Amplification of Light

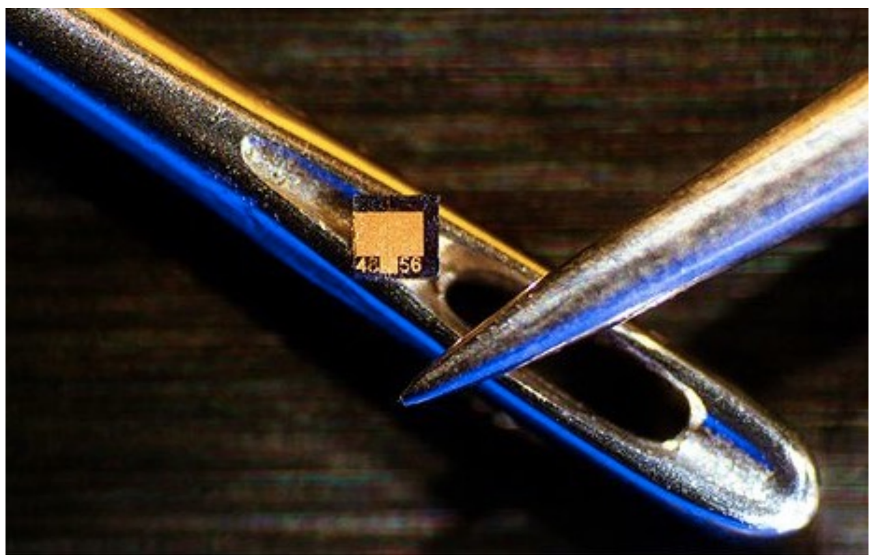
LASER

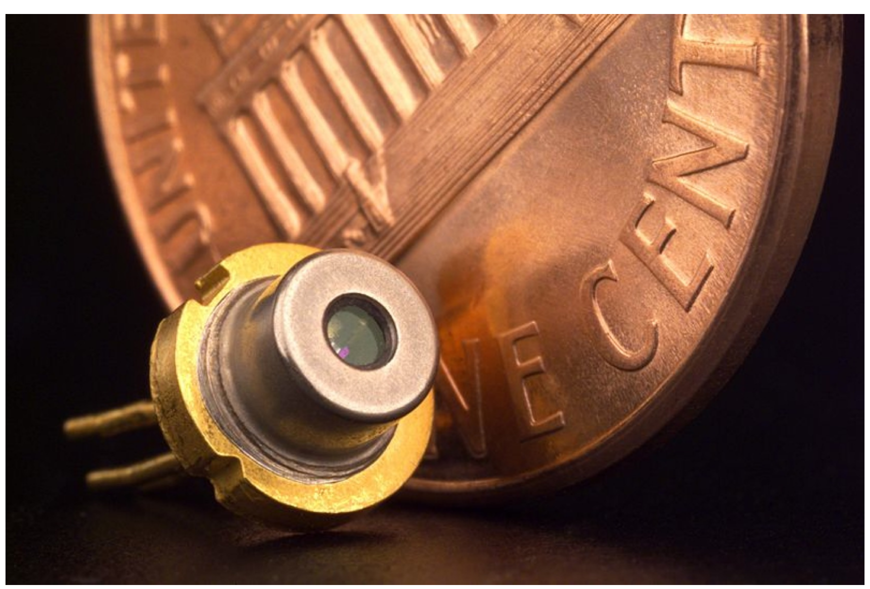
Miklós Kellermayer

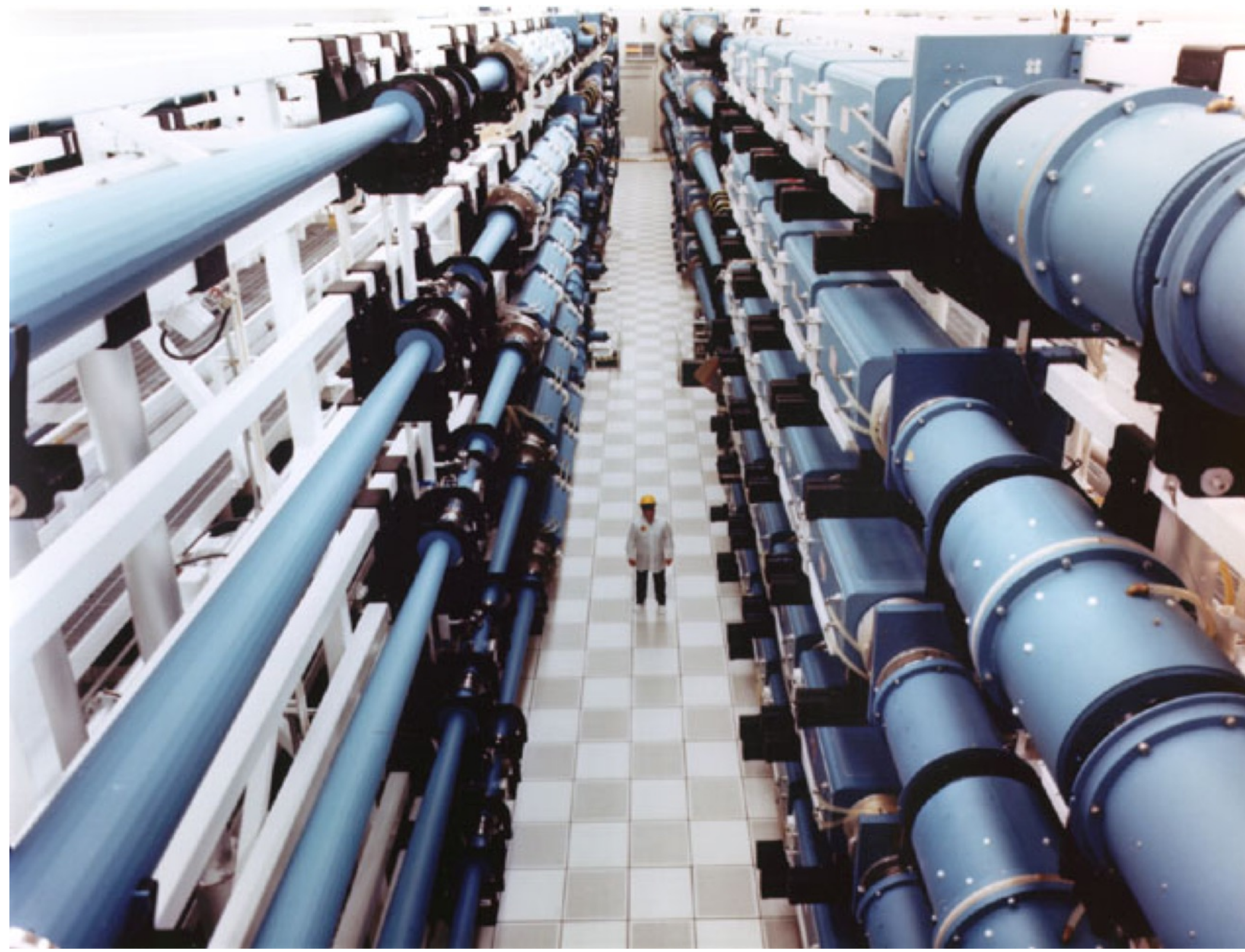
Lasers are everywhere

Laser: “Light Amplification by Stimulated Emission of Radiation”

Luminescent light source based on light amplification.







5 mW diode laser
few mms

Terawatt NOVA laser - Lawrence Livermore Laboratories
Size of a football field

Laser history in a nutshell

Albert Einstein
(1879-1955)

Arthur L. Schawlow
(1921-1999)

Theodore Maiman
(1927-2007)

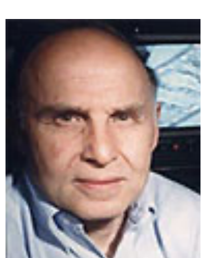
Nikolay G. Basow
(1922-2001)

Charles H. Townes
(1915-)

Alexander M. Prokhorov
(1916-2002)

Steven Chu
(1948-)

Gábor Dénes
(1900-1979)

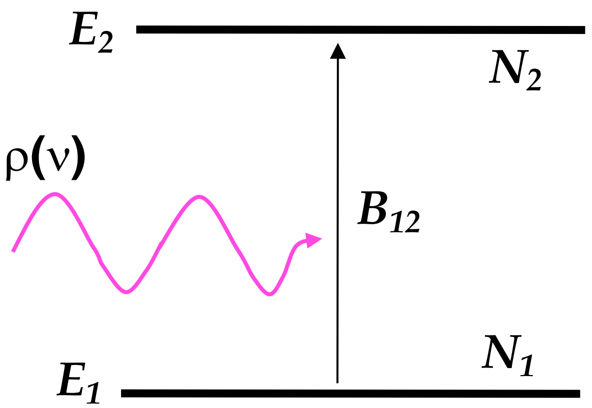


Arthur Ashkin
(1922-)

- 1917 - Albert Einstein: theoretical prediction of stimulated emission.
- 1946 - G. Meyer-Schwickerather: first eye surgery with light.
- 1950 - Arthur Schawlow and Charles Townes: emitted photons may be in the visible range.
- 1954 - N.G. Basow, A.M. Prochorow, and C. Townes: ammonia maser
- 1960 - Theodore Maiman: first laser (ruby laser)
- 1964 - Basow, Prochorow, Townes (Nobel-prize): quantum electronics
- 1970 - Arthur Ashkin: laser tweezers
- 1971 - Dénes Gábor (Nobel-prize): holography
- 1997 - S. Chu, W.D. Phillips and C. Cohen-Tanoudji (Nobel-prize): atom cooling with laser.
- 2013, october 8: NIF (National Ignition Facility, USA): launching nuclear fusion with 192 laser beams, positive energy balance.
- 2017 - ELI (Extreme Light Infrastructure), Szeged, Hungary. generation of attosecond (10^{-18} s) light pulses.
- 2018 - Nobel-prize in physics: Arthur Ashkin (laser tweezers), Gérard Mourou and Donna Strickland (ultrashort laser pulses)

Principles of laser I. stimulated emission

1. Absorption

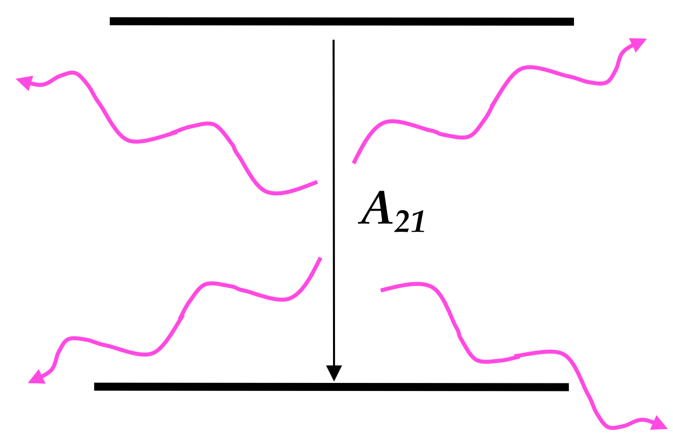


Frequency of transition:

$n_{12}=N_1B_{12}\rho(\nu)$

$\Delta E= E_2-E_1=h\nu$
energy quantum is absorbed.

2. Spontaneous emission

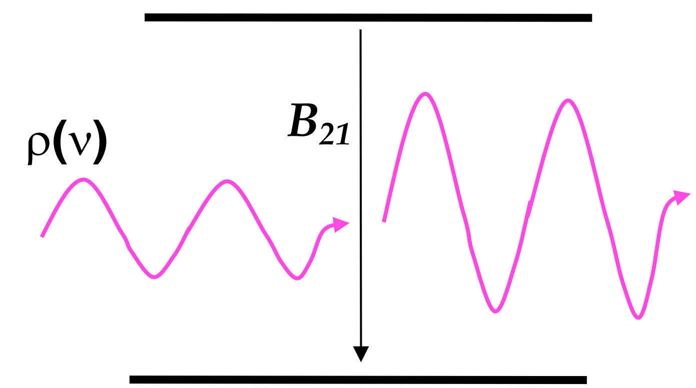


Frequency of transition:

$n_{21}=N_2A_{21}$

E_2-E_1 photons
travel independently in all directions.

3. Stimulated emission



Frequency of transition:

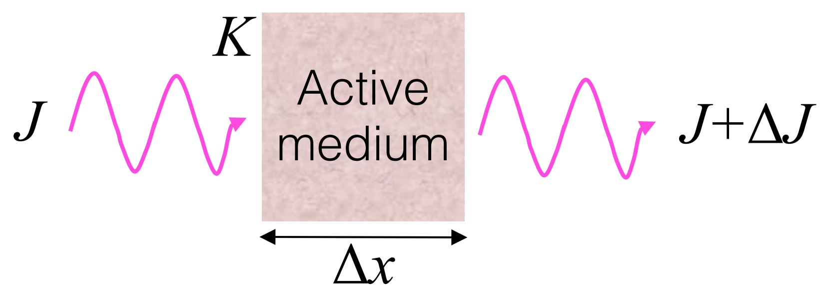
$n_{21}=N_2B_{21}\rho(\nu)$

In the presence of exernal field.
Field energy is increased.
Phase, direction and frequency of emitted and external photons are identical.

Explanation: two-state atomic or molecular system.
E_1, E_2 : energy levels, $E_2>E_1$
$\rho(\nu)$: spectral energy density of external field.
N_1, N_2 : number of atoms or molecules on the given energy level.
B_{12}, A_{21}, B_{21}: transition probabilities (Einstein coefficients), $B_{12} = B_{21}$

Principles of laser II. Population inversion

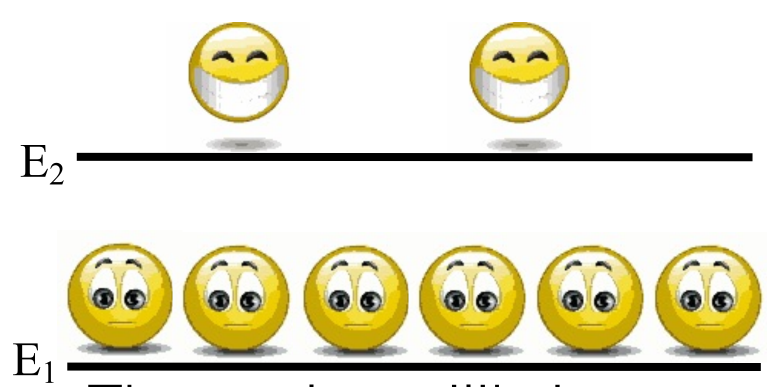
Light amplification depends on the relative population of energy levels.



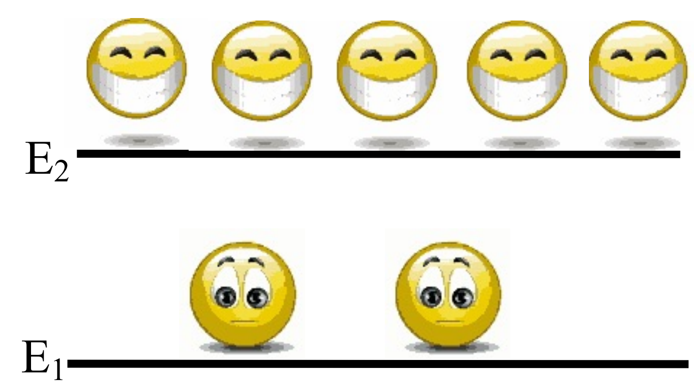
$$\Delta J = JK(N_2 - N_1)\Delta x$$

J = intensity
K = constant
x = distance travelled within medium
N_1, N_2 = number of atoms on the E level

N.B.: If ΔJ is positive, more light exits the medium, than has entered!

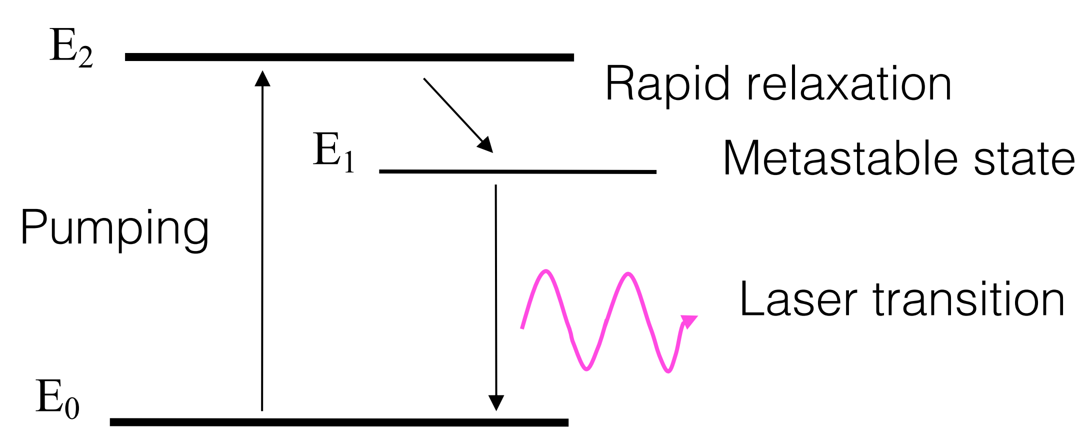


Thermal equilibrium

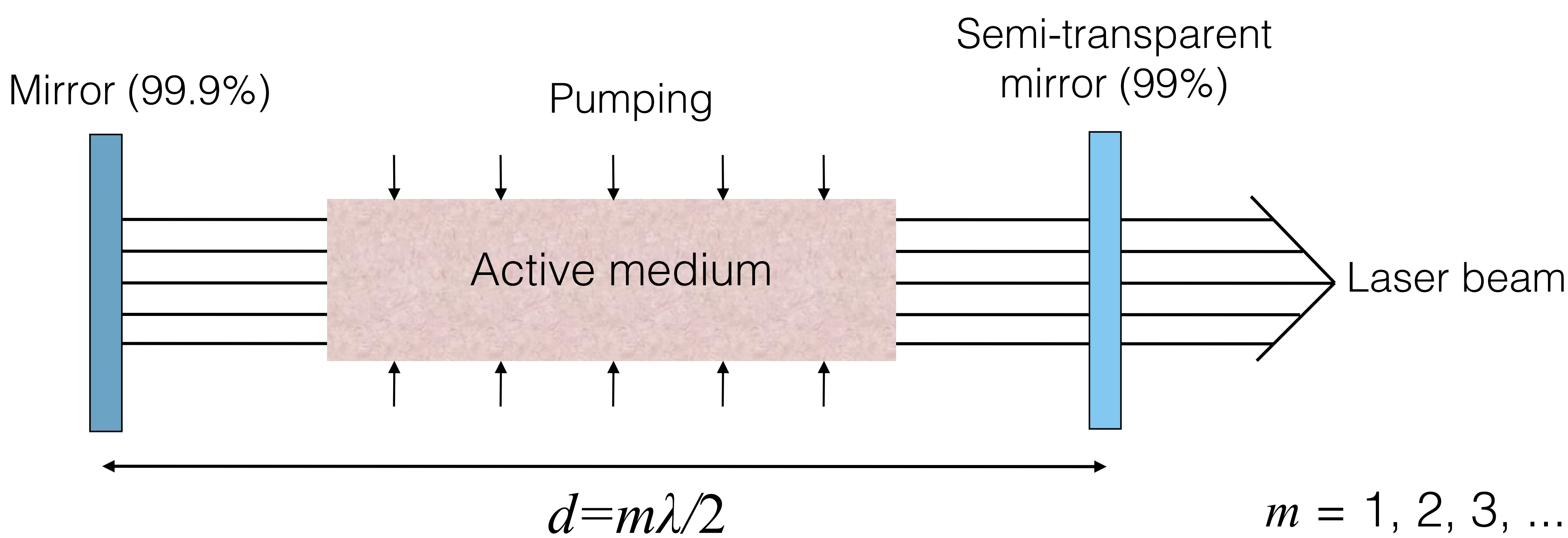


Population inversion

- Population inversion only in multiple-state systems!
- Pumping: electrical, optical, chemical energy



Principles of laser III. Optical resonance



Resonator:

- two parallel (or concave) mirrors
- part of the exiting light is coupled back into the medium
- positive feedback -> self-excitation -> resonance

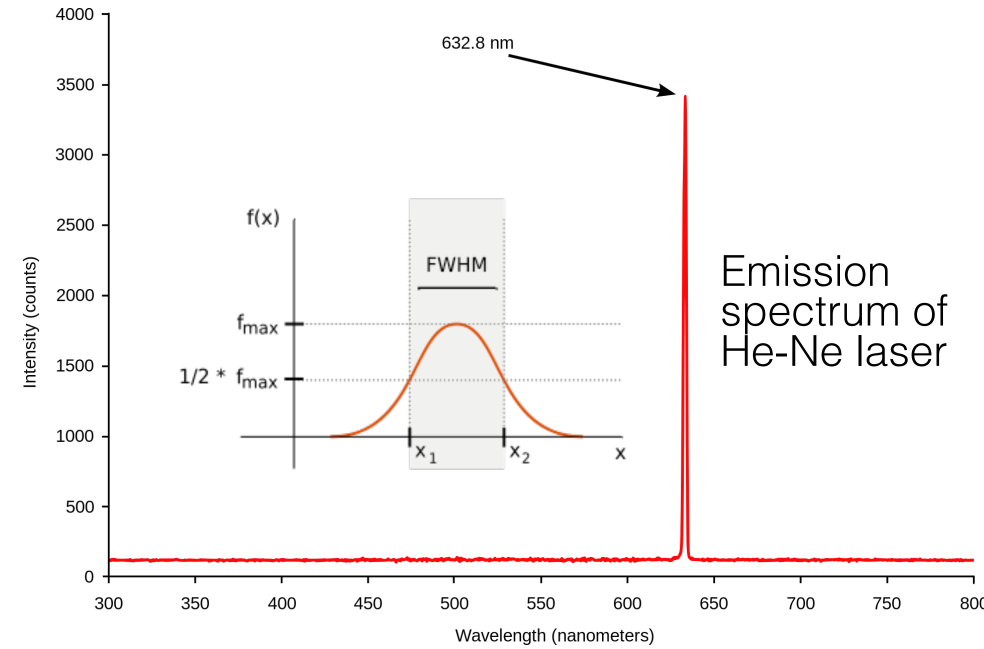
- Optical switch in the resonator: Q-switch, pulsed mode

Properties of laser light

1. Small divergence
   Parallel (collimated) beam

2. Large power
   In continuous (CW) mode, tens, hundreds of W (e.g., CO_2 laser)
   In Q-switched mode, momentary power is enormous (GW)
   Because of small divergence, large spatial power density.

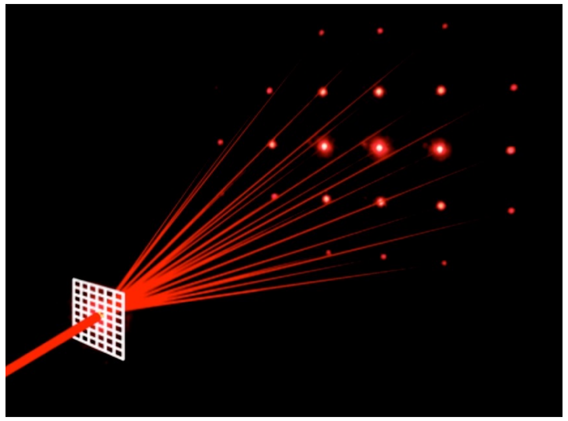
3. Small spectral bandwidth
   "Monochromaticity"
   Large spectral energy density



4. Often polarized

5. Possibility of extremely short pulses
   ps, fs

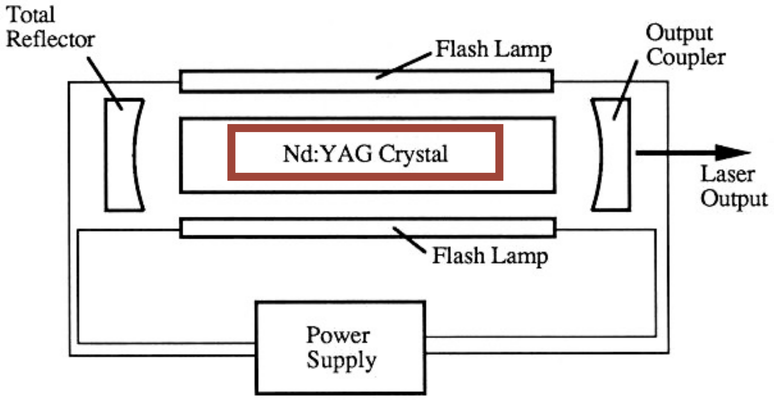
6. Coherence
   phase identity, interference tendency; temporal coherence (phase identity of photons emitted at different times); spatial coherence (phase identity across beam diameter). Application: holography, optical coherence tomography



Types of lasers

Based on **active medium**:

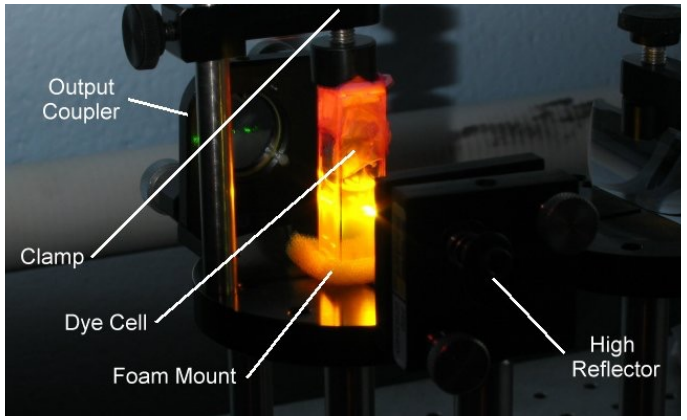
1. Solid state lasers
Metal doping in crystals or glasses; Ruby, Nd-YAG, Ti-sapphire
Red-infrared spectral range; CW, Q-switched mode, large power



2. Gas lasers
Best known: He-Ne laser (10 He/Ne). Small energy, wide use
CO_2 laser: CO_2-N_2-He mixture; λ~10 μm; Huge power (100 W)

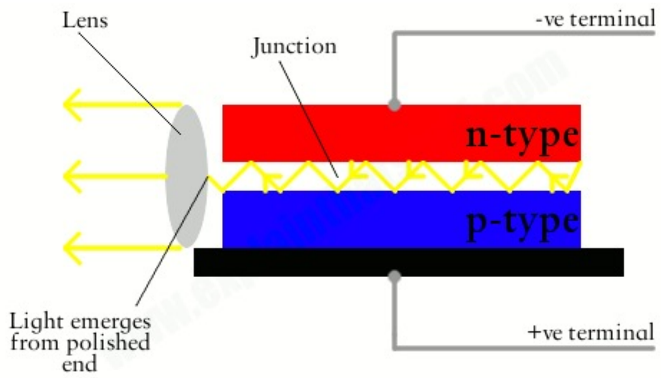
CO_2 laser (cutting a metal sheet)

3. Dye lasers
Dilute solution of organic dyes (e.g., rhodamine, coumarine);
Pumped by another laser.
Large power (Q-switched mode); Tunable



Dye laser

4. Semiconductor (diode) lasers
On the boundary of p- and n-type doped semiconductors.
No need for resonator mirrors (total internal reflection)
Red, IR spectral range. Huge CW power (up to 100W)
Beam characteristics are not very good. Wide use because of small size.



Diode laser

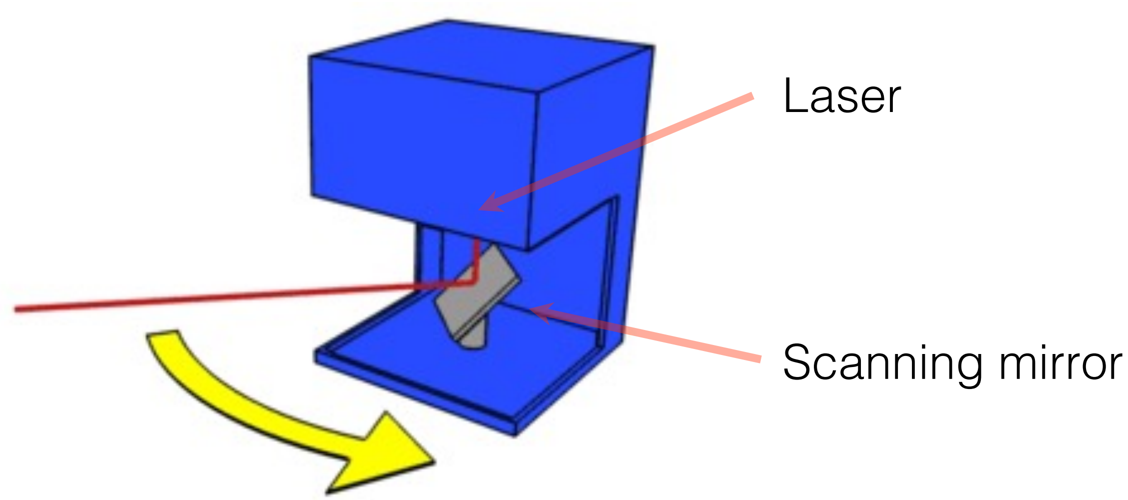
Today: laser lines (wavelengths) are available from X-rays to infrared light!

Factors to be considered in laser applications

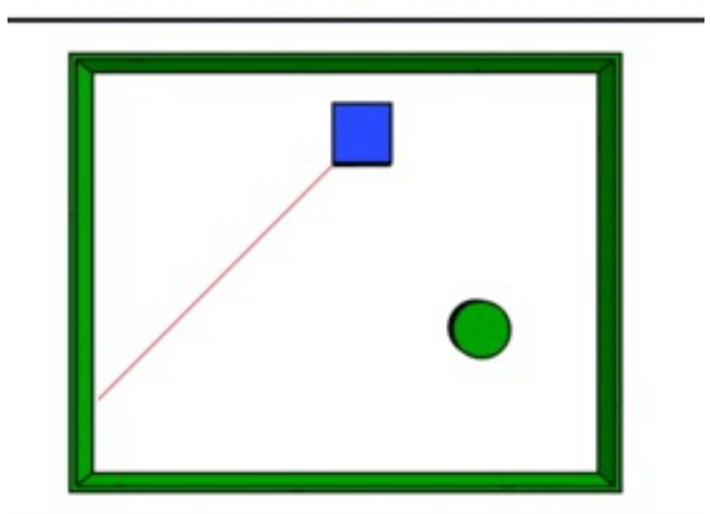
- Steerability (small divergence)
- Monochromaticity
- Coherence
- Possibility of short pulses
- Power:
  - 5 mW – CD-ROM drive
  - 5–10 mW – DVD player or DVD-ROM drive
  - 100 mW – high-speed CD-RW writer
  - 250 mW – DVD-R writer
  - 1–20 W – solid-state laser for micromachining
  - 30–100 W – surgical CO_2 laser
  - 100–3000 W – industrial CO_2 laser (laser cutter)
  - 1 kW – 1 cm diode laser bar

Speed measurement with laser

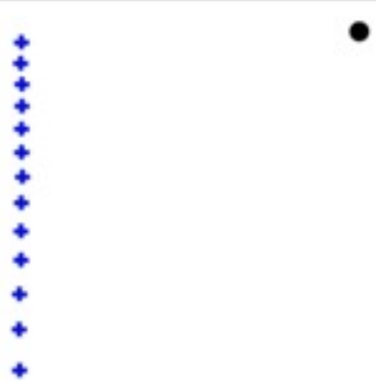
LIDAR: “Light Detection and Ranging”



Laser property utilized: Steerability

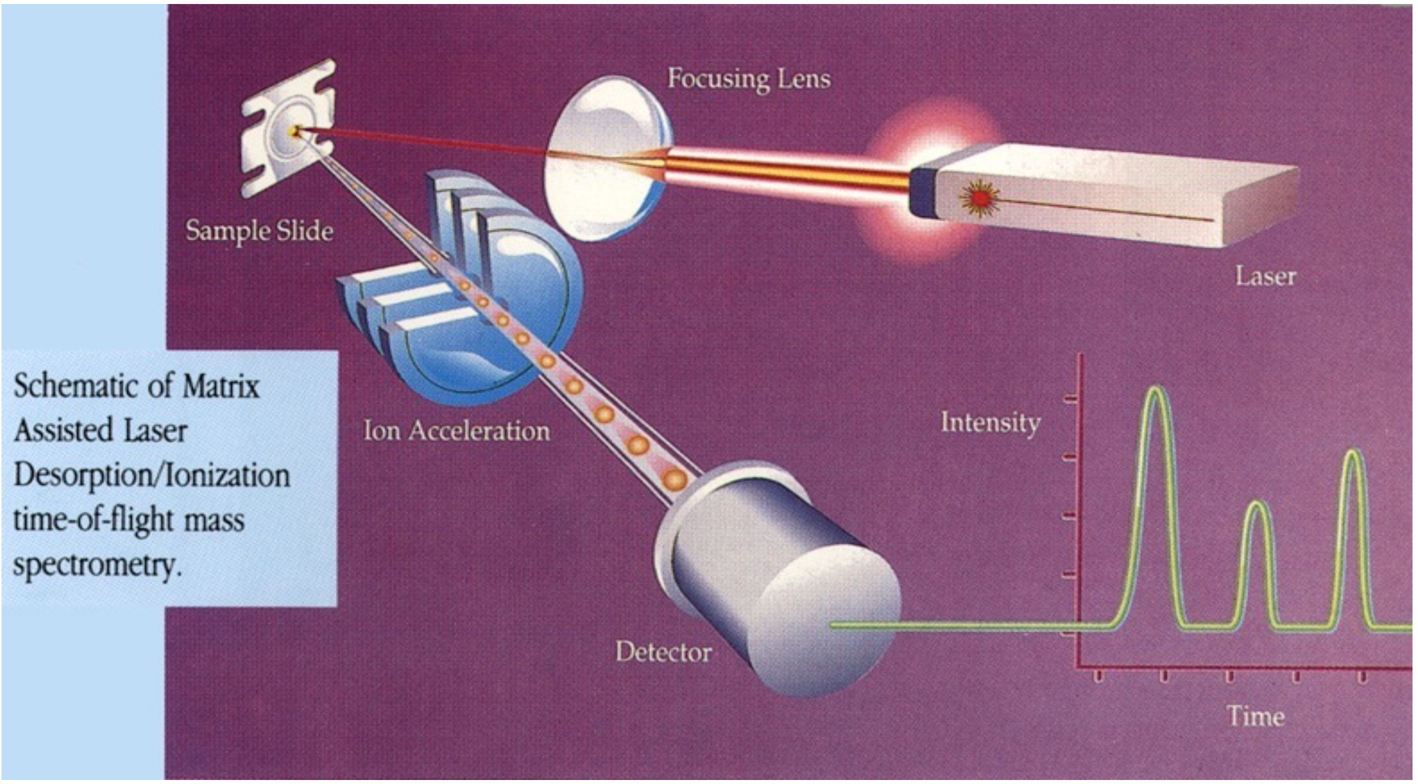


Top view

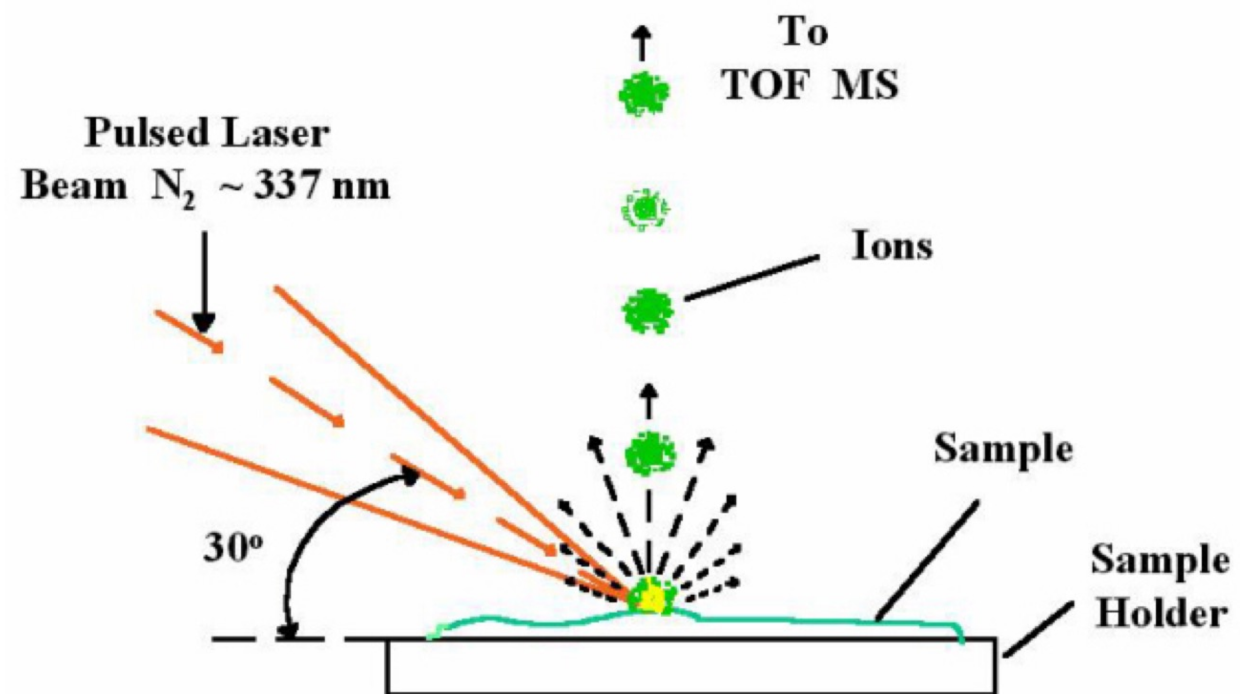


Recording: reconstructed spatial arrangement.
In traffic speedometer: 100 pulses in 0.3 s

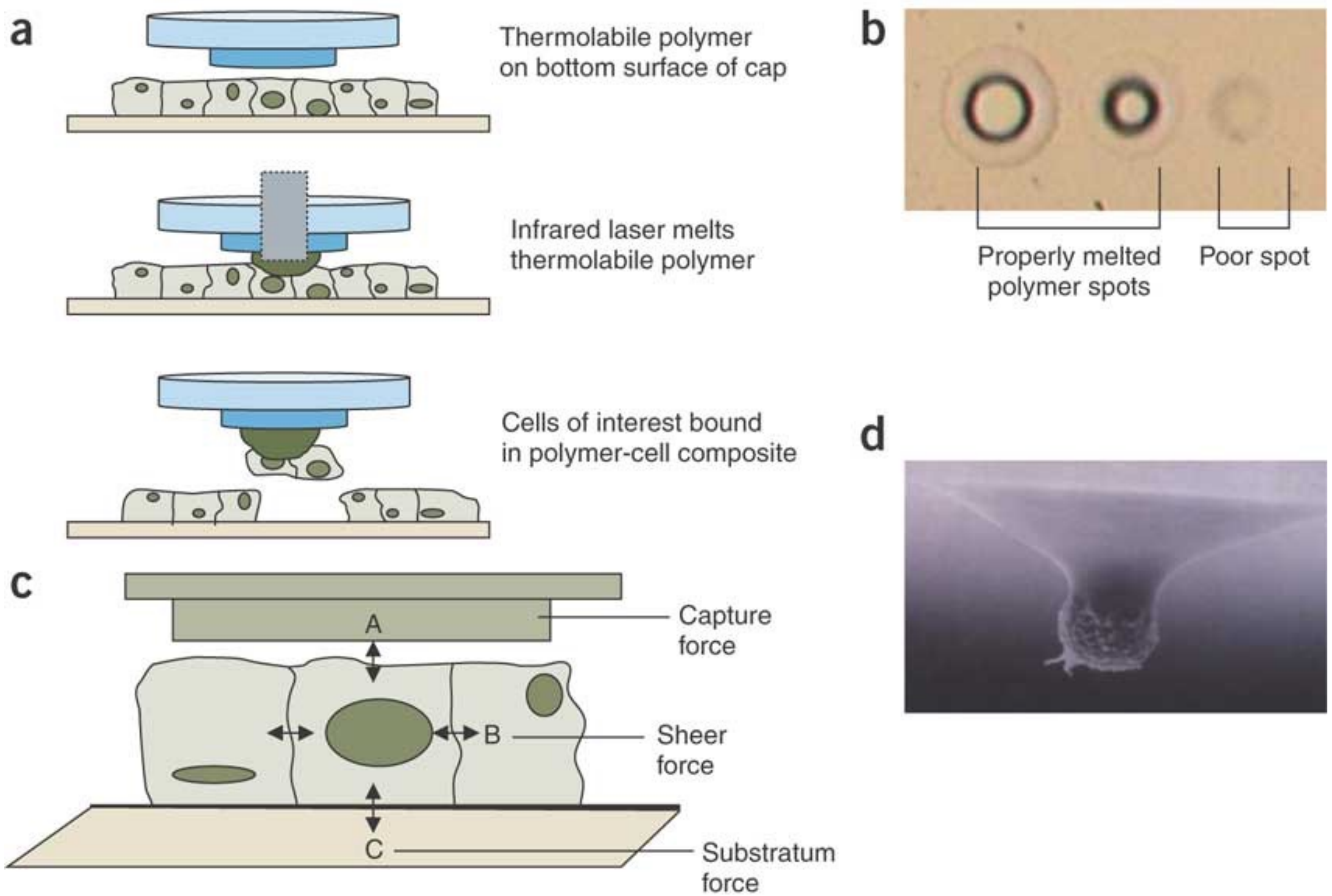
MALDI-TOF:
matrix-assisted laser desorption/ionization time of flight mass spectrometry



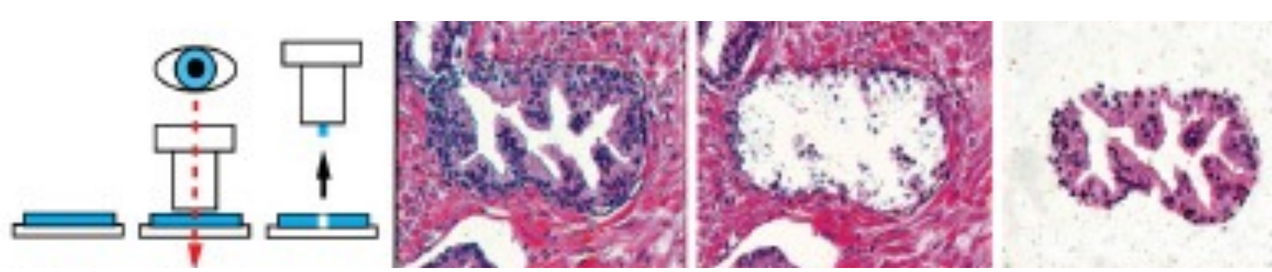
Laser property utilized: Power density



“Laser capture microdissection”



Laser property utilized: Power density, steerability

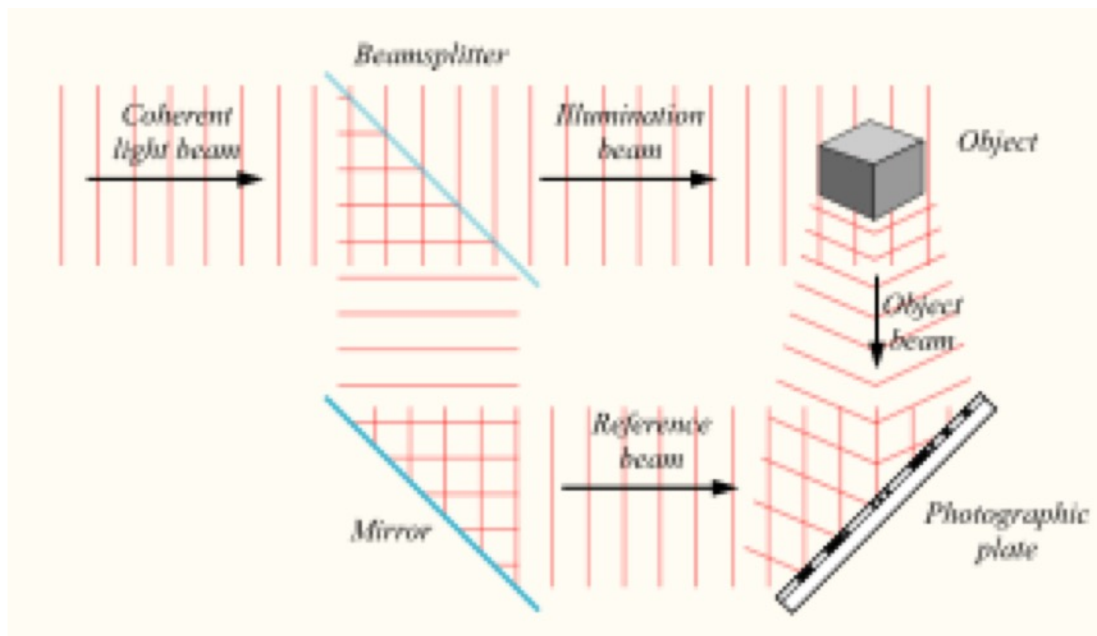


Significance: local analytics are possible analitika lehetősége (chemistry, genetics)

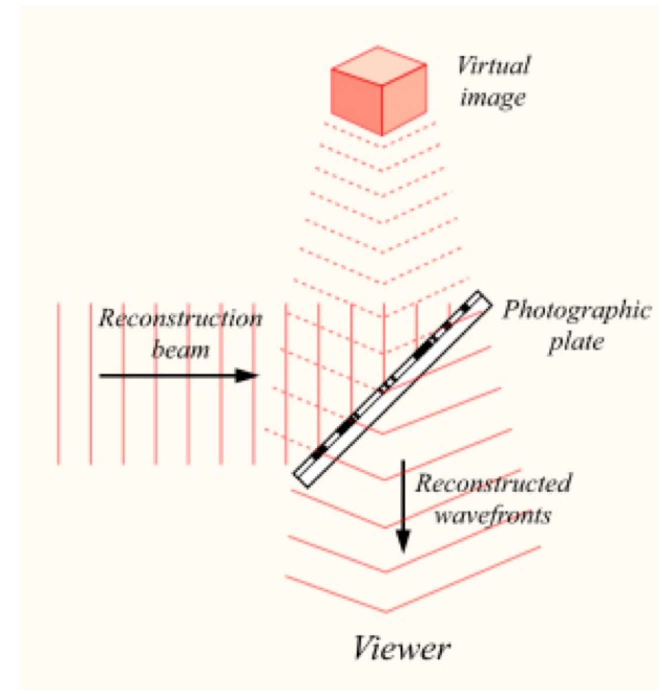
Holography

Laser property utilized: Coherence

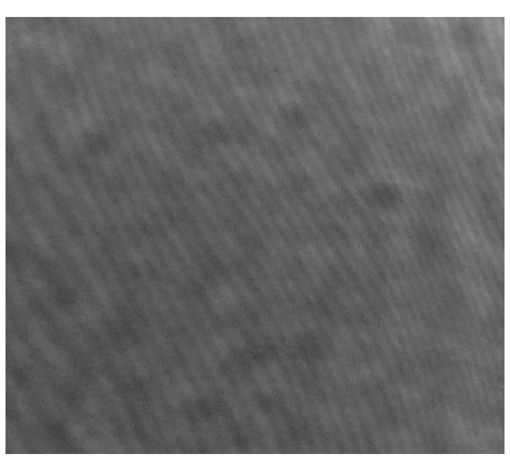
Dénes Gábor
(1900-1979)



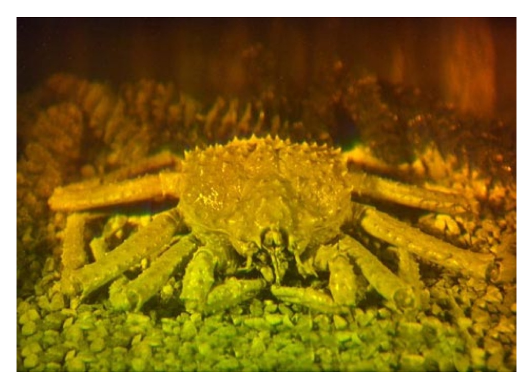
Recording a hologram

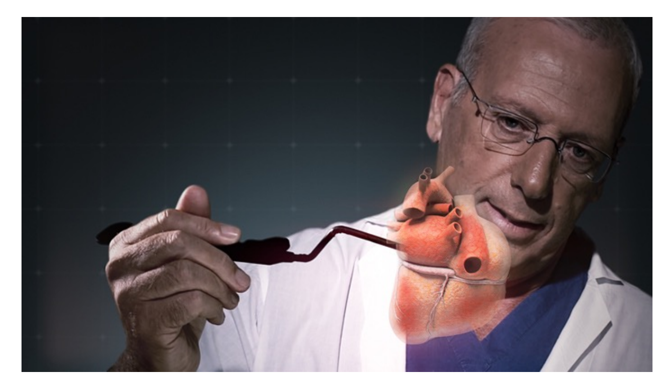


Visualization of a hologram



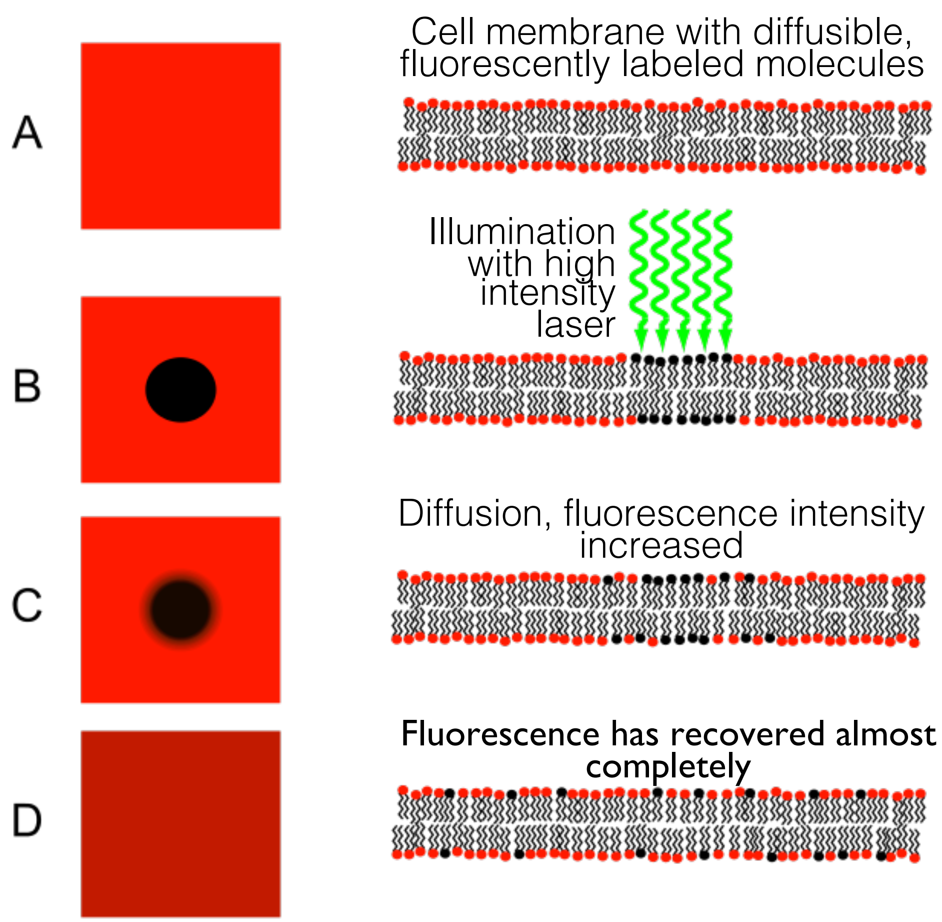
Surface of a hologram recording

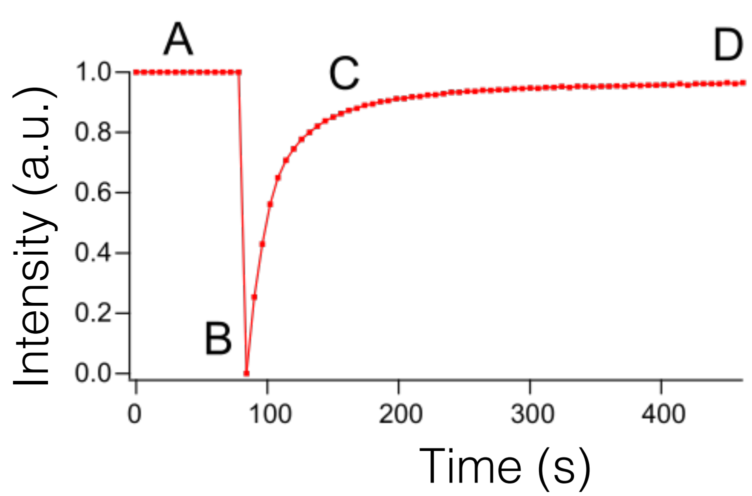




Holograms

Fluorescence Recovery After Photobleaching (FRAP)





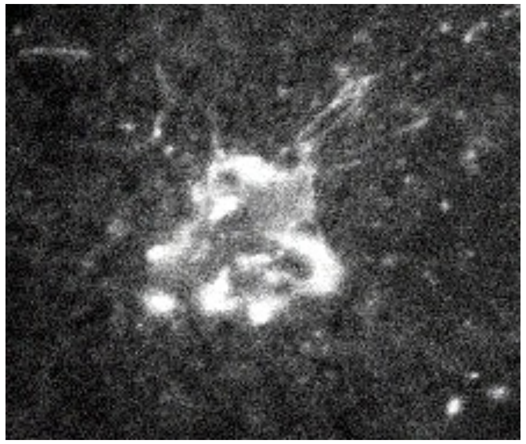


Image prior to bleaching

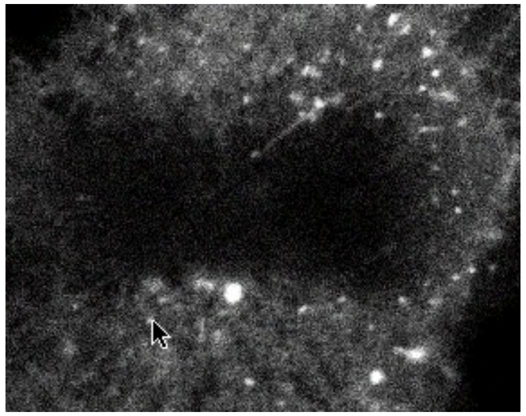
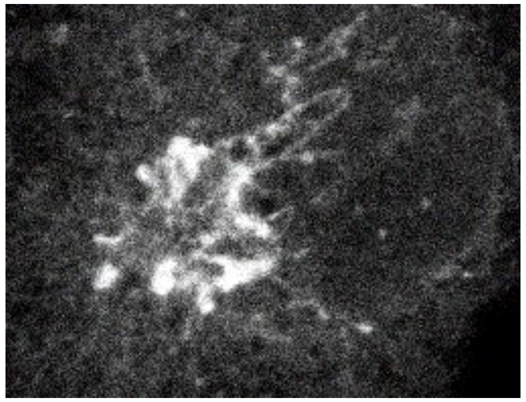


Image just after bleaching


Recovered fluorescence

Laser property utilized: Power density, steerability

The diffusion coefficient can be determined from the time-dependent recovery of fluorescence as:

$$D = \frac{w^2}{4t_D}$$

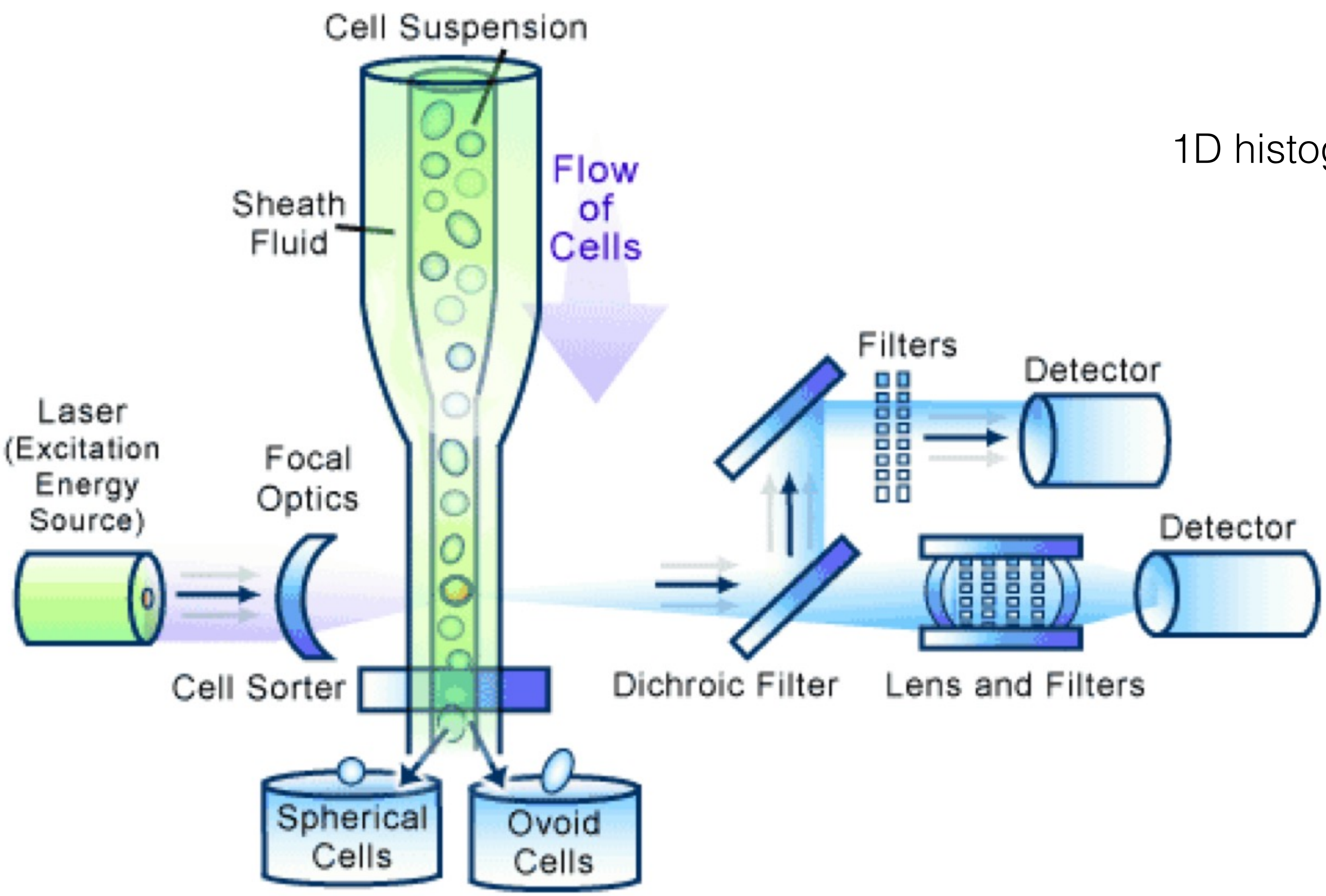
D = diffusion coefficient
w = width of bleached area
t_D = time constant

Fluorescence activated cell sorter (FACS)

Flow cytometry

- A cell suspension, fluorescently labeled by using specific antibodies, is analyzed cell-by-cell
- Numerous parameters are measured simultaneously (fluorescence intensity at several wavelengths, small- and large-angle scatter)
- Statistical analysis
- If needed, cells can be separated according to their fluorescence

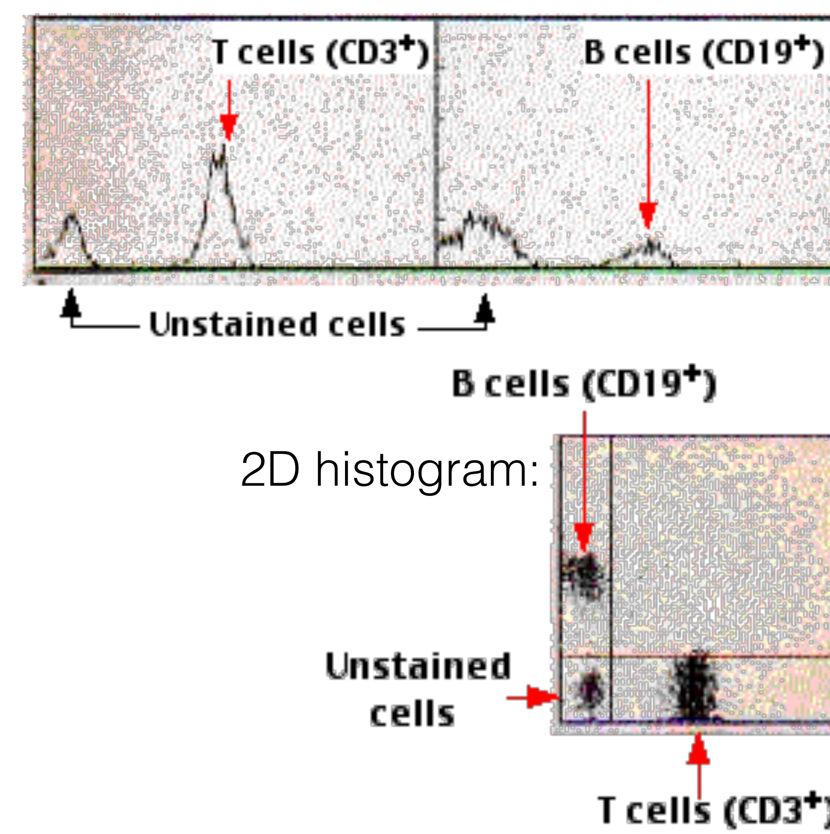
Laser property utilized: monochromaticity



Cytometry statistics

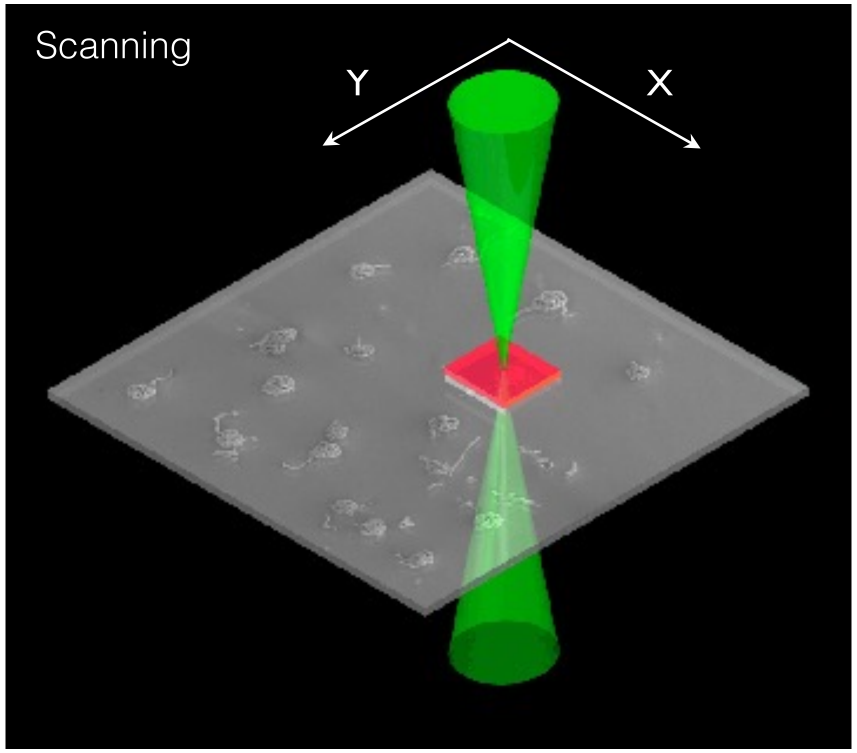
1D histograms:

2D histogram:

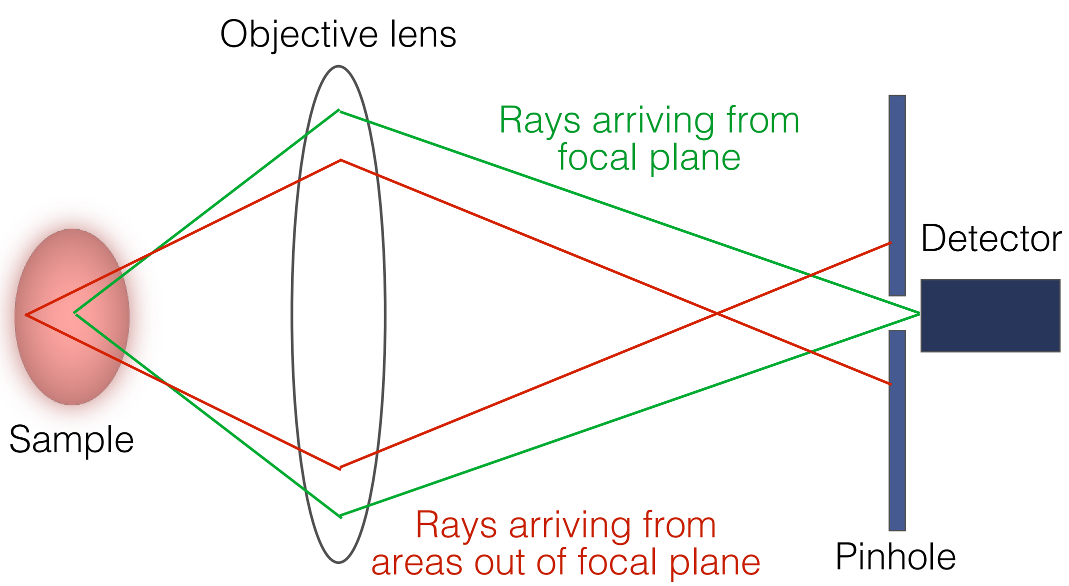


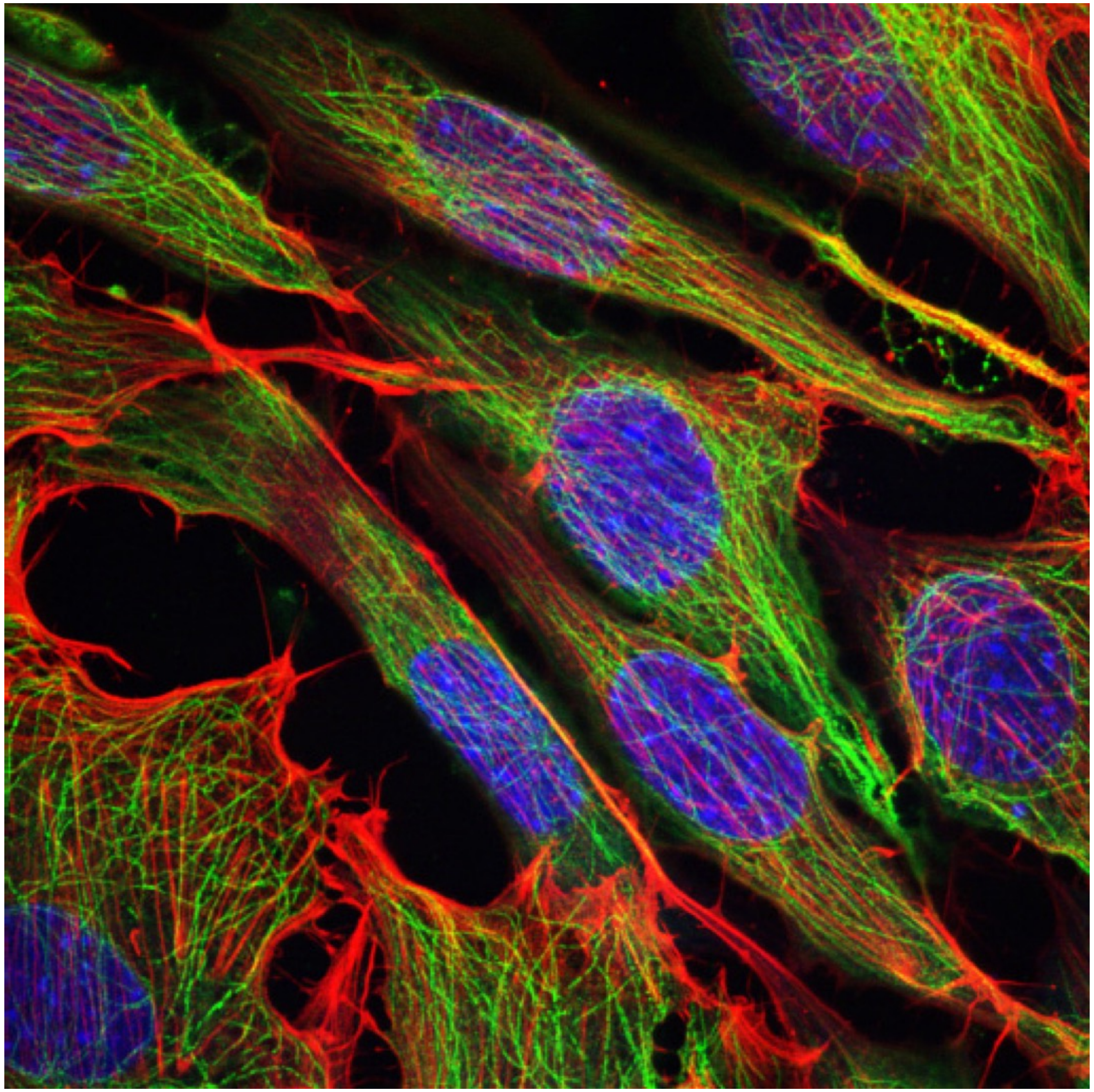
Laser scanning confocal microscopy

Laser property utilized: monochromaticity, steerability



"Confocal principle"



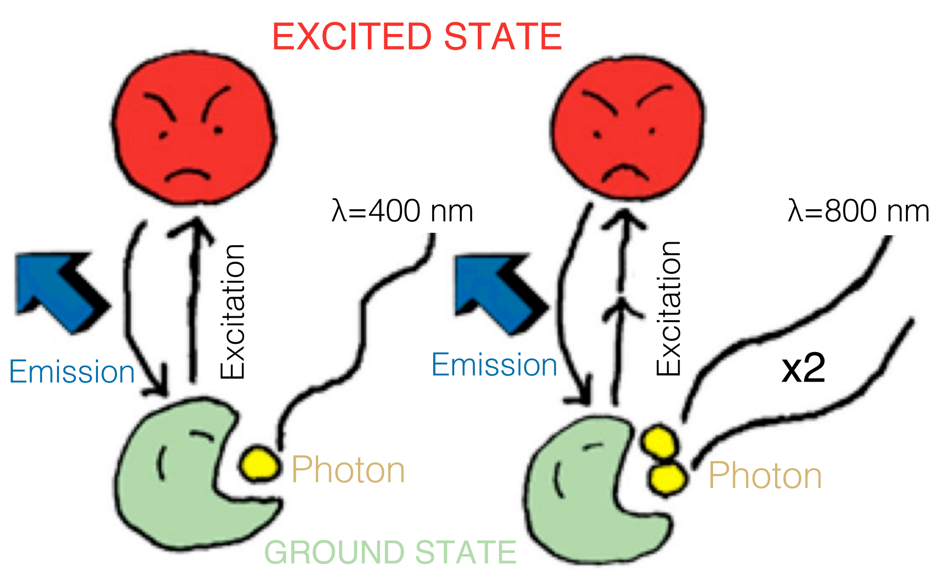


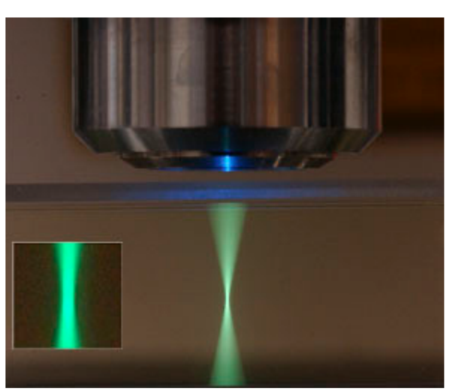
Green: microtubules; Red: actin; Blue: nuclei

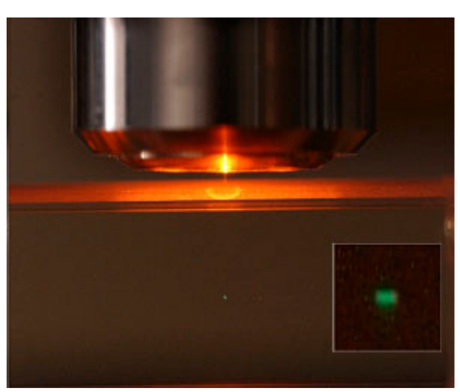
Multiphoton fluorescence microscopy

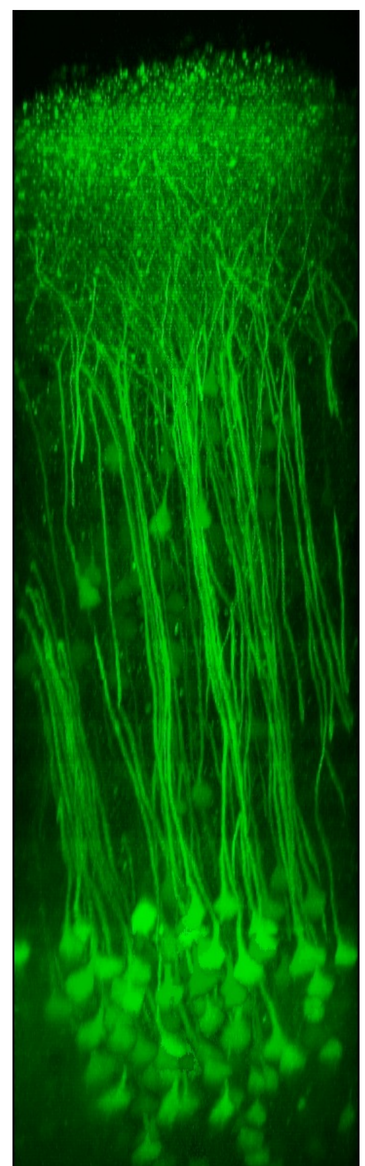
Laser property utilized: monochromaticity, steerability, short pulses

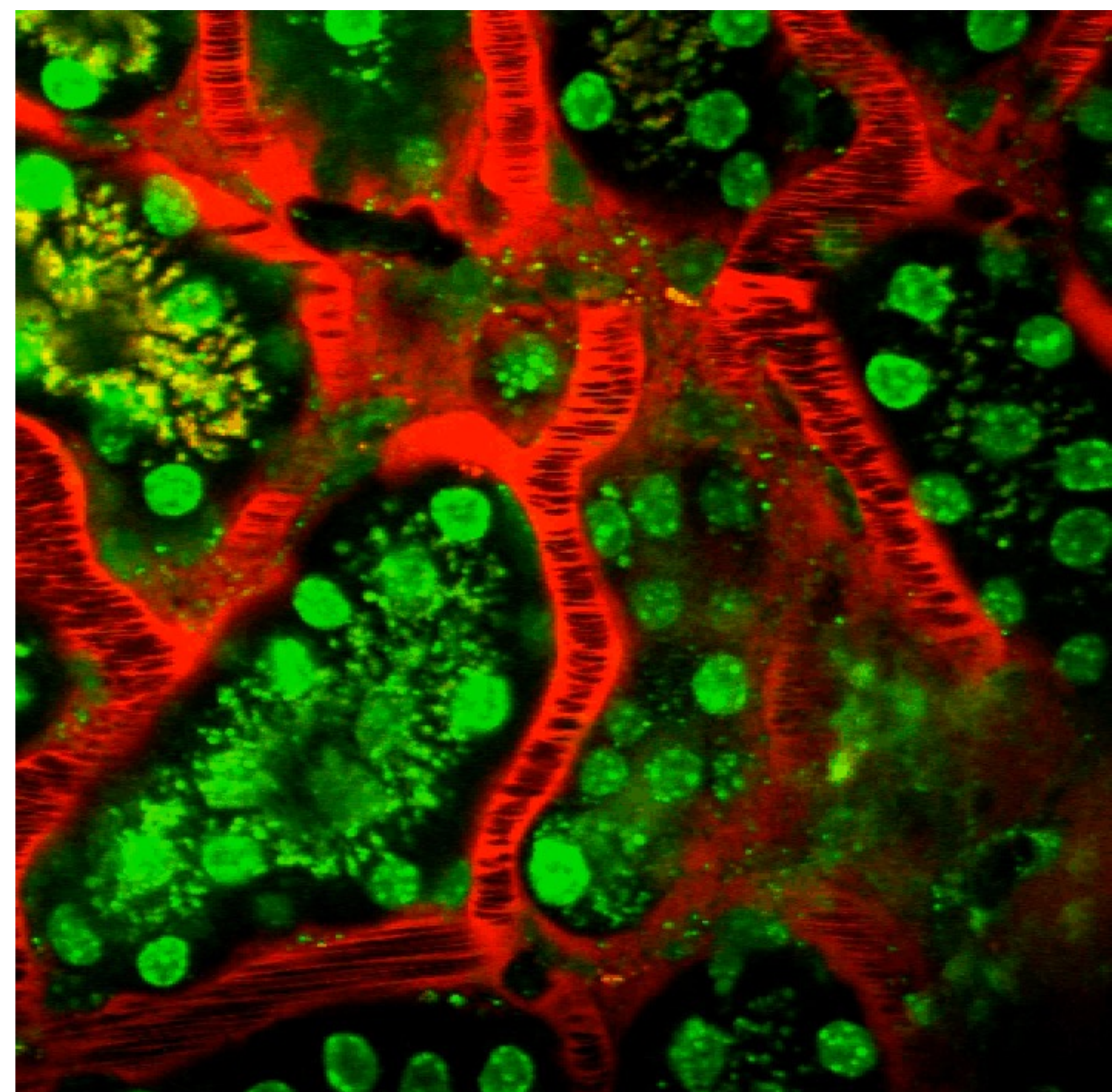
- Energy of two (or more) photons are added during excitation
- Excitation (hence emission) only in the focal point (limited photodamage)
- Excitation with long wavelength (near-IR), short (fs) light pulses
- Large (up to 2 mm) penetration due to long wavelength




Single-photon fluorescence

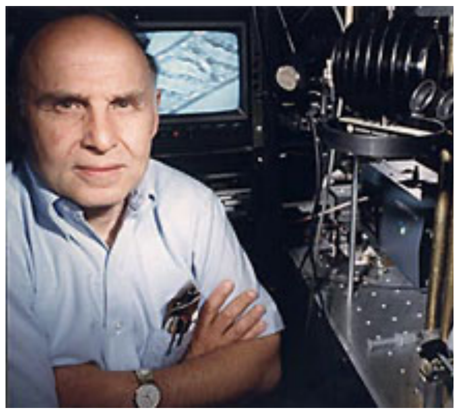

Two-photon fluorescence


Cortical pyramidal cells

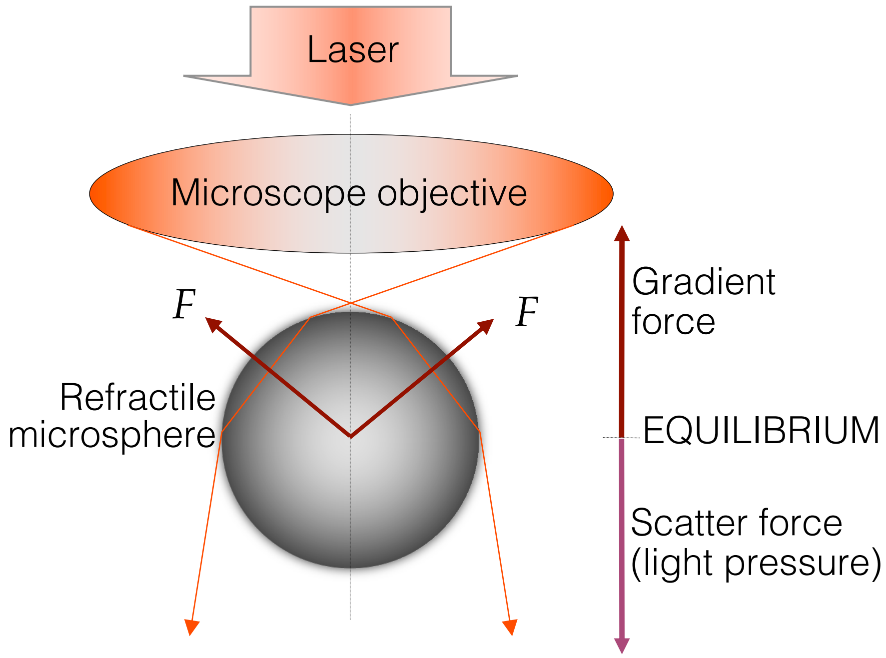

Green: proximal kidney tubules; Red: albumin (plasma)

Laser tweezers

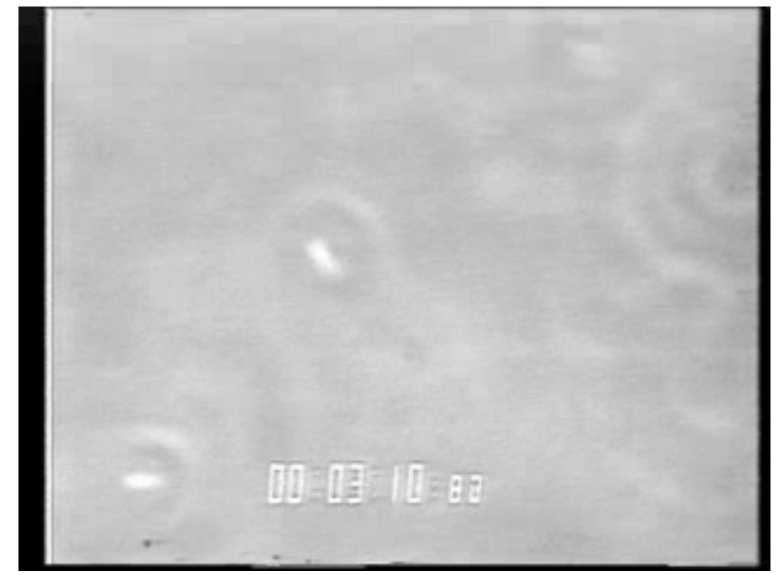
Laser property utilized: power density, steerability



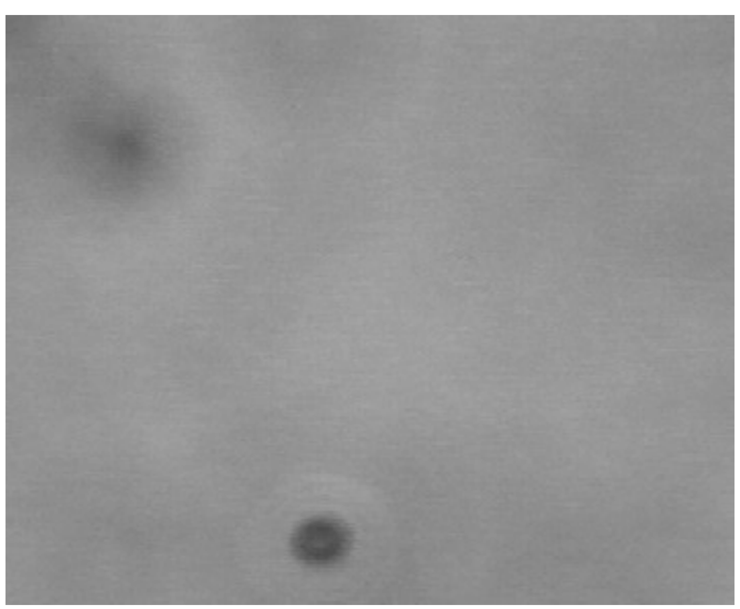
Arthur Ashkin (1970)



In the laser tweezer, momentum change occurs between the photons and the trapped particle.



Trapping bacterial cells with laser tweezers



3 µm latex (polystyrene) microspheres in the optical trap

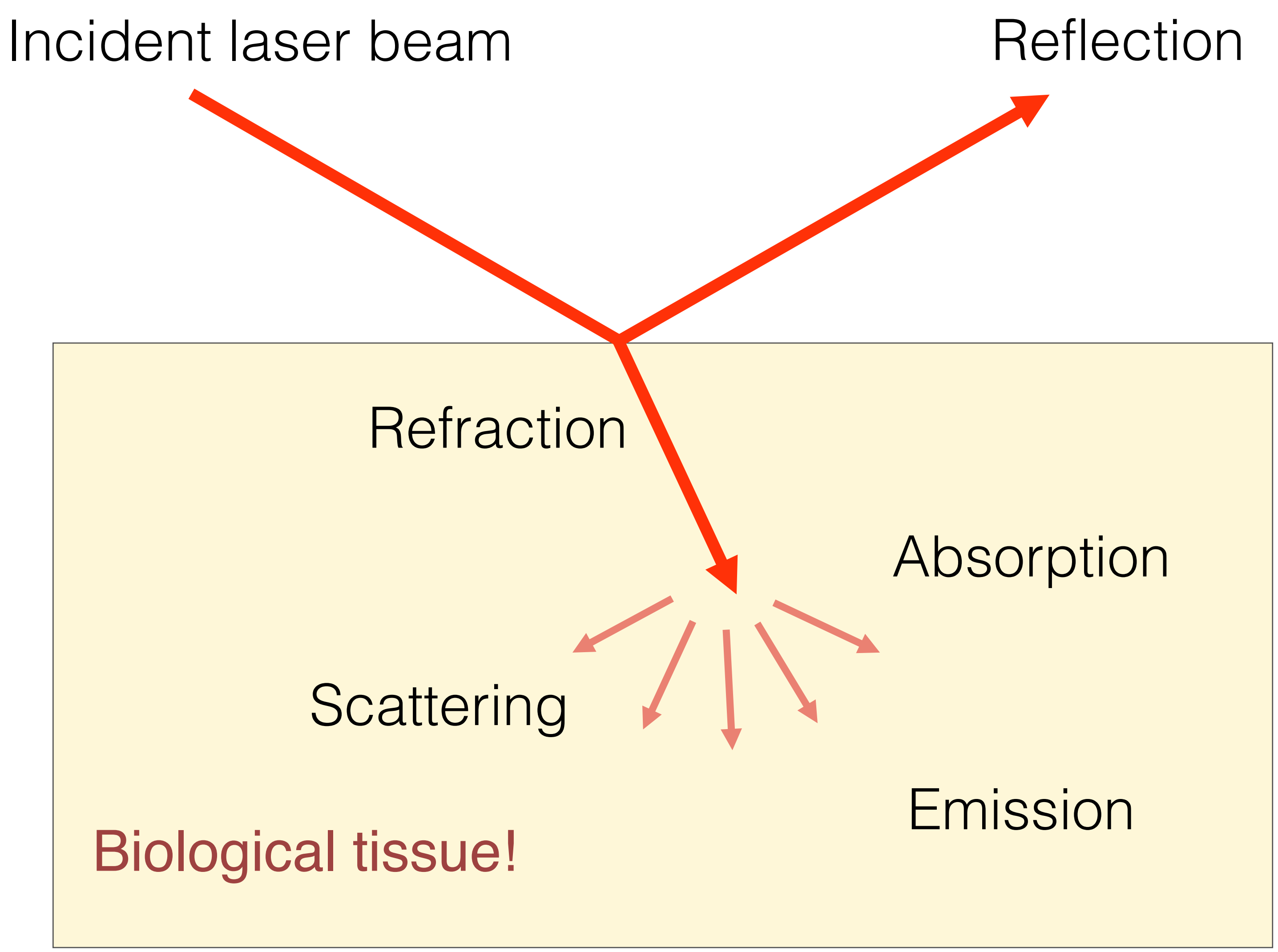
Manipulating molecules with laser tweezers

Actin filament

dsDNA

Molecular force measurement!

Medical applications of lasers



Laser properties to consider:

- Steerability (small divergence, surgeries)
- Power (surgical applications)
- Monochromaticity (tissue absorbance)
- Coherence (interference, image formation)

The effects depend not only on the properties of the laser, but also on those of the biological tissue: absorbance, transmittivity, light-induced reactions.

Medical applications of lasers

- Surgical disciplines: “laser knife”, coagulation, blood-less surgery.
- Tumor removal, tattoo removal: CO_2 and Nd:YAG lasers, holmium laser lithotripsy (urology).
- Dermatology: wide-spread uses (tattoo removal, naevus removal, etc.)
- Dentistry: caries treatment (caries absorbs preferentially).
- Photodynamic tumor therapy: laser acivation of photosensitive chemicals preferentially taken up by the tumor.
- Opthalmology: Retina lesions, photocoagulation, glaucoma, photorefractive keratektomy (PRK).

Dermatological applications

Hair removal

Phototricholysis, photoepilation

Mechanism: selective photothermolysis, selective absorption by chromophores

Employed chromophores:

1. Carbon (exogenous, carbon or graphite-containing creams)
2. Hemoglobin (endogenous)
3. Melanin (endogenous)

Before treatment

After treatment

Dermatological applications

Tattoo removal

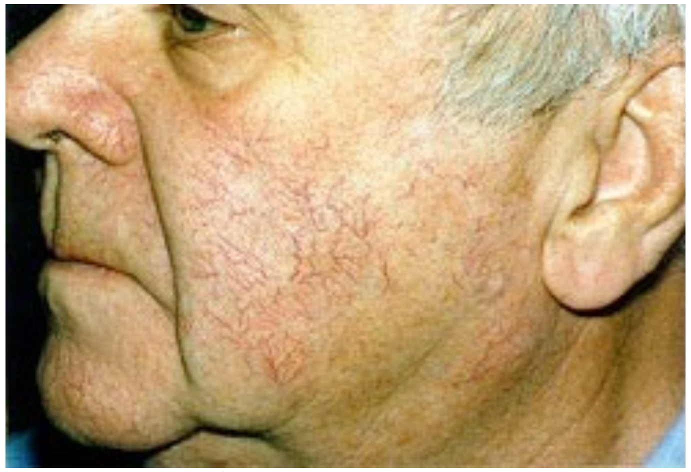
Before treatment | After treatment

Naevus removal

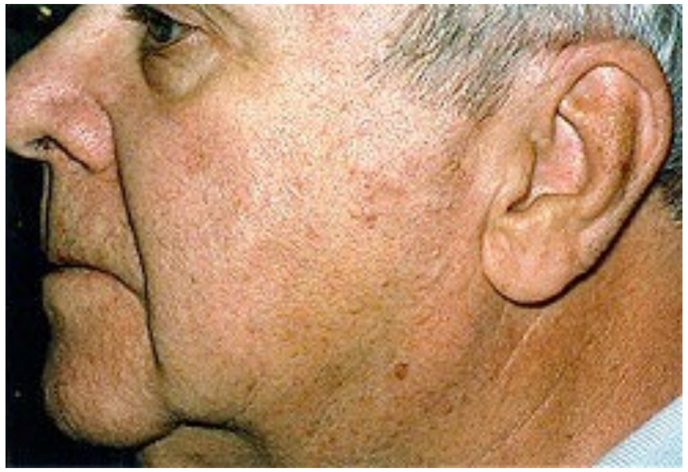
Before treatment | After treatment

Dermatological applications

Removal of superficial blood vessels



Before treatment



After treatment

Resurfacing

Wrinkle removal

Rhinophyma (sebaceous gland hypertrophy, fibrosis)

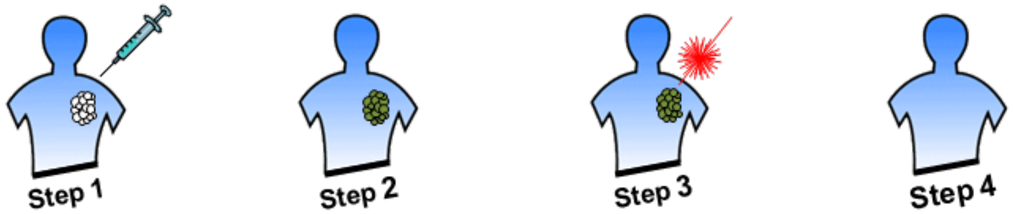
Oncological applications: Photodynamic therapy

Photodynamic therapy (PDT):
Roswell Park Cancer Institute 1970's.

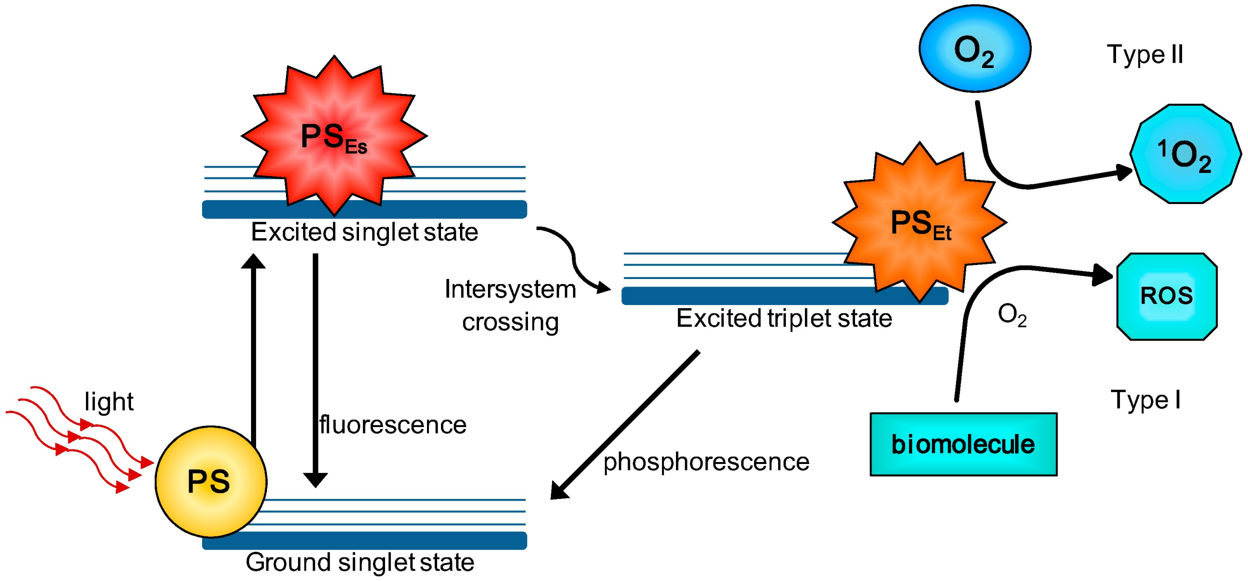
Three-component tumor therapeutic method:
1. Photosensitizing agent, 2. Light, 3. Oxygen.

Delivery of light into the patient: surface exposure, optical fiber

Steps:

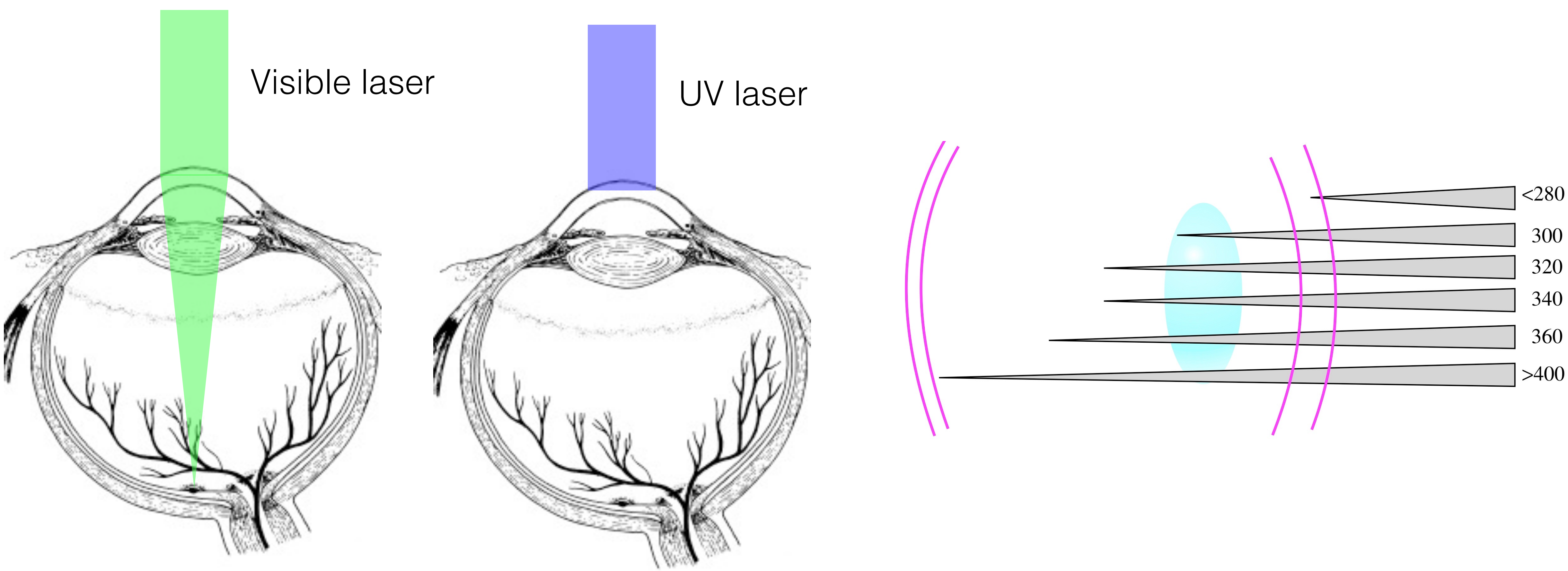


1. Administration of photosensitizing agent (aminolevulic acid, ALA).
2. Incubation for few hours. ALA is transformed into protoporhyrin IX.
3. Illumination of target area with diode laser (few minutes).
4. Protoporphyrin absorbs ➛ excited singlet state ➛ triplet state ➛ energy transfer with triplet oxygen ➛ excited, reactive oxygen ➛ tissue reaction. The illuminated area necrotizes in a few days.



Ophthalmologic applications:
Considerations

Transmittivity of optical media is wavelength-dependent



Ophthalmologic applications
LASIK

"Laser-assisted In Situ Keratomileusis"
A type of refractive laser eye surgery

History:

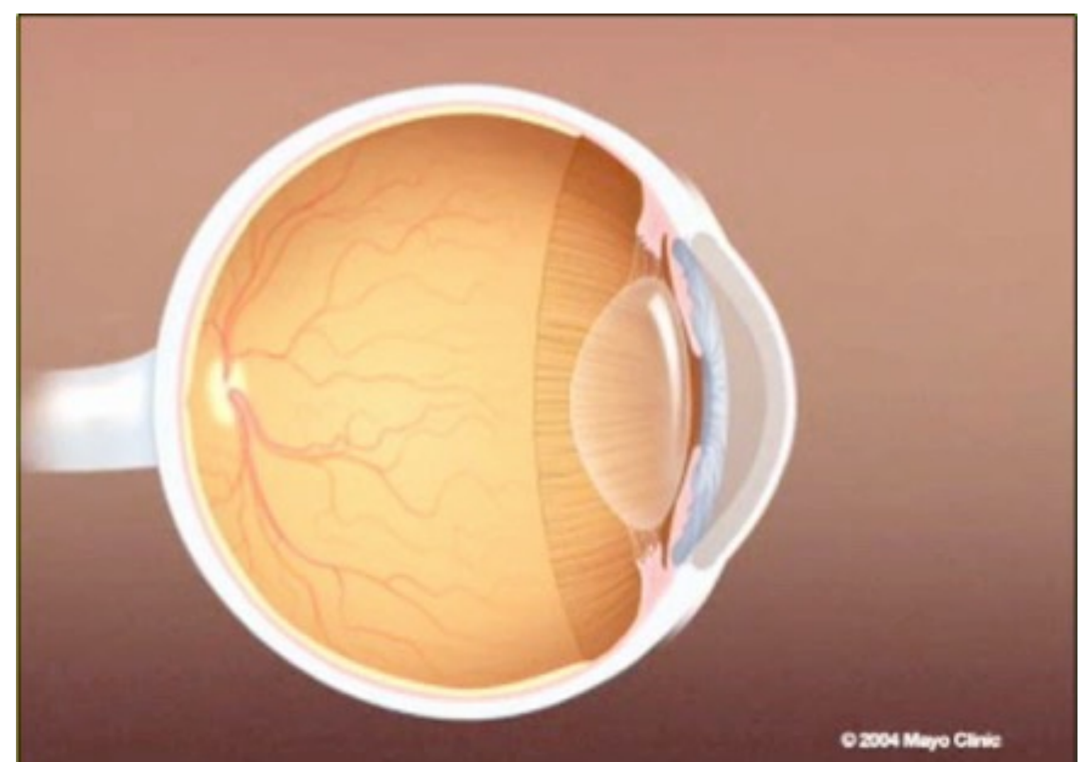
Jose Barraquer, 1970: construction of a microkeratome, with which he was able to cut lines and lobes in the cornea with laser (keratomileusis).

Lucio Buratto (Italian) and Ioannis Pallikaris (Greek), 1990: combination of keratomileusis photorefractive keratectomy.

Thomas and Tobias Neuhann (Germany), 1991: automated microkeratome.

Steps:

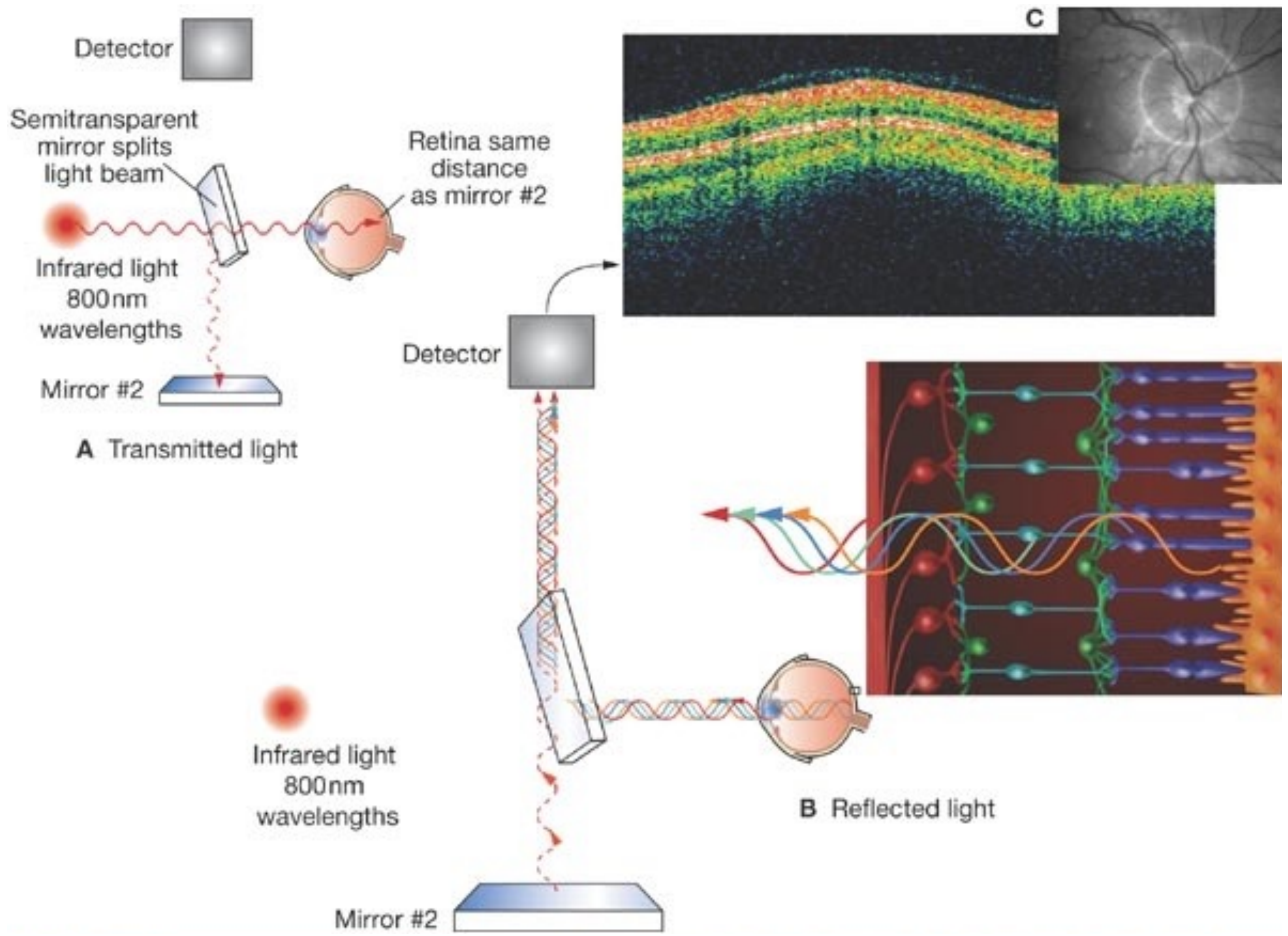
1. Removal of contact lens (7-10 days prior to treatment)
2. Scanning the topography of the cornea with low-power laser.
3. Cutting and lifting a layer of the cornea with femtosecond laser.
4. Removal of material from the corneal stroma (few tens of microns). Excimer laser (193 nm).

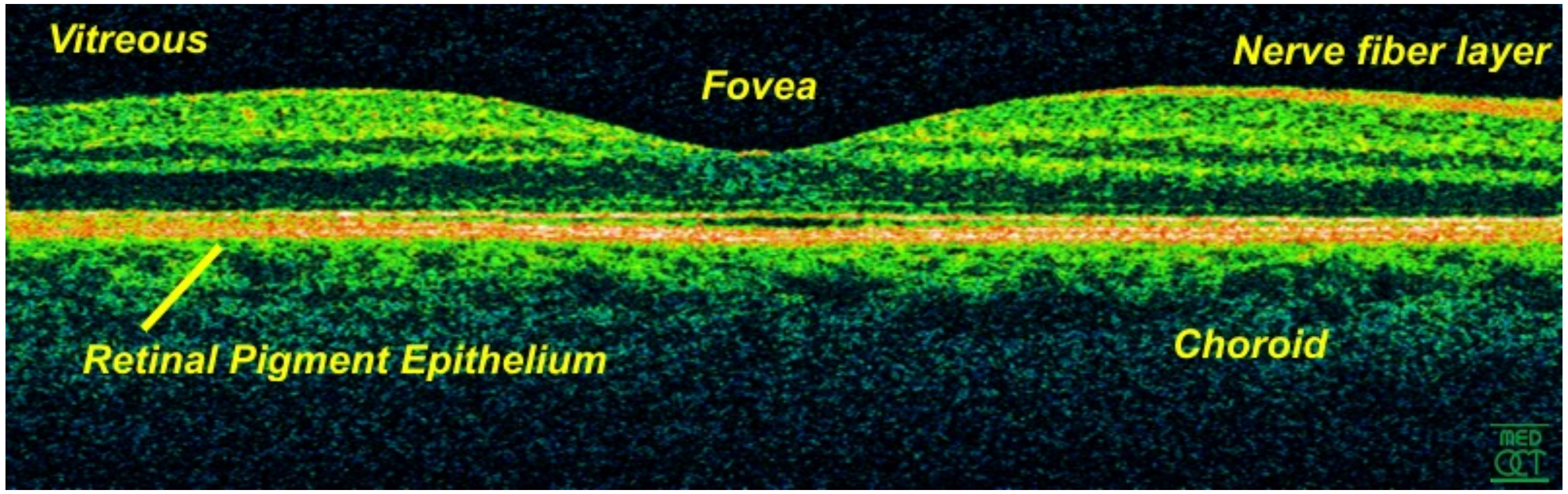


Ophthalmologic applications
Optical Coherence Tomography (OCT)

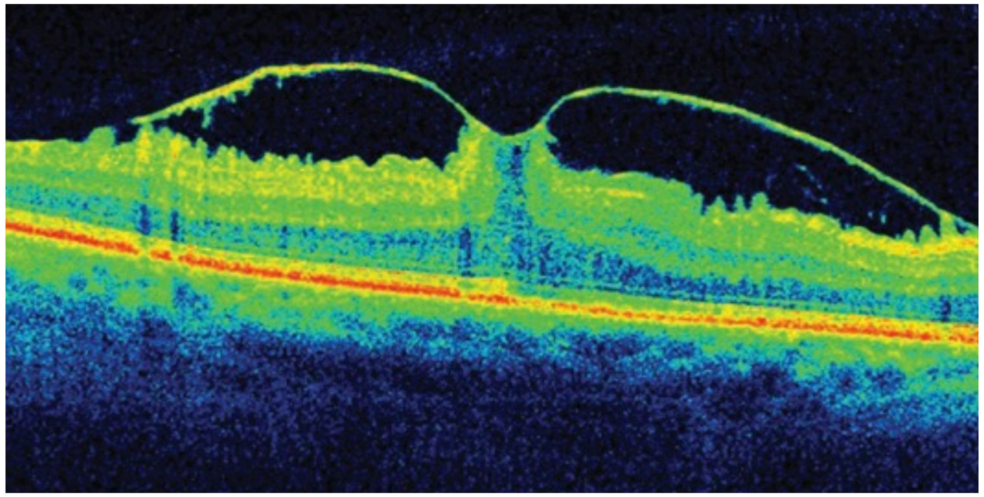
- Non-invasive
- Contrast-agent free
- Near microscopic resolution

Principles:
light rays reflected in deeper tissue layers can be separated from scatter by using interferometry. The spatial position of the reflecting layers can be determined. The structure of the illuminated sample can be resolved within 1-2 mm depth.





Normal retina



Macula degeneration

Feedback

https://feedback.semmelweis.hu/feedback/pre-show-
qr.php?type=feedback&qr=NCLAESAOBZI8SAB0