

LIGHT: WAVE AND PARTICLE

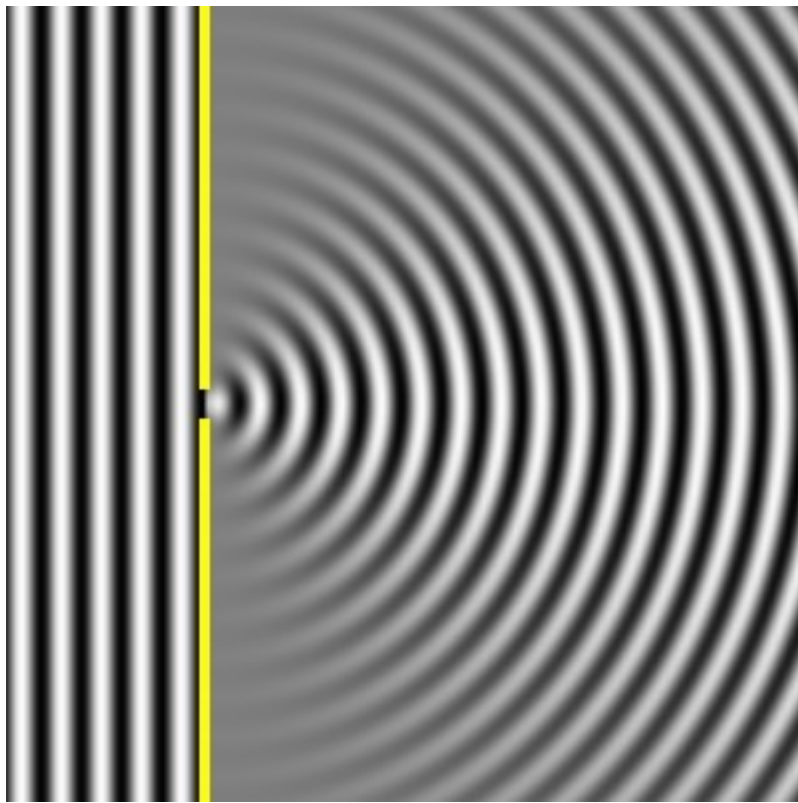
MIKLÓS KELLERMAYER

Biophysics of light

- Light as wave. Wave phenomena.
- Electromagnetic waves, spectrum.
- Light as particle. Photoelectric effect.
- Dual nature of light.
- Matter waves. Electron as wave.
- Applications

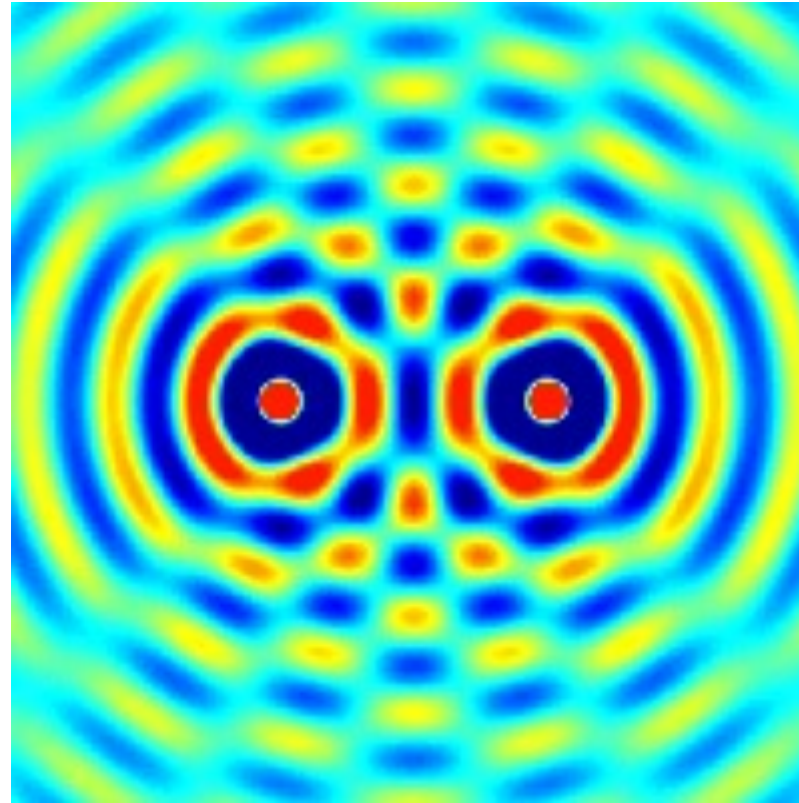
Light as wave: “wave phenomena” are displayed

Diffraction



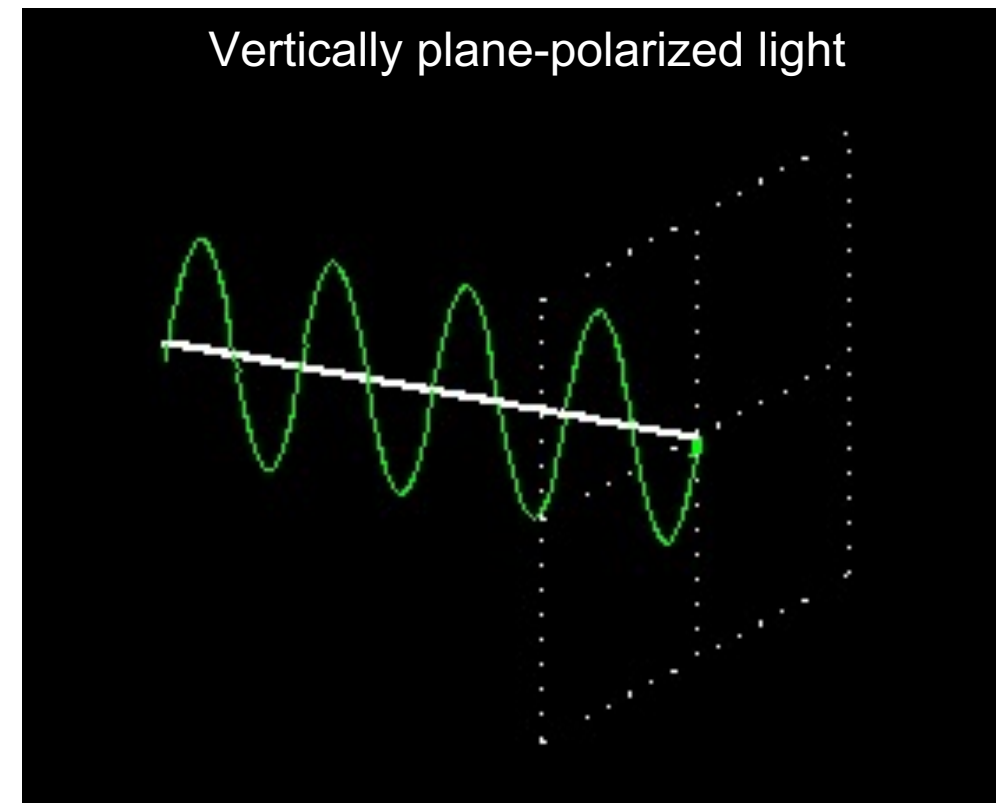
Light “bends” into unexpected areas

Interference



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

Polarization

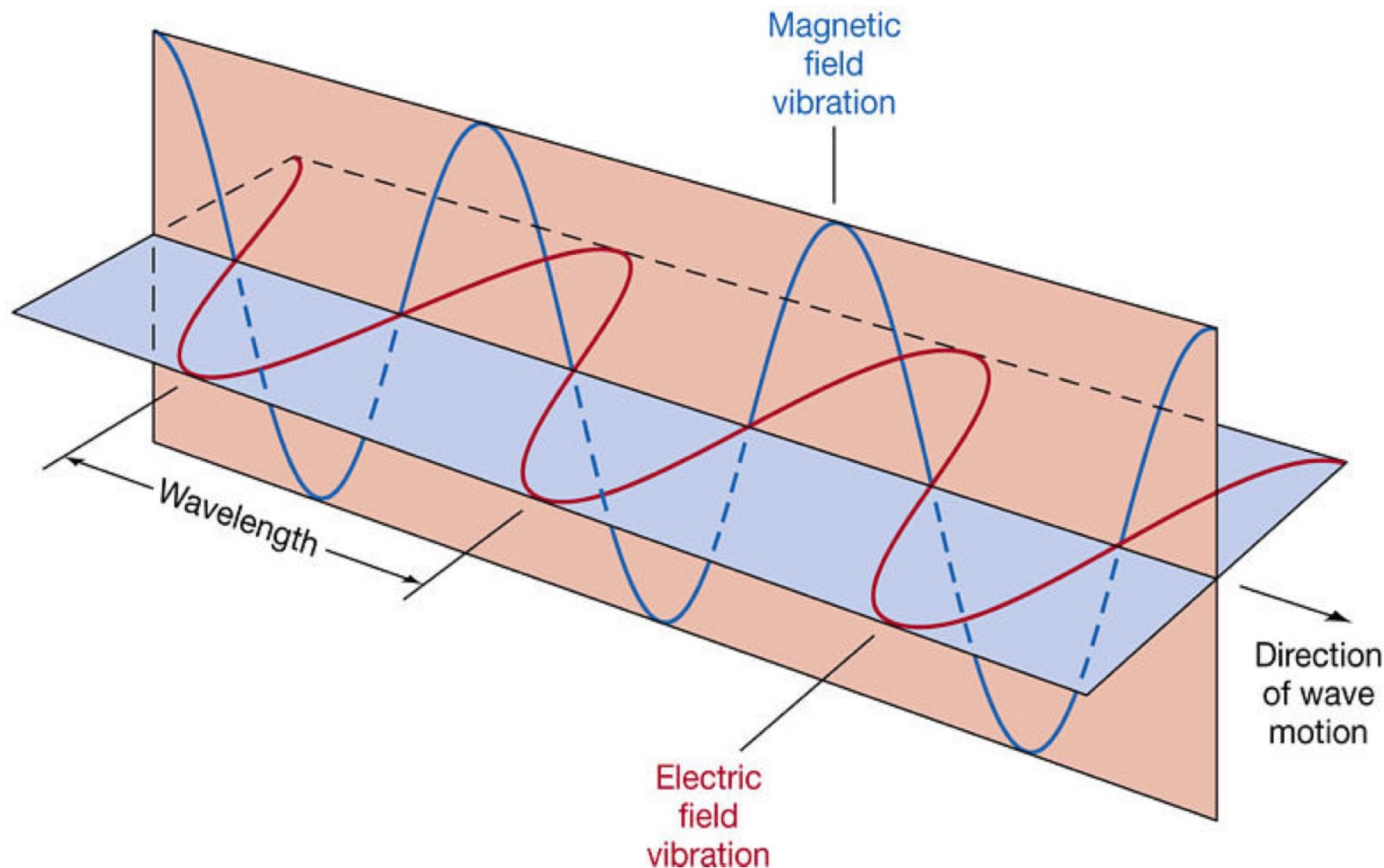


Oscillation occurs in a preferred direction

What kind of wave is light?

Electromagnetic wave

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



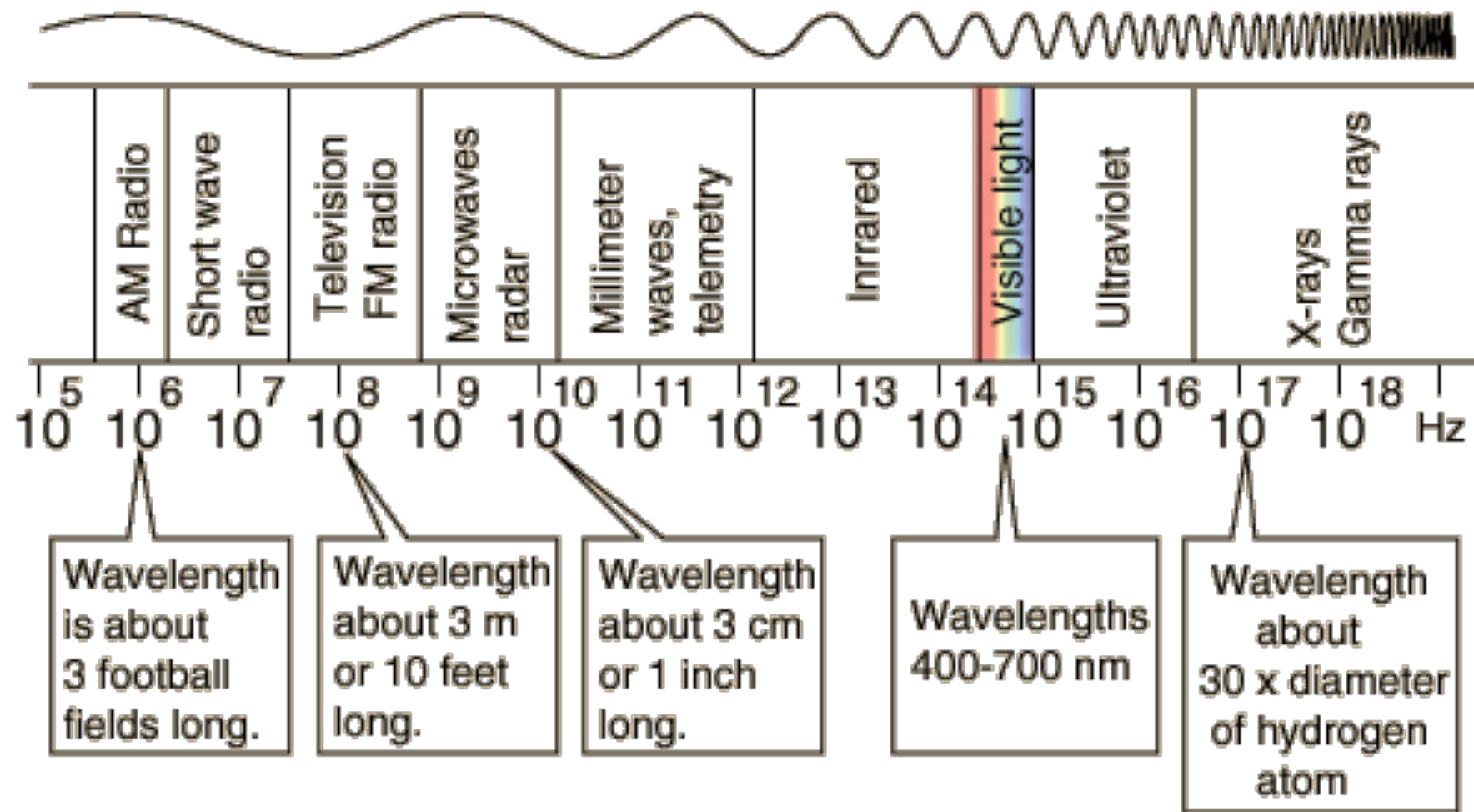
James Clerk Maxwell
(1831-1879)

Propagation velocity:

$$c = \lambda f$$

$$c_{\text{vacuum}} = 2.99792458 \times 10^8 \text{ ms}^{-1}$$

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

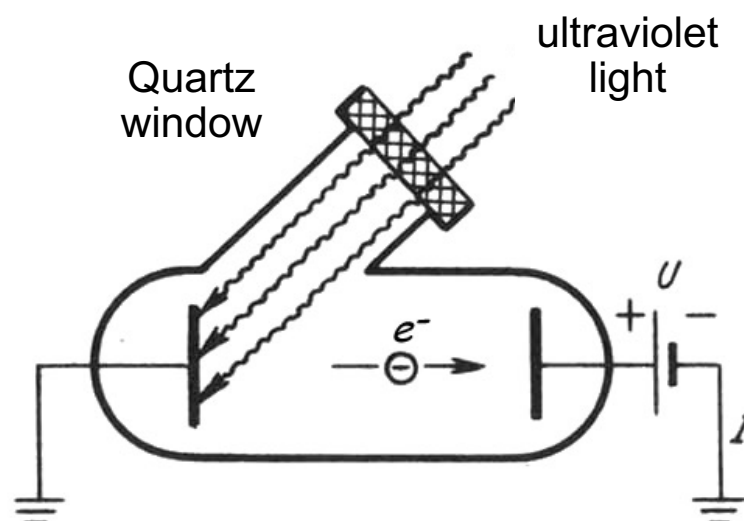
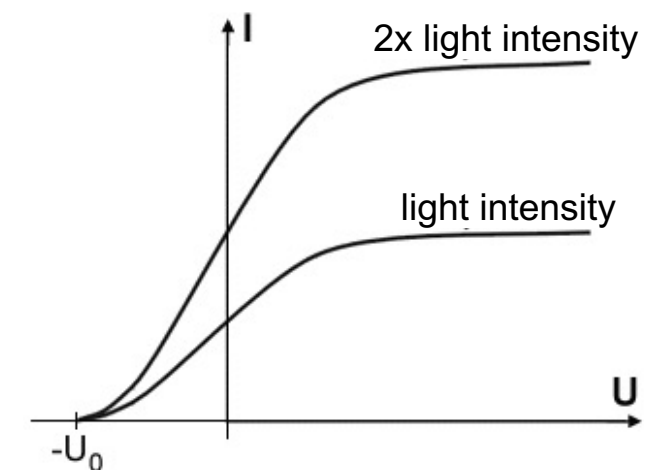


Wilhelm Hallwachs
(1859-1922)

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

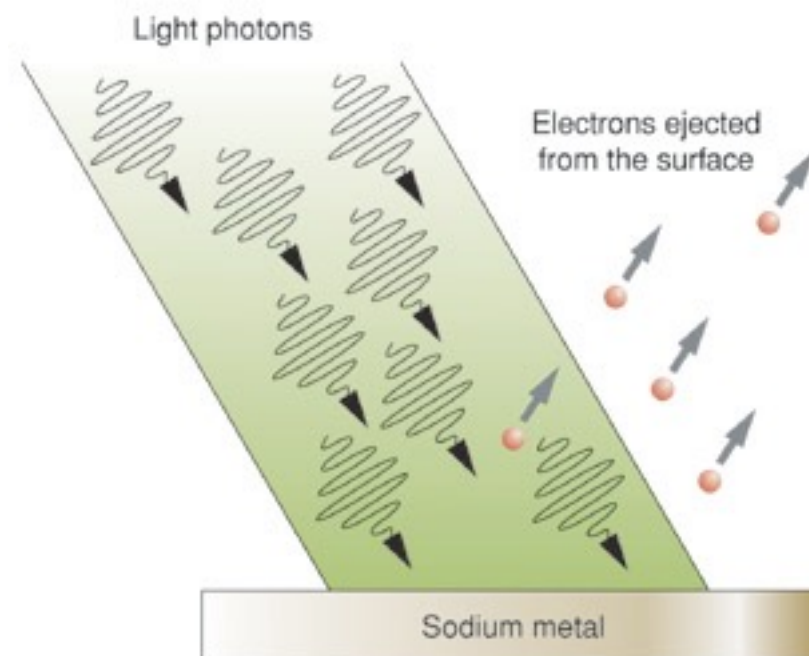
The explanation

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

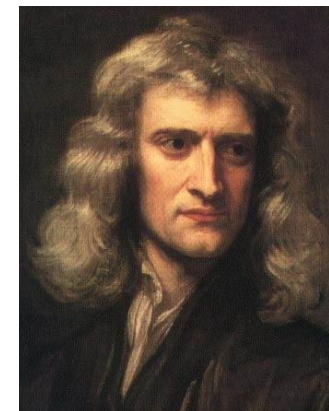
Light is *at once* wave and particle!



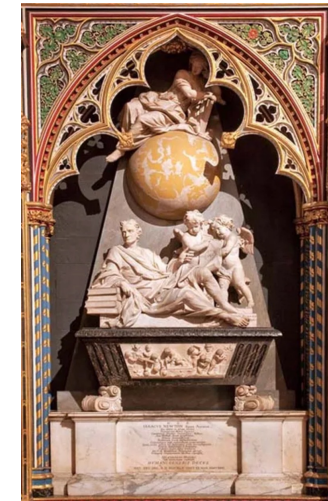
Grote Kerk church,
The Hague



Christiaan Huygens
(1629-1695)



Sir Isaac Newton
(1643-1727)



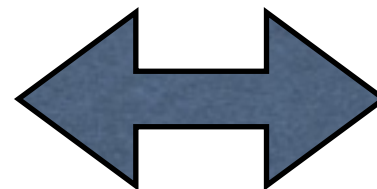
Westminster abbey

Wave

During propagation

Manifestations:

- Diffraction
- Interference
- Polarization



Particle

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!):

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

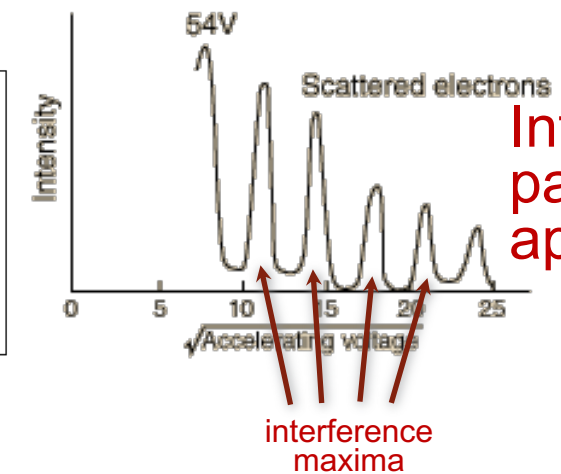
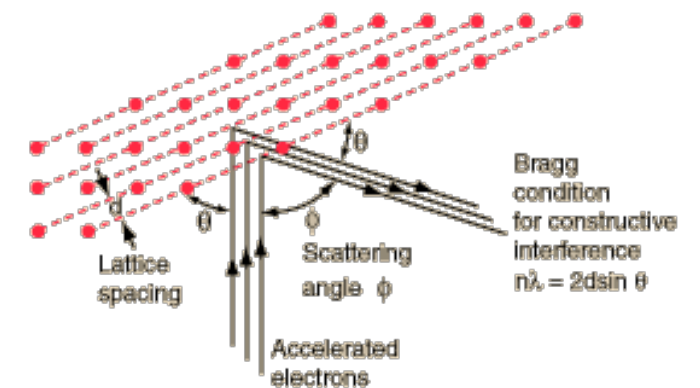
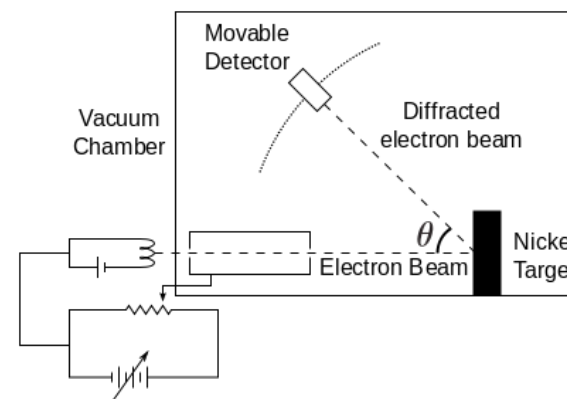
Wavelength of particle
("de Broglie wavelength"):

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

Davisson-Germer experiment



Clinton Joseph Davisson (1881-1958) Lester Halbert Germer (1896-1971)



Interference pattern appears!

The electron is thus a **wave**!

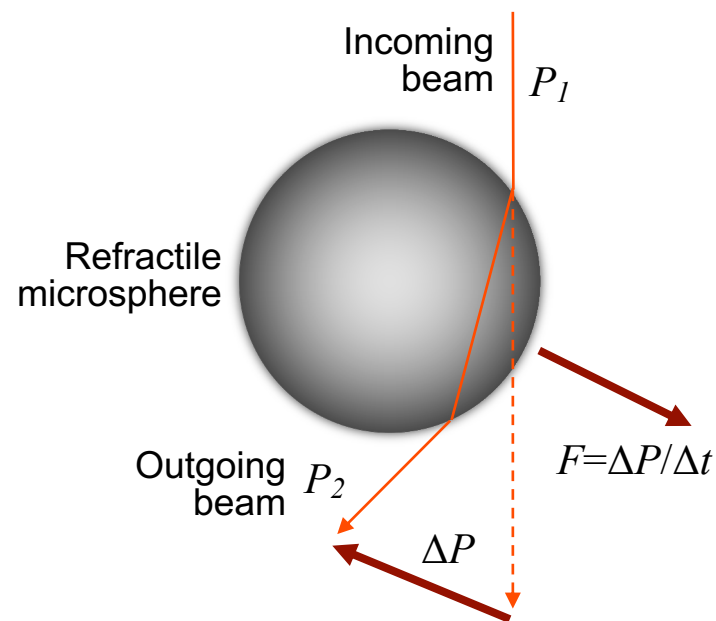
Why don't we experience the wave nature of macroscopic particles (e.g., bullet)?



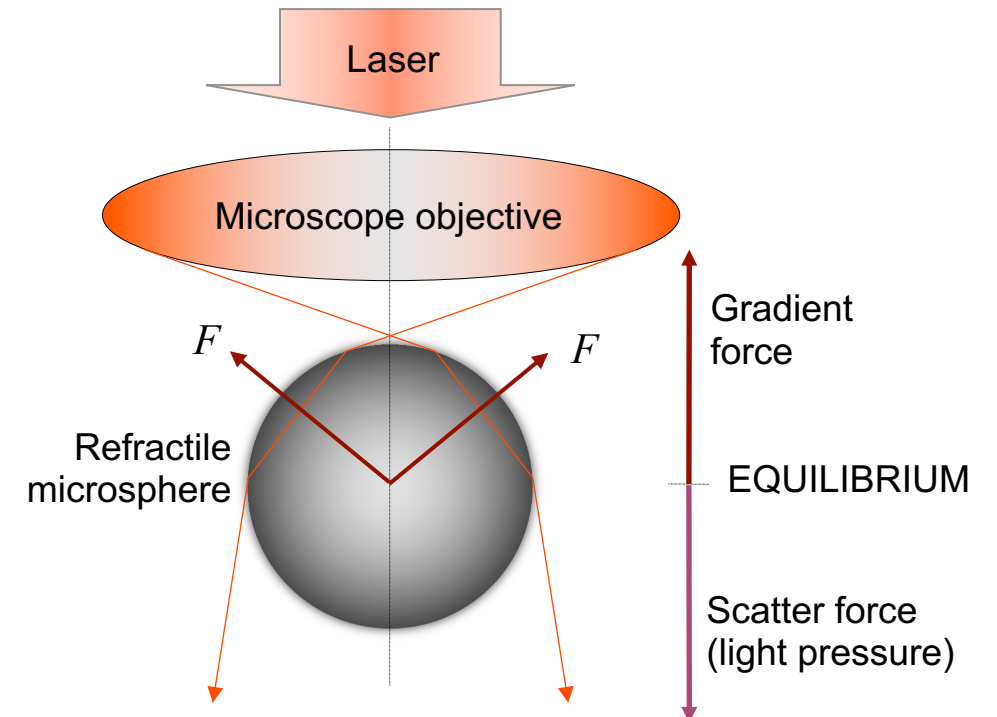
Bullet: for $m=1$ g and $v=1$ kms⁻¹,
 $\lambda = 6 \times 10^{-34}$ m!!

We can now better understand optical tweezers (applications I)

Refraction is accompanied by photonic momentum change (ΔP):

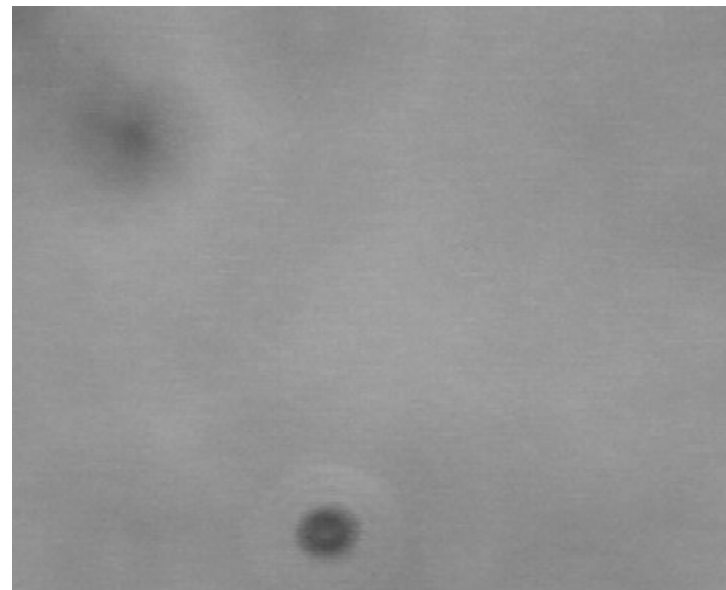


*Refractile particles may be **captured** with photonic forces:*



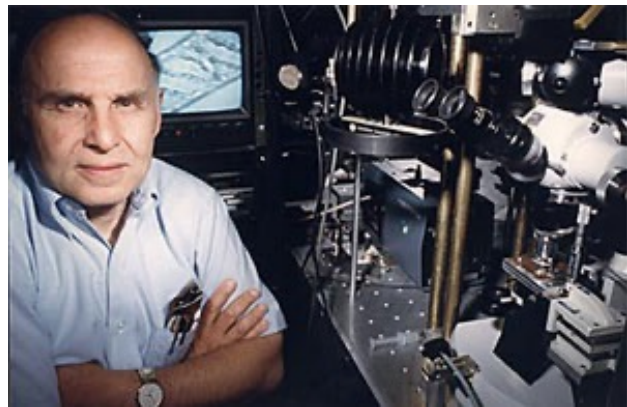
*In the **optical trap** a momentum change occurs between the photons and the trapped particle:*

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

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

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

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

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

2008: Bustamante, Tinoco: ribosome mechanics



J.Spudich



J.Finer



C.Bustamante



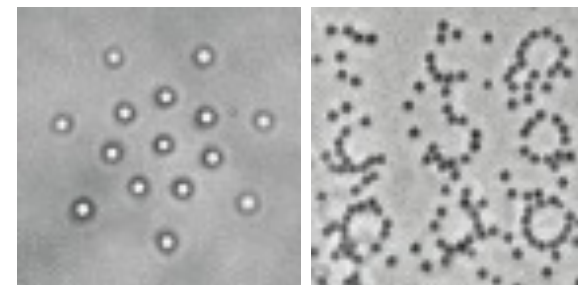
S. Chu, W.D. Phillips, C. Cohen-Tanoudji, Nobel-prize 1997



J.Molloy



Microfabricated propeller

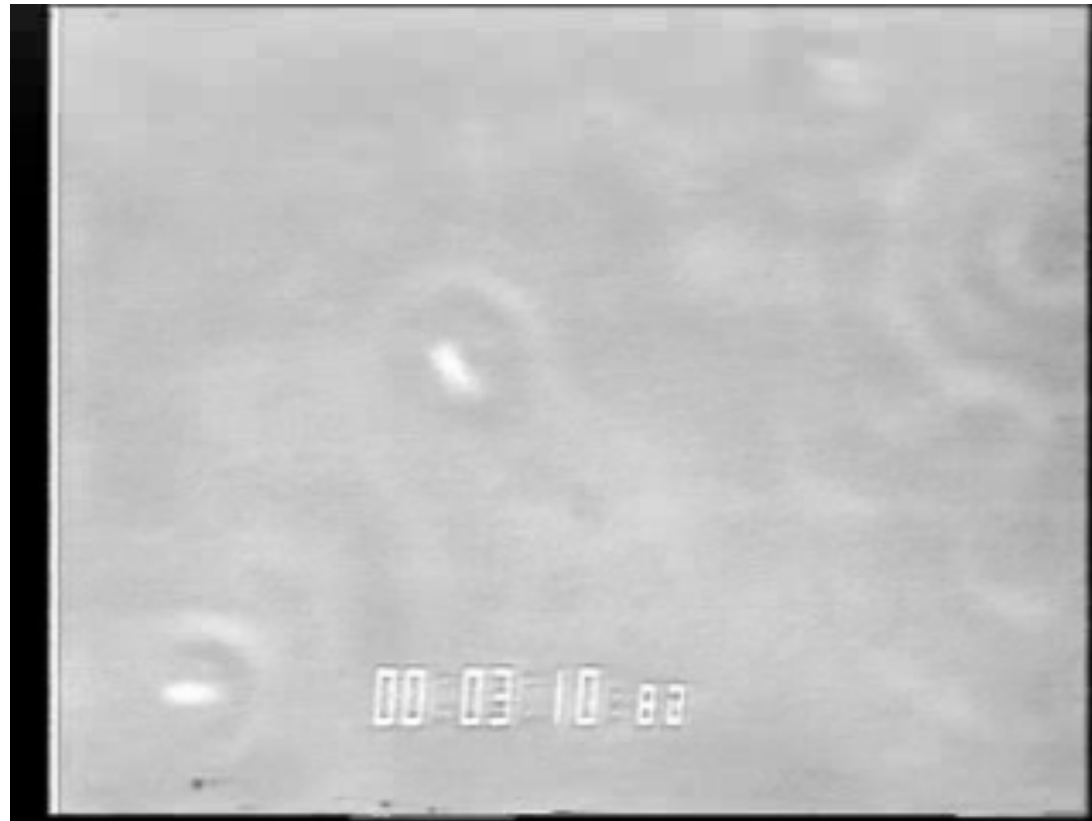


Simultaneous manipulation of multiple particles with holographic optical tweezers



S. Block

Capturing cells with optical tweezers



Trapping of bacterial cells

The optical trap is 3D handle without a shaft:

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

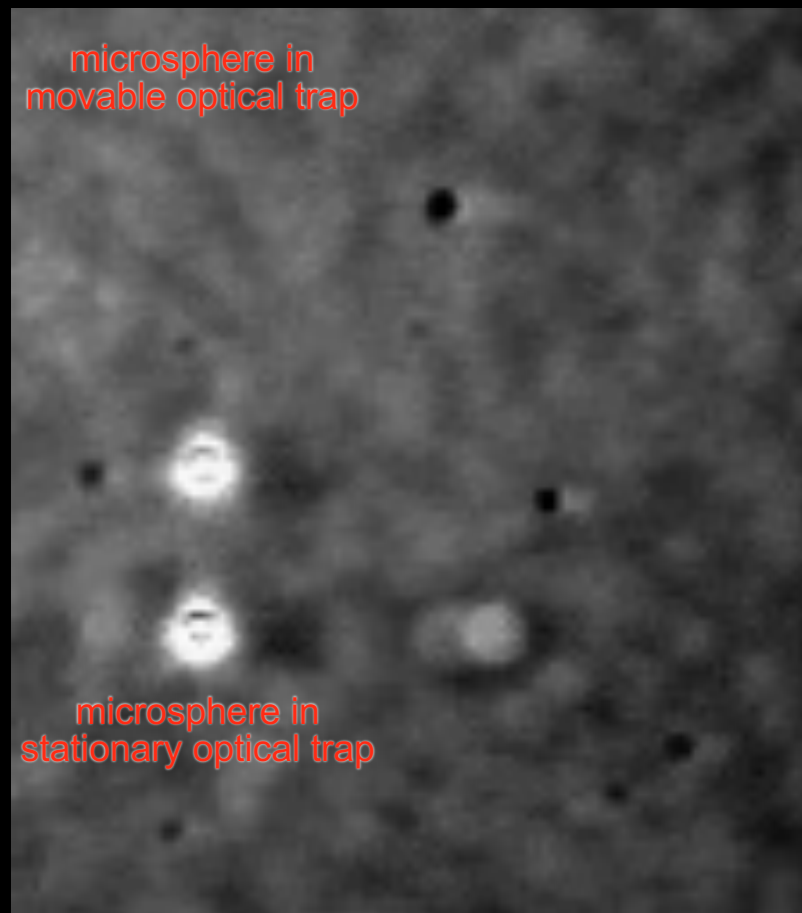
Actin filament



Fluorescence image

DNA

Phase contrast image

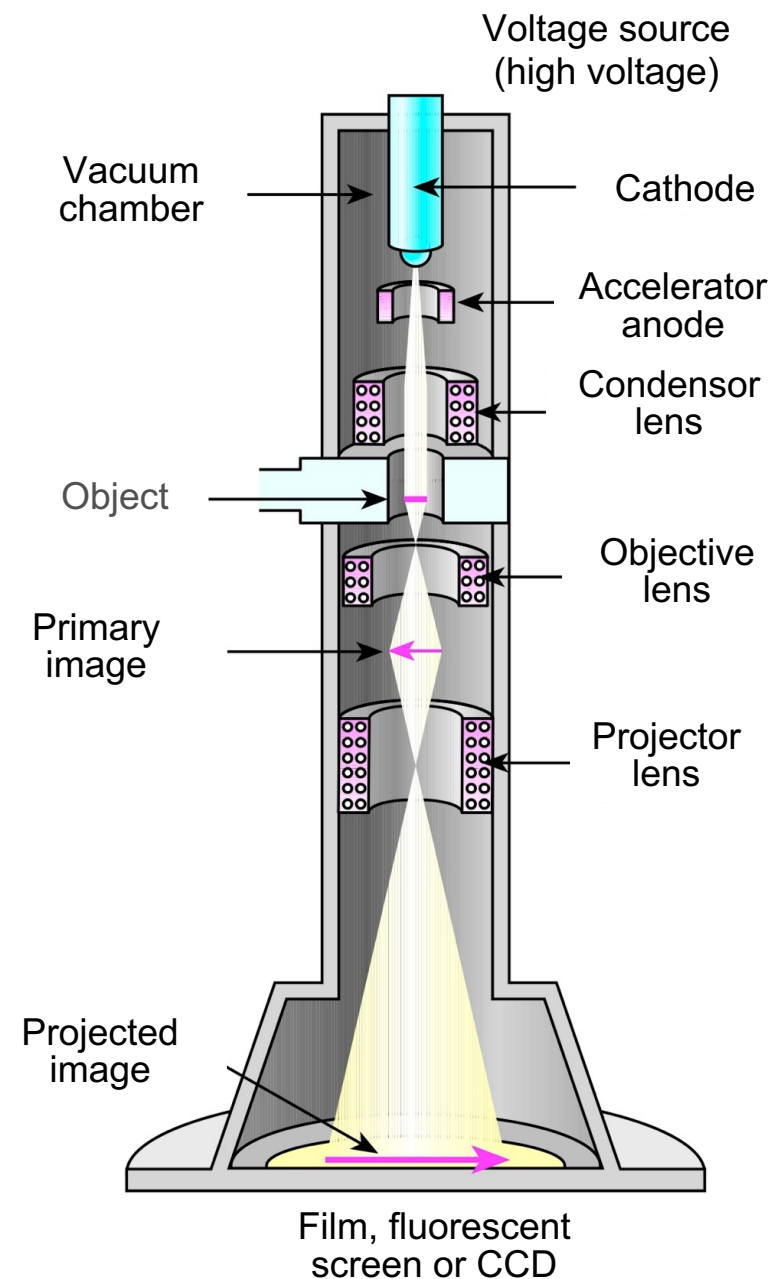


Fluorescence image



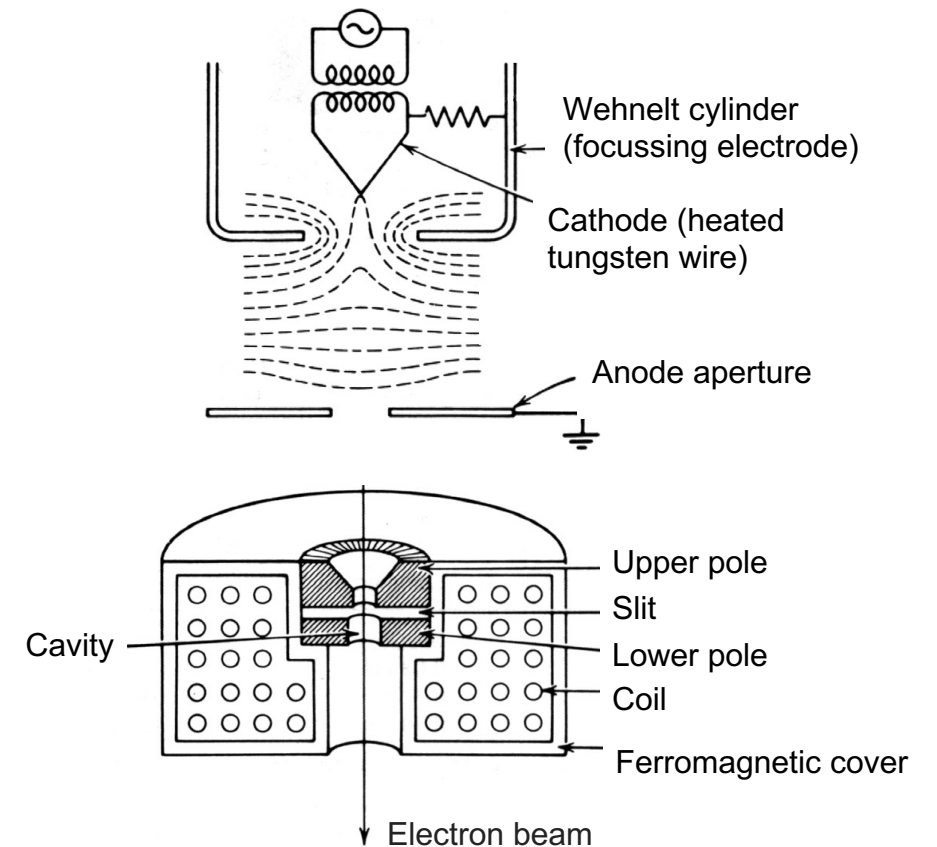
Applications II.

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:

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

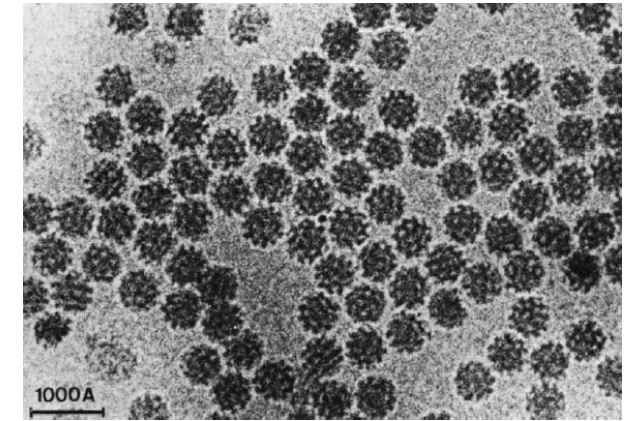
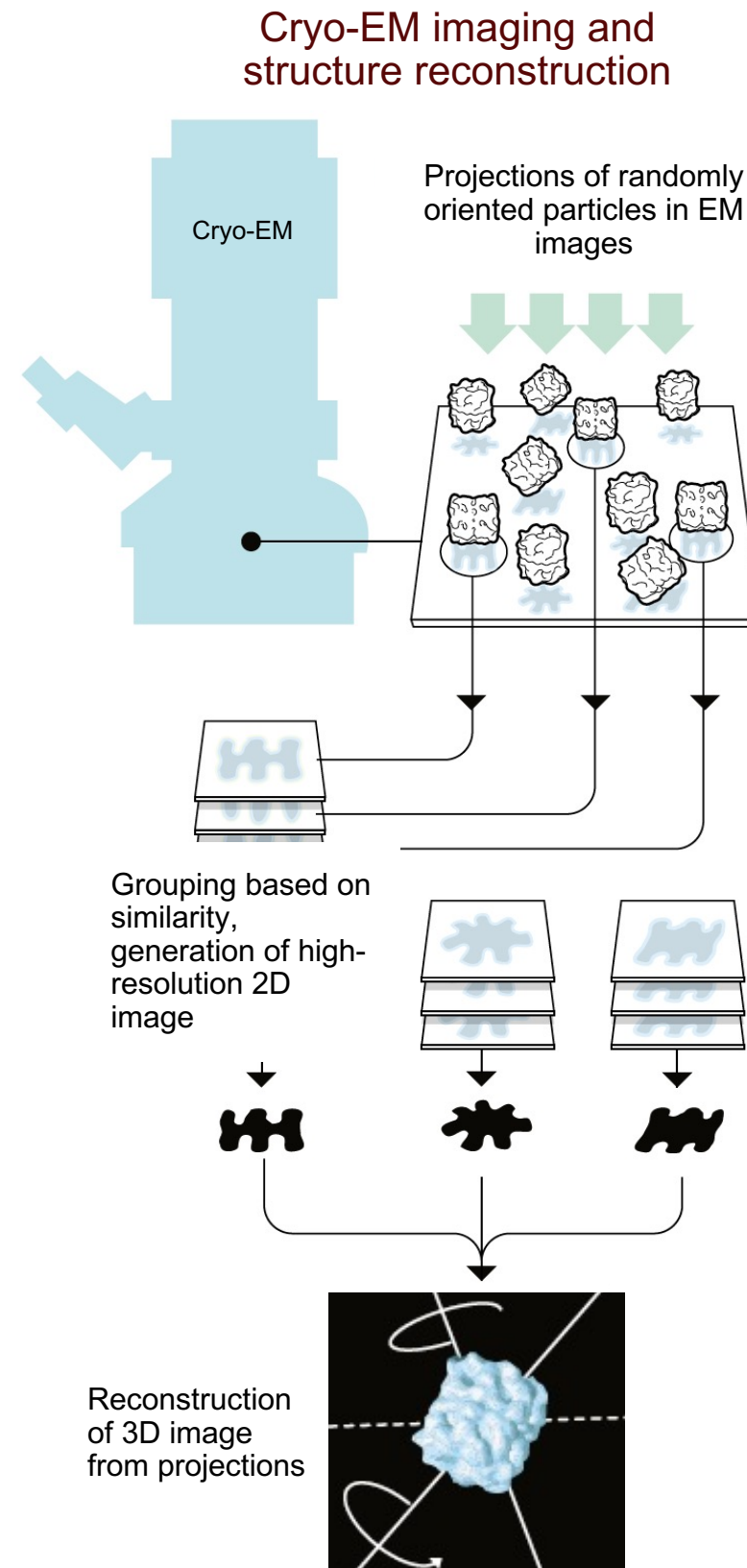
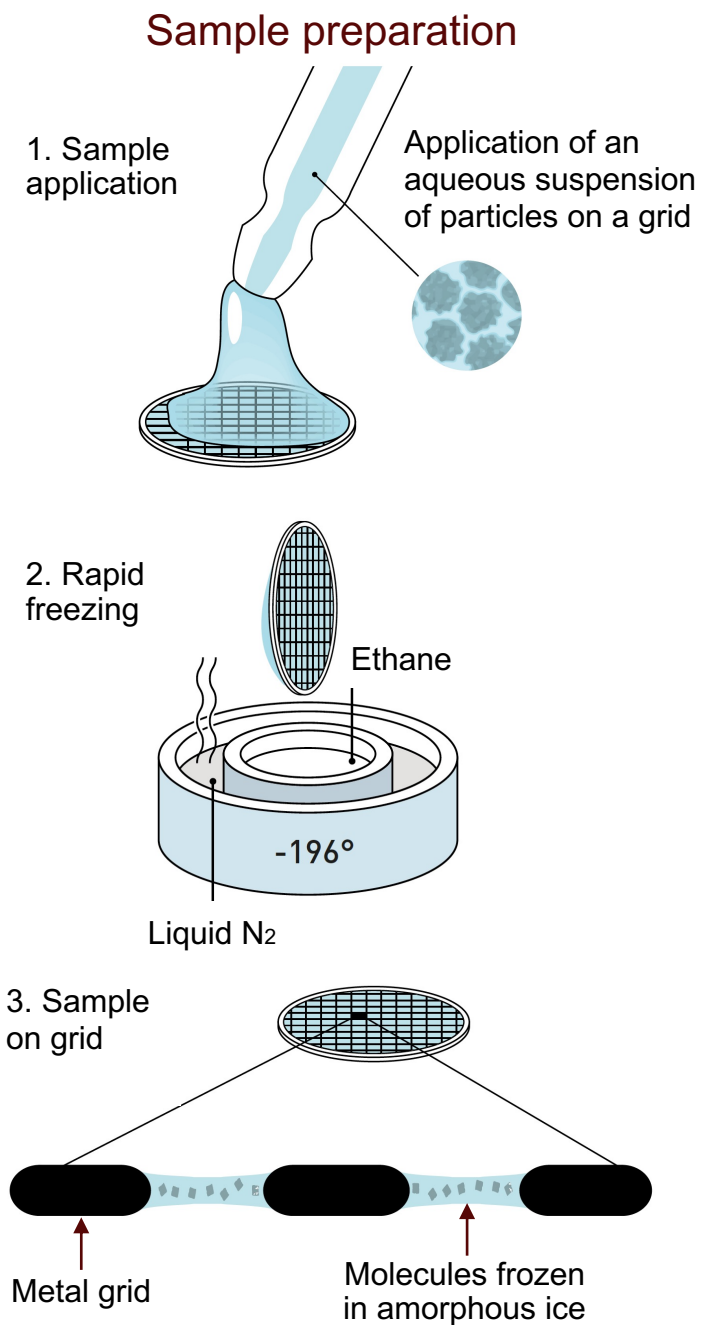
d =smallest resolved distance
 λ = "de Broglie" wavelength
 α =angle between the optical axis and
the direction of the magnetic field

Based on the de Broglie wavelength the
theoretical resolution is: $d \sim 0,005 \text{ nm}$ (=5 pm).

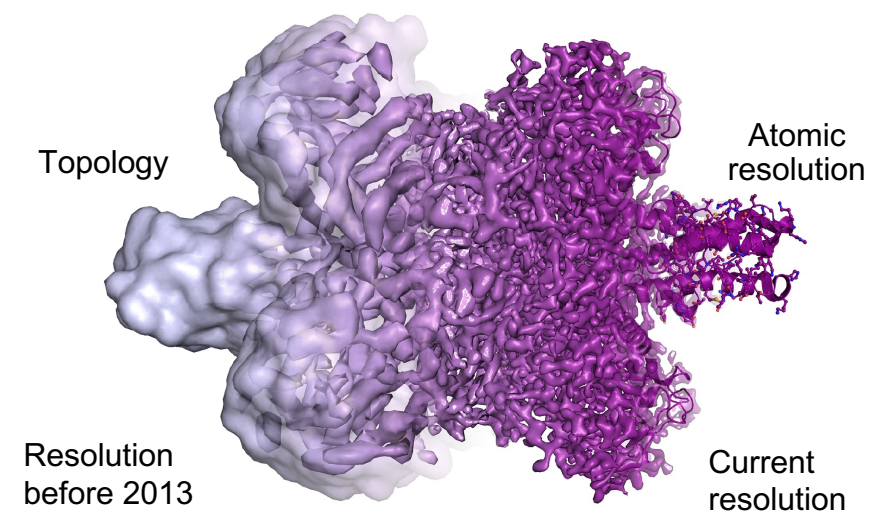
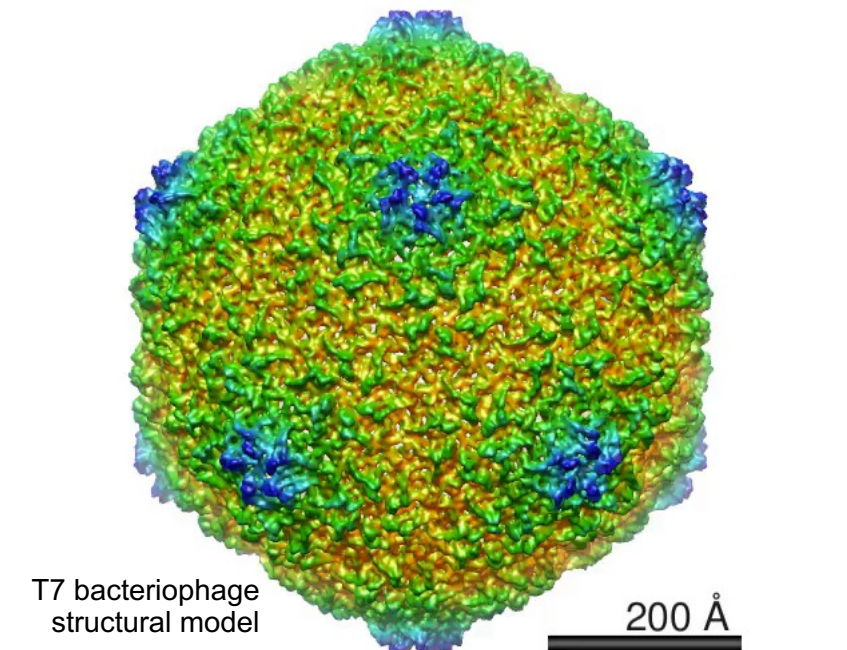
Cryo-electron microscopy (Nobel-prize 2017)



Jacques Dubochet, Joachim Frank, Richard Henderson



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



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*

Feedback



<https://feedback.semmelweis.hu/feedback/pre-show-qr.php?type=feedback&qr=R7V8G1O47SFTXIPC>