Light: wave and particle

Medical Biophysics I. 1 October, 2025.

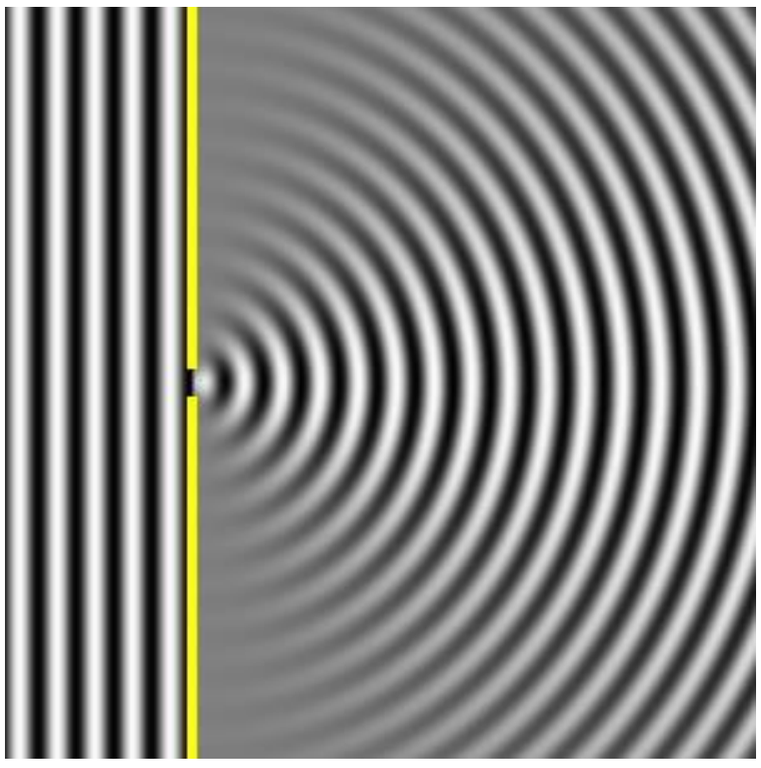
Miklós Kellermayer

Department of Biophysics and Radiation Biology

SEMMELWEIS
EGYETEM 1769

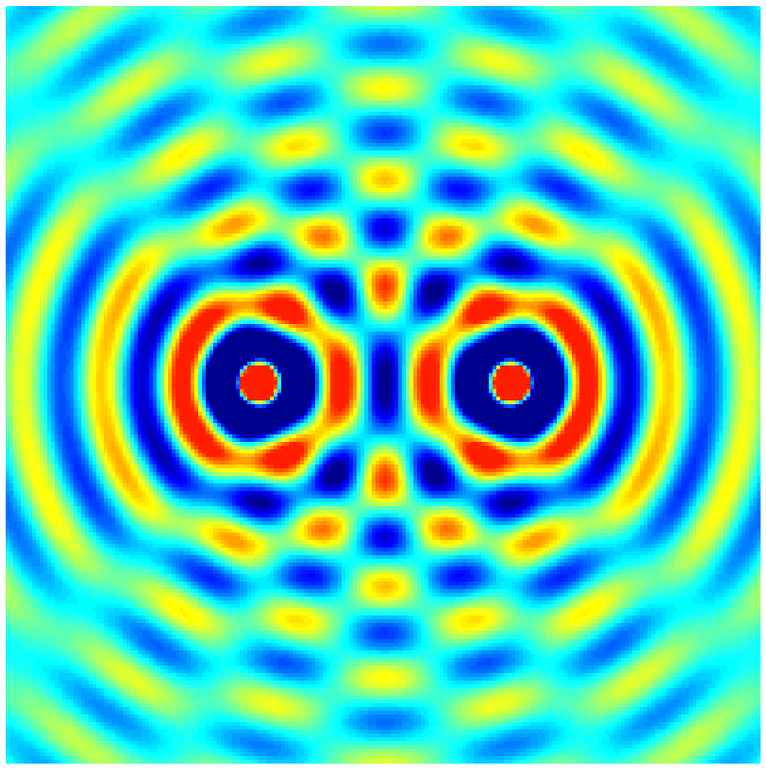
Light as wave: “wave phenomena” are displayed

Diffraction



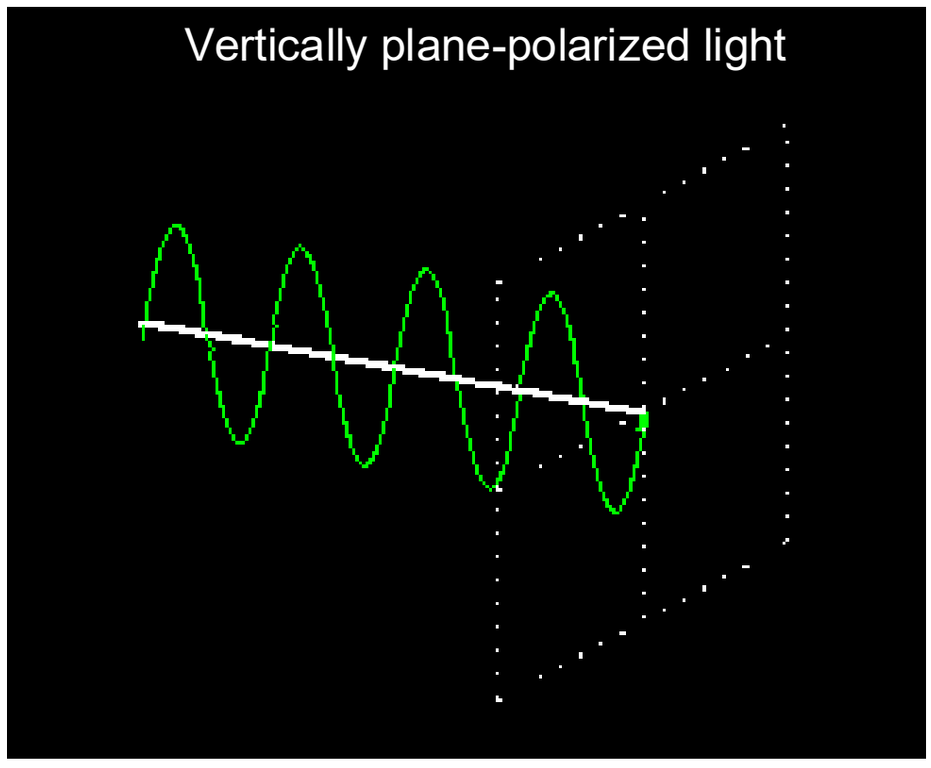
Light “bends” into unexpected areas

Interference



Spatial and temporal pattern of high- and low-amplitude regions

Polarization

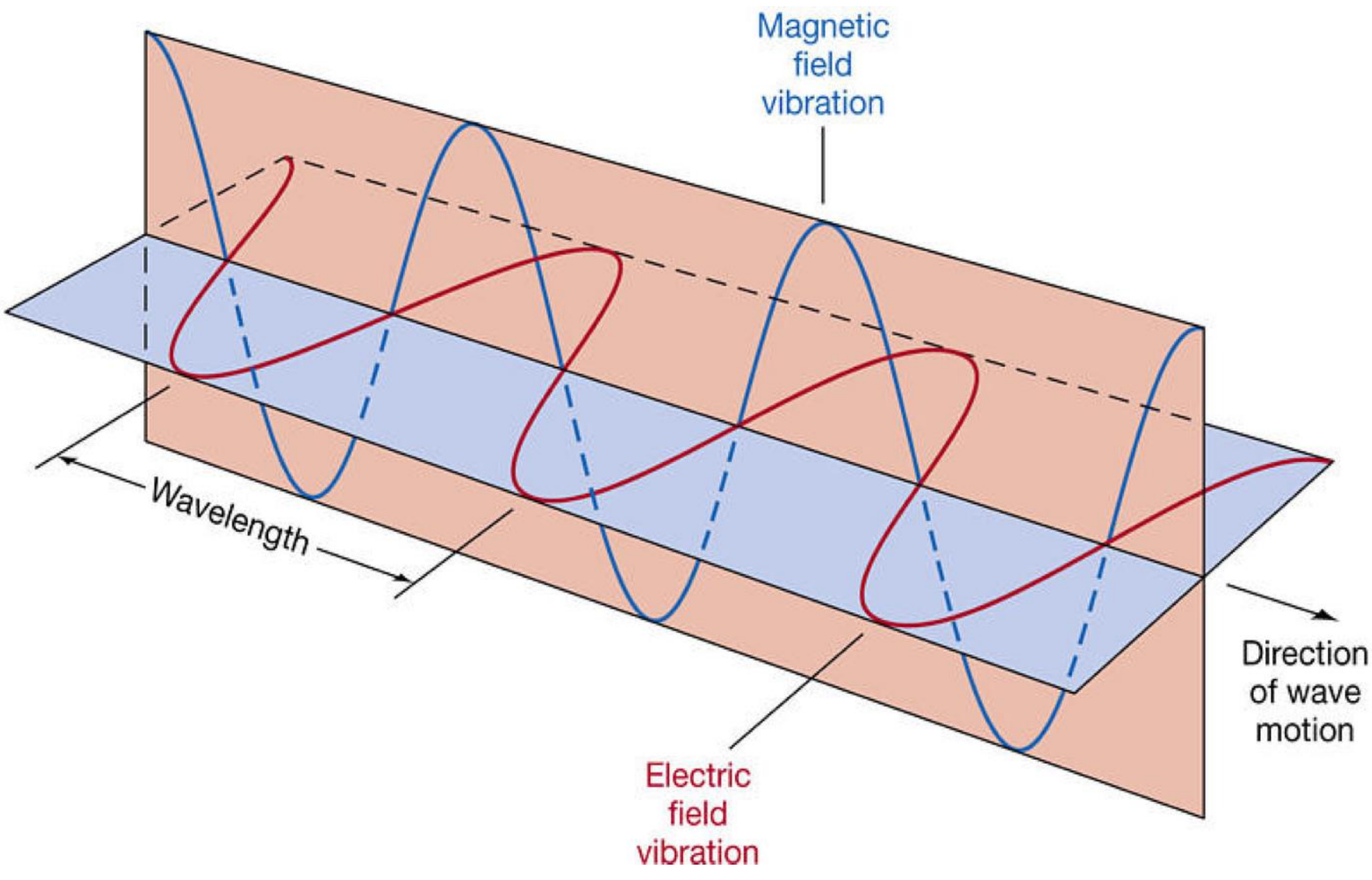


Oscillation occurs in a preferred direction

What kind of wave is light?

Electromagnetic wave

Electromagnetic disturbance propagating in space.
No elastic medium is required for its propagation.



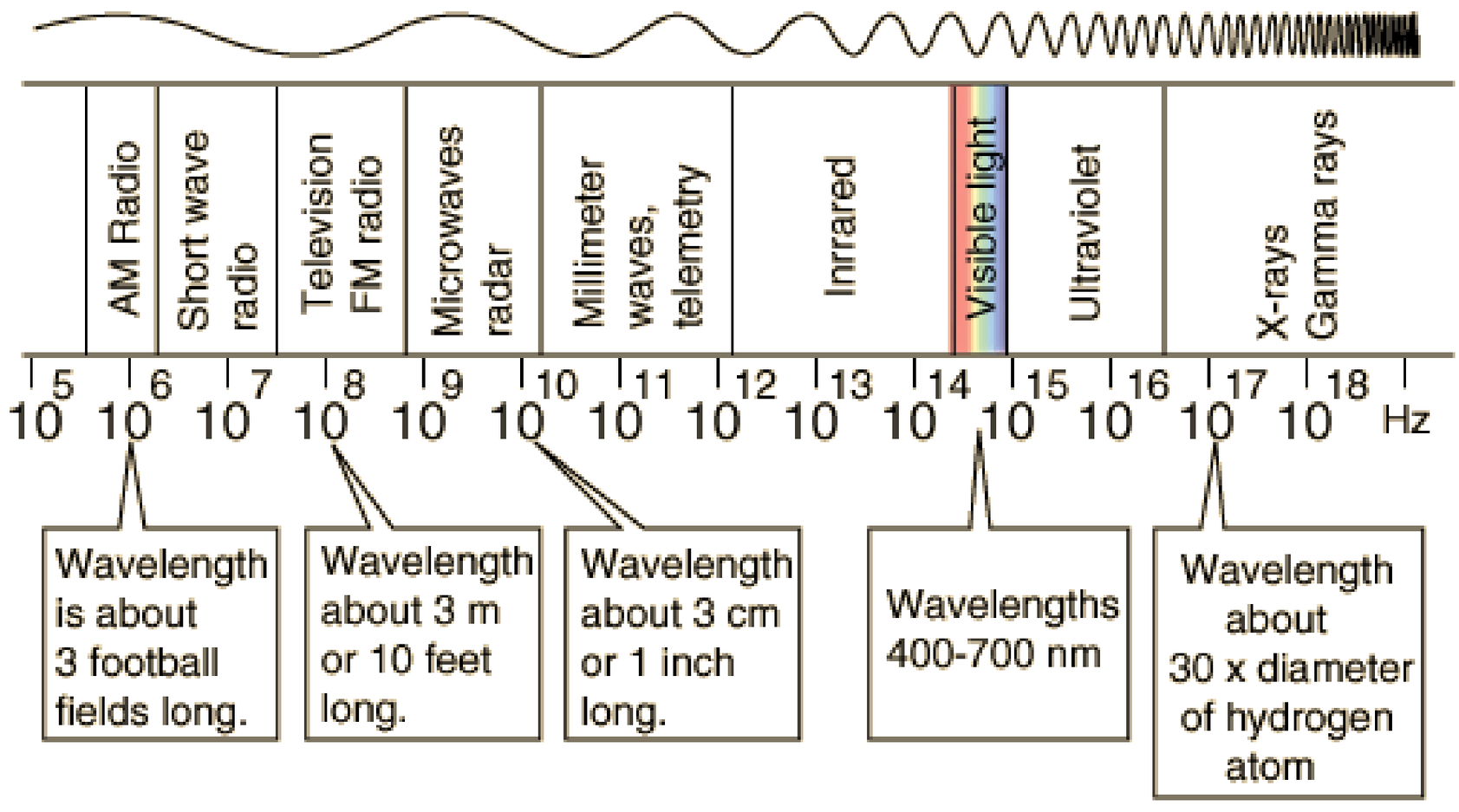
James Clerk Maxwell
(1831-1879)

Propagation velocity:

$$c = \lambda f$$

c_{vacuum}=2.99792458 x 10^8 ms^{-1}

The electromagnetic spectrum



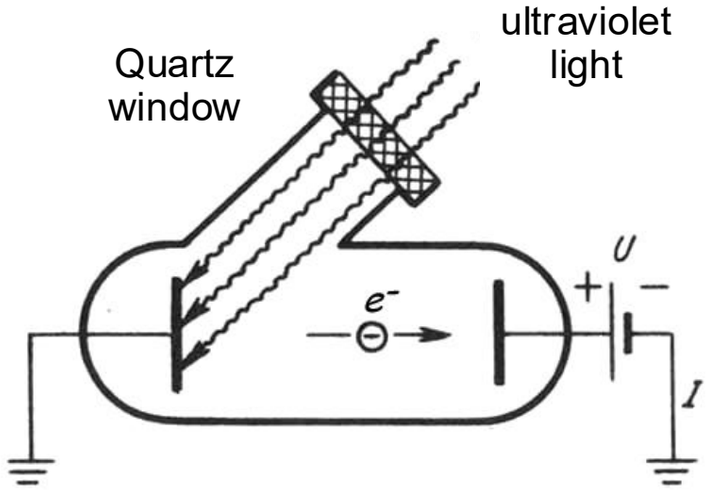
N.B.: 1) *"spectrum"* = function (intensity of EM radiation as a function of energy)
2) *"electromagnetic spectrum"* = types of radiation as a function of energy

What happens if an object is illuminated with light?

Photoelectric effect: The experiment

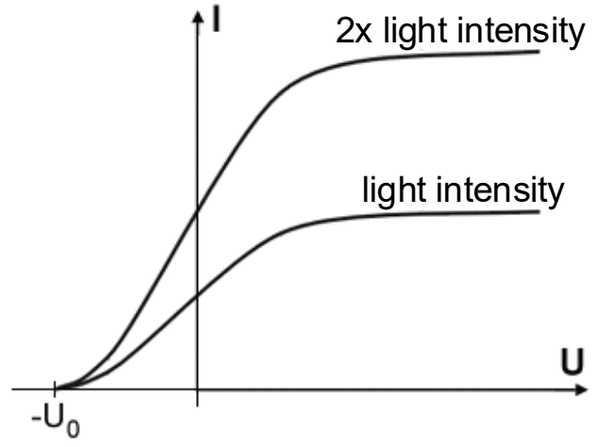
Hallwachs-effect:
Upon UV illumination, negative charges leave the metal surface

Wilhelm Hallwachs
(1859-1922)



Measurements, observations

Philipp Lenard/
Lénárd Fülöp
(1862-1947)



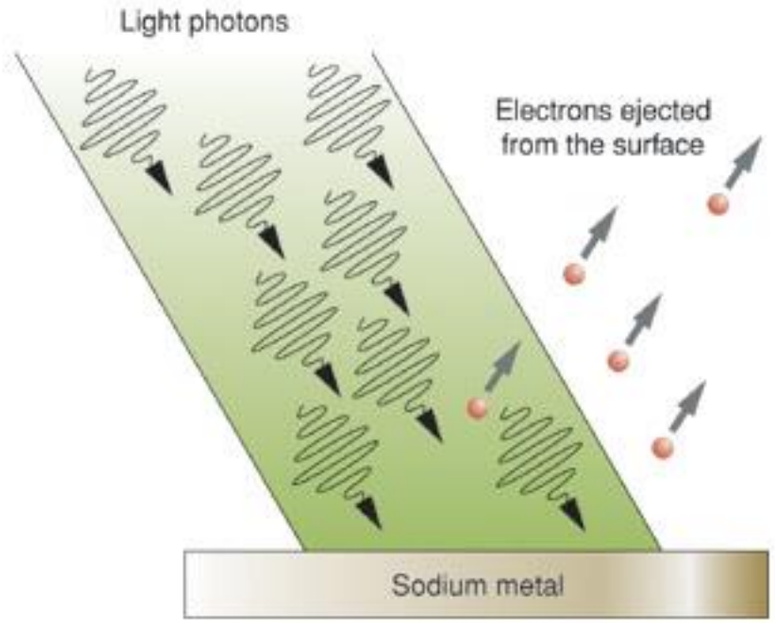
- Electron emission: instantaneous upon illumination
- Electron emission only in high-frequency (e.g., blue, UV) light
- No electron emission in low-frequency (e.g., red) light
- Photoelectric current: depends on light intensity
- Photoelectric current: does NOT depend on light color

Photoelectric effect

The explanation

1905: *"Annus mirabilis"*
- photoelectric effect
- diffusion
- special relativity

Albert Einstein
(1879-1955)



$$E_{kin} = hf - W_{ex}$$

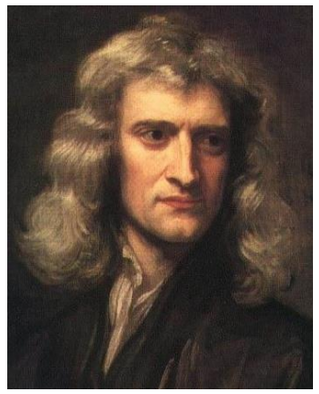
E_{kin} = kinetic energy of escaped electron
h = Planck's constant ($6.62 \cdot 10^{-34}$ Js)
f = frequency of light
hf = light energy = light quantum, ***"photon"***
W_{ex} = work necessary for the escape of the electron from the atom

***Photon**:*
- travels with the speed of light (c) in vacuum
- does not exist at rest
- has momentum
- has no rest mass

Light is *at once* wave and particle!

Grote Kerk church,
The Hague

Christiaan Huygens
(1629-1695)



Sir Isaac Newton
(1643-1727)

Westminster abbey

Wave

Particle

During propagation

Manifestations:
- Diffraction
- Interference
- Polarization

During interactions

Manifestations:
- Photoelectric effect
- Refraction
- Excitation, Ionization
- Compton scatter
- Pair production

If light can be a particle, then can a particle be a wave?

Matter waves: The electron as a wave

Einstein:
mass-energy equivalence

$$E = mc^2$$

Planck:
law of radiation

$$E = hf$$

Maxwell:
speed of light

$$c = \lambda f$$

Louis-Victor-Pierre-Raymond, 7th duc de Broglie (1892-1987)

$$mc^2 = h \cdot \frac{c}{\lambda}$$

Momentum of particle (or photon!):

$$P = \frac{h}{\lambda}$$

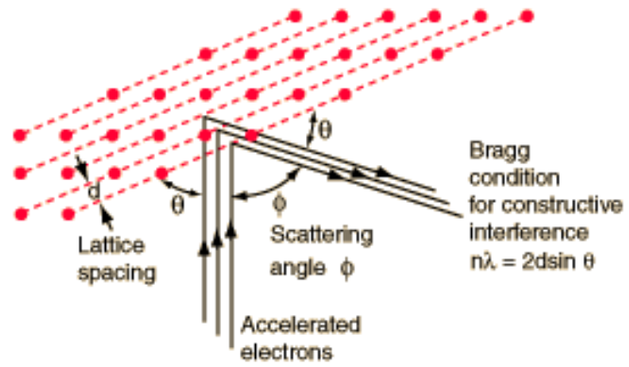
Wavelength of particle ("de Broglie wavelength"):

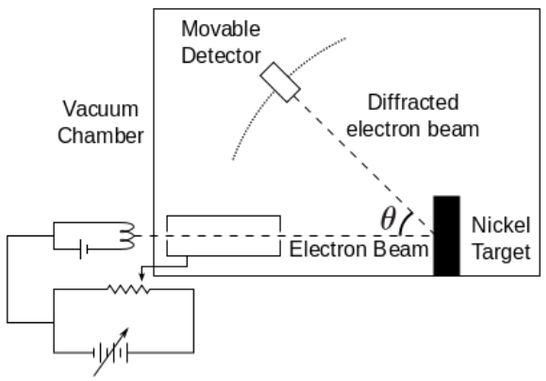
$$\lambda = \frac{h}{mv}$$

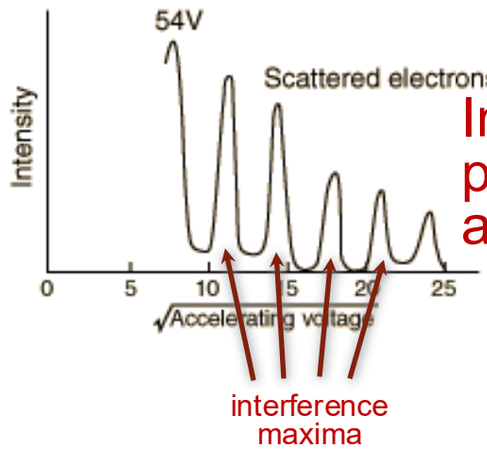
Davisson-Germer experiment

Clinton Joseph Davisson (1881 –1958)

Lester Halbert Germer (1896–1971)



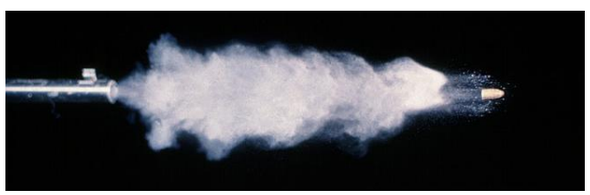




Interference pattern appears!

The electron is thus a ***wave***!

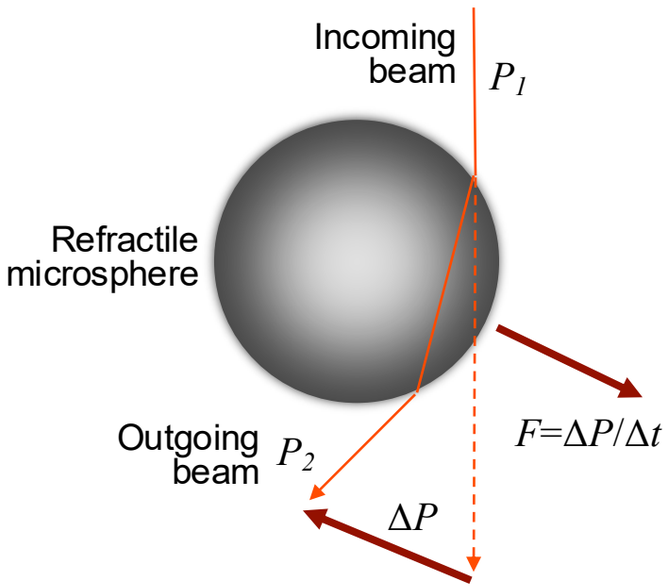
Why don't we experience the wave nature of macroscopic particles (e.g., bullet)?



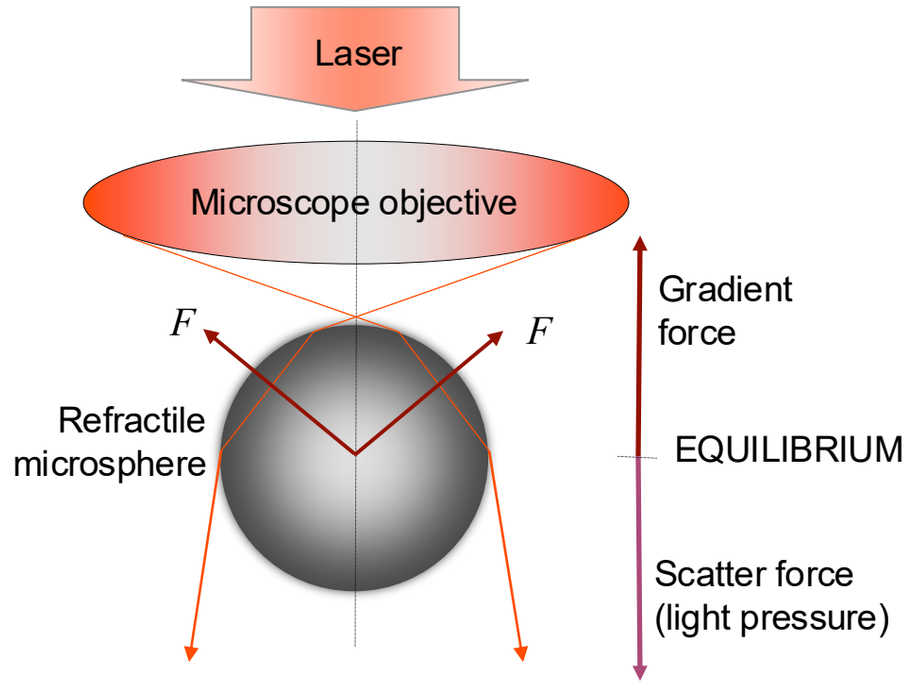
Bullet: for m=1 g and v=1 kms^{-1}, $\lambda = 6 \times 10^{-34}$ m!!

We can now better understand optical tweezers (applications I)

Refraction is accompanied by photonic momentum change (ΔP):

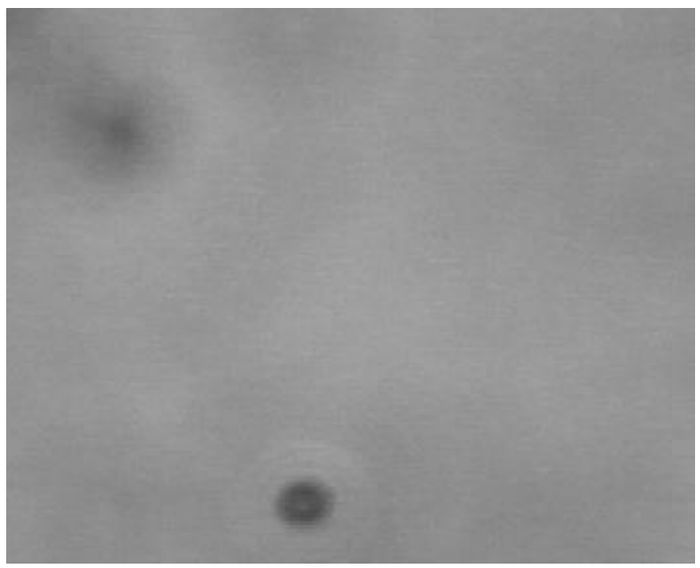


*Refractile particles may be **captured** with photonic forces:*



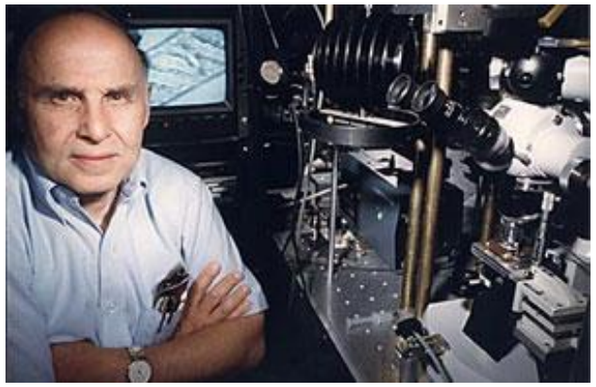
*In the **optical trap** a momentum change occurs between the photons and the trapped particle:*

N.B.: the terms optical tweezers, optical trap, laser tweezers, laser trap are synonymous



3 μm latex (polystyrene) microspheres in the optical trap

Milestones of optical tweezers



Arthur Ashkin (Nobel-prize 2018)

1970: Arthur Ashkin: optical tweezers

1991: J.Spudich, T.Yanagida, J.Molloy, single-molecule mechanics

1994: T.Yanagida, single ATP turnover on myosin

1994: K.Svoboda, S. Block, single kinesin mechanics

J.Spudich

J.Finer

1996: C.Bustamante, D.Bensimon, DNA molecule stretch

C.Bustamante

1997: S. Chu, W.D. Phillips, C. Cohen-Tanoudji (Nobel-prize): atom cooling with laser

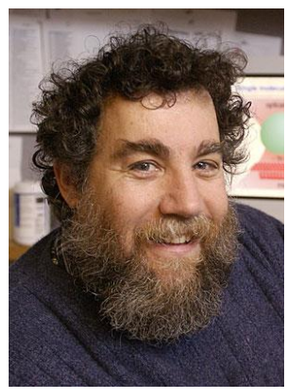
1997: M.Kellermayer, M.Rief, L.Tskhovrebova, protein molecule stretch

2000: Galajda P., Ormos O., microfabrication with optical tweezers, optically driven microscopic engines

S. Chu, W.D. Phillips, C. Cohen-Tanoudji, Nobel-prize 1997

2001: J.Liphardt, C.Bustamante, RNA molecule stretch

2002: Holographic optical tweezers (spatial light modulator, SLM)

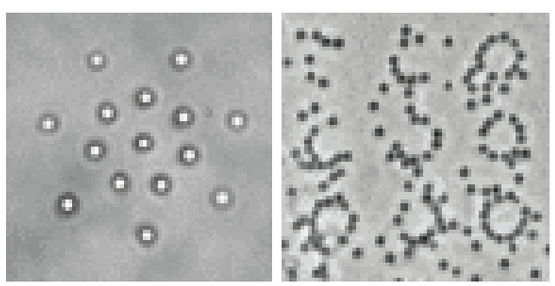


S. Block

2008: Bustamante, Tinoco: ribosome mechanics

J.Molloy

Microfabricated propeller



Simultaneous manipulation of multiple particles with holographic optical tweezers

The optical trap is 3D handle without a shaft:

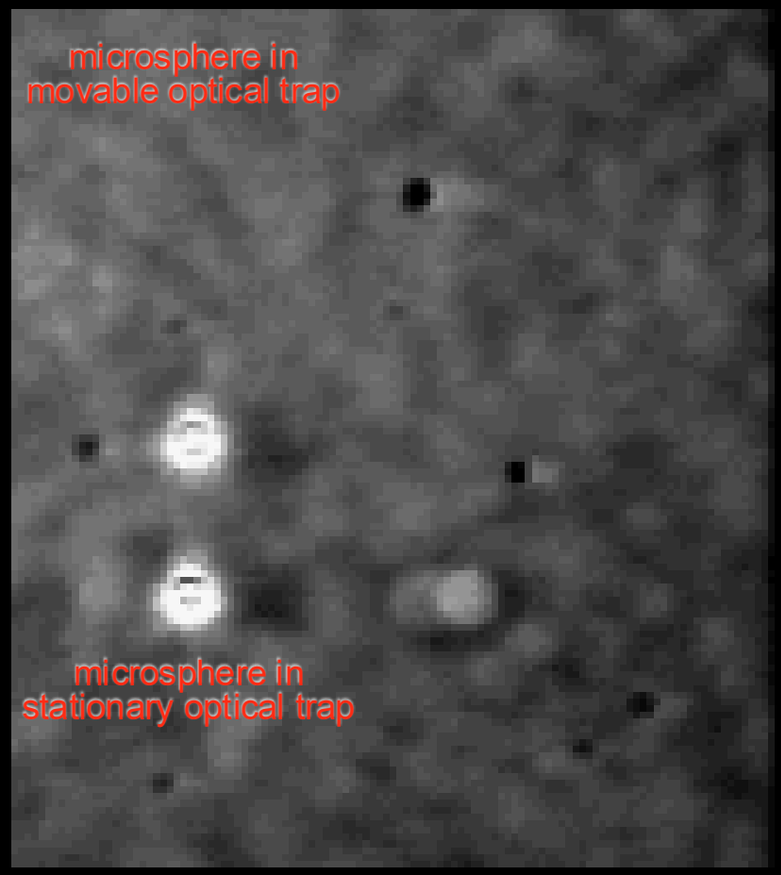
A knot can be tied on a molecular filament without releasing its ends

Actin filament

Fluorescence image

DNA

Phase contrast image

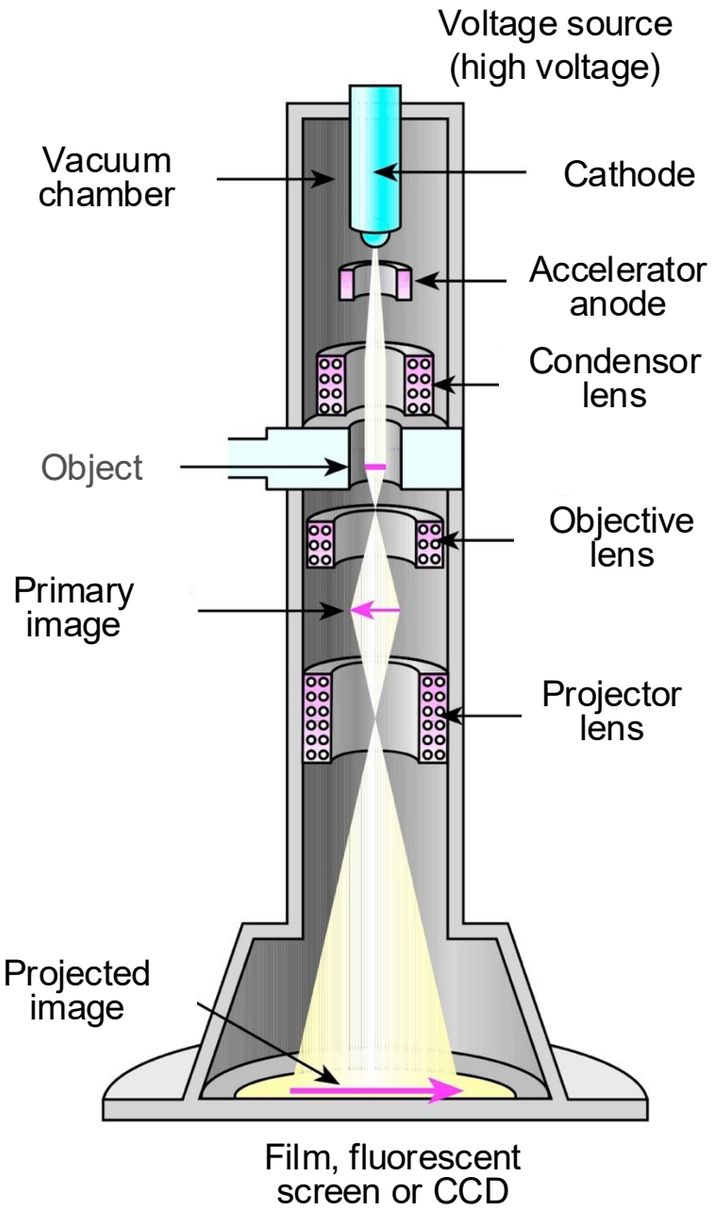


Fluorescence image

Arai et al. Nature 399, 446, 1999.

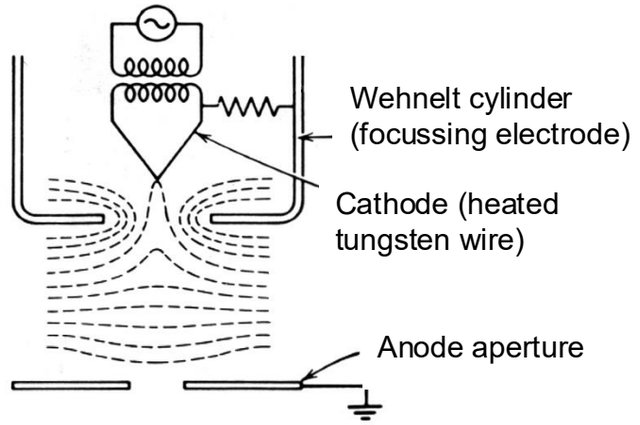
Applications II.

Matter waves: Electron microscope

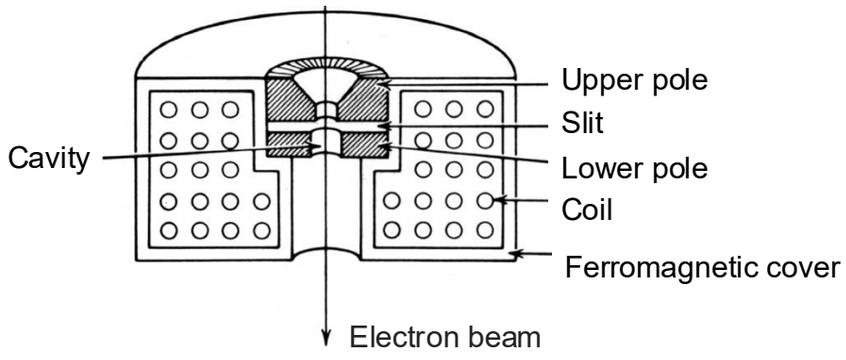


Transmission electron microscope (TEM)

Ray source:
electron
gun



Focusing:
diverting the electron
with magnetic lens



$$F = eBV_e \sin\alpha$$

F=force on the electron; e=electron's charge;
B=magnetic induction; V_e=electron's speed;
α=angle between the optical axis and the direction of the magnetic field

Resolution: $$d = \frac{\lambda}{\alpha}$$

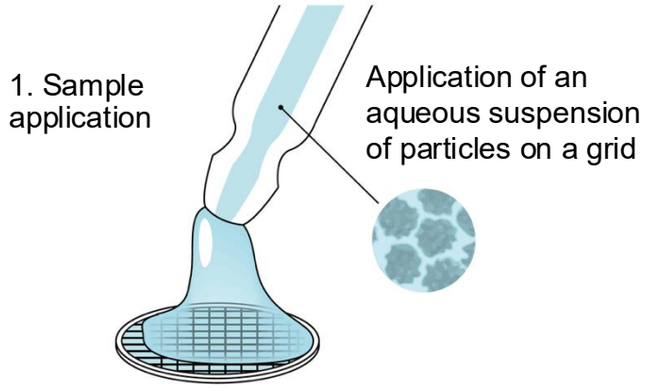
d=smallest resolved distance
λ="de Broglie" wavelength
α=angle between the optical axis and the direction of the magnetic field

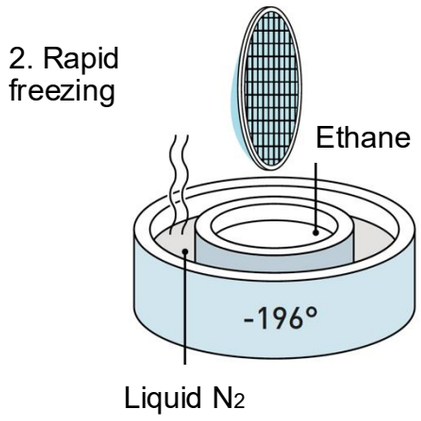
Based on the de Broglie wavelength the theoretical resolution is: d~ 0,005 nm (=5 pm).

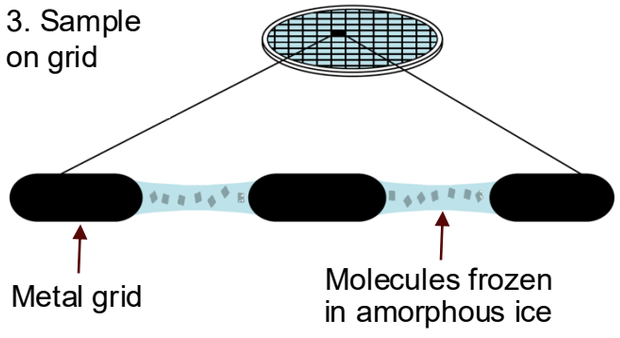
Cryo-electron microscopy (Nobel-prize 2017)

Jacques Dubochet, Joachim Frank, Richard Henderson

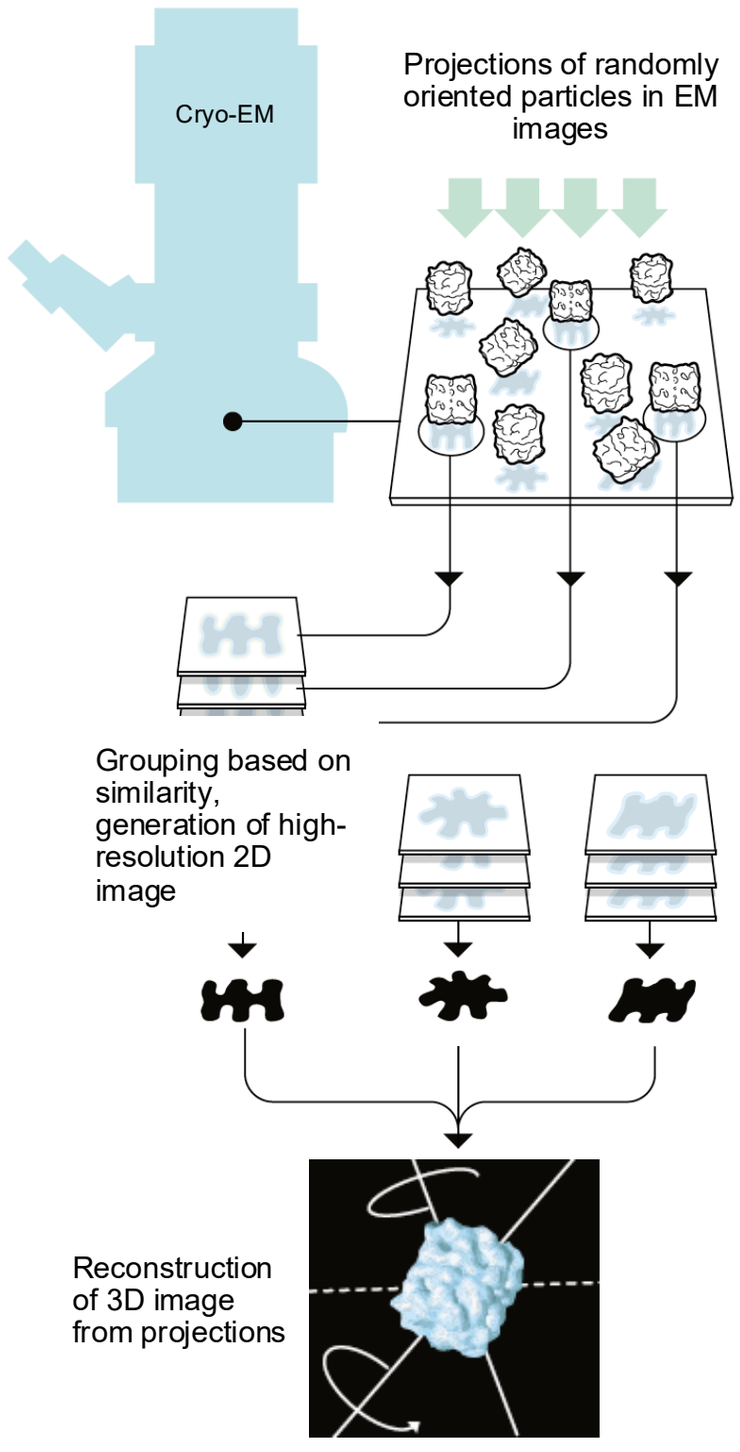
Sample preparation

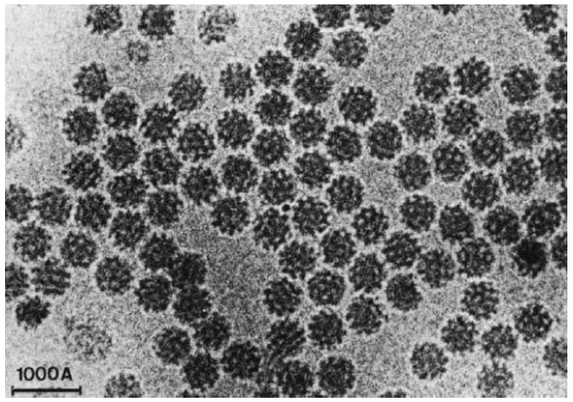




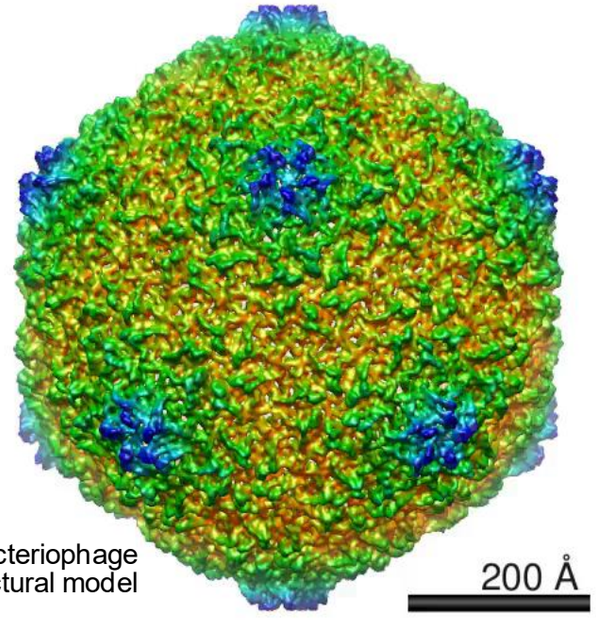


Cryo-EM imaging and structure reconstruction

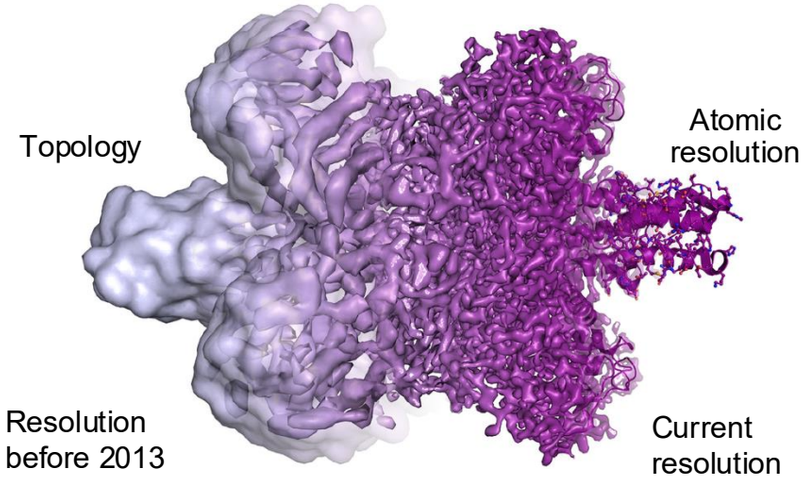




First cryo-EM image about viruses (Dubochet, 1984)



T7 bacteriophage structural model



Applications III.

Photoelectric effect: photodetection, photocell, CCD, etc, etc.....

Light detection, image recording, CCD camera

CCD chip in mobile-phone camera

Harvesting and transformation of light energy

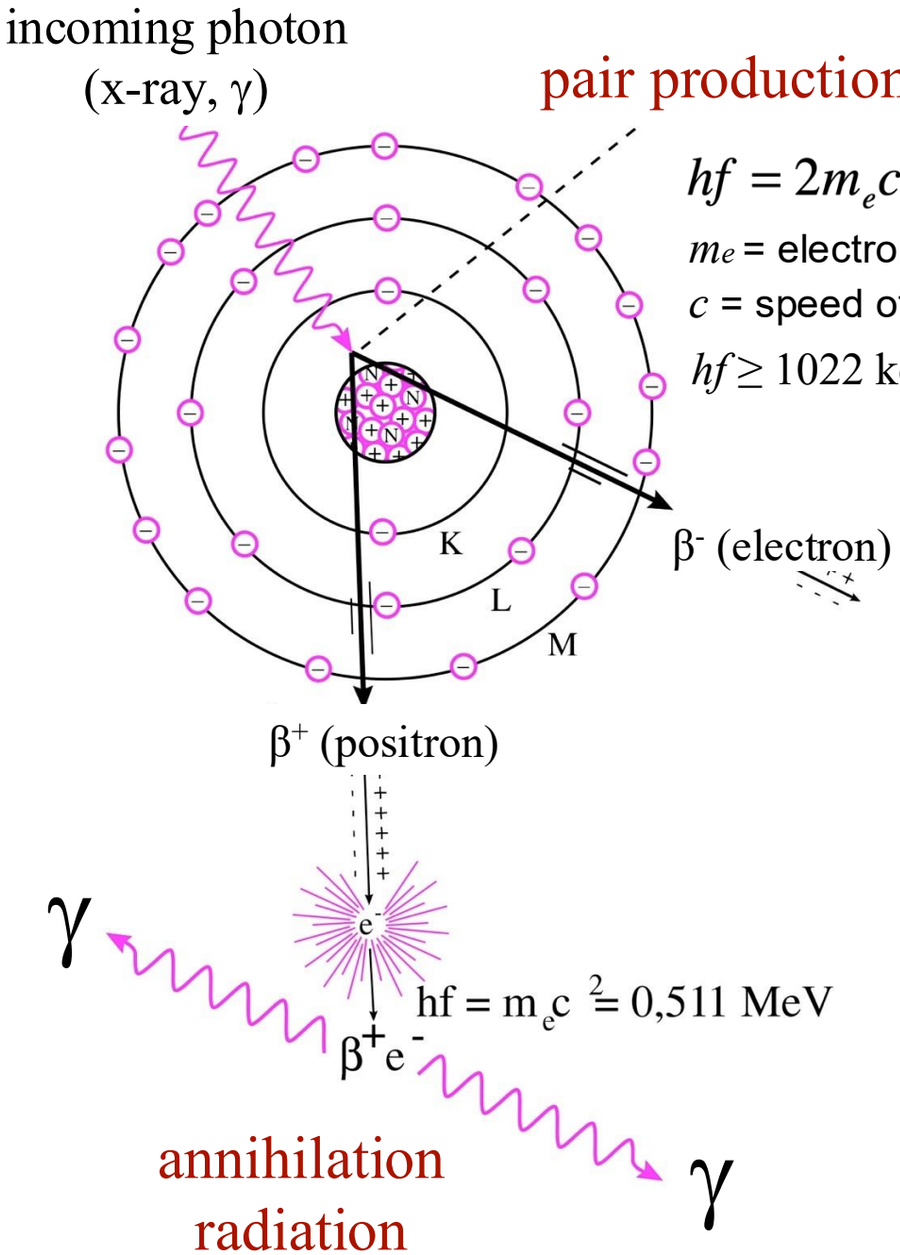
Solar panels

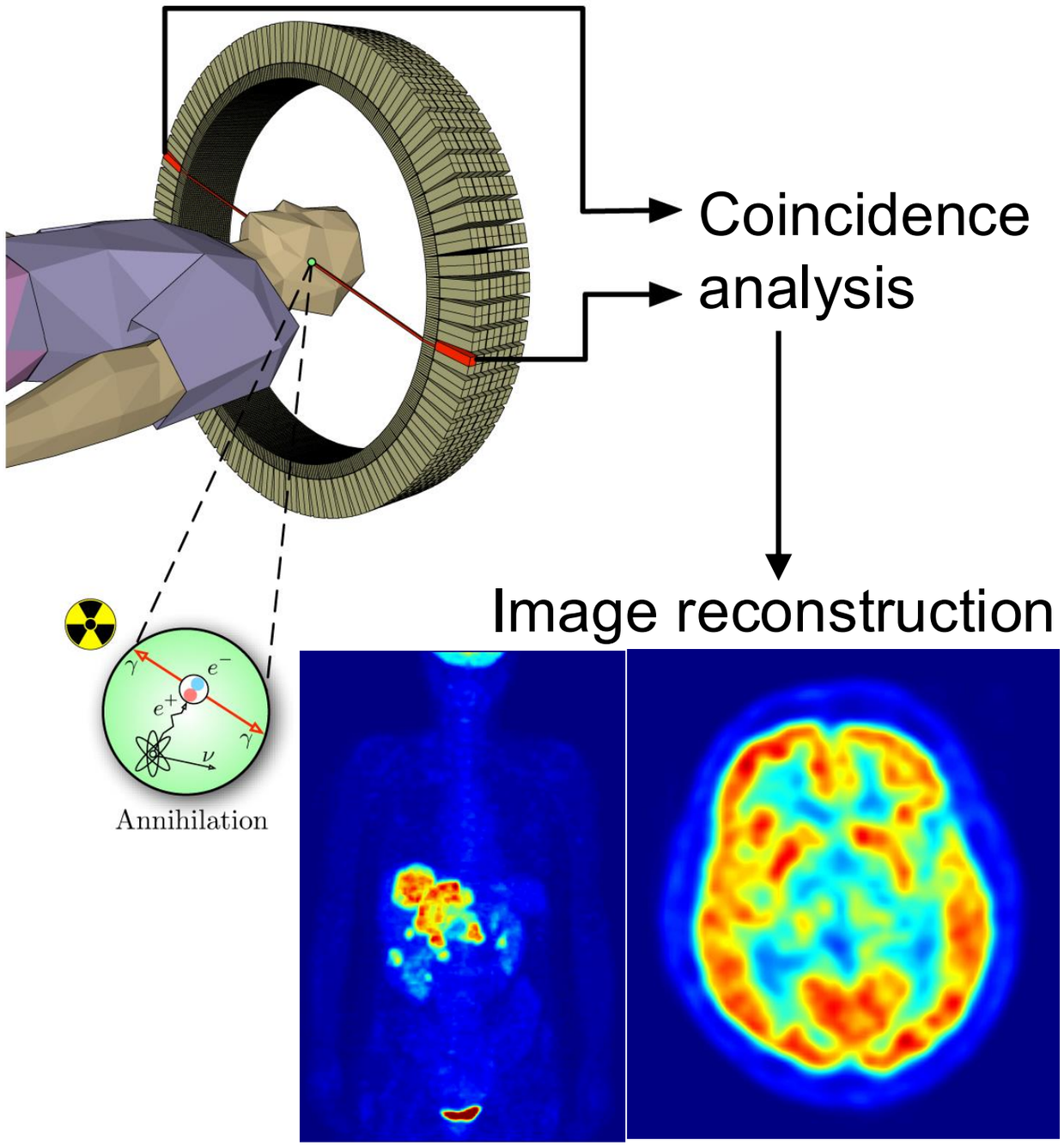
Light amplification, intensification

Silence of the lambs night vision scene: Buffalo Bill wearing a night-vision goggle - a microchannel-plate intensifier

Applications IV.

Pair production – annihilation radiation: Positron Emission Tomograhy (PET)





Feedback

https://feedback.semmelweis.hu/feedback/index.php?feedback-qr=MX6W9M8S0FZ3T394