Fifty Years of Laser Science

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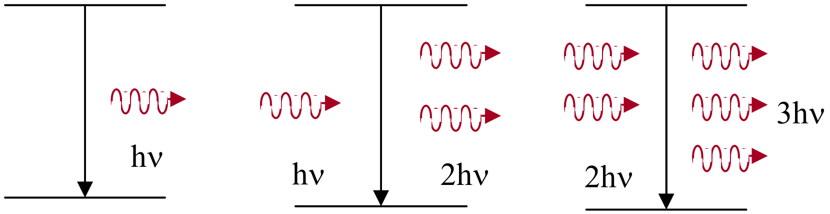
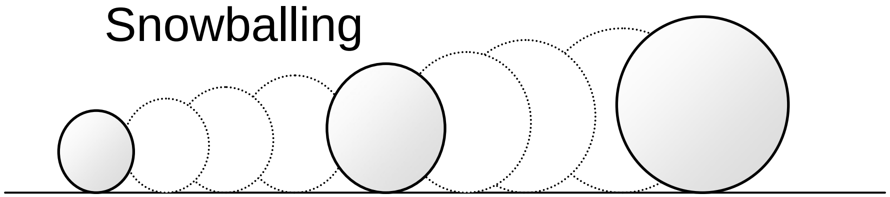
Light Amplification by Stimulated Emission of Radiation

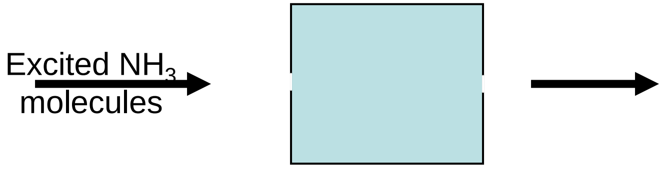
Stimulated emission rate ∝ Number of photons present in the emission mode (Einstein, 1916)





Invention of Maser

C.H. Townes, 1951



Excited NH_3 molecules

Microwave Cavity

Early Comments of Eminent Scientists on Townes' Maser Wrok

Rabi and Kusch:

> *You should stop the work you are doing. It isn't going to work. You are wasting* ***money****. Just stop.*

Bohr:

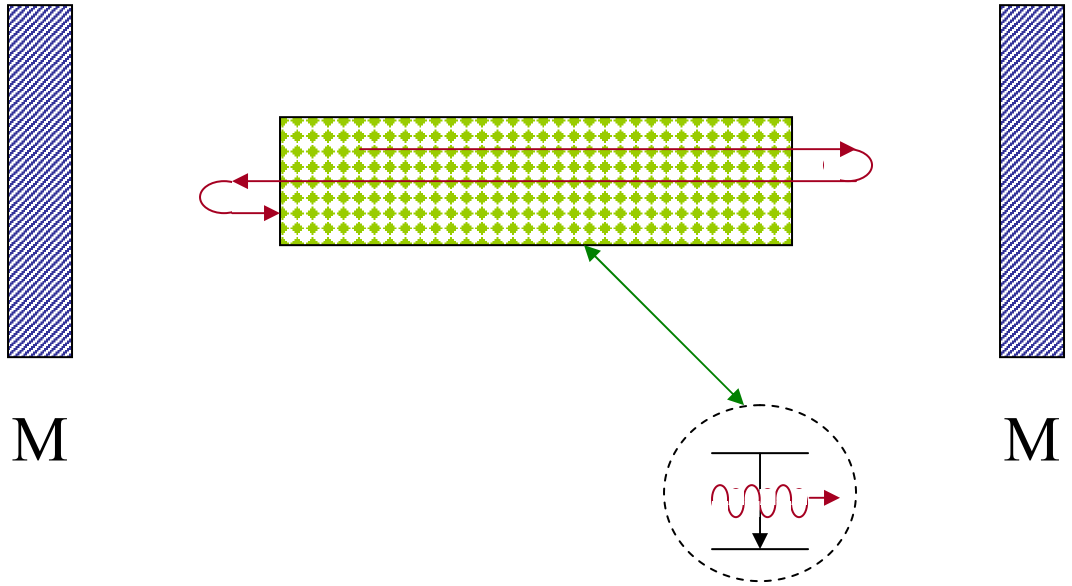
> *But this is not possible.*

Von Neumann:

> *That can't be right.*

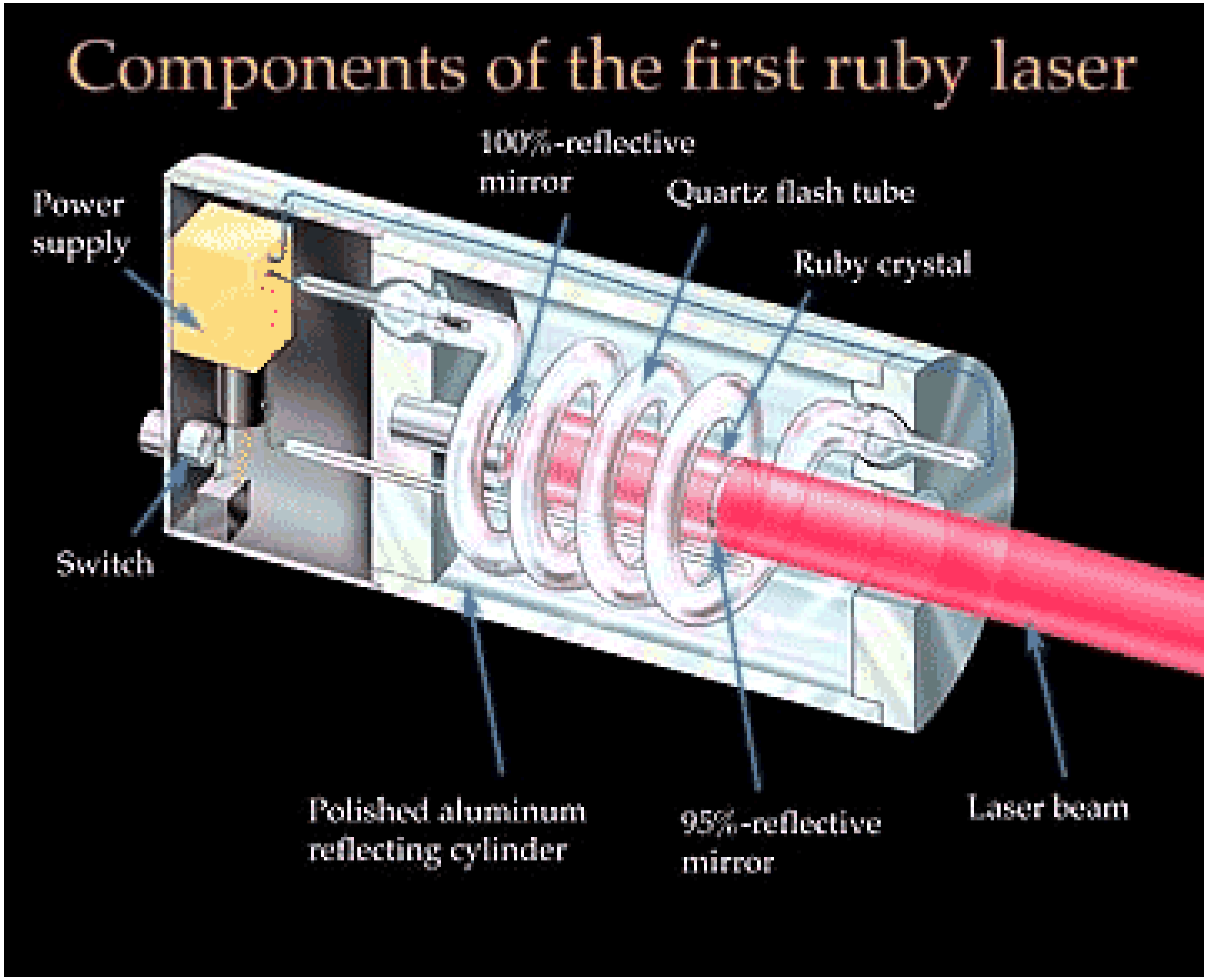
Invention of Laser

(Open Cavity) (Schawlow and Townes, 1958)



Light travels round and round in the cavity.
The effective length for stimulated emission increases drastically ⟶ High laser intensity.

Ruby Laser *(Maiman, May 16, 1960)*



Lasers come in all forms and colors:

Gas lasers
Solid-state lasers
Plastic lasers
Edible lasers

Liquid lasers
Liquid crystal lasers
Nano lasers
Drinkable lasers

Lasing frequency ranges
from far-infrared to X-ray

How does a laser beam differ from an ordinary light beam?

Directionality: $\theta_{dif} \sim 0.01^o$ for 1-cm diffraction-limited beam,
Smallest focal diameter ~ λ ~ 1 μm.

Power: CW laser > 100KW
Pulse laser > 10^{14} W (peak)
Maximum intensity at focus ~ 10^{26} W/m^2.

Minimum Pulsewidth: ~ 5×10^{-15} sec (1.5 μm pulse length)
$\Rightarrow$ < 10^{-15} sec (<300 nm pulse length)

Spectral Purity: $$\frac{\Delta\upsilon}{\upsilon} \sim \frac{1\ \text{Hz}}{10^{15}\ \text{Hz}} = 10^{-15}$$

Tunability: Far-IR→visible→UV→soft X-ray

Laser Applications

Entertainment:

CD player, Video player, Laser art show

Medical Care:

Laser diagnosis, Laser surgery

Technology:

Machining, Welding, Alignment

Optics communications (Kao, Nobel Prize, 2009)

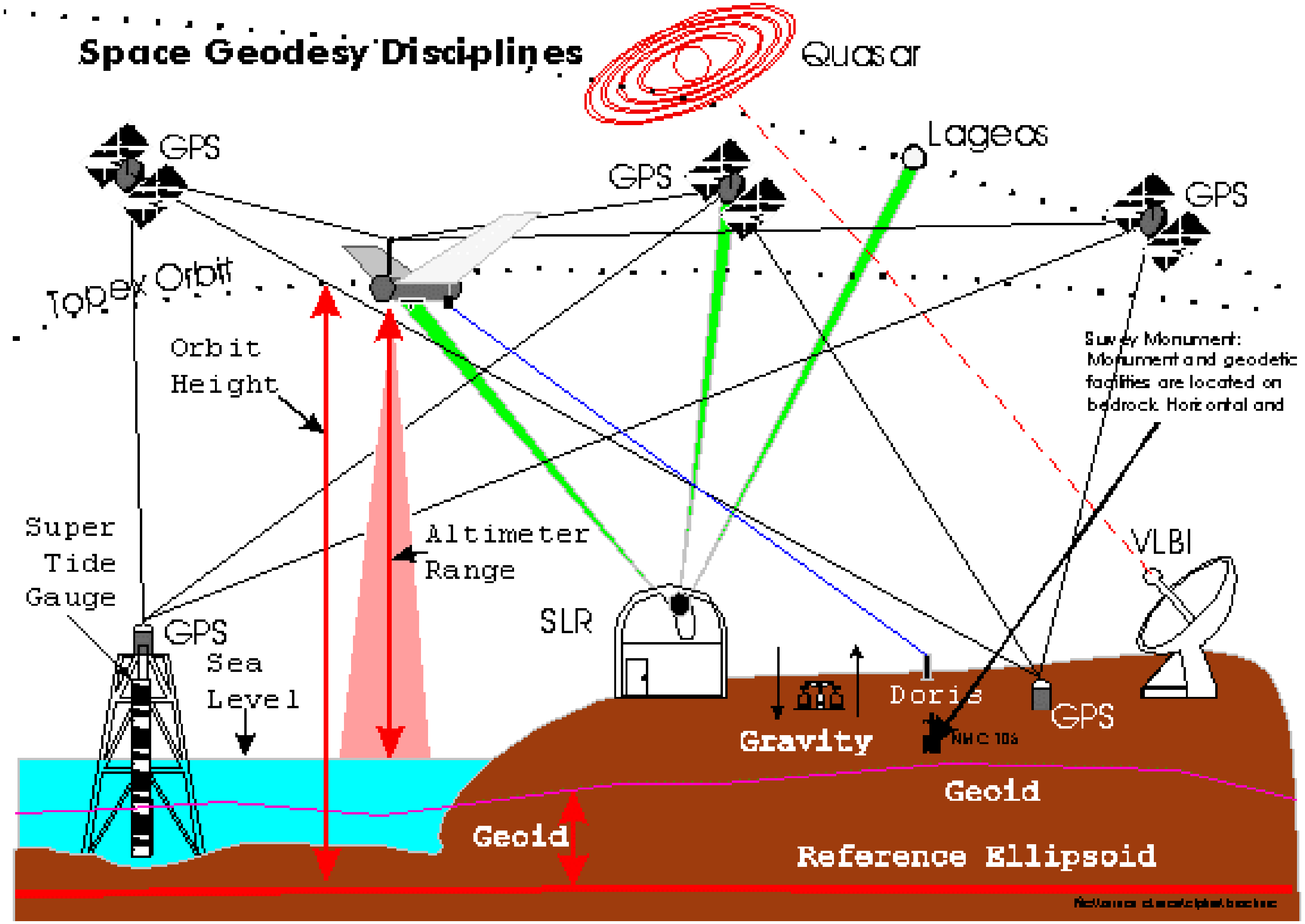
Ranging (GPS) *and sensing*

laser Weaponry

Science:

Laser Surgery *(Face Lifting)*

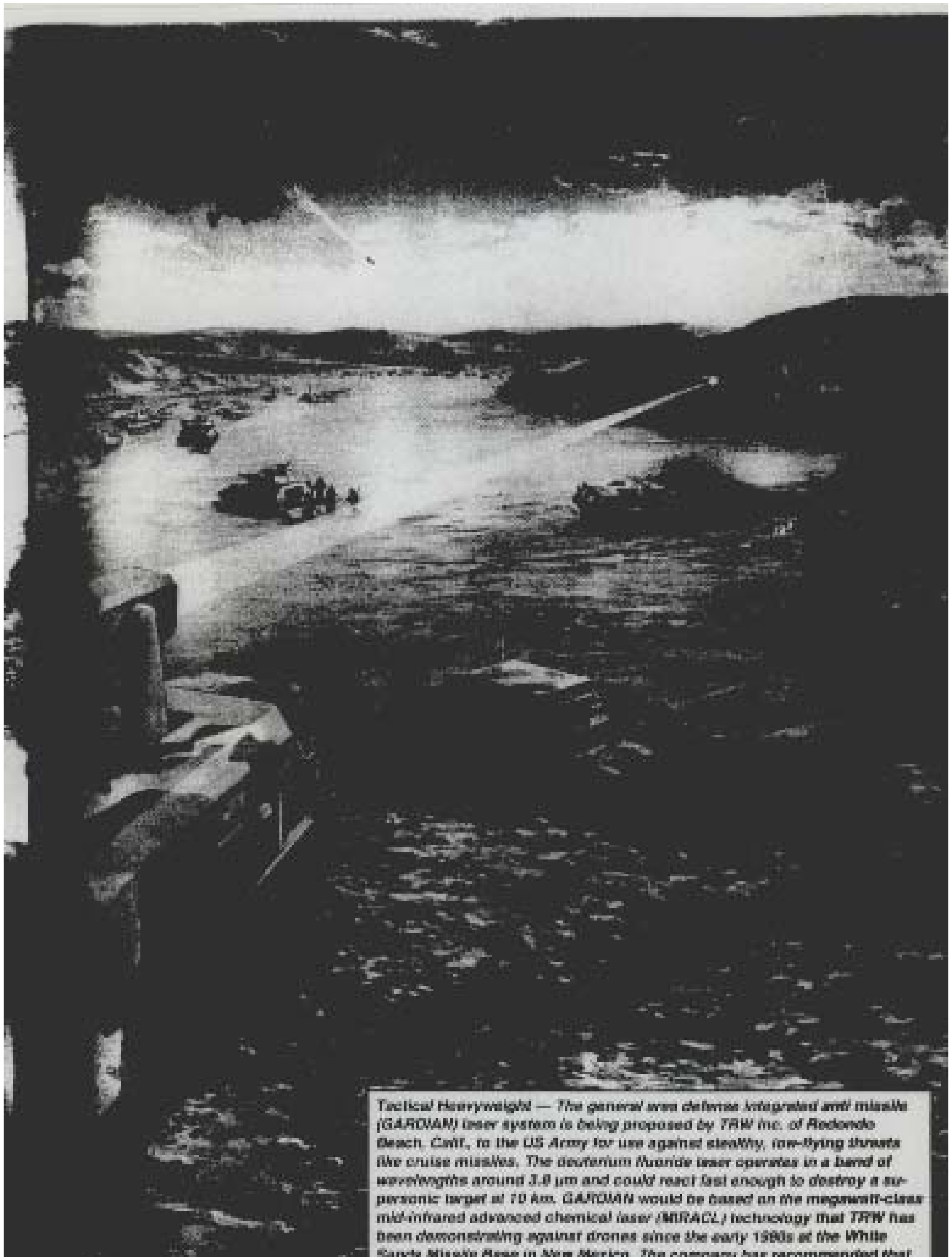
Laser Ranging



Laser Weapon

58-cm Diameter High Energy Laser Beam
(TRW, 2002)

Star War



Tactical Heavyweight — The general area defense integrated anti missile (GARDIAN) laser system is being proposed by TRW Inc. of Redondo Beach, Calif., to the US Army for use against stealthy, low-flying threats like cruise missiles. The deuterium fluoride laser operates in a band of wavelengths around 3.8 µm and could react fast enough to destroy a supersonic target at 10 km. GARDIAN would be based on the megawatt-class mid-infrared advanced chemical laser (MIRACL) technology that TRW has been demonstrating against drones since the early 1980s at the White Sands Missile Base in New Mexico. The company has recommended that

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laser Weaponry

Science:

Laser-Related Nobel Prizes

Basov, Prokhorov, Townes (1964): Invention of maser

Gabor (1971): Invention of halography

Penzias, Wilson (1978): Discovery of 3K cosmic background radiation

Bloembergen, Schawlow (1980): Development of laser spectroscopy

Ramsey (1989): Development of precision atomic spectroscopy

Chu, Cohen-Tannoudji, Phillips (1997): Development of laser cooling

Zewail (1999): Development of femtosecond laser chemistry

Alferov, Kroemer (2002): Development of semiconductor heterojunction laser

Cornell, Wieman, Ketterle (2001): Discovery of Bose-Einstein condensation

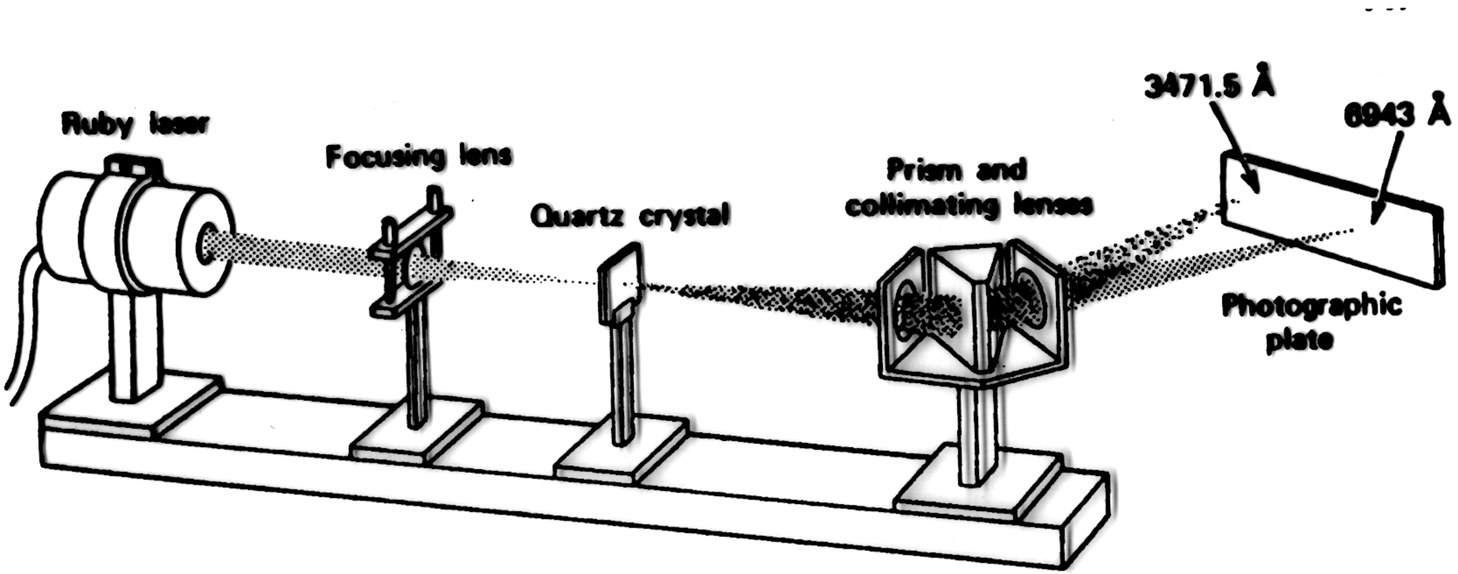
Glauber, Hall, Hansch (2006): Development of quantum optics;
Invention of frequency combs for precision spectroxcopy

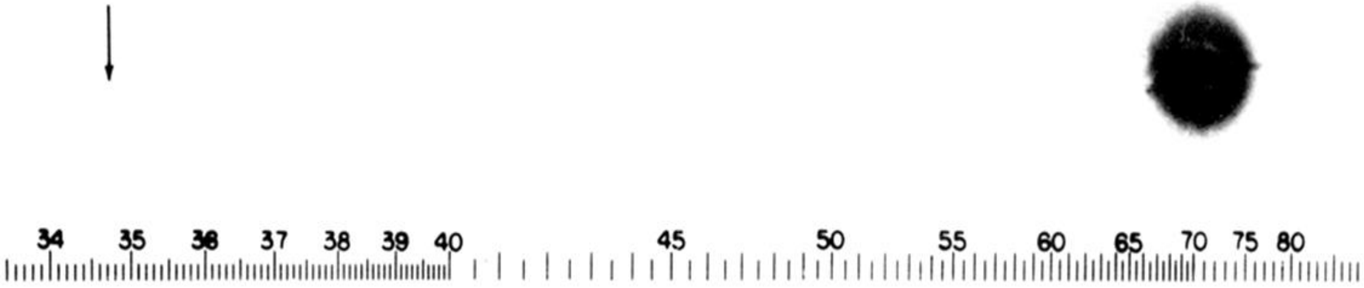
Shimomura, Chalfie, Tsien (2008): Discovery and development of green
fluorescent proteins

Kao (2009): Achievement concerning fibers for optics communications

Birth of Nonlinear Optics:

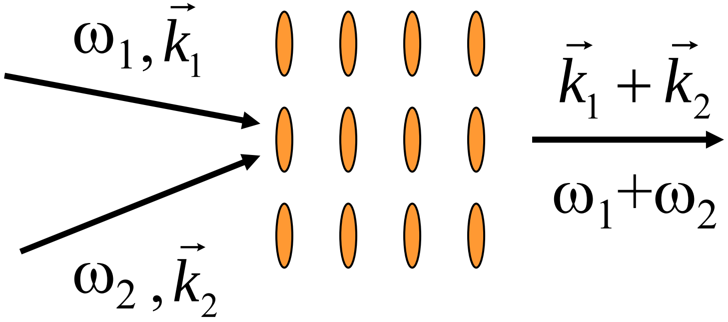
Second Harmonic Generation *(Franken, 1961)*





Nonlinear Optics: Wave Mixing

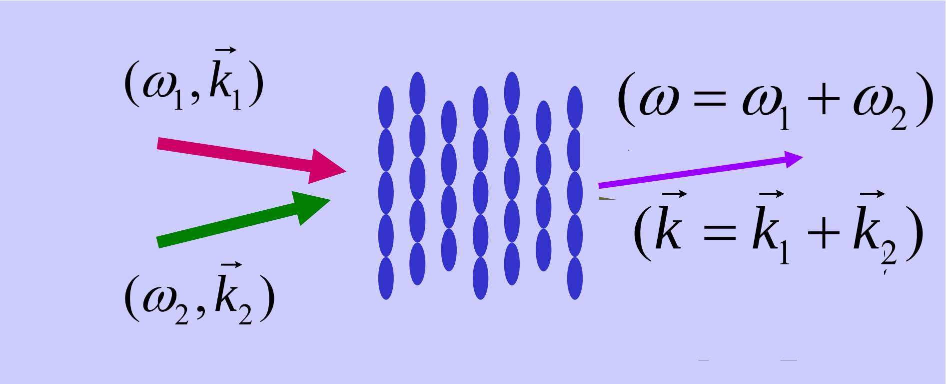
Theoretical Foundation (Bloembergen et al, 1962)



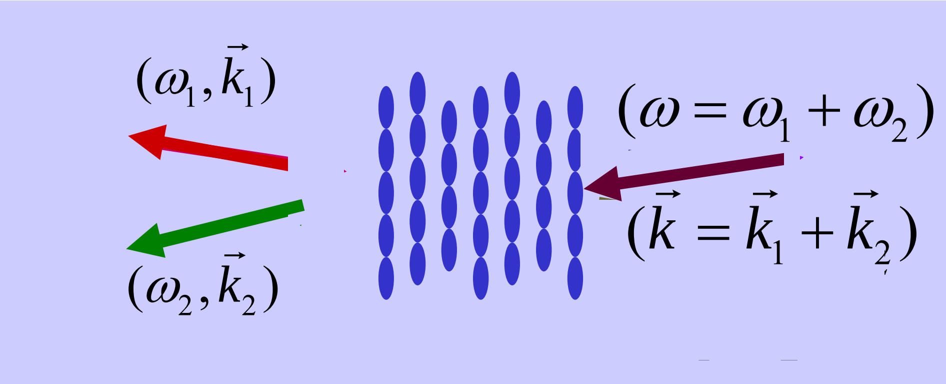
$$\vec{p}(\vec{E}) = \overleftrightarrow{\alpha}^{(1)} \cdot \vec{E} + \overleftrightarrow{\alpha}^{(2)} : \vec{E}\vec{E} + \overleftrightarrow{\alpha}^{(3)} : \vec{E}\vec{E}\vec{E} + - - -$$

Nonlinear response becomes important when E(~1 KV/cm) is sufficiently strong $\Rightarrow$ wave mixing.

Wave Mixing for Frequency Conversion

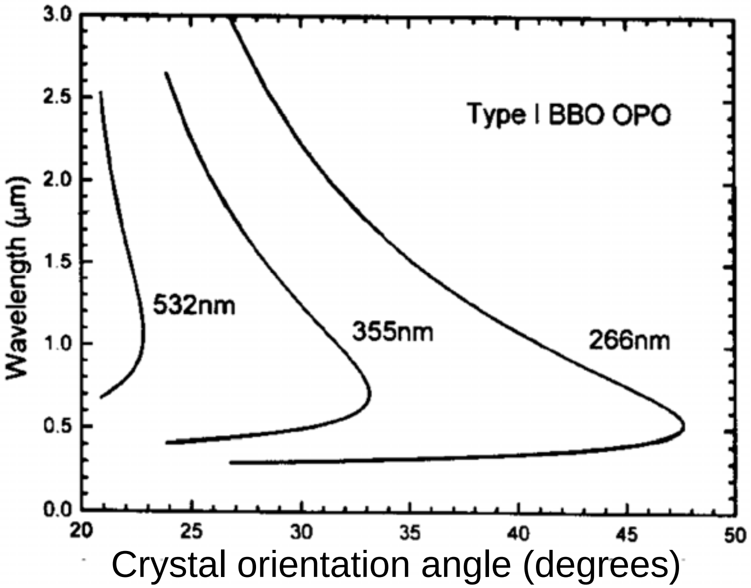


SFG

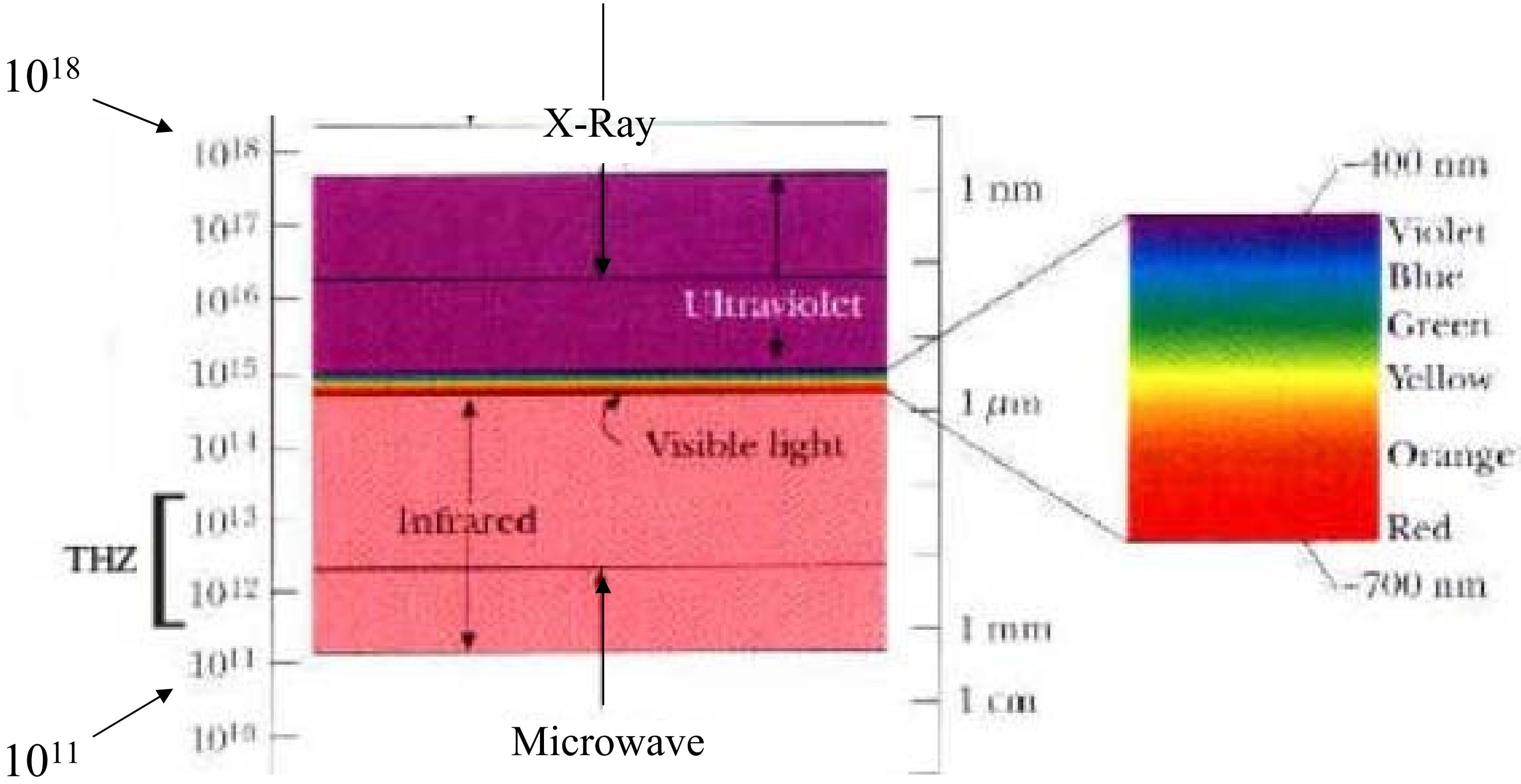


Inverse SFG: OPG

$\Rightarrow$ Tunable output



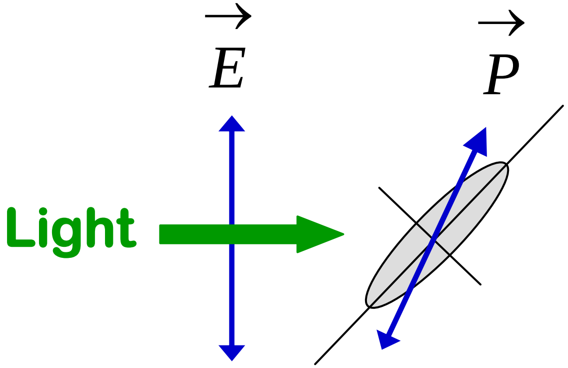
Tunable Coherent light Source from NLO spans from sub-THz to soft X-ray



Optical-Field-Induced Refractive Index Change (Δn)

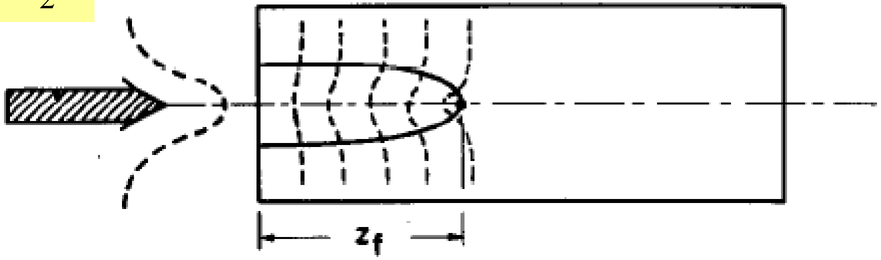
$$\Delta n = n_2 I > 0$$

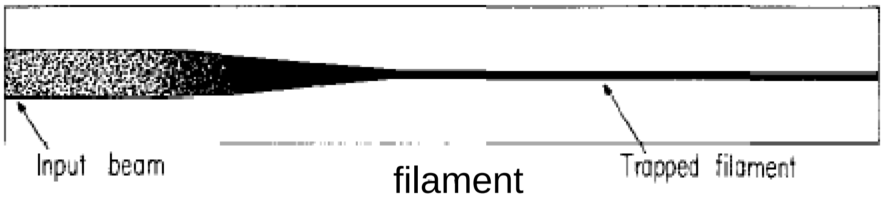
→ **Self-action of light**



Self-focusing

$$\Delta n = n_2 I$$



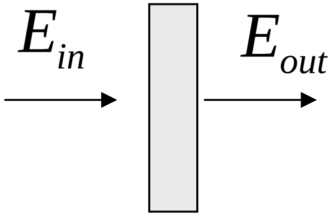


Self-Focused Filaments in Air

Light Bullet:

Laser pulse of 10^{-13} sec or 30 μm in width propagates in a straight channel.

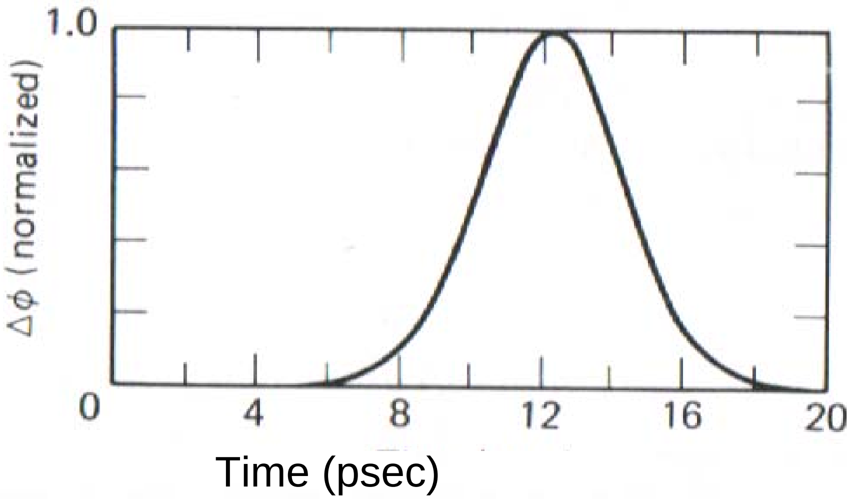
Self-Phase Modulation
⇒⇒ Spectral Broadening



$$E_{out} = E_{in}\cos(\omega t + \phi)$$

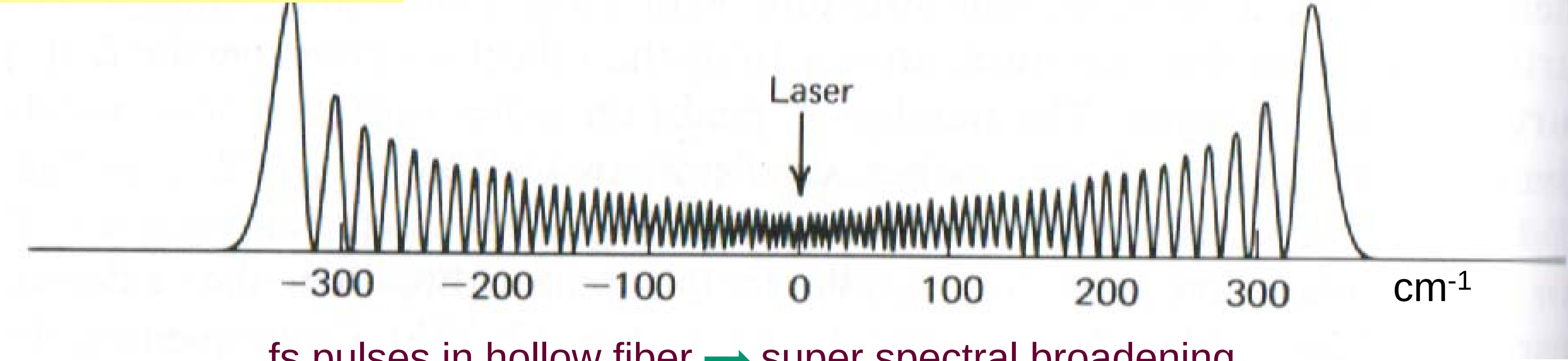
$$\phi(t) = \phi_0 + (\omega / c) d \Delta n$$

$$\Delta n = n_2 I(t)$$



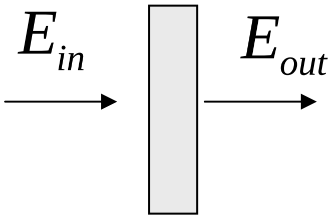
slope

$$\Delta\omega = \Delta\phi / \Delta t$$



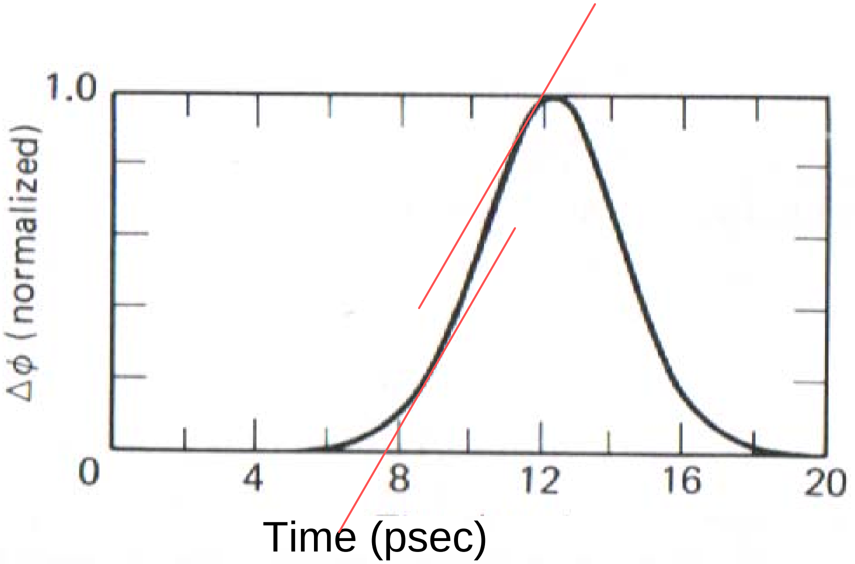
fs pulses in hollow fiber ⟹ super spectral broadening
⟹ fs frequency comb

Self-Phase Modulation
⇒⇒ Spectral Broadening



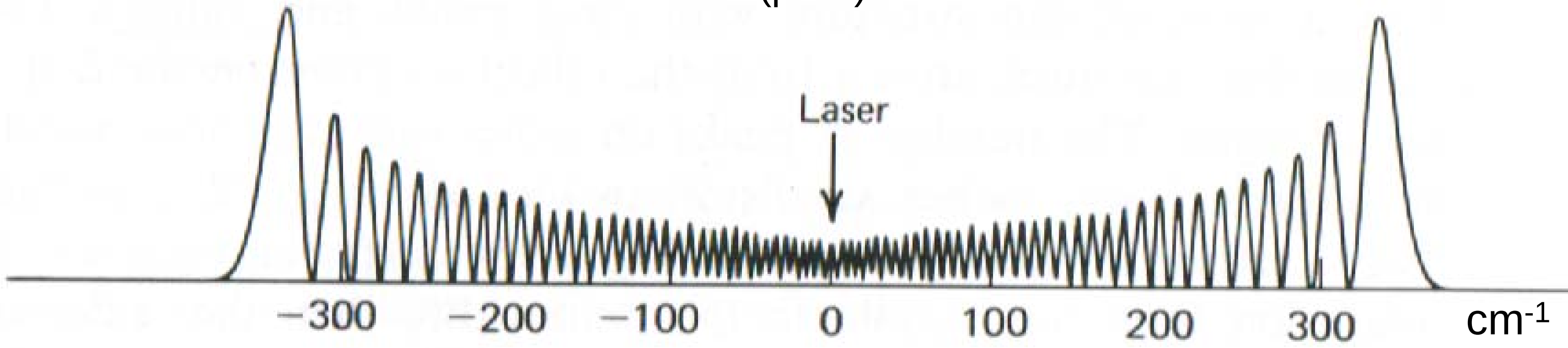
$$E_{out} = E_{in} e^{i(\omega/c)nd + i\Delta\phi}$$

$$\Delta\phi(t) = (\omega/c) d n_2 I(t)$$



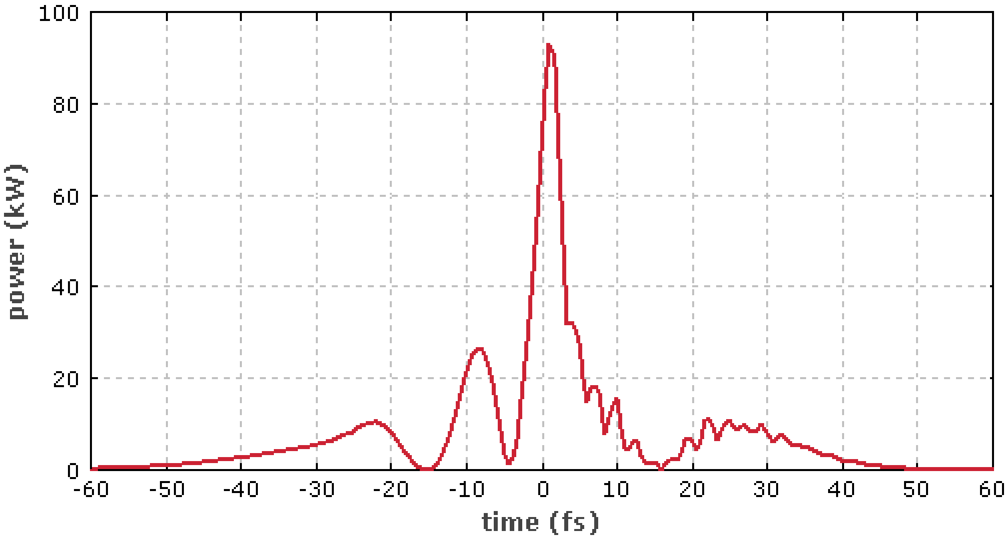
slope

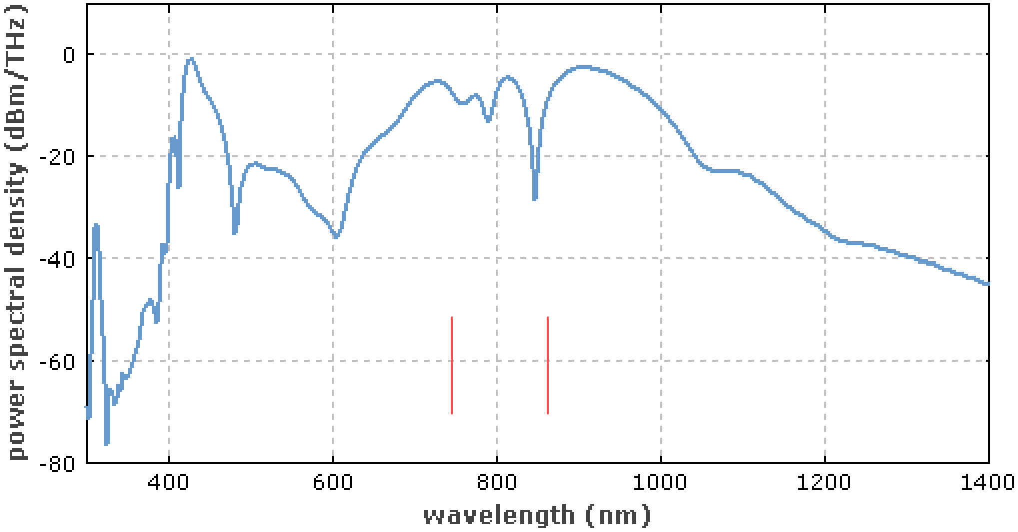
$$\Delta\omega = \Delta\phi / \Delta t$$



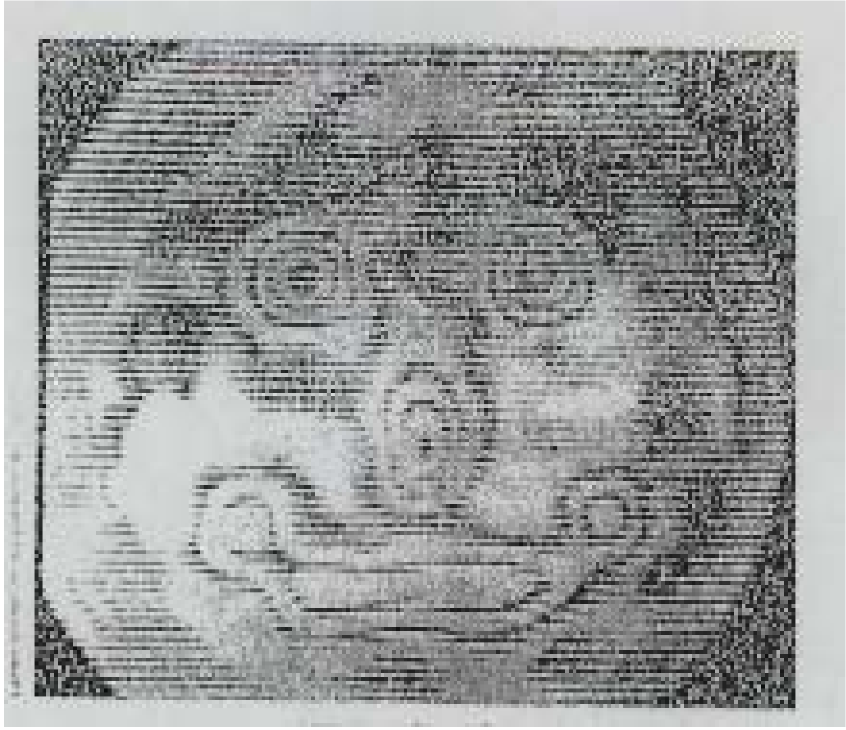
fs pulses in hollow fiber ⟹ super spectral broadening
⟹ fs frequency comb

Super Spectral Broadening in Fiber

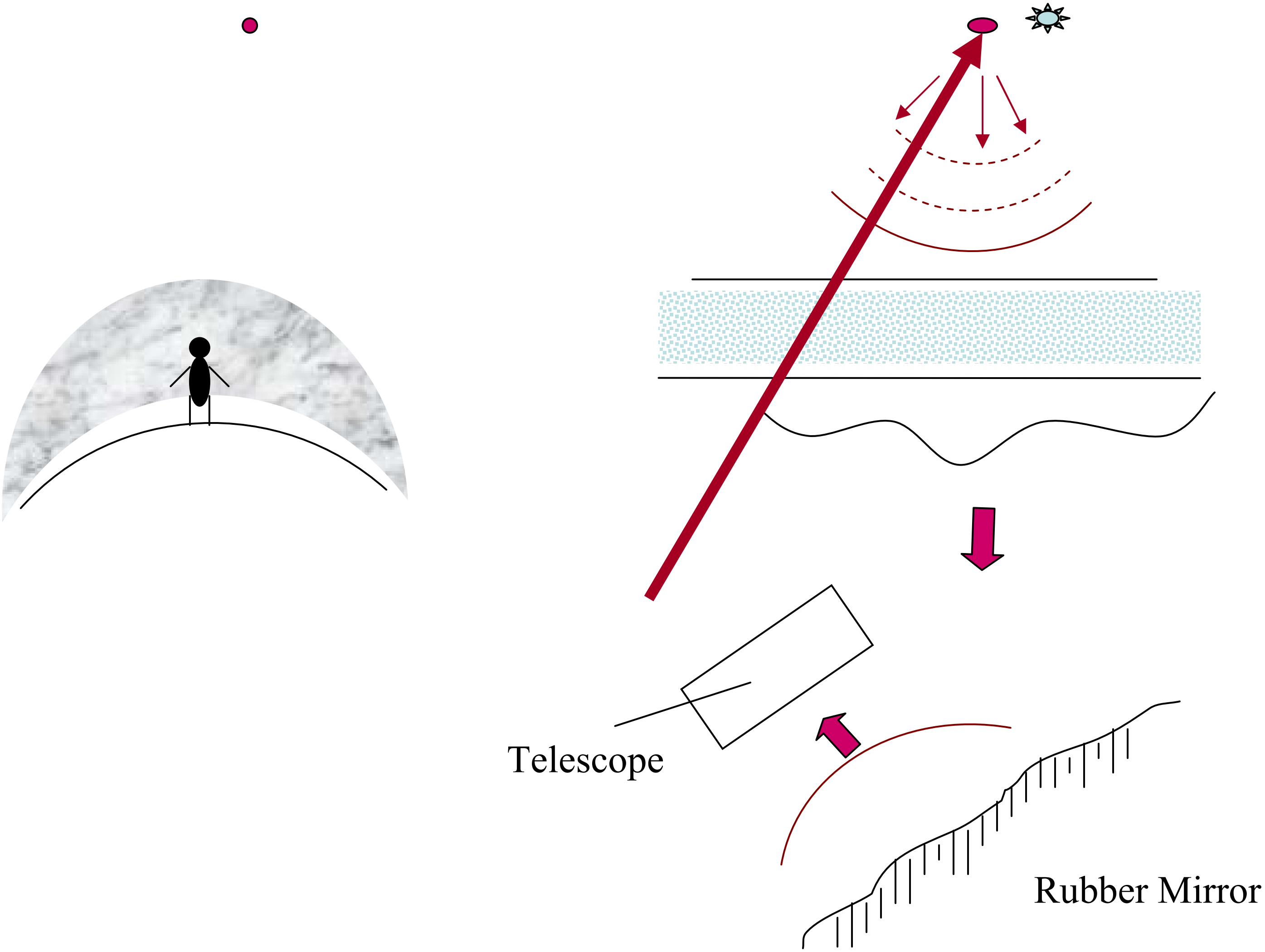




Adaptive Optics *(Rubber Mirror)*



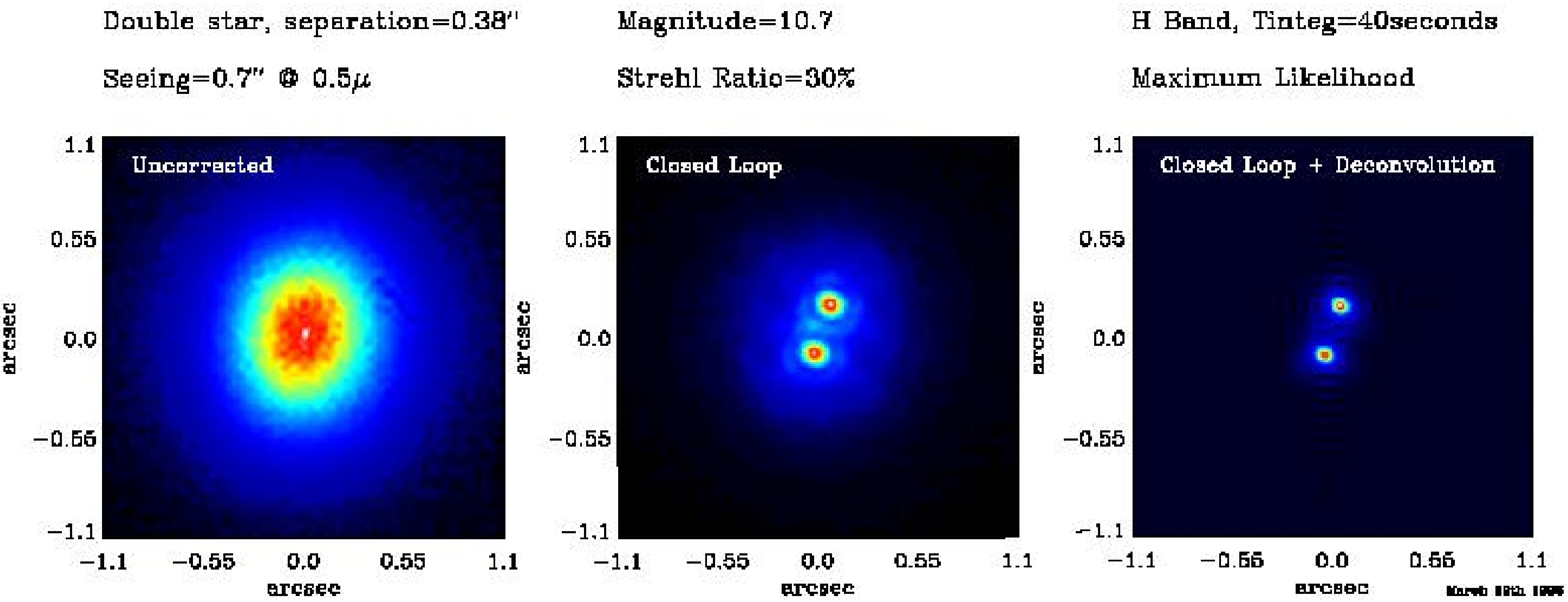
Laser Guide Star



Telescope

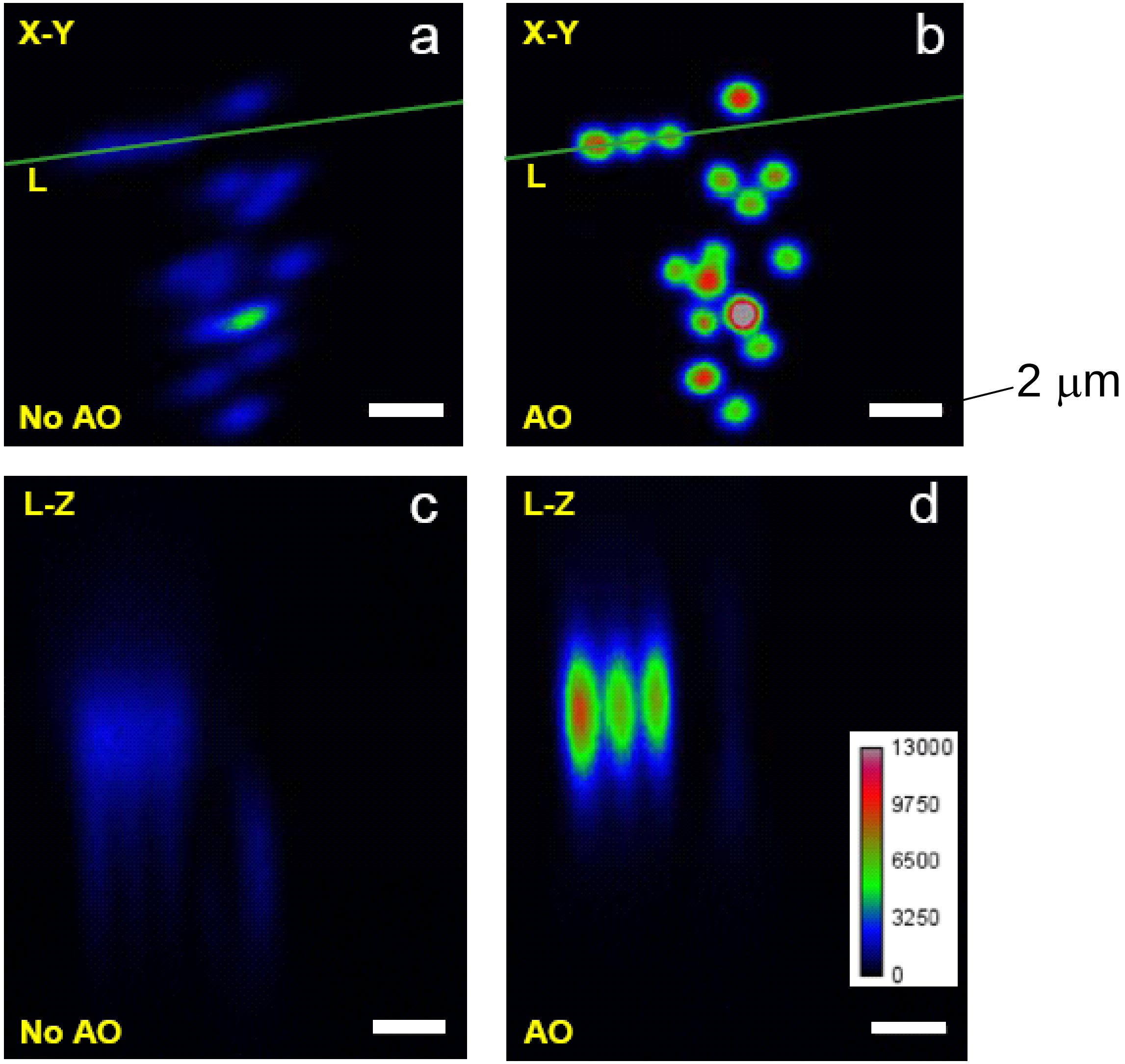
Rubber Mirror

Canada-France Hawaii Telescope
with and without Adaptive Optics



Adaptive Optical Microscopy

Ji, Milkid, Betzig (2010)



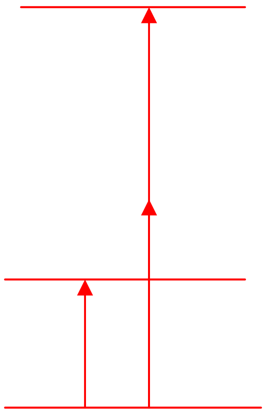
Laser Spectroscopy

Flourished with advances of nonlinear optics
and tunable lasers, and rejuvenated
the field of atomic and molecular sciences

Bloembergen, Schawlow (Nobel, 1980)

Lamb, Ramsey, Hansch, Cohen-Tannouji,
Hall, Chu, Zewail

Laser Spectroscopy



Ultrahigh Spectral Resolution

$f/\Delta f \sim 10^{15}$

Absolute Frequency of H(1S→2S)

= 2,466,061,413,187,103(±49) Hz

Rydberg Constant

R_∞ = 10973731.568639(±91) cm^{-1}

Are fundamental constants really constant?

Ultrahigh Sensitivity

Selective detection of single atoms and molecules

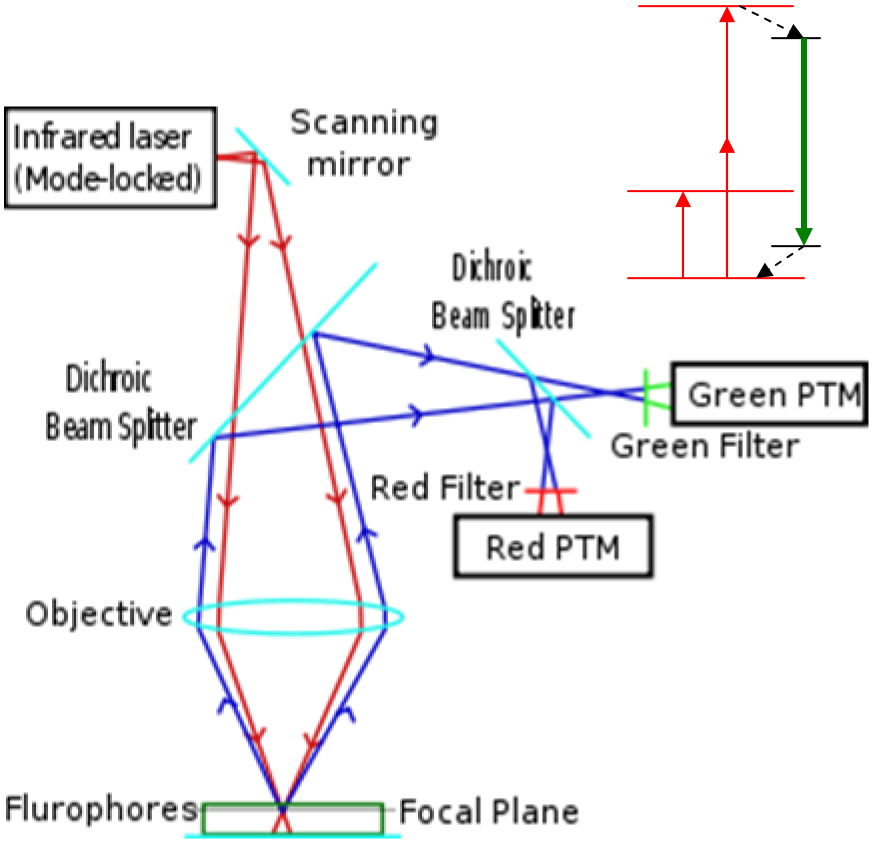
Ultrahigh Time Resolution

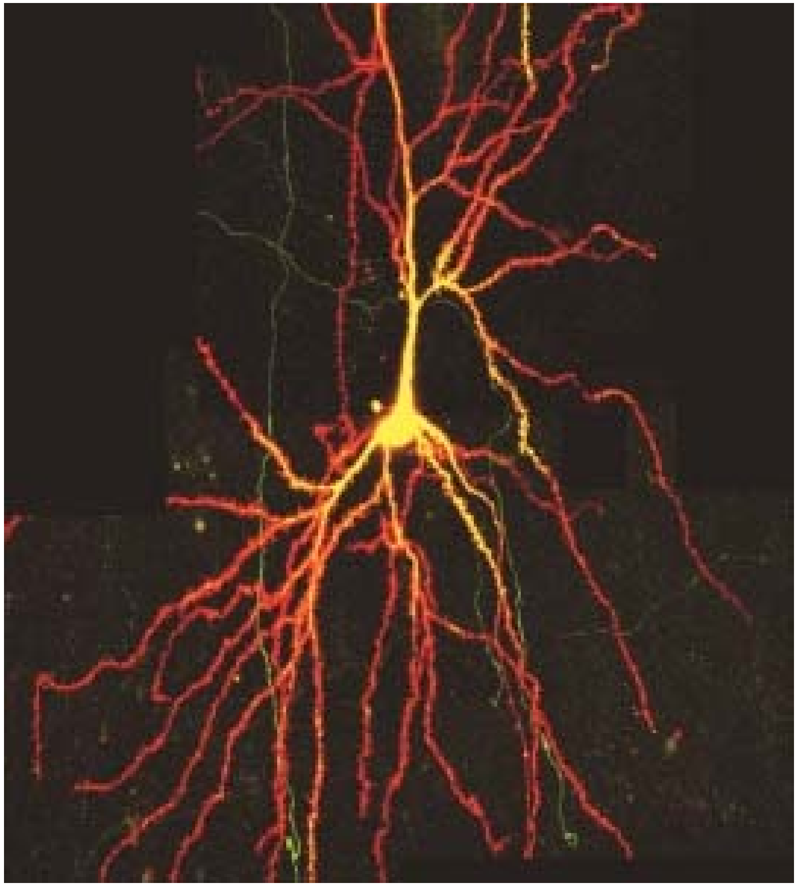
Study of ultrafast dynamics ($<10^{-15}$ sec)

Ultrahigh spatial resolution

Microscopic resolution beyond diffraction limit

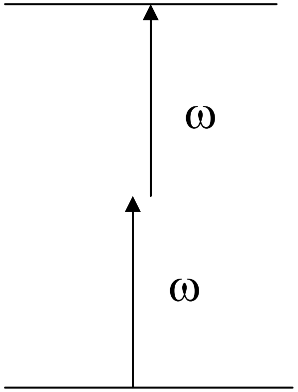
Two-Photon-Excited Fluorescence: Confocal microscopy



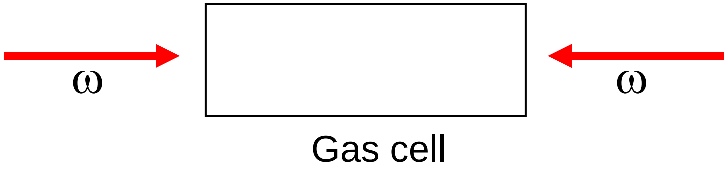


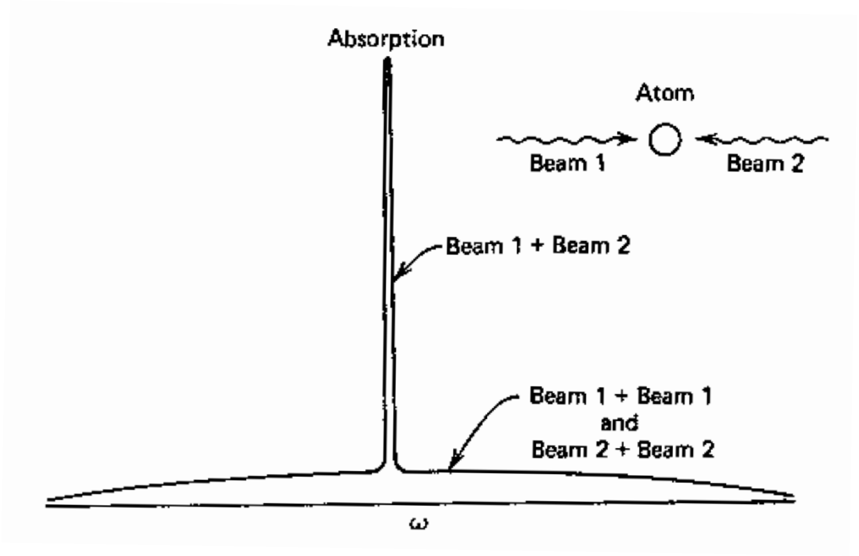
Tsien: Green fluorescent protein (Nobel, 2008)

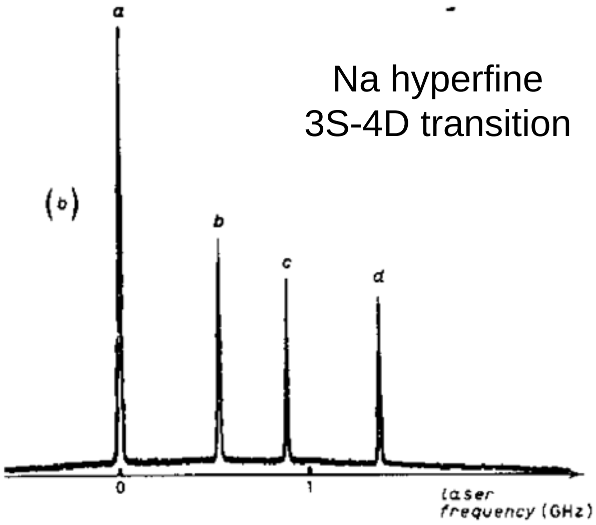
Two-Photon Doppler-Free Absorption Spectroscopy



$$(\omega + \vec{k}\cdot\vec{\mathrm{v}}) + (\omega - \vec{k}\cdot\vec{\mathrm{v}}) = 2\omega = \omega_0$$







Na hyperfine
3S-4D transition

Hansch: $F=1$ to $F'=1$ hyperfine component of 1S–2S transition of H with a resolution of $1.4\mathrm{x}10^{14}$.

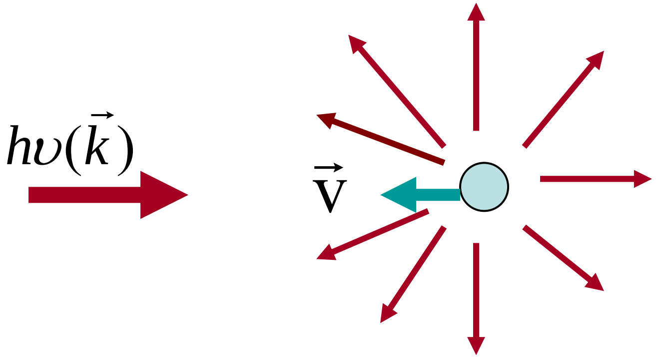
Laser Cooling and Trapping of Atoms

Photon momentum:

$hc/\lambda \sim 1.3\text{x}10^{-27}$ Kg-m/sec

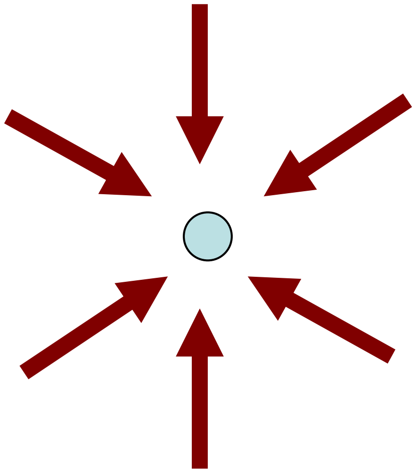
Atom momentum:

$m\text{v} \sim 10^{-23}\,\text{Kg-m}/\text{sec}$



It takes absorption/emission of ~10^4 photons or ~100 μs to reduce the atomic velocity v ~0.

Optical Molasses



Six orthogonal beams trap the atoms with v~0 or a temperature T ~ 1 μK

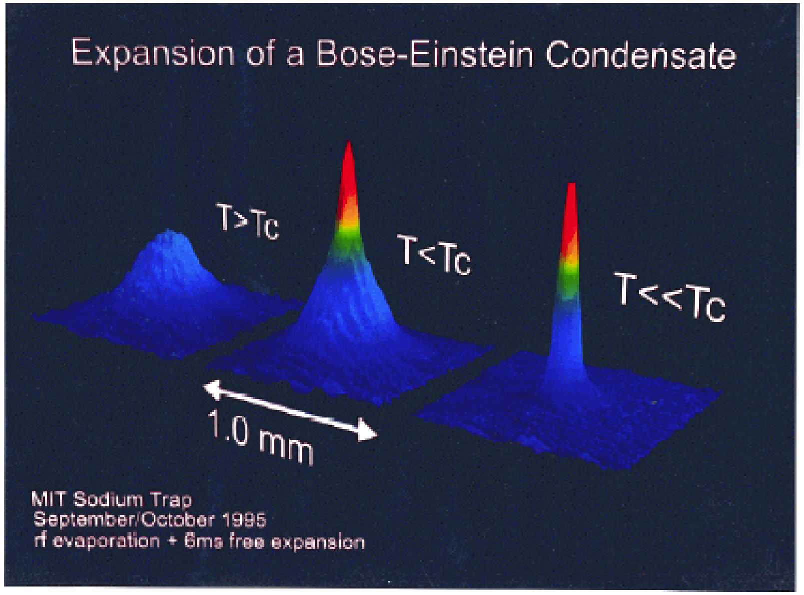
Laser Molasses *(S. Chu, Sci. Am. 174, 71(1992)*

Bose-Einstein Condensation

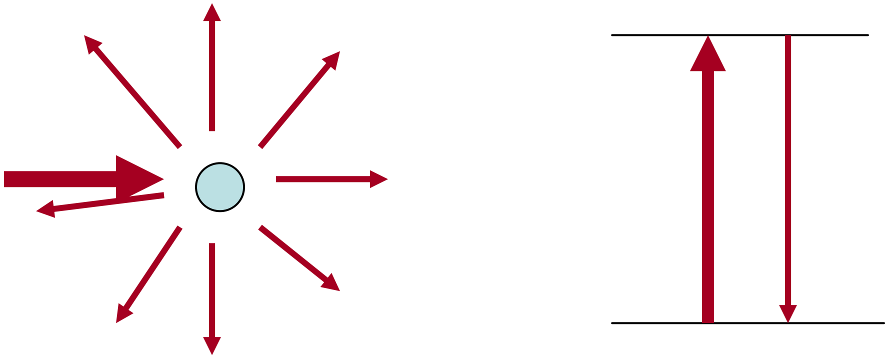
Atoms cooled by laser can be further cooled by evaporation to ~10 nK.

For a Na atom at T ~ 100 nK, it has a de Brogile wavelength λ_{dB} ~ 1 μm. Each atom appears as a wave packet.

When wave packets overlap, the atoms form a single giant wave packet, and have the coherent wave character like a laser beam.



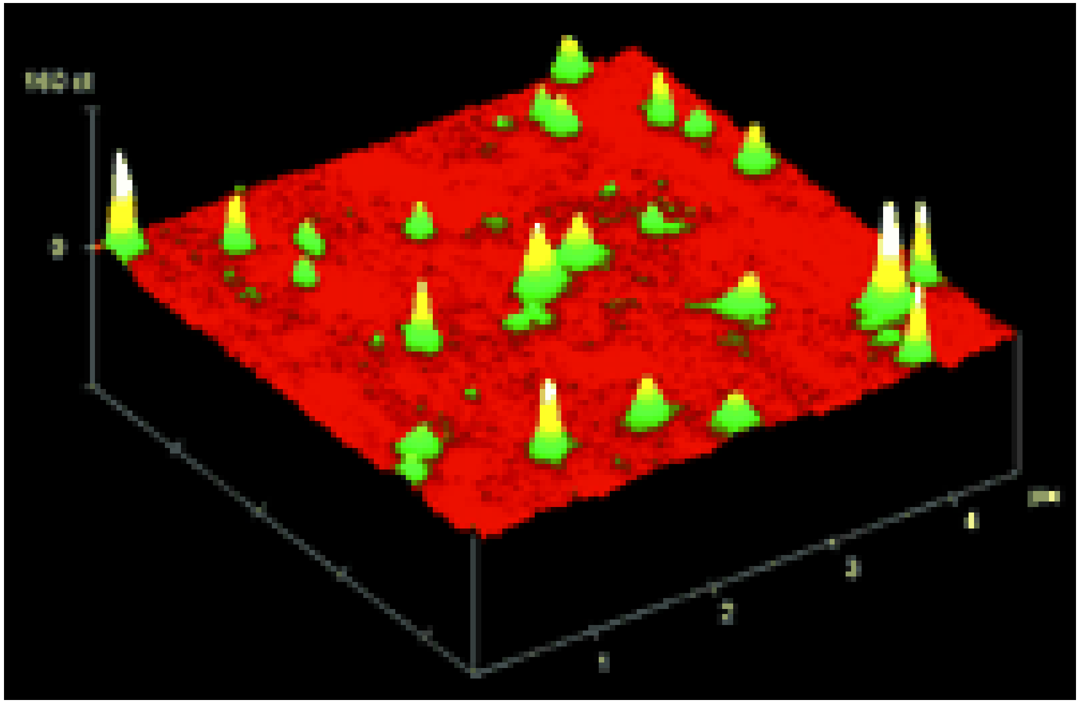
Detection of Single Atoms



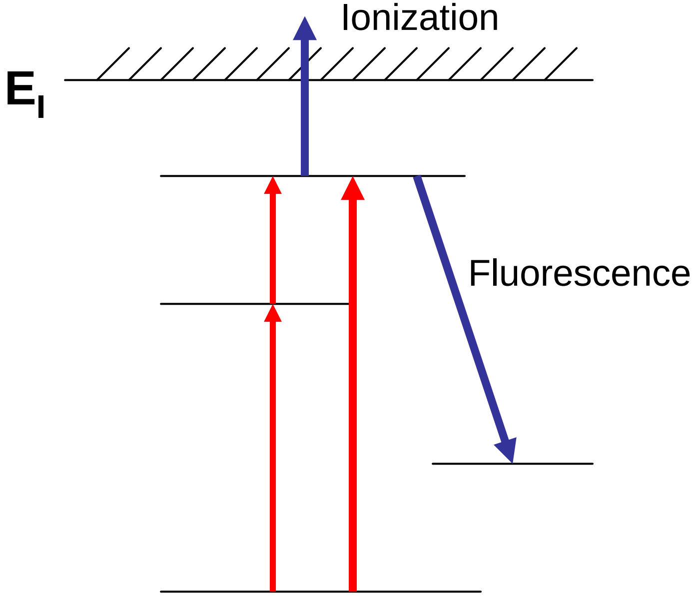
- Nearly instantaneous excitation by laser
- Fluorescence lifetime: 10^{-8} sec
- Excitation – Emission cycle: 10^{-8} sec
- # Photons emitted by an atom: ~ 10^{8} /sec

  (easily detectable by a photodetector)

Fluorescent Detection of Single Biological Molecules



Selective Detection of Single atoms and Molecules



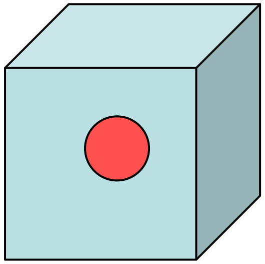
Applications

Studies of rare atoms and particles
(nuclear physics)
Studies of reaction dynamics
(chemical physics)
Dating (astrophysics, geophysics,
archeology, etc.)
Fluorescence labeling, two-photon
confocal microscopy
(biology)
Isotope separation

Can Nonlinear Optical Effects be Observed at Single Photon Levels?

Single Photon in a confined space (1 μm^3):

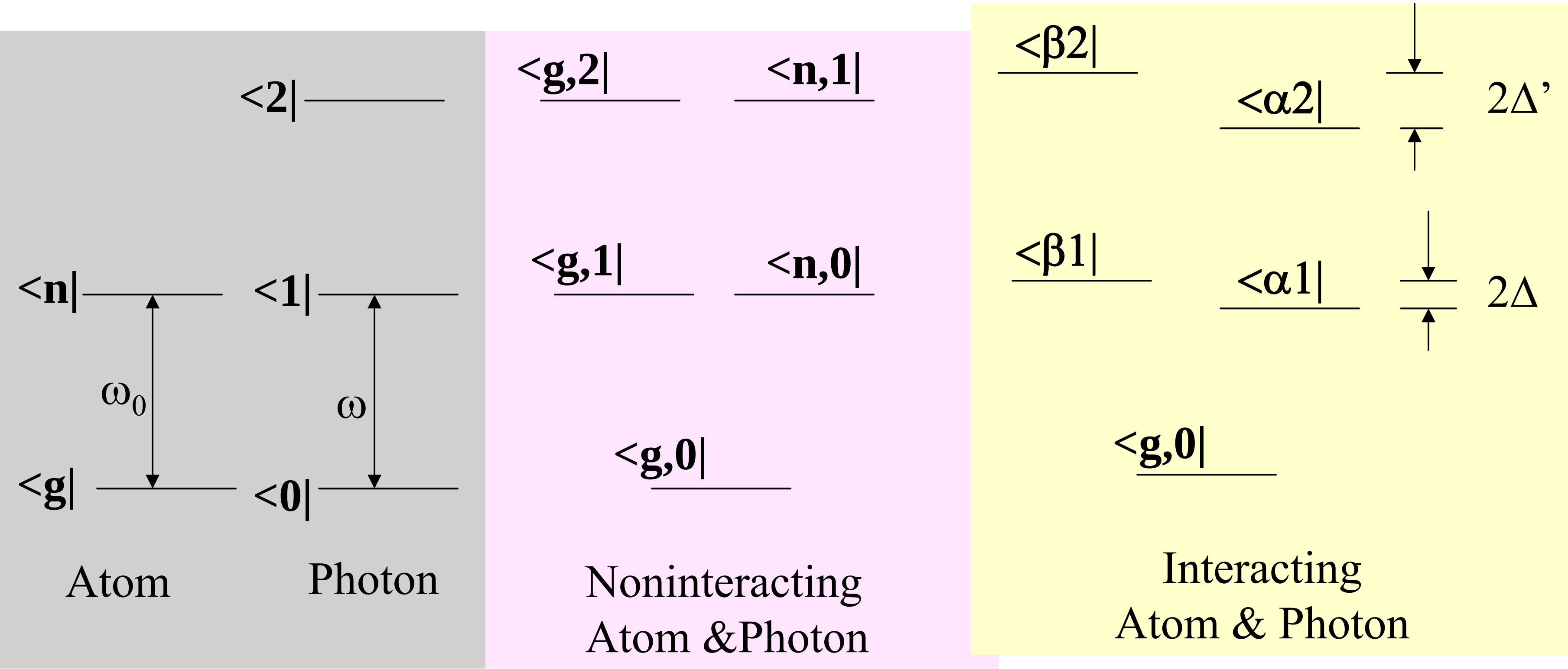
Energy Density = $|E|^2/2$
= $h\omega/V \sim 1$ erg/cm^3



$|E| \sim 1$ KeV/cm

Such a field is strong enough to induce observable nonlinear optical effects.
For example, the optical Stark shift can be appreciable near resonance.

Single Photon and Single Atom in a Microcavity *(Kimble)*



<2|

<n|

<1|

ω_0

ω

<g|

<0|

Atom

Photon

<g,2|

<n,1|

<g,1|

<n,0|

<g,0|

Noninteracting
Atom &Photon

<β2|

<α2|

2Δ’

<β1|

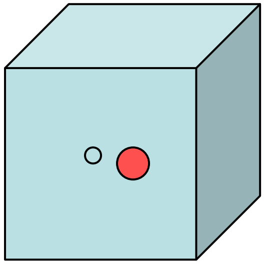
<α1|

2Δ

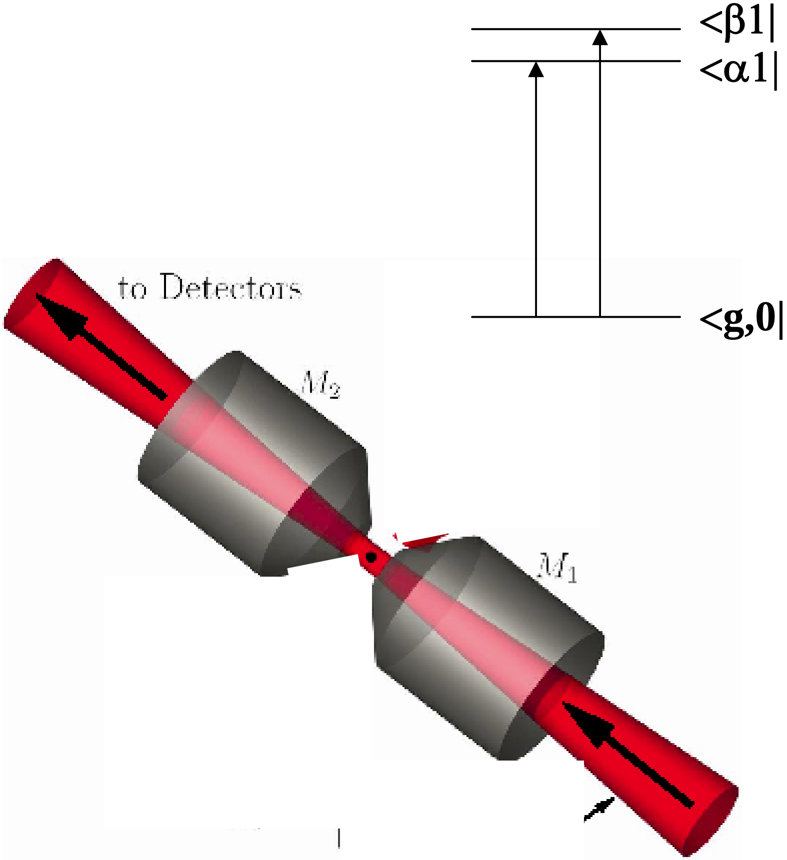
<g,0|

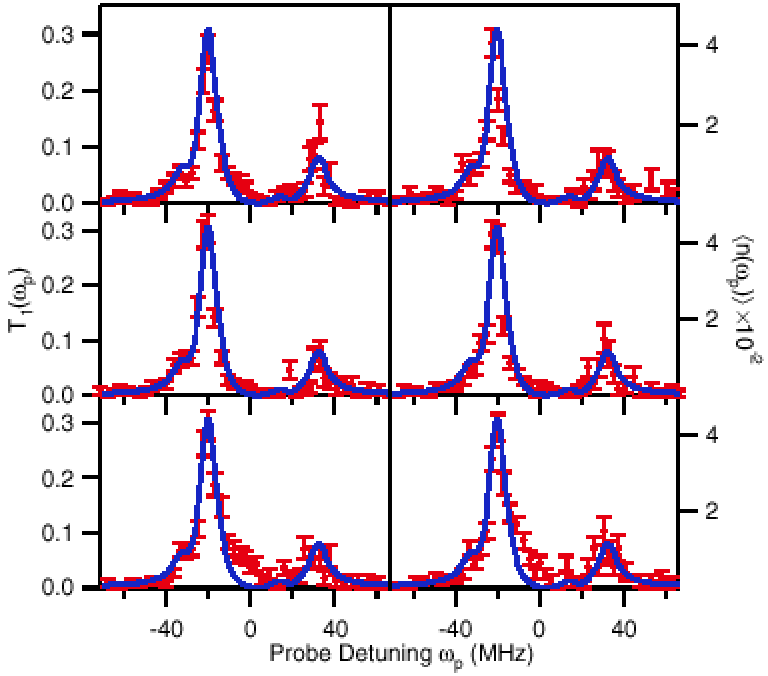
Interacting
Atom & Photon

$\omega = \omega_0$



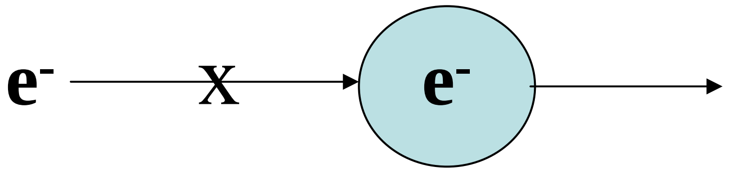
Experimental Observation





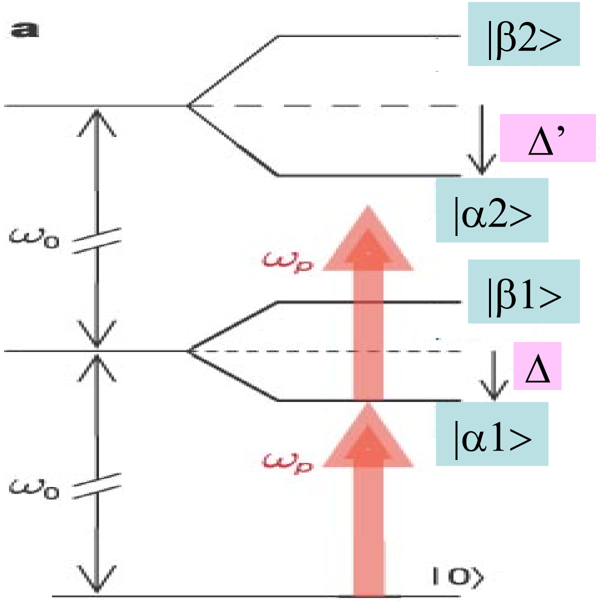
A. Boca et al, PRL 93, 233603 (2004)

Coulomb Blockade

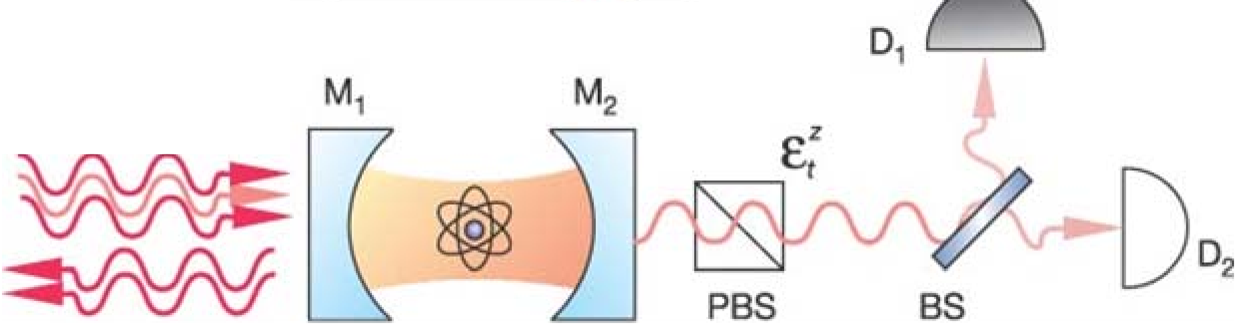


If an electron sits on a quantum dot (nanoparticle), its Coulomb potential is strong enough to repel another electron trying to get onto the dot.

Photon Blockade



$$\Delta' = \sqrt{2}\Delta$$



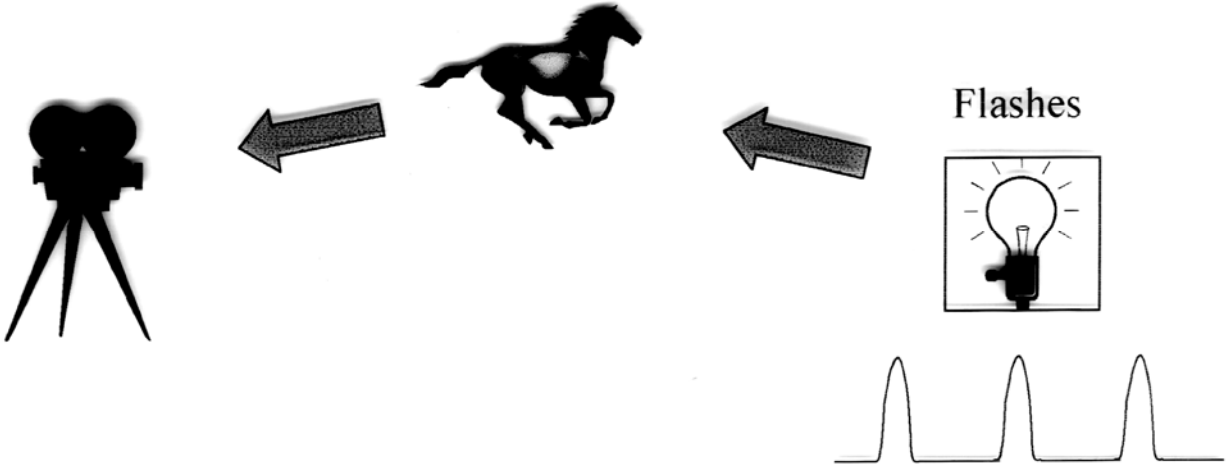
The existence of one photon in the cavity prevents another photon from entering the cavity.

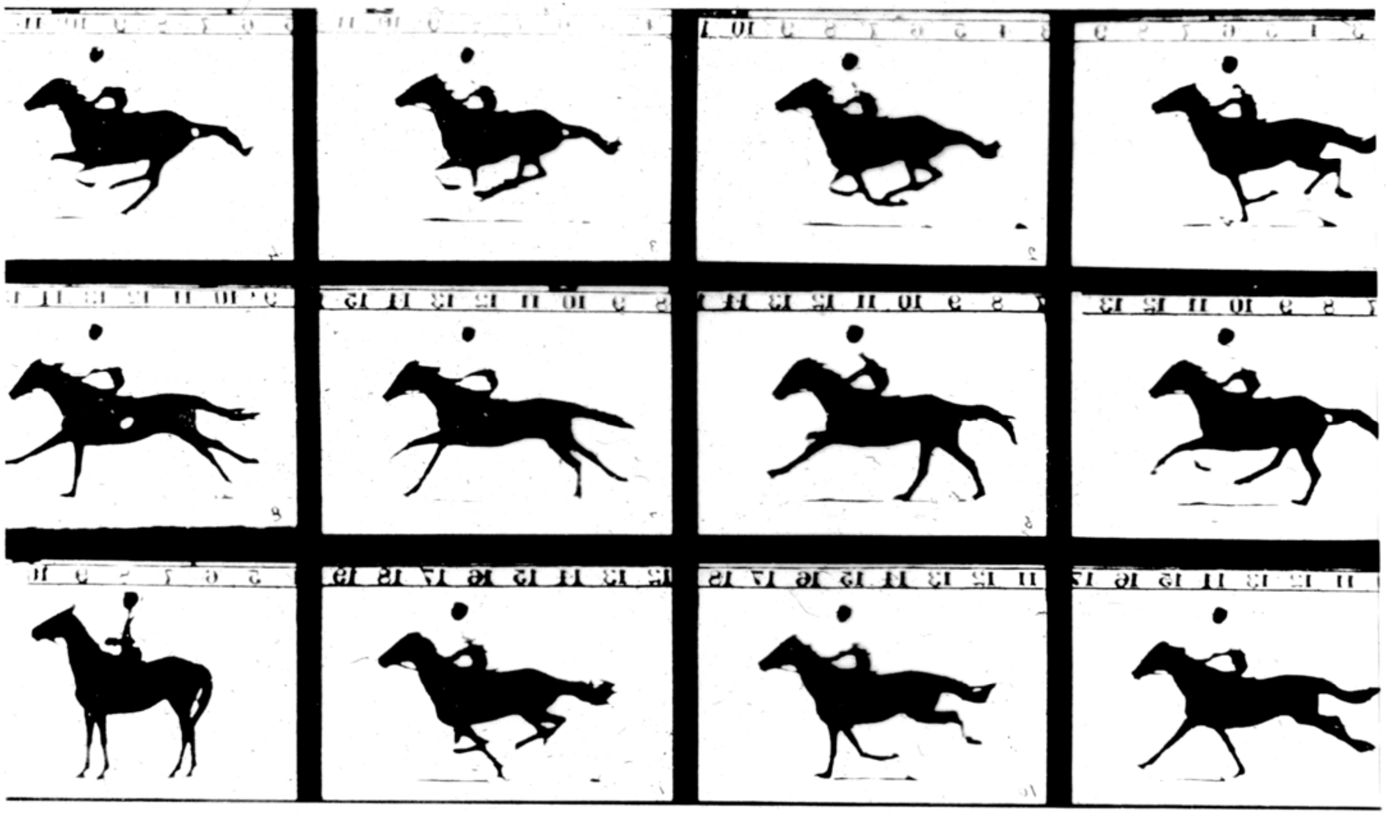
.Birnbaum et al, Nature 436, 454(2004).

Stroboscope

Photographs moving bodies intermittently
by illuminating the object
with brilliant flashes.

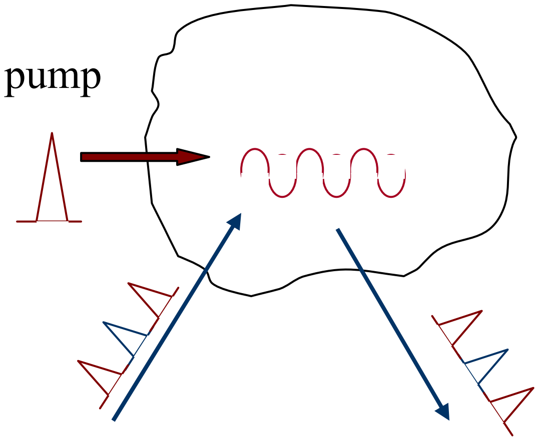
Inventors: E. Muybridge, Nature 19, 517 (1878)
H.E. Egerton, MIT, (1926-31)





Ultrafast Spectroscopy

How long does it take for a crystal to melt?

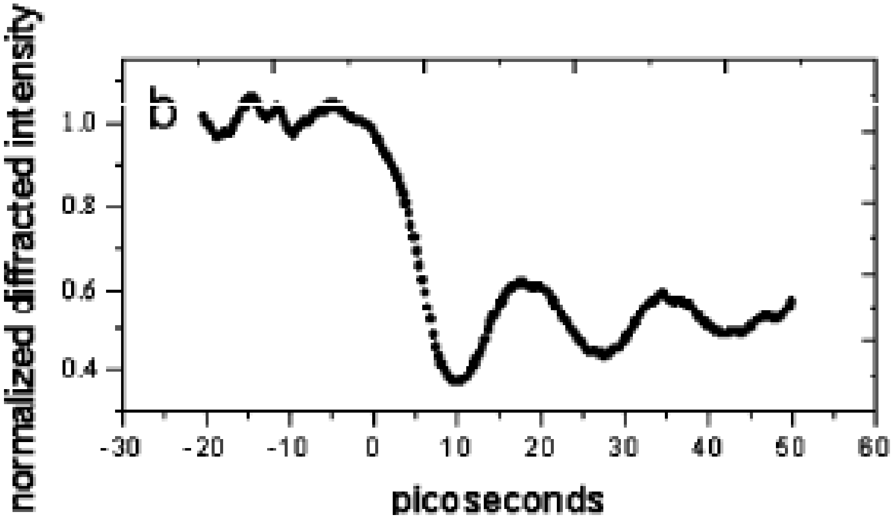


Delayed

Probe Pulse

Diffracted

Pulse



Limit of time resolution: ~10^{-16} sec

Applications of Ultrafast Spectroscopy

- **Gas Phases: Energy transfer, Reaction dynamics, femtosecond chemistry (Zewail).**

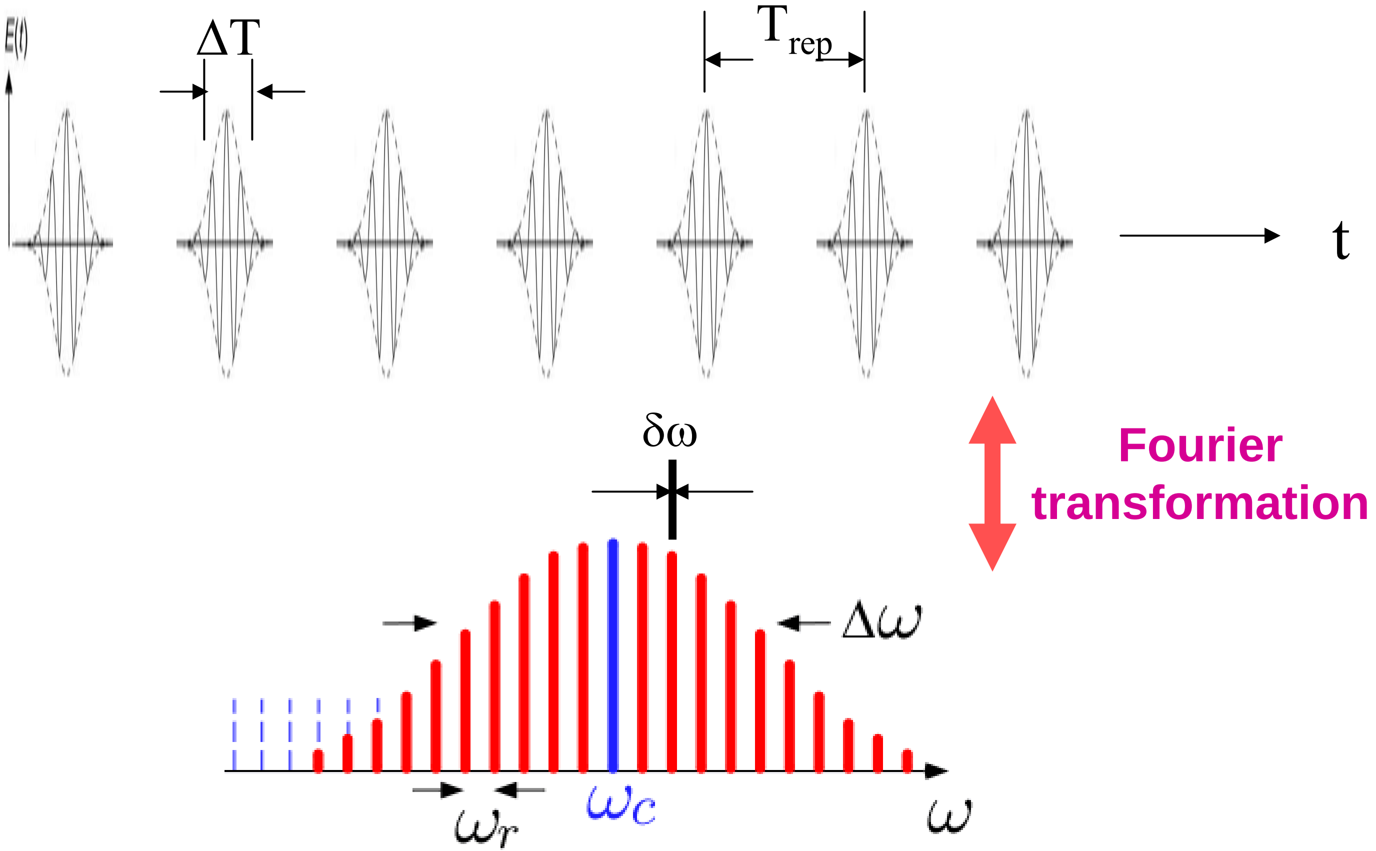
- **Condensed Phases:**

  Liquid: electron solvation, proton transfer

  Solid: relaxation of excitations, carrier dynamics, spin dynamics, surface dynamics

- **Biological molecules and systems**

Frequency Comb (2005 Nobel)



Fourier transformation

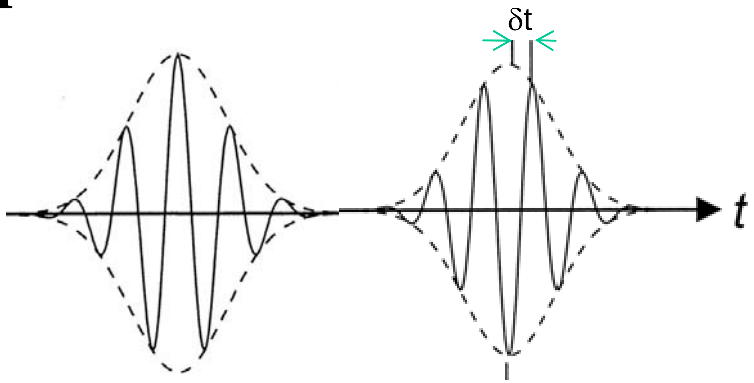
$$\Delta\omega = 1/\Delta T \qquad \omega_r = 1/\,T_{rep}$$

$$\delta\omega = 1/T$$

Characteristics of Frequency Comb

- **cw series of periodic femtosecond pulses**

  $A(\tau)=A(\tau+T)$ **with $T \sim 10$ ns**

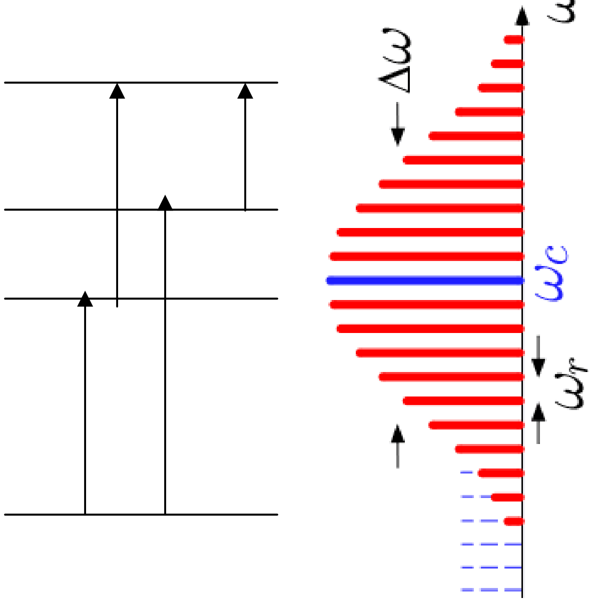


- **Well-defined optical field**

  $$E(t)=A(t)\cos(\omega t+\varphi)$$

- **Millions of spikes sharp spectral lines with a spectral width of a few KHz to few Hz**

- **Overall bandwidth extended over ~2eV, covering the entire visible range Extension into uv and IR possible.**



High-Intensity Femto-second Pulsed Lasers

Pulsed Energy:	1 mJ – 1 J
Pulse Width:	5 fs
Focused Peak Intensity:	10^{14}– 10^{25} W/m^2

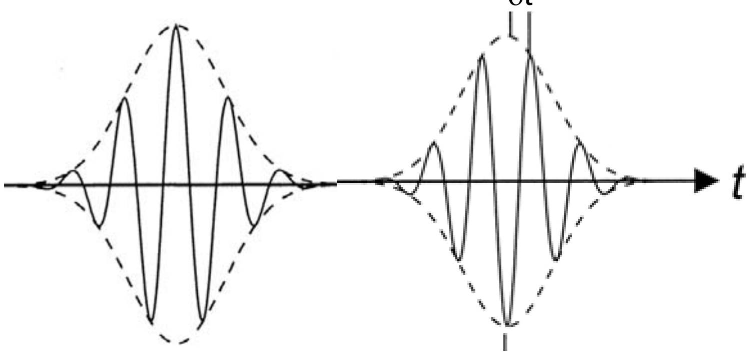
(for focal spot size of 10 μm^2– 1 cm^2)

Table Top Terawatt (T^3) Laser:

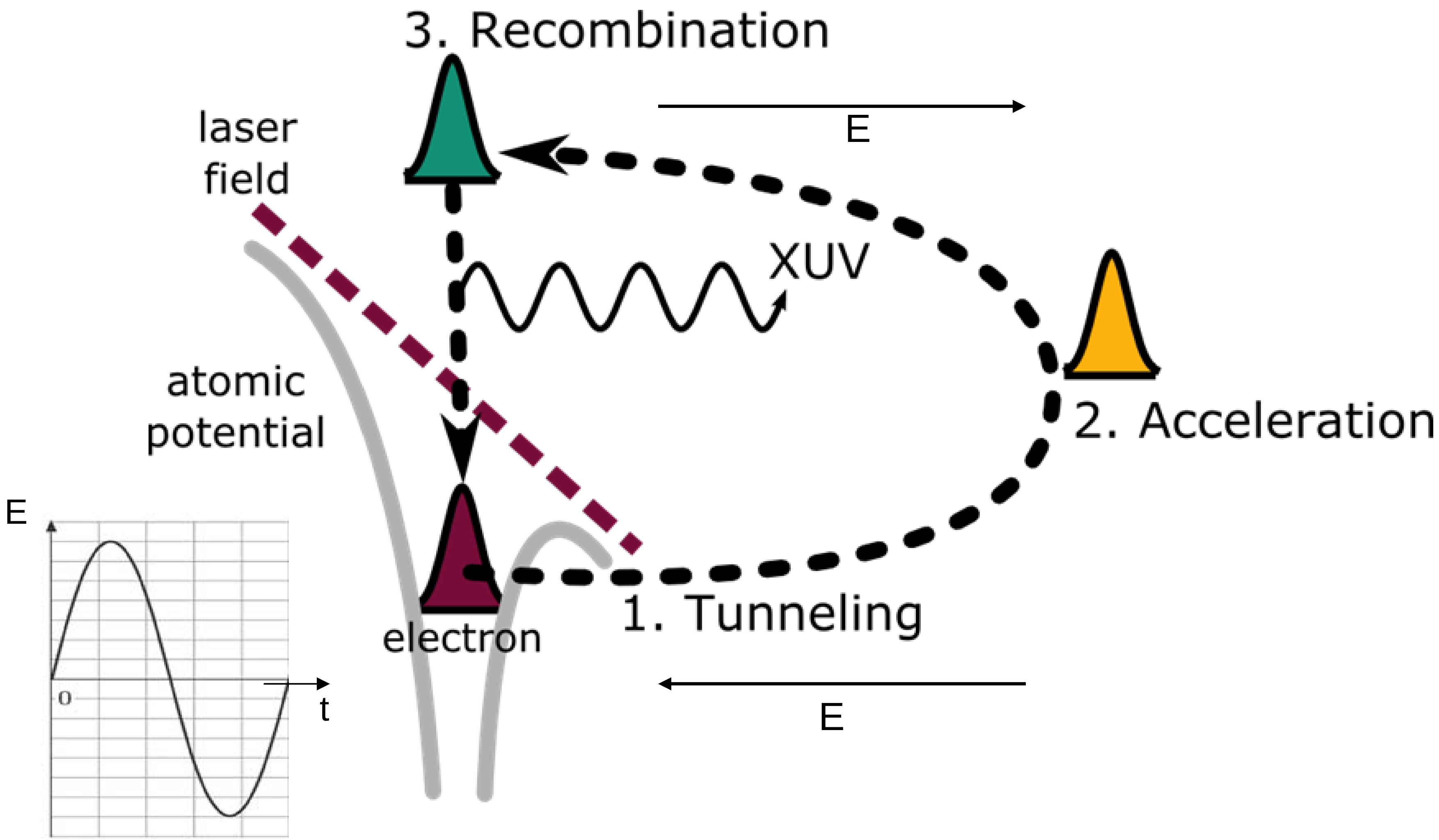
0.1 J/100 fs – 1 J/10 fs ~ 10^{12} –10^{14} Watts

Extraordinarily Strong NLO Effects

- **High-order nonlinear optics**
- **High-field laser physics**

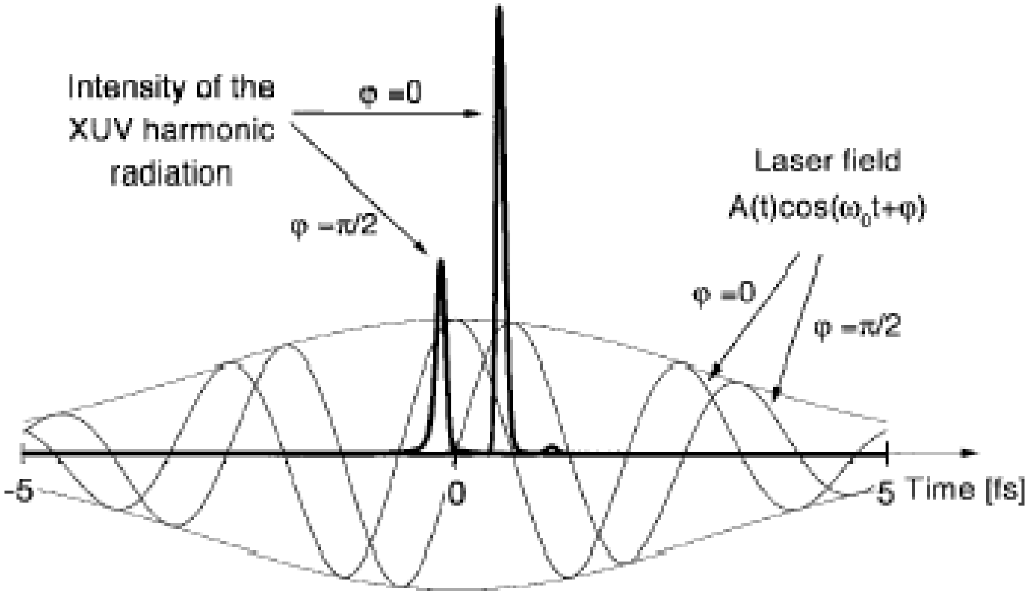


Mechanism for XUV Generation

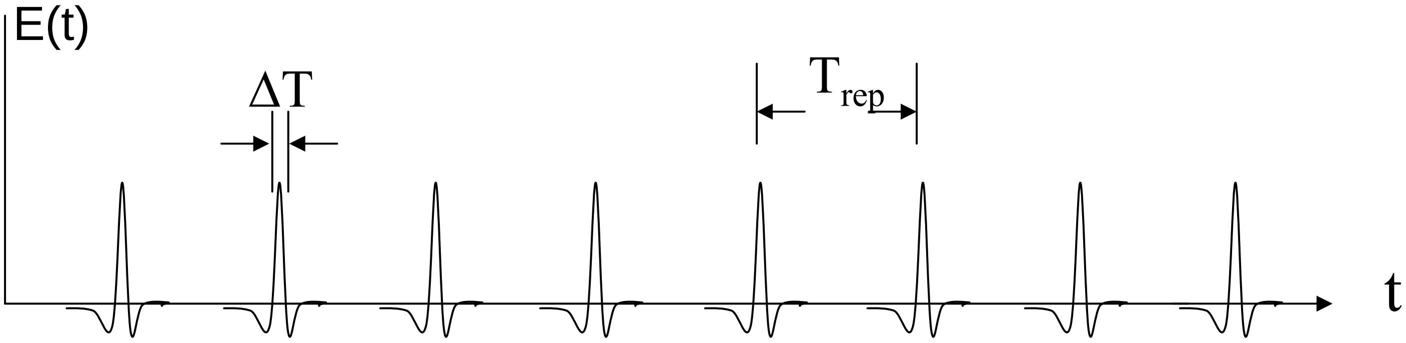


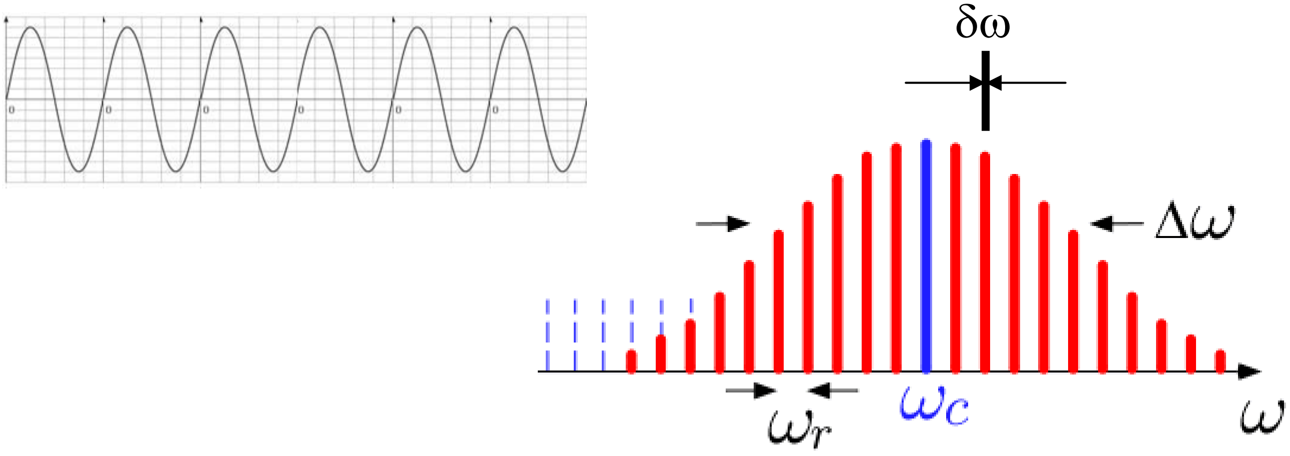
Generation of Attosecond Soft X-ray Pulses

Allows probing of electron dynamics and related phenomena



High-Order Harmonic Generation



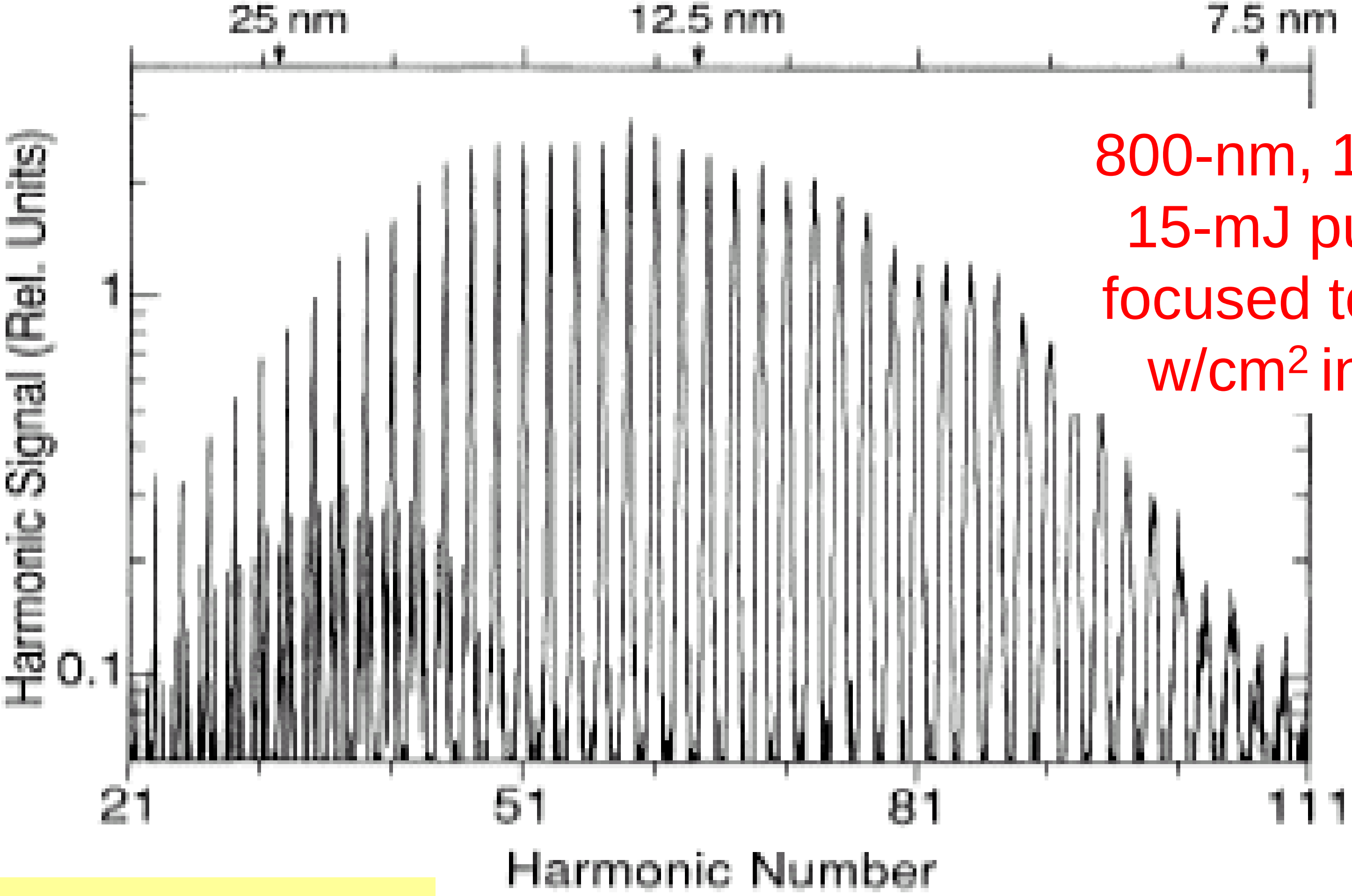


$\Delta\omega = 1/\Delta T \qquad \omega_r = 1/\,T_{rep}$

$\delta\omega = 1/T$

High Harmonic Generation

$$\hbar\omega_{cutoff} = I_p + 3e^2E^2/4m\omega^2$$



800-nm, 125-fs, 15-mJ pulses focused to 10^{15} w/cm^2 in Ne

Macklin et al, PRL 70, 766 (1993)

High-Intensity Laser Physics

Corresponding to a laser intensity of 10^{25} W/m^2,

$E = 6\text{x}10^{13}$ v/m

Acceleration for an electron:

$a = eE/m \sim 3\text{x}10^{23}$ g

$a\Delta t \sim (3\text{x}10^{23}\ g)(10^{-15}) > c$

Electron becomes relativistic.

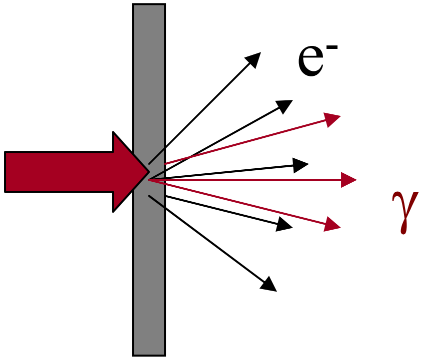


Photo-induced Nuclear Reactions:

Laser irradiation of target

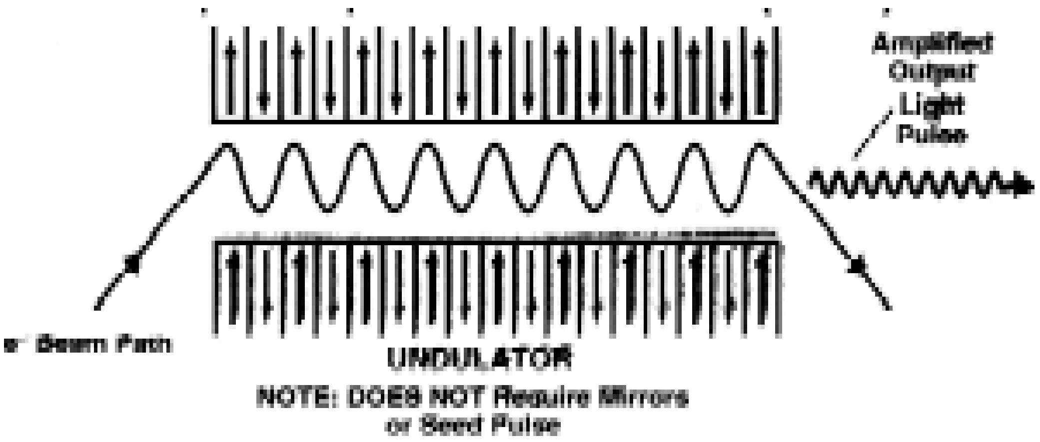
⇒⇒ High-energy electrons

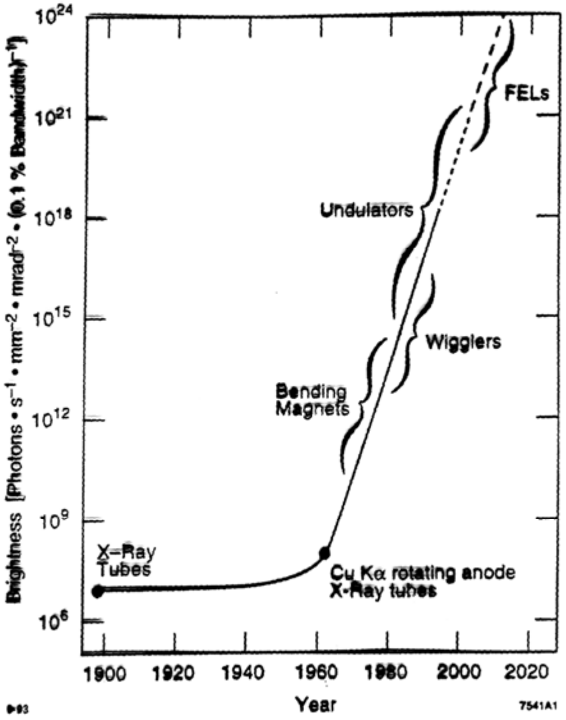
⇒⇒ Emission of γ-ray

⇒⇒ Nuclear fission (e.g., U^{238})

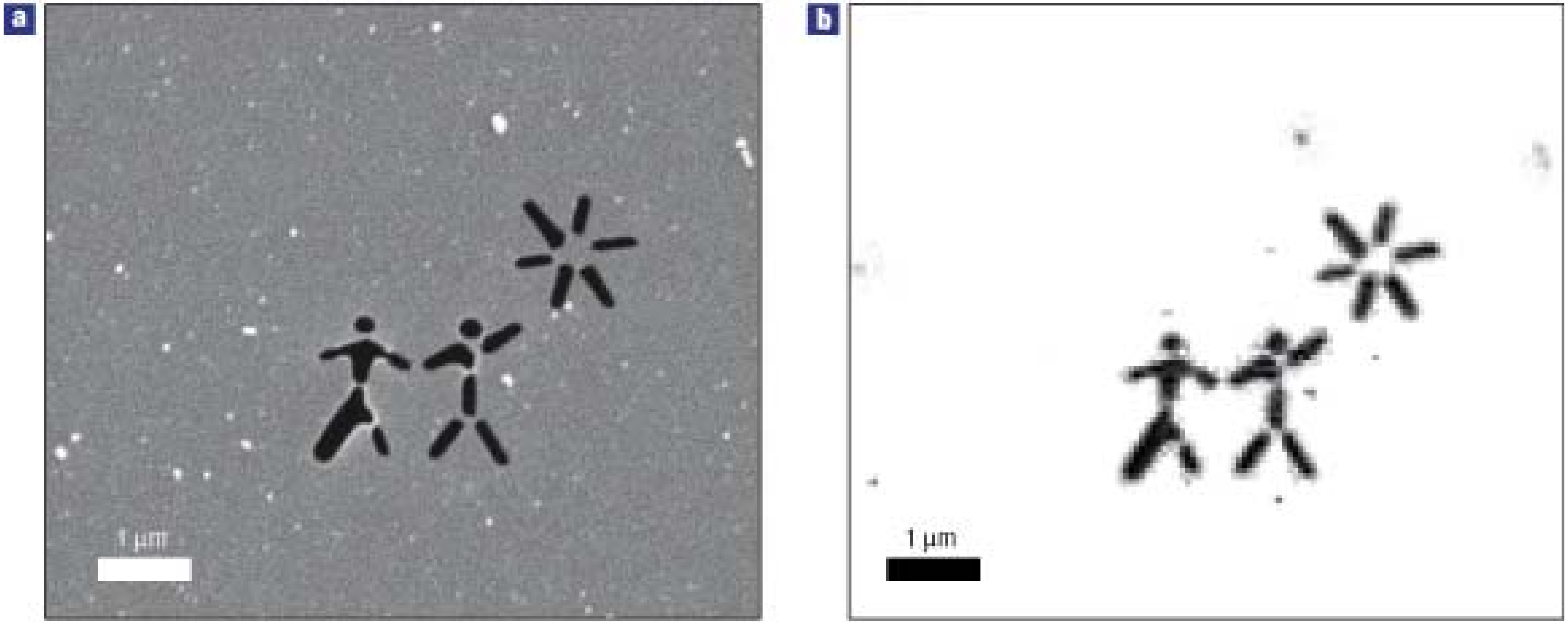
[PRL 84, 899, 903 (2000)]

Self-Amplified Spontaneous Emission Free Electron Laser (SASE-FEL)





The Ultimate Flash Photograph

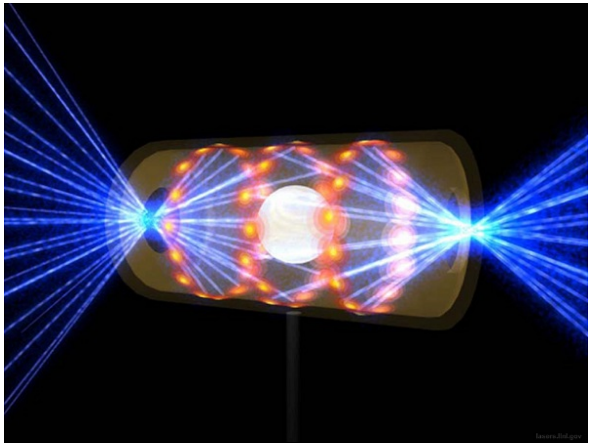


Chapman et al: “Femtosecond Diffractive Imaging with a Soft X-Ray Free Electron Laser” Nature Physics (on line, Nov., 2006)

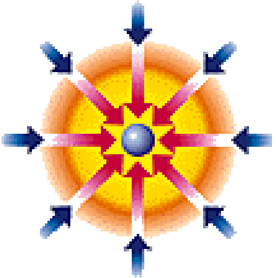
Laser Fusion *(Inertial Confinement)*

$$\mathrm{D} + \mathrm{T} \longrightarrow \mathrm{He}(3.5\ \mathrm{MeV}) + \mathrm{Neutron}(14\ \mathrm{MeV})$$

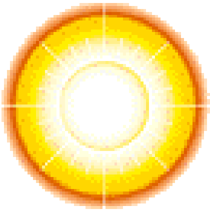
Ignition occurs if $T > 10^{8}$ K,
$(\mathrm{Density})(\mathrm{Time}) > 10^{14}\ \mathrm{sec/cm^{3}}$



Target Chamber



Implosion
& Heating



Burning

U.S. National Ignition Facility

(Largest Laser Project in the World)

1–2 MJ/pulse (20 ns pulses)

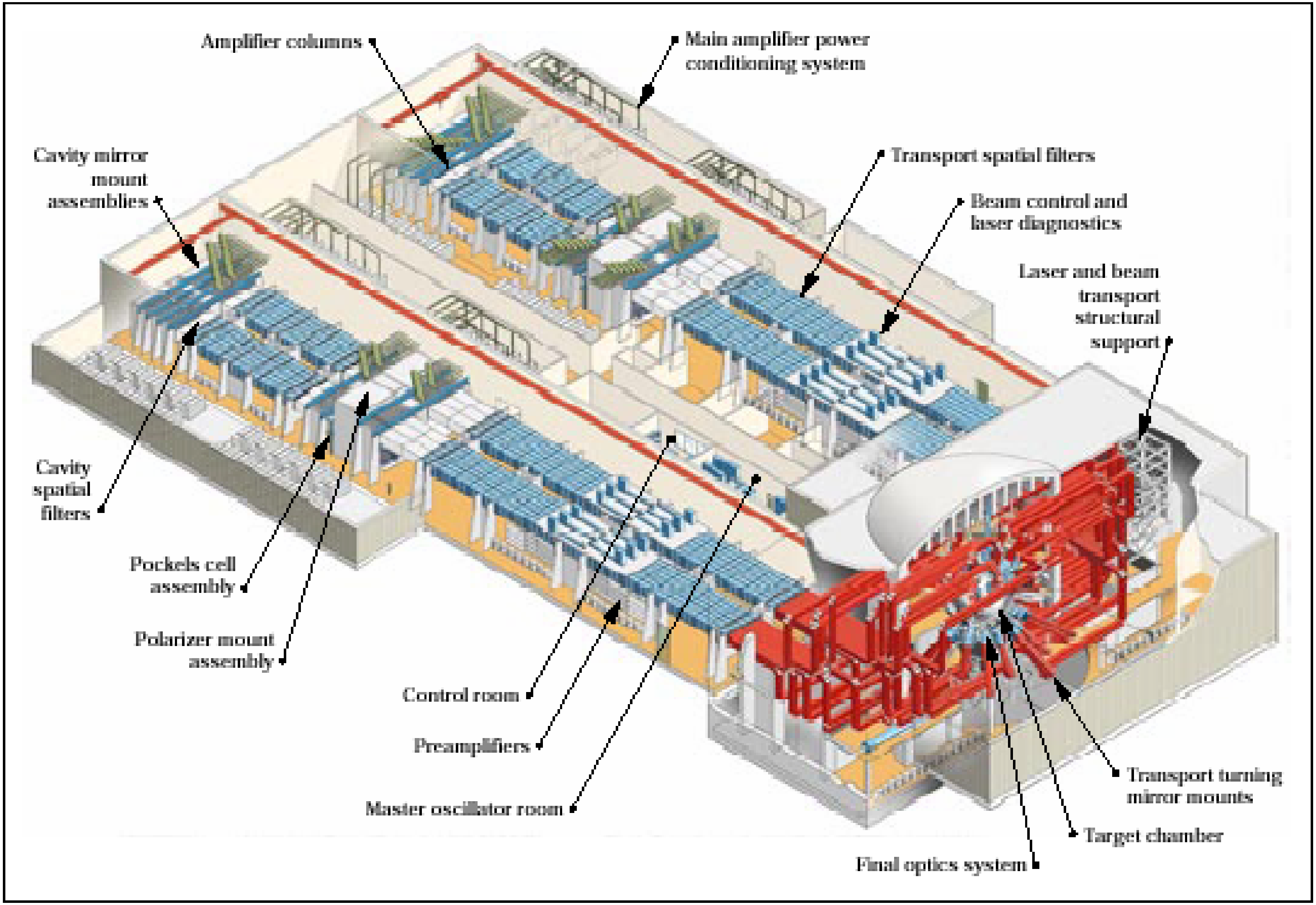
192 beams

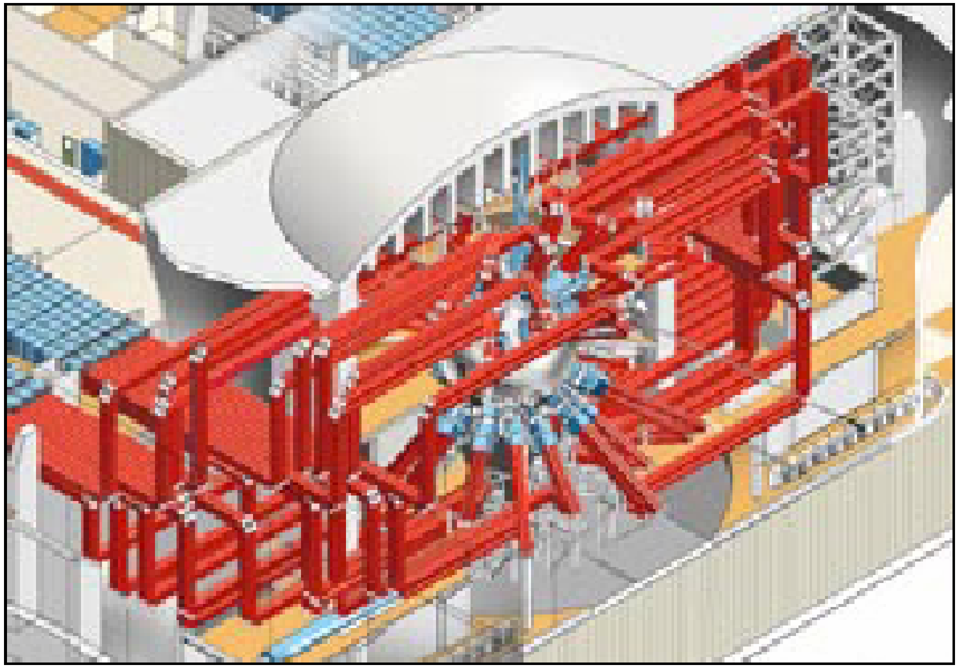
6.4 KJ/beam (10.4 KJ/beam)

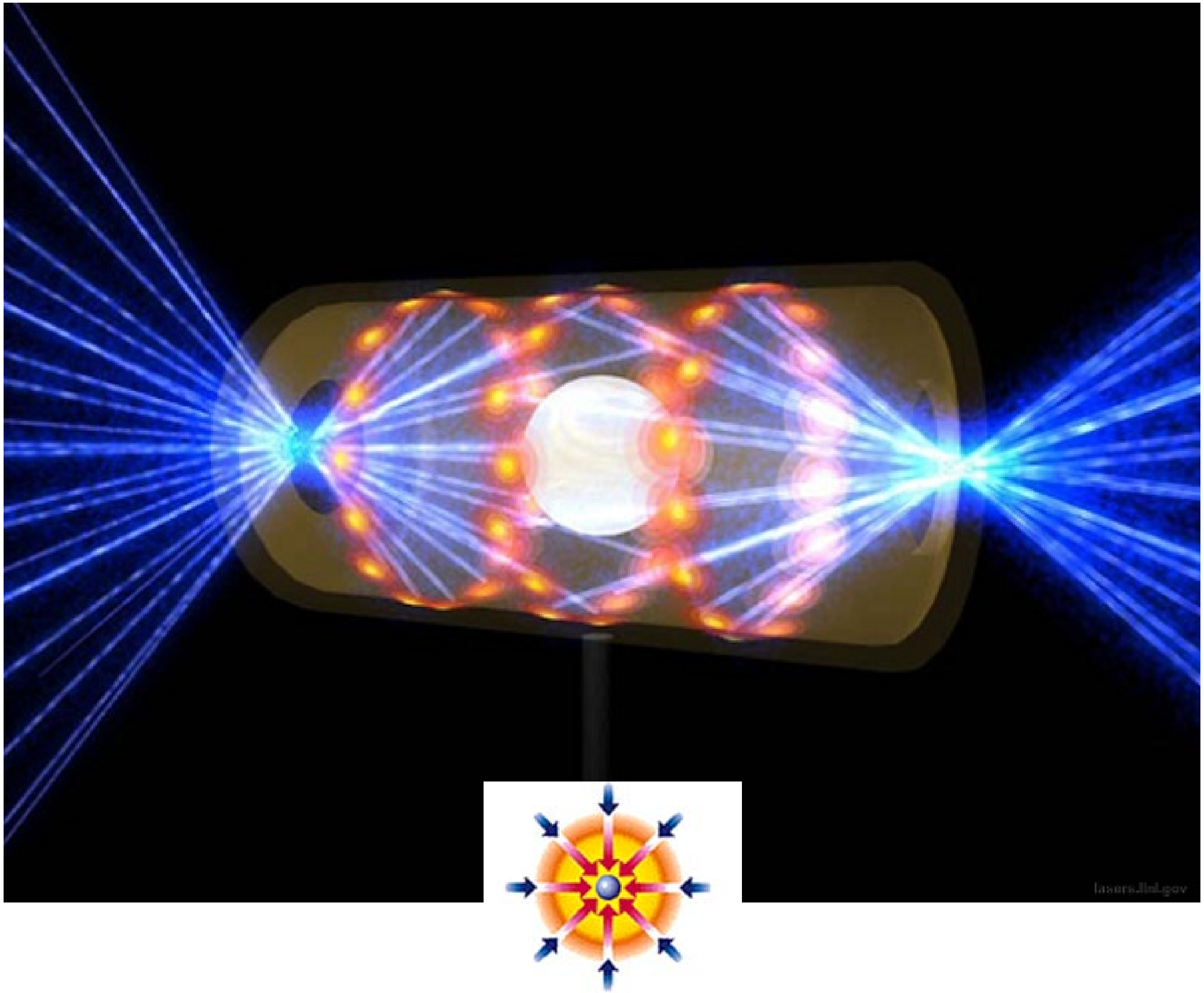
Cost: >$3.8 billions

Completion: Completion, 2008

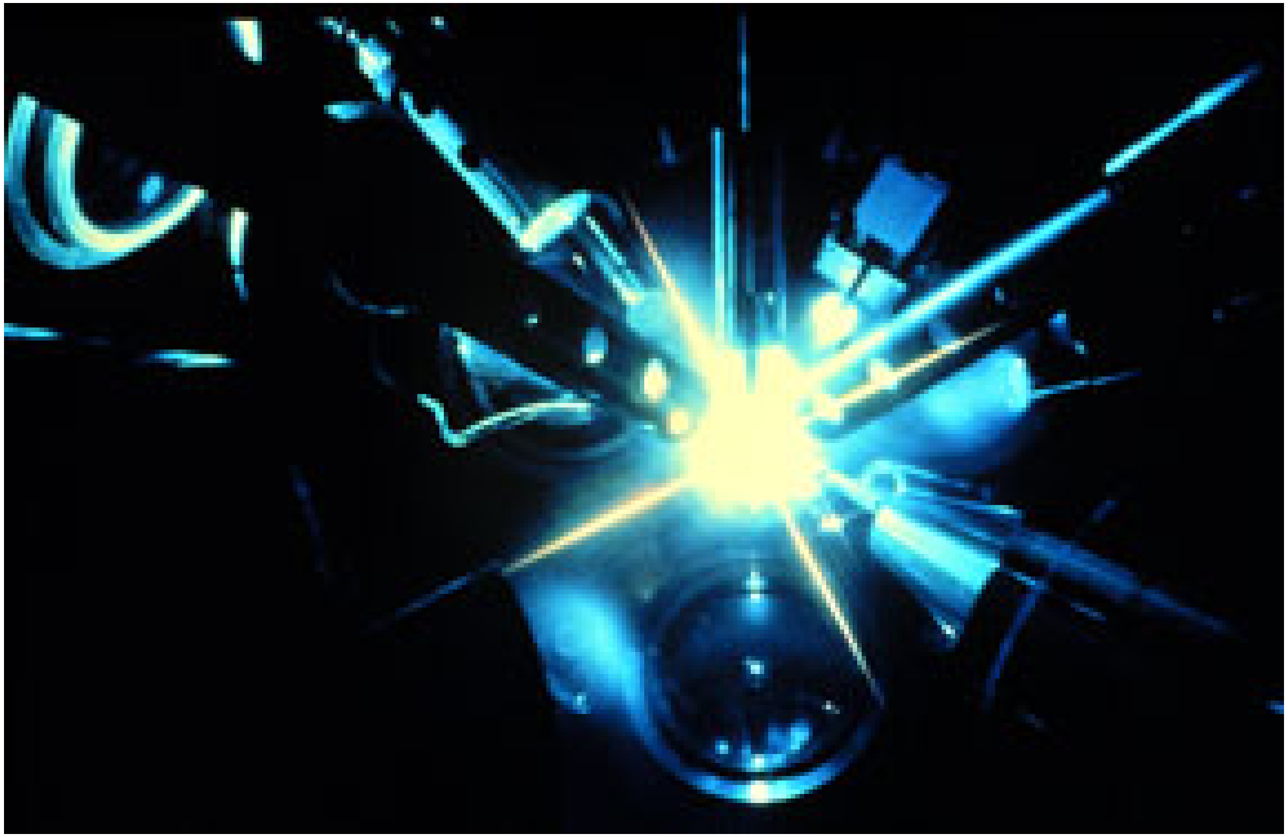
after Year 2016, 700 shots per year


Amplifier columns
Main amplifier power conditioning system
Cavity mirror mount assemblies
Transport spatial filters
Beam control and laser diagnostics
Laser and beam transport structural support
Cavity spatial filters
Pockels cell assembly
Polarizer mount assembly
Control room
Preamplifiers
Master oscillator room
Transport turning mirror mounts
Target chamber
Final optics system



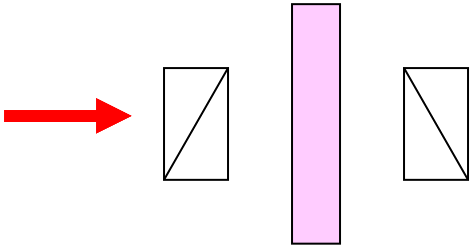

lasers.llnl.gov

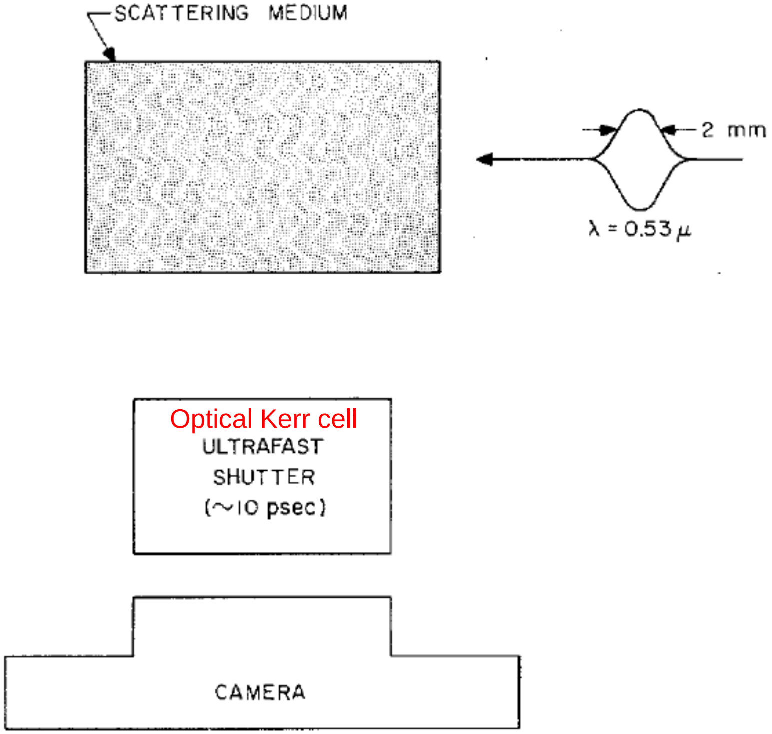
Laser Ignition

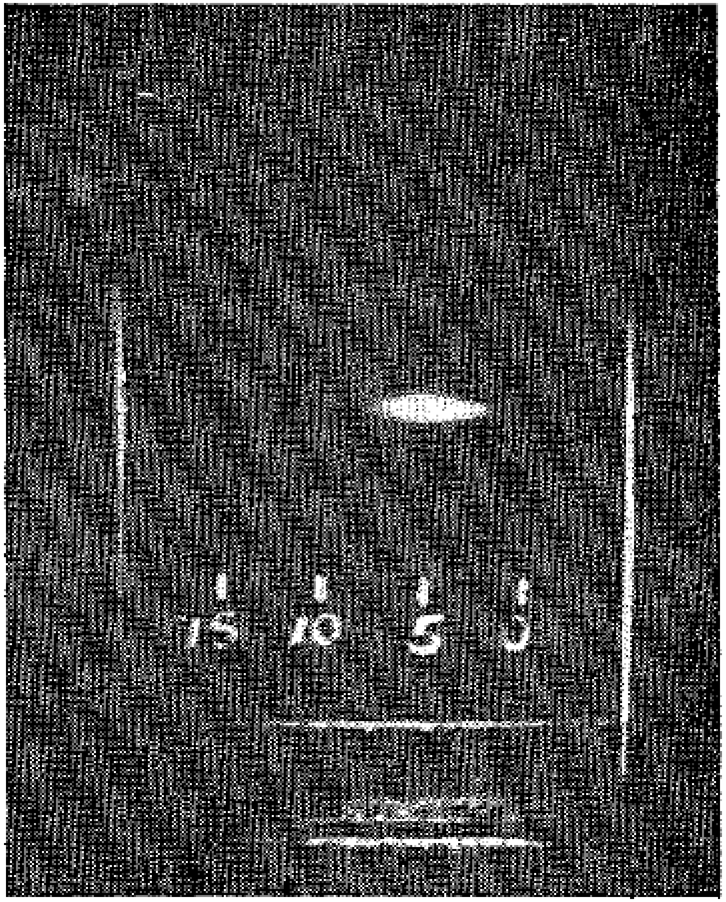


Future Must Be Bright

Optical Kerr effect ⇒ Induced birefringence
⇒ Ultrafast optical switching
⇒ Ultrafast Photography





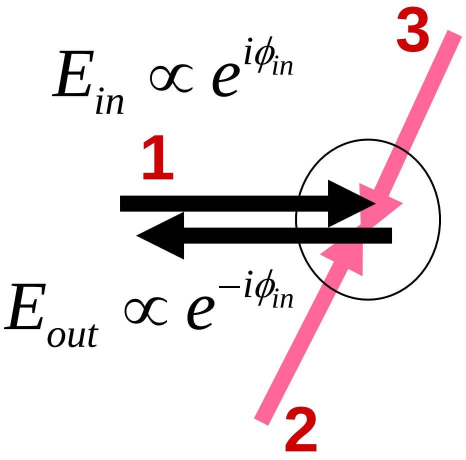


Duguay, Hansen, IEEE JQE 7, 37 (1971)

Phase Conjugation

(Photorefraction, Real-Time Halography)

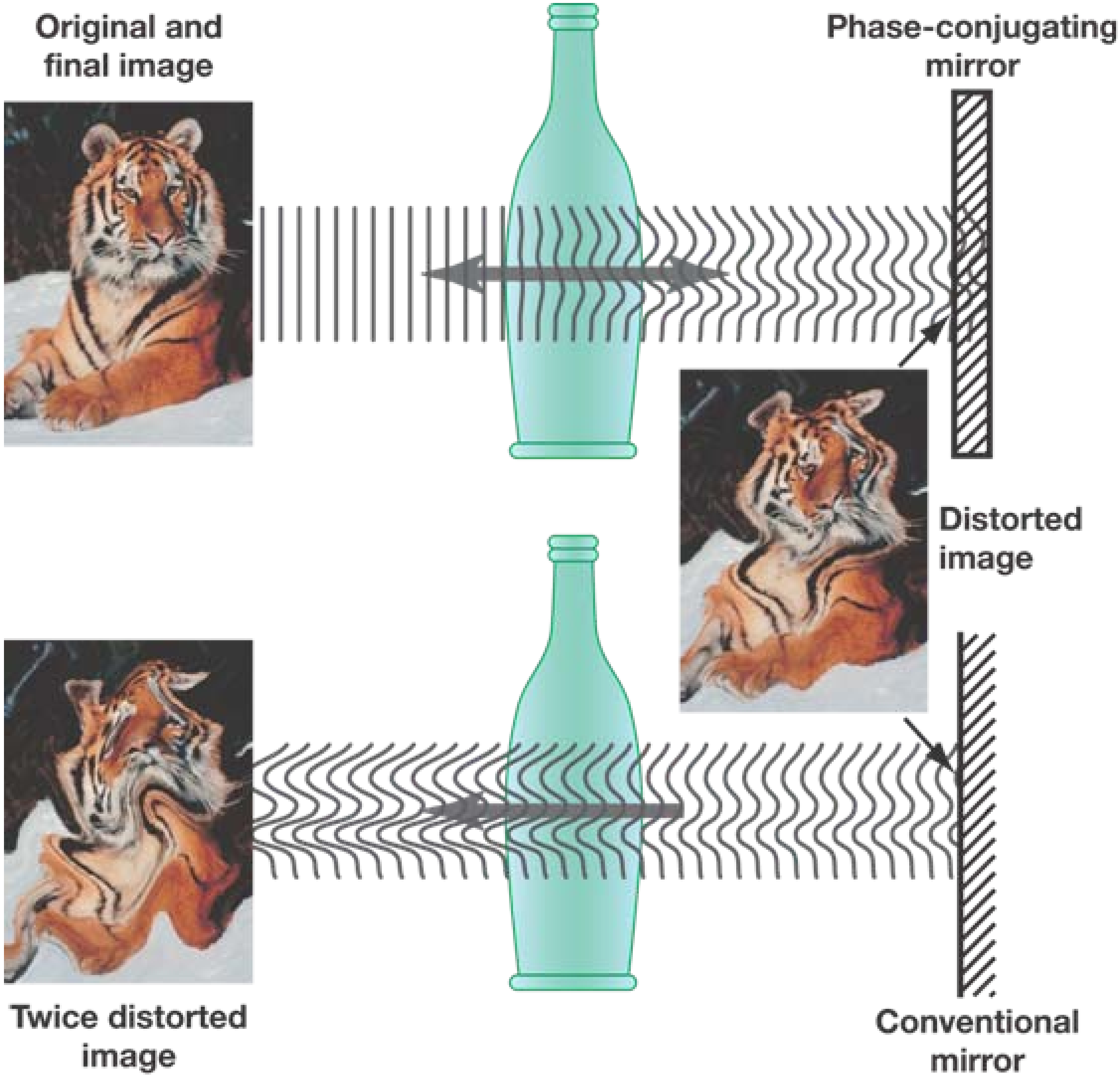
(Hellwarth, Bloom, Bjorklund, Yariv, Pepper, 1977)



$$E_{in} \propto e^{i\phi_{in}}$$

$$E_{out} \propto e^{-i\phi_{in}}$$

Wavefront reconstruction by phase conjugation

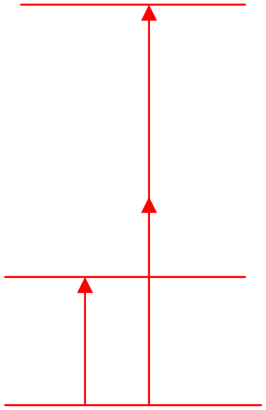


Laser Spectroscopy

Bloembergen, Schawlow (Nobel, 1980)

Lamb, Ramsey, Hansch, Cohen-Tannouji, Hall, Chu

- High intensity ⇒ better S/N
- Narrow linewidth ⇒ better spectral resolution
- Diffraction limit beam ⇒ better resolution in microscopy
- Narrow pulse width ⇒ ultrahigh temporal resolution in dynamic studies



⇒⇒
- ◦ New laser spectroscopic techniques
- ◦ Probing material properties not accessible earlier
- ◦ New areas of research

After quadratically adding a systematic error of 23 Hz, the frequency of the F=1 to F' =1 hyperfine component of the 1S–2S transition obtained in 2003 isThe uncertainty of 1.4 parts in 1014 is only slightly improved over that of the 1999 resultHere, we have added a pressure shift of 10 Hz that had not been included in the 1999 analysis and a systematic error of 28 Hz. However, we now have two independent measurements of this important transition which agree within their error limits. The difference of (−29±57) Hz in 44 months corresponds to a drift of the 1S–2S frequency relative to the caesium frequency standard of (−3.2±6.3)×10−15 per year, consistent with a zero drift.

3. Are the fundamental constants constant?

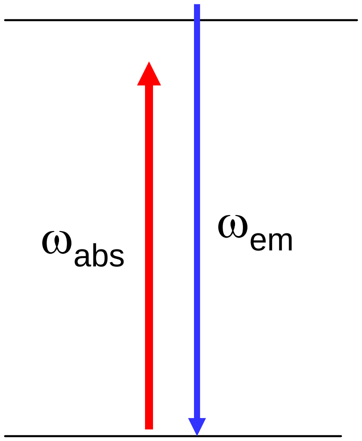
Boson and Fermion Condensates

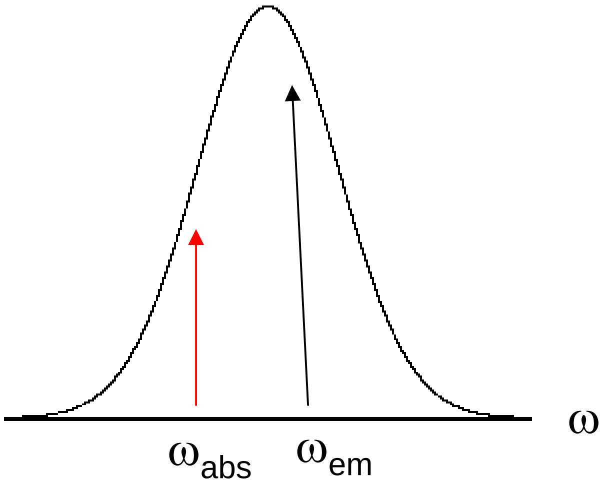
Bose-Einstein condensation occurs when

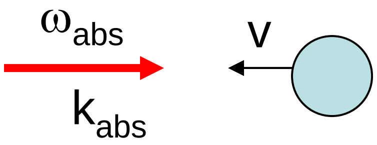
$$(N/V)\lambda^3 = 2.612 \qquad \text{at } T = T_c,$$

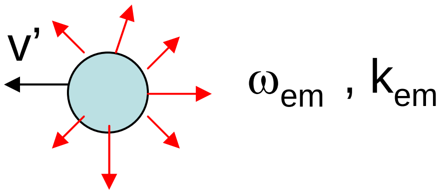
$$\lambda = h/p, \qquad p = (2\pi MkT)^{\frac{1}{2}}$$

Laser Cooling of Atoms and Molecules







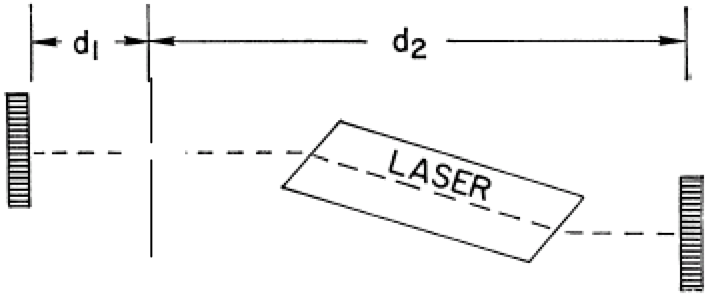


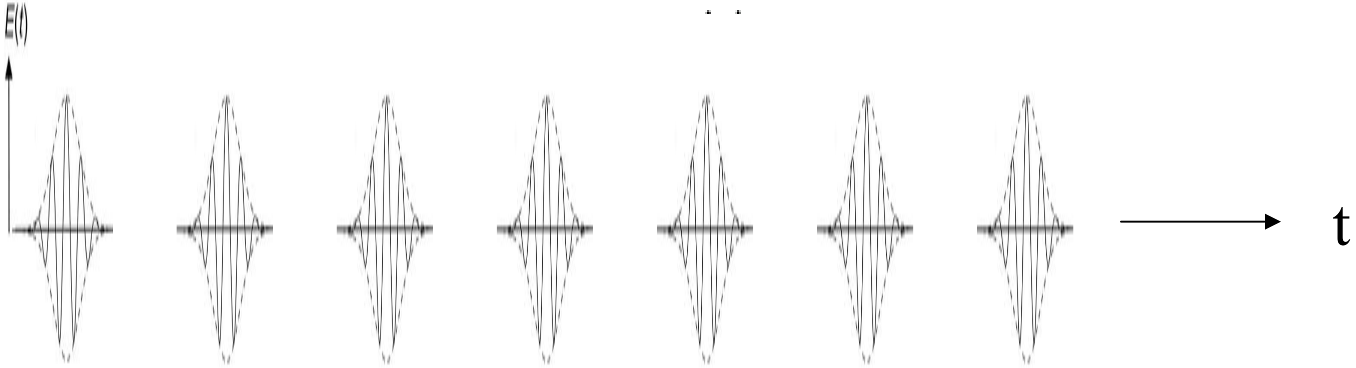
With k_{abs} opposite to v, we always have $\omega_{em} > \omega_{abs}$

Atom loses translational energy

Kerr Self-Mode-Locking of Ti:Sapphire Lasers:

Generation of Continuous fsec Pulses

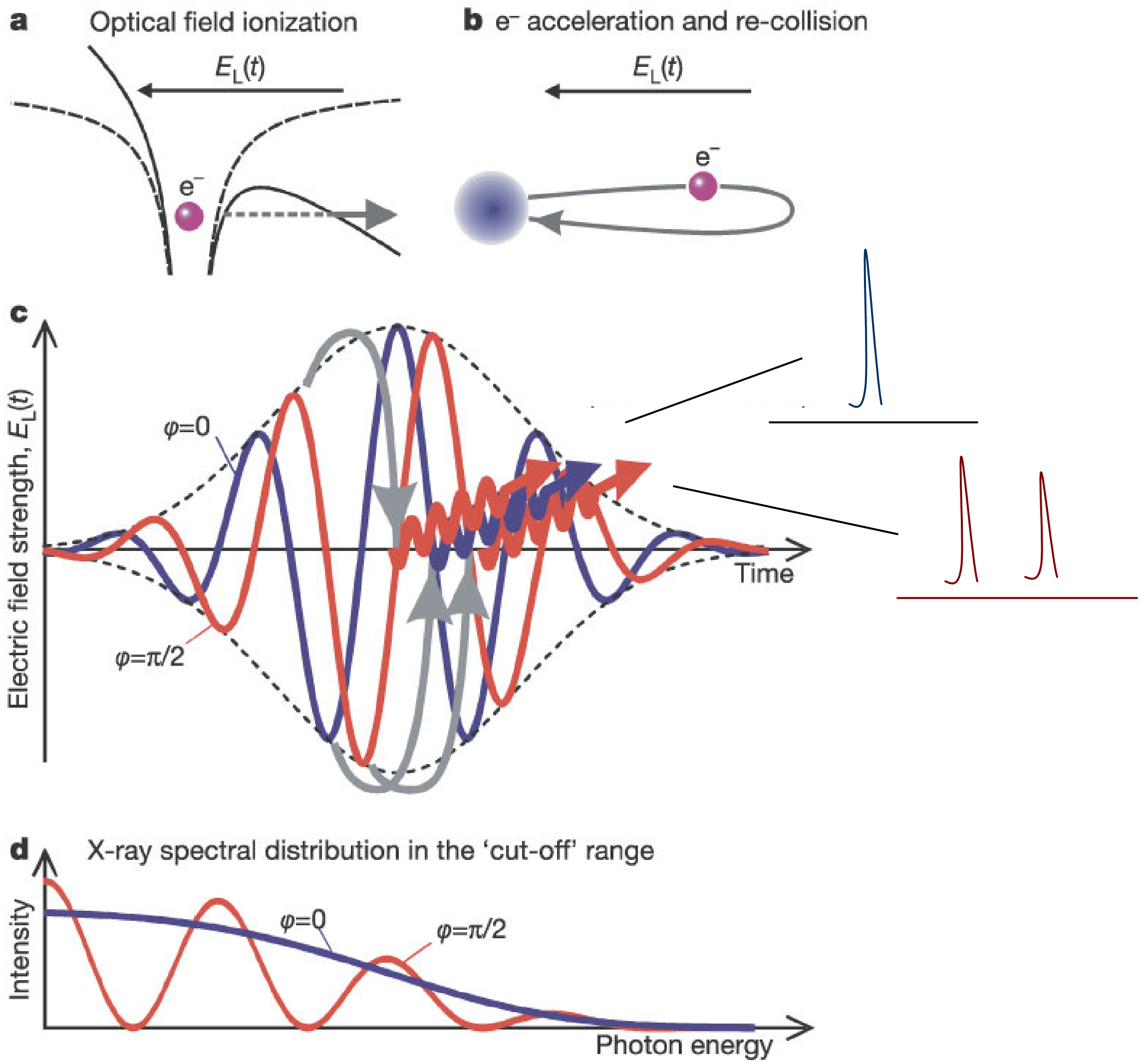




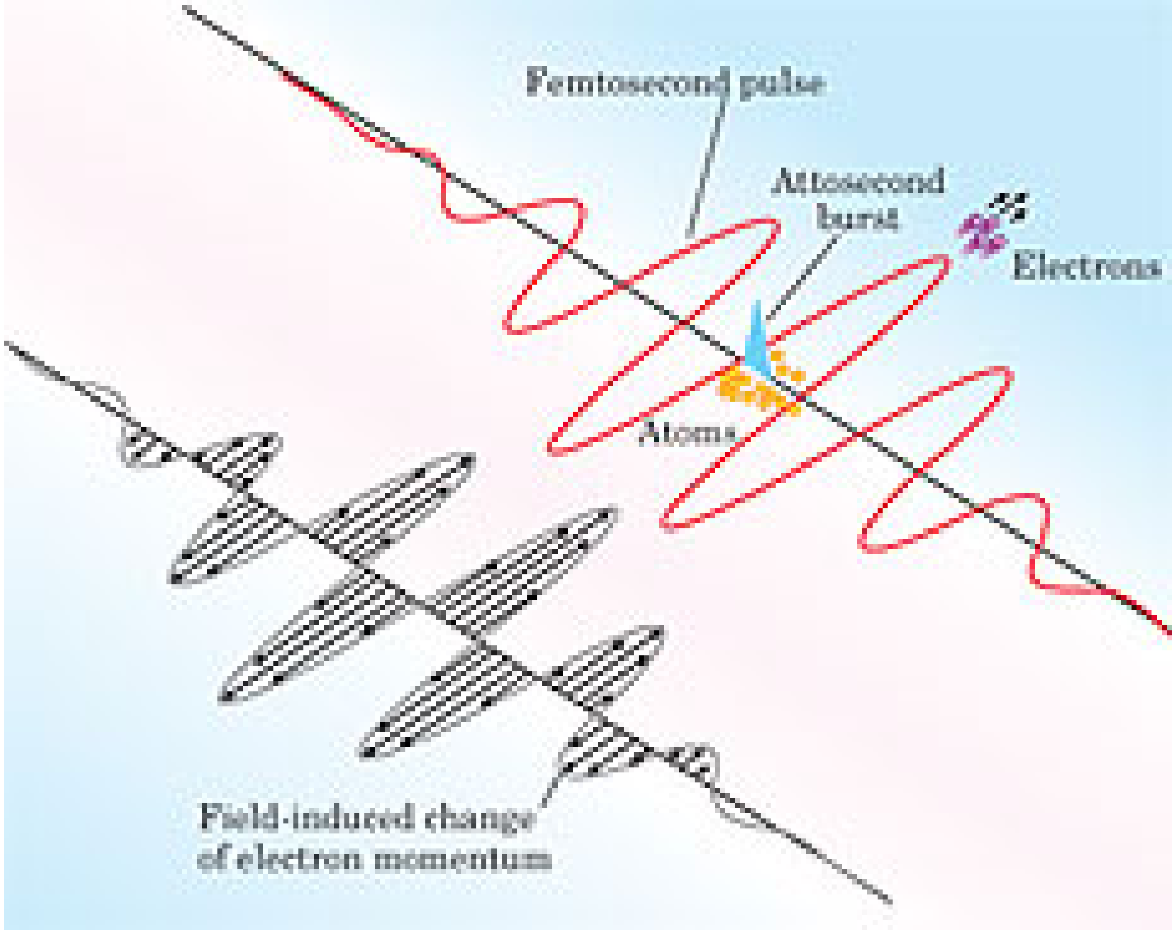
High-Order NLO

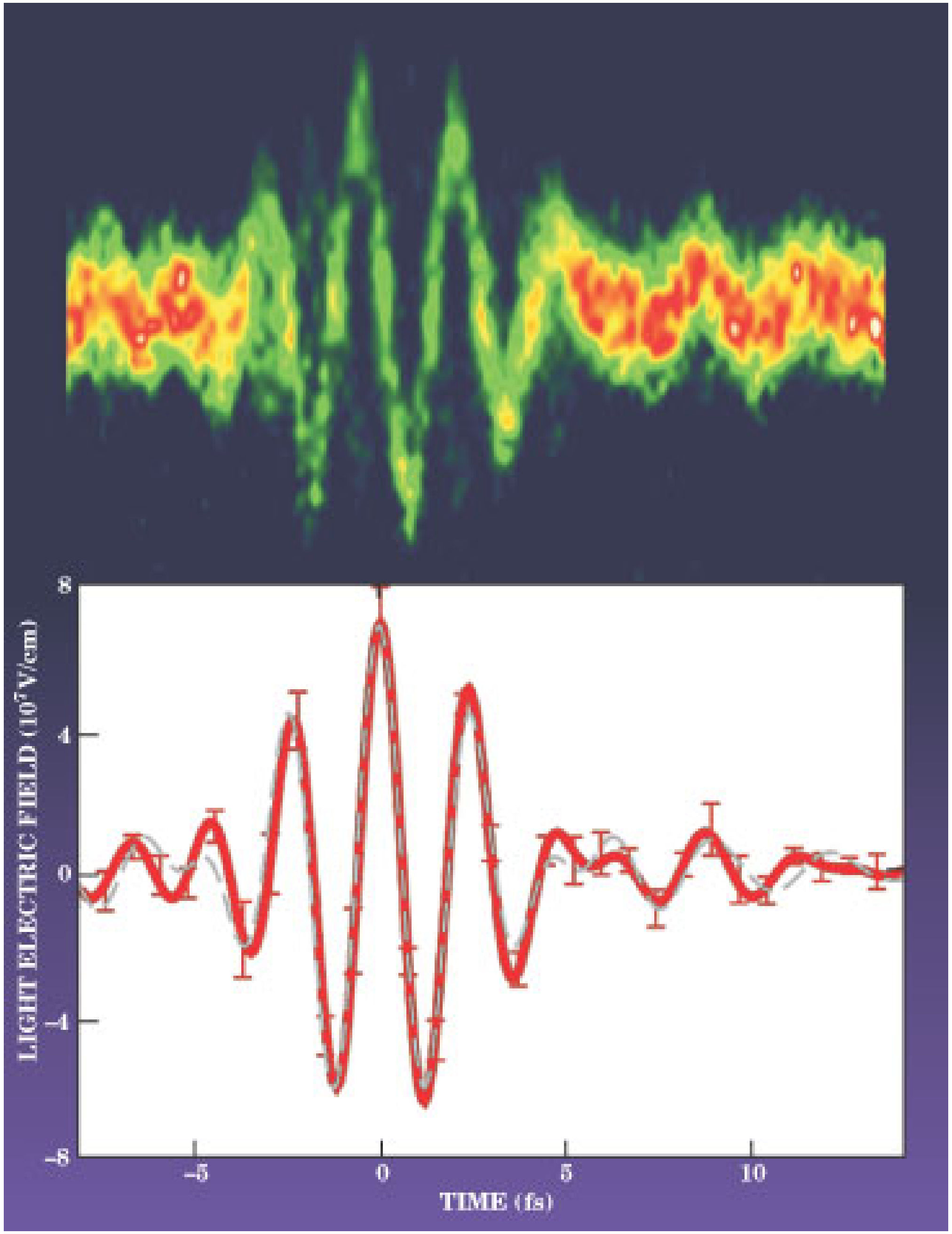
- Infrared multiphoton excitation and dissociation of molecules
- Multi-photon ionization
  - Above threshold ionization
  - Optical-field-induced tunneling
- High-harmonic generation
  - Soft X-ray coherent light source
  - Attosecond pulse generation
  - Phase-matching in hollow waveguides
  - Attosecond electron dynamics
- Laser-induced plasmas: Point X-ray sources

Generation of Attosecond Soft X-ray Pulses



Mapping Field of A Femtosecond Light Pulse




LIGHT ELECTRIC FIELD (10^7V/cm)
8
4
0
−4
−8
−5
0
5
10
TIME (fs)

Current Hot Topics in NLO

- Attosecond electron dynamics
- **High-field physics**
- NLO with frequency combs
  - Precision spectroscopy
- NLO of cold atoms and molecules
- X-ray nonlinear optics

High-Field Laser Physics

A 10-TW (100 mJ/10 fs) laser pulse, focused to a 10 um spot, has an intensity of $10^{19}\ \mathrm{W/cm^2}$,creates a pondermotive potential for electrons

$$U = \frac{e^2}{2mc^2} A^2 = \frac{e^2}{2m\omega^2} E^2$$

$$\sim 1\ \mathrm{MeV} \quad \text{at} \quad 10^{19}\ \mathrm{W/cm^2}$$

compared to 0.5 MeV for the rest mass of electrons

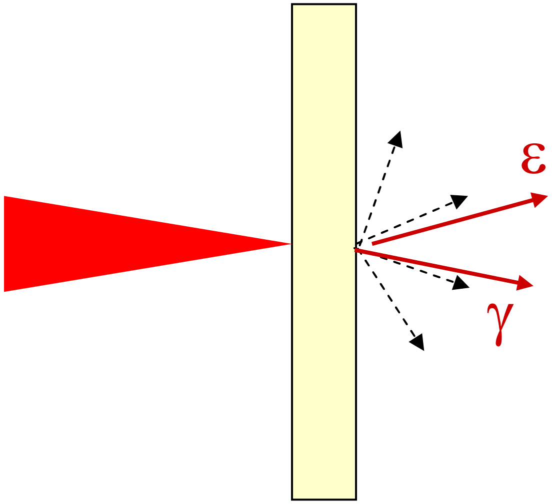
$$\text{Electron acceleration: } a = eE/m \sim 5x10^{20}\, g$$

$$\mathrm{v} = at/2 \rightarrow c \ \text{ in } \ 10\ \mathrm{fs}$$

$\Rightarrow$ Relativistic electron dynamics in laser-induced plasmas

$\Rightarrow$ Laser particle accelerator

Photo-Induced Nuclear Reactions



Laser irradiation of target

(10^{19}-10^{20} W/cm^{2})

⇒⇒ High-energy electrons

⇒⇒ High-energy photons

⇒⇒ Nuclear fission (U^{238})

[PRL 84, 899, 903 (2000)]

Laser Fusion