

# MICRO-523: Optical Detectors

Week One: Light

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The logo of the École polytechnique fédérale de Lausanne (EPFL), consisting of the letters 'EPFL' in a bold, red, sans-serif font.

# Outline

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- 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

# Literature

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- 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.)

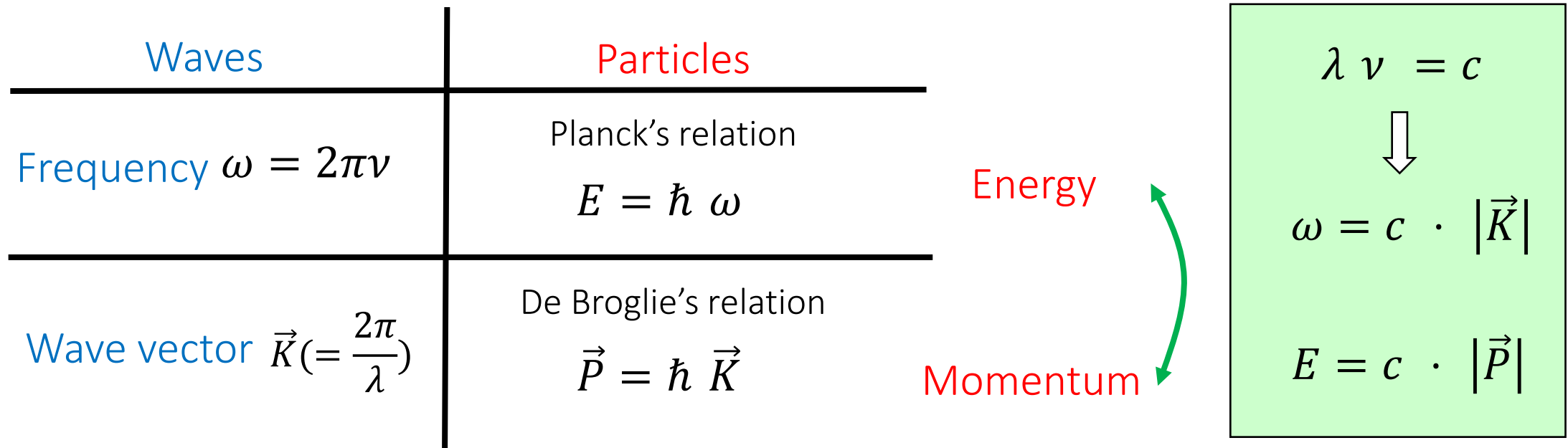
# 1.1 Characteristic Quantities of Light

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- Intensity:  $I$  Thermal detectors
- Number of photons: Photonic detectors
- Wavelength:  $\lambda$  Spectroscopy
- Phase:  $\phi$  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, ...



# 1.1 Quantum mechanical wave equation of light (1)

«Wave function»\*

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

«Quantum mechanical operators»

$$\frac{\partial}{\partial t} f = -i \omega \cdot f \Rightarrow$$

$$E = \hbar \omega = i\hbar \frac{\partial}{\partial t}$$

$$\frac{\partial}{\partial x} f = i K_x \cdot f \Rightarrow$$

$$P_{x,y,z} = \hbar \vec{K}_{x,y,z} = \frac{\hbar}{i} \nabla_{x,y,z}$$

Remember:

$$\nabla = \frac{\partial}{\partial x} \hat{i} + \frac{\partial}{\partial y} \hat{j} + \frac{\partial}{\partial z} \hat{k}$$

Nabla

$\nabla \cdot$

Divergence

$\nabla \times = \text{rot}$

Curl

$\Delta = \nabla^2$

Laplacian

$\nabla$

Gradient

*\*plane matter wave*

*NB: here in vacuum...*

# 1.1 Quantum mechanical wave equation of light (2)

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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 ??

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

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  $\rho=0$  and  $\mathbf{j}=0$

$$\text{rot rot } \dots = \text{grad (div } \dots) - \nabla^2 \dots$$

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

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

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

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



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

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

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

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

# 1.1 Wave Equations

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

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

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

$$\Delta \vec{E}_\omega = - \left[ \left( \frac{\omega}{c} \right)^2 \cdot \left( \mu \epsilon + i \frac{\mu \sigma}{\omega \epsilon_0} \right) \right] \cdot \vec{E}_\omega$$

$$\Delta \vec{H}_\omega = - \left[ \left( \frac{\omega}{c} \right)^2 \cdot \left( \mu \epsilon + i \frac{\mu \sigma}{\omega \epsilon_0} \right) \right] \cdot \vec{H}_\omega$$

Conditions at the interfaces (*continuity*)

$$E''_1 = E''_2$$

$$H''_1 = H''_2$$

rot... → 0

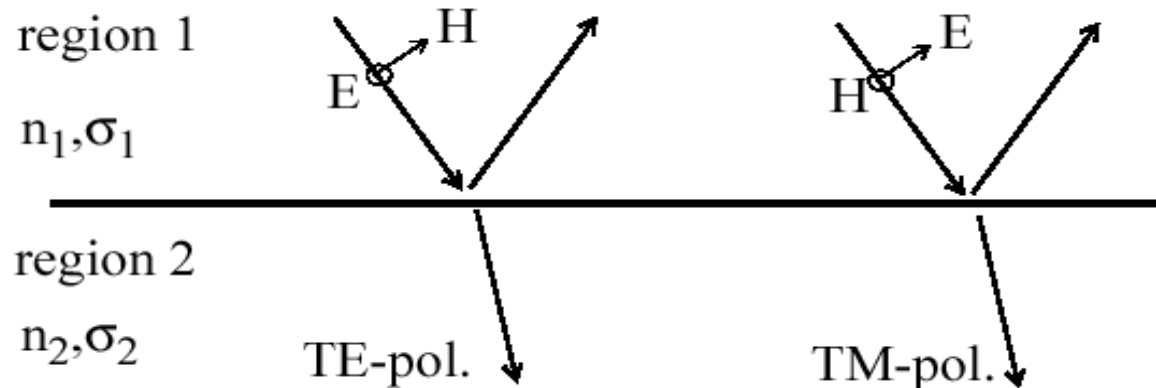
$$D^\perp_1 = D^\perp_2$$

$$B^\perp_1 = B^\perp_2$$

div... → 0



Reflection,  
Diffraction,  
...



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## 1.2 Black-body Radiation

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Spectral power emitted per unit solid angle and per area:

$$P_\nu \cdot d\nu = \frac{2h\nu^3}{c^2} \cdot \frac{1}{e^{(h\nu)/kT} - 1} \cdot d\nu \quad [W \text{ m}^{-2}] \quad \text{Planck's law}$$

Total power emitted per unit solid angle and per area:

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

$\sigma =$  Stefan-Boltzmann constant

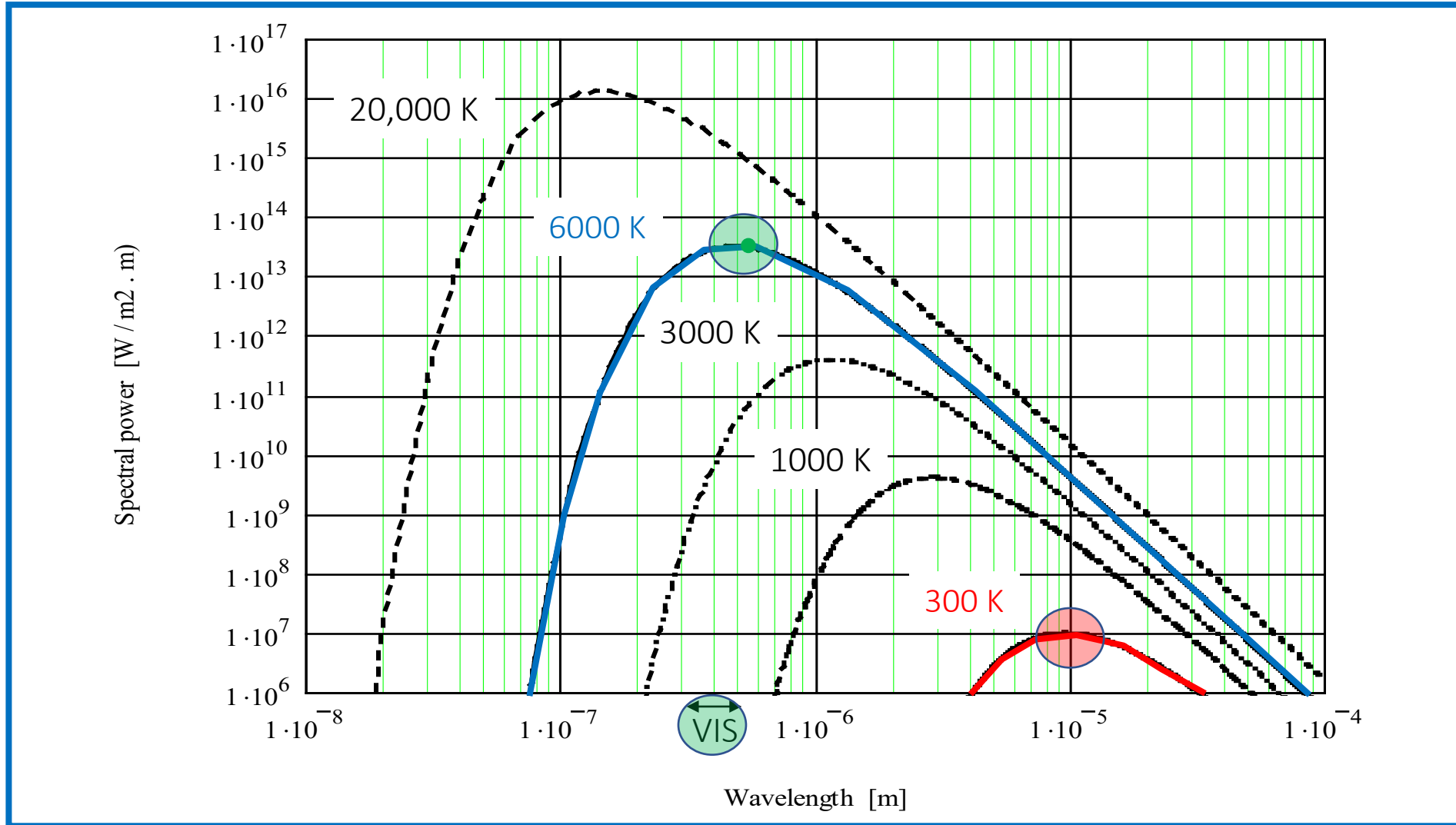
$$= \frac{2\pi^5 k^4}{15h^3 c^2} = 5.67 \cdot 10^{-8} [W \cdot m^{-2} \cdot K^{-4}]$$

Wien's law

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

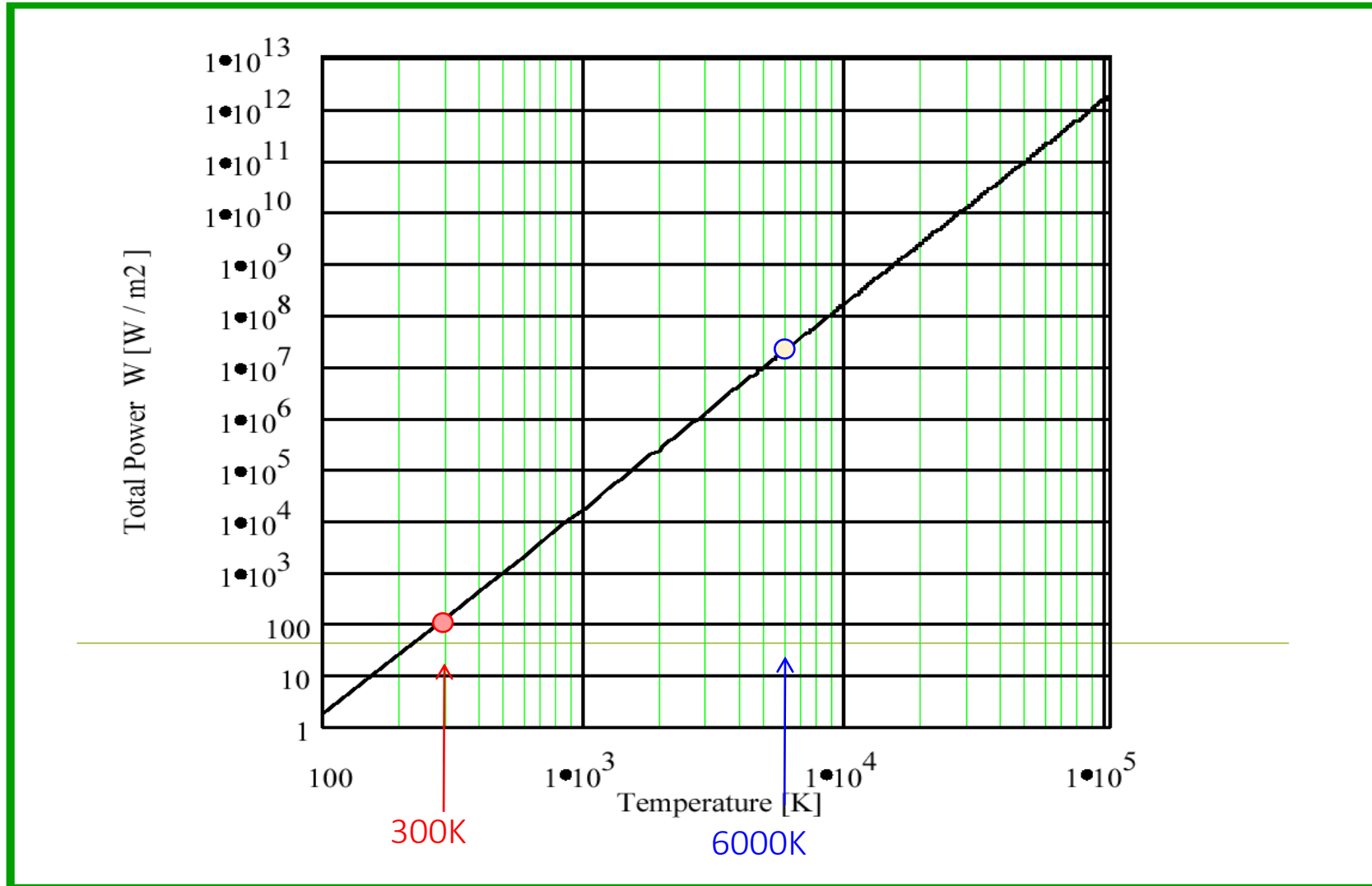
## 1.2 Example: Planck's Law

### 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

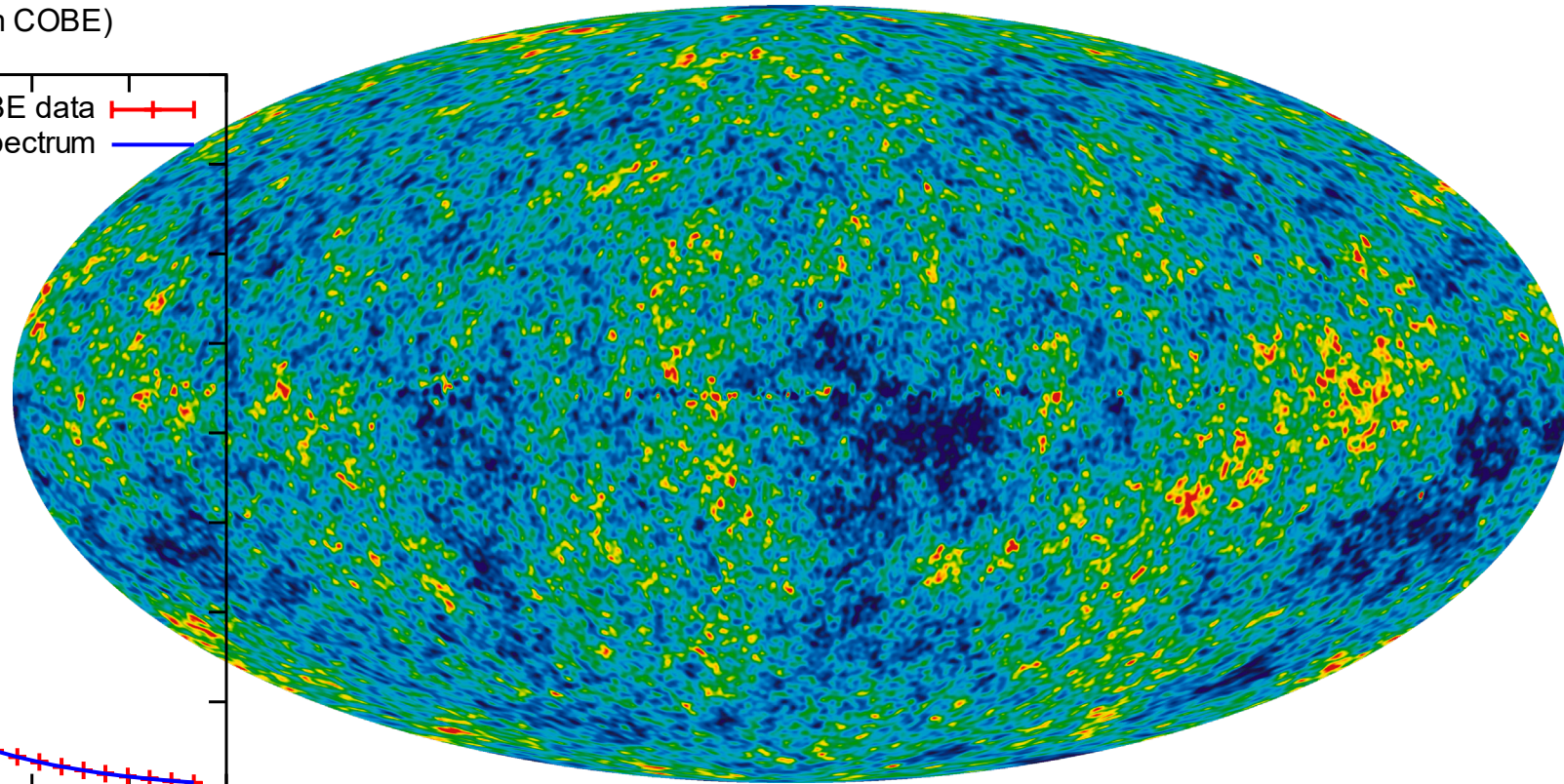
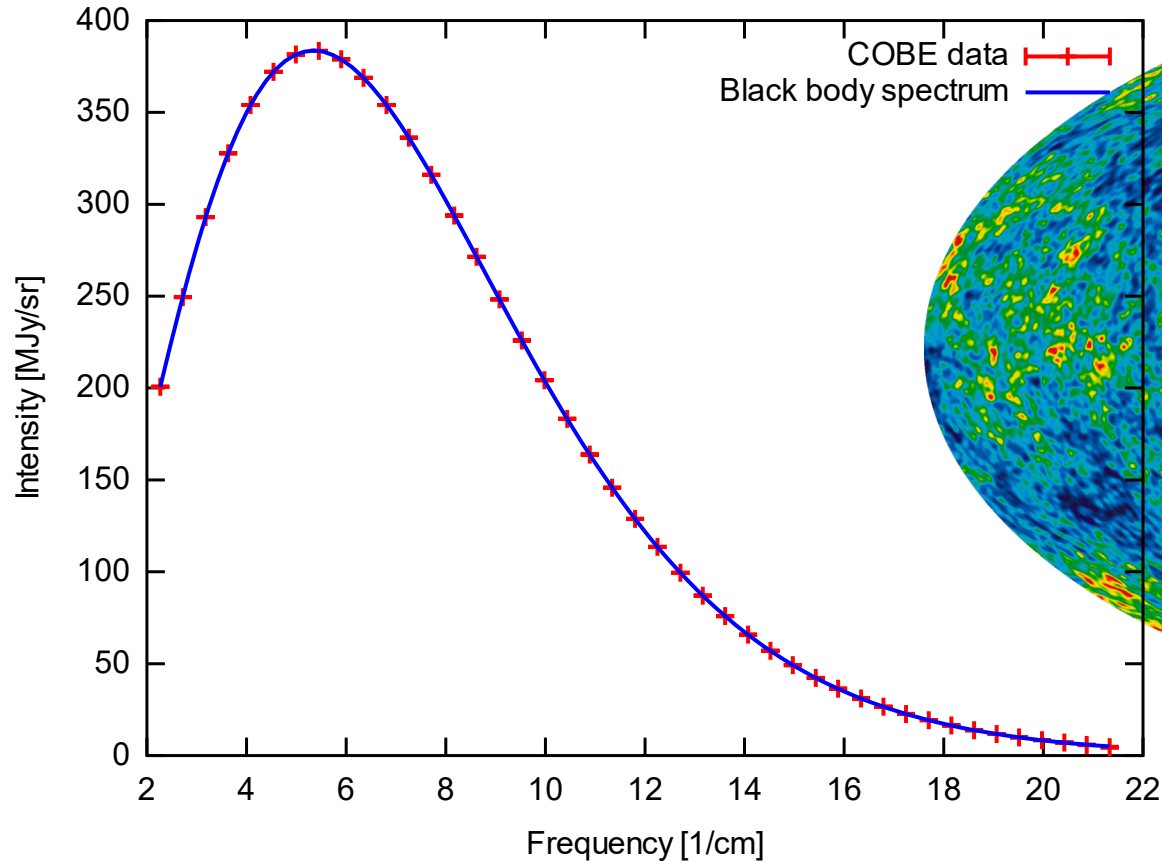


$$W \sim T^4$$

Stefan-Boltzmann  
formula

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

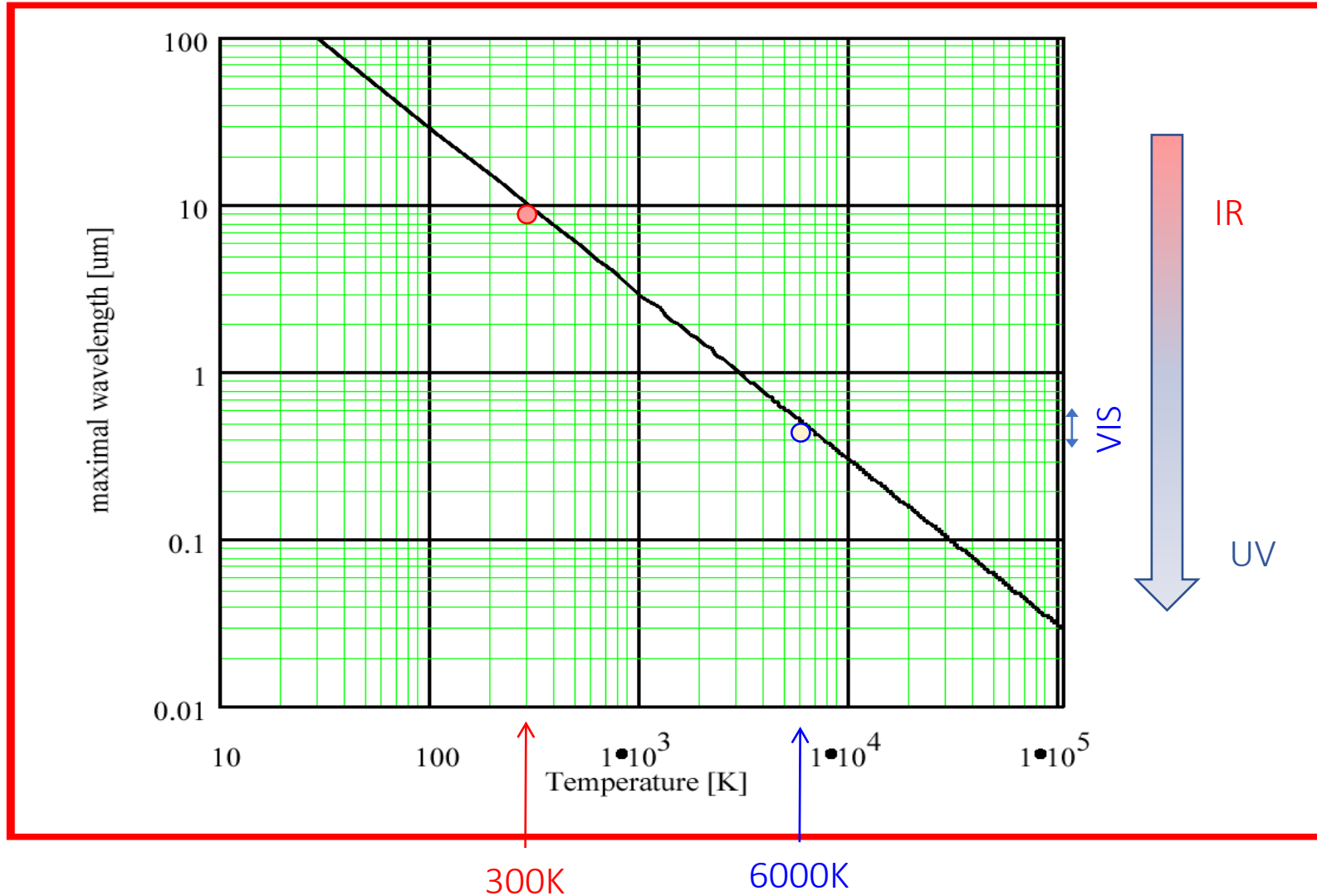
Cosmic microwave background spectrum (from COBE)



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

## 1.2 Example: Black body

### c) Peak emission wavelength



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

Wien's law

## 1.2 Black body definition

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

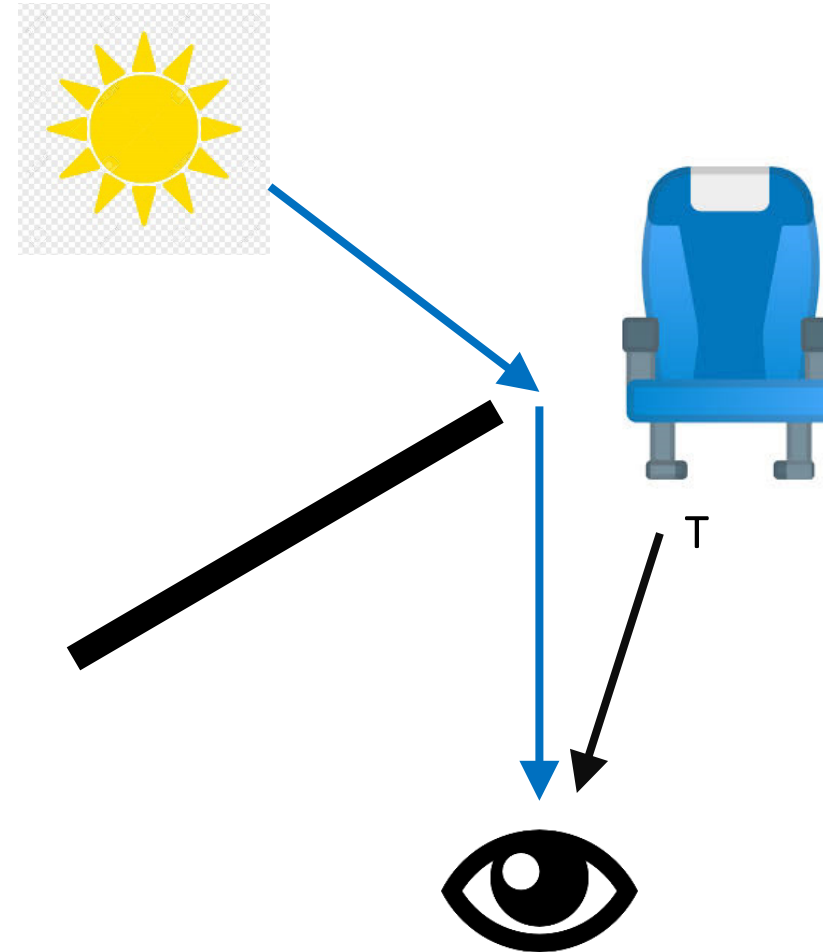
Why ? «black» ? body

- 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

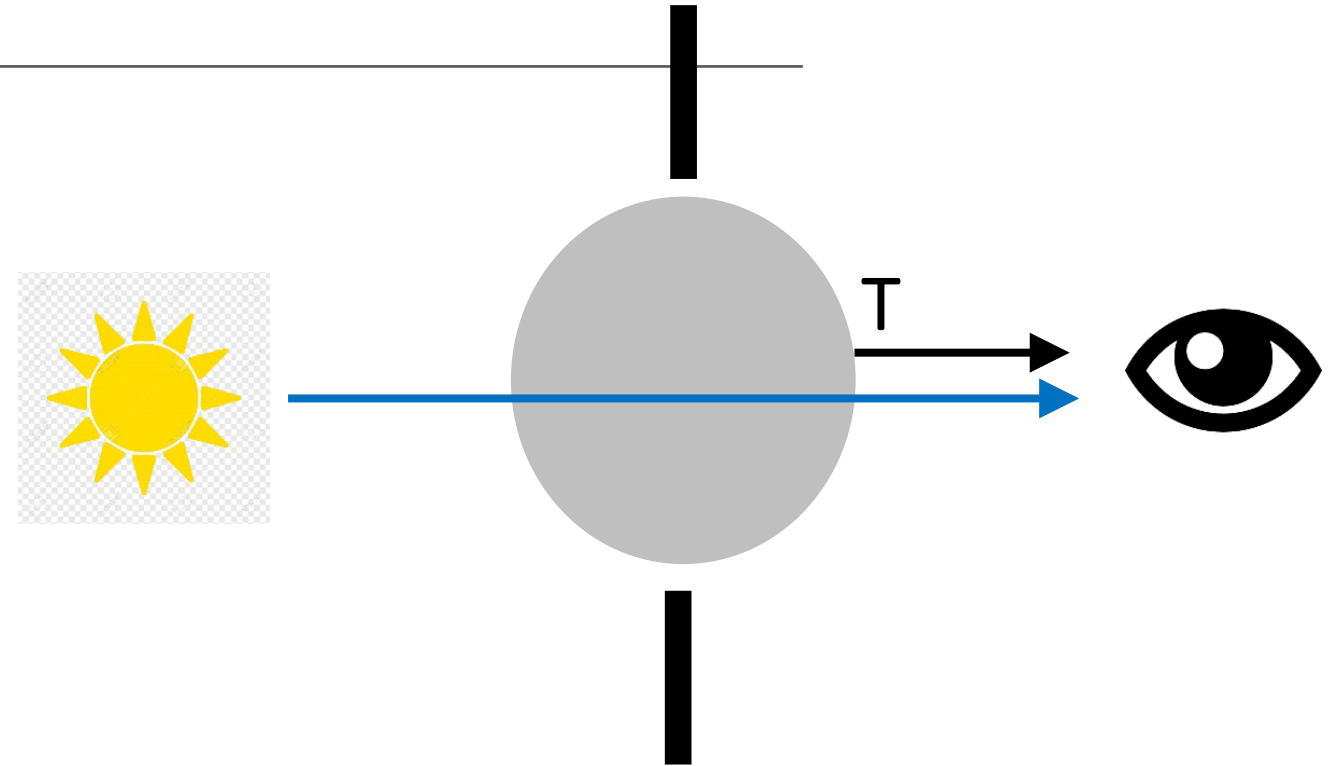
Is a blue chair a black body?



Black Body → no reflections!

## 1.2 Black body: transmission

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



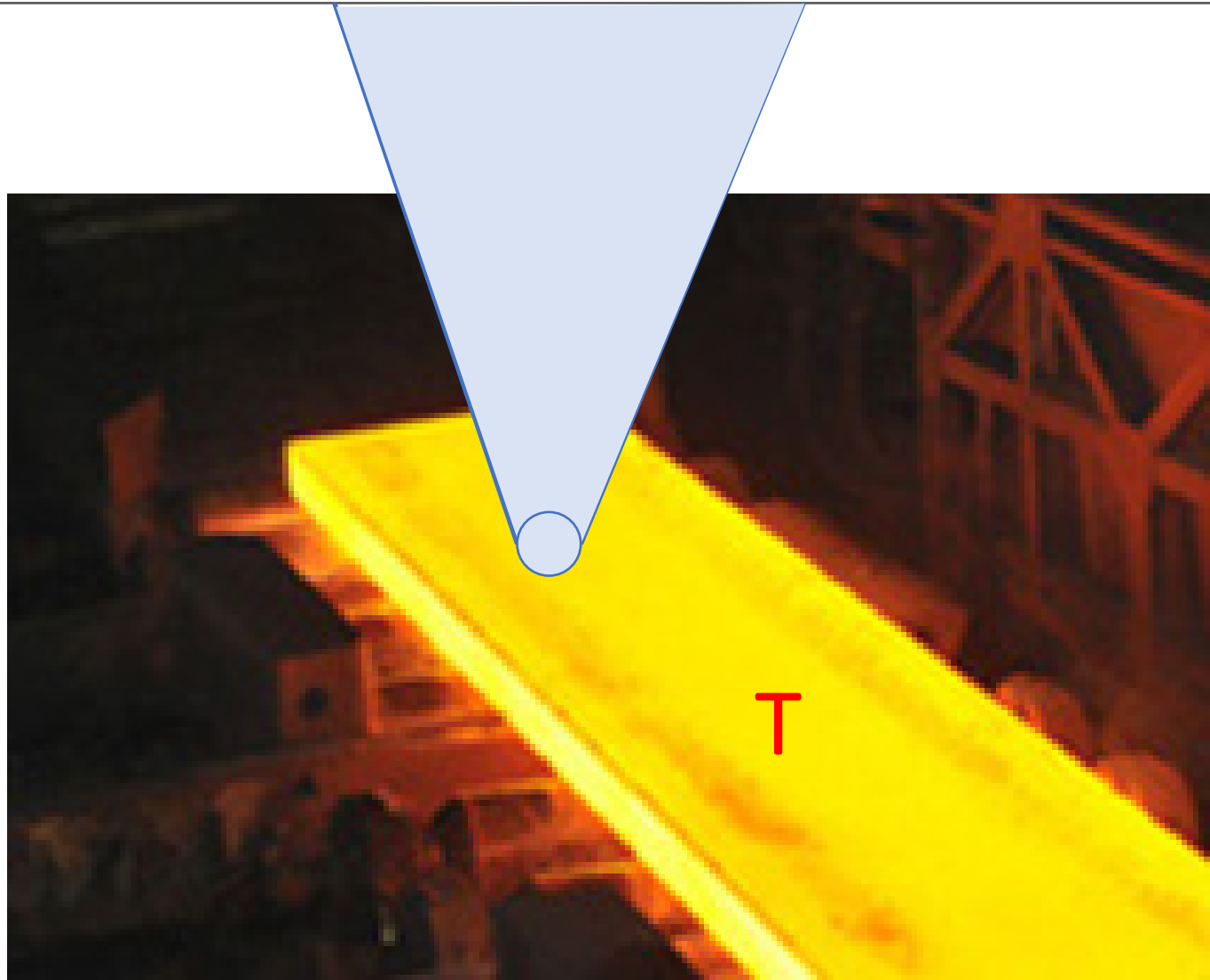
Is a semi-transparent object a black body?

Black body → no transmission!

A black body absorbs all the incident light.

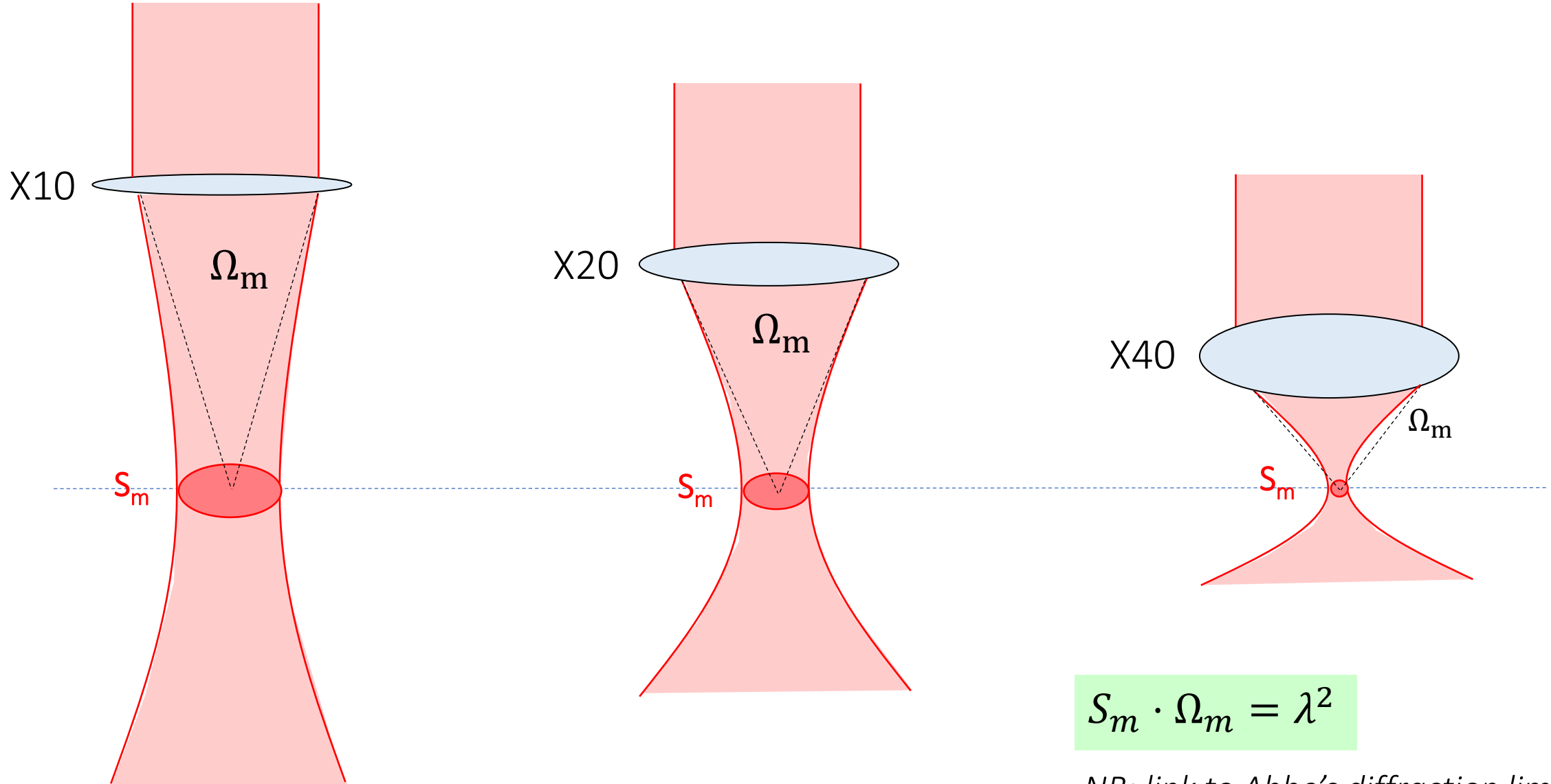
## 1.2 Black body equation (Planck's law): alternative derivation

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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

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

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

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

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

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

Planck's law

# Take-home Messages/W1-1

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## 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?

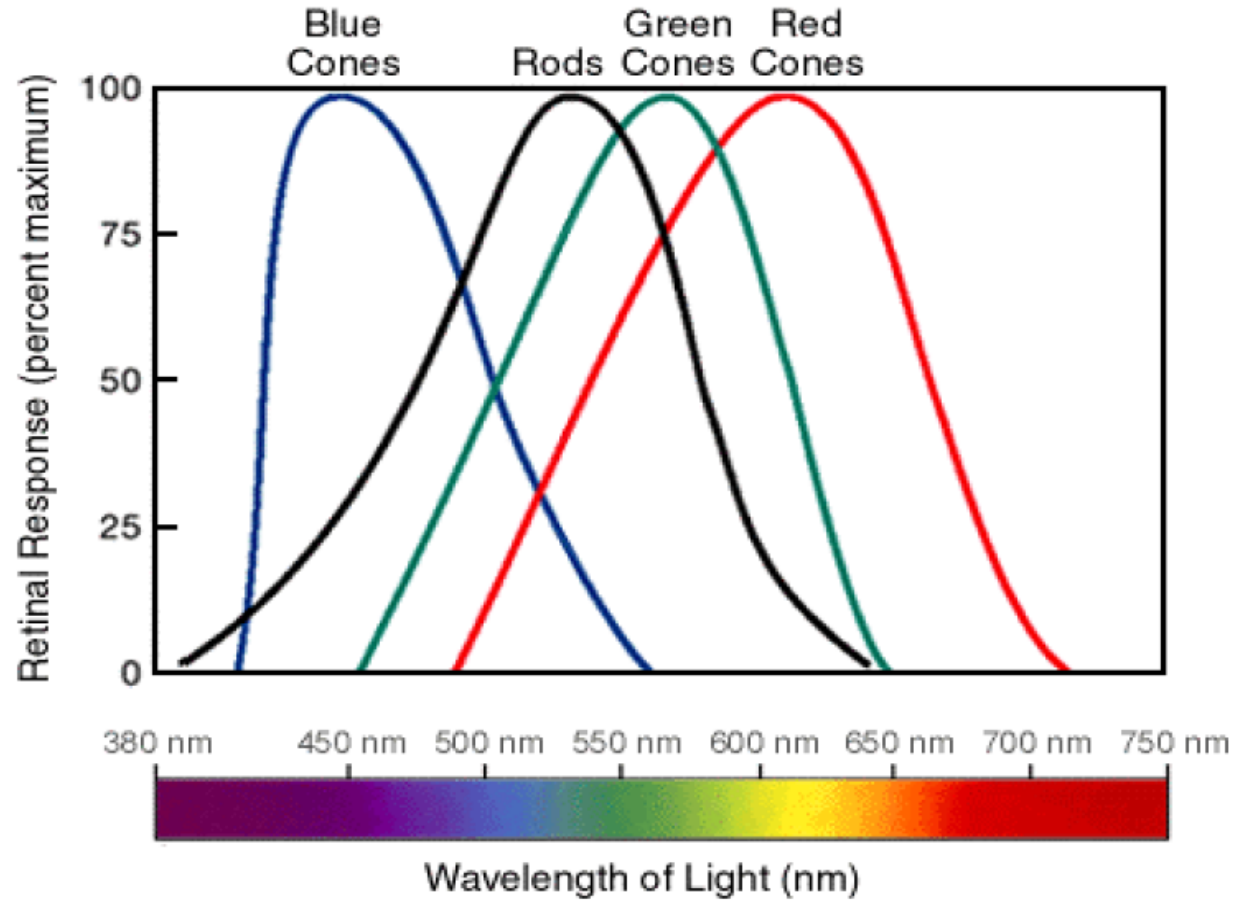
# Outline

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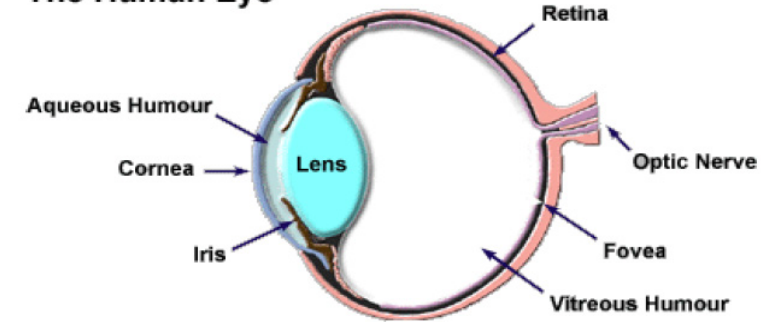
- 1.1 Fundamental properties of light
- 1.2 Black-body radiation
- 1.3 [Human vision and optical illusions](#)
- 1.4 Photometry
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# 1.3 Human Vision

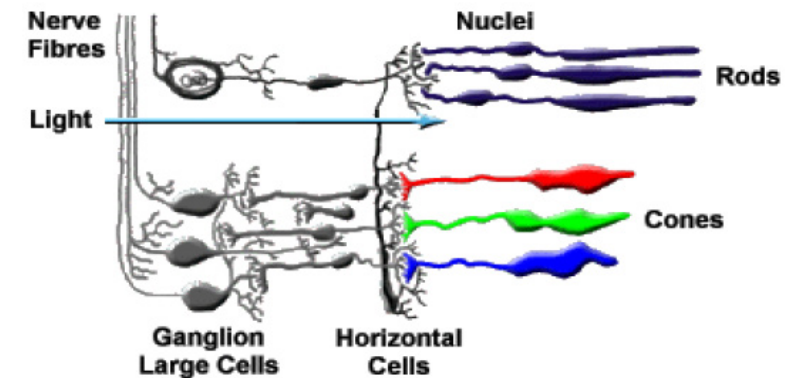
Relative perception inside the human eye



The Human Eye



The Retina



# 1.3 Measuring Colors

Decomposing a light source  $\varphi_\lambda$ :

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

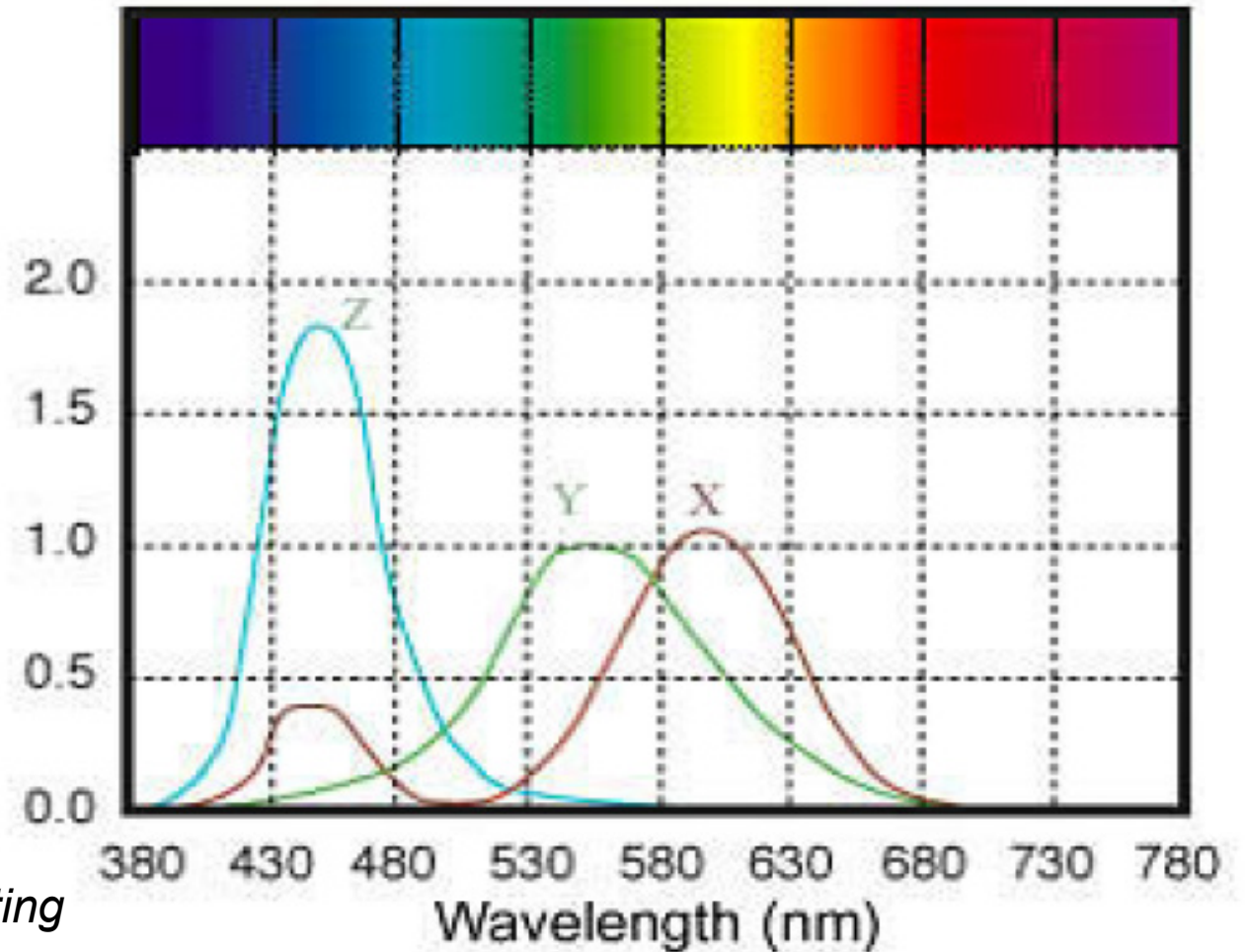
$$Y = k \int_{\lambda} \varphi_{\lambda}(\lambda) \cdot \bar{y}(\lambda) d\lambda$$

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

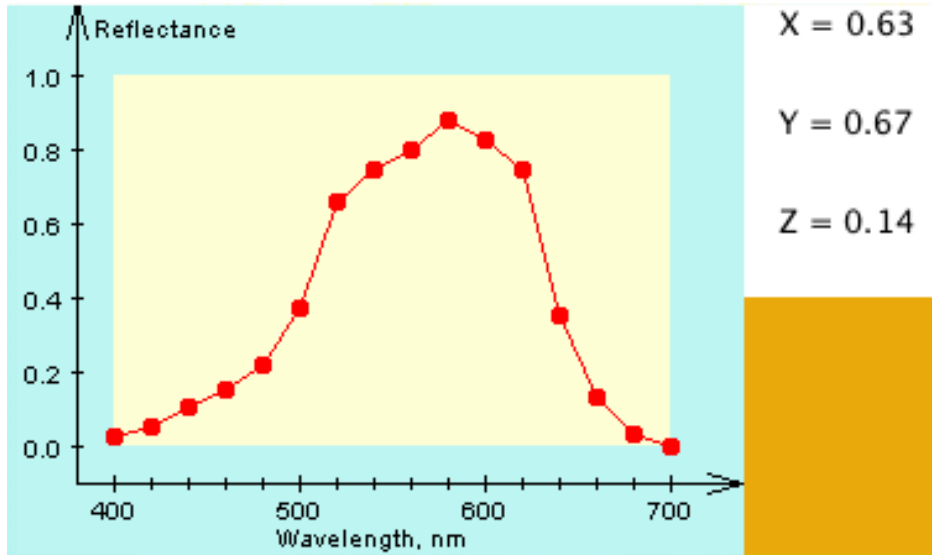
$$k=683 \text{ lm/W}$$

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

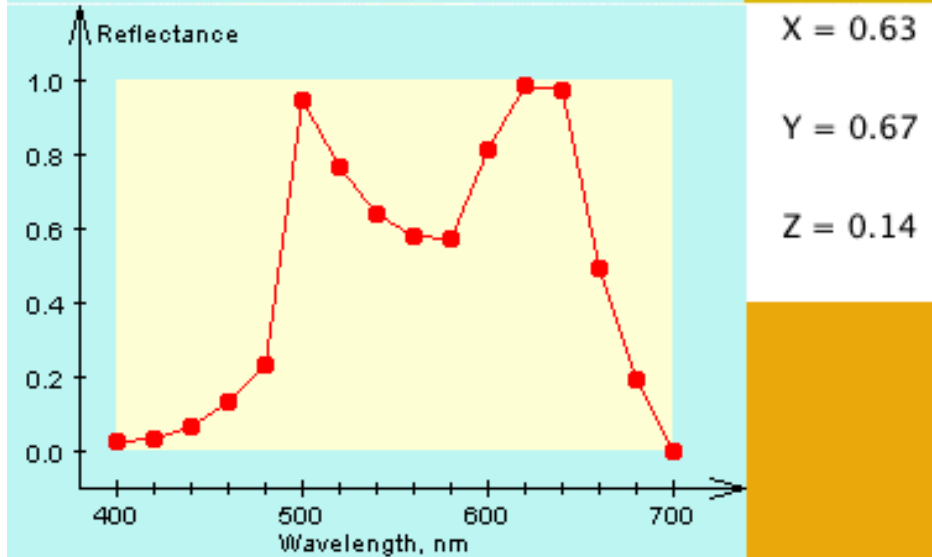
CIE 1931 Standard Observer



# 1.3 Identical Decompositions



16 points:  
- Different spectra

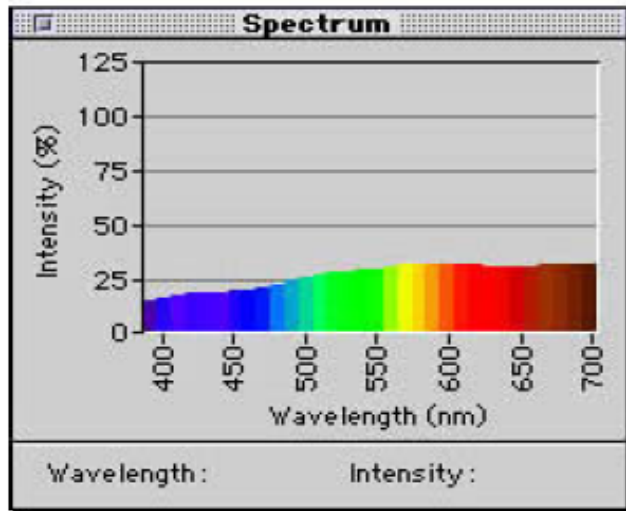
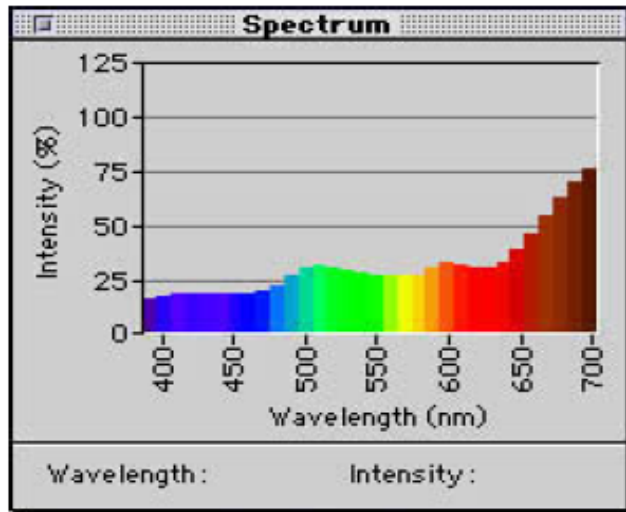


3 parameters:  
- identical X,Y,Z values

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

# 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



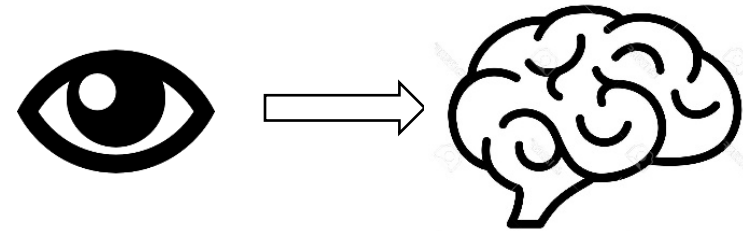
B. Fraser, "Out of Gamut: Why is Color", [www.creativepro.com](http://www.creativepro.com)

## 1.3 Mixed letters

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According to a research at Cambridge University, it doesn't matter in what order the letters in a word are, the only important thing is that the first and last letter be at the right place. The rest can be a total mess and you can still read it without problem. This is because the human mind does not read every letter by itself, but the word as a whole.

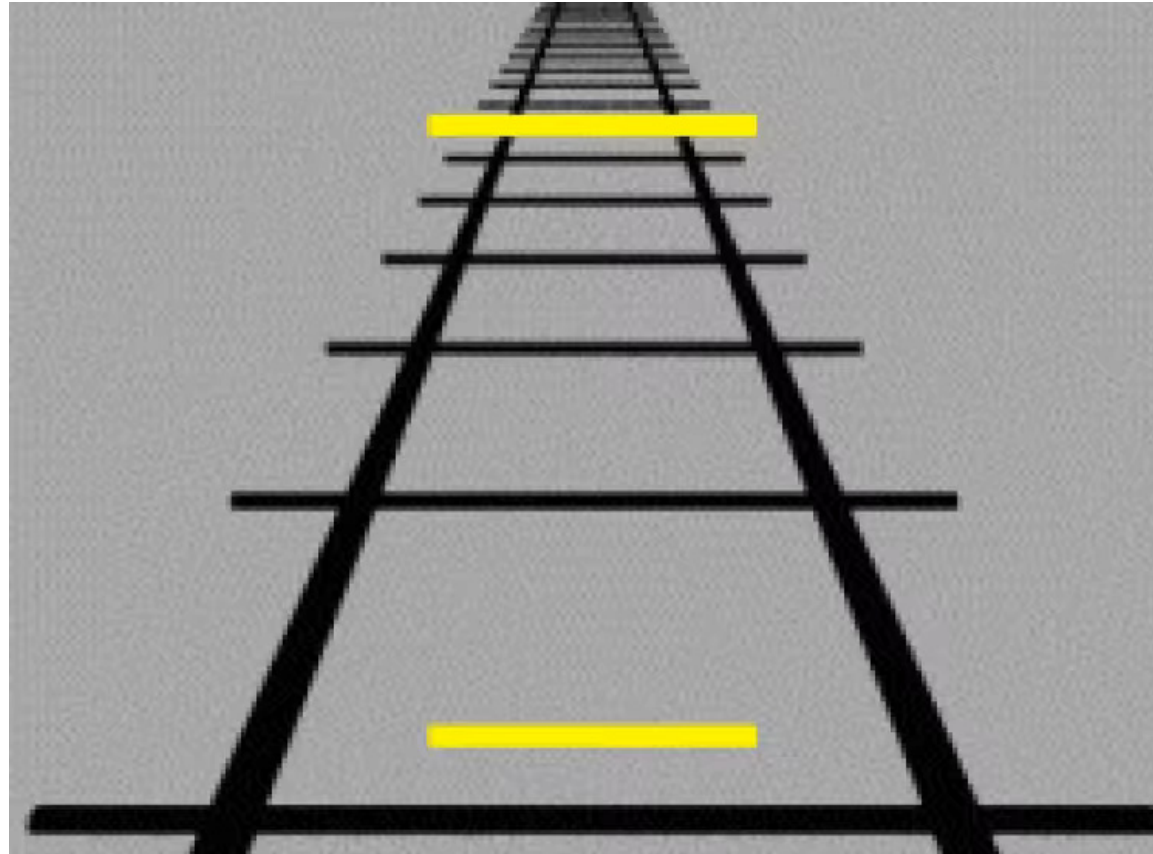
<http://www.mrc-cbu.cam.ac.uk/people/matt.davis/cmabridge/>



So in a study of a group of dyslexic children the order of the letters in a word is not important, what counts is the first and the last letter. The rest can be a total mess, you can still read it without problem.

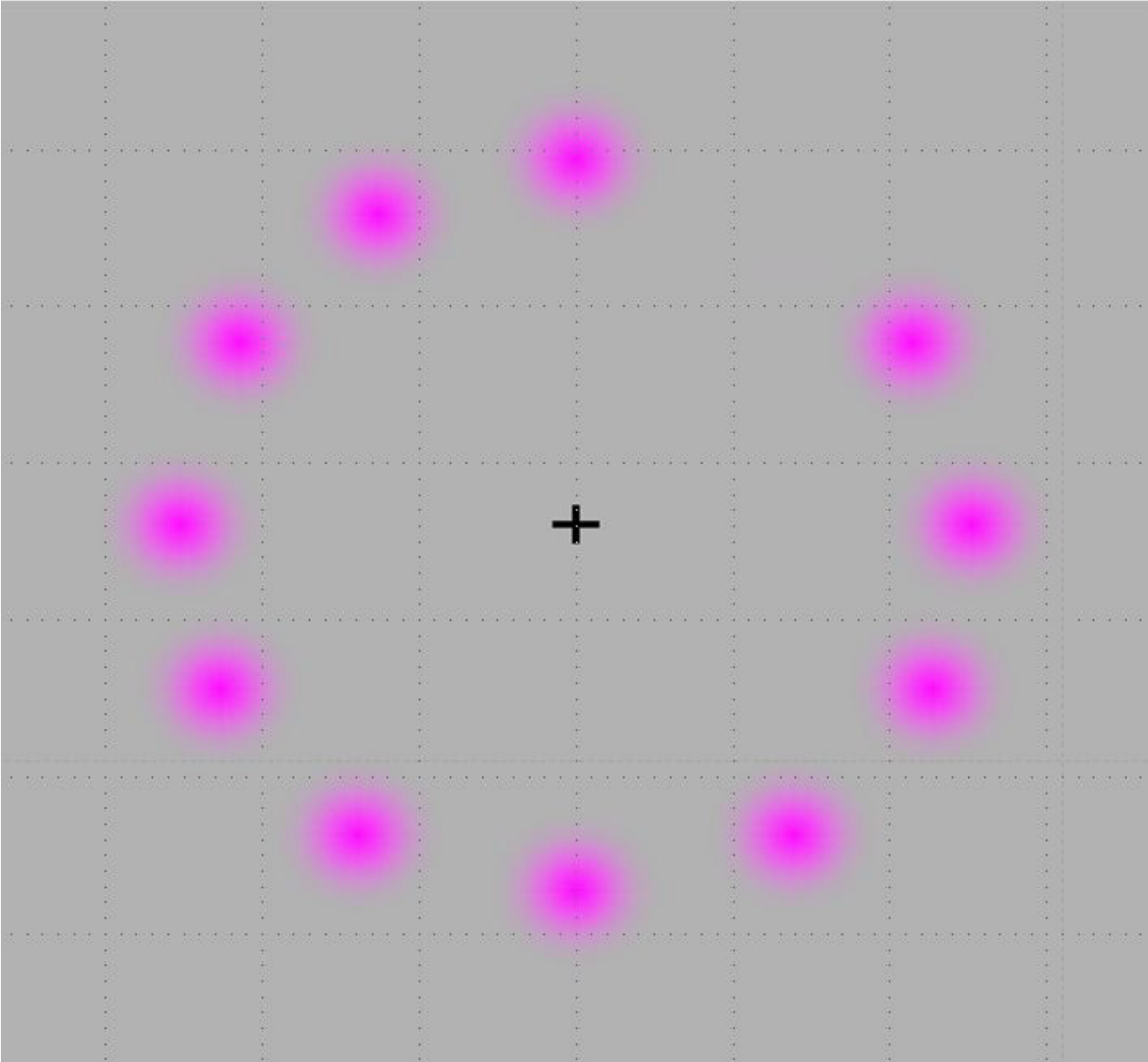
## 1.3 Optical illusions/1

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

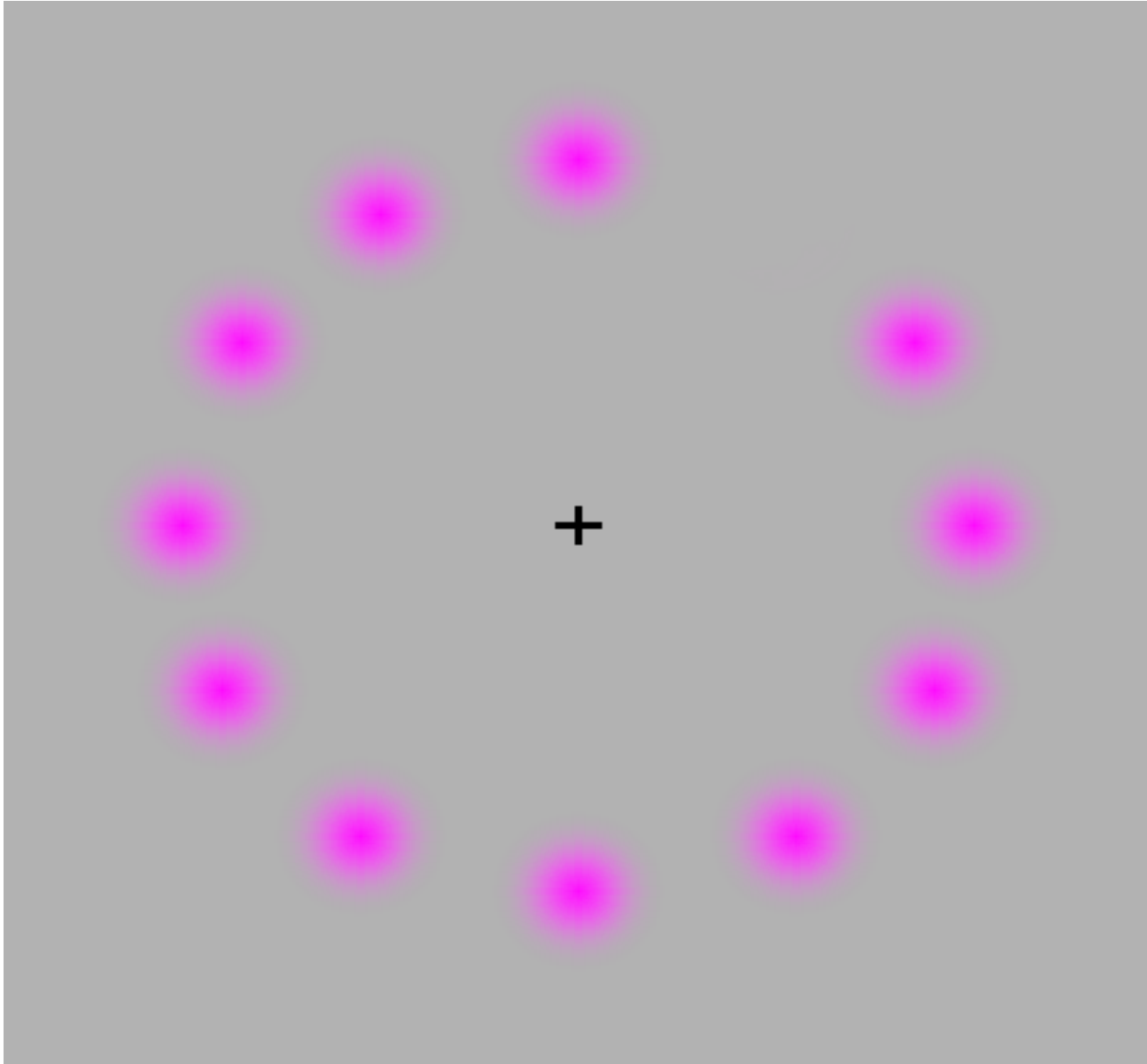
## 1.3 Optical illusion/2



Find out what happens  
if the missing point rotates...

## 1.3 Optical illusion/2

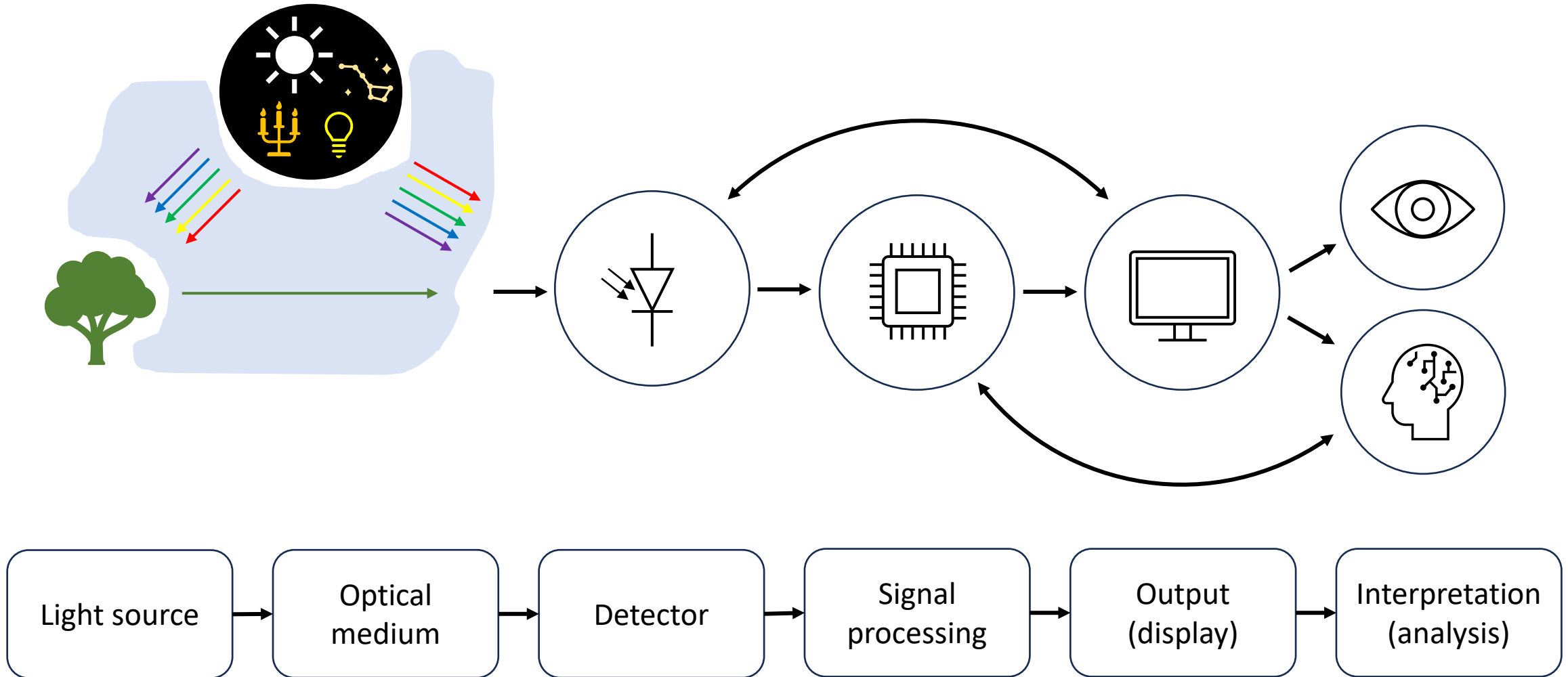
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Concentrate on the cross in the middle, and after a few seconds you'll notice that the spinning pink circle is actually GREEN!

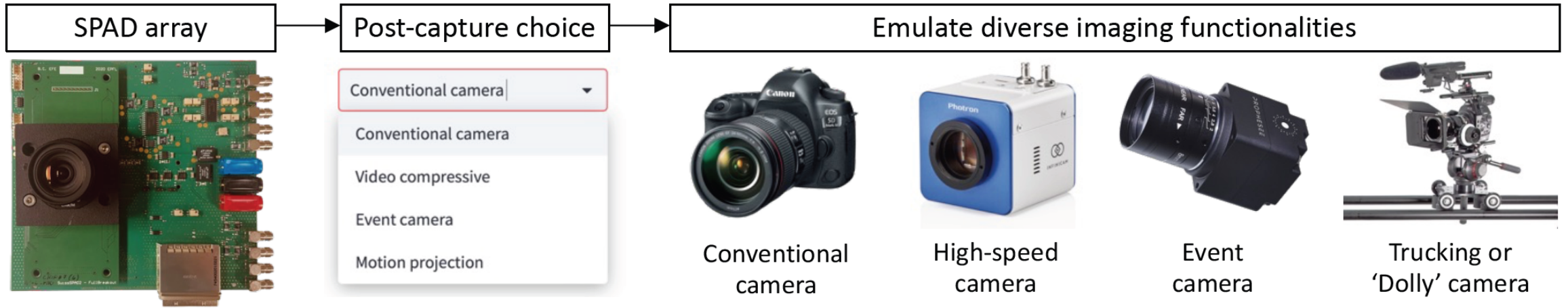
If you look at the cross in the middle, you'll see that the pink circles disappear and only the green circle (which is actually pink) remains!

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

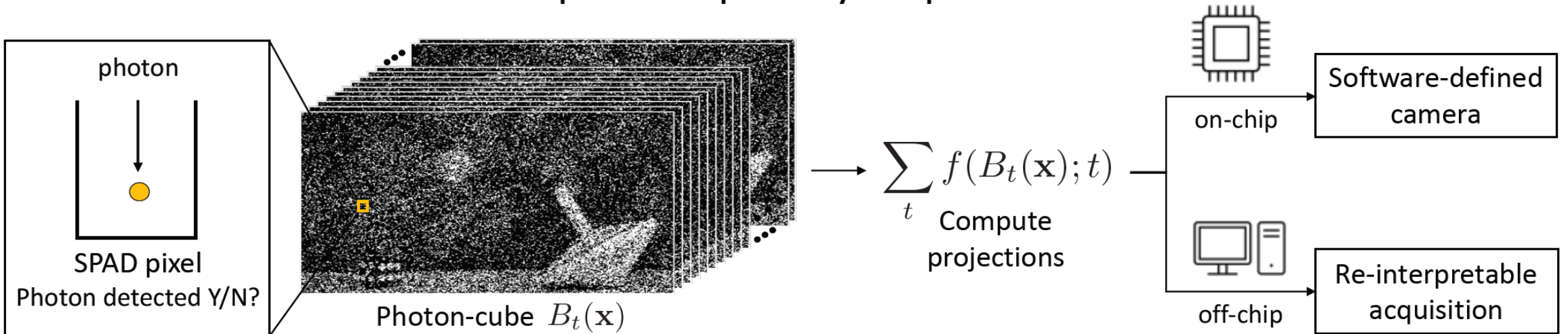


# Computational imaging example: software defined cameras

## Software-defined single-photon imaging

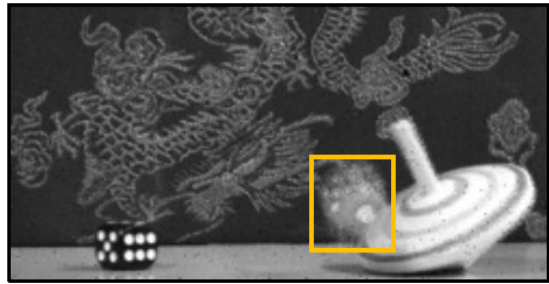


## Post-capture reinterpretability from photon-cubes

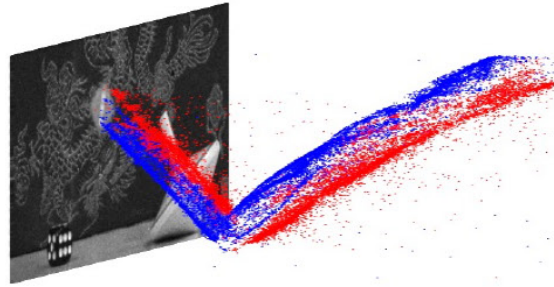


# Computational imaging example: software defined cameras

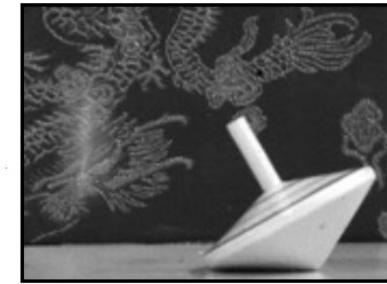
## Capabilities of photon-cube projections



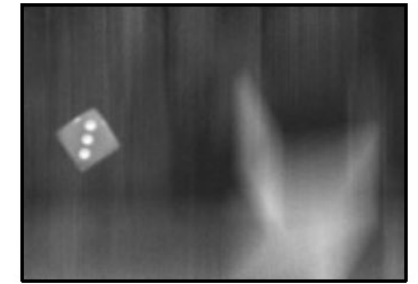
Coded exposure



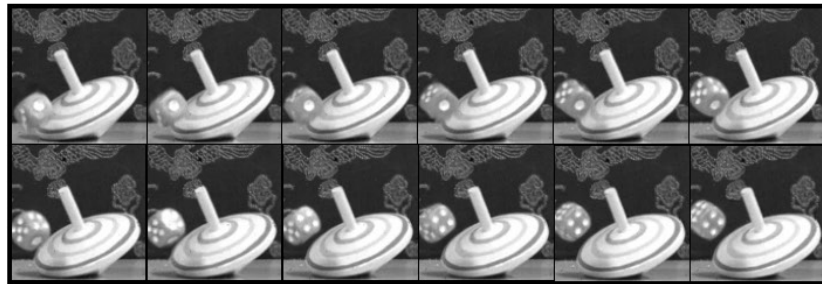
3D scatter plot,  $0 \leq t \leq 0.1$  s



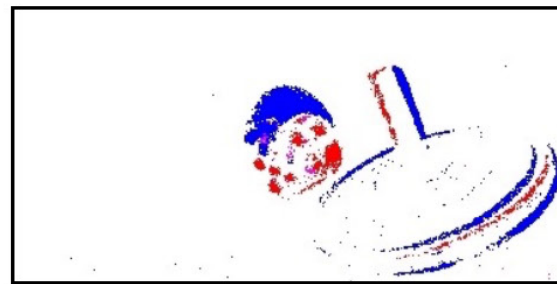
Static camera



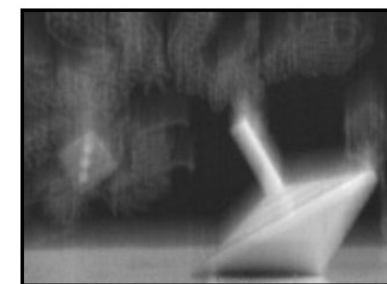
Linear trajectory



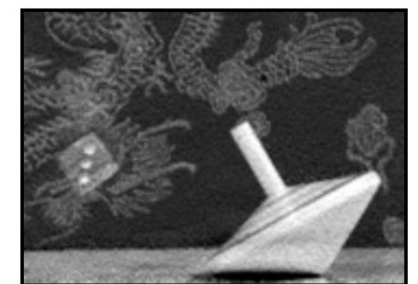
12x video reconstruction (raster order)  
Snapshot compressive imager (Sec. 5.1)



Event image,  $0.5 \leq t \leq 0.53$  s  
Event camera (Sec. 5.2)



Parabolic trajectory



Parabolic deblurred

Motion Projections (Sec. 5.3)

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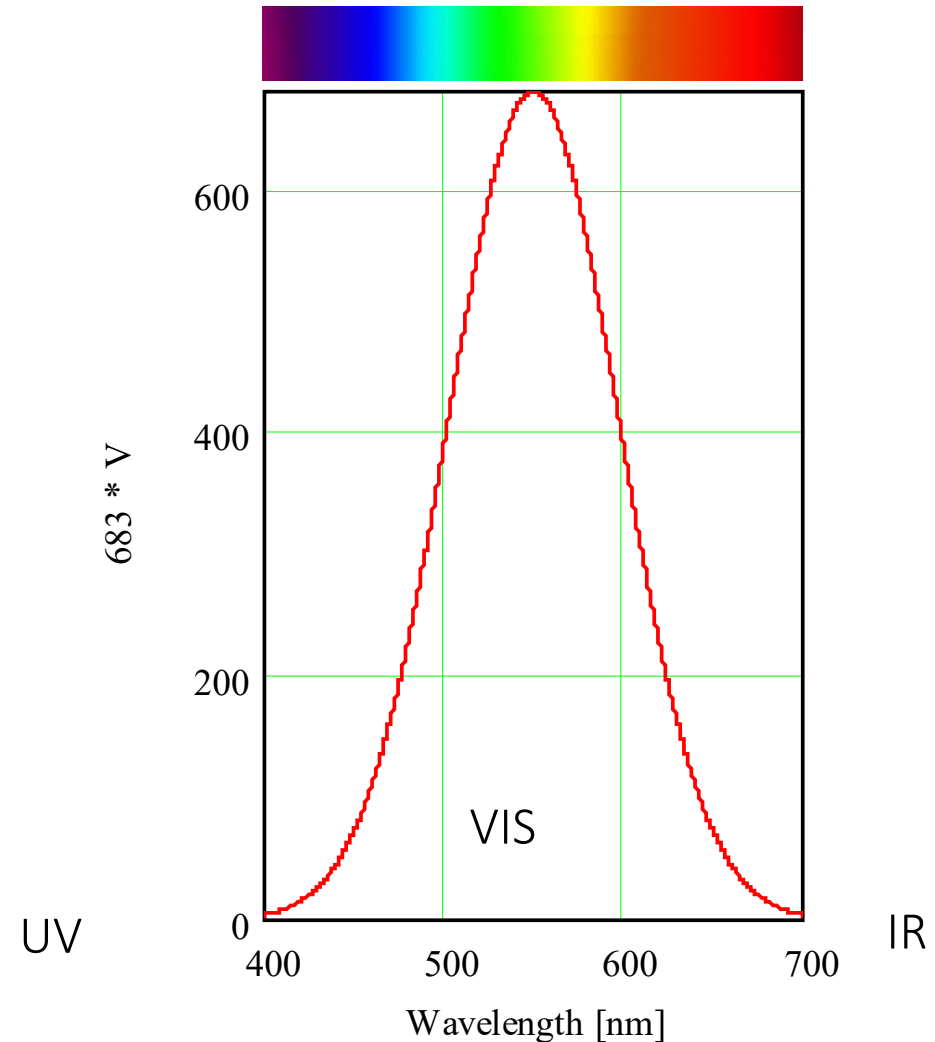
## 1.4 Photometry and the Relationship between *lumen* and *watt*

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

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

- "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

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

“intensity”

lm = lumen = “visible watts”

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

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

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

“intensity emitted within a unit solid angle”

cd = candela = «visible watts» per angle

## 1.4 Photometry: Detector

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

“intensity per surface area on the detector”

$lx = lux = \llcorner\text{visible watts}\llcorner [lm]$  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:	$2 \cdot 10^9$ cd/m <sup>2</sup>
Carbon lamp:	$10^8$ cd/m <sup>2</sup>
750 W filament lamp:	$2 \cdot 10^7$ cd/m <sup>2</sup>
60 W incandescent lamp:	$9 \cdot 10^4$ cd/m <sup>2</sup>
Clear sky:	$2 \cdot 10^4$ cd/m <sup>2</sup>
40 W fluorescent lamp:	$5 \cdot 10^3$ cd/m <sup>2</sup>
Overcast sky:	$2 \cdot 10^3$ cd/m <sup>2</sup>

## Detector Illuminance:

Sun at its zenith:	$1.2 \cdot 10^5$	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

683



Cd = “visible” intensity per unit solid angle

Lux = “visible” intensity per m<sup>2</sup>

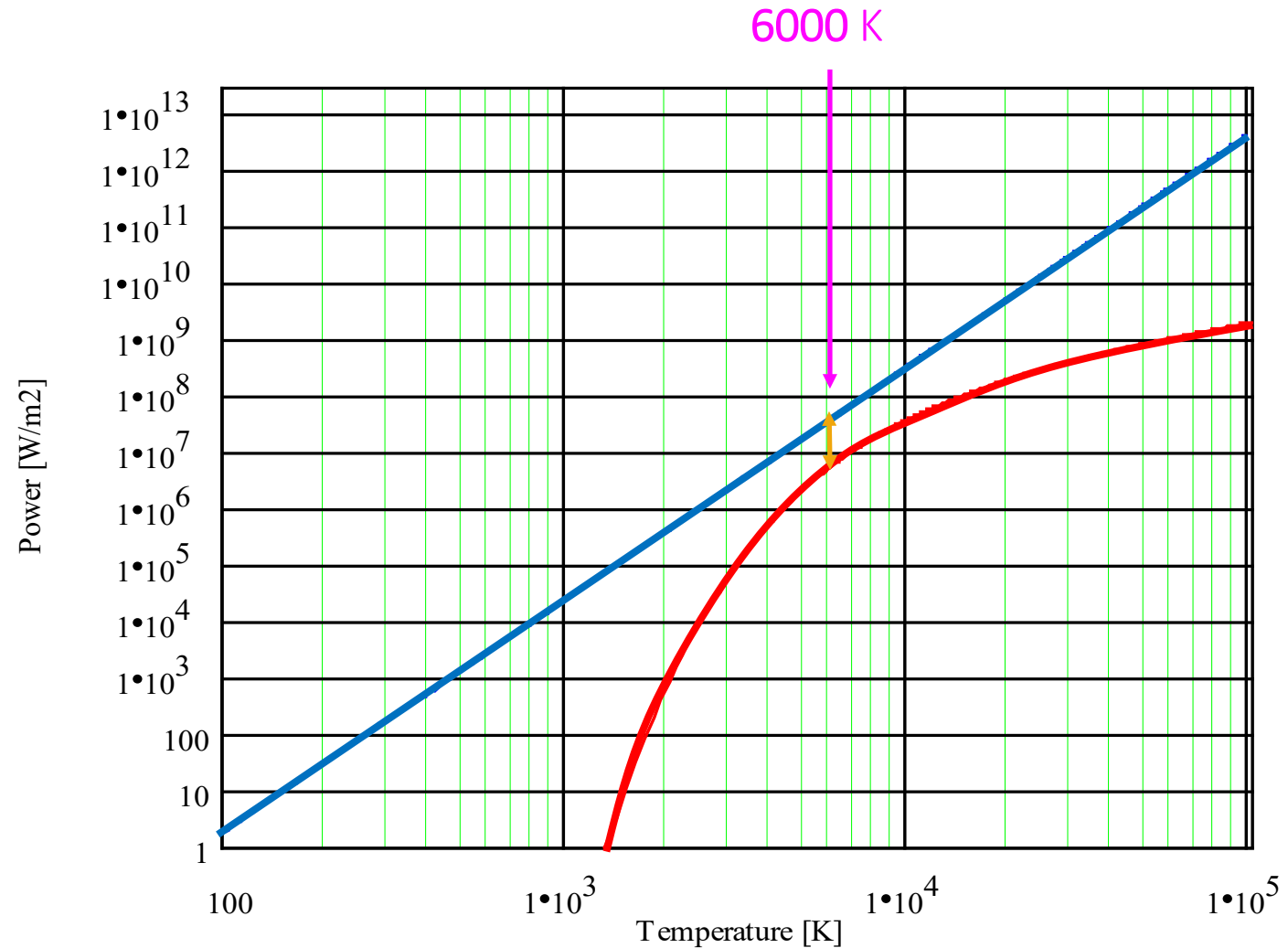
# 1.4 Black body: Total and Visible Power

Total power:

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

Visible power:

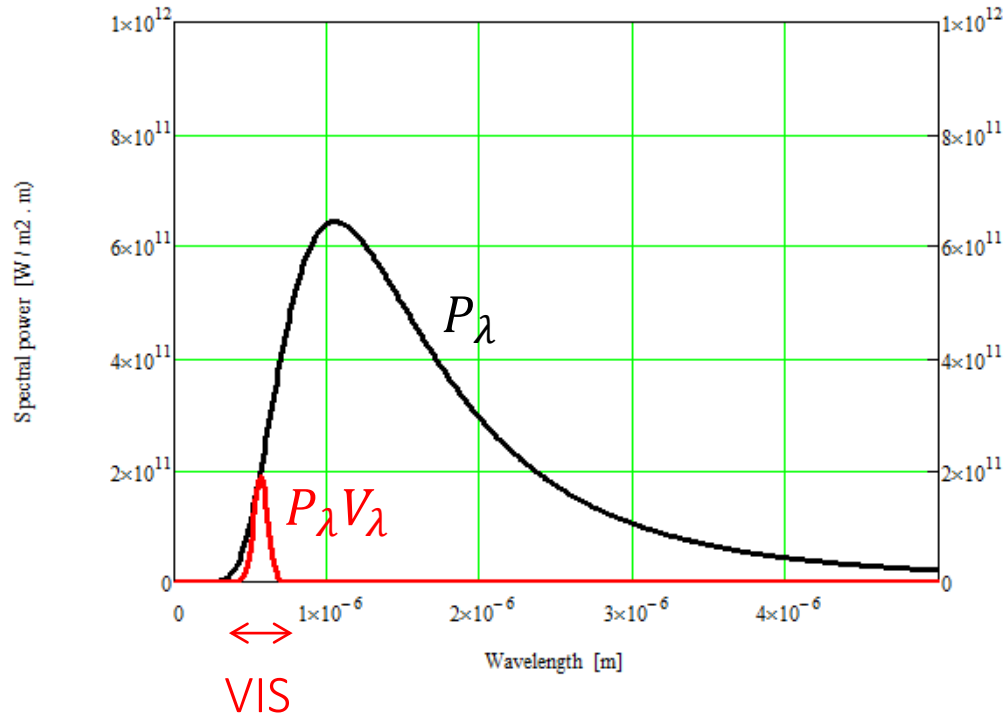
$$\int_0^{\infty} P_{\lambda} V_{\lambda} d\lambda$$



# 1.4 Efficiency of light sources in visible

## Incandescent lamp

T=2750 K



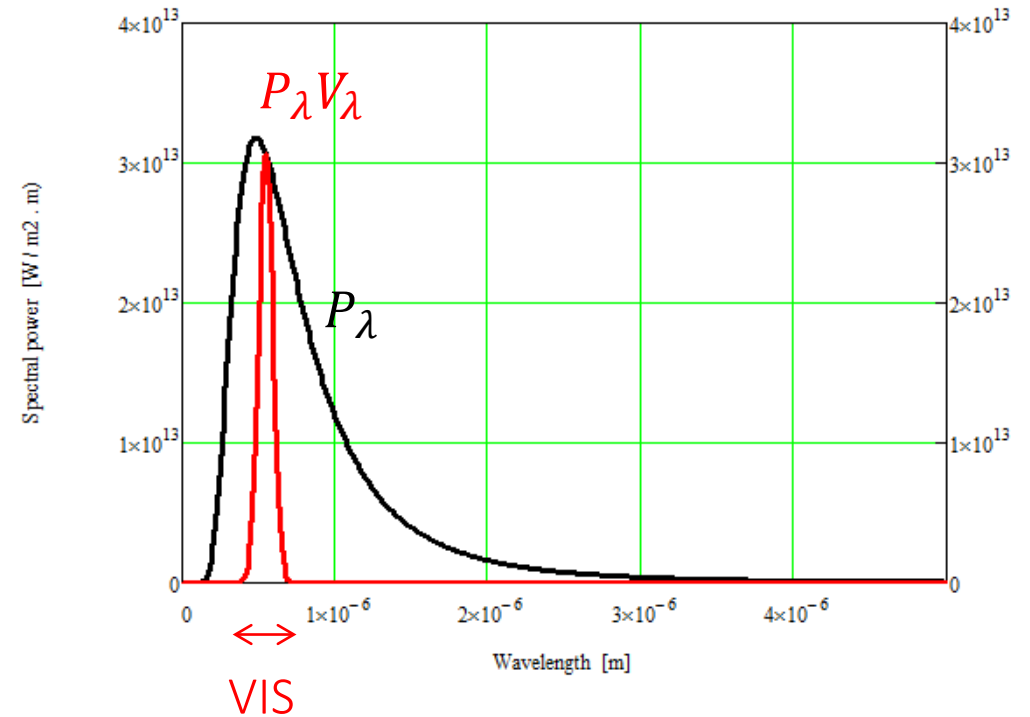
Typical: 2% efficiency

13 lm/W conversion

Conversion = 683 · efficiency

## Sun

T=6000 K

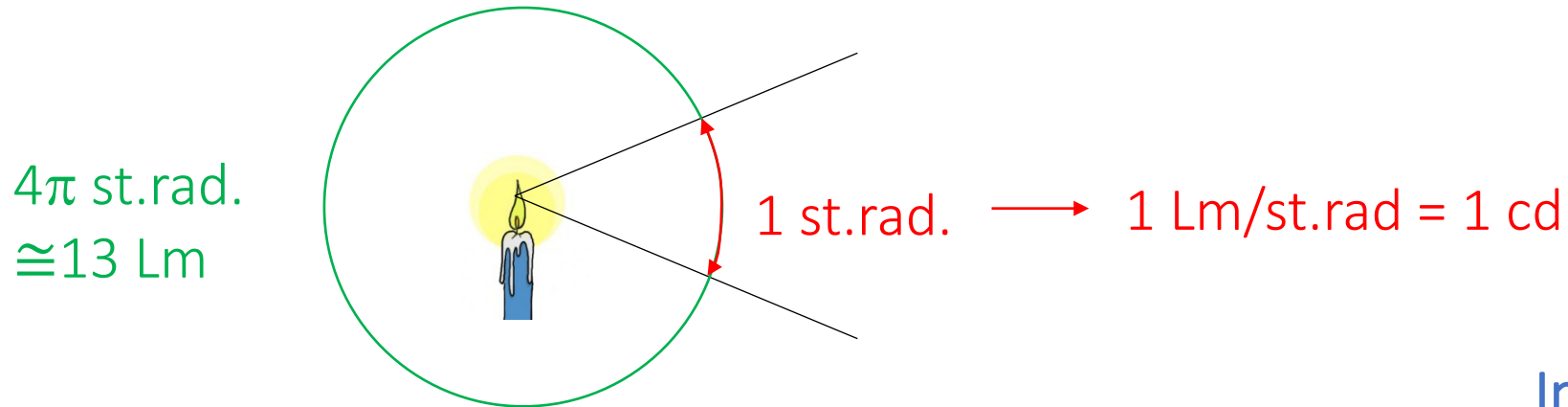


Typical: 15% efficiency

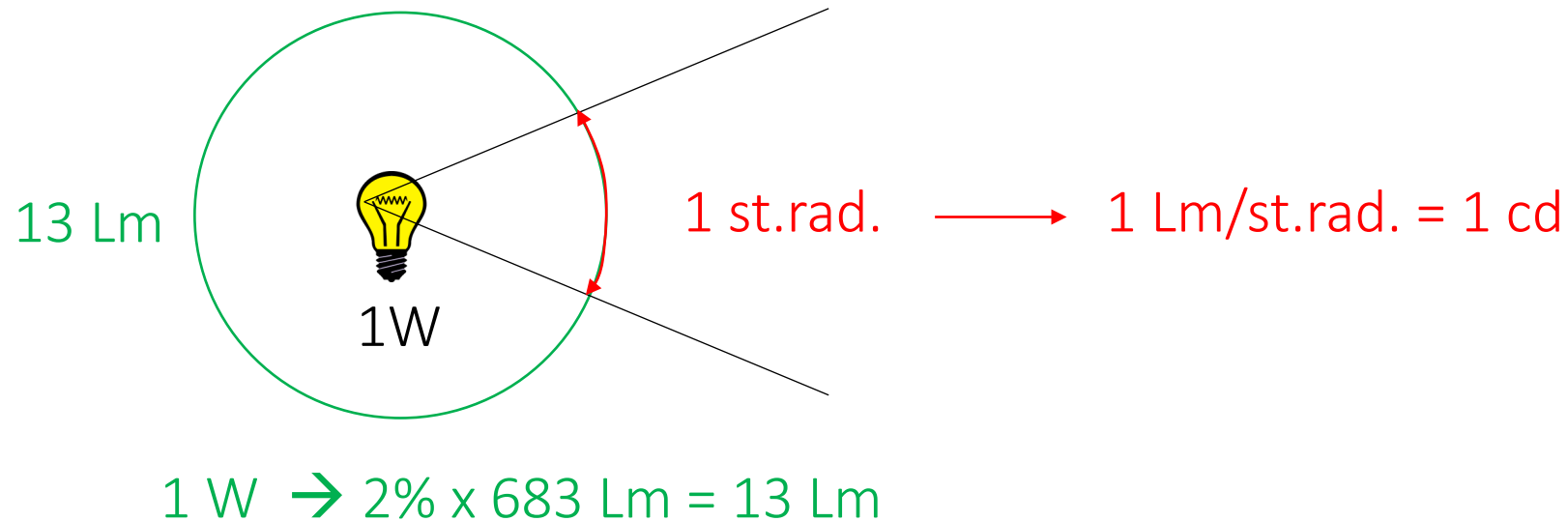
100 lm/W conversion

Comparable to white LED

## 1.4 Comparison: candle – incandescent light bulb



Incandescent lamp of X watts  
 $\cong$   
X candles



# Outline

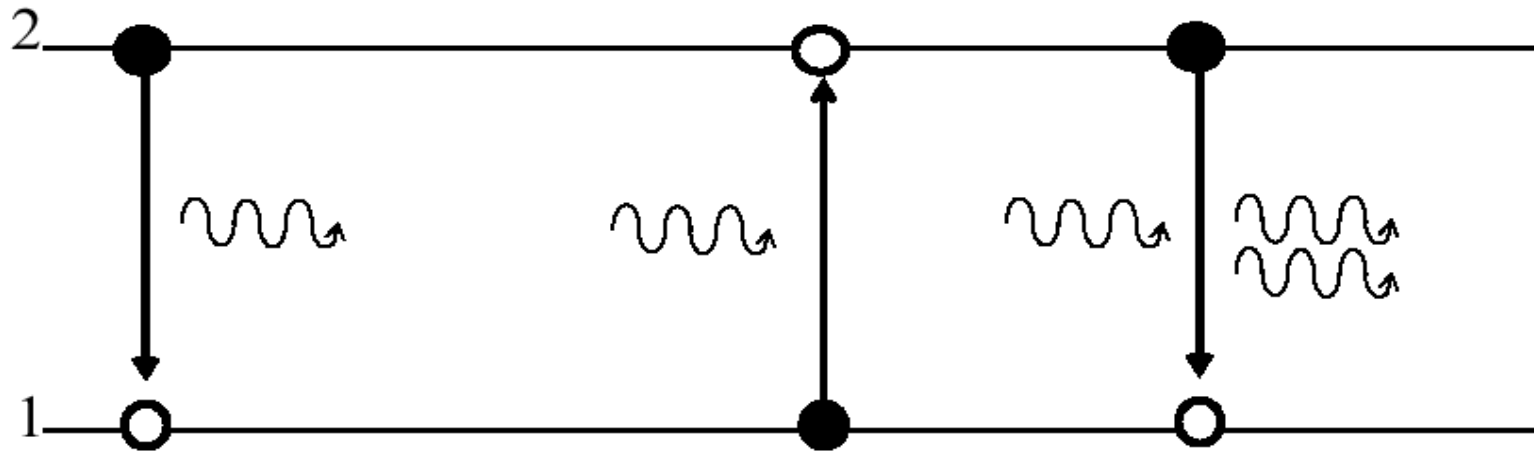
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- 1.1 Fundamental properties of light
- 1.2 Black-body radiation
- 1.3 Human vision and optical illusions
- 1.4 Photometry
- 1.5 Absorption:
  - Einstein coefficients
  - Semiconductors
- 1.6 Types of optical detectors:
  - Thermal detectors
  - Photonic detectors
  - Cameras

# 1.5 Absorption

## a) Principle

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



*Example with a two state system*

*Examples?*

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

Spontaneous emission

$$N_2 \cdot A_{21}$$

Absorption

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

Stimulated emission

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

Einstein coefficients

$$B_{12} = B_{21} = B$$

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

## 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:

$$N_i = \text{Const} \cdot e^{\frac{-\Delta E_i}{kT}} \implies \frac{N_1}{N_2} = e^{\frac{h\nu}{kT}}$$

- 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:

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

- Relationship between A and B:

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

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

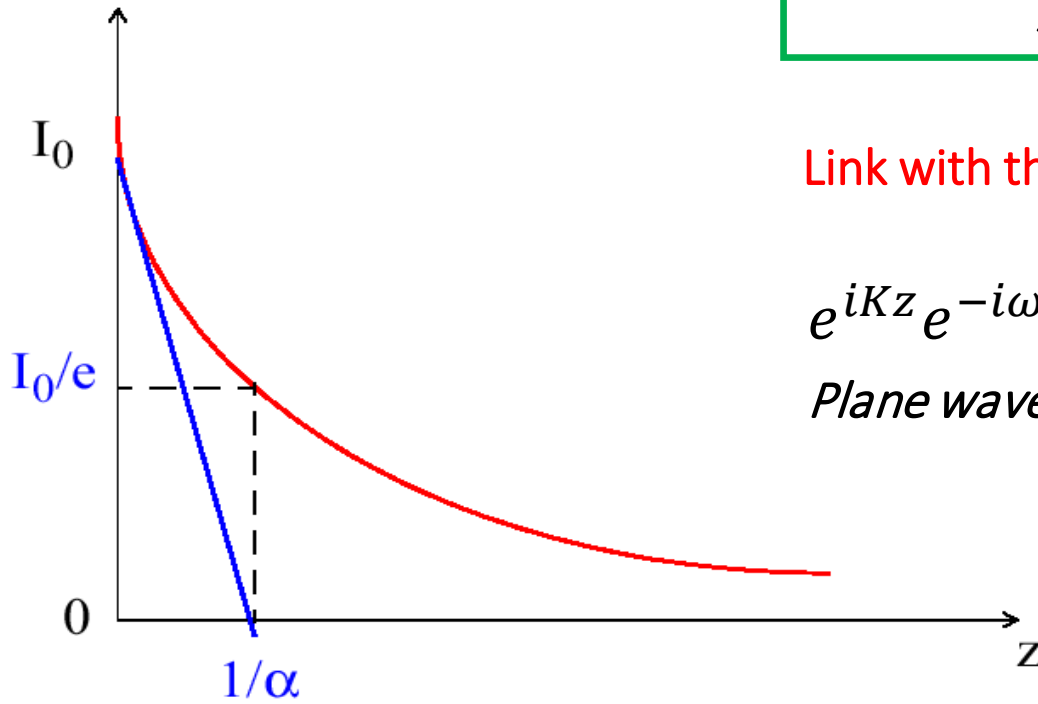
# 1.5 Absorption Coefficient $\alpha$

## Link with the B coefficient

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

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

*Absorption      Stim. emission*



## Link with the refractive index

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

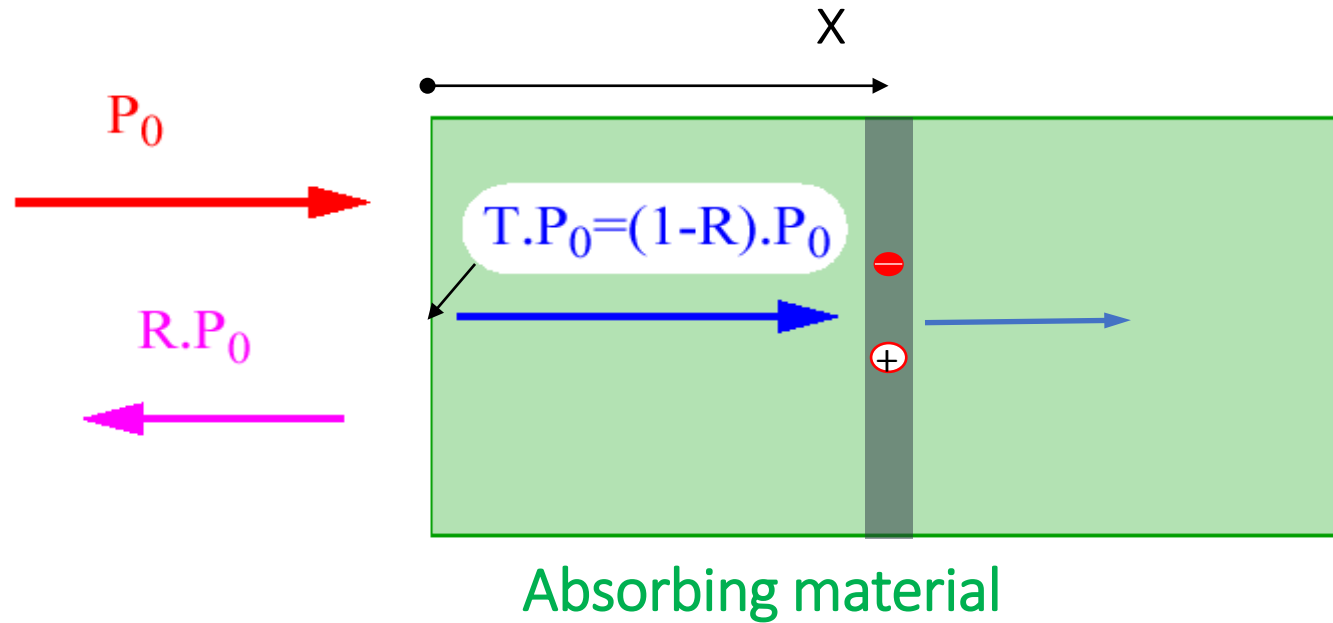
*Plane wave*

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

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

$\alpha$  = probability of photon absorption/cm

# 1.5 Absorption and Generation Rate



$R$  = reflection coefficient

$T$  = transmission coefficient

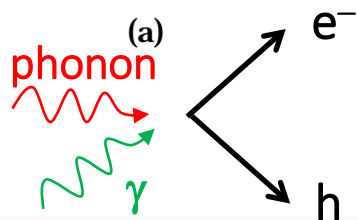
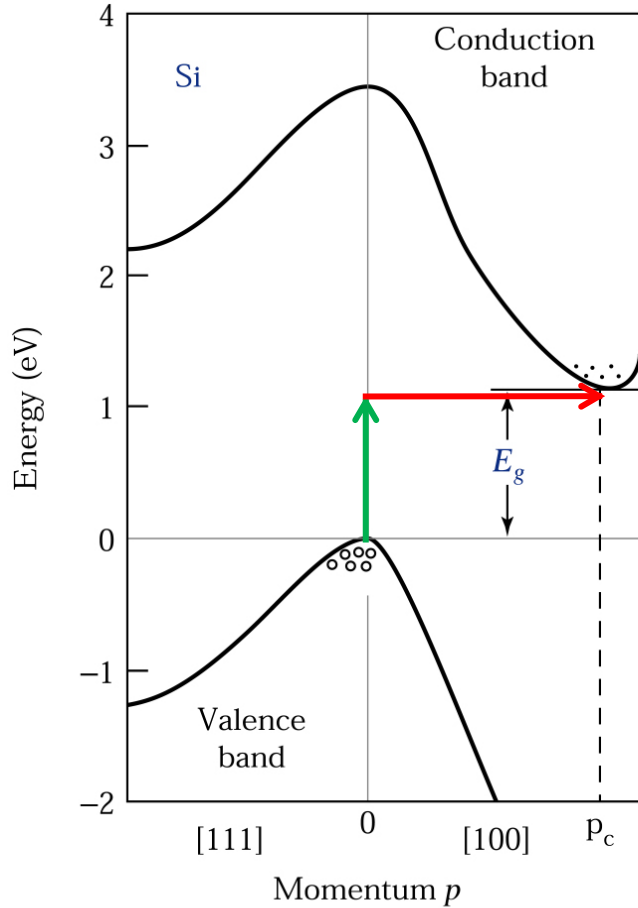
$g(x)$  = generation rate of carriers ( $e^-/h$  pairs)

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

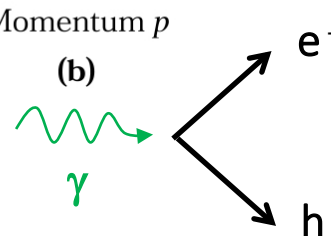
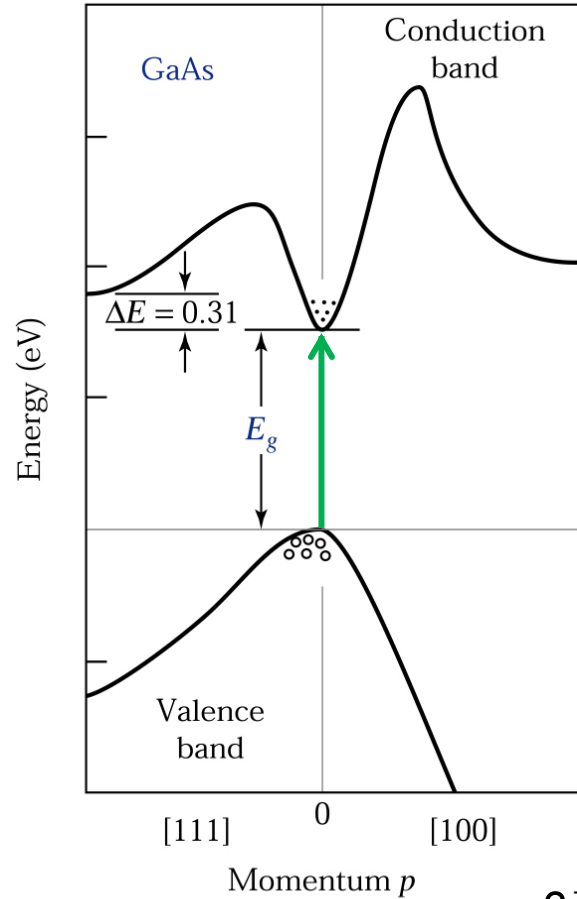
$g(x)$  = (#photons at depth  $x$ )  $\times$   
(probability that they are absorbed)

# 1.5 Band Diagram for Semiconductors

## Indirect



## Direct



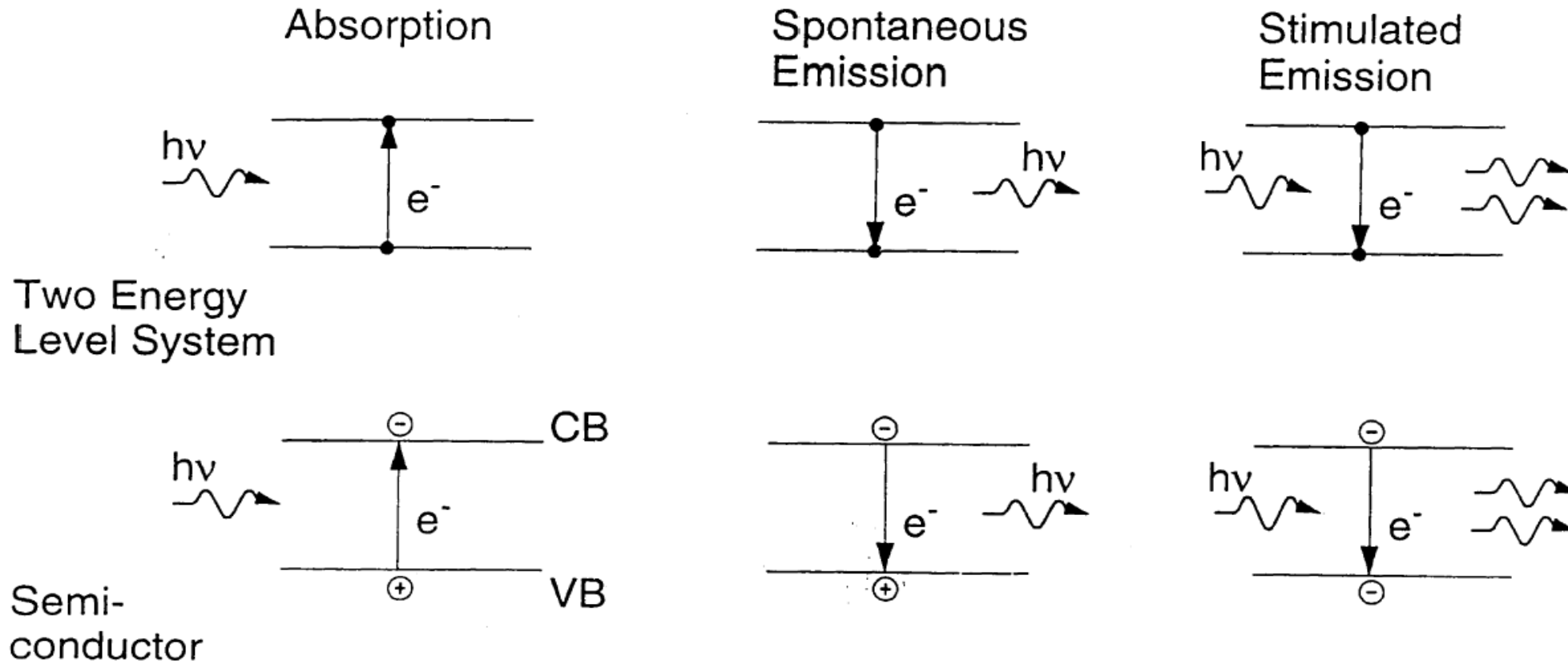
In an indirect semiconductor phonons are required to conserve momentum.

Its absorption is lower than that of a direct semiconductor.

$$B_{\text{indirect}} \ll B_{\text{direct}}$$

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:

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

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



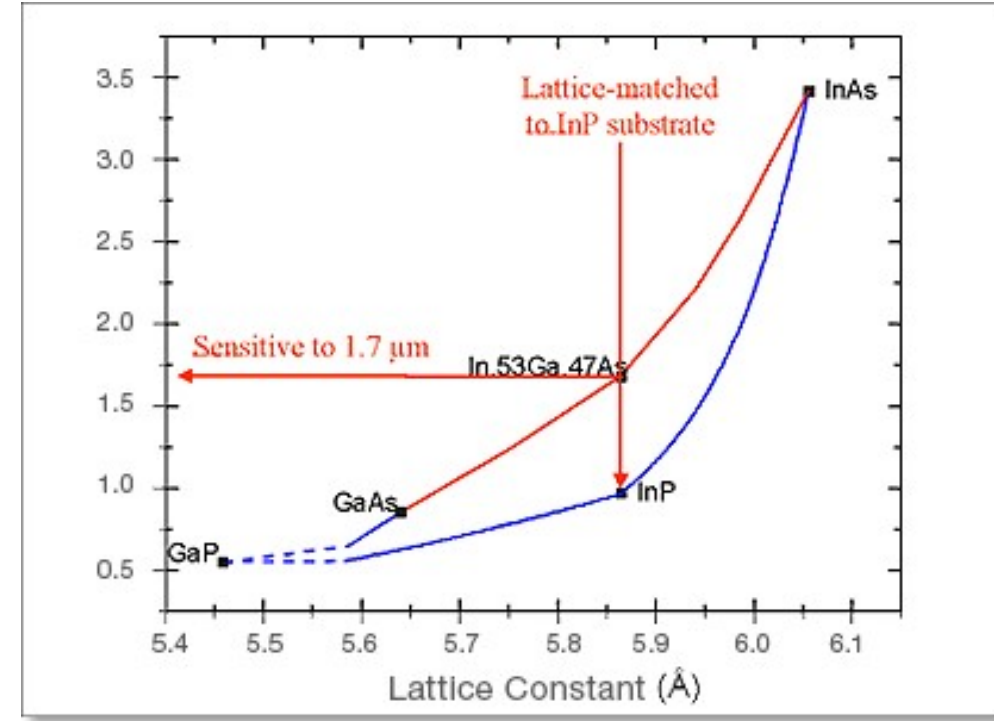
- Absorption increases with energy.  
Blue is absorbed at the surface, red penetrates deeper before it is absorbed.
- The formula above can also describe a gain ( $\alpha < 0$ , laser effect)

# 1.5 Semiconductor Table

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

# 1.5 Bandgaps

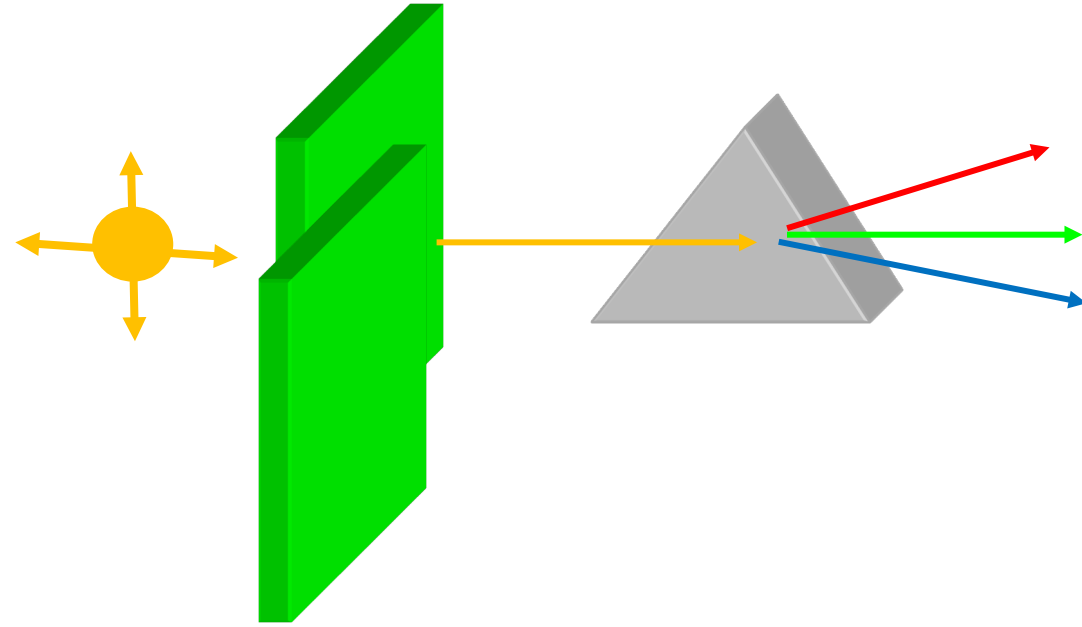
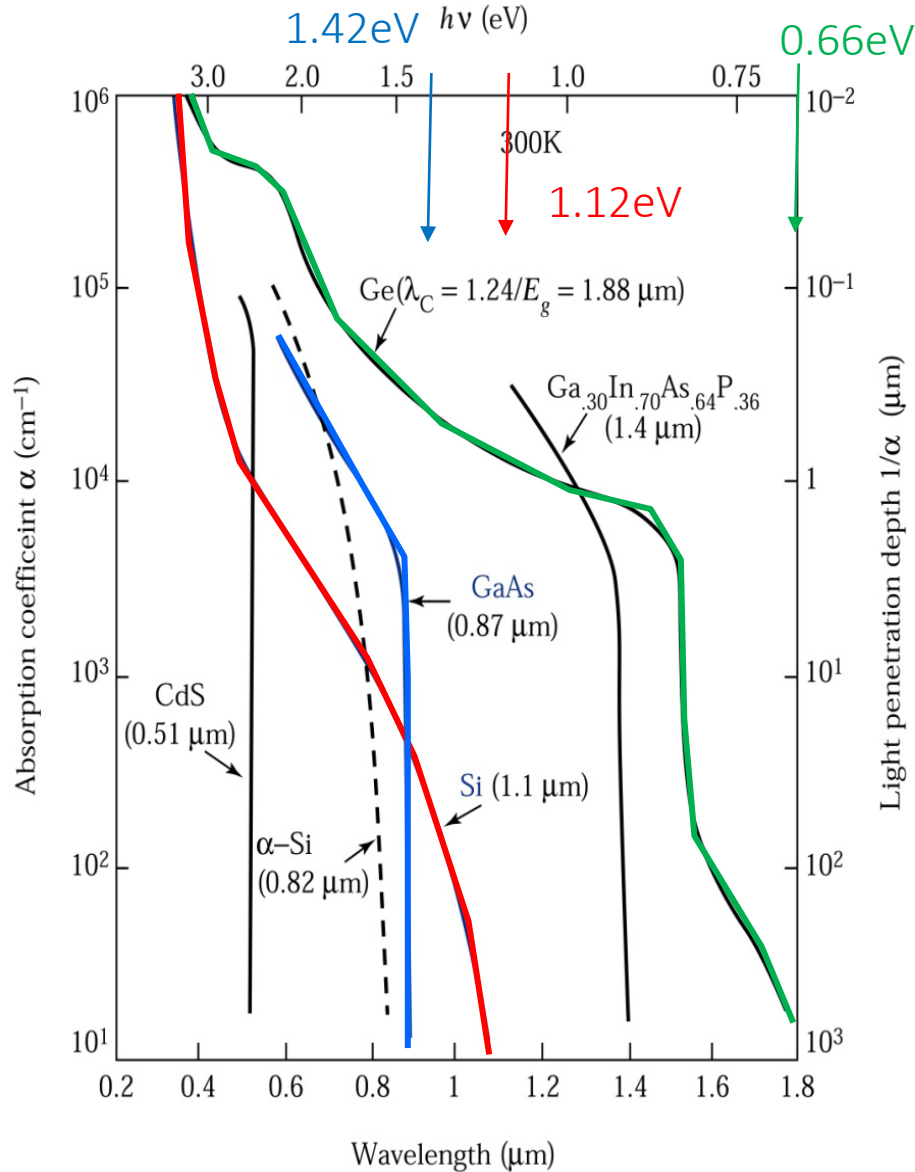
Group	Material	Bandgap Energy (eV)	Type of Bandgap	Cut-off Wavelength ( $\mu\text{m}$ )
<u>Element</u>	Si	1.12	I	1.1
	Ge	0.66	I	1.88
<u>III-V</u>	GaP	2.24	D	0.55
	GaAs	1.42	D	0.87
	InP	1.35	I	0.92
	InAs	0.36	D	3.44
	InSb	0.17	D	7.3
<u>II-VI</u>	CdS	2.42	D	0.52
	CdSe	1.70	D	0.73
	CdTe	1.56	D	0.83
	$\text{Hg}_{1-x}\text{Cd}_x\text{Te}$	0.08 - 1.56	D	0.83 - 16
IV-VI	PbS	0.41	I	3.0



*Tunability!*

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

# 1.5 Absorption Spectra



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

# Outline

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- 1.1 Fundamental properties of light
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## 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.  $\lambda$   
response curve at  
constant power!*

### c) Cameras:

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

# Take-home Messages/W1-3

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## 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?

# Appendix

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# A1 Fundamental equations (1)

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

2) Maxwell :

$$\text{div}(\vec{E}) = \frac{\rho}{\epsilon_0 \epsilon} = \frac{q (p + N_d^+ - n - N_a^-)}{\epsilon_0 \epsilon}$$

1D  $\Rightarrow$

$$E_x \propto \int \rho \cdot dx$$

The electric field is the integral of the net charges

$\propto$  = proportional

3) Maxwell :

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

1D  $\Rightarrow$

$$E_x \propto + \frac{\partial E_{vac}}{\partial x}$$

The electric field is the slope of the vacuum level

## A1.1 Fundamental equations (2)

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4) Poisson equation :  
from 2) and 3)

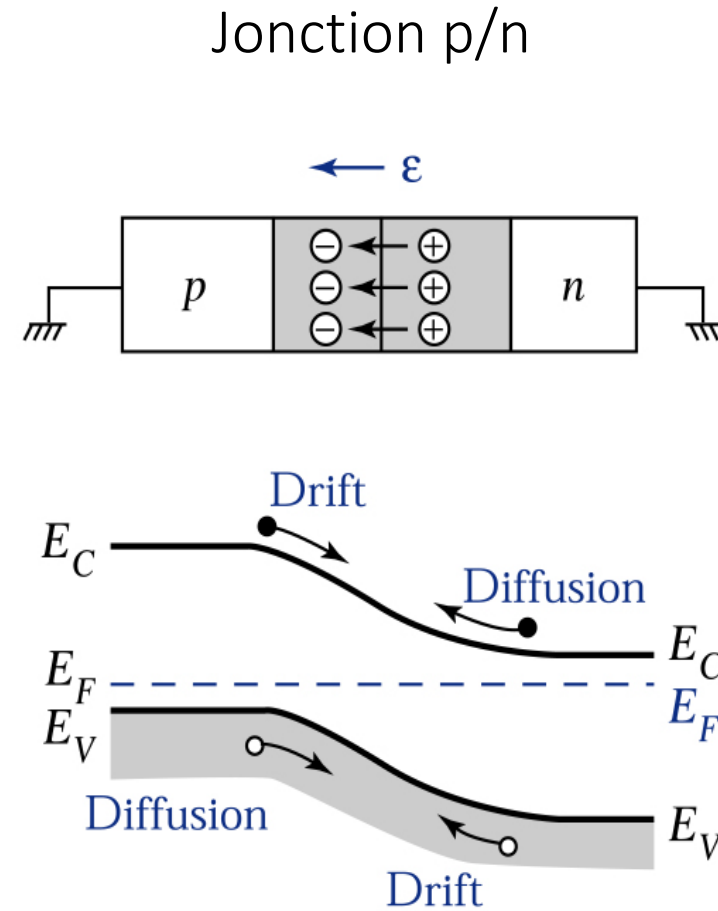
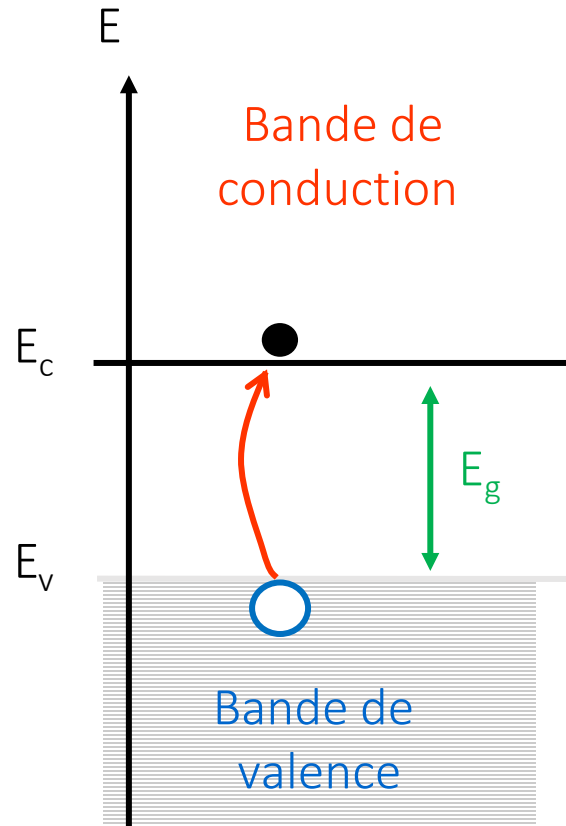
$$\Delta\varphi = -\frac{\rho}{\epsilon_0\epsilon} = -\frac{q(p + N_d^+ - n - N_a^-)}{\epsilon_0\epsilon} = -\frac{1}{q}\Delta E_{vac}$$

1D  $\Rightarrow$

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

The net charges are the curvature of the vacuum level

# A1.1 Band structure



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

# A1.1 Band diagram

