

## Motivation

- measurement of sub-band gap absorption by photoluminescence
- ⇒ no transmission needed, thick samples and substrates possible
- measurement technique with highest sensitivity for absorption
- ⇒ consistent determination of Urbach-tails at lower energies

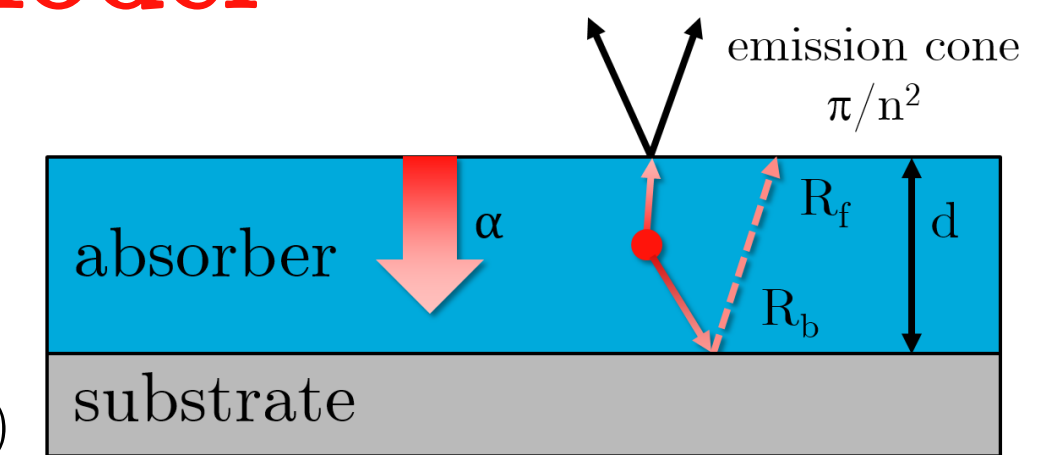
## Experimental methods

	UV-VIS	PDS	PL
$> E_g$	good	moderate	bad
$< E_g$	bad	moderate	good
$\alpha$ - range	3 orders	4 orders	$> 5$ orders

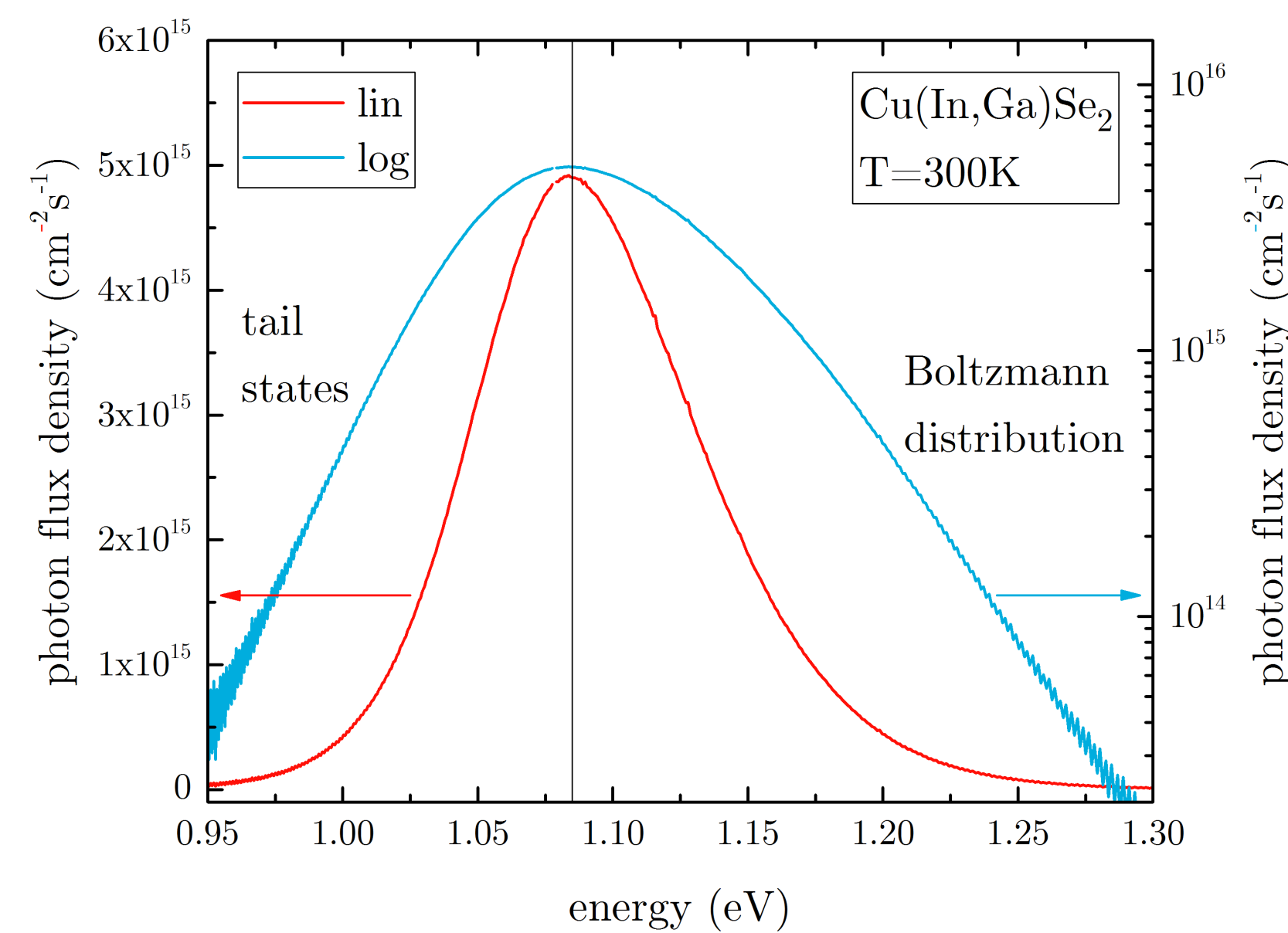
## Model

Parameters:

- absorber thickness  $d$
- front/back-reflection  $R_f, R_b$
- refractive index  $n$  (not needed)

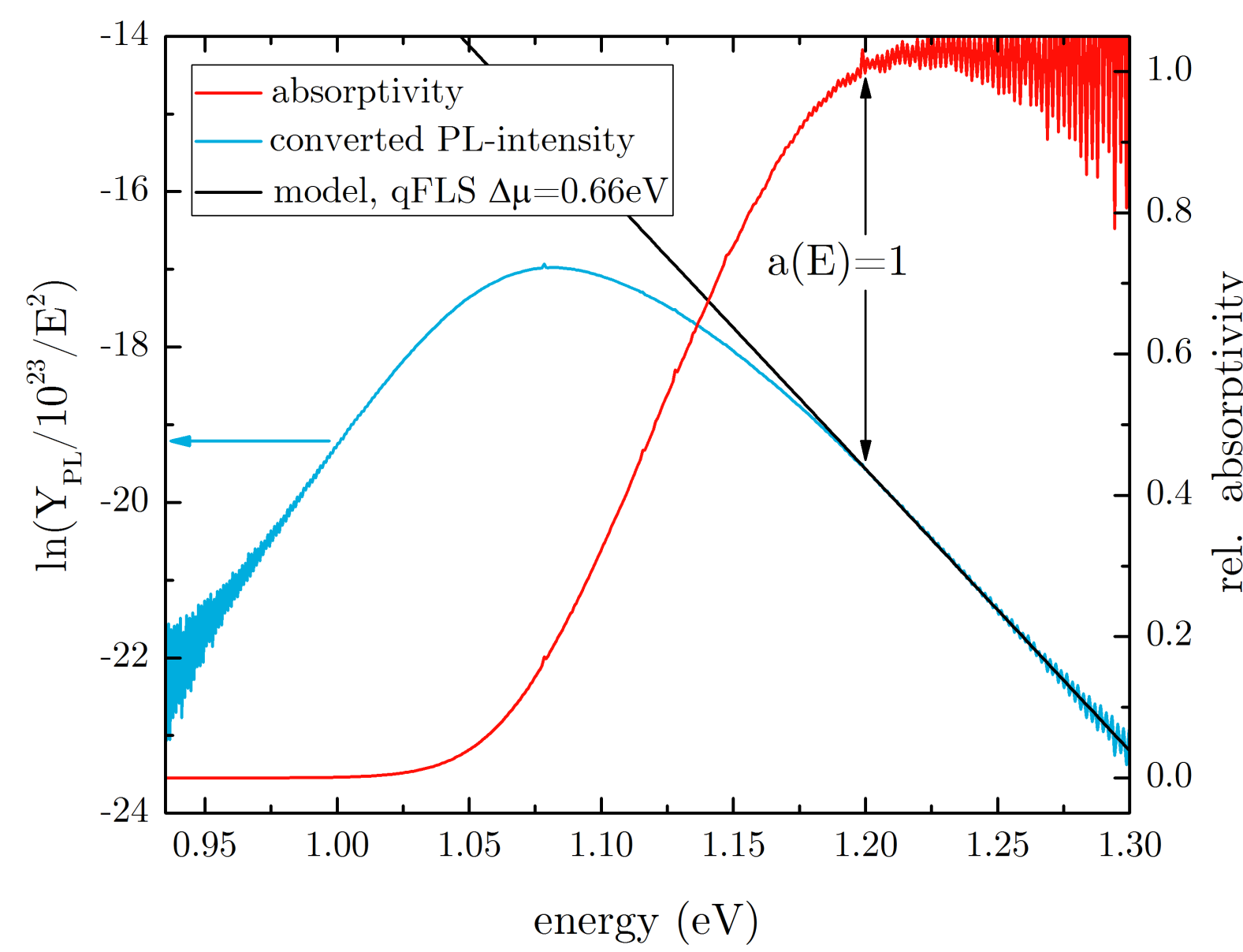


## Photoluminescence spectrum



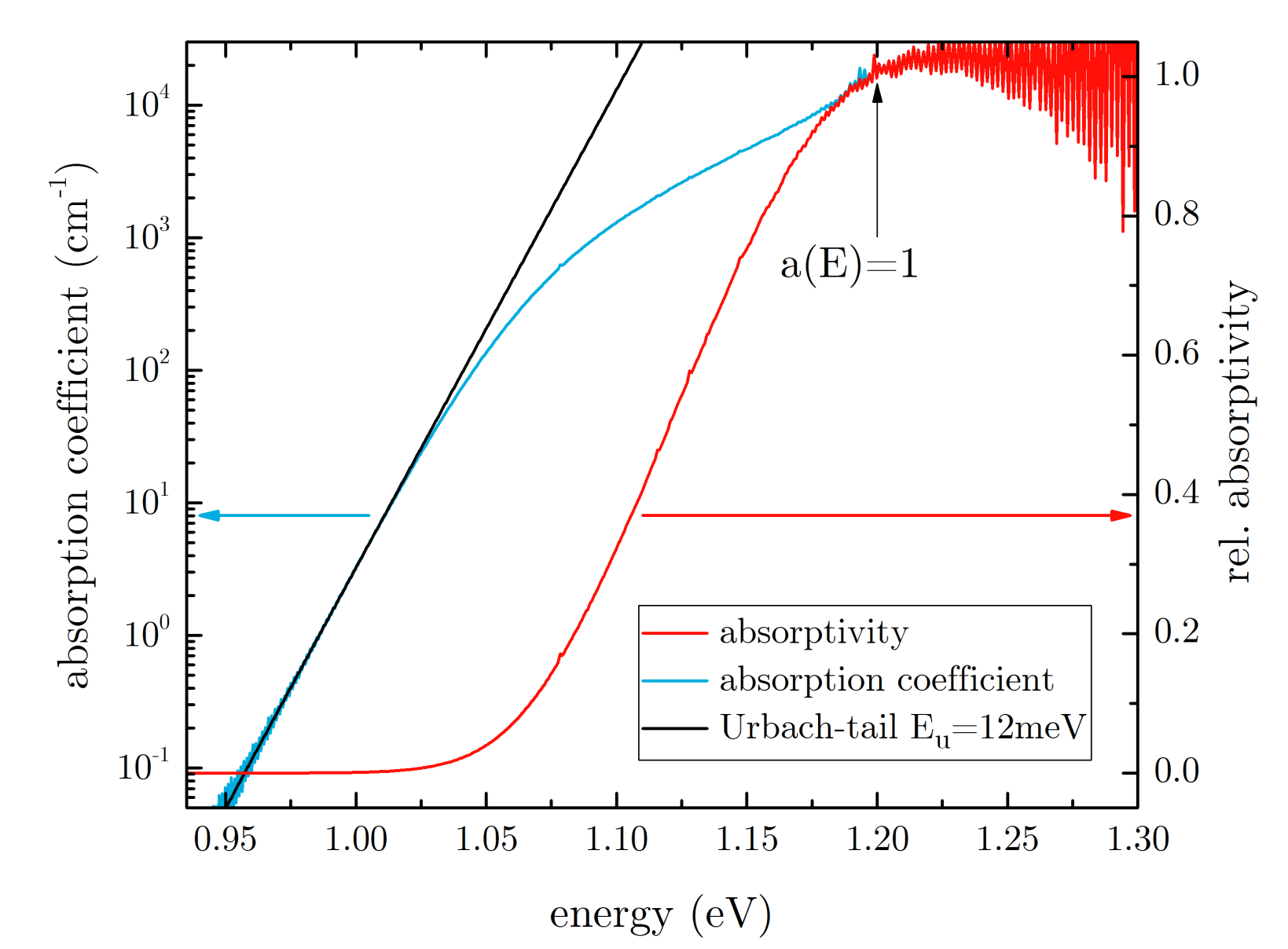
- pl spectrum measured with photon-flux equivalent to 1 sun (AM1.5)
- absolute intensity calibration for quasi-Fermi level splitting (qFLS)
- spectral dynamic range important for fitting model (2 orders of magn.)

## Fitting function



- linear fit of Boltzmann-distribution at least  $6k_B T$  above band gap
- fitting parameters are temperature (slope) and qFLS (interception)
- parameters re-inserted in gen. Planck's law to calculate absorptivity

## Absorption spectrum



- absorption coeff. calculated from absorptivity and sample thickness
- advanced model:
- front-reflection measured with spectrophotometer, assuming  $R_f = R_b$
- needed, if full absorption above  $E_g$  can not be measured and  $a(E) \neq 1$

## Generalized Planck's law

$$Y_{PL}(E) = \frac{1}{4\pi^2 \hbar^3 c^2} \frac{a(E) E^2}{\exp((E - \Delta\mu)/k_B T) - 1}$$

$$\Rightarrow \ln\left(\frac{Y_{PL}}{10^{23} E^2}\right) = \frac{E - \Delta\mu}{k_B T}$$

## Conditions for Fitting

$$E - \Delta\mu > 6k_B T$$

(no occupation dependent absorptivity  $\Rightarrow$  Boltzmann-approximation)

$$a(E) = 1 \text{ for } E - E_g > 6k_B T$$

(full absorption above the band gap and  $d \gg 1/\alpha$ )

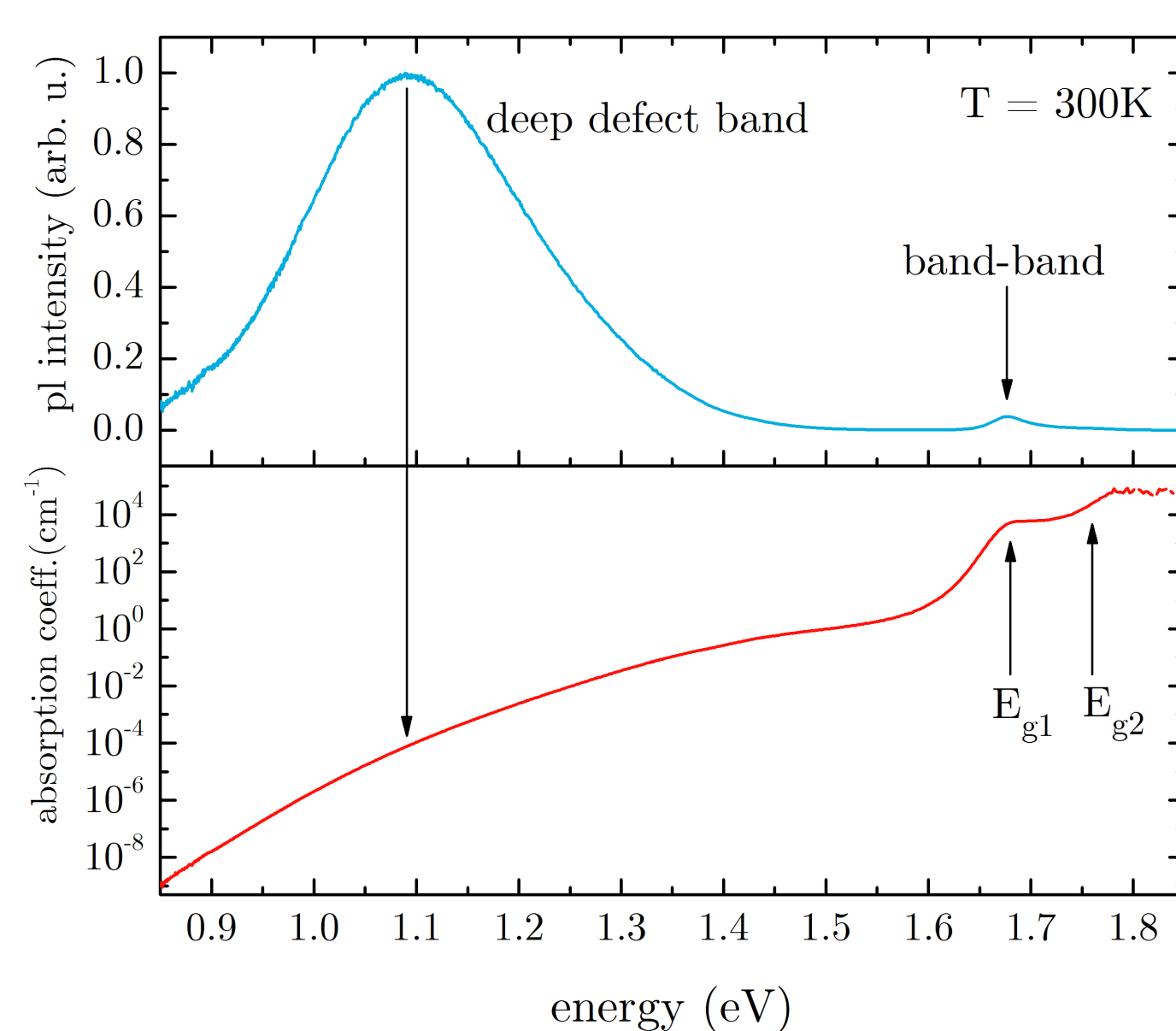
## Absorptivity $a(E) \rightarrow \alpha(E)$

$$a(E) = \frac{[1 - R_f(E)][1 - \exp(-\alpha(E)d)][1 + R_b(E)\exp(-\alpha(E)d)]}{1 + R_f(E)R_b(E)\exp(-2\alpha(E)d)}$$

often used simplification (simple model):

$$a(E) = 1 - \exp(-\alpha(E)d) \text{ with } R_f = R_b = 0$$

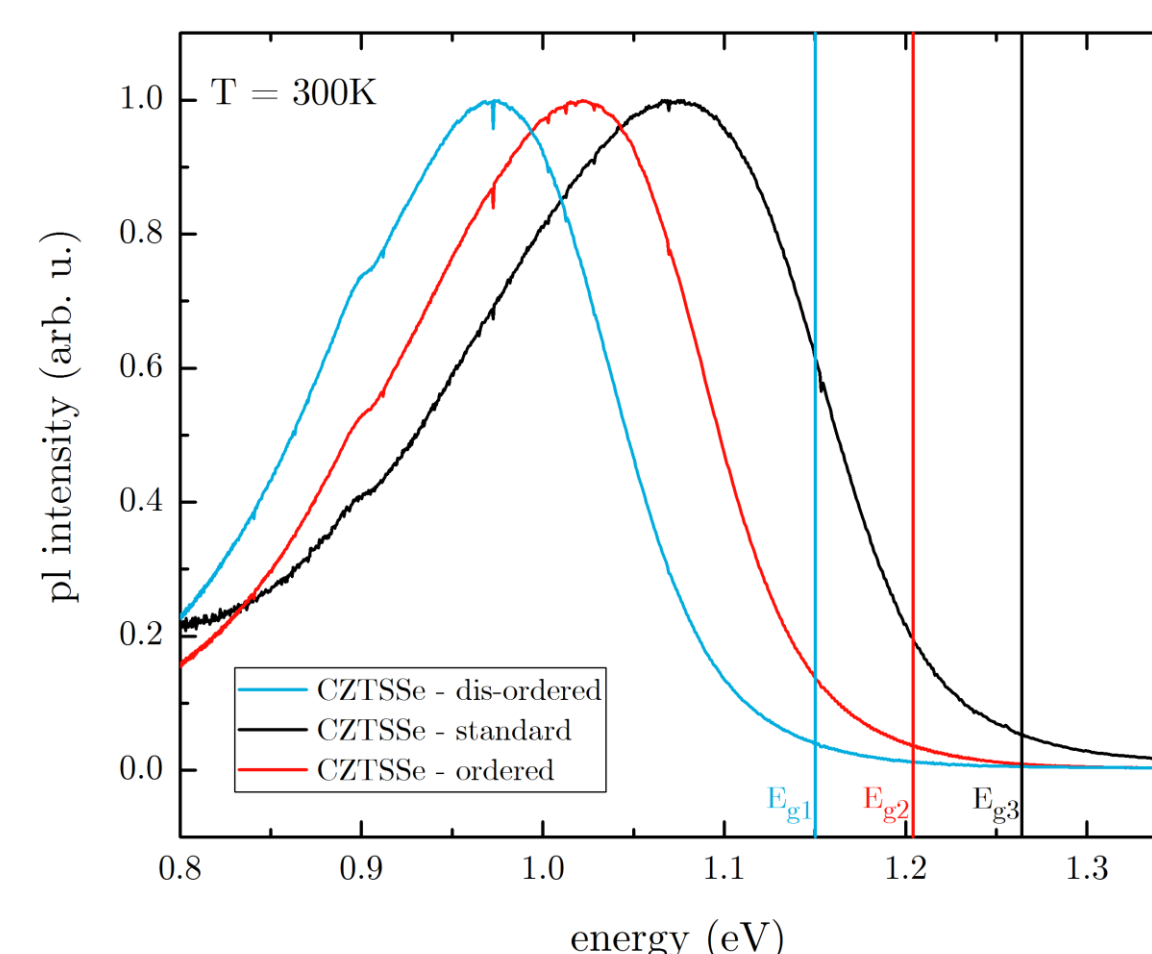
## Deep defect absorption CuGaSe<sub>2</sub>



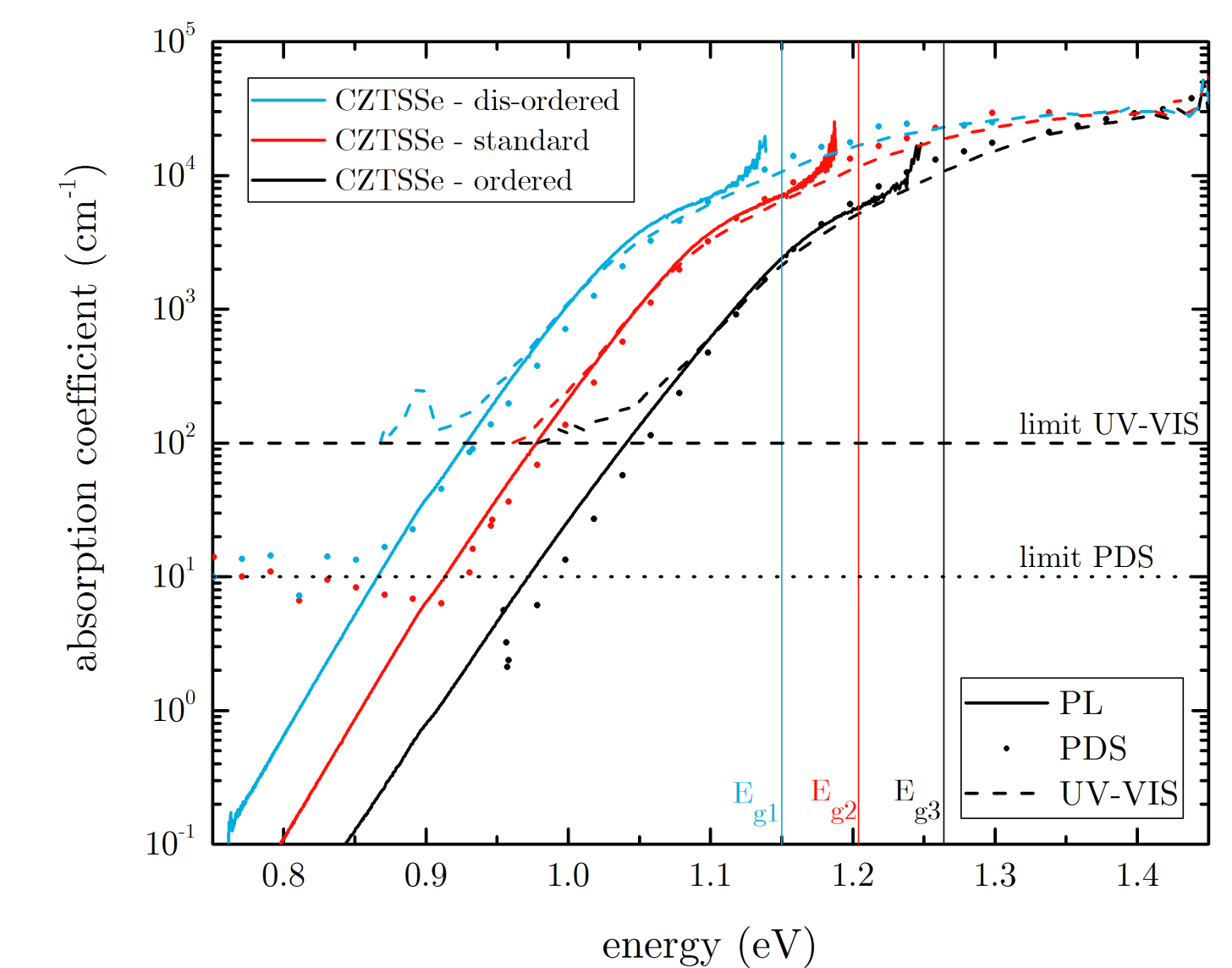
- high defect band intensity equals absorption values  $< 10^{-4} \text{ cm}^{-1}$
- but estimation of defect density needs precise lifetime measurements

## Advanced model: Cu<sub>2</sub>ZnSn(S,Se)<sub>4</sub>

Kesterites show strong edge-luminescence at room temperature  
 $\Rightarrow$  PL maximum and band gap differ much more than in other materials  
 $\Rightarrow$  full absorption condition above band gap is not fulfilled in experiment  
 $\Rightarrow$  advanced model with spectrophotometer measurements of reflection



## Comparison PL/UV-VIS/PDS



- good agreement of absorption coefficient from different methods
- photoluminescence limited by detector range not signal to noise ratio
- Urbach-energies within error of PDS, if advanced PL model is used

- PL is suitable to study sub-band gap absorption
- thin films and different substrates can be used
- absorption coefficient values  $10^{-8} \text{ cm}^{-1}$  measurable