PHYS 250

Lecture 5.2

Applications 2: Lasers

Today

Absorption, Spontaneous Emission, Stimulated Emission

Stimulated Emission Chain Reaction, Population Inversion

MASER - Microwave Amplification by Stimulated Emission of Radiation

Optical Pumping and the first LASER

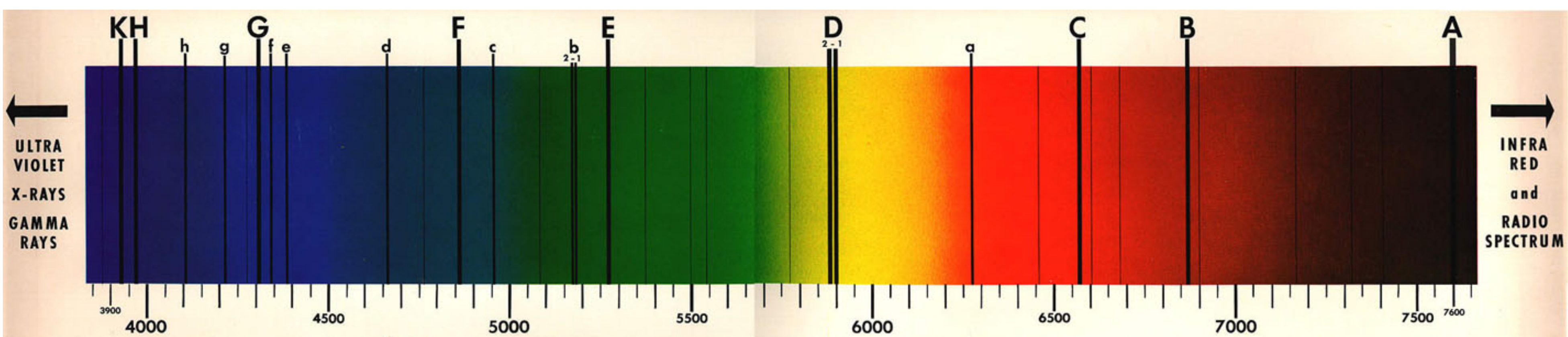
4-Level Pumping and Gas Discharge Lasers

Semiconductor Diode Lasers & Frequency Doubling

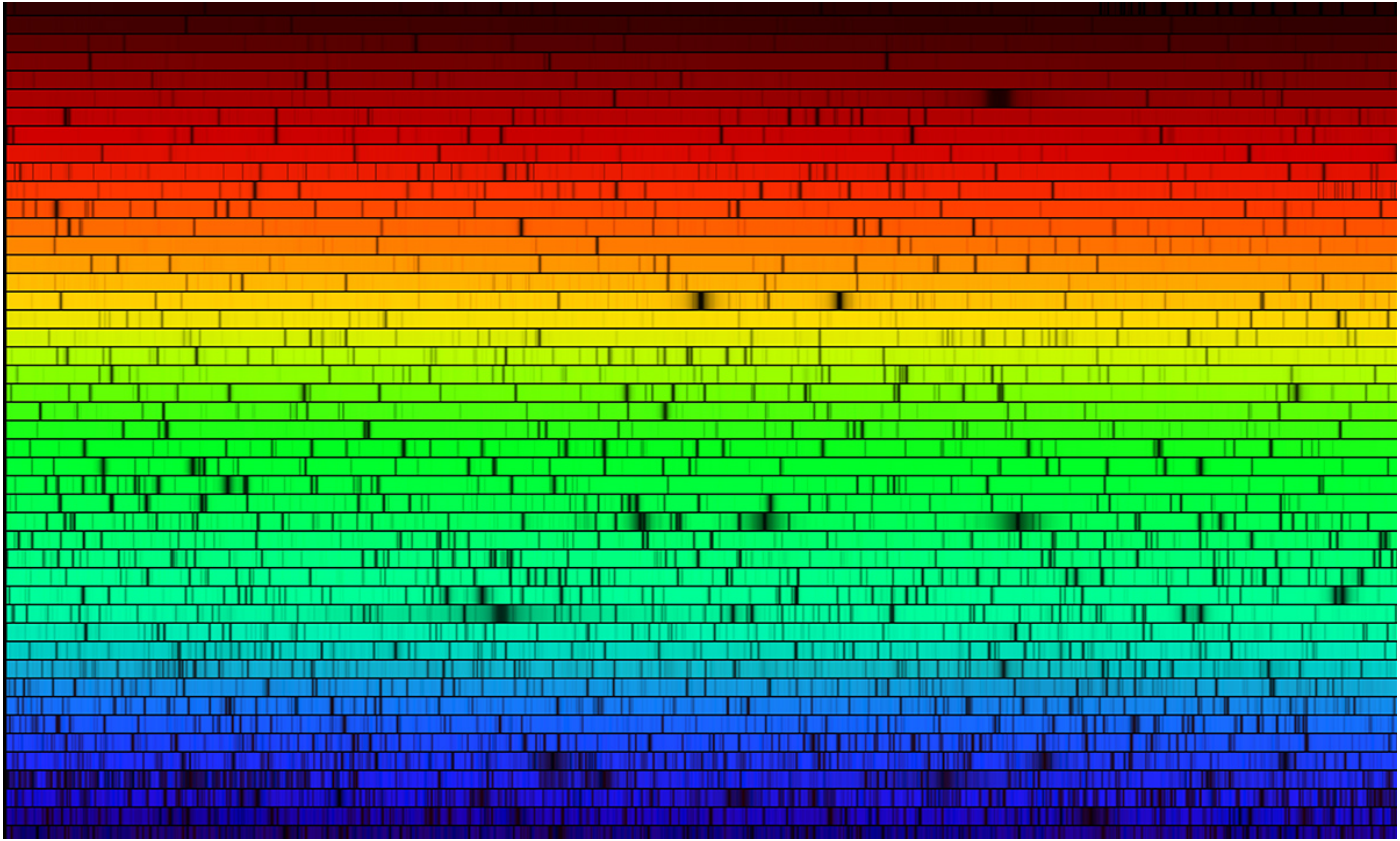
Absorption vs Emission

Normally the ground state is populated in a gas, and the higher states are empty. So there is only absorption, and no emission.

The Sun emits black-body radiation, but has a cooler atmosphere that absorbs photons (which are re-radiated in random directions). This results in dark lines in the black-body radiation spectrum.



Solar Absorption Lines



Absorption then Emission

High-energy photons illuminating a gas can eject electrons from atoms.
The atoms eventually absorb a free electron, resulting in emission of one of the spectral lines.

The Ring Nebula is an example.

Thermal UV photons from the hot blue star in the middle are absorbed by the gas cloud, which radiates visible spectral line photons of the elements in the gas cloud.

Photon Absorption Probability

We have been treating quantum bound states as perfectly stable.
We haven't talked about transitions between states.

The simplest case to think about is absorbing a photon of energy E_γ, causing an electron in a potential to go from a state with energy E_A to energy $E_B = E_A + E_\gamma$.

The initial state is $\Psi_I = \left[\psi_A\left(x_e\right)e^{-i\frac{E_A}{\hbar}t}\right]\cdot\left[\Gamma\left(x_\gamma\right)e^{-i\frac{E_\gamma}{\hbar}t}\right]$

This is $\psi_1\left(x_e\right)$, an electron in state A with energy E_A, times the "voltage wave" $\Gamma\left(x_\gamma\right)$ of a photon with energy E_γ .

The final state is $\Psi_F = \psi_B\left(x_e\right)e^{-i\frac{E_B}{\hbar}t}$.

This is an electron in state B, and no photon (because the atom absorbed it).

Photon Absorption Probability 2

The interaction amplitude T is the integral of the conjugate of the final state, times the electron charge q, times the initial state:

$$T = \int \Psi_F^* q \Psi_I \, dx \, dt$$

Expand that out:

$$T = \int \left(\psi_B e^{-i\frac{E_B}{\hbar}t} \right)^* \cdot q \cdot \left(\left[\psi_A e^{-i\frac{E_A}{\hbar}t} \right] \cdot \left[\Gamma e^{-i\frac{E_\gamma}{\hbar}t} \right] \right) dx \, dt$$

$$= \left\{ \int dt \, e^{-i\frac{E_A+E_\gamma-E_B}{\hbar}t} \right\} \cdot \left\{ \int dx \left[\psi_B^* \right] \cdot q \cdot \left[\psi_A \cdot \Gamma \right] \right\}$$

The complex conjugation flipped the sign of E_B.

If $E_A + E_\gamma = E_B$, the integrand in the first bracket equals 1, because the exponential argument is zero, and the integral grows with time.

Otherwise it just oscillates around zero.

Photon Absorption Probability 3

So the photon is absorbed only if energy of the the initial atom state,
plus the energy of the initial photon, equals the energy of the final atom state.

The EM field of the photon with frequency $E_\gamma / \hbar$ shakes the atom,
which has a resonant frequency $\left(E_B - E_A\right)/\hbar$, which is the photon frequency.

The space integral $\int \left[\psi_B^*\right] \cdot q \cdot \left[\psi_A \cdot \Gamma\right] dx$ depends on the wavefunctions.

So some transitions that are allowed could be faster or slower than others,
and some may not happen at all (the integral is zero).

Photon Emission Probability

For <u>emission</u> of a photon from state B, the initial state is $\Psi_I = \psi_B e^{-i\frac{E_B}{\hbar}t}$

and the final state is the atom in state A, plus a photon $\Psi_F = \left[\psi_A e^{-i\frac{E_A}{\hbar}t}\right]\cdot\left[\Gamma e^{-i\frac{E_\gamma}{\hbar}t}\right]$

The integral is

$$T = \int \Psi_F^* \cdot q \cdot \Psi_I \, dx\, dt$$

$$= \int \left(\left[\psi_A e^{-i\frac{E_A}{\hbar}t}\right]\cdot\left[\Gamma e^{-i\frac{E_\gamma}{\hbar}t}\right]\right)^* \cdot q \cdot \left(\psi_B e^{-i\frac{E_B}{\hbar}t}\right) dx\, dt$$

$$= \left\{\int dt\, e^{-i\frac{E_B - E_A - E_\gamma}{\hbar}t}\right\}\cdot\left\{\int dx \left[\psi_A^* \cdot \Gamma^*\right]\cdot q \cdot \left[\psi_B\right]\right\}$$

It still requires $E_B = E_A + E_\gamma$ or it's zero.

The space integral is similar, but not identical, to before.

Photon Emission Probability 2

This case is harder to visualize intuitively, because there is no initial EM field that can shake the atom at a resonant frequency.

The modern picture is that the EM field is itself quantized, and has zero point energy at all possible frequencies.

It's like the non-zero minimum energy of a particle in a square well, or harmonic-oscillator potential.

That zero-point energy can shake the atom at its resonant frequency and cause the photon to be emitted.

Stimulated Emission

An easier case to visualize is if an atom is in state B,
and a photon comes along with energy E_γ.

That would shake the atom at its resonant frequency $\left(E_B - E_A\right)/\hbar$,
which could cause it to emit a photon energy E_γ and go to state A.

But the initial photon with E_γ would still exist.

This is known as stimulated emission.

The energy conservation statement is $E_B + E_\gamma = E_A + E_\gamma + E_\gamma$
because the initial state has one photon and the final state has two photons.

Stimulated Emission 2

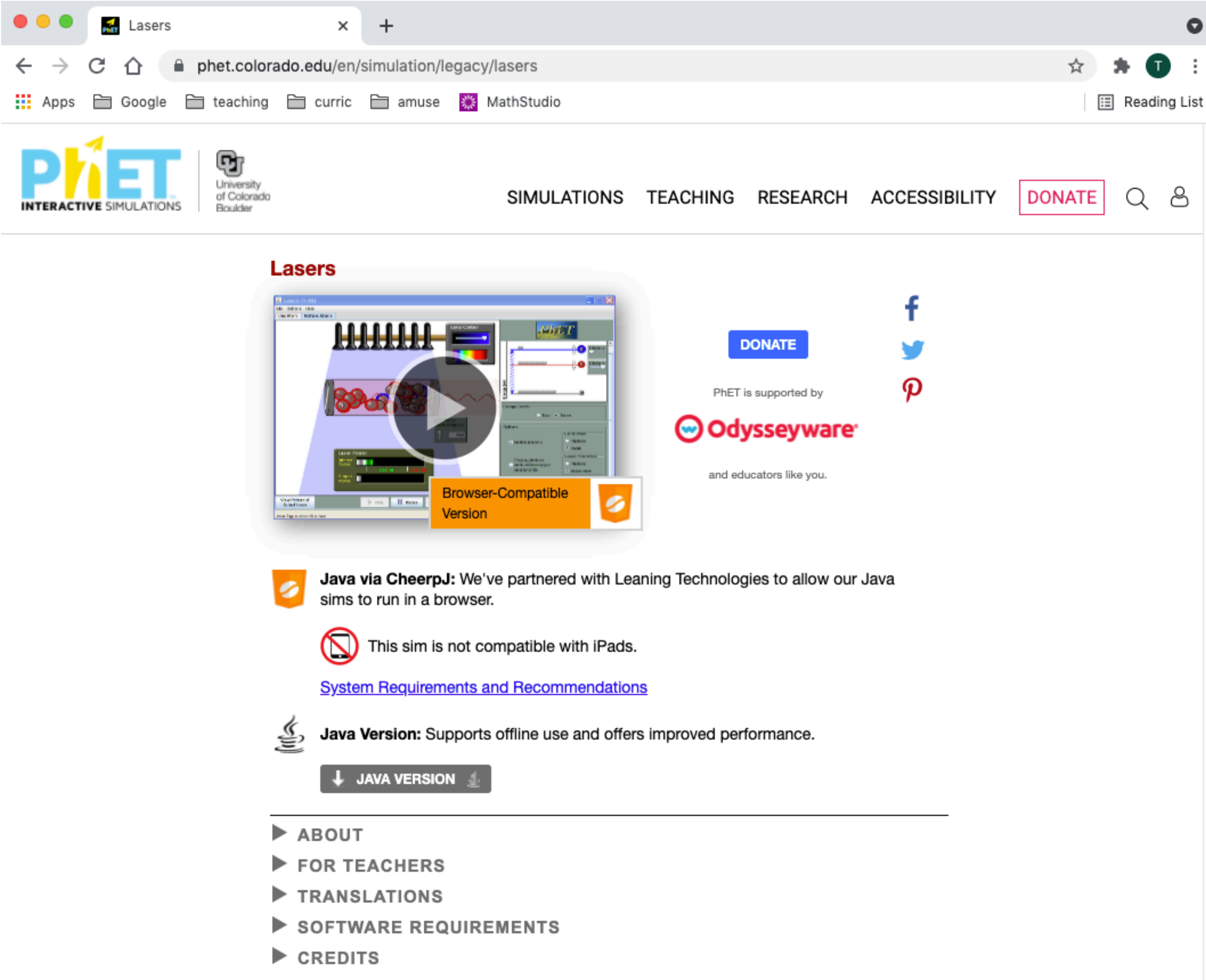
From very general arguments, before the Schrodinger Equation, Einstein deduced that stimulated emission had to exist in order for thermal equilibrium of blackbody radiation to work.

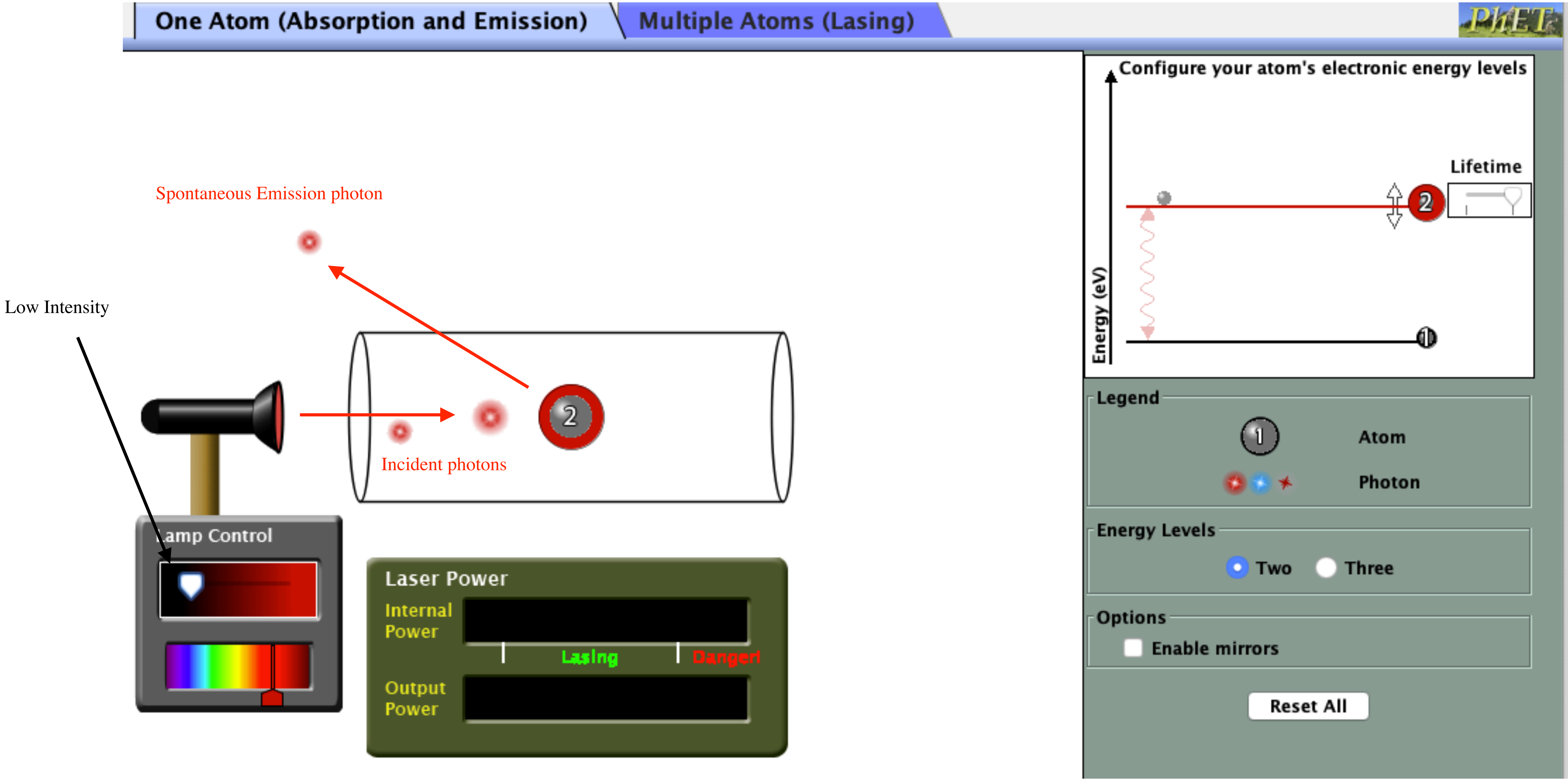
He also showed that the rate for stimulated emission had to be exactly the same as for photon absorption.

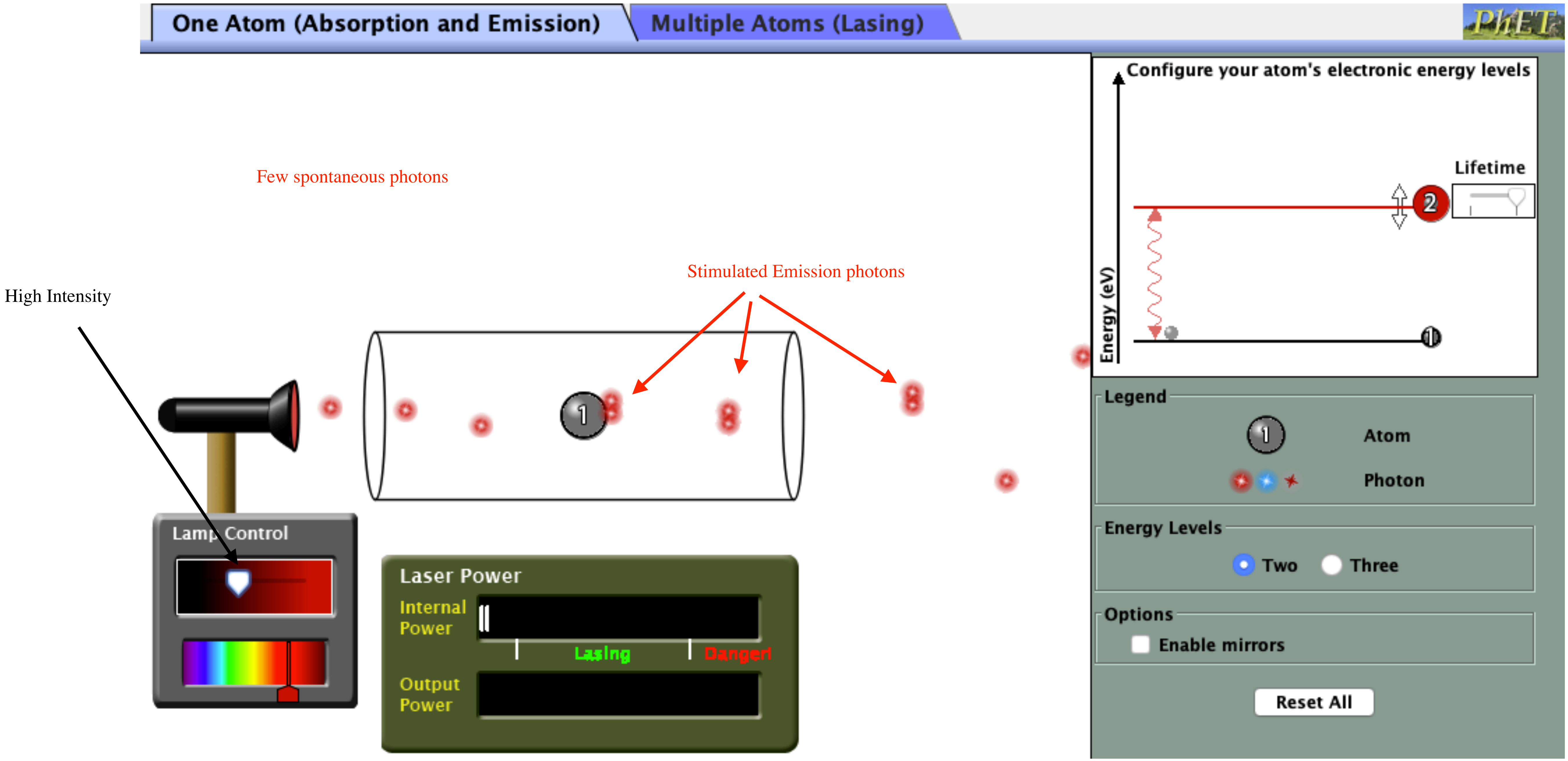
And he deduced the "spontaneous emission" rate from the absorption rate without being able to calculate it from first principles.

Something that is not obvious from these word-pictures is that the extra photon in stimulated emission is not random, but is emitted in exactly the same direction as the initial photon. with exactly the same phase as the original photon.

It's best to think of the process not as emitting an extra photon, but as increasing the intensity of the original photon field, from $n = 1$ to $n = 2$.


Lasers
phet.colorado.edu/en/simulation/legacy/lasers
Apps
Google
teaching
curric
amuse
MathStudio
Reading List
PhET INTERACTIVE SIMULATIONS
University of Colorado Boulder
SIMULATIONS
TEACHING
RESEARCH
ACCESSIBILITY
DONATE
Lasers
Browser-Compatible Version
DONATE
PhET is supported by
Odysseyware
and educators like you.
Java via CheerpJ: We've partnered with Leaning Technologies to allow our Java sims to run in a browser.
This sim is not compatible with iPads.
System Requirements and Recommendations
Java Version: Supports offline use and offers improved performance.
JAVA VERSION
ABOUT
FOR TEACHERS
TRANSLATIONS
SOFTWARE REQUIREMENTS
CREDITS


One Atom (Absorption and Emission)
Multiple Atoms (Lasing)
PhET
Spontaneous Emission photon
Low Intensity
Incident photons
2
Lamp Control
Laser Power
Internal Power
Lasing
Danger!
Output Power
Configure your atom's electronic energy levels
Lifetime
Energy (eV)
Legend
Atom
Photon
Energy Levels
Two
Three
Options
Enable mirrors
Reset All


One Atom (Absorption and Emission)
Multiple Atoms (Lasing)
PhET
Few spontaneous photons
Stimulated Emission photons
High Intensity
Lamp Control
Laser Power
Internal Power
Lasing
Danger!
Output Power
Configure your atom's electronic energy levels
Lifetime
Energy (eV)
Legend
Atom
Photon
Energy Levels
Two
Three
Options
Enable mirrors
Reset All

Stimulated Emission Chain Reaction

If there are atoms in excited states, a photon can cause stimulated emission.

One photon could cause an atom to emit a second photon,
which could generate more photons, which could make more….

But Einstein showed that the absorption integral
is exactly the same as the stimulated emission integral.

So ground-state atoms are just as likely to absorb the emitted photons
as excited-state atoms can be stimulated to emit them.

Since there are normally more ground-state atoms than excited atoms,
the absorption would be larger than the stimulated emission,
and the chain reaction would die out.

Population Inversion

To make the chain reaction work, we need what is called a population inversion: more atoms in the excited state than in the ground state.

This can't be done just by heating up the gas, because statistical mechanics says that the population of excited states is proportional to $e^{-\frac{\Delta E}{kT}}$, so they are always less populated than the ground state.

But there are some non-thermal tricks that let it be done.

MASER

Microwave Amplification by Stimulated Emission of Radiation.

Townes, Gorden & Ziegler made the first MASER in 1953.

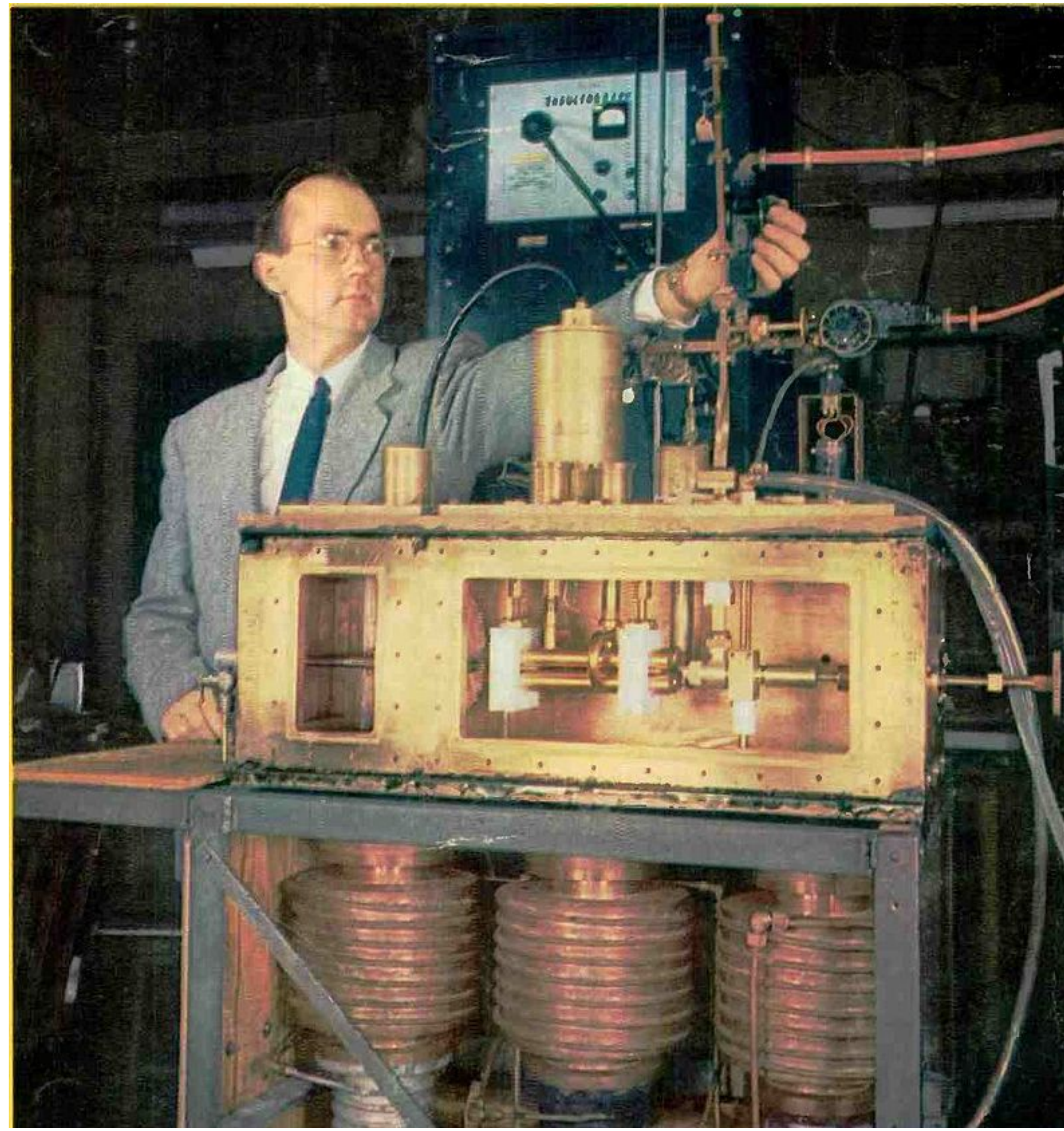
They used a vibration mode of NH_3 (ammonia) in the microwave region.

The energy of this relatively low-frequency mode is low, so room temperature NH_3 has a significant fraction of the molecules in this excited state.

It's possible to make a set of electrodes that block molecules in the ground state, but pass molecules in the excited state. (It's not easy to explain how this works).

MASER 2

A beam of NH_3 molecules from a pinhole went into vacuum, through the excitation filter, and into a microwave resonator.



Low-power microwaves went into the resonator, caused stimulated emission from the excited atoms, and microwaves came out with higher power.

Unfortunately, these tricks don’t work for visible light.

Optical Pumping

Can we make a stimulated-emission chain reaction for light photons?

We already know that exciting the gas thermally won't work.

Maybe we could shine light on the gas to excite atoms to the higher state in a non-thermal way, like in a nebula. This is called <u>optical pumping</u>.

The simplest approach to this doesn't work either.

We need to excite more than half of the ground state atoms to the excited state, to make sure that absorption is less than stimulated emission.

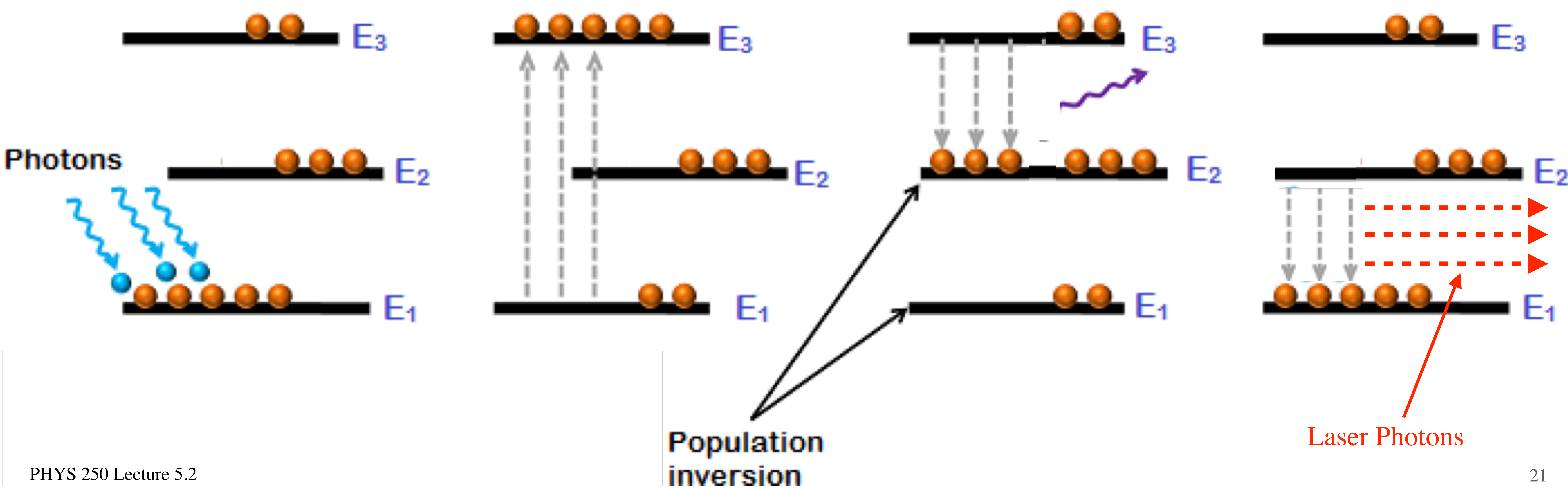
But the pumping light itself causes stimulated emission back to the ground state. All that a very strong light can do is make atoms go back and forth between the ground state and the excited state very rapidly, so there are equal numbers.

Optical pumping can't create a population inversion between two states.

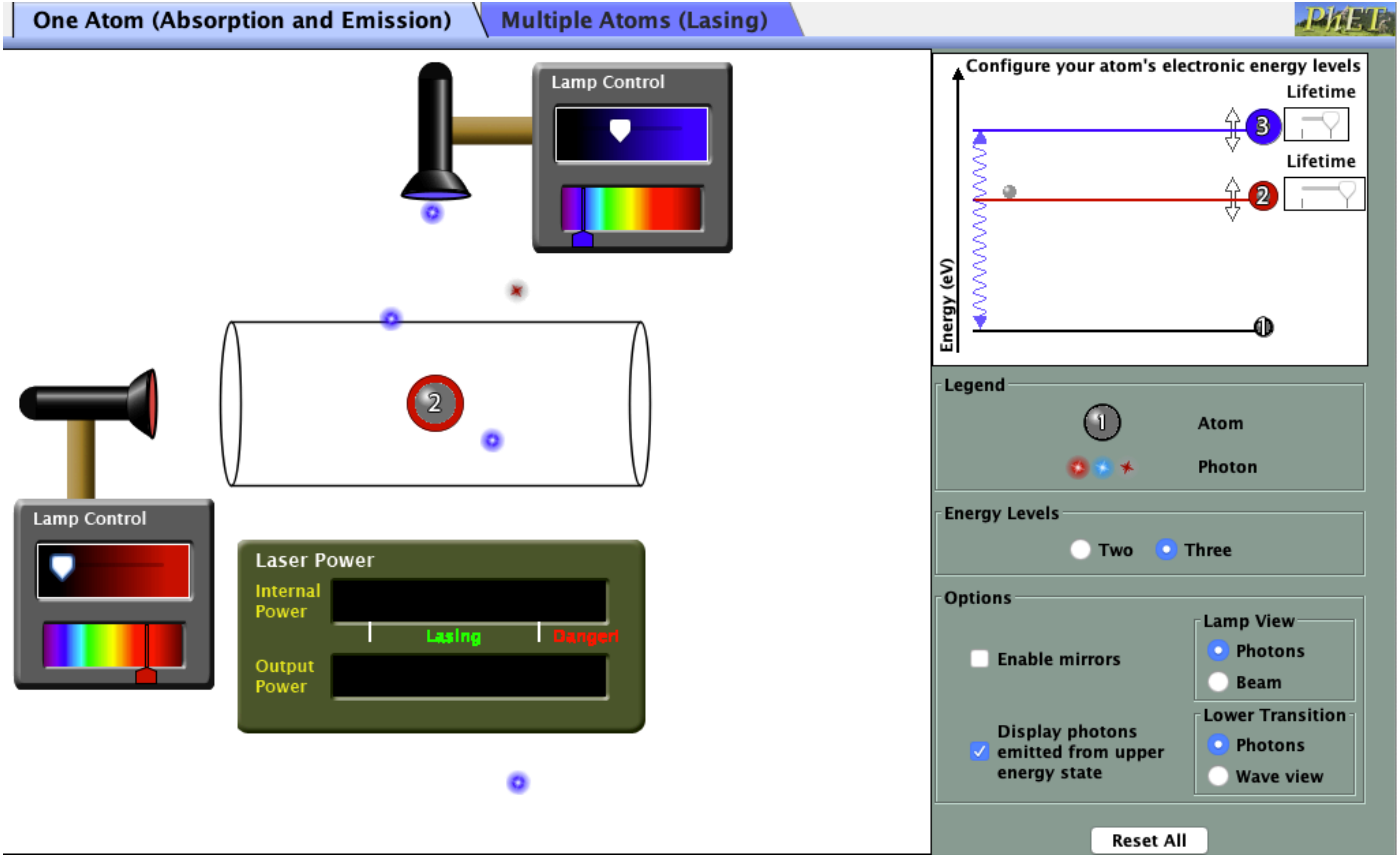
3-Level Optical Pumping

But it works if there is another state between the upper state and the ground state.

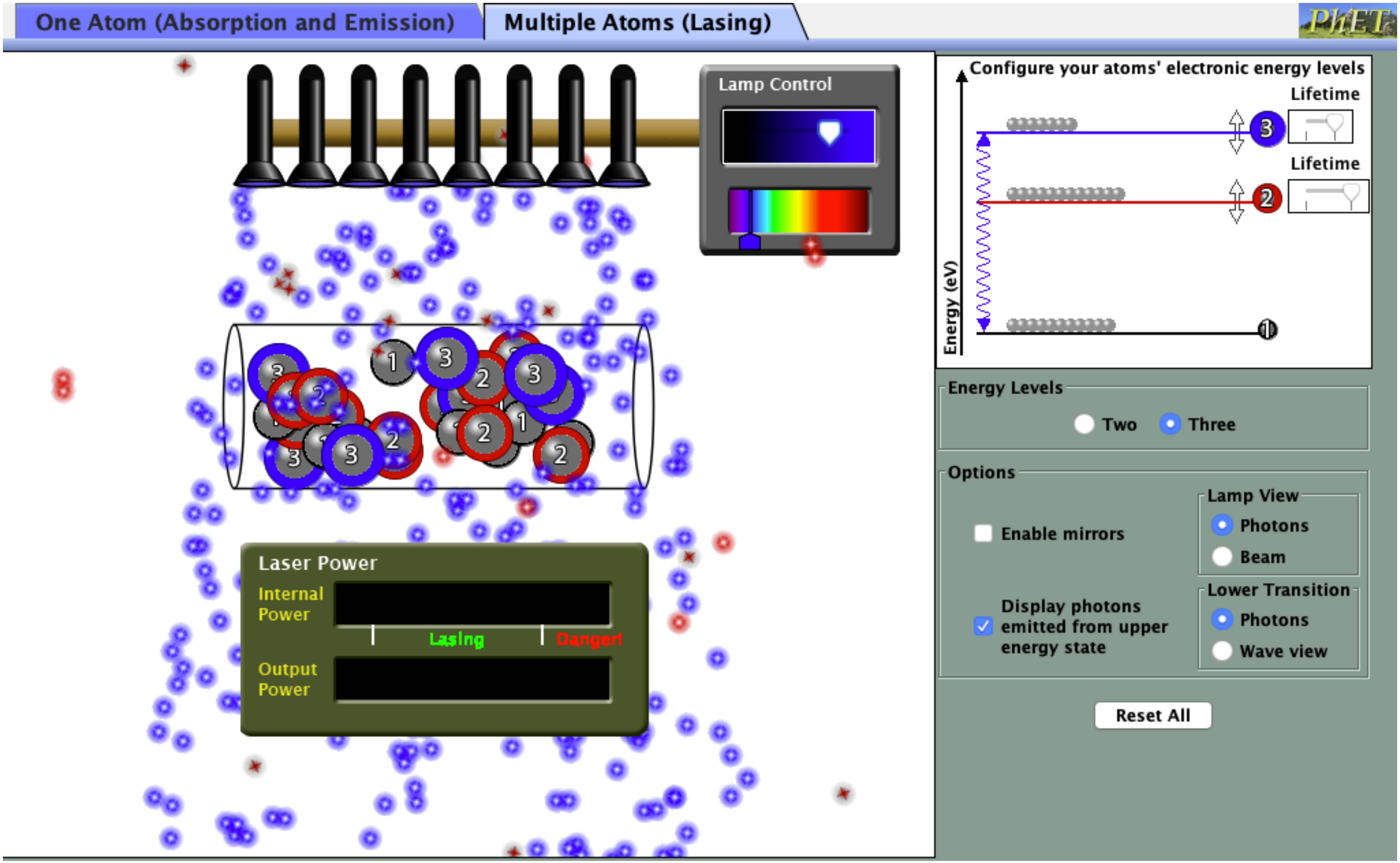
Start with high population in state E_1, and lower populations in states E_2 and E_3.
Populate state E_3 by optical pumping from E_1 .
Fast spontaneous emission from state E_3 populates state E_2.
If spontaneous emission from E_2 is slow, we have more atoms in E_2 than in E_1 .
So we have population inversion between E_2 and E_1.
Then we can get a stimulated chain reaction: a laser !



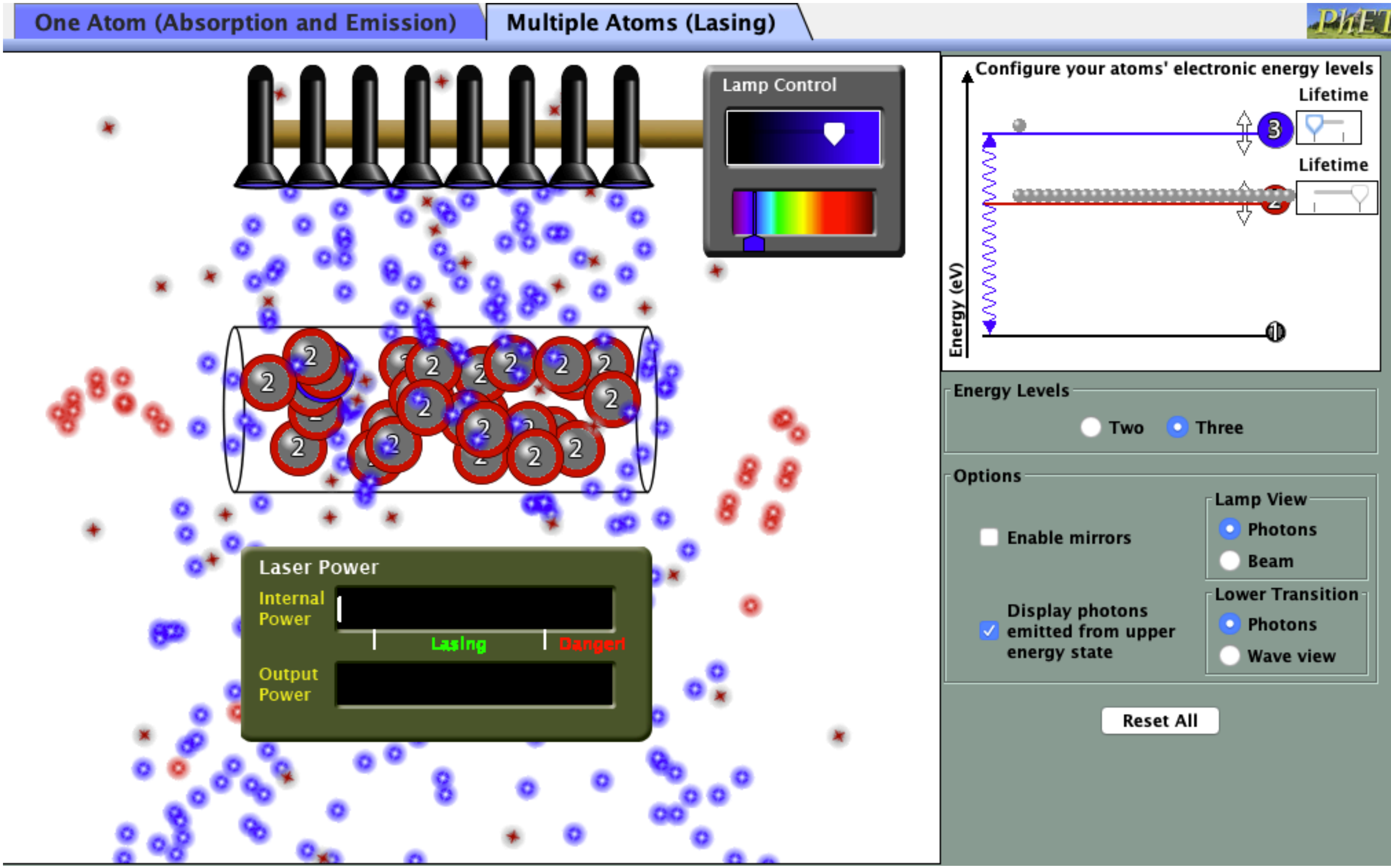
Single Atom, Side-Lighted



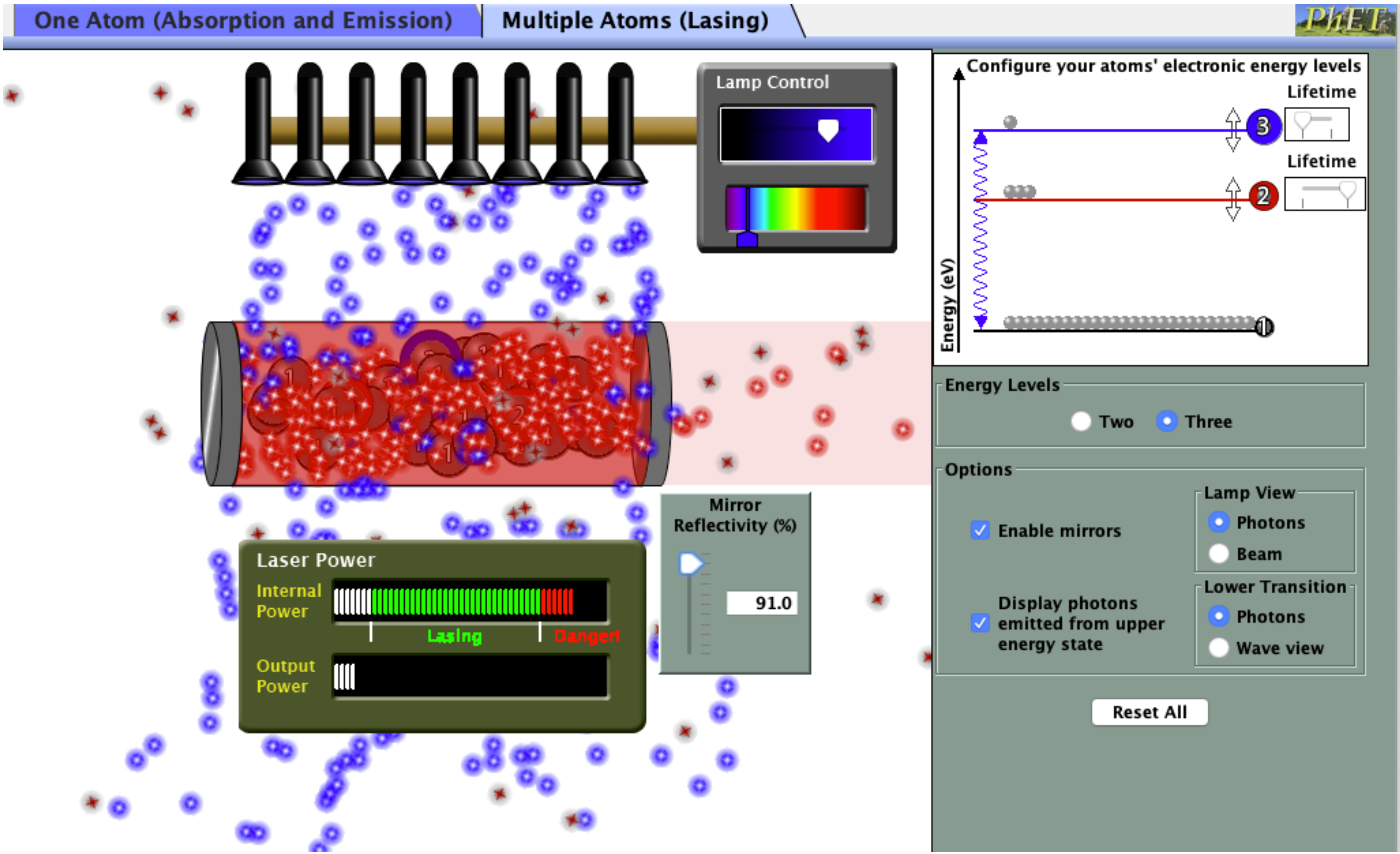
Many Atoms, Long E_3 Lifetime



Many Atoms, Short E_3 Lifetime



Add Mirrors



One Atom (Absorption and Emission)
Multiple Atoms (Lasing)
PhET
Lamp Control
Configure your atoms' electronic energy levels
Lifetime
Lifetime
Energy (eV)
Energy Levels
Two
Three
Options
Enable mirrors
Lamp View
Photons
Beam
Display photons emitted from upper energy state
Lower Transition
Photons
Wave view
Reset All
Mirror Reflectivity (%)
91.0
Laser Power
Internal Power
Lasing
Danger!
Output Power

The First Laser

Ruby is clear aluminum oxide made red by a small amount of chromium ions.

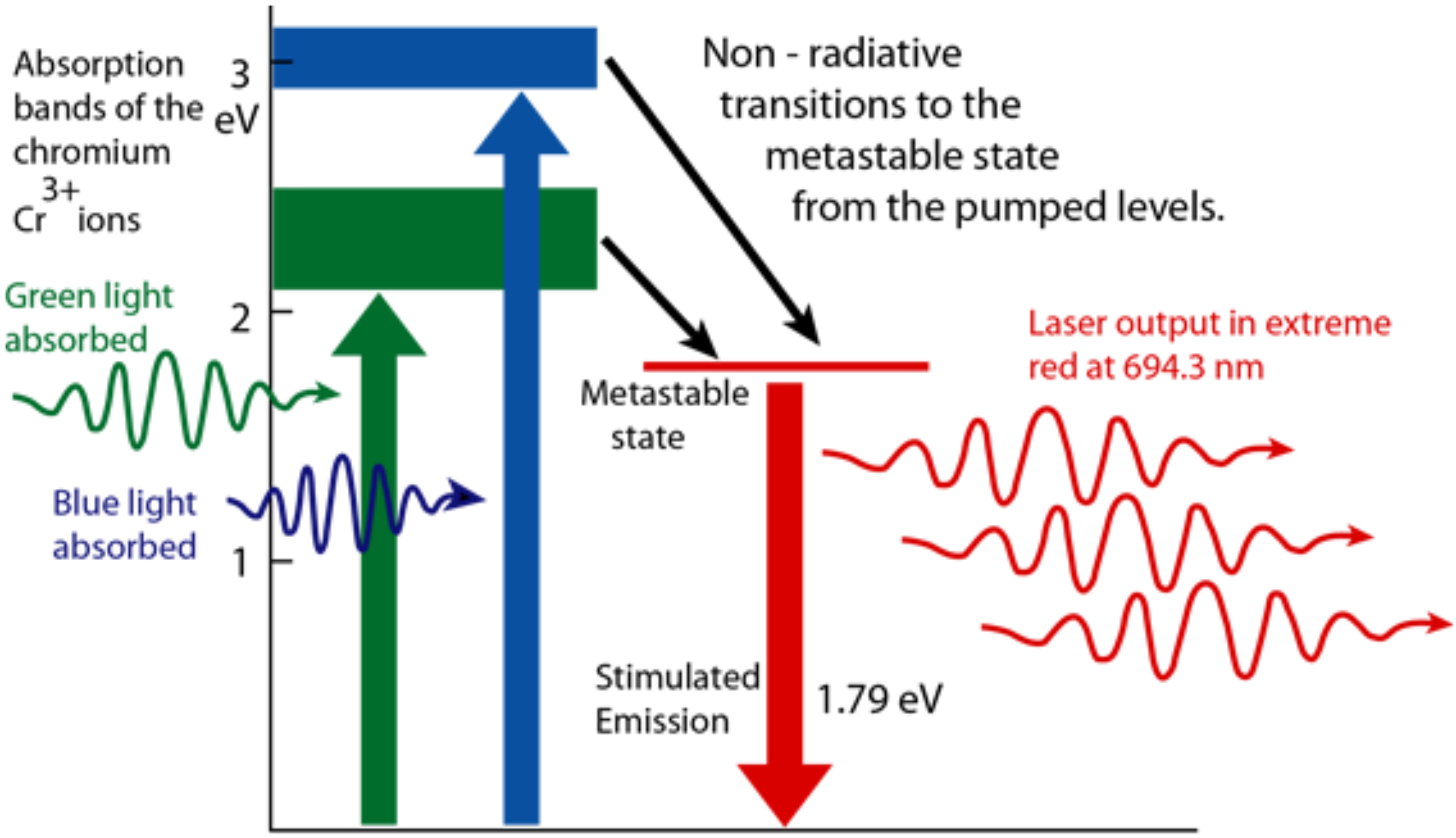
The chromium ions can absorb blue and green light,
then decay quickly by vibrational interactions with the aluminum oxide lattice
to a lower energy state, which has a longer lifetime and emits red photons.

So a powerful flash of white light can create a population inversion,
where there are more chromium ions in the excited state than the ground state.

Then we can get the stimulated-emission chain-reaction.

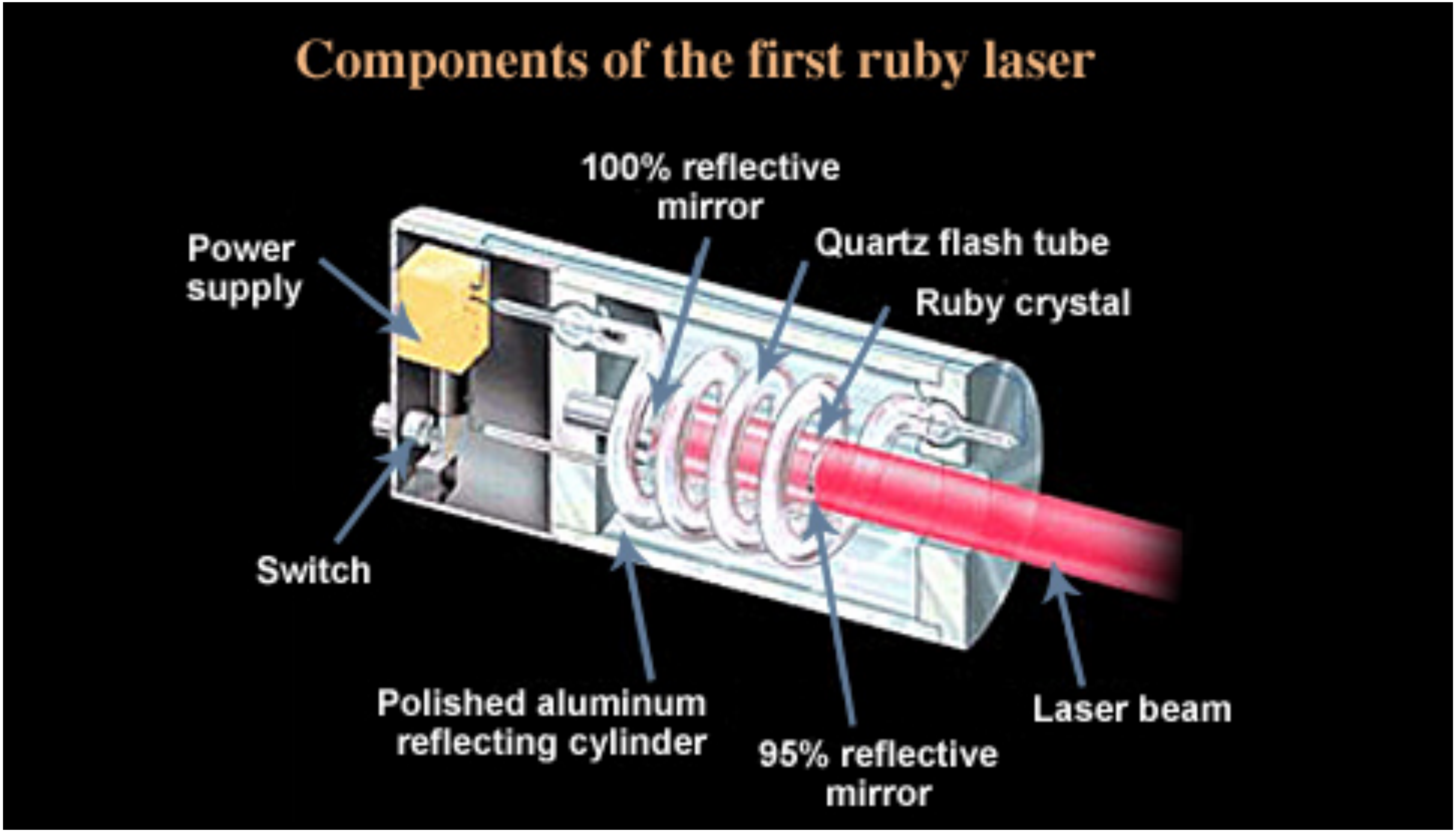
Theodore Maiman at (Howard) Hughes Research Lab
made the first ruby laser in 1960.

Ruby Laser



Absorption bands of the chromium Cr^{3+} ions
3
eV
2
1
Green light absorbed
Blue light absorbed
Non - radiative transitions to the metastable state from the pumped levels.
Metastable state
Laser output in extreme red at 694.3 nm
Stimulated Emission
1.79 eV

Ruby Laser


Components of the first ruby laser
100% reflective mirror
Power supply
Quartz flash tube
Ruby crystal
Switch
Polished aluminum reflecting cylinder
95% reflective mirror
Laser beam

Another Early Laser

4-Level Optical Pumping

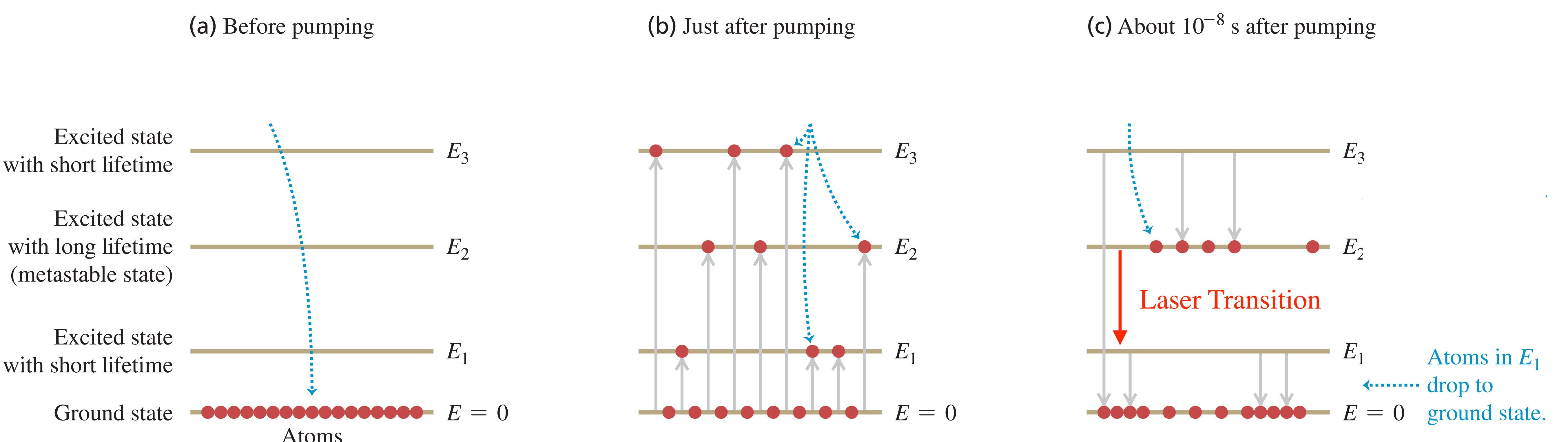
If there is another state with a very short lifetime between the long-lived state and the ground state, optical pumping works even better.

Atoms get pumped from ground to E_3, fall to E_2 where the population builds up.

The laser transition is between E_2 and E_1.

Then atoms decay from E_1 to the E_0 ground state because the E_1 life is short.

So it's easy to maintain a population inversion between E_2 and E_1.



Nd-YAG Laser

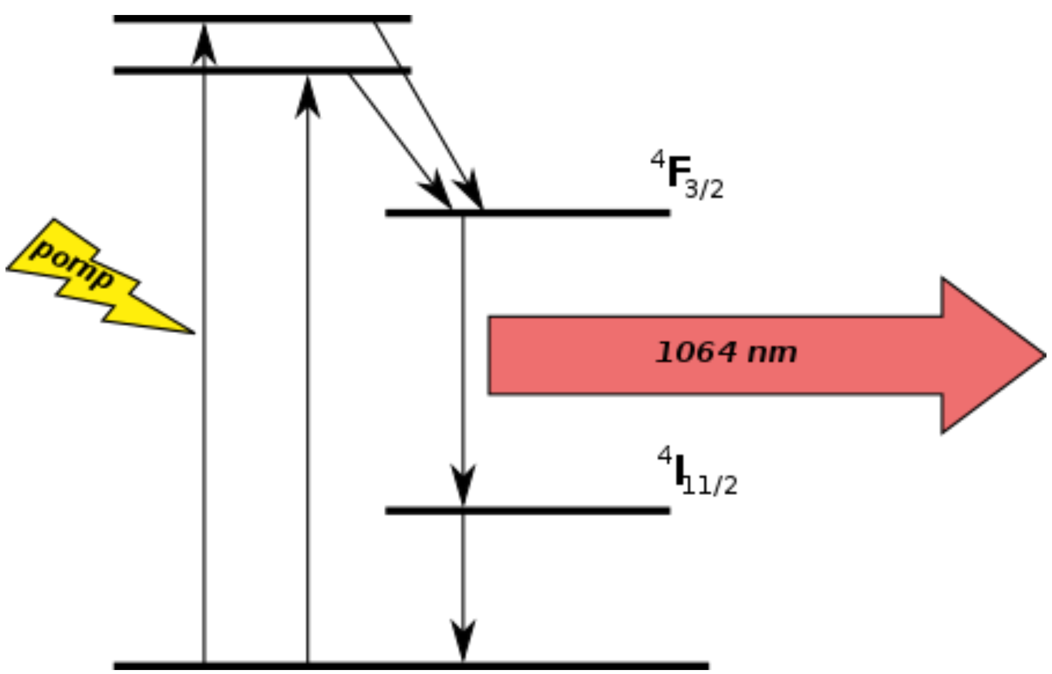
Neodymium ions in Yttrium-Aluminum-Garnet (analogous to chromium in ruby).

Optically pumped, produces 1064 nm (IR) light.

Easier to pump and more efficient than ruby.

A common near-IR high-power laser.

Often used for laser skin treatment (tattoo removal).



Gas Discharge Laser

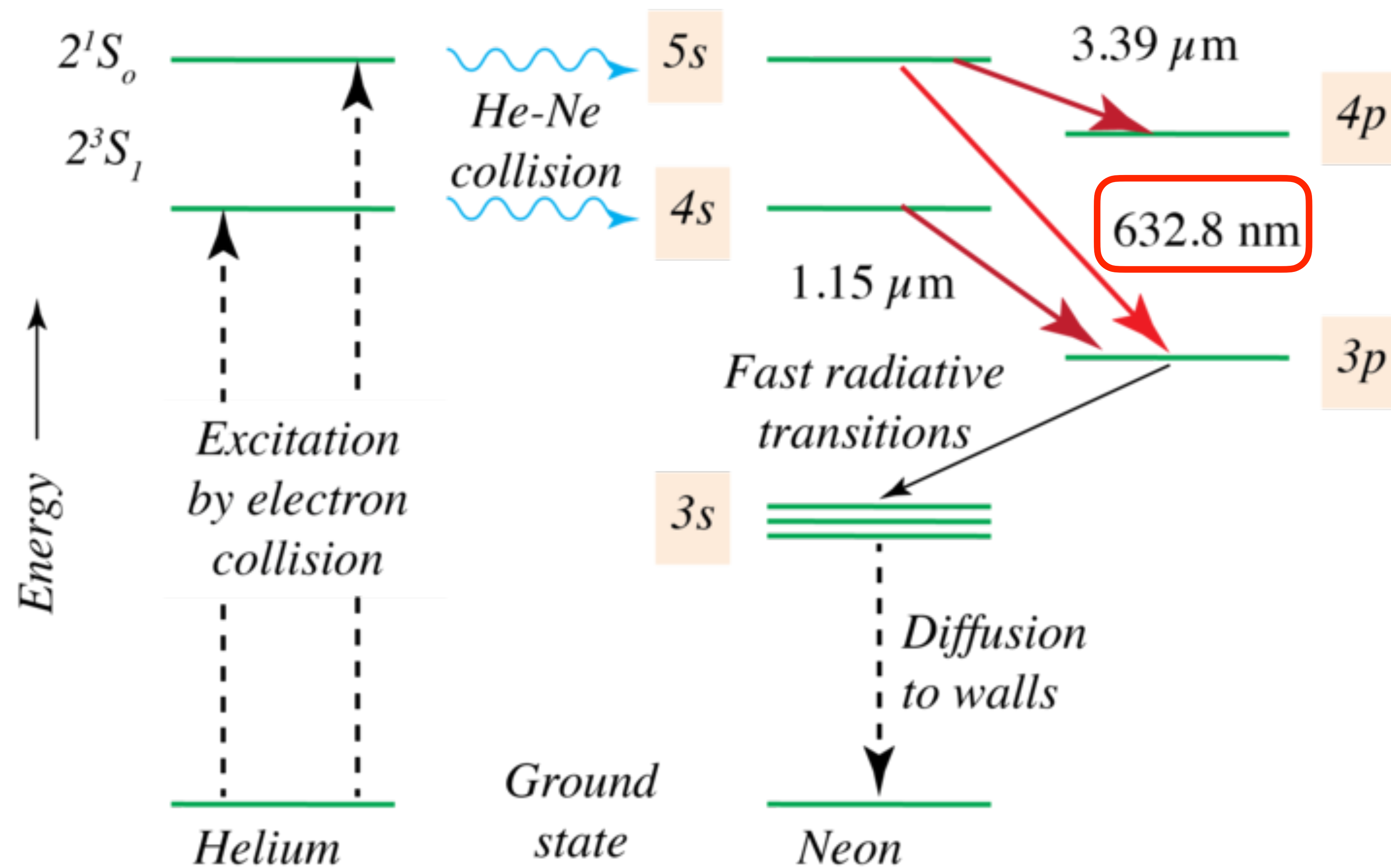
You can also excite gas atoms with an electrical discharge.

Often atoms of one gas are excited, and transfer their excitation to atoms of another gas, which does the actual lasing.

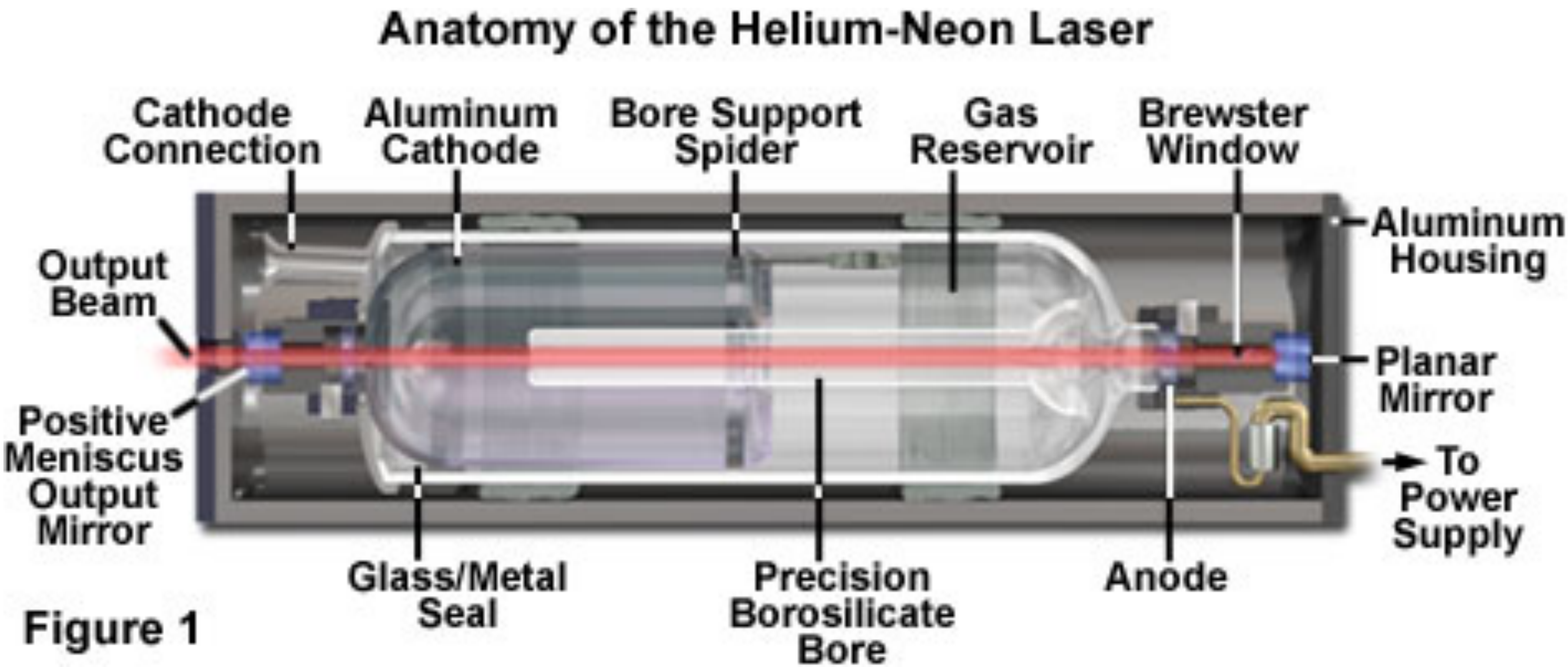
He-Ne lasers excite He,

which transfers to Ne,

which has the desired long and short lived states



Helium-Neon Laser



CO_2 Laser

Discharge excites N_2,

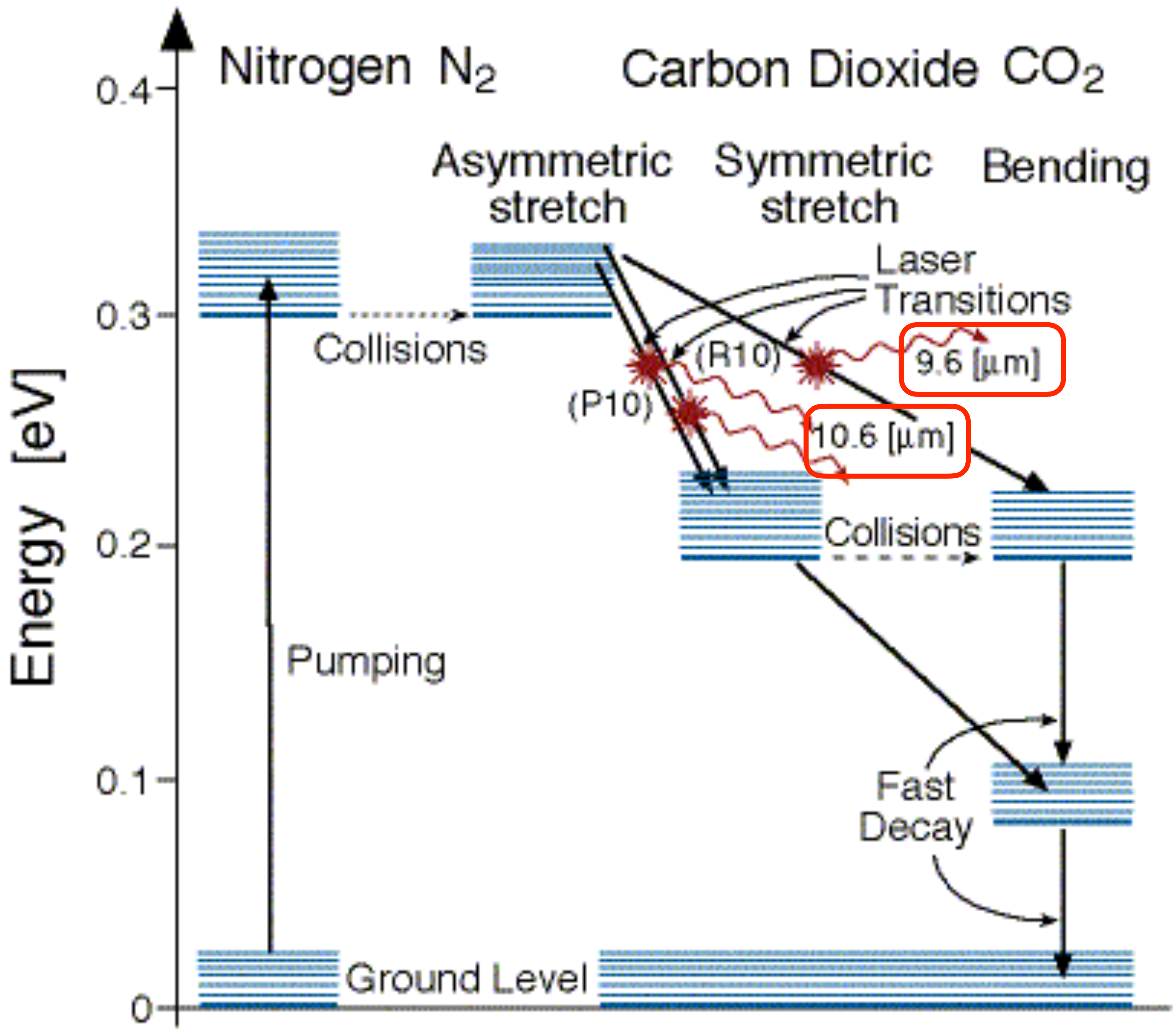
transfers to CO_2,

molecular vibrations make ~ 10μ photons.

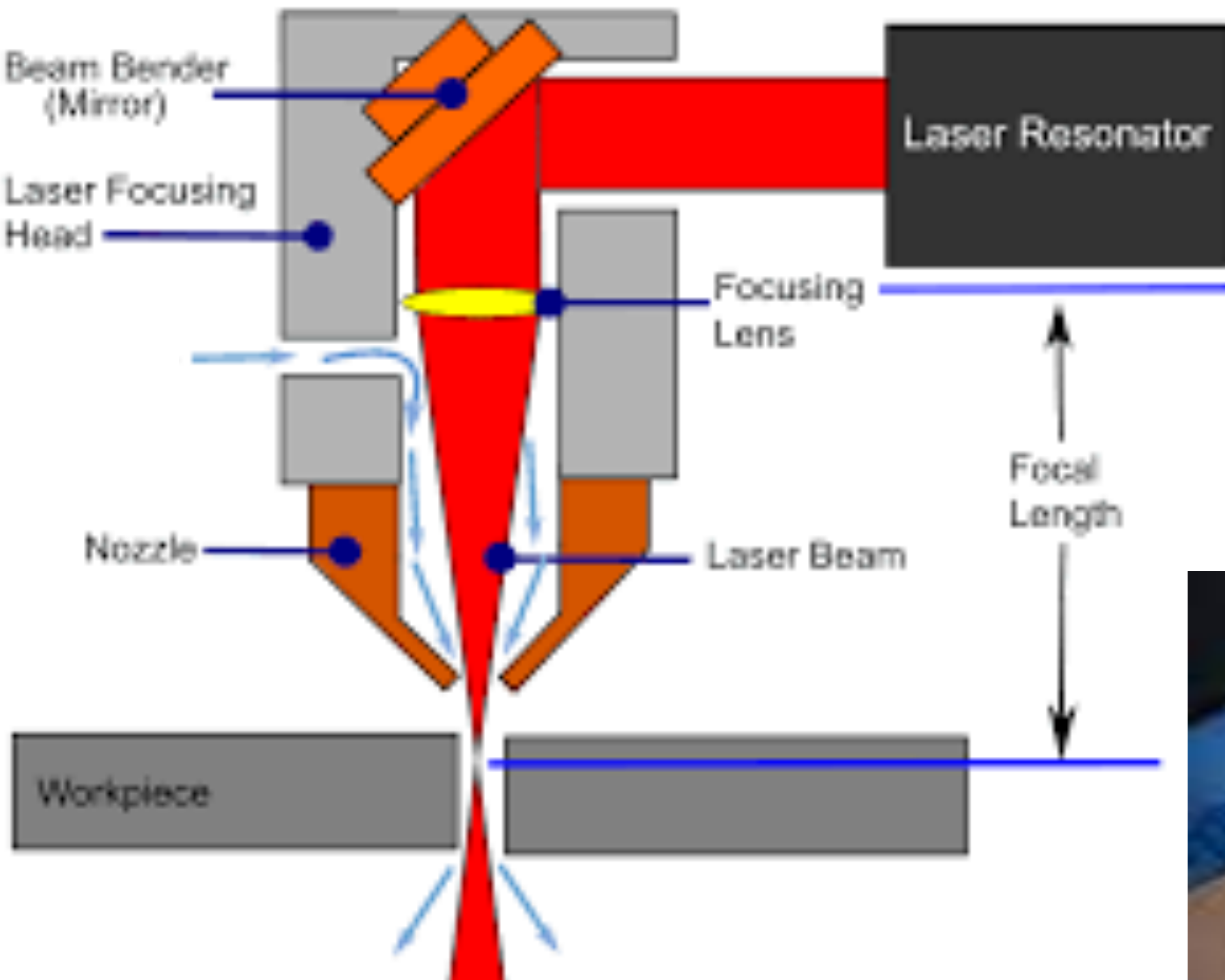
Lower laser state decays quickly.

Often also He in the tube for cooling.

A common high-power laser, in far-infrared.



Laser Cutter



Excimer Laser

A noble gas (Argon, Krypton, or Xenon) can form unstable compounds with itself or a halogen (Fluorine, Chlorine) in an electrical discharge.

The photon emitted when the compound decays can be in the ultraviolet.

This can be used to make an ultraviolet laser.

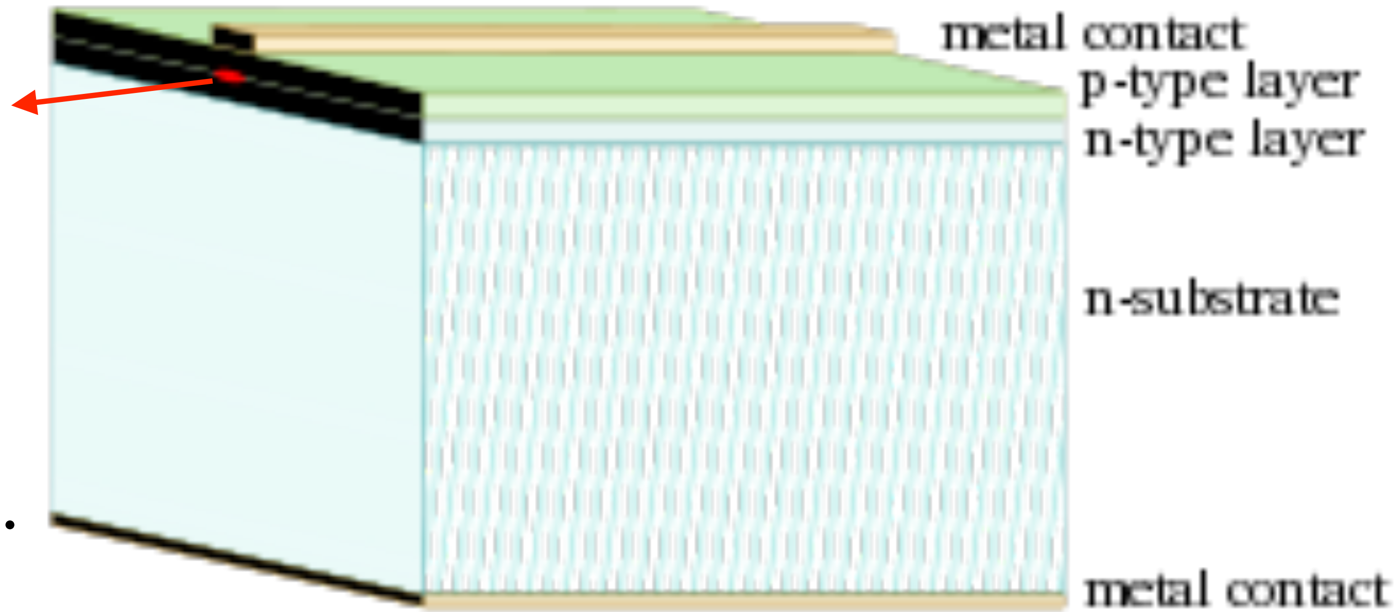
Ultraviolet light is strongly absorbed by tissue, so only the surface is affected.

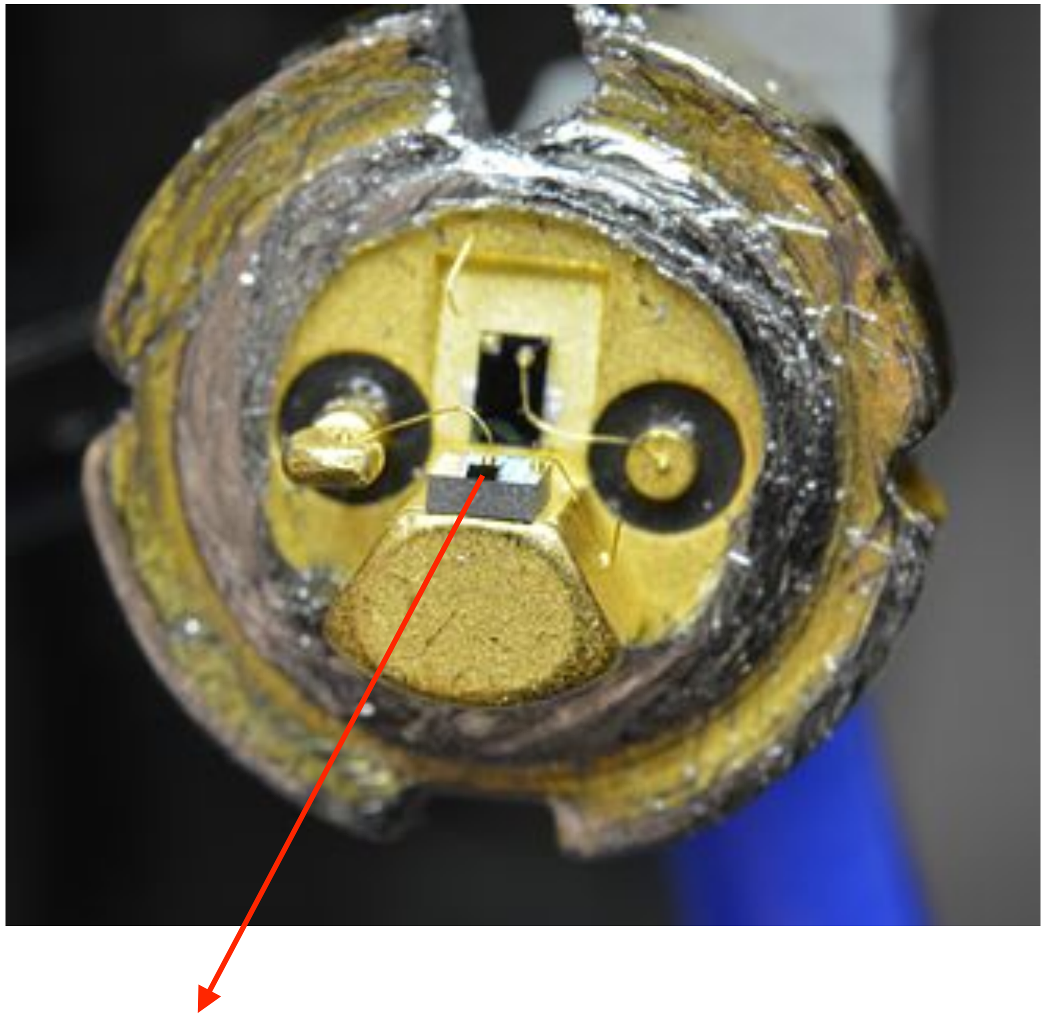
LASIK eye surgery uses excimer lasers.

Semiconductor Laser

PIN junction diode, with recombination of electrons and holes, making photons.

Manipulate the index of refraction to make a waveguide channel, and cleave crystal ends to make mirrors.





Frequency Doubling

Some crystals are “non-linear,” meaning there is significant dependence of their index of refraction on the intensity of light.

Quantum-mechanically, that means that they can absorb 2 photons, and emit one photon of twice the energy, or half the wavelength.

Lithium Triborate is often used to double the frequency of Nd-YAG laser light from infrared 1064 nm (infrared) to 532 nm (green).

My green laser pointer uses a semiconductor diode laser (808 nm infrared)
to optically pump a Nd-YAG laser (1064 nm infrared)
which is frequency-doubled to 532 nm (green).

Red semiconductor laser light is at the edge of the sensitivity of your eye.
Green light of the same power looks much brighter.

Beware that green laser pointers often have MUCH higher power in residual IR!

For Next Time

Homework 5 will be posted Thursday night, due Monday midnight.

Tutorial worksheet 5 on Friday as usual.

Next week will be Schrodinger in 3 dimensions.