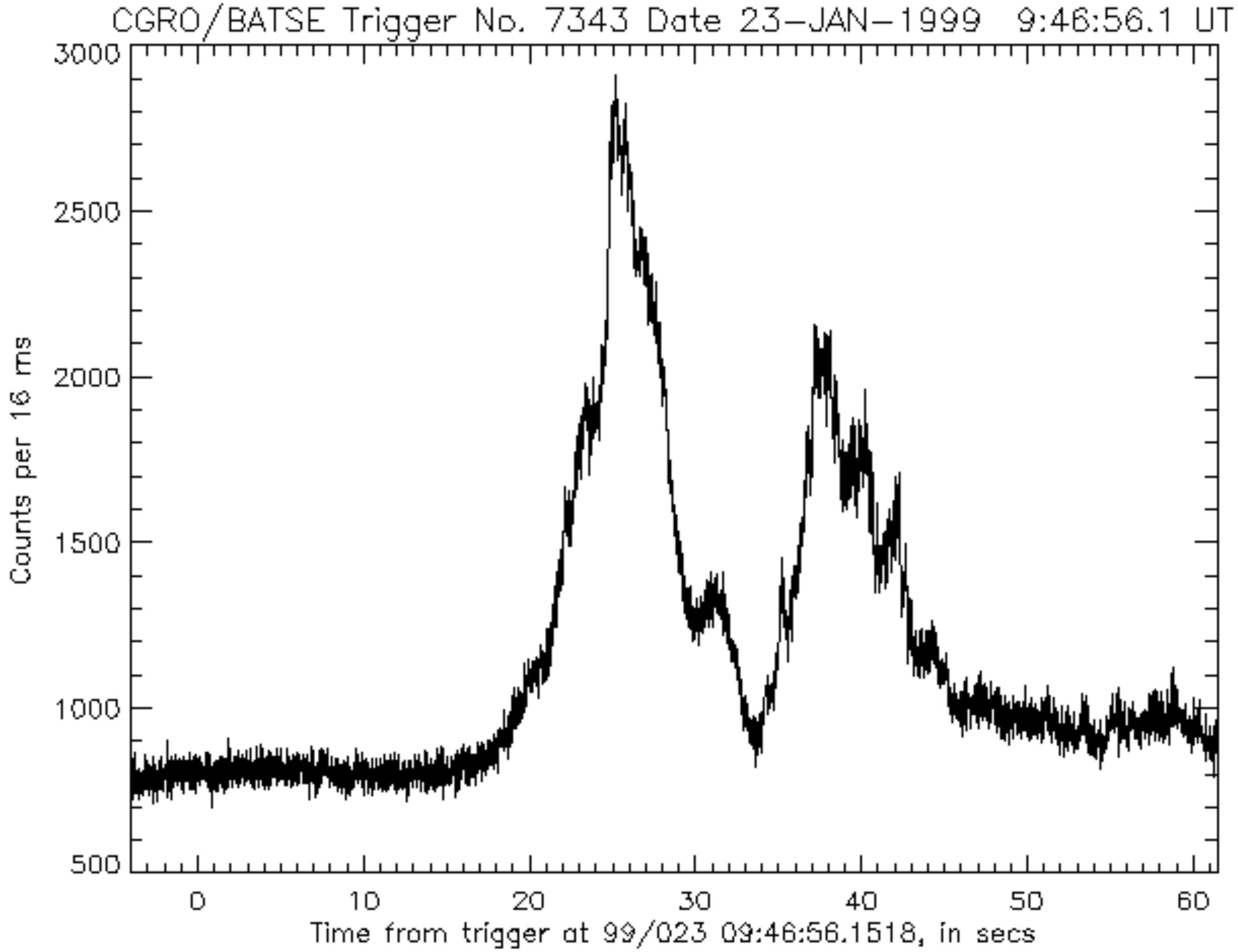
Astrofisica Nucleare e Subnucleare

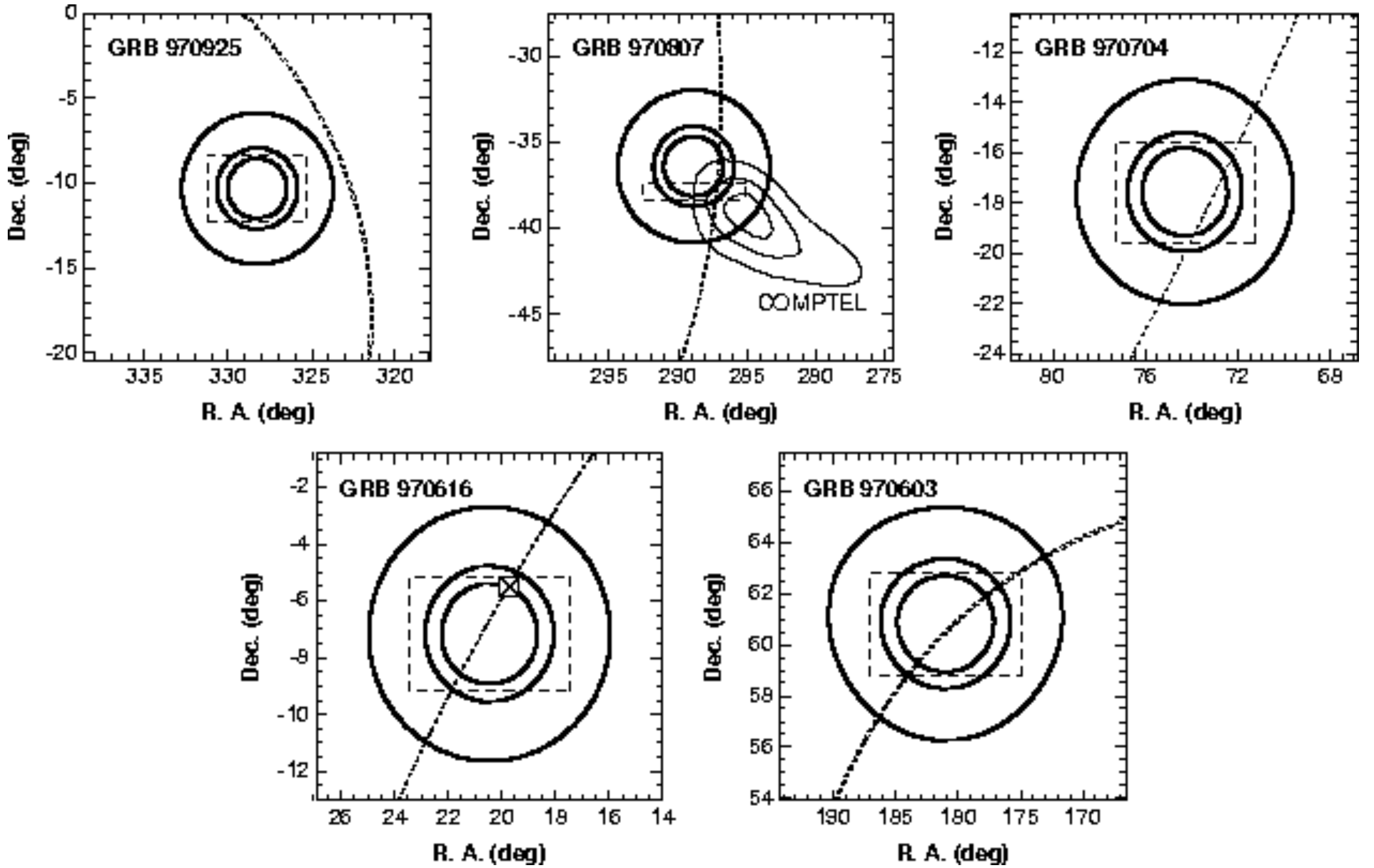
keV-MeV Astrophysics

GRB detectors I

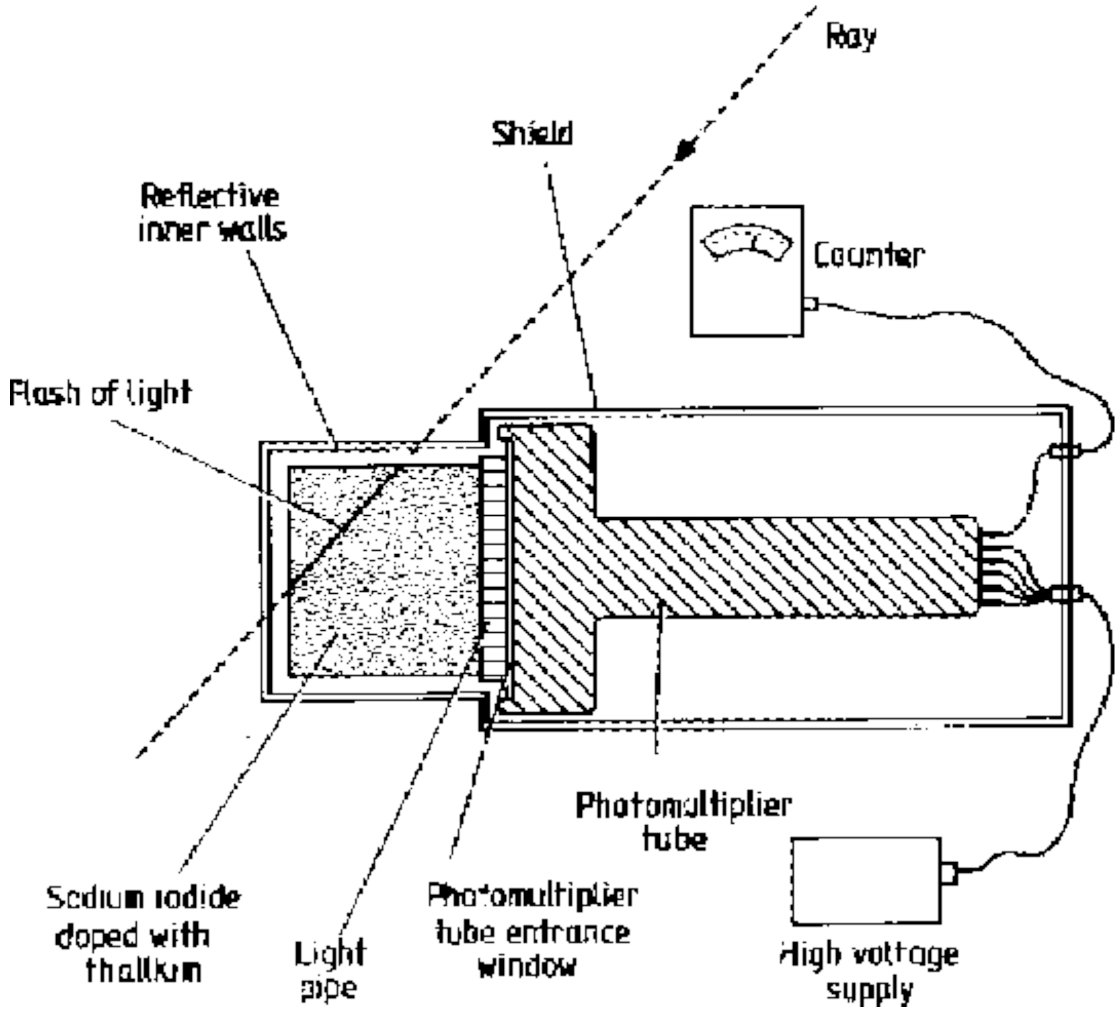
A GRB …


CGRO/BATSE Trigger No. 7343 Date 23-JAN-1999 9:46:56.1 UT
Counts per 16 ms
3000
2500
2000
1500
1000
500
0
10
20
30
40
50
60
Time from trigger at 99/023 09:46:56.1518, in secs

some GRB locations …

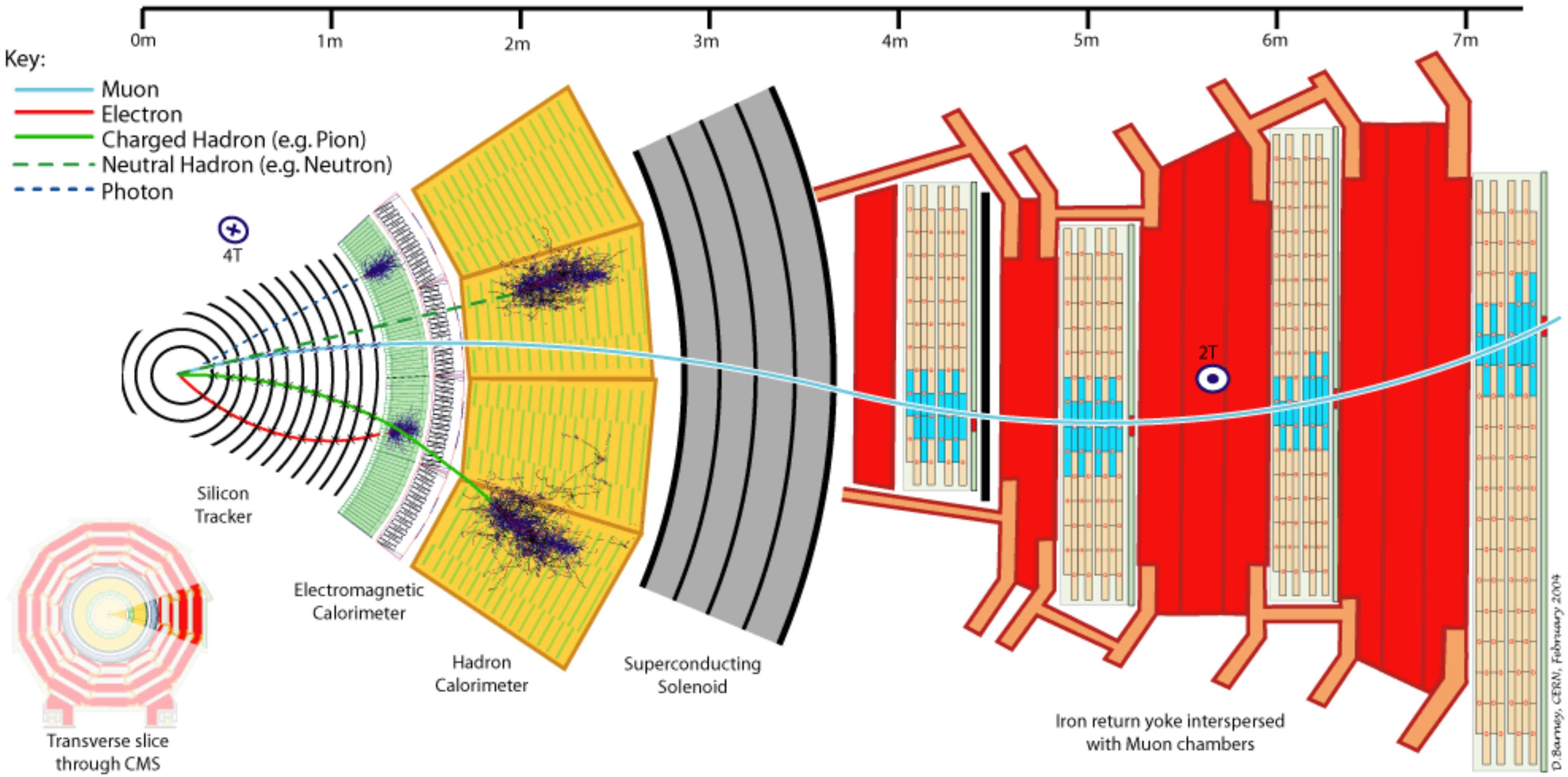


GRB Detectors



Astrofisica Nucleare e Subnucleare

Interazione Radiazione Materia

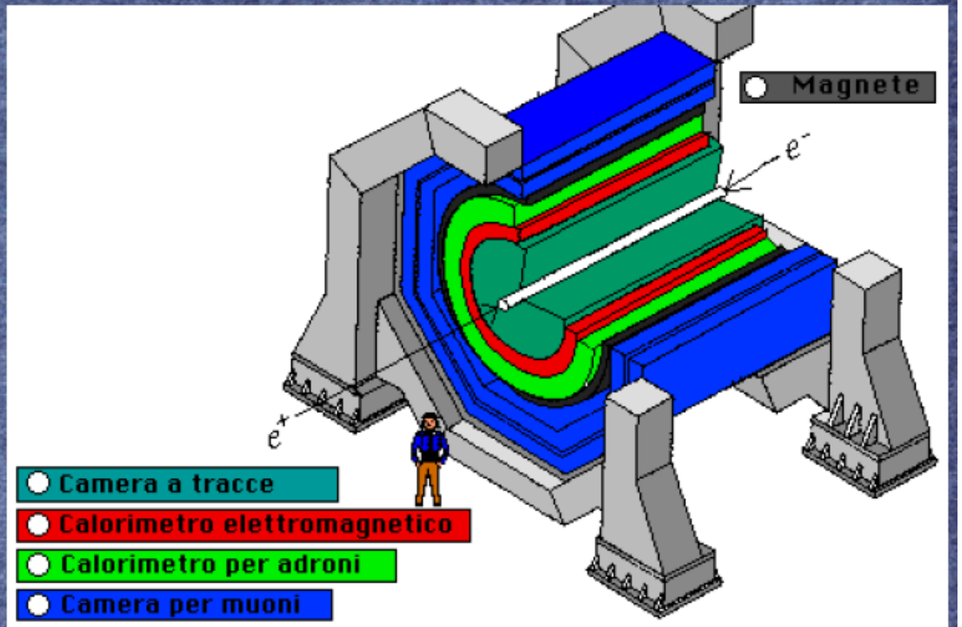


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February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

Rivelazione delle particelle elementari

Struttura tipica dei rivelatori

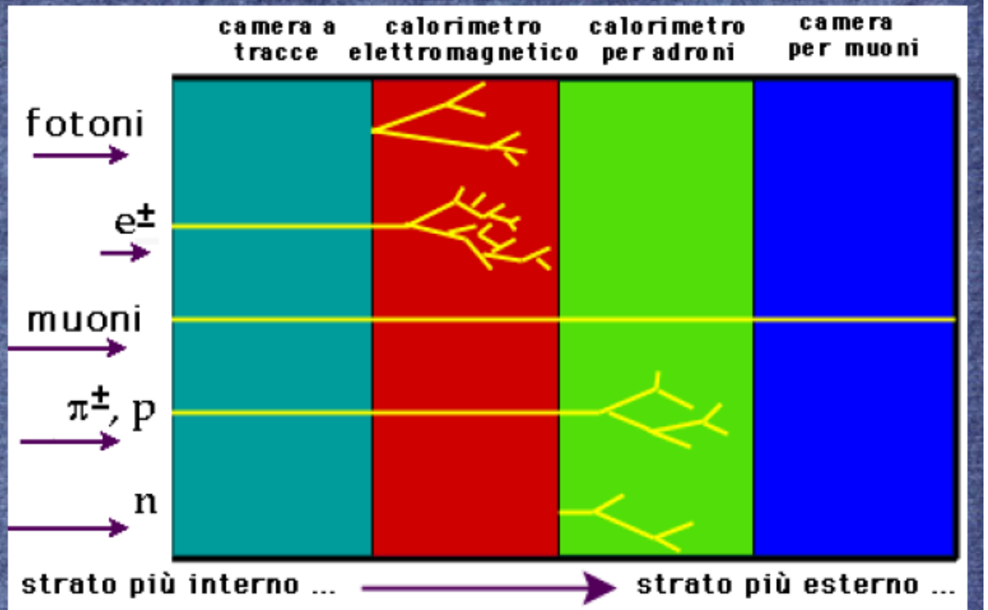
- I rivelatori di particelle sono costituiti da un insieme di sotto-rivelatori diversi.
- Le tecniche di rivelazione descritte precedentemente dettano una struttura a strati cilindrici concentrici dei rivelarori.
- Procedendo dall'asse del cilindro verso l'esterno tipicamente abbiamo:
  - un tracciatore immerso in un campo magnetico uniforme;
  - un "calorimetro elettro-magnetico" per misura-re 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

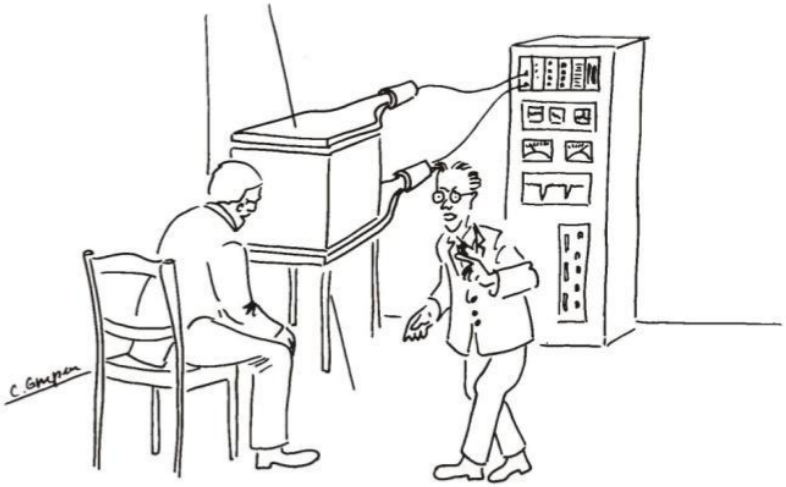
- History of Instrumentation ↔ History of Particle Physics
- The ‘Real’ World of Particles
- Interaction of Particles with Matter
- Tracking Detectors, Calorimeters, Particle Identification
- Detector Systems

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.

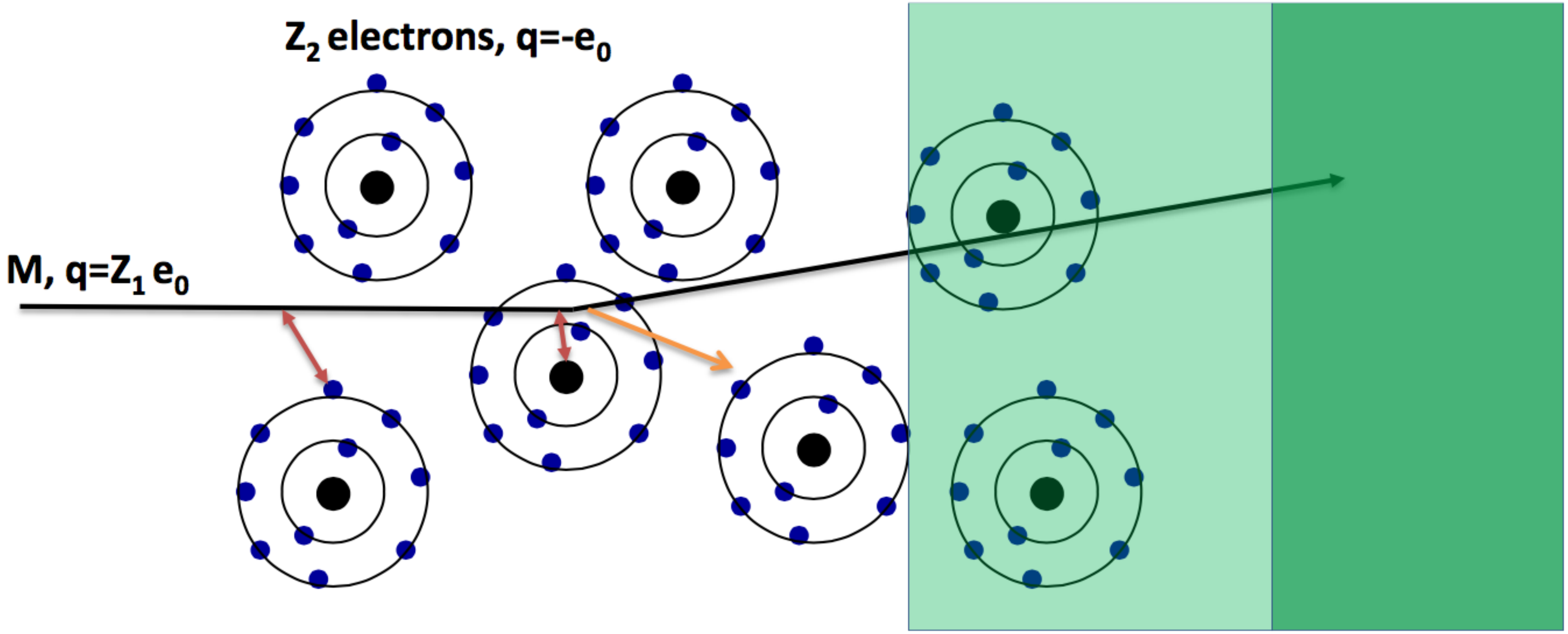
E.g. e^+e^- collider. $P_{tot}=0$,
If the $\Sigma\, p_i$ of all collision products is $\neq 0$ → neutrino escaped.



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

Claus Grupen, Particle Detectors, Cambridge University Press, Cambridge 1996 (455 pp. ISBN 0-521-55216-8)

Electromagnetic Interaction of Particles with Matter



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

Interaction with the atomic nucleus. The particle is deflected (scattered) causing <u>multiple scattering</u> of the particle in the material. During this scattering a <u>Bremsstrahlung</u> 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 <u>Cherenkov Radiation</u>. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called <u>Transition radiation</u>.

Astrofisica Nucleare e Subnucleare
Ionizzazione

Bethe Bloch Formula

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

Für Z>1, $I \approx 16 Z^{0.9}$ eV

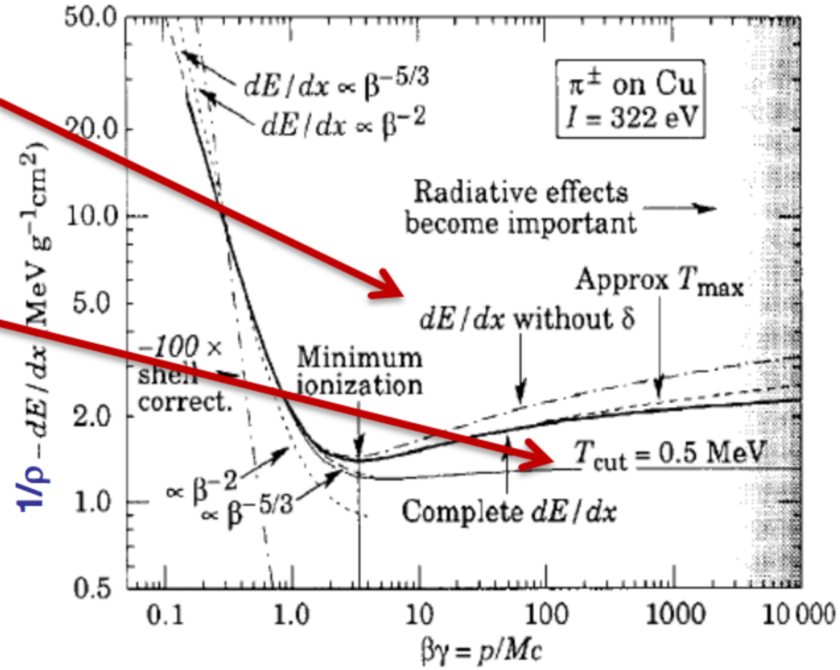
For Large $\beta\gamma$ the medium is being polarized by the strong transverse fields, which reduces the rise of the energy loss → density effect

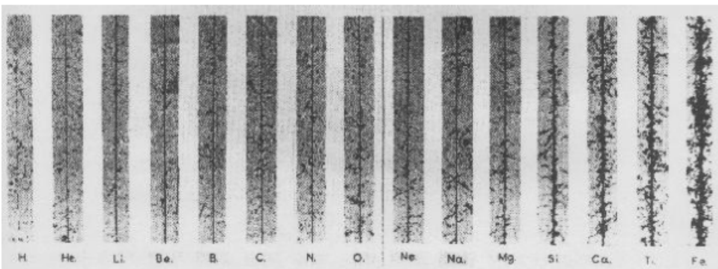
At large Energy Transfers (delta electrons) the liberated electrons can leave the material. In reality, E_{max} must be replaced by E_{cut} and the energy loss reaches a plateau (Fermi plateau).

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

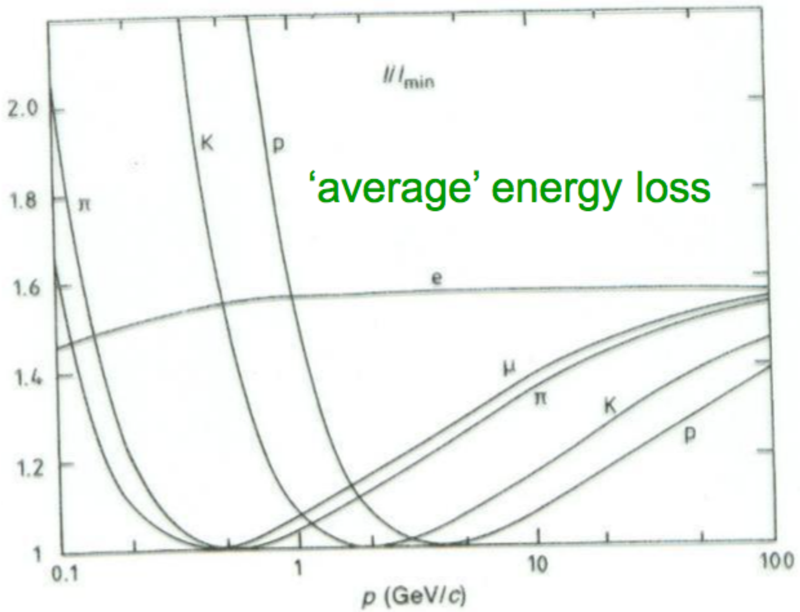
The specific Energy Loss $1/\rho\ dE/dx$

- first decreases as $1/\beta^2$
- increases with $\ln \gamma$ for $\beta = 1$
- is ≈ independent of M ($M \gg m_e$)
- is proportional to Z_1^2 of the incoming particle.
- is ≈ independent of the material (Z/A ≈ const)
- shows a plateau at large $\beta\gamma$ (>>100)
- dE/dx ≈ 1-2 x ρ [g/cm³] MeV/cm

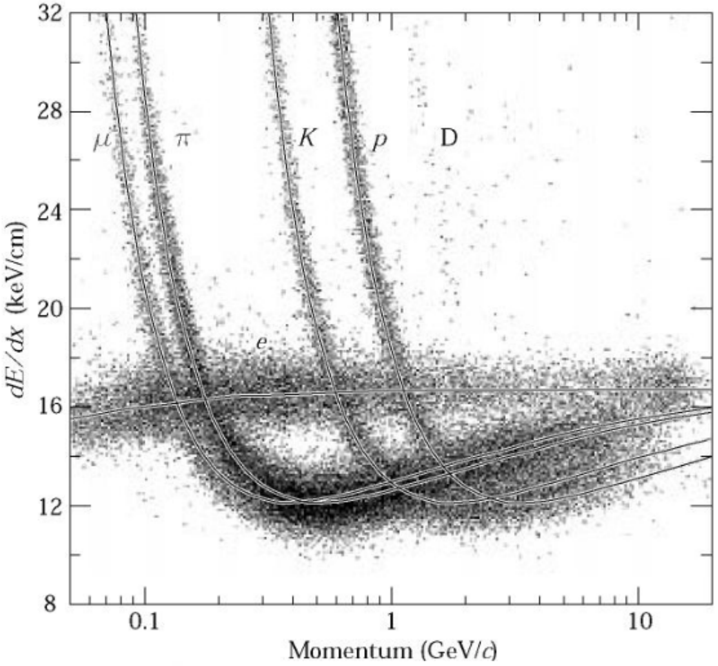




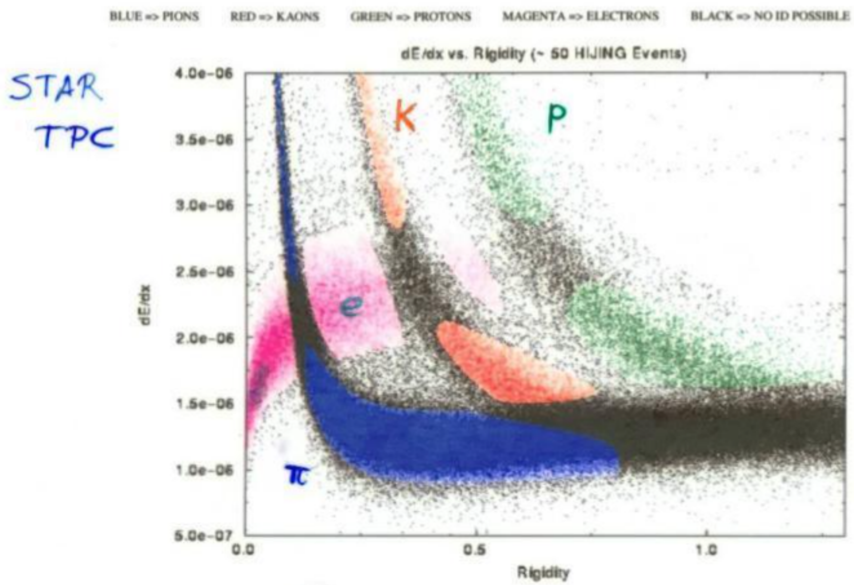
Particle Identification



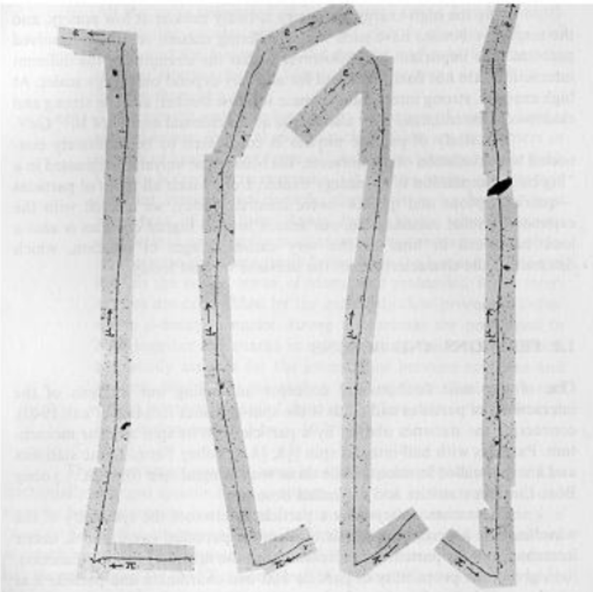
Measured energy loss



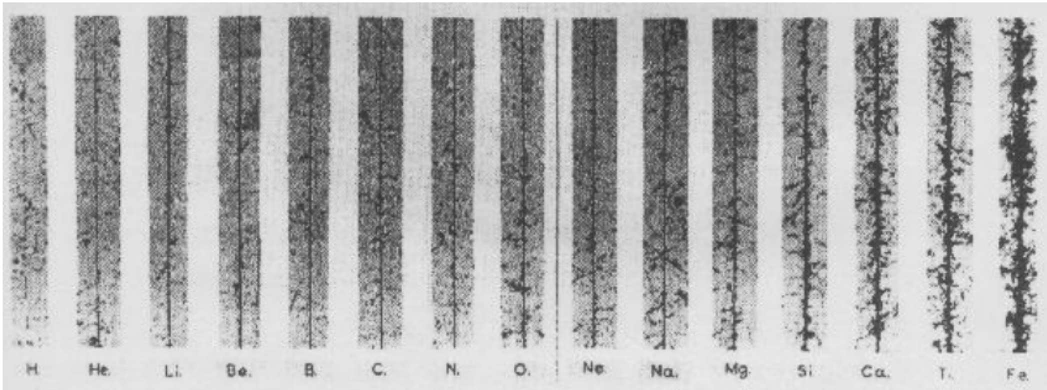
In certain momentum ranges, particles can be identified by measuring the energy loss.



Small energy loss
→ Fast Particle

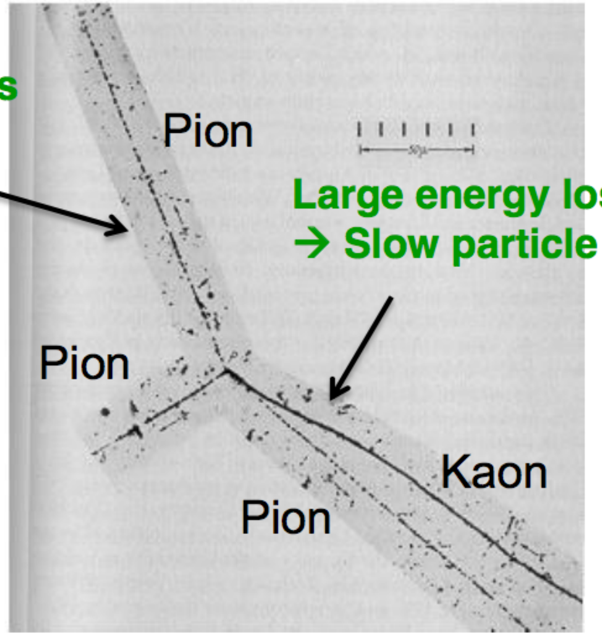


Discovery of muon and pion



Cosmis rays: dE/dx α Z^2

Small energy loss
→ Fast particle

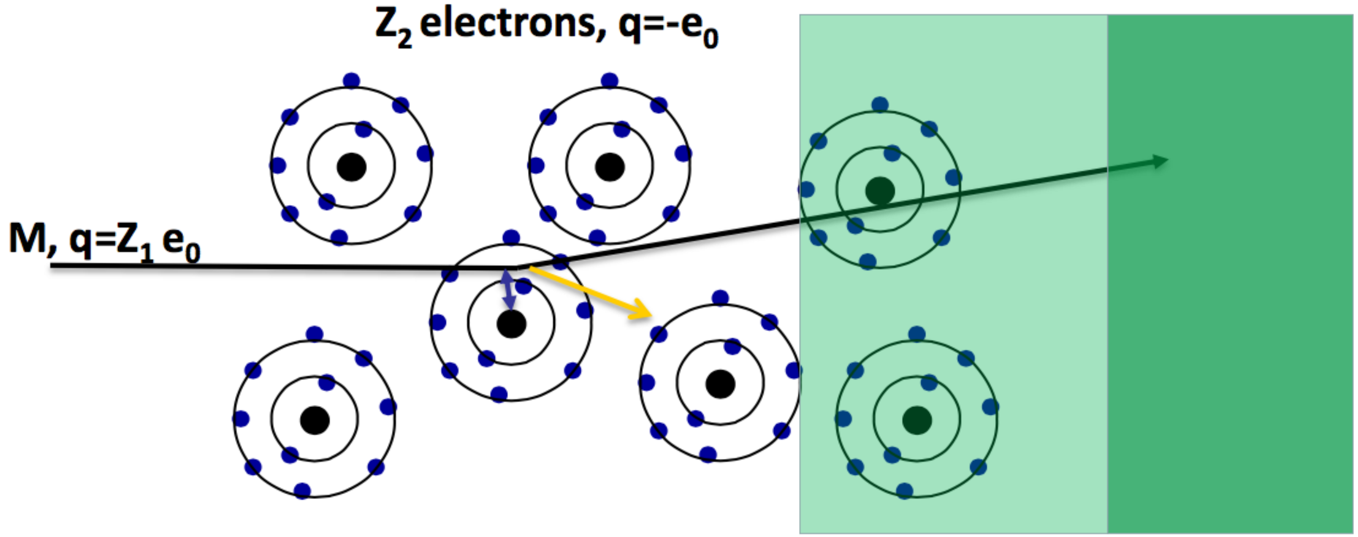


Large energy loss
→ Slow particle

Astrofisica Nucleare e Subnucleare
Bremsstrahlung

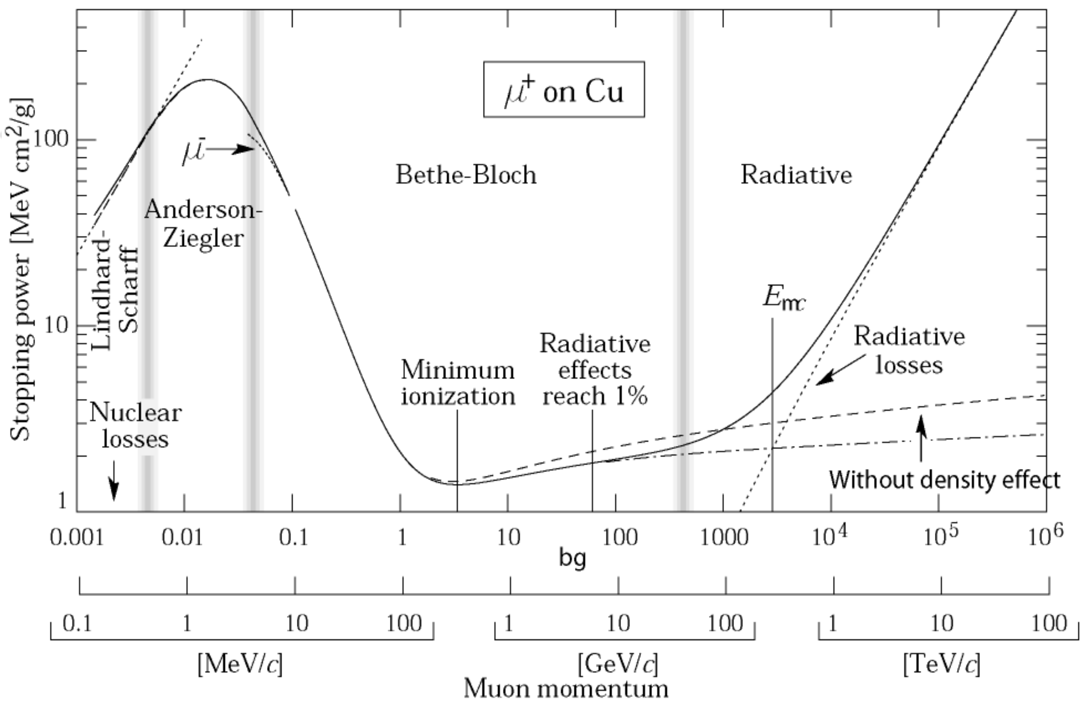
Bremsstrahlung

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 → Bremsstrahlung.



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

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.

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

Myon in Copper: p ≈ 400GeV
Electron in Copper: p ≈ 20MeV

Astrofisica Nucleare e Subnucleare

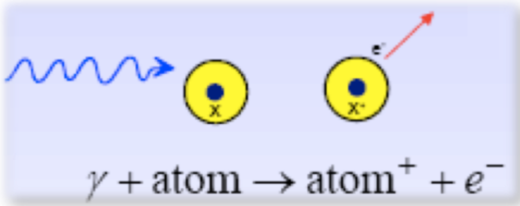
Interazione di Fotoni

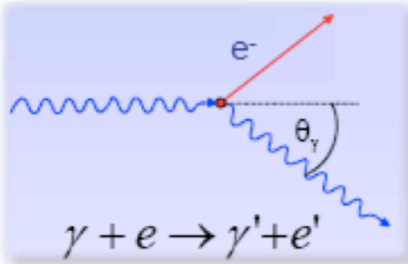
Interactions of photons with matter

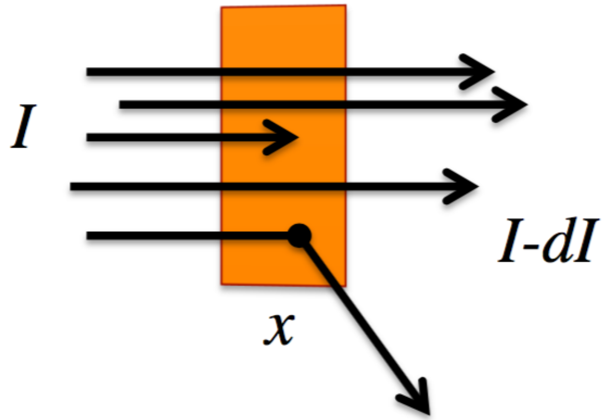
Characteristic for interactions of photons with matter:

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

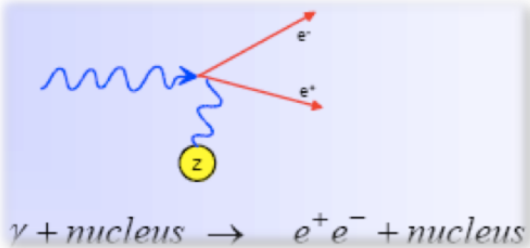
1) Photoelectric Effect 2) Compton Scattering







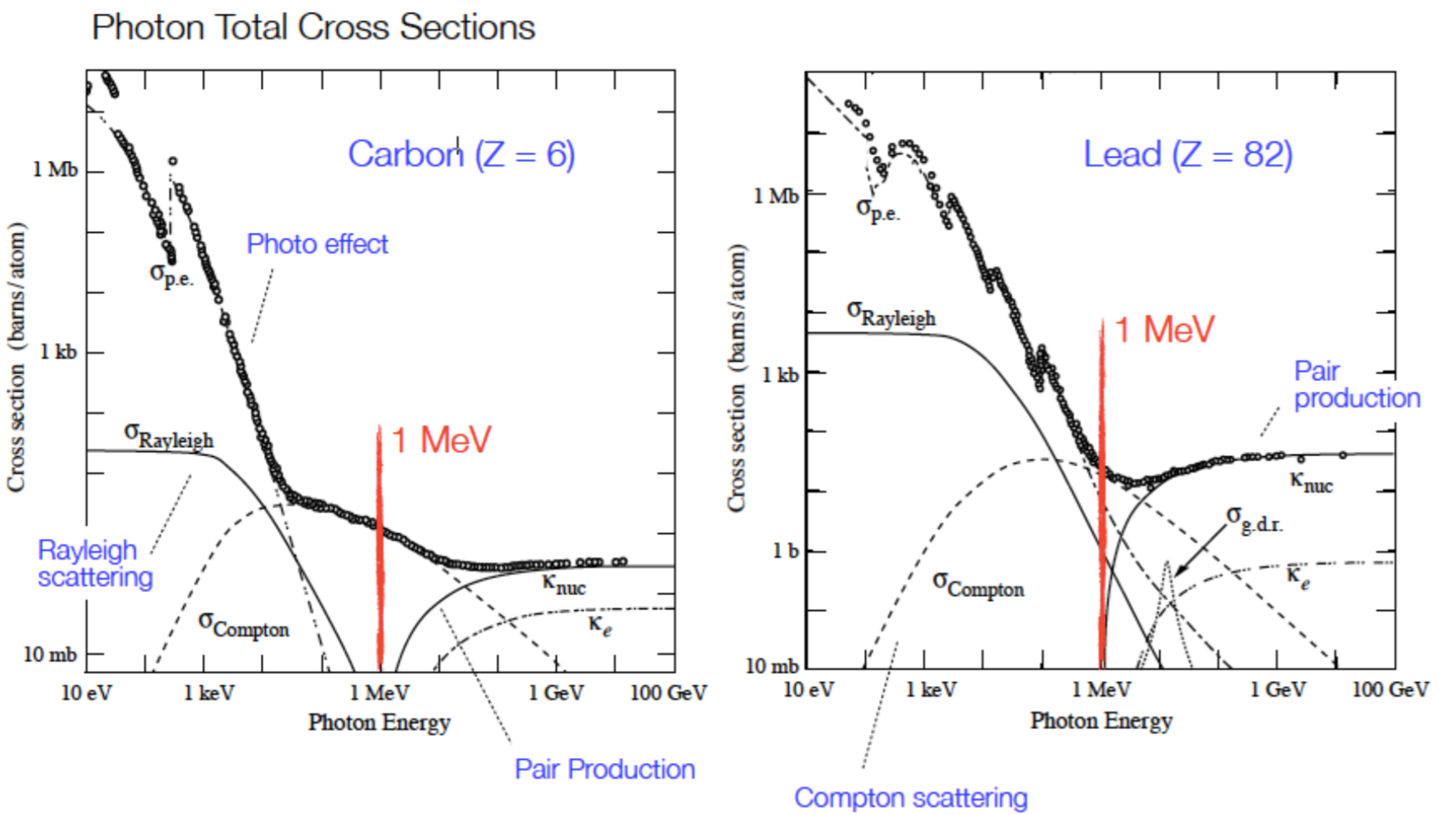
3) Pair Production



$$I(x) = I_0$$

$$\lambda = 1/\mu$$ Mean free path

Interactions of photons with matter

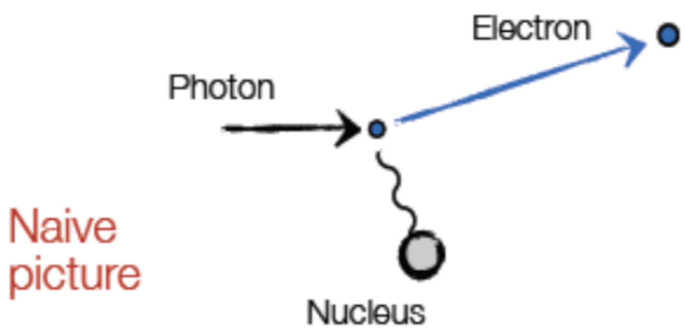


Photoelectric effect

From energy conservation:

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

I_b = Nucleus binding energy
introduces strong Z dependence



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

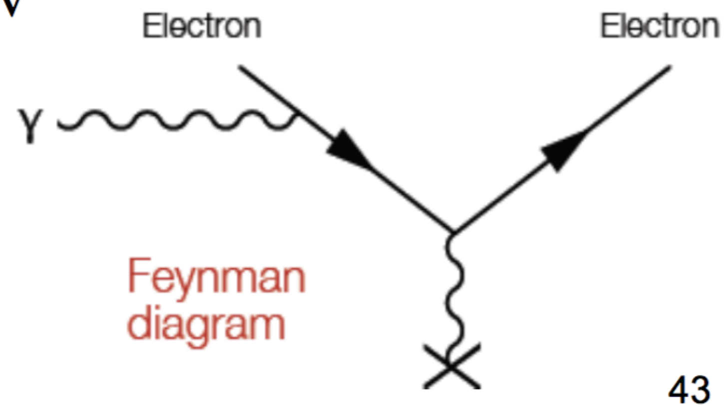
$$\sigma_{ph} = \alpha\pi a_B Z^5 (I_0 / E_\gamma)^{7/2}$$

$$a_B = 0.53\ \text{Å}$$
$$I_0 = 13.6\ \text{eV}$$

γ + atom → e^- + atom$^+$

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

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



Compton scattering

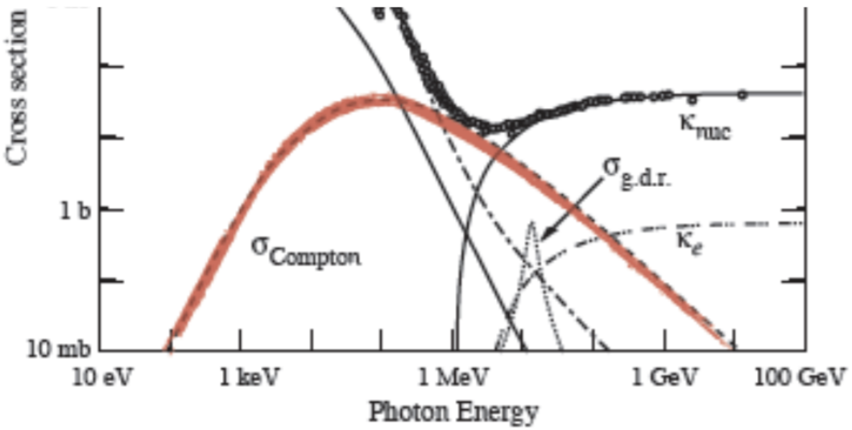
Best known electromagnetic process
(Klein–Nishina formula)

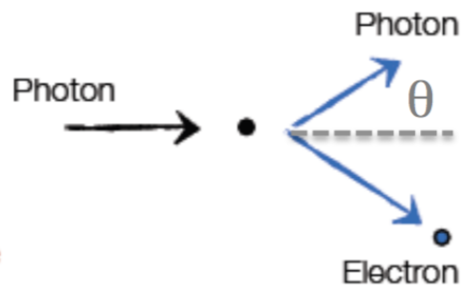
for $E_\lambda << m_e c^2$ $\quad \boxed{\sigma_c \propto \sigma_{Th}(1-2\varepsilon)}$

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

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

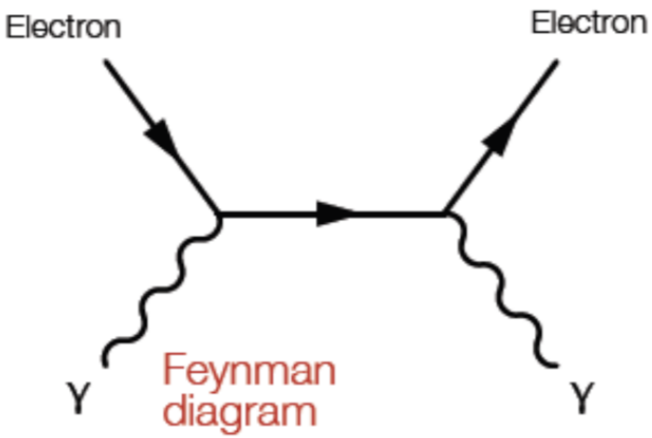
for $E_\lambda >> m_e c^2$ $\quad \boxed{\sigma_c \propto \frac{\ln \varepsilon}{\varepsilon} Z}$





Naive picture

$\gamma + e^- \rightarrow (\gamma)' + (e^-)'$



Feynman diagram

Compton scattering

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

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

Kinetic energy of the outgoing electron:

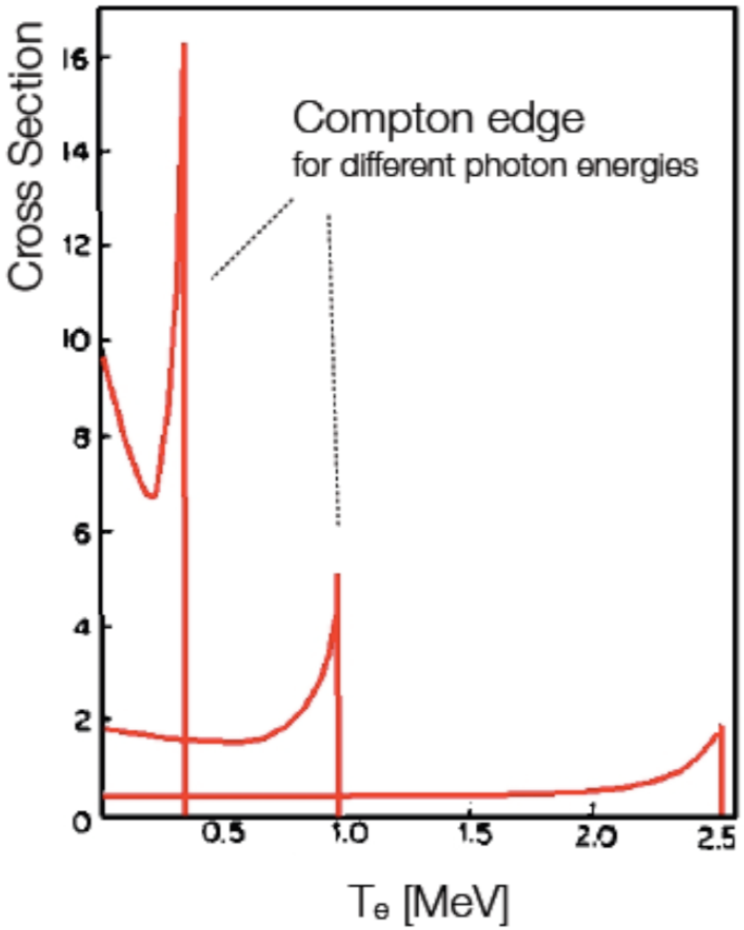
$$T_e = E_\gamma - E_\gamma' = E_\gamma \frac{\varepsilon(1-\cos\theta)}{1+\varepsilon(1-\cos\theta)}$$

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

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

Transfer of complete γ-energy via Compton scattering not possible:

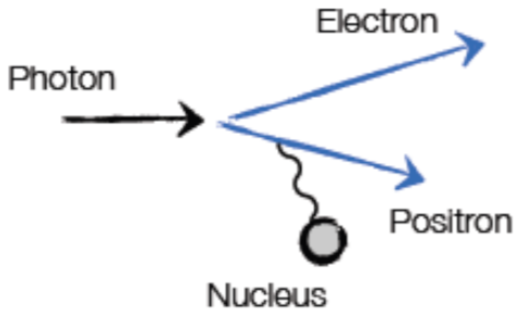
$$\Delta E = E_\gamma - T_{\max} = E_\gamma \frac{1}{1+2\varepsilon}$$



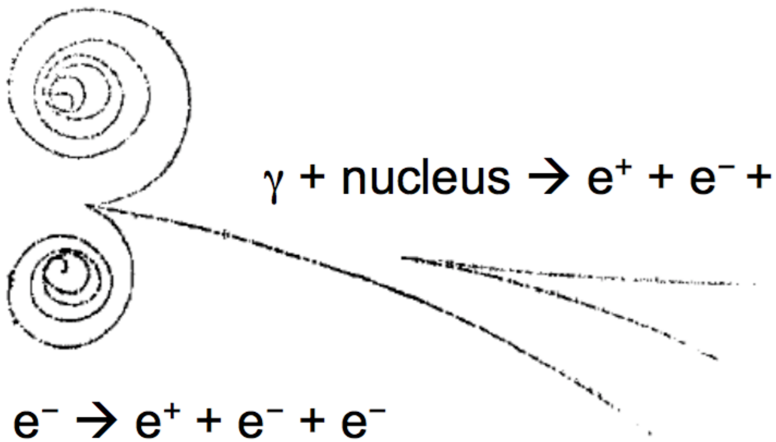
Pair production

Minimum energy required for this process
2 m_e + Energy transferred to the nucleus

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

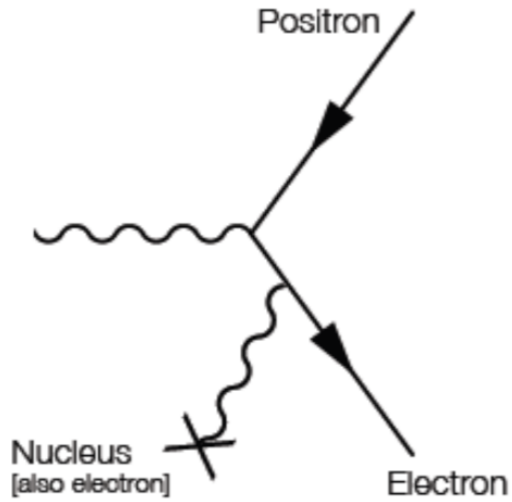


γ + atom → e⁺ + e⁻



γ + nucleus → $e^+ + e^-$ + nucleus'

$\gamma + e^- \rightarrow e^+ + e^- + e^-$

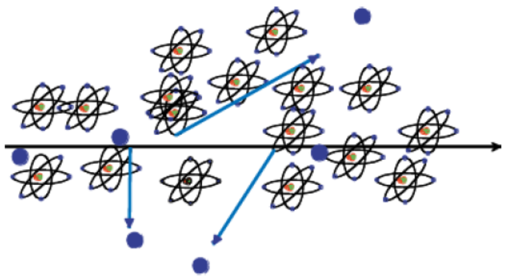


Astrofisica Nucleare e Subnucleare

Scintillation Detectors

Creation of the Signal

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

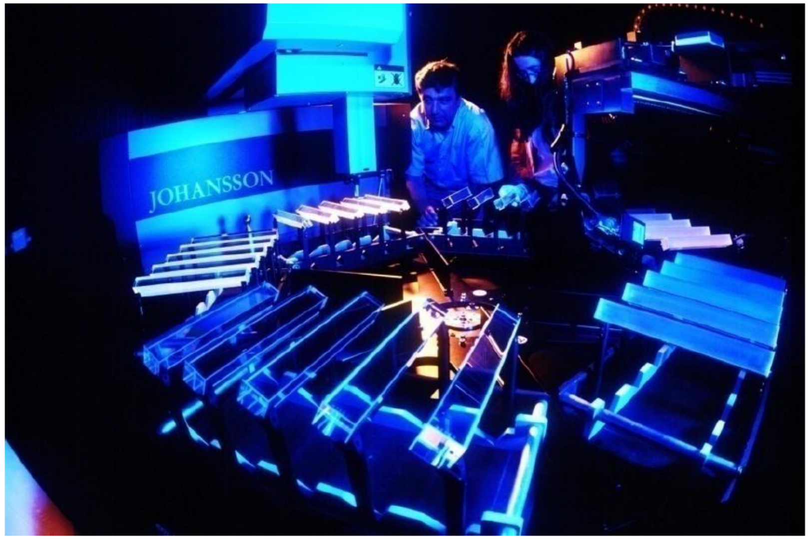


Excitation:

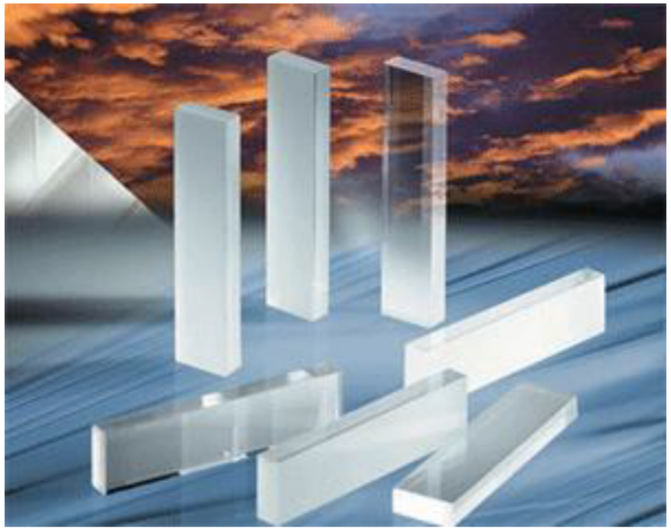
The photons emitted by the excited atoms in transparent materials can be detected with photon detectors like photomultipliers or semiconductor photon detectors.

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.

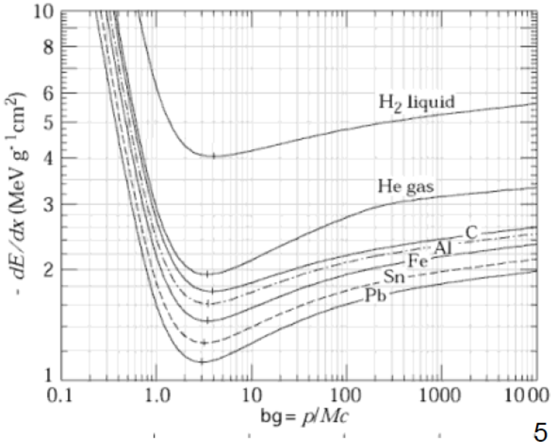
a) **Observed in Noble Gases (even liquid !)**

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) ≈ few % of the total energy Loss.
z.B. 1cm plastic scintillator, $\rho \approx 1$, dE/dx=1.5 MeV, ~15 keV in photons; i.e. ~ 15 000 photons produced.



Detectors based on Registration of excited Atoms → Scintillators

Organic ('Plastic') Scintillators

Low Light Yield **Fast: 1-3ns**

Type	Light[a] output	λ_{max}[b] (nm)	Attenuation[c] length (cm)	Risetime (ns)	Decay[d] 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	λ_{max} emission (nm)	Decay time (ns)	Density (g/cm^3)
Inorganic crystals				
NaI(Tl)	230	415	230	3.67
CsI(Tl)	250	560	900	4.51
$Bi_4Ge_3O_{12}$ (BGO)	23–86	480	300	7.13
Organic crystals				
Anthracene	100	448	22	1.25
Trans-stilbene	75	384	4.5	1.16
Naphthalene	32	330–348	76–96	1.03
p,p'-Quarterphenyl	94	437	7.5	1.20
Primary activators				
2,5-Diphenyl-oxazole (PPO)	75	360–416	5[a]	
2-Phenyl-5-(4-biphenylyl)-1,3,4-oxadiazole (PBD)	96	360–5		
4,4''-Bis(2-butyloctyloxy)-*p*-quaterphenyl (BIBUQ)	60	365,393	1.30[b]	

LEP bunchcrossing 25µs

Scintillators

Inorganic Scintillators – Properties

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	$8 \cdot 10^4$
NaI(Tl)	3.7	1.85	410	0.25	$4 \cdot 10^4$
CsI(Tl)	4.5	1.80	565	1.0	$1.1 \cdot 10^4$
$Bi_4Ge_3O_{12}$	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	$1.4 \cdot 10^4$
$PbWO_4$	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

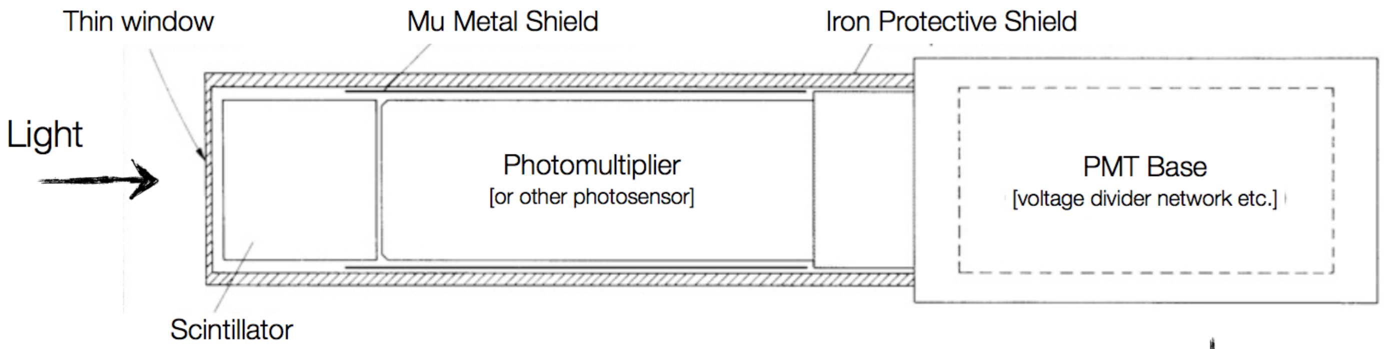
Organic Scintillators – Properties

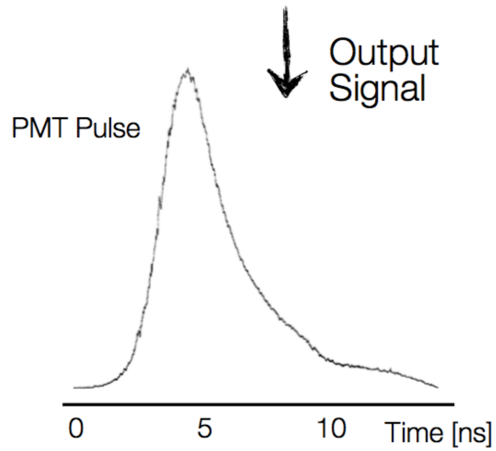
Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4 \cdot 10^3$
Antracene	1.25	1.59	448	30	$4 \cdot 10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2 \cdot 10^4$
NE102*	1.03	1.58	425	2.5	$2.5 \cdot 10^4$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

Scintillators

Scintillators – Basic Counter Setup





Scintillator Types:

Organic Scintillators
Inorganic Crystals
Gases

Photosensors

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

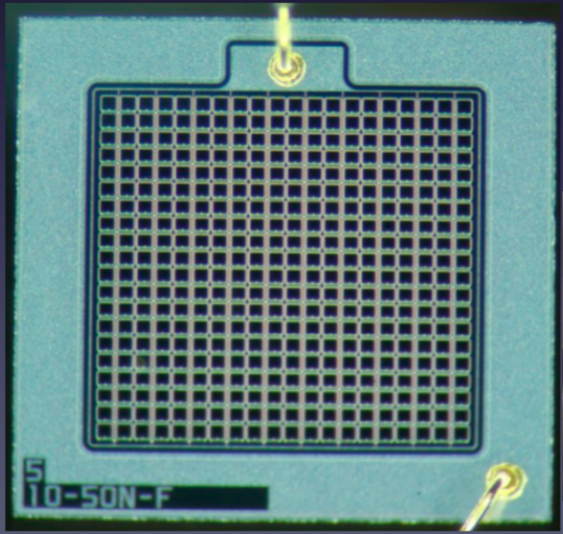
Photo-detectors

- 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; $Q.E. = N_{p.e.}/N_{photons}$

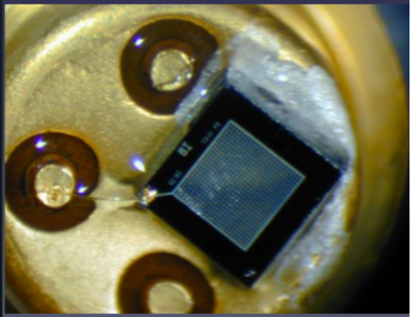
- Photomultipliers

- SiPM

Hamamatsu MPPC



One of the first SiPM
Pulsar, Moscow



PMTs

Photomultipliers

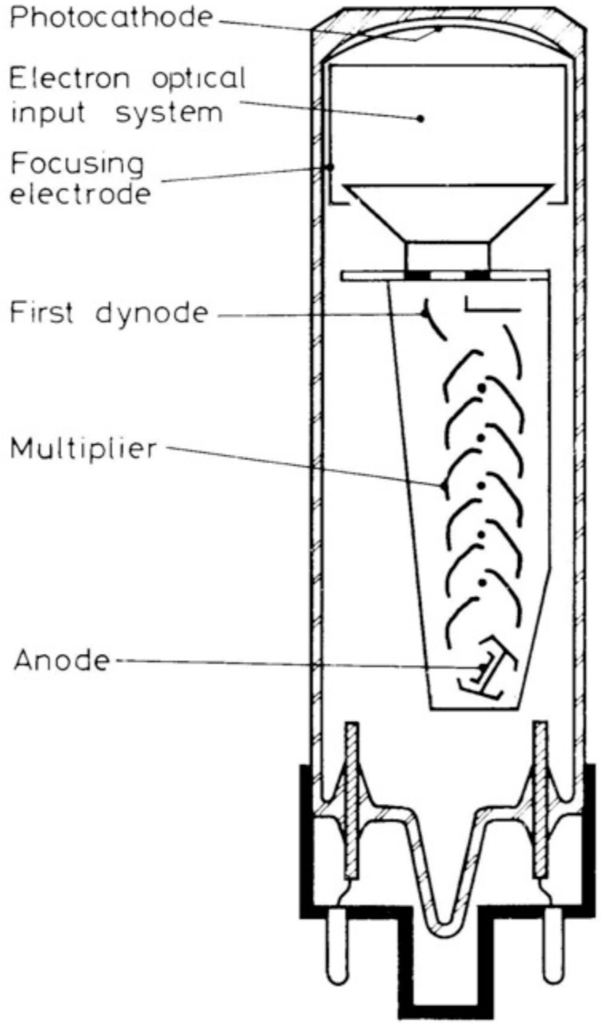
Principle:

Electron emission
from photo cathode

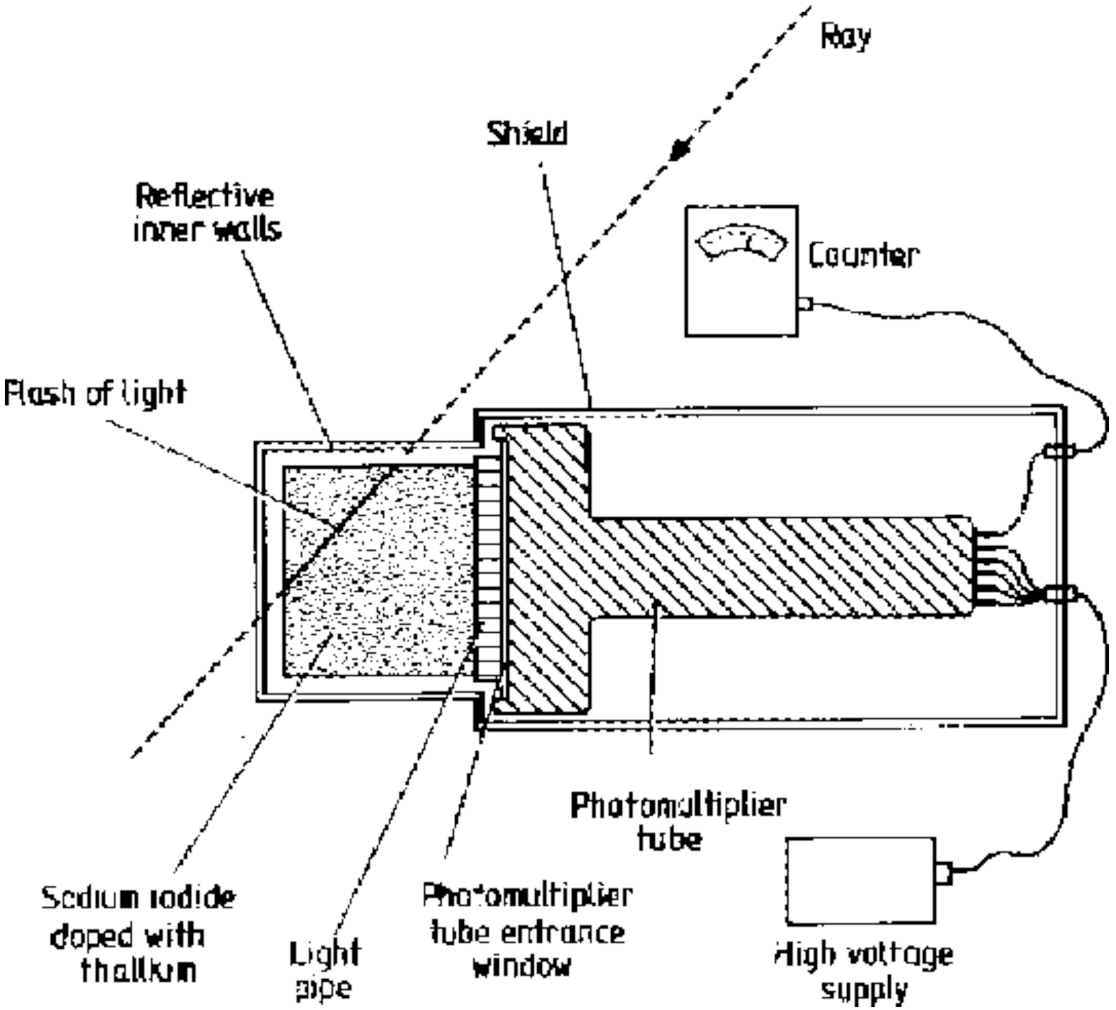
Secondary emission
from dynodes; dynode gain: 3-50 [f(E)]

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

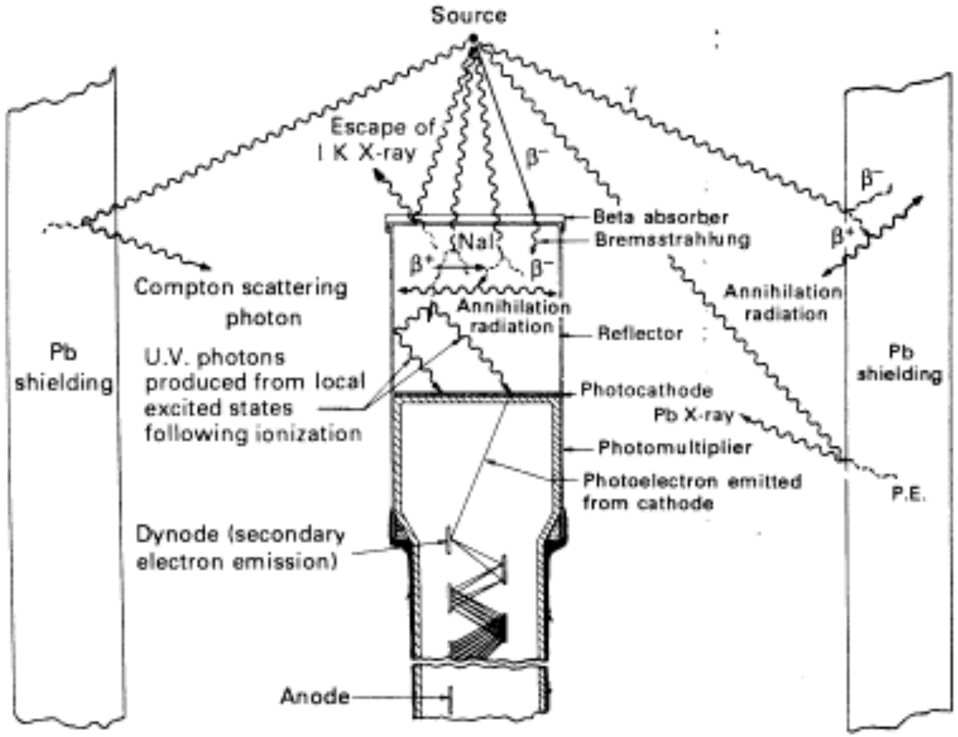
PMT Collection

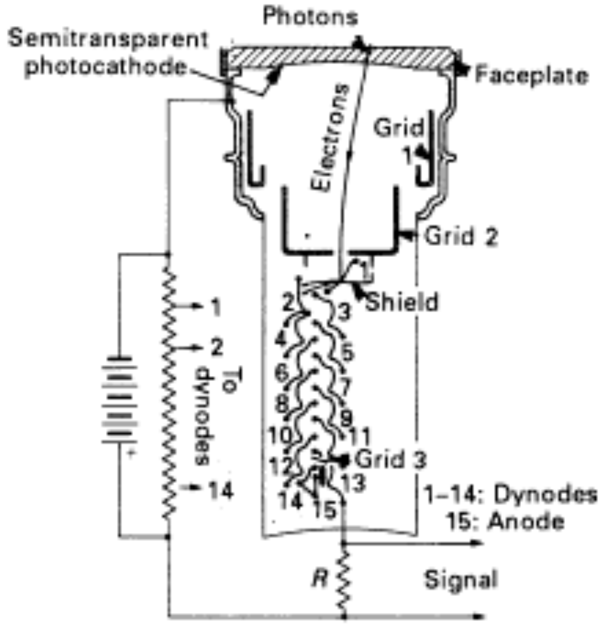


Scintillator Detectors

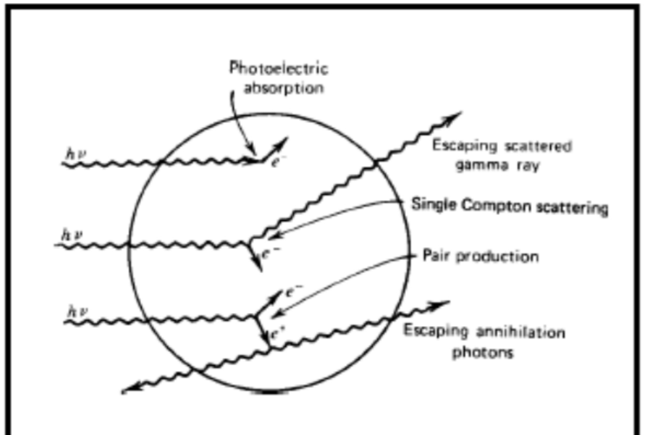


Scintillation Detectors



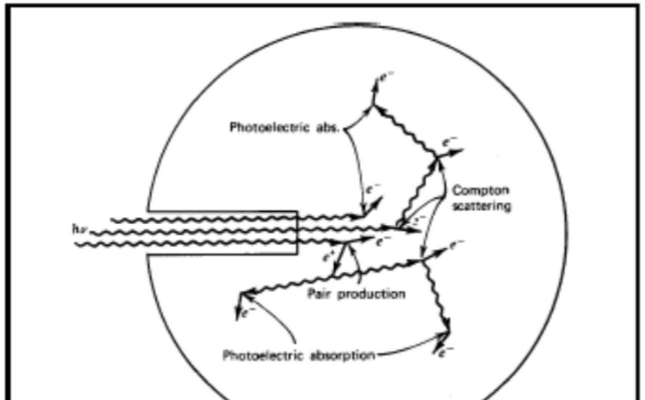


Risposta del rivelatore - 1



Only single interactions take place

Figure 9: "Small" detector



Also secondary radiations interact within the detector active volume

Figure 10: "Large" detector

most of the "secondary products" remain in the detector

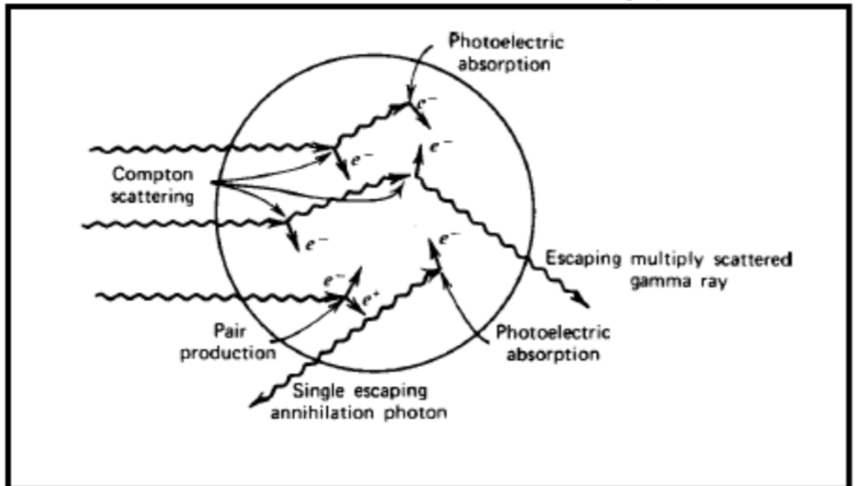


Figure 11: Intermediately sized detector

F. Knoll

Risposta del rivelatore - 2

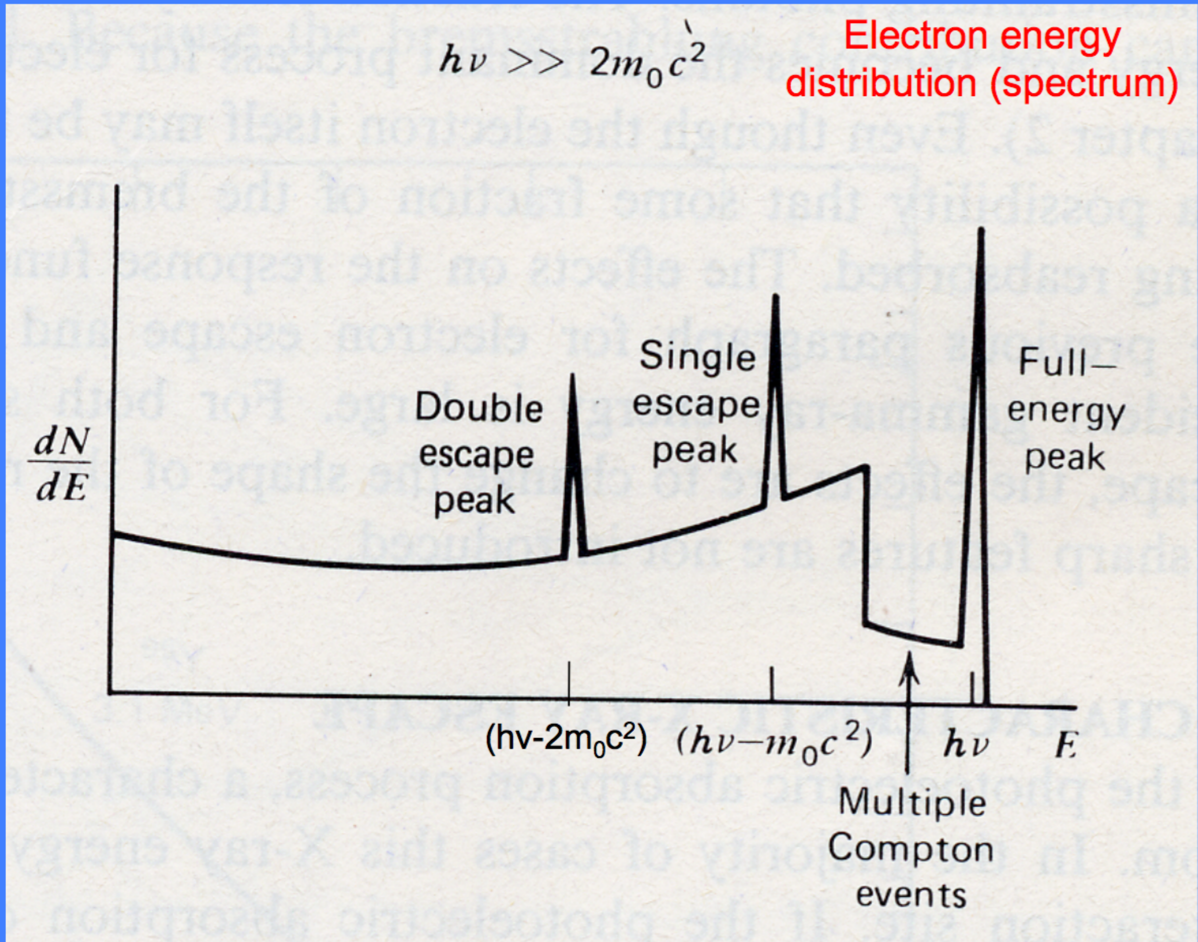
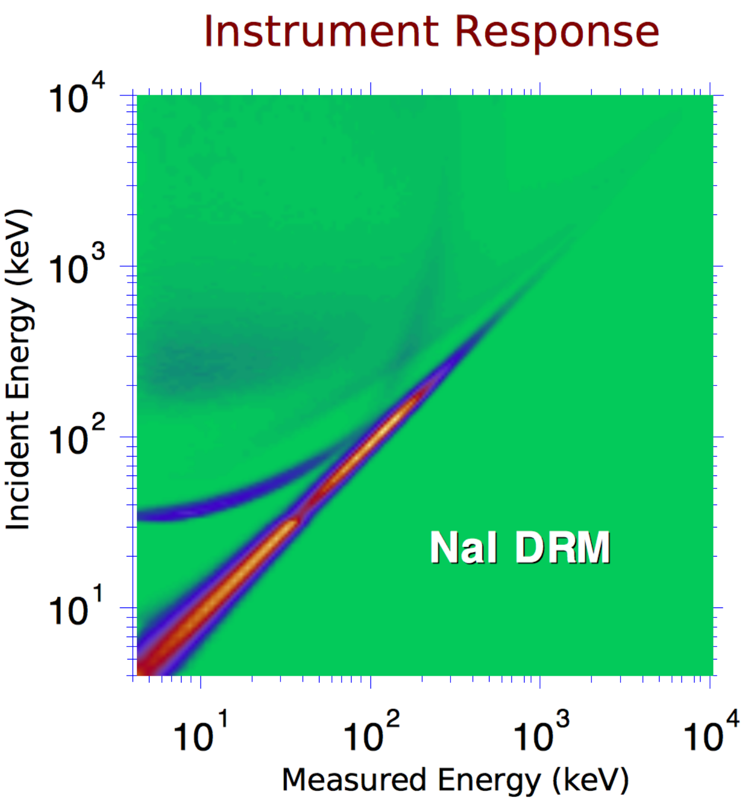


Photo-peak (full-energy peak): all photoelectric events remain in the detector and produce an energy deposit at the energy of the incoming photon
Single-escape peak: one annihilation photon leaves the detector without further interaction
Double-escape peak: both annihilation photons leave the detector (escape)

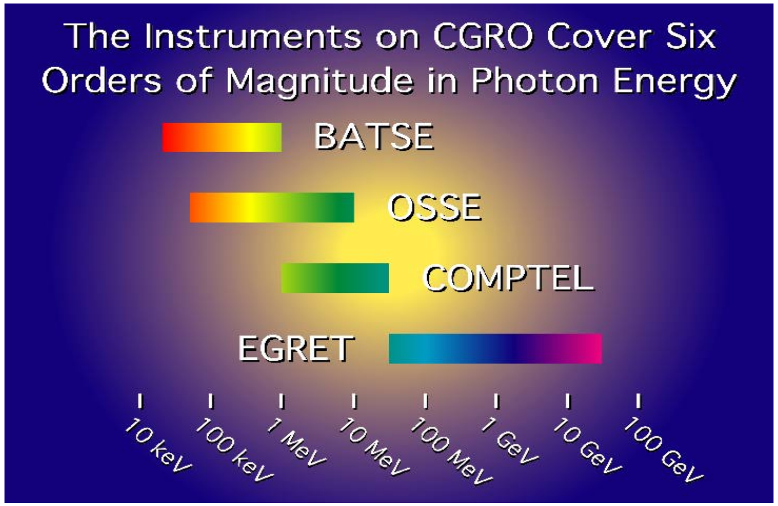
Case of intermediate-size detector (Knoll)

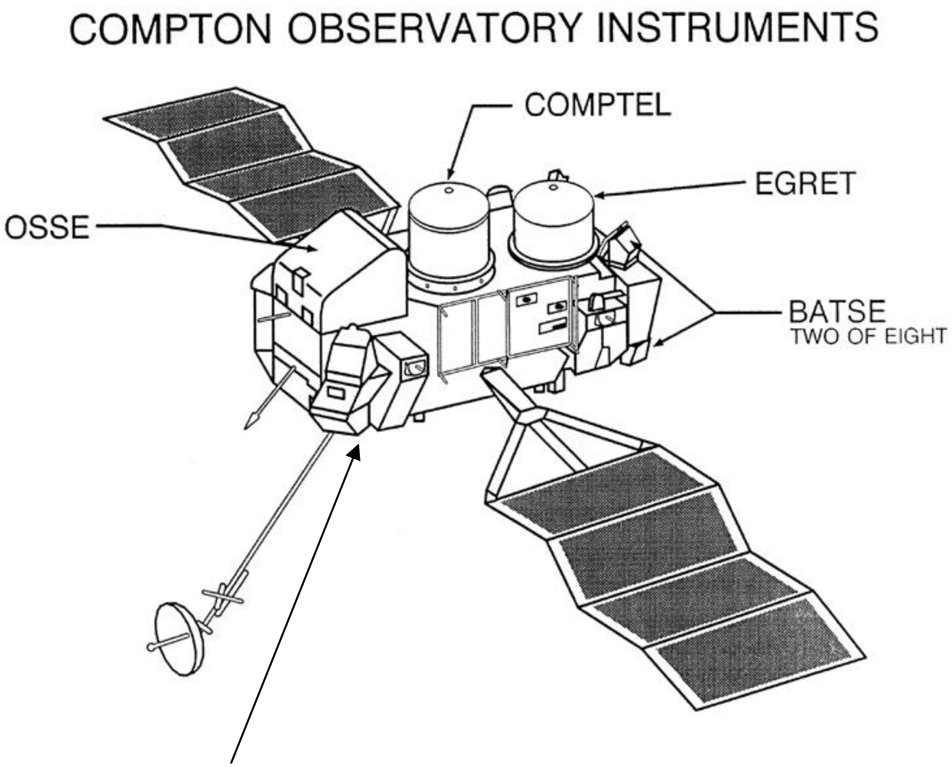
Detector Response Matrix



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)

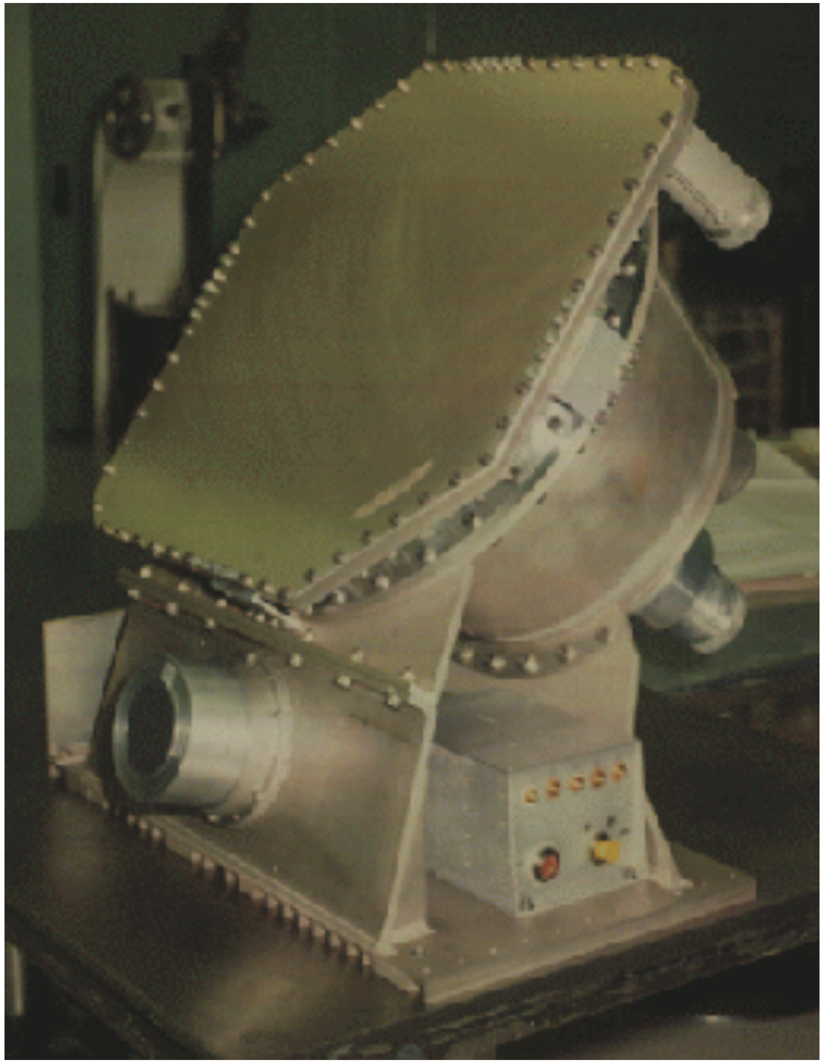




CGRO/BATSE (20 keV÷10 MeV)

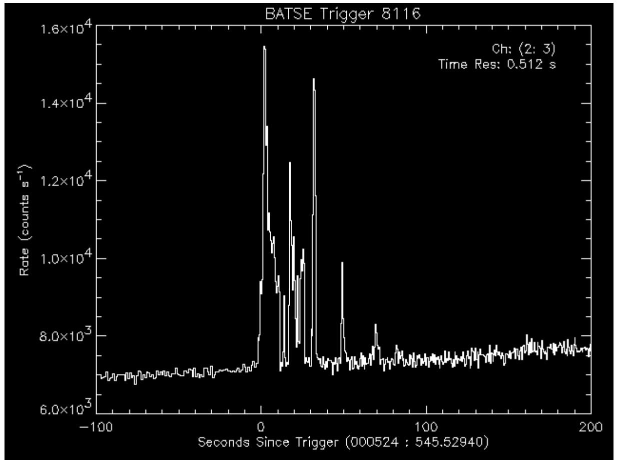
The BATSE instrument

- NaI scintillators
- 20 keV – 2 MeV
- FoV 4π (LAD)
- SD spectroscopy

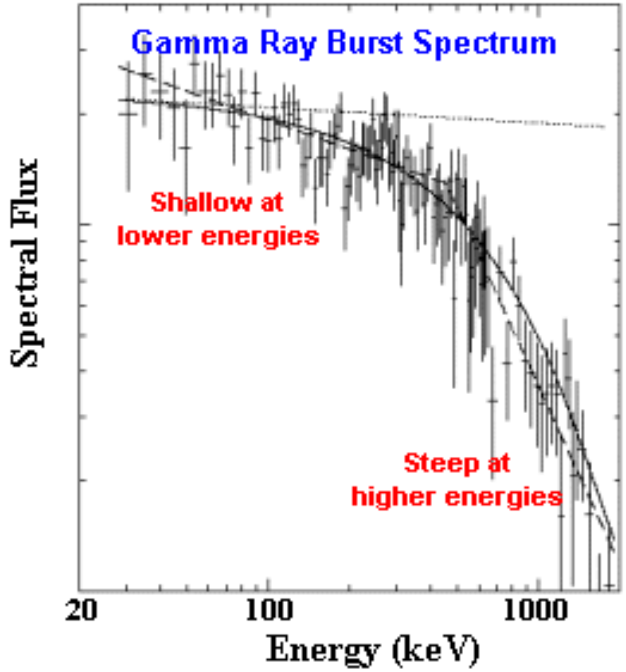


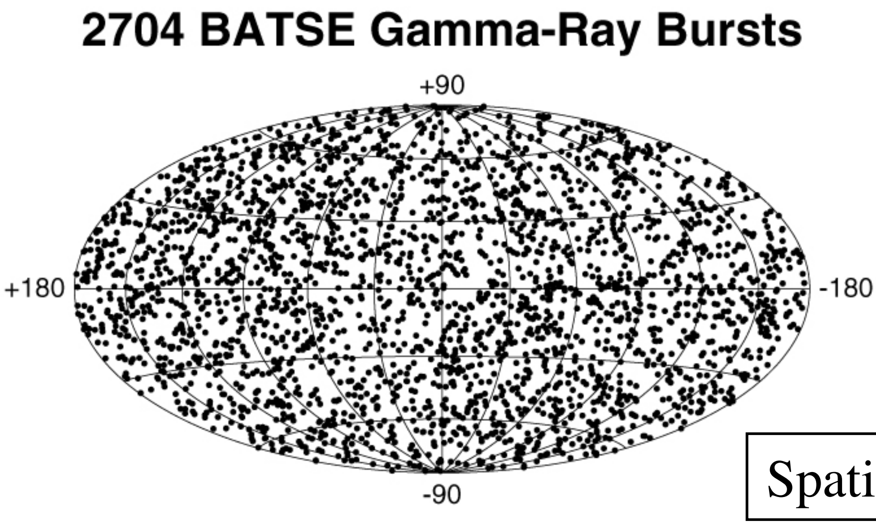
Gamma-Ray Bursts

Temporal behaviour



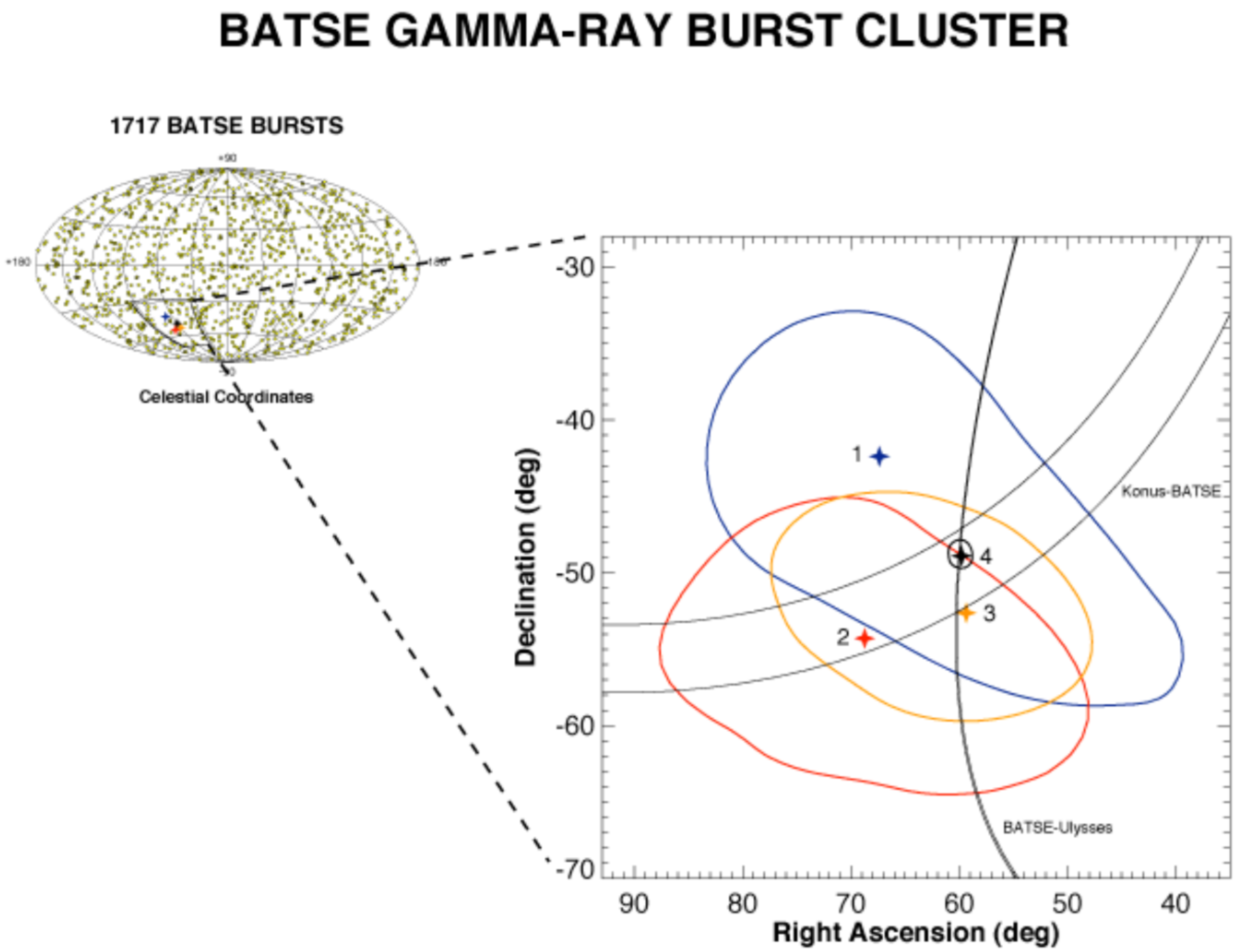
Spectral shape





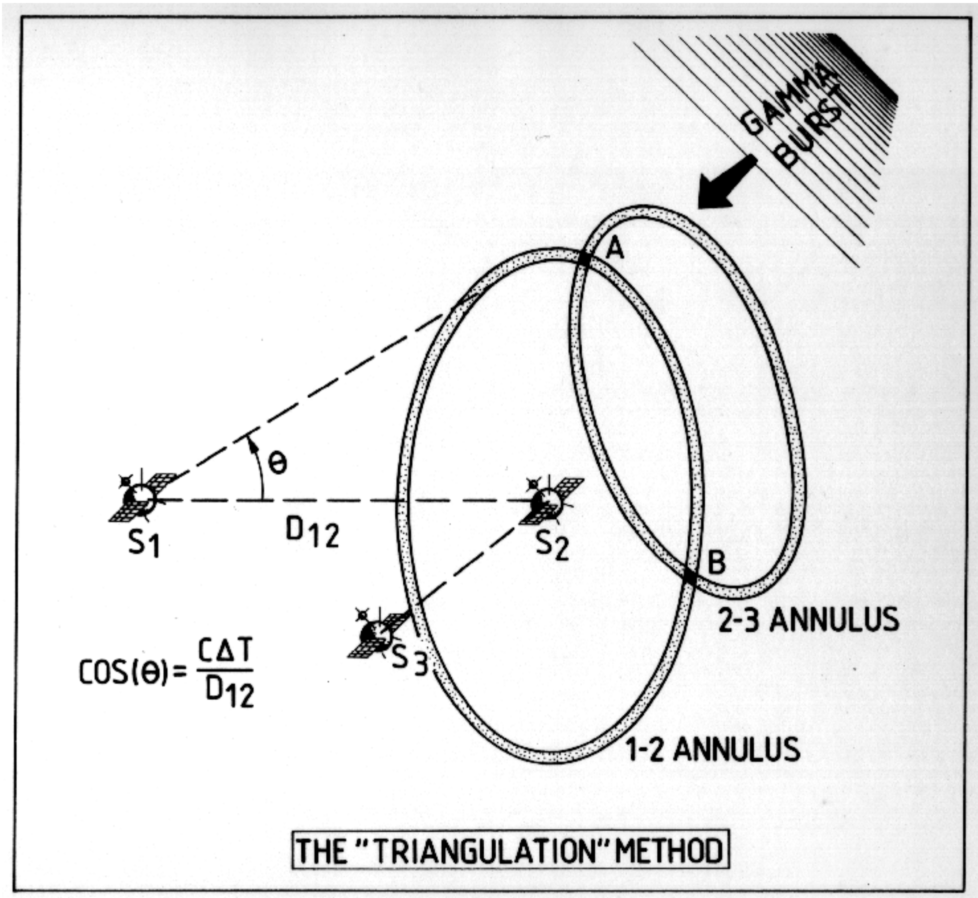
Spatial distribution

GRB localisation



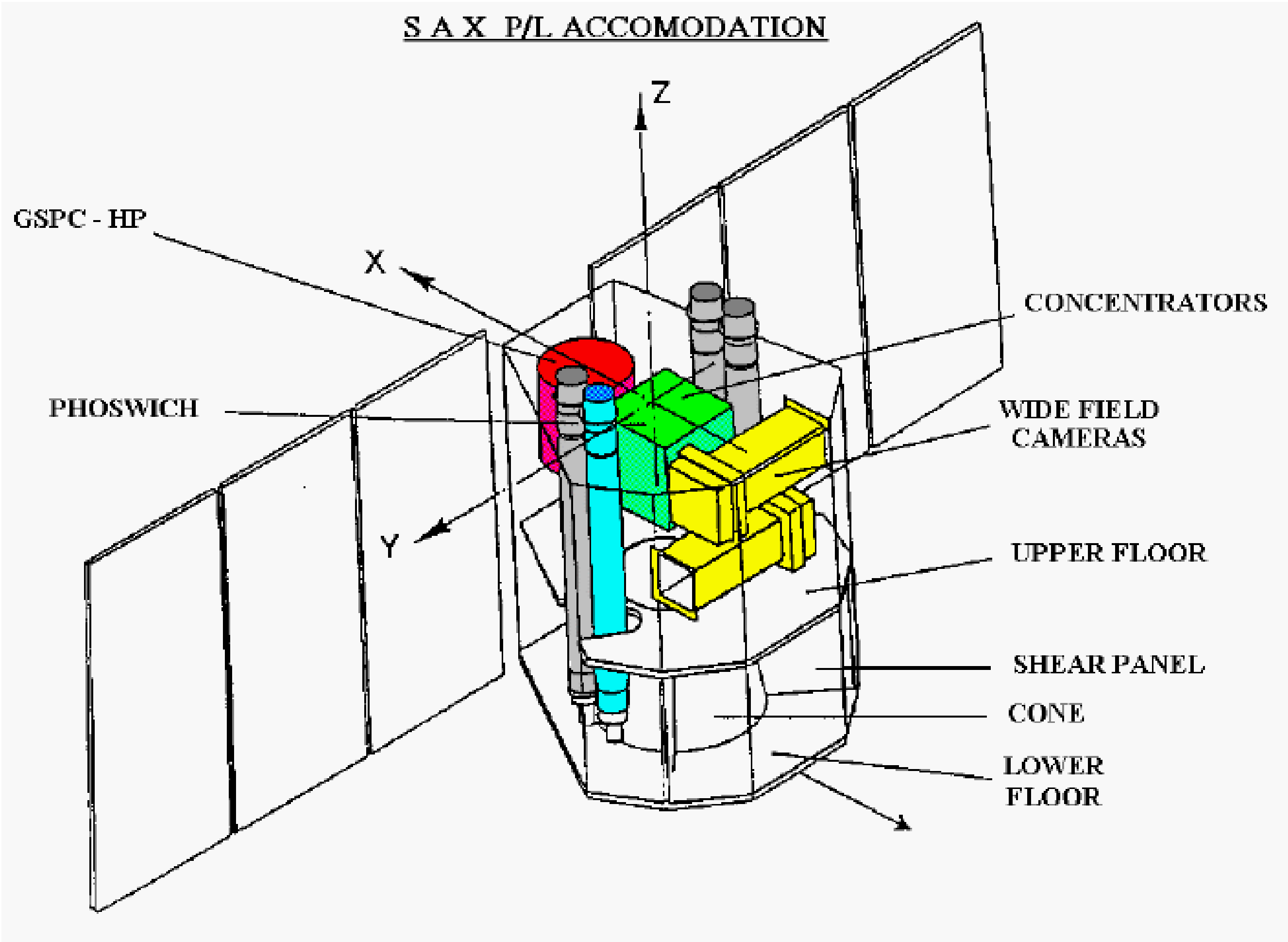
GRB History

- Interplanetary Network (IPN)

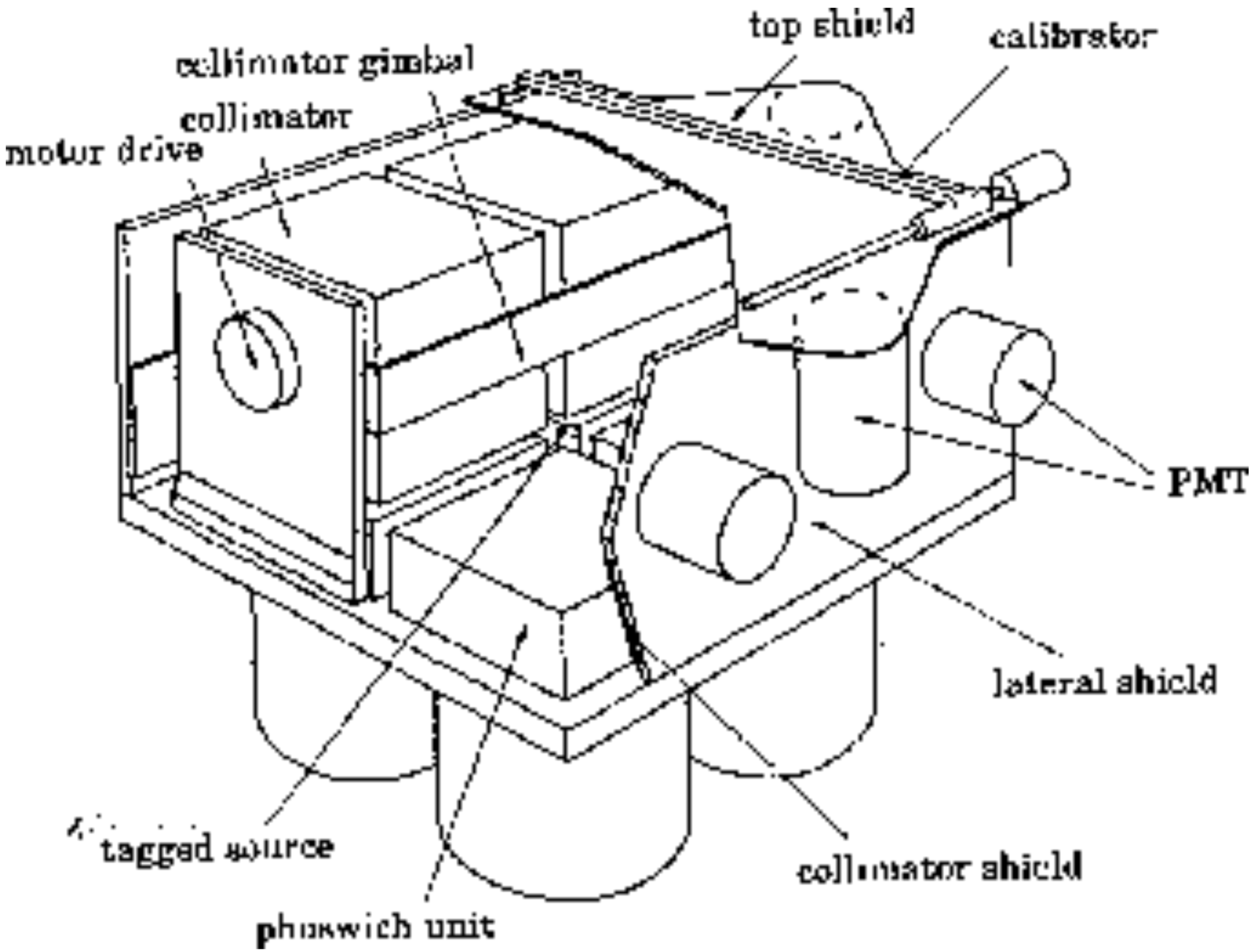


http://www.ssl.berkeley.edu/ipn3/

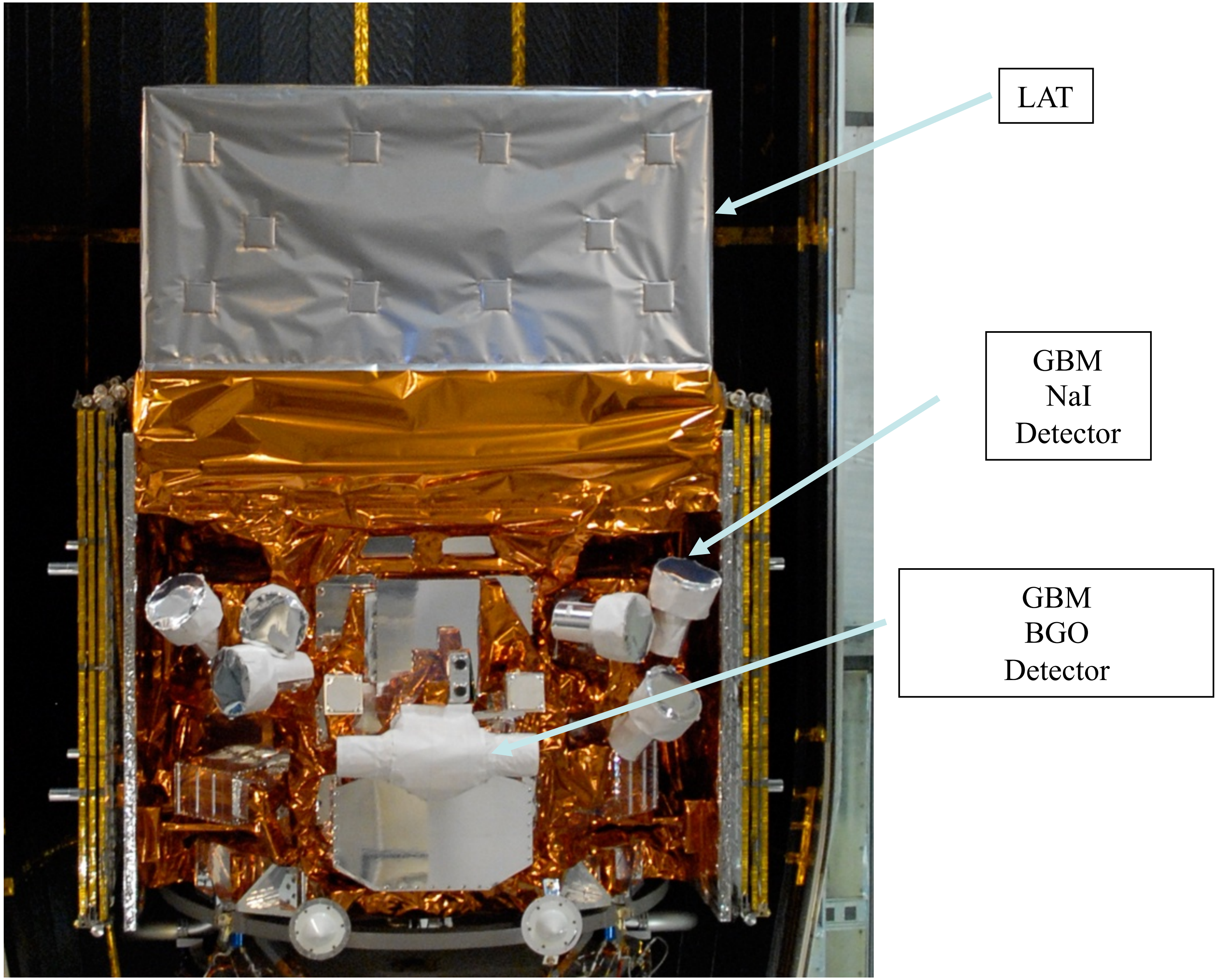
BeppoSAX (1995 - 2002)



BeppoSAX (1995 - 2002)

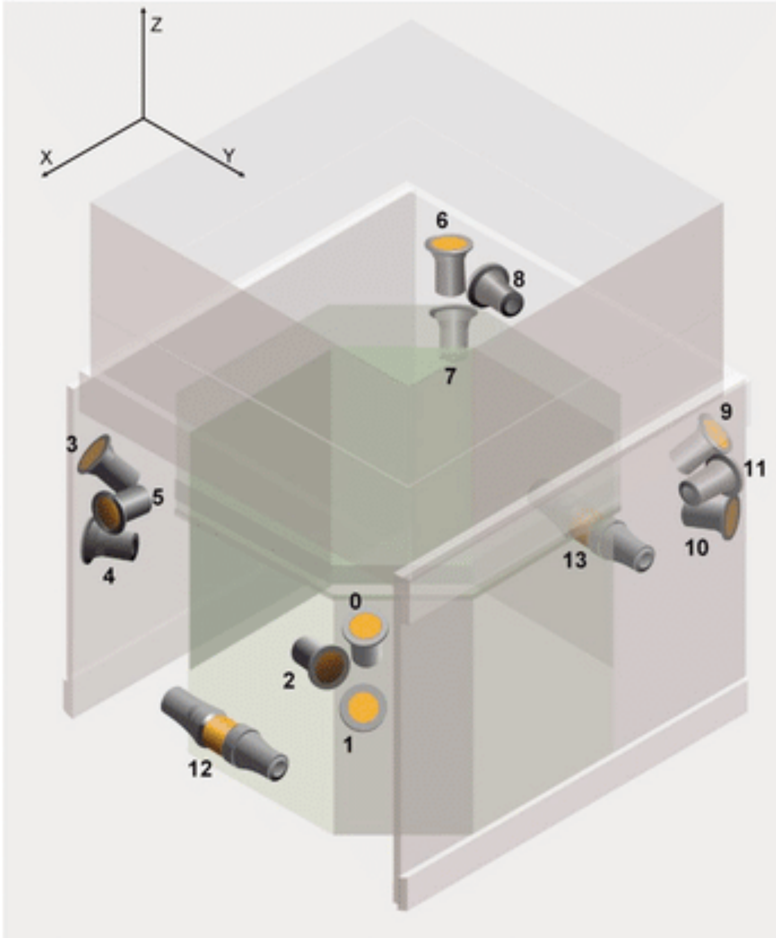


Fermi/GBM detector (2008 -- ..)

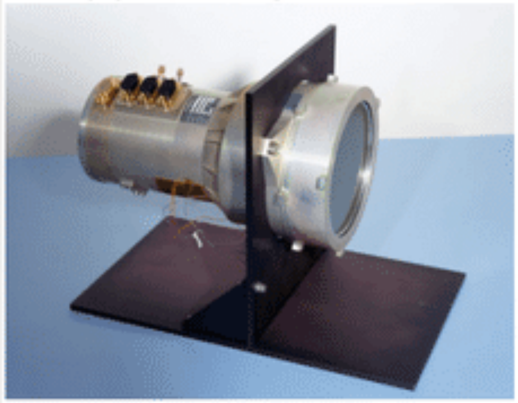


Fermi/GBM detector (2008 -- ..)

BGO detector unit



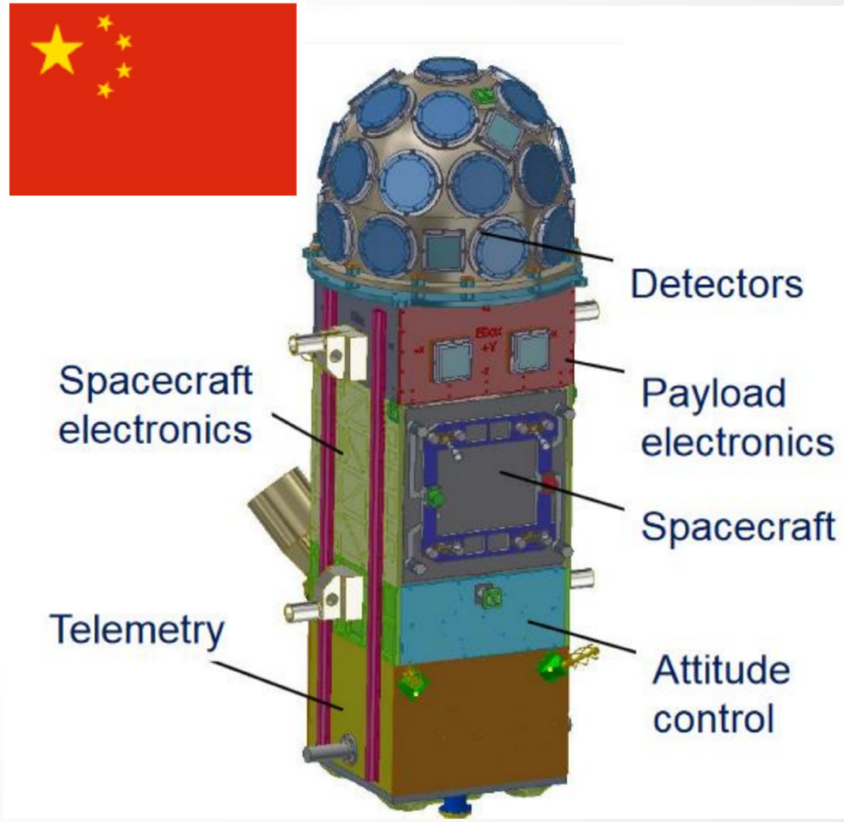
Nal(Tl)-detector flight unit



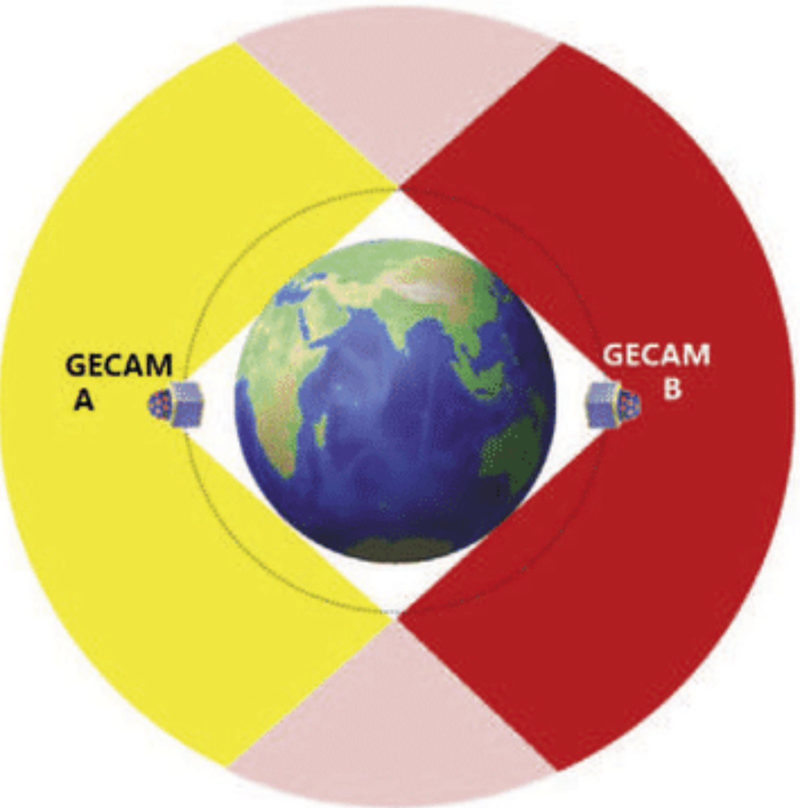
GECAM

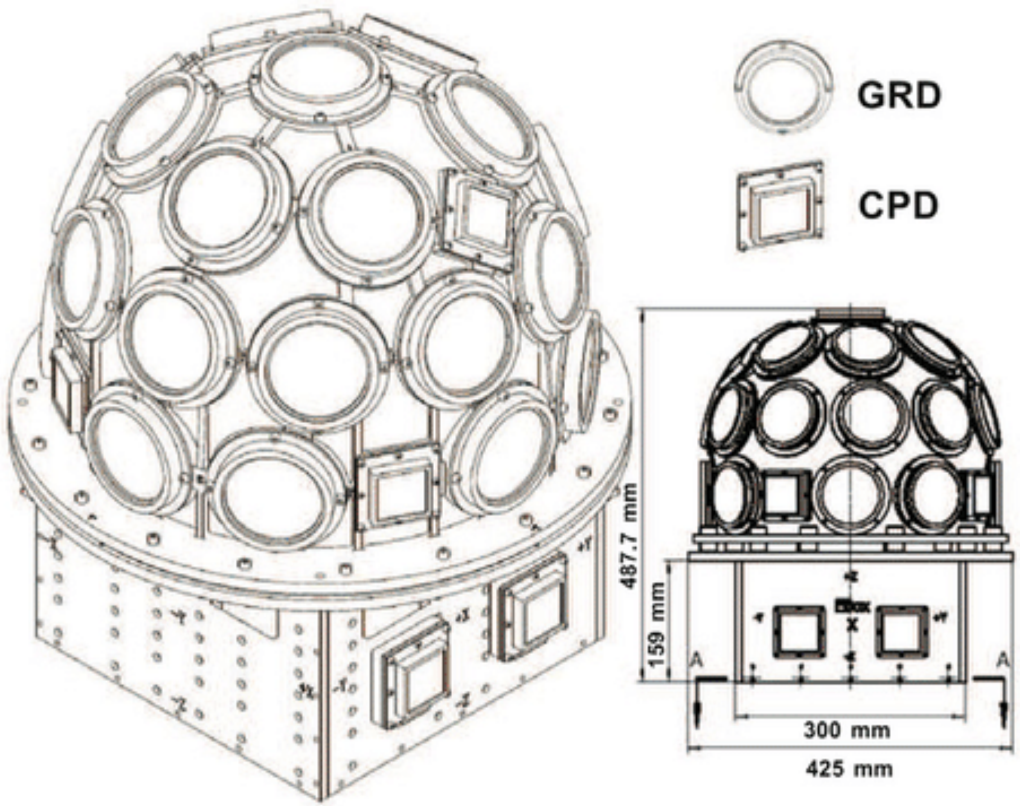
GCAM

Chinese mission
Launch 2021
2 satellites
100% sky coverage.
Very similar to GBM.
Positioning by triangulation
(need 3 participants)
Some directionality.
Cannot do the work to alert CTA all by itself.

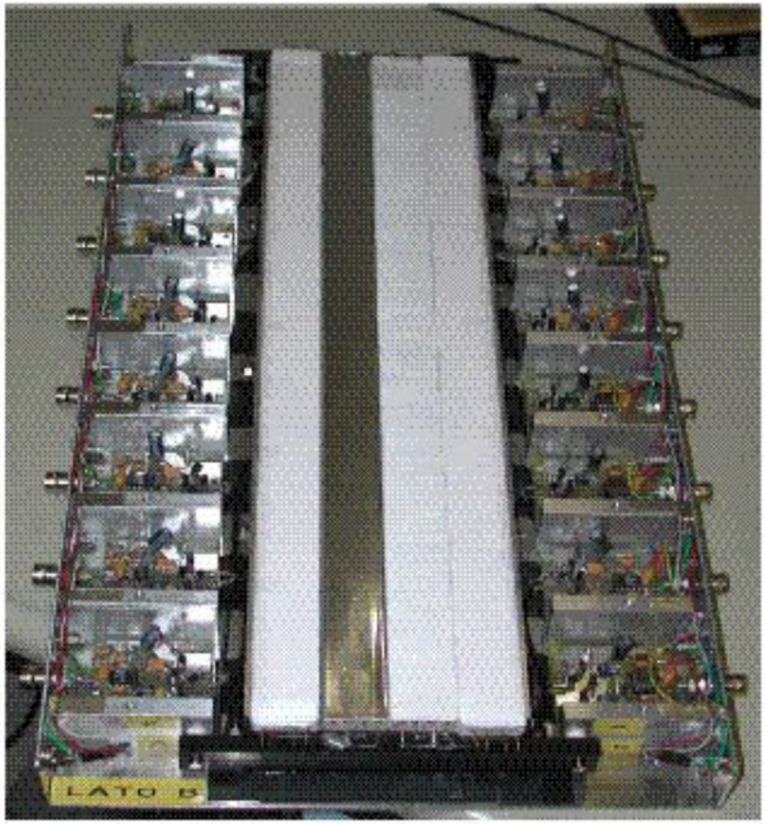


GECAM





AGILE MCAL



MINI-CALORIMETER

DETECTOR

30 CsI bars wrapped with tight diffusion material organized in 2 orthogonal trays
- bar dimension: 40x2.3x1.5 cm^3
- total radiation length: $1.5X_0$ (in axis)

FRONTEND ELECTRONICS

- 1 photodiode on each side of the bar
- optically coupled

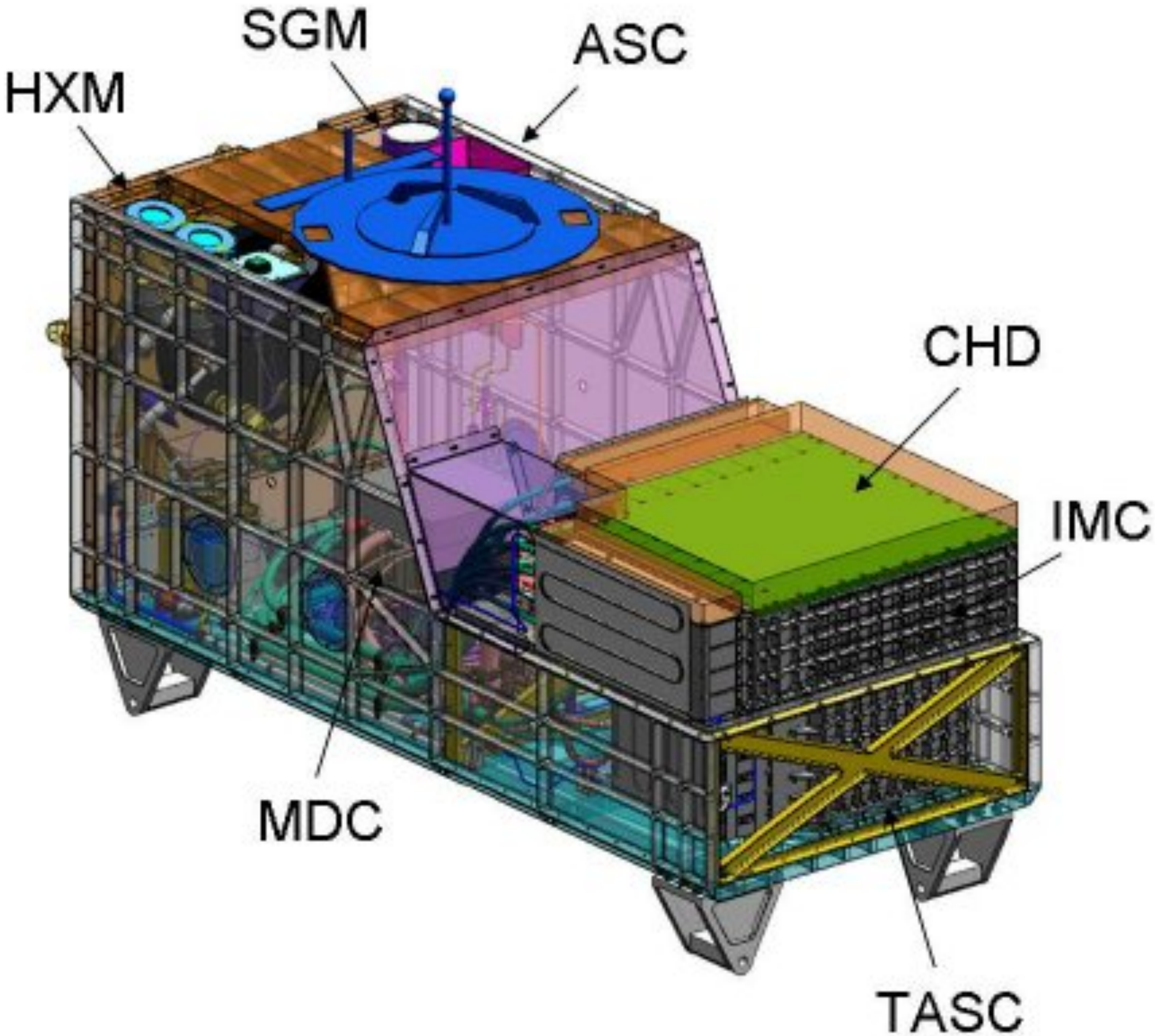
GOAL

- measure energy deposit of the photon conversion pair (GRID mode)
- detect GRBs and transients in the range 0.25-250MeV (BURST mode)

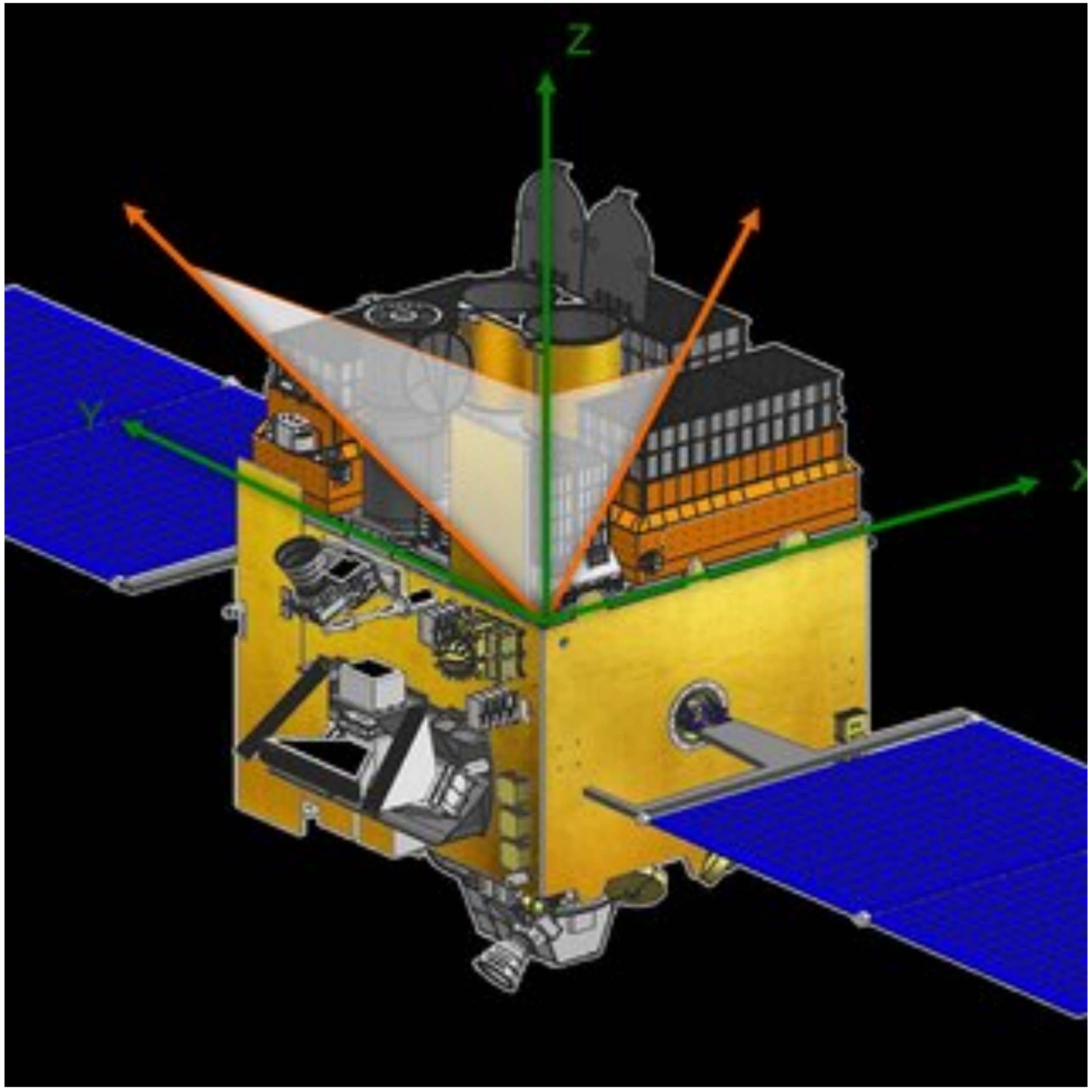
SCIENTIFIC FEATURES

- energy resolution: 22-24%(FWHM) @ 1MeV
0.7% @ 100MeV
- spatial resolution: 15mm @ 1MeV
2mm @ 100MeV
- timing resolution: 2μs (BURST mode)

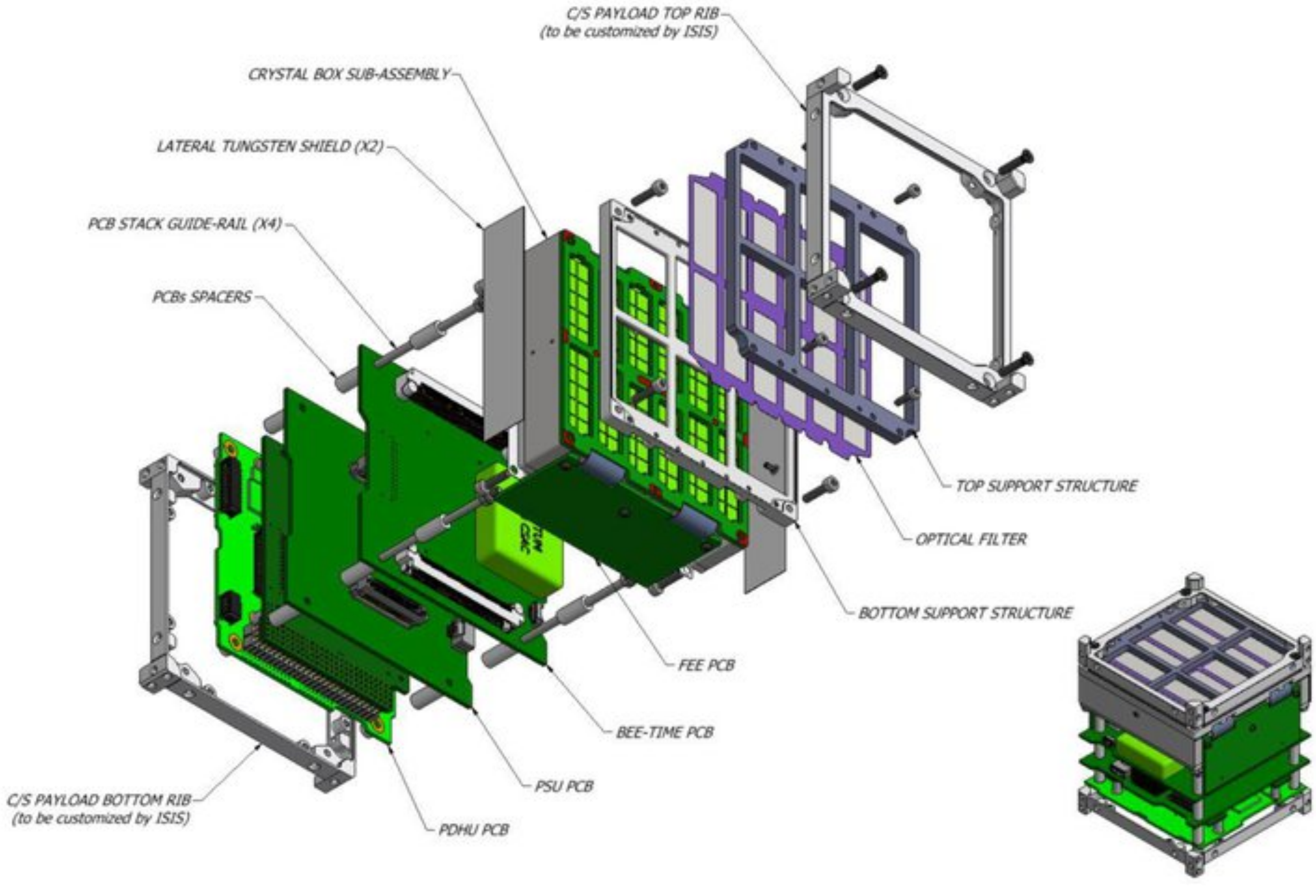
CALET



AstroSAT



HERMES



C/S PAYLOAD TOP RIB
(to be customized by ISIS)
CRYSTAL BOX SUB-ASSEMBLY
LATERAL TUNGSTEN SHIELD (X2)
PCB STACK GUIDE-RAIL (X4)
PCBs SPACERS
TOP SUPPORT STRUCTURE
OPTICAL FILTER
BOTTOM SUPPORT STRUCTURE
FEE PCB
BEE-TIME PCB
PSU PCB
C/S PAYLOAD BOTTOM RIB
(to be customized by ISIS)
PDHU PCB

Exercise #1

- Find the web sites of BATSE
- Find the web site (if any) of BeppoSAX
- Find the web site of Fermi/GBM
- Find the web site of AGILE/MCAL GRB catalog
- Find the web site of CALET GRBM
- Find the web site of AstroSAT CZTI GRB