

Principles, types and medical applications of lasers

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25/10/2024

Laser

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



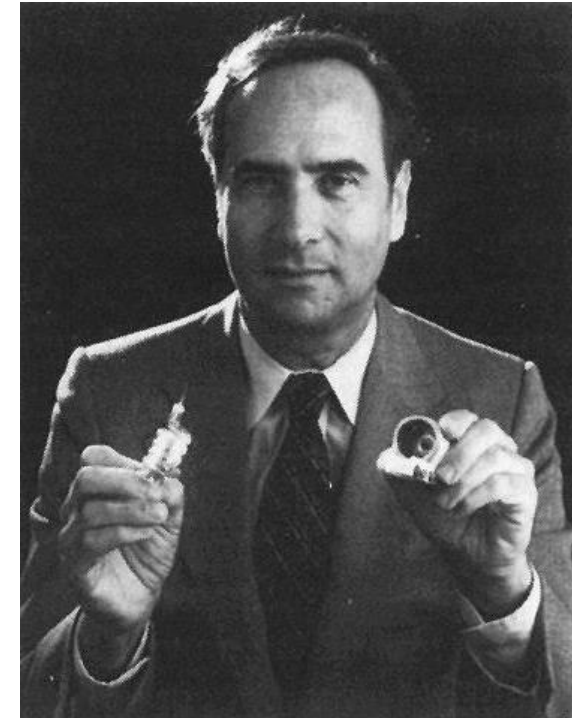
History of lasers in a nutshell...

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

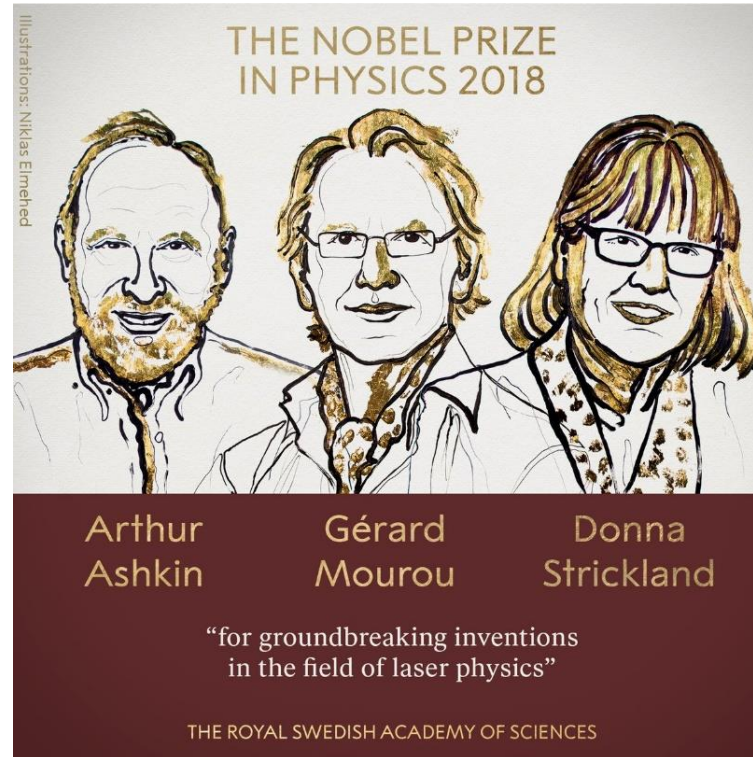
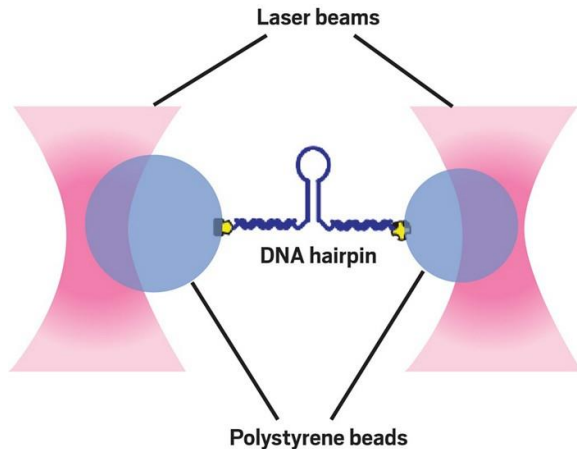
Nobel prize in Physics 2000
Semiconducting laser diode

Nobel prize in Physics 2018

"for groundbreaking inventions in the field of laser physics"

Ashkin,

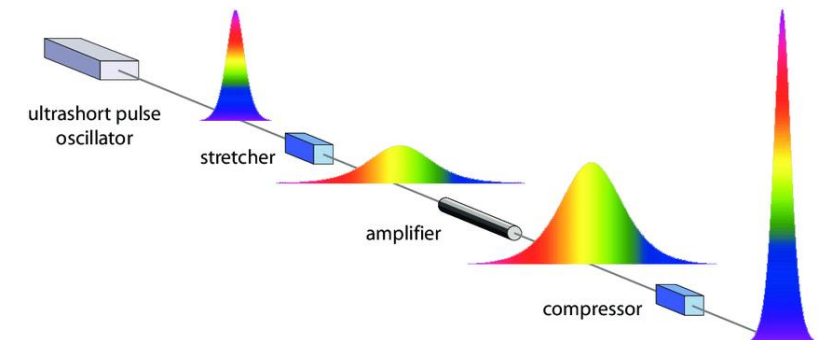
Arthur Ashkin invented optical tweezers that grab particles, atoms, molecules, and living cells with their laser beam fingers. The tweezers use laser light to push small particles towards the centre of the beam and to hold them there. In 1987, Ashkin succeeded in capturing living bacteria without harming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



Mourou and Strickland

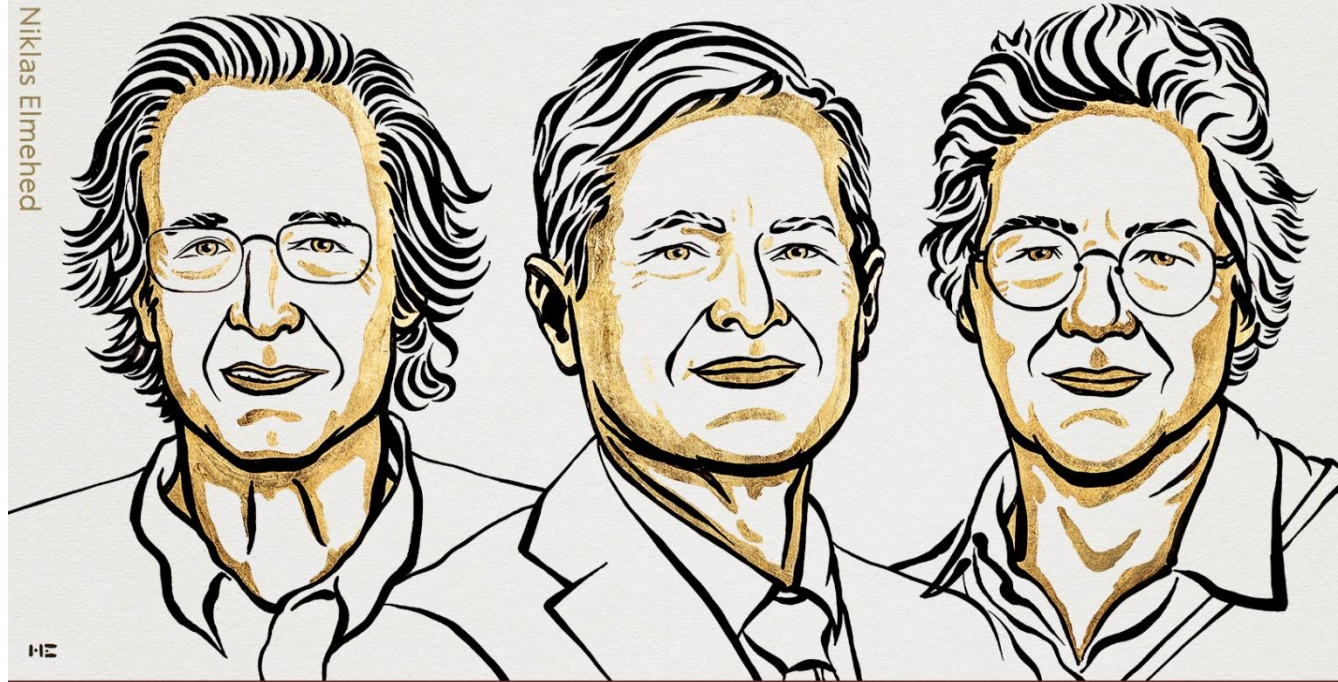
paved the way towards the shortest and most intense laser pulses ever created by mankind

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...



Illustrations: Niklas Elmehed

THE NOBEL PRIZE IN PHYSICS 2023



Pierre
Agostini

Ferenc
Krausz

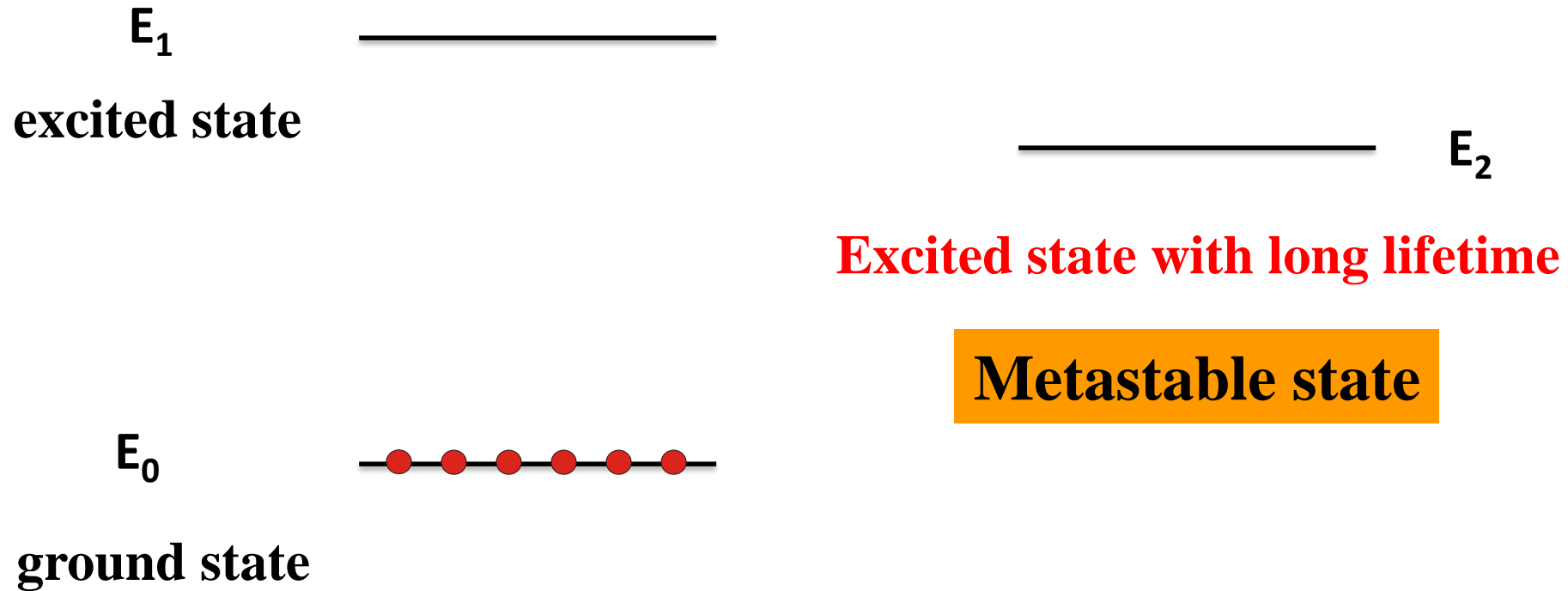
Anne
L'Huillier

"for experimental methods that generate
attosecond pulses of light for the study
of electron dynamics in matter"

THE ROYAL SWEDISH ACADEMY OF SCIENCES

Fundamentals of laser operation

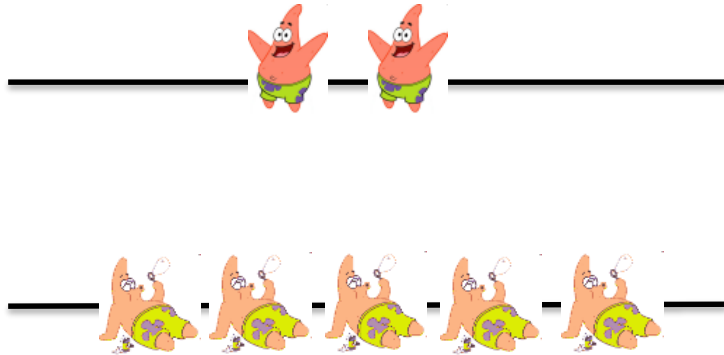
Special electronic energy states – I. at least a three-state system



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

II: Occupancy in energy levels

Population inversion

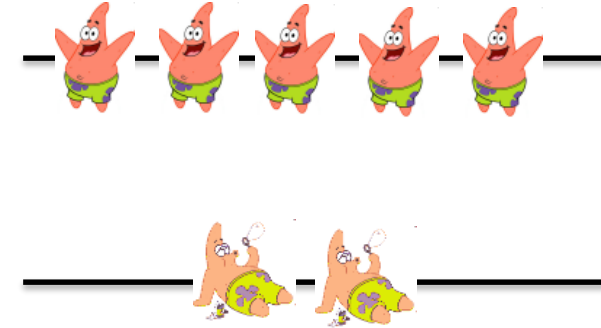


Thermal equilibrium

According to Boltzmann distribution

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

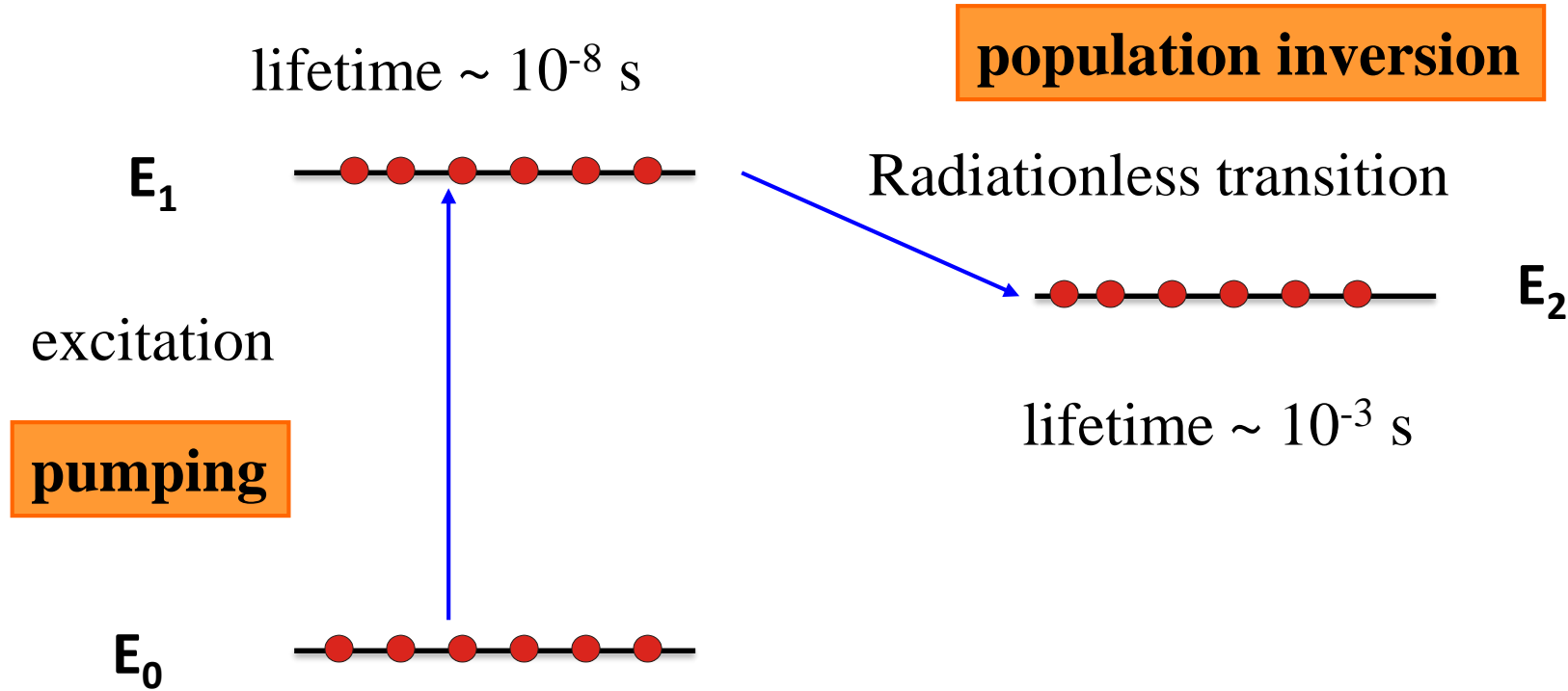
The number of atoms, \mathbf{n} , at an energy level $\Delta\epsilon$ higher than the ground level, if the number of atoms in the ground state is \mathbf{n}_0 in two energy levels separated by the energy difference.



Population inversion

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

III: Excitation Optical pumping

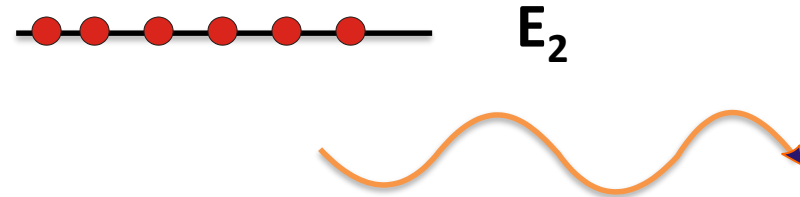


Optical pumping = energy input from an external source (electrical, optical, chemical energy)

Spontaneous photon emission

E_1 —————

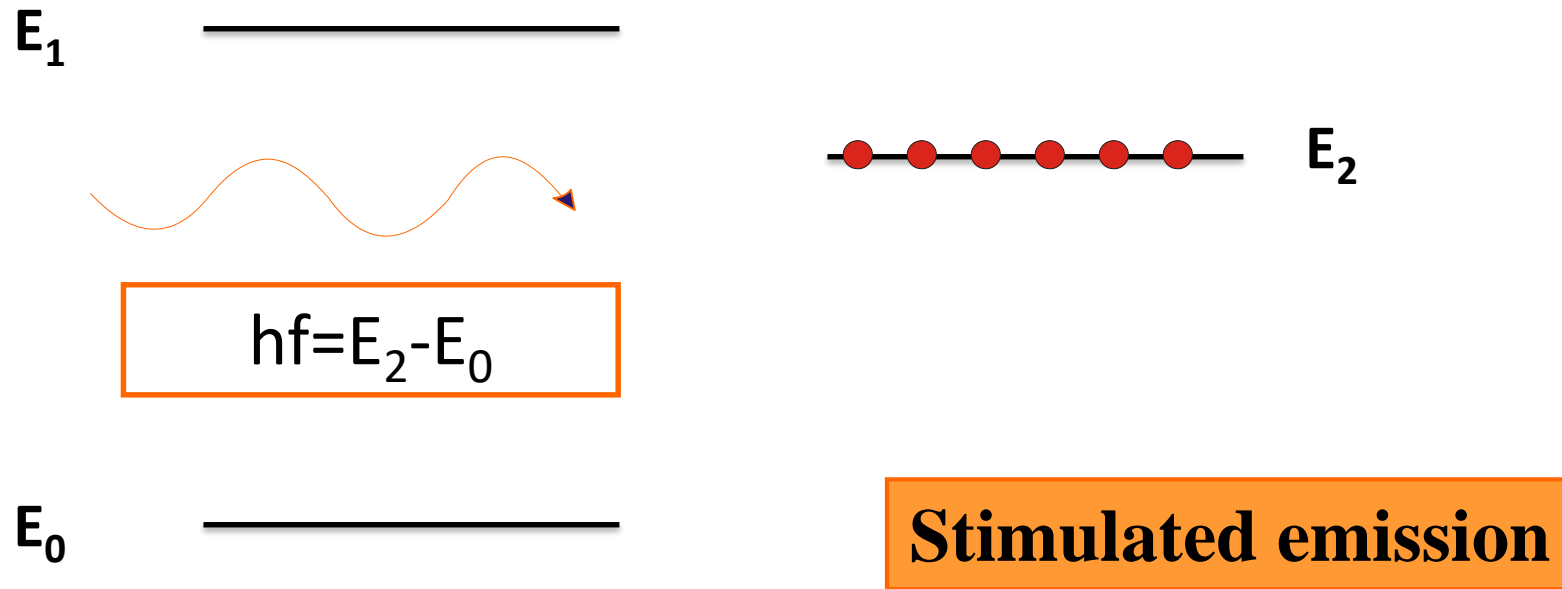
E_0 —————●



Spontaneous light emission

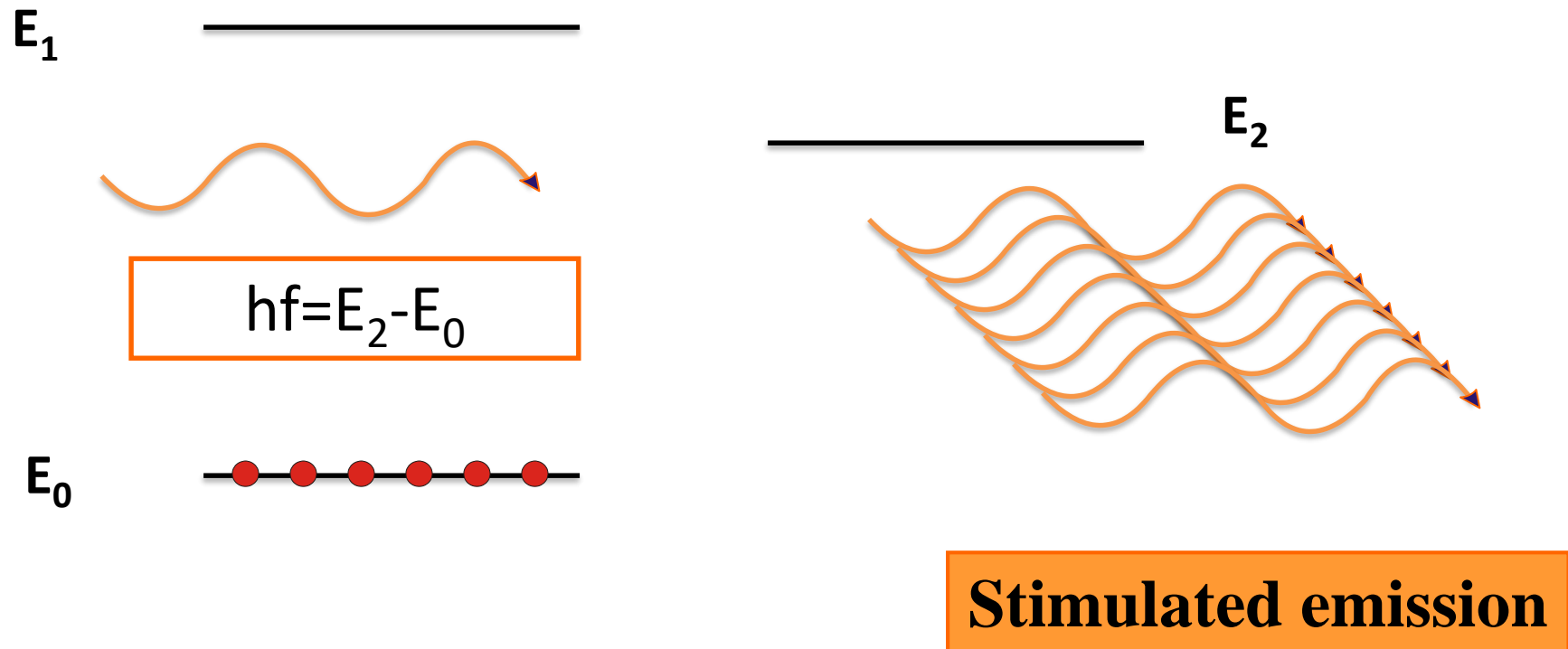
Low probability

Induction of atomic transition – relaxation of electrons from metastable state



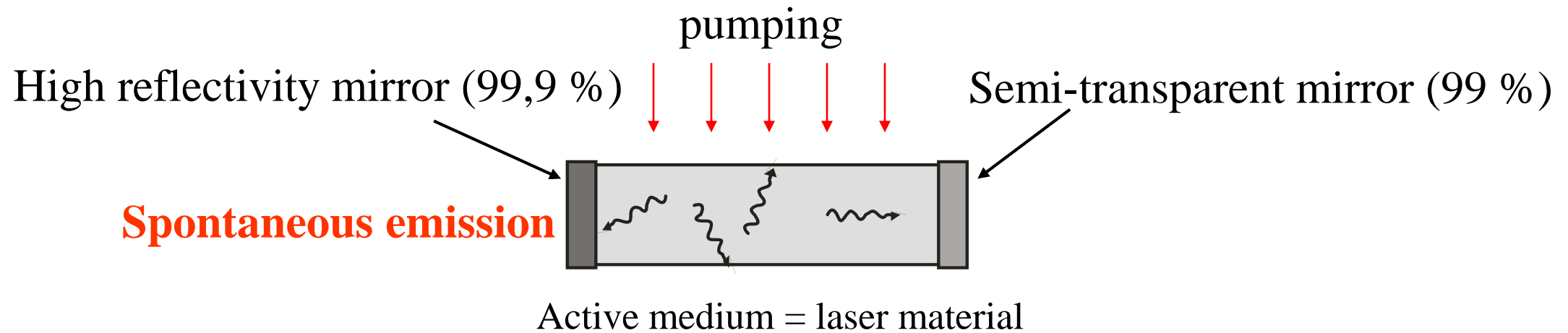
The incoming photon of $hf = E_2 - E_0$ can interact with electrons on metastable state causing them to drop to the lower energy level

Induction of atomic transition – relaxation of electrons from metastable state

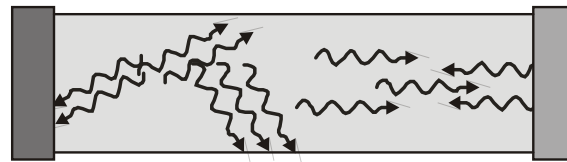


Phase, frequency, polarization, and direction of the photons emitted with the stimulated emission are identical with that of induced the stimulation.

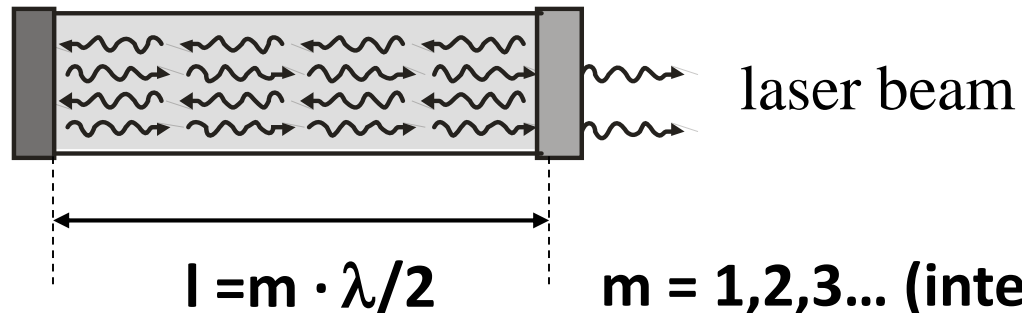
Optical resonator

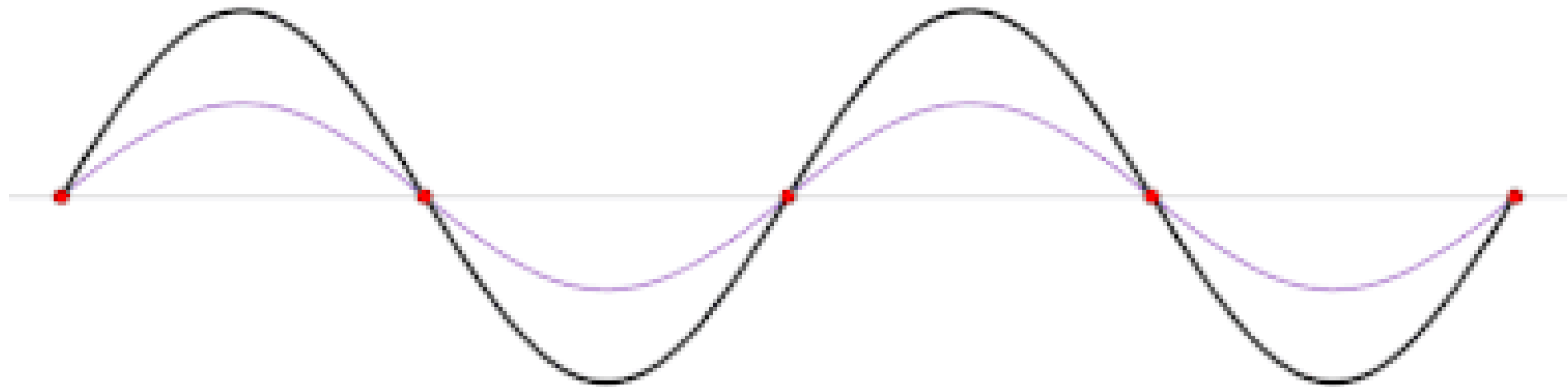
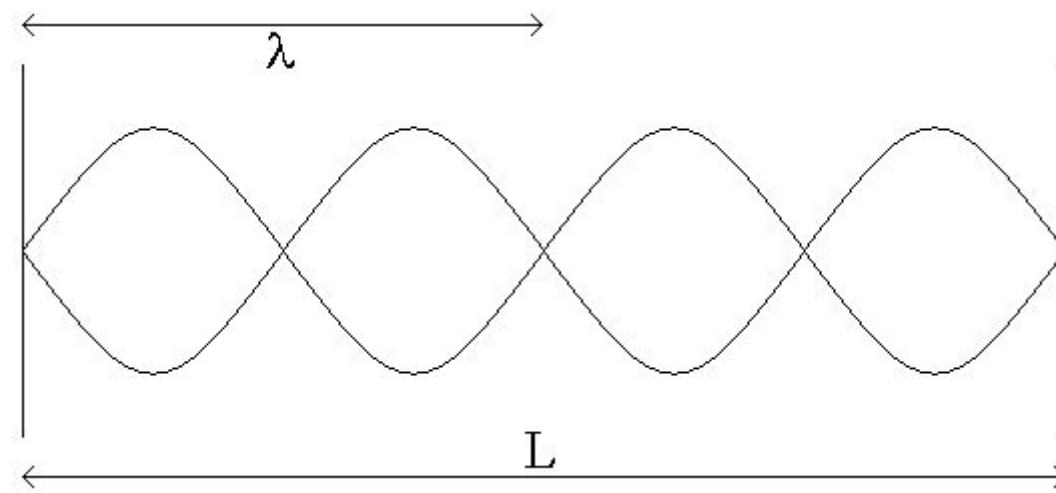


Spontaneous and stimulated emission



Stimulated emission



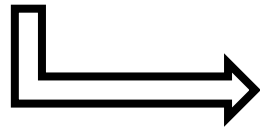


Standing waves in the optical resonator

General properties of laser light

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

- energy
- phase
- polarization
- direction



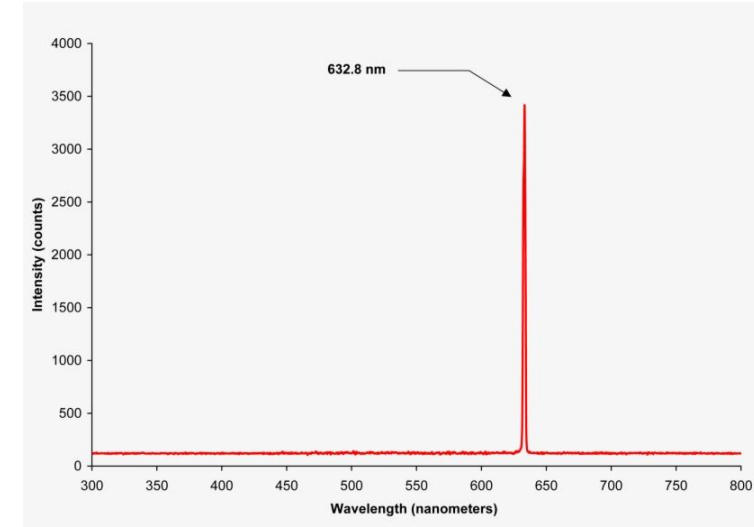
Consequently laser light is

- monochromatic
- coherent
- polarized
- parallel beam

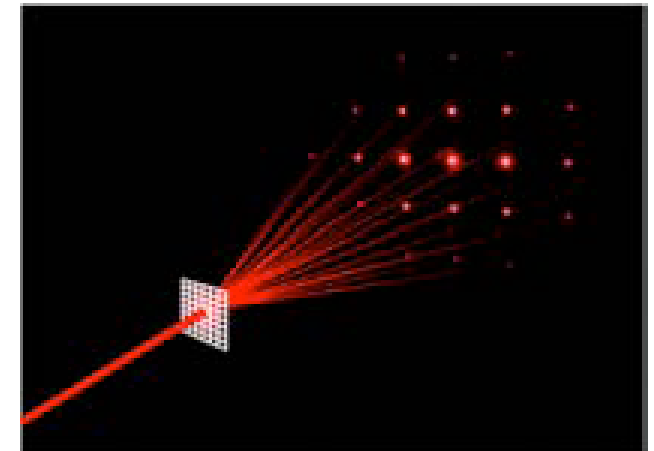


Light generated by stimulated emission

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



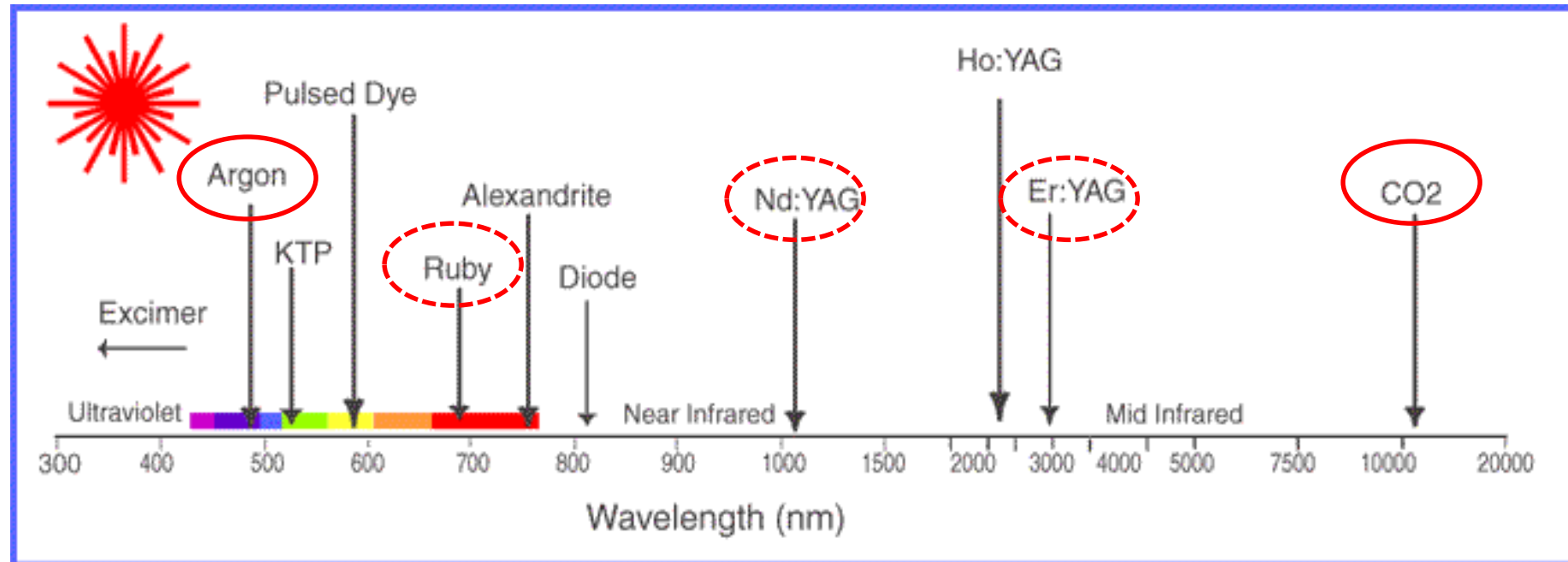
He-Ne laser emission spectrum



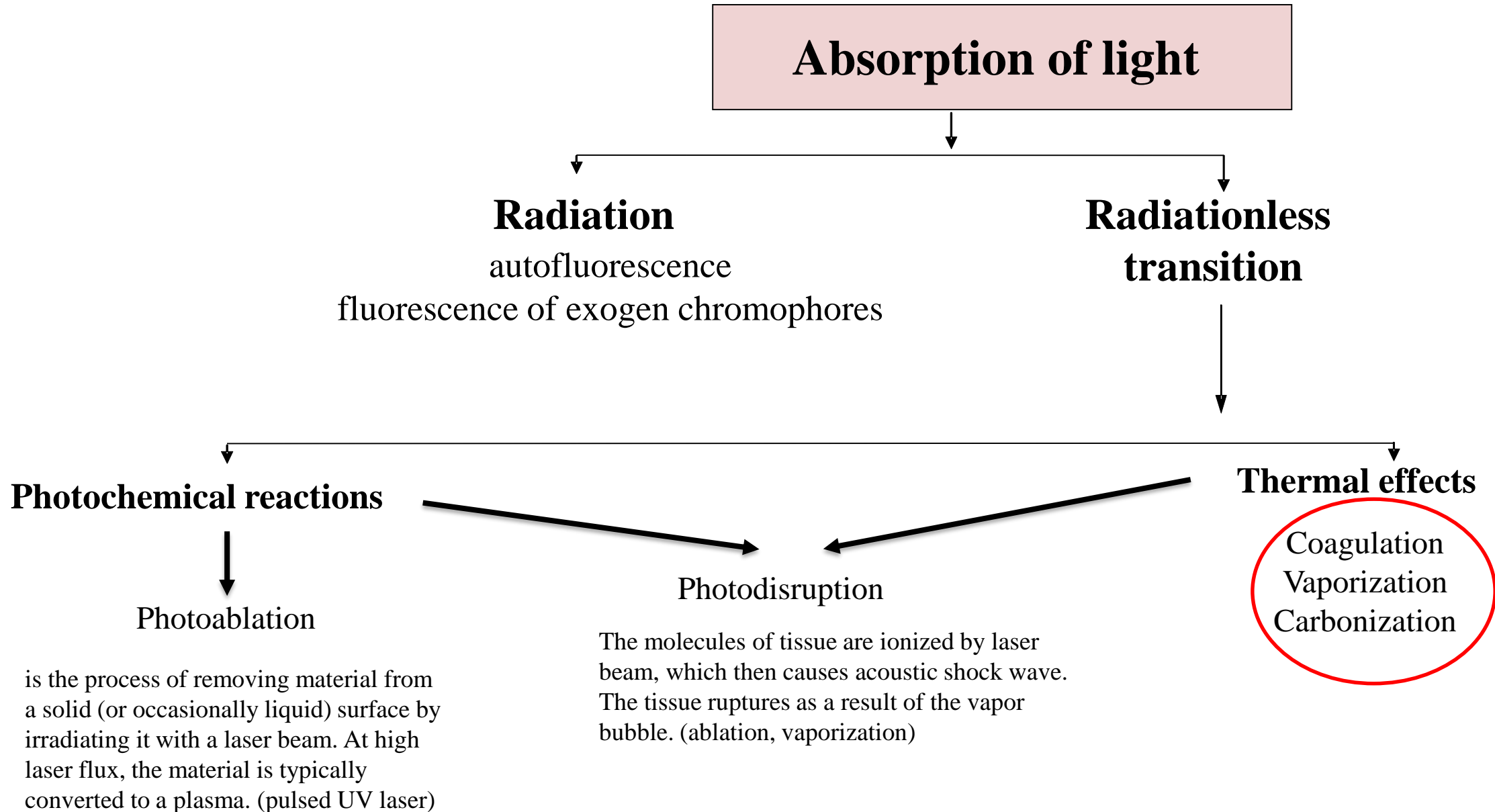
Interference pattern of laser beam

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

1. Solid state lasers: Metal doped crystals (Ruby, Nd-YAG yttrium-aluminium-garnet, Ti-sapphire)
2. Gas lasers: He-Ne, CO₂, Ar, Kr
3. Dye lasers: dilute solution of organic dyes (rhodamine, coumarin)
4. Semiconductor (diode) lasers: combination of p- and n-type doped semiconductors



Medical applications of lasers – interactions...



Thermal effects



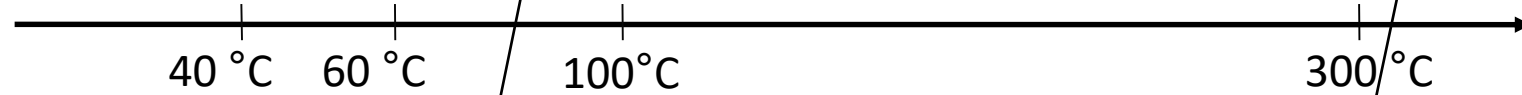
Orthopedics

biostimulation

coagulation

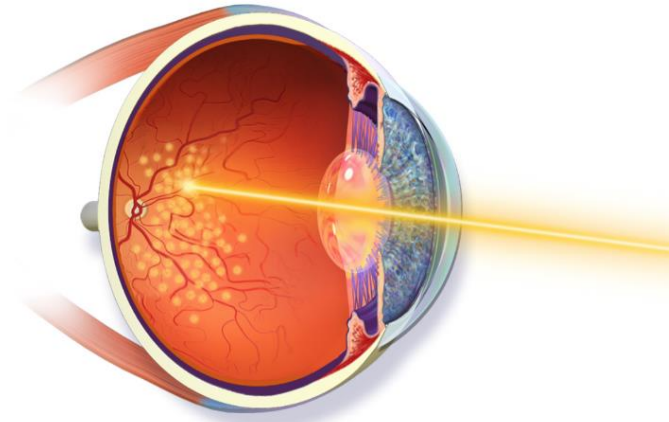
carbonization

vaporization

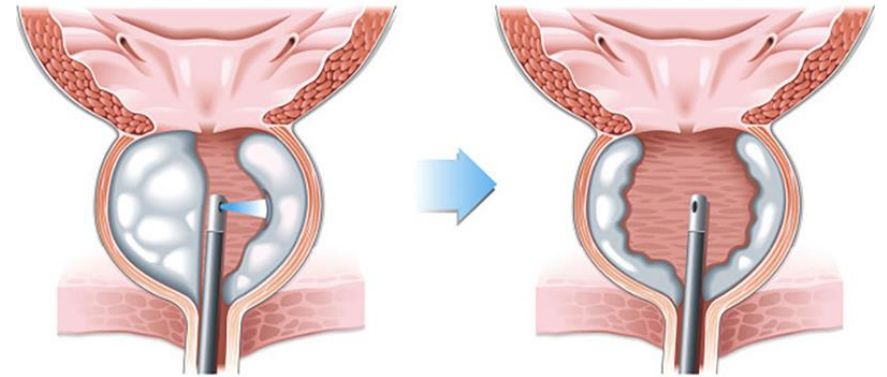


Oral Diagnosis
Herpes Treatment

48 Hours Later

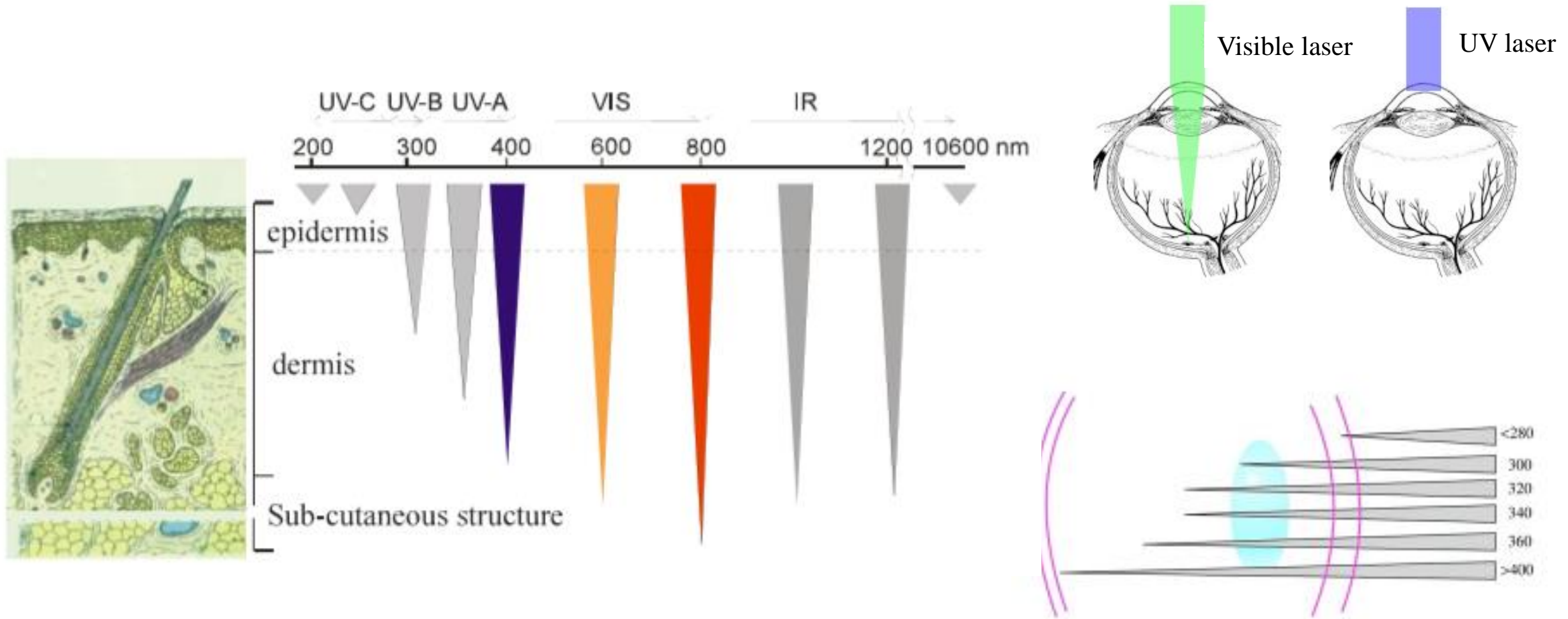


Retina treatment



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)

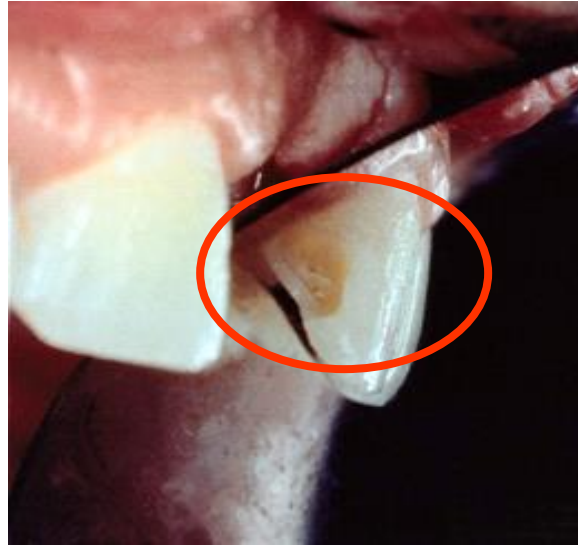
- Biostimulation
- Low power: 100-150 mW
- Two wavelength ranges applied:
650-660 nm – 3 cm depth
780-980 nm – 8-10 cm depth
- Faster wound healing
- Antimicrobial effect
- Bone restoring, implantology



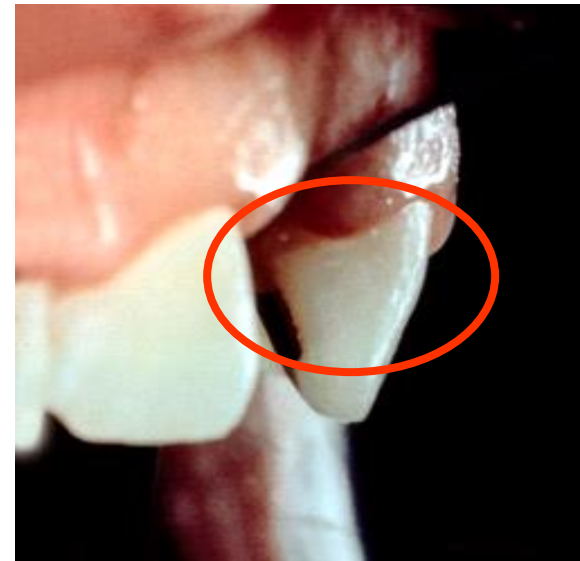
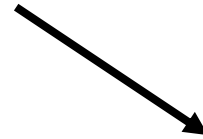
Caries removal

- Vaporization and mechanical shockwave
- ErYAG
- 2940 nm
- Absorption in water and hydroxyapatite
- No carbonization, no heat formation
- Superficial layer is treated





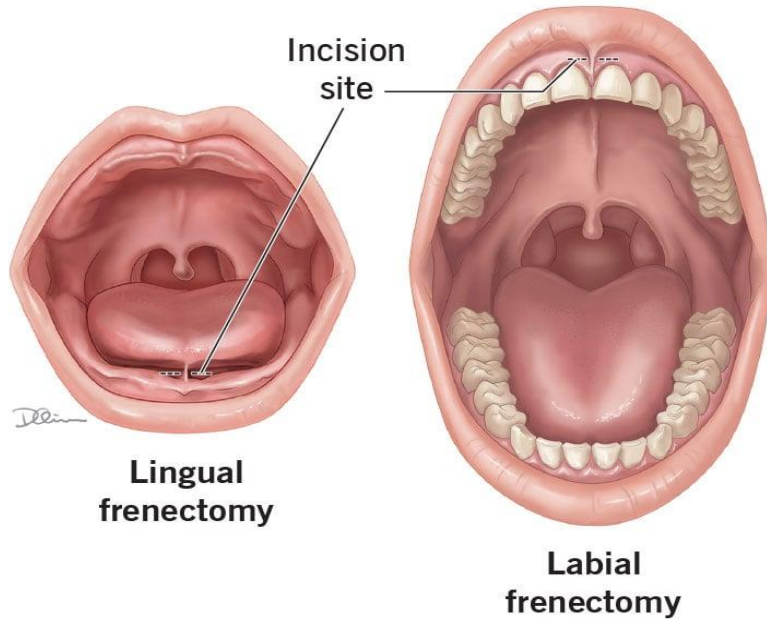
caries removal



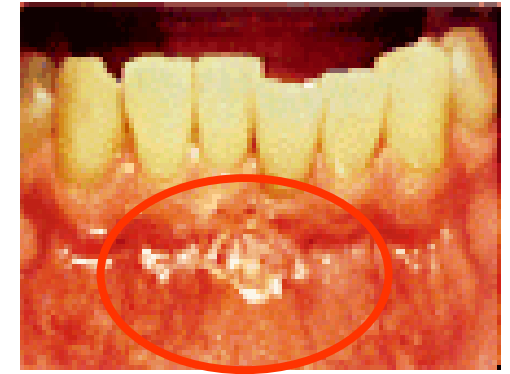
Oral surgery

Nd:YAP* laser
1340 nm

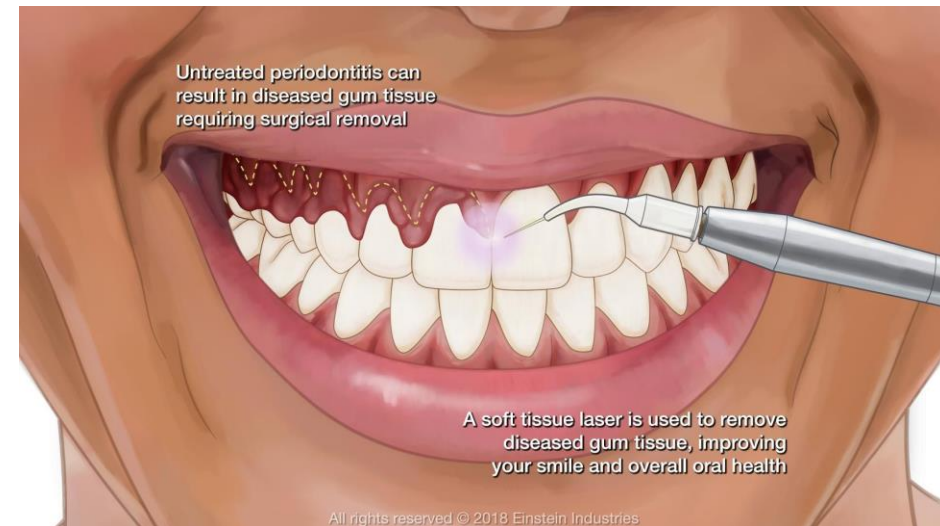
Frenectomy



Cleveland Clinic © 2022



frenectomy



gingivectomy

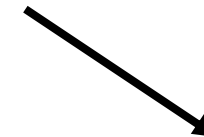
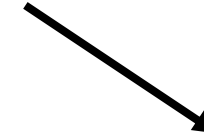
*YAlO₃:Nd Neodymium doped yttrium aluminium perovskite

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 ₂)[CW]	10 600nm	Actinic cheilitis, verrucae, rhinophyma
CO ₂ (high-energy, pulsed)	10 600nm	Skin resurfacing, epidermal/dermal lesions

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

Er:YAG laser

2940 nm

or

CO₂ laser

10600 nm

„*skin resurfacing*” – photoablative
technique



Removal of superficial blood vessels, veins

Photocoagulation

Potassium titanyl
phosphate (KTP)
pulsed laser

532 nm



chromophore: oxyhemoglobin with 418, 542 and 577 nm absorption maxima
BUT! Depth of vessels, thickness, skin phototype, avoid: melanocytes, hair follicles

Photocoagulation based correction of veins

Nd:YAG laser
1064 nm



chromophore: oxyhemoglobin with 418, 542 and 577 nm absorption maxima
BUT! Depth of vessels, thickness, skin phototype, avoid: melanocytes, hair follicles

Aesthetic applications: hair, tattoo removal



Hair removal

Ruby: 694 nm

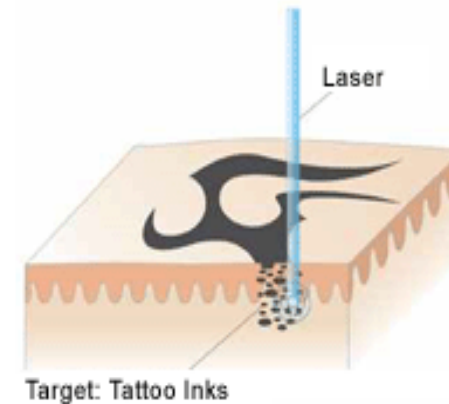
Alexandrite (BeAl_2O_4): 755 nm

NdYAG: 1064 nm



before

after

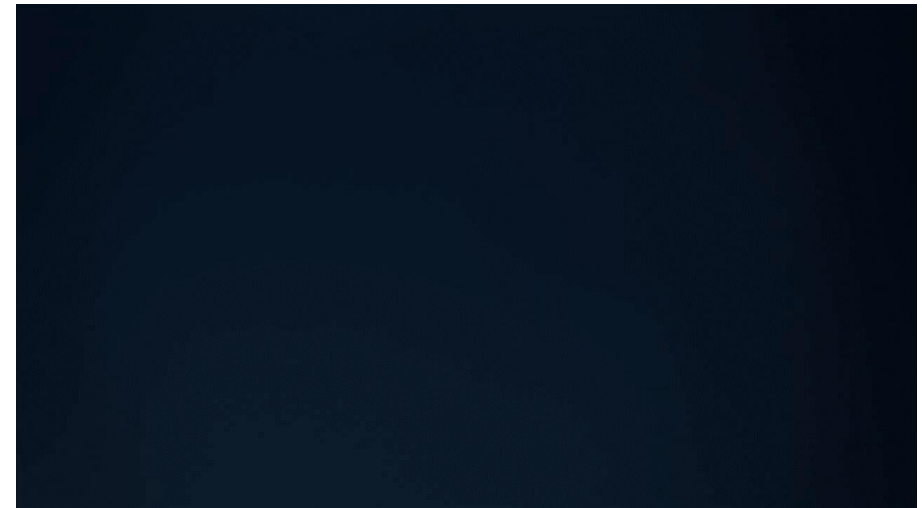
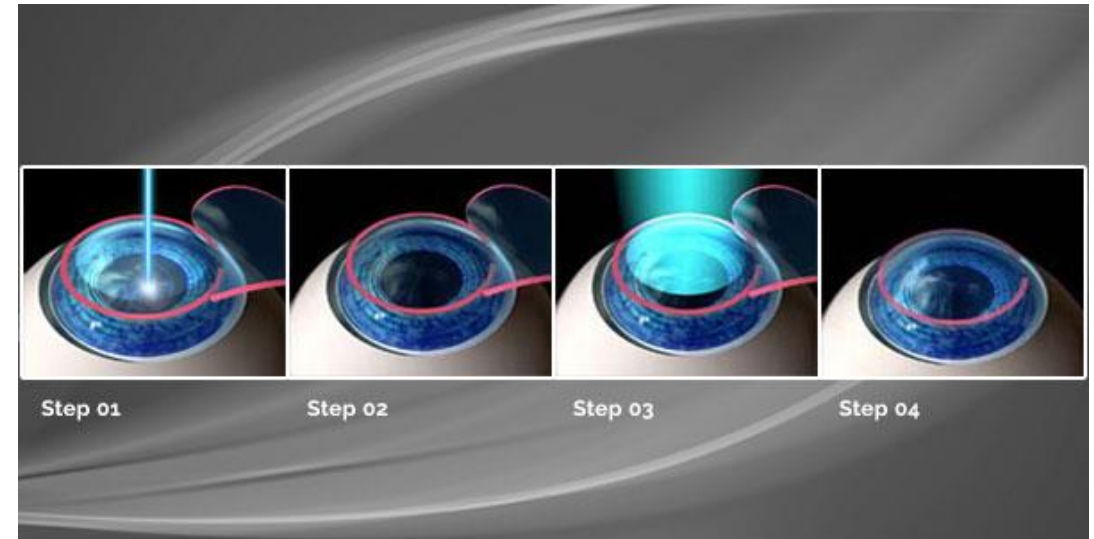


ruby laser (694 nm) is specifically absorbed by the color pigments in the tattoo - vaporization

Medical applications of lasers – OPHTHALMOLOGY

FEMTO-LASIK – Femtosecond-assisted Laser In Situ Keratomileusis

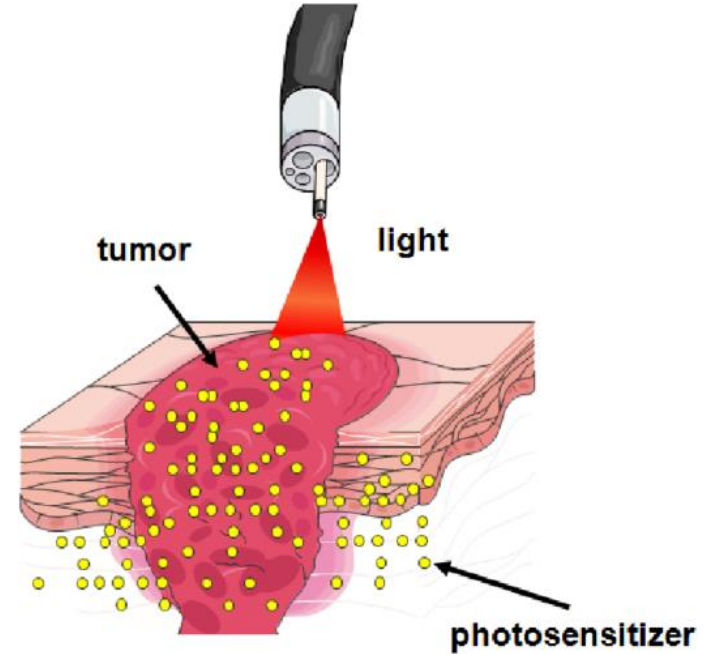
- is used to reshape the cornea of the eye
- correct refractive disorders
- femto laser – to create the corneal flap
- removal of material from the corneal stroma (few tens of μm)
- excimer laser at 193 nm – noble gases or the mixture of noble gas and halogen
- after surgery, the flap can be replaced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



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

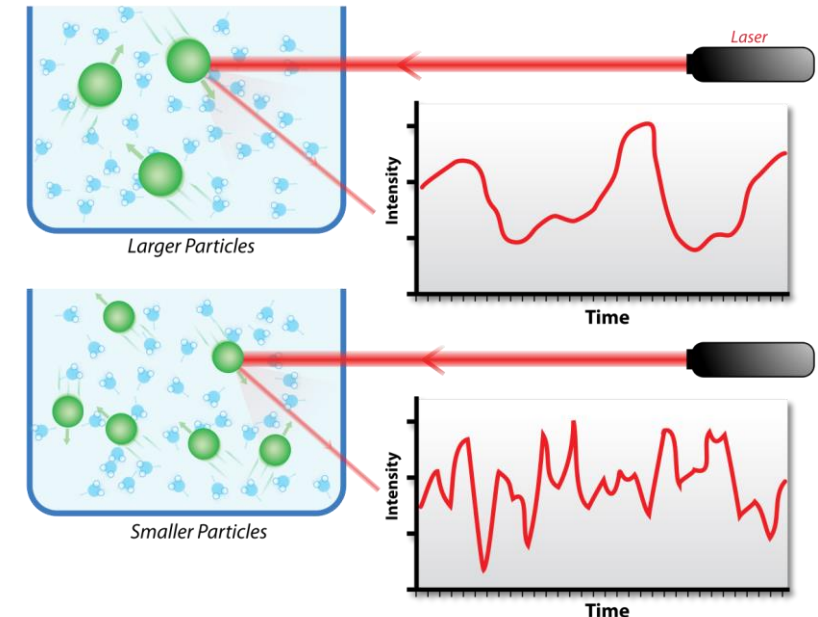
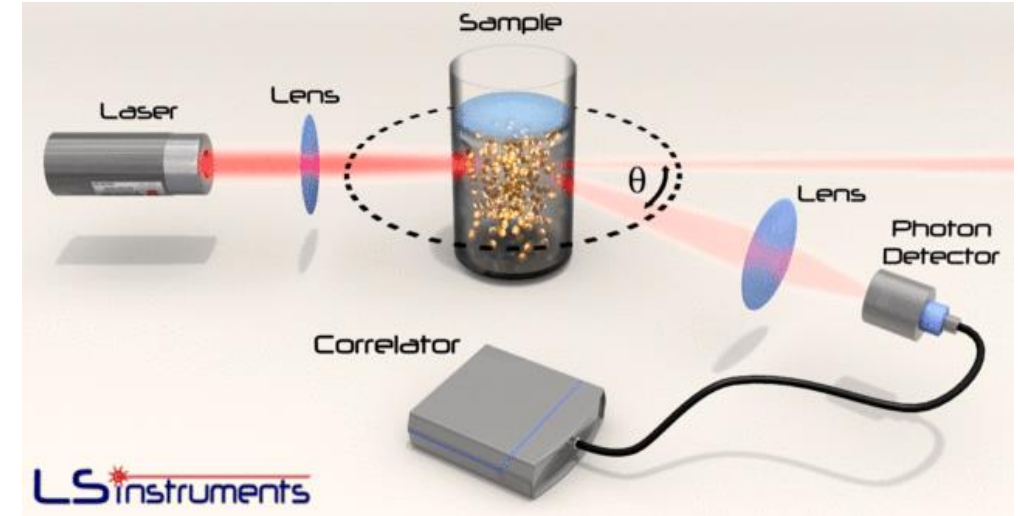
Supplement

Further techniques with lasers

Application of lasers – laboratory techniques

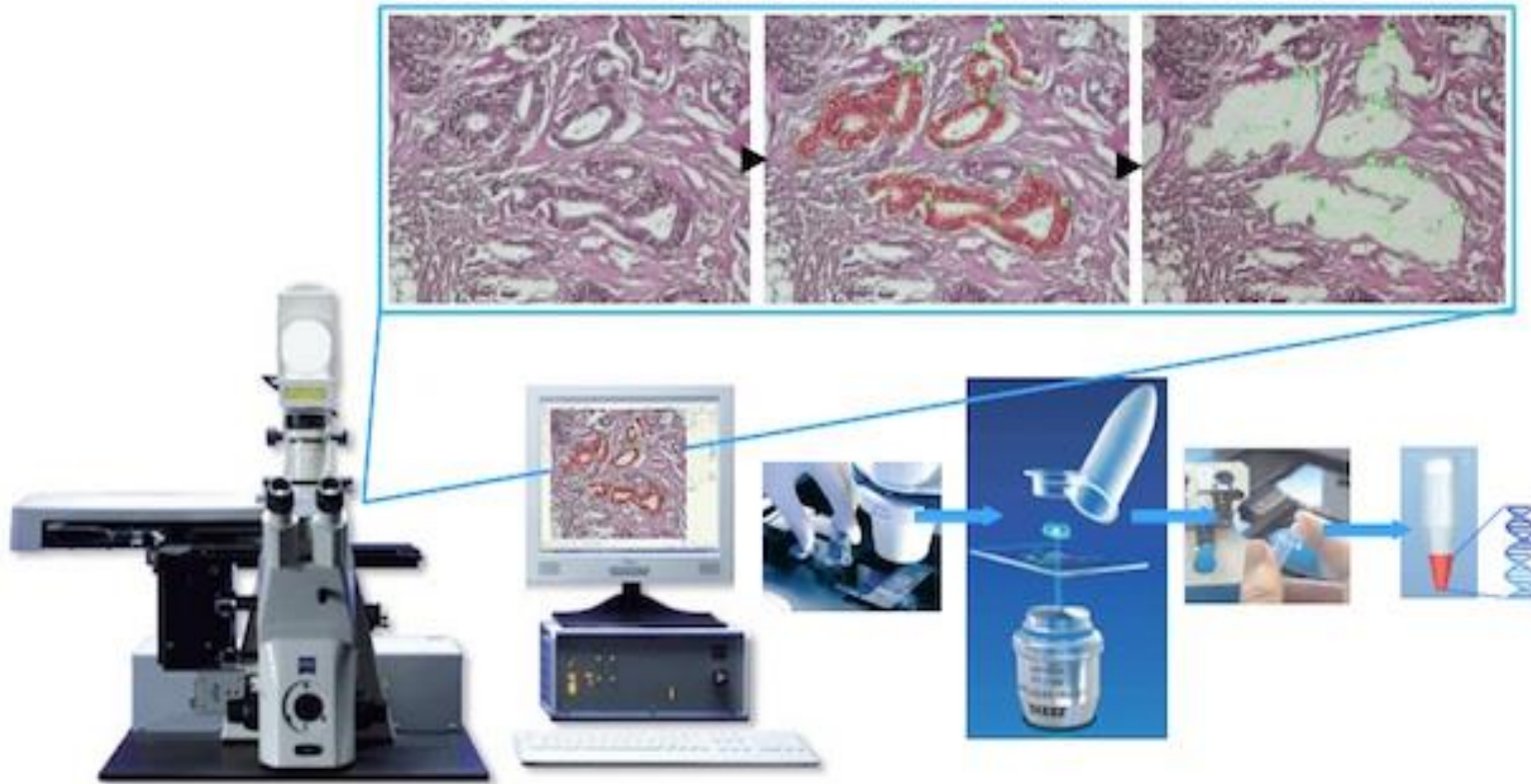
Dynamics Light Scattering (DLS)

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

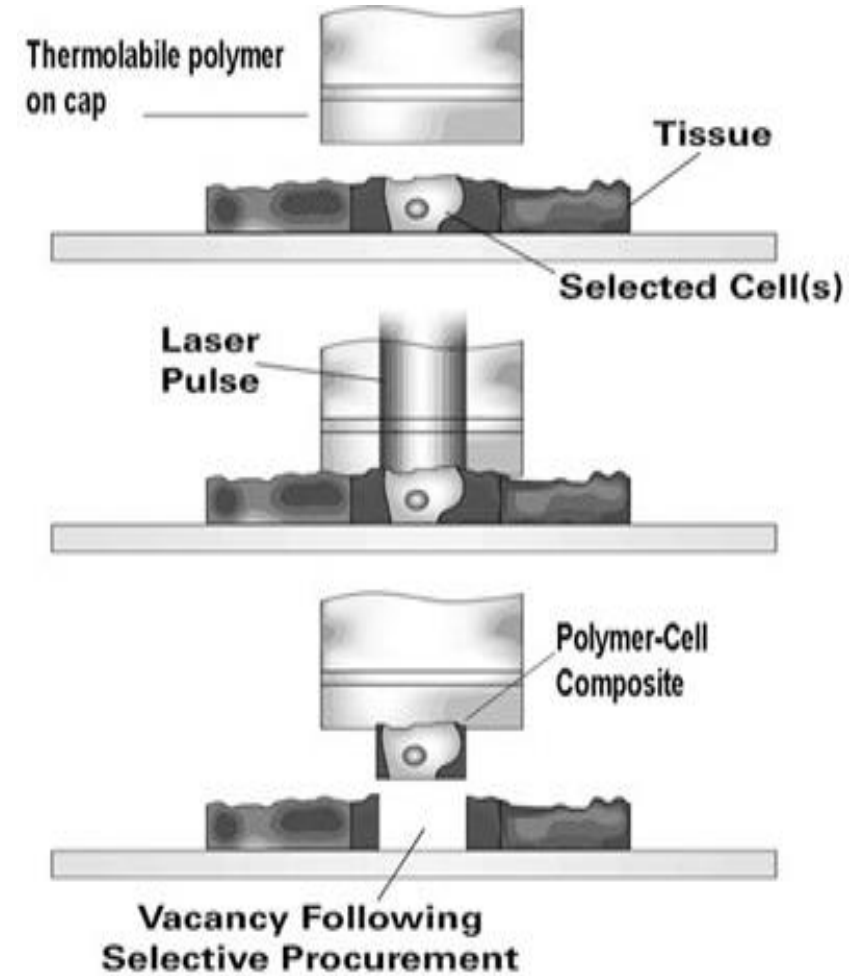


$$D = \frac{k_B T}{6\pi\eta r}$$

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

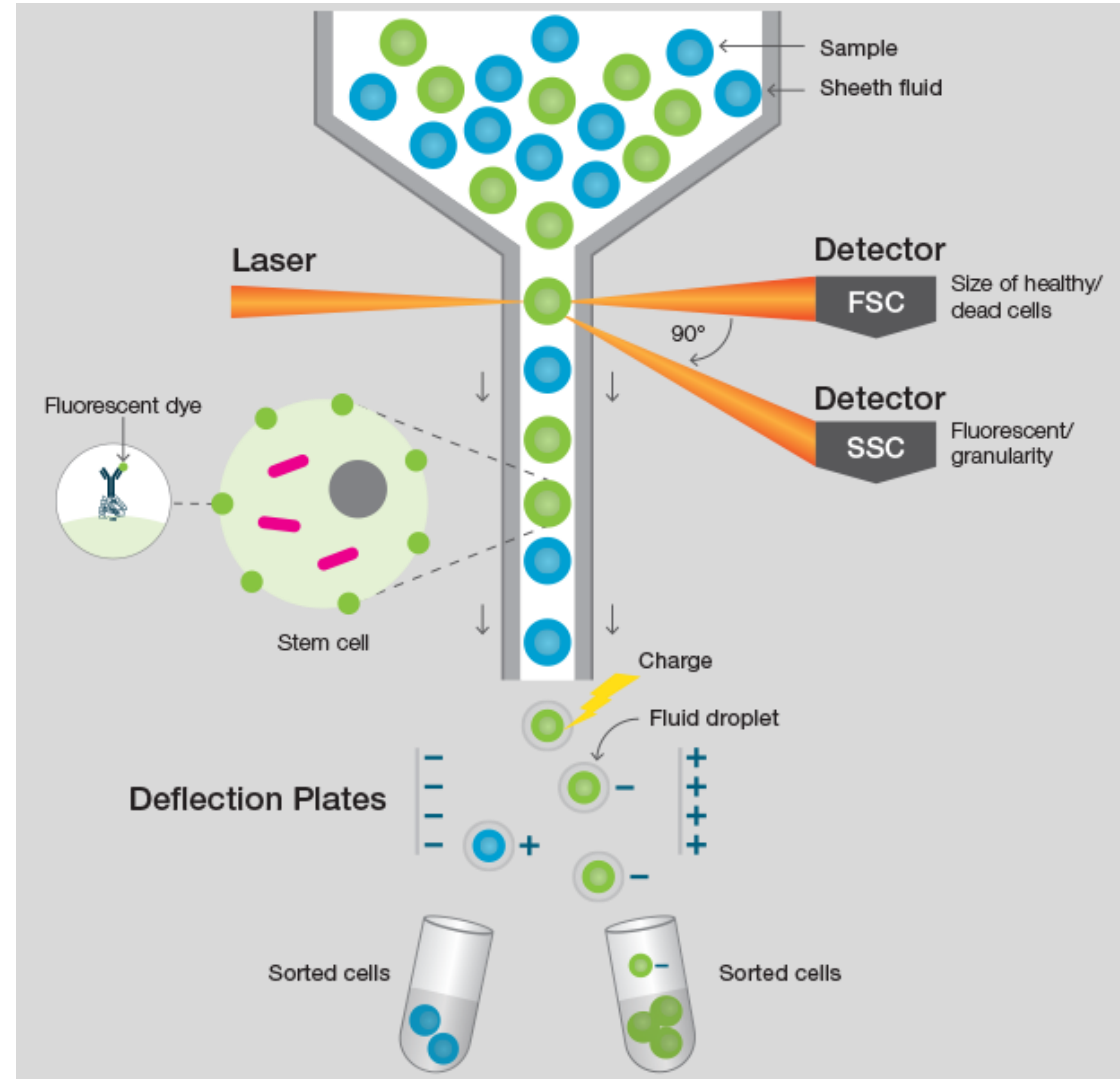


UV laser – cut

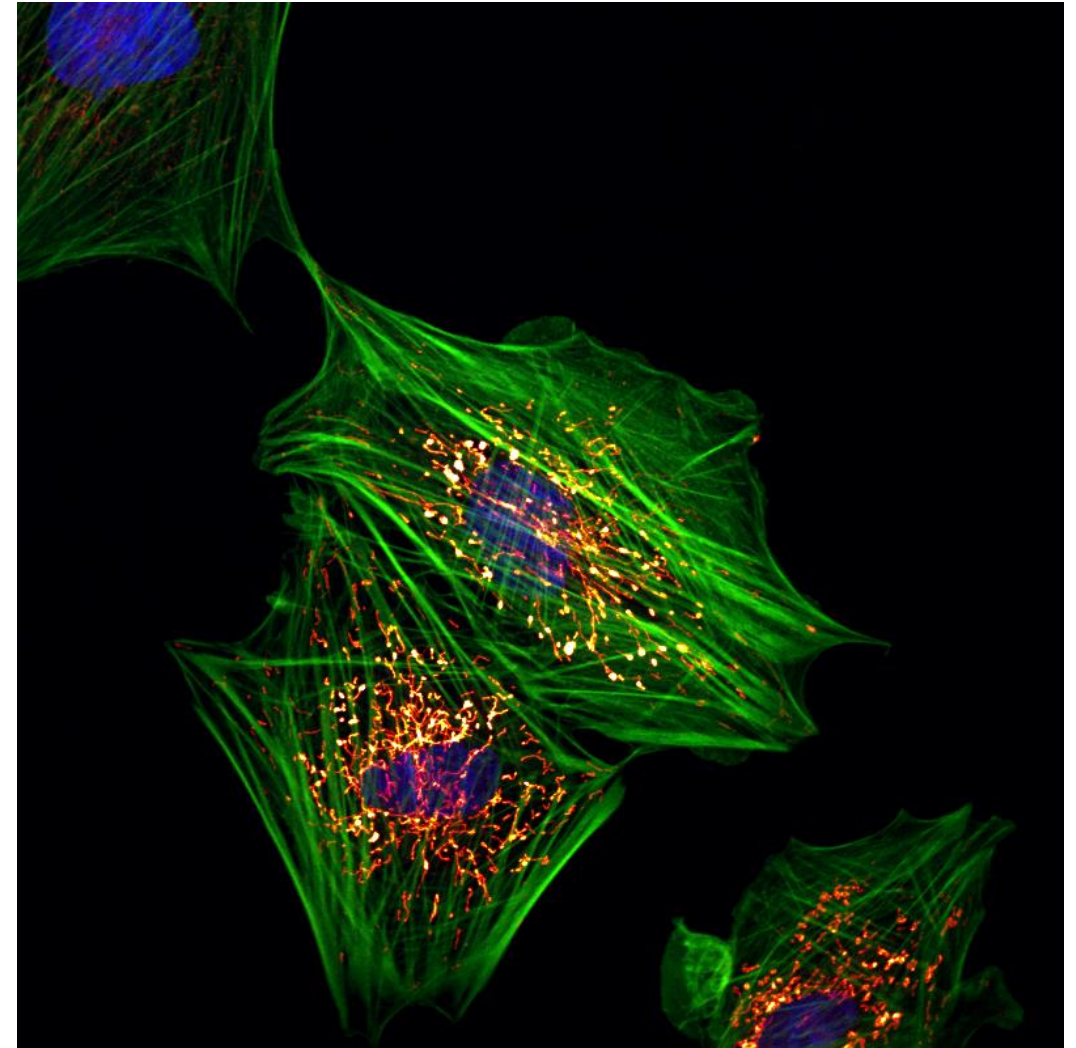
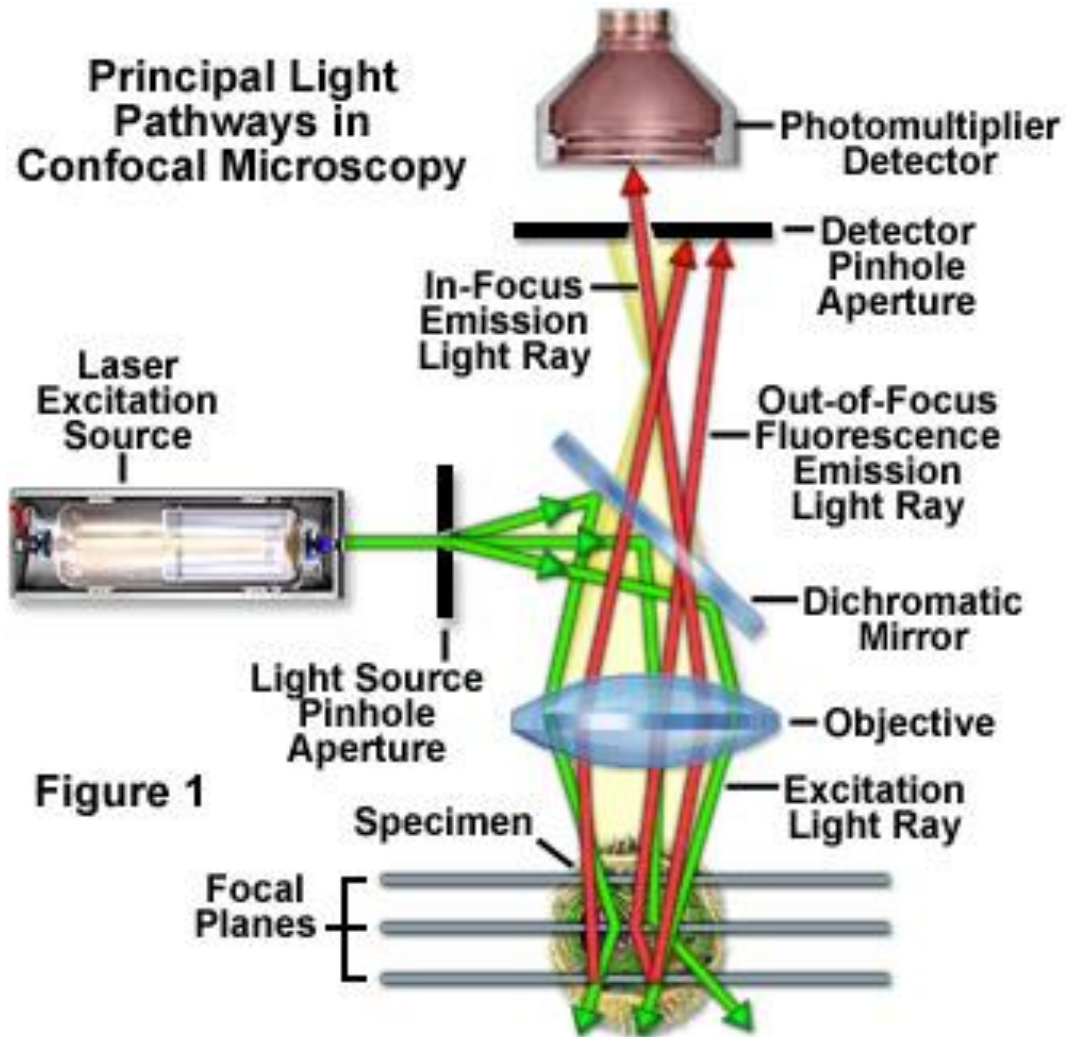
IR laser – heating the polymer cap

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



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

Medical applications of lasers – OPHTHALMOLOGY

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.

