

**Lecture 1 : Introduction to the
course,
lasers fundamentals**

**Attosecond
Radiation
Sources -
PHSY761**

Lecture 01

11 September

2025

Lectures typically on Tuesdays CH B2 355

- Fabrizio Carbone
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- Guest: Matteo Savoini (TBC)



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ETH zürich

Lectures typically on Thursdays [CH H1 604](#)

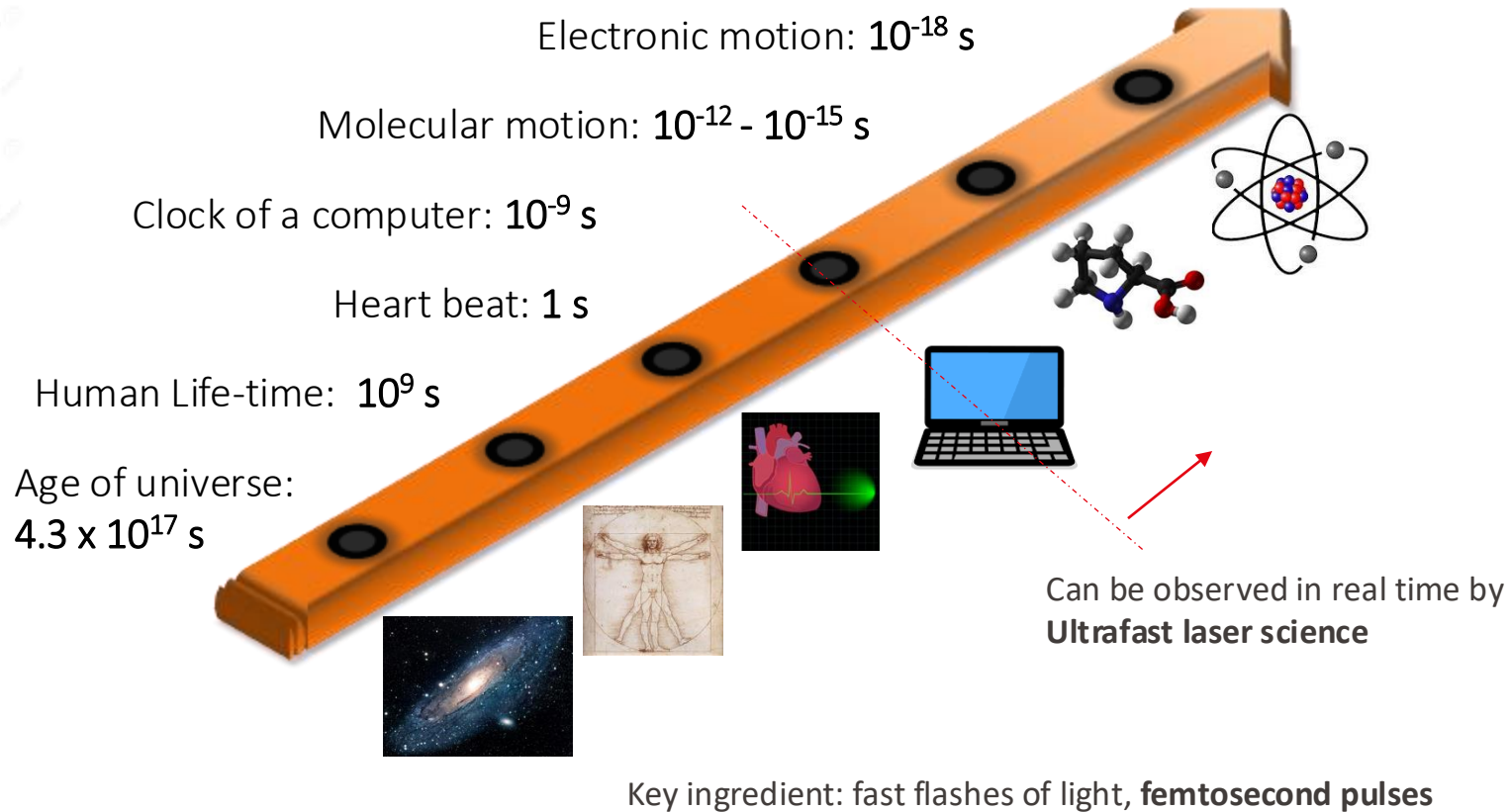


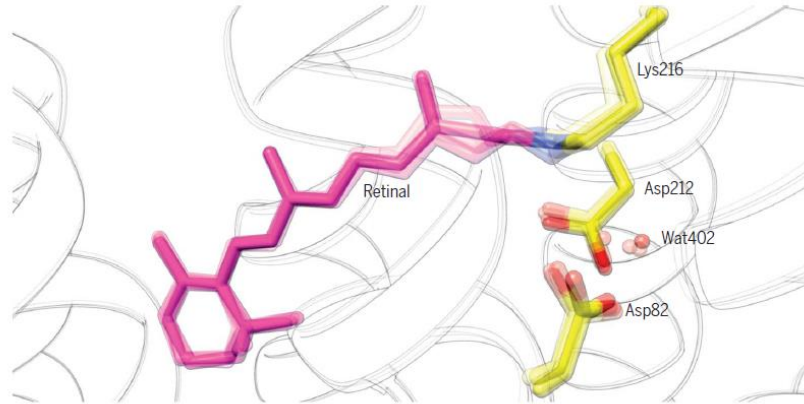
Antoine Andrieux

- Hands-on sessions with lasers
- Numerical demos (Python) / exercises

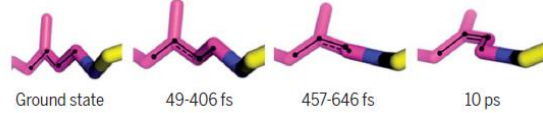
No “homeworks” , attendance is strongly encouraged.

Time scales in nature





All-trans retinal -----> 13-cis retinal



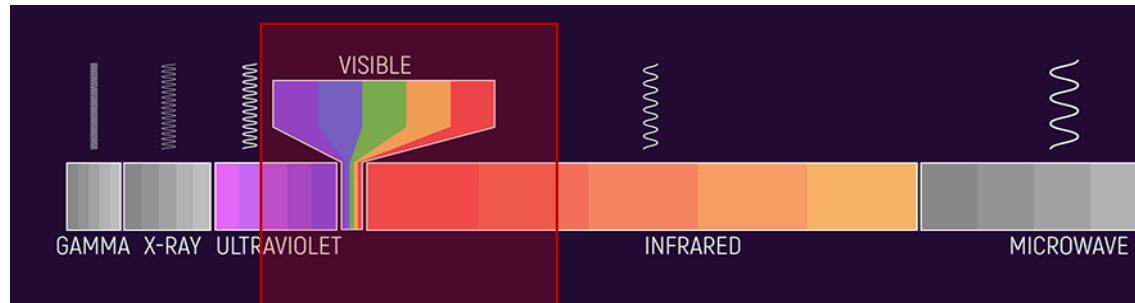
Nogly et al., Science 361, 145 (2018)

Light detection in biological system

Photon absorption by a retinal molecule triggers complex chemical reactions which culminate in the stimulation of the optic nerve.

What are the early steps of the process?
How fast they proceed?

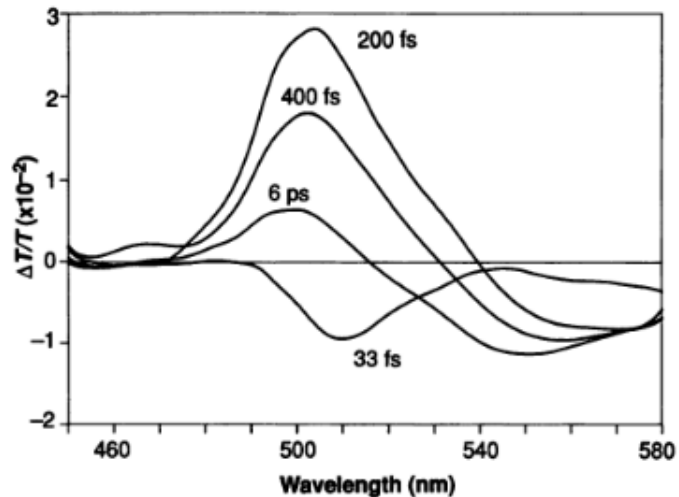
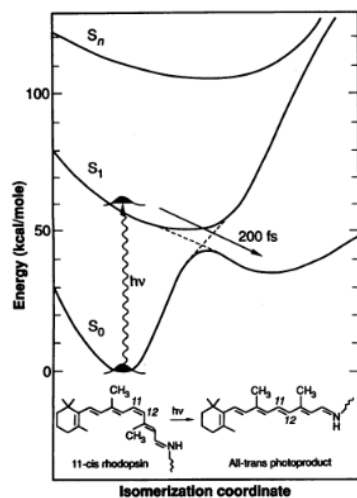
Early 1990's introduction of the first femtosecond lasers (UV/VIS/NIR)



The First Step in Vision: Femtosecond Isomerization of Rhodopsin

Science, 1991

R. W. SCHOENLEIN, L. A. PETEANU, R. A. MATHIES, C. V. SHANK



- Spectrum of molecules as a function of time detects the electronic population
- Isomerization occurs on very fast time scales (200 fs)

Chemistry



The Nobel Prize in Chemistry 1999

"for his studies of the transition states of chemical reactions using femtosecond spectroscopy"



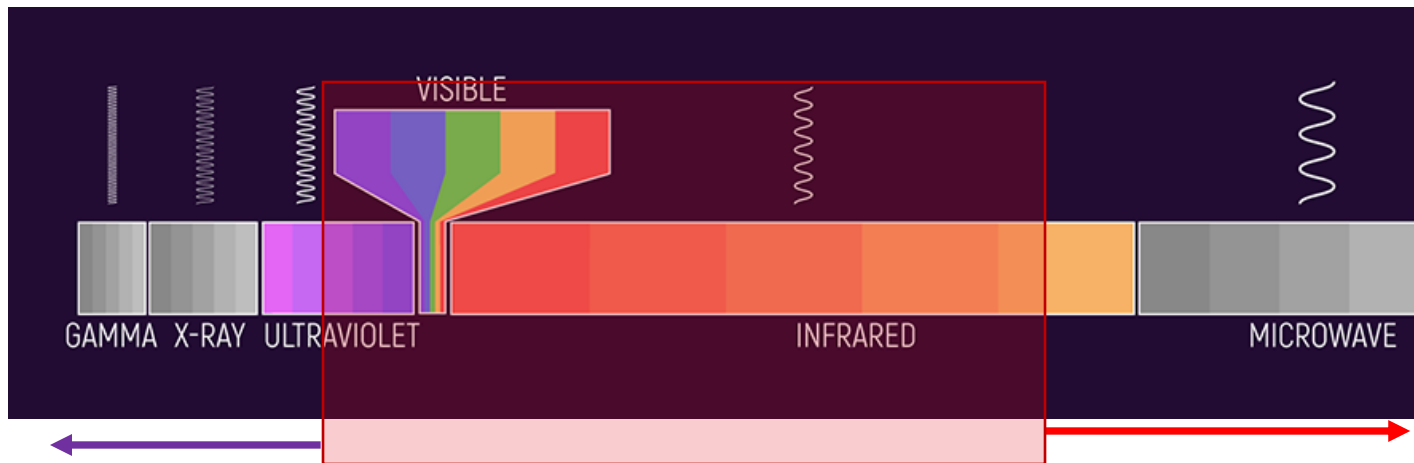
Ahmed H. Zewail

Egypt and USA

California Institute of
Technology (Caltech)
Pasadena, CA, USA

b. 1946

Ahmed Zewail
performed the first
femtosecond
spectroscopy on
molecular:
Femtochemistry!



Towards the XUV and X-Ray

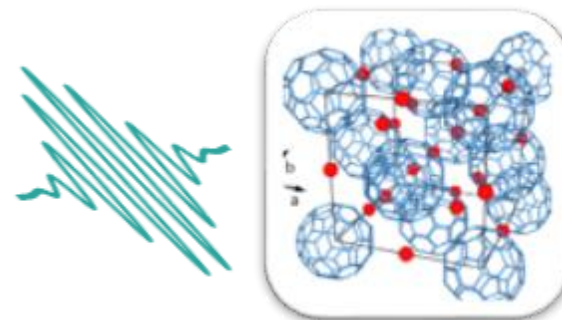
Ionization: photoelectron spectroscopy

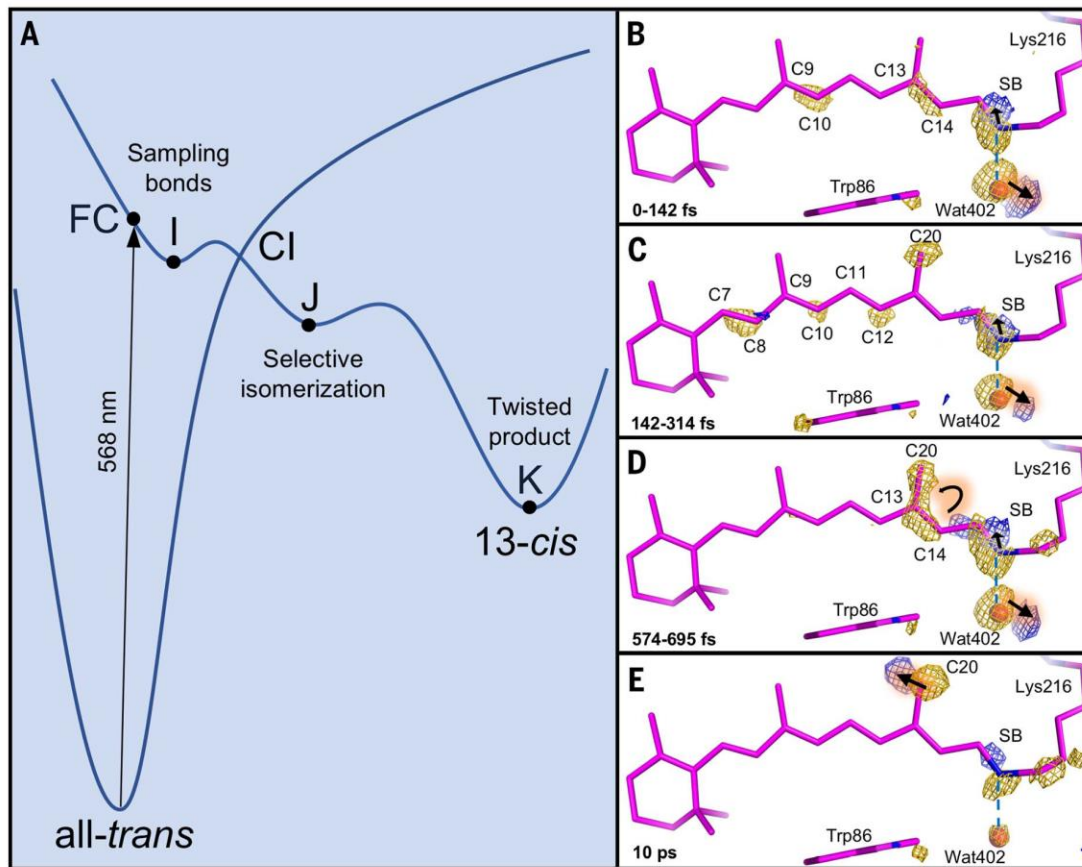
Electronic State-specific probes

Diffraction (also with electrons)

Towards the IR and THz

We can directly couple to atomic vibrations

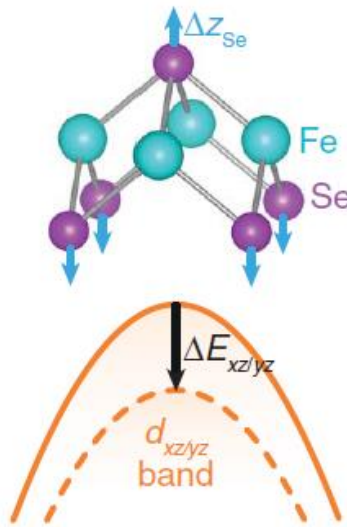
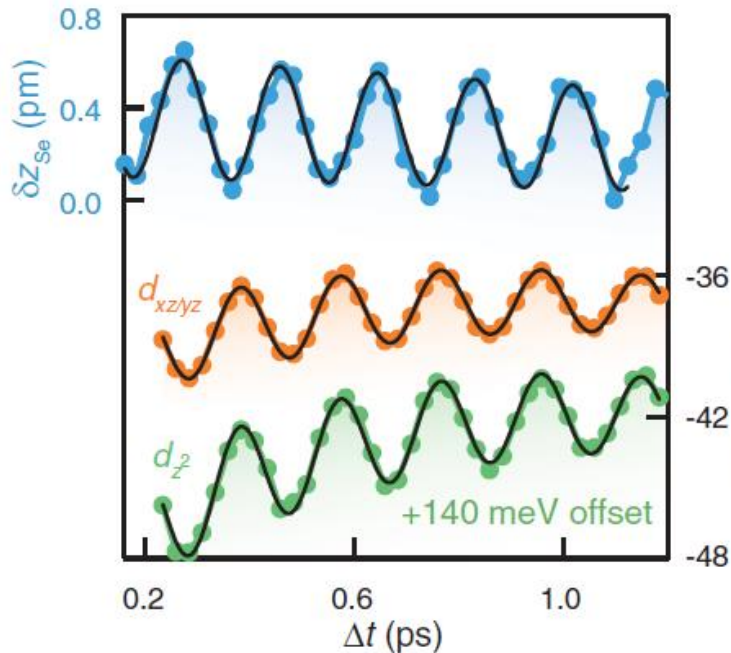




Same experiment:
atomic position as a
function of time

“Molecular movie”

Coupled electronic and atomic motion in real time



Atomic positions
fs X-ray pulses

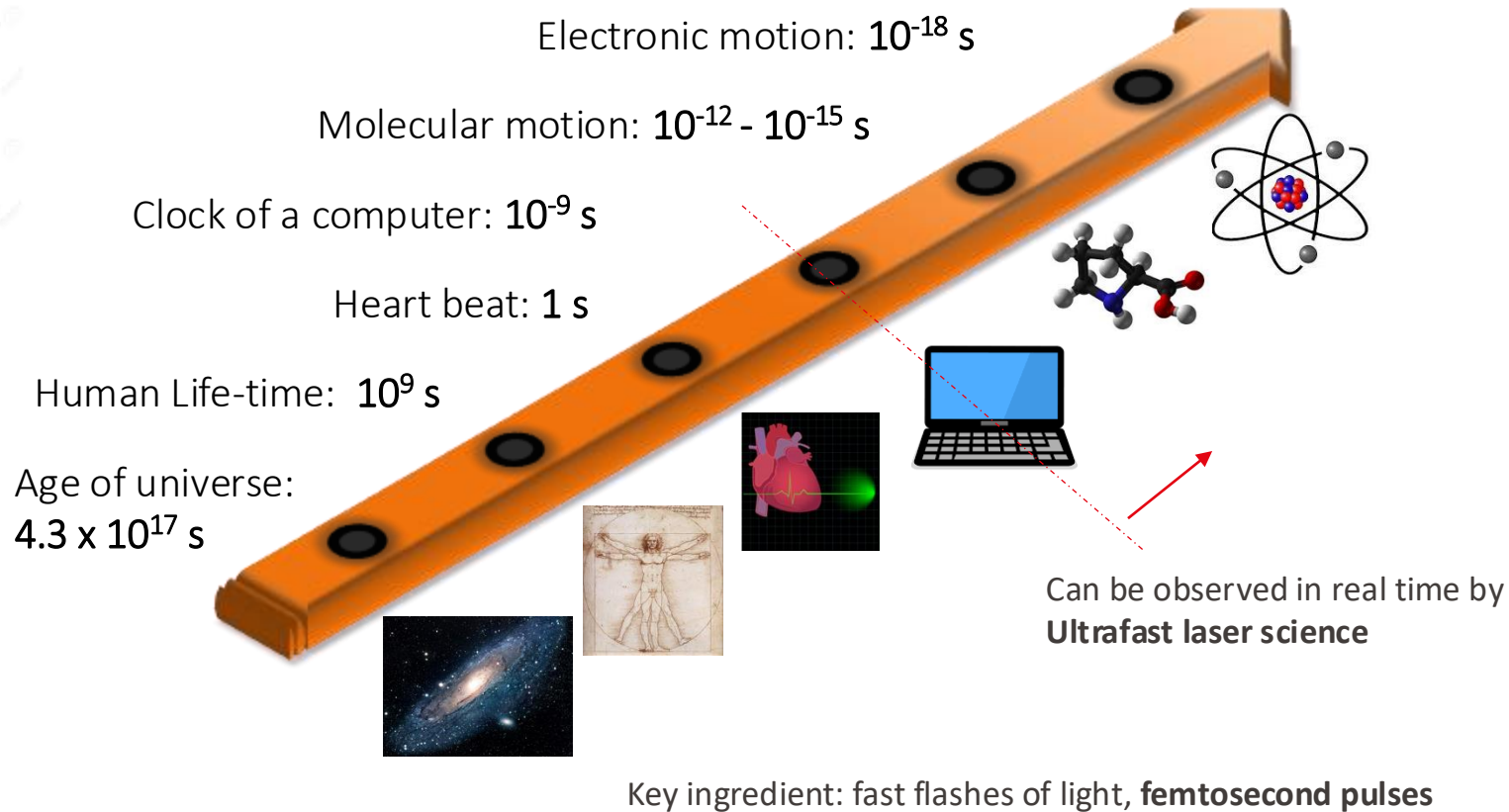
Electronic states
fs XUV pulses

Gerber et al., Science 357, 71–75 (2017)

Coupling of electrons and lattice in an iron-based superconductor

Motivation: understand couplings in complex materials

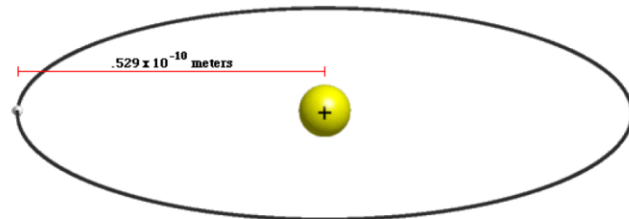
Time scales in nature



Attosecond: ultimate timescales in atomic physics

$$\frac{\text{Distance}}{\text{Speed}} = \frac{5.29 \times 10^{-11} \text{ m}}{2.19 \times 10^6 \text{ m/s}} = \mathbf{24 \text{ as}} \quad (24 \times 10^{-18} \text{ s})$$

Atomic unit of time



The Nobel Prize in Physics 2023



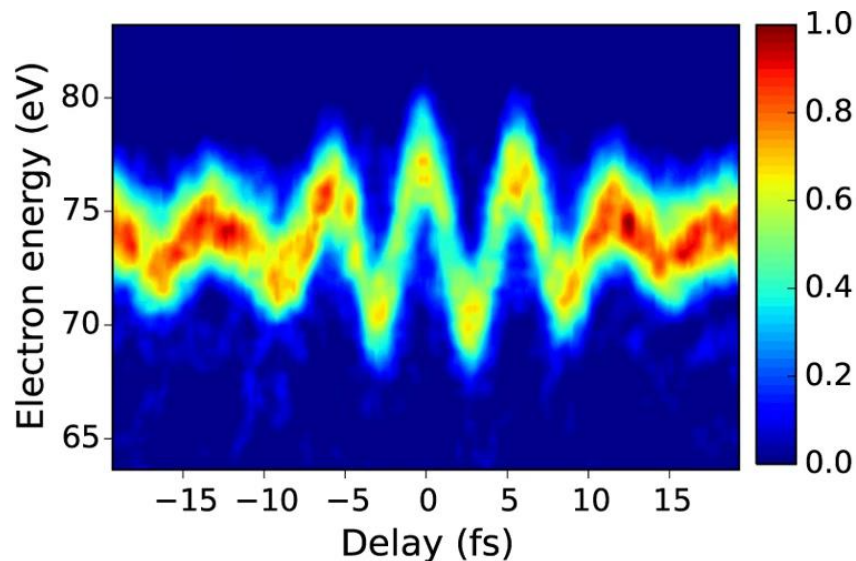
III. Niklas Elmehed © Nobel Prize Outreach
Pierre Agostini
Prize share: 1/3



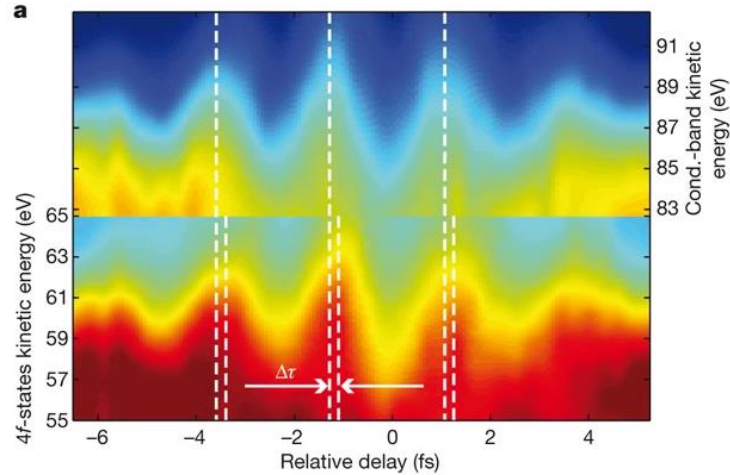
III. Niklas Elmehed © Nobel Prize Outreach
Ferenc Krausz
Prize share: 1/3



III. Niklas Elmehed © Nobel Prize Outreach
Anne L'Huillier
Prize share: 1/3



Processes like photoemission or electronic tunneling are instantaneous only in first approximation. How long does it take to photo-emit an electron? How long does it take to tunnel out of a barrier?



Cavaleri, *Nature* volume 449, (2007)

How do we treat time, and time intervals in quantum mechanics?

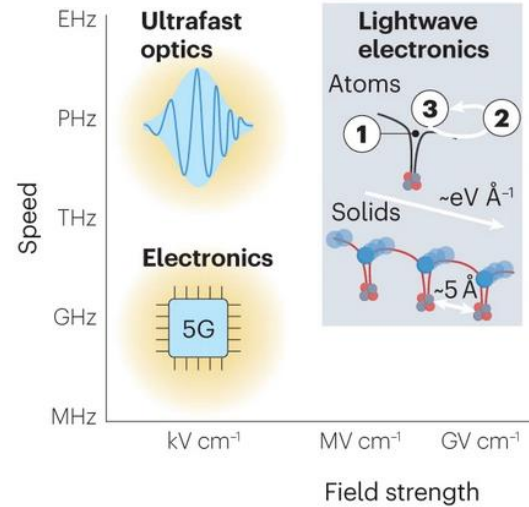
Light wave electronics, Petahertz electronics

Attosecond science is based on technologies controlling short light fields (few cycles), and their phase with subcycle precision

Light cycle (few fs)



Current electronics
GHz (ns)



Borsch, *Nature Reviews Materials* volume 8 (2023)

Can we directly drive electrons with strong controlled electric fields within a material and perform useful (quantum) operations?

Our goals:

Step 1 - Achieve a practical understanding on the operation of femtosecond lasers and amplifiers.

Step 2 - Understand how (extreme) nonlinear optics is used to obtain

- 1) Few-cycle pulses
- 2) Extreme ultraviolet radiation
- 3) Attosecond pulse trains and isolated as pulses

Step 3 – Femtosecond Electrons and X-rays pulses, how to?

LASER:

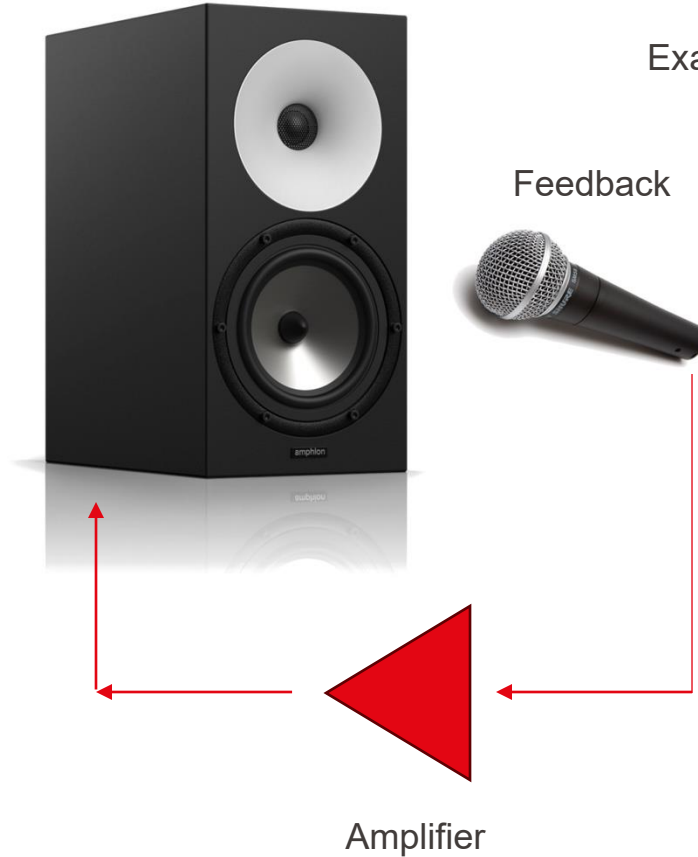
Light-Amplification by Stimulated Emission of Radiation



Typical properties of LASER radiation:

- **Directionality:** the radiation is concentrated in a narrow beam with low divergence, which can be focused to a «diffraction limited» spot, achieving **high intensity**
- **Monochromaticity:** the light emission is concentrated in a narrow linewidth.

The radiation of a laser has high **temporal coherence** and **spatial coherence**. How is this achieved?



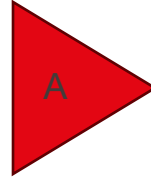
- Start from broadband noise in the audio system
- Grows rapidly into a loud sound, at some resonant frequency of the system

Self-Oscillations:

Amplifier:

Input voltage

V_{in}

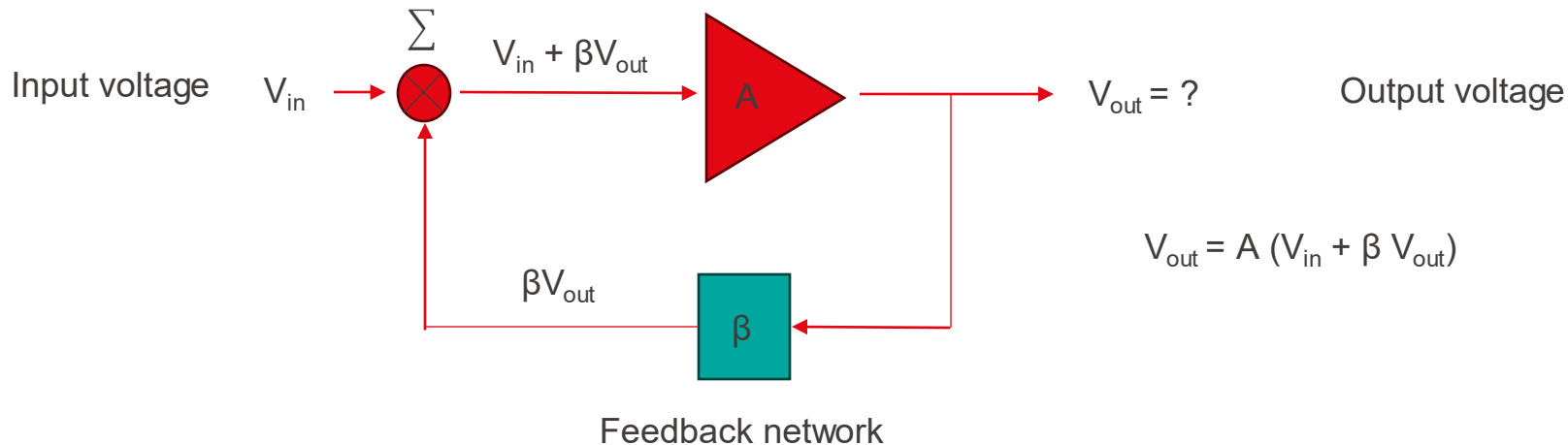


$V_{out} = A V_{in}$

Output voltage

Gain = A

Amplifier with positive feedback:



$$V_{out} = A (V_{in} + \beta V_{out})$$

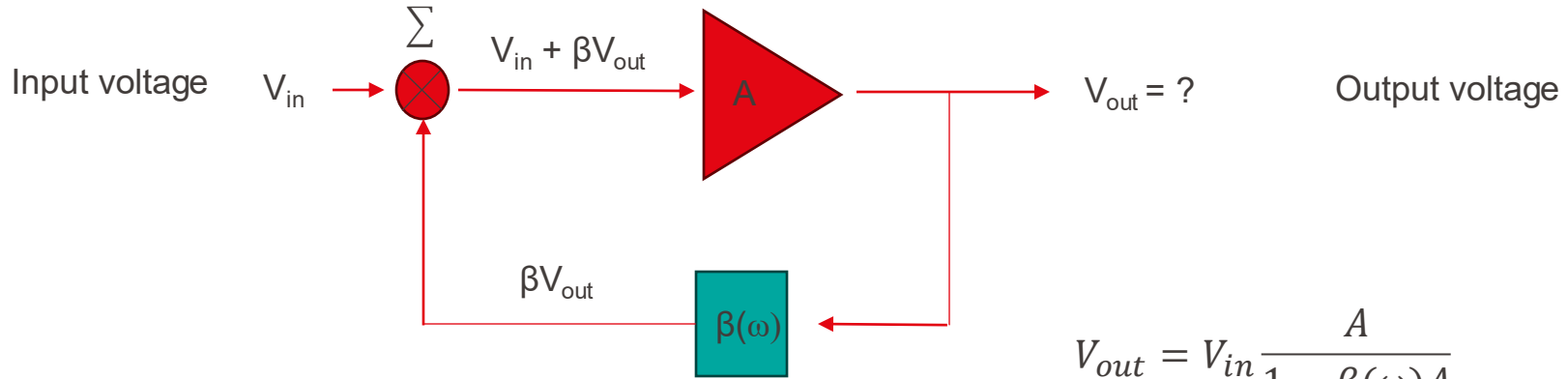
$$V_{out} = V_{in} \frac{A}{1 - \beta A}$$

Very large output
 $\beta A \rightarrow 1$

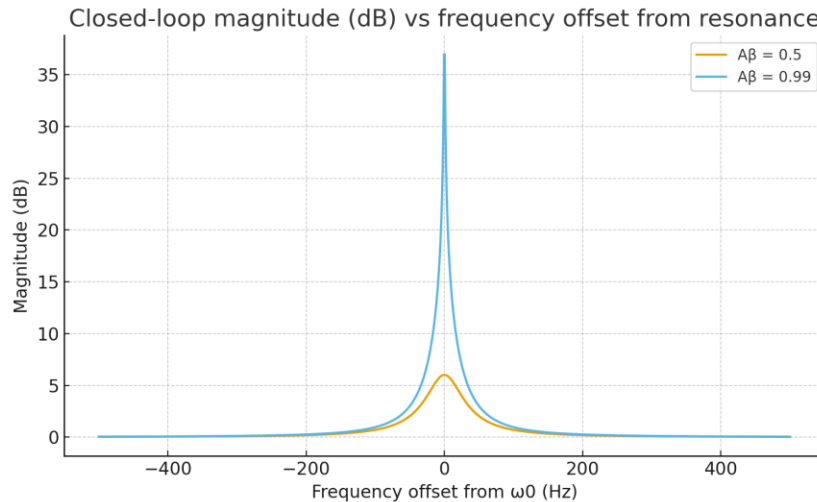
$\rightarrow \infty$? No

Saturation, breakdown of linear regime

Oscillator with a resonant frequency:



$$V_{out} = V_{in} \frac{A}{1 - \beta(\omega)A}$$



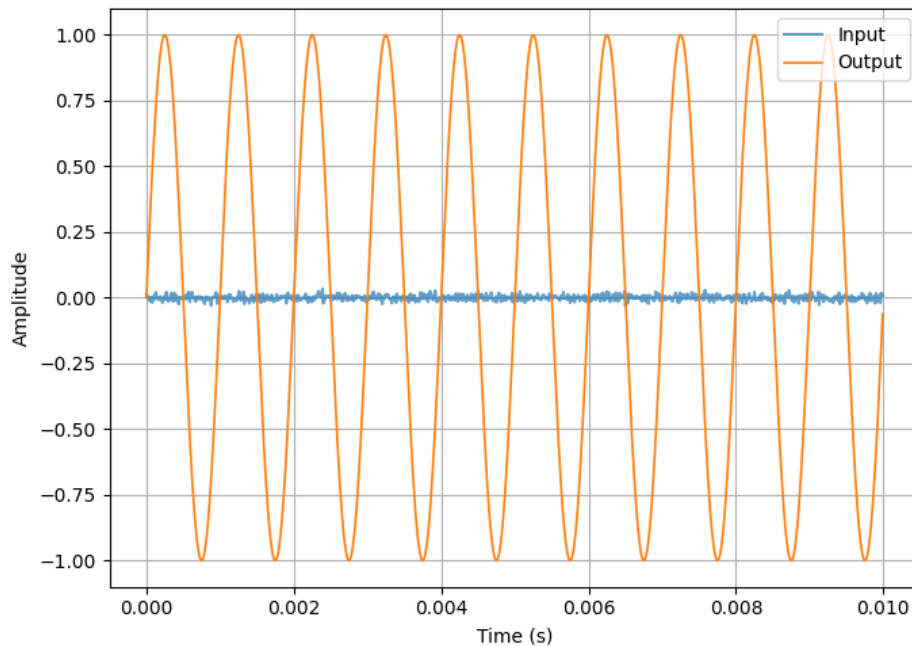
Feedback network with a resonant frequency (eg. LC circuit, quartz crystal..)

- Narrower and more intense as $A\beta \rightarrow 1$

Self-Oscillations:

Key concepts:

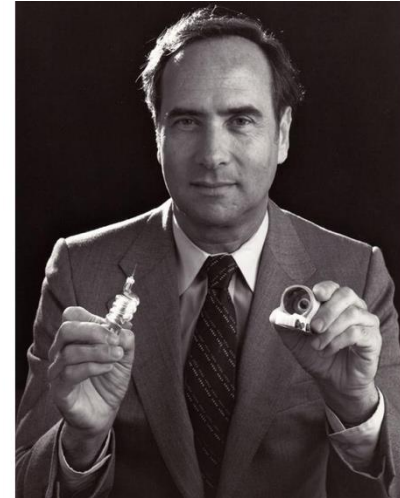
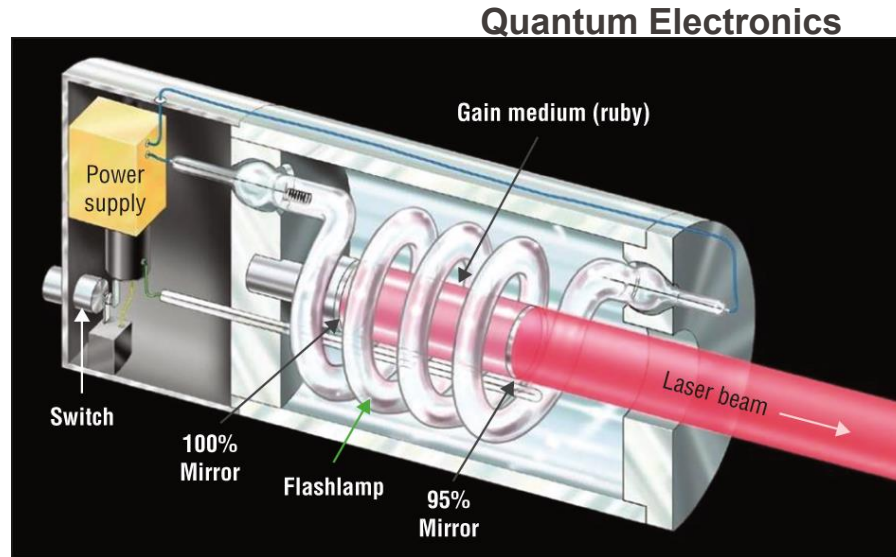
1. Gain (Amplifier)
2. Positive feedback with resonant frequency
3. Finite oscillations produced from weak input (e.g. noise)
4. Gain saturation



A laser oscillator extend the same concept to the optical regime.

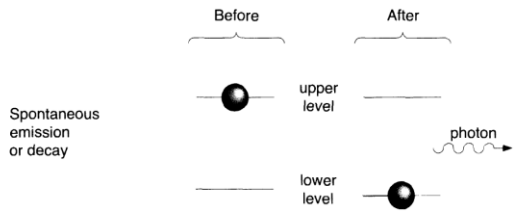
Practical realization of the laser 1960s (Maiman/Basov) :

- Microwave technology well-developed (electronic engineers)
- Quantum mechanics and light matter interaction well understood (physicist)



Ruby laser demonstrated by Hughes aircraft (T.H. Maiman, Nature, 187 (1960) 493)

Basic ideas of light-matter interaction, A and B



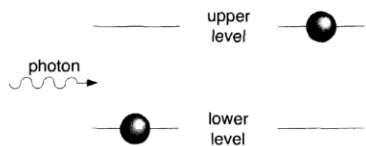
Handwritten notes:

$$|2\rangle, N_2 \quad \left(\frac{\text{atoms}}{\text{L}^3} \right)$$

$$\dot{N}_2 = A_{21} N_2$$

$$|1\rangle, N_1$$

Stimulated absorption



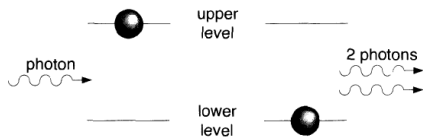
Handwritten notes:

EN. DENSITY PER UNIT FREQ.

$$u(\omega)$$

$$u_T = \int_{-\infty}^{\infty} u(\omega) d\omega$$

Stimulated emission



Handwritten notes:

$$\dot{N}_1 = u(\omega) B_{21} N_2$$

RESPONSIBLE FOR AMPLIFICATION

Relations between A,B:

$$\frac{A_{21}}{B_{21}} = \frac{\hbar \omega^3}{\pi^2 c^3}$$

$$B_{12} = \frac{g_2}{g_1} B_{21}$$

$$-\frac{dI}{dz} = \frac{h\nu}{c} (N_1 - N_2) B_{12} F(\nu) I$$

Assume a small initial signal ($N_1 - N_2$) independent on I

$$I(\nu, z) = I(\nu, 0)e^{-\alpha(\nu)z}$$

With population inversion the absorption coefficient is negative, a weak signal experiences exponential growth:

$$\alpha(\nu) = [N_i - (g_i/g_k)N_k]\sigma(\nu)$$

Absorption (Gain) coefficient

$N_u < N_l$ ($N_u > N_l$)



Population inversion

$$= \left[N_u - \frac{g_u}{g_l} N_l \right] \underbrace{\left(\frac{c^2}{8\pi\eta^2\nu^2} \right)}_{\text{STIMULATED EMISSION COEFFICIENT}} \times \underbrace{\left[\frac{\gamma_{ul}^T/4\pi^2}{(\nu - \nu_0)^2 + (\gamma_{ul}^T/4\pi)^2} \right]}_{\text{LINESHAPE BROADENING}} A_{ul}$$

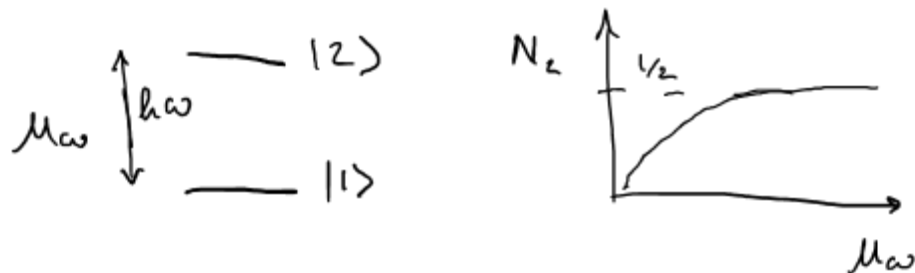
POP. DIFFERENCE (pointing to the bracketed term $N_u - \frac{g_u}{g_l} N_l$)

(e.g. HOMOGENEOUS BROADENING) (pointing to the lineshape term)

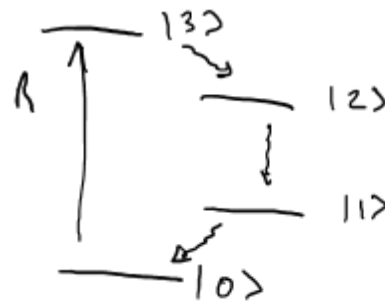
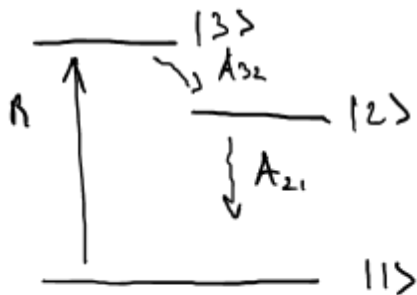
One of the challenges is to find a suitable excitation method and electronic levels to achieve population inversion

$$\alpha(\nu) = [N_i - (g_i/g_k)N_k]\sigma(\nu)$$

Cannot be reached in a two-level system (exercise session)

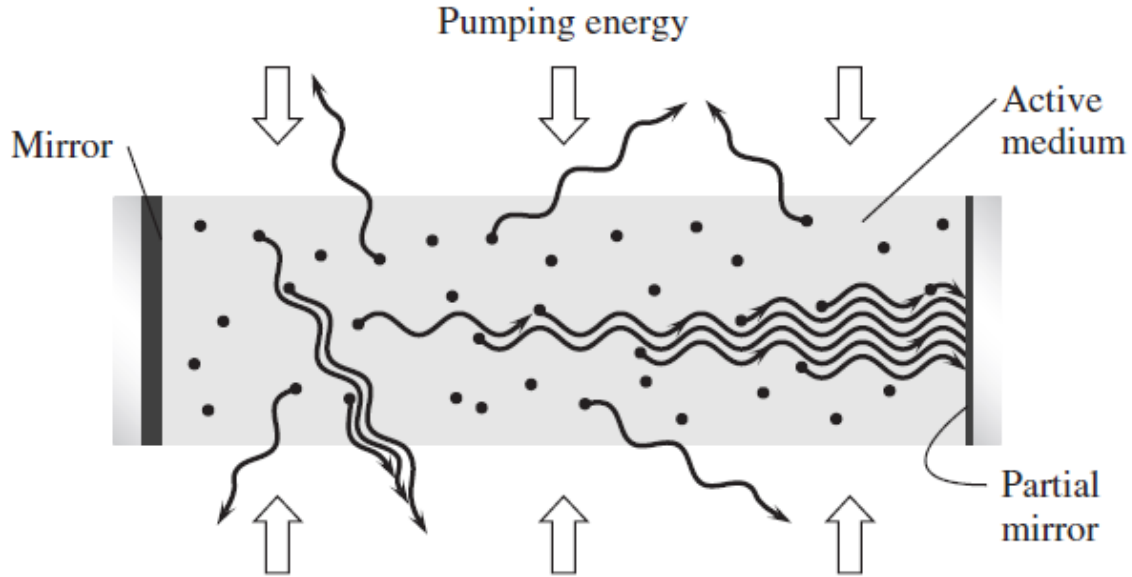


3 (or better 4) levels are required

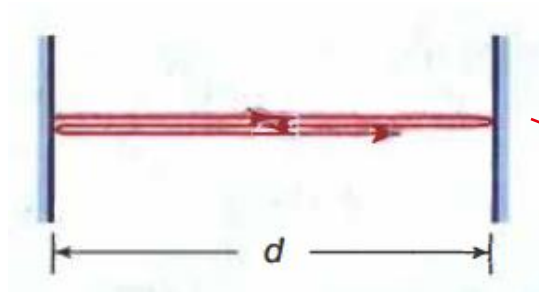
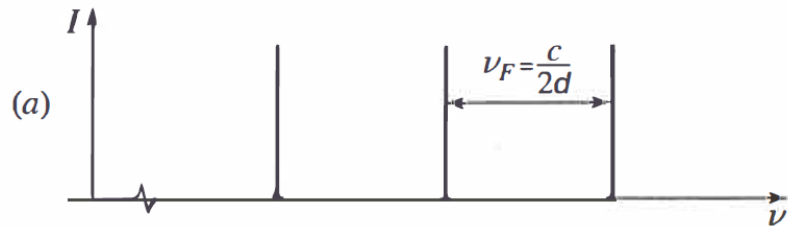


"RATE EQUATIONS"

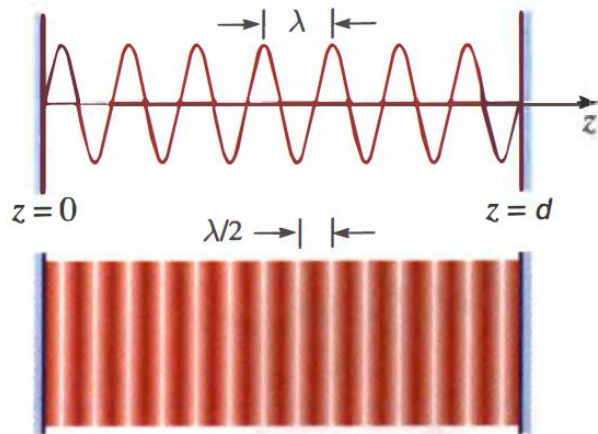
Anatomy of a LASER



- 1) Active medium
- 2) Pump
- 3) Resonator

 $R < 1$ 

$$c = \lambda \nu$$



Resonance condition: standing wave

$$k_n 2d = n 2\pi$$

$$\nu_n = \frac{c}{\lambda_n} = \frac{c}{2d} n$$

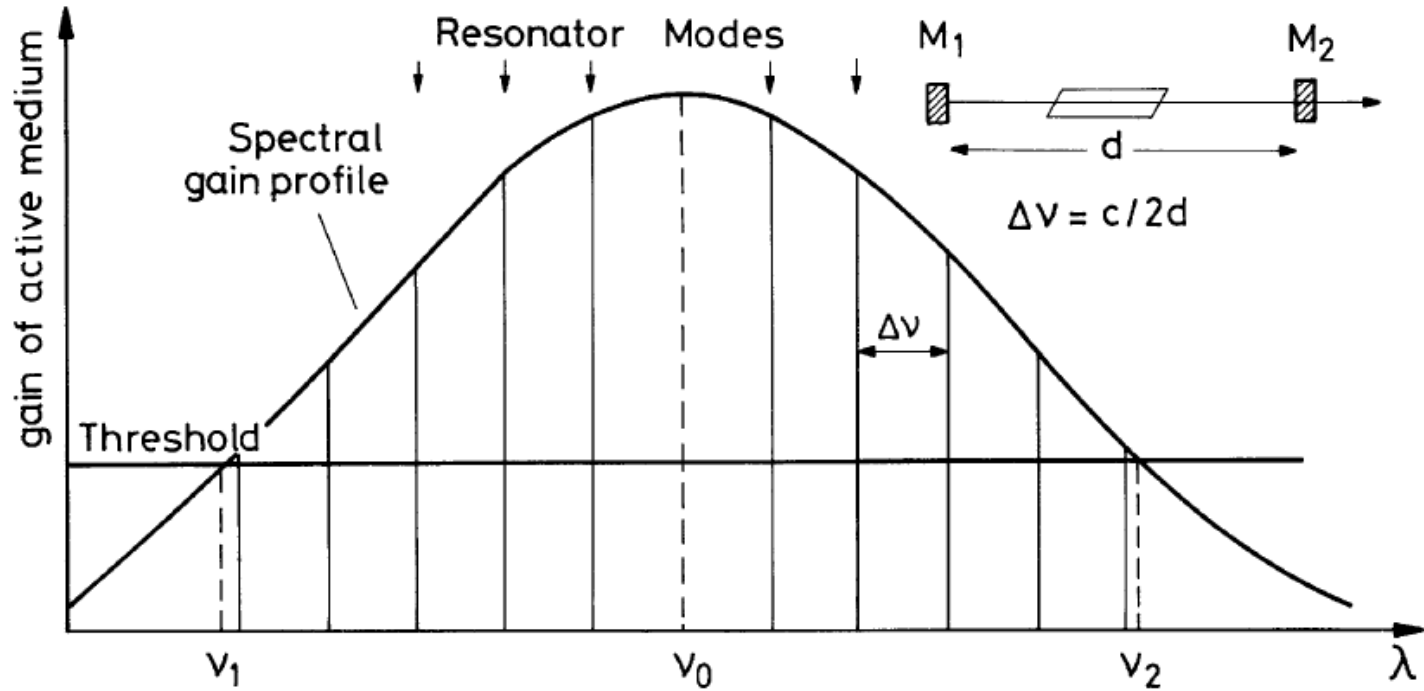
$$2\pi \frac{2d}{\lambda_n} = n 2\pi$$

$$\nu_F = \nu_{n+1} - \nu_n = \frac{c}{2d}$$

$$(2d) = n \lambda_n$$

FREE SPECTRAL RANGE

(MODE SEPARATION)



In most cases gain profile overlaps multiple cavity modes!

Connect the dots:

Electronic oscillator

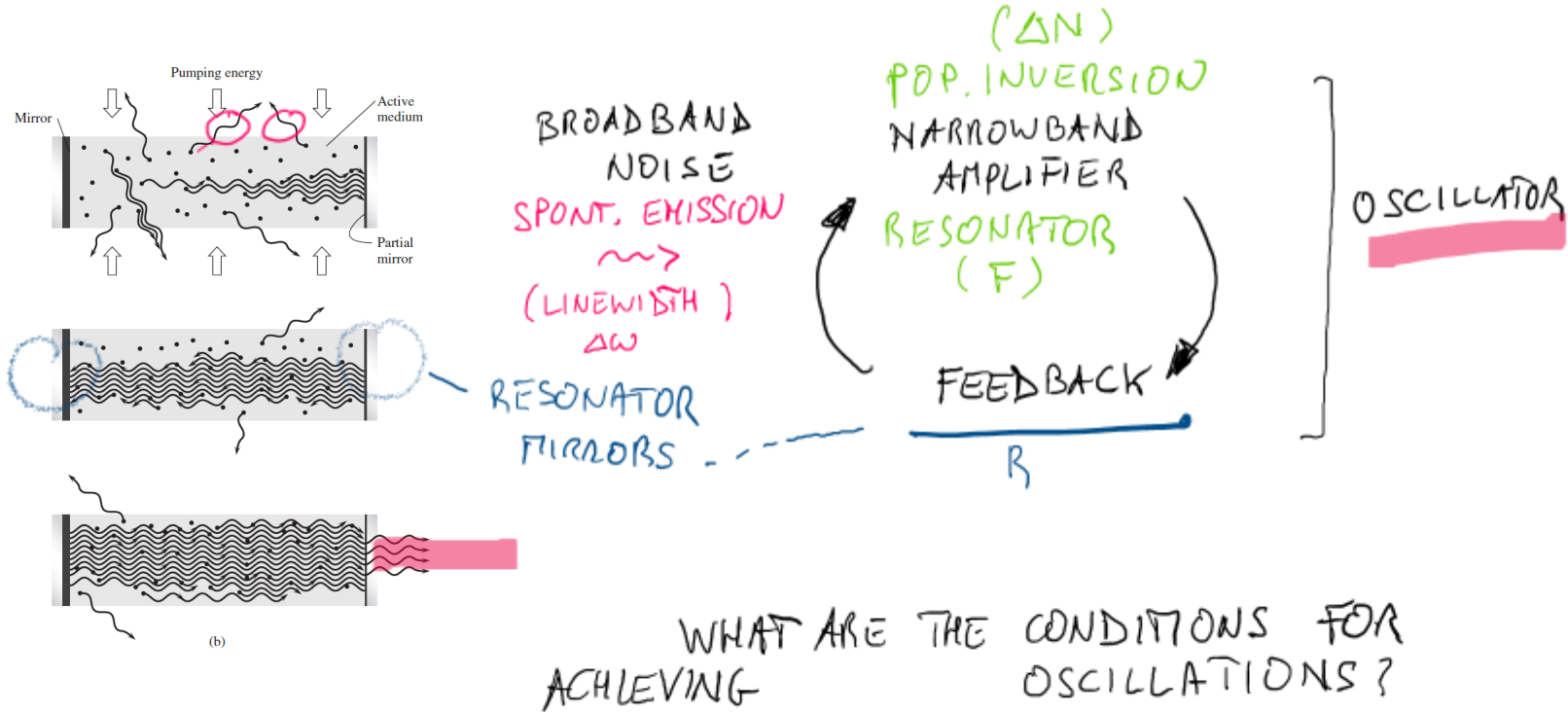
1. Gain (Amplifier)
2. Positive feedback with resonant frequency
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4. Gain saturation

LASER

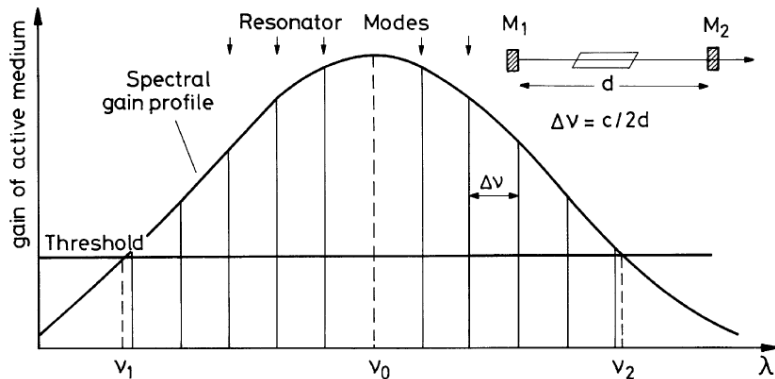
- A. INVERSION DEPLETION
- B. Optical resonator (Fabri-Perot)
- C. SPONTANEOUS EMISSION
- D. STIMULATED EMISSION, Atoms with POPULATION INVERSION

Laser oscillators

- Amplifier: Medium with inversion symmetry
- Resonator: open mirror resonator, can store the energy of the modes



Lifetime of photons in a cavity mode



- Lasing will start if the gain per round trip is balancing the losses.

OPTICAL ENERGY IN THE k-TH MODE

$$\frac{dW_k}{dt} = -\beta_k W_k \Rightarrow W_k(t) = W_k(0) e^{-\beta_k t}$$

$\frac{1}{\beta_k} = \text{PHOTON LIFETIME}$

- Losses: reflection (output coupler), diffraction, scattering/absorption, ..

REFLECTION LOSSES

$$I(2d) = I_0 R_1 R_2 = I_0 e^{-\gamma_R}$$

PHOTON LIFETIME $\rightarrow \tau_R = \frac{2d}{c \ln(R_1 R_2)}$

$$\gamma_k = \beta_k \frac{2d}{c}$$

LOSSES PER ROUND-TRIP

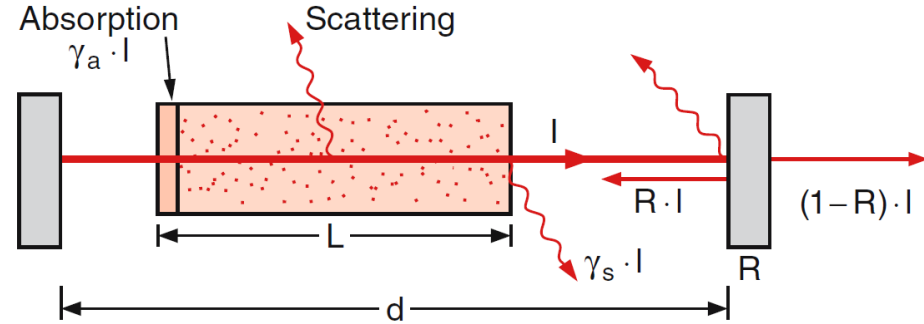
LOW LOSSES ; LONG LIFETIME

- Below the gain profile several modes can «lase», if above a certain threshold condition

Cavity losses (mode dependent):
 (β = loss coefficient (s^{-1}),
 γ = loss factor per roundtrip)

$$I = I_0 e^{-\gamma}$$

$$\gamma = \beta \cdot (2d/c)$$



With population inversion the absorption coefficient is negative, a weak signal experience exponential growth:

$$\alpha(\nu) = [N_i - (g_i/g_k)N_k]\sigma(\nu)$$

$$I(\nu, z) = I(\nu, 0)e^{-\alpha(\nu)z}$$

Gain factor per roundtrip

$$G(\nu) = \frac{I(\nu, 2L)}{I(\nu, 0)} = e^{-2\alpha(\nu)L}$$

$$I(\nu, 2d) = I(\nu, 0) \exp[-2\alpha(\nu)L - \gamma]$$

$$I(\nu, 2d) = I(\nu, 0) \exp[-2\alpha(\nu)L - \gamma]$$

$$-2L\alpha(\nu) > \gamma$$

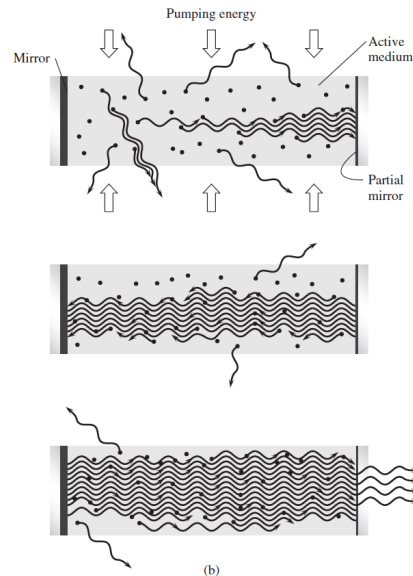
$$\alpha \rightarrow \Delta N \sigma$$

$$\Delta N = N_k (g_i / g_k) - N_i > \Delta N_{\text{thr}} = \frac{\gamma}{2\sigma(\nu)L} .$$

Above this threshold a spontaneously emitted photon in the cavity mode will initiate an avalanche which starts lasers oscillations.

This cannot grow indefinitely: we have to solve the rate equation model.

Include an equation for the population in the relevant cavity mode and the **cavity losses**



Rate equations including a cavity mode:

DECAY RATE TO OTHER LEVELS

PUMP RATE

$|2\rangle$

$|1\rangle$

$N_1 B_{12} \cdot n \cdot h \cdot \nu$

$N_2 B_{21} \cdot n \cdot h \cdot \nu$

$N_2 A_{21}$

$N_2 R_2$

$N_1 R_1$

$$\frac{dN_1}{dt} = (N_2 - N_1)B_{21}nh\nu + N_2A_{21} - N_1R_1$$

$$\frac{dN_2}{dt} = P - (N_2 - N_1)B_{21}nh\nu - N_2A_{21} - N_2R_2$$

$$\frac{dn}{dt} = -\beta n + (N_2 - N_1)B_{21}nh\nu$$

↑ WE MUST INCLUDE A RATE EQ. FOR THE PHOTONS

Steady state conditions: continuous wave (CW) lasing

$$a) \quad \frac{dN_1}{dt} = (N_2 - N_1)B_{21}nh\nu + N_2A_{21} - N_1R_1, \quad = 0$$

$$b) \quad \frac{dN_2}{dt} = P - (N_2 - N_1)B_{21}nh\nu - N_2A_{21} - N_2R_2, \quad = 0$$

$$c) \quad \frac{dn}{dt} = -\beta n + (N_2 - N_1)B_{21}nh\nu. \quad = 0$$

Under steady state conditions the pump balances the cavity losses and the total relaxation rate of the upper level :

$$P = \beta n + N_2(A_{21} + R_2)$$