MICRO-523: Optical Detectors

Week One: Light - Solutions

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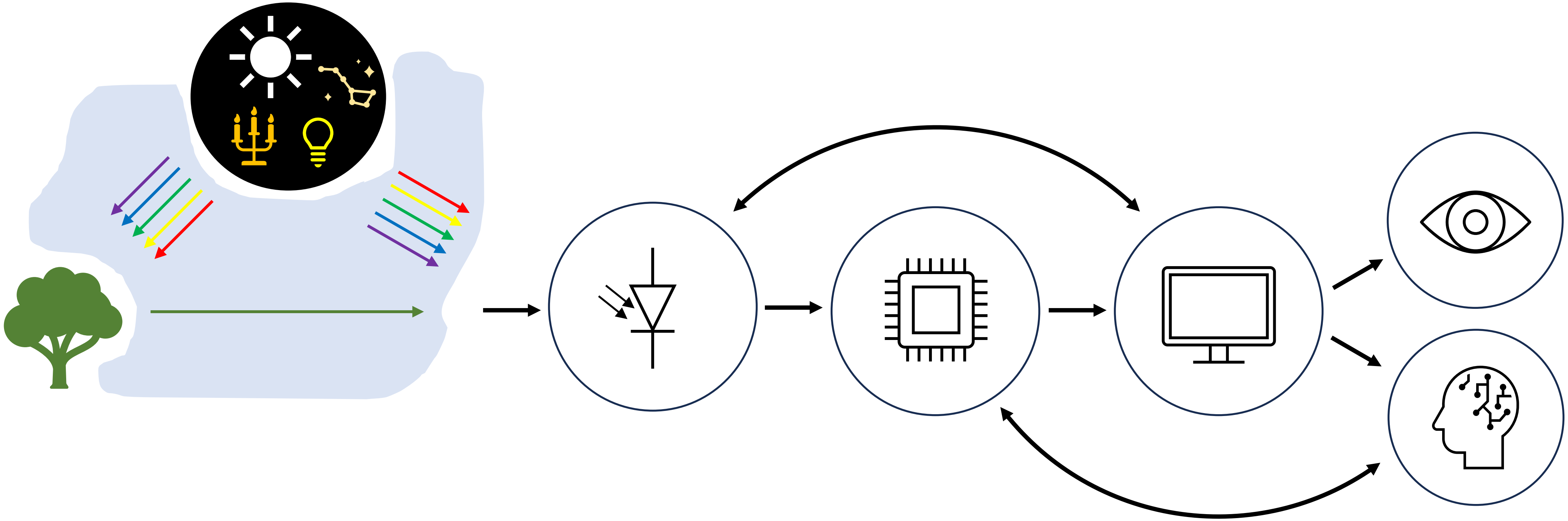
Based on MICRO-523, P.-A. Besse, 2023

TAs: Samuele Bisi, Kodai Kaneyasu

Outline

Exercise 1.1: Components of an optical system



Light source → Optical medium → Detector → Signal processing → Output (display) → Interpretation (analysis)

Exercise 1.1: Components of an optical system

Select 1-2 key blocks in the previous slide:

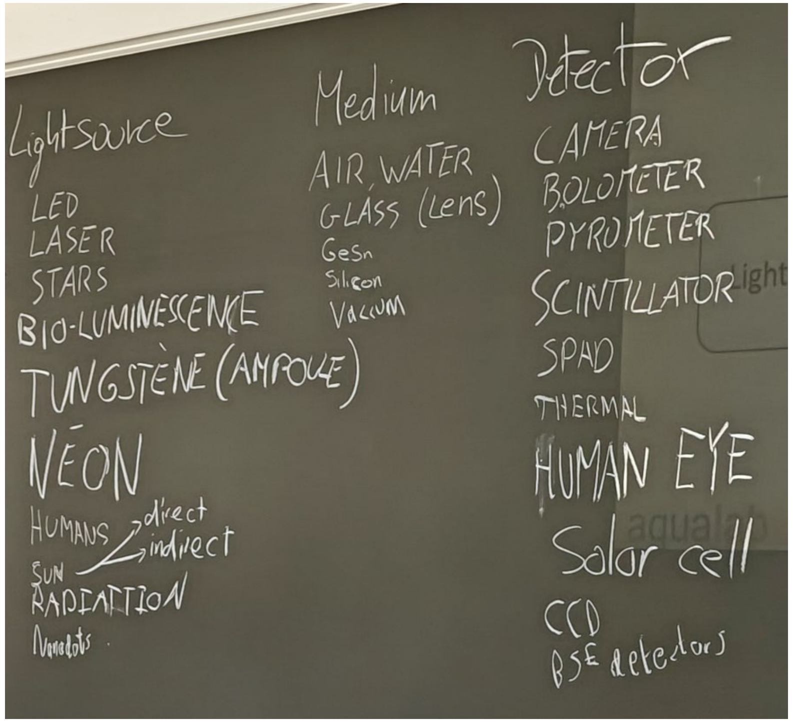
- What are their main parameters?
- Can you think of examples?

Ideas:

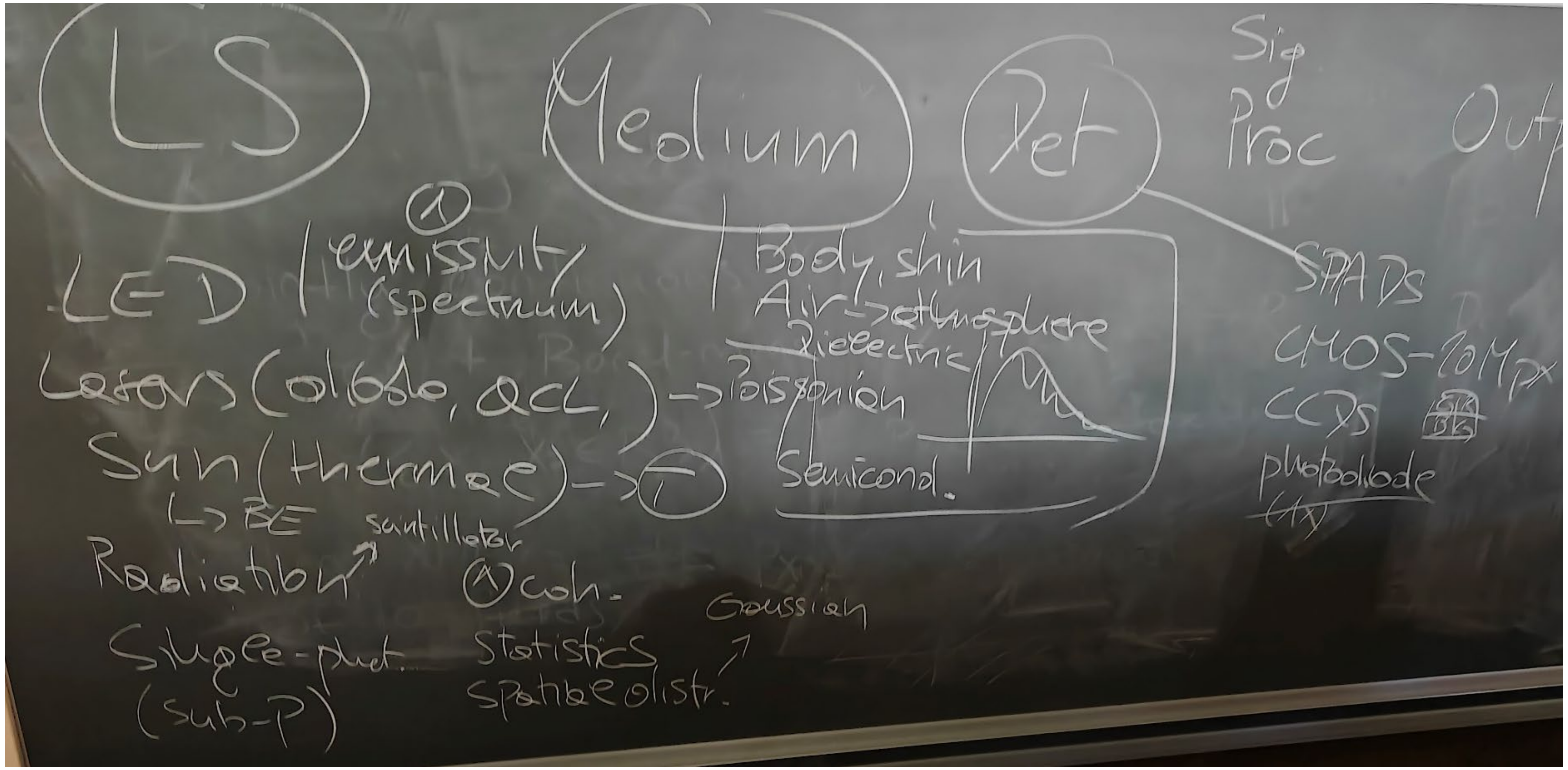
- Light source: laser vs thermal light, CW vs pulsed operation, wavelength, …
- Optical medium: air, tissue, …, close by, far, …
- Detectors: single-point vs 2D camera, all-solid-state vs photomultiplier tube, size, number of pixels, …
- Signal processing: one single image vs a movie, averaging (mean value) vs peak finding, …
- Output (display) : human eye vs screen, colour palette, bit depth, …
- Interpretation: simple intensity, time of arrival = distance, multispectral -> fruit ripening, …

Exercise 1.1: Results

Current year

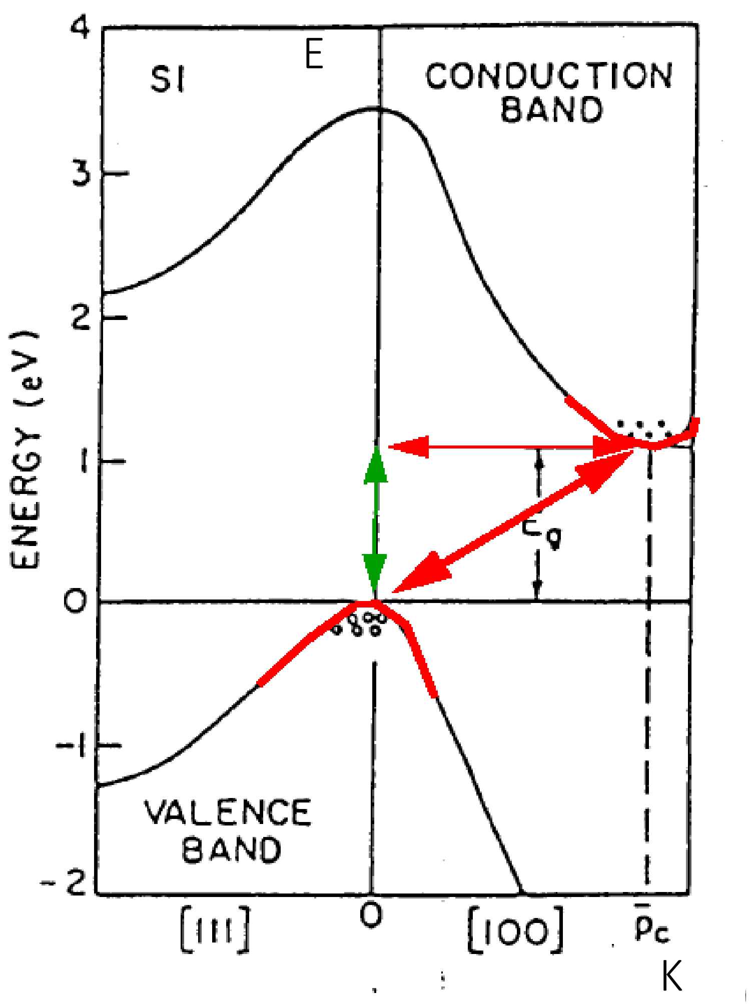


Previous year



Outline

Exercise 1.2: Band structure: photons and acoustic phonons



Questions

Consider a semiconductor with an indirect bandgap, for example silicon:

1) What is the maximum value of the horizontal axis (wave vector K) for a crystal with spacing a_p=3 Å? (the spacing a_p corresponds to the spacing of the primary cell, i.e. to half of the crystal lattice).

2) What are the wave vector K and the energy E (in eV) of a photon of wavelength λ=1 μm?

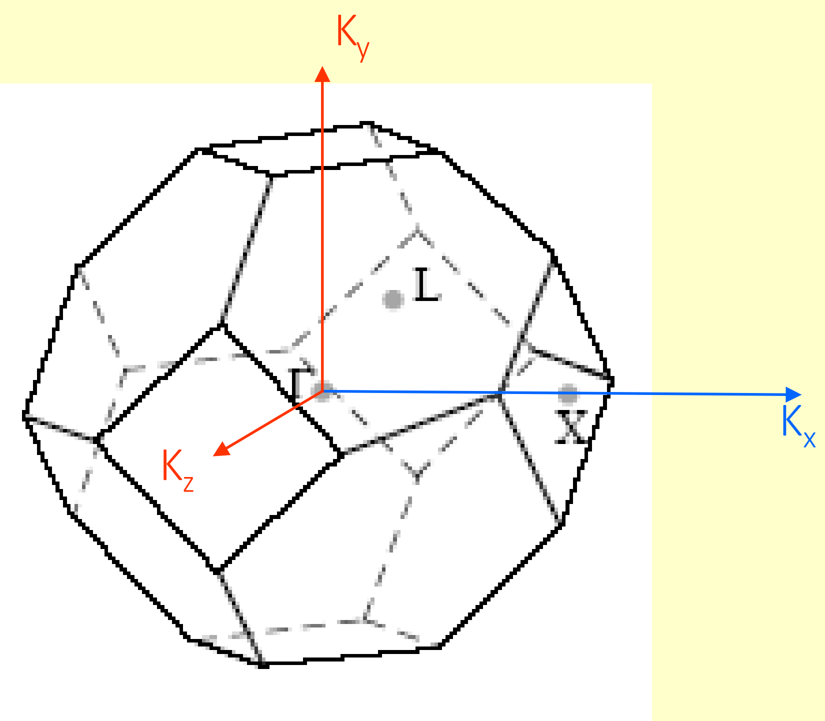
3) An acoustic phonon is a crystal vibration that propagates at the speed of sound (about v_a = 1500 m/s). What is the energy of such a phonon, knowing that its wave vector is at its maximum value (see question 1)?

Exercise 1.2: Table of summary

	Photon	Phonons
Wavelength		
Speed		
K		
E/q in [eV]		

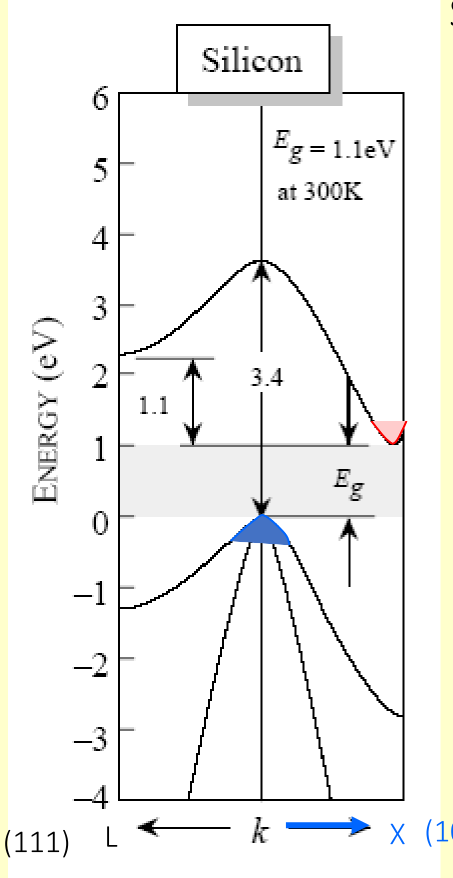
Exercise 1.2: Bands in silicon

Brillouin zone

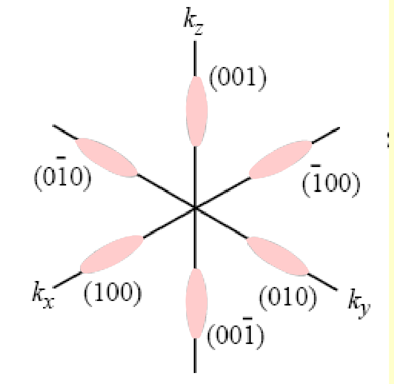


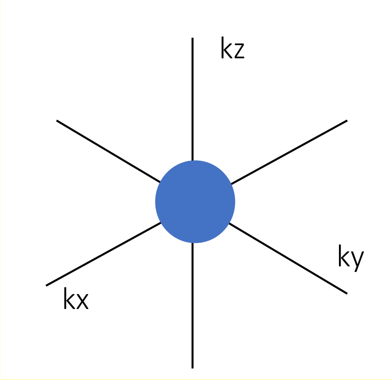
J. Singh "Semiconductor Devices"

Dispersion relation and valleys of energy



Surfaces d'énergie constante

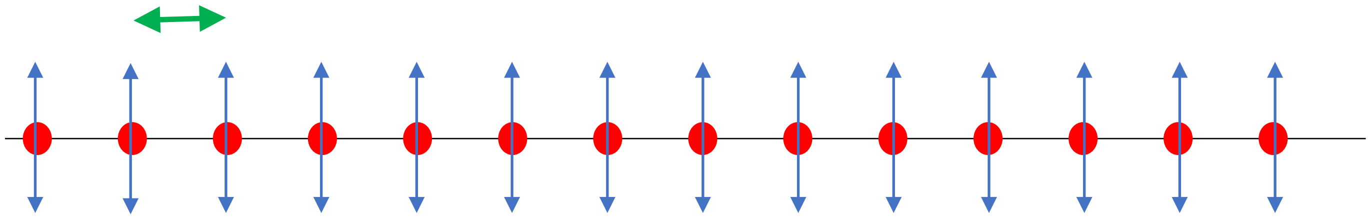


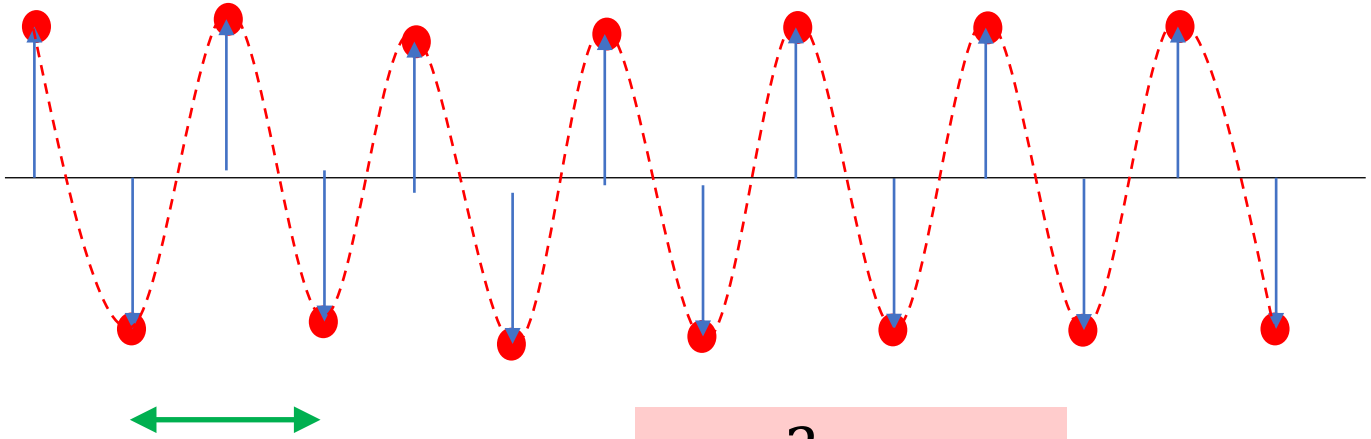


E_g=1.1eV

Exercise 1.2: Largest K-vector

a_p: Spacing between atoms





$\lambda = 2 \cdot a_p \Rightarrow$

$$K = \frac{2\pi}{\lambda} = \frac{\pi}{a_p}$$

Exercise 1.2: Main Equations

$$E_{[eV]} = \frac{h\nu}{q} \quad \text{and} \quad \lambda\nu = \text{speed} \quad \text{and} \quad K = \frac{2\pi}{\lambda}$$

Photon: $\lambda_\gamma = 1\ [\mu m]$

$$K_\gamma = \frac{2\pi}{\lambda_\gamma} = 6 \cdot 10^6\ [m^{-1}]$$

$$E_\gamma = \frac{h}{q}\frac{c}{\lambda_\gamma} = 1.24\ [eV]$$

Phonon: $\lambda_a = 0.6\ [nm]$

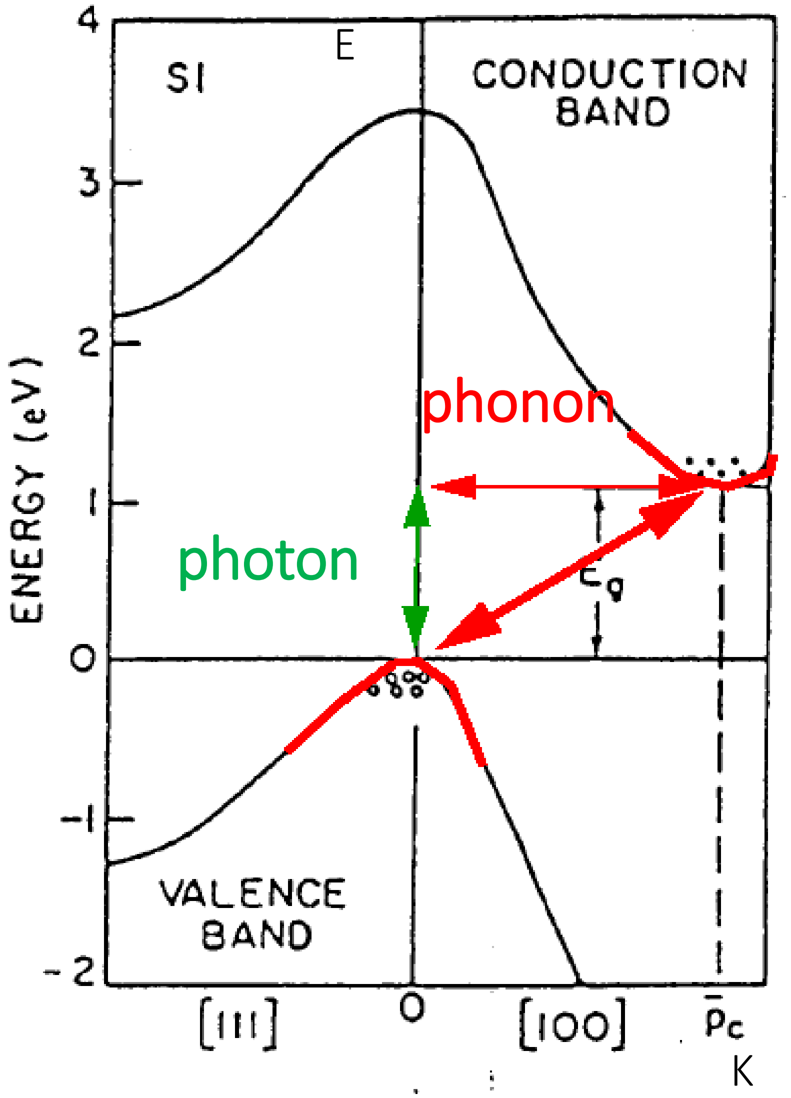
$$K_a = \frac{2\pi}{\lambda_a} = 10^{10}\ [m^{-1}]$$

$$E_a = \frac{h}{q}\frac{v_a}{\lambda_a} = 0.01\ [eV]$$

Exercise 1.2: Summary Table

	Photon	Phonons	
Wavelength	$\lambda = 1\ \mu m$	$2\ a_p = 0.6\ nm$	$\ll \lambda_\gamma$
Speed	$c = 3.10^8\ m/s$	$v_a = 1500\ m/s$	$\lll\ll c$
K	$2\pi \cdot \frac{1}{\lambda} = 6 \cdot 10^6\ m^{-1}$	$2\pi \cdot \frac{1}{2a_p} = 10^{10}\ m^{-1}$	$\gg K_\gamma$
E/q in [eV]	$\frac{1}{q} \cdot h \frac{c}{\lambda} = \frac{\hbar}{q}\quad c \cdot K_\gamma$ $= 1.24\ [eV]$	$\frac{1}{q} \cdot h \frac{v_a}{2a_p} = \frac{\hbar}{q}\quad v_a \cdot K_{phon}$ $= 0.01\ [eV]$	$\ll E_\gamma$

Exercise 1.2: Band structure: photons and acoustic phonons



$$E_\gamma = \frac{h}{q}\frac{c}{\lambda_\gamma} = 1.24\ [eV]$$

$$K_\gamma = \frac{2\pi}{\lambda_\gamma} = 6 \cdot 10^6\ [m^{-1}]$$

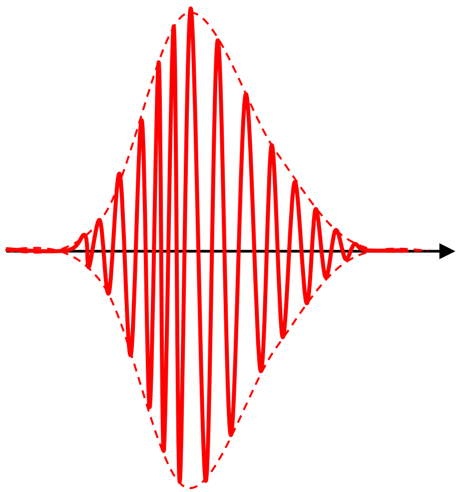
$$E_a = \frac{h}{q}\frac{v_a}{\lambda_a} = 0.01\ [eV]$$

$$K_a = \frac{2\pi}{\lambda_a} = 10^{10}\ [m^{-1}]$$

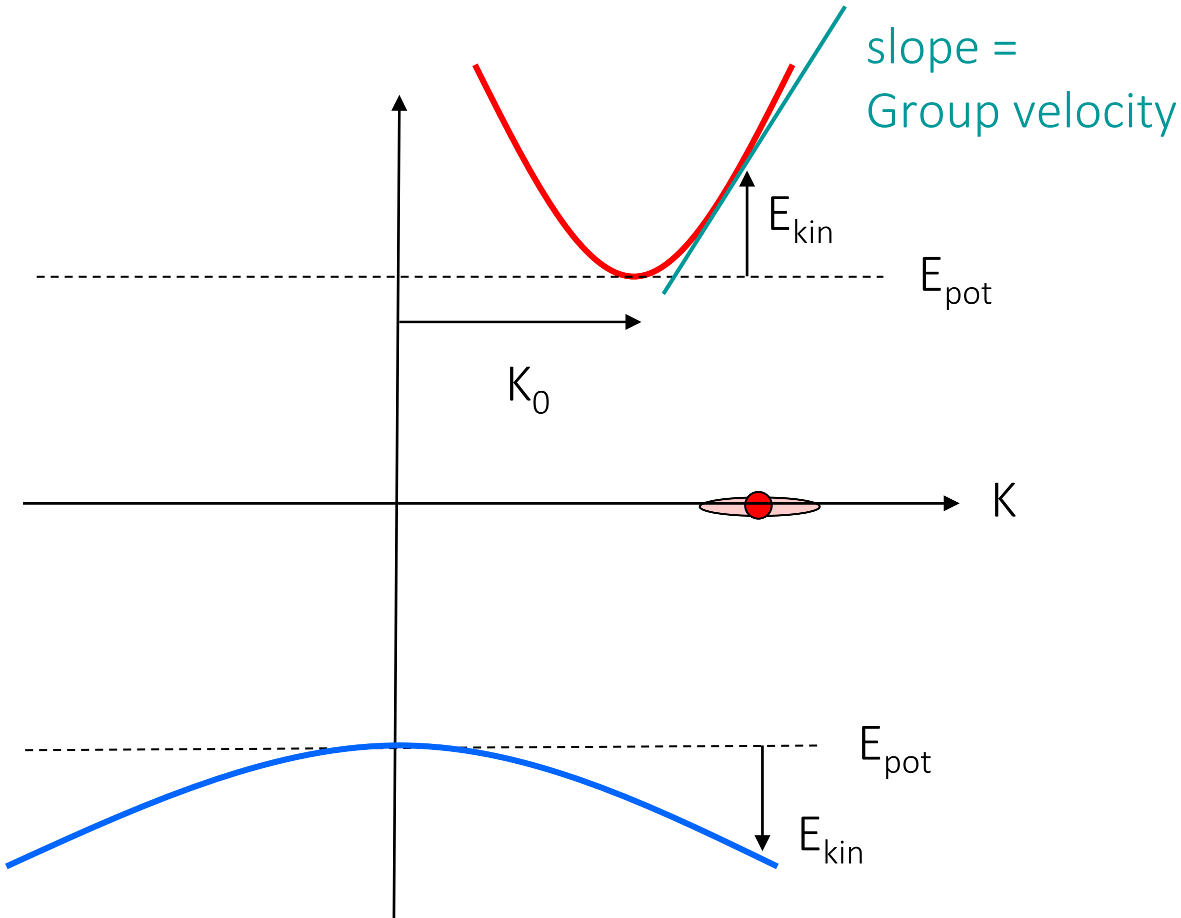
Exercise 1.2: Band structure

$$E = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m}$$

Particle =Wave packet



Carrier frequency
+
envelope



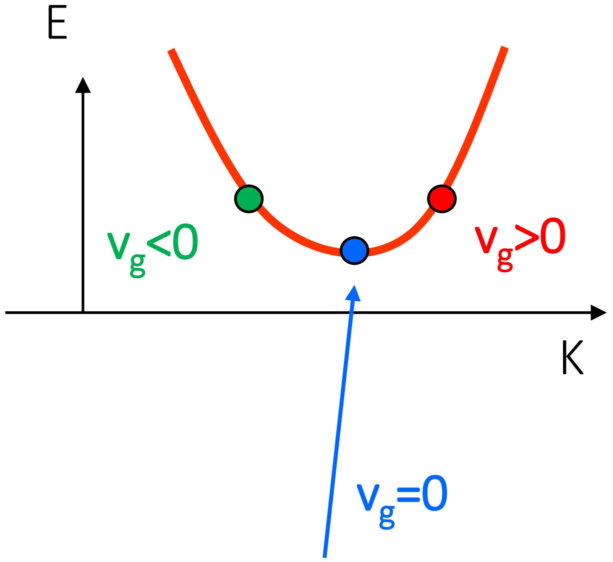
$$\frac{\partial E}{\partial k} = \frac{\hbar^2 k}{m}$$

$$\frac{\partial E}{\partial k}\frac{1}{\hbar} = \frac{p}{m} = v_g$$

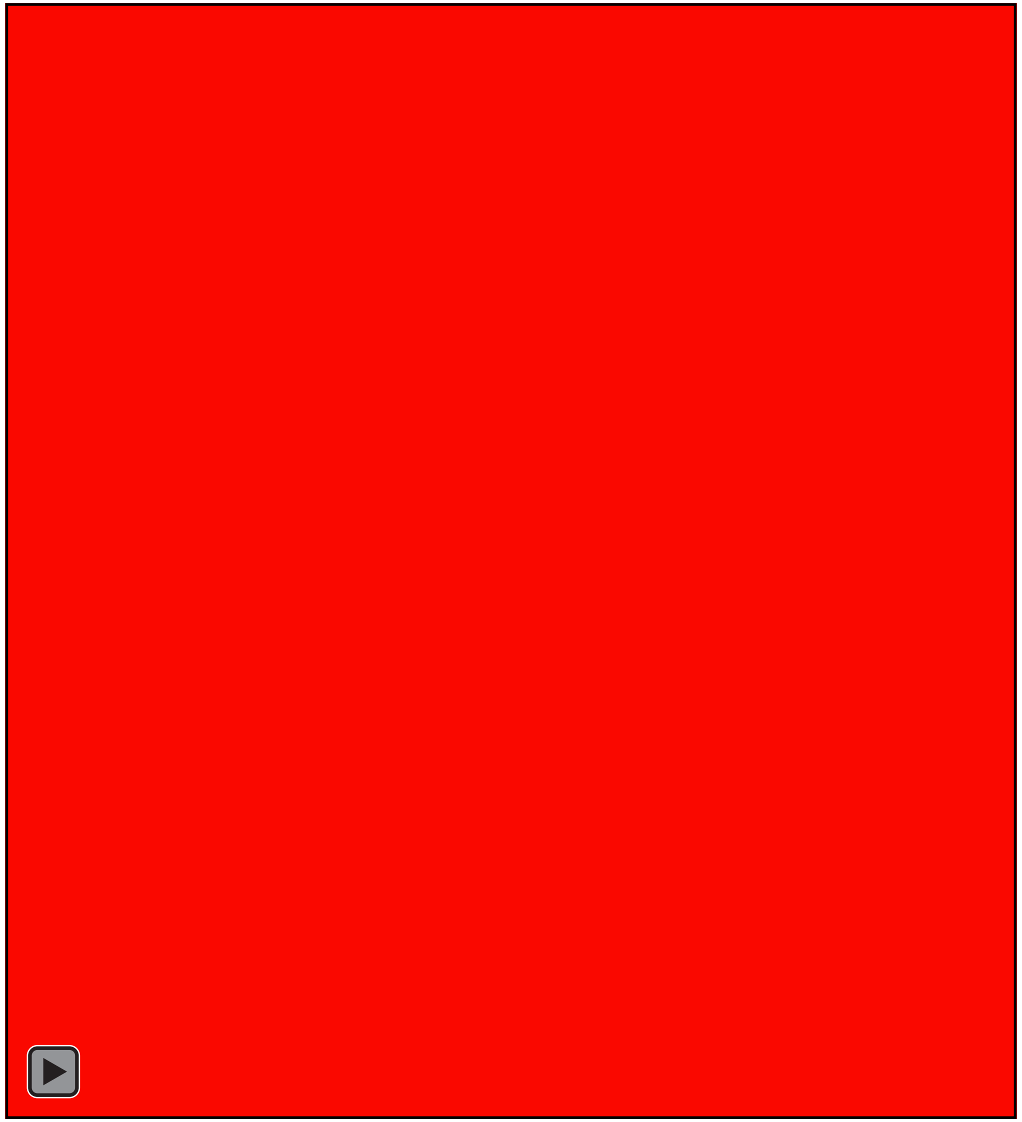
Mass =
1/curvature

$$\frac{\partial^2 E}{\partial k^2}\frac{1}{\hbar^2} = \frac{1}{m}$$

Exercise 1.2: Minima of the conduction band

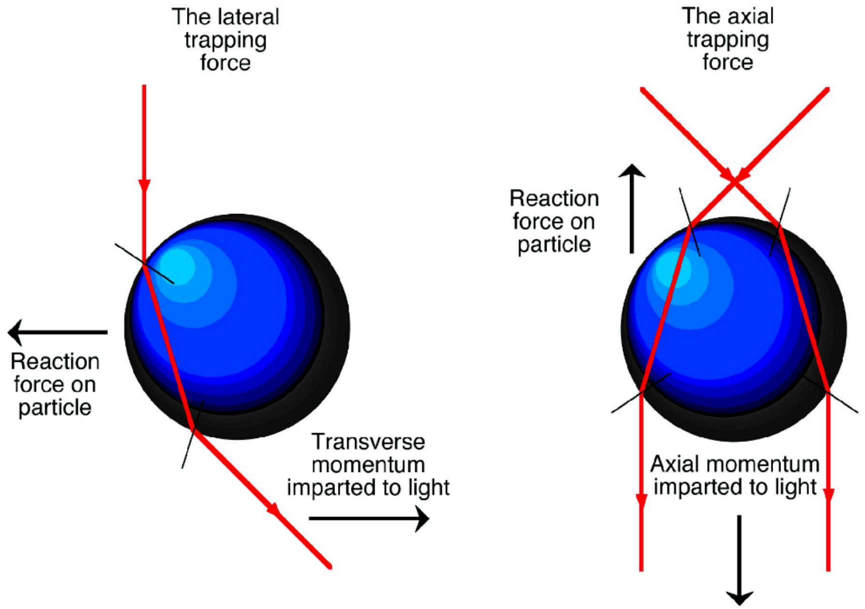


Impulse non-vanishing but no speed !!

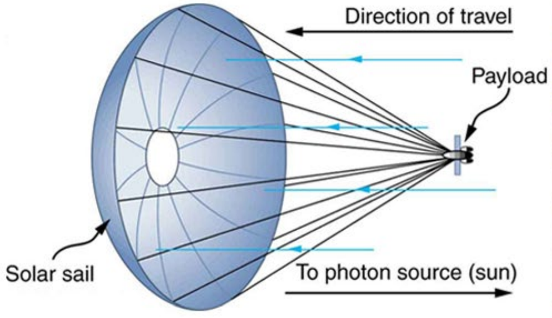


Exercise 1.2: Impulse of a photon?

Optical tweezers



Space sails



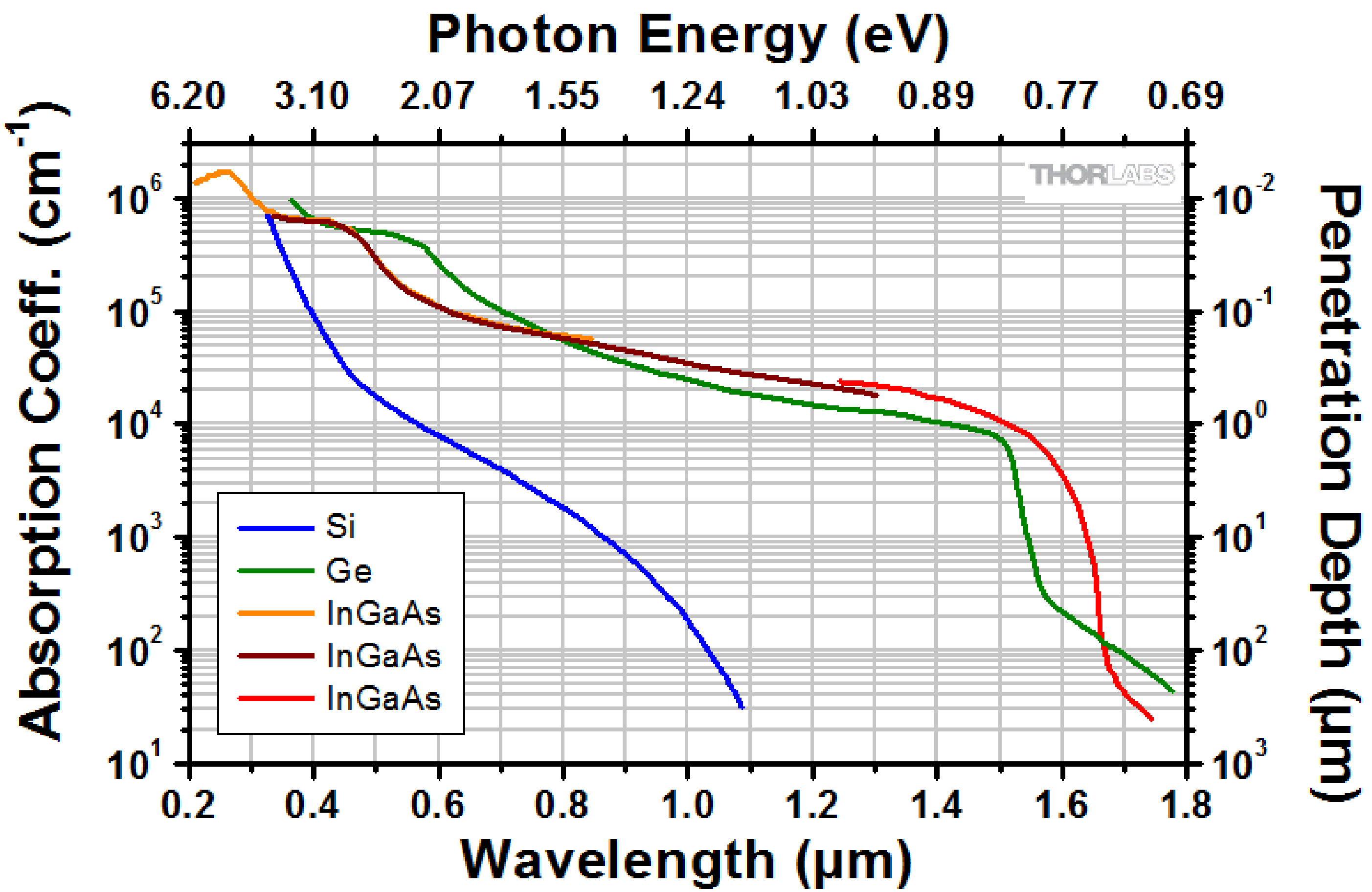
(a)


(b)

https://phys.libretexts.org/Bookshelves/College_Physics/College_Physics_1e_(OpenStax)/29%3A_Introduction_to_Quantum_Physics/29.04%3A_Photon_Momentum
https://www.analogictips.com/optical-tweezers-move-nano-objects-part-1-the-principles/

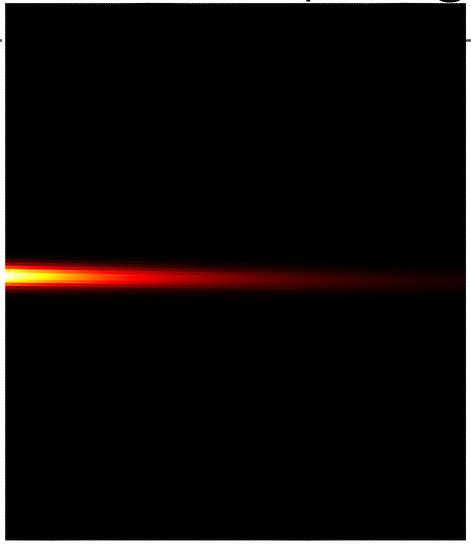
Outline

Exercise 1.3: Absorption in Semiconductors

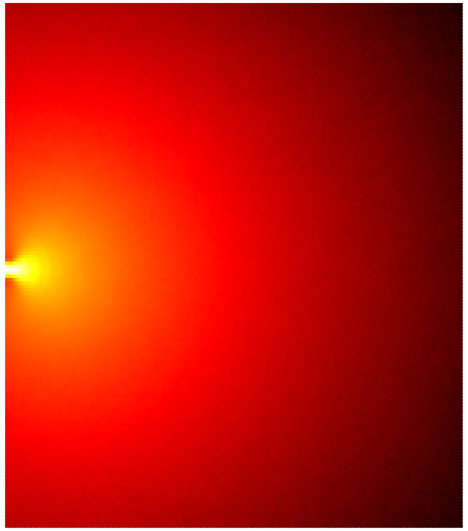


https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=14218

Exercise 1.3: (Bouger-)Beer-Lambert in tissue



Absorption



Scattering

Questions

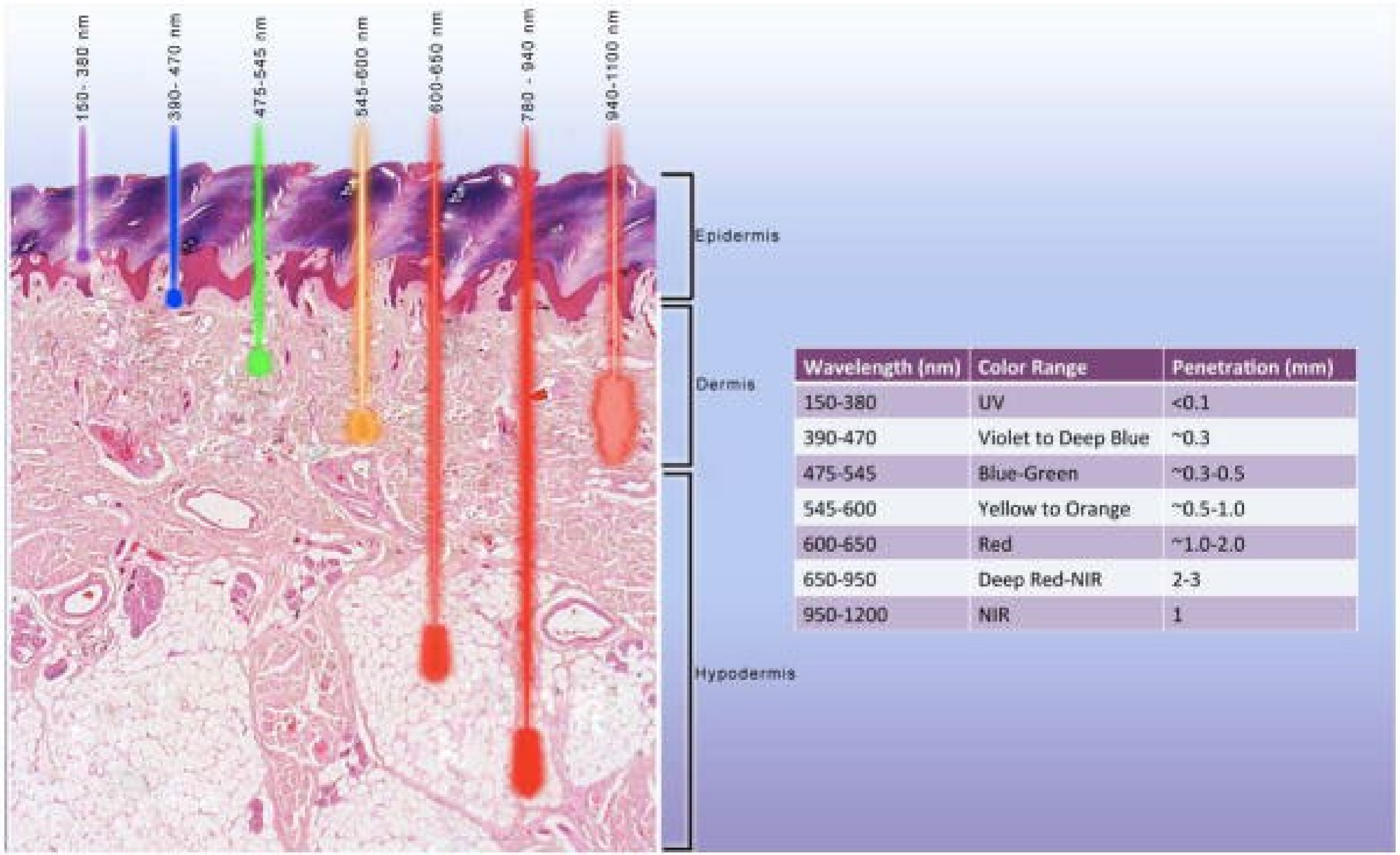
In tissue, scattering can represent an important component in addition to absorption

- Can you think of the related implications?
- Which kind of measurement set-up could be used?

μ *= attenuation coefficient*

$$I(z) = I_0 e^{-\mu \cdot z}, with\ \mu = \mu_a + \mu_s$$

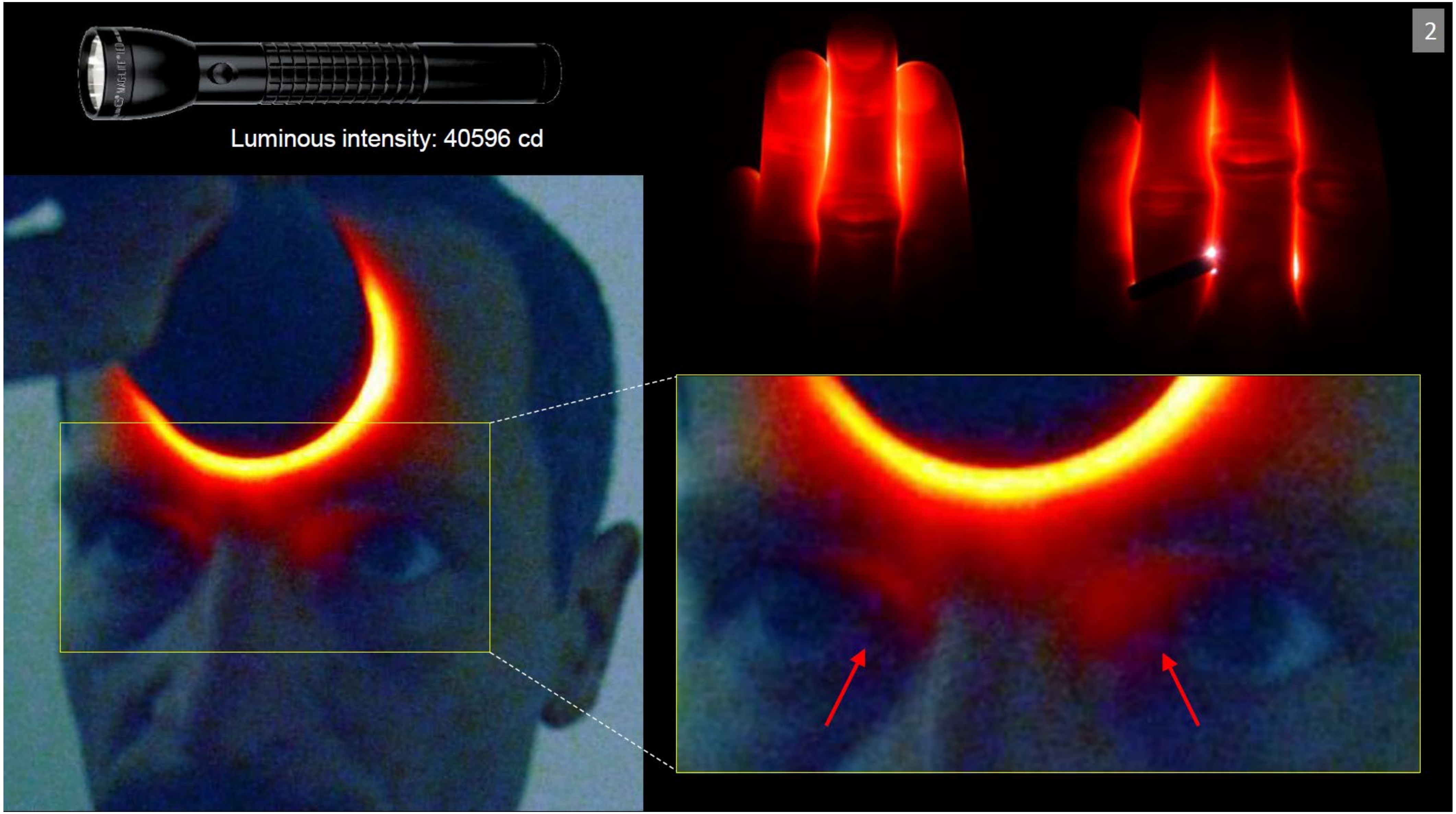
Exercise 1.3: (Bouger-)Beer-Lambert in tissue



Wavelength (nm)	Color Range	Penetration (mm)
150-380	UV	<0.1
390-470	Violet to Deep Blue	~0.3
475-545	Blue-Green	~0.3-0.5
545-600	Yellow to Orange	~0.5-1.0
600-650	Red	~1.0-2.0
650-950	Deep Red-NIR	2-3
950-1200	NIR	1

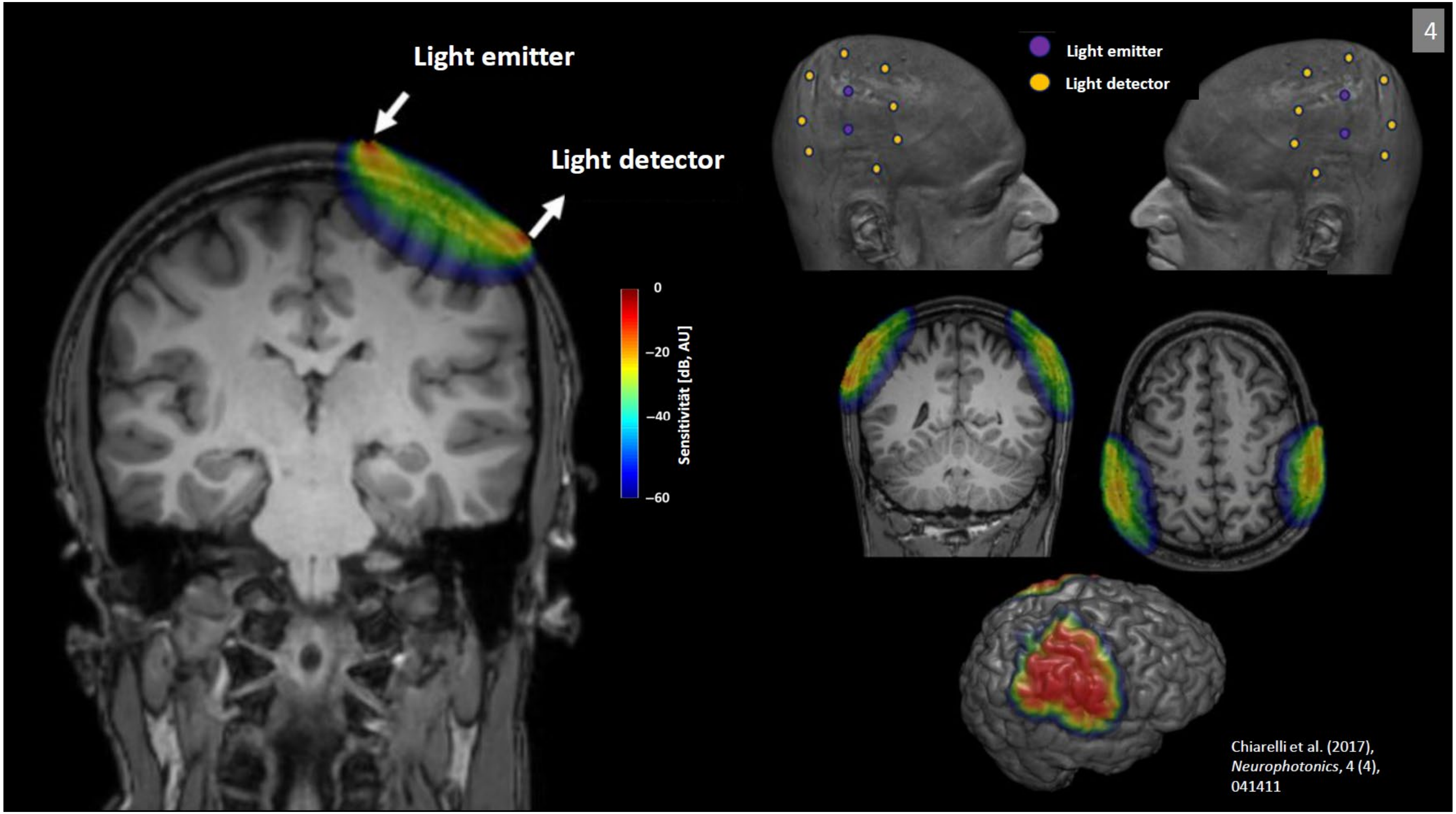
Avci, Pinar, et al. "Low-level laser (light) therapy (LLLT) in skin: stimulating, healing, restoring." *Seminars in cutaneous medicine and surgery*. Vol. 32. No. 1. NIH Public Access, 2013.

Exercise 1.3: (Bouger-)Beer-Lambert in tissue



Felix Scholkmann, Univ. Zurich & Univ. Bern, 2023

Exercise 1.3: (Bouger-)Beer-Lambert in tissue



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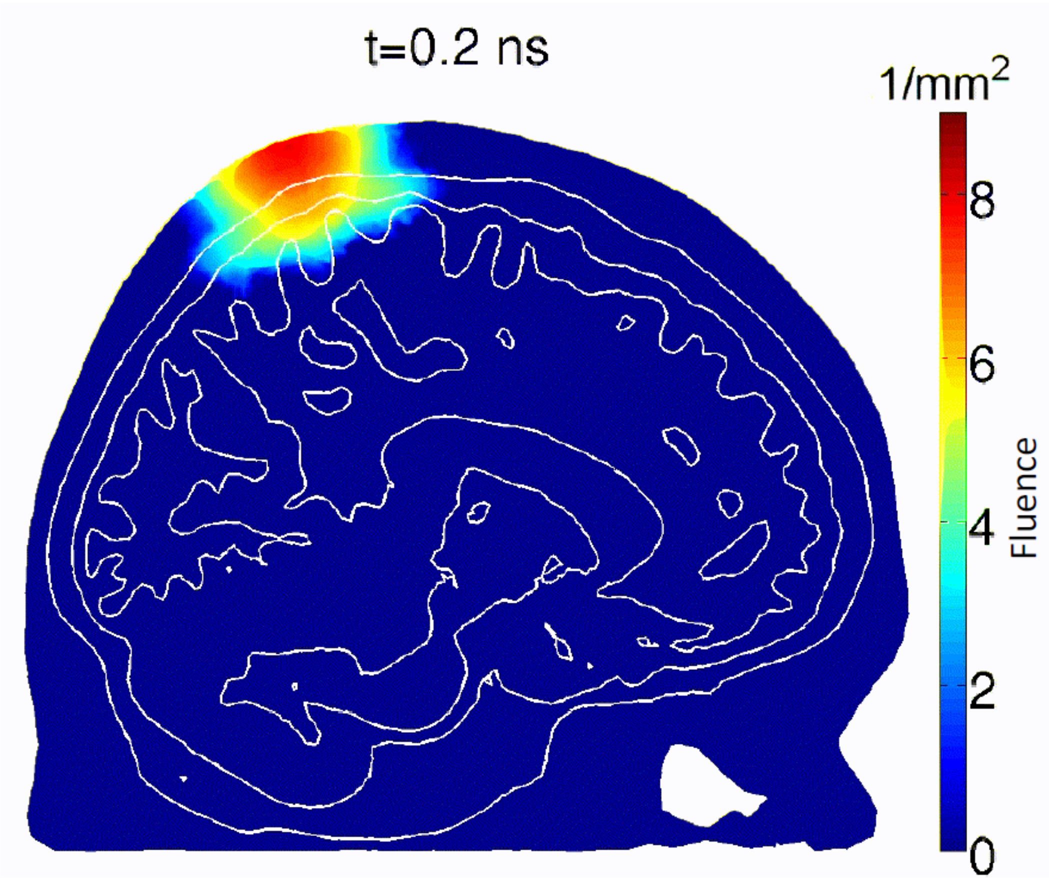
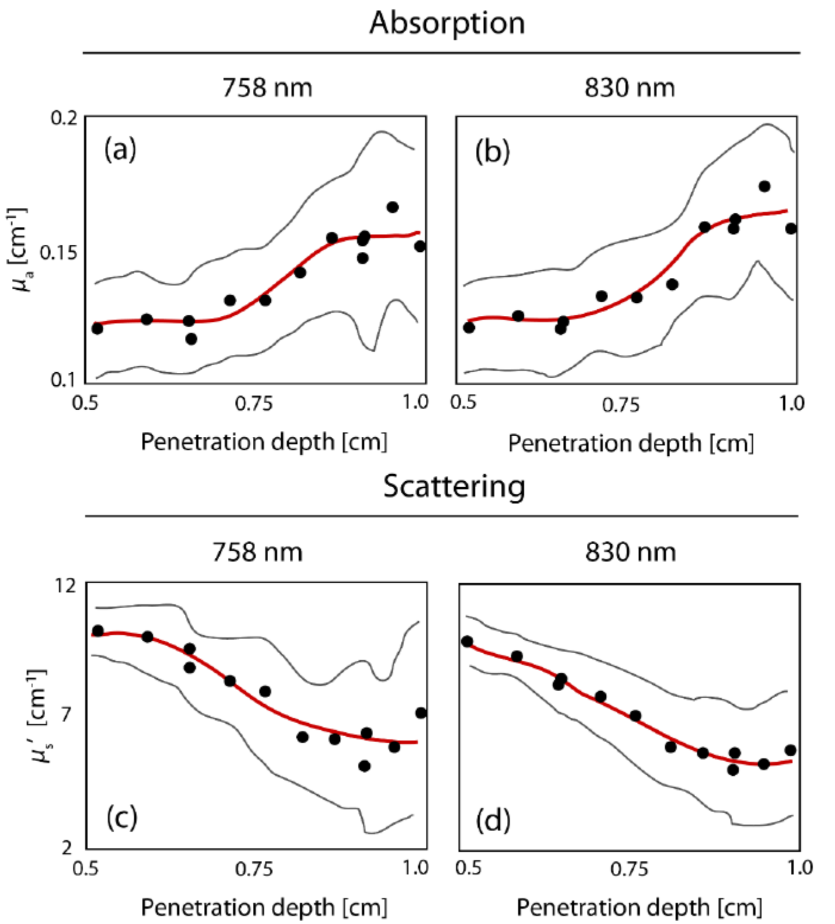
Exercise 1.3: (Bouger-)Beer-Lambert in tissue

5

Light propagation in head tissue



Fang, Q. (2010). Mesh-based Monte Carlo method using fast ray-tracing in Plücker coordinates. *Biomedical Optics Express*, 1(1), 165-175.

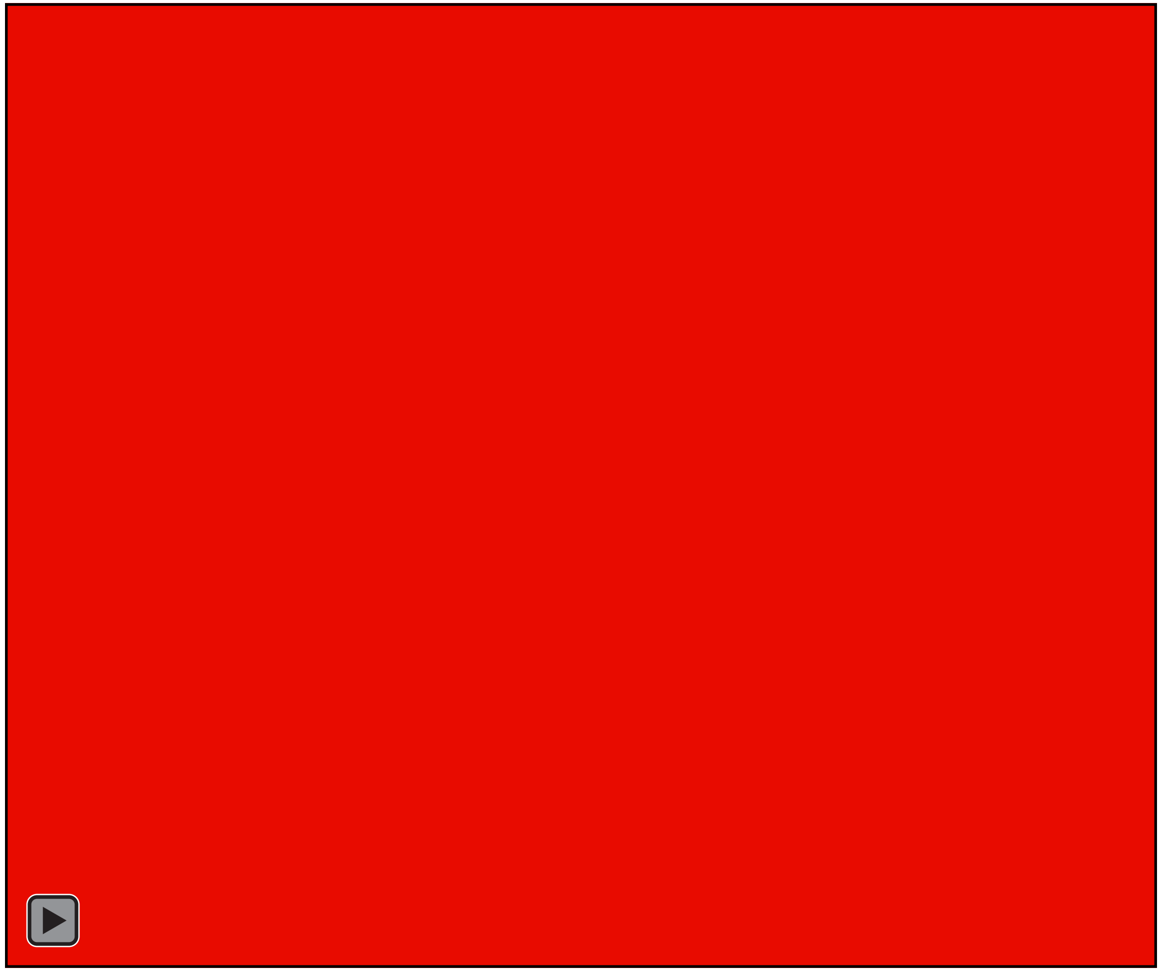


In vivo FD-NIRS measurements

Choi et al. (2004) Noninvasive determination of the optical properties of adult brain: near-infrared spectroscopy approach. *Journal of Biomedical Optics*, 9 (1): 221–229.

Felix Scholkmann, Univ. Zurich & Univ. Bern, 2023

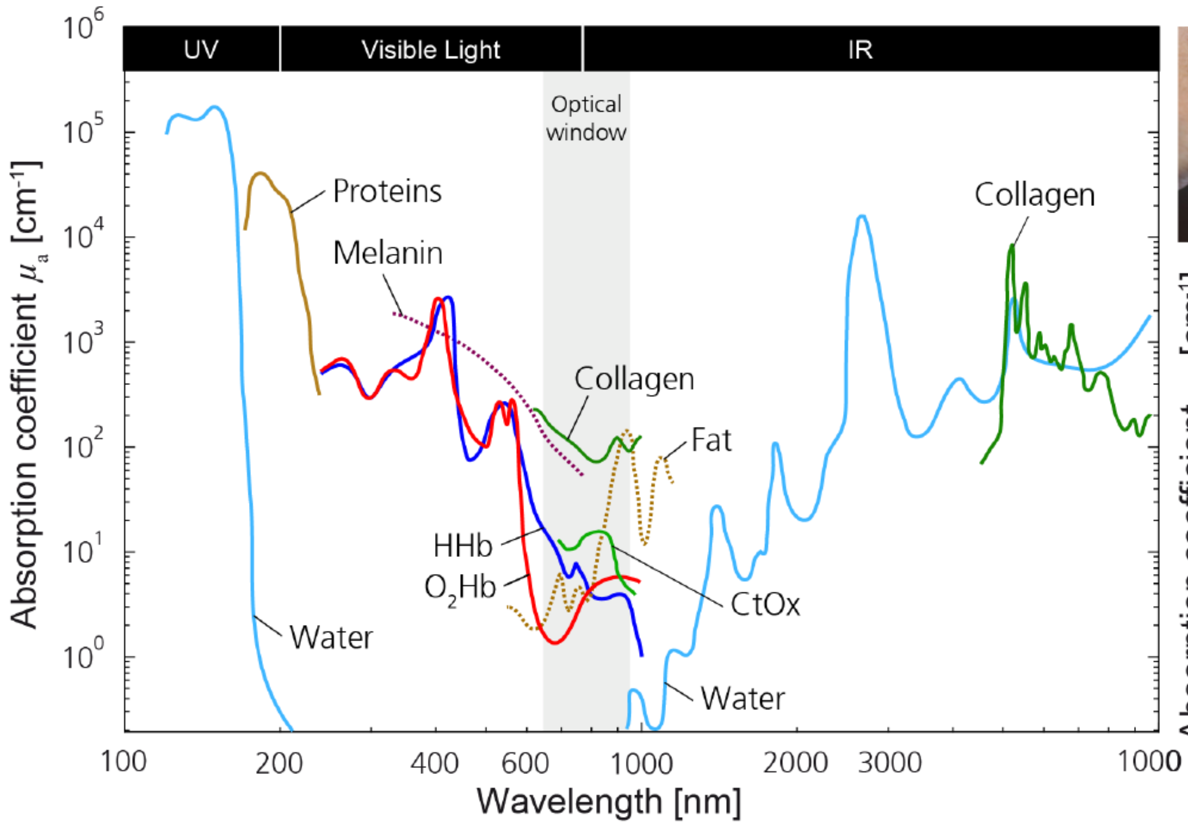
Exercise 1.3: (Bouger-)Beer-Lambert in tissue

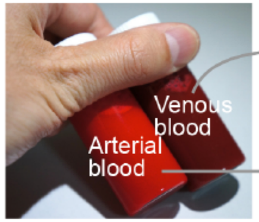


Q. Fang, BiomedOpEx(1) 2010, Supp.Mat.

Exercise 1.3: (Bouger-)Beer-Lambert in tissue

Chromophores and hemoglobin spectra

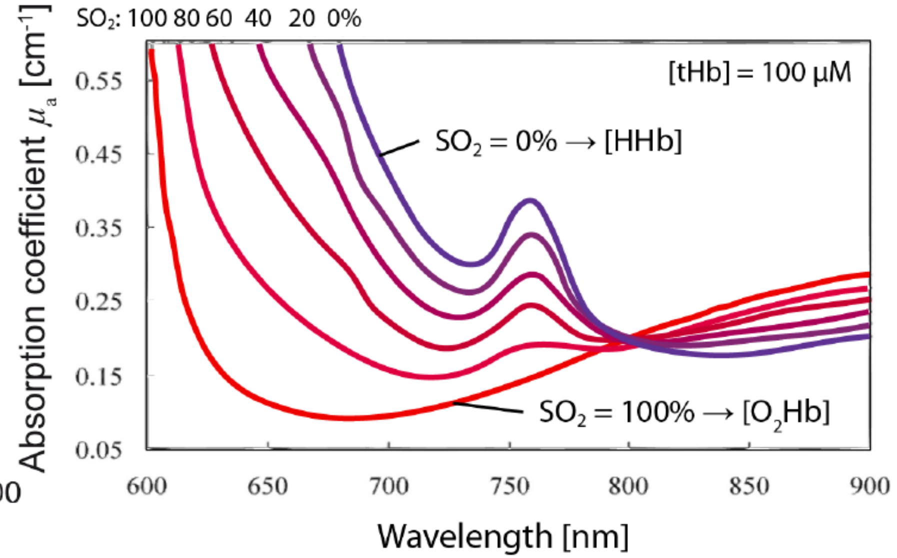




$[O_2Hb]$: low
$[HHb]$: high

$[O_2Hb]$: high
$[HHb]$: low

Blood color
↓
Blood oxygenation



Scholkmann et al. (2014). A review on continuous wave functional near-infrared spectroscopy and imaging instrumentation and methodology. *Neuroimage*, 85, 6-27.

Franceschini et al. (1985). Near-infrared spiroximetry: noninvasive measurements of venous saturation in piglets and human subjects. *J. Appl. Physiol.*, 92 (1), 372-384.

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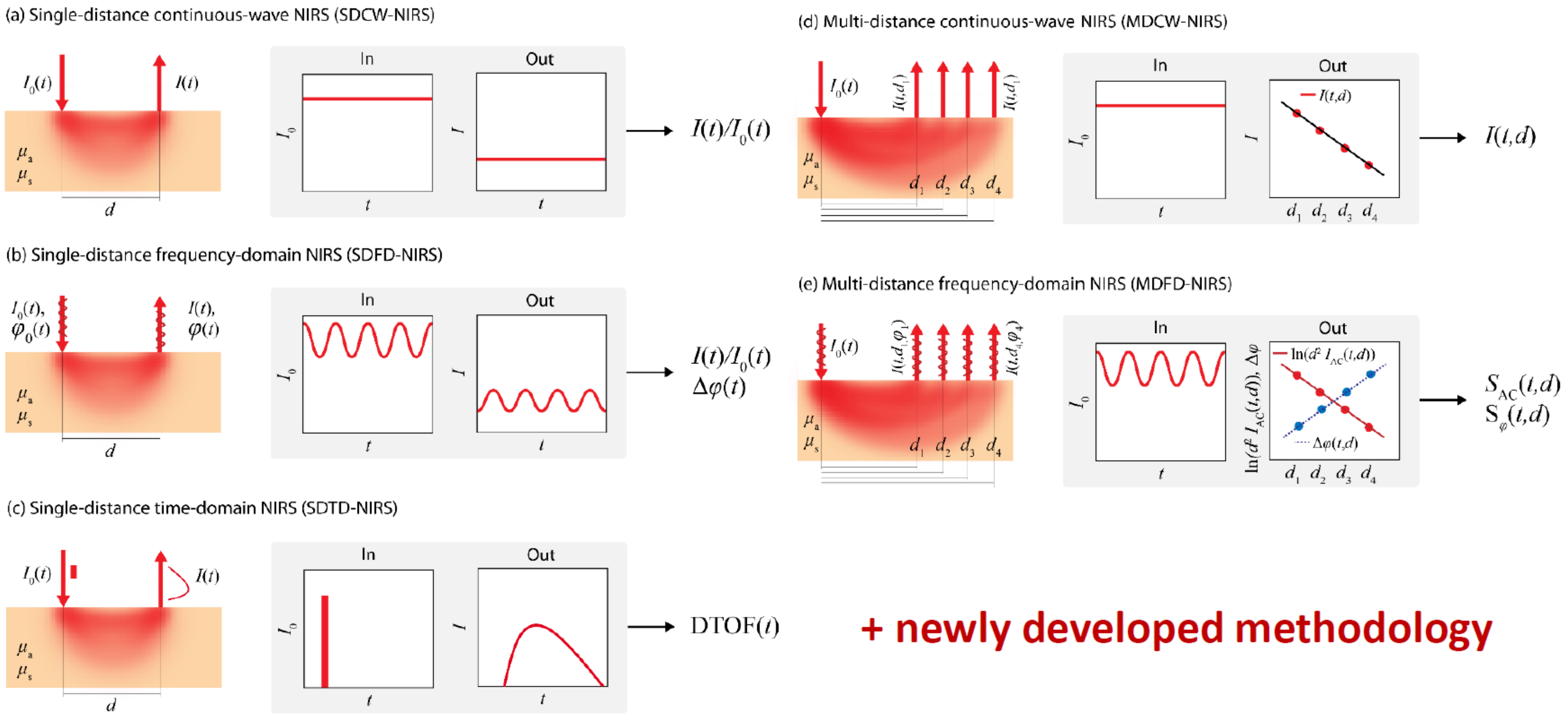
Exercise 1.3: (Bouger-)Beer-Lambert in tissue

9

fNIRS & NIRCO: Technical implementations



+ newly developed methodology

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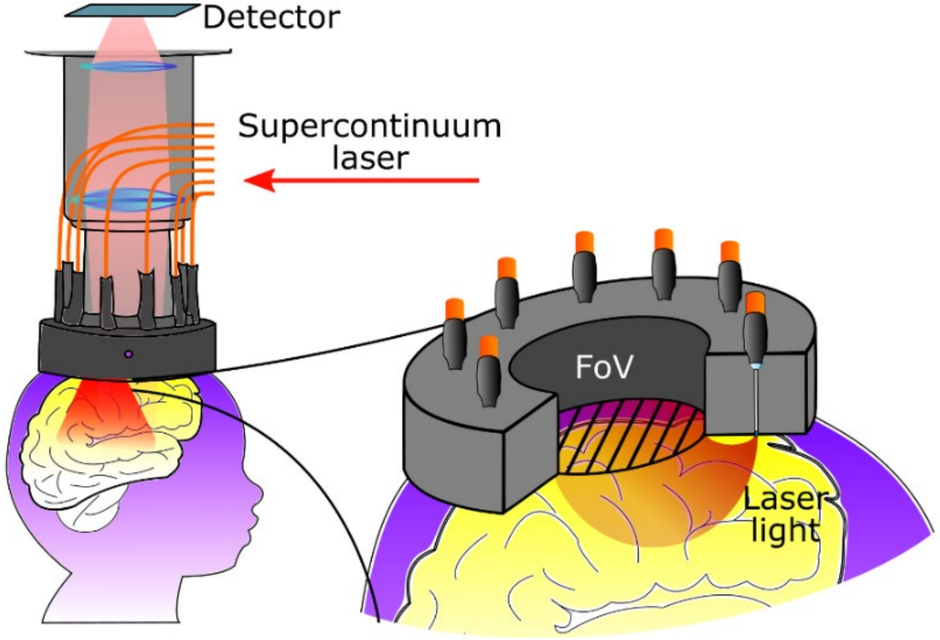
Exercise 1.3: Near-infrared Optical Tomography (NIROT) Basics

Preterm brain imaging



Martin Wolf et al, UZH

Outline

Homework 1.1: Boltzmann vs. FD vs. BE

1) Sketch the Boltzmann, Fermi-Dirac and Bose-Einstein distributions at T=300K.

2) For a single state, how do a) photons, b) electrons, and c) gas atoms distribute?

3) For a two-level system describe all the possible configurations for the three kind of particles, assuming to have either two photons, or two electrons, or two gas atoms.

   3.1) How many different configurations are possible for each case?

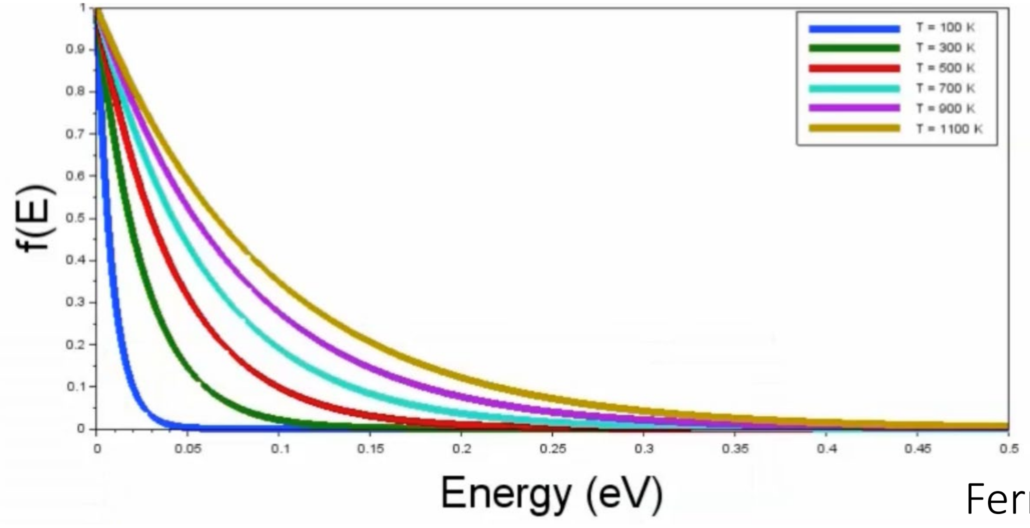
   3.2) If 10 photons arrive at the same time, can they all enter into the same state?

   3.3) If 10 electrons try to enter the same state, what happens?

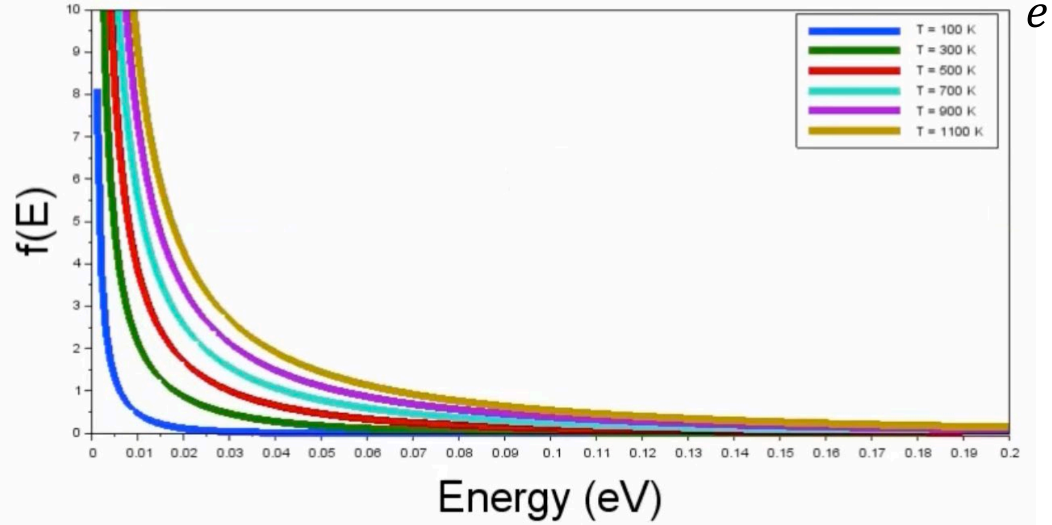
   3.4) If 10 gas atoms try to enter the system, how do they distribute?

Homework 1.1 Solution

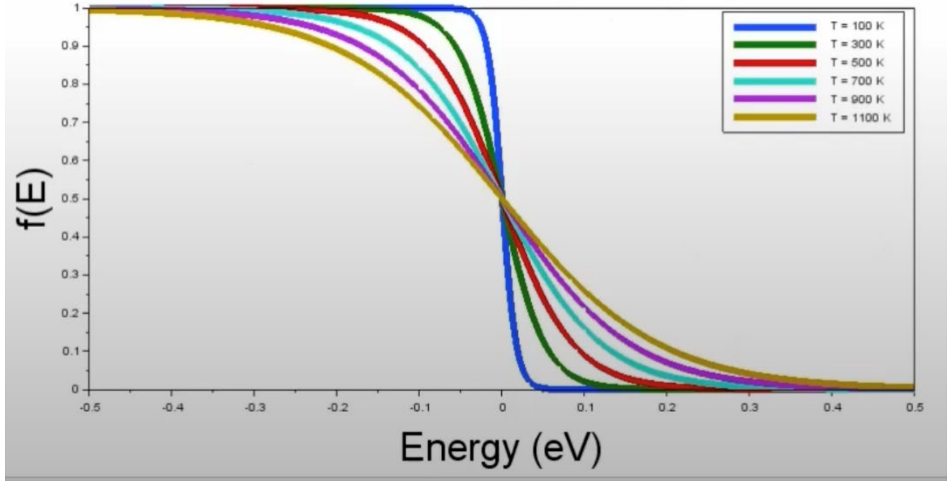
Boltzmann distribution $f_{MB}(E) = \frac{1}{e^{\frac{E-\mu}{kT}}}$



Bose-Einstein distribution $f_{BE}(E) = \frac{1}{e^{\frac{E-\mu}{kT}} - 1}$



Fermi-Dirac distribution



$$f_{FD}(E) = \frac{1}{e^{\frac{E-\mu}{kT}} + 1}$$

Source: $https://www.youtube.com/watch?v = QZN2oNRVai8\&ab\_channel = PracticalHOPE\%28Experimentsinphysics\%29$

Homework 1.1 Solution

2) For a single state, how do a) photons, b) electrons, and c) gas atoms distribute?

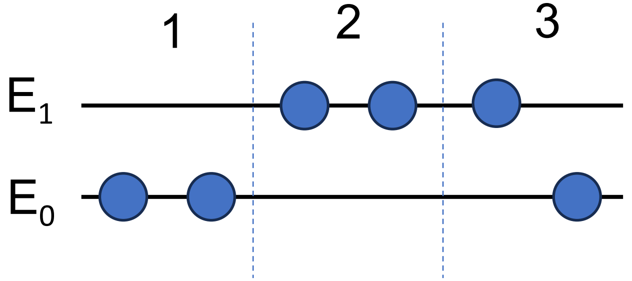
Photons follow a Bose-Einstein, electrons a Fermi-Dirac, and gas atoms a Boltzmann distribution.

3) For a two-level system describe all the possible configurations for the three kinds of particles, assuming to have either two photons, or two electrons, or two gas atoms.

Configuration 1: photons.

Particles are identical, multiple occupancy allowed.

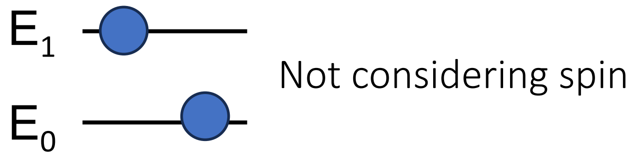
→ 3 possible configuration: both in E_0, both in E_1, or one in each state.



Configuration 2: electrons.

Particles are identical, Pauli exclusion principle applies (max 1 per state, or 2 if we consider the opposite spin).

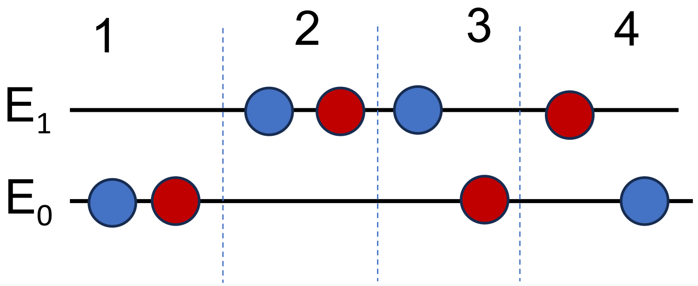
→ 1 possible configuration: one in each state.



Configuration 3: gas atoms.

Particles are distinguishable, independent choice of state.

→ 4 possible configurations: both in E_0, both in E_1, atom A in E_0 and B in E_1, atom B in E_0 and A in E_1.



Homework 1.1 Solution

3.2) If 10 photons arrive at the same time, can they all enter into the same state?

→ Yes, since they follow a Bose-Einstein distribution.

3.3) If 10 electrons try to enter the same state, what happens?

→ Only one electron (or 2 if we consider opposite spin) can enter a given state.

3.4) If 10 gas atoms try to enter the system, what happens?

→ They distribute according to a Boltzmann distribution so there are more atoms in the first (ground) level and less on the second (excited). The real numbers depend on the energy difference between the levels and the temperature.