MICRO-523: Optical Detectors

Week One: Light - Solutions

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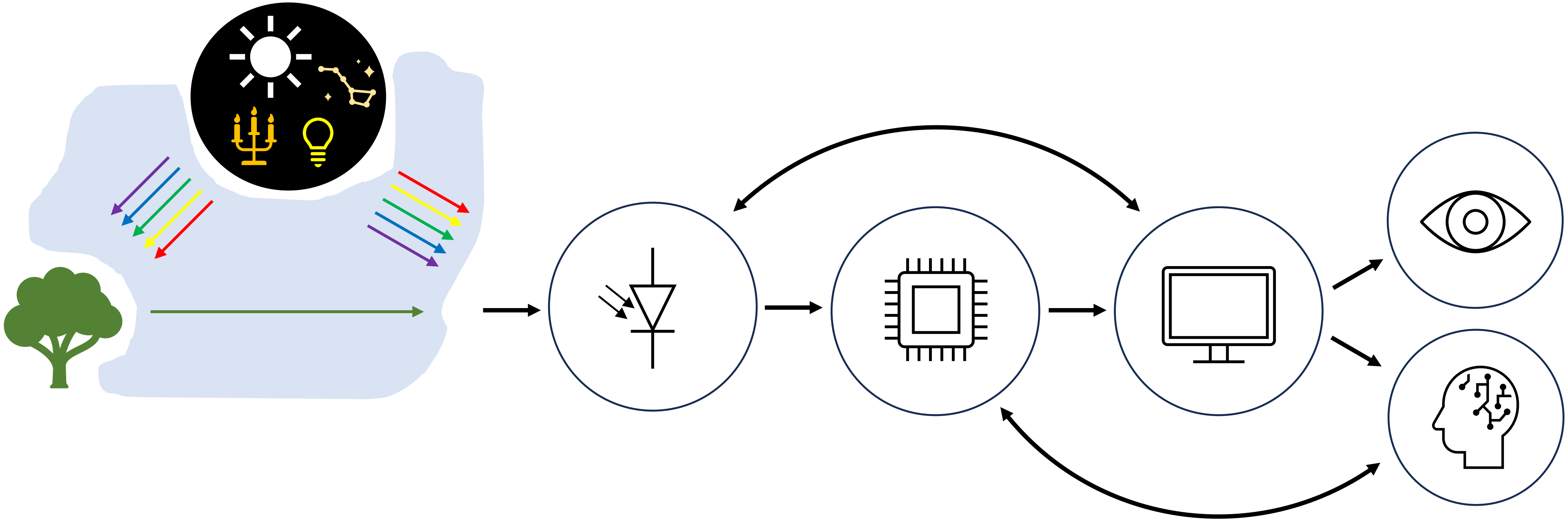
Based on MICRO-523, P.-A. Besse, 2023

TAs: Samuele Bisi, Yazan Lampert

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:

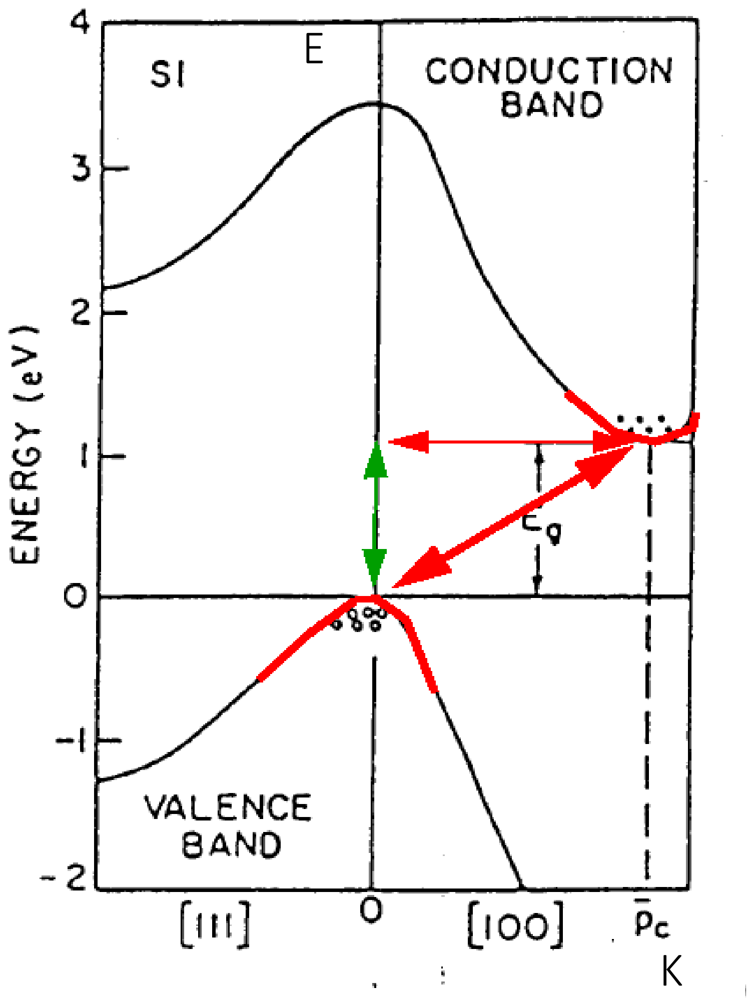
- What are their main parameters?
- Can you think of examples?

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, …

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?

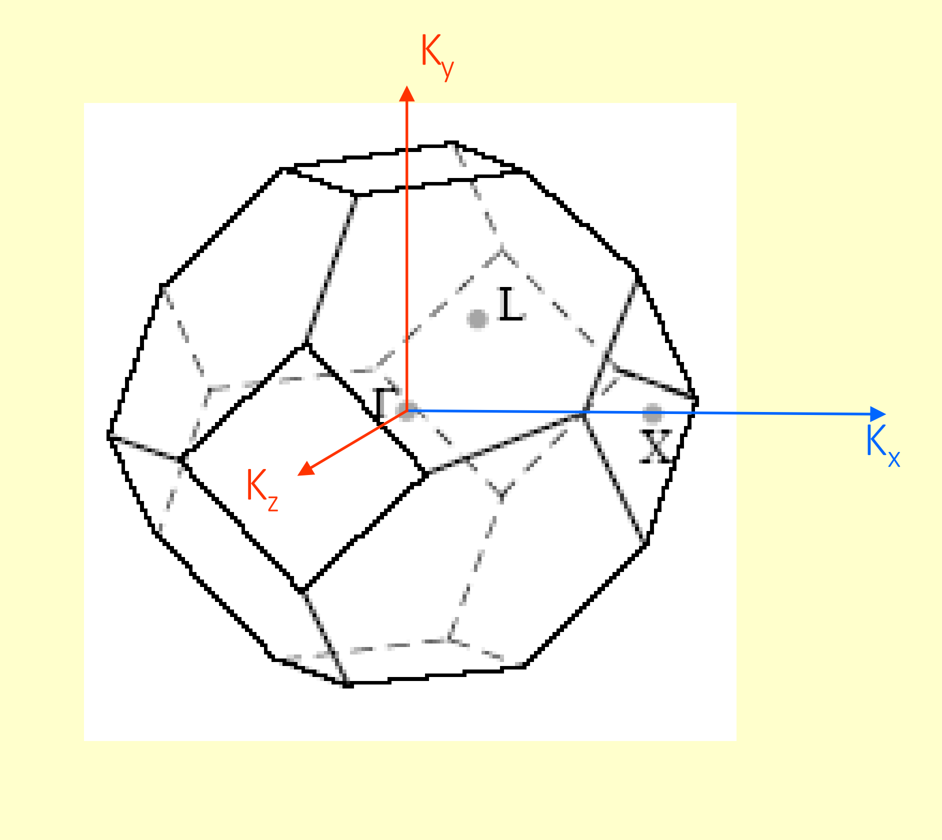
3) An acoustic phonon is a crystal vibration that propagates at the speed of sound (about v_a = 1500 m/s). What is the energy of such a phonon, knowing that its wave vector is at its maximum value (see question 1)?

Exercise 1.2: Table of summary

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

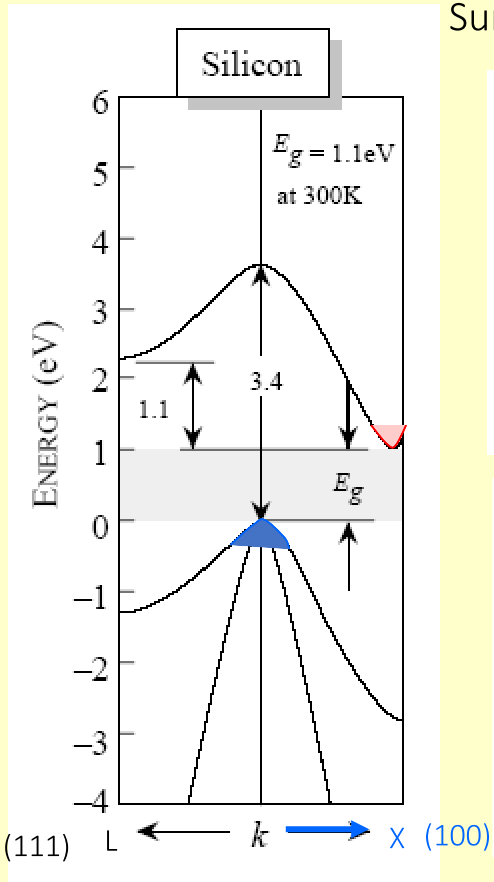
Exercise 1.2: Bands in silicon

Brillouin zone

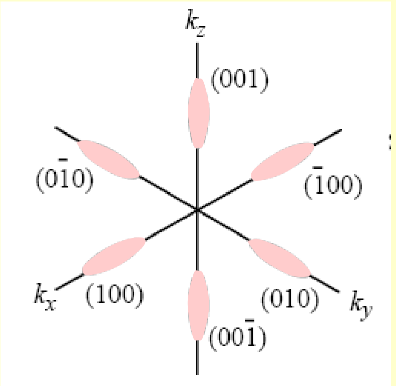


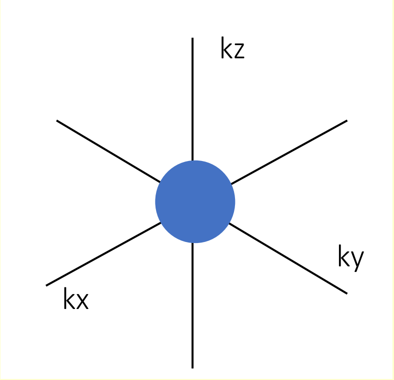
J. Singh "Semiconductor Devices"

Dispersion relation and valleys of energy



Surfaces d'énergie constante

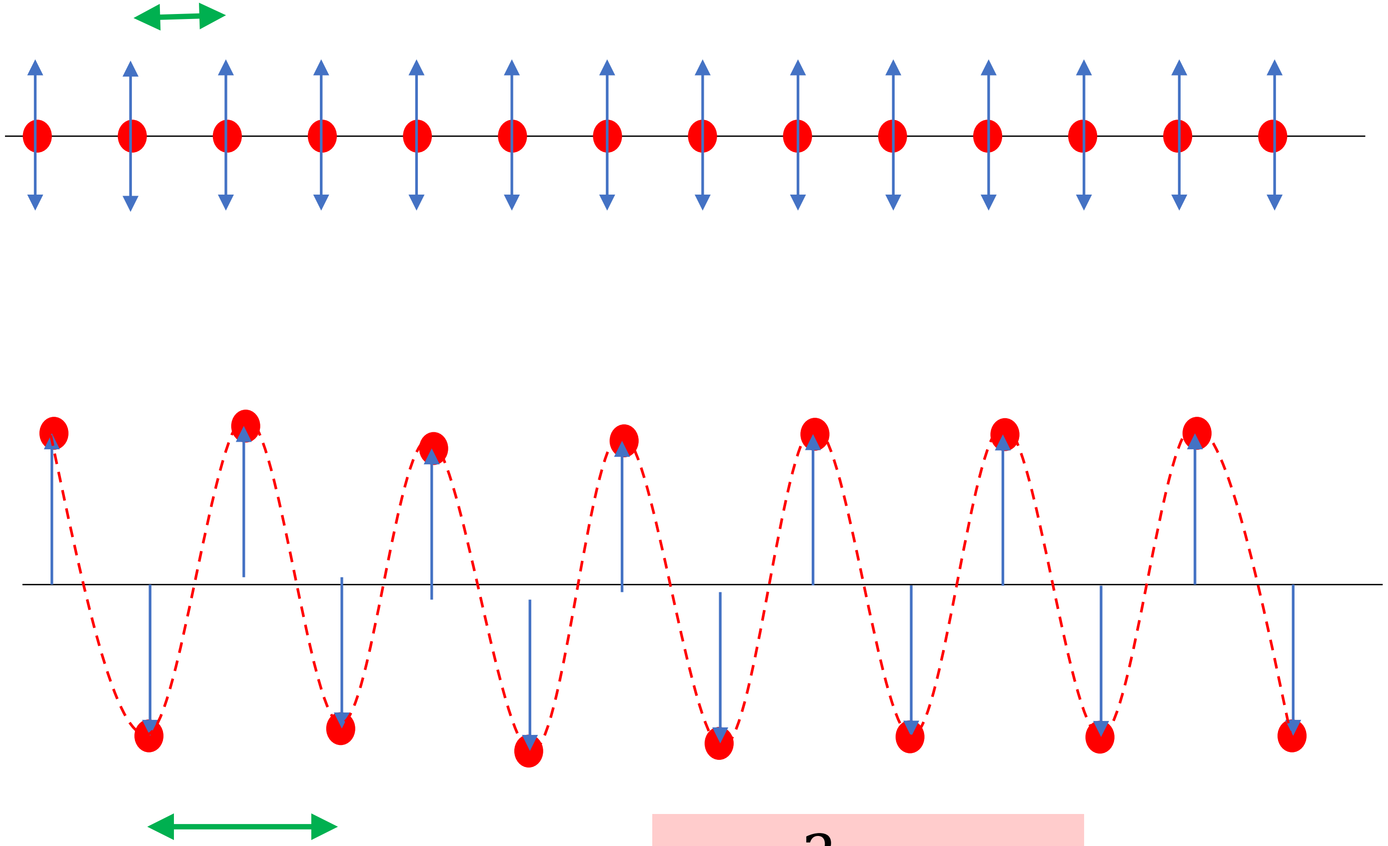




E_g=1.1eV

Exercise 1.2: Largest K-vector

a_p: Spacing between atoms



$\lambda = 2 \cdot a_p$ $\Longrightarrow$

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

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

$$\Rightarrow \quad K_\gamma = \frac{2\pi}{\lambda_\gamma} = 6 \cdot 10^6\ [m^{-1}] \qquad E_\gamma = \frac{h}{q}\frac{c}{\lambda_\gamma} = 1.24\ [eV]$$

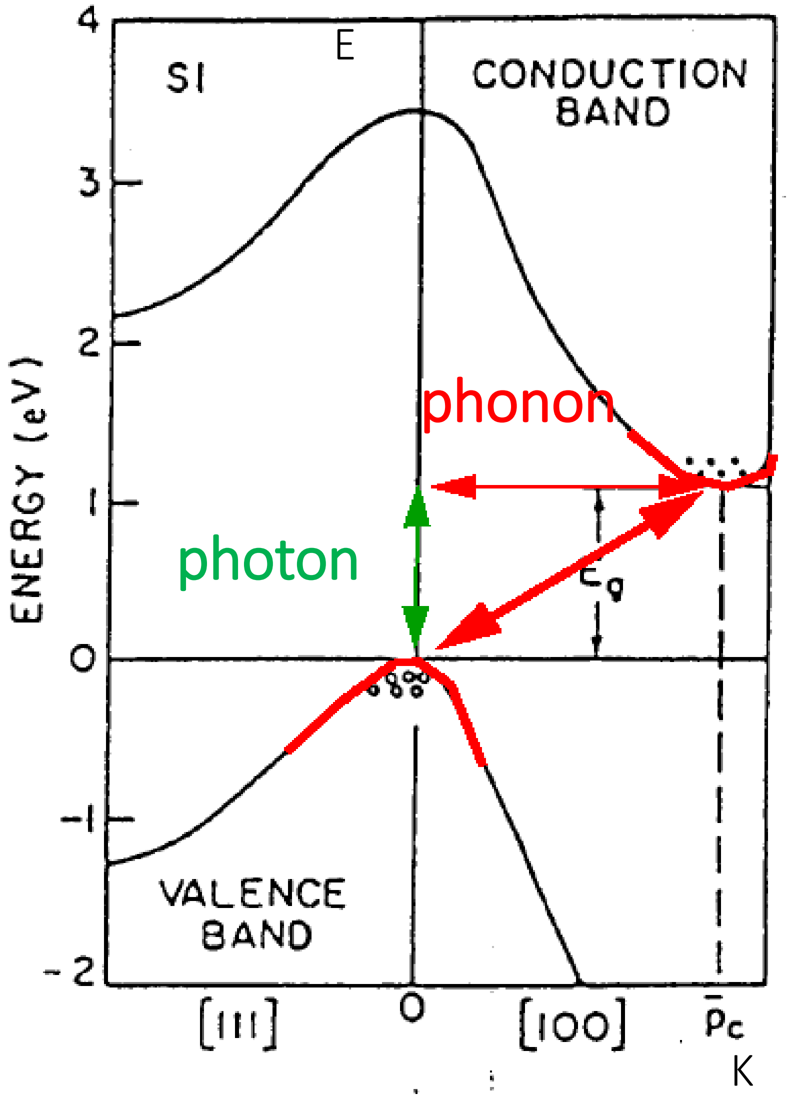
Phonon: $\lambda_a = 0.6\ [nm]$

$$\Rightarrow \quad K_a = \frac{2\pi}{\lambda_a} = 10^{10}\ [m^{-1}] \qquad E_a = \frac{h}{q}\frac{v_a}{\lambda_a} = 0.01\ [eV]$$

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



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

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

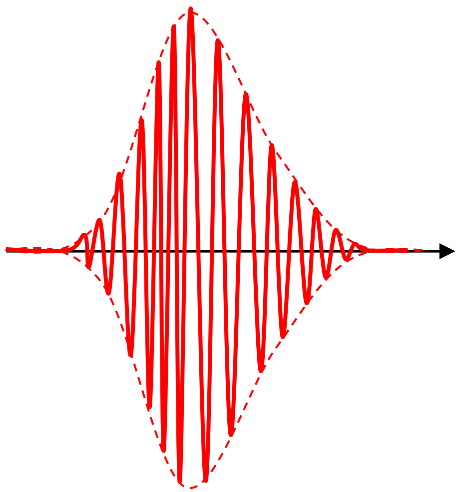
$$E_a = \frac{h}{q}\frac{v_a}{\lambda_a} = 0.01\ [eV]$$

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

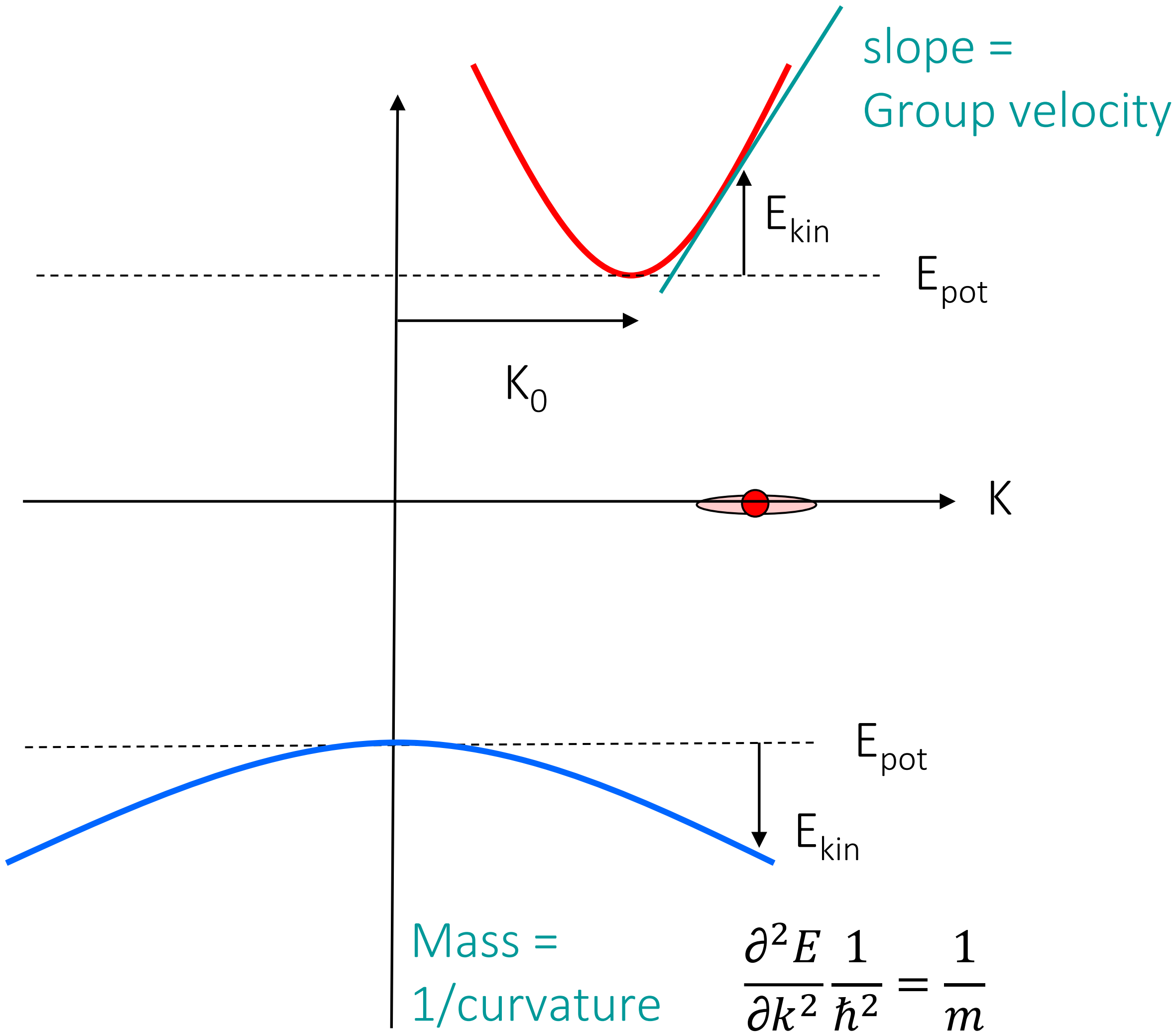
Exercise 1.2: Band structure

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

Particle =Wave packet



Carrier frequency
+
envelope

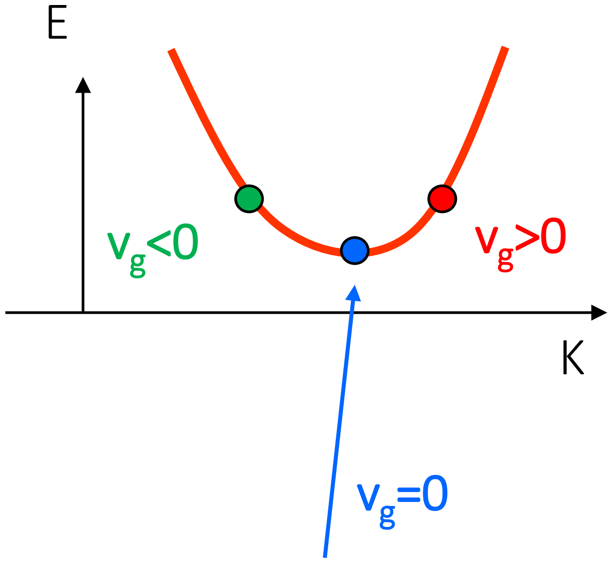


$$\frac{\partial E}{\partial k} = \frac{\hbar^2 k}{m}$$

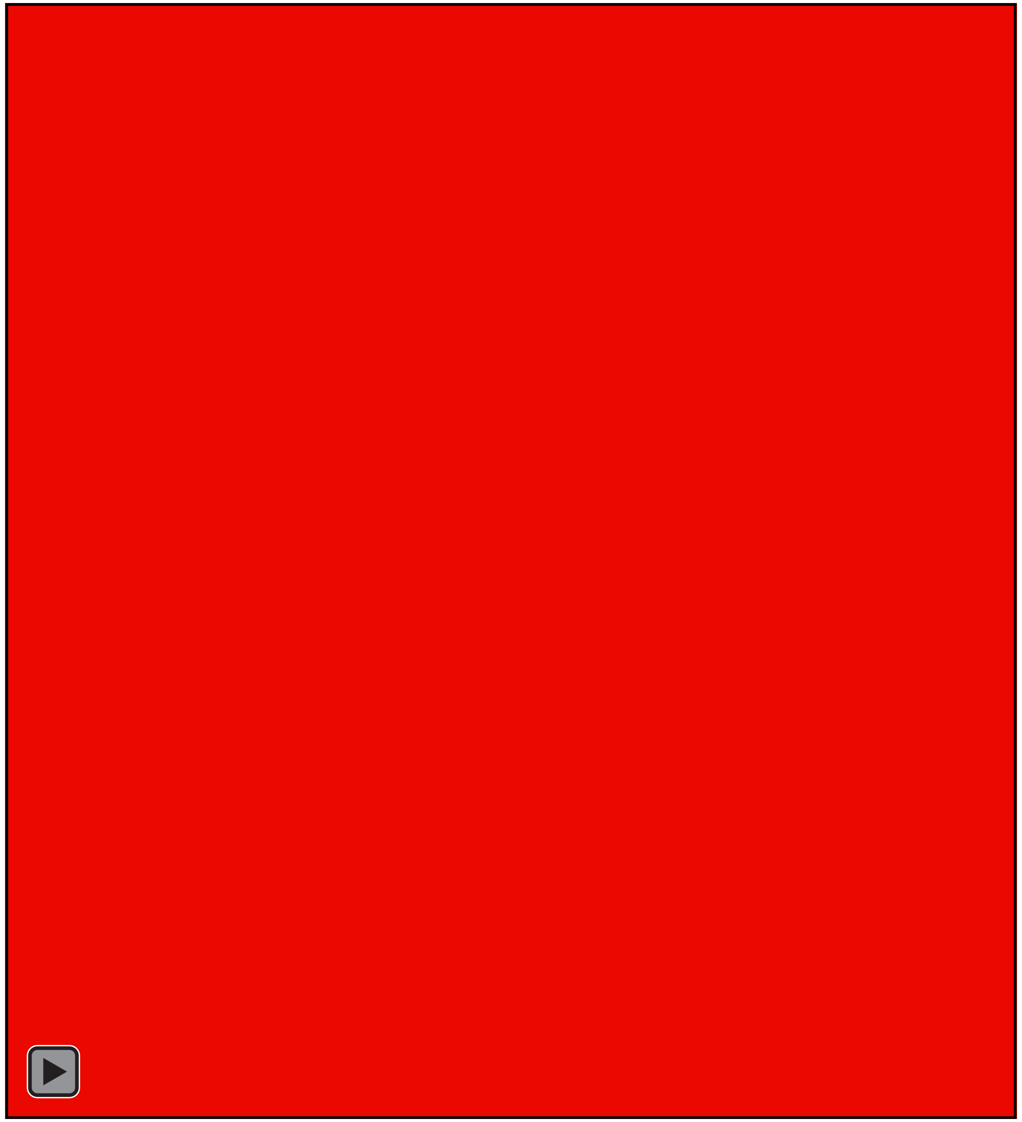
$$\frac{\partial E}{\partial k}\frac{1}{\hbar} = \frac{p}{m} = v_g$$

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

Exercise 1.2: Minima of the conduction band

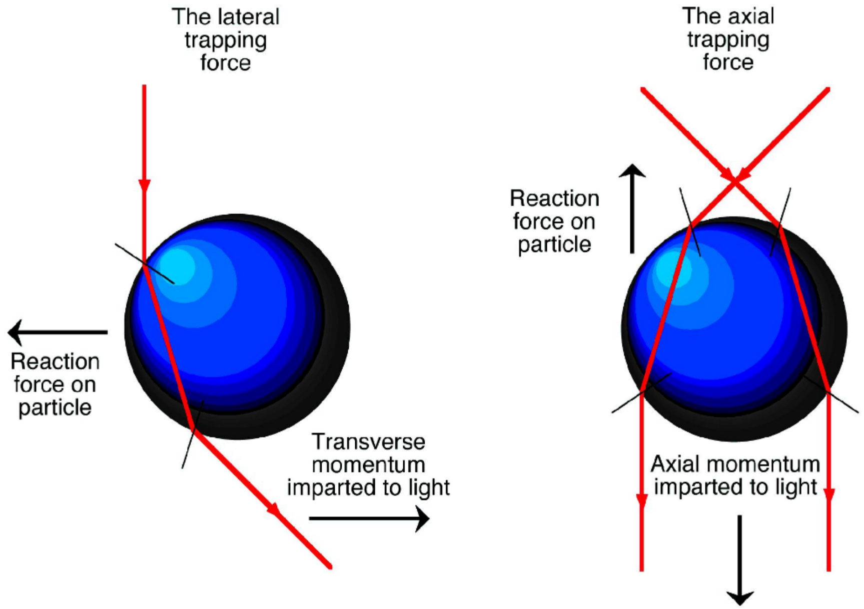


Impulse non-vanishing but no speed !!

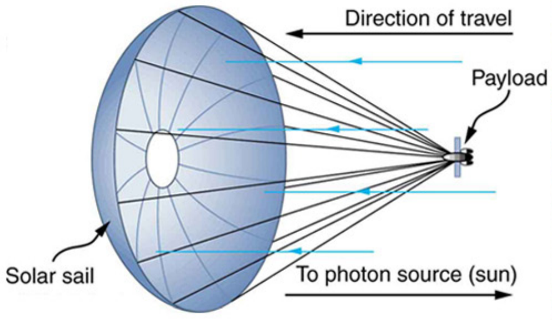


Exercise 1.2: Impulse of a photon?

Optical tweezers



Space sails



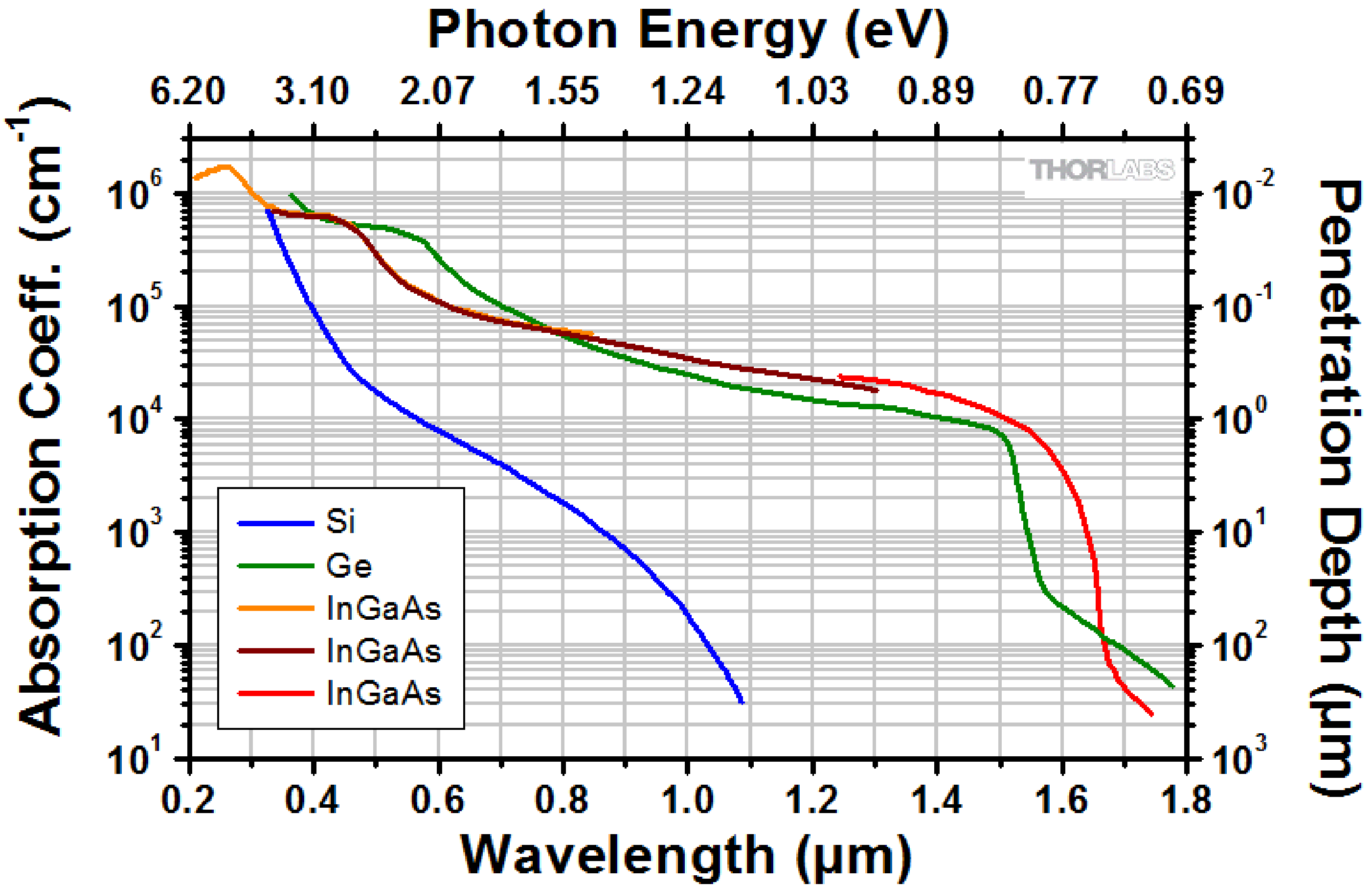
(a)


(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/

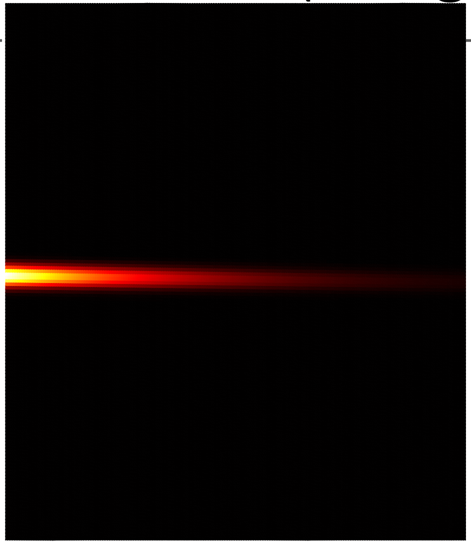
Outline

Exercise 1.3: Absorption in Semiconductors

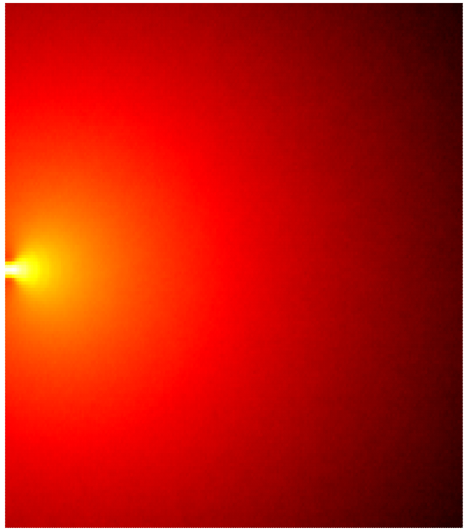


https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=14218

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



Absorption



Scattering

Questions

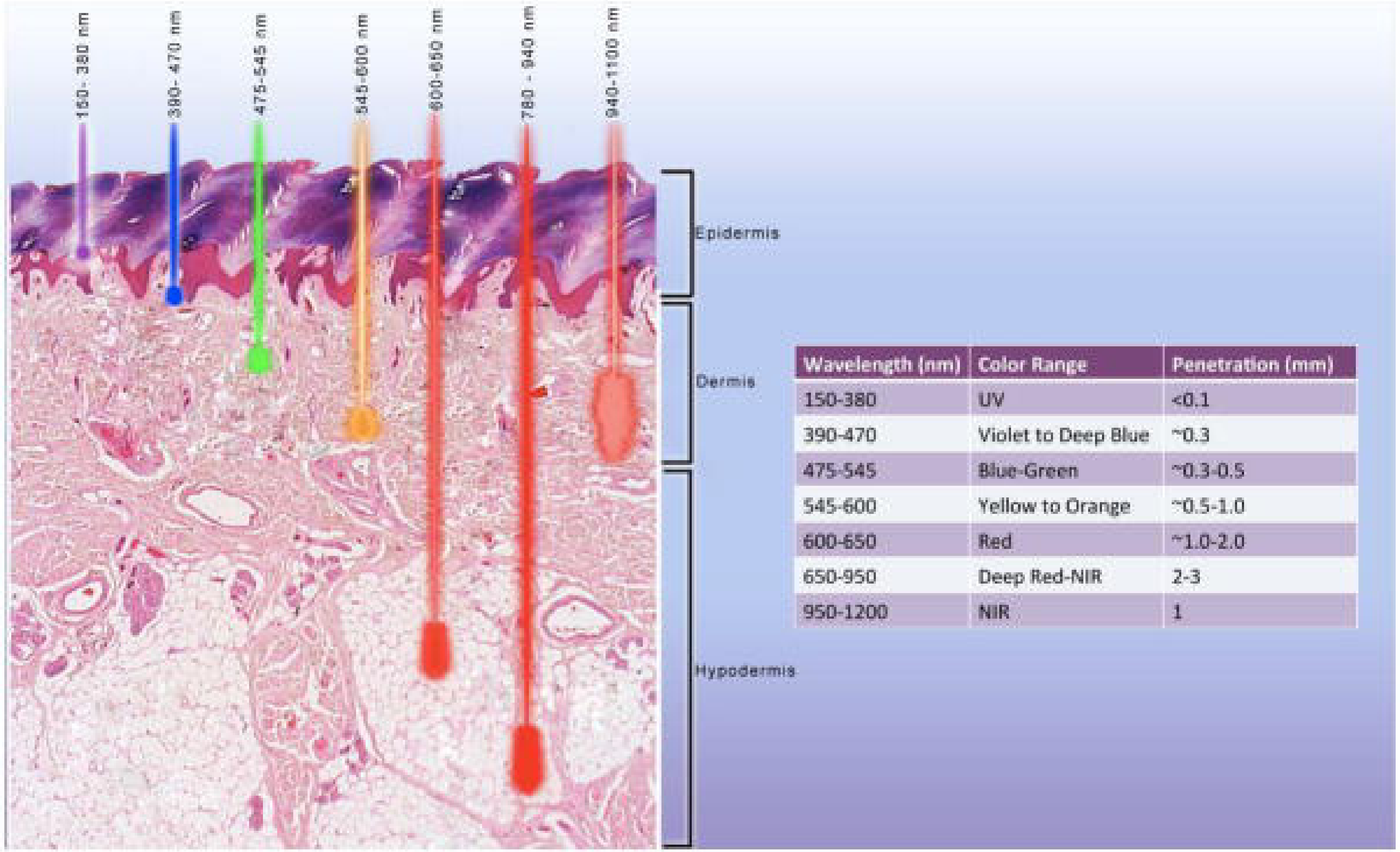
In tissue, scattering can represent an important component in addition to absorption

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

μ = *attenuation coefficient*

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

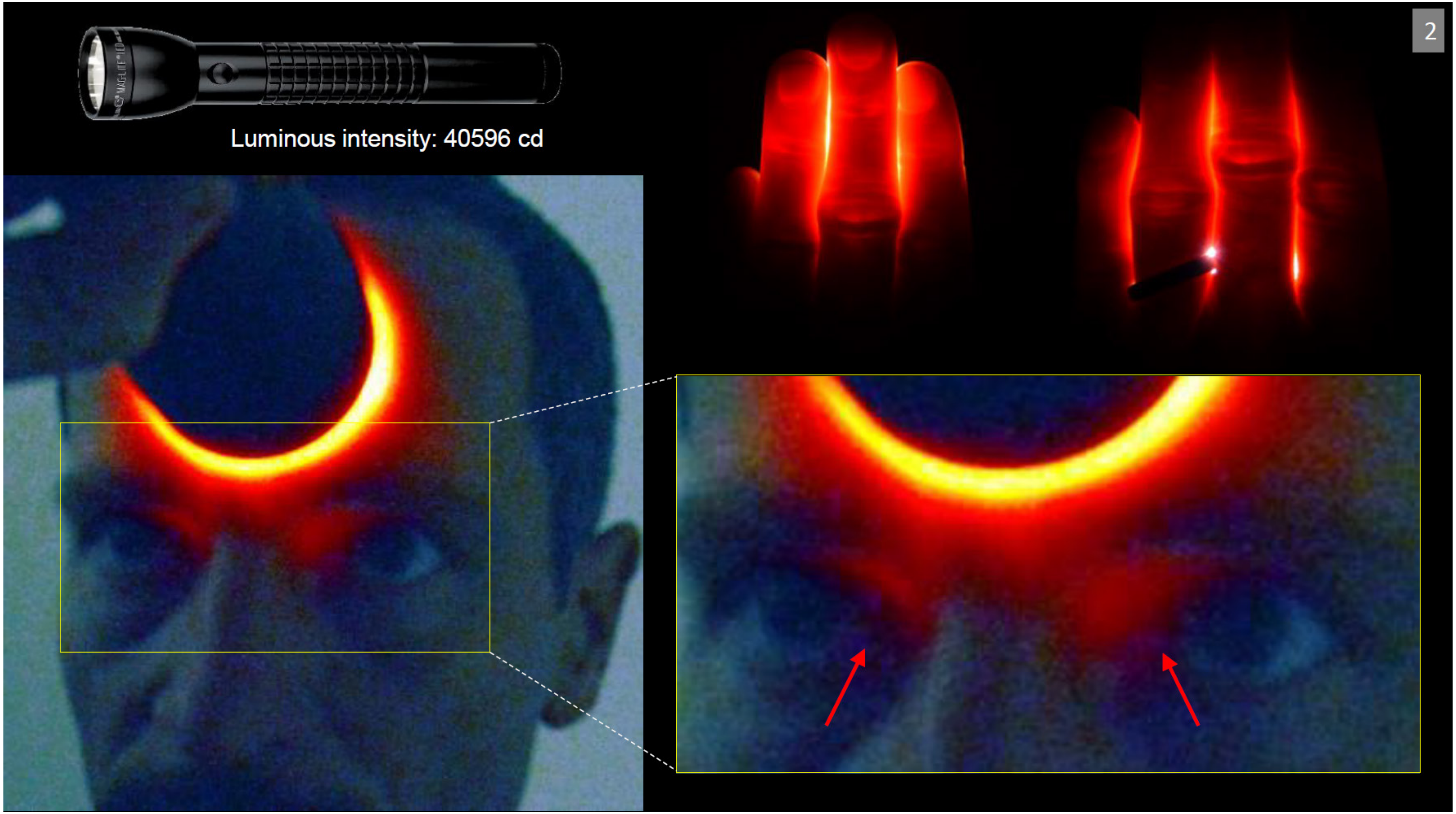
Exercise 1.3: (Bouger-)Beer-Lambert in tissue



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

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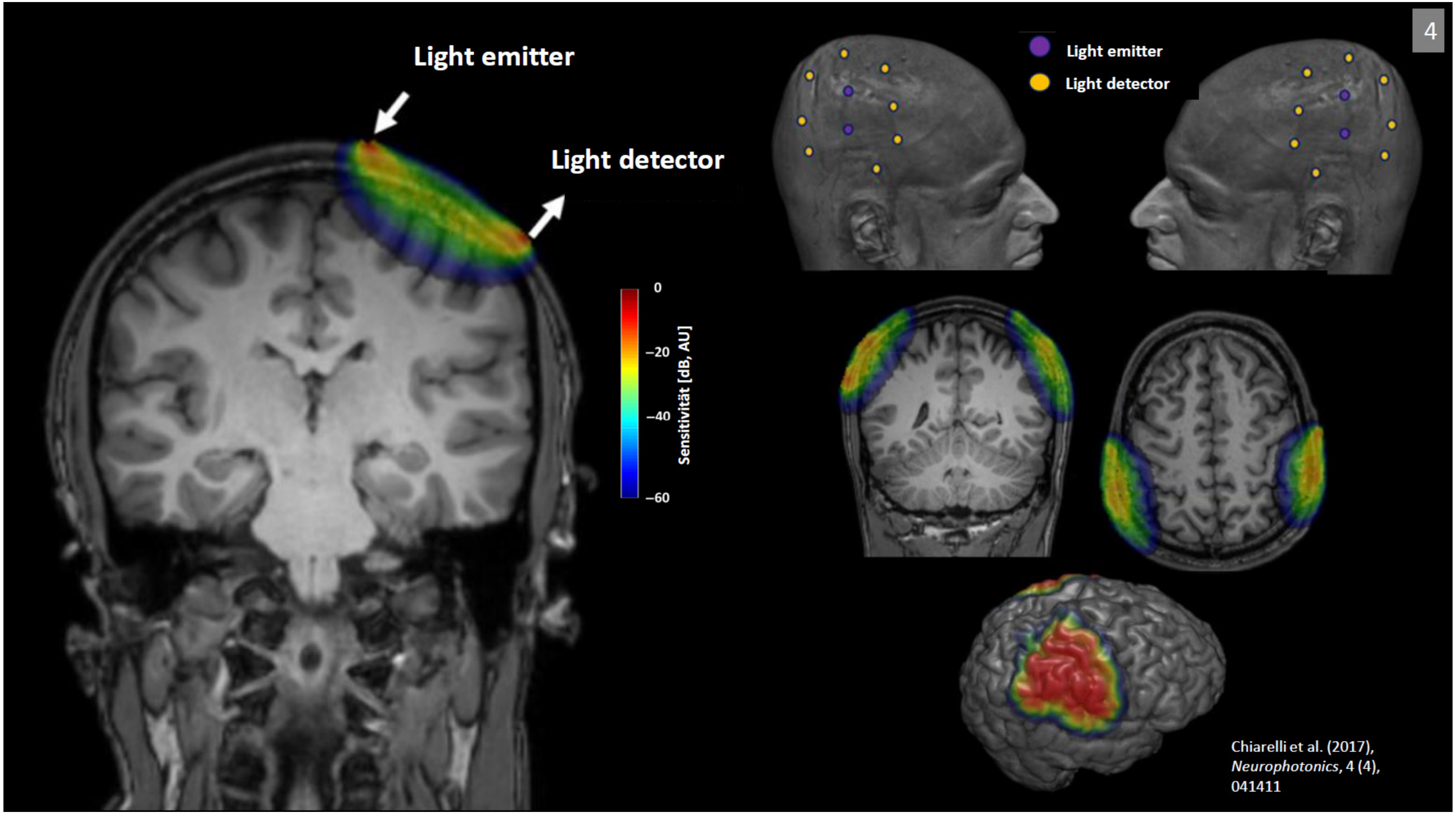

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Exercise 1.3: (Bouger-)Beer-Lambert in tissue

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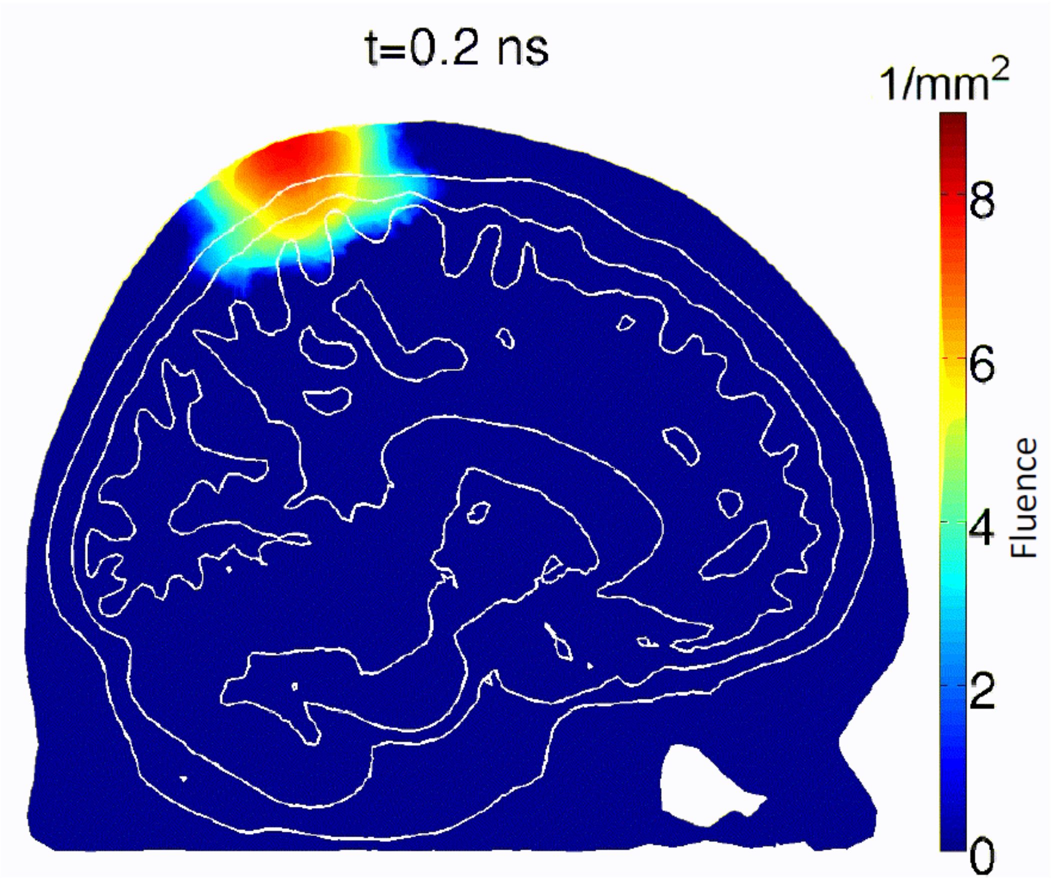
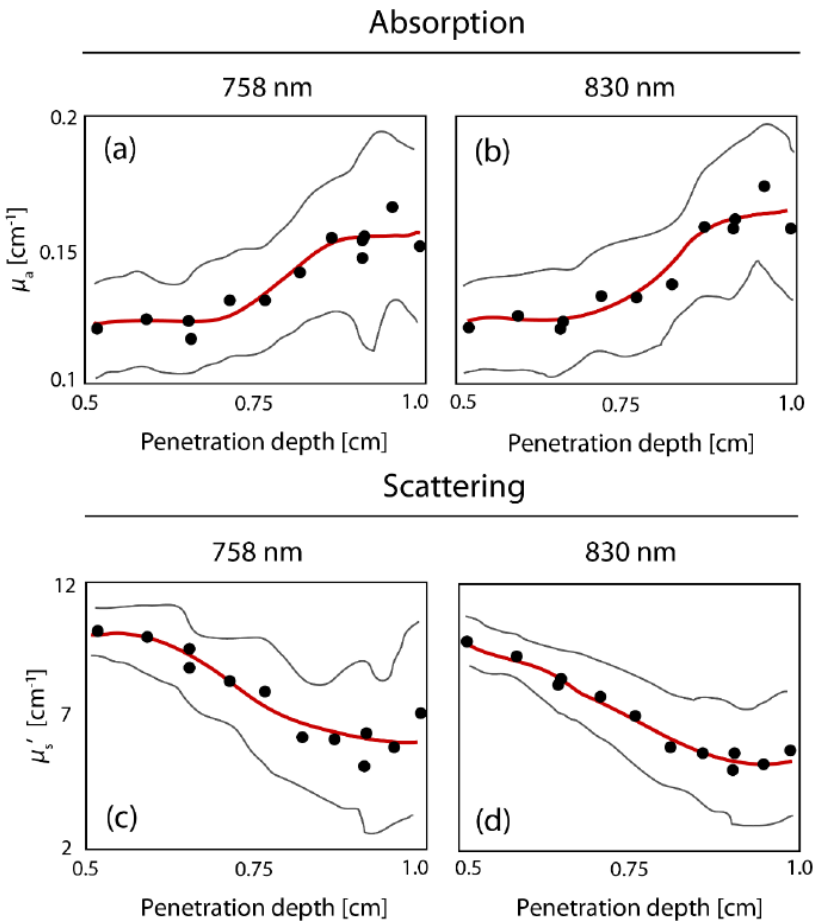
Light propagation in head tissue





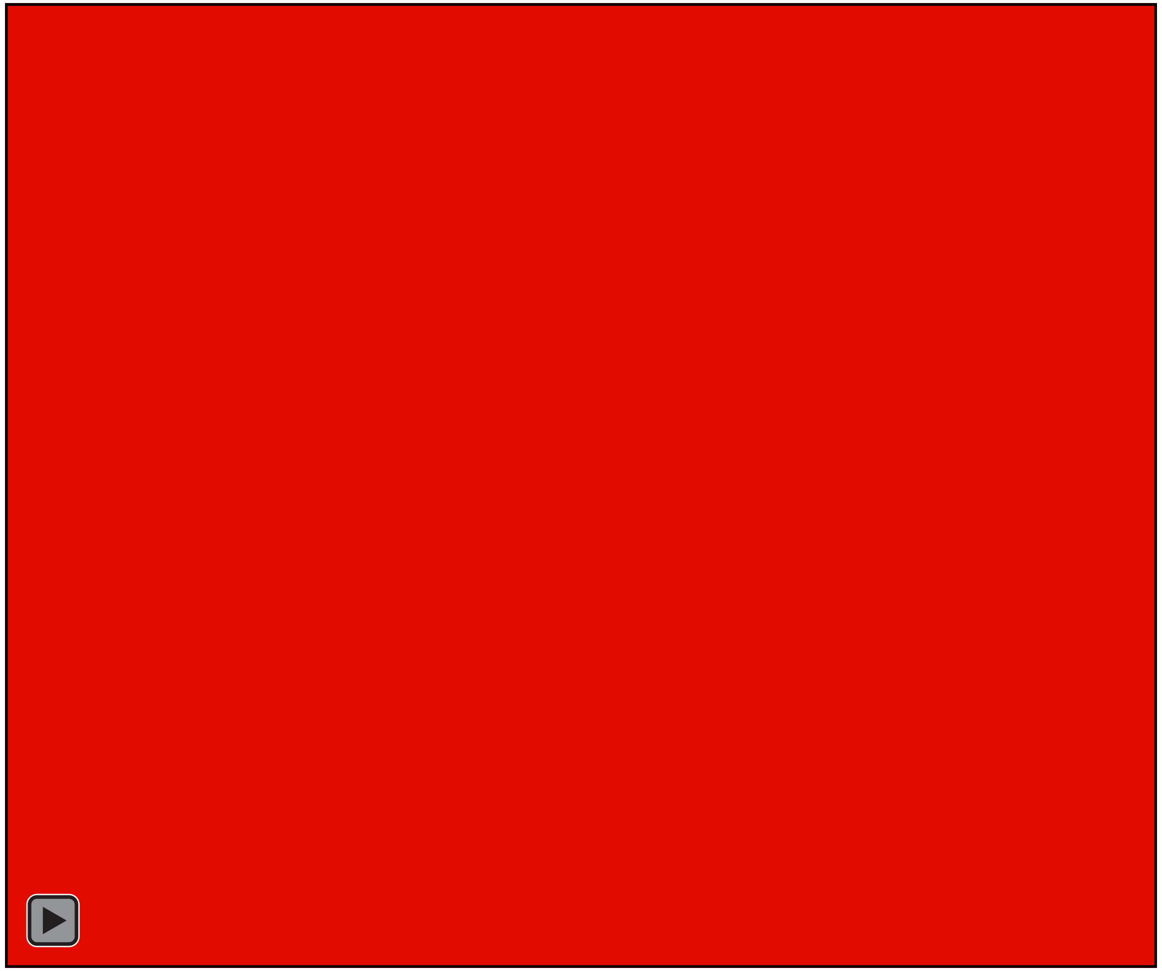
In vivo FD-NIRS measurements

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

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

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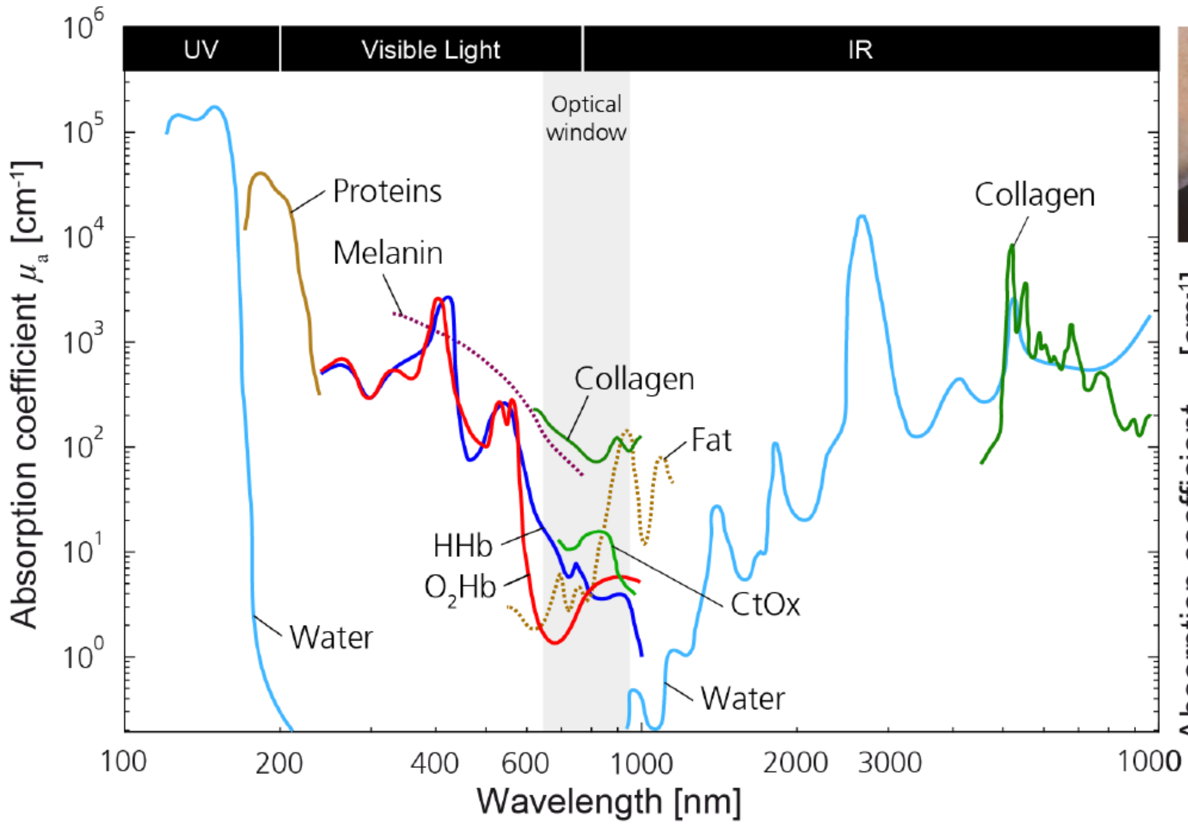
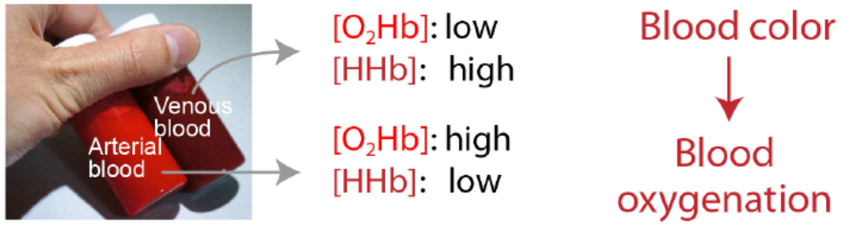
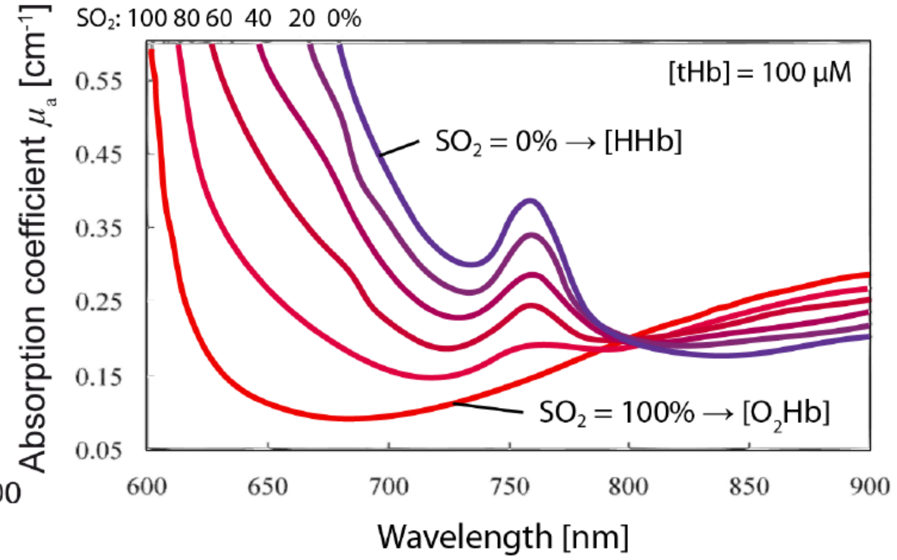
Chromophores and hemoglobin spectra







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.

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

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

fNIRS & NIRCO: Technical implementations

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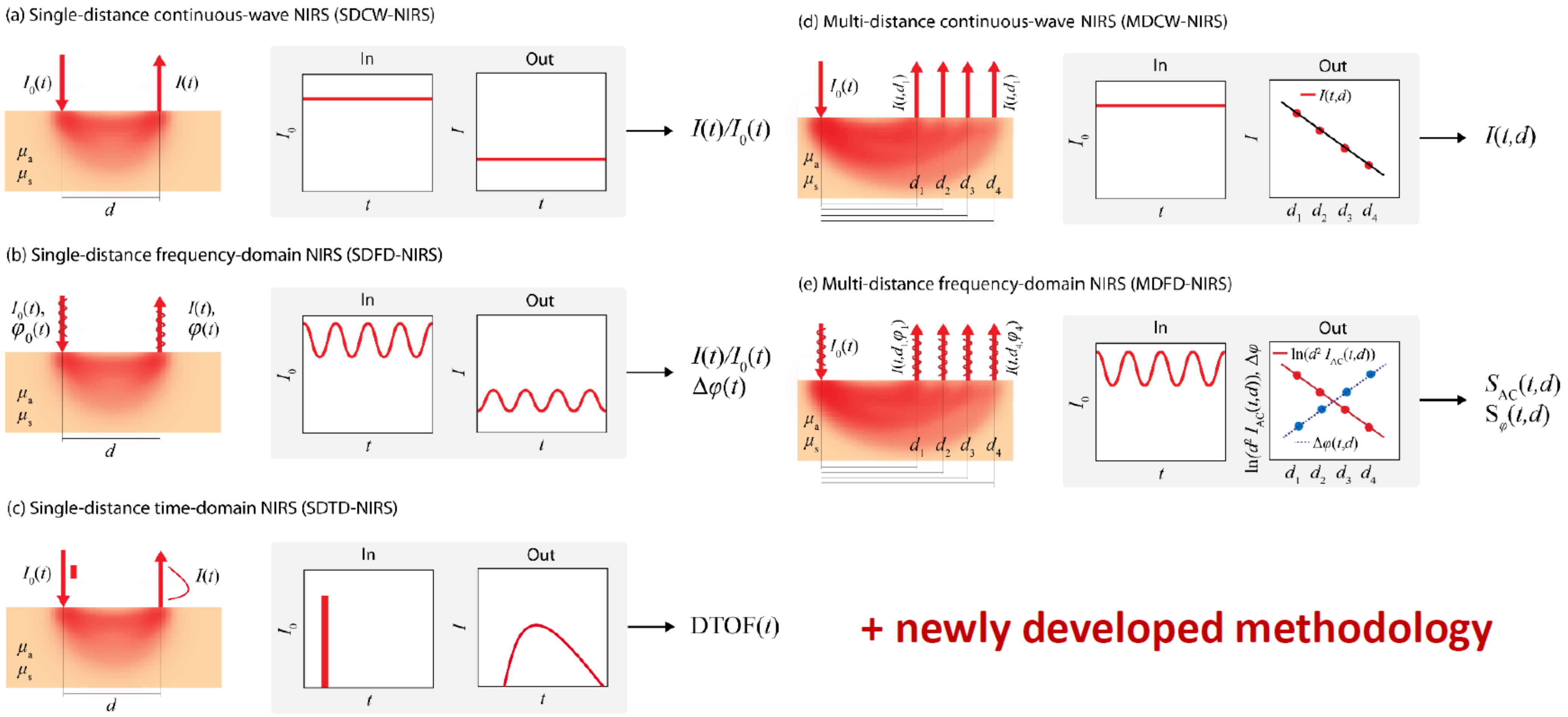

+ newly developed methodology

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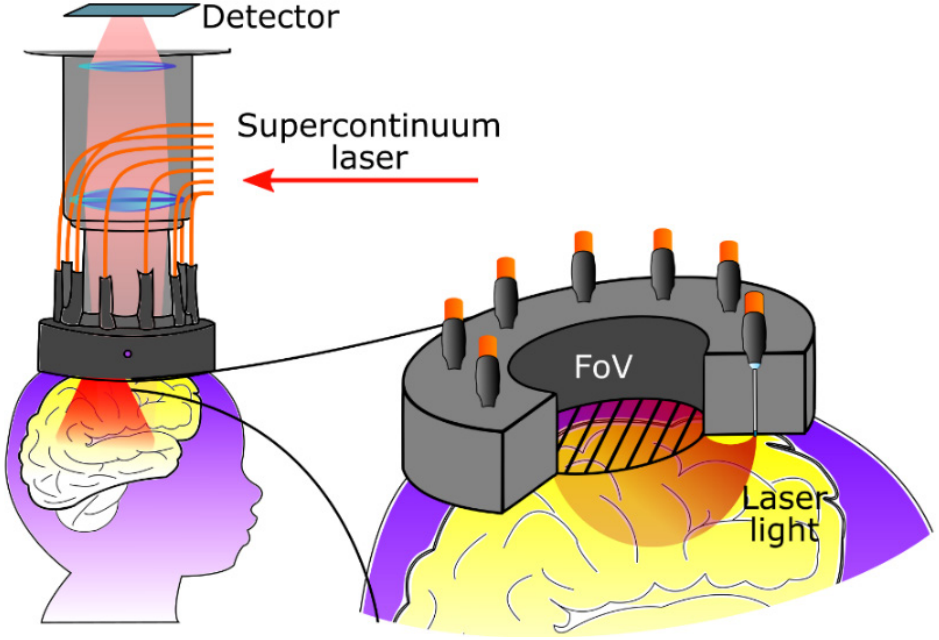
Exercise 1.3: Near-infrared Optical Tomography (NIROT) Basics

Preterm brain imaging



Martin Wolf et al, UZH