Optics & Photonics Winter School 2016

College of Optical Sciences
THE UNIVERSITY OF ARIZONA

Branches of Optics

- Geometrical Optics → light as a ray
- Physical Optics → light as a wave
- Quantum Optics → light as wave/particle

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Fields in Optical Sciences

- Optical Engineering
- Imaging Science
- Photonics
- Optical Physics

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Optical Physics & Lasers

R. Jason Jones
College of Optical Sciences
University of Arizona

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Outline

- Light, matter, and their interaction: overview of optical physics
- Quantum description of matter
- The semi-classical model
- Lasers
- Lasers as precision tools

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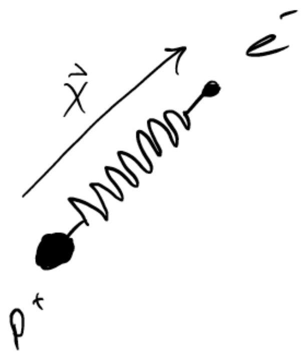
Models of Light-Matter Interaction

Classical picture:	"classical" light, "classical" matter
Semi-classical picture:	classical light, quantum matter
Quantum picture:	quantum light, quantum matter

Classical electron-oscillator model

(~1900) Lorentz ad hoc hypothesis: atom responds as if it were attached to nucleus with a spring.



$$\vec{F}_{atom} = -k\vec{x}$$

$$\vec{F}_{light} = -e\vec{E} \quad \text{(Lorentz force)}$$

$\vec{E}$ → light field

$$k = \omega_0^2 m$$

ω_0 → natural oscillation frequency

m → center of mass

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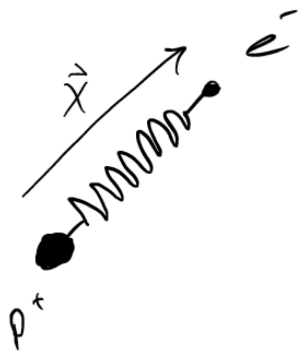

From Newton:

$$\vec{F}_{total} = m\vec{a} = m\frac{d^2\vec{x}}{dt^2}$$

$$\rightarrow \quad m\frac{d^2\vec{x}}{dt^2} = e\vec{E} - m\omega_0^2\vec{x}$$

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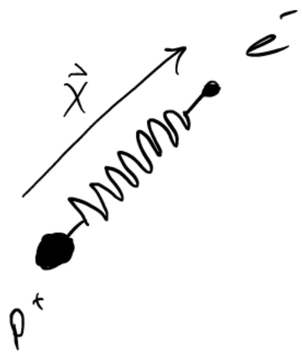

Solution w/o light field

$$\left(\vec{F}_{light} = 0 \right)$$

$$\vec{x}(t) = \vec{x}(0)\cos(\omega_0 t)$$

$\Rightarrow$ simple harmonic oscillator

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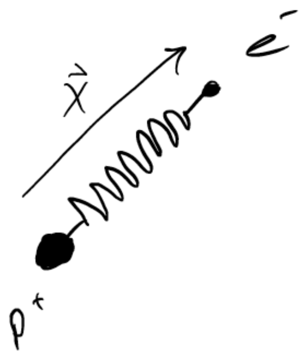

Solution w/o light field

$(\vec{F}_{light} = 0)$

$$\vec{x}(t) = \vec{x}(0)\cos(\omega_0 t)$$

$\Rightarrow$ simple harmonic oscillator

Add damping term:

$$\vec{F}_{friction} = -b\vec{v} = -b\frac{d\vec{x}}{dt}$$

Why?

Classical electron-oscillator model

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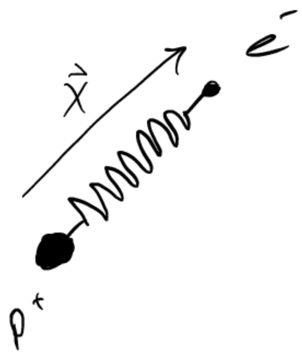


Damped & driven simple harmonic oscillator:

$$\frac{d^2\vec{x}}{dt^2} + \left(\frac{b}{m}\right)\frac{d\vec{x}}{dt} + \omega_0^2\,\vec{x} = \left(\frac{e}{m}\right)\vec{E}$$

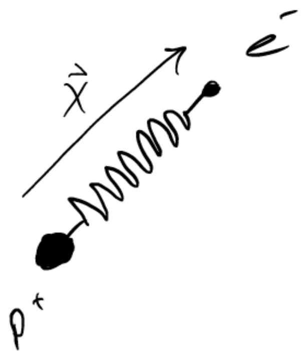
⇒ classical expression for atomic response to light field.

Predicts average dipole response for ensemble of atoms

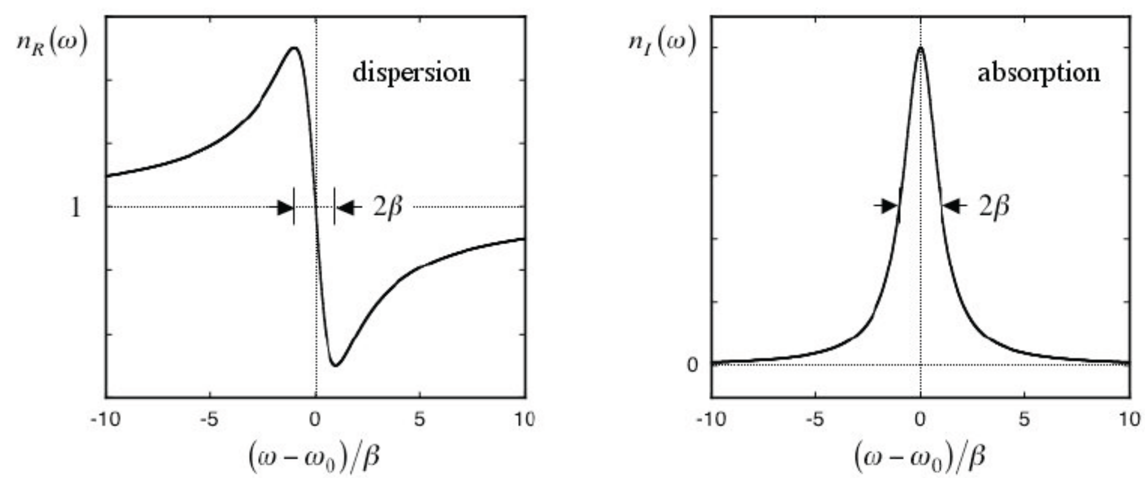
$$\vec{d} = -e\,\vec{x}(t) = \alpha(\omega)\,\vec{E}(t)$$

$\alpha(\omega)$: polarizability of atomic ensemble

Predictions of the CEO model:



index of refraction→ absorption, dispersion



where $\beta \equiv b/2m$

However, fails to predict: saturation, optical gain, spontaneous emission…

→ **We need a better model for the atom!**

Quantum matter

Elements of quantum theory

Wave equations for light and matter

Quantum description of the atom

Quantum matter

Historical events in the development of quantum theory

1901: Planck and Blackbody Radiation
1905: Einstein and the photoelectric effect
} Wave-particle duality of light

1913: Bohr model of the atom
} Atomic energy levels

1924: de Broglie and wave-particle duality of matter
1927: Davisson & Germer experiment
} Electron diffraction

Historical events in the development of quantum theory

1924: de Broglie and wave-particle duality of matter

Louis de Broglie

de Broglie wavelength:

$$\lambda_{matter} = \frac{h}{p}$$

h → Planck's constant

p → particle momentum

Quantum matter

- Analogy with "classical" light waves

- Analogy with "classical" light waves

Maxwell's Equations: (no free charges, no currents → dielectrica)

(i)	$\nabla \cdot \mathbf{D} = \rho \equiv 0$	$\mathbf{D}$: Dielectric displacement
(ii)	$\nabla \cdot \mathbf{B} \equiv 0$	$\mathbf{B}$: Magnetic induction
(iii)	$\nabla \times \mathbf{E} = -\partial\mathbf{B}/\partial t$	$\mathbf{E}$: Electric field
(iv)	$\nabla \times \mathbf{H} = \partial\mathbf{D}/\partial t + \mathbf{J} = \partial\mathbf{D}/\partial t$	$\mathbf{H}$: Magnetic field

↓

$$\nabla^2 \mathbf{E} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\mathbf{E} = 0$$

Wave equation for light

→

Plane waves

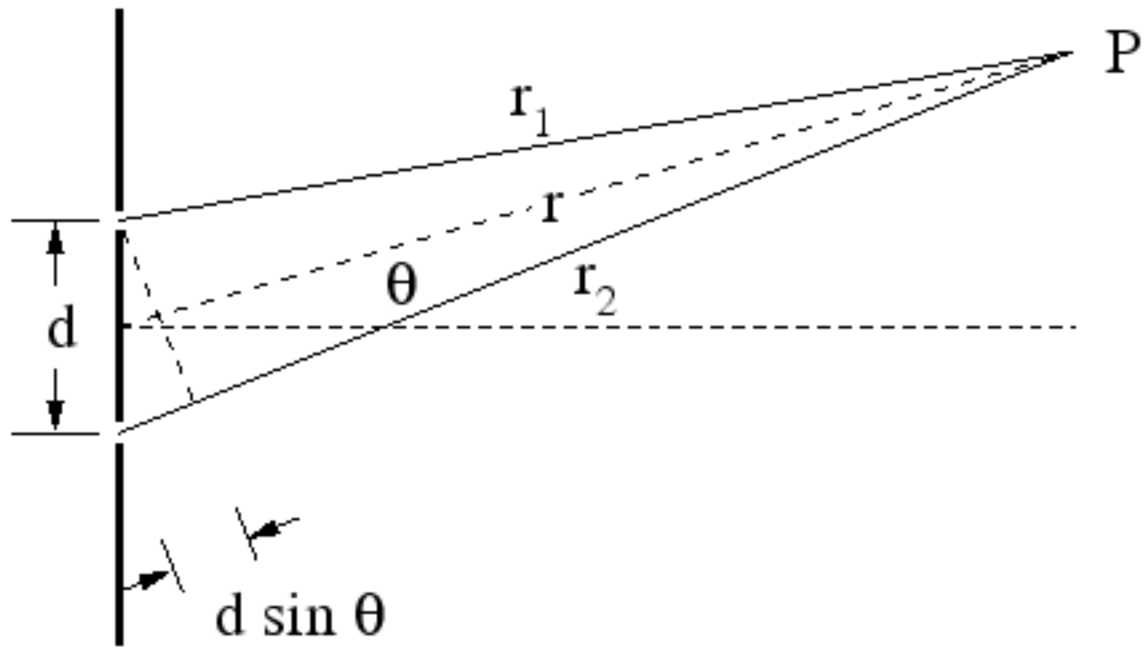
$$E(\vec{r},t) = E_0 \cos(\omega t - \vec{k}\cdot\vec{r})$$

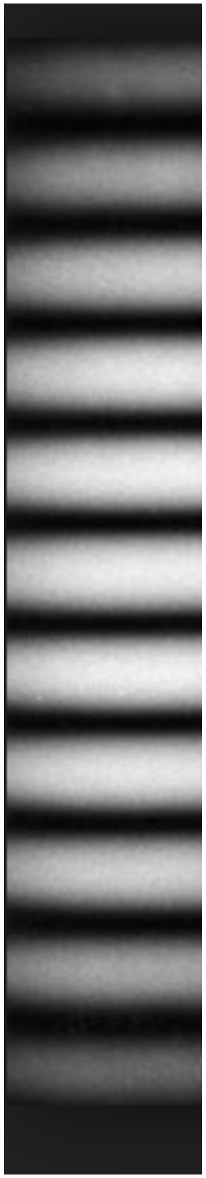
Spherical waves

$$E(\vec{r},t) = \frac{1}{r} E_0 \cos(\omega t - k\cdot r)$$

Quantum matter

2-slit diffraction of light





For constructive interference,

need $d \sin\theta = m\lambda$

↖ integer

Quantum matter

1927: Davisson & Germer experiment → electron diffraction

Quantum matter

How to describe the "matter waves"?

→ See next talk on "atom optics"

Quantum matter

Some postulates of quantum mechanics:

- The wavefunction for a particle tells us everything we can know about that particle.

$$\Psi(\vec{r}, t) \sim \text{probability amplitude}$$

(1-dimension)

$$\int_{x_1}^{x_2} |\Psi(x,t)|^2 \, dx = \left\{ \begin{array}{l} \text{Probability to find the} \\ \text{particle between} \\ x_1 \text{ \& } x_2 \text{ at time } t \end{array} \right.$$

(Born's statistical interp.)

Quantum matter

Some postulates of quantum mechanics:

- The Schrodinger equation describes the time evolution of the wavefunction.

$$i\hbar \frac{\partial}{\partial t}\Psi = -\frac{\hbar^2}{2m}\nabla^2\Psi + V(\vec{r},t)\Psi$$

→ The wave equation for matter!

Quantum matter

For time-independent problems, it can be shown…

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(\vec{r})\right]\Psi_n = E\,\Psi_n$$

or

$$\hat{H}\Psi_n = E_n\Psi_n$$

Where E_n is the total energy of the particle in quantum state Ψ_n.

Quantum matter

For example, if it is a free particle (V=0)…

1 - dimension

$$-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi_{(x)} = E\,\psi_{(x)}$$

Quantum matter

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$$-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi_{(x)} = E\,\psi_{(x)}$$

$$\hookrightarrow \quad \frac{d^2}{dx^2}\psi_{(x)} = \left(-\frac{2m}{\hbar^2}E\right)\psi_{(x)}$$

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1 - dimension

$$-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi(x) = E\,\psi(x)$$

$$\hookrightarrow \quad \frac{d^2}{dx^2}\psi(x) = \left(-\frac{2m}{\hbar^2}E\right)\psi(x)$$

$\Rightarrow$ plane wave solutions or

$$\psi(x) = \psi_0 \sin\left(\sqrt{2mE/\hbar^2}\,x\right) \qquad \psi(x) = \psi_0\, e^{i\sqrt{2mE/\hbar^2}\,x}$$

Free particle continued...

$$\psi(x) = \psi_0 \sin\left(\sqrt{2mE/\hbar^2}\, x\right)$$

$$k = \frac{2\pi}{\lambda} = \frac{\sqrt{2mE}}{\hbar}$$

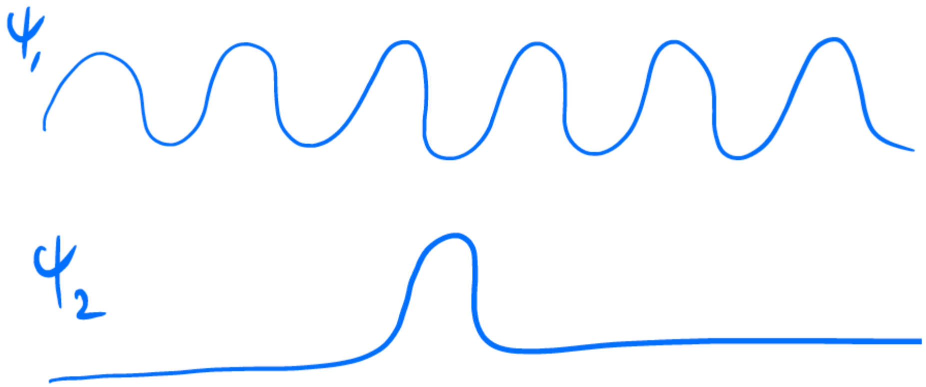
$$\rightarrow \lambda = \frac{2\pi\hbar}{\sqrt{2mE}} = \frac{h}{\sqrt{2mE}}$$

$$E = p^2/2m$$

$$\lambda = \frac{h}{p} \checkmark$$

single λ → well defined momentum p

Now consider these two wavefunctions:



Δx large, λ well defined

Δx small, λ not as certain

~~where is the particle?~~

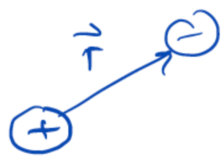
Since $\lambda = \frac{h}{p}$

$$\Delta x \propto \frac{1}{\Delta p}$$

more rigorous calculation shows

$$\boxed{\Delta x \cdot \Delta p \geq \hbar/2}$$ H.U.P.!

Quantum model of the hydrogen atom



Coulomb potential:

$$V(r) = \frac{-e^2}{r}$$

Using the Coulomb potential in the Schrodinger equation, one can now obtain the allowed quantum states and energies for the hydrogen atom.

$$\Rightarrow \quad E_n = \frac{-13.6}{n^2}\,eV \quad ; \quad n = 1, 2, 3 \ldots$$

$$\Psi_n(x, y, z)$$

Quantum matter

Graphs of hydrogen atom wavefunctions

Semi-classical model of light-matter interaction

Classical light field - quantum atom: solve the full Schrodinger equation

$$i\hbar \, \partial/\partial t \, \Psi(\vec{r},t) = -\frac{\hbar^2}{2m} \nabla^2 \Psi(\vec{r},t) + V(\vec{r},t)\, \Psi(\vec{r},t)$$

Coulomb force
+
Lorentz force

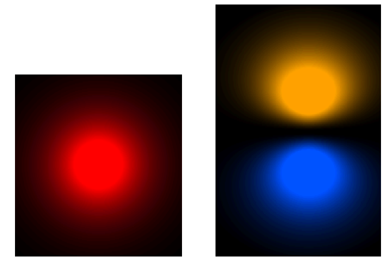
Several assumptions built into solution
e.g. light field is a small perturbation

video for numerical simulations of solution…

(http://www.falstad.com/mathphysics.html)

Semi-classical model of light-matter interaction

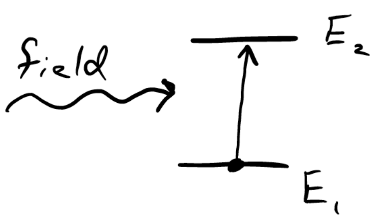
Semi-classical picture predicts:



n=1 n=2

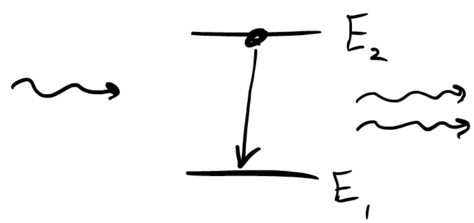
-real atom with discrete energy levels (infinite lifetime)

-optical absorption



energy removed from field

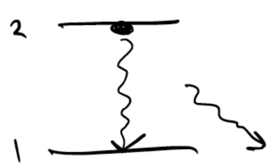
-optical gain



energy added to field → stimulated emission

-saturation of absorption or gain

spontaneous emission?

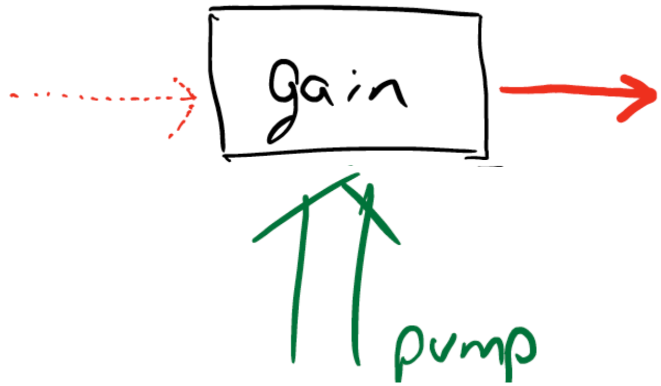


need full quantum theory
"quantum optics"

Lasers

Light **A**mplification by **S**timulated **E**mission of **R**adiation

Basic elements:

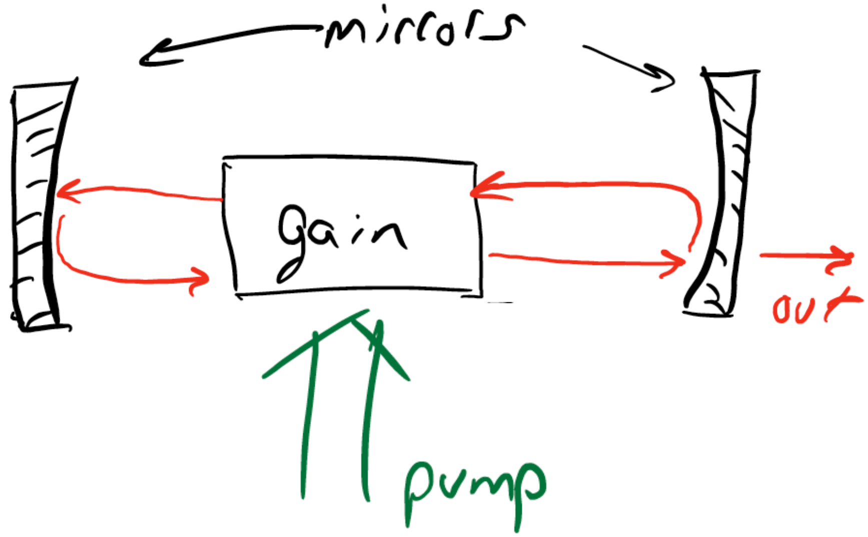


1) optical amplifier
2) pump source (power)

Lasers

Light Amplification by Stimulated Emission of Radiation

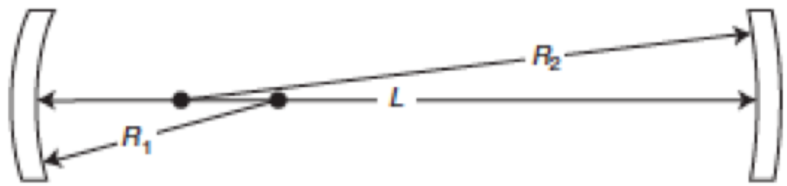
Basic elements:



1) optical amplifier
2) pump source (power)
3) optical cavity → feedback

Lasers

Optical cavities & Gaussian beams



Resonant modes of the optical cavity:

-find solutions of the wave equation given certain **approximations** and **boundary conditions**

$$\nabla^2 E(\mathbf{r}, t) - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}E(\mathbf{r}, t) = 0.$$

$$E(\vec{r},t) = \frac{1}{2}\left[\mathcal{E}(\vec{r})\, e^{-i\omega t} + c.c.\right]$$

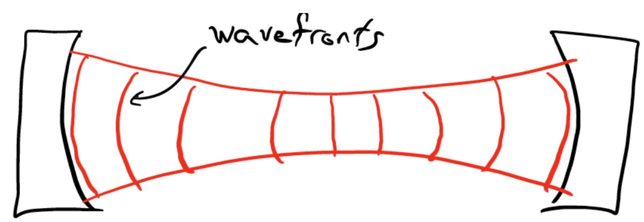
monochromatic field

"paraxial approximation"

$$\mathcal{E}(\vec{r}) = \mathcal{E}_0(x,y,z)\, e^{ikz}$$

$$\nabla_T^2 \mathcal{E}_0 + 2ik\frac{\partial \mathcal{E}_0}{\partial z} = 0,$$

Paraxial wave equation



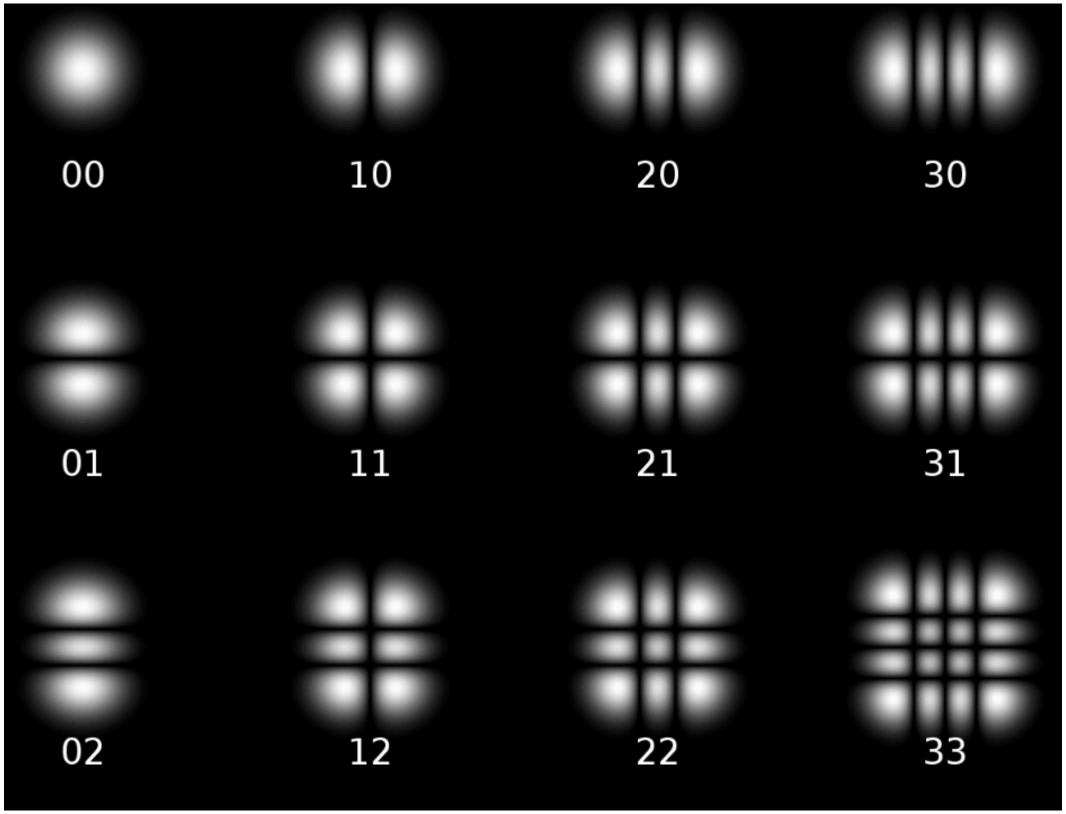
Lasers

$$\nabla_T^2 \mathcal{E}_0 + 2ik \frac{\partial \mathcal{E}_0}{\partial z} = 0,$$

Paraxial wave equation

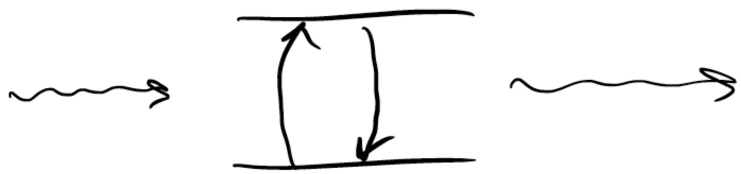
Solutions to the paraxial wave equation:

Example: Hermite-Gaussian polynomials



Lasers

Optical gain: need at least 3 energy levels to have more gain than absorption



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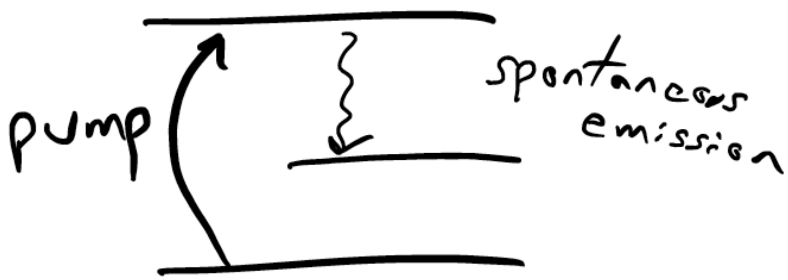

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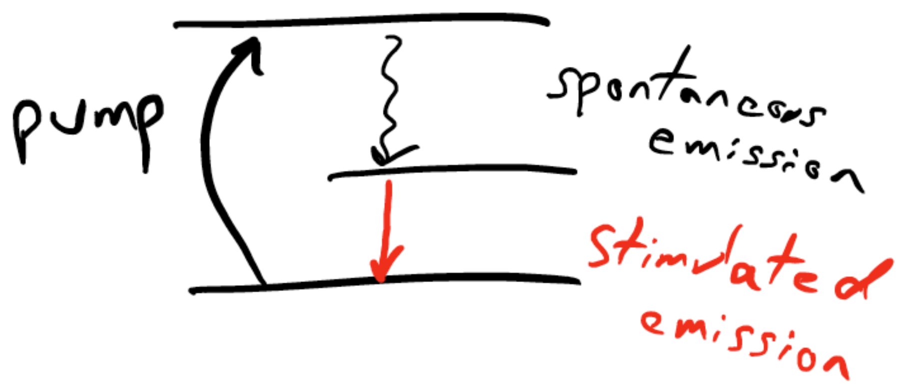
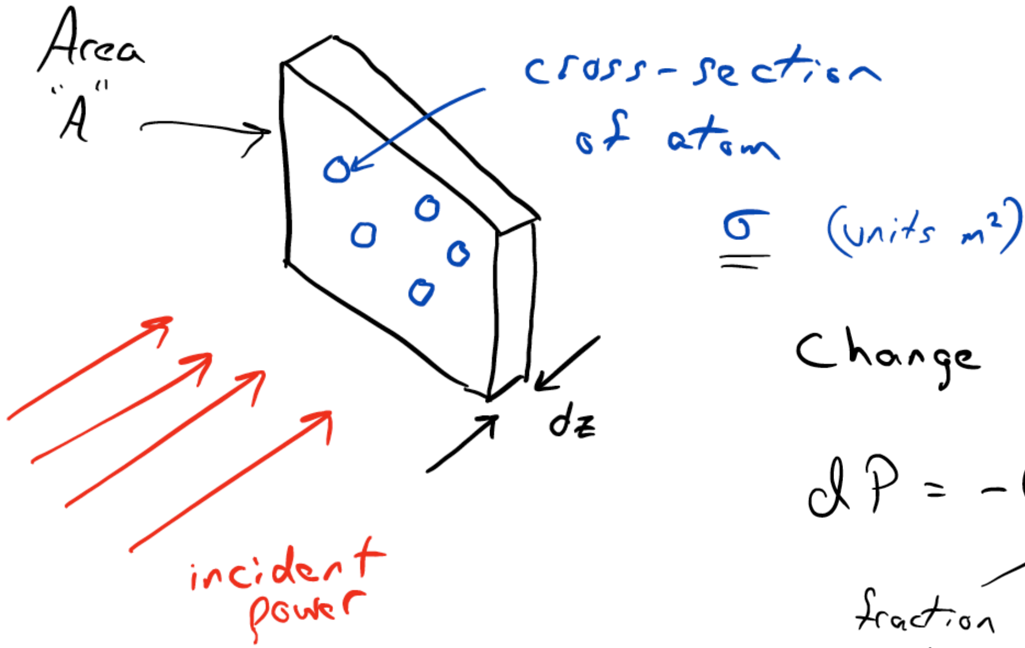


Rate equations determine population densities
i.e. pumping rate, decay rate, emission rate

Lasers

Characterizing optical gain: the atomic cross-section

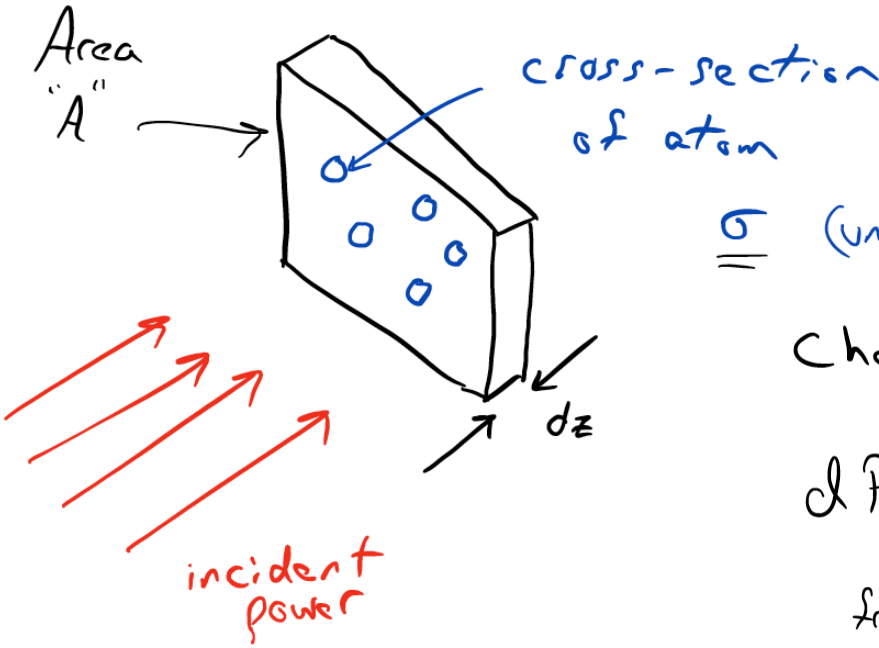


Change in power P

$$dP = -\left(\frac{\sigma}{A}\right)\cdot(N_1 - N_2)\cdot(A\cdot dz)\;P$$

- $\frac{\sigma}{A}$: fraction blocked/atom
- $(N_1 - N_2)$: # density of atoms in states 1 or 2
- $(A\cdot dz)$: volume

Characterizing optical gain: the atomic cross-section



σ (units m^2)

Change in power P

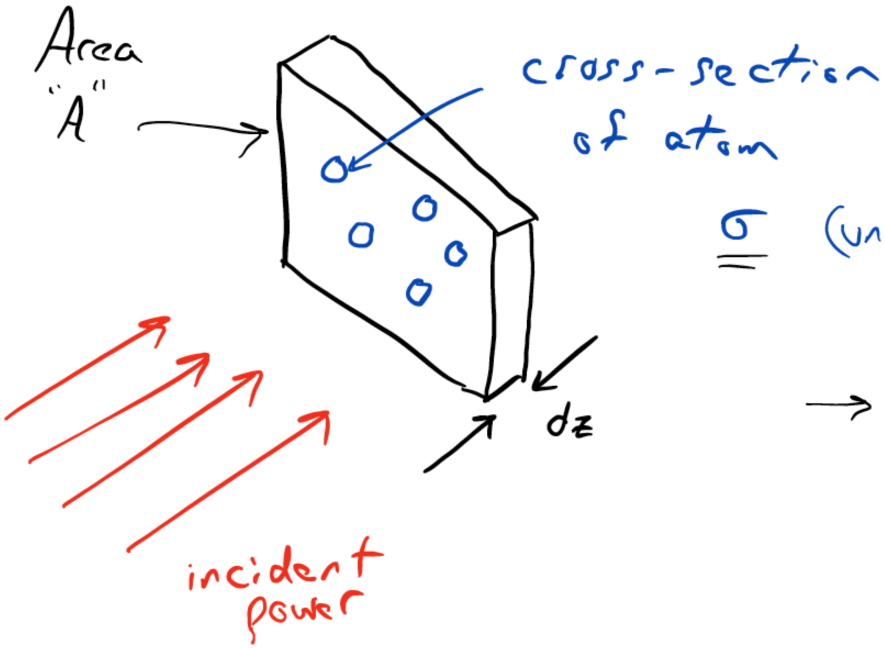
$$dP = -\left(\frac{\sigma}{A}\right) \cdot (N_1 - N_2) \cdot (A \cdot dz)\ P$$

- $\frac{\sigma}{A}$: fraction blocked/atom
- $(N_1 - N_2)$: # density of atoms in states 1 or 2
- $(A \cdot dz)$: volume

Rearranging

$$\boxed{\frac{dP}{dz} = -\sigma (N_1 - N_2) P}$$

Characterizing optical gain: the atomic cross-section



σ (units m^2)

$$\rightarrow \quad P(z) = P_0 \, e^{-\alpha z}$$

where $\alpha \equiv \sigma (N_1 - N_2)$
$= \sigma \Delta N$

If atoms in ground state, $\Delta N = N_1$

→ absorption (Beer's law)

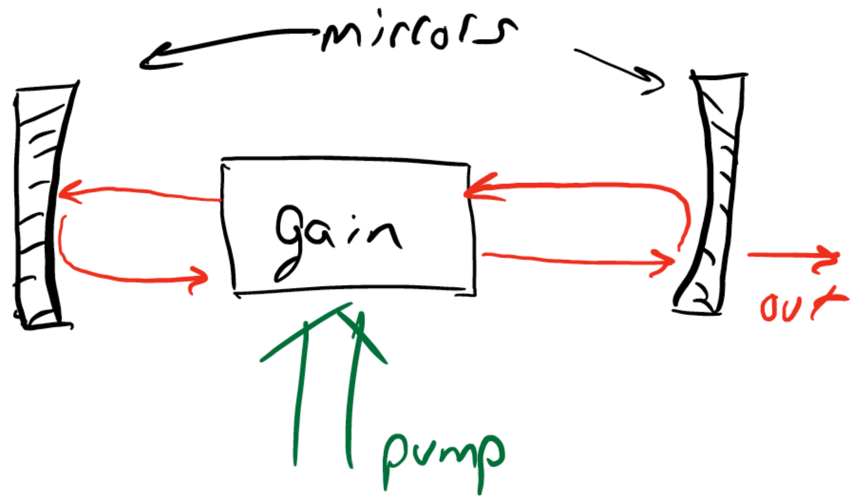
If $N_2 > N_1$ (population inversion)

→ gain!

Lasers

Steady-state lasing:

- gain requires population inversion
- initial field provided by spontaneous emission
- power in field grows until it significantly reduces population in level 2 → gain saturation
- steady-state lasing threshold is reach when round-trip gain = round-trip losses



Lasers as precision tools

Precision spectroscopy and atomic clocks

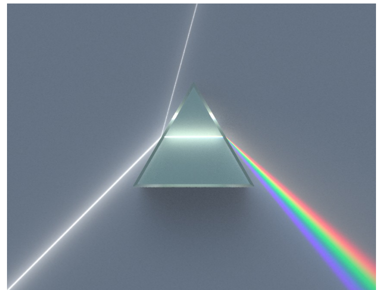
Femtosecond frequency combs

Generating laser light in the extreme ultraviolet

Precision Spectroscopy: unveiling the quantum world

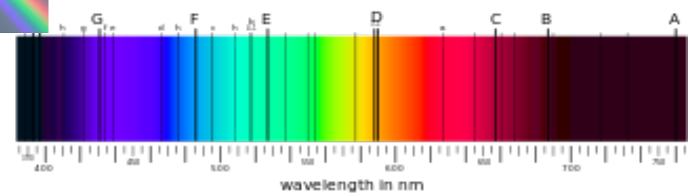
Dispersive spectrometer

- Spectral resolution 10^{-7}



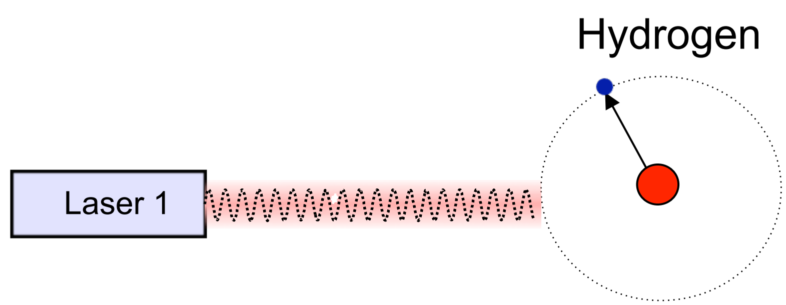
Joseph von Fraunhofer
1787- 1826

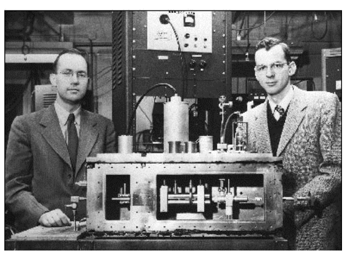
Sir Isaac Newton
1642-1726



High-resolution laser spectroscopy

- Spectral resolution 10^{-15}





ca. 1960
C. Townes

Maser

Tests of fundamental science:
- QED, Lamb Shift
- Rydberg constant
- α variation?
- Proton rms charge radius

State-of-the-art in precision spectroscopy

nature photonics
ARTICLES
PUBLISHED ONLINE: 9 SEPTEMBER 2012 | DOI: 10.1038/NPHOTON.2012.217

A sub-40-mHz-linewidth laser based on a silicon single-crystal optical cavity

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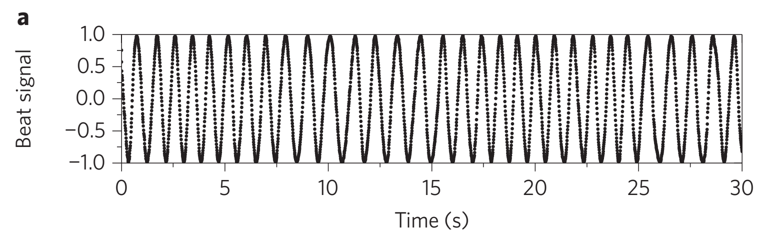

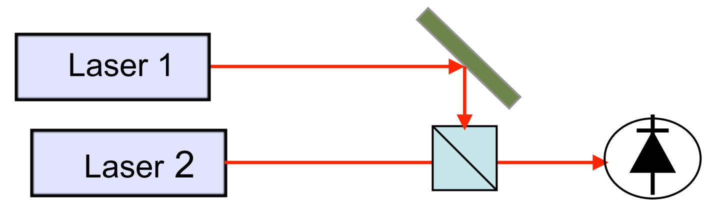

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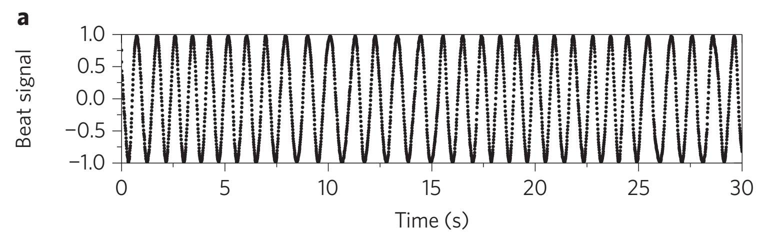
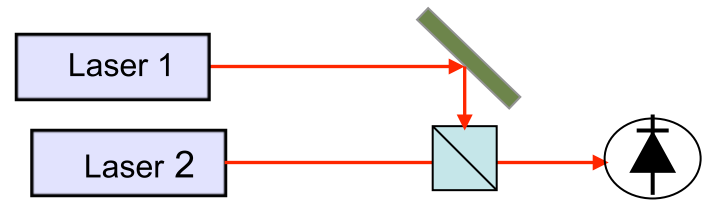
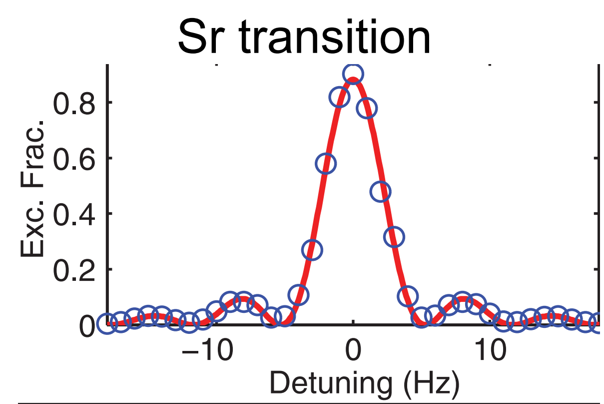




LETTER
doi:10.1038/nature12941

An optical lattice clock with accuracy and stability at the 10^{-18} level

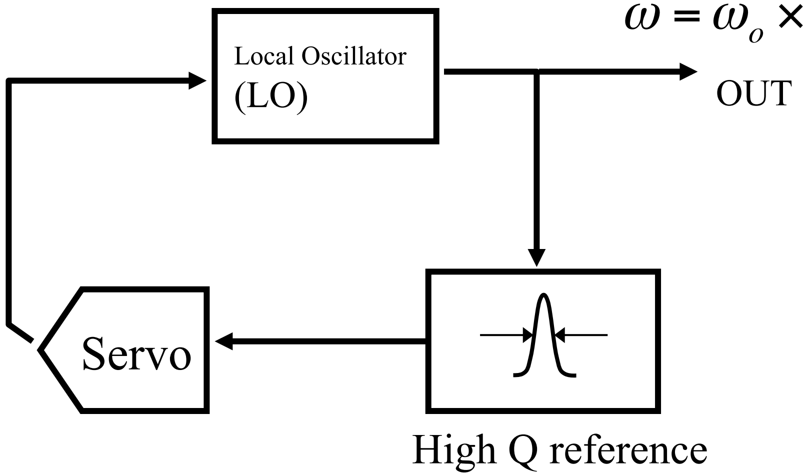
B. J. Bloom[1,2]*, T. L. Nicholson[1,2]*, J. R. Williams[1,2]†, S. L. Campbell[1,2], M. Bishof[1,2], X. Zhang[1,2], W. Zhang[1,2], S. L. Bromley[1,2] & J. Ye[1,2]



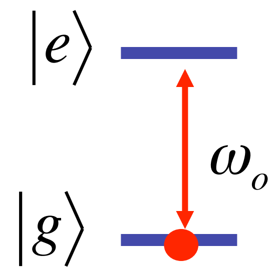
- Laser coherence lasting several seconds
- Precision spectroscopy at the Hz level

Atomic clock basics

$$\omega = \omega_o \times (1 + \varepsilon + \alpha(t))$$



Unperturbed atom

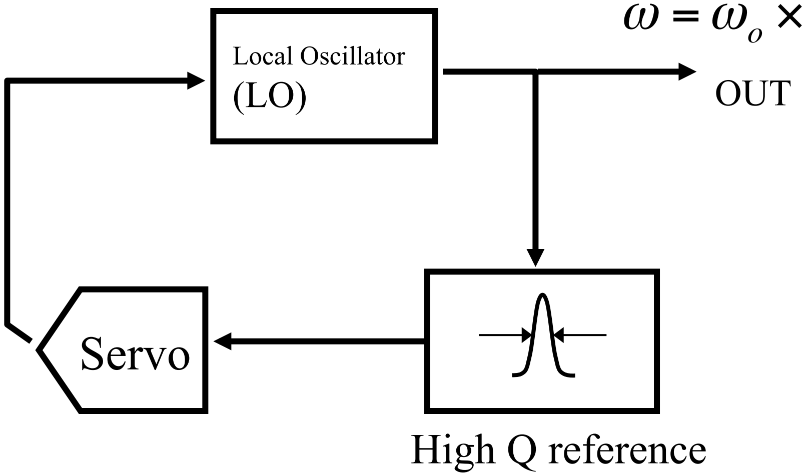


Cs microwave fountain

$$stability \sim 10^{-14}$$

Atomic clock basics

$$\omega = \omega_o \times (1 + \varepsilon + \alpha(t))$$



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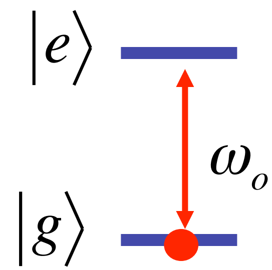
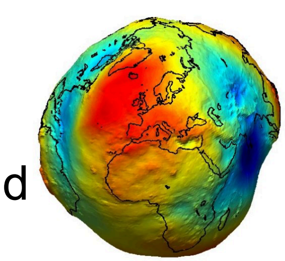


Cs microwave fountain

$$stability \sim 10^{-14}$$

Optical transitions → $stability \sim 10^{-18}$

Example: mapping the geoid

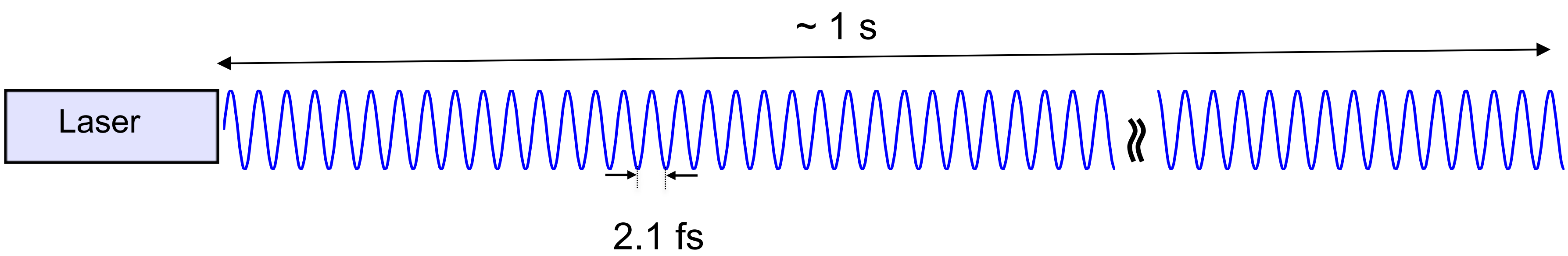


From the ultrastable to the ultrafast

The femtosecond frequency comb

From the ultrastable to the ultrafast

From seconds to femtoseconds…



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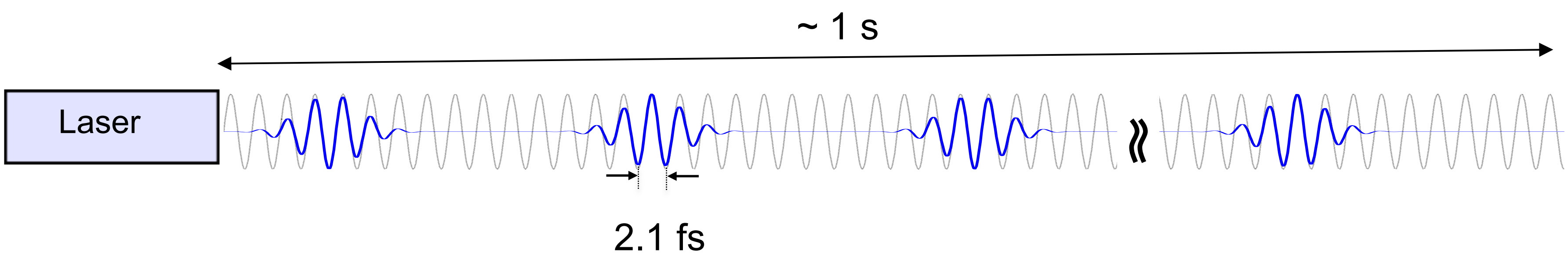

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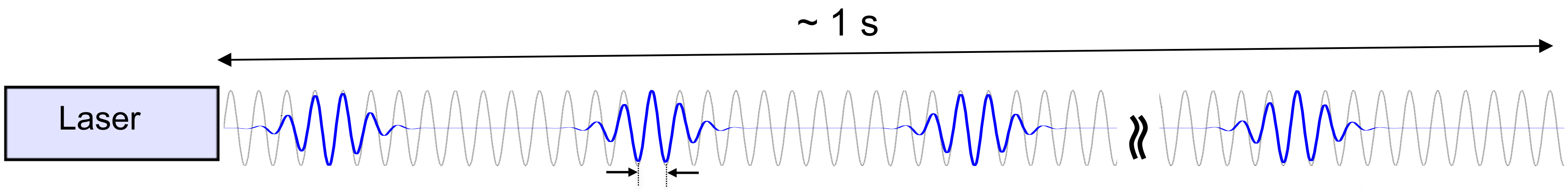
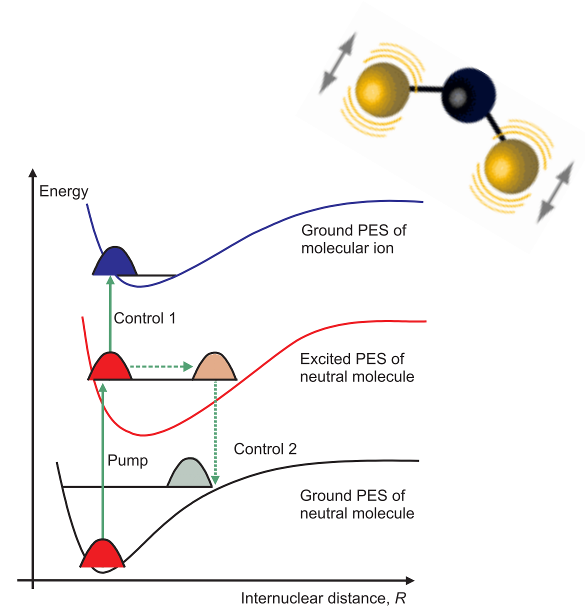




e.g. nuclear wavepacket control

Ultrafast Science

Probing (and control) of electronic and nuclear motion on femtosecond time scales.

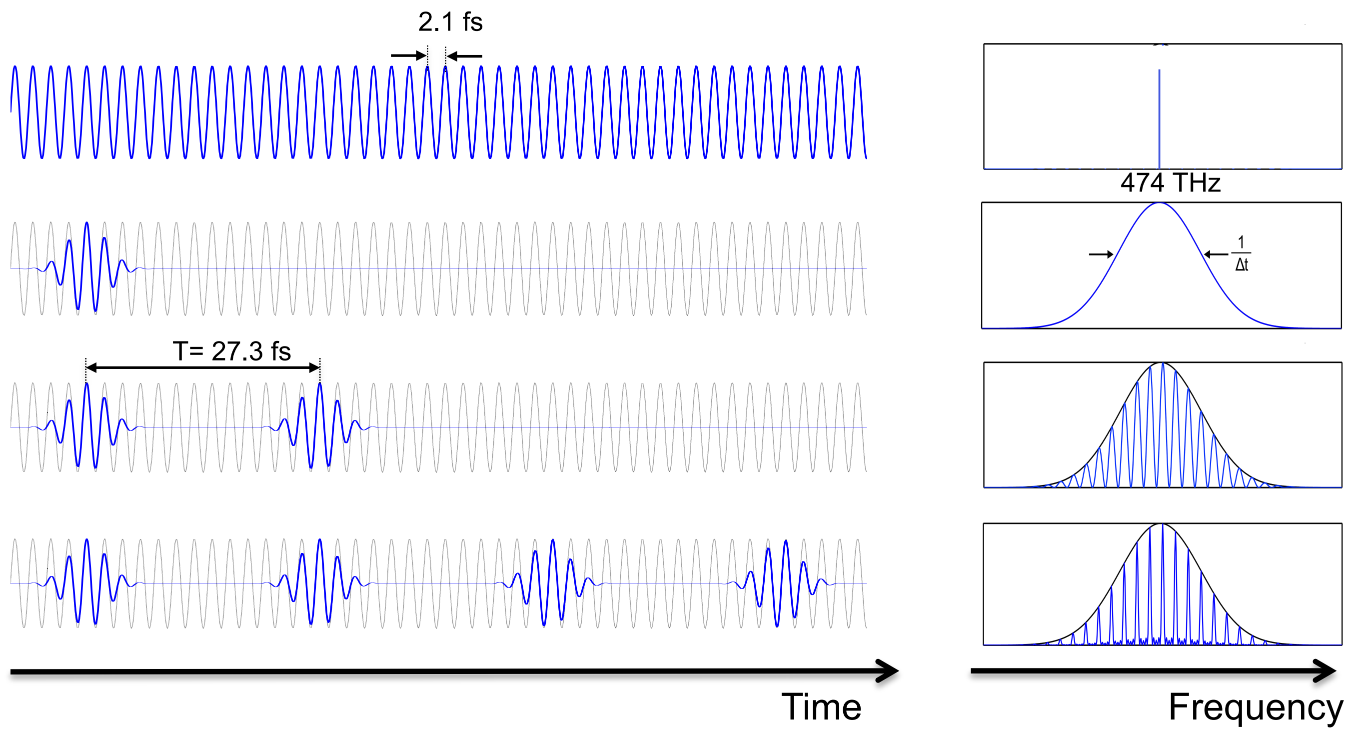
"Femtochemistry"

The Nobel Prize in Chemistry 1999
Ahmed Zewail

Fig. from F. Krausz and M. Ivanov, *Rev. Mod. Phys. Vol 81, 163 (2009)*

From the ultrastable to the ultrafast

From seconds to femtoseconds…



Spacing between fs comb “teeth” = 1/T

2005 Nobel Prize

"…for their contributions to the development of laser-based precision spectroscopy, including the ***optical frequency comb technique****".*

The Nobel Prize in Physics 2005

"for his contribution to the quantum theory of optical coherence"

"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"

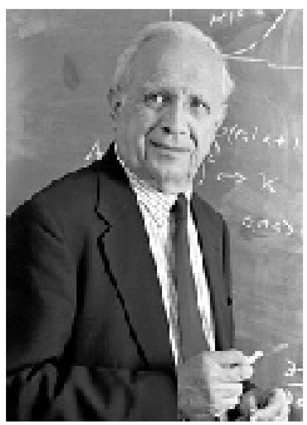


Photo: J.Reed

Roy J. Glauber

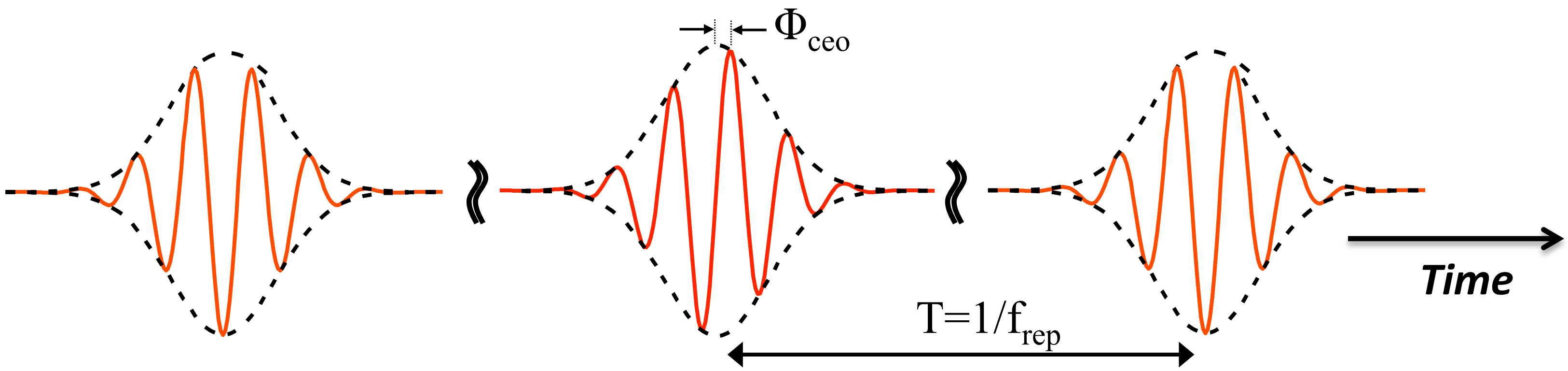
Photo: Sears.P.Studio

John L. Hall

Photo: F.M. Schmidt

Theodor W. Hänsch

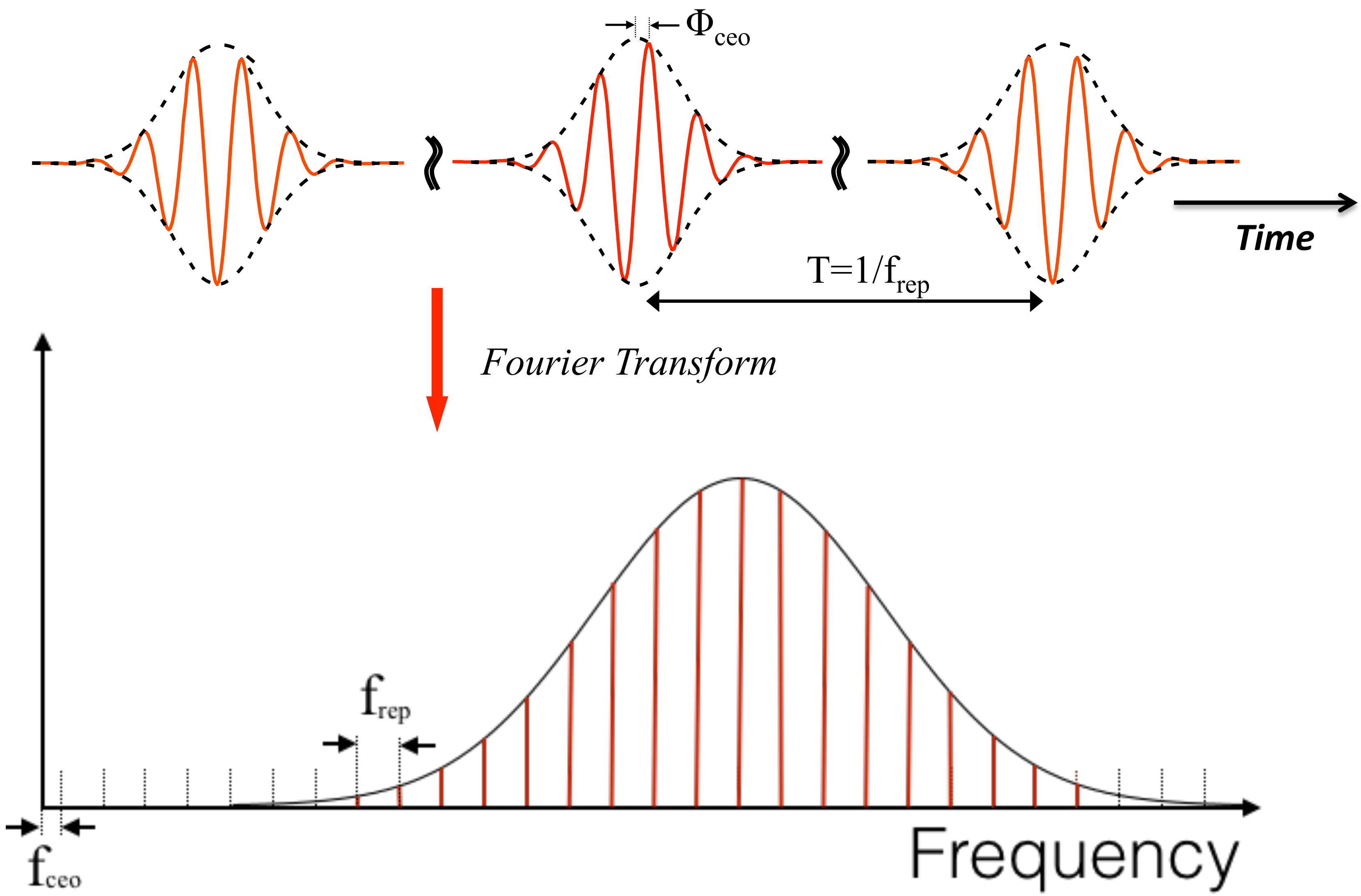
femtosecond frequency combs



Pulses are not identical…

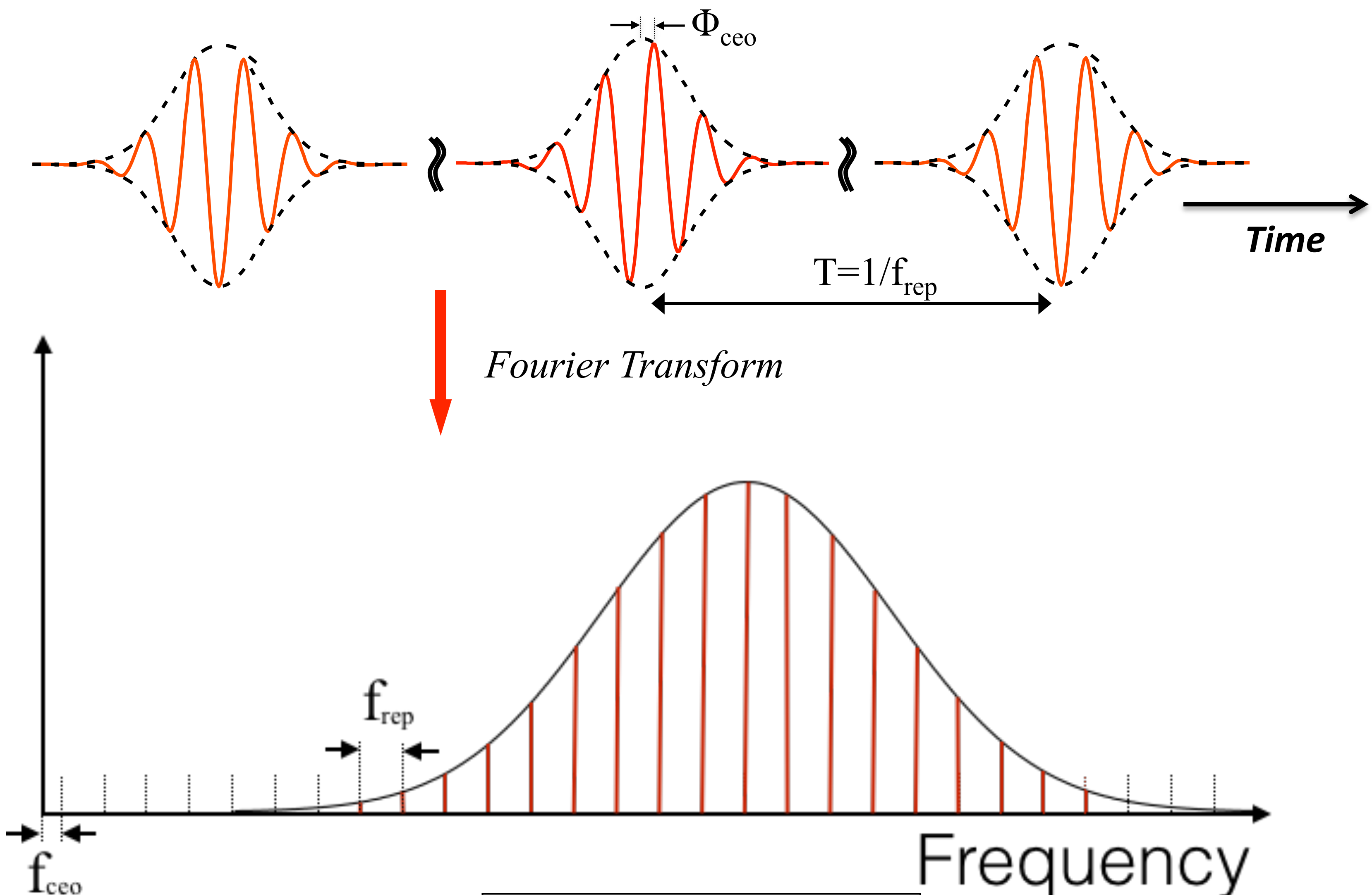
Any phase relationship between pulses?

femtosecond frequency combs



$f_{ceo} = \Delta\Phi_{ceo}/(2\pi T)$

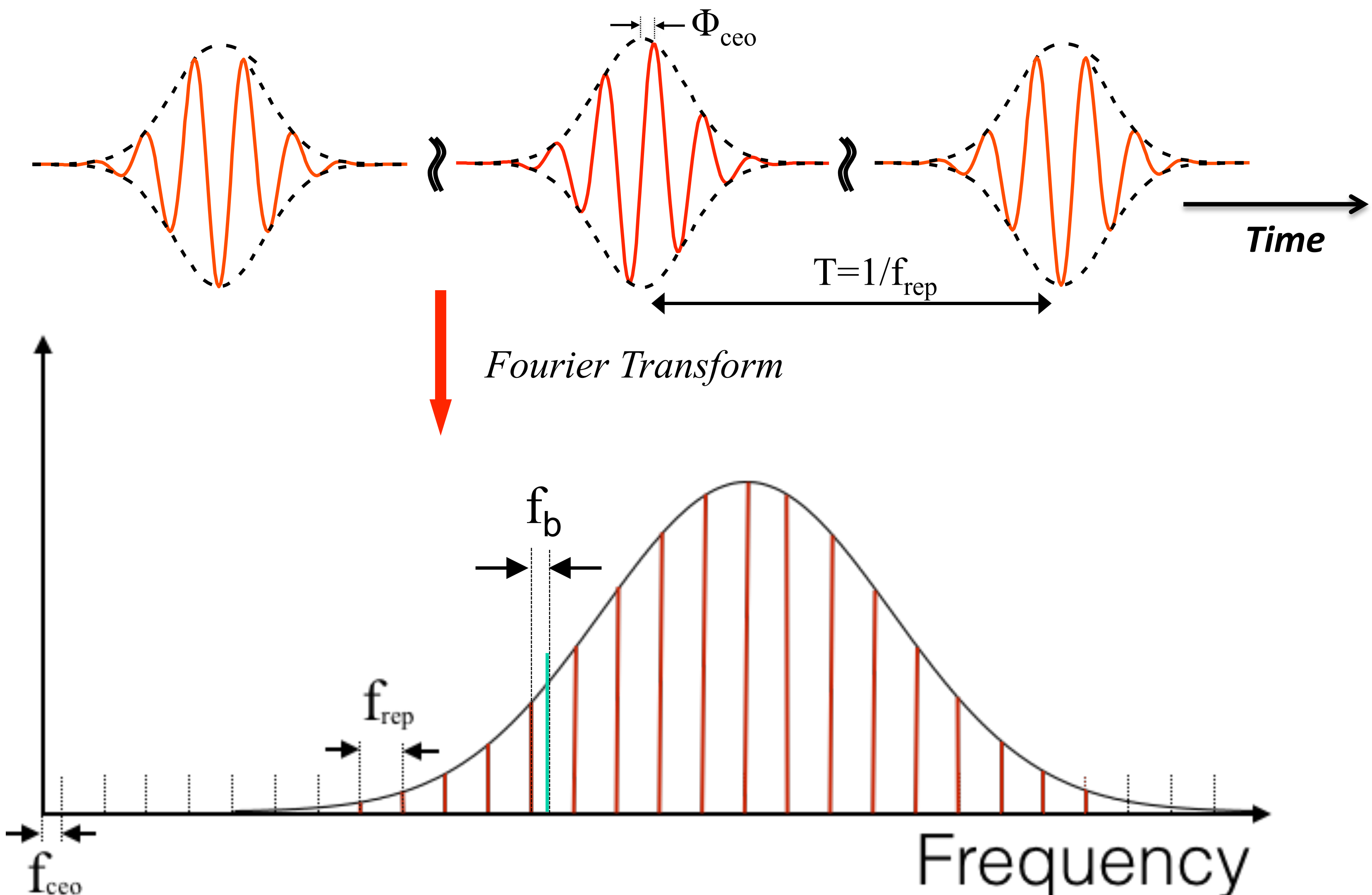
femtosecond frequency combs



$f_{ceo} = \Delta\Phi_{ceo}/(2\pi T)$

$$\nu_{optical} = m\, f_{rep} + f_{ceo}$$

femtosecond frequency combs

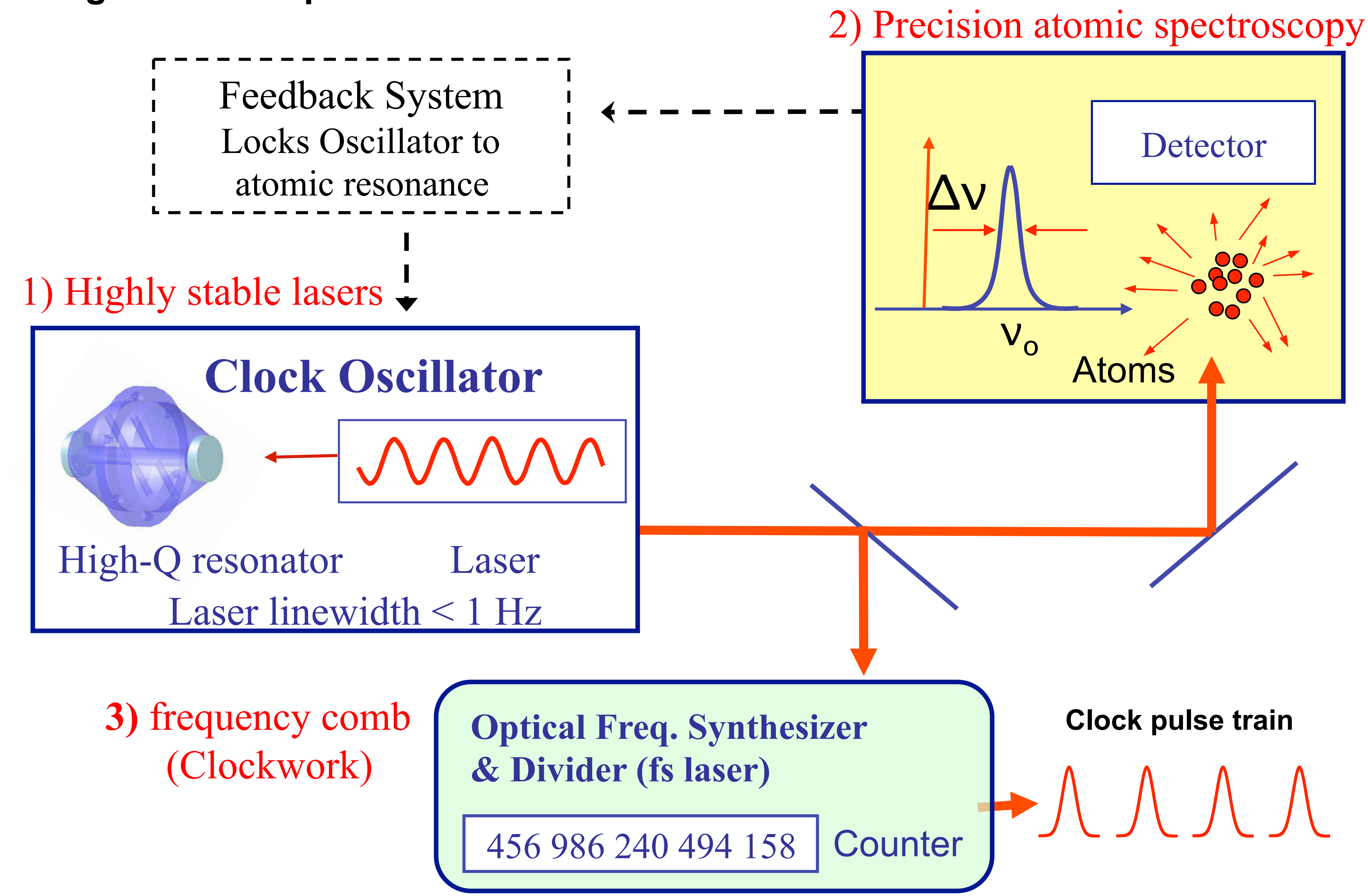


$f_{ceo} = \Delta\Phi_{ceo}/(2\pi T)$

$$\nu_{optical} = m\, f_{rep} + f_{ceo} + f_b$$

Applications of frequency combs

Next generation optical atomic clocks



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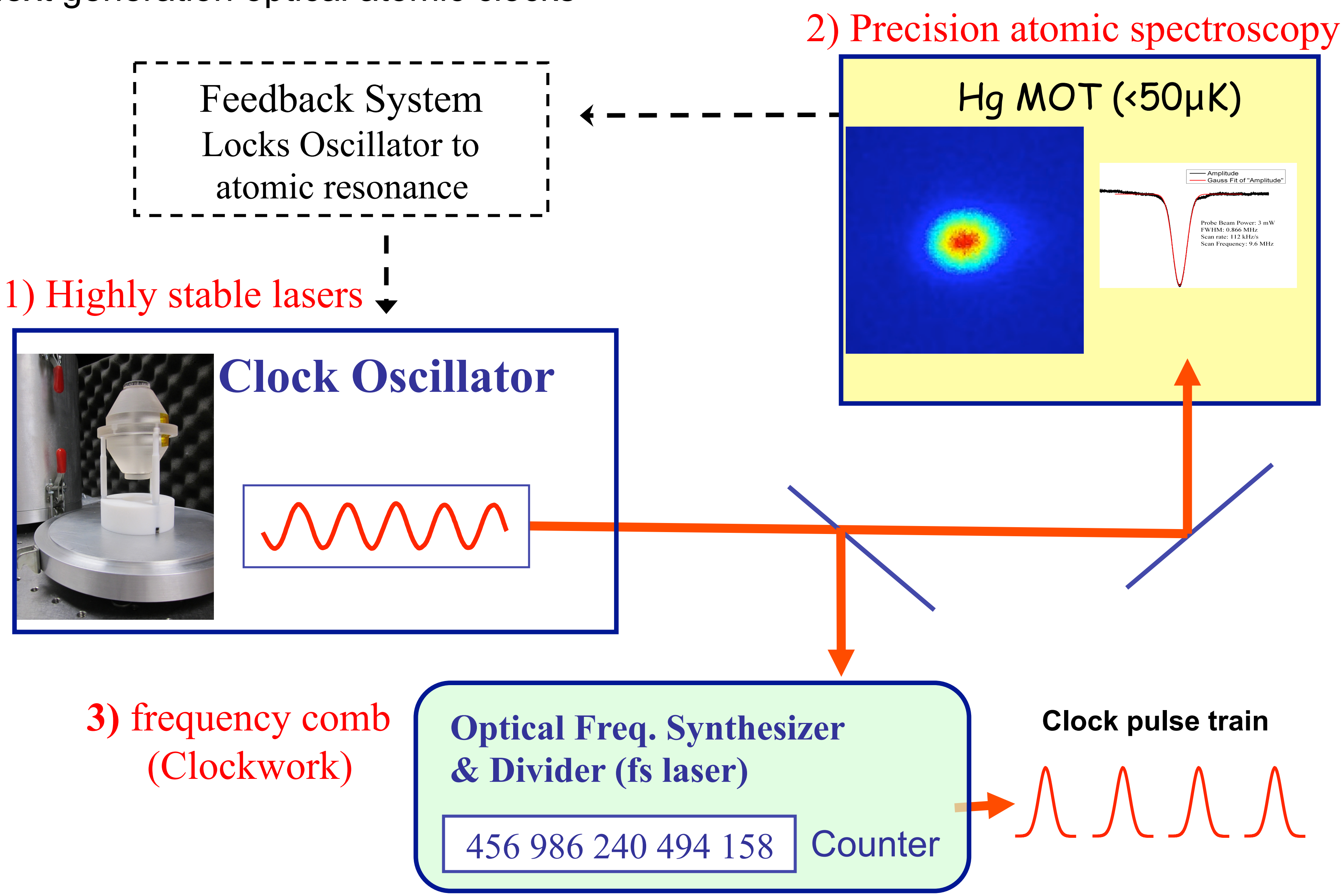
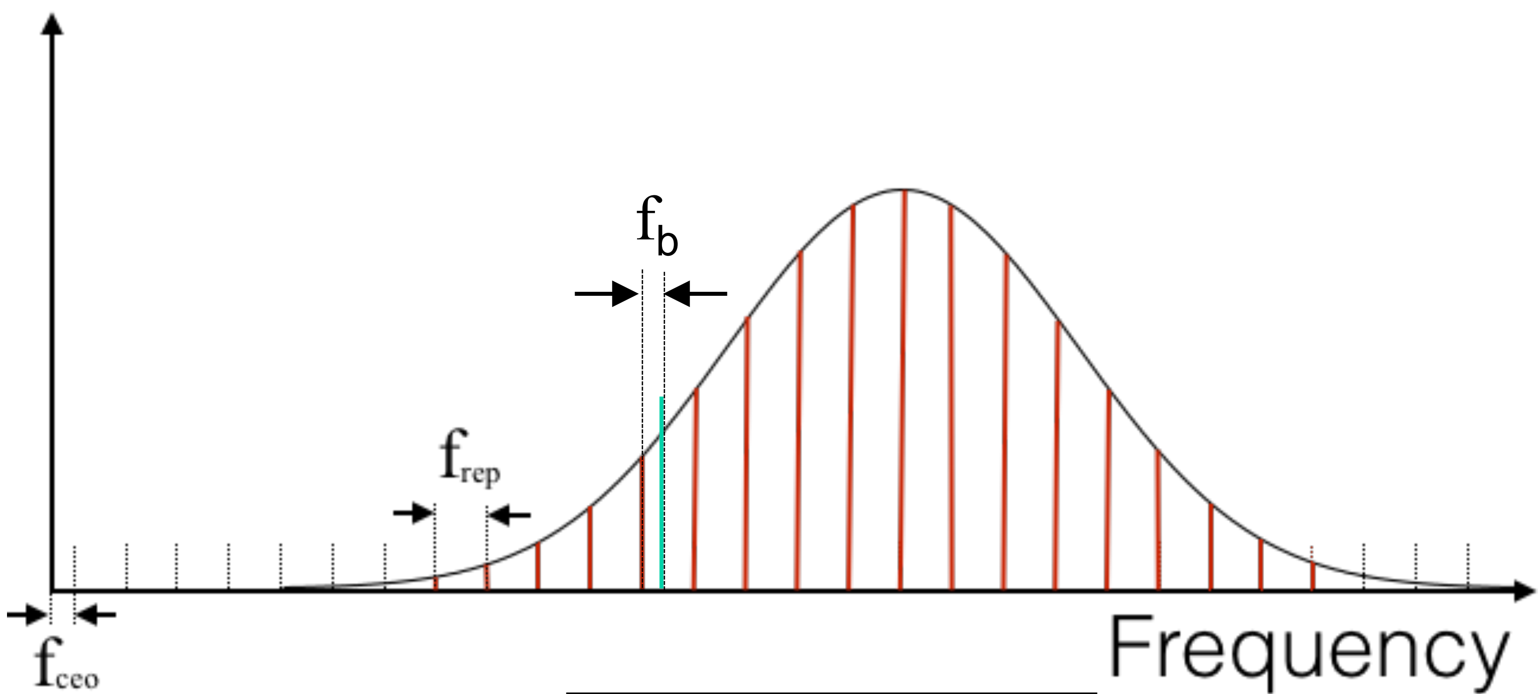
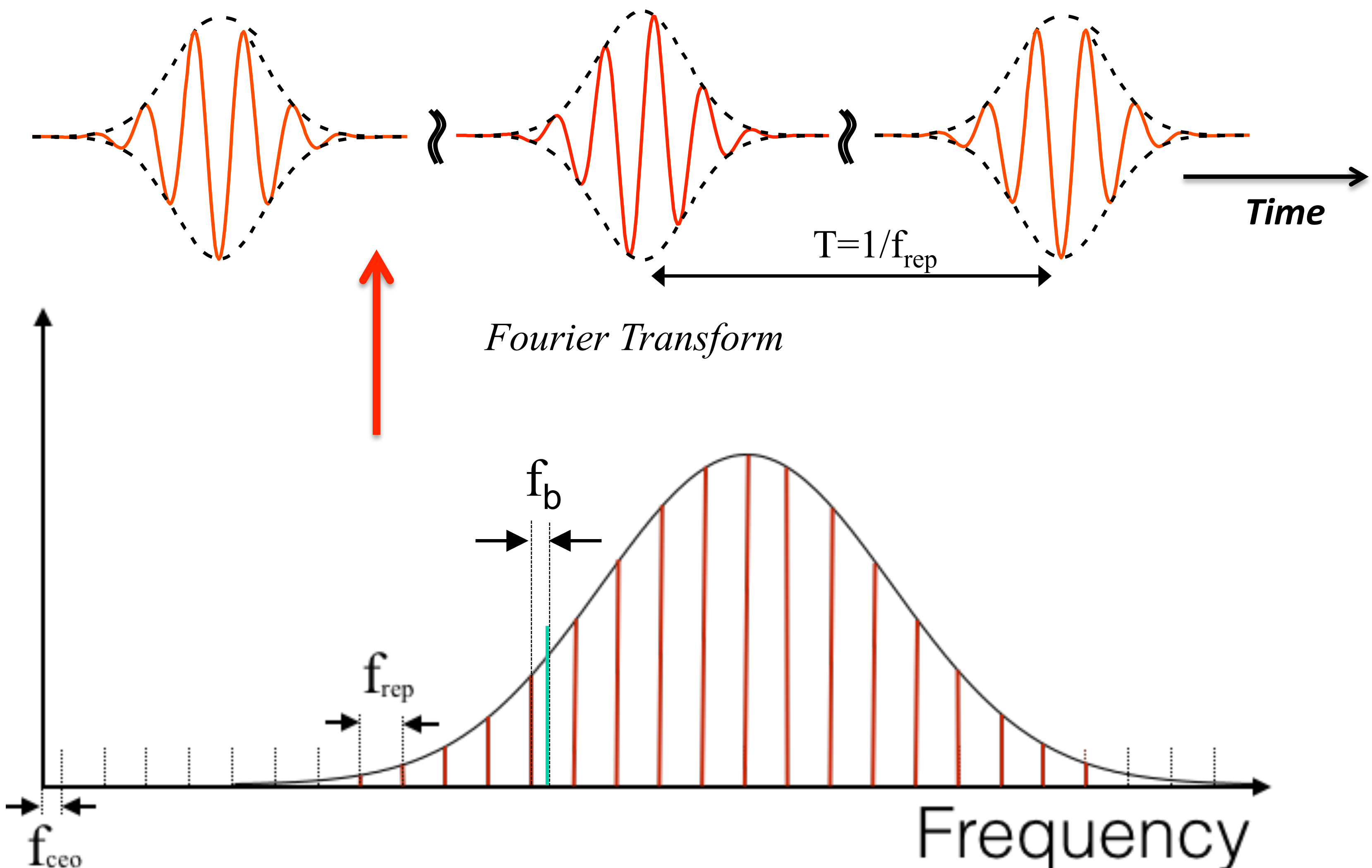


Time domain implications of the fs comb



$$\nu_{optical} = m f_r + f_o + f_b$$

Time domain implications of the fs comb



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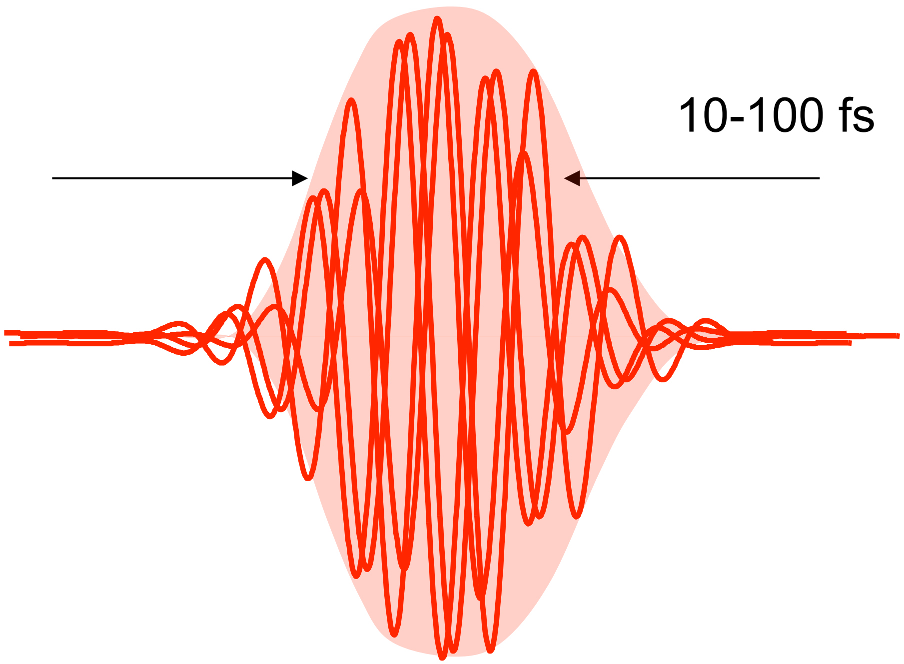
Attosecond time dynamics

Implications for the time domain….



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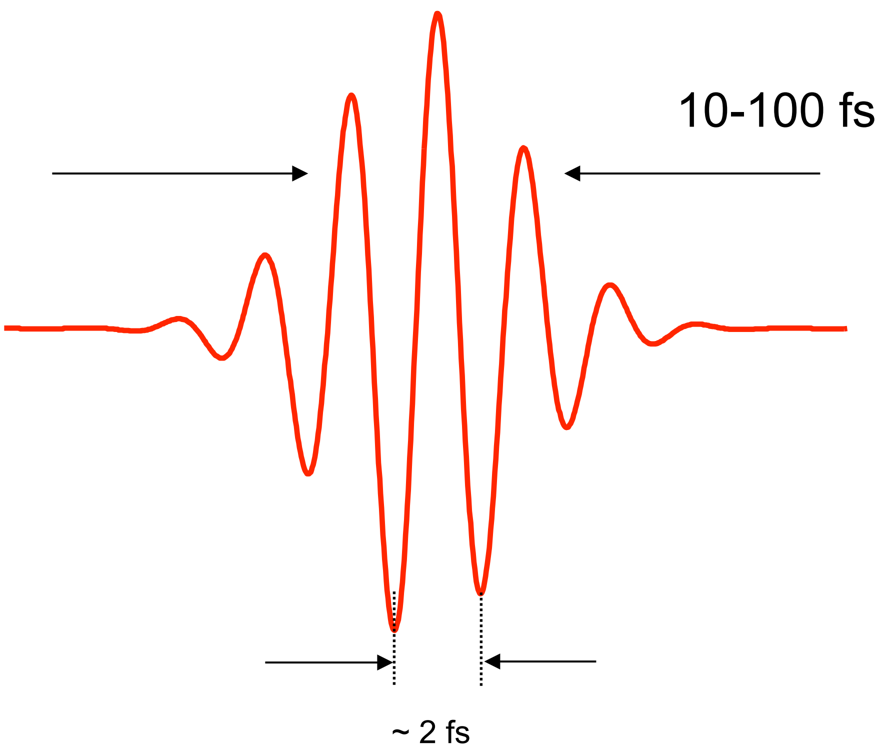

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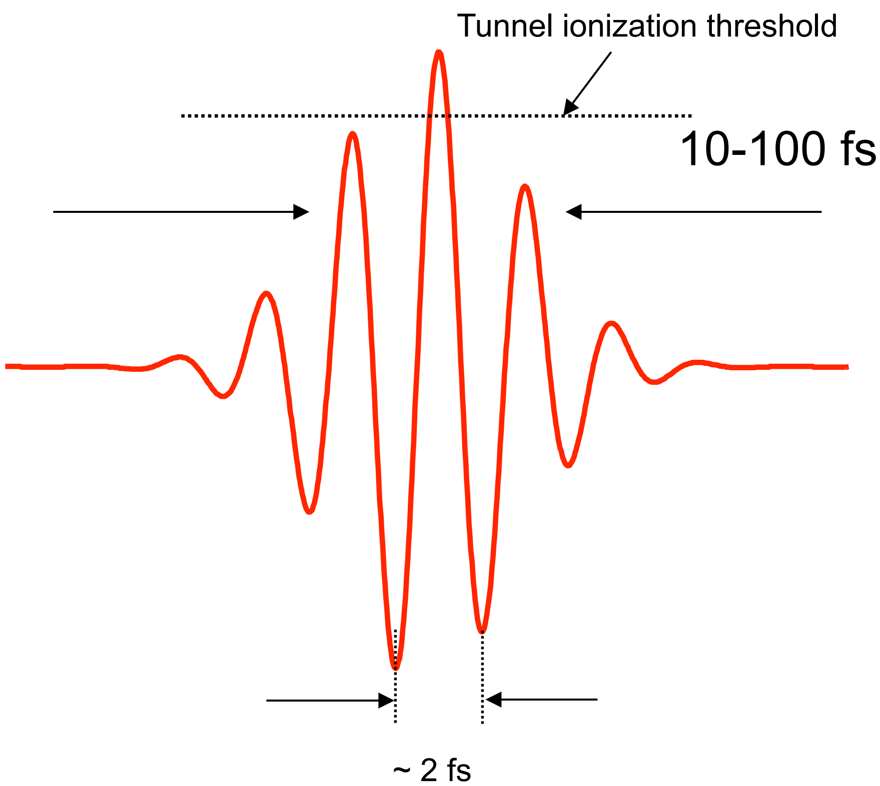


•Access controlled, high electric field strengths

•Femtosecond pulse synchronization

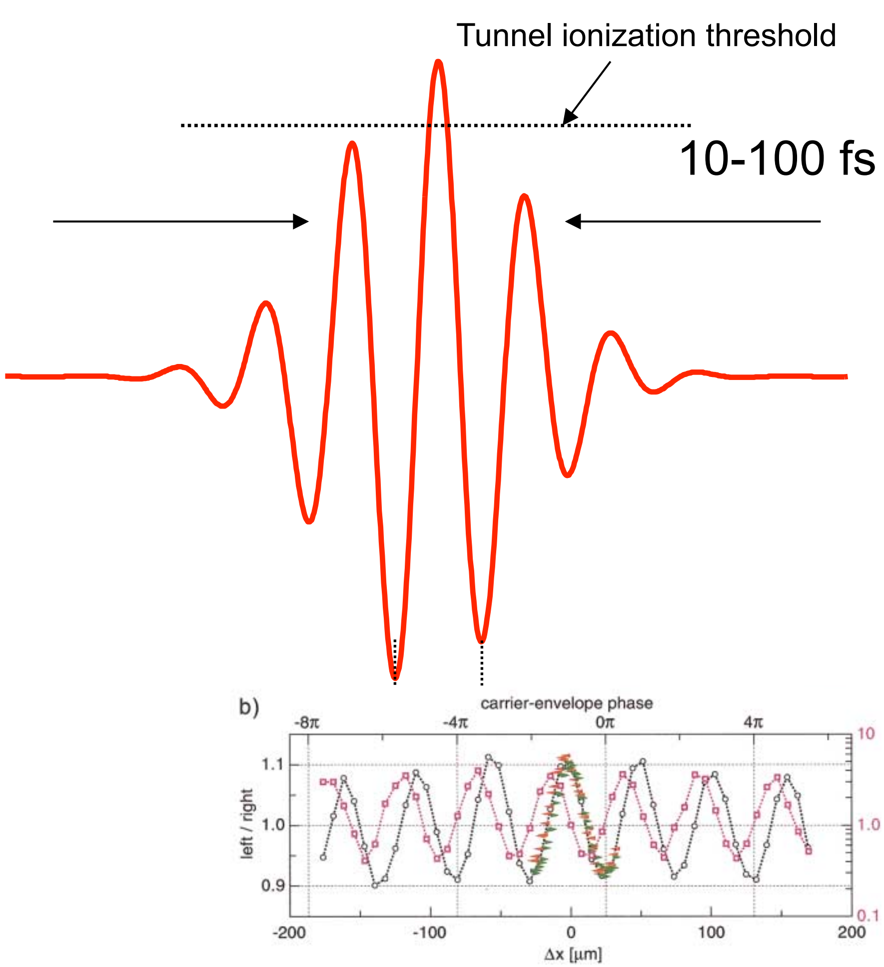
•Sub-cycle control of ionization dynamics

→"Absolute" phase detection
→Auger pump/probe spectroscopy

- Attosecond bursts of XUV light

Attosecond time dynamics

Implications for the time domain….



•e.g. G.G. Paulus et al., PRL 91, 253004 (2003).

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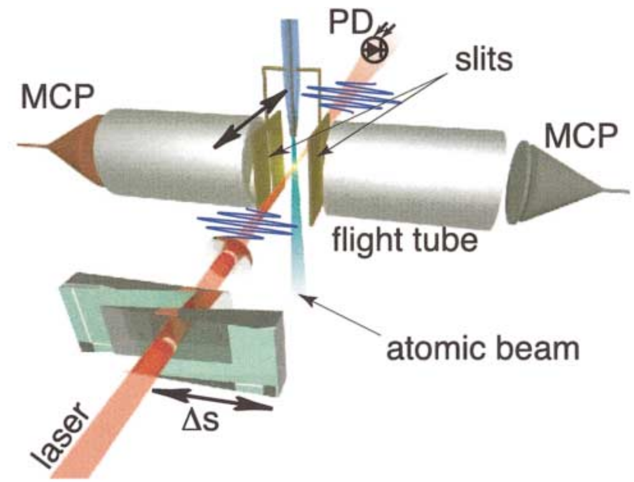
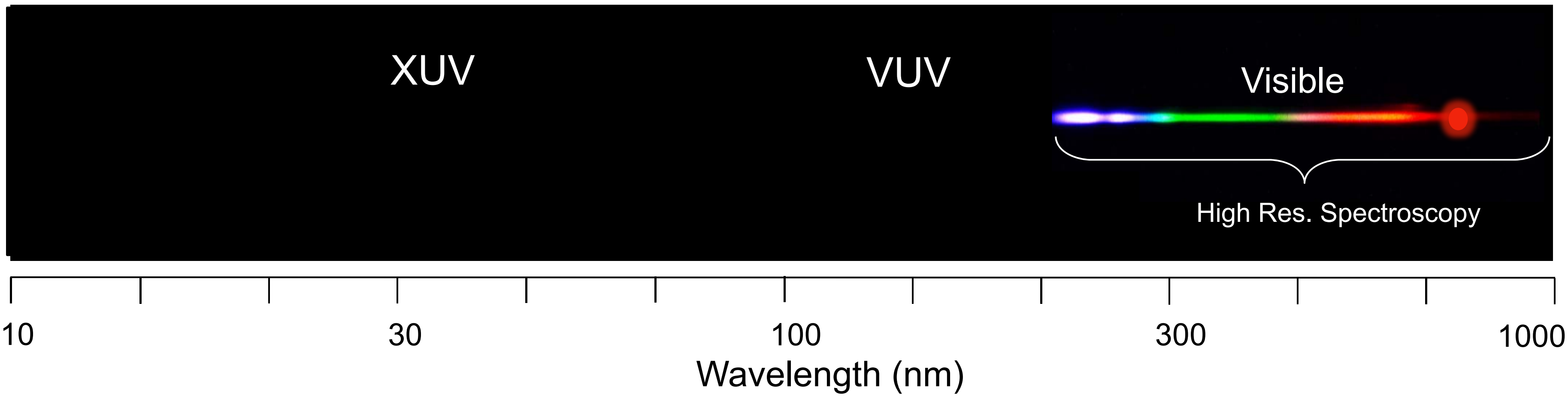


Extension to the VUV and XUV



Extending the fs frequency comb to the XUV

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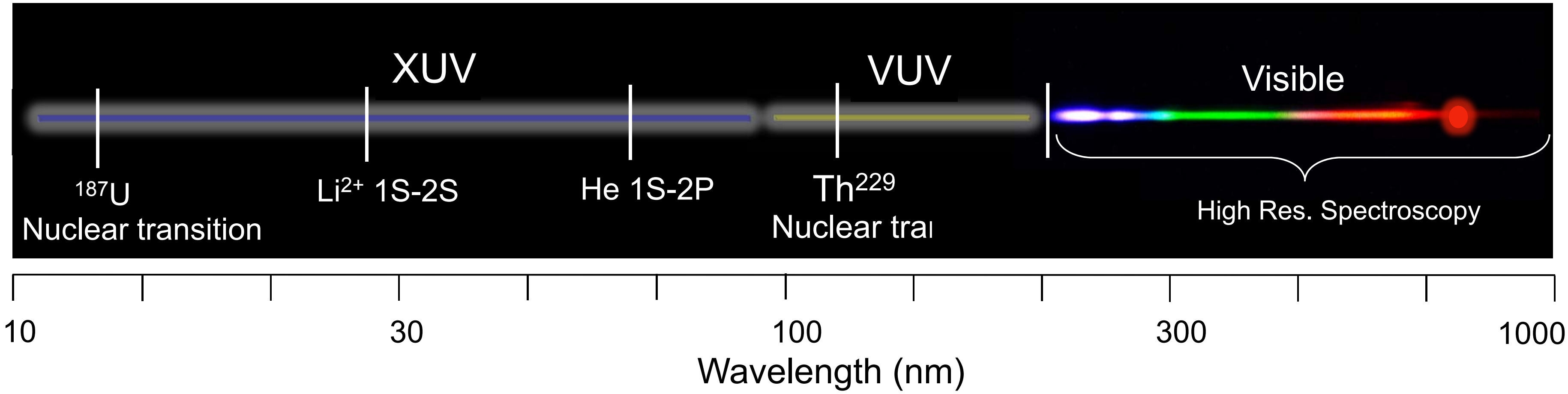

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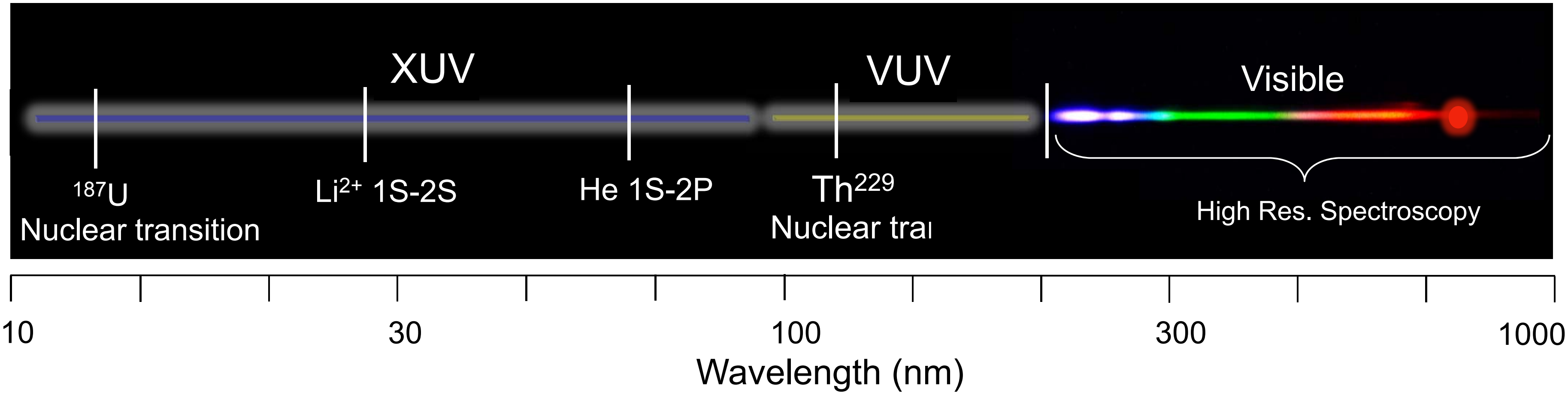
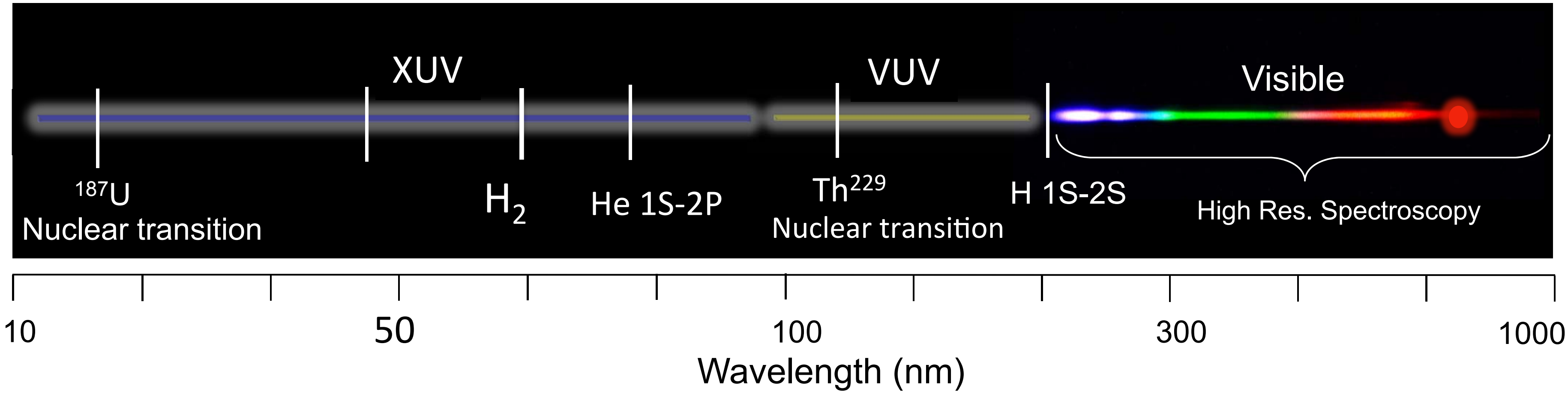
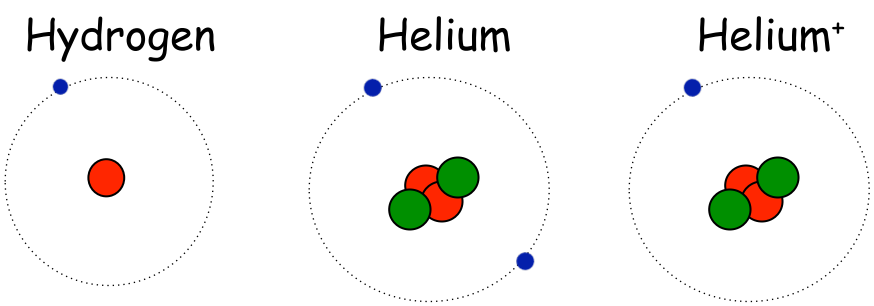


VUV spectroscopy still dominated by dispersive spectrometers

- Spectral resolution 10^{-7}

Extension to the VUV and XUV



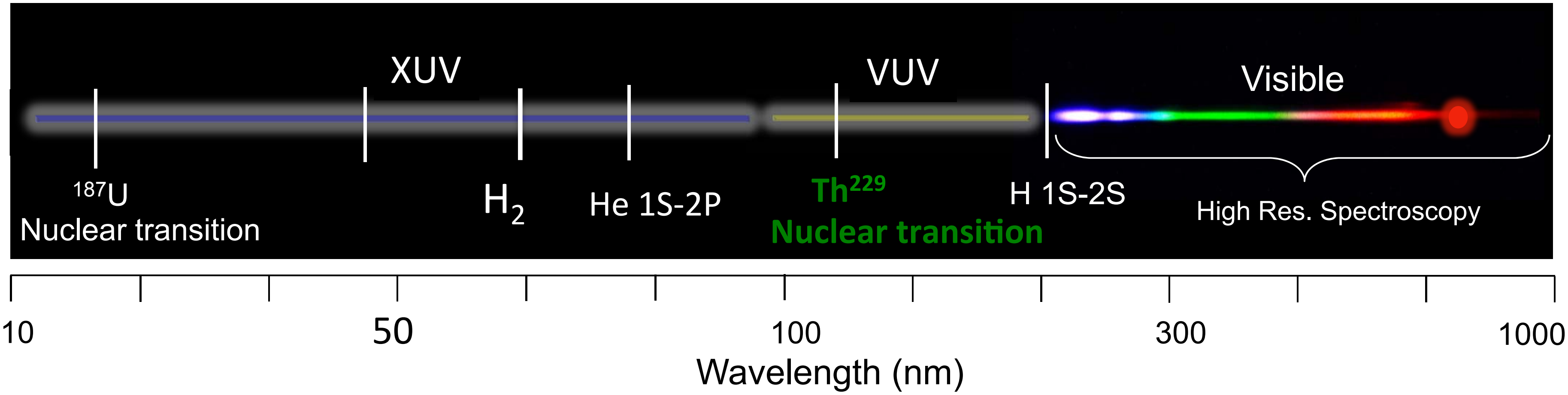


- Atomic/molecular spectroscopy

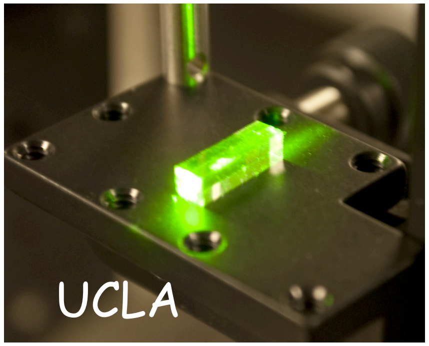
(e.g. H, He, He^+ H_2,H_2^+ O_2, NH_3, H_2O…)

- precision tests of fundamental constants (α , m_e/m_p) and QED
- Molecular spectroscopy of astrophysical importance.
- Direct measurement of Rydberg transitions.
  → H_2 dissociation energy

Extension to the VUV and XUV



- **Nuclear Spectroscopy?**
  - Isomeric M1 transition in Th-229 (~160 nm)
  - Thorium doped LiCAF crystals
  - A solid-state nuclear frequency standard?



Peik et al, Europhys Lett. 61, 181 (2003)
Beck et al, PRL 98, 142501 (2007)
Rellergert et al, PRL 104, 200802(2010)
Campbell, et al, PRL 106, 226001 (2011)

Extension to the VUV and XUV

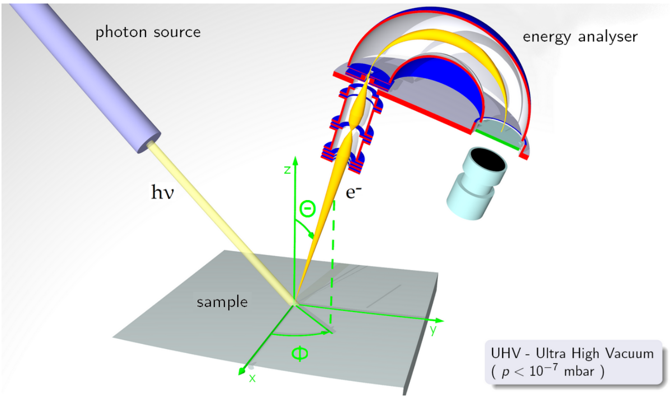
Ultrafast science MHz repetition rates → higher photon flux

Extension to the VUV and XUV

Ultrafast science MHz repetition rates → higher photon flux

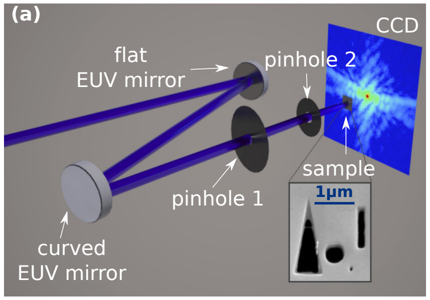
- **Photoemission spectroscopy of condensed matter**

→Signal limited by space charge effects per pulse



- **Coherent diffractive imaging**

→High flux short wavelength source



Zhang et. al., Opt. Express, 21, 2197 (2013)

High Harmonic Generation

- “Robust” approach: harmonics generated into “soft” x-ray regime

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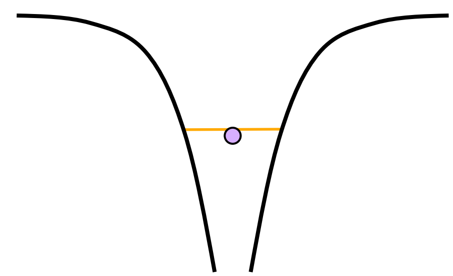
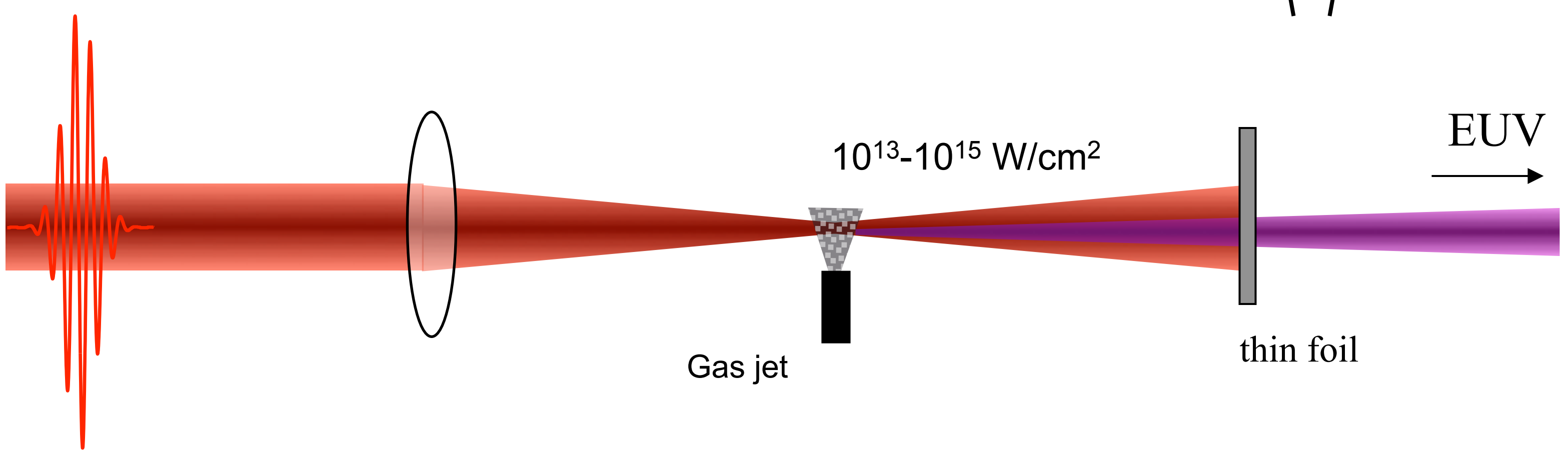
- Main features explained by simple "three-step" model

Step 1: Tunnel ionization

Step 2: Electron evolution and acceleration

Step 3: Recollision with ionic core.





<u>Single</u> amplified pulse

P.B. Corkum, PRL 49, 2117 (1994)
M. Lewenstein et. al., PRA 49, 2117 (1994)

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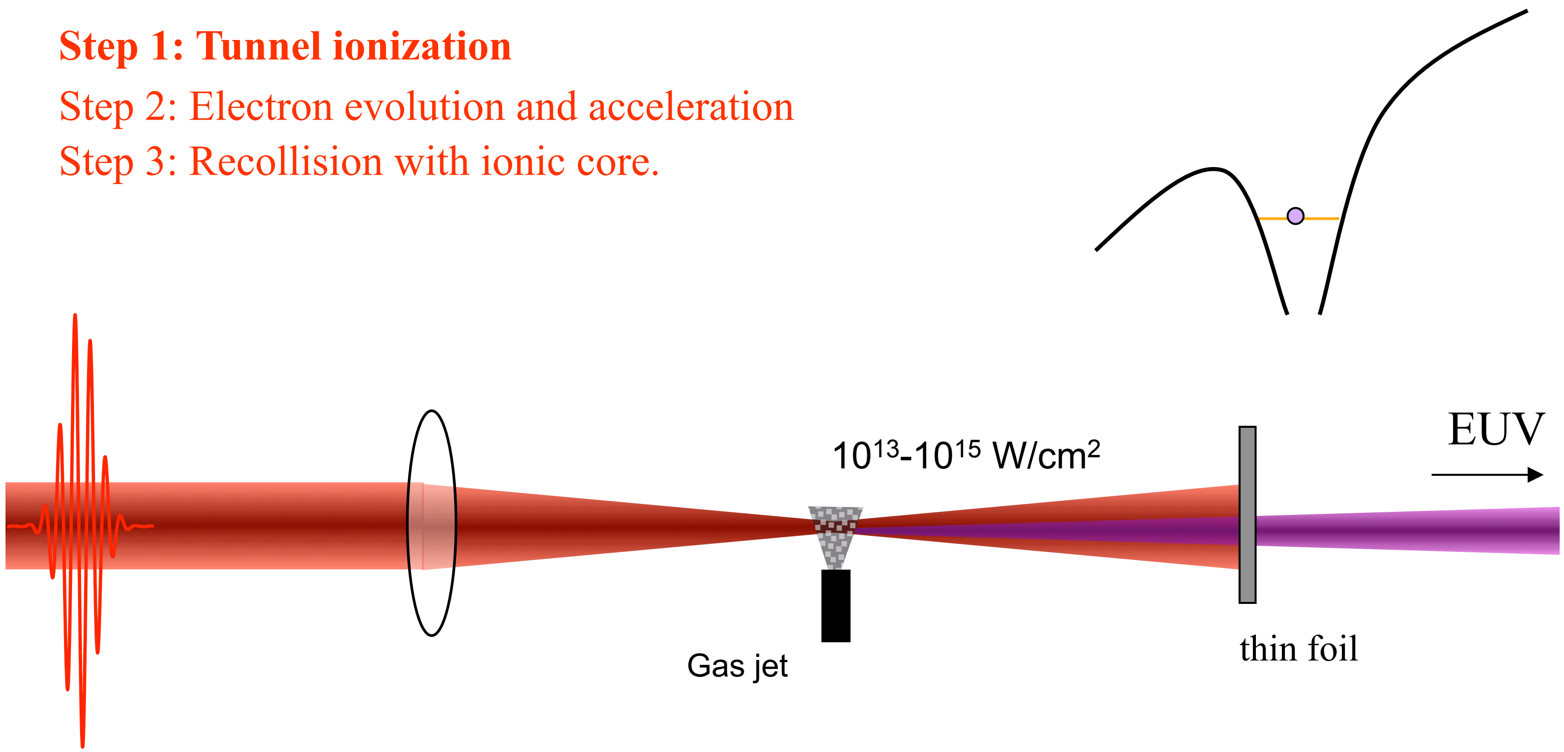

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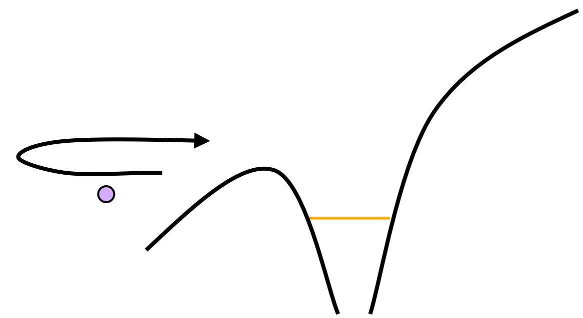

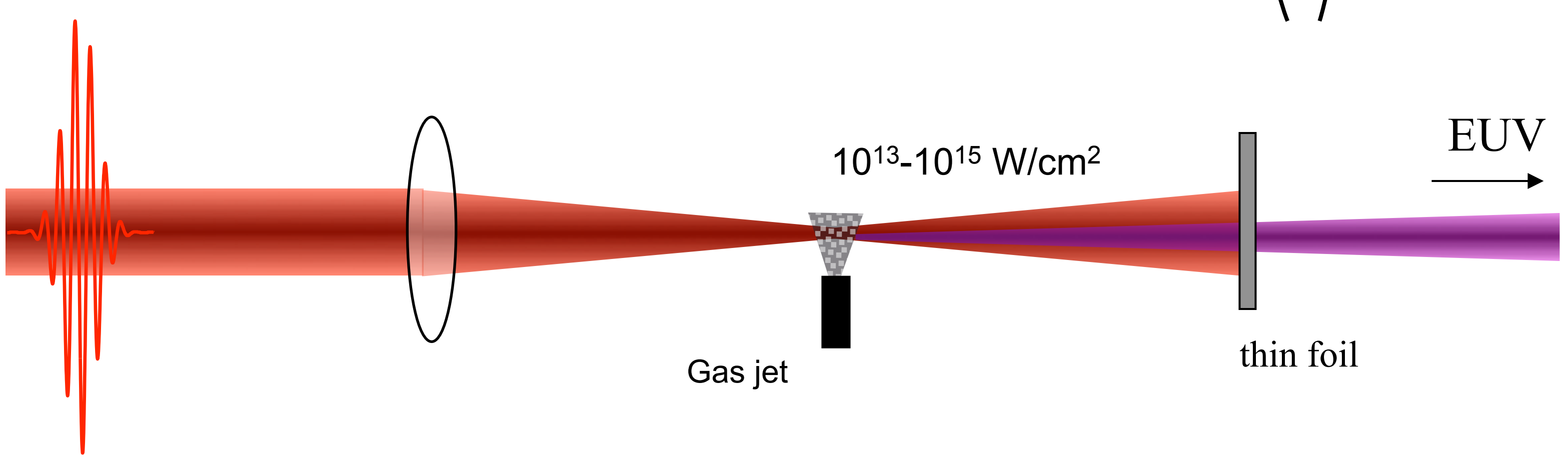

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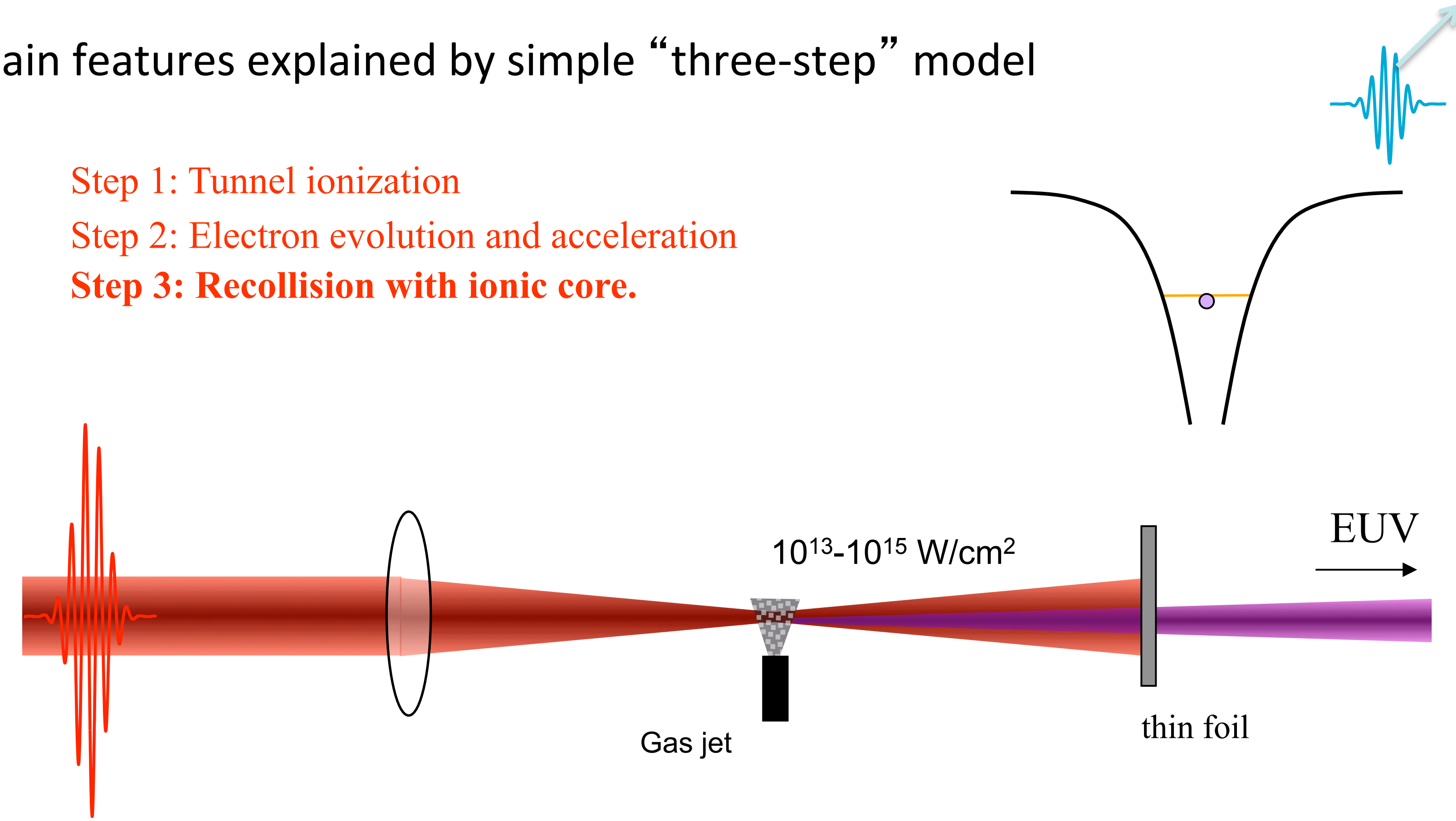

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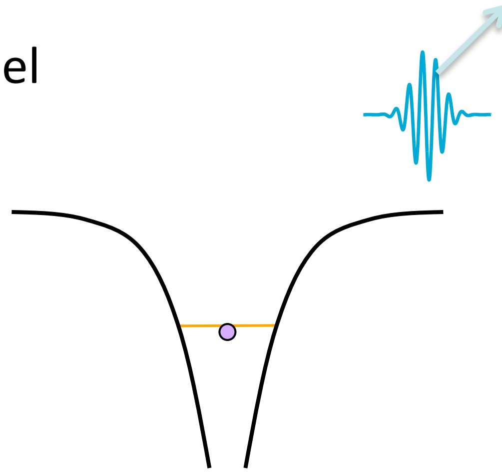

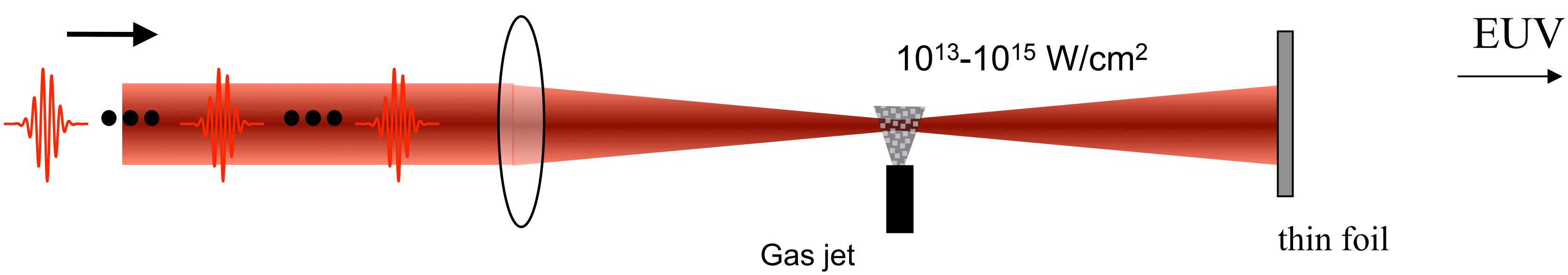

fs pulse train→ low energy per pulse

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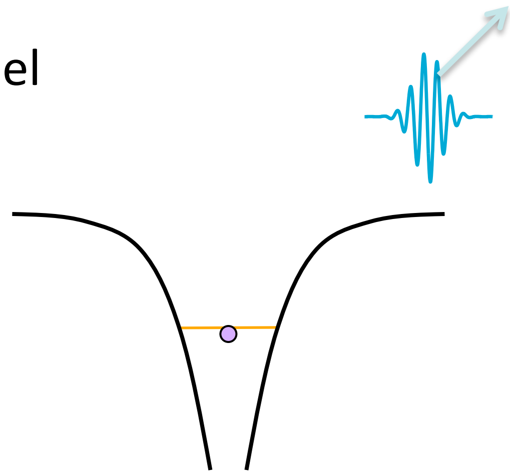

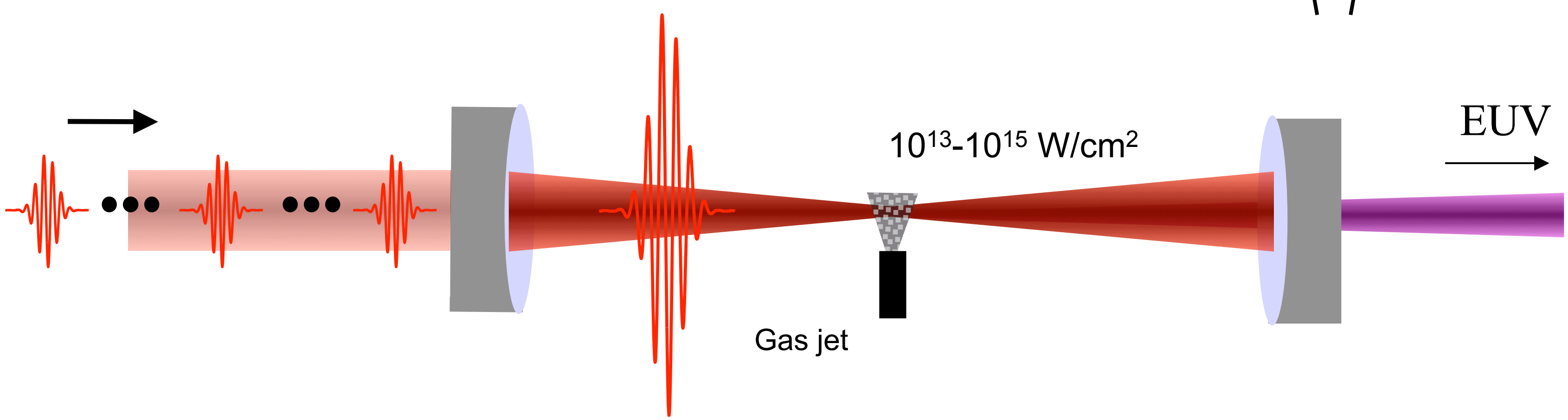

Use optical cavity to enhance power

P.B. Corkum, PRL 49, 2117 (1994)
M. Lewenstein et. al., PRA 49, 2117 (1994)

Thanks for your attention!