

# AMPLIFICATION OF LIGHT LASER

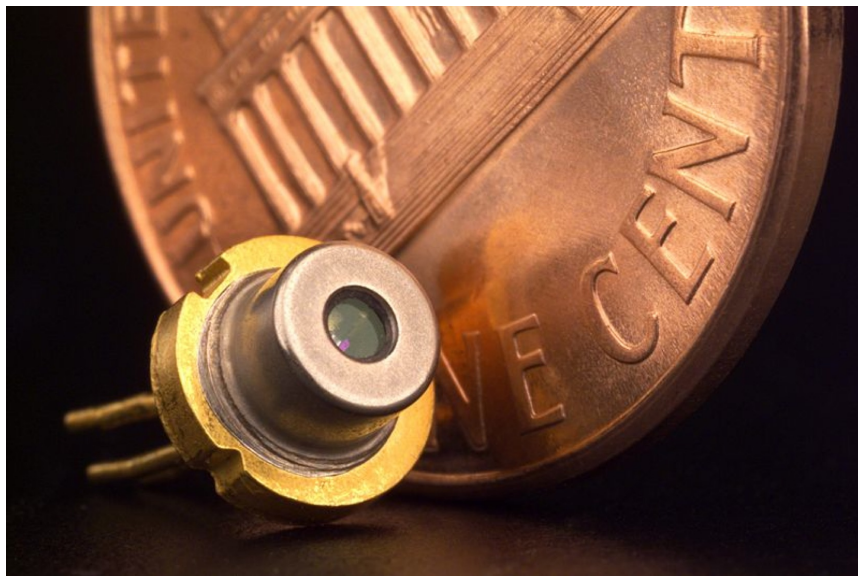
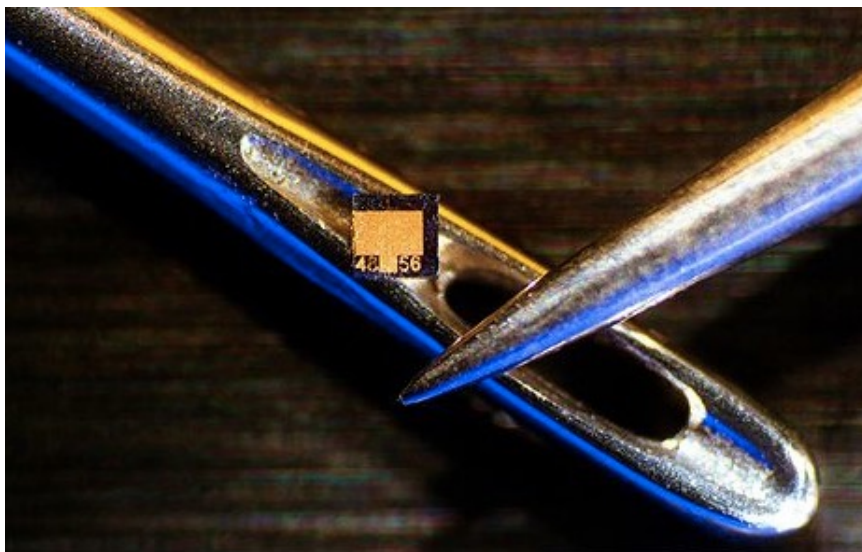
MIKLÓS KELLERMAYER



# 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)



- 1917 - Albert Einstein: theoretical prediction of stimulated emission.



Theodore Maiman  
(1927-2007)

Arthur L. Schawlow  
(1921-1999)



- 1946 - G. Meyer-Schwickerather: first eye surgery with light.

- 1950 - Arthur Schawlow and Charles Townes: emitted photons may be in the visible range.



Nikolay G. Basov  
(1922-2001)

- 1954 - N.G. Basov, A.M. Prochorow, and C. Townes: ammonia maser

- 1960 - Theodore Maiman: first laser (ruby laser)

- 1964 - Basov, 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)



Charles H. Townes  
(1915-)

Alexander M. Prokhorov  
(1916-2002)



Steven Chu  
(1948-)

Gábor Dénes  
(1900-1979)

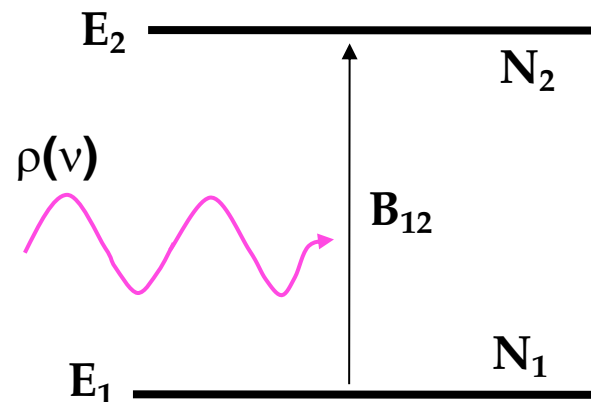


Arthur Ashkin  
(1922-)



# Principles of laser I. stimulated emission

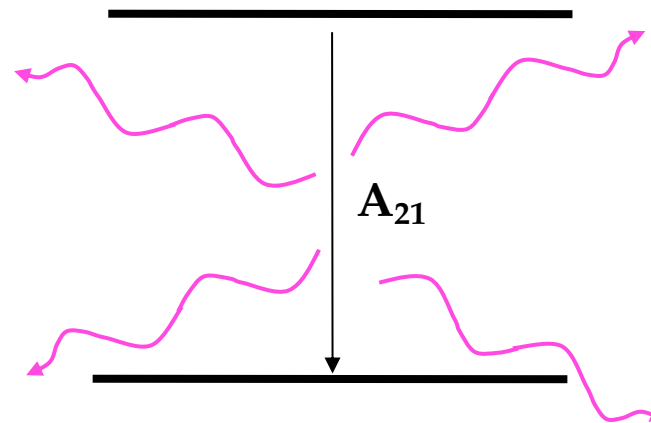
## 1. Absorption



Frequency of transition:  
 $n_{12} = N_1 B_{12} \rho(\nu)$

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

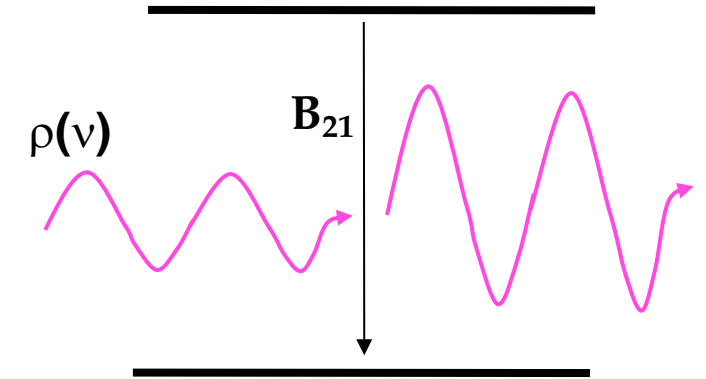
## 2. Spontaneous emission



Frequency of transition:  
 $n_{21} = N_2 A_{21}$

$E_2 - E_1$  photons  
 travel independently in all  
 directions.

## 3. Stimulated emission



Frequency of transition:  
 $n_{21} = N_2 B_{21} \rho(\nu)$

In the presence of external 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.

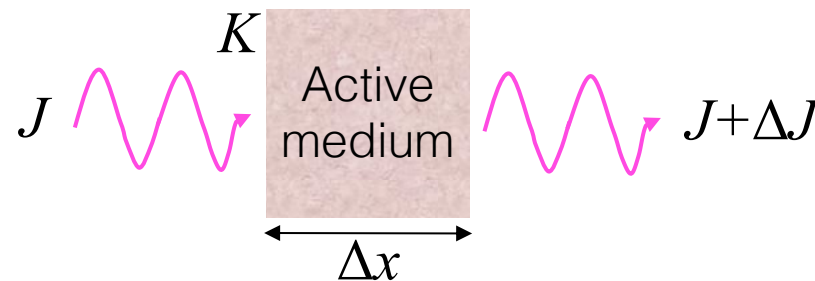
$N_1, N_2$  : number of atoms or molecules on the given energy level.

$B_{12}, A_{21}, B_{21}$  : transition probabilities (Einstein coefficients),  $B_{12} = B_{21}$

# Principles of laser II.

## Population inversion

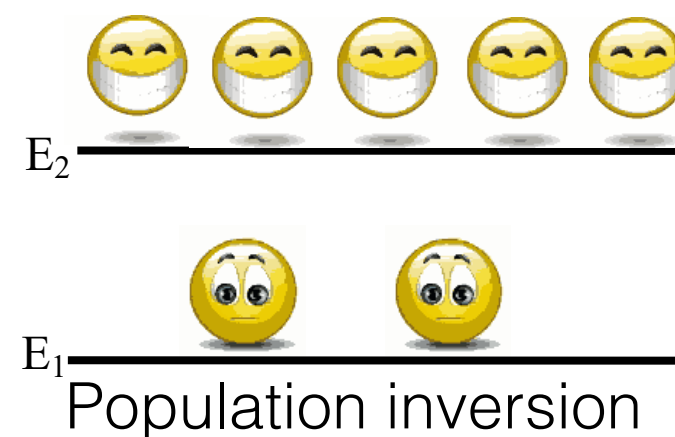
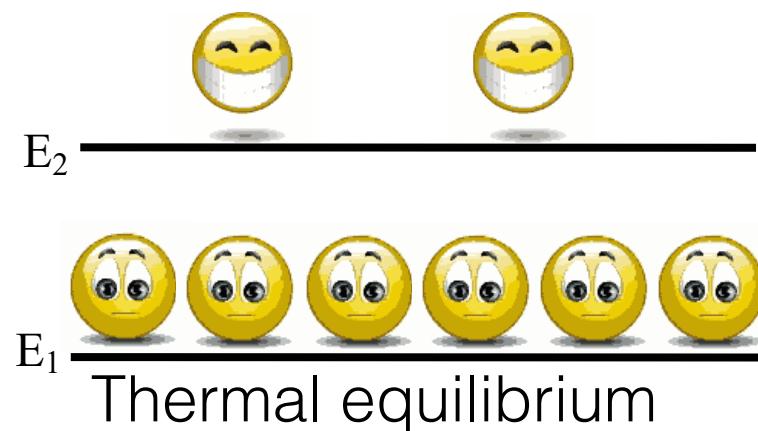
Light amplification depends on the relative population of energy levels.



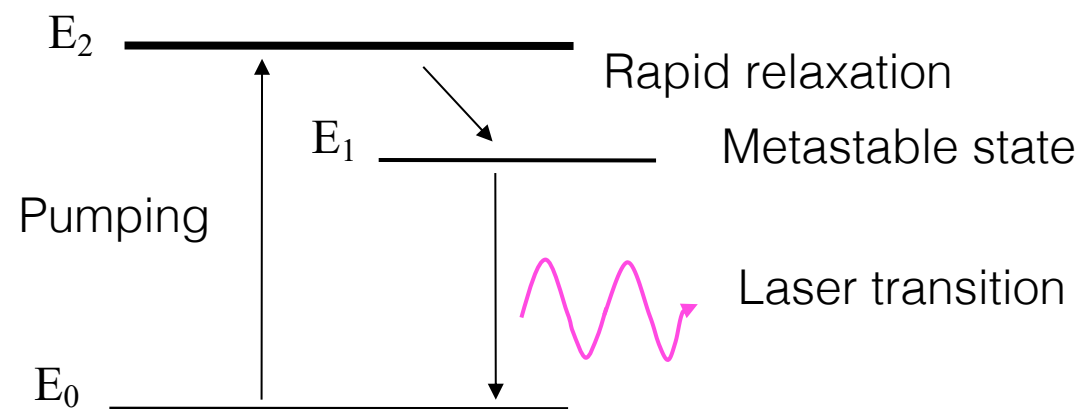
$$\Delta J = JK(N_2 - N_1)\Delta x$$

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

N.B.: If  $\Delta J$  is positive, more light exits the medium, than has entered!

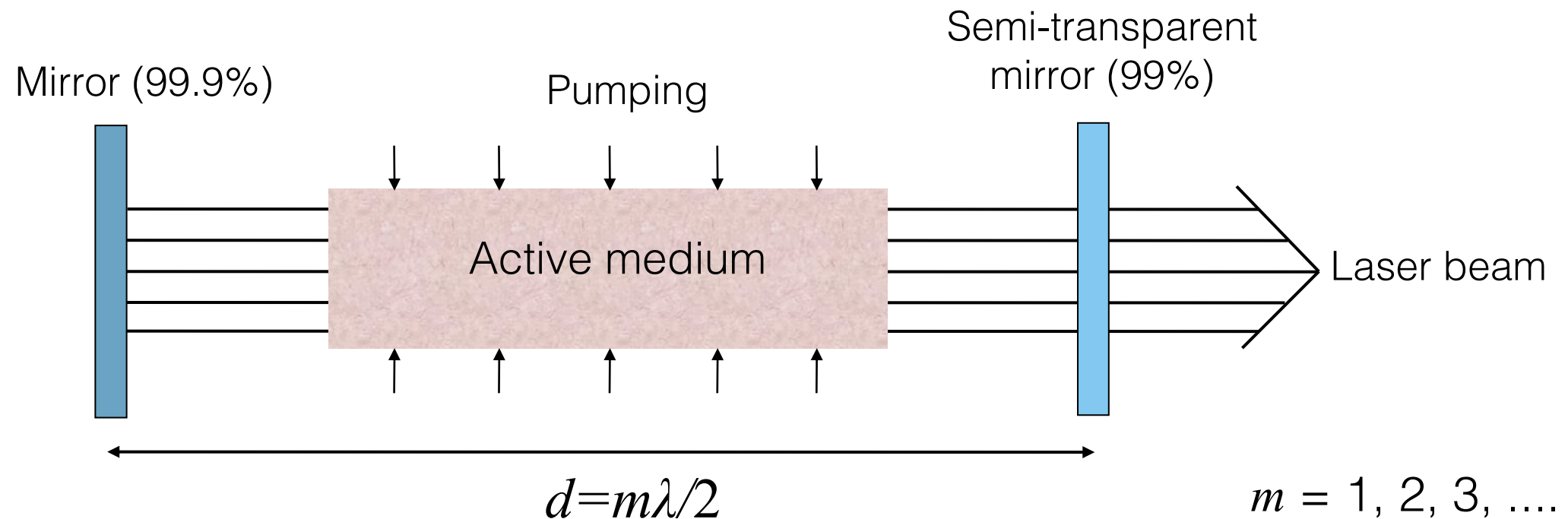


- Population inversion only in multiple-state systems!
- Pumping: electrical, optical, chemical energy



# Principles of laser III.

## Optical resonance

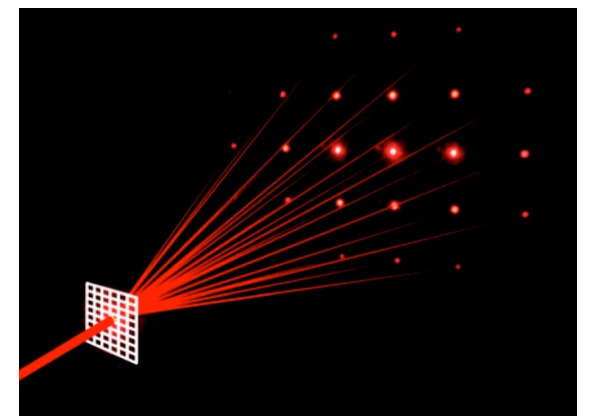
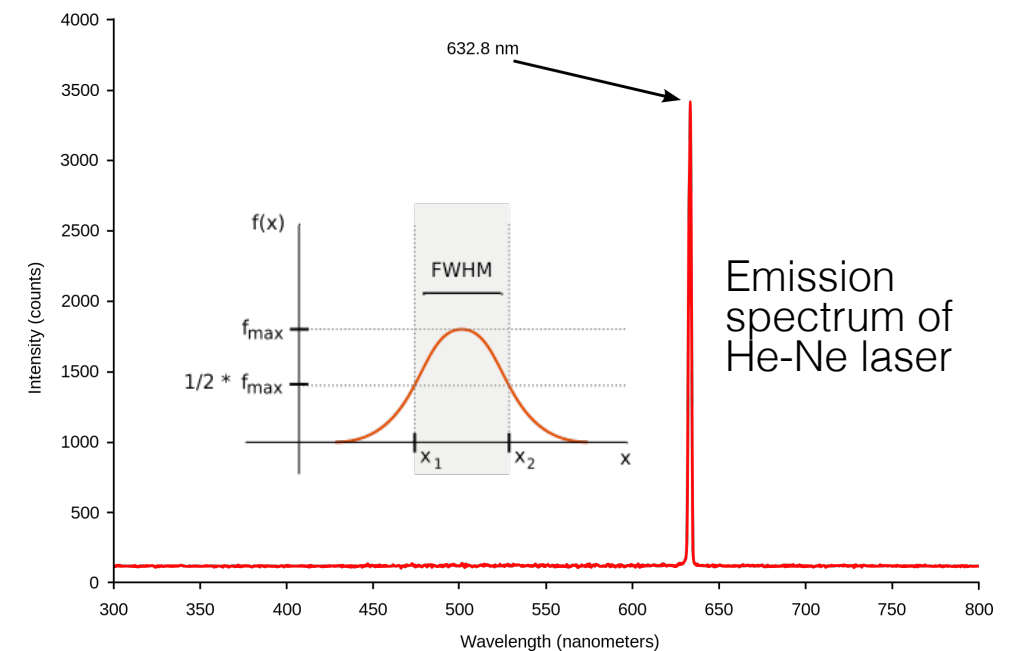


Resonator:

- 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<sub>2</sub> 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<sub>2</sub> laser: CO<sub>2</sub>-N<sub>2</sub>-He mixture;  $\lambda \sim 10 \mu\text{m}$ ; Huge power (100 W)

## 3. Dye lasers

Dilute solution of organic dyes (e.g., rhodamine, coumarine);  
Pumped by another laser.

Large power (Q-switched mode); Tunable

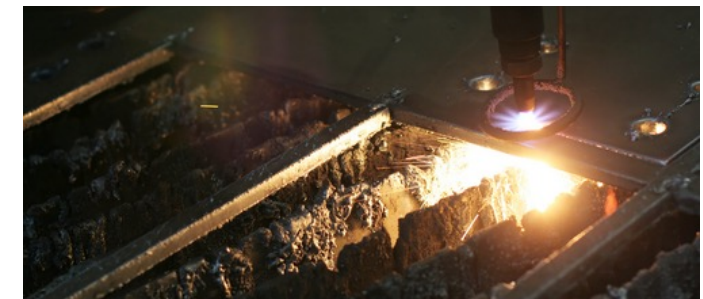
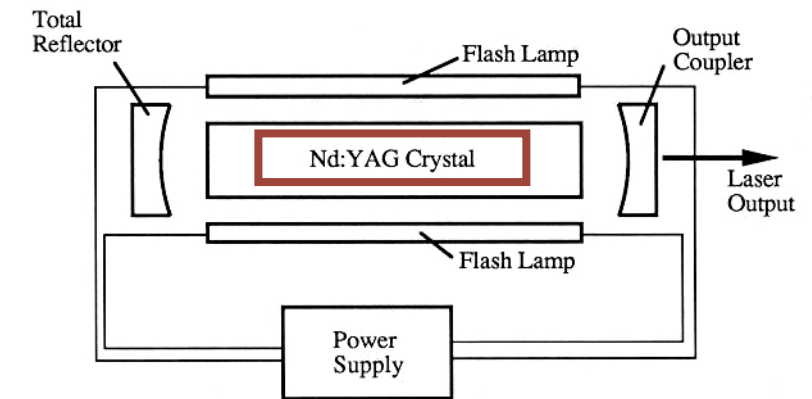
## 4. Semiconductor (diode) lasers

On the boundary of p- and n-type doped semiconductors.

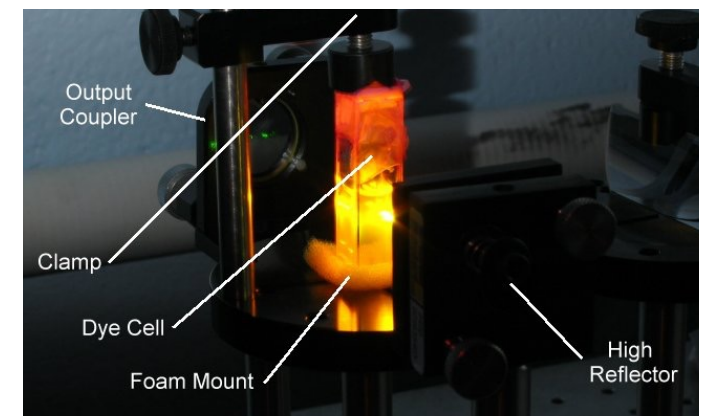
No need for resonator mirrors (total internal reflection)

Red, IR spectral range. Huge CW power (up to 100W)

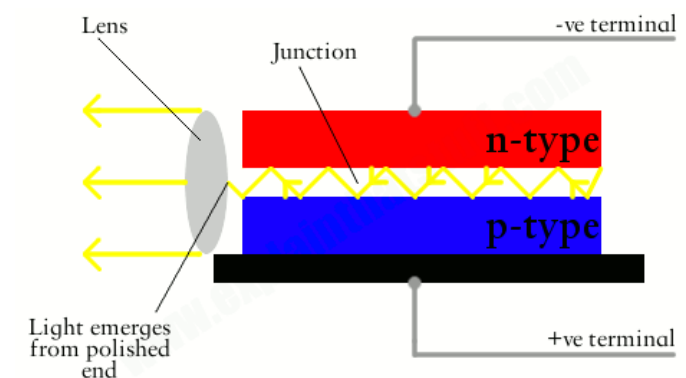
Beam characteristics are not very good. Wide use because of small size.



CO<sub>2</sub> laser  
(cutting a metal sheet)



Dye laser



Diode laser

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

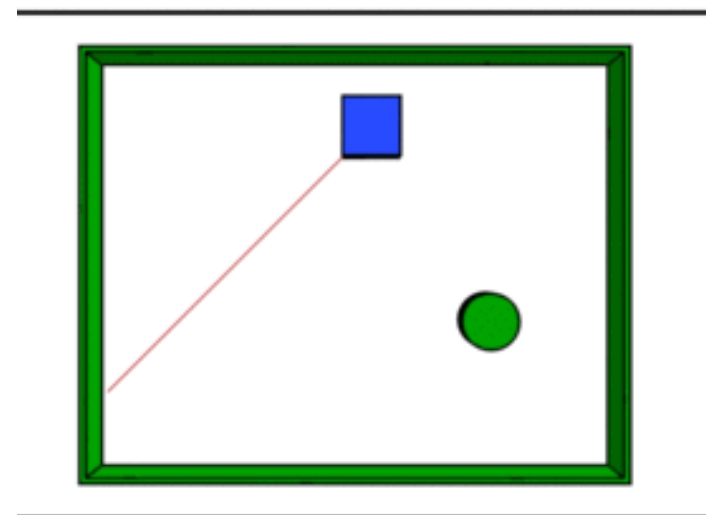
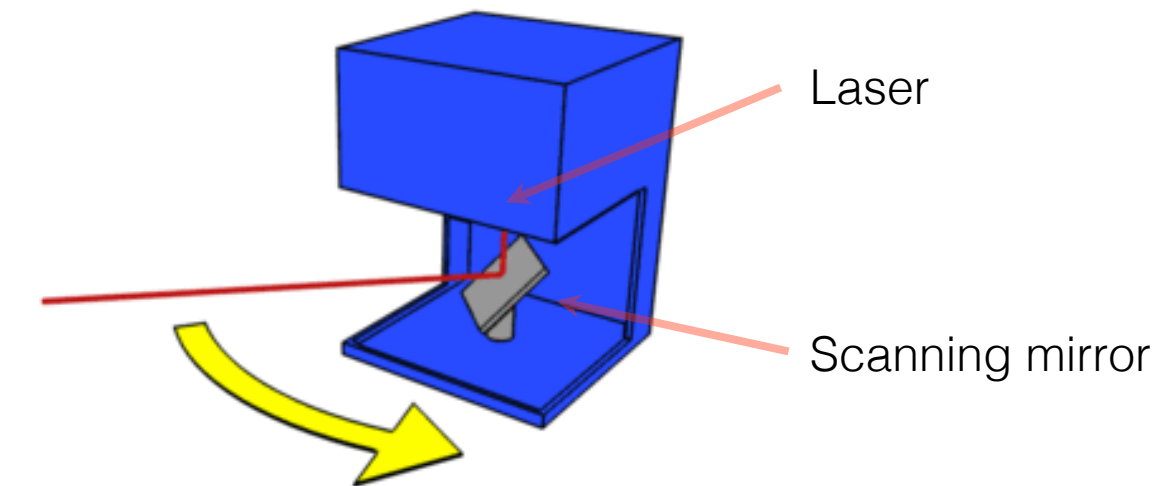


# Factors to be considered in laser applications

- 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<sub>2</sub> laser
  - 100–3000 W – industrial CO<sub>2</sub> laser (laser cutter)
  - 1 kW – 1 cm diode laser bar

# Speed measurement with laser

LIDAR: “Light Detection and Ranging”



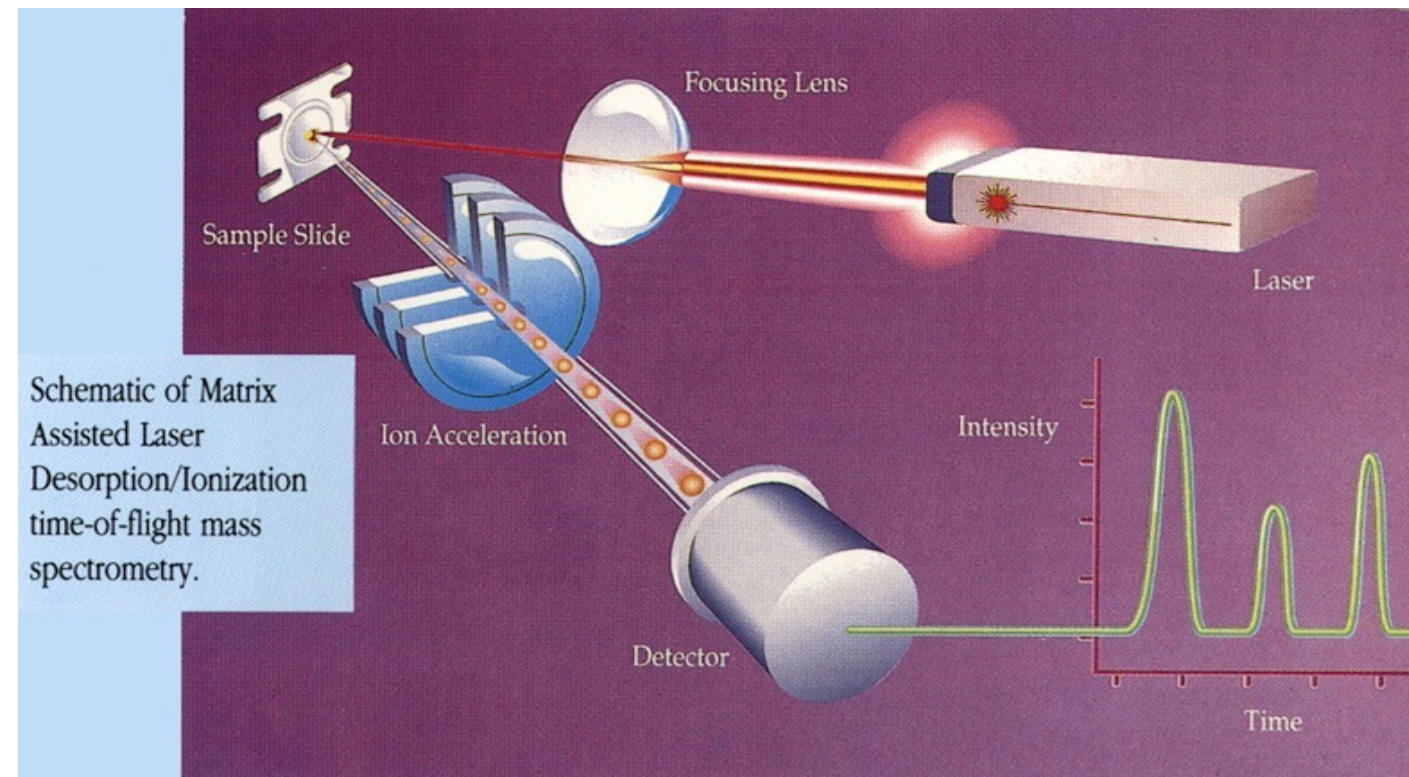
Recording:  
reconstructed spatial  
arrangement.  
In traffic speedometer:  
100 pulses in 0.3 s

Laser property  
utilized:  
Steerability

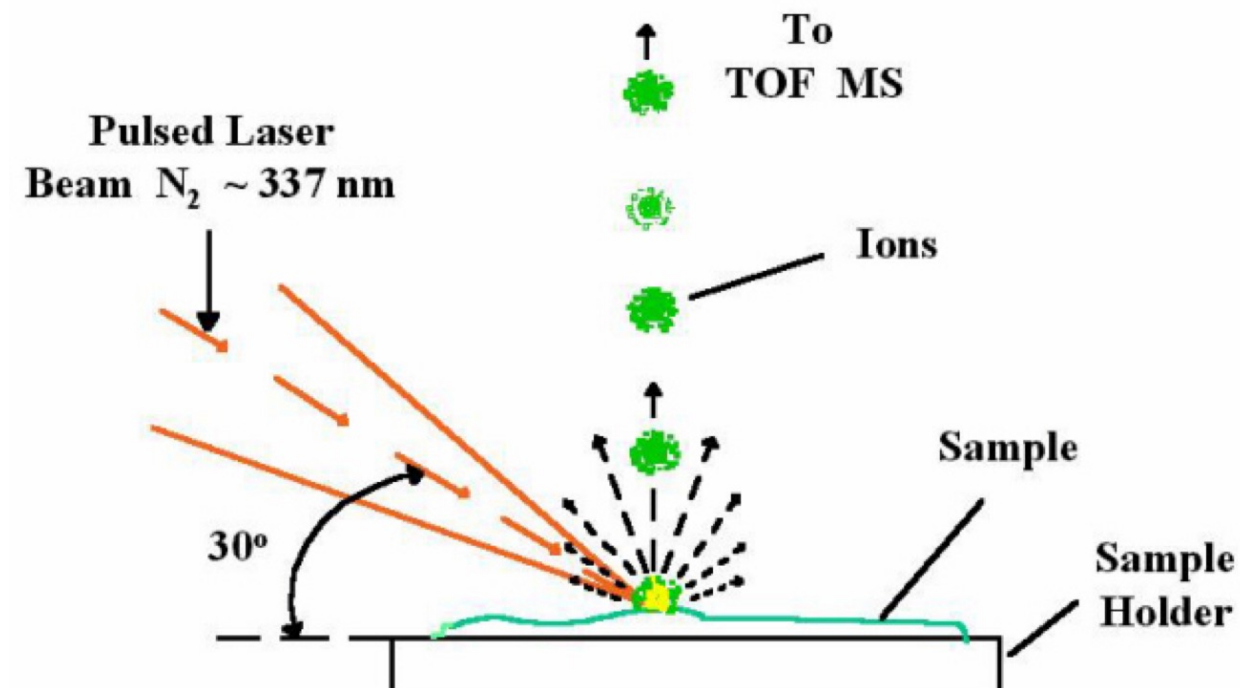


# MALDI-TOF:

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

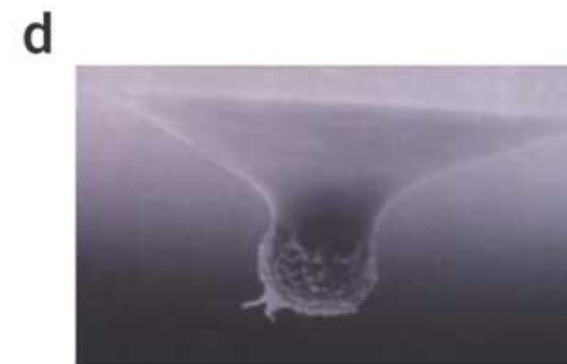
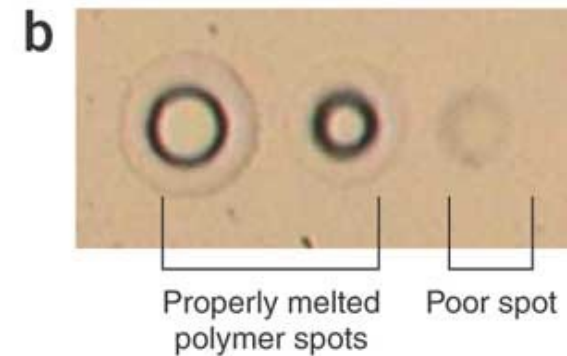
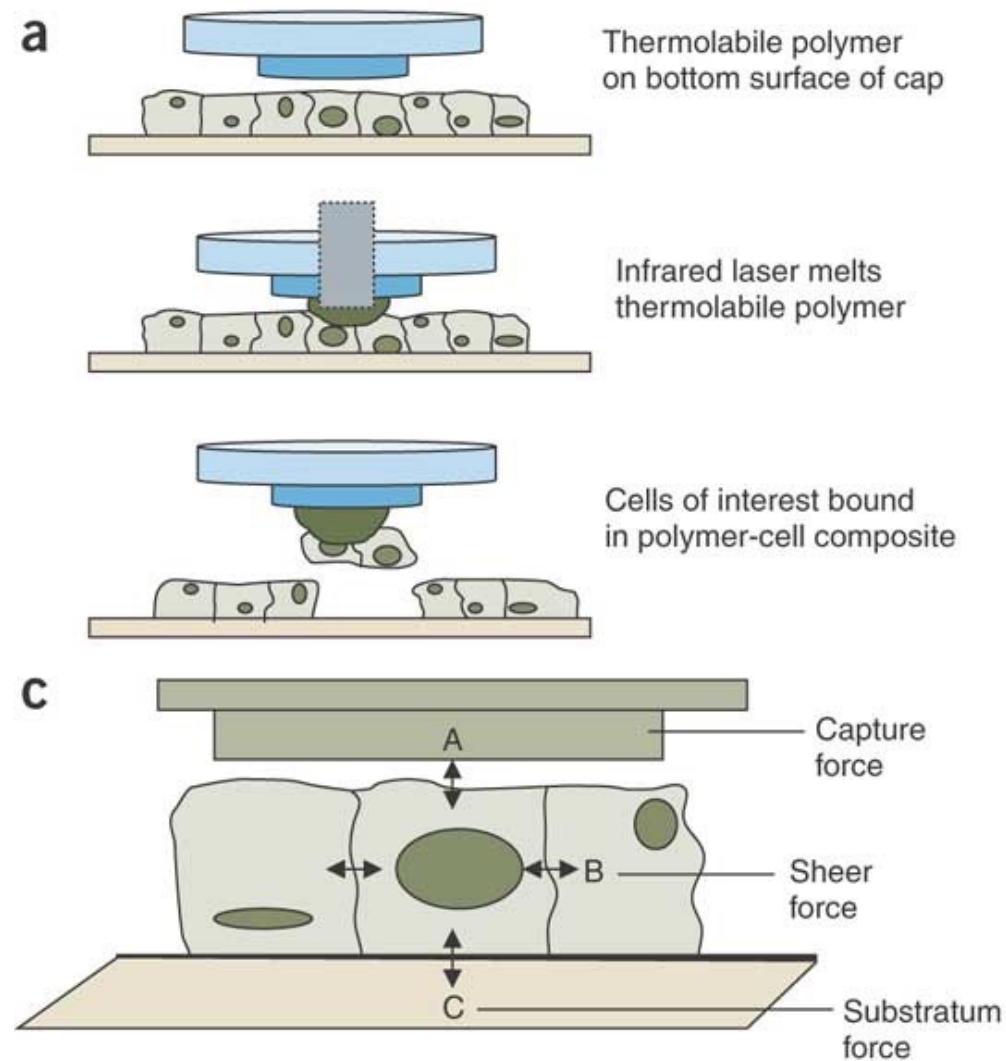


Laser  
property  
utilized:  
Power  
density

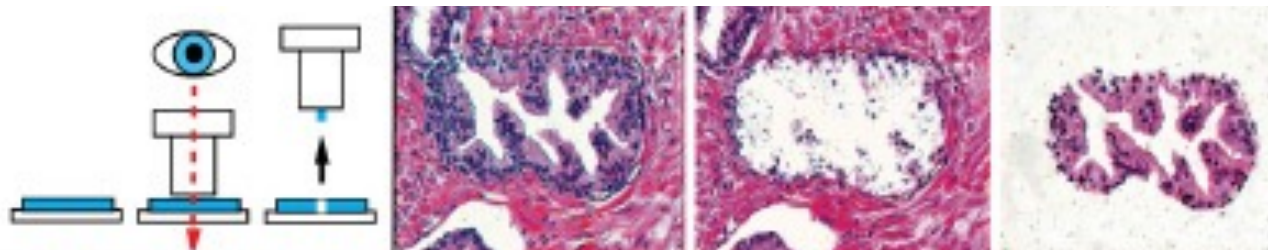




# “Laser capture microdissection”



Laser property utilized:  
Power density,  
steerability



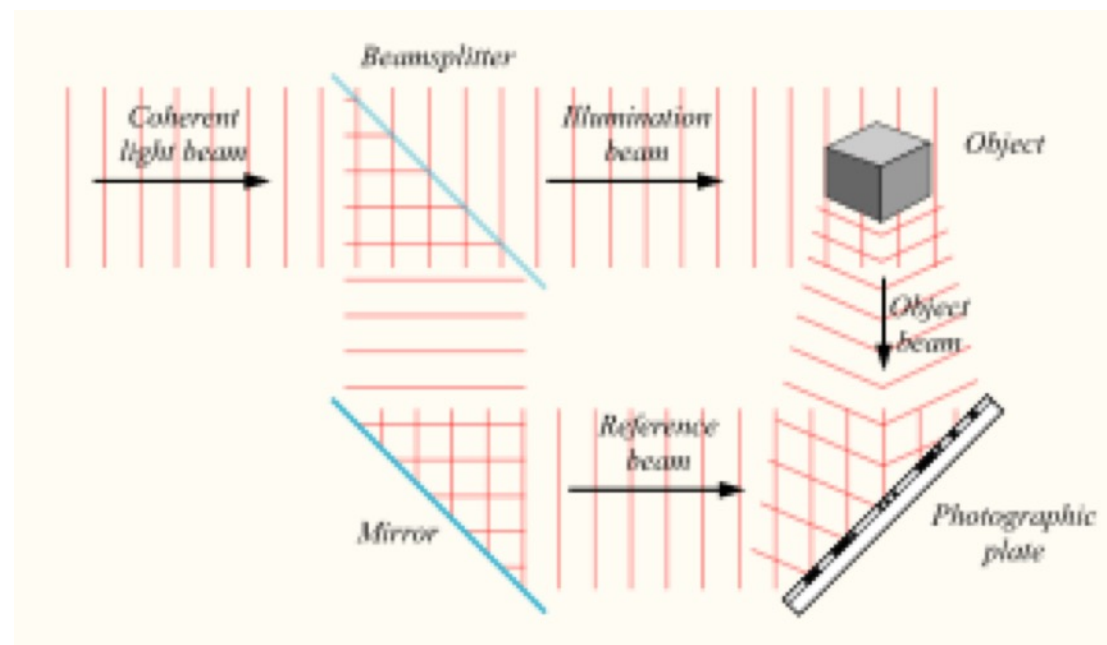
**Significance:** local analytics are possible  
analitika lehetősége (chemistry, genetics)

# Holography

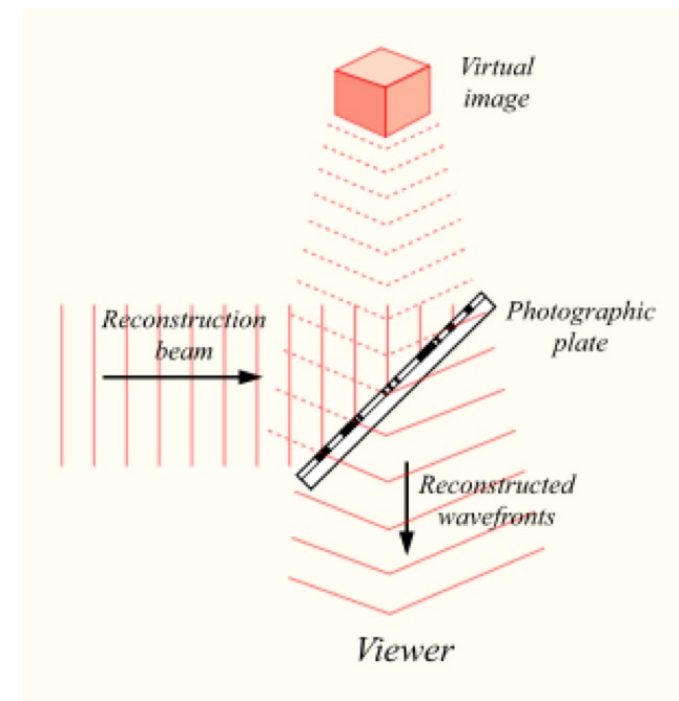
Laser property utilized: Coherence



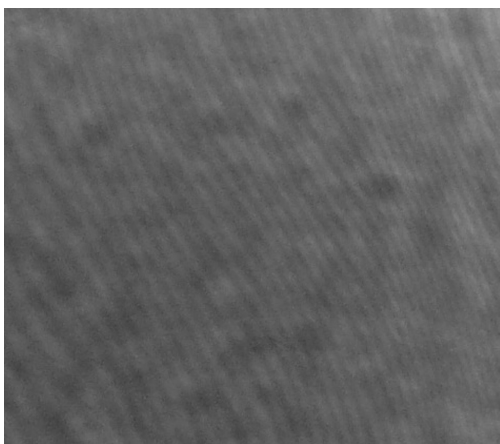
Dénes Gábor  
(1900-1979)



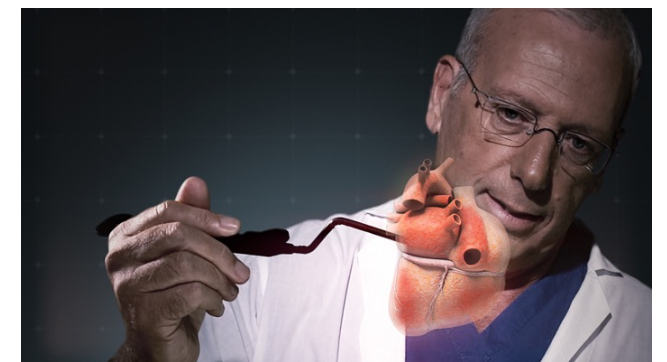
Recording a hologram



Visualization of a hologram



Surface of a hologram recording



Holograms



# Fluorescence Recovery After Photobleaching (FRAP)

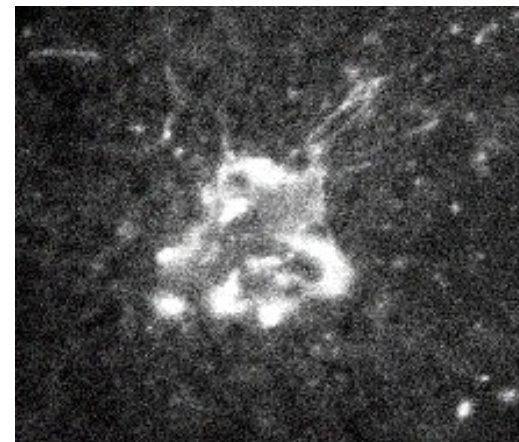
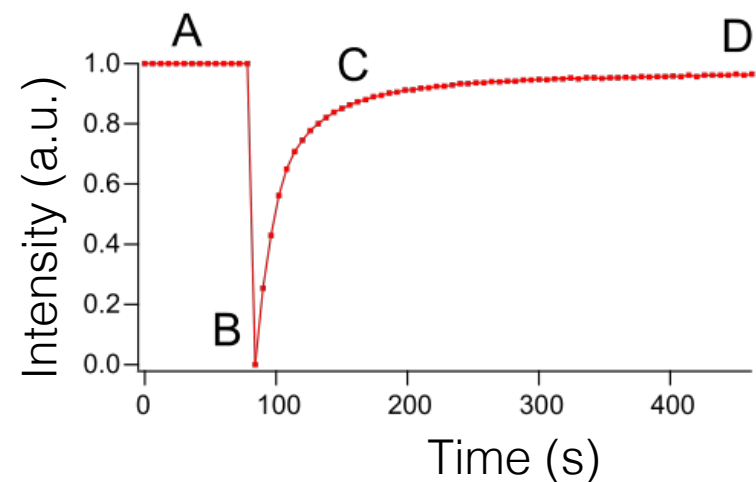
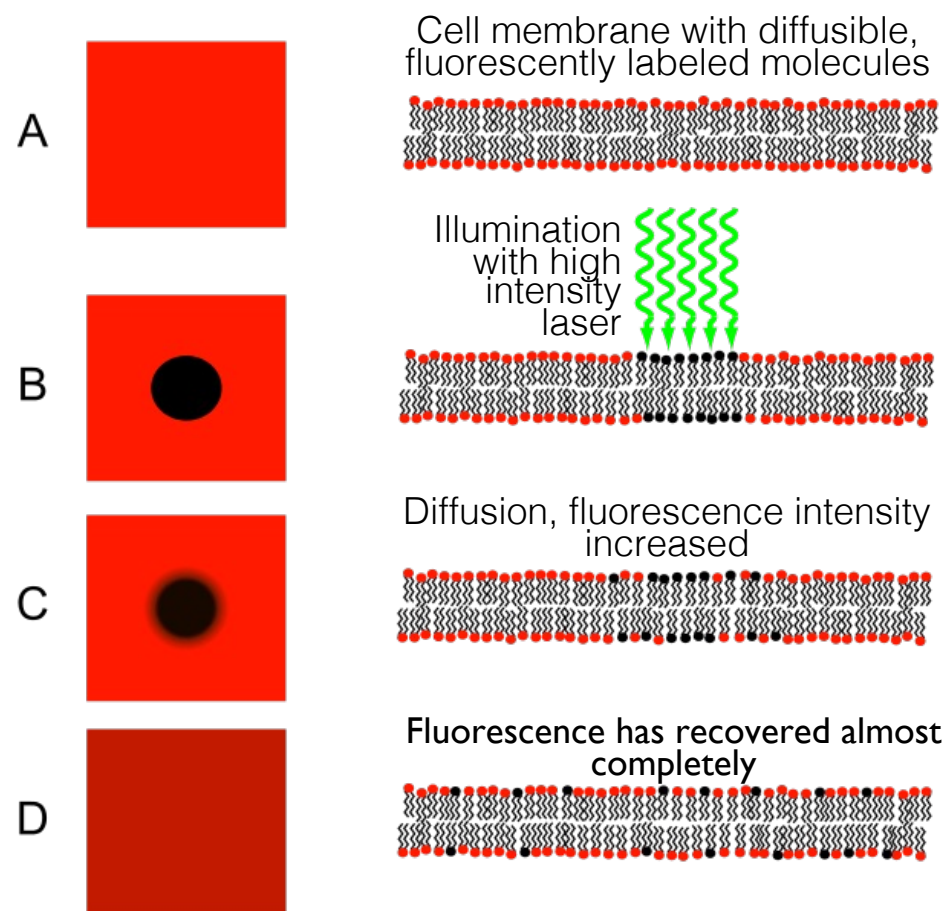


Image prior to bleaching

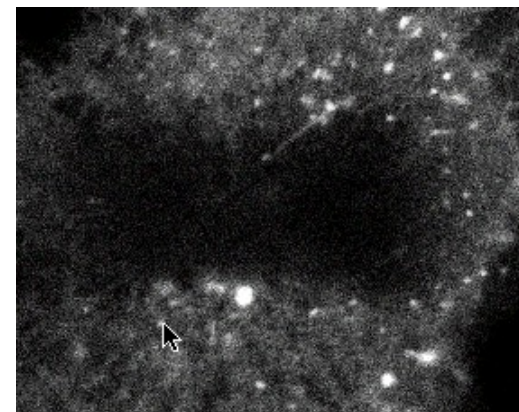
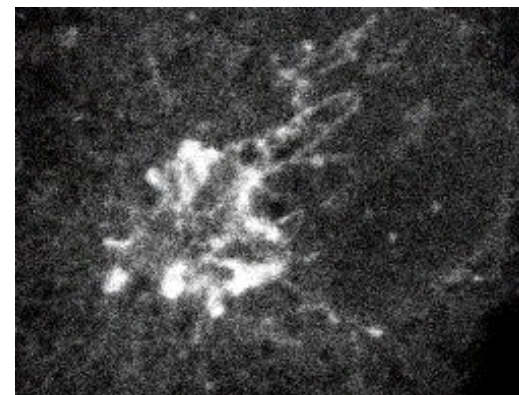


Image just after bleaching



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

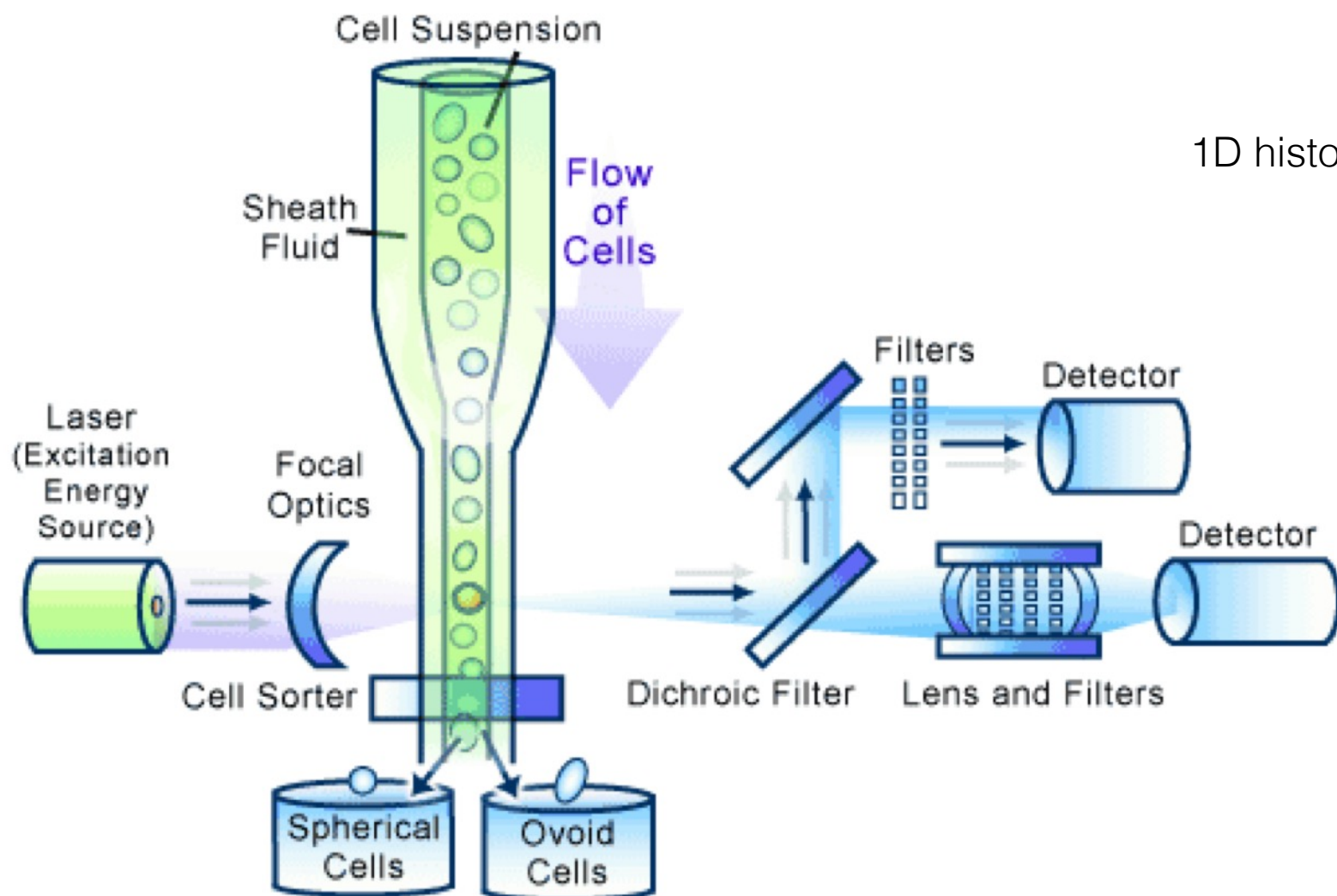


# Fluorescence activated cell sorter (FACS)

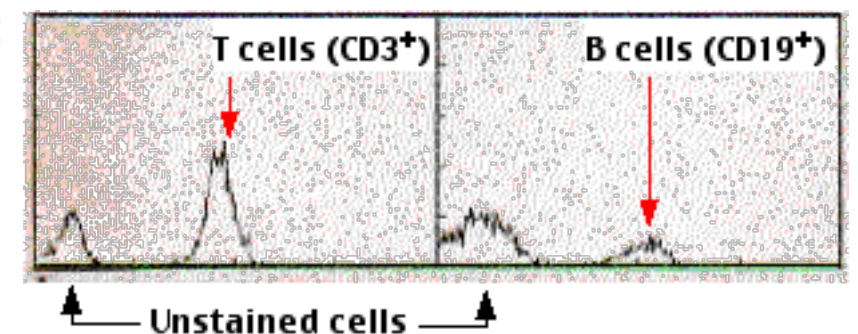
## Flow cytometry

- 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

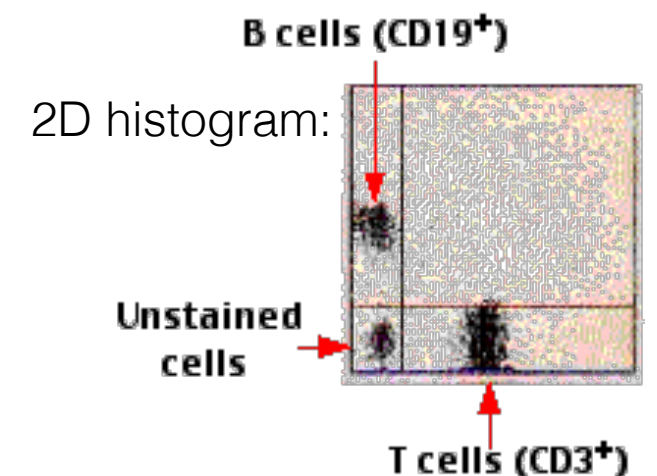
Laser property utilized: monochromaticity



1D histograms:



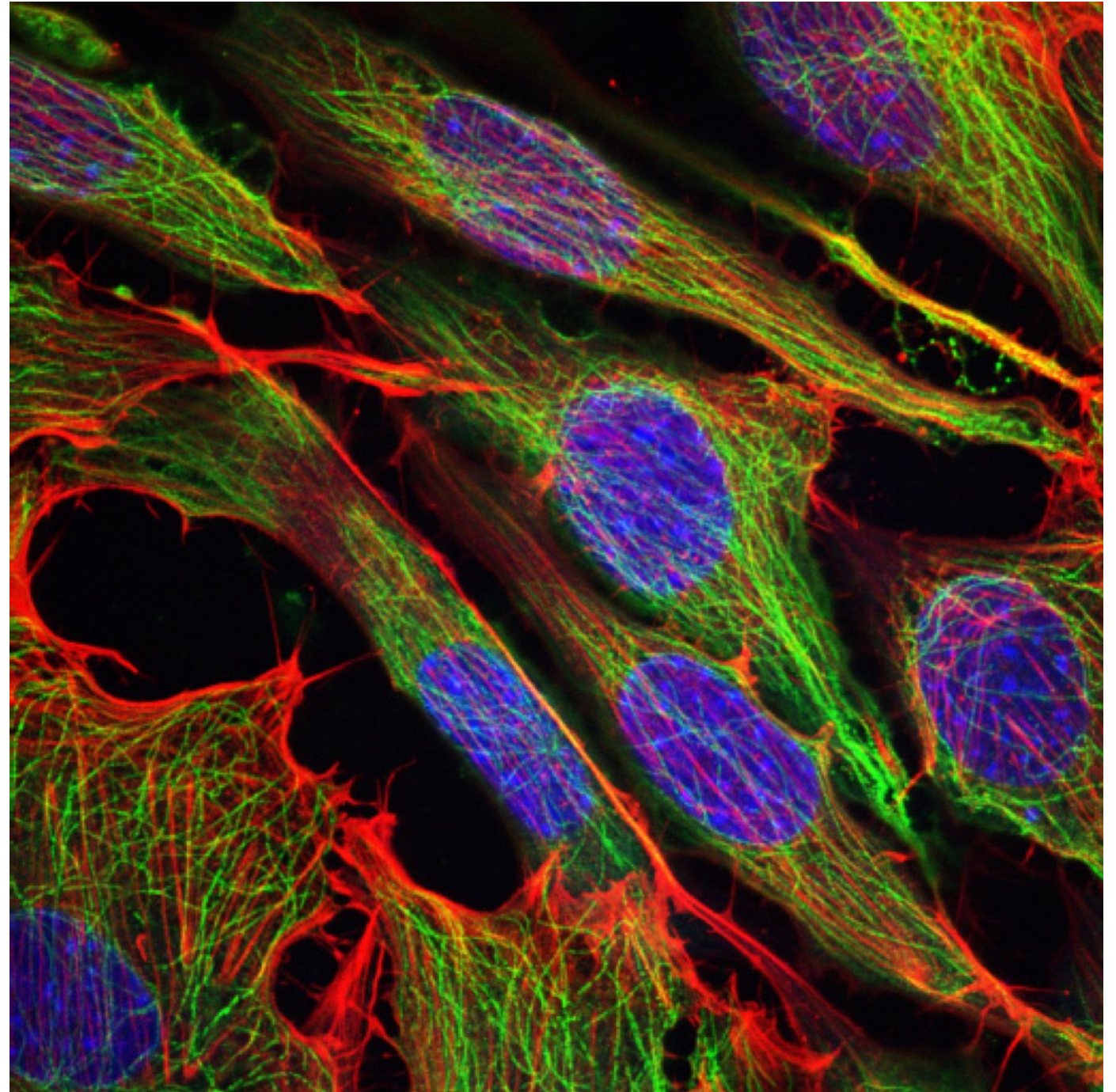
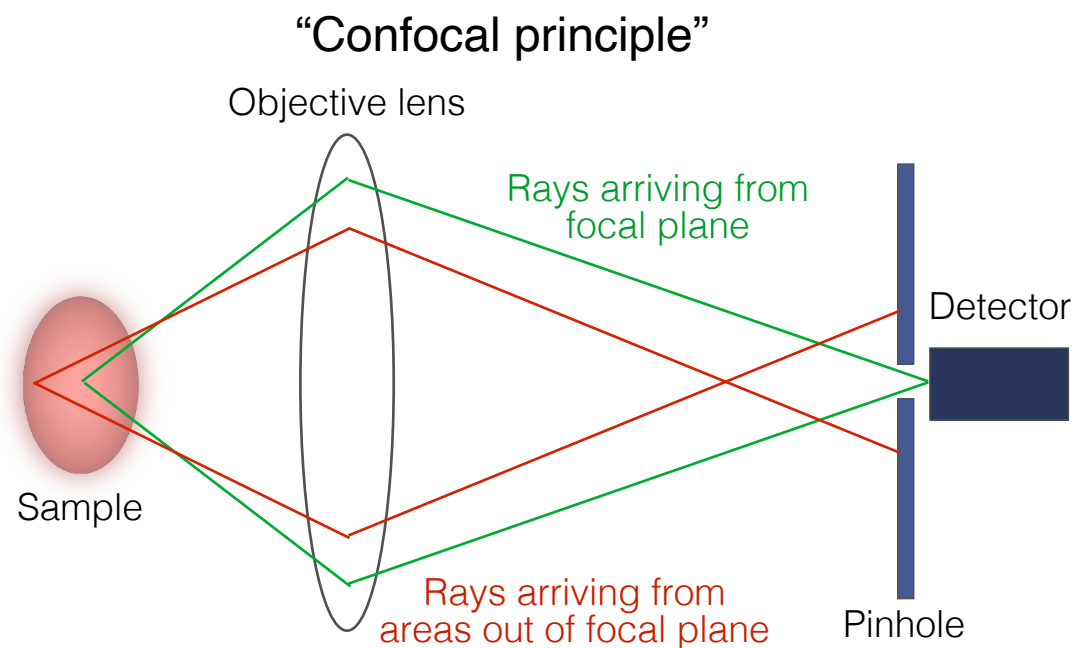
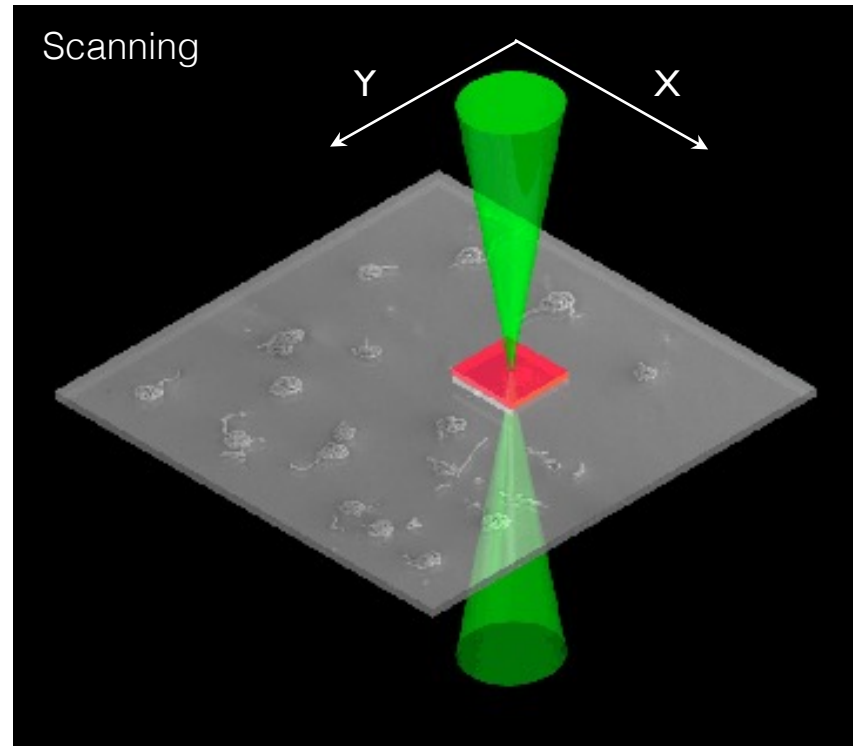
Cytometry statistics





# Laser scanning confocal microscopy

Laser property utilized: monochromaticity, steerability



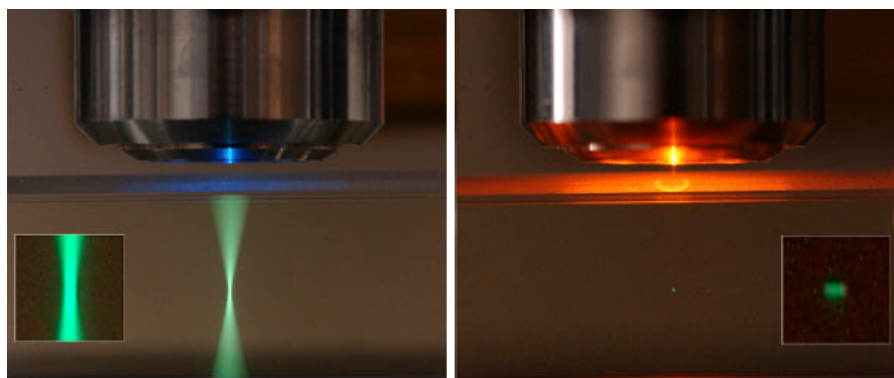
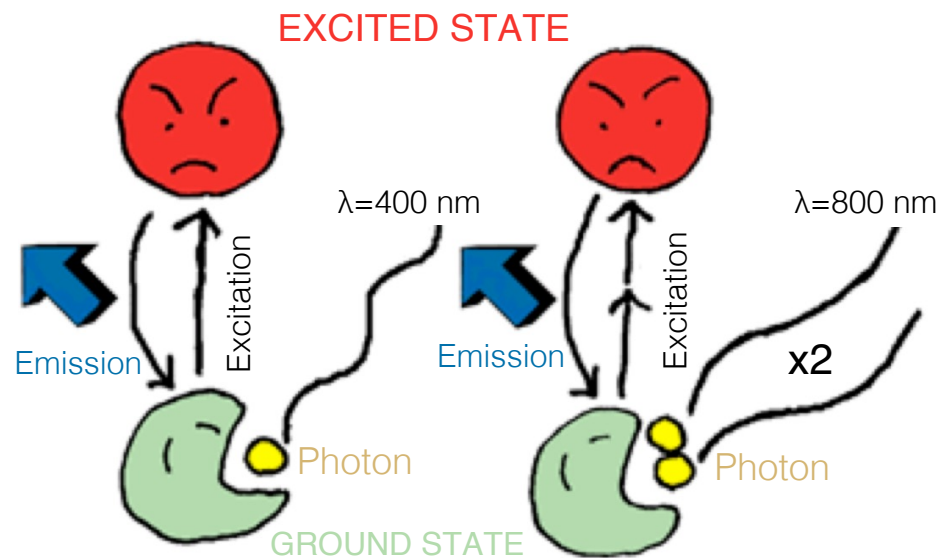
*Green: microtubules; Red: actin; Blue: nuclei*



# Multiphoton fluorescence microscopy

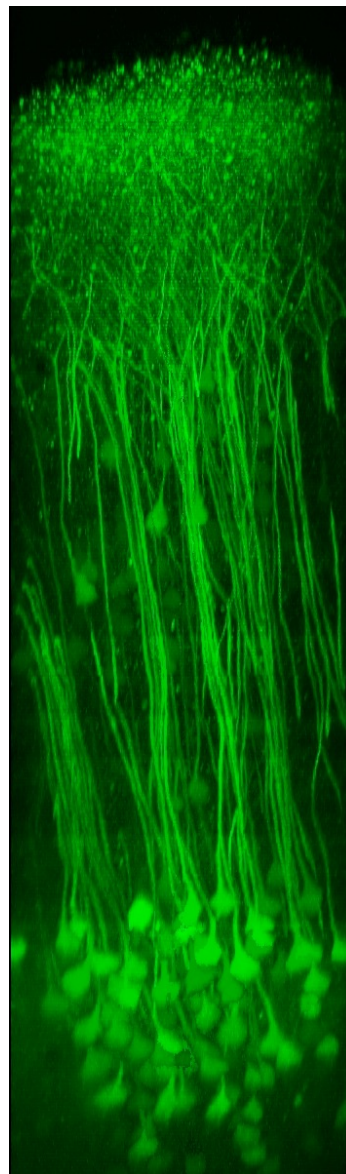
Laser property utilized: monochromaticity, steerability, short pulses

- 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

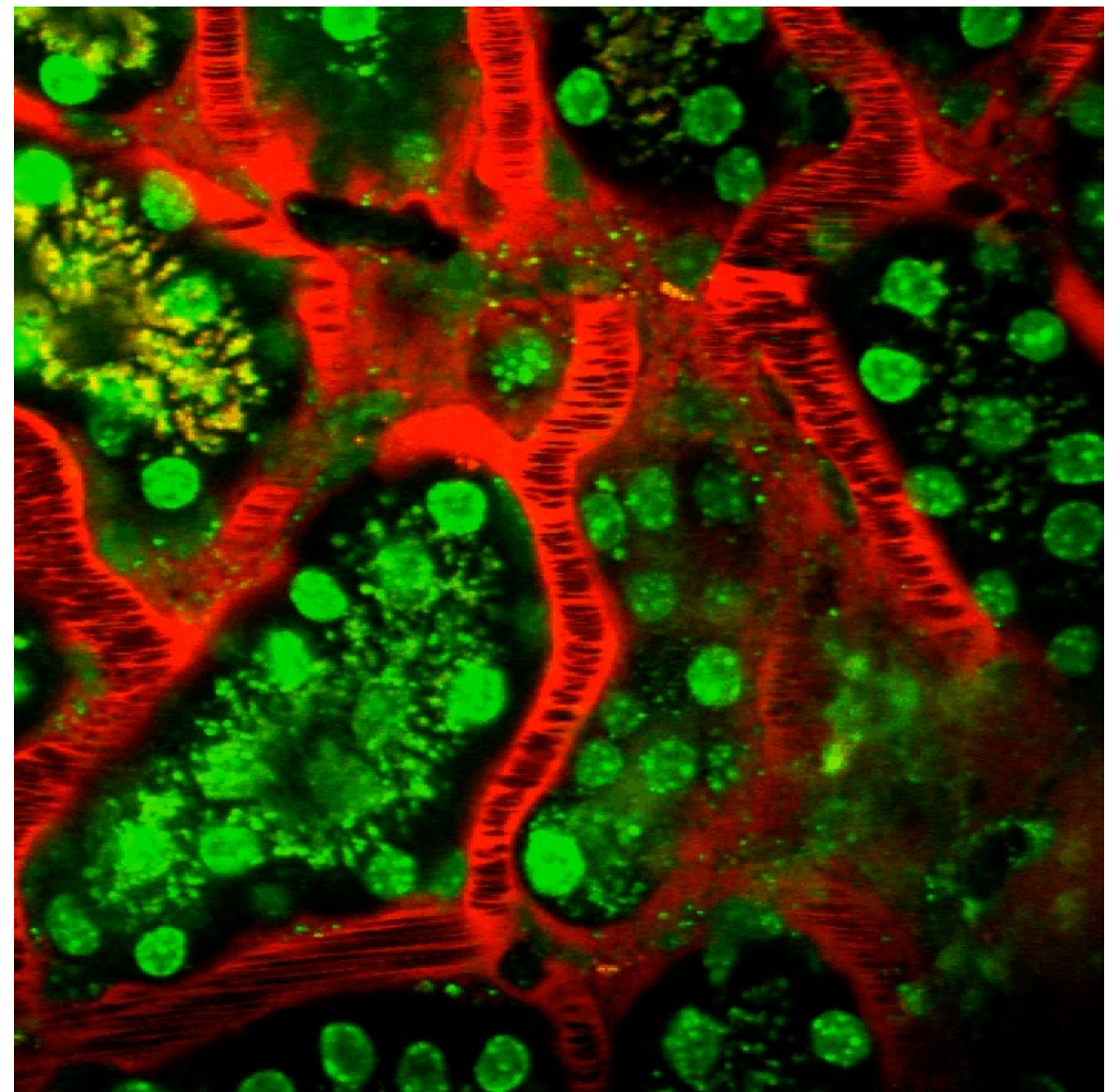


Single-photon  
fluorescence

Two-photon  
fluorescence



*Cortical pyramidal cells*

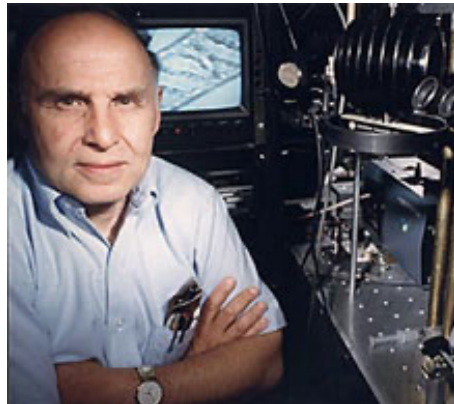


*Green: proximal kidney tubules; Red: albumin (plasma)*

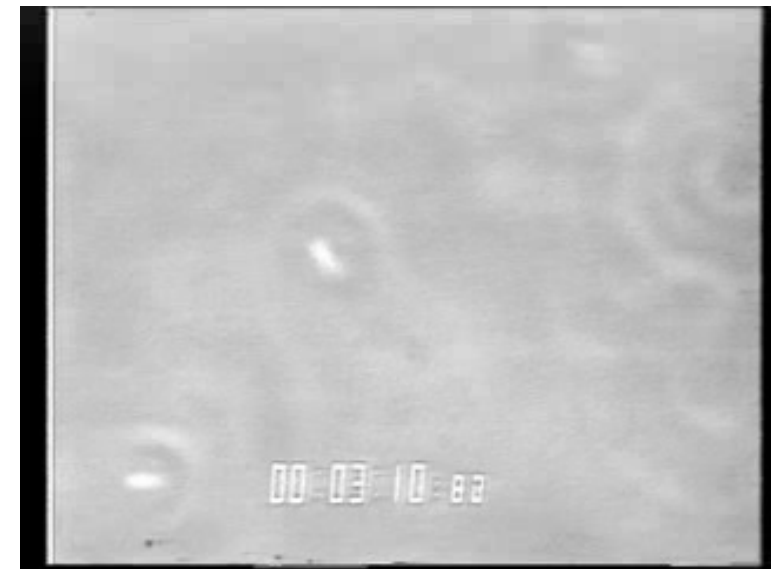
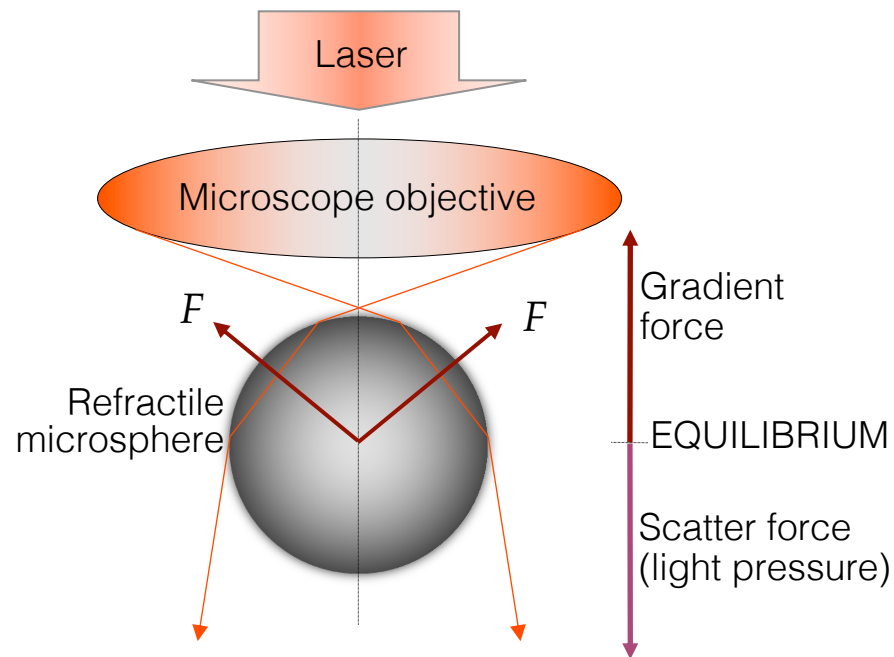


# Laser tweezers

Laser property utilized: power density, steerability

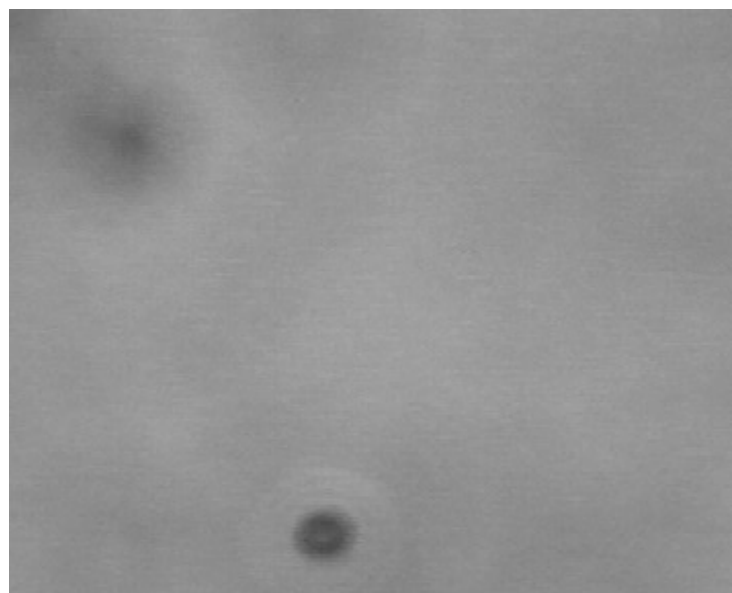


Arthur Ashkin (1970)



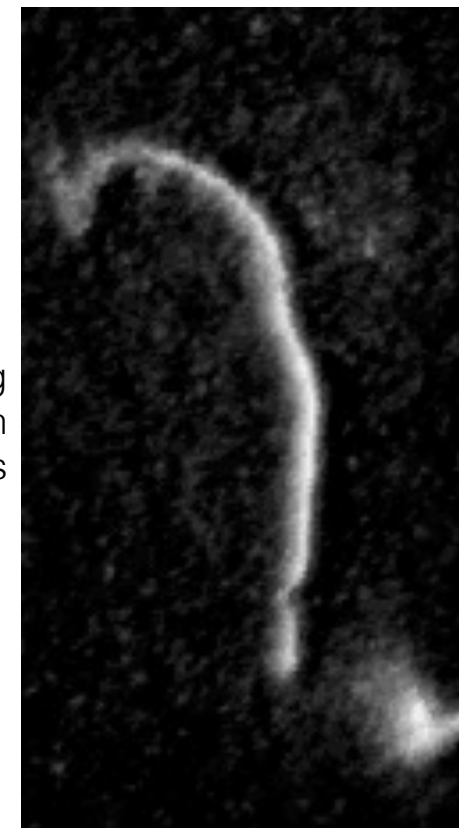
Trapping bacterial cells with laser tweezers

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



3 µm latex (polystyrene) microspheres in the optical trap

Manipulating molecules with laser tweezers

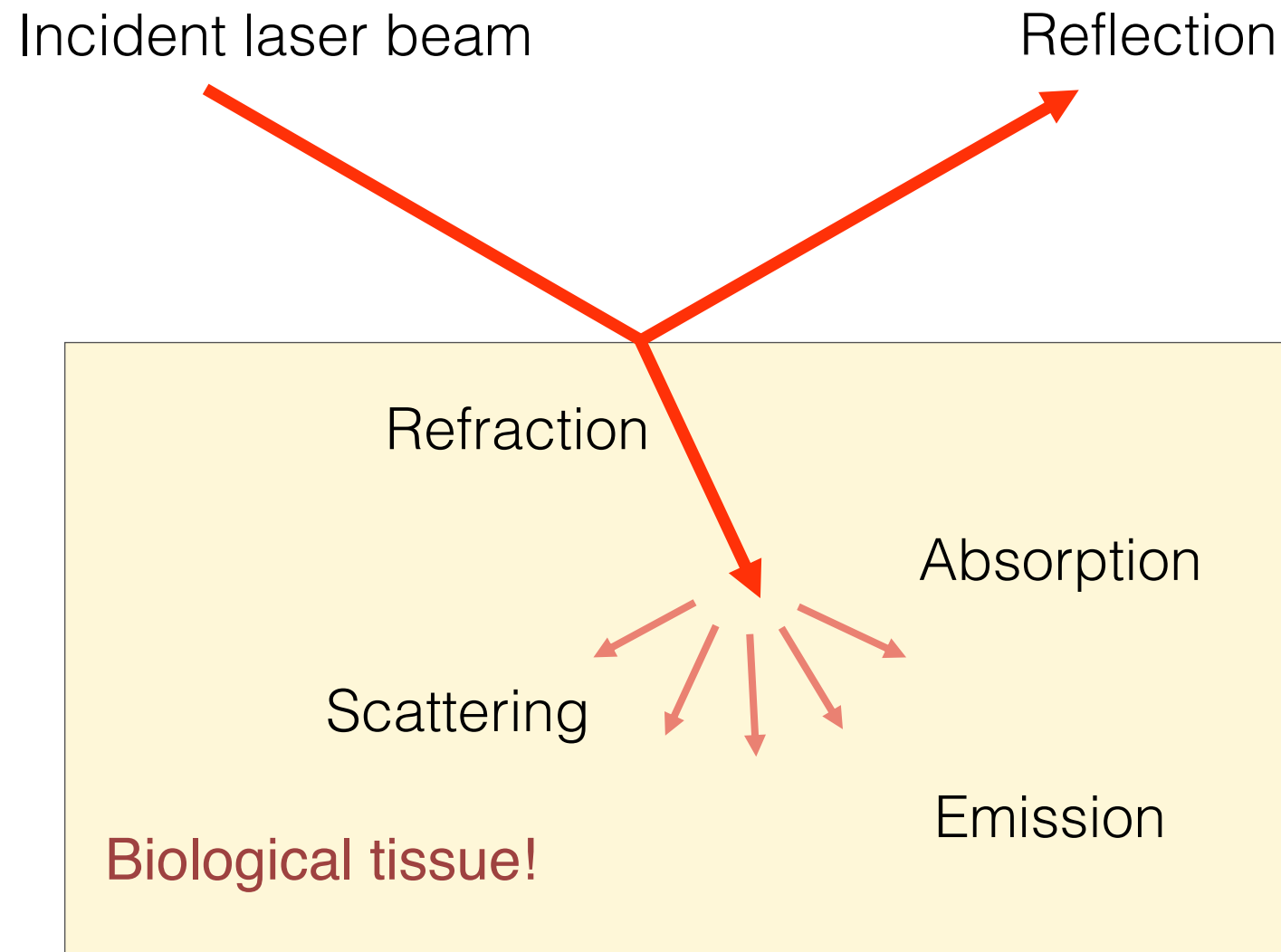


Actin filament



dsDNA

# 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<sub>2</sub> 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 activation of photosensitive chemicals preferentially taken up by the tumor.
- **Ophthalmology:** Retina lesions, photocoagulation, glaucoma, photorefractive keratectomy (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

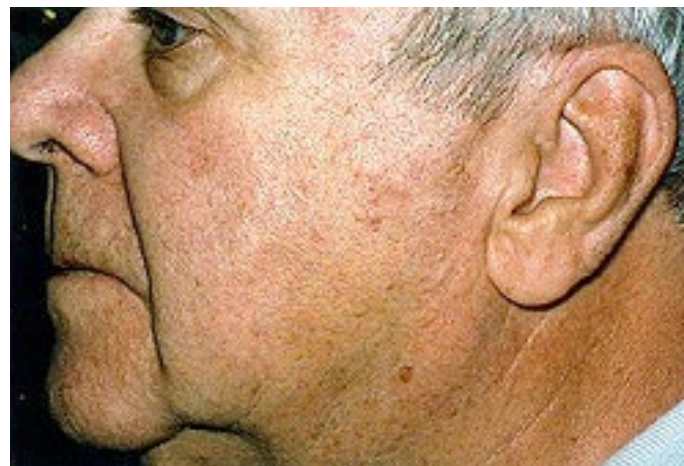


# Dermatological applications

## Removal of superficial blood vessels



Before treatment



After treatment

## Resurfacing



Wrinkle removal



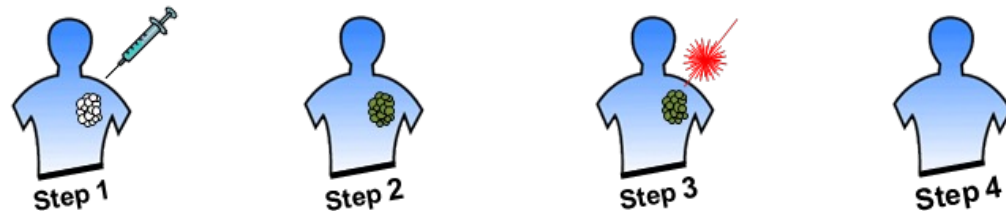
Rhinophyma (sebaceous gland hypertrophy, fibrosis)

# 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.

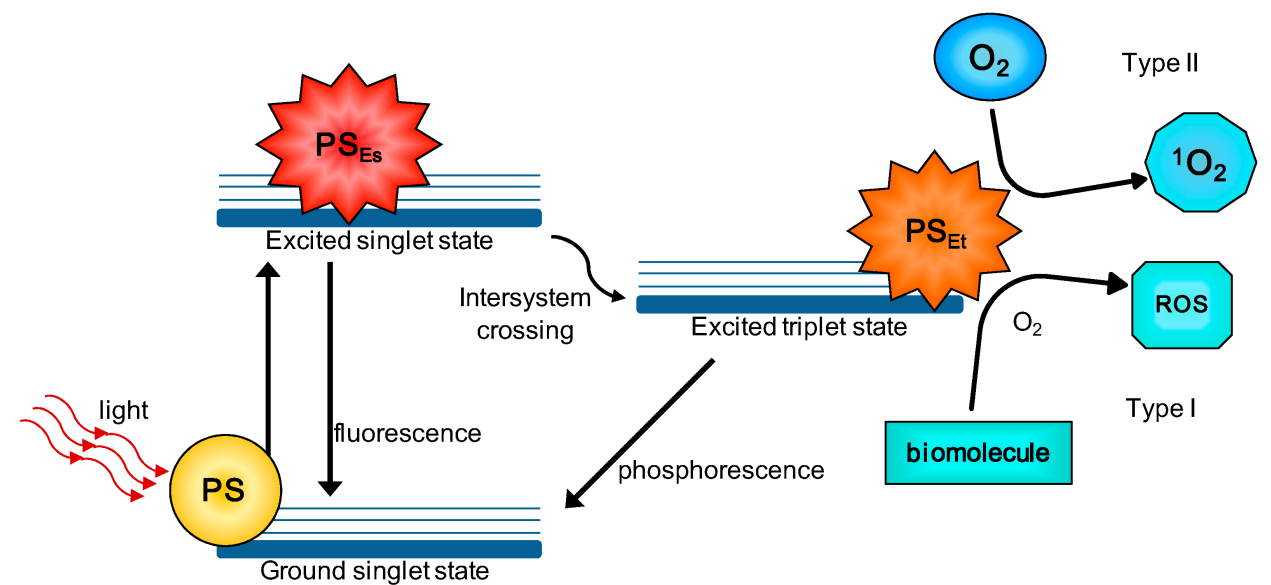
Steps:



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



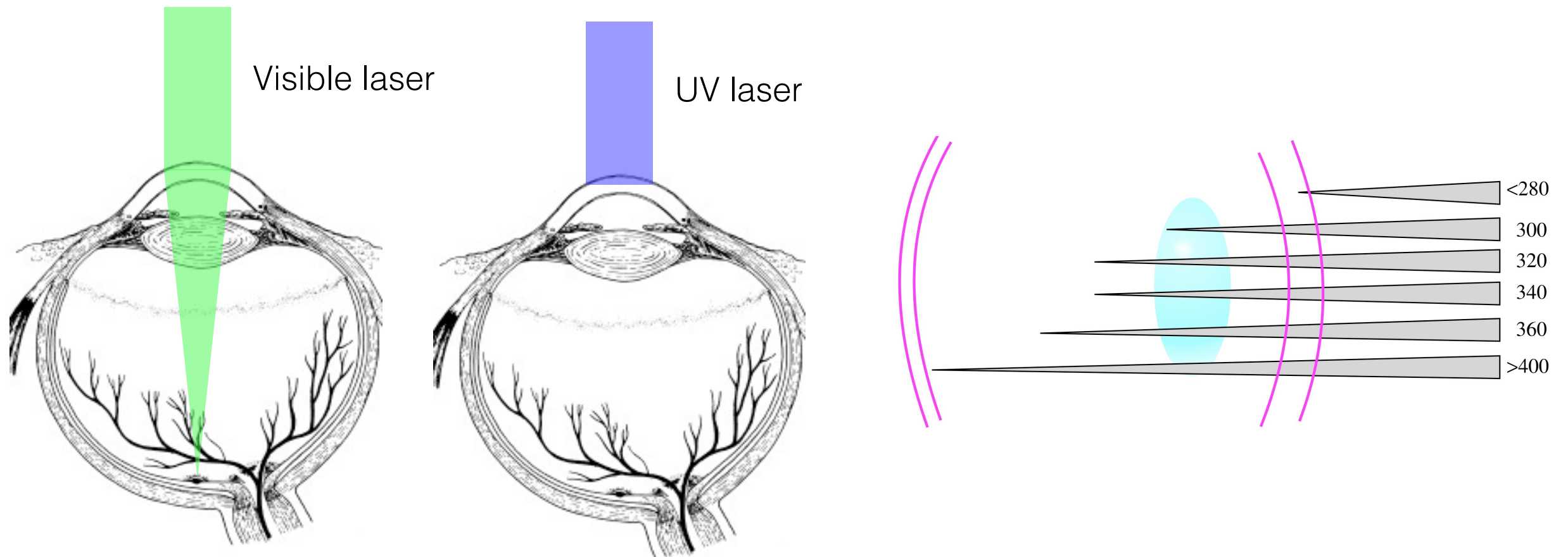
Delivery of light into the patient: surface exposure, optical fiber





# 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:

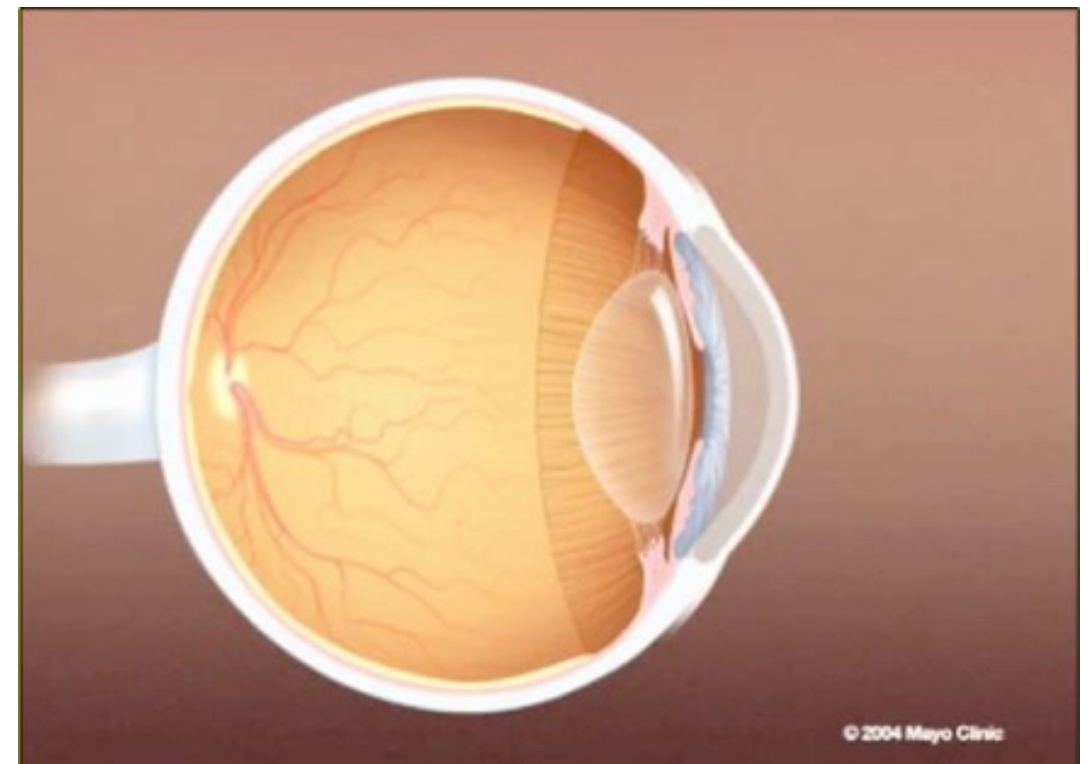
**Jose Barraquer, 1970:** construction of a microkeratome, with which he was able to cut lines and lobes in the cornea with laser (keratomileusis).

**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).





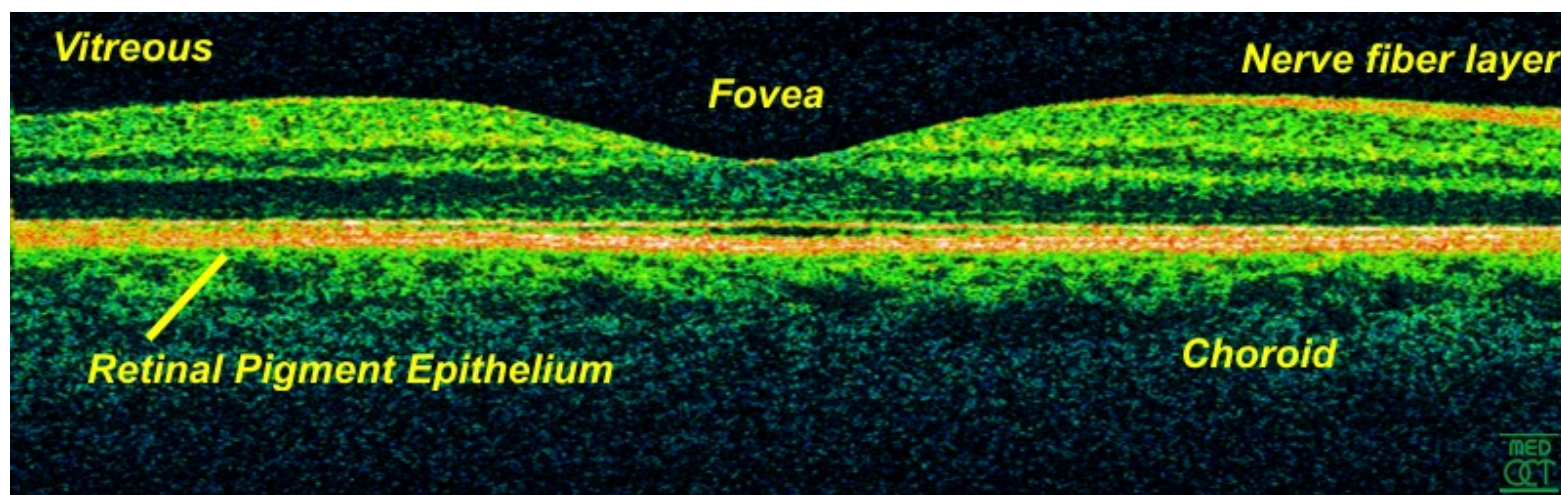
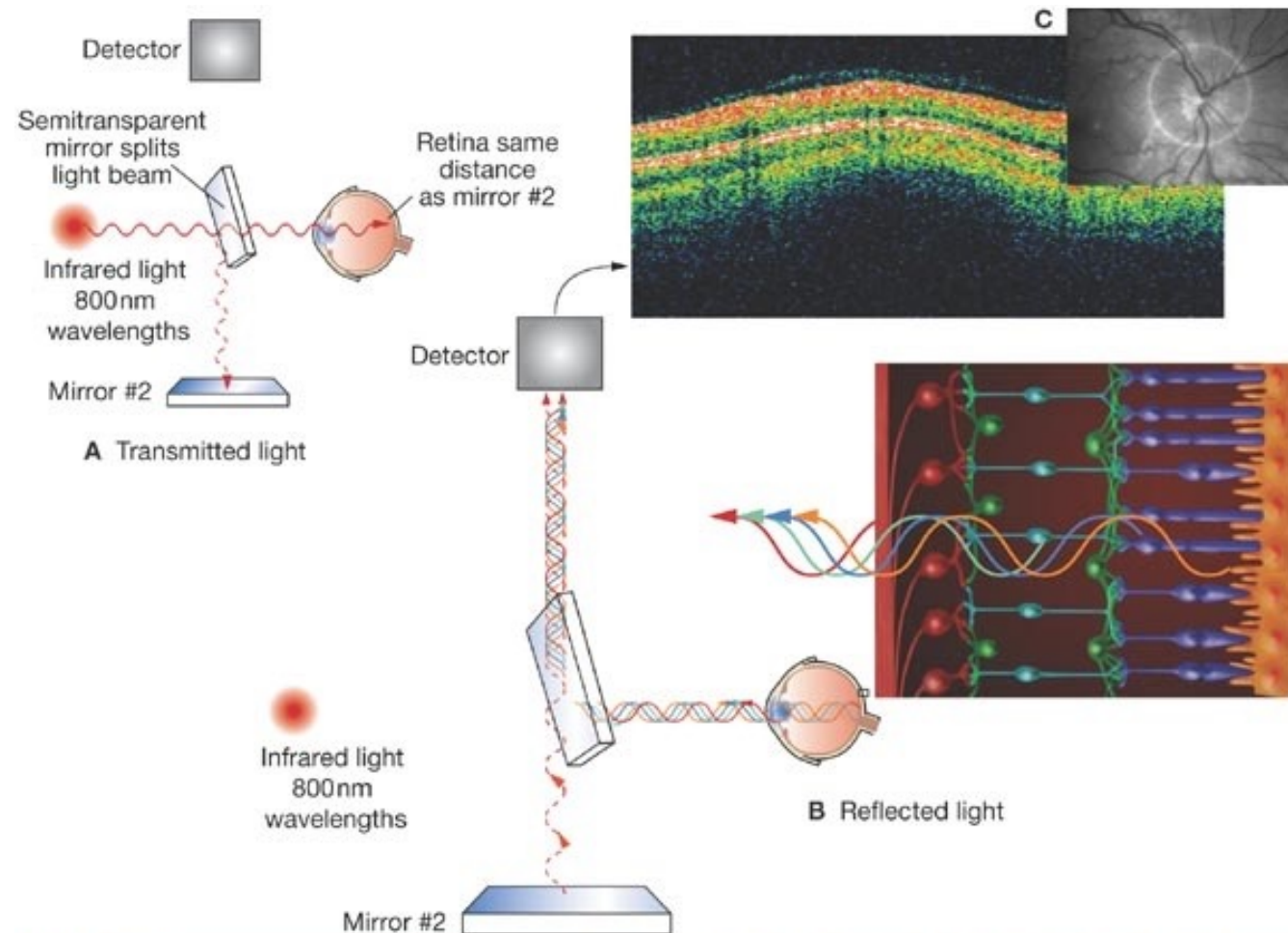
# Ophthalmologic applications

## Optical Coherence Tomography (OCT)

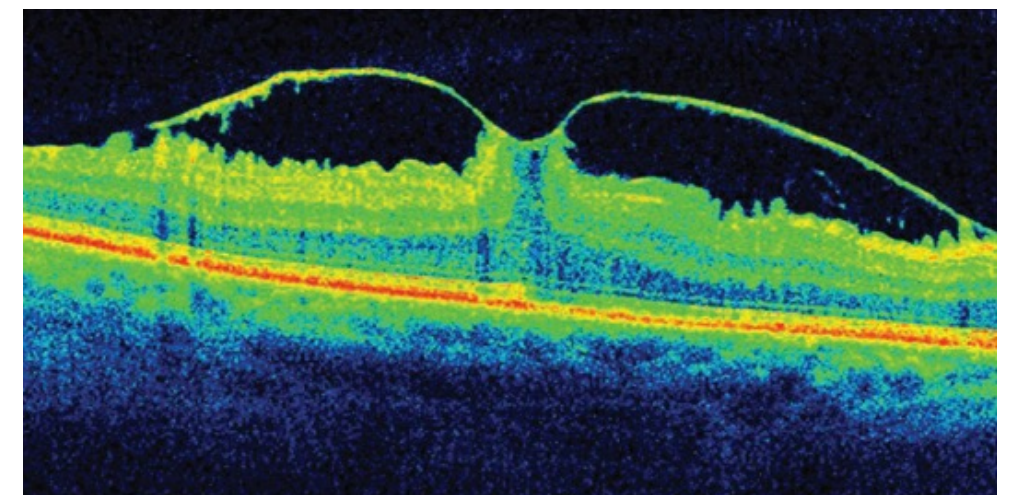
- Non-invasive
- Contrast-agent free
- Near microscopic resolution

### 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=2WYLRF6GVRE5KCO2>