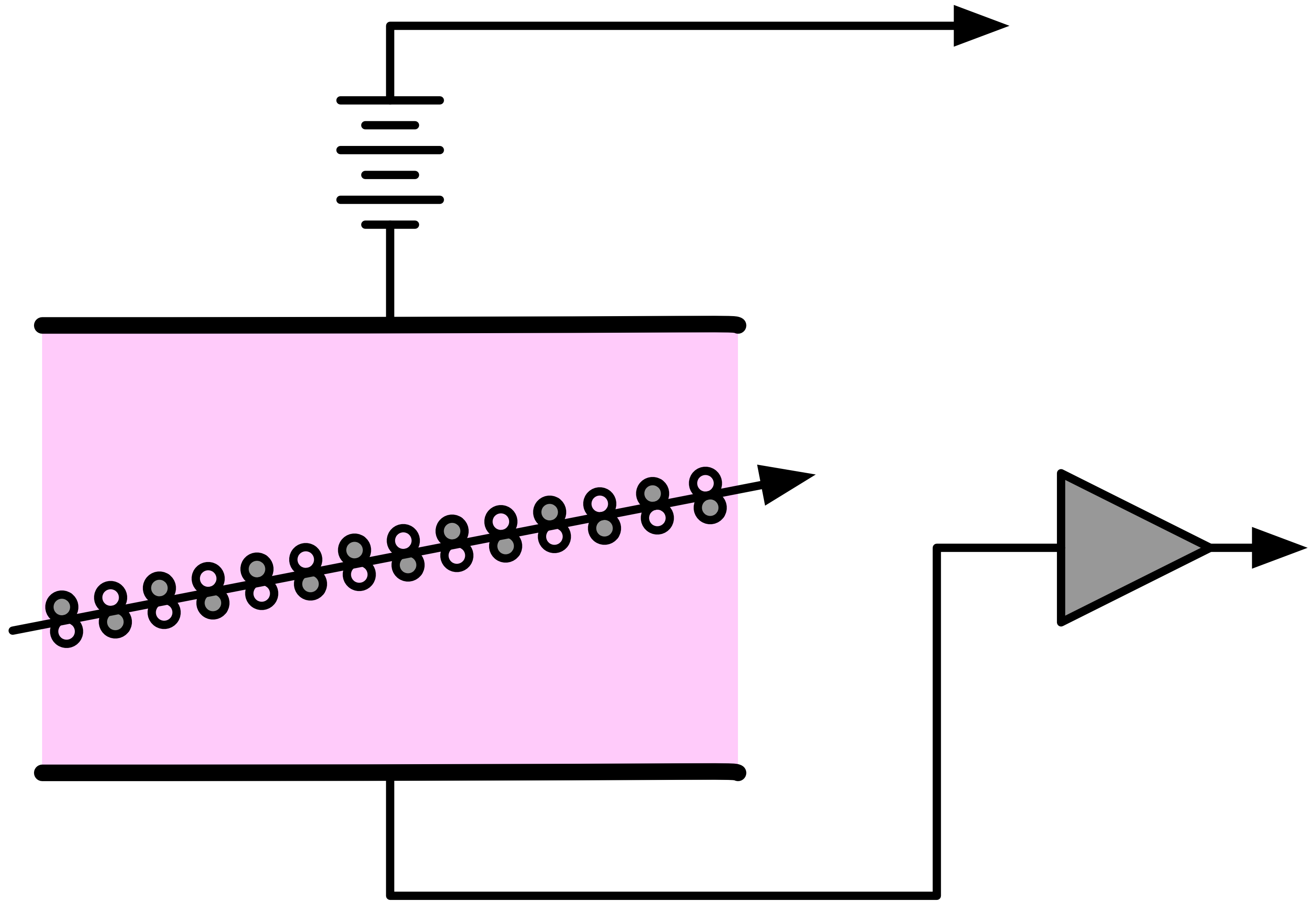
1) separate and collect the charges

or

2) use the ionized/excited states to create an optical signal

Question 2

We want to separate and collect the electrons and ions, what kind of material will NOT work?



A. conductor

B. insulator

C. semiconductor

Question 2

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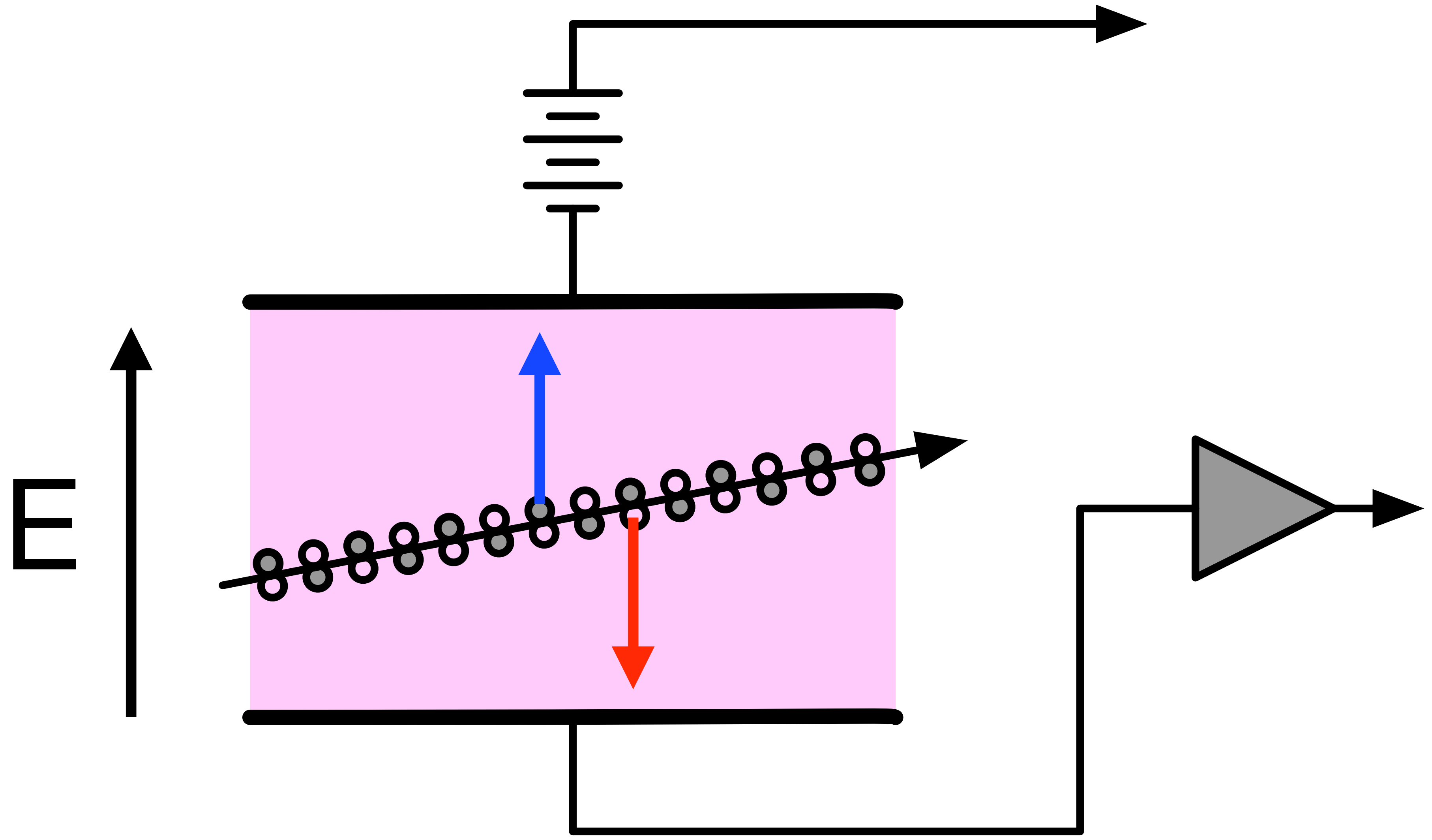


A. conductor

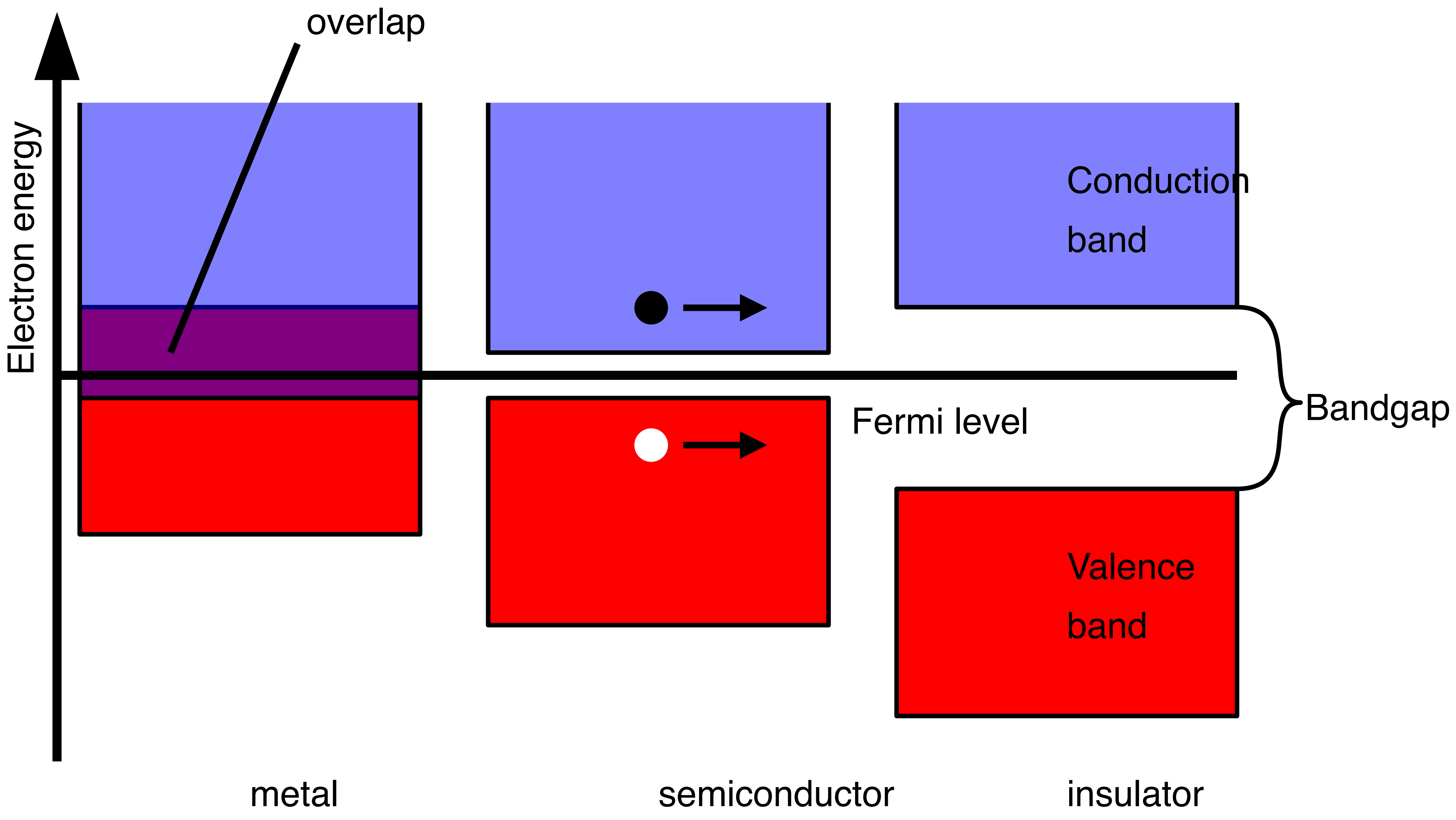
B. insulator

C. semiconductor

We need an internal electric field to drift the e- and positively charged ions in opposite directions. Conductors cannot support internal E-fields.

Metals, Semiconductors, Insulators

The quantum states of the atoms in crystalline solids form bands: the energies become essentially continuous,



- electrons in the valence band are localized near their parent atoms
- electrons in the conduction band can move “freely” through the crystal
- the bands overlap in metals [free electrons]
- the bands are widely separated by a gap in insulators
  - no or very few conduction electrons
- in semiconductors, the gap is smaller and some electrons can thermally “jump” into the conduction band leaving holes behind
  - holes can move in the valence band just like electrons in the conduction band

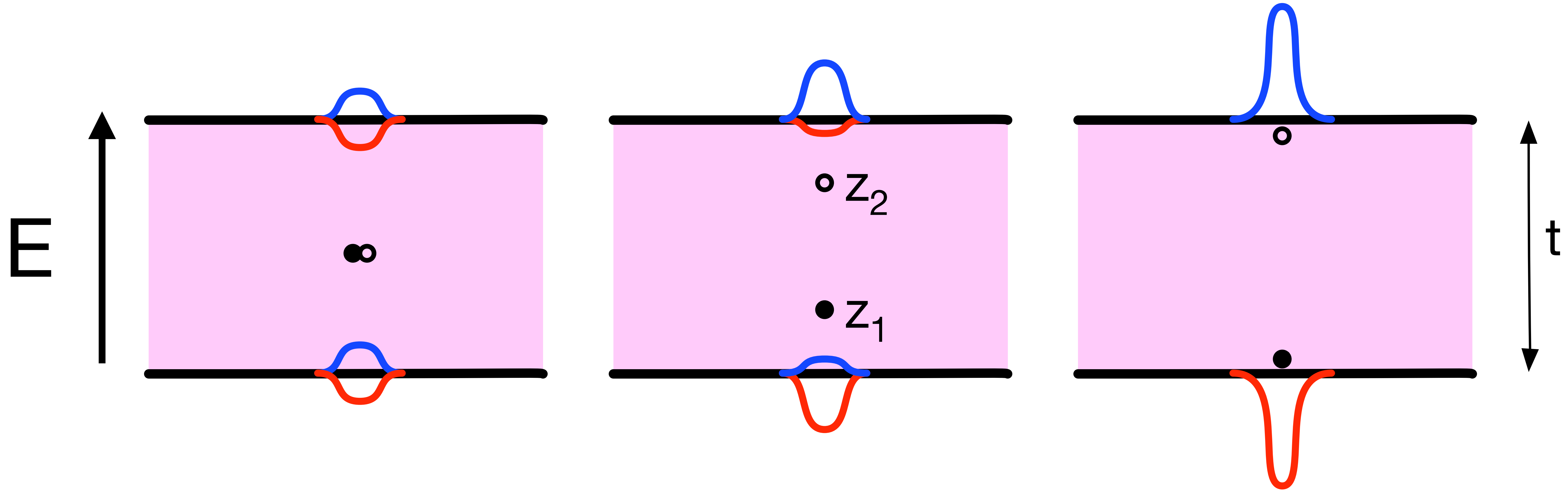
Detector Materials

There are not many insulating materials that permit free electrons or ions to move over macroscopic distances:

- all noble gases and some others like methane CH_4 and ethane C_2H_6
- cryogenic noble liquids
  - low temperatures complicate the detectors but “freeze out” impurities that eat electrons
- some room temperature liquids like TMP C_9H_{20} and TMS $(CH_3)_4Si$
  - impurities don’t “freeze out”
- semiconductors like Si or diamond [C]
  - even high resistivity Si conducts too well and needs specialized design
  - the fabrication of Si devices is a huge, well-developed, and sophisticated industry
    - very small features lead to very precise localization of charge deposits

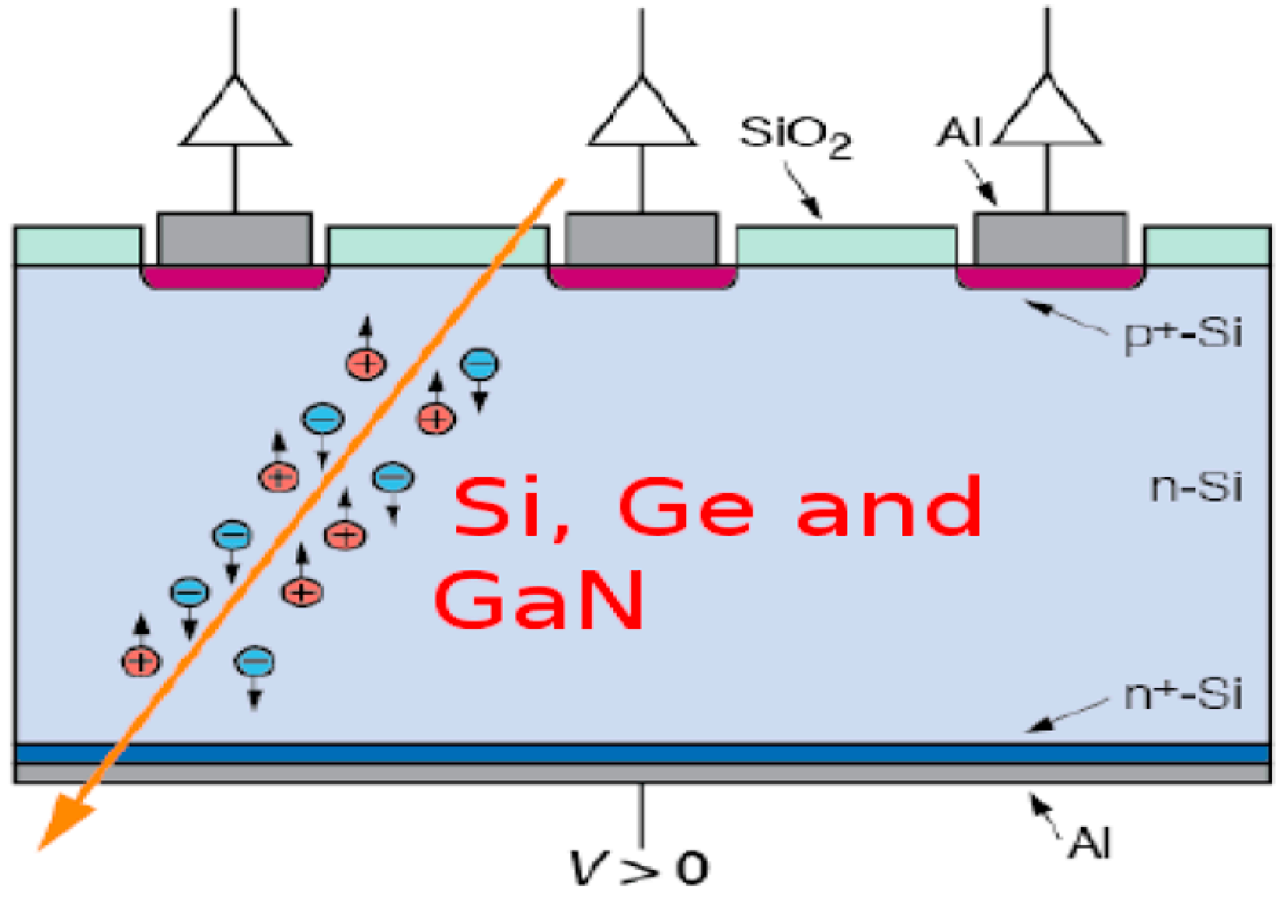
Charge Collection in High Resistivity Materials

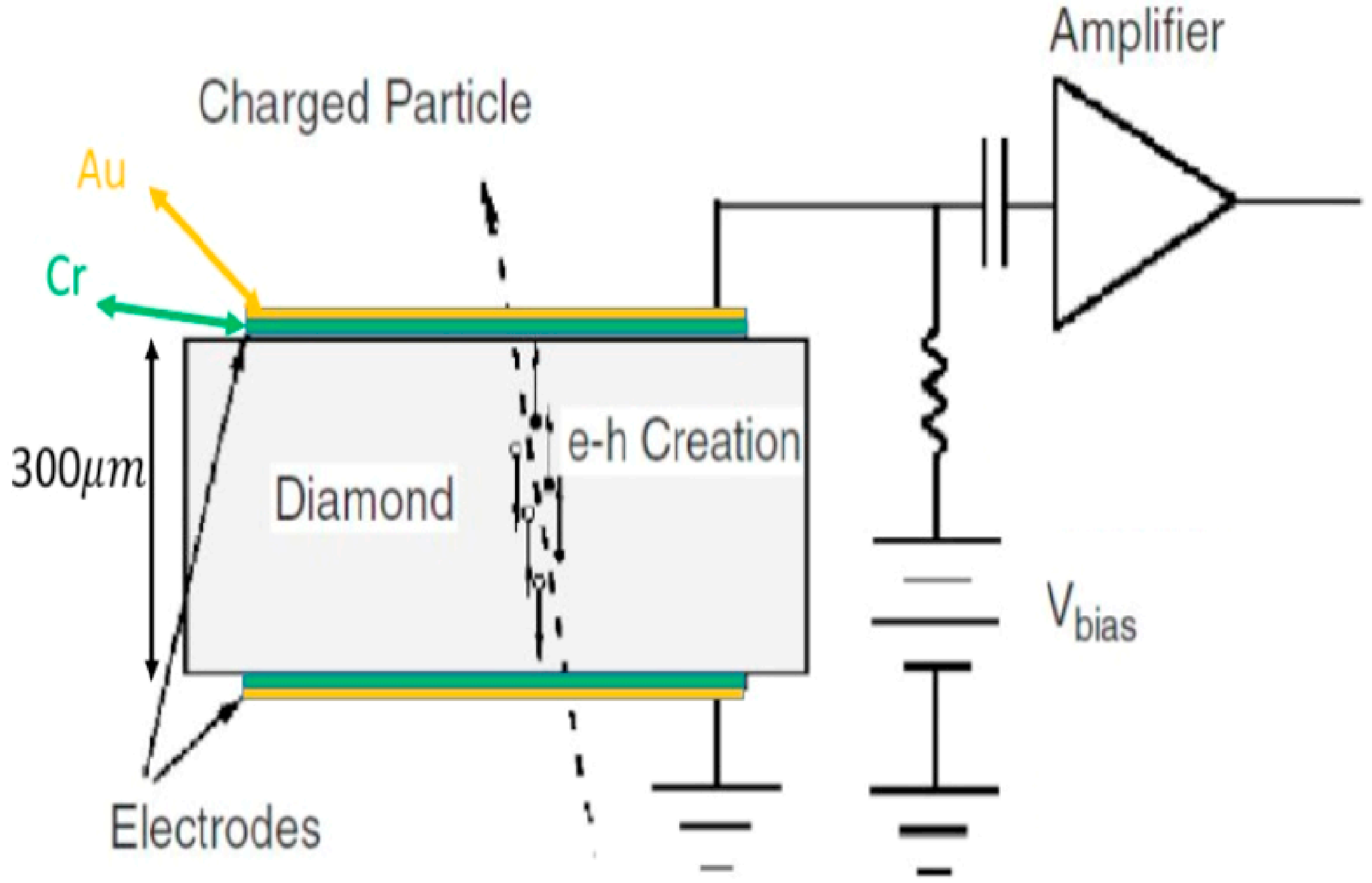
Consider the charge induced by an electron-ion pair in a parallel plate capacitor just after deposition [they are close together] and later if they separate



- at zero separation, the induced charges cancel [no signal can be observed]
- if they move apart, then the net induced charge is $Q_{ind} = q(z_1 - z_2)/t$
  - depends upon the *separation* of the charges
- if they move to the electrodes, they neutralize the charge that has flowed onto the plate
  - “collecting” charge is a uniform process … the signal does not change discontinuously

We discussed charge collection by reverse biased silicon diodes two years ago, there are other alternatives such as diamond or liquid argon





- Reversed biased diodes can have a large “depleted” thickness that supports an E-field
  - otherwise too conductive to support E-field and too much current to see the ionization signal
- Chemical Vapor Deposition (CVD) diamond has a large band gap and high resistivity
  - can work as a simple ionization detector: bias it with simple electrodes, no diode needed
  - high radiation tolerance
  - 2.4 times less signal than silicon [large 5.2 eV bandgap requires more energy/e-ion pair]
  - expensive, large capacitance problematic for electronics

Gas Detectors

In gas detectors, we typically have 20-100 e-ion pairs produced by the passage of a minimum ionizing particle

E_i ionization energy, W_i average energy per e-ion pair, n_p average number of primary e-ion pairs per cm, n_T average number of e-ion pairs per cm

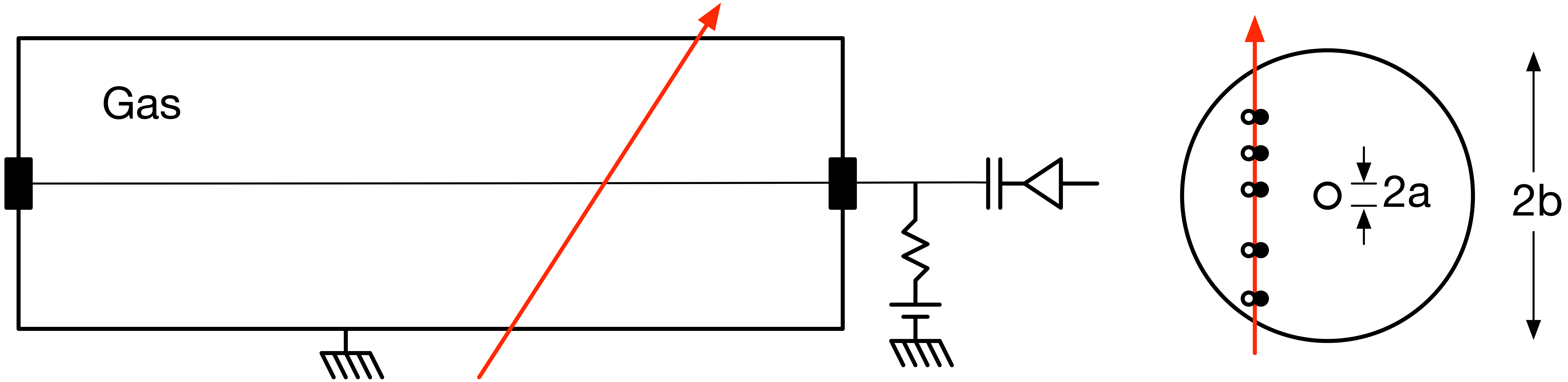
Gas	<Z>	ρ [g/cm^3]	E_i [eV]	W_i [eV]	dE/dx [keV/cm]	n_p [cm^{-1}]	n_T [cm^{-1}]
He	2	$1.66\cdot10^{-4}$	24.6	41	0.32	5.9	7.8
Ar	18	$1.66\cdot10^{-3}$	15.8	27	2.44	29.4	94
CH_4	19	$6.7\cdot10^{-4}$	13.1	28	1.48	18	53
C_4H_{10}	34	$2.42\cdot10^{-3}$	10.6	23	4.50	46	195

Extra energy per e-ion pair is due to non-zero T of the electrons and some energy that excites but does not ionize the material

Drift Tube

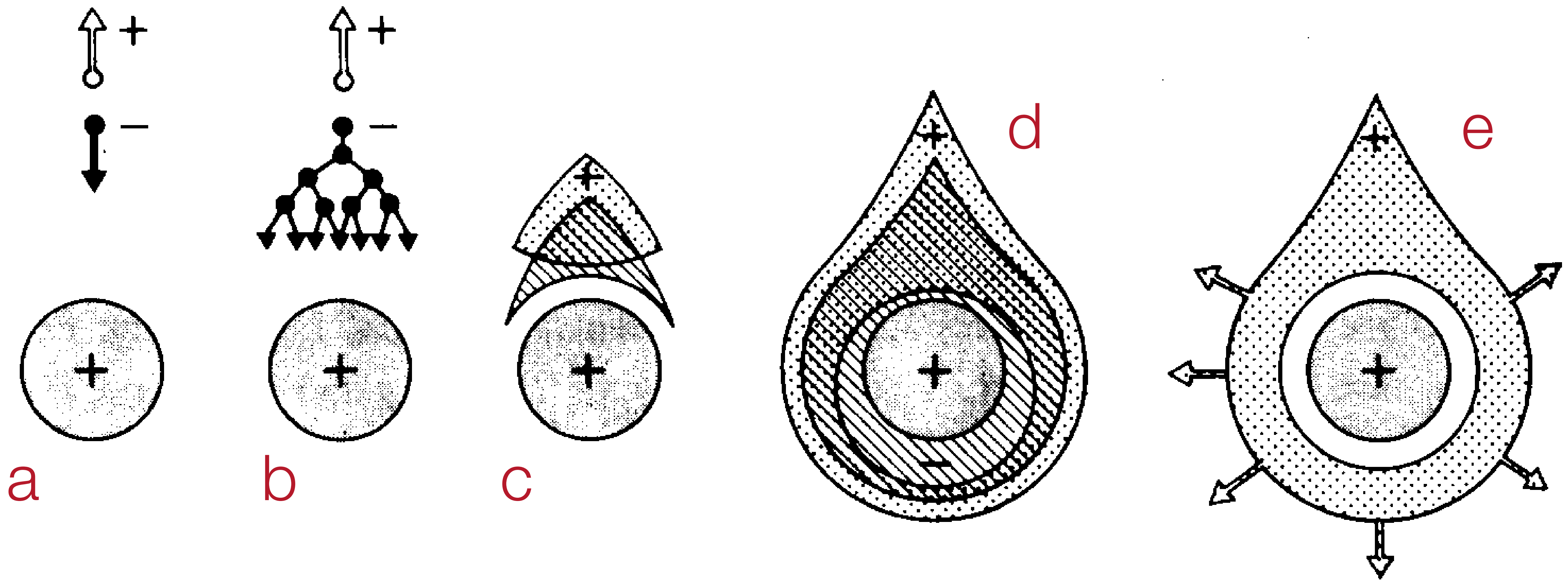
The cylindrical drift tube is a common geometry used to track particles. The electric field near the surface of central wire [typical radius ~ 10μm] is quite large [~few x 100kV/cm].

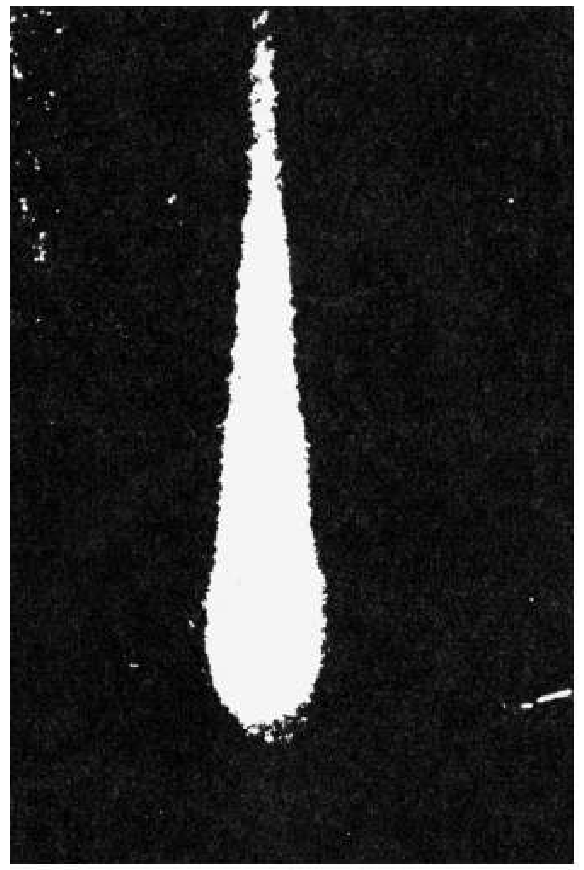
$$|\vec{E}| = \frac{V}{\ln(b/a)} \cdot \frac{1}{r}$$



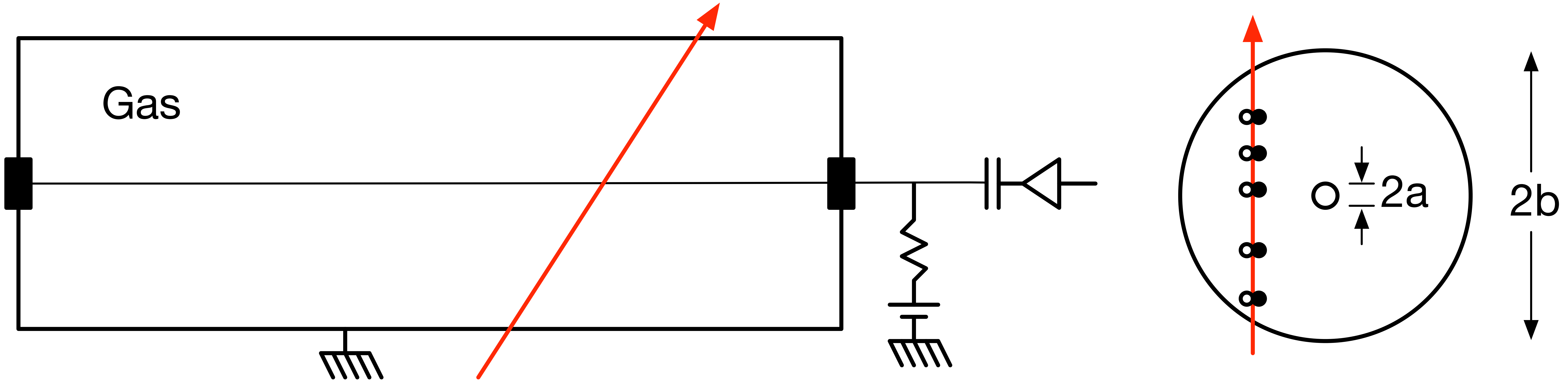
- The number of e-ion pairs is not large enough even with a sensitive amplifier
  - the large E-field near the wire produces an avalanche and gas amplification
  - the e scatter off of atoms/molecules with a mean free path
  - in high E-fields, the energy gain over the mean free path can increase the energy enough that it ionizes another atom/molecule
  - the 2 electrons gain energy and ionize more molecules

The avalanche increases the signal by factors of typically 10^4-10^5





- Noble gases work well for this with one small caveat
    - de-exciting ions can emit UV photons which travel far away from the wire and ionize more gas molecules: the process can run-away
    - add gases that have large UV absorption cross sections to prevent the photons from traveling far [known as “quencher” gases]
    - use hydrocarbons for this purpose [like C_2H_6]



- 1D position resolution from drift time: 50-100 µm is typical
- Gas drift detectors are cheap and can cover large areas [used a lot in muon systems at LHC]
- Gas drift detectors are not very radiation tolerant
  - ionized molecules can bond chemically and form polymers
  - polymers can deposit on the electrode surfaces
  - use other gas additives to suppress polymerization

Gas detectors can also operate in higher gain but lower rate modes.

Ionization mode:

full charge collection
no multiplication; gain ≈ 1

Proportional mode:

multiplication of ionization
signal proportional to ionization
measurement of dE/dx
secondary avalanches need quenching;
gain ≈ $10^4 – 10^5$

Limited proportional mode:

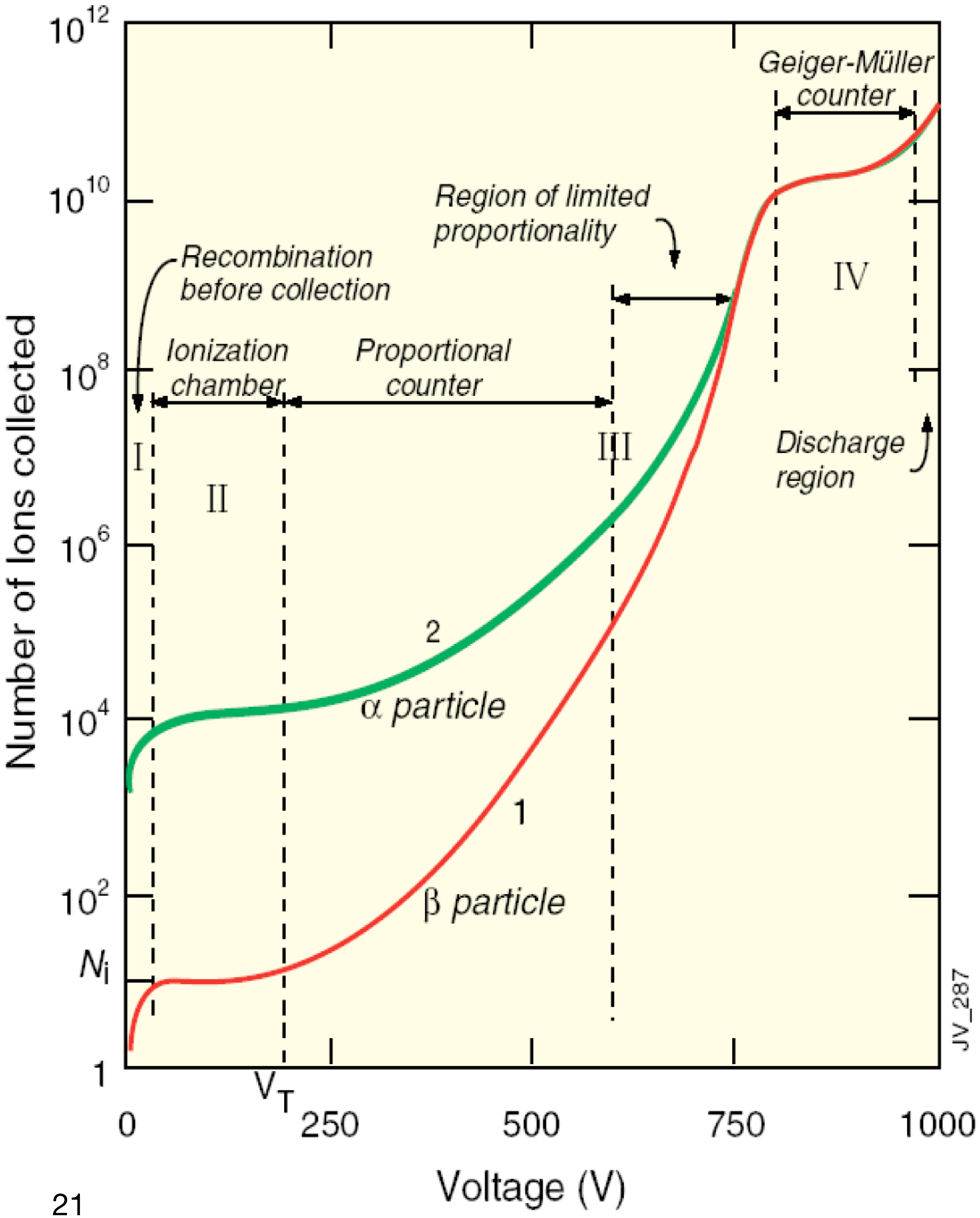
[saturated, streamer]

spark chambers

strong photoemission
requires strong quenchers or pulsed HV;
gain ≈ 10^{10}

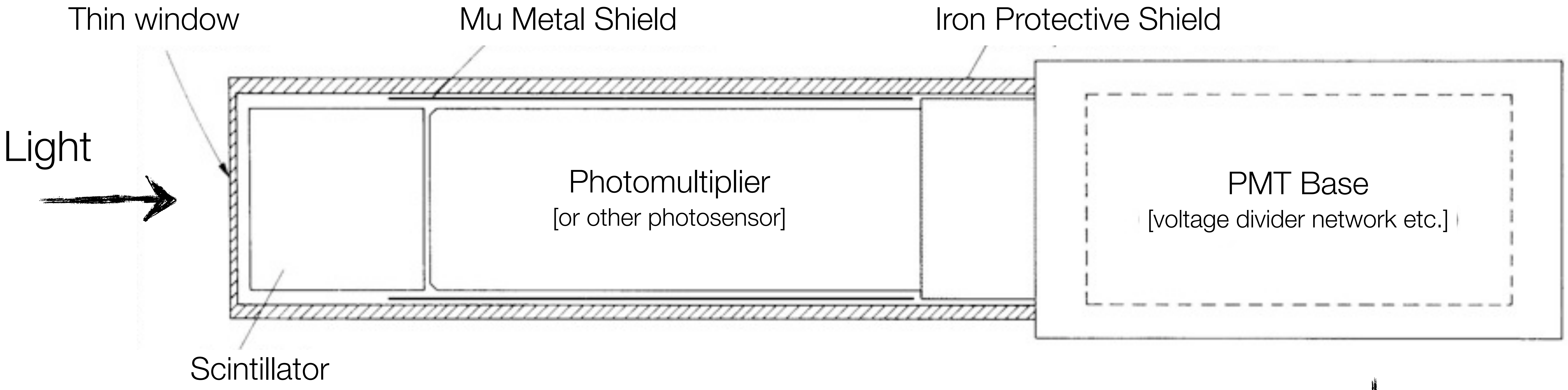
Geiger mode:

massive photoemission;
full length of the anode wire affected;
discharge stopped by HV cut



Scintillation Detectors

Scintillators convert dE/dx into photons that are then detected by photosensors



Thin window

Mu Metal Shield

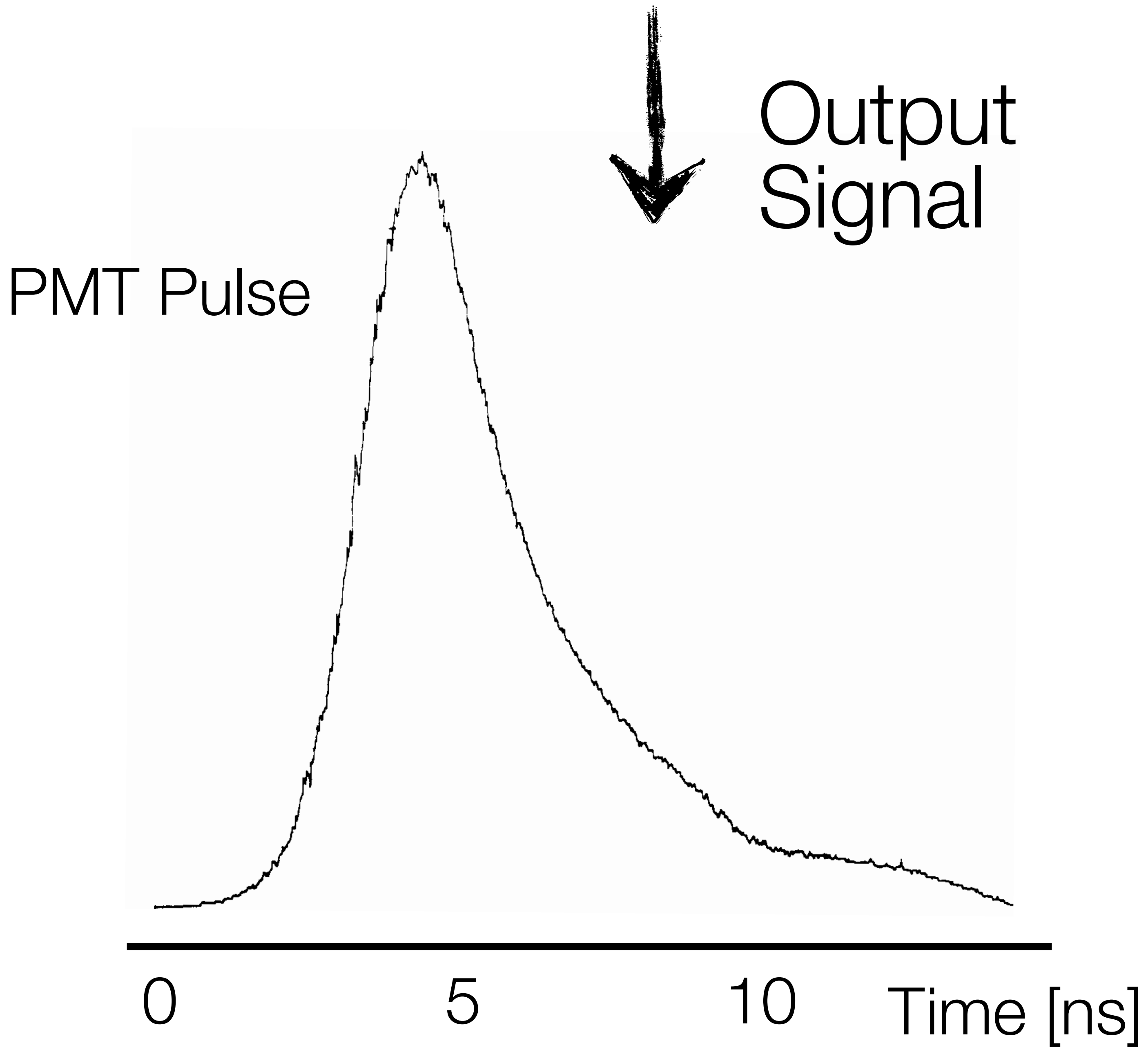
Iron Protective Shield

Light

Photomultiplier
[or other photosensor]

PMT Base
[voltage divider network etc.]

Scintillator



Output Signal

PMT Pulse

Scintillator Types:

Organic Scintillators
Inorganic Crystals
Gases

Photosensors

Photomultipliers
Micro-Channel Plates
Hybrid Photo Diodes
Visible Light Photon Counter
Silicon Photomultipliers

Inorganic Scintillators

Materials:

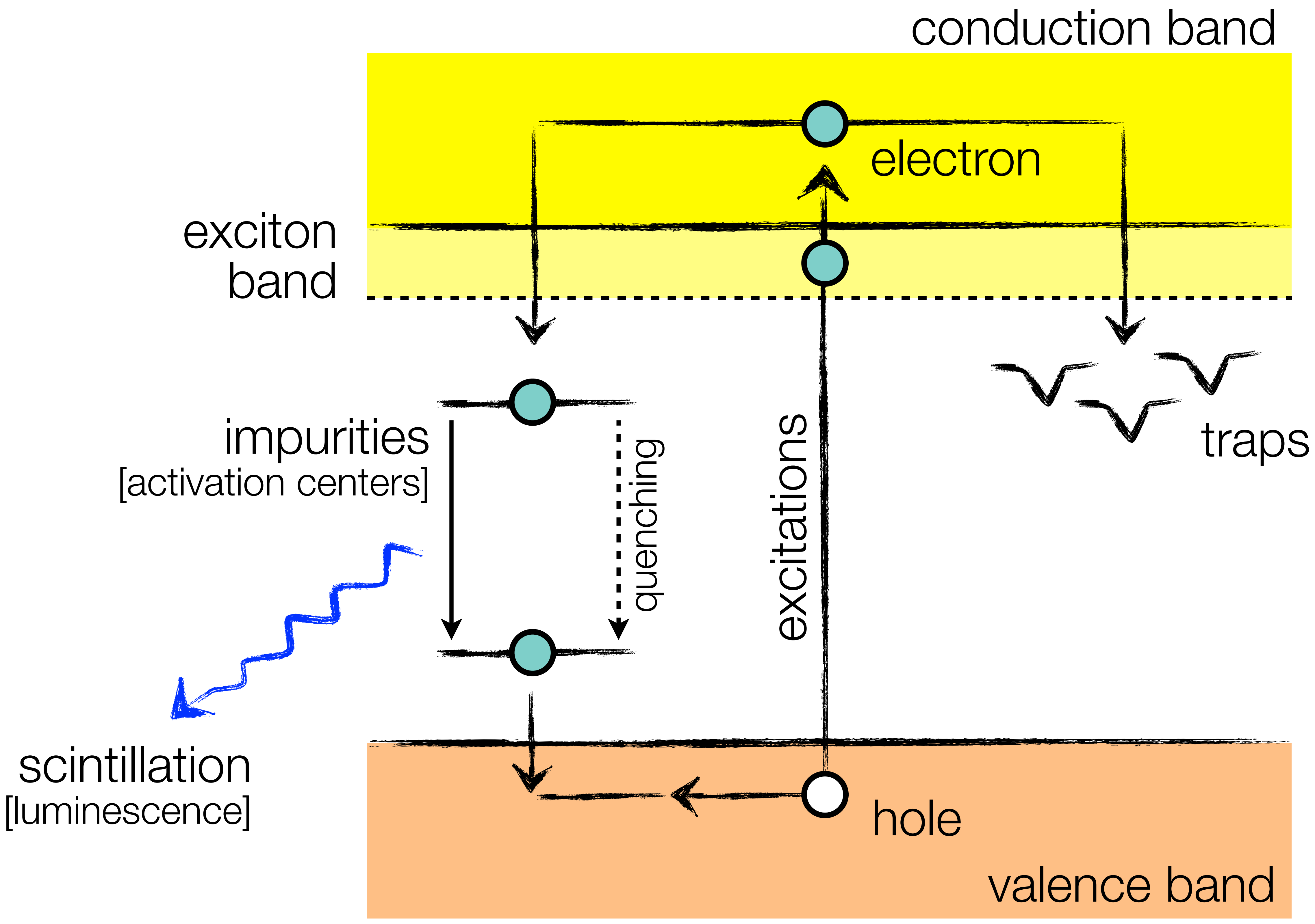
Sodium iodide (NaI)
Cesium iodide (CsI)
Barium fluoride (BaF_2)
...

Mechanism:

Energy deposition by ionization
Energy transfer to impurities
Radiation of scintillation photons
Dopant shifts wavelength to avoid re-absorption

Time constants:

Fast: recombination from activation centers [ns ... µs]
Slow: recombination due to trapping [ms ... s]

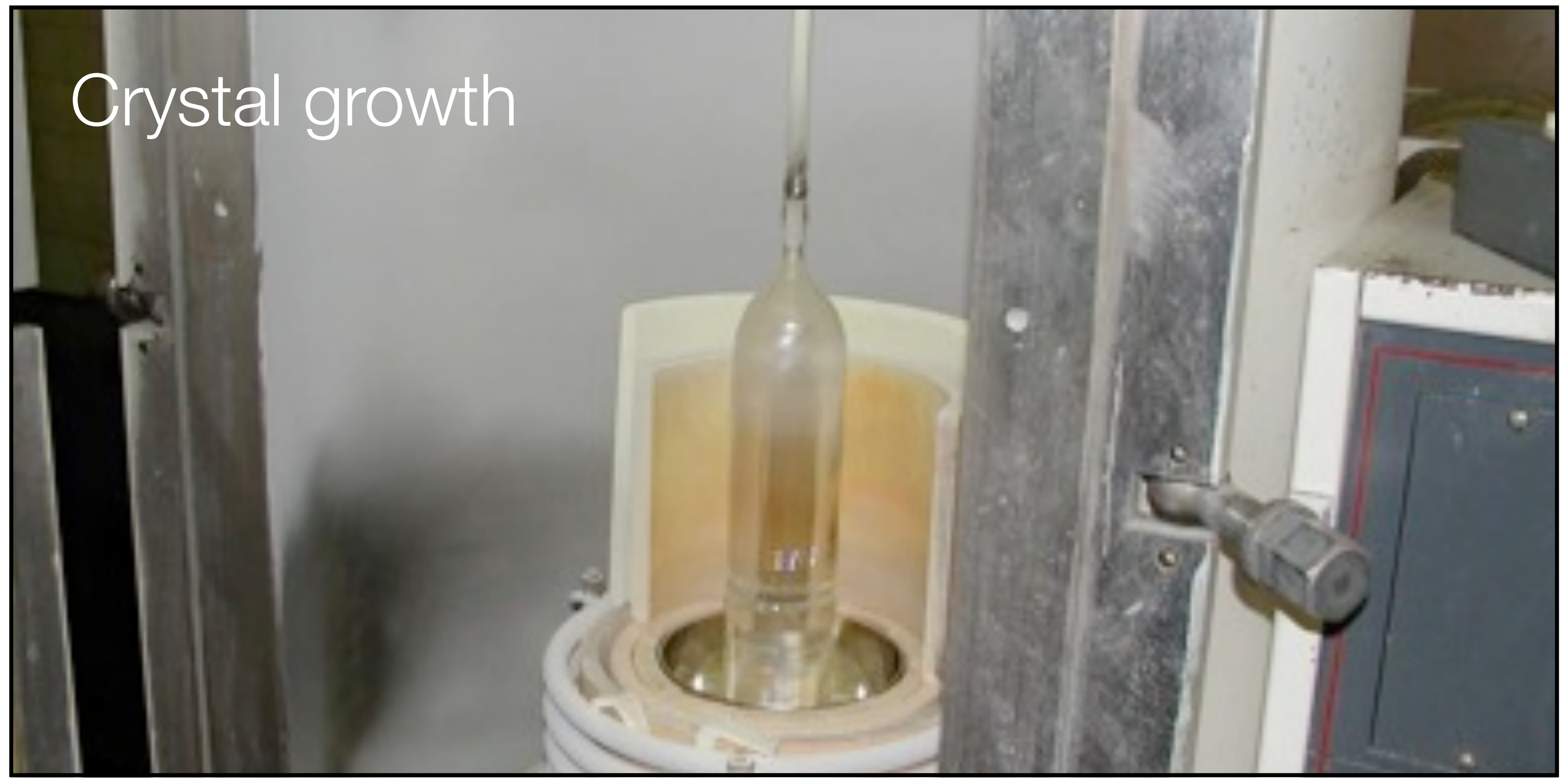


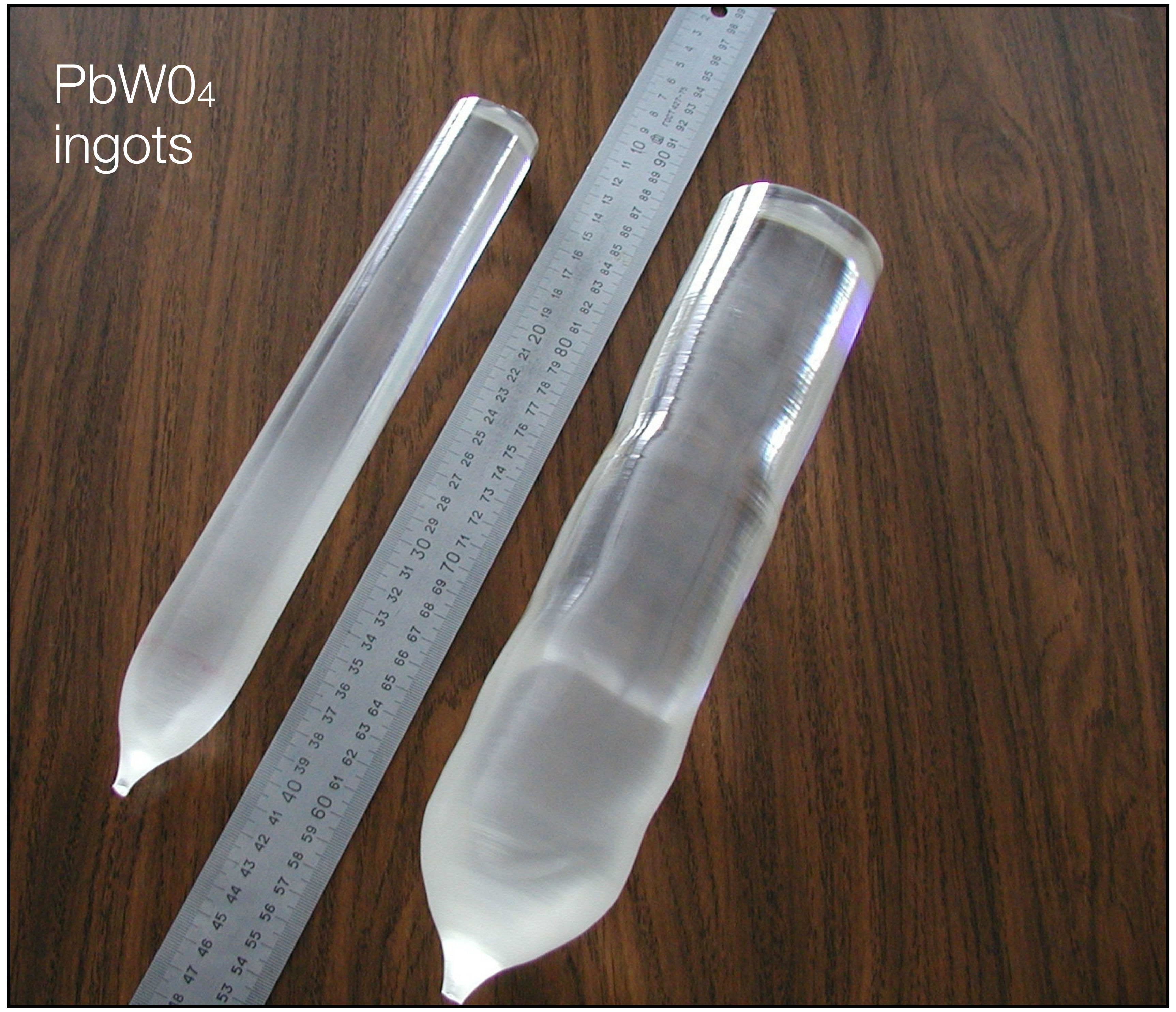
Energy bands in impurity activated crystal

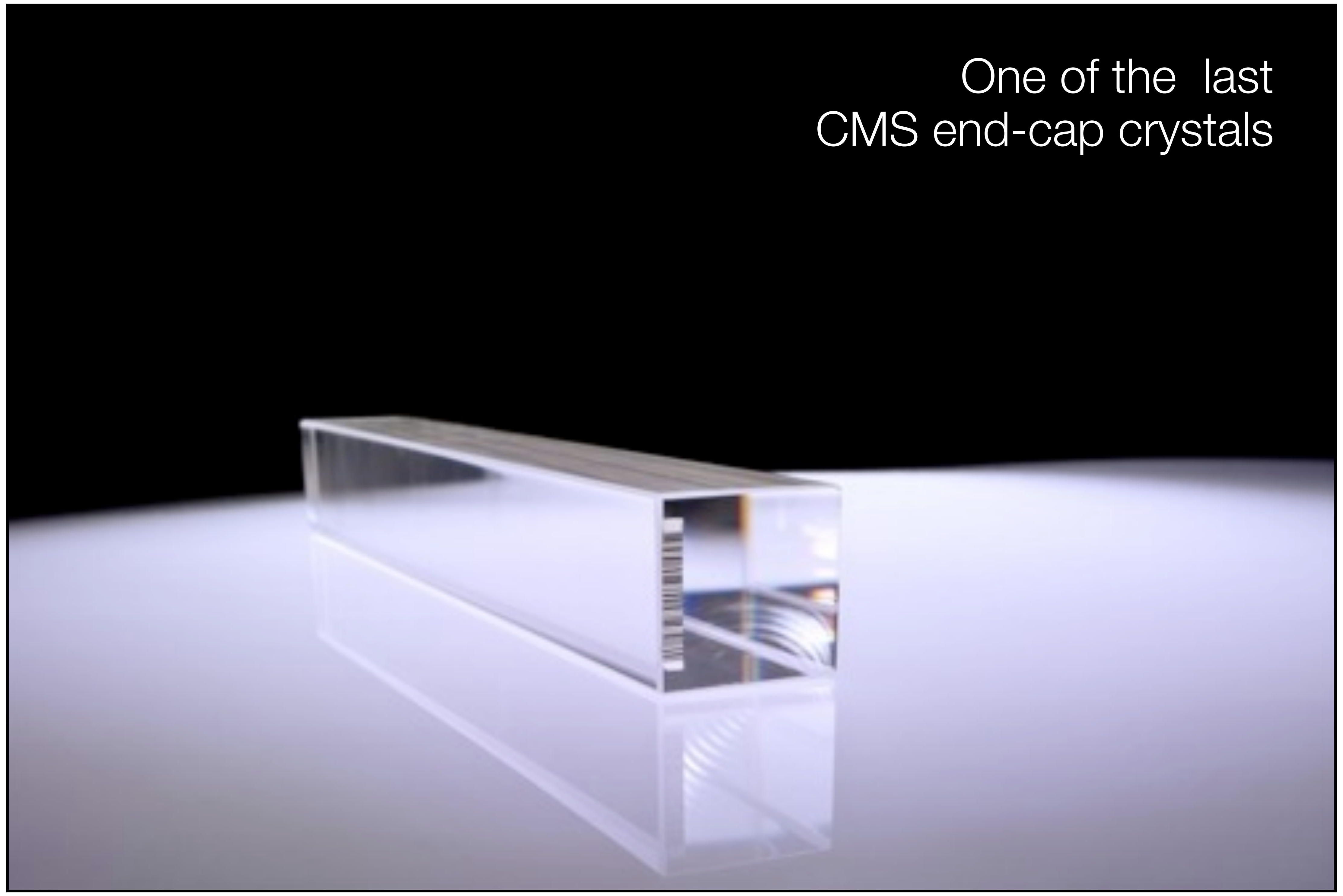
showing excitation, luminescence, quenching and trapping

Inorganic Scintillators

Example CMS
Electromagnetic Calorimeter

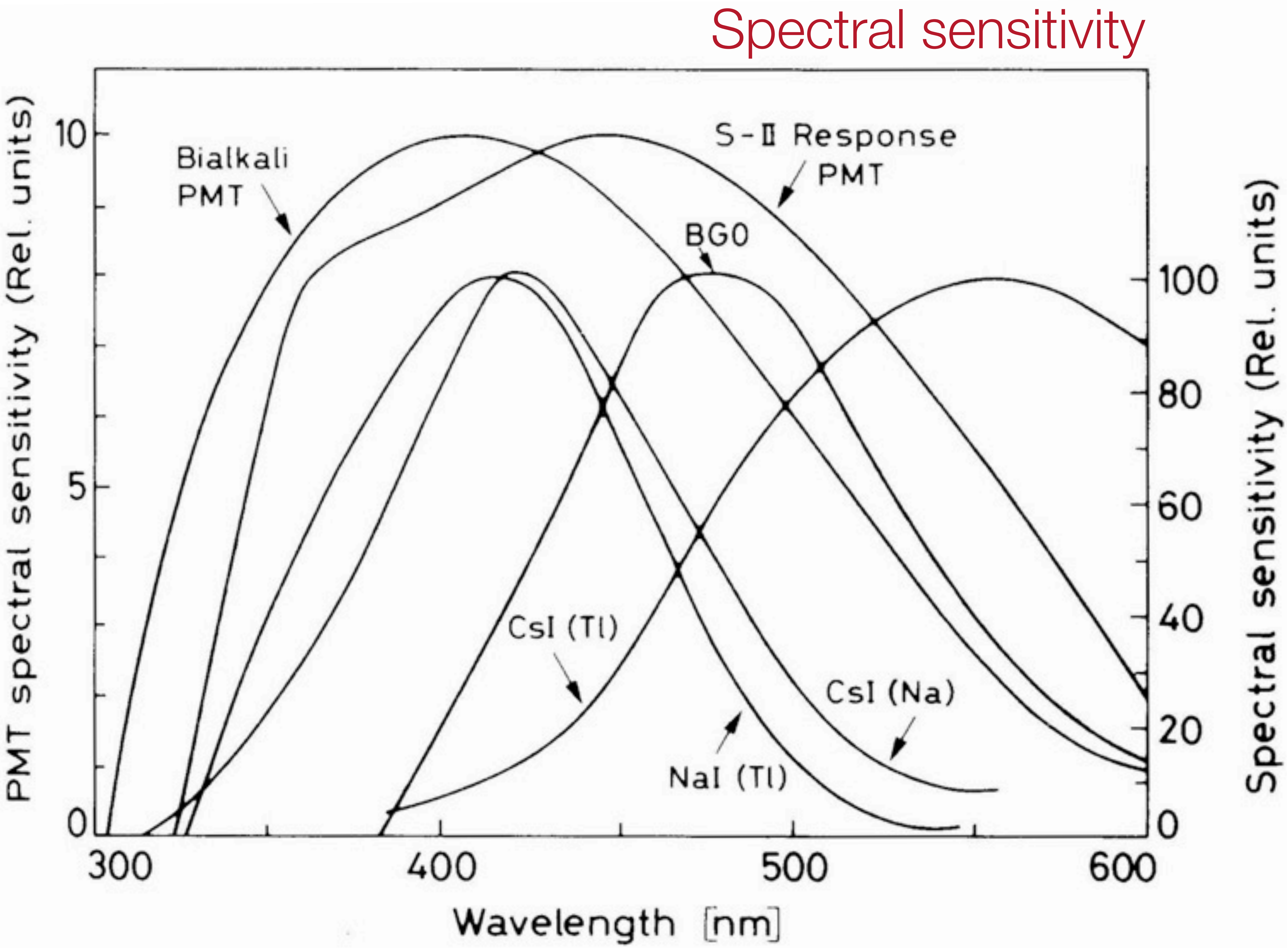

Crystal growth


$PbW0_4$
ingots


One of the last
CMS end-cap crystals

Scintillators

The spectrum of the emitted photons should always match the sensitivity of the photosensor



Inorganic Scintillators

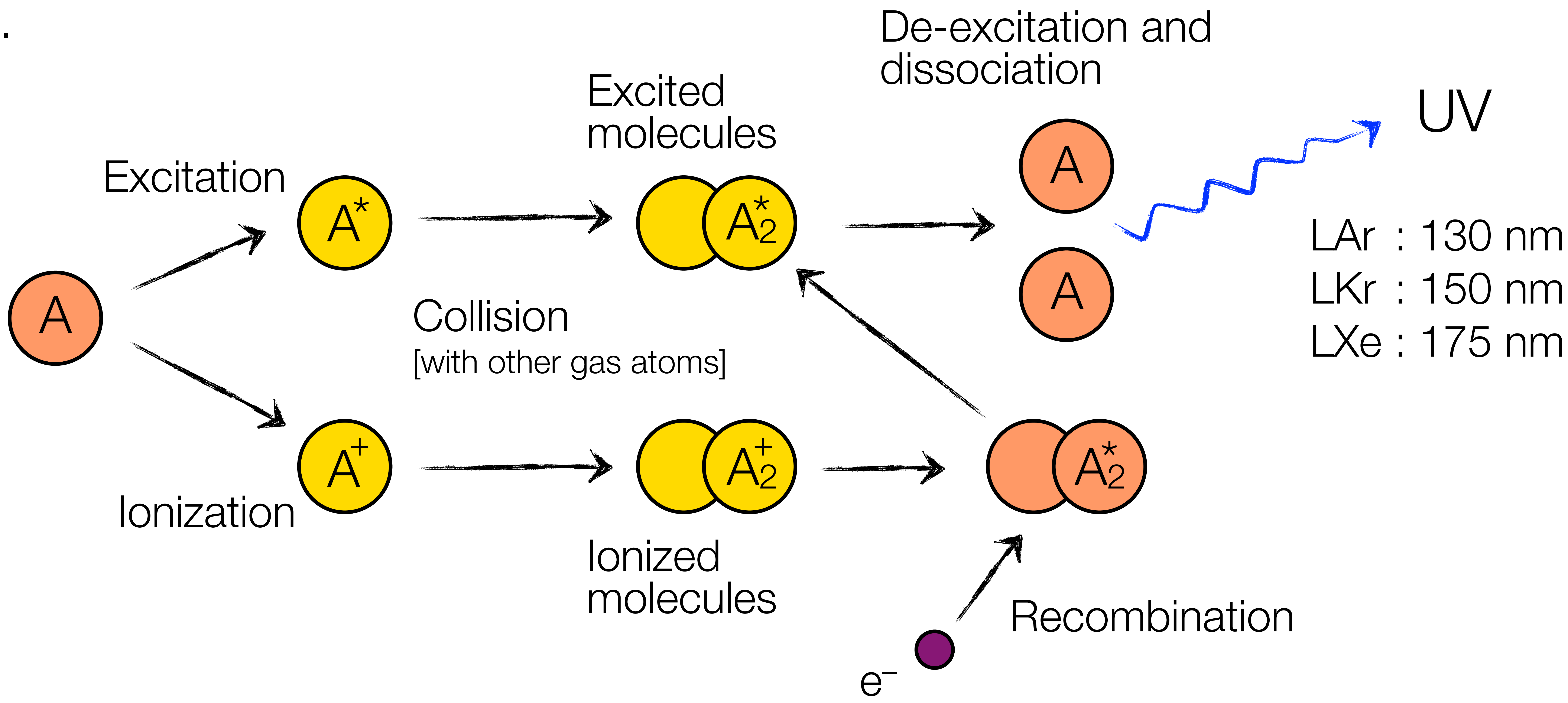
Noble gases and liquids work because they involve de-exciting molecules (shifts λ)

Materials:

Helium (He)
Liquid Argon (LAr)
Liquid Xenon (LXe)
...

Decay time constants:

Helium : $\tau_1 = .02\ \mu s$, $\tau_2 = 3\ \mu s$
Argon : $\tau_1 \leq .02\ \mu s$



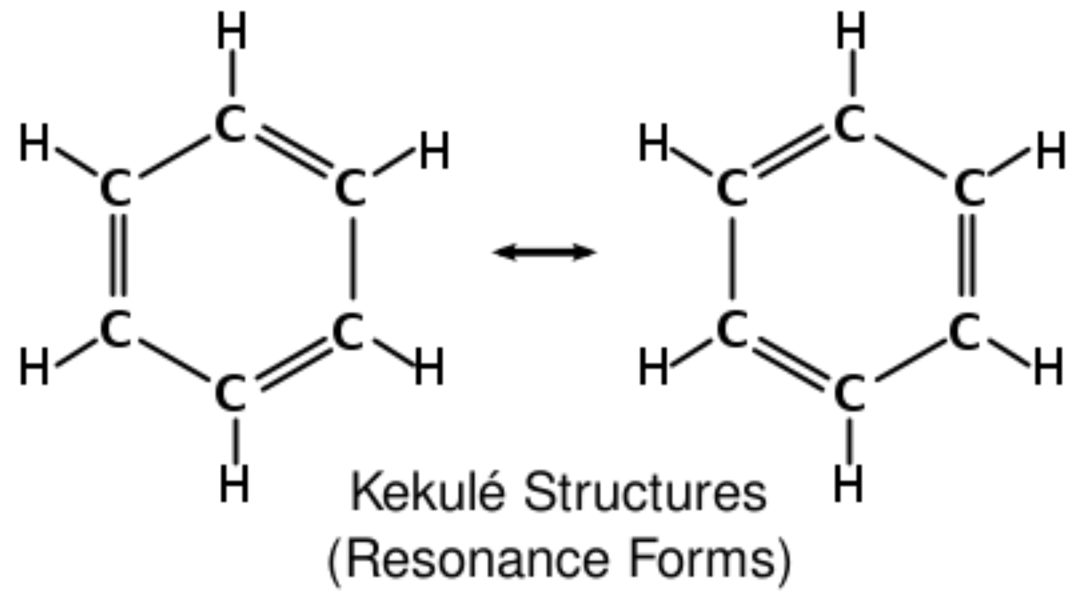
LAr : 130 nm
LKr : 150 nm
LXe : 175 nm

Inorganic Scintillators

Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [µs]	Photons/MeV
NaI	3.7	1.78	303	0.06	$8\cdot10^4$
NaI(Tl)	3.7	1.85	410	0.25	$4\cdot10^4$
CsI(Tl)	4.5	1.80	565	1.0	$1.1\cdot10^4$
$Bi_4Ge_3O_{12}$	7.1	2.15	480	0.30	$2.8\cdot10^3$
CsF	4.1	1.48	390	0.003	$2\cdot10^3$
LSO	7.4	1.82	420	0.04	$1.4\cdot10^4$
$PbWO_4$	8.3	1.82	420	0.006	$2\cdot10^2$
LHe	0.1	1.02	390	0.01/1.6	$2\cdot10^2$
LAr	1.4	1.29*	150	0.005/0.86	$4\cdot10^4$
LXe	3.1	1.60*	150	0.003/0.02	$4\cdot10^4$

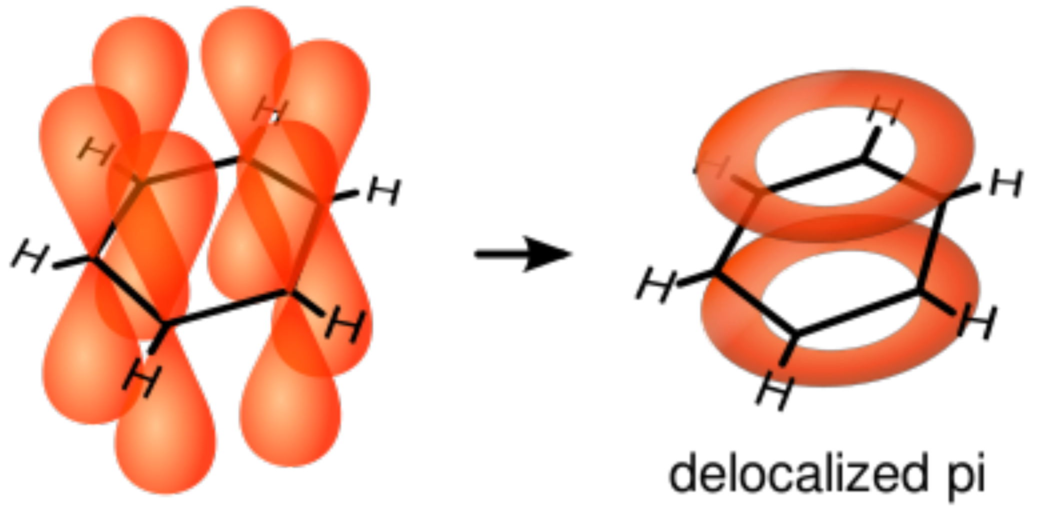
* at 170 nm

Organic Scintillators


Kekulé Structures
(Resonance Forms)

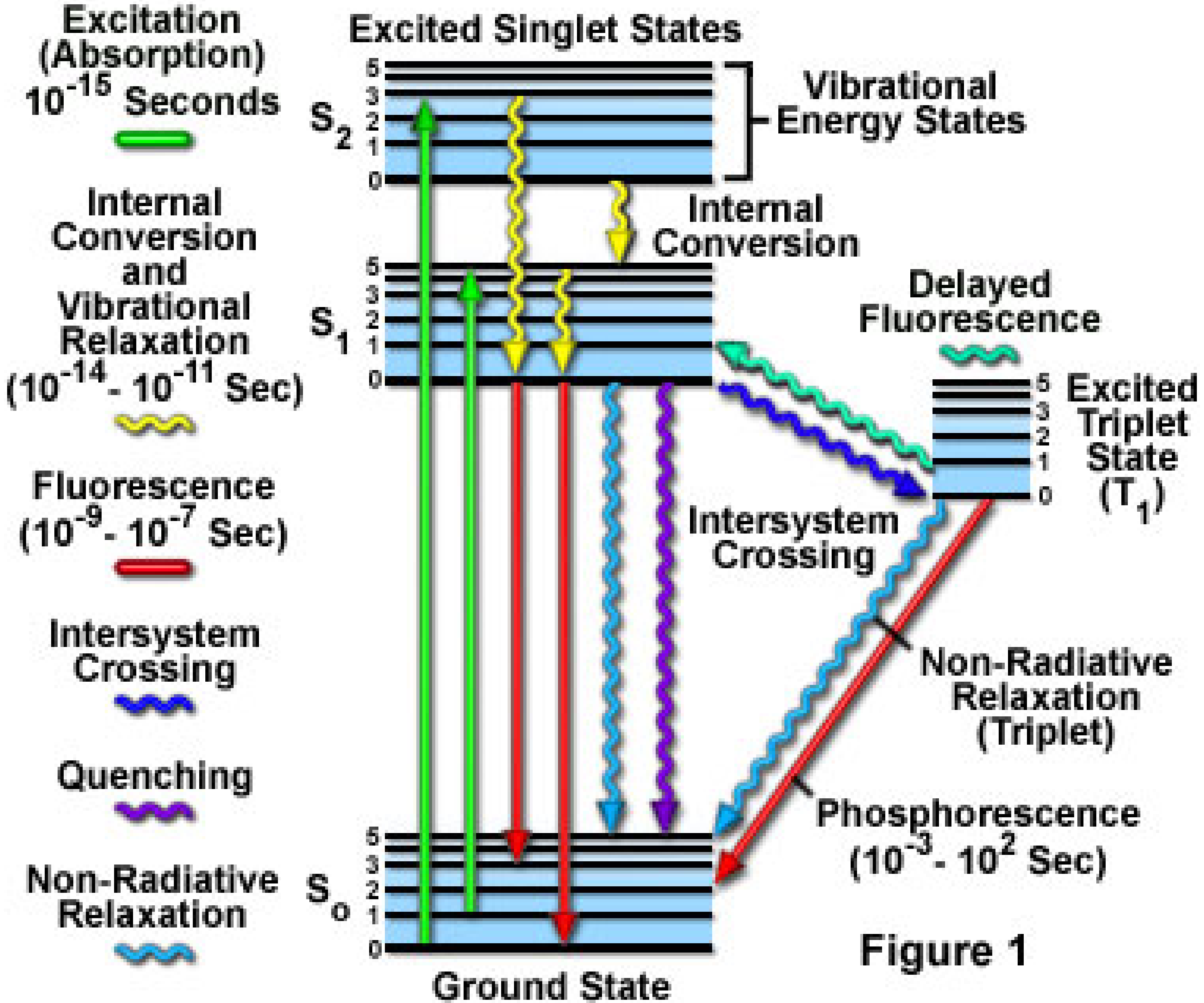
Based on molecules with benzene rings and multiple C=C double bonds (delocalized pi orbitals):

- Delocalized e have an interesting spectroscopy: electron pairs in spin 0 [S] and spin 1[T] states
- Charged particles excite the S_0 -> S_1, S_2 transitions: 3-4 eV
- Excited states de-excite/mix with neighboring states
- Transitions back to the ground state yield lower E photons
  - material is transparent to produced light
  - fast S->S transitions [fluorescence], few ns decay times
  - slow S->T->S transtions [phophorescence] ms or longer decay times
  - UV photons produced [~320 nm]: poor match to photosensor response


6 p_z orbitals

delocalized pi system

Jablonski Energy Diagram



Organic Scintillators

Organic scintillators are typically dissolved in plastic or a liquid solvent. They use wavelength shifters to match the emitted UV light to the sensitive wavelengths of the photosensors

A

Energy deposit in base material ➛ excitation

Primary fluorescent

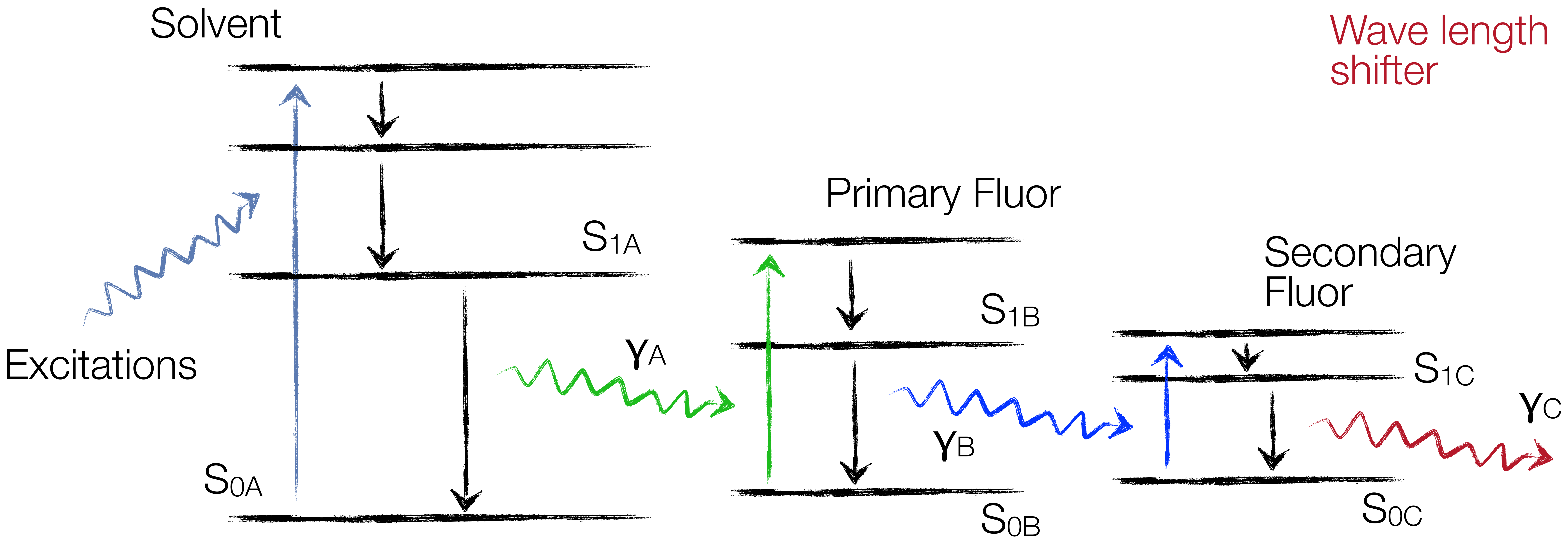
- Good light yield ...
- Absorption spectrum matched to excited states in base material ...

B

Secondary fluorescent

C

Wave length shifter

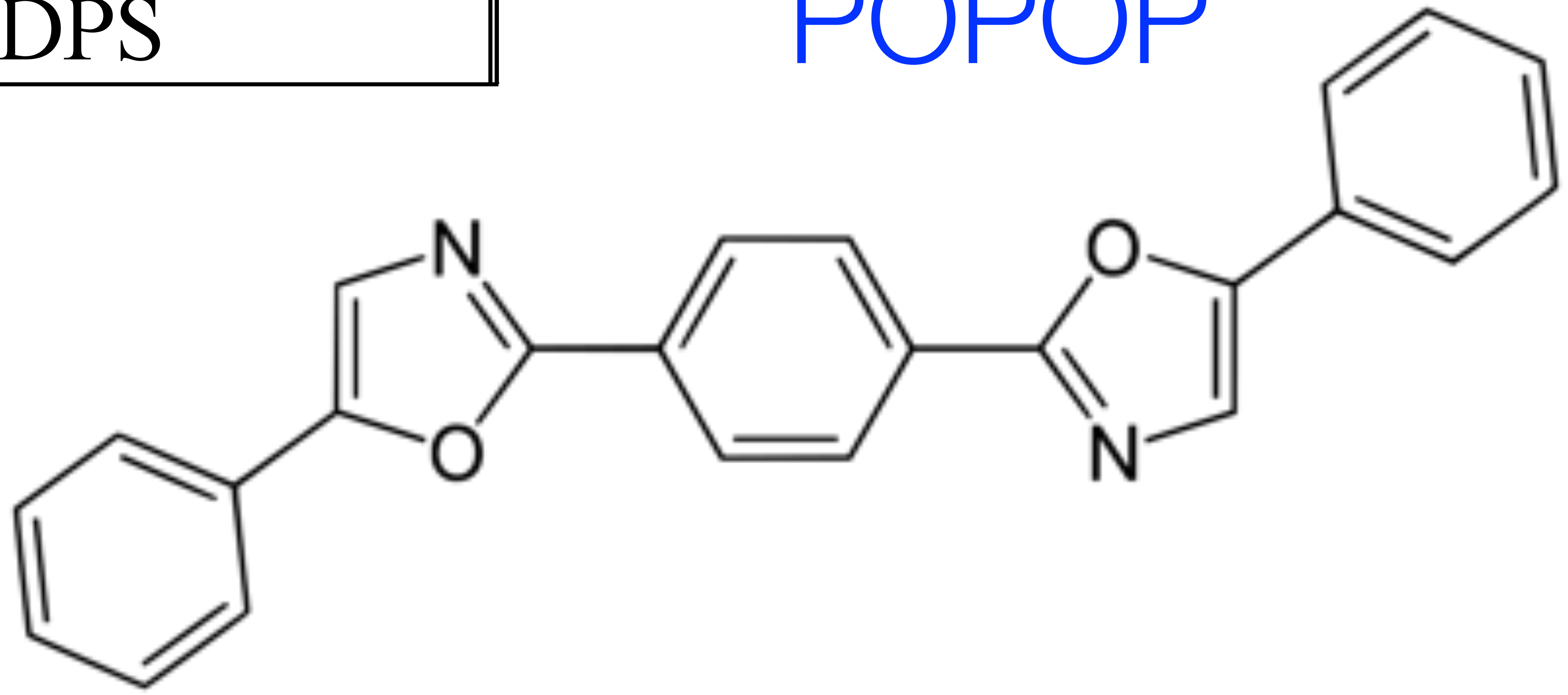


Organic Scintillators

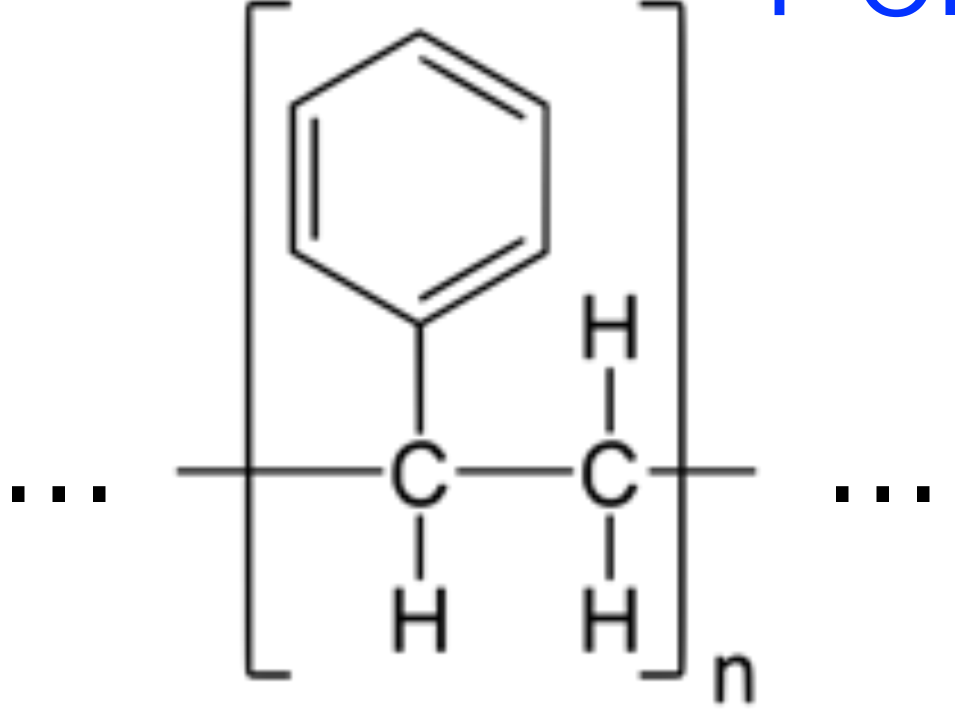
Some widely used solvents and solutes

	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

POPOP



Polystyrene



p-Terphenyl

Wavelength Shifting

Principle:

Absorption of primary scintillation light

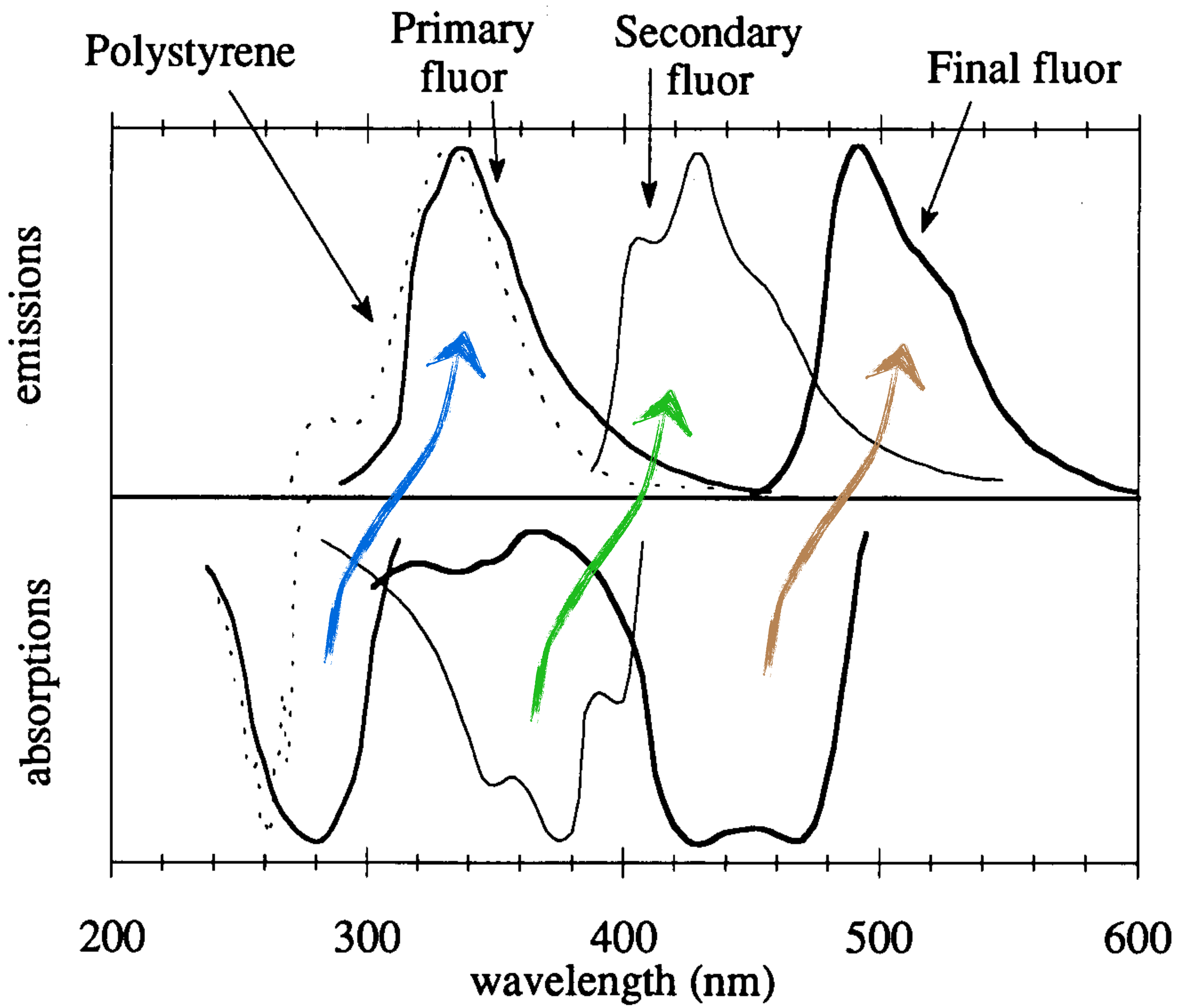
Re-emission at longer wavelength

Adapts light to spectral sensitivity of photosensor

Requirement:

Good transparency for emitted light

Schematics of wavelength shifting principle



Organic Scintillators

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	$4 \cdot 10^3$
Antracene	1.25	1.59	448	30	$4 \cdot 10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2 \cdot 10^4$
NE102*	1.03	1.58	425	2.5	$2.5 \cdot 10^4$
NE104*	1.03	1.58	405	1.8	$2.4 \cdot 10^4$
NE110*	1.03	1.58	437	3.3	$2.4 \cdot 10^4$
NE111*	1.03	1.58	370	1.7	$2.3 \cdot 10^4$
BC400**	1.03	1.58	423	2.4	$2.5 \cdot 10^2$
BC428**	1.03	1.58	480	12.5	$2.2 \cdot 10^4$
BC443**	1.05	1.58	425	2.2	$2.4 \cdot 10^4$

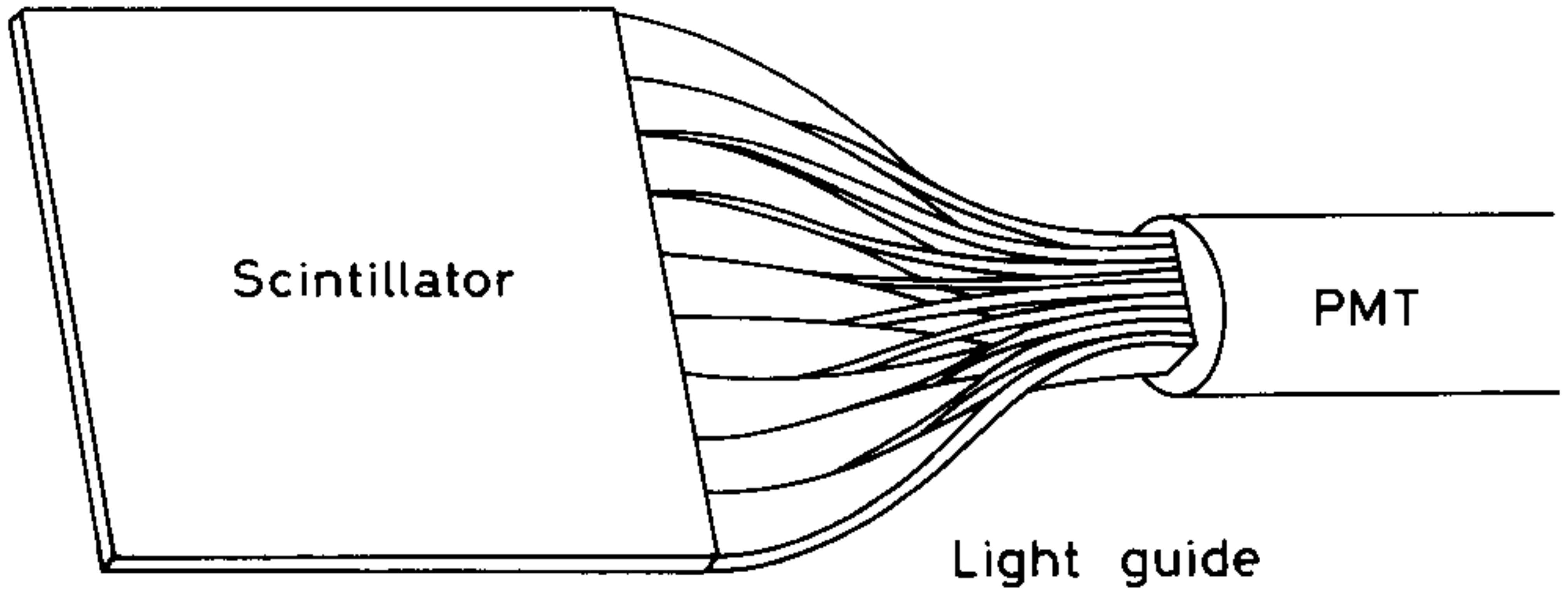
* Nuclear Enterprises, U.K.
** Bicron Corporation, USA

Light Collection/Transmission

Scintillator light to be guided to photosensor

➛ Light guide
[Plexiglas; optical fibers]

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

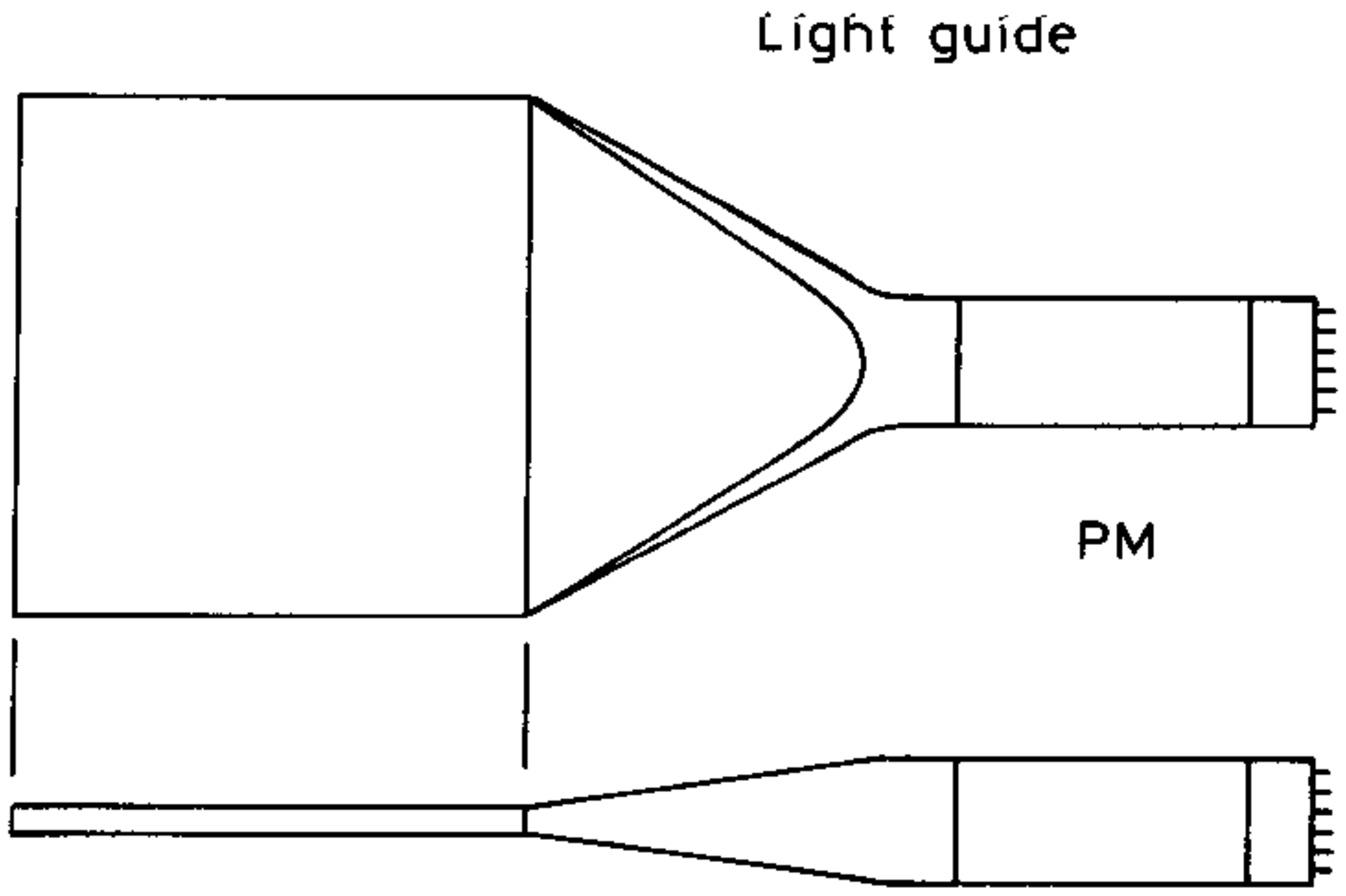


Liouville's Theorem:

Complete light transfer impossible as Δx Δθ = const.
[limits acceptance angle]

Use adiabatic light guide like 'fish tail';

➛ appreciable energy loss



'fish tail'

Photomultipliers

Principle:

Electron emission

from photo cathode

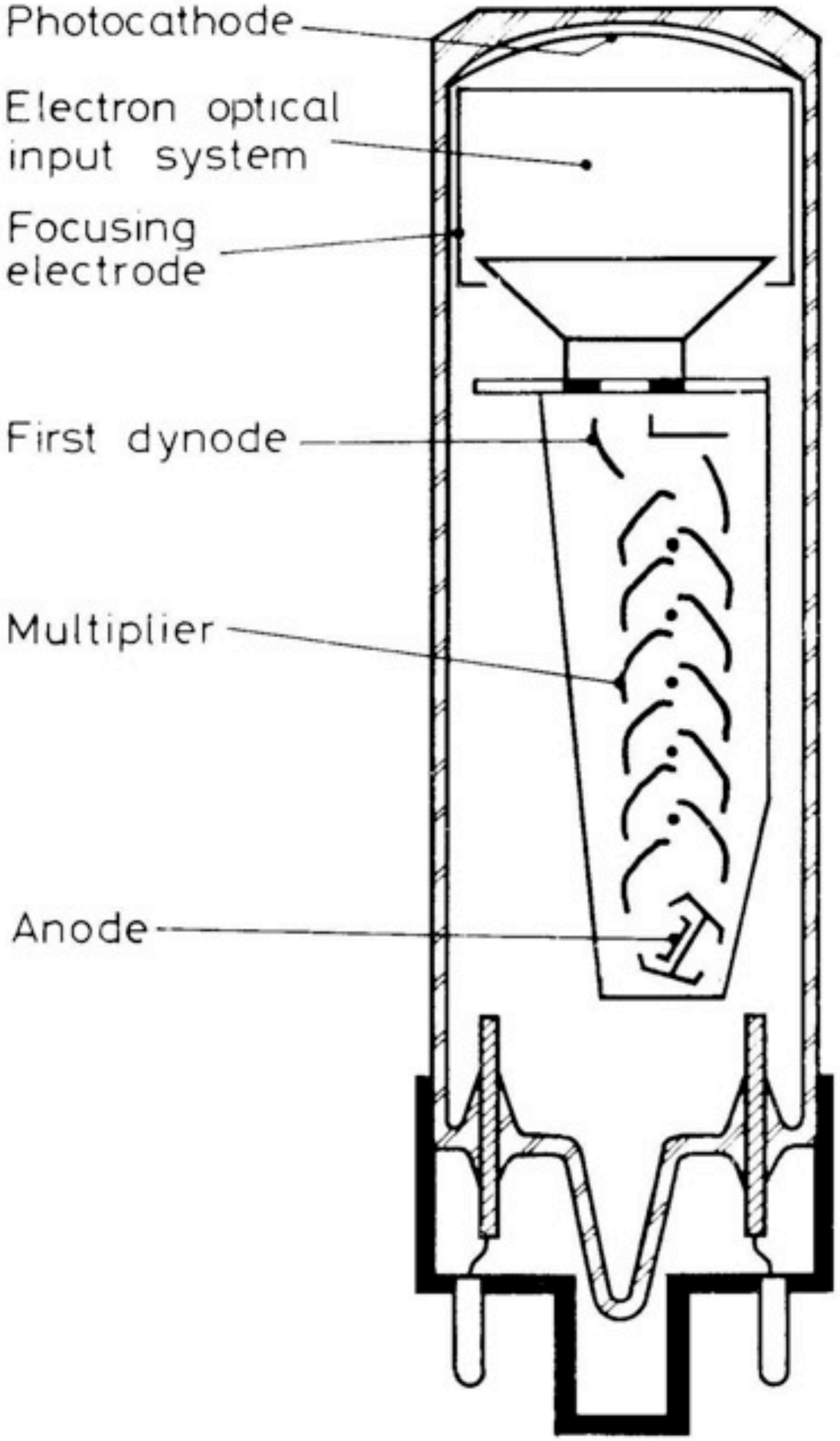
Secondary emission

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

Typical PMT Gain: > 10^6

[PMT can see single photons ...]

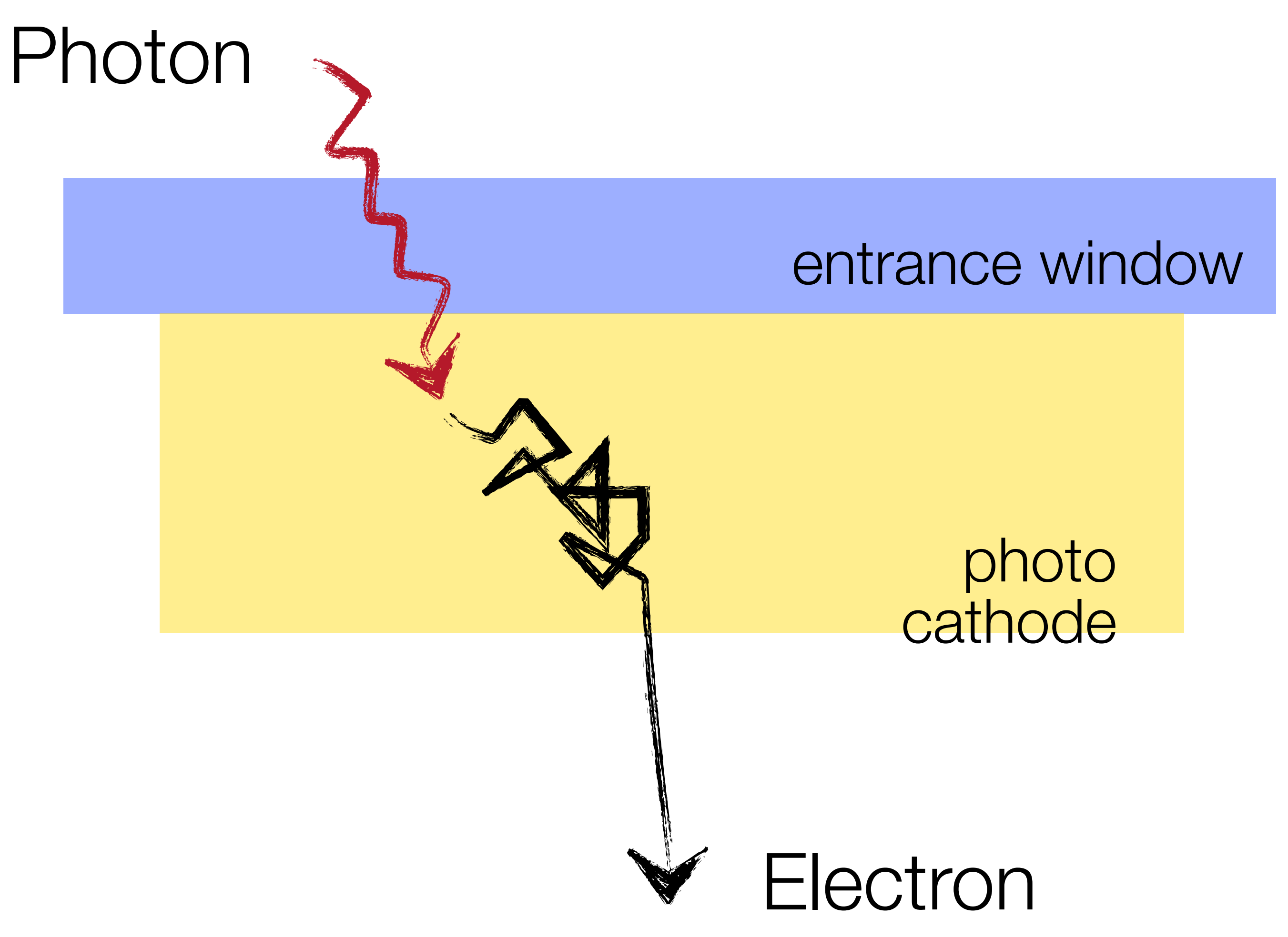
PMT Collection



Photocathodes

γ-conversion

via photo effect ...

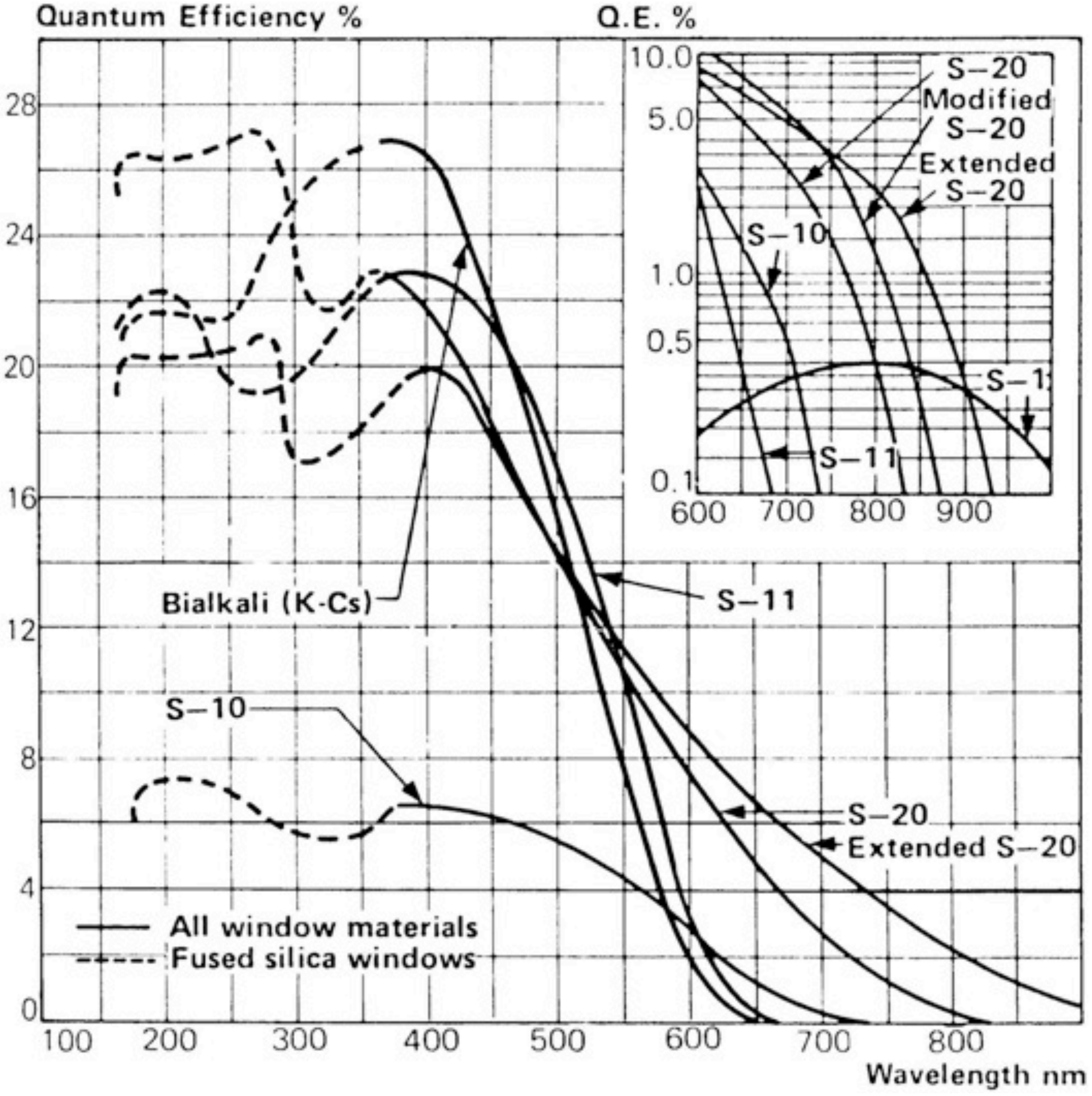


3-step process:

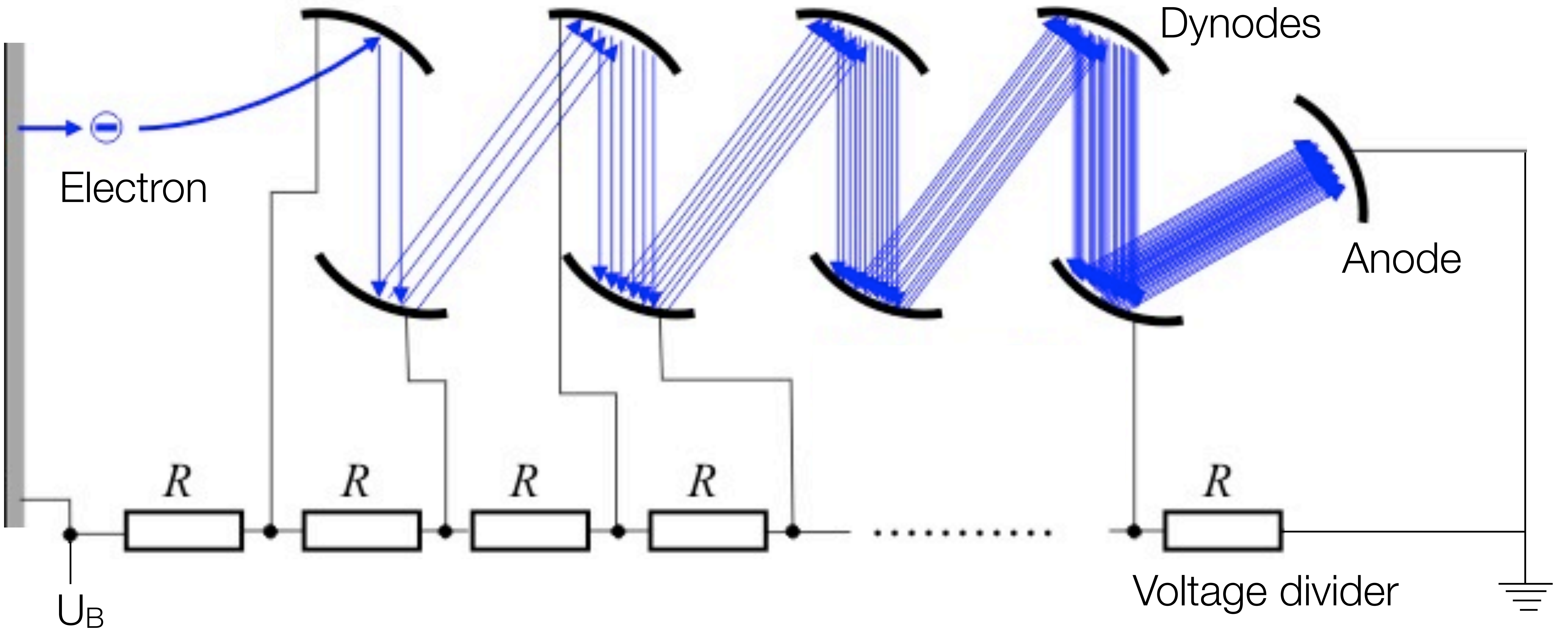
Electron generation via ionization
Propagation through cathode
Escape of electron into vacuum

Q.E. ≈ 10-30%

[need specifically developed alloys]



Electron Multiplication



Multiplication process:

Electrons accelerated toward dynode
Further electrons produced ➛ avalanche

Secondary emission coefficient:
δ = #(e⁻ produced)/#(e⁻ incoming)

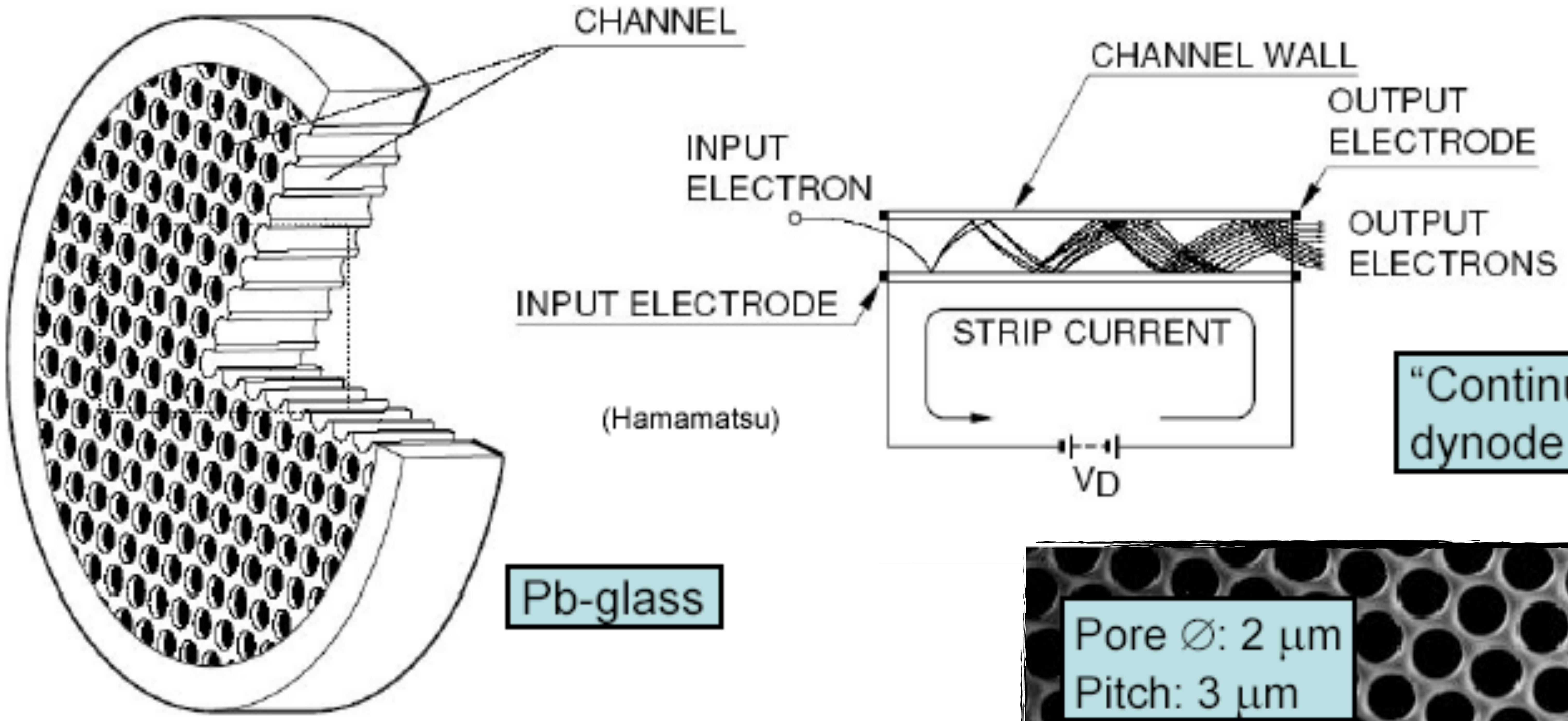
Typical: $\delta = 2 - 10$, $n = 8 - 15$ ➛ $G = \delta^n = 10^6 - 10^8$

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

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

Microchannel Plate

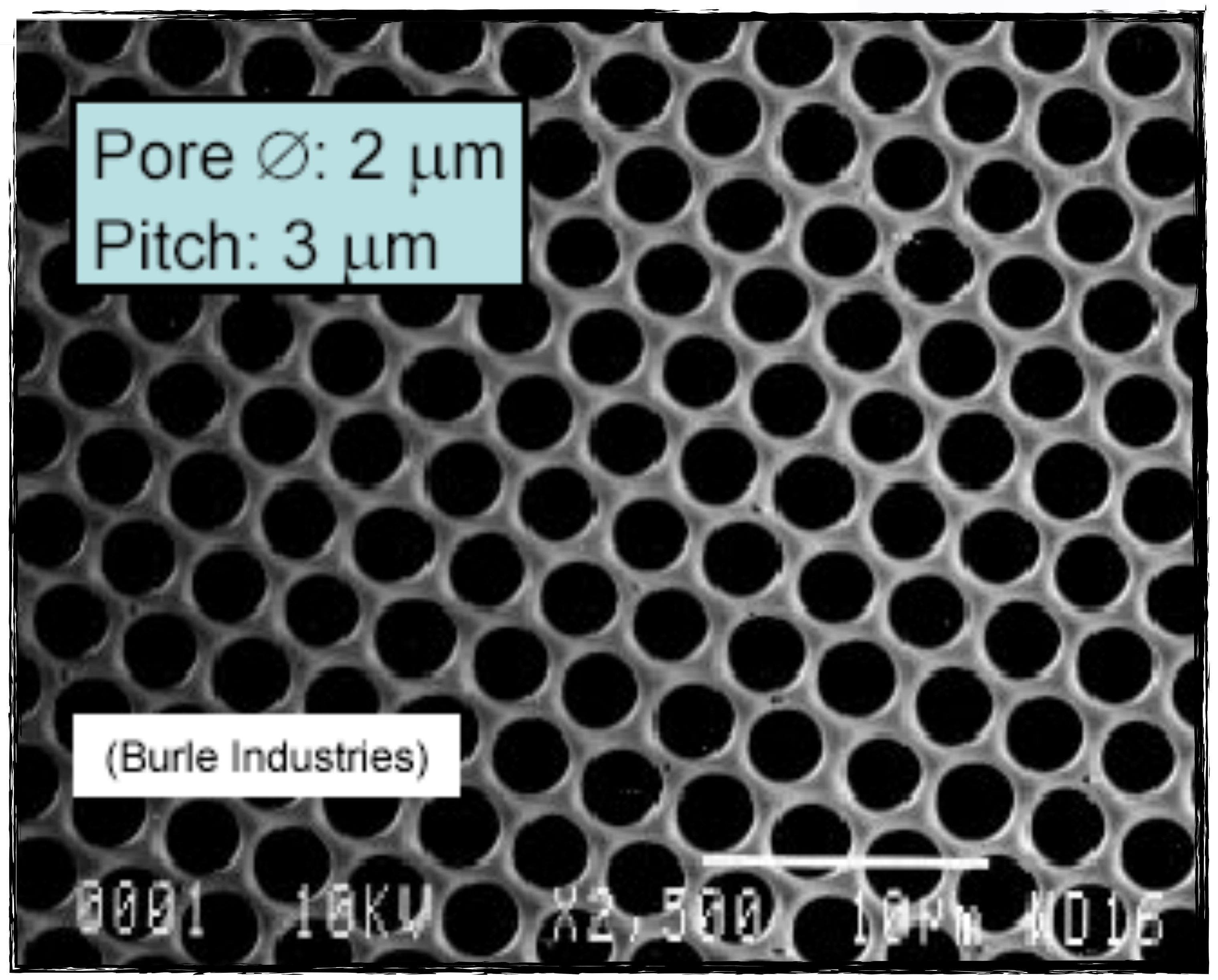
Thin 2D photomultiplier that preserves position information



(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

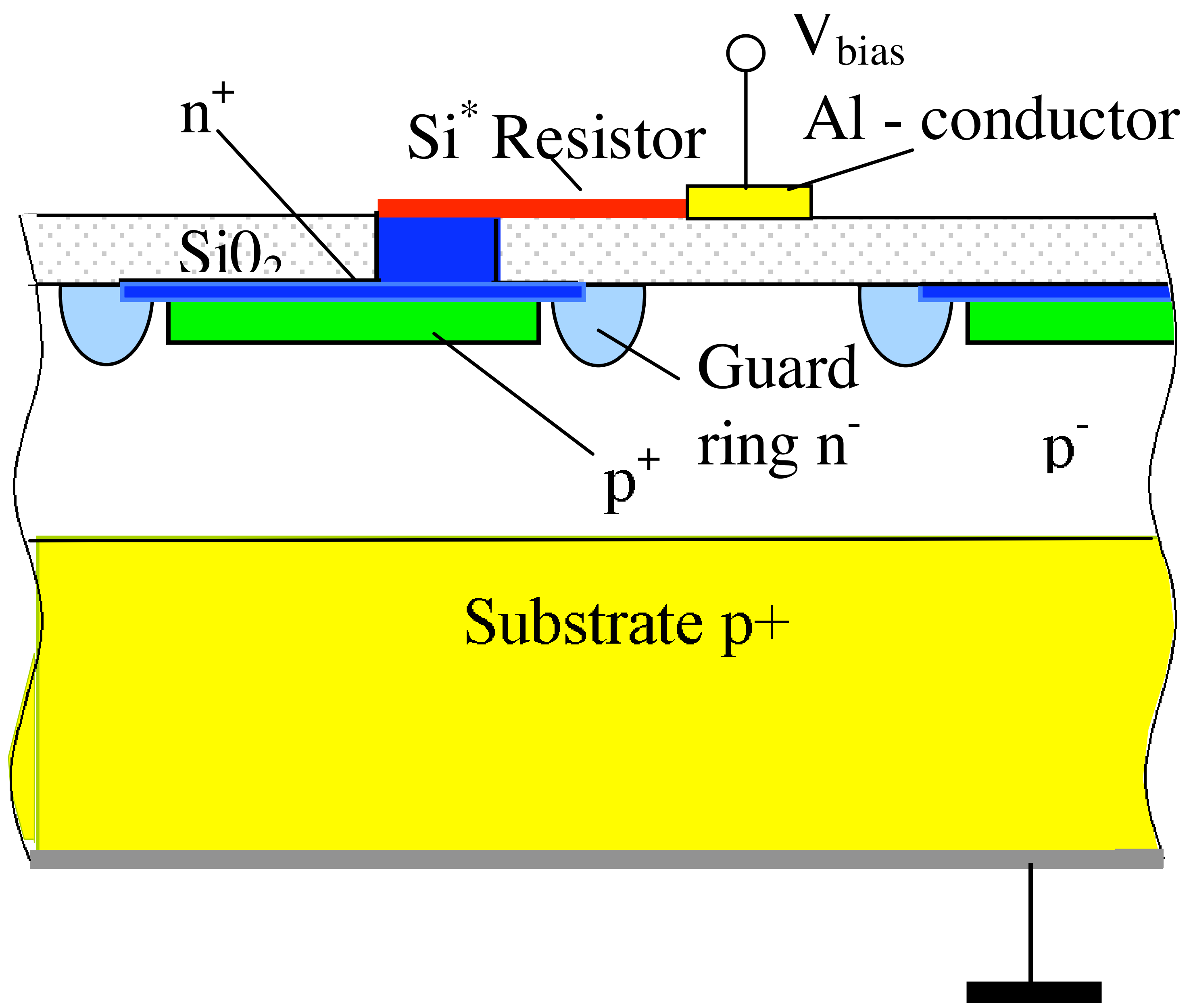
Silicon Photomultiplier

Principle:

Pixelized photo diodes operated in Geiger Mode

Single pixel works as a binary device

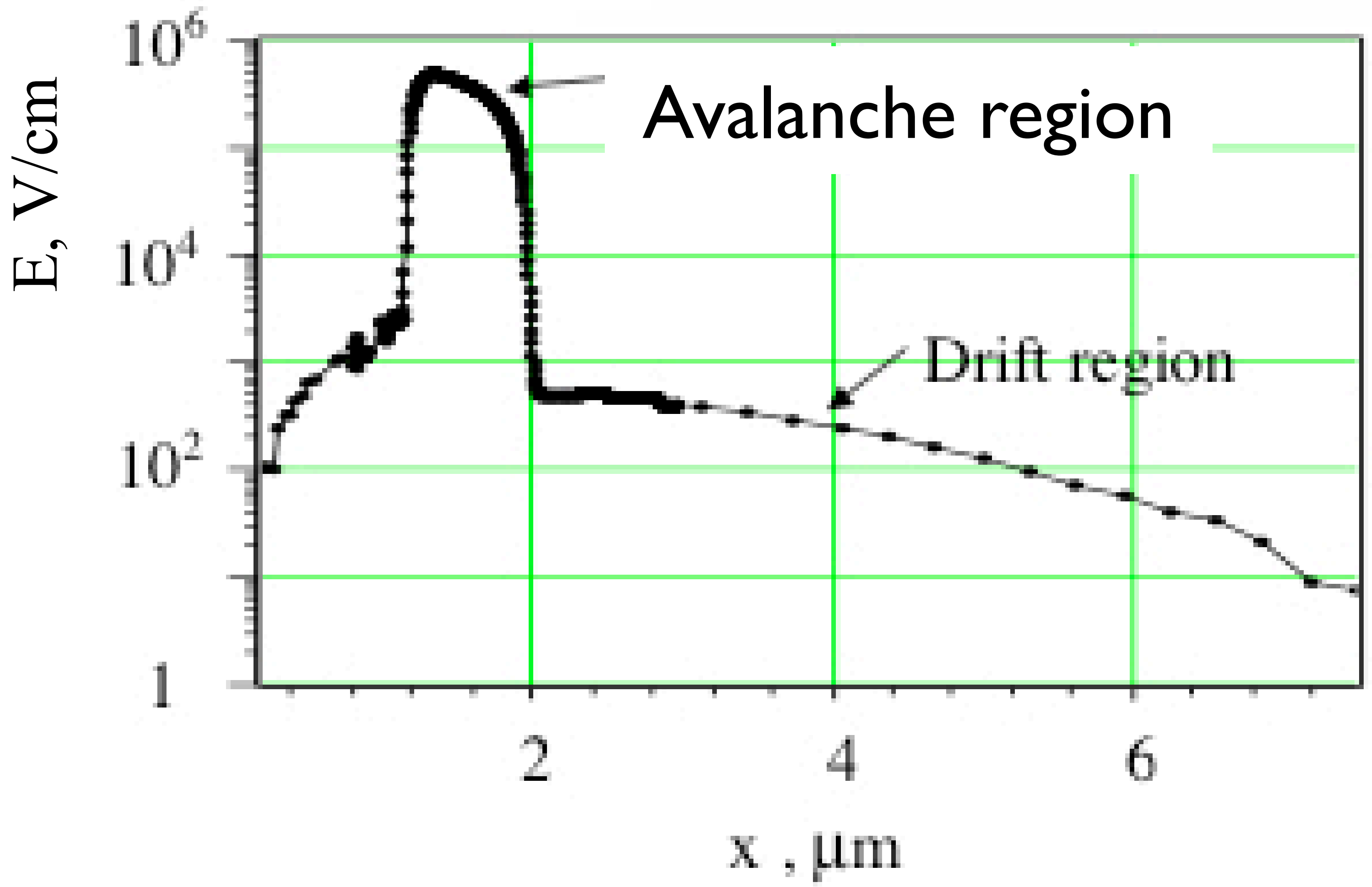
Energy = #photons seen by summing over all pixels



Features:

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

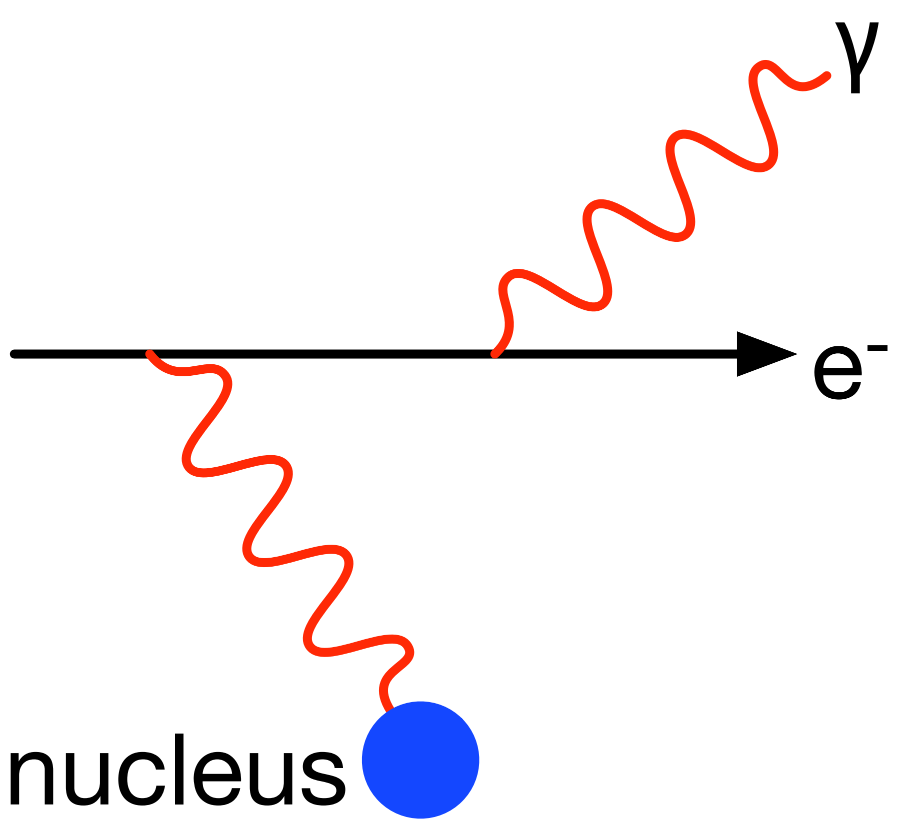
Insensitive to magnetic fields!
Works at room temperature ...



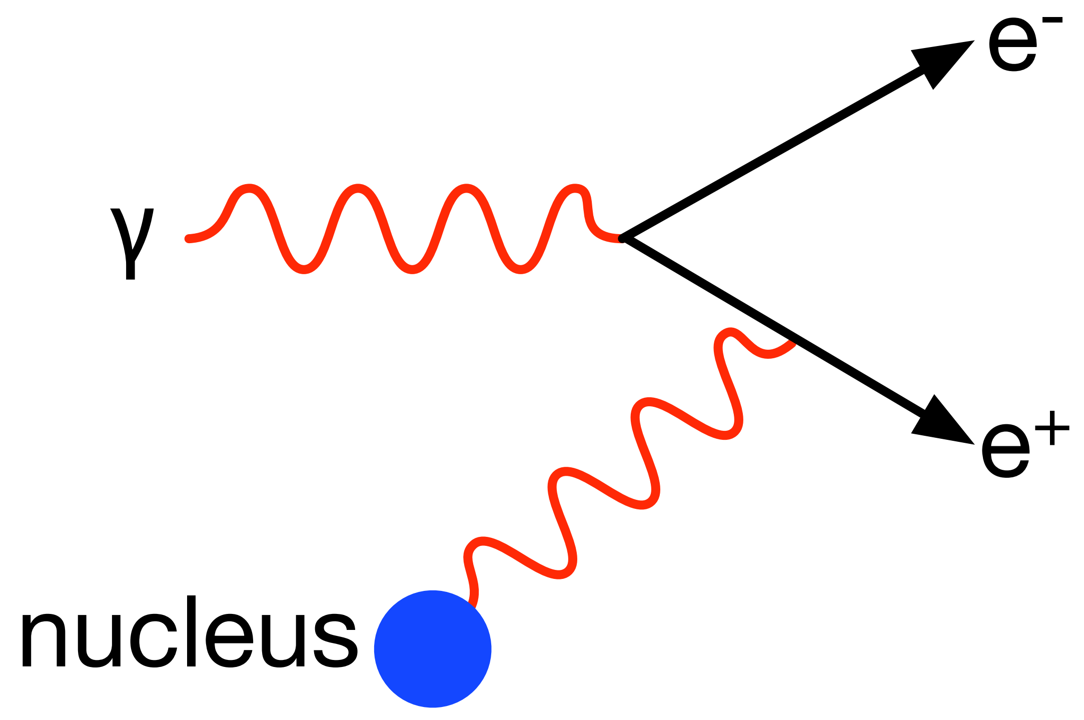
Electromagnetic Showers

Electrons, positrons, and photons interact with nuclei in matter to produce each other

- High energy electrons radiate all but e^{-1} of their energy in a radiation length X_0
- The mean free path of a high energy photon is 9/7 X_0
- X_0 scales as A/Z^2 and becomes small for heavy atoms
- The two processes together produce electromagnetic showers



Bremmstrahlung



Pair Production

$$\frac{1}{E}\frac{dE}{dx} = -\frac{1}{X_0}$$

$$\ell = \frac{9}{7}X_0$$

$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln(183/Z^{\frac{1}{3}})}$$

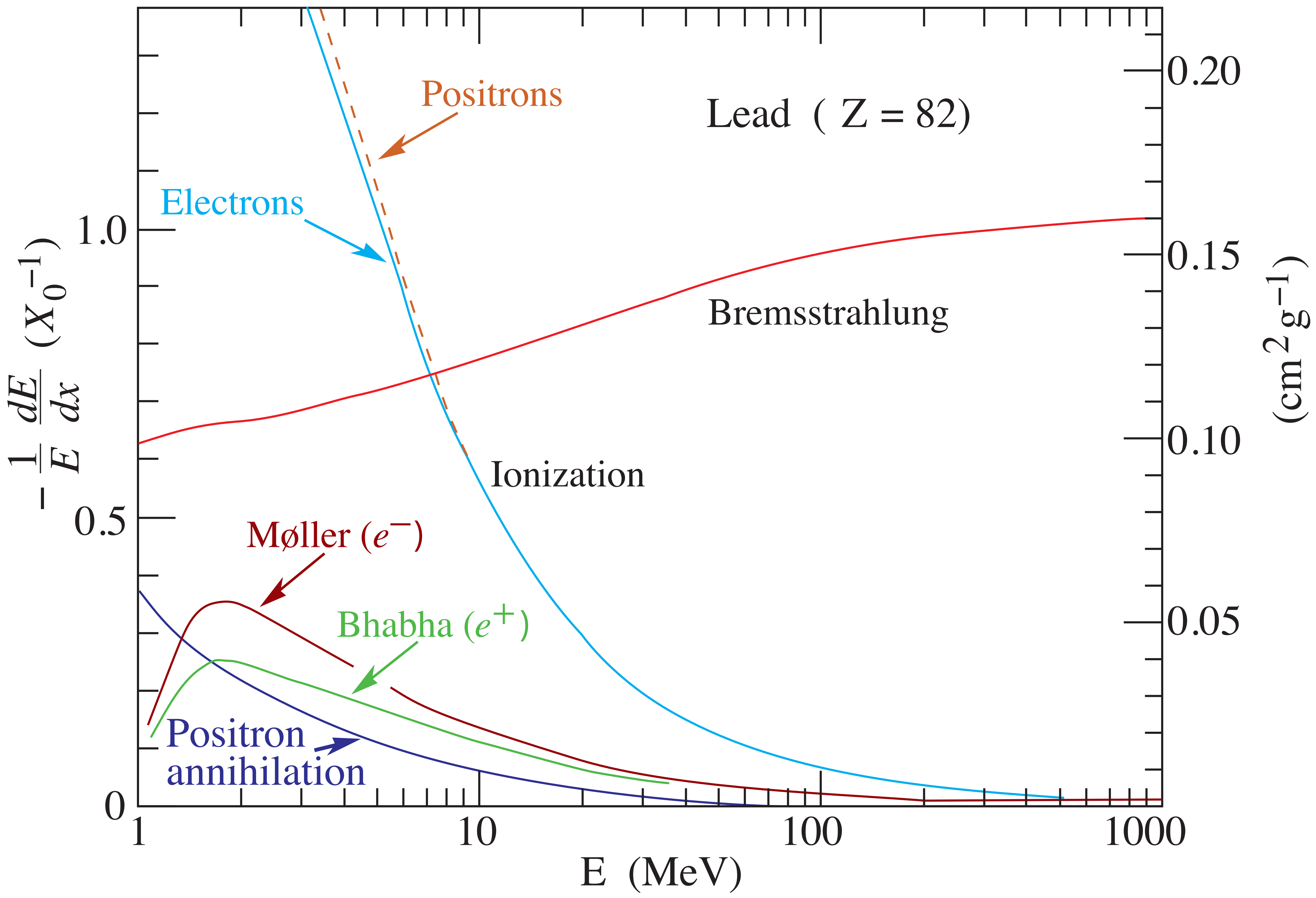
Electromagnetic Showers

At high energies, Bremmstrahlung dominates the energy loss of electrons. As the electron energy decreases, the ionization loss increases. They become equal at the critical energy E_c.

$$E_c = \begin{cases} \frac{710\ \mathrm{MeV}}{Z+0.92} & \text{Gases} \\ \frac{610\ \mathrm{MeV}}{Z+1.24} & \text{Solids/Liquids} \end{cases}$$

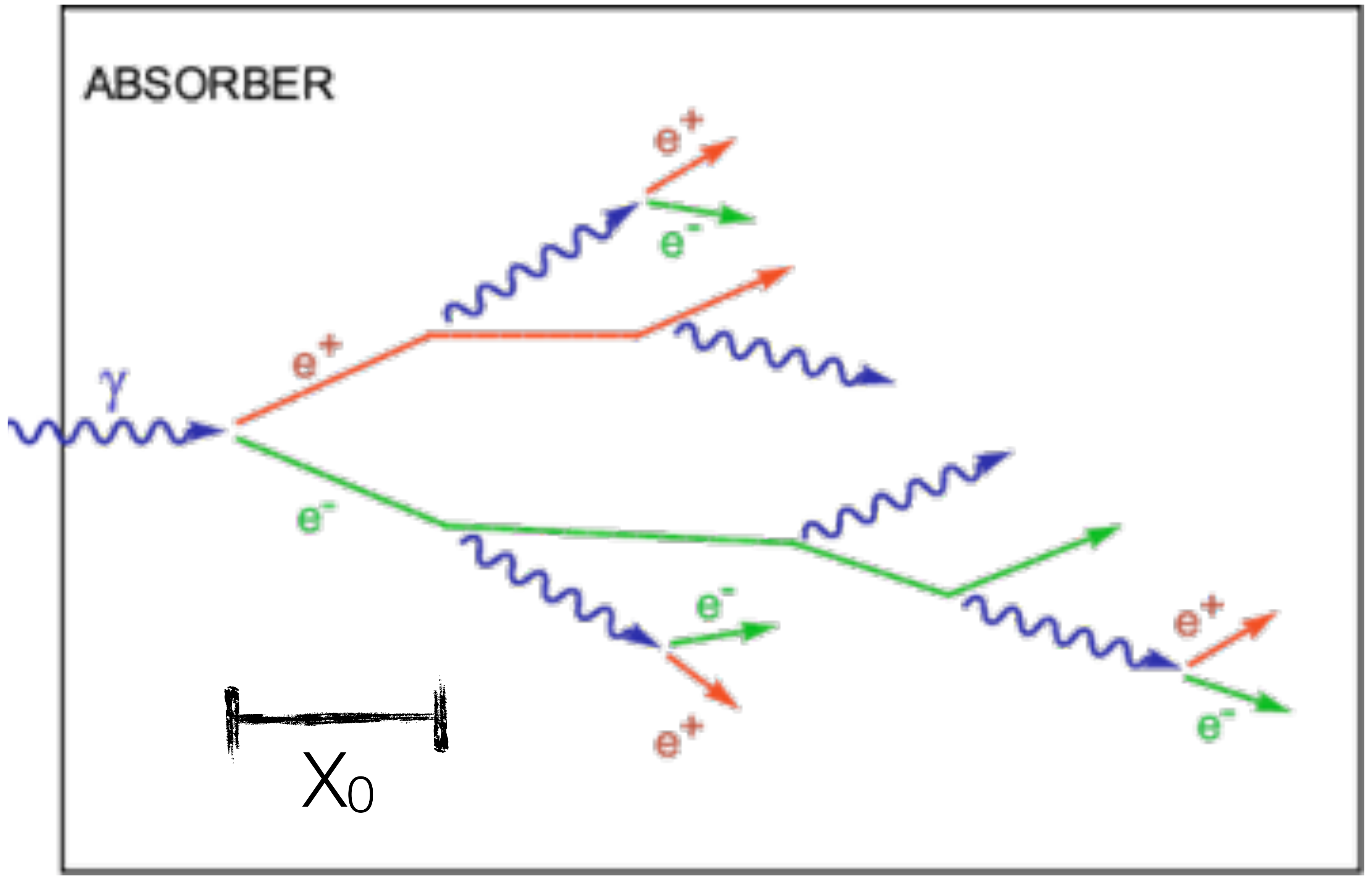
- Below E_c, e± lose their energy quickly and stop or annihilate [e+]
- A useful related quantity is the Moliere radius R_M which is related to the transverse size of an electromagnetic shower:

$$R_M = \frac{21\ \mathrm{MeV}}{E_c} X_0$$

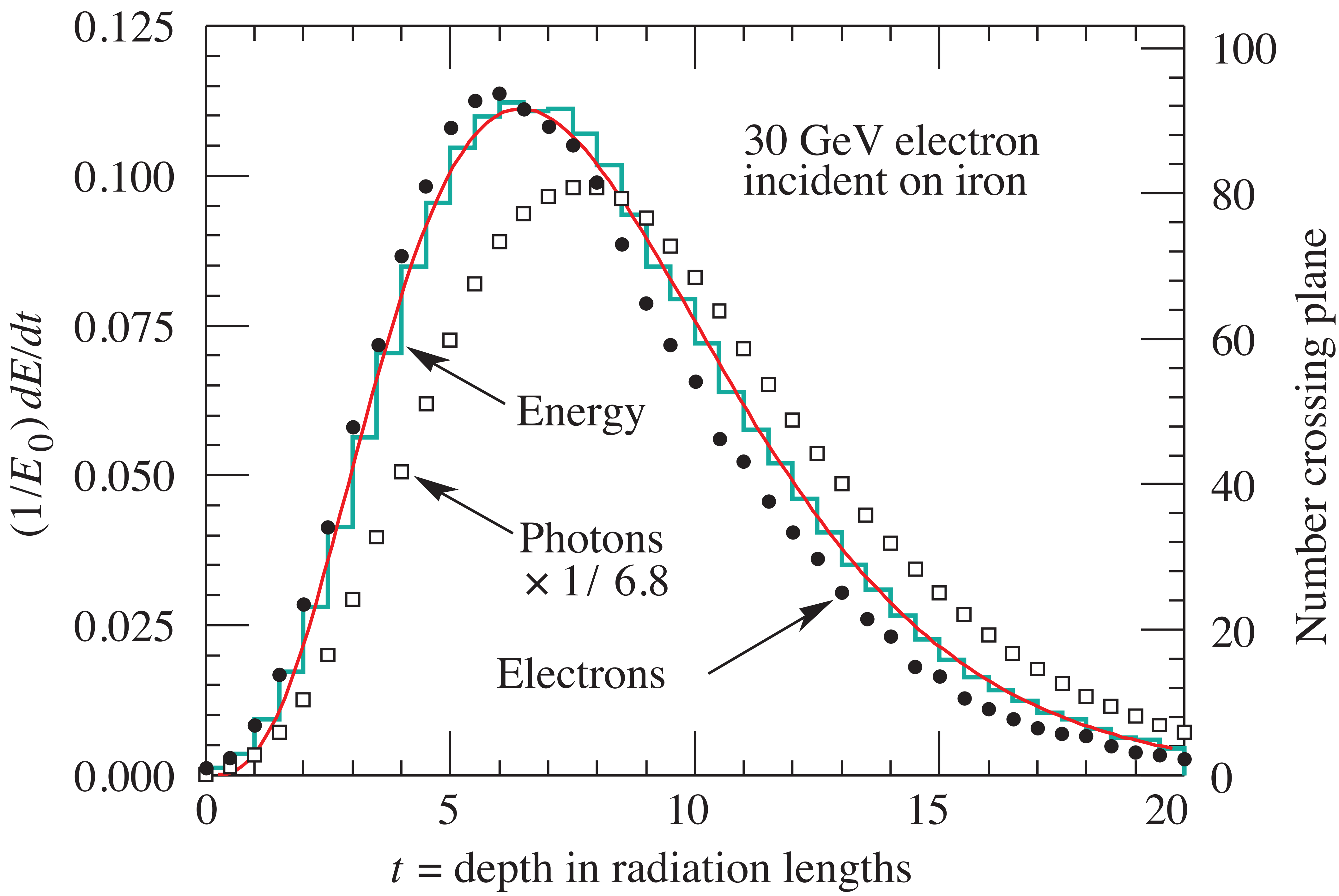


Electromagnetic Showers

The shower features many generations of electrons/positrons and photons propagating in material until all of the energy has been deposited. Most of the electrons/positrons have the critical energy by the shower maximum.



- Shower distribution approx scales vs depth as $t = x/X_0$
  - energy and number of electrons have similar dists
- Shower max $t_{\max} = \ln \frac{E}{E_c} - \begin{cases} 1.0 & e \text{ induced} \\ 0.5 & \gamma \text{ induced} \end{cases}$
- Shower length $L(95\%) = t_{\max} + 0.8Z + 9.6$
- Shower radius $R = \begin{cases} R_M & 90\% \\ 2R_M & 95\% \end{cases}$



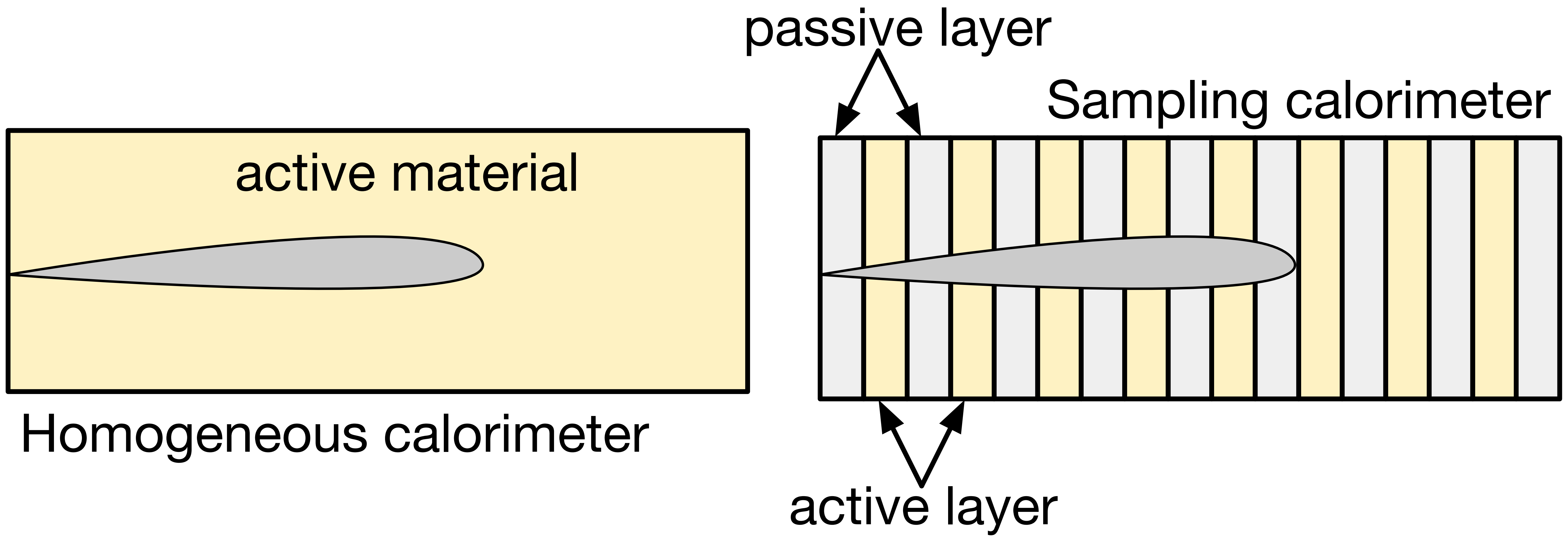
Electromagnetic Showers

The shower parameters for several materials used to detect and measure electromagnetic showers.

	X_0 [cm]	E_c [MeV]	R_M [cm]
Pb	0.56	7.2	1.6
Scintillator (Sz)	34.7	80	9.1
Fe	1.76	21	1.8
Ar (liquid)	14	31	9.5
BGO	1.12	10.1	2.3
Sz/Pb	3.1	12.6	5.2
PB glass (SF5)	2.4	11.8	4.3

Calorimetry

Calorimeters are designed to measure the energies [and directions sometimes] of particles by detecting the energy deposited by showering particles. There are two main types:

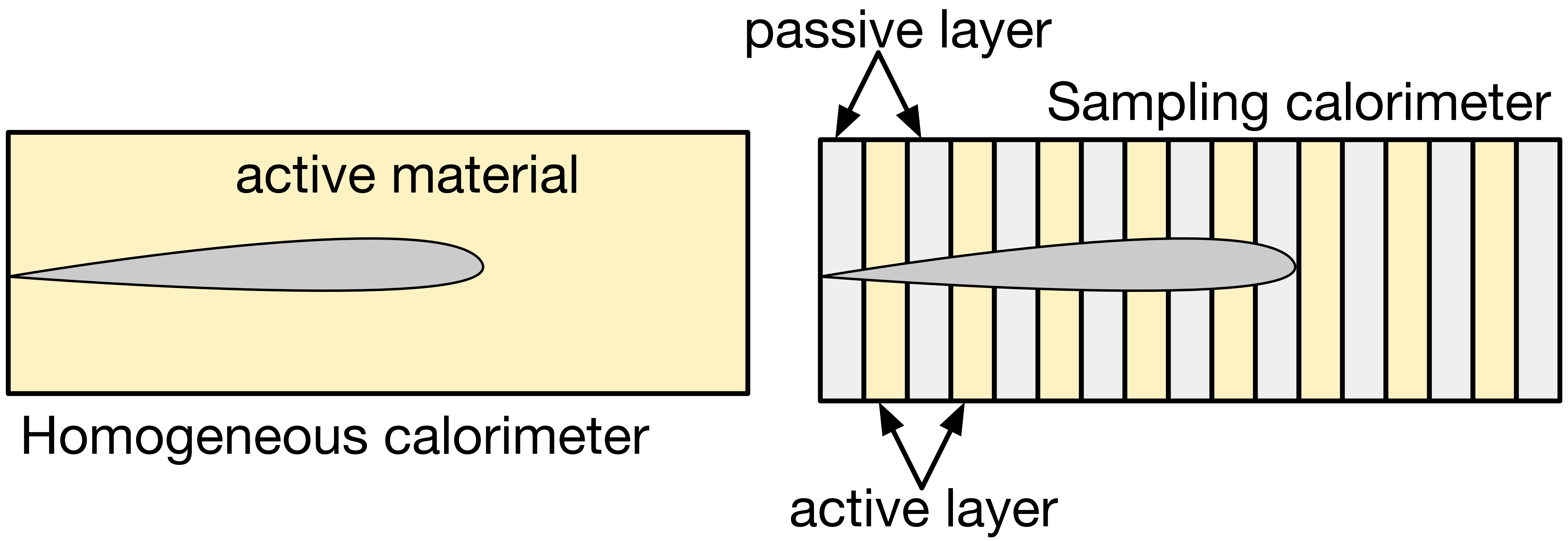


- Homogeneous calorimeters contain the entire shower in a dE/dx sensitive medium
  - expensive, higher resolution, limited to calorimeters for electrons and photons

Signal	Material
Scintillation light	BGO, BaF_2, CeF_3, ...
Ionization signal	Liquid noble gases (Ar, Kr, Xe)
Cerenkov light	Lead Glass

Calorimetry

Calorimeters are designed to measure the energies [and directions sometimes] of particles by detecting the energy deposited by showering particles. There are two main types:

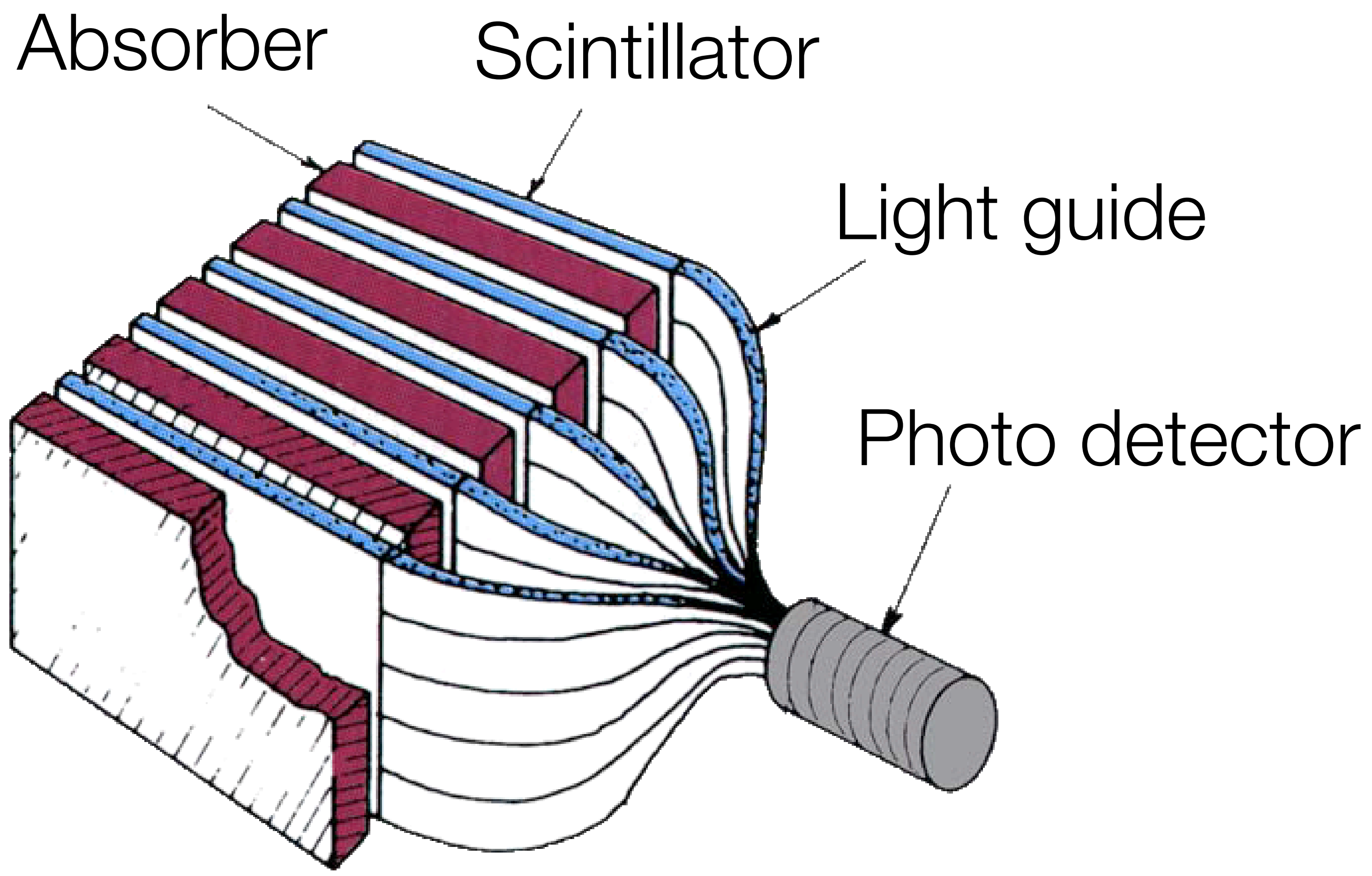


- Sampling calorimeters intersperse passive and active layers
  - can use dense passive layers to evolve showers in a smaller region, cheaper, lower resolution from sampling fluctuations
  - passive materials: Iron, Lead, Uranium (U-238)
  - active materials: plastic scintillator, silicon detectors, liquid noble gases, gases

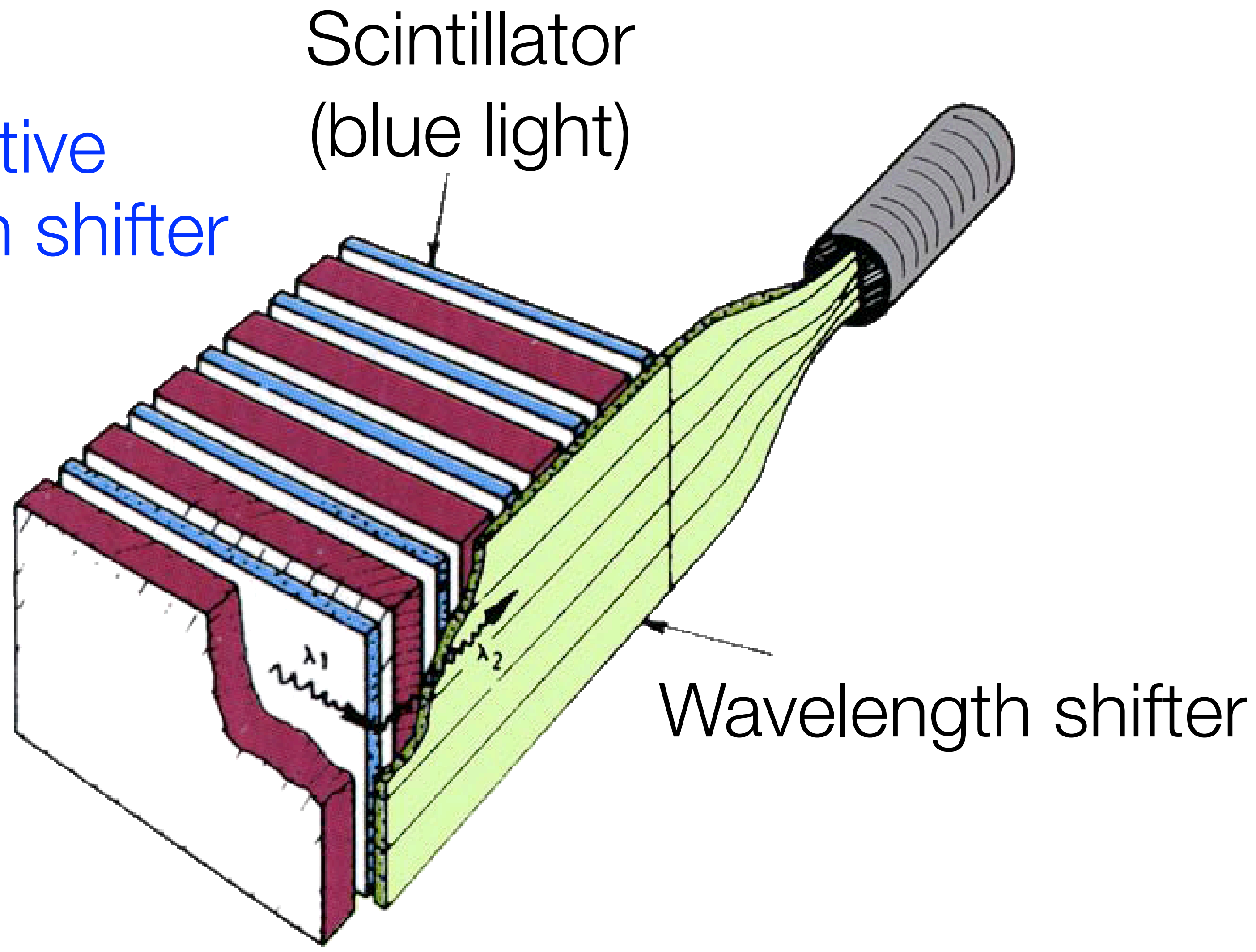
Sampling Calorimetry

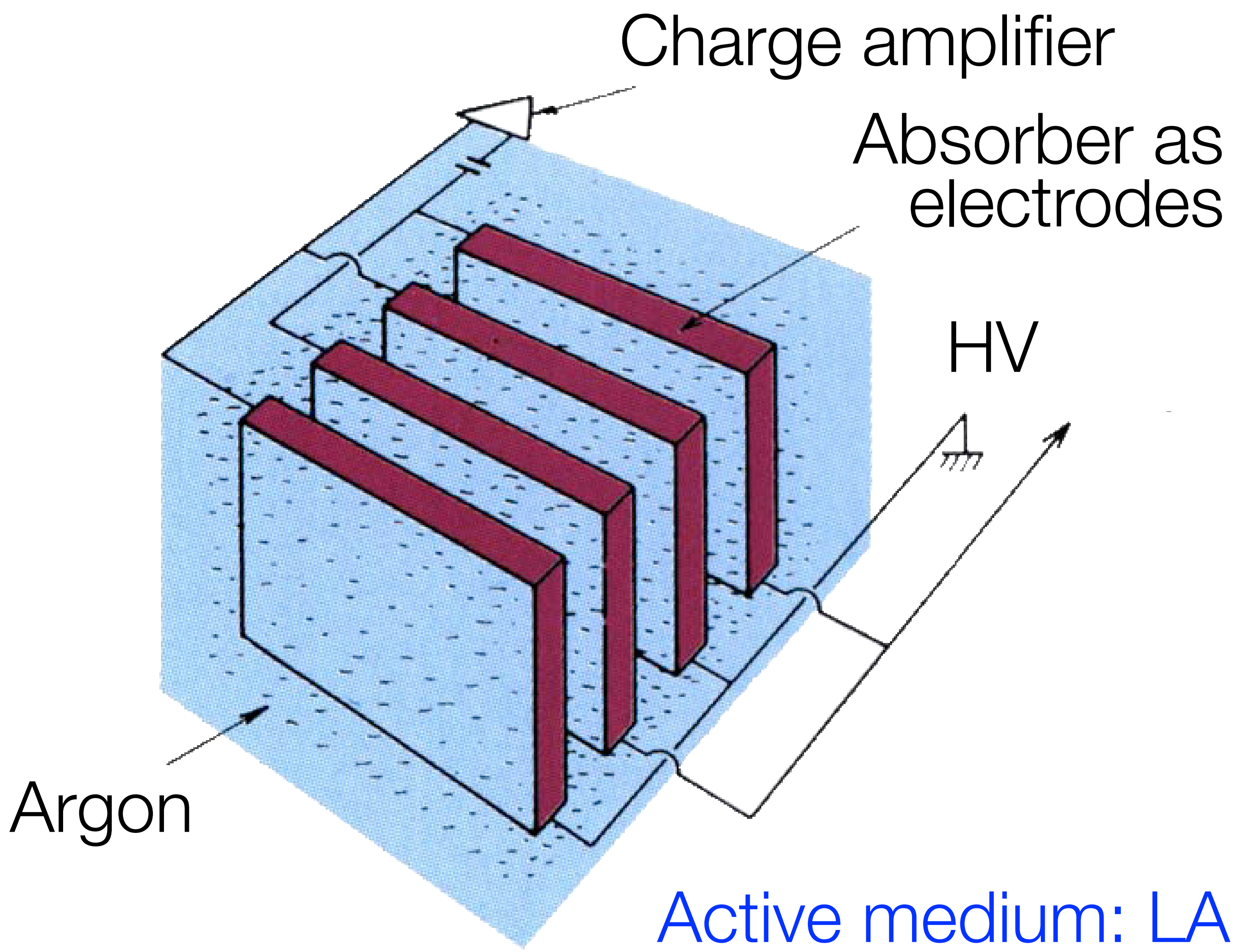
Possible setups

Scintillators as active layer;
signal readout via photo multipliers



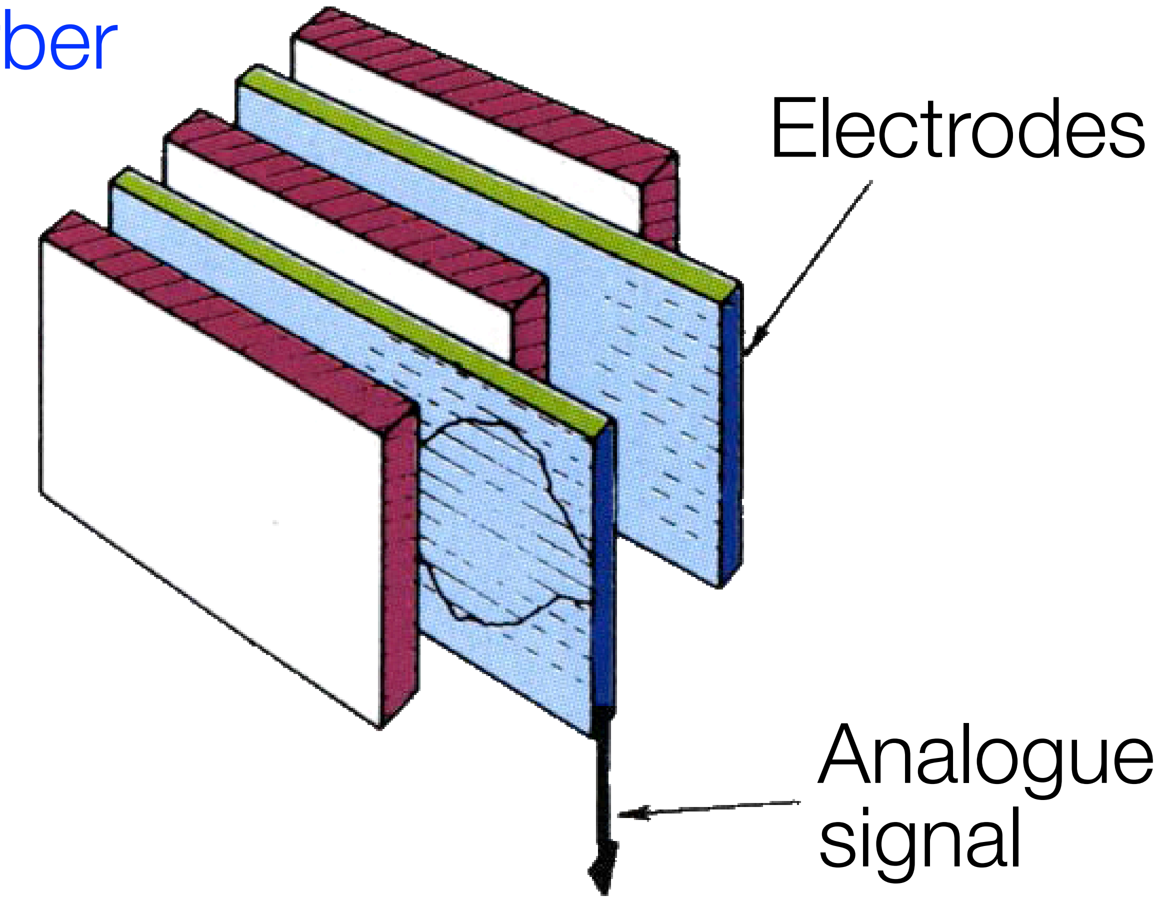
Scintillators as active layer; wave length shifter to convert light





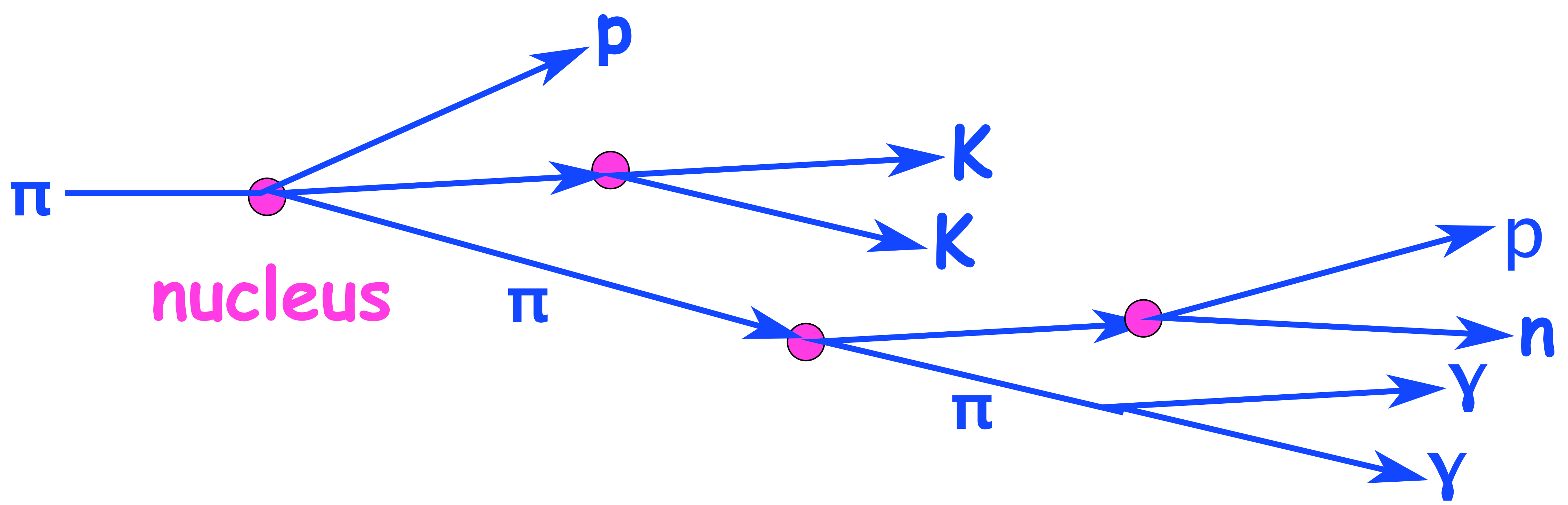
Active medium: LAr; absorber embedded in liquid serve as electrods

Ionization chambers between absorber plates



Hadronic Showers

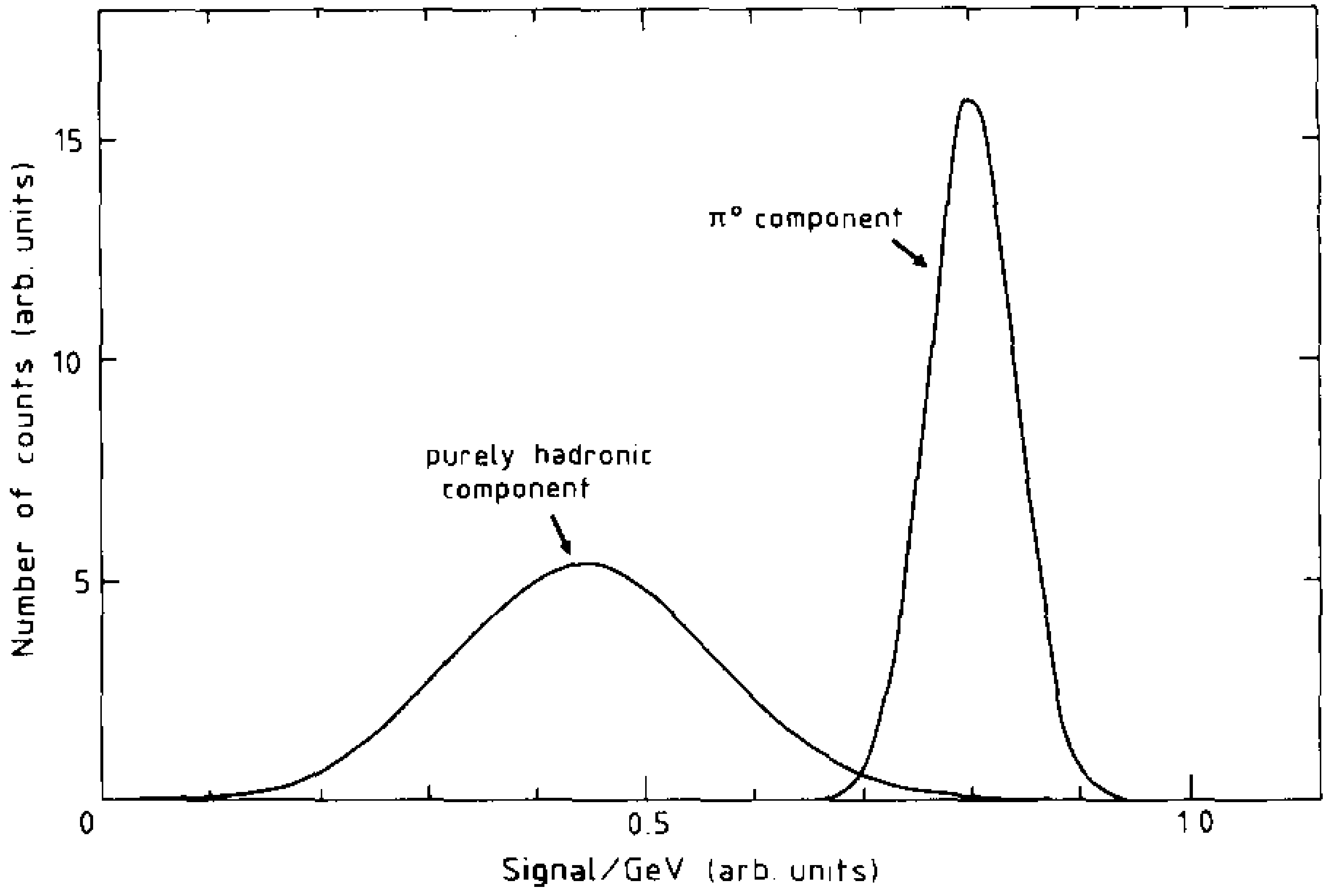
HIgh energy hadrons interact with nuclei and also produce showers in the calorimeters

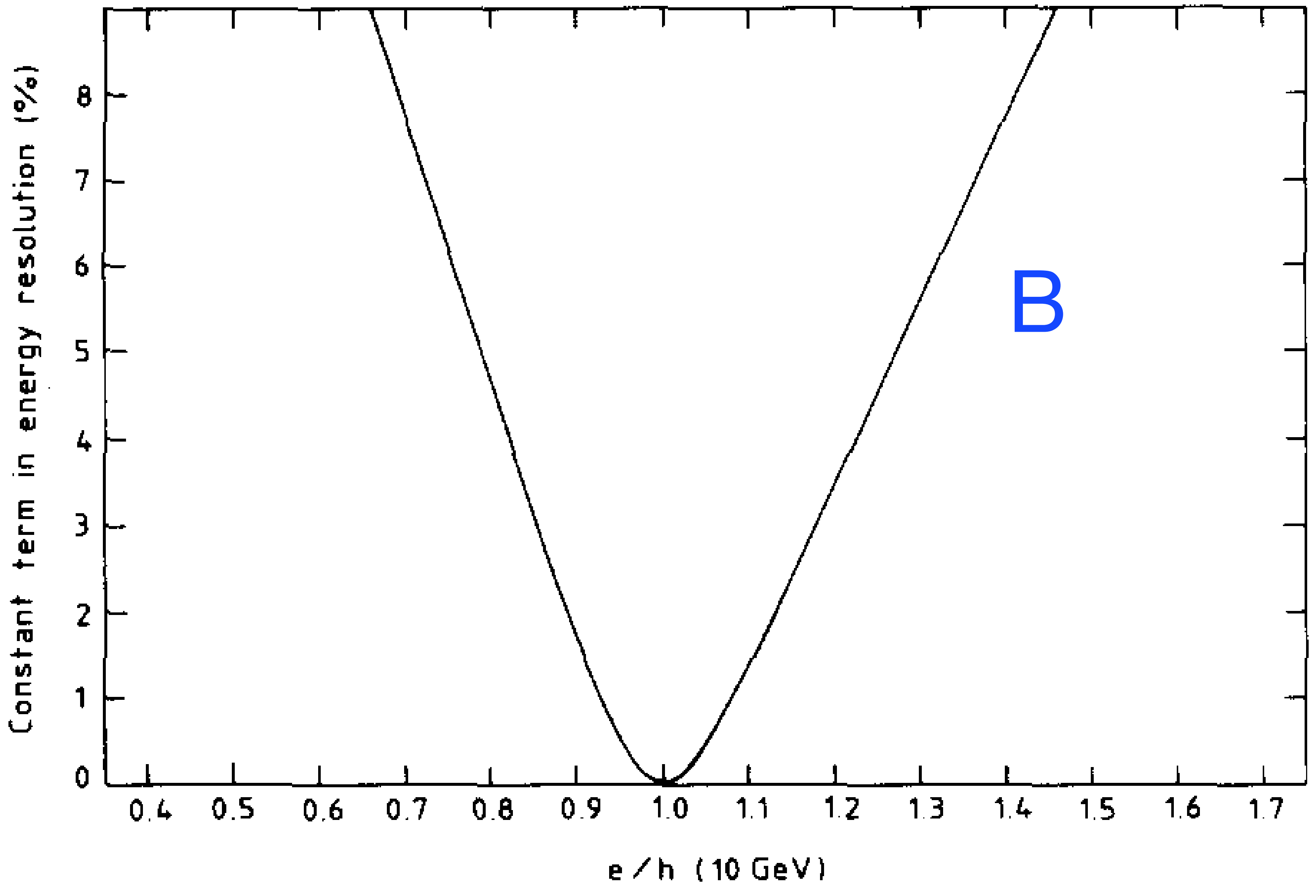


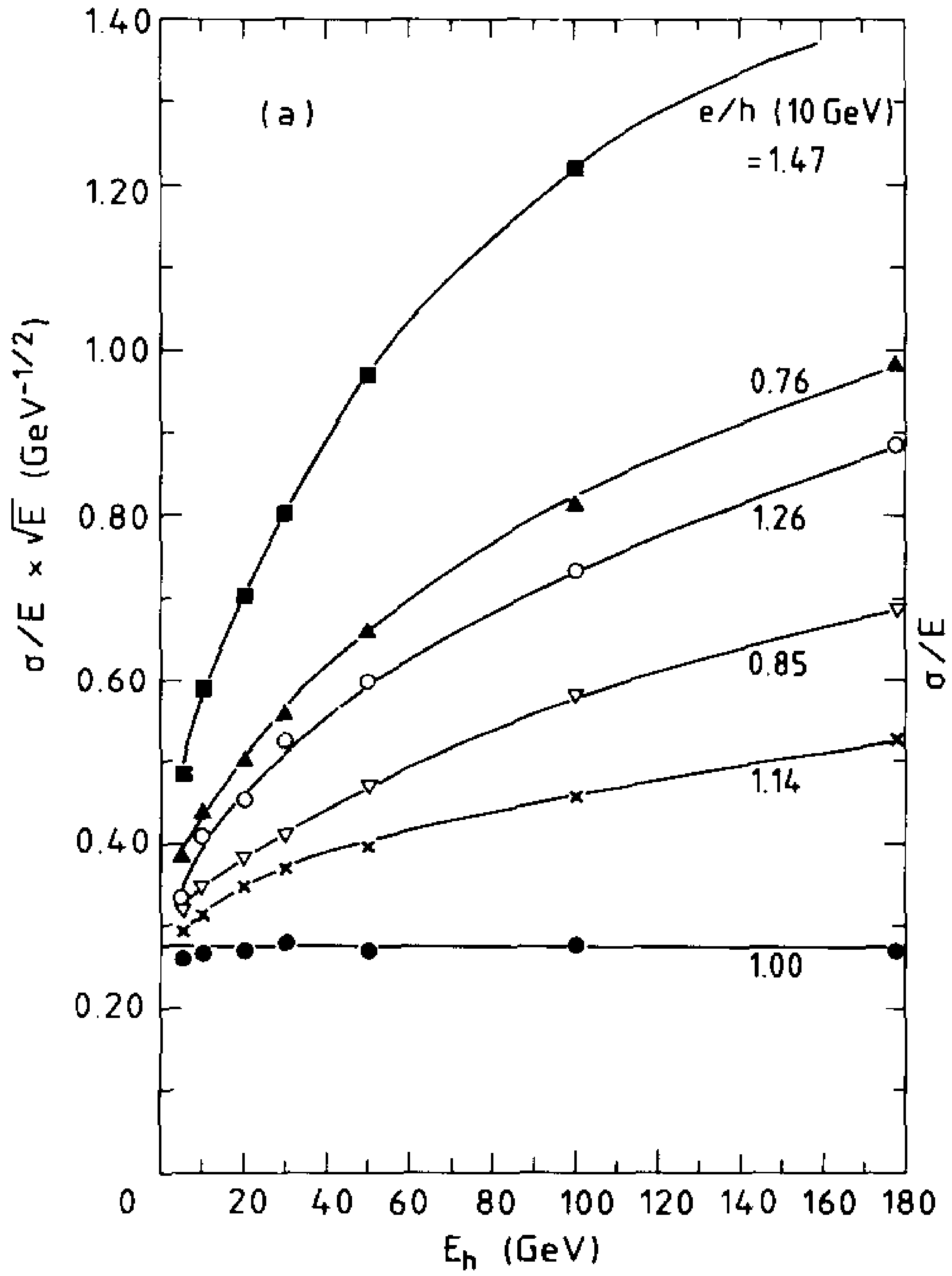
- Length scale of the shower is determined by the nuclear absorption length of the material λ_{abs}
  - defined as the mean free path for inelastic scattering
  - most shower particles are gone by 5-10 λ_{abs}
- The pions produced in the shower come in 3 charge states: π^+, π^0, π^-
  - the charged pions have relatively long lifetimes and interact with nuclei
  - the neutral pions decay promptly to photon pairs: π^0 -> 2γ
    - ✳ the photons initiate electromagnetic showers which produce larger signals in the calorimeter
    - ✳ fluctuations in the number/energy of em showers limits the energy resolution of the calorimeter

Compensating Calorimeters

- It was understood many years ago [1970s] that it was desirable to make a calorimeter that responded in incident hadrons in the same way as e/γ: ratio e/h = 1
  - optimizes the resolution for incident hadrons $\frac{\sigma_E}{E} = \frac{A}{E^{\frac{1}{2}}} + B$







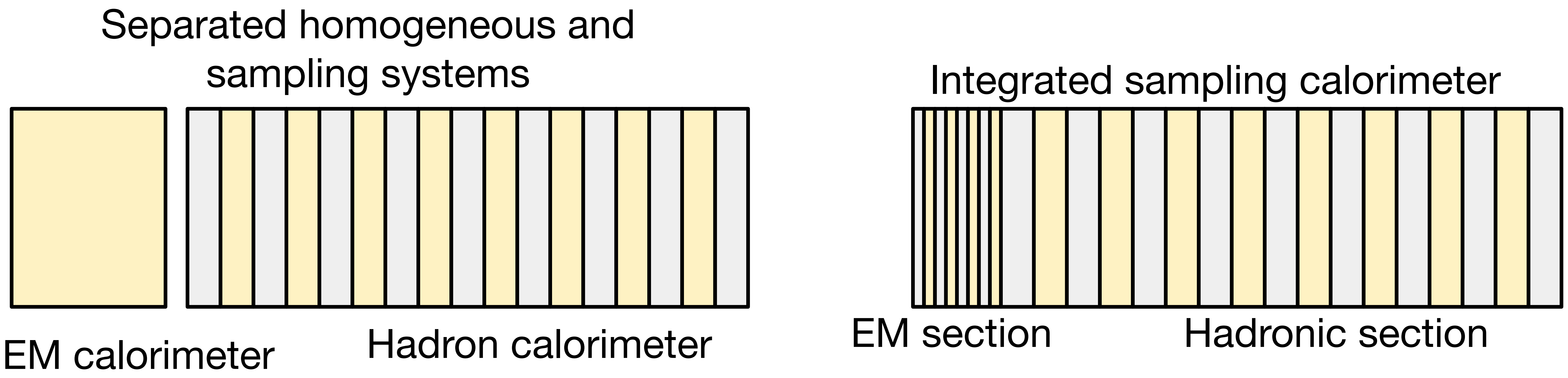
- Resolution limited by sampling fraction of dE/dx
- Ultimate resolution limited by fluctuations in nuclear binding enery losses [unlike e/γ shower case]

Compensating Calorimeters

- Results from the Willis group at CERN [1975-1976] U/plastic scintillator suggest that sampling calorimeters with uranium absorber achieve e/h = 1!
  - explained that fission n from the U magically compensate the larger signals from π^0
  - idea readily accepted by the HEP community: D0 experiment at the FNAL Tevatron incorporates a U-LAr calorimeter
- R. Wigmans [1987] uses simulation to show that this is not exactly true
  - there are lots of slow neutrons in any hadronic shower
  - need hydrogen in the active layer to detect the neutrons [large np cross section]
  - must adjust the thickness of thin plates of absorber material to tune the e/γ response
  - can make compensating calorimeters with Pb plates too!
  - U-LAr calorimeter can never be compensating!

Calorimeter systems

We want ~10 λ_{abs} and ~25 X_0 to fully contain hadronic and em showers. In lead, that's 1m and 14 cm. It's clearly too expensive to use homogeneous calorimeters for hadrons and it's not possible to adjust their e/h ratios. The solution is to segment the calorimeter into e/γ and h sections



- Homogeneous EM calorimeter and sampling hadronic calorimeter
  - very good e/γ energy resolution
  - need software algorithms to combine information for hadron energies
- Integrated calorimeter: finely sampled e/γ section and more coarsely sampled h section
  - poorer e/γ resolution but better hadronic resolution [shower direction in LAr devices]

CMS System

Inner Detector:

$\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$

[vergl. ATLAS $\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$]

Hadron Calorimeter:

$\sigma/E \approx 100\%/\sqrt{E} \oplus 5\%$

[vergl. ATLAS: $\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$]

EM Calorimeters:

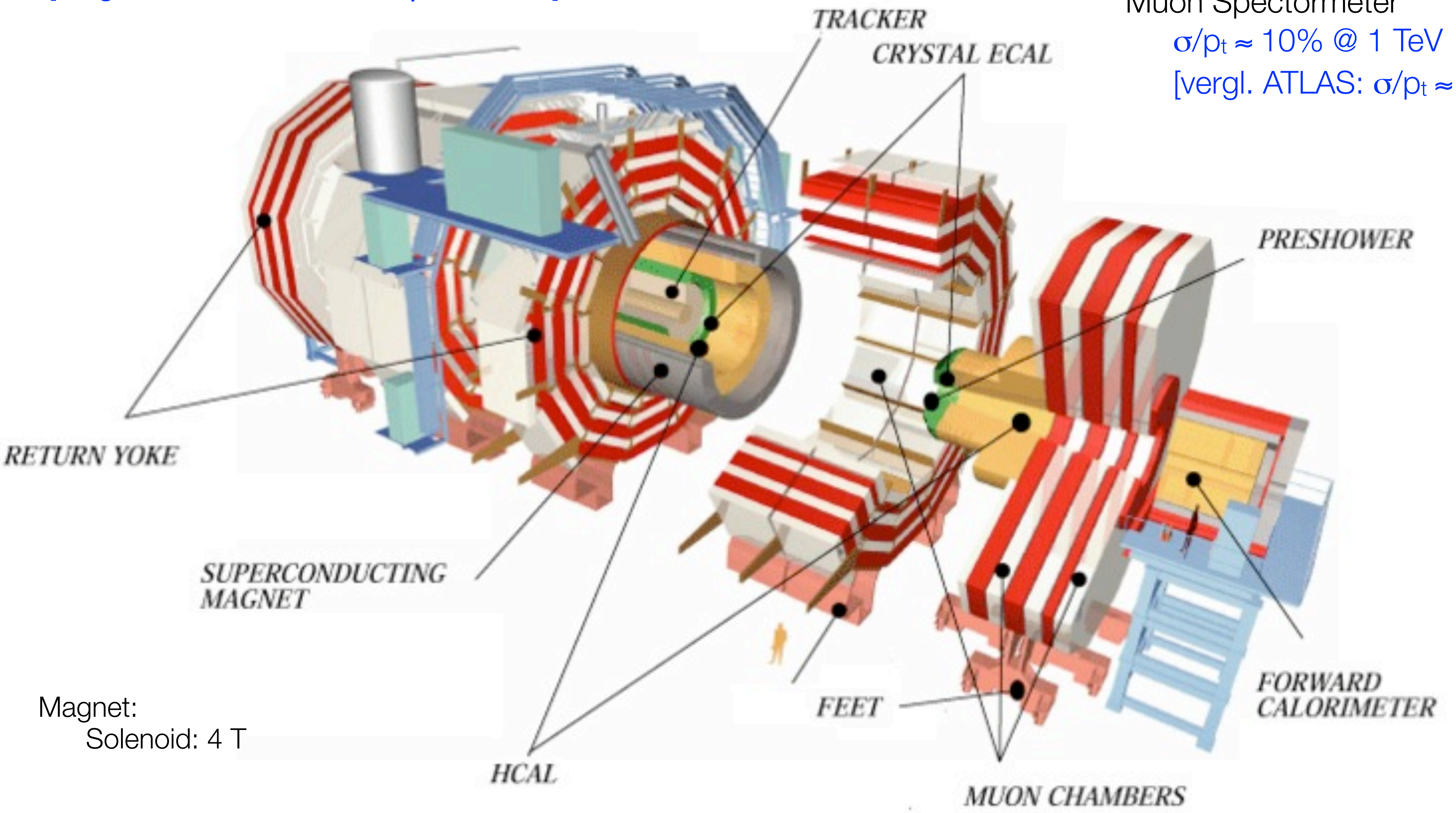
$\sigma/E \approx 3\%/\sqrt{E} \oplus 0.5\%$

[vergl. ATLAS: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$]

Muon Spectormeter

$\sigma/p_t \approx 10\%$ @ 1 TeV

[vergl. ATLAS: $\sigma/p_t \approx 10\%$ @ 1 TeV]

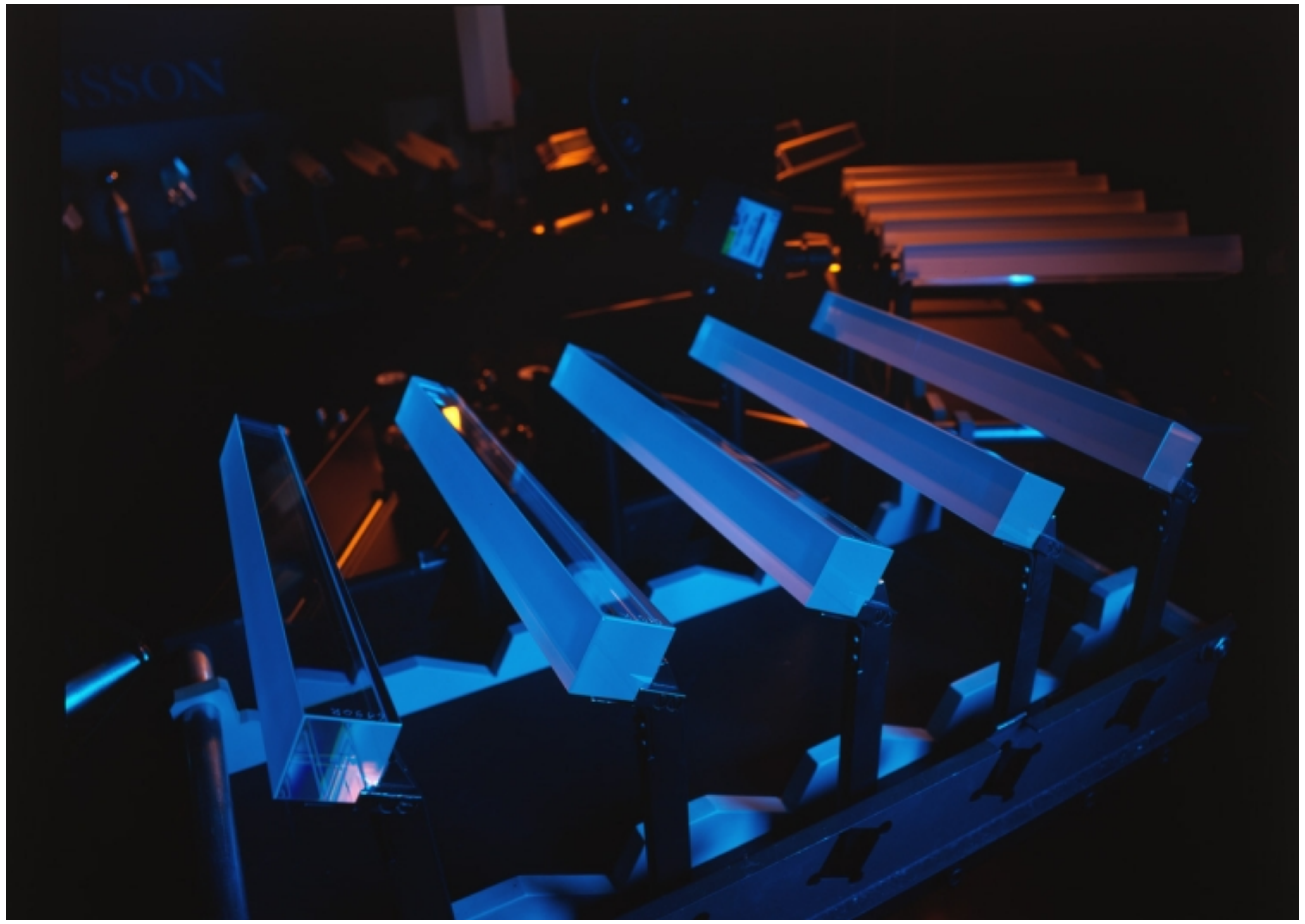


Magnet:

Solenoid: 4 T

CMS System

ECAL

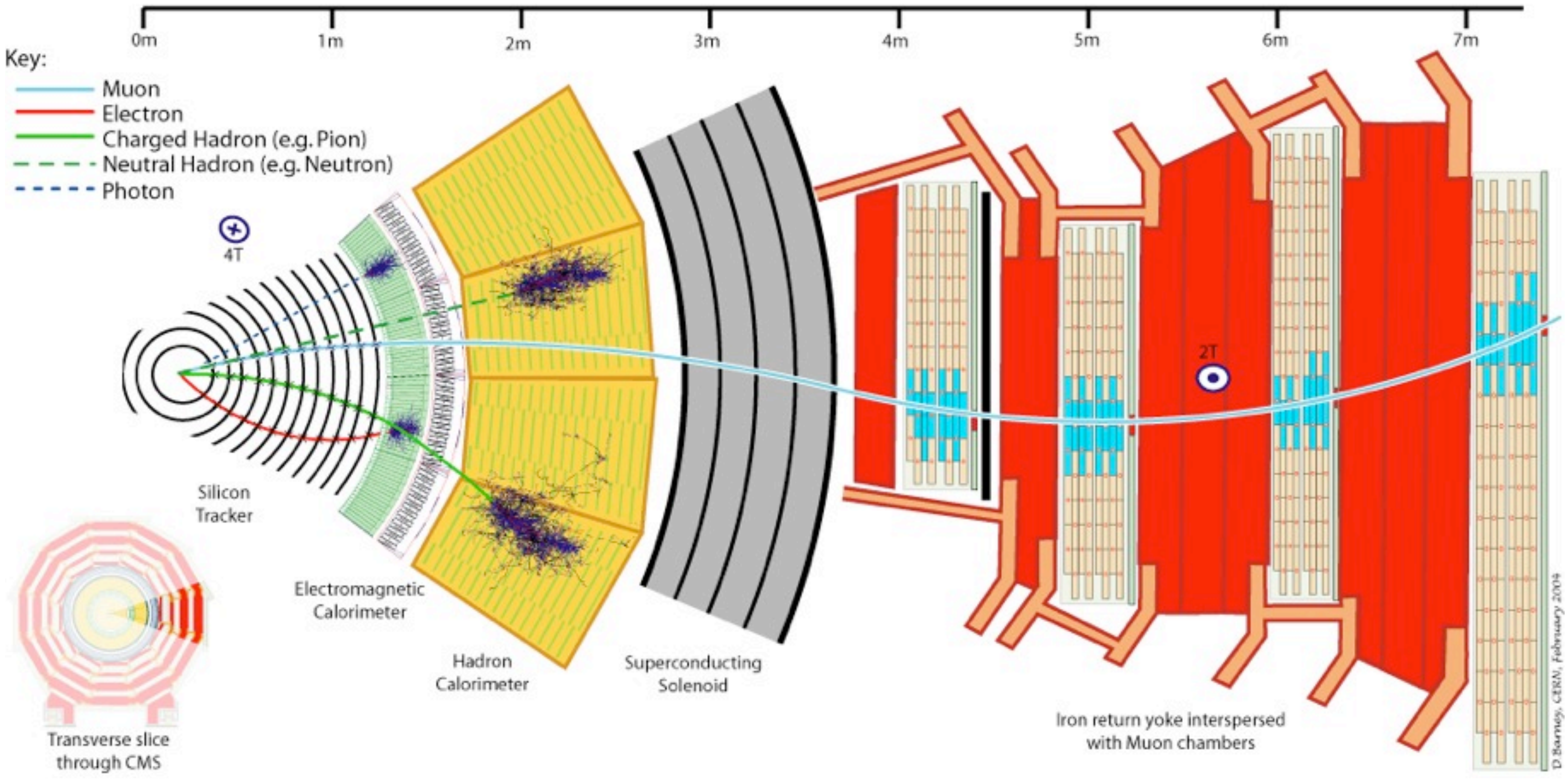


PbWO4

HCAL

Brass-scintillator

CMS


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004