IQE and all that jazz: the temperature dependence of semiconductor light emission

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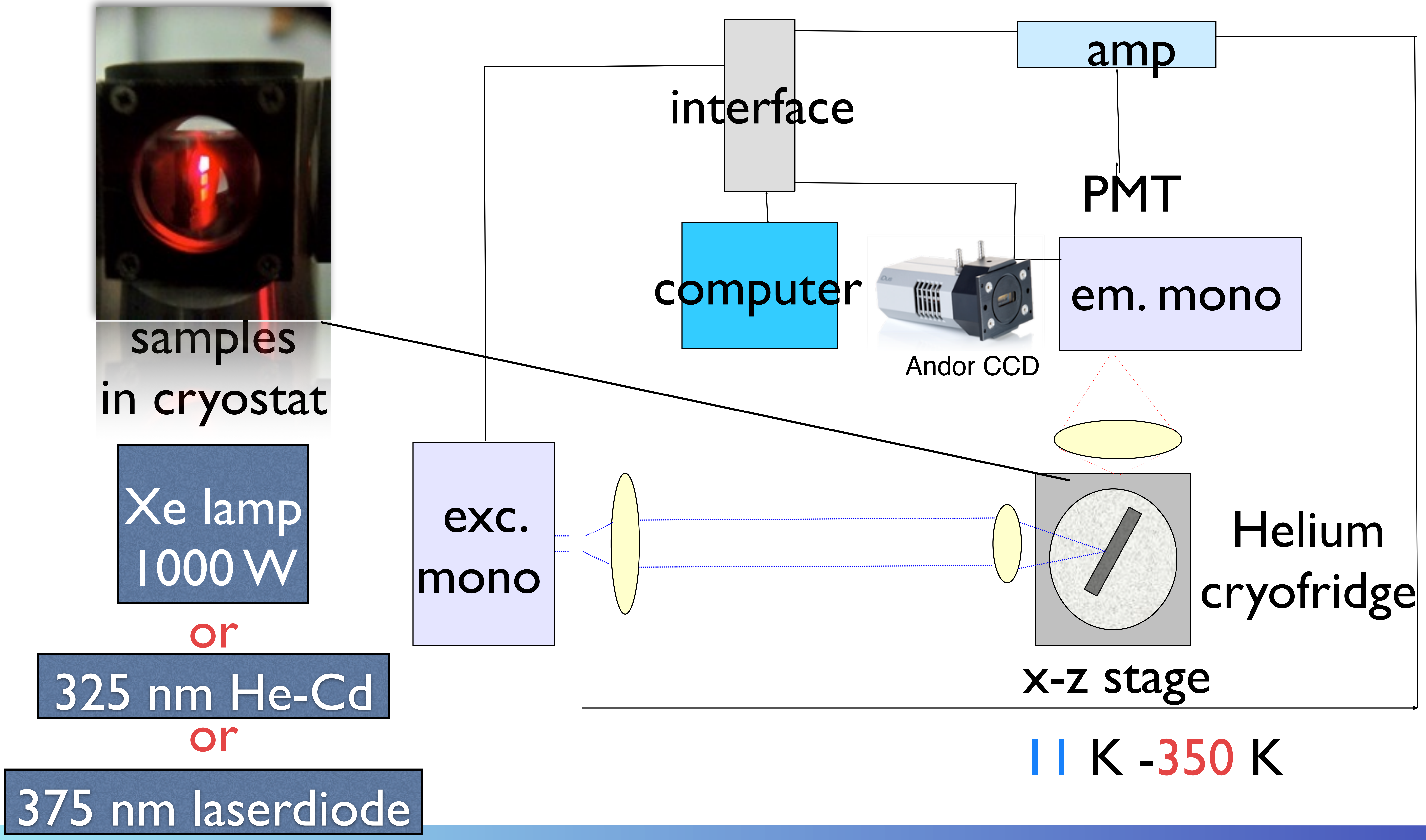
PL/E data acquisition



samples in cryostat

Xe lamp 1000 W

or

325 nm He-Cd

or

375 nm laserdiode

exc. mono

interface

computer

Andor CCD

amp

PMT

em. mono

Helium cryofridge

x-z stage

11 K -350 K

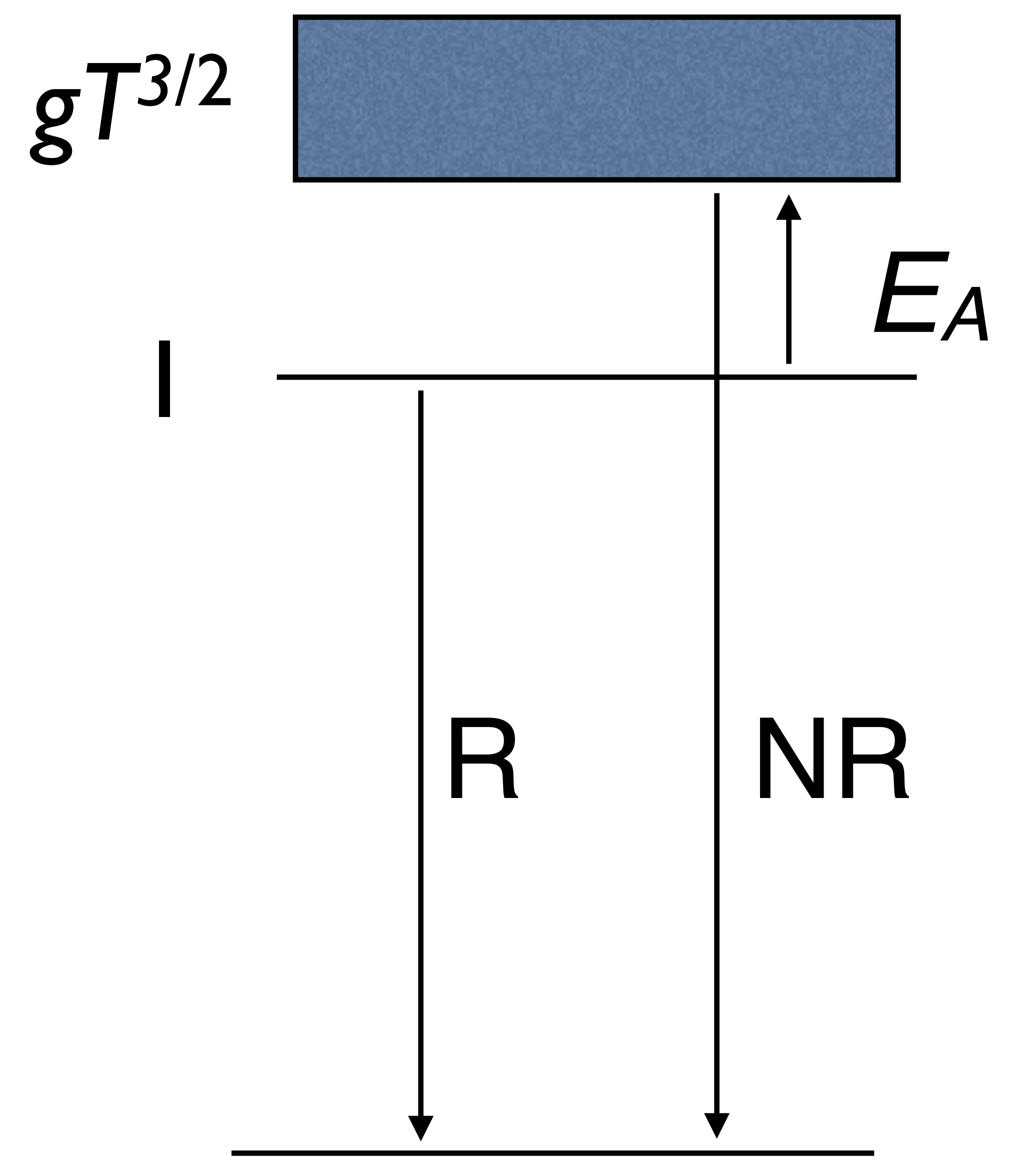
For temperature dependences:

cool to ~10 K @ ~5 K per minute

take one whole spectrum (in 1 s) every 0.5 K or 1 K.

The R-NR luminescence model

In the conventional model, an activation energy E_A separates a radiative (localised) state from a band of delocalised states, with a relative degeneracy ratio of $1{:}gT^{3/2}$.

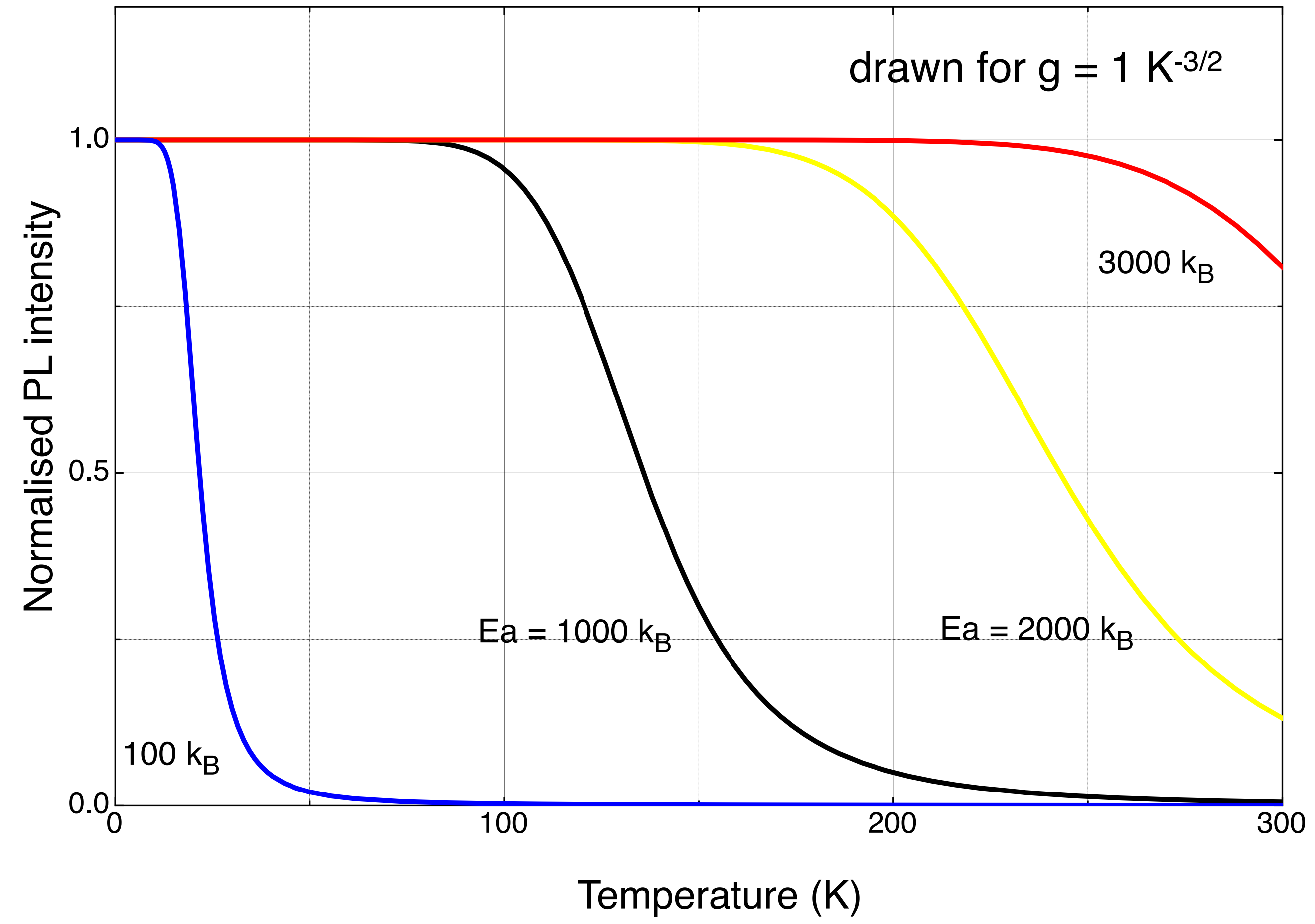


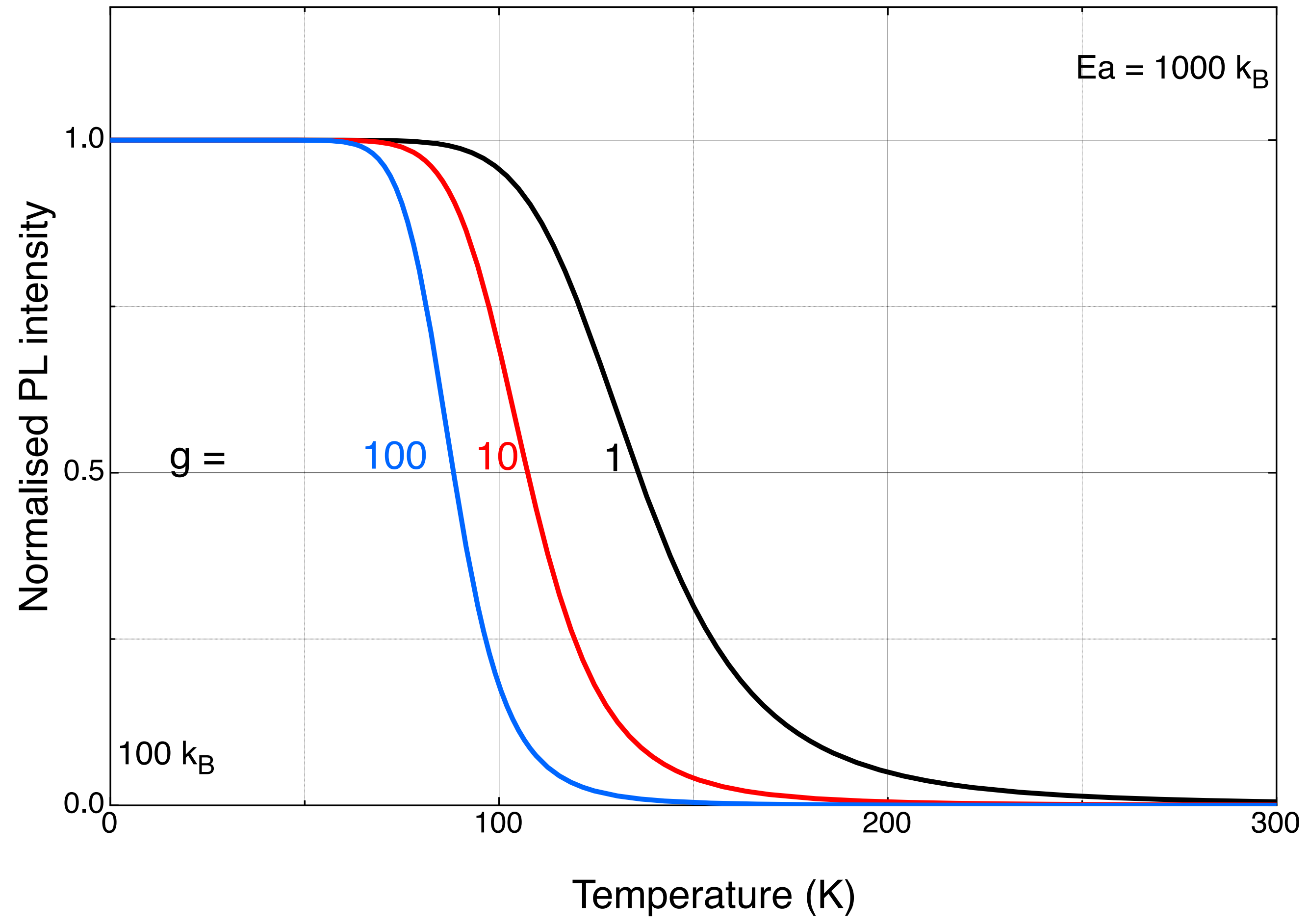
The *radiative fraction* is then given by:

$$\boxed{IQE(T) = \frac{I(T)}{I(0)} = \frac{1}{1 + gT^{3/2}\exp(-E_A / k_B T)}}$$

which shows the well-known general form, with a nearly constant intensity up to a temperature $\sim E_A/10k_B$ followed by a fairly rapid decline as T increases further.

Note: $E_A = k_B T_A$; 1 eV ~ 11 600 K



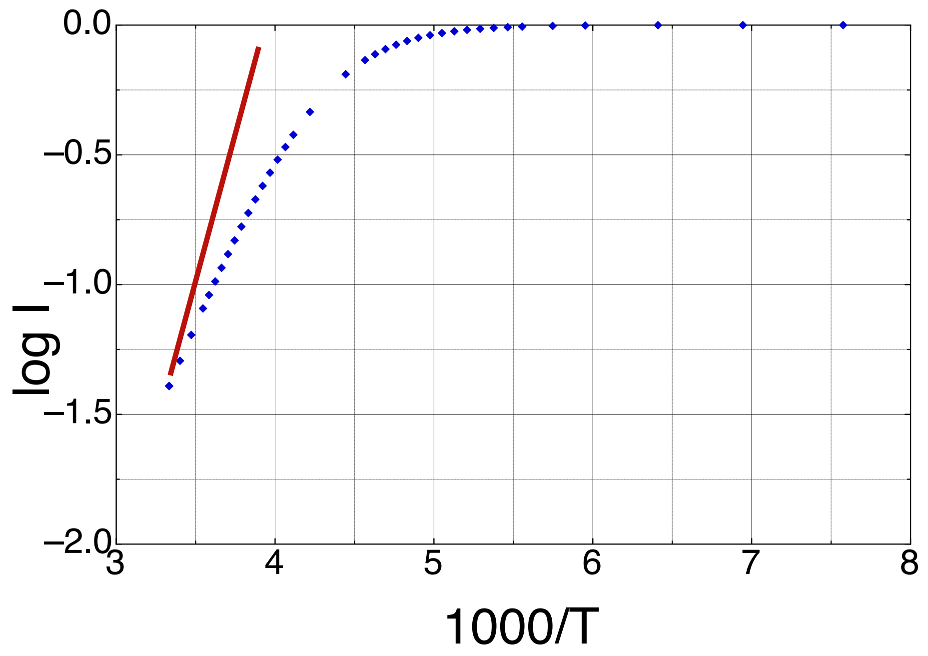


$$\boxed{IQE(T)=\frac{I(T)}{I(0)}=\frac{1}{1+gT^{3/2}\exp(-E_A/k_BT)}}$$

- The $T^{3/2}$ dependence is relatively weak and is often ignored. It makes little practical difference to the goodness of fit for most data. Simplifying and approximating the formula* produces the Arrhenius form of the relation.:

$$\frac{I(T)}{I(0)}=\frac{1}{1+G\exp(-E_A/k_BT)}\sim G^{-1}\exp(E_A/k_BT)$$

A plot of *log(I)* vs *1/T* can be fitted *asymptotically* with a straight line to yield an *estimate* of E_A.



- IQE(T = 300 K) is the value most often quoted, but the formula carries the implication that <u>all</u> semiconductor luminescence is 100% efficient at low temperatures: this is unlikely to be true.

- We can usefully define the *half-power point* at which temperature the luminescence intensity drops to half-maximum:

$$T_{1/2}=\frac{E_A}{k_B\ln G}$$

This parameter provides a ‘sanity check’ on the fitness of the model (see later).

*as is my wont

Some comments on the R-NR model

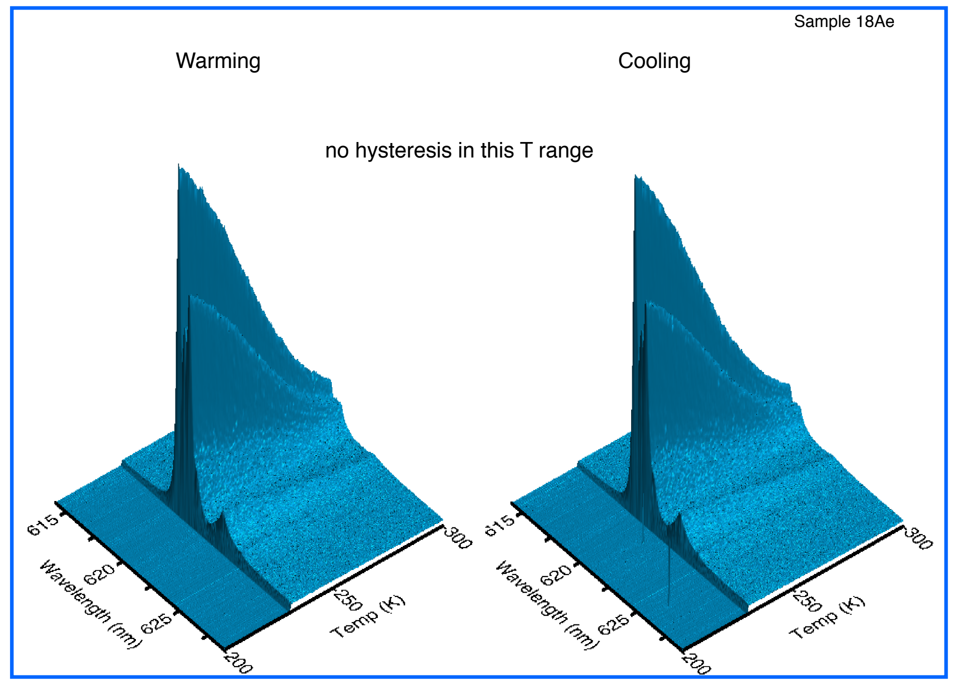
Introducing the sigmoidal fit

GaN:Mg template

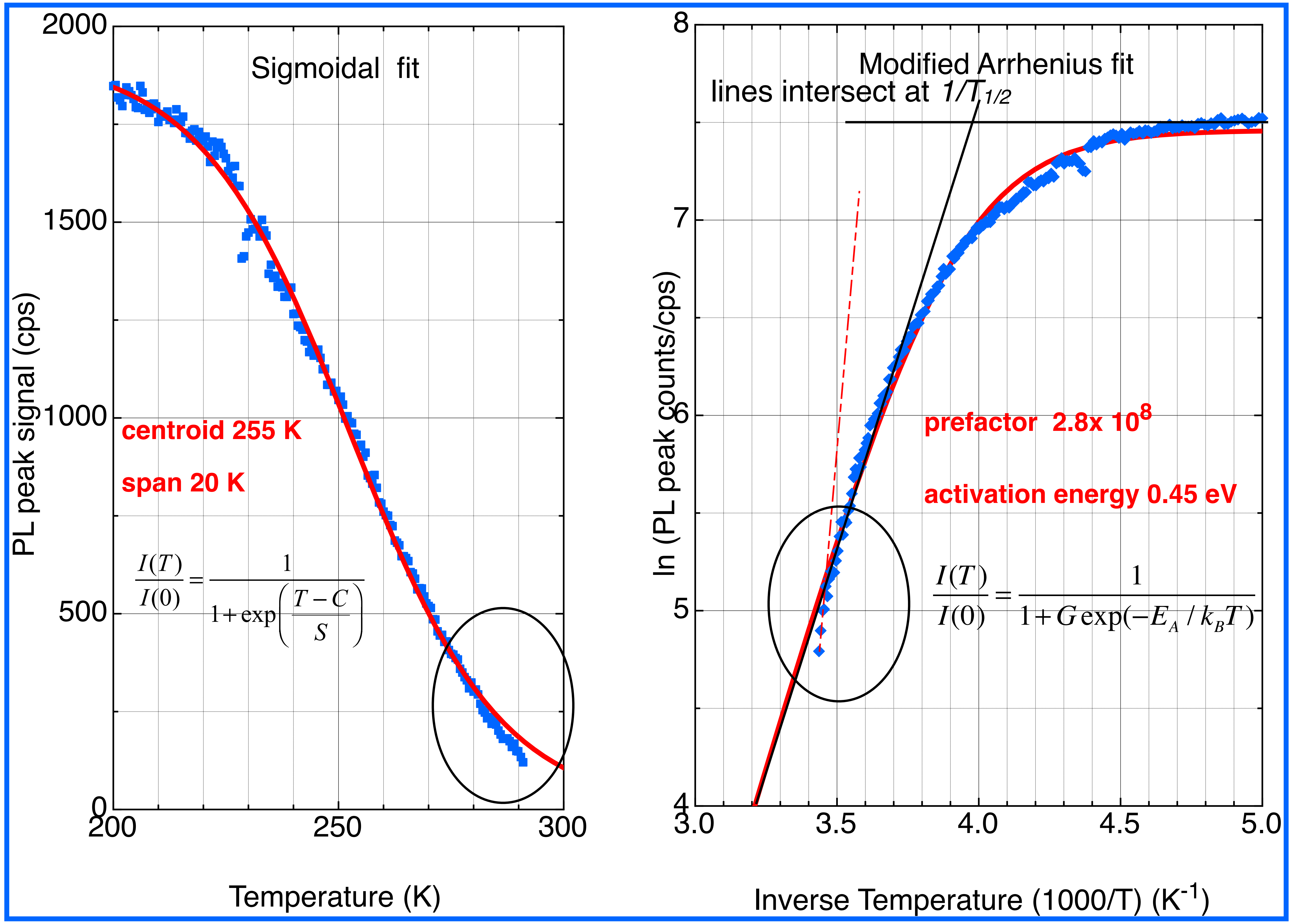
Eu ion implantation

HTHP annealing

Defect Eu0 is dominant near room temperature.



$^5D_0$ to $^7F_2$ transition



K. P. O'Donnell, P. R. Edwards, M. J. Kappers, K. Lorenz, E. Alves and M. Boćkowski

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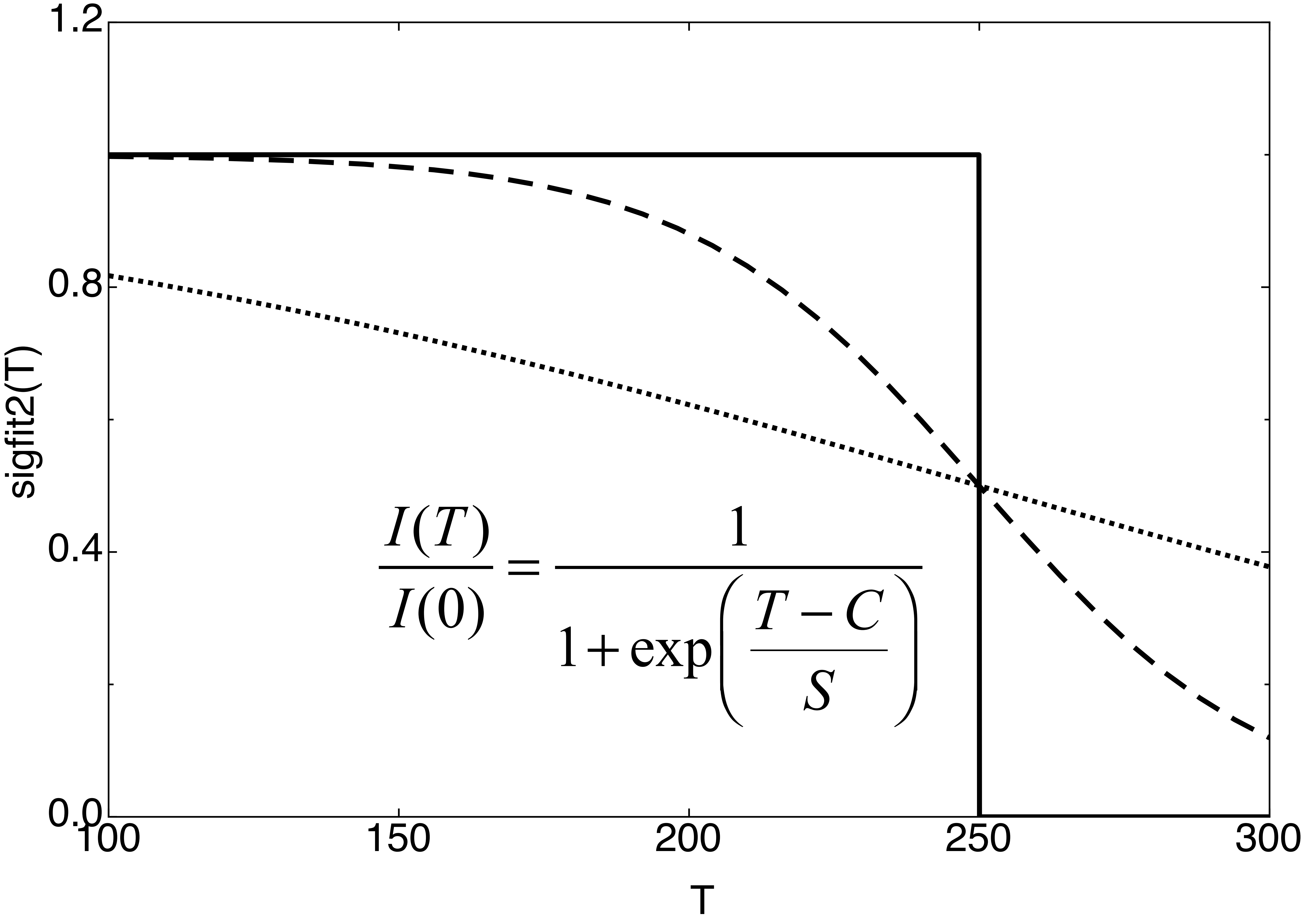
All fits tend to deviate at low PL intensity, due partly to errors in background subtraction.



$$\frac{I(T)}{I(0)} = \frac{1}{1+\exp\left(\frac{T-C}{S}\right)}$$

C - centroid (= $T_{1/2}$)

S - span

The sigmoid as a smoothed step function

Solid State Communications
Volume 34, Issue 10, June 1980, Pages 833–836

The temperature dependence of photoluminescence in a-Si: H alloys

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Abstract

Photoluminescence intensity observed near 1.3 eV in sputtered a-Si : H has been measured as a function of temperature for several samples prepared under differing conditions. The data are shown to obey an expression derived from a law of the form

$$\frac{\rho_{NR}}{\rho_R} \sim e^{T/T_0}$$

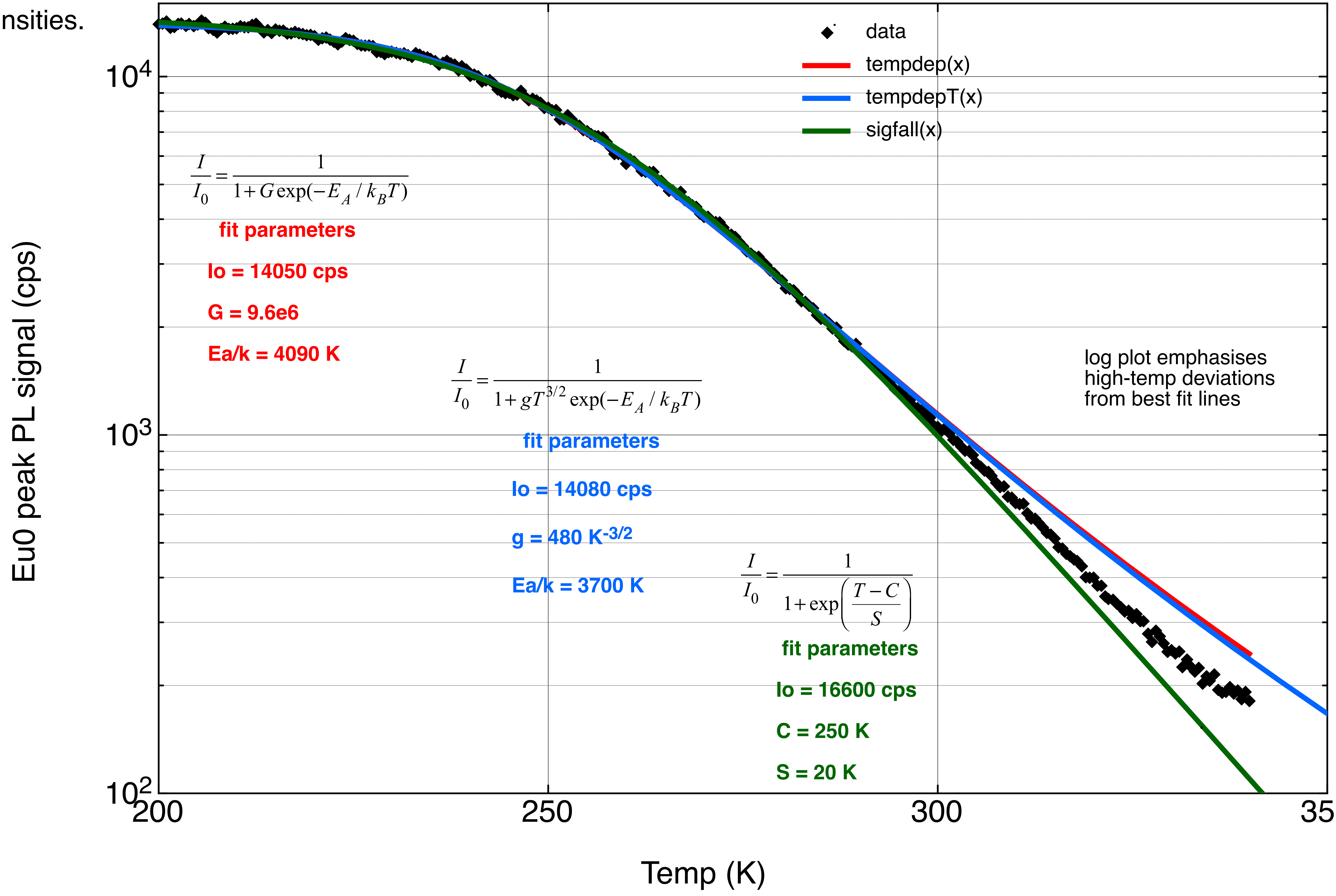
where pnr and pnr are the probabilities for non-radiative and radiative recombination. We find $T_0 \approx 23$ K independent of sample preparation conditions.

The temp dependences are similar since the radiative fraction $\dfrac{\rho_R}{\rho_R + \rho_{NR}} \sim \dfrac{1}{1+\exp\left(\dfrac{T}{T_0}\right)}$ is a sigmoid with $T_{1/2} = 0$ K and $S = T_0$

Sigmoid: some physical justification

Data 13Af

Note restricted range of intensities.



$$\frac{I}{I_0}=\frac{1}{1+G\exp(-E_A/k_BT)}$$

fit parameters

Io = 14050 cps

G = 9.6e6

Ea/k = 4090 K

$$\frac{I}{I_0}=\frac{1}{1+gT^{3/2}\exp(-E_A/k_BT)}$$

fit parameters

Io = 14080 cps

g = 480 K$^{-3/2}$

Ea/k = 3700 K

$$\frac{I}{I_0}=\frac{1}{1+\exp\left(\frac{T-C}{S}\right)}$$

fit parameters

Io = 16600 cps

C = 250 K

S = 20 K

log plot emphasises
high-temp deviations
from best fit lines

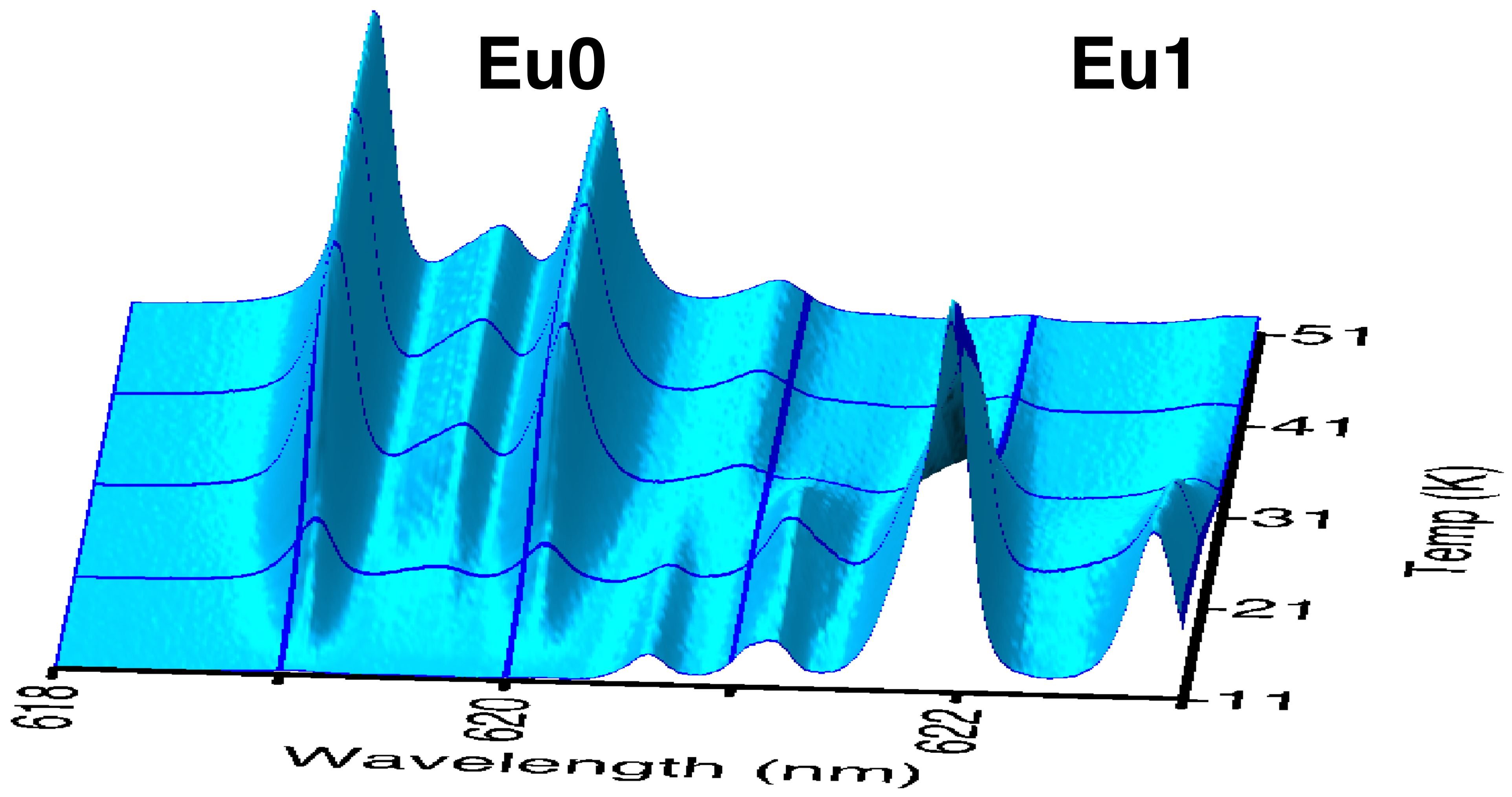
The fits are naturally weighted towards the low temperature region where intensities are higher.

High temperature intensity values suffer more from errors in background subtraction.

Comparing fits and fit parameters

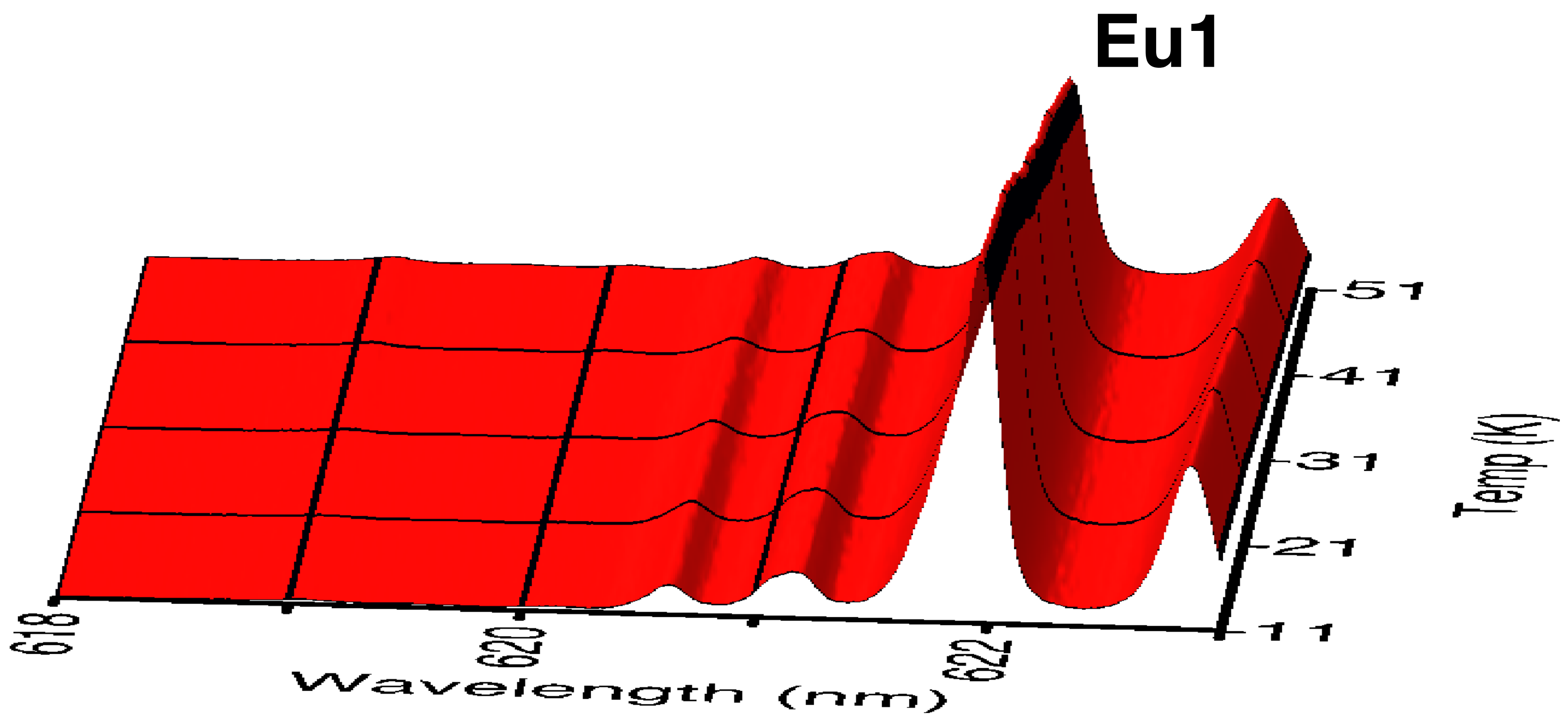
Luminescence hysteresis

Cooling



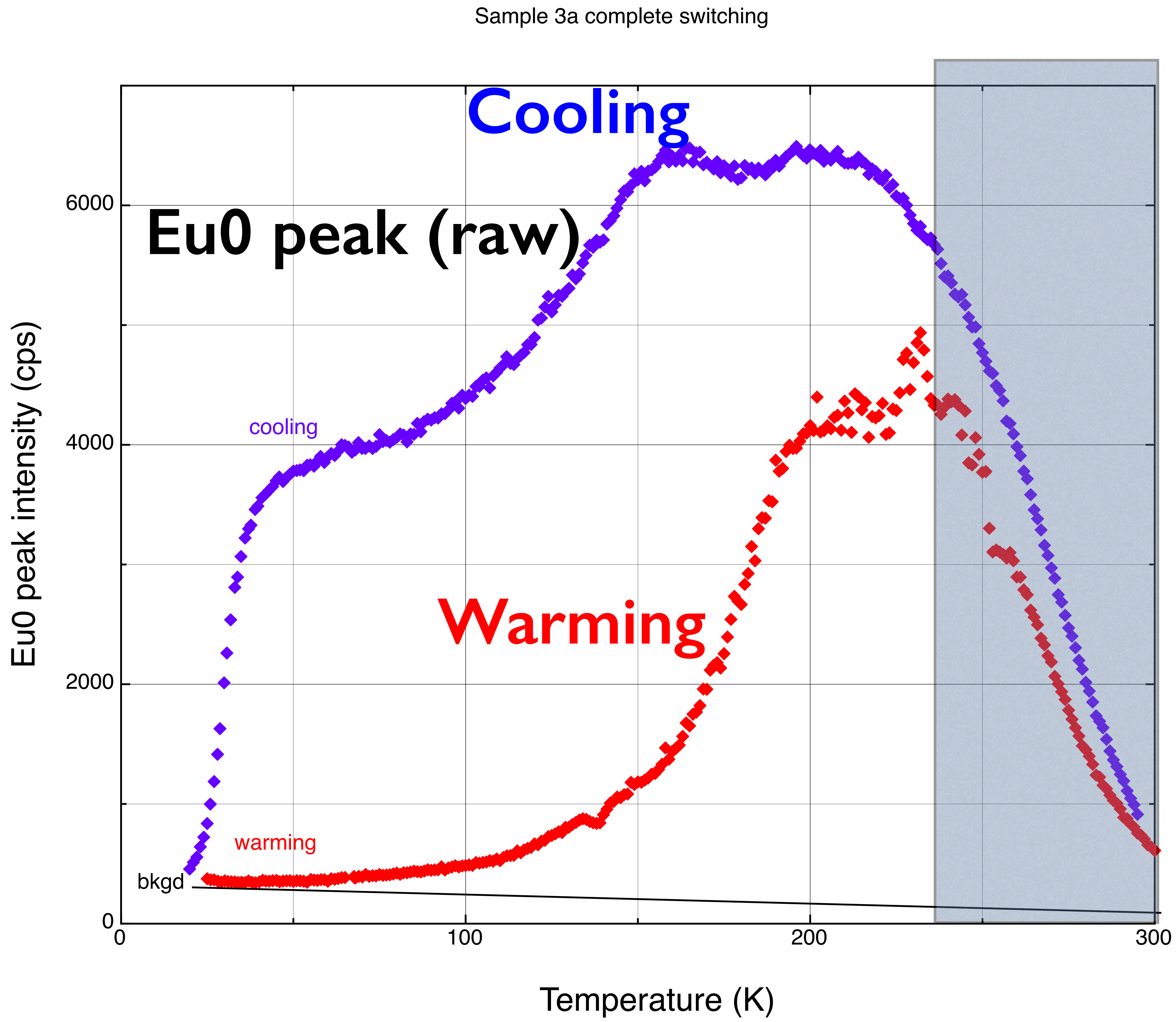
Eu0 anomalous;
Eu1 quasi-normal.

Warming



Eu0 absent;
Eu1 normal.

The anomalous (hysteretic) behaviour here can be described by the usual equations if we allow negative energy as a fit parameter.



The shaded region has a normal temp. dependence: whether warming or cooling, the intensity is lower at higher temperature.

PL hysteresis loops

A rising step is just the complement of a falling step- Sigmoid Frond

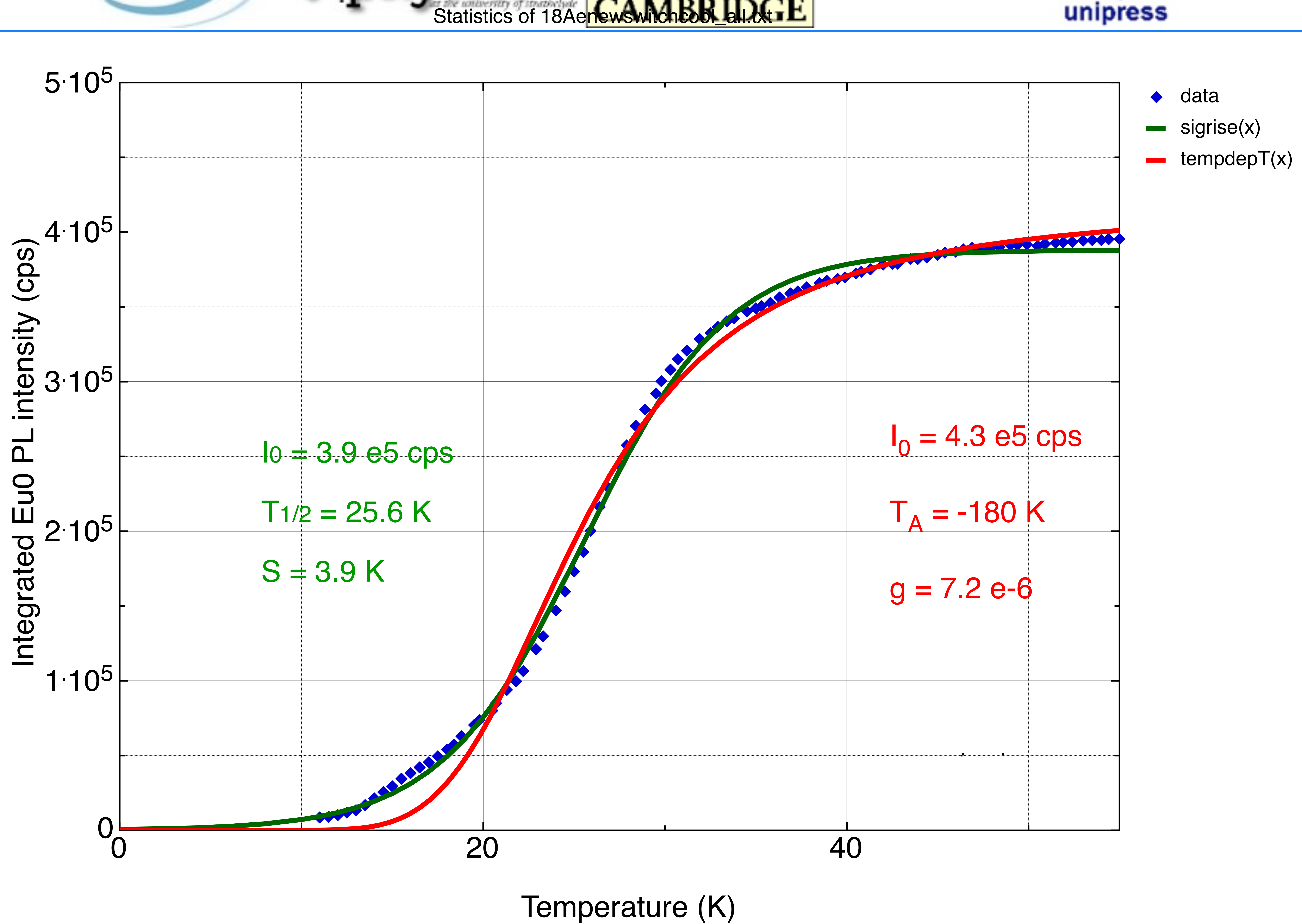
$$1-\frac{1}{1+gT^{3/2}\exp\left(\frac{-E_A}{k_BT}\right)}=\frac{1}{1+(1/gT^{3/2})\exp\left(\frac{E_A}{k_BT}\right)}$$

$$1-\frac{1}{1+\exp\left(\frac{T_{1/2}-T}{S}\right)}=\frac{1}{1+\exp\left(-\left(\frac{T_{1/2}-T}{S}\right)\right)}$$

fall rise

Algebra never lies

Datafits are not perfect



Odd behaviour of the BL band in high-resistivity GaN:Zn: power-tuneable **thermal quenching**

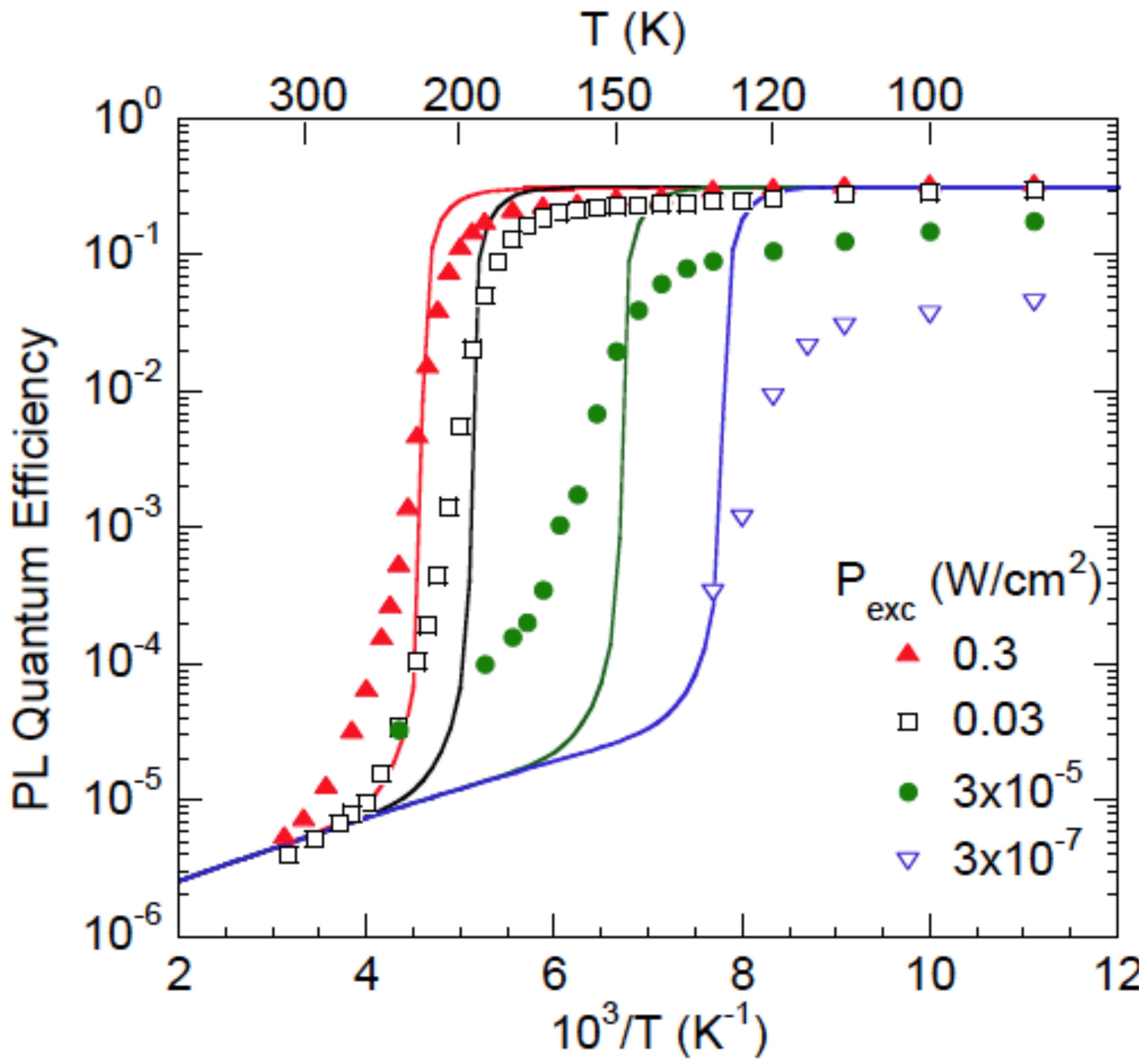


Figure 2 Temperature dependence of the quantum efficiency of the BL band in high-resistivity Zn-doped GaN for selected P_{exc}.

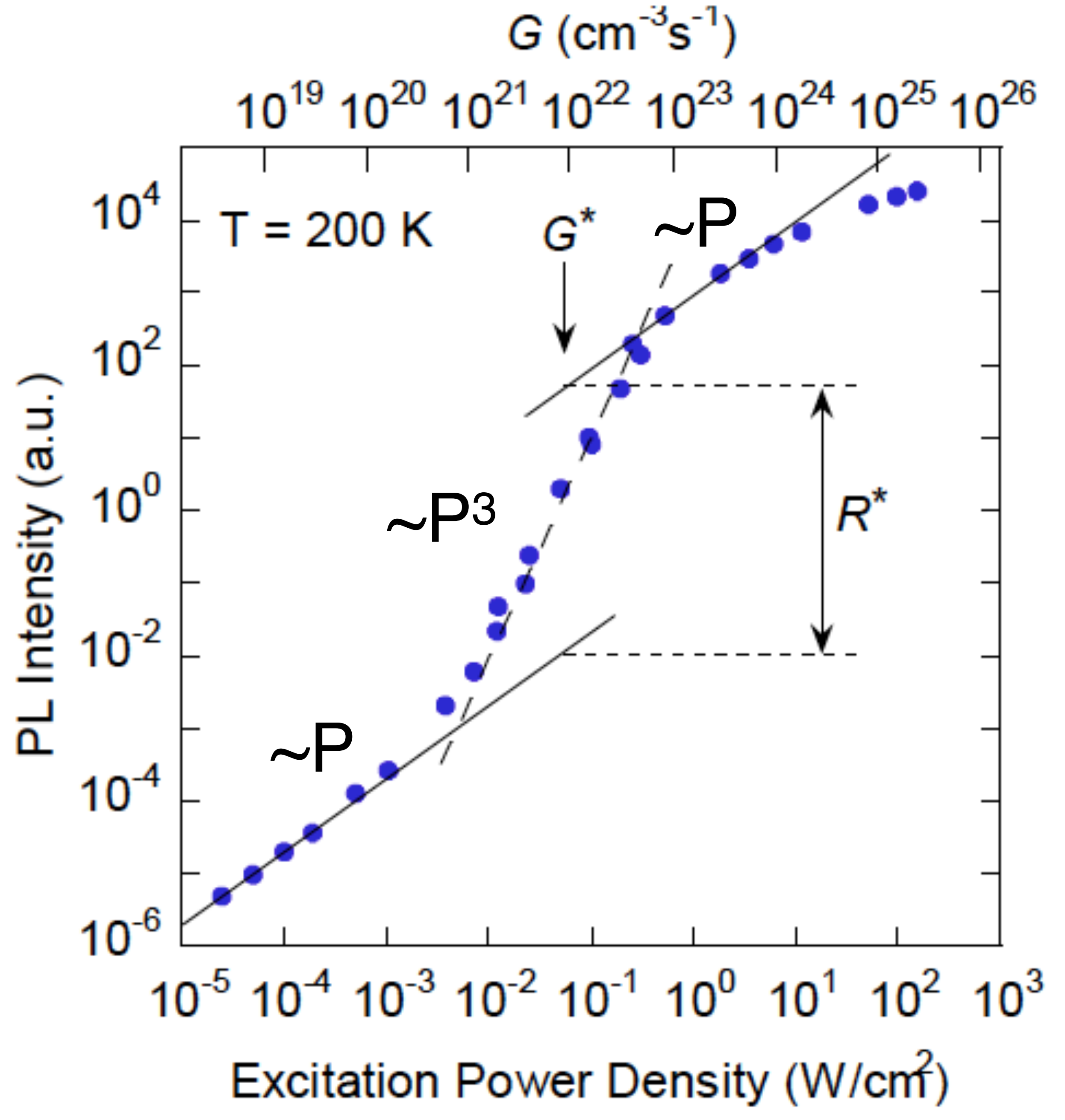
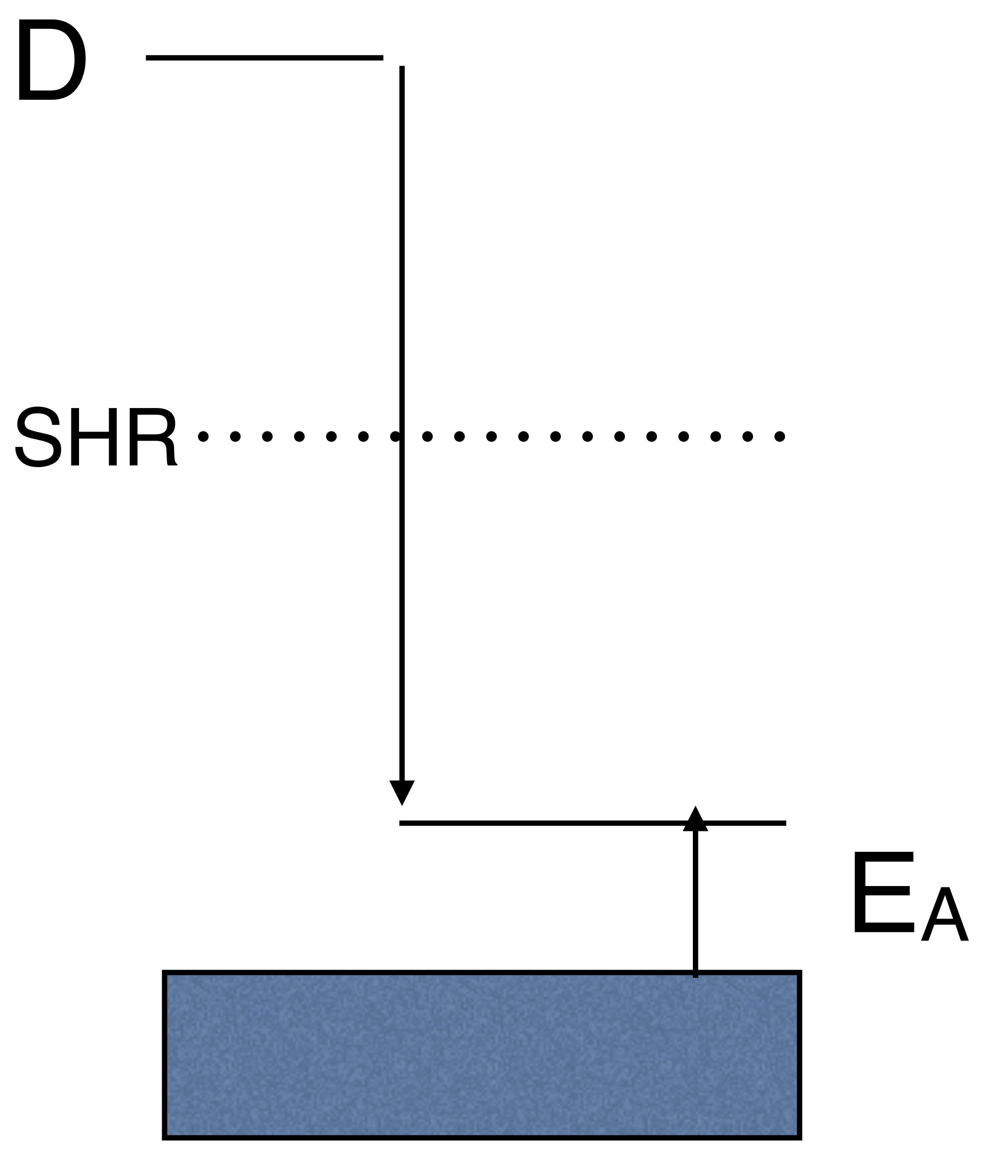


Figure 4 Dependence of the BL band intensity on the excitation intensity at T = 200 K.

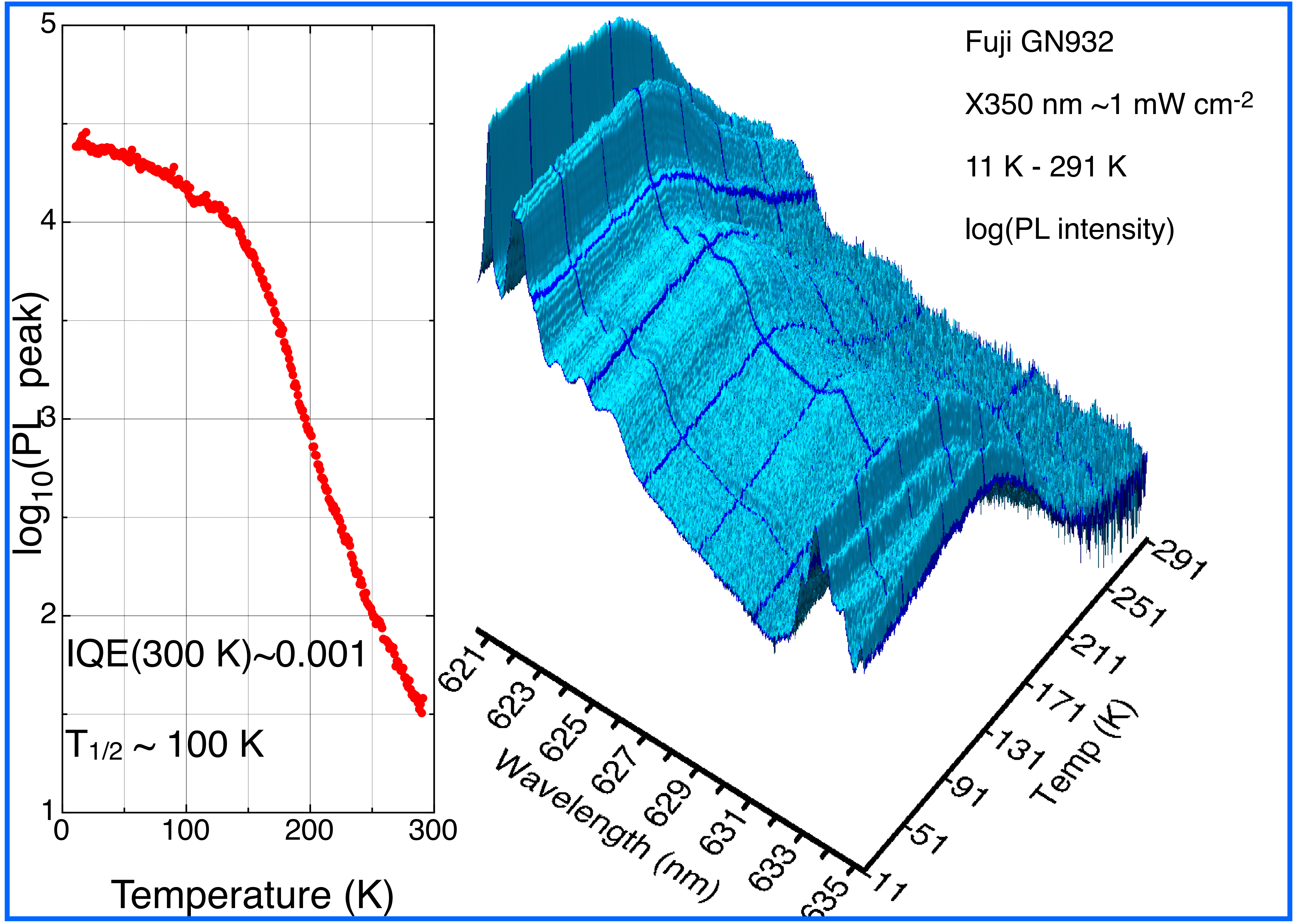


GaN:Zn (deep acceptor) with shallow donor and *Shockley-Hall-Reed* e-h recombination centre.

Phys. Status Solidi C 10, No. 3, 515–518 (2013)

Add a deep defect…Reshchikov model

Temp-dependence and power-dependence



IQE(300 K)~0.001

$T_{1/2}$ ~ 100 K

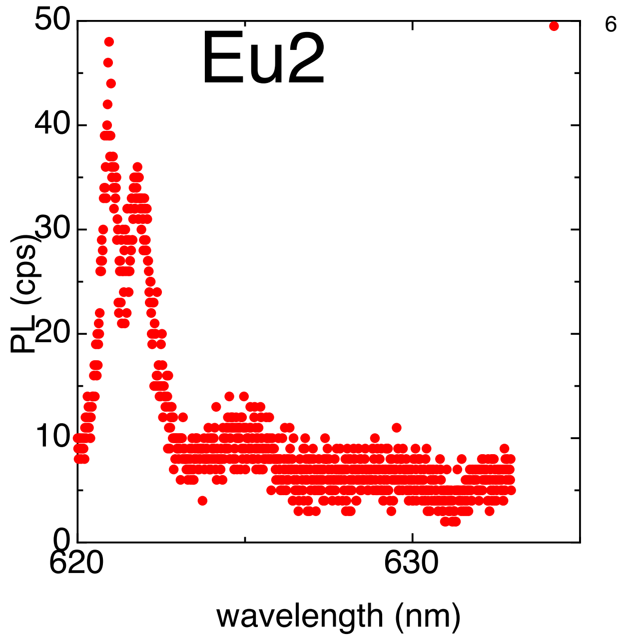
Fuji GN932

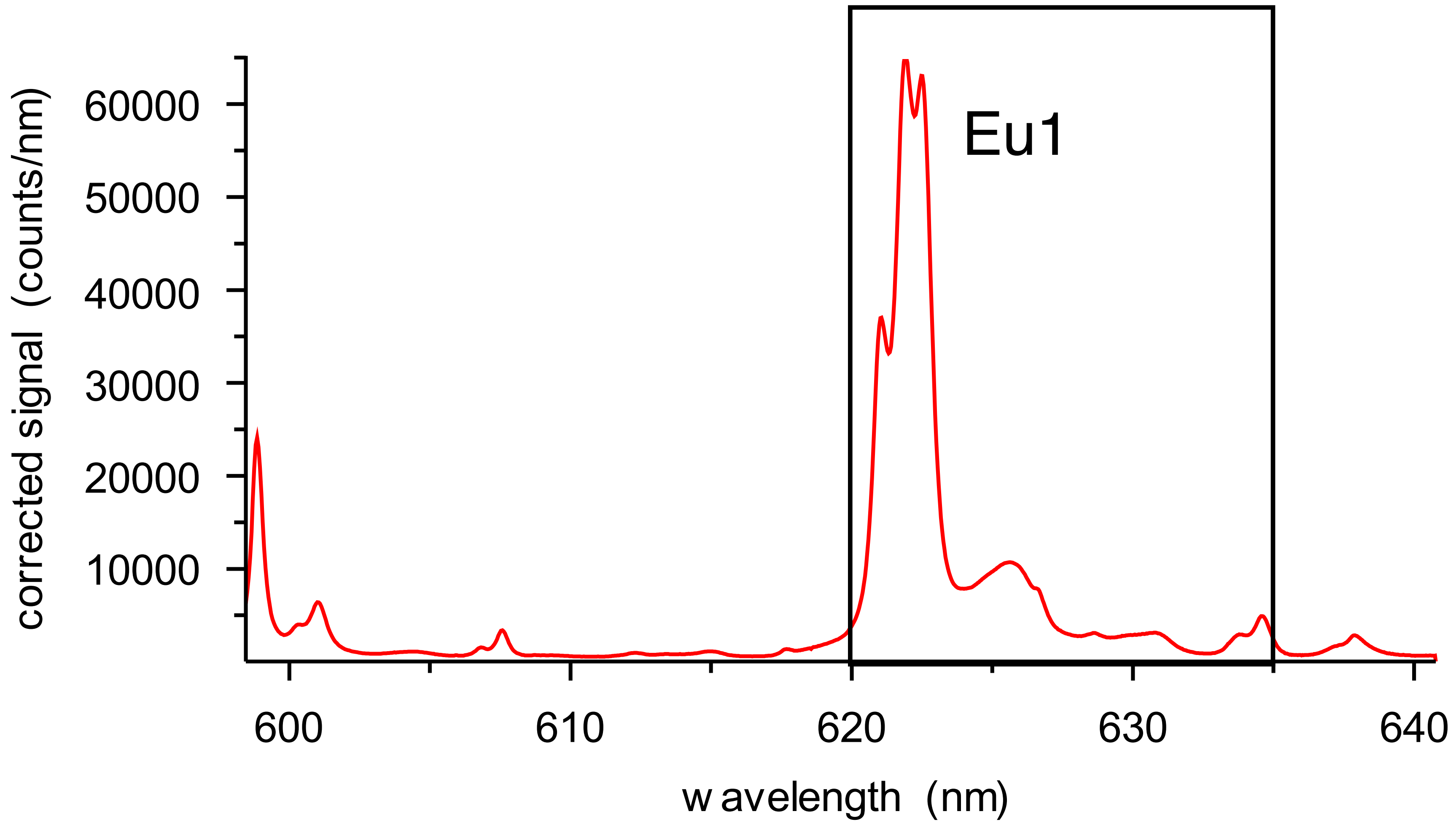
X350 nm ~1 mW cm^{-2}

11 K - 291 K

log(PL intensity)

Low power photoexcitation- room temp. spectrum





High power cathodoexcitation- room temp. spectrum fig2data

P.N. Favennec et al. (1989)

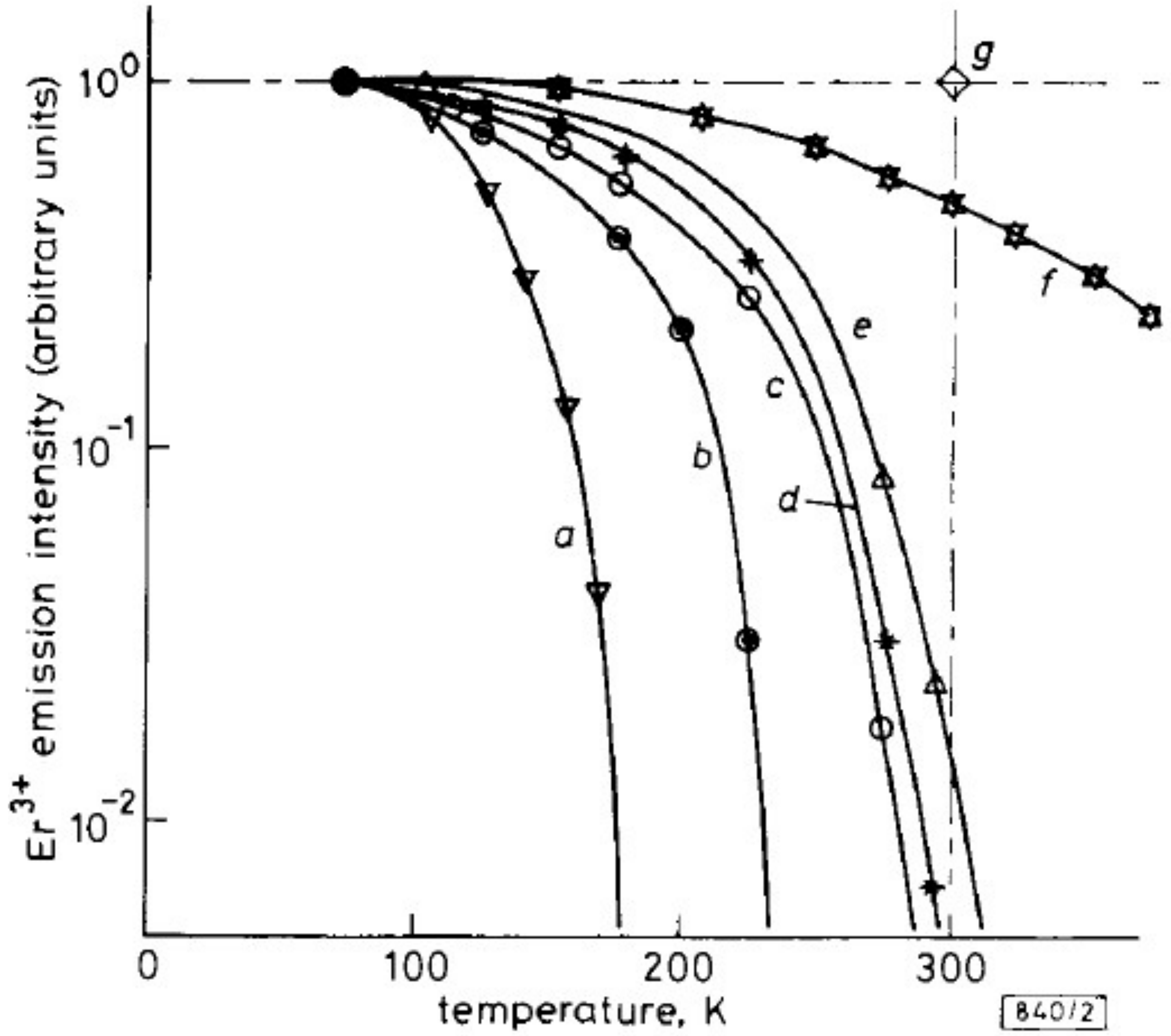
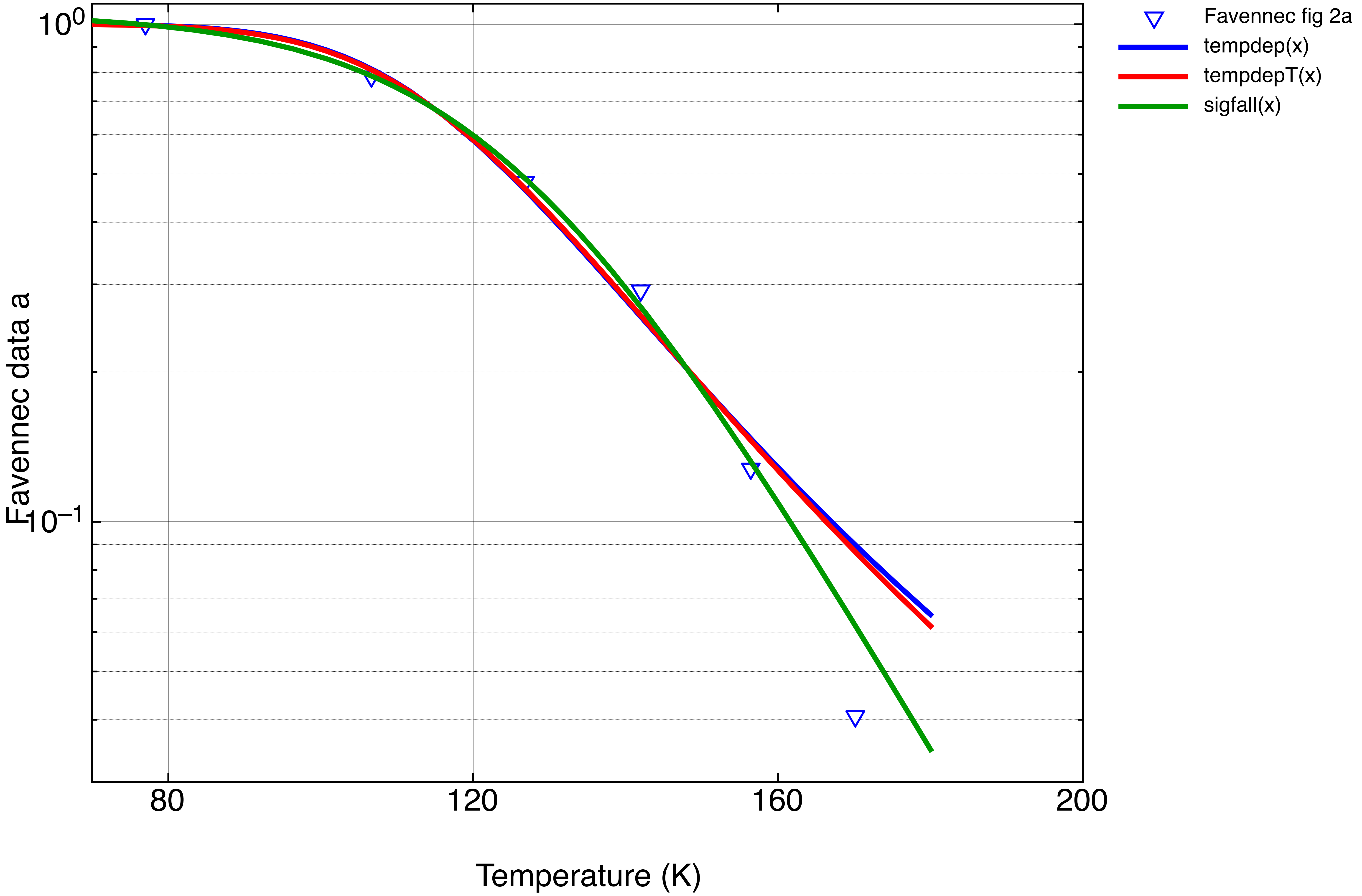


Fig. 2 *Er^{3+} emission intensity against host semiconductor temperature*

Materials are implanted with Er ions: $E = 330$ keV, $\phi = 10^{13}$ Er^+ cm^{-2}. E_G values are given at room temperature

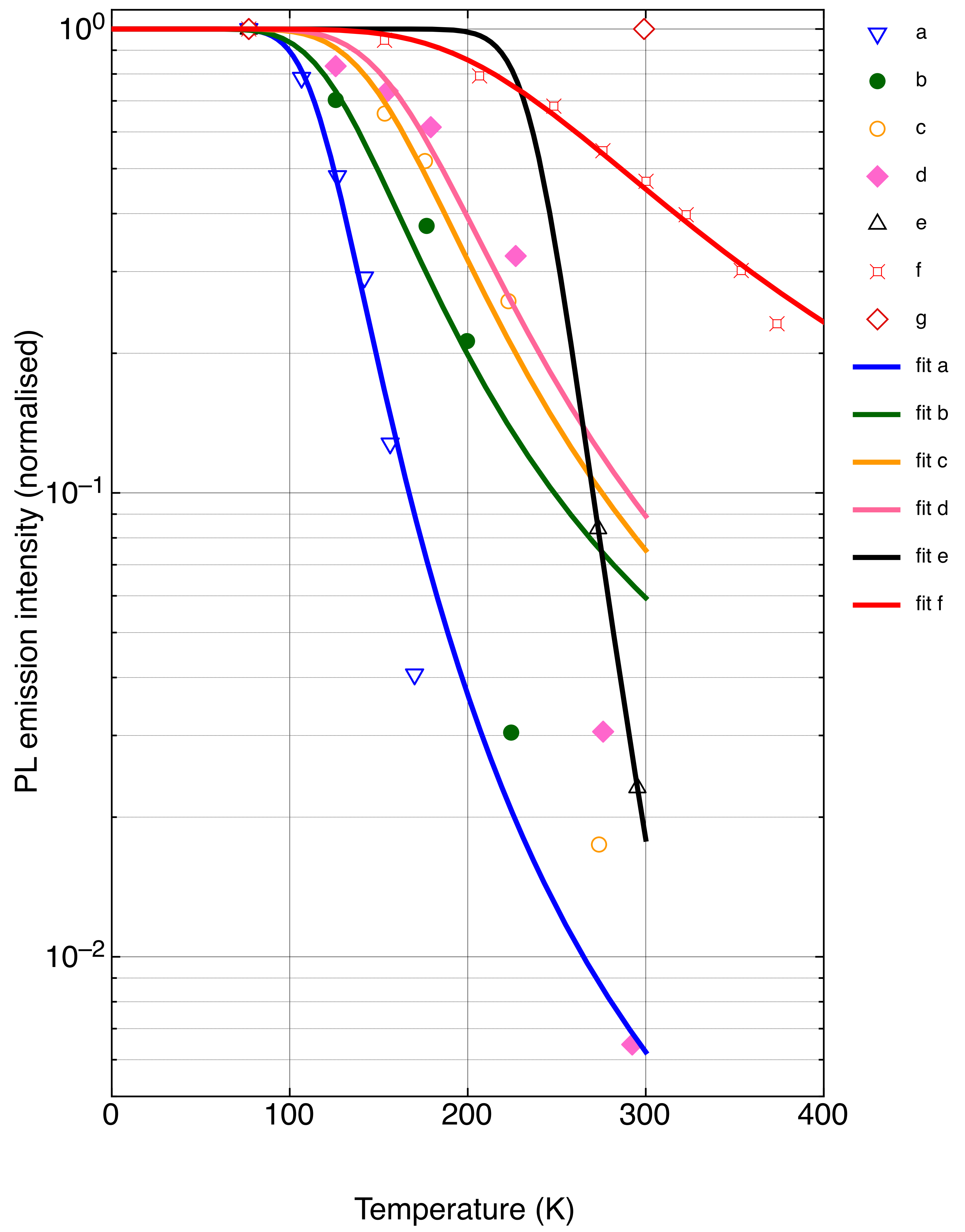
a $Ga_{0.38}In_{0.62}As_{0.84}P_{0.12}$ ($E_G = 0{\cdot}807$ eV)
b Si ($E_G = 1{\cdot}12$ eV)
c InP ($E_G = 1{\cdot}27$ eV)
d GaAs ($E_G = 1{\cdot}43$ eV)
e $Al_{0.17}Ga_{0.83}As$ ($E_G = 1{\cdot}67$ eV)
f ZnTe ($E_G = 2{\cdot}26$ eV)
g CdS ($E_G = 2{\cdot}42$ eV)

ECTRONICS LETTERS 25th May 1989 Vol. 25 No. 11



Favennec, 25 years on

After Favennec et al (1989)



sample	semic. gap	G	Ta (K)	T1/2 (K)
a	GaInAsP 0.807 eV	5900	1100	130
b	Si 1.12 eV	240	820	150
c	InP 1.27 eV	400	1050	175
d	GaAs 1.43 eV	440	1130	190
e	AlGaAs 1.67 eV	7.50E+08	4900	240
f	ZnTe 2.26 eV	65	1190	285
g	CdS 2.42 eV	-	-	

LUMINESCENCE OF ERBIUM IMPLANTED IN VARIOUS SEMICONDUCTORS: IV, III-V AND II-VI MATERIALS

11th April 1989

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Y. LE GUILLOU
CNETILABIOCM
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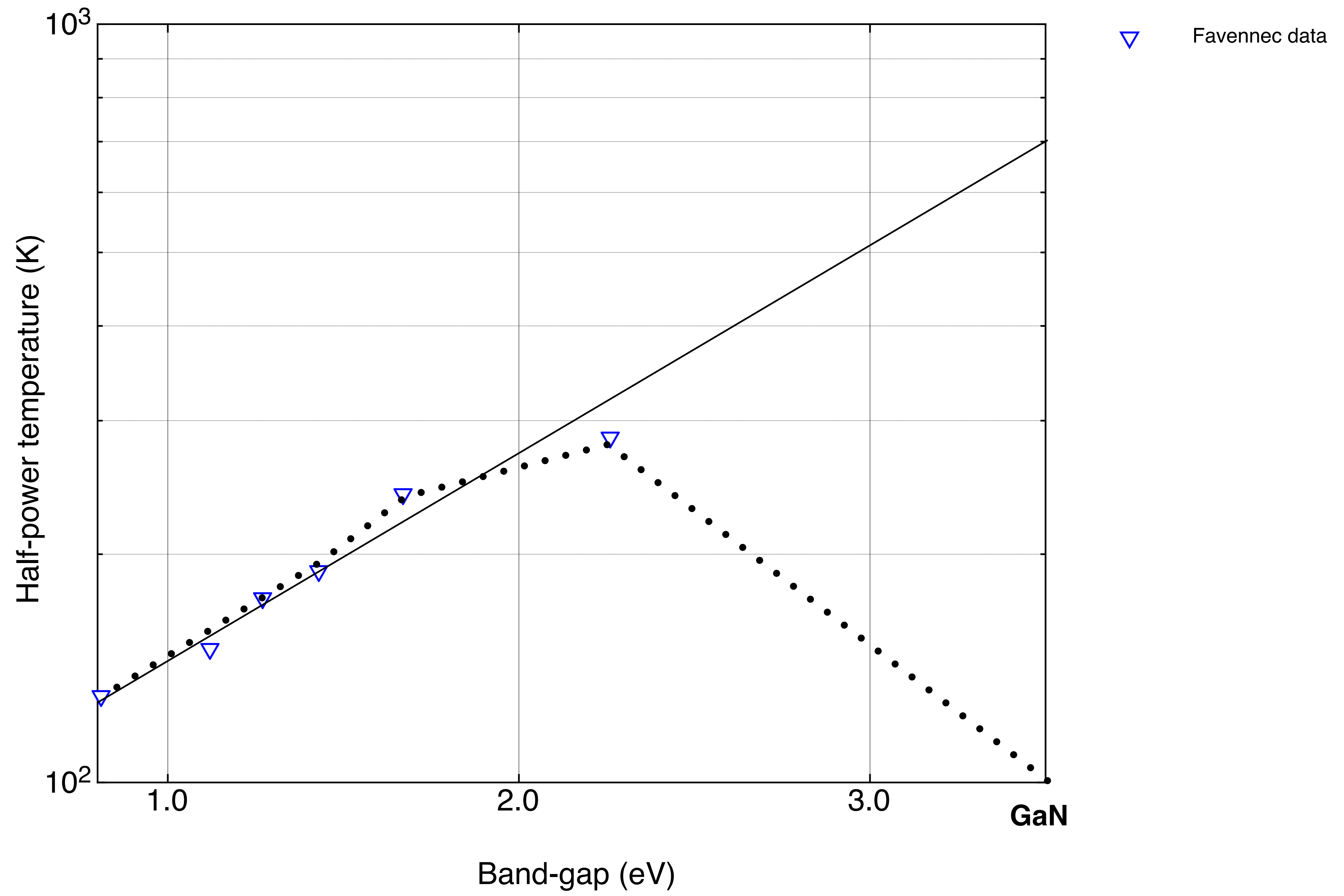
22301 Lurinion Cedex. France

calc T1/2 vs bandgap



Favennec, 25 years on

Summary and conclusions

- **The temperature dependence of luminescence from semiconductors is well described by the conventional R-NR model, unless it isn't.**

- **A parameter that can be extracted from the data is E_A, the activation/localisation/binding energy (delete as appropriate).**

- **More useful in a practical sense is the IQE (RT), but you may prefer to quote the half-power temperature $T_{1/2}$.**

- **In terms of the fitting parameters for the modified Arrhenius fit, $T_{1/2} = \dfrac{E_A}{k_B \ln G}$; for the sigmoidal fit $T_{1/2} = T_{1/2}$. (The derivation of an expression for $T_{1/2}$ in the conventional R-NR model is left as an exercise for ~~Phil Dawson~~ students.)**

- **In Reschikov's work, a slight modification of the simple temperature-dependence model produces wonderful complications.**

- **A reanalysis of Favennec's data 25 years on teaches us that extrapolation is dangerous.**