Detectors in Particle Astrophysics

Fermi Summer School 2012

Nepomuk Otte

School of Physics &
Center for Relativistic Astrophysics
Georgia Institute of Technology

Plan

- Why a lecture on detector physics?
- A particle physics experiment: requirements
- Interaction of ionizing radiation with matter
- Detector Technologies
  - Scintillators
  - Photon detectors
  - Semiconductor detectors

Why you should know about Detector Physics!

Because this is how you understand the instrument

Helps in several aspects:

Understanding the physical limits of the experiments

Development of new analysis methods

Making non standard measurements

....

You can design a new experiment

This lecture can only serve as a starting point
If you want to learn more

Try the reviews published by the particle data group:
http://pdg.lbl.gov/

Or any other good book about detectors in high energy physics

Radiation Detection and Measurement by Knoll
Particle Detectors by Claus Grupen & Boris Schwartz
Detectors for Particle Radiation by Konrad Kleinknecht

Particle Detectors: Requirements

What you want to know:

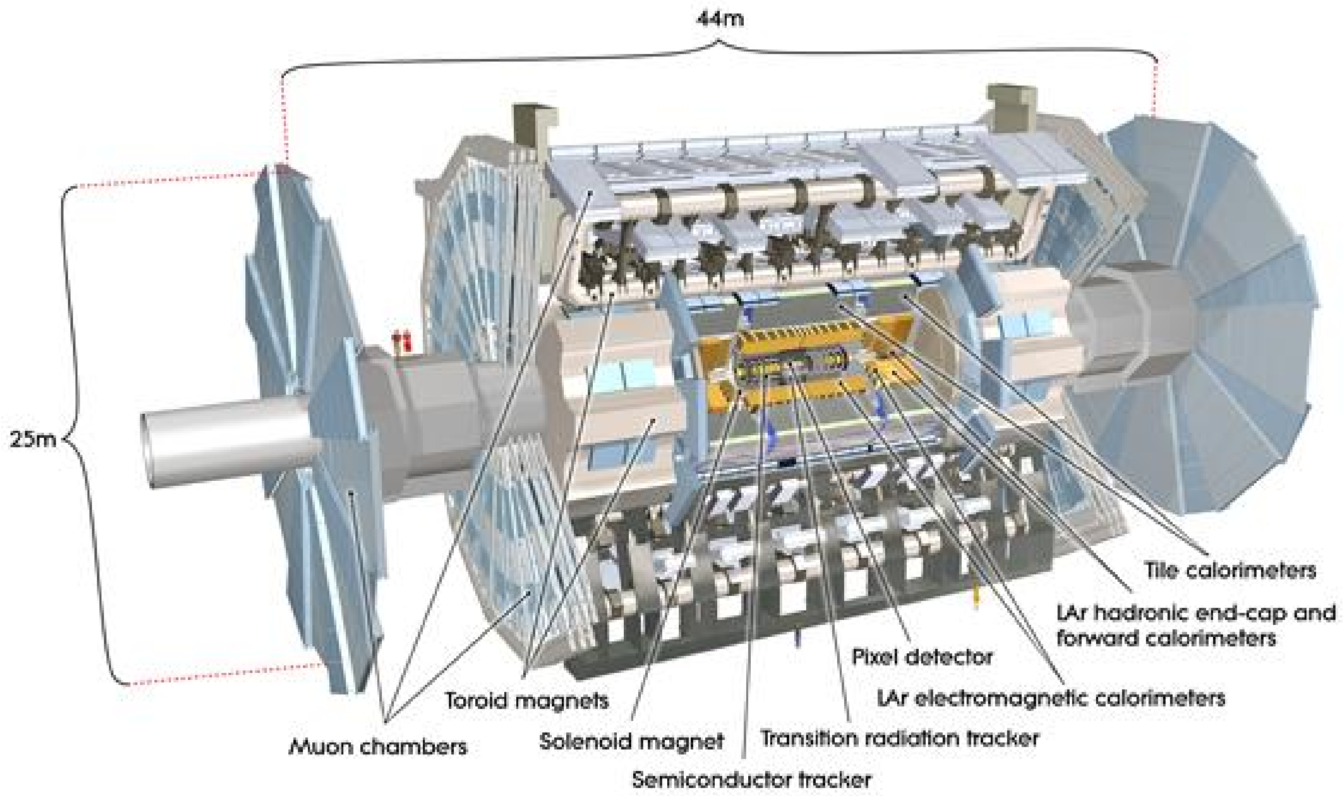
- Particle detection
- Momentum / energy measurement
- Particle identification
- Arrival direction
- Measurements of particle decay length
- ...

To extract this information

You need to know

1. How particles “interact” in matter
2. How materials “respond”
3. What technologies exist to “read out” detector medium

Things can become pretty complex

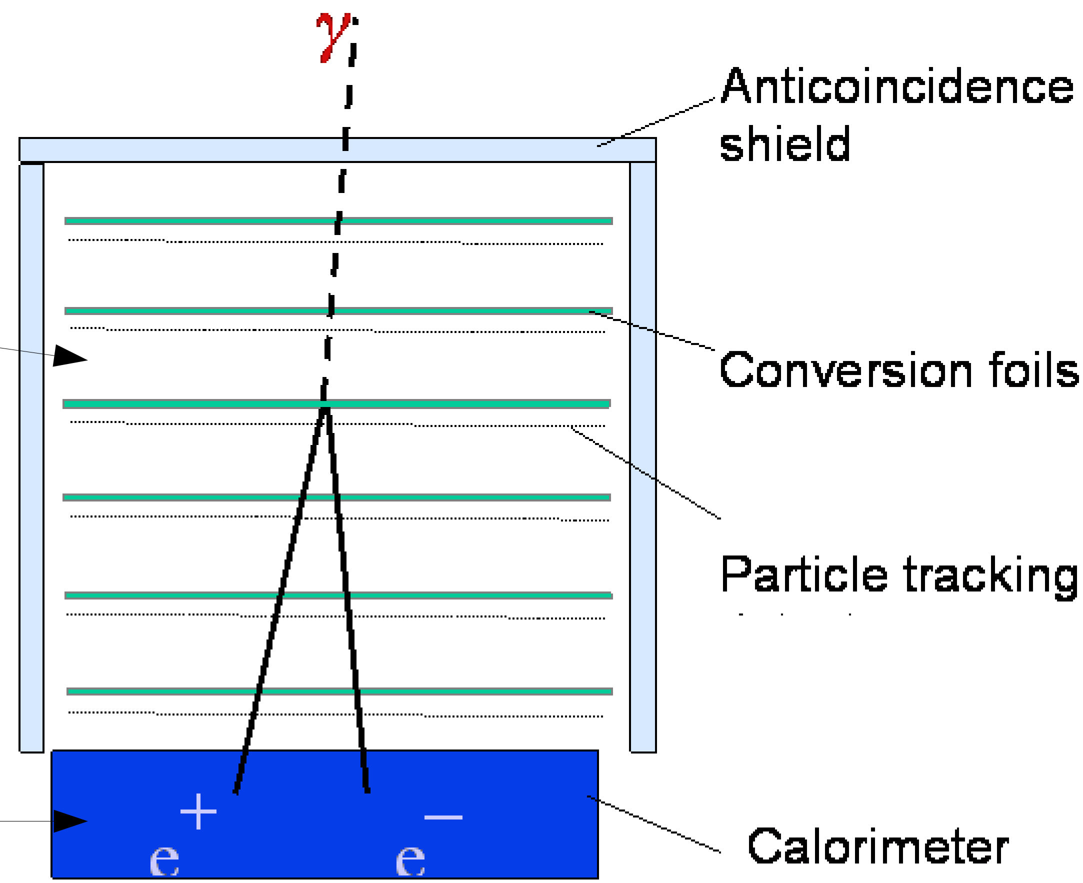


Most often a common Principle

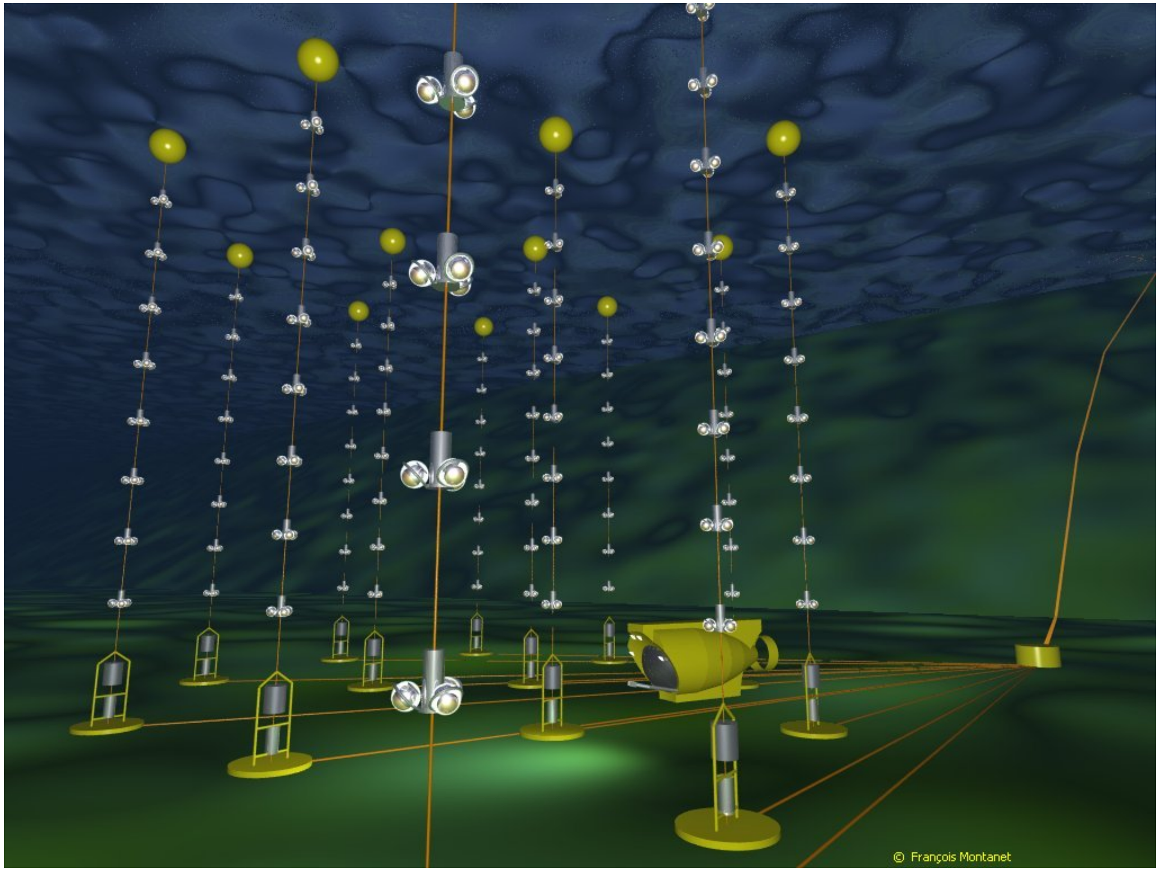
Tracker

+

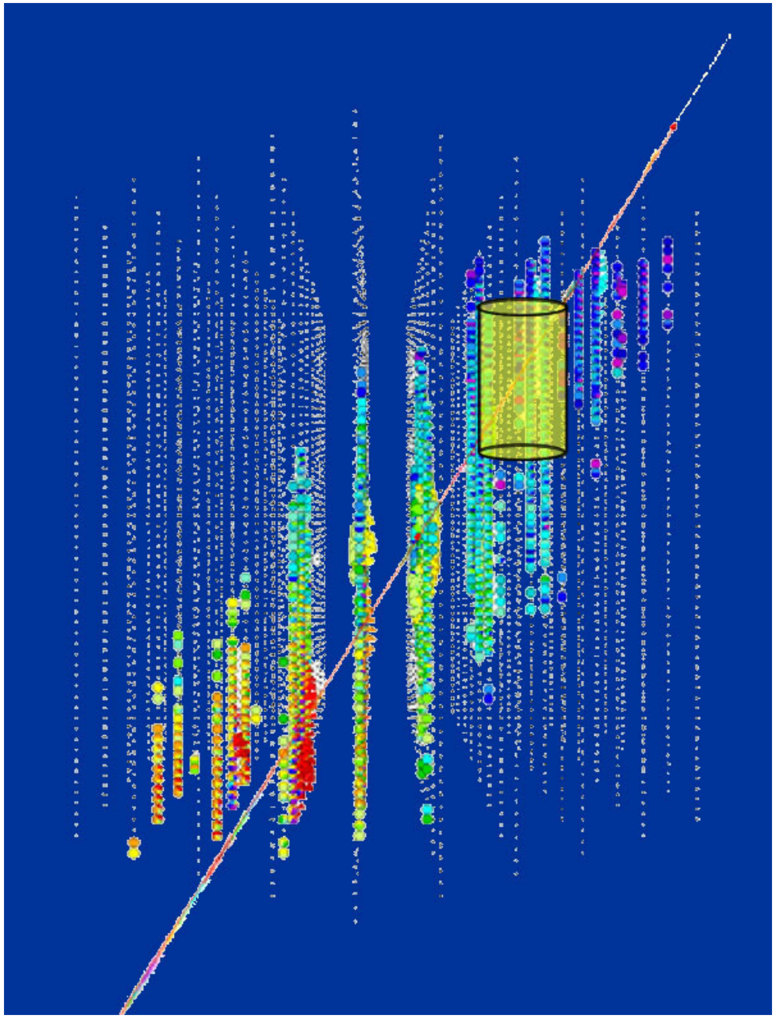
Calorimeter



Neutrino Astrophysics



Antares

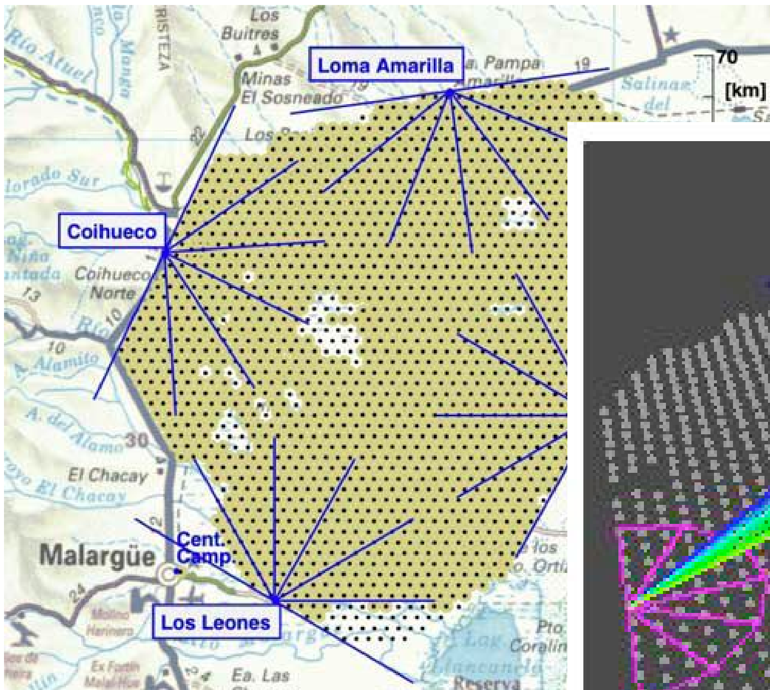


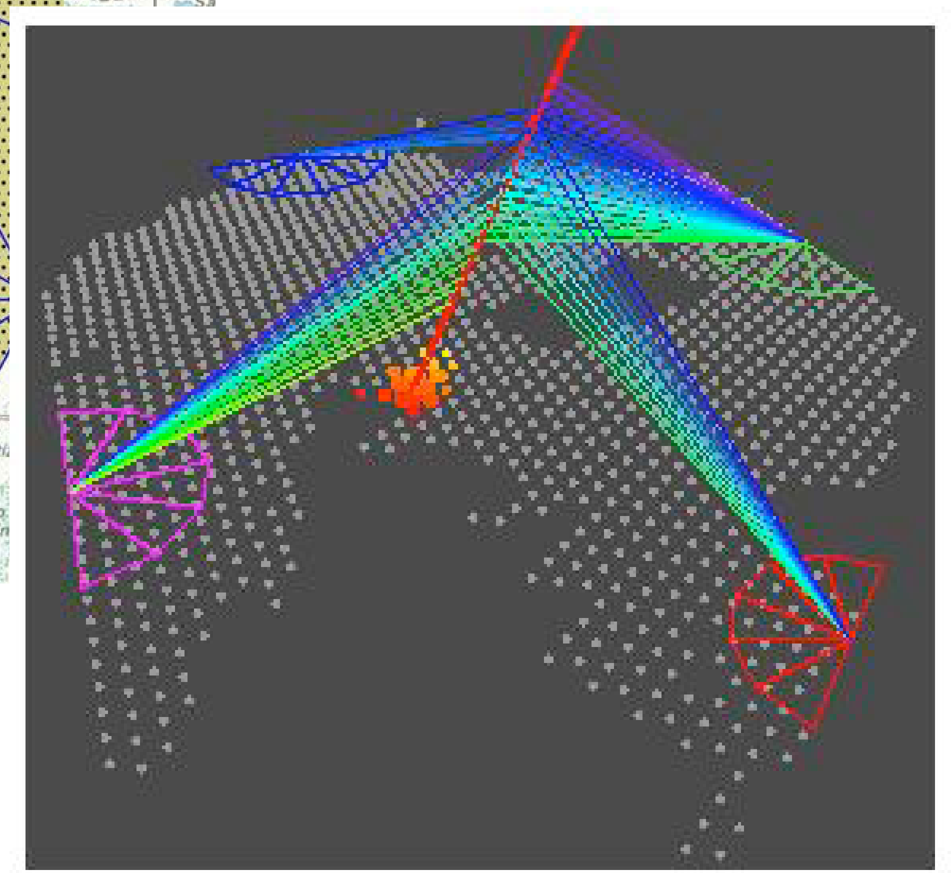
Ice Cube

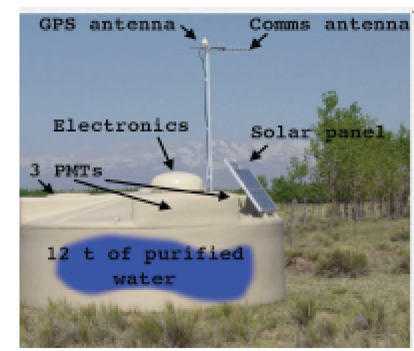
Tracker and Calorimeter in one

Pierre Auger Observatory

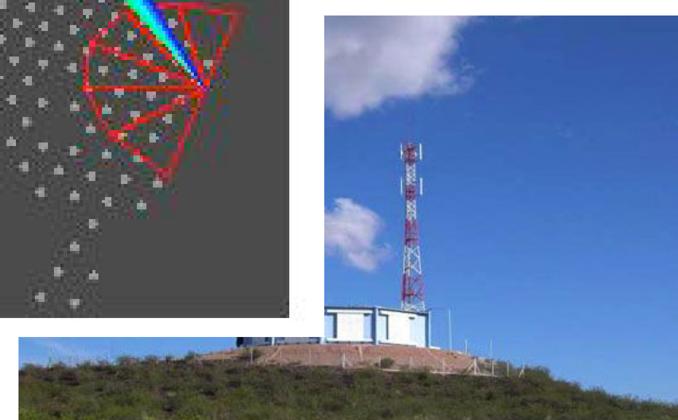
Detection of cosmic rays above 10^{16} eV







; coming to ground



Tracker and Calorimeter in one

24 telescopes in total

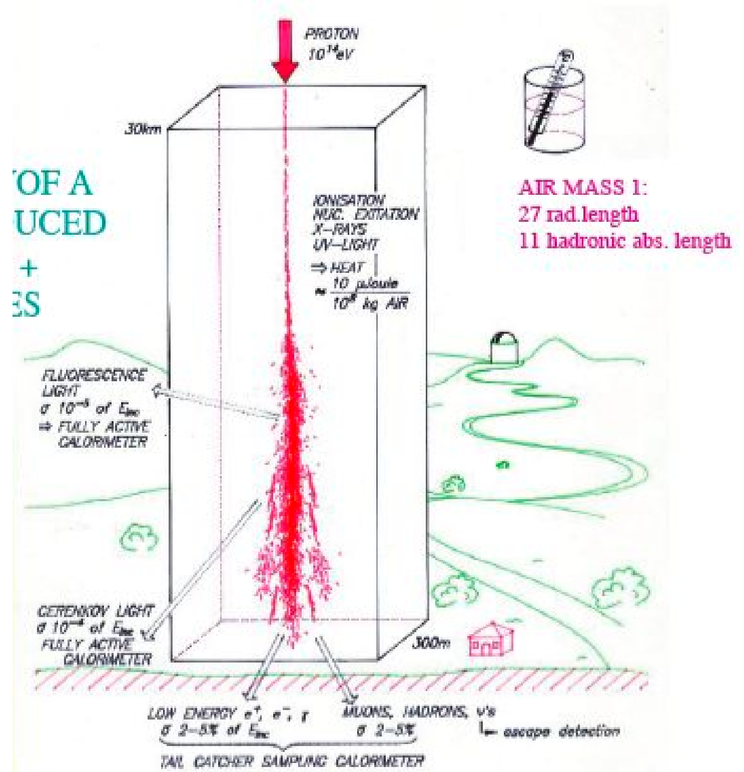
Air Showers

Use measured air shower characteristics for:

- **calorimetry**
- **particle ID**
- **tracking**

Readout:

- Fluorescence light
- Cherenkov light
- Particles
- Radio



E. Lorenz

Not like in a laboratory

Remote places

Weather

Inhomogenous detector medium

Background (light from the sky)

Interaction of ionizing radiation with matter

Heavy charged particles (everything but electrons)

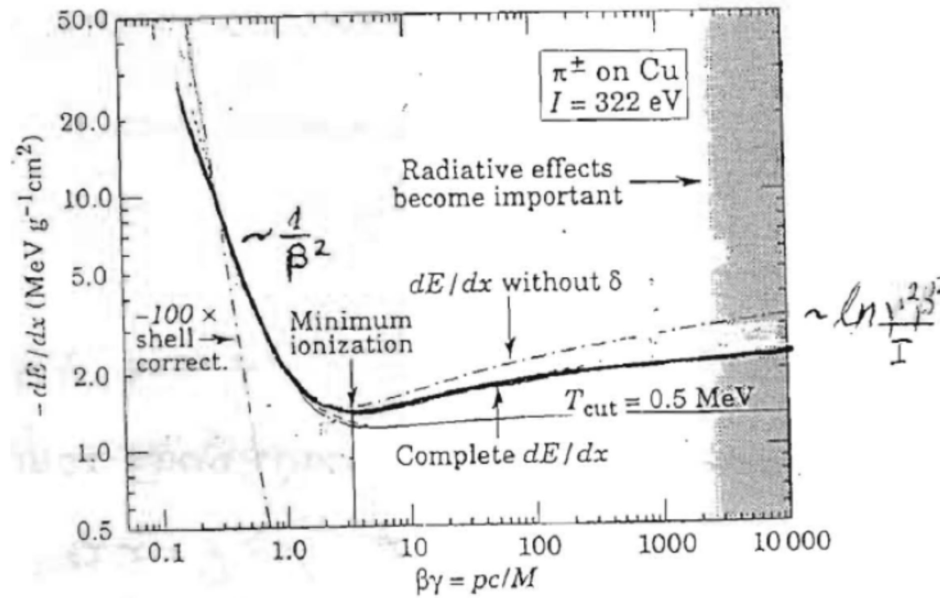
Electrons/positrons

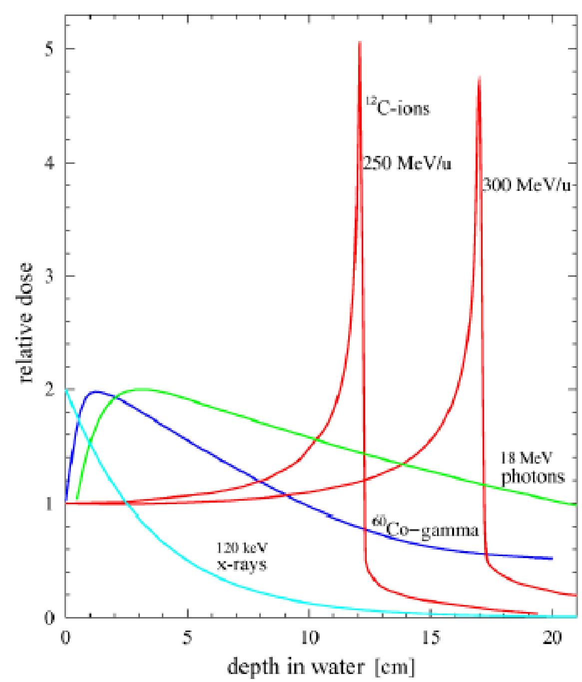
Photons

Charged particles ≠ electrons

Energy Loss of heavy ($M \gg m_e$) charged Particles in Matter

- Energy loss described by Bethe-Bloch formula
- Ionisation through inelastic scattering & atomic excitation
- Global minimum in dE/dX @ **βγ~3.5** -> Minimum Ionizing Particle (MIP)
- dE/dx at minimum ~ **2 MeV cm² / g** (multiply with density and thickness of material to get total energy loss)
- dE/dx **~ Z** with Z=atomic number of absorber
- dE/dx **~z²** with z=charge of incident particle
- Hadronic interactions come in addition (needed for shower development)





What would you chose?

High density and **high Z?**
or
Low density and **low Z?**

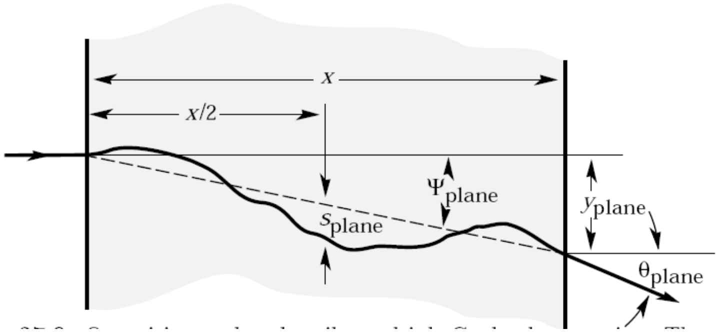
Small Angle Scattering (also for electrons)

- single scattering for very thin absorbers:

Rutherford-Scattering: $\frac{d\sigma}{d\Omega} \sim \frac{1}{\sin^4 \frac{\theta}{2}}$

- multiple scattering: N < 20

Difficult to describe



- multiple scattering N>20

Statistical treatment: Molière-theory

$$\left[\langle \Theta^2(x) \rangle\right]^{1/2} = \frac{13.6MeV}{\beta \cdot p \cdot c} \cdot z \sqrt{\frac{x}{X_0}} \cdot \left(1 + 0.038 \ln \frac{x}{X_0}\right)$$

X_0 = radiation length = material constant $\sim \frac{1}{Z^2}$

Central 98% are normal distributed
Limit for resolving momentum, vertex, and arrival direction

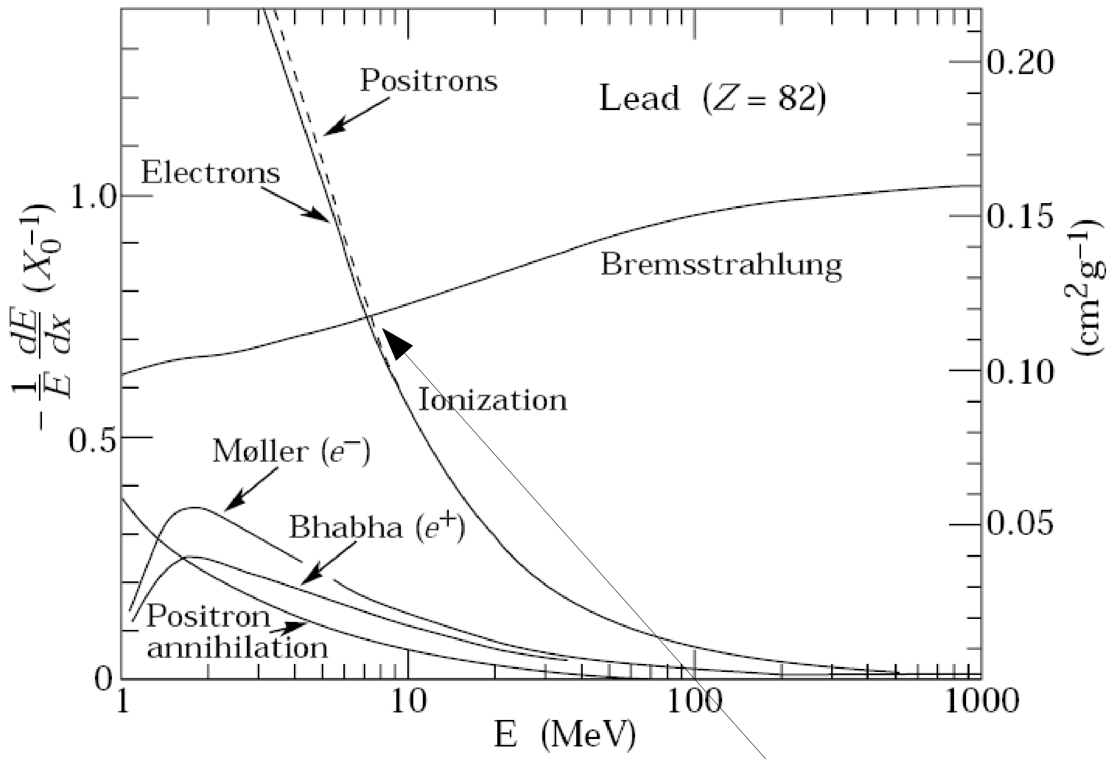
Electrons

Energy Loss of Electrons

Modified Bethe-Bloch:

Scattering of same type of particle
masses are the same

In addition to ionisation
Bremsstrahlung



$$\frac{dE}{dX} = \left.\frac{dE}{dX}\right|_{\mathrm{Ion}} + \left.\frac{dE}{dX}\right|_{\mathrm{Brems}}$$

Critical energy: $dE/dx_{\mathrm{Ion}} = dE/dx_{\mathrm{Brems}}$

E_C=560MeV/Z

Energy Loss due to Bremsstrahlung

Probability $\sim \dfrac{1}{m_e^2}\dfrac{1}{E_\gamma}$

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} \cdot r_e^2 \cdot E \, \ln \frac{183}{Z^{1/3}} = \frac{E}{X_0}$$

Radiation length $X_0 = \dfrac{716.4 \cdot A}{Z(Z+1)\ln(287/\sqrt{Z})}$ [g/cm²]

Energy loss by Bremsstrahlung: $\sim Z^2$

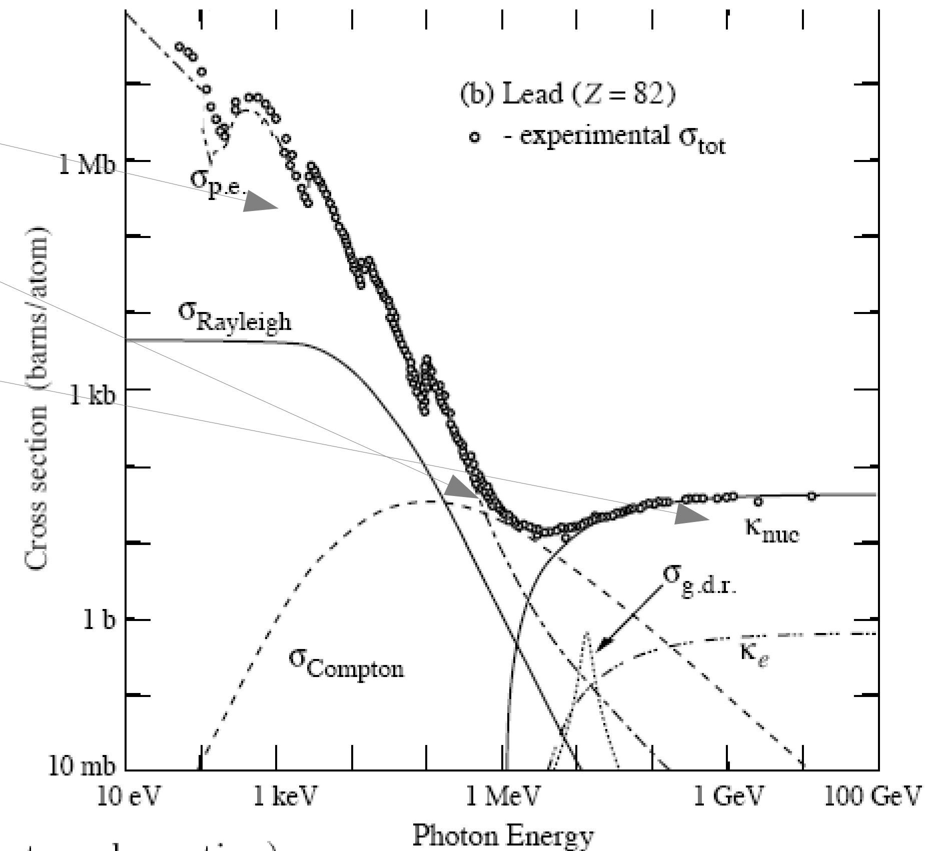
$\sim N_A/A \,\hat{=}$ Nuclear density

Exponential energy loss $-\dfrac{dE}{dx} = \dfrac{E}{X_0} \rightarrow E(X) = E_0 \exp \dfrac{-x}{X_0}$

Photons

Interaction of Gamma-Rays with Matter

- Photoelectric effect
- Compton scattering
- Pair production



In general absorption:
-> Attenuation of photon intensity

$$I(x) = I_0 \exp(-\mu x)$$

µ = Attenuation coefficient

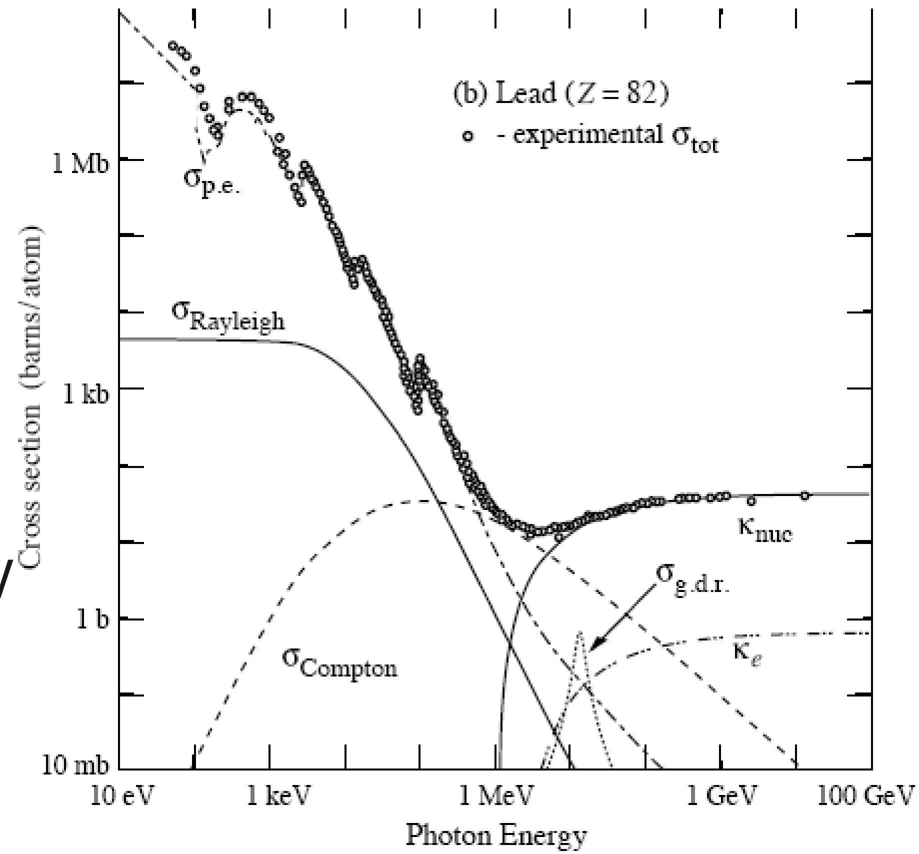
$\sigma_{p.e.}$ = Atomic photoelectric effect (electron ejection, photon absorption)
$\sigma_{Rayleigh}$ = Rayleigh (coherent) scattering–atom neither ionized nor excited
$\sigma_{Compton}$ = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{g.d.r.}$ = Photonuclear interactions, most notably the Giant Dipole Resonance [46]. In these interactions, the target nucleus is broken up.

Interaction of Photons in Matter

- Attenuation of intensity

  $I(x) = I_0 e^{-\mu x}$ μ = attenuation coefficient

- Photoeffect
  - Photon energy > binding energy of electron
  - $\mu \sim Z^5/E_\gamma^{7/2}$
- Compton scattering
  - Relevant between ~100 keV and ~ few MeV
  - $\mu \sim Z/E_\gamma$
- Pair creation
  - Relevant above kinematically allowed threshold: $E_\gamma > 2m_e$
  - $\mu \sim Z^2/E_\gamma \approx 9/(7X_0)$



Large Z helps

And...

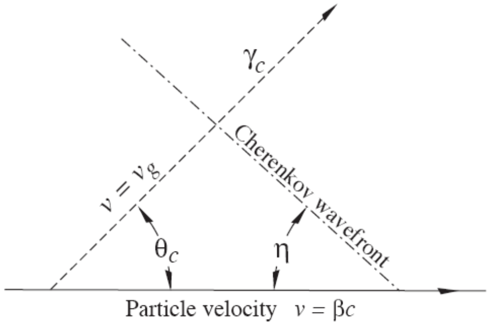
Cherenkov Effect

- Not important for energy loss but very important mechanism in most astroparticle experiments

$$\cos\theta_c = (1/n\beta)$$

$$\text{or} \quad \tan\theta_c = \sqrt{\beta^2 n^2 - 1}$$

$$\approx \sqrt{2(1 - 1/n\beta)} \quad \text{for small } \theta_c, \ e.g. \text{ in gases.}$$



$$\frac{d^2N}{dE\,dx} = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c = \frac{\alpha^2 z^2}{r_e\, m_e c^2}\left(1 - \frac{1}{\beta^2 n^2(E)}\right)$$

$$\approx 370 \sin^2\theta_c(E) \ \mathrm{eV^{-1}cm^{-1}} \qquad (z = 1)\ ,$$

$$\frac{d^2N}{dx\,d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

Ionization → free electrons?

Ionization yield

- E_I = Ionization energy
- $W = \langle E_{\text{e-ion pair}} \rangle$
- $W > E_I$
- N_p = primary generated e^-/Ion pairs (per cm)
- $N_T = \Delta E/W > N_p$ = total ionization yield (per cm)

Want that large for energy measurements

Gas	Density, mg cm^{-3}	E_x eV	E_I eV	W_I eV	$dE/dx\|_{\min}$ keV cm^{-1}	N_P cm^{-1}	N_T cm^{-1}
Ne	0.839	16.7	21.6	30	1.45	13	50
Ar	1.66	11.6	15.7	25	2.53	25	106
Xe	5.495	8.4	12.1	22	6.87	41	312
CH_4	0.667	8.8	12.6	30	1.61	37	54
C_2H_6	1.26	8.2	11.5	26	2.91	48	112
iC_4H_{10}	2.49	6.5	10.6	26	5.67	90	220
CO_2	1.84	7.0	13.8	34	3.35	35	100
CF_4	3.78	10.0	16.0	54	6.38	63	120

For MIPs

A number to remember: Silicon W~3.6 eV

Why large N_T? -->Example: Energy measurements

N = Number of pairs generated after energy loss E

$\Rightarrow$ E~ N and ΔE ~ sqrt(N)

Energy loss is a statistical process

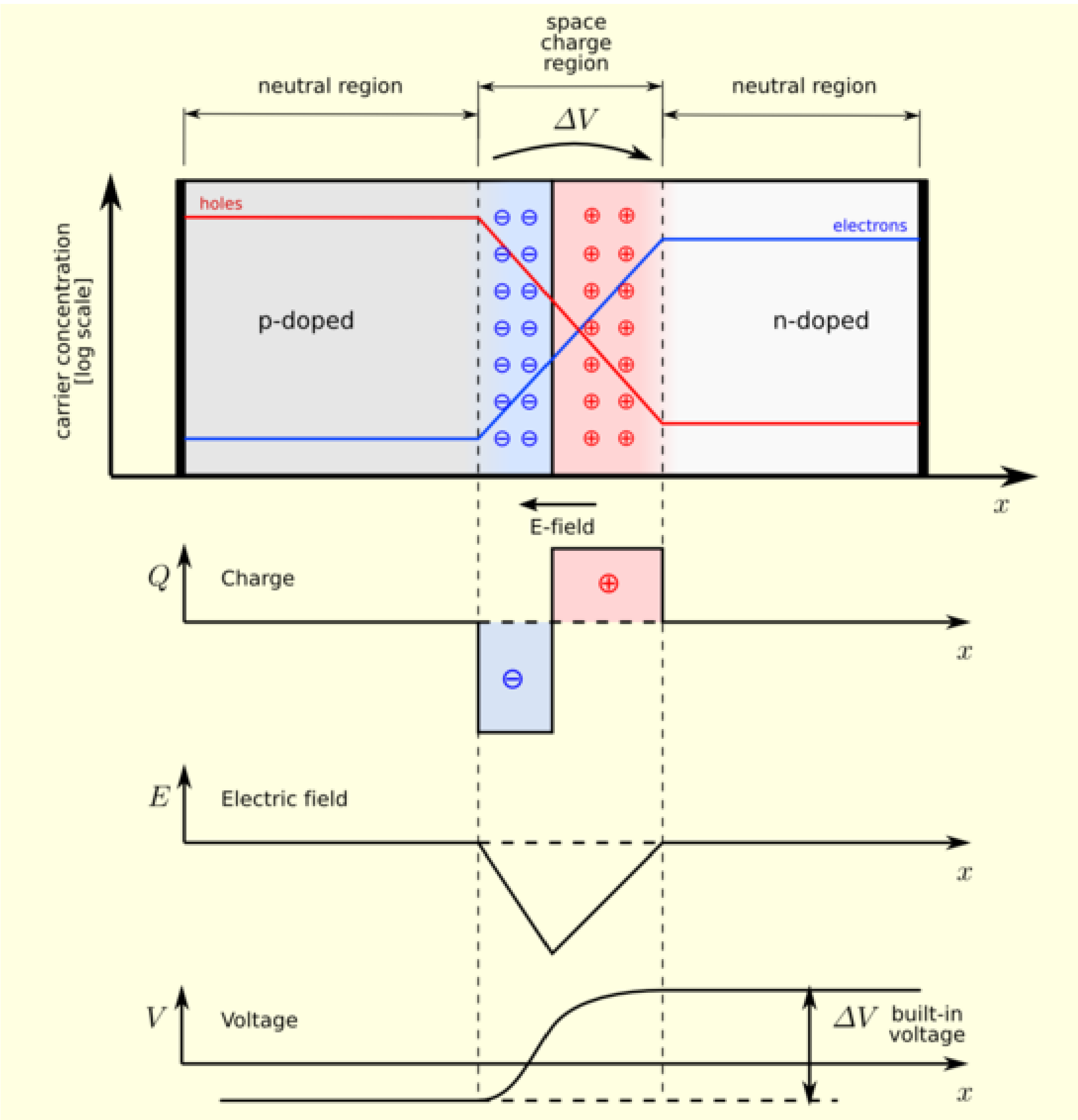
-> energy resolution ΔE/E ~ sqrt(N)/N ~ 1/sqrt(N)

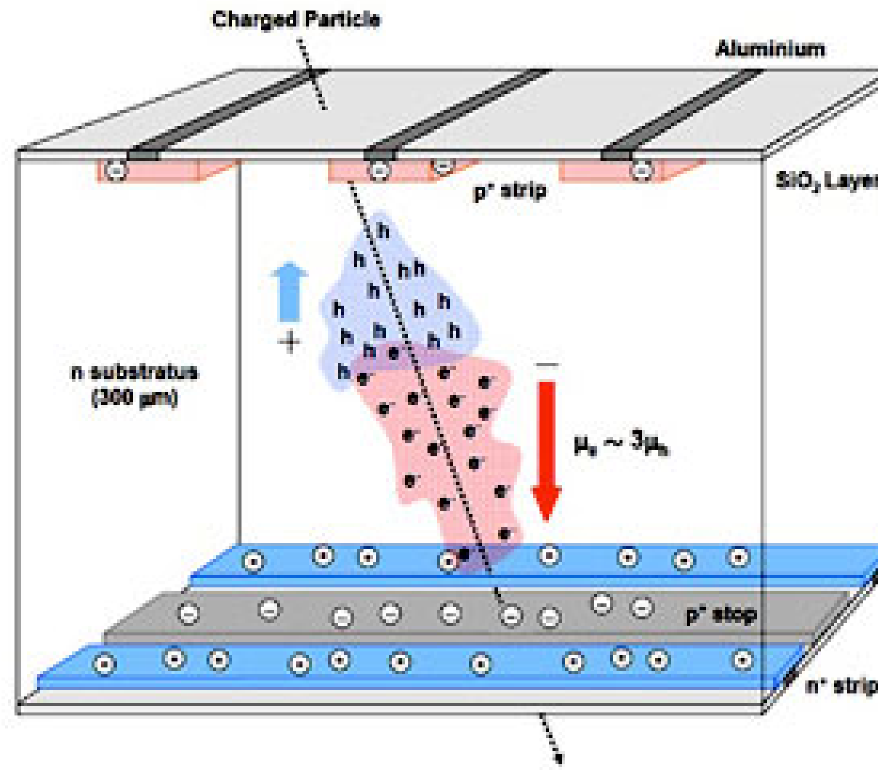
Note that energy resolution also depends on the energy of the primary

→ ΔE/E ~ 1/sqrt(N) ~ 1/sqrt(E)

Under the condition that all the energy is deposited in the detector -> energy resolution improves with increasing particle energy

Semiconductor Detectors





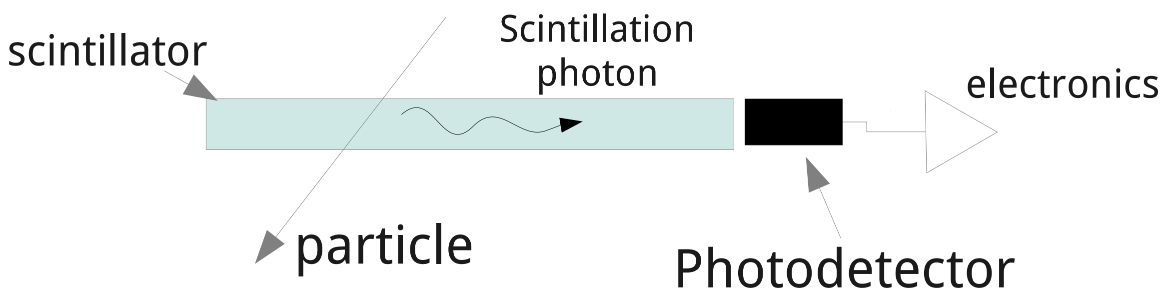
How many electron/hole pairs are produced by a MIP going through 300 um thick silicon?

Scintillators

- Organic scintillators
- Inorganic scintillators
- Scintillating gases

Some of the ionized electrons can produce light in some materials

If material is transparent --> light can be detected with photon detector



Scintillation mechanisms are complicated and not fully understood
-> several contributions with different time constants.

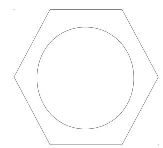
What makes a good Scintillator

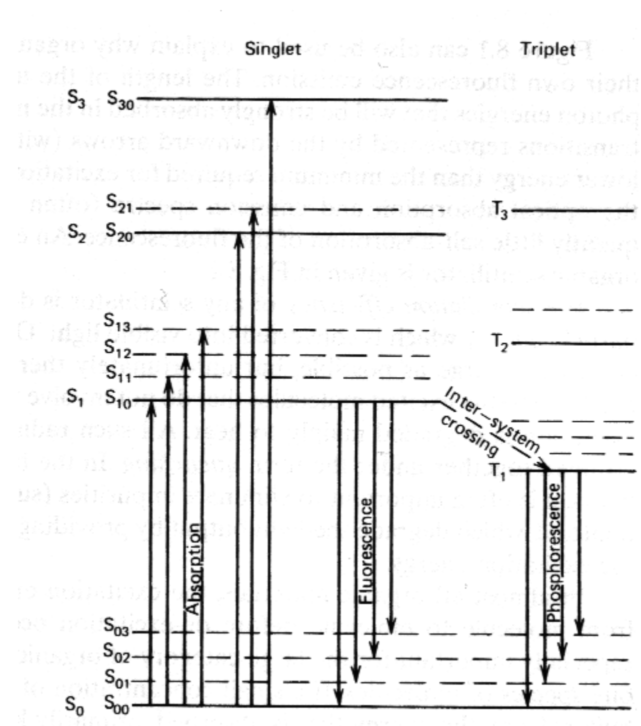
- High conversion efficiency of deposited energy into photons
- Light yield should be proportional to deposited energy over as wide a range as possible
- Medium should be transparent to the wavelength of its own emission
- Fast decay time of the induced luminescence
- Good optical quality and available in large quantities
- Index of refraction ~1.5 to allow good coupling to photo detector (glass surface)

Difficult to achieve everything simultaneous

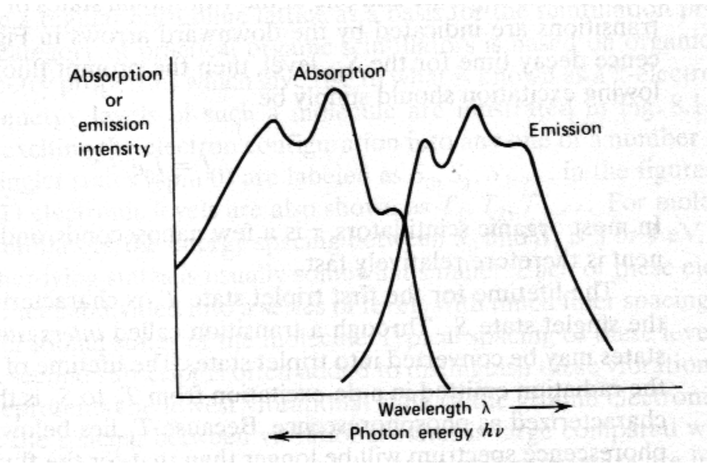
Organic scintillators (plastic)

- Organic (aromatic) molecules
- π-electron structure
- Large band gap between S_0 and S_1 ~3-4 eV
  - Molecules normally in S0 state
- Excitation into multiple possible configuration
  - Rapid deexcitation (radiationless) into S_1 state
- Fluorescence $S_{10} \rightarrow S_0$
  - Time constant τ
  - Intensity $I(t)=I_0 e^{-t/\tau}$
  - τ~ns
- Phosphorescence T_1 to S_0
  - τ~ms
  - Excitation back into S1 possible





Transmission and Absorption



is used as wavelength shifter

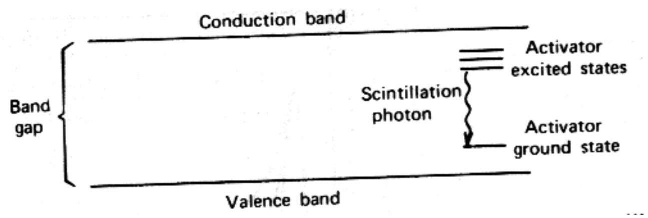
e.g. matching to spectral response of photo detector

Typical characteristics

Density	1.03 g/cm^3
Index of refraction	1.58
X_0	44 cm
Light yield	100 eV/γ
Attenuation length	1-2 m
decay time	2-3 ns
λ_{max}	~400nm

Inorganic scintillators

- **Much higher density than organic scintillators ~3-4 g/cm^3**
  - High stopping power
  - High conversion efficiency for electrons/photons
  - **Good for energy measurements (calorimetry)**
- Bandgap of 5-10 eV
- Some crystals are intrinsic scintillators others require dopant (Thallium or Cerium)
- Need activator in the band gap
  - Need several excited states in the activator
- Exitons (bound electron/hole pairs) are created
  - Large lifetime
- Exitons de-excite via activators
- **Decay time constant ~10^{-7} s**
- Much less quenching than in organic scintillators



Characteristics of typical inorganic scintillators

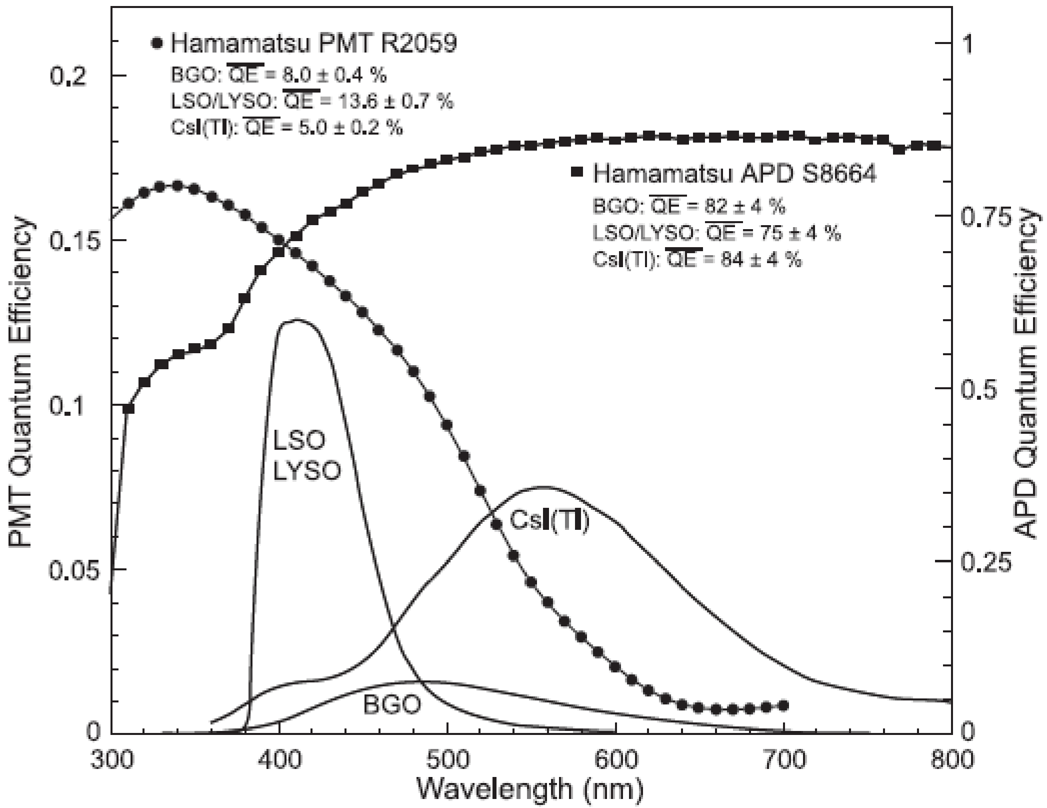
Table 28.4: Properties of several inorganic crystal scintillators. Most of the notation is defined in Sec. 6 of this *Review*.

Parameter:	ρ	MP	X_0^*	R_M^*	dE/dx	λ_I^*	τ_{decay}	λ_{max}	$n^\natural$	Relative output†	Hygro-scopic?	$d(\mathrm{LY})/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	230	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.6	30.7	630^s	300^s	1.50	36^s	no	-1.3^s
							0.9^f	220^f		3.4^f		$\sim 0^f$
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1300	560	1.79	165	slight	0.3
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	35^s	420^s	1.95	3.6^s	slight	−1.3
							6^f	310^f		1.1^f		
$PbWO_4$	8.3	1123	0.89	2.00	10.2	20.7	30^s	425^s	2.20	0.083^s	no	−2.7
							10^f	420^f		0.29^f		
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	420	1.82	83	no	−0.2
GSO(Ce)	6.71	1950	1.38	2.23	8.9	22.2	600^s	430	1.85	3^s	no	−0.1
							56^f			30^f		

40,000 ph/MeV

* Numerical values calculated using formulae in this review.
$^\natural$ Refractive index at the wavelength of the emission maximum.
† Relative light output measured for samples of 1.5 X_0 cube with a Tyvek paper wrapping and a full end face coupled to a photodetector. The quantum efficiencies of the photodetector is taken out.
‡ Variation of light yield with temperature evaluated at the room temperature.
f = fast component, s = slow component

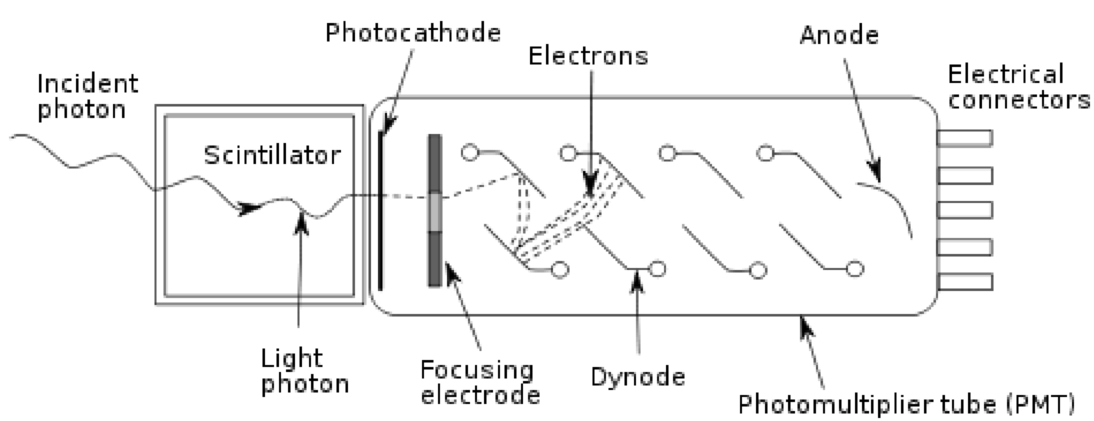
Emission spectra of a few scintillators



Response of photon detector and emission spectrum should match

Photomultipliers PMT

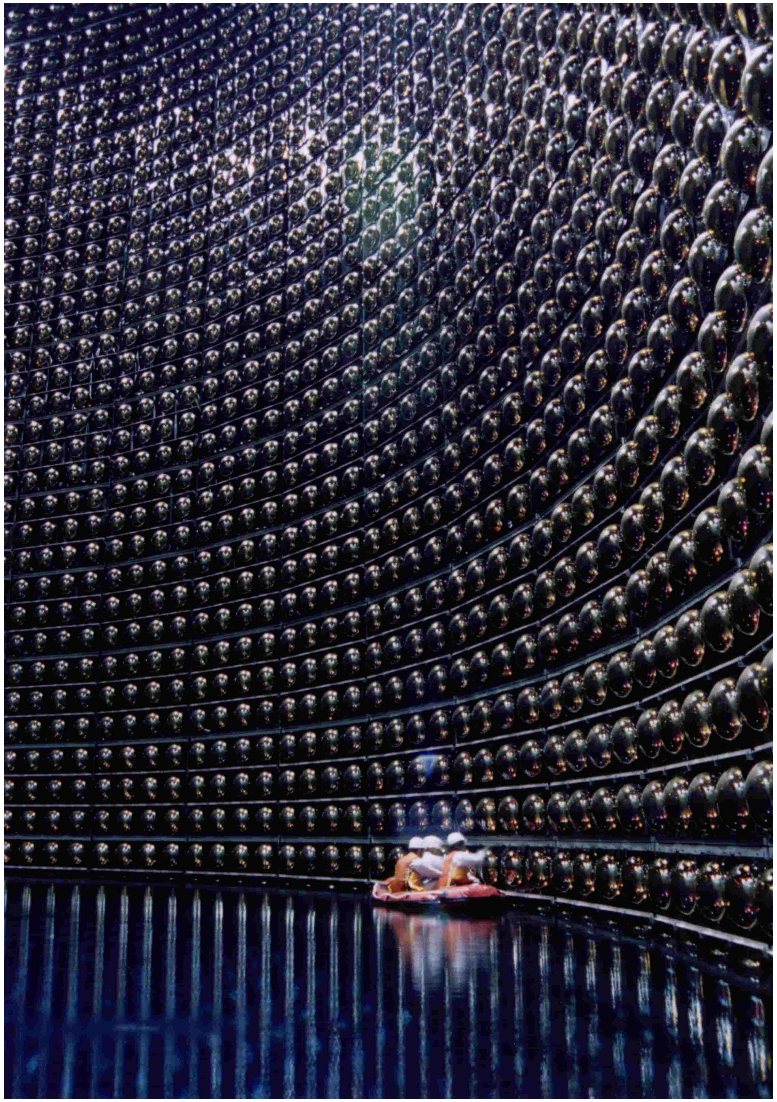
- Absorption of photon and emission of a photoelectron (Photoeffect)
  - 1. absorption of photon and energy transfer to one electron
  - 2. electron migrates to the surface
  - 3. escape of the electron from the surface
  - 4. multiplication of electron in dynode structure -> gains of several million possible



PMT handbook available for download

http://sales.hamamatsu.com/assets/applications/ETD/pmt_handbook/pmt_handbook_complete.pdf

The world biggest



Kamiokande

Photocathode

$$E_{kin} = h\nu - \phi$$

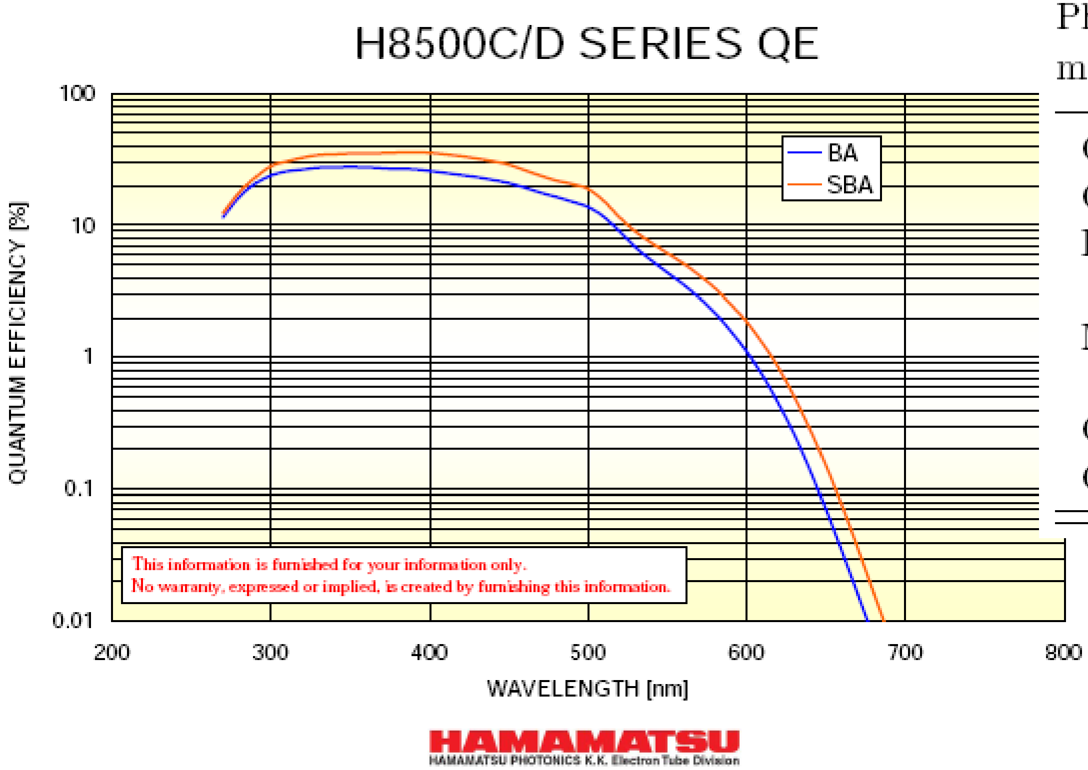
- Photoeffect
- Electron migration through cathode material
  - Minimize energy losses: electron must have enough kinetic energy to overcome work function φ
  - “escape depth” depth from which electrons make it to the surface
    - In metals a few nm
    - In semiconductors up to 25nm
    - Small compared to absorption length of visible light

Surface activation with Cs

Photocathode = Semiconductor + alkalimetals

Quantum Efficiency

$$QE = \frac{\text{photoelectrons}}{\text{photons at cathode}}$$

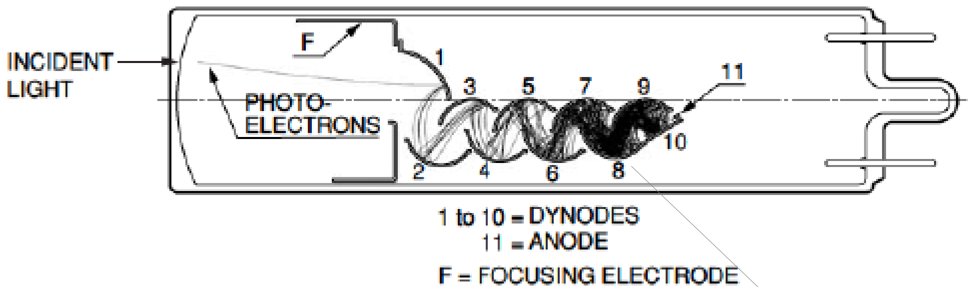


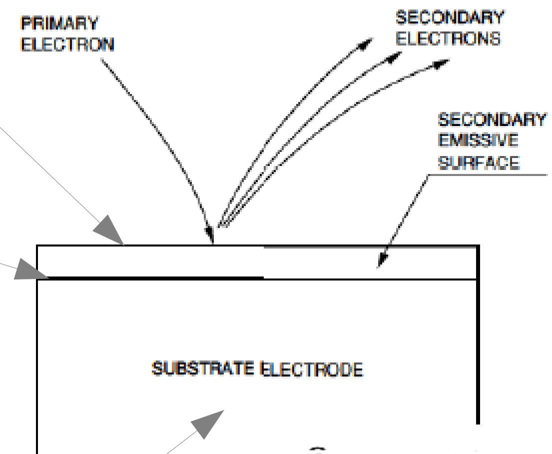
Photocathode material	λ (nm)	Window material	Peak ϵ_Q (λ/nm)
CsI	115–200	MgF_2	0.15 (135)
CsTe	115–240	MgF_2	0.18 (210)
Bi-alkali	300–650	Borosilicate	0.27 (390)
	160-650	Quartz	0.27 (390)
Multi-alkali	300–850	Borosilicate	0.20 (360)
	160-850	Quartz	0.23 (280)
GaAs(Cs)*	160–930	Quartz	0.23 (280)
GaAsP(Cs)	300-750	Borosilicate	0.42 (560)

Some cathodes now reach efficiencies of 35% or more. First PMT had an efficiency of 0.4%

Electron Multiplication

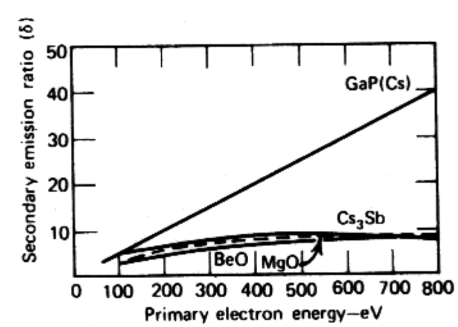
Electrons are accelerated
-> bombard dynodes
-> secondary electron emission
-> only a few of the electrons make it out of the dynode





Alkali antimode
Berylium oxide BeO
Magnesium oxide (MgO)
Gallium phosphide (GaP)
Gallium Arsenide phosphide (GaAsP)

Nickel, stainless steel, or copper-beryllium alloy



$$\delta = \frac{\text{number of electrons emitted}}{\text{primary incident electron}}$$

Typically 4-5