Scintillators - Fundamentals

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Outlook

- Lecture 1: Scintillator fundamentals
  - Organic scintillators
  - Inorganic scintillators
    - Scintillation mechanisms
    - Limits to the light yield and decay time
    - Energy resolution and non-proportionality
- Lecture 2: Scintillator applications
  - Crystal growth techniques
  - High energy physics and dark matter searches
  - Medical applications
  - Space borne missions
  - Geophysical exploration
  - Homeland security

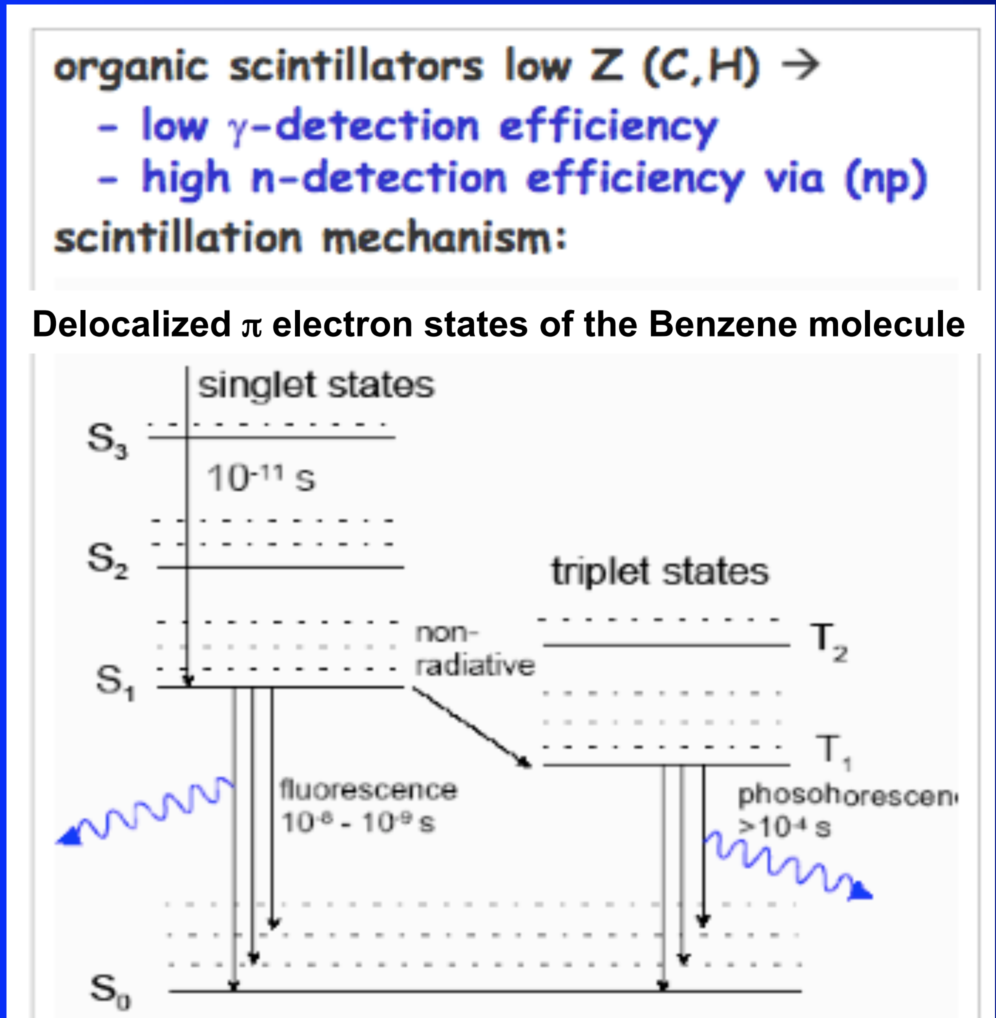
Scintillators according to various schemes

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

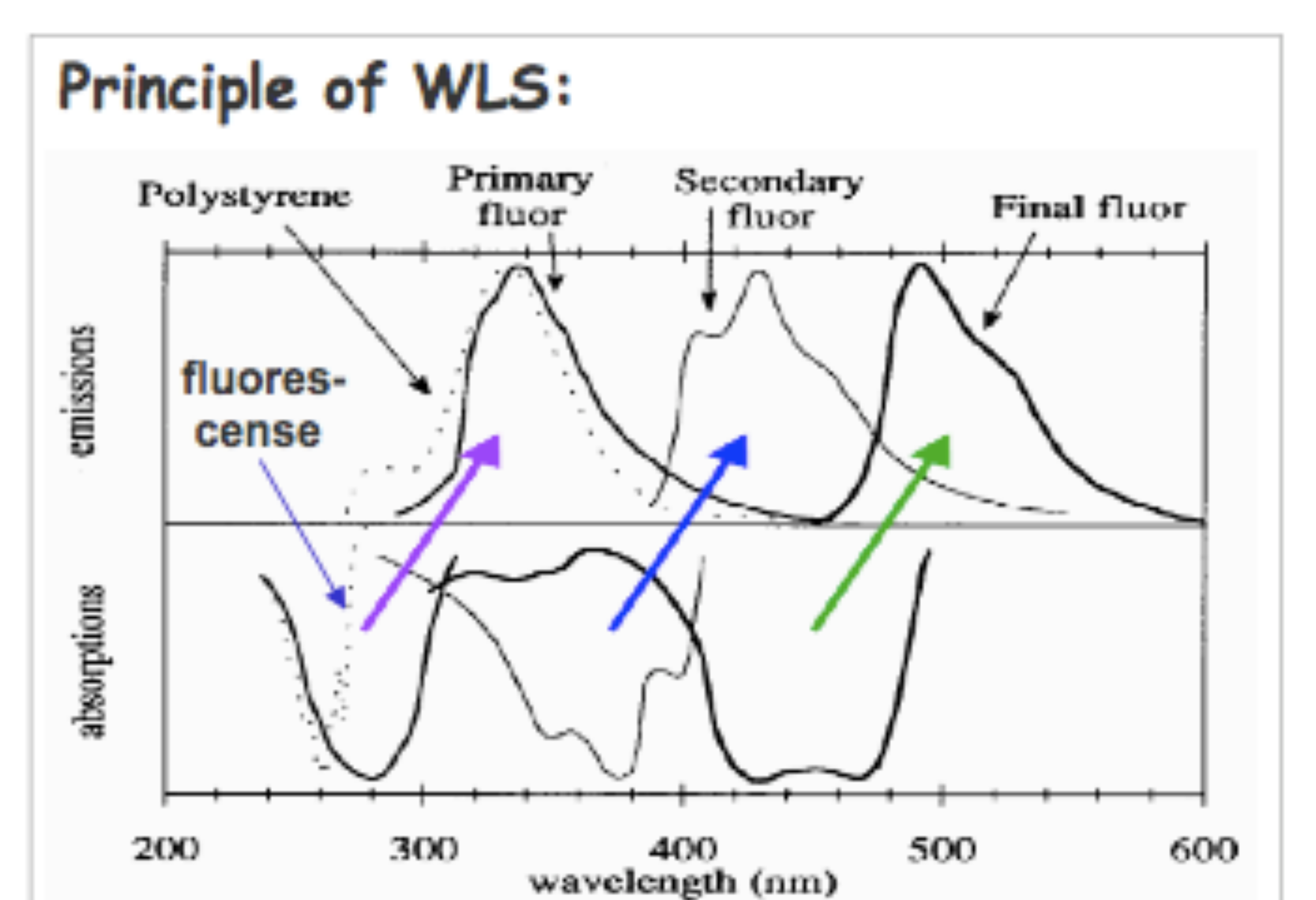
Organic scintillators

Convert PART of the energy of the incident particle



- Organic 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

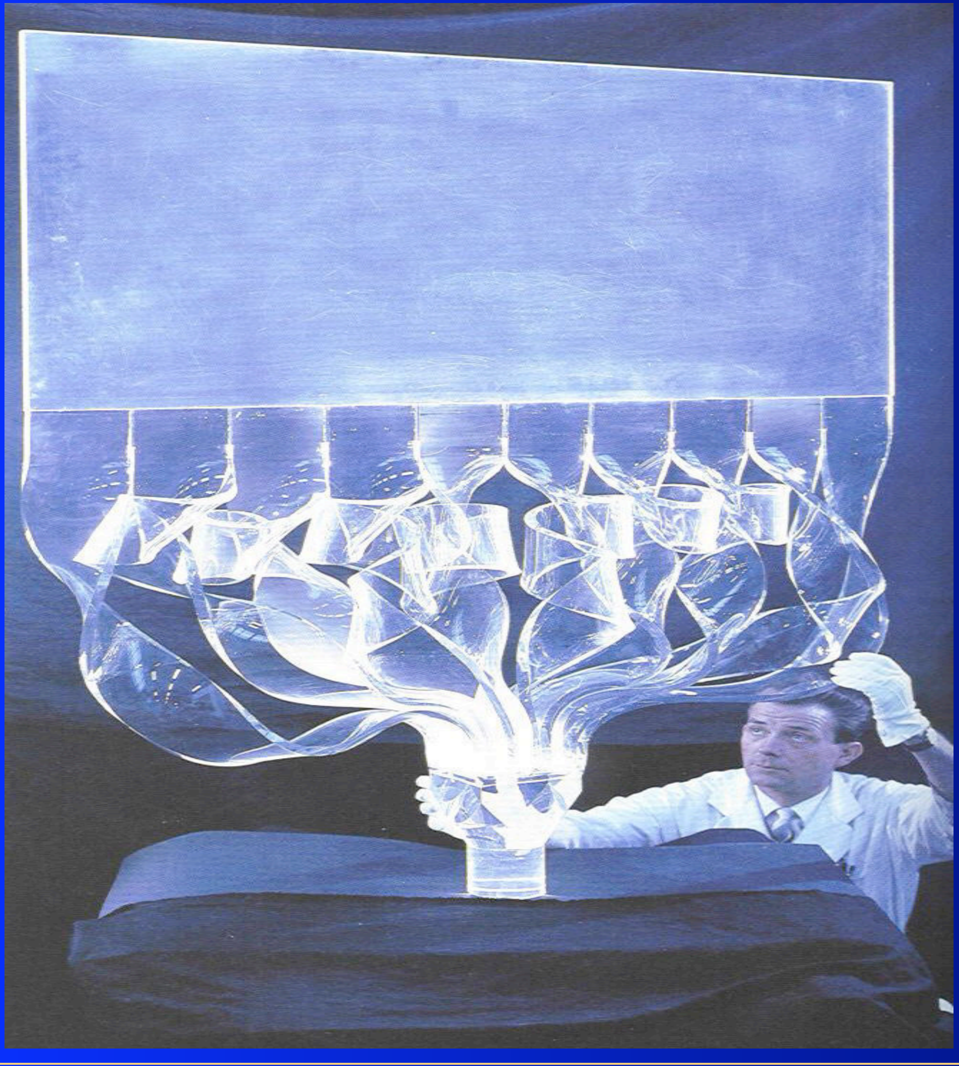


Crystaline organic scintillators

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

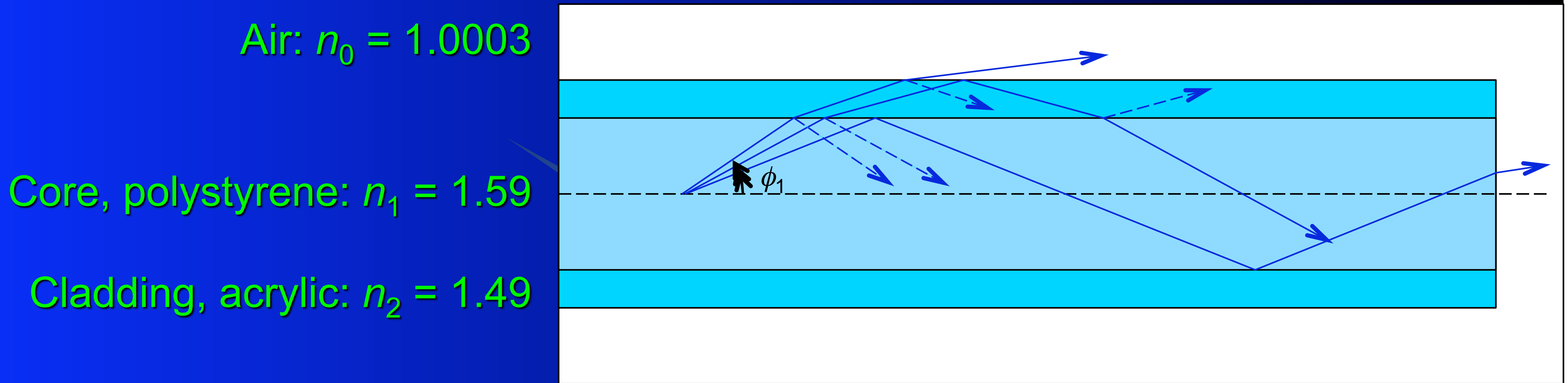
Plastic organic scintillator: plates



- 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

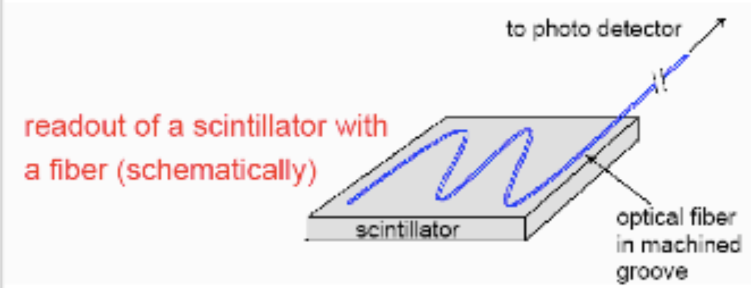
Plastic organic scintilator: fibers



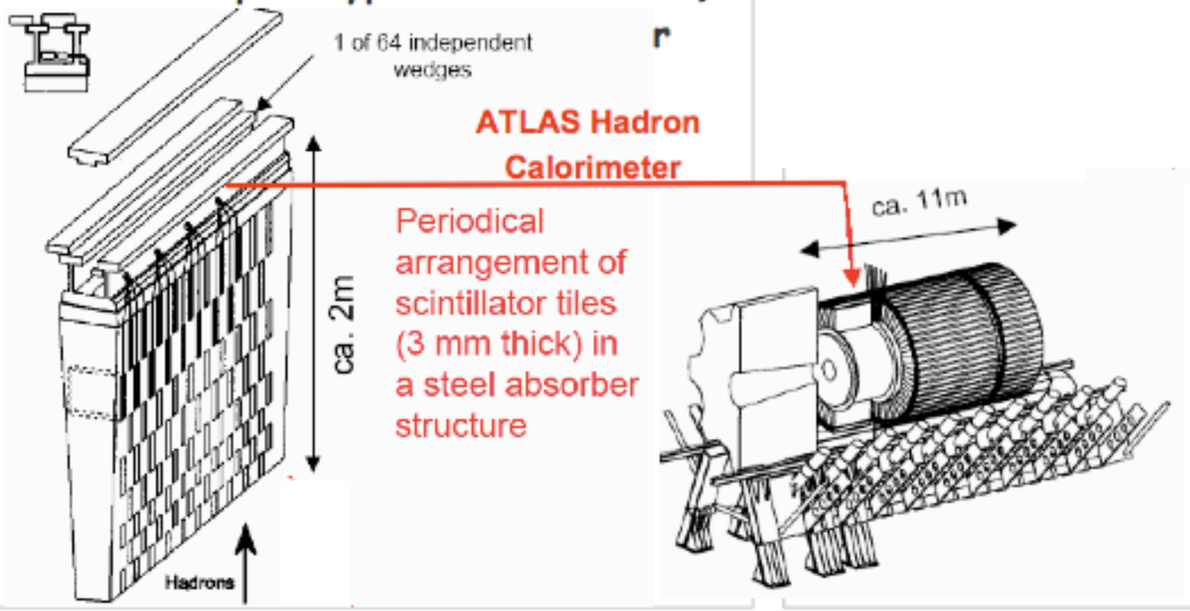
- Propagation in the core: $\phi_1 < 20.2^o$, $f_1 = 1-n_2/n_1 = 6.2\%$
- Propagation in the cladding: $20.2^o < \phi_1 < 51^o$, $f_2 = n_2/n_1 - n_0/n_1 = 31\%$
- Lost in air: $\phi_1 > 51^o$, $f_0 = n_0/n_1 = 63\%$

Tile calorimeters: ATLAS, CALICE

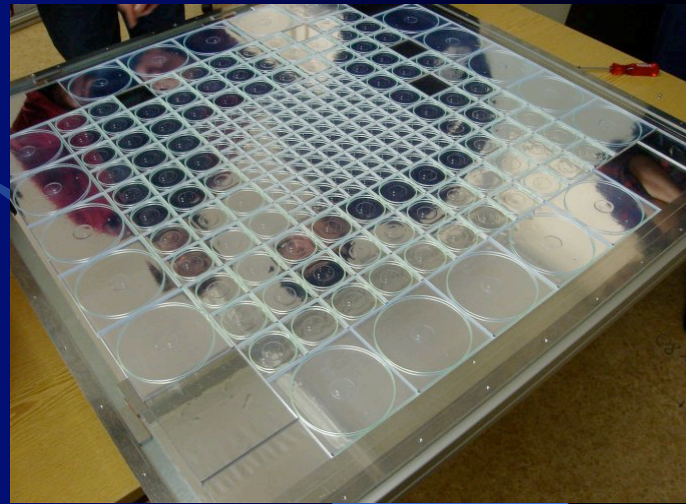
Fibres can be embedded in scintillator:

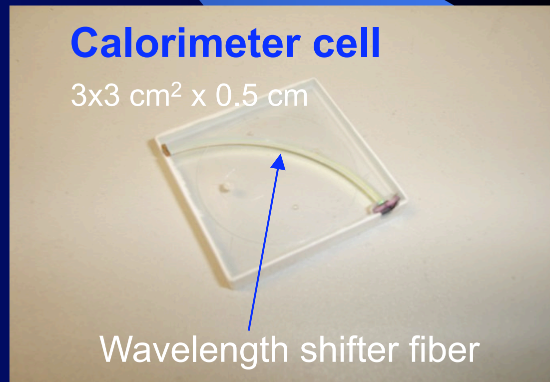


(with miniaturised Si-PM no transport needed → prototype calorimeter ILC)

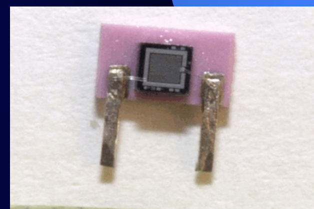


Read out 216 tiles/module
~8000 channels



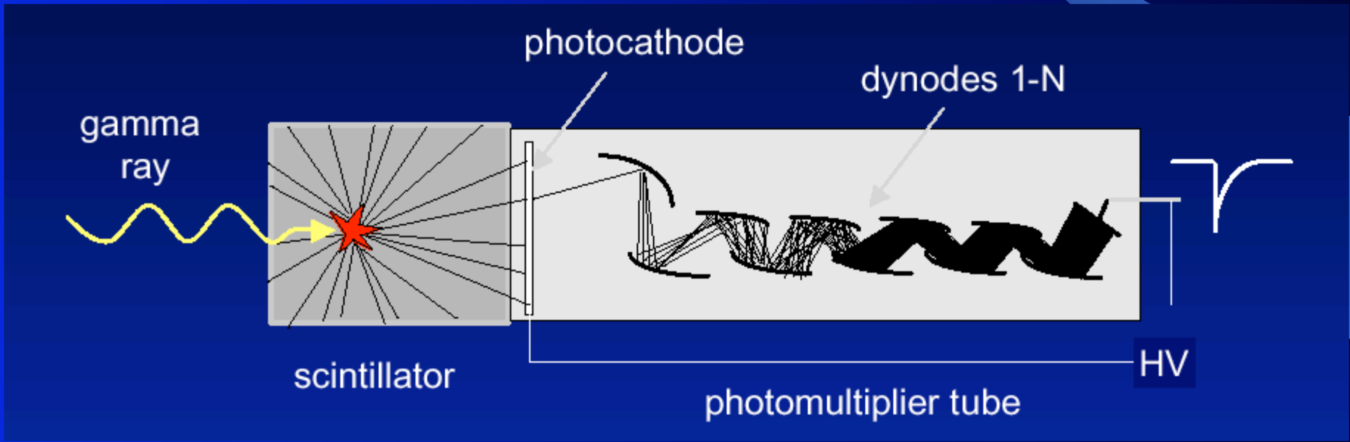


Single tile readout with SiPM



Scintillating crystals for homogeneous calorimeters

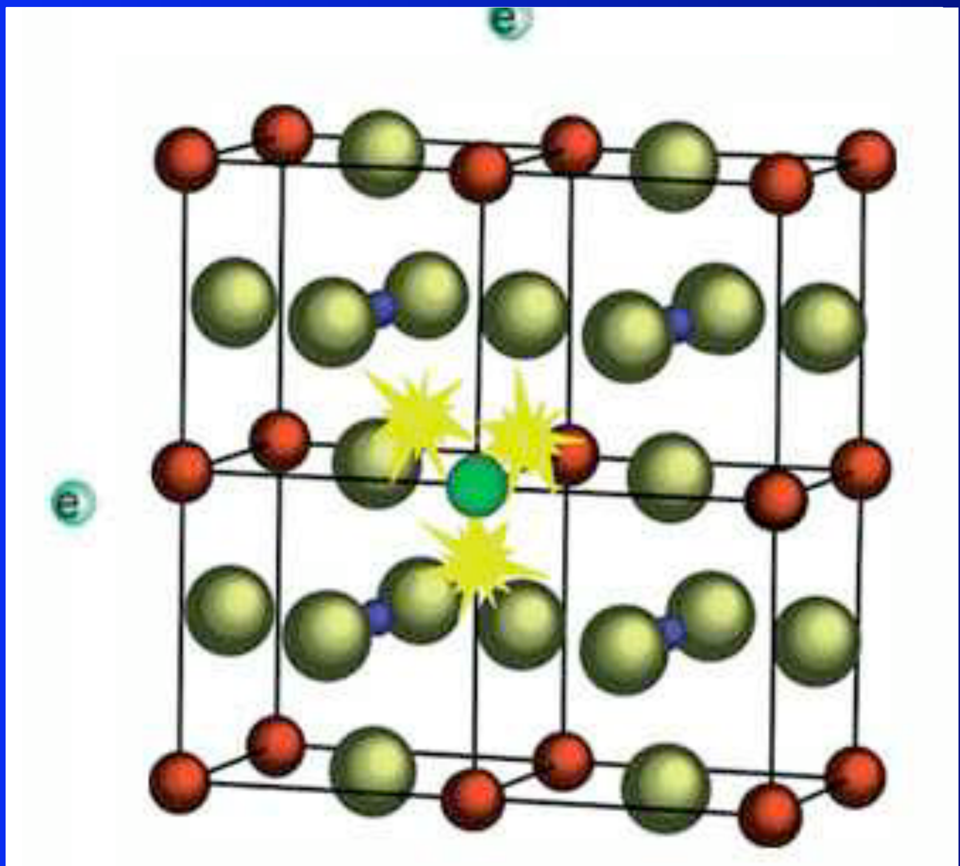
- To convert ALL the energy of the incident particle in to light
- Necessity to use dense materials

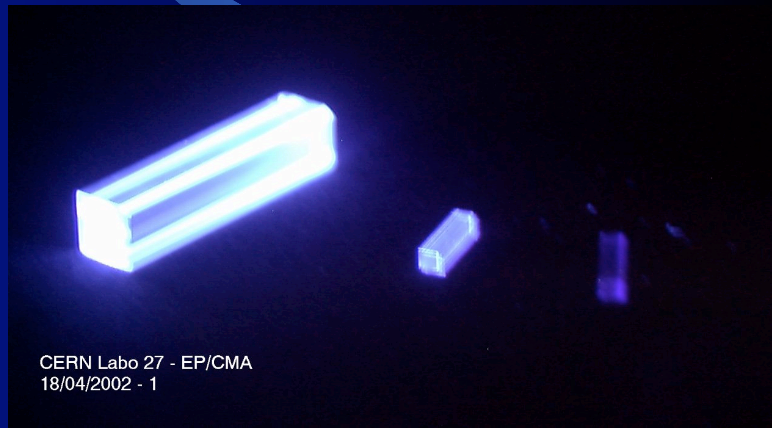


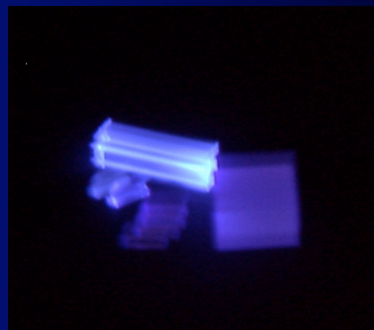
- Above certain minimum level most scintillators are linear with respect to the energy deposited
- Light output is directly proportional to energy deposited

Why a crystal?

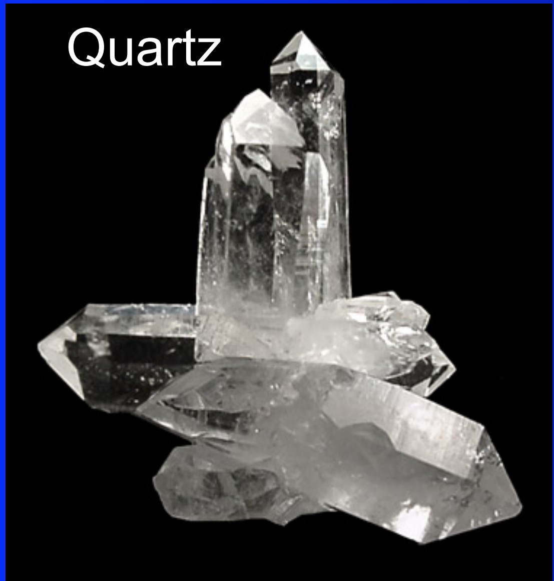
- Heavy material are rich in electrons, which interact strongly with light
- Only ordered system can confine electrons in well separated energy bands, so that the material is transparent to its scintillation light







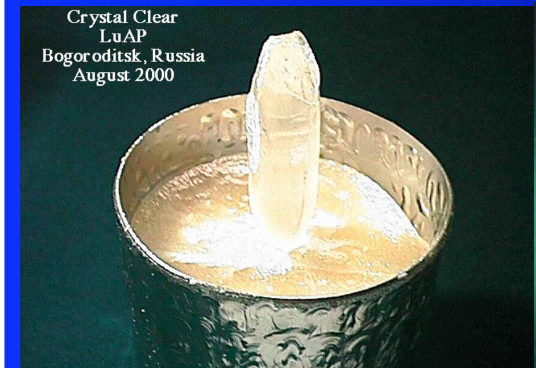
Examples of crystals

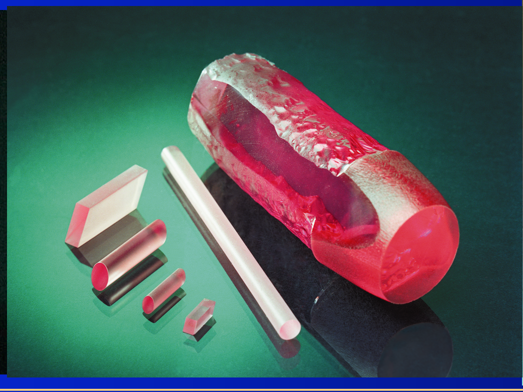


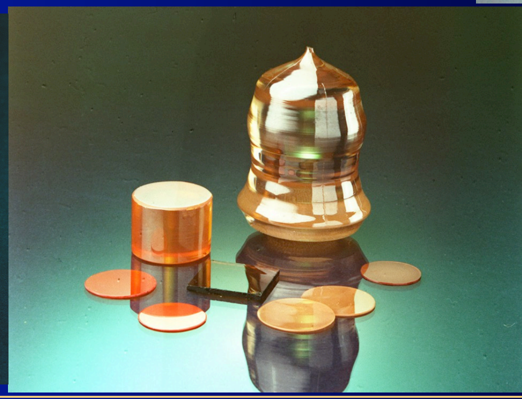
Natural

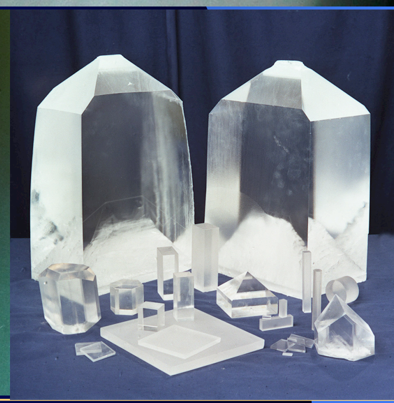
Lead Tungstate

Synthetic



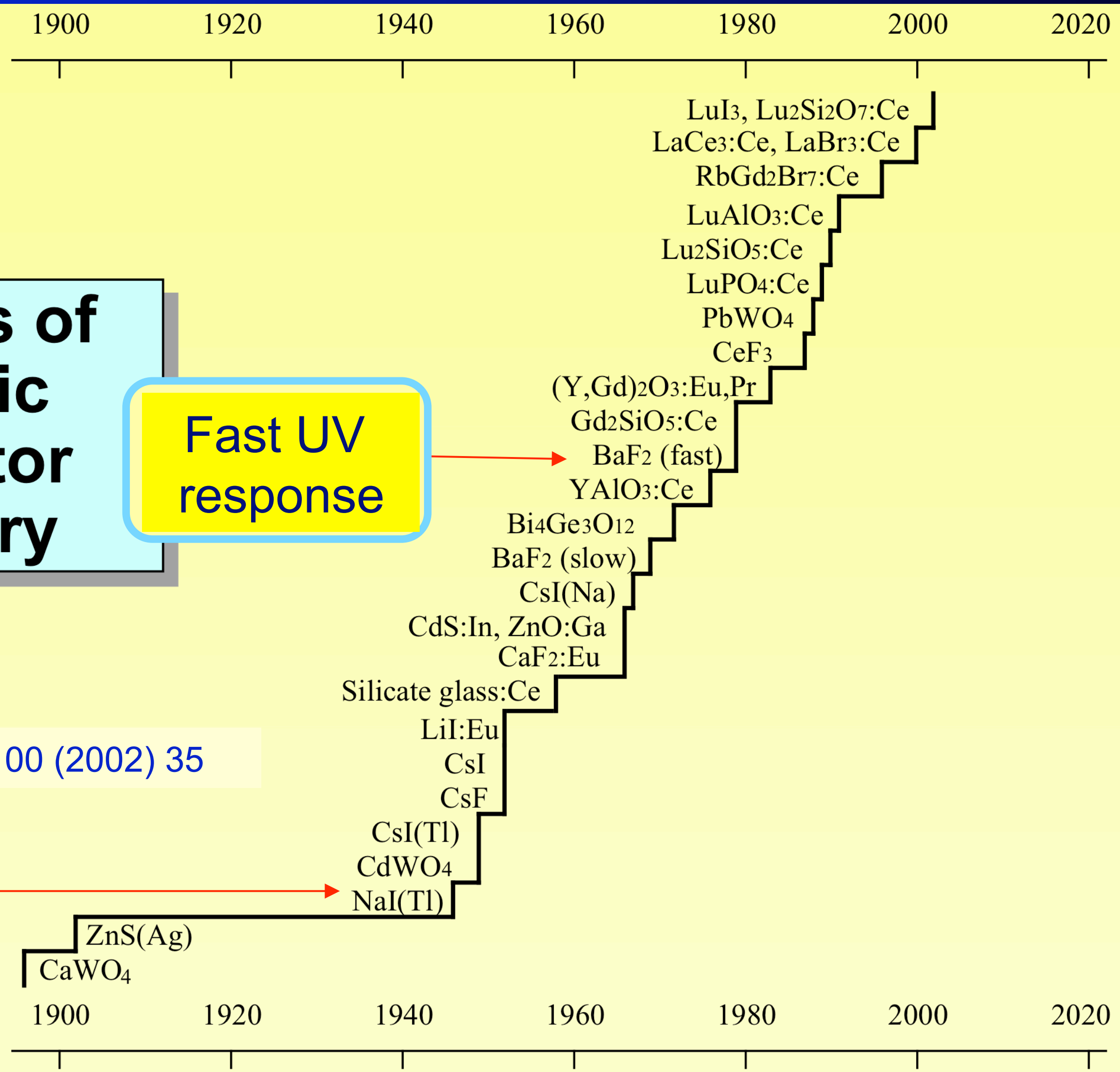






History of scintillator discovery

105 Years of Inorganic Scintillator Discovery

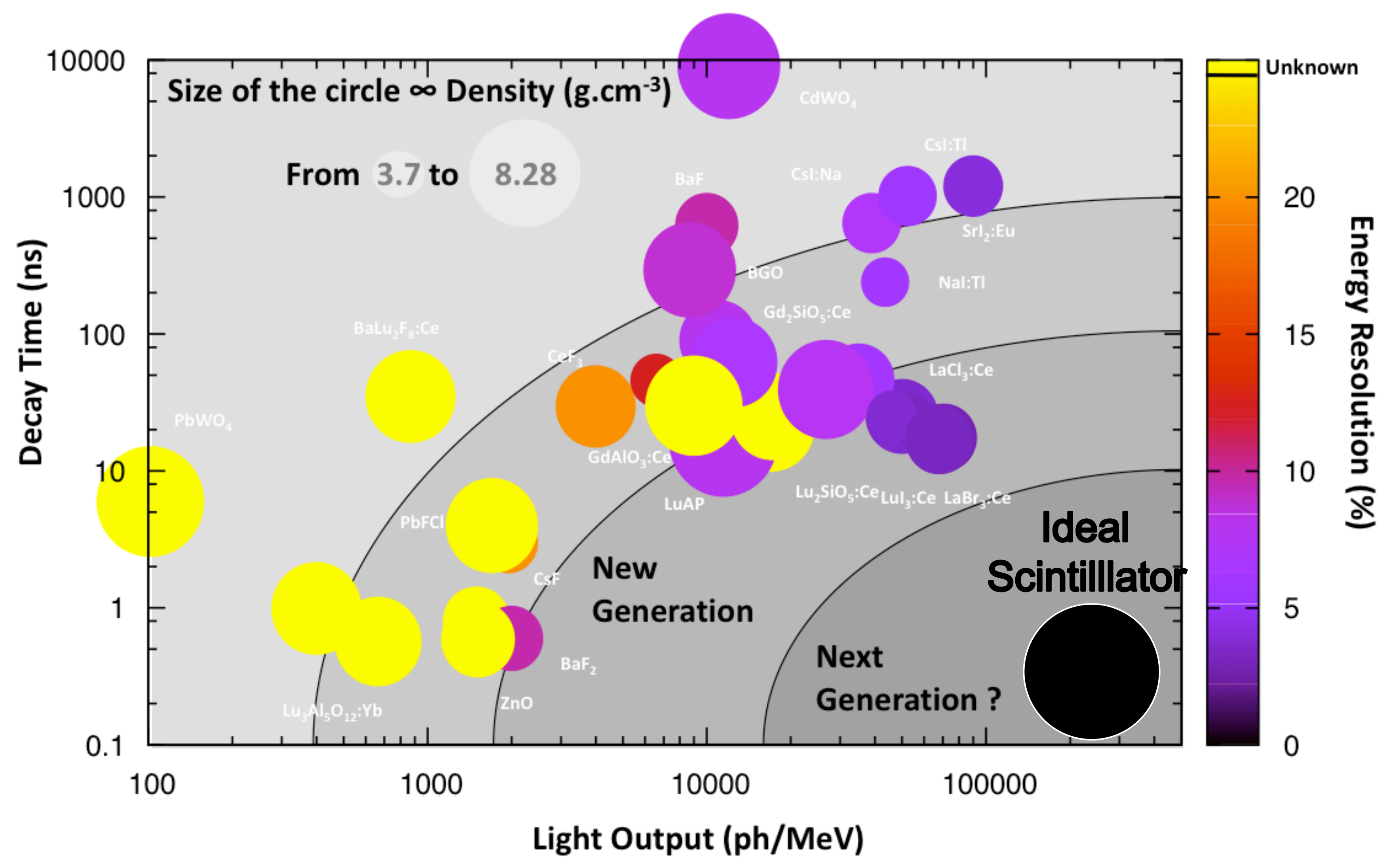


Fast UV response

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

Invention of the photomultiplier tube

Classification of scintillators

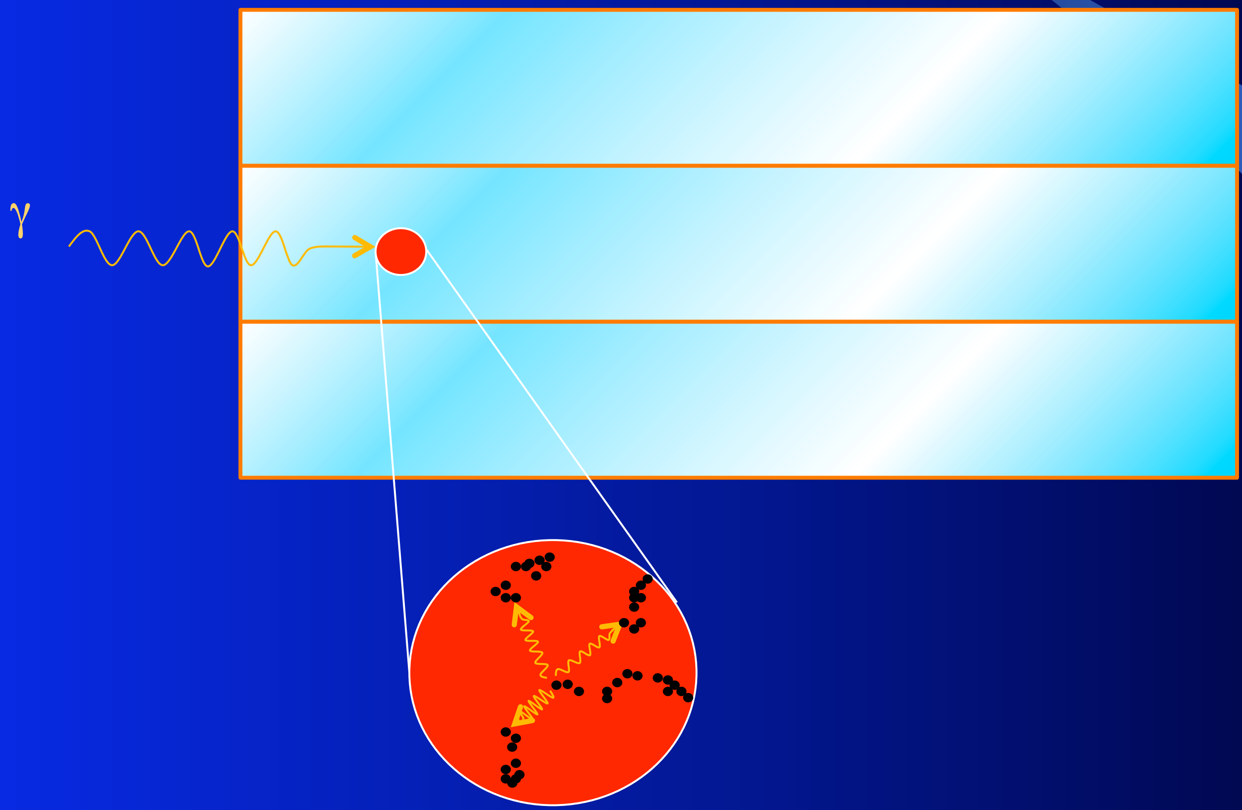


A zoom on the conversion process (HEP)

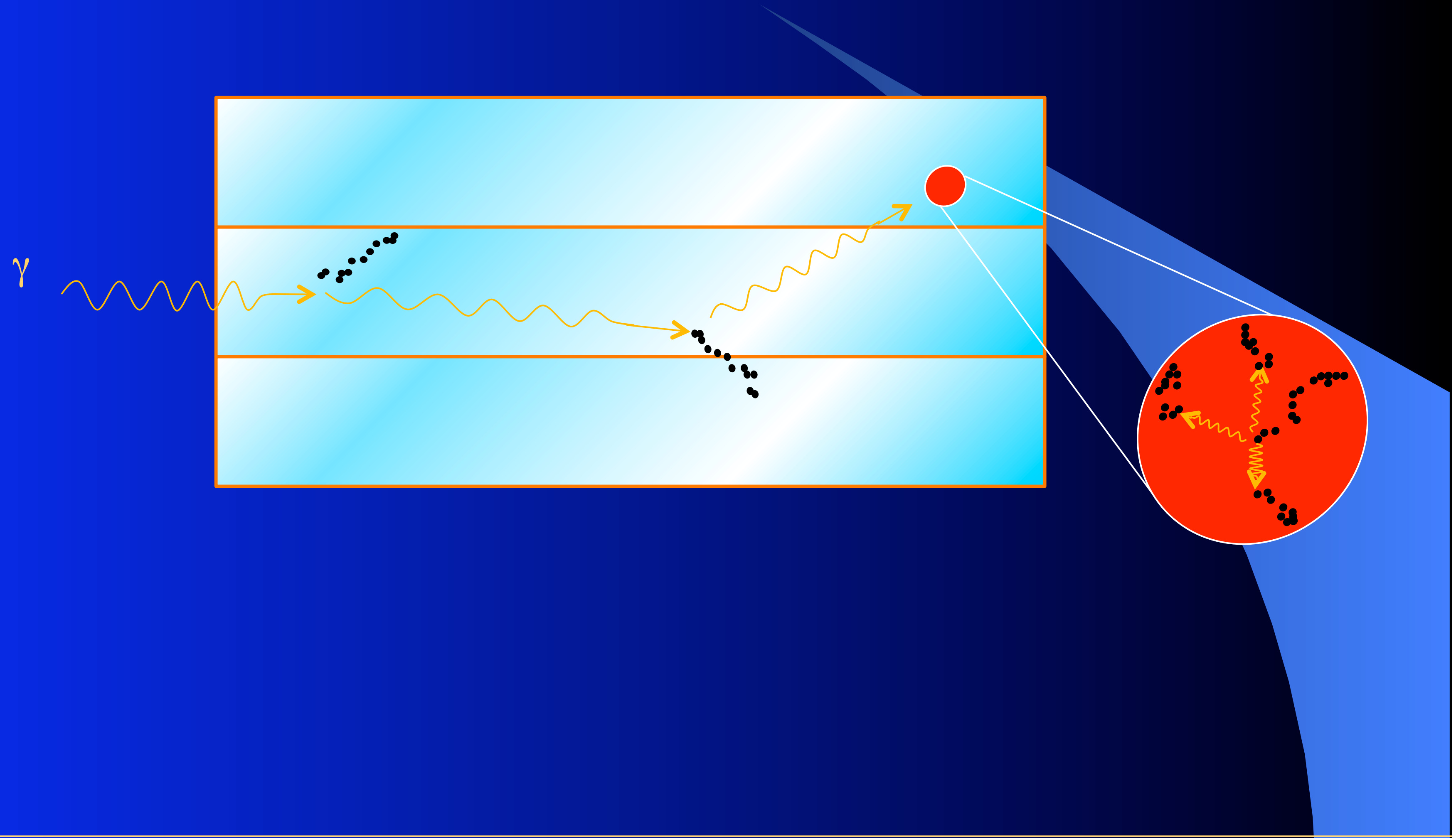
- The energy conversion from incoming X or γ Rays is a complex process resulting from a cascade of events.

- 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)

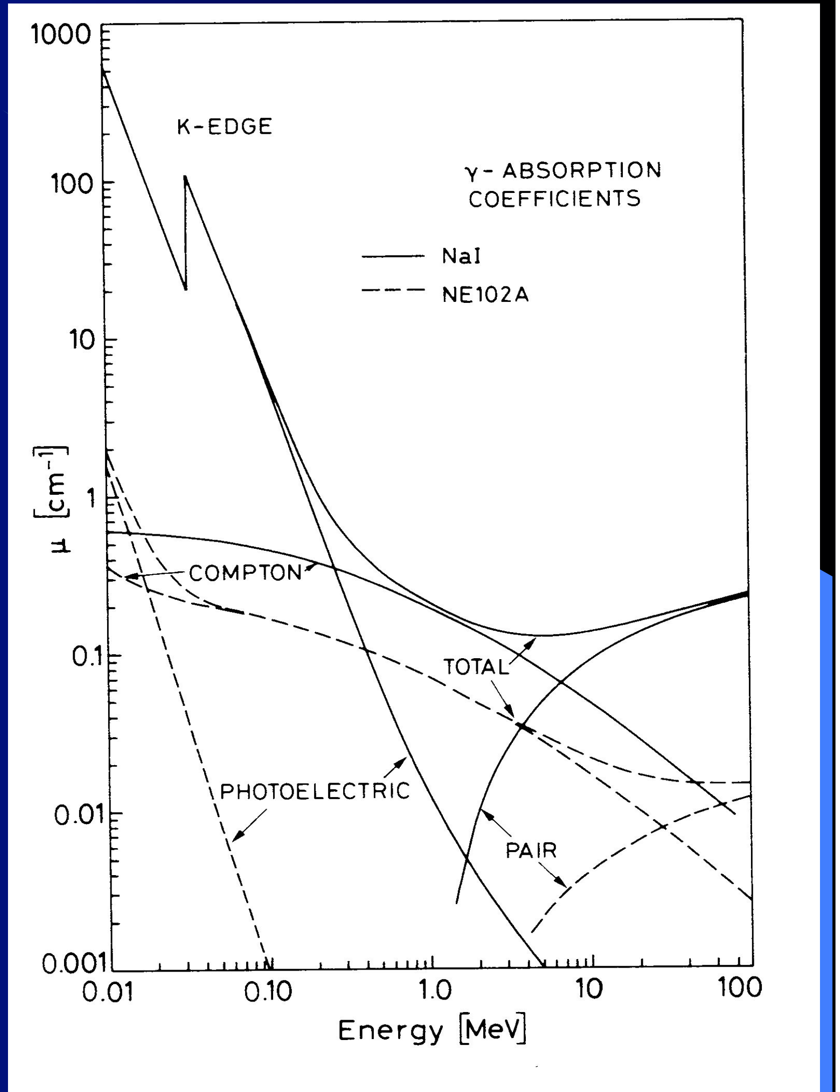


A zoom on the conversion process (low energy)

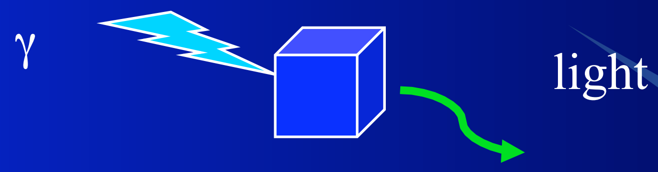


How to choose a scintillator

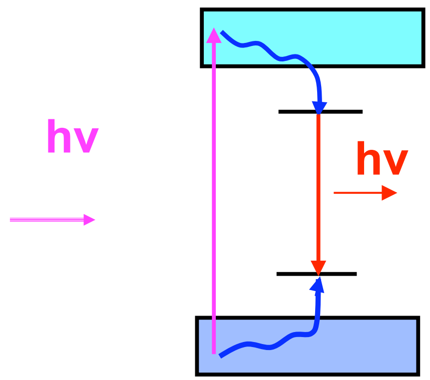
- For charged particles: high ρ materials to increase dE/dx
- For X and γ-rays (but also high energy electrons, which radiate γ-rays by bremstrahlung)
  3 mechanisms:
  - Photoelectric: $\sigma_{ph} \propto \frac{Z^5}{E_\gamma^{7/2}}$
  - Compton: $\sigma_c \propto Z$
  - Pair poduction: $\sigma_{pair} \propto Z^2 \ln(2E_\gamma)$
- 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: $R_M \approx X_0 \frac{Z+1.2}{37.74} \propto 1/\rho$



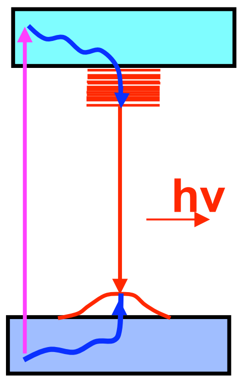
Fundamental aspects of Scintillation



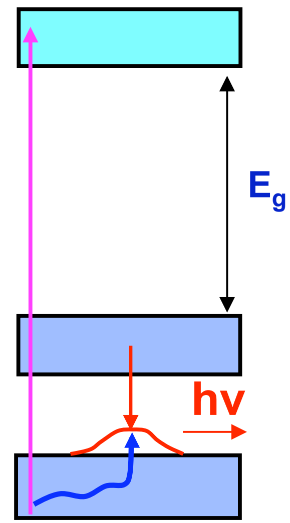
Different scintillation mechanisms



A – Doped ion, or intrinsic defect

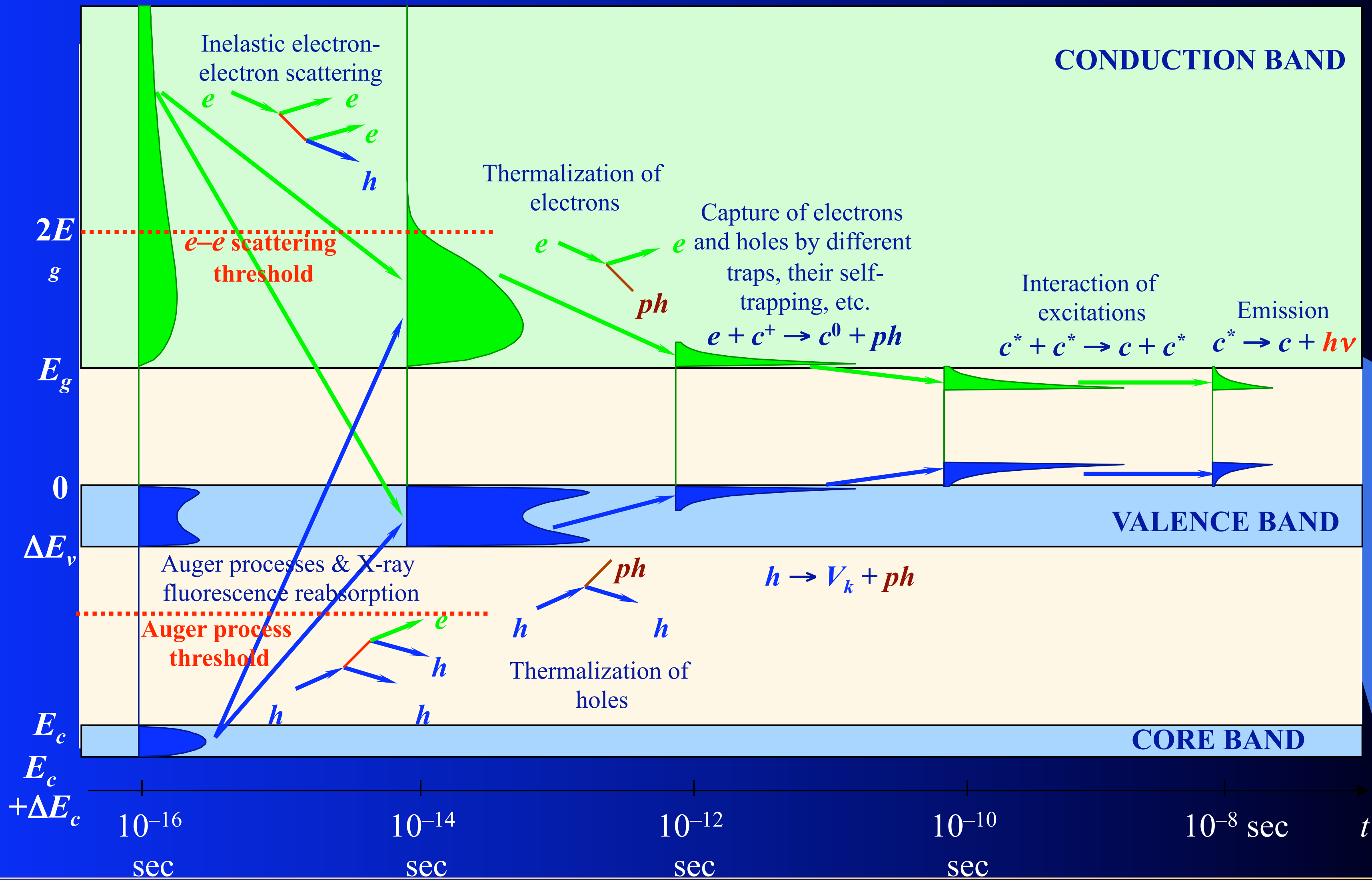


B – Self- trapped exciton

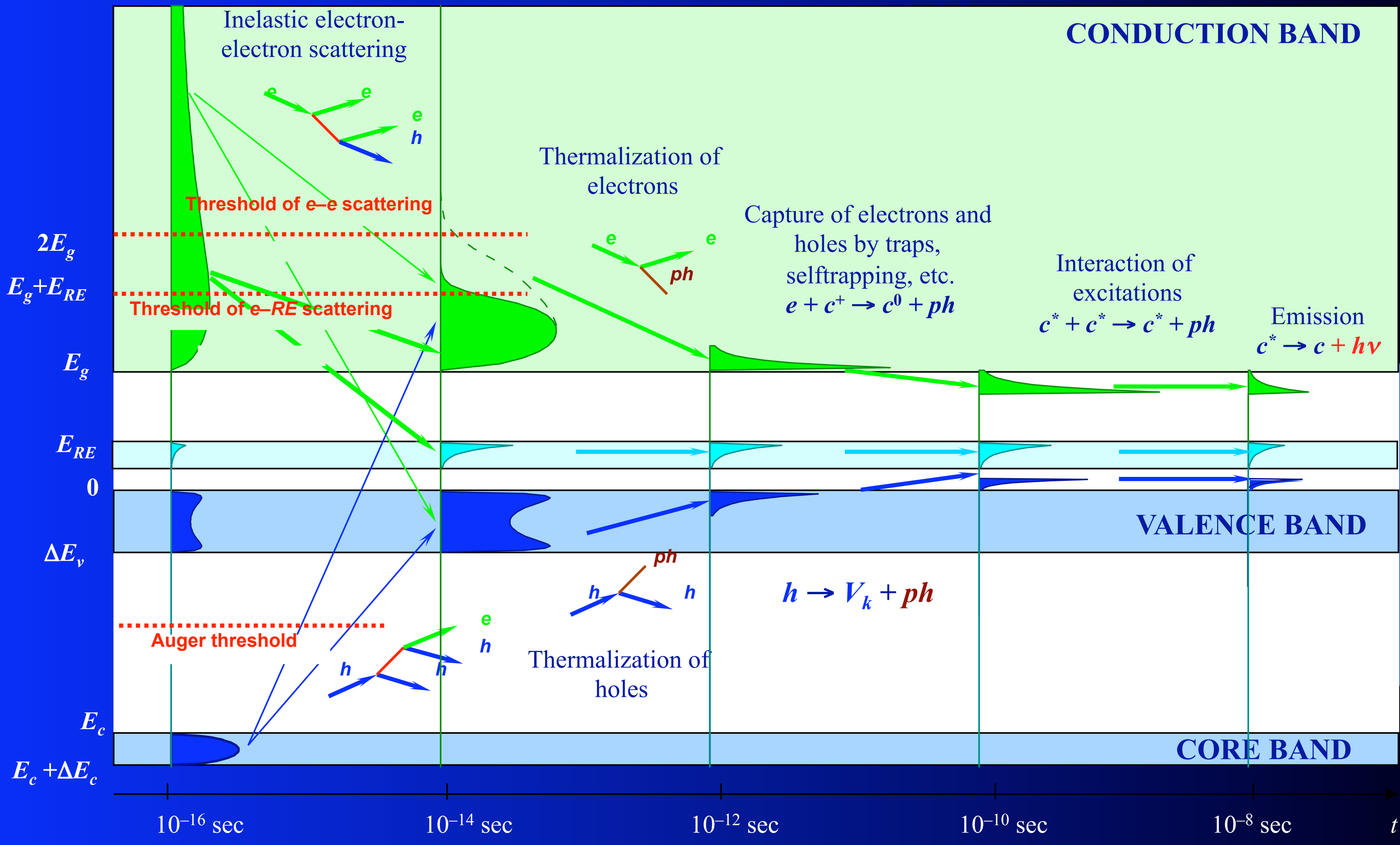


C – Crossluminescence

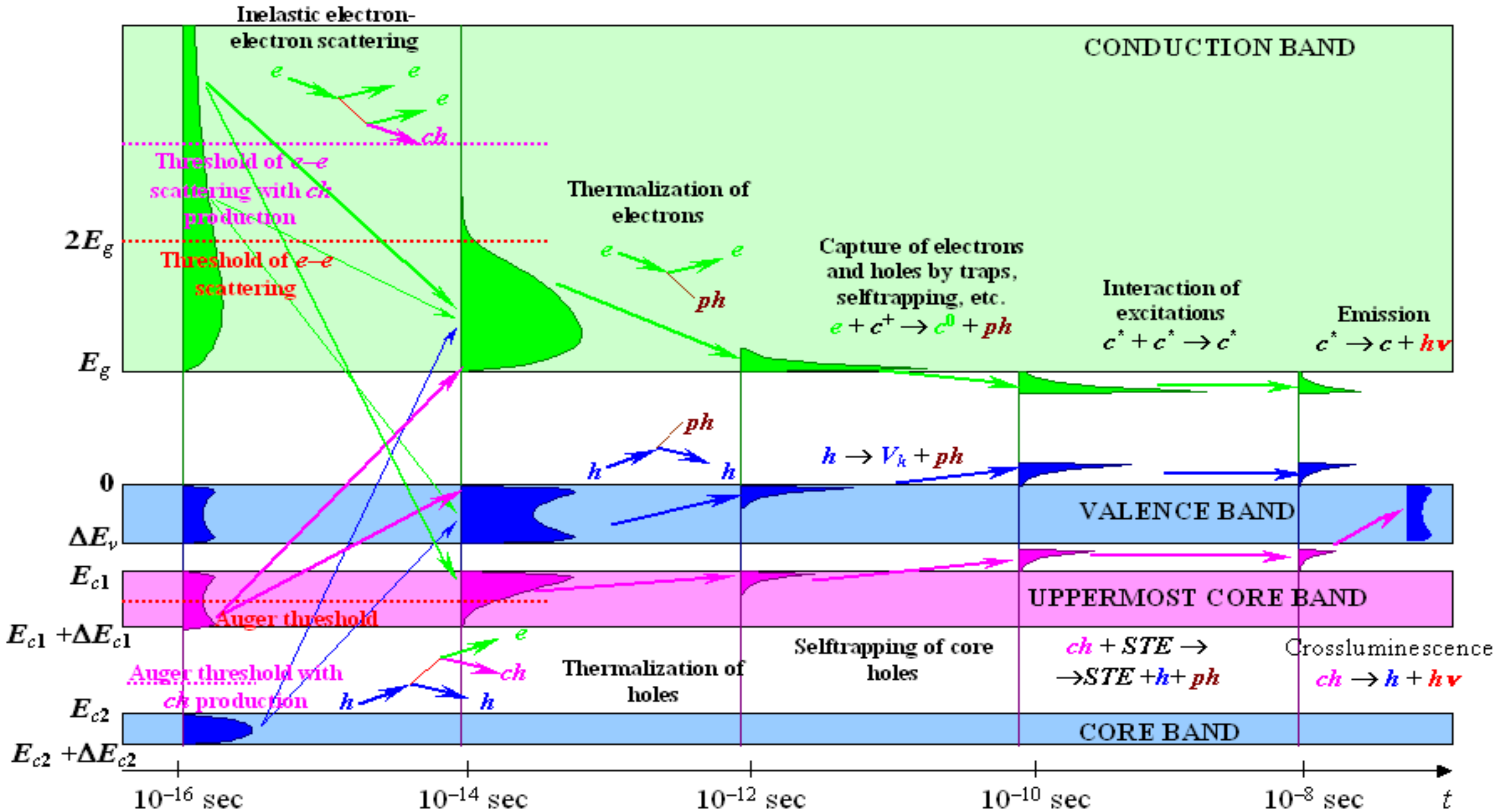
Relaxation of electronic excitations *intrinsic luminescence*



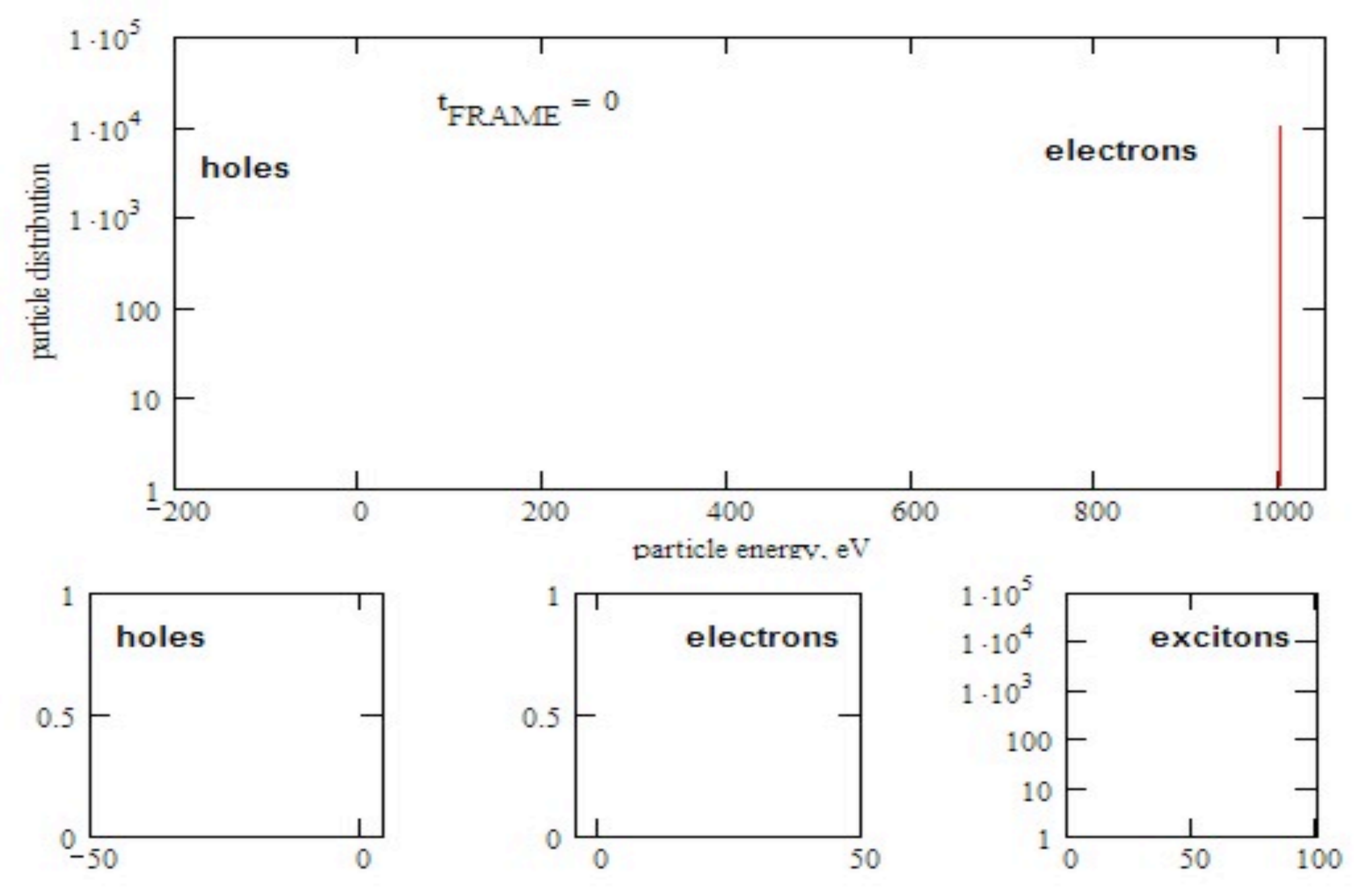
Relaxation of electronic excitations *extrinsic luminescence*



Relaxation of electronic excitations
Cross-luminescence



Evolution of energy distribution for 1000 eV electrons



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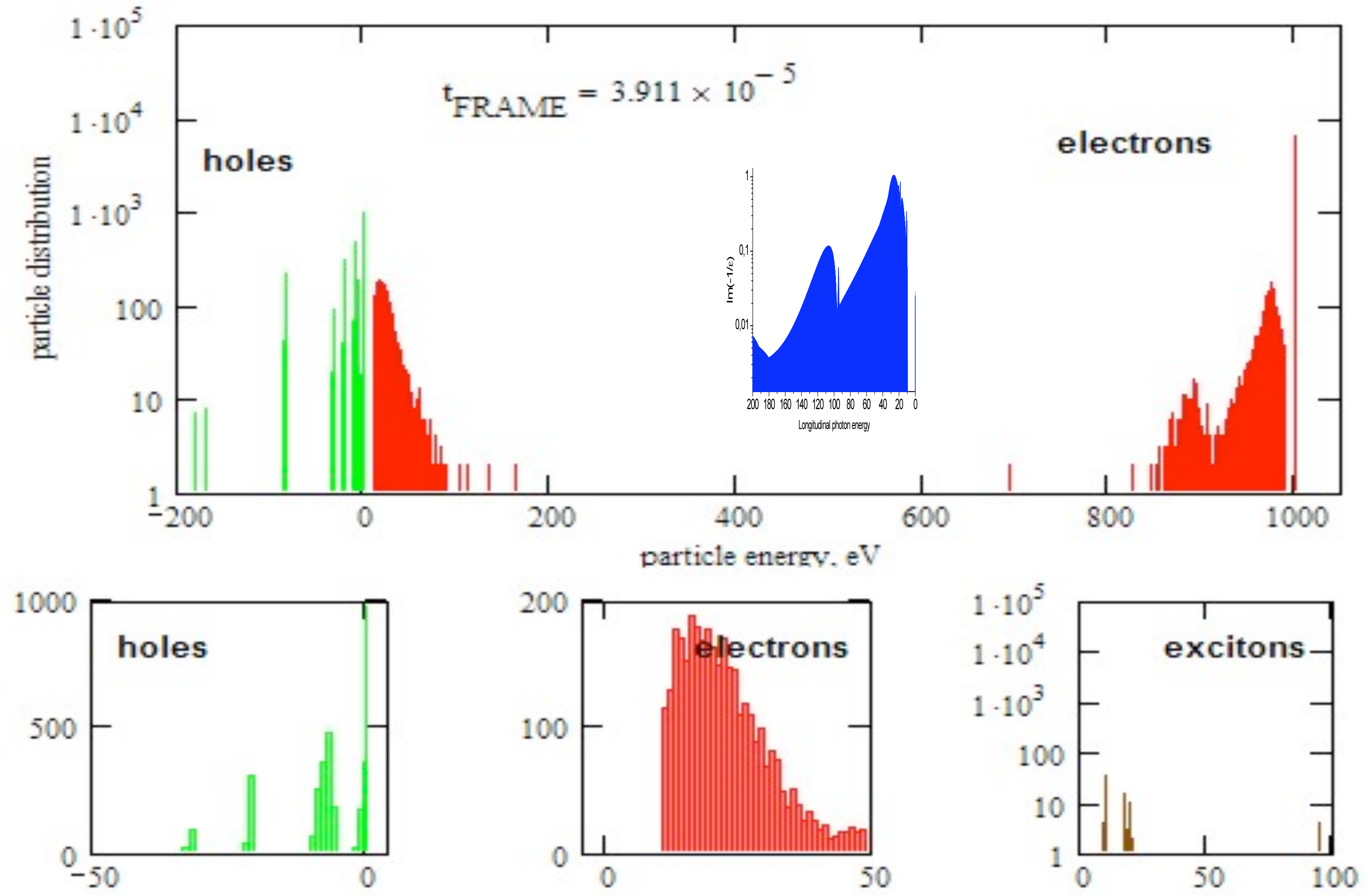

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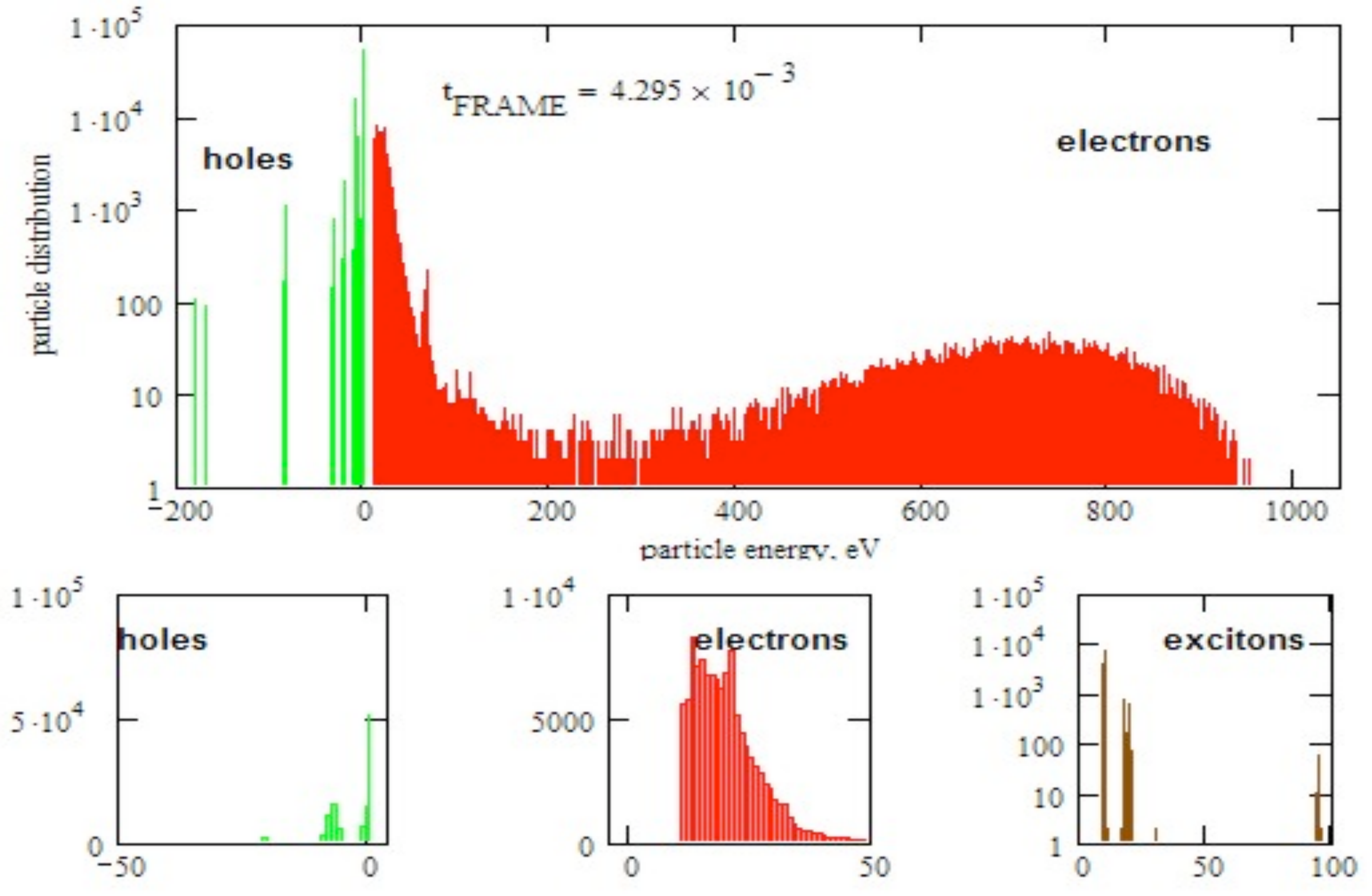

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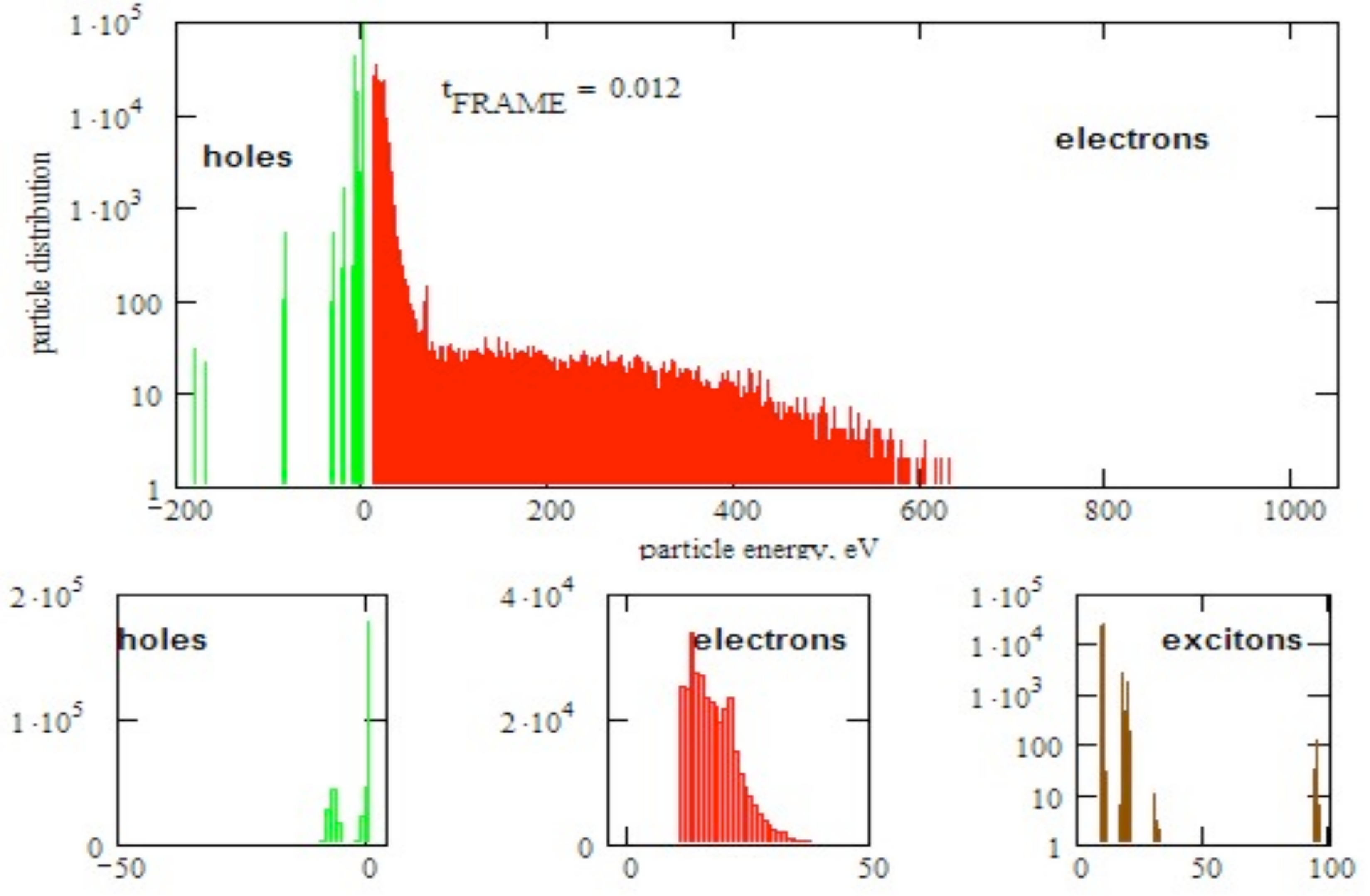
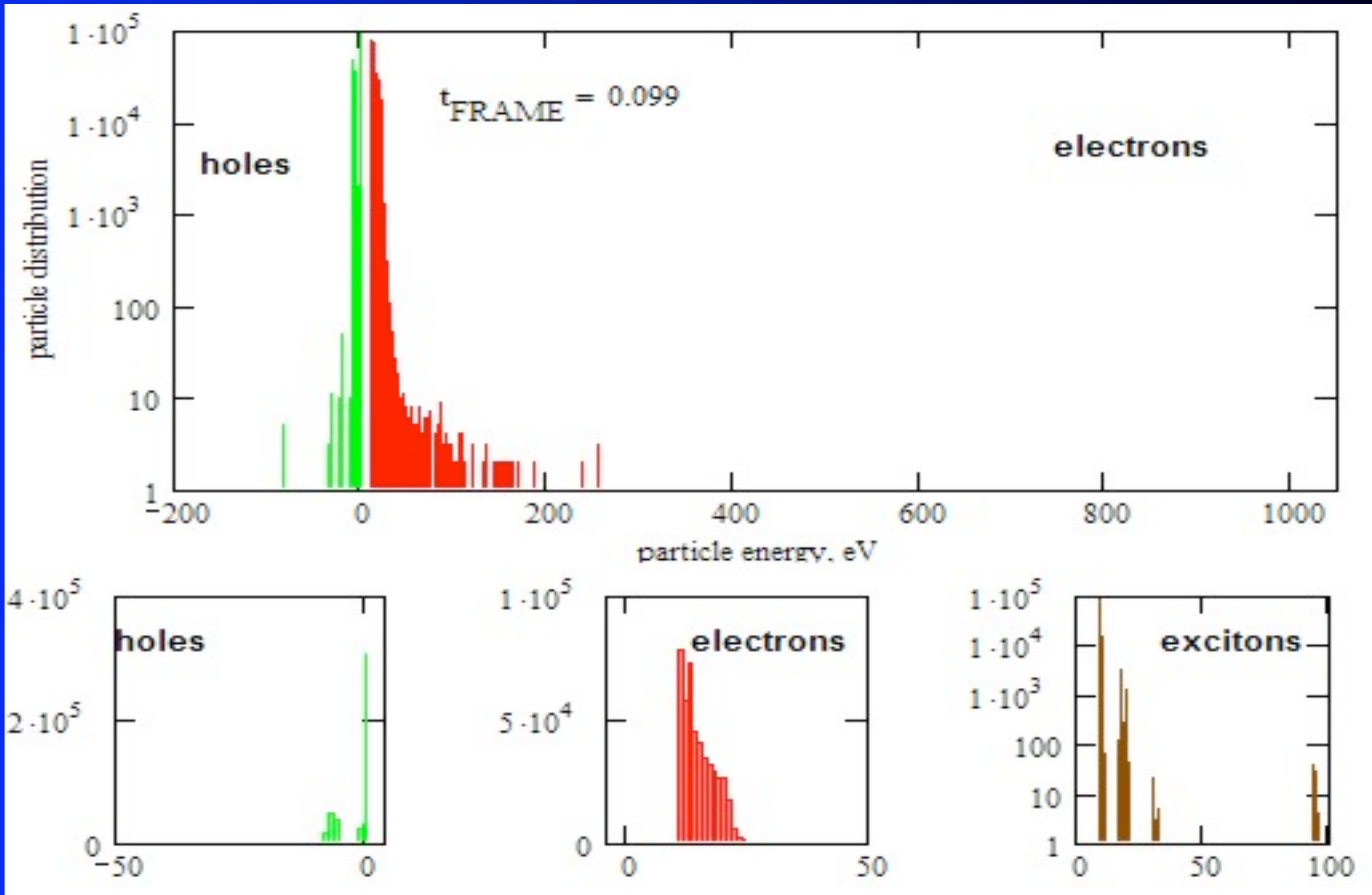
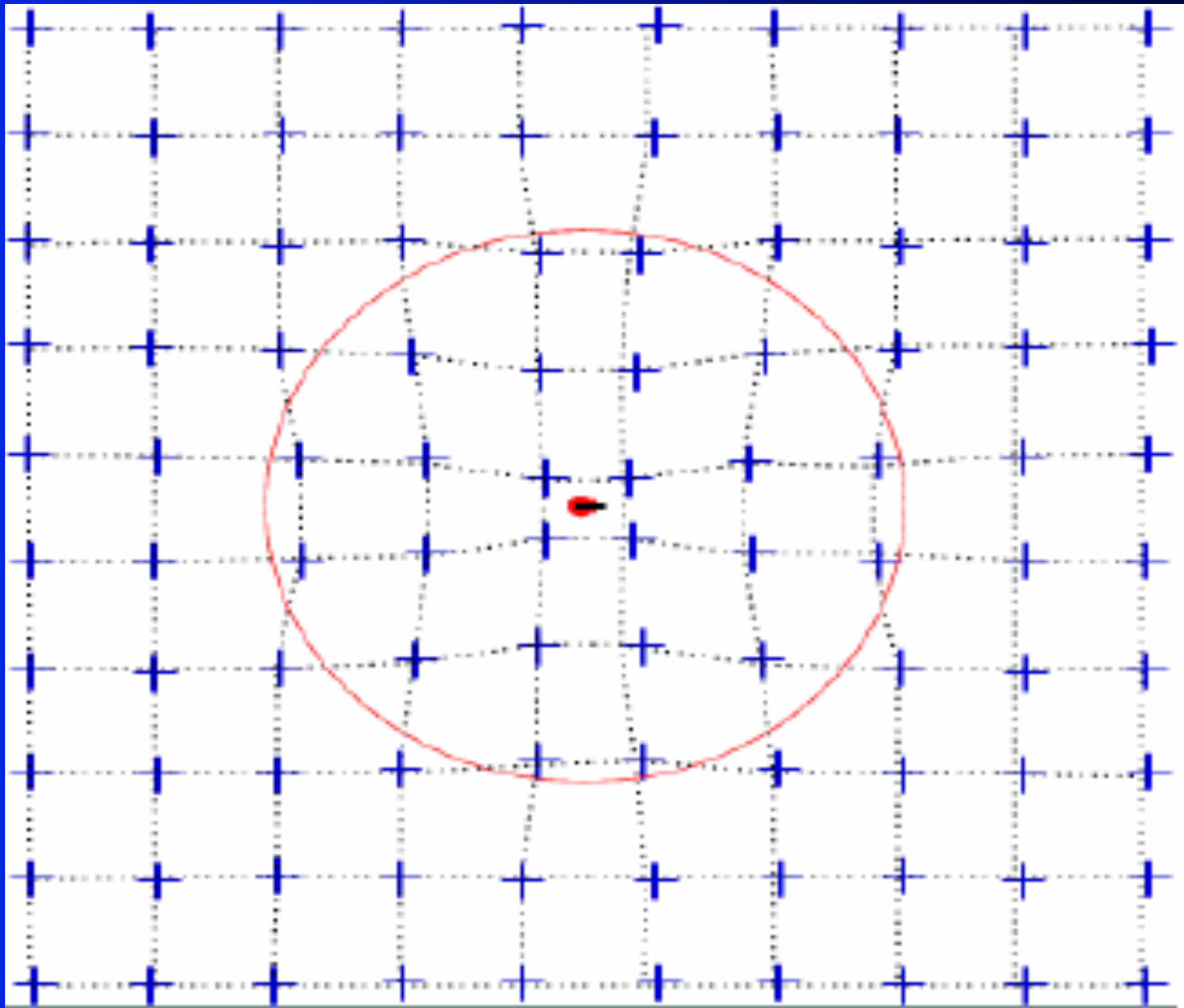


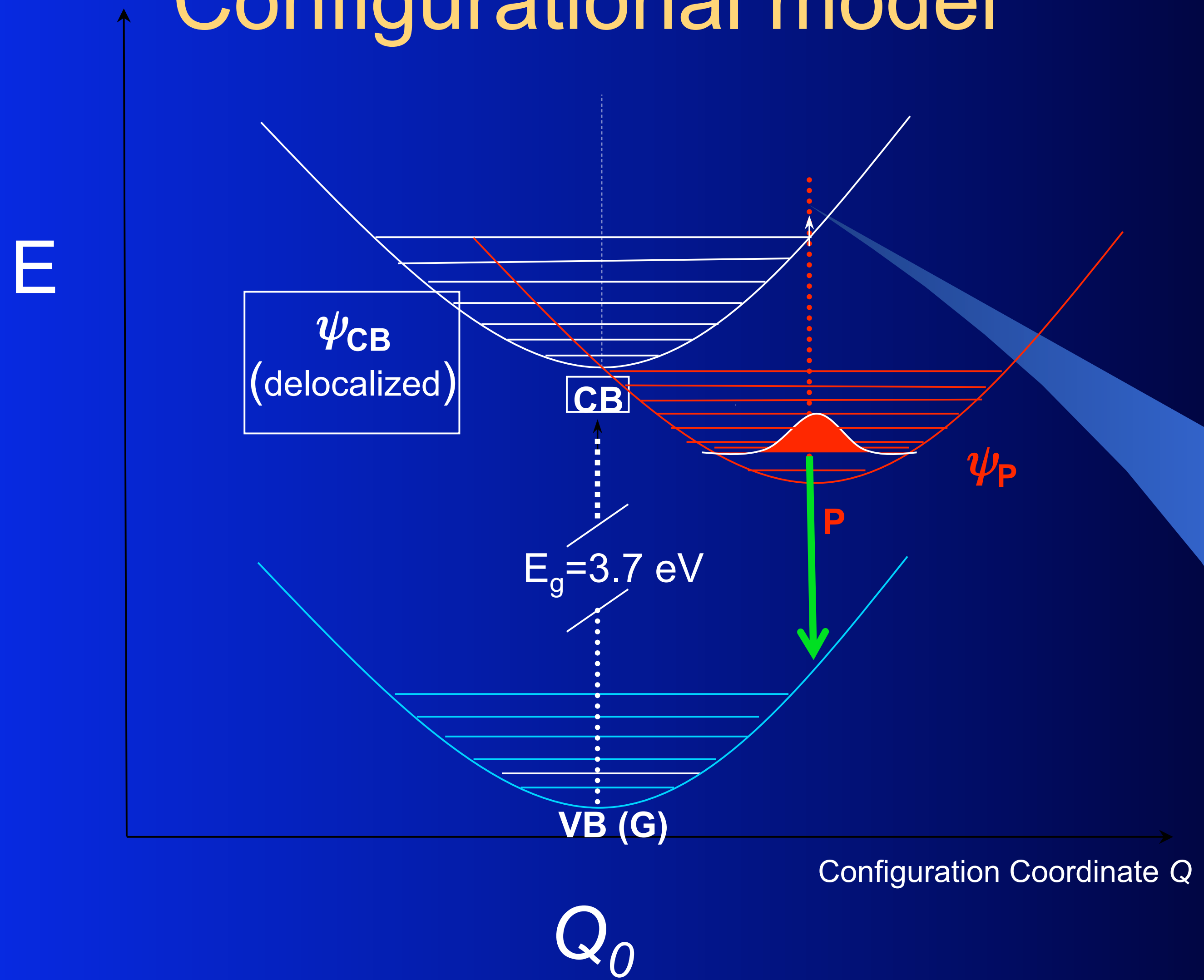
Evolution of energy distribution for 1000 eV electrons





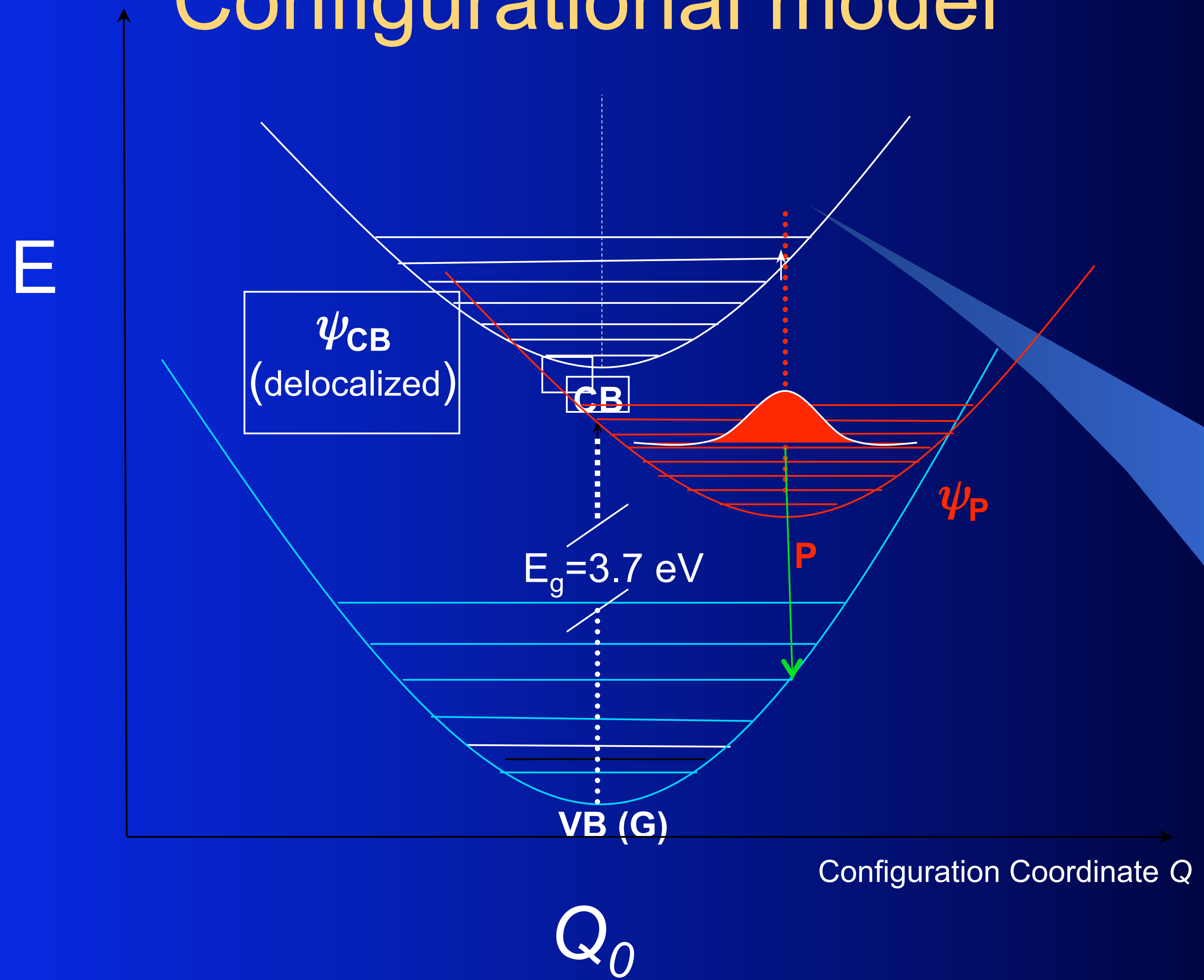
polaron - electron+ distorted lattice

Configurational model



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

Configurational model



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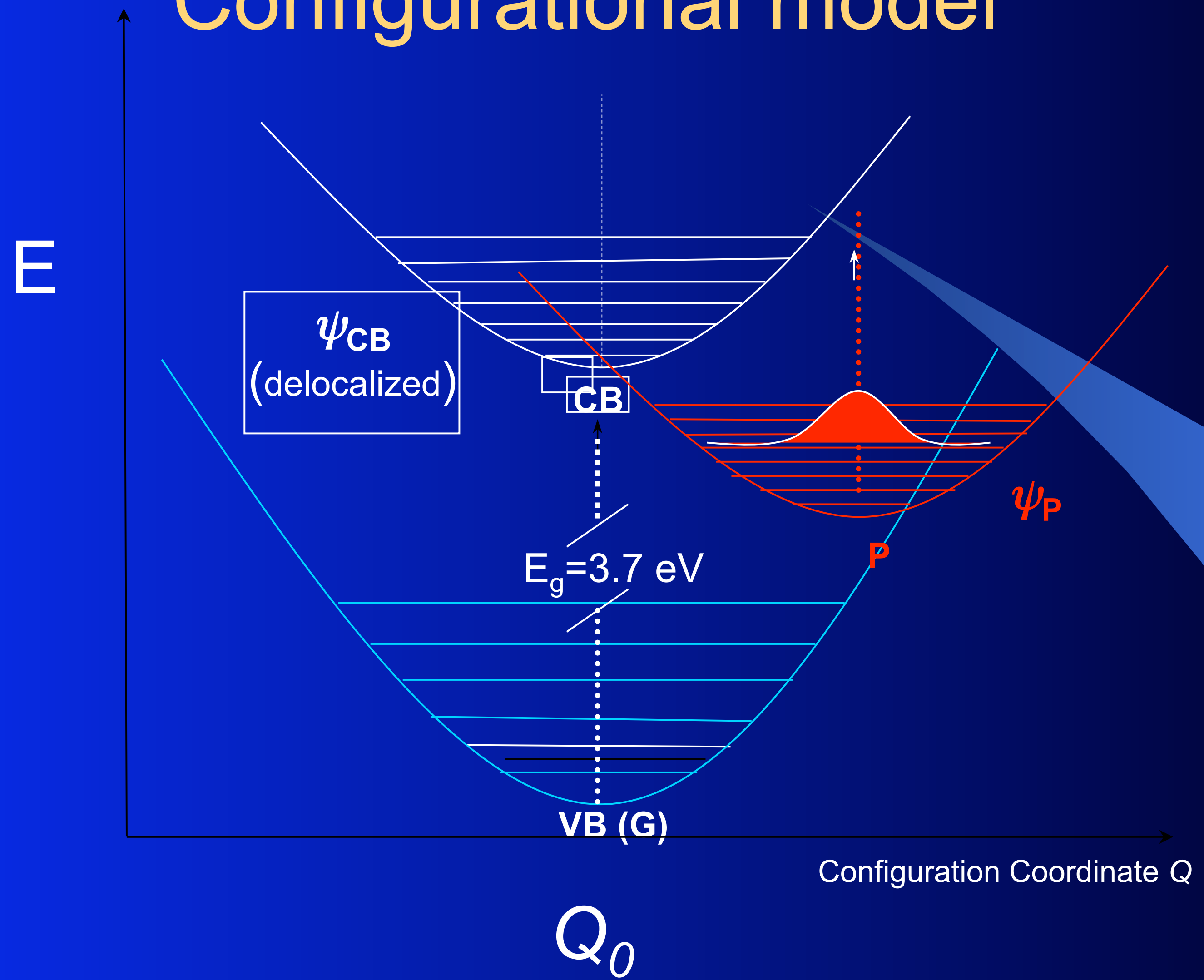
Configurational model



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

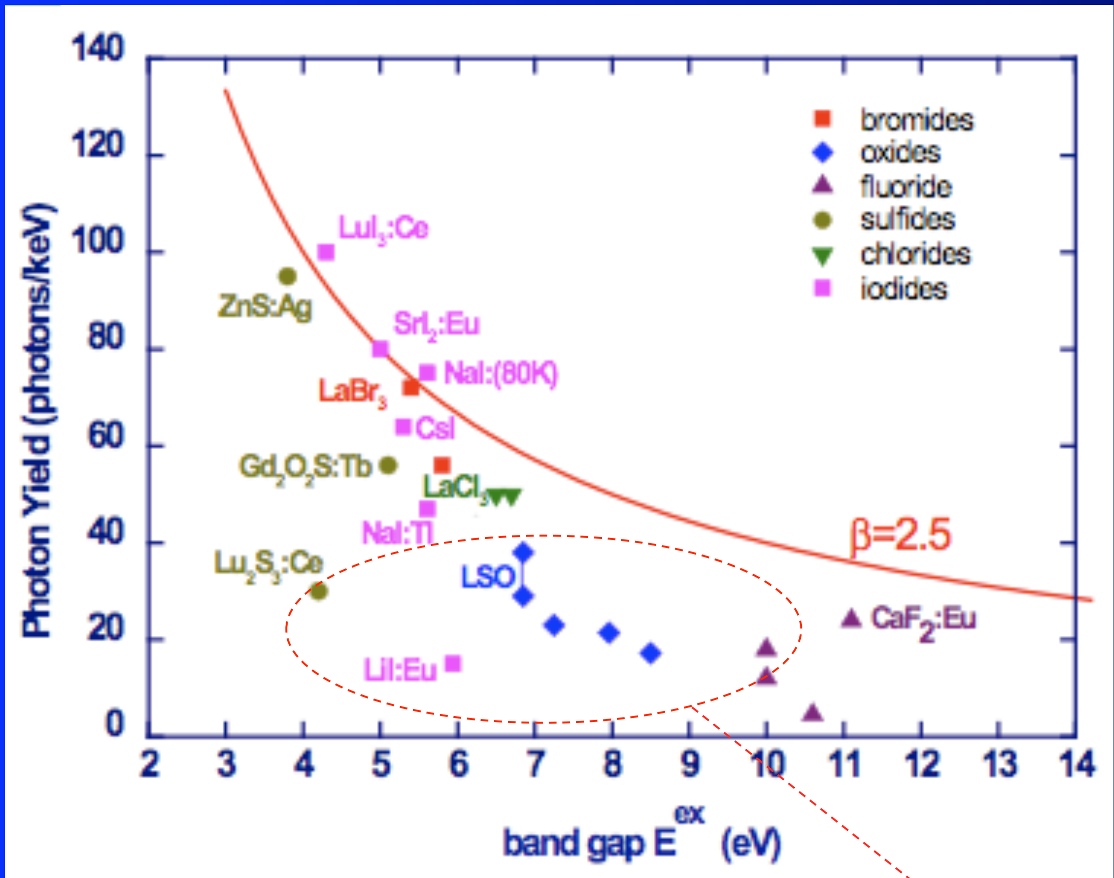
$$n_{photon} = n_{eh} Sq = \frac{E_\gamma}{\beta E_g} Sq$$

Determination of the maximum of light

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

Usually β = 2 to 4

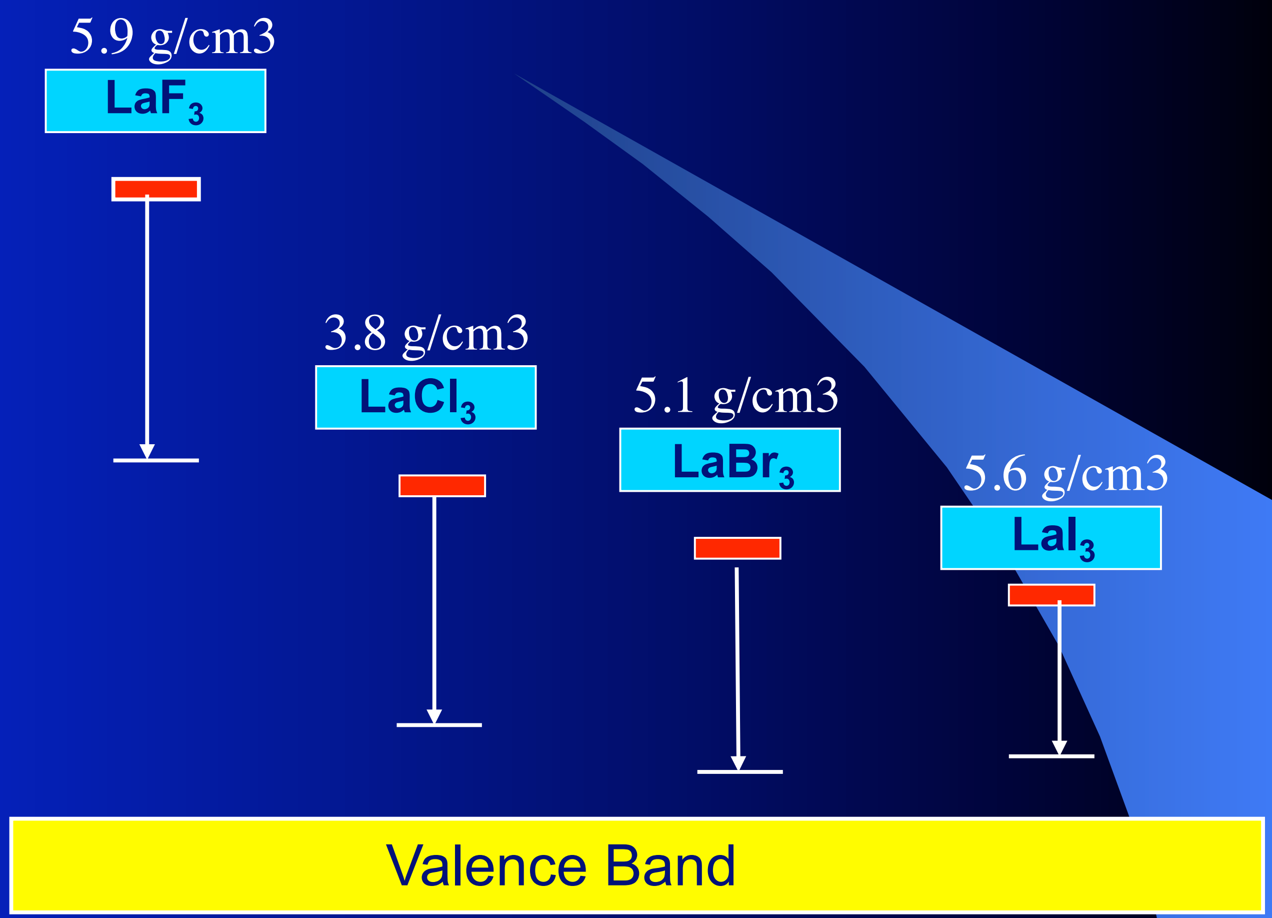
Fundamental limits to the LY



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

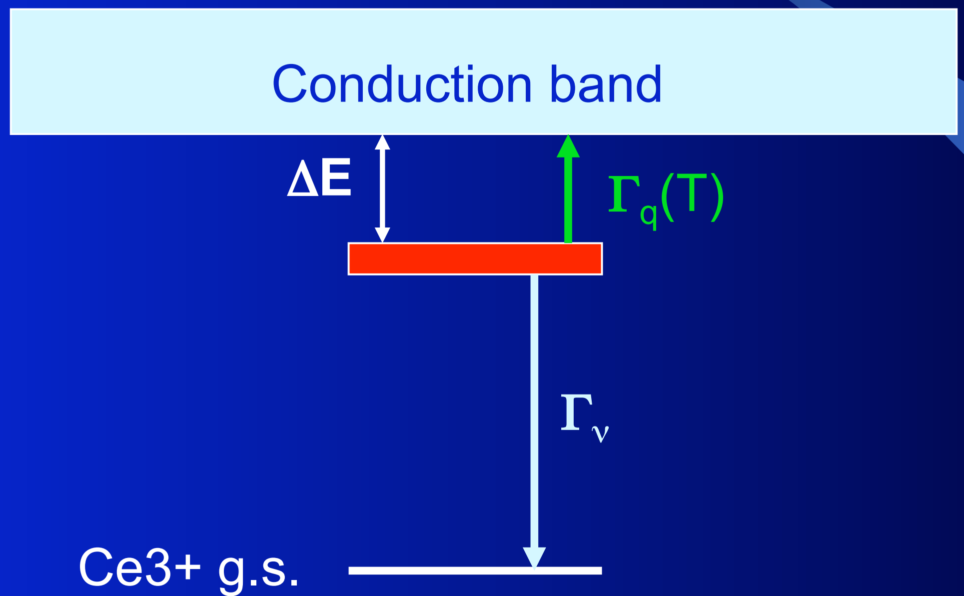
Why?

Towards smaller band gap compounds



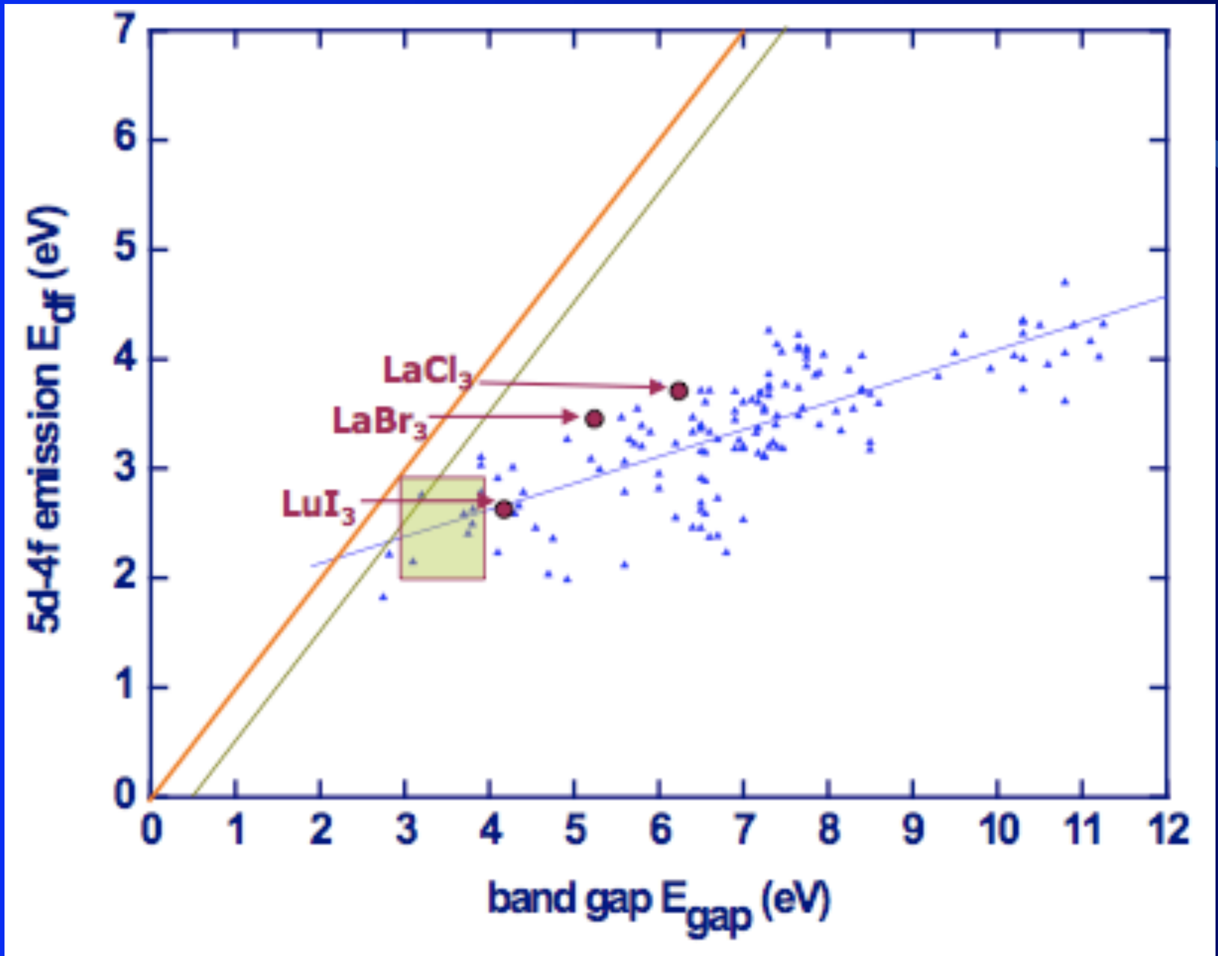
Light yield (10^3 ph/MeV)	2	53	73	0

Luminescence quenching in LaI_3:Ce



Absolute location of doping levels is crucial

The host lattice must be transparent to the Ce^{3+} emission



Ultimate Ce^{3+} Scintillator

E_{gap}>2.5-3 eV

Y_{ph}≤140000/MeV

λ_{em} ≈ 600 nm

Best result LuI_3: Ce^{3+}

E_{gap} = 4.2eV

Y_{ph}=100000/MeV

λ_{em} ≈ 470 nm

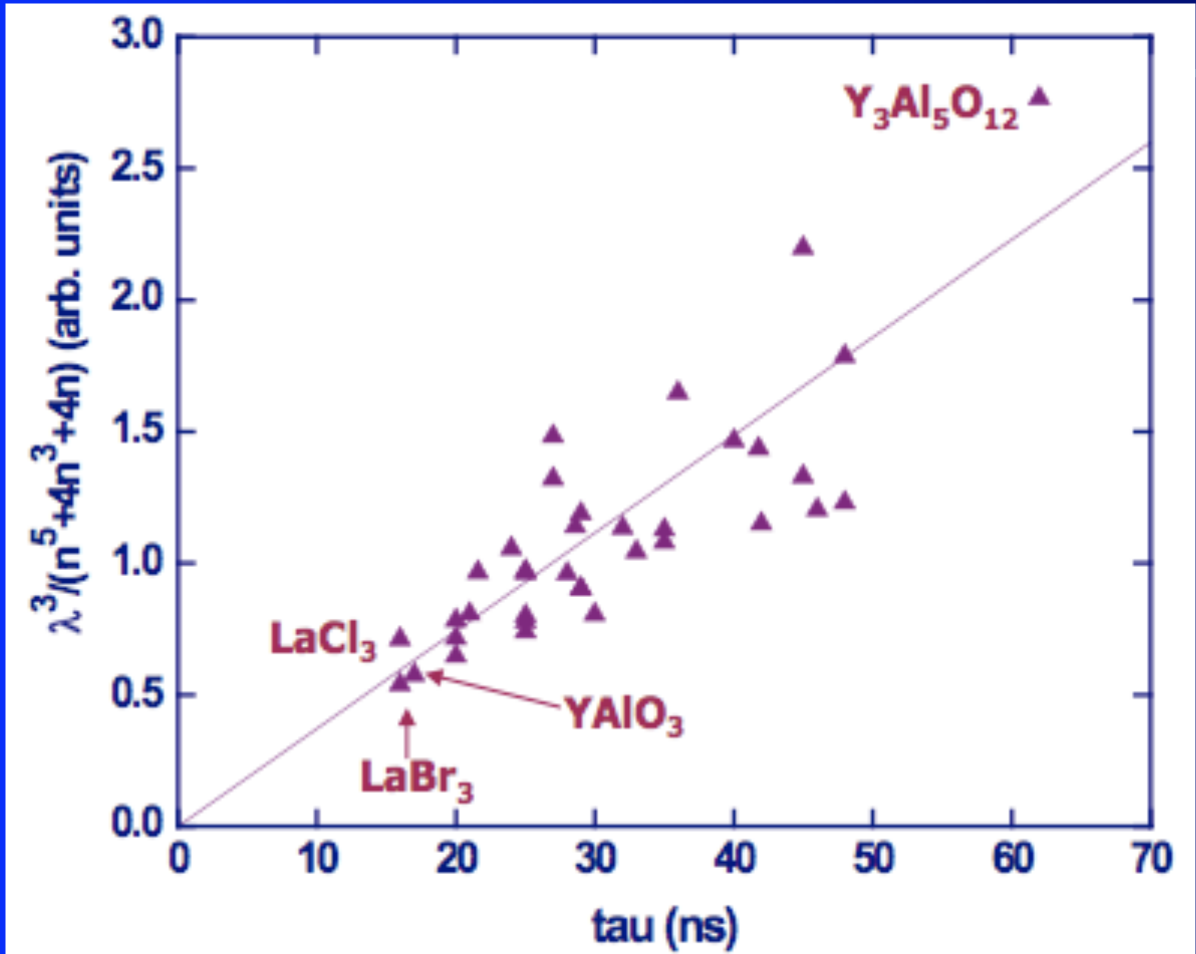
Why is Ce^{3+} so popular? Limits on the scintillation speed

$$\Gamma_\nu = \frac{1}{\tau_\nu} \propto \frac{n}{\lambda^3}\left(\frac{n^2+2}{3}\right)^2 \sum_f \left|\langle f|\mu|i\rangle\right|^2$$

Three important aspects

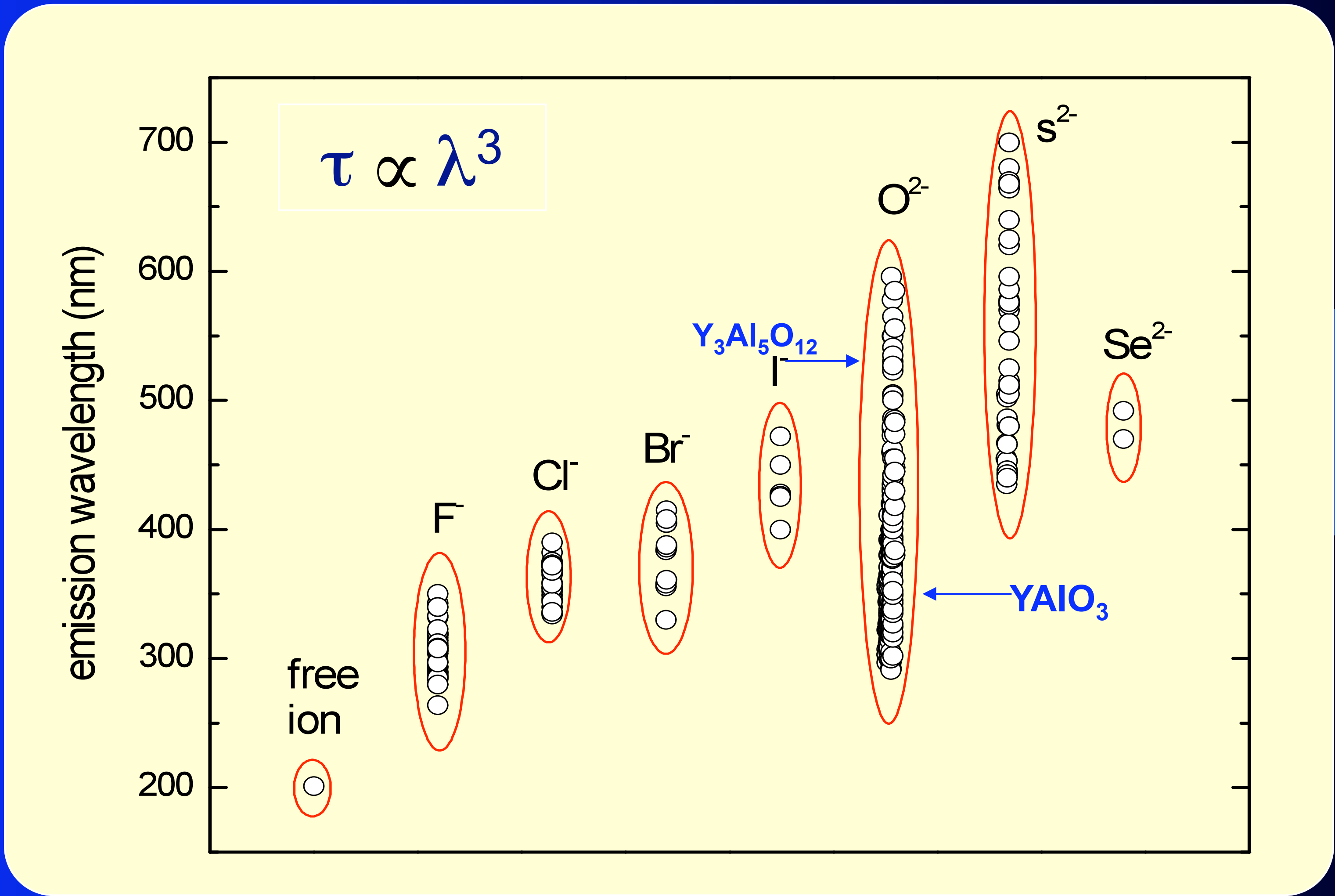
- Dipole and spin allowed transitions
- Short wavelength of emission
- High refractive index

Decay time of Ce^{3+} 5d-4f emission

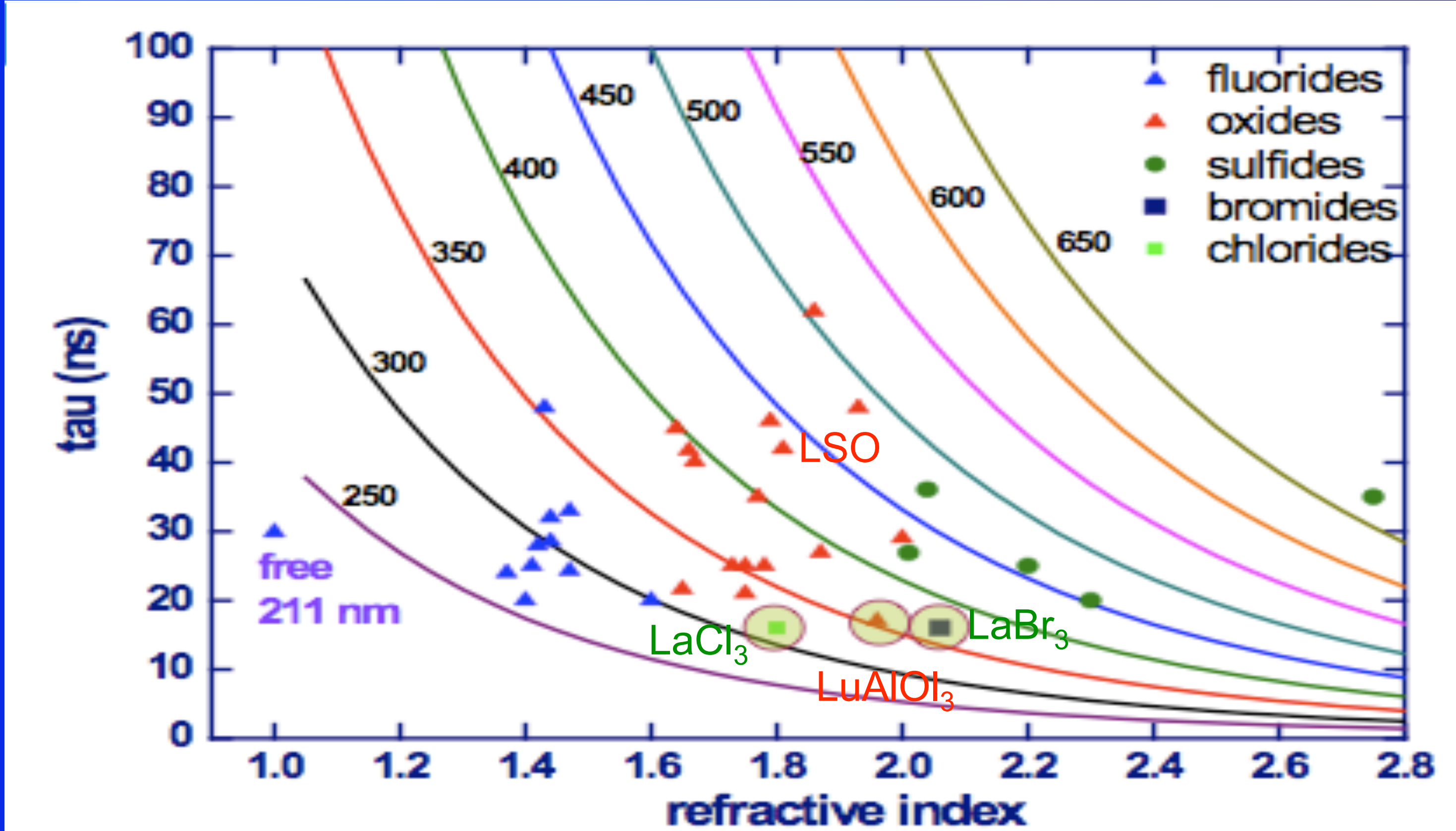


$$\tau \approx A \times \frac{\lambda^3}{n^5 + 4n^3 + 4n}$$

5d-4f emission wavelength of Ce^{3+}



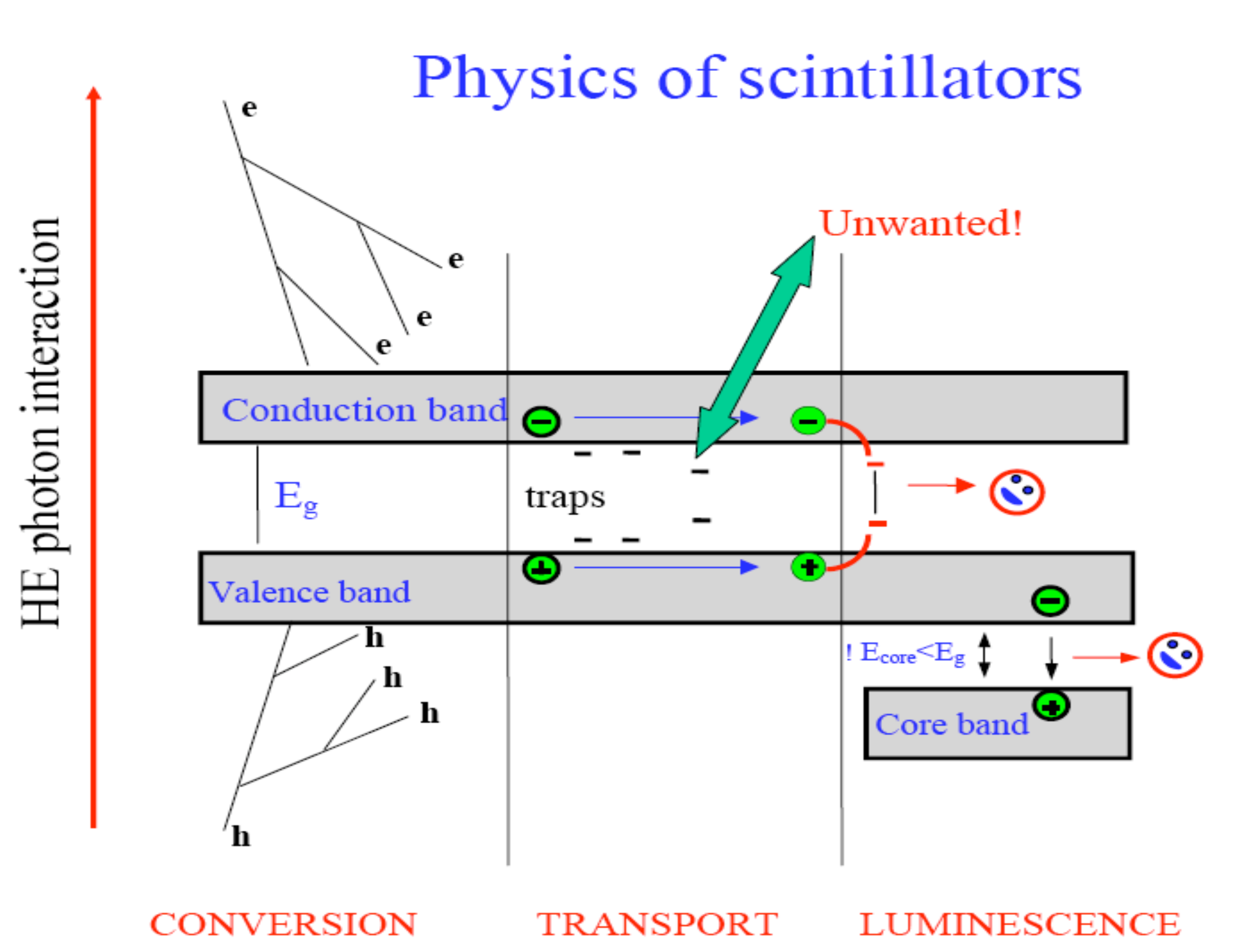
Decay time of Ce^{3+} 5d-4f emission



P. Dorenbos, Presented at SCINT09, Jeju Island, Korea, June 2009

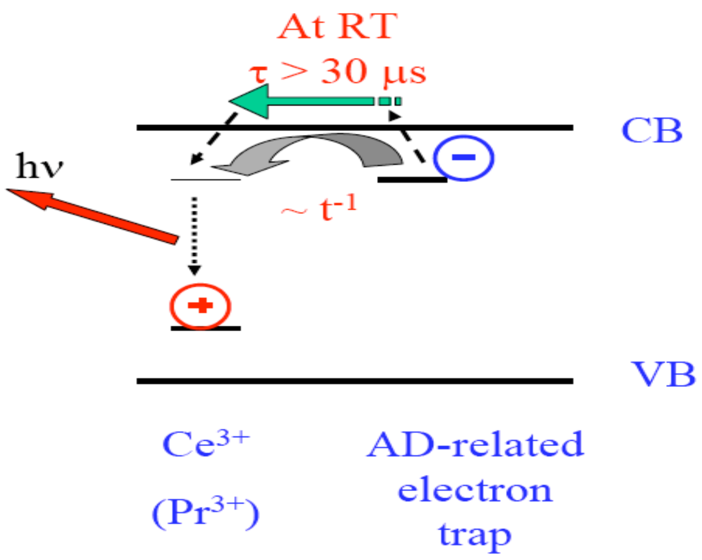
- λ tends to lengthen from F → O → Cl → Br → S 300nm-600nm
- n tends to increase from F → O → Cl → Br → S 1.4 – 2.4
- shortest τ of 17ns for $YAlO_3$, $LuAlO_3$, $LaCl_3$, $LaBr_3$

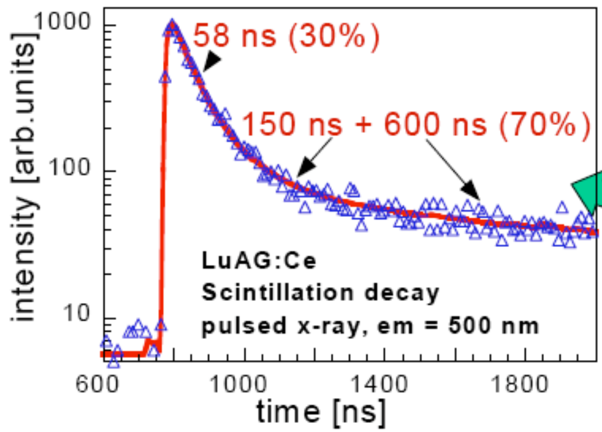
Effect of traps



Effect of traps

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





Light yield (1 μs time gate)

Best YAG:Ce ~ 3x BGO

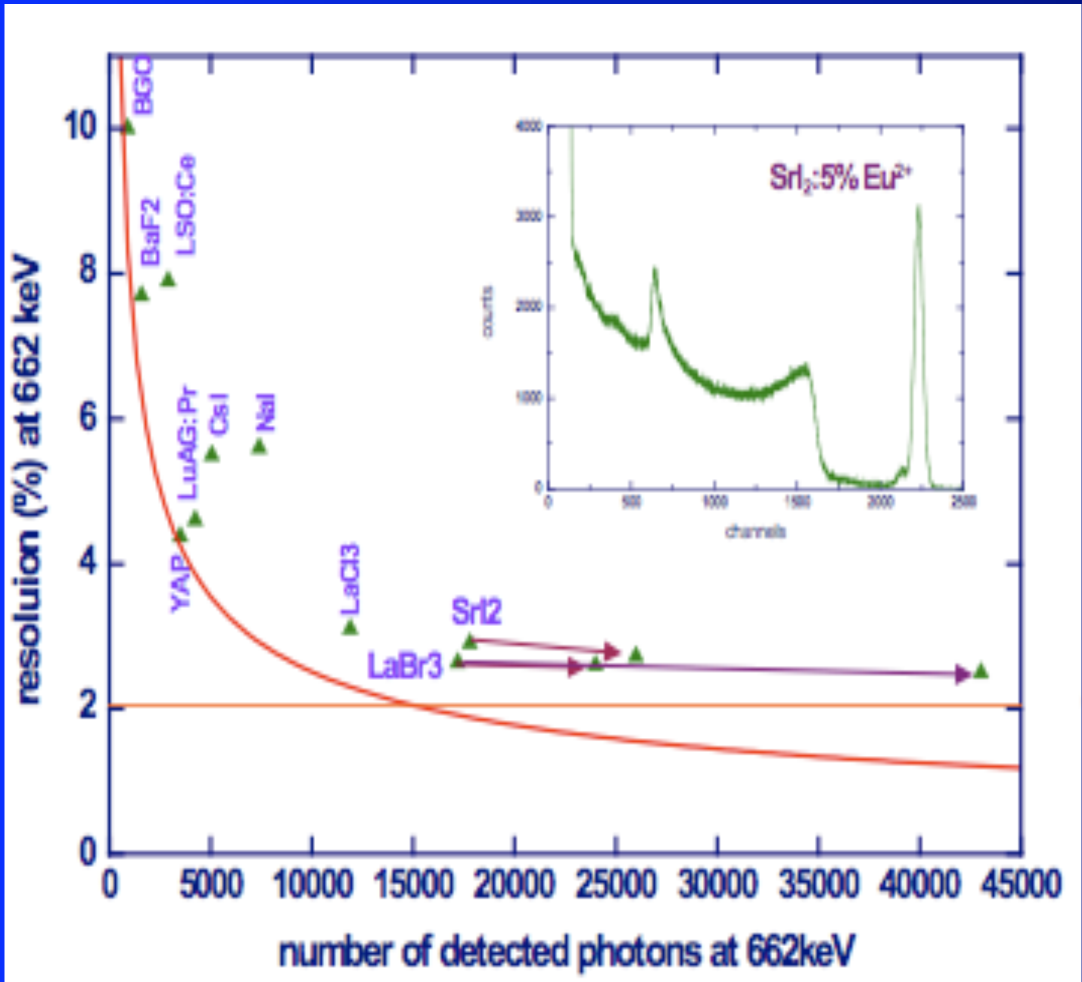
Best LuAG:Ce ~ 60% of YAG:Ce

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)

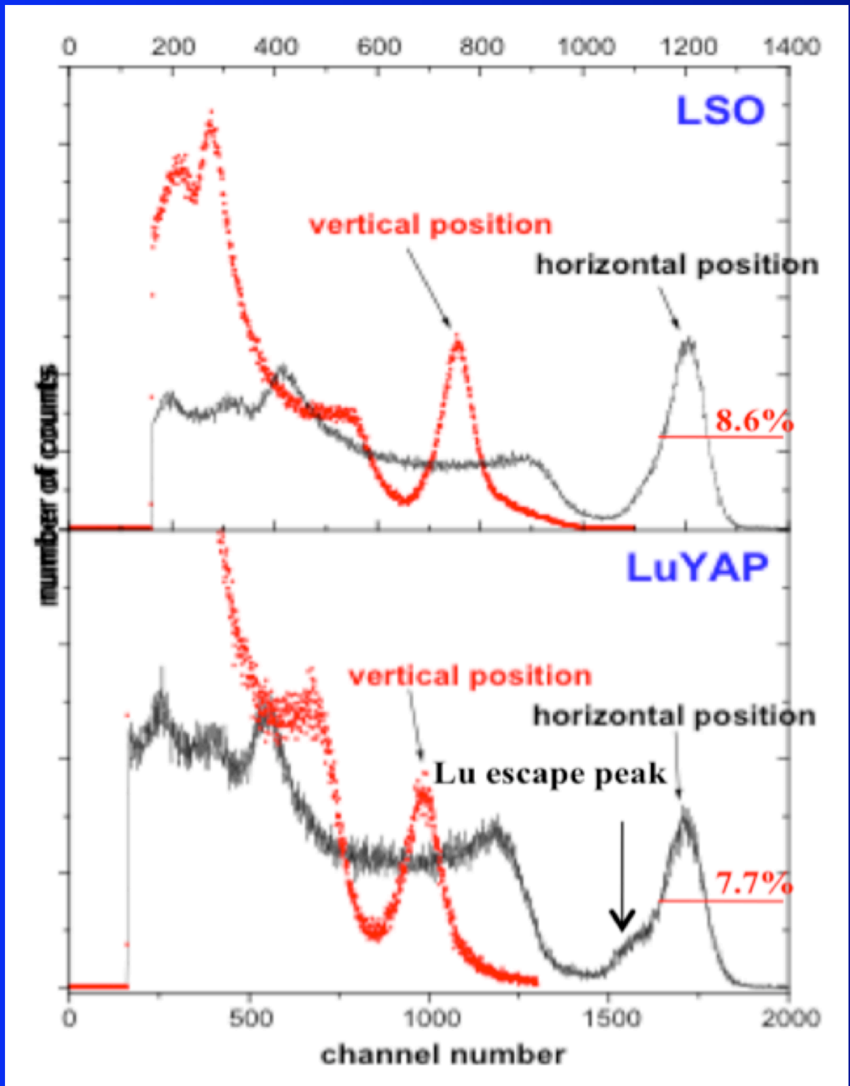
Energy resolution



$$R_{\text{stat}} = 2.35\sqrt{\frac{1+0.15}{N_{dph}}}$$

- Some crystals are far from the theoretical limit
- $LaBr_3$ and SrI_2 measured with standart and new high QE PMT
- Significantly higher number of detected photons
- No significant improvement resolution
- Can we pass the 2% barrier?

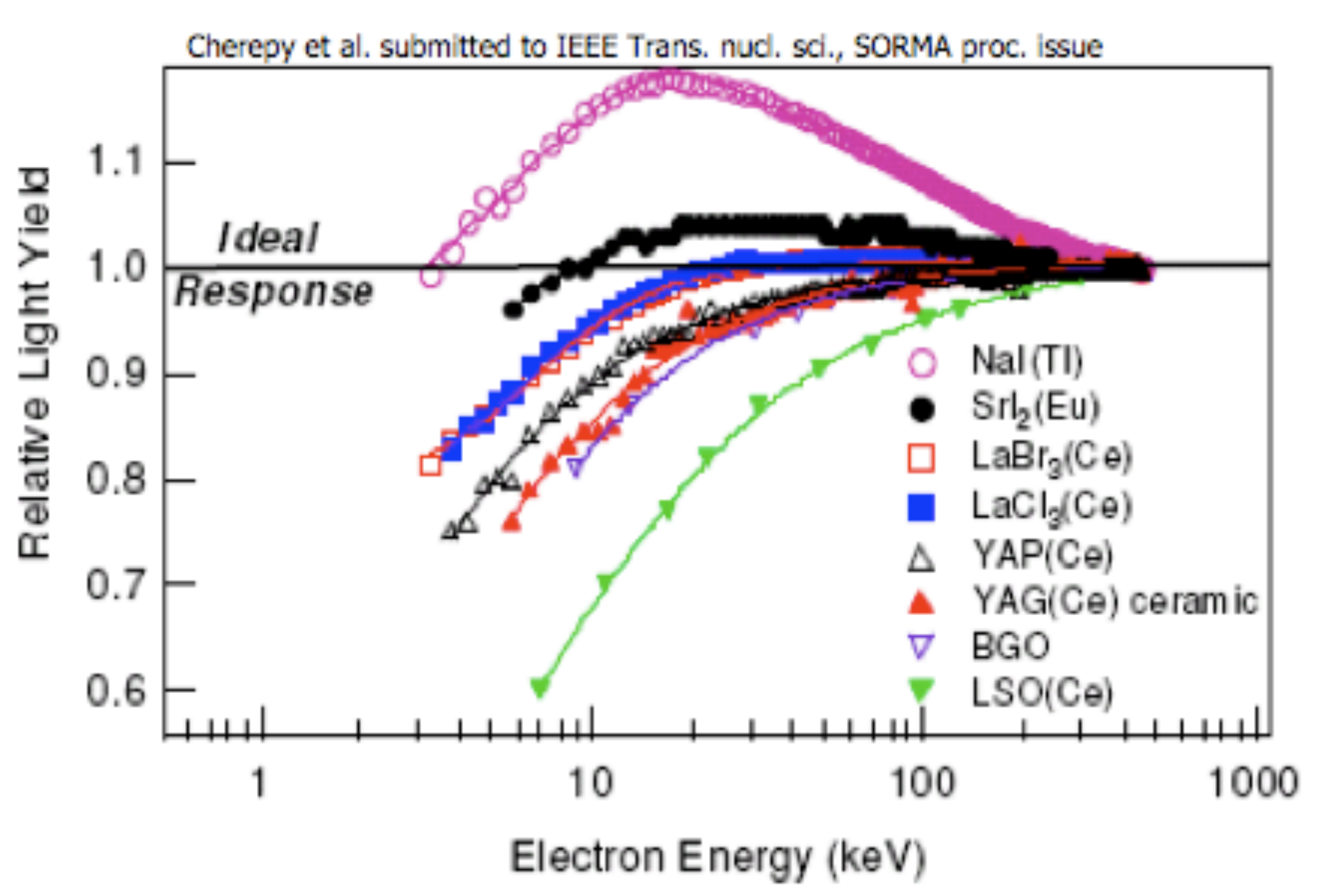
Comparison LSO - LuYAP



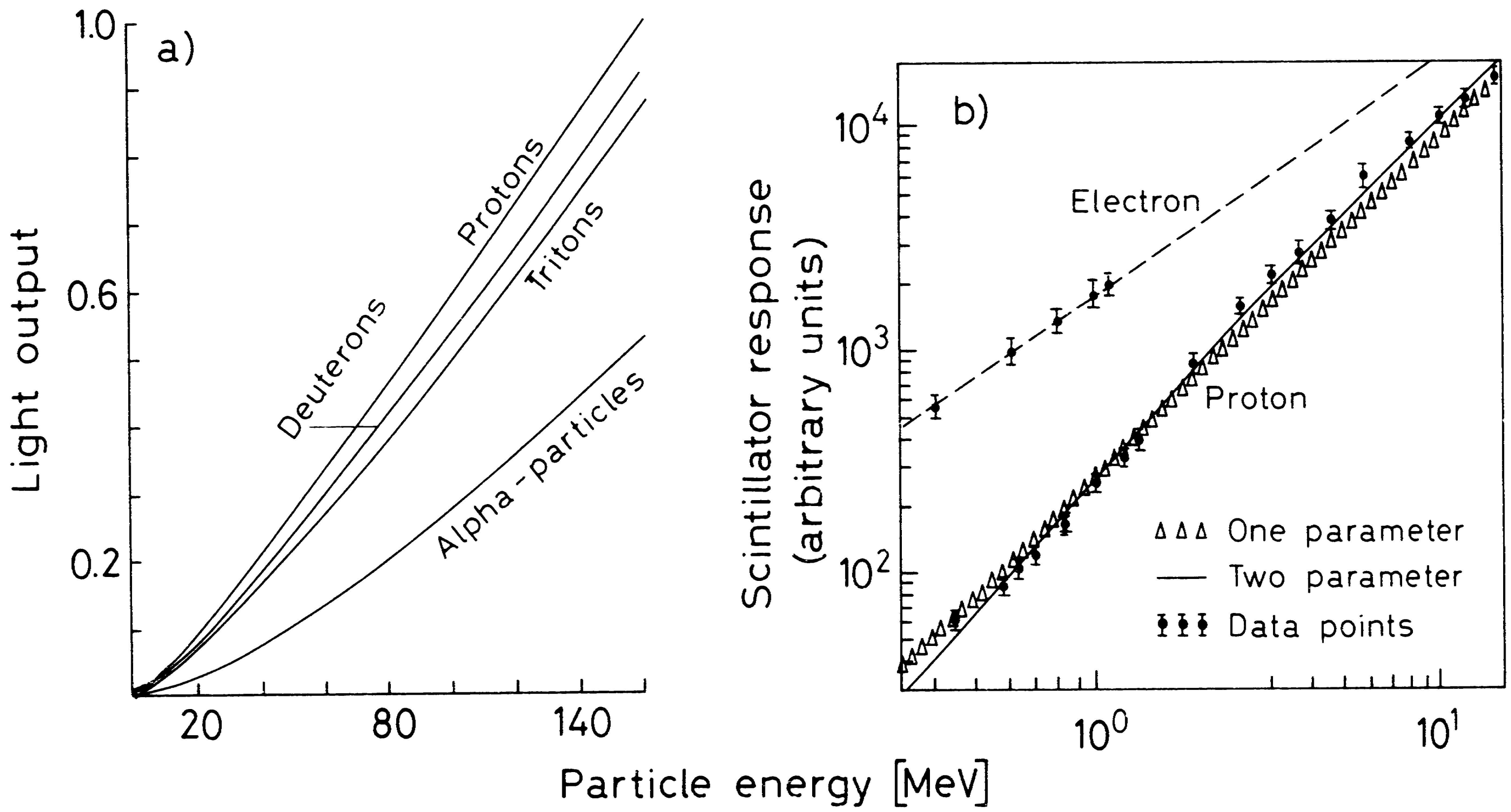
- 2x2x10 mm3 crystals
  - LSO: 6000 pe/MeV
  - LuYAP: 2000 pe/MeV
- Each crystal in 2 positions
  - Vertical
  - Horizontal
- Gain LuYAP=3xgain LSO

Same energy resolution

Low energy non-proportionality

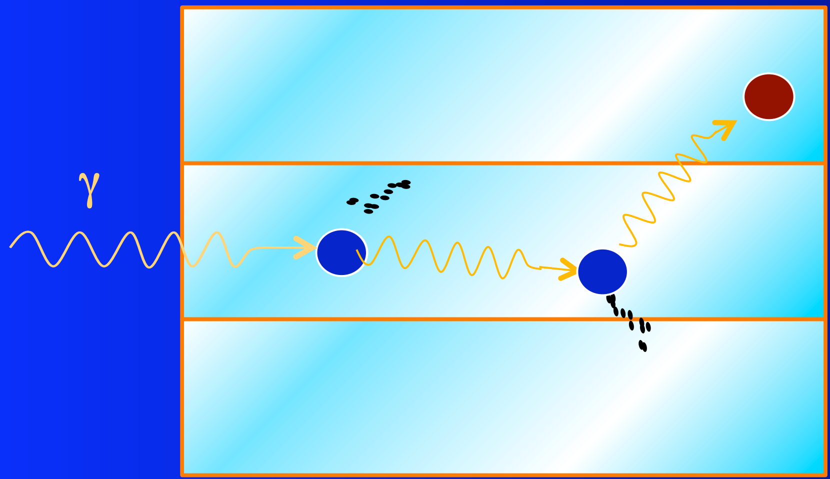


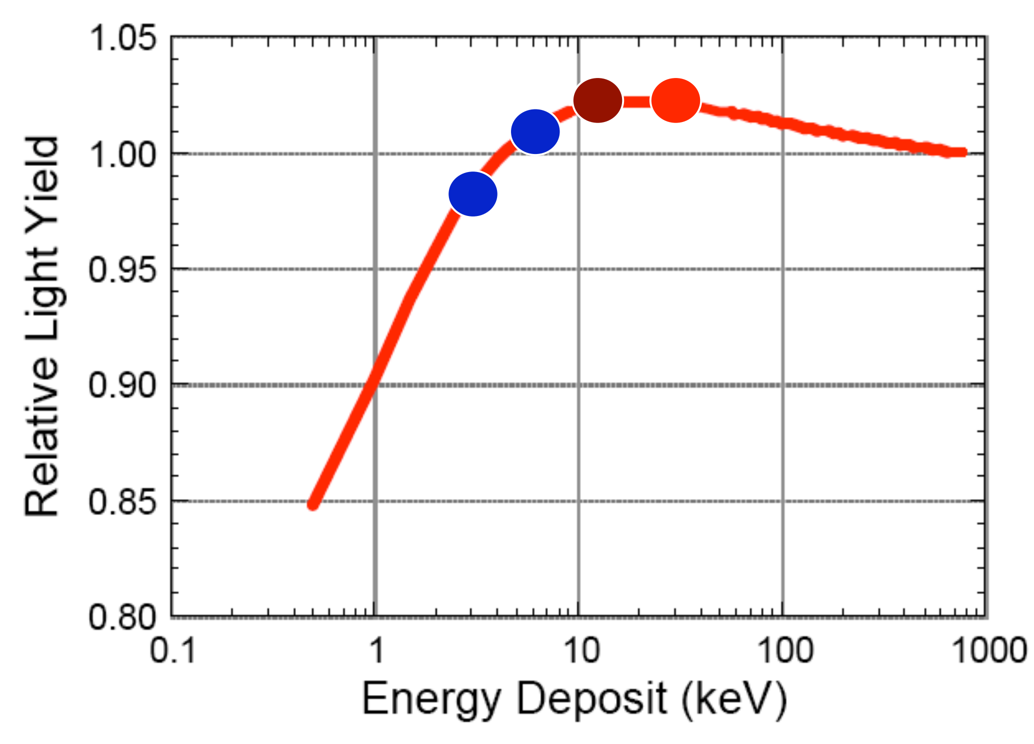
Non-proportionality



- **Light Yield *Not* Constant**
- **Depends on Particle Energy & Type**

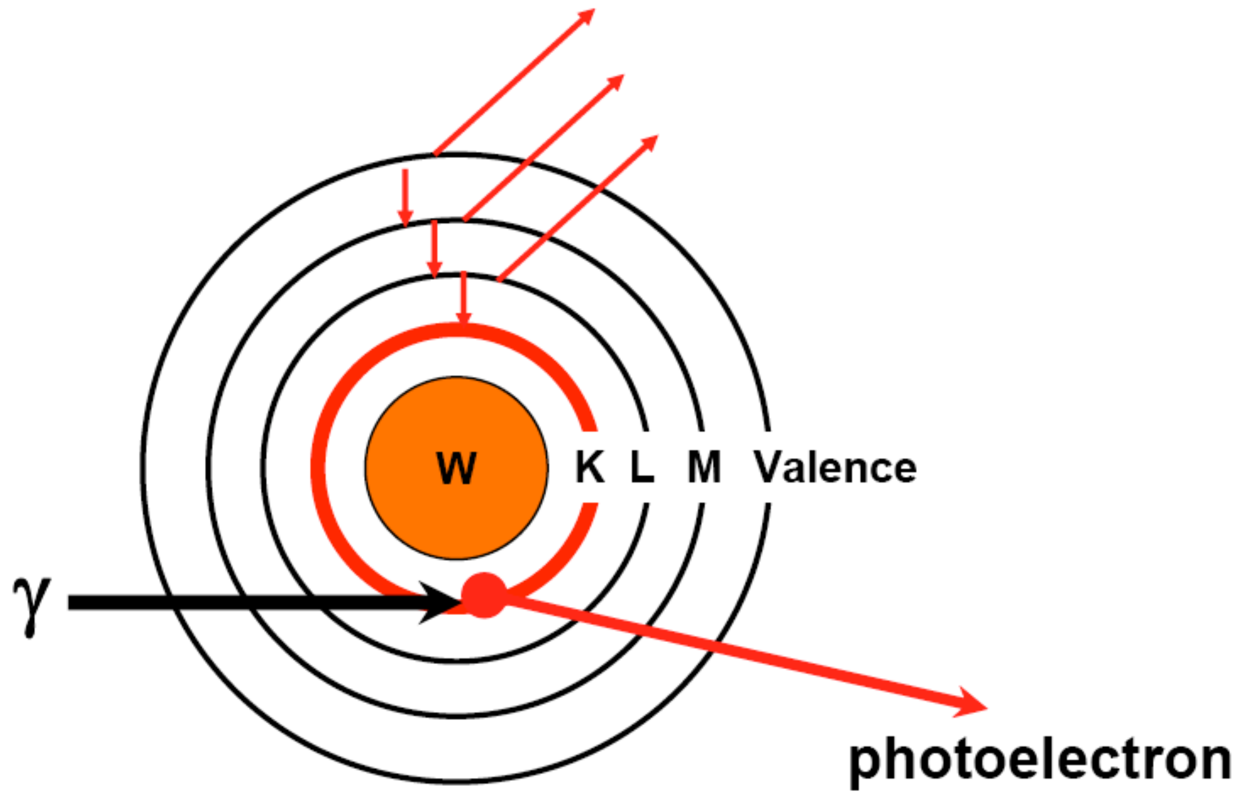
Initial interaction:
Compton versus Photoelectric





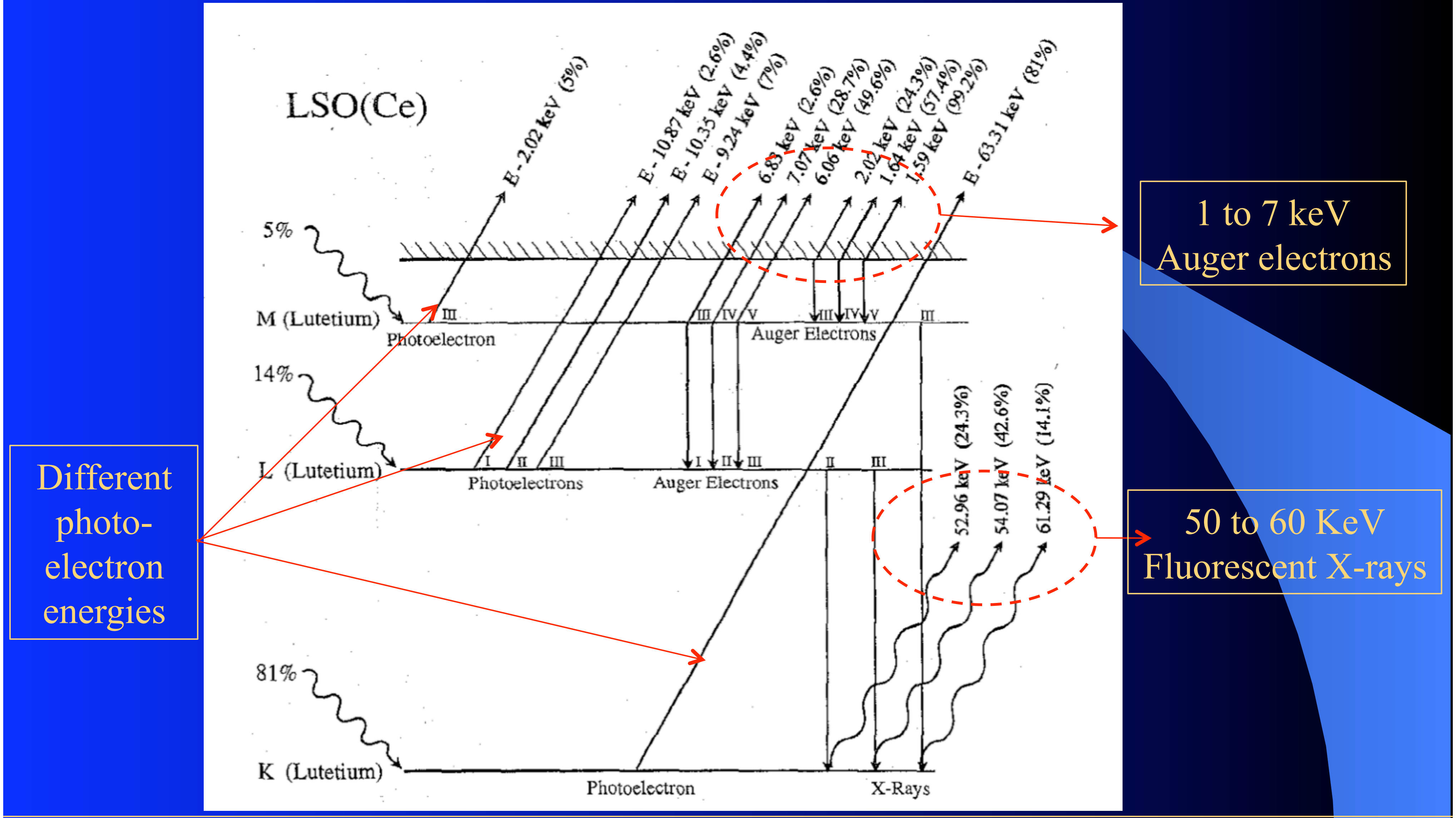
Non-Proportionality + Multiple Energy Deposit
⇒ Degraded Energy Resolution

Photoelectric interactions

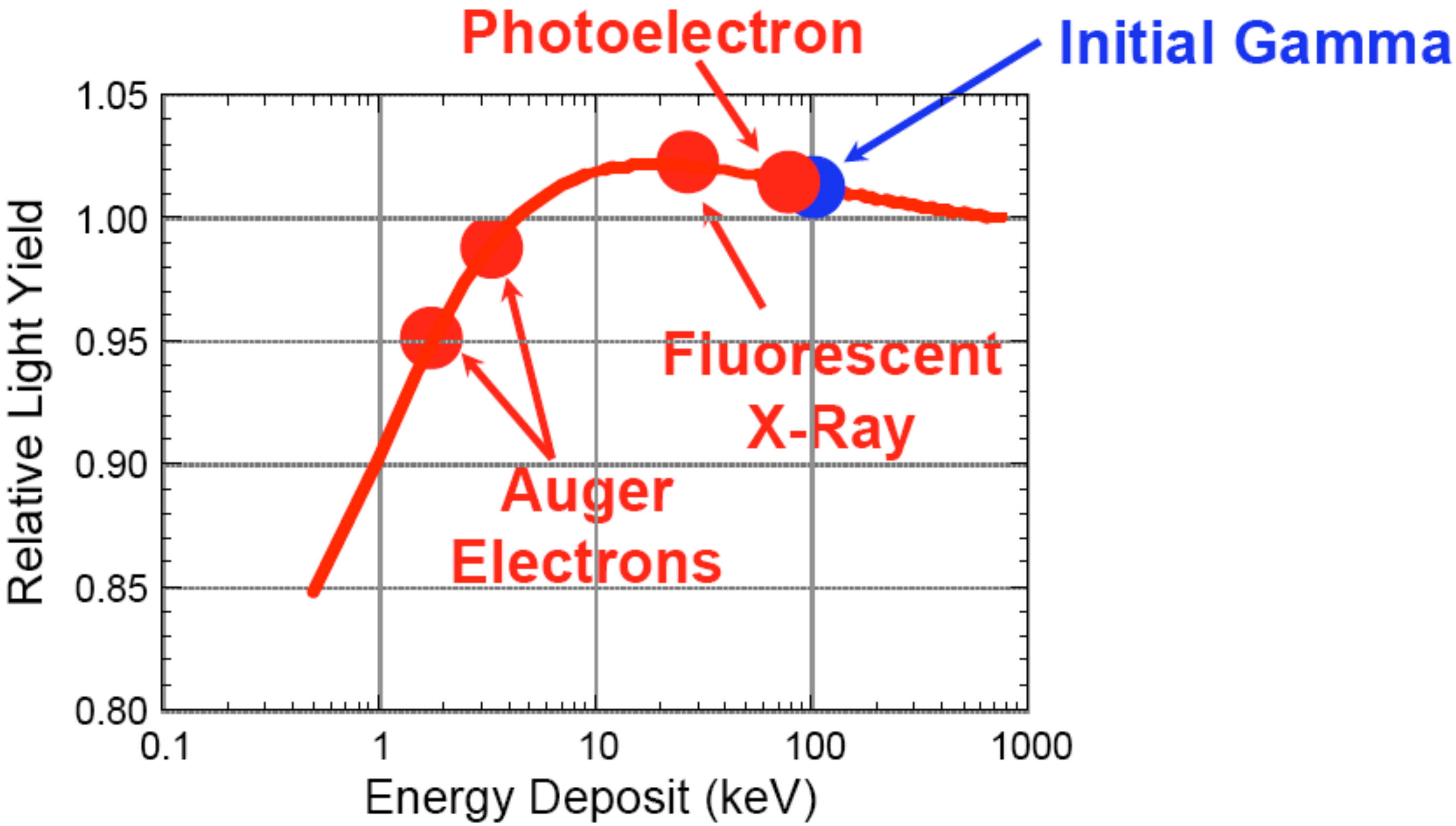


- Usually Occur with *Inner* Shell Electrons
  $\Rightarrow$ Inner Shell Hole Filled via Cascade

Simplified cascade model for LSO

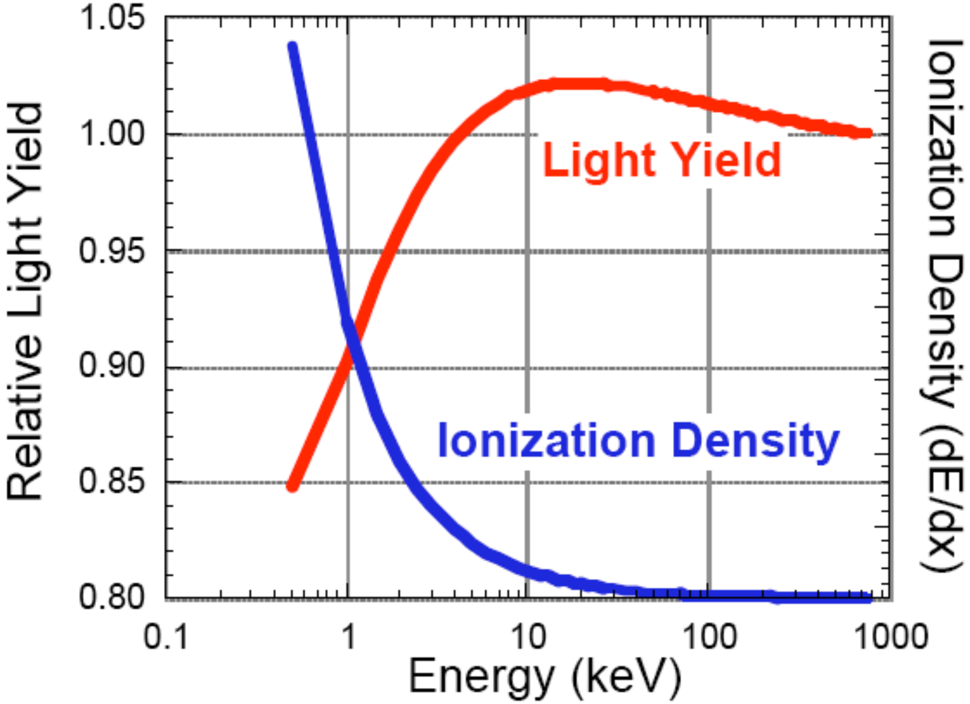


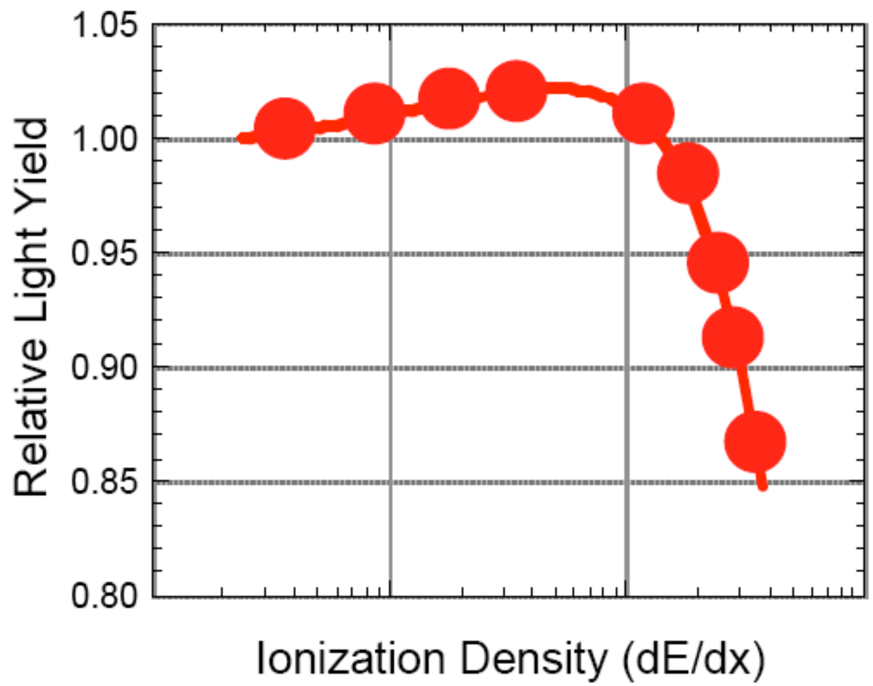
Photoelectric cascade interaction



Non-Proportionality + Multiple Energy Deposit
⇒ Degraded Energy Resolution

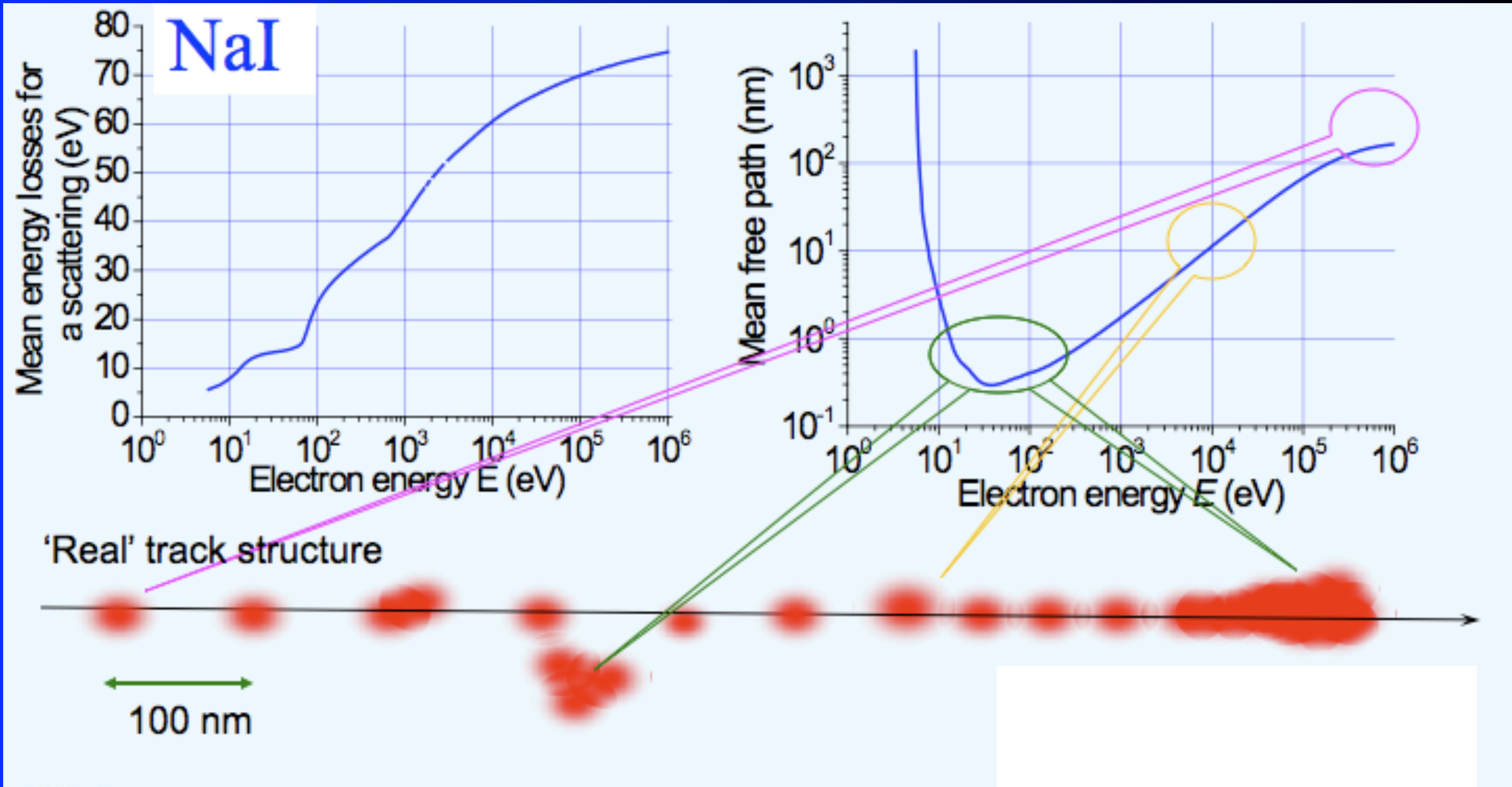
Yield depends on electron ionization density





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

Non-uniformity of electron energy deposit

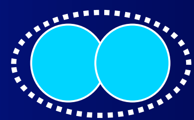


EE interactions in scintillators

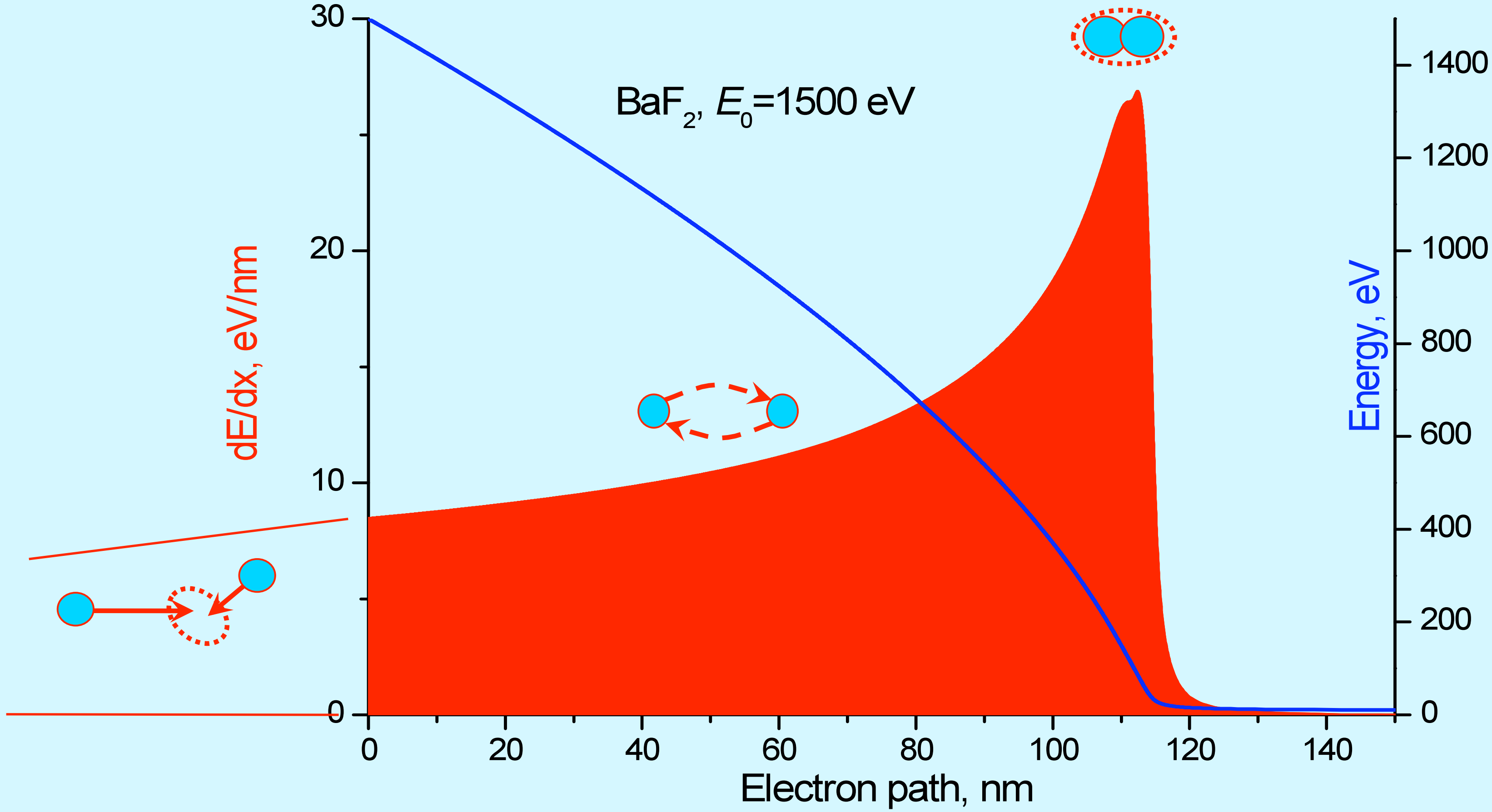
- Weak interaction by collision

- Interaction due to energy exchange

- Strong interaction:
  - new type of excitations
  - specific paths of localization
  - defects creation

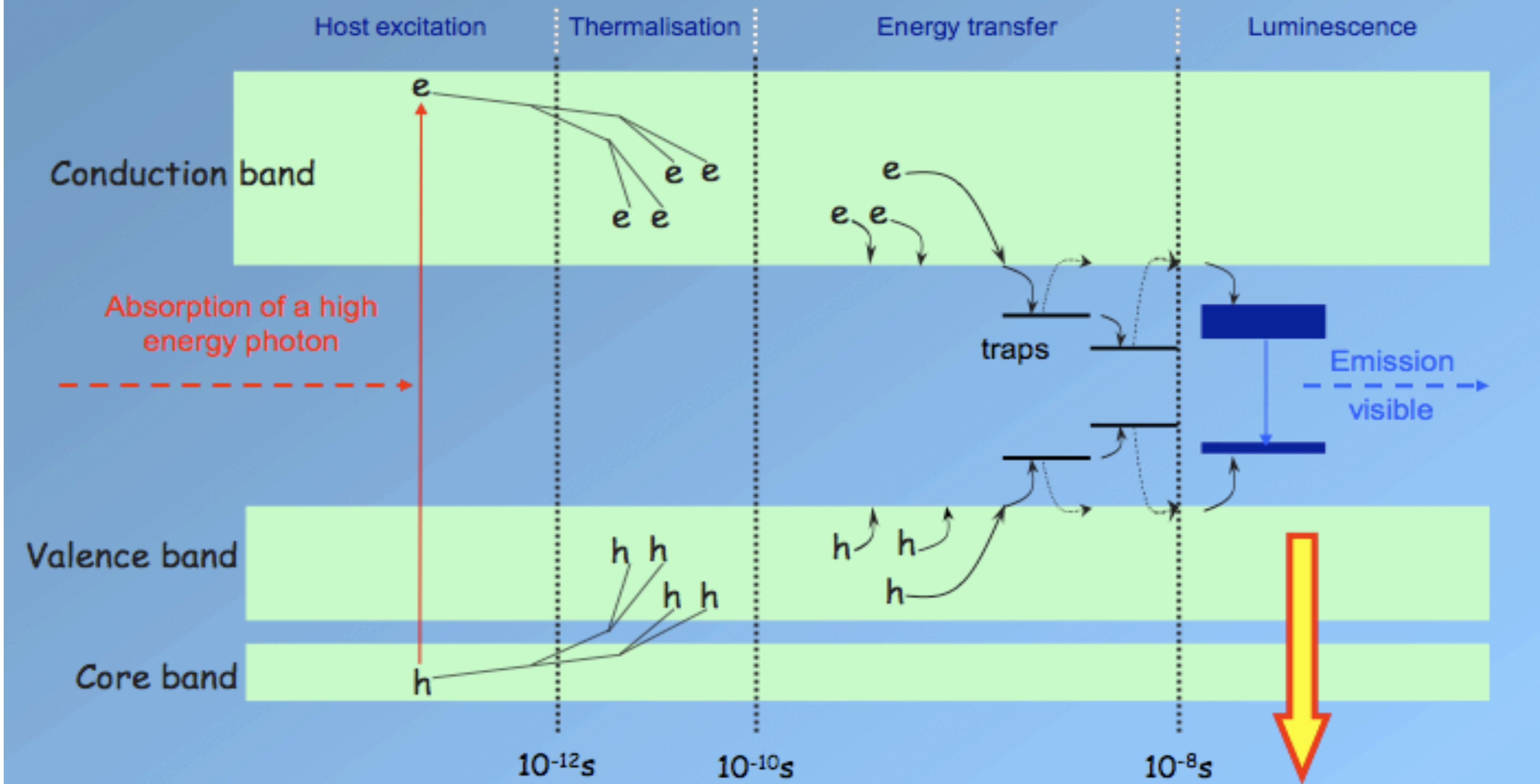


EE density effect in scintillators



End of Part 1

Scintillation process



Main changes when size is decreased?

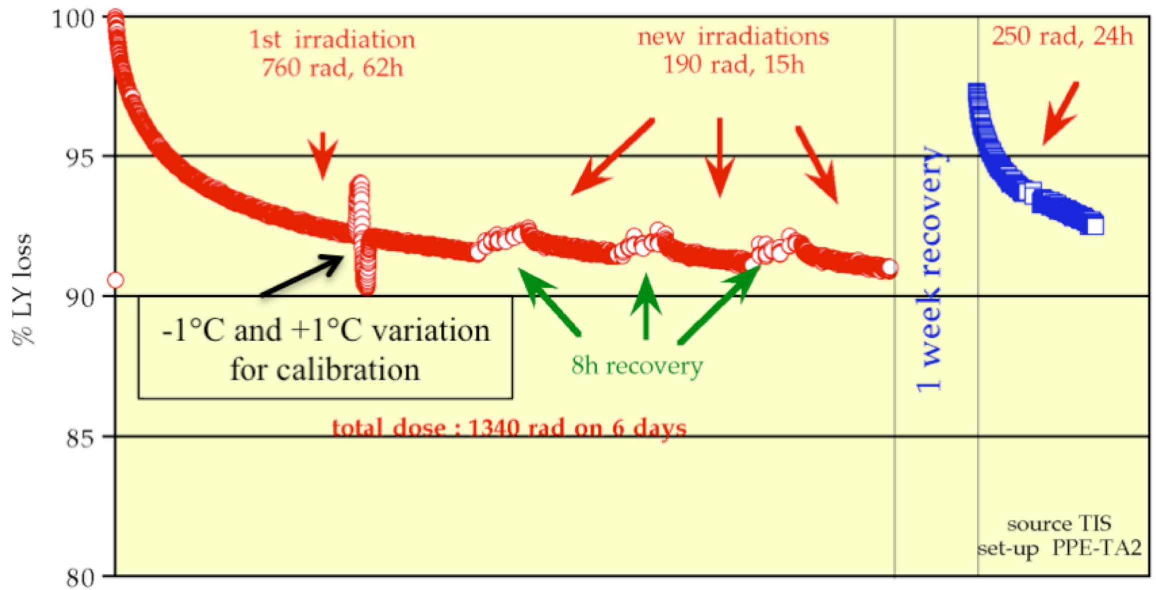
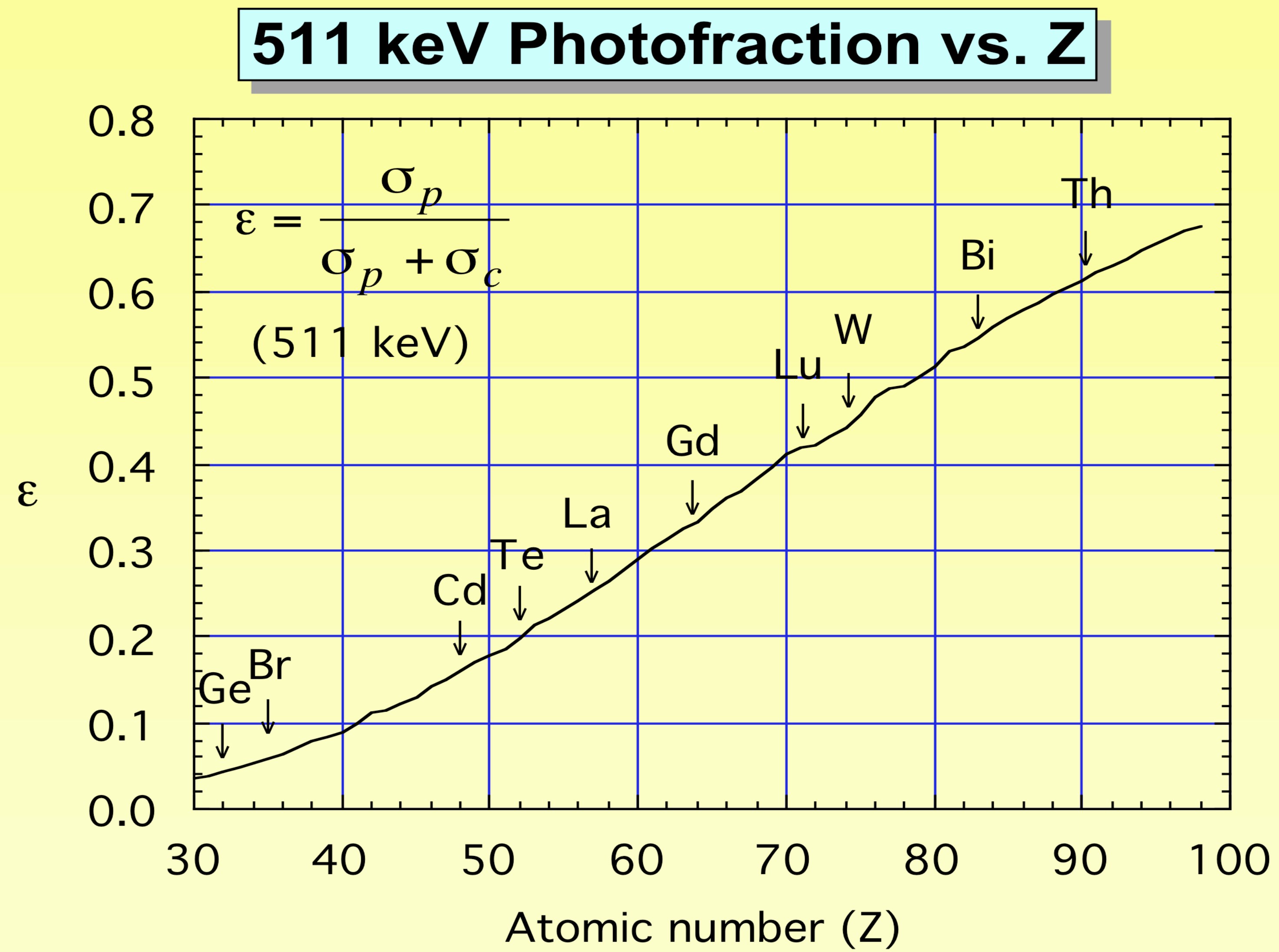
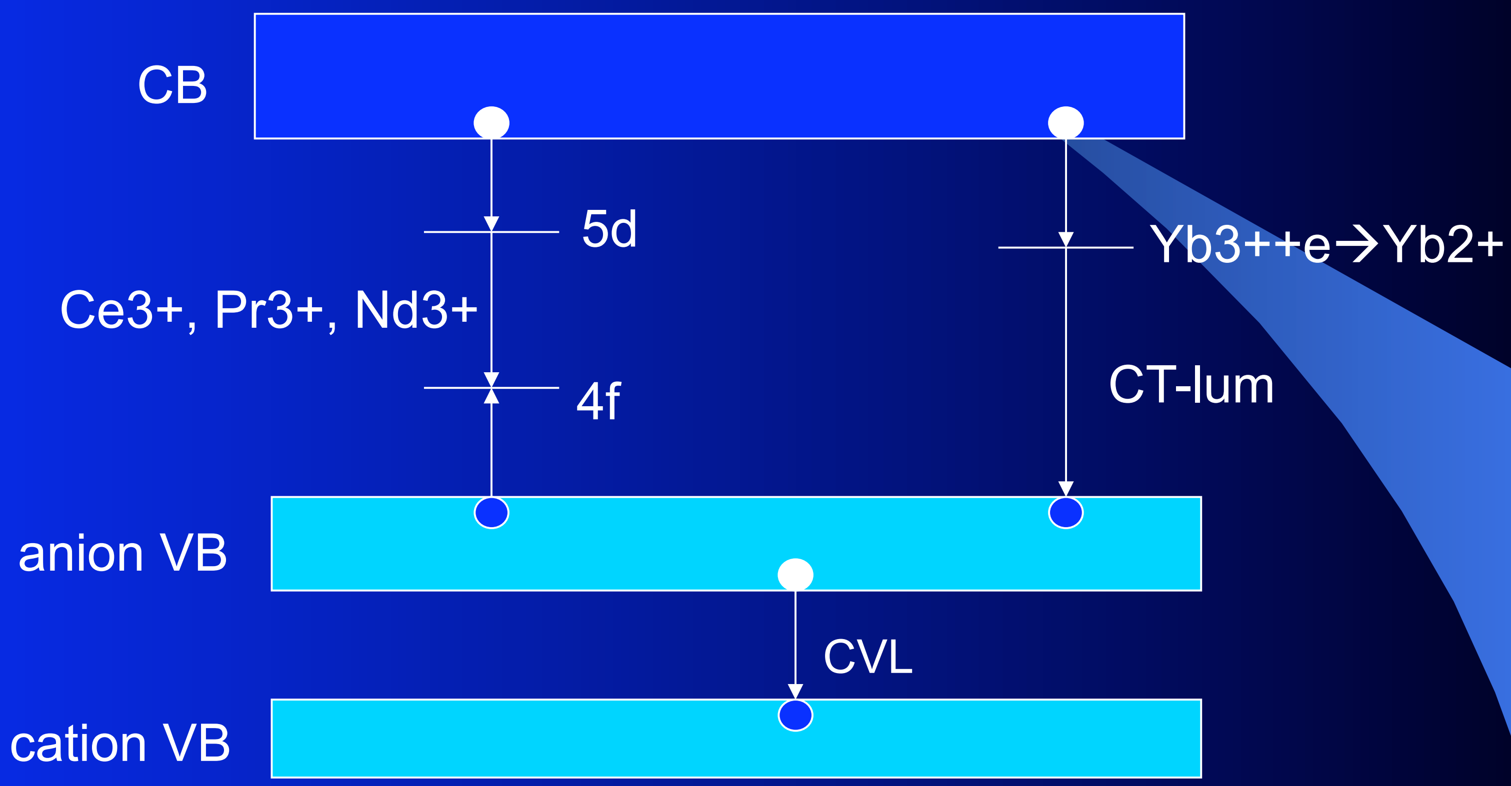


Fig.15: Variations of light output for a PWO crystal exposed to a cycle of several irradiations separated by periods of recovery at 18°C
(Courtesy CMS collaboration)

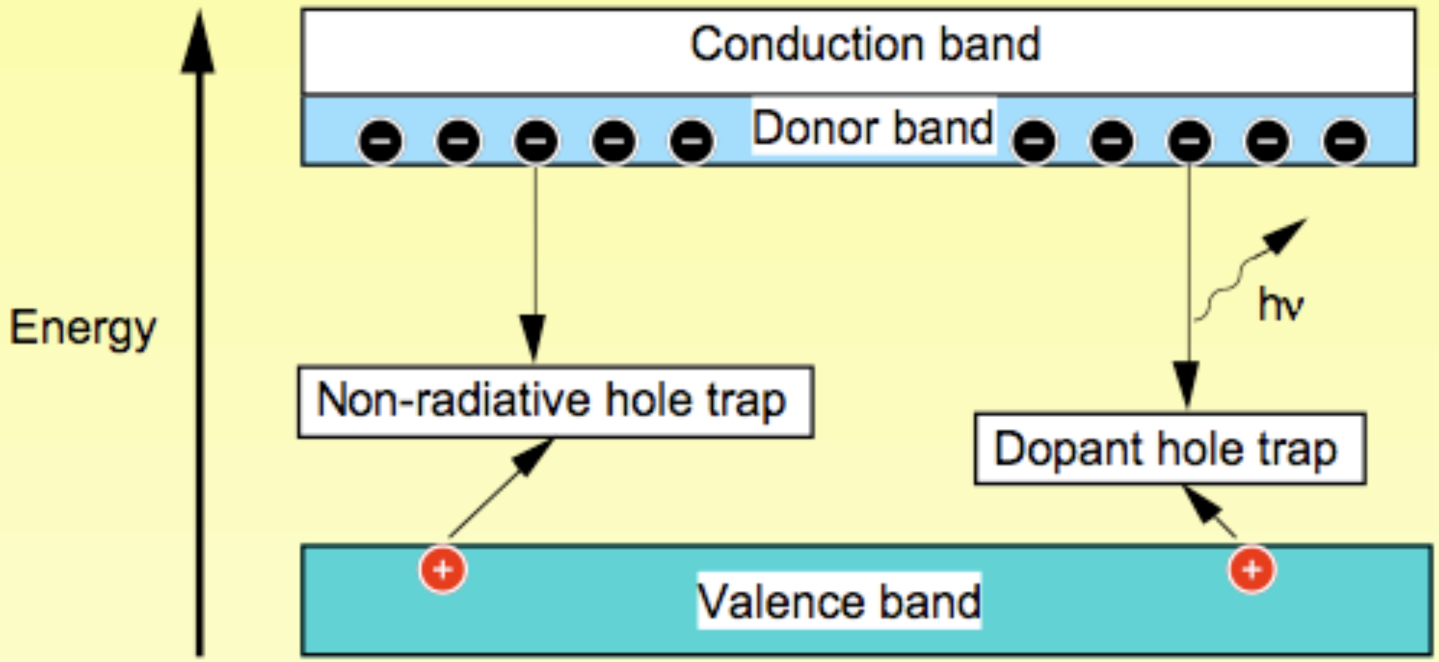
How to choose a scintillator



Dipole and spin allowed transitions
Charge transfer or 5d-4f transitions



Co-doped semiconductors Faster than Ce3+?



- Direct-gap semiconductor host with E_g = >2.5 eV
- Prompt (<50 ps), efficient trapping of hot holes by dopant ions
- Fast (~1 ns) recombination with donor band electrons

Ultrafast semiconductor scintillators