Introduction to Lasers I

October 14th-19th 2012, GANIL, Caen, France

1st LA³NET School Laser Applications at Accelerators

Luis Roso

LA³NET

CLPU CENTRO DE LASERES PULSADOS ULTRACORTOS ULTRAINTENSOS

Centro de Laseres Pulsados

Salamanca

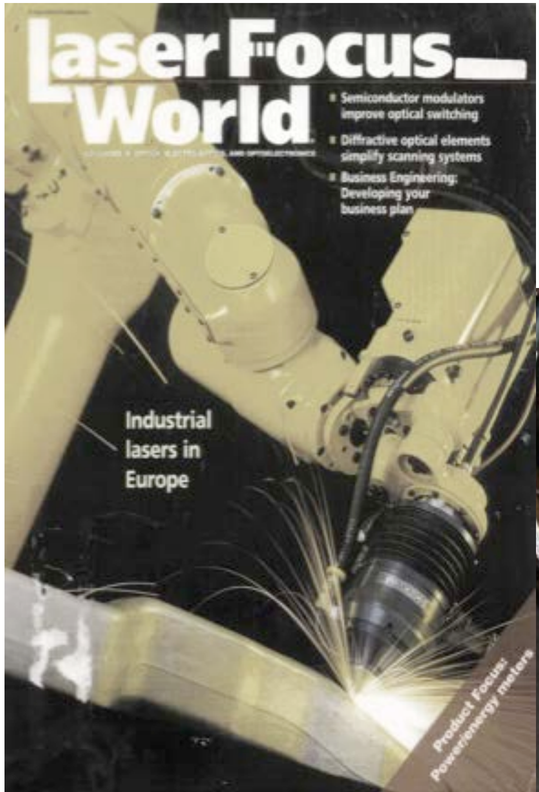
www.clpu.es

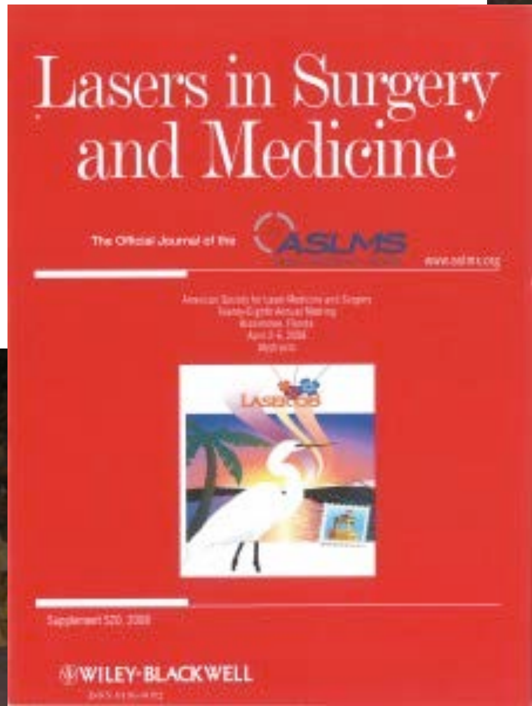
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

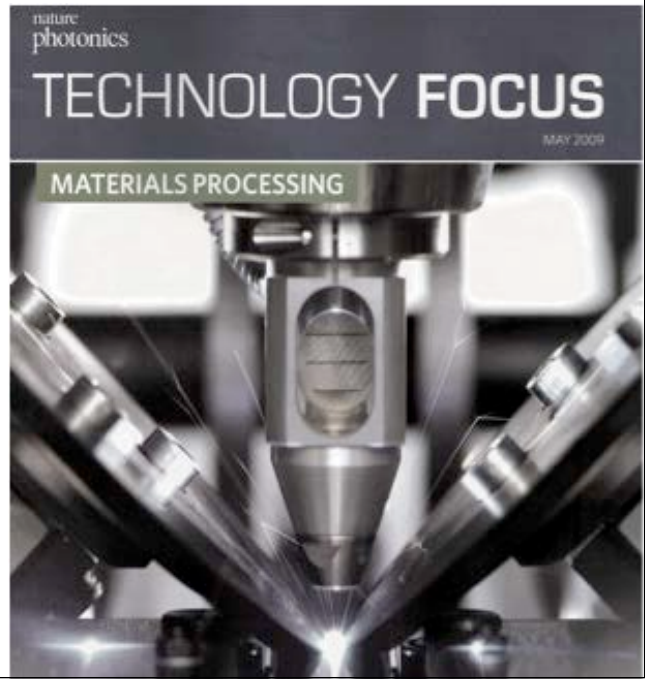
Junta de Castilla y León

VNiVERSiDAD D SALAMANCA

Lasers are very popular







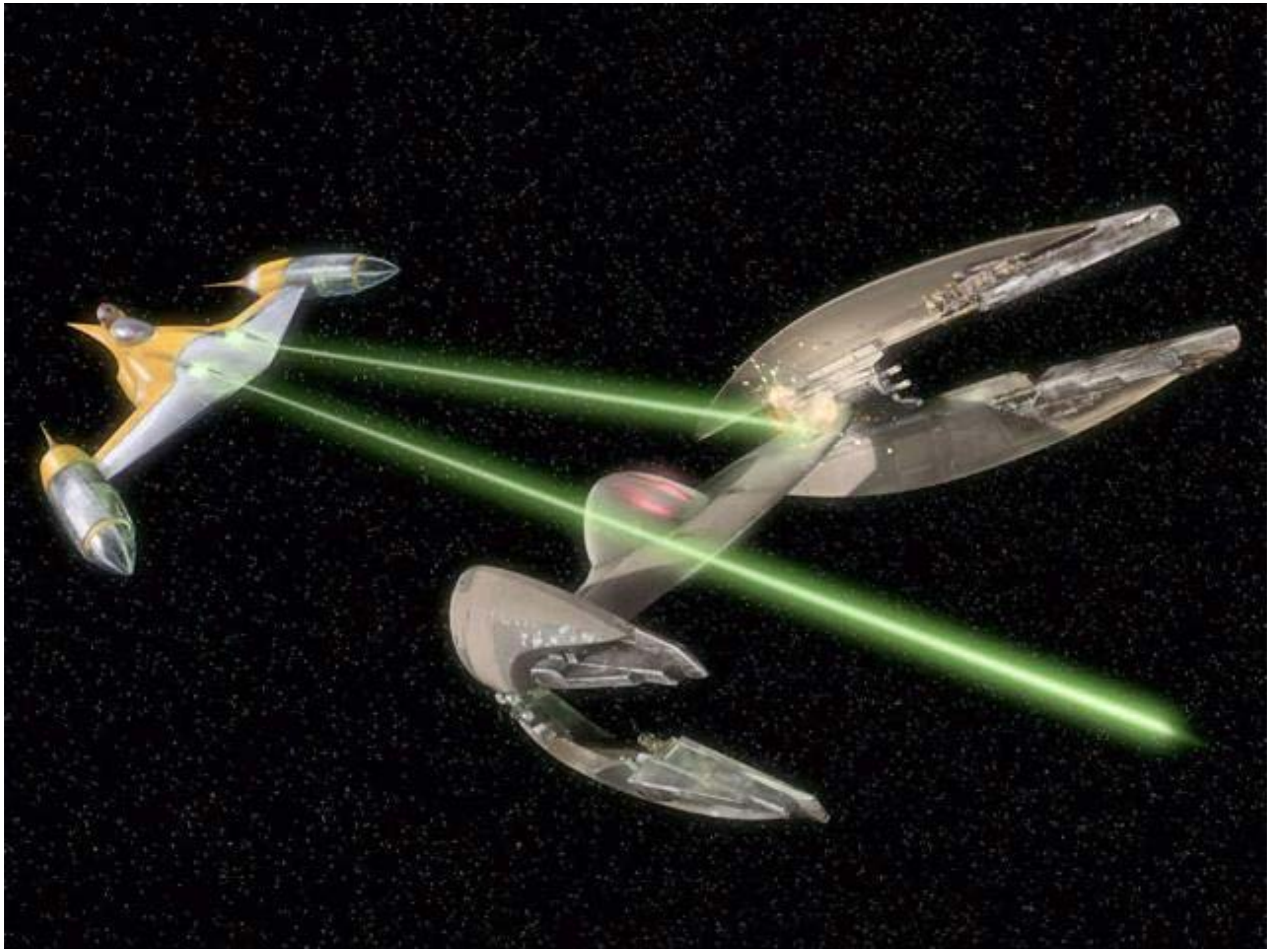
Lasers have many applications

- laser spectroscopy
- optical communications
- holography
- laser cut and industrial applications
- medical applications: surgery, oftalmology, ...
- laser hair removal
- ...
- laser acceleration

New sciences as Photonics have appeared

And very fantastic applications !

light in vacuum



Introduction to Lasers I

- Laser fundamentals
- Optical resonators
- Gaussian Beams
- Laser Pumping
- Multimode lasing

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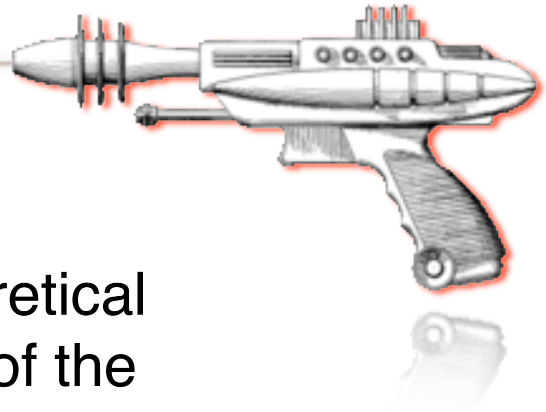
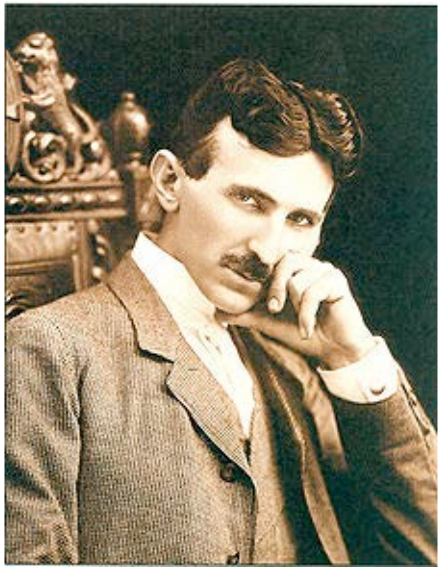
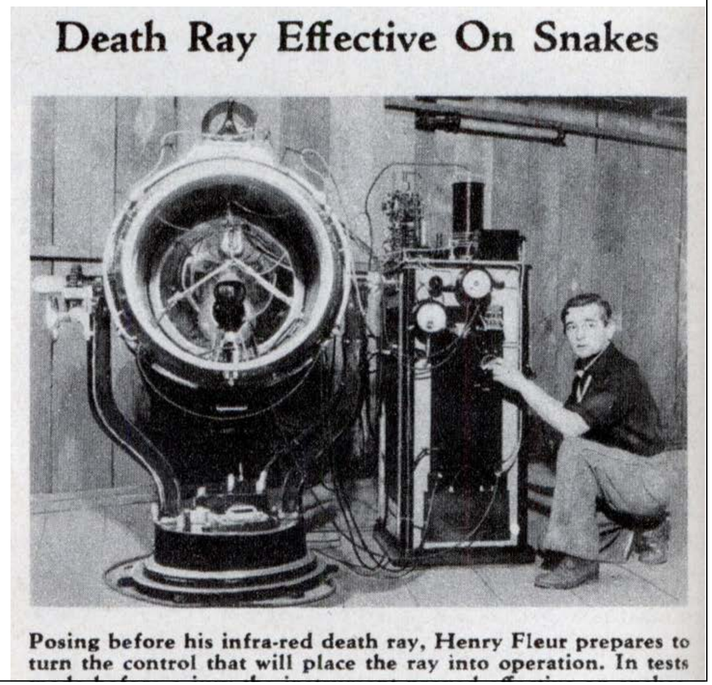
First is Imagination



Death ray From Wikipedia

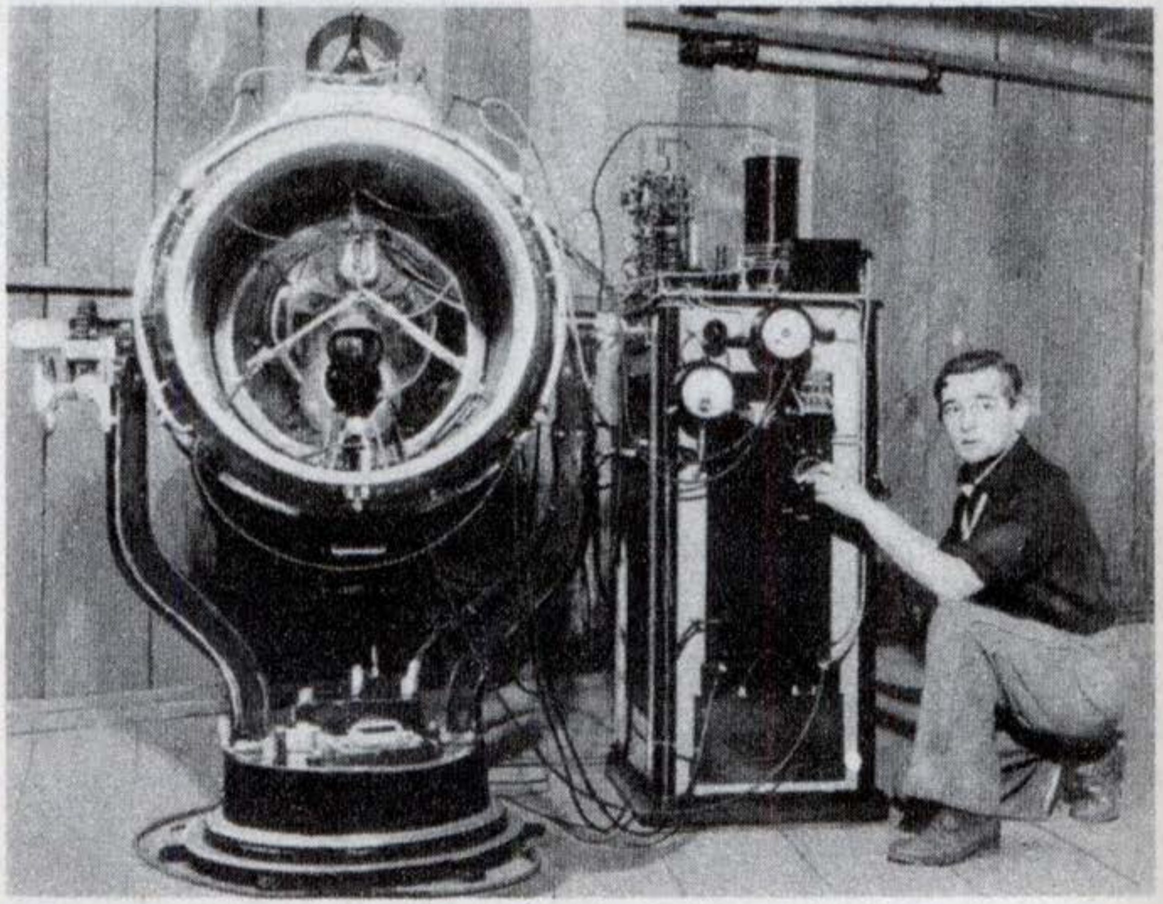
The **death ray** or **death beam** was a theoretical particle beam or electromagnetic weapon of the 1920s through the 1930s that was claimed to have been invented independently by Nikola Tesla, ..., as well as others.




Death Ray Effective On Snakes

Posing before his infra-red death ray, Henry Fleur prepares to turn the control that will place the ray into operation. In tests

Death Ray Effective On Snakes



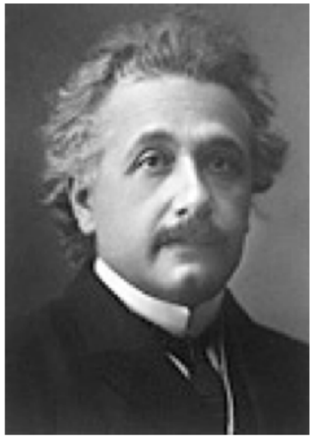
Posing before his infra-red death ray, Henry Fleur prepares to turn the control that will place the ray into operation. In tests made before a jury the instrument proved effective on snakes.

1936

Then comes Science

LEIPZIG, 1905.

ANNALEN
DER
PHYSIK.



6. ***Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt; von A. Einstein.***

Zwischen den theoretischen Vorstellungen, welche sich die Physiker über die Gase und andere ponderable Körper gebildet haben, und der Maxwellschen Theorie der elektromagnetischen Prozesse im sogenannten leeren Raume besteht ein tiefgreifender formaler Unterschied. Während wir uns

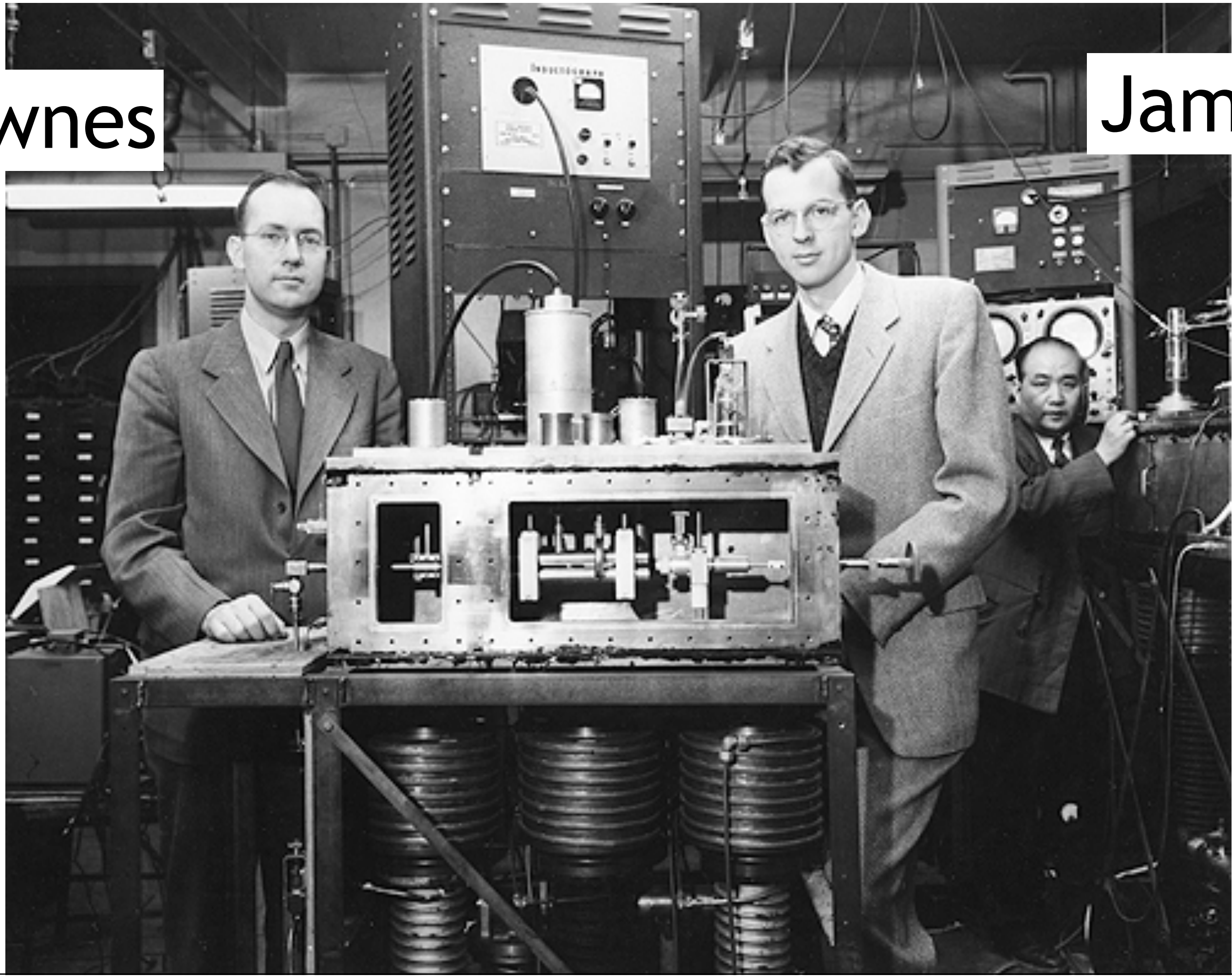
1905

Maser came first

Microwave Amplification by Stimulated Emission of Radiation

Charles Townes

James Gordon



Credit: Bettmann/Corbis

1955

Laser Fundamentals

Charles Townes

Nicolay Basov

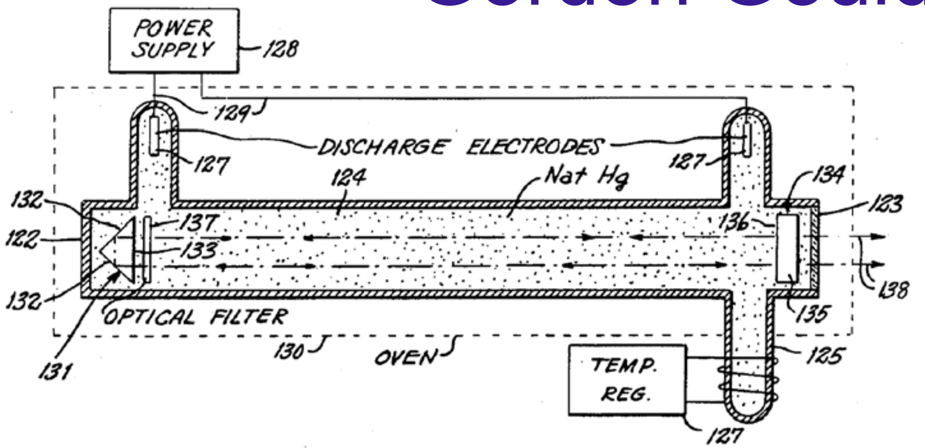
Aleksandr Prokhorov

Physics 1964

"for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle"

To publish or to patent?

Gordon Gould



United States Patent [19]

Gould

[54] **LIGHT AMPLIFIERS EMPLOYING COLLISIONS TO PRODUCE A POPULATION INVERSION**

[76] Inventor: **Gordon Gould,** 1200 N. Nash Ave., Arlington, Va. 22209

[21] Appl. No.: **823,611**

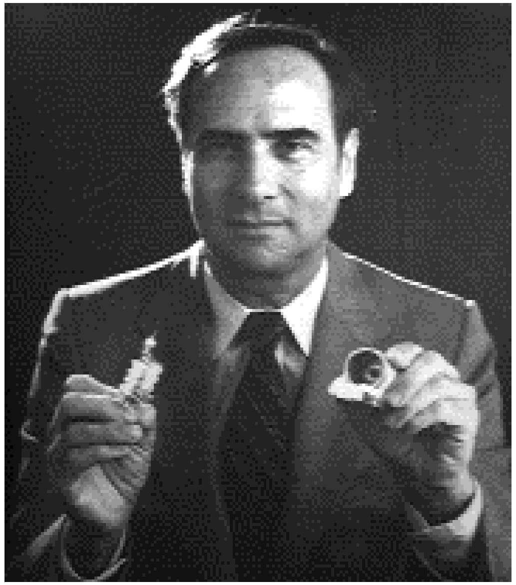
[22] Filed: **Aug. 11, 1977**

Related U.S. Application Data

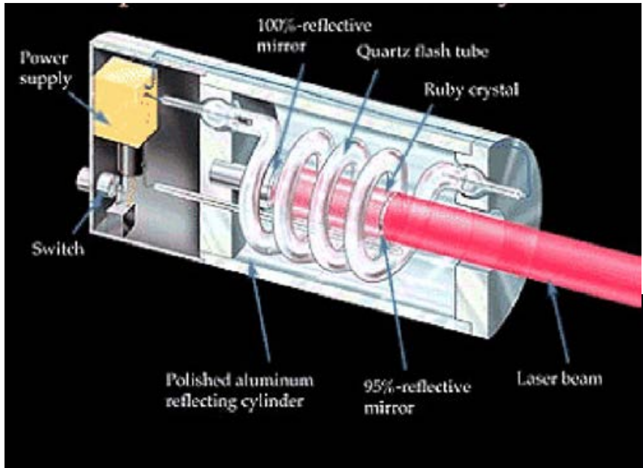
[60] Division of Ser. No. 498,065, Aug. 16, 1974, Pat. No. 4,053,845, which is a continuation of Ser. No. 644,035, Mar. 6, 1967, abandoned, and Ser. No. 804,540, Apr. 6, 1959, abandoned, said Ser. No. 644,035, is a division of Ser. No. 804,540, Apr. 6, 1959, abandoned, and a continuation-in-part of Ser. No. 804,539, Apr. 6, 1959, abandoned.

... and finally the first laser ... 1960

Light Amplification by Stimulated Emission of Radiation

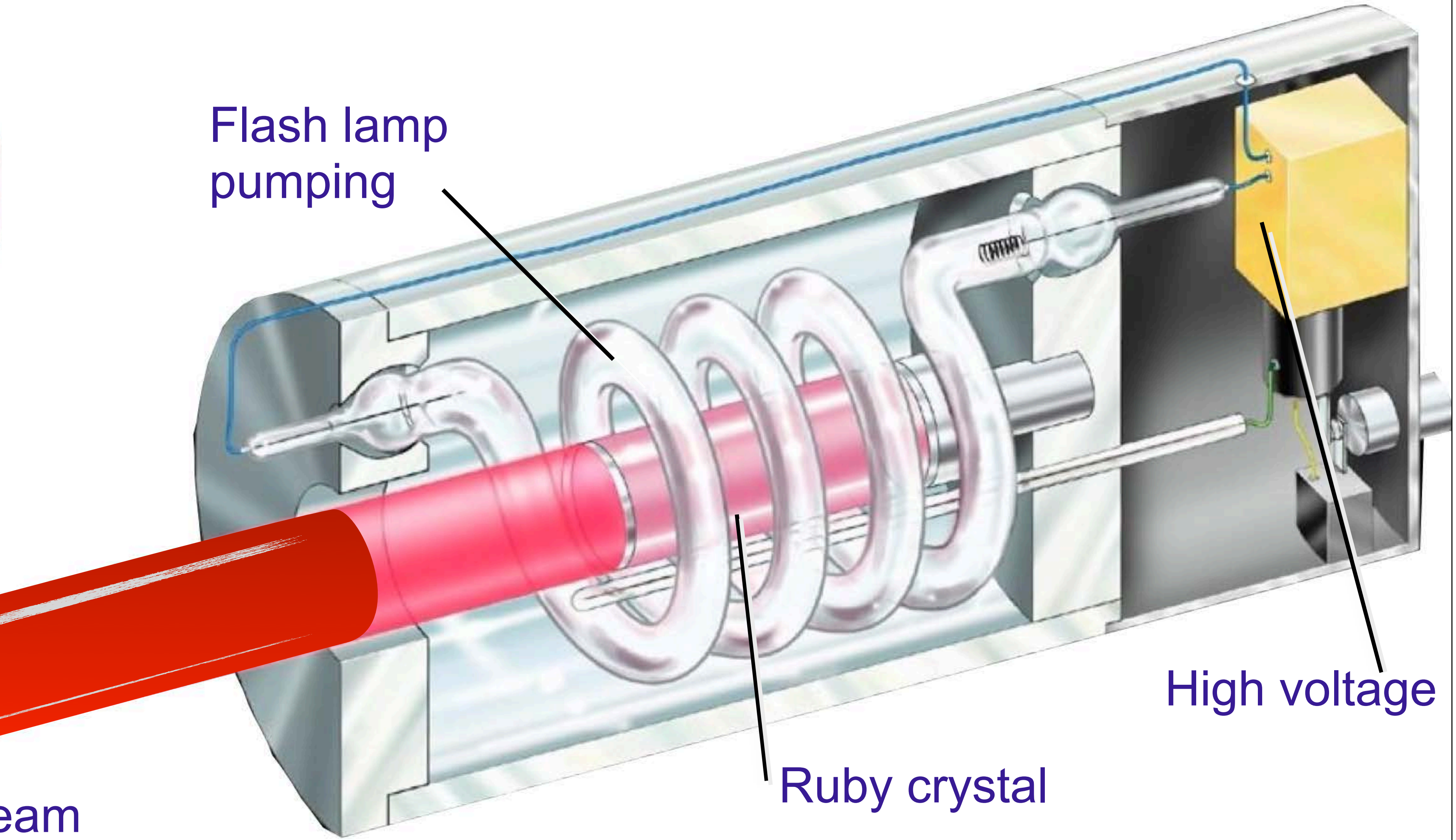


T H Maiman Rubi laser @ 694 nanometers

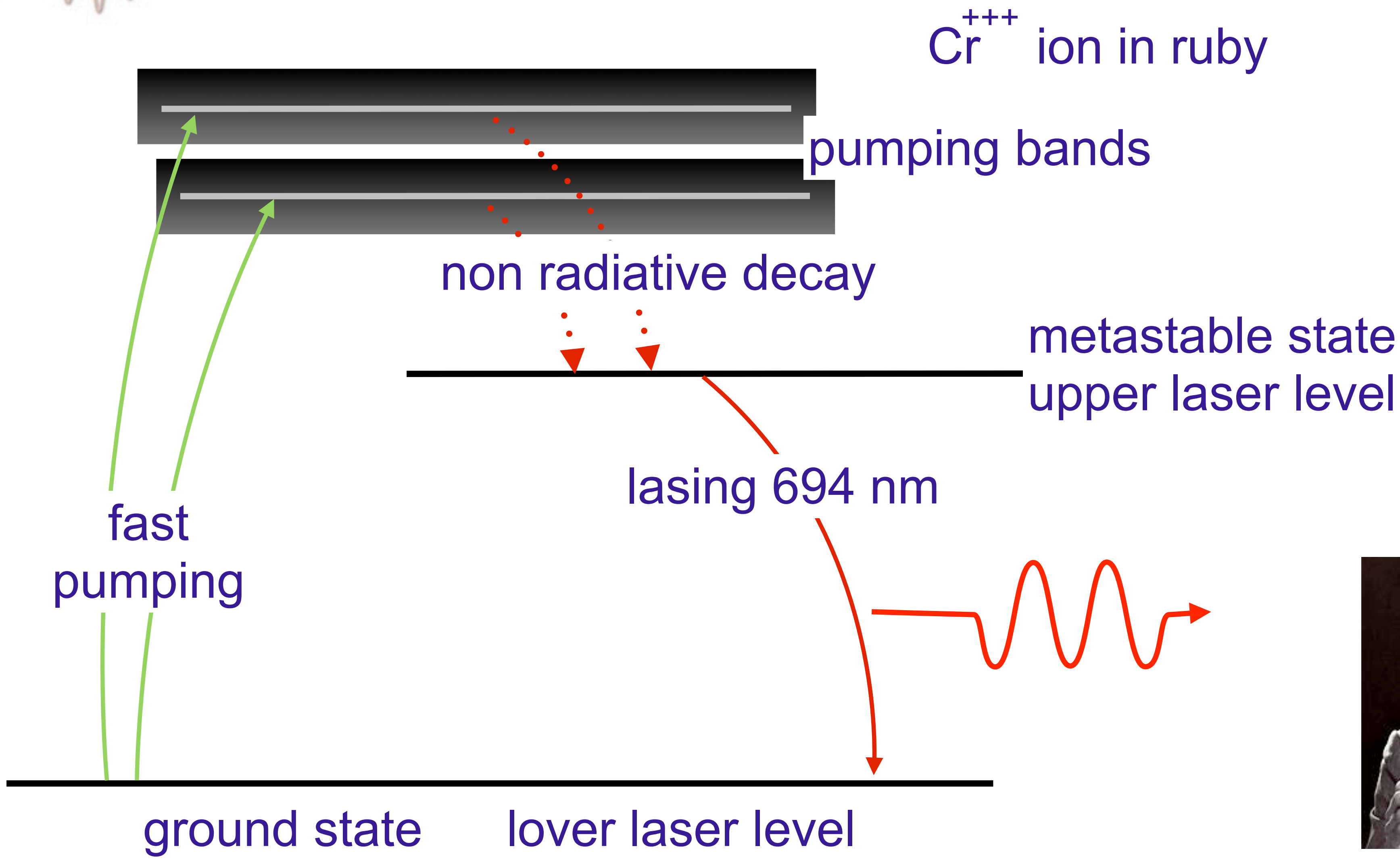


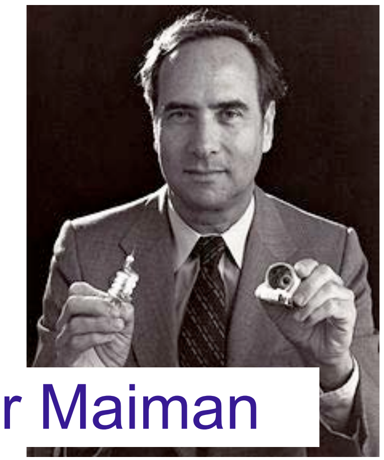
First laser was named as first optical maser

Ruby Laser ... 1960



Chromium-ion laser (ruby laser)

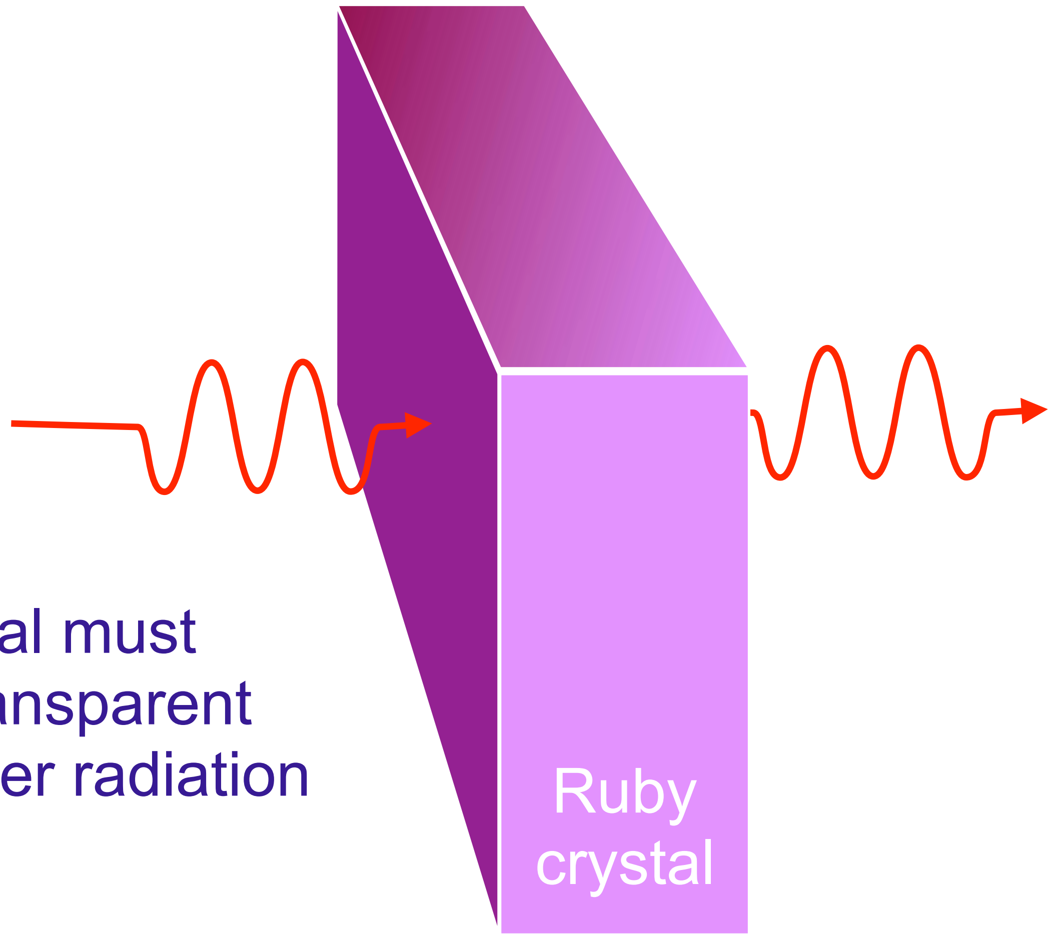




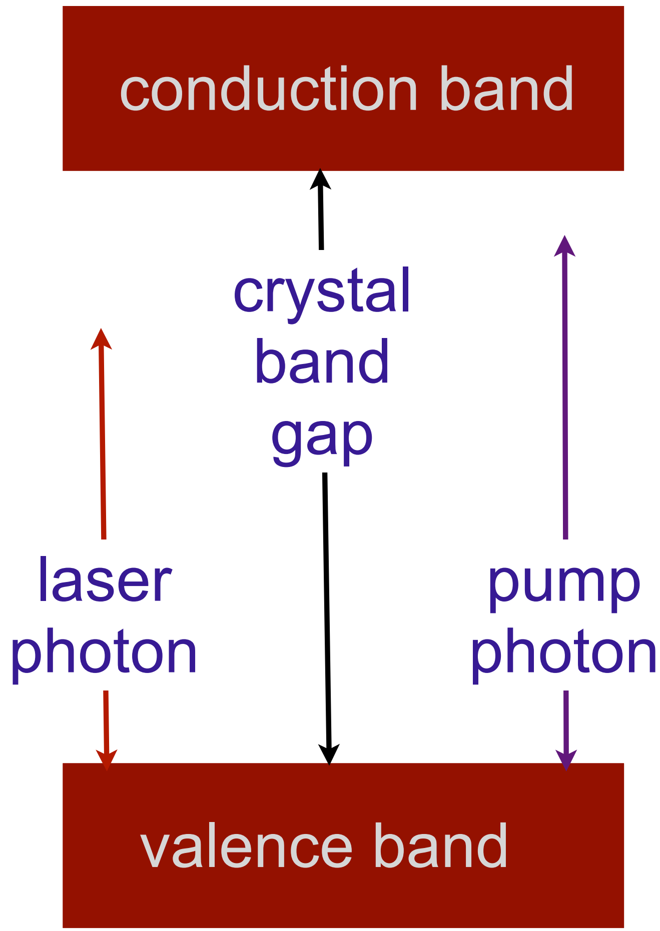
Theodor Maiman

Role of the crystal matrix (ruby)

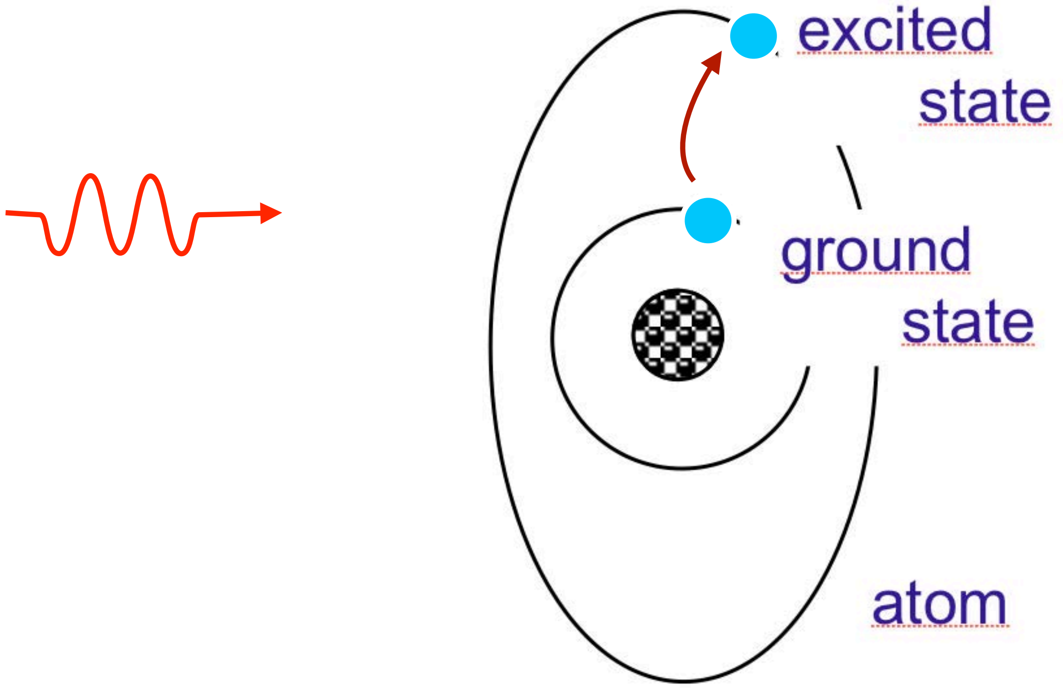
Just do not disturb!



Crystal must
be transparent
to laser radiation

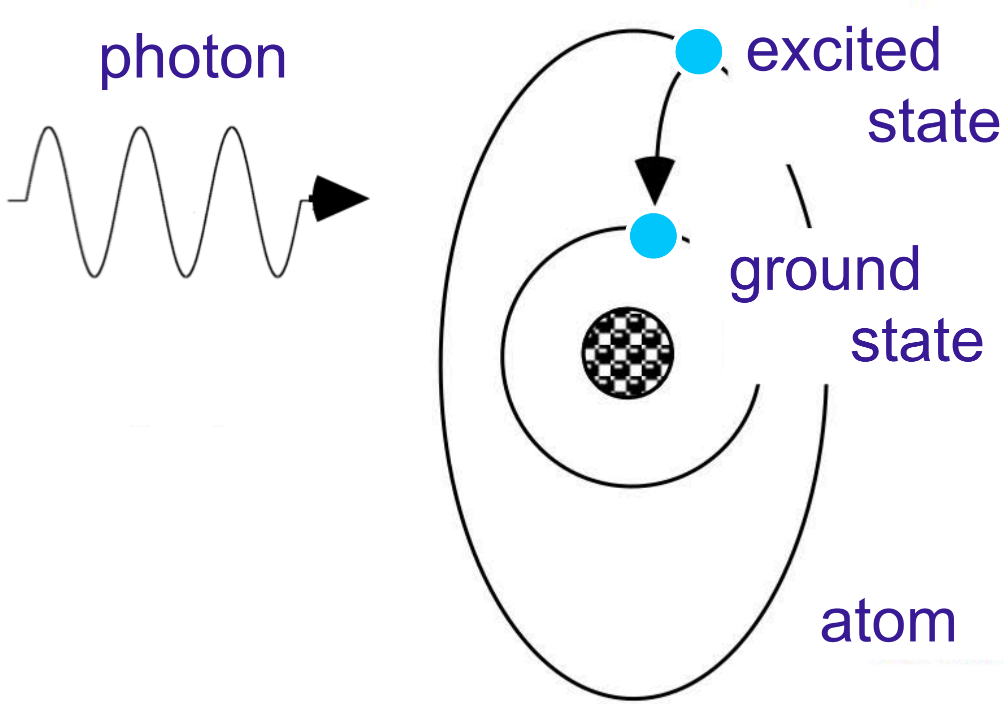


Photon absorption



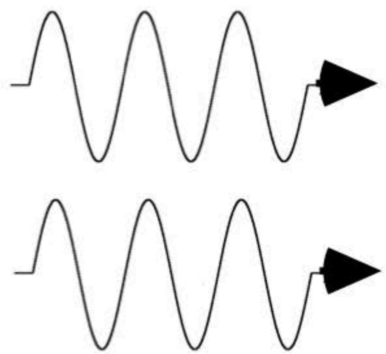
All that in dipole approx

Stimulated emission



laser

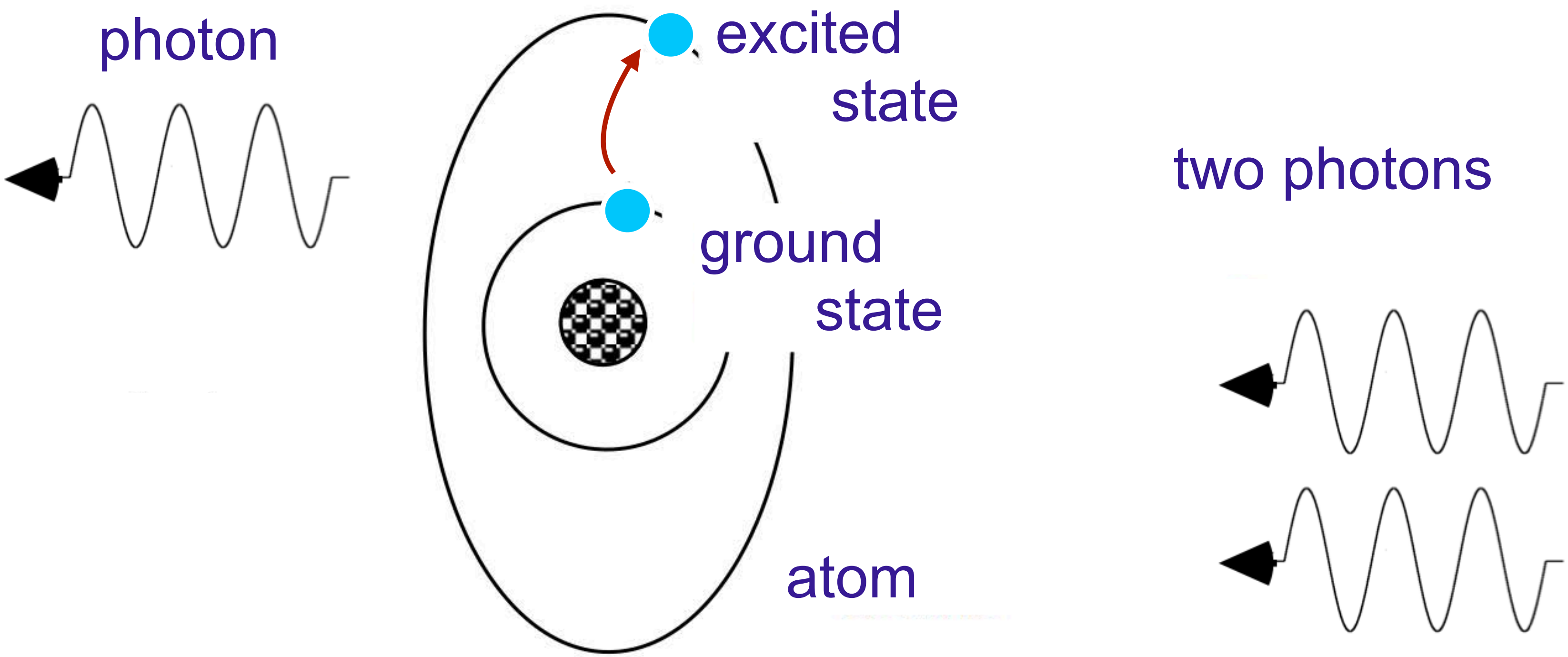
two identical copies of the initial photon



Similar to cloning the photon !!!

Photon absorption

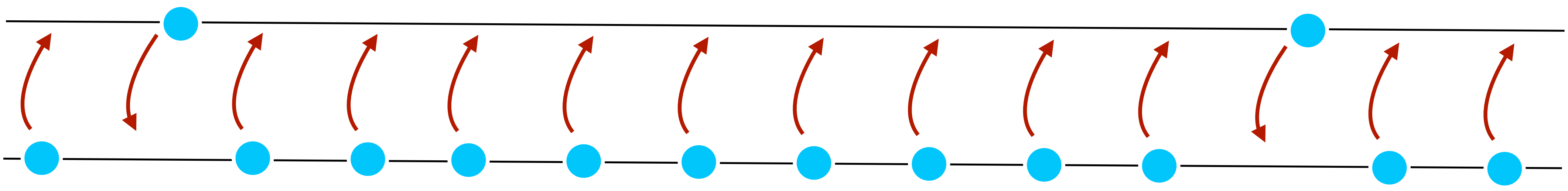
Change arrow of time



stimulated emission and absorption
are inverse processes ...

... so they compete

Photon absorption

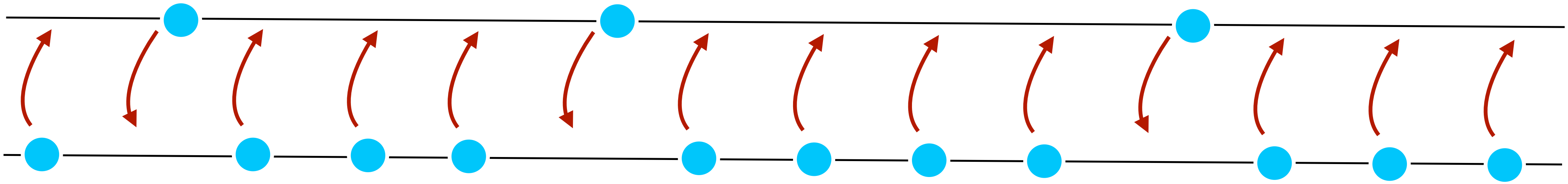


Normally, more electrons in the ground state than in the excited state

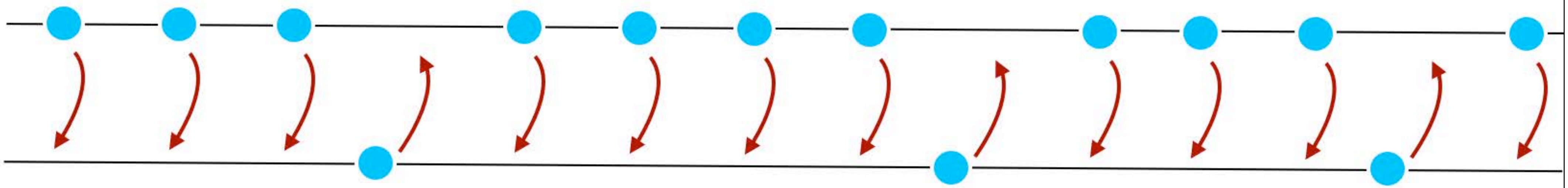
Absorption dominates over stimulated emission ...

... no lasing

Absorption vs stimulated emission

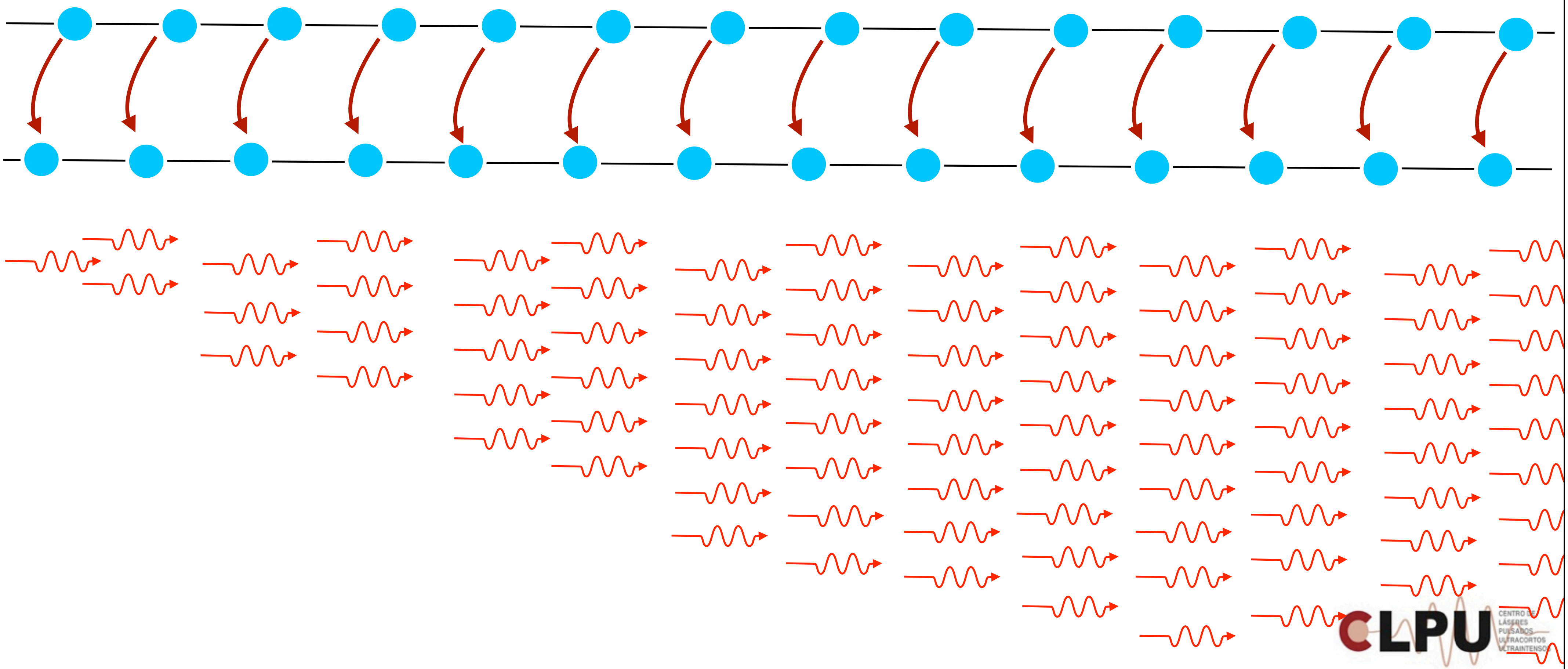


Normally, more electrons in the ground state than in the excited state
Absorption dominates over stimulated emission ... no lasing

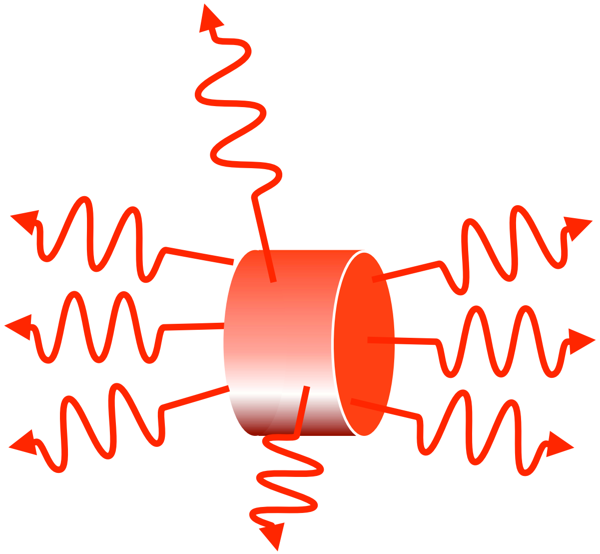


If, more electrons in the excited state than in the ground state
then stimulated emission dominates over absorption ...
lasing !!!

Chain reaction



Anisotropy



Why a preferred direction for
stimulated emission?

A preferred direction is given by a very long active material

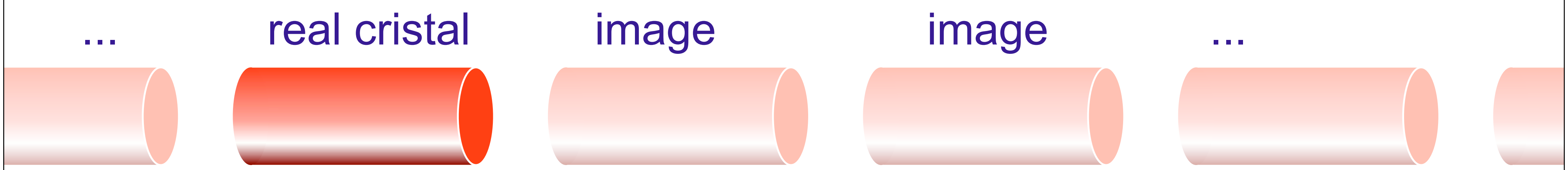
Very long active material

A preferred direction is given by a very long active material

Two options:

A real very long material: an optical fiber (with guiding)

A virtual very long material: a laser cavity



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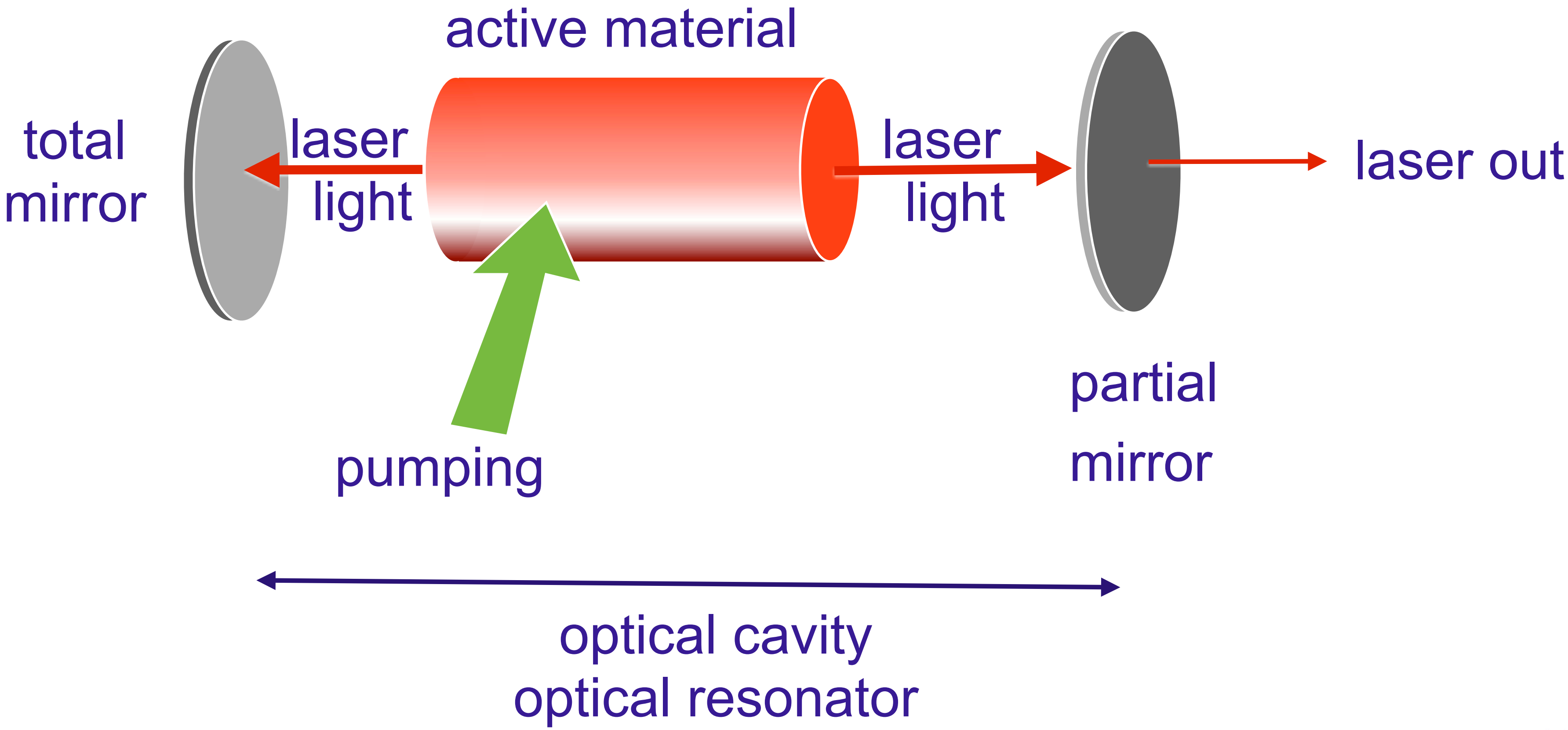
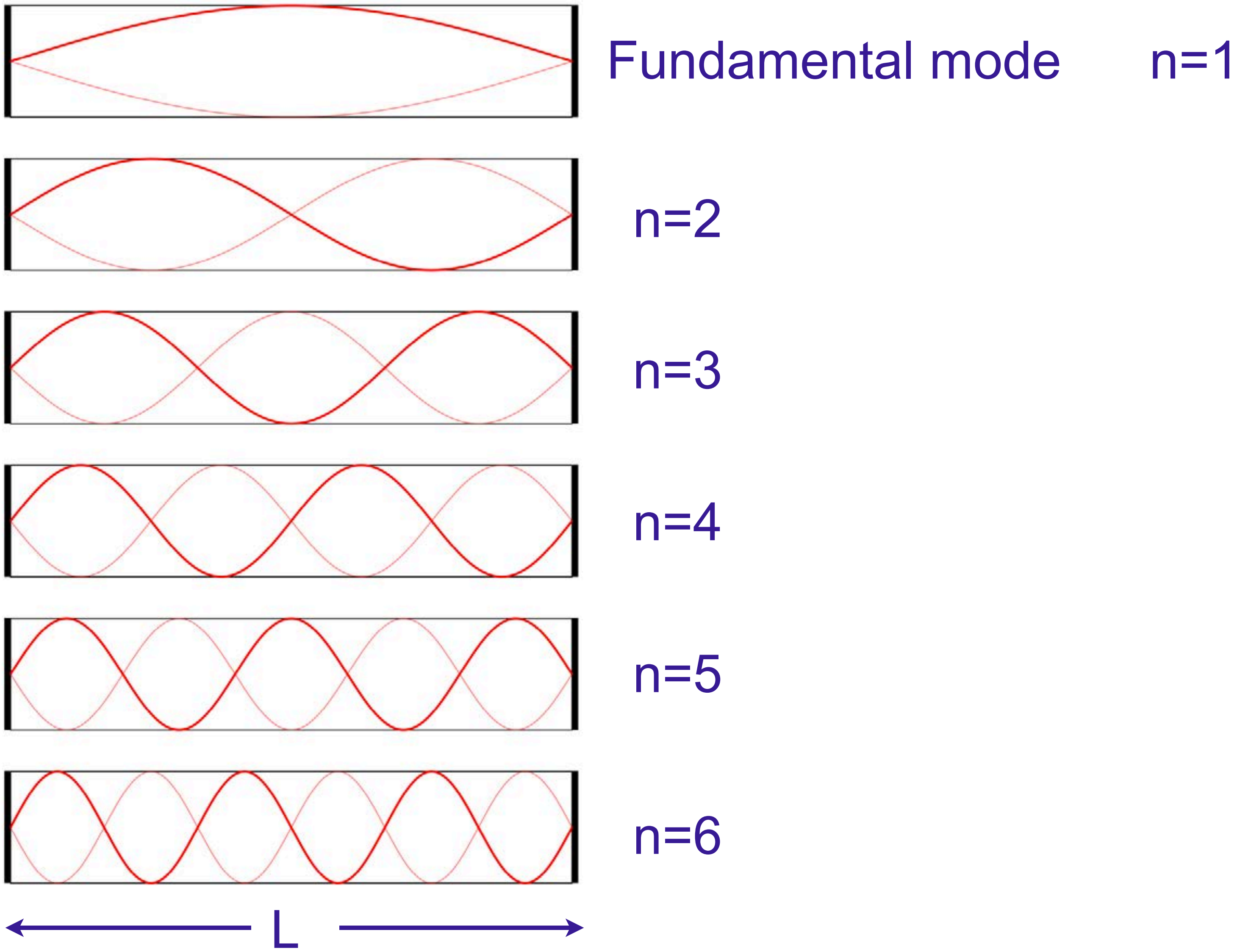
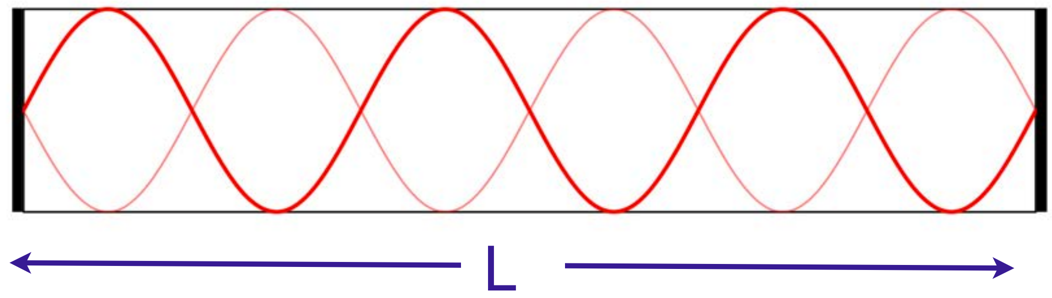
Optical cavity



Cavity modes



Cavity modes



Electric field inside the cavity $$E(z,t) = E_0 \cos(kz)\cos(\omega_L t)$$

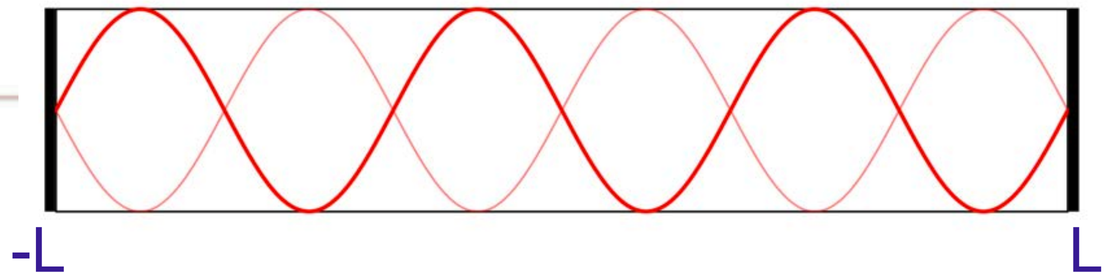
Boundary conditions $$E(L,t) = E(-L,t) = 0$$

Allowed wavelengths $$n\lambda = 2L \qquad n = 1, 2, 3, \ldots$$

Cavity modes $$k = \frac{2\pi}{\lambda} = \frac{n\pi}{L}$$

Resonant frequencies $$\omega = kc = \frac{2\pi c}{\lambda} = n\frac{\pi c}{L}$$

Cavity modes



Example, L = 25 cm and
500 nm wavelength (green)
corresponds to n = 1 000 000

Consecutive frequencies

$$\Delta\omega = \omega_{n+1} - \omega_n = \frac{\pi\, c}{L}$$

$$\lambda = \frac{2L}{n} = \frac{50\,cm}{1000000} = \frac{1000.}{1.}\,nm = 500\,nm$$

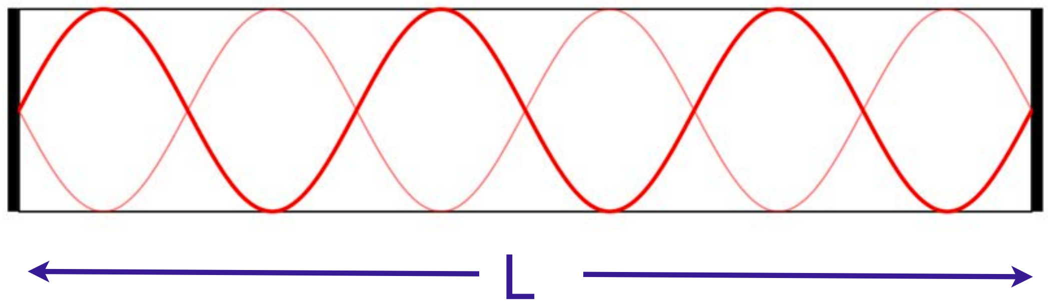
$$\nu_n = n\frac{c}{2L}$$

$$\lambda = \frac{2L}{n+1} = \frac{50\,cm}{1000001} = \frac{500.}{1.000001}\,nm = 499.995\,nm$$

$$\nu_{n+1} = (n+1)\frac{c}{2L}$$

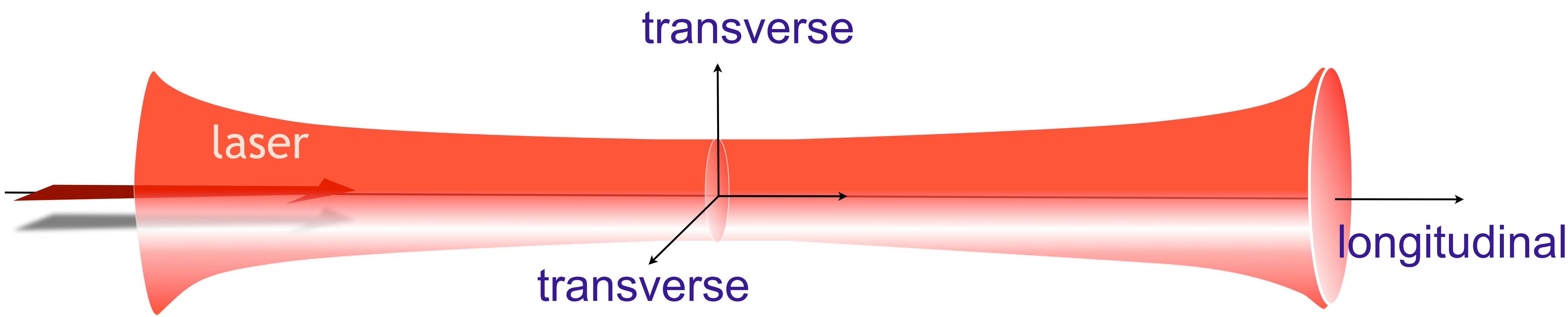
$$\Delta\nu = \frac{c}{2L} = \frac{300\,000\,000\,m/s}{0.5m} = 600\ MHz = 0.6\ GHz$$

Cavity longitudinal modes



Just longitudinal ... plane waves

Real waves have a transverse profile!



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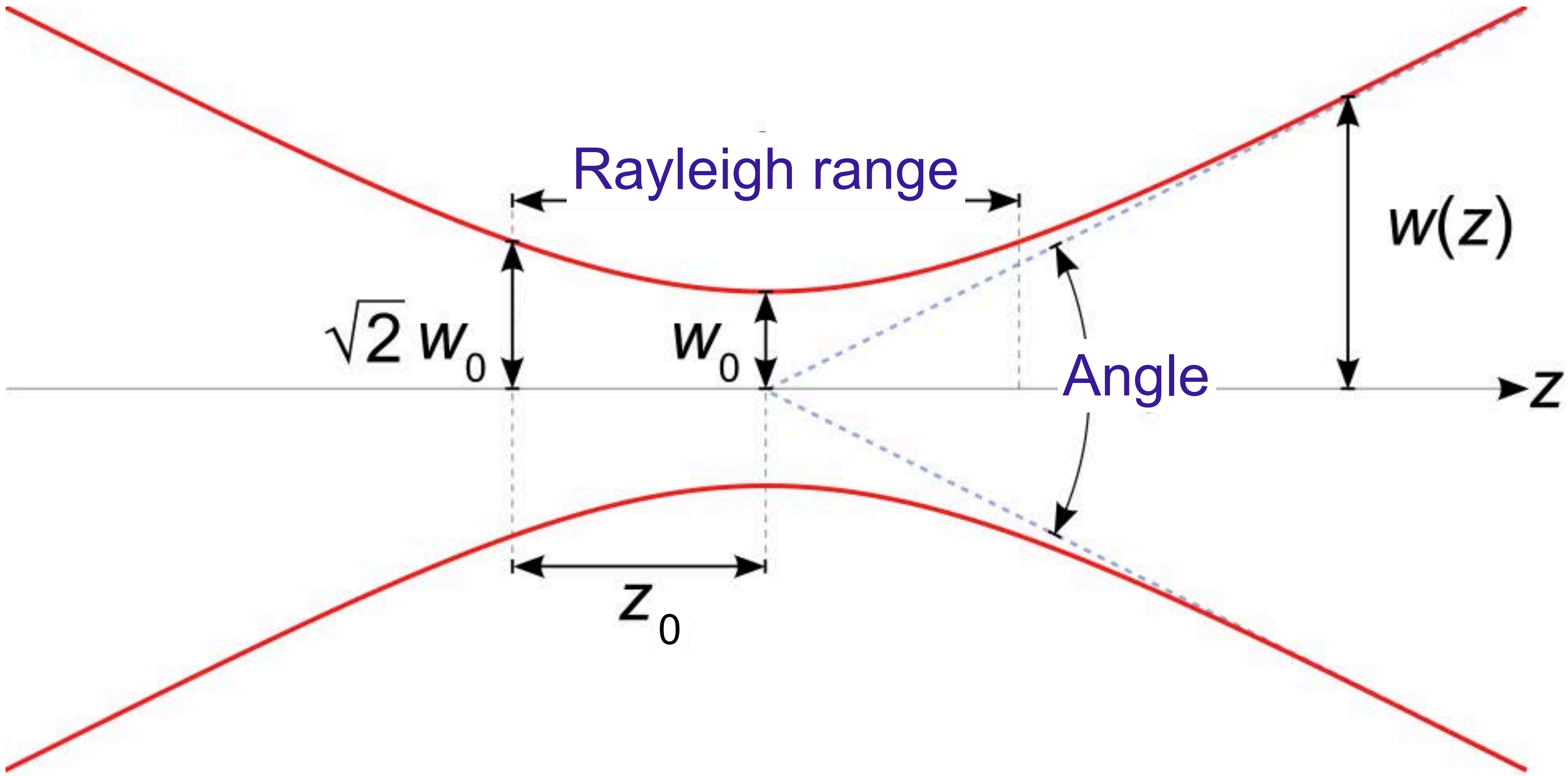
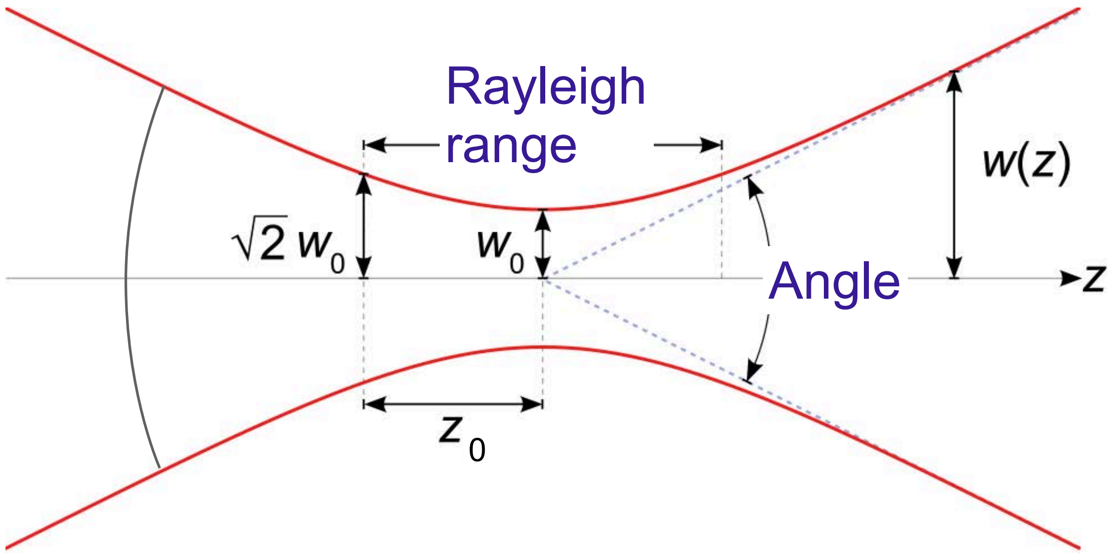
Gaussian beam



Gaussian beam (monochromatic) k



Radius

$$R(z) = z + \frac{z_0^2}{z}$$

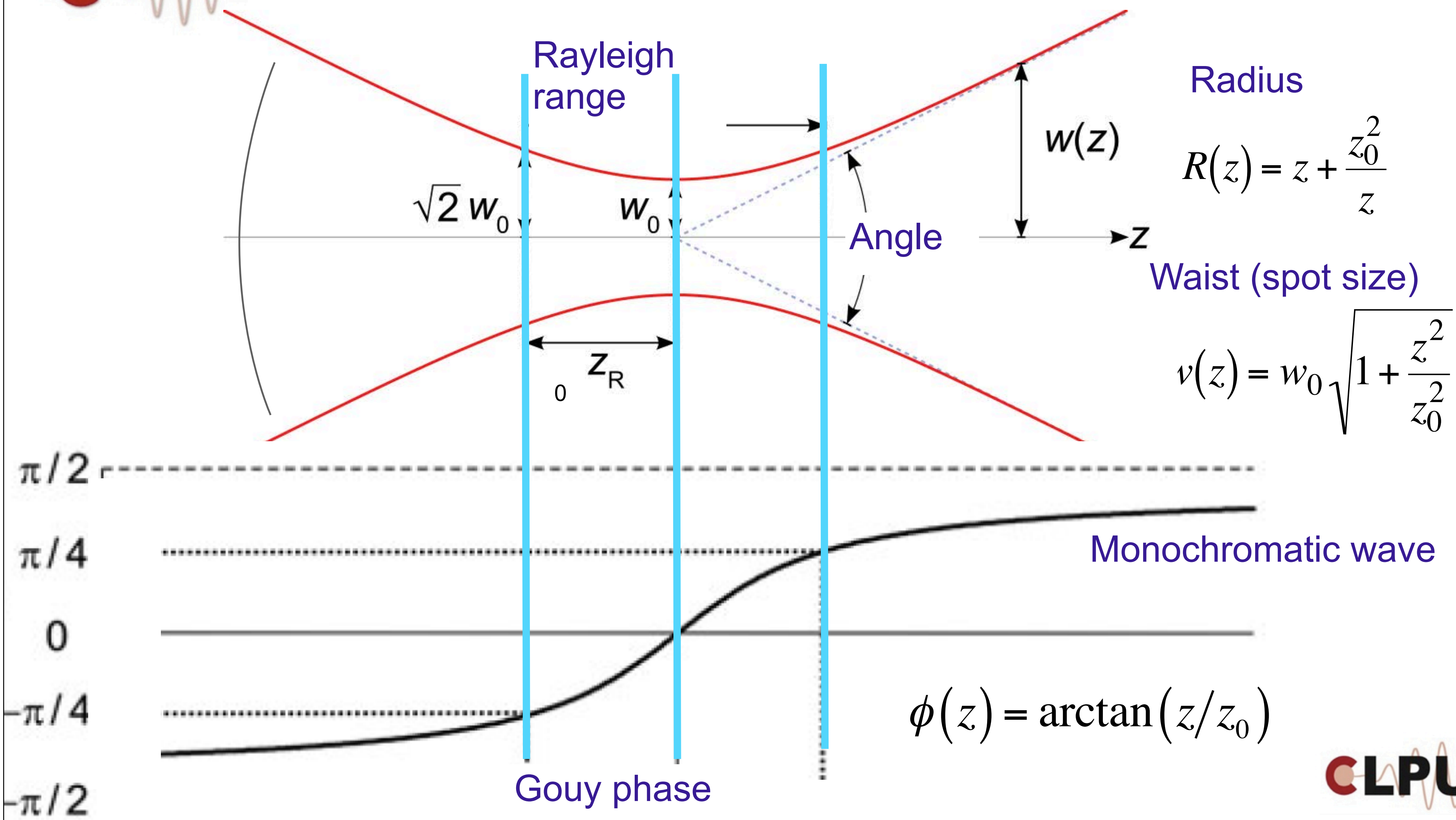
Waist (spot size)

$$w(z) = w_0 \sqrt{1 + \frac{z^2}{z_0^2}}$$

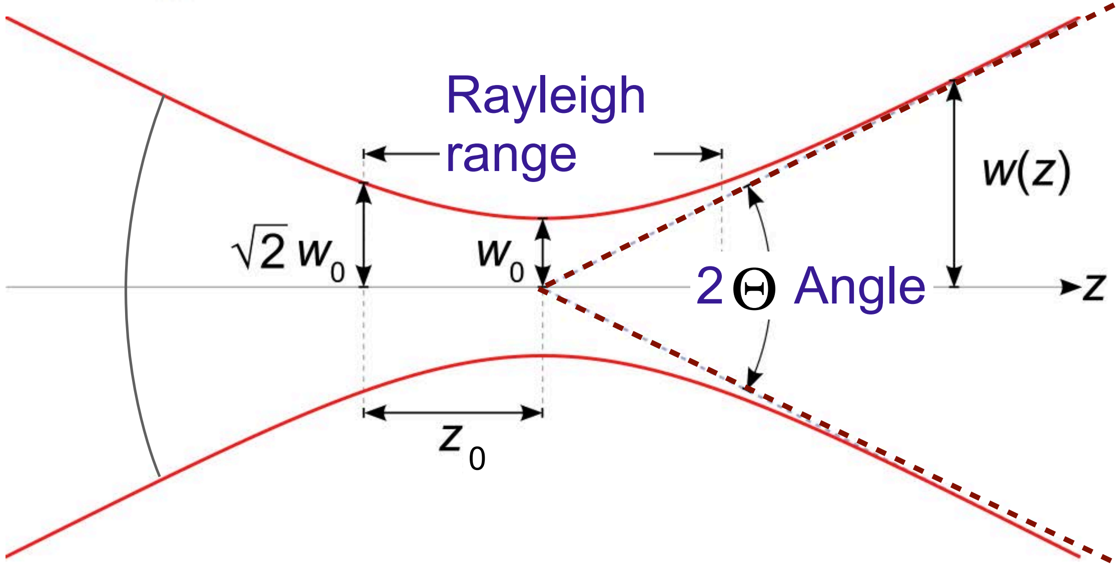
$$E(x,y,z) = A\frac{w_0}{w(z)}\exp\left[i\left(kz-\phi(z)\right)\right]\exp\left[ik\frac{x^2+y^2}{2R(z)}\right]\exp\left[-\frac{x^2+y^2}{w^2(z)}\right]$$ Monochromatic wave

$$\phi(z) = \arctan\left(z/z_0\right)$$ Gouy phase

Gouy phase


Rayleigh
range
$\sqrt{2}\,w_0$
w_0
z_R
0
$w(z)$
Angle
z
Radius
$R(z) = z + \frac{z_0^2}{z}$
Waist (spot size)
$v(z) = w_0\sqrt{1+\frac{z^2}{z_0^2}}$
$\pi/2$
$\pi/4$
0
$-\pi/4$
$-\pi/2$
Monochromatic wave
$\phi(z) = \arctan(z/z_0)$
Gouy phase

Divergence



Radius

$$R(z) = z + \frac{z_0^2}{z}$$

Waist (spot size)

$$w(z) = w_0\sqrt{1 + \frac{z^2}{z_0^2}}$$

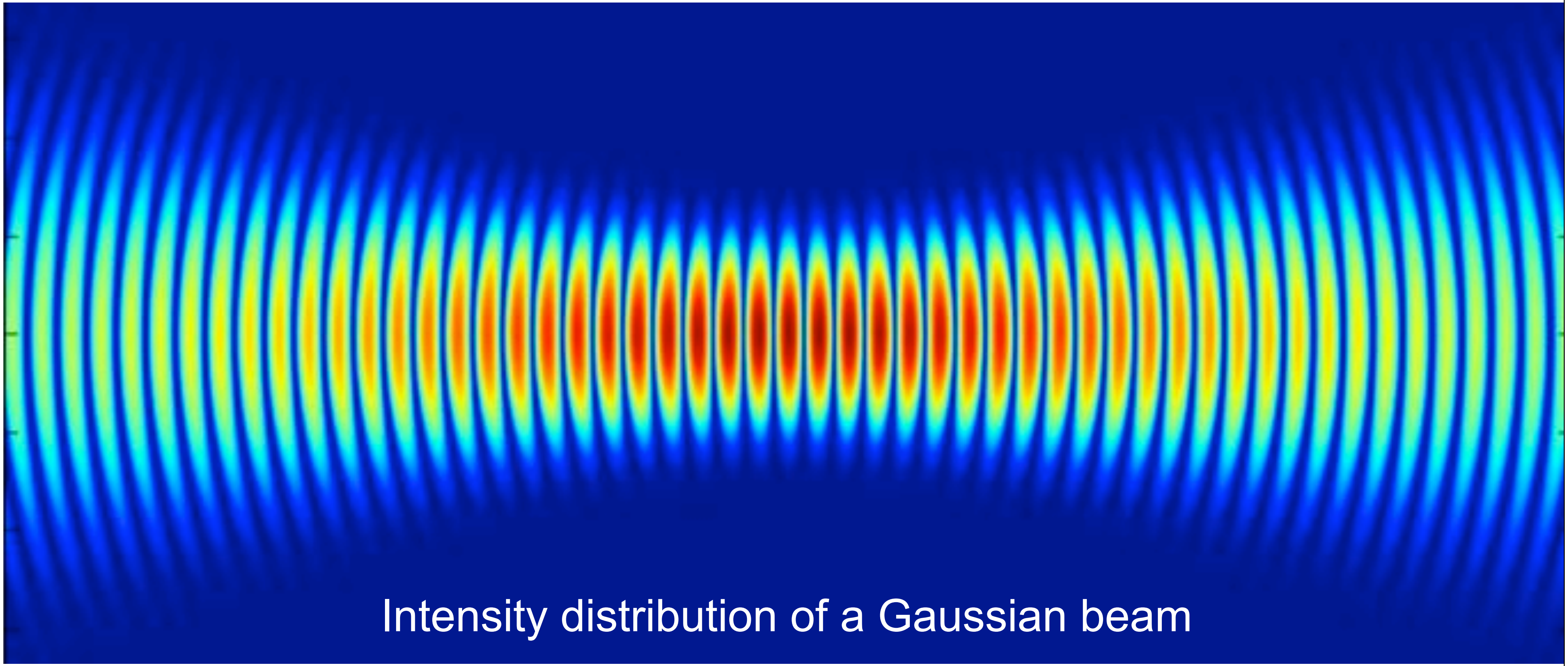
$$E(x,y,z) = A\frac{w_0}{w(z)}\exp\left[i\left(kz - \phi(z)\right)\right]\exp\left[ik\frac{x^2+y^2}{2R(z)}\right]\exp\left[-\frac{x^2+y^2}{w^2(z)}\right]$$

Monochromatic wave

Divergence angle

$$\Theta = \frac{w_0}{z_0} = \frac{\lambda}{\pi\, w_0}$$

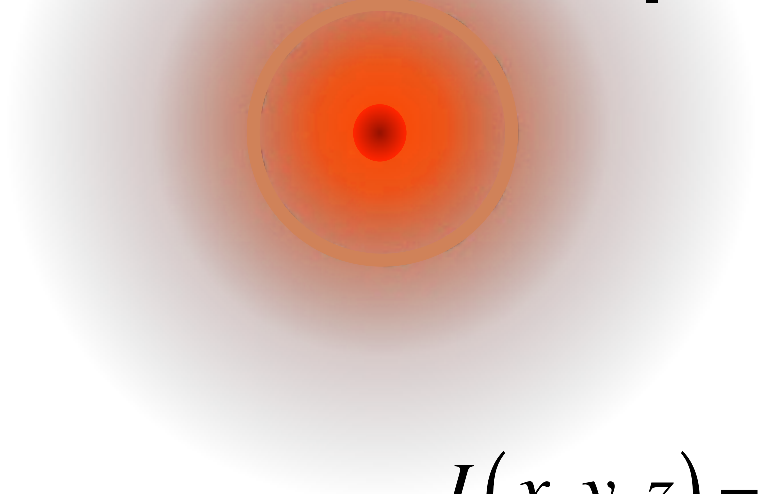
Gaussian beam



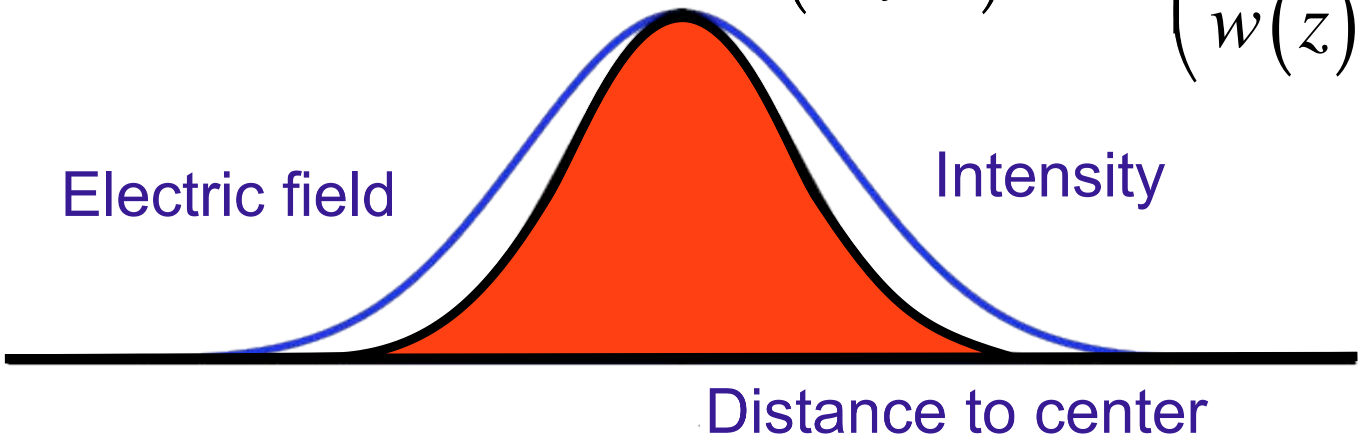
Intensity distribution of a Gaussian beam

Gausian field vs Gaussian intensity

$$E(x,y,z) = A\frac{w_0}{w(z)}\exp\left[i\left(kz-\phi(z)\right)\right]\exp\left[ik\frac{x^2+y^2}{2R(z)}\right]\exp\left[-\frac{x^2+y^2}{w^2(z)}\right]$$

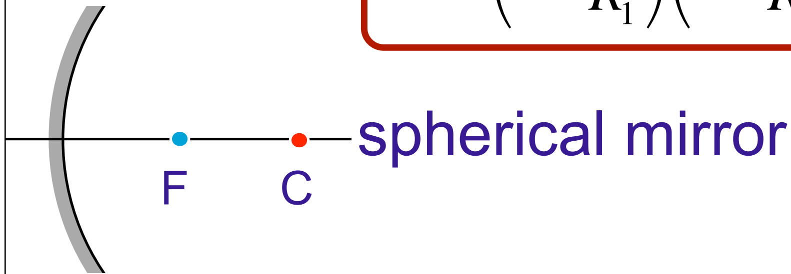


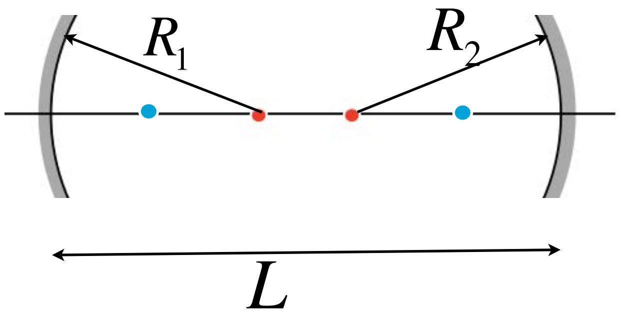
$$I(x,y,z) = A^2\left(\frac{w_0}{w(z)}\right)^2\exp\left[-2\frac{x^2+y^2}{w^2(z)}\right]$$

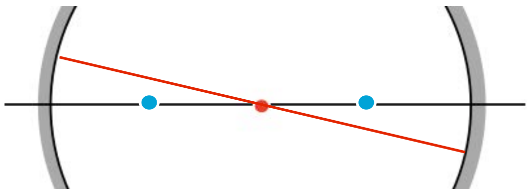


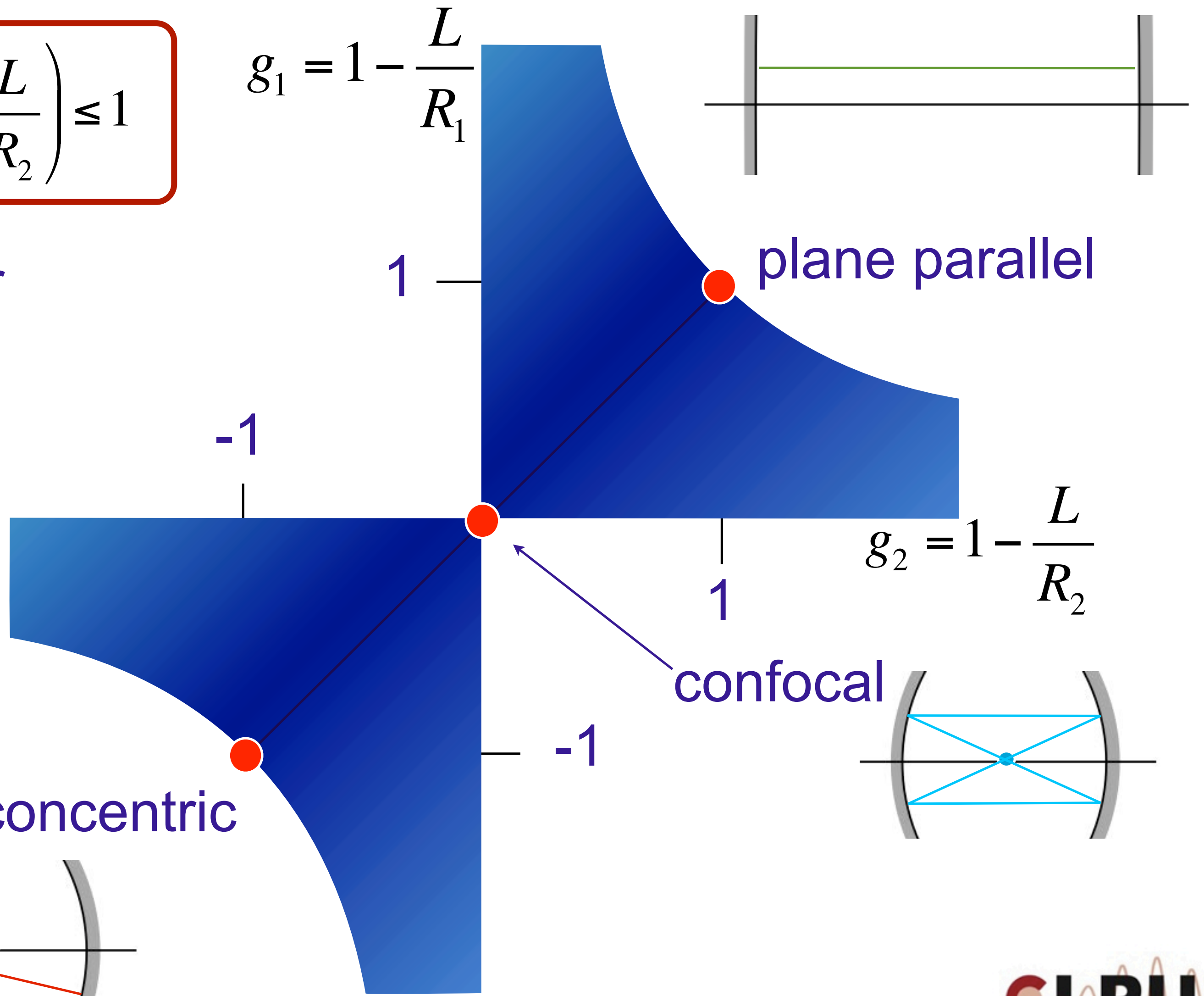
Stable cavities ...

$$0 \le \left(1 - \frac{L}{R_1}\right)\left(1 - \frac{L}{R_2}\right) \le 1$$





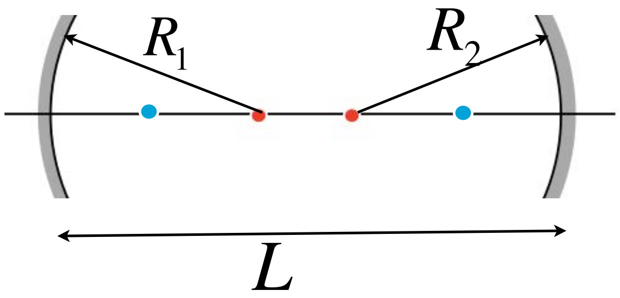


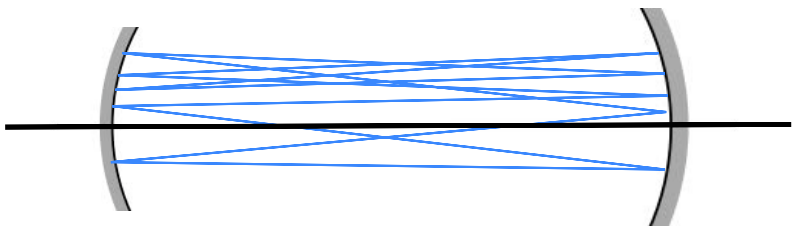


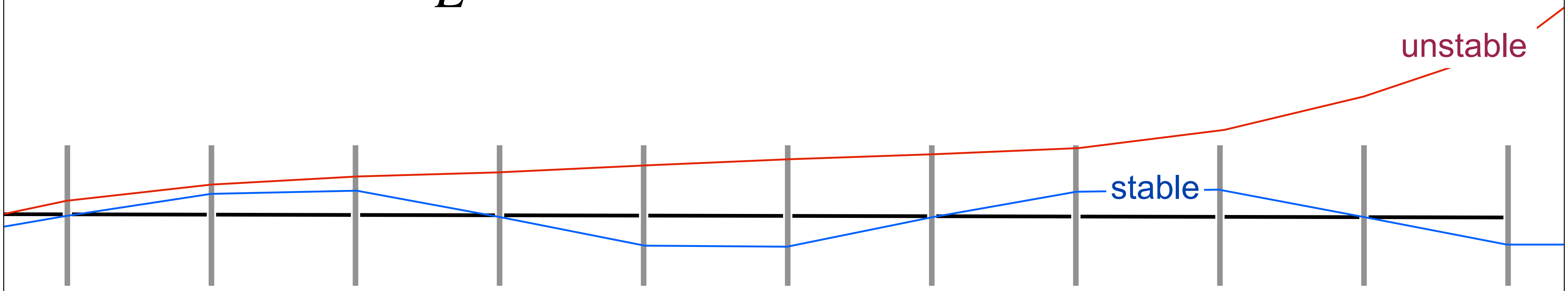
Stable cavities ...

$$0 \le \left(1-\frac{L}{R_1}\right)\left(1-\frac{L}{R_2}\right) \le 1$$

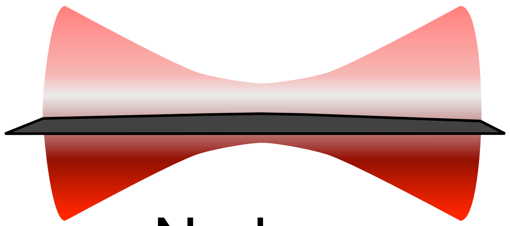
stability condition





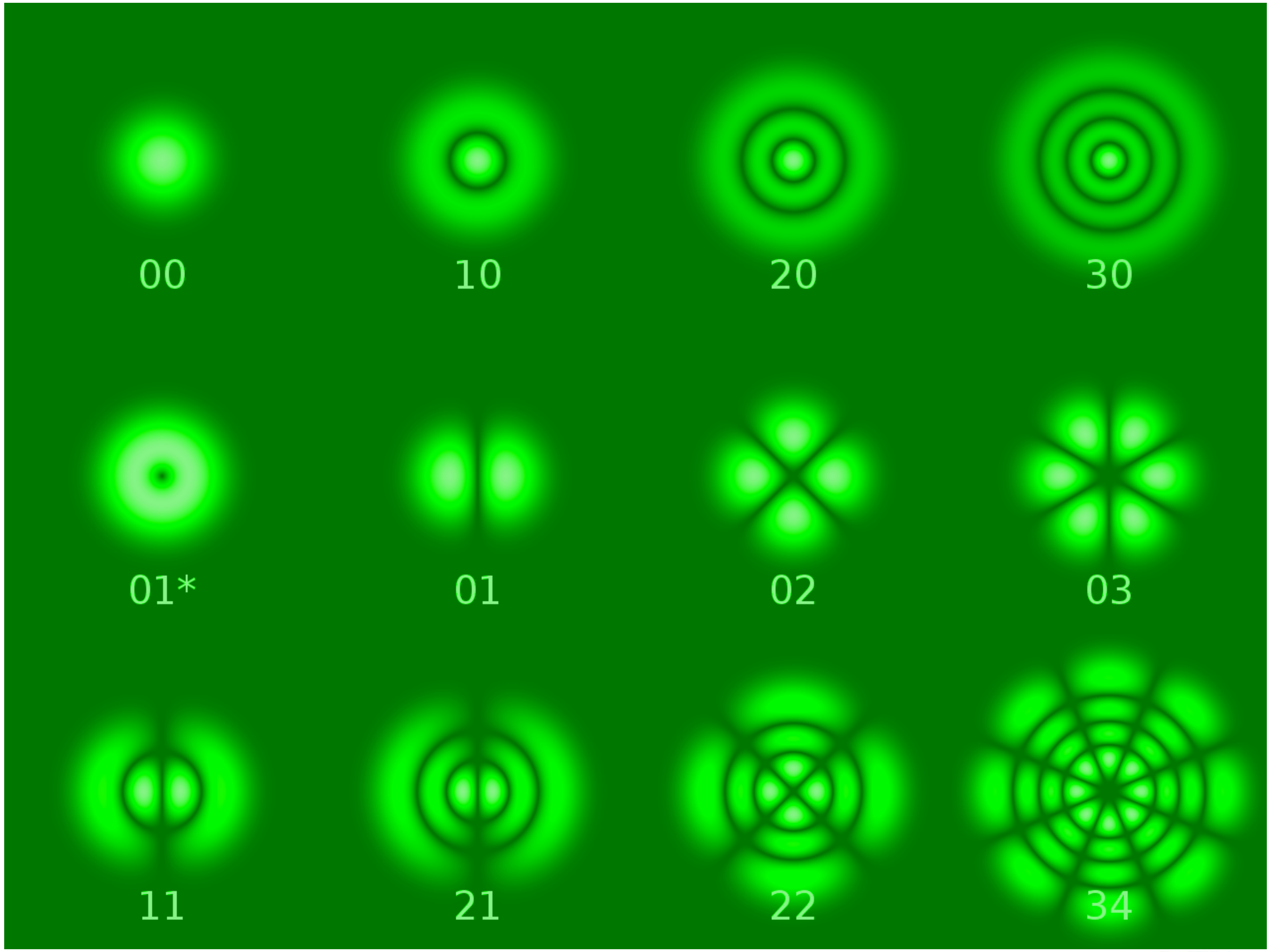


Transverse modes

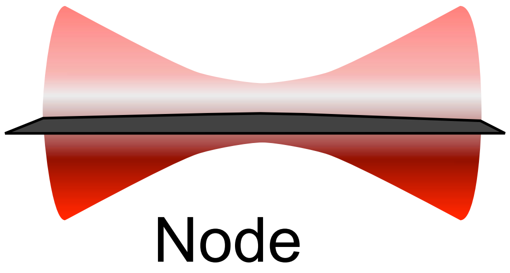


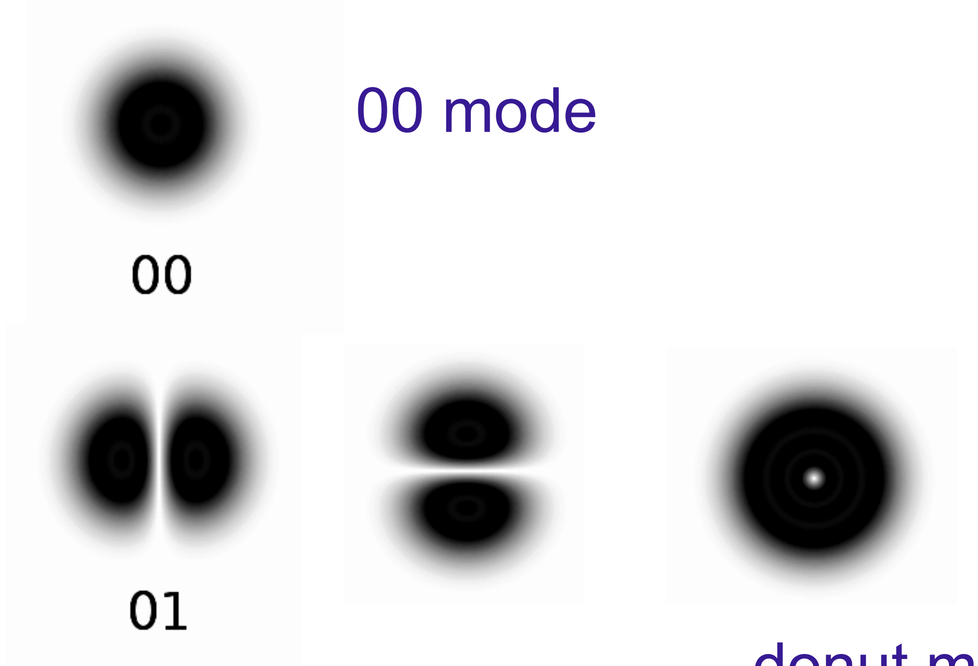
Node

Laguerre-Gauss modes
for cylindrical boundary conditions



Transverse modes





Laguerre-Gauss modes
for cylindrical boundary conditions

... all this is scalar,
with vectors, polarization modes

Introduction to Lasers I

- Laser fundamentals
- Optical resonators
- Gaussian Beams
- Laser Pumping
- Multimode lasing

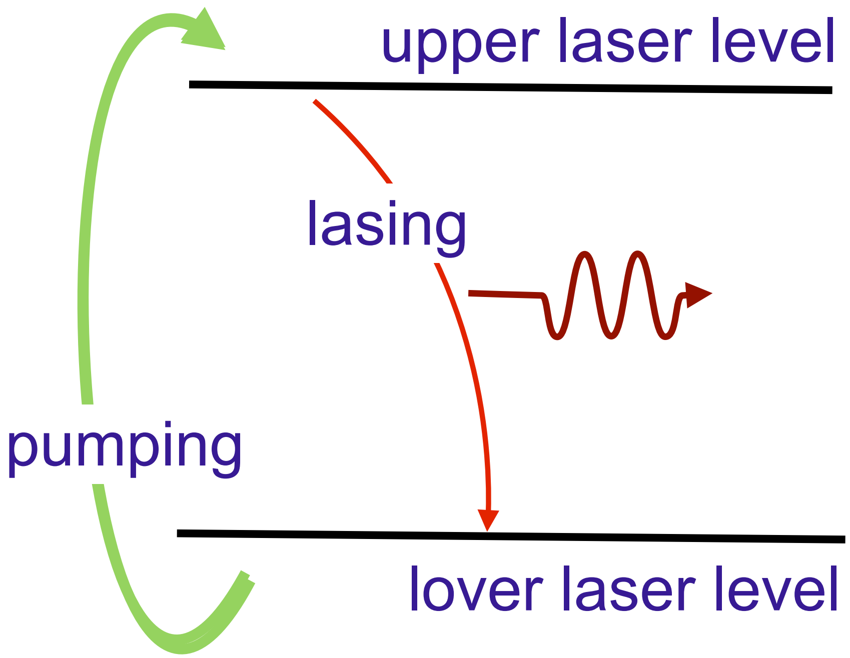
CENTRO DE
LÁSERES
PULSADOS
ULTRACORTOS
ULTRAINTENSOS

Pumping

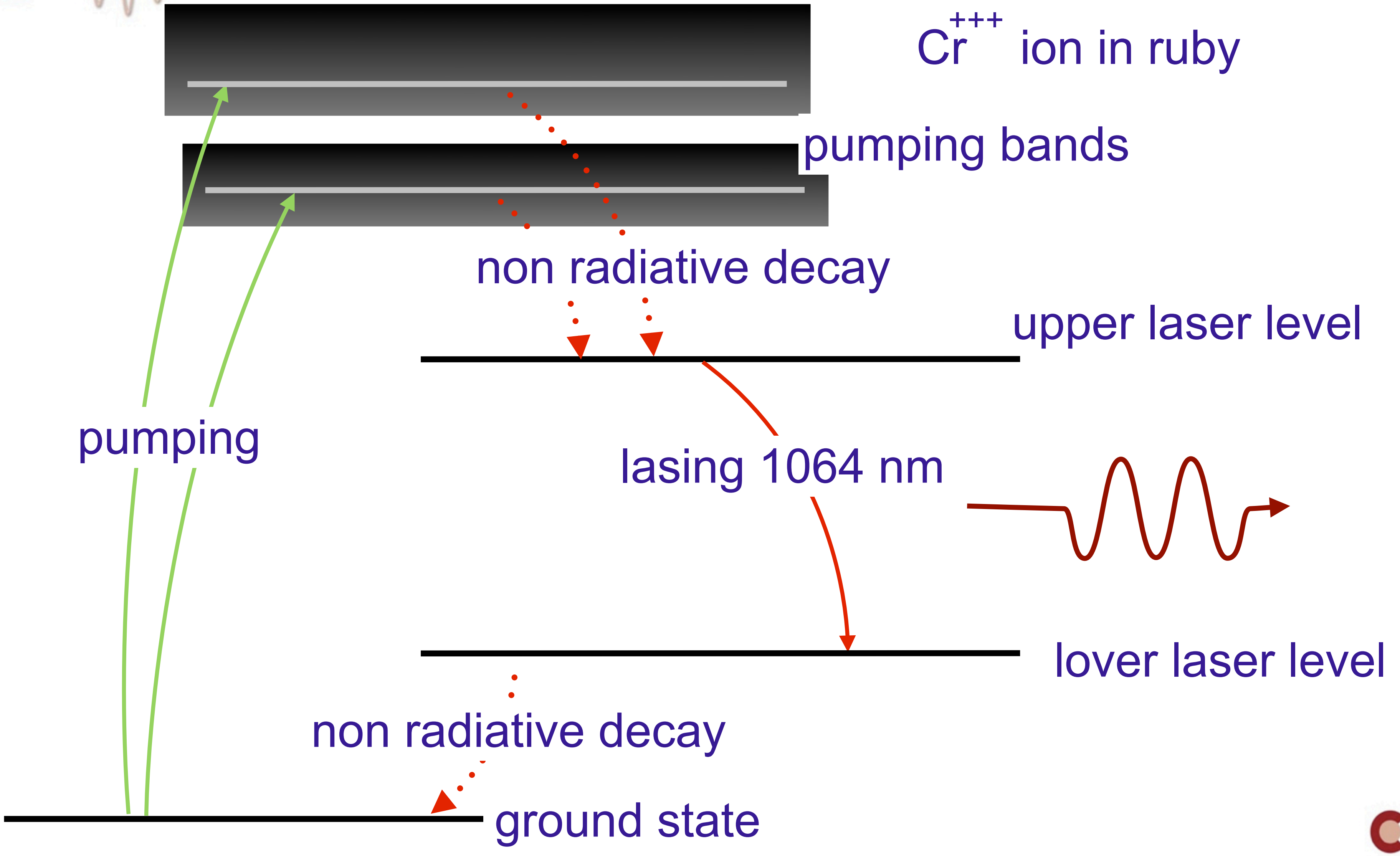
Is the way the active material gets the inversion.

Many kinds of pumping ...

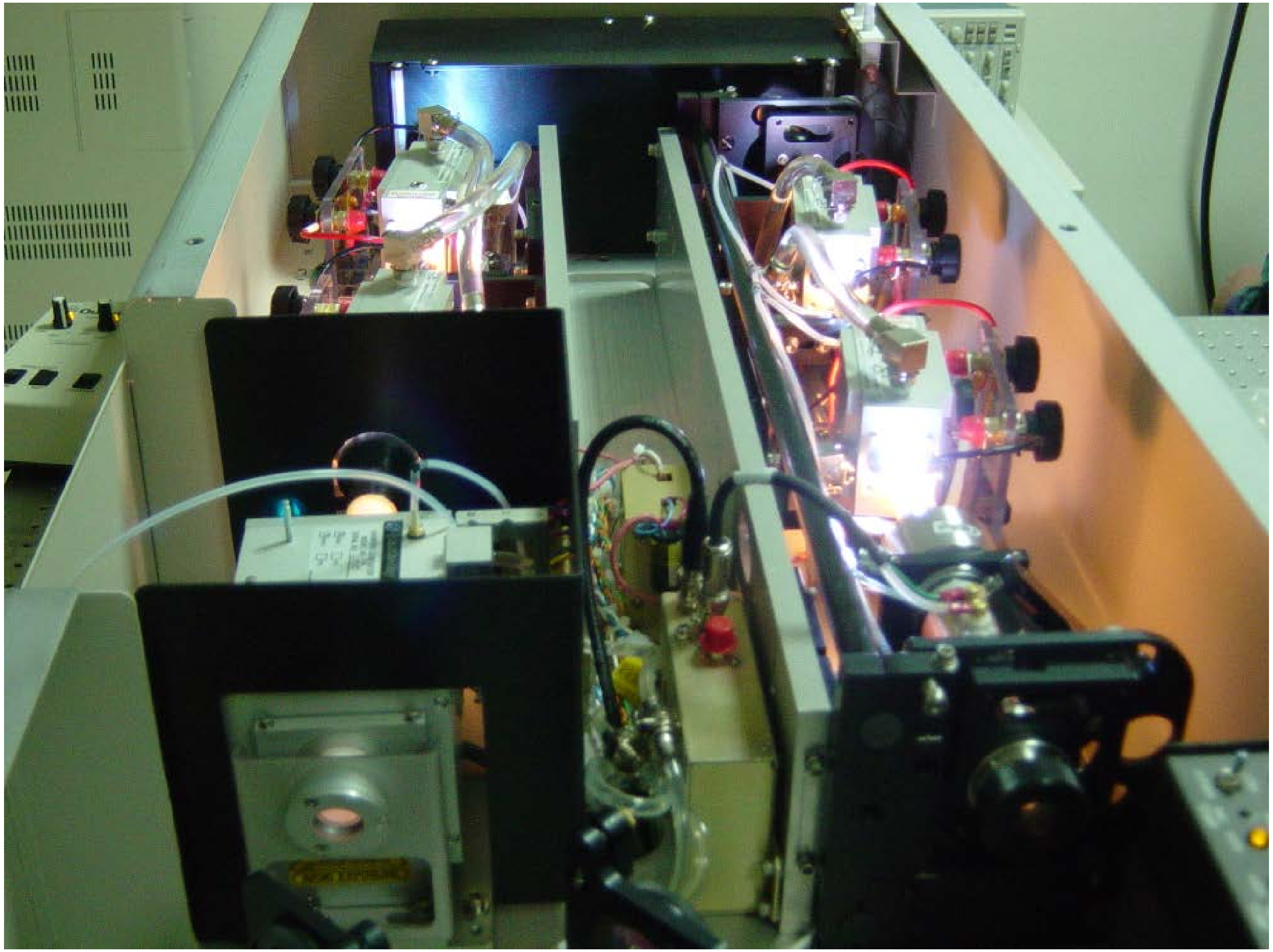
Collisions with electrons, plasmas.
Conventional light ... flash lamp
Chemical reactions
Voltage in a semiconductor
A wiggling relativistic electron
... and many many many more,
also pumped by another laser



Neodymium-ion laser (YAG laser)

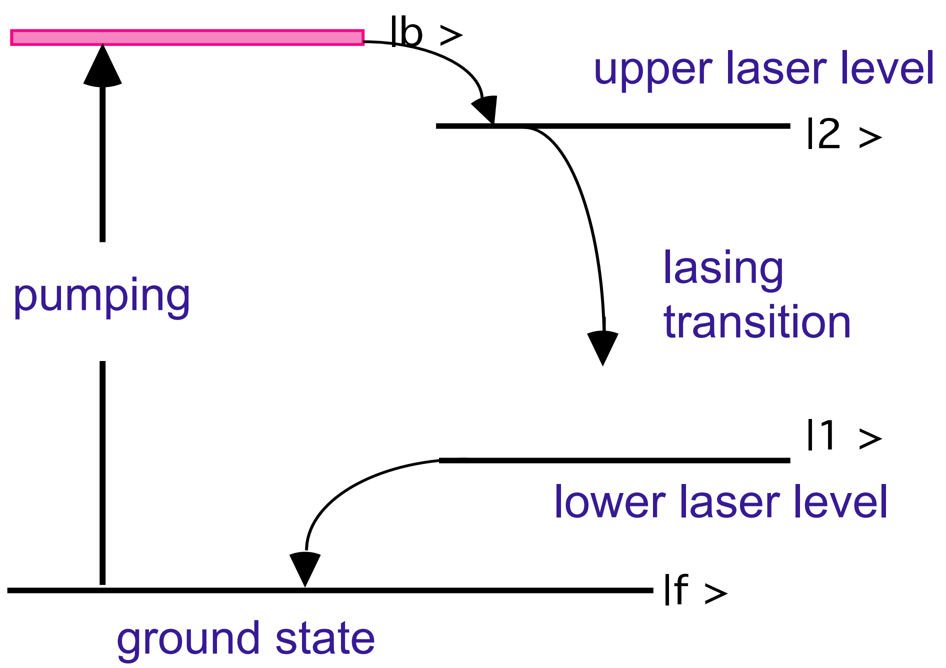


Nd ion laser



Nd:YAG laser
1064 nm

Four-level laser



$$\frac{dP_b}{dt} = -\gamma_b\, P_b + b\, P_f$$

$$\frac{dP_2}{dt} = -\gamma_2\, P_2 + \gamma_b\, P_b$$

$$\frac{dP_1}{dt} = -\gamma_1\, P_1 + \gamma_2\, P_2$$

$$\frac{dP_f}{dt} = -b\, P_f + \gamma_1\, P_1$$

steady state solution

$$0 = -\gamma_b\, P_b + b\, P_f$$

$$0 = -\gamma_2\, P_2 + \gamma_b\, P_b$$

$$0 = -\gamma_1\, P_1 + \gamma_2\, P_2$$

$$0 = -b\, P_f + \gamma_1\, P_1$$

population inversion

$P_1 < P_2$ if $\gamma_1 > \gamma_2$

Rate equations model

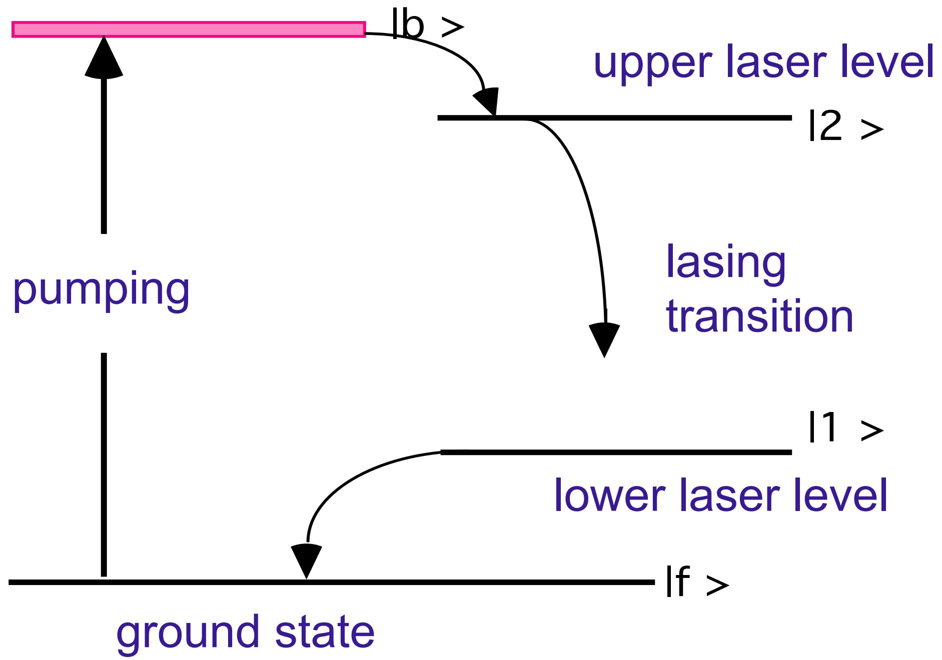
$$\frac{d}{dt}P_b = -\gamma_b\, P_b + b\, P_f$$

$$\frac{d}{dt}P_2 = -C\left(P_2 - P_1\right) I - \gamma_2\, P_2 + \gamma_b\, P_b$$

$$\frac{d}{dt}P_1 = \quad C\left(P_2 - P_1\right) I - \gamma_1\, P_1 + \gamma_2\, P_2$$

$$\frac{d}{dt}P_f = -b\, P_f + \gamma_1\, P_1$$

$$\frac{d}{dt}I = -\gamma_c\, I + G\left(P_2 - P_1\right) I$$

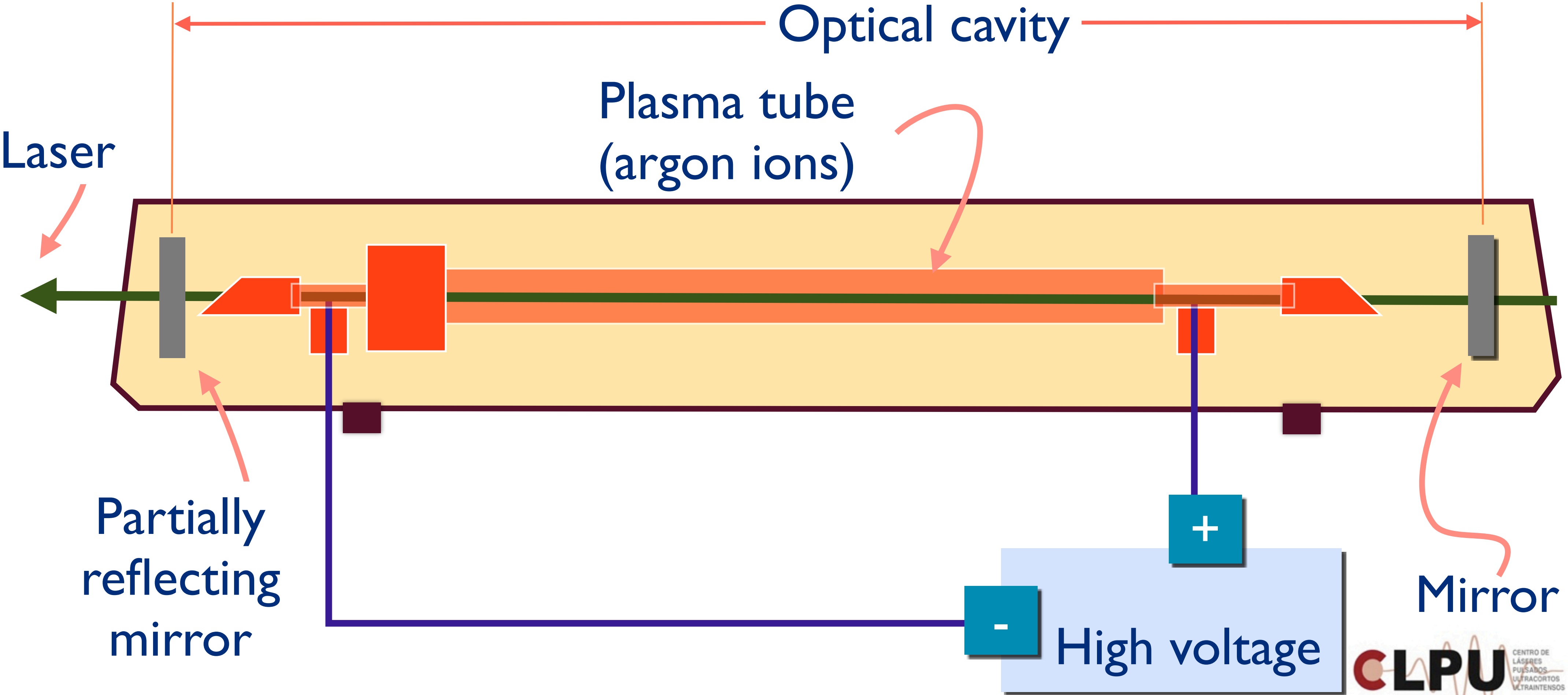


$$\boxed{G\left(P_2 - P_1\right) > \gamma_c}$$

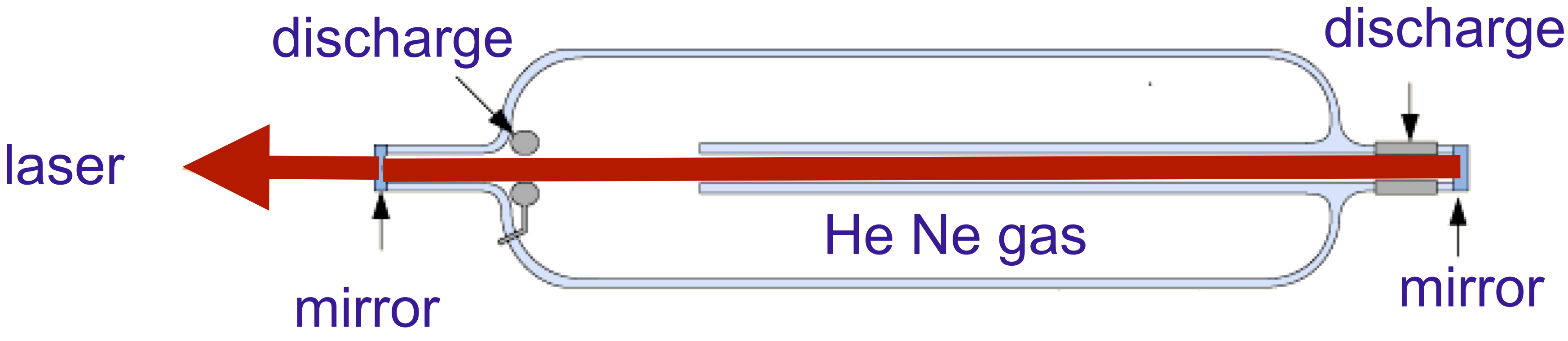
threshold for lasing

gain loss loss

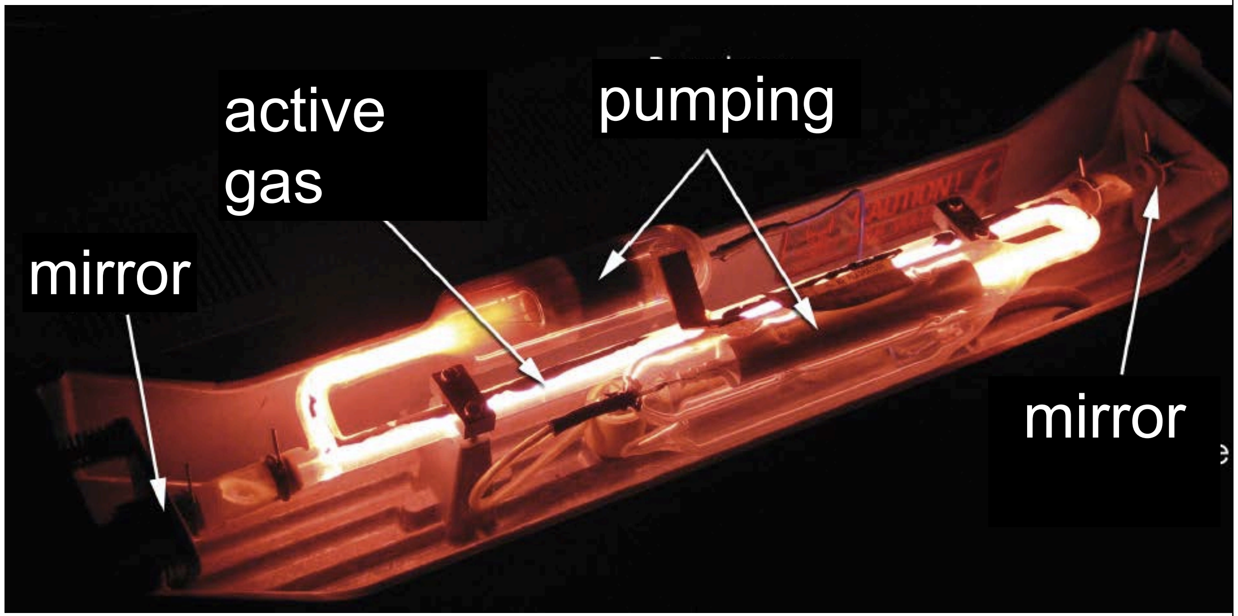
Argon ion laser   514 nm



Helium neon laser   632 nm

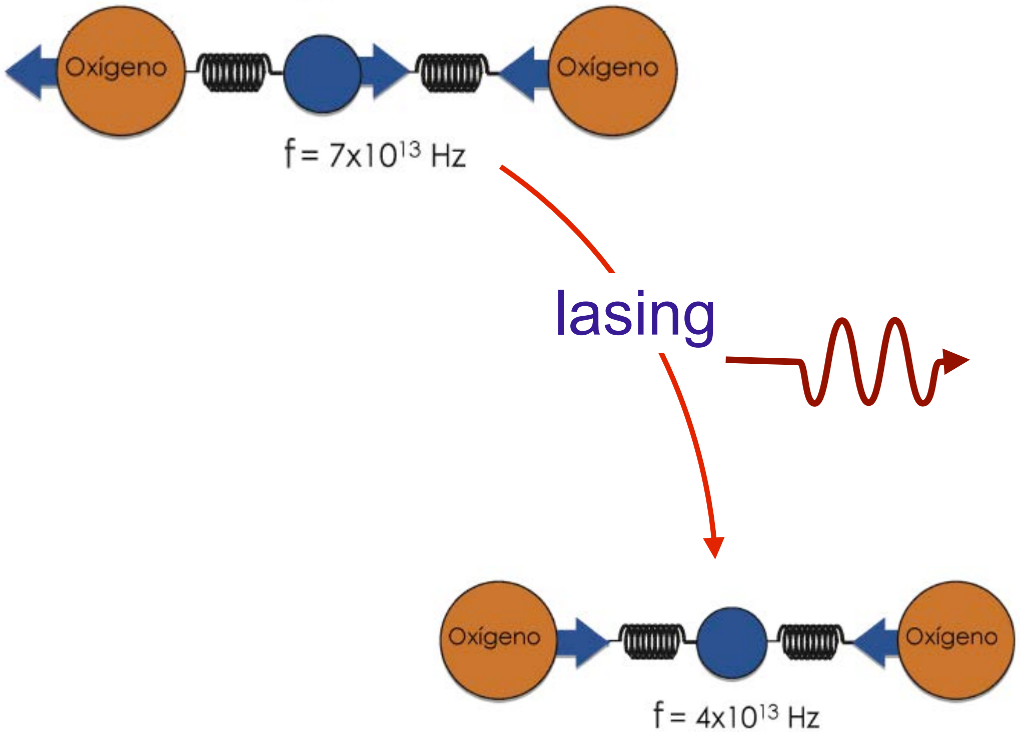


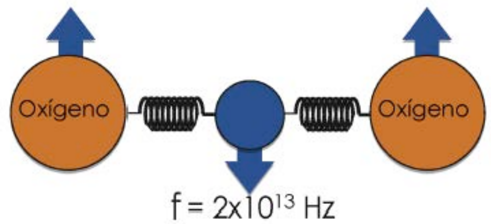
Pumping: electric discharge



CO2 laser 10.6 mirons FIR

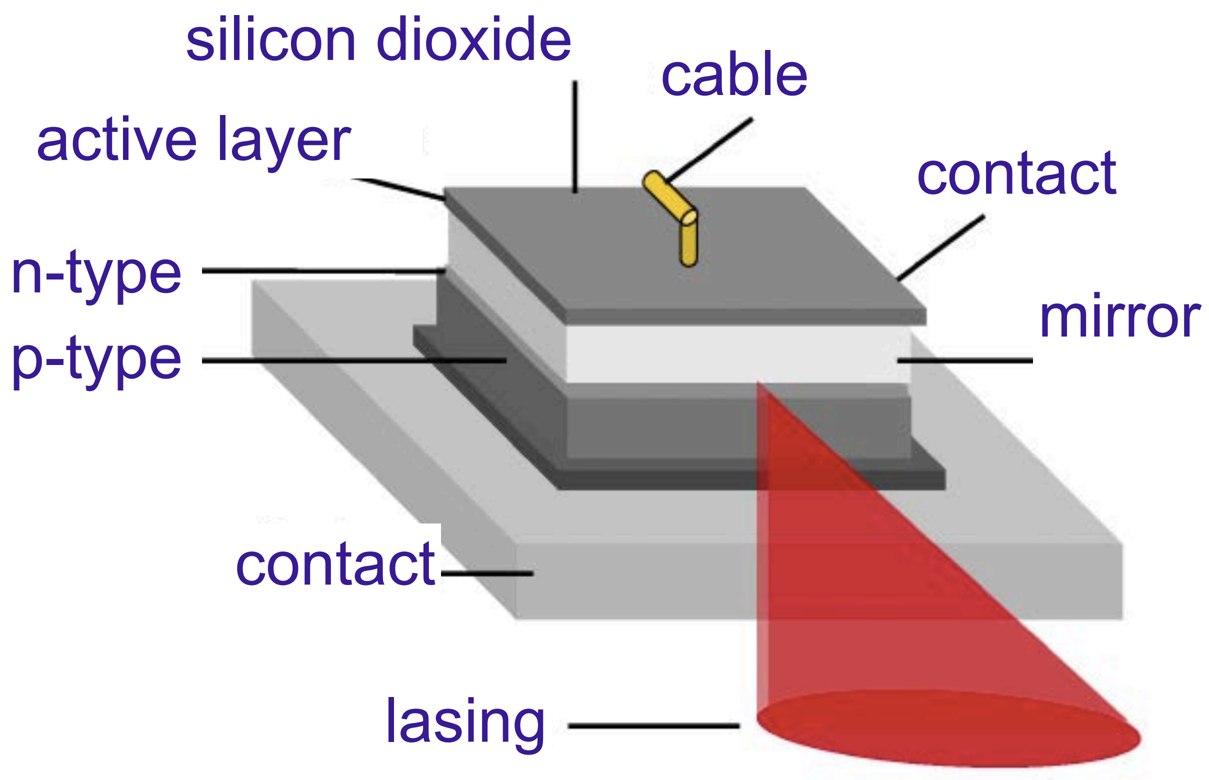
Molecular laser
vibrations of the CO2 molecule



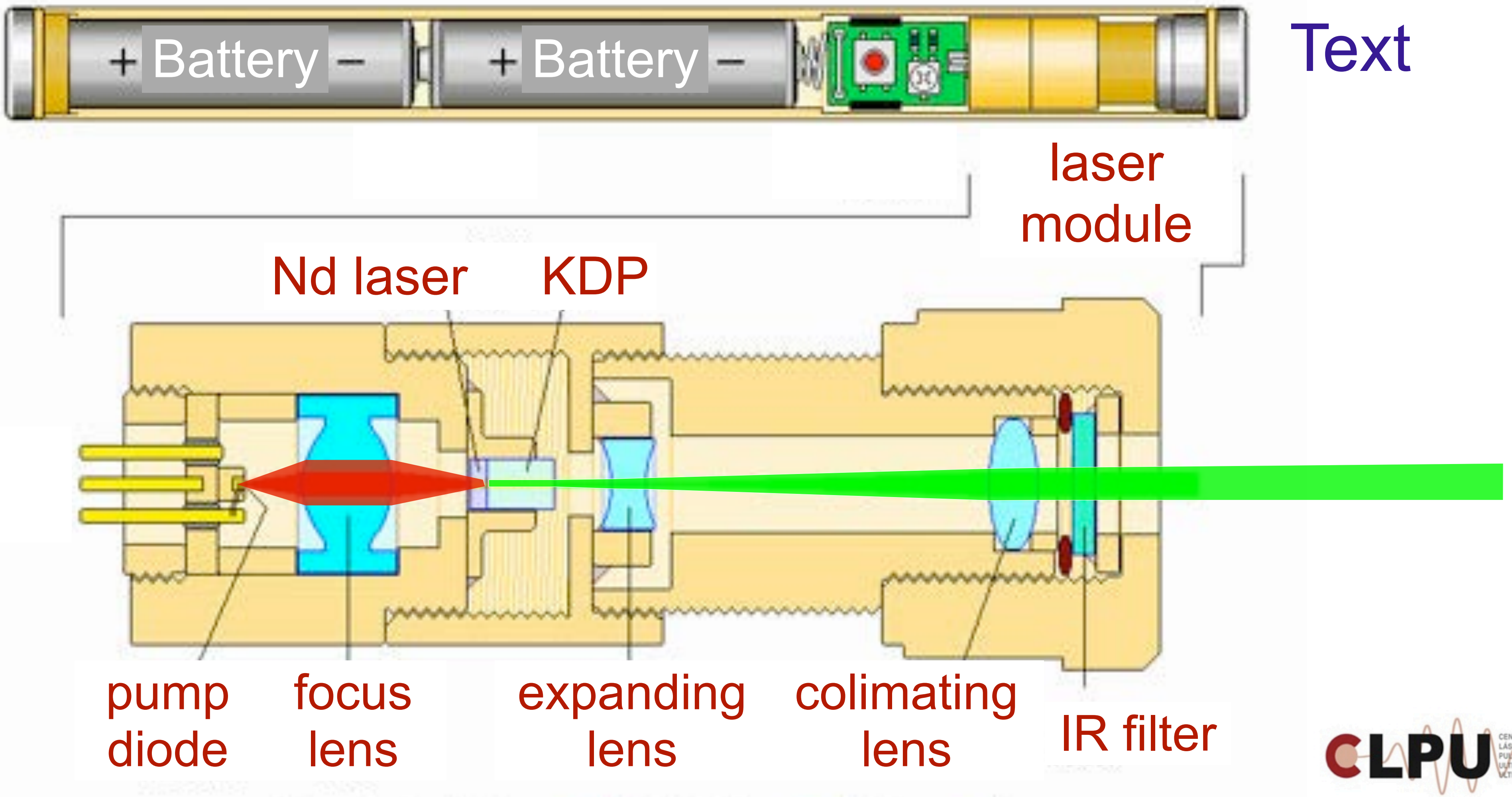


Semiconductor lasers

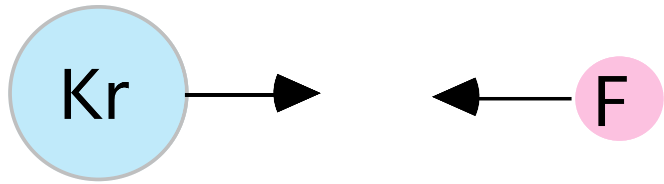
The laser of the XXI Century !!!



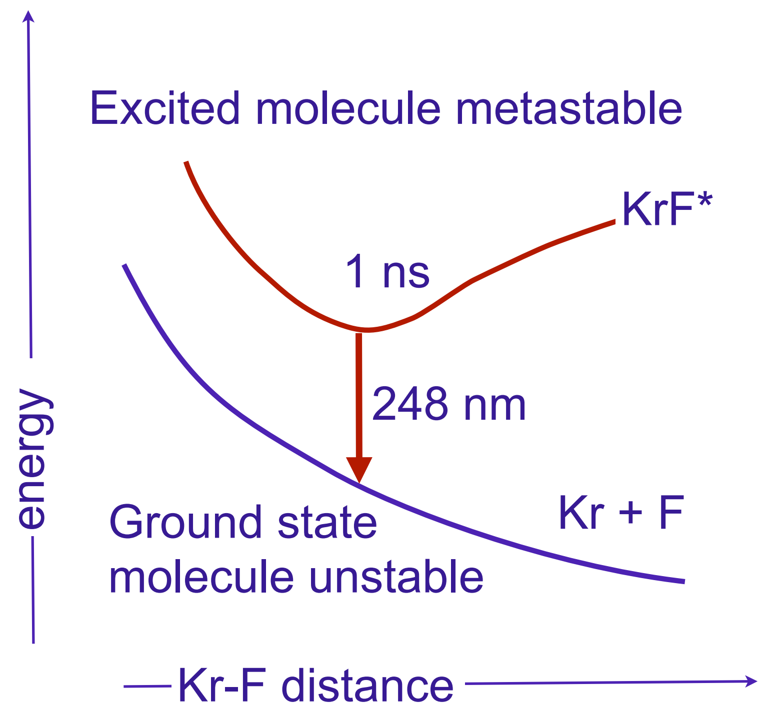
Laser pointer



Excimers



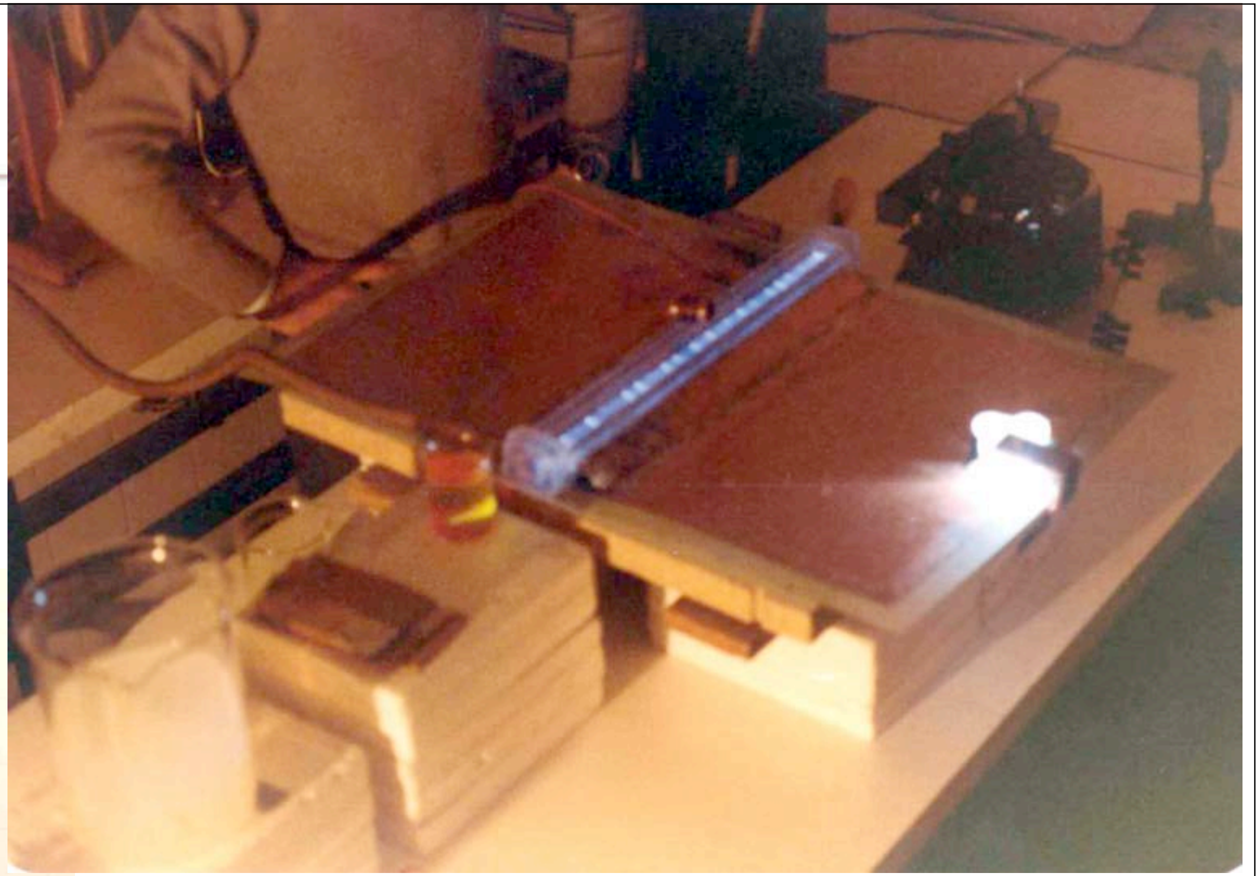
Excimer: Excited dimer (two equal atoms) e.g.
Exciplet: Excited molecular complex (different atoms) e.g. KrF



Ar-Ar dimer	126 nm
Kr-Kr dimer	146 nm
Xe-Xe dimer	172 nm
Ar-F molec	193 nm
Kr-F molec	248 nm
Xe-Cl molec	351 nm
Kr-Br molec	206 nm
Ar-Br molec	161 nm
Ne-F molec	108 nm

Air laser !!!

Home made air laser
N_2 laser
near UV   337 nm



All you need is
two cooper plates
(capacitor)
a high voltage source

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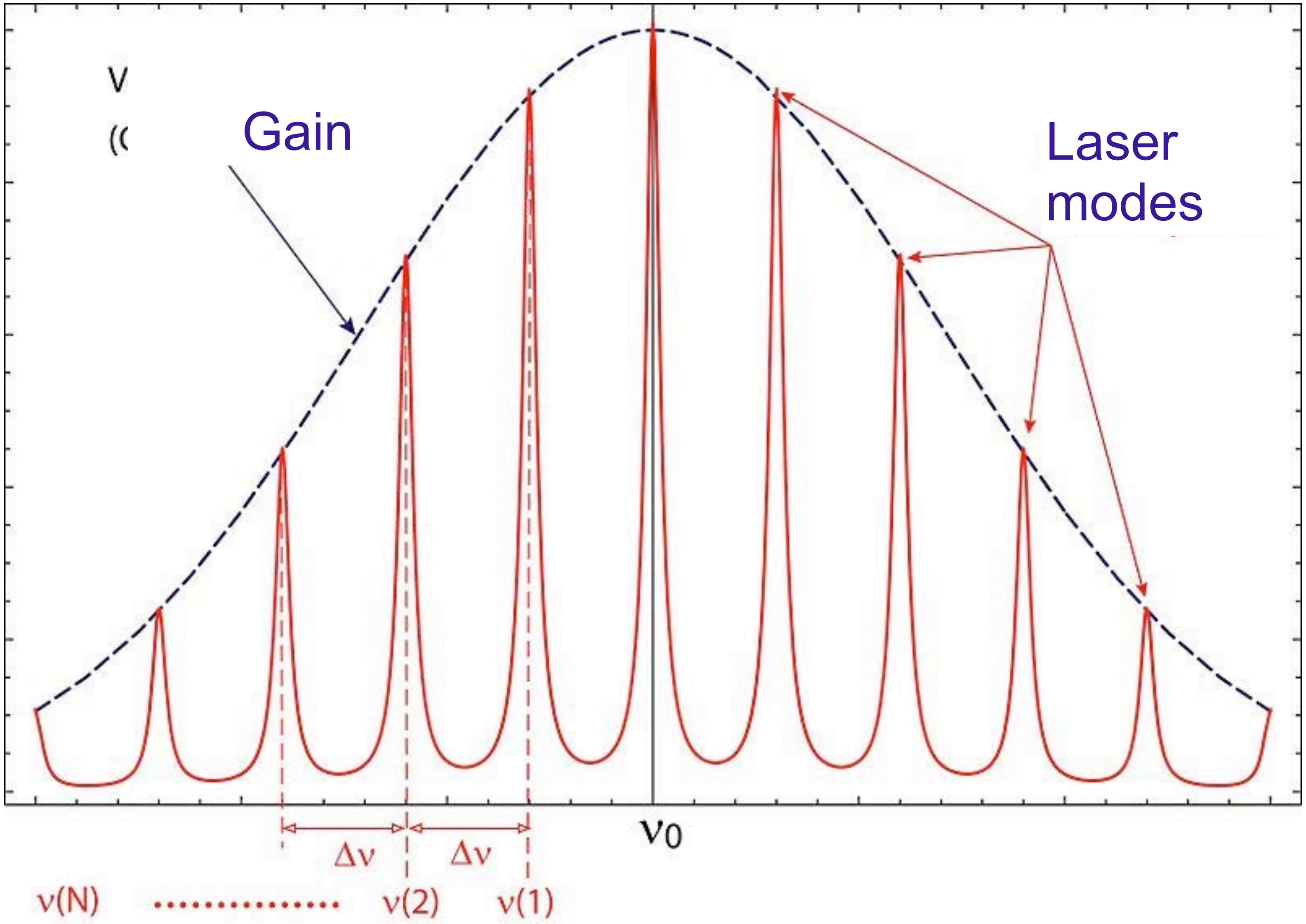
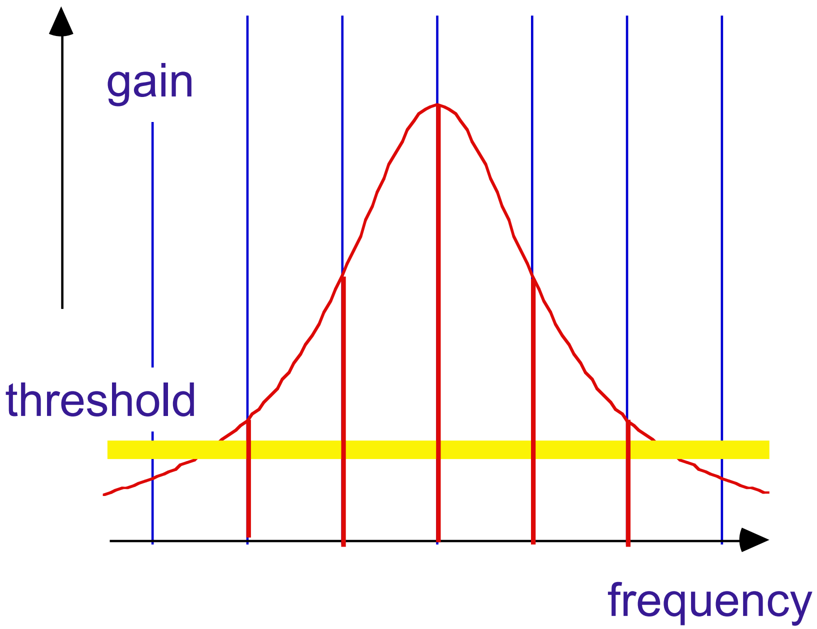
Longitudinal modes

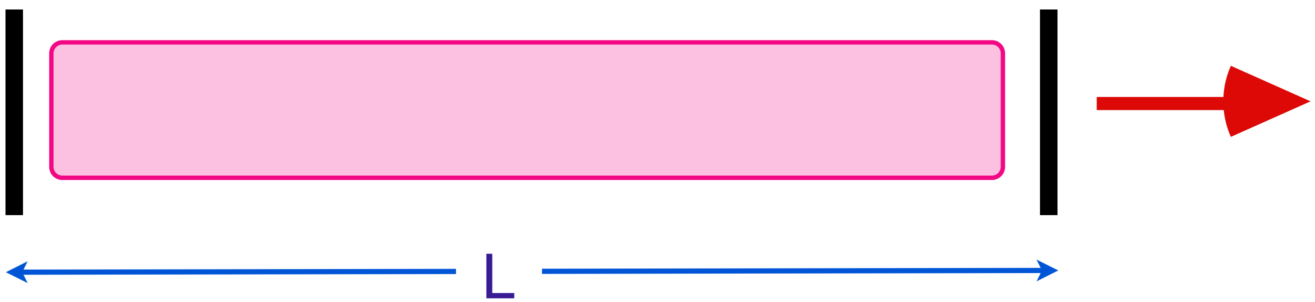


Multimode laser

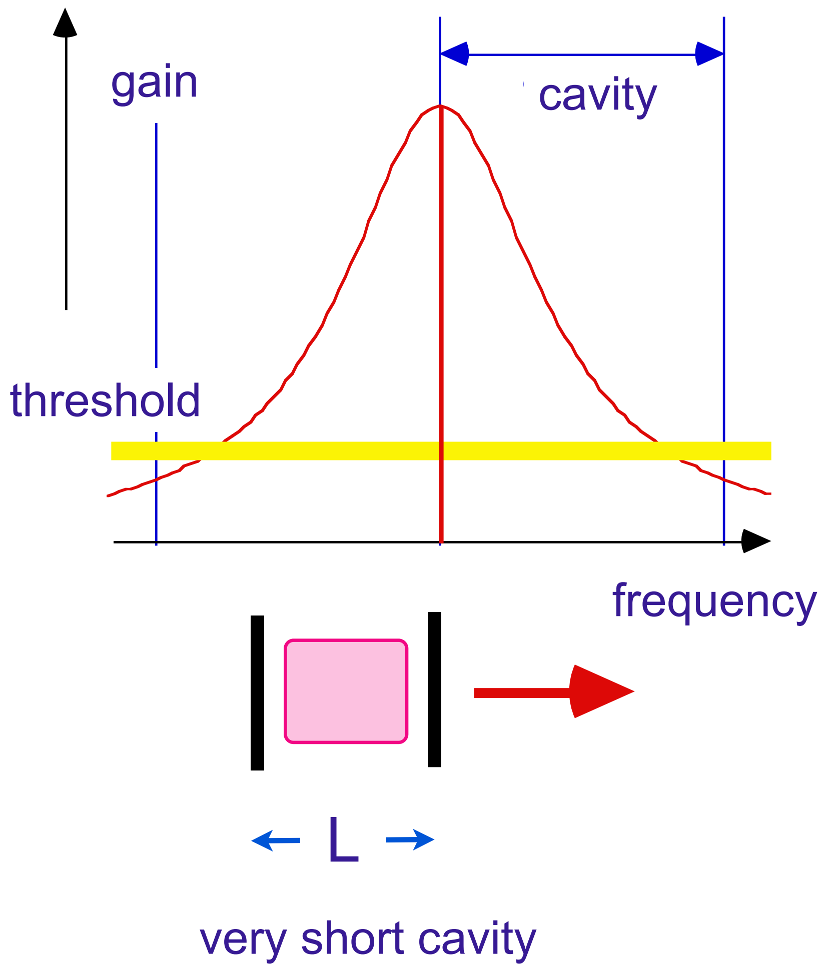


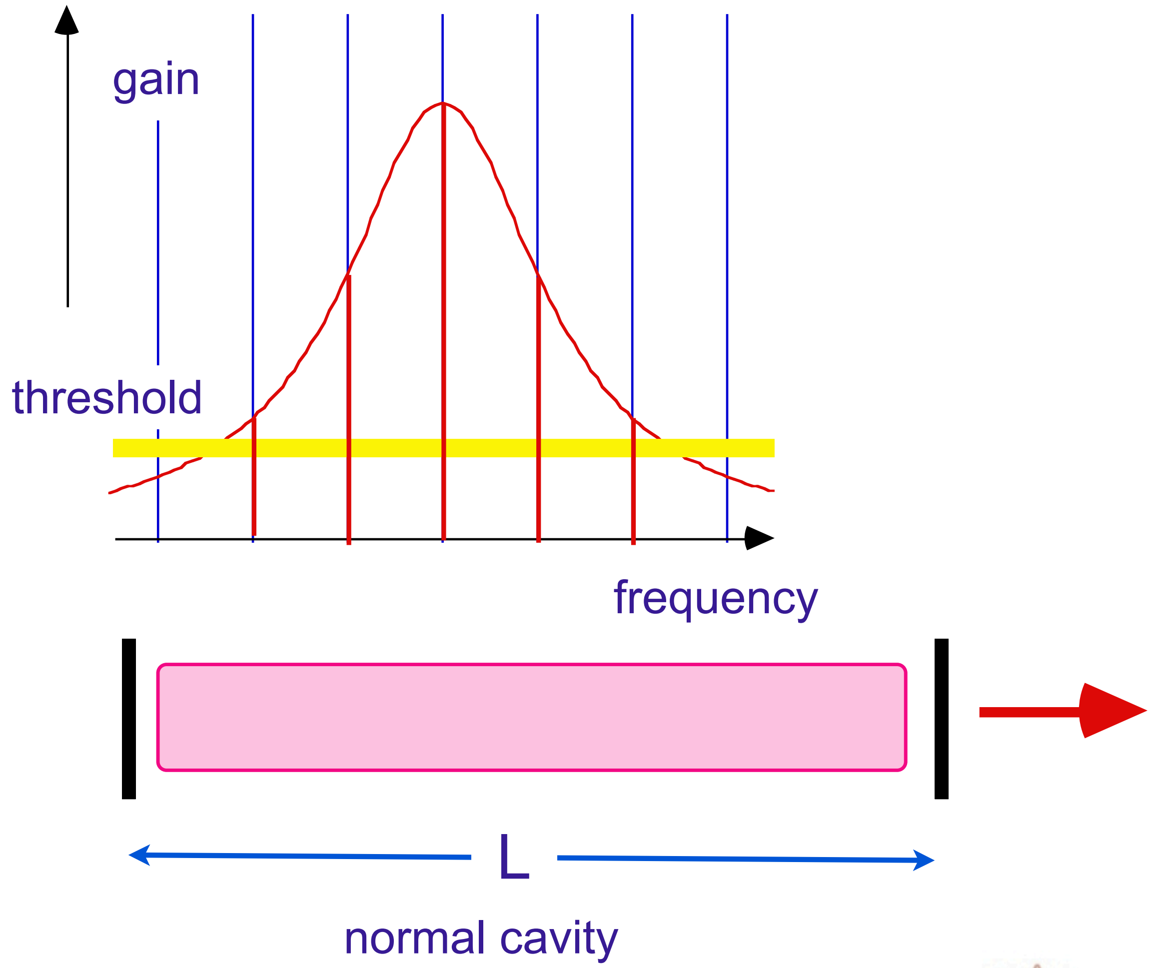
Consecutive frequencies

$$\Delta\omega = \omega_{n+1} - \omega_n = \frac{\pi\, c}{L}$$

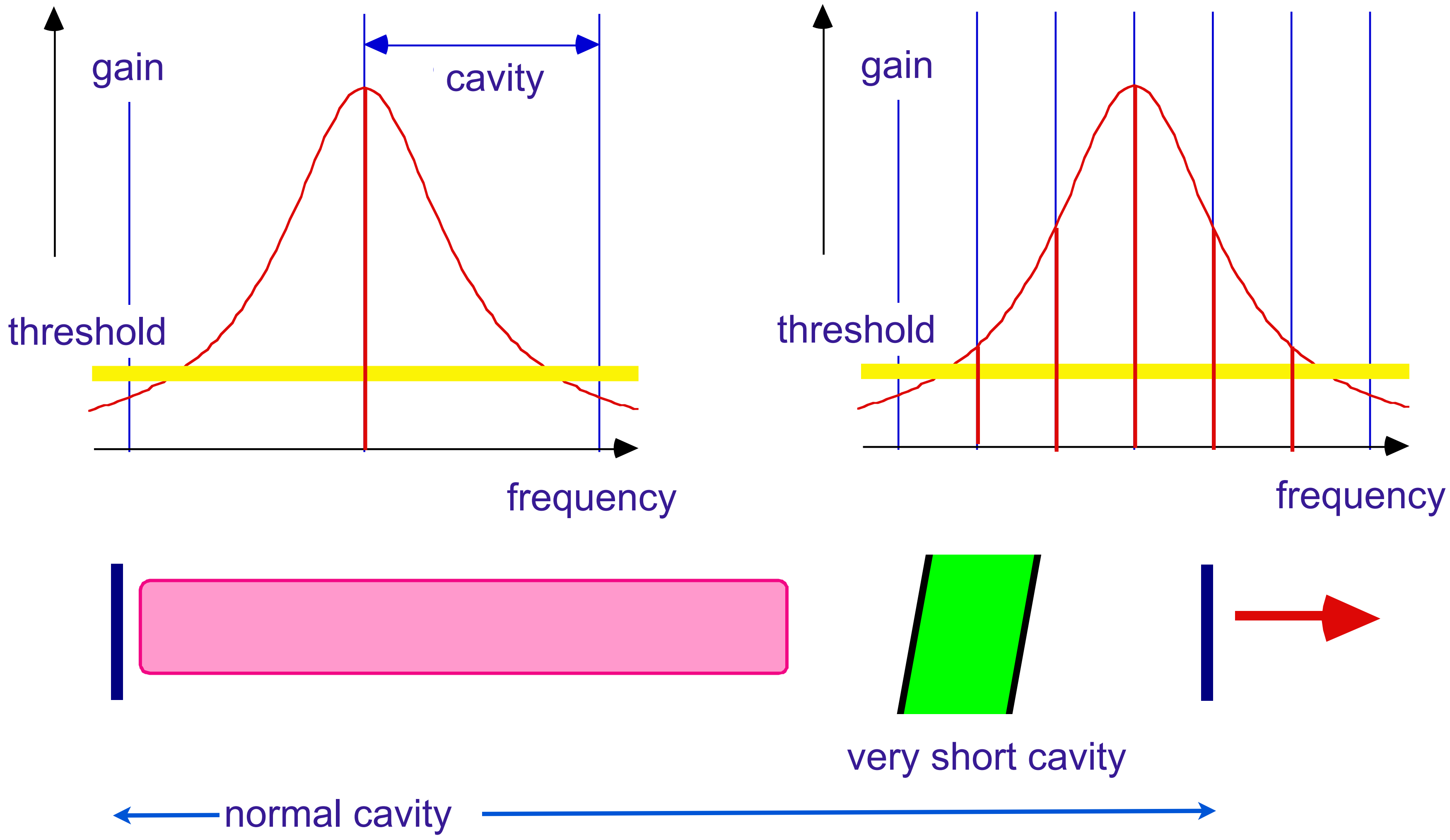


Monomode laser



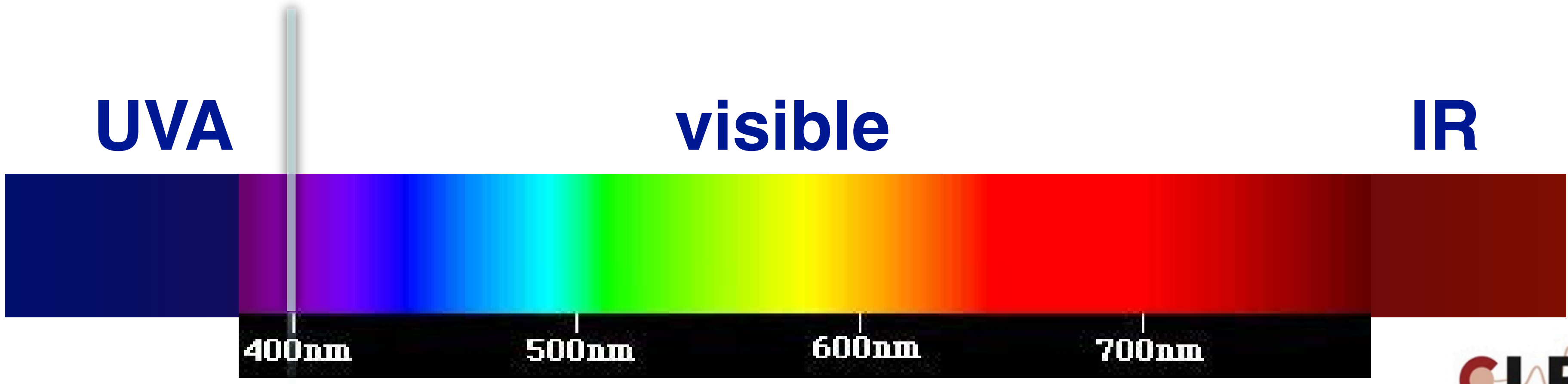


Etalon


gain
cavity
threshold
frequency
gain
threshold
frequency
very short cavity
normal cavity

Broad band lasers

long pulse ... quasi monochromatic

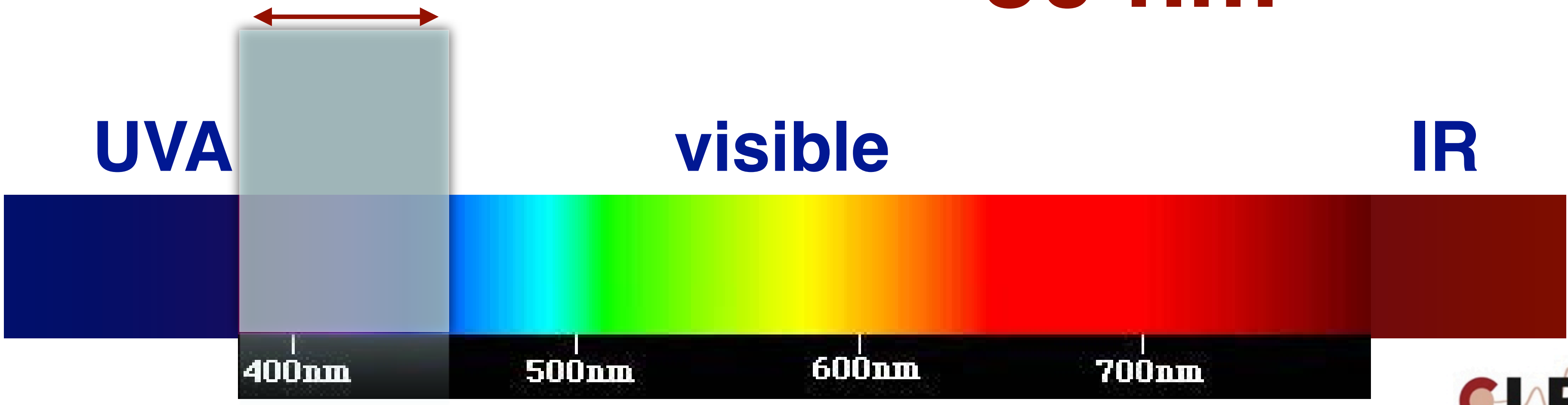


Broad band lasers

short pulse ... broadband

30 fs

30 nm

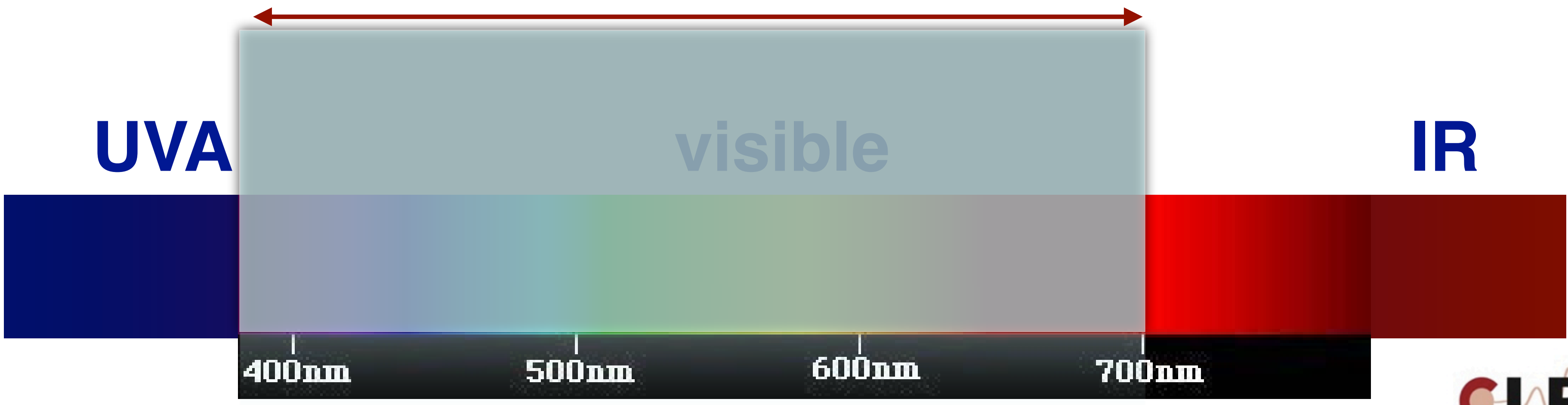


Broad band lasers

ultra short pulse ... very broad band

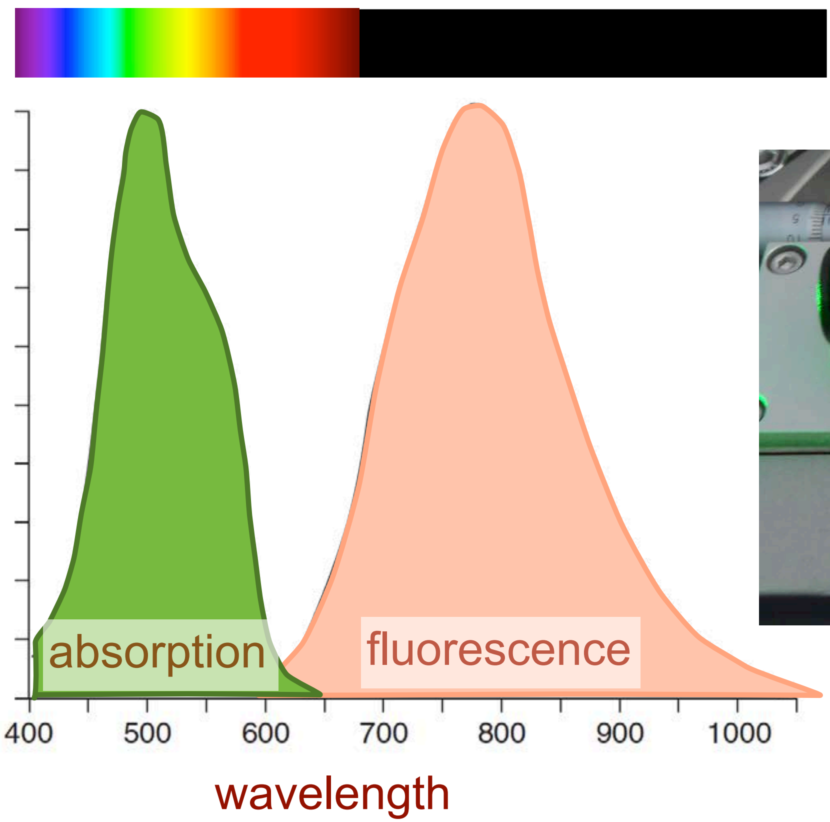
few fs

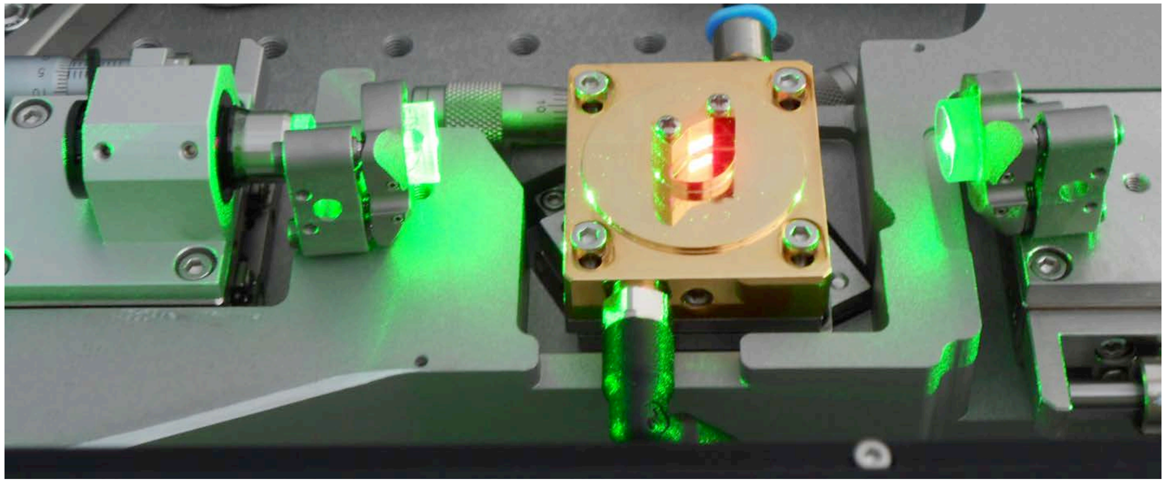
all visible



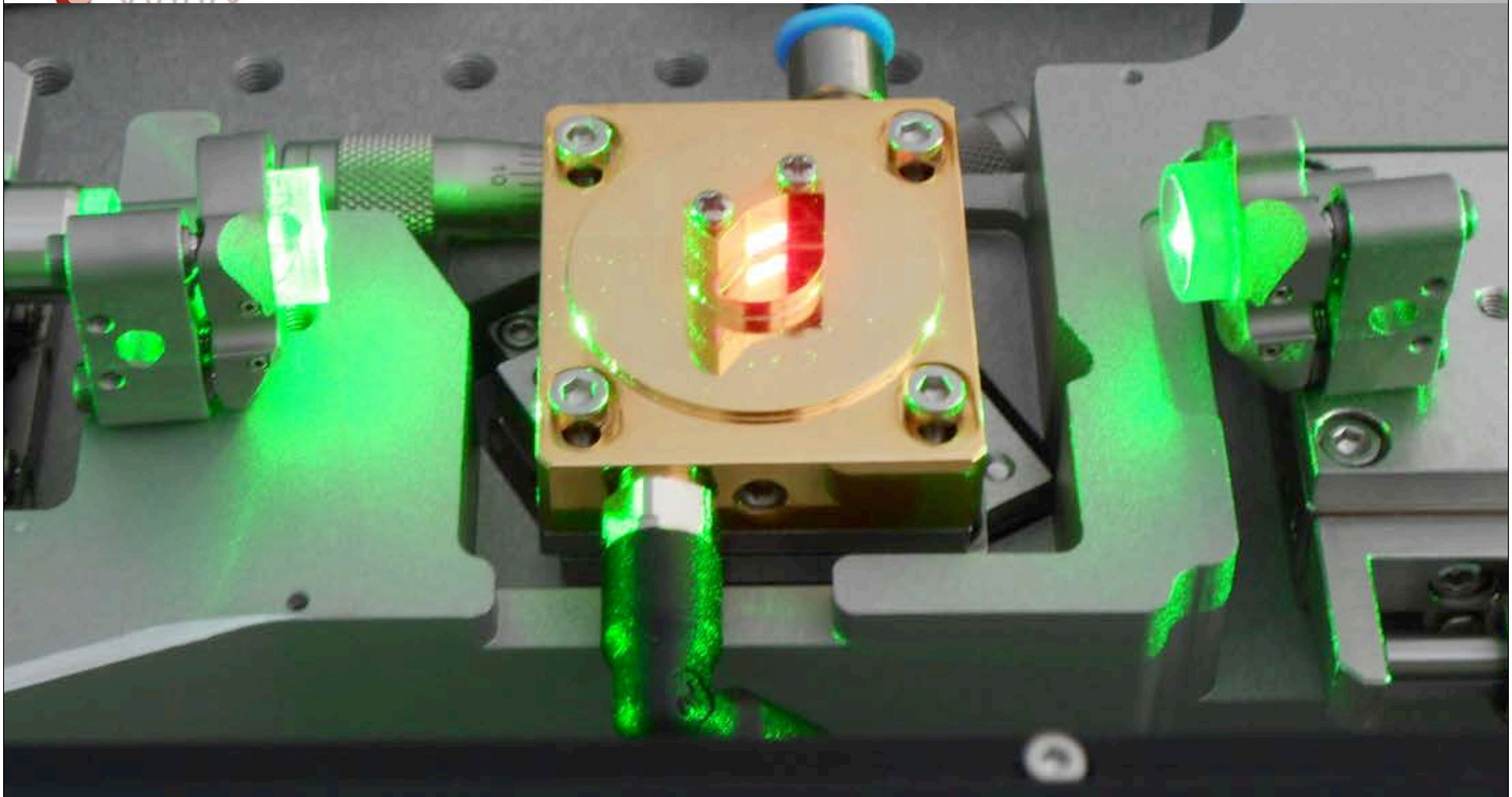
Ti:sapphire laser

short pulses ⟷ broad band



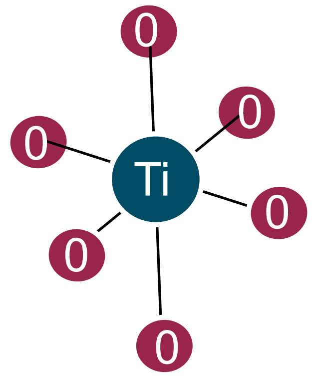


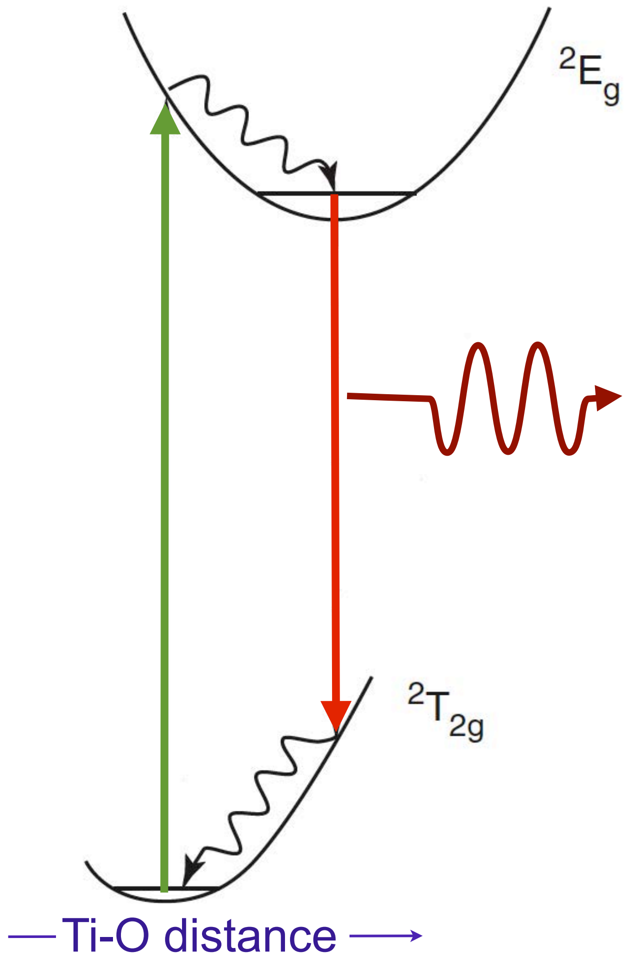
Ti:sapphire laser

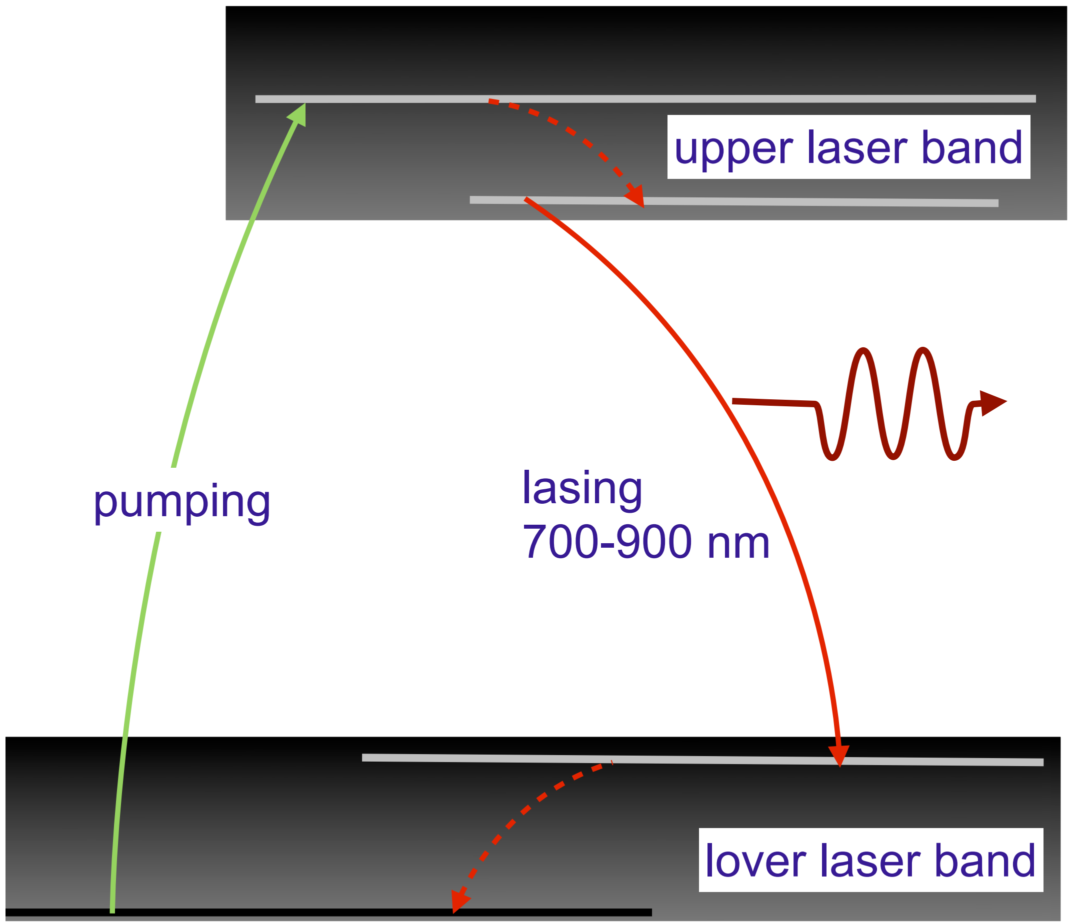


Vibronic laser, Ti:sapphire

Ti^{+++} ion in sapphire

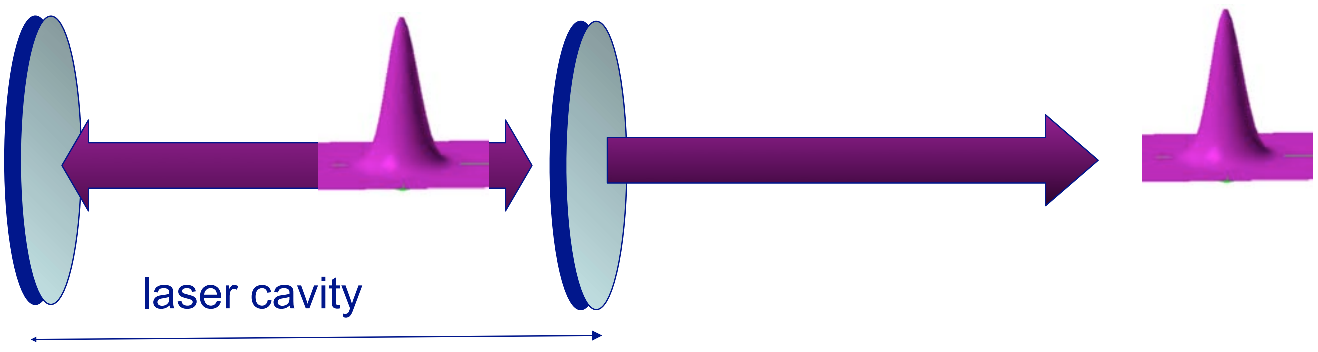


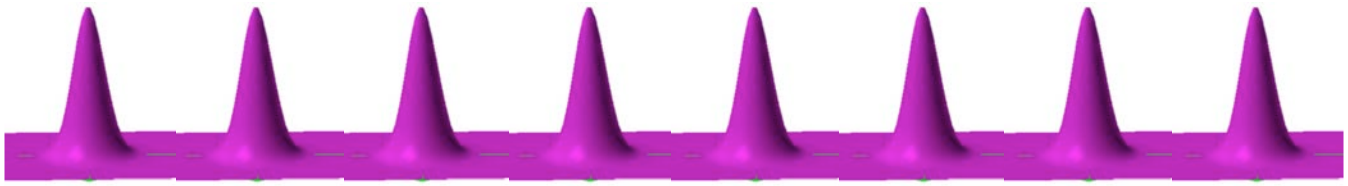




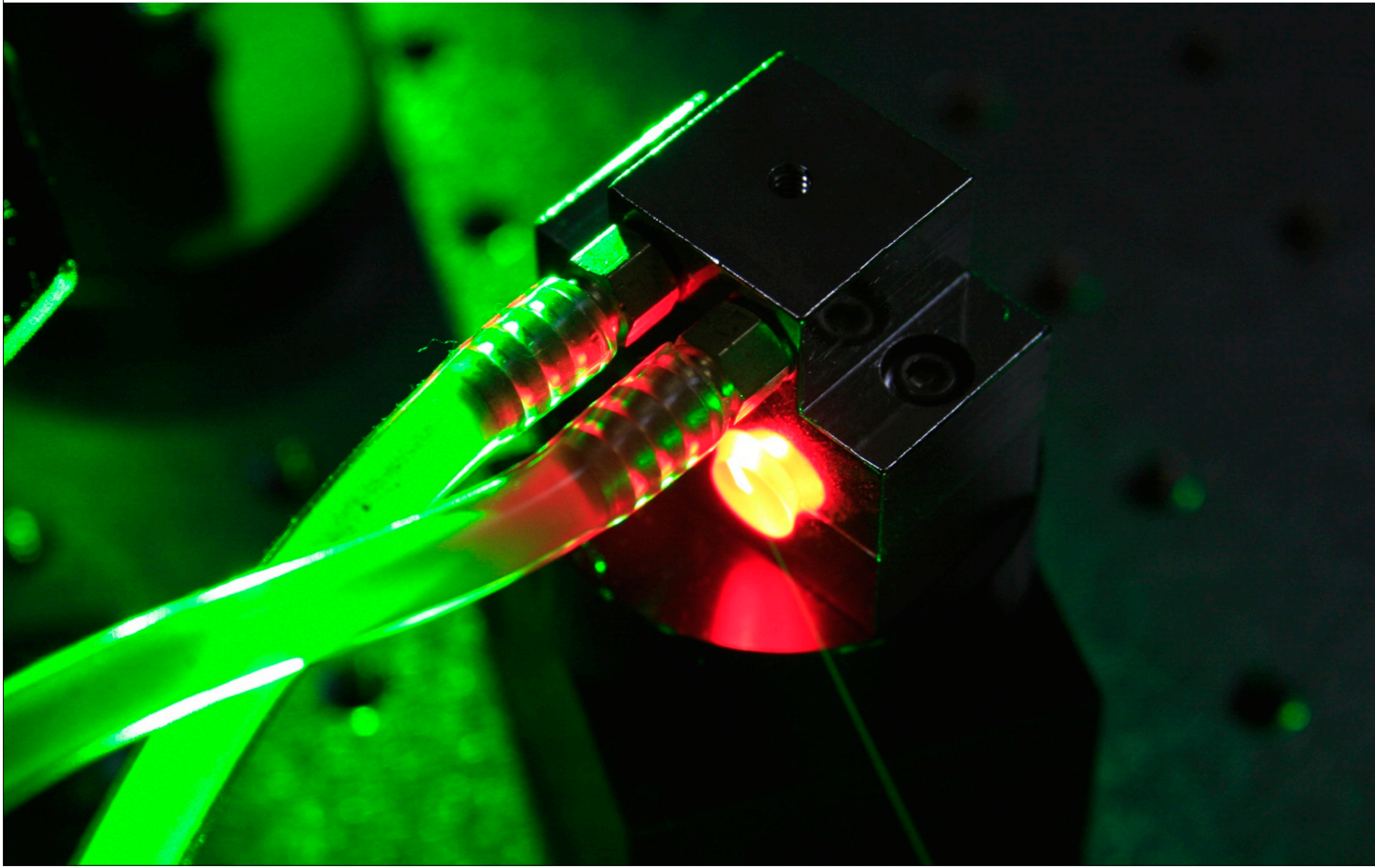
Mode-loking lasers

A pulse is generated each round trip of

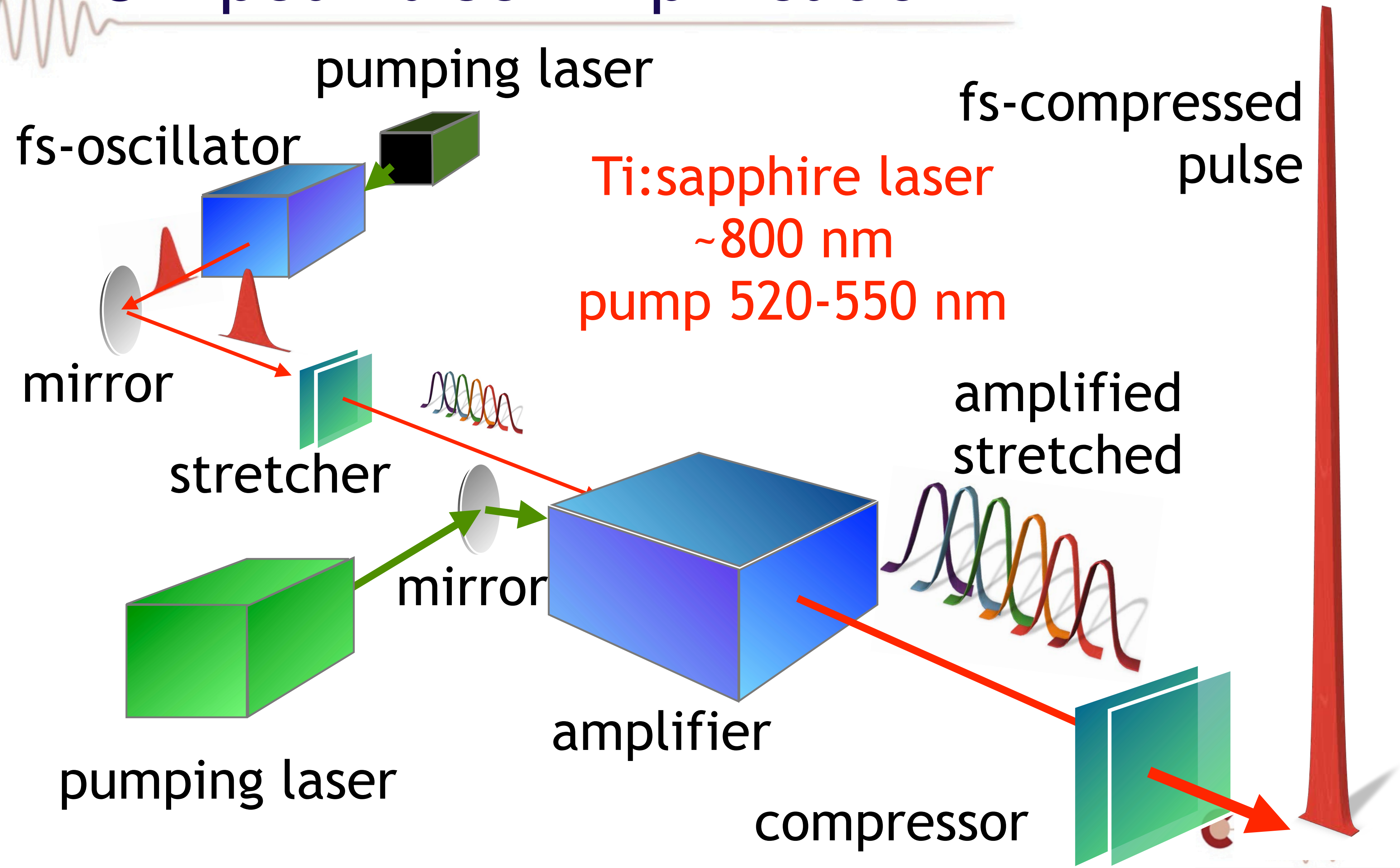




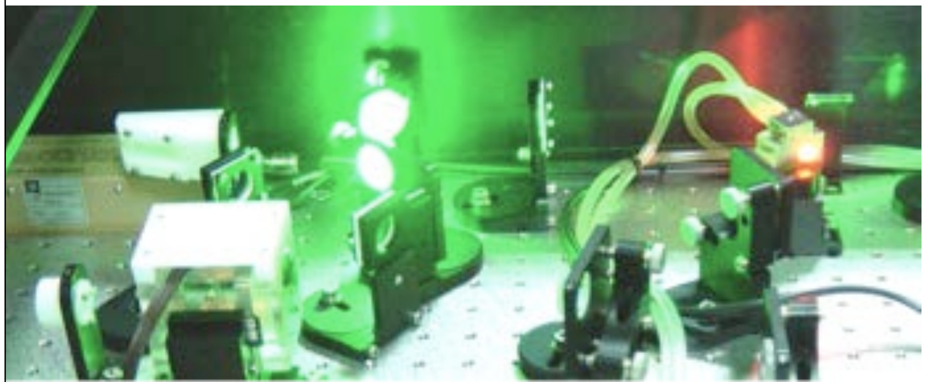
Ultrashort pulses imply many many modes in phase: for example,
- one picoseg implies a 1 nm bandwidth
- 10 femtosecons imply 100 nanómetres (almost all the visible)



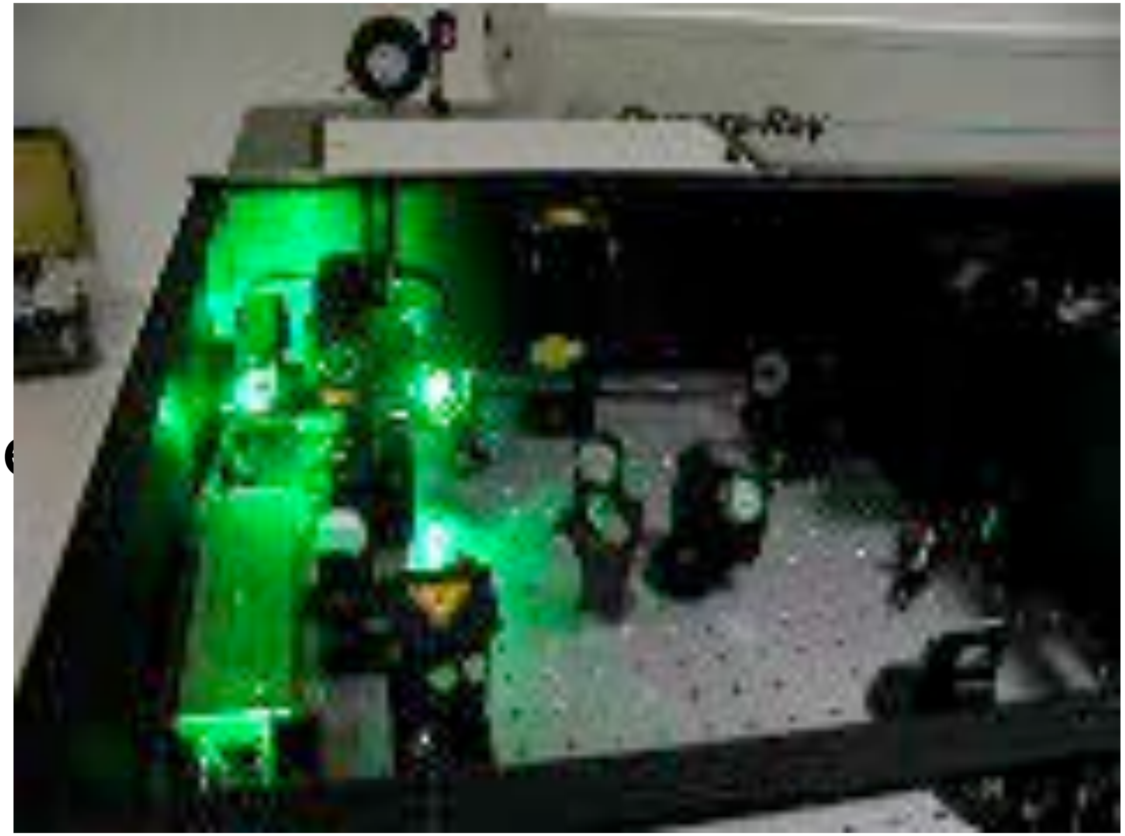
Chirped Pulse Amplification

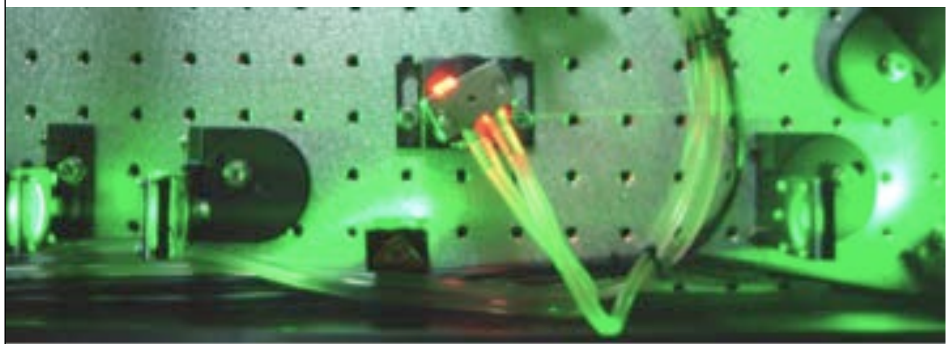


Titanium:Sapphire amplifier

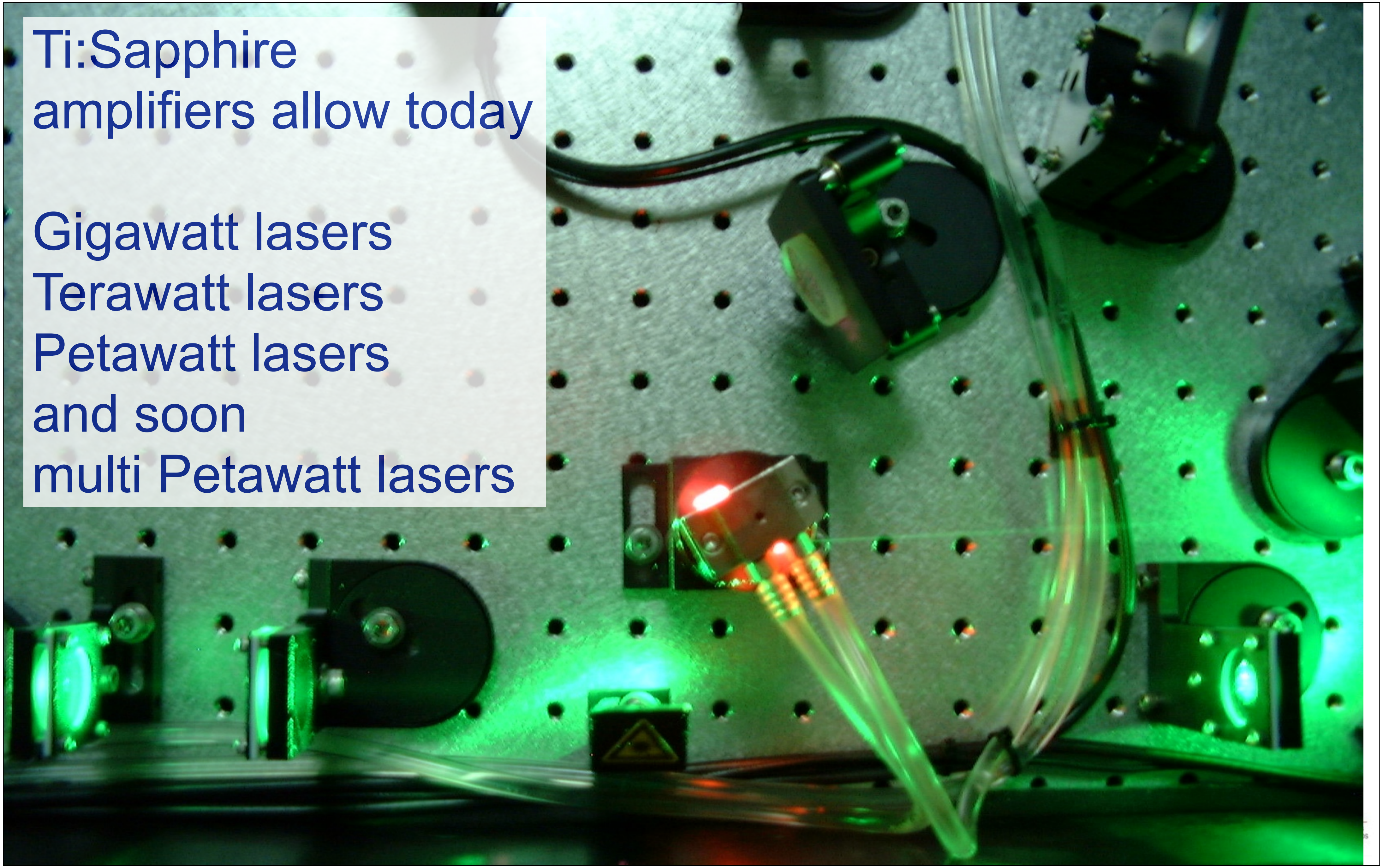


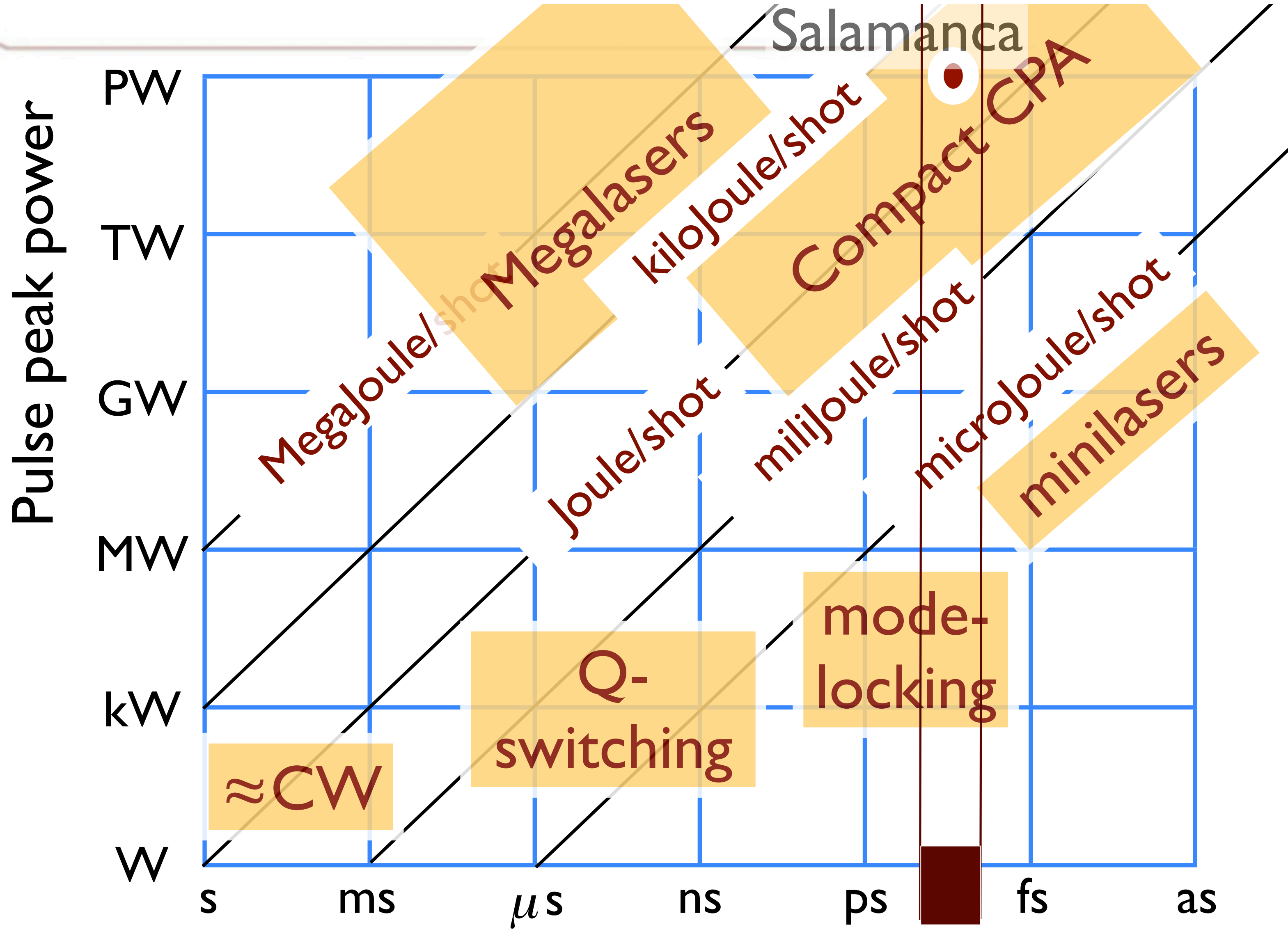
Regenerative amplifier (side vi





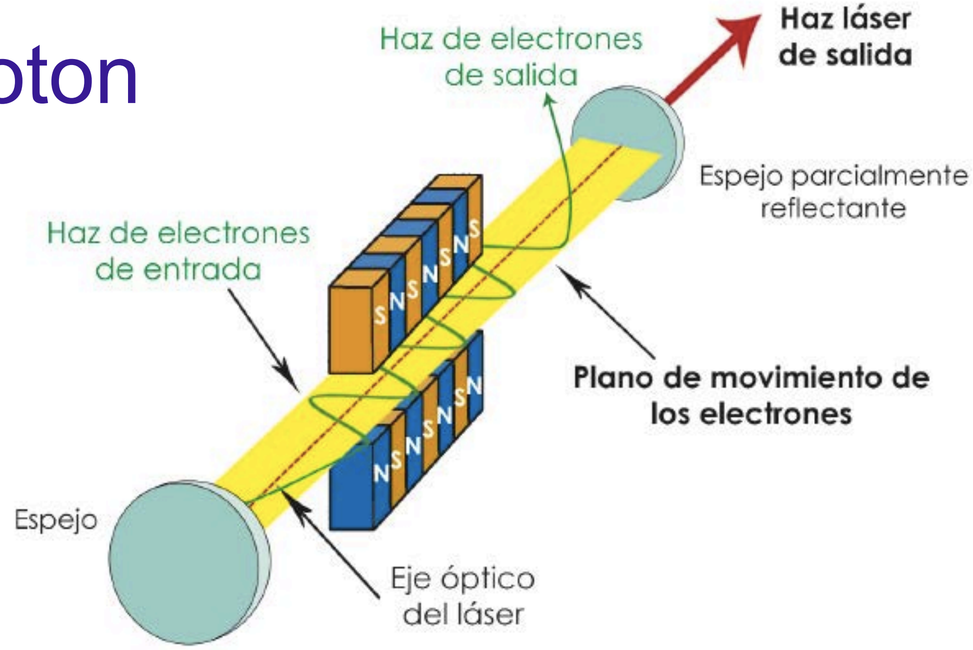
Regenerative amplifier (top view)


Ti:Sapphire
amplifiers allow today
Gigawatt lasers
Terawatt lasers
Petawatt lasers
and soon
multi Petawatt lasers


Salamanca
PW
TW
GW
MW
kW
W
Pulse peak power
s
ms
μs
ns
ps
fs
as
Pulse duration
Megalasers
kiloJoule/shot
Compact CPA
MegaJoule/shot
Joule/shot
miliJoule/shot
microJoule/shot
minilasers
mode-locking
Q-switching
≈CW

Other schemes for laser light ...

Inversion-less lasers
Quantum lasers ... single photon
X-ray lasers
Nuclear lasers
Free electron lasers



Natural lasers (astrophysical lasers)

CLPU CENTRO DE LÁSERES PULSADOS ULTRACORTOS ULTRAINTENSOS

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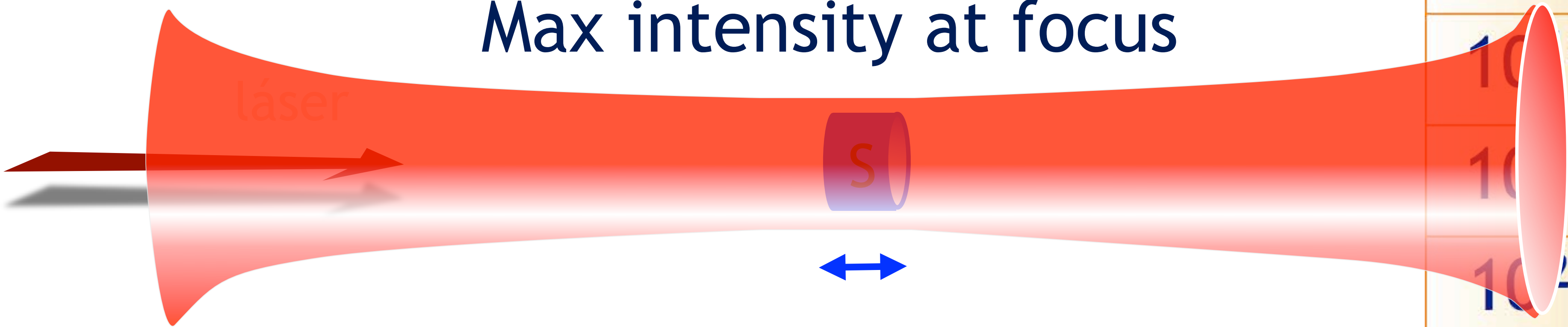
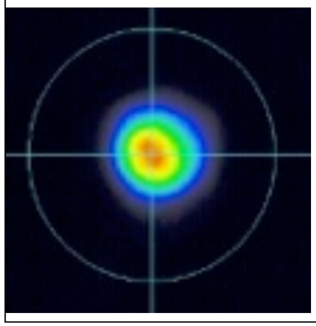
- Final considerations

Intensity is the key parameter

$$Intensity = \frac{power}{surface}$$

Max intensity at focus

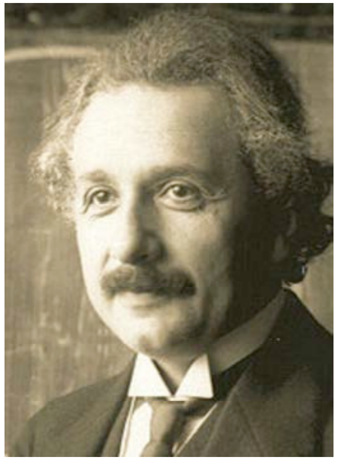




Todays world record

10^{15} W/cm^2
10^{16} W/cm^2
10^{17} W/cm^2
10^{18} W/cm^2
10^{19} W/cm^2
10^{20} W/cm^2
10^{21} W/cm^2
10^{22} W/cm^2
10^{23} W/cm^2
10^{24} W/cm^2

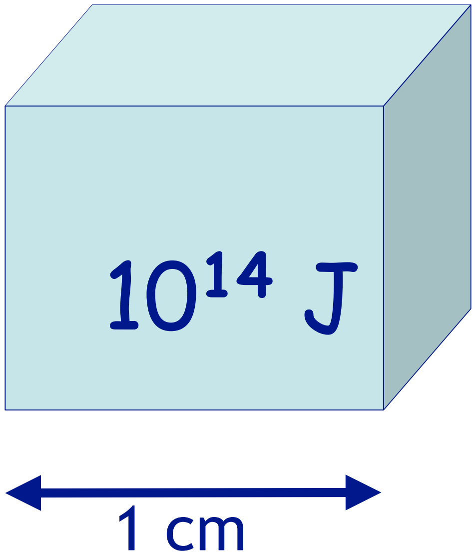
Energy and mass



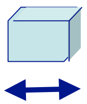
$$E=mc^2$$

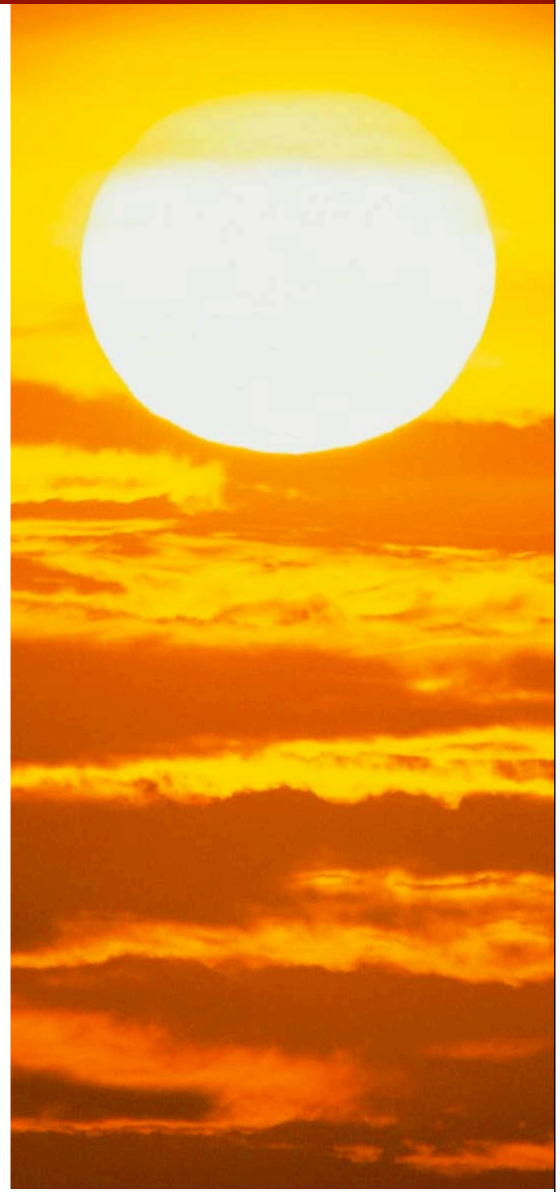
$$E=8.9876\ 10^{16}\ J/kg$$

water density 1 gram/cm3

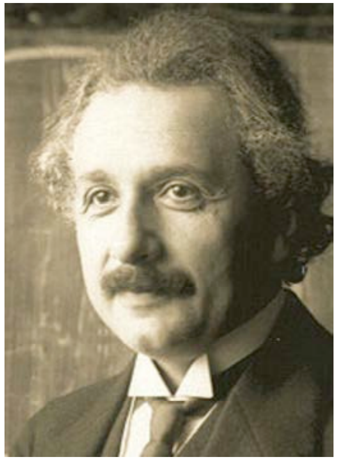


100 Joule





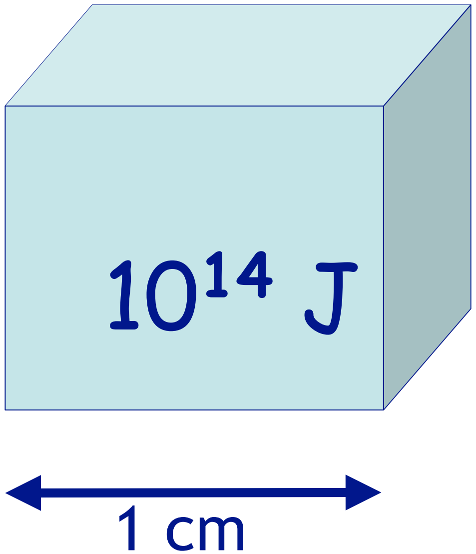
Energy and mass



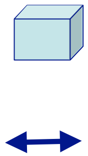
$\cancel{E=mc^2}$

$$I = \rho\, c^3$$

water density 1 gram/cm3



100 Joule



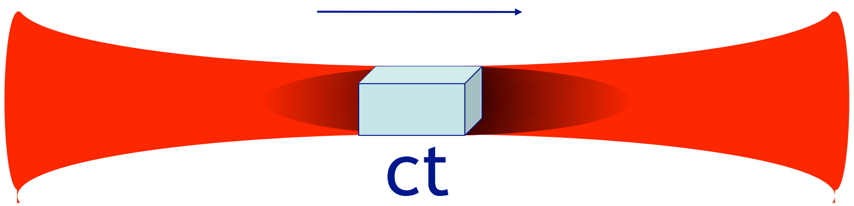
Intensity

$E=mc^2$

Air ... 1 mgr/cm^3

$E/V = 90\ mJ/\mu m^3$

$= 2.7\ 10^{21}\ W/cm^2$



$E/V = 90\ J/\mu m^3$

$2.7\ 10^{24}\ W/cm^2$

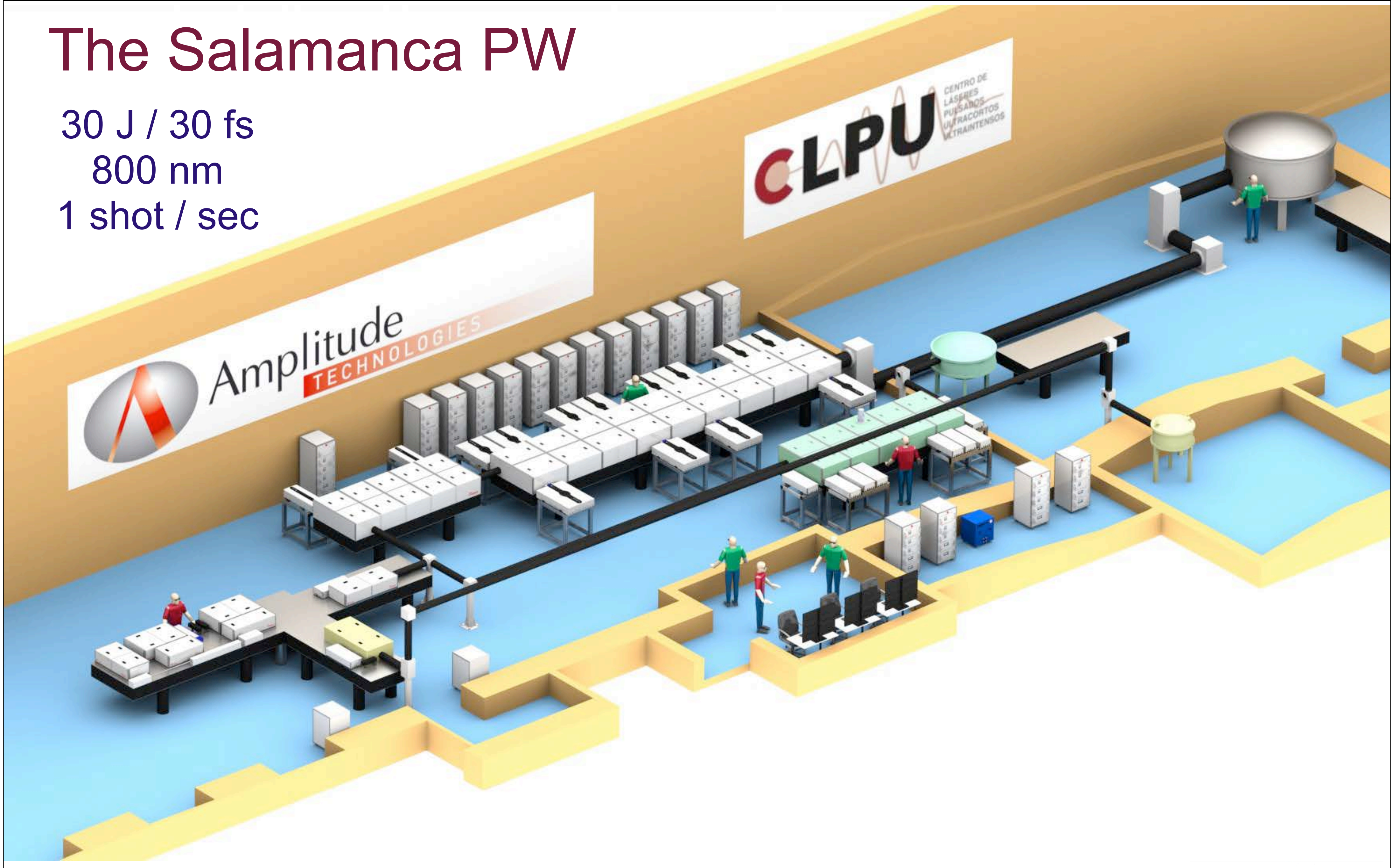
Water ... 1 gr/cm^3

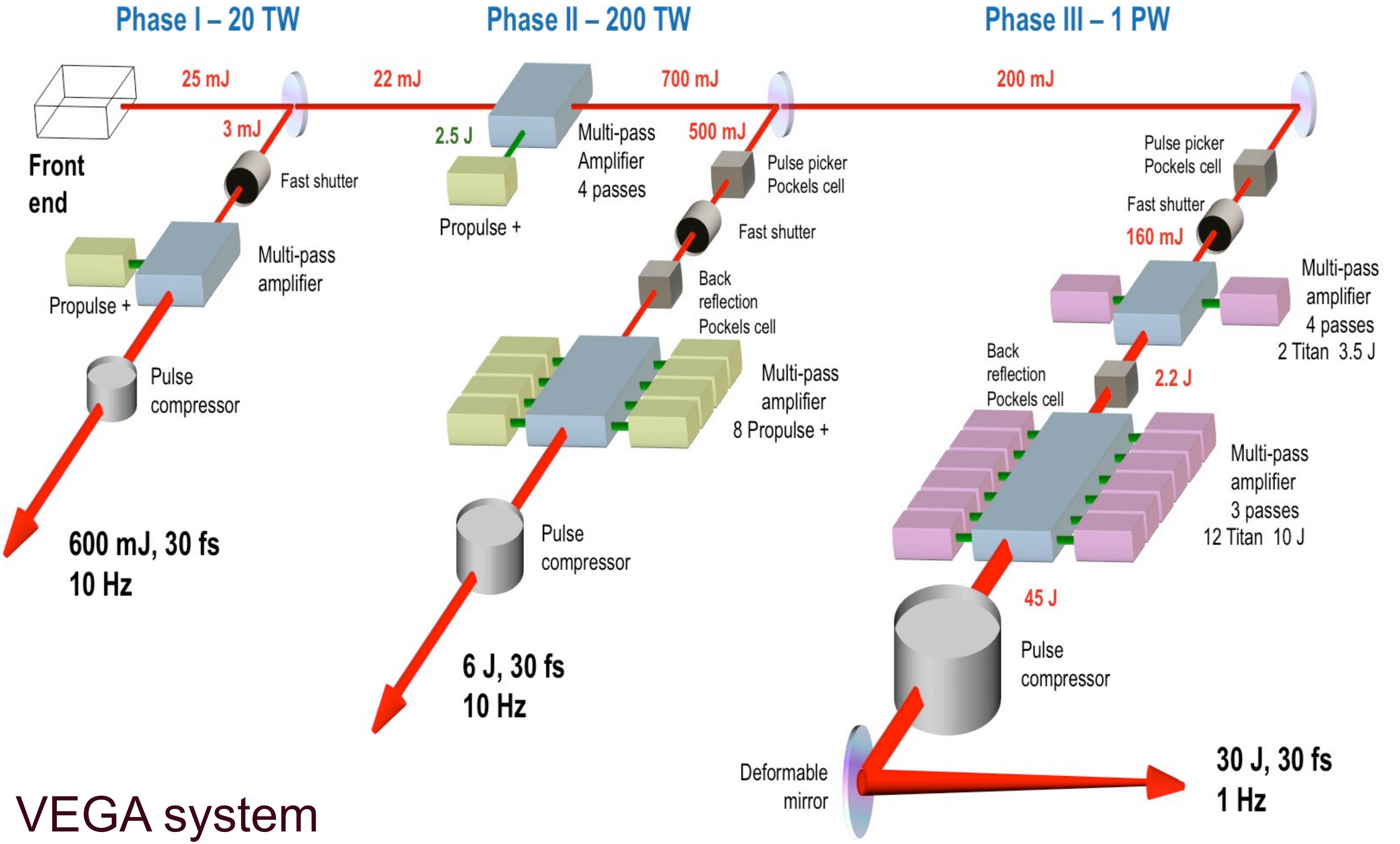
Energy concentration

light *denser* than matter

The Salamanca PW

30 J / 30 fs
800 nm
1 shot / sec




Phase I – 20 TW
Phase II – 200 TW
Phase III – 1 PW
25 mJ
22 mJ
700 mJ
200 mJ
3 mJ
2.5 J
500 mJ
Front end
Fast shutter
Multi-pass Amplifier 4 passes
Propulse +
Pulse picker Pockels cell
Pulse picker Pockels cell
Fast shutter
Fast shutter
160 mJ
Multi-pass amplifier
Propulse +
Back reflection Pockels cell
Multi-pass amplifier 4 passes 2 Titan 3.5 J
Multi-pass amplifier 8 Propulse +
Back reflection Pockels cell
2.2 J
Pulse compressor
Multi-pass amplifier 3 passes 12 Titan 10 J
600 mJ, 30 fs 10 Hz
Pulse compressor
45 J
Pulse compressor
6 J, 30 fs 10 Hz
Deformable mirror
30 J, 30 fs 1 Hz

VEGA system

Laser Fundamentals I arrives to the end ...

Thanks !

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