

# Principles, types and medical applications of lasers

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# Laser

light **a**mplification by **s**timulated **e**mission of **r**adiation



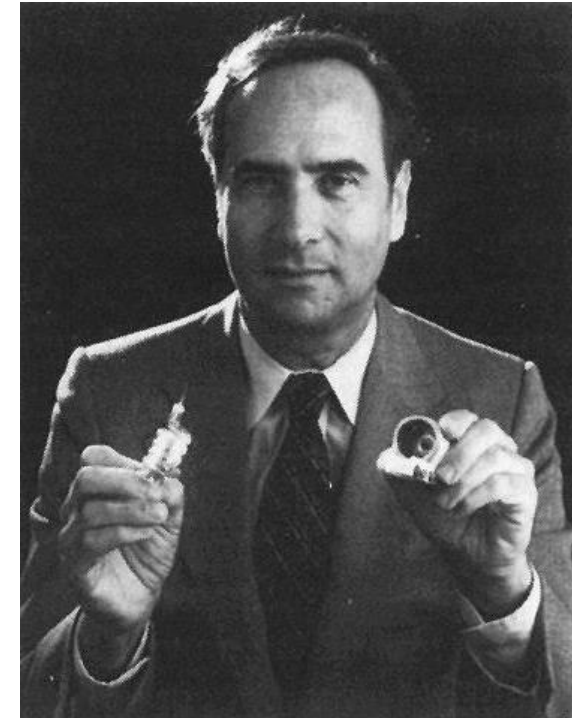
# History of lasers in a nutshell...

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

**1954 - *N.G. Basow, A.M. Prochorow, C. Townes*:** ammonia maser  
(**M**icrowave **A**mplification by **S**timulated **E**mission of **R**adiation)

**1960 - *Theodore Maiman*:** first laser in the visible spectral range (ruby laser)

a flashlamp-pumped synthetic ruby crystal  
to produce red laser light at 694 nm  
wavelength



## **Nobel prize in Physics 1964**

for work in quantum electronics leading to lasers and masers



**Alexander Prochorow**



**Charles H. Townes**



**Nicolay Basow**

## **Nobel prize in Physics 1971**

For invention of holography



XI. kerület, Magyar tudósok körútja 2.



**Gábor Dénes**



**Steven Chu**



**William D. Phillips**



**Claude Cohen-Tannoudji**

**Nobel prize in Physics 1997**  
for development of methods to cool and trap  
atoms with laser light



**Zhores Ivanovich Alferov**



**Herbert Kroemer**

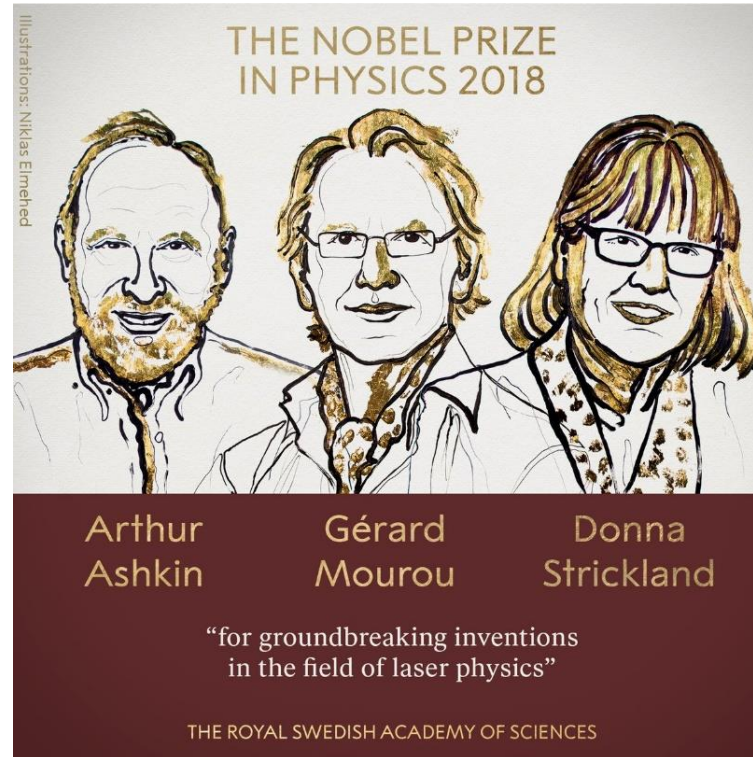
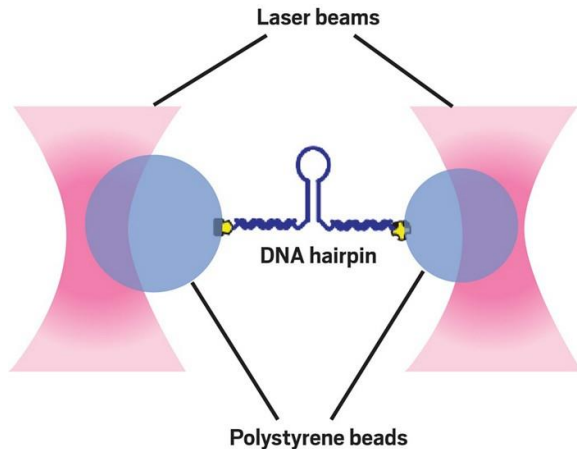
**Nobel prize in Physics 2000**  
Semiconducting laser diode

# Nobel prize in Physics 2018

"for groundbreaking inventions in the field of laser physics"

## Ashkin,

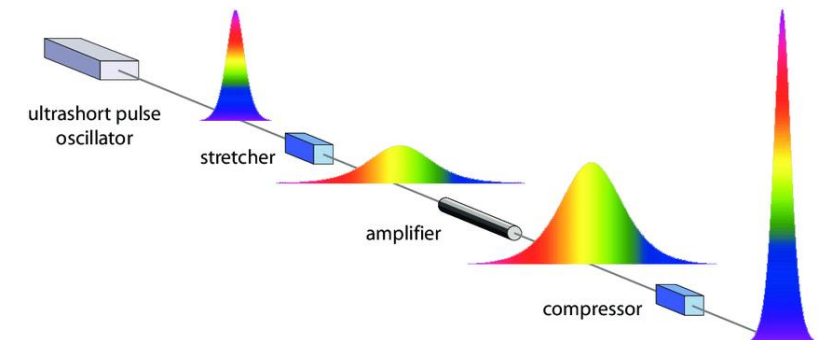
Arthur Ashkin invented optical tweezers that grab particles, atoms, molecules, and living cells with their laser beam fingers. The tweezers use laser light to push small particles towards the centre of the beam and to hold them there. In 1987, Ashkin succeeded in capturing living bacteria without harming them. Optical tweezers are now widely used to investigate biological systems.



## Mourou és Strickland

paved the way towards the shortest and most intense laser pulses ever created by mankind

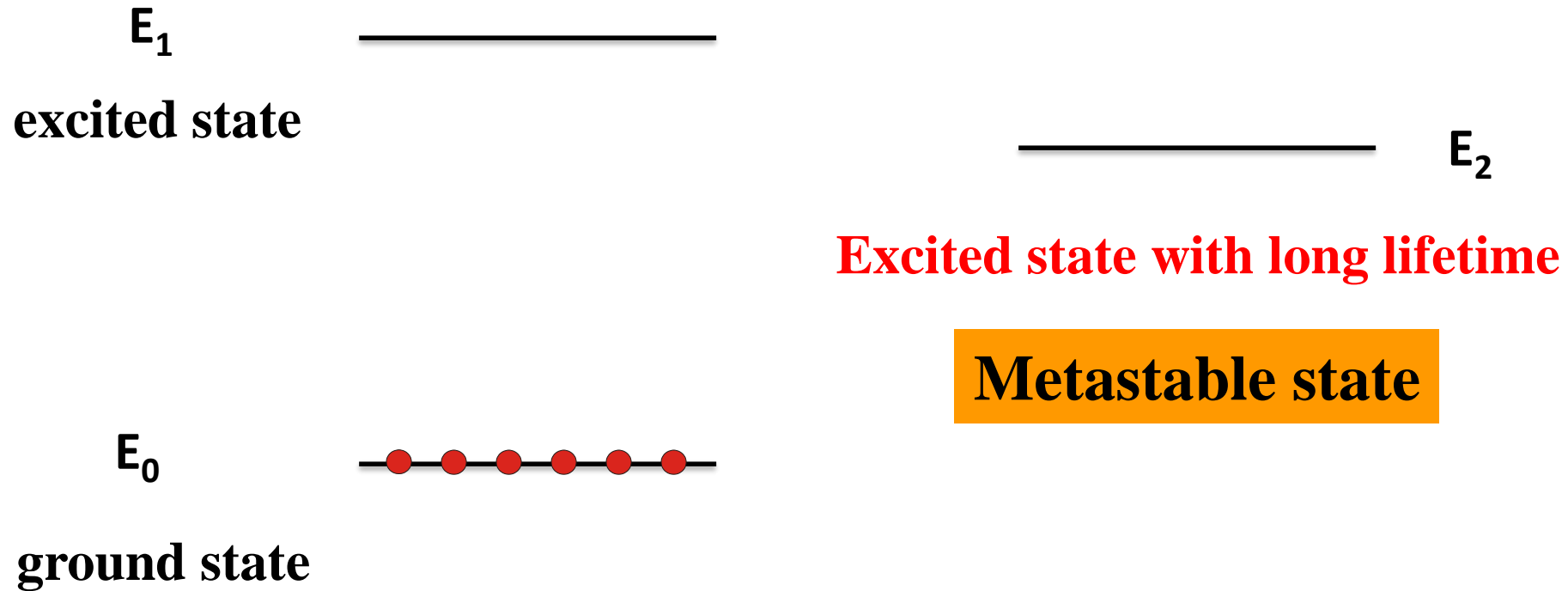
First they stretched the laser pulses in time to reduce their peak power, then amplified them, and finally compressed them. If a pulse is compressed in time and becomes shorter, then more light is packed together in the same tiny space – the intensity of the pulse increases dramatically. The innumerable areas of application have not yet been completely explored...



# Fundamentals of laser operation



# Special electronic energy states – I. at least a three-state system

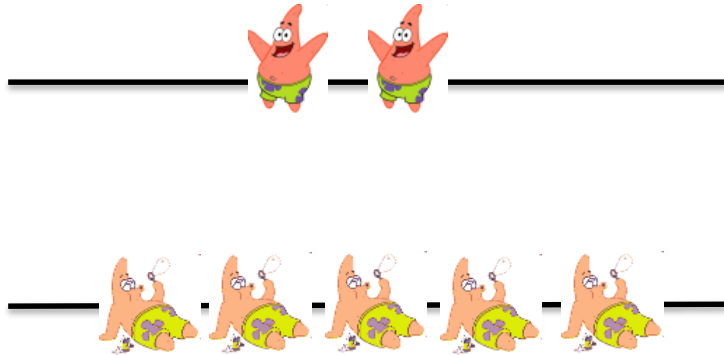


Laser material: doped crystal, mixture of gases, solution of organic dyes



## II: Occupancy in energy levels

### Population inversion

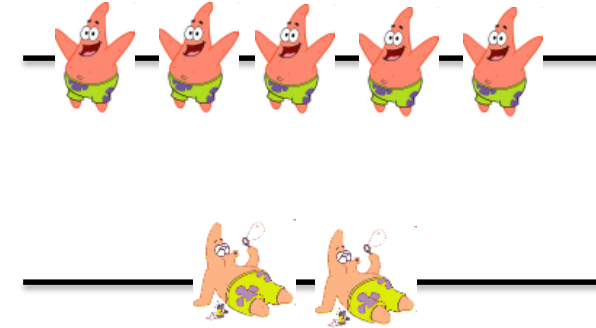


### *Thermal equilibrium*

According to Boltzmann distribution

$$\frac{n_i}{n_0} = e^{-\frac{\epsilon_i - \epsilon_0}{k_B T}}$$

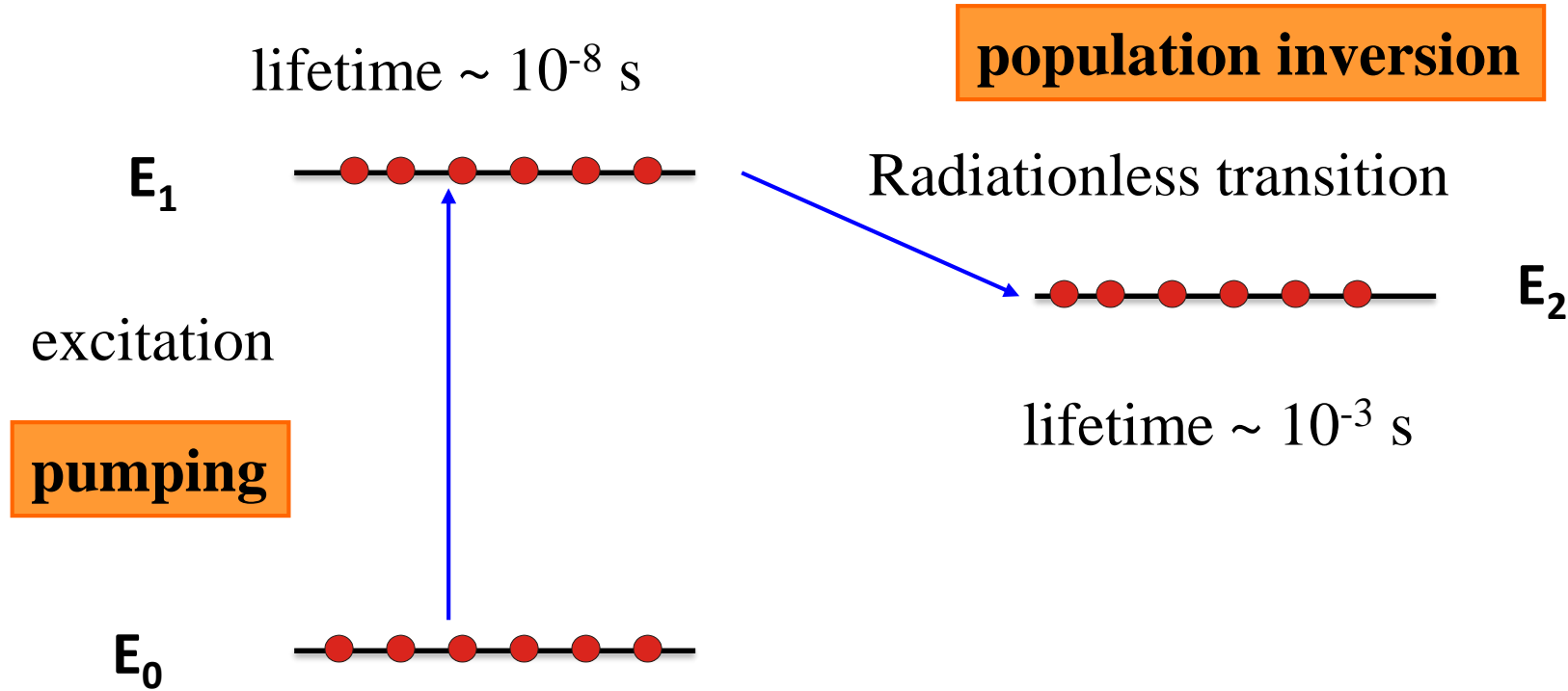
The number of atoms,  $\mathbf{n}$ , at an energy level  $\Delta\epsilon$  higher than the ground level, if the number of atoms in the ground state is  $\mathbf{n}_0$  in two energy levels separated by the energy difference.



### *Population inversion*

“opposite” distribution – more electrons are in the excited state than in the ground state

# III: Excitation Optical pumping

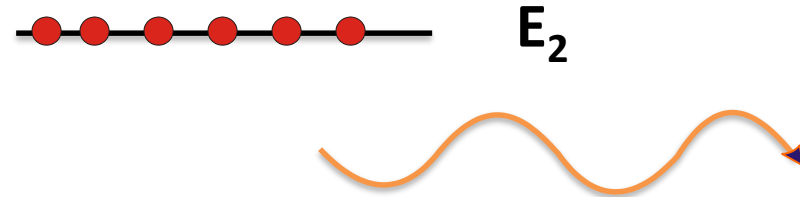


Optical pumping = energy input from an external source (electrical, optical, chemical energy)

# Spontaneous photon emission

$E_1$  —————

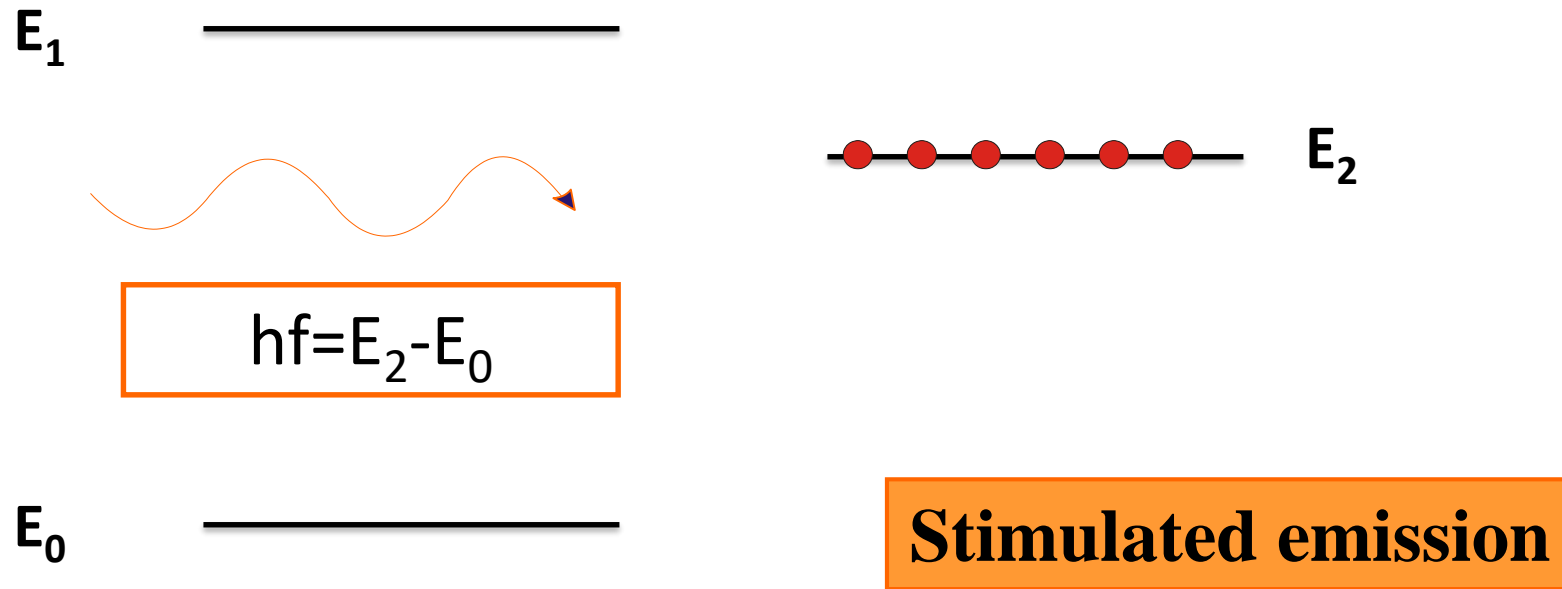
$E_0$  —————●



Spontaneous light emission

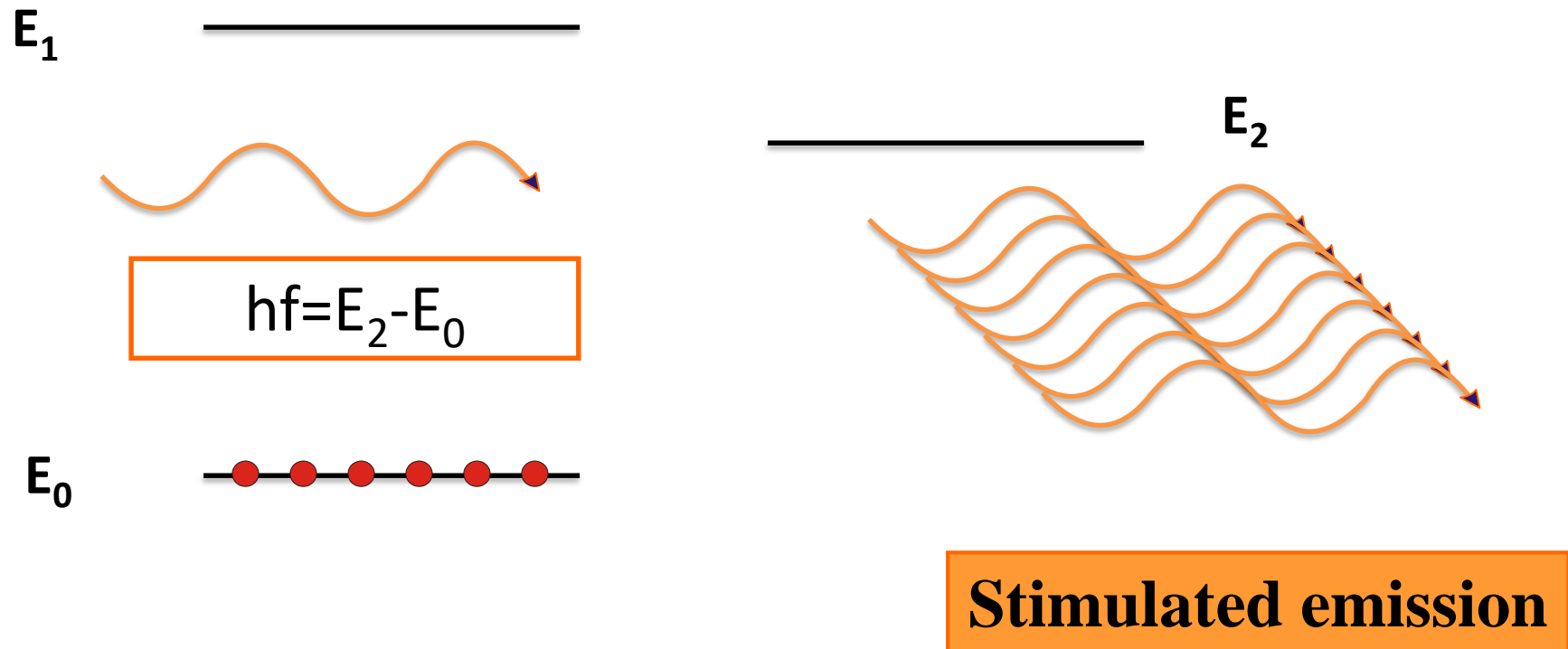
*Low probability*

# Induction of atomic transition – relaxation of electrons from the metastable state



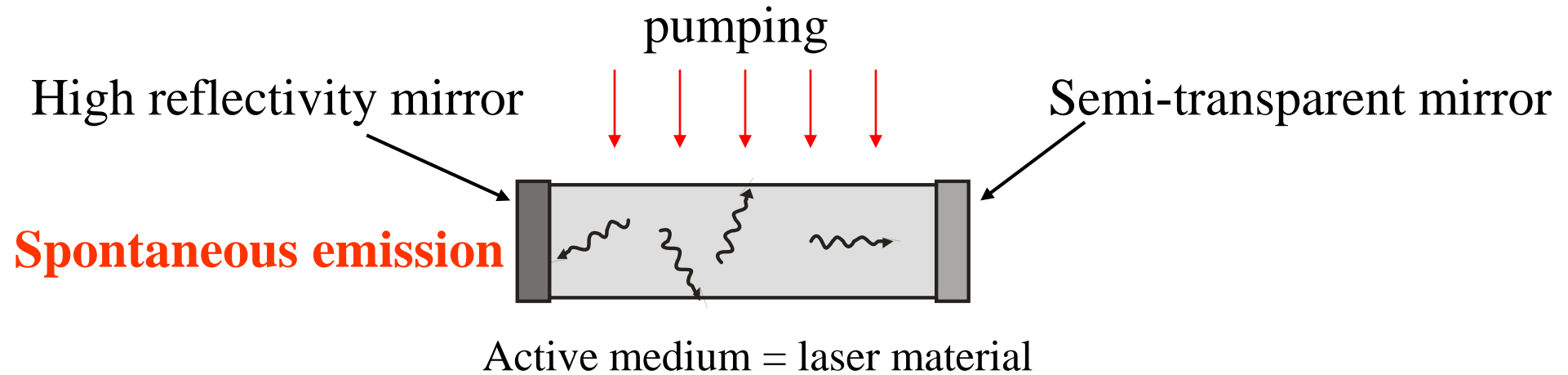
The incoming photon of  $hf = E_2 - E_0$  can interact with electrons on metastable state causing them to drop to the lower energy level

# Induction of atomic transition – relaxation of electrons from metastable state

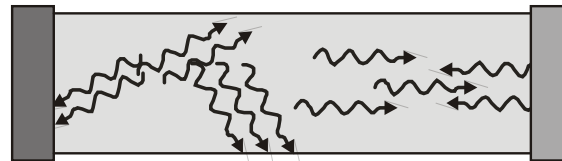


**Phase, frequency, polarization, and direction of the photons emitted with the stimulated emission are identical with that of induced the stimulation.**

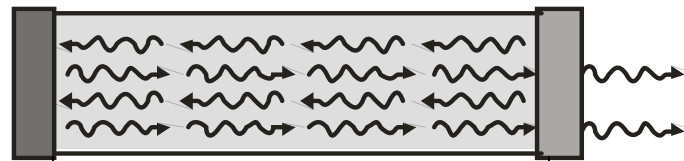
# Optical resonator



**Spontaneous and  
stimulated emission**



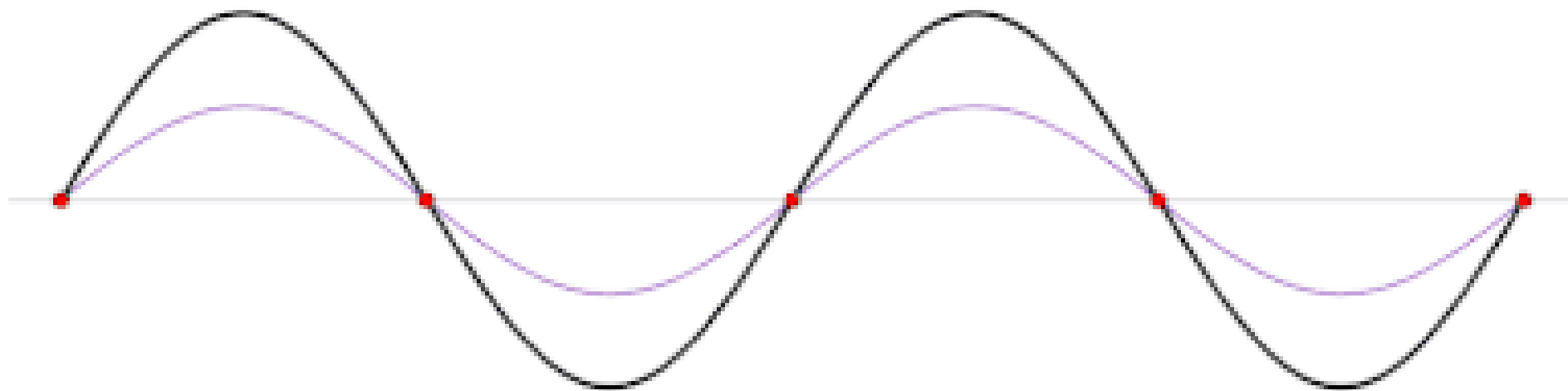
**Stimulated emission**



laser beam

$$l = m \cdot \lambda / 2$$

$m = 1, 2, 3 \dots$  (integer number)



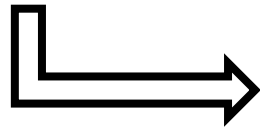
Standing wave in the optical resonator



# General properties of laser light

Photons emitted by stimulated emission and the inducing photons are identical:

- energy
- phase
- polarization
- direction



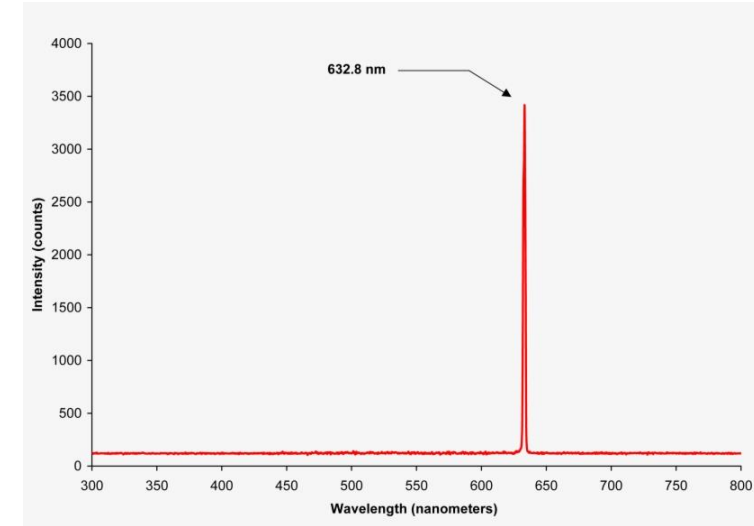
**Consequently laser light is**

- monochromatic
- coherent
- polarized
- parallel beam

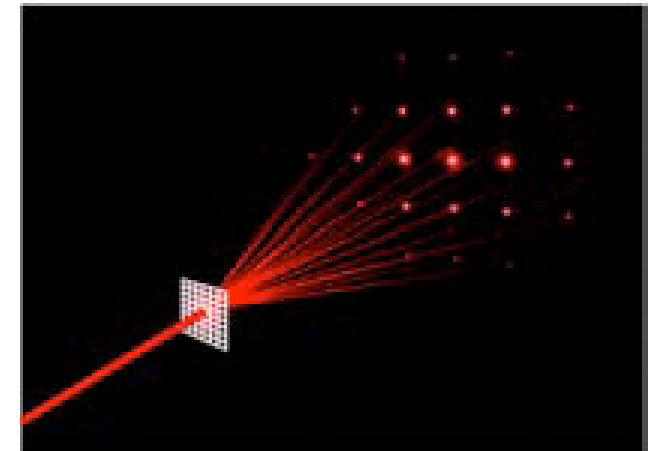


# Light generated by stimulated emission

1. monochromatic – narrow spectral width
2. coherent – phase identity
  - temporal coherence: (phase identity of photons emitted at different times)
  - spatial coherence: (phase identity across beam diameter)
3. Small divergence: parallel beam
4. Polarized: electric field vector oscillates in a single plane
5. Extremely short pulses: fs, ps, as
6. High power (kW-GW): large spatial power density,  
e.g.: Nd-YAG laser pulse energy 2 J, 20 ns, 10 Hz → emitted average power:  
 $2 \text{ J} / 0,1 \text{ s} = 20 \text{ W}$ , power of single pulse:  $2 \text{ J} / 20 \text{ ns} = 10^8 \text{ W}$
7. Continuous wave or pulsed lasers



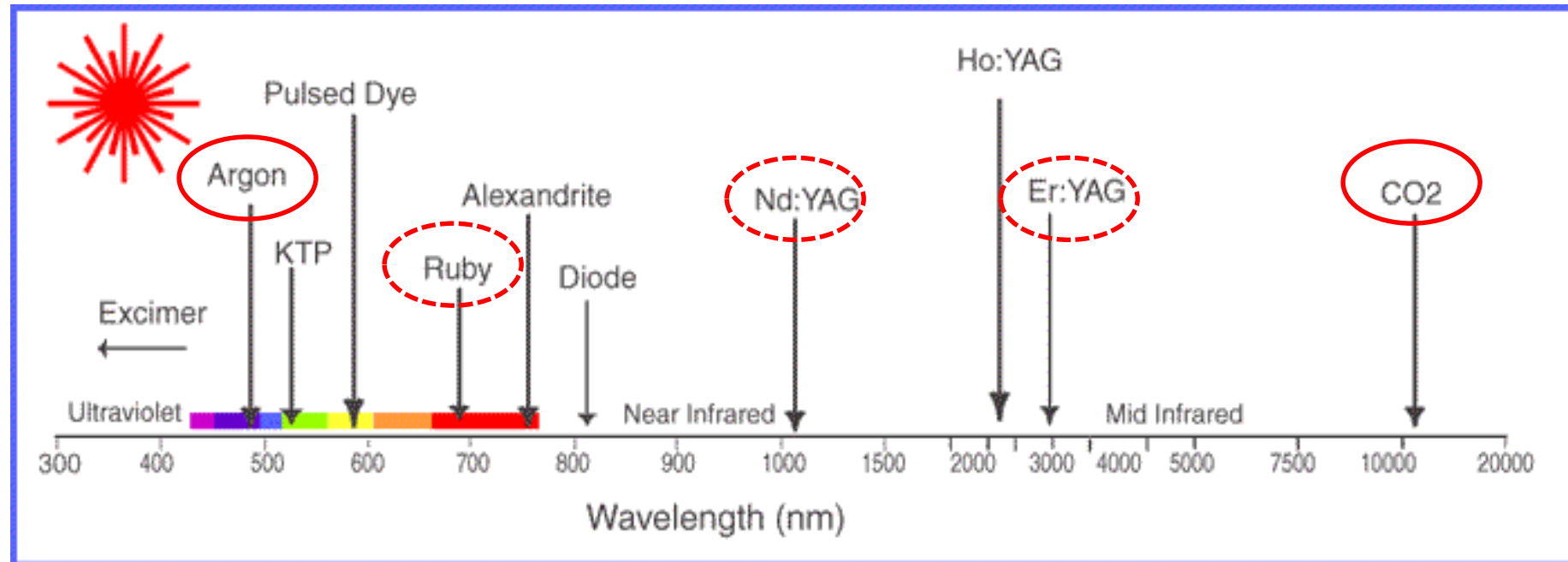
He-Ne laser emission spectrum



Interference pattern of laser beam

# Types of lasers – *based on material (active medium)*

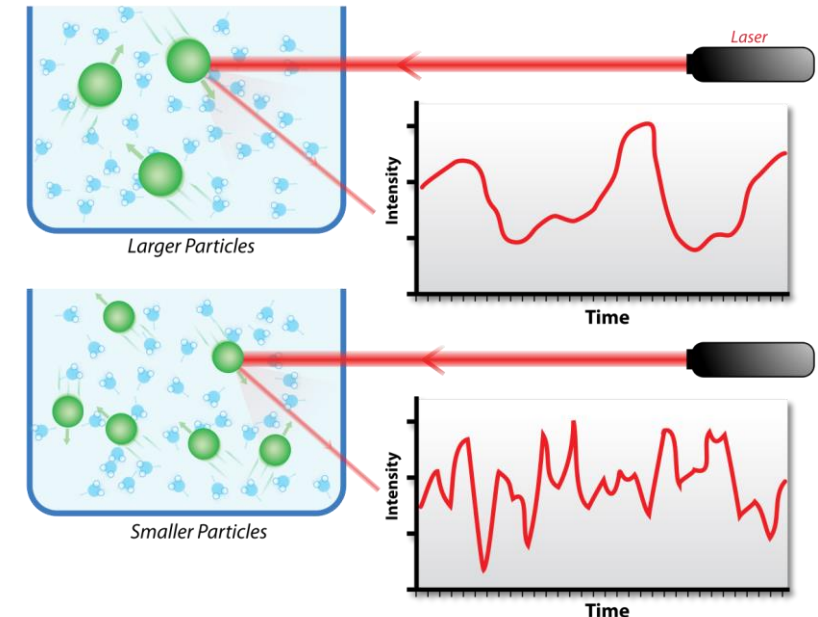
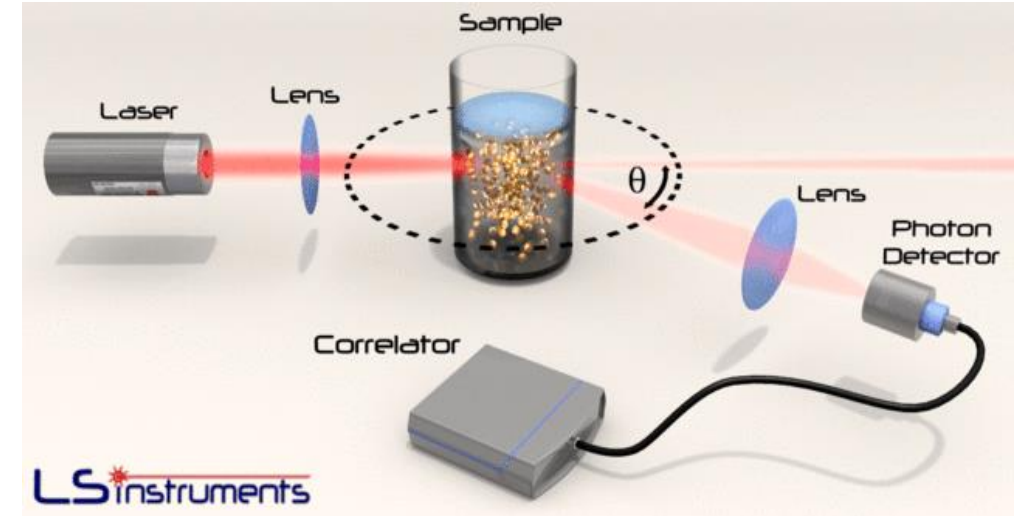
1. Solid state lasers: Metal doping crystals (Ruby, Nd-YAG yttrium-aluminium-garnet, Ti-sapphire)
2. Gas lasers: He-Ne, CO<sub>2</sub>, Ar, Kr
3. Dye lasers: dilute solution of organic dyes (rhodamine, coumarin)
4. Semiconductor (diode) lasers: combination of p- and n-type doped semiconductors



# Application of lasers – laboratory techniques

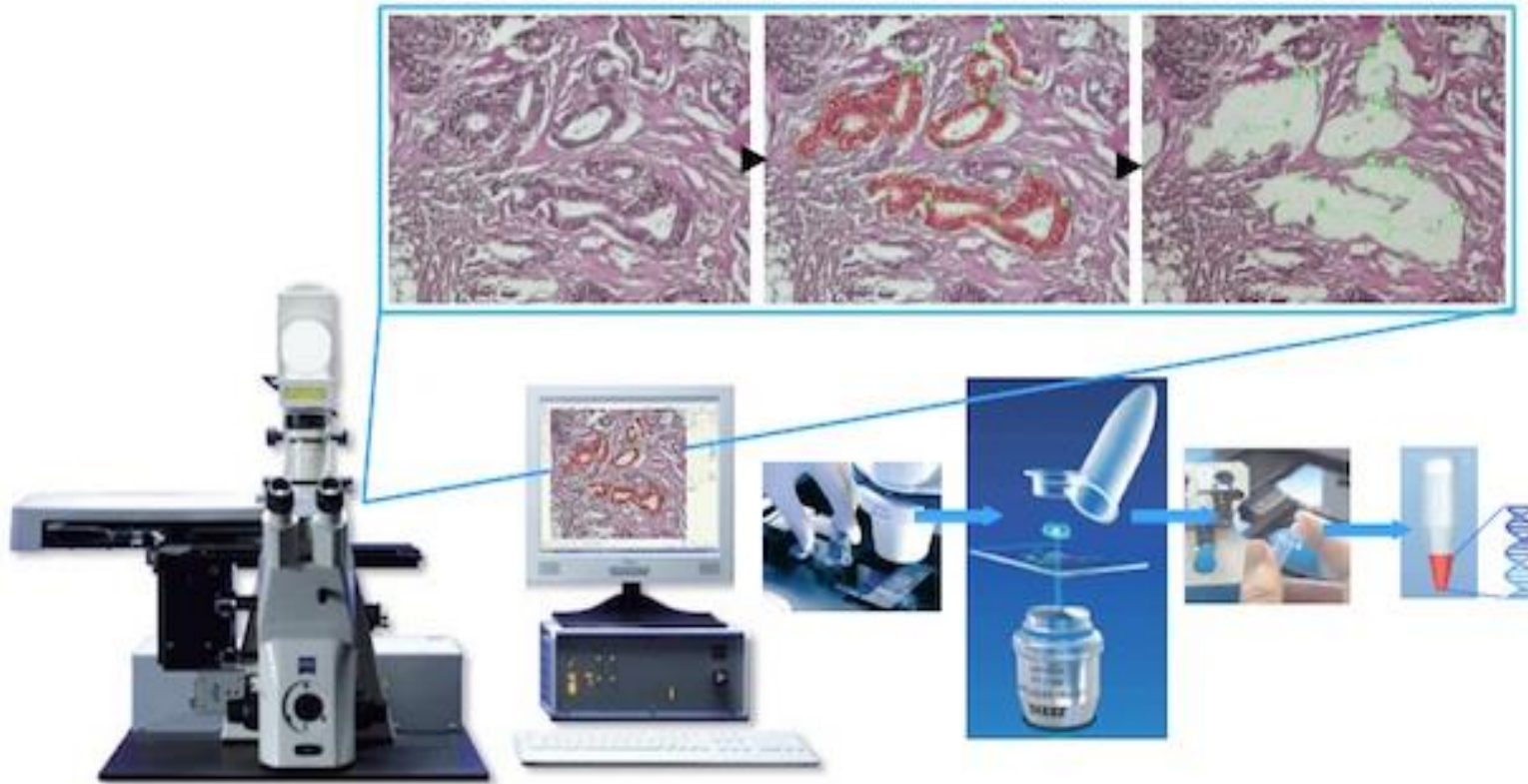
## Dynamics Light Scattering (DLS)

- nm-sized diffusing particles
- particles in suspension scatter the light
- the intensity of scattered light fluctuate in time
- related to the size of particles
- diffusion coefficient can be deduced
- radius of particle can be calculated
- viruses, vesicles, nanoparticles, liposomes

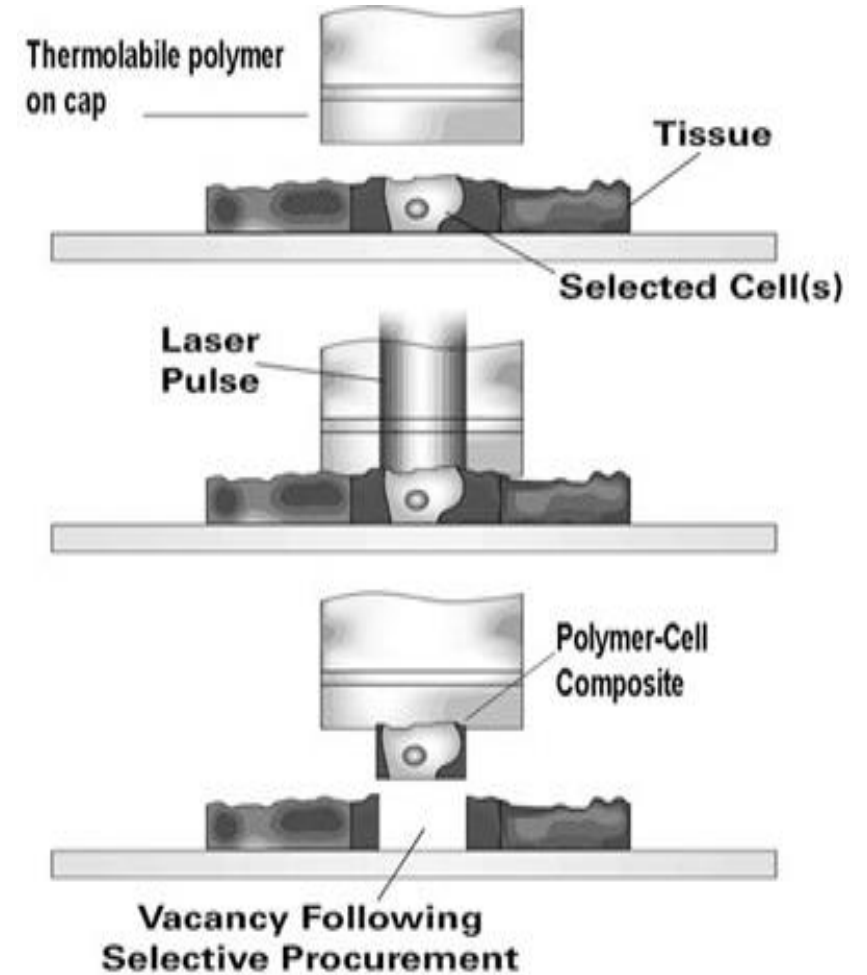


$$D = \frac{k_B T}{6\pi\eta r}$$

# Laser capture microdissection (LCM)



Local genetics/proteomics: KRAS somatic mutation, important diagnostic tumor marker in colon cancer, DNA from cancer cells can be tested, mixture of healthy and cancerous cells – false negative, improving selectivity/sensitivity

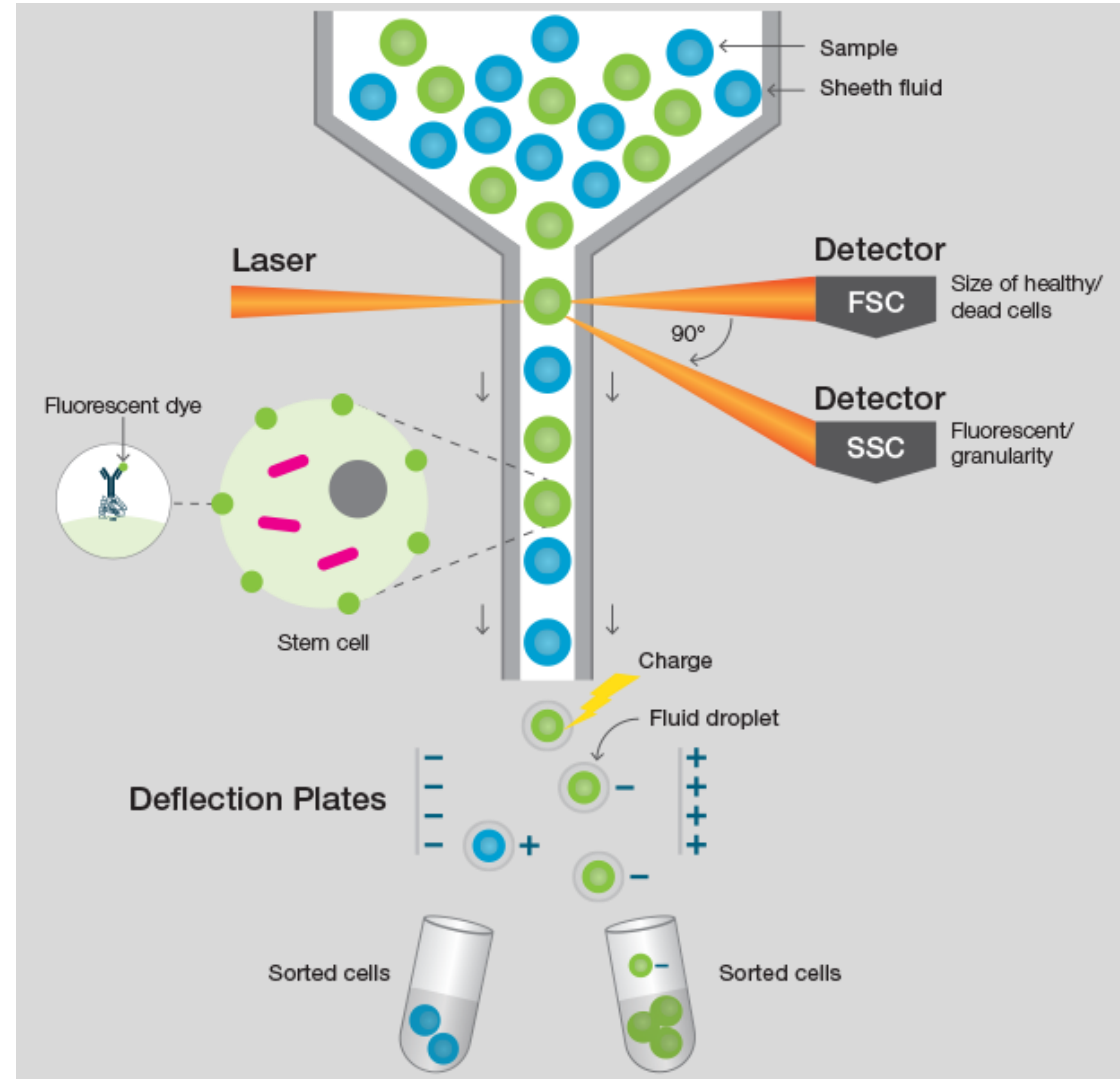


UV laser – cut

IR laser – heating the polymer cap

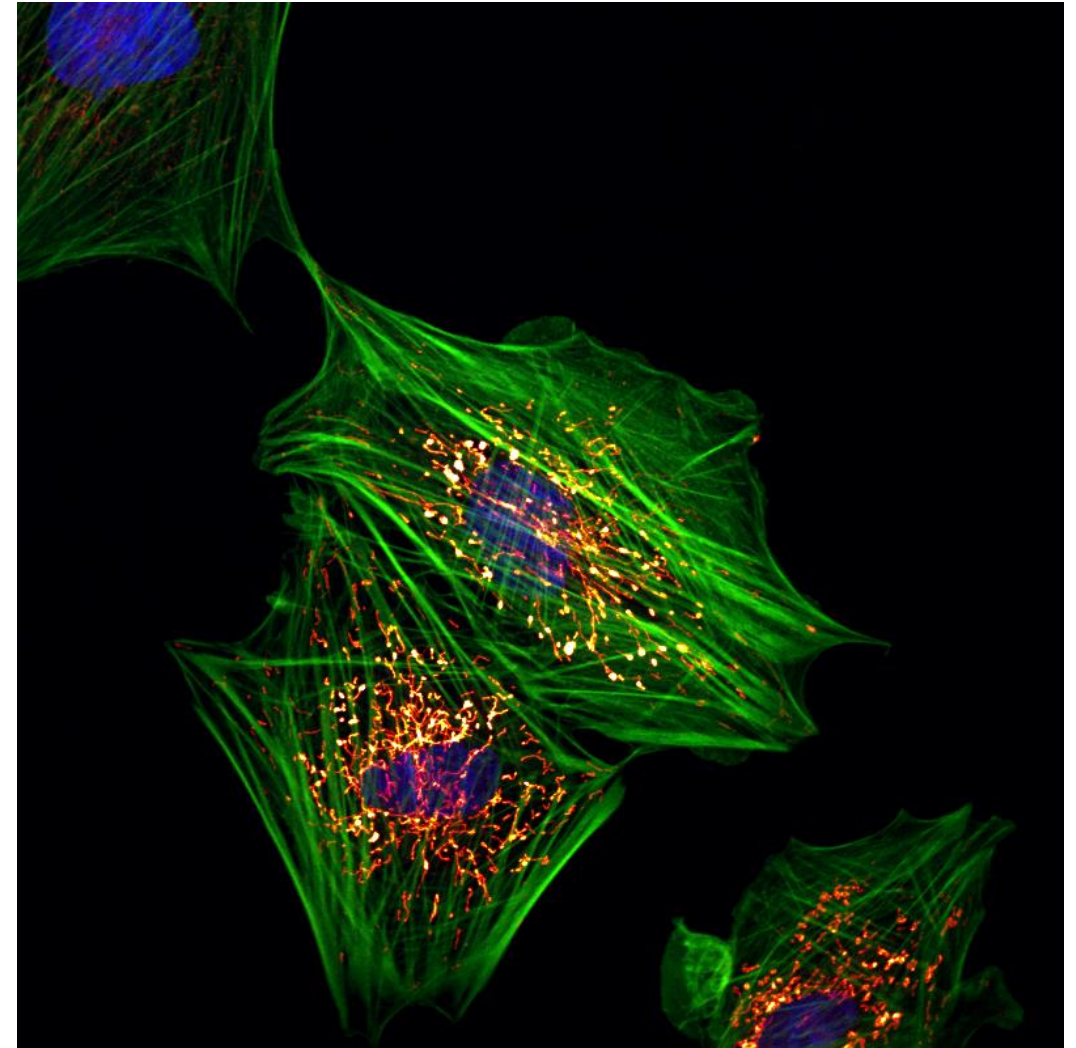
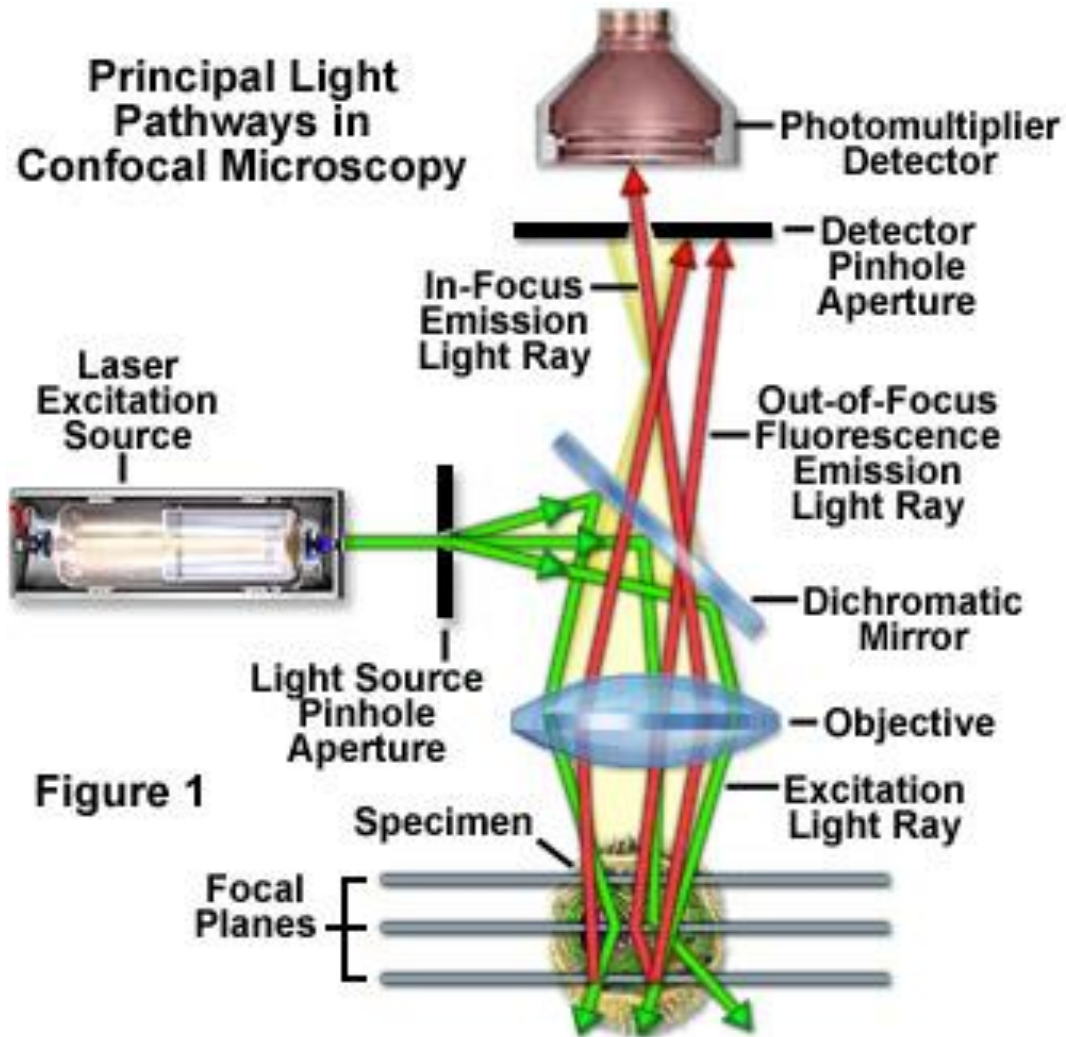
# FACS (Fluorescence activated cell sorter)

- counting, sorting, isolation of living cell population
- Fluorescent labeling of cells (specific antibodies)
- Hydrodynamic focusing = cells are separated in a laminar flow
- One cell at a time passes through a perpendicular laser beam
- Cells can be sorted by the emitted fluorescent wavelength
- Immunology, cell biology





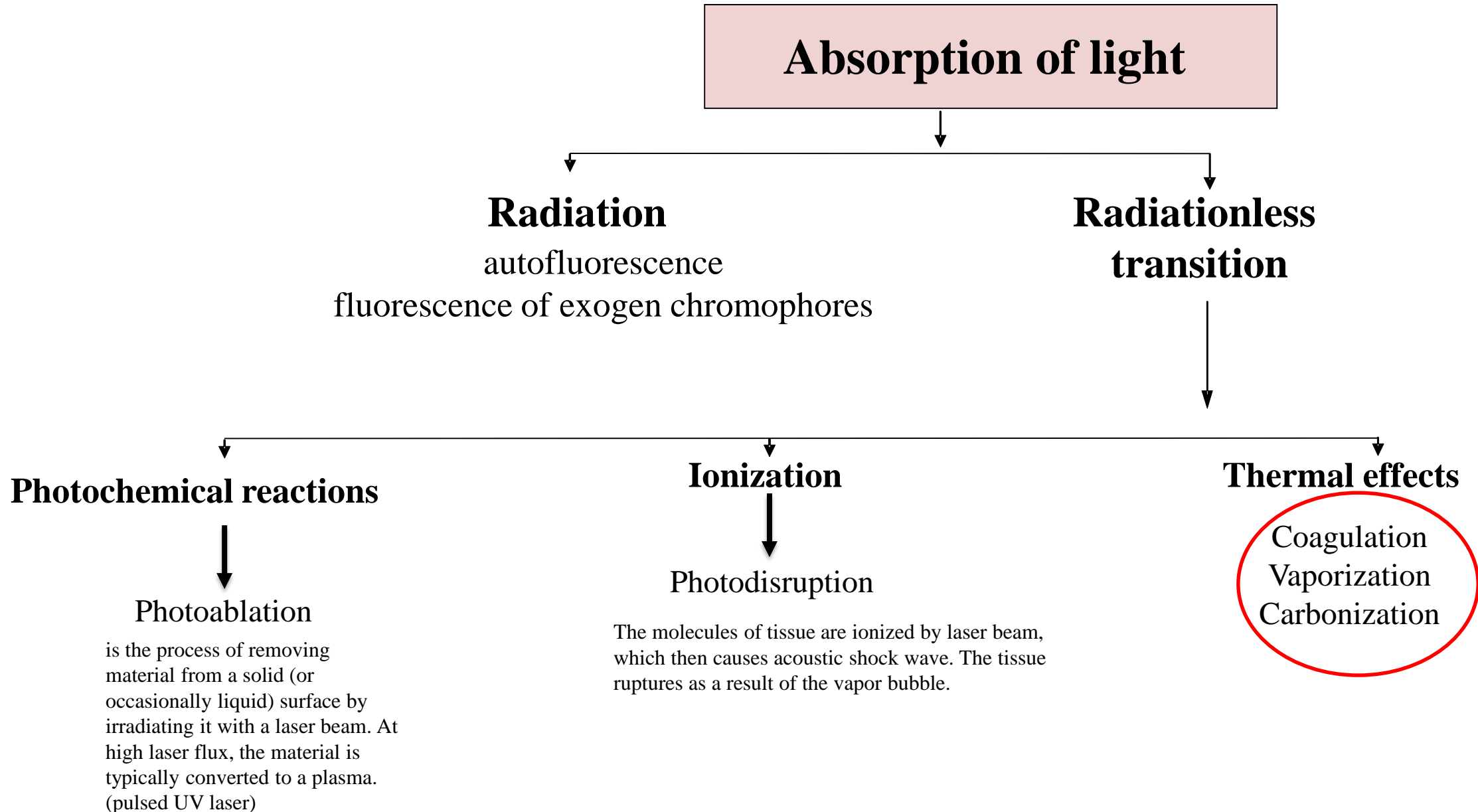
# Laser scanning confocal microscopy (spoiler alert!)



Fluorescent labeling of fibroblast cells: blue – nucleus, green – microtubules, red - mitochondria



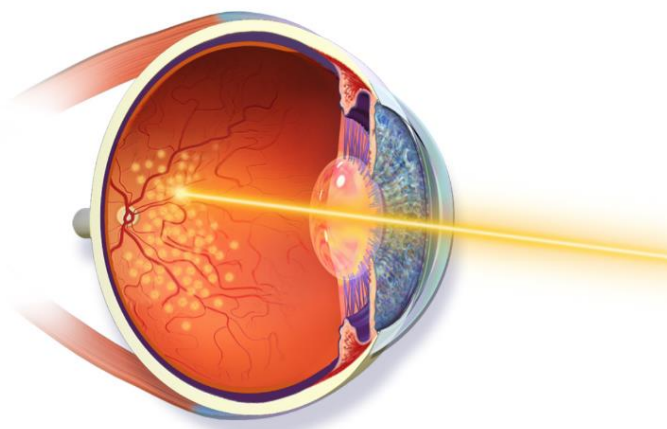
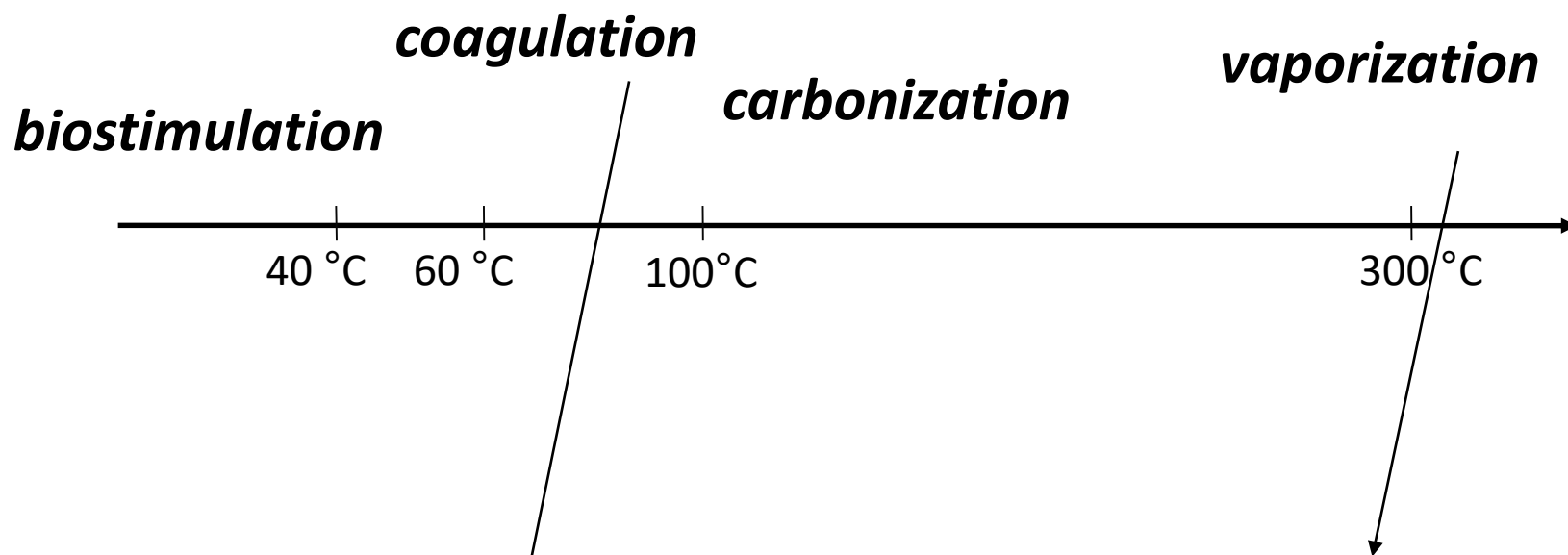
# Medical applications of lasers – interactions...



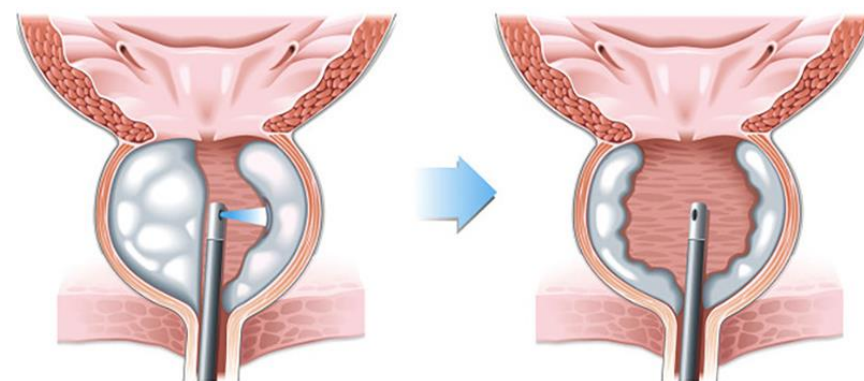
# Thermal effects



Orthopedics

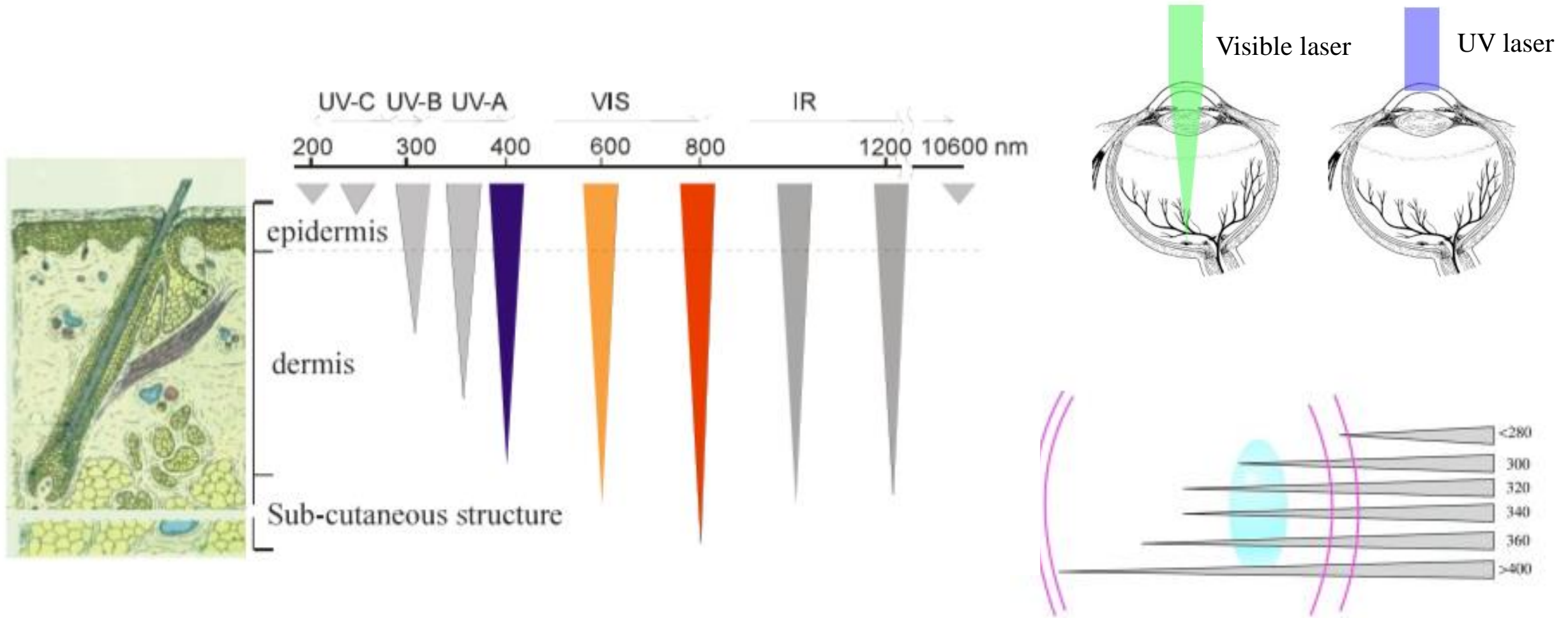


Retina treatment



Laser surgery of benign prostatic hyperplasia

# Penetration ability of light in tissue highly depends on its wavelength!



# Medical applications of lasers – DENTISTRY

## Soft laser therapy (SLT)

- Biostimulation
- Low power: 100-150 mW
- Two wavelength ranges applied:  
650-660 nm – 3 cm depth  
780-980 nm – 8-10 cm depth
- Faster wound healing
- Antimicrobial effect
- Bone restoring, implantology

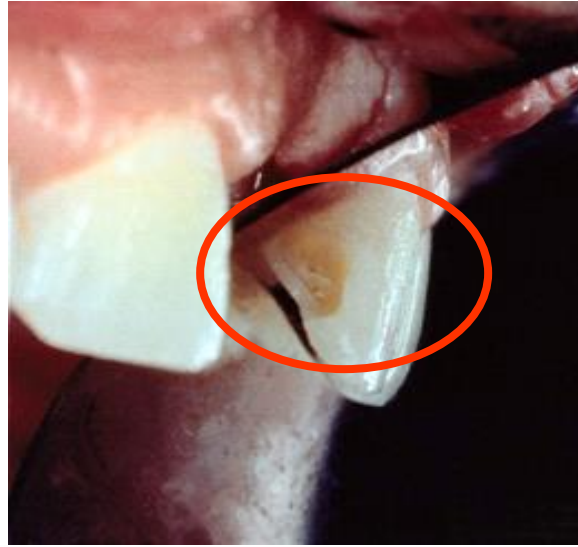


# Caries removal

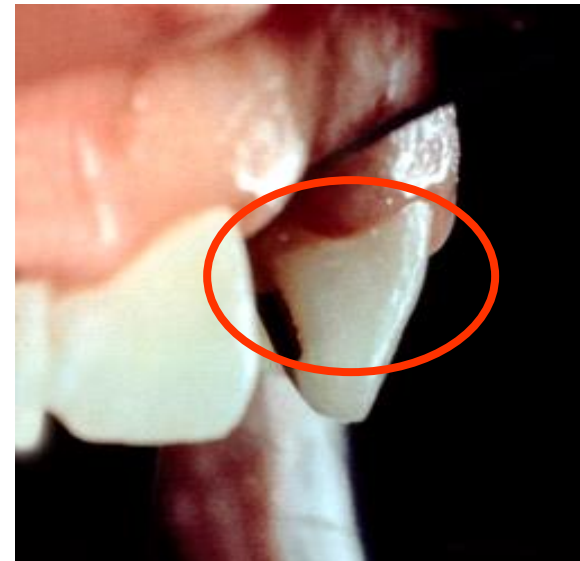
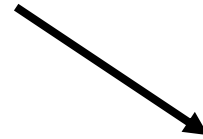
- Vaporization and mechanical shockwave
- ErYAG
- 2940 nm
- Absorption in water and hydroxyapatite





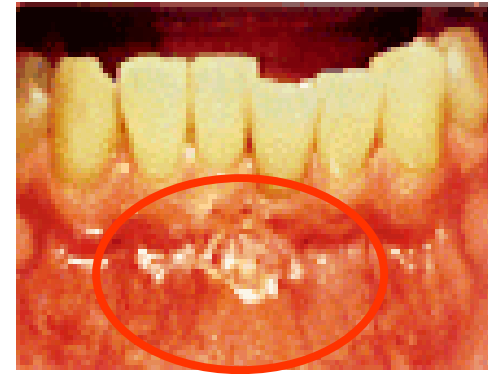


caries removal

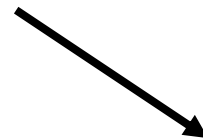


# Oral surgery

Nd: YAG or CO<sub>2</sub> laser



frenectomy



gingivectomy

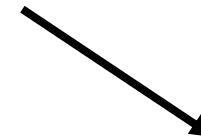
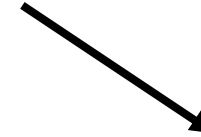


# Teeth whitening

- Argon laser
- 488 nm



Ad of whitening pen...



# Medical applications of lasers – DERMATOLOGY

Laser type	Wavelength	Cutaneous application
Copper vapor/bromide (quasi-CW)	510nm	Pigment
	578nm	Vascular lesions
Pulsed dye	510nm	Superficial pigment, red/yellow/orange tattoos
	585nm	Vascular lesions, warts, hypertrophic scars, striae
Potassium titanyl phosphate (KTP)	532nm	Pigmented/vascular lesions
Neodymium:yttrium-aluminium-garnet (Nd:YAG) [frequency-doubled]	532nm	Superficial pigment, red/orange/yellow tattoos
Tunable dye argon (quasi-CW)	577/585nm	Vascular lesions
Ruby	694nm	
Q-switched		Pigment, blue/black/green tattoos
Normal mode		Hair
Alexandrite	755nm	
Q-switched		Pigment, blue/black/green tattoos
Long-pulsed		Hair
Nd:YAG	1064nm	
Q-switched		Pigment, blue-black tattoos
Long-pulsed		Hair (darker skin phototypes)
Nd:YAG	1320nm	Nonablative skin resurfacing
Erbium:YAG (pulsed)	2940nm	Skin resurfacing, epidermal lesions
Carbon dioxide (CO <sub>2</sub> )[CW]	10 600nm	Actinic cheilitis, verrucae, rhinophyma
CO <sub>2</sub> (high-energy, pulsed)	10 600nm	Skin resurfacing, epidermal/dermal lesions

**CW** = continuous wave; **Q-switched** = quality-switched.

Er:YAG laser

2940 nm

vagy

CO<sub>2</sub> laser

10600 nm

„*skin resurfacing*” – photoablative  
technique



# Removal of superficial blood vessels, veins

Nd:YAG laser  
1064 nm





## Photocoagulation based correction of veins

Nd:YAG laser  
1064 nm



# Aesthetic applications: hair, tattoo removal



Hair removal

Ruby: 694 nm

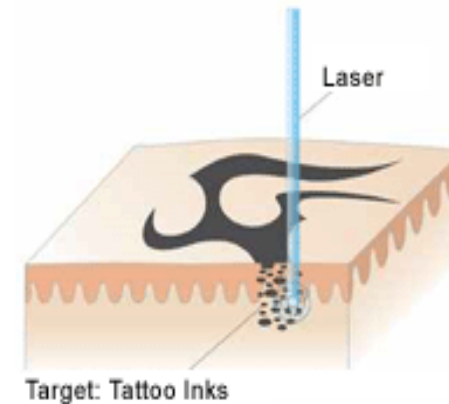
Alexandrite: 755 nm

NdYAG: 1064 nm



before

after

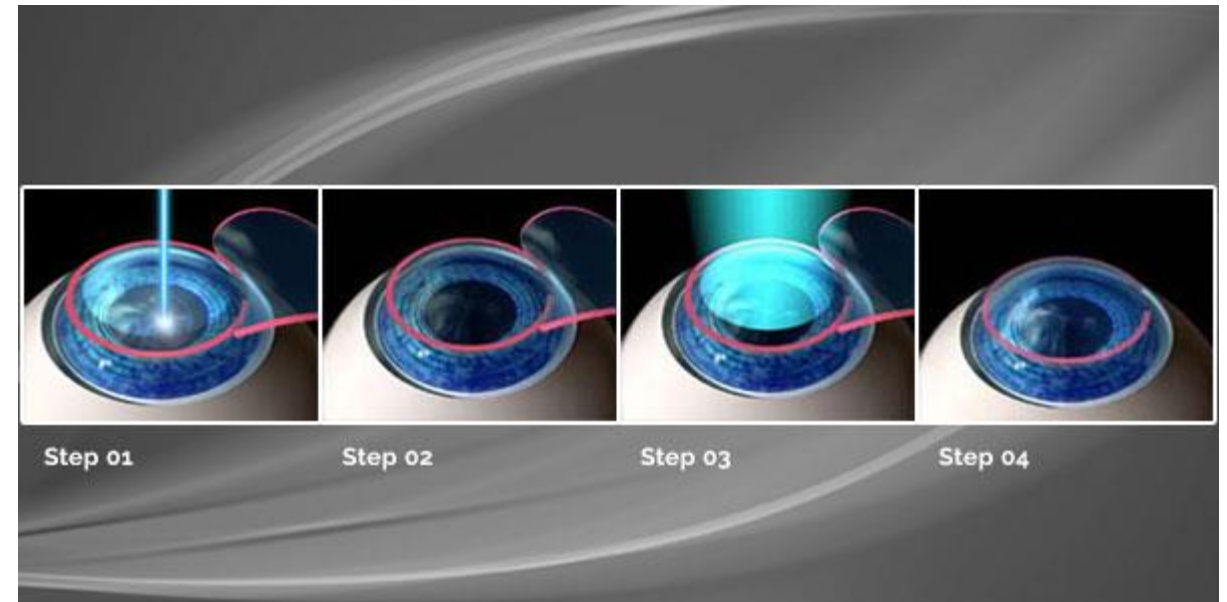


ruby laser (694 nm) is specifically absorbed by the color pigments in the tattoo - vaporization

# Medical applications of lasers – OPHTHALMOLOGY

## FEMTO-LASIK – Femtosecond-assisted Laser In Situ Keratomileusis

- is used to reshape the cornea of the eye
- correct refractive disorders
- femto laser – to create the corneal flap
- removal of material from the corneal stroma (few tens of microns)
- excimer laser (193 nm) (noble gases or the mixture of noble gas and halogen)
- after surgery, the flap can be replaced without sutures, allowing for quicker healing



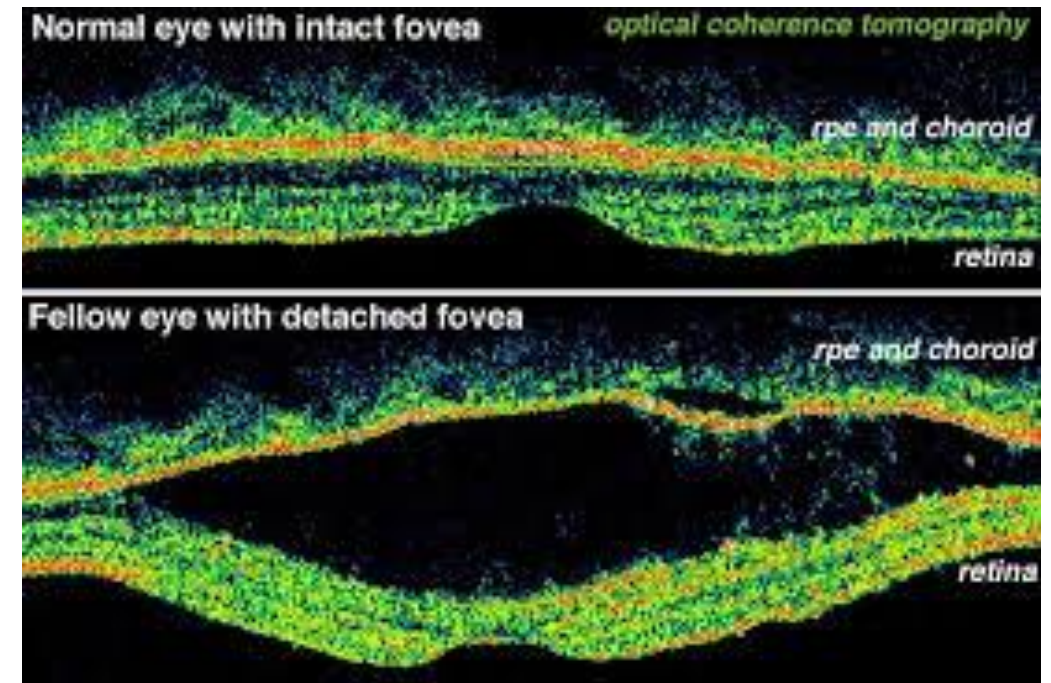
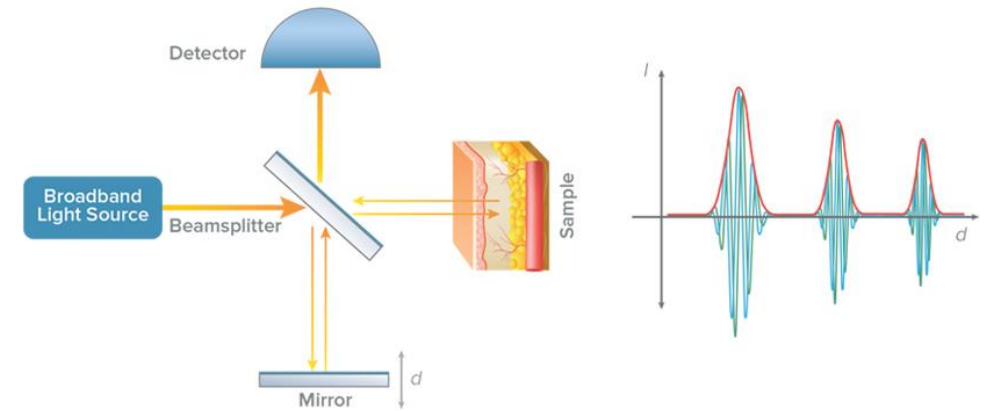


# OCT – Optical coherence tomography

- diagnostic method in ophthalmology
- show cross-sections of retina layers with micrometer resolution
- glaucoma, macular degeneration, diabetic macular oedema, multiple sclerosis

## Principles:

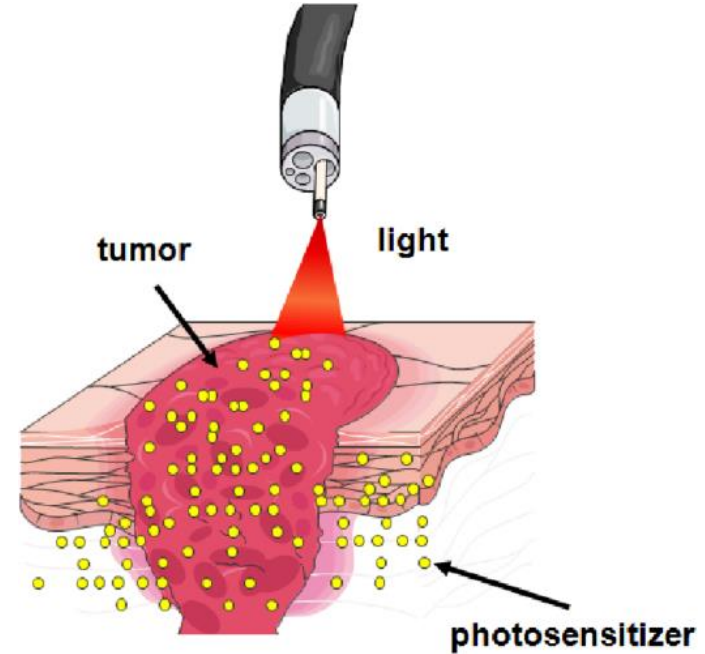
light rays reflected in deeper tissue layers can be separated from scatter by using interferometry. The spatial position of the reflecting layers can be determined. The structure of the illuminated sample can be resolved within 1-2 mm depth.



# Medical applications of lasers – ONCOLOGY

## PDT – Photodynamic therapy

1. administration of photosensitizing agent (porphyrins or 5-aminolaevulinic acid)
2. the photosensitizer concentrated in cancer tissue
3. activation of photosensitizer with light
4. the excited photosensitizer produces free radicals and reactive oxygen species (ROS)
5. tissue reaction
6. neighbouring healthy tissues remain intact



superficial skin cancers, tumor of cavity organs - oesophagus, bronchus, ureters, bladder



Laser types:  
Ar, NdYAG, TiS  
310-1285 nm-tunable

# Checklist

- Requirements of laser operation
  - 3 energy levels (metastable)
  - Population inversion (pumping)
  - Stimulated emission
- Optical resonator
- Properties of laser light (coherence, polarized, monochromatic, high power, parallel beam)
- Types of lasers
- Laboratory and medical applications
  - Absorption in tissue
  - Thermal effects
  - Penetration depth in tissues

## **Related chapters:**

*Damjanovich, Fidy, Szöllősi: Medical Biophysics*

**II. 2.2**

**2.2.5**

**2.2.7**

**2.2.8**

**IX. 1.1**

**IX. 1.2**