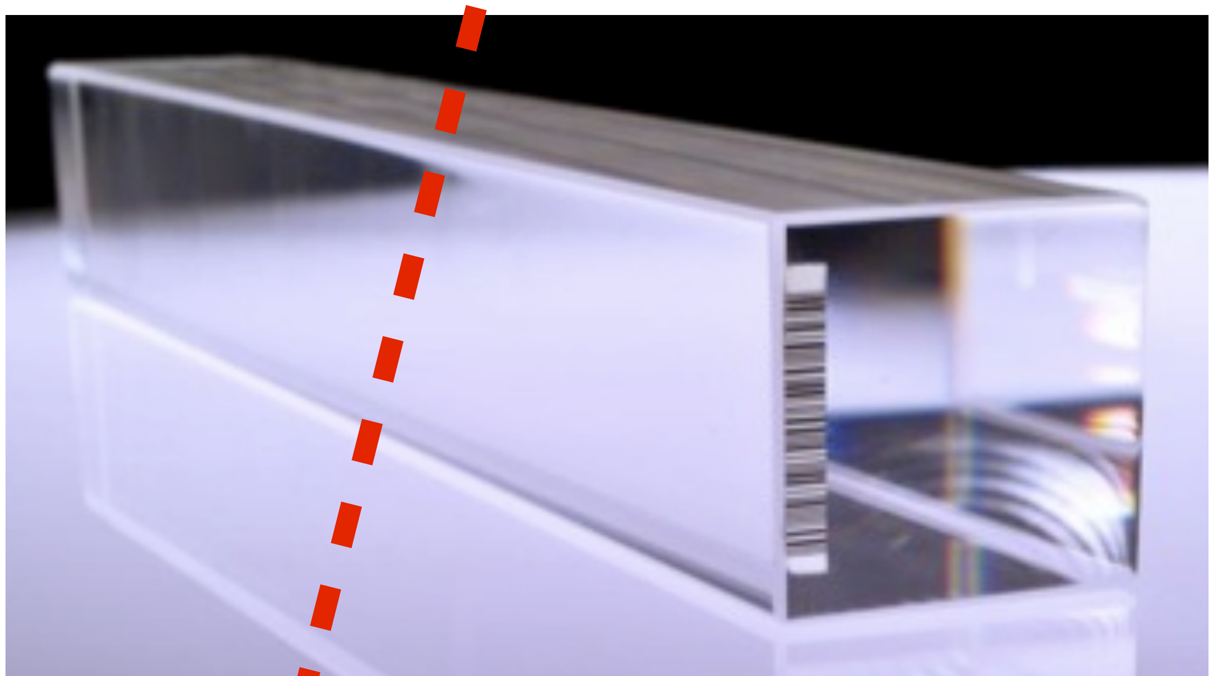
EDIT 2011

Excellence in Detectors and Instrumentation Technologies
CERN, Geneva, Switzerland - 31 January - 10 February 2011

Detection of cosmic muons passing through a Lead Tungstate crystal



Chiara Casella , ETH Zurich
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EDIT school, CERN - February 2011

HERE / NOW : small example of calorimetry
i.e. energy measurement of incoming particles

Needed basic ingredients :

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i.e. energy measurement of incoming particles

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- incoming particles
- detector / calorimeter
- readout system

HERE / NOW : small example of calorimetry
i.e. energy measurement of incoming particles

Needed basic ingredients :

- incoming particles → cosmic muons
- detector / calorimeter → one scintillator crystal [$PbW0_4$], coupled to a photomultiplier
- readout system → digital oscilloscope

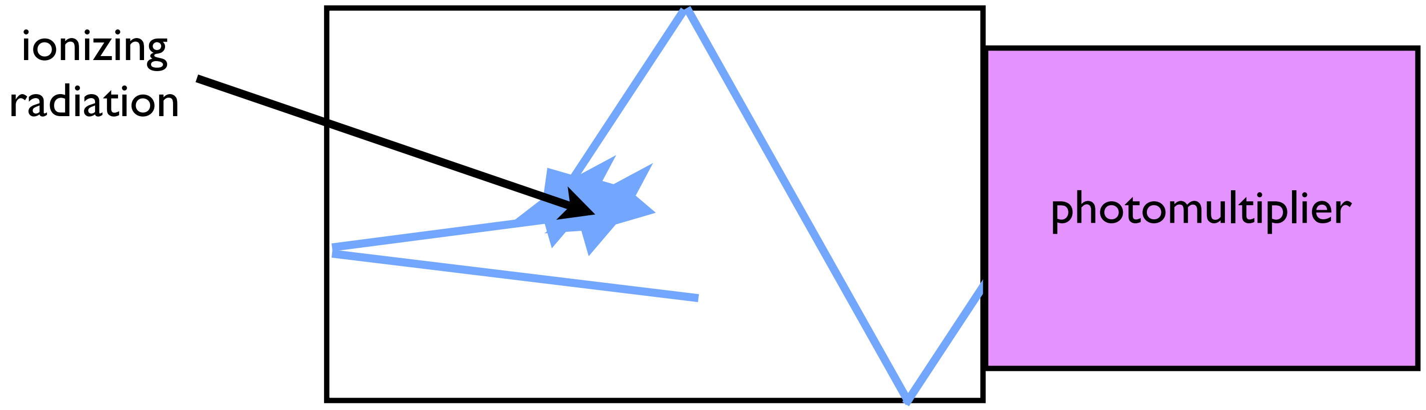
OUTLINE

- **Introduction** :
  - Scintillators & Photomultipliers
  - Cosmic muons and their interaction with matter
  - Our setup : $PbWO_4$ and PMT XP2262B
- **Hands - On :**
  - PMT gain measurements (single photoelectron noise)
  - measurement of the muon energy deposition in $PbWO_4$
- **$PbWO_4$ crystals in CMS - ECAL** (during data taking)

Scintillators

Scintillators

special class of materials in which the energy loss by an incoming ionization radiation is converted into luminescence



- **Energy loss from ionizing radiation in the material**
- **Scintillation** : emission of visible (or near-visible) light in the material
- **Transmission** of the scintillation light in the material and **collection** by total internal reflection
- **Detection** of the scintillation light and conversion into an electrical pulse

Parenthesis : ionizing radiation

Base of the scintillation mechanism : **energy loss from ionizing radiation i.e. IONIZATION and/or EXCITATION of the medium atoms / molecules** (i.e. Coulomb interactions between incoming radiation and the electrons of the scintillating medium)

Typical radiation observable with scintillators :

- **heavy charged particles ($M >> m_e$)**
- **electrons ($e^{\pm}$)**
- **photons (elm radiation, X and γ)**
- **neutrons**

Energy deposited in the material by ionization / excitation either directly by the charged particles or by the conversion of neutral into charged ones (e.g. photons interacting with matter => electrons, positrons)

Scintillators

ORGANIC	INORGANIC

Significant difference in the scintillation mechanism

ORGANIC

- inherently molecular property
- characteristic of the material, independent on its physical state (e.g. crystal, liquid...)
- typically plastic scintillators

Up to 10000 photons per MeV
Low Z
ρ~1gr/cm3
Doped, large choice of emission wavelength
ns decay times
Relatively inexpensive

Tracking, TOF, trigger, veto counters, sampling calorimeters.
Medium Rad. Hard (10 kGy/year)

examples : plastic, liquids...

INORGANIC

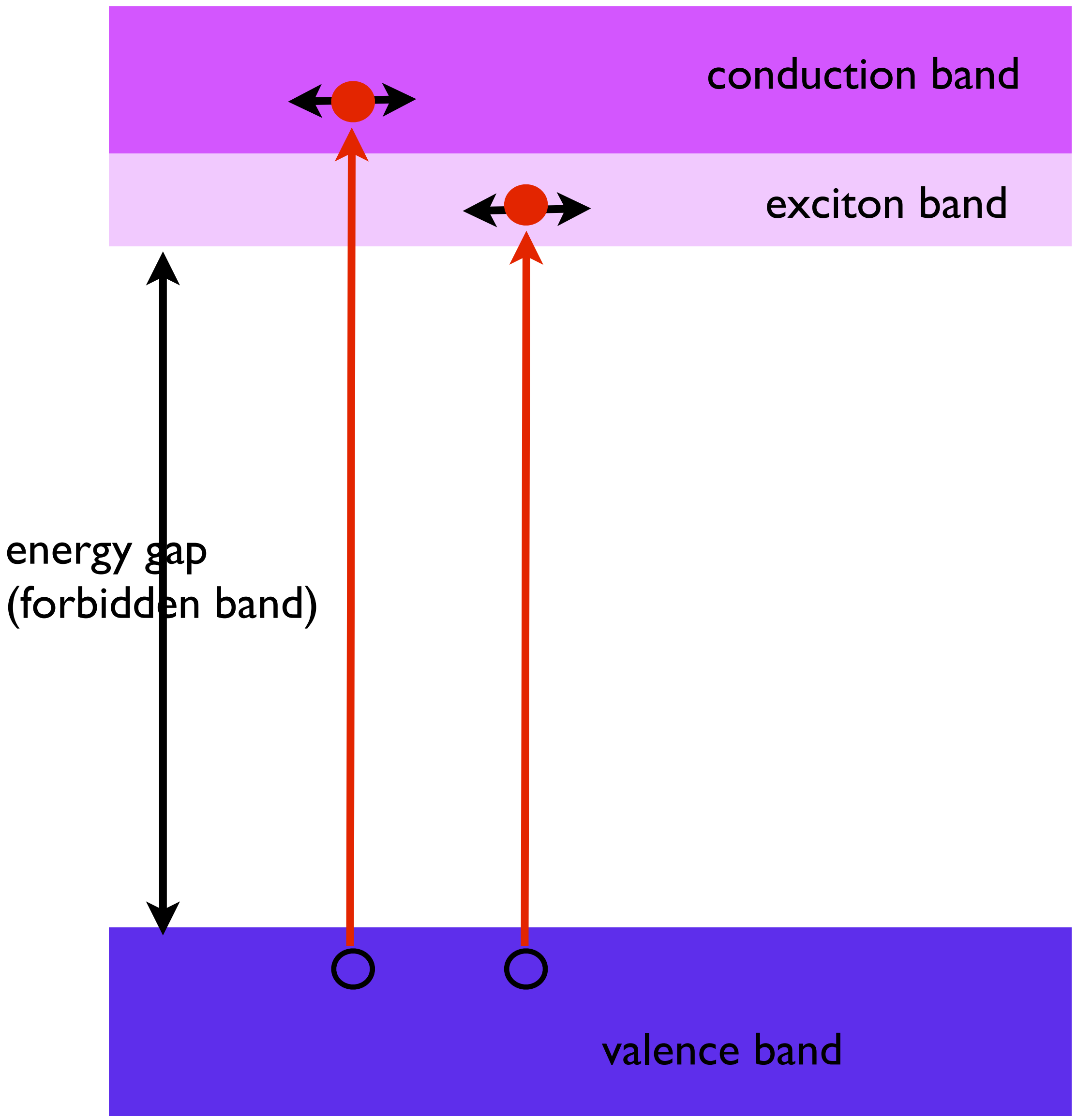
- requires the crystal band structure
  (you can't dissolve NaI in water / melt it and still get scintillation)
- mostly activated by impurities - luminescence centers associated with the activator in the lattice (either extrinsic e.g. doping or intrinsic e.g. defects)

Up to 40000 photons per MeV
High Z
Large variety of Z and ρ (~ 4-8 g/cm^3)
Undoped and doped
ns to µs decay times
Expensive

E.m. calorimetry (e, γ)
Medical imaging
Fairly Rad. Hard (100 kGy/year)

examples : NaI(Tl) ; CsI ; LYSO ; **$PbWO_4$** ...

Inorganic scintillators: working principle



1. Incoming radiation
   => IONIZATION or EXCITATION
   ionization : free e (cond.) + free h (val.)
   excitation : exciton (loosely coupled e-h pair in the exciton band) - e-h bound together but free to move inside the crystal

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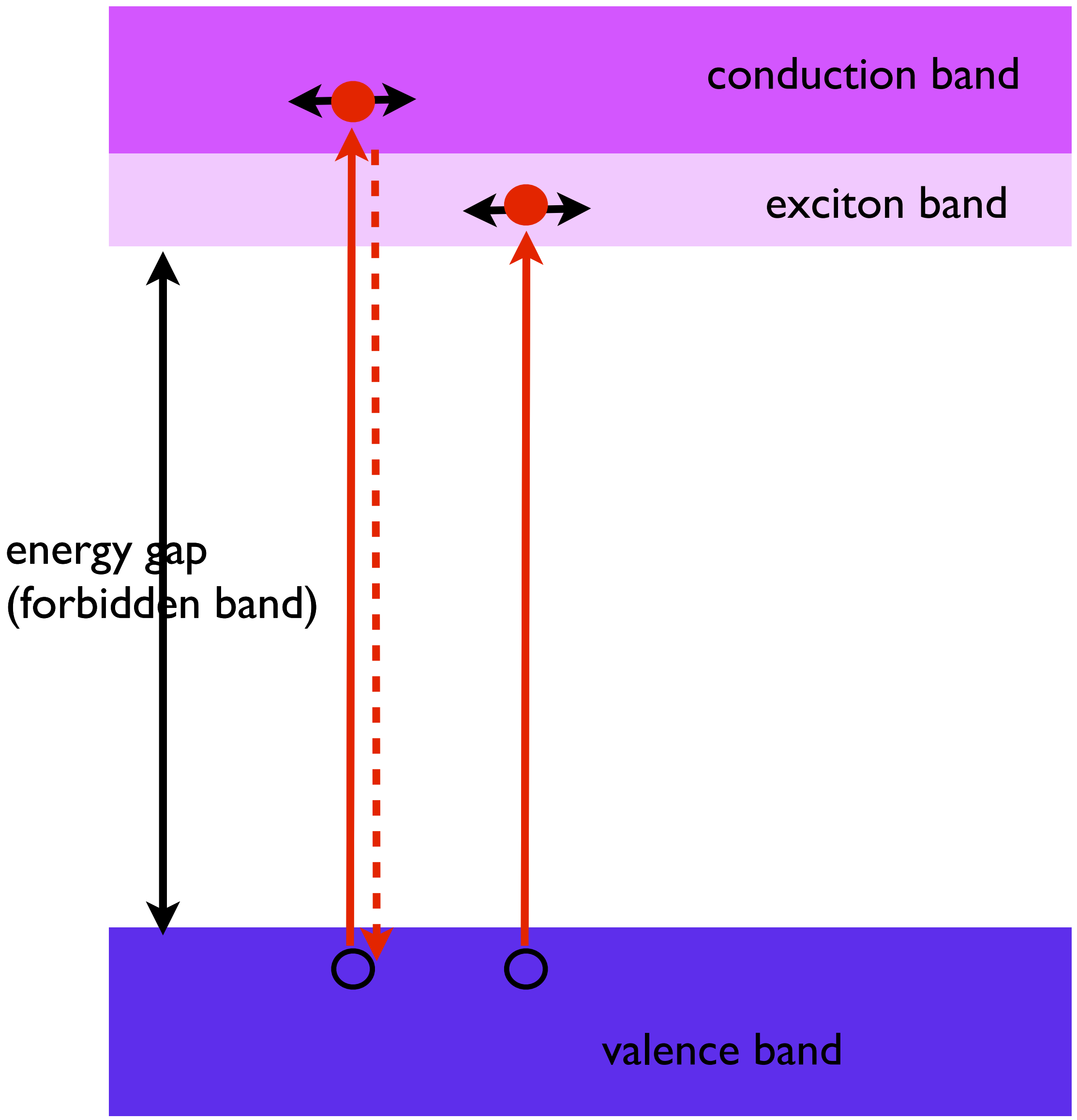

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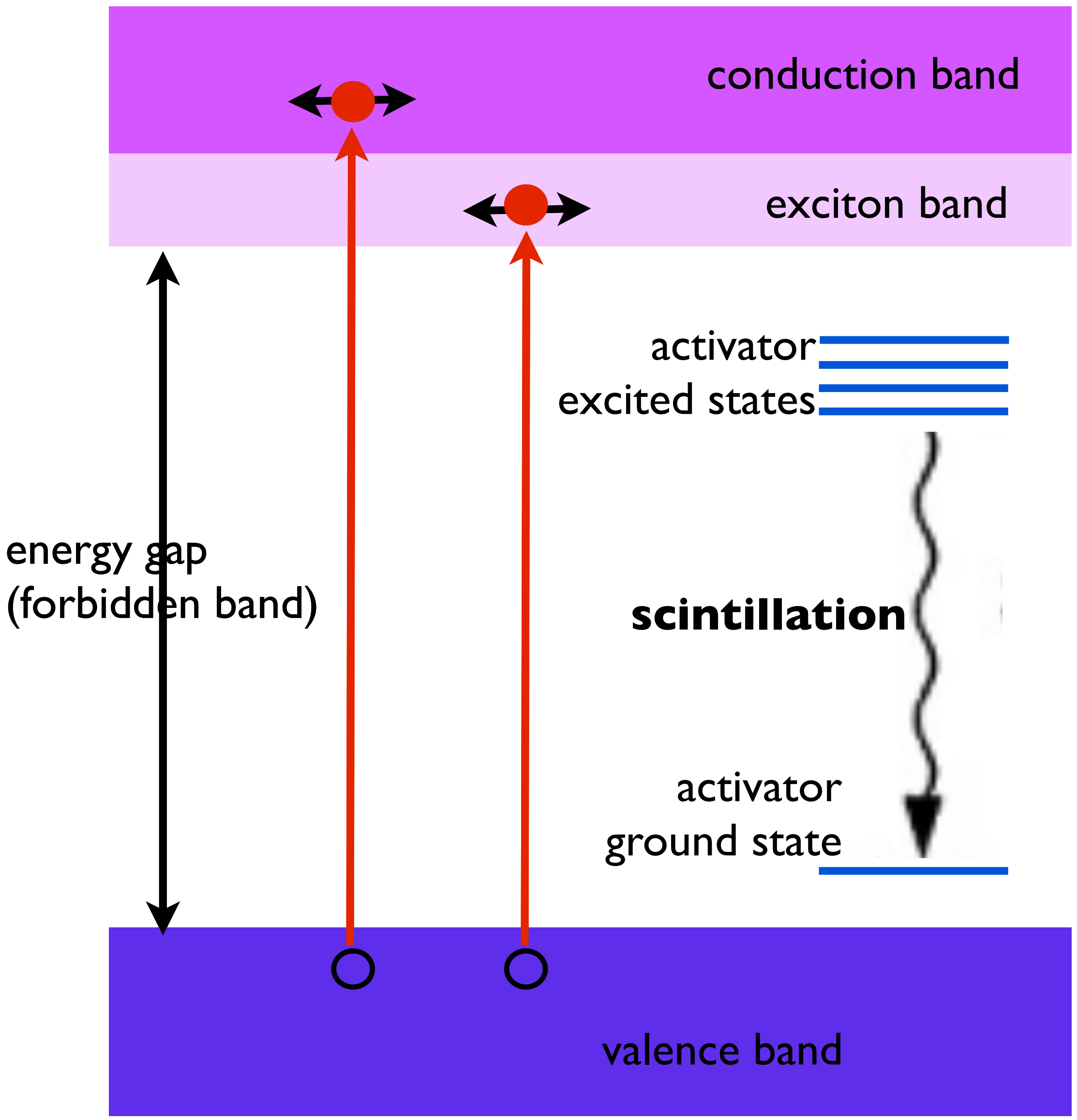

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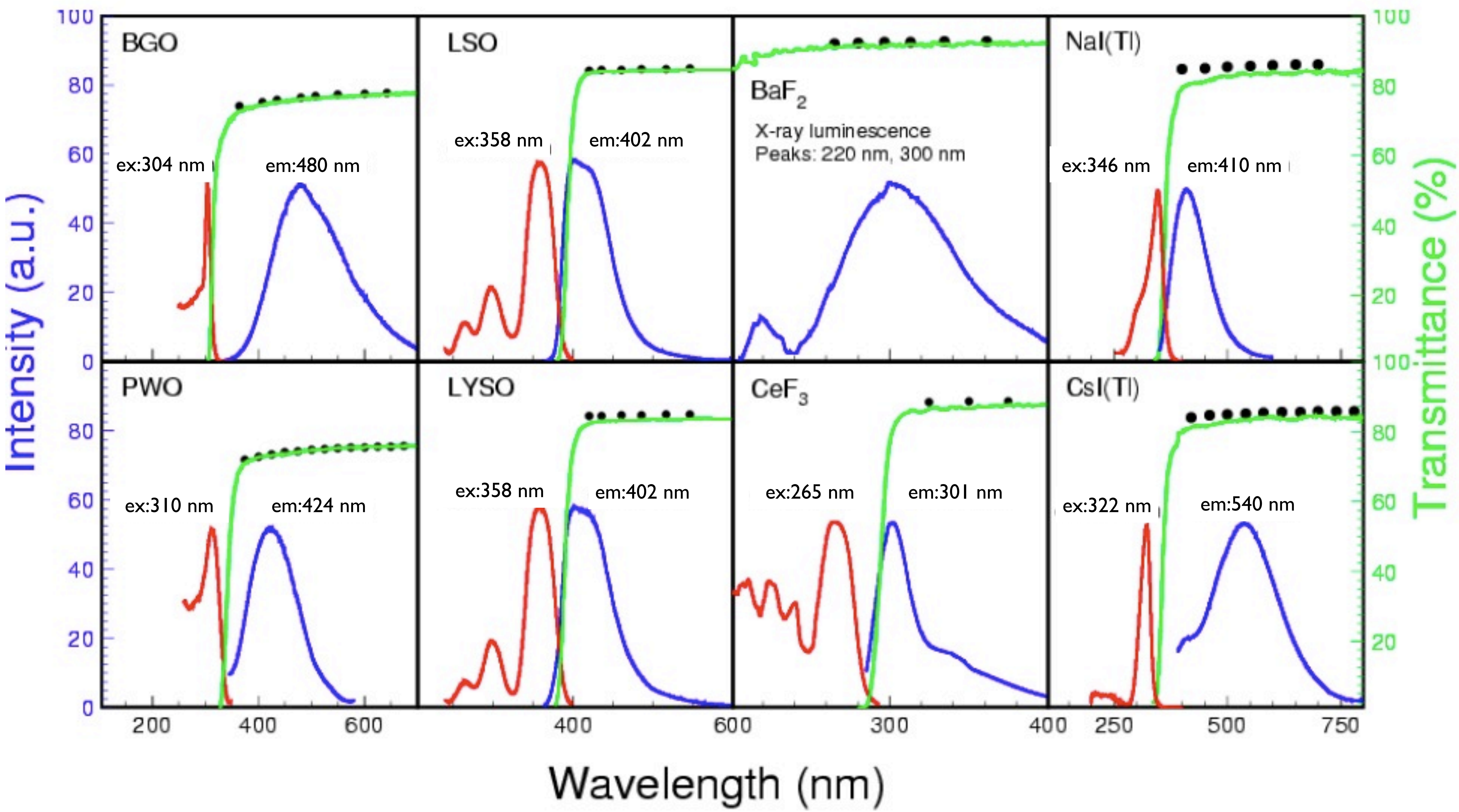
3. If the crystal contains **impurities** (defects or additional activators) => electronic levels in the forbidden gap are locally created
=> deexcitation = **SCINTILLATION LIGHT**

Inorg. Scintillators : excitation, emission, transmission



Ren-Yuan Zhu , SCINT09

Inorganic Scintillators

from Particle Data Group, Review of Particle Physics

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?	$d(LY)/dT$
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	6.5	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	10.1	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	402	1.82	83	no	−0.2
$LaBr_3$(Ce)	5.29	788	1.88	2.85	6.9	30.4	20	356	1.9	130	yes	0.2

* 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

<u>for comparison : typical organic plastic scintillator</u>

	ρ	MP	τ_{decay}	λ_{max}	Relative output
NE102A	1.03	75	2	423	26

Inorganic Scintillators

from Particle Data Group, Review of ParticleP

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Light yield

4×10^4 γ/MeV

~ 30 γ/MeV
~ 110 γ/MeV

Nr of photons produced in the scintillation, **not number of detected photons!!!**

Photomultipliers

incoming radiation

↓ interaction with matter

energy deposition ΔE

↓ scintillation

light (visible or nearly visible)

↓ photodetection

electronic signal

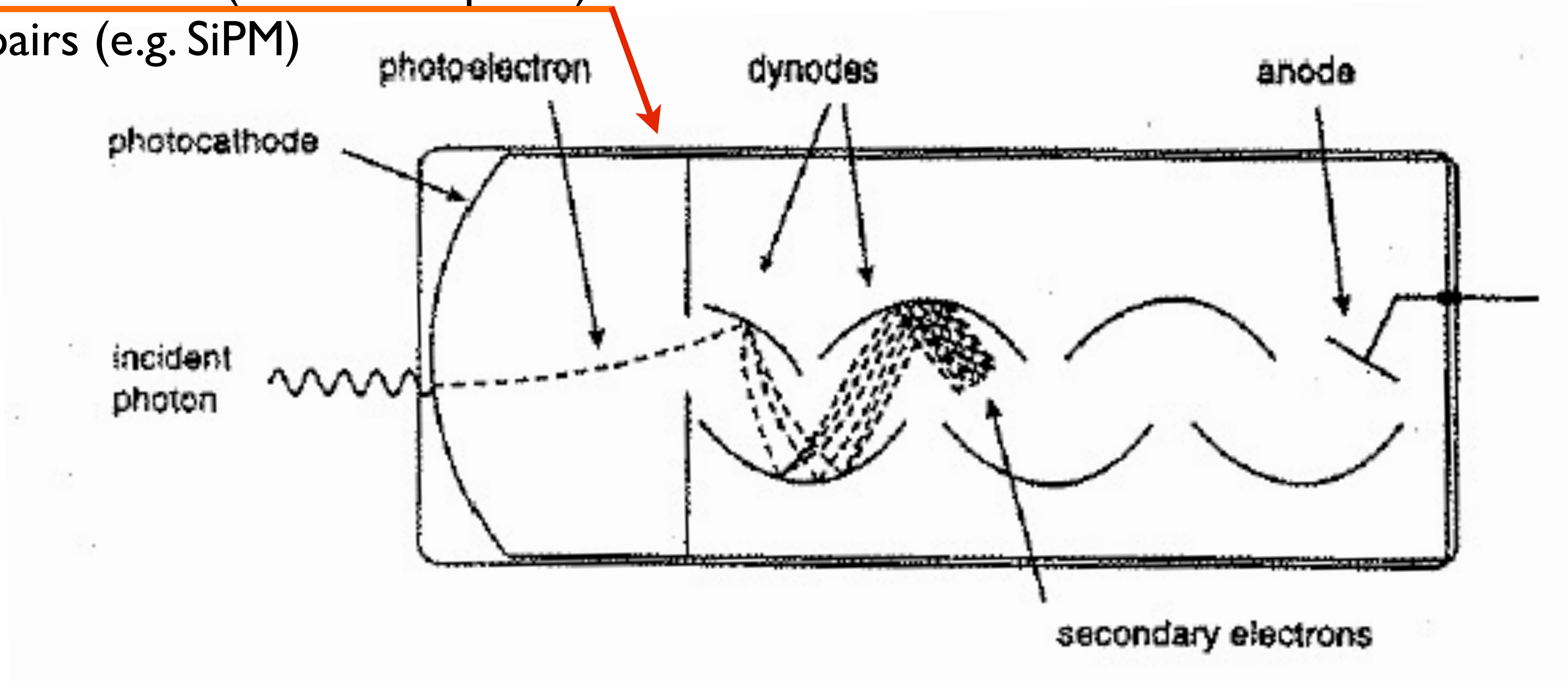
Photodetector / Photomultiplier

Purpose : Convert the light into a detectable (quantifiable) electrical signal

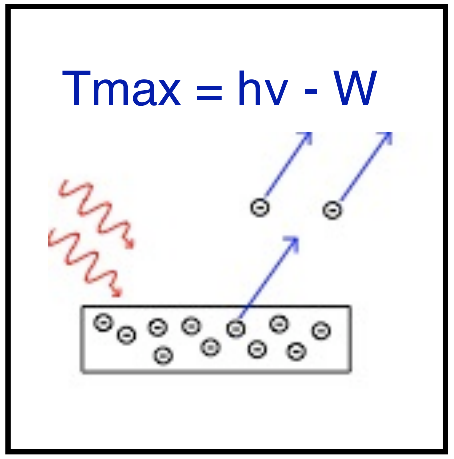
Different classes of light detectors :

a) light produces photoelectrons (Photomultipliers)

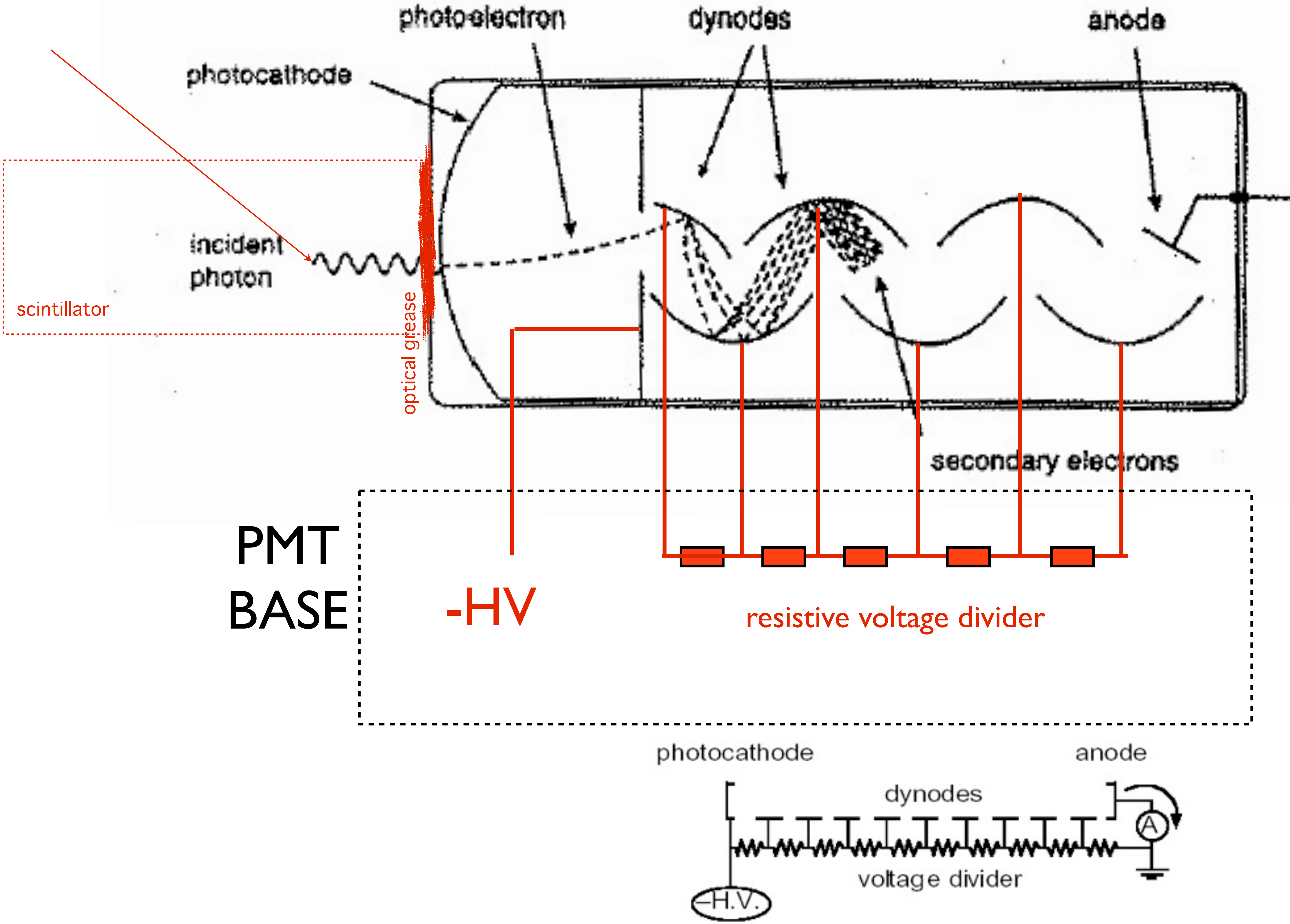
b) light produces e-h pairs (e.g. SiPM)



- photo emission from photocathode (photolectric effect)
  Q.E. = Np.e./Nphotons (quantum efficiency)
- secondary emission from dynodes (i.e. amplification)
  - single dynode gain *g* = 3 - 50 (f(E))
  - N_dynodes ~ 10 - 14
- collection of the secondary el. to form the electrical signal (at the anode)



- PMT gain: n dynodes ; g => *Gain_PMT* = g^n
  (gain ~ 10^7 -10^8 is accessible)


photoelectron
dynodes
anode
photocathode
incident photon
scintillator
optical grease
secondary electrons
PMT BASE
-HV
resistive voltage divider
photocathode
anode
dynodes
A
voltage divider
-H.V.

PMT Dark Noise

dark current = anode current, even when no photons arrive at the photocathode

Several sources :

- **<u>thermionic emission from the cathode and dynodes</u>**
  - ✦_most significant source of random noise
  - ✦ spontaneous emission of electrons due to their thermal kinetic energy / “thermal noise”
  - ✦ **pulse resulting from the thermal noise corresponds to the signal of <u>one single photoelectron</u>**
  - ✦ proportional to the photocathode surface ; depends on the material

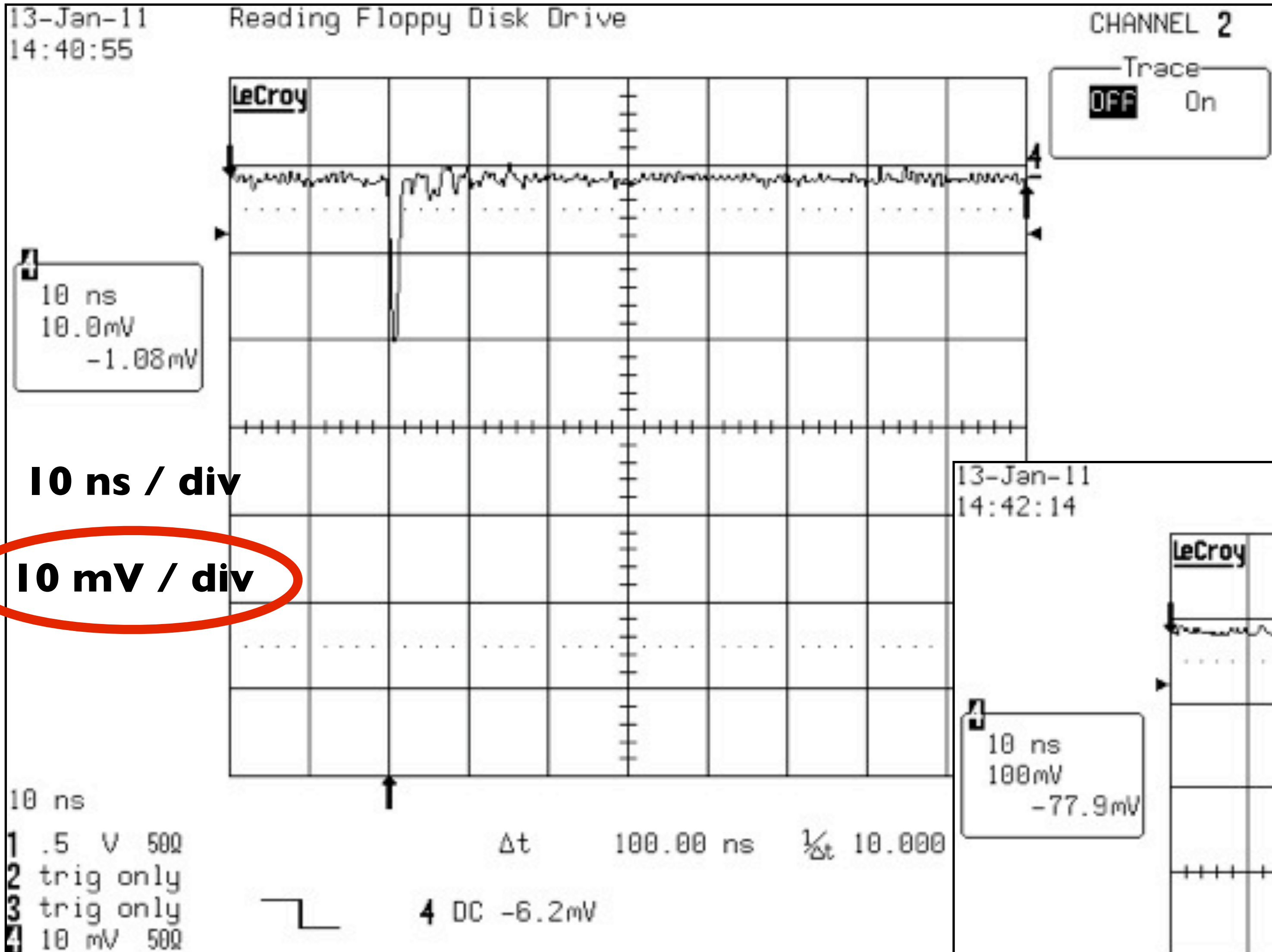
- **leakage current**
  - ✦through the electrode supports and the pins at the base

- **natural radioactivity** in the structure of the tube

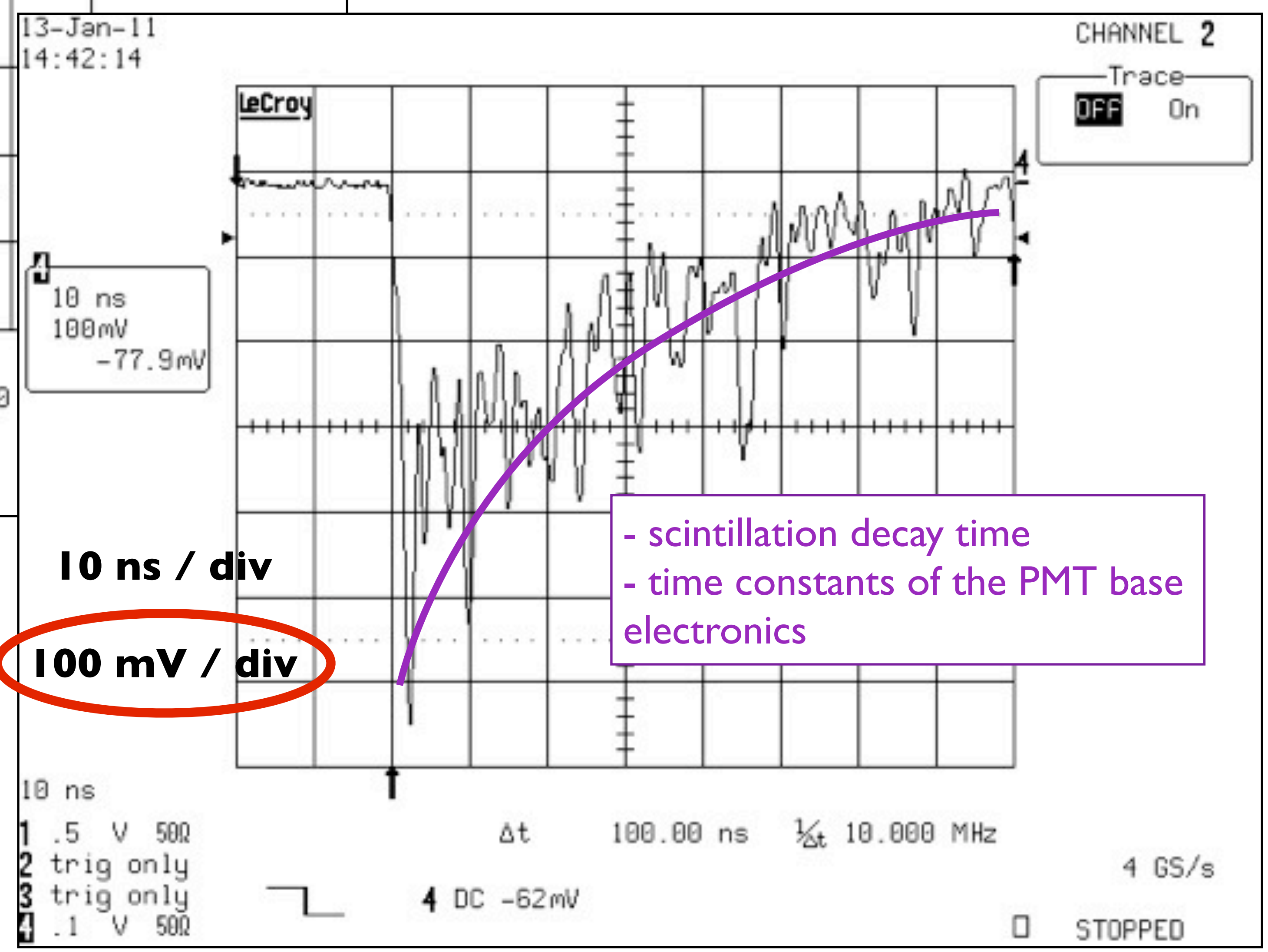
PMT signals : examples

PMT Hamamatsu Photonics K.K., Model R7400U coupled to a LYSO scintillator

Typical single photoelectron signal :

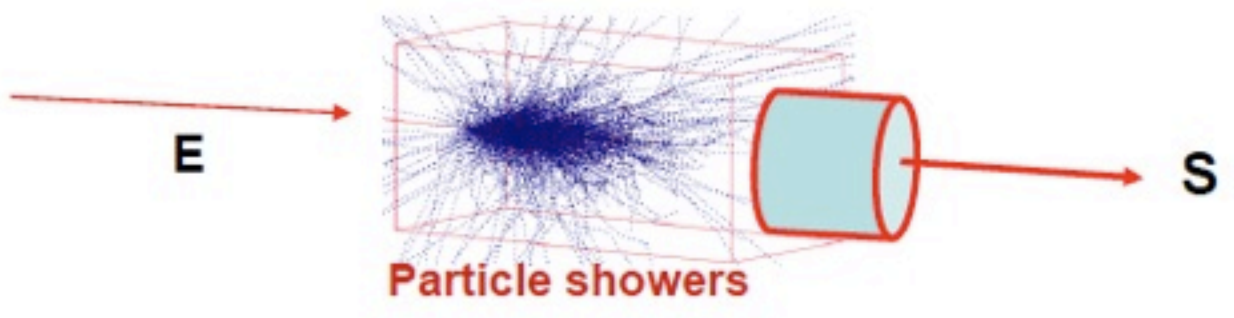


Scintillation pulse due to LYSO intrinsic radioactivity:



MUONS

Calorimetry / Muons in calorimetry (1/2)



basic mechanism in calorimetry:
development of a electromagnetic
or hadronic shower

if electromagnetic shower
=> particles initiating the shower = e / γ **(NOT μ !!!)**

e± , γ : multi-step process in energy loss

e: ionization & bremsstrahlung - <u>critical energy : Ec</u> (dE/dx)ion. ≈(dE/dx)brem.

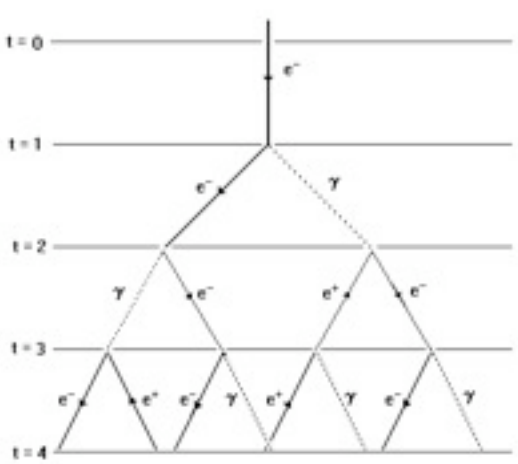
γ: photoelectric , Compton, pair production

<u>=> shower development</u>

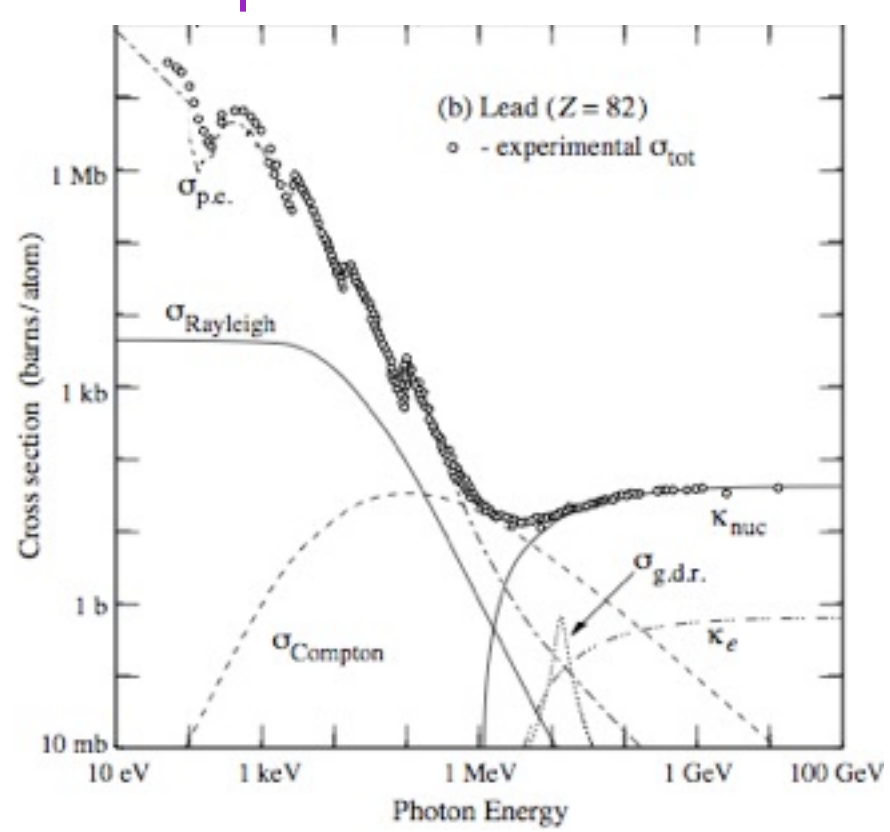
photons

electrons

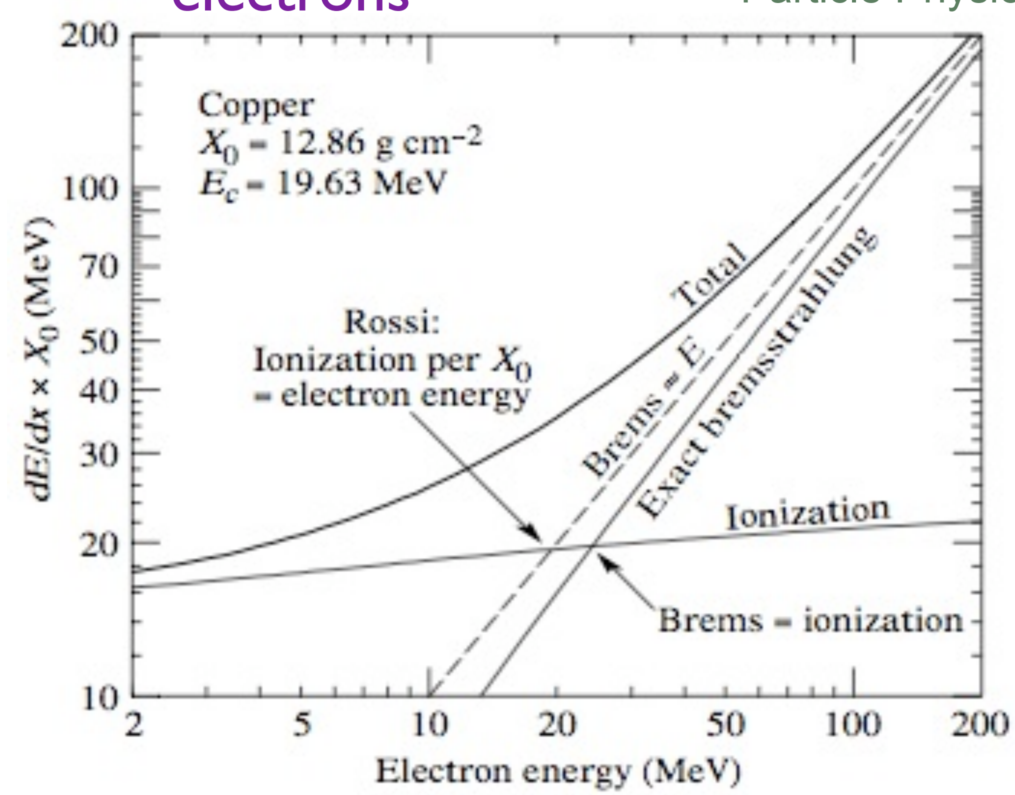
from Particle Data Group, Review of Particle Physics



particles multiplication driven by bremsstrahlung and pair production, until energy below E_c



Photons cross section (in Pb)



Electrons energy loss by ionization and bremsstrahlung (in Cu)

Calorimetry / Muons in calorimetry (2/2)

What about MUONS?

- μ are subject only to elm interaction (like e and γ) but behave in a totally different way!
- muon energy loss : primarily by ionization (and δ-rays)
- higher order QED processes (brem / pair prod.) do occur for μ absorption as well, but suppressed by a factor $(m_\mu/m_e)^2 \approx 40000$

$$(E_c)_e \simeq 5 - 20\ MeV \Rightarrow (E_c)_\mu \simeq 200\ GeV - 1\ TeV$$

- muons never reach the domain in which the energy loss mechanism is dominated by the radiative part (brem) - Major energy loss mechanism = ionization
- E loss: $$\frac{1}{\rho}\frac{dE}{dx} = \frac{1}{\rho}\frac{dE}{dx}|_{ioniz.} \simeq 1 - 2\ \frac{MeV}{g/cm^2}$$

- high energy muons are not absorbed =>
  - ✓ HEP detectors : external muon chambers ; only small signal in the calorimeter
  - ✓ cosmic muons arrive at the Earth surface
  - ✓ deep underground experiments, if cosmic muons are important background

Interactions particles / matter : Bethe-Bloch

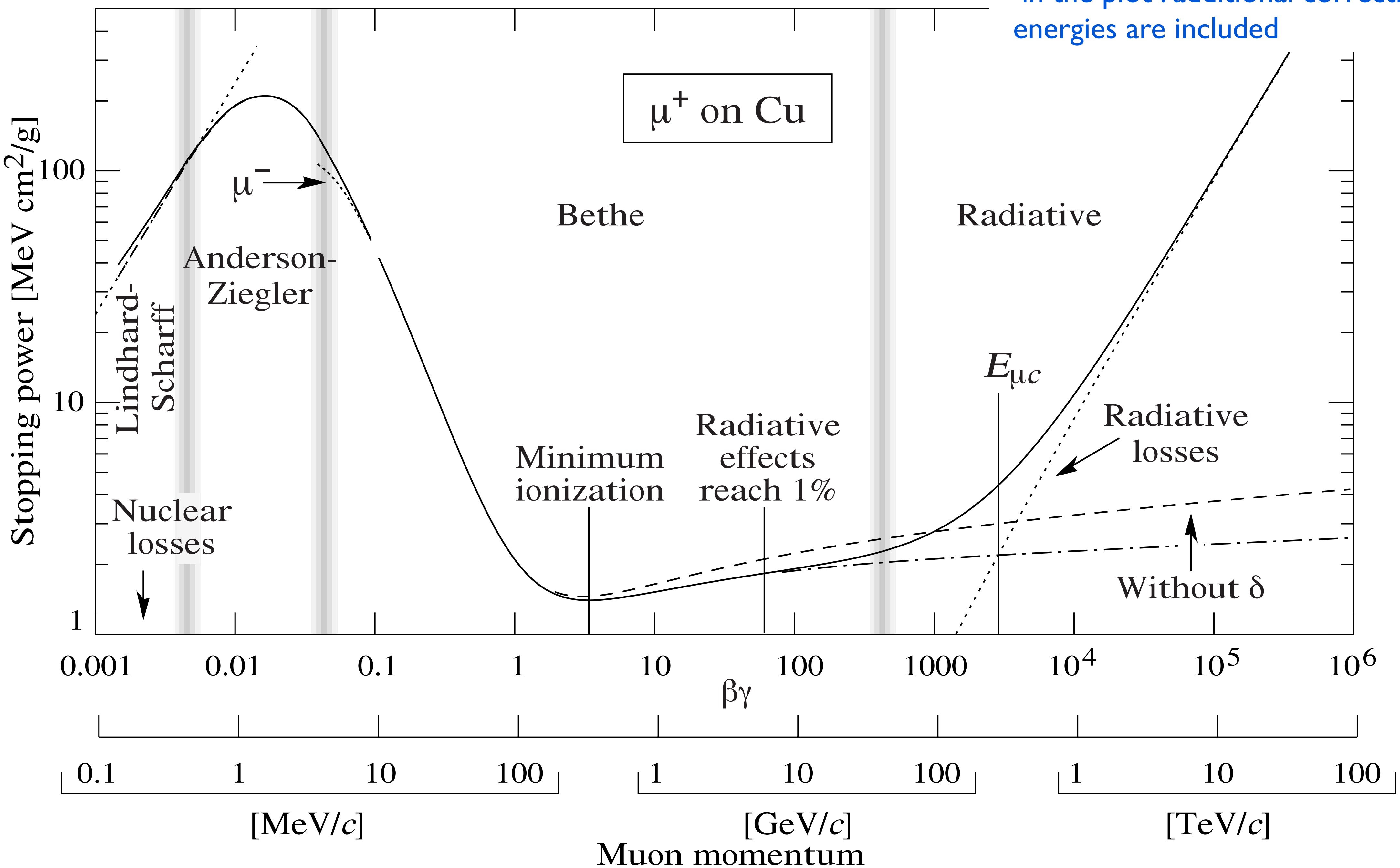
Bethe - Bloch formula : basic expression for energy loss calculation

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

mean excitation energy (I)   max energy transfer per collision (T_{max})

- dE/dx for ionization for heavy charged particles
- depends on energy of the particle / on absorber
- does not depend on the mass of the particle
- valid for any charged particle passing through matter. But for electrons additional terms are needed.

- in the plot : additional correction for low / high energies are included

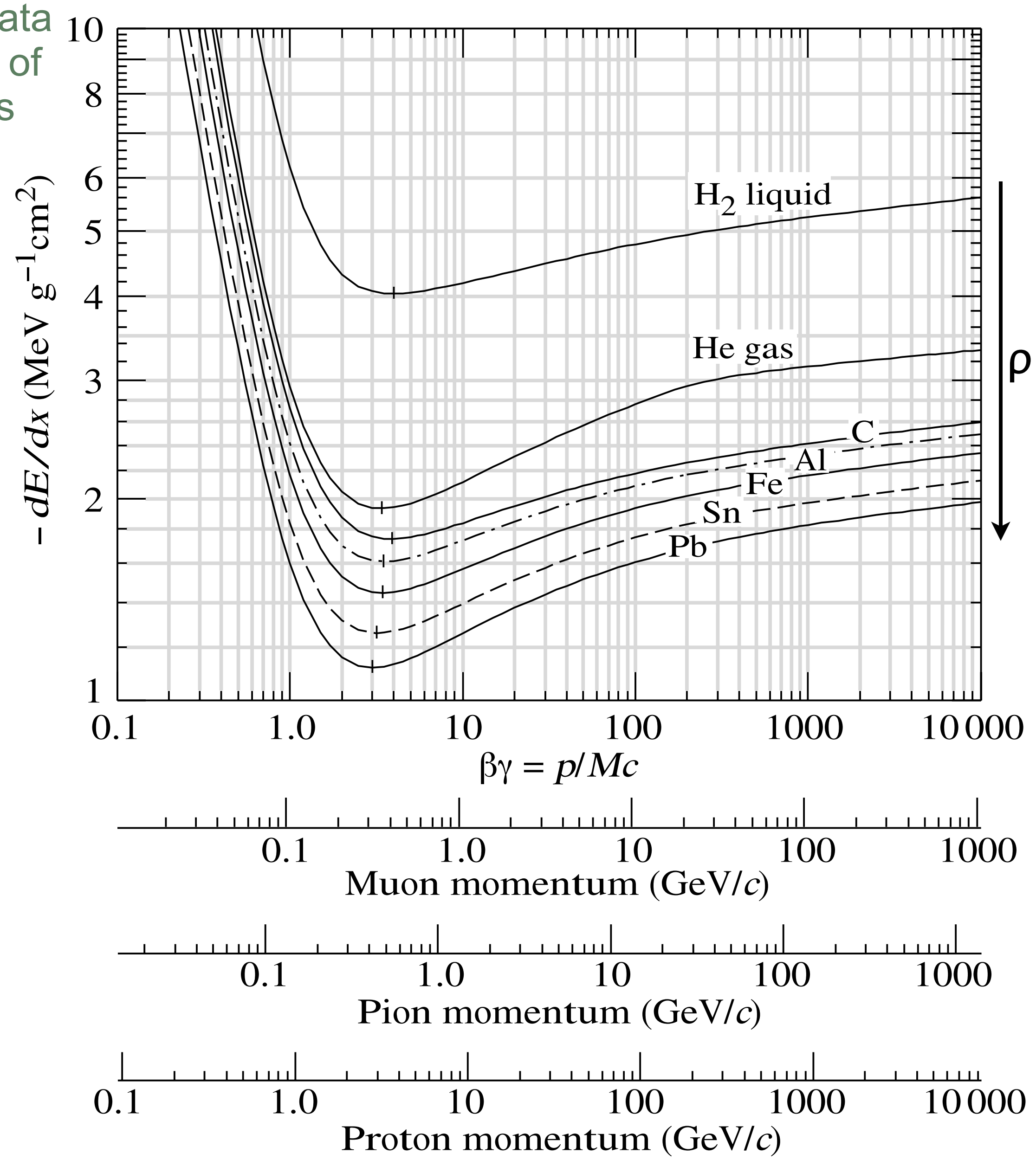


from Particle Data Group, Review of Particle Physics

Density dependence / MIP

Zoom of the stopping power trend in the Bethe - region
(where the Bethe-Bloch formula is exactly valid)

from Particle Data Group, Review of Particle Physics

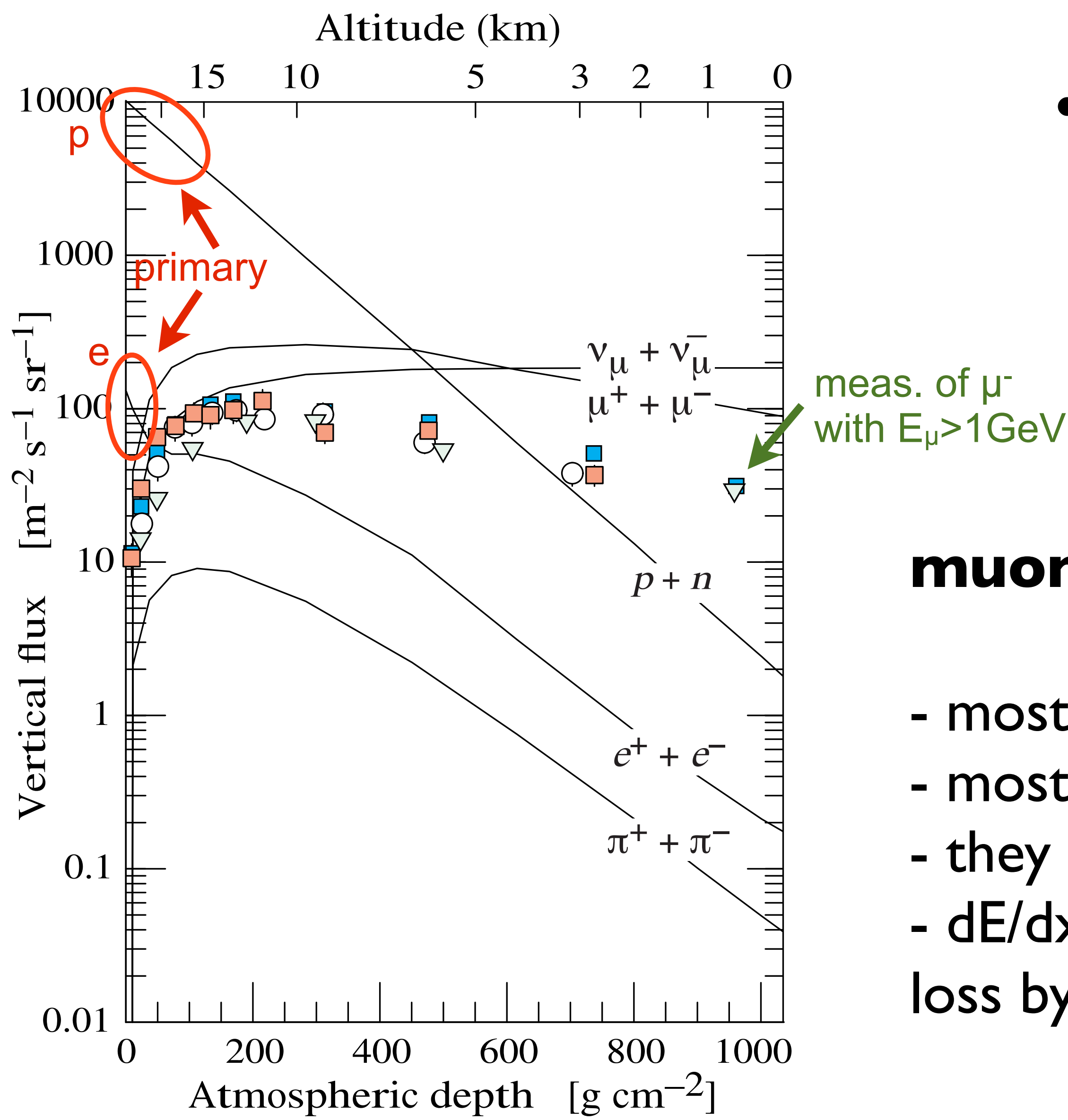


- $\pi^{\pm}$, μ, p with the same velocity have similar rate of energy loss in different materials
  "universality of Bethe-Bloch formula"
- the minimum is approximatively independent on the material
- there is a (small) dependence with Z of the absorber material
- $dE/dx|_{mip}$ ~ 1-2 MeV / g/cm^2

a **minimum ionizing particle** (or **mip**) is a particle whose mean energy loss rate through matter is close to the minimum. (broad minimum => ~ constant dE/dx)

Cosmic muons

from Particle Data Group,
Review of Particle Physics



Estimated vertical flux of cosmic rays in the atmosphere with E > 1 GeV

- primary cosmic rays: particles accelerated at astrophysical sources (~ 80% are free p)
- secondary cosmic rays: particles produced in the interaction of the primary with the interstellar gas

muons in cosmic rays (i.e. secondary):

- most numerous charged particles at sea level
- most muons are produced high in the atmosphere (~ 15 km)
- they are essentially **mips**
- dE/dx ~ 2 MeV/g/cm² ; depth ~1000 g/cm² => Total energy loss by ionization before reaching the ground ~ 2 GeV

- mean energy at ground : **$<E_\mu>$ ~ 4 GeV**
- integral intensity of vertical muons (>1GeV) ~ 70 m^{-2} s^{-1} sr^{-1}

Rate ~ 1 cm^{-2} min^{-1}

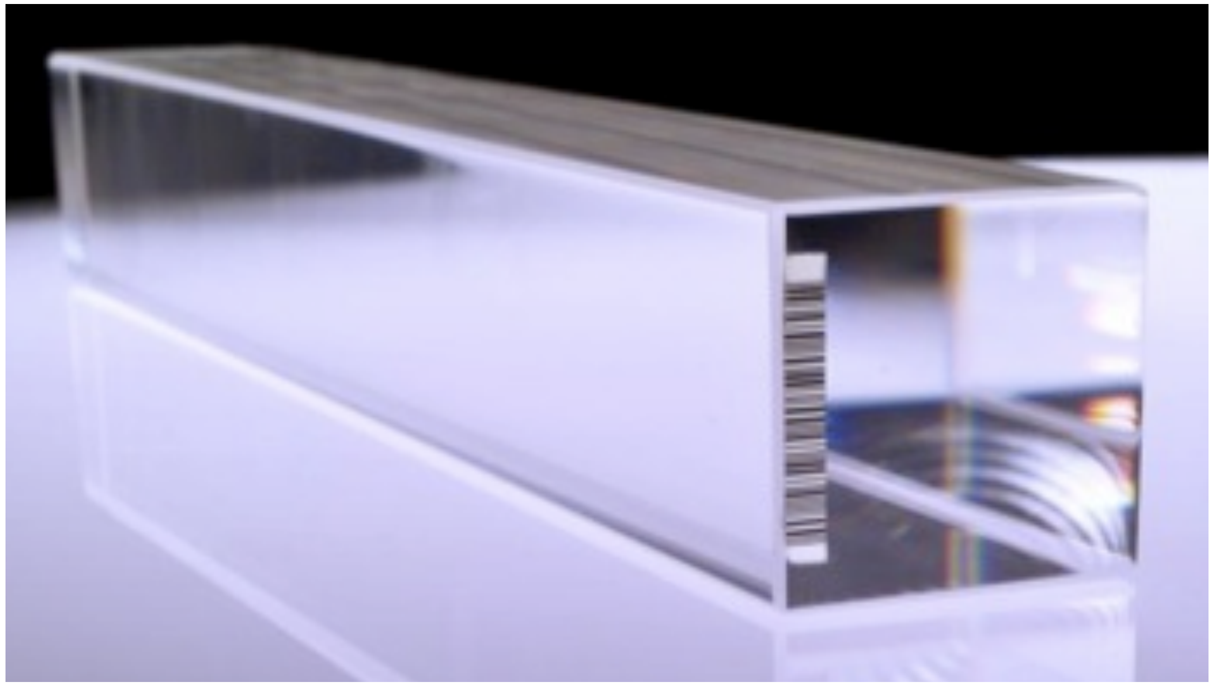
from Particle Data Group, Review of Particle Physics

SETUP

OUR SETUP

scintillator

Lead Tungstate : $PbWO_4$

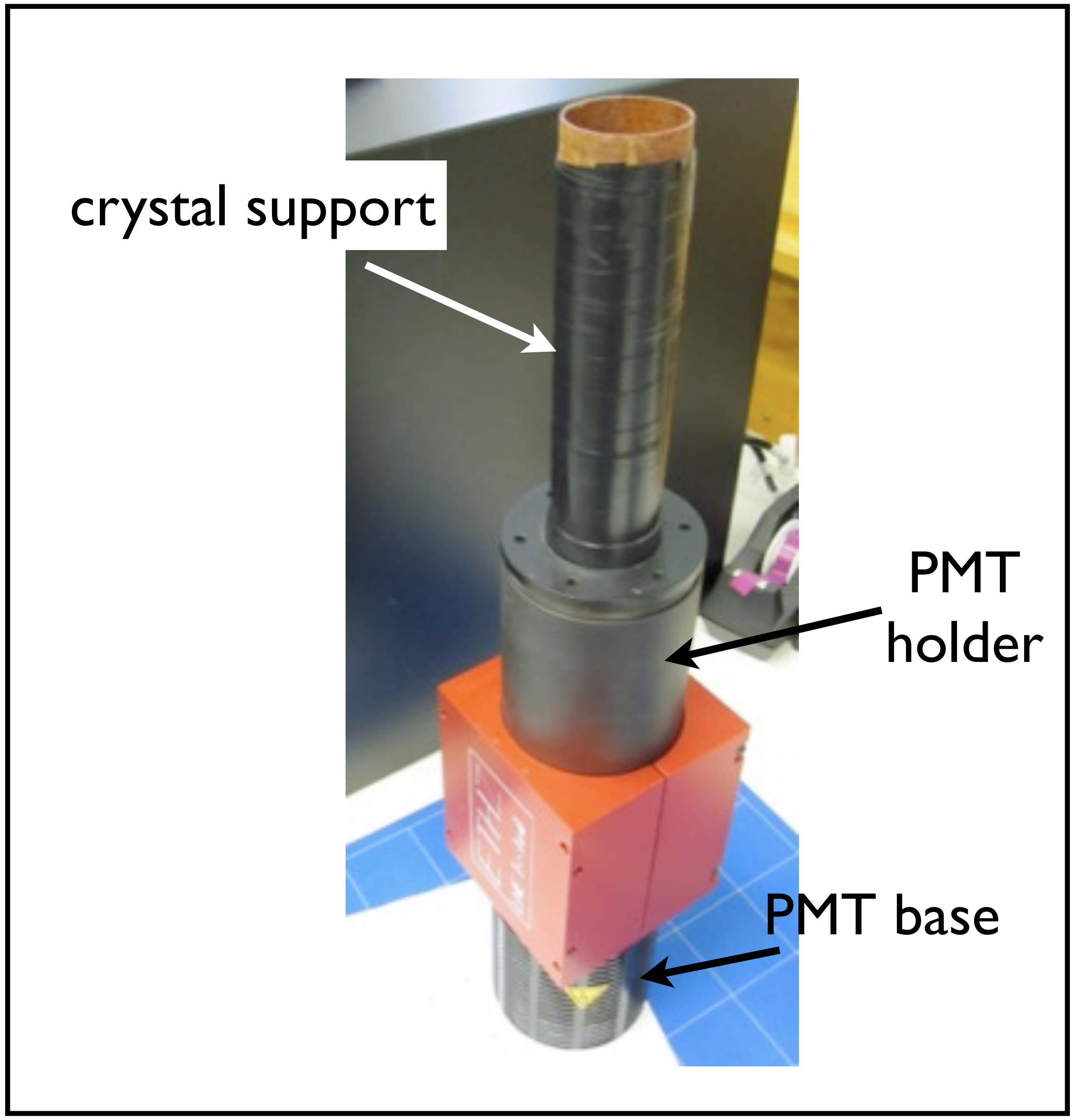


dimensions ~ 23 x 2.5 x 2.5 cm^3
X_0 = 8.9 mm, ρ_M = 20 mm, ρ = 8.3 g/cm^3
weight = 1.2 kg, polished
$\delta LY/\delta T$ (18°C) = -2.7%/°C

one of the prototype crystals for the CMS ECAL

photomultiplier

XP2262B , Photonis



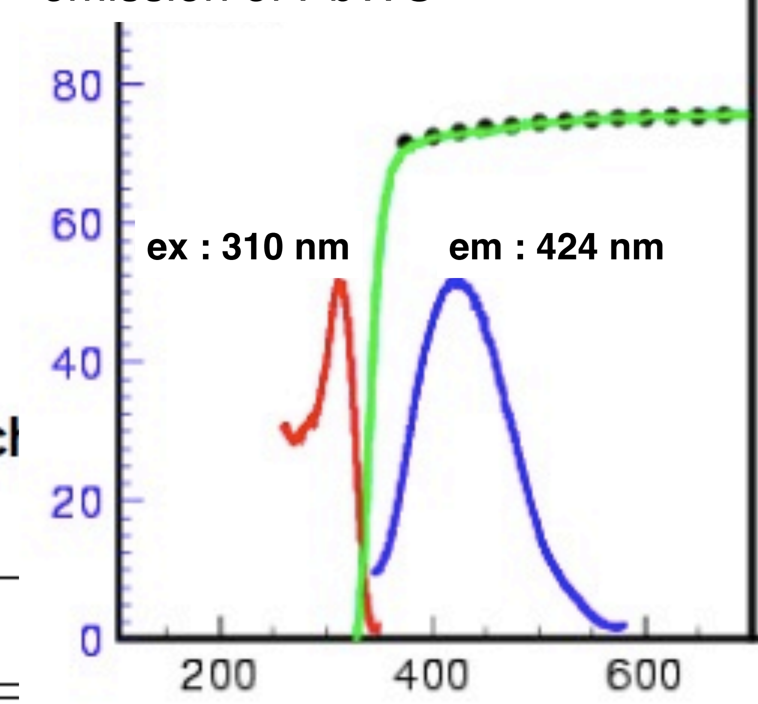
OUR SETUP

XP2262B

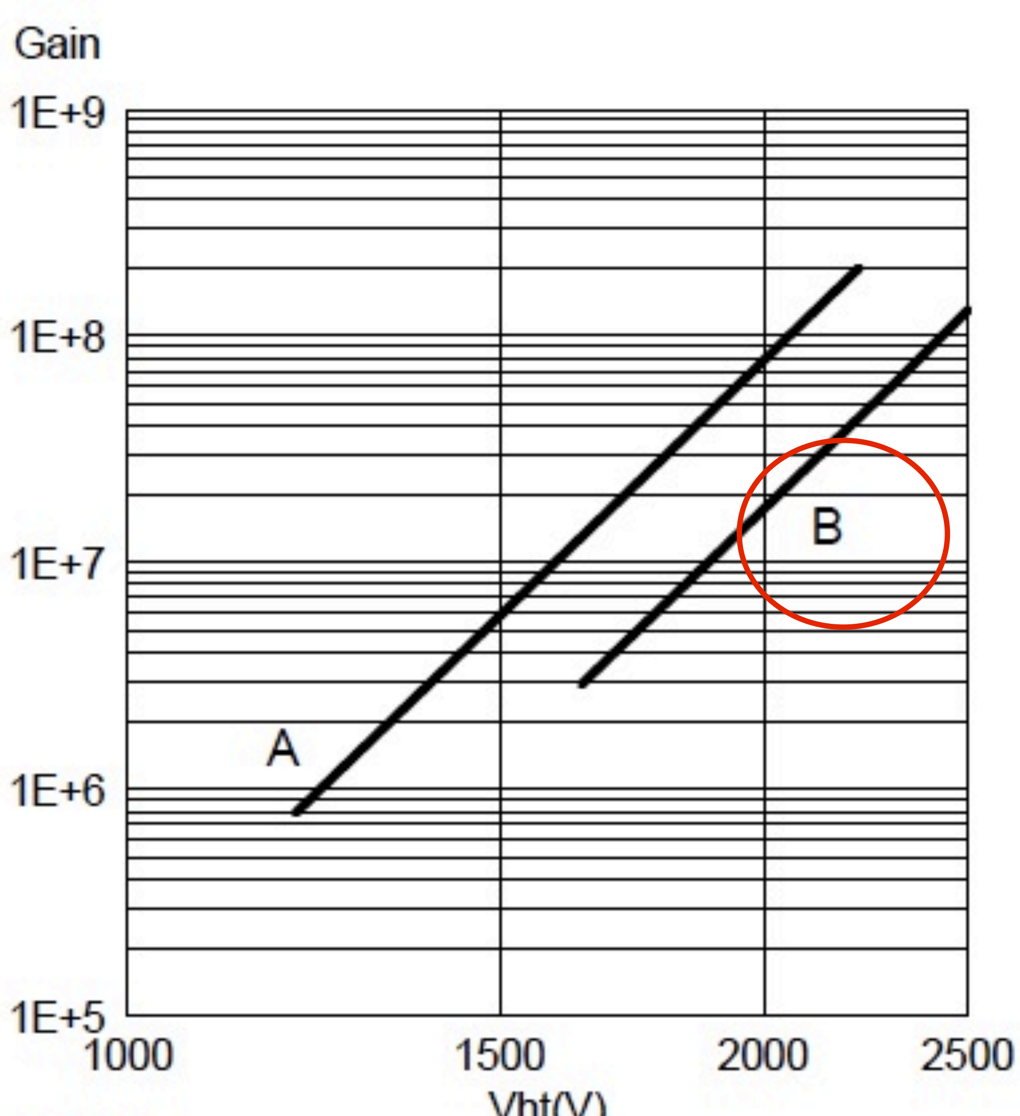
A standard fast, 12-stage, 51mm (2") tube

Applications :	High and medium energy physics.		
Description :	Window :	Material : Photocathode : Refr. index at 420 nm :	lime glass bi-alkali 1.54
	Multiplier :	Structure : Nb of stages :	linear focused 12
	Mass :	176 g	

emission of PbWO

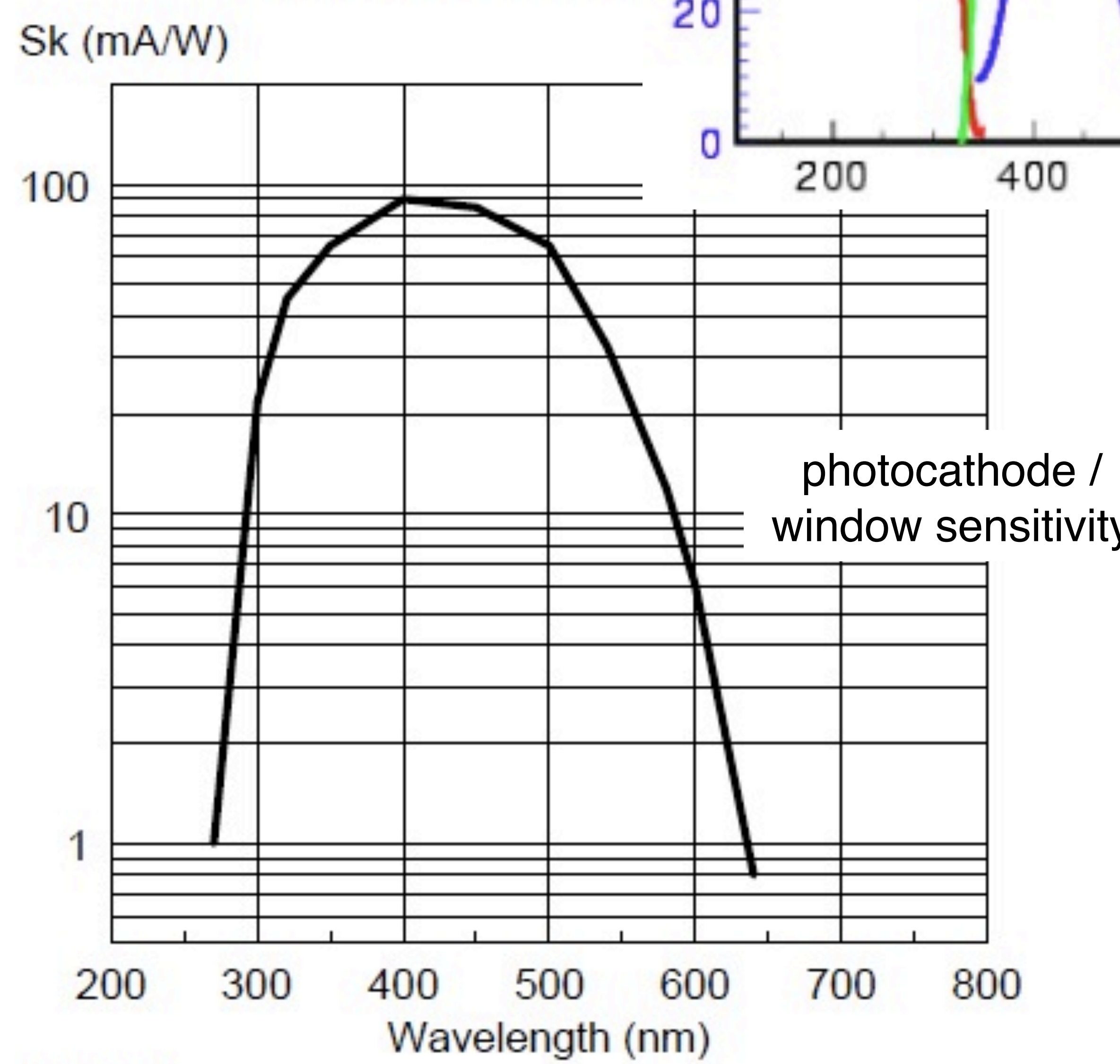


Typical gain curve



XP2262

Typical spectral cl



photocathode / window sensitivity

XP2262

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PMT : XP2262B

from CMS E-CAL TDR (Chapter 2 - Lead tungstate crystal) :

Light yield values in excess of **10 photoelectrons/MeV** are now systematically observed in a gate of 200 ns on a photomultiplier (XP2262B) covering all the back face of 23-cm-long crystals.

hands on

(1) Compute the gain of the PMT

(2) Measure cosmic muons energy deposition

(1) Compute the gain of the PMT

- Inject known charge (Q) - Measure detected charge by PMT (Q_PMT) => G = Q_PMT / Q
- Do we have any known charge available ? Yes => Single photoelectron from thermal noise (Q = 1e)

cable the setup / HV = - 2450 V

on the scope :

- adjust the settings to **observe single photoelectron pulses**
- acquire the histogram for the integral of the single photoelectron noise i.e. **measure the collected charge (after PMT multiplication) corresponding to one electron**
- **compute the gain**

(follow experimental protocol)

(2) Measure cosmic muons energy deposition

(1) Compute the gain of the PMT

- Inject known charge (Q) - Measure detected charge by PMT (Q_PMT) => G = Q_PMT / Q
- Do we have any known charge available ? Yes => Single photoelectron from thermal noise (Q = 1e)

cable the setup / HV = - 2450 V

on the scope :

- adjust the settings to **observe single photoelectron pulses**
- acquire the histogram for the integral of the single photoelectron noise i.e. **measure the collected charge (after PMT multiplication) corresponding to one electron**
- **compute the gain**

(follow experimental protocol)

(2) Measure cosmic muons energy deposition

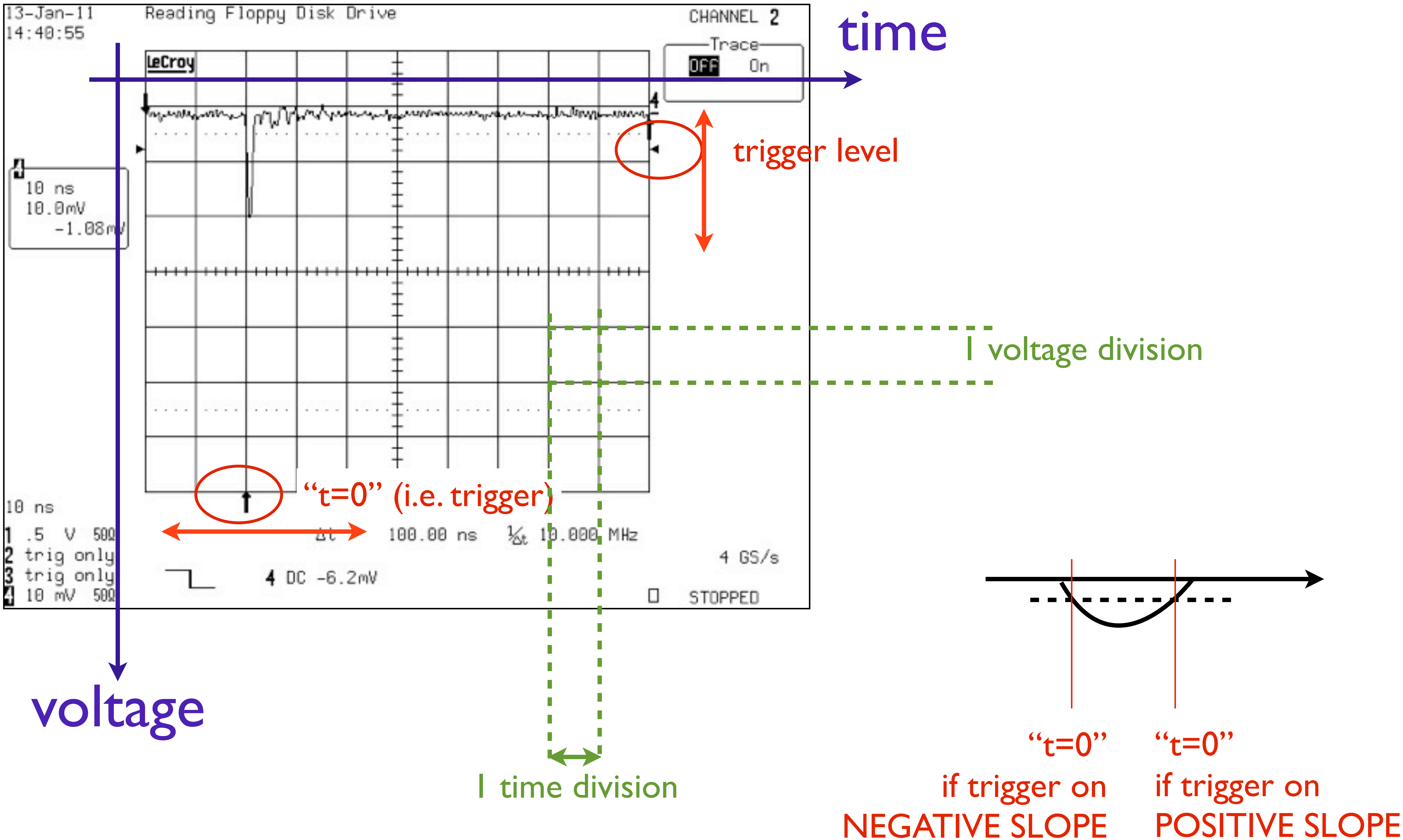
on the scope :

- adjust the settings to **observe muon pulses** while **suppressing single photoelectrons**
- a proper **attenuation** factor is required (Volts/division = 1V max on the scope)
- acquire the histogram for the integral of the integrated charge from muon interaction

make a prediction of the expected results
compare results and predictions

(follow experimental protocol)

OSCILLOSCOPE



Attenuation (dB)

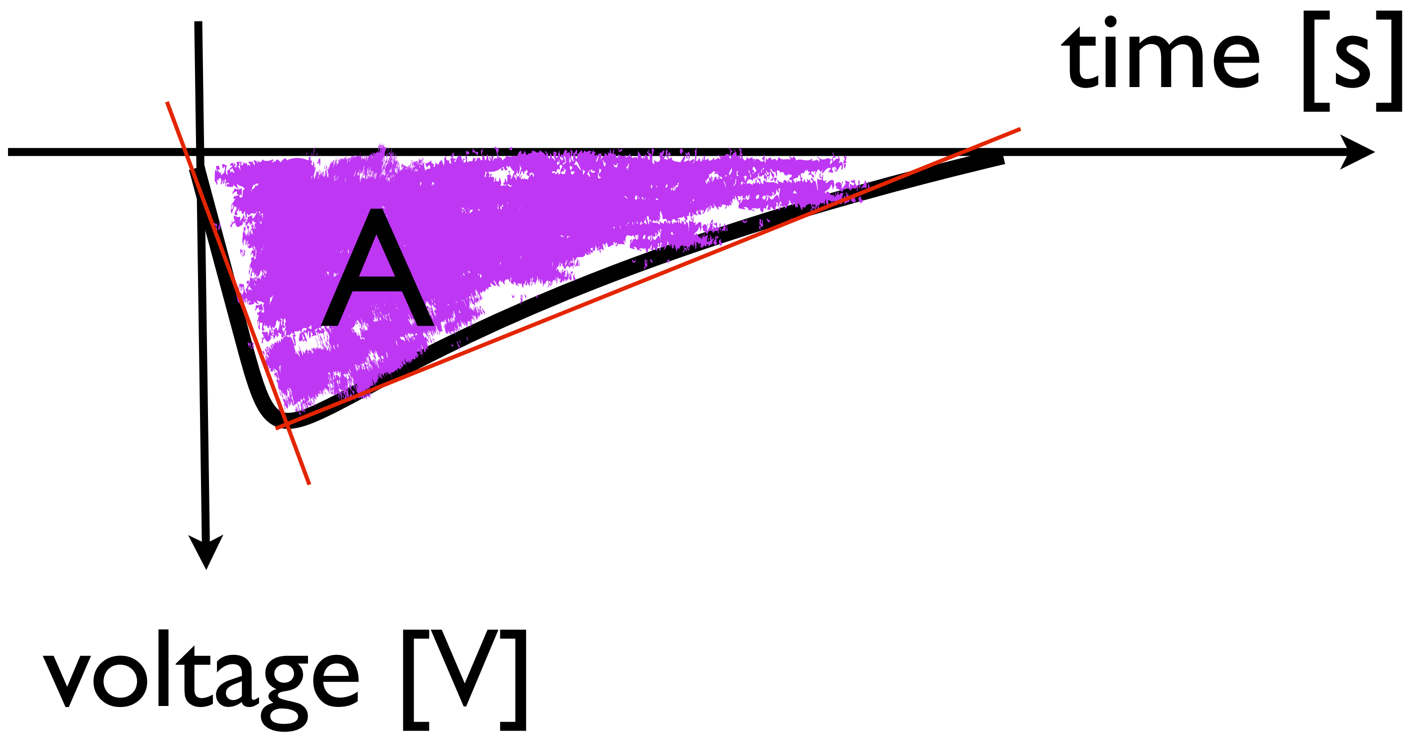
Decibel (dB) = unit to express the ratio of **power** of 2 signals

$$dB = 10\ log_{10}(\frac{P_1}{P_2})$$

dB can be also used for the ratio of signals **amplitudes**.
(power proportional to signal amplitude^2 $P \div V^2$)

$$dB = 20\ log_{10}(\frac{A_1}{A_2})$$

dB	$R = A_1/A_2$ = 10^(-dB/20)
2	0.79
6	0.50
12	0.25
14	0.20
18	0.13



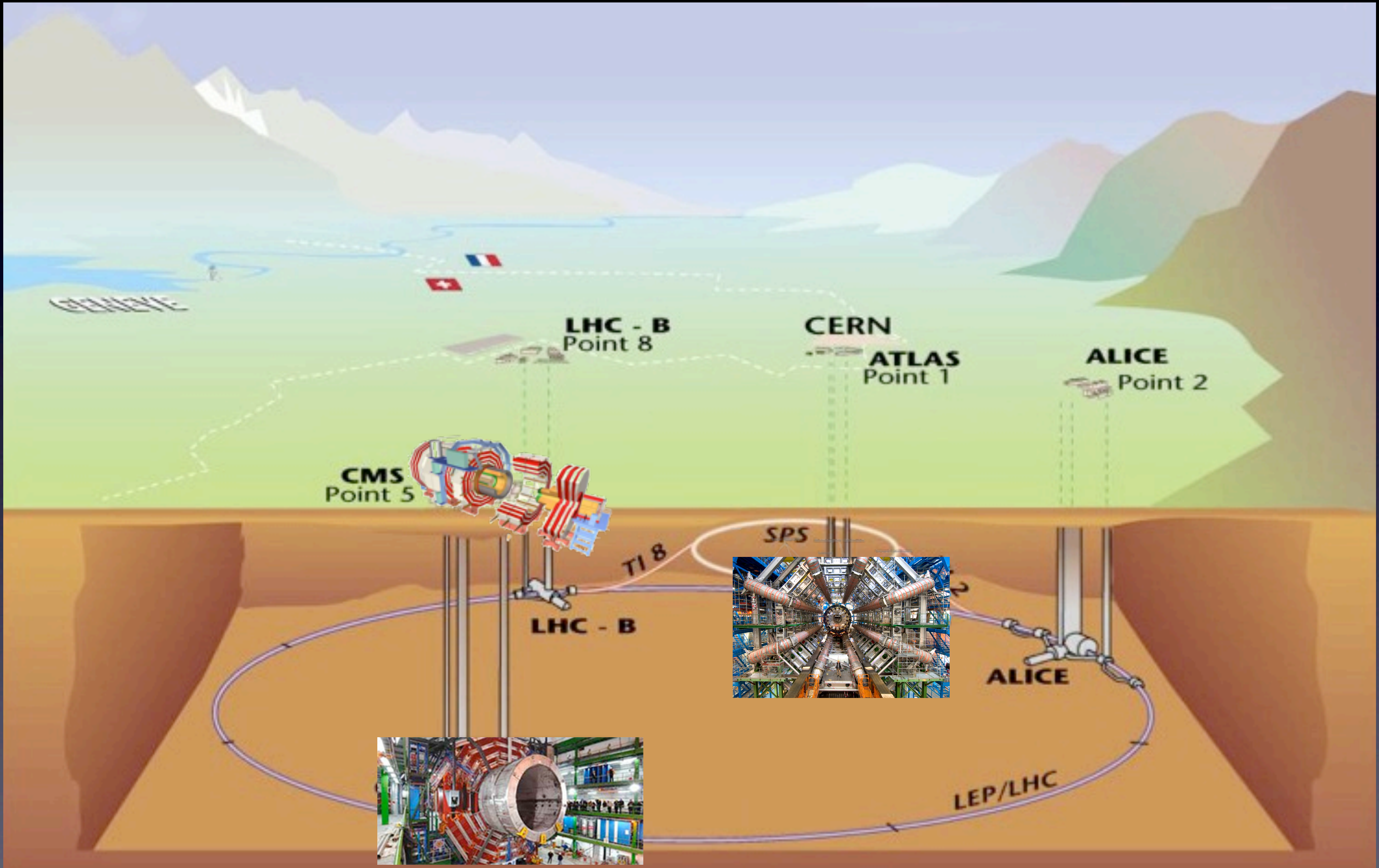
$$A = \int V(t)\,\mathrm{d}t = R \int I(t)\,\mathrm{d}t = R\,Q$$

A [Vs] => indication of the total collected charge

A/50Ω = Q [Vs/Ω=C] = total collected charge

CMS-ECAL

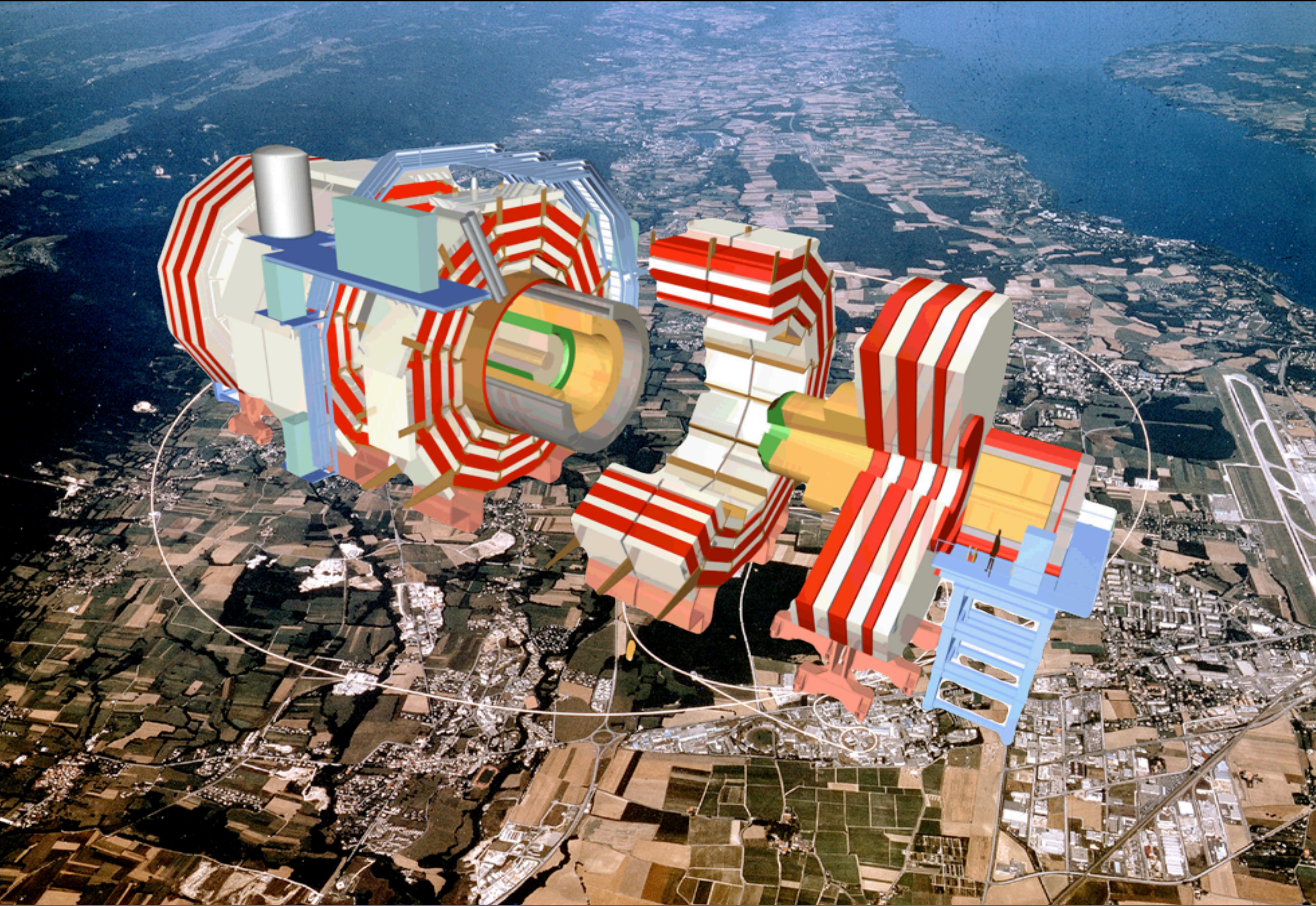
LHC



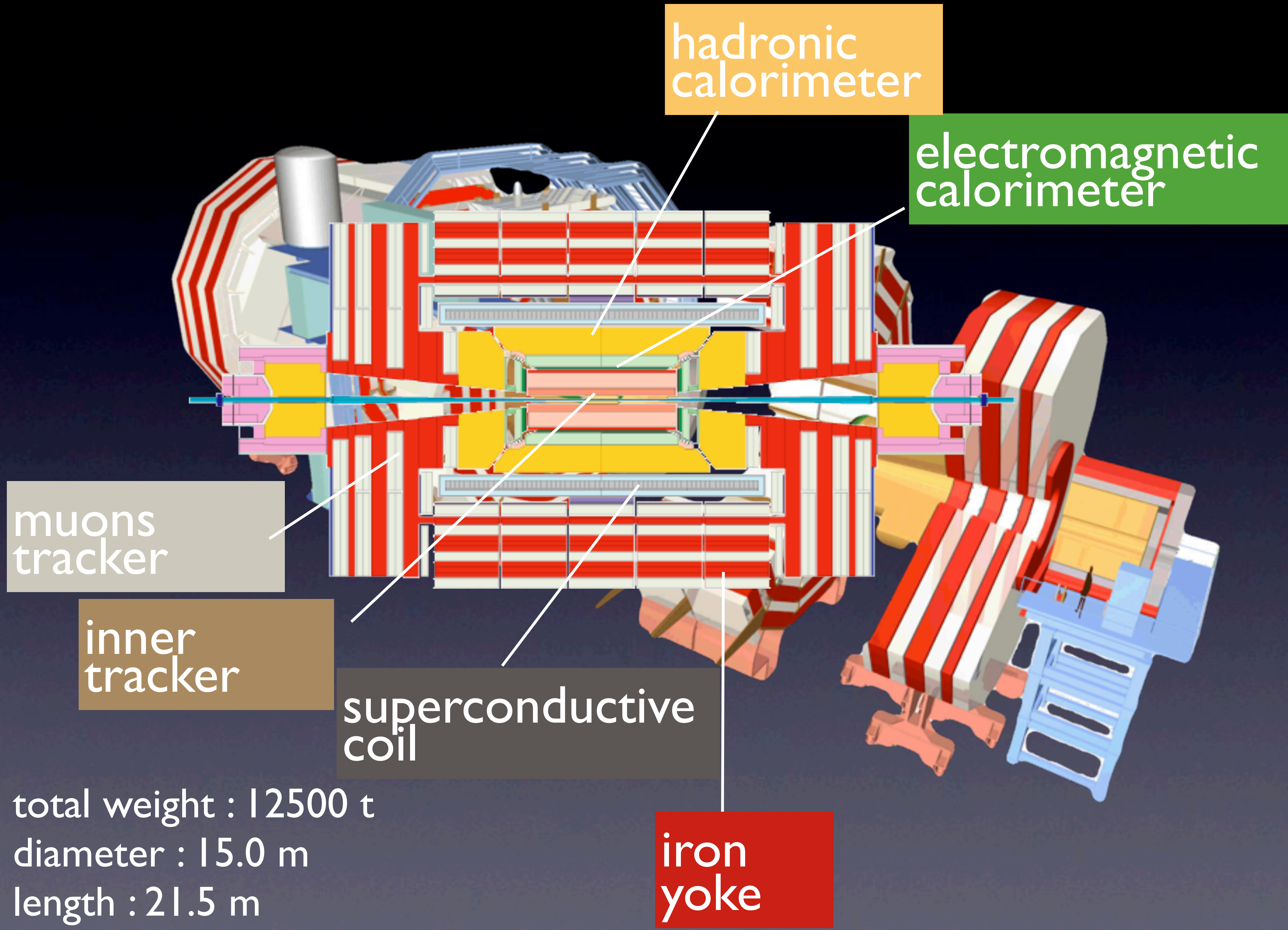
ATLAS: A Toriodal LHC ApparatuS (collisioni p-p)
CMS: Compact Muon Solenoid (collisioni p-p)

ALICE: A Large Ion Colider Experiment
LHCb: CP-violation studies in B-meson decays

CMS detector

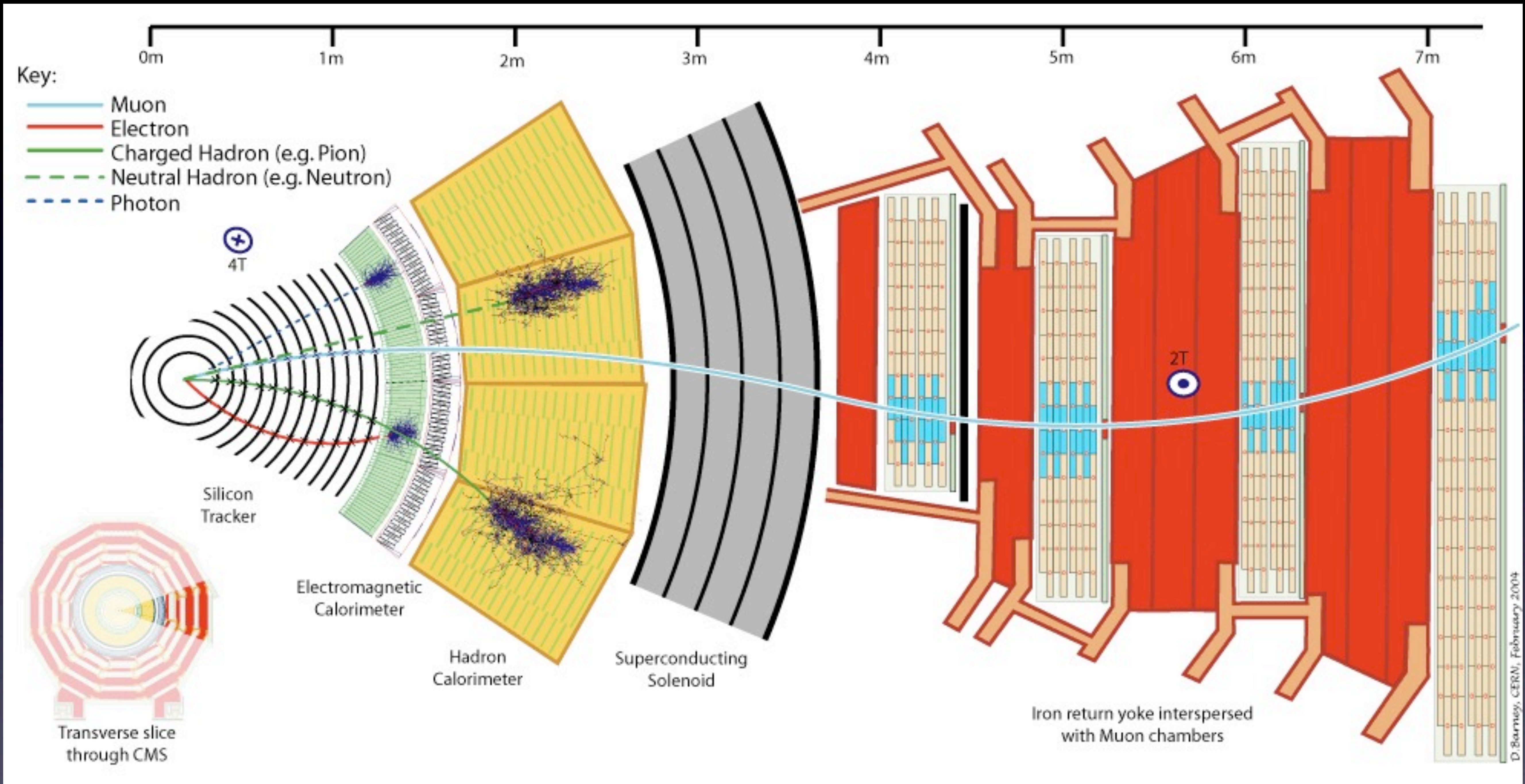


CMS detector



total weight : 12500 t
diameter : 15.0 m
length : 21.5 m
magnetic field : 4 Tesla

CMS detector



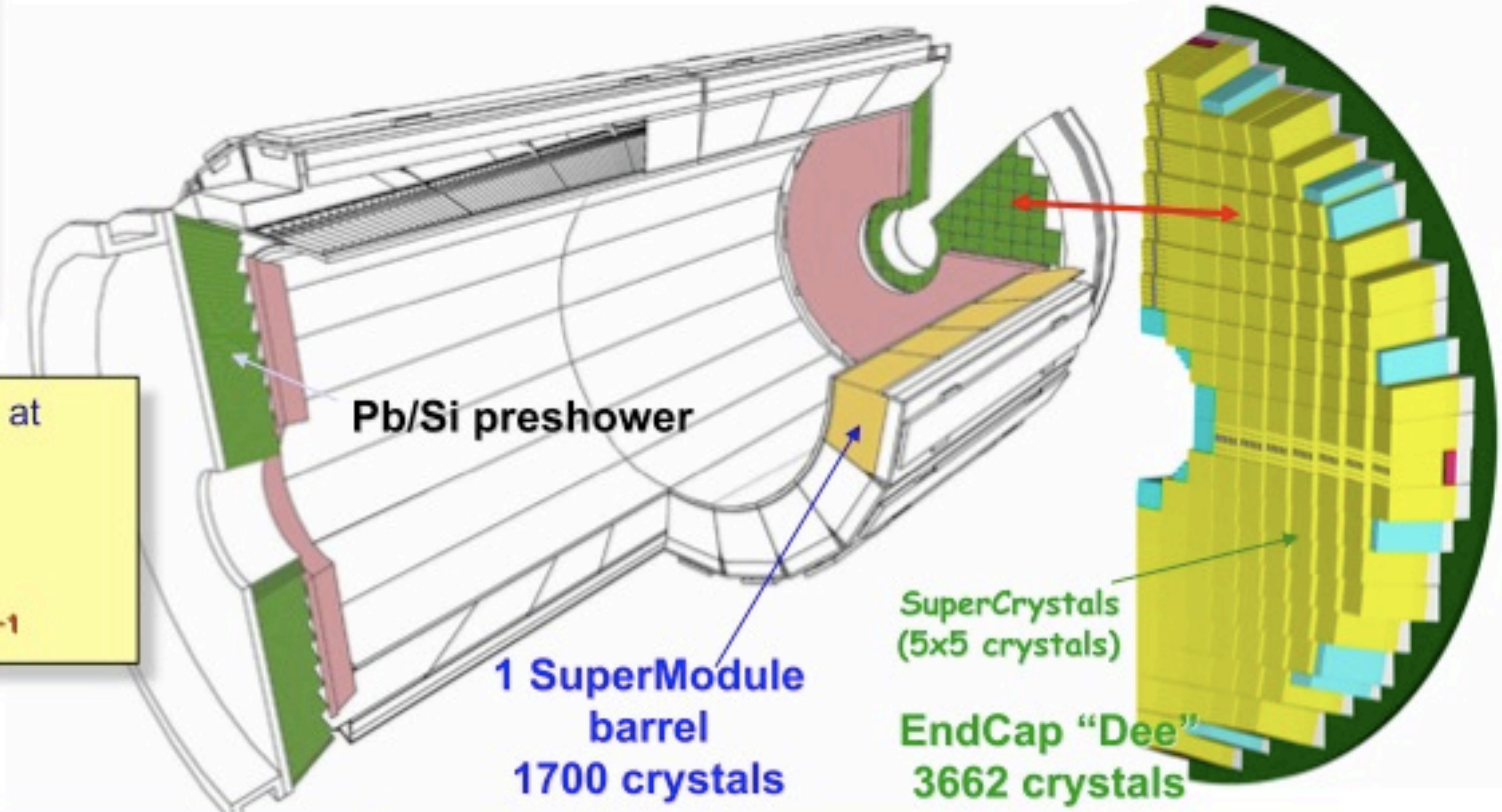
total weight : 12500 t
diameter : 15.0 m
length : 21.5 m
magnetic field : 4 Tesla

CMS Electromagnetic calorimeter

Homogenous crystal calorimeter
Lead tungstate ($PbWO_4$)
~10 m^3, 90 tons

Energy resolution goal: 0.5% at high energy

⇒ Higgs @120 GeV discovery with ≤10 fb^{-1}
100 days @ 2 10^{33} $cm^{-2}s^{-1}$



Barrel: $|\eta| < 1.48$
36 SuperModules
61200 crystals (2.2x2.2x23cm^3)

EndCap: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals(3x3x22cm^3)

from CMS-ECAL TDR

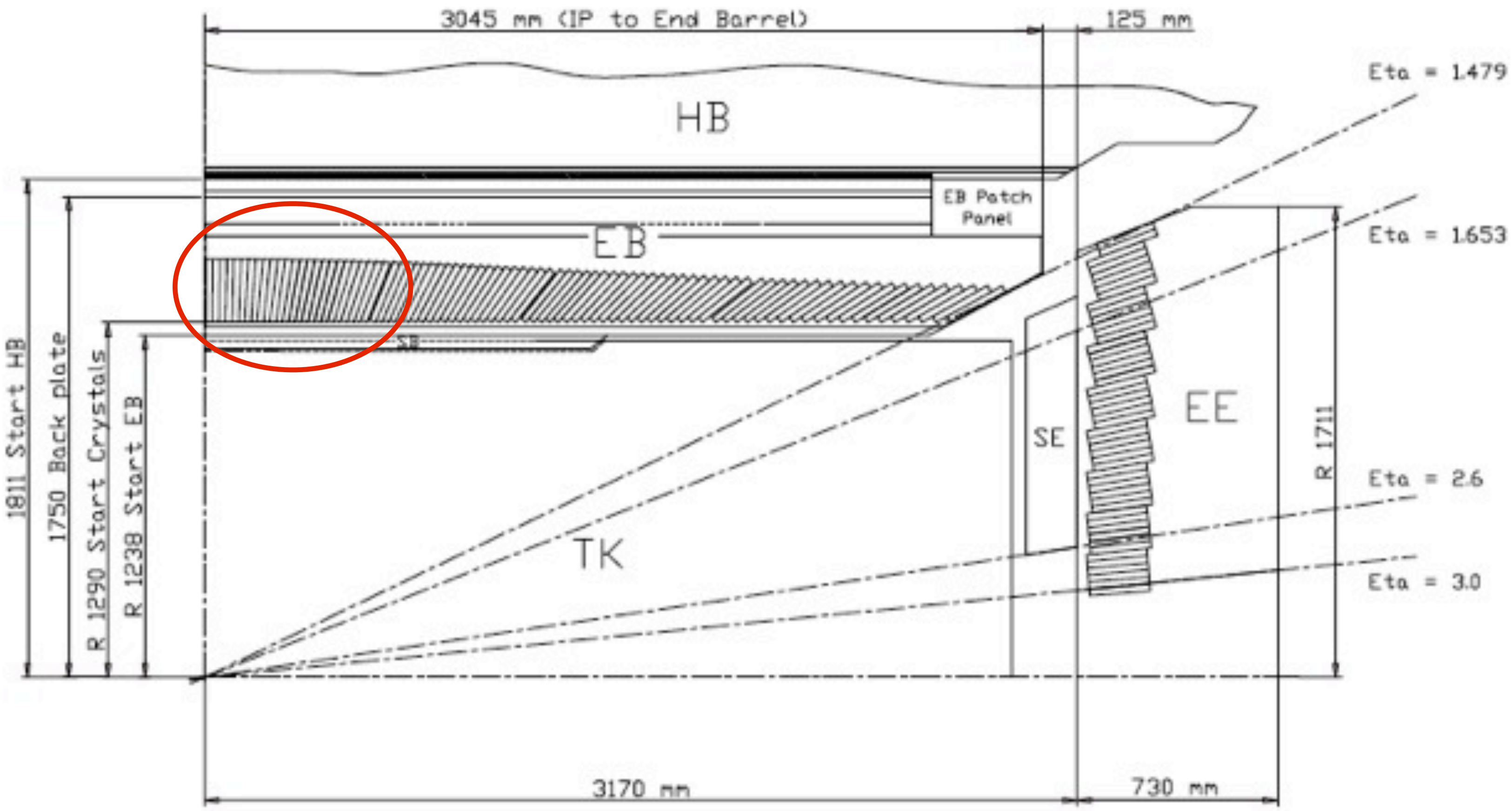
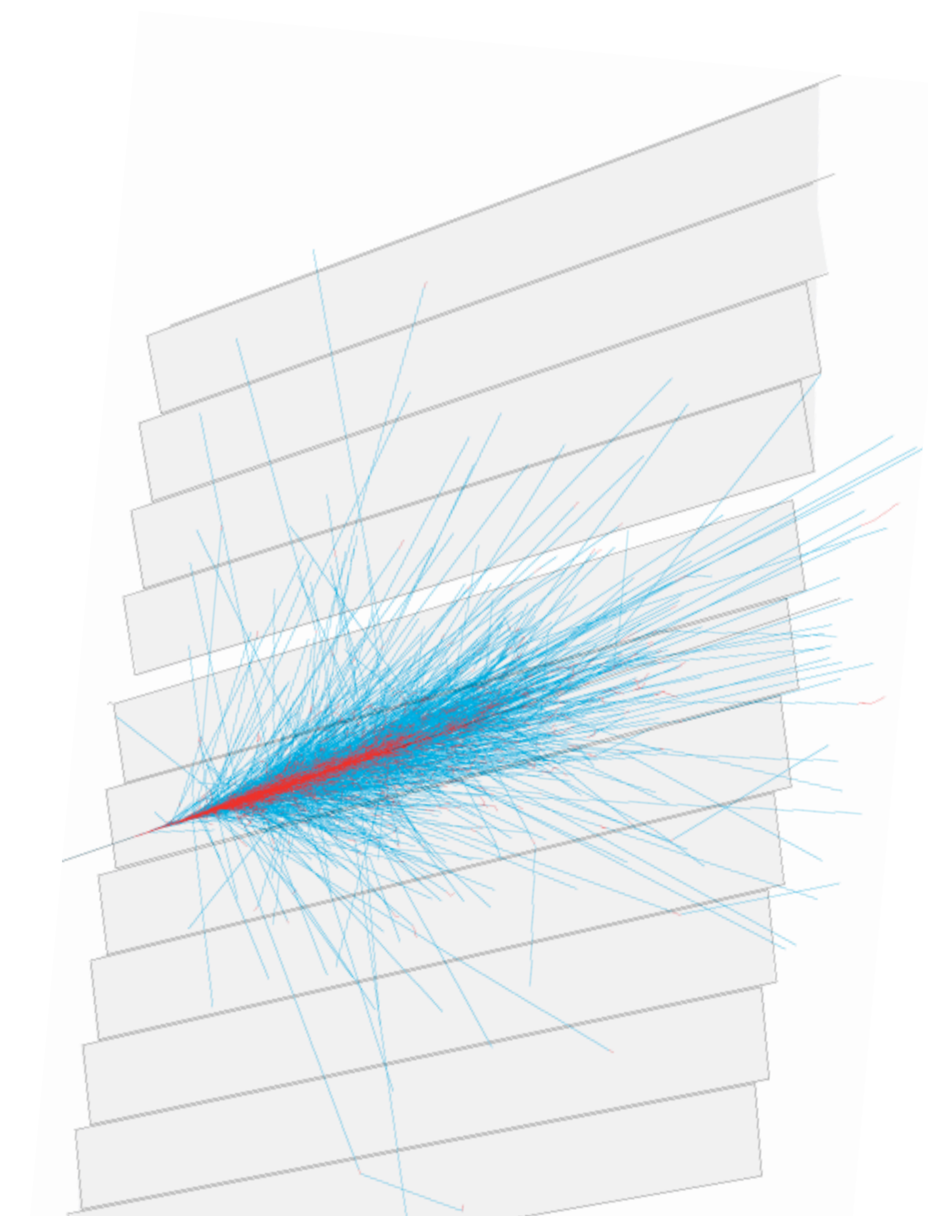
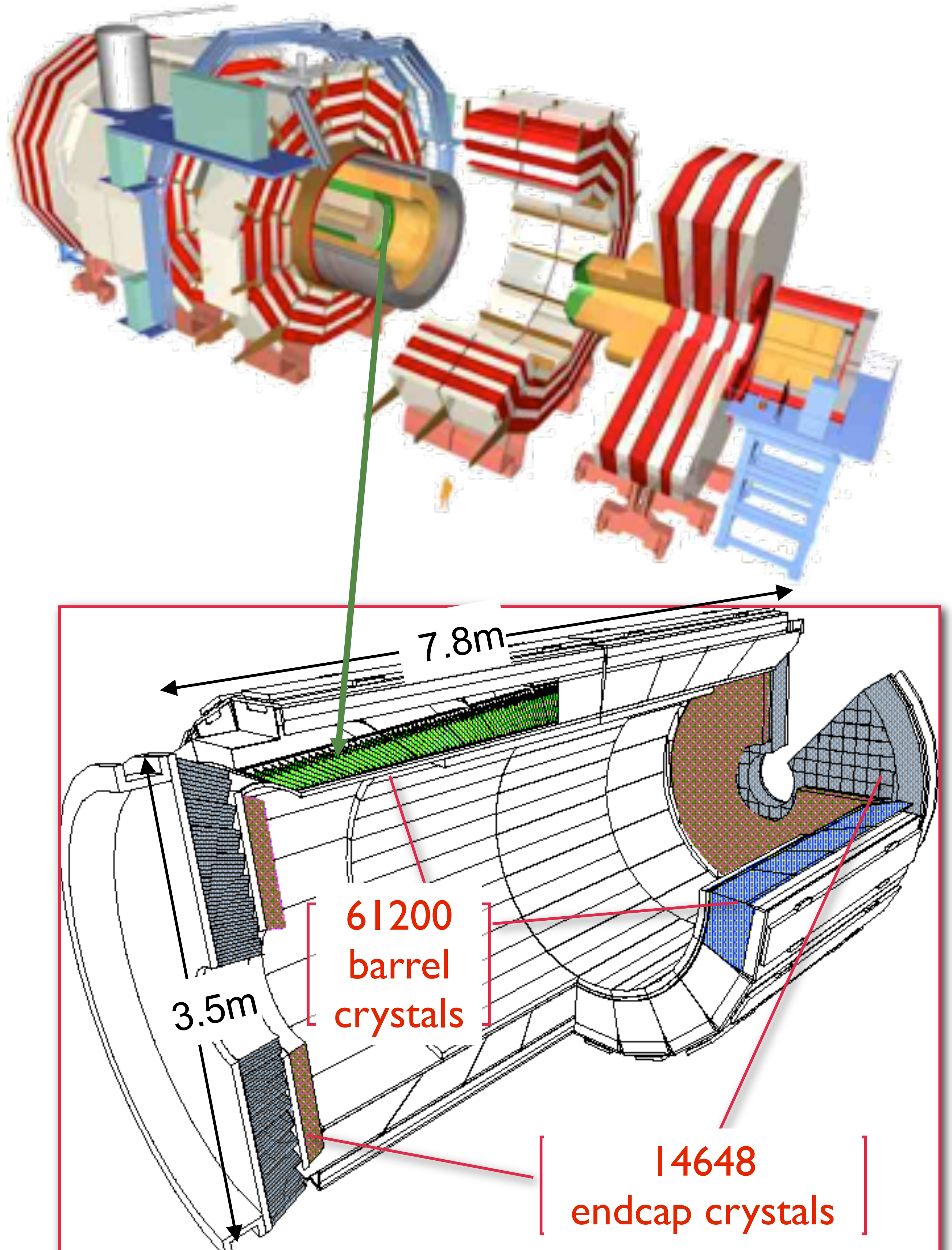


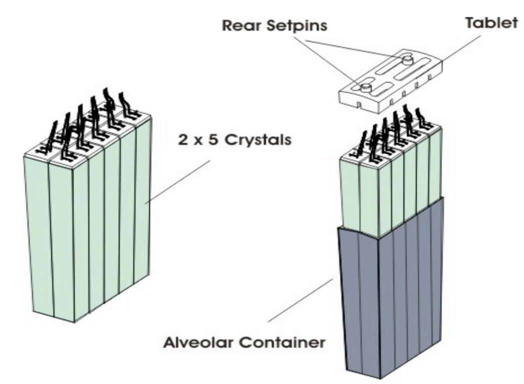
Fig. 1.6: Longitudinal section of the electromagnetic calorimeter (one quadrant).

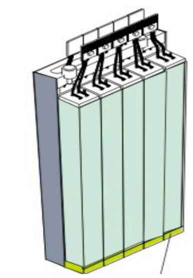


simulation of the shower development in the ECAL

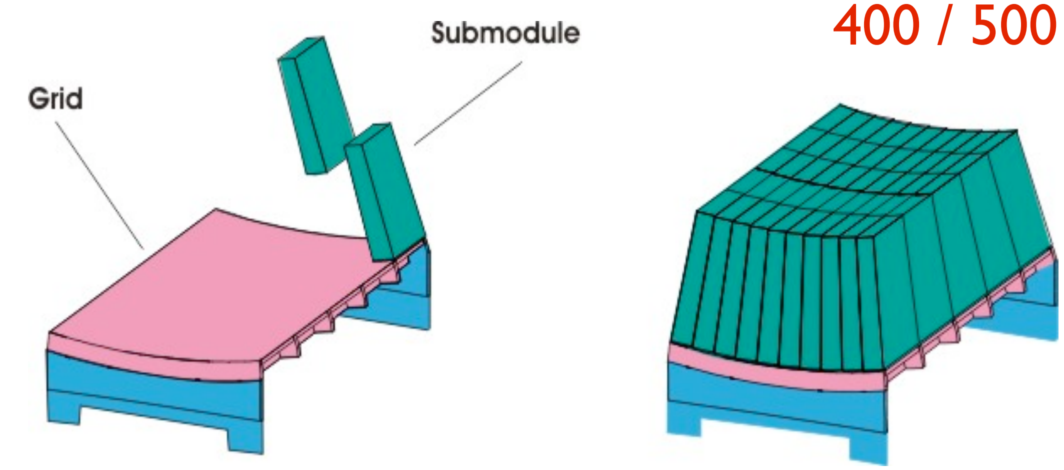


SubModule
10 crystals

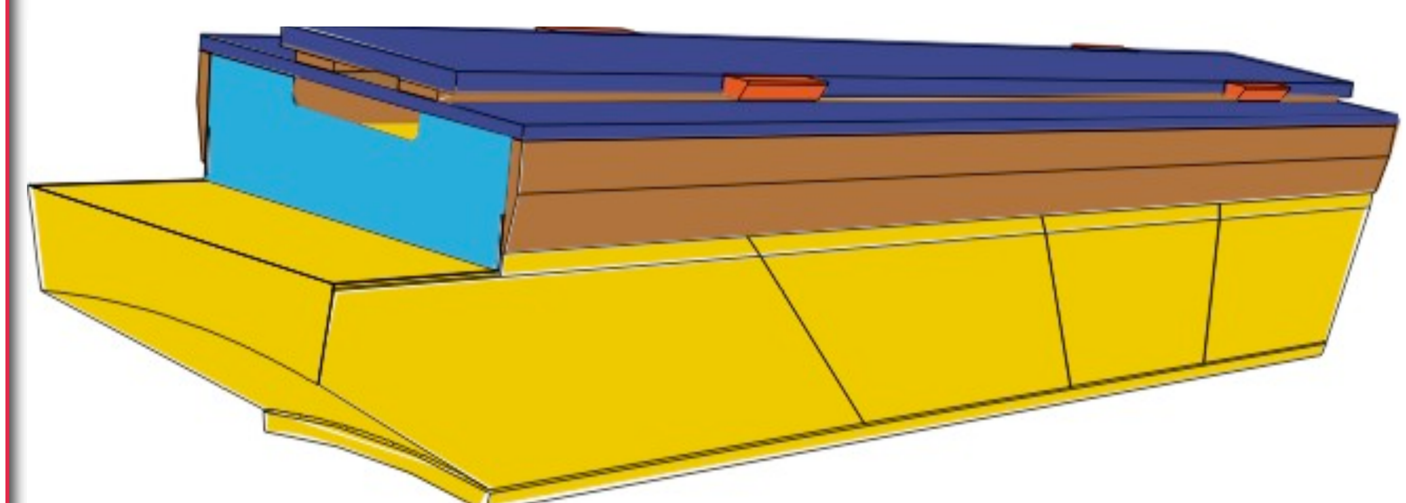




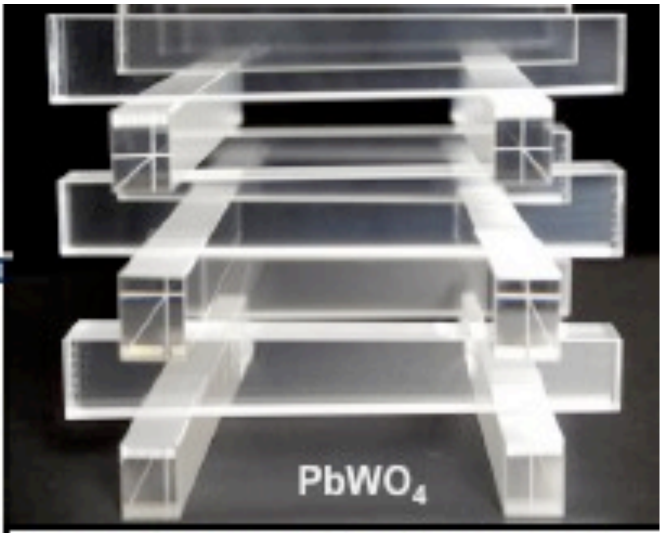
Module
400 / 500 crystals



SuperModule
4 Modules, 1700 crystals



LHC/ECAL Requirements



BTCP (Bogoroditsk, Russia)
SIC (Shanghai, China)

Every 25 nsec: 20 events, 1000 tracks (high luminosity)

→ fast, high granularity, triggering capability

High radiation levels: direct from collisions

ECAL Barrel: ≤ 0.3 Gy/h (x 10-50 Endcaps)

→ high radiation tolerance

Strong magnetic field: 3.8 Tesla

ECAL detector is barely or practically unserviceable

→ very high reliability

→ On-detector signal processing

Reasons for $PbWO_4$ choice

Homogeneous medium	
Fast light emission	~80% in 25 ns
Short radiation length	X_0 = 0.89 cm
Small Molière radius	R_M = 2.10 cm
Emission peak	425nm

Reasonable radiation resistance to very high doses

Caveats

LY temperature dependence -2.7 %/C

Stabilise to ≤ 0.1°C → need cooling

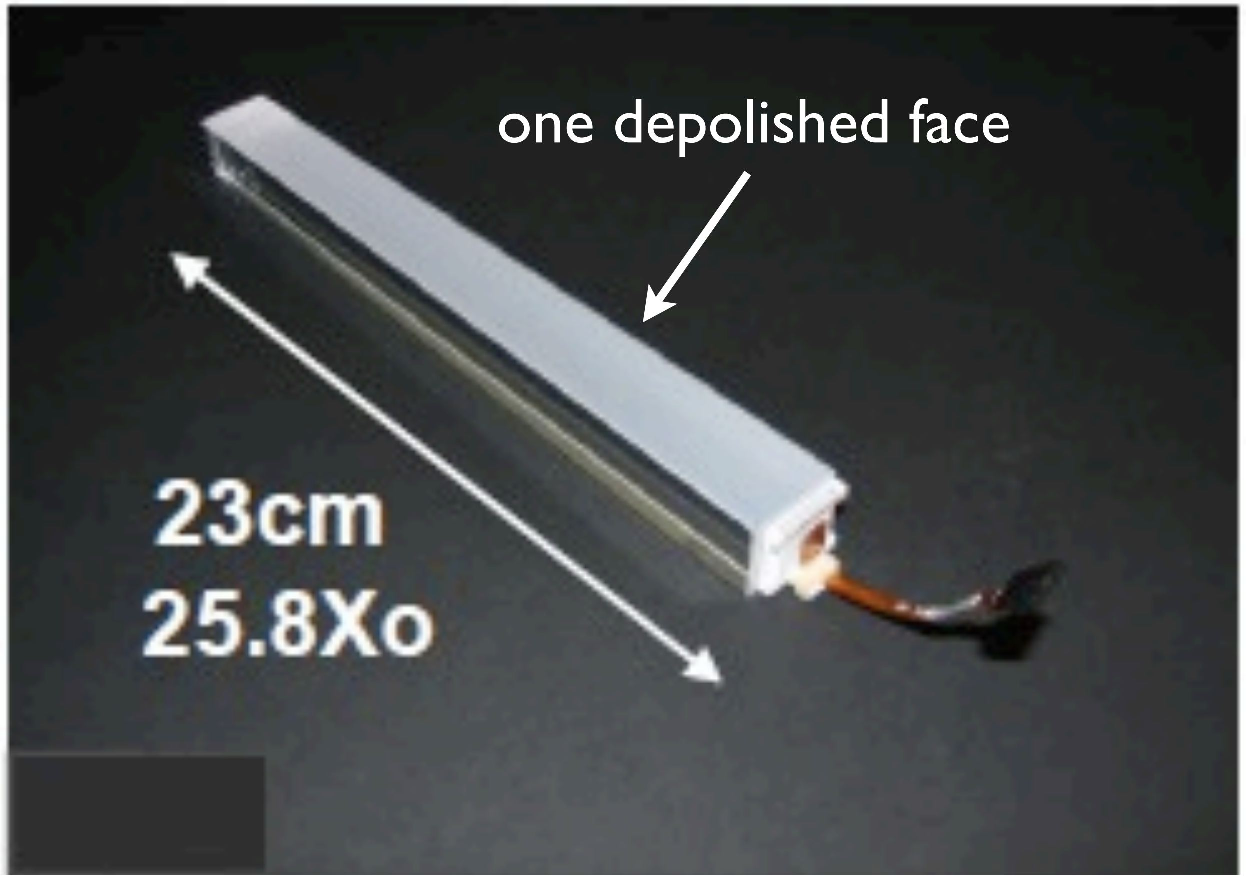
Formation/decay of colour centres

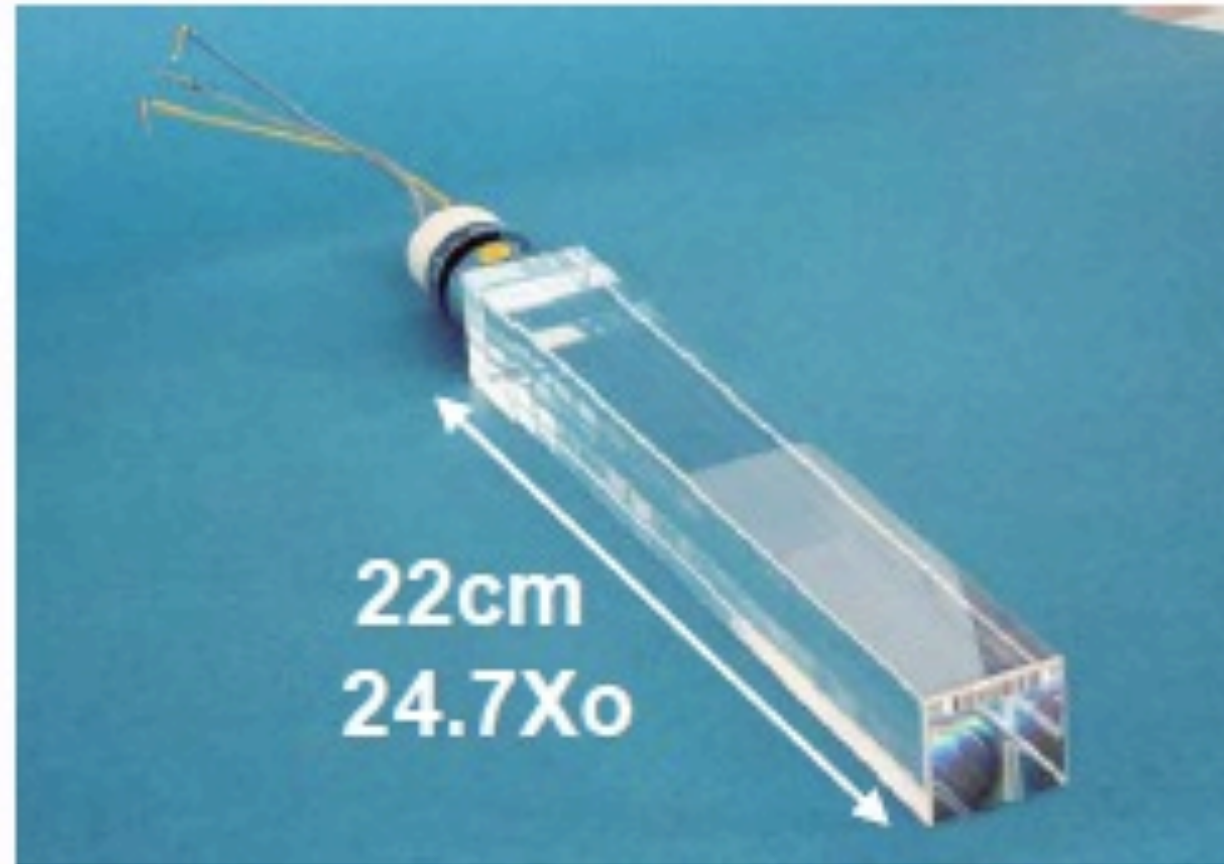
Need precise light monitoring system

Low light yield (100 γ/MeV: 1.3% NaI)

Need photodetectors with gain in magnetic field

CMS ECAL Crystals





CMS Barrel crystal, tapered
~2.6x2.6 cm^2 at rear
Avalanche Photo Diode
readout

CMS Endcap crystal,
tapered, 3x3 cm^2 at rear
Vacuum Photo Triode
readout

Homogeneous calorimetry

CMS $PbWO_4$ - photodetectors

Barrel

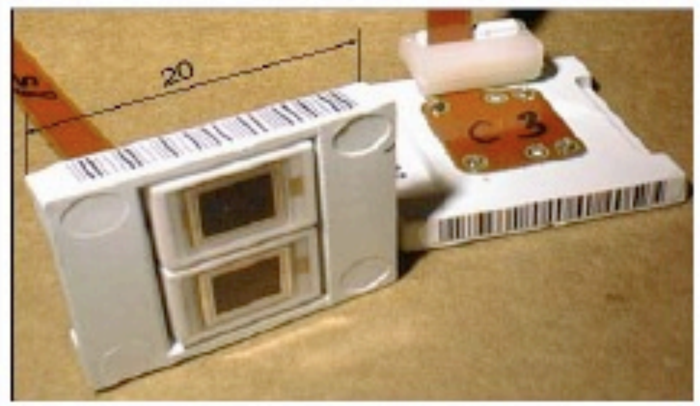
Avalanche photodiodes(APD)

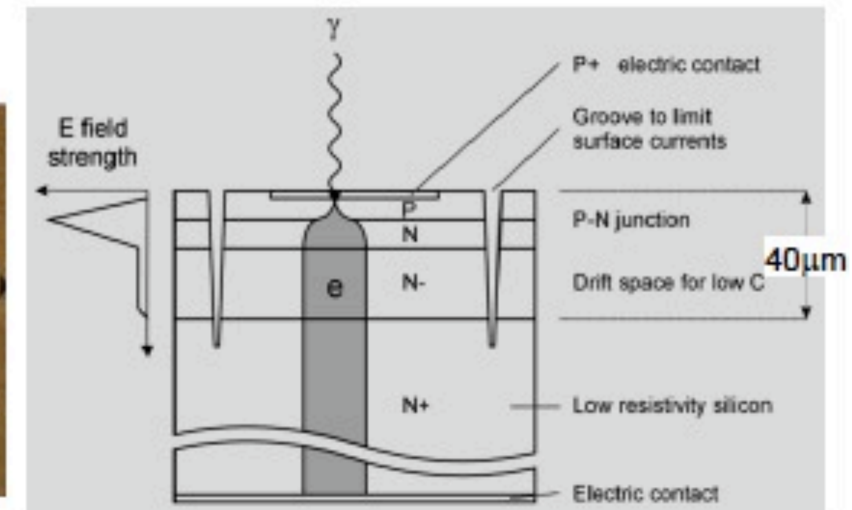
Two 5x5 mm^2 APDs/crystal

Gain 50

QE ~75%

Temperature dependence -2.4%/^{O}C



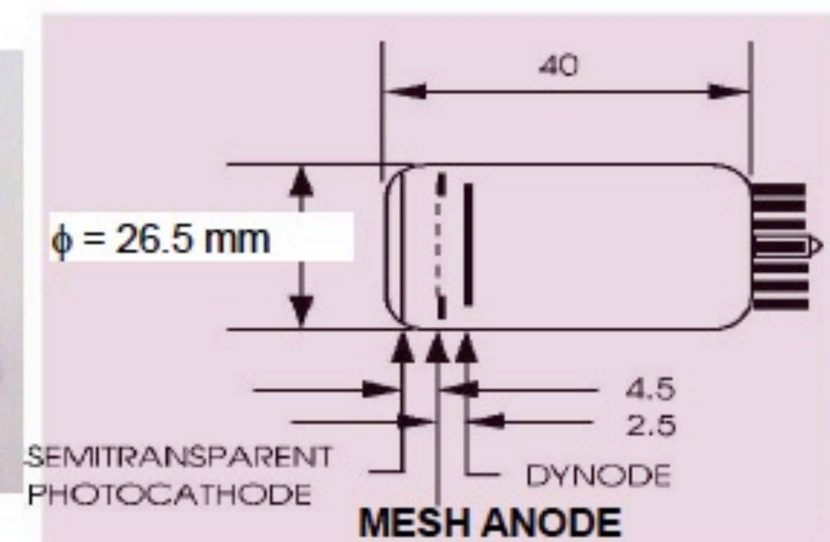


Endcaps

Vacuum phototriodes(VPT)

More radiation resistant than Si diodes

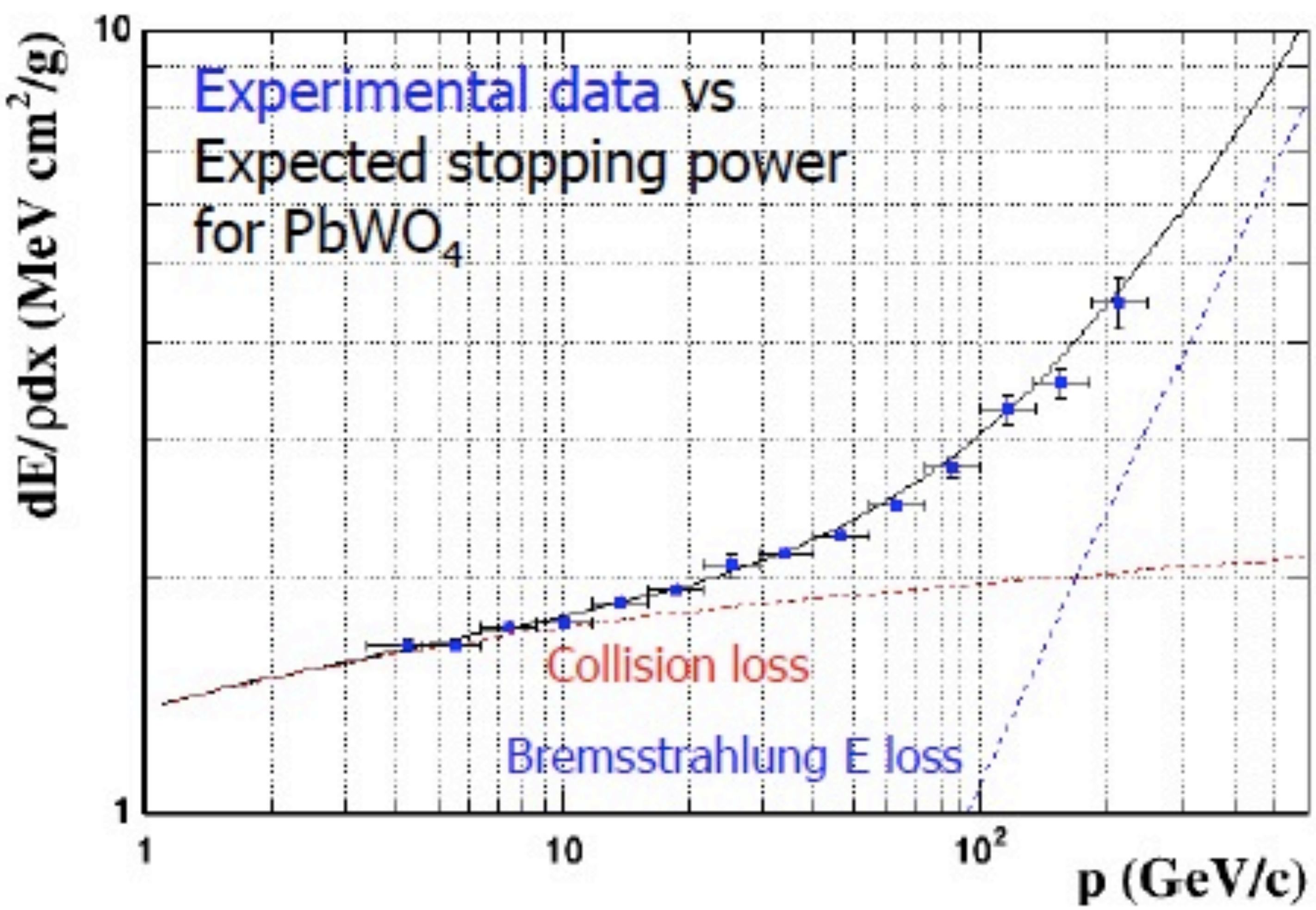
- UV glass window
- Active area ~ 280 mm^2/crystal
- Gain 8 -10 (B=4T)
- Q.E. ~20% at 420nm



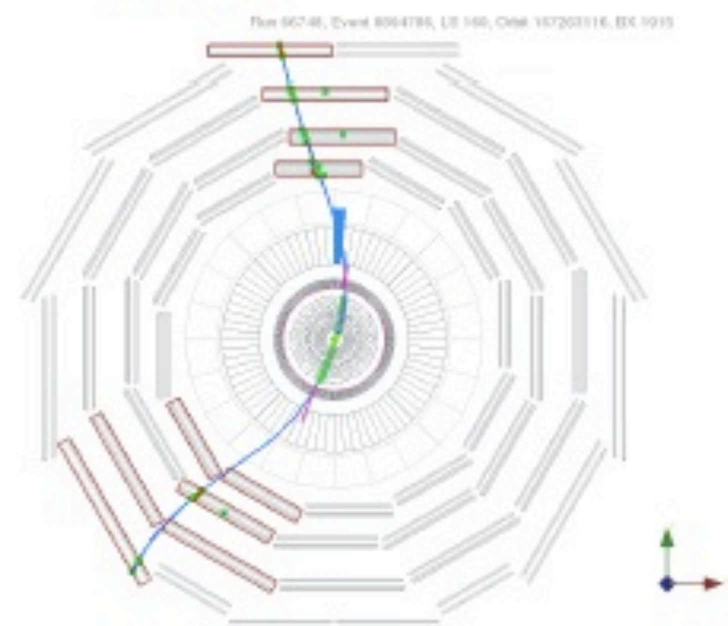
Stopping Power dE/dx with Cosmics

dE/ρdx of cosmic muons traversing ECAL vs muon momentum

- *Events for dE/dx selected to be loosely pointing: d0<1m, |dz|<1m*
- *dE: energy from ECAL clusters*
- *dx: length traversed in ECAL crystals*
- *Momentum measured by silicon tracker*



Results indicate the correctness of the tracker momentum scale and ECAL energy scale.



CMS paper - 2010 JINST 5 P03007

Measurement of the muon stopping power in Lead Tungstate.

References :

- PDG : Review of Particle Physics
K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010)
http://pdg.lbl.gov/

Detectors / Interactions - Text books (small selection):

- R. Wigmans, Calorimetry: energy measurement in particle physics; Oxford Univ. Press
- G.F. Knoll, Radiation detection and measurement; John Wiley & Sons
- W.R.Leo , Techniques for Nuclear and Particle Physics Experiments; Springer-Verlag

Schools of instrumentation :

- XI ICFA SCHOOL ON INTRUMENTATION IN ELEMENTARY PARTICLE PHYSICS
Marzio Nessi, Calorimetry :
http://particulas.cnea.gov.ar/workshops/icfa/wiki/index.php/Electromagnetic_and_Hadronic_Calorimetry
- 1st EIROforum school on Instrumentation
David Cockerill, Calorimetry :
http://eiro-school.web.cern.ch/eiro-school/

CMS ECAL :

- CMS ECAL TDR : http://cms-ecal.web.cern.ch/cms-ecal/ECAL_TDR/ecal.html