

Theoretical aspects of fast timing in scintillator materials and COST FAST Activity in Moscow State University

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The goal: scintillator should emit at least 10 photons during first 10 ps

All excitations are created without delay, all emit photons, high value of dipole matrix element

- Number of excitations: $N_{excitations} = \frac{E_\gamma}{(1.5 \div 2.5) E_g}$
- Number of photons per Δt : $N_{photons}^{\Delta t} = \frac{\Delta t}{\tau_{rad}} N_{excitations}$
- Radiation rate of photon emission (allowed transition): $\tau_{rad} \approx 1 \text{ ns} \left(\frac{5 \text{ eV}}{h\nu_{emission}} \right)^2$, $h\nu_{emission} \approx \frac{1}{2} E_g$
 $\tau_r \approx 1 \text{ ns}$ for $h\nu_{emission} = 5 \text{ eV}$
 $\tau_r \approx 6.2 \text{ ns}$ for $h\nu_{emission} = 2 \text{ eV}$
 $\tau_r \approx 25 \text{ ns}$ for $h\nu_{emission} = 1 \text{ eV}$
- For 511 keV γ :

$$N_{photons}^{10\text{ps}} = \frac{10 \text{ ps}}{1 \text{ ns}} \left(\frac{E_g}{10 \text{ eV}} \right)^2 \frac{511 \text{ keV}}{(1.5 \div 2.5) E_g} \approx (20 \div 35) E_g [\text{eV}]$$

- But ... in most cases:
- not all excitations are created without delay
- not all excitations emit photons
- dipole matrix element is not high

Energy transfer processes in scintillators (Ce activated)

- Electron intraband luminescence (e-IBL): $\text{Hot } e \rightarrow e + h\nu$
- Hole intraband luminescence (h-IBL) or crossluminescence (CL): $\text{Hot } h \rightarrow h + h\nu$
- Exciton creation: $e+h \rightarrow \text{FE}$
- Exciton self-trapping: $\text{FE} \rightarrow \text{STE}$
- Exciton emission: $\text{STE} \rightarrow h\nu$
- Exciton to Ce diffusion-controlled dipole-dipole transfer: $\text{STE} + \text{Ce}^{3+} \rightarrow \text{Ce}^{3+*}$
- Ionization of Ce by free exciton: $\text{FE} + \text{Ce}^{3+} \rightarrow e + \text{Ce}^{4+}$
- Capture of electron by Ce^{4+} : $e + \text{Ce}^{4+} \rightarrow \text{Ce}^{3+*}$
- Capture of hole by Ce^{3+} : $h + \text{Ce}^{3+} \rightarrow \text{Ce}^{4+}$
- Ce emission: $\text{Ce}^{3+*} \rightarrow \text{Ce}^{3+} + h\nu$
- Quenching Auger processes ($\text{STE} + \text{STE} \rightarrow \text{STE}$, $\text{STE} + \text{Ce}^{3+*} \rightarrow e + h$, $e + \text{Ce}^{3+*} \rightarrow e$, $2e + h \rightarrow e$, ...)

Types of possible candidates for fast timing

- IntraBandLiminescence+CrossLuminescence
- Excitonic emission in bulk crystals
- Activator emission with fast energy transfer to activator
- Nanoparticles with excitonic (bi-excitonic) emission (giant oscillator strength?) and quantum wells

2 types of processes

- Mono-molecular



$$w_{\text{FE} \rightarrow \text{STE}} = \gamma_{\text{FE} \rightarrow \text{STE}} n_{\text{FE}}$$

- Bi-molecular



$$w_{eh \rightarrow \text{FE}} = \beta_{eh \rightarrow \text{FE}}(t) n_e n_h$$



$$w_{ex-ex} = \beta_{ex-ex}(t) n_{ex}^2$$

$$n_i \sim \langle r_{i-i} \rangle^{-3}$$

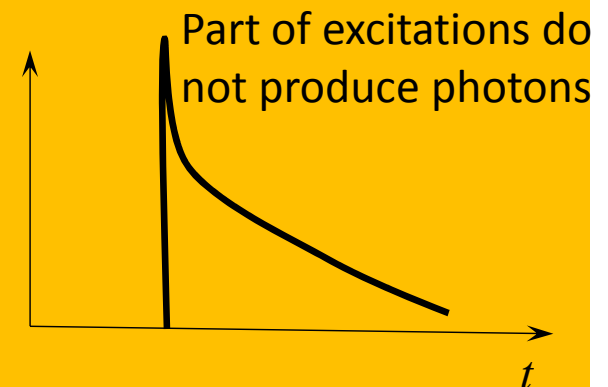
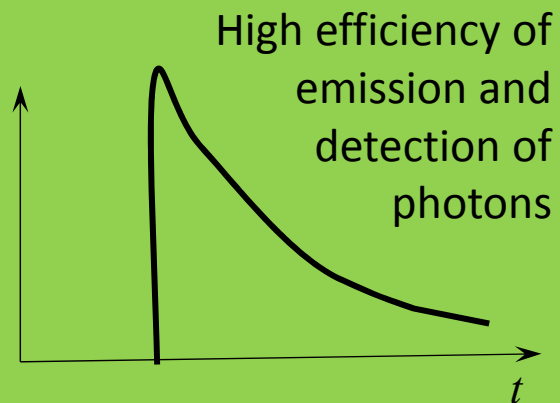
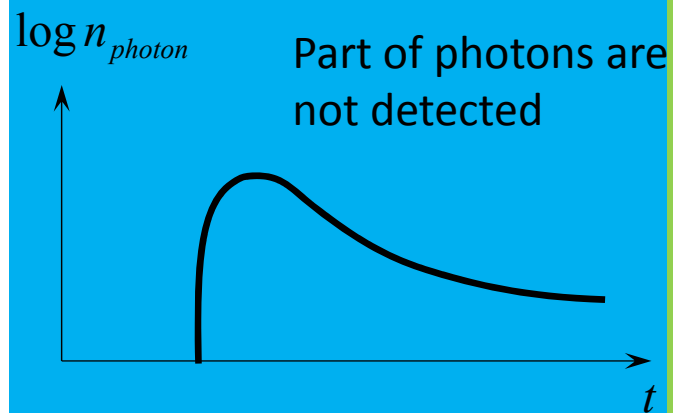
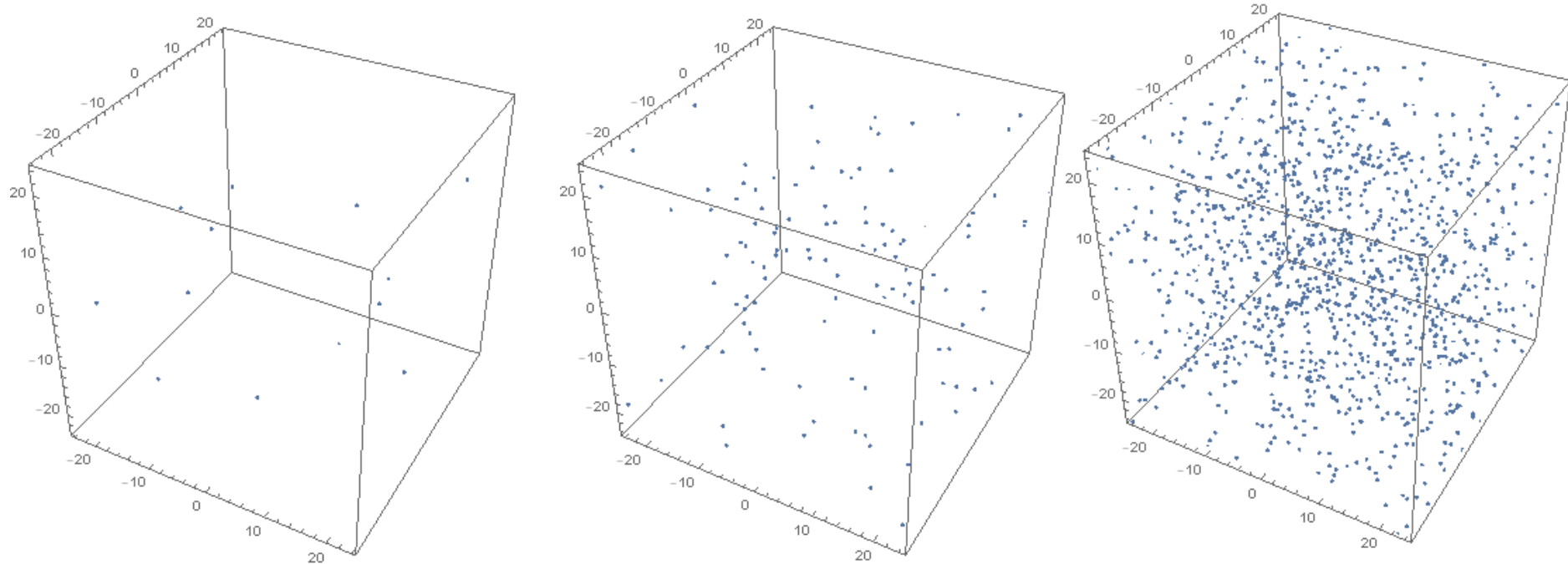
$\beta_{jk}(t)$ depends on time due to initial correlation between excitations (correlation function $g_{jk}(r) > 1$ for $t = 0$) and induced correlation due to interaction (when $g_{jk}(r) \rightarrow 0$ with increase of t for small distances)

$$\frac{\partial n_i(\mathbf{r}, t)}{\partial t} - D_i \frac{\partial^2 n_i(\mathbf{r}, t)}{\partial \mathbf{r}^2} = - \sum_j \alpha_{ij} n_j(\mathbf{r}, t) - \sum_{jk} \beta_{i,jk}(t) n_j(\mathbf{r}, t) n_k(\mathbf{r}, t)$$

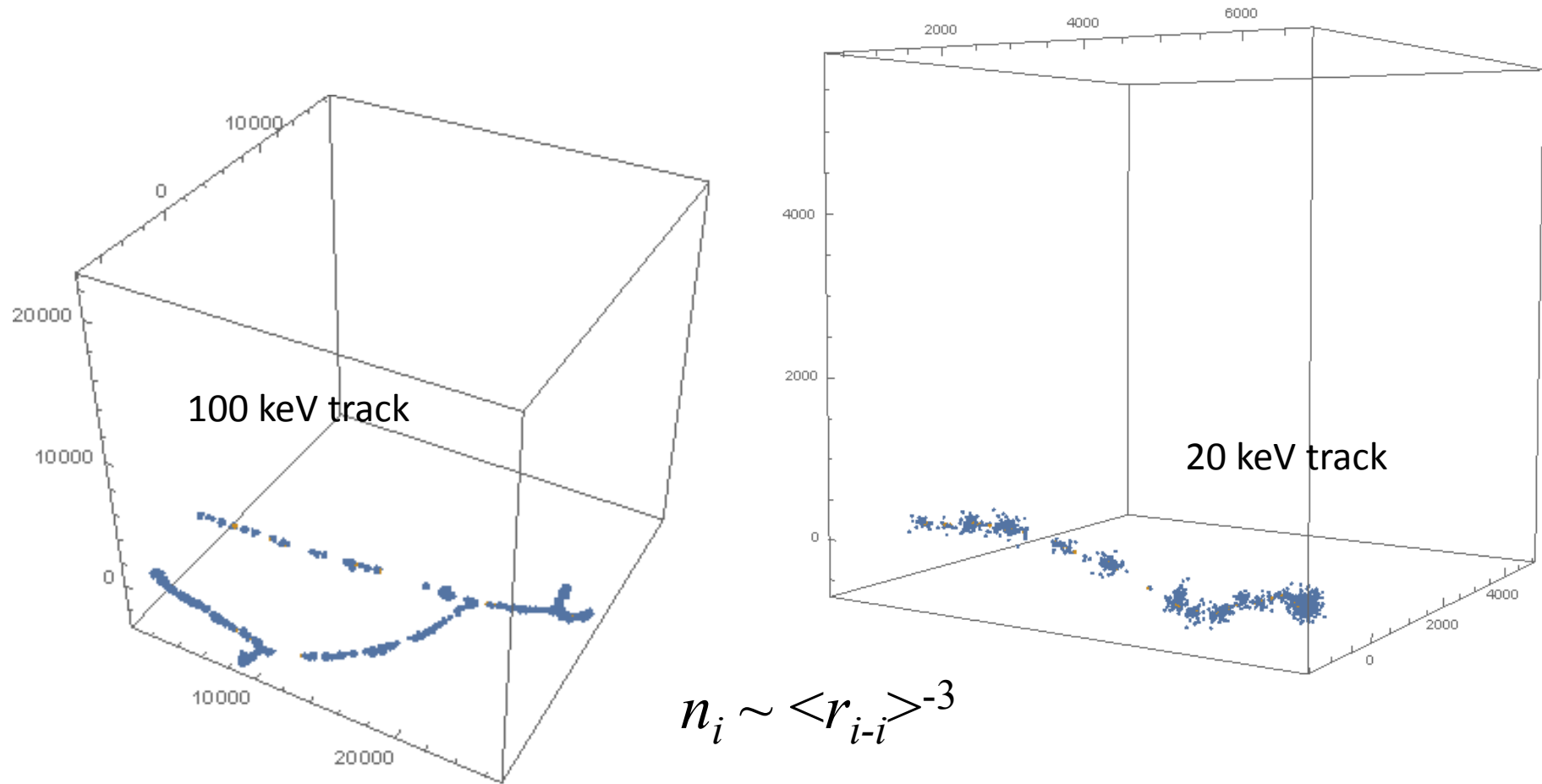
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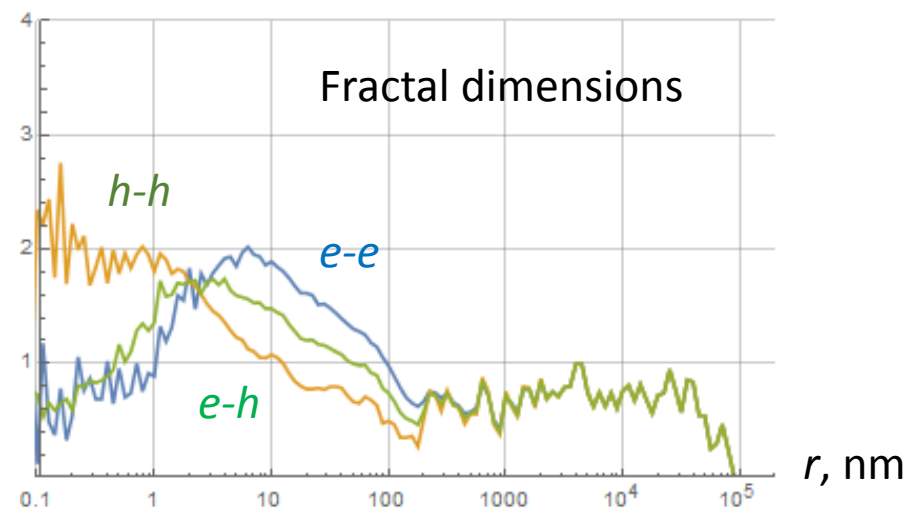
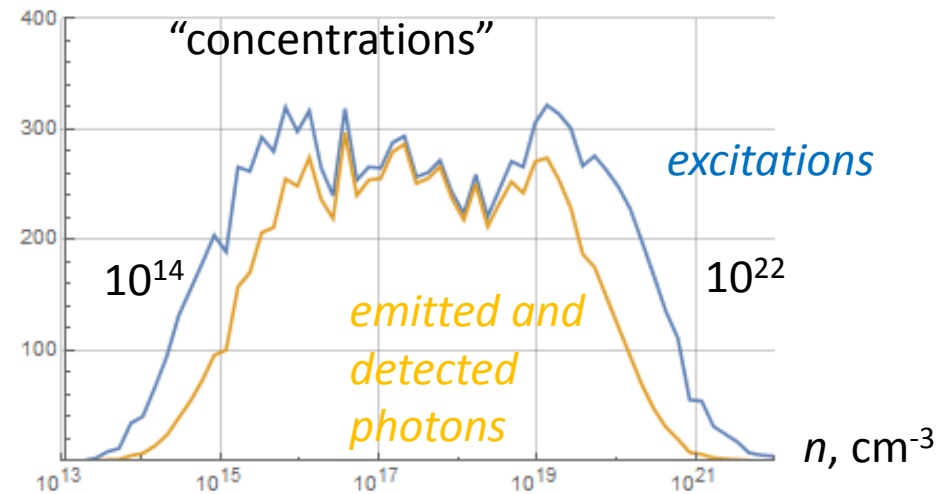
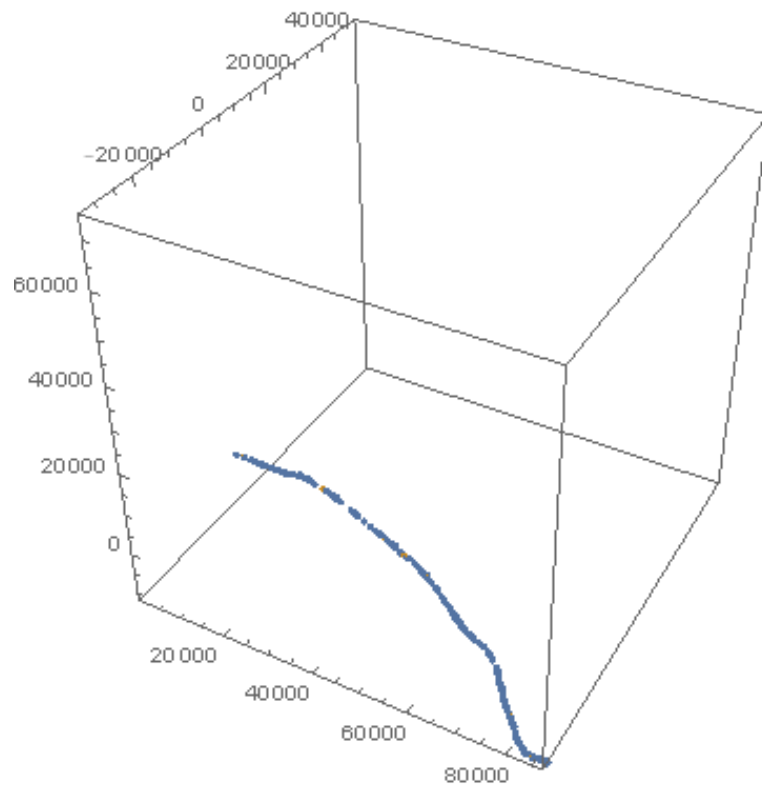
Bi-molecular processes depend on concentration of components



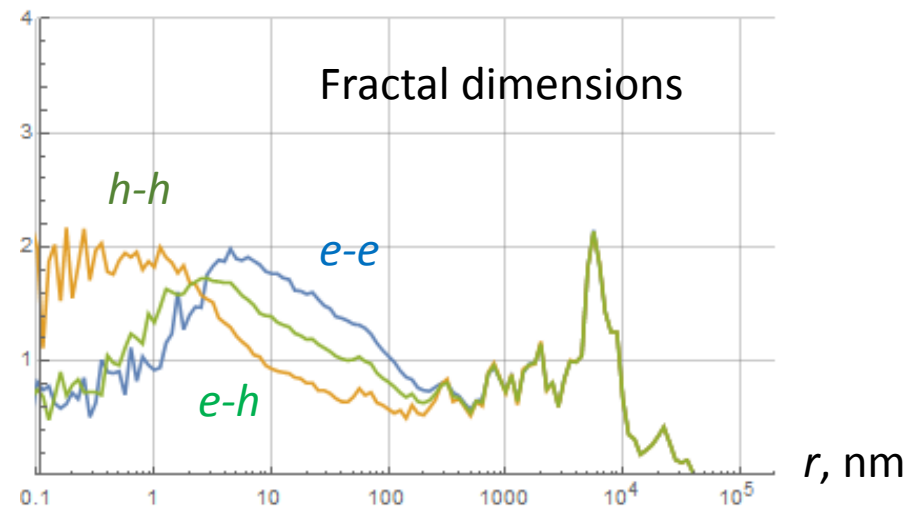
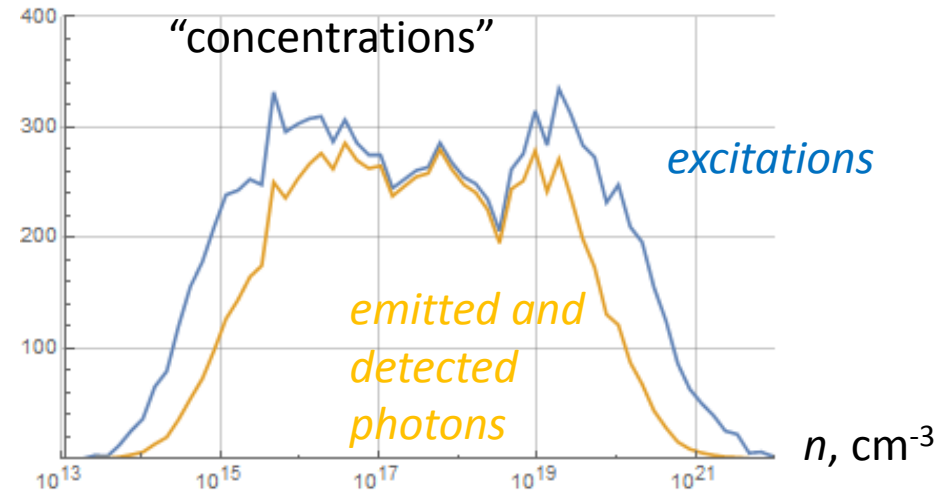
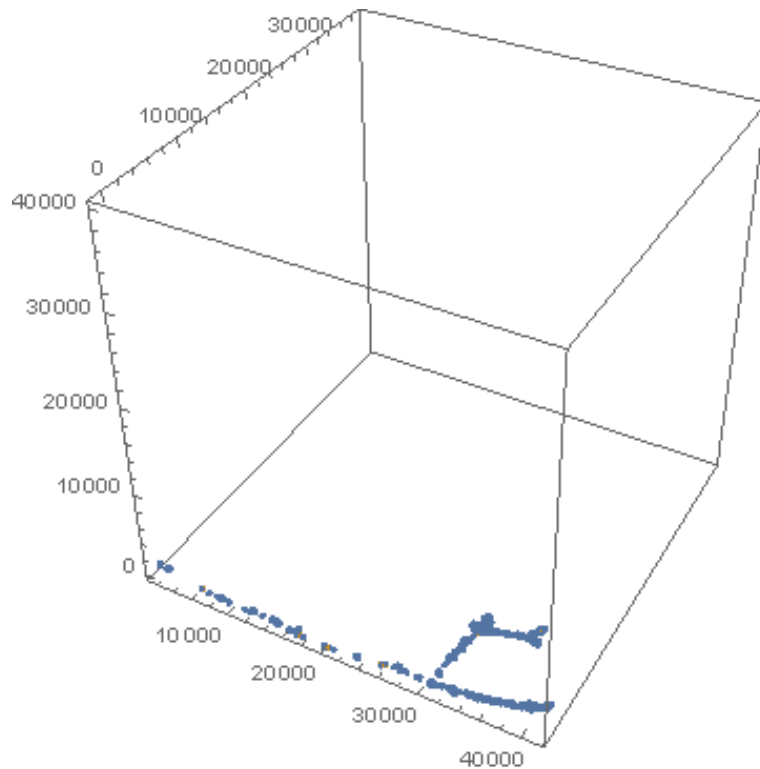
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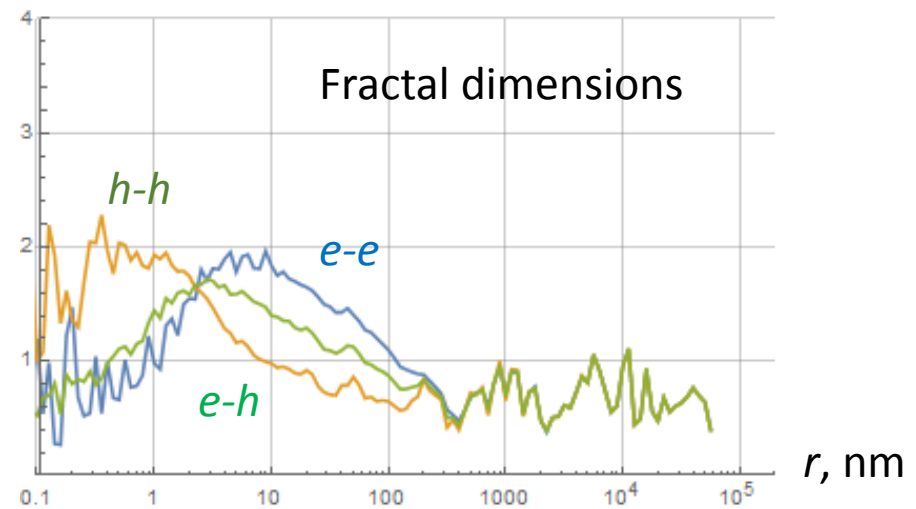
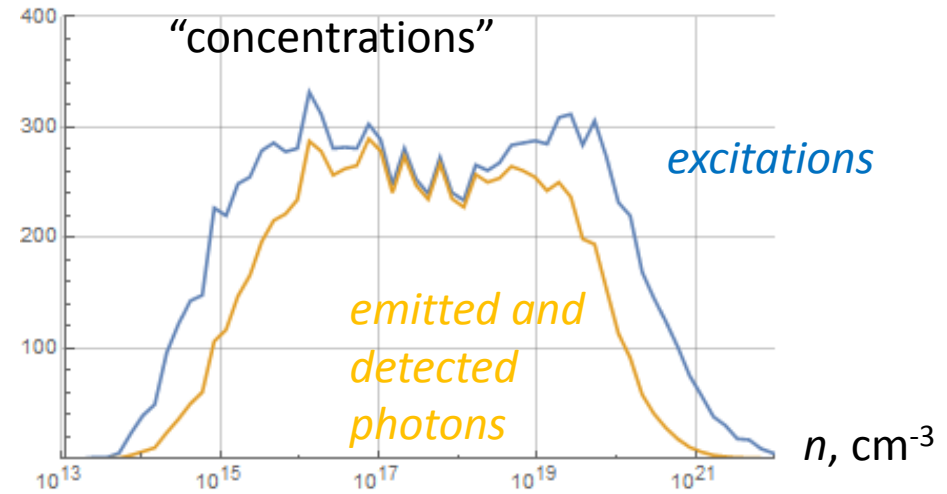
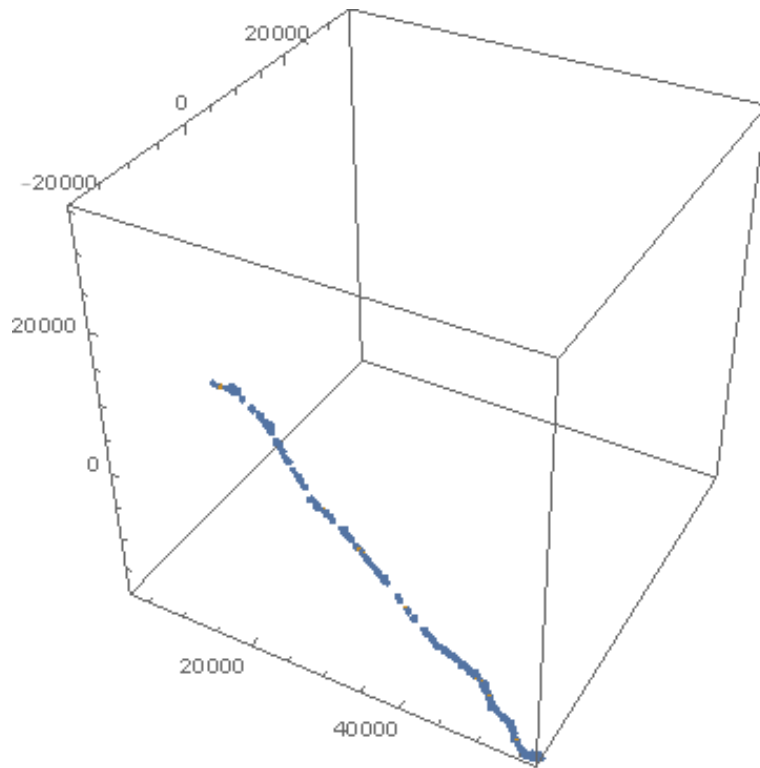
Distribution of “concentrations” and fractal dimensions for ee, hh and eh distribution function



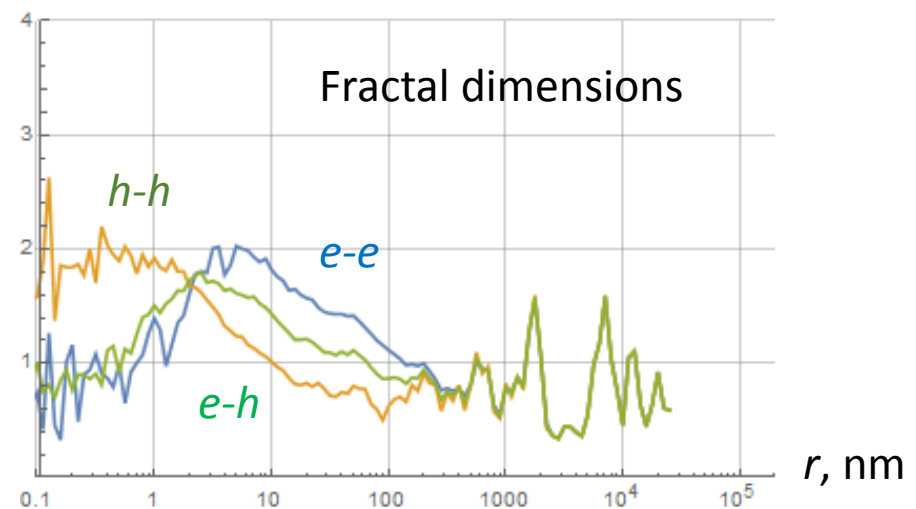
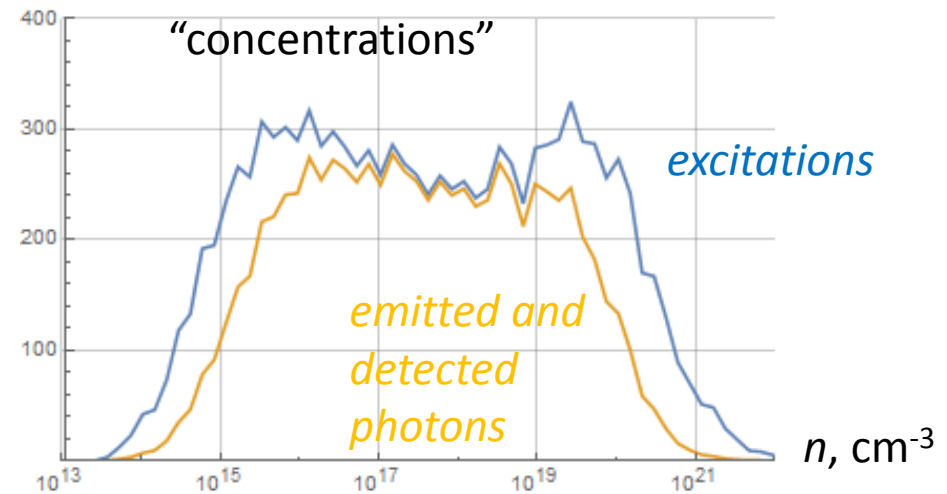
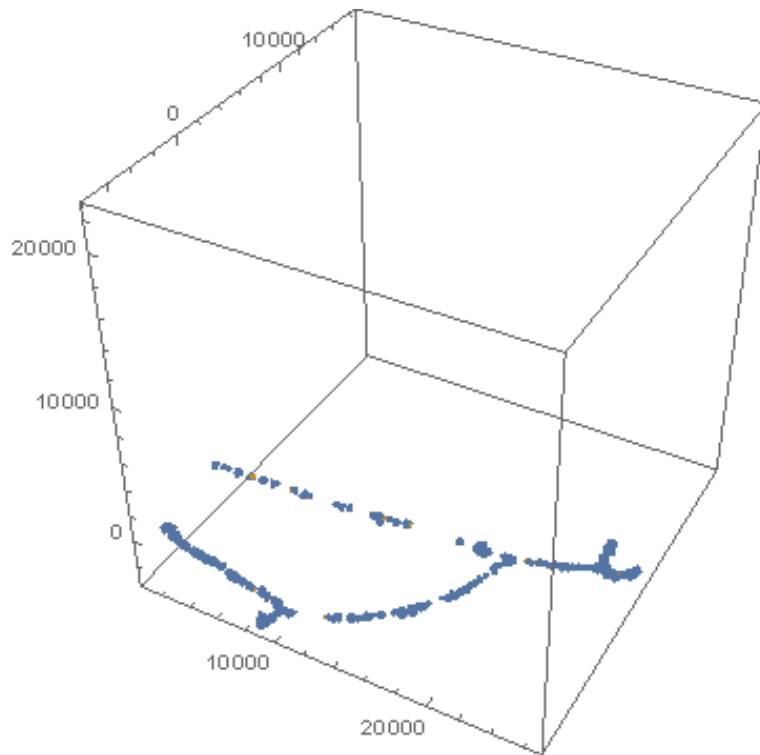
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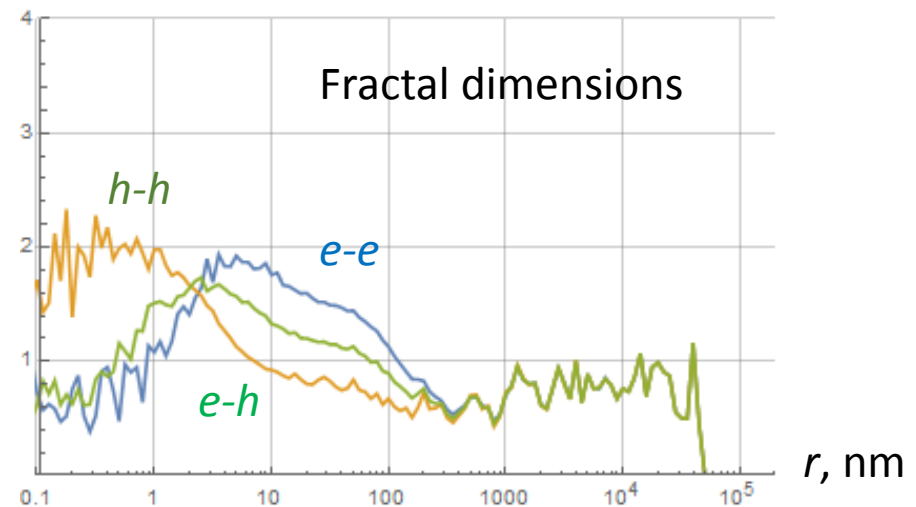
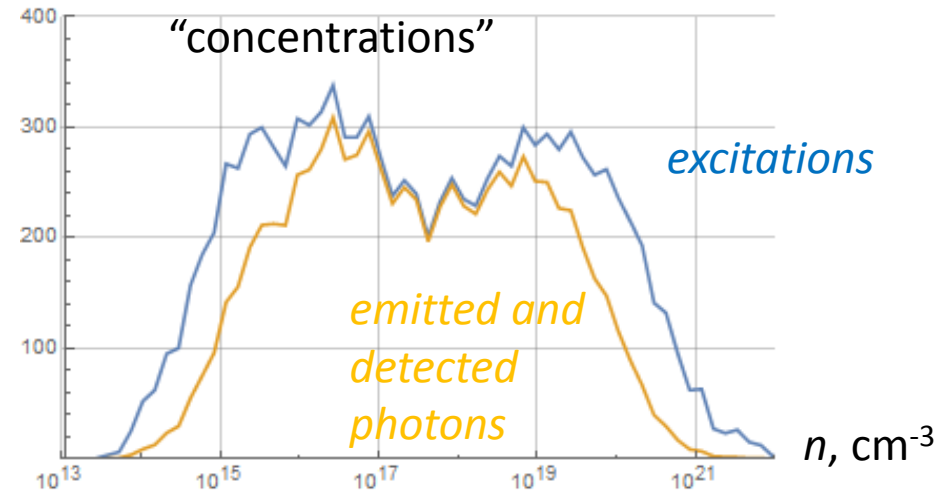
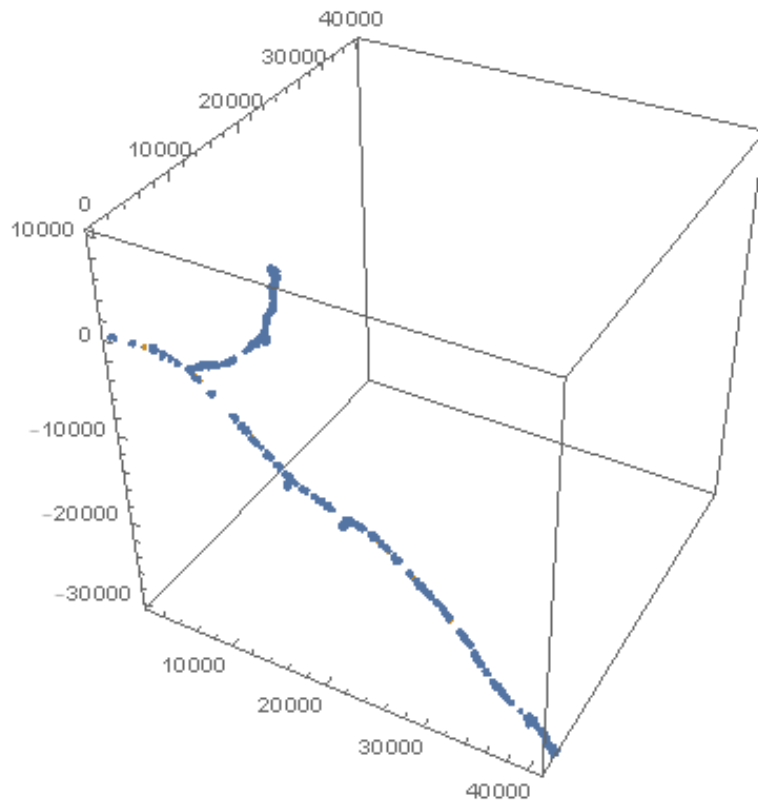
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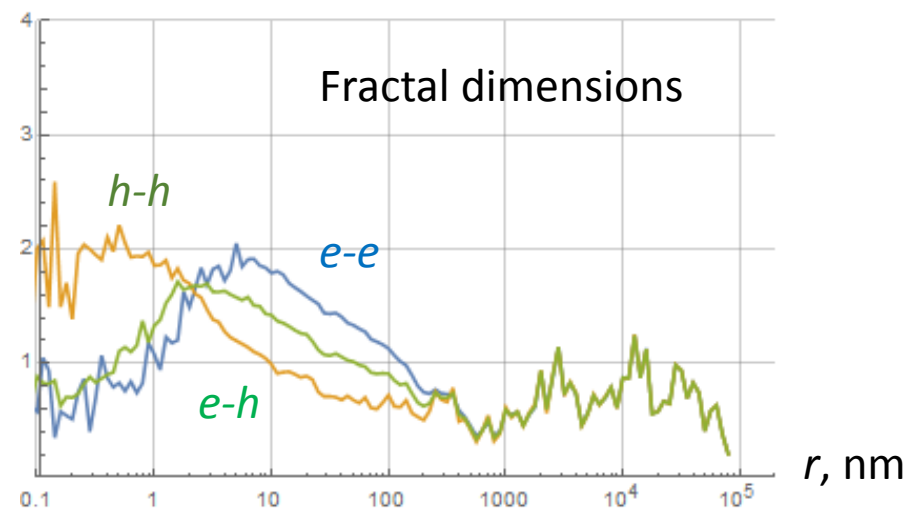
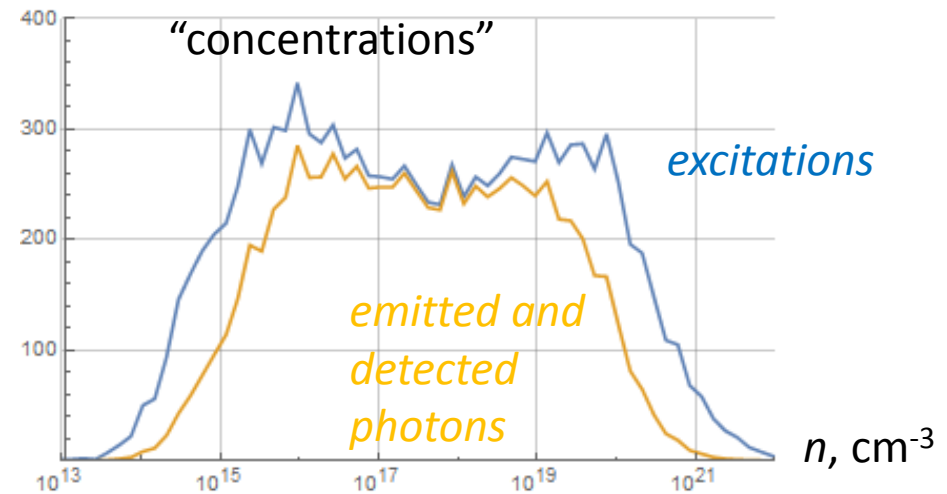
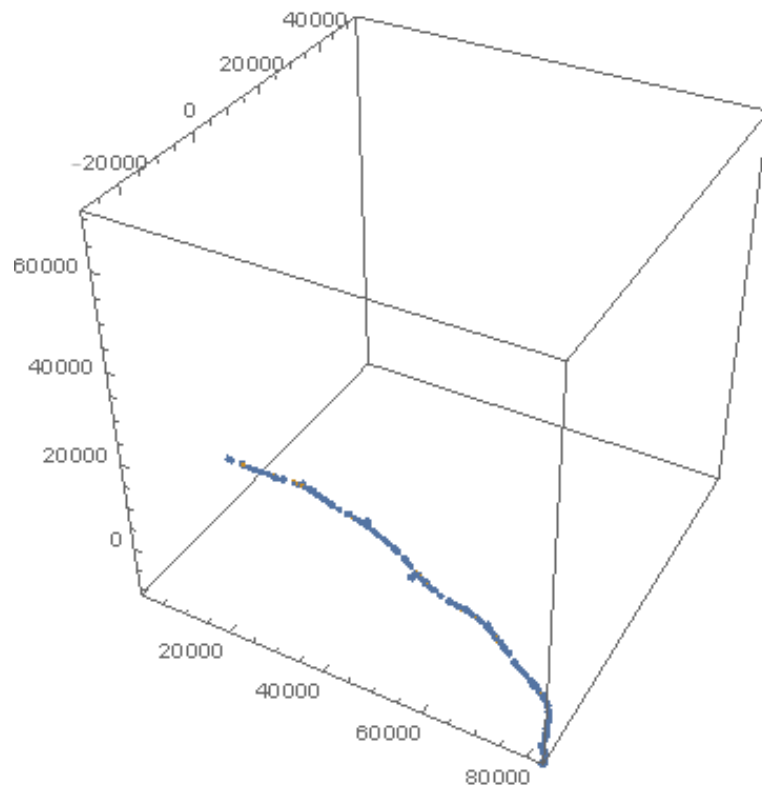
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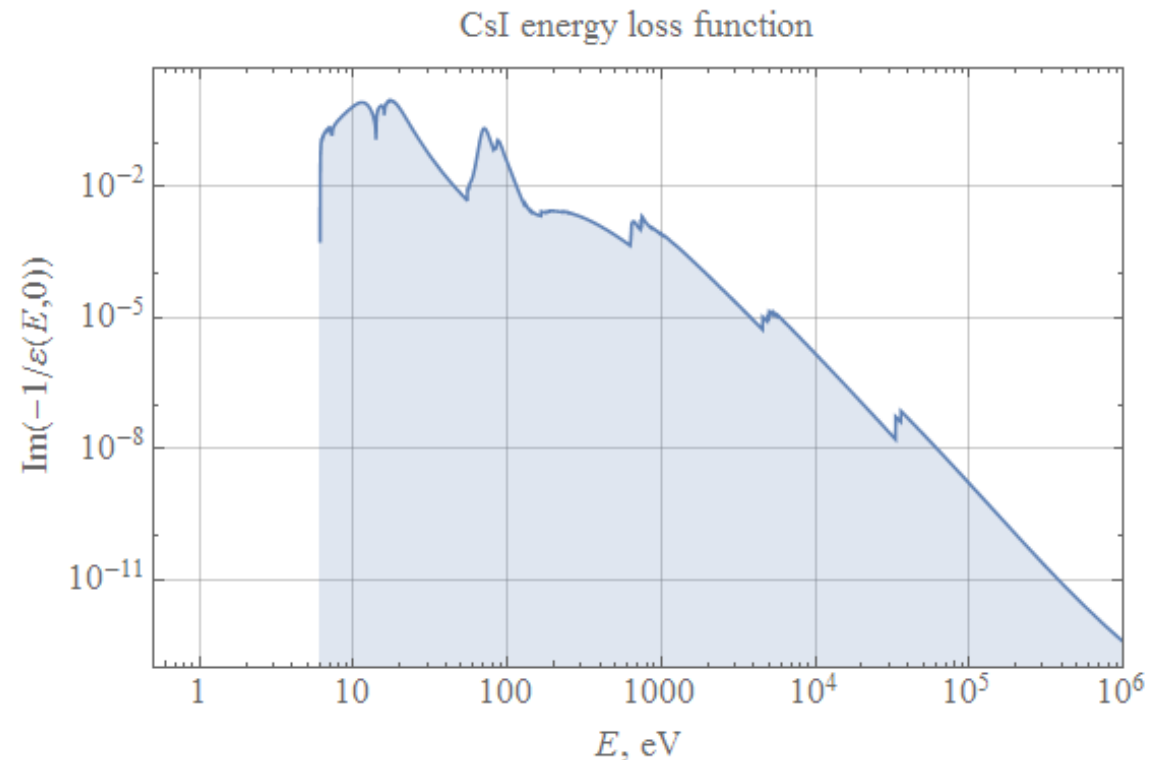


How to take non-uniformity of e-h distribution in the excited region into account

1) Calculation of energy loss function

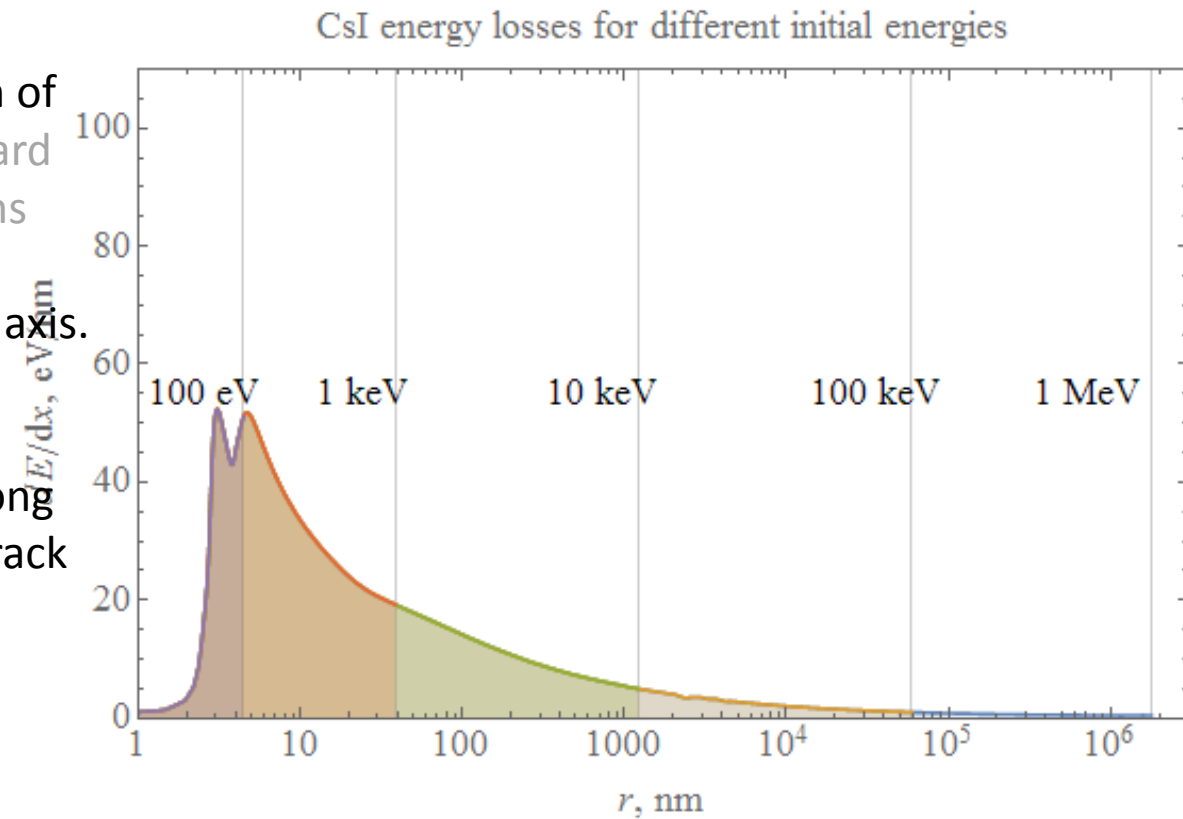
$\text{Im}(-1/\epsilon(E, q=0))$ (disregard of large-angle scattering like δ -electron production) based on atomic photoabsorption cross-sections with chemical shift and population corrections for ionic crystals

(see, e.g., G. Bizarri et al, J. Appl. Phys., 105, 044507 (2009))

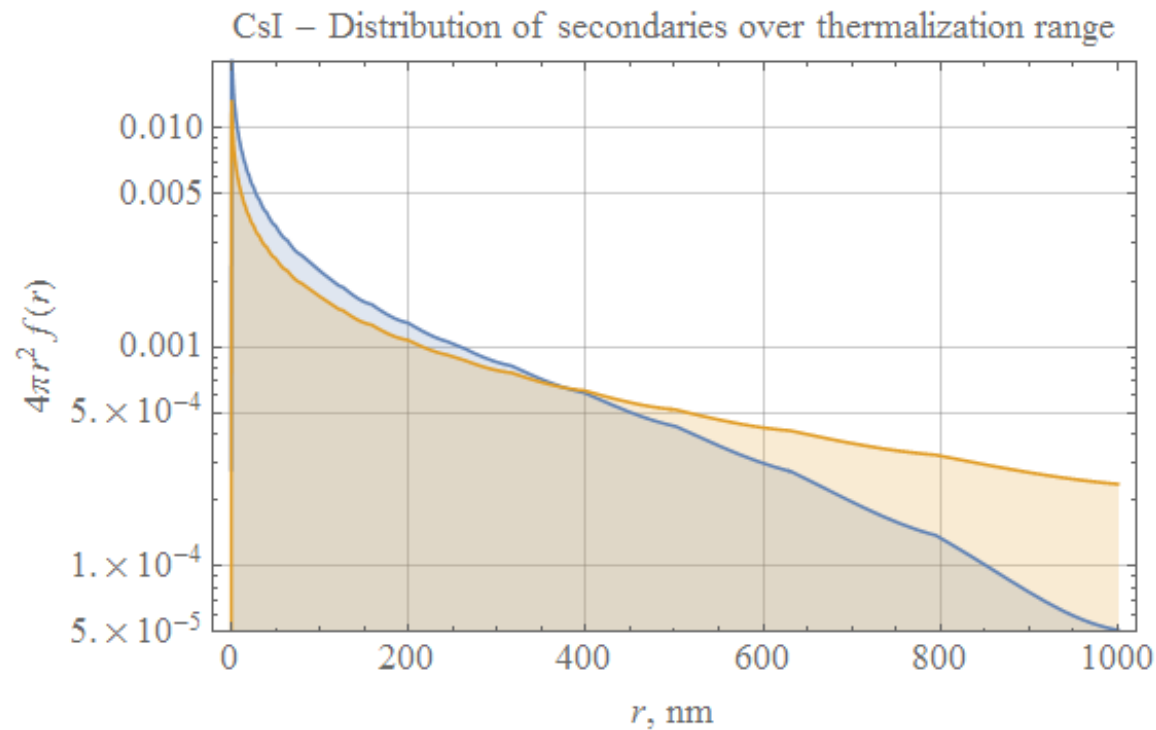


A. N. Vasil'ev. *Microtheory of scintillation in crystalline materials*. In *Engineering of Scintillation Materials and Radiation Technologies*, volume 200 of Springer Proceedings in Physics, pages 3–34. Springer, 2017

2) Calculation of 1D distribution of hot e-h pair creation (disregard of clusterization of excitations due to e.g. Auger processes) along the straightened track axis. Tracks for different initial electron energies are superposed, the distance along the track is taken from the track end.



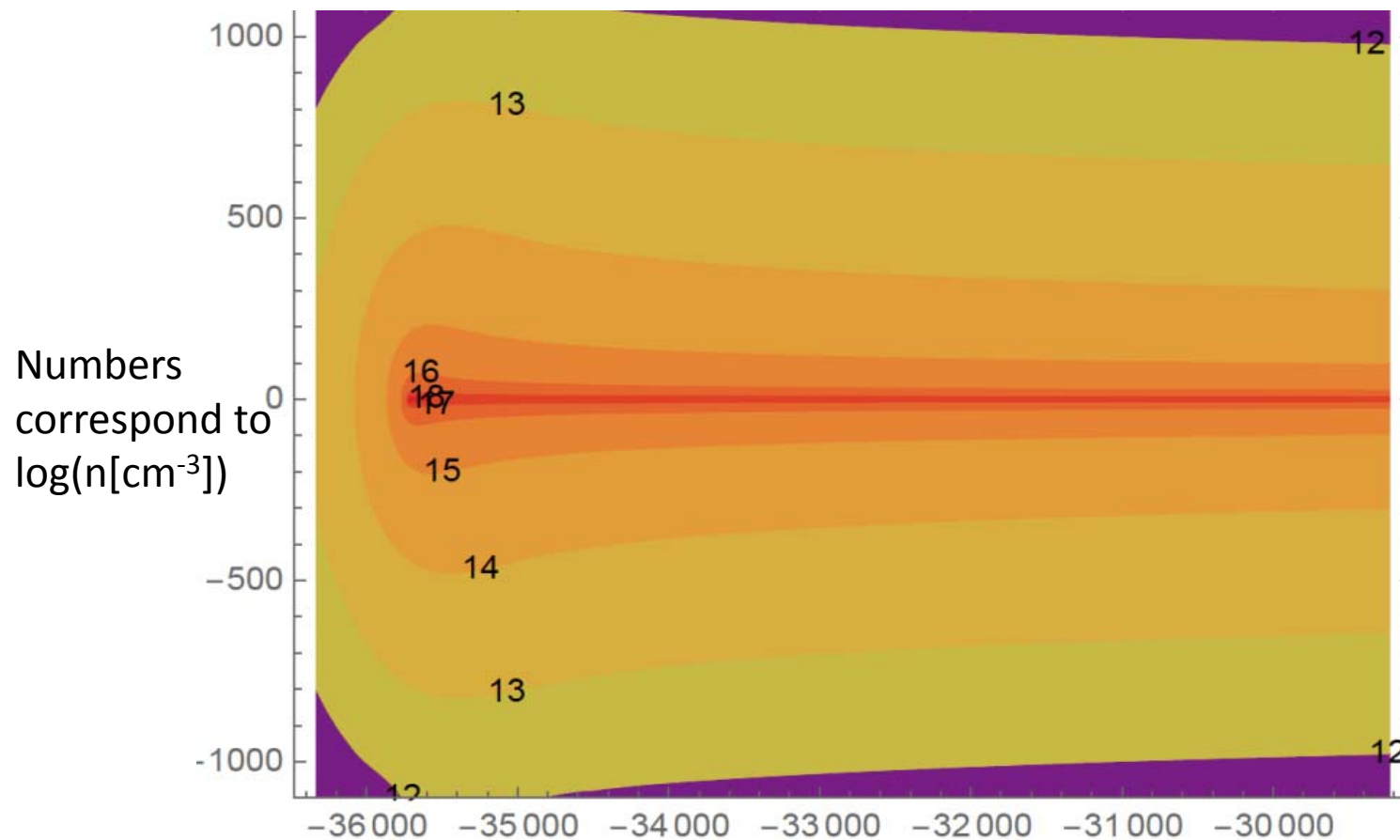
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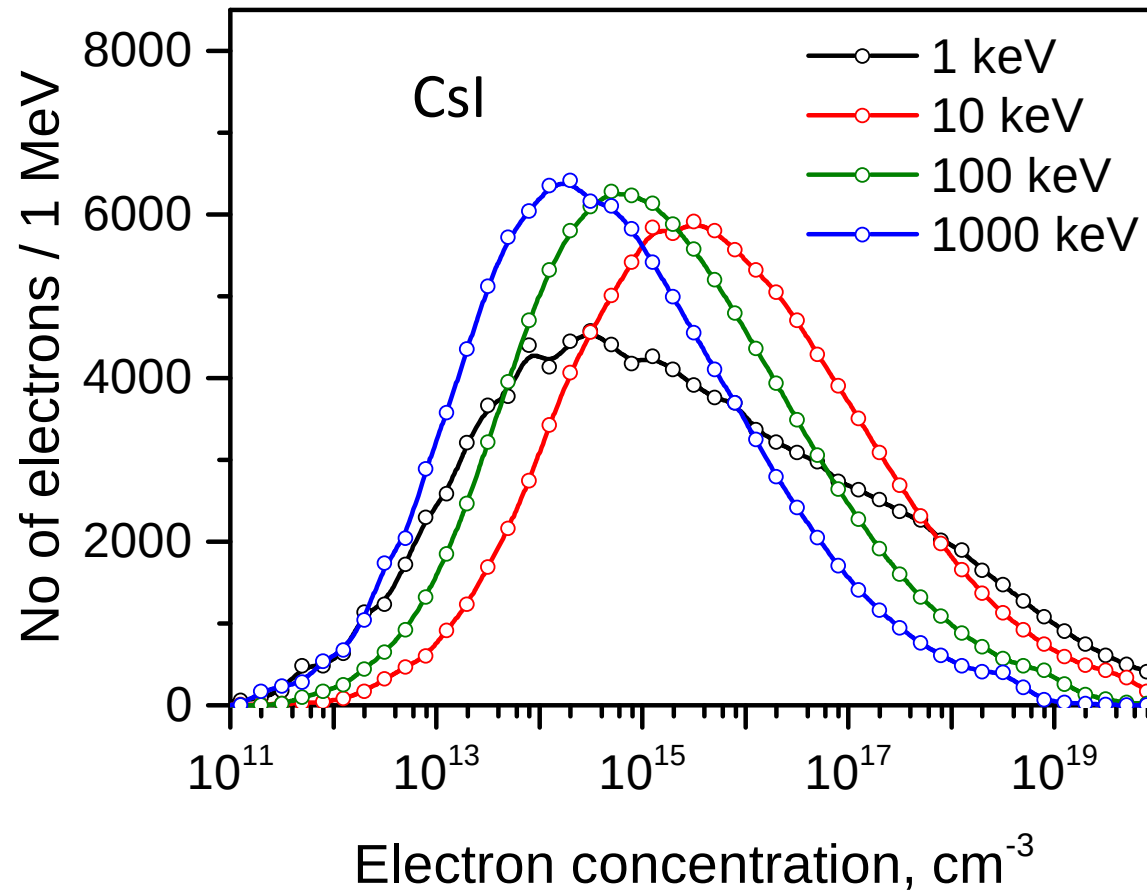
- 3) Calculation of 3D distribution of thermalized electrons and holes initially distributed in kinetic energy between 0 and threshold of inelastic scattering (about E_g) (A.Vasil'ev, A.Gektin, IEEE TNS, 61 (2014) 235-245)

A. N. Vasil'ev. *Microtheory of scintillation in crystalline materials*. In *Engineering of Scintillation Materials and Radiation Technologies*, volume 200 of Springer Proceedings in Physics, pages 3–34. Springer, 2017

- 4) Convolution of 1D distribution of energy losses in track and 3D distribution of thermalized electrons and holes produces spatial distribution of excitation density in a high energy electron track in CsI. (Disregard of Coulomb interaction of carriers due to thermalization)

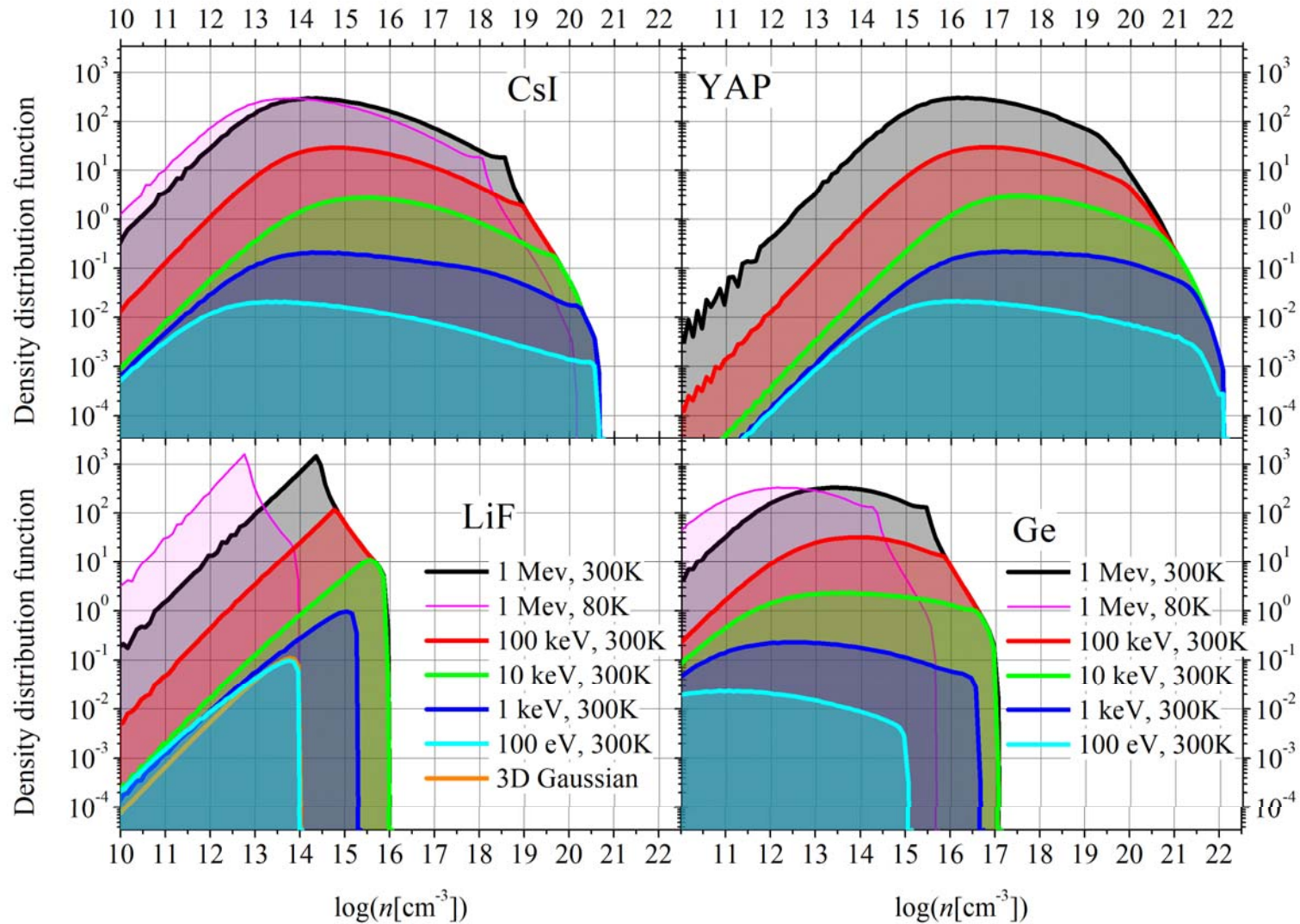


5) Calculation of weight functions – how many of electrons are in the regions with concentration 10^x to $10^{x+0.1}$, $x=10, 10.1...21$.



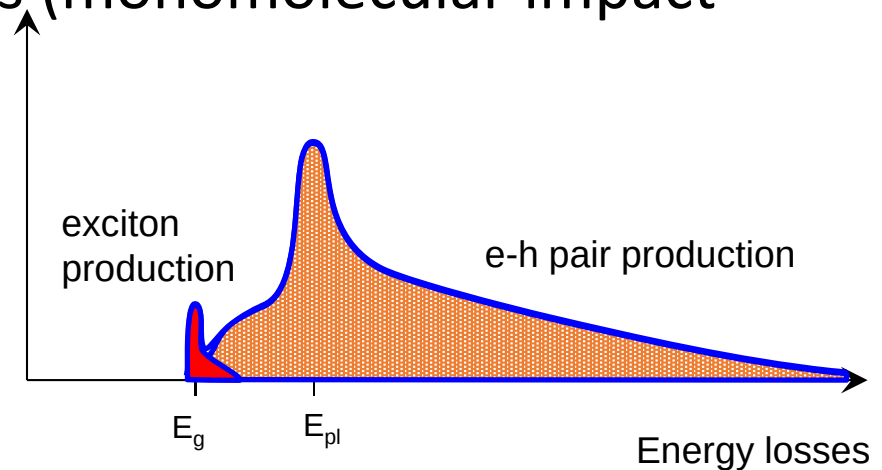
A. N. Vasil'ev. *Microtheory of scintillation in crystalline materials*. In *Engineering of Scintillation Materials and Radiation Technologies*, volume 200 of Springer Proceedings in Physics, pages 3–34. Springer, 2017

Density distribution functions for different materials



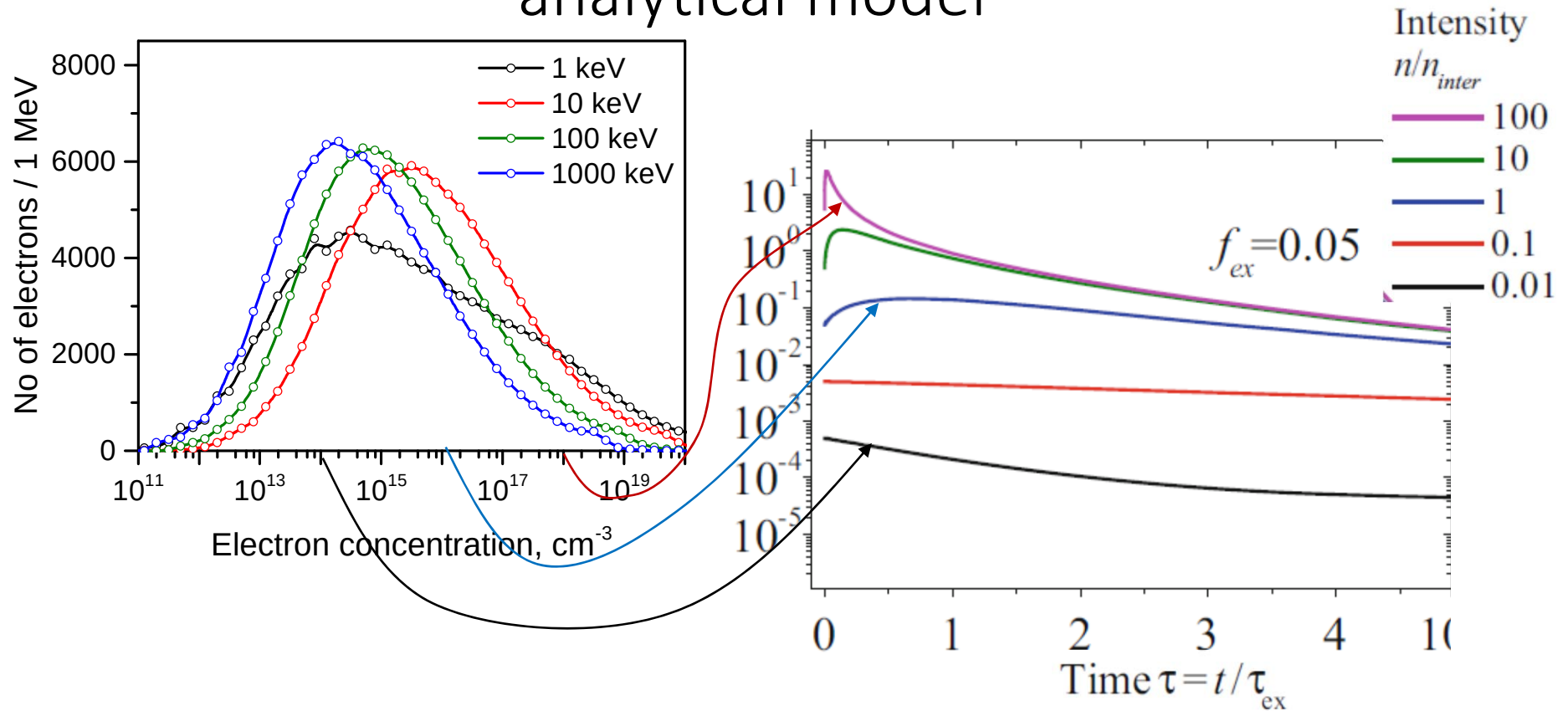
Excitonic luminescence

- Mainly bi-molecular process (monomolecular impact creation of excitons <5%)



- Rise time decreases with increase of concentration of e and h
- Quenching increases with increase of concentration of e and h

Exciton decay kinetics in $e+h \rightarrow ex$; $ex+ex \rightarrow ex$ analytical model



G.Bizarri et al, J.Lumin., 129 (2009) 1790-1793; A. N. Vasil'ev. *Microtheory of scintillation in crystalline materials*. In Engineering of Scintillation Materials and Radiation Technologies, volume 200 of Springer Proceedings in Physics, pages 3–34. Springer, 2017

f_{ex} – fraction of instantly created excitons, n_{inter} – concentration at which rate of $ex+ex$ quenching equals to τ_{ex}

Dependence of rise time for $e+h \rightarrow FE$ on electron excess energy in solid Xe

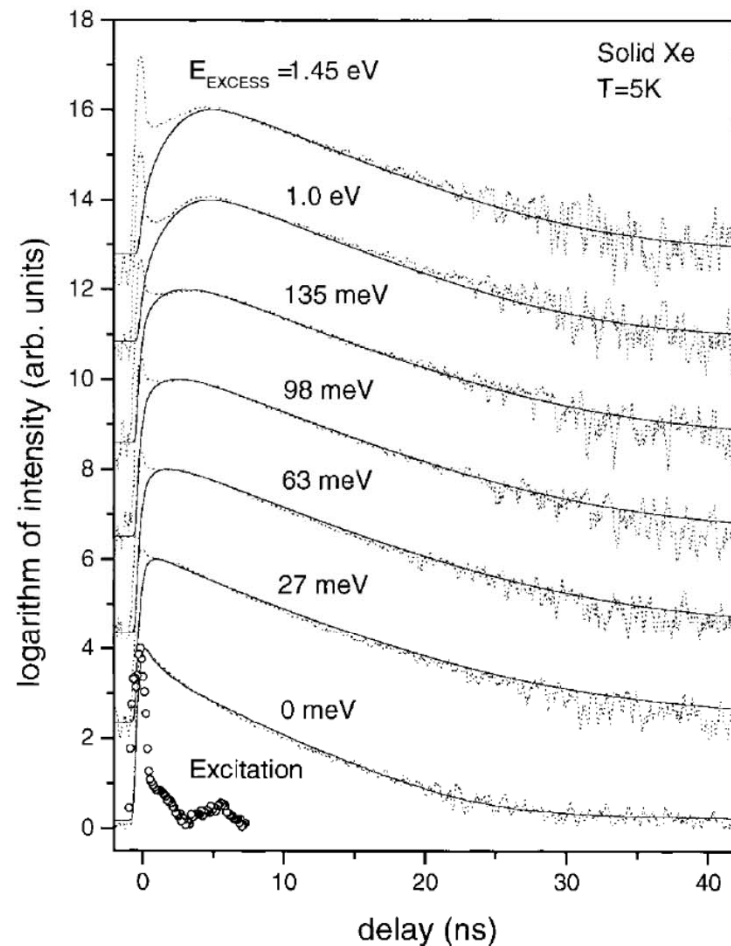


Fig. 2. Decay curves of the FE-luminescence line of solid Xe at $T = 5$ K, excited with different photon energies of excitation, $h\nu_{\text{ex}}$. The parameter given in the figure is the excess energy, $E_{\text{excess}} = h\nu_{\text{ex}} - E_g$ (E_g is the band gap energy). The dotted lines are measurements, the full curves are results of model calculations. For comparison purposes, the apparatus function (open circles) is included

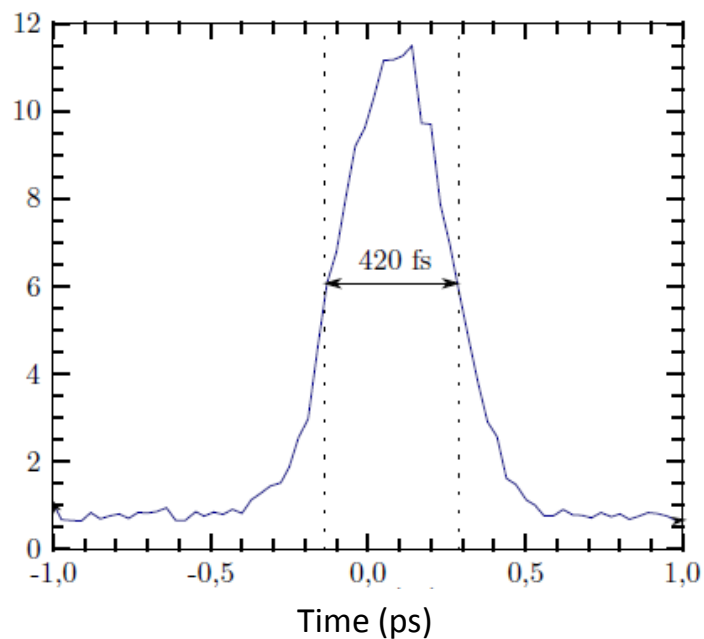
phys. stat. sol. (b) **214**, 81 (1999)

Subject classification: 71.35.Aa; 78.47.+p; 78.55.Hx; S5.2

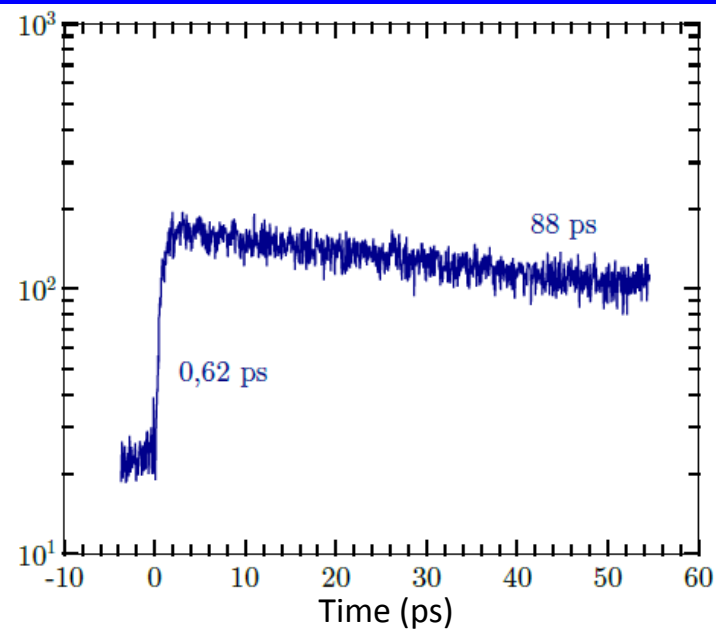
An Analysis of Electron–Hole Recombination in Solid Xenon with Time-Resolved Luminescence Spectroscopy

I. REIMAND (a), E. GMINDER (b), M. KIRM (b), V. KISAND (b), B. STEEG (b), D. VARDING (b), and G. ZIMMERER¹⁾ (b)

Upconversion detection of emission of ZnO crystal



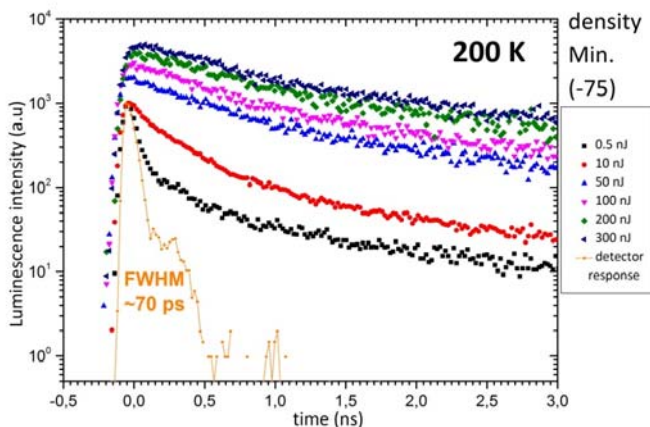
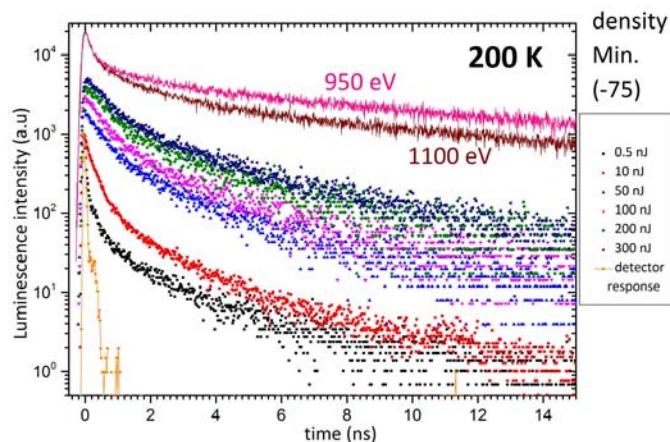
Response function of the set up
(400 nm + 800 nm)



Decay of the UV luminescence of ZnO crystal:
15K , 266 nm (**1 μ J/pulse** - focalization)

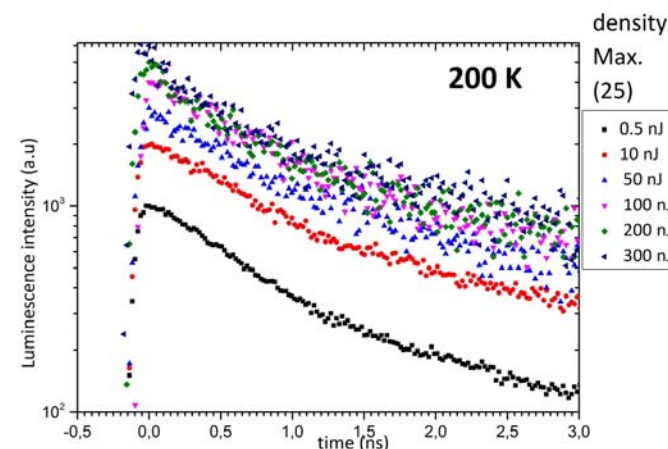
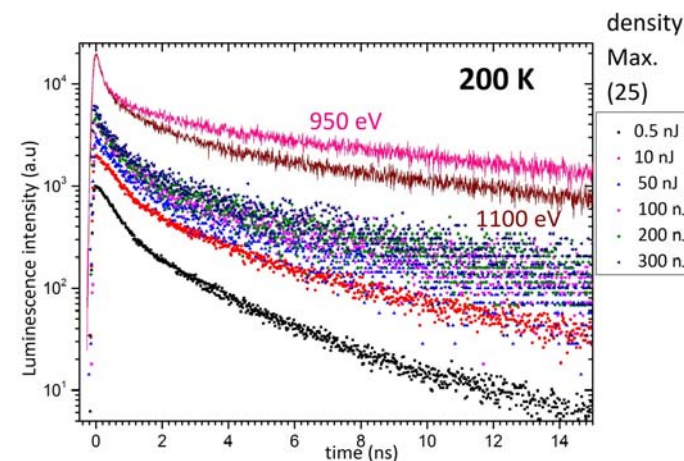
P.Martin et al, SCINT2017

Exciton emission of ZnO. Luminescence decays of free exciton: excitation: 266nm- X pulses



- X: microscopic high density zones
- UV: macroscopic dense zones
- Fast component at low density
- Slowing down when density increases
- local heating...: 10nJ density max $\sim 60\text{K}$ – very fast thermal diffusivity $\sim$ after 100ps, T decreases in 10 times
- excitons interactions (crossing interactions)
-

Still under interpretation



P.Martin et al, SCINT2017

CrossLuminescence and IntraBand Luminescence

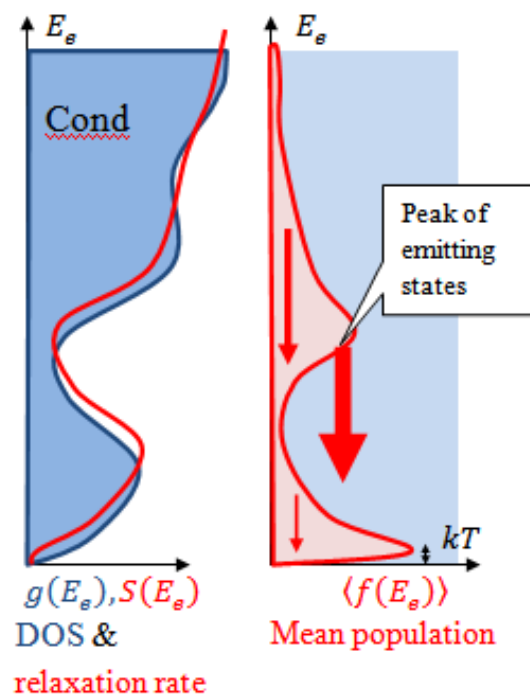
- Processes parallel to thermalization
- Only high energy excitations are active

$$N_{active} \sim N_{excitons} / 5$$

- For IBL lifetime = thermalization time (<1ps)
- For CL lifetime = Min(Radiation time *or* multiphonon emission time) (>10ps)

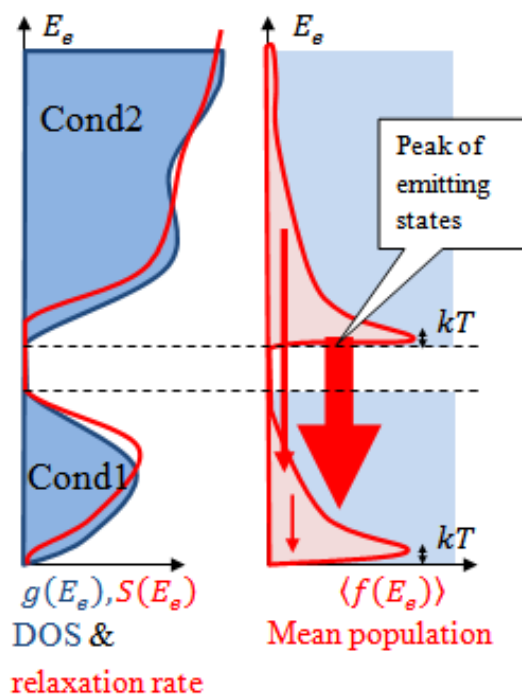
Intra-band luminescence for complex band structure (schemas)

Crystals with **dip** in the conduction or valence band



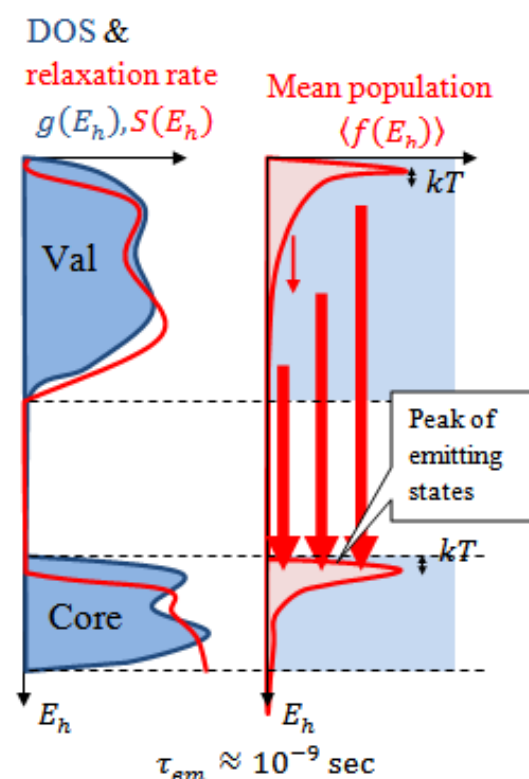
$$\tau_{em} \approx 10^{-12} \text{ sec}$$

Crystals with **gap** in the conduction or valence band



$$\tau_{em} \approx 10^{-10} \text{ sec}$$

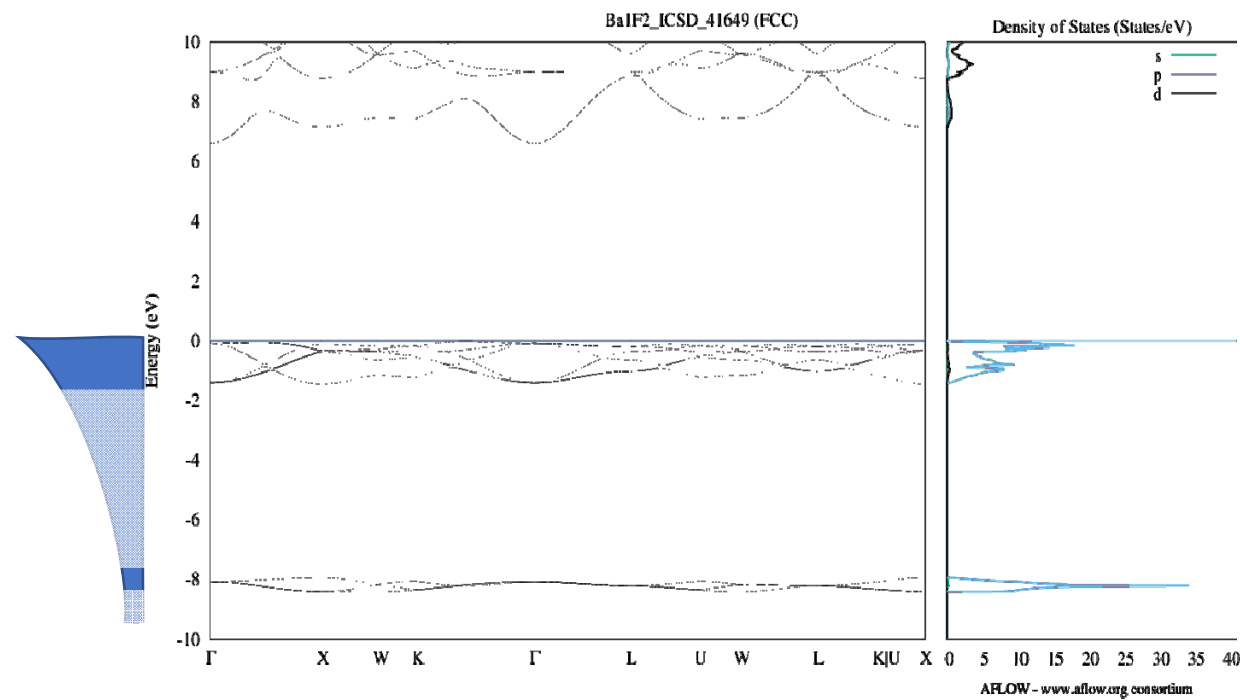
Crossluminescent crystals (wide gap in valence band)



$$\tau_{em} \approx 10^{-9} \text{ sec}$$

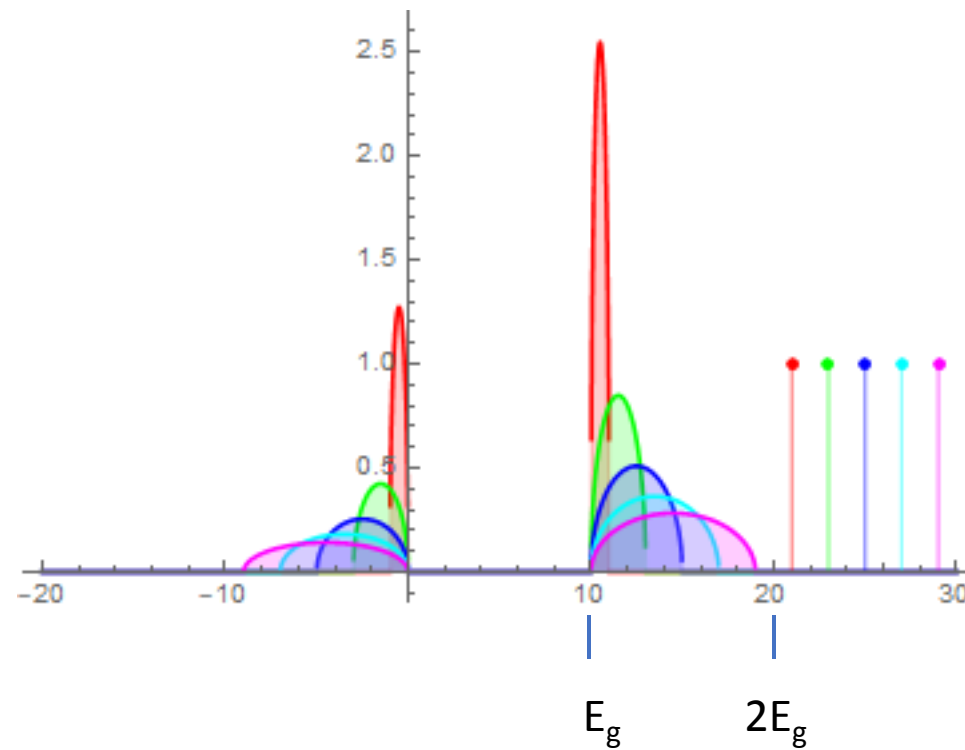
The gaps within the conduction bands occur in crystals with *d*-electrons (e.g. Cond2 arises from *s*-electrons, whereas Cond1 – from *d*-electrons: CeF₃, crystals with WO₄ and MoO₄ groups, etc.) and in spin-orbit split valence bands

How many electrons and holes with high energy could be created after cascade stage?



BaF₂ band structure (AFLOW)

Why low energy states are populated with high efficiency?



Why low energy states are populated with high efficiency?

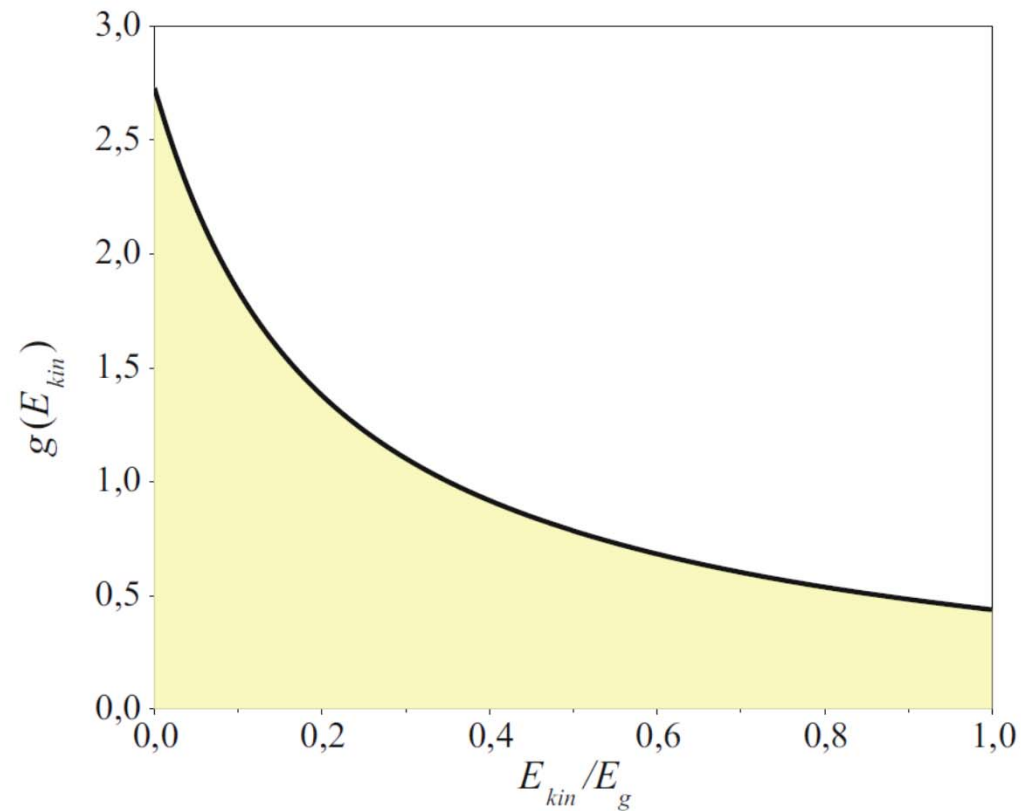
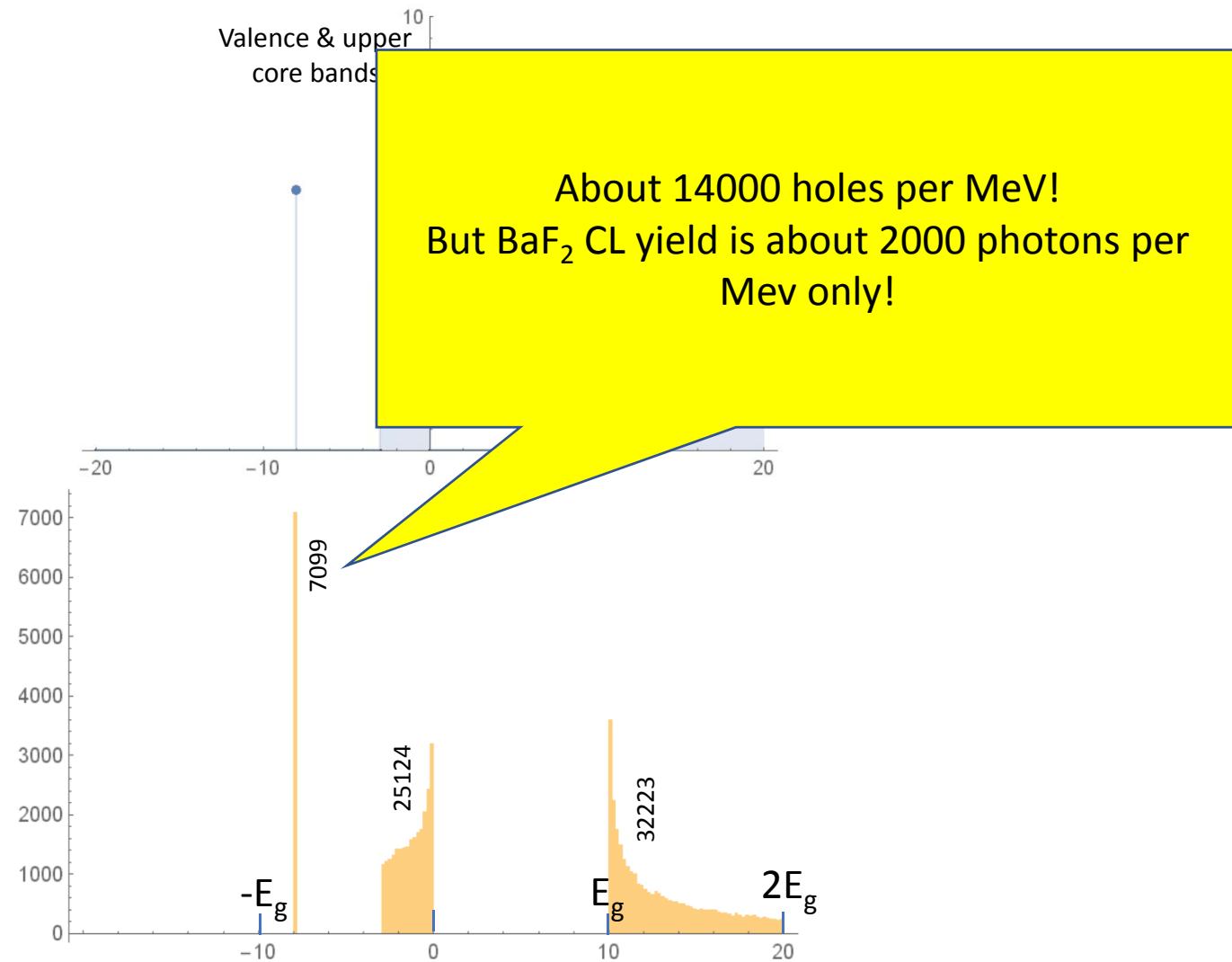


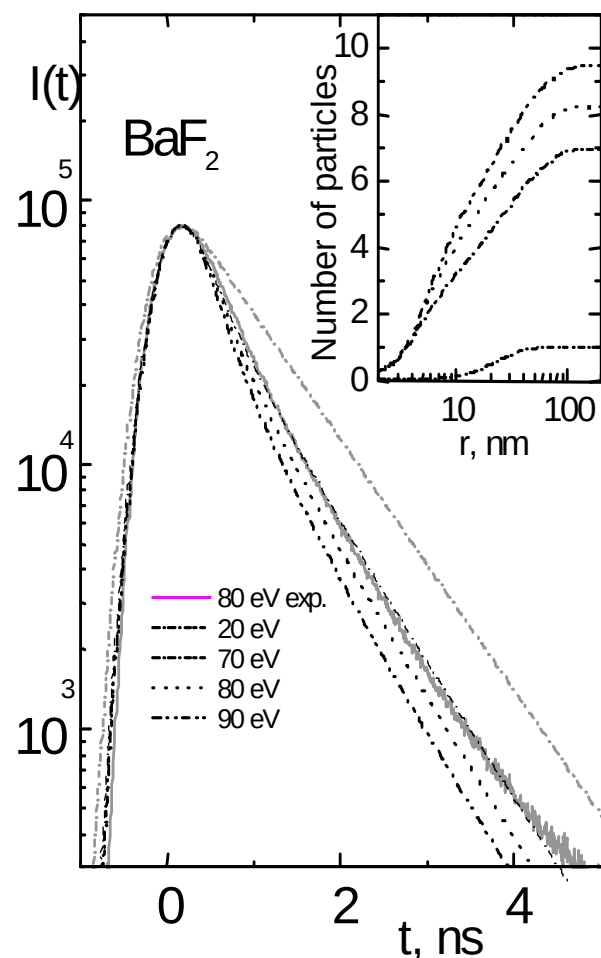
Fig. 7. Distribution of secondary electrons after the cascade in case of narrow valence band and uniform distribution of kinetic energy E_{kin} of secondary electrons between 0 and $E - E_g$ after scattering of an electron with energy E

Energy distribution of the population of electrons and holes after cascade (Monte Carlo)



Monte-Carlo simulation of distribution of electrons and holes (bottom panel) for DOS presented in upper panel (case of BaF₂) Distribution is calculated for 511 keV.

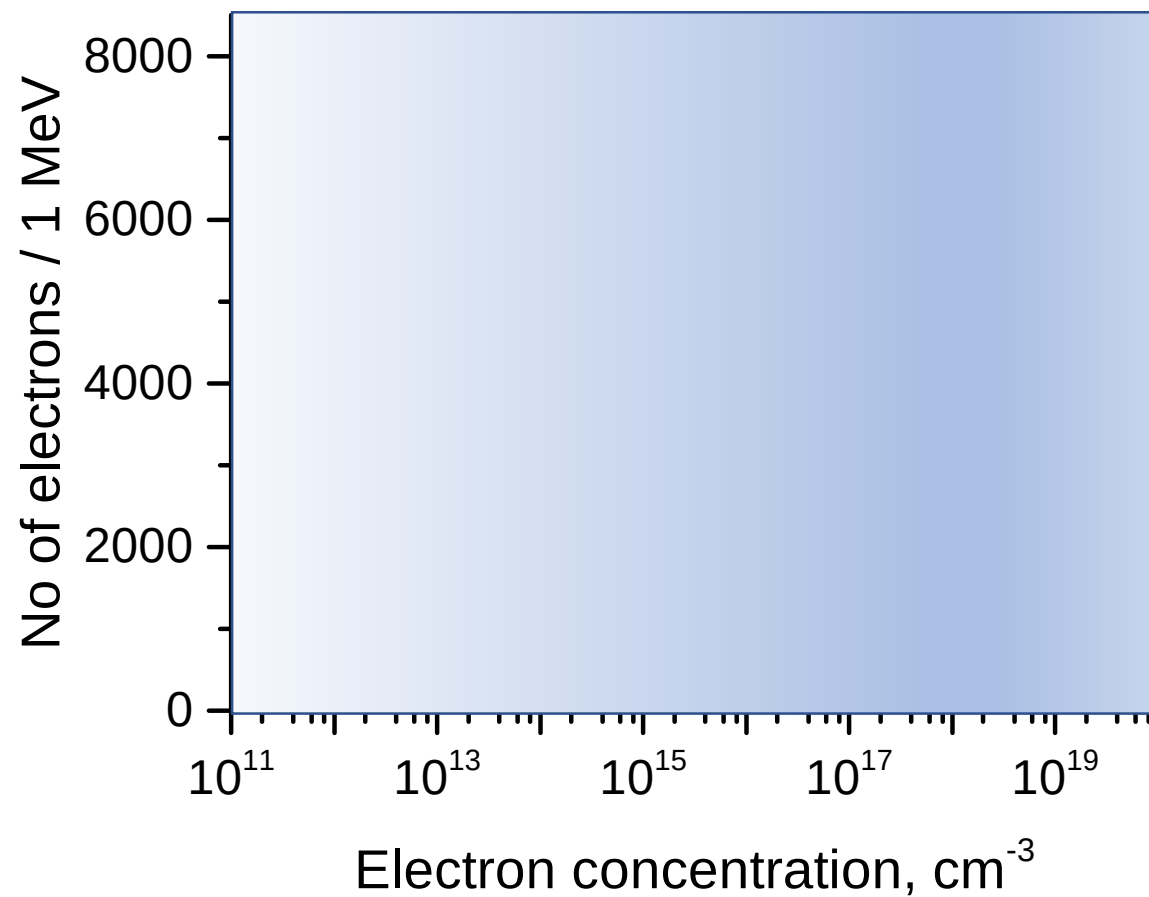
Quenching of BaF₂ crossluminescence vs excitation energy



Dependence of kinetics of crossluminescence on the excitation energy is explained in terms of the increase of number of neighbor excitations resulting in additional quenching of the luminescence

Simulation of BaF₂ crossluminescence decay kinetics after excitation by photons with different energy and the corresponding distribution of neighbor excitations (in the inset) [Glukhov R.A., Kamada M., Kubota S., Nakamura E., Ohara S., Terekhin M. A., Vasil'ev A. N., Proc. Int. Conf. on Inorganic Scintillators and Their Applications, SCINT95, Delft University Press, The Netherlands (1996) 204].

CrossLuminescence is emitted mainly from low concentration regions, but at initial stages it is not quenched yet



IBL/CL from the crystals with gap about 1 eV in the valence/conduction band are still the good candidates:

- Emission energy is not so high
- Quenching through multi-phonon process has time > 10 ps and thus do not influence on emission within 10 ps interval
- This quenching reduce the background emission of delayed photons

Fast timing with RE activators

Excitations are created with some delay, all emit,
dipole matrix element for RE d→f transition

- Number of excitations: $N_{excitations}(t) = \frac{E_\gamma}{(1.5 \div 2.5) E_g} \frac{t}{\tau_{rise}}$
- Number of photons per Δt : $N_{photons}^{\Delta t} = \frac{\Delta t}{\tau_{rad}} \frac{\Delta t}{\tau_{rise}} \frac{E_\gamma}{(1.5 \div 2.5) E_g}$ for $\tau_{rise} > \Delta t$
- Radiation rate of photon emission (RE allowed d→f transition): $\tau_{rad} \approx 10 \text{ ns} \left(\frac{5 \text{ eV}}{h\nu_{emission}} \right)^2$, $h\nu_{emission} \approx \frac{1}{2} E_g$
 $\tau_r \approx 10 \text{ ns}$ for $h\nu_{emission} = 5 \text{ eV}$
 $\tau_r \approx 60 \text{ ns}$ for $h\nu_{emission} = 2 \text{ eV}$
- For 511 keV γ : $N_{photons}^{10 \text{ ps}} = \frac{(10 \text{ ps})^2}{(10 \text{ ns}) \tau_{rise}} \left(\frac{E_g}{10 \text{ eV}} \right)^2 \frac{511 \text{ keV}}{(1.5 \div 2.5) E_g} \approx$
 $(2.0 \div 3.5) \frac{10 \text{ ps}}{\tau_{rise}} E_g [\text{eV}]$ for $\tau_{rise} > 10 \text{ ps}$

Energy transfer to Ce^{3+} in YAG

ECS Proceedings Volume 99-40, (2000) p.113-122.

INVESTIGATION OF LUMINESCENCE PROPERTIES OF PURE AND Ce^{3+} DOPED $\text{Y}_3\text{Al}_5\text{O}_{12}$ CRYSTALS USING VUV RADIATION

M. Kirm^a, A. Lushchik^b, Ch. Lushchik^b and G. Zimmerer^a

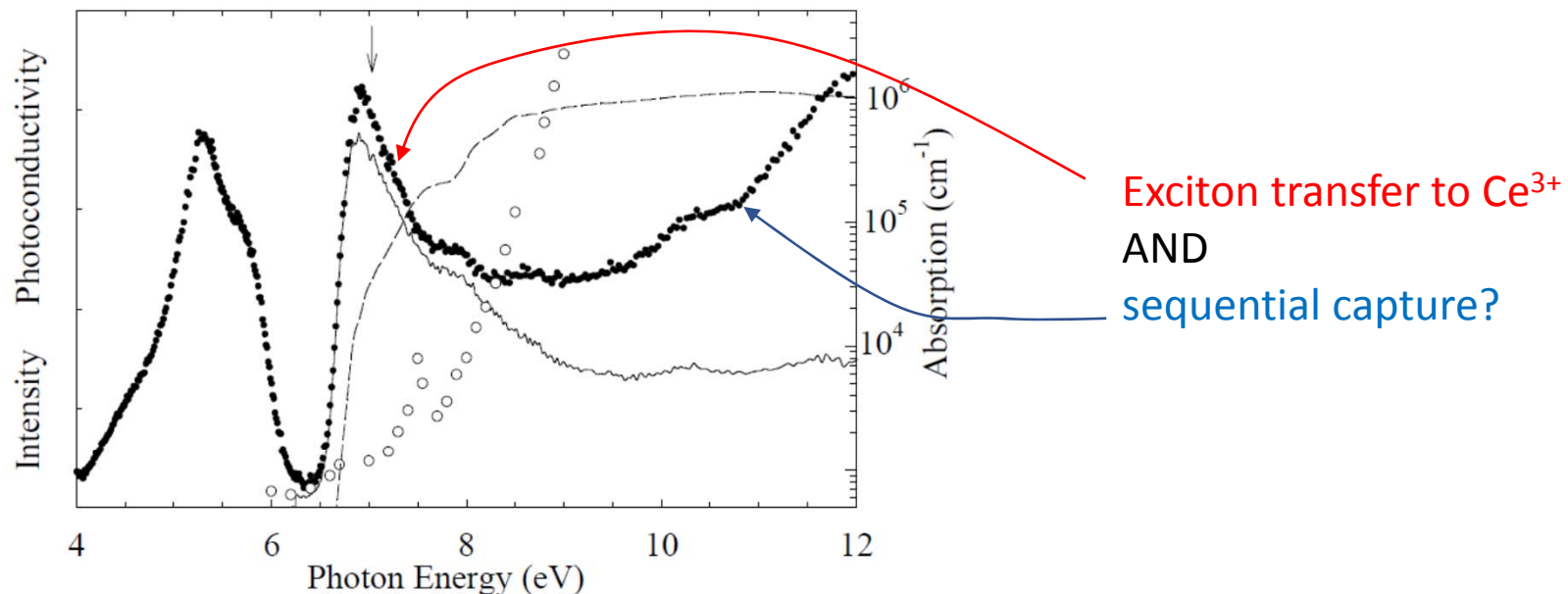


Figure 2. The excitation spectra of 2.38 eV Ce^{3+} emission (●) and 4.13 eV emission (solid line) for a YAG:Ce crystal at 300 K. The spectrum of photoconductivity (○, Ref. 21) and the absorption spectrum (dashed line, Ref. 11) for a pure YAG at 300 K.

Charge carrier and exciton dynamics in $\text{LaBr}_3:\text{Ce}^{3+}$ scintillators

G. Bizarri* and P. Dorenbos

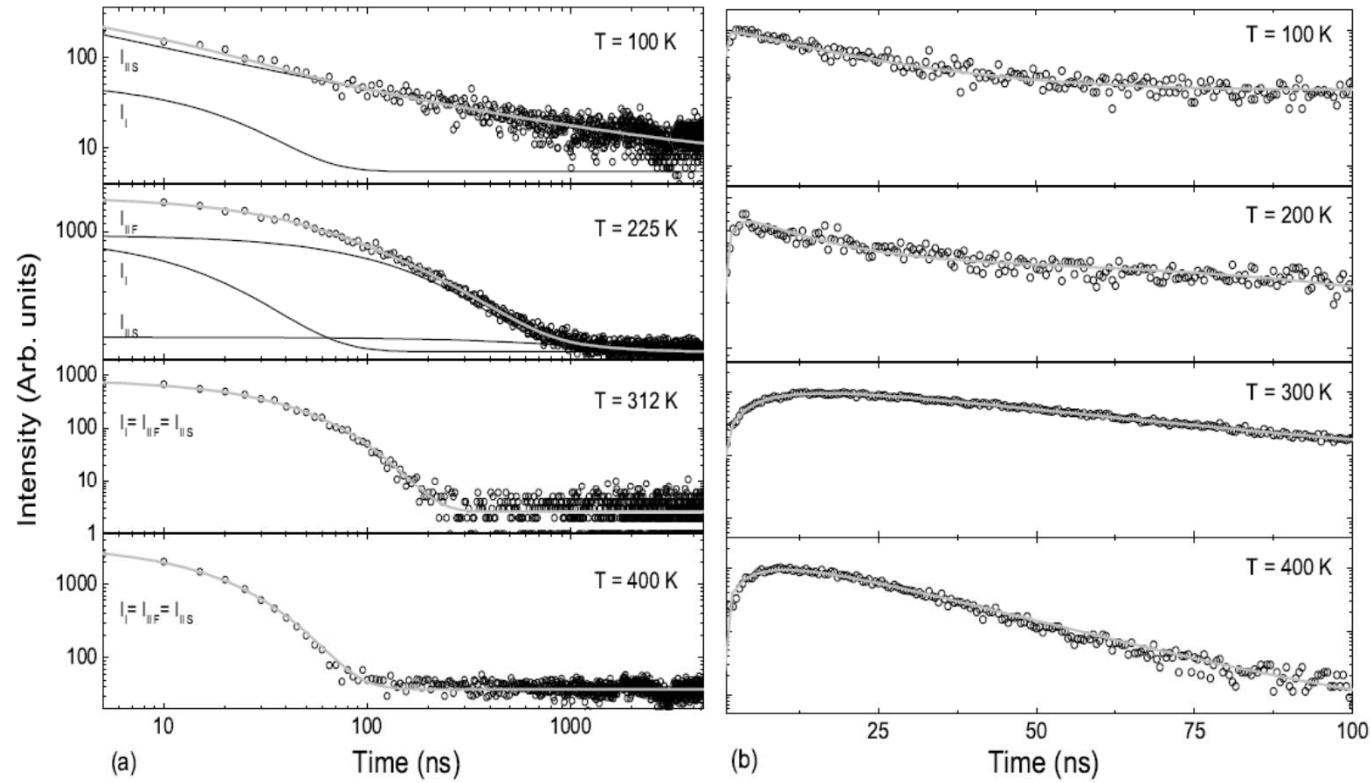


FIG. 5: Temperature dependence of Ce scintillation time profiles in $\text{LaBr}_3:0.2\%\text{Ce}^{3+}$ a) for a measurement recorded on a long time domain in a log-log scale representation and b) for one recorded on a short time domain in a log-lin scale representation. Curves labelled I_I , $I_{II F}$, $I_{III S}$ are the fitted decay components.

Dependence of rise time for $e + \text{Ce}^{4+} \rightarrow \text{Ce}^{3+*}$ process on electron energy

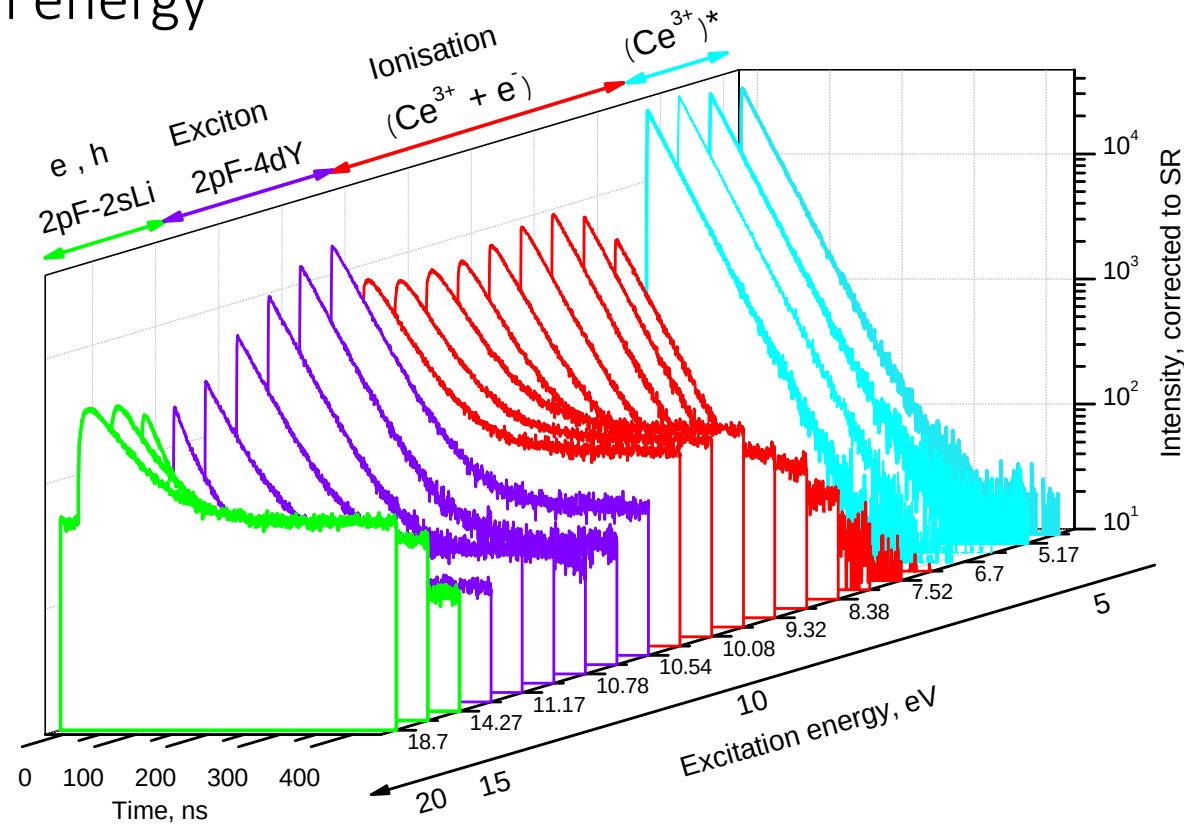


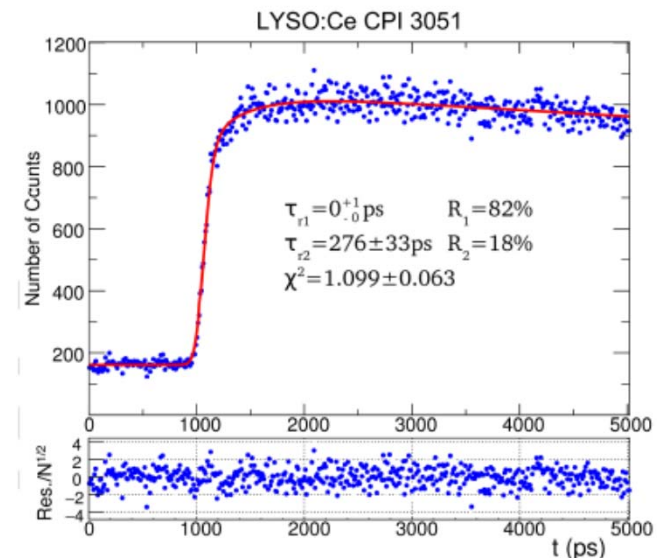
Figure 2. Fluorescence decay curves of $\text{LiYF}_4:\text{Ce}^{3+}$ for different excitation energies from 5.17 to 11.17 eV. The red line is a guide to the eye to point out the occurrence of the slow component for excitation energies above 8 eV. The curves with substantial rise-on regions are also indicated. Three regions of interest (direct excitation—ionization to the Y4d and to Li2s as well as exciton formation) are mentioned.

A. Belsky, K. Ivanovskikh, A. Vasil'ev, M.-F. Joubert, and C. Dujardin, *Estimation of the Electron Thermalization Length in Ionic Materials*, J. Phys. Chem. Lett. 2013, 4, 3534–3538

Excitonic energy transfer to Ce^{3+}

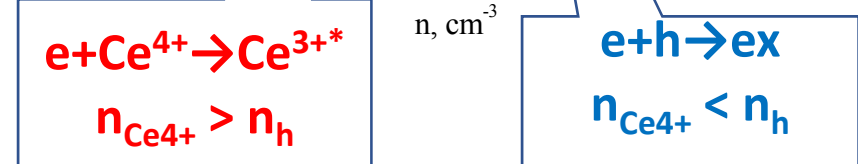
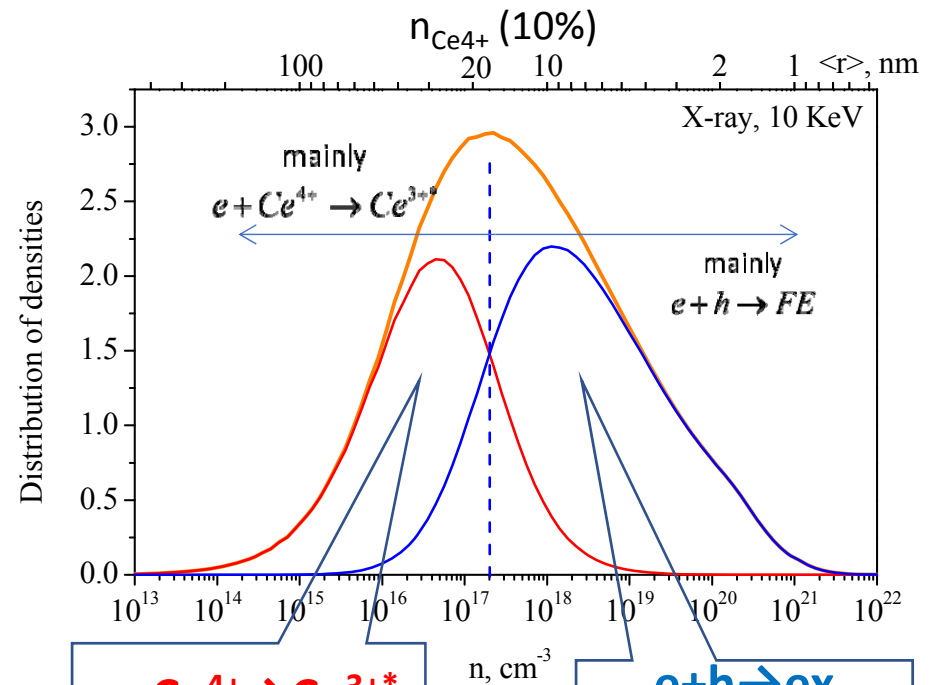
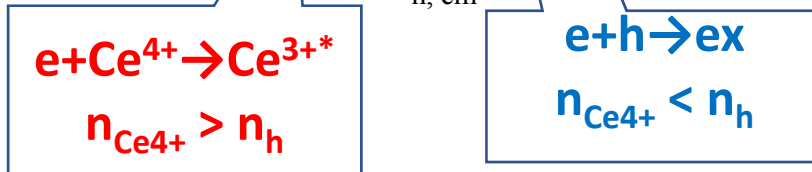
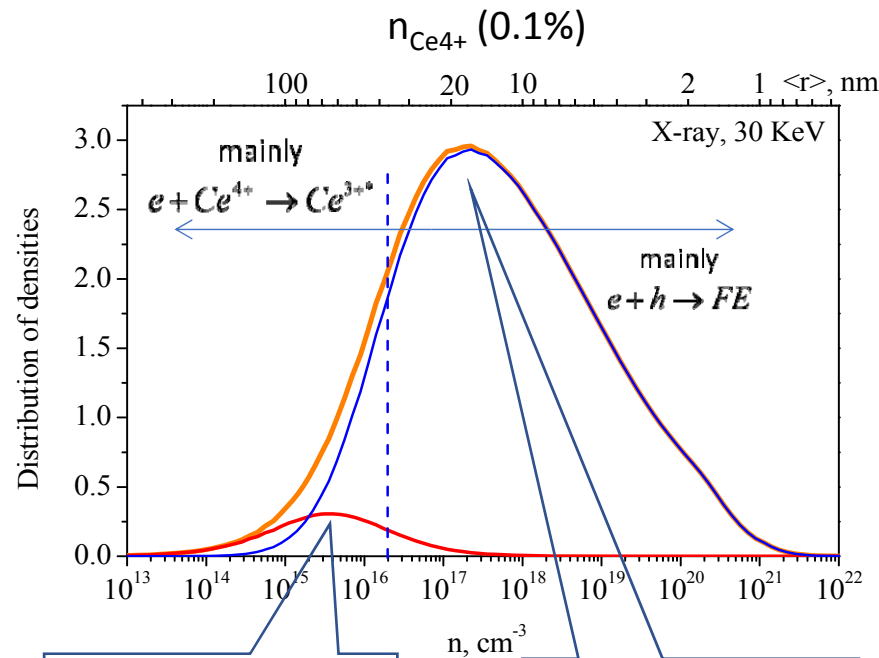
- Three sequential processes:
- bi-molecular $e+h \rightarrow \text{FE}$
- monomolecular $\text{FE} \rightarrow \text{STE}$
- bi-molecular $\text{STE} + \text{Ce}^{3+} \rightarrow \text{Ce}^{3+*}$

After averaging over distribution of concentrations rise time becomes multi-component



S. Gundacker, R.M. Turtos, E. Auffray, P. Lecoq, Precise rise and decay time measurements on inorganic scintillators by means of X-ray and 511 keV excitation, Nuclear Inst. and Methods in Physics Research, A (2018), <https://doi.org/10.1016/j.nima.2018.02.074>

The balance of two transfer channels is controlled by Ce^{4+} concentration

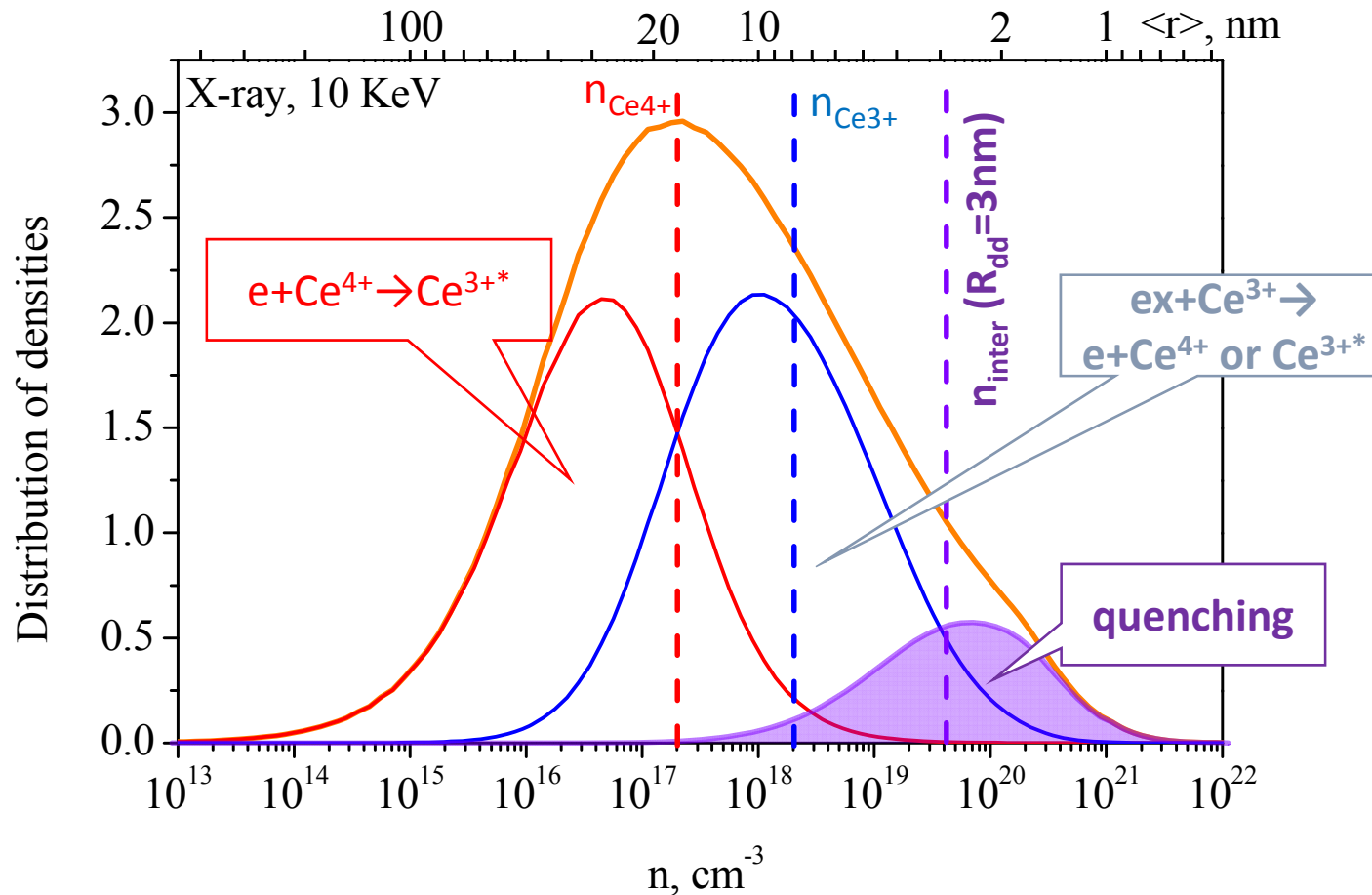


$$\frac{dn_e}{dt} = -4\pi D_e R_{\text{Ons}}^{\text{scr}} n_{\text{Ce}^{4+}} n_e - 4\pi (D_e + D_h) R_{\text{Ons}}^{\text{scr}} n_h n_e - \dots$$

Ce⁴⁺ captures the electron in low density part of track

Exciton creation in high density part of track

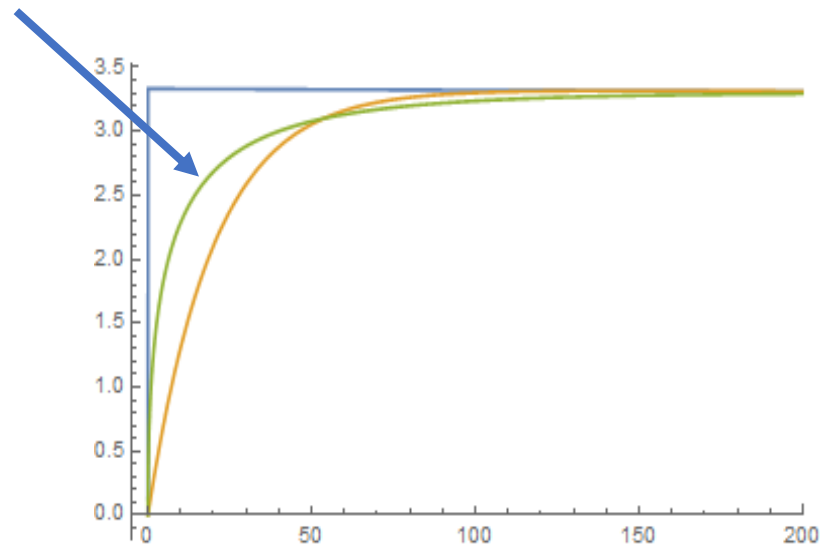
Quenching of cerium in the high density area



Transfer to Ce^{3+} from exciton occurs in the high density part of track, as consequence the probability of quenching of excited cerium is high.

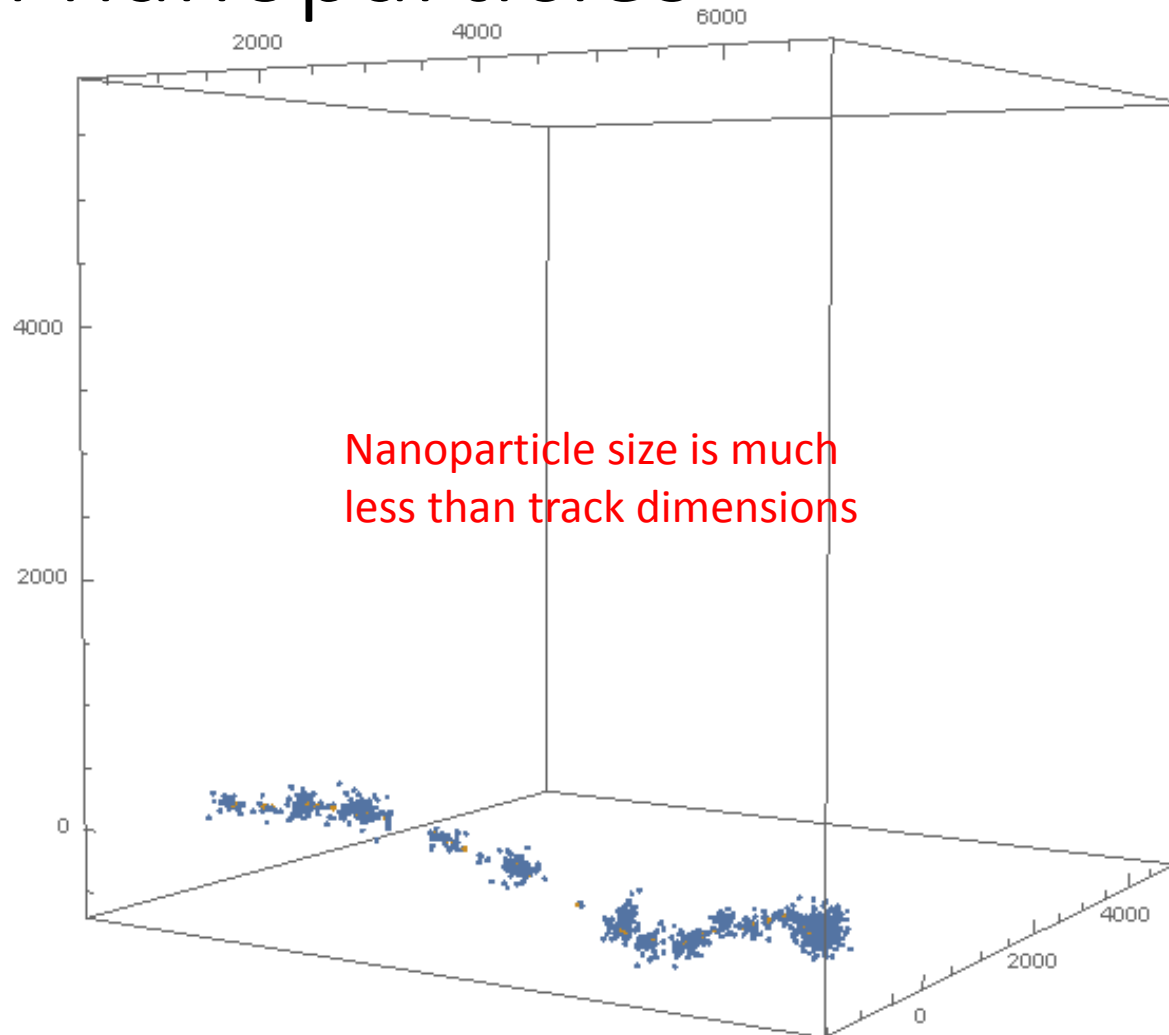
Capture of electron by Ce^{4+} occurs in low density part of track – low probability of quenching

- The goal of engineering scintillators with RE activators is to increase the fraction of ps rise time components



- But still low d-f matrix element is a problem

Interaction of ionizing radiation with nanoparticles



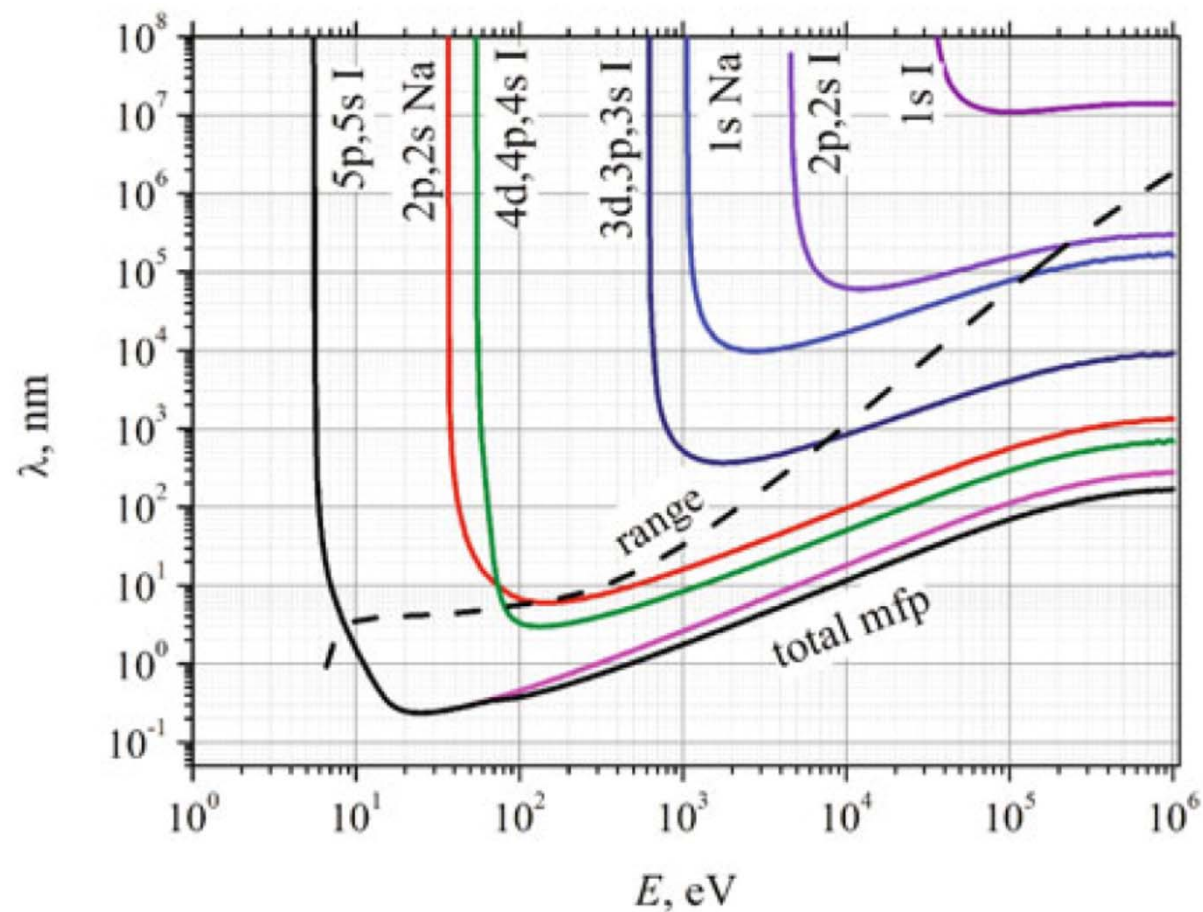
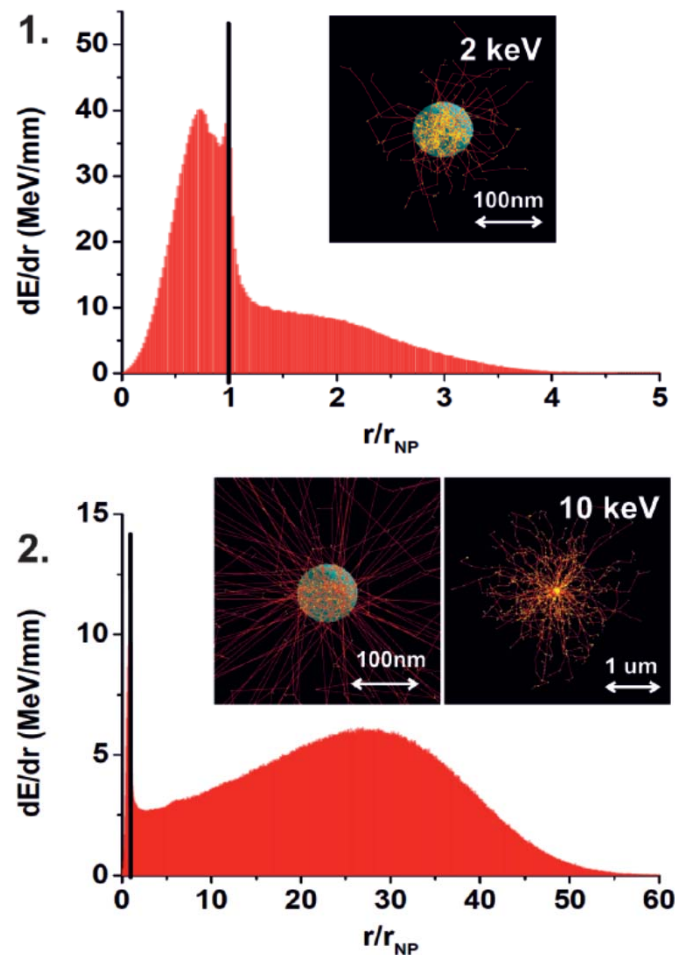


Fig. 4. Total (black) and partial mean free paths for production of excitations from different core levels in NaI. The range of electron with energy is also shown by dashed line

A. N. Vasil'ev. *Microtheory of scintillation in crystalline materials*. In *Engineering of Scintillation Materials and Radiation Technologies*, volume 200 of Springer Proceedings in Physics, pages 3–34. Springer, 2017

Fraction of energy of γ -quantum deposited in NP



A.-L. Bulin, A. Vasil'ev, A. Belsky, D. Amans, G. Ledoux and C. Dujardin, *Modelling energy deposition in nanoscrollators to predict the efficiency of the X-ray-induced photodynamic effect*, *Nanoscale*, 2015, 7, 5744-5751

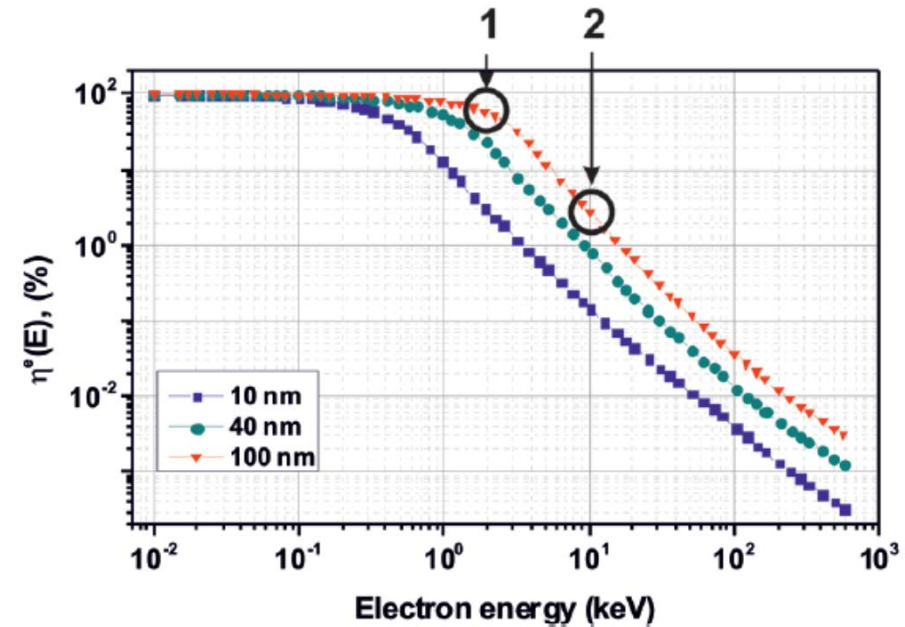
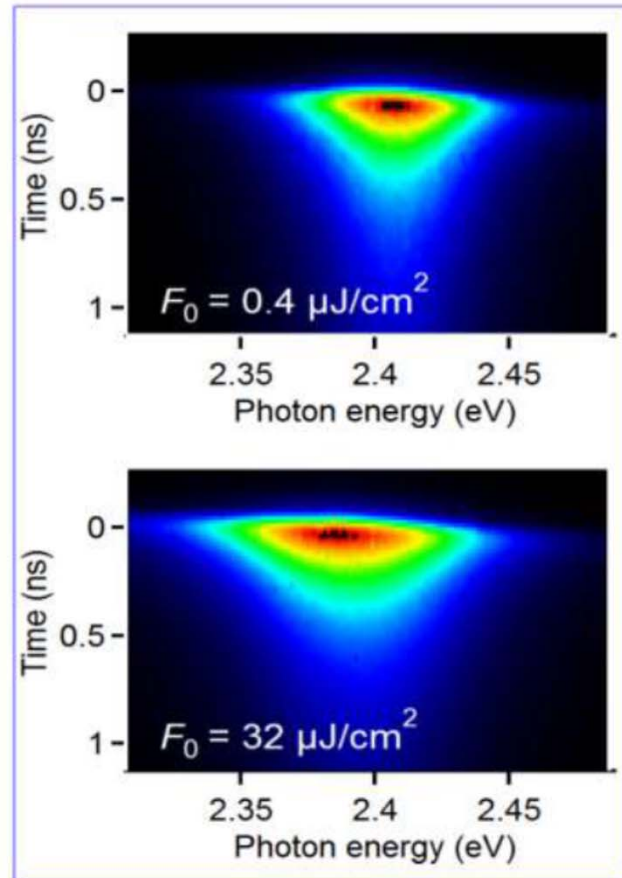
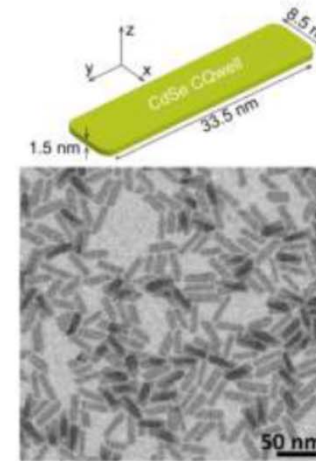
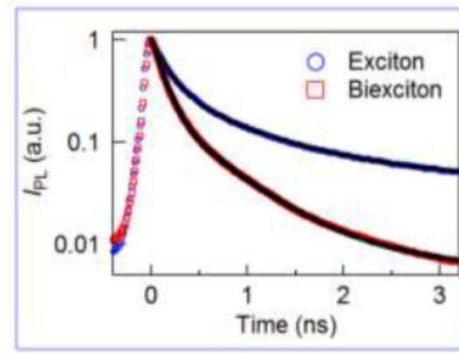


Fig. 3 Top: Deposited energy per unit of normalized radial distance from the center of the NP (diameter of 100 nm of Gd_2O_3) for (1) – 2 keV electrons and (2) – 10 keV electrons. Visualisation of the spatial distribution of the deposited energy is shown as insets. Bottom: Percentage of deposited energy per electron generated in a Gd_2O_3 nanoparticle for three different diameters, as a function of the primary electron energy.

Colloidal CdSe nanosheets (quantum wells)



Emission 500-520 nm
Exciton lifetime: **440 ps**
Biexciton lifetime: **125 ps**



- 1D Quantum confinement implies strict selection rules
- In-plane delocalization implies fast exciton recombination rate (giant oscillator strength transition).
- Strongly suppressed Auger recombination in 2D CQwells.

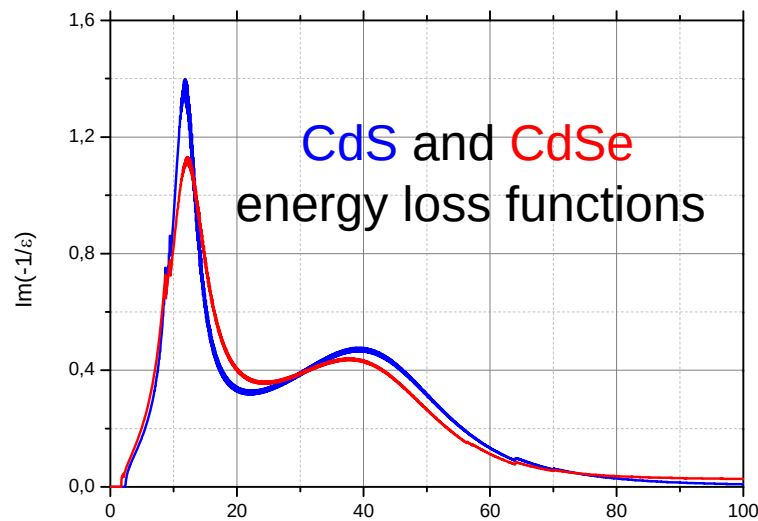
Increased exciton coherence volume → Reduced Auger $\tau_R^{-1} > \tau_{Auger}^{-1}$

Enhanced emission rate: $\tau_R^{2D} \propto \frac{\Delta\lambda}{E_b^{2D}}$

J. Grim et al. *Nature nanotech.* **9**, 891–895 (2014)

Can 2X and 3X be created in NPs by ionizing particle?

$E_g = 1.74$ eV for CdSe and 2.42 eV for CdS



Bulk crystal: plasmon is peak of $\text{Im}(-1/\epsilon)$

Surface plasmon is peak of $\text{Im}(-1/(\epsilon+1))$

Plasmon in NP depends on size and shape of NP $\text{Im}(-1/(\epsilon+1))$

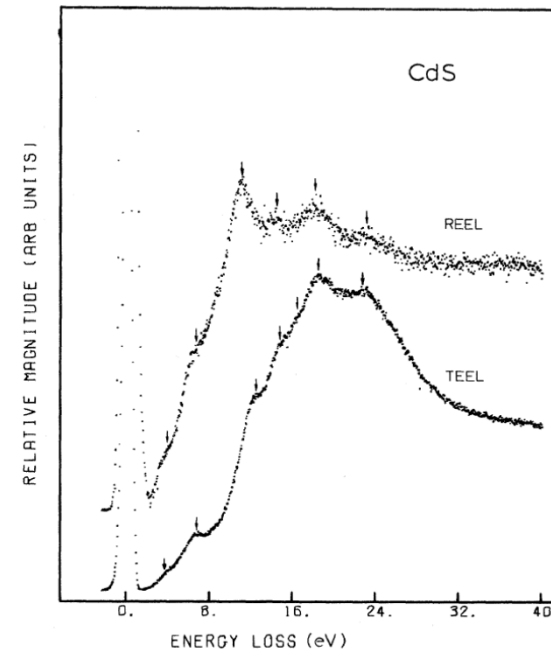


FIG. 3. Comparison of the REEL and TEEL spectra of CdS.

PHYSICAL REVIEW B

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Electron Energy-Loss Spectra of CdS, CdSe, and CdTe

R. L. Hengehold

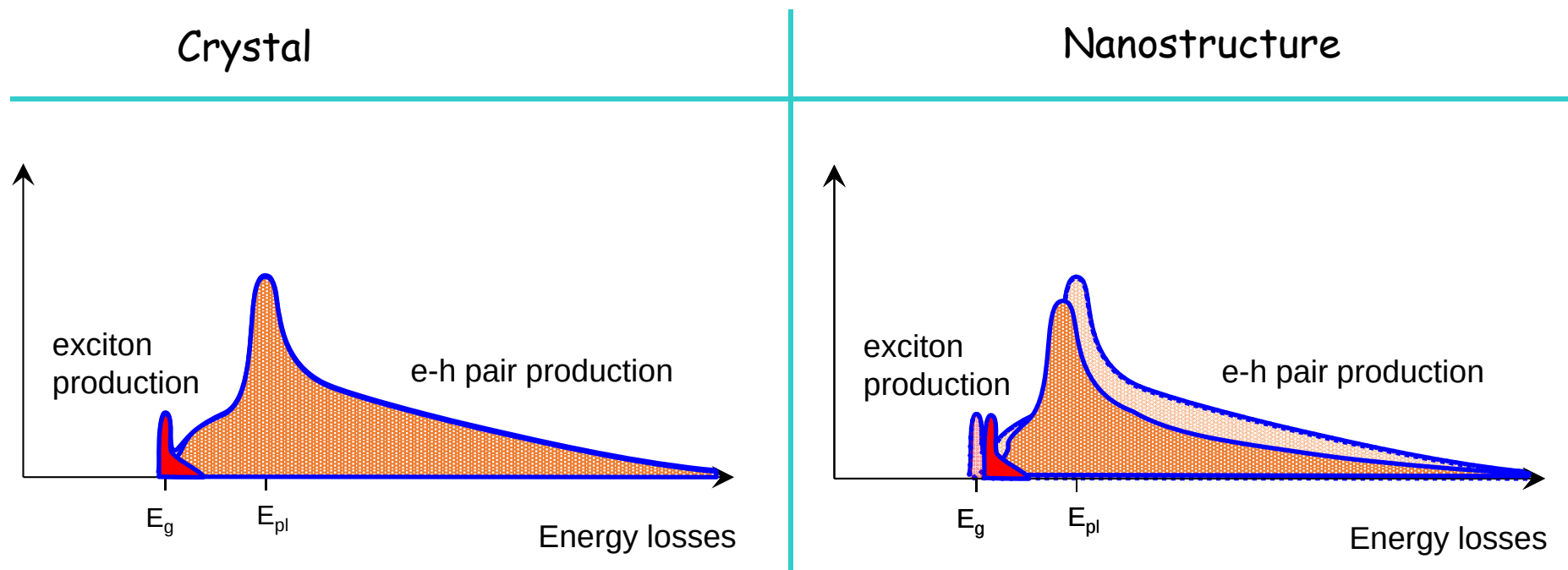
Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio 45433

and

F. L. Pedrotti*

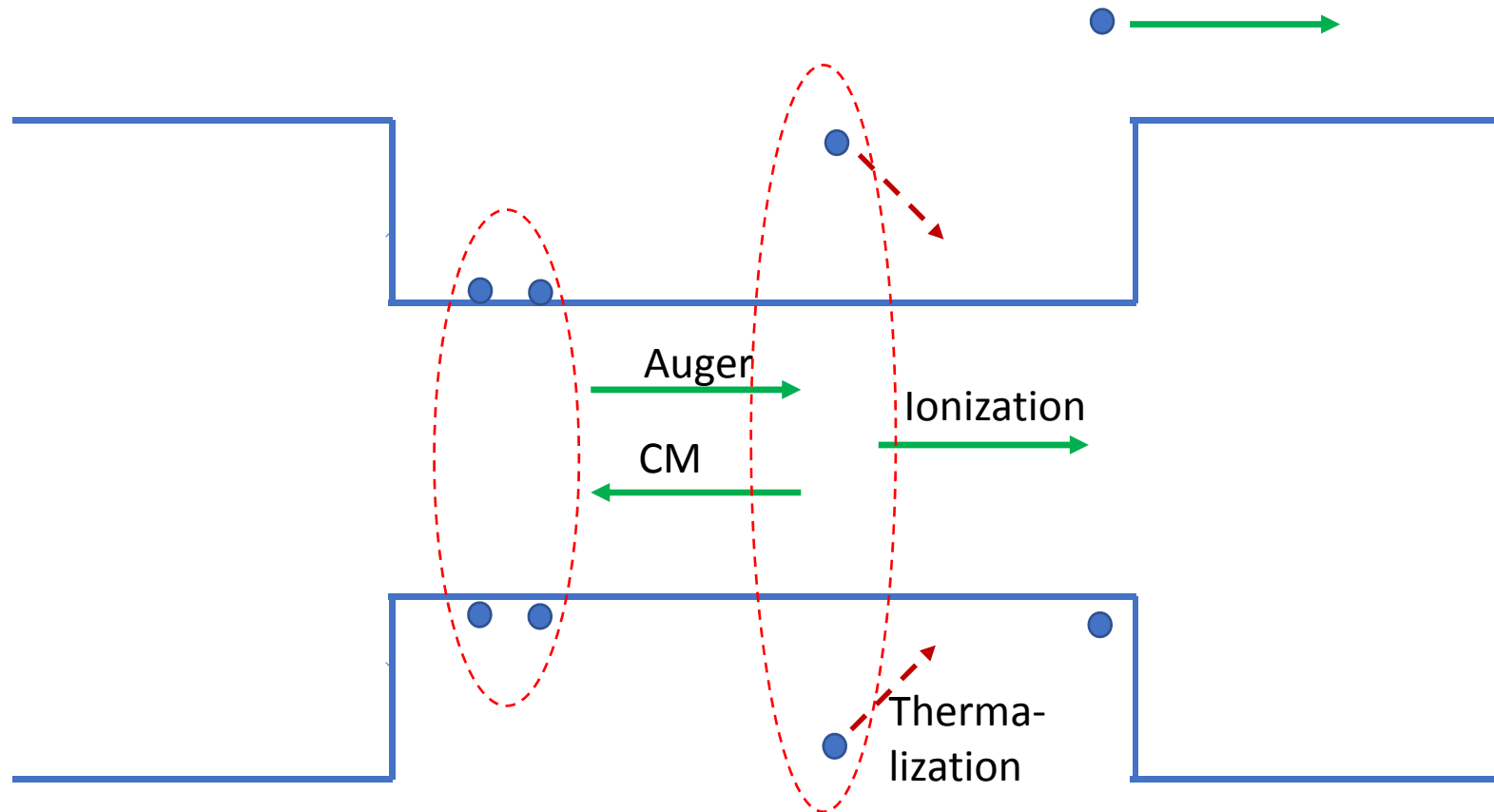
Aerospace Research Laboratories, Wright-Patterson Air Force Base, Ohio 45433

Modification of energy loss function



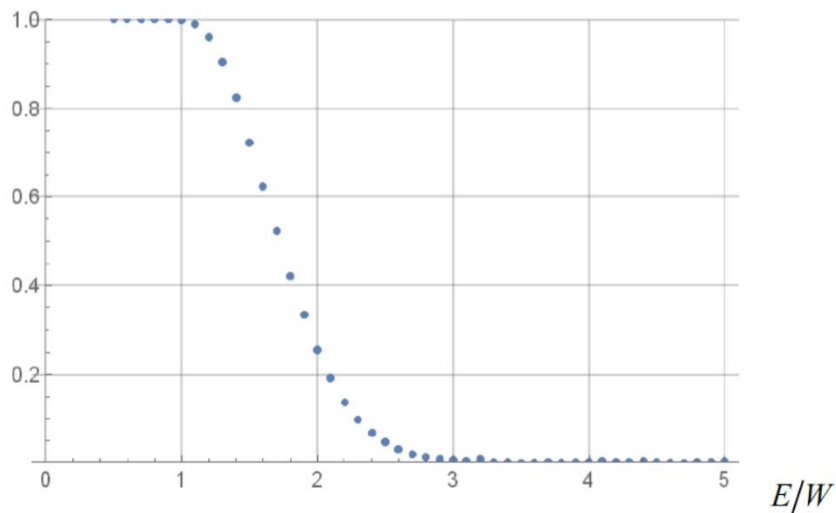
Modification of energy loss function either in exciton range (quantum confinement effect) or in e-h pairs range (lower plasmon energy)

Interchanging types of high-energy excitations in NPs

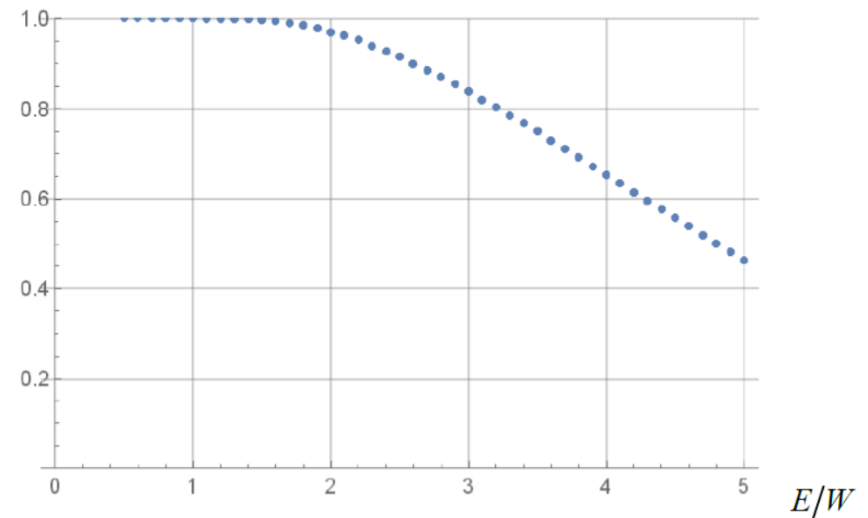


Creation of charged NPs: probability of surviving of neutral excited NP

$R=3\text{nm}$, $W=1\text{ eV} \rightarrow Y=0.53$



$R=50\text{nm}$, $W=1\text{ eV} \rightarrow Y=0.53$



Electrons with initial energy higher than work function W escape from small NP thus creating charged NPs

Types of possible candidates for fast timing

- IntraBandLiminescence+CrossLuminescence
- Excitonic emission in bulk crystals
- Activator emission with fast energy transfer to activator
- Nanoparticles with excitonic (bi-excitonic) emission (giant oscillator strength?) and quantum wells

All types of candidates have limitations in efficiency and/or rise time, but engineering is possible

FAST WG2 activity in MSU

IntraBand Luminescence Spectra in Multiple Parabolic Branch Band

Estimation of spectrum of IBL

Russian Physics Journal, Vol. 40, No. 11, 1997

**TWO TYPES OF FUNDAMENTAL LUMINESCENCE OF
IONIZATION-PASSIVE ELECTRONS AND HOLES IN
OPTICAL DIELECTRICS — INTRABAND-ELECTRON AND
INTERBAND-HOLE LUMINESCENCE (THEORETICAL
CALCULATION AND COMPARISON WITH EXPERIMENT)**

D. I. Vaisburd and S. V. Kharitonova

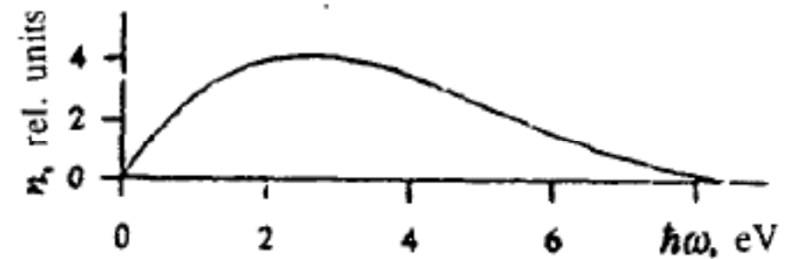
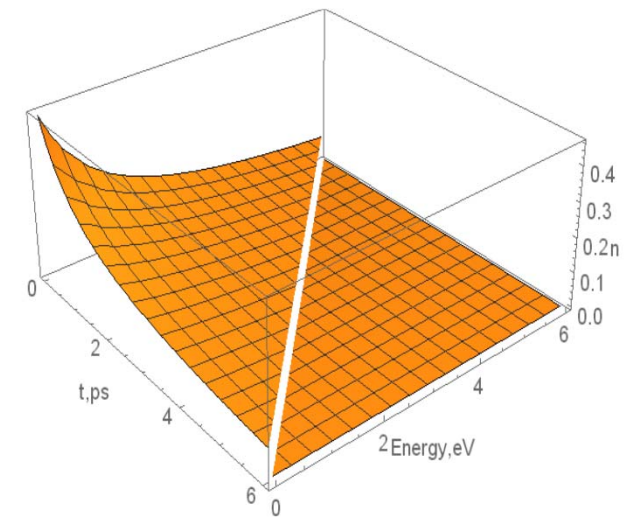
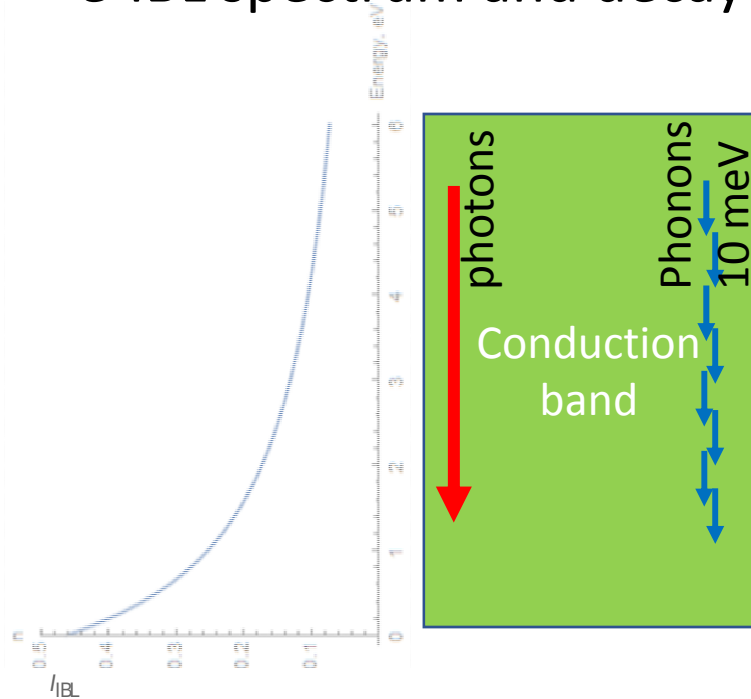


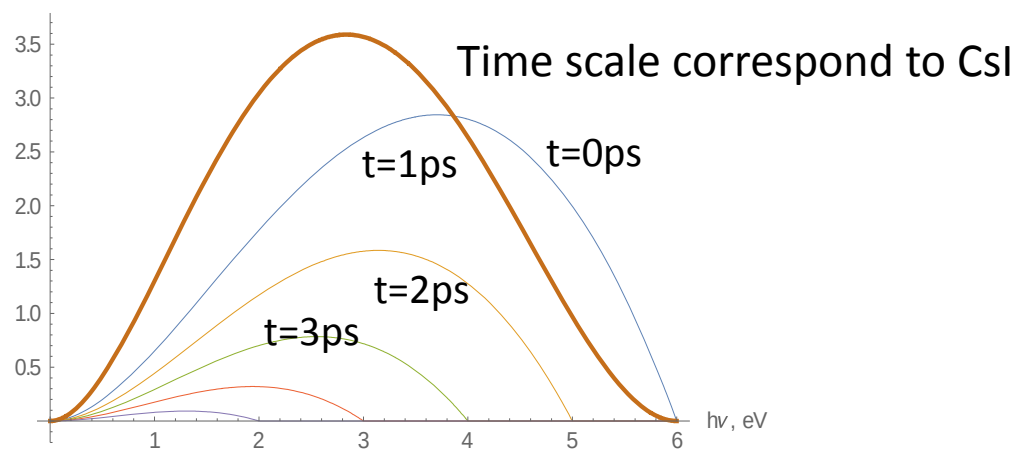
Fig. 17

Fig. 17. Calculated spectrum of intraband electron luminescence of CsI excited by a pulsed electron beam.

e-IBL spectrum and decay (continuous distribution of branches)



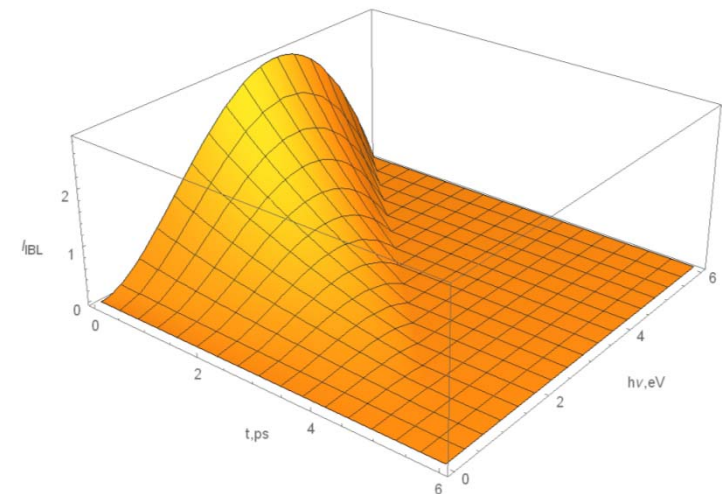
Evolution of electron energy distribution in time



Evolution of e-IBL spectrum in time

14.06.2018

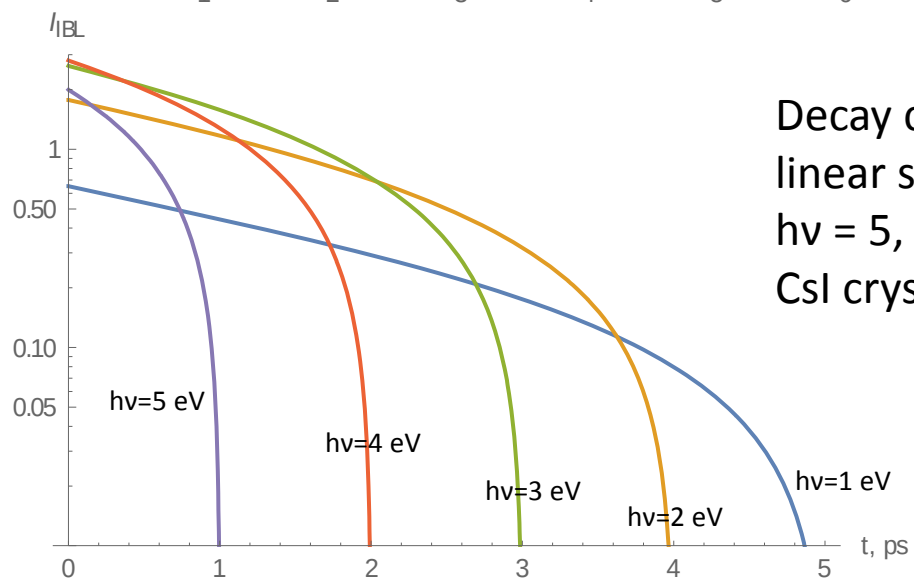
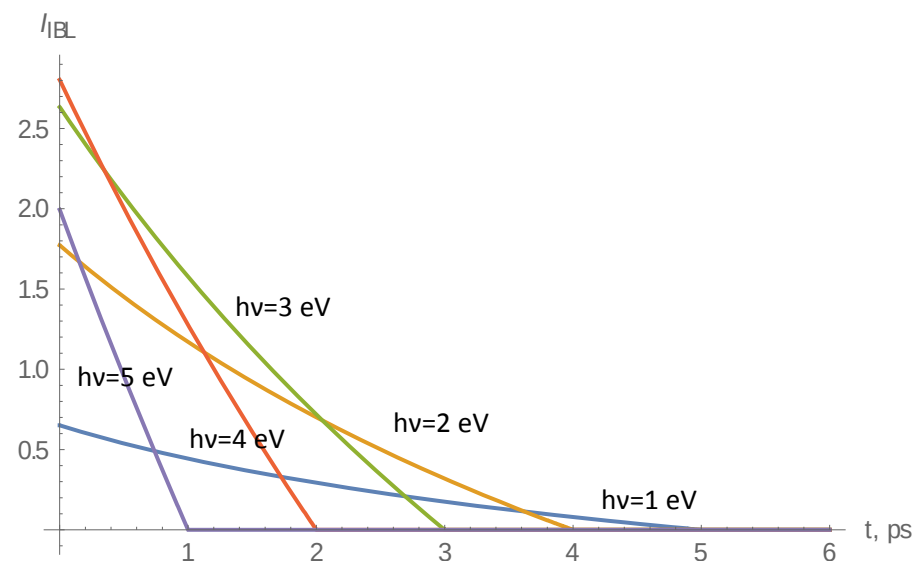
A.Vasil'ev COST FAST WG2 Prague meeting



Evolution of e-IBL spectrum in time

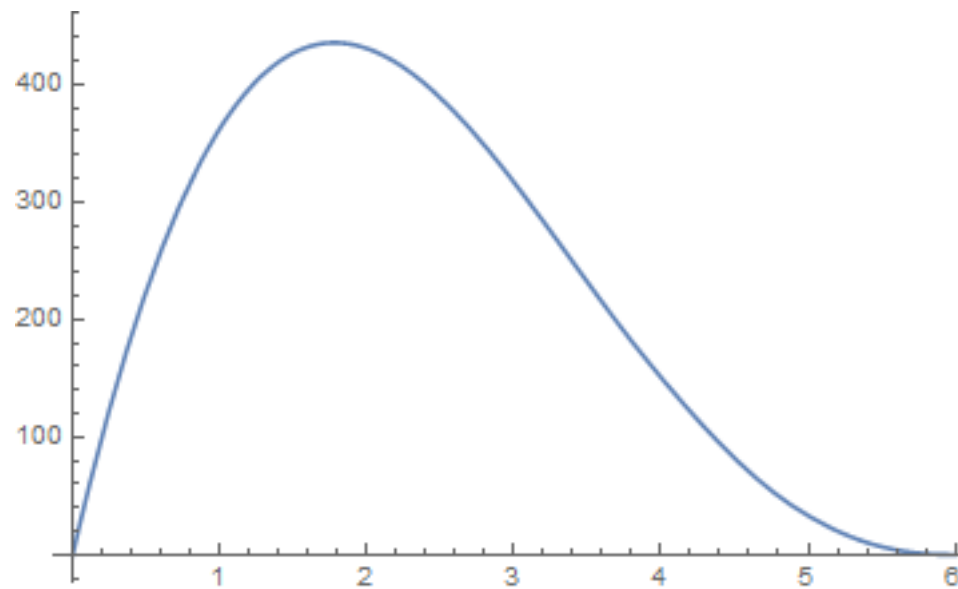
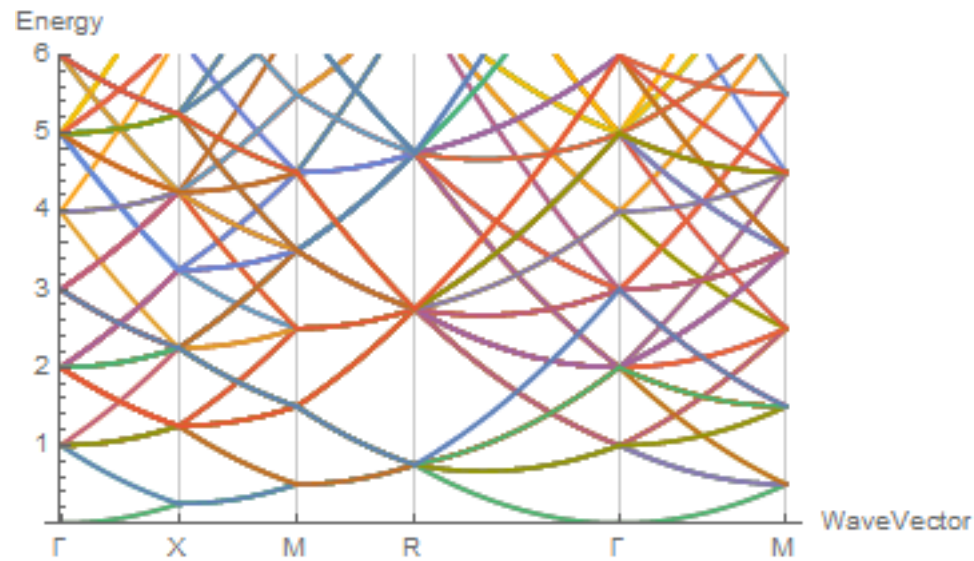
30

e-IBL spectrum and decay (continuous distribution of branches)

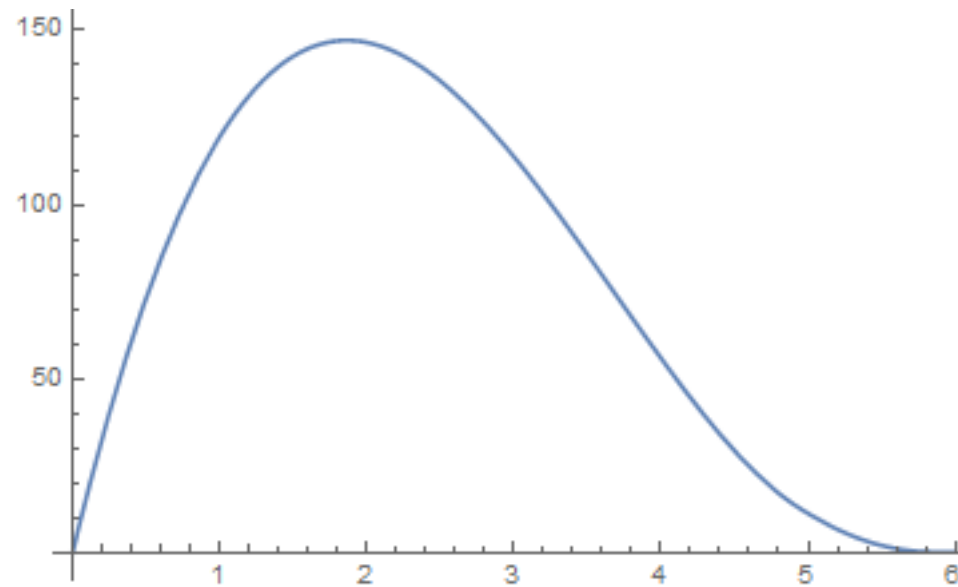
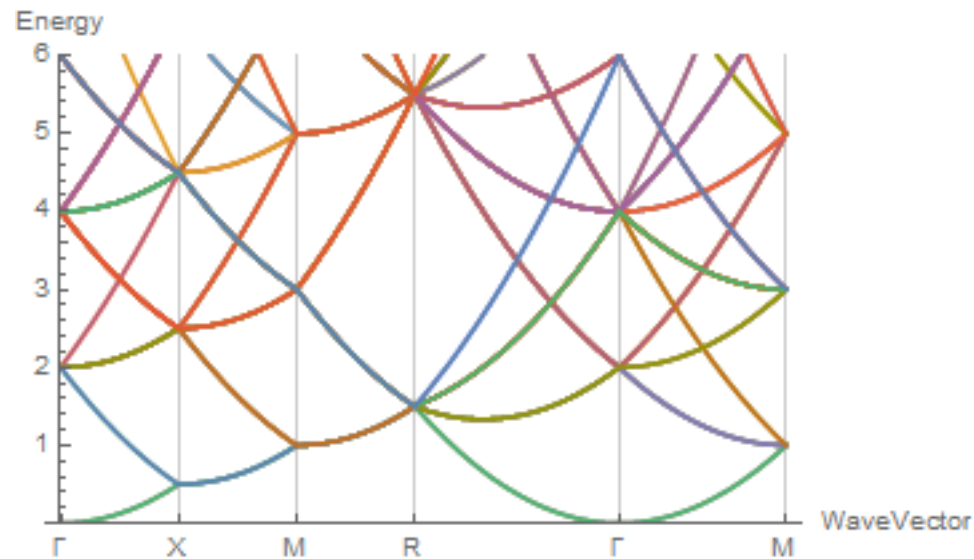


Decay curves for different photon energies: top – linear scale, bottom – semilogarithmic scale for $h\nu = 5, 4, 3, 2, 1 eV$. Time scale corresponds to CsI crystal (phonon energy 10 meV)

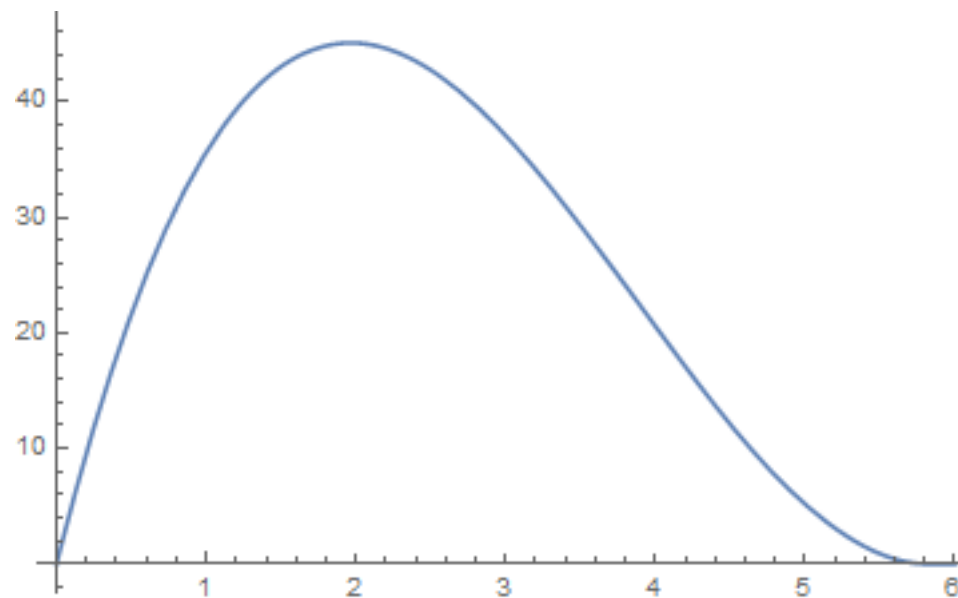
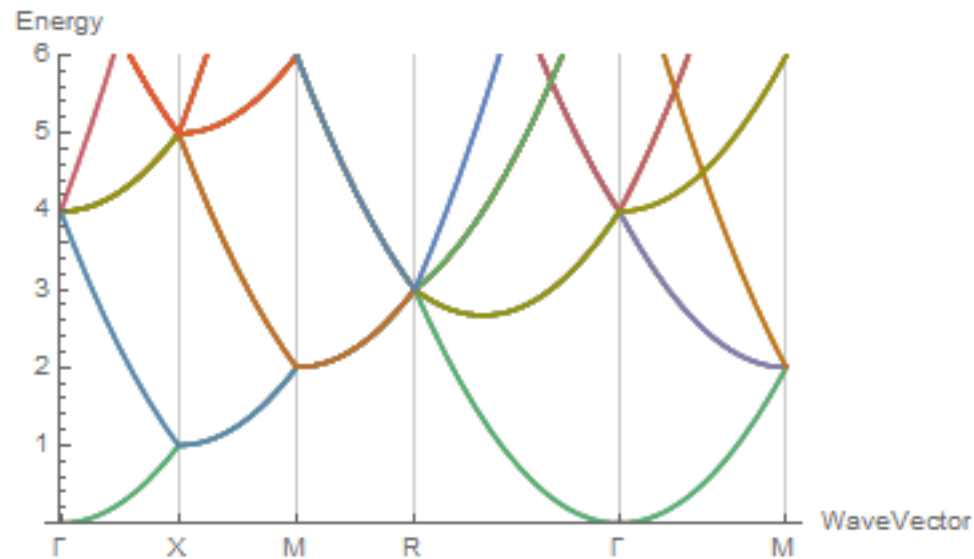
e-IBL emission spectrum for the model of Multiple Parabolic Band approximation (nearly free electrons) - dependence on electron mass (number of branches up to E_g kinetic energy)



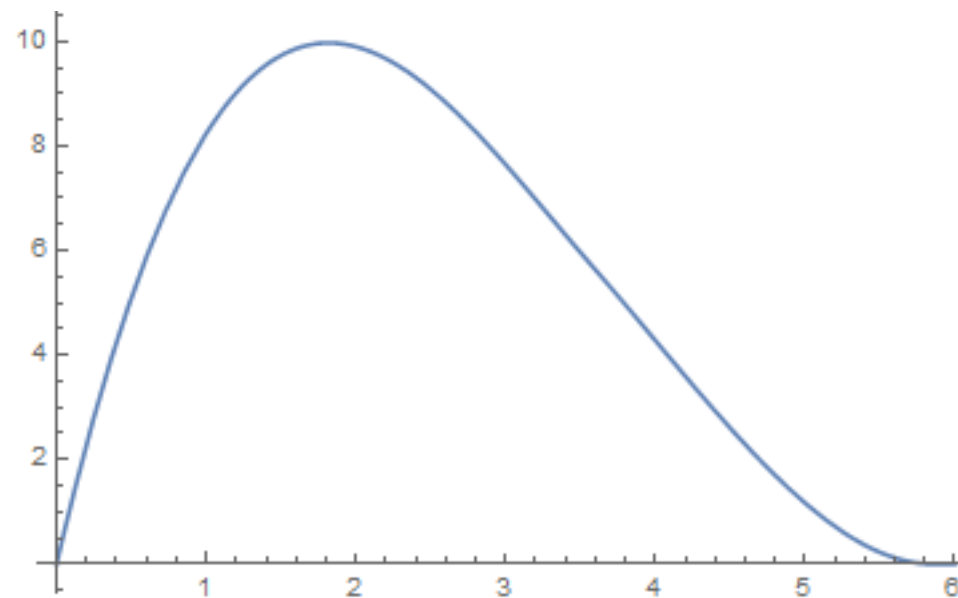
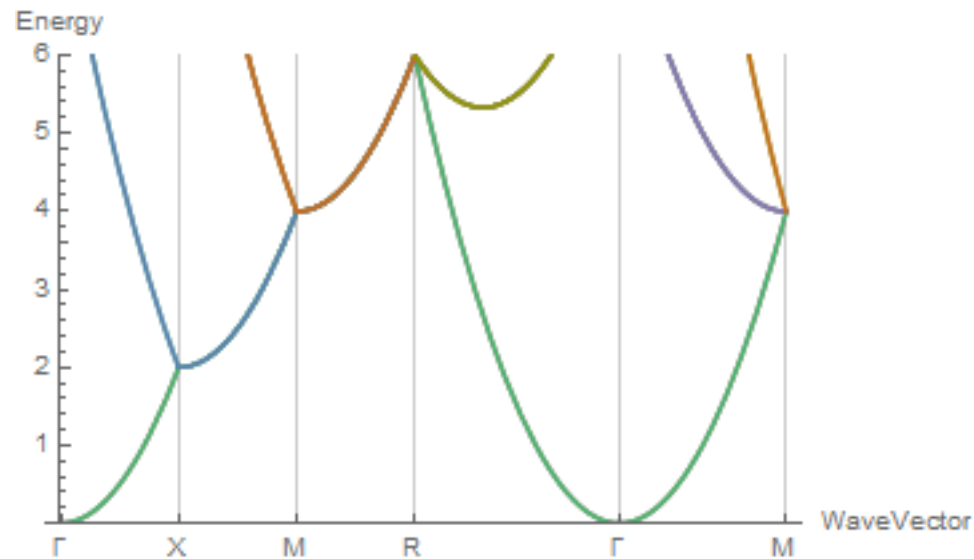
e-IBL emission spectrum for the model of Multiple Parabolic Band approximation (nearly free electrons) - dependence on electron mass (number of branches up to E_g kinetic energy)

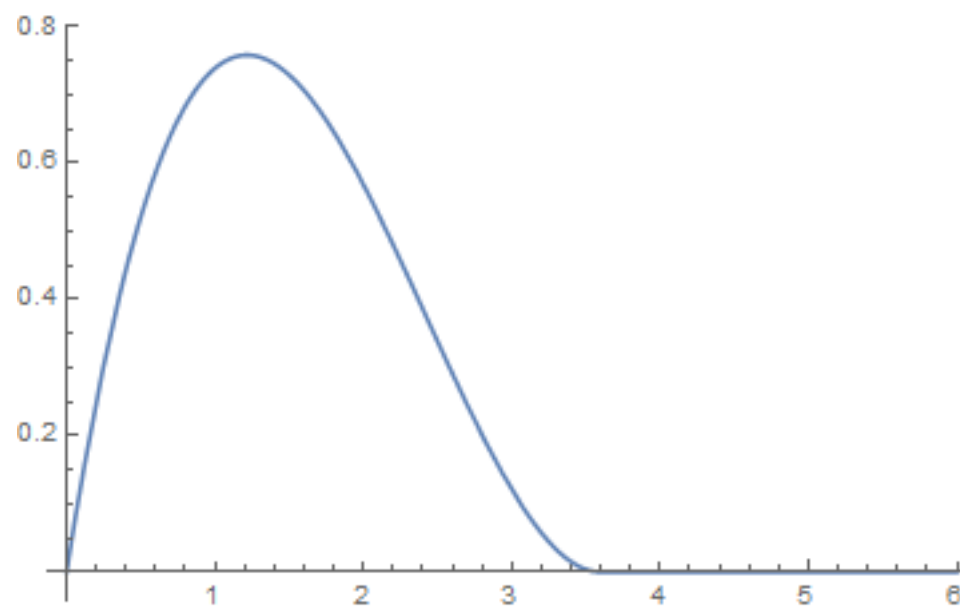
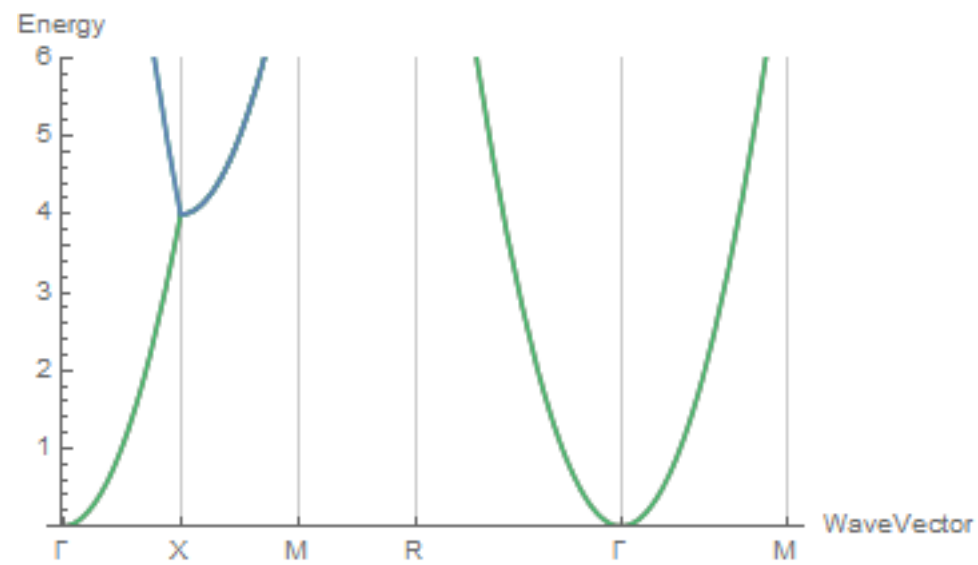


e-IBL emission spectrum for the model of Multiple Parabolic Band approximation (nearly free electrons) - dependence on electron mass (number of branches up to E_g kinetic energy)



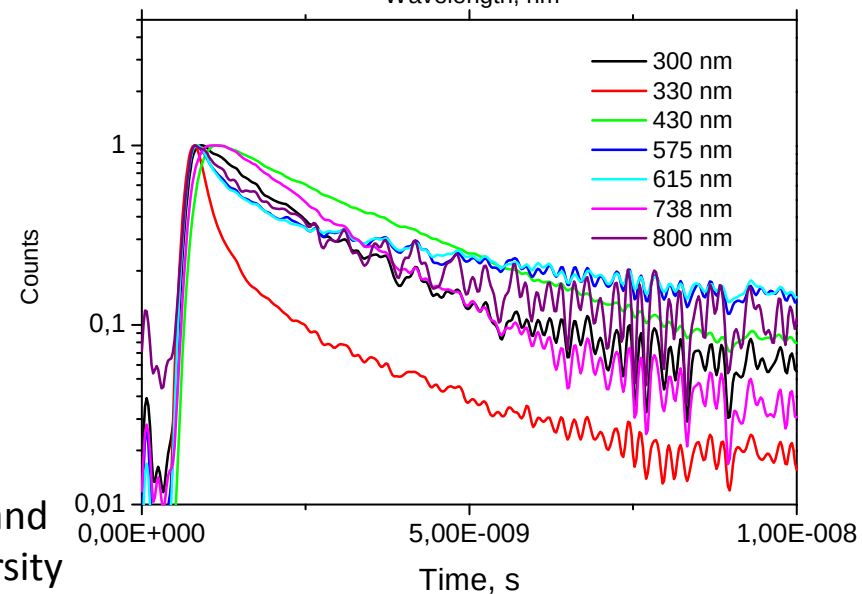
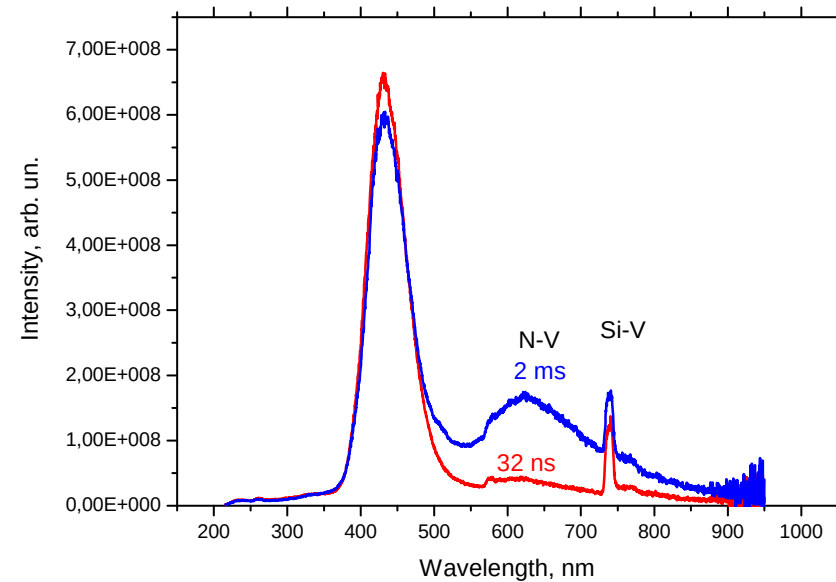
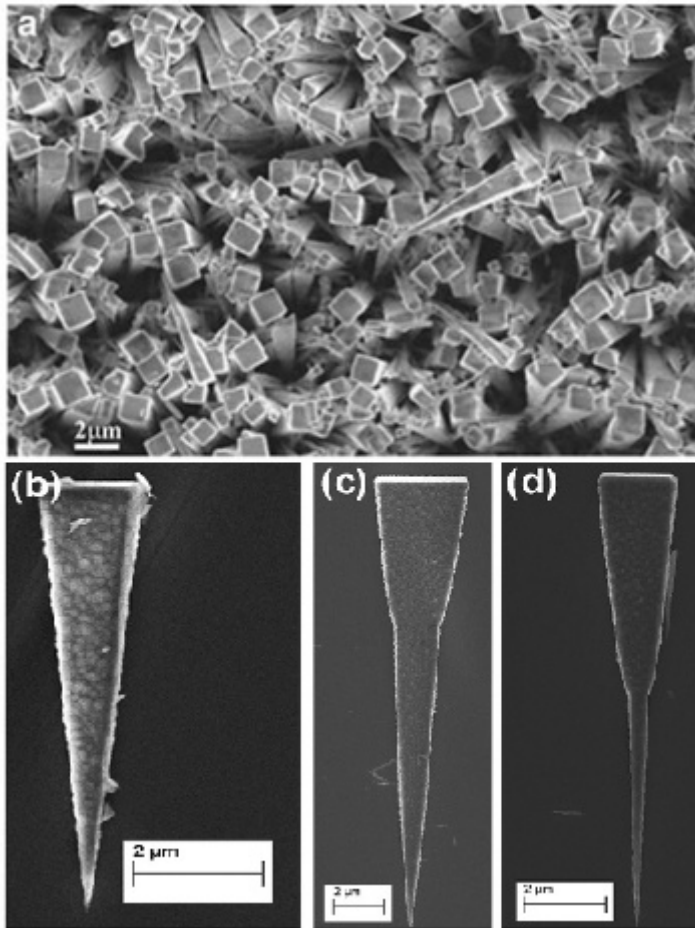
e-IBL emission spectrum for the model of Multiple Parabolic Band approximation (nearly free electrons) - dependence on electron mass (number of branches up to E_g kinetic energy)





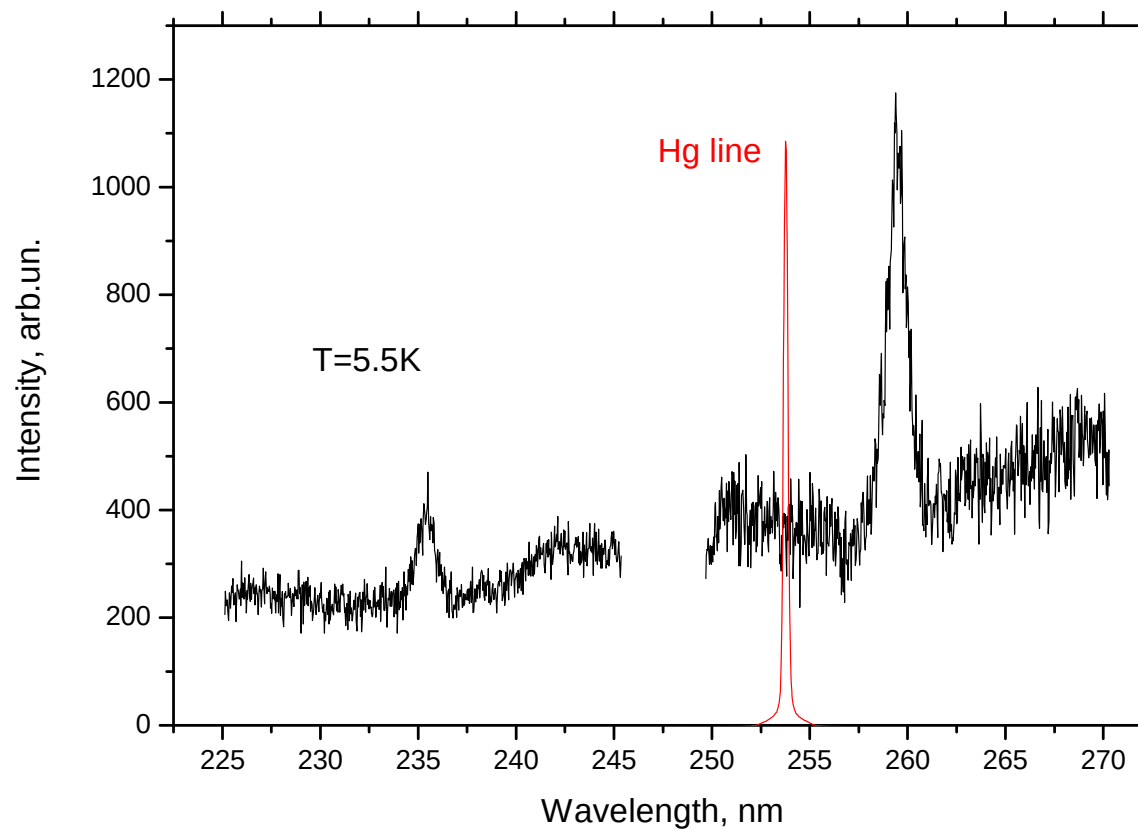
Diamond micropiramides cathodoluminescence

Diamond micropylramids (I.Kamenskikh, Tartu group)



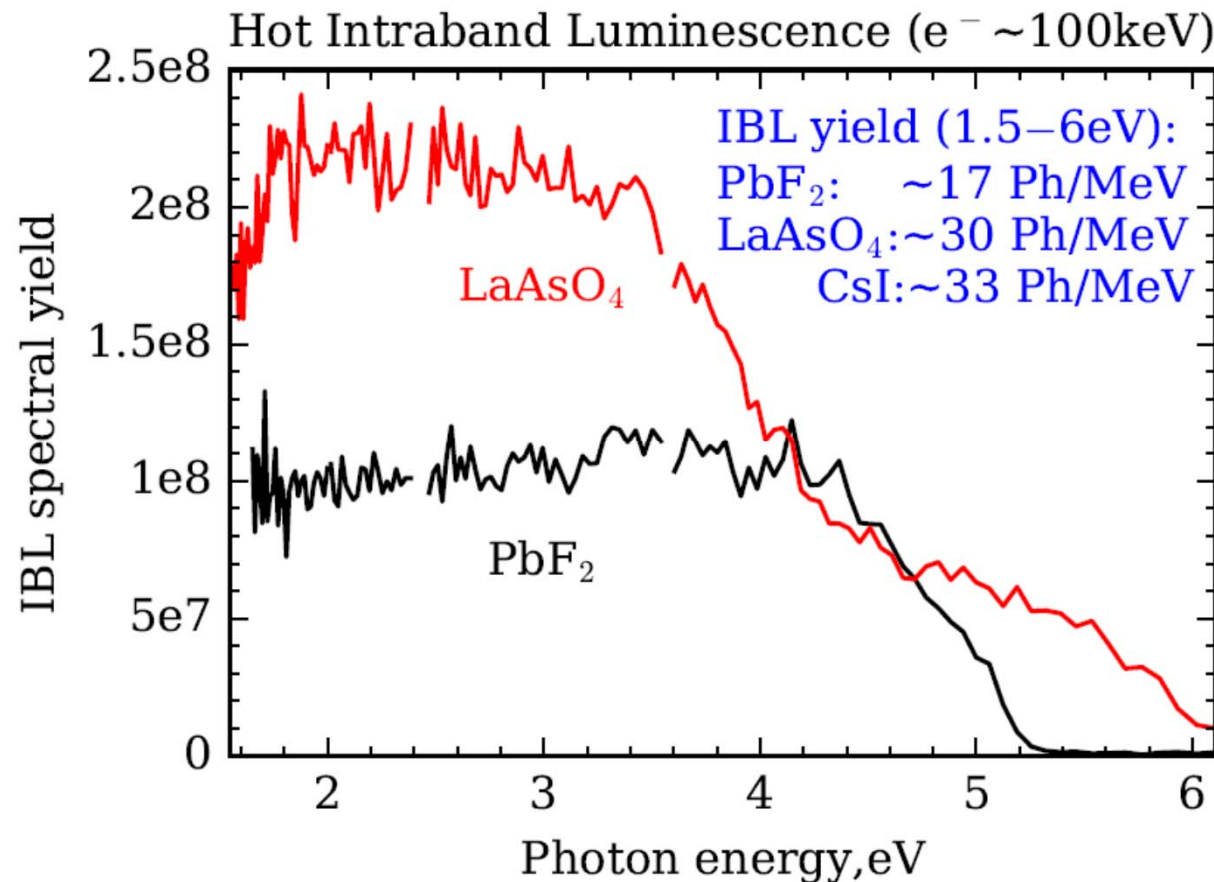
Samples are grown at Department of polymers and crystals, Faculty of physics, Moscow State University

Diamond micropylramids



Cathodoluminescence spectrum with high resolution

IBL of La arsenate (D.Spassky & Tartu group)



Thank you for your attention!