

# Astrofisica Nucleare e Subnucleare

## “GRB” Astrophysics

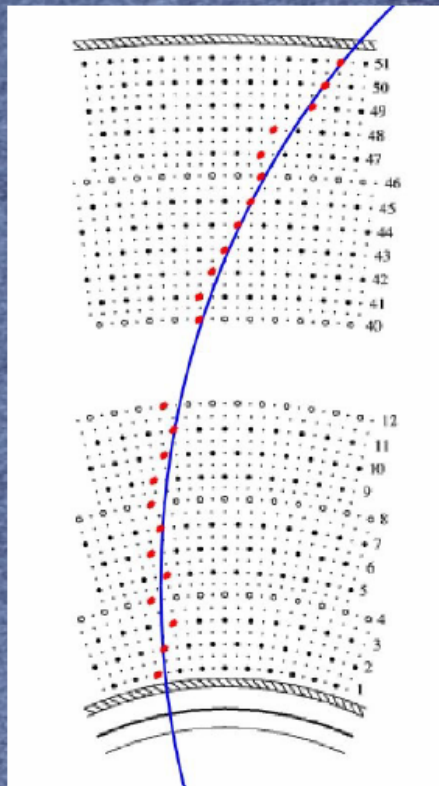
# Astrofisica Nucleare e Subnucleare

## Interazione Radiazione Materia



# Rivelazione delle particelle elementari

## Misura del momento e della carica elettrica delle particelle cariche (elettroni, muoni, adroni carichi)



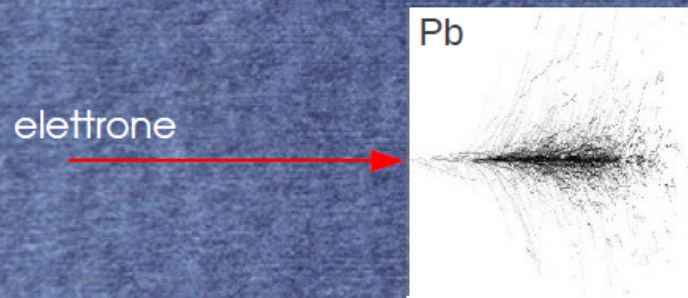
- ◆ Facciamo passare le particelle create nella collisione dentro un campo magnetico uniforme e ne ricostruiamo la traiettoria o "traccia":
- ◆ una serie di rivelatori disposti nello spazio attorno al punto della collisione ("tracciatori") indicano dove la particella carica è passata;
- ◆ cerchiamo l'arco di circonferenza che meglio approssimi i punti misurati e ne determiniamo il raggio;
- ◆ la carica della particella è data dal verso di curvatura della traiettoria, orario o antiorario.



# Rivelazione delle particelle elementari

## Misura dell'energia delle particelle (elettroni, fotoni, adroni carichi e neutri)

- ◆ Per misurare l'energia degli elettroni, dei fotoni e degli adroni carichi e neutri usiamo i "calorimetri":
  - ◆ le particelle vengono fatte passare attraverso una grossa quantità di materiale molto denso (ferro, tungsteno, piombo ...) dove dissipano tutta la loro energia e si fermano;



- ◆ intervallando il materiale dissipatore con materiale sensibile, l'energia della particella viene convertita in un segnale misurabile che è proporzionale all'energia.
- ◆ A differenza della misura del momento nei tracciatori, la misura dell'energia nei calorimetri rappresenta una "misura distruttiva" della particella.

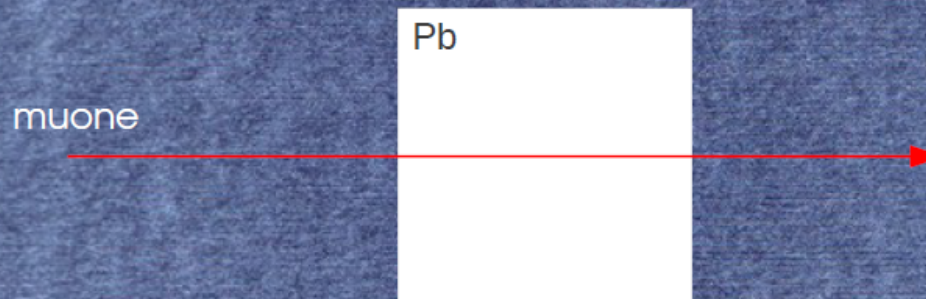


# Rivelazione delle particelle elementari

## Un caso un po' particolare: i muoni

### ♦ I muoni

- ♦ perdono pochissima energia quando passano attraverso anche la materia più densa, sono particelle altamente "penetranti";



- ♦ rilasciano solo una frazione piccolissima della loro energia nei calorimetri, però sono particelle cariche e producono una traccia nel tracciatore, da cui si misura il momento;
- ♦ questa loro peculiarità li rende facilmente identificabili.



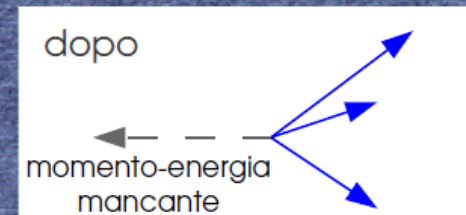
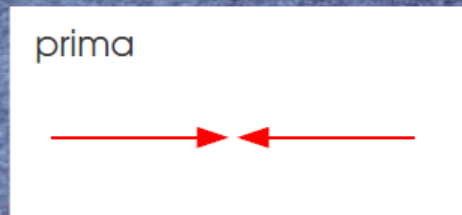
# Rivelazione delle particelle elementari

## Un caso ancora più particolare: i neutrini

### ♦ I neutrini

- ♦ sono particelle neutre, che interagiscono pochissimo con la materia che attraversano;
- ♦ non vengono rivelati direttamente: non lasciano tracce nel tracciatore né energia nei calorimetri;
- ♦ la loro presenza è però indicata indirettamente dal **momento ed energia mancanti**:

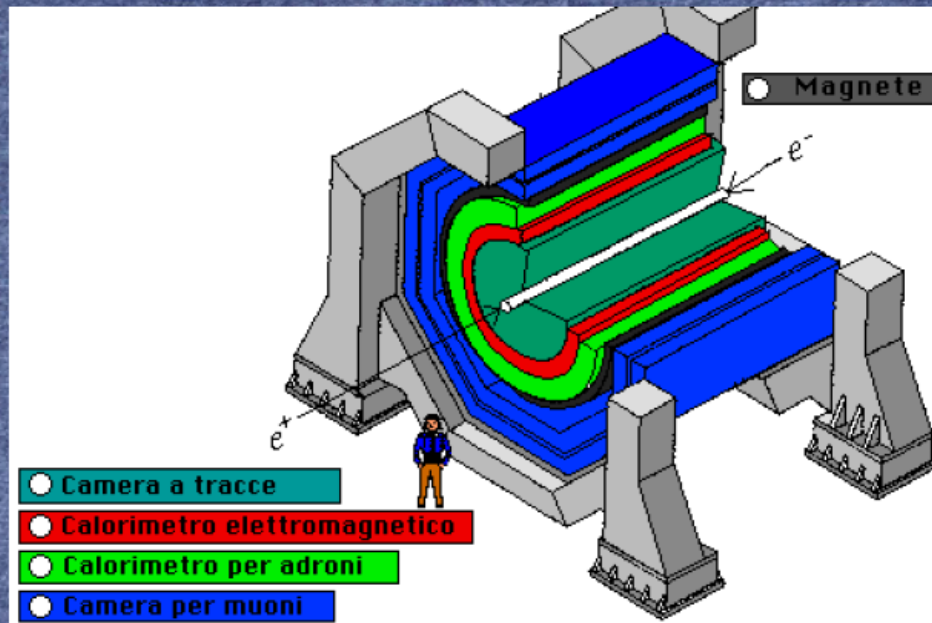
momento ed energia totali si conservano tra prima e dopo la collisione, una mancanza di momento o energia indicano la presenza di particelle non rivelate.



# Rivelazione delle particelle elementari

## Struttura tipica dei rivelatori

- ◆ I rivelatori di particelle sono costituiti da un insieme di sotto-rivelatori diversi.
- ◆ Le tecniche di rivelazione descritte precedentemente dettano una struttura a strati cilindrici concentrici dei rivelatori.
- ◆ Procedendo dall'asse del cilindro verso l'esterno tipicamente abbiamo:
  - ◆ un tracciatore immerso in un campo magnetico uniforme;
  - ◆ un "calorimetro elettromagnetico" per misurare l'energia degli elettroni e dei fotoni;
  - ◆ un "calorimetro adronico" per misurare l'energia degli adroni;
  - ◆ "rivelatori di posizione" per rivelare il passaggio dei muoni.



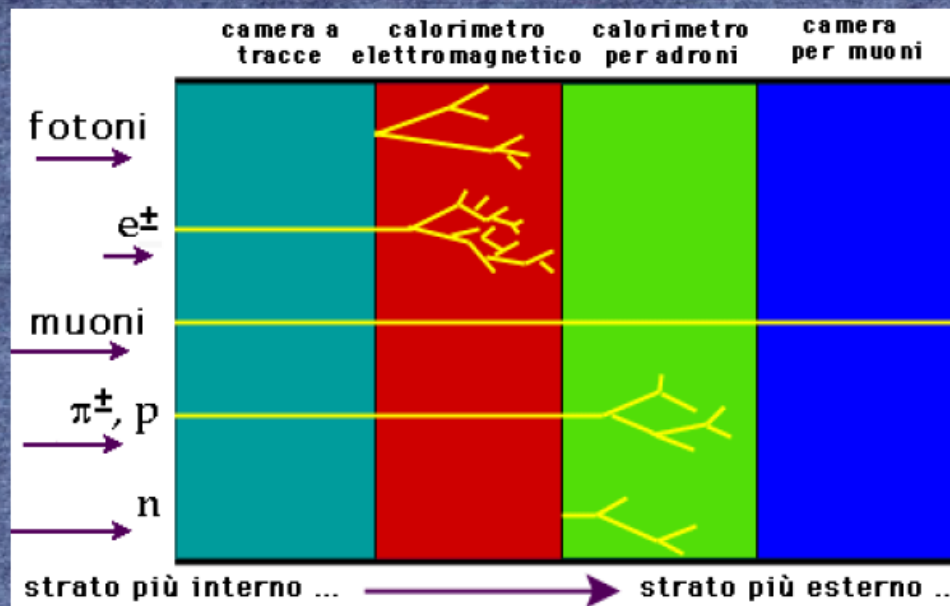


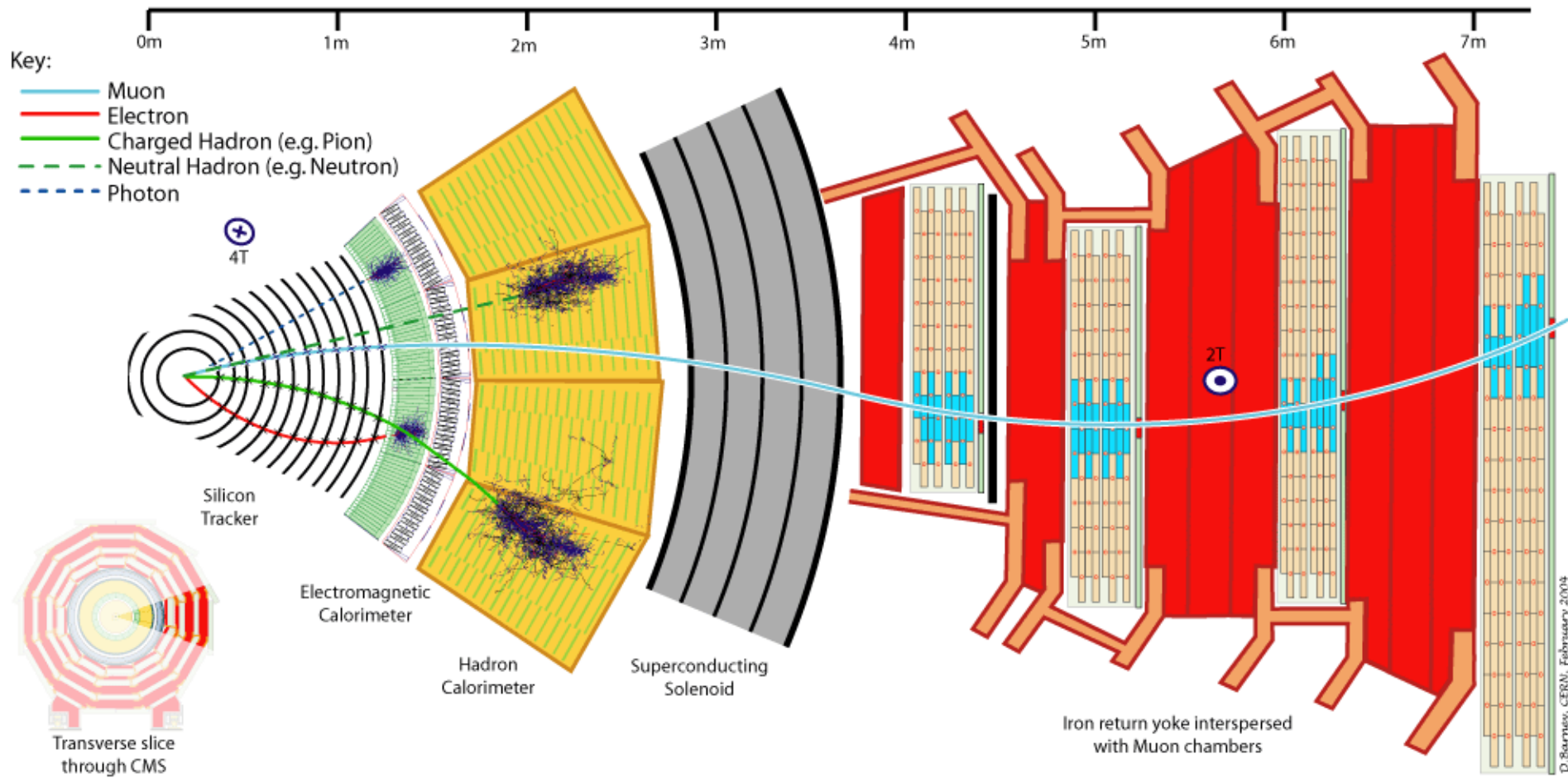
# Come?

## Identificazione delle particelle

◆ Quindi, disponendo i rivelatori in un certo ordine e combinandone le informazioni, è possibile identificare diversi tipi di particelle:

- ◆ **fotone**: energia nel calorimetro elettromagnetico;
- ◆ **elettrone**: traccia + energia nel calorimetro elettromagnetico;
- ◆ **muone**: traccia + segnale nei rivelatori di muoni;
- ◆ **adrone carico**: traccia + energia nel calorimetro adronico;
- ◆ **adrone neutro**: energia nel calorimetro adronico.





# Particle Detectors

Summer Student Lectures 2010  
Werner Riegler, CERN, [werner.riegler@cern.ch](mailto:werner.riegler@cern.ch)

- ◆ **History of Instrumentation ↔ History of Particle Physics**
- ◆ **The 'Real' World of Particles**
- ◆ **Interaction of Particles with Matter**
- ◆ **Tracking Detectors, Calorimeters, Particle Identification**
- ◆ **Detector Systems**

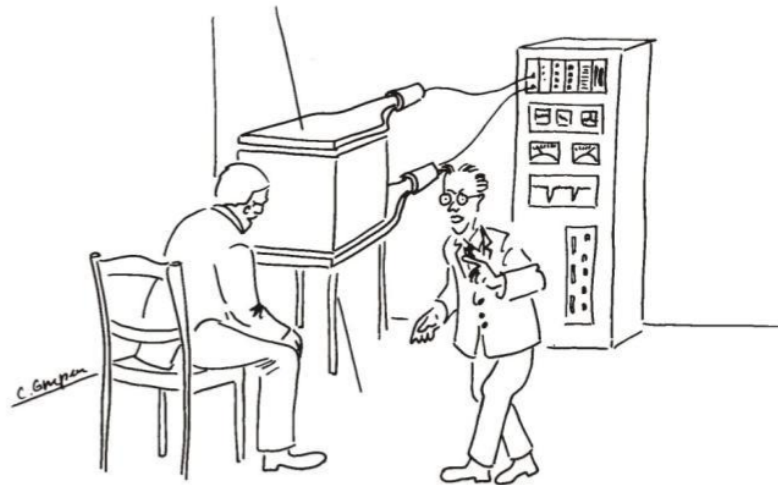


## Interaction of Particles with Matter

Any device that is to detect a particle must interact with it in some way → almost ...

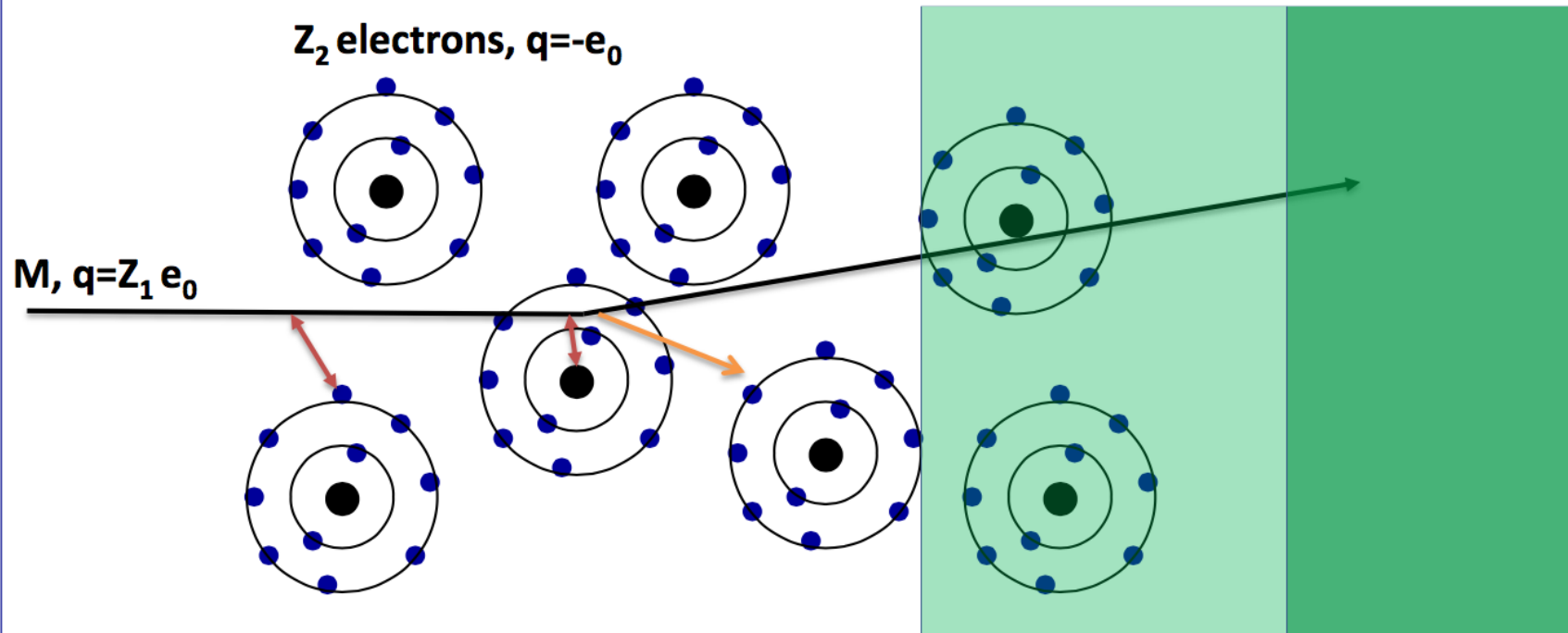
In many experiments neutrinos are measured by missing transverse momentum.

E.g.  $e^+e^-$  collider.  $P_{\text{tot}}=0$ ,  
If the  $\Sigma p_i$  of all collision products is  $\neq 0$  → neutrino escaped.



“Did you see it?”  
“No nothing.”  
“Then it was a neutrino!”

# Electromagnetic Interaction of Particles with Matter



Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremstrahlung photon can be emitted.

In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produce and X ray photon, called Transition radiation.

# Astrofisica Nucleare e Subnucleare

## Ionizzazione

## Bethe Bloch Formula

$$\frac{1}{\rho} \frac{dE}{dx} = -4\pi r_e^2 m_e c^2 \frac{Z_1^2}{\beta^2} N_A \frac{Z}{A} \left[ \ln \frac{2m_e c^2 \beta^2 \gamma^2 F}{I} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Für  $Z > 1$ ,  $I \approx 16Z^{0.9} \text{ eV}$

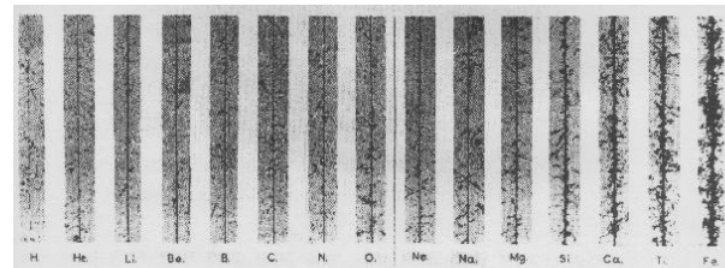
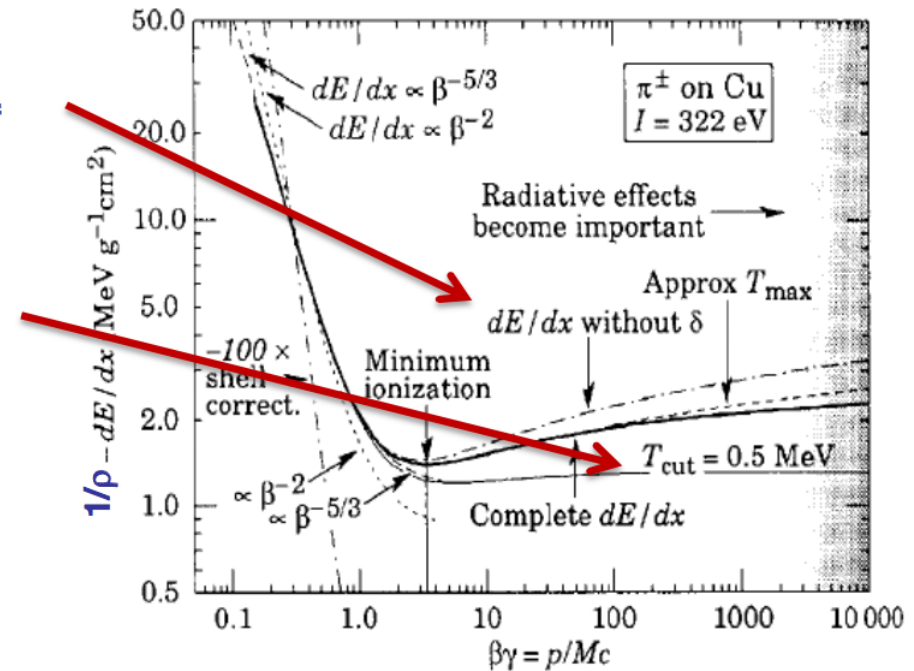
For Large  $\beta\gamma$  the medium is being polarized by the strong transverse fields, which reduces the rise of the energy loss  $\rightarrow$  density effect

At large Energy Transfers (delta electrons) the liberated electrons can leave the material. In reality,  $E_{\text{max}}$  must be replaced by  $E_{\text{cut}}$  and the energy loss reaches a plateau (Fermi plateau).

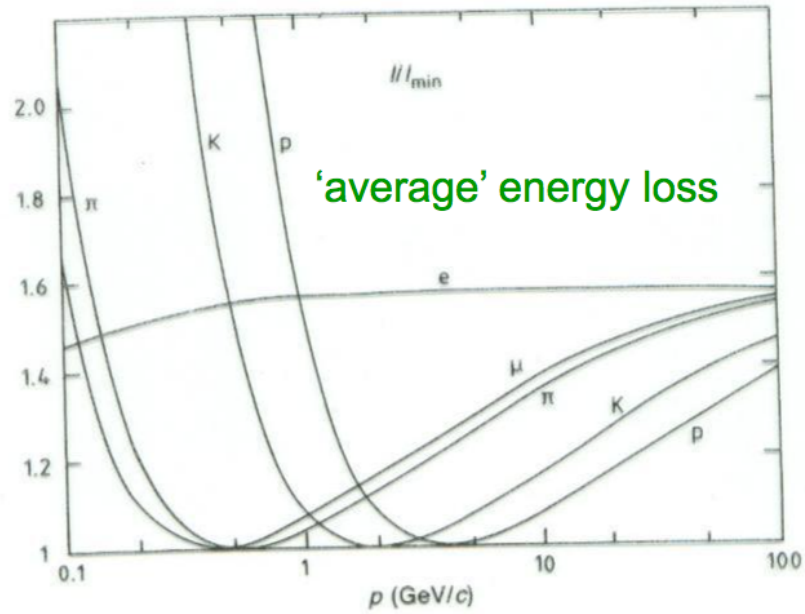
Characteristics of the energy loss as a function of the particle velocity ( $\beta\gamma$ )

The specific Energy Loss  $1/\rho \, dE/dx$

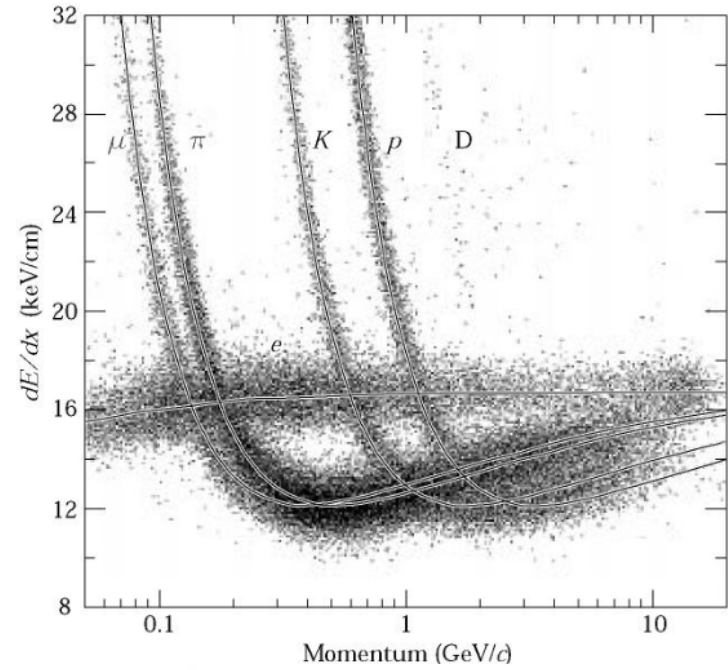
- first decreases as  $1/\beta^2$
- increases with  $\ln \gamma$  for  $\beta = 1$
- is  $\approx$  independent of  $M$  ( $M \gg m_e$ )
- is proportional to  $Z_1^2$  of the incoming particle.
- is  $\approx$  independent of the material ( $Z/A \approx \text{const}$ )
- shows a plateau at large  $\beta\gamma$  ( $\gg 100$ )
- $dE/dx \approx 1-2 \times \rho \text{ [g/cm}^3\text{]} \text{ MeV/cm}$



# Particle Identification

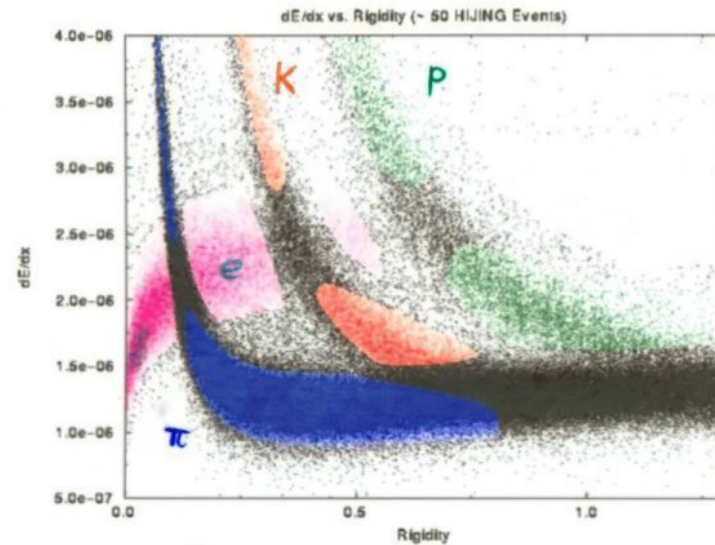


# Measured energy loss



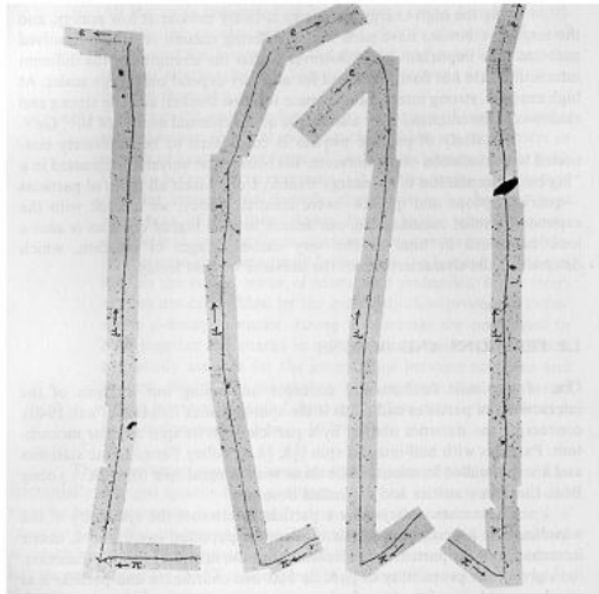
In certain momentum ranges, particles can be identified by measuring the energy loss.

STAR  
TPC

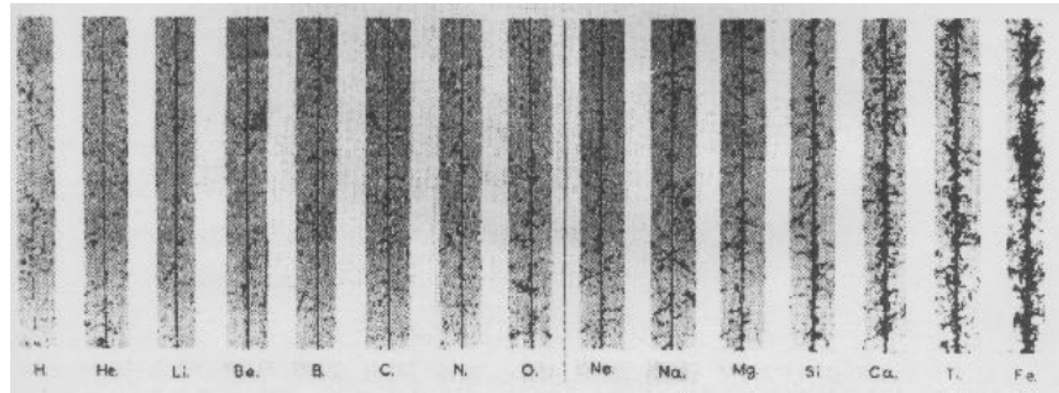




Small energy loss  
→ Fast Particle

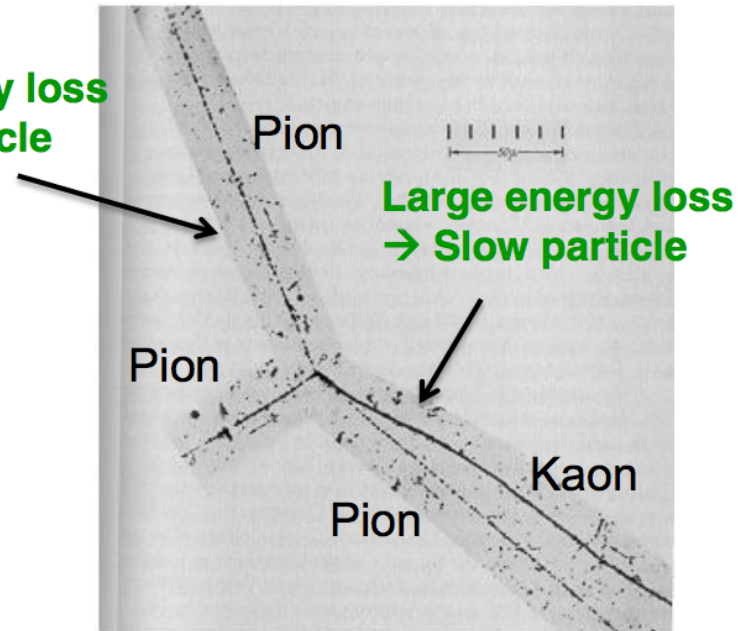


Discovery of muon and pion



Cosmis rays:  $dE/dx \propto Z^2$

Small energy loss  
→ Fast particle



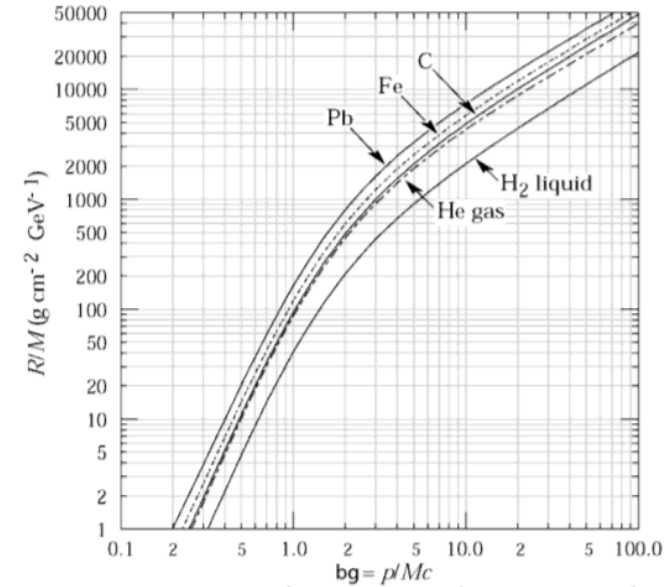
## Range of Particles in Matter

Particle of mass  $M$  and kinetic Energy  $E_0$  enters matter and loses energy until it comes to rest at distance  $R$ .

$$R(E_0) = \int_{E_0}^0 \frac{-1}{dE/dx} dE$$

$$R(\beta_0 \gamma_0) = \frac{Mc^2}{\rho} \frac{1}{Z_1^2} \frac{A}{Z} f(\beta_0 \gamma_0)$$

$$\frac{\rho}{Mc^2} R(\beta_0 \gamma_0) = \frac{1}{Z_1^2} \frac{A}{Z} f(\beta_0 \gamma_0) \quad \approx \text{Independent of the material}$$

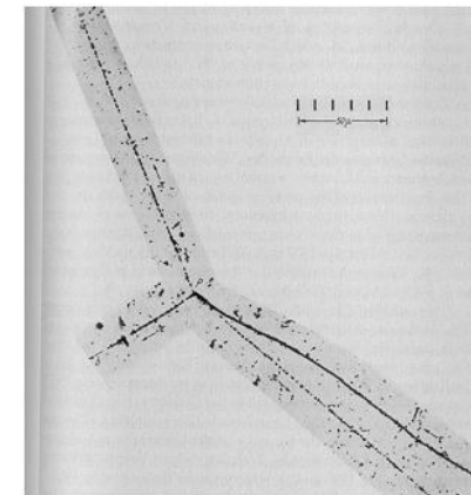
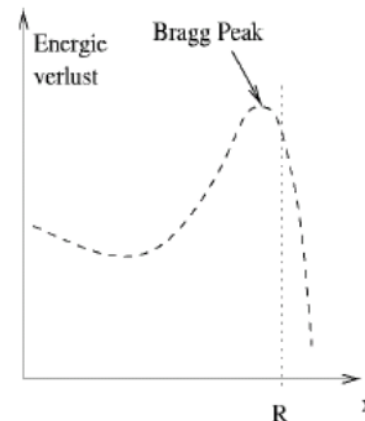


### Bragg Peak:

For  $\beta\gamma > 3$  the energy loss is  $\approx$  constant (Fermi Plateau)

If the energy of the particle falls below  $\beta\gamma = 3$  the energy loss rises as  $1/\beta^2$

Towards the end of the track the energy loss is largest  $\rightarrow$  Cancer Therapy.



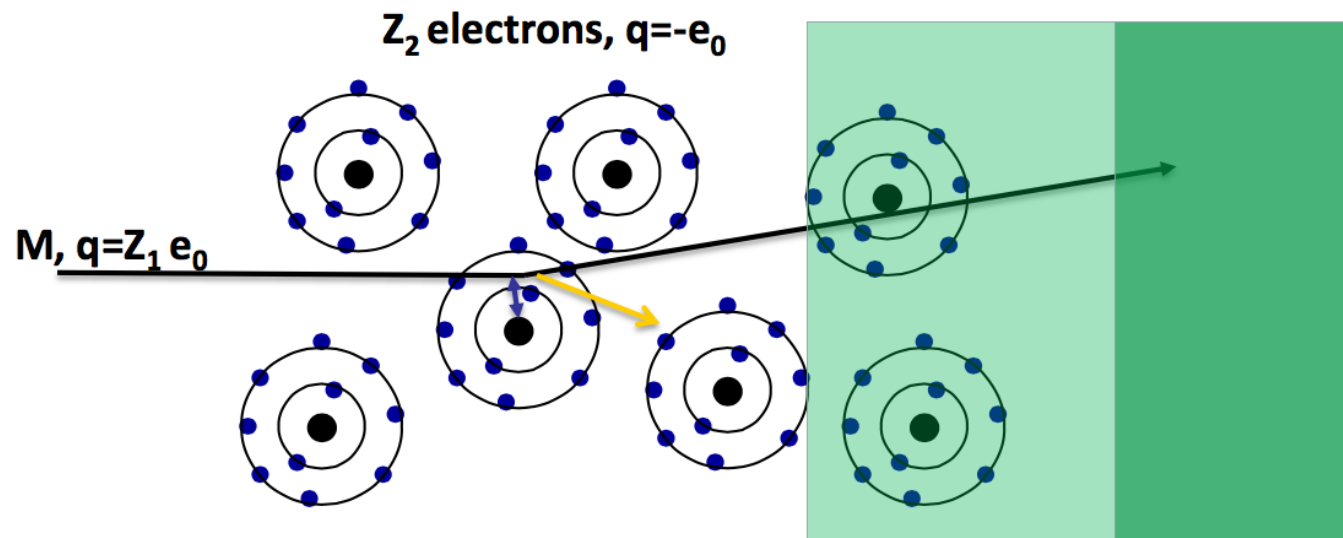
# Astrofisica Nucleare e Subnucleare

## Bremsstrahlung



# Bremsstrahlung

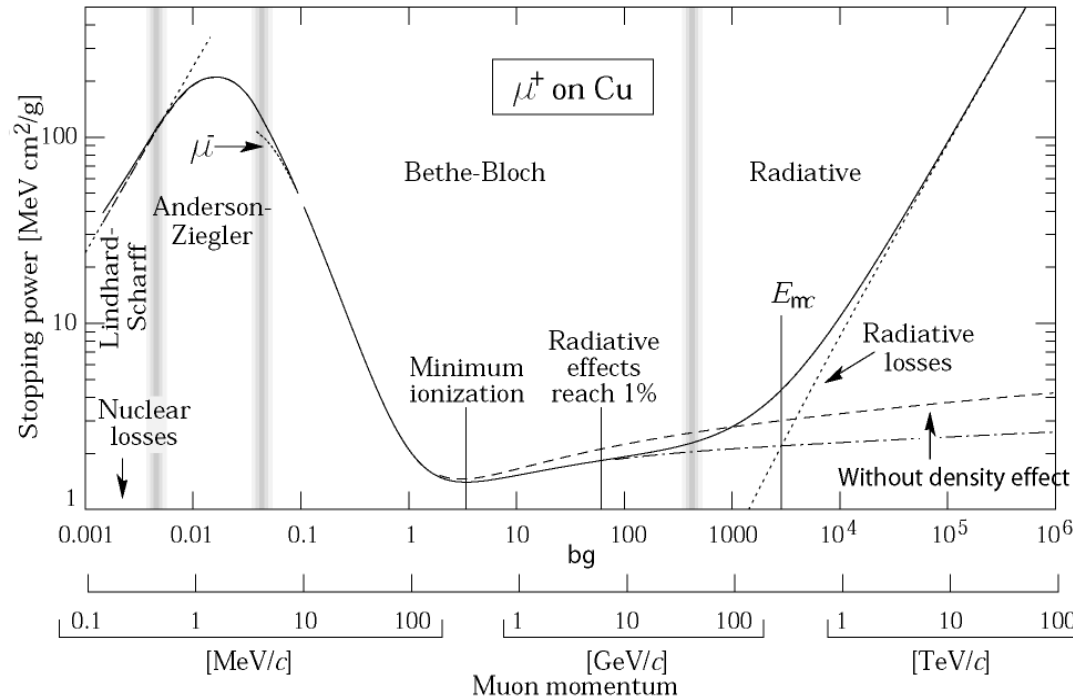
A charged particle of mass  $M$  and charge  $q=Z_1e$  is deflected by a nucleus of charge  $Ze$  which is partially 'shielded' by the electrons. During this deflection the charge is 'accelerated' and it therefore radiated  $\rightarrow$  Bremsstrahlung.



7/15/2010

# Critical Energy

such as copper to about 1% accuracy for energies between about 6 MeV and 6 GeV



**Electron Momentum      5      50      500      MeV/c**

**Critical Energy: If  $dE/dx$  (Ionization) =  $dE/dx$  (Bremsstrahlung)**

**Myon in Copper:       $p \approx 400\text{GeV}$**

**Electron in Copper:       $p \approx 20\text{MeV}$**

**For the muon, the second lightest particle after the electron, the critical energy is at 400GeV.**

**The EM Bremsstrahlung is therefore only relevant for electrons at energies of past and present detectors.**

# Astrofisica Nucleare e Subnucleare

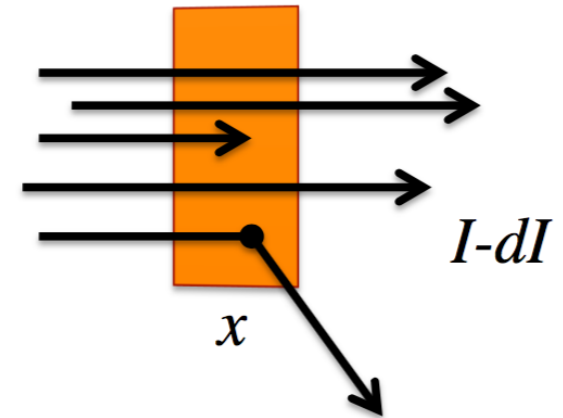
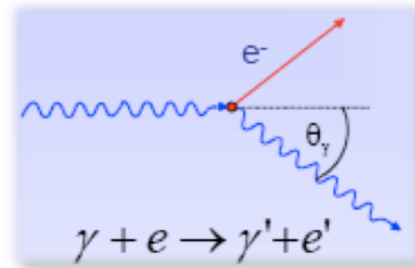
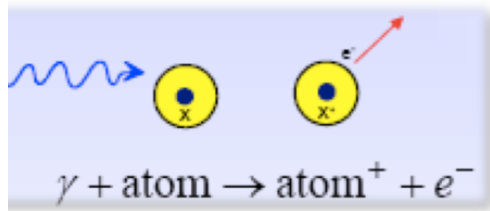
## Interazione di Fotoni

# Interactions of photons with matter

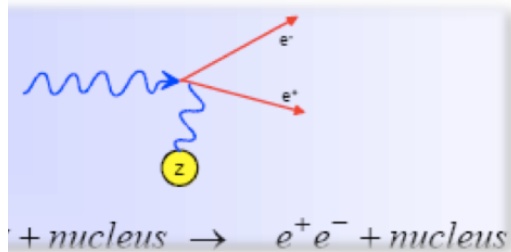
Characteristic for interactions of photons with matter:

Each photon is removed from the beam after one single interaction either because of total absorption or scattering

1) Photoelectric Effect    2) Compton Scattering



3) Pair Production

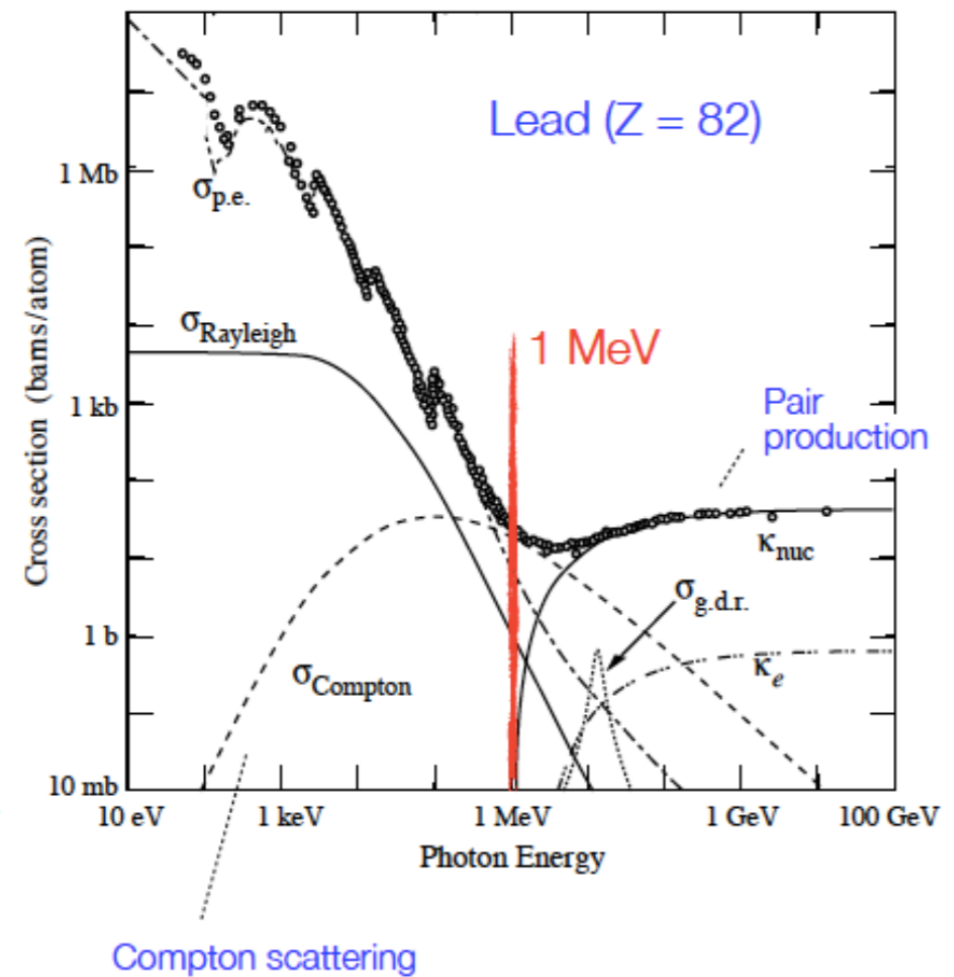
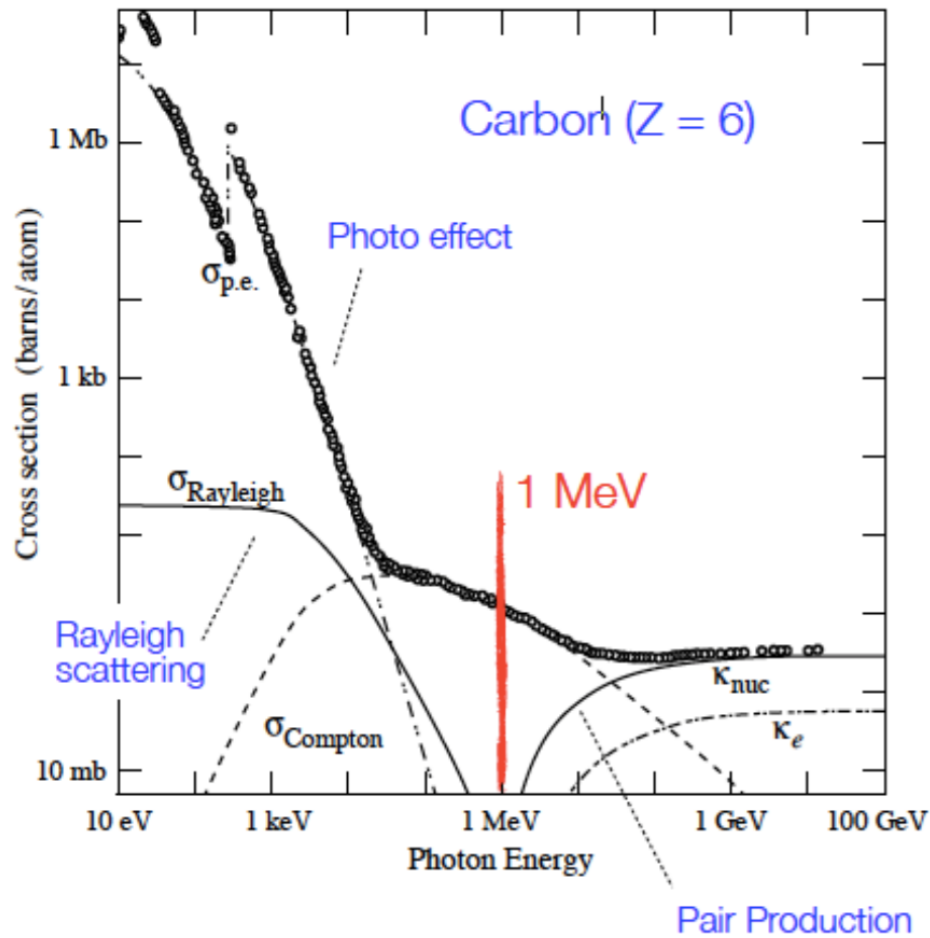


$$I(x) = I_0 e^{-\mu x}$$

$$\lambda = 1 / \mu \quad \text{Mean free path}$$

# Interactions of photons with matter

Photon Total Cross Sections



# Photoelectric effect

From energy conservation:

$$E_e = E_\gamma - E_N = h\nu - I_b$$

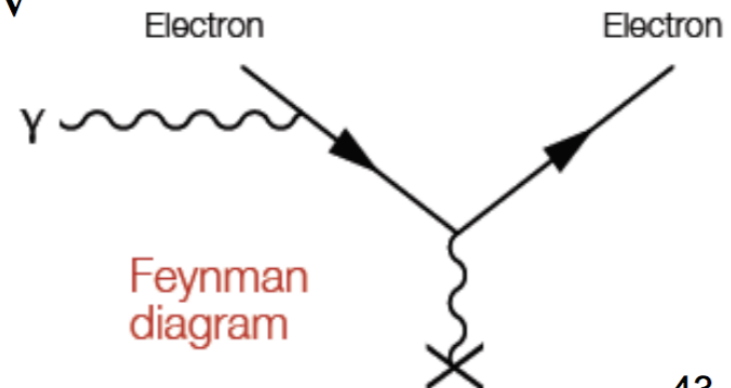
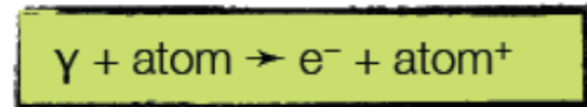
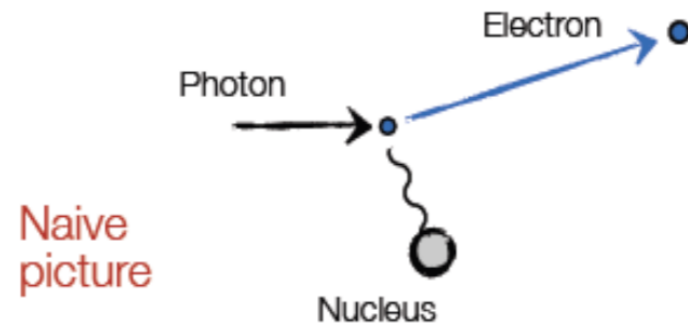
$I_b$  = Nucleus binding energy  
introduces strong Z dependence

Cross-section largest for  $E_\gamma \approx$  K-shell energy  
Strongest E dependence for  $I_0 < E_\gamma < m_e c^2$

$$\sigma_{ph} = \alpha \pi a_B^2 Z^5 (I_0 / E_\gamma)^{7/2} \quad \begin{matrix} a_B = 0.53 \text{ \AA} \\ I_0 = 13.6 \text{ eV} \end{matrix}$$

E-dependence softer for  $E_\gamma > m_e c^2$

$$\sigma_{ph} = 2\pi r_e^2 \alpha^4 Z^5 (mc)^2 / E_\gamma$$



# Compton scattering

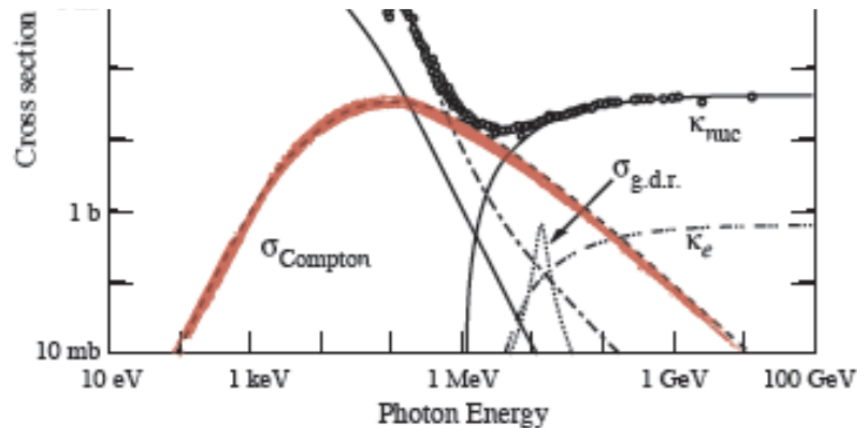
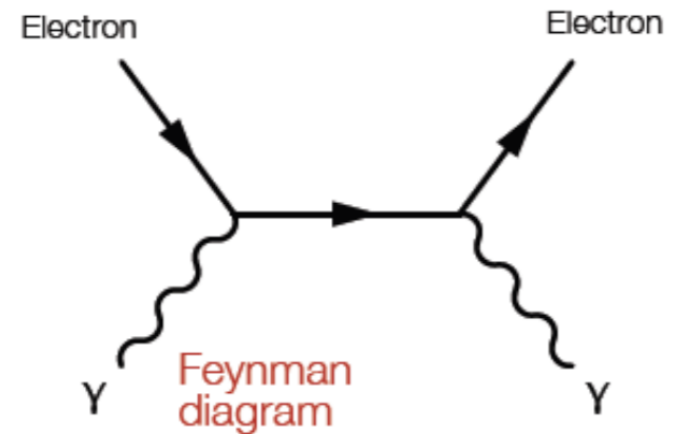
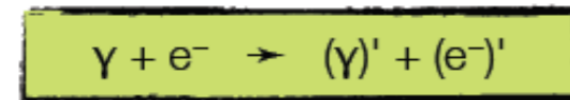
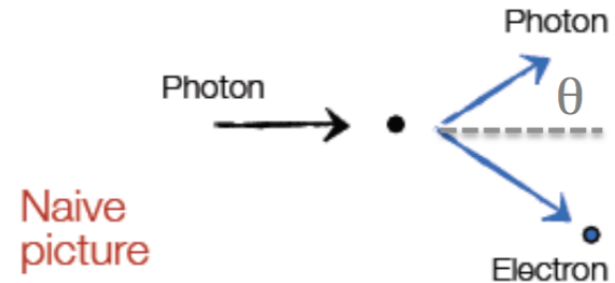
Best known electromagnetic process  
(Klein–Nishina formula)

for  $E_\lambda \ll m_e c^2$   $\sigma_c \propto \sigma_{Th} (1 - 2\varepsilon)$

Thompson cross-section:  
 $\sigma_{Th} = 8\pi/3 r_e^2 = 0.66$  barn

$$\varepsilon = \frac{E_\lambda}{m_e c^2}$$

for  $E_\lambda \gg m_e c^2$   $\sigma_c \propto \frac{\ln \varepsilon}{\varepsilon} Z$



# Compton scattering

From E and p conservation get the energy of the scattered photon

$$E_{\gamma}' = \frac{E_{\gamma}}{1 + \varepsilon(1 - \cos\theta)} \quad \varepsilon = \frac{E_{\lambda}}{m_e c^2}$$

Kinetic energy of the outgoing electron:

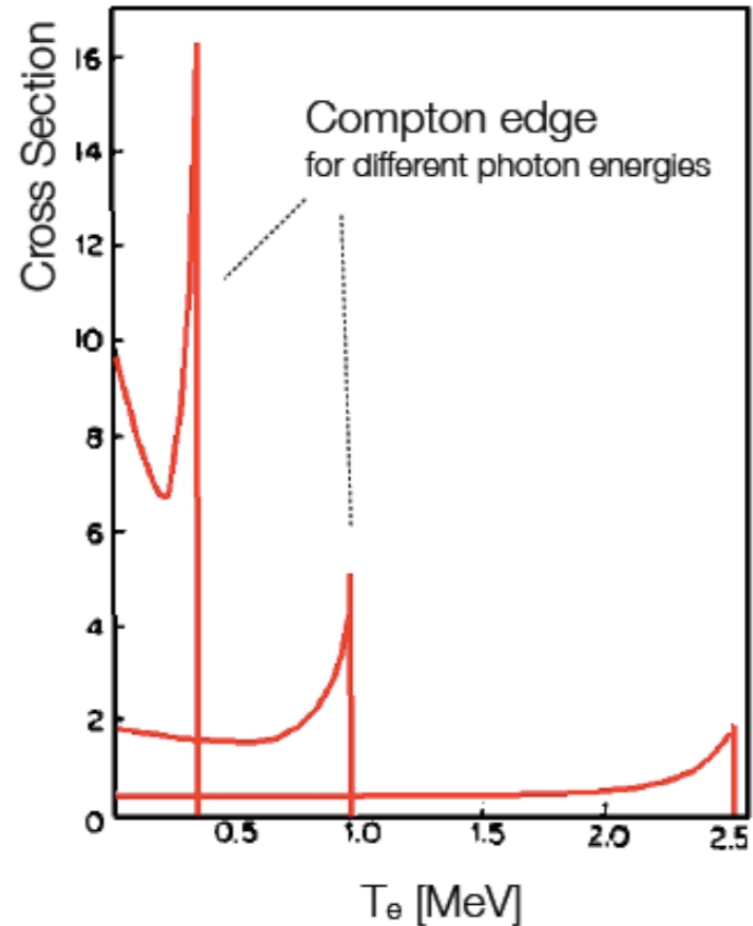
$$T_e = E_{\gamma} - E_{\gamma}' = E_{\gamma} \frac{\varepsilon(1 - \cos\theta)}{1 + \varepsilon(1 - \cos\theta)}$$

Max. electron recoil energy for  $\theta = \pi$ :

$$T_{\max} = E_{\gamma} \frac{2\varepsilon}{1 + 2\varepsilon}$$

Transfer of complete  $\gamma$ -energy via Compton scattering not possible:

$$\Delta E = E_{\gamma} - T_{\max} = E_{\gamma} \frac{1}{1 + 2\varepsilon}$$

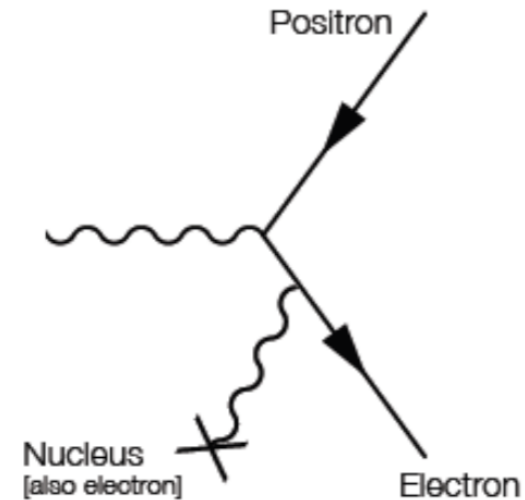
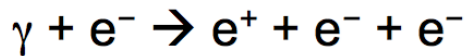
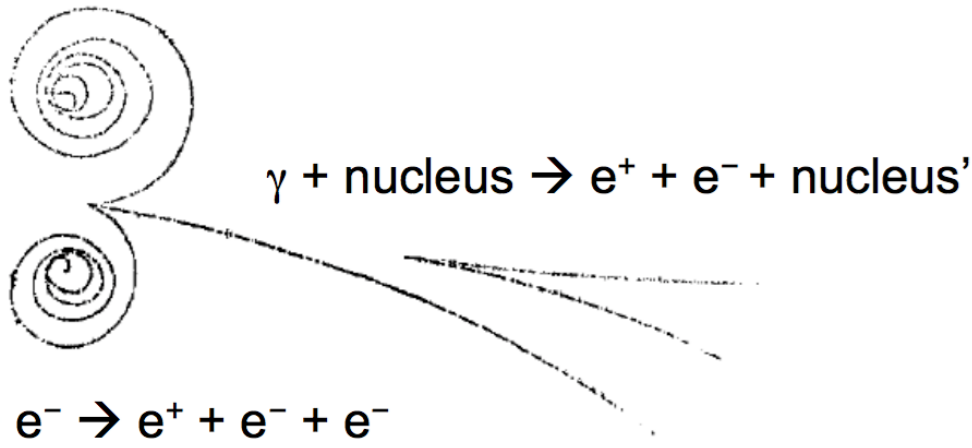
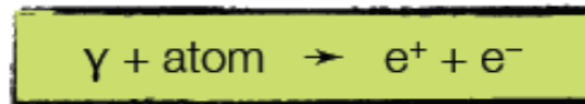
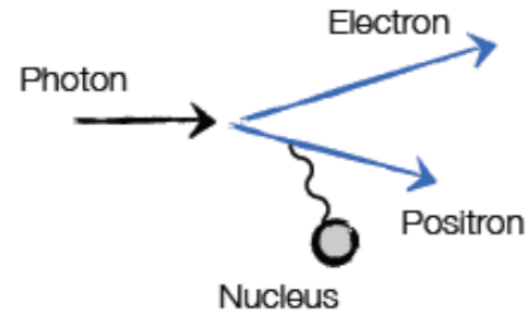




# Pair production

Minimum energy required for this process  
 $2 m_e c^2 + \text{Energy transferred to the nucleus}$

$$E_\gamma \geq 2m_e c^2 + \frac{2m_e c^2}{m_{\text{Nucleus}}}$$



# Pair production

for  $E_\lambda \gg m_e c^2$        $\sigma_{\text{pair}} = 4\alpha r_e^2 Z^2 \left( \frac{7}{9} \ln \frac{183}{Z^{1/3}} - \frac{1}{54} \right)$  [cm<sup>2</sup>/atom]

Using as for Bremsstrahlung the radiation length

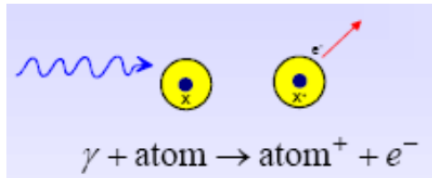
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln \frac{183}{Z^{1/3}}}$$

$$\sigma_{\text{pair}} = \frac{7}{9} \frac{N_A}{A} \cdot \frac{1}{X_0}$$

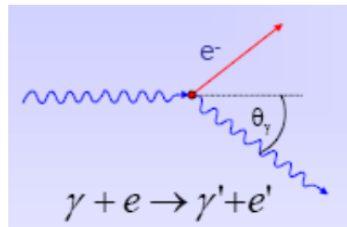
	$\rho$ [g/cm <sup>3</sup> ]	$X_0$ [cm]
H <sub>2</sub> [fl.]	0.071	865
C	2.27	18.8
Fe	7.87	1.76
Pb	11.35	0.56
Luft	$1.2 \cdot 10^{-3}$	$30 \cdot 10^3$

# Electromagnetic interactions

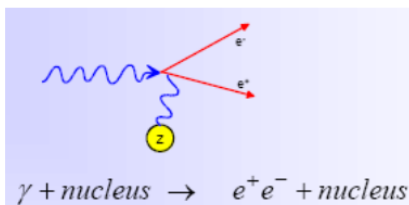
Gammas



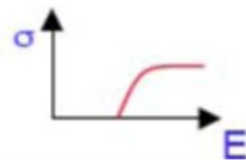
- Photoelectric effect



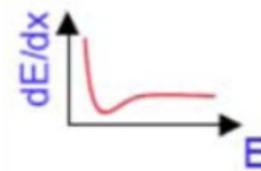
- Compton effect



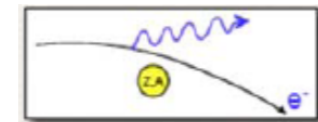
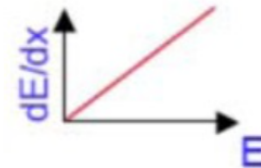
- Pair production



- Ionisation



- Bremsstrahlung



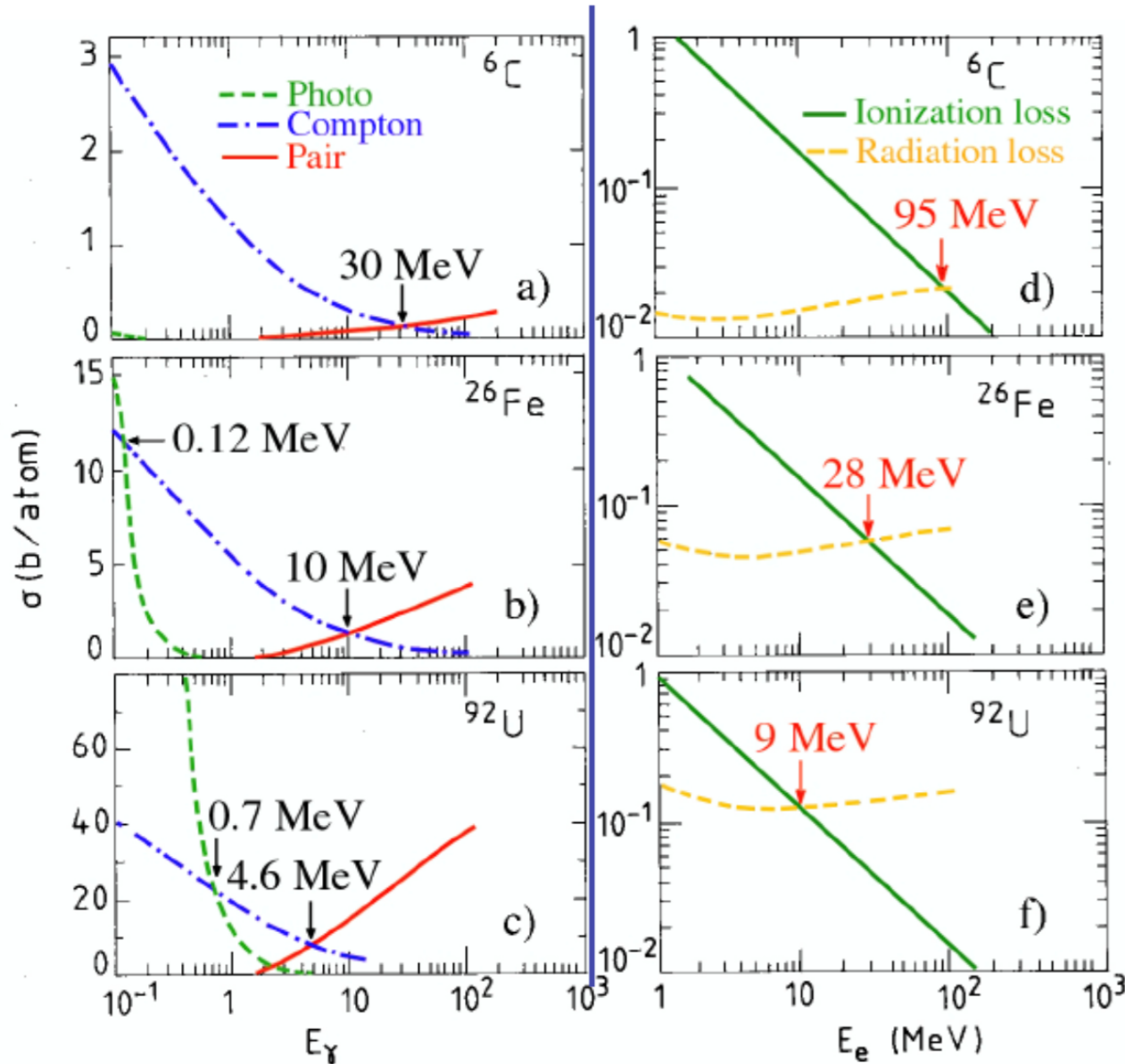
Electrons

# Material dependence

Increasing Z

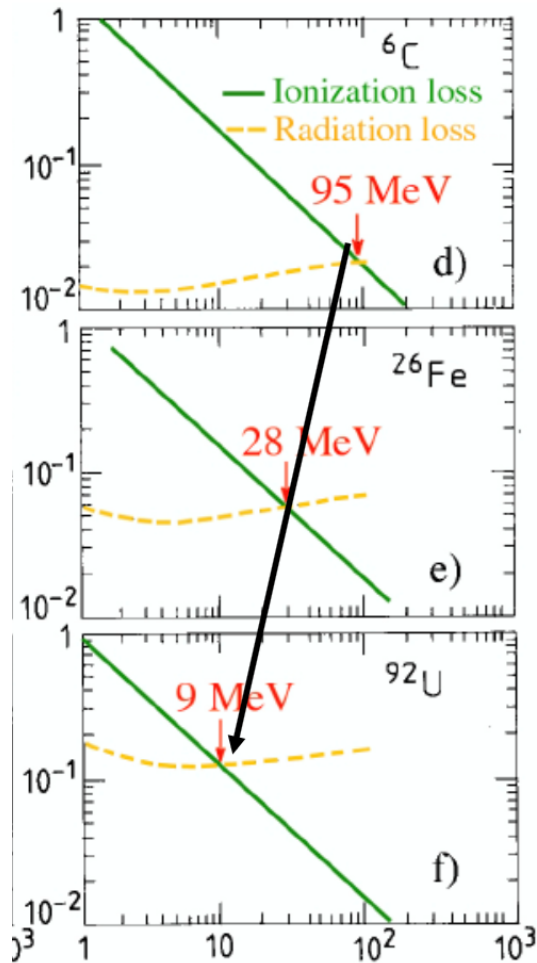


Gamma



Electrons

# Electrons



Increasing Z

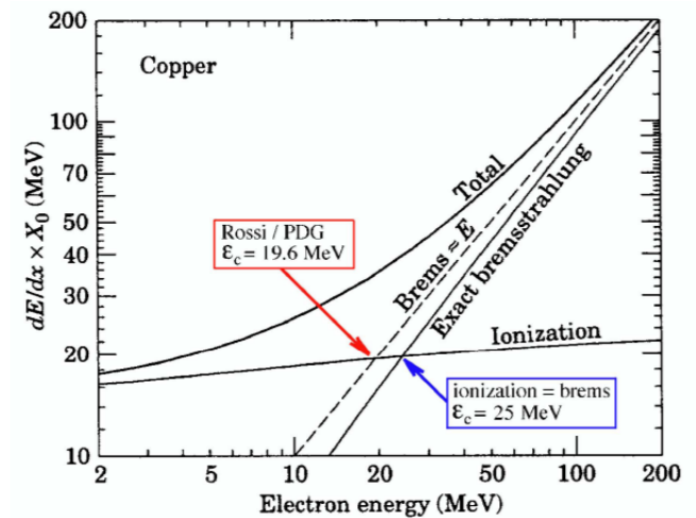
*Electrons* lose energy by: *ionization* = *radiation*

Critical energy  $\epsilon_c$ :

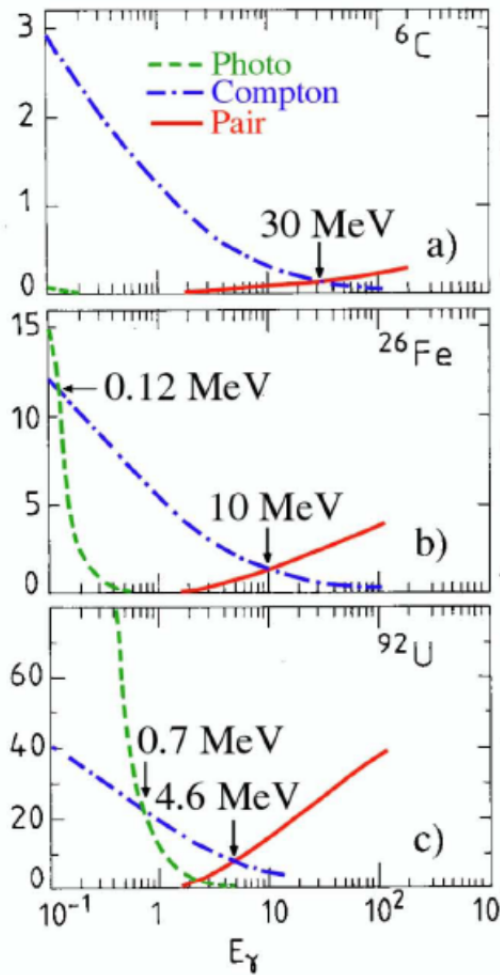
$$\frac{dE}{dx} (\text{ion}) = \frac{dE}{dx} (\text{rad})$$

$$\epsilon_c \propto 1/Z \quad \text{PDG: } \epsilon_c = 610 \text{ MeV}/(Z + 1.24)$$

In high Z materials  
particle multiplication  
at lower energies



# Photons



↓ Increasing Z

• *Photons* interact by:

1) Photoelectric effect

$$\sigma \propto Z^5, E^{-3}$$

2) Compton scattering

$$\sigma \propto Z, E^{-1}$$

3) Conversion into  $e^+e^-$

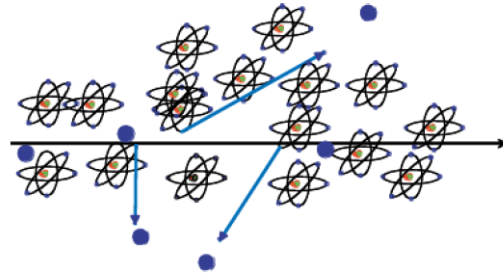
$\sigma$  increases with  $E, Z$ , asymptotic at  $\sim 1$  GeV

# Astrofisica Nucleare e Subnucleare

## Scintillation Detectors

# Creation of the Signal

Charged particles traversing matter leave excited atoms, electron-ion pairs (gases) or electrons-hole pairs (solids) behind.



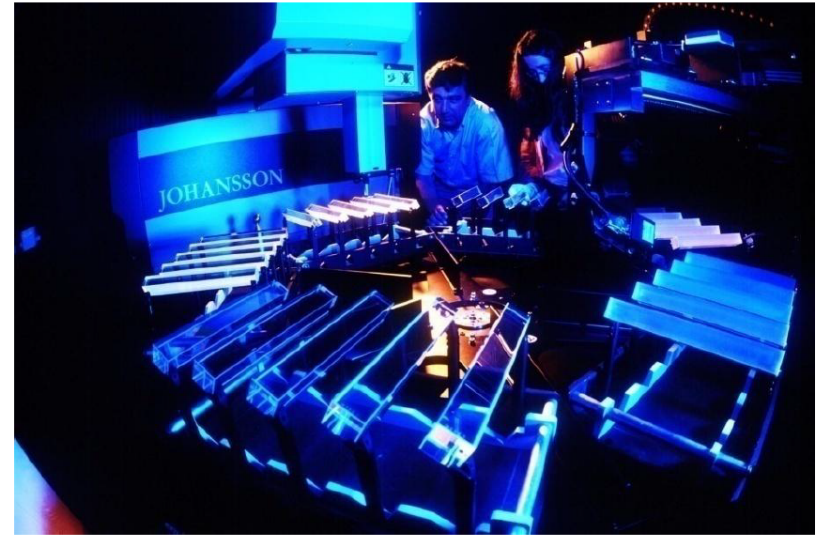
## Excitation:

The photons emitted by the excited atoms in transparent materials can be detected with photon detectors like photomultipliers or semiconductor photon detectors.

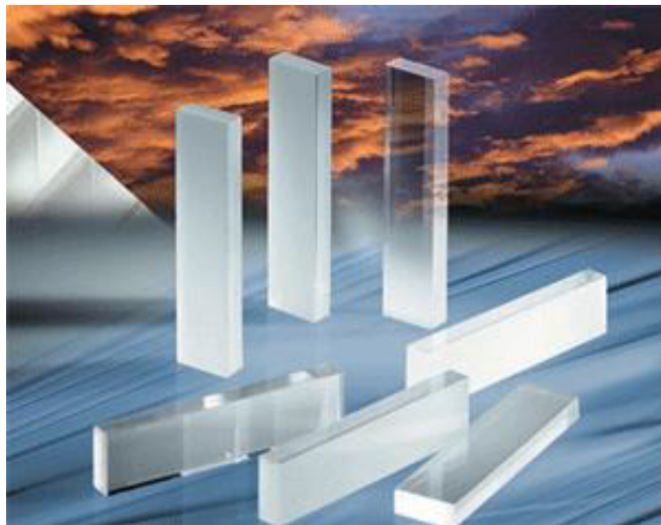
## Ionization:

By applying an electric field in the detector volume, the ionization electrons and ions are moving, which induces signals on metal electrodes. These signals are then read out by appropriate readout electronics.





## Detectors based on registration of excited Atoms → Scintillators



# Detectors based on Registration of excited Atoms → Scintillators

Emission of photons of by excited Atoms, typically UV to visible light.



a) Observed in Noble Gases (even liquid !)

b) Inorganic Crystals

→ Substances with largest light yield. Used for precision measurement of energetic Photons. Used in Nuclear Medicine.

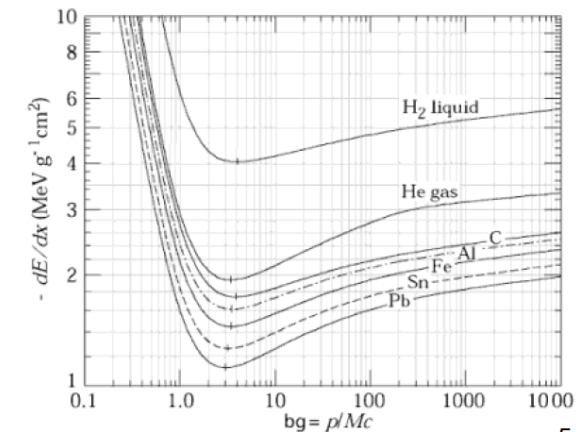
c) Polyzyclic Hydrocarbons (Naphtalen, Anthrazen, organic Scintillators)

→ Most important category. Large scale industrial production, mechanically and chemically quite robust. Characteristic are one or two decay times of the light emission.

Typical light yield of scintillators:

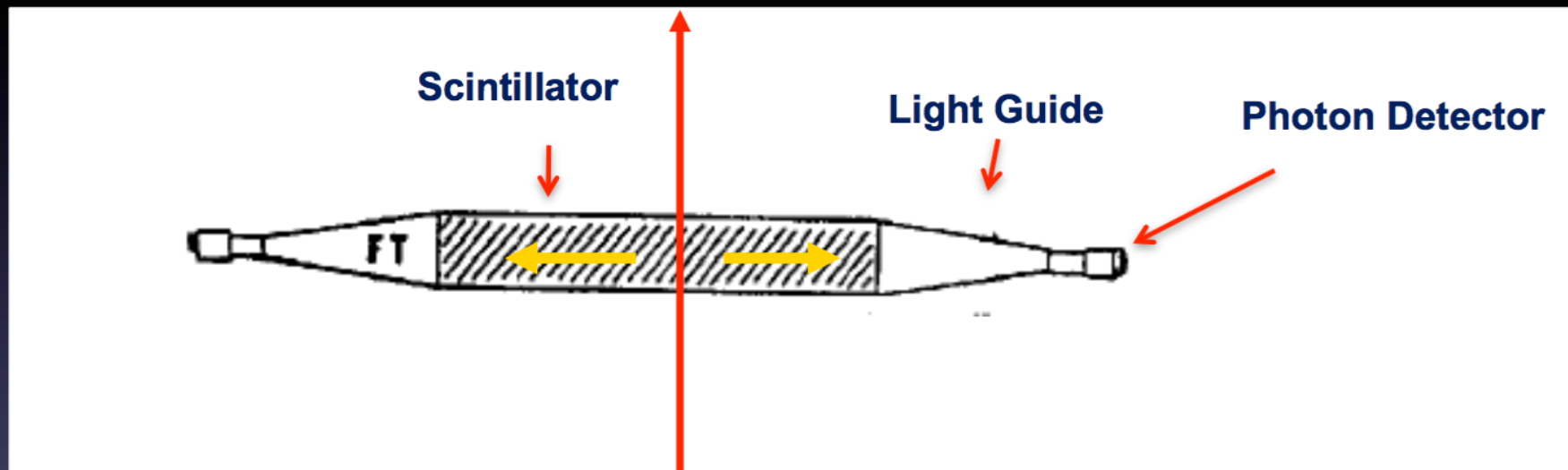
Energy (visible photons)  $\approx$  few % of the total energy Loss.

z.B. 1cm plastic scintillator,  $\rho \approx 1$ ,  $dE/dx=1.5$  MeV,  $\sim 15$  keV in photons;  
i.e.  $\sim 15\,000$  photons produced.



# Scintillators

- Photons are being reflected towards the ends of the scintillator.
- A light guide brings the photons to the Photomultipliers where the photons are converted to an electrical signal.



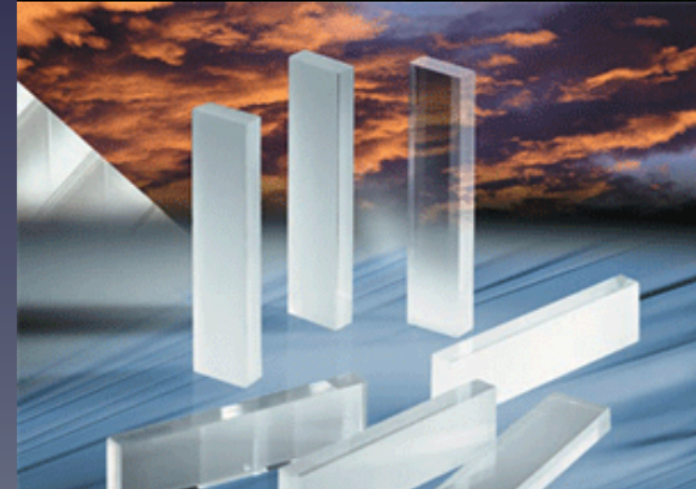
- By segmentation one can obtain spatial resolution.
- Because of the excellent timing properties ( $<1\text{ns}$ ) the arrival time, or time of flight, can be measured very accurately  $\rightarrow$  Trigger, Time of Flight.

# Scintillators

- $dE/dx$  converted into light and then it is detected via photo-sensor (photomultipliers, SiPM,....)
- Main features
  - Sensitivity to energy
  - Fast time response
  - Pulse shape discrimination
- Requirements:
  - High efficiency for conversion of exciting energy to fluorescent radiation
  - Transparency to its fluorescent radiation to allow transmission of light
  - Emission of light in a spectral range detectable for photo-sensors
  - Short decay time to allow fast response



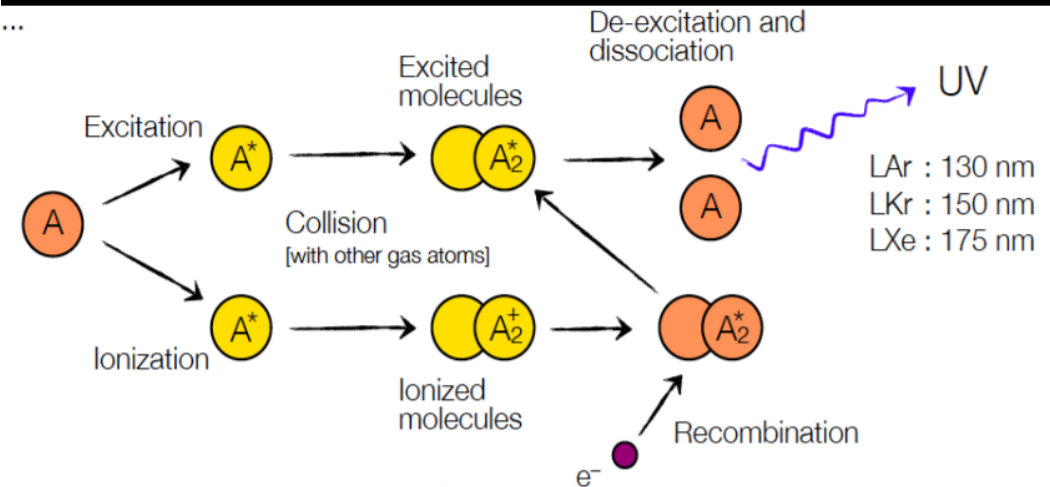
Plastic Scintillator BC412



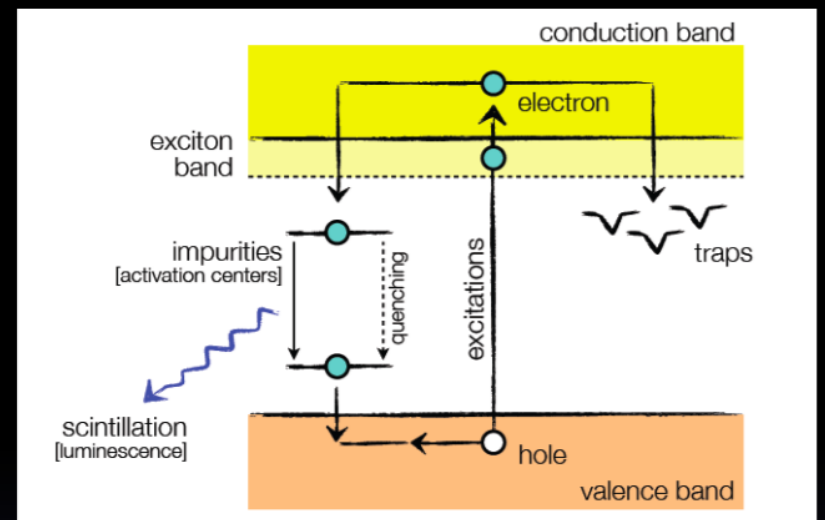
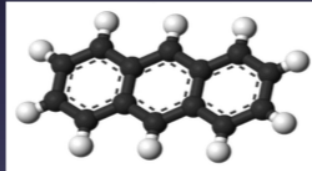


# Scintillators

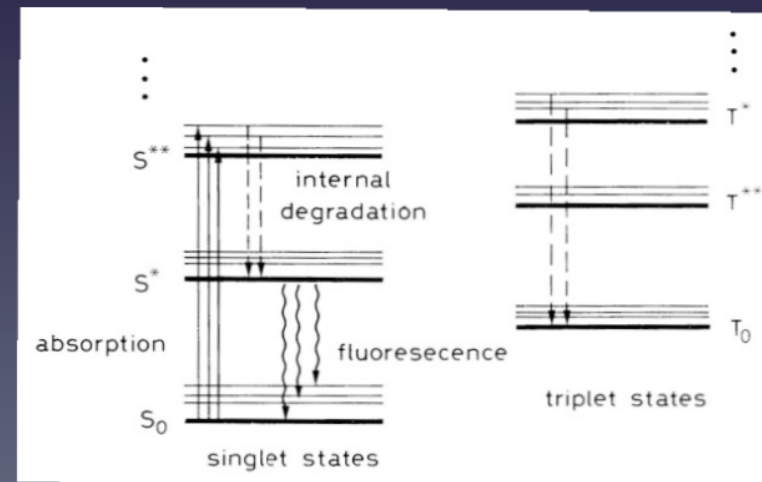
- Inorganic (Sodium iodide (NaI), Cesium iodide (CsI),...)



- Organic crystals
  - Aromatic hydrocarbon compounds with benzene rings such as Anthracene ( $C_{14}H_{10}$ ), etc
- Plastic scintillators
  - Organic scintillators suspended in the aromatic polymer (easy to mold and machine)
- Liquid scintillators



- Noble gases (Liquid Argon, Liquid Xenon...)
- Molecule structure generates energy levels with transition  $\lambda=360-500$  nm





# Detectors based on Registration of excited Atoms → Scintillators

## Organic ('Plastic') Scintillators

Low Light Yield

Fast: 1-3ns

Type	Light <sup>a</sup> output	$\lambda_{max}$ <sup>b</sup> (nm)	Attenuation <sup>c</sup> length (cm)	Risetime (ns)	Decay <sup>d</sup> time (ns)	Pulse FWHM (ns)
NE 102A	58-70	423	250	0.9	2.2-2.5	2.7-3.2
NE 104	68	406	120	0.6-0.7	1.7-2.0	2.2-2.5
NE 104B	59	406	120	1	3.0	3
NE 110	60	434	400	1.0	2.9-3.3	4.2
NE 111	40-55	375	8	0.13-0.4	1.3-1.7	1.2-1.6
NE 114	42-50	434	350-400	~1.0	4.0	5.3
Pilot B	60-68	408	125	0.7	1.6-1.9	2.4-2.7
Pilot F	64	425	300	0.9	2.1	3.0-3.3
Pilot U	58-67	391	100-140	0.5	1.4-1.5	1.2-1.9
BC 404	68	408	—	0.7	1.8	2.2
BC 408	64	425	—	0.9	2.1	~2.5
BC 420	64	391	—	0.5	1.5	1.3
ND 100	60	434	400	—	3.3	3.3
ND 120	65	423	250	—	2.4	2.7
ND 160	68	408	125	—	1.8	2.7

LHC bunchcrossing 25ns

## Inorganic (Crystal) Scintillators

Large Light Yield

Slow: few 100ns

	Relative light output	$\lambda_{max}$ emission (nm)	Decay time (ns)	Density (g/cm <sup>3</sup> )
<i>Inorganic crystals</i>				
Nal(Tl)	230	415	230	3.67
CsI(Tl)	250	560	900	4.51
Bi <sub>4</sub> Ge <sub>3</sub> O <sub>12</sub> (BGO)	23-86	480	300	7.13
<i>Organic crystals</i>				
Anthracene	100	448	22	1.25
Trans-stilbene	75	384	4.5	1.16
Naphthalene	32	330-348	76-96	1.03
<i>p,p'</i> -Quarterphenyl	94	437	7.5	1.20
<i>Primary activators</i>				
2,5-Diphenyl-oxazole (PPO)	75	360-416	5 <sup>a</sup>	
2-Phenyl-5-(4-biphenyl)- 1,3,4-oxadiazole (PBD)	96	360-5		
4,4'-Bis(2-butyloctyloxy)- <i>p</i> - quaterphenyl (BIBUQ)	60	365,393	1.30 <sup>a</sup>	

LEP bunchcrossing 25μs

# Scintillators

## Inorganic Scintillators – Properties

Scintillator material	Density [g/cm <sup>3</sup> ]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [μs]	Photons/MeV
NaI	3.7	1.78	303	0.06	$8 \cdot 10^4$
NaI(Tl)	3.7	1.85	410	0.25	$4 \cdot 10^4$
CsI(Tl)	4.5	1.80	565	1.0	$1.1 \cdot 10^4$
Bi <sub>4</sub> Ge <sub>3</sub> O <sub>12</sub>	7.1	2.15	480	0.30	$2.8 \cdot 10^3$
CsF	4.1	1.48	390	0.003	$2 \cdot 10^3$
LSO	7.4	1.82	420	0.04	$1.4 \cdot 10^4$
PbWO <sub>4</sub>	8.3	1.82	420	0.006	$2 \cdot 10^2$
LHe	0.1	1.02	390	0.01/1.6	$2 \cdot 10^2$
LAr	1.4	1.29*	150	0.005/0.86	$4 \cdot 10^4$
LXe	3.1	1.60*	150	0.003/0.02	$4 \cdot 10^4$

\* at 170 nm

# Scintillators

## Organic Scintillators – Properties

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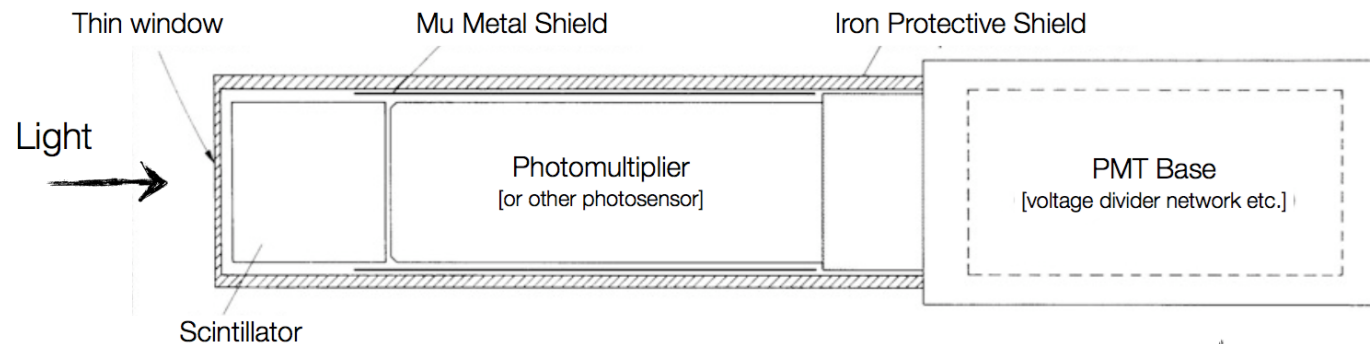
Scintillator material	Density [g/cm <sup>3</sup> ]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4 \cdot 10^3$
Antracene	1.25	1.59	448	30	$4 \cdot 10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2 \cdot 10^4$
NE102*	1.03	1.58	425	2.5	$2.5 \cdot 10^4$
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

# Scintillators

## Scintillators – Basic Counter Setup

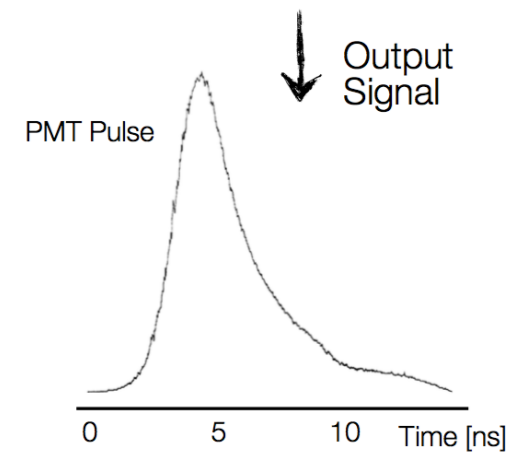


### Scintillator Types:

#### Photosensors

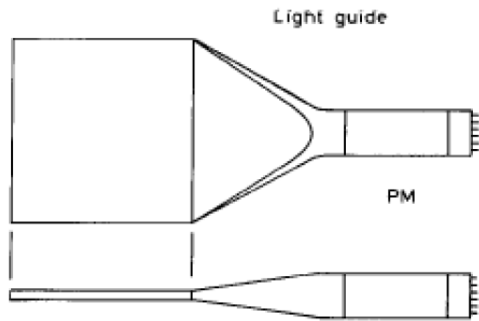
- Photomultipliers
- Micro-Channel Plates
- Hybrid Photo Diodes
- Visible Light Photon Counter
- Silicon Photo Multipliers

- Organic Scintillators
- Inorganic Crystals
- Gases

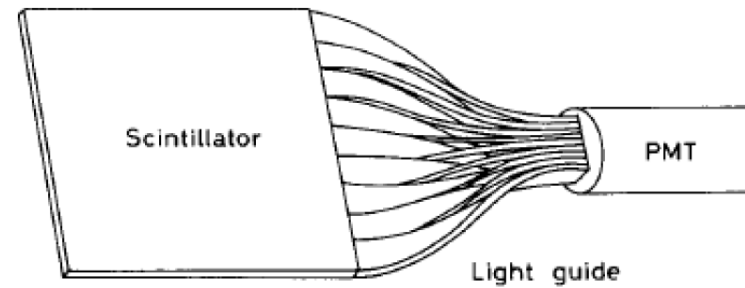


## Typical Geometries:

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

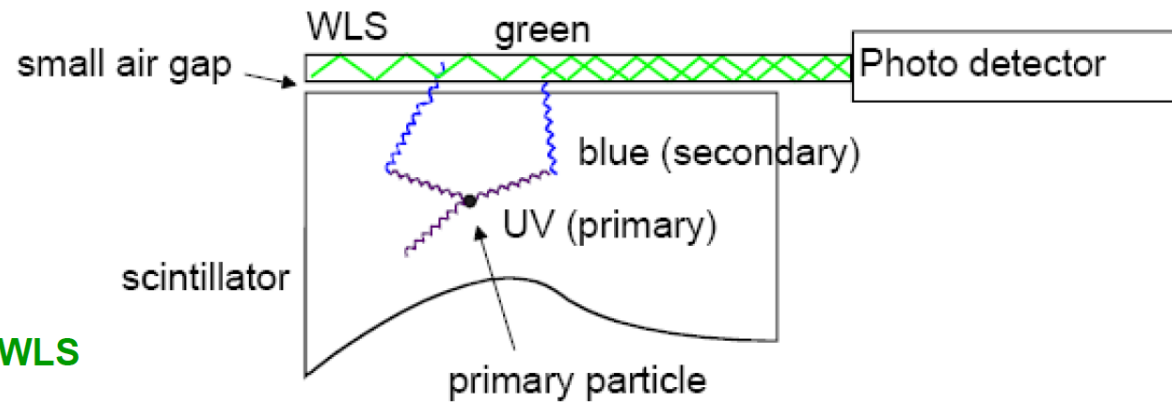


“fish tail”



adiabatic

- wavelength shifter (WLS) bars



UV light enters the WLS material  
 Light is transformed into longer wavelength  
 → Total internal reflection inside the WLS material  
 → ‘transport’ of the light to the photo detector



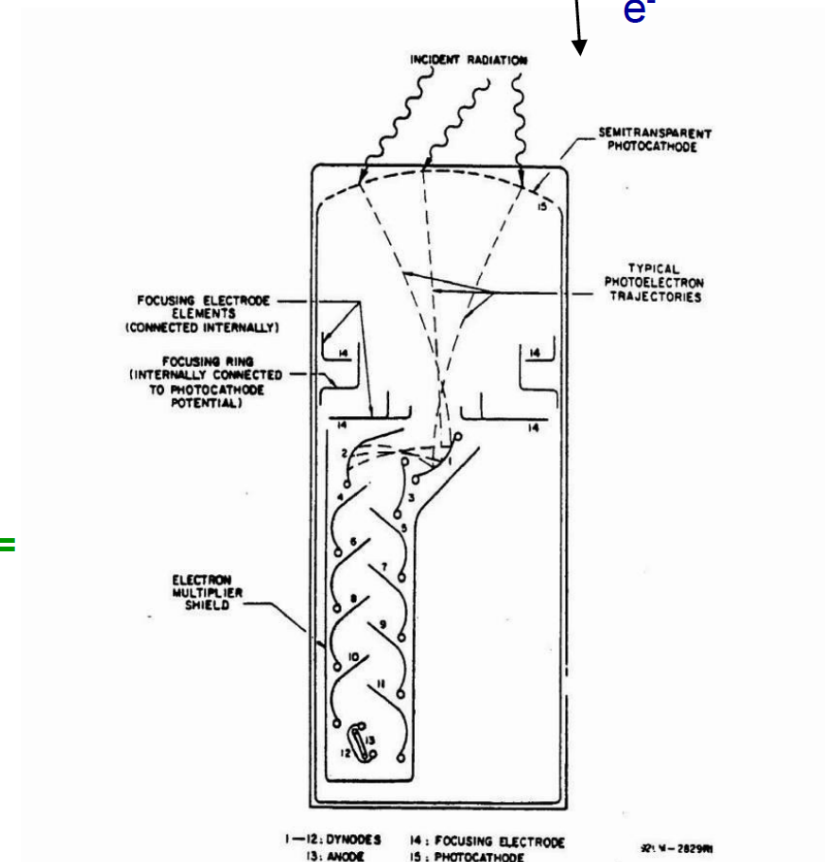
The frequent use of Scintillators is due to:

Well established and cheap techniques to register Photons → Photomultipliers  
and the fast response time → 1 to 100ns

### Schematic of a Photomultiplier:

- Typical Gains (as a function of the applied voltage):  $10^8$  to  $10^{10}$
- Typical efficiency for photon detection:
  - < 20%
- For very good PMs: registration of single photons possible.
- Example: 10 primary Elektronen, Gain  $10^7$  →  $10^8$  electrons in the end in  $T \approx 10$ ns.  $I=Q/T = 10^8 \cdot 1.603 \cdot 10^{-19} / 10 \cdot 10^{-9} = 1.6$ mA.
- Across a  $50 \Omega$  Resistor →  $U=R \cdot I = 80$ mV.

Semitransparent photocathode



# Photo-detectors

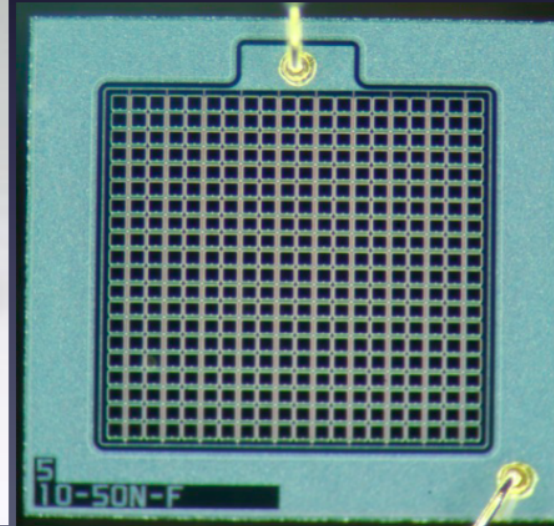
- Convert light into an electronic signal by using the photo-electric effect to convert photons into photo-electrons (p.e.)
- Requirement :
  - High Photon Detection Efficiency (PDE) or
  - Quantum Efficiency;  $Q.E. = N_{p.e.}/N_{photons}$

## ■ Photomultipliers

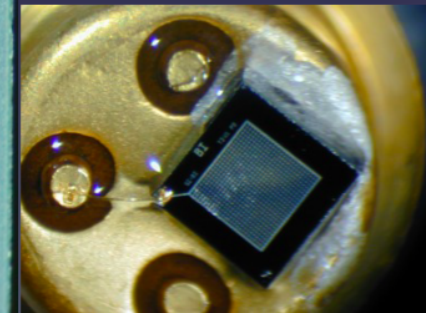


## ■ SiPM

### Hamamatsu MPPC



One of the first  
SiPM  
Pulsar, Moscow



# PMTs

## Photomultipliers

---

### Principle:

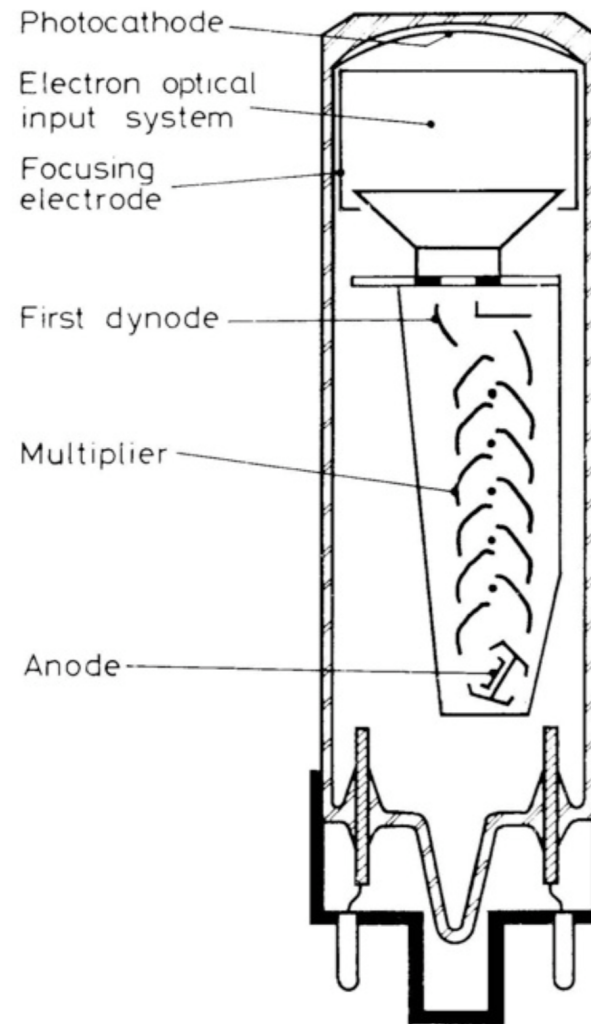
Electron emission  
from photo cathode

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

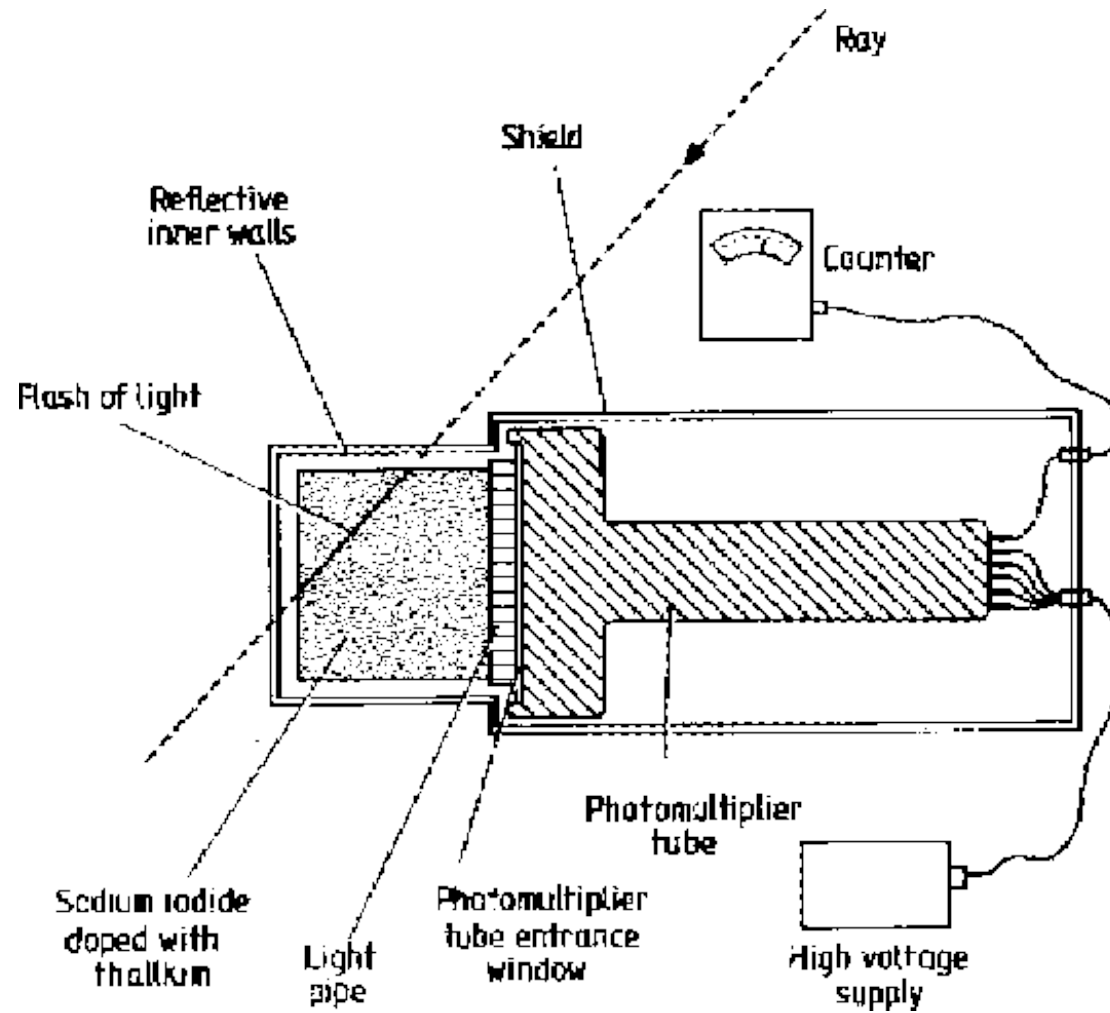
Typical PMT Gain:  $> 10^6$   
[PMT can see single photons ...]



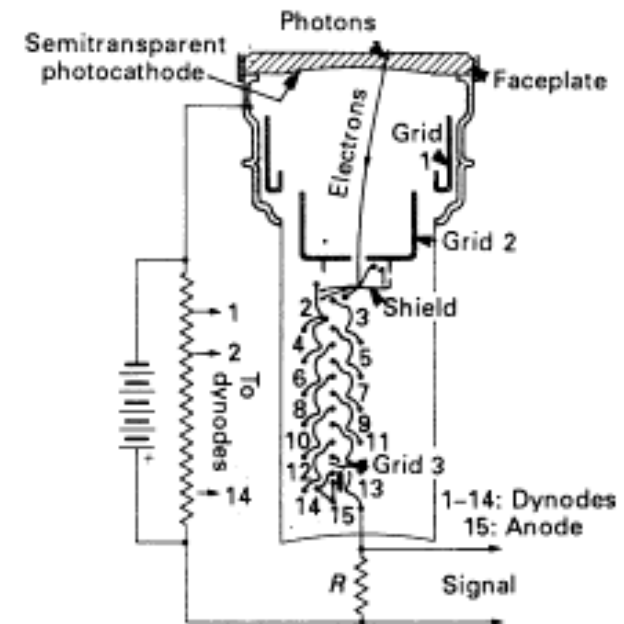
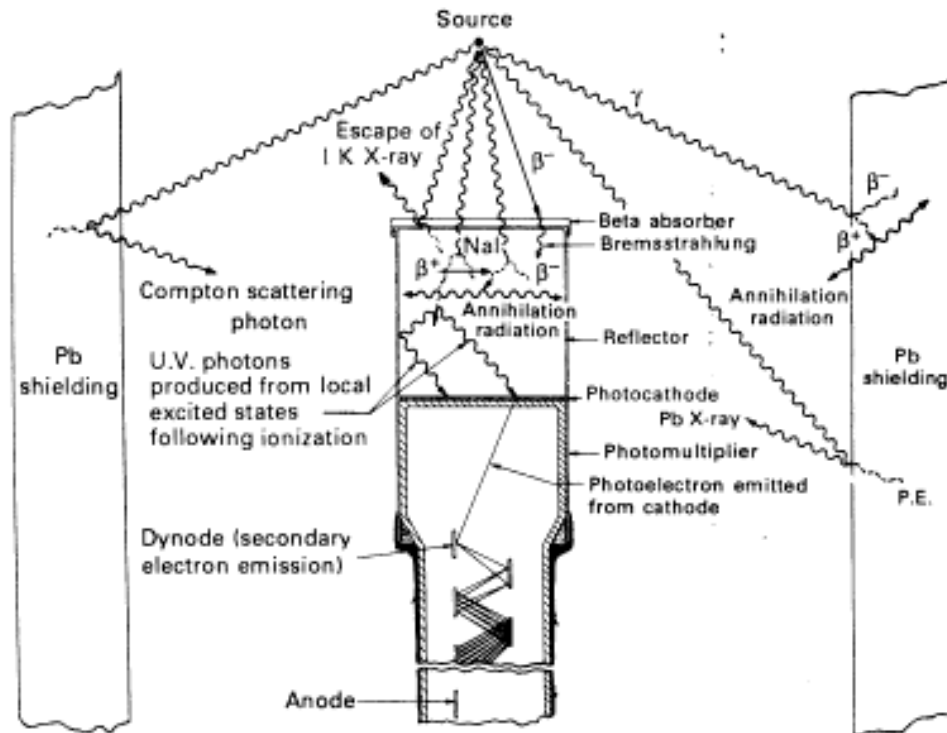
PMT  
Collection



# Scintillator Detectors



# Scintillation Detectors





# Risposta del rivelatore - 1

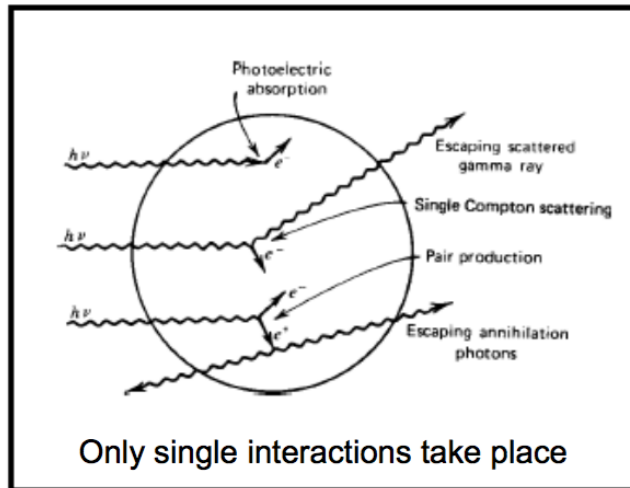


Figure 9: "Small" detector

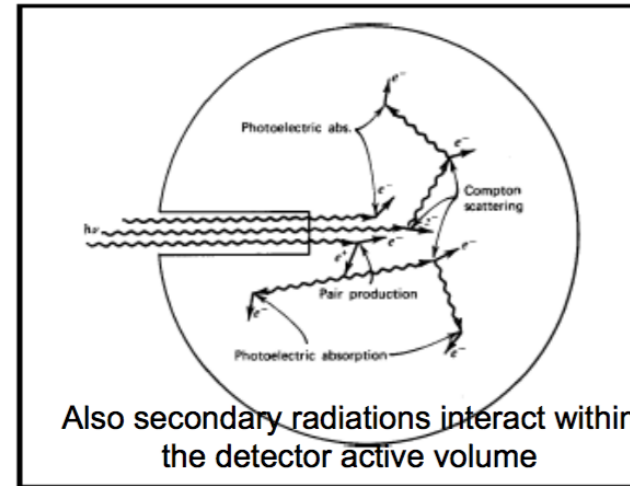


Figure 10: "Large" detector

most of the "secondary products" remain in the detector

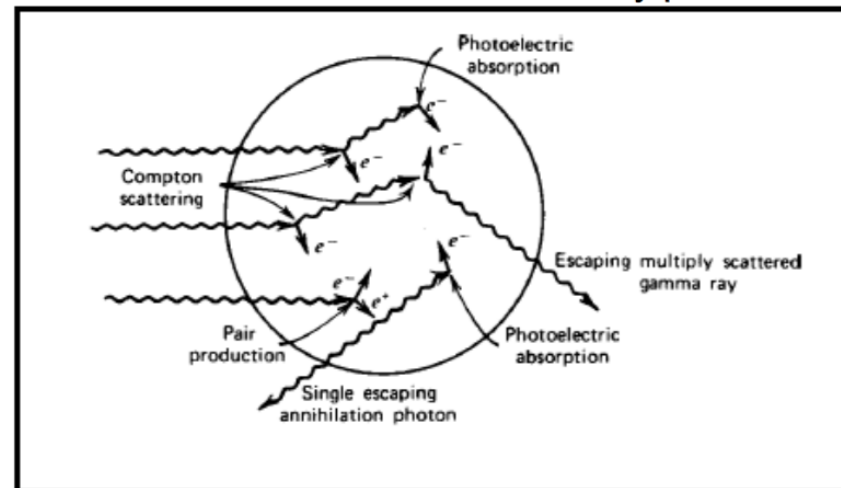
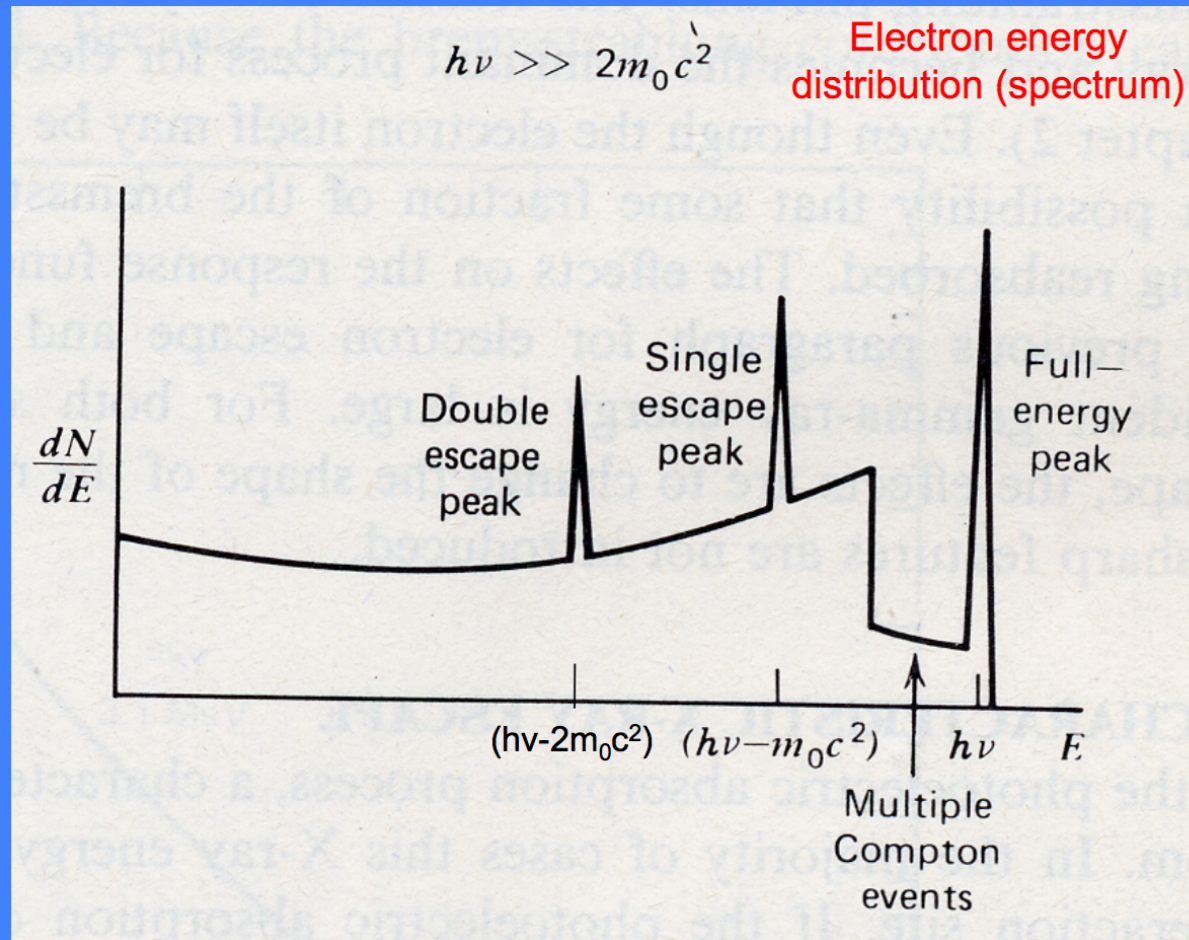


Figure 11: Intermediately sized detector

# Risposta del rivelatore - 2



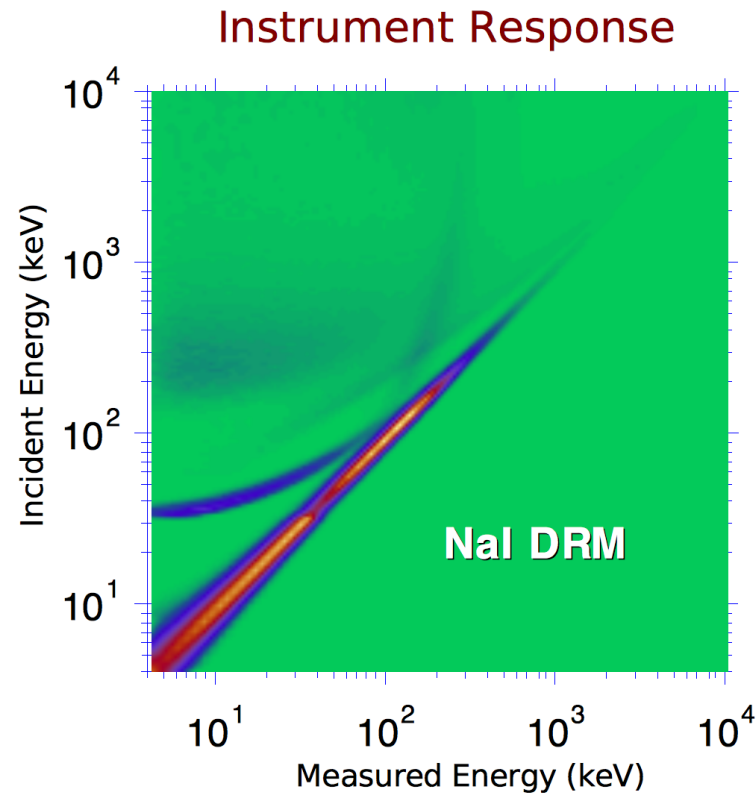
**Photo-peak (full-energy peak):** all photoelectric events remain in the detector and produce an energy deposit at the energy of the incoming photon

**Single-escape peak:** one annihilation photon leaves the detector without further interaction

**Double-escape peak:** both annihilation photons leave the detector (escape)

Case of intermediate-size detector (Knoll)

# Detector Response Matrix

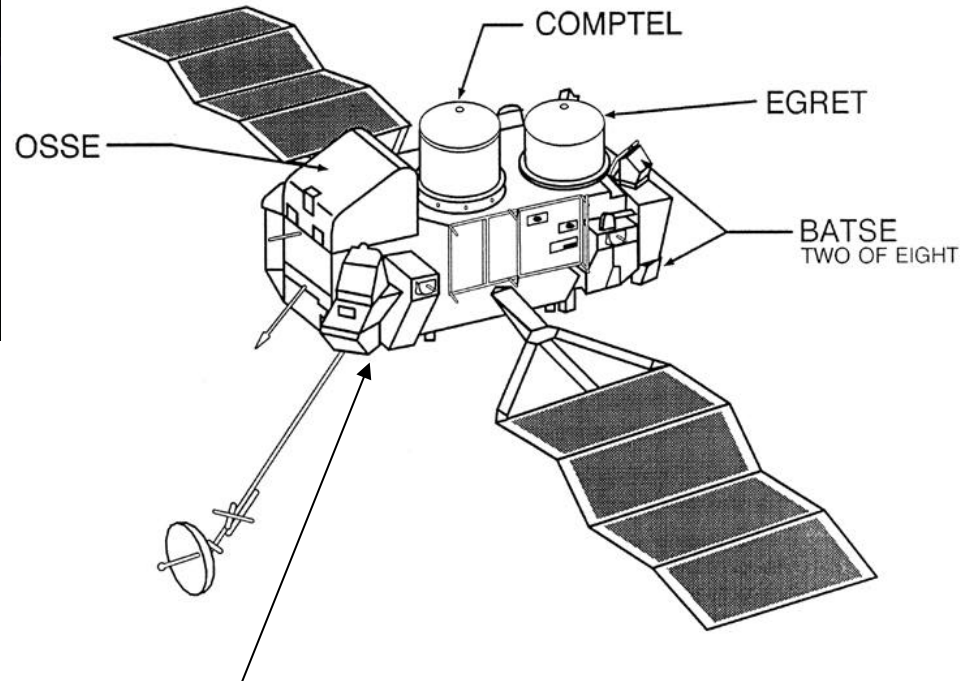


The response of a detector, which signal depends of the energy of an incoming photon, distributes the photon of a certain energy over many pulse height channels according to the gain and energy resolution of the detector. Usually this resolution function is relative complicated and depends on the photon energy. Since the energy acceptance and resolution of a given detector is determined by its design it is convenient to table this function while the photon energy serves as a parameter. This procedure leads directly to a form of a matrix and gives the whole data set the name *detector response matrix*.

# CGRO-BATSE (1991-2000)



COMPTON OBSERVATORY INSTRUMENTS



The Instruments on CGRO Cover Six Orders of Magnitude in Photon Energy



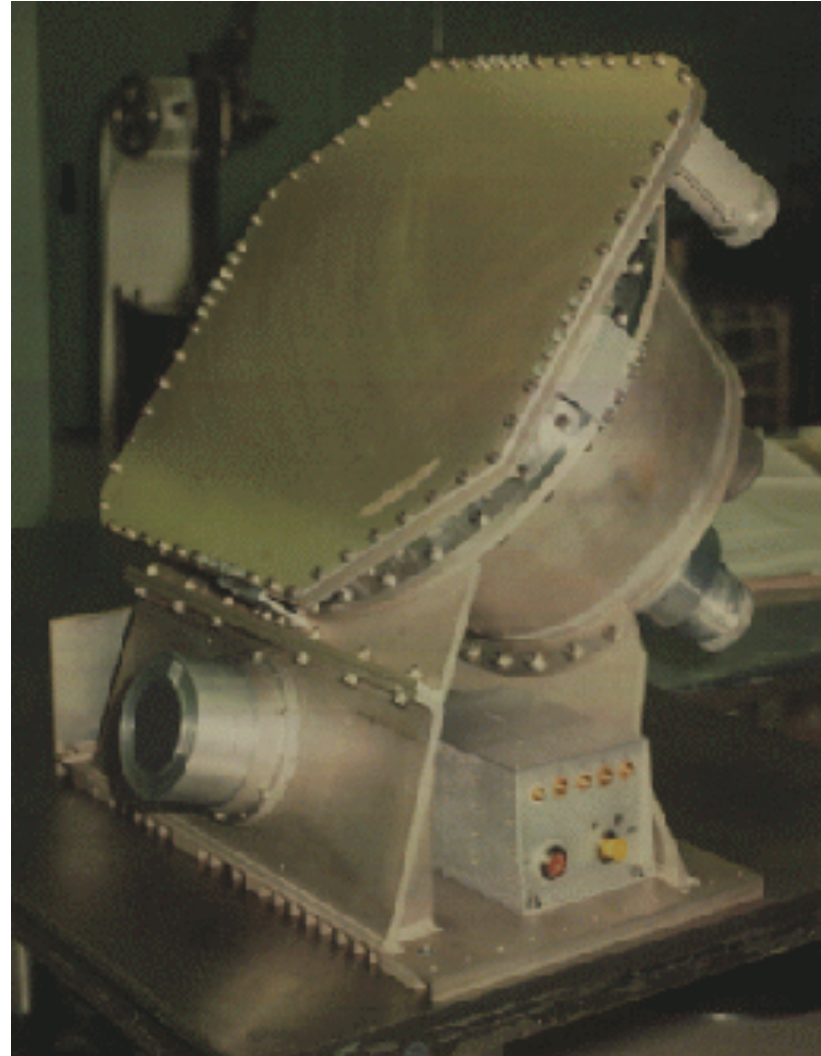
10 keV 100 keV 1 MeV 10 MeV 100 MeV 1 GeV 10 GeV 100 GeV

CGRO/BATSE (20 keV ÷ 10 MeV)



# The BATSE instrument

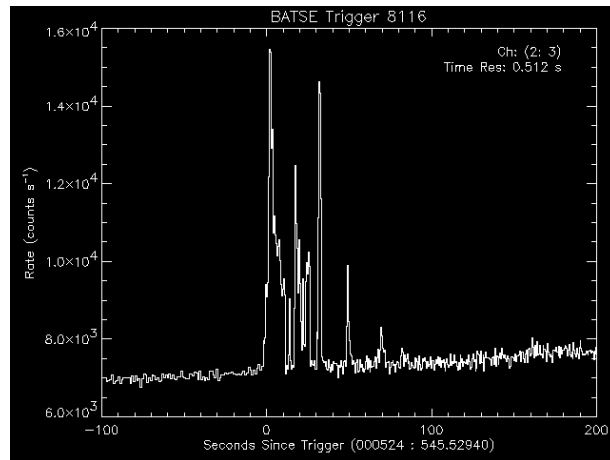
- NaI scintillators
- 20 keV – 2 MeV
- FoV  $4\pi$



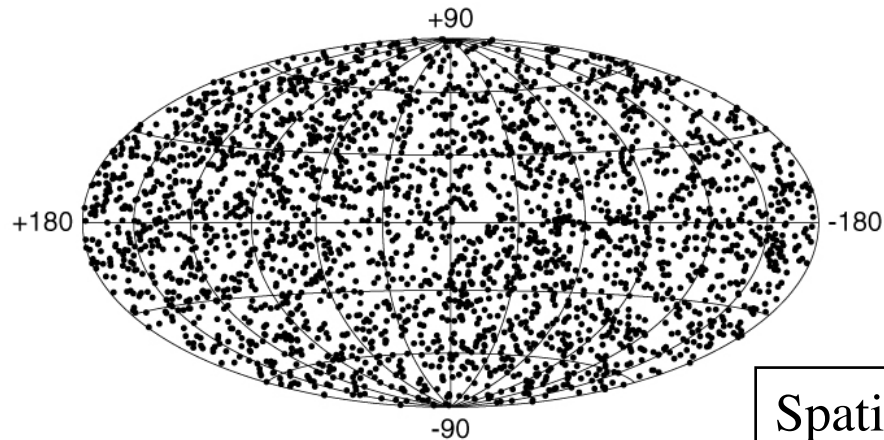


# Gamma-Ray Bursts

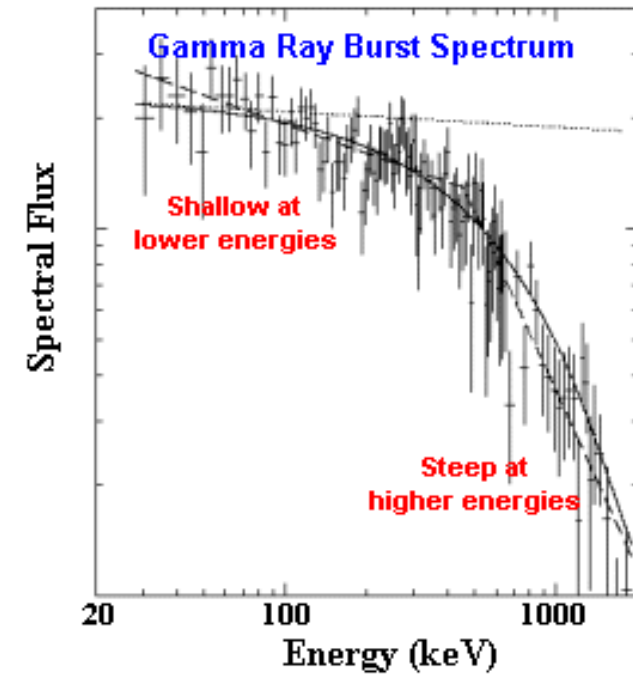
Temporal behaviour



2704 BATSE Gamma-Ray Bursts



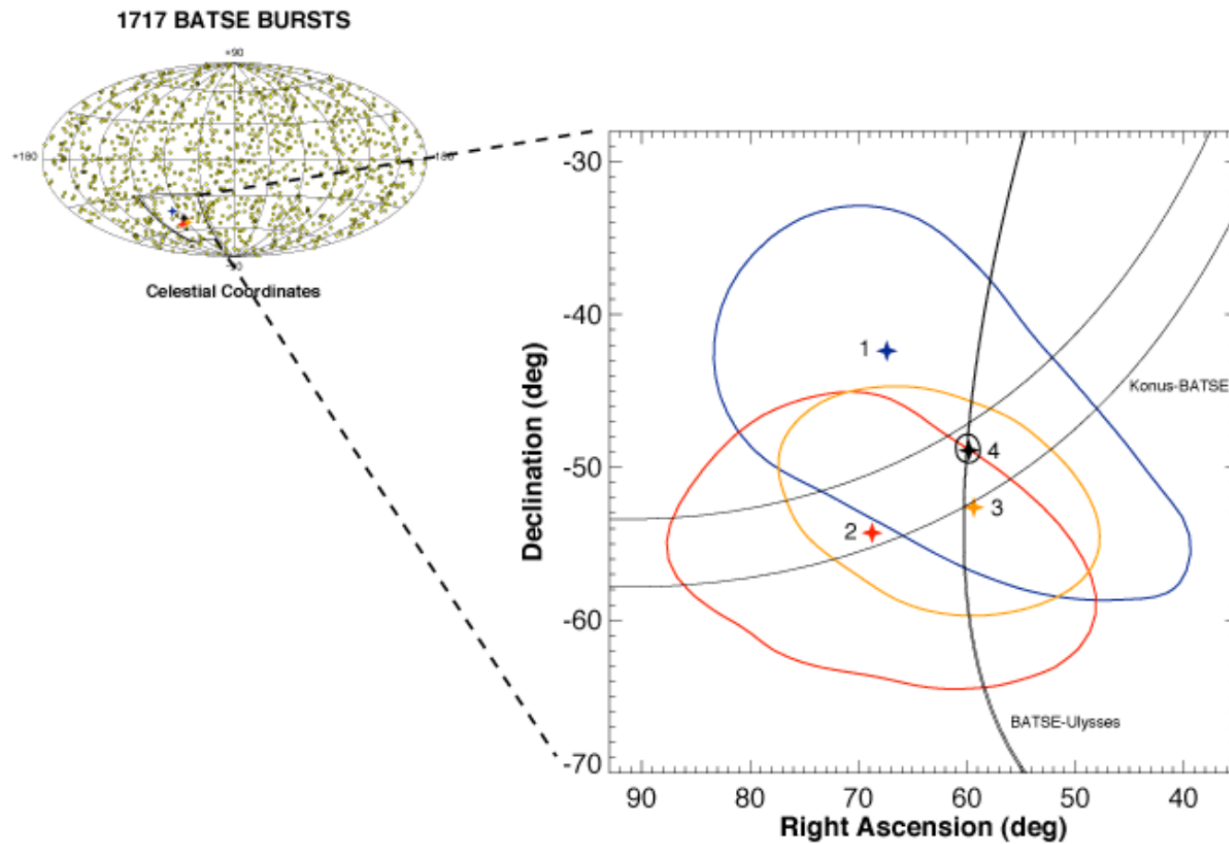
Spectral shape



Spatial distribution

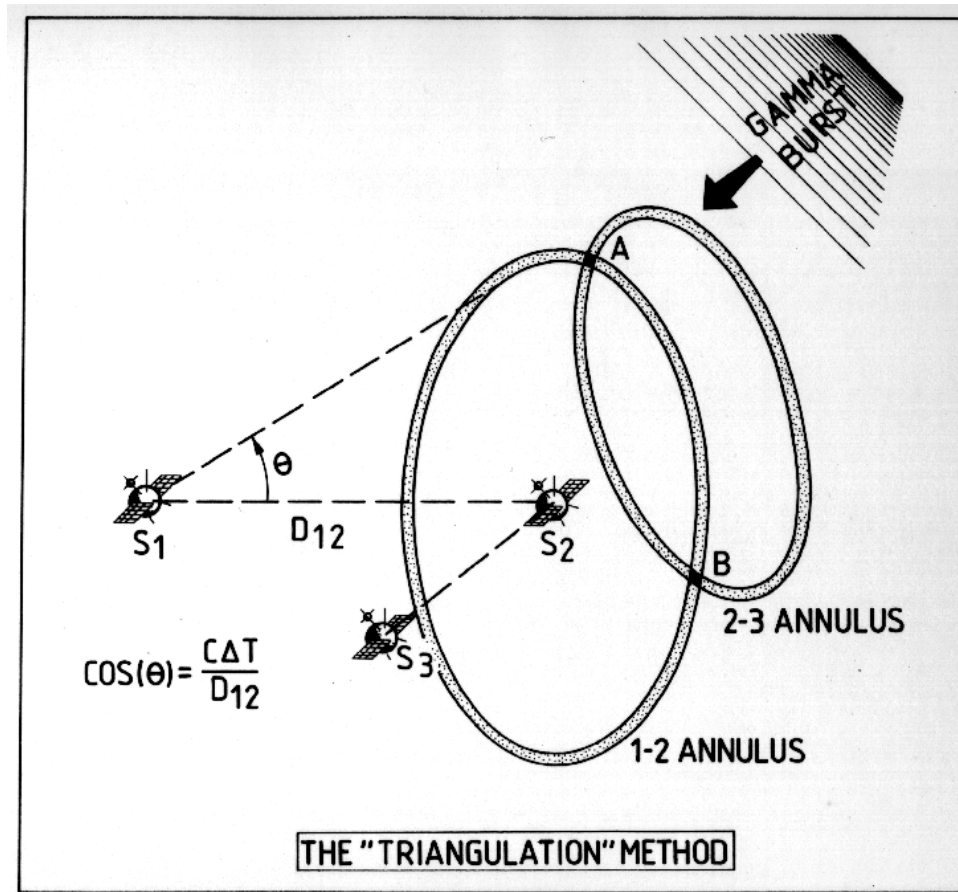
# GRB localisation

## BATSE GAMMA-RAY BURST CLUSTER



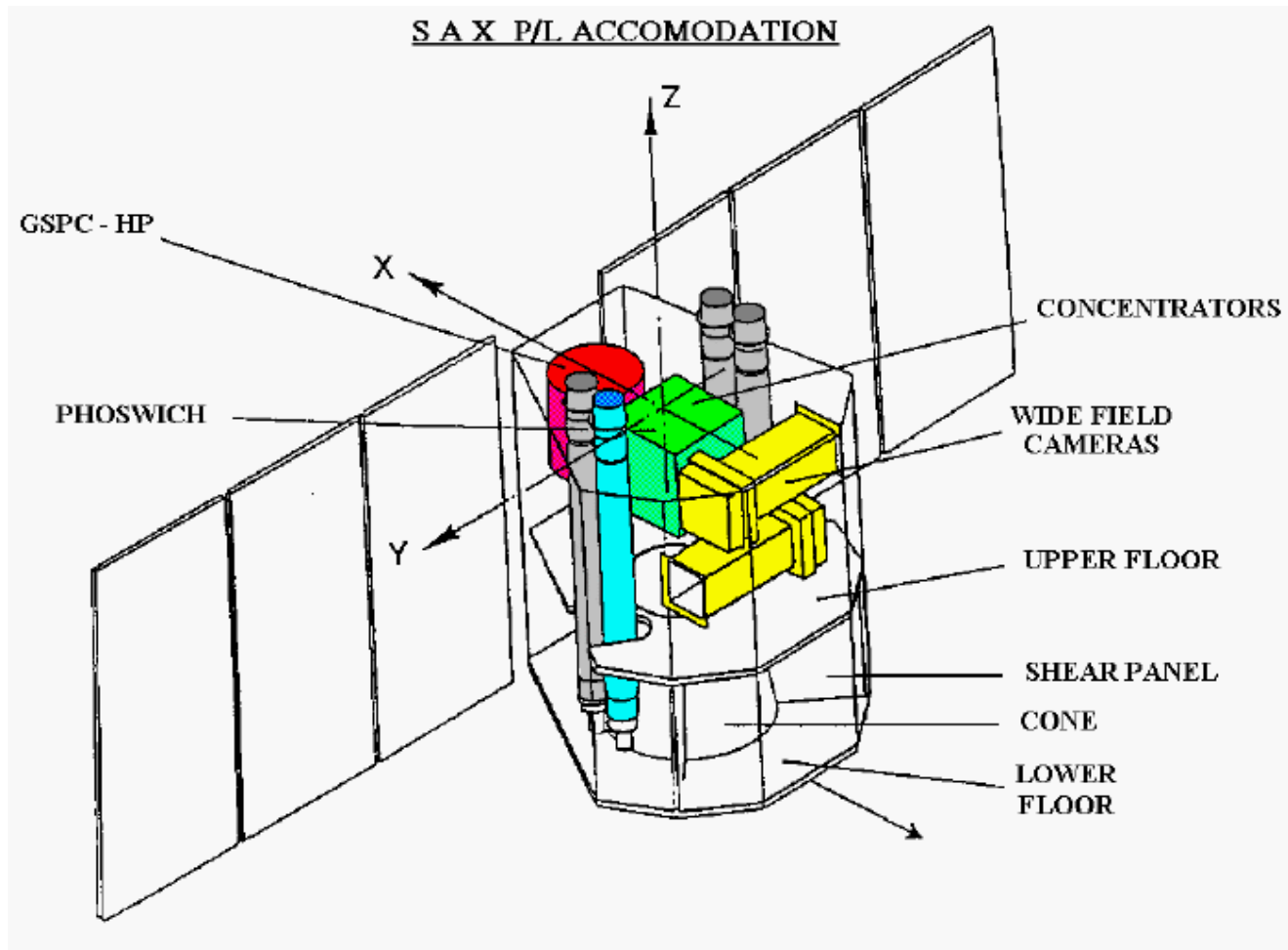
# GRB History

- Interplanetary Network (IPN)

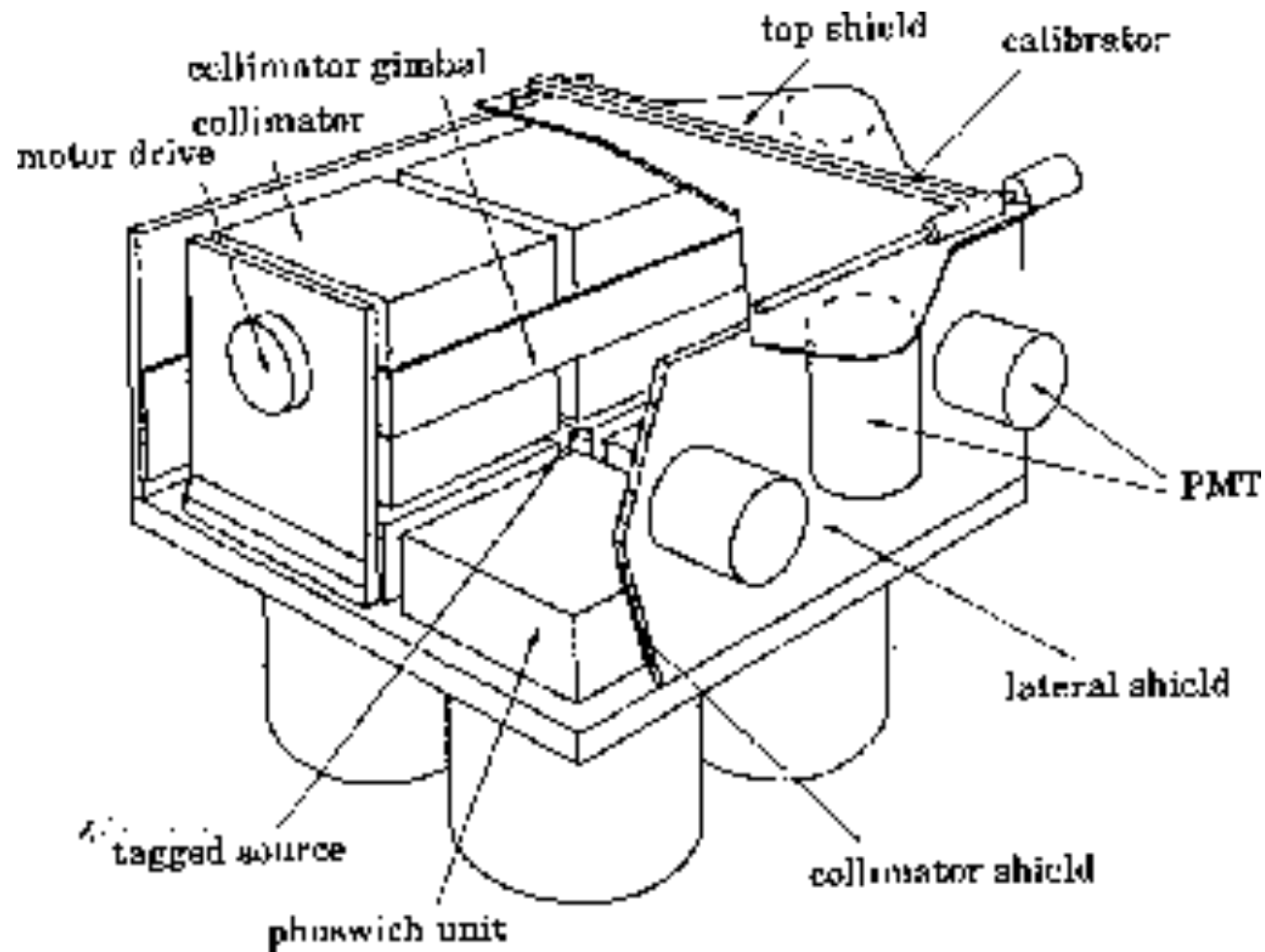


<http://www.ssl.berkeley.edu/ipn3/>

# BeppoSAX (1995 - 2002 )

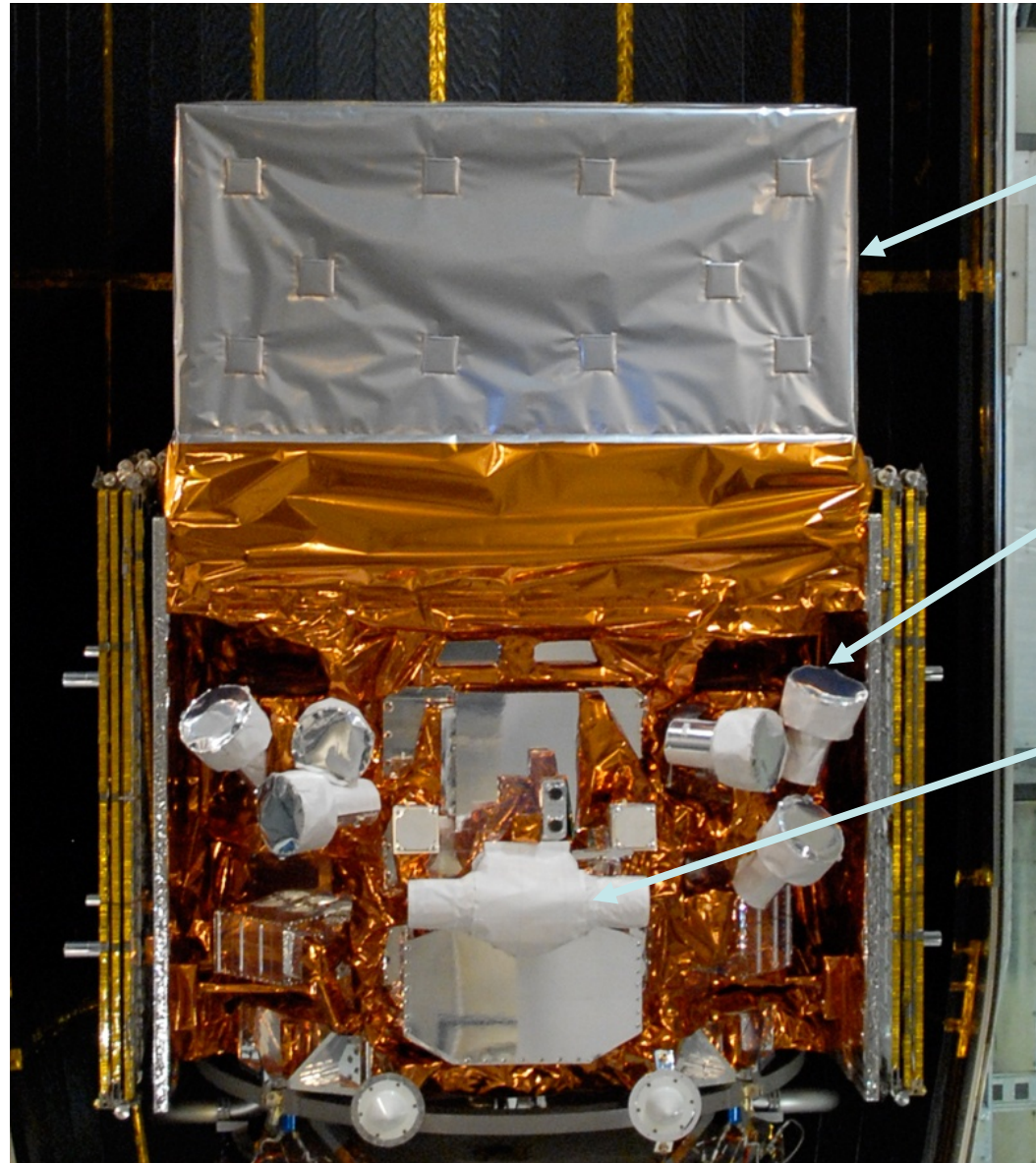


# BeppoSAX (1995 - 2002 )





# Fermi/GBM detector (2008 -- ..)



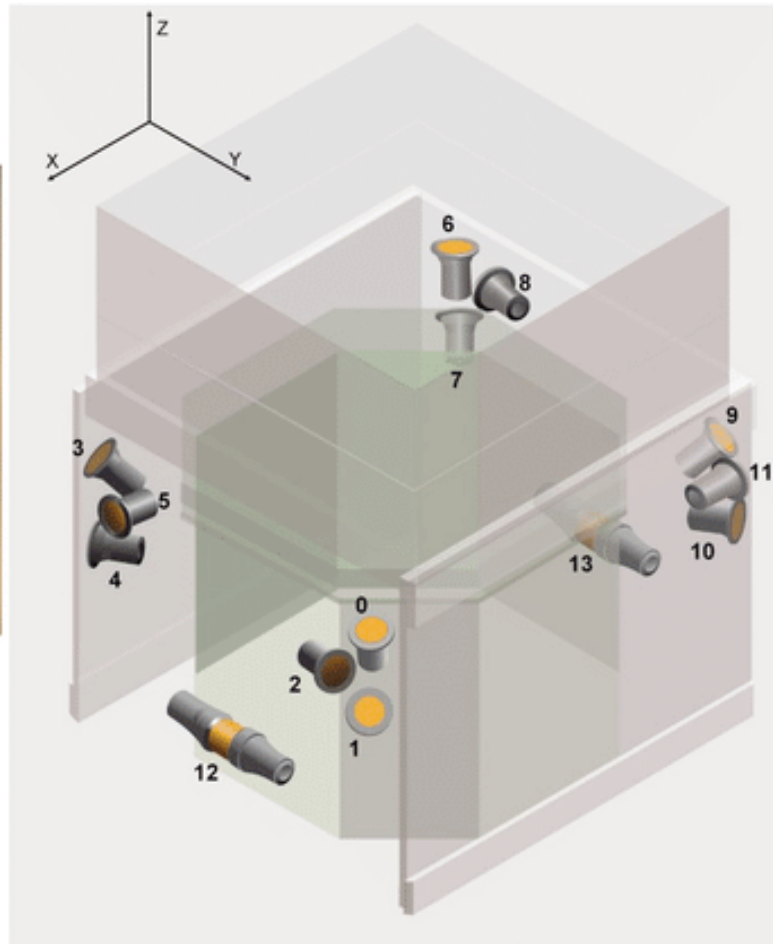
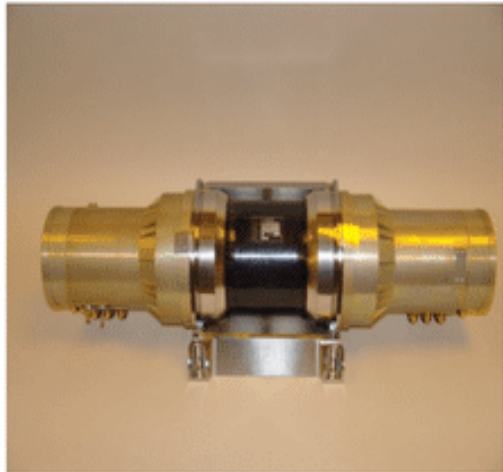
LAT

GBM  
NaI  
Detector

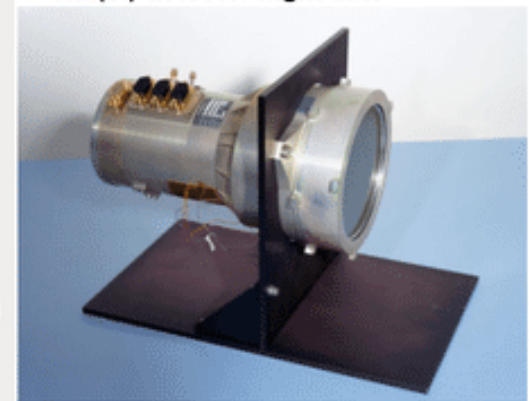
GBM  
BGO  
Detector

# Fermi/GBM detector (2008 -- ..)

BGO detector unit



Nal(Tl)-detector flight unit



# Exercise #1

- Find the web sites of BATSE
- Find the web site (if any) of BeppoSAX
- Find the web site of Fermi/GBM