For when we get there…
detectors @ 5-50 eV*

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**Electron Recoil scale*

Motivation

	CDMSlite	DAMIC
Noise	3.3 e / 10 eV	1.8 e / 7 eV
Thresh.	> 60 eV (~80 eV)	> 20 eV (~40 eV)

Leading experiments demonstrate potential for operation < 50 eV

Practically other (non-physics) issues result in higher thresholds

At < 5 eV statistics limits science

e.g: in Si, for 5 eV, $N_{electrons} = 1.32 \pm 0.39$

Thus 5-50 eV is the next energy range for us

Questions

These experiments measure ionization,
produced in semiconductors from particle recoils

From $N_{electrons}$ we *infer* the physics behind the recoil

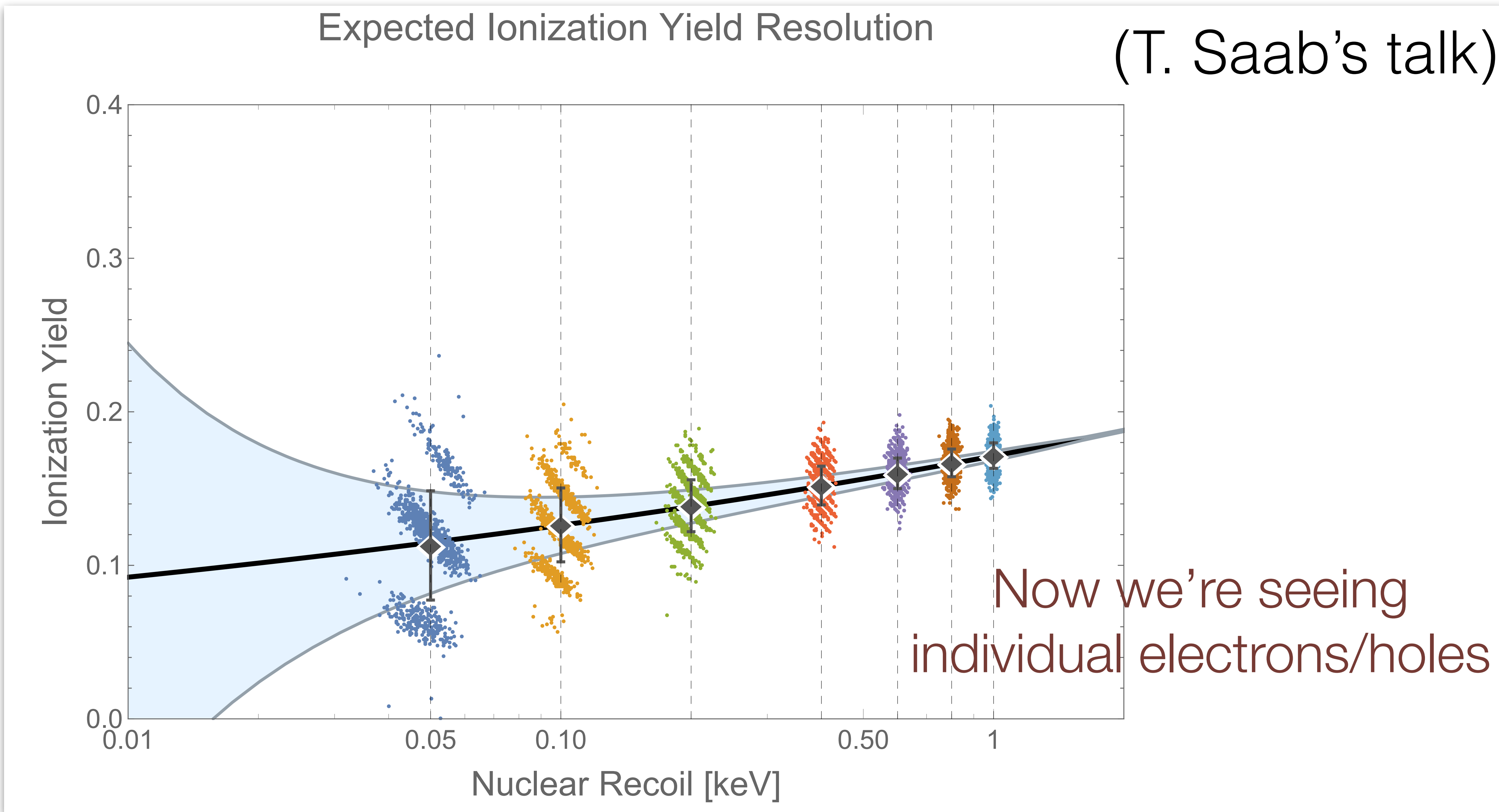
How well do we understand:

- $N_{electrons}$ (Energy input) ?
- $N_{electrons}$ (Temperature, electric field etc.) ?
- $N_{electrons}$ (Incoming particle type) ?

How well do we infer our results ?

Caveat

If CDMSlite++ is successful in “counting” electron hole pairs, this talk might be moot



Rubric

D. Mei (first talk) introduced standard rule-of-thumb expressions for ionization in semiconductors.

We keep P. Sorenson's physics picture in mind ….

This talk will "analyze" the fundamentals behind,

$$\epsilon = (14/5)\, E_G + r(\hbar\omega_R),$$

C. Klein, Raytheon

$$\sigma_i = \sqrt{\frac{E_0}{\varepsilon_i}} \cdot \sqrt{\frac{E_x}{E_i}\left(\frac{\varepsilon_i}{E_i} - 1\right)}$$

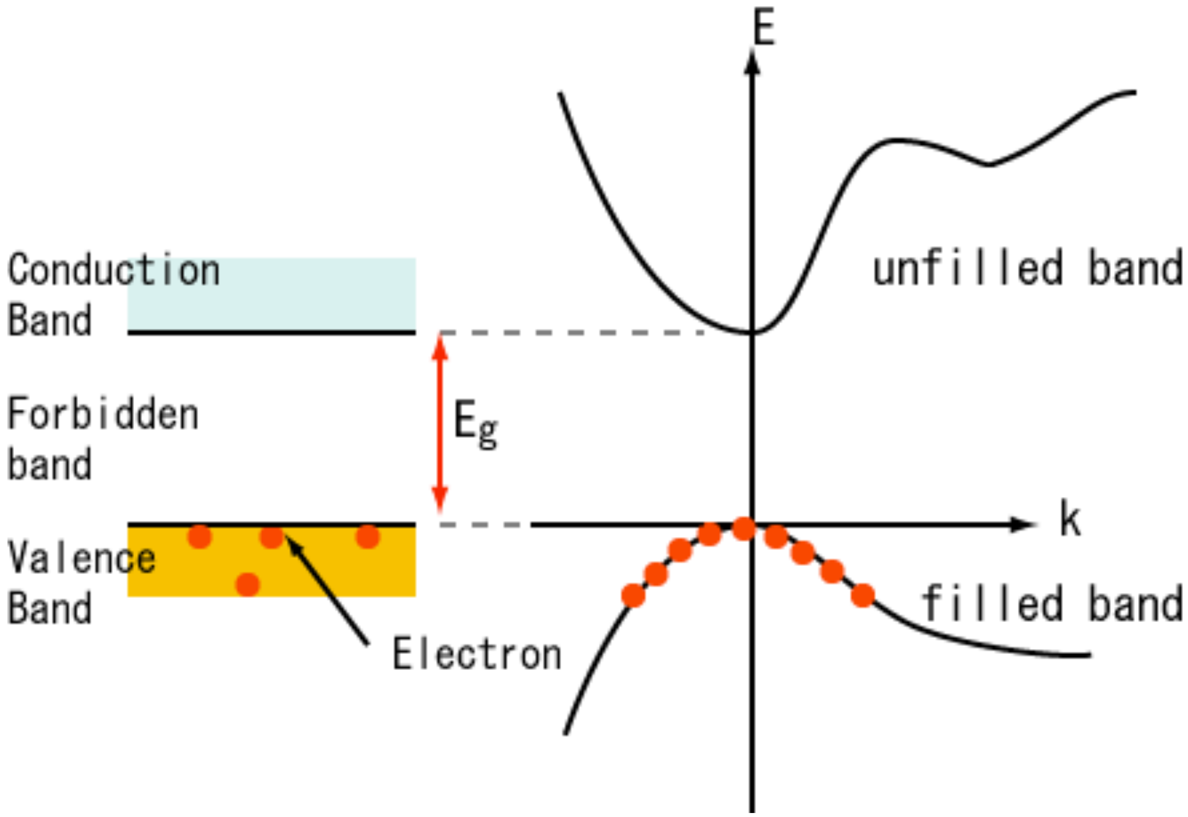
The second factor on the right hand side is called the Fano factor F.

Since σ_i is the variance in signal charge Q and the number of charge pairs is $N_Q = E_0/\varepsilon_i$

$$\sigma_Q = \sqrt{F N_Q}$$

H.Spieler, Berkeley

$N_{electrons}$ (Energy input)



N_e excited should depend on band-gap and energy input :

$$N_e \propto E_{in}$$

$$N_e \sim E_g$$

Experiments (circa Schottky, Bardeen, Klein et al.) found offsets, and excitation was thus parametrized as

$$N_e = E_{in}/\epsilon$$

$$\epsilon = a_1 E_g + a_0$$

$N_{electrons}$ (Energy input)

JOURNAL OF APPLIED PHYSICS VOLUME 39, NUMBER 4 MARCH 1968

Bandgap Dependence and Related Features of Radiation Ionization Energies in Semiconductors*

CLAUDE A. KLEIN

Raytheon Research Division, Waltham, Massachusetts

(Received 23 October 1967)

The problems dealt with concern the production of electron–hole pairs in a semiconductor exposed to high-energy radiation. The goal is to develop a simple phenomenological model capable of describing the present experimental situation from the standpoint of yield, variance, and bandgap dependence. We proceed on the premise that ϵ, the average amount of radiation energy consumed per pair, can be accounted for by a sum of three contributions: the intrinsic bandgap (E_G), optical phonon losses $r(\hbar\omega_R)$, and the residual kinetic energy $(9/5)E_G$. The approach differs from prior treatments in the sense that the residual kinetic energy relates to a threshold for impact ionization taken to be $\frac{3}{2}E_G$ in accordance with indications stemming from studies of avalanching in p–n junctions. This model is subjected to three quantitative tests: (a) Fano-factor variations are found to reflect the relative weight of phonon losses [$\mathcal{K}=r(\hbar\omega_R)/E_G$], but residual energy fluctuations govern the statistical behavior for $\mathcal{K}^2 \lesssim 0.3$. An application to Ge yields good agreement with the best measurements available ($F=0.13\pm0.02$ at 77°K). (b) The bandgap dependence of pair-creation energies conforms to the model [$\epsilon=(14/5)E_G+r(\hbar\omega_R)$] and suggests that optical phonon losses remain essentially constant [$0.5\leq r(\hbar\omega_R)\leq 1.0$ eV]. This would imply that the mean-free-path ratio for pair production and phonon emission ($r=\bar{\lambda}_I/\lambda_R$) is of the order of 10 or 20 for most semiconductors. (c) A detailed assessment of the situation in Si leads to the conclusion that, in this material, $\bar{\lambda}_I$ is approx 400 Å. The figure accords, roughly, with inferences made from the spectral distribution of hot electrons emitted by shallow junctions and thus points to "average" impacts occurring at about 5 eV; by the same token, it substantiates the conception of pairs originating either through plasmon decay or in the final stages of a branching process.

Pivotal paper: Source of all our numbers

$N_{electrons}$ (Energy input)

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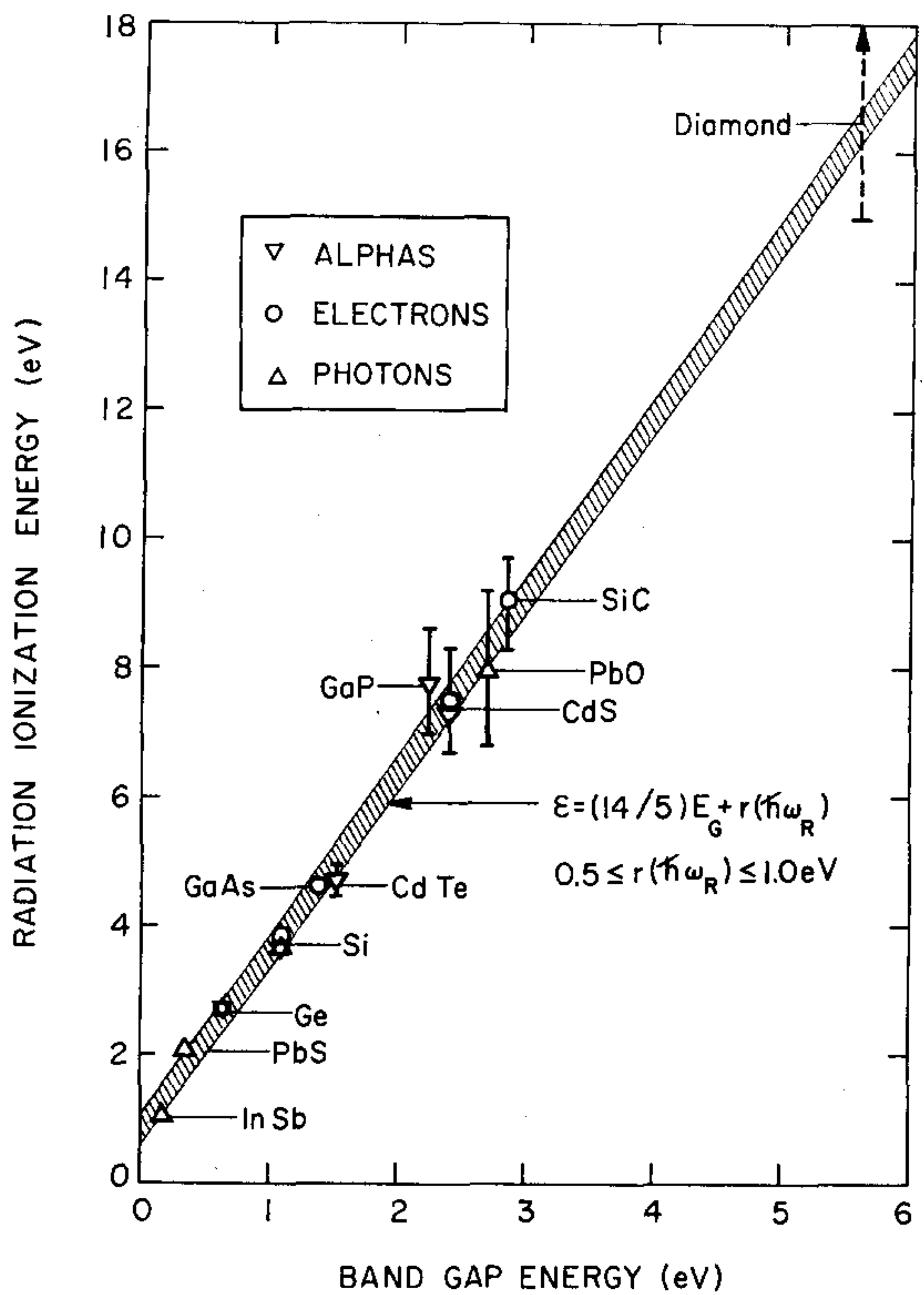
$N_{electrons}$ (Energy input)



In summary, we shall proceed on the premise that the amount of radiation energy consumed per electron–hole pair generated in a semiconductor must be accounted for by a sum of three contributions: the intrinsic bandgap (E_G), optical phonon losses $r(\hbar\omega_R)$, and the residual kinetic energy $(9/5)E_G$. Thus, we take it that ϵ can be related to bandgap and Raman-phonon energies simply by writing

$$\epsilon = (14/5)E_G + r(\hbar\omega_R), \quad (9)$$

where r is to be treated as an adjustable parameter.[24]

N$_{\text{electrons}}$ (Energy input), *theory review*

$$\epsilon = E_G + \langle E_R \rangle + \langle E_K \rangle$$

Gap + optical phonons + thermalization

$N_{electrons}$ (Energy input), *theory review*

$$\epsilon = E_G + \langle E_R \rangle + \langle E_K \rangle$$

Gap + optical phonons + thermalization

$\langle E_R \rangle = r(\hbar\omega_R)$, optical phonons approximated as const. Raman scale

An assumption introduced by Shockley and used for quick calculations, totally works at high energies.

$N_{electrons}$ (Energy input), *theory review*

$$\epsilon = E_G + \langle E_R \rangle + \langle E_K \rangle$$

Gap + optical phonons + thermalization

$$\langle E_K \rangle = 2\mathcal{L} E_I = 3\mathcal{L} E_G$$

"$\mathcal{L}$ … depends on the shape of the charge-carrier spectrum … This shape is difficult if not impossible to predict, …. assume…uniformly distribute in momentum space… simple two-band configuration"

$N_{electrons}$ (Energy input), *practical issues*

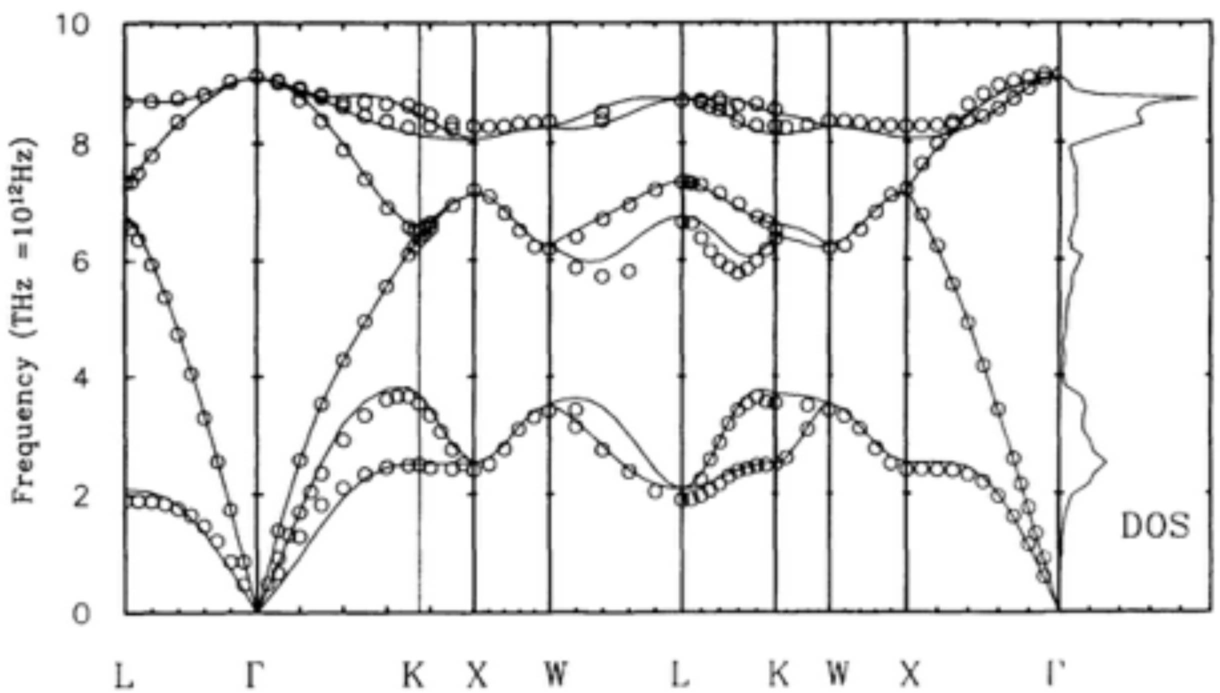
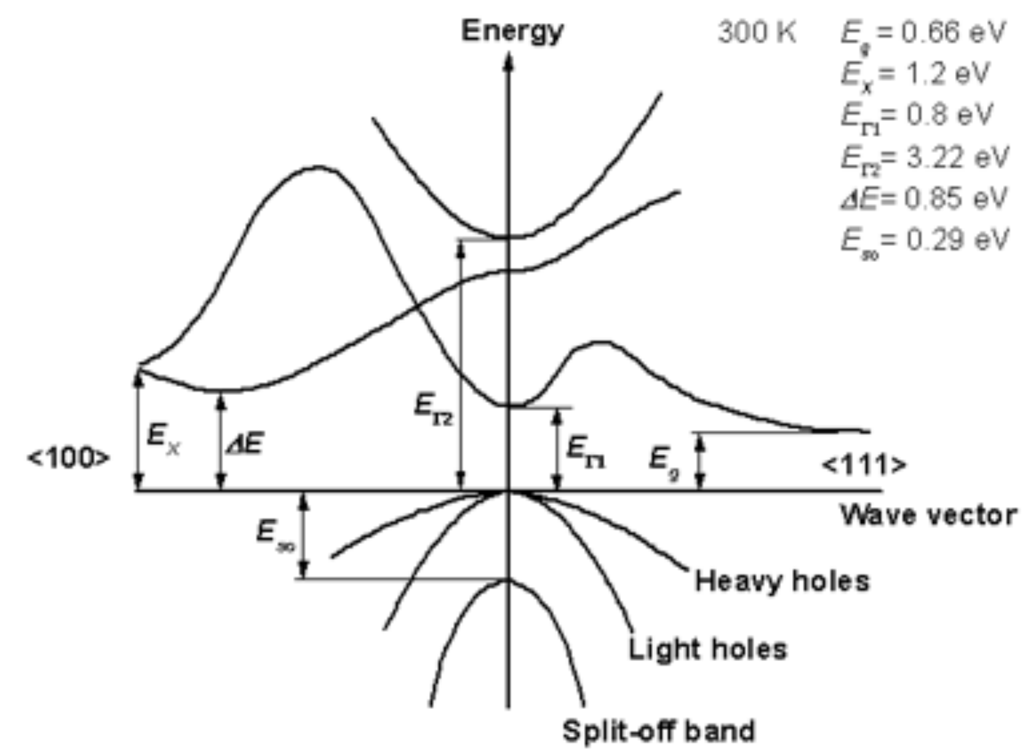


FIG. 5. Phonon dispersion and density of state for Ge.



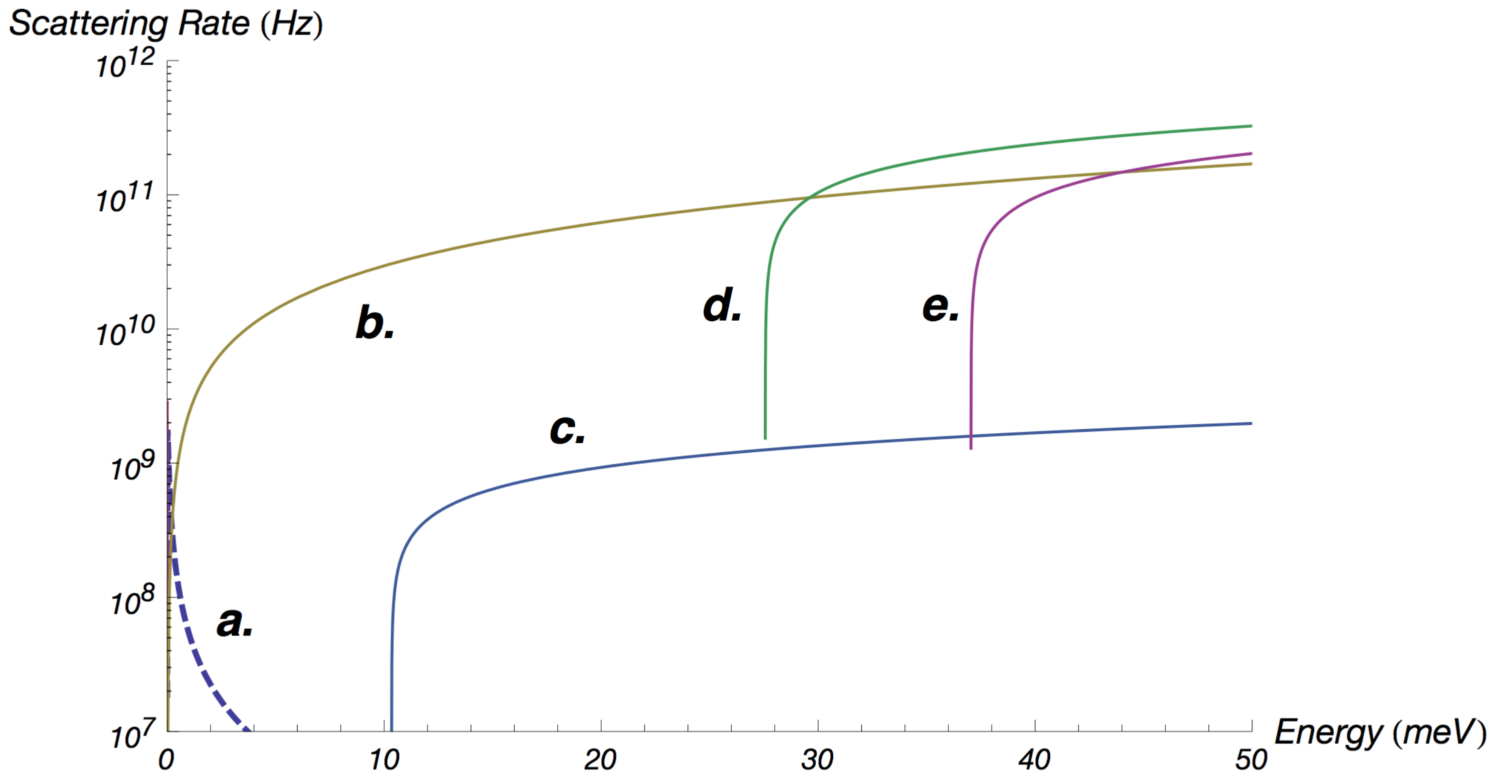
Phonon branches and electronic bands in Ge

ω vs k rep.

$N_{electrons}$ (Energy input), *practical issues*

Phonon spectrum is far richer than *one* Raman band.

At low ~eV energies, other (acoustic, inter-valley etc.) phonon contributions matter. Furthermore, rates "turn-on" w/ energy



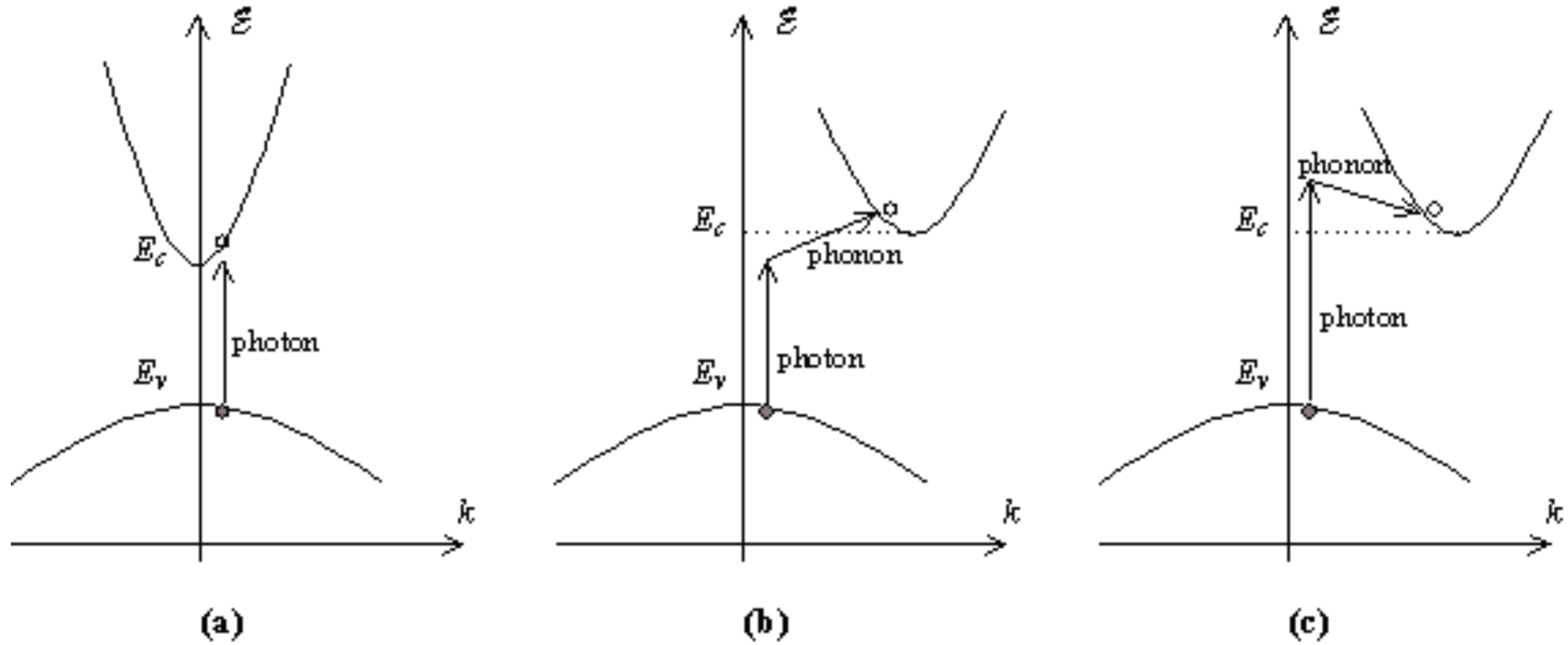
Kyle Sundqvist's thesis

Figure 2.15: Total scattering rates used for ELECTRONS at $T = 40\ mK$, calculated under isotropic approximations. **a.** Conwell-Weisskopf ionized impurity scattering rate at $N_I = 10^{10}\ cm^{-3}$ **b.** acoustic phonon emission **c.** slow-transverse intervalley phonon emission **d.** intervalley phonon emission **e.** optical phonon emission

$N_{electrons}$ (Energy input), *practical issues*

Thermalization is actually complicated: e/h spectrum is not two II bands

Multiple electron-phonon excitations between multiple quantum states, with transition probabilities that change with energy and "temperature"

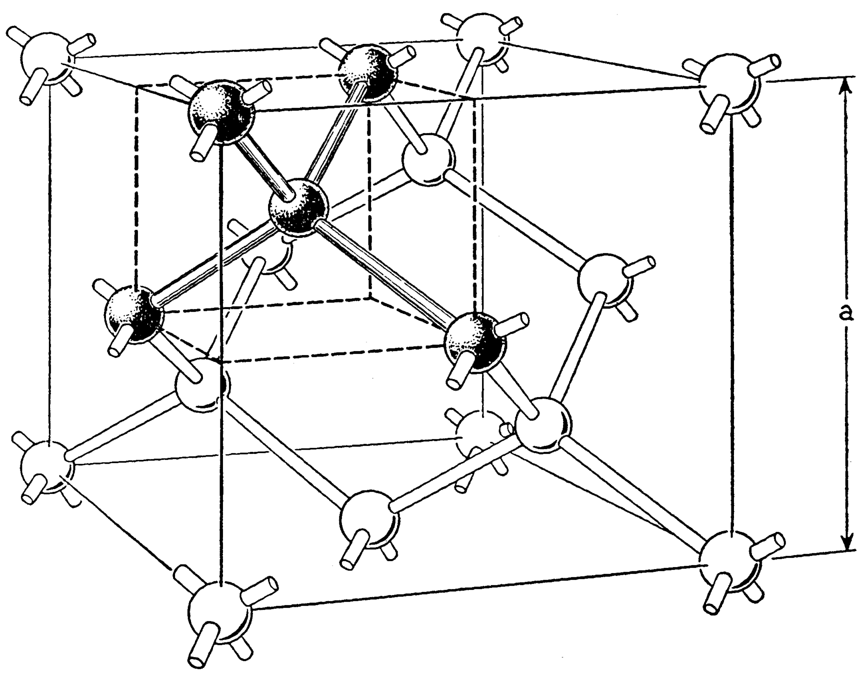


Interlude

How do we compute bands ?

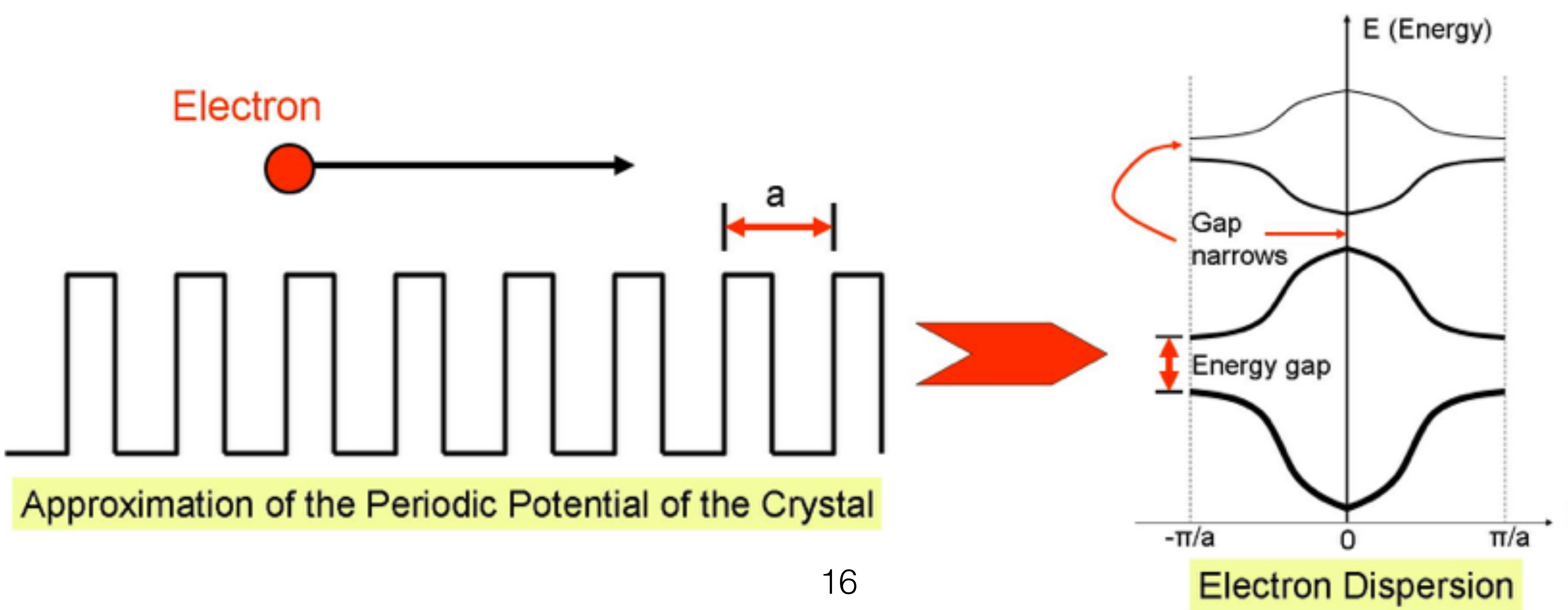
Semiconductor Crystals

Lattice structure of diamond, Si, Ge ("diamond lattice")



(from Schockley)

Fixed lattice, Bloch wave functions



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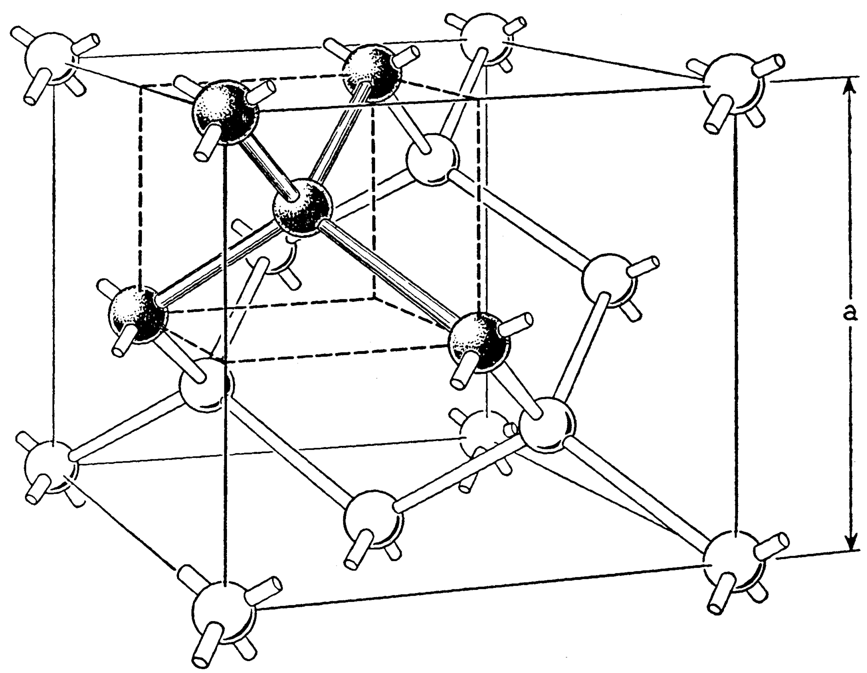

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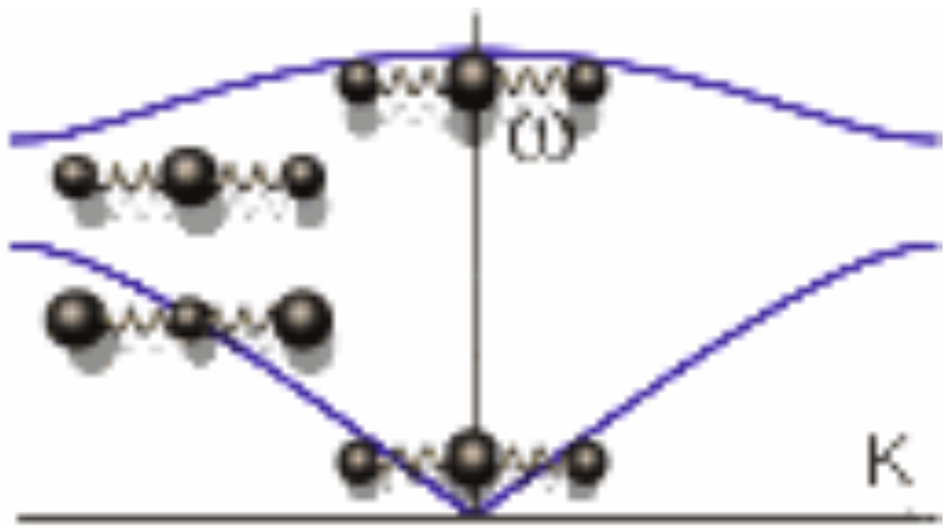


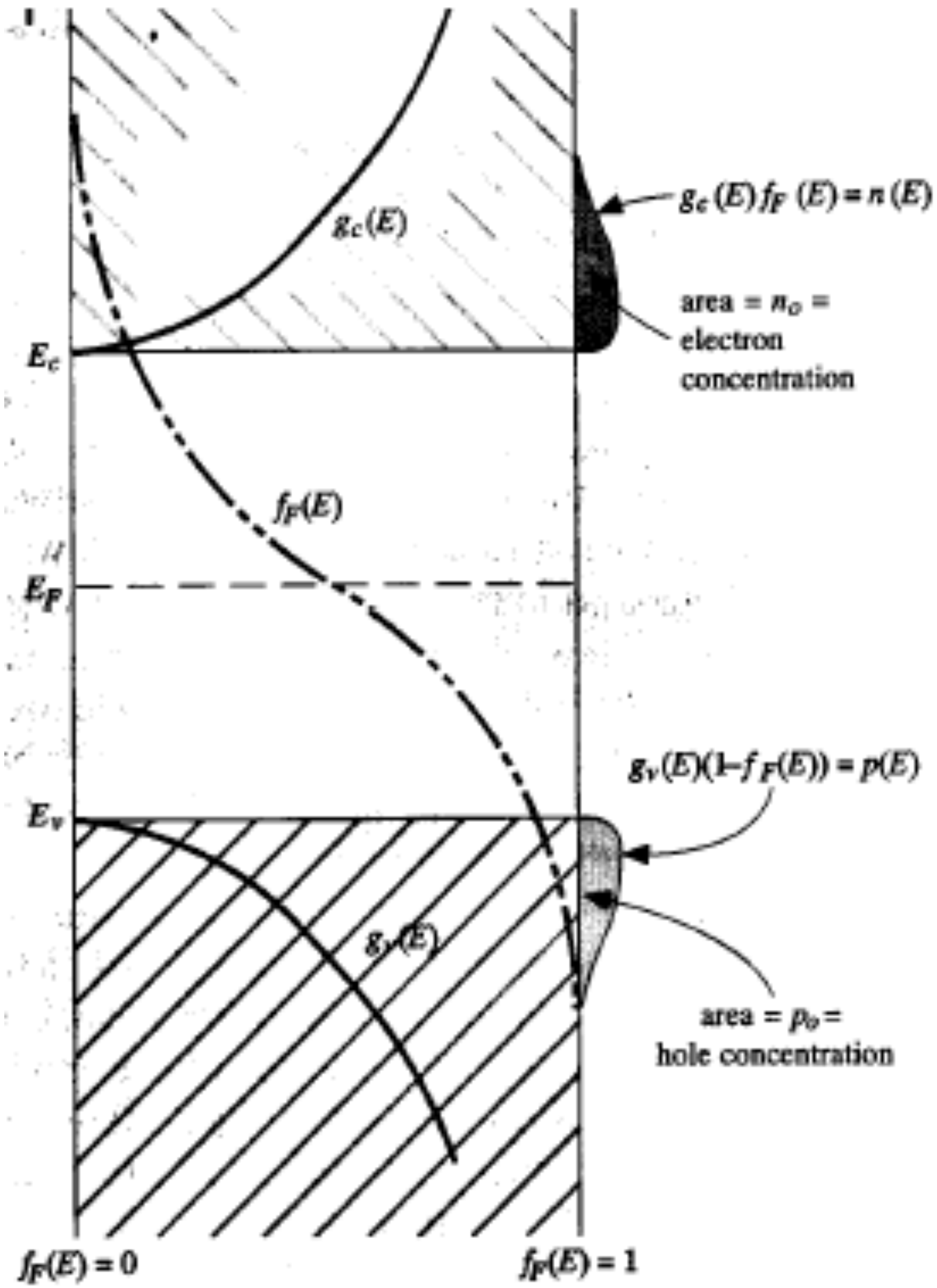
Eigen-modes, perturbations around a fixed lattice

Hamiltonian (total energy) $H = T + V$ for the system into the sum of the energies of the normal modes of oscillations:

$$H = \sum_{\kappa=1}^{3N} \frac{1}{2}(P_\kappa^2 + \omega_\kappa^2 Q_\kappa^2), \tag{2.8}$$

where $\{Q_\kappa, P_\kappa\}$ are the normal coordinates and momenta, and $\{\omega_\kappa\}$ are normal-mode frequencies. Note that there are exactly $3N$ normal modes.

Interlude



How do we compute Electrons (VB/ CB)?

$$n(E) = \frac{g(E)}{\exp\left(\frac{E-\mu}{kT}\right) + 1}$$

viz. what's the temperature ?

Interlude

During the initial high energy cascades,
there is no “fixed” lattice, or “small” perturbations.

Dislocations and large amplitude nuclear motion, imply
very high local temperatures & nonlinear potentials

We do not have a solid any more !!

Non-equilibrium stat. mech. can’t integrate away !!

Interlude

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there is no “fixed” lattice, or “small” perturbations.

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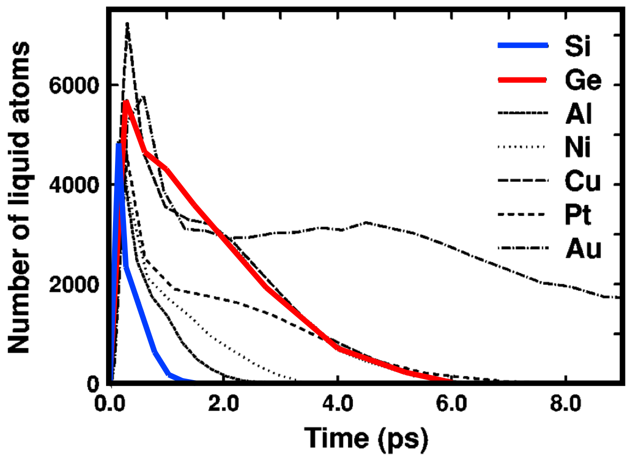
We do not have a solid any more !!

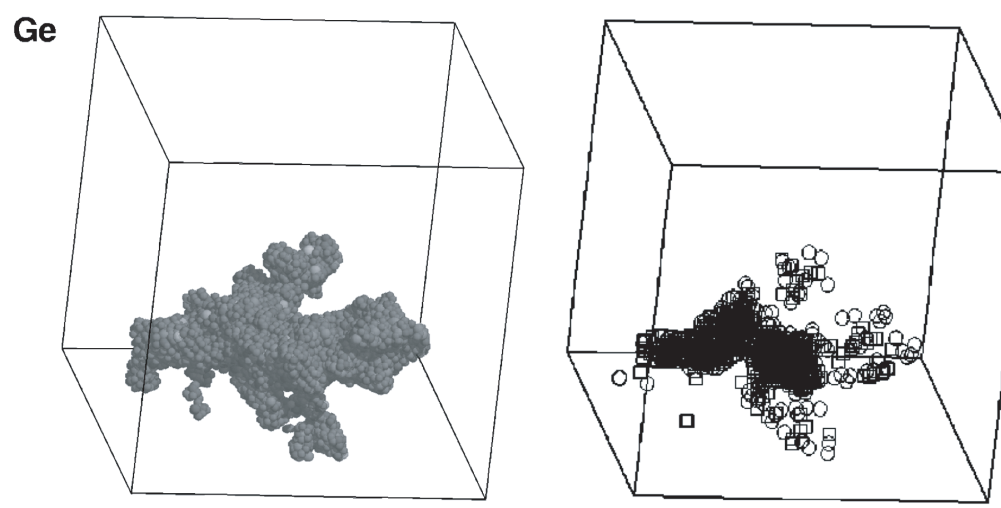
Non-equilibrium stat. mech. can’t integrate away !!

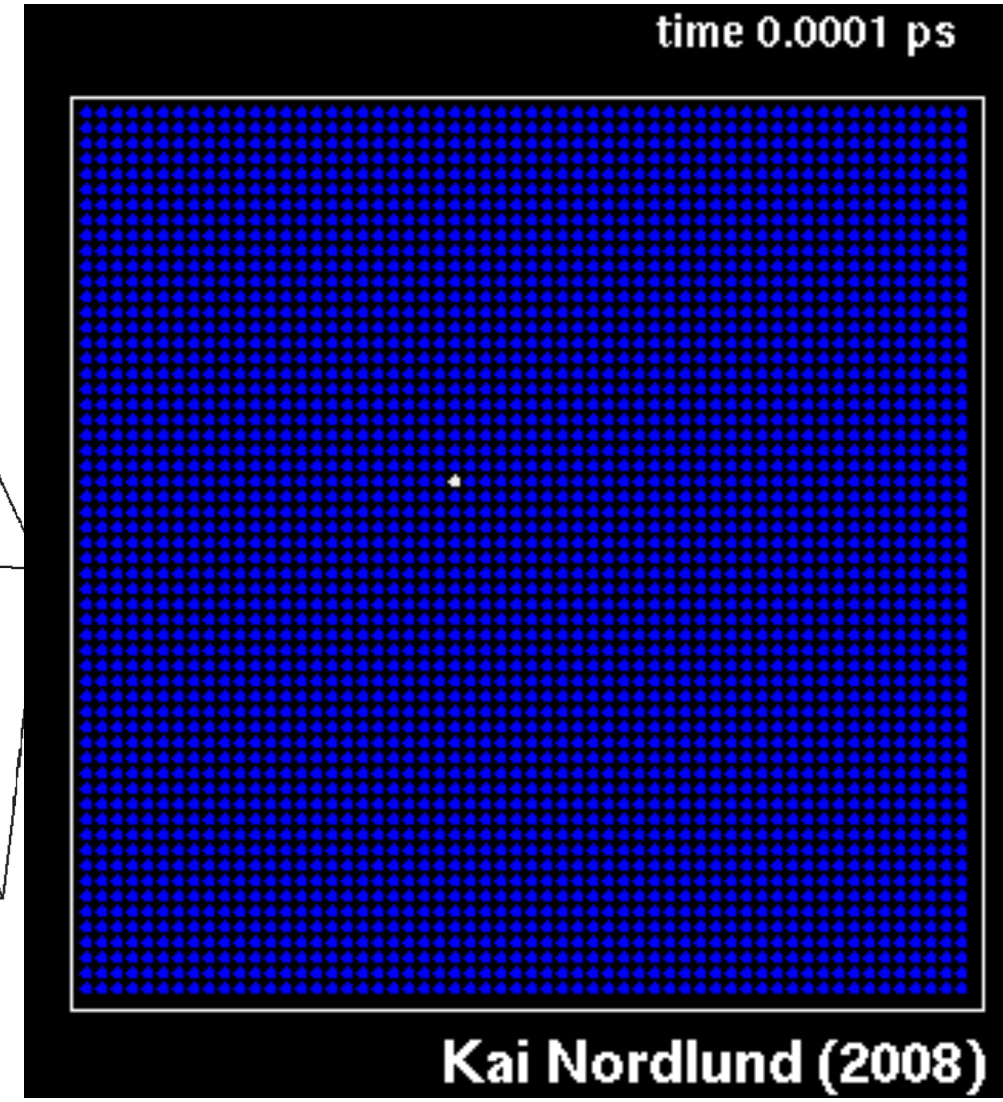
“… that’s good, equilibrium thermodynamics is the only thermodynamics I know.” — E.Dahl, earlier today

→ *thus, we are not-good ?*

Interlude

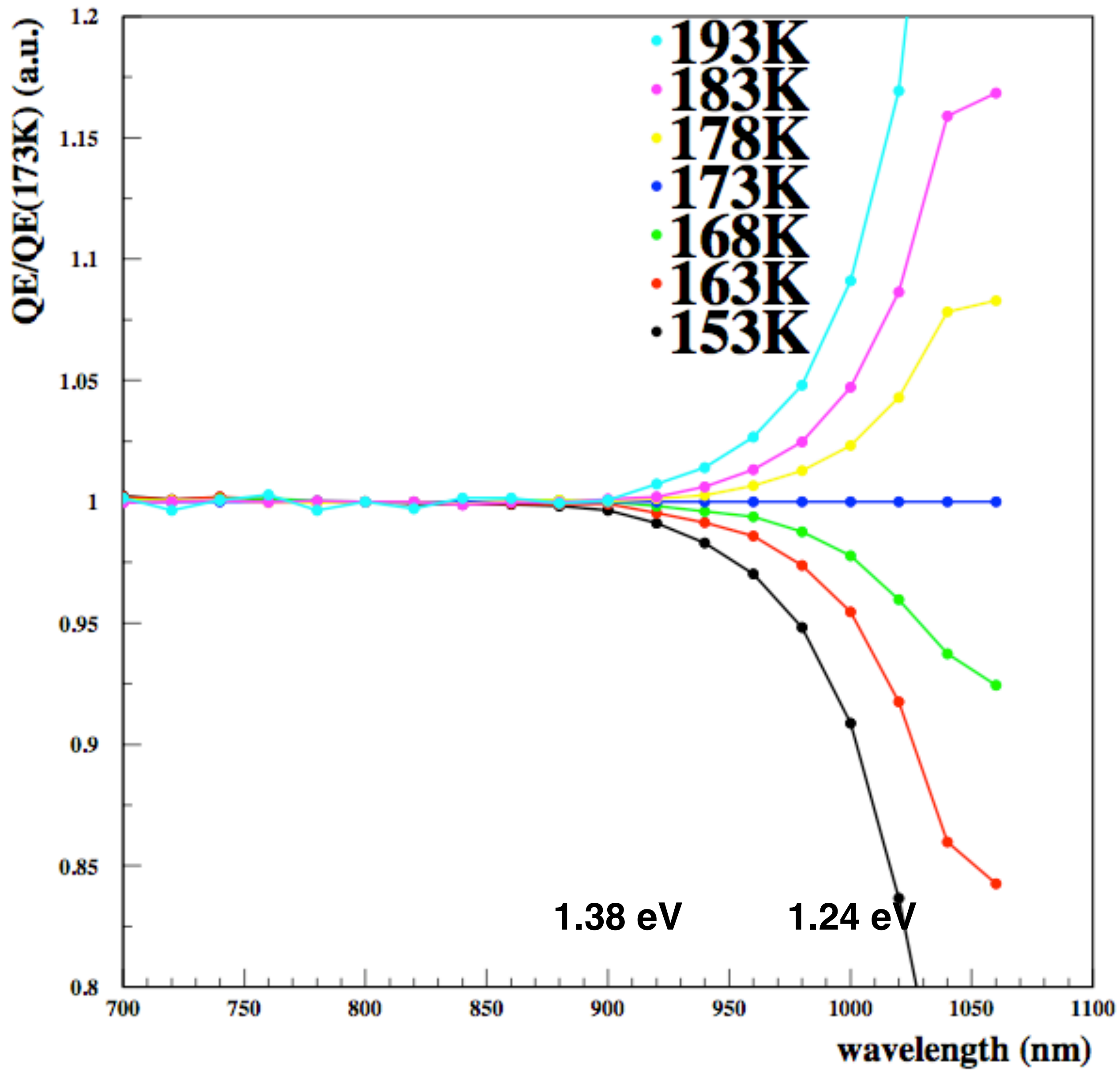






Yet it might also be possible that a general theory could not be found for non-equilibrium, like Goldenfeld and Kadanoff's opinion, "there no general laws for complexity…Maybe physics studies will become more like human experience".

$N_{electrons}$ (Energy input & temperature)



Focal Plane Detectors for Dark Energy Camera (DECam)

J. Estrada[1], R. Alvarez[2], T. Abbott [2], J. Annis[1], M. Bonati[2], E. Buckley-Geer[1], J. Campa[3], H. Cease[1], S. Chappa[1], D. Depoy[4], G. Derylo[1], H. T. Diehl[1], B. Flaugher[1], J. Hao[1], S. Holland[5],

This matters (a lot / little ?)

Ionization efficiency clearly changes with *base temperature*

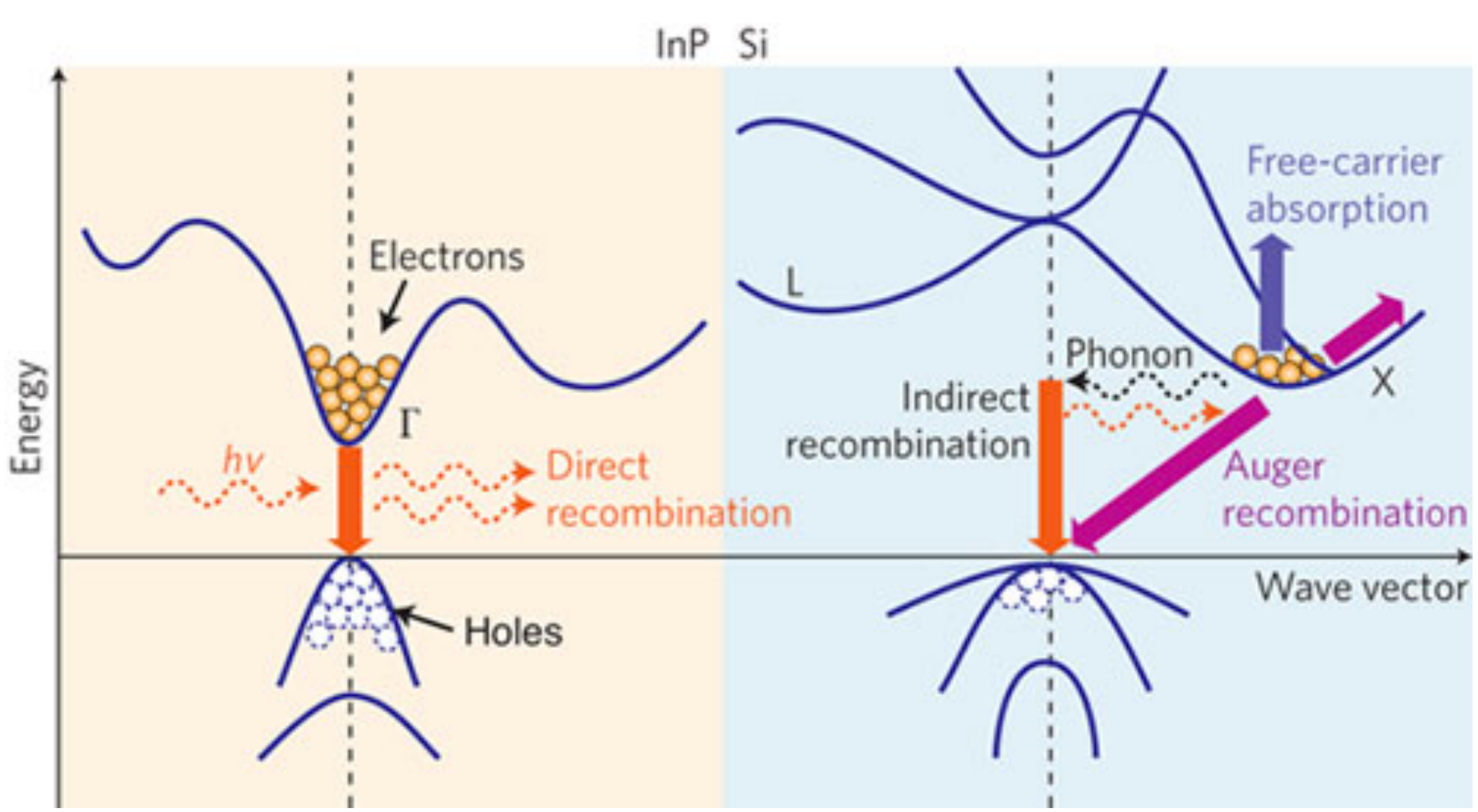
thermally assisted e/h production is often used, but not characterized at low energies

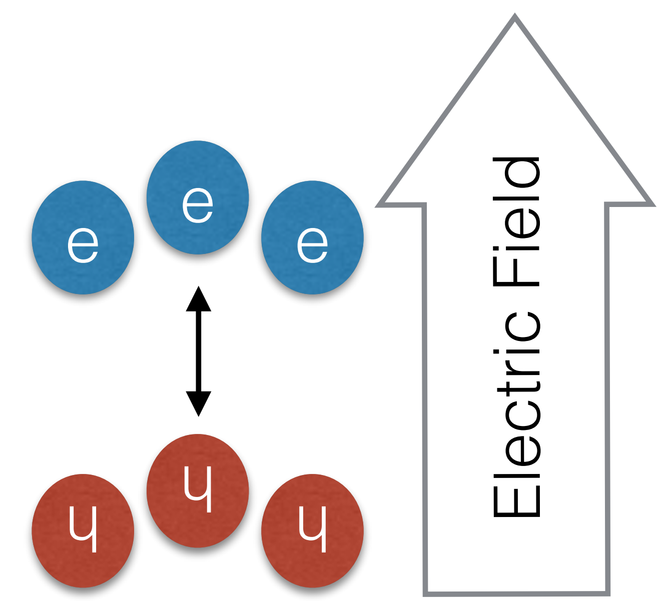
$N_{electrons}$ (Energy input & temp. & electric field)

Temperature statistically increases probability of V -> C

Increased electric field can assist by fighting recombination

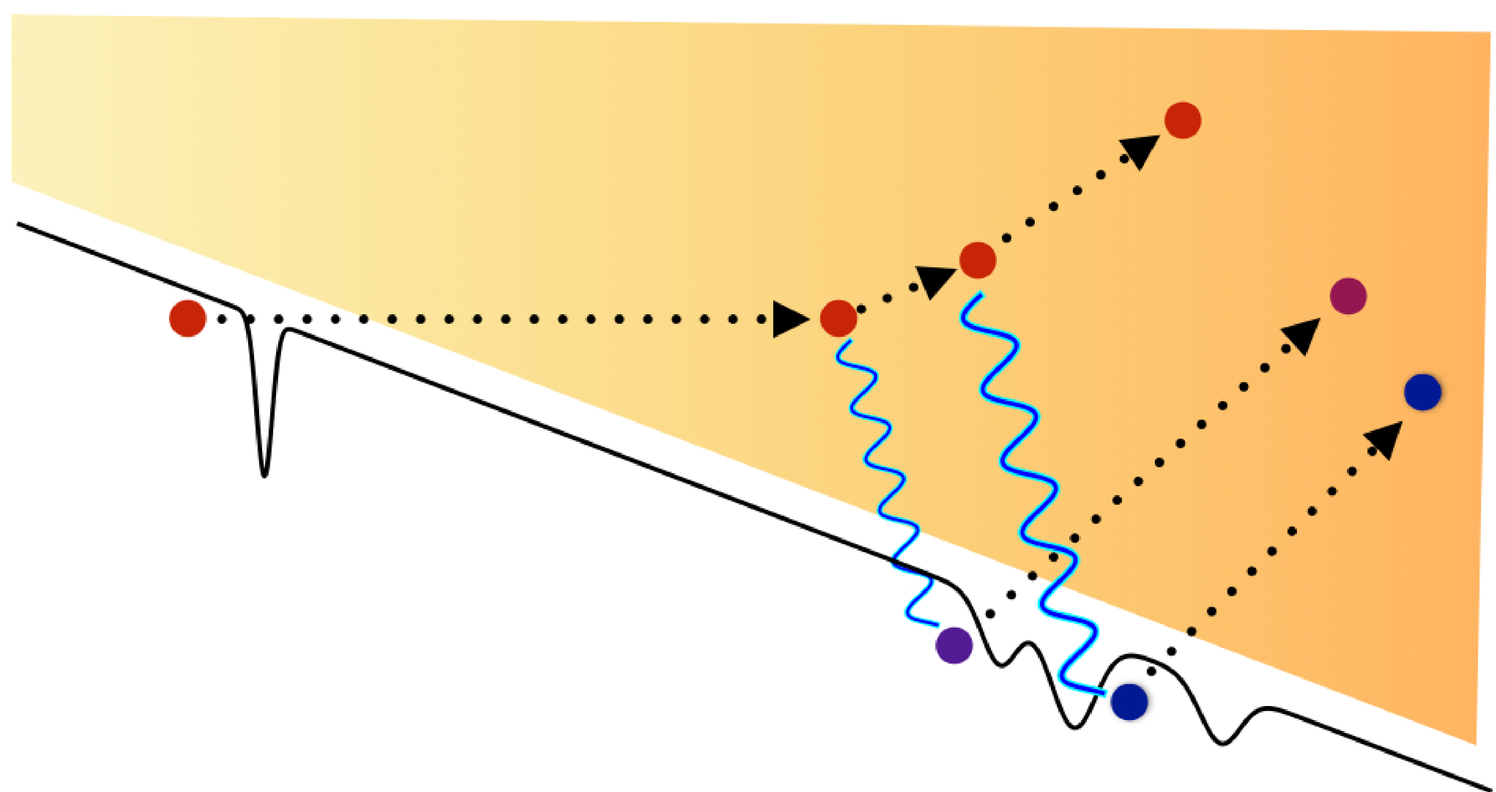
Crystal symmetry can matter





$N_{electrons}$ (Energy input & temp. & electric field)

Increased electric field can over-assist via impact Ionization

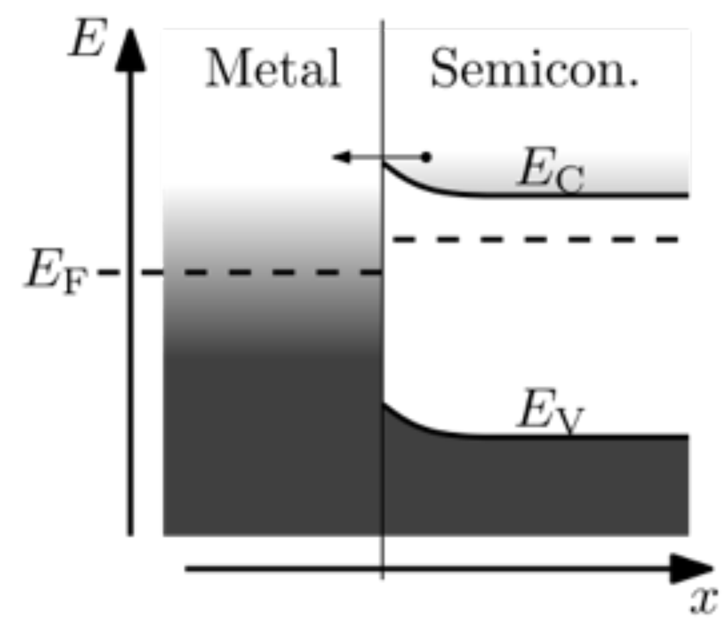


RBT's thesis

Fig. B.3 shows a sketch of impact ionization. An electron (red) is tunneled out, gains sufficient kinetic energy to impact and knock out successive electrons in shallow traps (blue and purple).

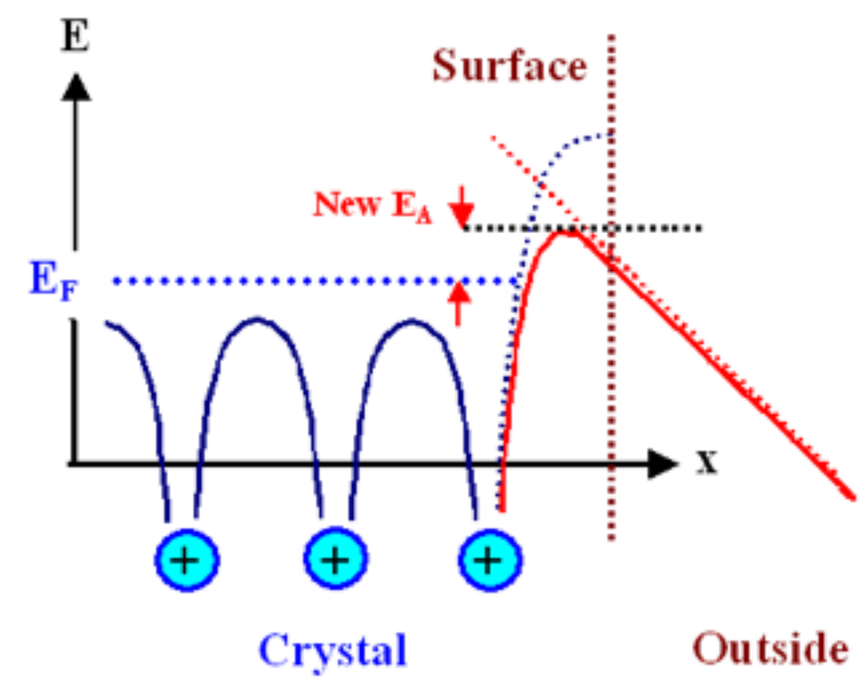
$N_{electrons}$ (Energy input & temp. & electric field)

Other issues:



Auto-ionization: D^- / A^+ impurities ionize due to an external electric field. Anion states may ionize at fields of ~O(10) V/cm

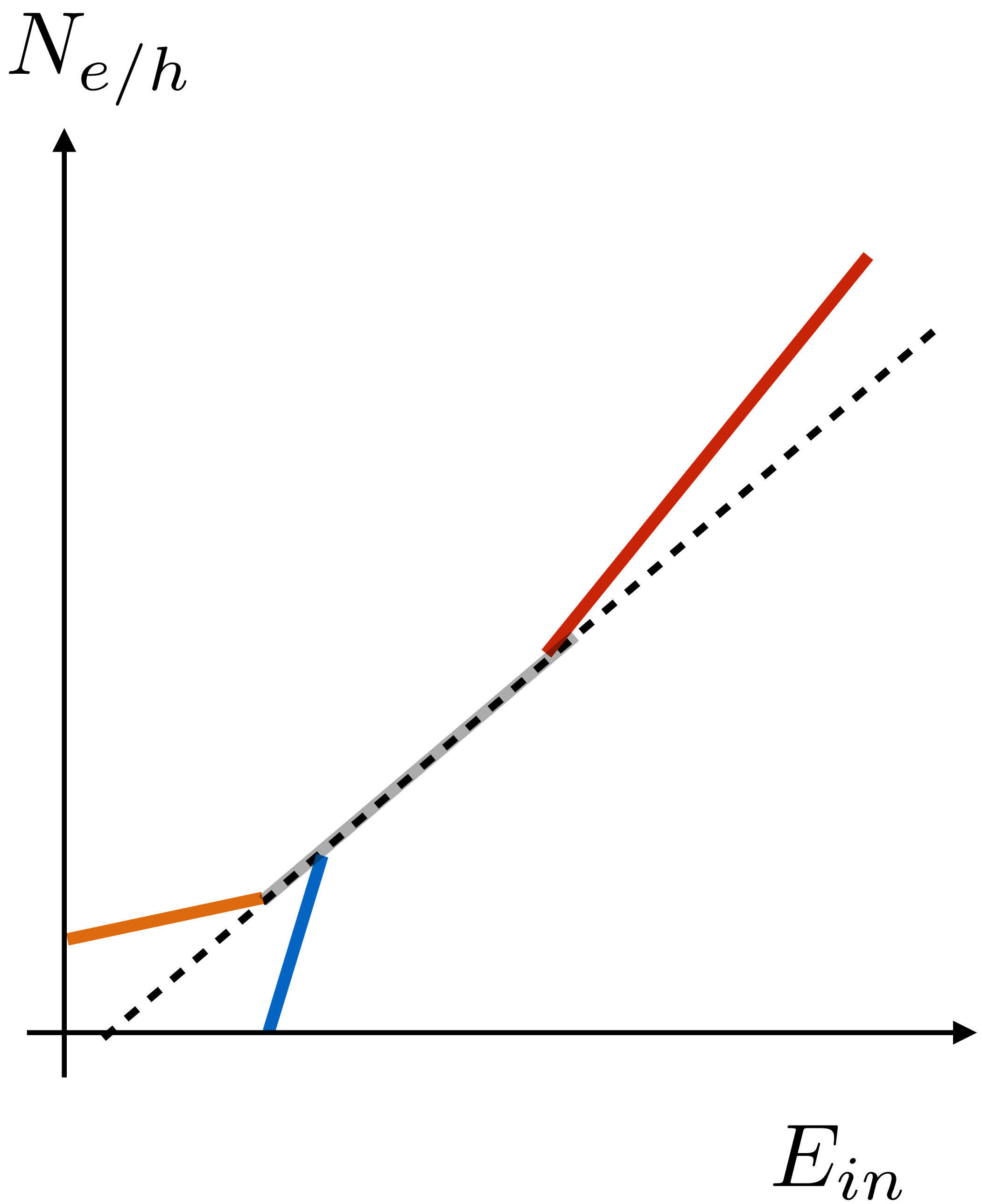
Field emission: Potential drops at Si / metal junction can induce tunneling



Schottky effects: Band-gap upturns play against field and thermally assisted charge propagation

…. oblique propagation / charge trapping etc.
how do these factor when $N_{electron}$ ~ O(1)

$N_{electrons}$ (Energy input & temp. & electric field)



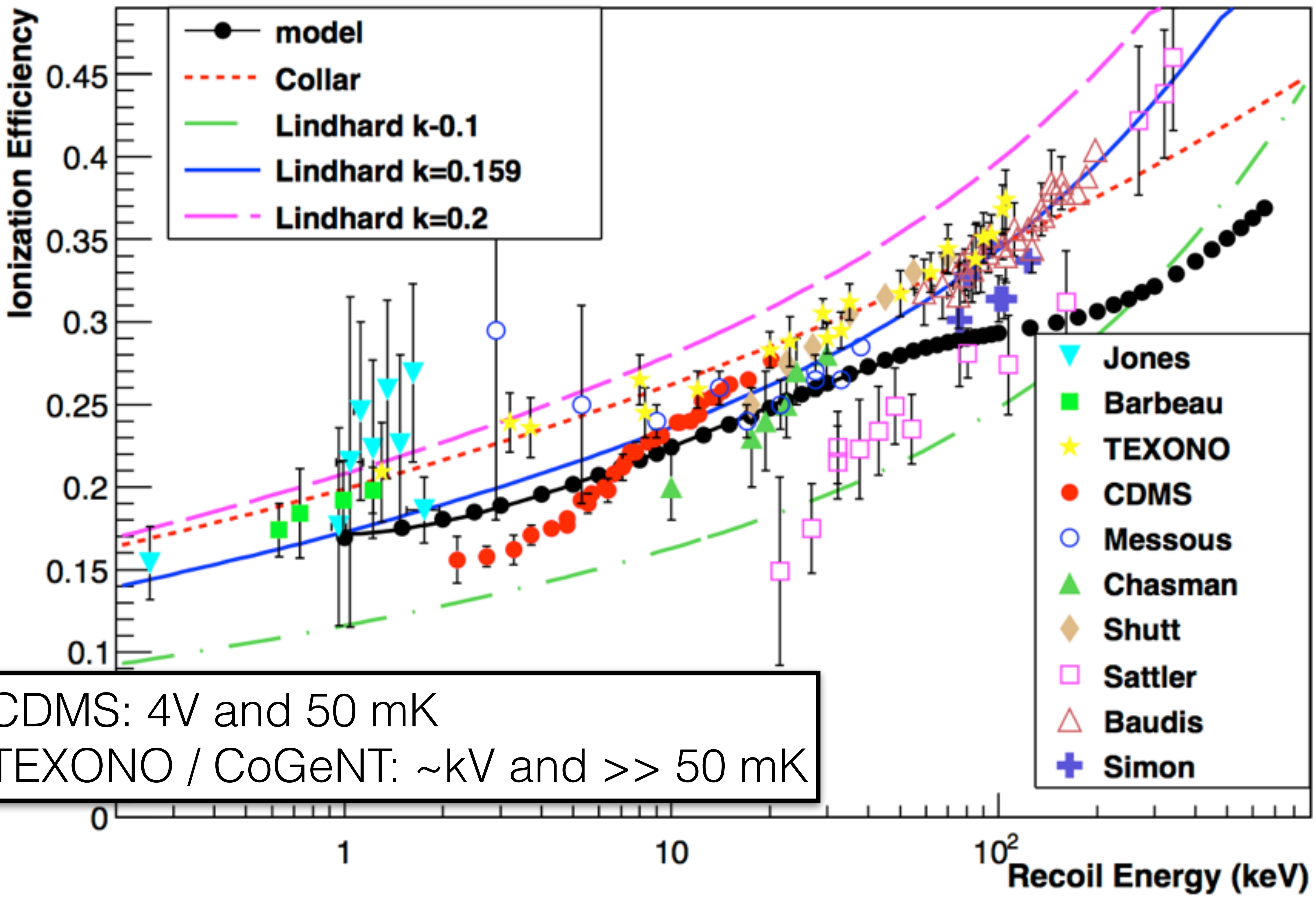
Normal Linear

High Field

Low Fileld

High Temp

$N_{electrons}$ (nuclear recoils x everything else)



CDMS: 4V and 50 mK
TEXONO / CoGeNT: ~kV and >> 50 mK

Ending comments

Detectors will be probing ~O(10) eV range very soon

We must include atomic physics nuances in our studies

Parallel to all our calibration efforts, we must test systematics to get a better handle on how we infer energy scales

Note:
I didn't comment on Fano or second moment, just the mean ionization efficiencies… we'd need to nail down Fano as well!

Thanks!