MICRO-523: Optical Detectors

Week One: Light

Claudio Bruschini

Institute of Electrical and Micro Engineering (IEM), School of Engineering (STI)

Ecole polytechnique fédérale de Lausanne (EPFL), Neuchâtel, Switzerland

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

TAs: Samuele Bisi, Yazan Lampert

EPFL

Outline

Literature

1) Saleh, Teich: “Fundamentals of Photonics” Wiley Interscience, Chapter 17.
   http://onlinelibrary.wiley.com/book/10.1002/0471213748
   (General textbook on optics, with chapter 17 dedicated to photodetectors)

2) Ohta: “Smart CMOS Image Sensors and Applications,” CRC Press, 2007.
   (Book on CMOS cameras)

3) Seitz, Theuwissen: “Single Photon Imaging,” Springer Series in Optical Sciences, 2011.
   (Book on the detection of very weak signals and photon counting.)

4) S.M. Sze, Kwok K. Ng: “Physics of Semiconductor Devices,” Wiley.
   http://onlinelibrary.wiley.com/book/10.1002/0470068329
   (Overview of the fundamentals of semiconductor components, e.g. diodes and transistors)

5) A. Theuwissen: "Solid-State Imaging with Charge-Coupled Devices,” Kluwer, 1995.
   No electronic version available. (Book about CCDs.)

1.1 Characteristic Quantities of Light

• Intensity: I	Thermal detectors
• Number of photons:	Photonic detectors
• Wavelength: λ	Spectroscopy
• Phase: ϕ	Interferometry
• Polarization:	Ellipsometry
• Modulation and impulse:	Time-of-flight
• Spectral and spatial coherence:	Lasers, LEDs or white light interferometry
• Information parallelism--> images:	Fourier transformations using a lens
	Spatial filtering of images

1.1 Fundamental Properties of Light: Wave or Particle?

- Wave-like propagation:
  - Interference phenomena, diffraction, ...
  - Electromagnetic waves and Maxwell's equations
- Particle-like interaction:
  - Photons
  - Absorption, spontaneous and stimulated emissions, ...

Waves	Particles
Frequency $\omega = 2\pi\ \nu$	Planck's relation $E = \hbar\ \omega$
Wave vector $\vec{K}$	De Broglie's relation $\vec{P} = \hbar\ \vec{K}$

Energy ↔ Momentum

Dispersion

$$\lambda\ \nu\ = c$$

$$\Downarrow$$

$$\omega = c\ \cdot\ |\vec{K}|$$

$$E = c\ \cdot\ |\vec{P}|$$

1.1 Quantum mechanical wave equation of light (1)

<u>«Wave function»*</u>

$$f \cong e^{i(\vec{k}\cdot\vec{x}-\omega\ t)}$$

<u>«Quantum mechanical operators»</u>

$$\frac{\partial}{\partial t} f = -i\ \omega \cdot f \quad \Rightarrow \quad \boxed{E = \hbar\omega = i\hbar \frac{\partial}{\partial t}}$$

$$\frac{\partial}{\partial x} f = i\ K_x \cdot f \quad \Rightarrow \quad \boxed{P_{x,y,z} = \hbar\vec{K}_{x,y,z} = \frac{\hbar}{i}\nabla_{x,y,z}}$$

Remember:

$\nabla = \frac{\partial}{\partial_x}\hat{\imath} + \frac{\partial}{\partial_y}\hat{\jmath} + \frac{\partial}{\partial_x}\hat{k}$	Nabla
$\nabla \cdot$	Divergence
$\nabla \times = rot$	Curl
$\Delta = \nabla^2$	Laplacian
∇	Gradient

**plane matter wave*

NB: here in vacuum…

1.1 Quantum mechanical wave equation of light (2)

Schrödinger equation for electrons

$$E = \frac{P^2}{2m} + V \quad \Rightarrow \quad i\hbar \frac{\partial}{\partial t} \cdot \psi = \left(-\frac{\hbar^2}{2m} \nabla^2 + V \right) \cdot \psi$$

And for light ?? «Schrödinger like» equation for photons ??

$$E = c\,\left|\vec{P}\right| \quad \Rightarrow \quad E^2 = c^2\,\left(P_x^2 + P_y^2 + P_z^2\right) \quad \Rightarrow \quad -\hbar^2 \frac{\partial^2}{\partial t^2} \cdot \psi = -c^2 \hbar^2 \nabla^2 \cdot \psi$$

Maxwell

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) \cdot \psi = 0$$

Classical electromagnetic wave equation (*in vacuum*)

1.1 Classical derivation of wave equation

Maxwell equations for ρ=0 and j=0

$$rot\ rot\ \ldots = grad\ (div\ \ldots) - \nabla^2 \ldots$$

$$div\ \vec{E} = 0$$

$$div\ \vec{B} = 0$$

$$rot\ \vec{E} = -\frac{\partial}{\partial t}\vec{B}$$

$$rot\ \frac{\vec{B}}{\mu_0 \mu} = \varepsilon_0 \varepsilon\ \frac{\partial}{\partial t}\vec{E}$$

⇨

$$rot\ rot\ \vec{E} = grad\ (div\ \vec{E}) - \nabla^2 \vec{E} = -\frac{\partial}{\partial t}(rot\ \vec{B})$$

$$\nabla^2 \vec{E} = \frac{n^2}{c^2}\frac{\partial^2}{\partial t^2}\ \vec{E}$$

$$rot\ rot\ \vec{B} = grad\ (div\ \vec{B}) - \nabla^2 \vec{B} = \frac{n^2}{c^2}\frac{\partial}{\partial t}(rot\ \vec{E})$$

$$\nabla^2 \vec{B} = \frac{n^2}{c^2}\frac{\partial^2}{\partial t^2}\ \vec{B}$$

1.1 Wave Equations

$$rot(rot\ \vec{V}) = \nabla \times (\nabla \times \vec{V}) = \nabla(\nabla \cdot \vec{V}) - \Delta\vec{V} = grad(div\ \vec{V}) - \Delta\vec{V}$$

$$\vec{E} = \vec{E}_\omega \cdot e^{-i\omega t}$$

$$\vec{H} = \vec{H}_\omega \cdot e^{-i\omega t}$$

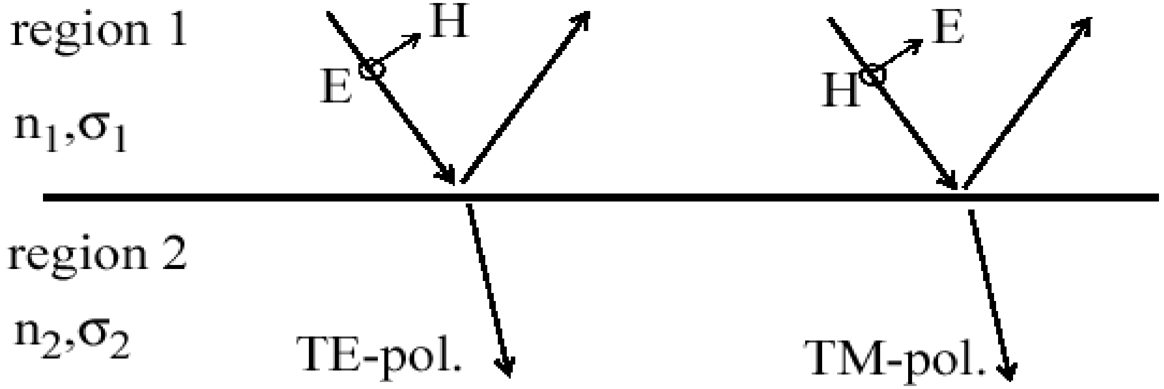
$$\Delta\vec{E}_\omega = -\left[\left(\frac{\omega}{c}\right)^2 \cdot \left(\mu\varepsilon + i\frac{\mu\sigma}{\omega\varepsilon_0}\right)\right] \cdot \vec{E}_\omega$$

$$\Delta\vec{H}_\omega = -\left[\left(\frac{\omega}{c}\right)^2 \cdot \left(\mu\varepsilon + i\frac{\mu\sigma}{\omega\varepsilon_0}\right)\right] \cdot \vec{H}_\omega$$

Conditions at the interfaces (*continuity*)

$E^{//}_1 = E^{//}_2$ $\quad$ $H^{//}_1 = H^{//}_2$ $\quad$ $rot\ldots \rightarrow 0$

$D^{\perp}_1 = D^{\perp}_2$ $\quad$ $B^{\perp}_1 = B^{\perp}_2$ $\quad$ $div\ldots \rightarrow 0$



Reflection,
Diffraction,
…

Outline

1.1 Fundamental properties of light

1.2 Black-body radiation

1.3 Human vision and optical illusions

1.4 Photometry

1.5 Absorption:

- Einstein coefficients
- Semiconductors

1.6 Types of optical detectors:

- Thermal detectors
- Photonic detectors
- Cameras

1.2 Black-body Radiation

Spectral power emitted per unit solid angle and per area:

$$P_\nu \cdot d\nu = \frac{2h\nu^3}{c^2} \cdot \frac{1}{e^{(h\nu)/kT} - 1} \cdot d\nu \qquad [W\ m^{-2}]$$

Planck's law

Total power emitted per unit solid angle and per area:

$$W = \int_0^\infty P_\lambda \, d\lambda = \frac{\sigma}{\pi} \cdot T^4 \left[Wm^{-2}\right]$$

$\sigma =$ Stefan–Boltzmann constant

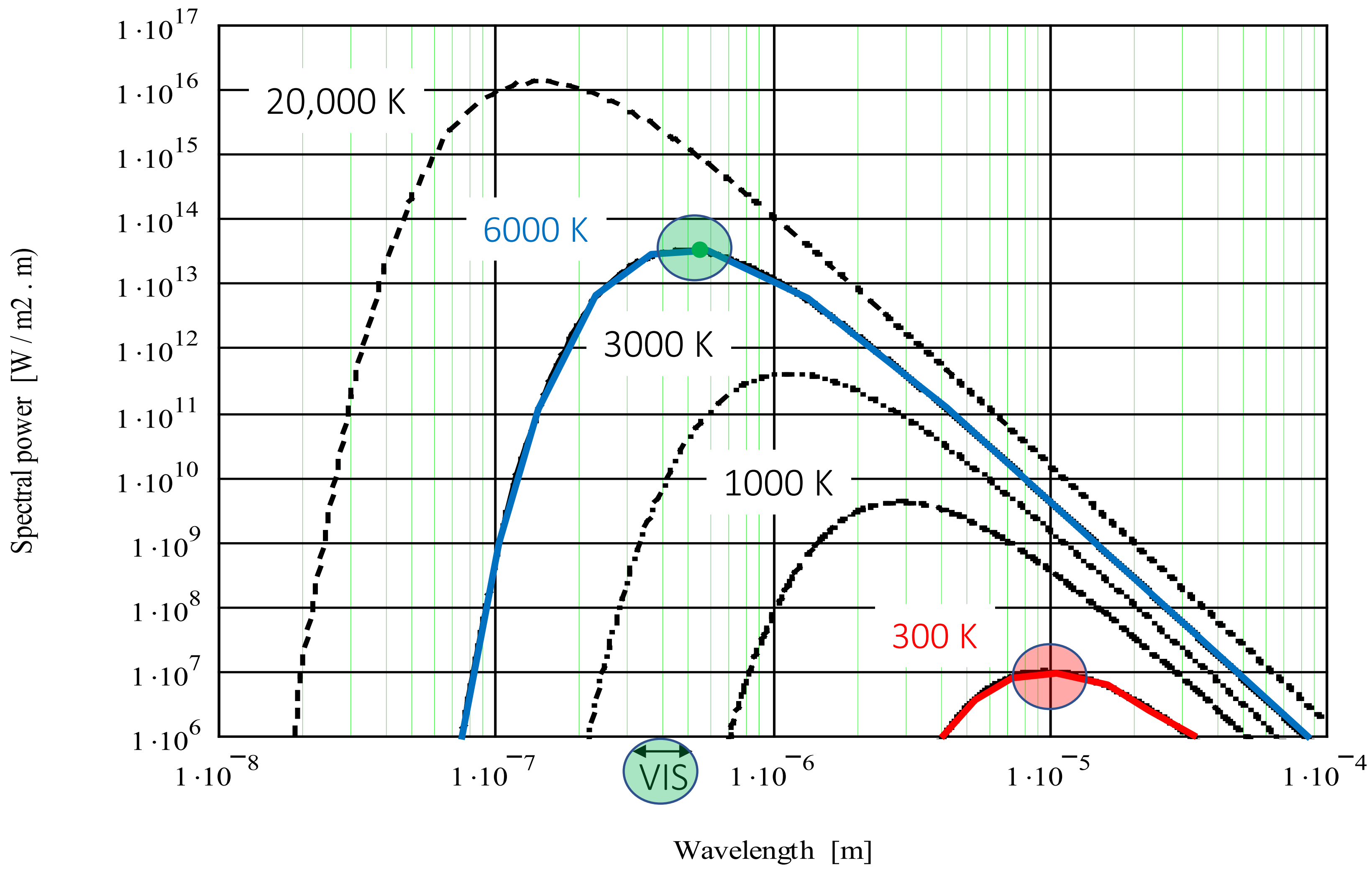
$$= \frac{2\pi^5 k^4}{15 h^3 c^2} = 5.67 \cdot 10^{-8} \quad \left[W \cdot m^{-2} \cdot K^{-4}\right]$$

Wien's law

$$\lambda_{max} = \frac{2897}{T} [\mu m]$$

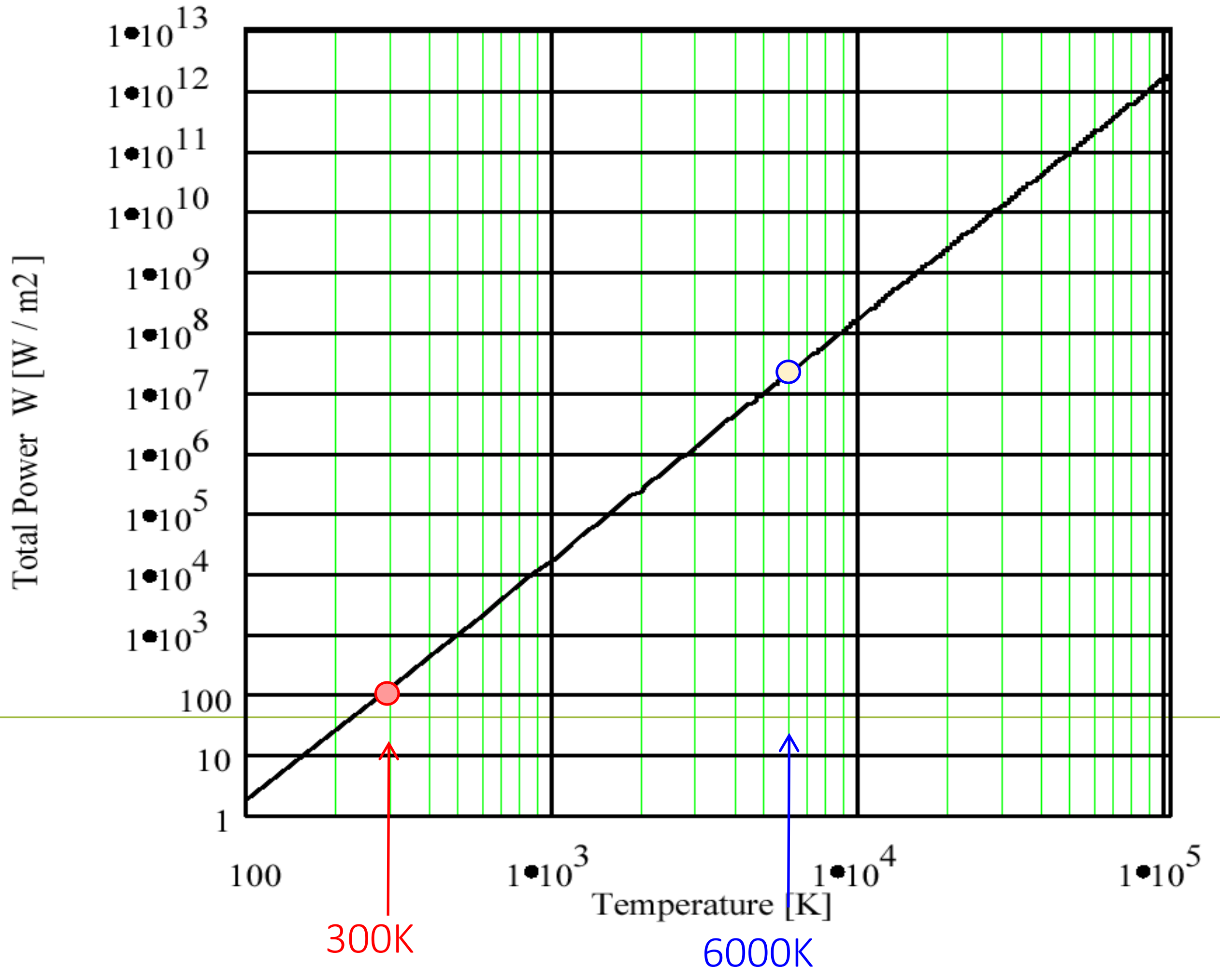
1.2 Example: Planck's Law

a) Black-body emissions at 300, 1000, 3000, 6000 and 20,000 K



1.2 Example: Black body

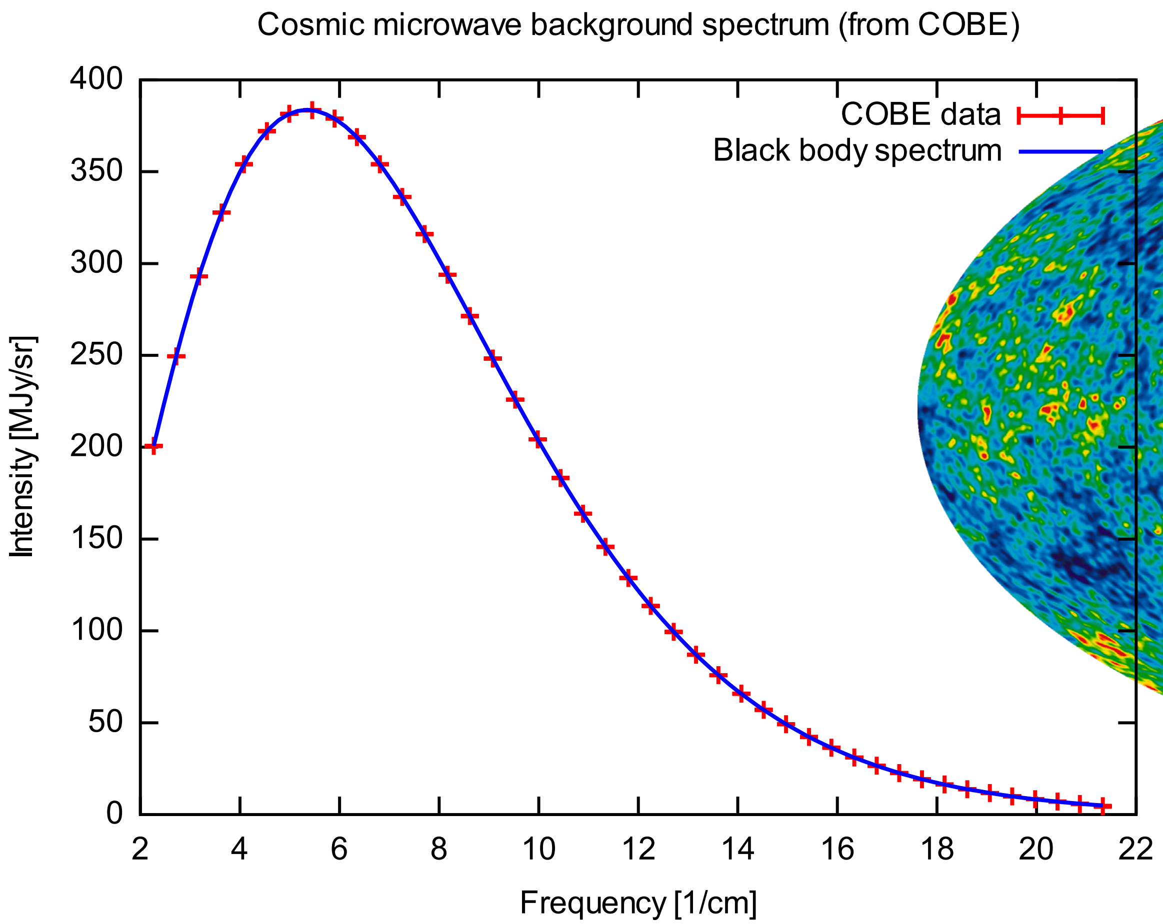
b) Total power emitted per solid angle and area

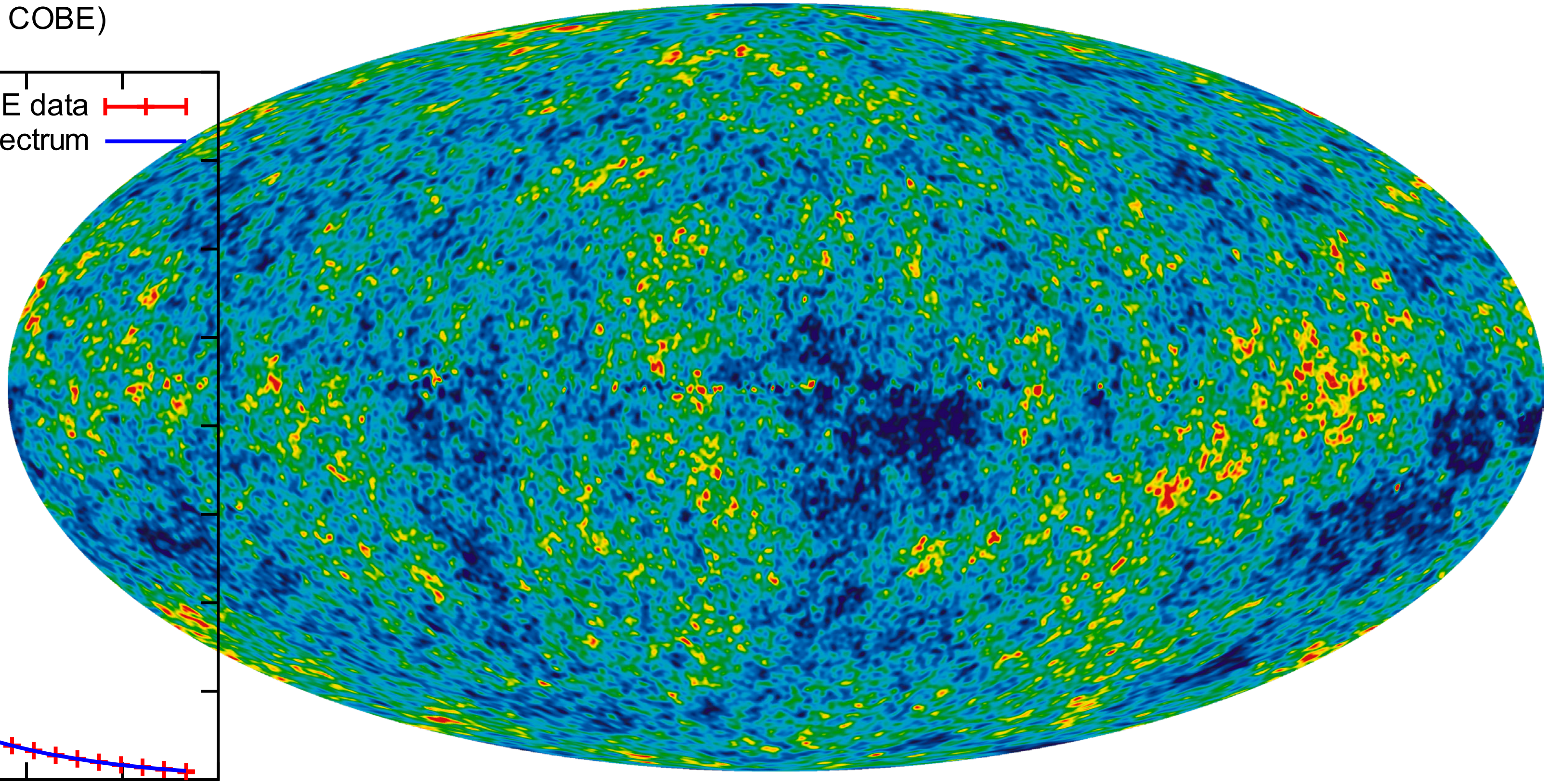


$$W \sim T^4$$

Stefan-Boltzmann formula

1.2 Universe’s black-body radiation and temperature (2.7K)

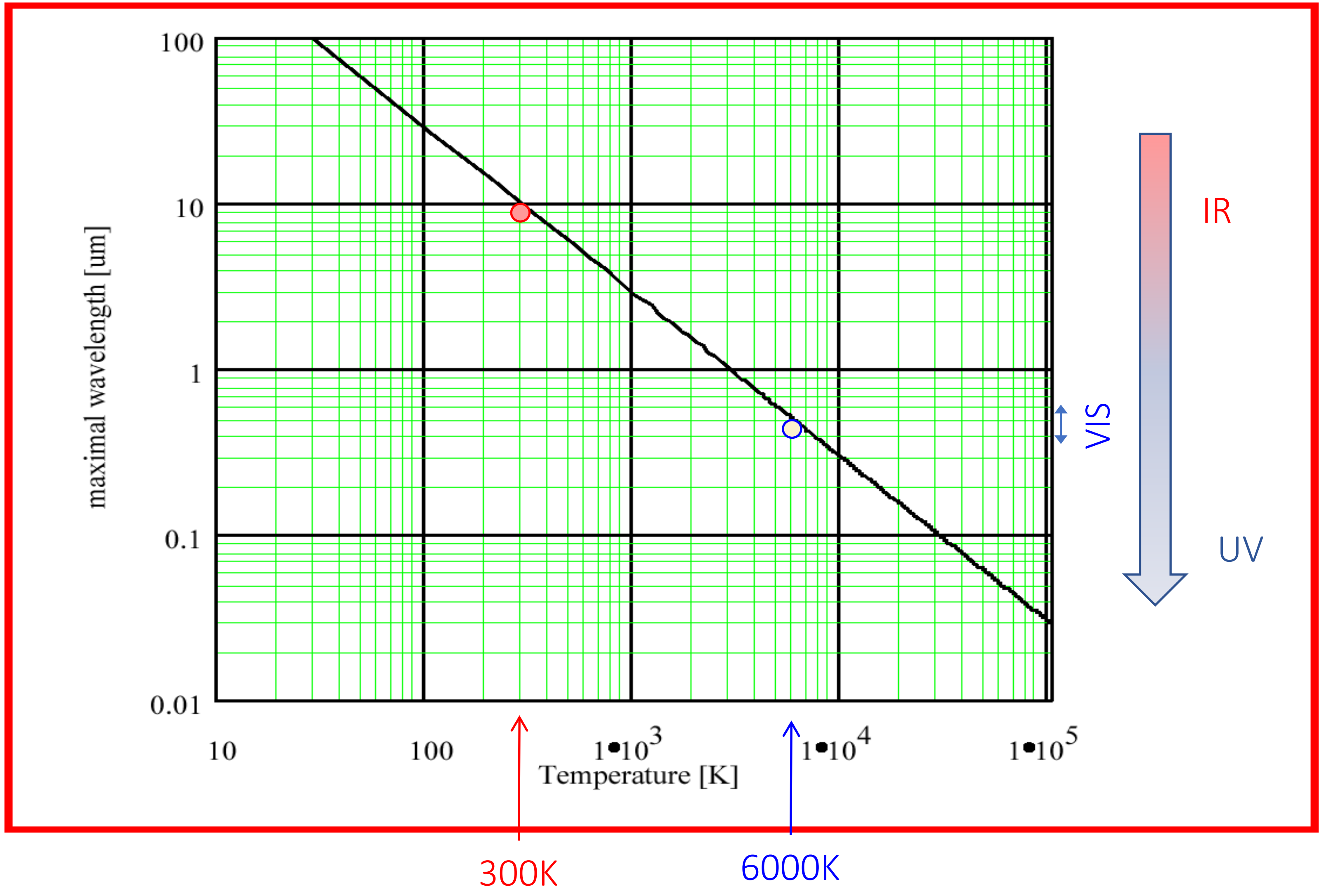




Nine-year [Wilkinson Microwave Anisotropy Probe](#) heat map of temperature fluctuations in the cosmic microwave background
Temperature range of ± 200 microKelvin. Signal from our galaxy was subtracted.

1.2 Example: Black body

c) Peak emission wavelenght



$$\lambda_{\max} \sim \frac{1}{T}$$

Wien's law

1.2 Black body definition

The «black body» optical emission depends only on its temperature and size.

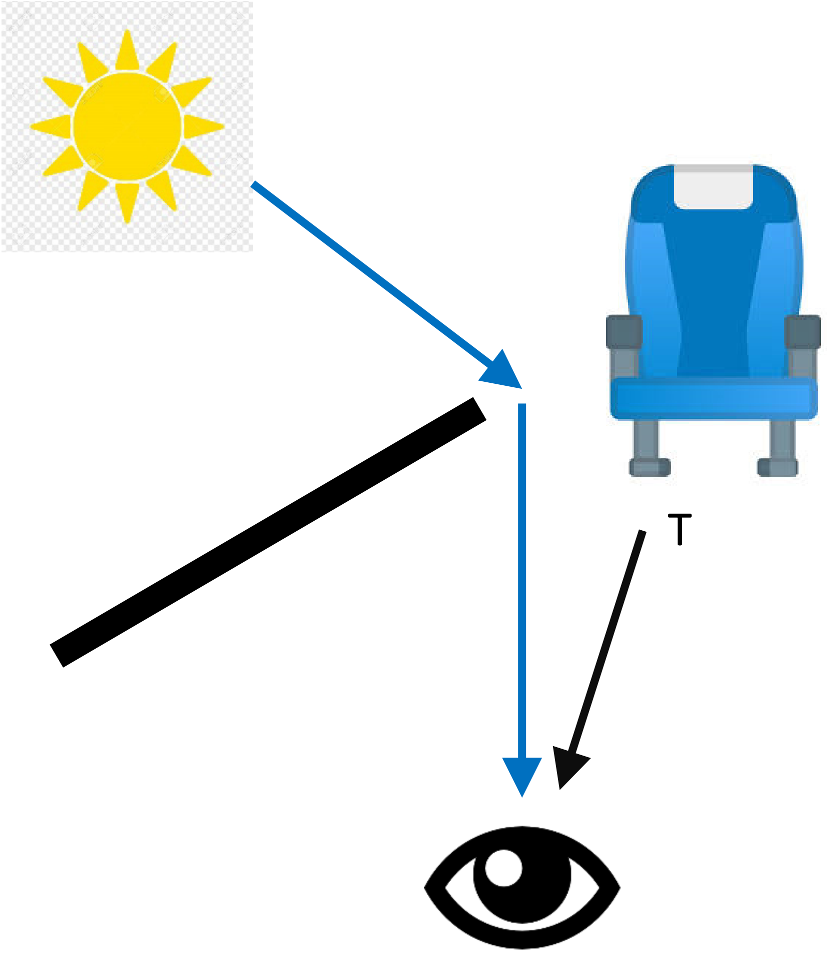
Why ? «black» ? body

- The sun **is** a black body !!
- A blue chair **is not** !!

1.2 Black Body: reflection

The spectrum of a black body depends only on its temperature and geometry

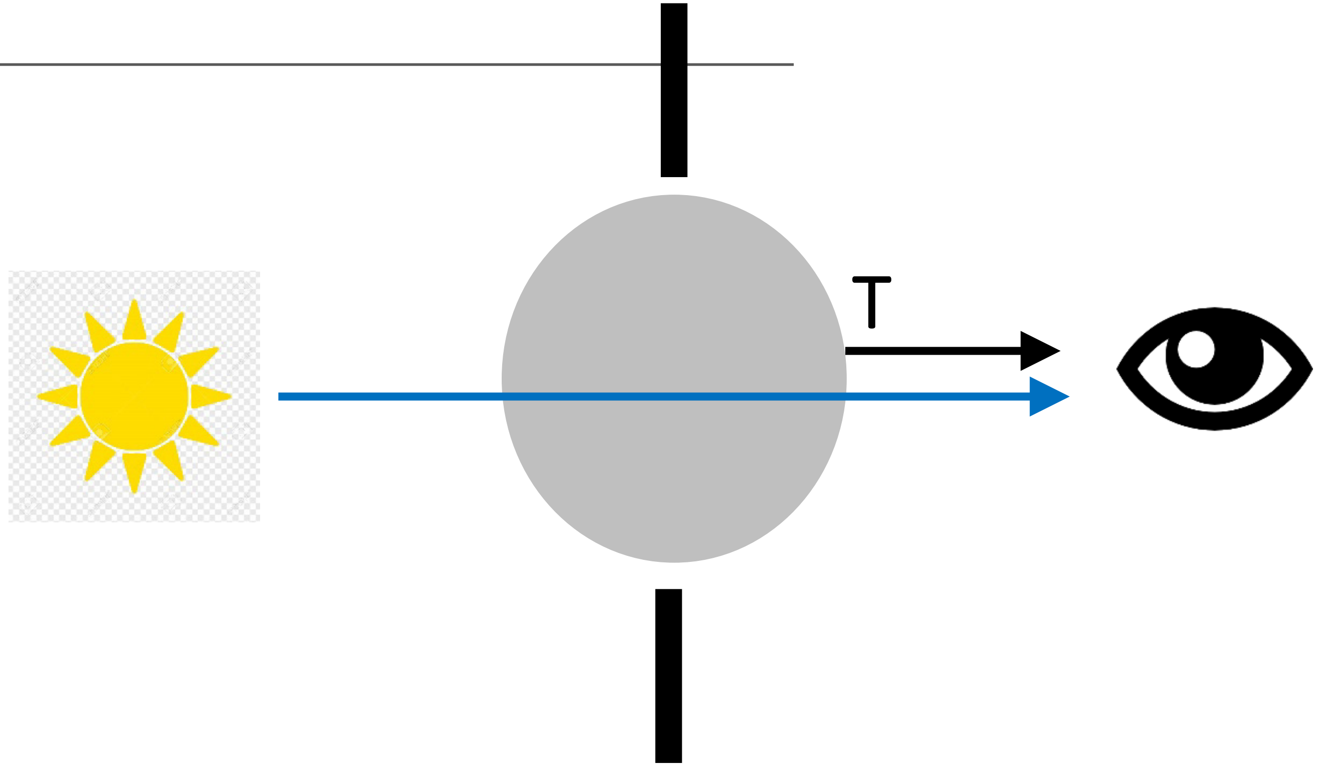
Is a blue chair a black body?



Black Body → no reflections!

1.2 Black body: transmission

The spectrum of a black body depends only on its temperature and geometry

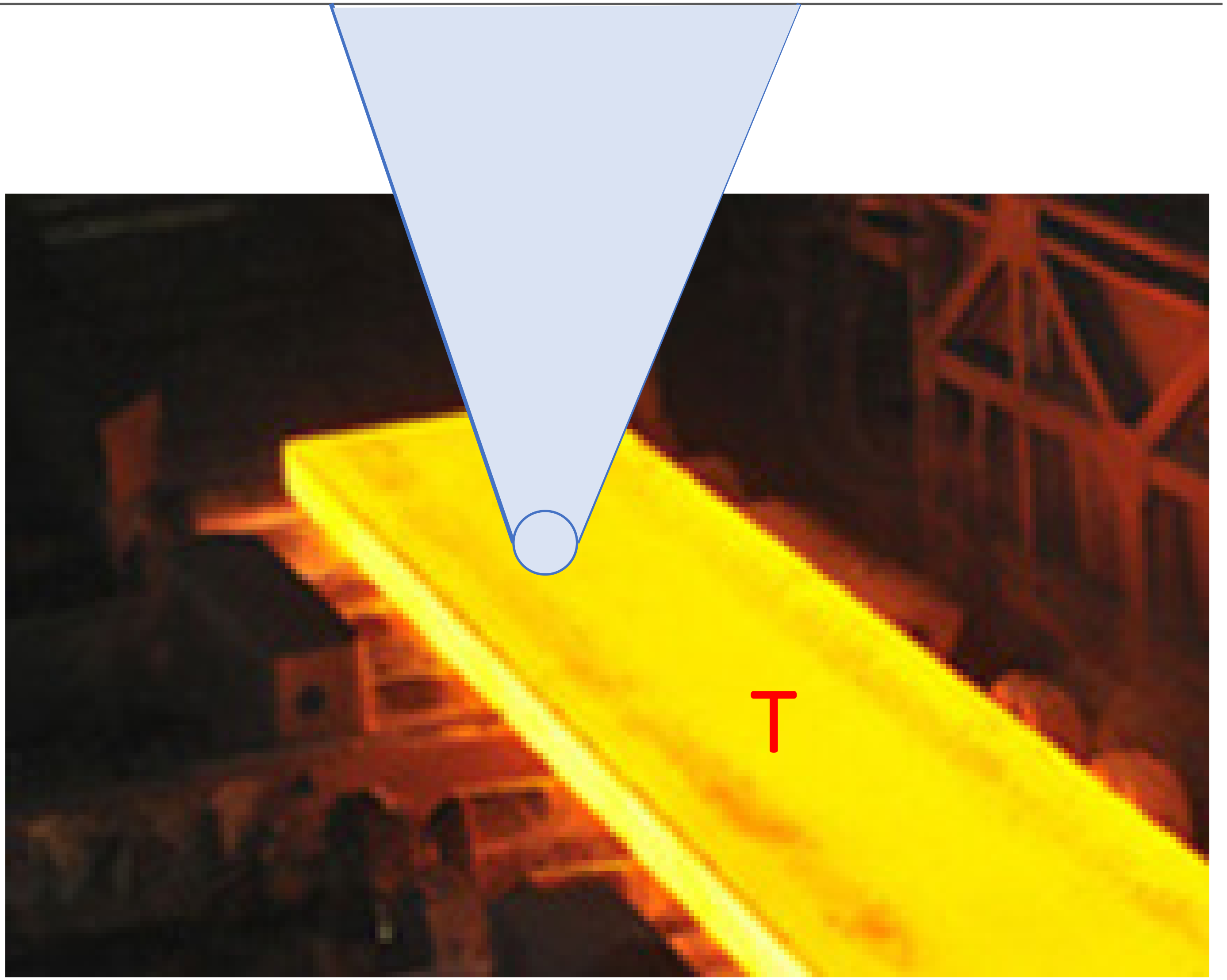


Is a semi-transparent object a black body?

Black body → no transmission!

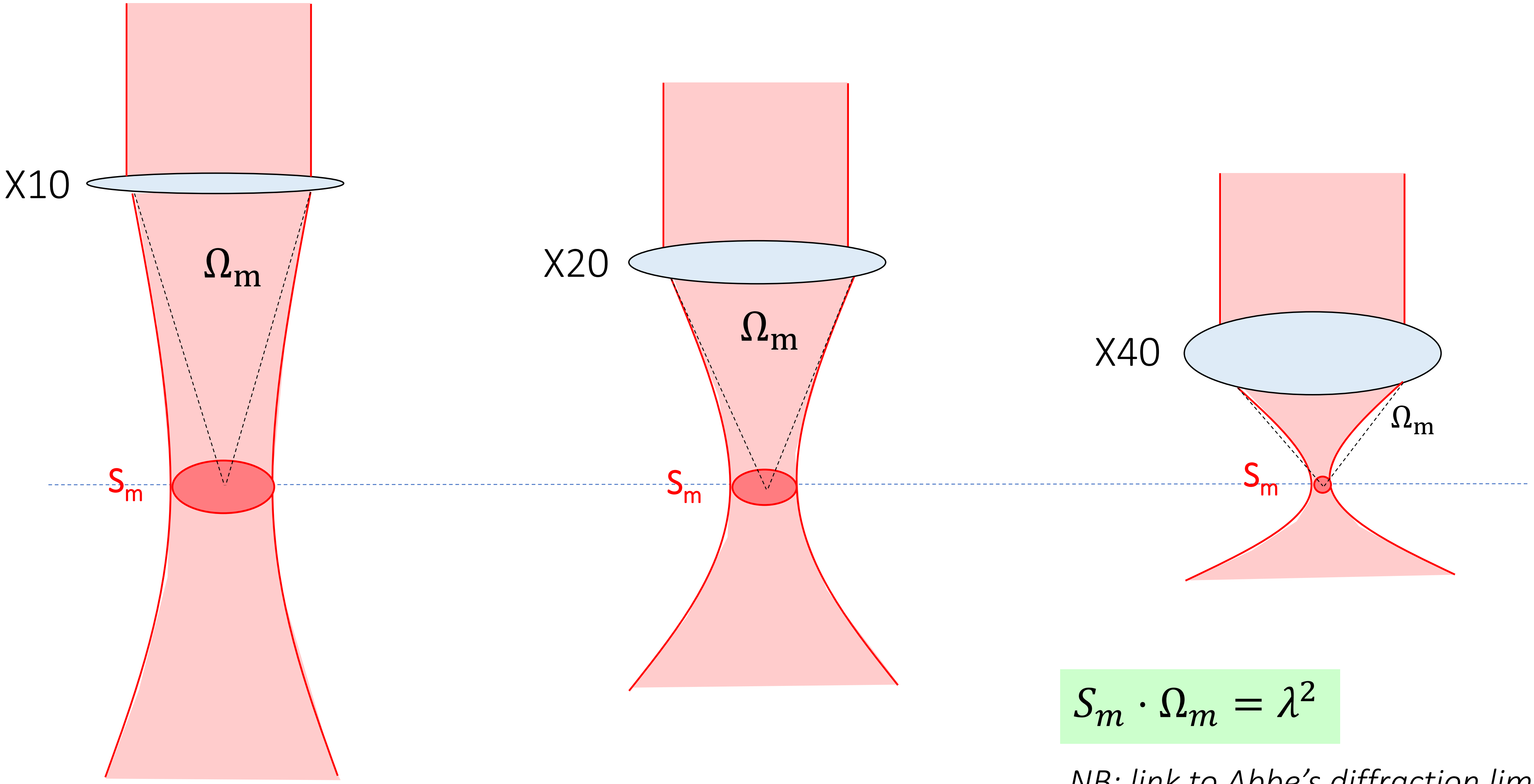
A black body absorbs all the incident light.

1.2 Black body equation (Planck's law): alternative derivation



How many spots to cover the body with a given emission angle ?

1.2 «Surface-angle product» of a Gaussian beam



$$S_m \cdot \Omega_m = \lambda^2$$

NB: link to Abbe's diffraction limit

1.2 Crude derivation of Planck's equation

$$P = \frac{\textit{Photon energy}}{\textit{measurement time}} \cdot \text{number of modes} \cdot \textit{occupancy} \cdot \textit{polarisation}$$

$$P = \frac{\mathrm{h}\nu}{(1/\Delta\nu)} \cdot \frac{S\Omega}{S_m \Omega_m} \cdot \frac{1}{e^{\frac{h\nu}{kT}} - 1} \cdot 2$$

$$\frac{P}{S\Omega} = 2 \cdot \mathrm{h}\nu \cdot \frac{1}{\lambda^2} \cdot \frac{1}{e^{\frac{h\nu}{kT}} - 1} \cdot \Delta\nu$$

$$\frac{1}{\lambda^2} = \frac{\nu^2}{c^2}$$

$$\frac{P}{S\ \Omega} = \frac{2\ \mathrm{h}\nu^3}{c^2} \cdot \frac{1}{e^{\frac{h\nu}{kT}} - 1} \cdot \Delta\nu$$

Planck's law

Take-home Messages/W1-1

1.1 **Light properties:**

- Give some characteristic properties of light.
- Provide examples of measurements and experiences using these properties.

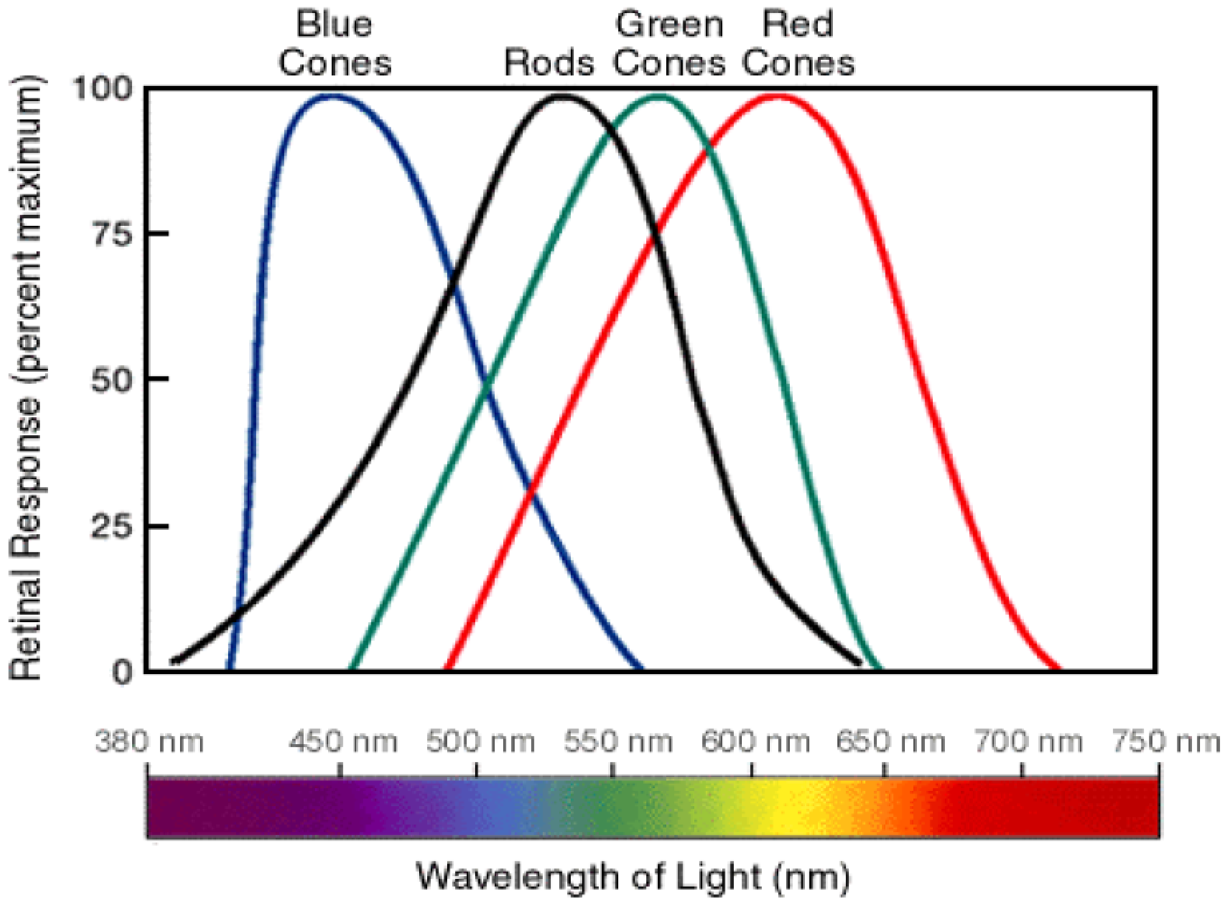
1.2 **Black body:**

- What is a black body?
- What are its emission characteristics?
- How can this influence the detector choice?

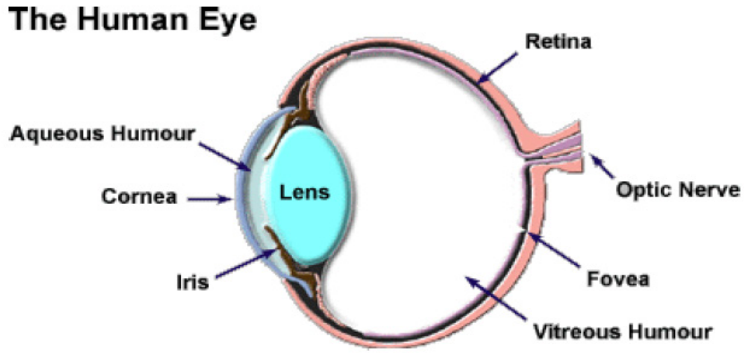
Outline

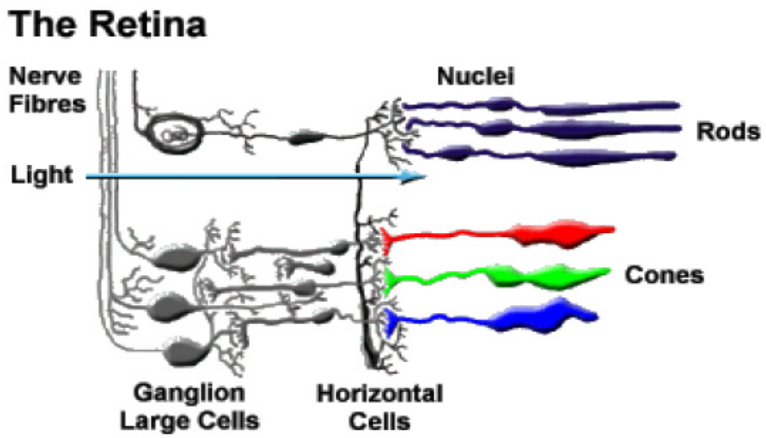
1.3 Human Vision

Relative perception inside the human eye



Tutorial Gigahertz-Optik





http://www.photo.net/photo/edscott/vis00010.htm

1.3 Measuring Colors

Decomposing a light source φ_λ:

$$X = k \int_\lambda \varphi_\lambda(\lambda) \cdot \bar{x}(\lambda) d\lambda$$

$$Y = k \int_\lambda \varphi_\lambda(\lambda) \cdot \bar{y}(\lambda) d\lambda$$

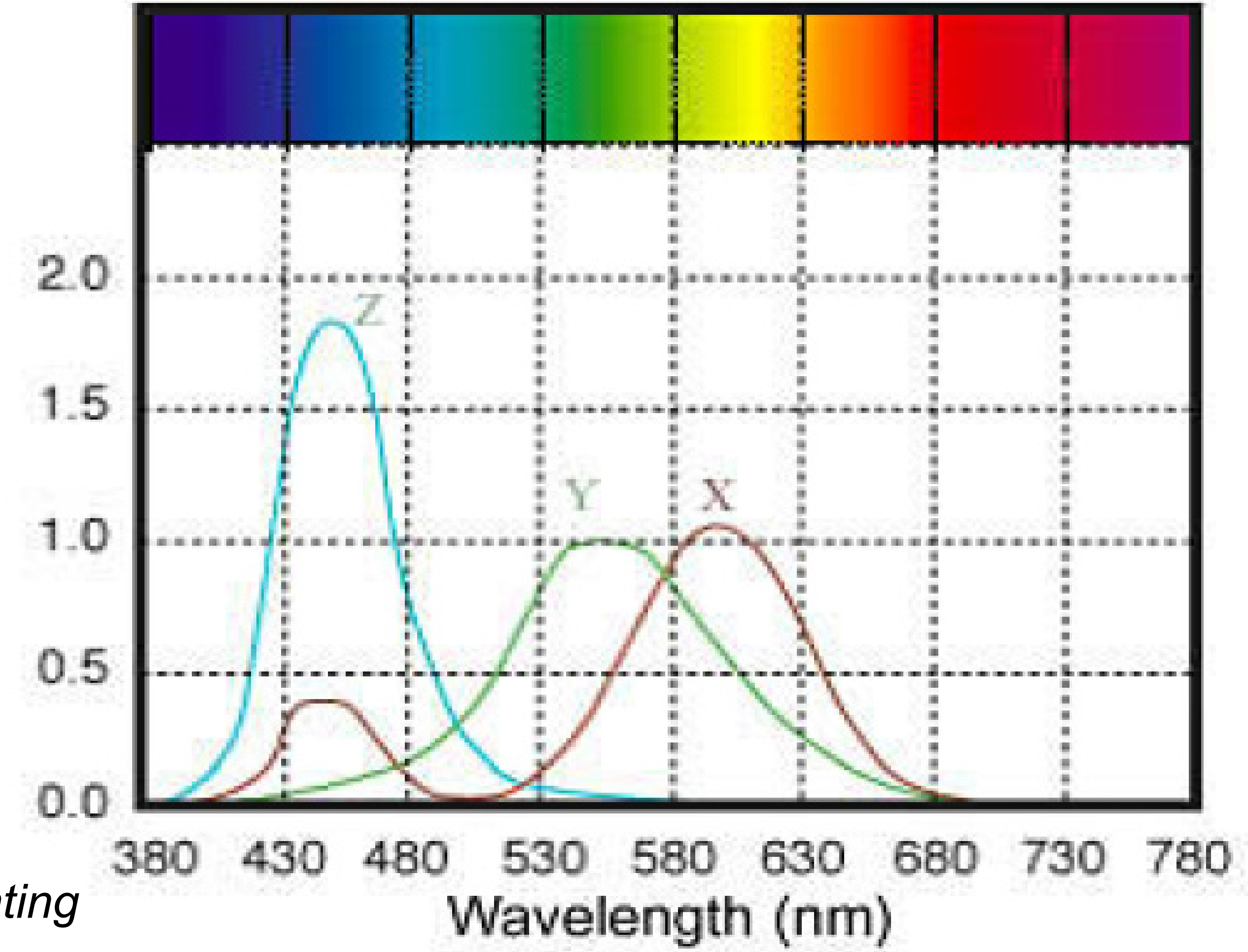
$$Z = k \int_\lambda \varphi_\lambda(\lambda) \cdot \bar{z}(\lambda) d\lambda$$

k=683 lm/W

$\varphi_\lambda(\lambda) = spectrum$, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ = *weighting*

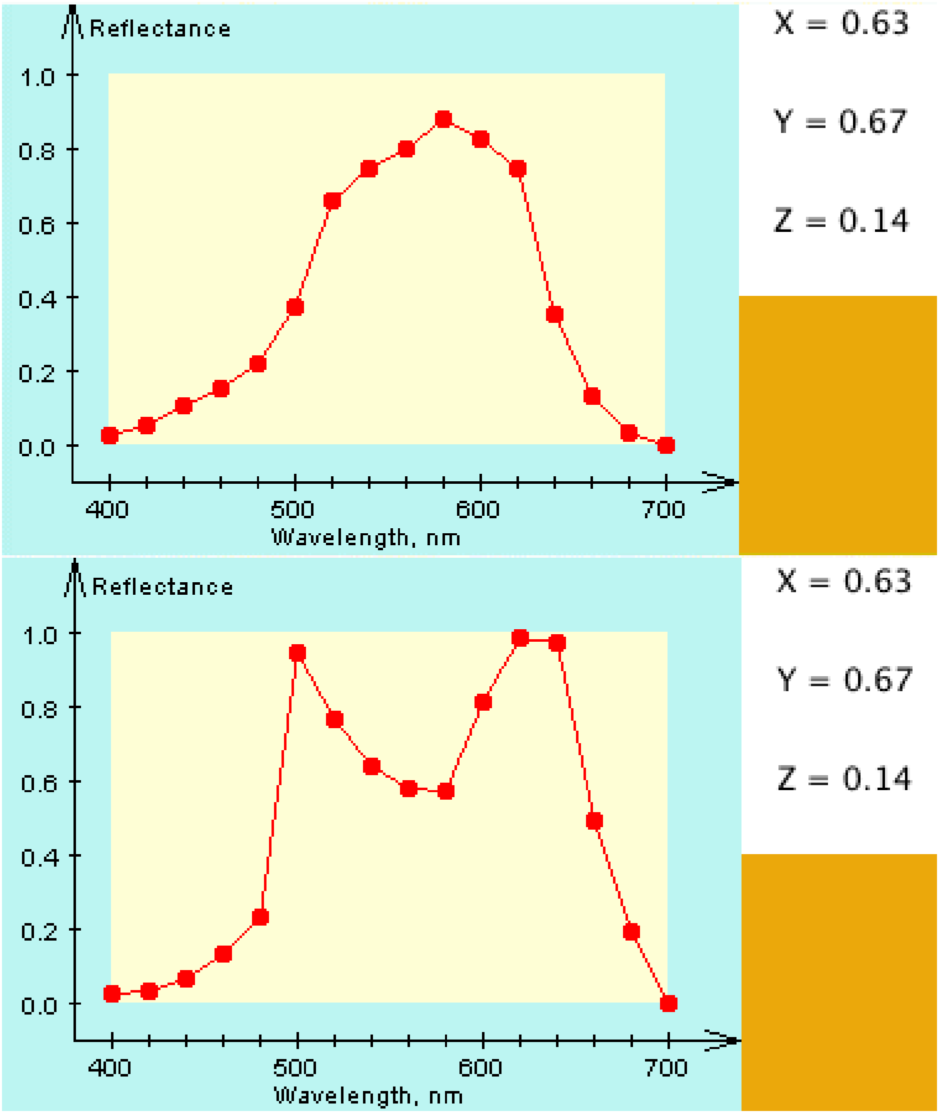
Tutorial Gigahertz-Optik

CIE 1931 Standard Observer



B. Fraser, "Out of Gamut: Why is Color," www.creativepro.com

1.3 Identical Decompositions



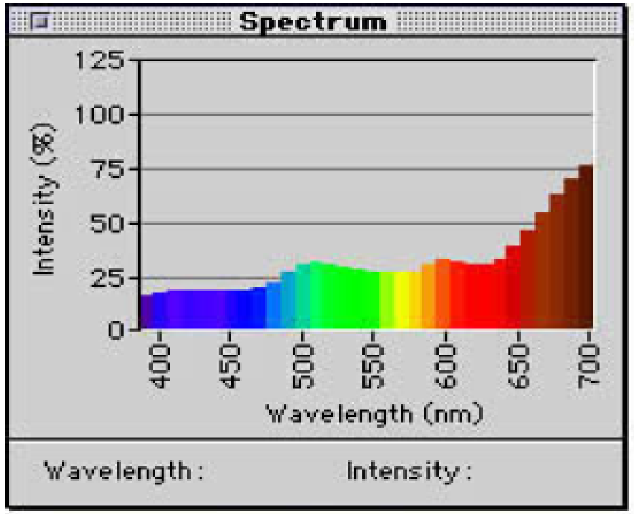
http://tecfa.unige.ch/perso/lombardf/formcont/couleurs/2-spectres-jaune.gif

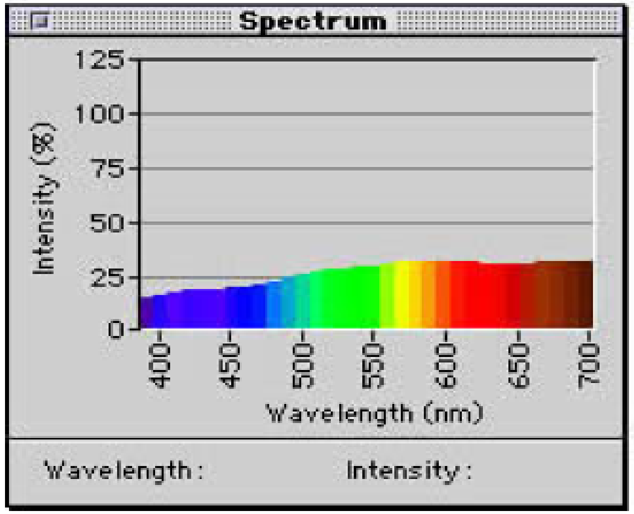
16 points:
- Differents spectra

3 parameters:
- identical X,Y,Z values

1.3 Metamerism

Spectral response of objects under white light





Visual perception under two different light sources

D65 light source (less red)

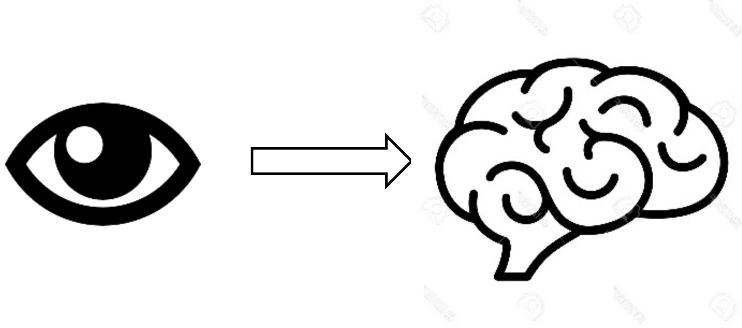
Incandescent room lighting

B. Fraser, "Out of Gamut: Why is Color", www.creativepro.com

1.3 Mixed letters

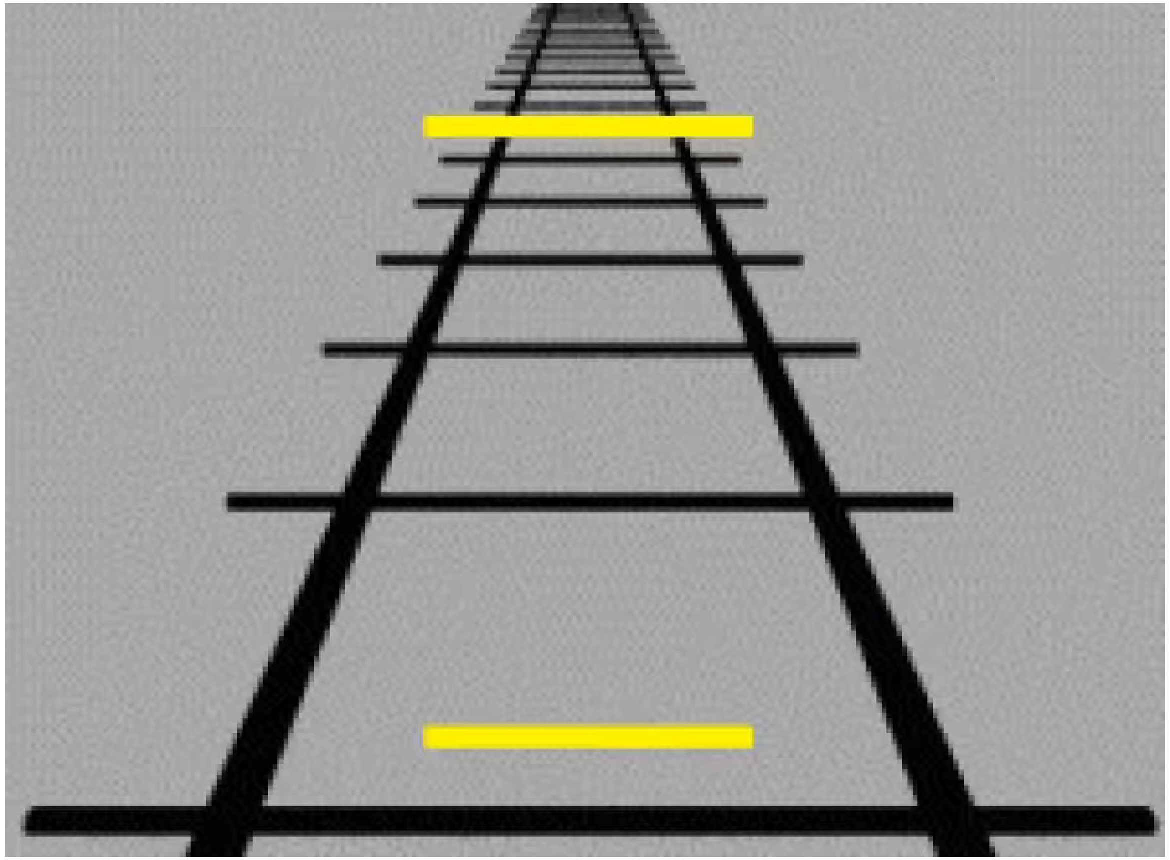
Aoccdrnig to a rscheearch at Cmabrigde Uinervtisy, it deosn't mttaer in waht oredr the ltteers in a wrod are, the olny iprmoetnt tihng is taht the frist and lsat ltteer be at the rghit pclae. The rset can be a toatl mses and you can sitll raed it wouthit porbelm. Tihs is bcuseae the huamn mnid deos not raed ervey lteter by istlef, but the wrod as a wlohe.

http://www.mrc-cbu.cam.ac.uk/people/matt.davis/cmabridge/



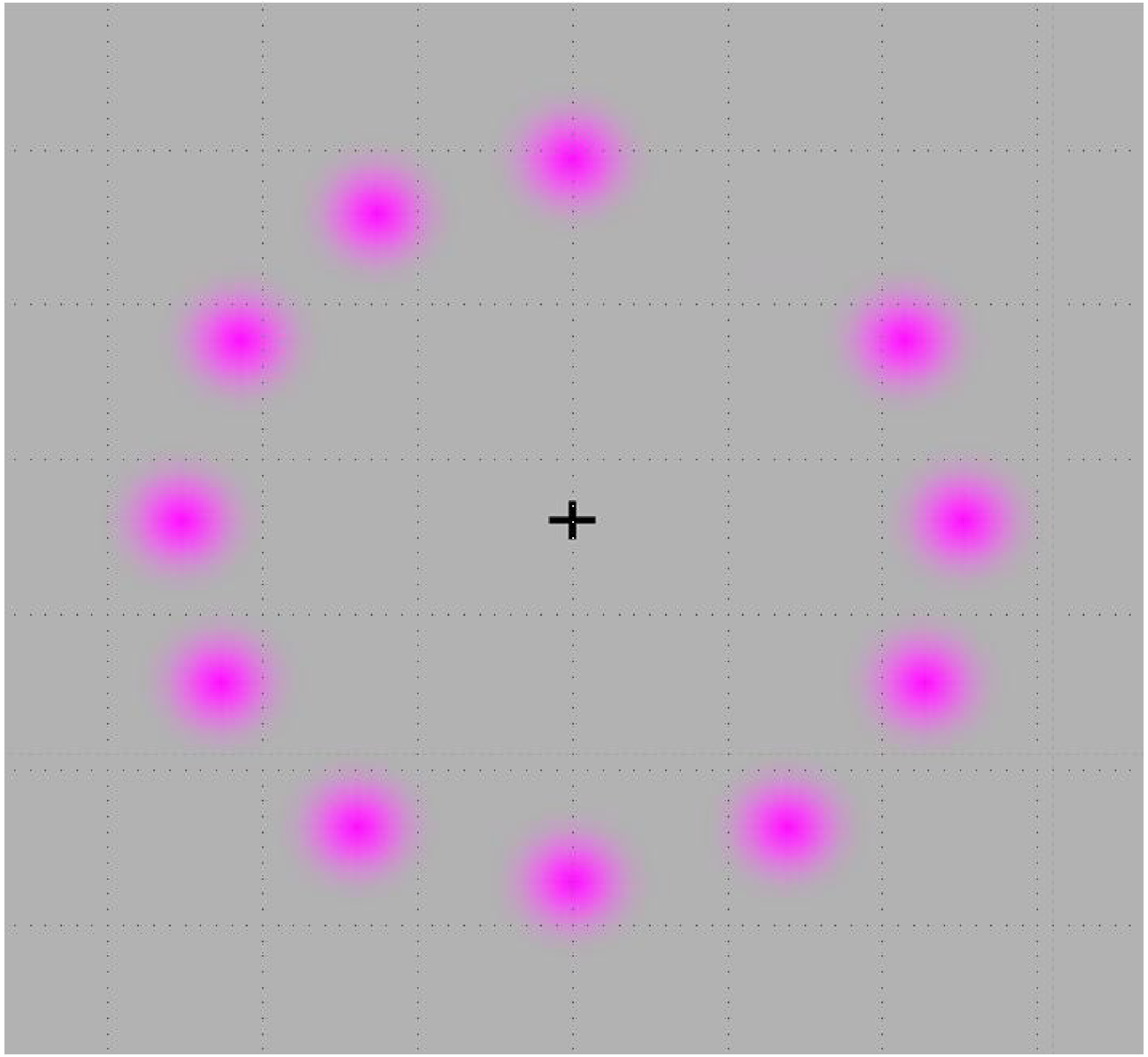
Soeln une éudte d´une uvriseinté agnliase l´odrre des lttrees dnas un mot n´est pas ipmrtnaot, ce qui cmptoe c´est la pmereire et la dinreere lertte. Le rtsee puet erte n´ipmrote qoui, tu puex qnaud mmee le lrie snas pbolrmee.

1.3 Optical illusions/1



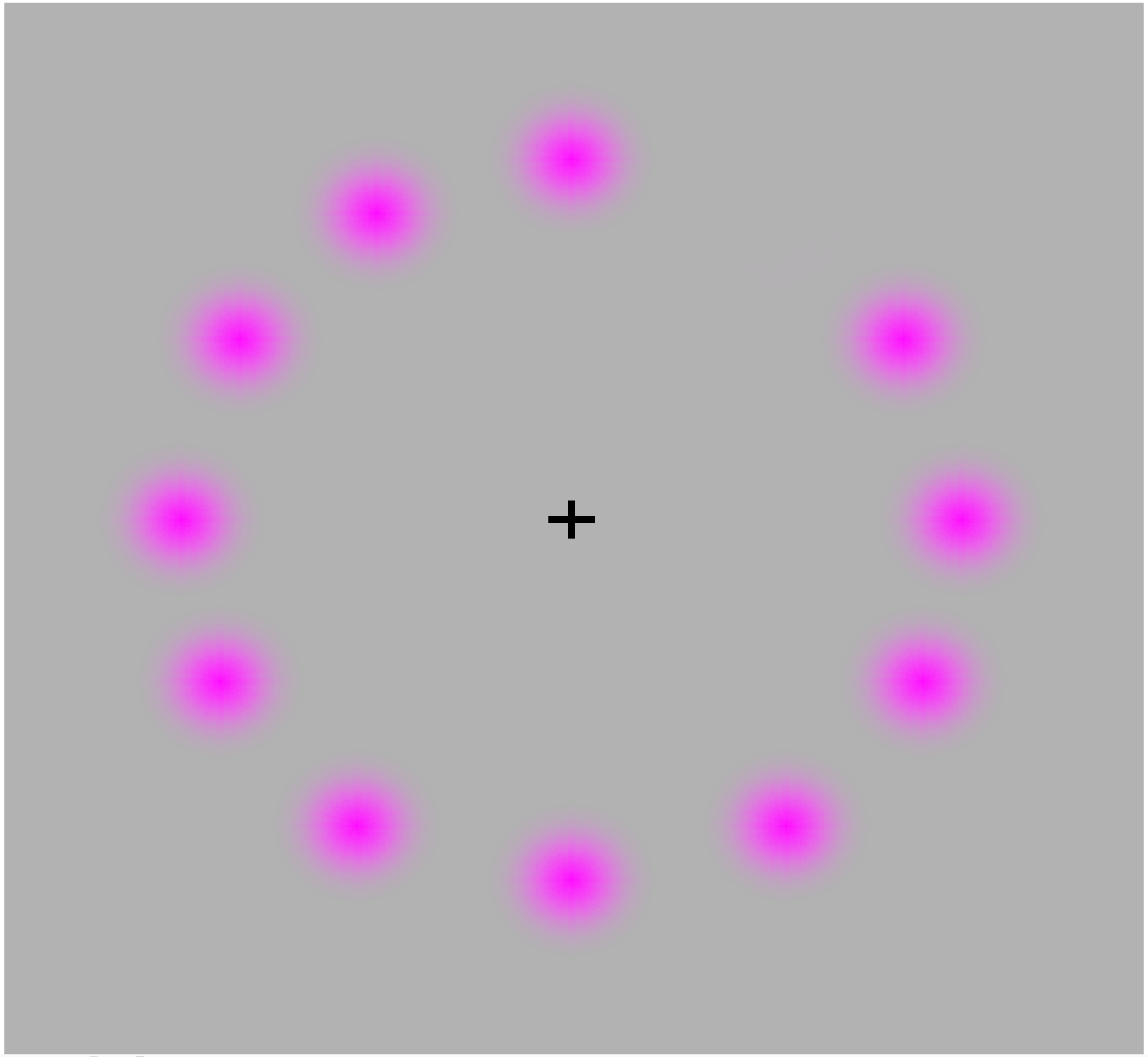
https://www.verywellmind.com/cool-optical-illusions-2795841

1.3 Optical illusion/2



Find out what happens
if the missing point rotates…

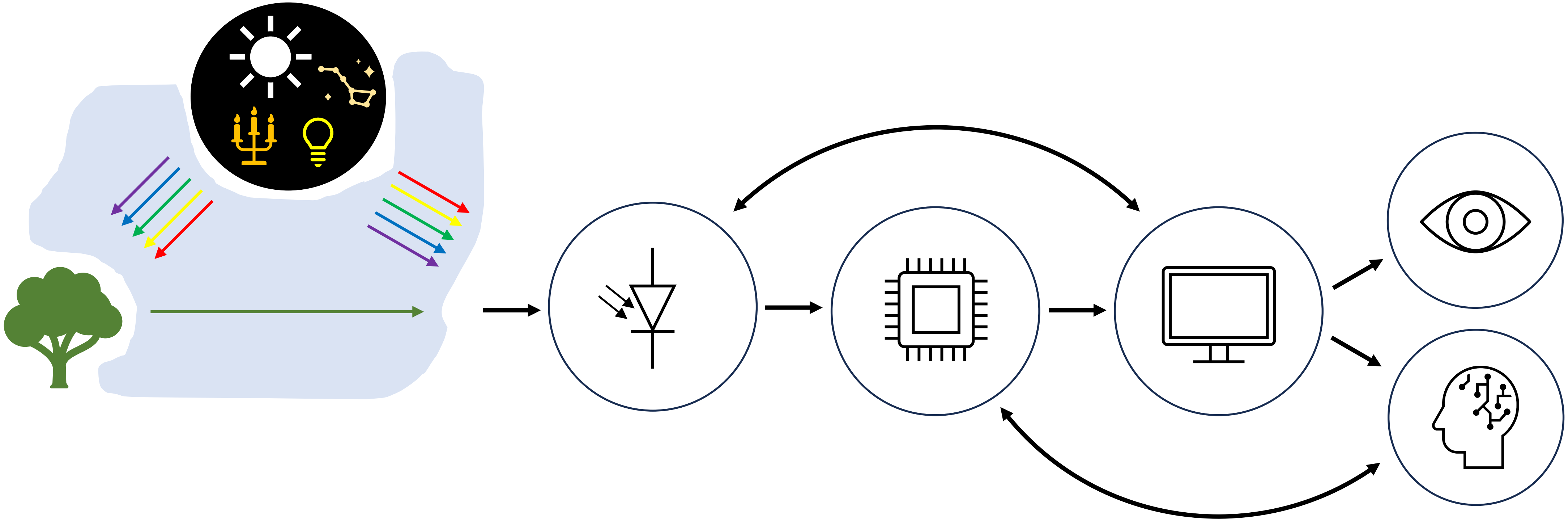
1.3 Optical illusion/2



Concentrate on the cross in the middle, and after a few seconds you'll notice that the spinning pink circle is actually GREEN!

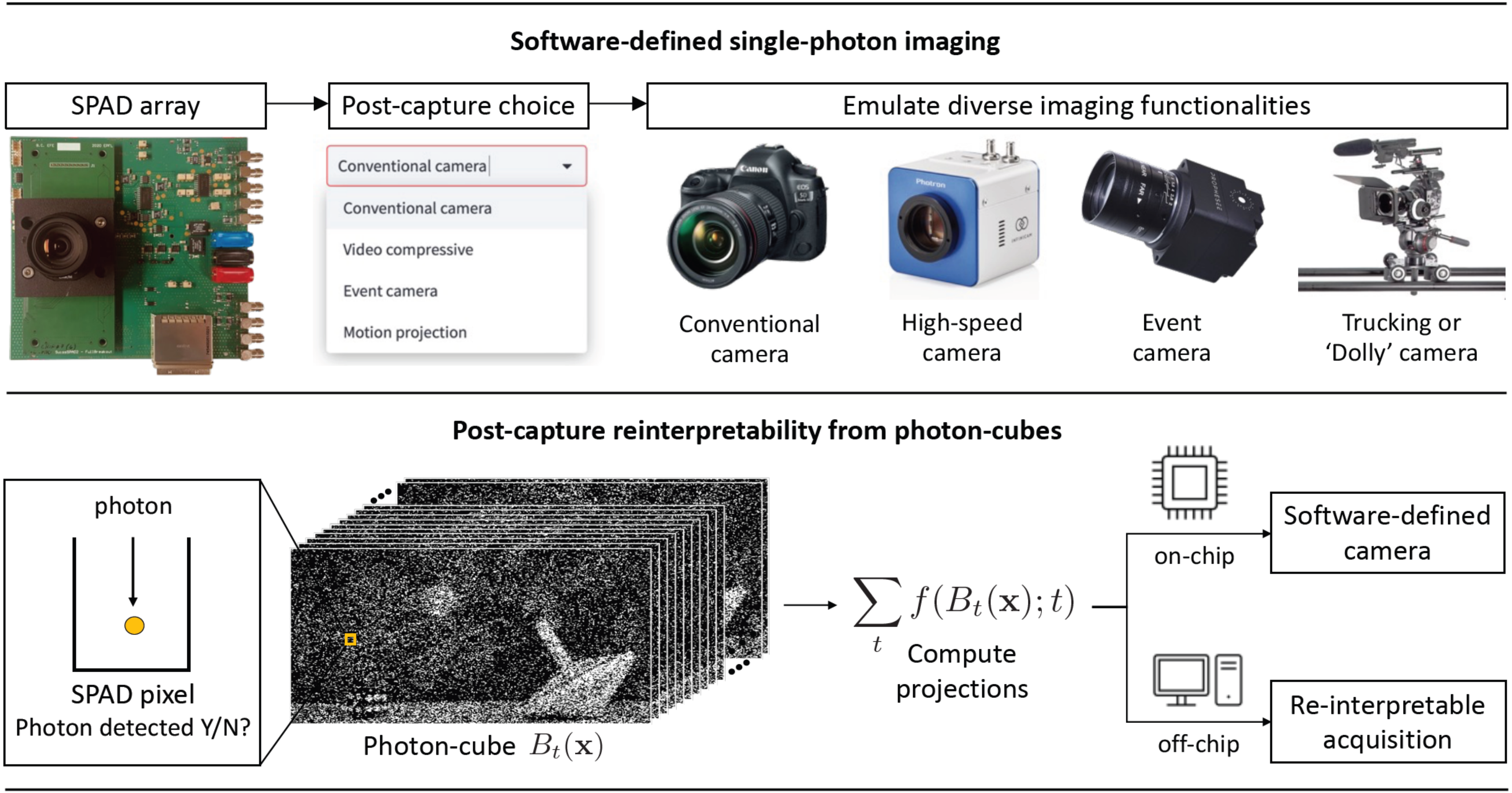
If you look at the cross in the middle, you'll see that the pink circles disappear and only the green circle (which is actually pink) remains!

Take-home Messages/W1-2: Components of an optical system



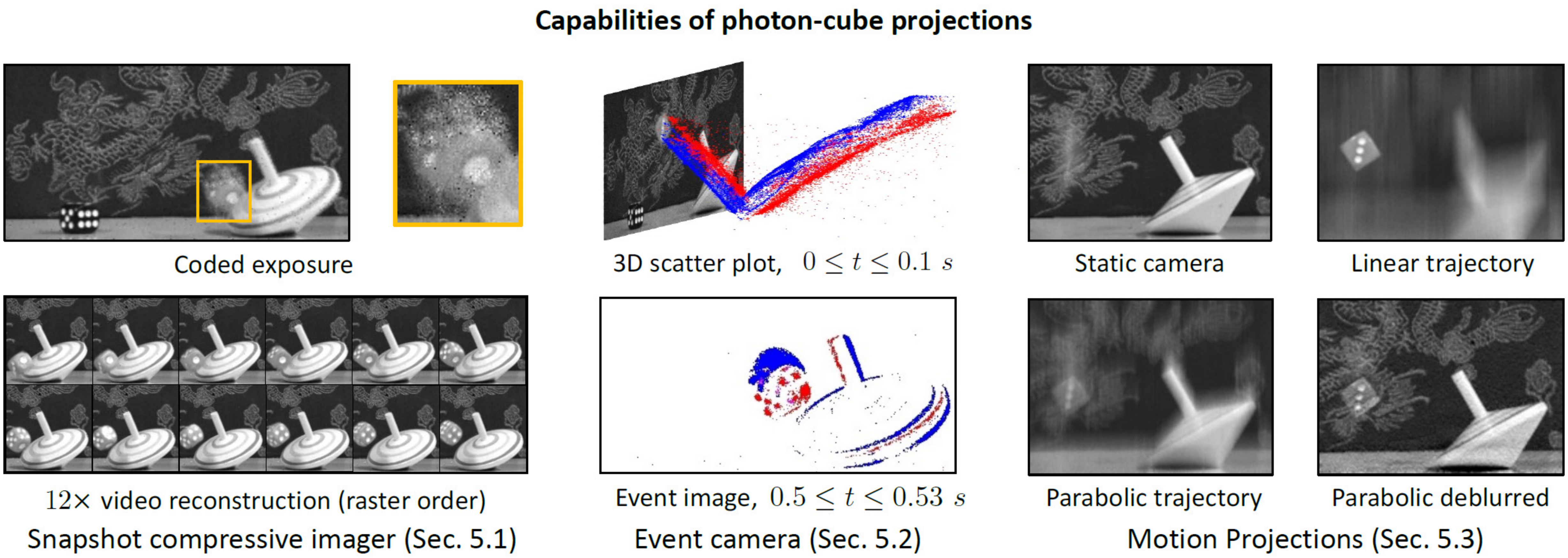
Light source → Optical medium → Detector → Signal processing → Output (display) → Interpretation (analysis)

Computational imaging example: software defined cameras



V. Sundar, et al. ICCV 2023

Computational imaging example: software defined cameras



V. Sundar, et al. ICCV 2023

Outline

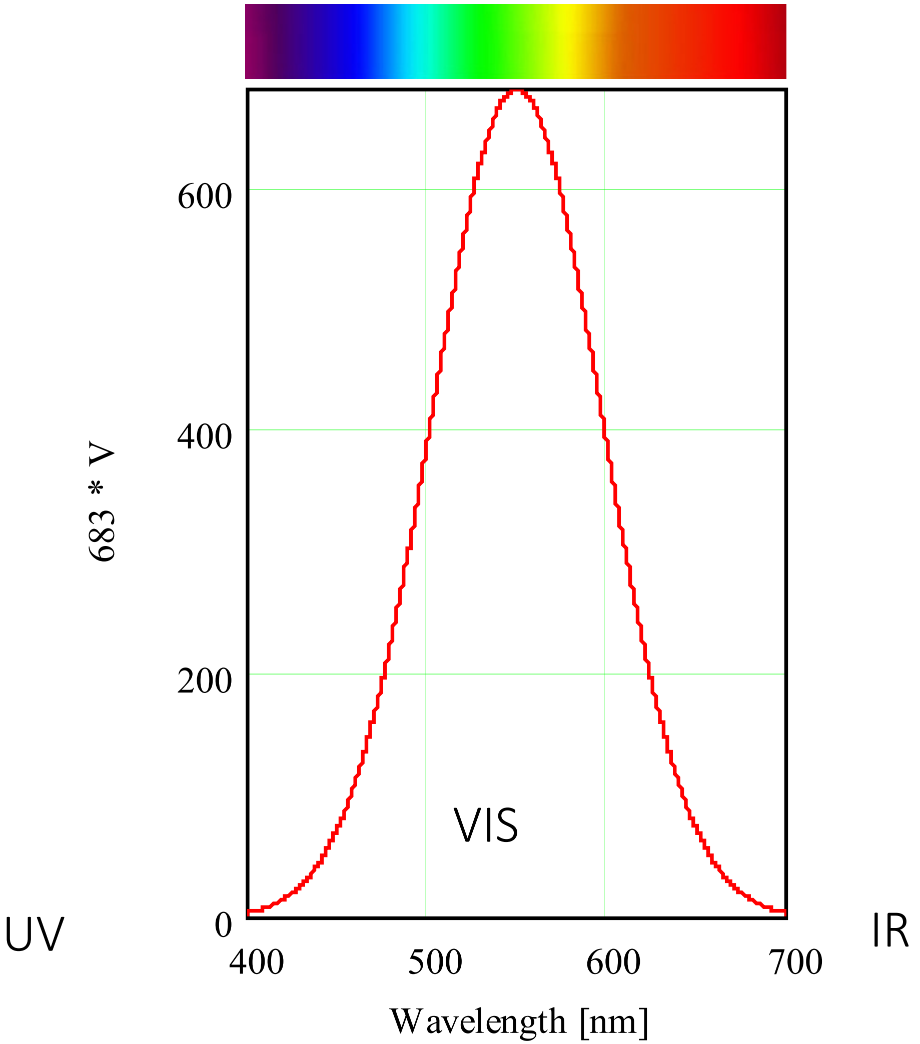
1.4 Photometry and the Relationship between *lumen* and *watt*

$$1\ [W]_{at\ \lambda} = 683 \cdot V_\lambda\ [lm]$$

$$V_\lambda \cong e^{-\left(\frac{\lambda - 550nm}{67nm}\right)^2}$$

- "lumen": unit of **luminous flux**, but based on the sensation perceived by the average human eye = "visible watt" - @550nm: 1 W = 683 lumen
- 1 W in blue or red = weaker sensation on the eye -> less lumen

Sensitivity of the human eye



1.4 Photometry: Source

$$\text{Luminous flux} = \text{Luminance} \cdot S_{source} \cdot \Omega_{source} \ [\text{lm}]$$

“intensity”

lm = lumen = “visible watts”

$$\text{Luminance} = 683 \cdot \int_0^\infty P_\lambda V_\lambda \ d\lambda \quad [cd/m^2]$$

“luminous intensity per unit solid angle and per surface area on the source.”

$$\text{Luminous intensity} = \text{Luminance} \cdot S_{source} \ [\text{cd}]$$

“intensity emitted within a unit solid angle”

cd = candela= «visible watts» per angle

1.4 Photometry: Detector

$$\text{Illuminance} = \text{Luminance} \cdot \Omega_{\text{det.}}\ [lx]$$

"intensity per surface area on the detector"

lx = lux = «visible watts» [*lm*] per surface

$$\text{Luminous flux on the detector} = \text{Illuminance} \cdot S_{\text{det.}}\quad [lm]$$

"intensity"

1.4 Photometry: Examples

Source Luminance:

Surface of the sun:	$2\ 10^9$ cd/m^2
Carbon lamp:	10^8 cd/m^2
750 W filament lamp:	$2\ 10^7$ cd/m^2
60 W incandescent lamp:	$9\ 10^4$ cd/m^2
Clear sky:	$2\ 10^4$ cd/m^2
40 W fluorescent lamp:	$5\ 10^3$ cd/m^2
Overcast sky:	$2\ 10^3$ cd/m^2

Cd = "visible" intensity per unit solid angle

Detector Illuminance:

683

Sun at its zenith:	$1.2\ 10^5$	lux
Clear sky:	10^4	lux
Overcast sky:	10^3	lux
60 W lamp at 1m:	10^2	lux
Candle at 1m:	1	lux
Full moon at its zenith:	0.27	lux
Moonless night sky:	10^{-4}	lux

Lux = "visible" intensity per m^2

R.W. Boyd "Radiometry and the detection of optical radiation"

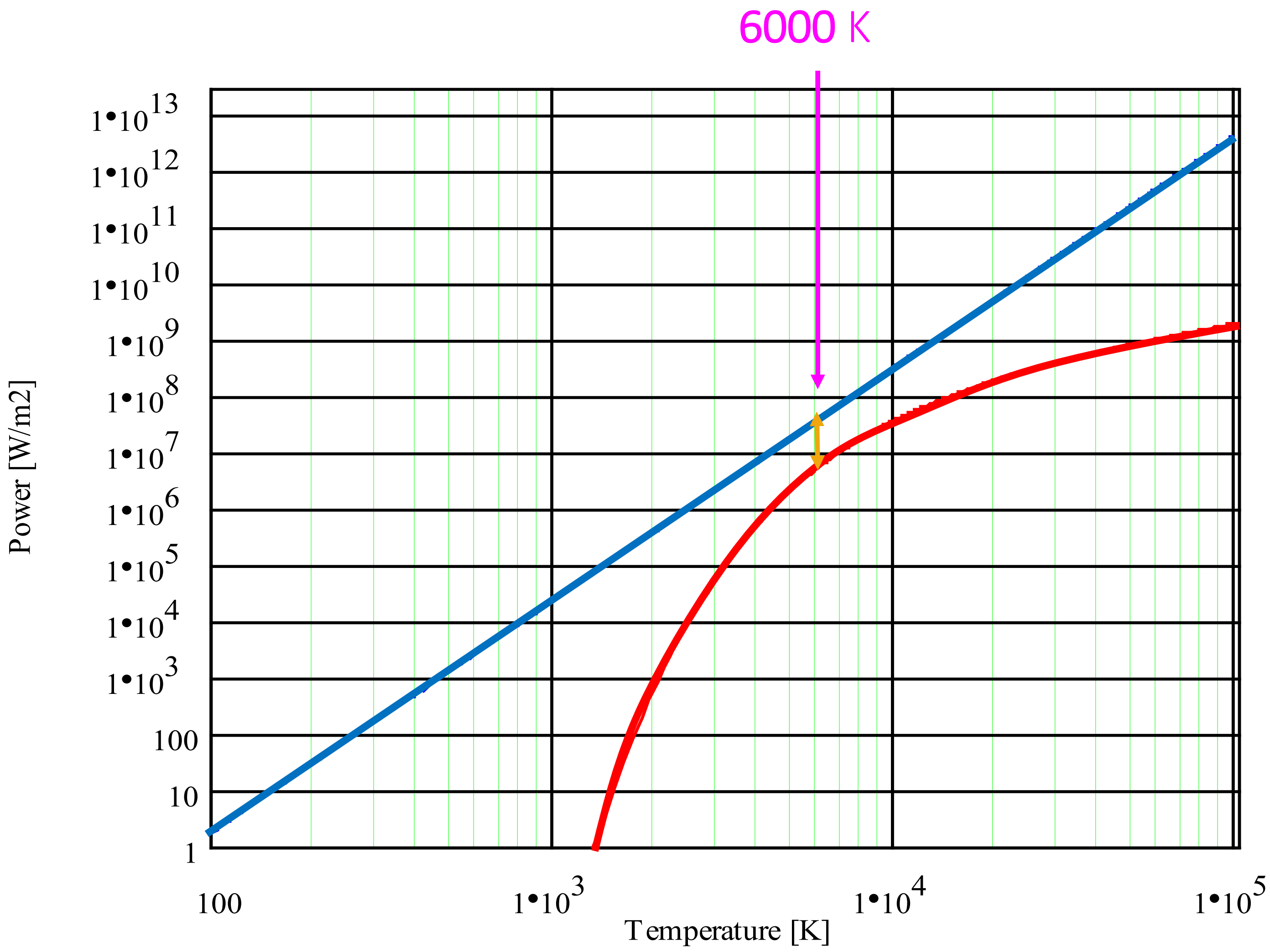
1.4 Black body: Total and Visible Power

Total power:

$$\int_0^\infty P_\lambda \; d\lambda = \frac{\sigma}{\pi} \cdot T^4$$

Visible power:

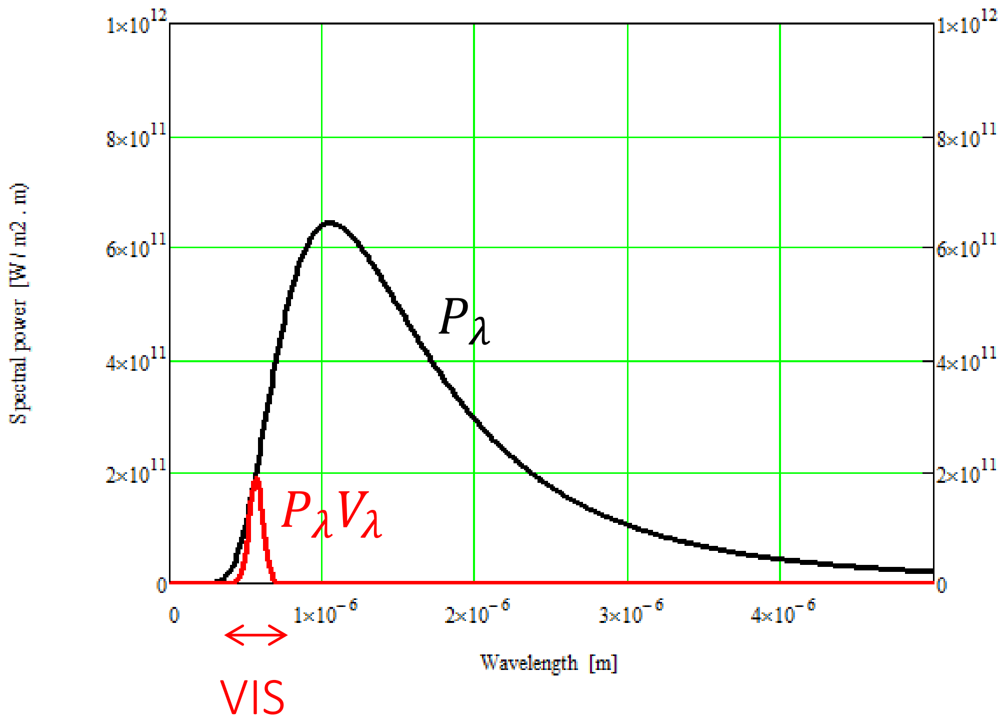
$$\int_0^\infty P_\lambda \, V_\lambda \; d\lambda$$



1.4 Efficiency of light sources in visible

Incandescent lamp

T=2750 K



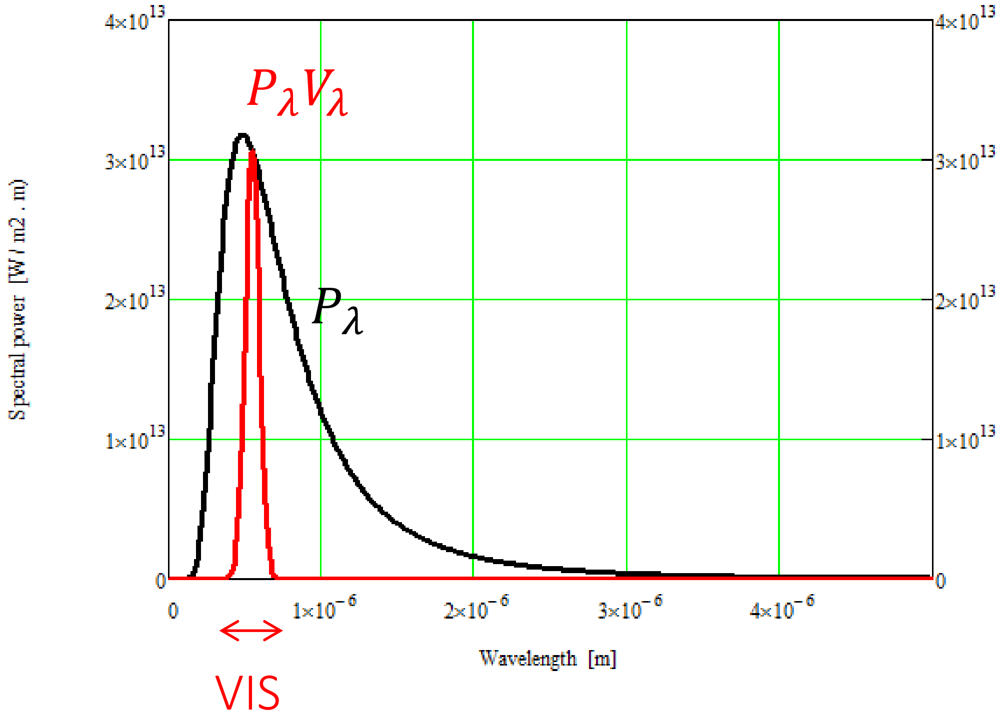
Typical: 2% efficiency

13 lm/W conversion

$$\text{Conversion} = 683 \cdot \text{efficiency}$$

Sun

T=6000 K



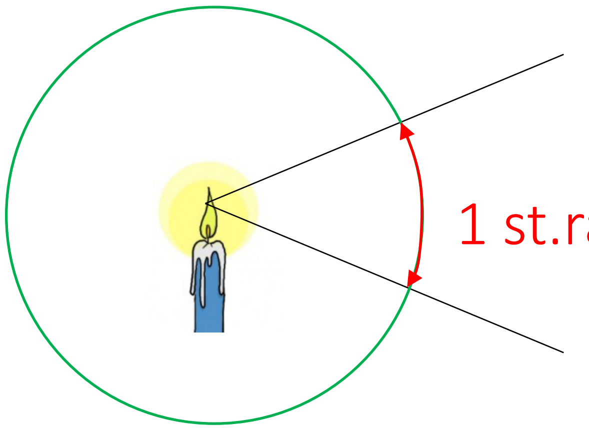
Typical: 15% efficiency

100 lm/W conversion

Comparable to white LED

1.4 Comparison: candle – incandescent light bulb

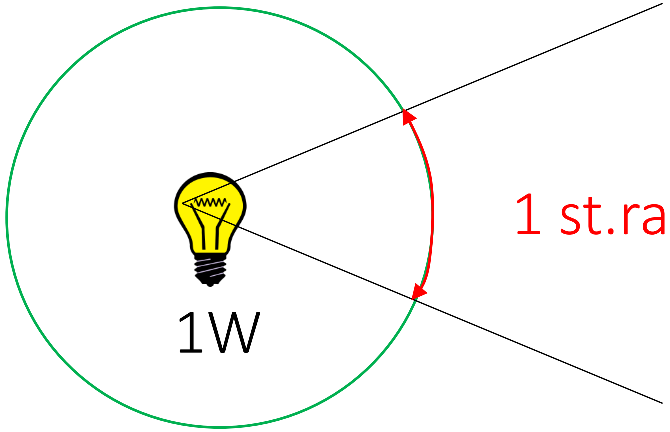
4π st.rad.
≅13 Lm



1 st.rad. → 1 Lm/st.rad = 1 cd

Incandescent lamp of X watts
≃
X candles

13 Lm



1 st.rad. → 1 Lm/st.rad. = 1 cd

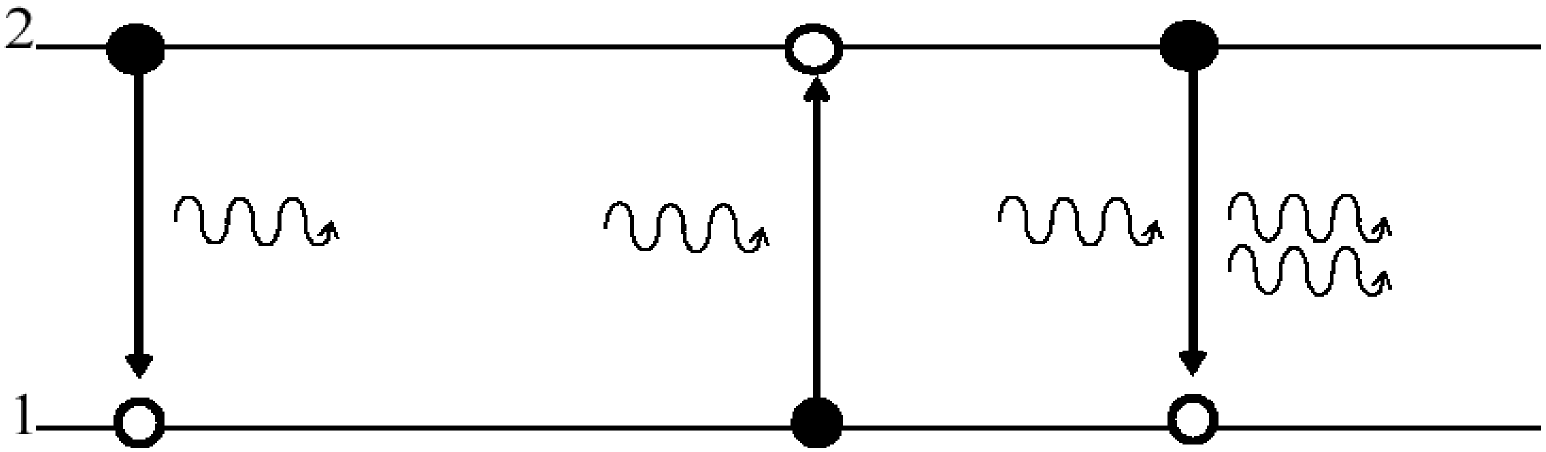
1 W → 2% x 683 Lm = 13 Lm

Outline

1.5 Absorption

a) Principle

Interaction between light and matter is necessary to enable optical detection!



Spontaneous emission — $N_2 \cdot A_{21}$

Absorption — $N_1 \cdot B_{12} \cdot w(\nu)$

Stimulated emission — $N_2 \cdot B_{21} \cdot w(\nu)$

Example with a two state system

Examples?

$w(\nu)$ = spectral optical energy density per volume (# *of photons*)

Einstein coefficients

$$B_{12} = B_{21} = \mathrm{B} \qquad \frac{A_{21}}{B} = \frac{8\pi}{c^3} \cdot h \cdot \nu^3$$

1.5 Einstein Coefficients (1)

- Absorption: $N_1 \cdot B_{12} \cdot w_\nu$

- Stimulated emission: $N_2 \cdot B_{21} \cdot w_\nu$

- Spontaneous emission: $N_2 \cdot A_{21}$

- Boltzmann's probability: $N_i = Const \cdot e^{\frac{-\Delta E_i}{kT}} \Longrightarrow \frac{N_1}{N_2} = e^{\frac{h\nu}{kT}}$

- Spectral energy density:

$$w_\nu = \frac{4\pi}{c} \cdot P_\nu = \frac{8\pi}{c^3} \cdot h \cdot \nu^3 \cdot \left(e^{\frac{h\nu}{kT}} - 1\right)^{-1}$$

1.5 Einstein Coefficients (2)

- Equilibrium:

$$N_2 \cdot A_{21} + N_2 \cdot B_{21} \cdot w_\nu = N_1 \cdot B_{12} \cdot w_\nu$$

- Equilibrium at high temperatures:

$$(T \to \infty) \Rightarrow (w_\nu \to \infty)\ and\ (N_2 = N_1) \Longrightarrow \boxed{B_{21} = B_{12} \equiv B}$$

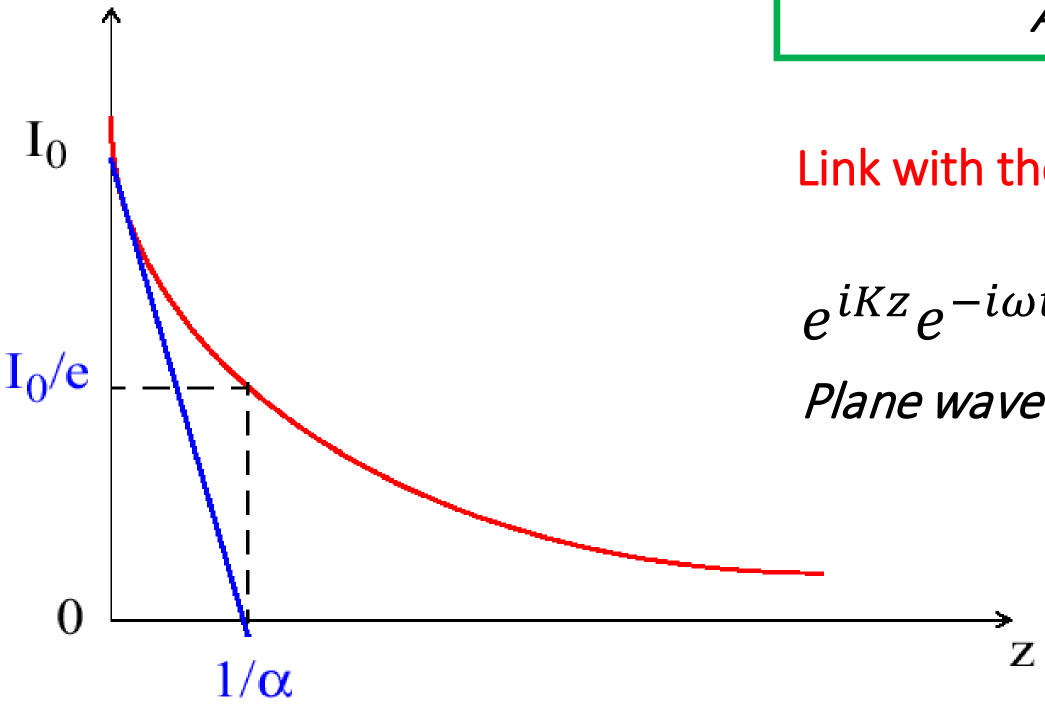
- Relationship between A and B:

$$N_2 \cdot A_{21} = B \cdot w_\nu \cdot (N_1 - N_2)$$

$$\frac{A_{21}}{B} = w_\nu \cdot \left(\frac{N_1}{N_2} - 1\right) \Longrightarrow \boxed{\frac{A_{21}}{B} = \frac{8\pi}{c^3} \cdot h \cdot \nu^3}$$

1.5 Absorption Coefficient α

$$I(z) = I_0 \cdot e^{-\alpha z}$$



$$|u(z)| = \sqrt{I} = \sqrt{I_0} \cdot e^{-\frac{\alpha}{2}z}$$

Link with the B coefficient

$$\alpha = \frac{n}{c} \cdot (B_{12}N_1 - B_{21}N_2) = \frac{n}{c} \cdot \mathrm{B} \cdot (N_1 - N_2)$$

Absorption *Stim. emission*

Link with the refractive index

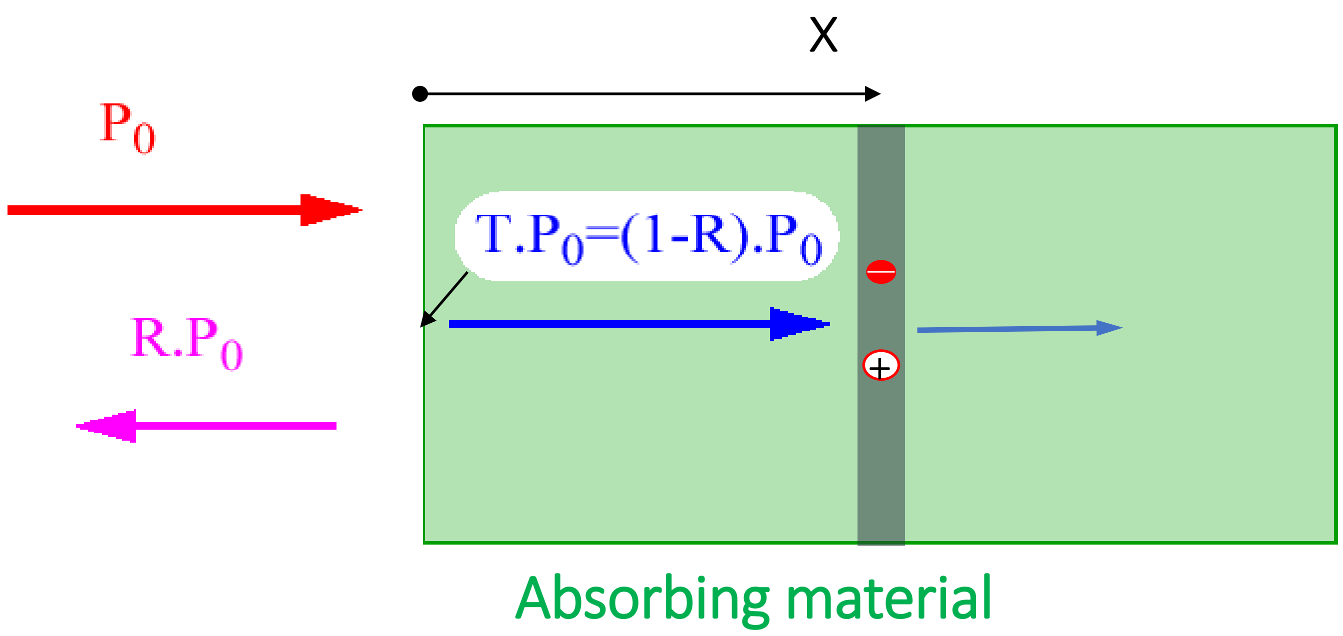
$$e^{iKz}e^{-i\omega t} = e^{i\frac{2\pi}{\lambda}\cdot(n+i\kappa)\cdot z}e^{-i\frac{2\pi}{\lambda}\cdot ct} = e^{i\frac{2\pi}{\lambda}(n\cdot z-ct)} \cdot e^{-\frac{2\pi}{\lambda}\kappa\cdot z}$$

Plane wave

$$v_{phase} = \frac{c}{n} \qquad \frac{\alpha}{2} = \frac{2\pi}{\lambda}\kappa$$

α = *probability of photon absorption/cm*

1.5 Absorption and Generation Rate



R= reflection coefficient

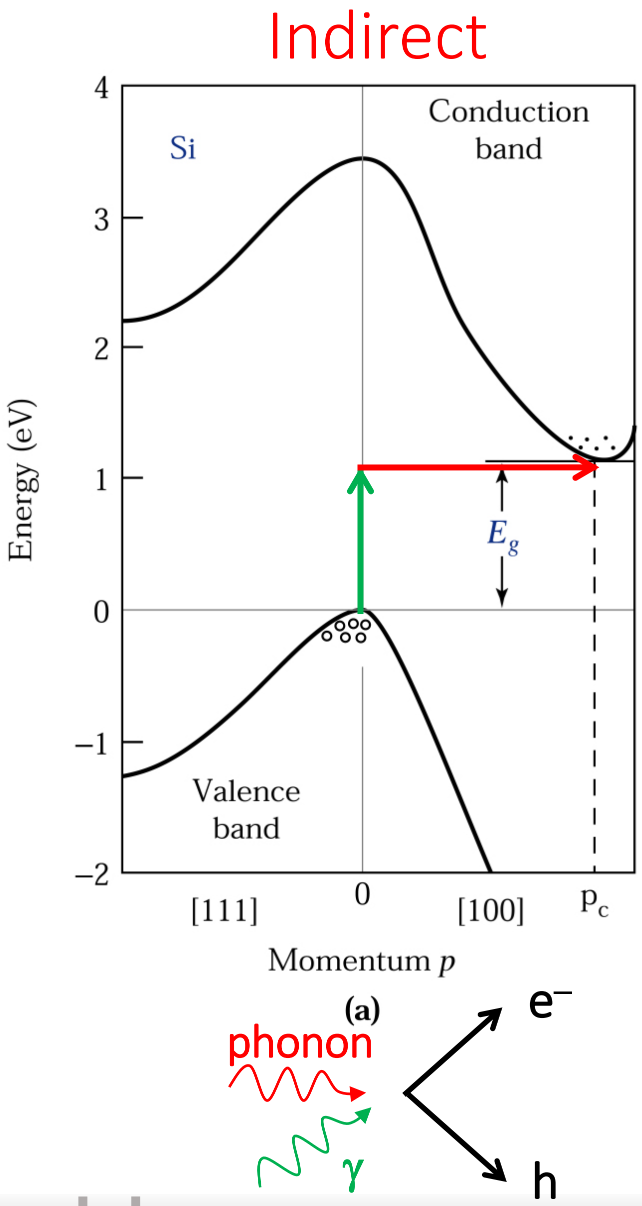
T= transmission coefficient

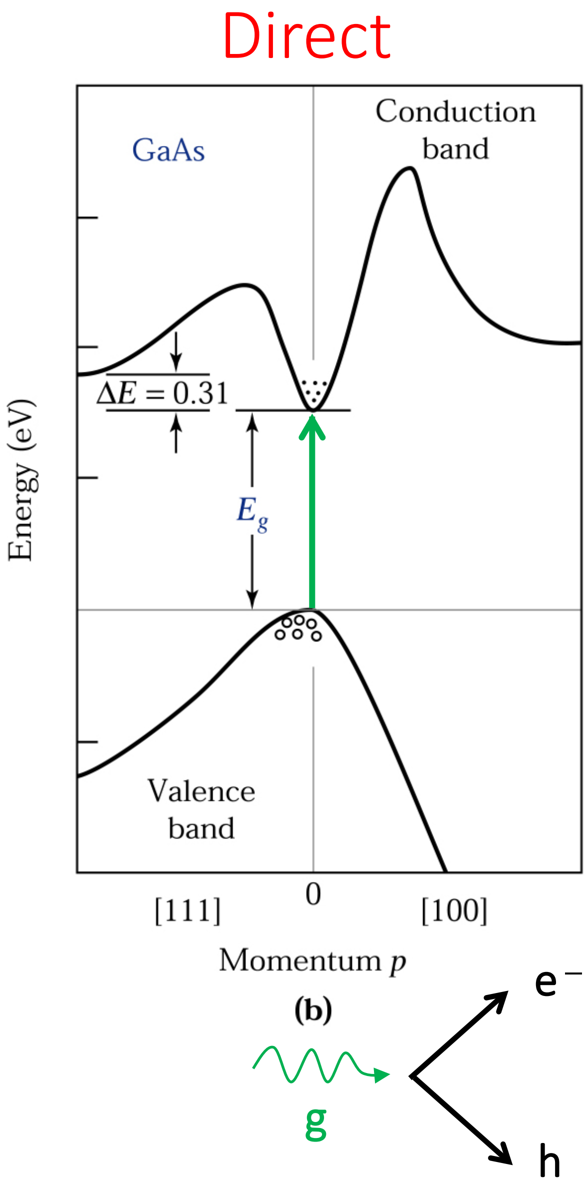
$g(x)$ = generation rate of carriers (e⁻/h pairs)

$$g(x) = \frac{P(x)}{h\nu} \cdot \alpha = \frac{P_0}{h\nu} \cdot (1-R) \cdot e^{-\alpha x} \cdot \alpha \quad \left[\frac{1}{cm \cdot s}\right]$$

g(x) = (#photons at depth x) x (probability that they are absorbed)

1.5 Band Diagram for Semiconductors





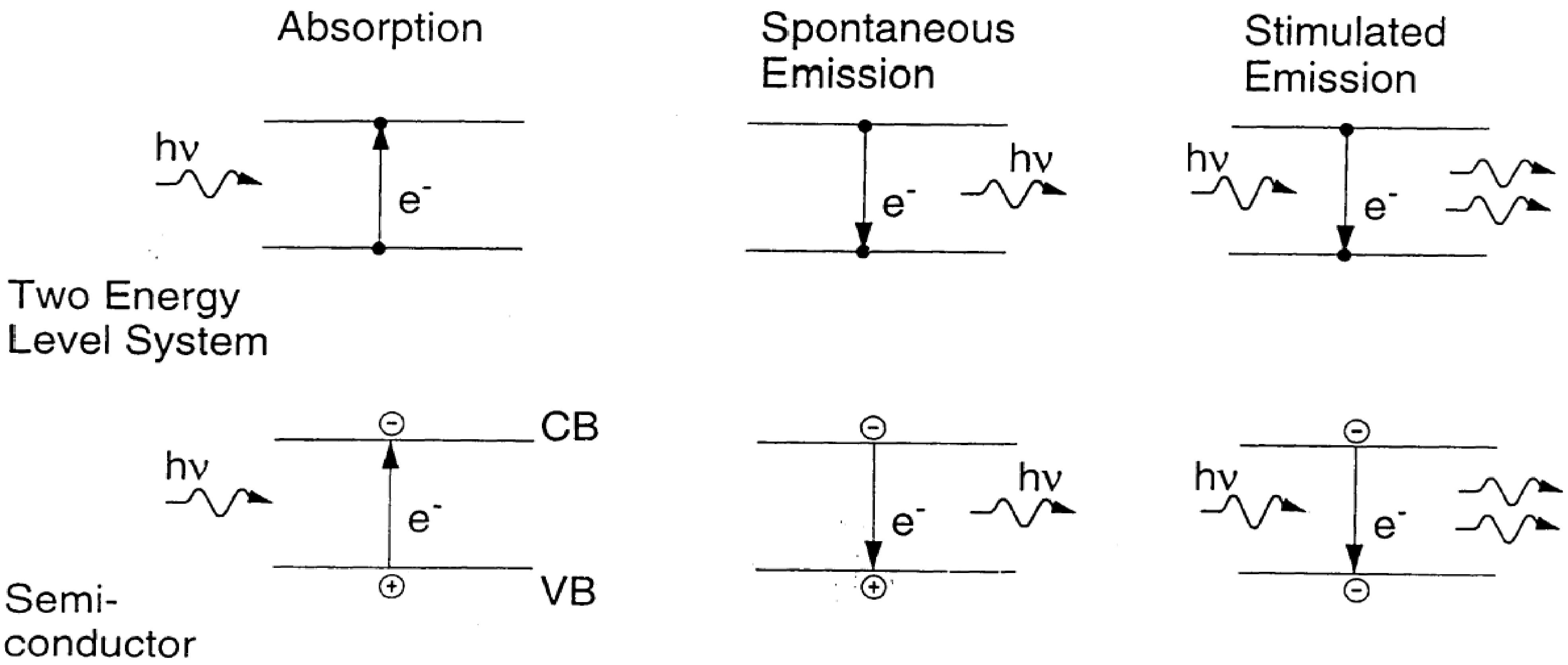
In an indirect semiconductor phonons are required to conserve momentum.

Its absorption is lower than that of a direct semiconductor.

$B_{indirect} << B_{direct}$

S. M. Sze "*Semiconductor Devices*"

1.5 Light – Semiconductor Interactions



- The valance band and the conduction band replace the ground state and the excited state
- The photon must have a minimum energy of $h\nu > E_g$
- We need to take into account all possible transitions

1.5 Light – Semiconductor Interactions

If we assume that the coefficient B is constant for all transitions:

absorption

$$\alpha(E) \cong \left(\frac{n}{c}\right) \cdot B \cdot \int_{-\infty}^{E_v} [\rho_v(E')(1 - f_v(E'))\rho_c(E' + E)(1 - f_c(E' + E))] - [\rho_c(E' + E) f_c(E' + E) \rho_v(E') f_v(E')] \cdot dE'$$

Stimulated emission

$$\alpha(E) \cong \left(\frac{n}{c}\right) \cdot B \cdot \int_{-\infty}^{E_v} [\rho_v(E') \cdot \rho_c(E' + E) \cdot (1 - f_v(E') - f_c(E' + E))] d\, E'$$

- Absorption increases with energy.
  Blue is absorbed at the surface, red penetrates deeper before it is absorbed.
- The formula above can also describe a gain ($\alpha < 0$, laser effet)

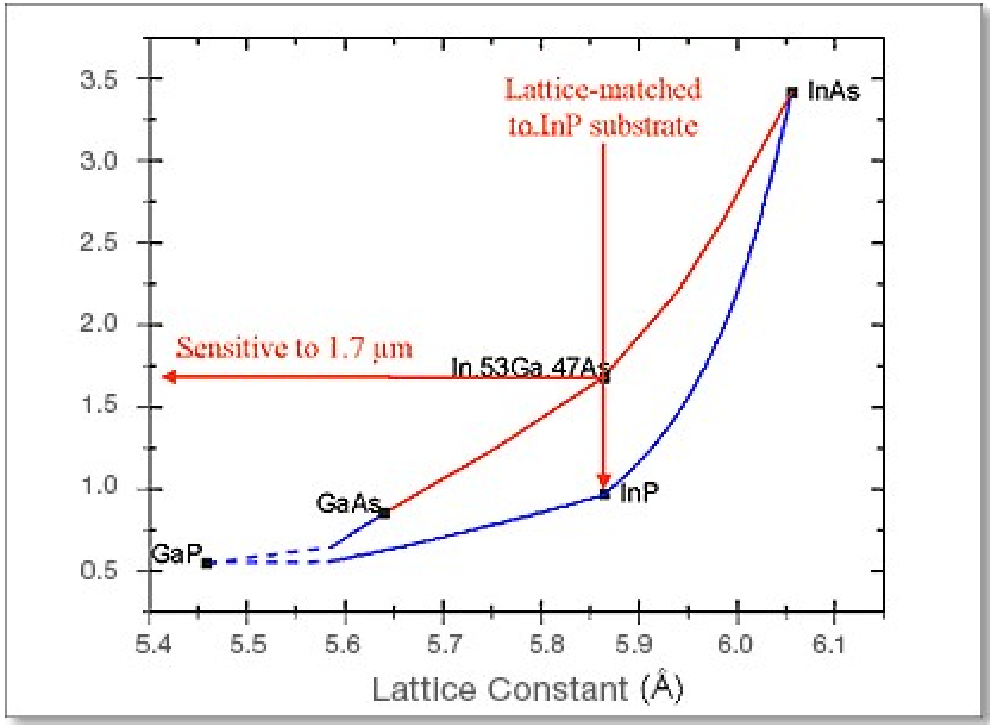
1.5 Semiconductor Table

Column II	III	IV	V	VI
	B Boron	C Carbon	N Nitrogen	
Mg Magnesium	Al Aluminium	Si Silicon	P Phosphorus	S Sulfur
Zn Zinc	Ga Gallium	Ge Germanium	As Arsenic	Se Selenium
Cd Cadmium	In Indium	Sn Tin	Sb Antimony	TE Tellurium
Hg Mercury		Pb Lead		

1.5 Bandgaps

Group	Material	Bandgap Energy (eV)	Type of Bandgap	Cut-off Wavelength (μm)
Element	Si	1.12	I	1.1
	Ge	0.66	I	1.88
III-V	GaP	2.24	D	0.55
	GaAs	1.42	D	0.87
	InP	1.35	I	0.92
	InAs	0.36	D	3.44
	InSb	0.17	D	7.3
II- VI	CdS	2.42	D	0.52
	CdSe	1.70	D	0.73
	CdTe	1.56	D	0.83
	$Hg_{1-x}Cd_xTe$	0.08 - 1.56	D	0.83 -16
IV-VI	PbS	0.41	I	3.0

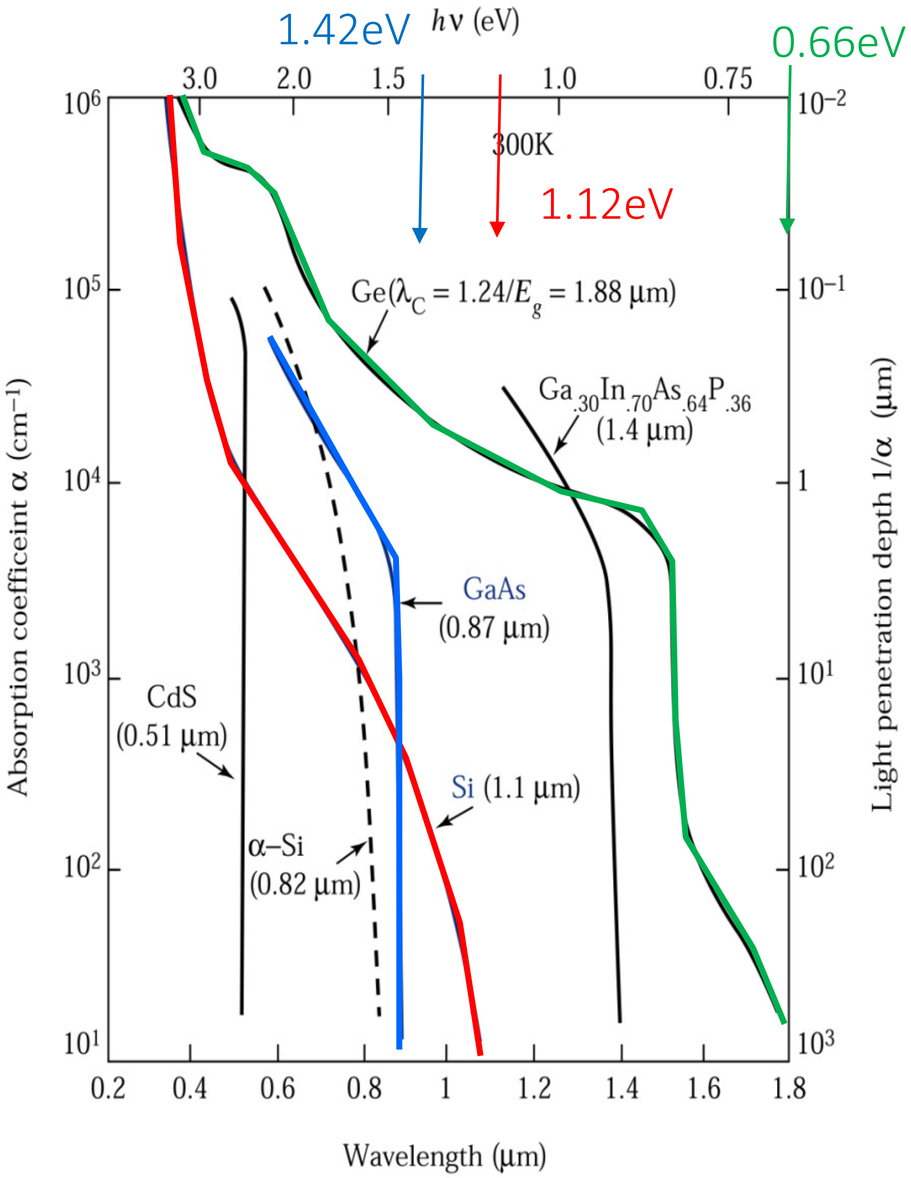
$In_{1-x}Ga_xAs_yP_{1-y}$

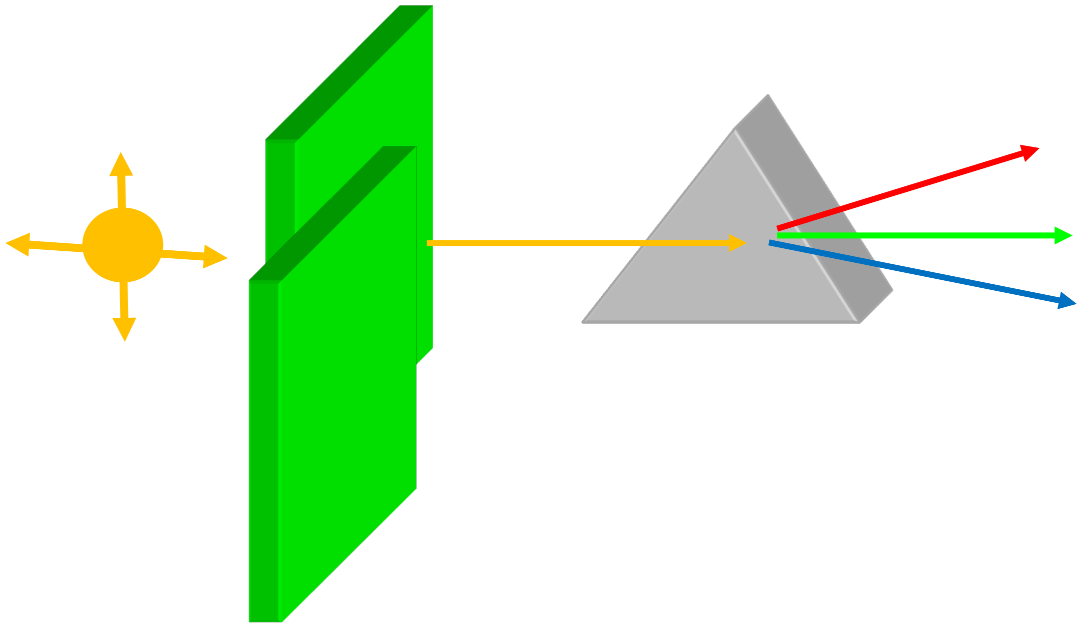


Tunability!

https://www.sensorsinc.com/technology/what-is-ingaas

1.5 Absorption Spectra





$$E_{[eV]} = \frac{h\nu}{q} = \frac{hc}{q} \cdot \frac{10^6}{\lambda_{[\mu m]}} \cong \frac{1.24}{\lambda_{[\mu m]}}$$

Outline

1.6 Types of Optical Detectors

a) Thermal detectors: *measure heat -> 1W blue vs 1W red?*

1) Bolometers or thermistors
2) Thermocouples and thermopiles
3) Golay cells and photoacoustic sensors
4) Pyrodetectors

b) Photonic detectors: photons -> charge carriers; *1W blue vs 1W red?*

1) Photodiodes: p-n, p-i-n or Schottky
2) Photoconductors
3) Avalanche photodiodes, photomultipliers.

Draw an I vs. λ response curve at constant power!

c) Cameras:

1) Charge Coupled Devices (CCD)
2) CMOS, smart pixels

Take-home Messages/W1-3

1.4 **Photometry**:

- What is a « Lumen »? Why is the underlying concept important?

1.5 **Light-matter interaction:**

- Describe it in a two-level system and in a semiconductor.
- Link it to the absorption coefficient.

1.6 **Bandgap / Absorption spectra:**

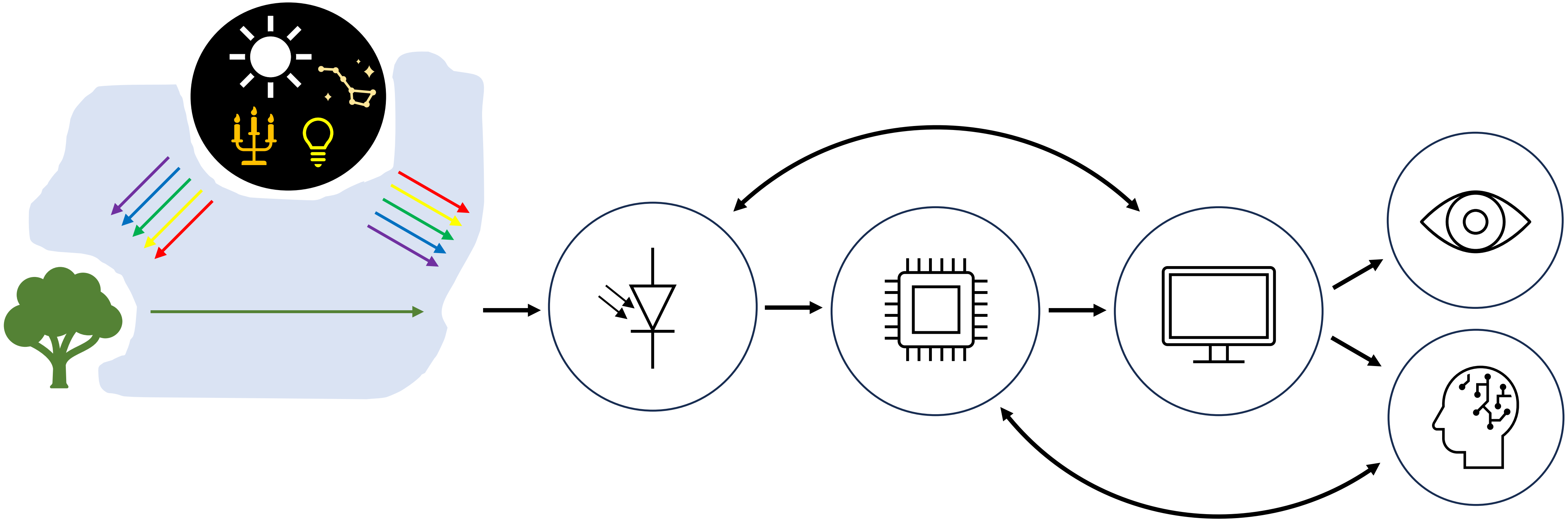
- Explain the difference between a semiconductor with direct and indirect bandgap - what are the consequences for the absorption of light and on the optical detector properties?

1.7 **Thermal vs photonic detector:**

- What are the differences between a thermal and a photonic detector?
- What is typically the spectral detectivity for these two kinds of sensors and why?

Exercises – Week 1

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

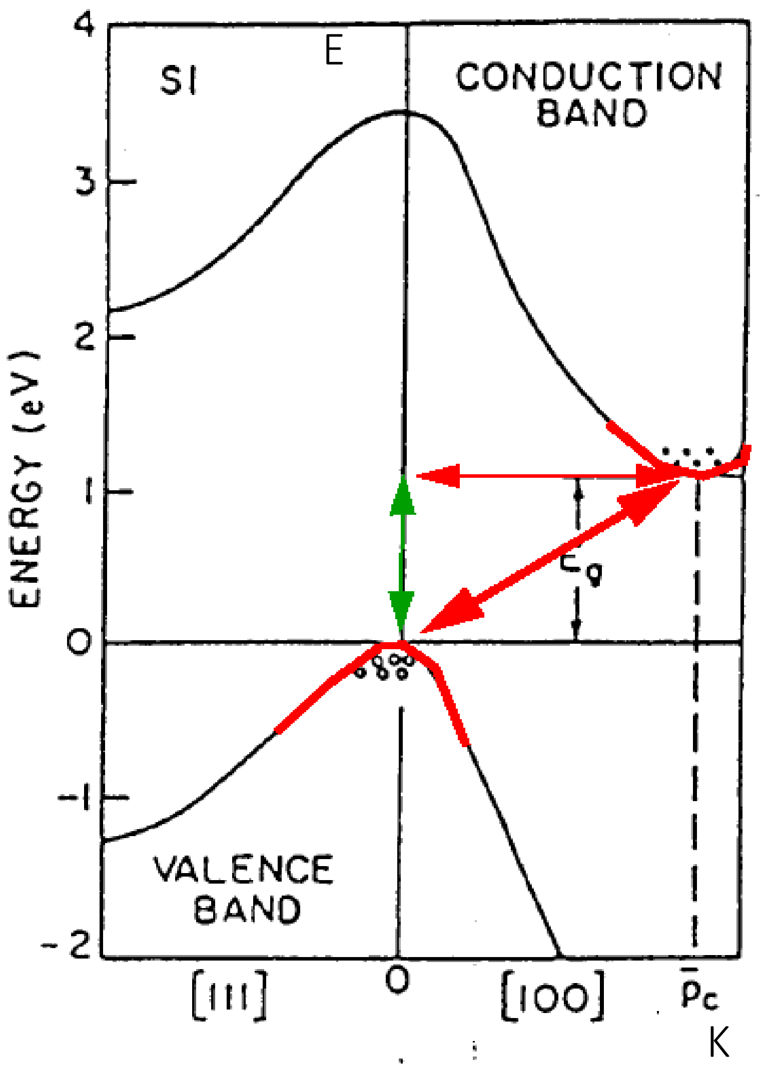
Select 1-2 key blocks in the previous slide:

- 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 1.2: 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).

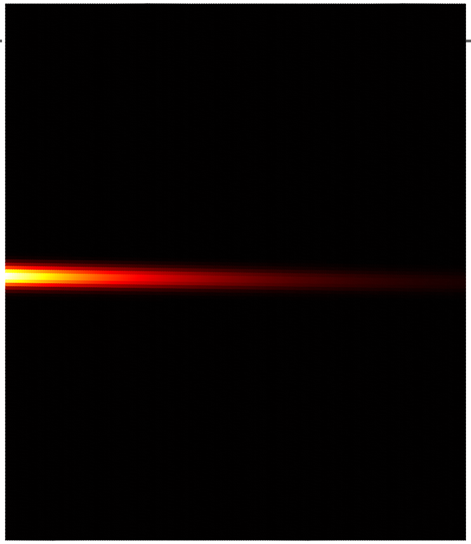
2) What are the wave-vector K and the energy E (in eV) of a photon of wavelength λ=1 mm?

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)?

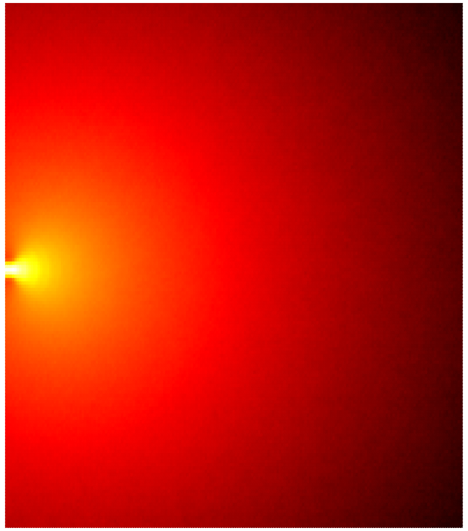
Exercise 1.2: Summary Table (to be completed)

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

Exercise 1.3: 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?
- Which kind of illuminator could be used?
- Which kind of detector?

Appendix

A1 Fundamental equations (1)

1) Potential energy : $E_{pot} = E_{vac} = (-q) \cdot \varphi$ The potential energy is the vacuum level

2) Maxwell :

$$div(\vec{E}) = \frac{\rho}{\varepsilon_0 \varepsilon} = \frac{q\ (p + N_d^+ - n - N_a^-)}{\varepsilon_0 \varepsilon}$$

1D ⇨ $E_x \propto +\int \rho \cdot dx$ The electric field is the integral of the net charges

$\propto$ = proportional

3) Maxwell :

$$rot(\vec{E}) = -\frac{\partial \vec{B}}{\partial t} = 0 \quad \Rightarrow \quad \vec{E} = -\overrightarrow{grad}(\varphi) = \frac{1}{q}\overrightarrow{grad}(E_{vac})$$

1D ⇨ $E_x \propto +\frac{\partial E_{vac}}{\partial x}$ The electric field is the slope of the vacuum level

A1.1 Fundamental equations (2)

4) Poisson equation :
from 2) and 3)

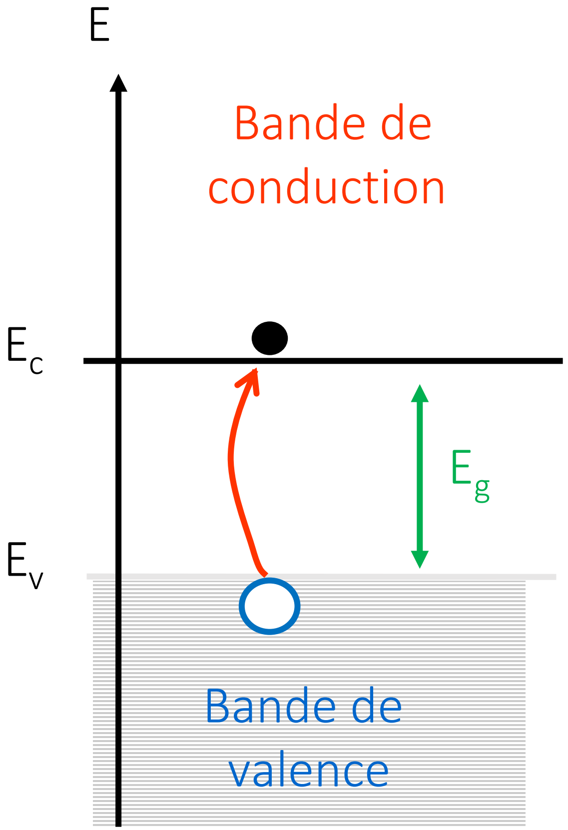
$$\Delta\varphi = -\frac{\rho}{\varepsilon_0\varepsilon} = -\frac{q\ (p + N_d^+ - n - N_a^-)}{\varepsilon_0\varepsilon} = -\frac{1}{q}\Delta E_{vac}$$

1D ⇨

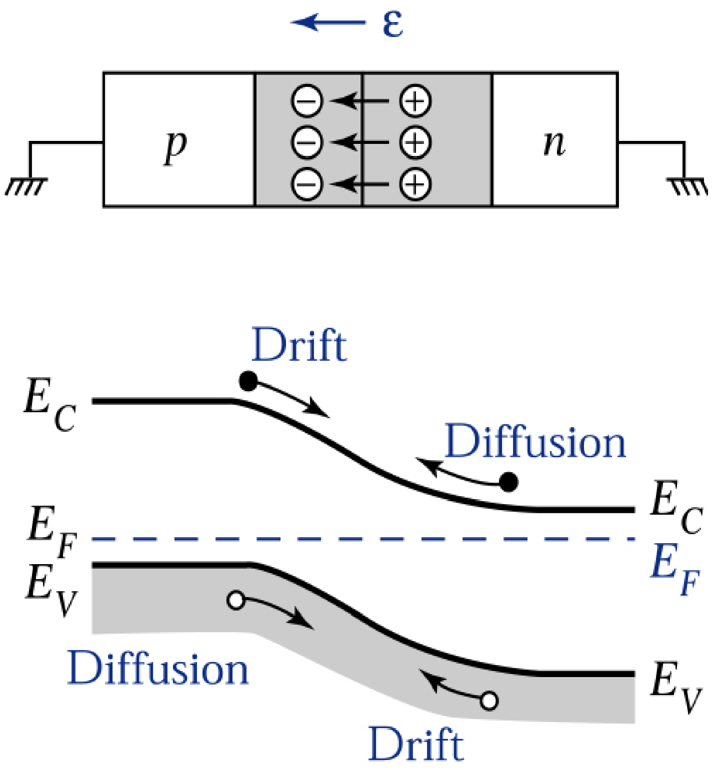
$$\rho \propto +\frac{\partial^2 E_{vac}}{\partial x^2}$$

The net charges are the curvature of the vacuum level

A1.1 Band structure



Jonction p/n



S.M. Sze, « Semiconductor devices, physics and technology »

A1.1 Band diagram