# Biophysics I

# 1. Introduction, Radiations

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# What is the subject of biophysics?

## Physical backgrounds of biological processes

E.g.: electrophysiology of heart, structure and function of membranes, sensory functions,...
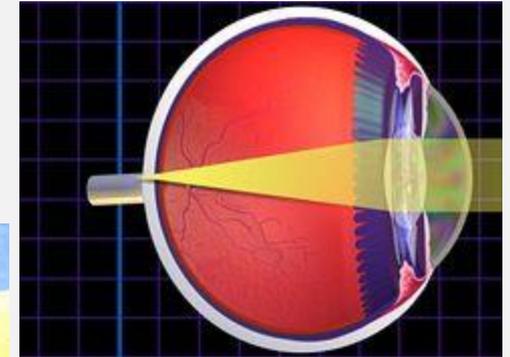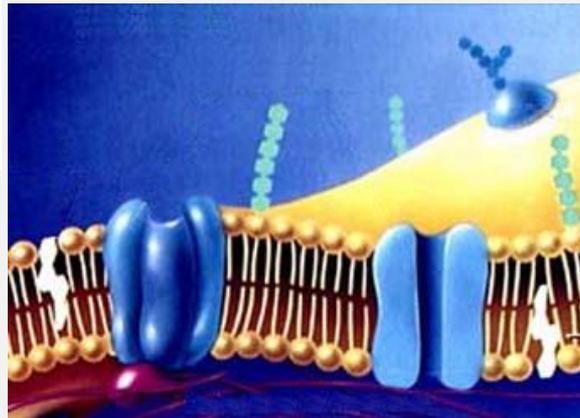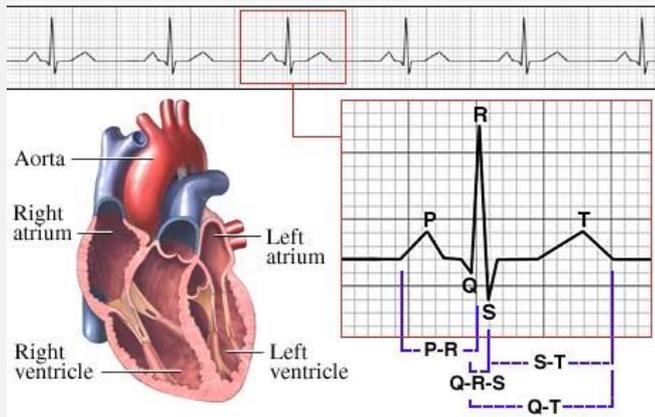
# What is the subject of biophysics?

## Physical methods in biology and medicine

E.g.,  ECG, X-ray diagnostics, microscopy….
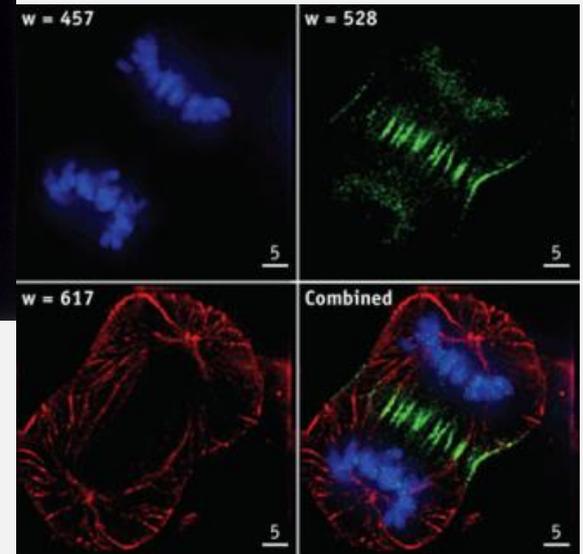
# Scientific method

Observations, experiments = data collection

Data analysis = finding causative relations among data

Relations = mathematical models describing the dependence of observations on independent variables (parameters)

Model building is always simplification. Based on a model, we make assumptions out of the known observation to validate them experimentally. If the new results agree with the model prediction than we keep the model, if not than we must modify the model = models are ***falsifiable***! = experimental results support or disprove a model. Occam's razor = from alternative explanations (models) of a phenomenon, we should select the one posits the fewest assumptions.

Medical sciences (!)

# Math and physics we need for biophysics
## *(formula collection)*

quantitative models = mathematical functions

an example – how the index of refraction changes as a function
of the concentration of soluts in diluted solutions?   $n = n_0 + k*c$

*what we need:*

- *linear function*
- *power function*
- *exponential and
  logarithmic function*
- *harmonic function*

*good to know:*
- *transformations of
  formulas*
- *vectors*
- *units*

$$y = 0{,}0384x + 1{,}3324$$
$$R^2 = 0{,}9981$$

index of refraction

concentration of glycerol [mol/l]
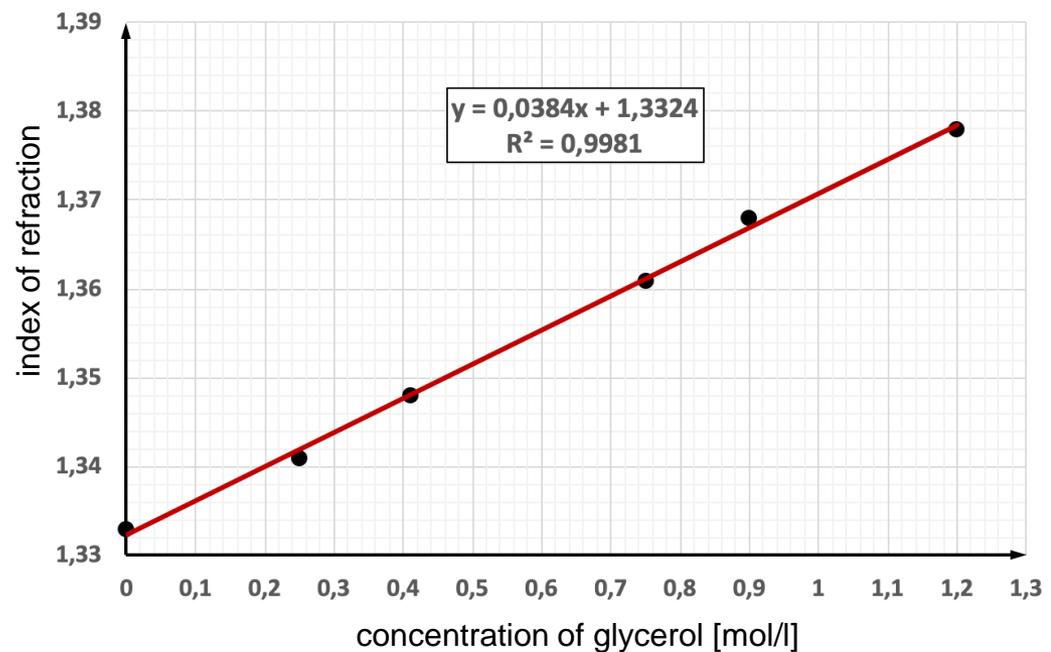
# Physical bases of biophysics
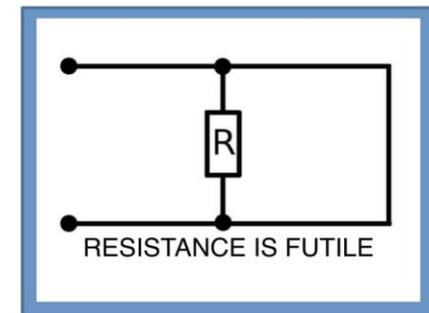


Important concepts: energy (work, power), momentum, force (fields), kinematics (velocity, acceleration)...

# Topic list of the first semester

| | |
|---|---|
| 1 | Introduction to biophysics, radiations, elektromagnetic spectrum |
| 2 | Ray optics: Fermat's principle, refraction, lenses, microscope |
| 3 | Wave optics: Huygens's principle, diffraction, interference, resolution |
| 4 | Light interacting with matter: scattering, absorption, reflection, color vision |
| 5 | Atoms, molecules, structure of matter |
| 6 | Thermal emission; emission of human body infradiagnostics |
| 7 | Luminescence, applications in medicine |
| 8 | Lasers, applications in medicine |
| 9 | Modern microscopy techniques |
| 10 | X-ray: production, characteristics, and applications |
| 11 | Photobiology, applications in medicine |
| 12 | Bases of X-ray diagnostics |
| 13 | Nuclear radiations, bases of isotope diagnostics |
| 14 | Clinical applications of nuclear radiations |

# Radiations

radiation = release (emission) and transfer (propagation) of energy (in the form of waves or particles)

Examples:

sound, light

radiowaves, X-ray

nuclear radiations
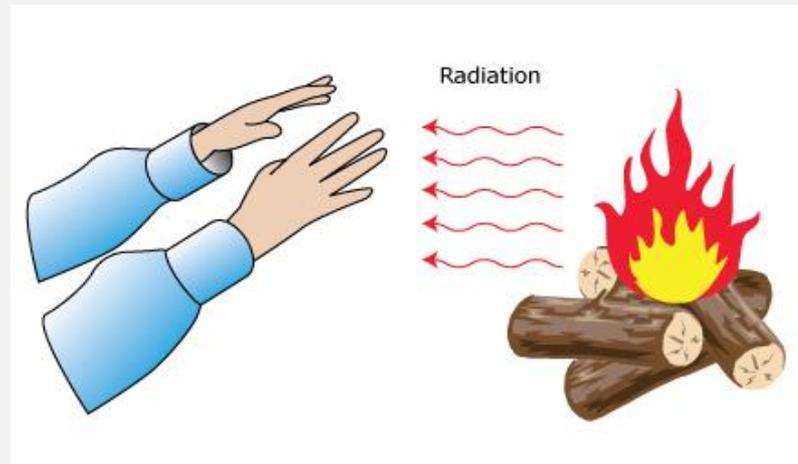
# Classification of radiations
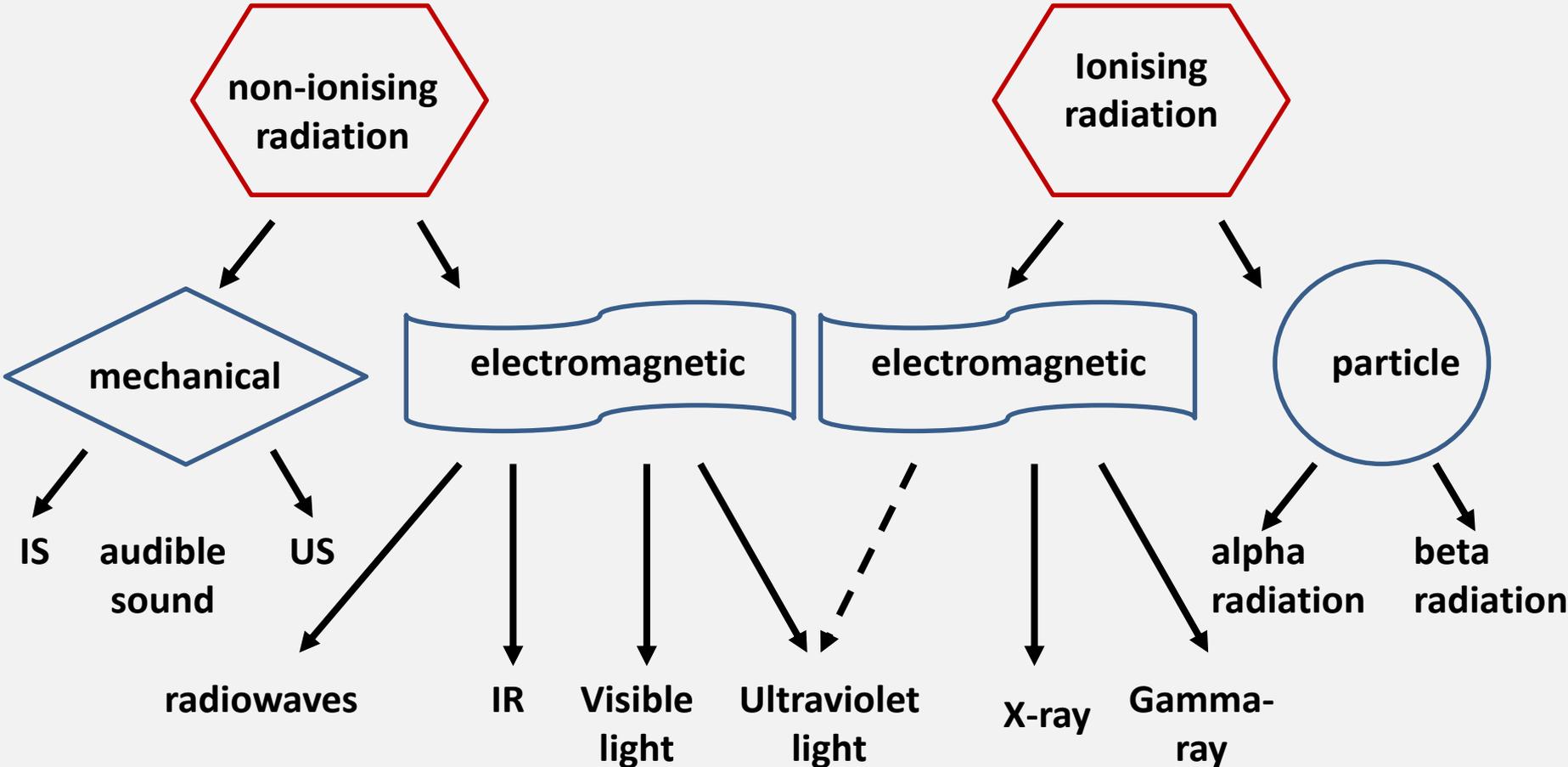
# Classification of radiations

non-ionising radiation

Ionising radiation

## What is the basis of classifications?

### IONISATION
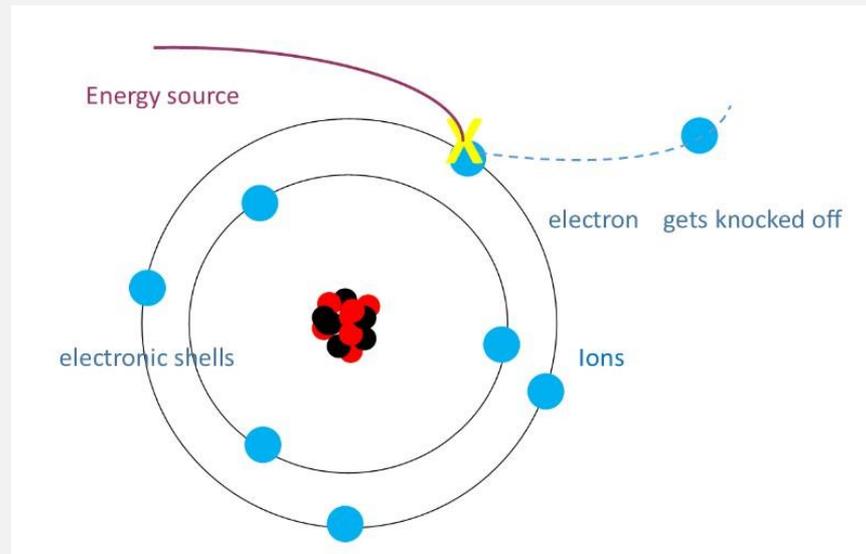
# Radiometric quantities

$M = \Delta P/\Delta A = \Delta E/\Delta t \Delta A$
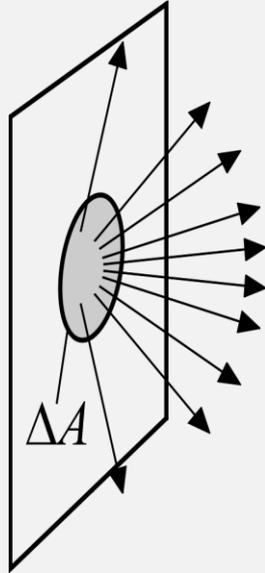
$E_{be} = \Delta P/\Delta A$ (W/m$^2$)
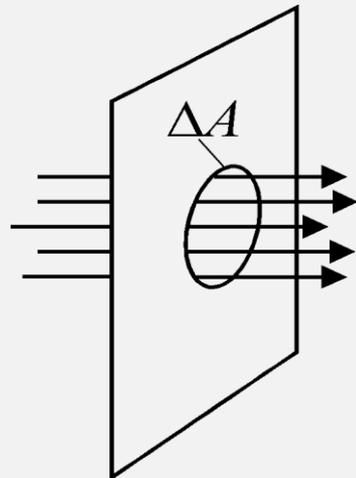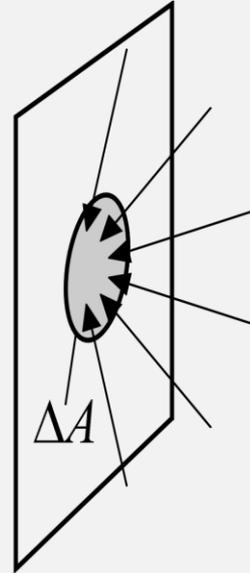
Intensity = energy flow density
$J_E = \Delta E/\Delta t \Delta A$

# Intensity change by distance from the source
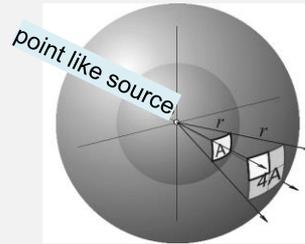


Point like source:
$A \sim r^2$ ➜ $J \sim 1/r^2$



line source:
$A \sim r$ ➜ $J \sim 1/r$
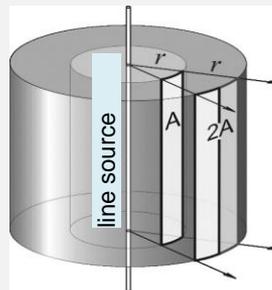
only close to the source!
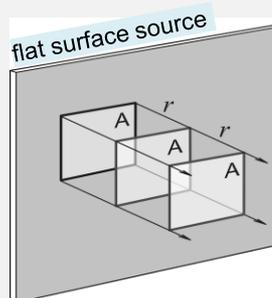


flat surface source:
$A \sim$ constant ➜ $J \sim$ constant

# General description of waves

periodic disturbances in space and time, transferring energy




Waves differ in
type of energy
intensity
mechanism of propagation

# Characteristic values

Period in space – *wavelength*

$\lambda$ [m] or [nm]

displacement – *amplitude*

$$E \sim A^2$$

Period in time     – *period, T*
        – *frequency, f*

$$f = \frac{1}{T}\left[\frac{1}{s}\right]$$

velocity of waves:   c = $\lambda$/T = $\lambda$f
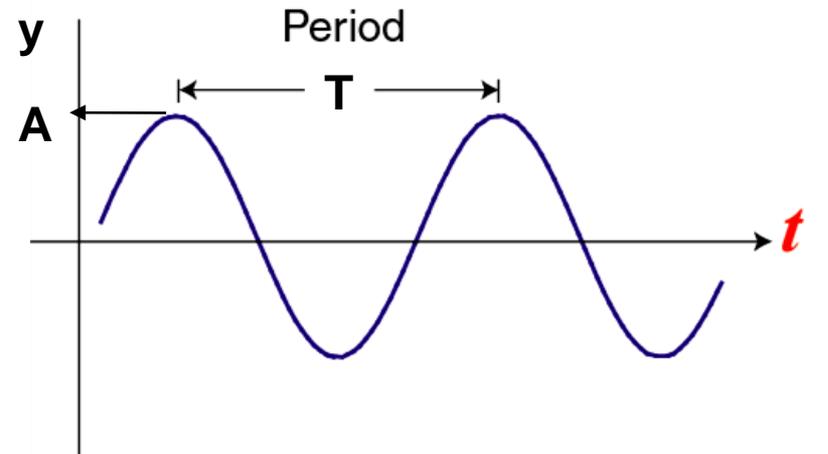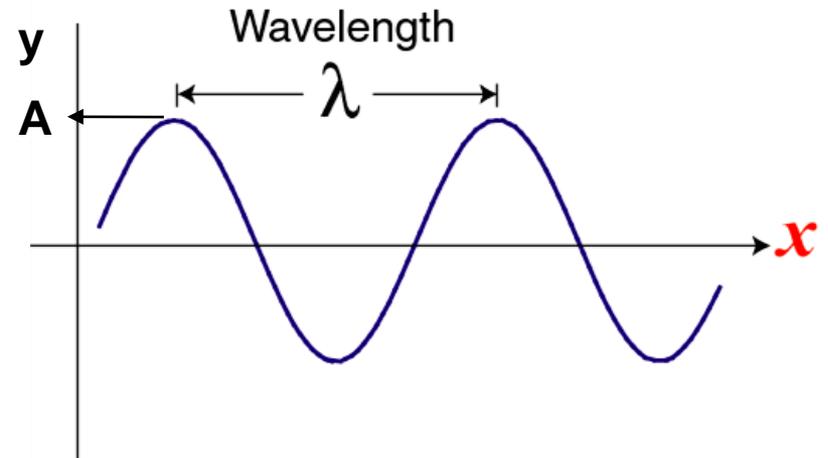
# *Phase*: the location or timing of a point within a period



Wavenumber $k=2\pi/\lambda$

Angular frequency: $\varpi=2\pi/T=2\pi f$
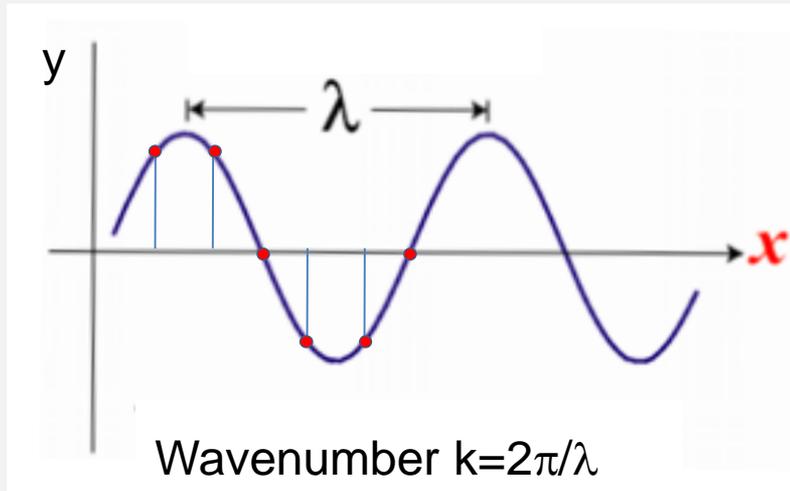
$$\phi(x)=kx+\phi_0$$
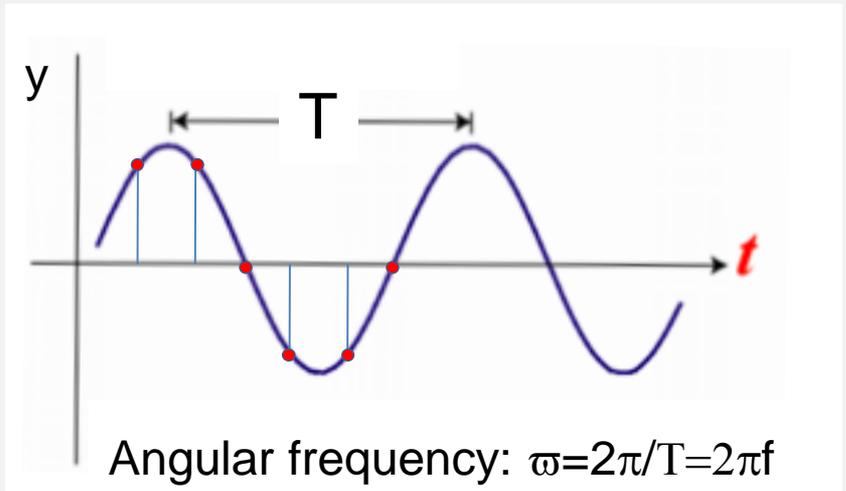
$$\phi(t)=\varpi t+\phi_0$$

$$\phi=\varpi t+kx+\phi_0$$

Phase: fraction of the wave cycle that has elapsed relative to the origin

# Indications for a wave nature:

- diffraction
- superposition / interference
- polarisation
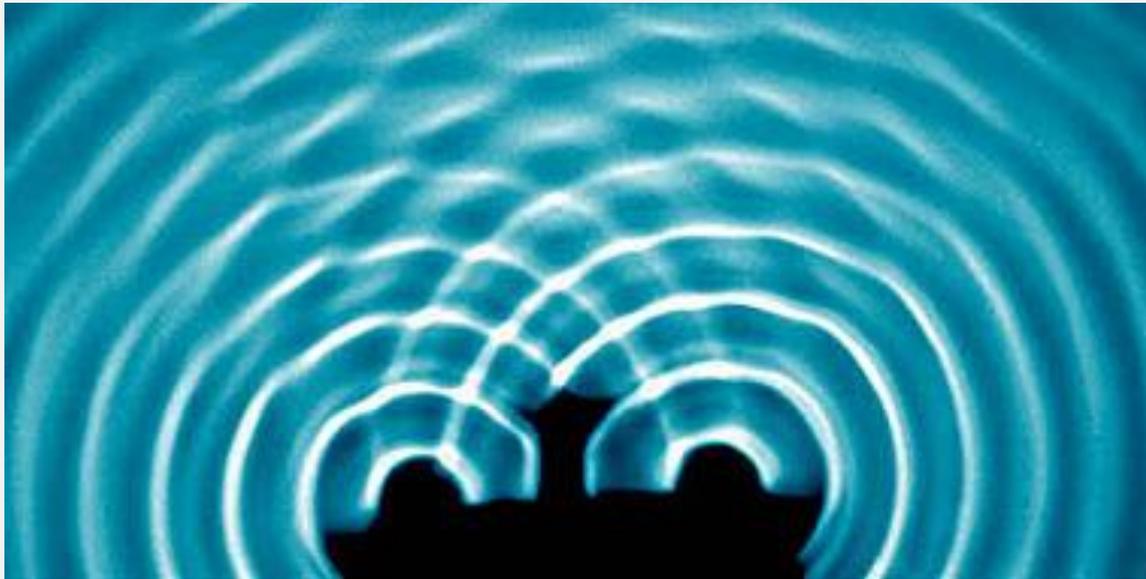
# *Diffraction*
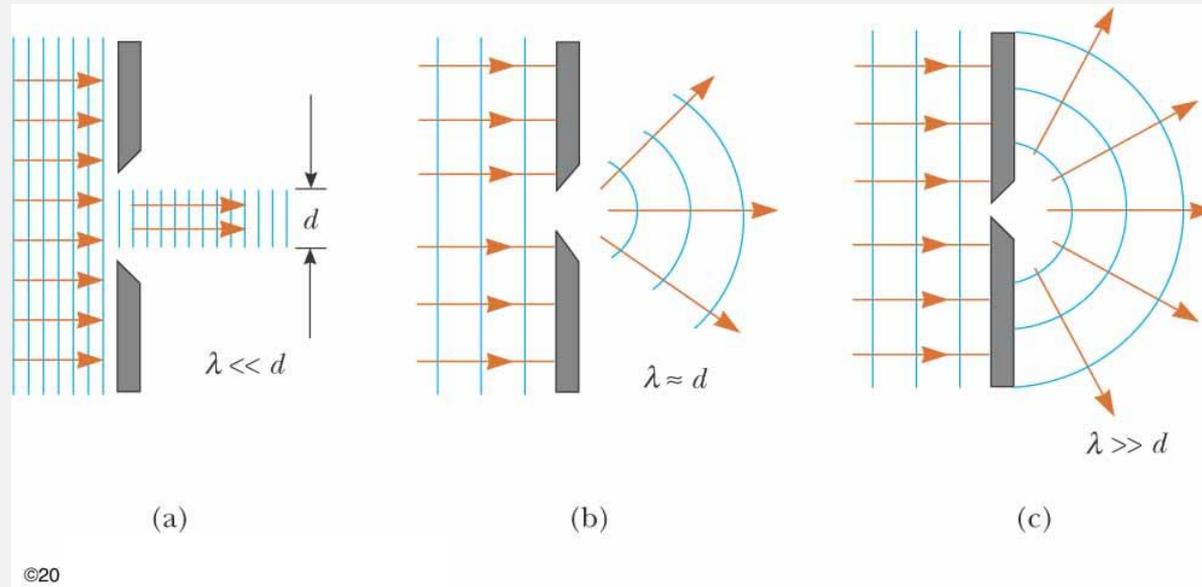


Huygens' principle: every point in a propagating wavefront serves as the source of spherical secondary wavelets, such that the wavefront at some later time is the envelope of these wavelets.
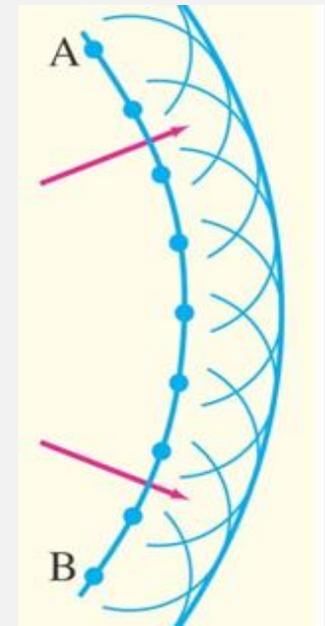
*Superposition:* The principle of superposition applies to waves whenever two (or more) waves traveling through the same medium at the same time. The net amplitude of the waves at any point in space or time, is simply the sum of the individual wave amplitudes.
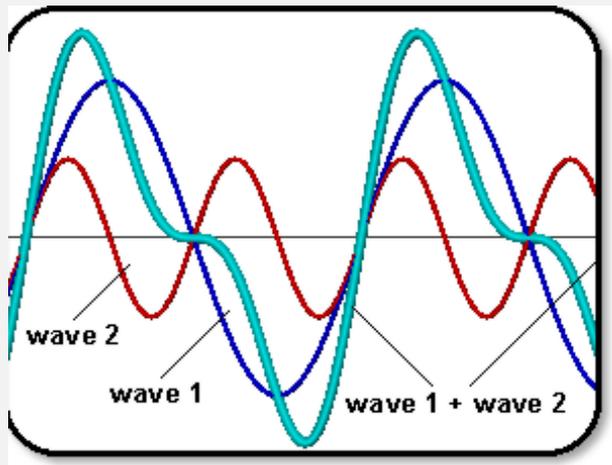


Un-equal frequencies
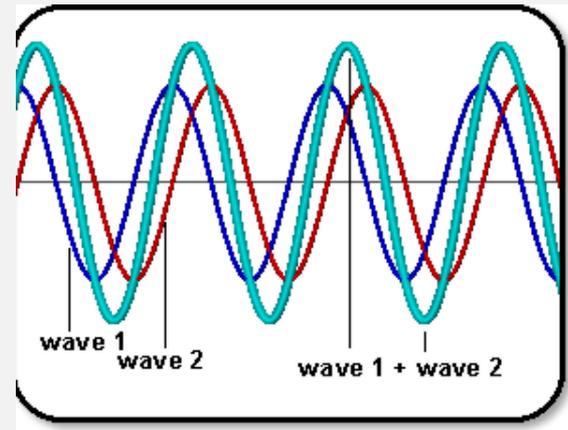


Equal frequencies

# *Interference:* superposition of coherent waves
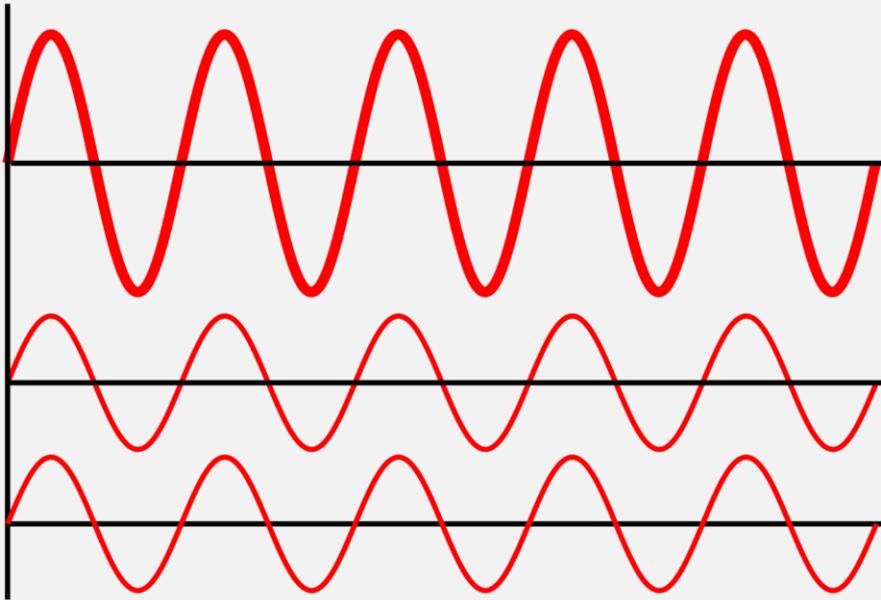


Similar phases

Constructive interference

$\Delta\Phi = 0°$
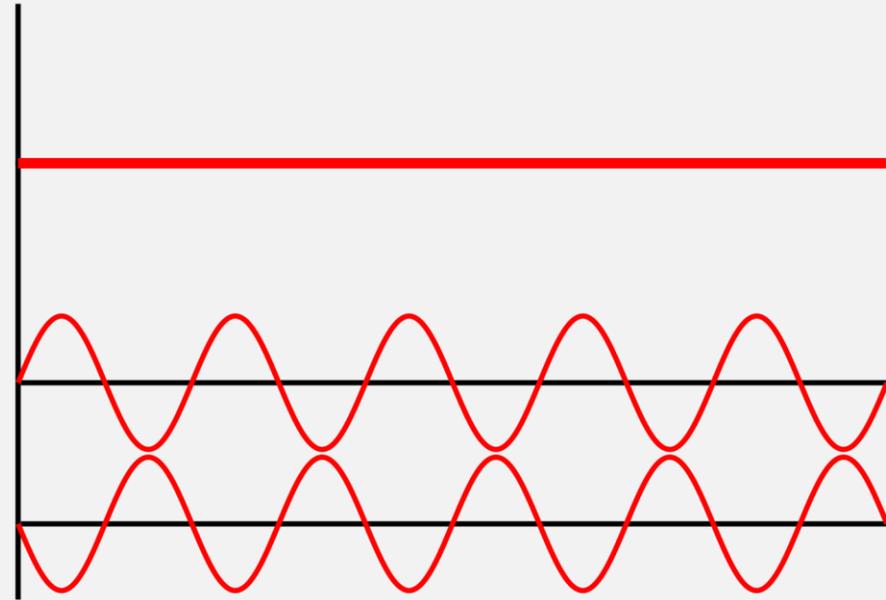
Opposite phases

Destructive interference

$\Delta\Phi = 180°$

# The nature of light is...

a wave?                                              particle?



**Christiaan Huygens**                    **Isaac Newton**
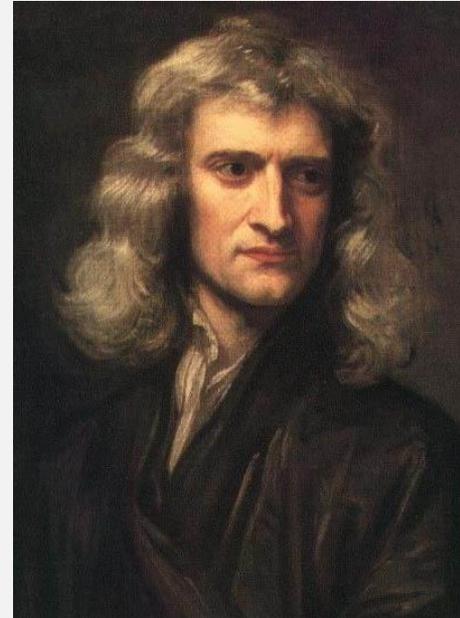
(1629 - 1695)                              (1642 - 1727)

*Traité de la lumière*                     *Opticks*
1690                                        1704

# Wave or particle?

**Thomas Young**
(1773-1829)

1. Thomas Young's double-slit experiment

Light beams

$S_1$

$S_2$

Viewing screen

(a)

Viewing screen
(particle theory
prediction)
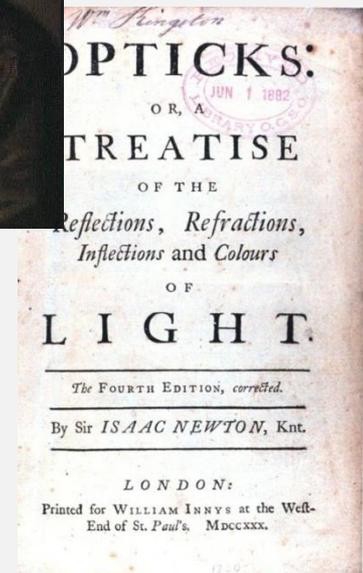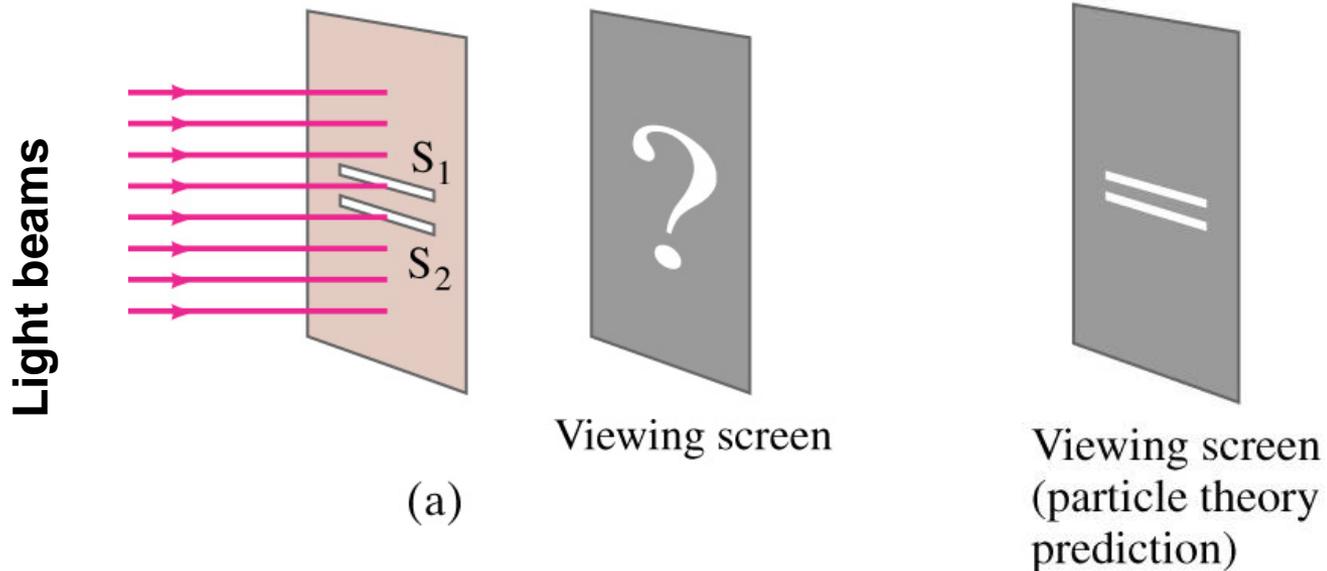
# Wave or particle?

**Thomas Young**
(1773-1829)

1. Thomas Young's double-slit experiment
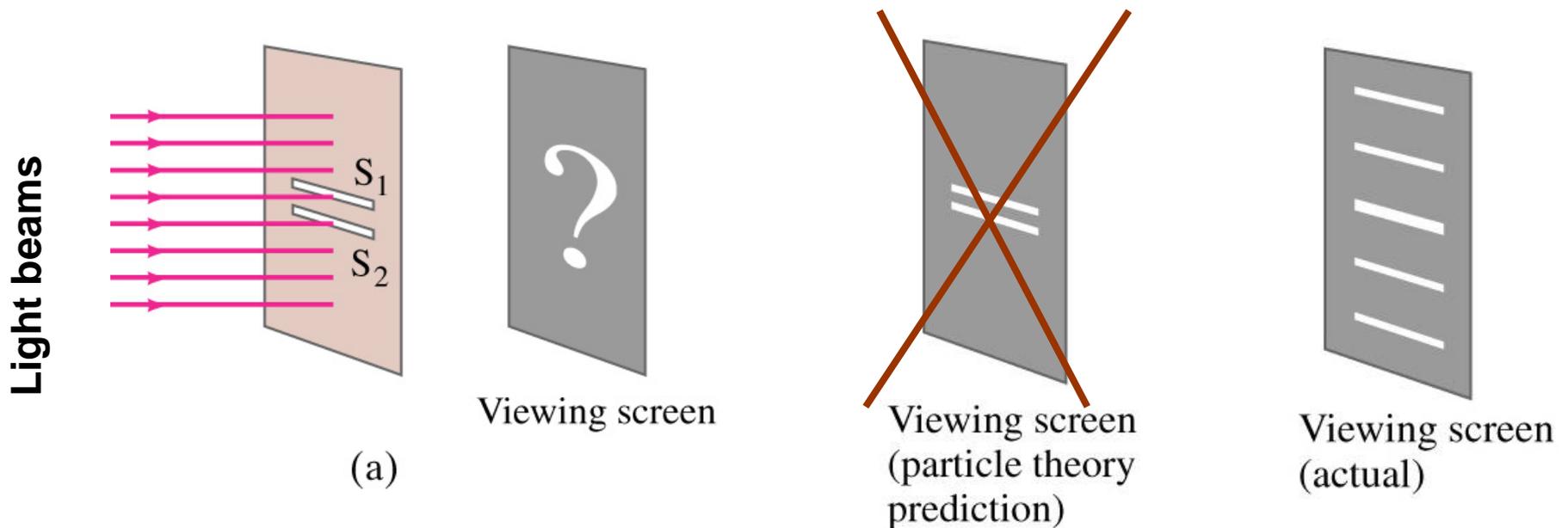
## Interpretation of Thomas Young's double-slit experiment

S$_1$ and S$_2$ slits are wavesources

Two waves from S$_1$ and S$_2$ originates

from the same wavefront, that is they

are in the same phase.

⇓⇓

# interference
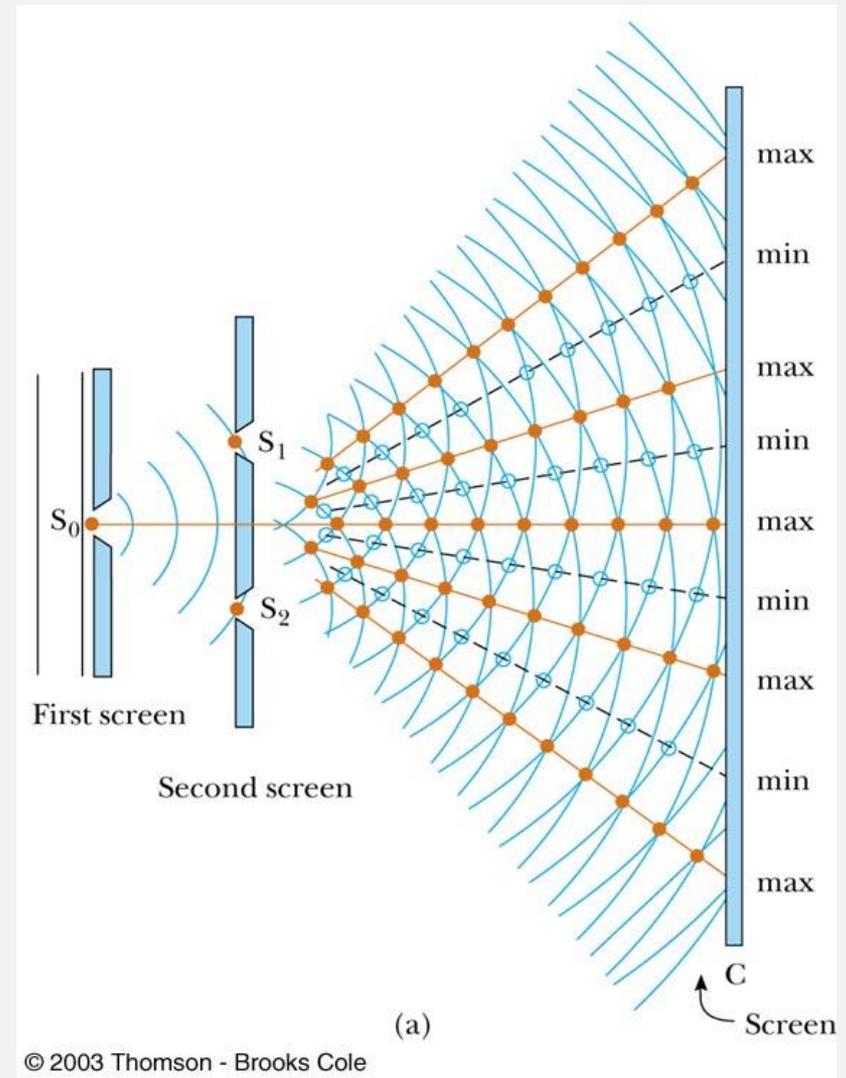


Interference fringes on a screen

# *Dispersion of light by a diffraction grating*
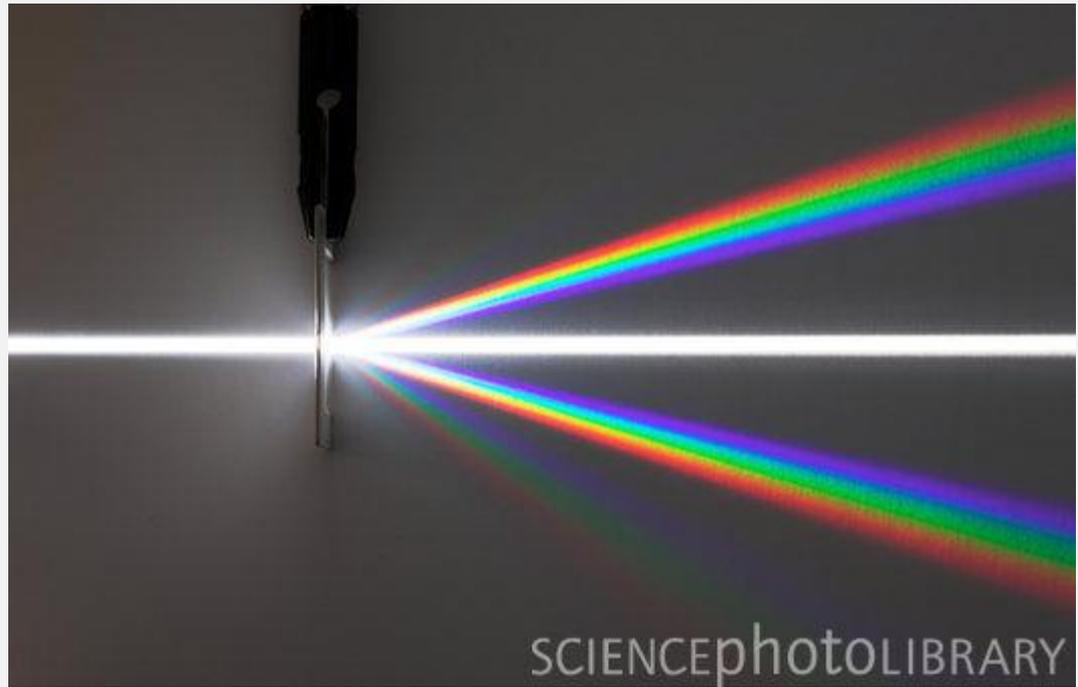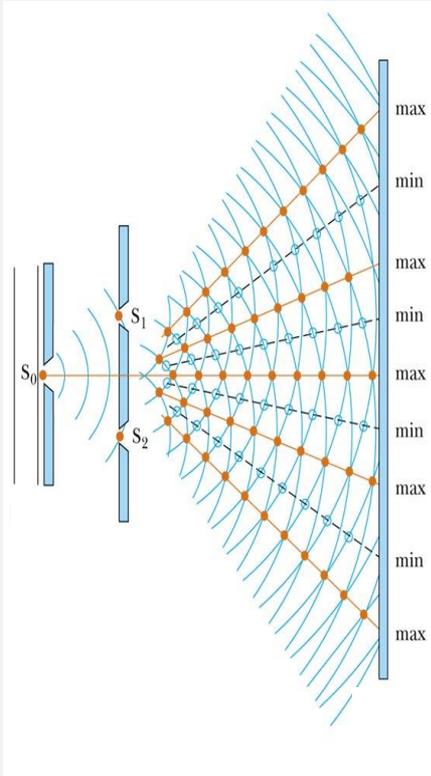
# Wave or particle?

## 2. Hertz's experiment



**Heinrich Hertz
1887**
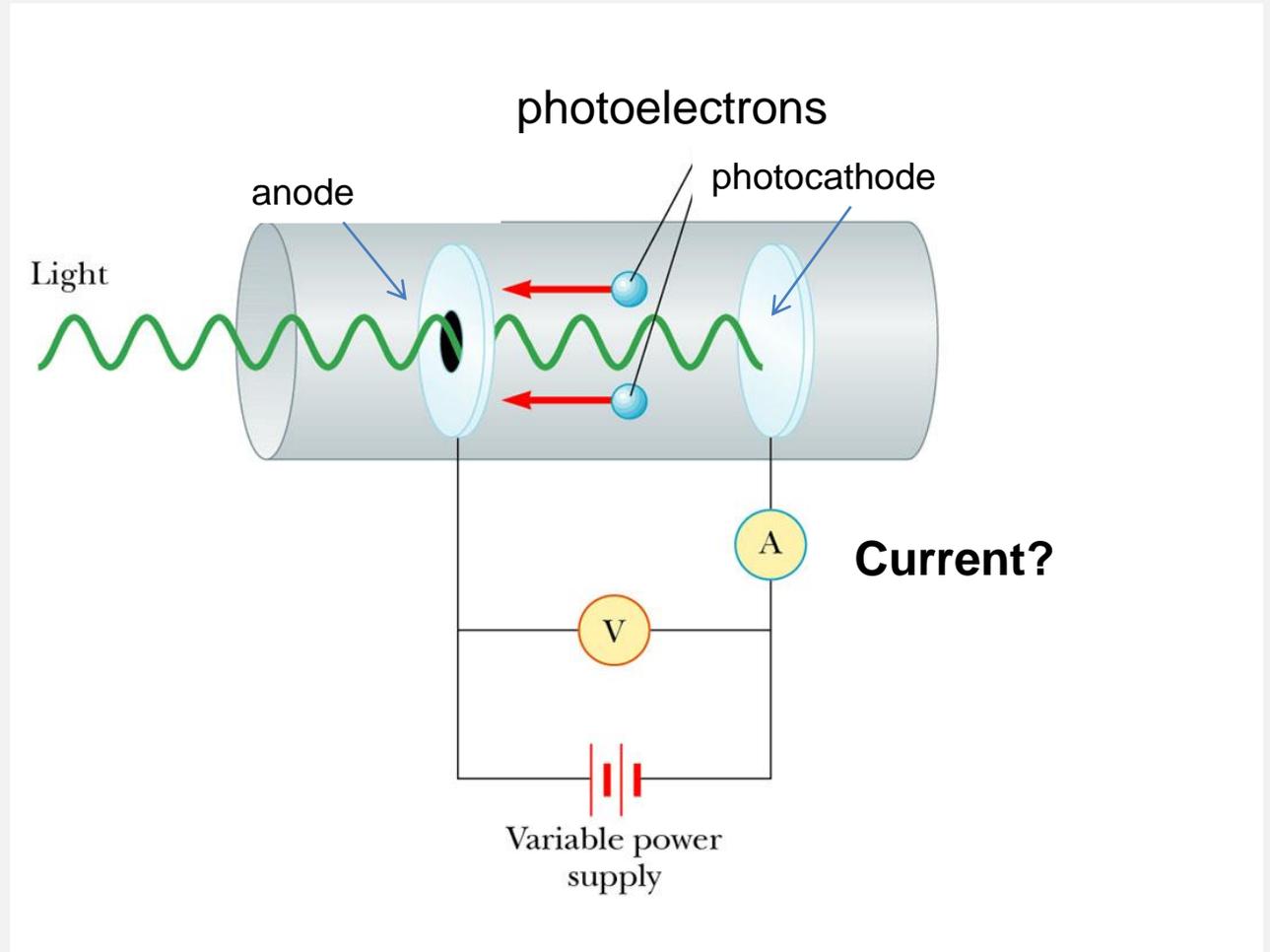
Fotoelectric effect

# Light irradiation with

## Similar color / wavelength

increasing
amplitude / intensity

Current?

no

no

no

no

## Similar amplitude

variation in color / wavelength

Current?

no

yes

yes
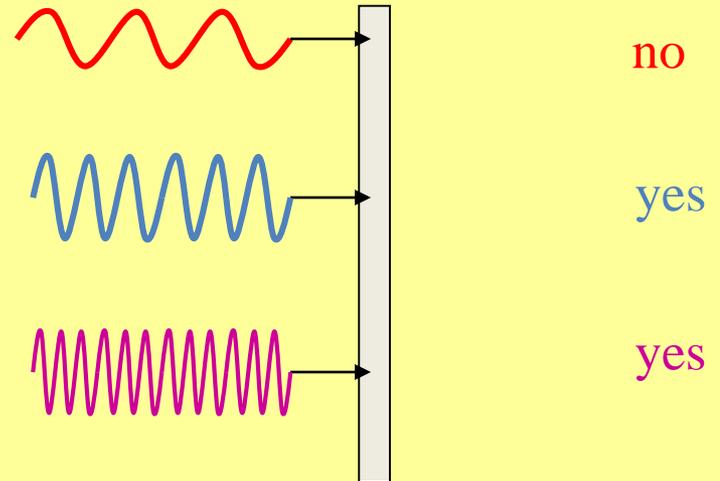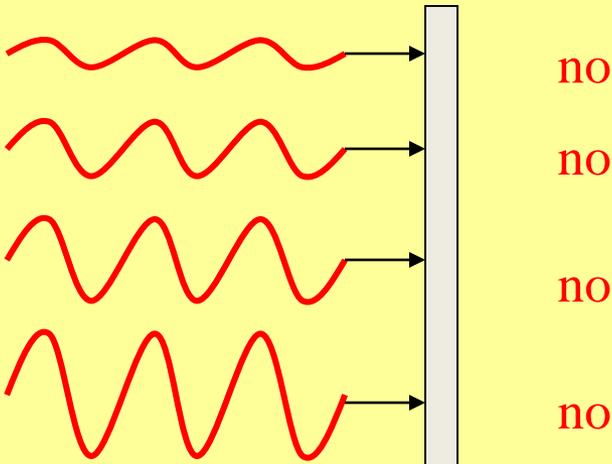
# No current below a critical frequency!

# Interpretation of photoelectric effect

- Based on the wave character it is not possible!

- Planck - foundation of quantum physics (1900): E=hf

- Einstein's concept is based on quantum theory (1905)
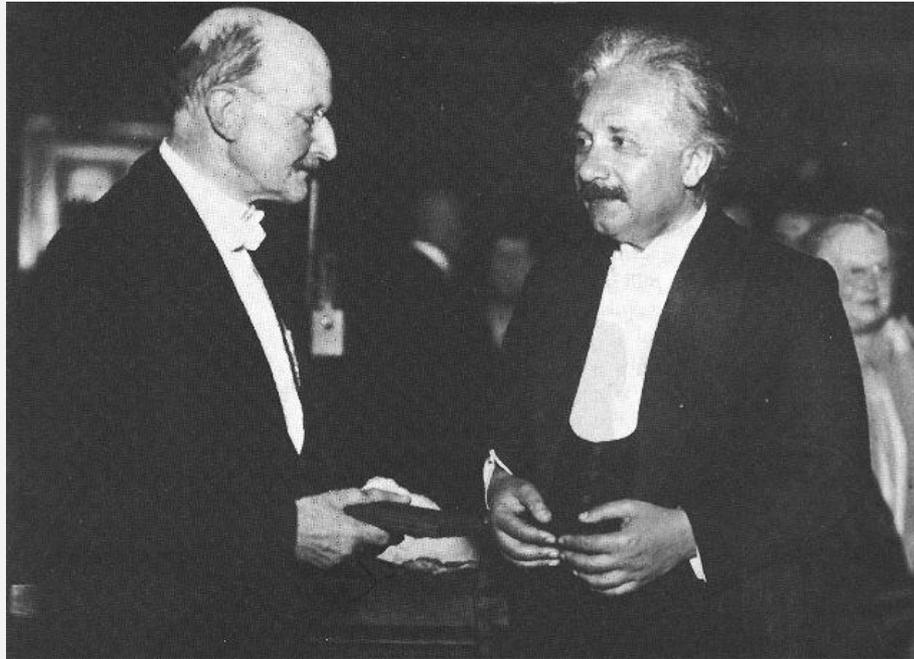
**Max Planck**



**Albert Einstein**

Nobel Prize in physics  1918

*"in recognition of the services he rendered
to the advancement of Physics
by his discovery of energy quanta".*

Nobel Prize in physics 1921

*for his services to Theoretical Physics,
and especially for his discovery
of the law of the photoelectric effect".*

# *Einstein's interpretation*

- Light consists of a finite number of energy quanta - photons

- The energy of a photon: $E = hf$

- Photon can be absorbed or generated only as complete units

- A photon transfers its energy to one electron if the photon energy is equal or higher than the work function (A)

- No interaction, if the photon energy is below the work function

- 1 photon – 1 electron interaction

- Kinetic energy of the released electron: $E_{kin} = hf - A$

# *Einstein's interpretation and the frequency limit*

Kinetic energy of the emitted electron is proportional to the frequency.

Intercept with the *x* axis is the smallest frequency inducing photoelectric effect

$f_{min}$ depends on the cathode material:

$$A = hf_{min}$$

$$E_{kin} = hf - A$$
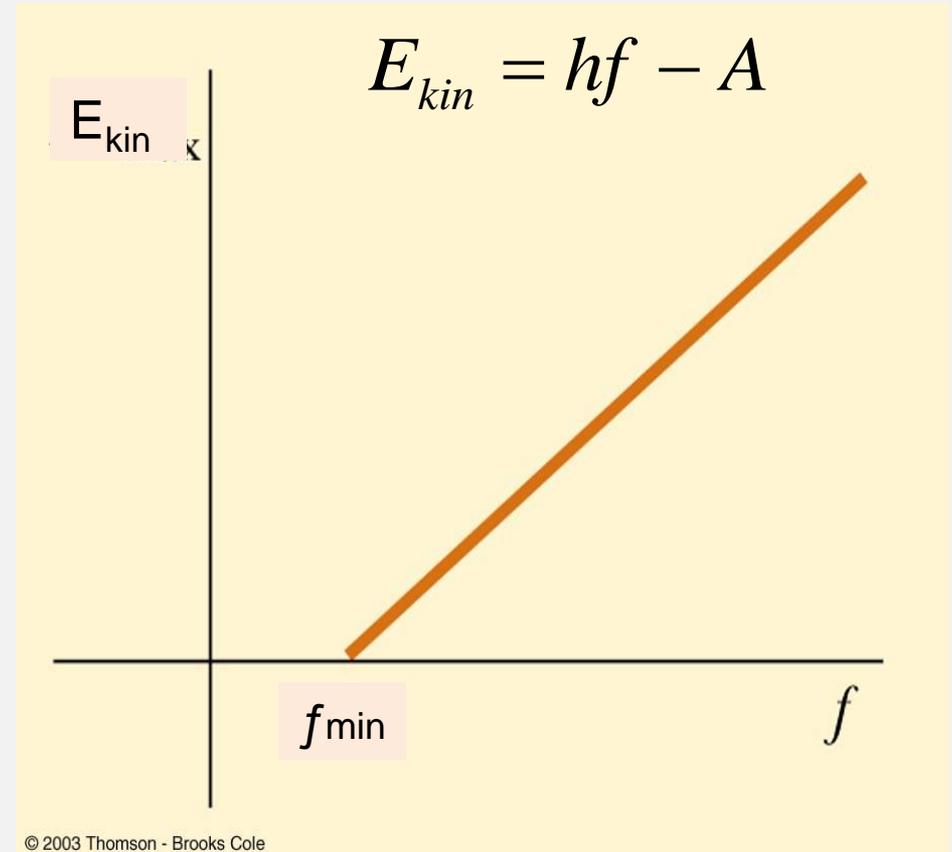
# Dual nature of light

Particle – its energy is quantized, a photon is an elementary particle, the quantum of the electromagnetic interaction

Energy of photon: $$E = hf = h\frac{c}{\lambda}$$

Planck constant: $$h = 6.62 \cdot 10^{-34} \, Joule \cdot s$$

Photons have no resting mass and propagate in vacuum

# Dual nature of light

Wave – electric and magnetic fields vary sinusoidally

Electromagnetic radiation
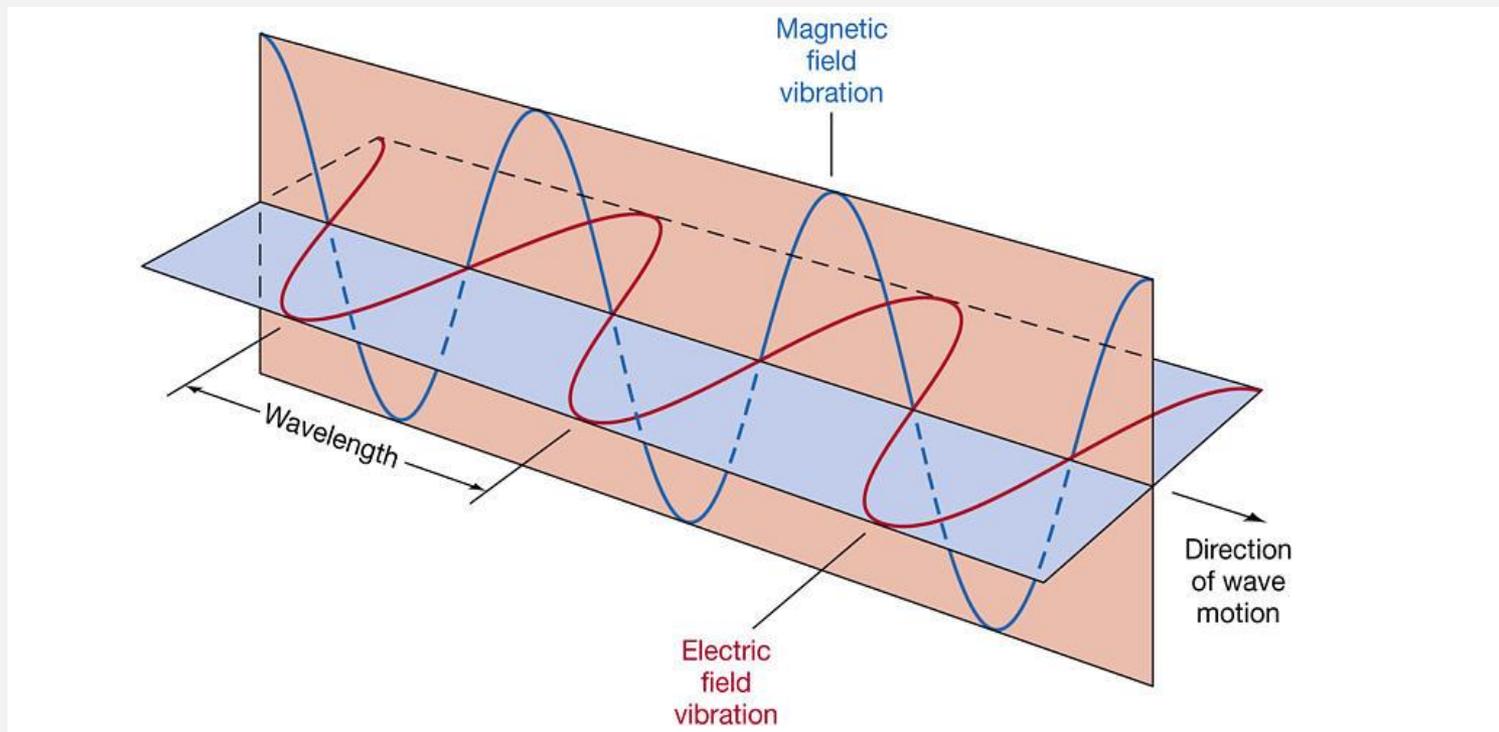
# Ranges of electromagnetic radiation
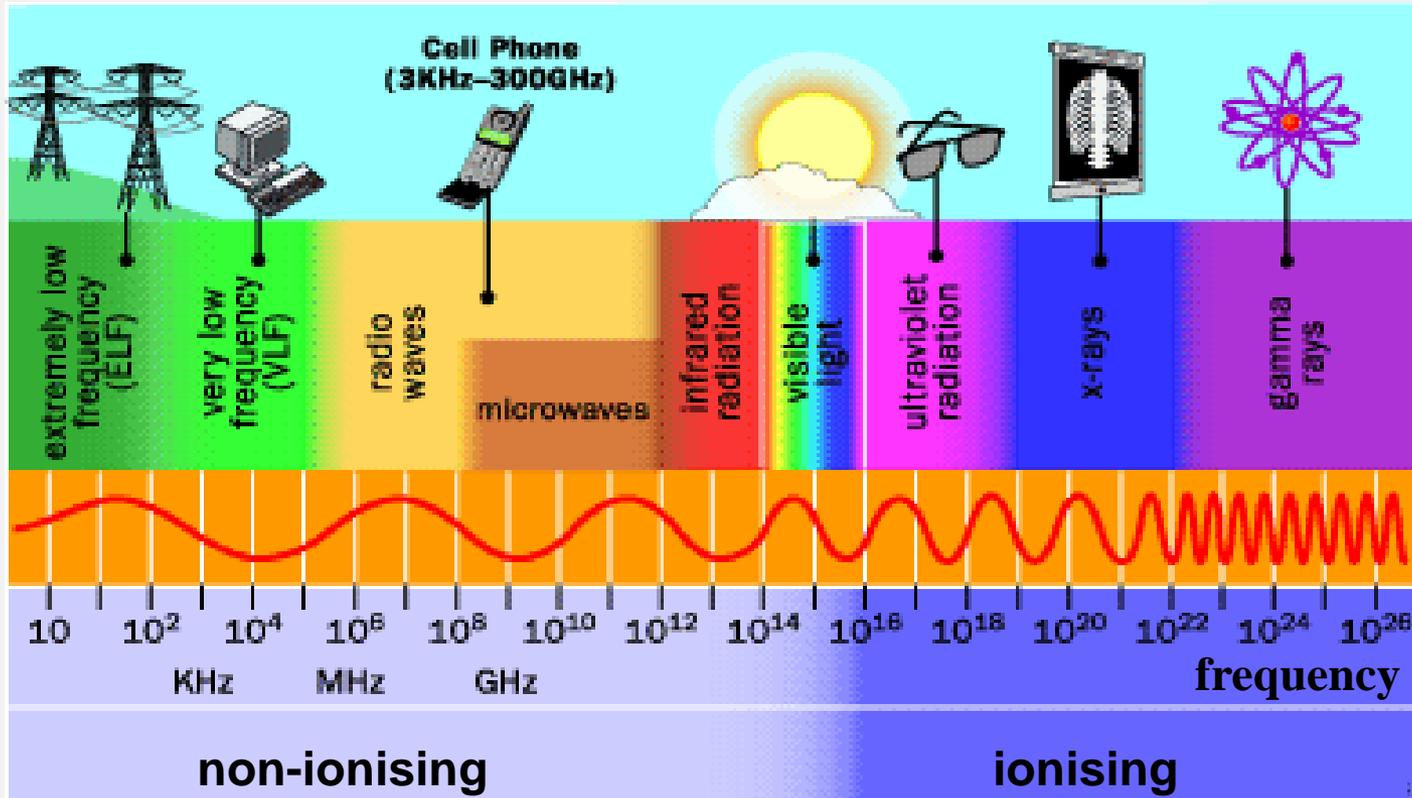
# Optical range
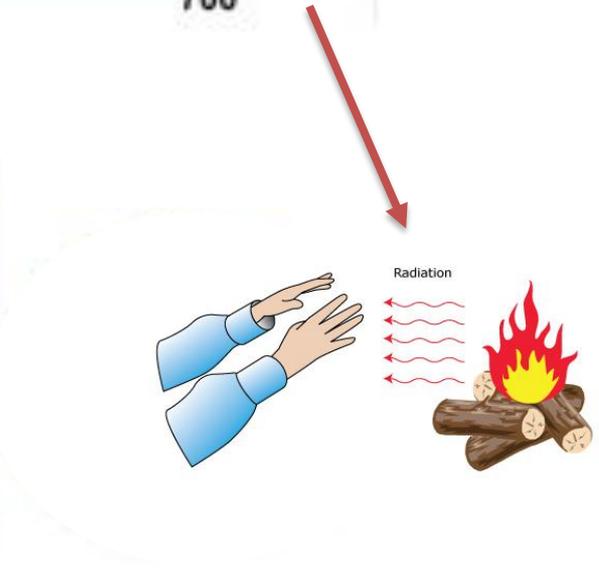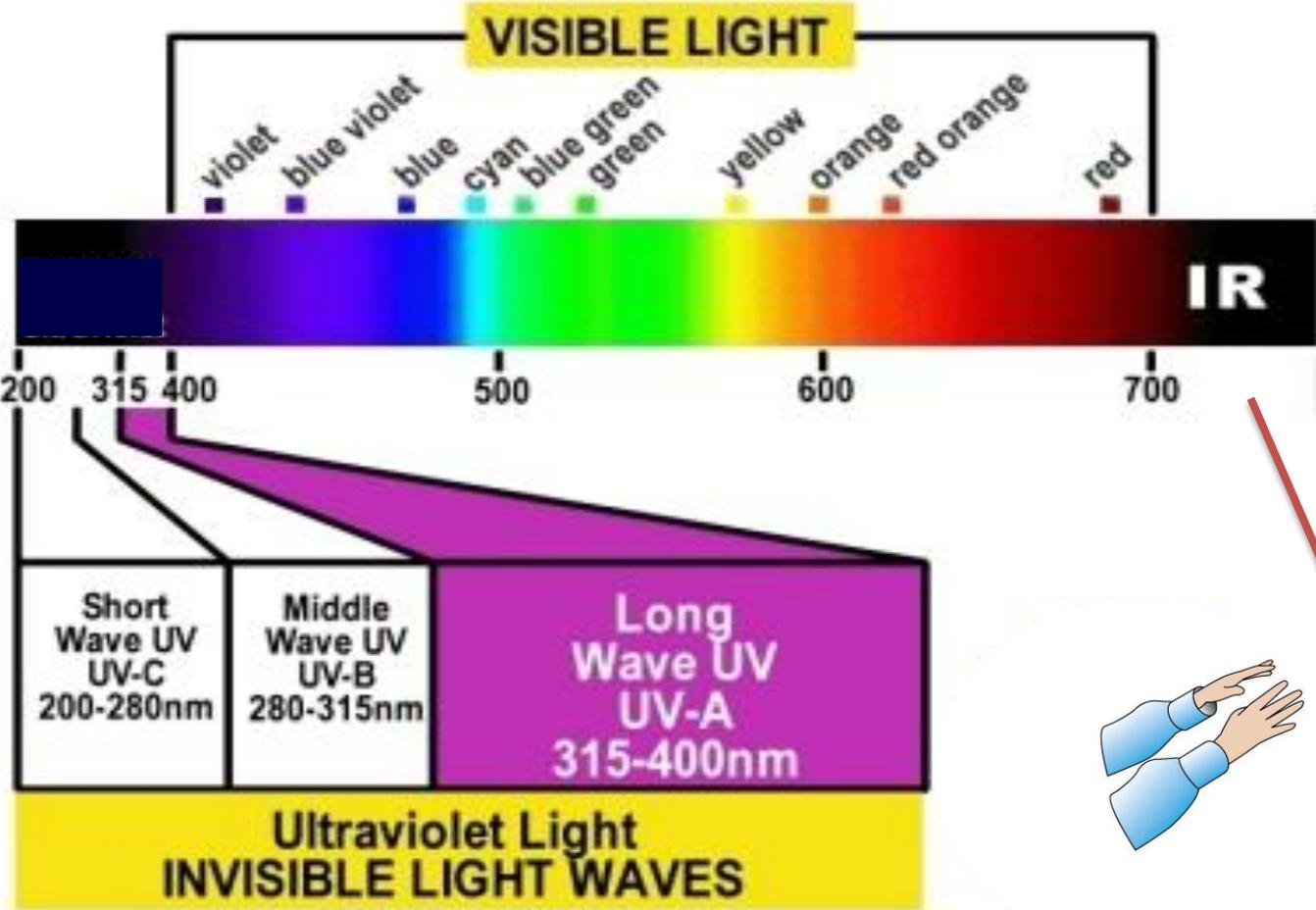
# Why only light could have dual nature?

De Broglie's concept: the wave–particle duality

All particles exhibit both wave and particle properties

Momentum of the electron:   $p = m_e v$



"After long reflection in solitude and meditation, I suddenly had the idea, during the year 1923, that the discovery made by Einstein in 1905 should be generalised by extending it to all material particles and notably to electrons."

Louis-Victor de Broglie
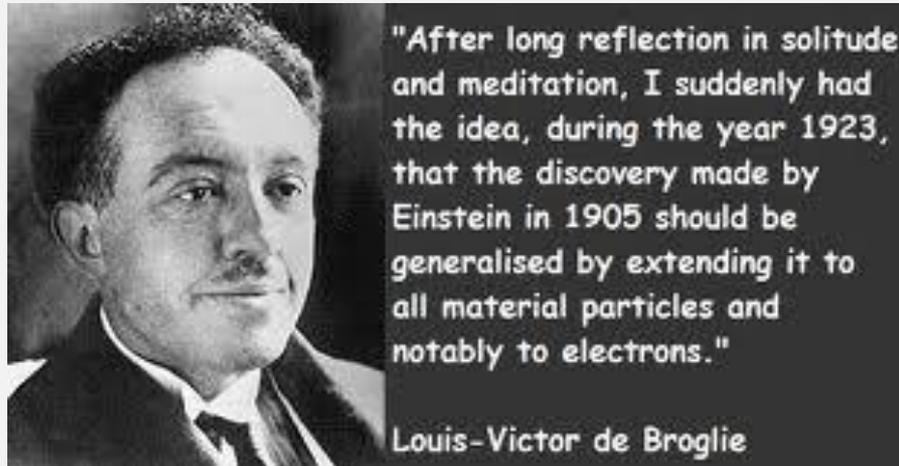
$$\lambda = h / p$$

Nobel prize in 1929

# Particles can behave as waves!
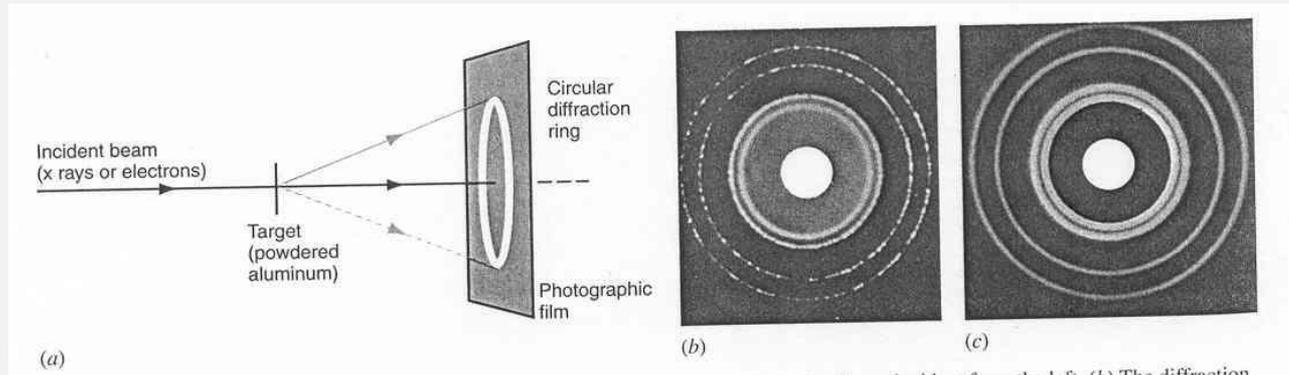


Electrons indeed behave exactly as if they were waves.



Clinton Joseph Davisson

George Paget Thomson

Nobel Prize in Physics 1937

*"for their experimental discovery of the diffraction of electrons by crystals"*

# Checklist

What is a radiation?
What are the parameters of waves?
What does the dual nature of light mean?
How can one prove the wave nature of light?
How can one prove the particle nature of light?
How can we give the energy of the photon?
What is the matter wave?


Measures and units
wavelength
frequency
energy
intensity

Related chapters in

*Damjanovich, Fidy, Szöllősi: Orvosi Biofizika*

II. 2. 1.

2.1.1
2.1.2
2.1.3
2.1.4
2.1.5
2.1.8