Inorganic Scintillators - An overview

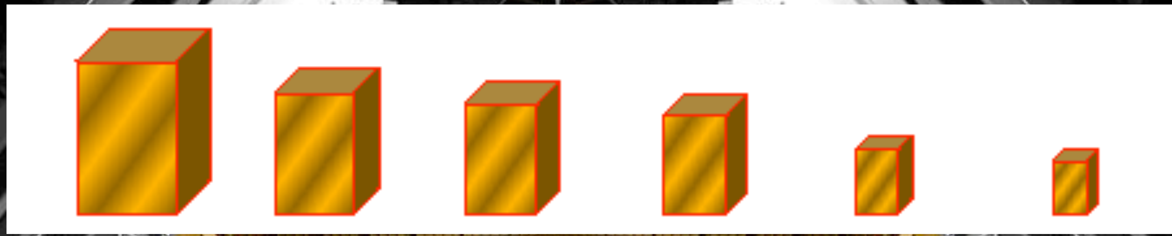
Paul Lecoq
CERN, Geneva

HEP and PET use the largest volume of scintillators

High energy physics
(e.g. CMS)
80,000 crystals; 12,000 liters; highest production rate in 2005
4100 liters/yr (34 tons/yr)

Positron Emission Tomography
in 2003, 450 sc/yr x 10 liters/sc
= 4500 liters/yr (33 tons/yr)

Some popular crystals in HEP



	NaI(Tl)	BaF_2	CsI(Tl)	CeF_3	BGO $Bi_4Ge_3O_{12}$	PWO $PbWO_4$
Xo [cm]	2.59	2.03	1.86	1.66	1.12	0.92
ρ [g/cm^3]	3.67	4.89	4.53	6.16	7.13	8.2
τ [ns]	230	0.6 620	1050	30	340	15
λ [nm]	415	230 310	550	310 340	480	420
$n@\lambda_{max}$	1.85	1.56	1.80	1.68	2.15	2.3
LY [%NaI]	100	5 16	85	5	10	0.5

Scintillators for PET

Scintillators for PET

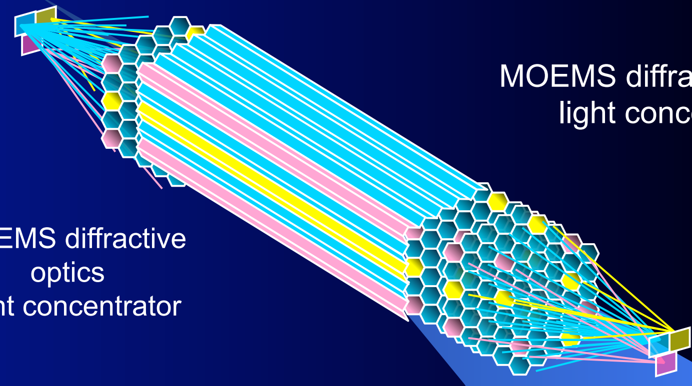
	1962	1977	1995	1999	2001	2003	2007
	NaI	BGO	GSO:Ce	LSO:Ce	LuAP:Ce	$LaBr_3$:Ce	LuAG:Ce
Density (g/cm^3)	3.67	7.13	6.71	7.40	8.34	5.29	6.73
Atomic number	51	75	59	66	65	47	63
Photofraction	0.17	0.35	0.25	0.32	0.30	0.13	0.30
Decay time (ns)	230	300	30-60	35-45	17	18	60
Light output (hν/MeV)	43000	8200	12500	27000	11400	70000	>25000
Peak emission (nm)	415	480	430	420	365	356	535
Refraction index	1.85	2.15	1.85	1.82	1.97	1.88	1.84

Dual readout based on Metamaterials

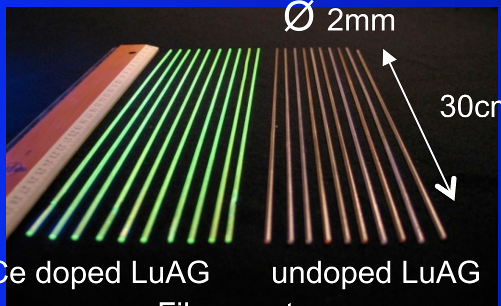
- Select a non-intrinsic scintillating material (unlike BGO or PWO) with high bandgap for low UV absorption

- The undoped host will behave as an efficient Cerenkov: heavy material, high refraction index n, high UV transmission

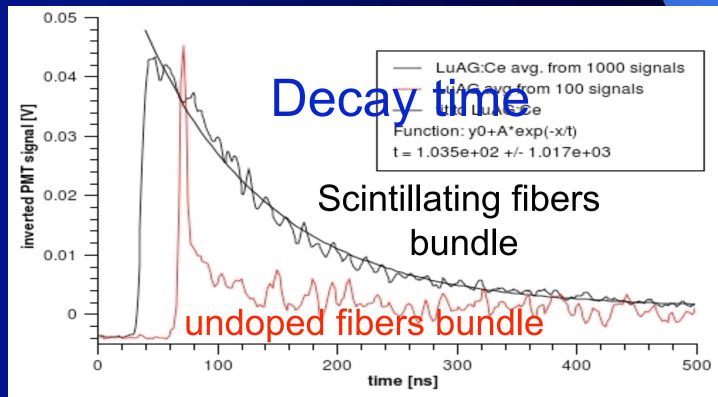
- Cerium or Praesodinum doped host will act as an efficient and fast scintillator
  - ≈ 60ns decay for Ce
  - ≈ 20ns decay for Pr



LuAG is an excellent candidate

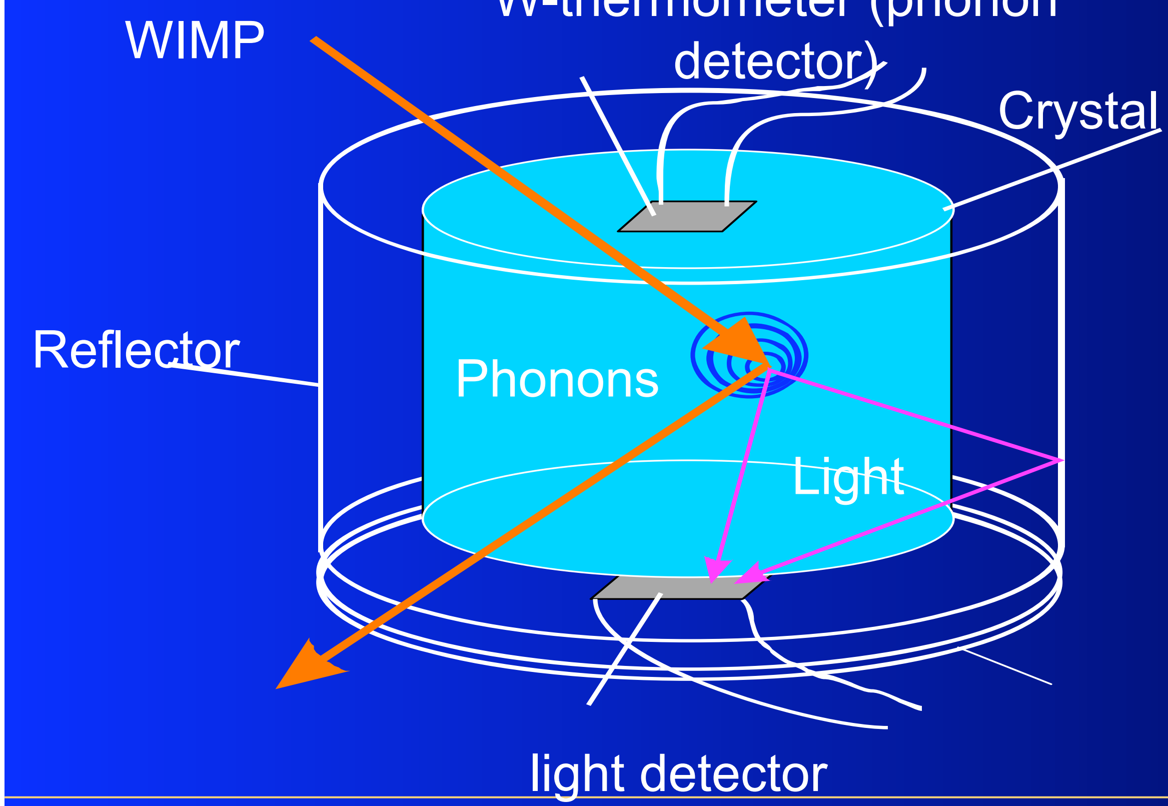


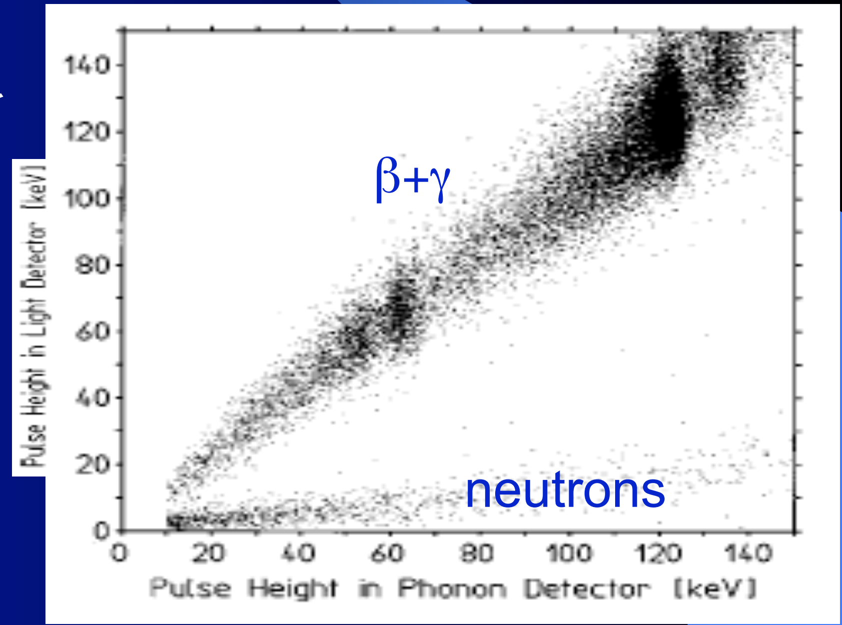
Fibercryst



Dark matter search

- **Sensitivity + Selectivity**
  high-energy resolution of cryogenic phonon detector + discrimination of events with low detection threshold (≤10 keV)





P.Meunier et al, Appl.Phys.Let 75 (1999) 1335

Scintillator requirements

- high light yield at low temperatures
  - ✓ low threshold,
  - ✓ good energy resolution
- Radiopurity (ex Lu, Rb, K, U, Th)

- Possible candidates
  - ✓$CaWO_4$ – satisfactory choice, currently in use, large ongoing effort to improve the material
  - ✓$ZnWO_4$ – scintillator under development for cryogenic application
  - ✓$CaMoO_4$ and $CdMoO_4$– material under investigation

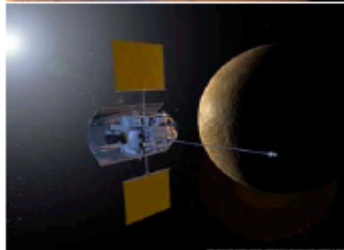
Scintillation Detectors on Space Missions

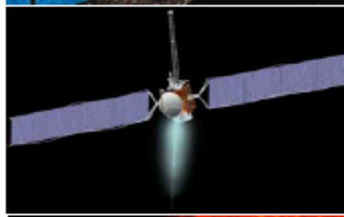
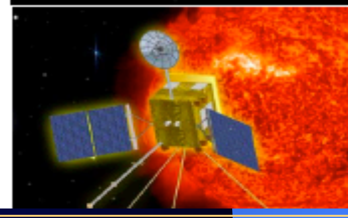




		GRS	NS	PS
• Past missions		GRS	NS	PS
–	Phobos	CsI	Stilben,plastic	yes
–	Lunar Prospector	BGO/BC454	BC454	
–	Near	NaI/BGO		
–	Mars Observer	HPGe/BC454	BC454	
–	Mars Odyssey	HPGe	BC454,Stilben,plastic	CsI
• Current missions				
–	Ulysses	CsI/GRB		Plastic
–	Messenger	HPGe/BGO	GS20,BC454	
• Missions in implementation				
–	Dawn	CZT/BGO	BGO,BC454, G20	
–	Phobos Grunt	$LaBr_3$	BC454,Stilben,plastic	
–	Solar Orbiter	$LaBr_3$	plastic	
–	BepiColombo	$LaBr_3$		CsI

GRS=gamma-ray spectrometer
NS=neutron spectrometer
PS=particle spectrometer

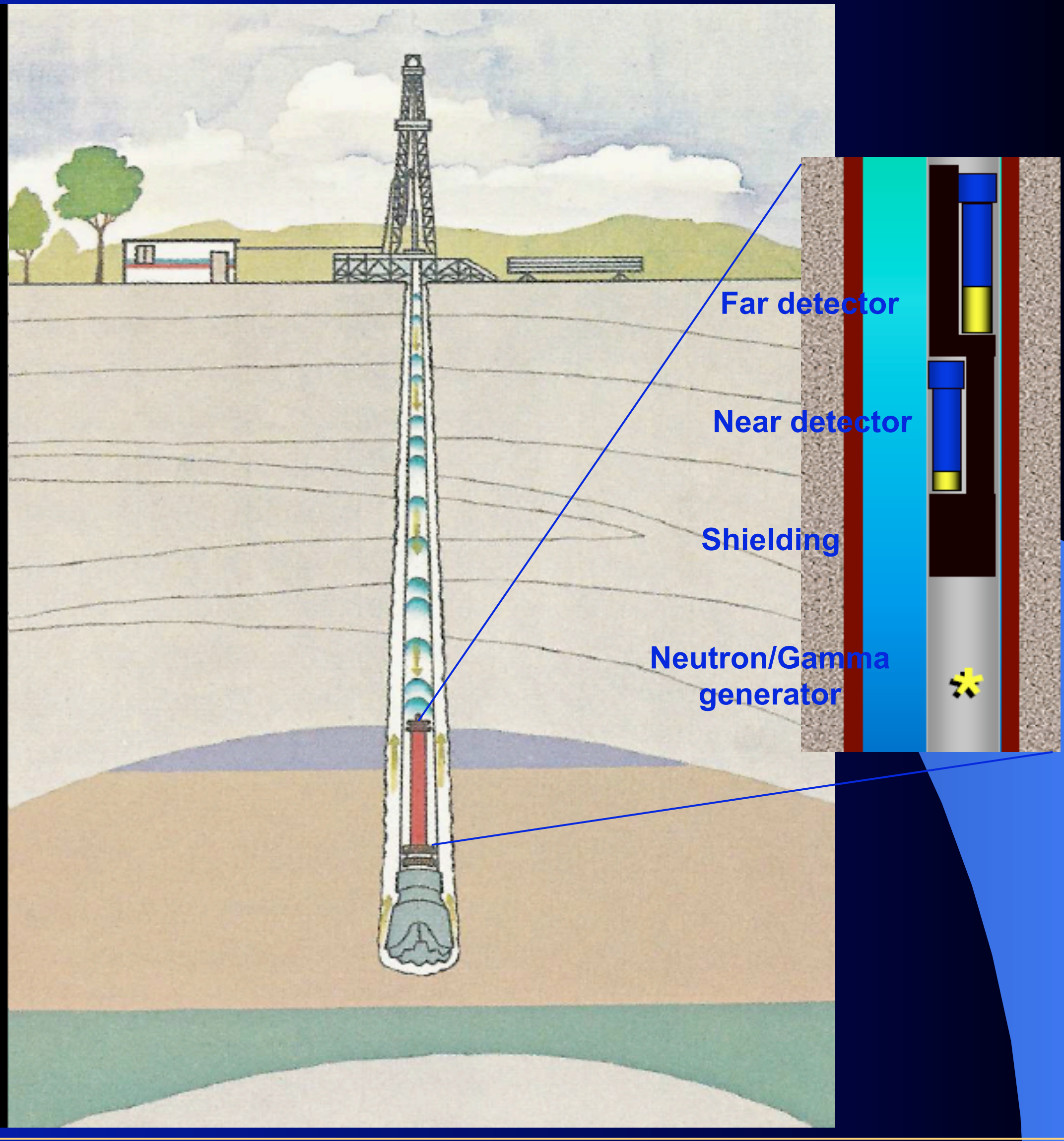



Oil Well Logging

Measurement Issues

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



Homeland security

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

NaI, $CdWO_4$, BGO

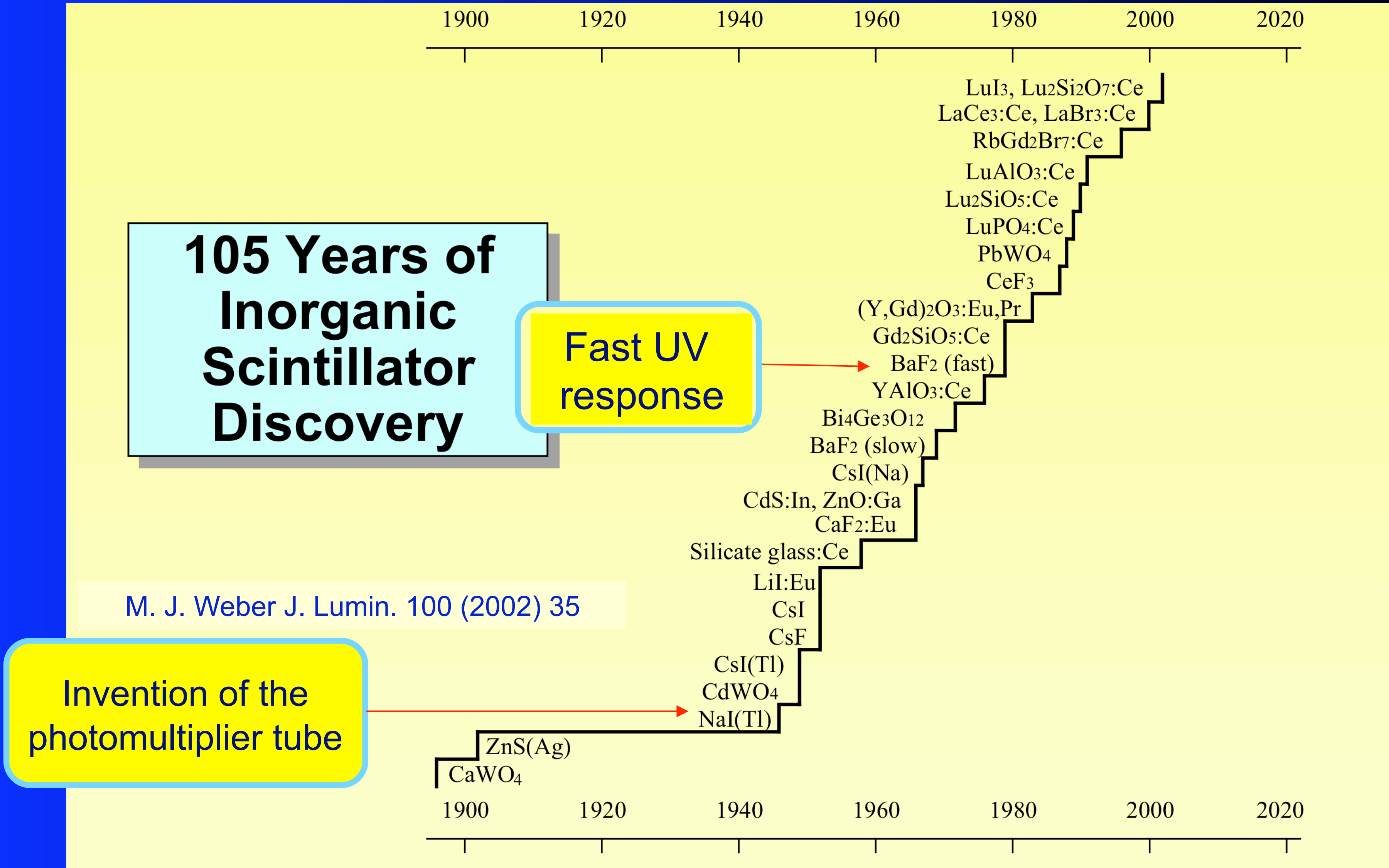
Spectrometers, counters, imagers

8 Managed by UT-Battelle
for the Department of Energy

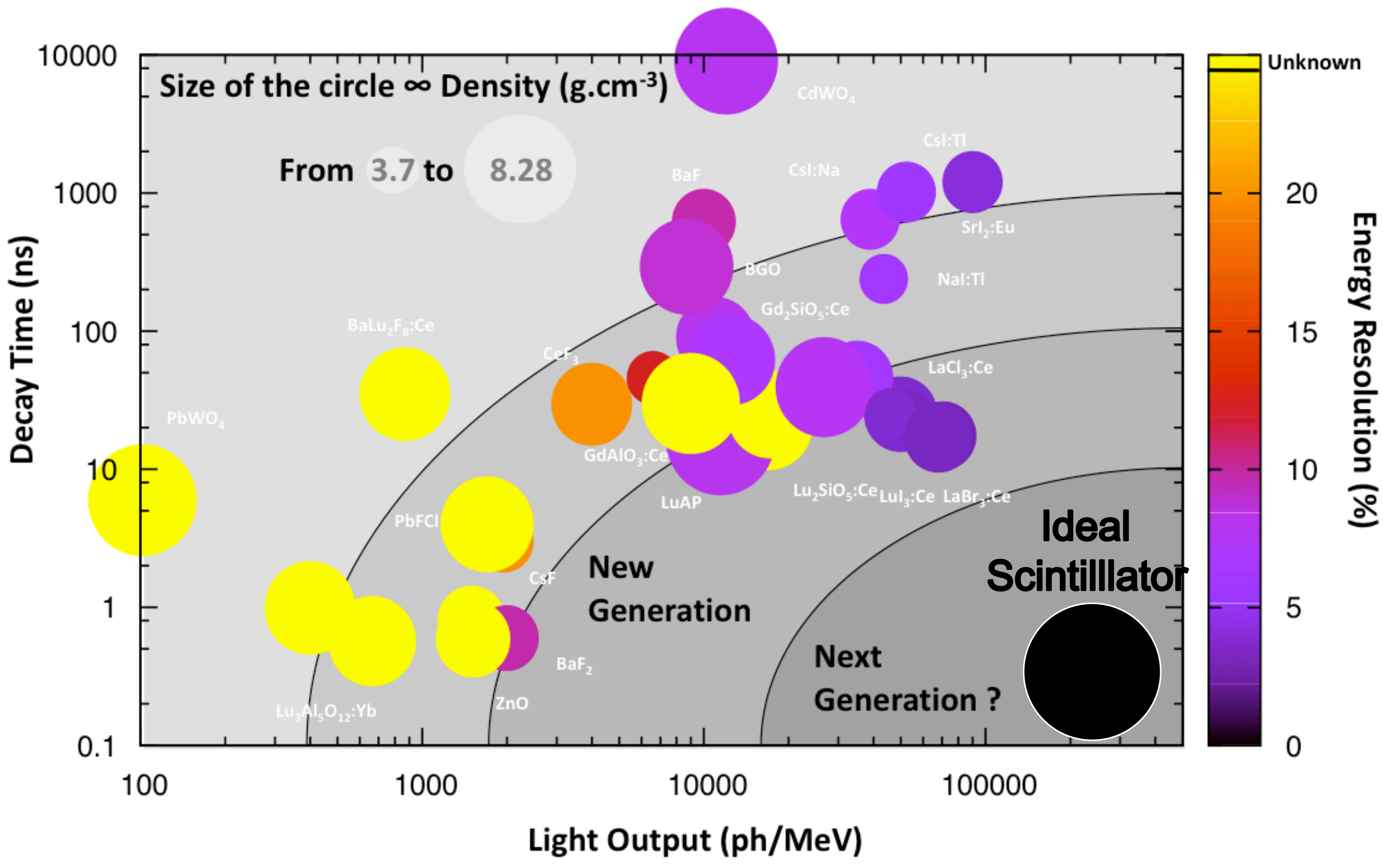
Scintillator Applications in Homeland Security

OAK RIDGE National Laboratory

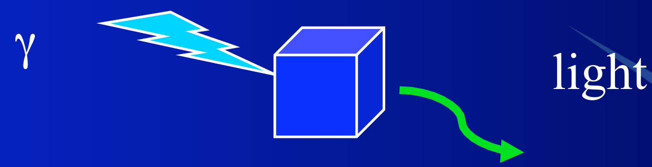
History of scintillator discovery



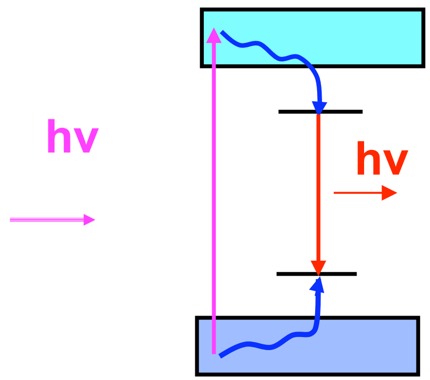
Classification of scintillators



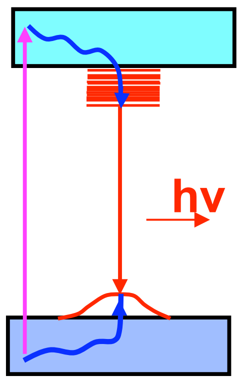
Fundamental aspects of Scintillation



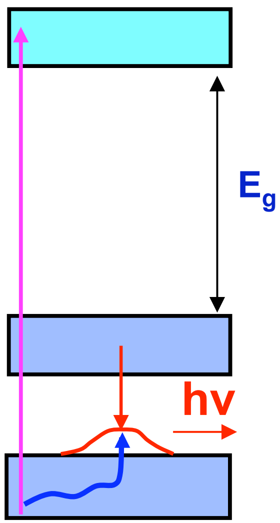
Different scintillation mechanisms



A – Doped ion, or intrinsic defect

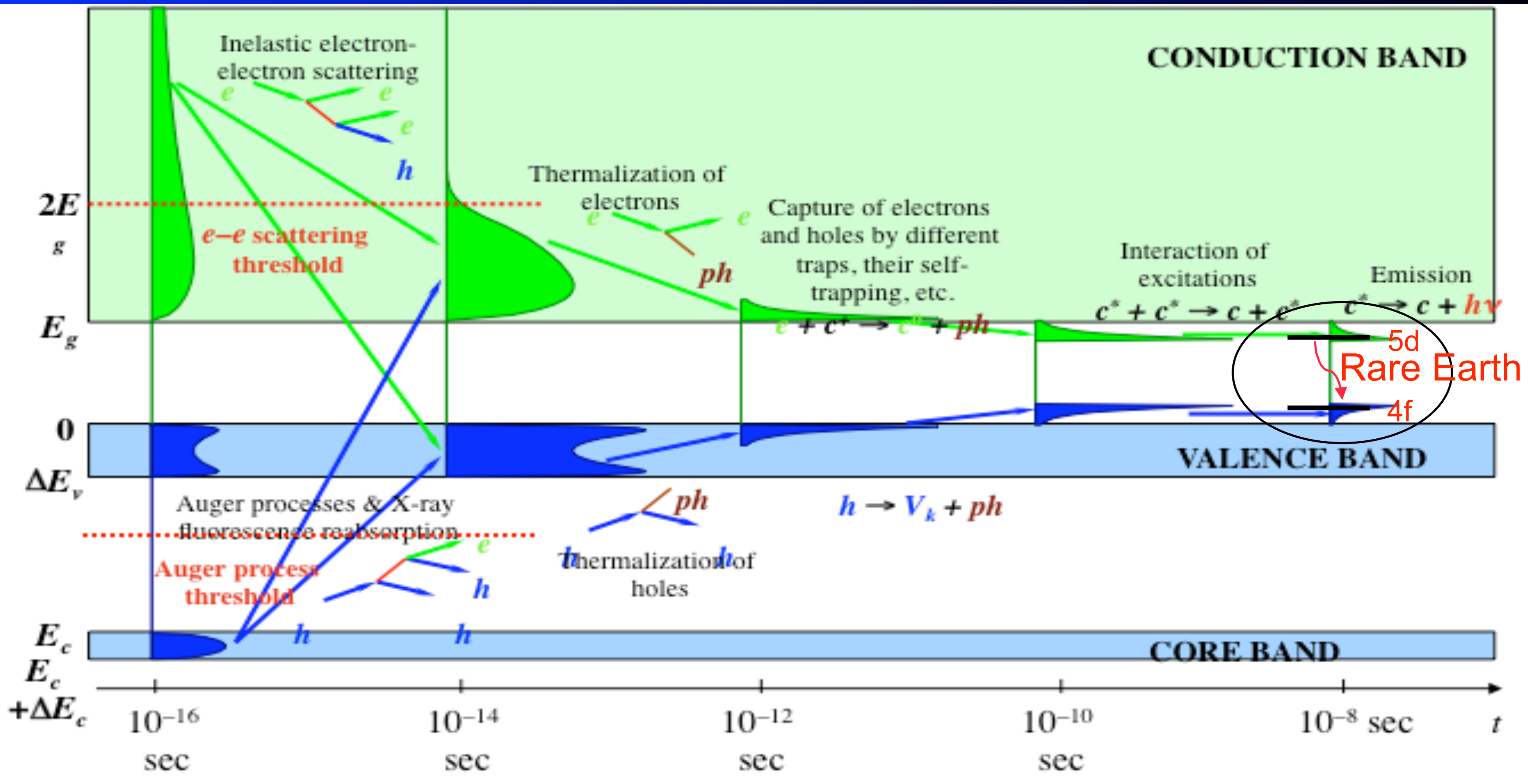


B – Self- trapped exciton



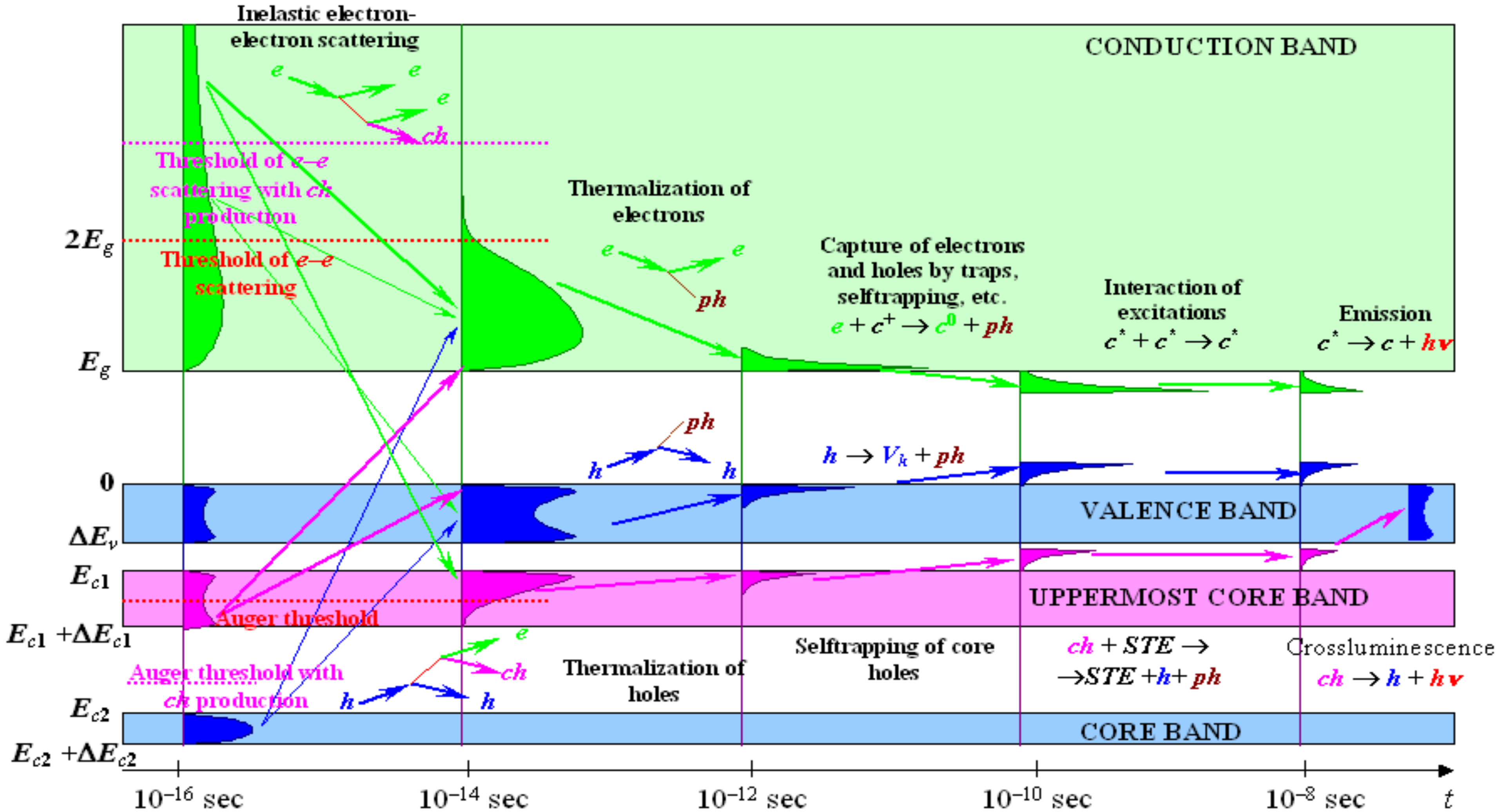
C – Crossluminescence

Relaxation of electronic excitations
intrinsic luminescence

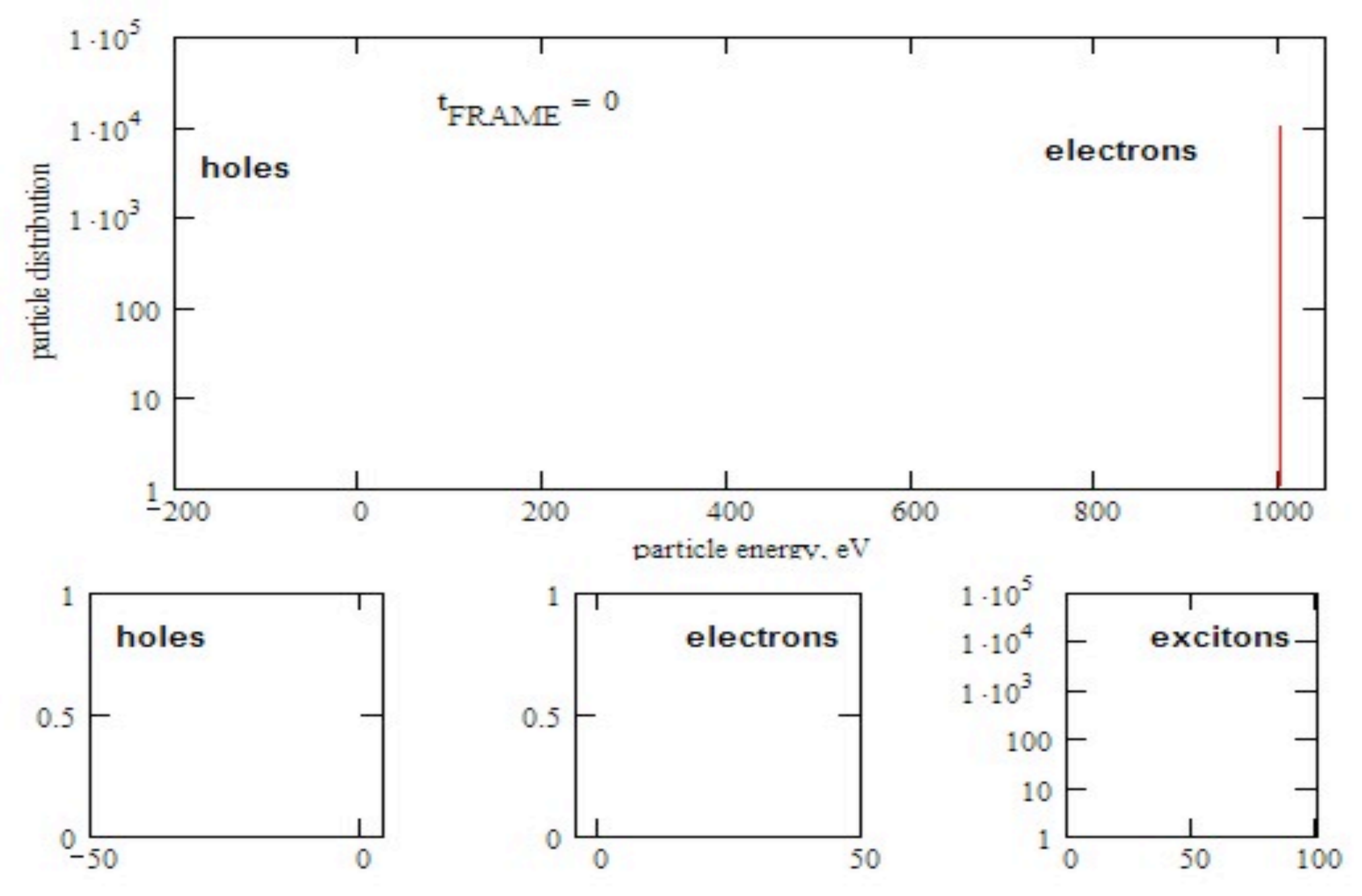


A. Vasil'ev, SCINT2001 proceedings, NIMA 486 (2002) 367

Relaxation of electronic excitations
Cross-luminescence



Evolution of energy distribution for 1000 eV electrons



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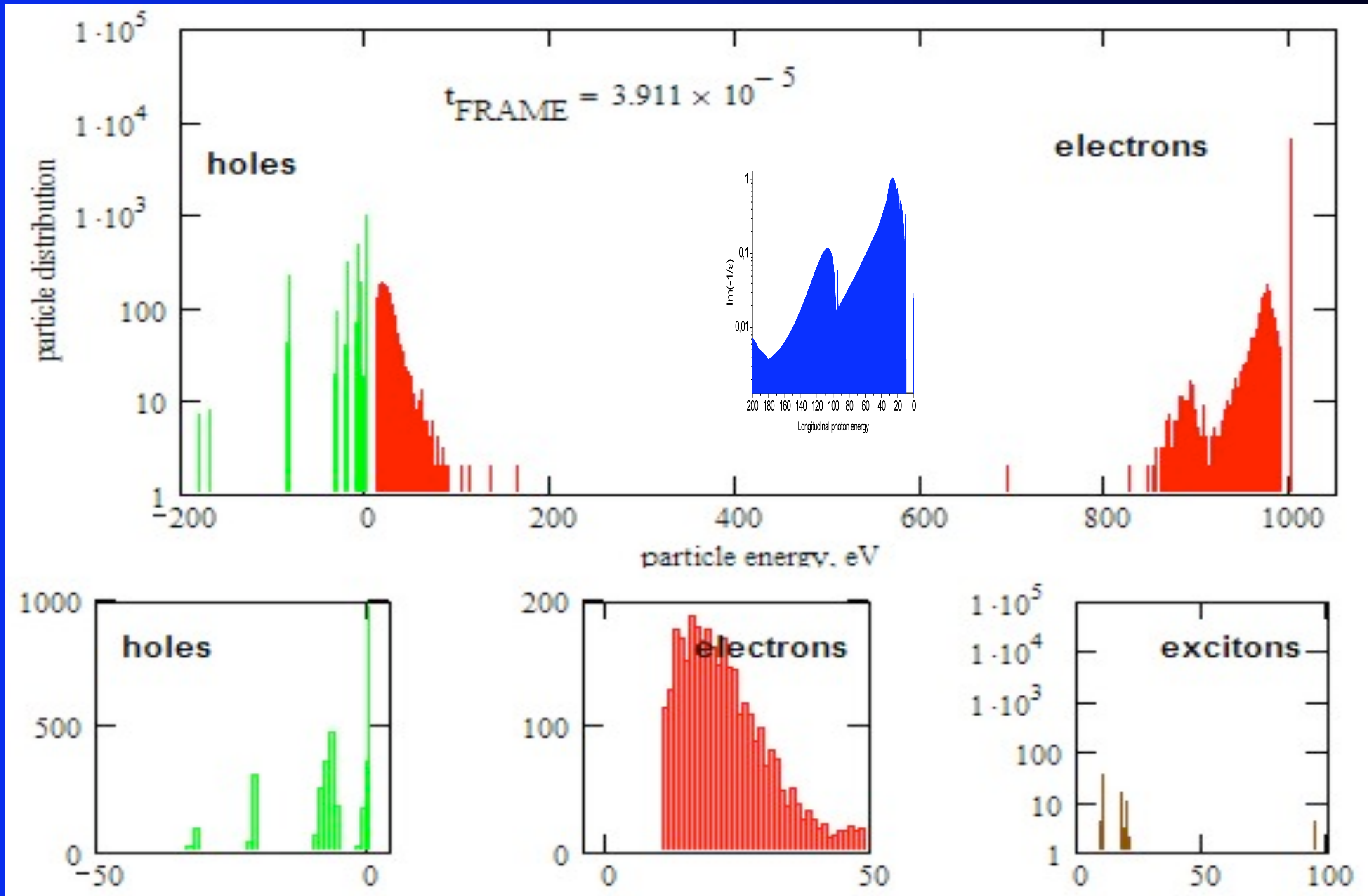

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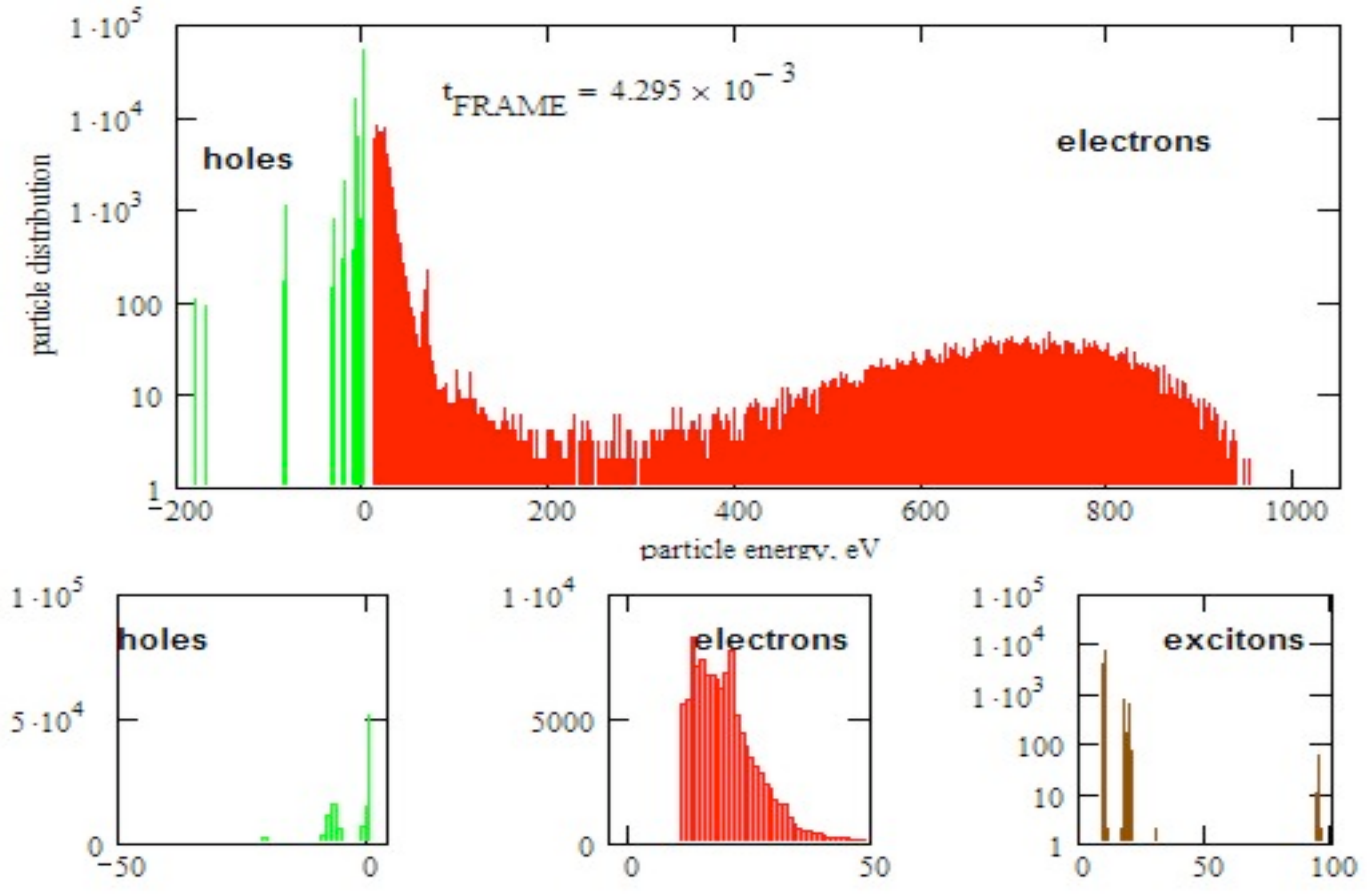

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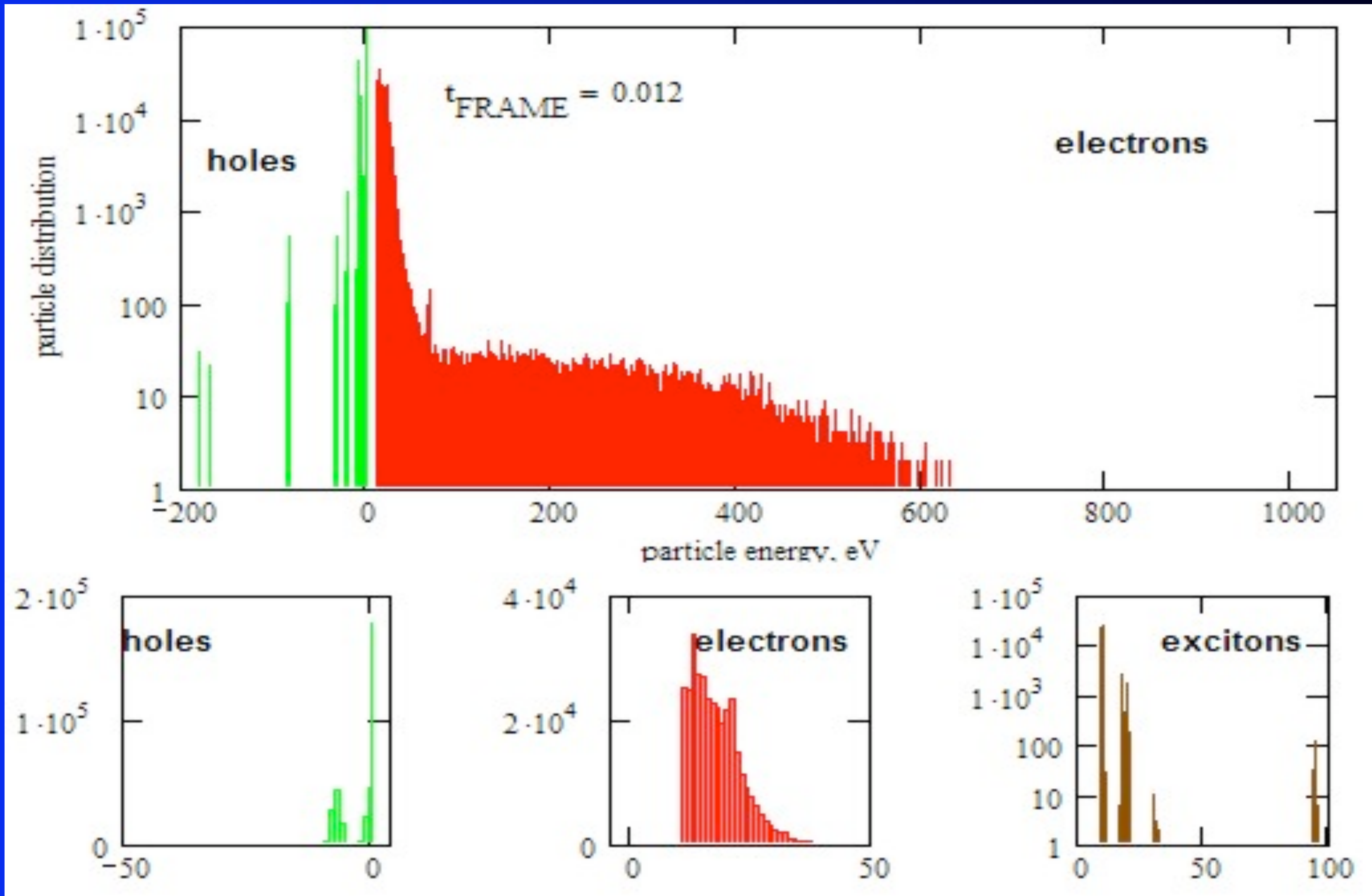

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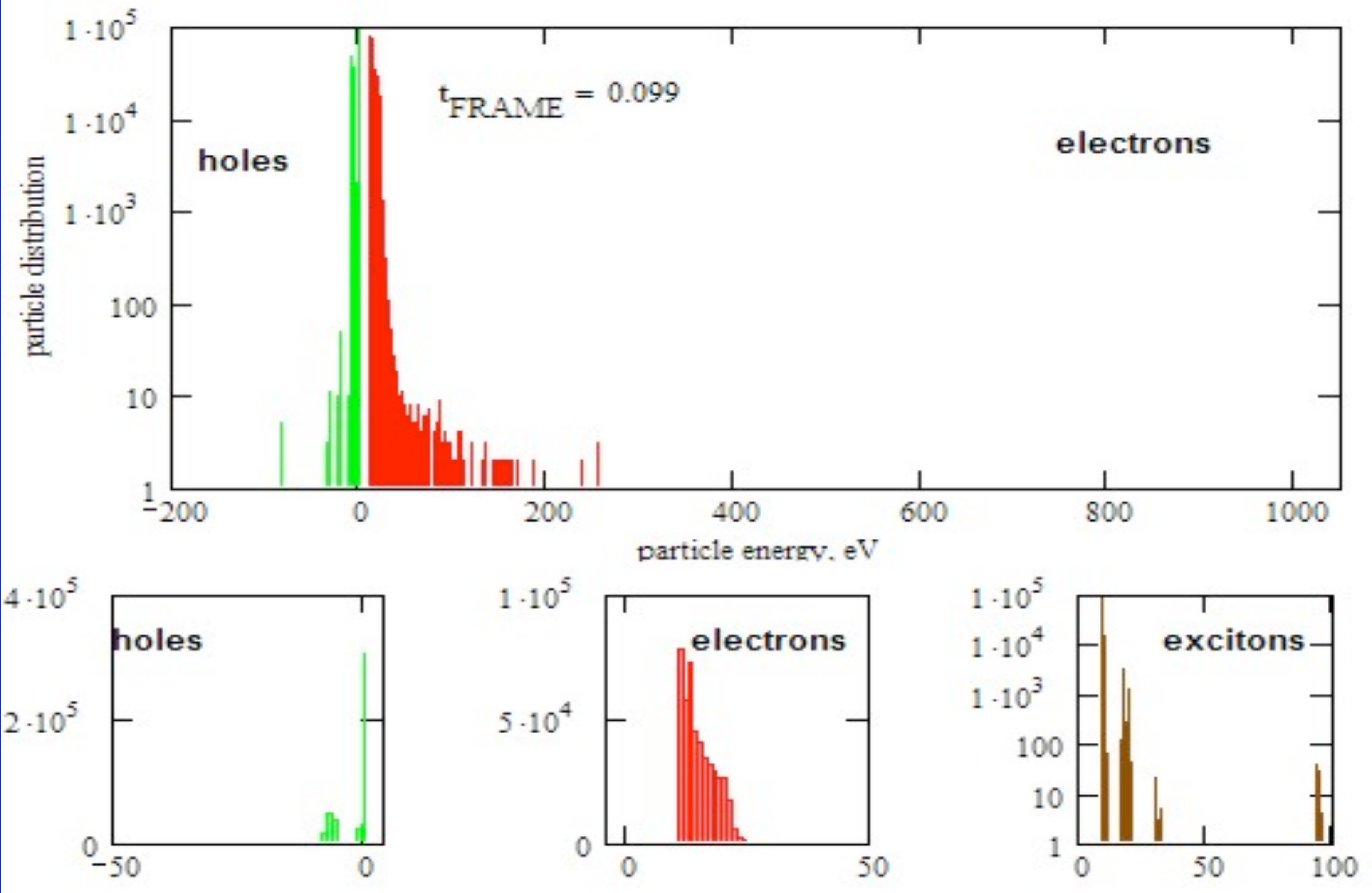
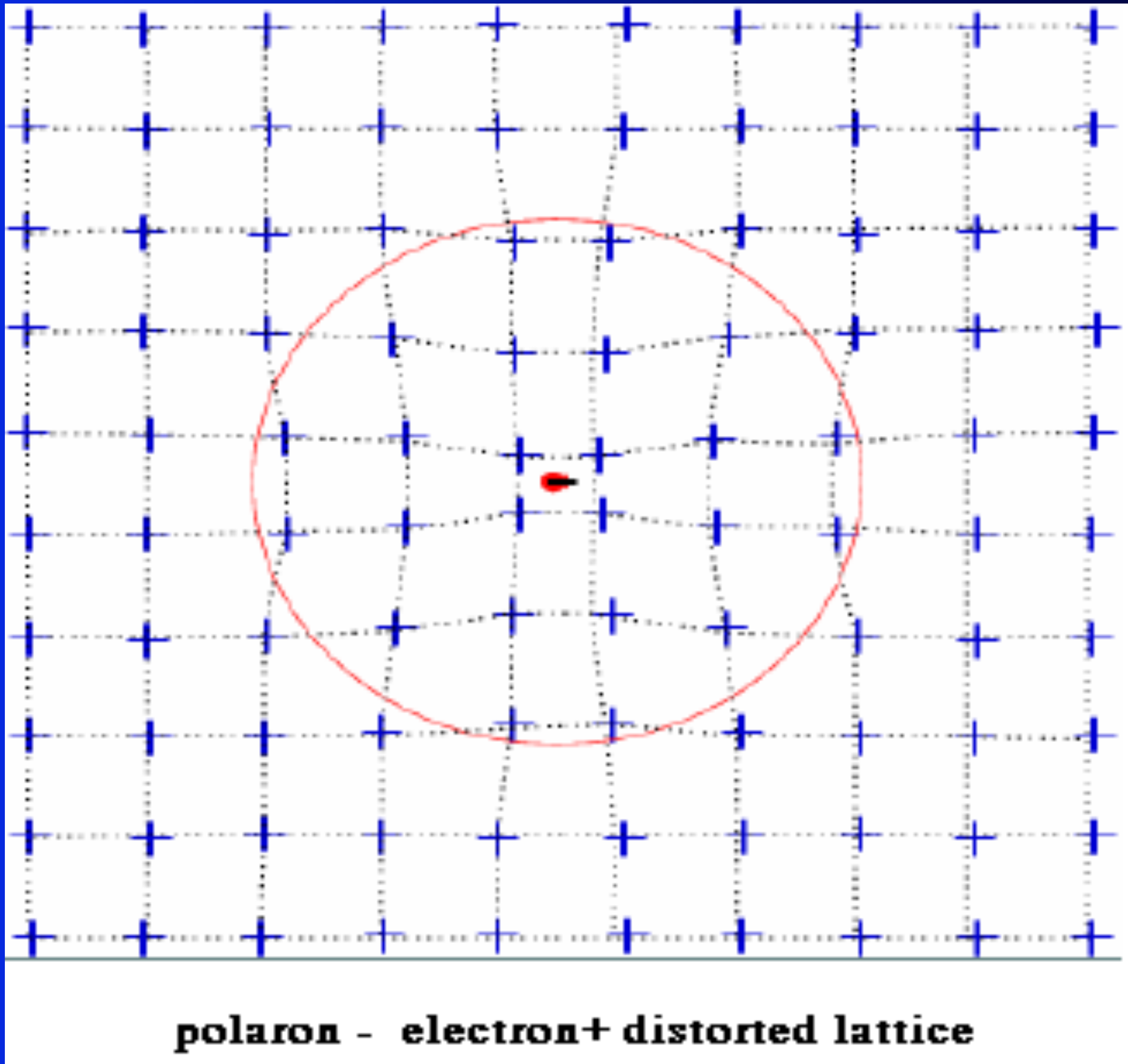
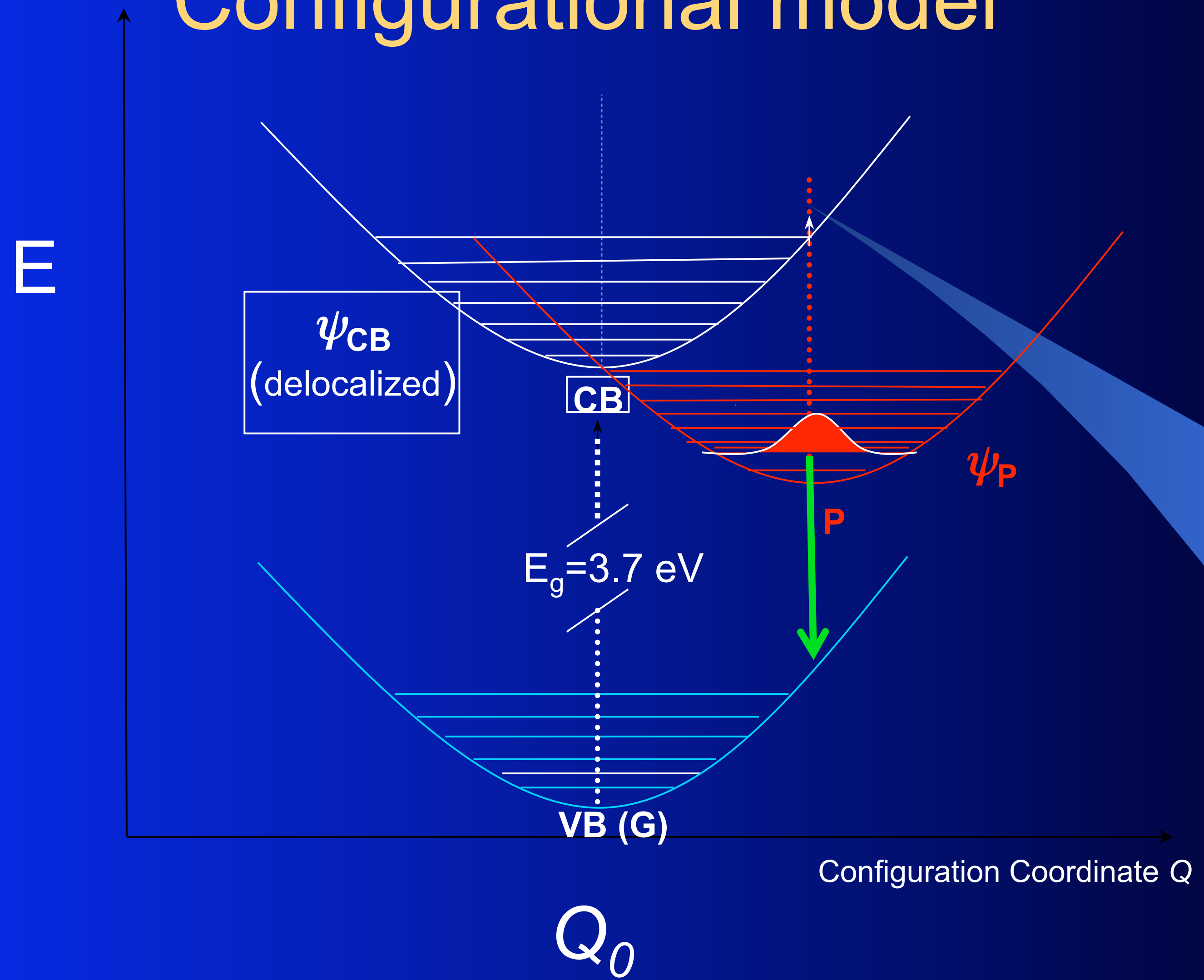


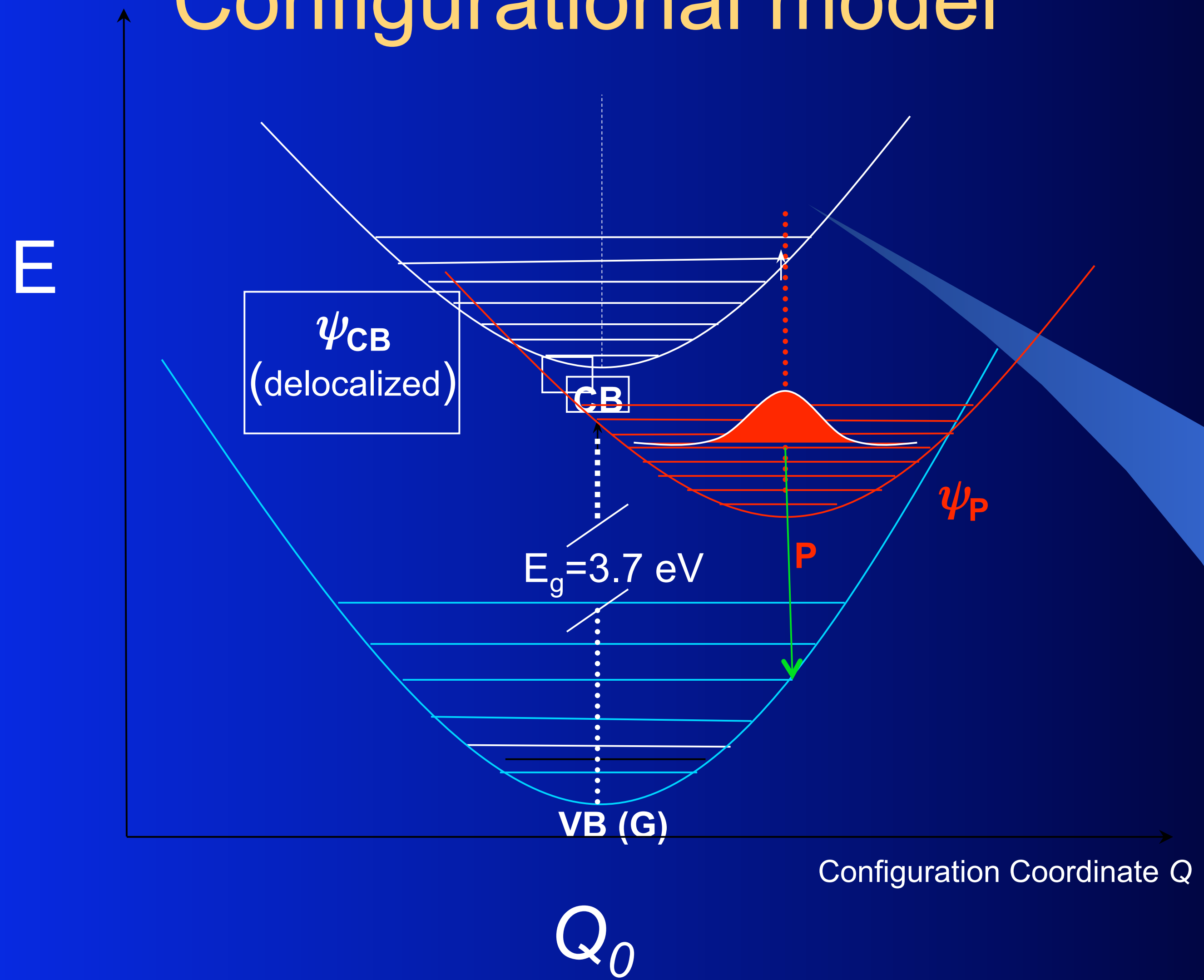

polaron - electron+ distorted lattice

Configurational model



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

Configurational model



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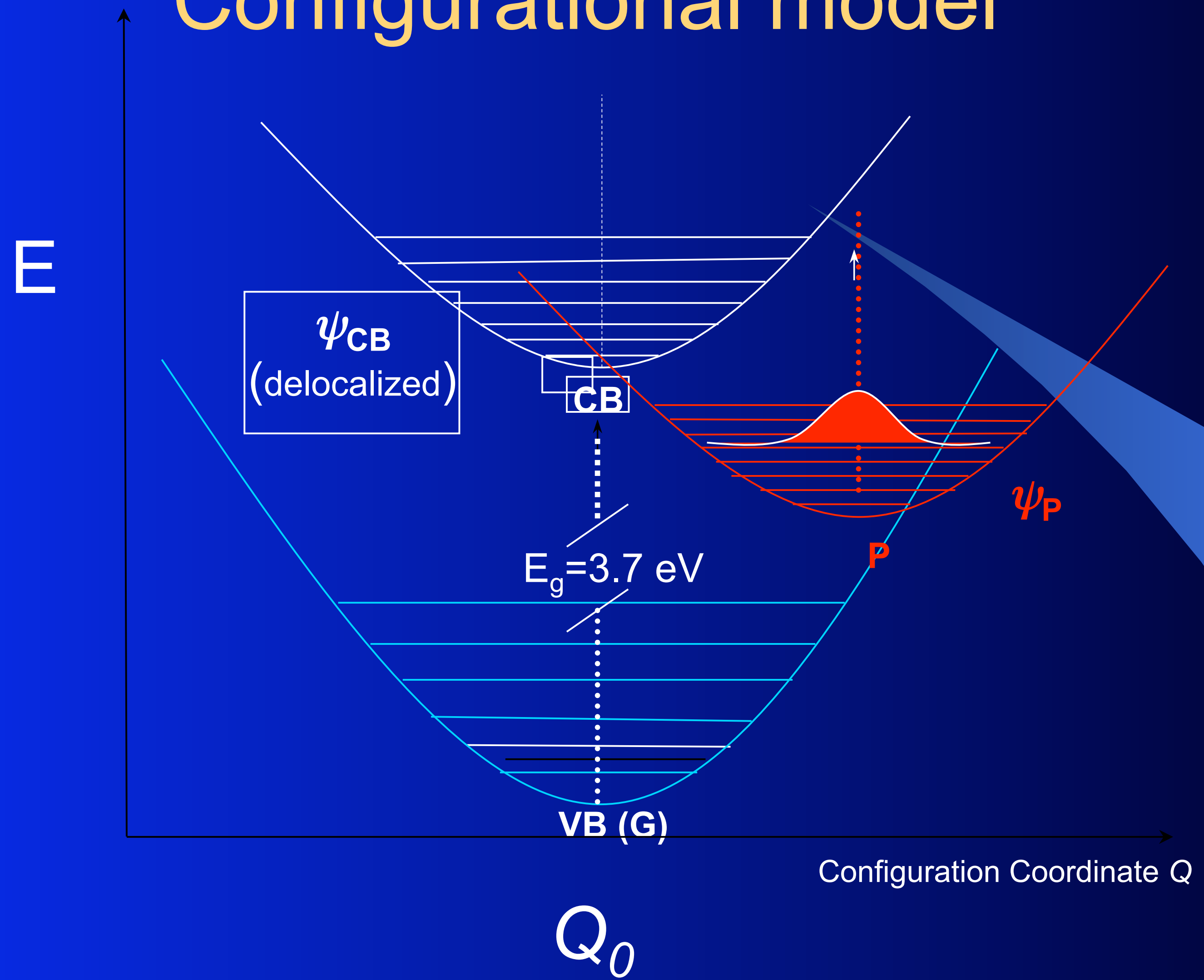


Configuration coordinate model for the local lattice with electron in **valence** and **conduction** ***band*** states and in ***localized*** **polaron** state.

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

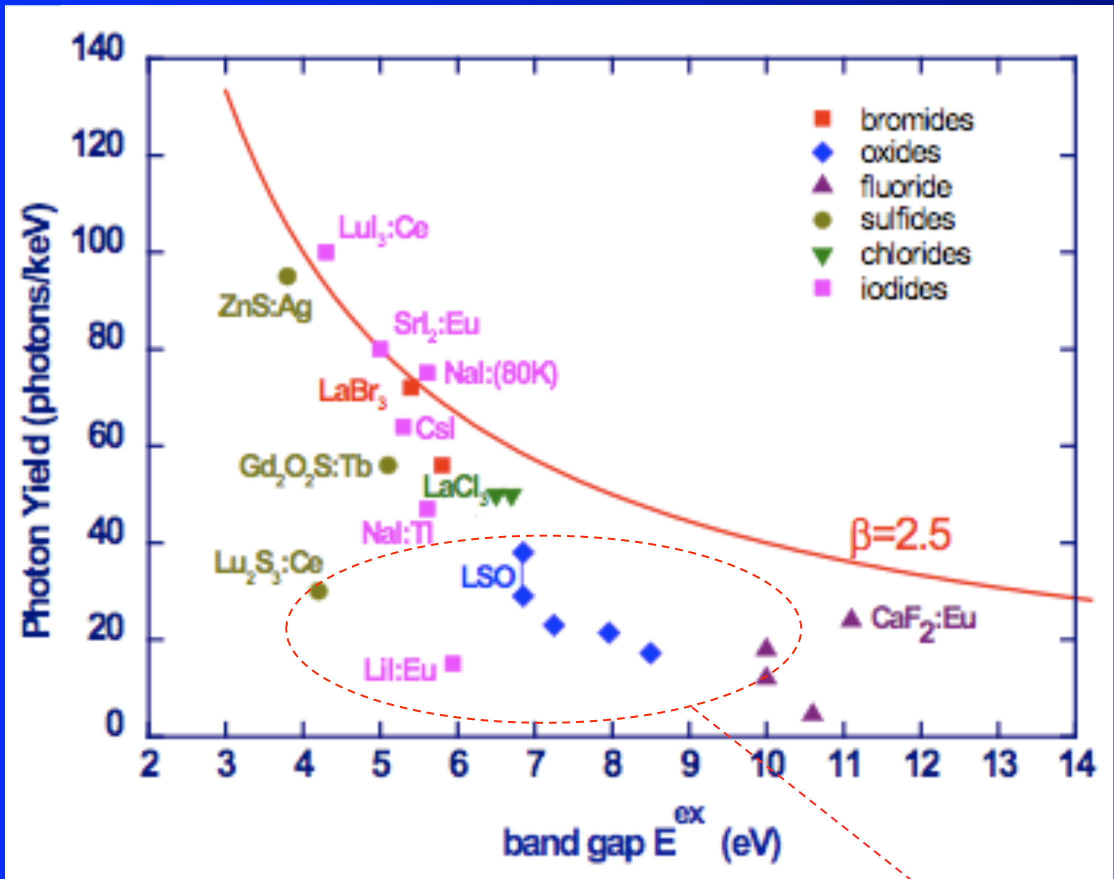
$$n_{photon} = n_{eh} S q = \frac{E_\gamma}{\beta' E_g} S q$$

Determination of the maximum of light

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

Usually $\beta = 2$ to 4

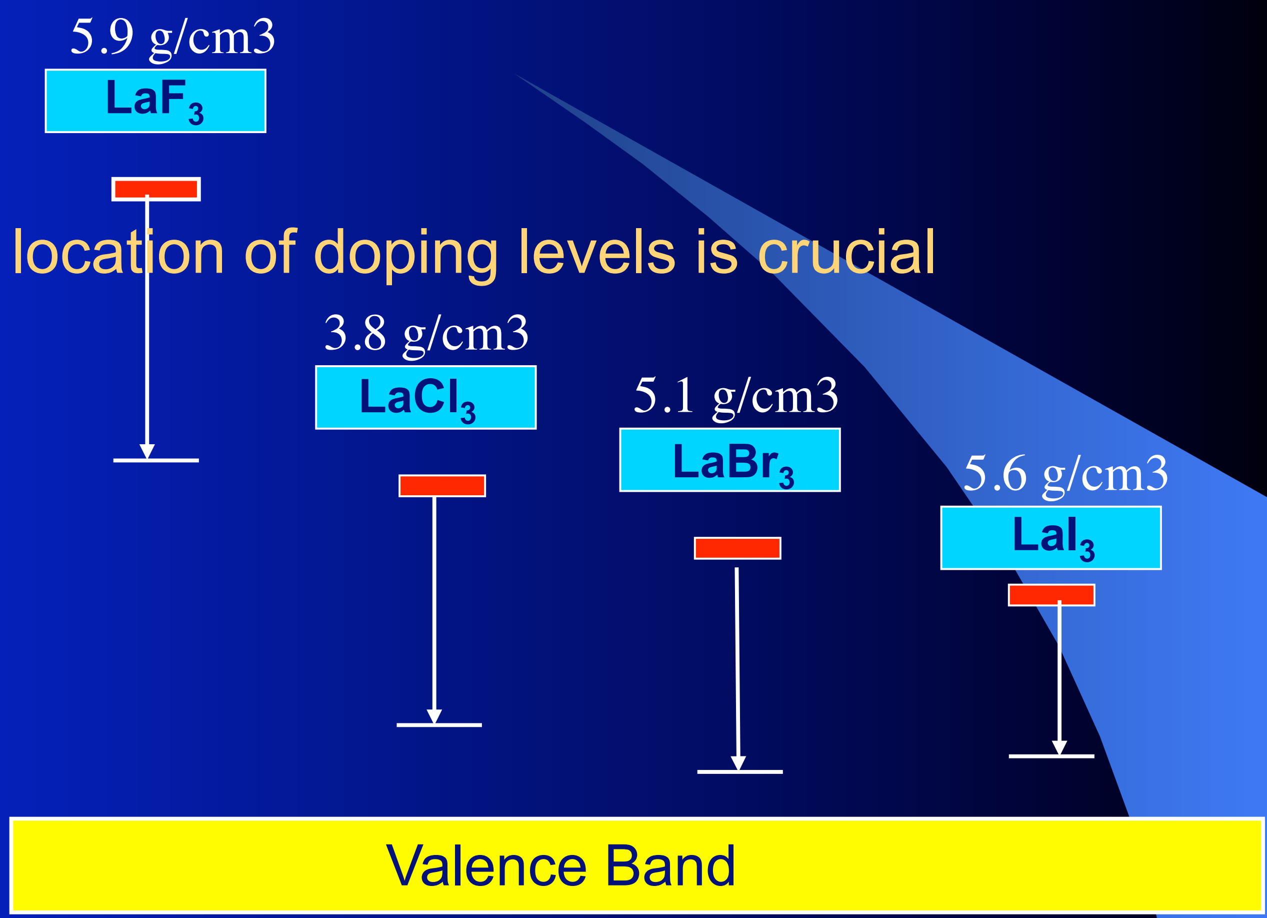
Fundamental limits to the LY



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

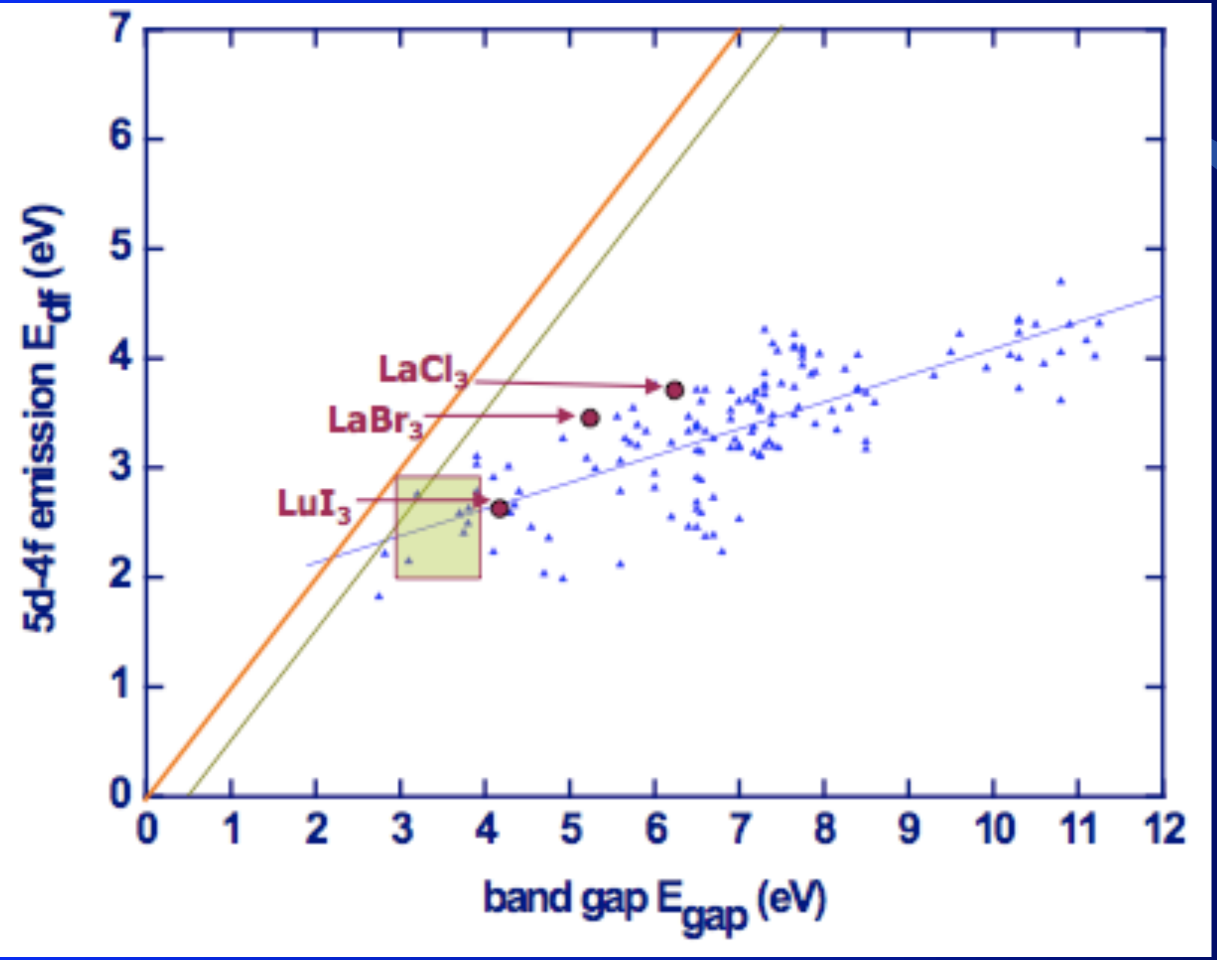
Why?

Towards smaller band gap compounds



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

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



Best result
LuI_3: Ce^{3+}

E_{gap} = 4.2eV

Y_{ph}=100000/MeV

$\lambda_{em} \approx$ 470 nm

Ultimate Ce^{3+} Scintillator

E_{gap}>2.5-3 eV

$Y_{ph} \leq$140000/MeV

$\lambda_{em} \approx$ 600 nm

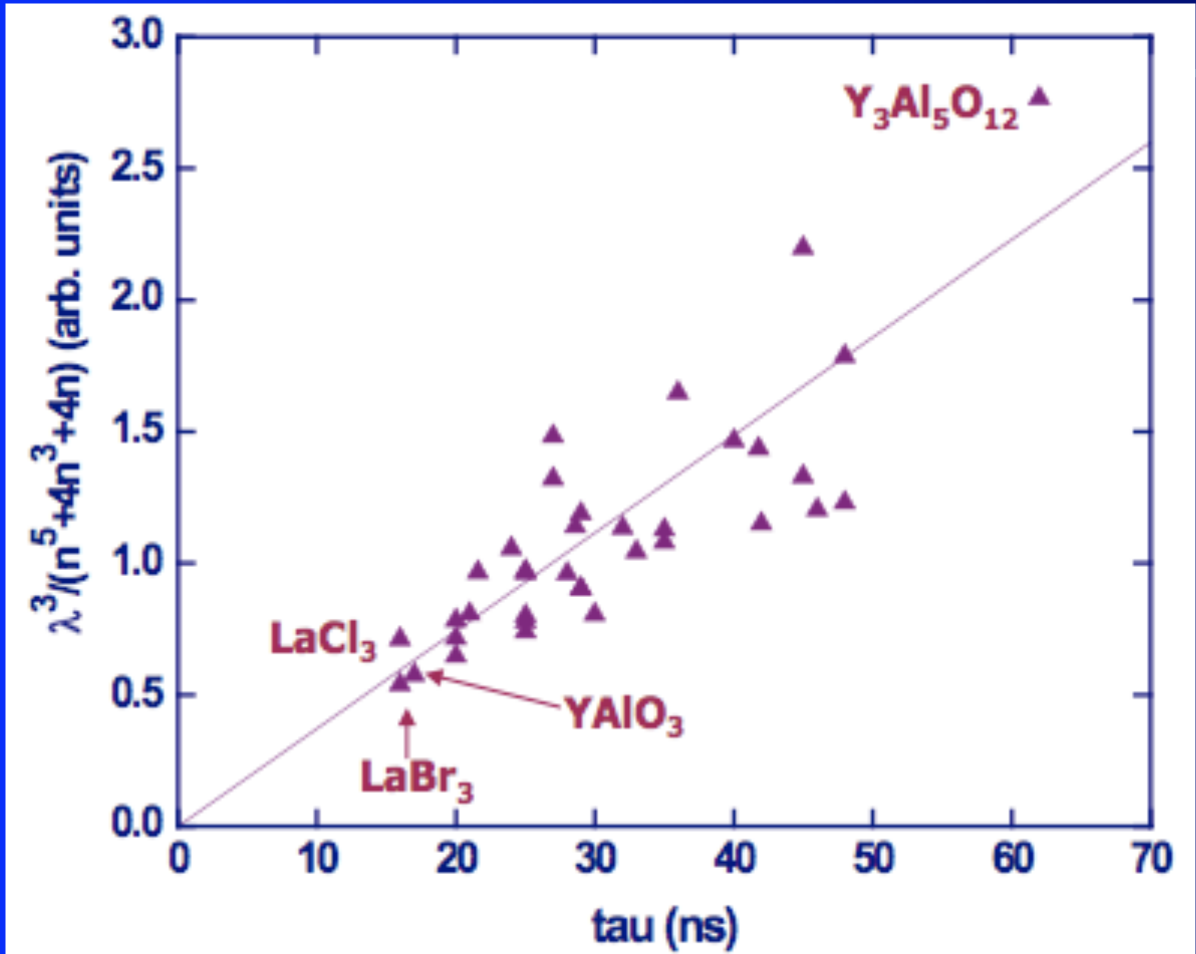
Why is Ce^{3+} so popular?
Limits on the scintillation speed

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

Three important aspects

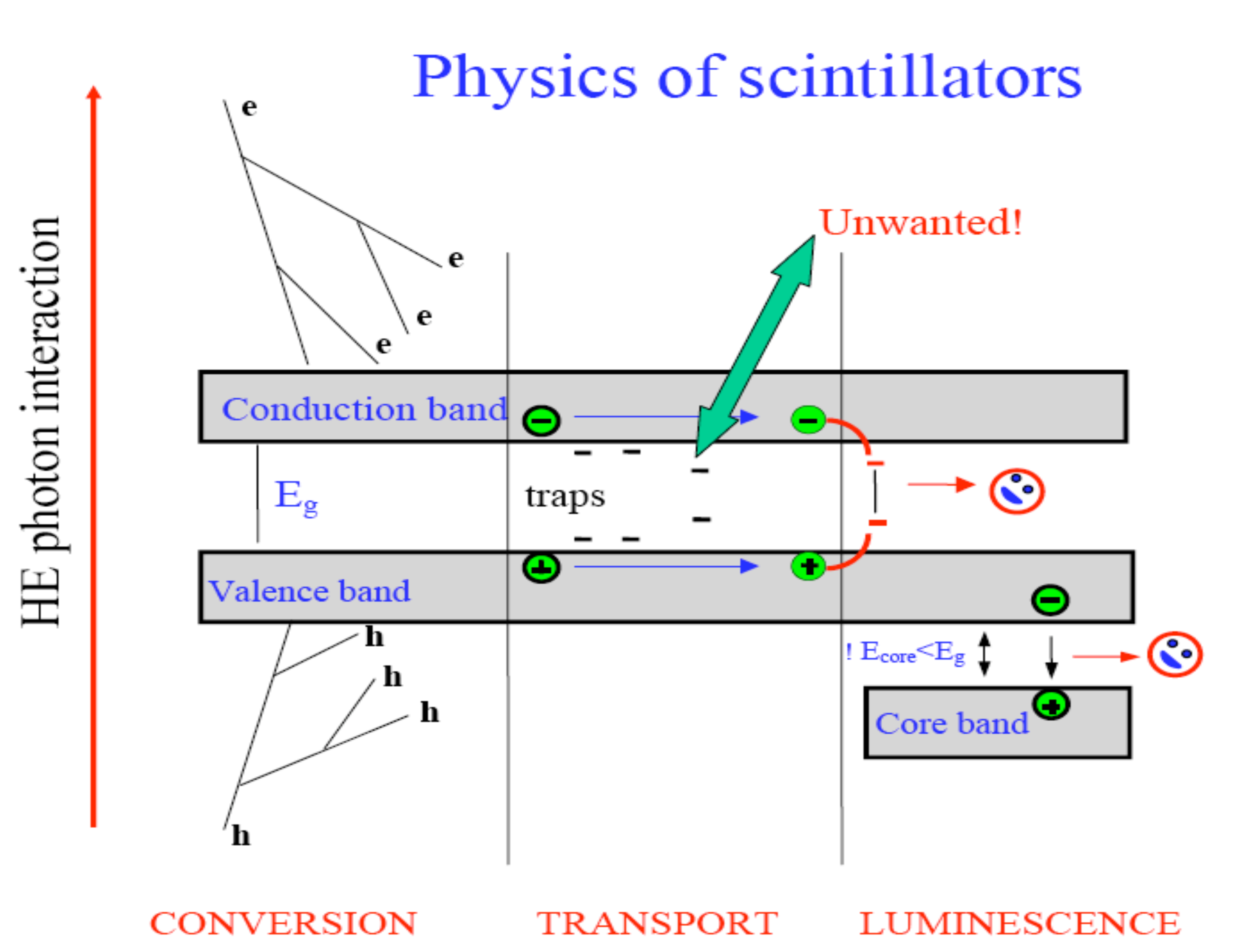
- Dipole and spin allowed transitions
- Short wavelength of emission
- High refractive index

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



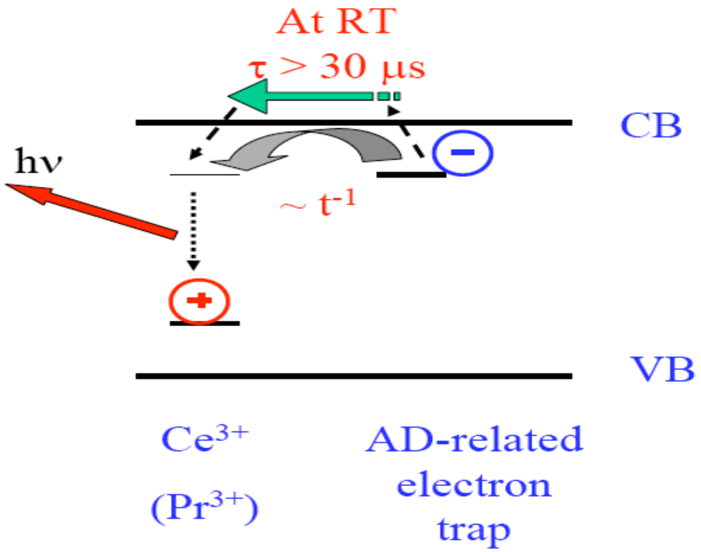
$$\tau \approx A \times \frac{\lambda^3}{n^5 + 4n^3 + 4n}$$

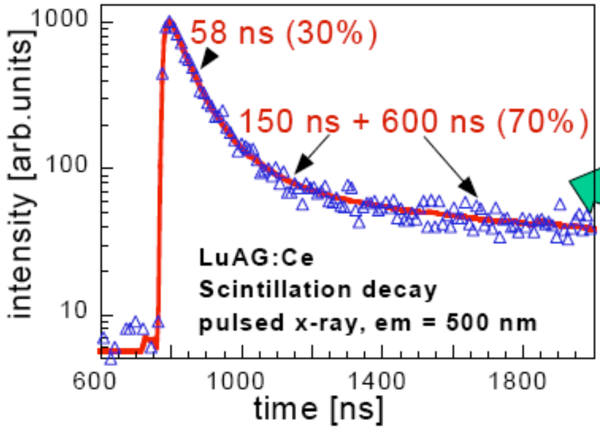
Effect of traps



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)

Conclusions

- Luminescence (laser)
  - Characterized by direct interband excitation and relaxation
  - Performance determined by Kramers-Kronig relations for the optical transitions
- Scintillation
  - Characterized by higher excitation energy than interband transitions
  - Performance characterized by:
    - Cooling and relaxation of hot e-h pairs
    - Density and possible interaction of excitations
    - Luminescence mechanism

Thank you