

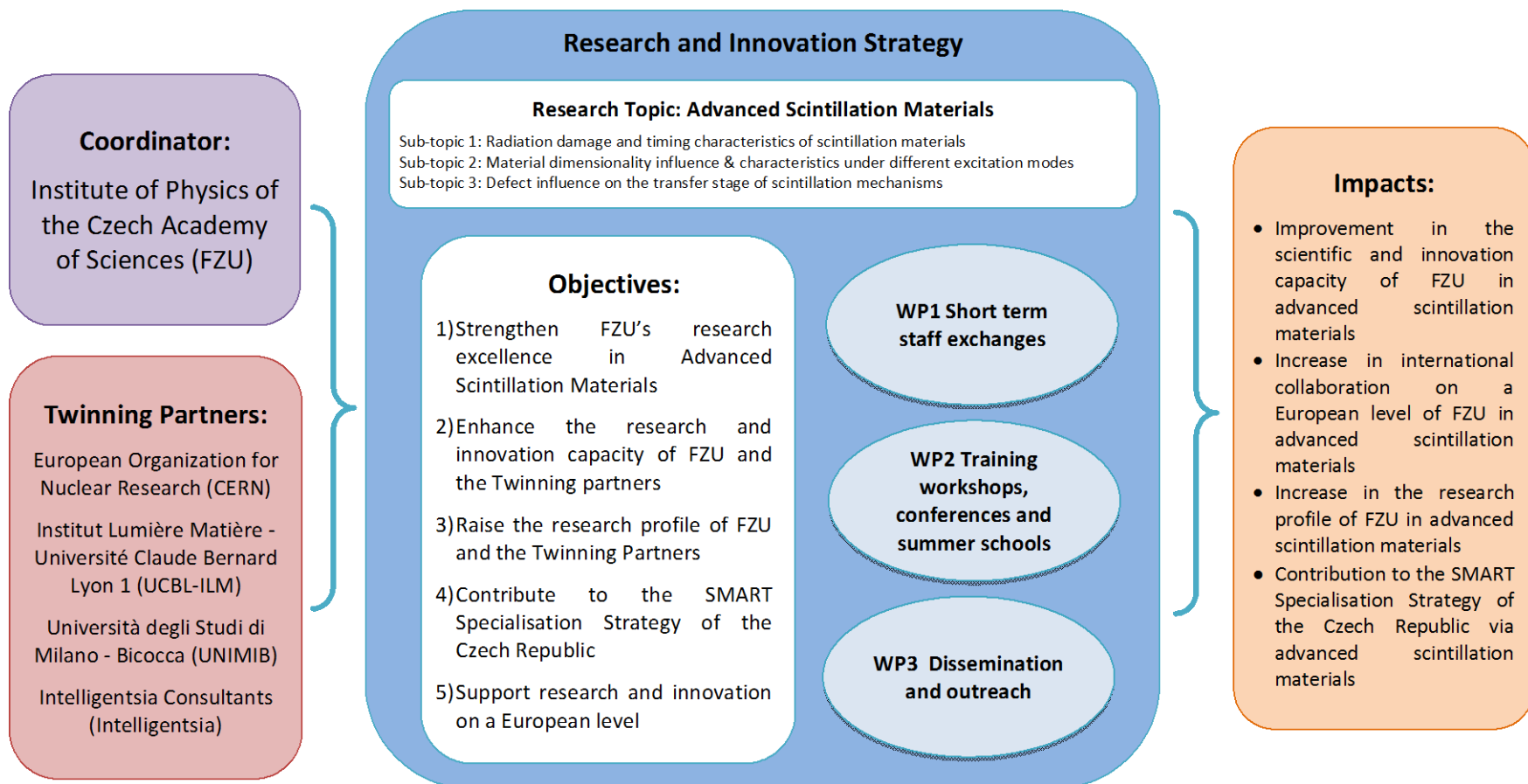
ASCIMAT: Increasing the scientific excellence and innovation capacity in Advanced Scintillation Materials of the Institute of Physics from the Czech Academy of Sciences

First periodic review

Date: 29/06/2017

Venue: EC, Covent Gardens Building, Brussels

Introduction: ASCIMAT High-Level View

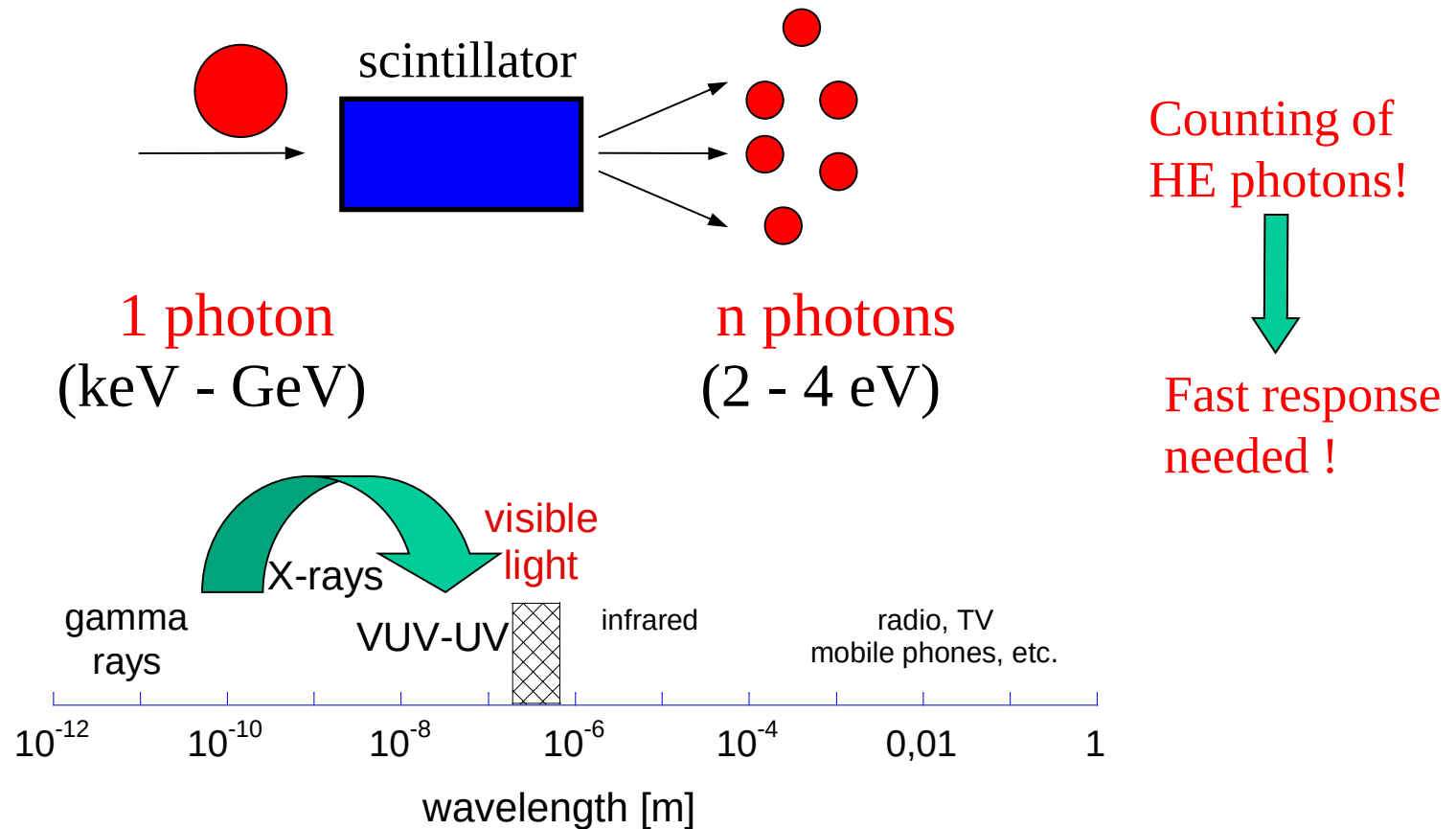


Scintillator materials – physical mechanism, role of defects and bottlenecks

Martin Nikl

Institute of Physics, AS CR, Prague, Czech Republic

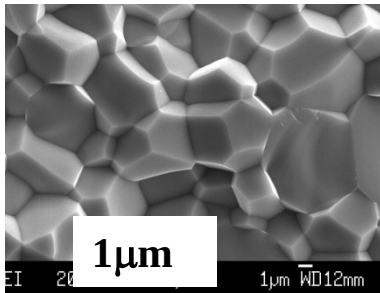
Principle of scintillators



Single crystals, ceramics, films, glasses and more...



Czochralski grown PbWO_4 ,
IP Prague



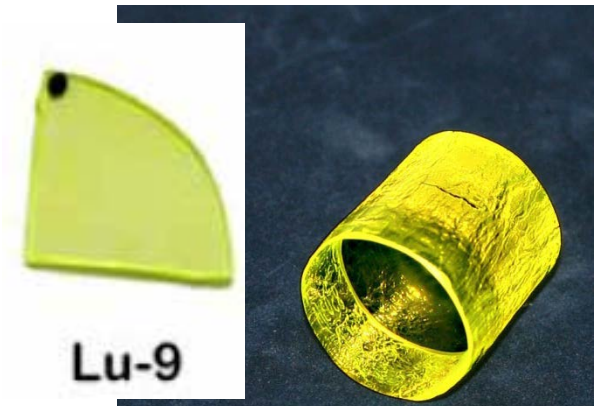
Ce-doped YAG ceramics
SICCAS Shanghai



Ce-doped silica glass,
DMS-University of Milano-Bicocca



0.25-1mol% Pr-doped $\text{Lu}_3(\text{Al,Ga})_5\text{O}_{12}$
micropulling-down grown, IMRAM,
Tohoku university, Sendai, Japan

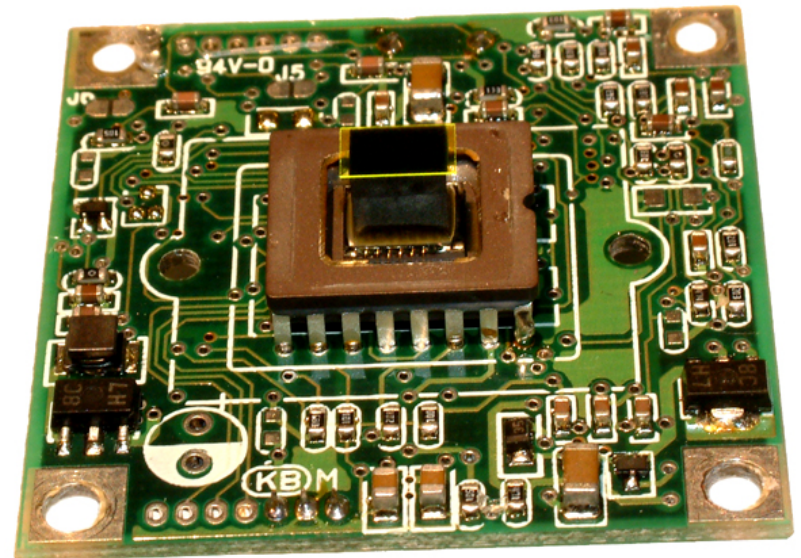


Czochralski&LPE grown (Y-
Lu)AlO₃, $\text{Lu}_3\text{Al}_5\text{O}_{12}:\text{Ce}$,
CRYTUR Ltd., CR and I.F.
University Lviv, Ukraine

Scintillation detector =
scintillator+photodetector

⇒ registration of X-rays or γ -radiation, energetic particles or ions.

Scintillator TRANSFORMS high-energy photons into photons in UV/VIS spectral region, which one can easily and with high sensitivity register by the conventional photodetectors.

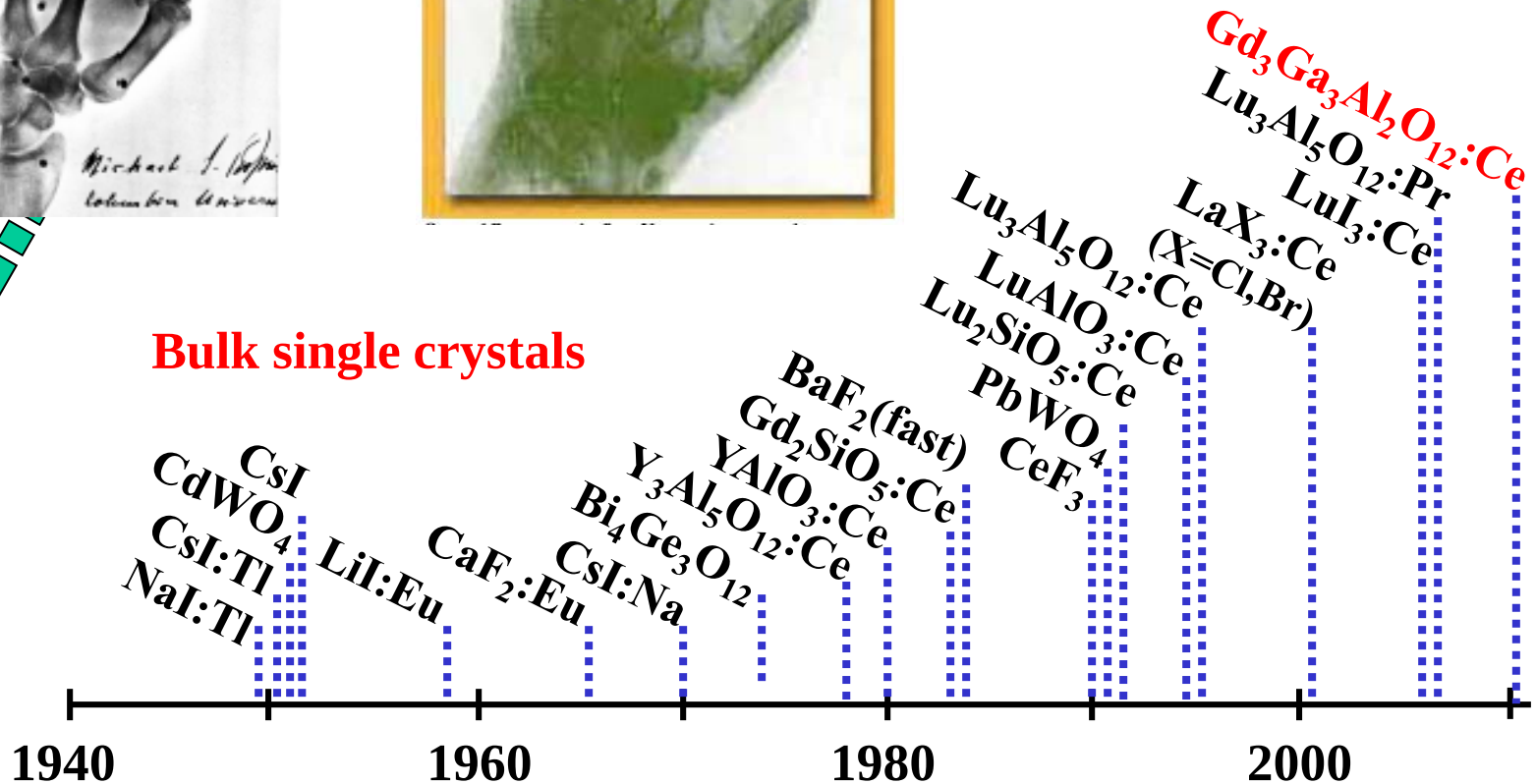




History of scintillators starts short after the discovery of X-rays at the end of 19th century ... today mainly the **DOPED** materials in use

CaWO₄
powder
in 1896

Bulk single crystals



Year of introduction of a scintillation material

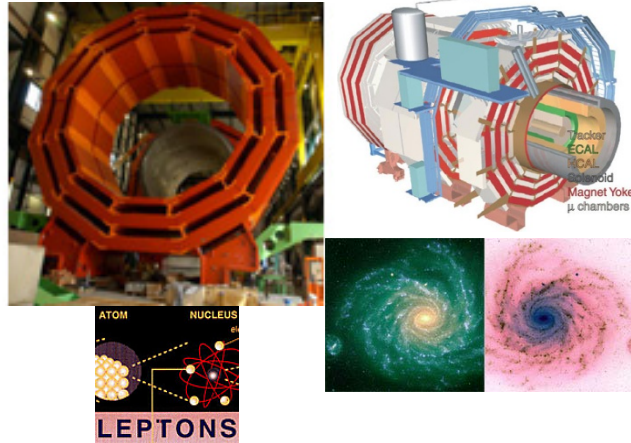
Applications of scintillators

Medical application



PET, SPECT, CT

High energy physics



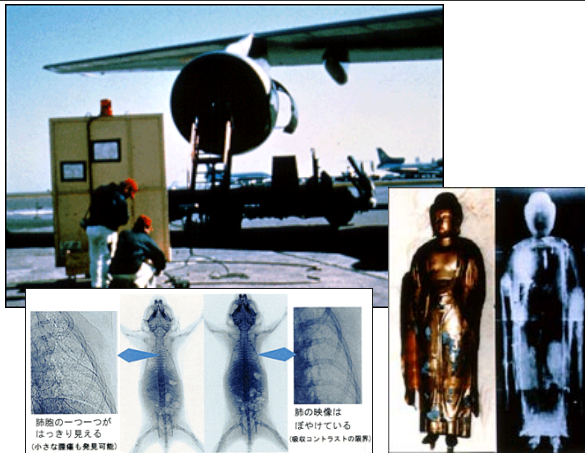
Particle physics, ...

Security check



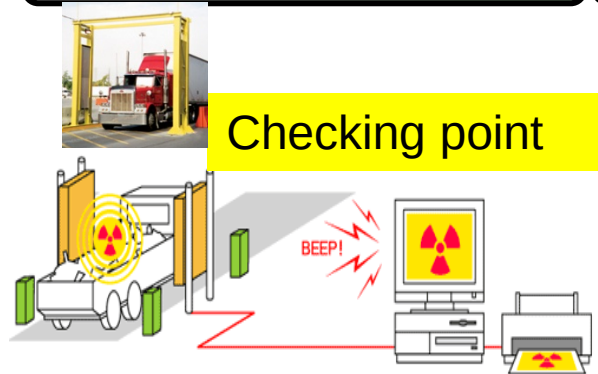
X-ray scanning

Nondestructive analysis



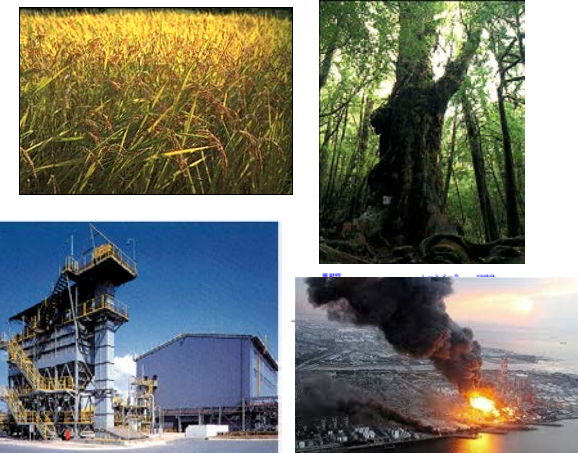
Computed tomography

X&Neutron-based



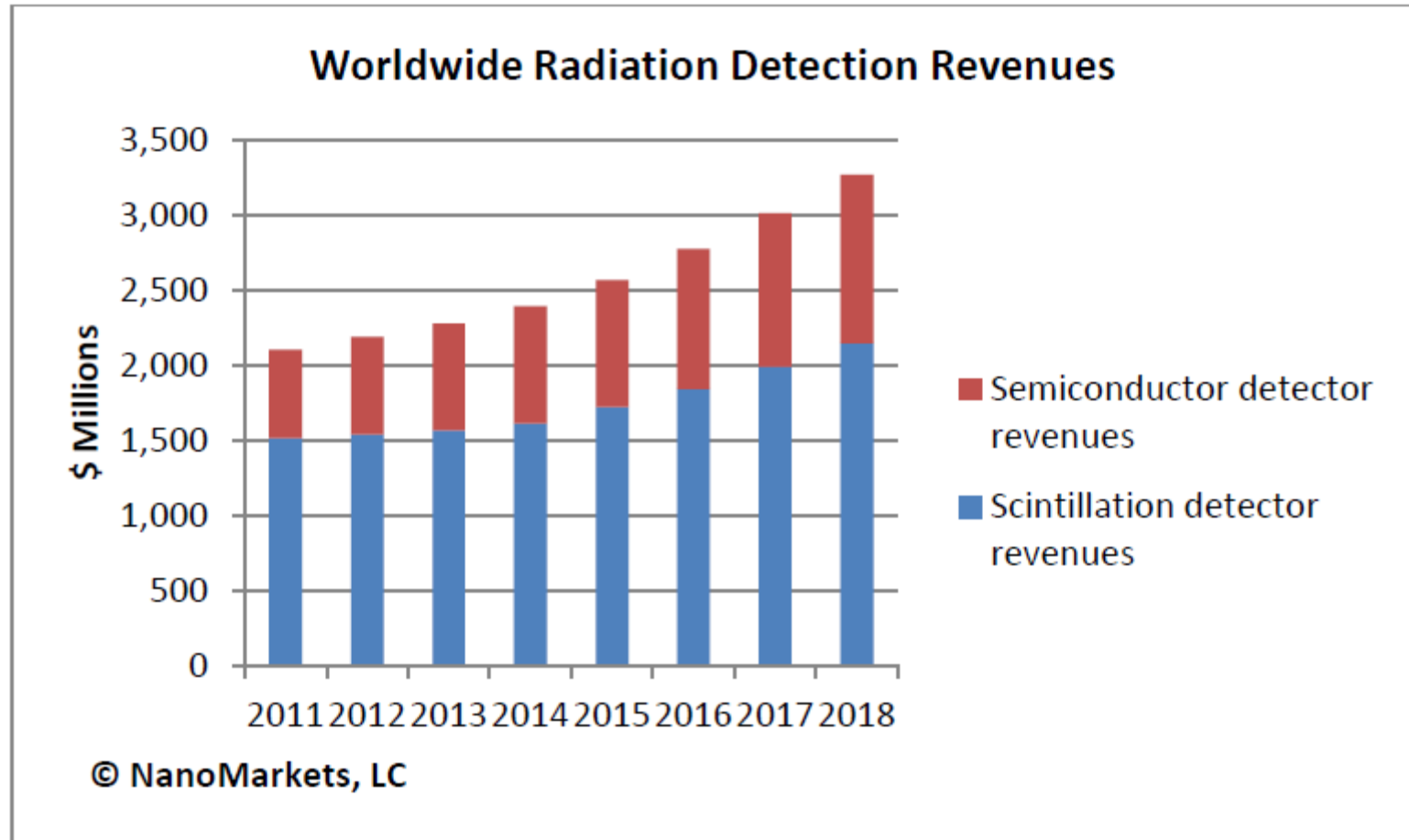
Remote detection

Other applications



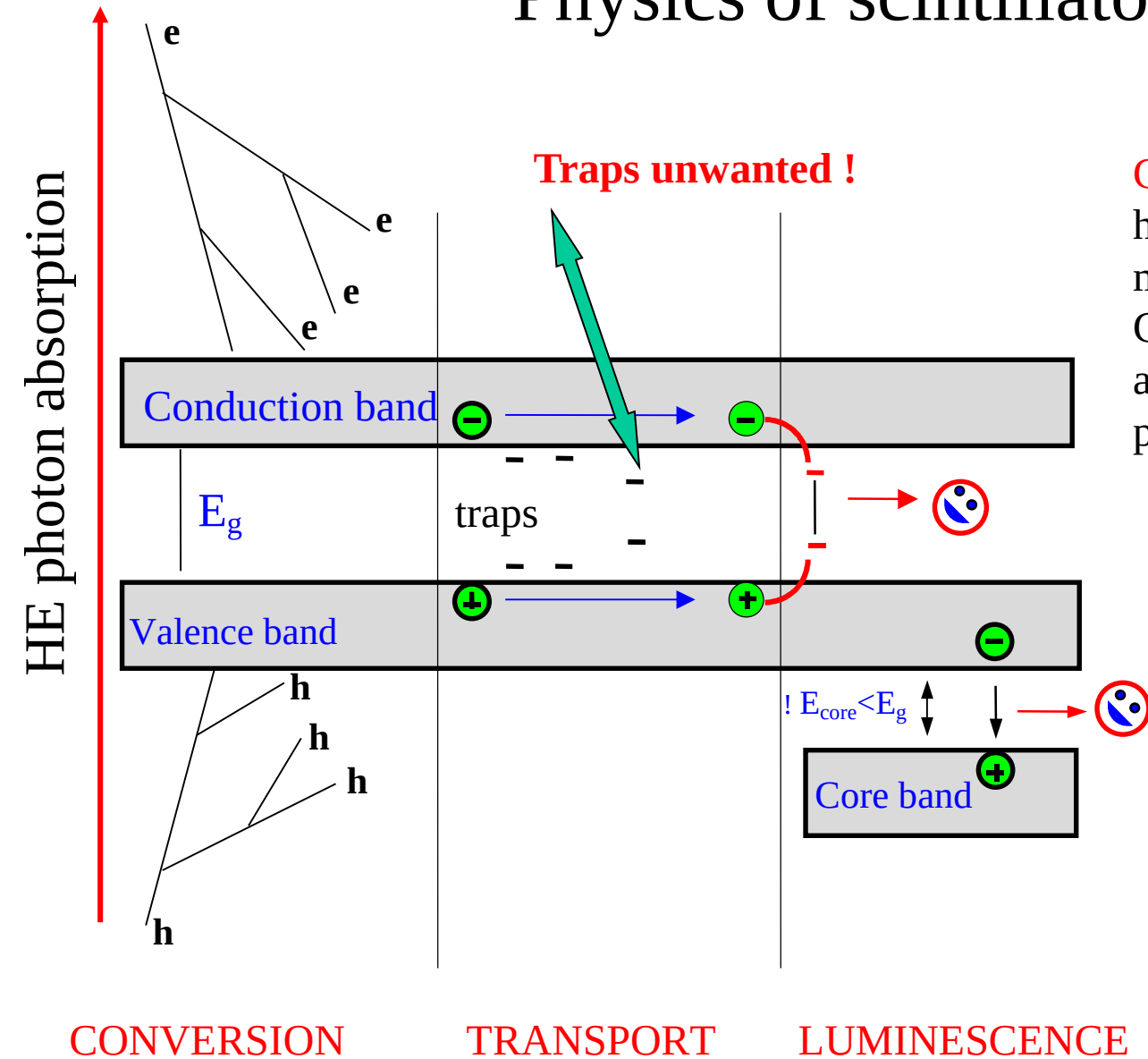
Hazards, disasters, geology

Radiation detectors - Revenues worldwide



70-75% of revenues comes from scintillation detectors

Physics of scintillators



CONVERSION -interaction of a high-energy photon with a material through photoeffect, Compton effect, pair production, appearance of electron-hole pairs and their thermalization

TRANSPORT - diffusion of electron-hole pairs (excitons) through the material, possible (repeated) trapping at defects, nonradiative recombination

LUMINESCENCE -trapping of charge carriers at the luminescence centre and their radiative recombination

Conversion HE photon→e-h pairs

The intensity I of a gamma beam traversing a target of thickness d is

$$I = I_0 e^{-\mu d}$$

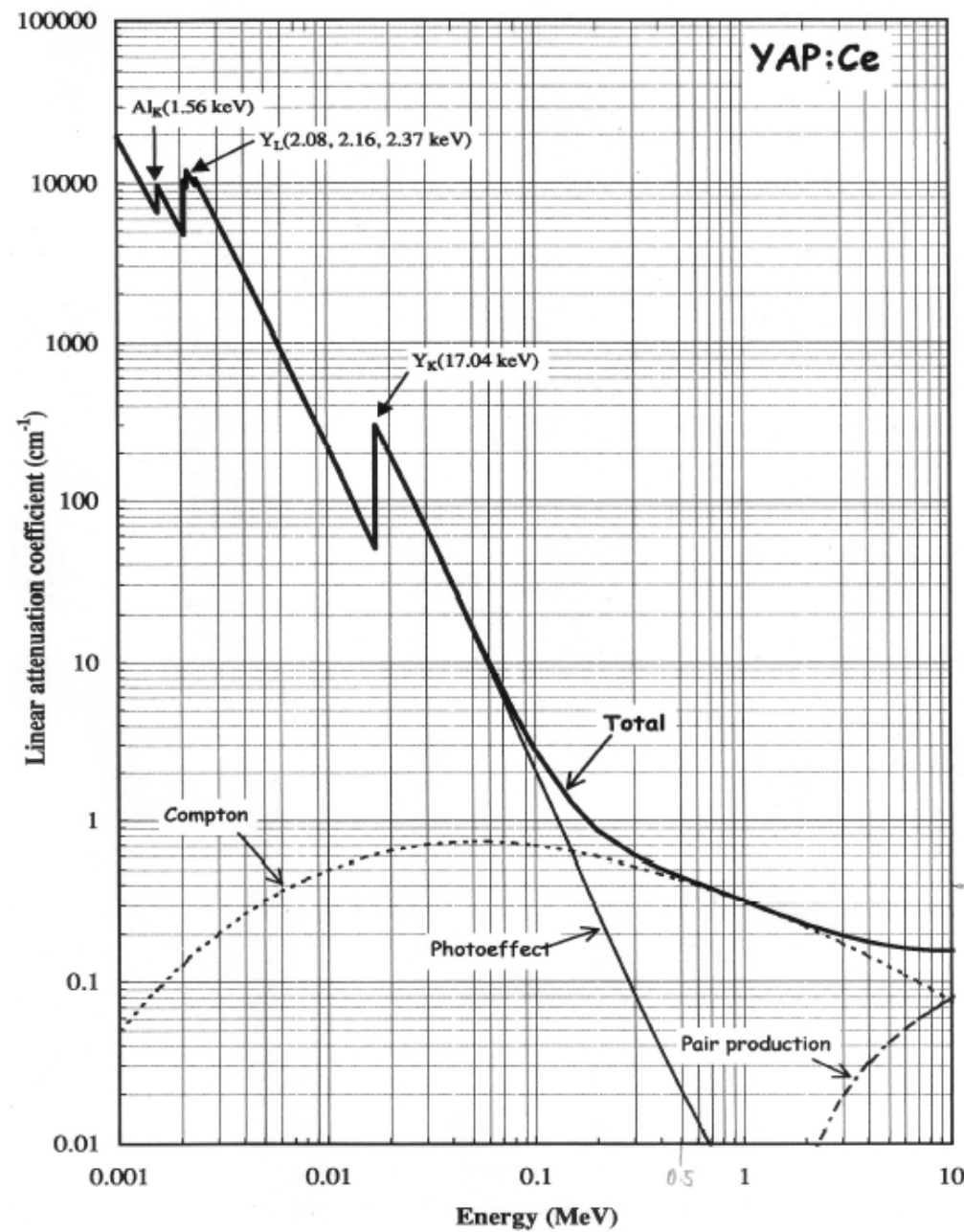
Where μ is the sum of three processes taking place in the material:

Photoel. Abs. $\rightarrow Z^4$ to Z^5

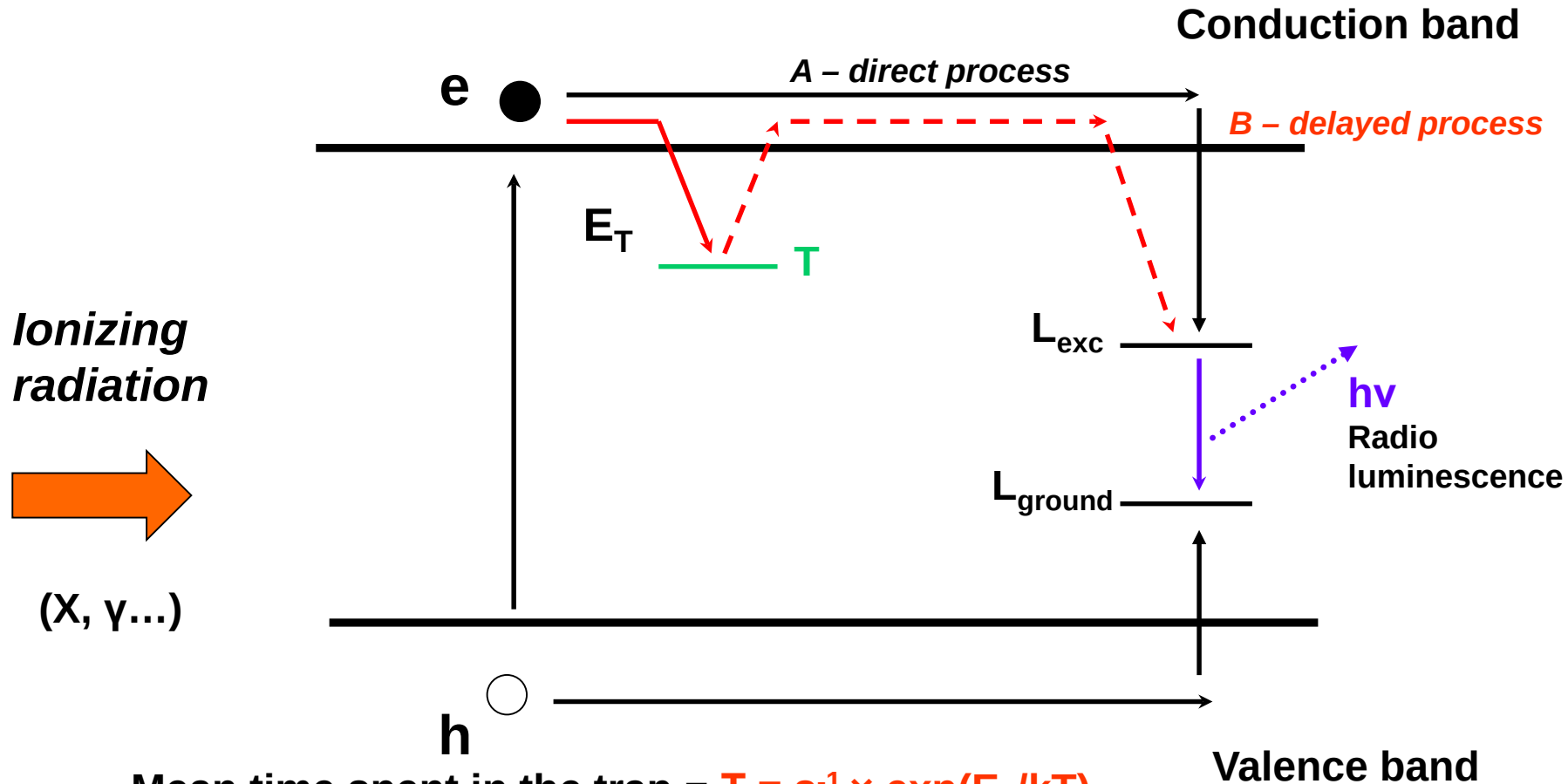
Compton scatt. $\rightarrow Z$ -

Pair production $\rightarrow Z^2$ -

The processes in this stage affect nonproportionality!



TRAPPING-DETRAPPING PROCESSES in TRANSPORT



Mean time spent in the trap = $T = s^{-1} \times \exp(E_T/kT)$

According to the E_T value (0.01-1 eV) and ambient temperature a very wide range of T can be measured ($1 \mu s - 10^6$ years)

TRAP ARISE DUE TO POINT OR EXTENDED MATERIAL DEFECTS!

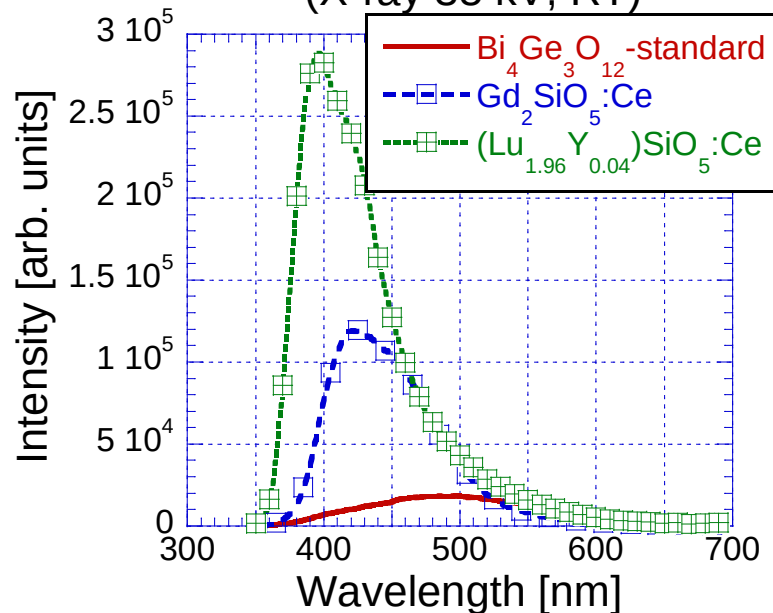
Parameters, characteristics and methods

- Integral efficiency
- **Light yield and Energy resolution**
- Emission wavelength
- **Speed of scintillation response**
- Density
- **Radiation resistance**
- Chemical composition
- Price

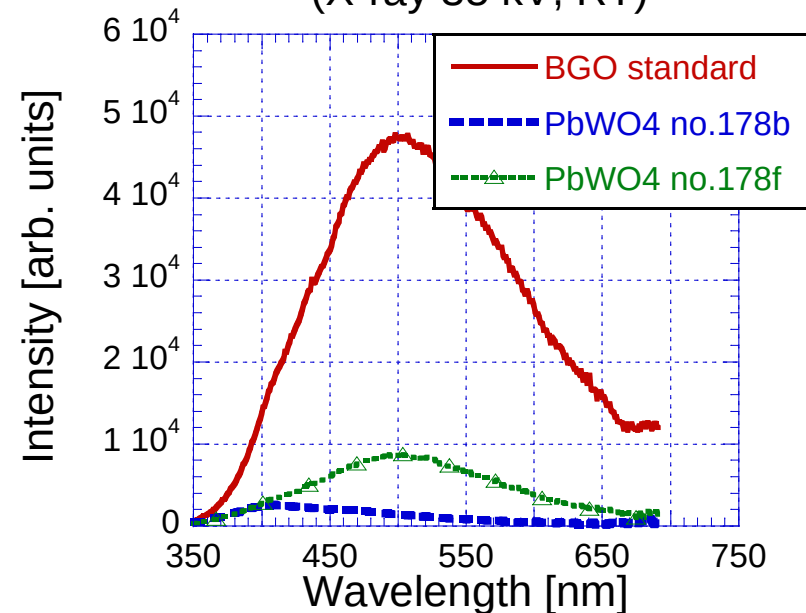
Integral efficiency

Absolute comparison of radioluminescence spectra of a material with the standard sample in the same experimental conditions

Radioluminescence spectra
(X-ray 35 kV, RT)

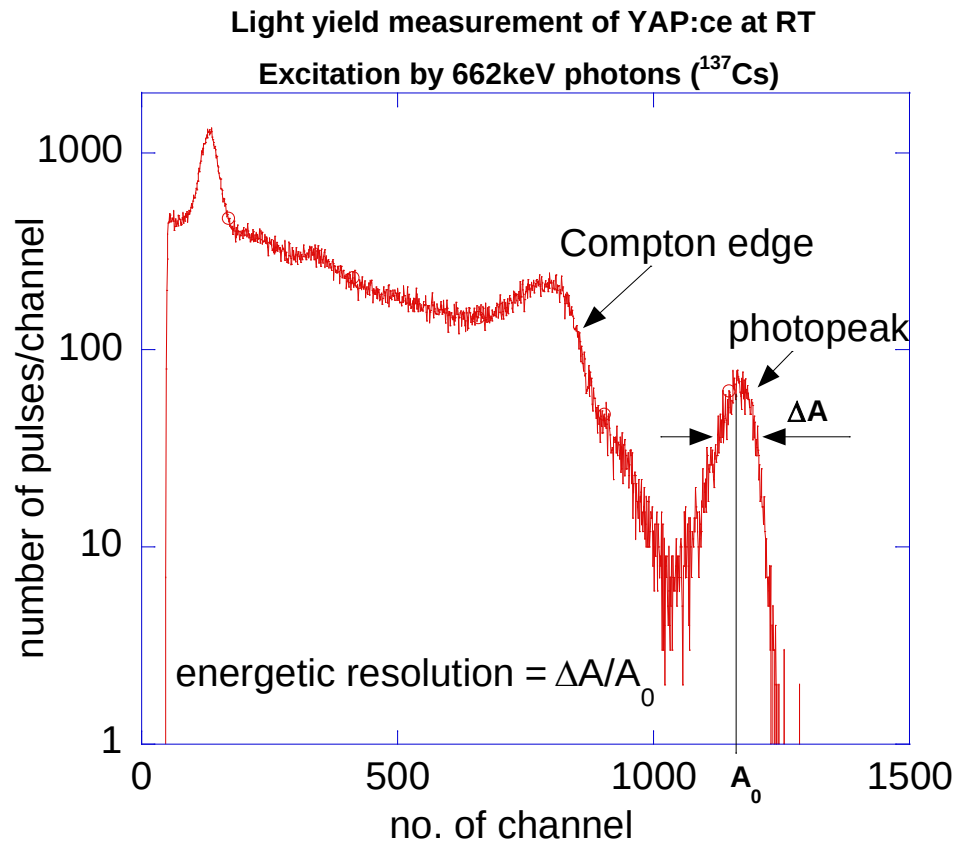


Radioluminescence spectra
(X-ray 35 kV, RT)



Integral efficiency $\eta = \beta \cdot S \cdot Q$ equals to multiplied sub-efficiencies of the conversion, transport and luminescence stages

Light yield



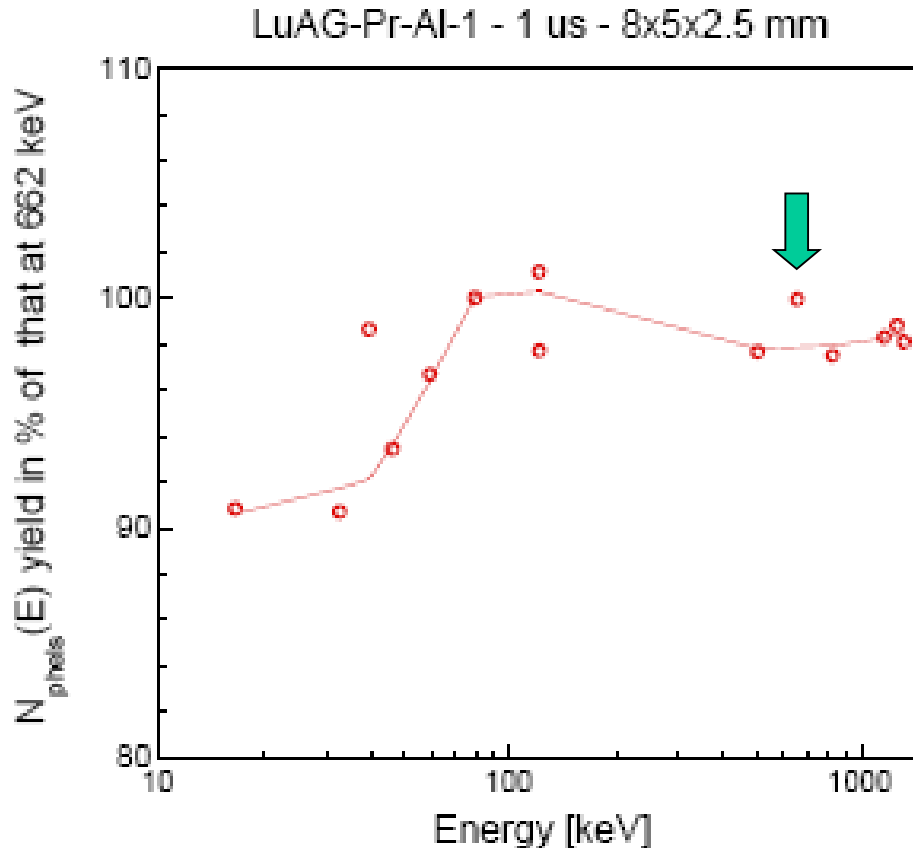
Using known quantum efficiency of PMT photocathode, photoel. Yield is recalculated in Light yield given in [photons/MeV]

the best classical materials as NaI:Tl, CsI:Tl give 40 000-50 000 phot/MeV, BGO gives 8 000 phot/MeV.

Photoelectron yield measurement consists in the **measurement of the charge collected at the photomultiplier anode within certain time gate** (typ. 1 μs), i.e. **$U \cdot I \cdot \Delta t$** , after the absorption of high energy photon. Result of measurement is scaled within multichannel analyzer memory (**pulse height analysis** mode) and repeated many times to get reasonable statistics and well-resolved photopeak (obtained only if complete absorption of HE photon can be obtained in the sample, i.e. sufficiently big sample is needed).

Energy resolution is defined from the **FWHM of the photopeak**. (typical values are 5-15% at 662 keV). **It is negatively affected by nonproportionality.**

Photoelectron (light) yield nonproportionality



The non-proportionality of the $N_{\text{phels}}(E)$ photoelectron yield of LuAG:Pr Cz-grown crystal normalized to N_{phels} yield of ^{137}Cs 662 keV energy line

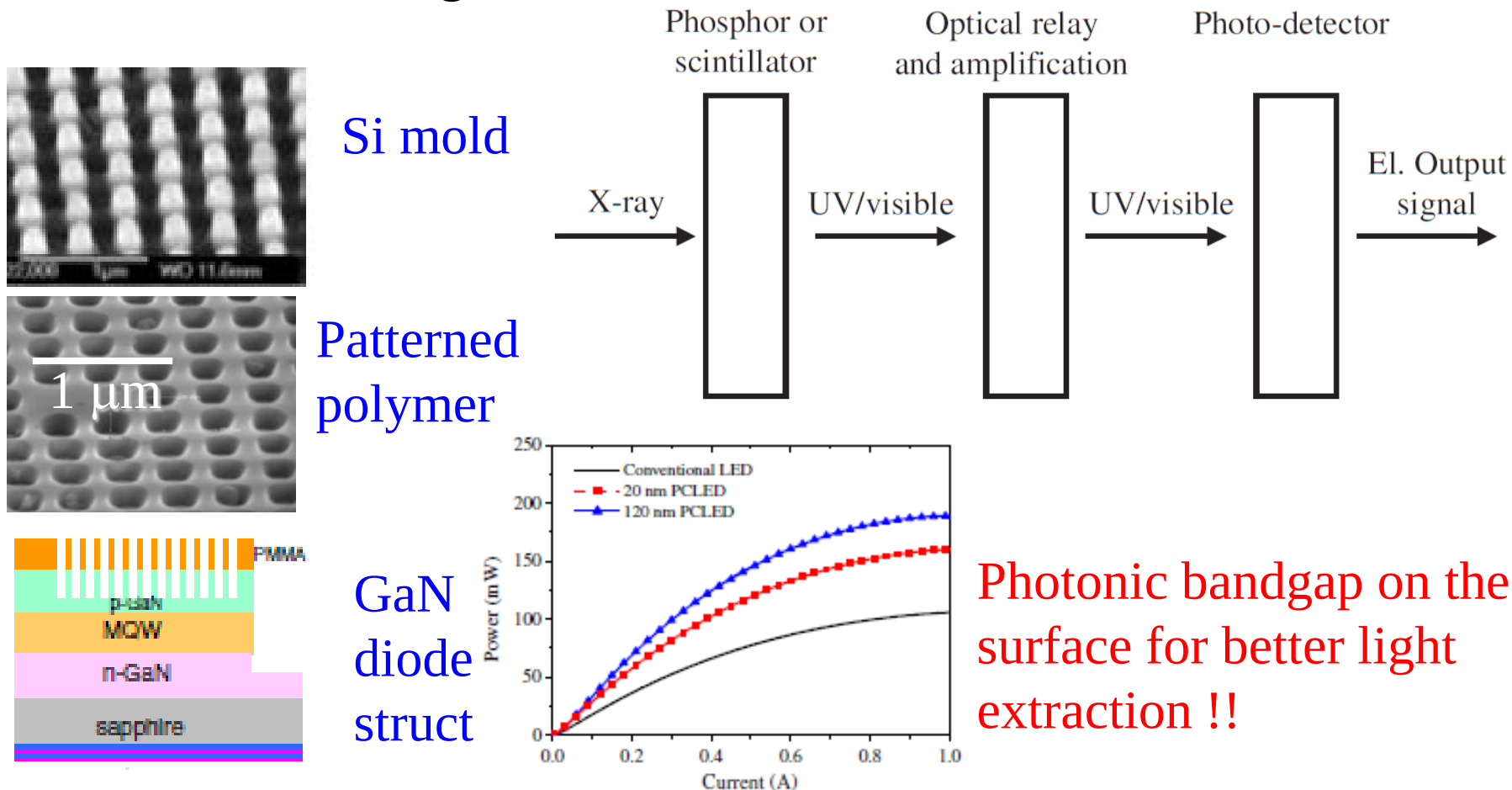
Photoelectron yield value (per MeV) depends on the energy of the incoming HE photons !!

Conversion of high energy photon into many electron-hole pairs at the end of Conversion stage is **many-step process with non-unique pathway**. Elementary steps are differing in “production yield” of final e-h pairs, closely spaced excitations may interact, material defects make it even more complex, etc.

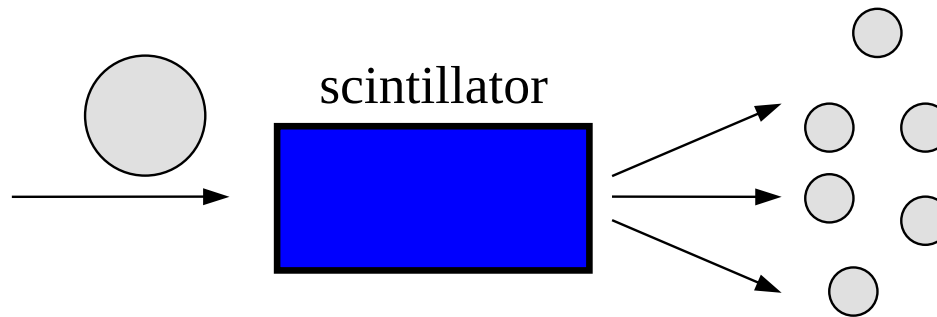
(Bizarri, *J. Appl. Phys.* **105**, 044507 (2009))

Optical coupling between scintillator and photodetector

By far not all the UV/visible light generated in scintillator can be delivered to the photodetector due to self-absorption, **internal reflection**, scattering losses, etc.

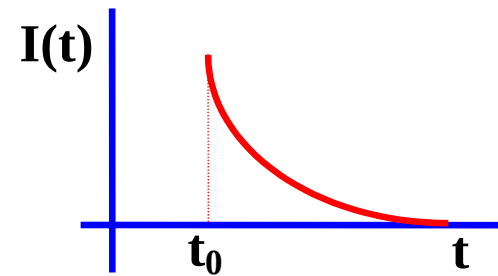
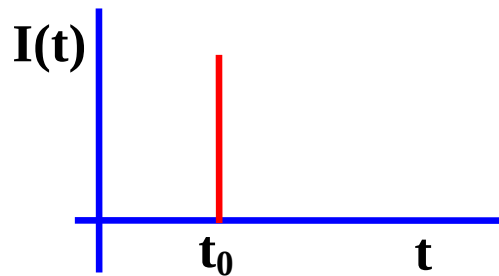


Speed of scintillation response



1 photon
(keV - GeV)

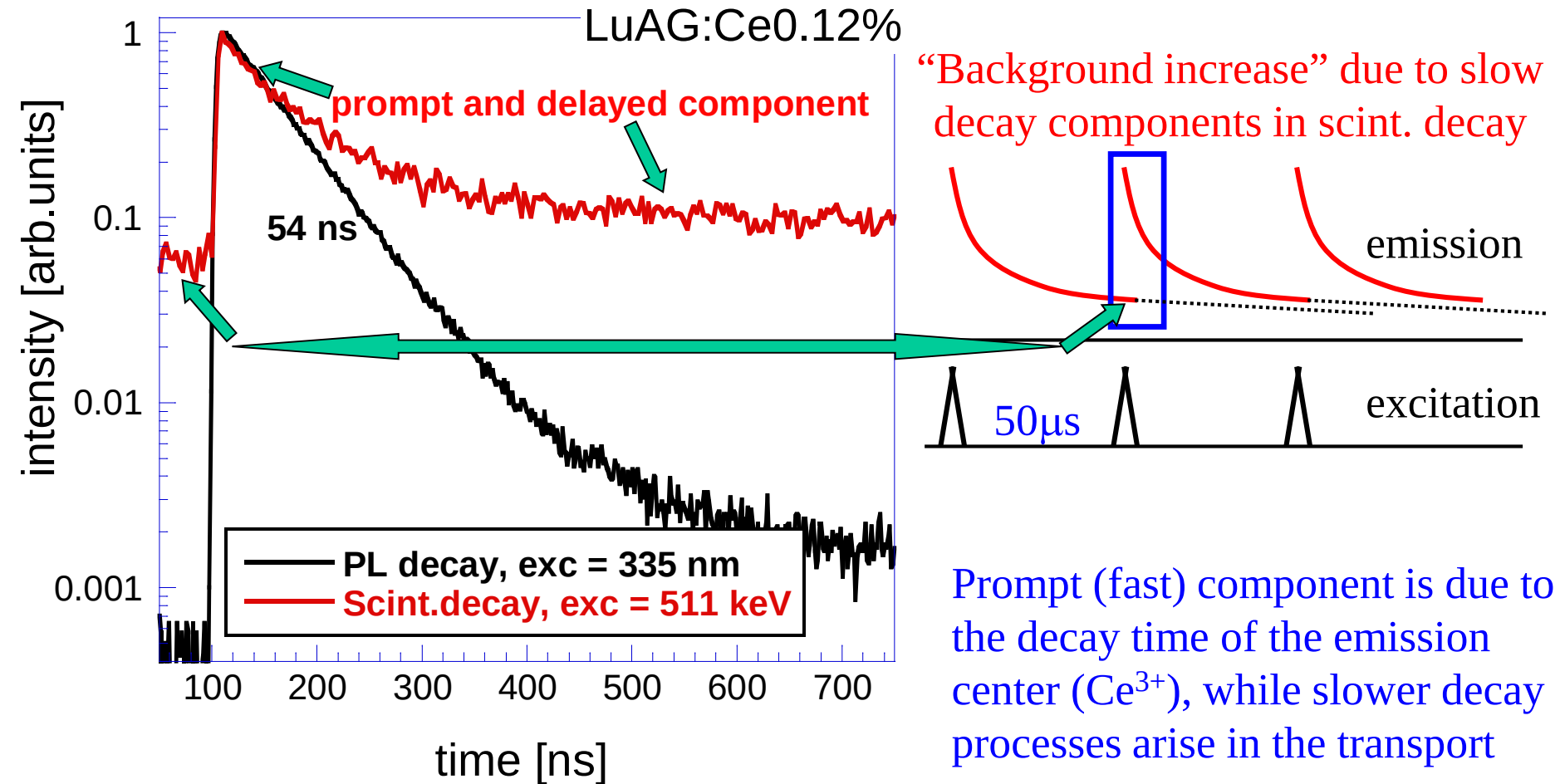
n photons
(1 - 6 eV)



$$I(t) = \sum A_i \exp[-t/\tau_i]$$

Duration of the output light pulse is determined by the **luminescence decay time of the emission centers**, but also by the **timing characteristics of the transport stage**

Scintillation and photoluminescence decay

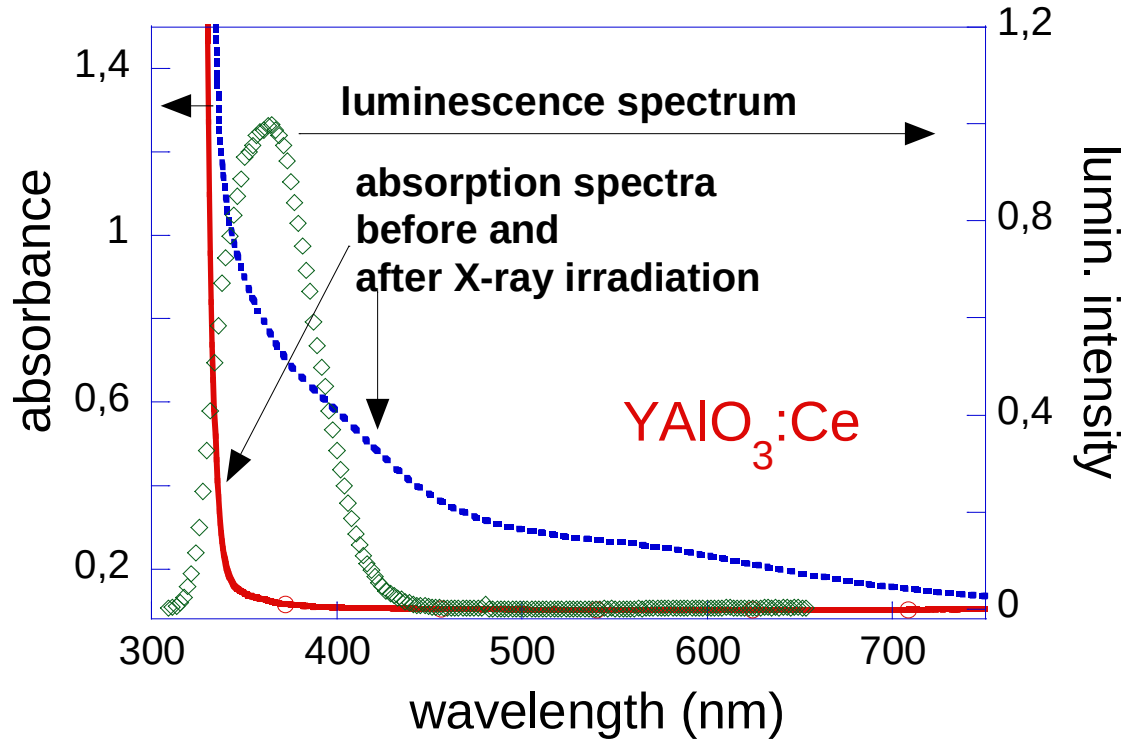


Usually the decay approximation is made by $I(t) = \sum A_i \exp(-t/\tau_i)$

Prompt (fast) component is due to the decay time of the emission center (Ce^{3+}), while slower decay processes arise in the transport stage

Radiation damage

Usually dealing with a passive process, i.e. induced absorption



Reabsorption of scintillation light results in gradual LY loss and its instabilities in time due to spontaneous recovery of induced absorption !!

Strategy for point defect study in scintillator materials

Correlation of several techniques at specifically prepared sample set under well-defined technological conditions:

➤ **Thermoluminescence** – to visualize trapping states, which take part in the radiative processes, spectra can advise on recombination sites

➤ **Thermally stimulated currents** – to visualize complementary nonradiative processes

➤ **Electron paramagnetic (spin) resonance** – to understand location and nature of unpaired-spin-containing trapping centers

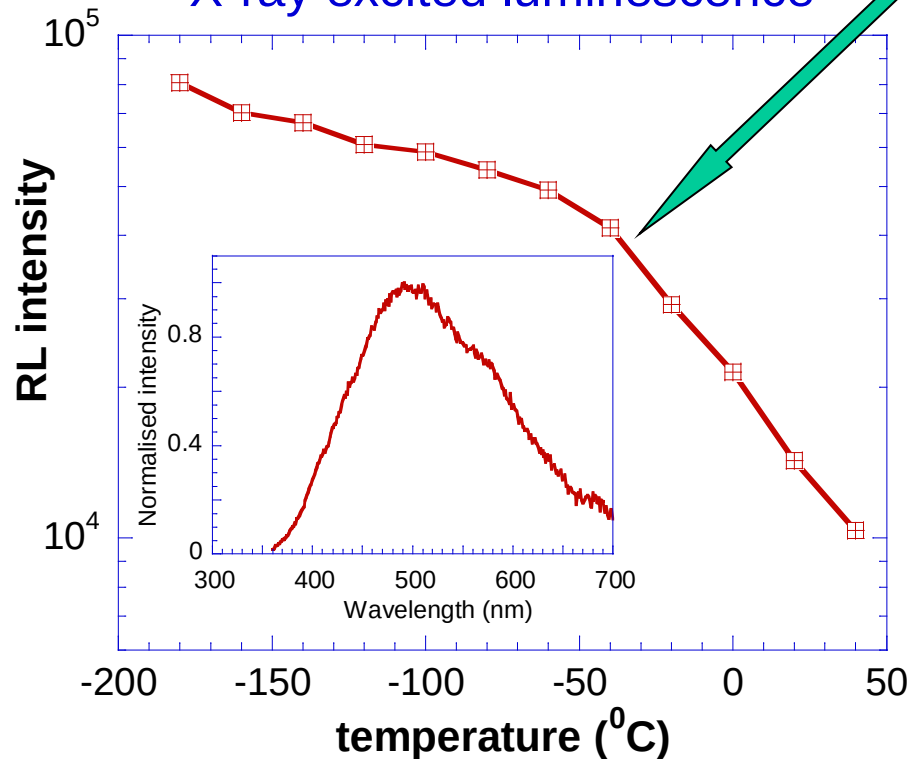
➤ **Time-resolved emission spectroscopy** – to interconnect the luminescence (scintillation) kinetics with the occurrence or non of the defects visualized by the above techniques

These techniques are correlated with the evaluation of practical scintillator characteristics mentioned before

Intrinsic scintillators

$\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (BGO)

X-ray excited luminescence



❑ The onset of thermal quenching of BGO luminescence ($Q=0.13$ at RT)

❑ Thermal quenching of BGO emission center is responsible for lower LY of BGO and its strong temperature dependence around RT

❑ It is an intrinsic property of BGO structure as well as its decay time of about 300 ns at RT.

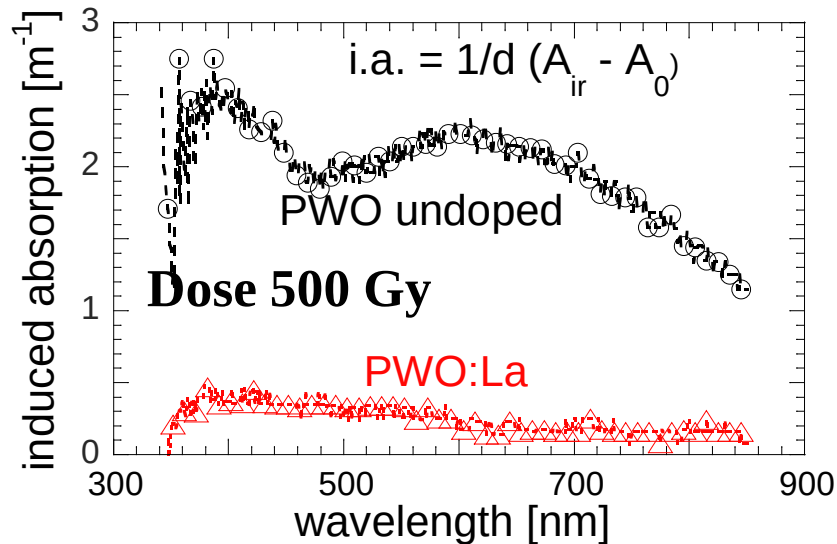
Moncorge, J. Lumin. 1976

$\text{Bi}(\text{GeO}_4)_6$ STexciton emission centers

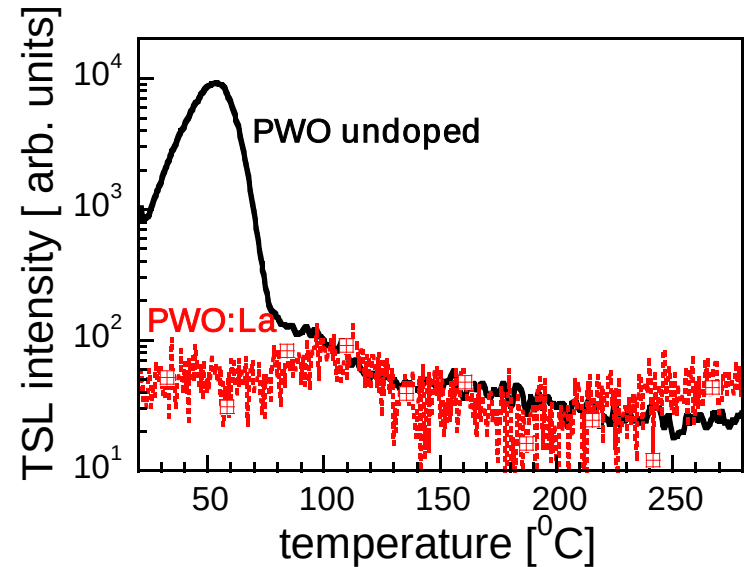
Weber, Monchamp, J. Appl. Phys. 1973
pioneering work on BGO

Radiation resistance improvement in PbWO_4

Induced absorption of PbWO_4 after gamma irradiation (^{60}Co) at RT



Thermoluminescence glow curves after X-ray irradiation at RT, PbWO_4

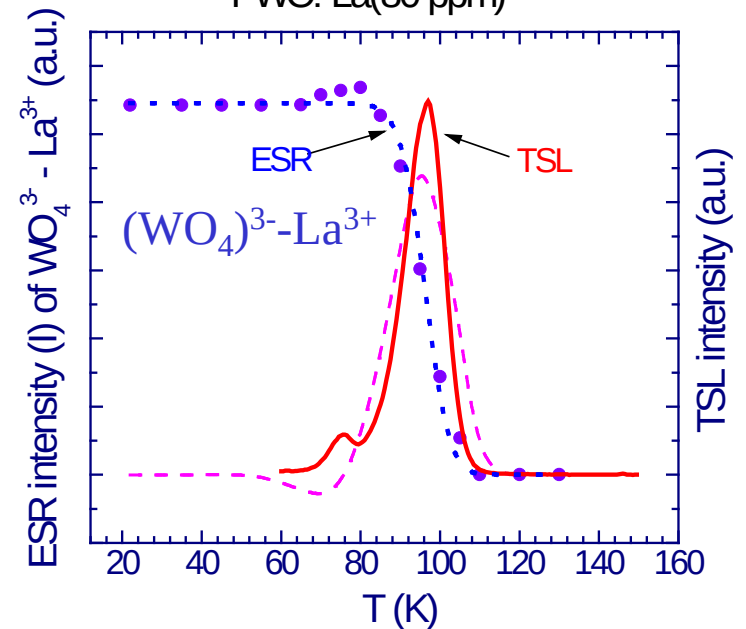
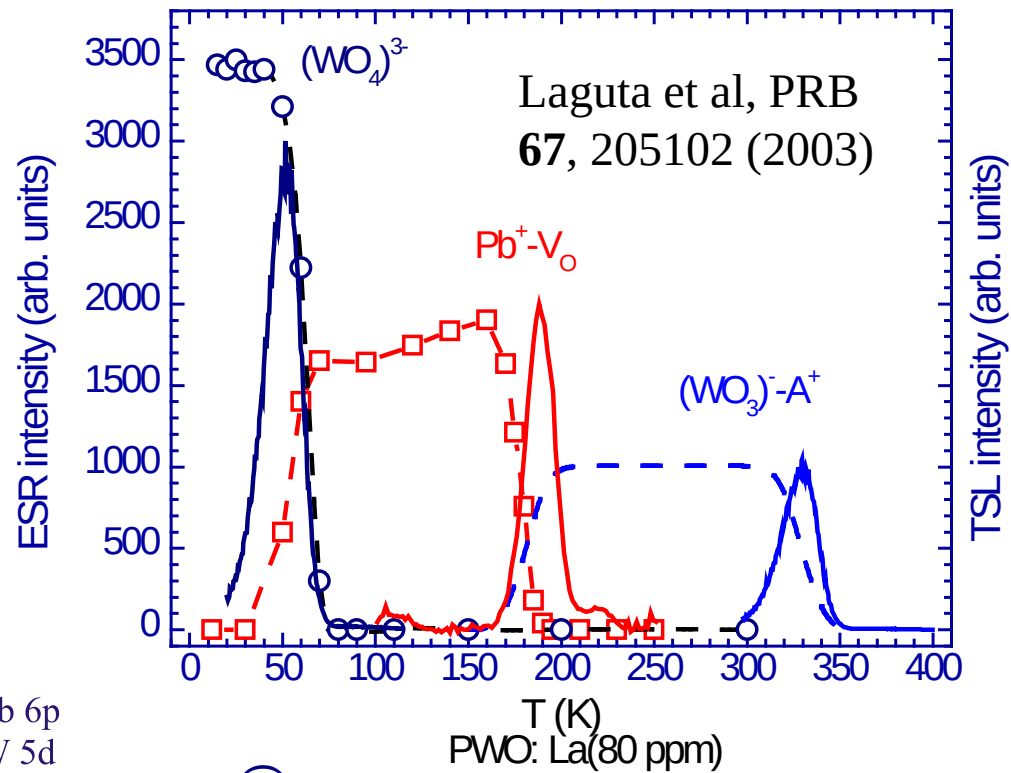
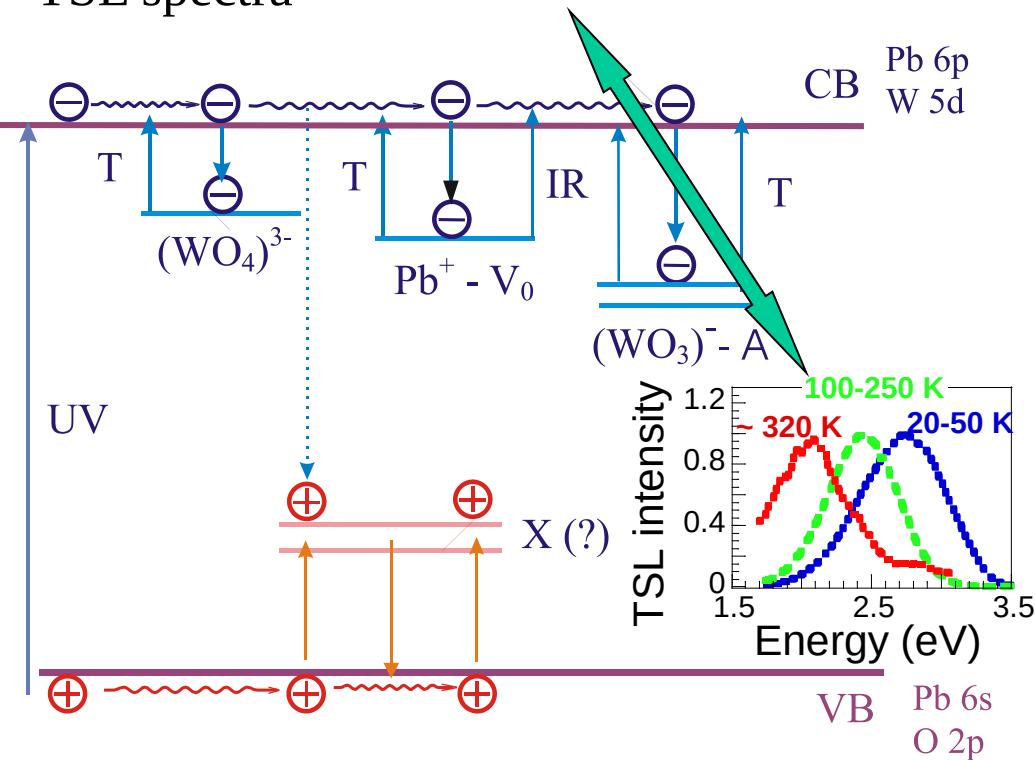


Induced absorption is caused by the **relocation of charge carriers into the deep traps** monitored by TSL measurement above RT. **Occupied deep traps introduce the additional=induced absorption bands**. In the case of PbWO_4 such traps are efficiently suppressed by the selected trivalent ion doping (La, Y, Gd, Lu).

However, what is the nature of these traps ???

PbWO₄ – electron and hole traps

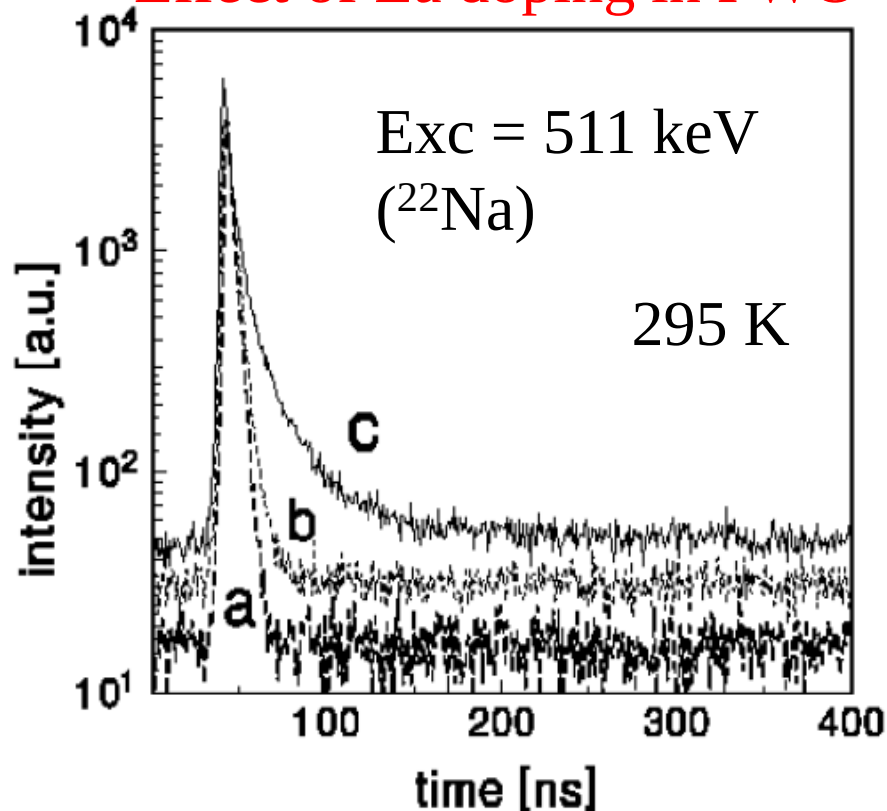
EPR clarified: electron self-trapping, further strengthened by La³⁺, key role of the **oxygen vacancy and its suppression by La doping**. Hole states of O- type evidenced, at least three different configurations evidenced in TSL spectra



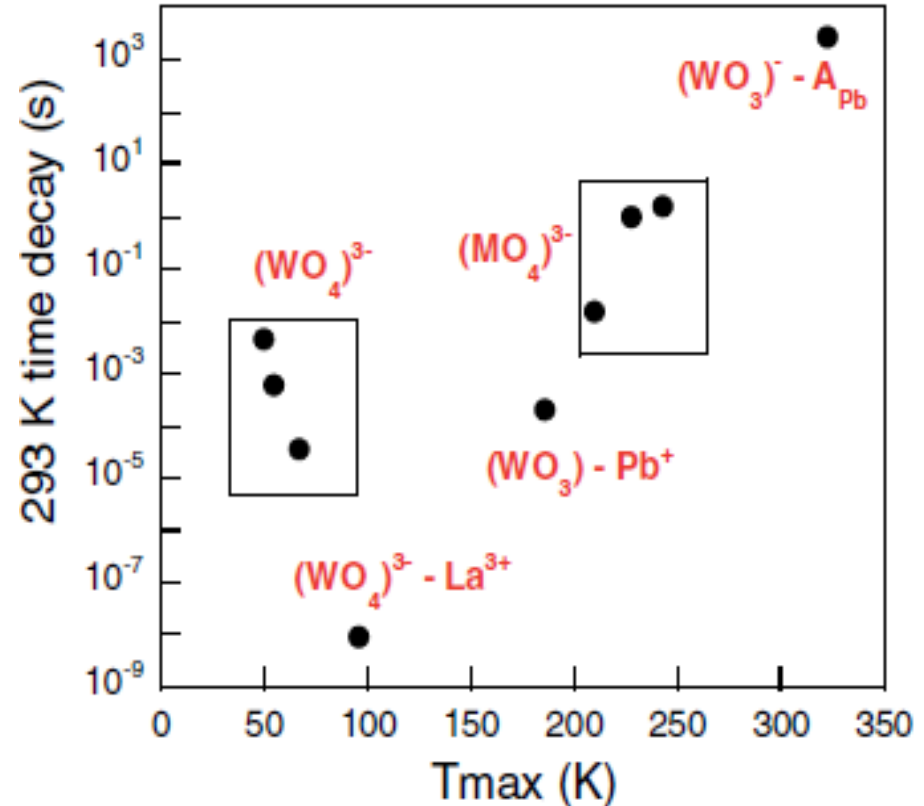
Scintillation decay and detrapping times at RT



Effect of La doping in PWO



Spectrally unresolved scintillation decays of **La (400 ppm)** (curve a), **La (80 ppm)** (curve b) and **Undoped** (curve c) PWO crystals.. Curves are vertically shifted for clarity.



Room temperature decay times of an electron from various electron traps in PbWO₄ single crystals

Energy storage and trapping sites in PbWO_4

- ❑ Electron capture governed by self-trapping at $(\text{WO}_4)^{2-}$ groups and by centres containing oxygen vacancy (ies) in intrinsically pure crystal
- ❑ There are at least three hole trapping sites, some or all of them of O^- type (PRB2011), most probably around lead vacancy (ies)
- ❑ A^{3+} -doping (La,Y,Gd,Lu) results in the oxygen vacancy suppression, hole trapping sites suppression or compensation and finally excess electrons are found in the conduction band, which can fill potential electron traps of any kind. All these phenomena diminish substantially the ability of PbWO_4 lattice for energy storage resulting in the increase of radiation hardness and speed-up of scintillation response. An important condition for a doped A^{3+} ion is that it doesn't introduce any new trapping level in the forbidden gap.

Sub-gap tunnelling Processes-driven Radiative Recombination in Complex Oxide Scintillators

Radiative recombination processes

in:

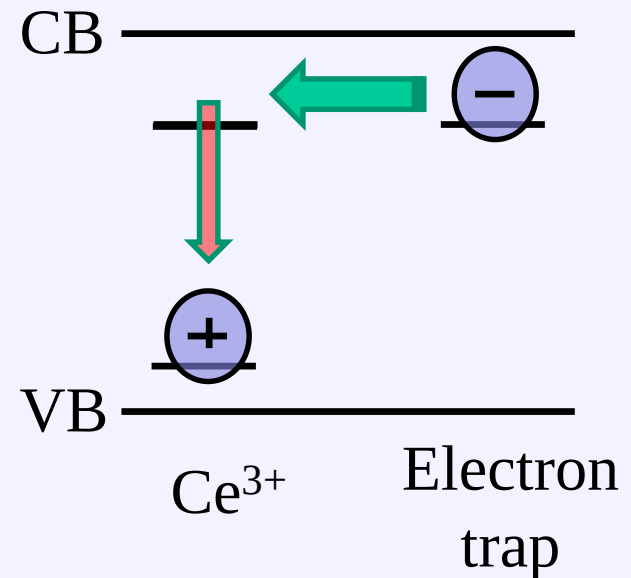
aluminum garnets

aluminum perovskites

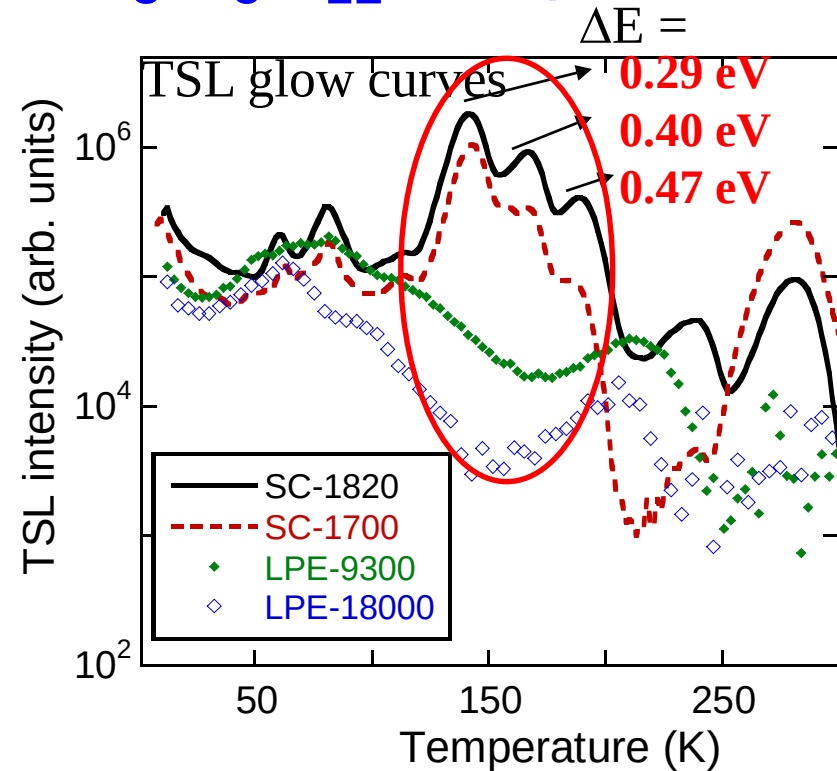
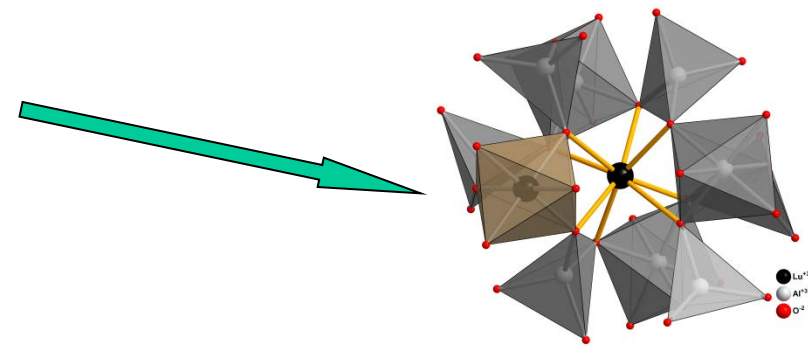
orthosilicates

single crystal scintillators

Closely spaced trap and recombination center!



Electron traps related to the antisite Lu_{Al} defects in $\text{Lu}_3\text{Al}_5\text{O}_{12}:\text{Ce}$ (LuAG:Ce)



Triple peak structure at 142 K, 167 K and 190 K is **always dominant in single crystals**, while it is **completely absent in LPE layers**. (TSL spectra contain only Ce^{3+} emission)

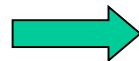
In SC liberation of electrons from the antisite-defect-related trap and their recombination with Ce^{4+} is proposed to explain TSL characteristics in this temperature region

Nikl, phys.stat.sol. (b) 242, R119 (2005)

Detrapping times at RT:

Peak at 140 K 30-100 μs

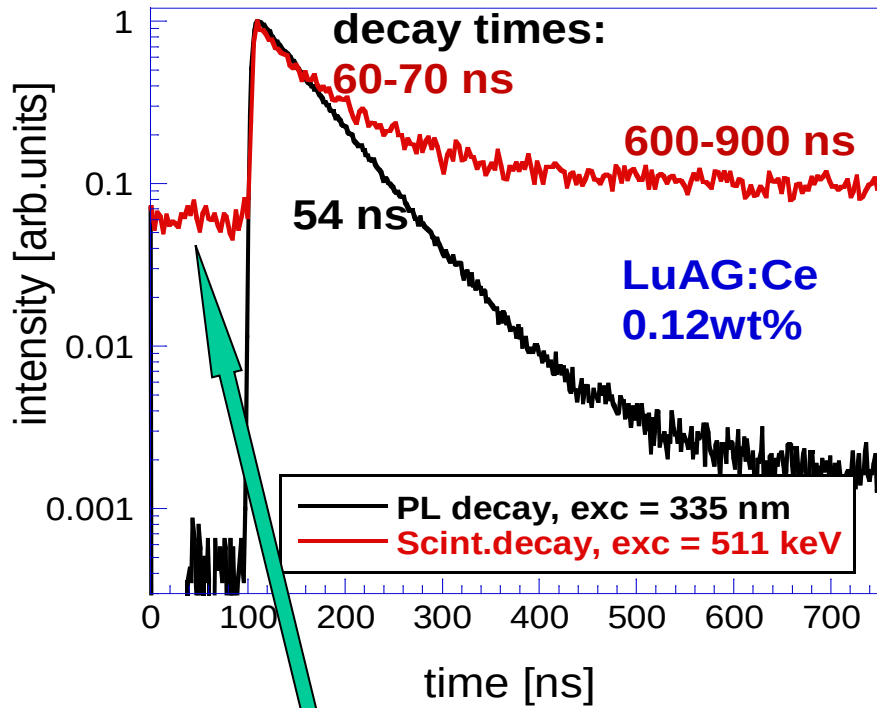
Peak at 168 K 200-400 μs



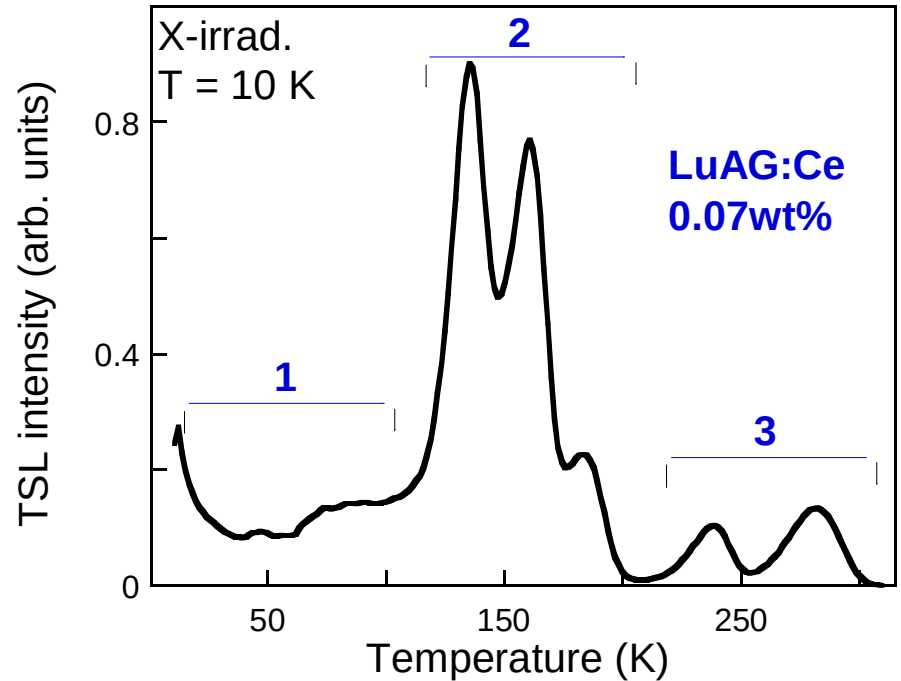
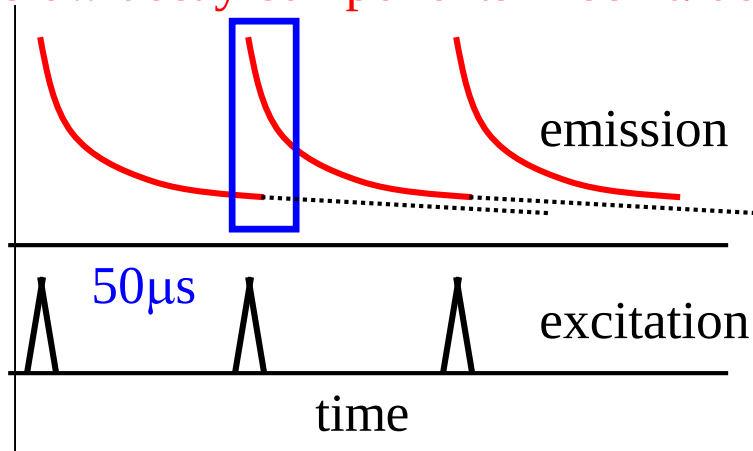
Can't explain the submicrosecond decay times in the slower scintillation component !

Emission decay at RT $\text{Lu}_3\text{Al}_5\text{O}_{12}:\text{Ce}$

TSL glow curve



“Background increase” due to very slow decay components in scint. decay



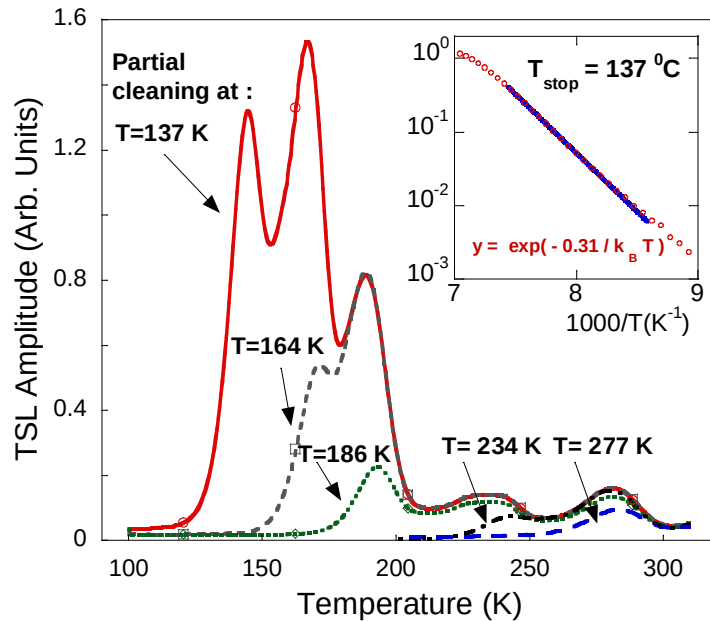
TSL spectrum - Ce^{3+} emission only

1 – athermal tunneling

2 – dominant shallow el. traps

3 – sample dependent el. traps

Analysis of TSL glow curve in LuAG:Ce



Initial rise analysis $\Rightarrow$ trap depth E

Dose depend. $\Rightarrow$ 1st order kinetic

Frequency factor calculation as
 $s = (\beta E / k T_m) \times \exp[E / k T_m]$

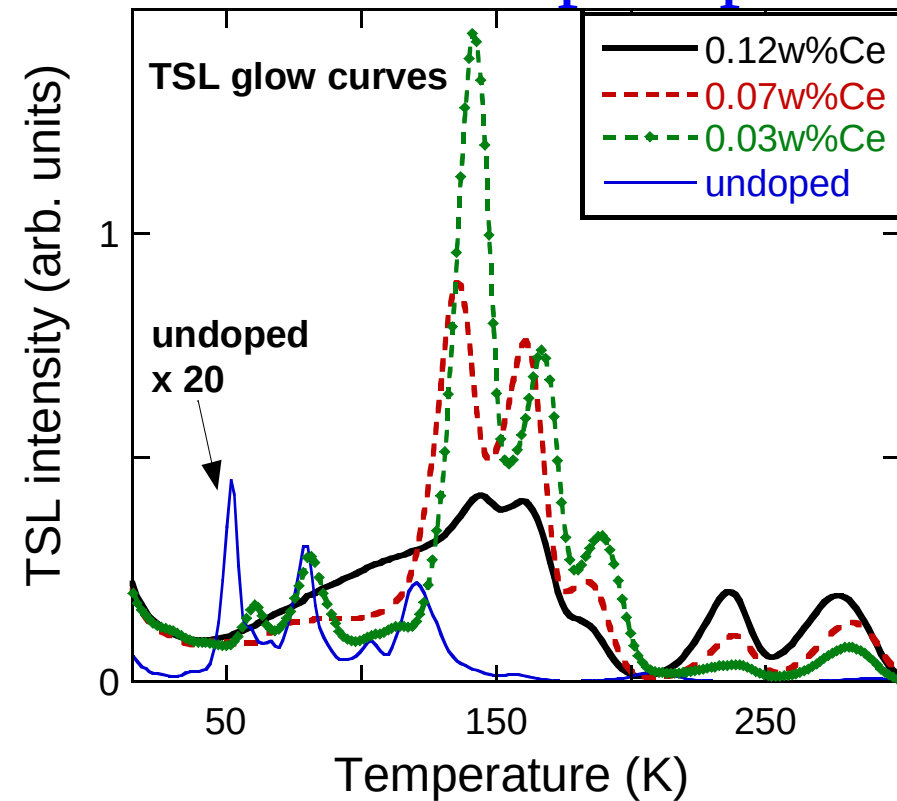
Detrapping time at 295 K as
 $\tau = s^{-1} \times \exp[E / (k \times 295 \text{ K})]$

T_m [K]	E [eV]	s [s^{-1}]	τ [ms]
142	0.31	10^9	0.12
166	0.38	5×10^9	0.63
187	0.47	5×10^{10}	1.7
237	0.57	10^{10}	400
280	0.49	5×10^6	56000

Detrapping times can account for the increased “background” but **are far too long** to explain the existence of slower sub- μs component in scintillation decay!!

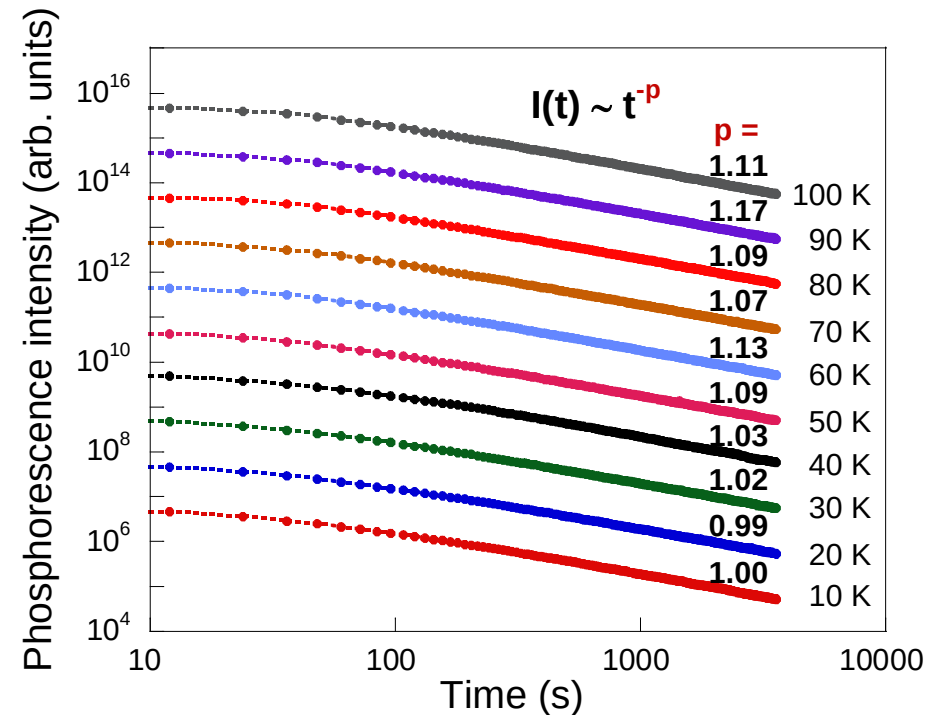
What is the mechanism of related radiative recombination?

Athermal tunnelling in LuAG:Ce – TSL and phosphorescence decay



Diminishing of “undoped-related” TSL features within 50-80 K with increasing Ce concentration

Competition between TSL signals within 50-120 K and 120-200 K !



After X-ray irradiation at any $T \in (10-100)$ K **phosphorescence decay doesn't depend on temperature and follows t^{-1} law**



Tunneling process between the trapped electron and hole counterparts (**spatially correlated**)

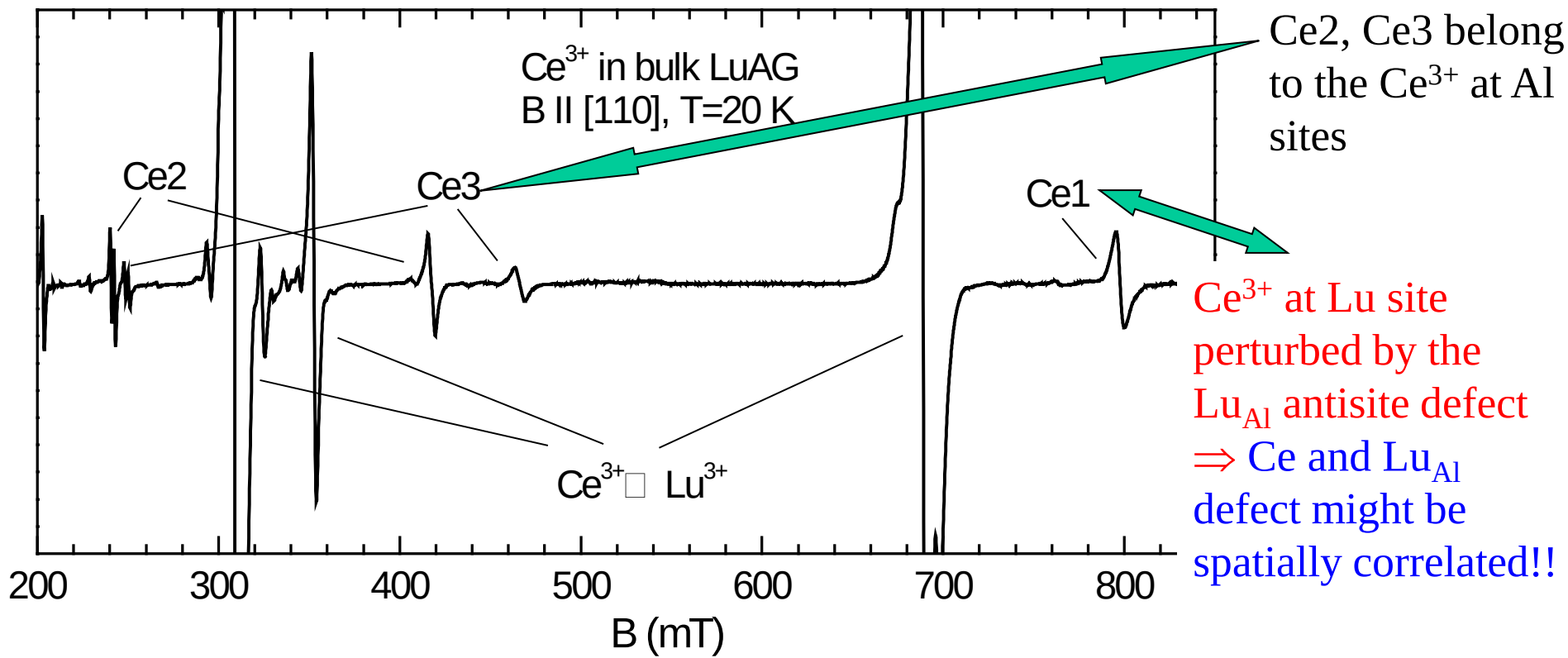
Antisite defects in Al garnets – EPR study

Newly by EPR evidenced $\text{Ce}^{3+}_{\text{Al}}$ and Ce^{3+} perturbed by Lu_{Al} centers!

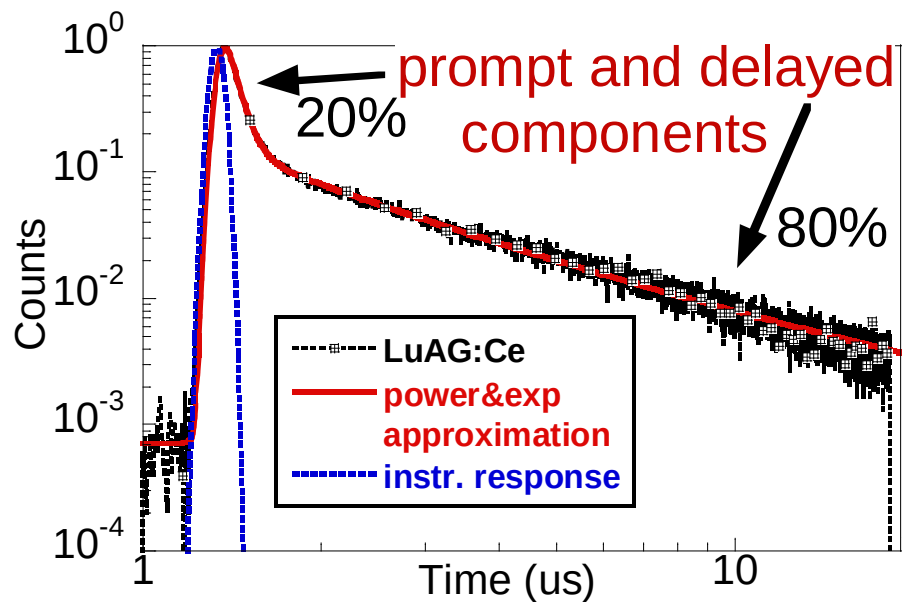
Laguta et al, Rad.Meas. 42 835 (2007)

High-resolution spectroscopy of the Nd^{3+} satellite emission lines in YAG:Nd
Lupei et al., Phys. Rev. B 51, 8 (1995)

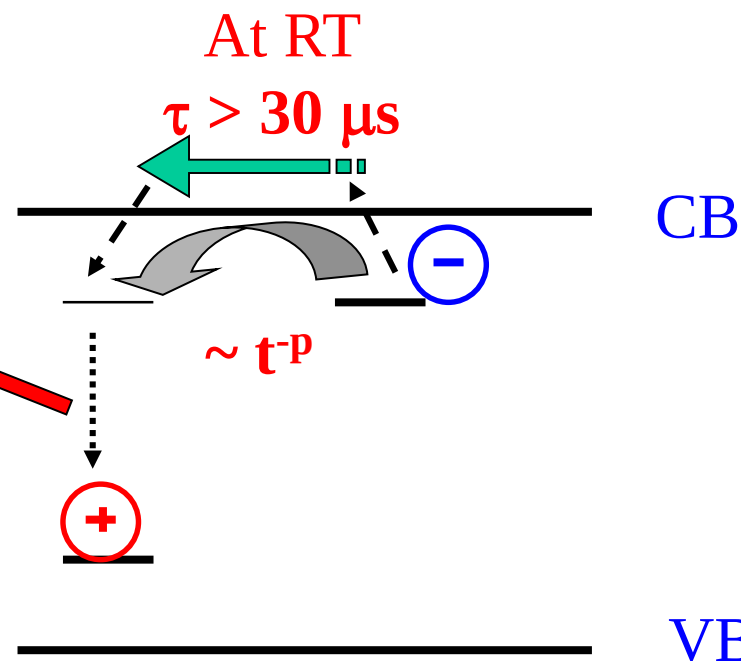
XRD from an increase of lattice constant in YGG:Yb single crystal and ceramics
Shirinyan et al, NIM A 537 (2005)



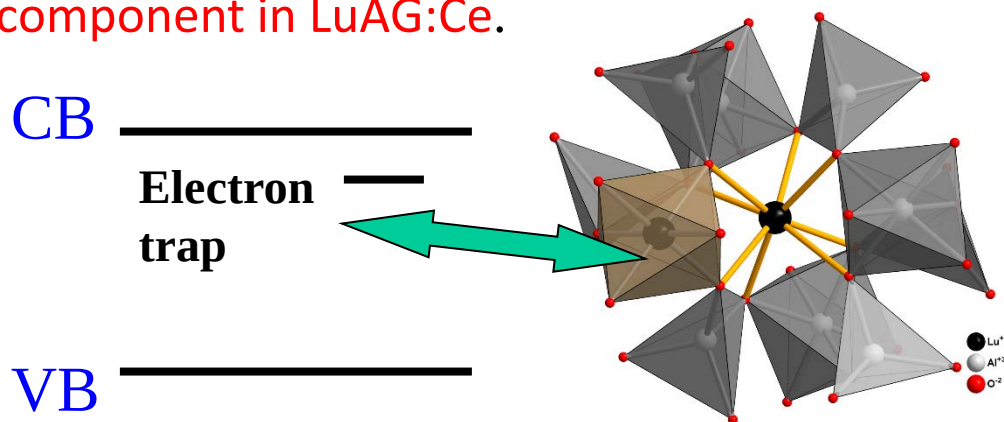
Scintillation decay of LuAG:Ce (Pr) at RT



Correlated TSL and EPR study designed the key processes:



Consideration of tunneling-driven recombination **provides a physical ground** for the slower scintillation decay component in LuAG:Ce.



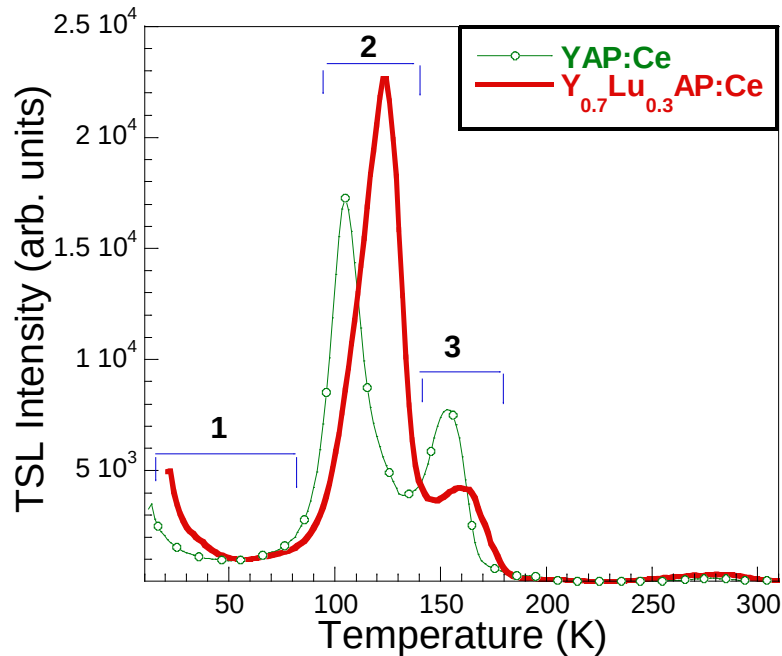
Ce³⁺
(Pr³⁺)

AD-related
electron
trap

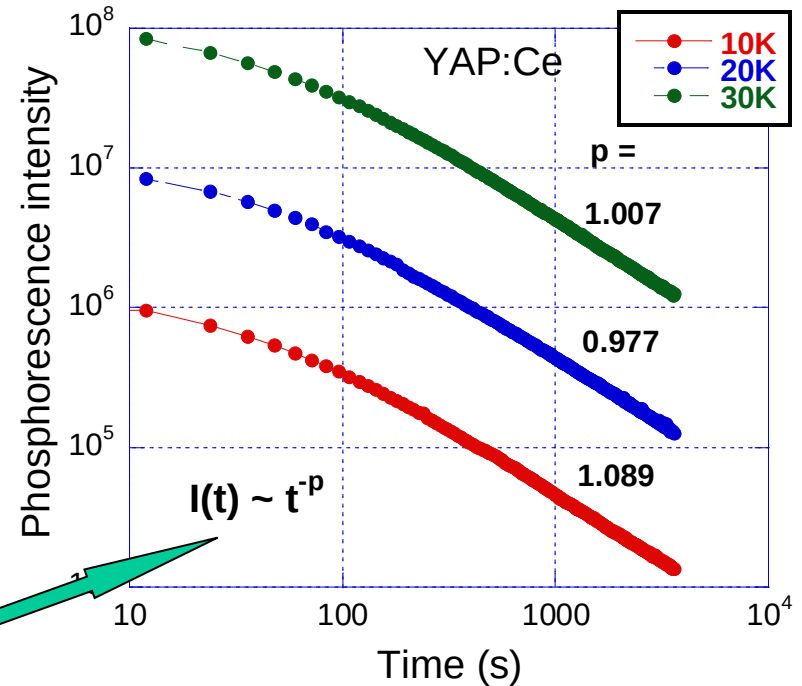
Nikl et al, Phys. Rev. B 76,195121(2007)

Ce-doped (Y-Lu)AlO₃ perovskite

TSL glow curves



Phosphorescence decay



Region 1 - tunnelling process:

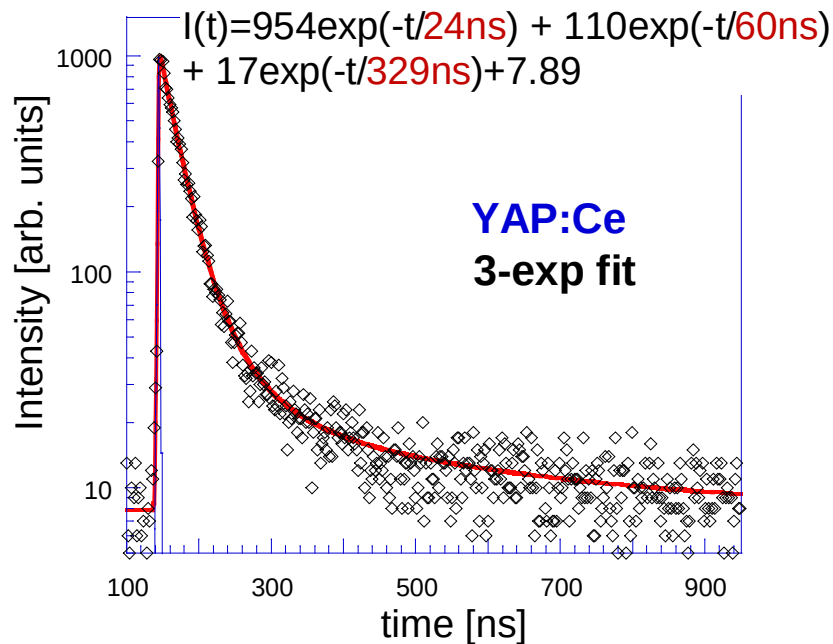
In YAP:Ce detrapping times at 295 K are about 100 μ s and 200 μ s for TSL peaks at 105 K and 153 K, respectively. Dominant TSL peak shifts to higher temperature with the Lu admixture.

Fasoli et al, IEEE TRANS. NUCL. SCI. 55, 1114 (2008)

Nikl et al, IEEE TRANS. NUCL. SCI. 55, 1035 (2008)

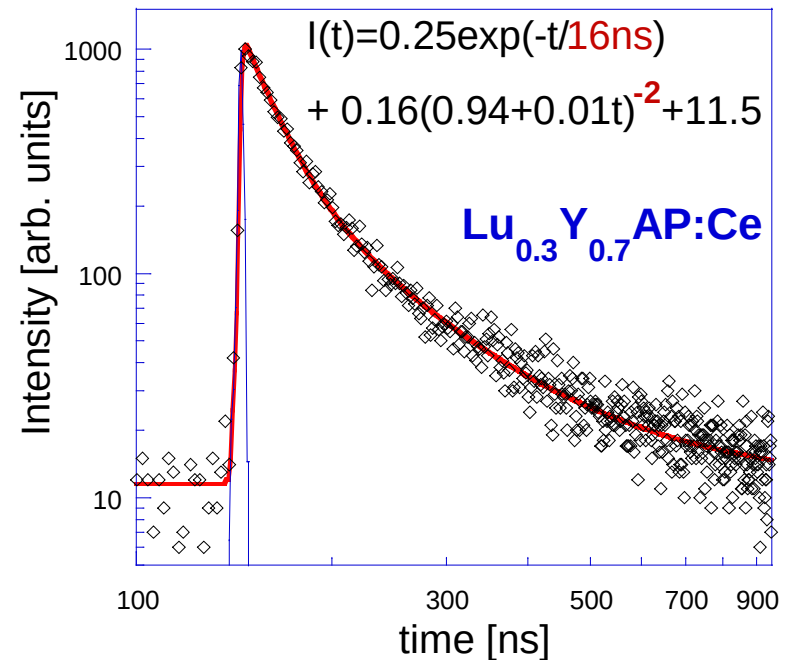
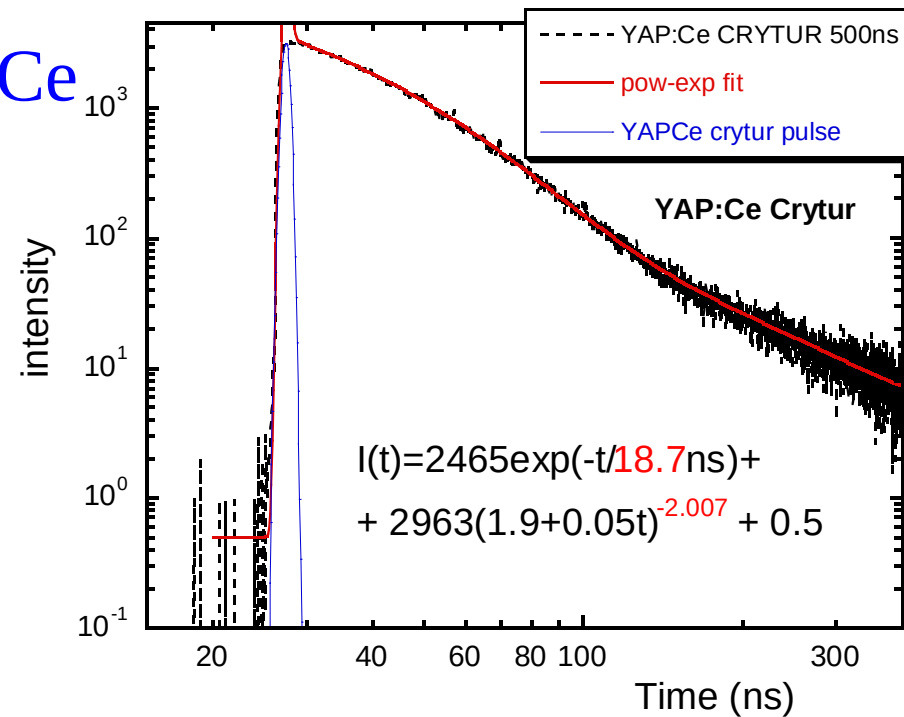
**Analogous to
garnets!!!**

Scintillation decays -Y_xLu_{1-x}AP:Ce



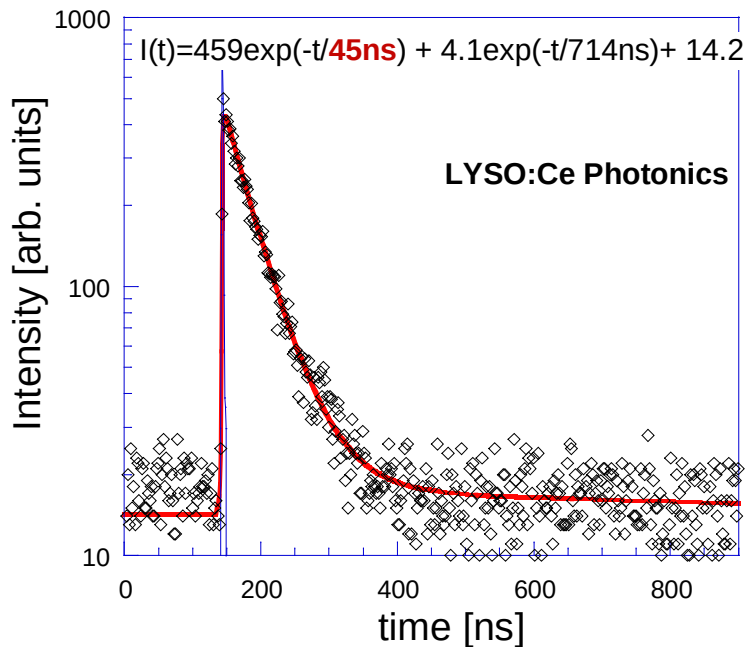
Detrapping times at RT related to 105K and 153 K TSL peaks **again too long** to explain slower components in 3-exp fit

t^p decay doesn't work so well in LuYAP:Ce respect to LuAG:Ce, p is slightly out from theoretical limits **0.95-1.5** (Huntley, JPCM **18**, 1359 (2006))

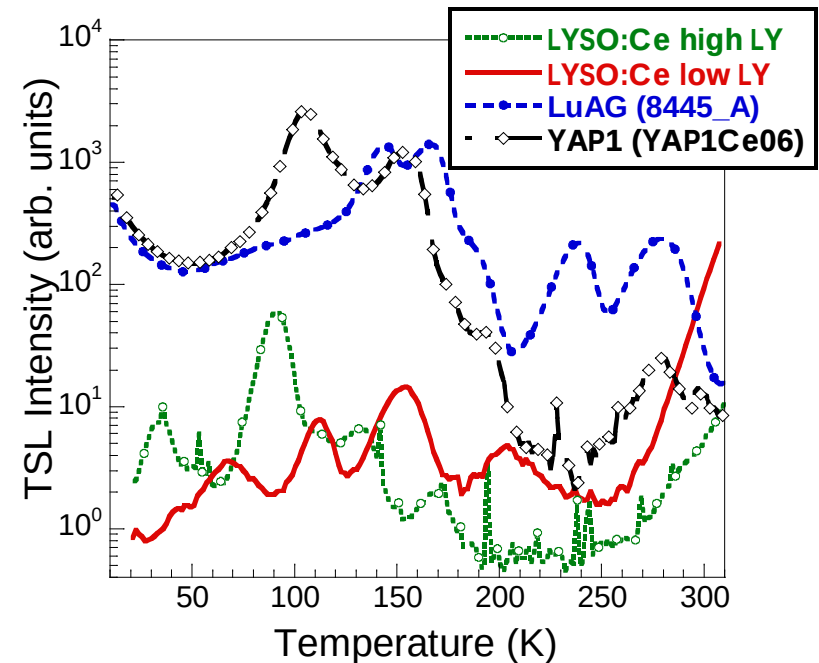


Shallow traps in orthosilicates $\text{Lu}_x\text{Y}_{2-x}\text{SiO}_5\text{:Ce}$

Scintillation decay at RT

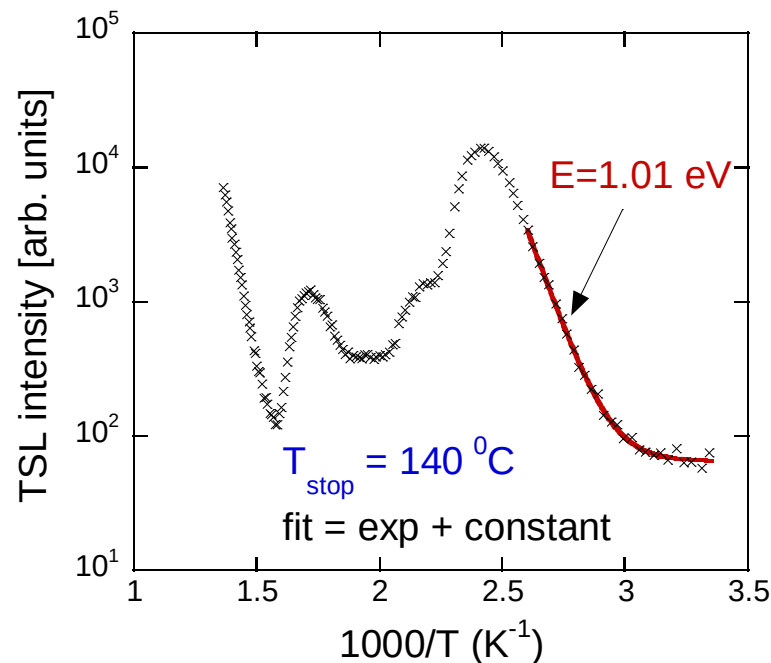
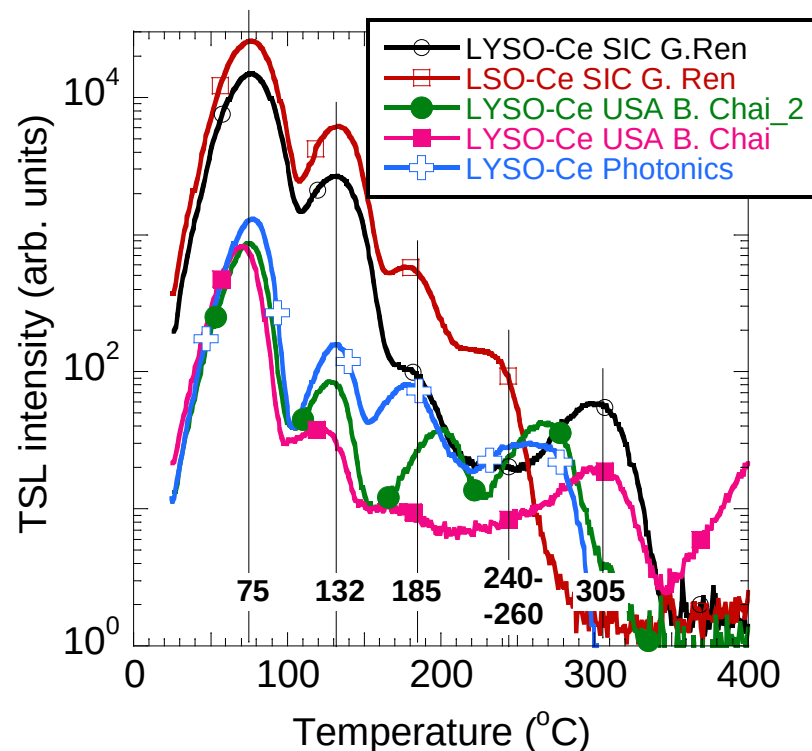


TSL glow curves, x-irr. at 10 K



LYSO and LSO crystals show noticeably lower concentration of shallow electron traps with respect to Al garnets and perovskites!

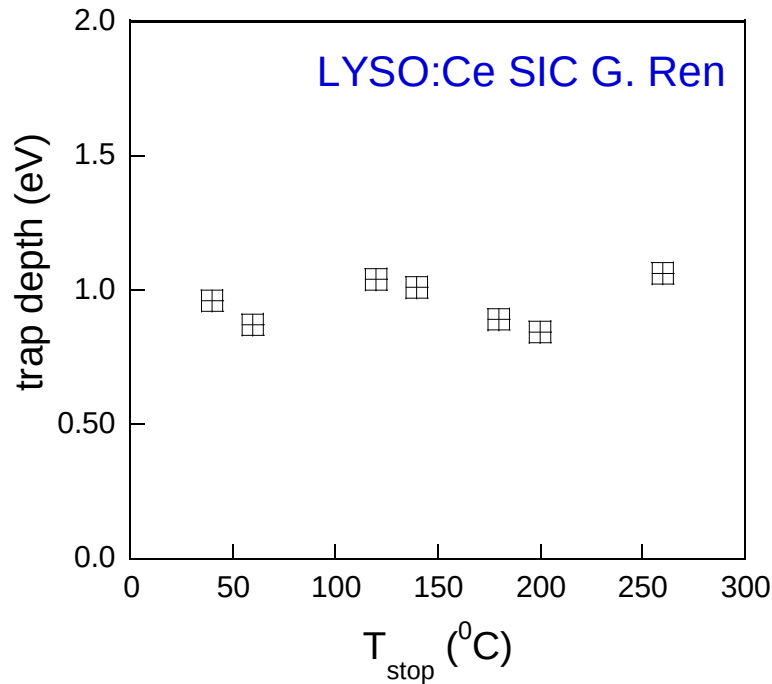
Deep electron traps in LSO and LYSO



Despite of large differences in TSL intensity, position of at least first three peaks is coinciding among the samples from different producers

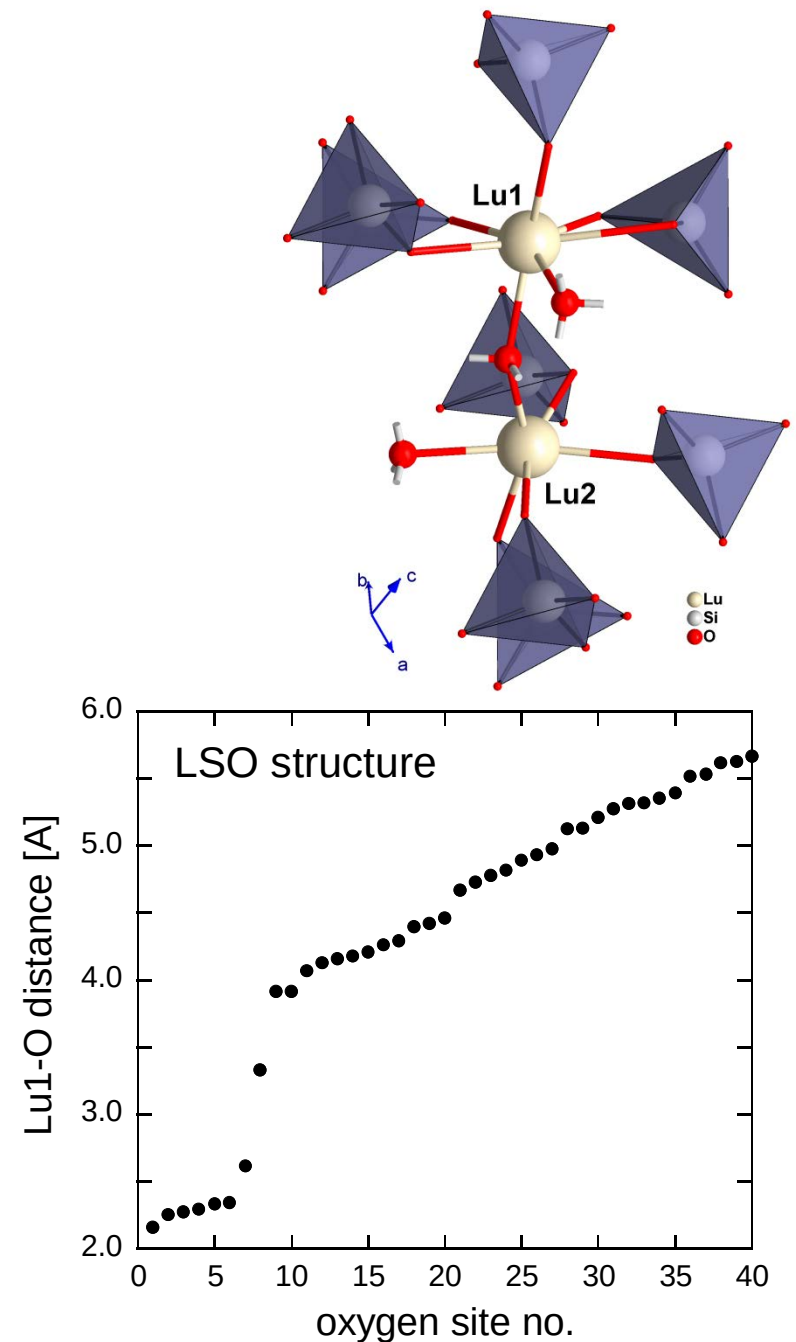
Using partial cleaning procedure the trap depth related to each peak was obtained

TSL mechanism above RT in LSO:Ce

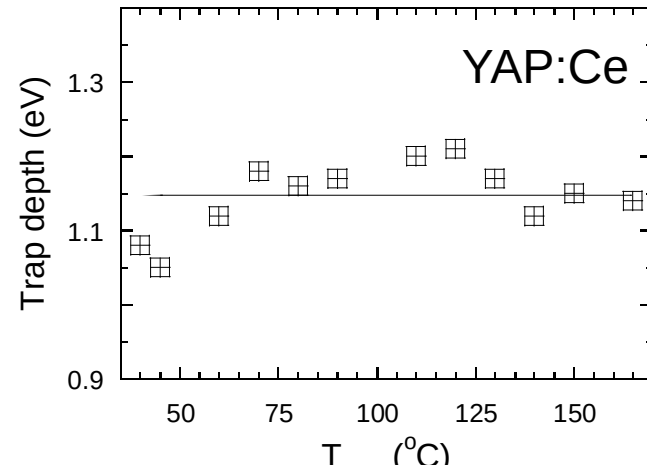
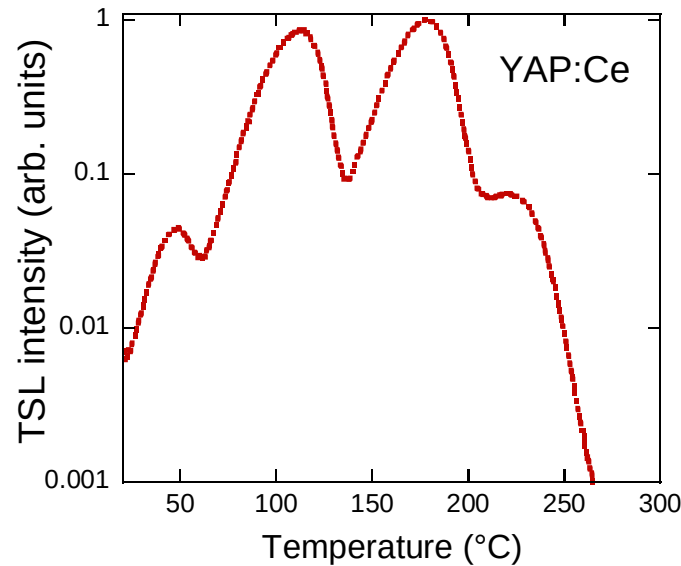


Oxygen sites/vacancies are electron traps –
recent EPR study
Cooke et al, IEEE TNS 55, 1118 (2008)

But in TSL the TD of trap depth **doesn't**
point to a usual thermal detrapping via CB



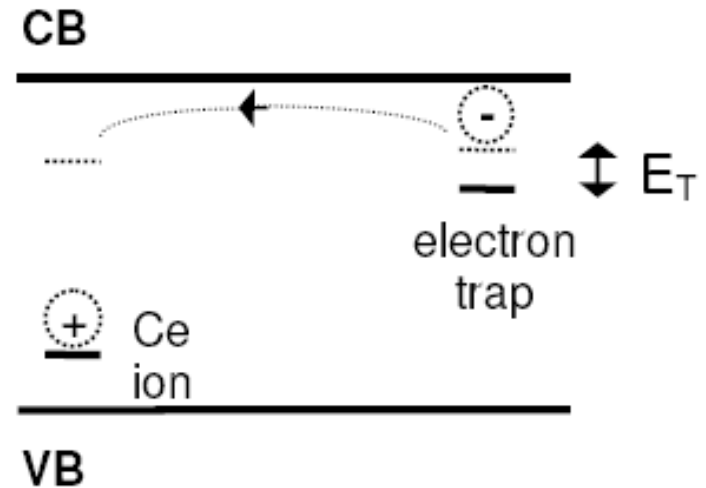
Thermally assisted tunneling in TSL mechanism above RT



Electron in the trap is thermally promoted to an excited level in the trap and tunnel to the adjacent Ce^{3+} recombination site. **Distance dependence of frequency factor and discrete set of distances due to crystal structure** give rise to the observed TSL glow curve pattern.

(Lu-Y)AP:Ce - Vedda et al, PRB 61, 8081 (2000)

(Lu-Y)SO:Ce - Vedda et al, presented at ICL08, submitted to PRB,



What we have learnt about tunneling processes in radiative recombination

- ❖ Shallow electron traps adjacent to Ce^{3+} ions in LuAG:Ce and YAP:Ce enable tunneling process towards the hole localised at Ce^{3+} ion. Evidenced by phosphorescence decay at low temperatures, might be responsible for slower scintillation decay components in sub- μs time scale at RT.
- ❖ Deep oxygen vacancy-based electron traps adjacent to Ce^{3+} ions in YAP:Ce and (Lu-Y)SO:Ce give rise to thermally assisted tunnelling-driven radiative recombination in TSL mechanism which is further shaped by the discrete distances between electron and hole trap due to crystal structure.

Strategies in the material engineering and optimization

- **Band-gap engineering** – more profound changes in the material electronic band structure due to admixing (alloying) of another chemical component, which is usually possible only in the solid solutions
- **Defect engineering** – targeted codoping (cations) or annealing (anions) to disbalance “natural” defect/trap occurrence and concentration in the material structure

Defect occurrence is always related to technological recipe!

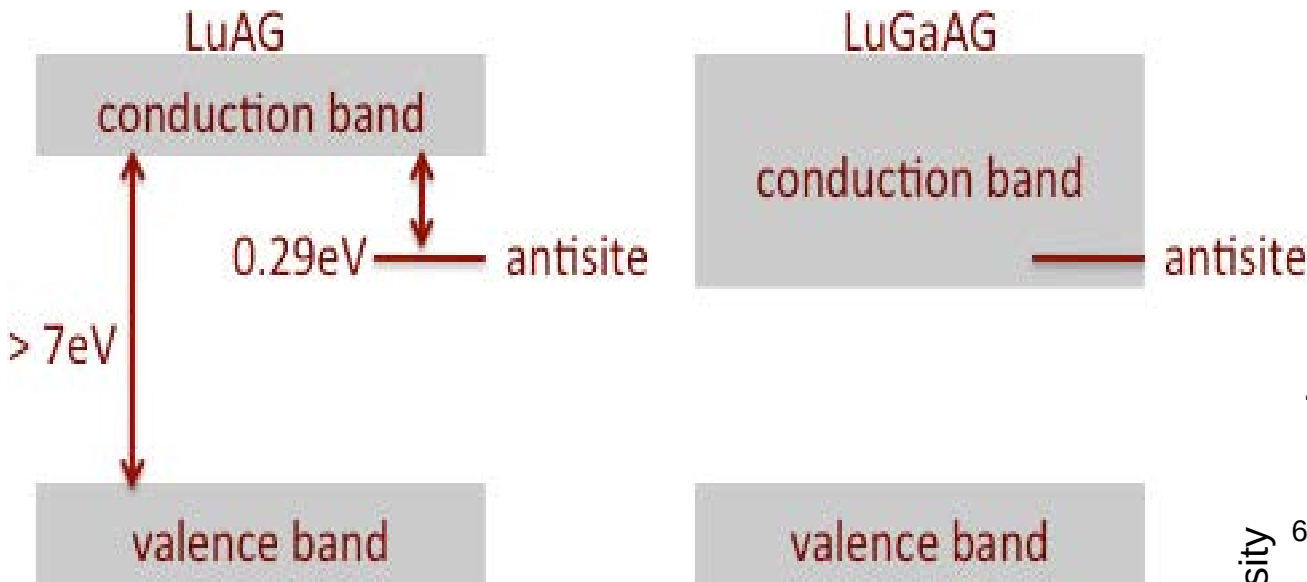
BGE: The first innovation step in garnet

RAPID COMMUNICATIONS

PHYSICAL REVIEW B **84**, 081102(R) (2011)

Band-gap engineering for removing shallow traps in rare-earth $\text{Lu}_3\text{Al}_5\text{O}_{12}$ garnet scintillators using Ga^{3+} doping

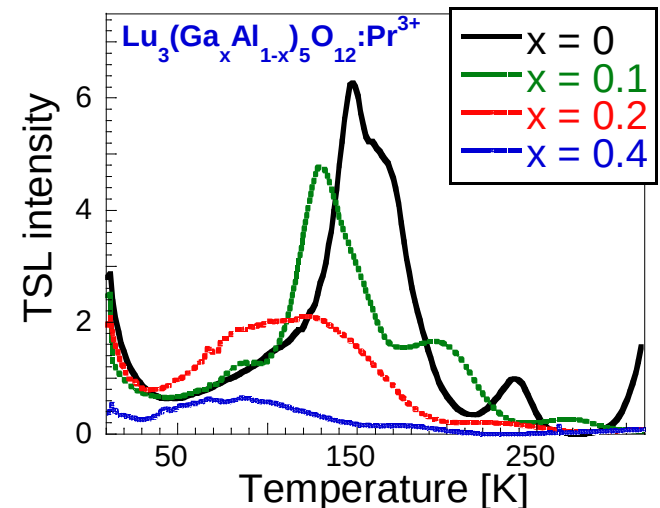
M. Fasoli,¹ A. Vedda,¹ M. Nikl,² C. Jiang,³ B. P. Uberuaga,³ D. A. Andersson,³ K. J. McClellan,³ and C. R. Stanek^{3,*}



Experimentally shown earlier: Nikl et al, Appl.Phys.Lett. **88**, 141916 (2006).



TSL glow curves, X-irr. at 10 K



Micropulling down technology for single crystal growth critically essential in these studies!

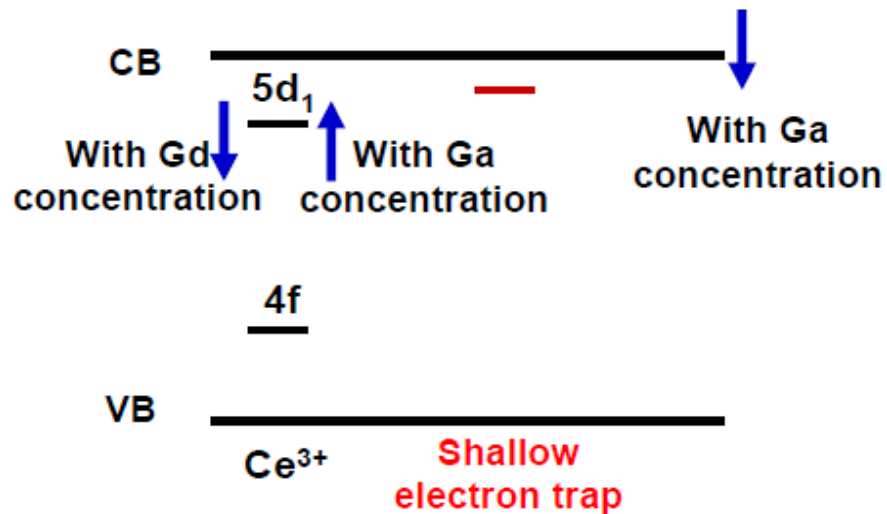
Yoshikawa et al, *Optical Materials* **30**, 6 (2007)

Multicomponent garnets



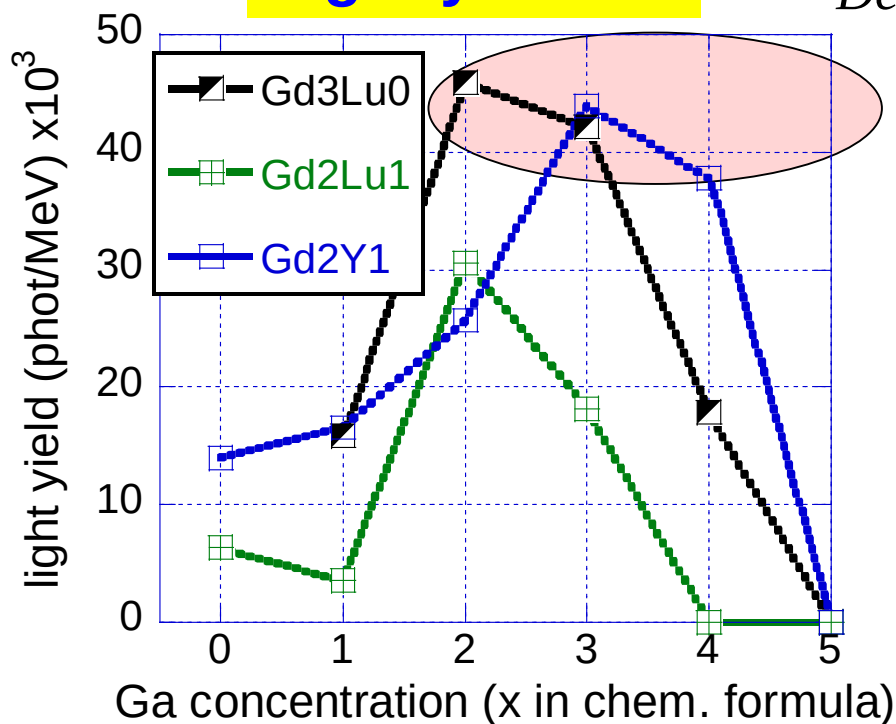
In Ga-admixed LuAG the $5d_1$ level of $\text{Ce}(\text{Pr})^{3+}$ gets closer to CB edge $\Rightarrow$ thermally induced ionization & LY loss

The Gd admixture can help!

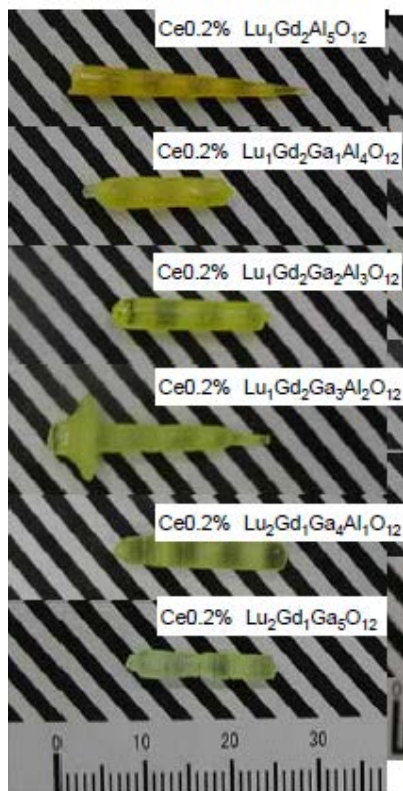


Kamada et al, Crystal Growth & Design **11**, 4484 (2011)

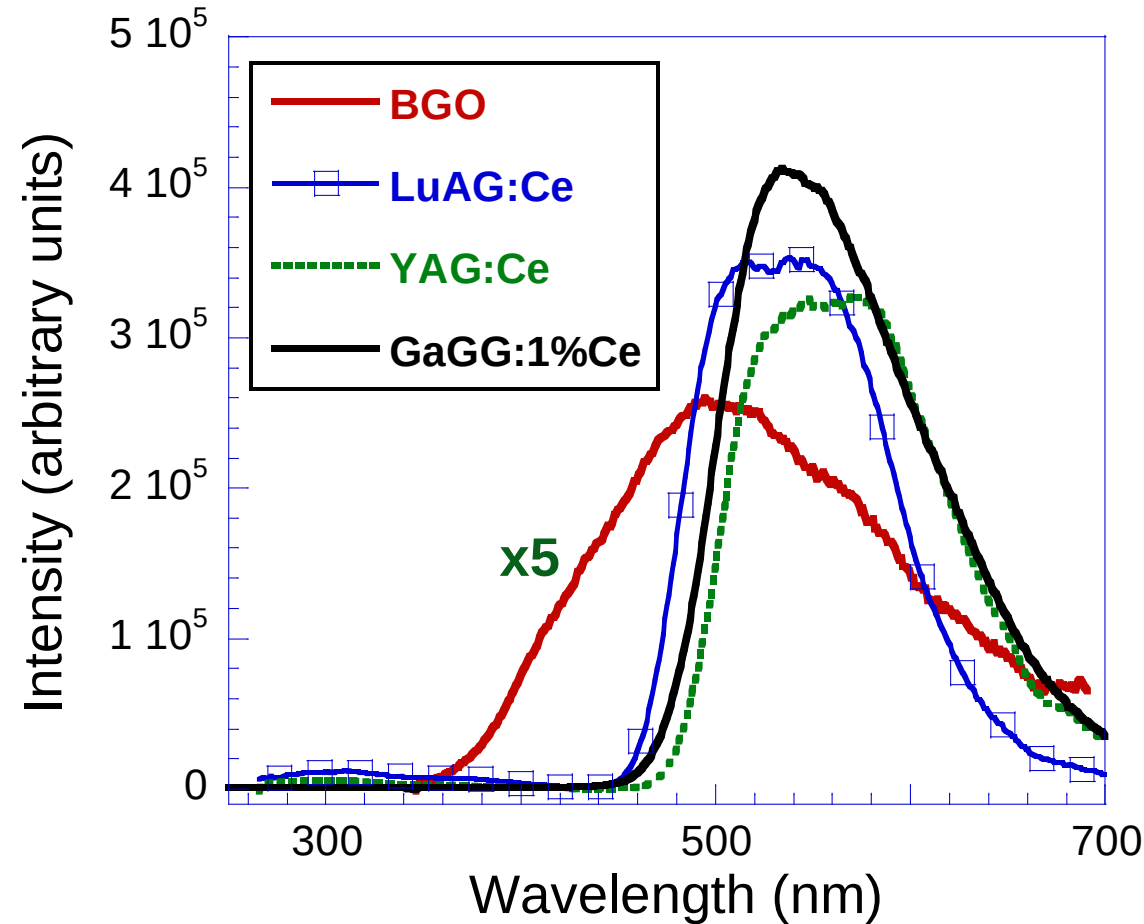
Light yield



LY increase more than three times for x=2-3
Scintillation decay dominated by PL decay time for x=3, weak slow component remains



RL spectra of Ce-doped YAG, LuAG and GAGG



Scintillation efficiency (integral of RL spectrum) of **GAGG:Ce** ($\text{Gd}_3\text{Al}_2\text{Ga}_3\text{O}_{12}:\text{Ce}$) is only about 10-20% higher than that of YAG:Ce and LuAG:Ce, i.e. **huge LY increase shows that the slow part of scintillation response was transformed into fast one.**

The highest LY of GAGG:Ce (spectrally corrected) measured so far is approaching 60 000 phot/MeV close to theoretical limit

Kamada et al., J. Phys. D **44**, 505104 (2011)

Prusa et al, Rad. Meas. **56**, 62 (2013)

Kamada et al, Optical Materials **36**, 1942 (2014)

Dorenbos, IEEE TNS **57**, 1162 (2010))

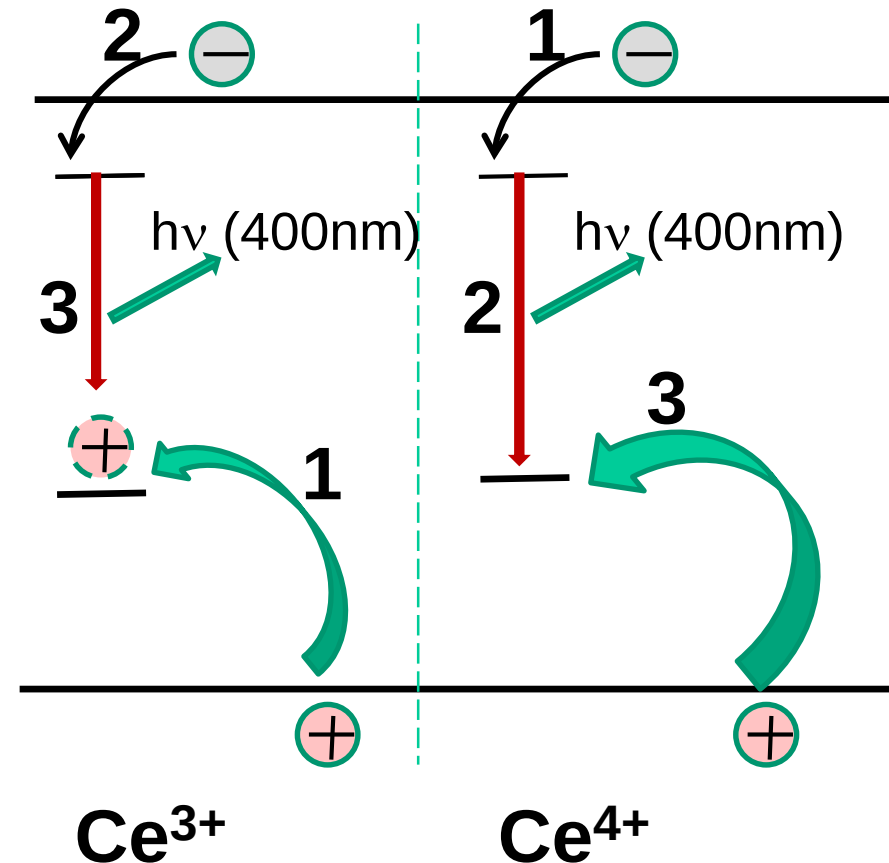
DE strategy: Stable Ce^{4+} role in scintillation mechanism in oxide scintillators

In 1990's it was general opinion that Ce^{4+} is scintillation killer in aluminum perovskite (YAP) host, but **we have to change our mind now as far as its role in Ce-doped orthosilicates and garnets ...**

LYSO:Ce,Mg :Blahuta et al, IEEE TNS 61, 3134 (2013)

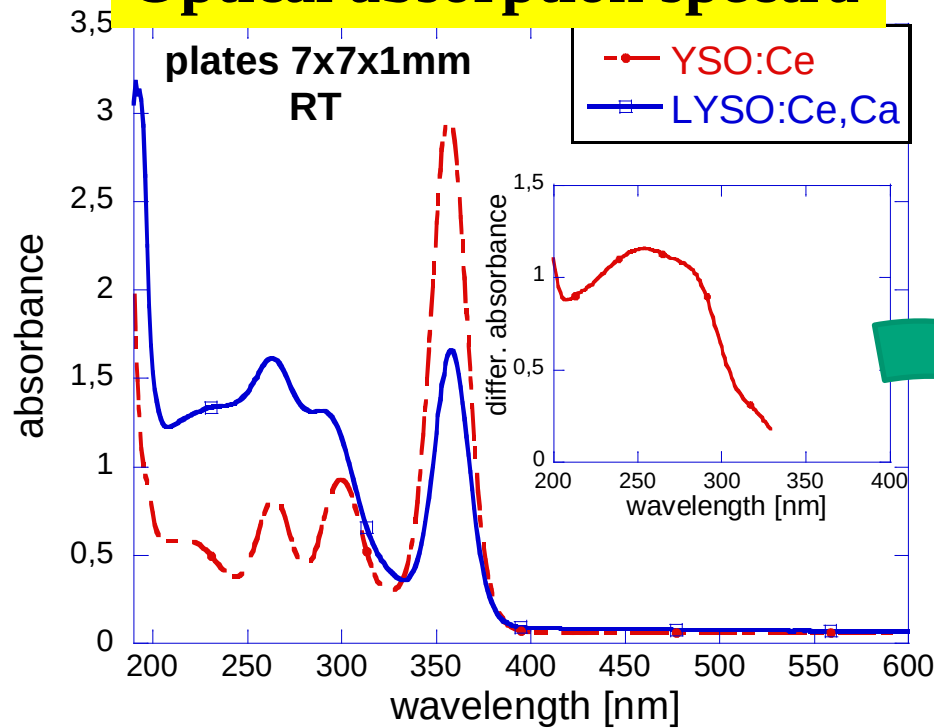
In LYSO:Ce,Mg, **the Mg^{2+} codoping and air annealing** induce the presence of Ce^{4+} (proved by XANES, optical absorption), **LY is enhanced and afterglow strongly diminished also because the oxygen vacancy concentration is diminished!**

LY increase in LSO:Ce,Mg reported earlier, but no explanation provided (*Spurrier et al, IEEE TNS 55,1178 (2008)*)



Ce^{4+} center in $\text{LYSO}:\text{Ce},\text{Me}^{2+}$

Optical absorption spectra



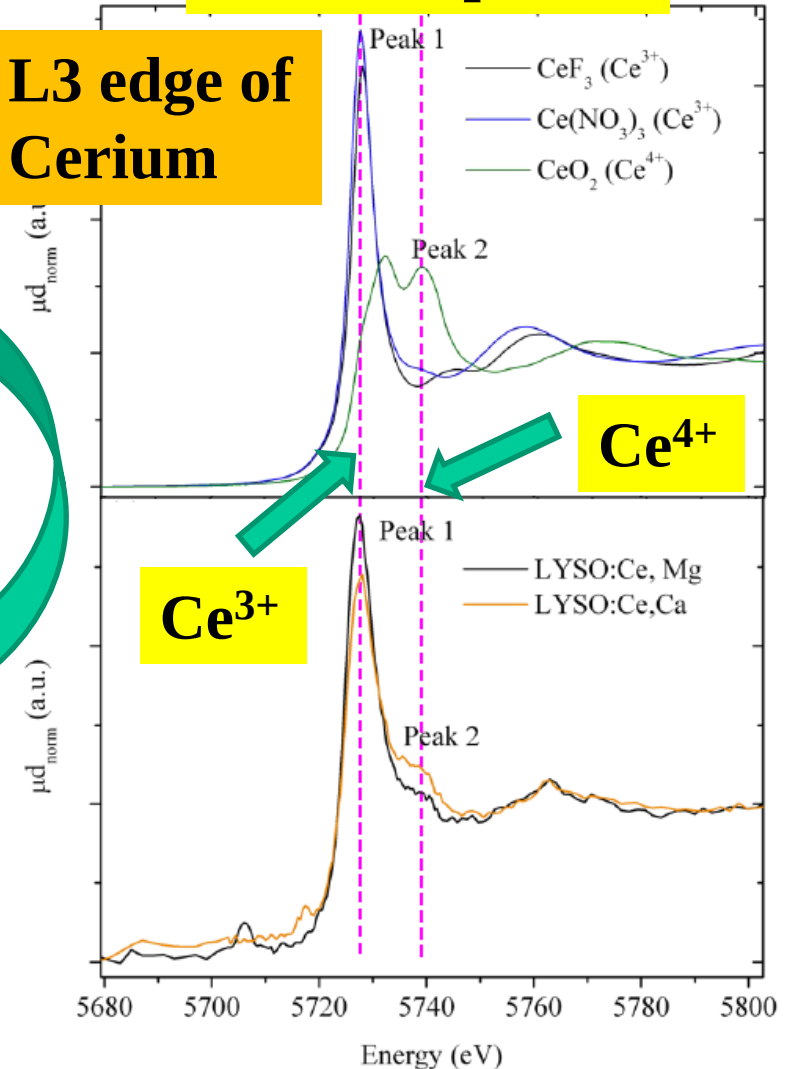
Charge transfer (CT) absorption of Ce^{4+}

The light yield of about 32,000 ph/MeV was obtained for $\text{LYSO}:\text{Ce},\text{Ca}$, which is among the highest ones ever reported in literature. **Ca content of about 60 at. ppm was confirmed by GDMS.**

Chewpraditkul et al, Opt. Mat. 35, 1679 (2013)

XANES spectra

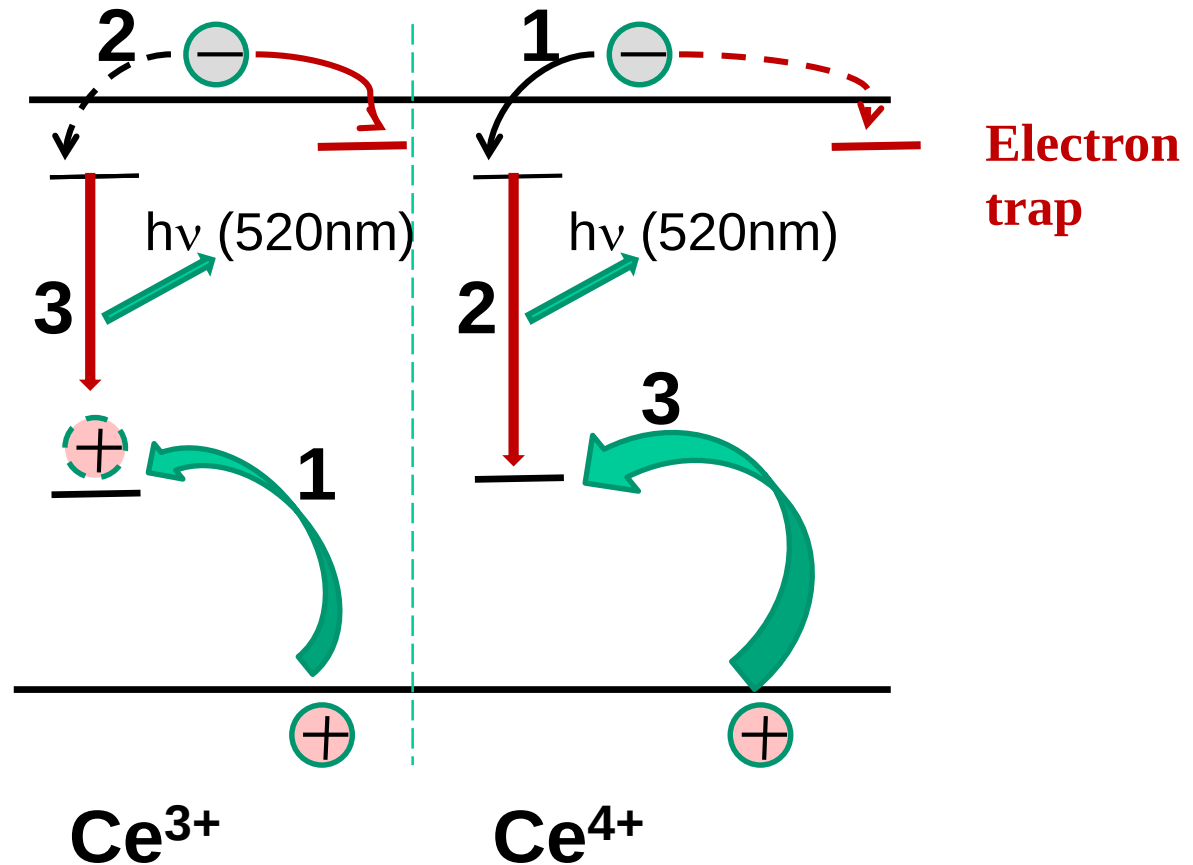
L3 edge of Cerium



Up to 35% of Ce^{4+} in total Ce content

Why stable Ce^{4+} is that good for LY increase in oxide single crystal (ceramic) scintillators

Ce^{4+} center can directly compete with any electron trap for electron capture in the first instants of scintillator mechanism so that **it will directly convert a fraction of slow part of scintillation response to the fast one**. Ce^{3+} cannot make this as it must capture the hole first.

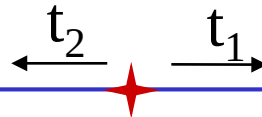


Ce^{4+} works in parallel with Ce^{3+} center, they are not competing!

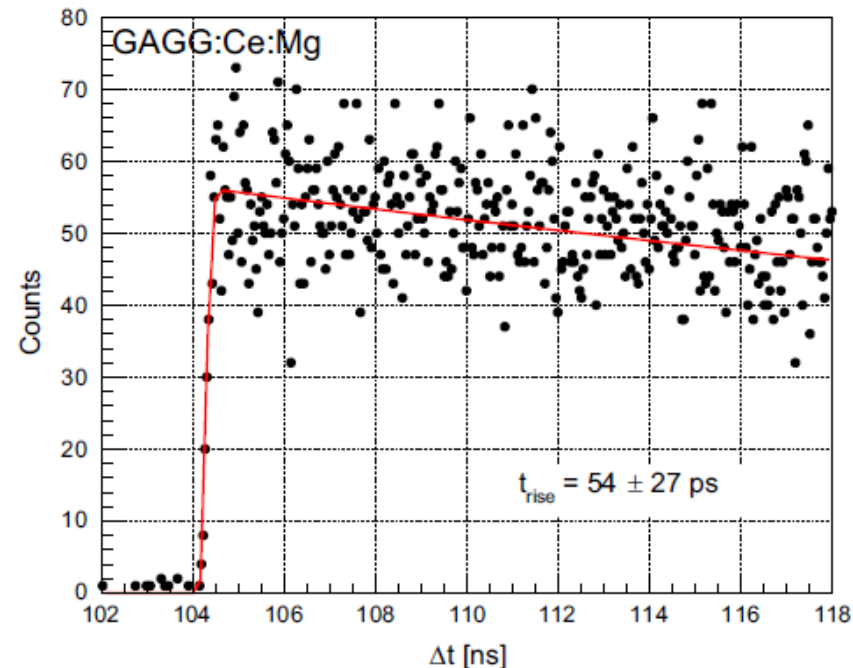
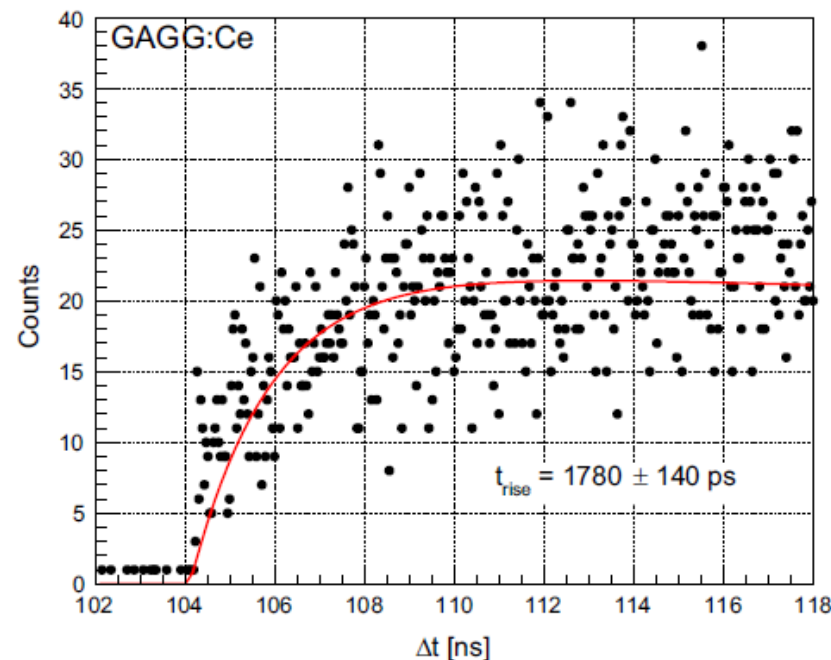
Timing coincidence resolution - Mg^{2+} codoped GAGG:Ce

Critical parameter for usage of fast scintillators in time-of-flight measurements

detector



detector

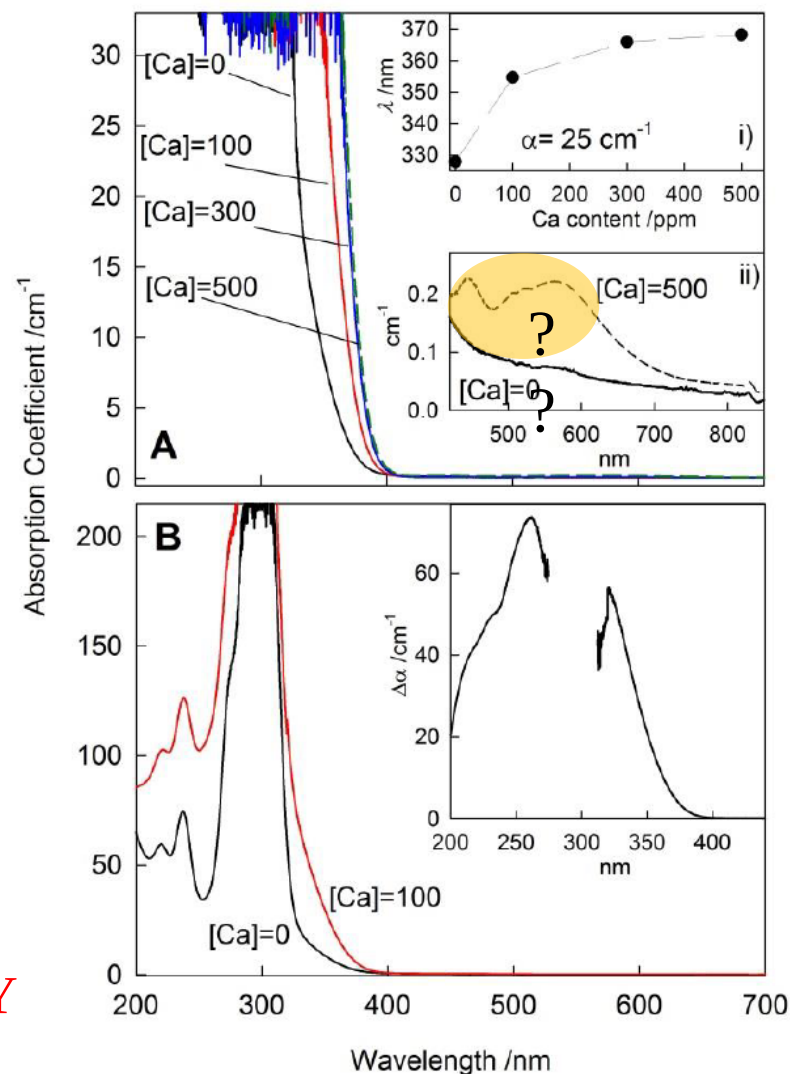
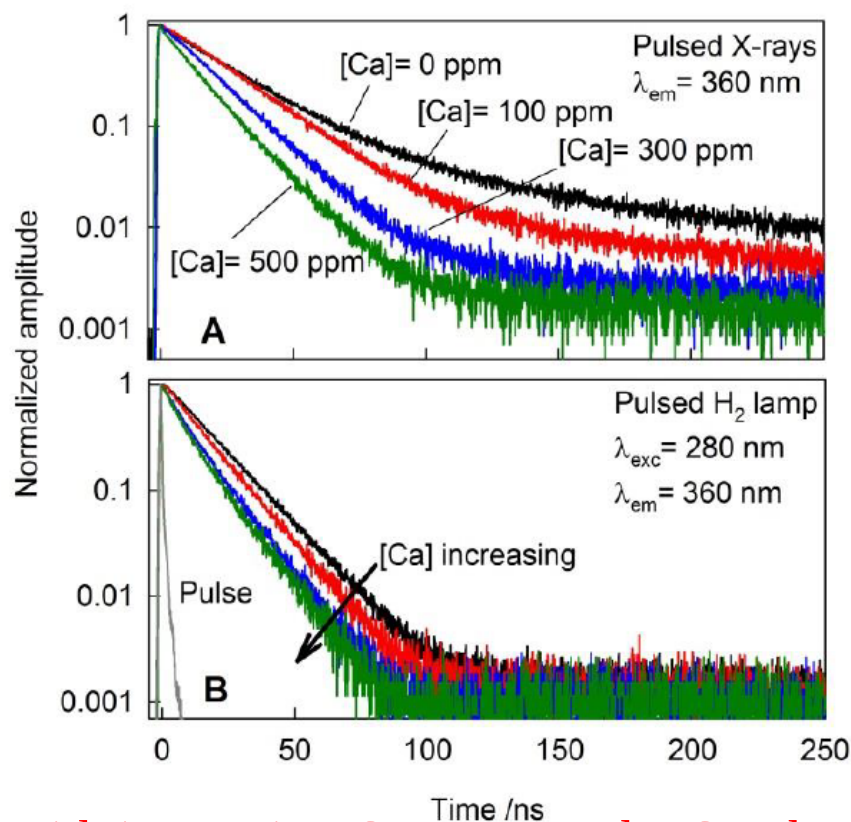


Mg codoping in GAGG:Ce almost erased the rise time in scintillation decay and TCR is improved from about 540 ps to 230 ps. Comparable values with LYSO:Ce,Ca ➡ candidate for PET!!! (Lucchini, NIM A **816**, 176 (2016))

Better quality GAGG:Ce,Mg - TCR of 165 ps achieved (Kamada, JCG **468**, 467 (2017))

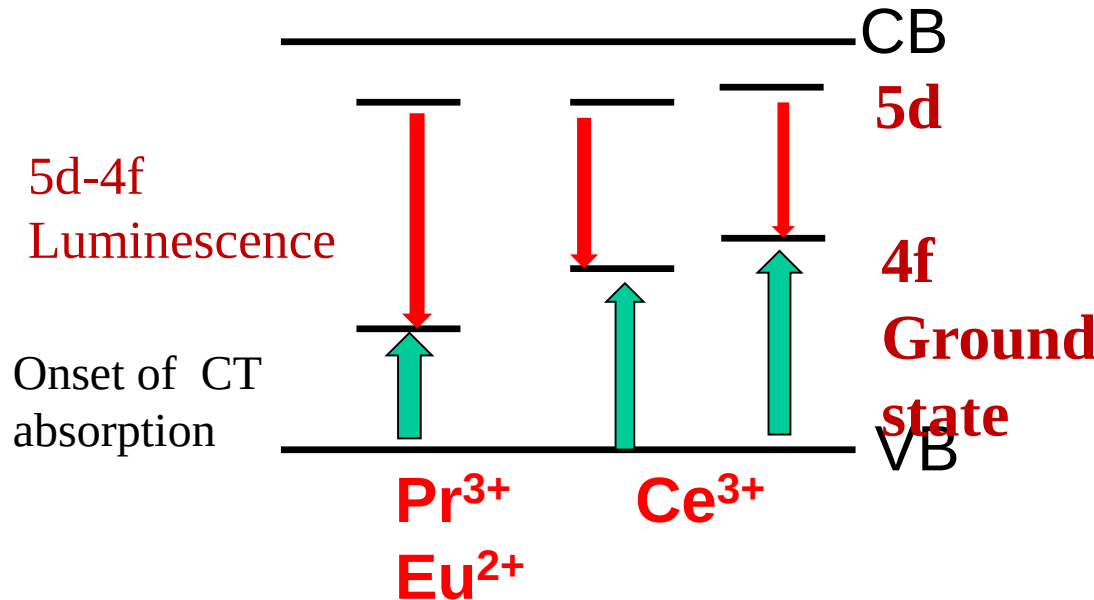
Consequences of Ca codoping in $\text{YAlO}_3\text{:Ce}$ single crystals

Federico Moretti^{*[a]†}, Karine Hovhannesian^[b], Marina Derdzian^[b], Gregory A. Bizarri^[c], Edith D. Bourret^[c], Ashot Petrosyan^[b], and Christophe Dujardin^{*[a]}

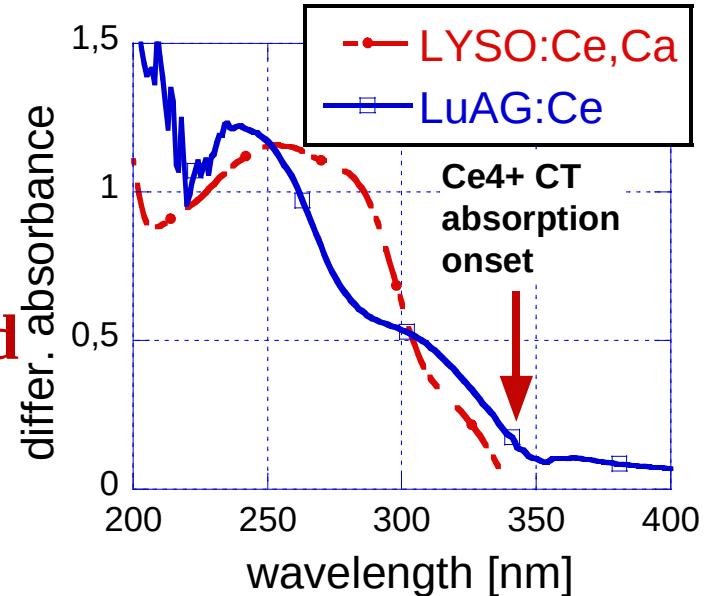


With increasing Ca content, the CT absorption of Ce^{4+} appears, scintillation decay accelerates, but LY strongly decreases due to reabsorption effect!

$\text{Ce}^{4+}, \text{Pr}^{4+}$ in LuAG, YAP, LYSO hosts



Charge transfer absorption of Ce^{4+}



CT absorption of Ce^{4+} (Pr^{4+} , Eu^{3+}) is analogous to well-studied CT of Yb^{3+} . Within the class of materials constituted by the same anion (e.g. oxides) its onset will be very similarly positioned. For the Ce^{4+} center in garnet, silicate and perovskite oxide hosts it will be positioned around 340-380 nm. **Thus it will re-absorb scintillation of Ce^{3+} in YAP, but will not in silicates and garnets.** No problem of this kind for Eu^{2+} in fluorides. Energy transfer from Gd^{3+} sublattice towards CT absorption of Ce^{4+} might be one of the reasons of decrease of LY in GGAG:Ce,Mg. Absorption of a color centre within 500-600 nm (such a center found in YAP:Ce,Mg) can be another one.

Conclusions – pathways to material optimization

- Engineering of the conduction band bottom edge enables to burry electron traps in it which can accelerate transfer stage of scintillation mechanism in Ce(Pr)-doped oxide scintillators.
- In Ce-doped orthosilicate and garnet scintillators the role of Ce^{4+} must be revisited. It contributes positively to fast scintillation response by providing new fast radiative recombination pathway. Similar effect is achieved in Eu-doped LiCAF, here we have engineered transition between Eu^{2+} - Eu^{3+} charge states.
- Ce^{4+} can make such a positive job in any oxide scintillator where CT absorption of Ce^{4+} does not overlap with emission spectrum of the material (i.e. not only that of Ce^{3+} , but e.g. also Gd^{3+} and any other one related to the host) . Pr^{4+} is excluded in bulk samples! Annealing in air also helps due to the diminished deep oxygen vacancies-based traps.
- We can monitor hole O^- centers by EPR experiment in Mg-doped garnets, correlation with TSL becomes possible and timing characteristics of Ce^{4+} scintillation cycle can be determined!

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(Ascimat). Crystal Clear Collaboration, COST
FAST TD1401.

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Recent R&D Trends in Inorganic Single-Crystal Scintillator Materials for Radiation Detection

Martin Nikl and Akira Yoshikawa*

Adv. Opt. Mater. **3**, 463–481
(2015).

Thank you
for your attention

