Principles and Applications of Scintillators

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Scintillators according to various schemes

Transform dE/dx of an ionizing particle into light that can be measured by a photodetector

- Physical state
  - Solid
  - Liquid
  - Gas
- Composition
  - Organic
  - Inorganic
- Structure
  - Single crystal
  - Ceramic
  - Glass
- Scintillation mechanism
  - Intrinsic
  - Activated
  - Core-valence

Organic scintillators

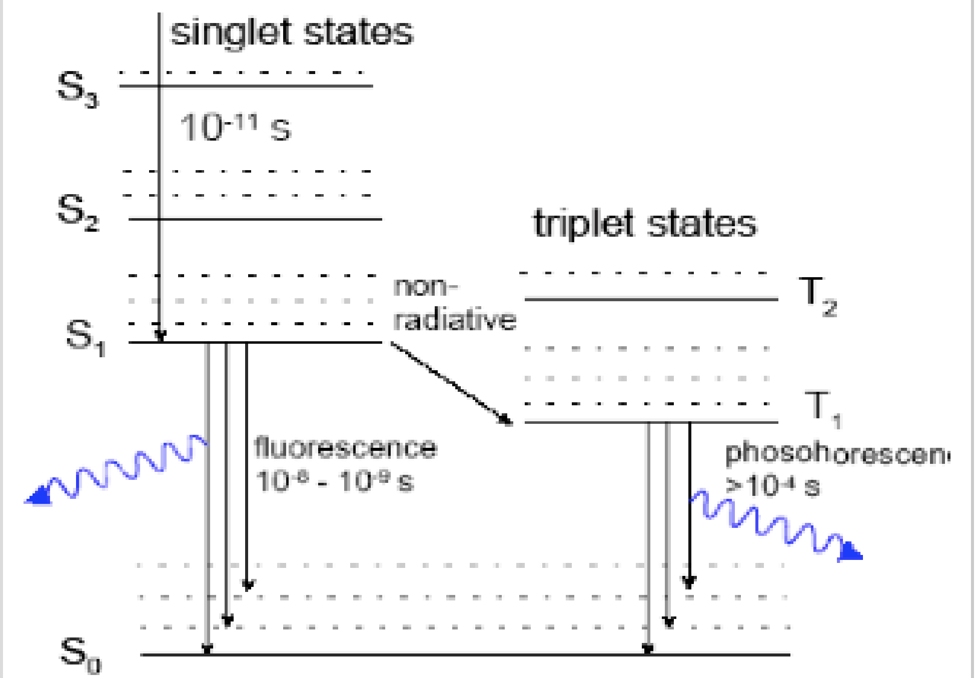
Convert PART of the energy of the incident particle

organic scintillators low Z (C,H) →

- low γ-detection efficiency
- high n-detection efficiency via (np)

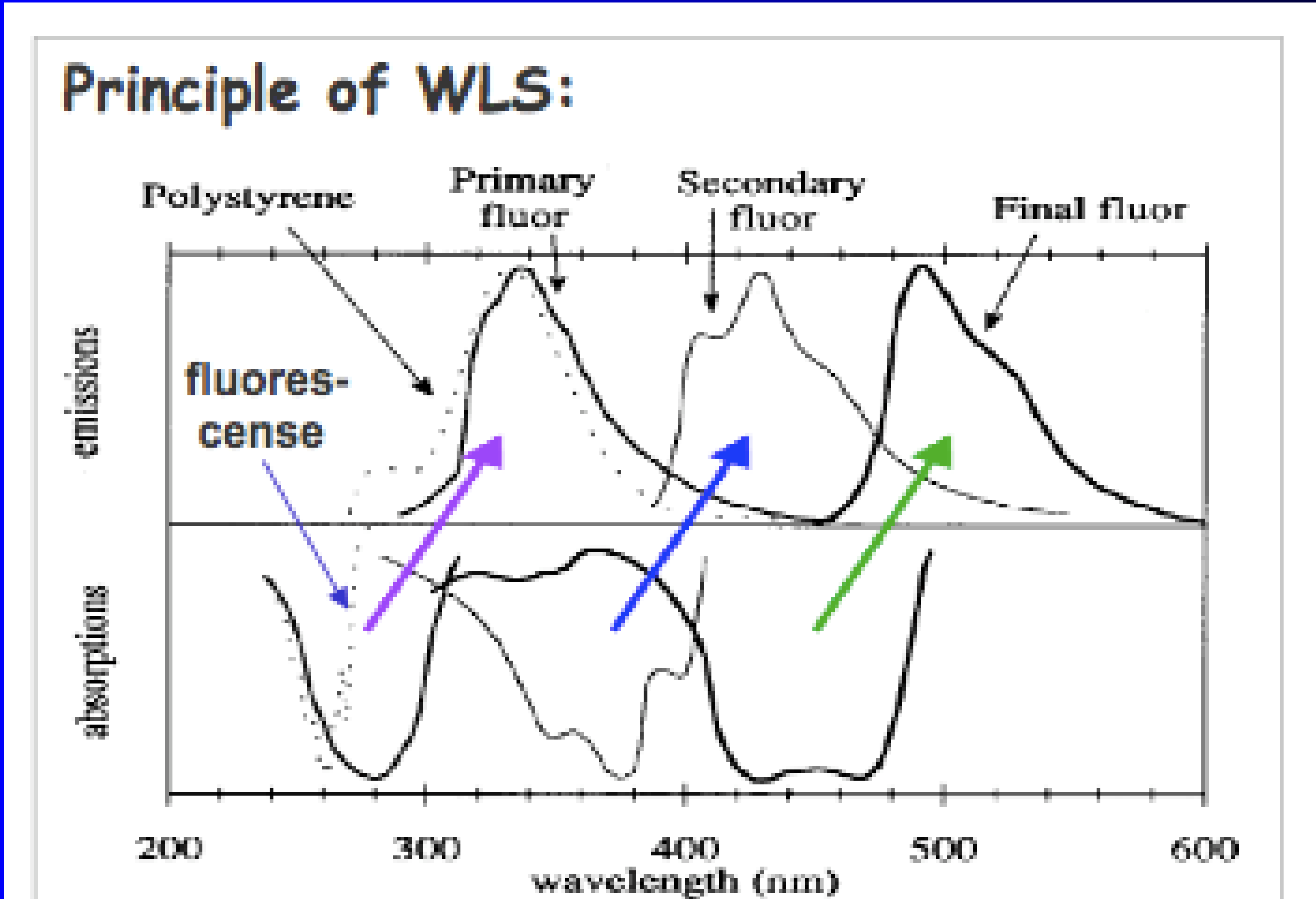
scintillation mechanism:

Delocalized π electron states of the Benzene molecule



- Organic crystals
  Anthracène, Trans-Stilbène, Naphtaline
- Organic liquids
  Solvent: Xylène, Toluène, benzène
  Solute: p-Terphénil, PBD, PPO, POPOP, 3g/l
- Plastics
  Solvent: polyvinyletoluène, polyphénilbenzène, polystyrène
  Solute: PBD, pTerphénil, PBO, second soluté POPOP, 10g/l for wavelength shifting

Wavelength shifter

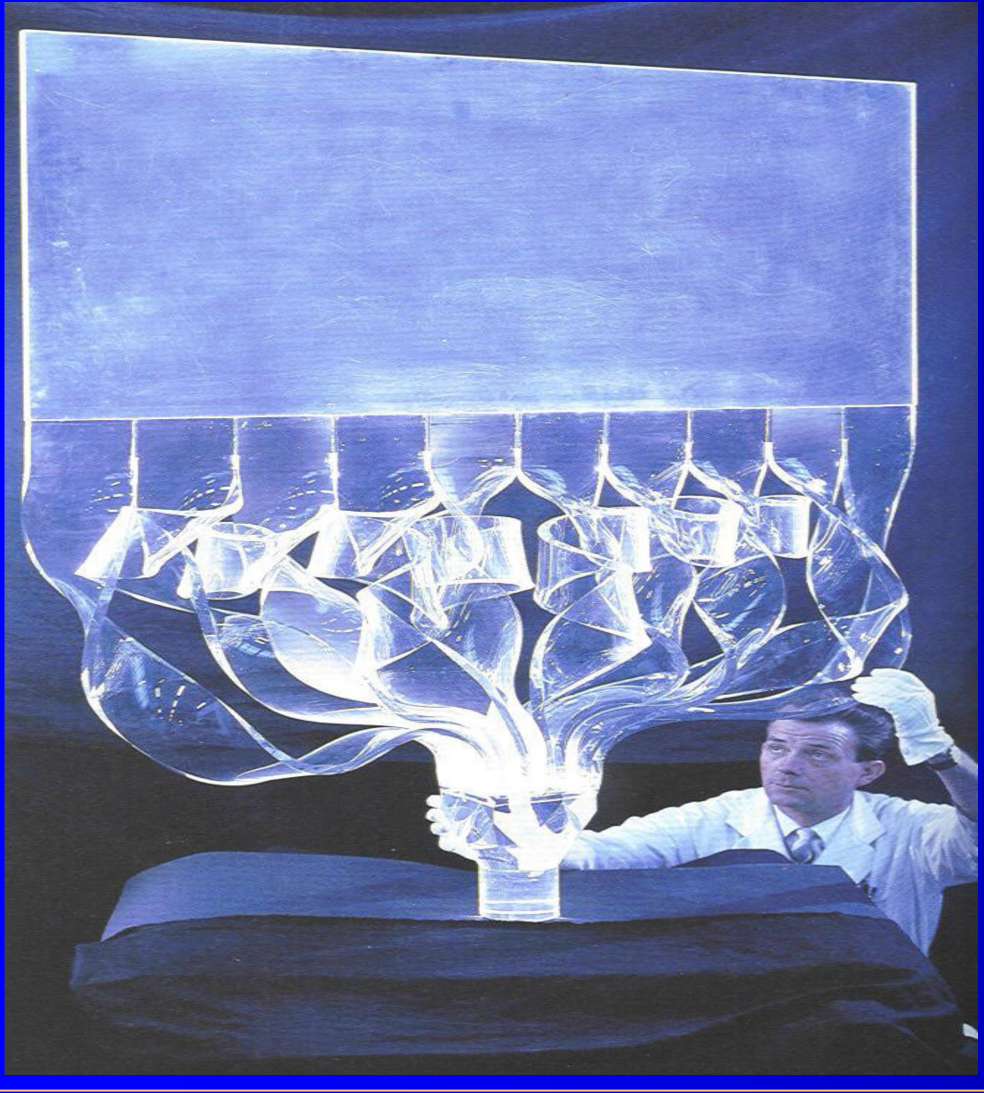


Crystaline organic scintillators

crystal	Chemical formula	density	n	yield	emission wavelengthn nm
anthracene	$C_{14}H_{10}$	1,25	1,62	100	447
Trans-stilbene	$C_{14}H_{12}$	1,16	1,62	50	410
naphtalene	$C_{10}H_{8}$	1,162	1,62	30	340

- organic scintillators are usually very fast (a few ns)
- used for fast detection, time tagging, time of flight
- Anthracene has a very good yield: 1 optical photon per 60eV deposited energy

Plastic organic scintillator: plates



- Easily machined
- Large sizes available
- Good light transport with wavelength shifting using primary and secondary fluors
- Very fast~ns,
- Cheap
- Not very radiation hard

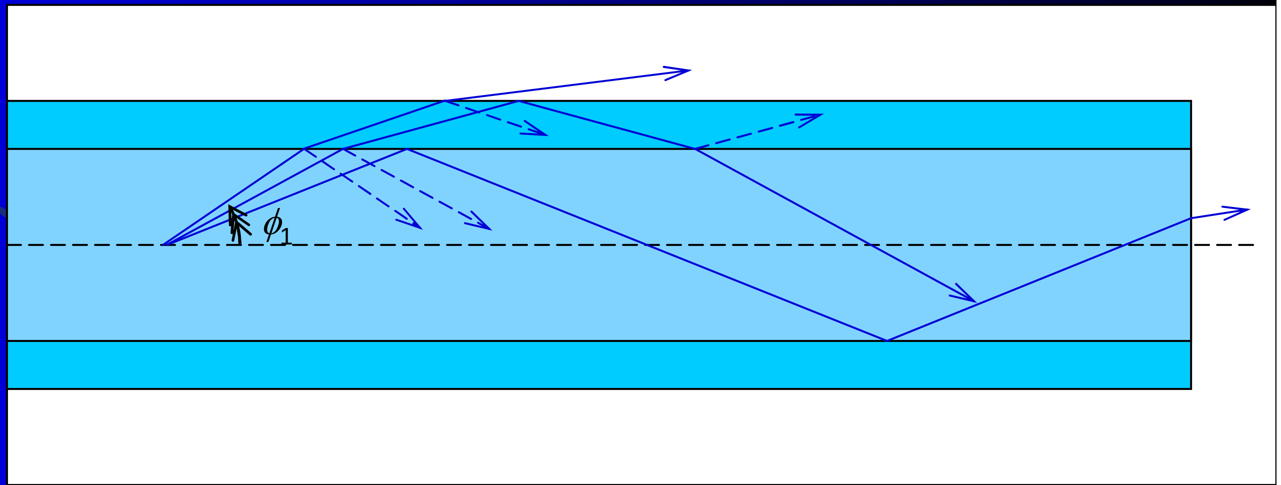
1 optical photon per 100 eV deposited energy

Plastic organic scintilator: fibers

Air: n_0 = 1.0003

Core, polystyrene: n_1 = 1.59

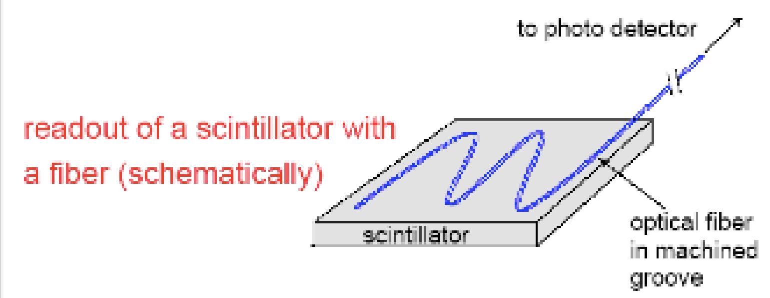
Cladding, acrylic: n_2 = 1.49



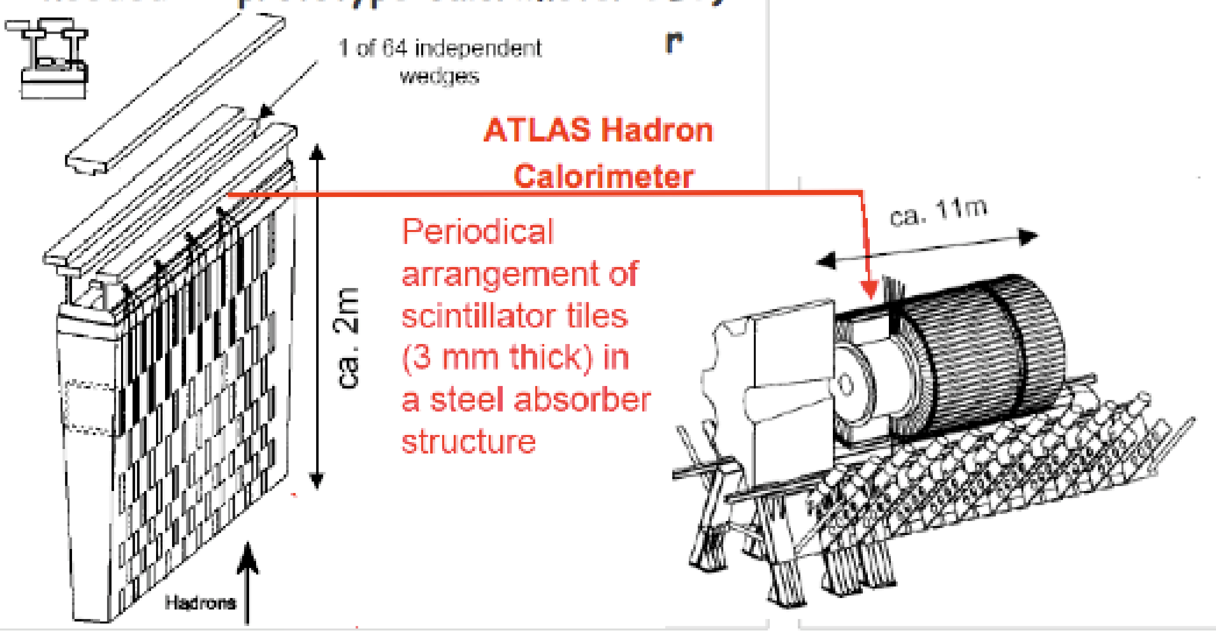
- Propagation in the core: $\phi_1 < 20.2^o$, $f_1 = 1 - n_2/n_1 = 6.2\%$
- Propagation in the cladding: $20.2^o < \phi_1 < 51^o$, $f_2 = n_2/n_1 - n_0/n_1 = 31\%$
- Lost in air: $\phi_1 > 51^o$, $f_0 = n_0/n_1 = 63\%$

Tile calorimeters: ATLAS, CALICE

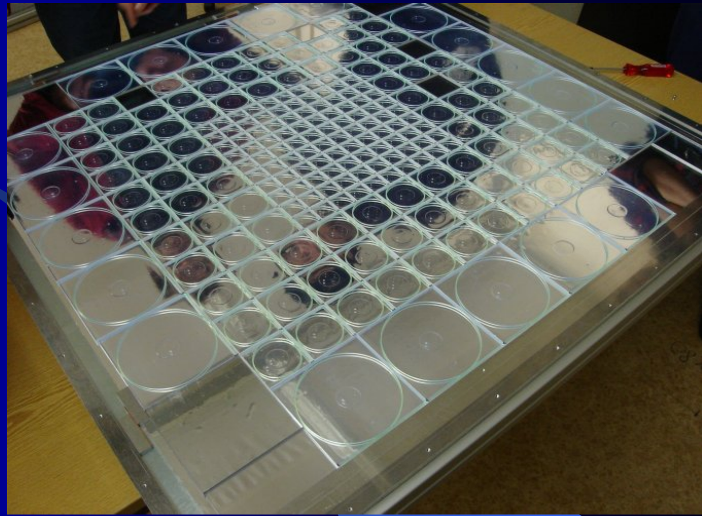
Fibres can be embedded in scintillator:

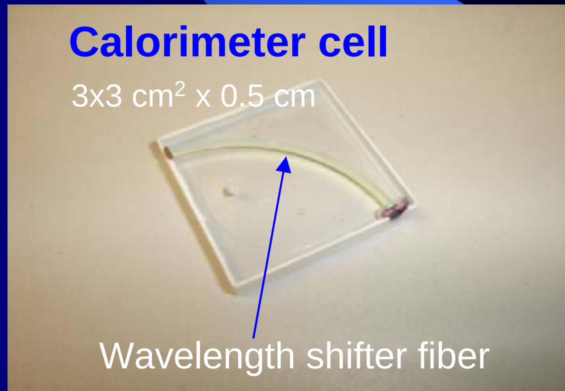


(with miniaturised Si-PM no transport needed → prototype calorimeter ILC)

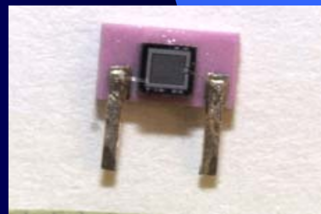


Read out 216 tiles/module
~8000 channels



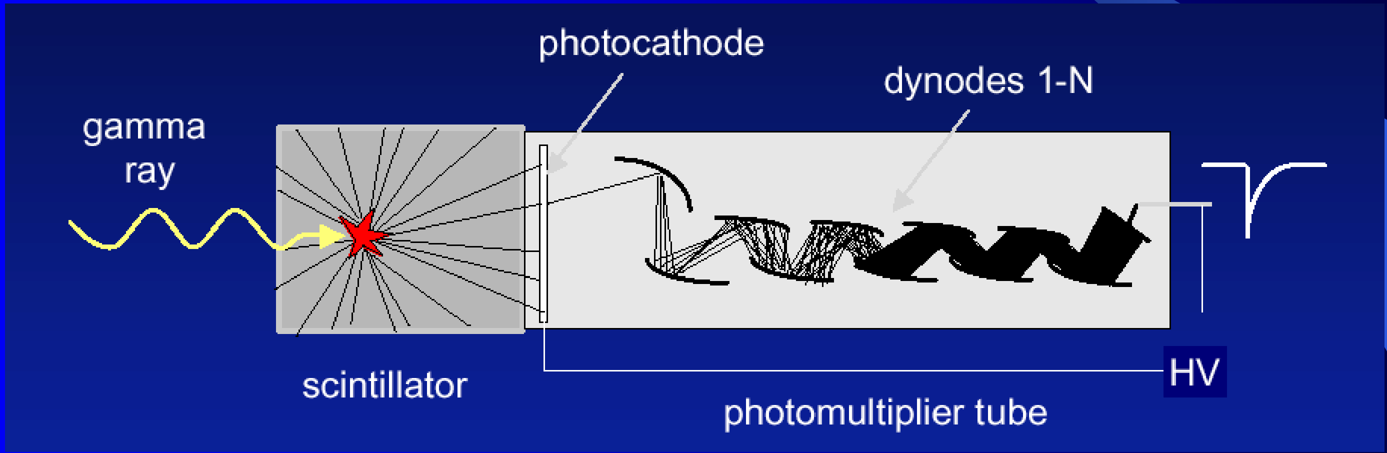


Single tile readout with SiPM



Scintillating crystals for homogeneous calorimeters

- To convert ALL the energy of the incident particle in to light
- Necessity to use dense materials

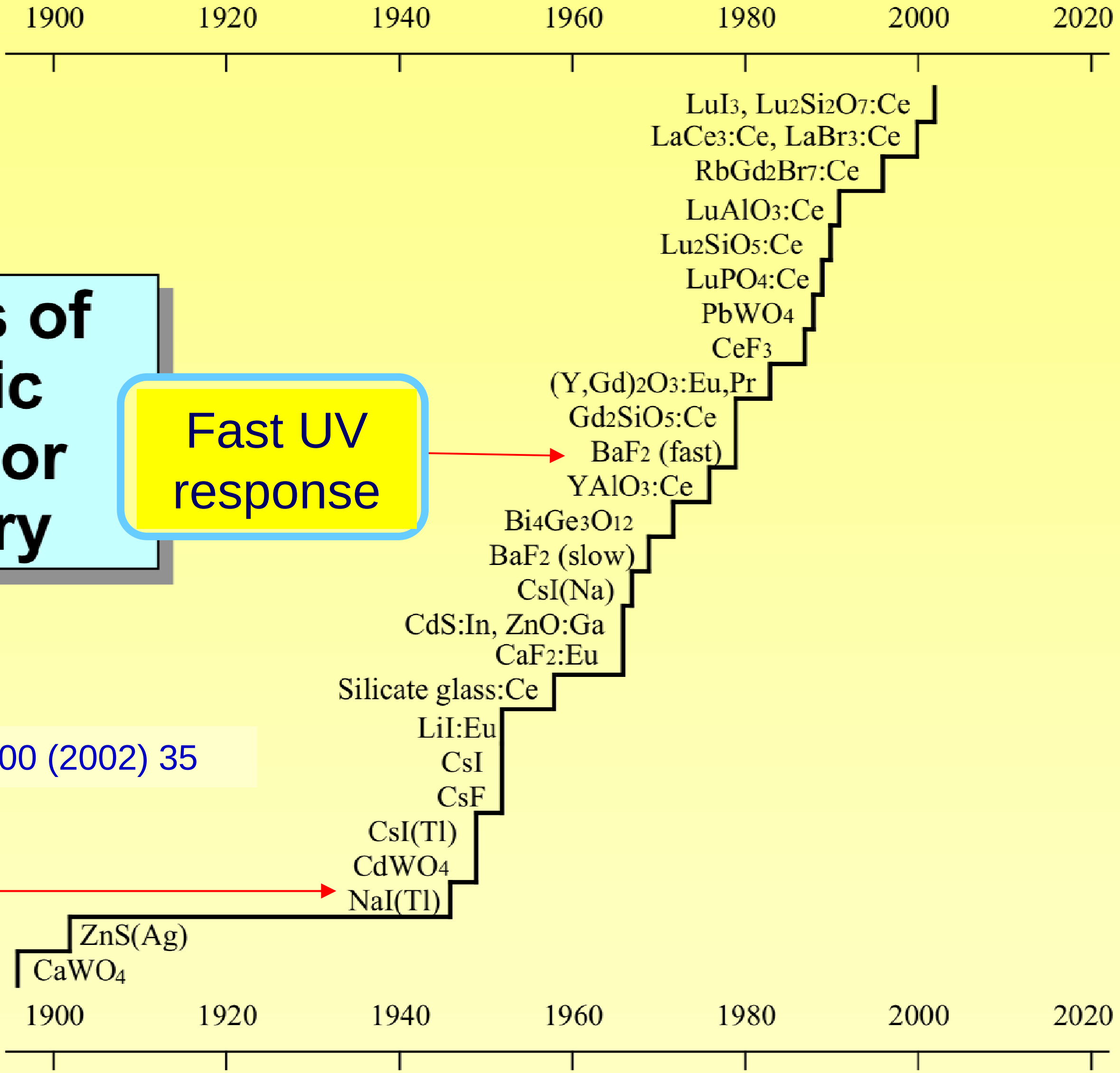


- Above certain minimum level most scintillators are linear with respect to the energy deposited
- Light output is directly proportional to energy deposited

History of scintillator discovery

105 Years of Inorganic Scintillator Discovery

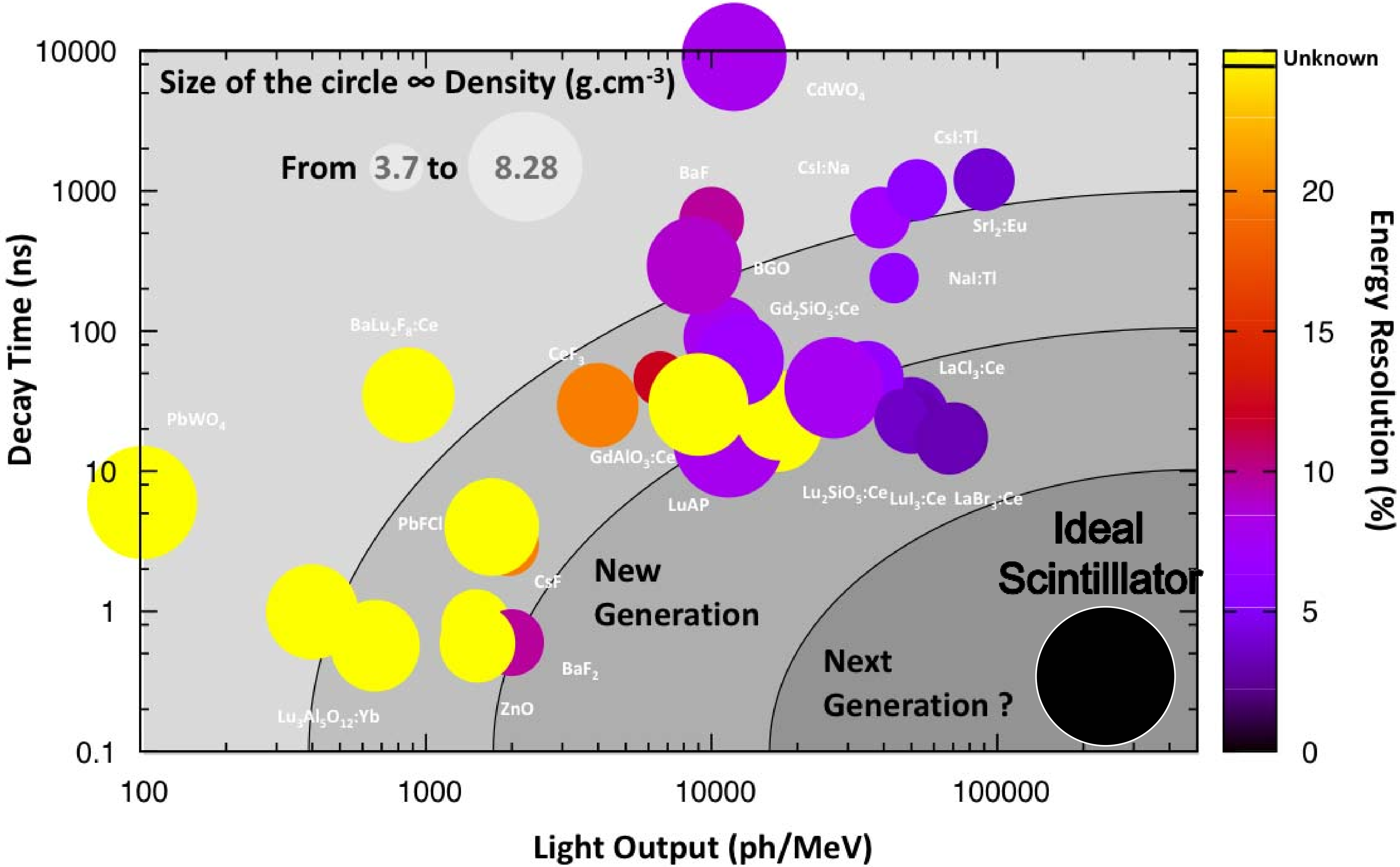
Fast UV response



M. J. Weber J. Lumin. 100 (2002) 35

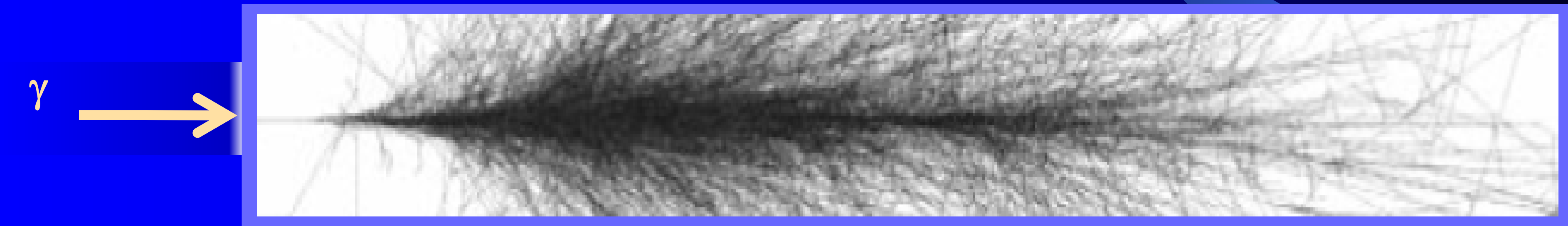
Invention of the photomultiplier tube

Classification of scintillators



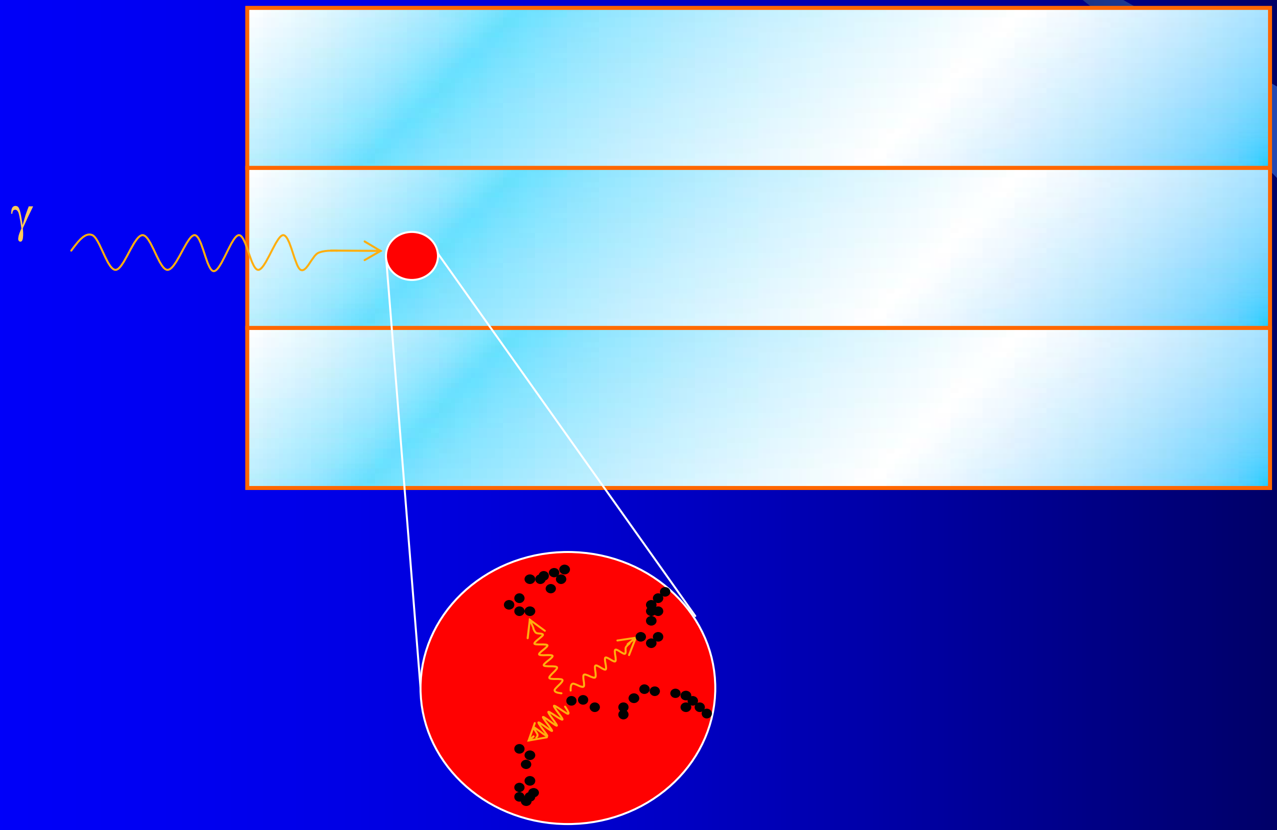
A zoom on the conversion process (HEP)

- The energy conversion from incoming X or γ Rays is a complex process resulting from a cascade of events.

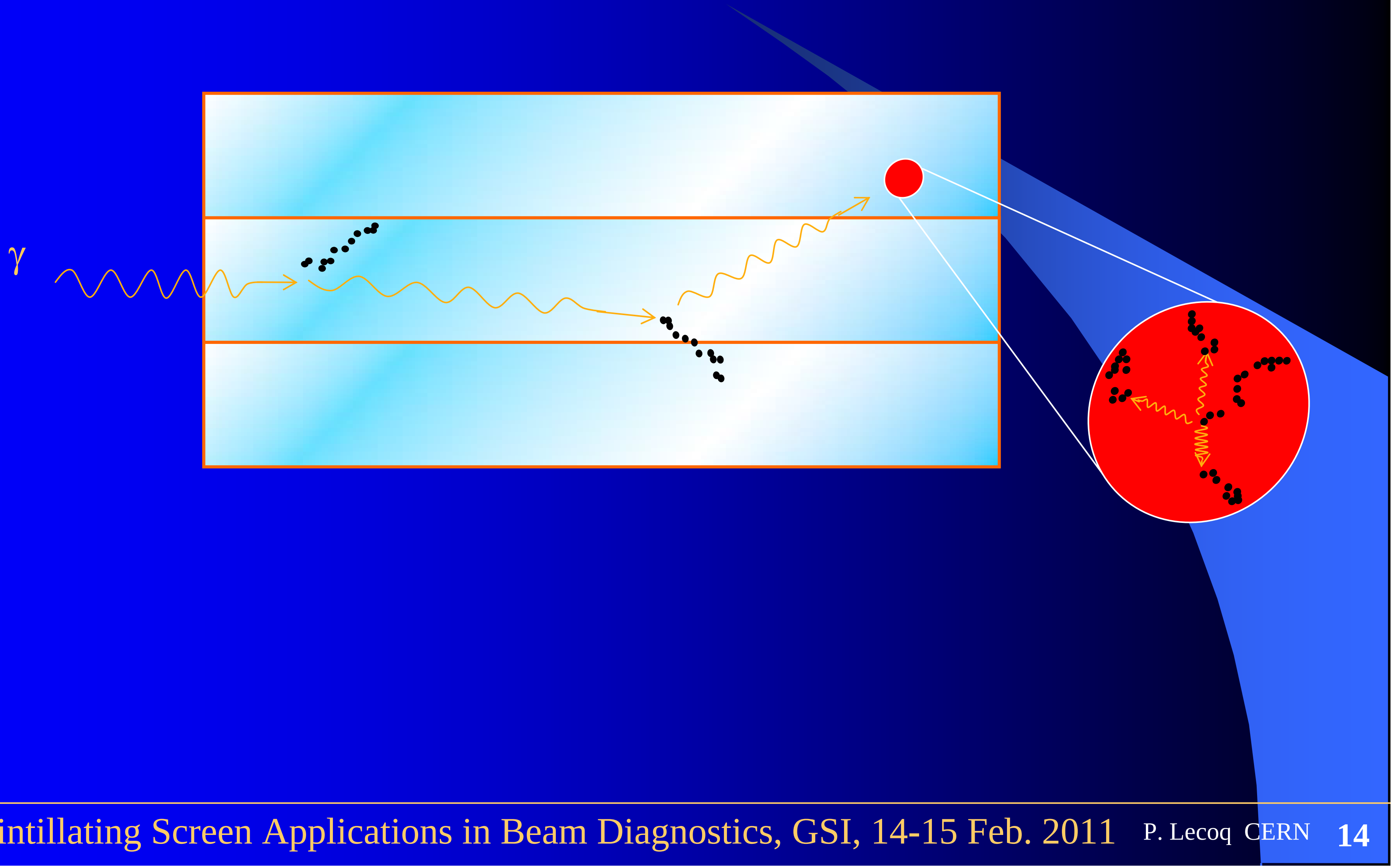


- Hadronic events are even more complex
  - Details of the full cascade for HEP with contributions from different conversion mechanisms: scintillation and Cerenkov, would lead to particle identification within the shower

A zoom on the conversion process (low energy)

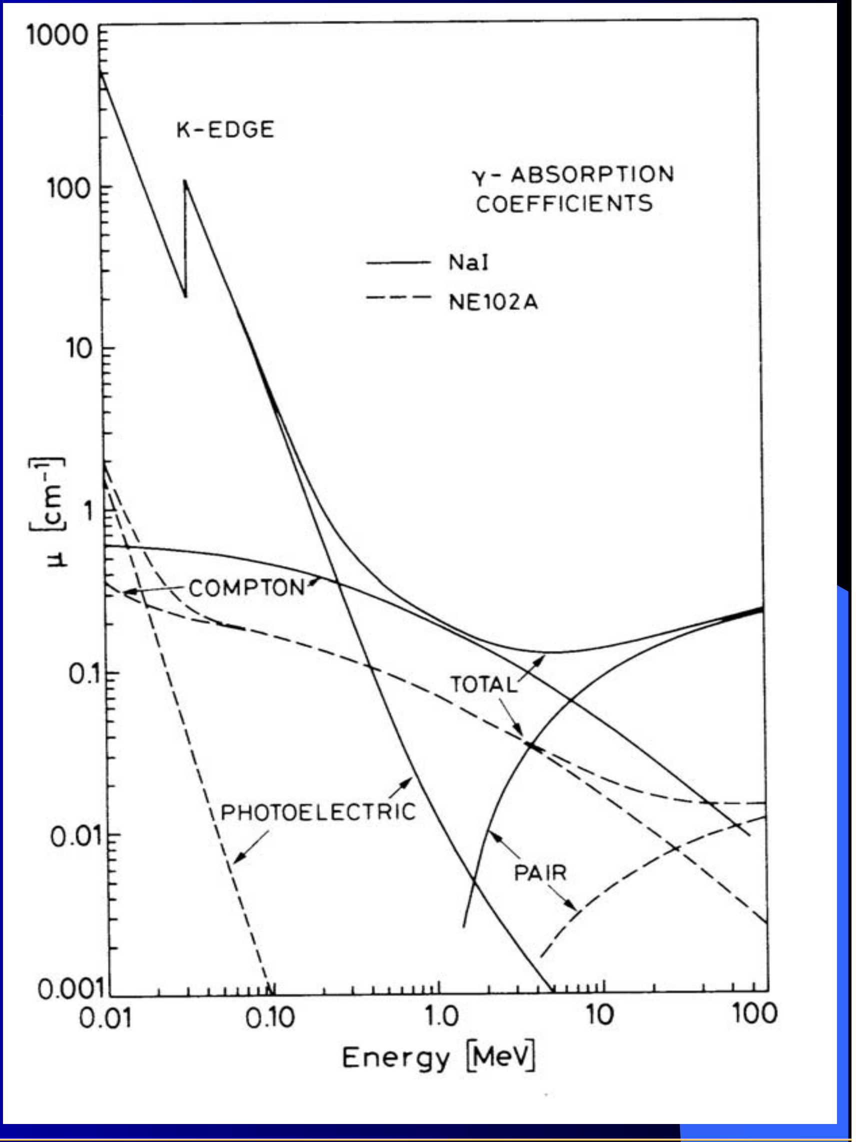


A zoom on the conversion process (low energy)

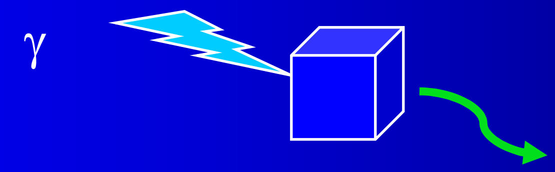


How to choose a scintillator

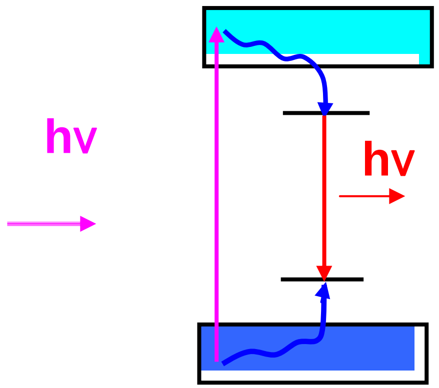
- For charged particles: high ρ materials to increase dE/dx
- For X and γ-rays (but also high energy electrons, which radiate γ-rays by bremstrahlung)
  3 mechanisms:
  - Photoelectric: $\sigma_{ph} \propto \frac{Z^5}{E_\gamma^{7/2}}$
  - Compton: $\sigma_c \propto Z$
  - Pair poduction: $\sigma_{pair} \propto Z^2 \ln(2E_\gamma)$
- At low energy high photoelectric cross-section is desired
- At high energy good shower containment requires
  - Small radiation length: $X_0 = \frac{A}{\rho} \frac{716.4 gcm^{-2}}{Z(Z+1)\ln(287/Z)}$
  - Small Moliere radius: $R_M \approx X_0 \frac{Z+1.2}{37.74} \propto 1/\rho$



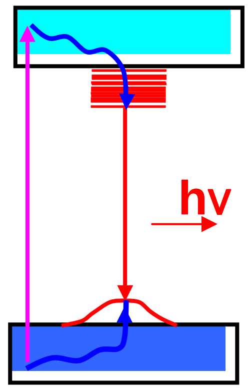
Fundamental aspects of Scintillation



Different scintillation mechanisms

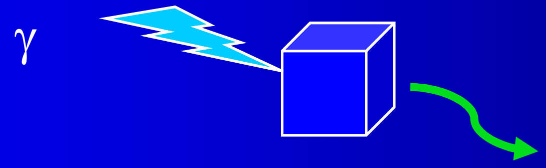


A – Doped ion,
or intrinsic defect



B – Self- trapped exciton

Fundamental aspects of Scintillation



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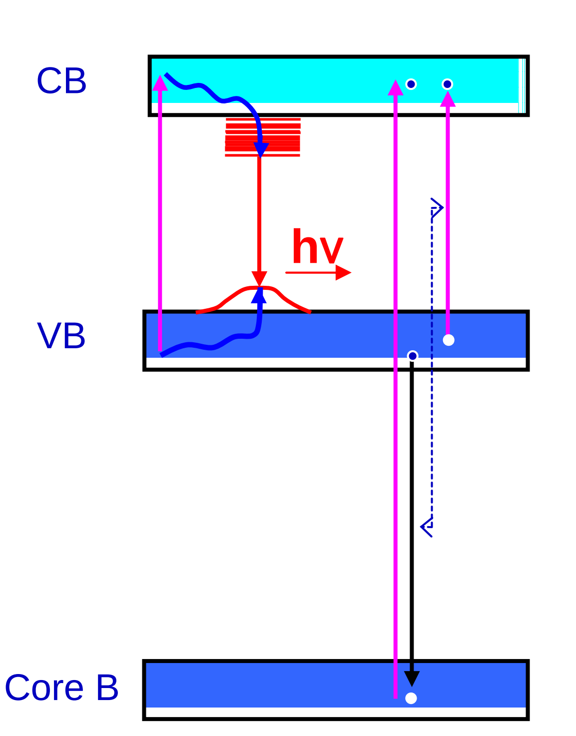
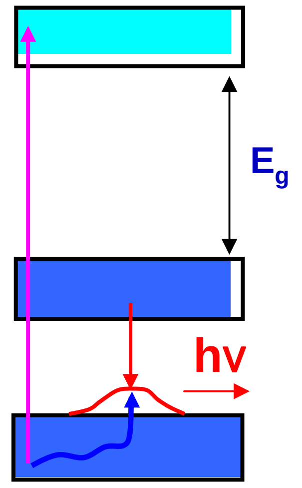
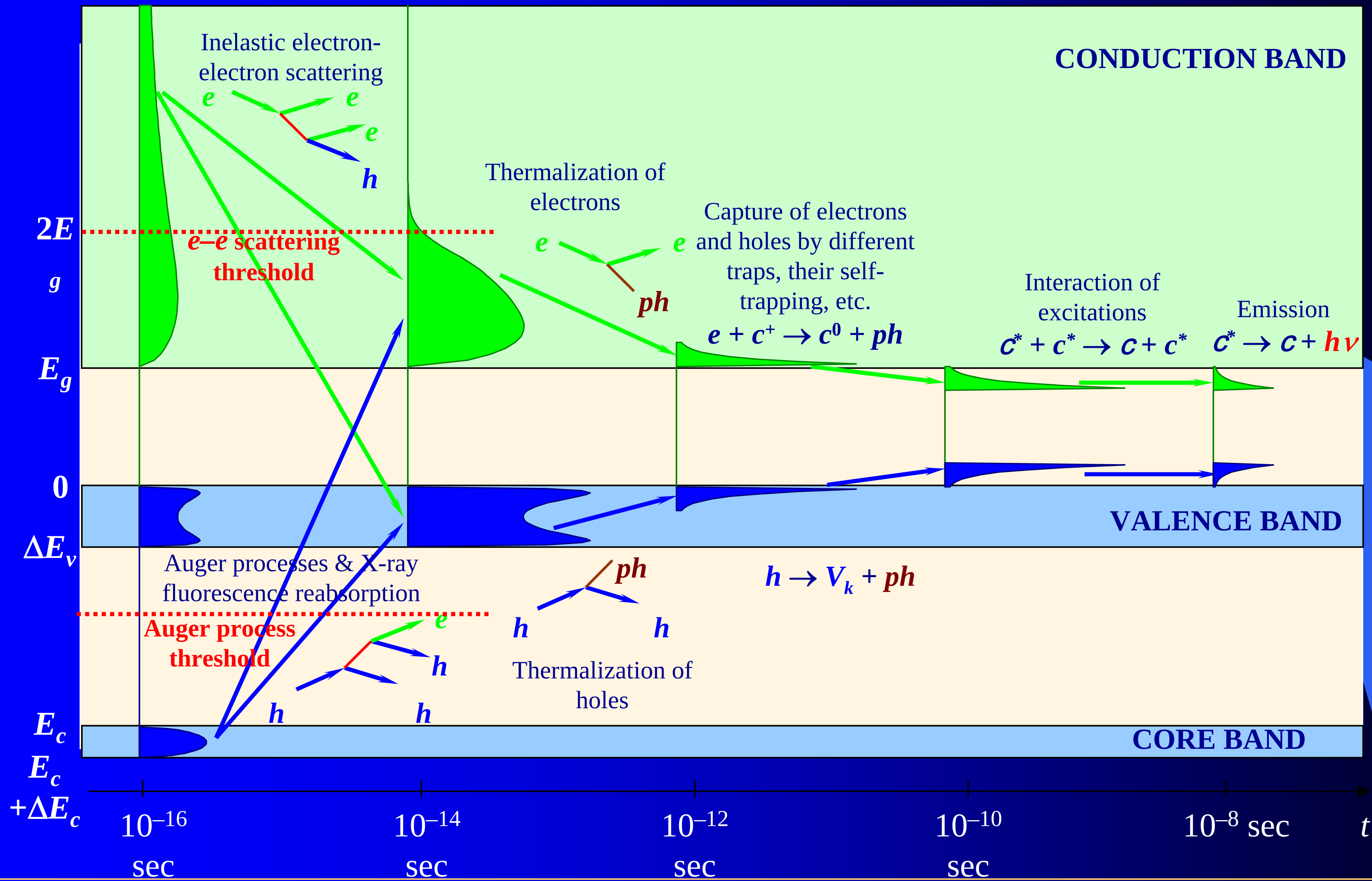


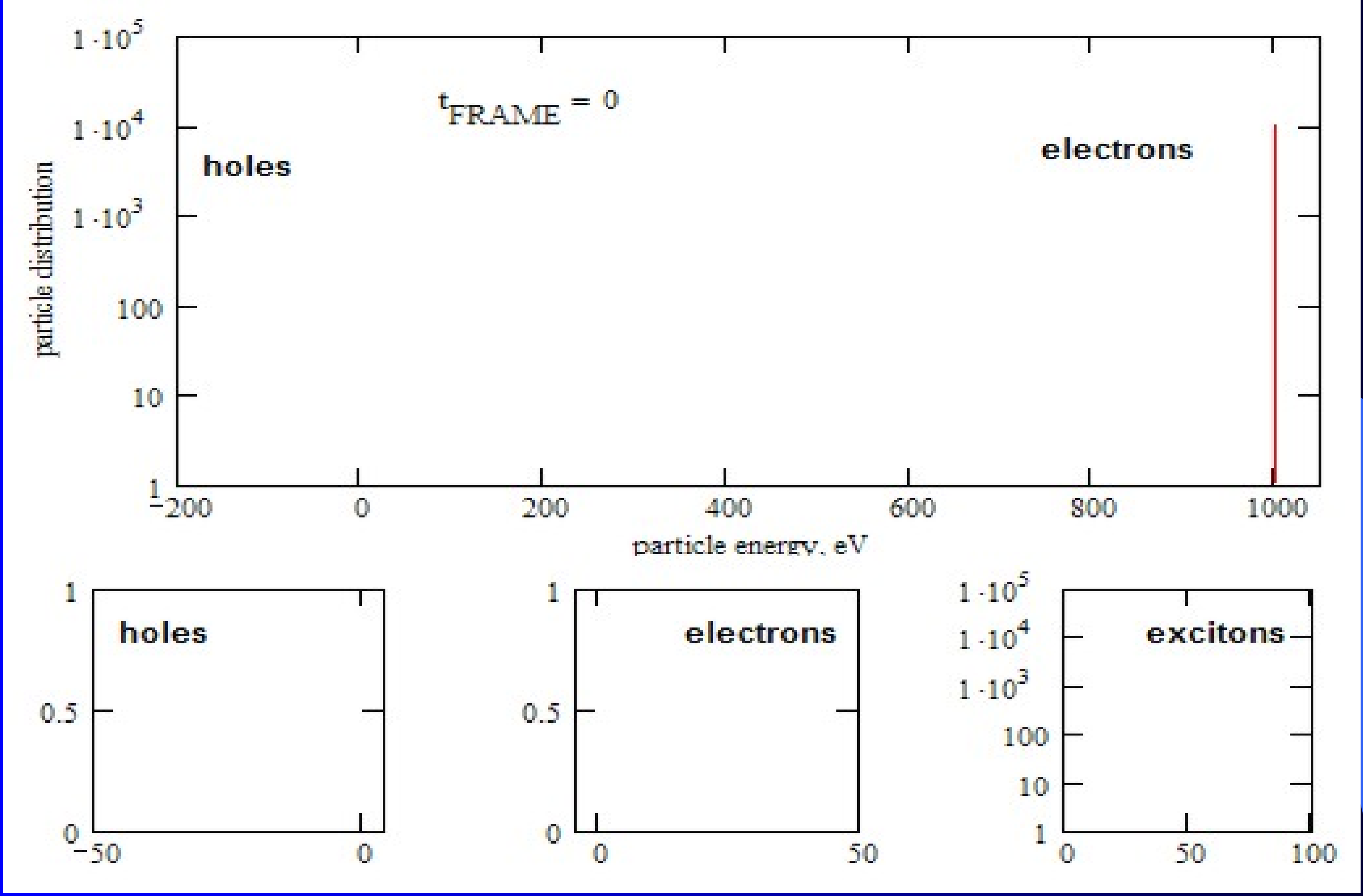


C – Crossluminescence

Relaxation of electronic excitations
intrinsic luminescence



Evolution of energy distribution for 1000 eV electrons



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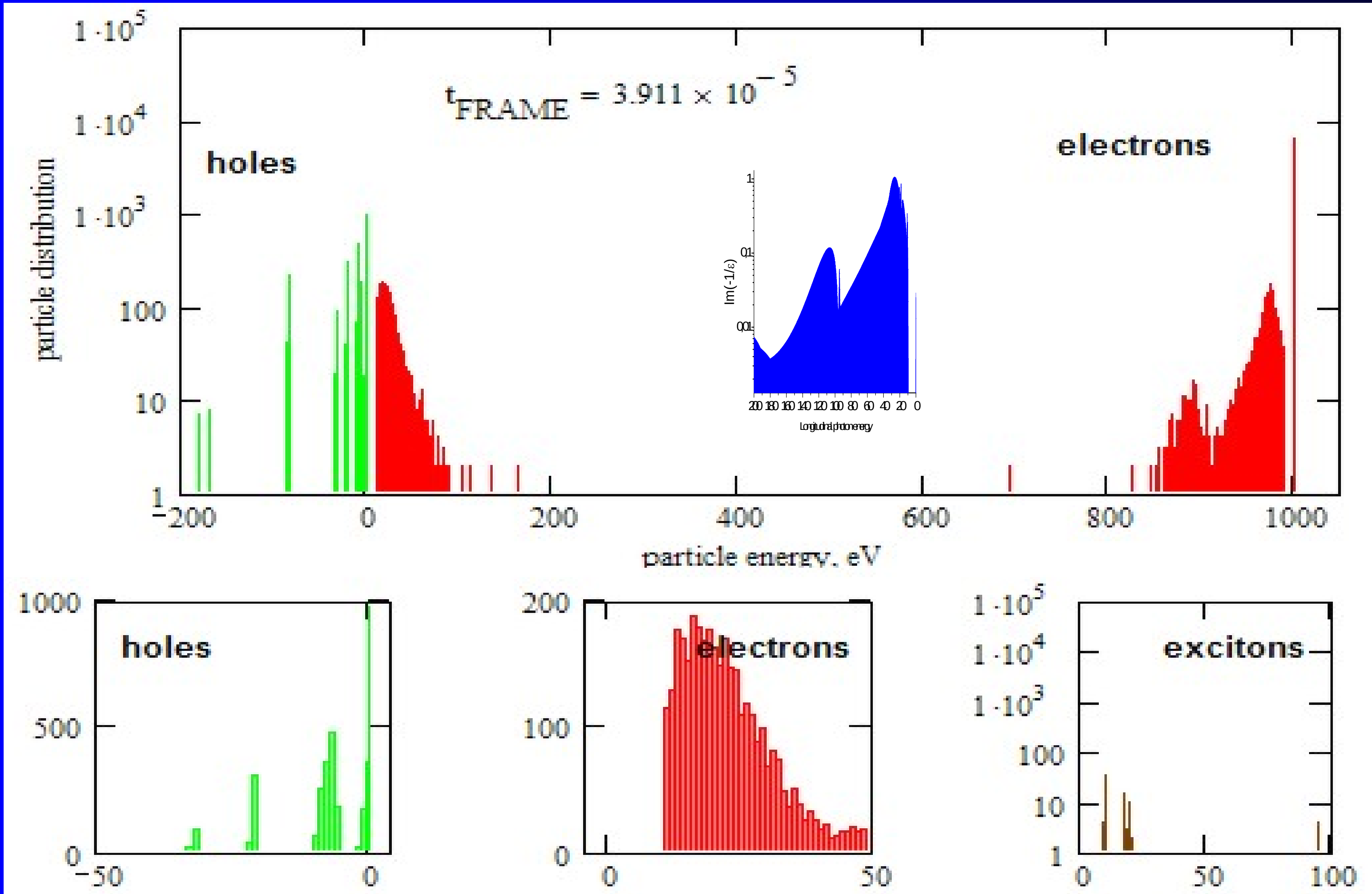

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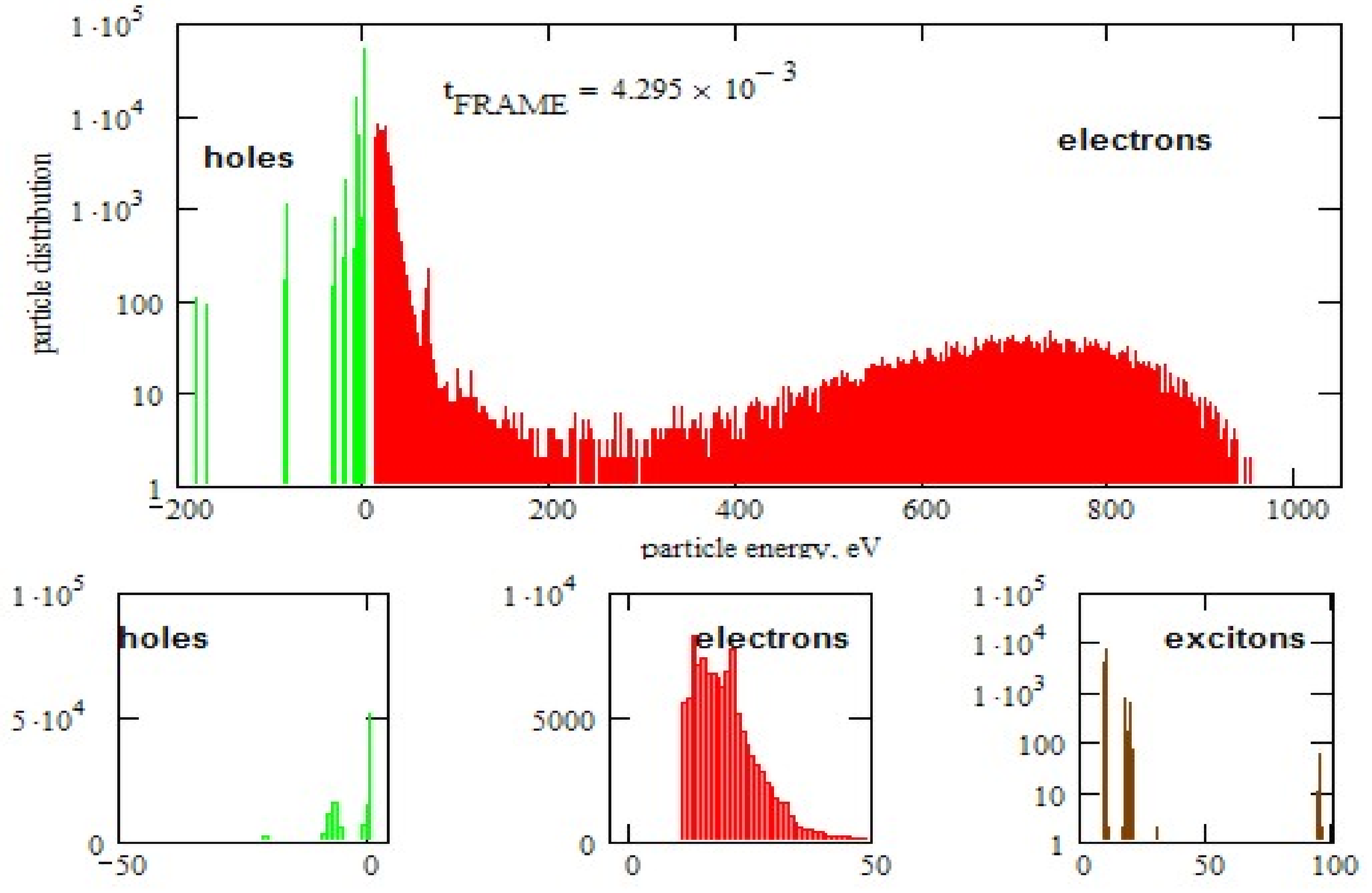

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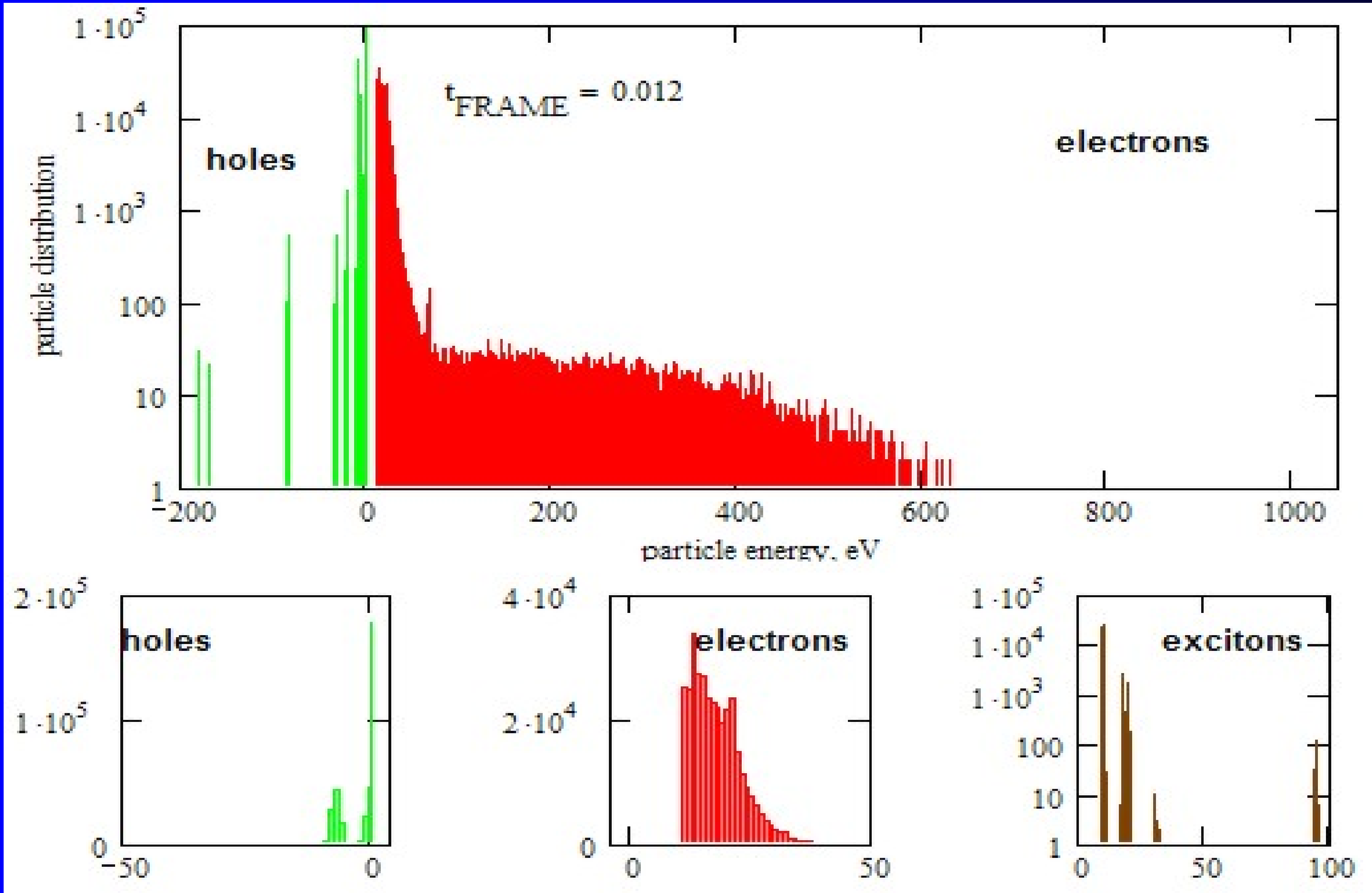

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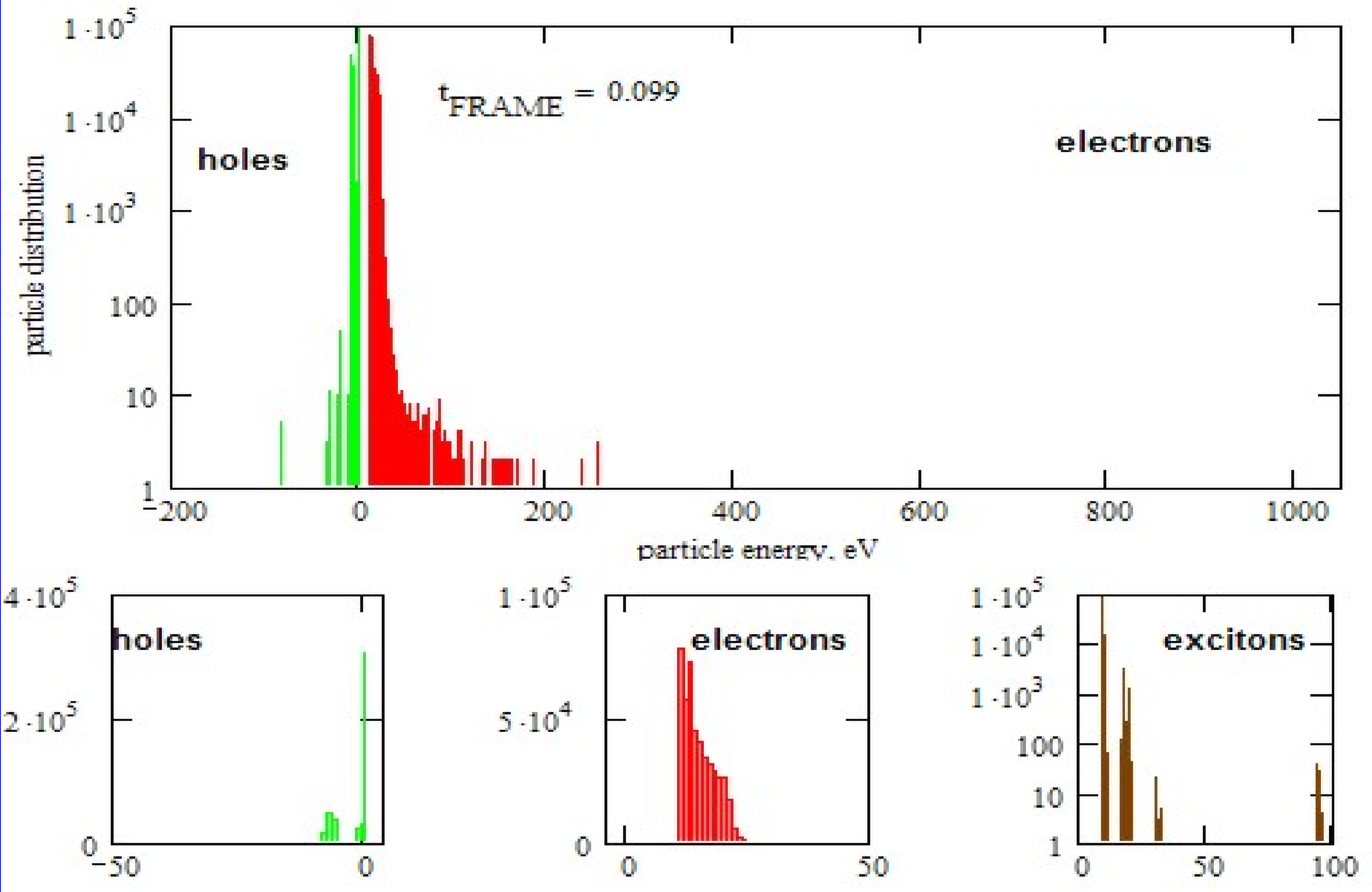
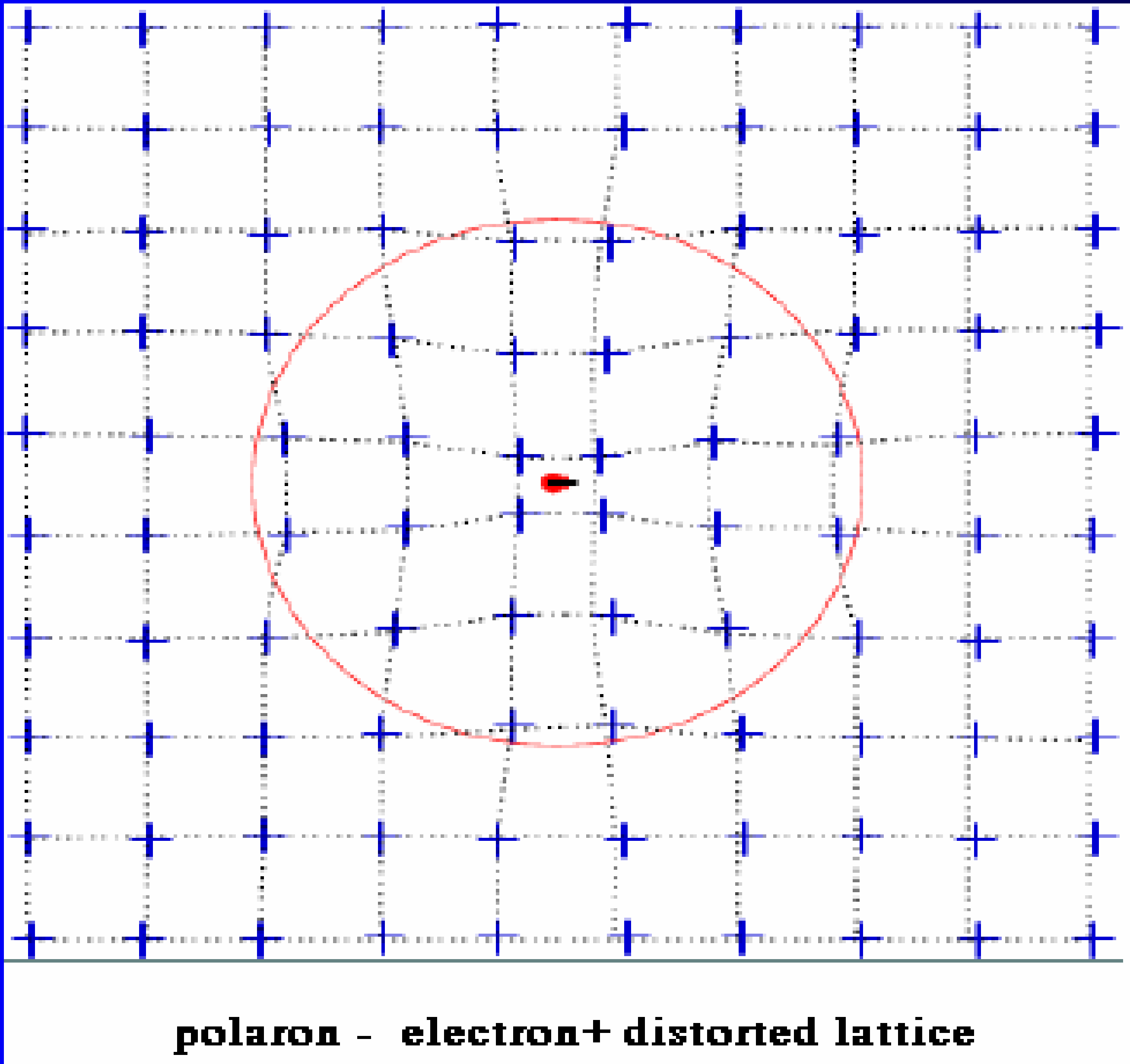
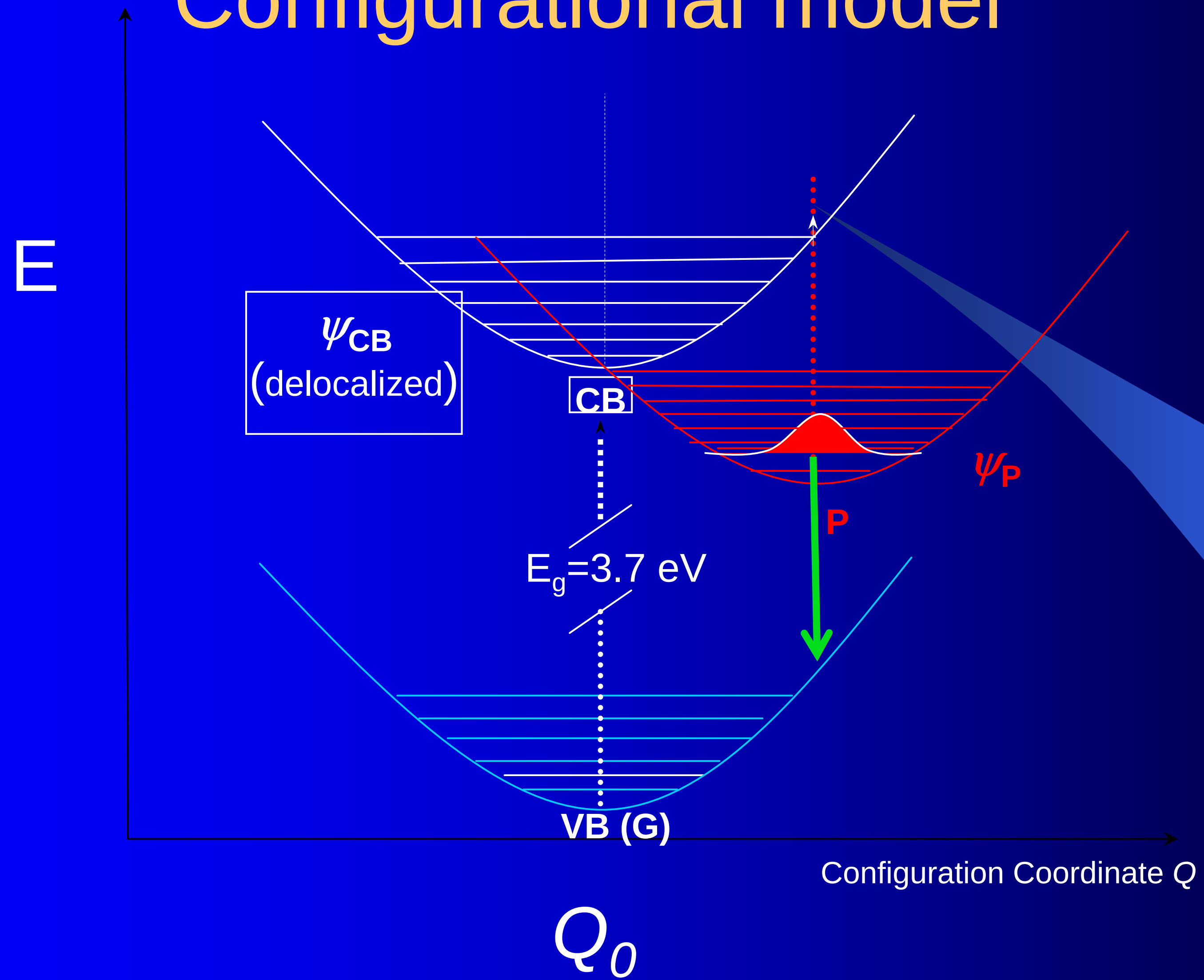


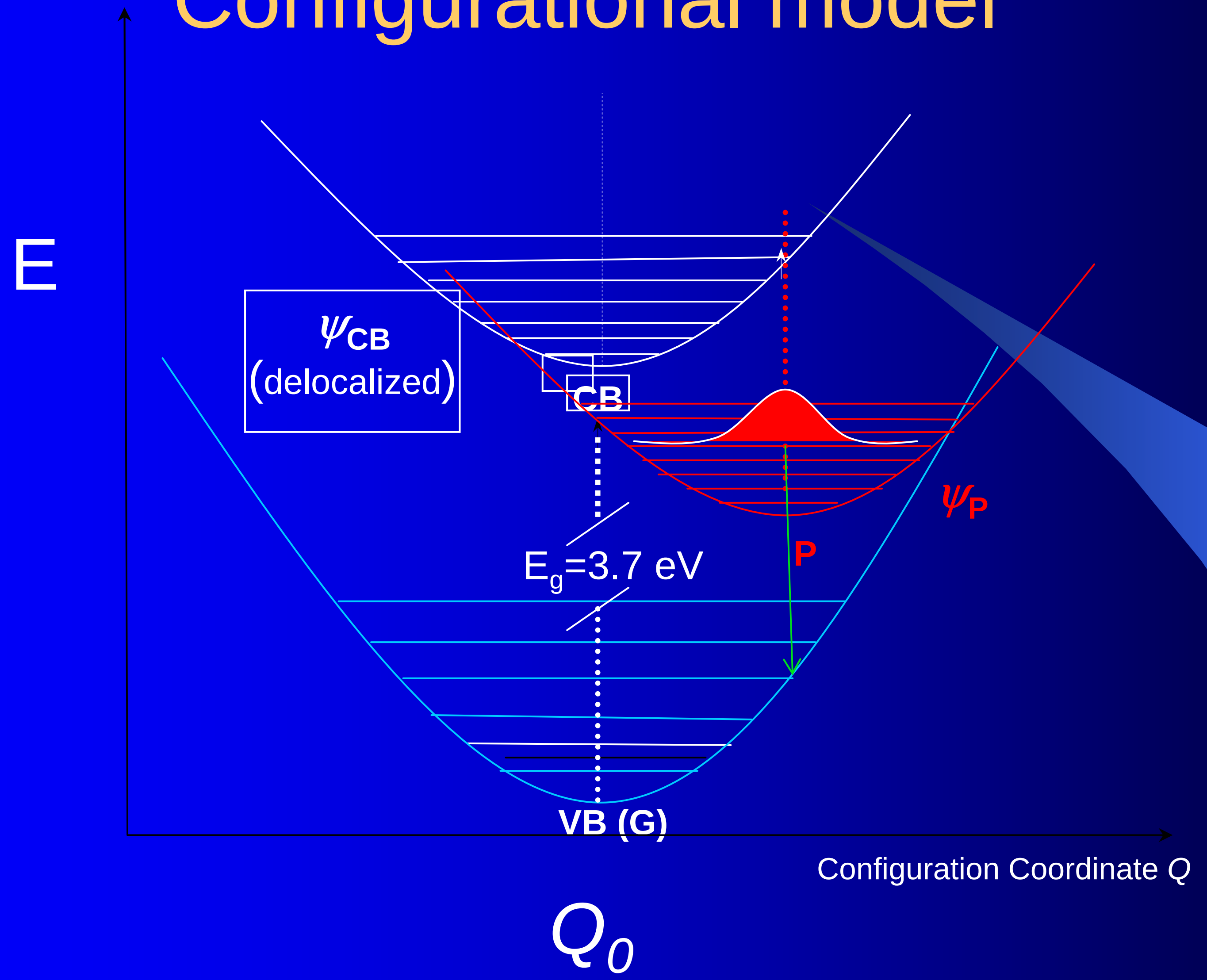

polaron - electron+ distorted lattice

Configurational model



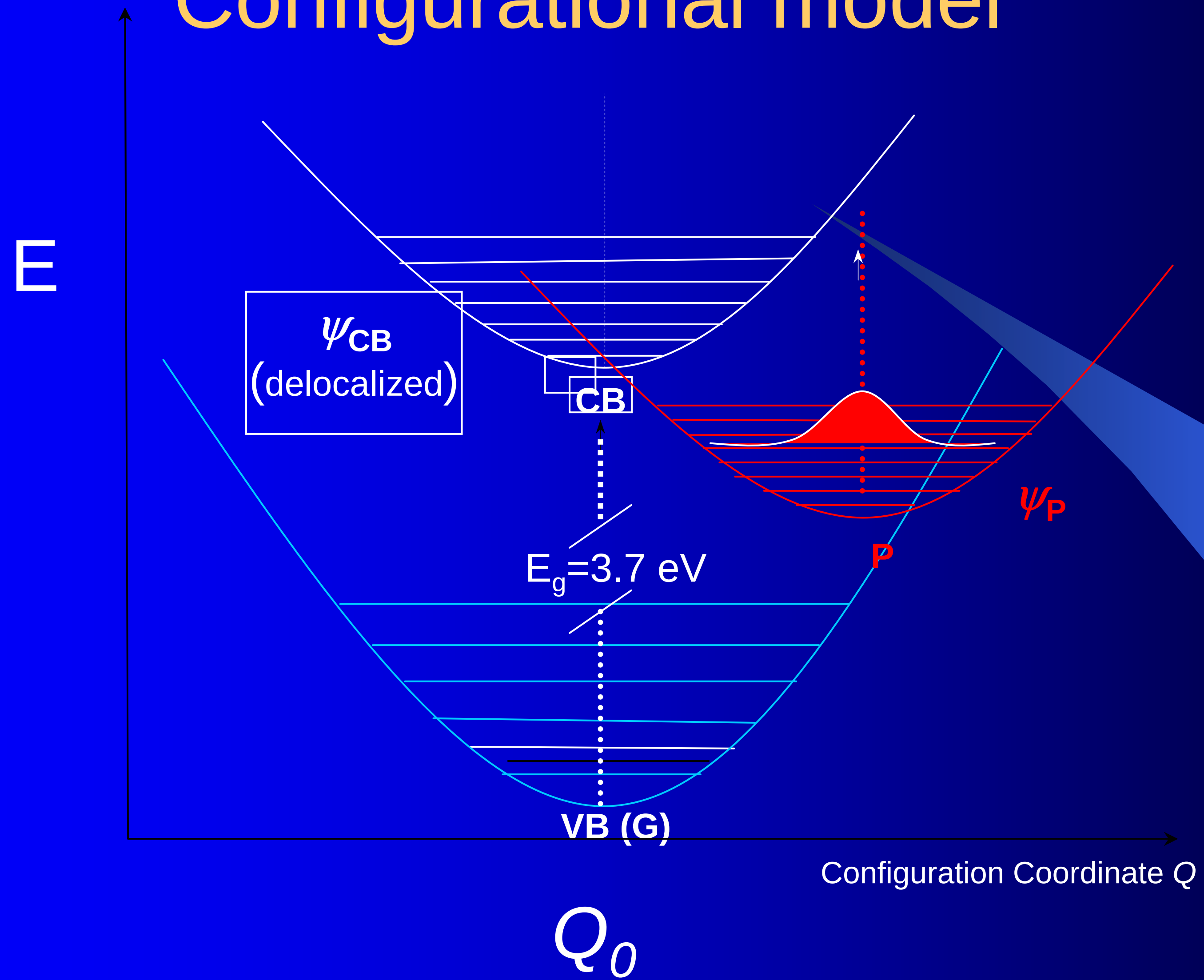
Configuration coordinate model for the local lattice with electron in **valence** and **conduction *band*** states and in ***localized* polaron** state.

Configurational model



Configuration coordinate model for the local lattice with electron in **valence** and **conduction *band*** states and in ***localized*** **polaron** state.

Configurational model



Configuration coordinate model for the local lattice with electron in **valence** and **conduction** ***band*** states and in ***localized*** **polaron** state.

Fundamental aspects of Scintillation

The 3 phases of the scintillation mechanism

1. Absorption : Creation of pair e-h

$$n_{e-h} = \frac{E_\gamma}{\beta E_{gap}}$$

2. Transfer to the luminescence centre

Efficiency of energy transfer : S

3. Emission

Efficiency of emission : q

Efficiency of scintillation

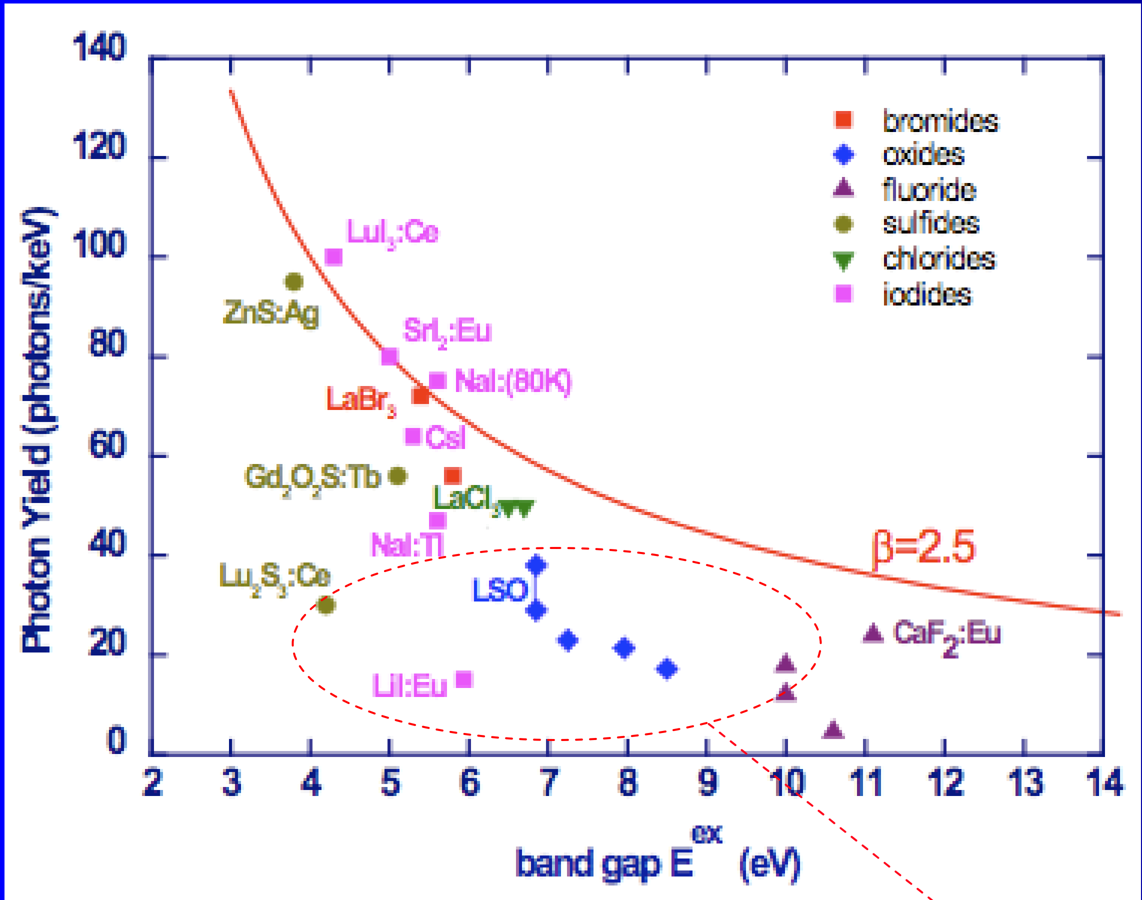
$$n_{photon} = n_{eh} Sq = \frac{E_\gamma}{\beta E_g} Sq$$

Determination of the maximum of light

$$LY_{\max} = \frac{n_{photon}}{E_\gamma} = \frac{1}{\beta E_g}$$

Usually β = 2 to 4

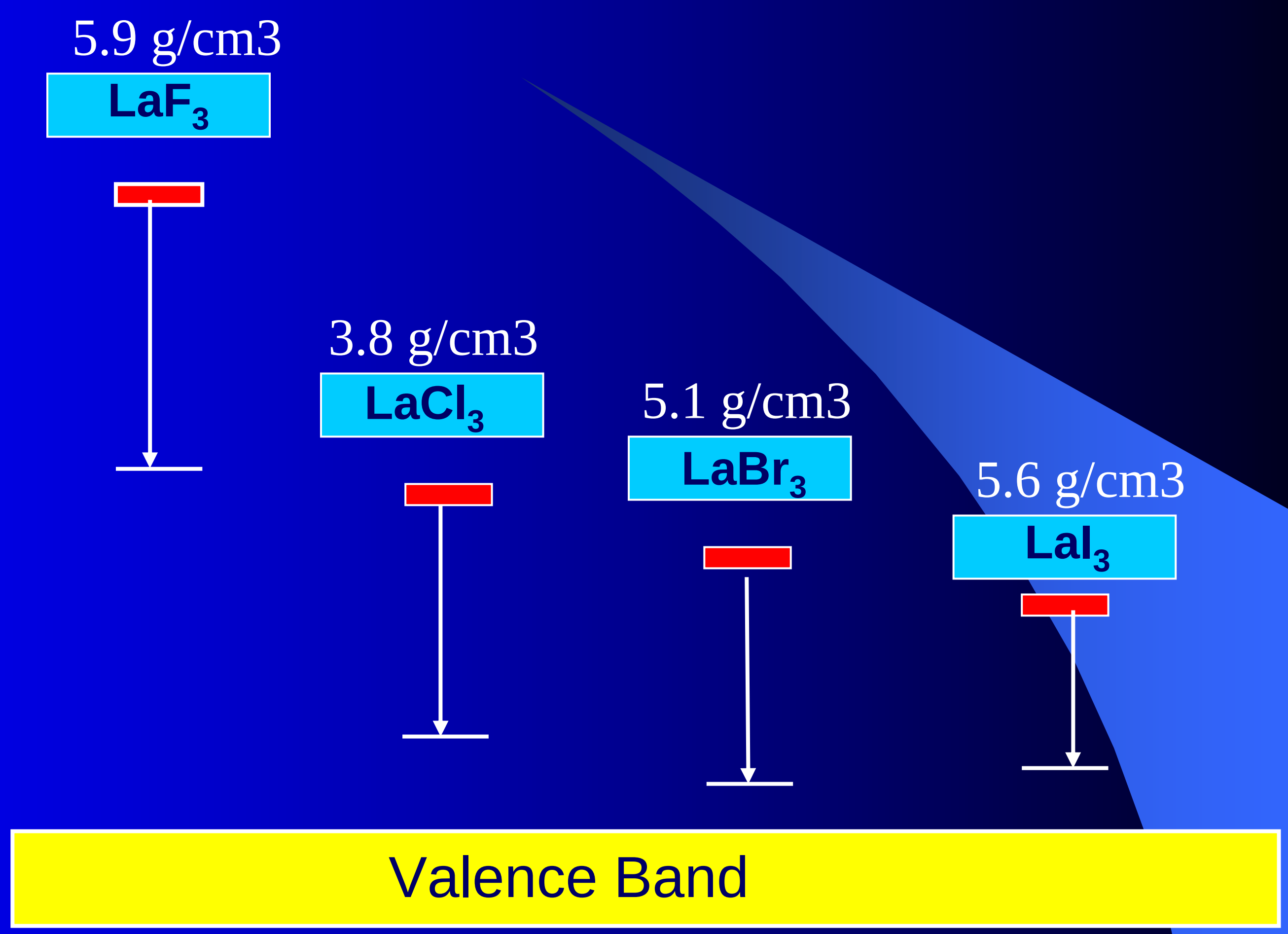
Fundamental limits to the LY



$$N_{ph} \leq N_{eh} = \frac{E_\gamma}{\beta E_{gap}}$$

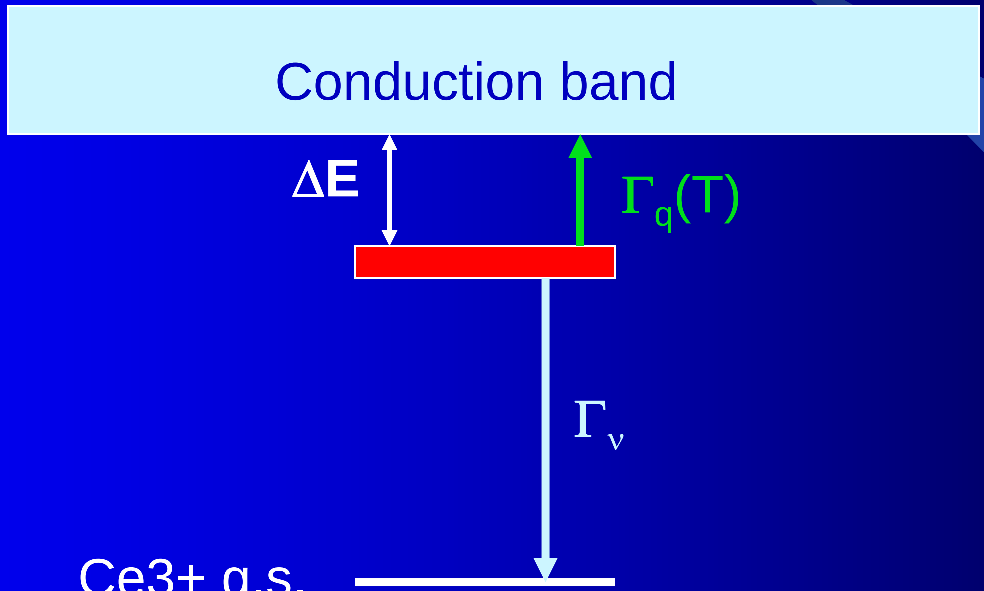
Why?

Towards smaller band gap compounds



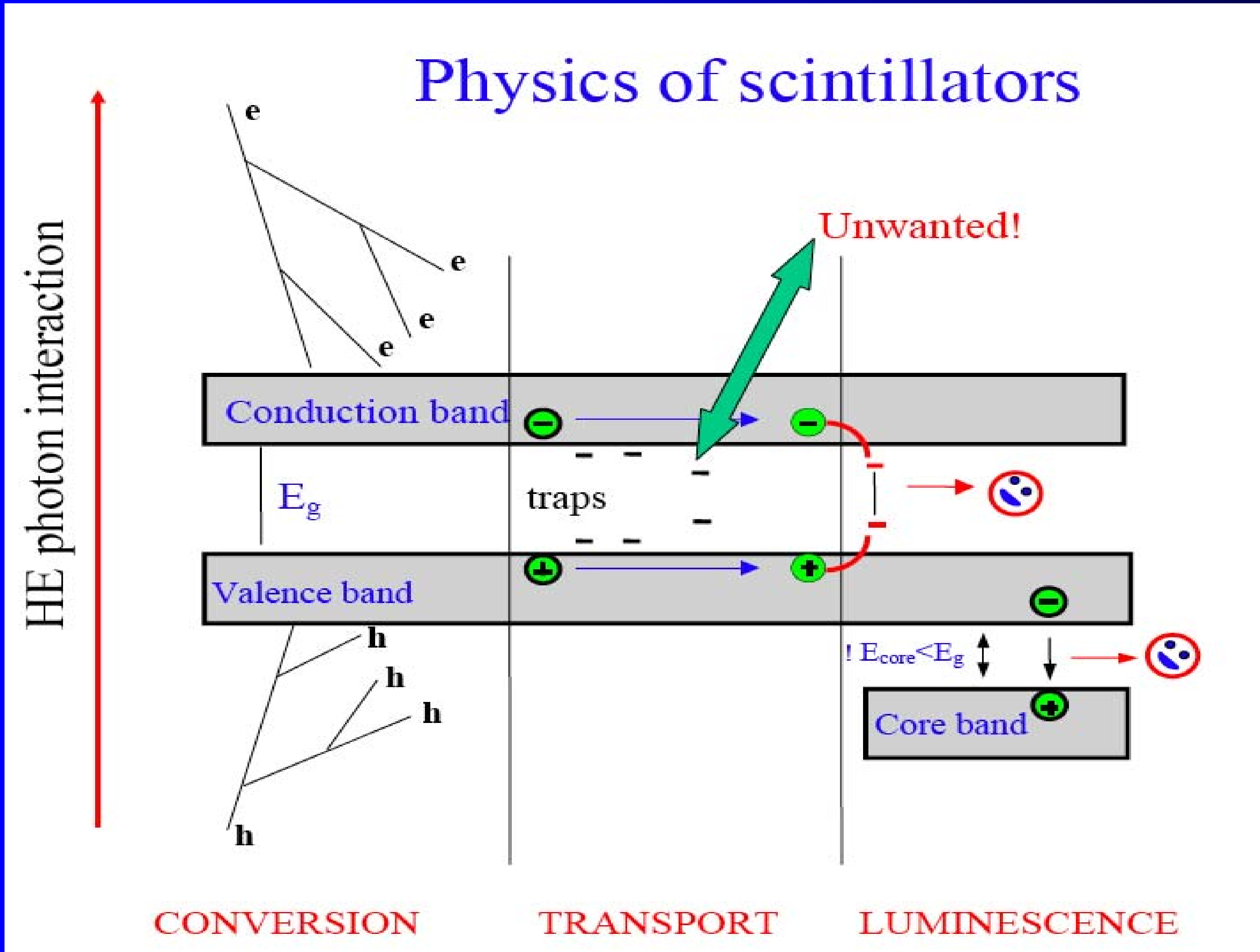
Light yield (10^3 ph/MeV) 2 53 73 0

Luminescence quenching in LaI_3:Ce



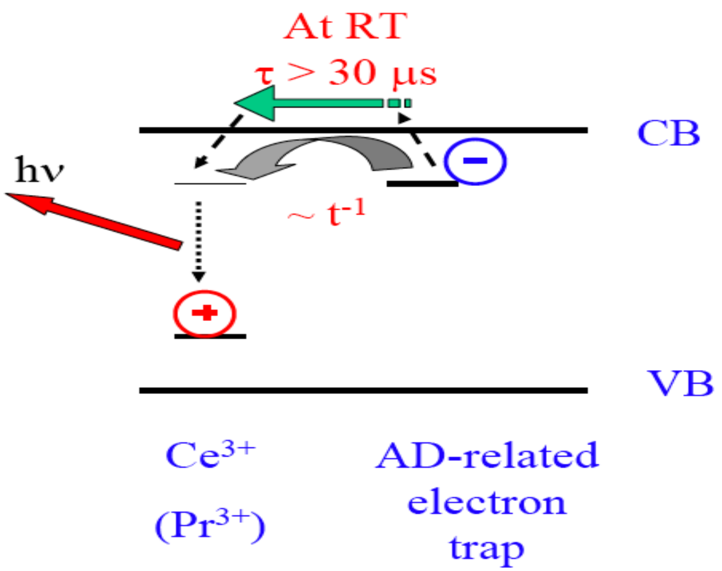
Absolute location of doping levels is crucial

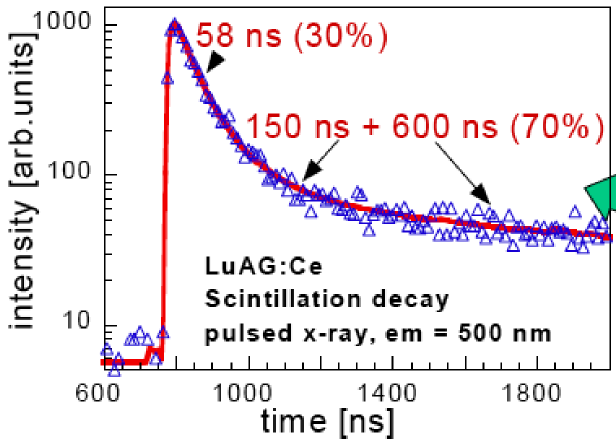
Effect of traps



Effect of traps

Ce^{3+} and Pr^{3+}-doped $Lu_3Al_5O_{12}$





Light yield (1 μs time gate)

Best YAG:Ce ~ 3x BGO

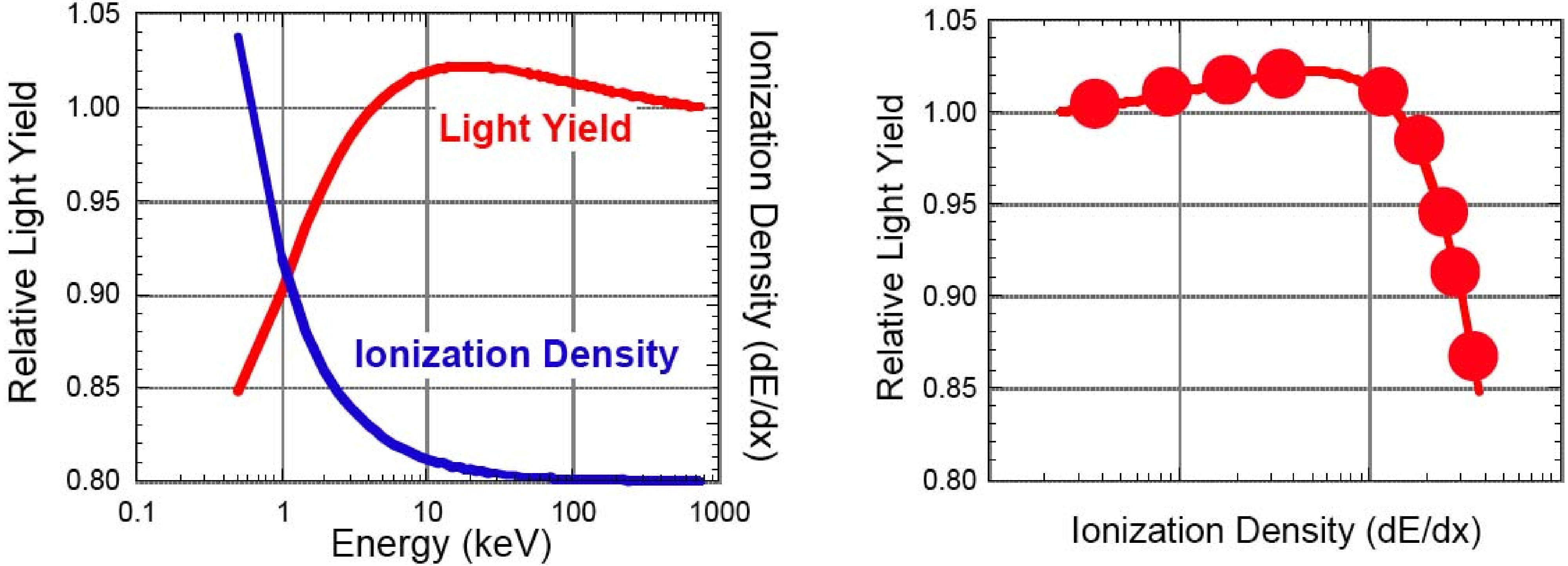
Best LuAG:Ce ~ 60% of YAG:Ce

A lot of "slow light" in these materials

Retrapping of electrons at shallow traps before their radiative recombination at Ce^{3+} ions

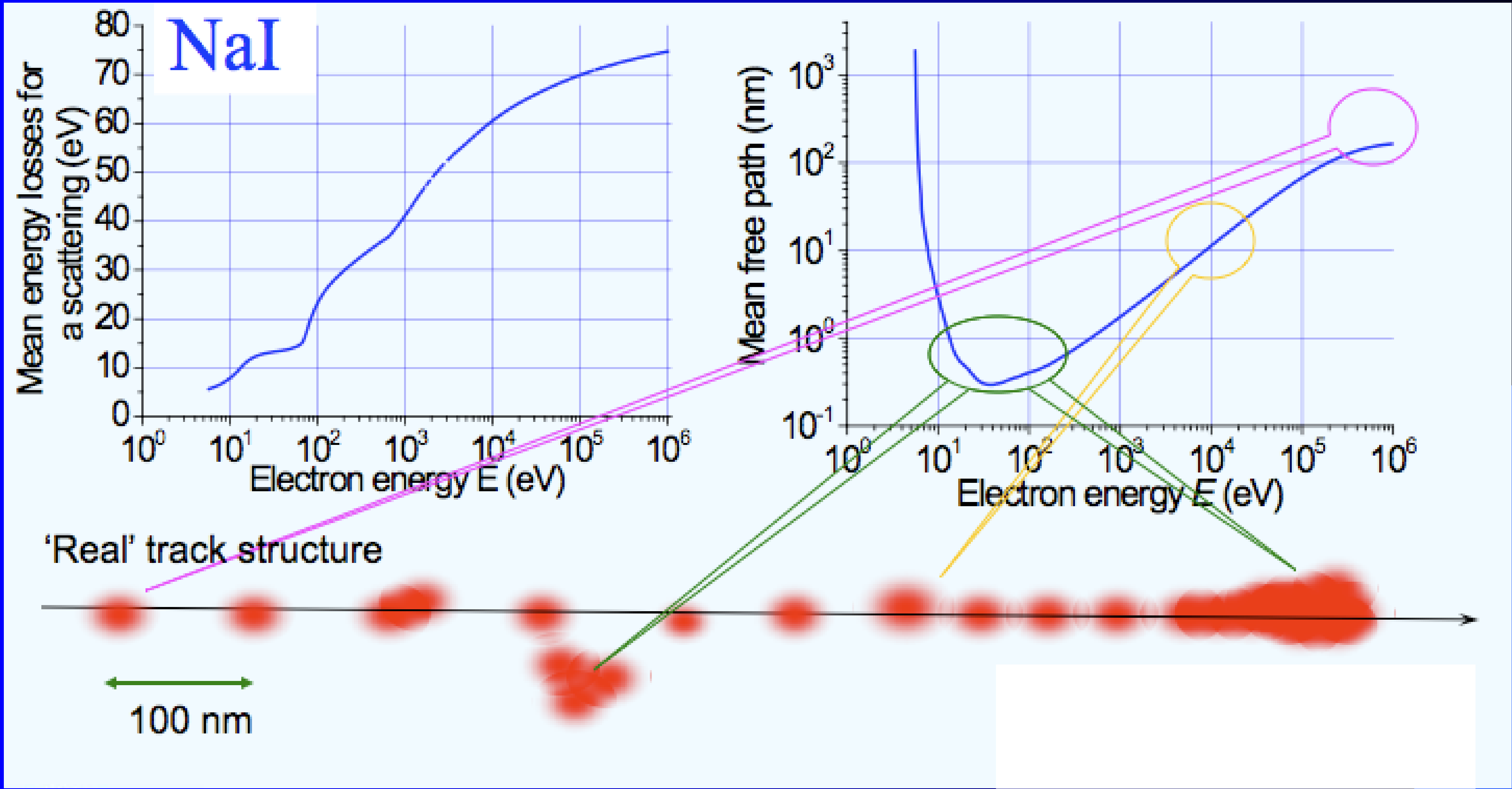
Nikl et al, pss (a) **201**, R41 (2004)

Yield depends on electron ionization density

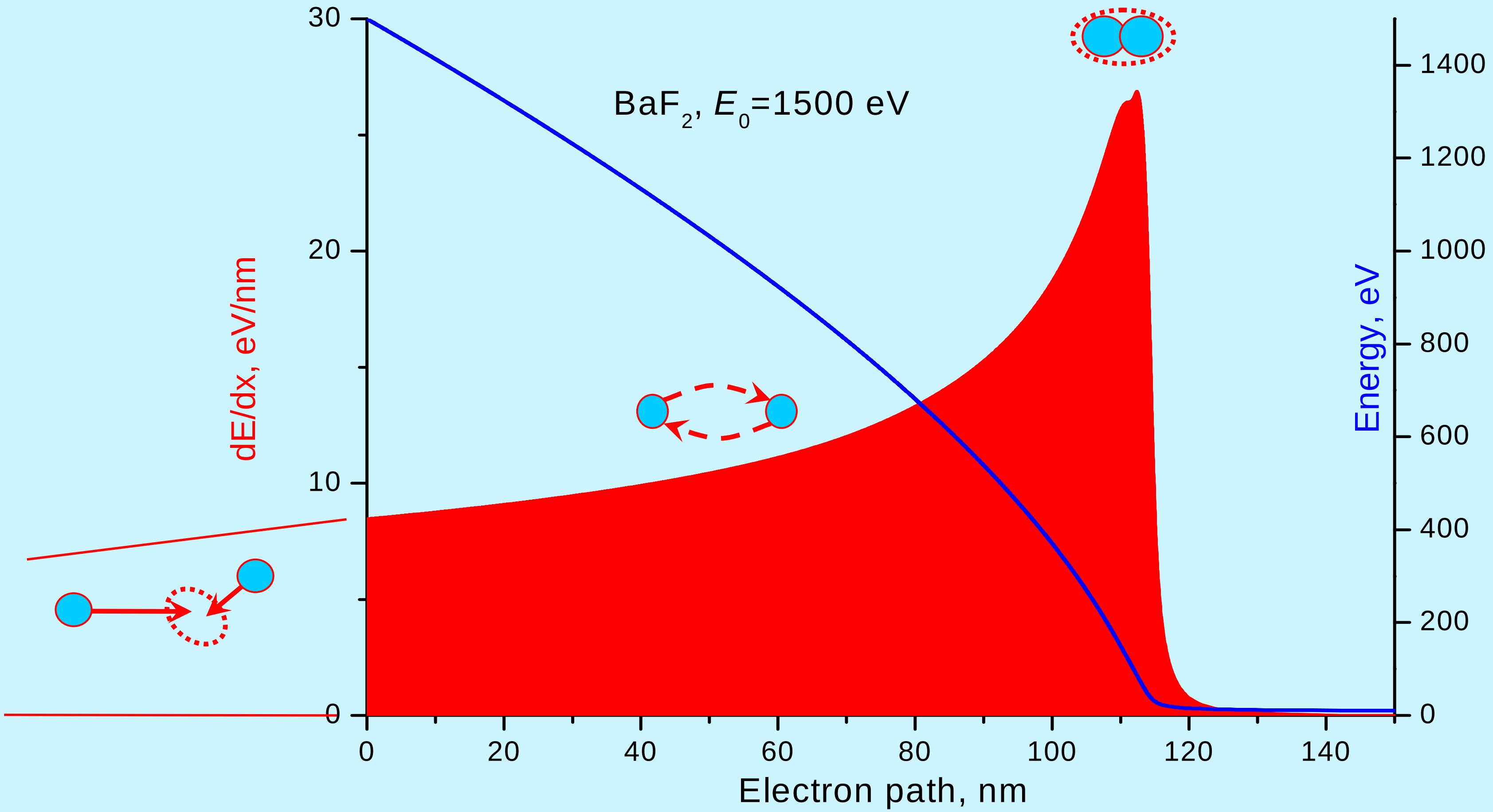


Non-Proportionality + Non-Uniform Energy Deposit
⇒ Degraded Energy Resolution

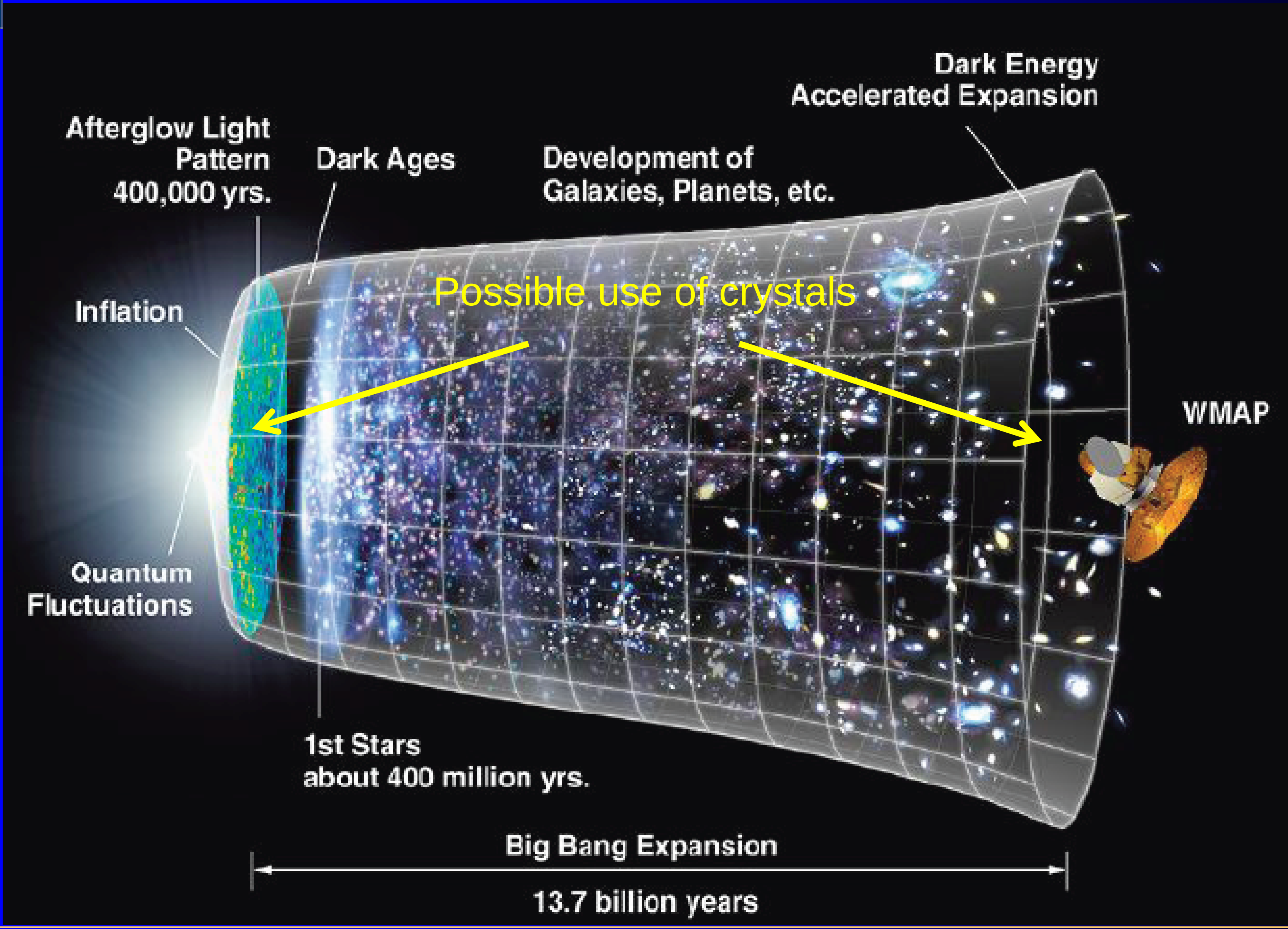
Non-uniformity of electron energy deposit



EE density effect in scintillators

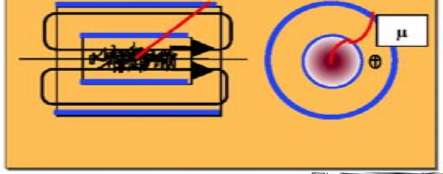


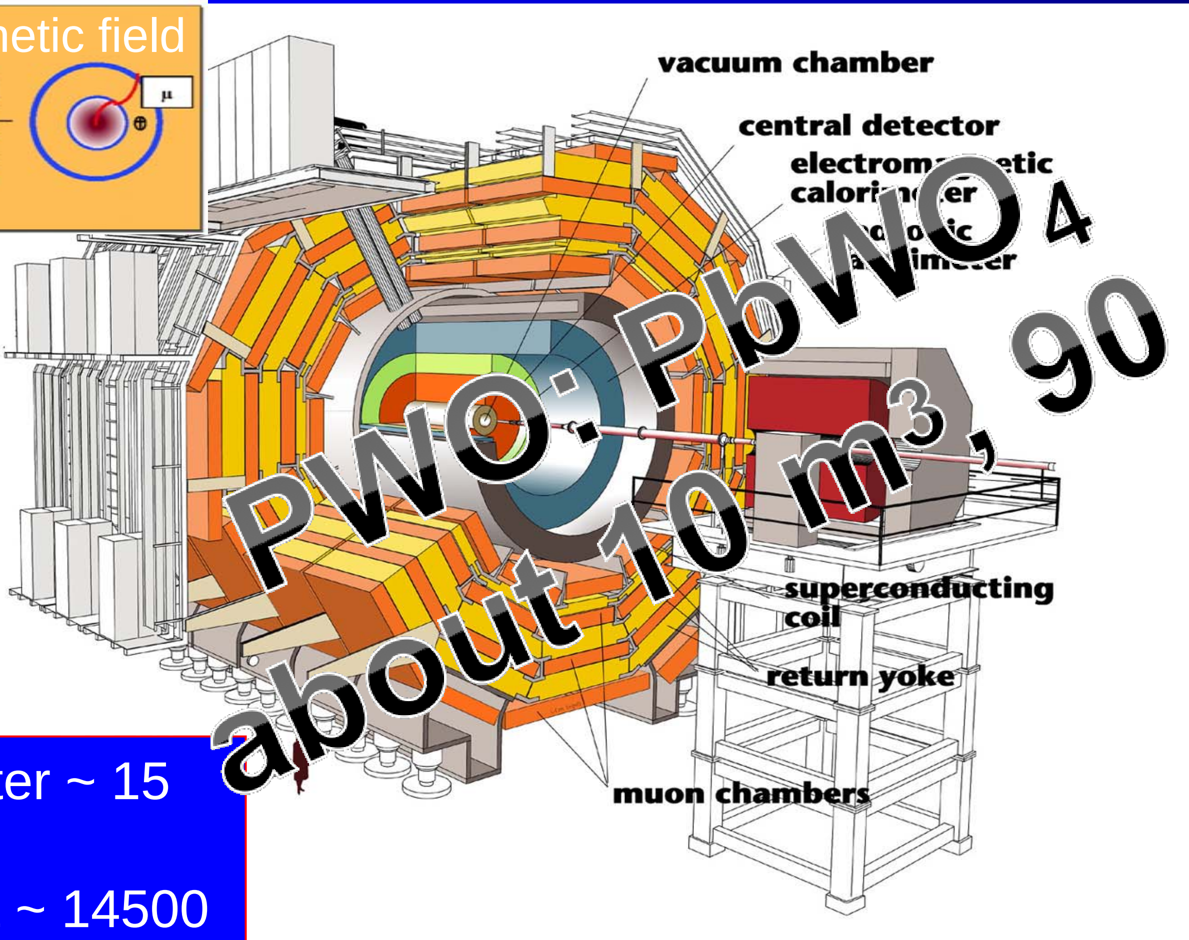
Back to Creation



Compact Muon Solenoid

4 T magnetic field

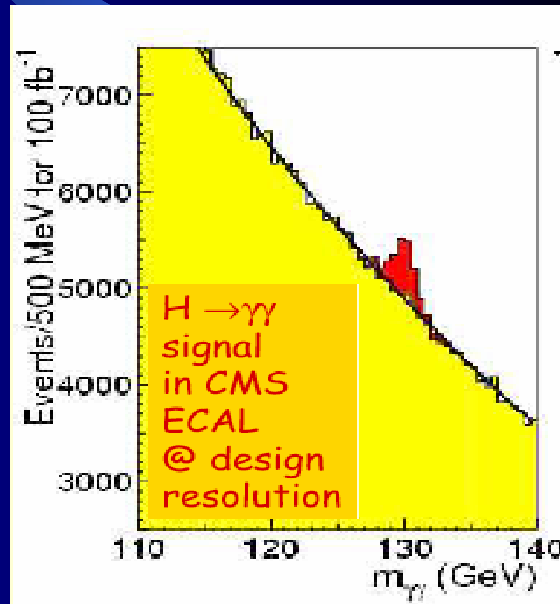




PWO: PbWO$_4$
about 10 m^3, 90 t

- Diameter ~ 15 m
- Weight ~ 14500 t

Main CMS goal: search for Higgs and new physics

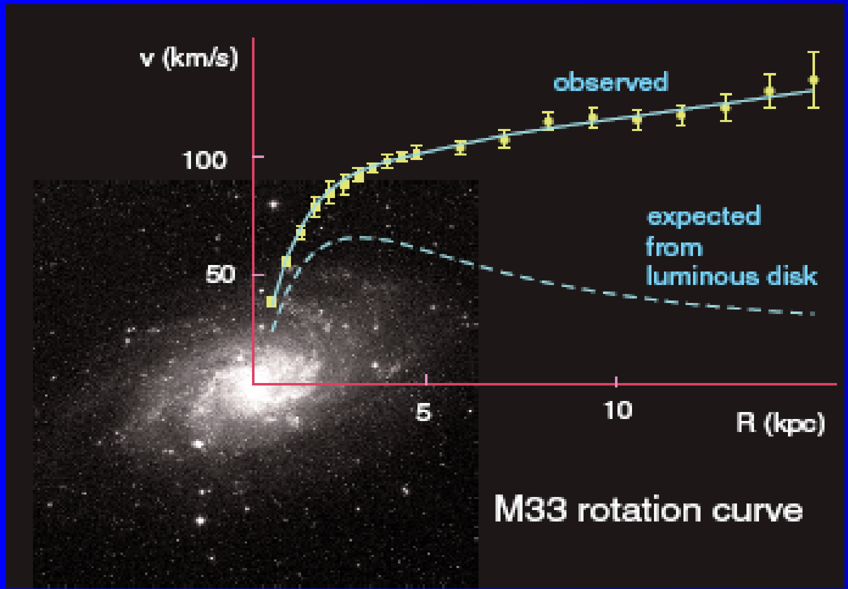


For a light Higgs (as suggested by present data)
H→γγ best channel. Narrow width, irreducible background:
ECAL resolution crucial !

WIMP-Dark matter searches

Evidence of Dark Matter

Rotation curve of spiral galaxies

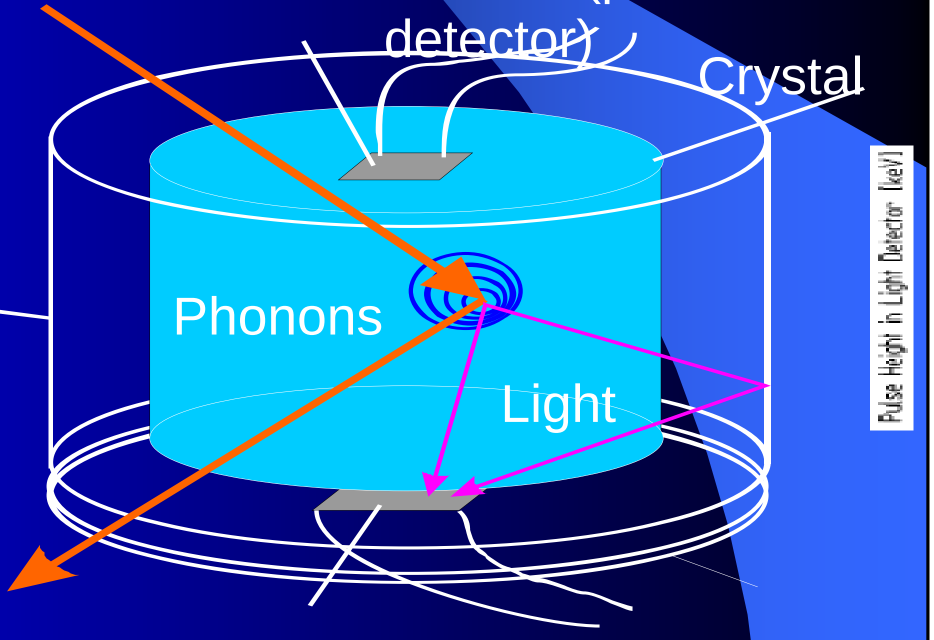


Direct detection - elastic scattering off nuclei

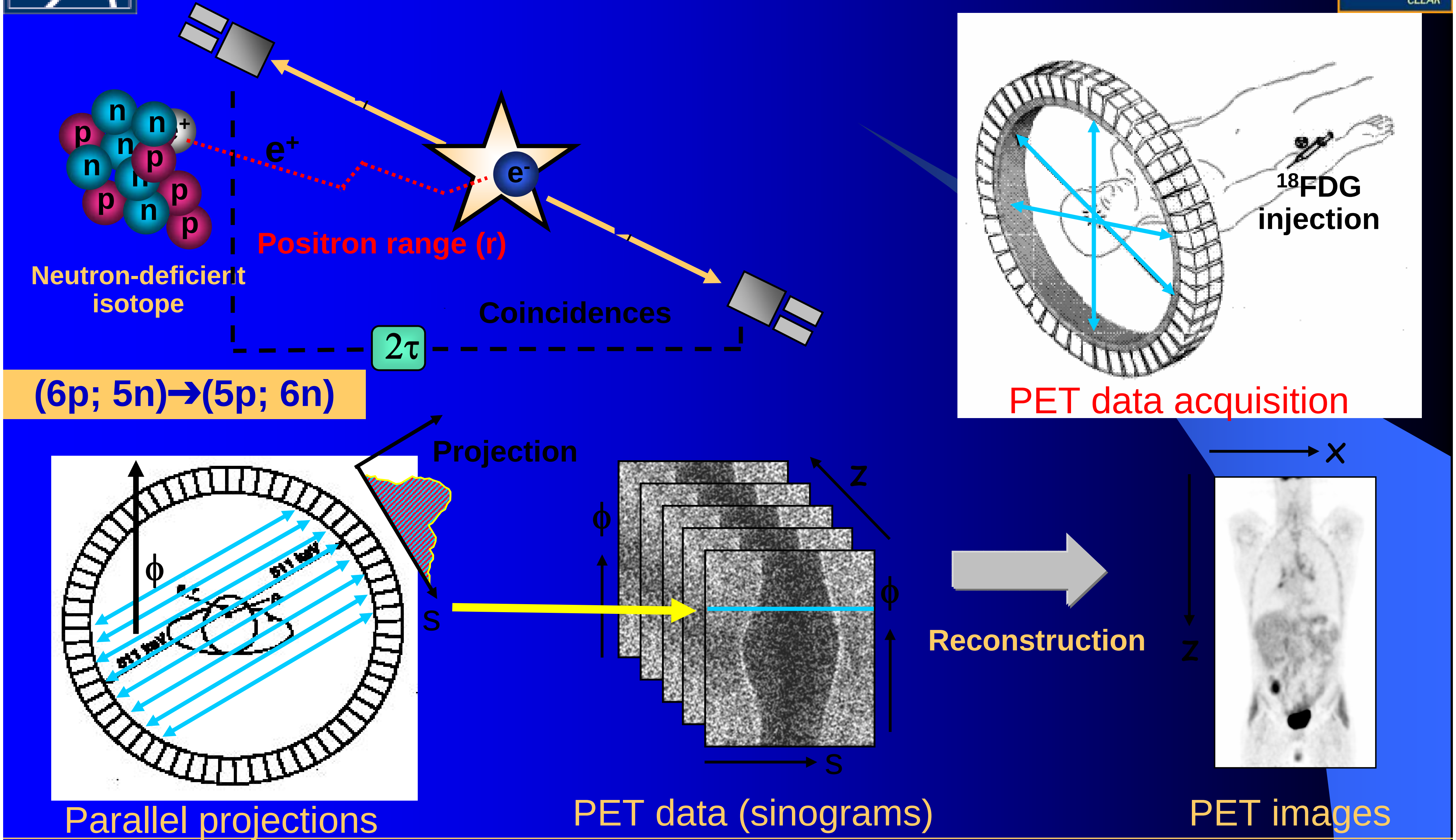
Expected event rate < 0.1/kg day

Detector mass 1kg-100 kg

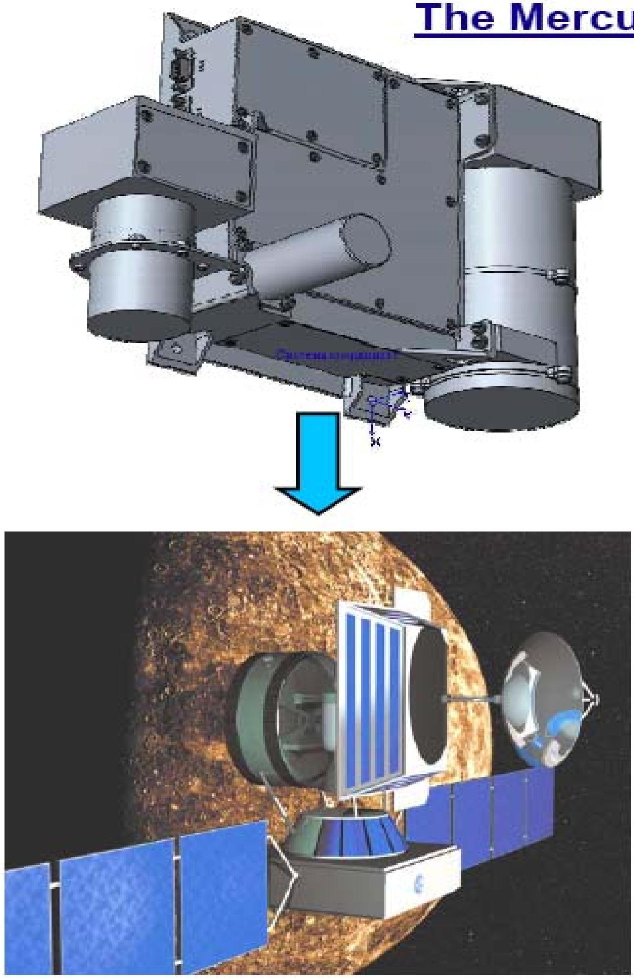
High radiopurity of detector



PET Principles



The BepiColombo Mercury mission



The Mercury Gamma-ray and Neutron Spectrometer (MGNS)

Main characteristics

Goal: The gamma and neutron mapping of Mercury surface

Science objectives:

- The mapping of water content in Mercury subsurface
- The mapping of Mercury soil composition

Parameters:

PARAMETER	VALUE
Mass	5.2 kg
Power	5 W
Volume	-
Surface Resolution	400 km
Minimal time resolution	2-4 sec
Energy range, neutrons	Multi energy bands covering 10^{-3} eV – 15 кeV
Energy range, gamma	300 keV – 10 MeV
Energy resolution, gamma	3% at 660 keV
Detectors	3He – proportional counters, stilben crystal, $LaBr_3$ crystal
Temperature range	(-20C, 40C)
Position	ESA: BepiColombo
Altitude	400 km – 1500 km

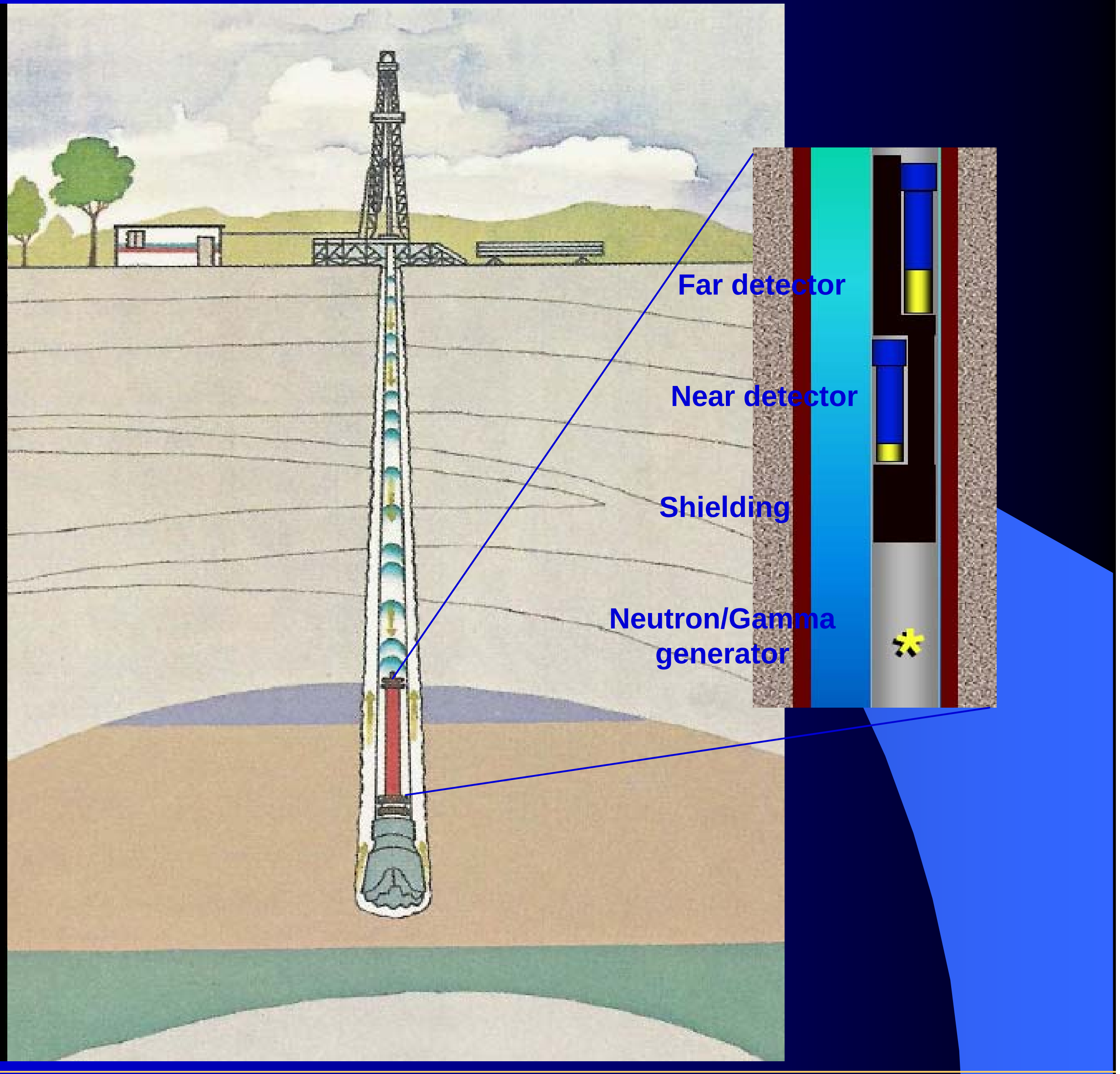
esa

Science Payload and Advanced Concepts

Oil Well Logging

Measurement Issues

- Source and sensor both in borehole
- Usually want to measure Formation
- Need to make measurement with 1-3 seconds of data



Active Instrumentation

Mobile and fixed position; X ray, ^{60}Co, ^{137}Cs

NaI, $CdWO_4$, BGO

Spectrometers, counters, imagers

8 Managed by UT-Battelle
for the Department of Energy

OAK RIDGE
National Laboratory

Thank you