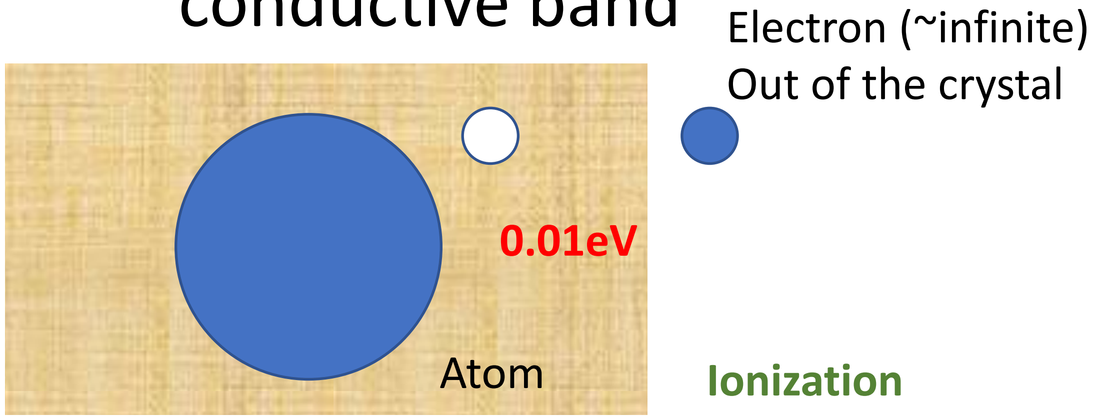
Development of the physics process in Ge detector

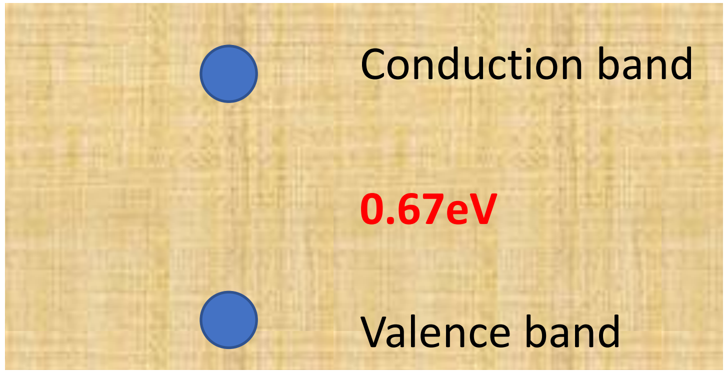
Chih-Hsiang Yeh

Definition clarification

- Since in the most of the paper
- ➔ Electron-hole pair used for both “ionization” and “excitation”
- ➔ Check with the definitions
- ➔ “Ionization” is for “An electron gets rid of the nuclear and goes to infinite place” (Ion-electron pair => electron-hole pair)
- ➔ “Excitation” is for “An electron jumps from valence band to conductive band”



Ionization



Excitation

Extreme temperature-20K

- *ionization energy of the dopants*!
- Require some energy to ionize and produce carriers in the semiconductor. This energy is usually thermal! (From temperature fluctuation)
- If the temperature is too low, the dopants will not be sufficiently ionized and there will be insufficient carriers.
- The result is a condition called "freeze-out." For example, Si (dopant ionization energy ~0.05 eV) freezes out at about 40 K and Ge (ionization energy ~0.01 eV) at about 20 K. Thus, for example, Ge devices in general operate to lower temperatures than Si devices.

4K and 77K different – 20K different

- In 77K
- ➔ Thermally, carrier (electron/hole) will pop up without any signal
- ➔ It need to totally depletion with the high voltage

- In 4K
- ➔ It will be in a low temperature
- ➔ It needs only a low voltage to drift the electron-hole pair
- ➔ Below the 20K

Bulk leakage current
Surface leakage current

- Below 20K
- ➔ There is no thermal excitation
- ➔ No leakage current to be supposed

- Higher than this one
- ➔ Need to find out the relation between.

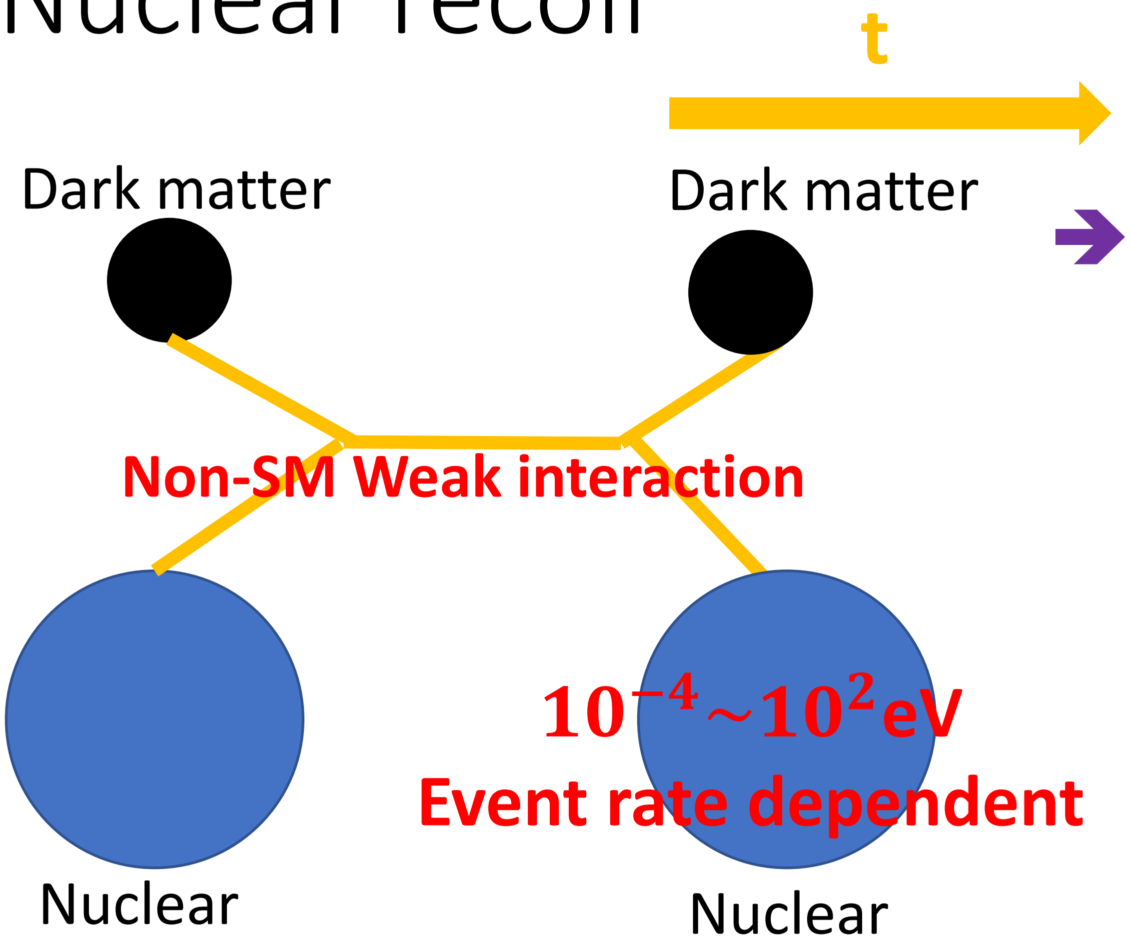
Well-defined! The initial process

- When the dark matter comes....

- Nuclear recoil v.s Electron recoil

- Let define it well to see how we can process

Nuclear recoil



Fake-Feynman diagram of DM-Nuclear scattering

Nuclear recoil (scattering off)

NR

dEdX only!

After Nuclear recoil

➔ It will collide with electrons and atoms

Electrons ➔ e-h pairs

(Effective ionization energy)

Electronic stopping of heavy ion

Atoms➔ phonons

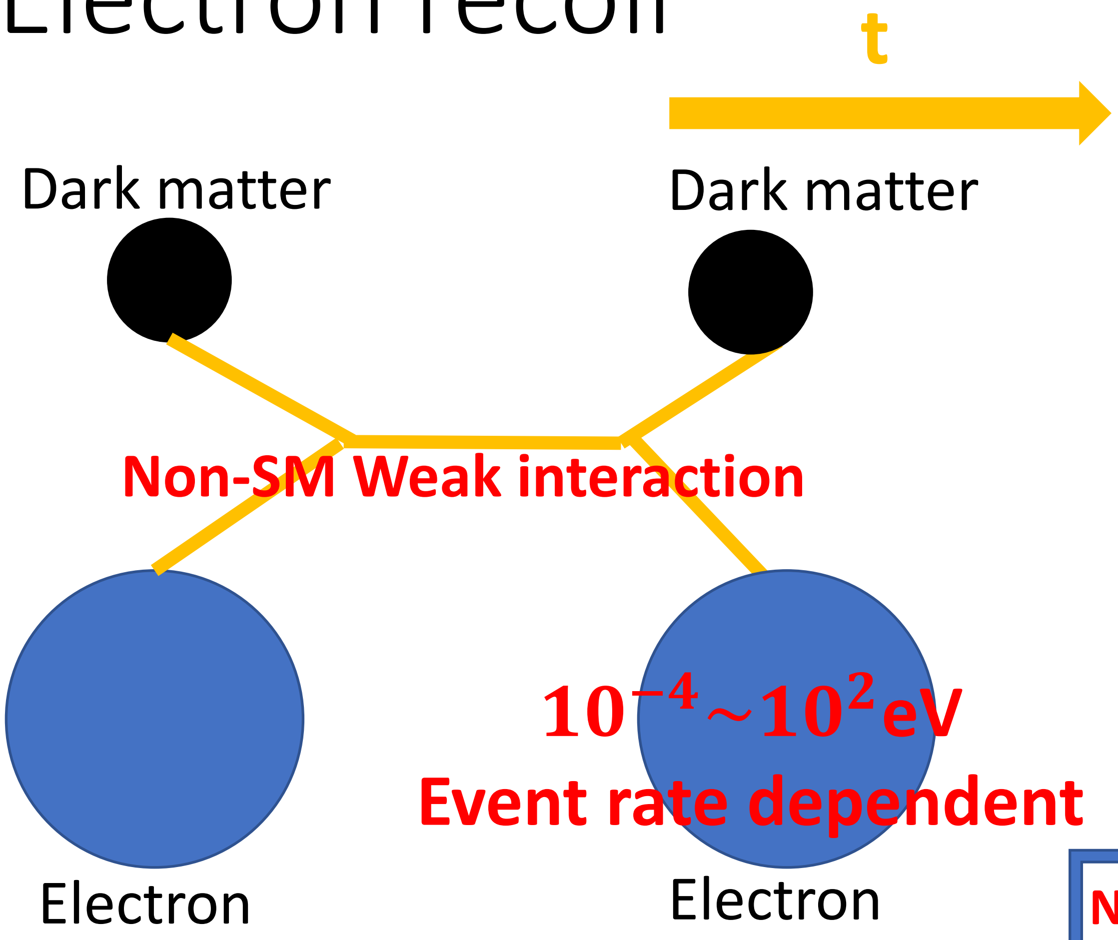
Nuclear stopping of heavy ion

What's the fraction of them?

We need to know this to initiate!

Depend on the velocity of DM

Electron recoil



Fake-Feynman diagram of DM-electron scattering

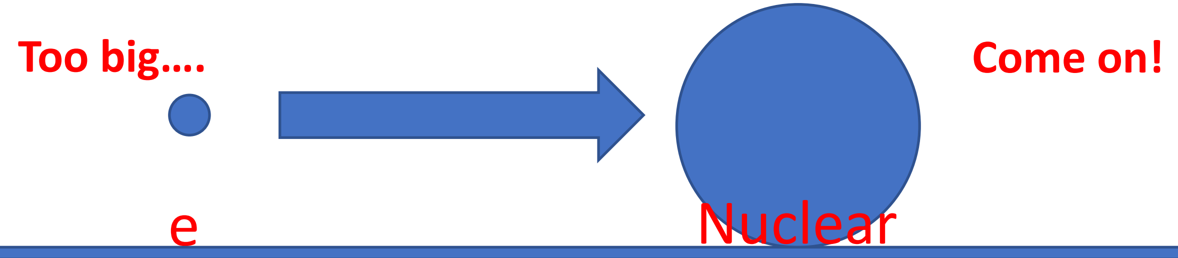
Electron recoil (scattering off)
ER

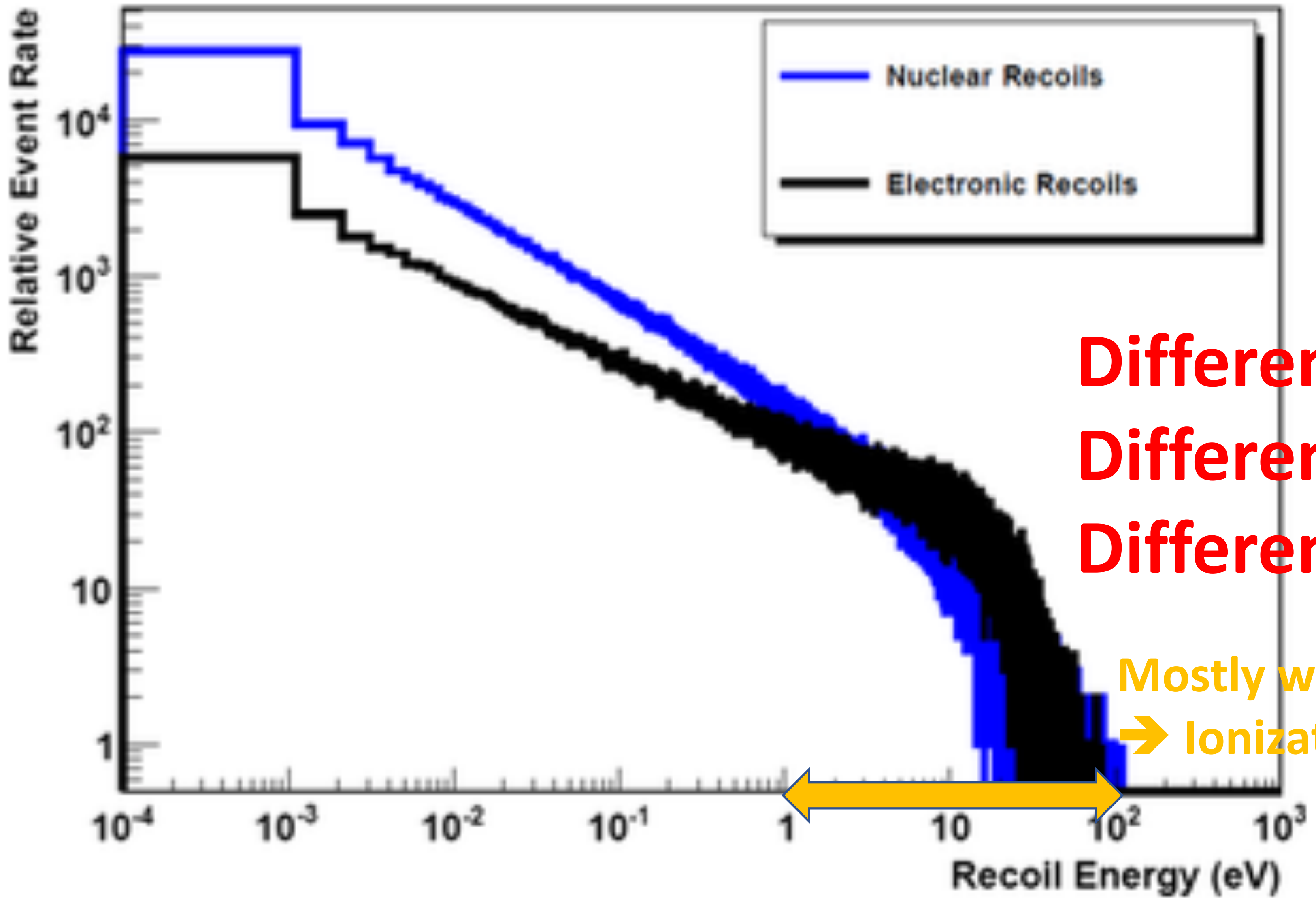
After the Electron recoil
➔ It will collide with electrons

Electrons ➔ e-h pairs
(Effective ionization energy)

Since 50eV DM➔ e-h pair 3eV
(Impact Ionization)

No phonon basically! Can't give nuclear much energy



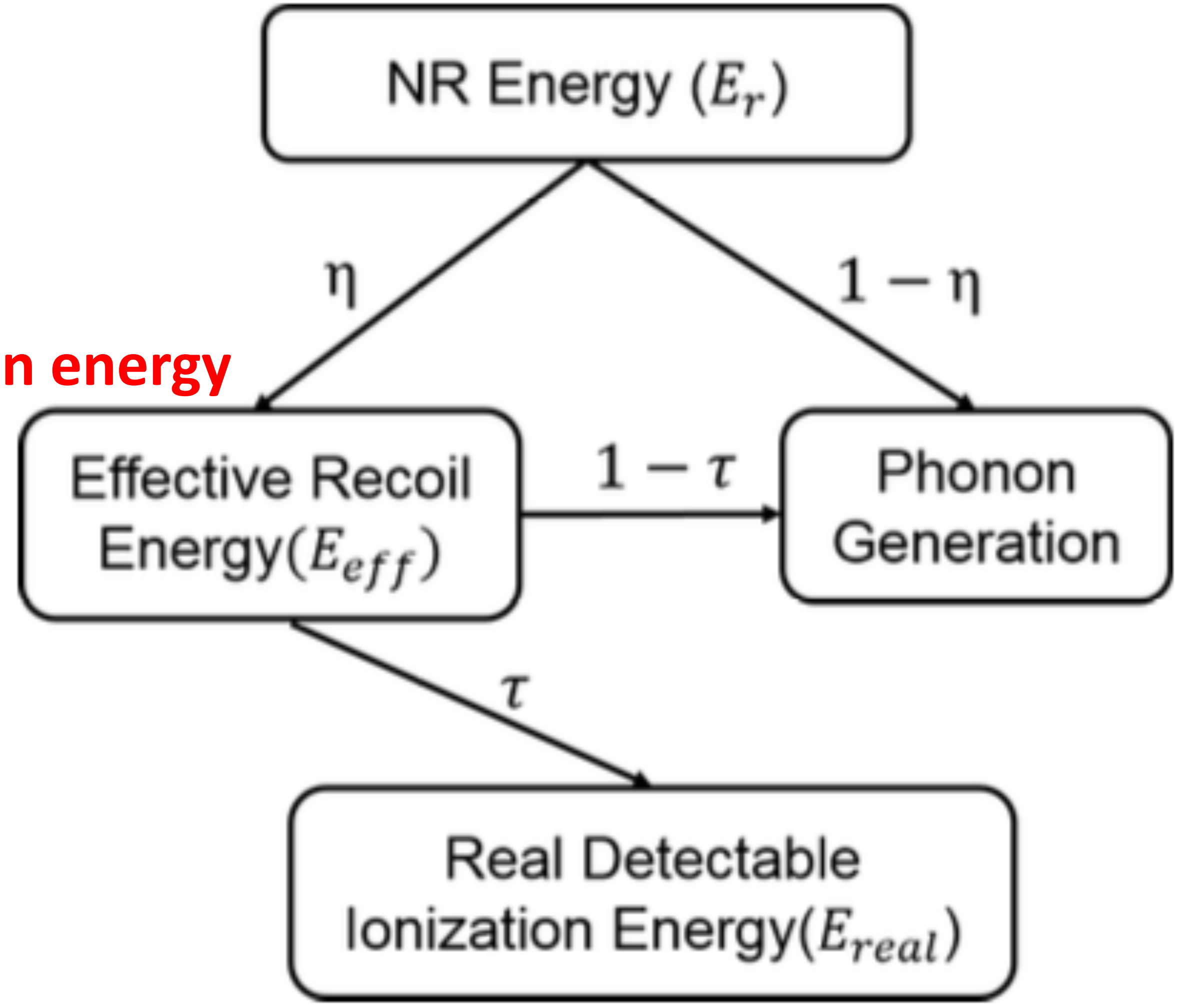


Different DM Mass
Different Recoil energy
Different Relative event rate!

Mostly we care this range.
→ Ionization limitations with impurities

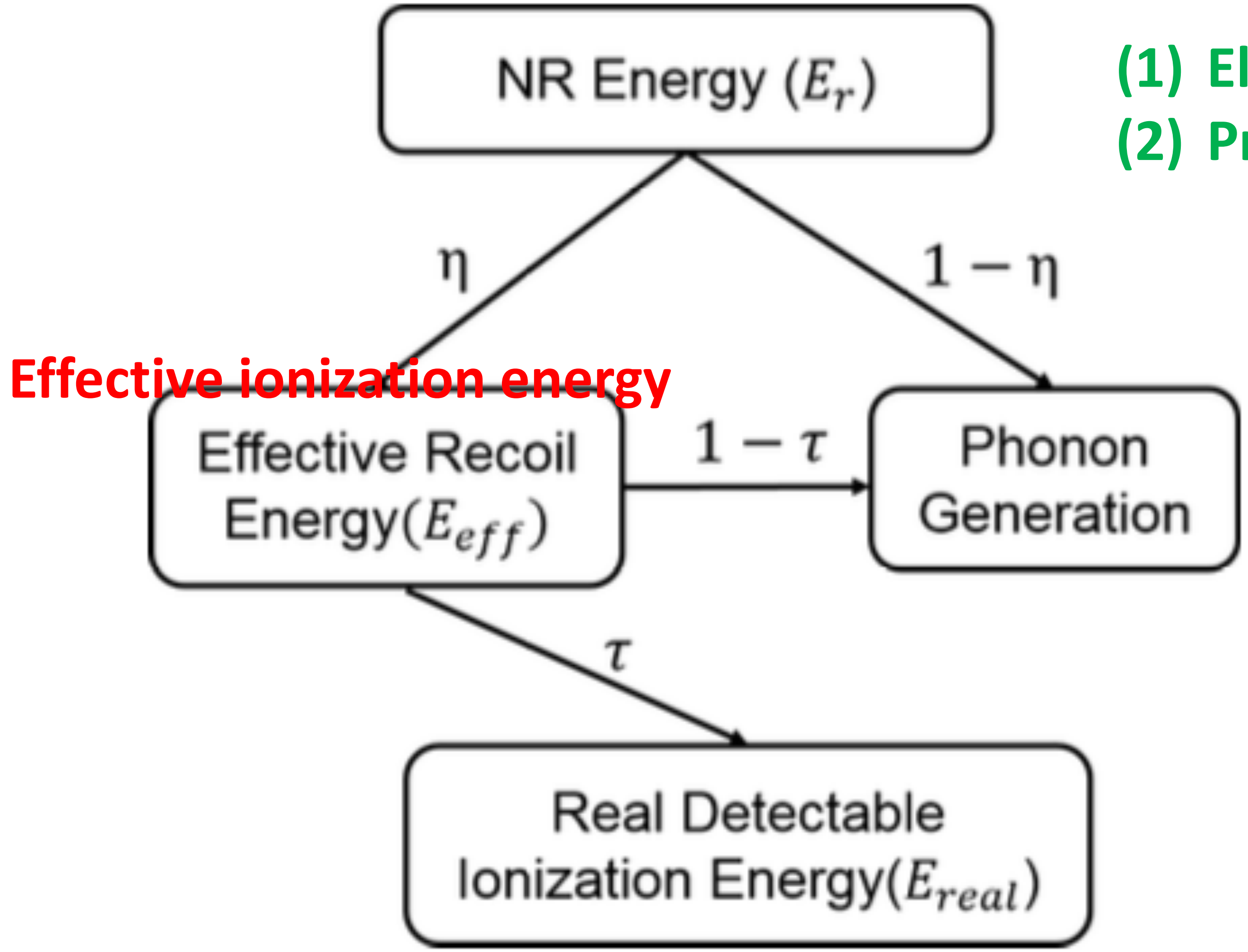
Fig. 1 The relative event rate as a function of recoil energy for DM with masses between 0.1 MeV/c^2 to 1 GeV/c^2

Initiated by Prof. Dongming



Effective ionization energy

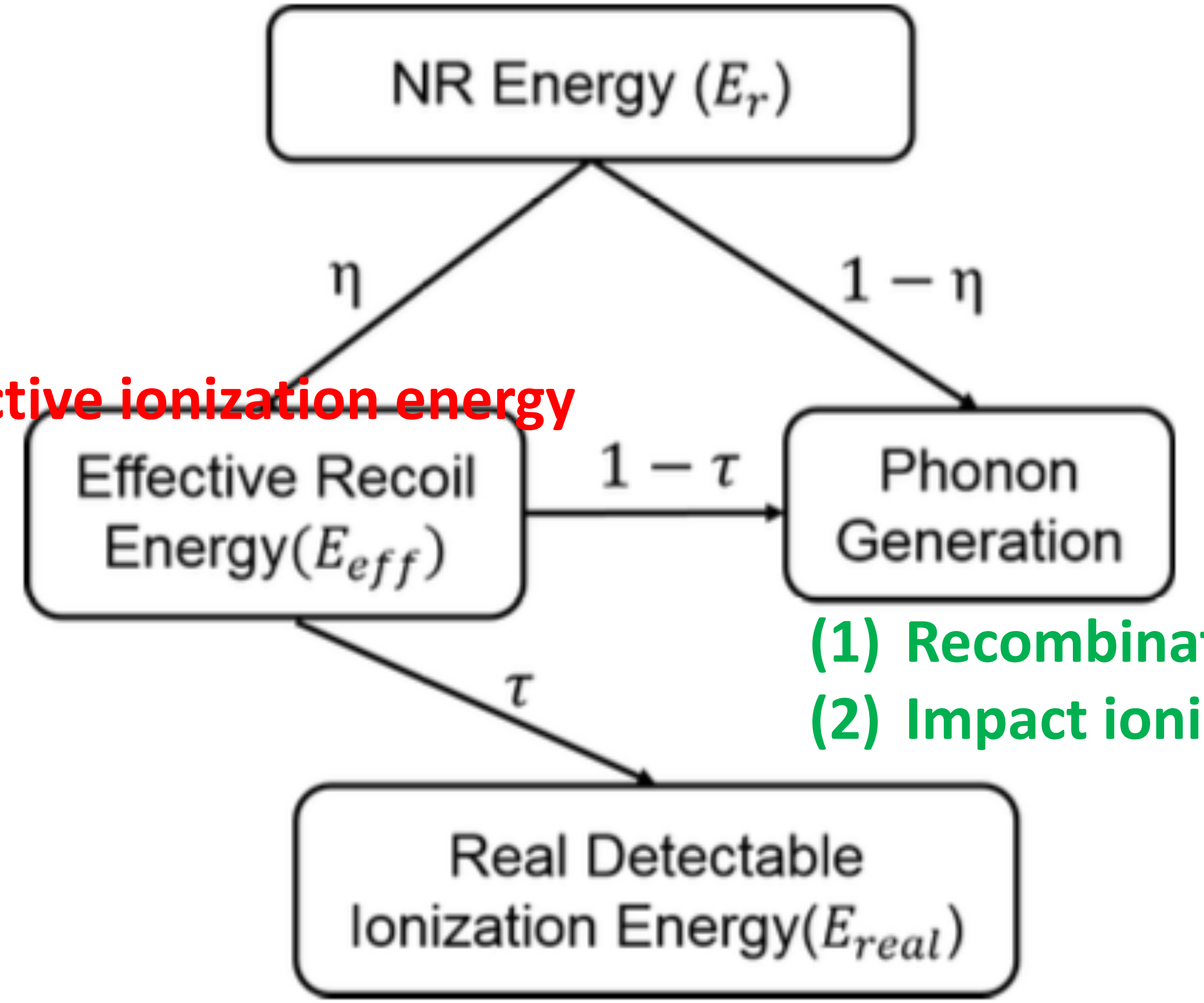
Initiated by Prof. Dongming



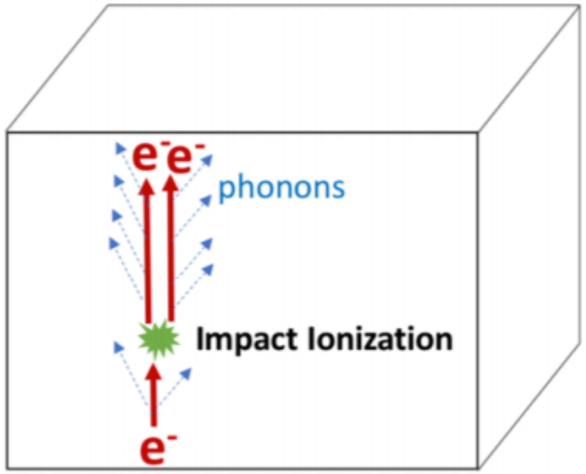
(1) Electronic and nuclear stopping power (dEdX)
(2) Primary phonon

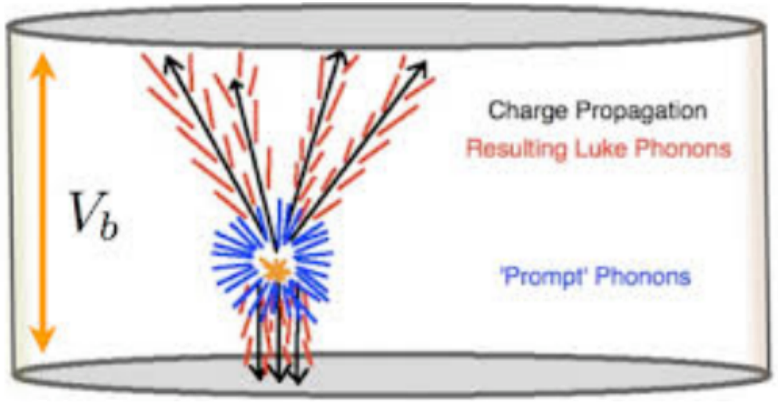
Not related to temperature!

Initiated by Prof. Dongming



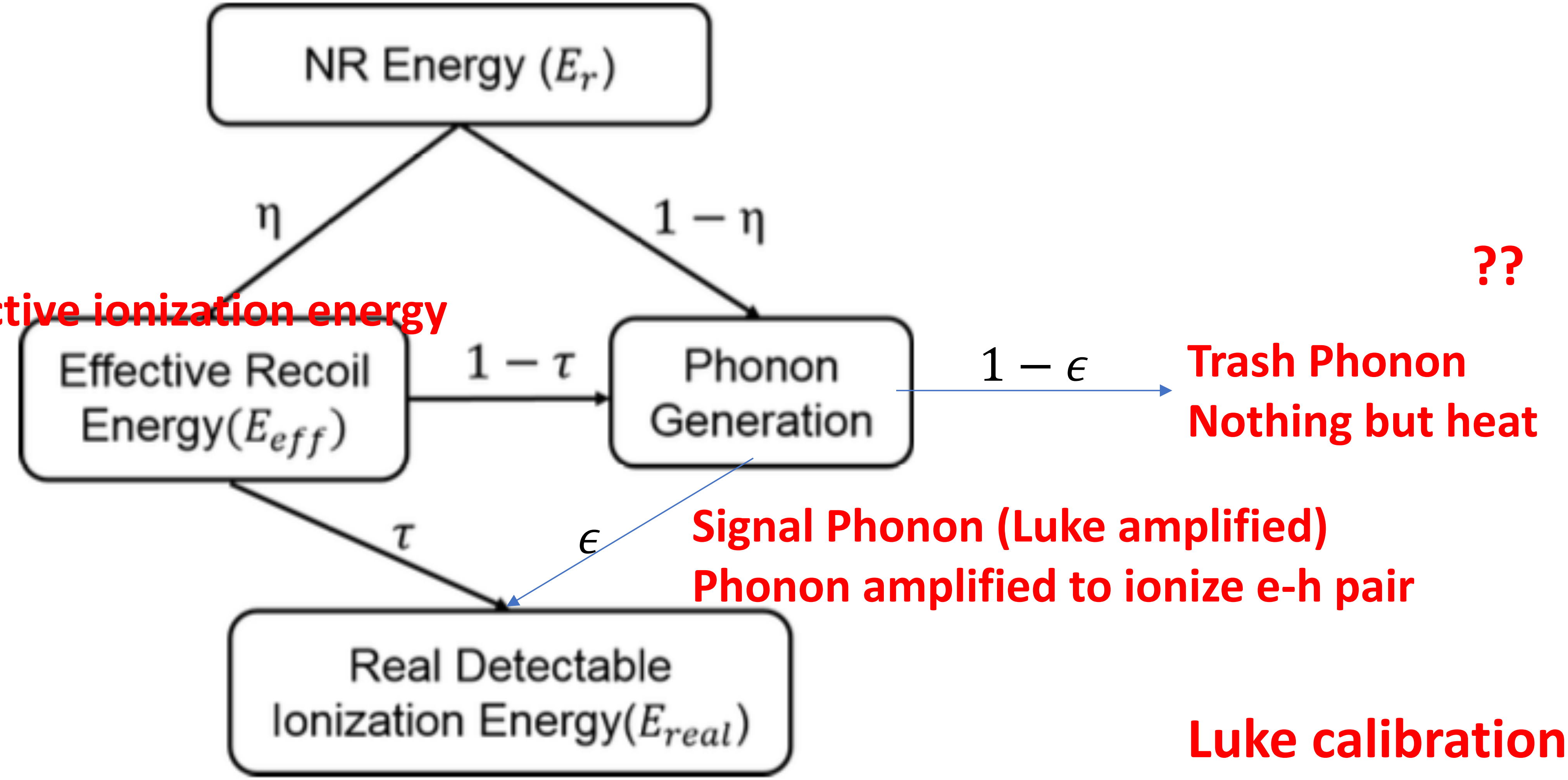
Effective ionization energy





(1) Recombination(ignored) phonon, Luke effect phonon
(2) Impact ionization(Non-uniform effect?)

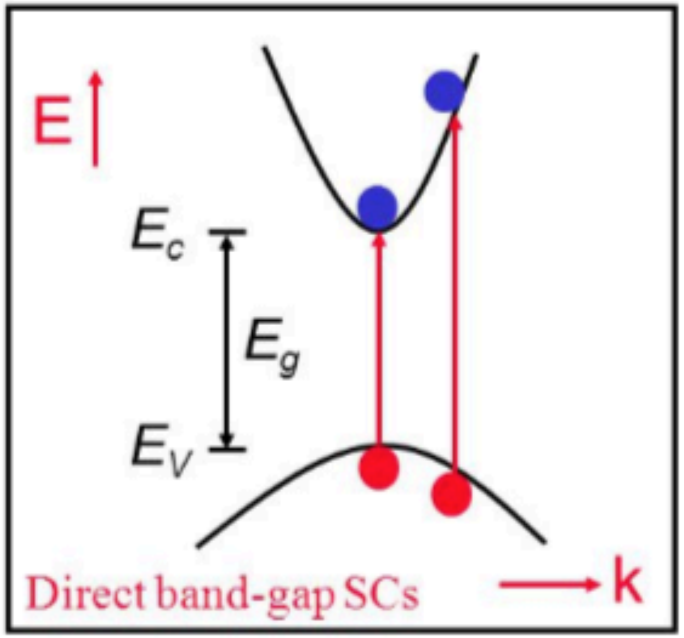
Initiated by Prof. Dongming

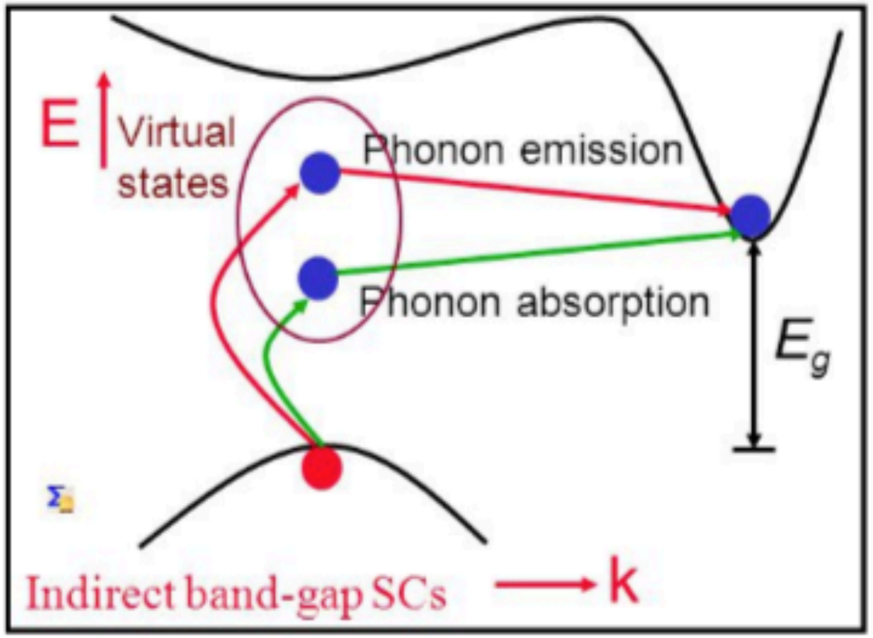


??

Luke calibration?

- Photogeneration ➔ band-diagramatic description:





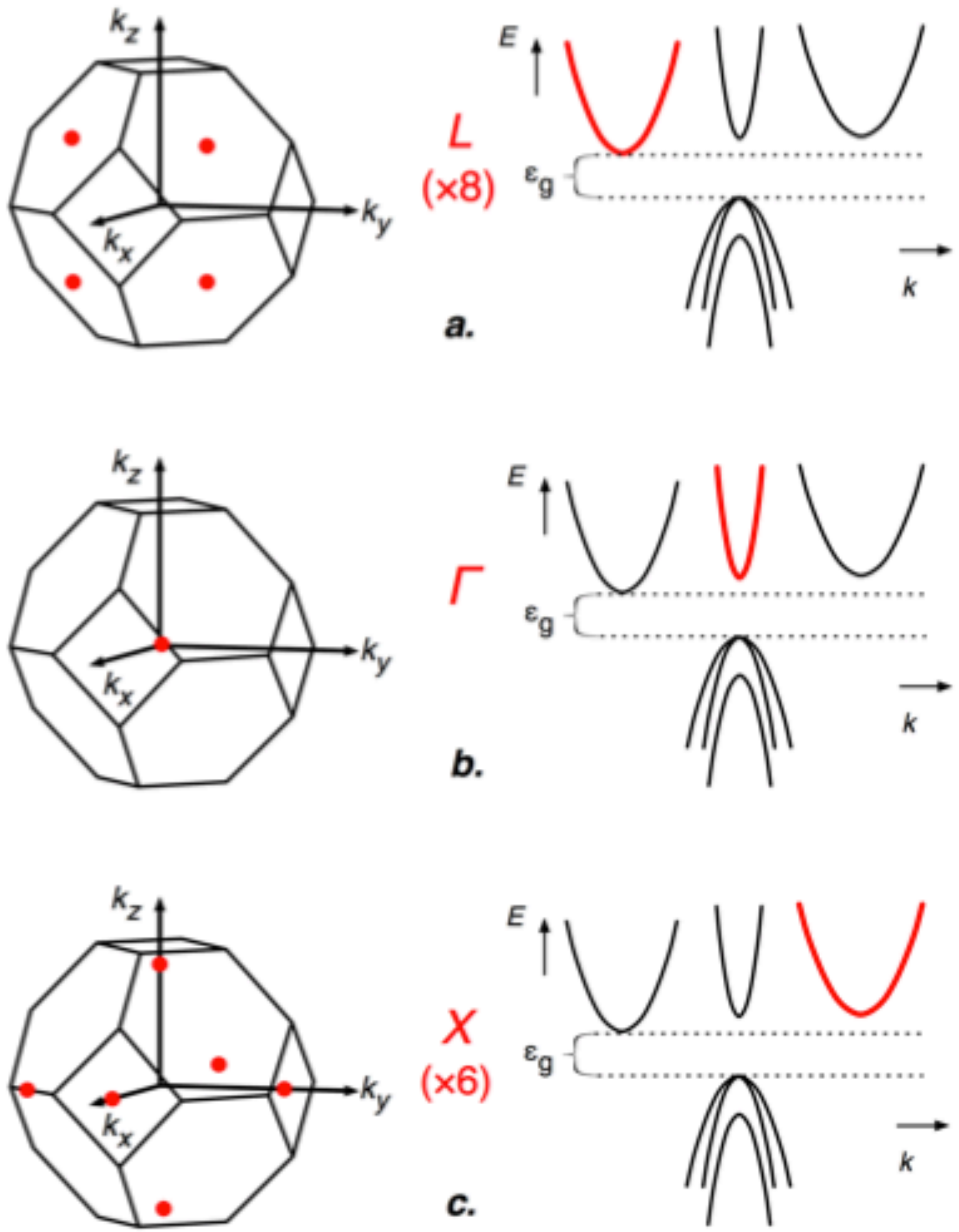
Momentum and energy conservation:

$$p_f = p_i$$
$$E_f = E_i + E_{ph}$$

final initial photon

$$p_f = p_i \mp p_s$$
$$E_f = E_i \mp E_s + E_{ph}$$

final initial phonon photon



Direct band gap

The energy produce e-h pair
➔ Bandgap

Indirect band gap

The energy produce e-h pair
➔ Average all the gap

Let define the parameters

- $N_{pair}{}' = \frac{E_r * \eta}{E_g}$ (Expected – non phonon)
- $N_{pair} = \frac{E_r * \eta}{\varepsilon}$ (Consider Phonon)

E_r (Nuclear recoil energy)
E_g (Energy band gap)

The issue we can concern to explore

- 1. Explore the total signal
- ➔ Since in our experiment, we don’t try to divide our signal into two types – electron recoil and Nuclear recoil, but add them together

- ➔ a. Do we need to distinguish them by some other things?
- ➔ (Maybe we can have a shield outside.)
- ➔ b. Or maybe we can think of the other method to do it?

The issue we can concern to explore

- 2. Luke phonon calibration
- ➔ Since in our case of the shallow doping, we can give out many electron-hole pair
- ➔ Also it will give us much Luke-phonon
- ➔ Those phonon could also give us the electron-hole pair
- ➔ Under "**High voltage**"! – In superCDMS (ignored)

Problem

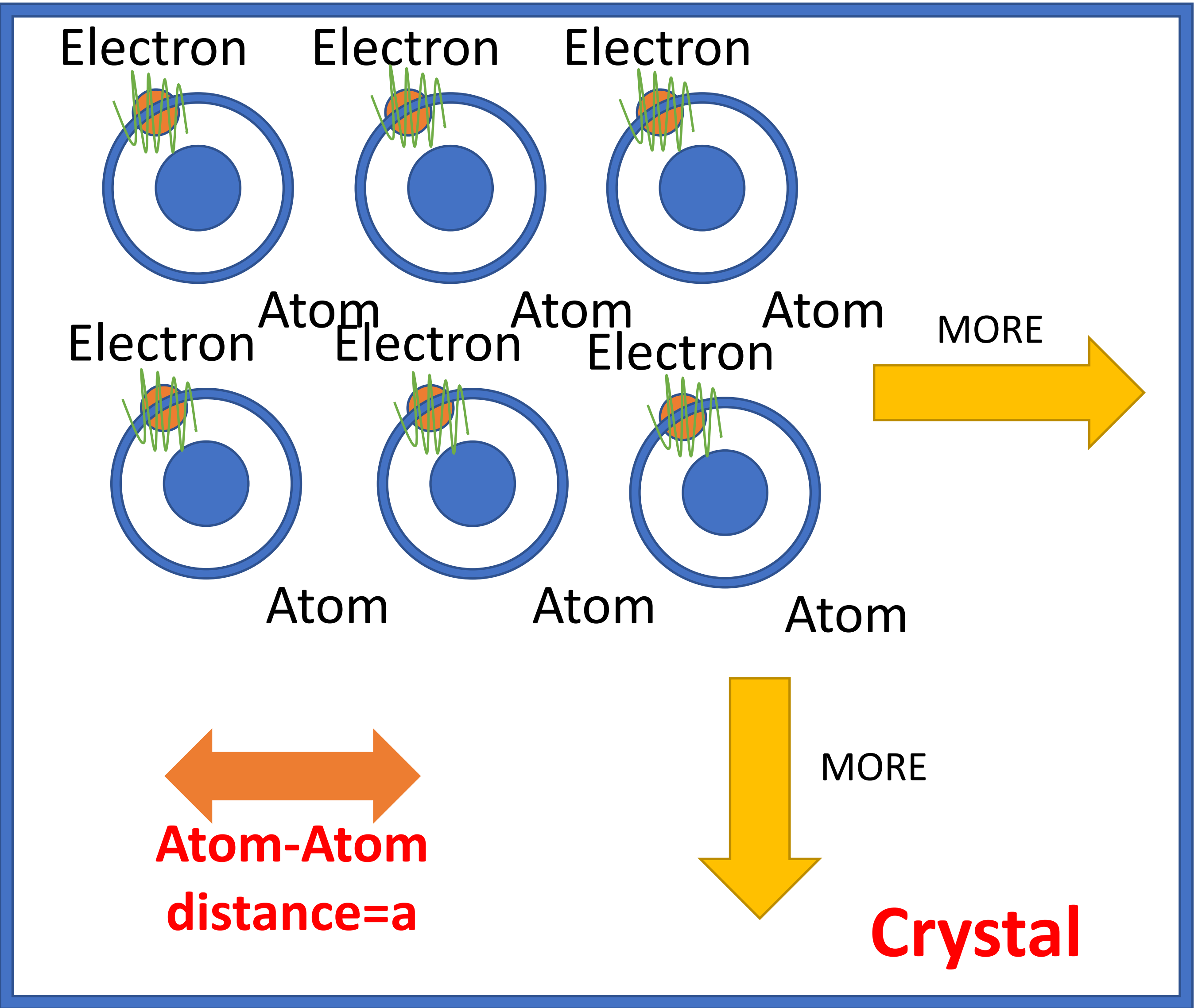
- 1. Since we know the impurities (Shallow doping), do we need to care about the band gap for ionization?

- 2. Phonon emission and absorption

- 3. Ionization energy and bandgap

First:
Basic Solid-State Physics in Crystal

Bloch's theorem- Electron wave function



Bloch's theorem(Definition)

$$\varphi(r) = e^{ik \cdot r} u(r)$$

(Next page will show the wave)

Using in:
A particle in repeating-periodically environment.

r is position
k is wave vector
u(r) is periodic function

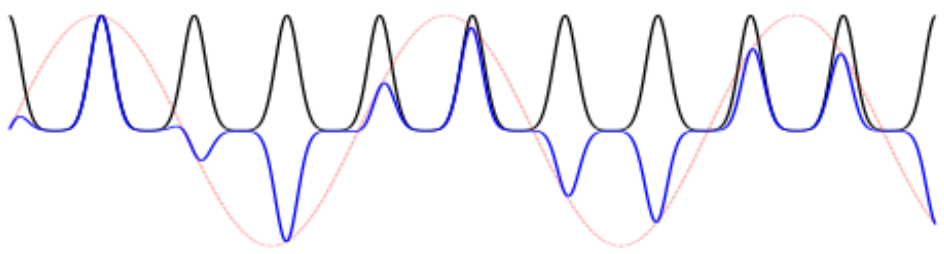
$$u(r) = u(r + a)$$

The picture for the Bloch wave

Black: $u(r)$ Periodic wave function

Pink: $\boxed{e^{ik\cdot r}}$

Blue: The Bloch wave function



$$\varphi(r) = e^{ik\cdot r}u(r)$$

Temperature, voltage

➔ Change the wave vector k

➔ Because: Change the status of electrons

Quantum mechanism:
(A particle momentum)
(Wave package)

$$\mathrm{p} = \hbar k$$

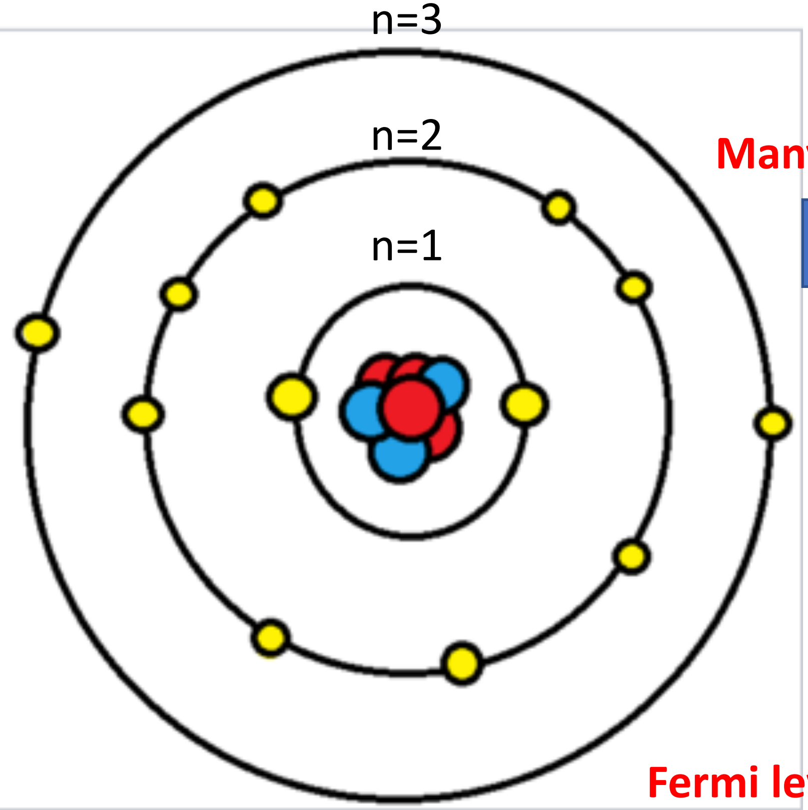
The same definition for **crystal momentum**

k is the Bloch wave vector

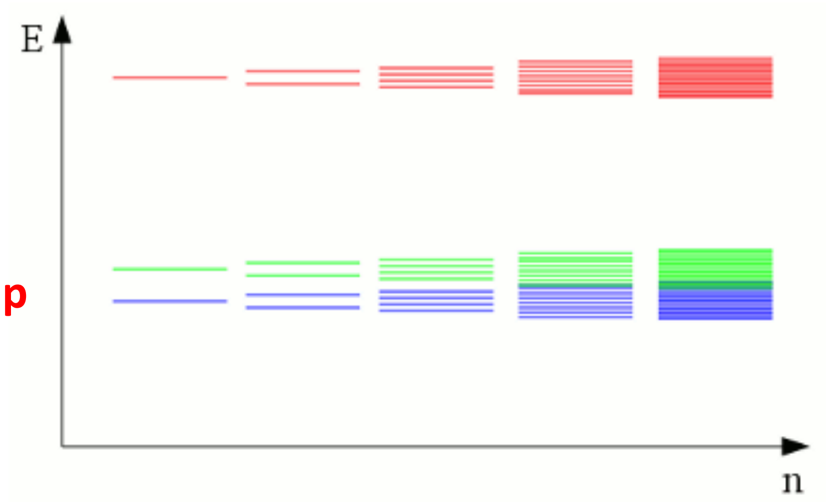
$$(k = \frac{2\pi}{\lambda})$$

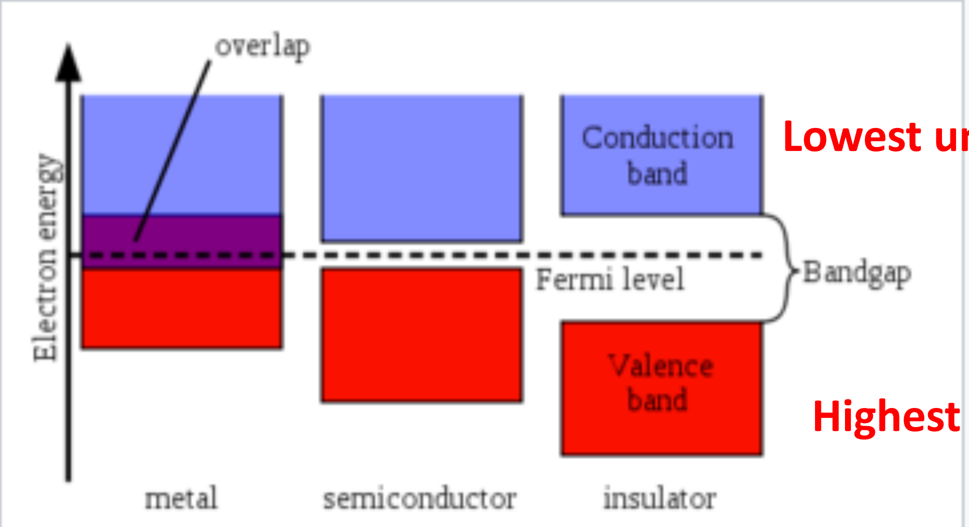
Band theory and Band gap

Outermost electrons: valence electron



Crystal:
Many orbital electrons overlap





Lowest unoccupied

Highest occupied

Fermi level:

0K, the electron can fill the highest level in valence band

Direct and indirect band gap
-Energy and momentum conservation

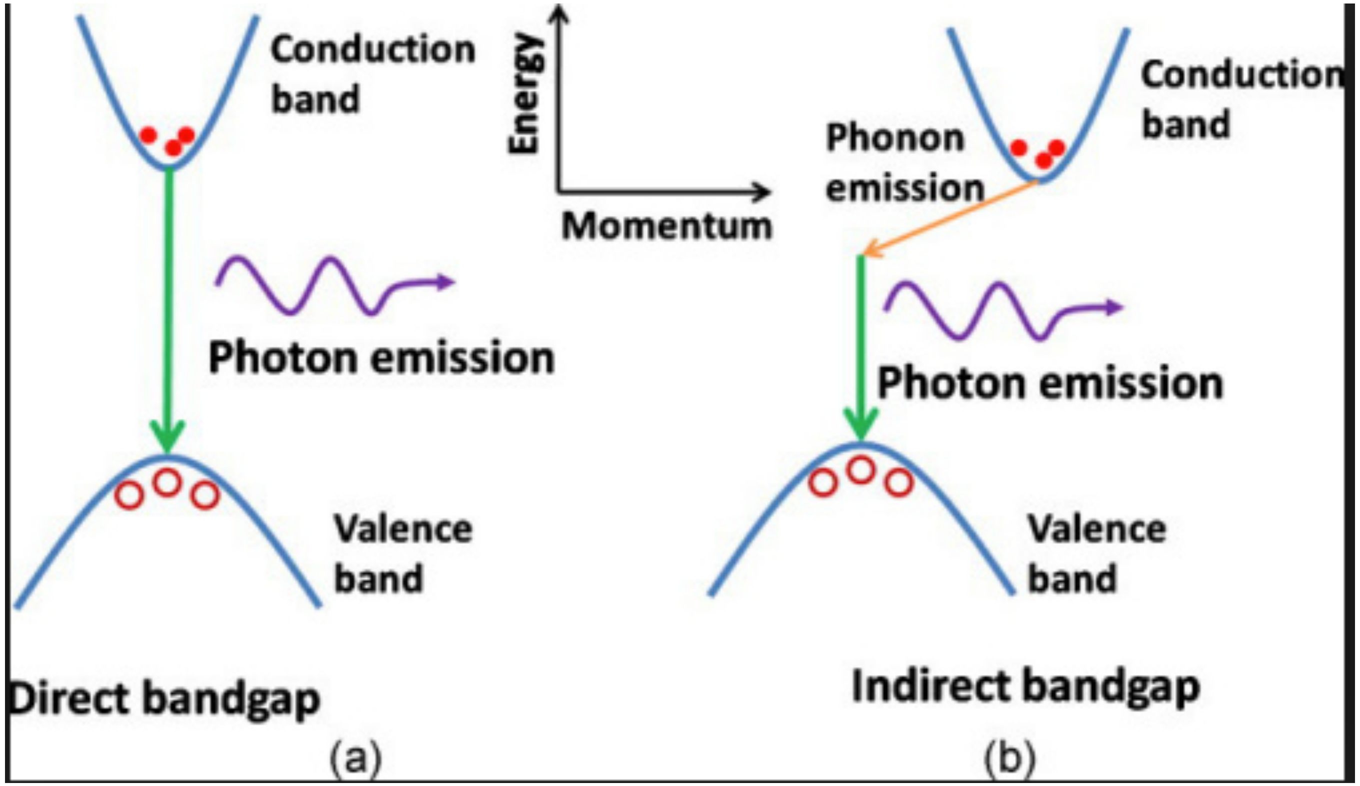
Dispersion relation

E versus. k

Momentum conserves.

Momentum don’t conserve.

Same k or not.



Photon will be absorbed/emitted !

Photon will be absorbed/emitted !

Phonon will be absorbed/emitted !

Direct and indirect band gap
-Energy and momentum conservation

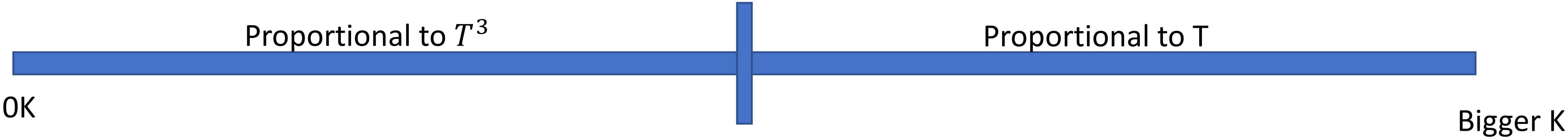
Important point 1:

➔ Under 4K(liquid Helium) and 77K(liquid Nitrogen), what’s the different of the band gap between this two temperature?

Debye model – Debye temperature

- Estimate the phonon contribution in specific heat.
- Low temperature ➔ Specific heat proportional to T^3

- What's the standard of this specific heat issue?



Debye temperature:

$$\boldsymbol{\theta_D = \frac{\hbar}{k_B}\omega_D}$$

$$\boldsymbol{{\omega_D}^3 = 6\pi^2 \rho {v_s}^3}$$

ρ is crystal density, v_s is sound wave speed in crystal

Connection between:

Phonon and temperature

➔ Our band gap also involve in!

Next page

Band gap under the 4K and 77K

- $E_g = E_0 - \alpha \frac{T^2}{T+\beta}$
- E_g is direct or indirect band gap
- E_0 is the band gap of 0K
- α and β are the constants in experiment

- $T \ll \theta$ ➔ $\Delta E_g \propto T^2$

Indirect band gap
➔Lower band gap
➔Prefer to use it!

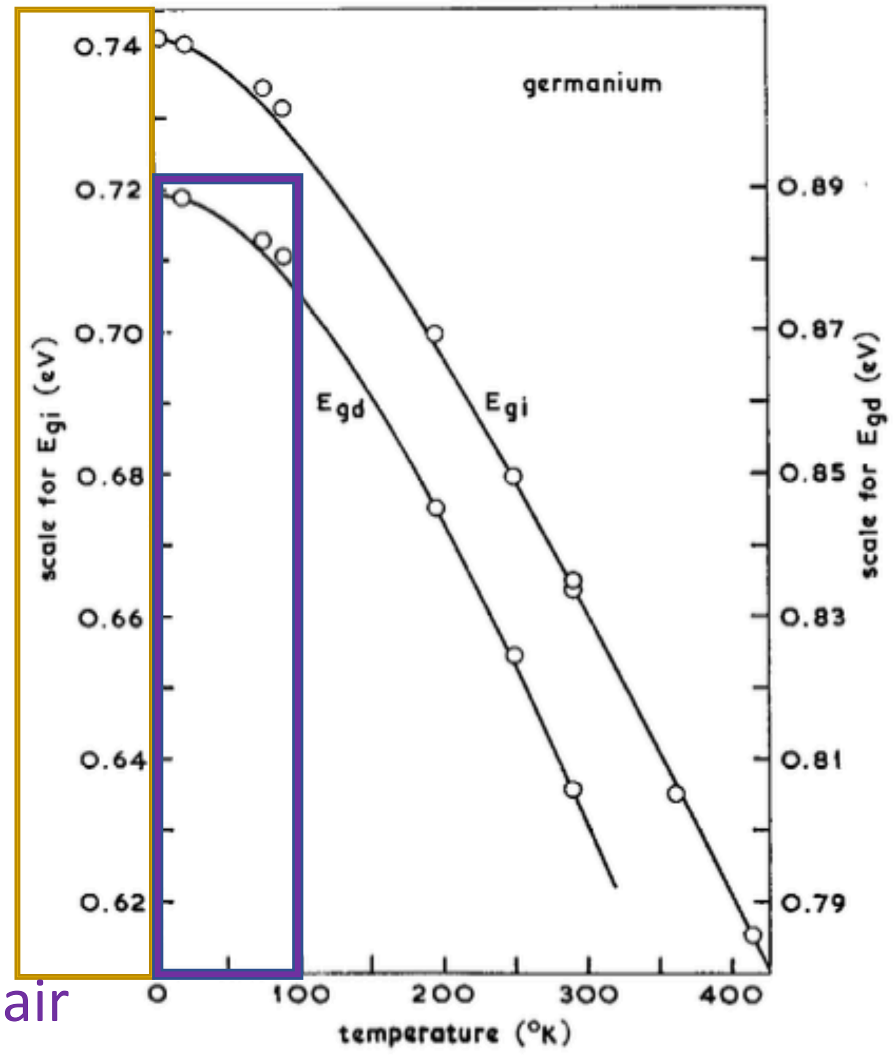


Fig. 3. Germanium, indirect and direct gaps.

Since it will go down
➔Higher temperature(77K)
➔Can get more electron-hole pair

[Paper]

Tabla 1. Banda prohibida de energía entre las bandas de valencia y de conducción

(i = banda indirecta; d = banda directa)

Cristal	Banda	E_g, eV 0 K	E_g, eV 300 K	Cristal	Banda	E_g, eV 0 K	E_g, eV 300 K
Diamante	i	5.4		HgTe[a]	d	−0.30	
Si	i	1.17	1.11	PbS	d	0.286	0.34–0.37
Ge	i	0.744	0.66	PbSe	i	0.165	0.27
αSn	d	0.00	0.00	PbTe	i	0.190	0.29
InSb	d	0.23	0.17	CdS	d	2.582	2.42
InAs	d	0.43	0.36	CdSe	d	1.840	1.74
InP	d	1.42	1.27	CdTe	d	1.607	1.44
GaP	i	2.32	2.25	ZnO		3.436	3.2
GaAs	d	1.52	1.43	ZnS		3.91	3.6
GaSb	d	0.81	0.68	SnTe	d	0.3	0.18
AlSb	i	1.65	1.6	AgCl		—	3.2
SiC(hex)	i	3.0	—	AgI		—	2.8
Te	d	0.33	—	Cu_2O	d	2.172	—
ZnSb		0.56	0.56	TiO_2		3.03	—

[a] El HgTe es un semimetal; las bandas se solapan.

α and β could be found!

Second:
Our study topic of Ge detector

Shallow doping
Trap

Table 2 Ionization energies of shallow impurities in Ge

Impurity	Boron	Aluminum	Gallium	Phosphorus
Ionization energy (eV)	0.0104	0.0102	0.0108	0.012

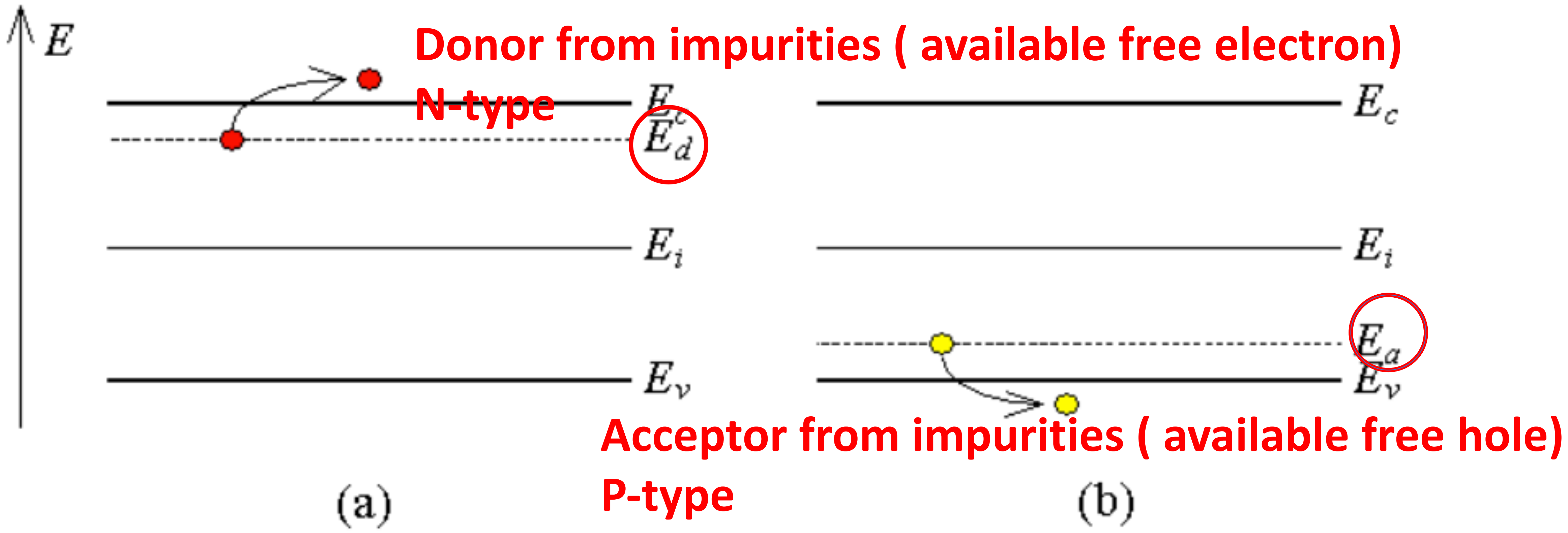
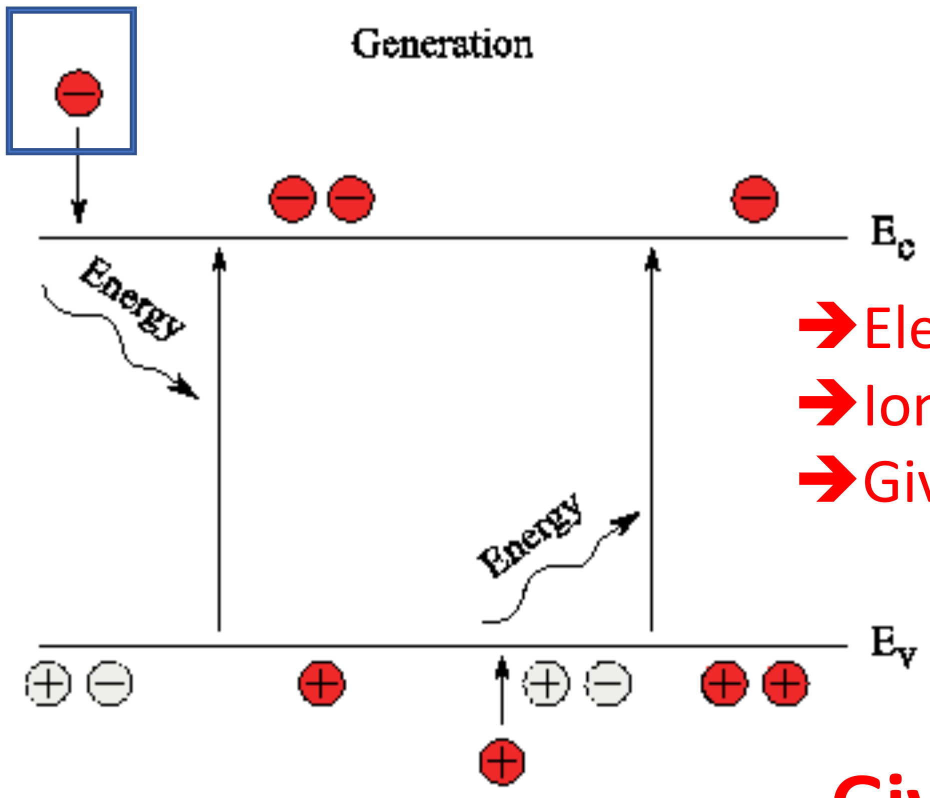


Figure 2.6.5: Ionization of a) a shallow donor and b) a shallow acceptor

Let us divide the topic into two parts: Nuclear recoil and Electron recoil

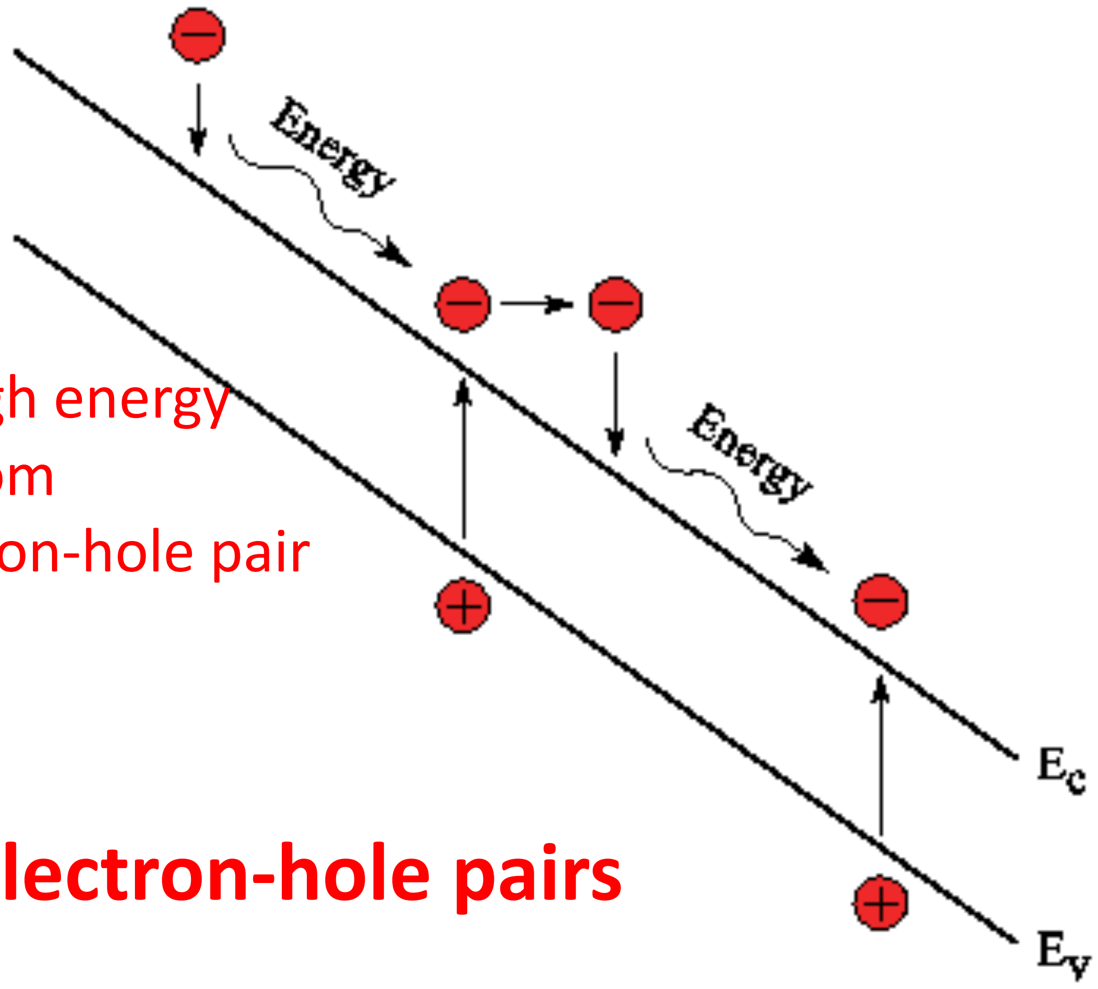
Auger recombination-electron and hole pair
Impact ionization

High energy electron under the high voltage



Avalanche Auger generation

➔Electron will have high energy
➔Ionize the nearby atom
➔Give out many electron-hole pair



Give out many electron-hole pairs
➔ Then?

Phonon emission/absorption-Shockly-Read-Hall(SRH) recombination

Trap:

1. **The defect of crystal**
2. **impurity**

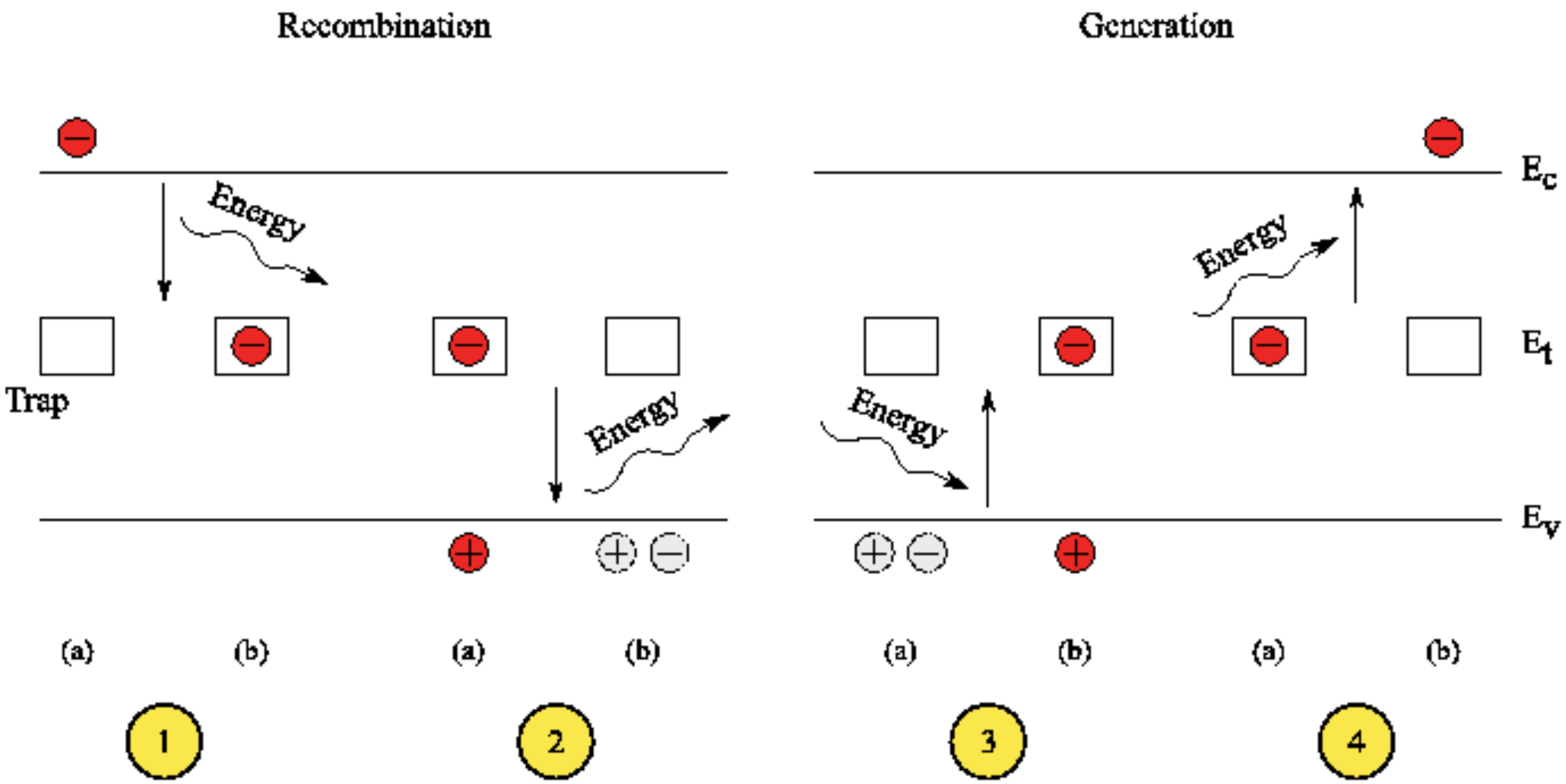


Figure 2.2: Four sub-processes in the Shockley–Read–Hall generation/recombination process. 1. electron capture, 2. hole capture, 3. hole emission, and 4. electron emission.

Reverse bias Breakdown

- Maximum reverse bias voltage

- Two type of breakdown
- - **Avalanche breakdown**
  - Charge Multiplication (impact ionization) under the electric field
  - In the depletion of the region
- - Zener breakdown
  - Quantum mechanical tunneling of carriers through the bandgap
  - Highly doped p-n junctions.

What’s Depletion layer in this case?