

# Welcome to Ultrafast Optics

- Who am I:** Daniel Middleman (office hours: to be determined)
- When, where:** Tues / Thurs @ 9am
- Web page:** see canvas
- Prerequisites:** Quantum mechanics and E&M at an undergraduate level, or permission of instructor. Come talk to me if you are uncertain.
- Grading:** Lecture attendance (**mandatory**)  
Problem sets (occasional)  
Research presentations (everybody)



# Textbooks

No required text! But if you will be working in this field, you will want to own some of these...

## Recommended reading - lasers and nonlinear optics:

- *Lasers*, by A. Siegman  
(University Science Books, 1986)
- *Fundamentals of Photonics*, by Saleh and Teich  
(Wiley, 1991)
- *The Principles of Nonlinear Optics*, by Y. R. Shen  
(Wiley, 1984)
- *Nonlinear Optics*, by R. Boyd  
(Academic Press, 1992)
- *Optics*, by Eugene Hecht  
(Addison-Wesley, 1987)

## Recommended reading - ultrafast phenomena:

- *Ultrashort laser pulse phenomena*, by J.-C. Diels and W. Rudolph  
(Second Edition, Academic Press, 2006)
- *Ultrafast Optics*, by Andrew Weiner  
(Wiley, 2009)

# Topics to be covered

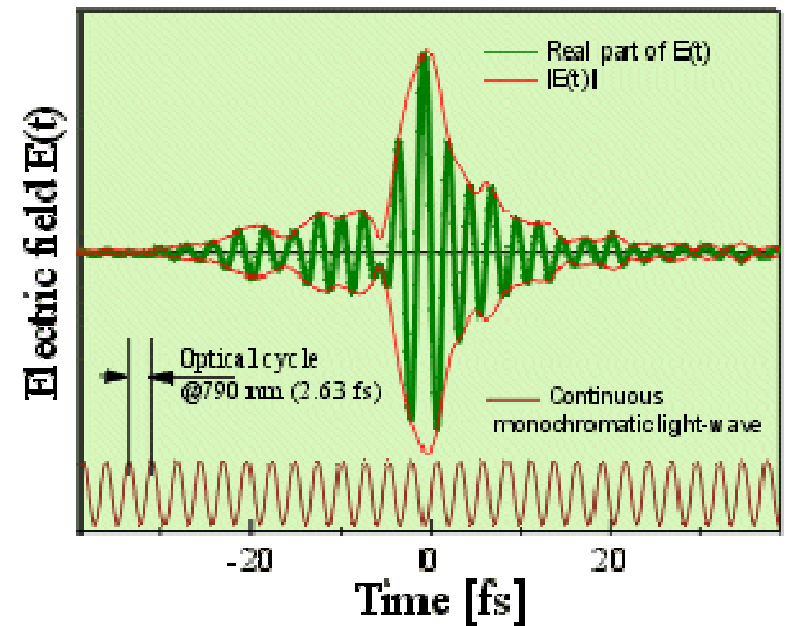
- Basic optical physics
- Pulse propagation
- 2nd and 3rd-order non-linearities
- Mode-locking



How do they do this?  
(and why)



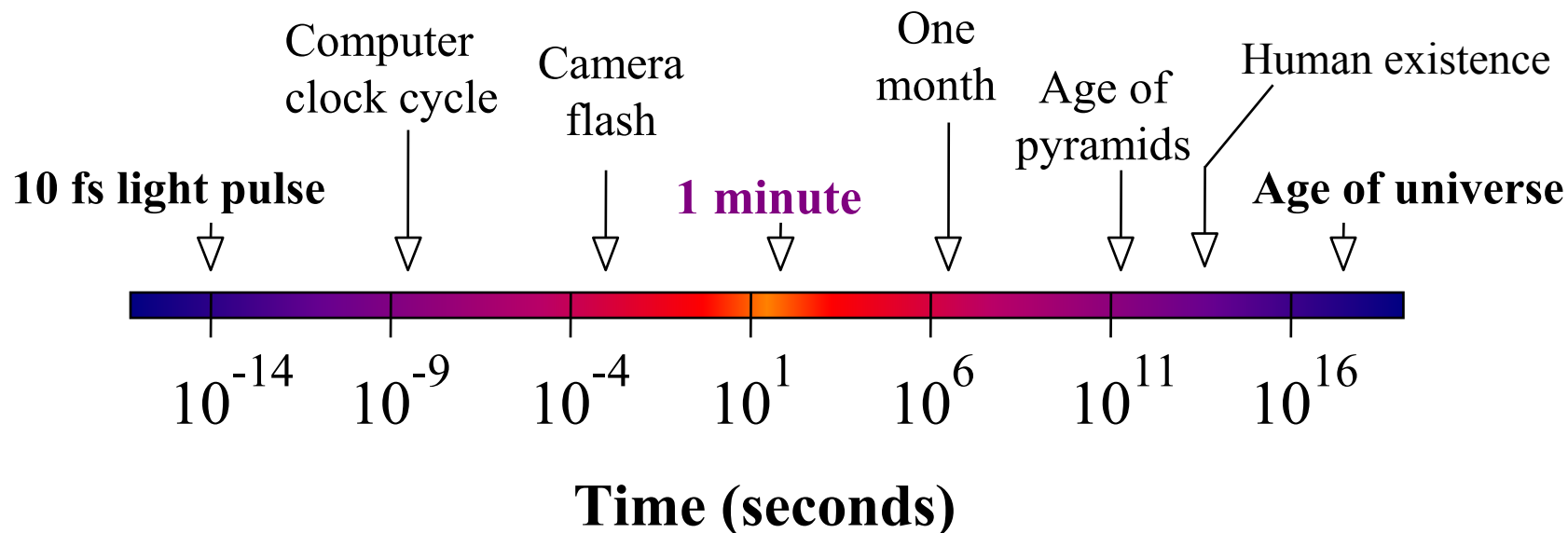
Other topics pending...



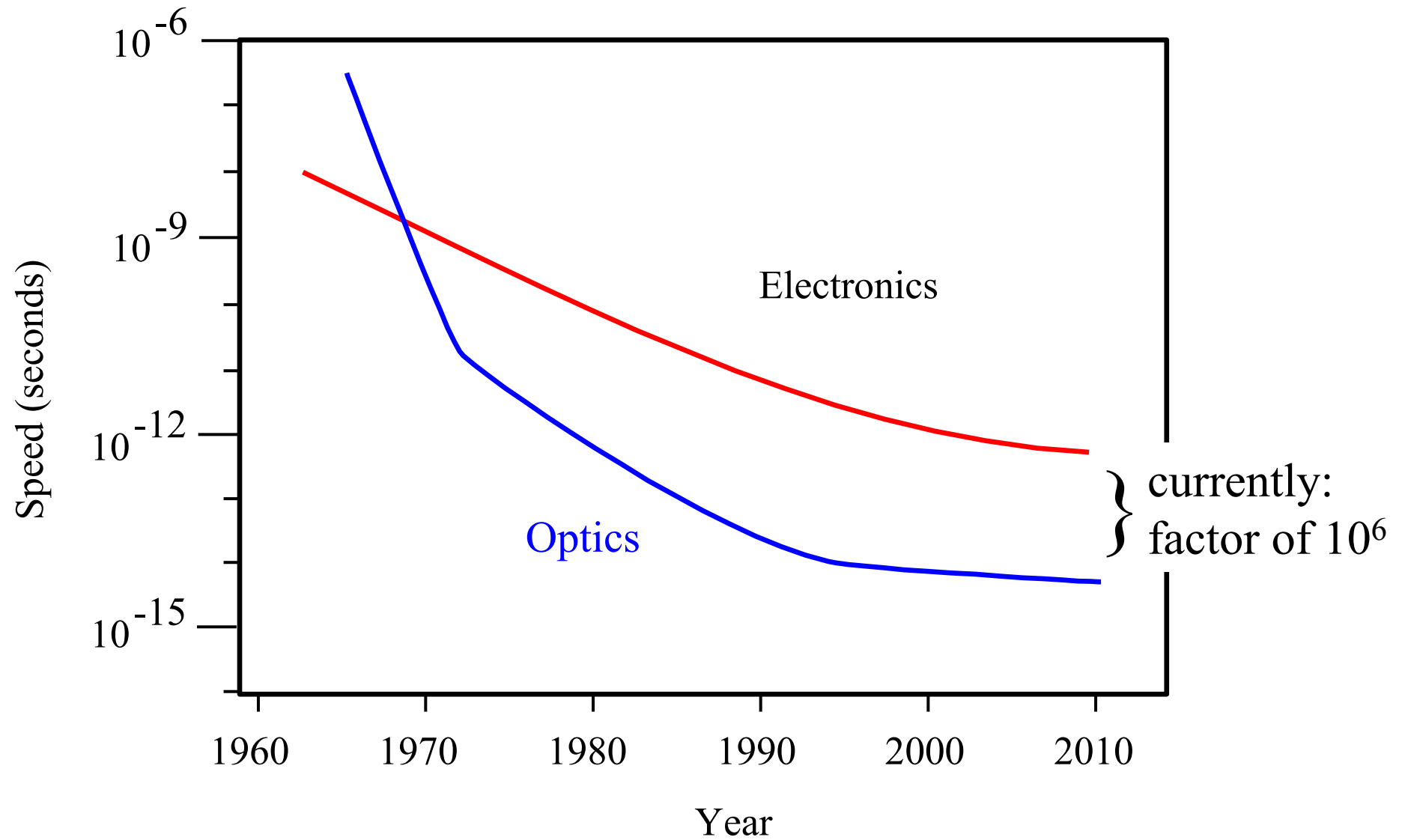
# How big and how small?

Prefixes:

<u>Small</u>		<u>Big</u>	
Milli (m)	$10^{-3}$	Kilo (k)	$10^{+3}$
Micro ( $\mu$ )	$10^{-6}$	Mega (M)	$10^{+6}$
Nano (n)	$10^{-9}$	Giga (G)	$10^{+9}$
Pico (p)	$10^{-12}$	Tera (T)	$10^{+12}$
Femto (f)	$10^{-15}$	Peta (P)	$10^{+15}$
Atto (a)	$10^{-18}$	Exa (E)	$10^{+18}$
Zepto (z)	$10^{-21}$	Zetta (Z)	$10^{+21}$
Yocto (y)	$10^{-24}$	Yotta (Y)	$10^{+24}$

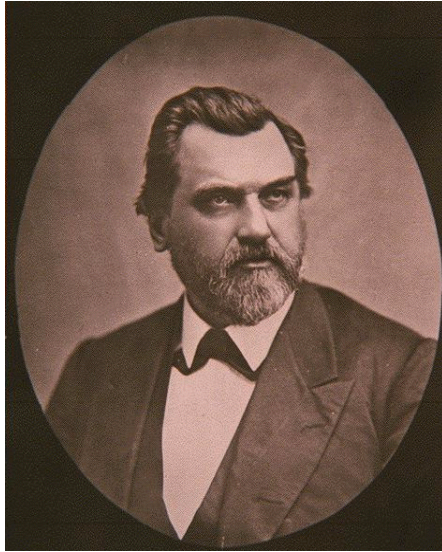


# Ultrafast Phenomena - The Evolution of Speed

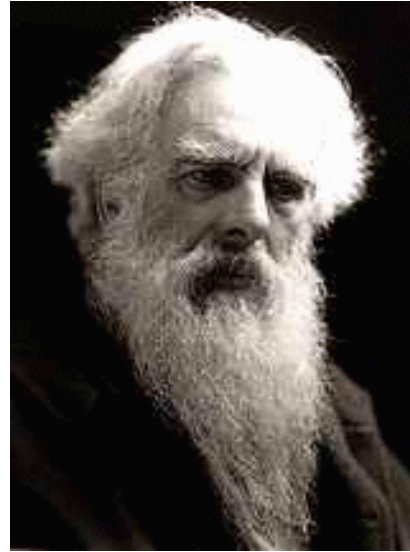


# A brief history of time resolution

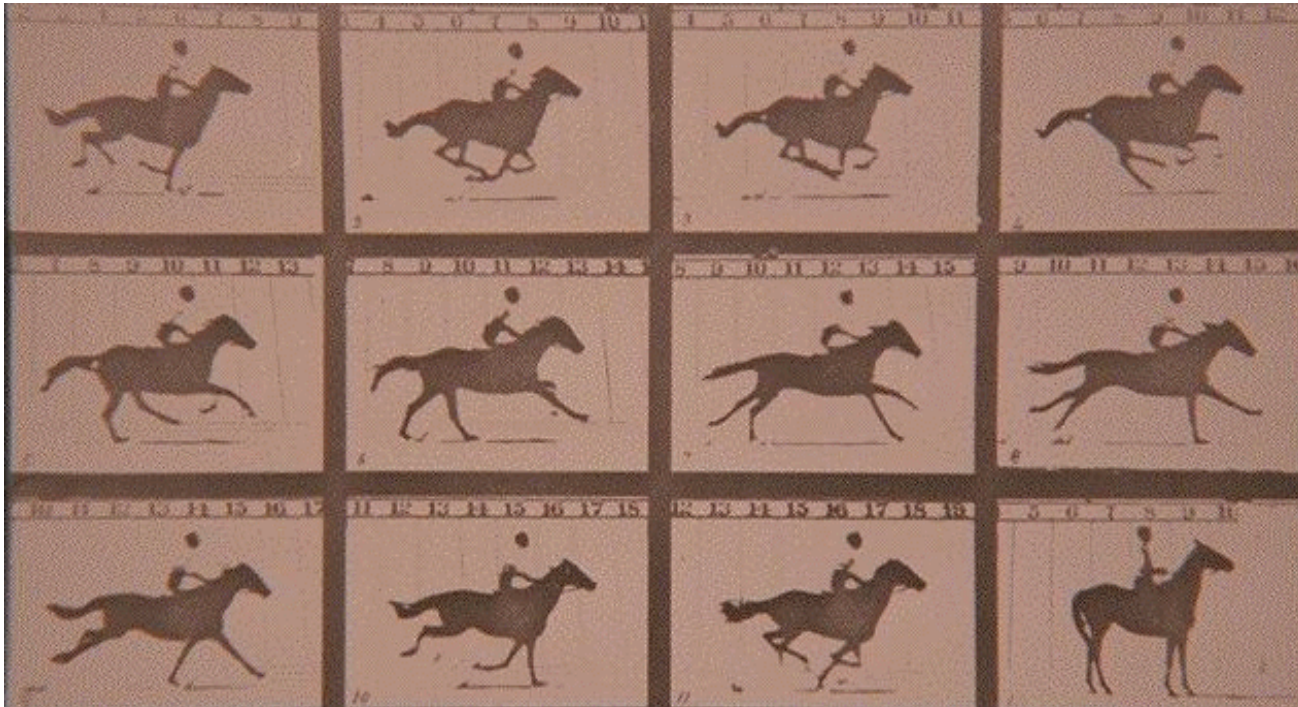
Leland  
Stanford



Eadweard  
Muybridge



The "Trotting Horse" Controversy Palo Alto, CA 1872

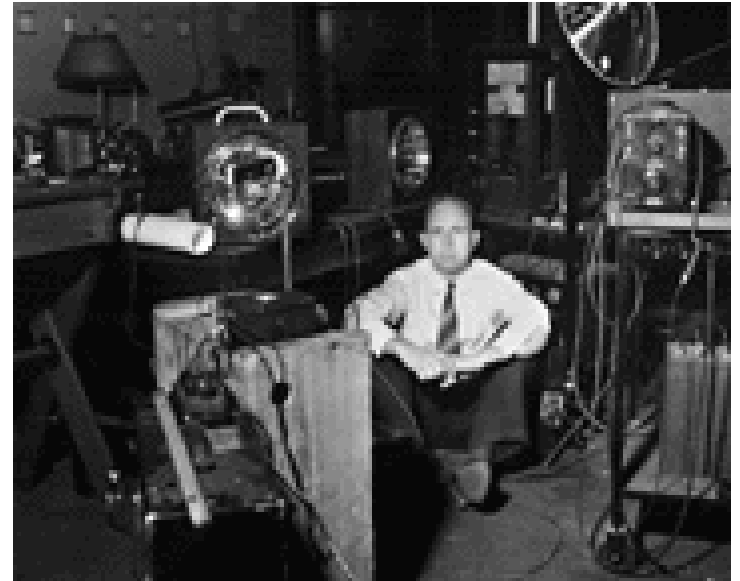


Time Resolution:  
1/60th of a second

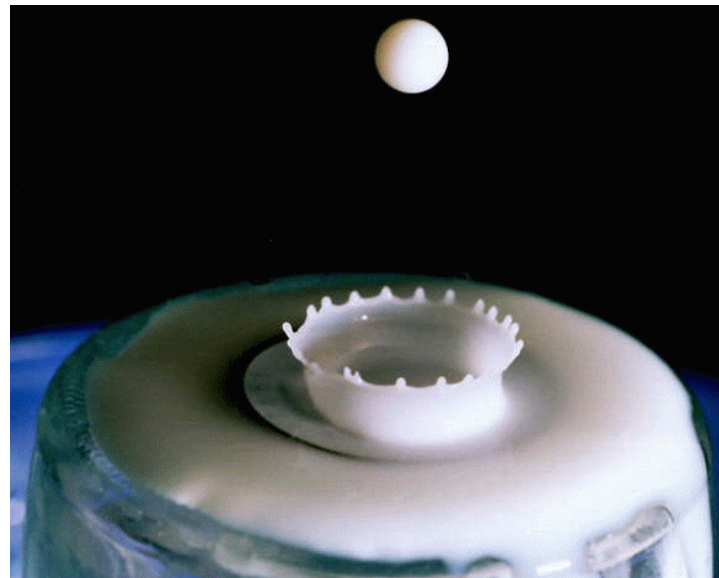


# 'Doc' Edgerton - Strobe Photography

Harold Edgerton      1942  
MIT Research Laboratory for Electronics



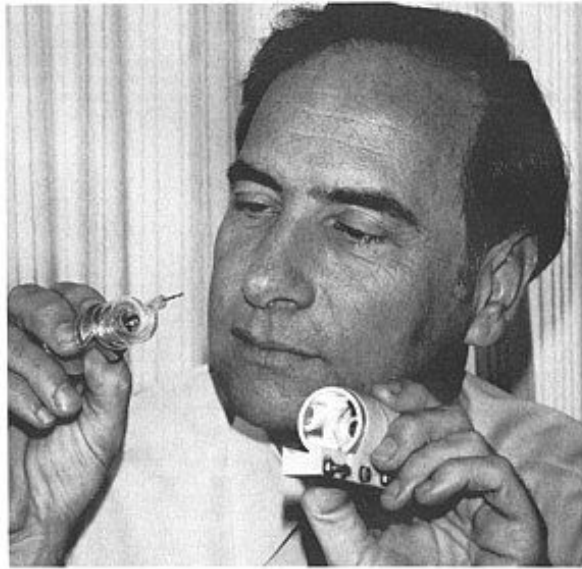
“How to Make Apple sauce at MIT”  
H. Edgerton, 1964



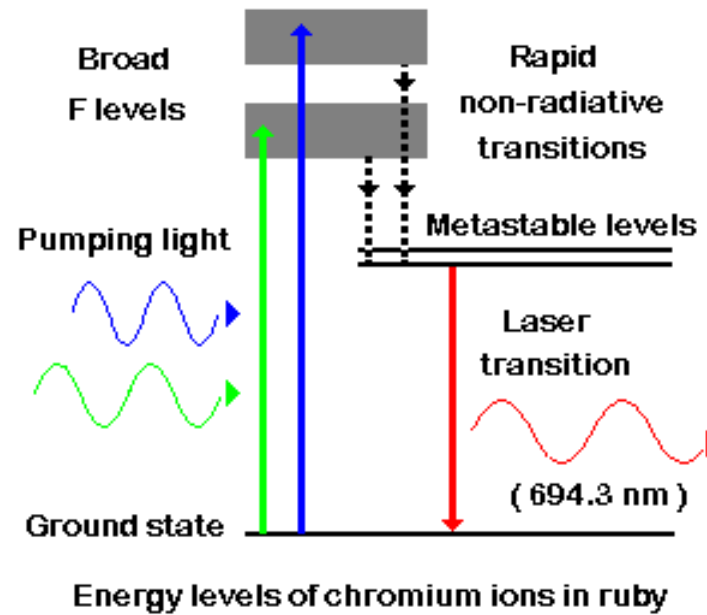
“Splash on a Glass”  
Curtis Hurley  
Junior High  
School student  
1996

Time Resolution: a few microseconds

# It all started with the laser...



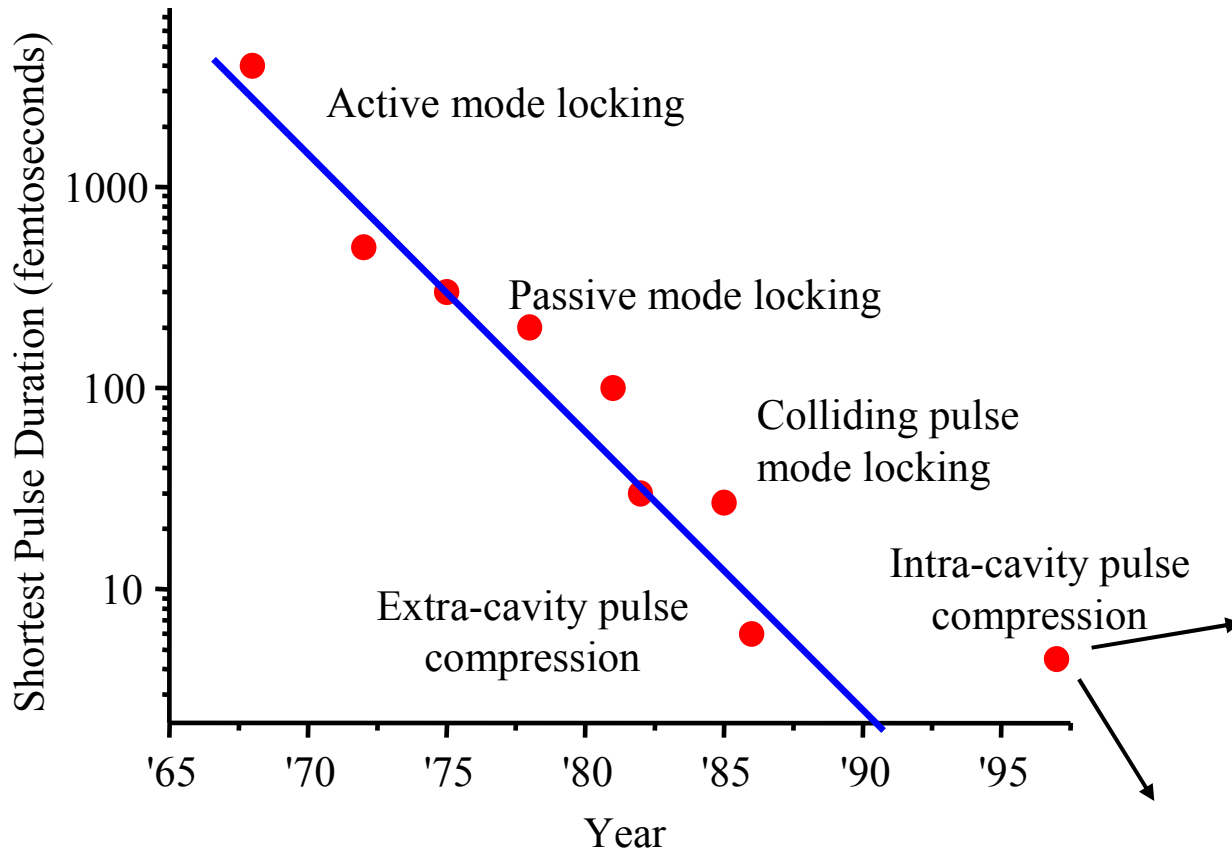
Maiman examines first ruby laser built at Hughes Research Laboratories, (circa 1960)



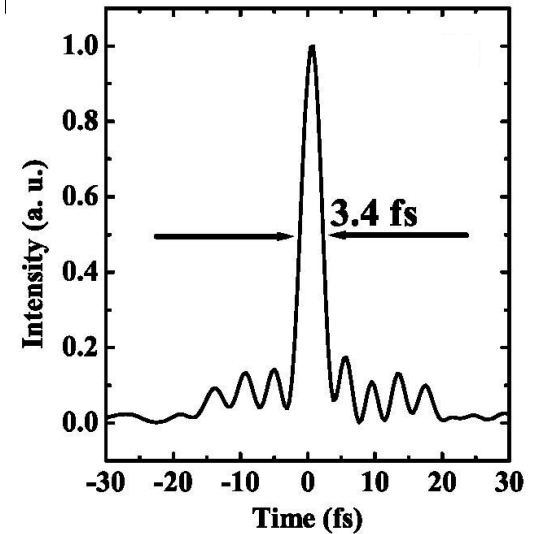
Theodore Maiman (Hughes Research Lab),  
inventor of the laser, holding his invention (1960)



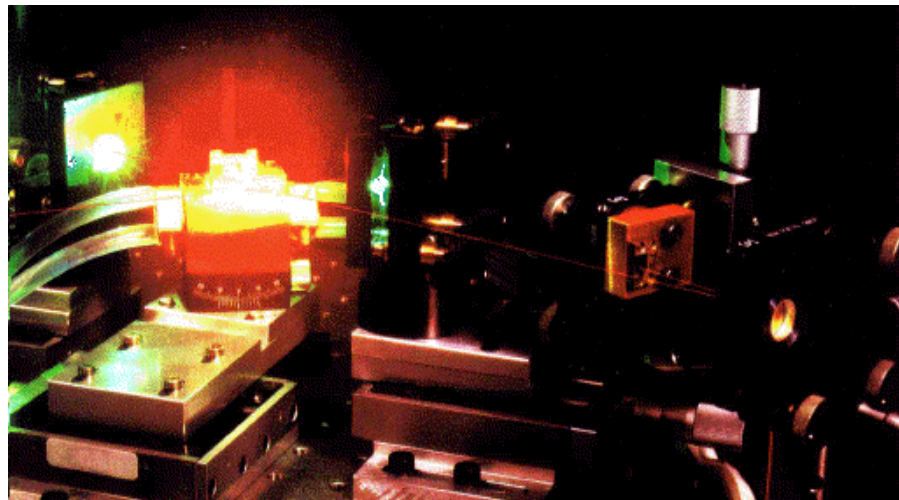
# The Laser - Mode Locking



Current record  
(visible light):  
3.4 fsec  
Yamane, et al. Nov. 2003

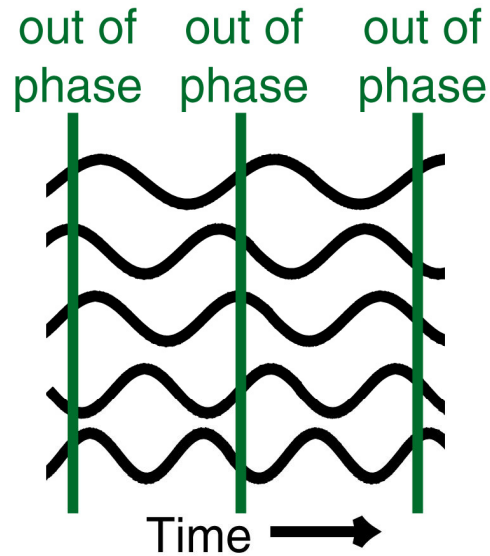


Mode-locked  
Ti:sapphire laser

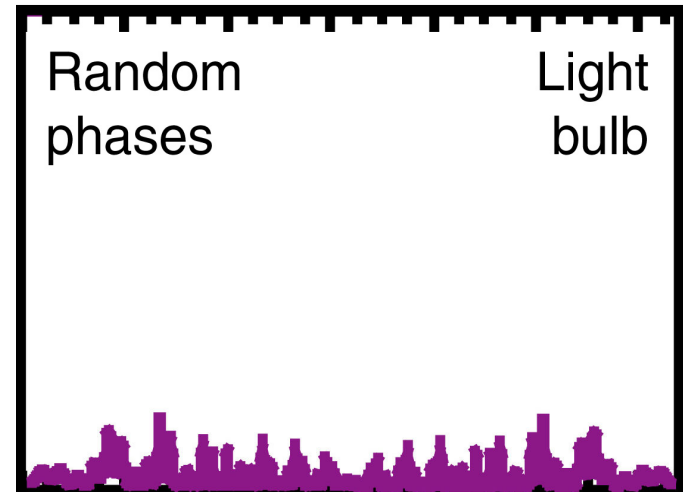


# Generating ultrashort pulses: mode locking

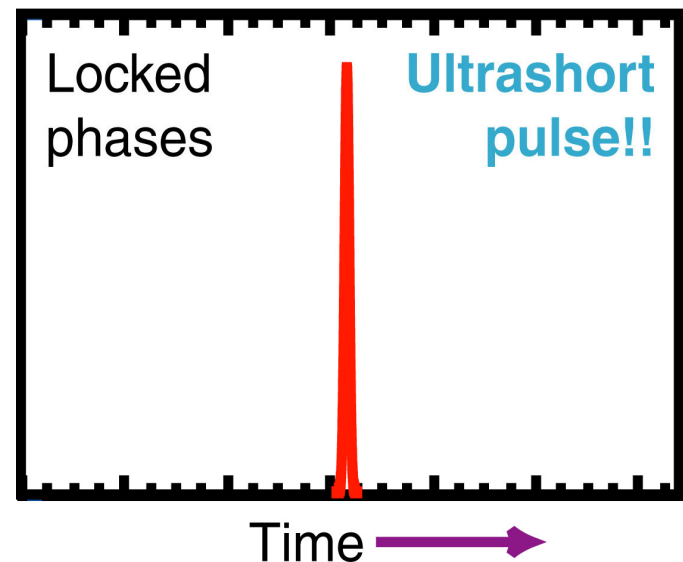
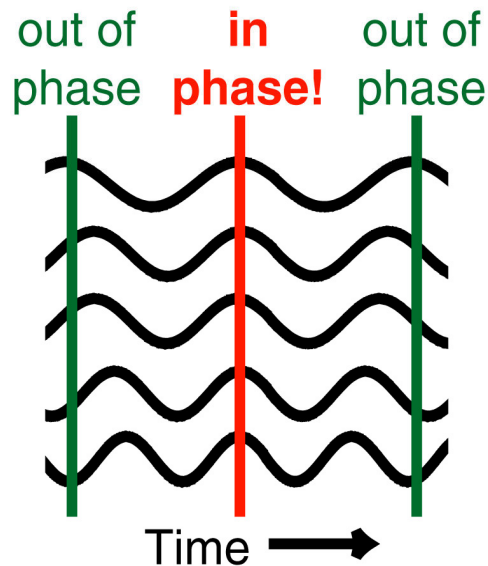
**Random**  
phases  
of all  
laser  
modes



Irradiance vs. time

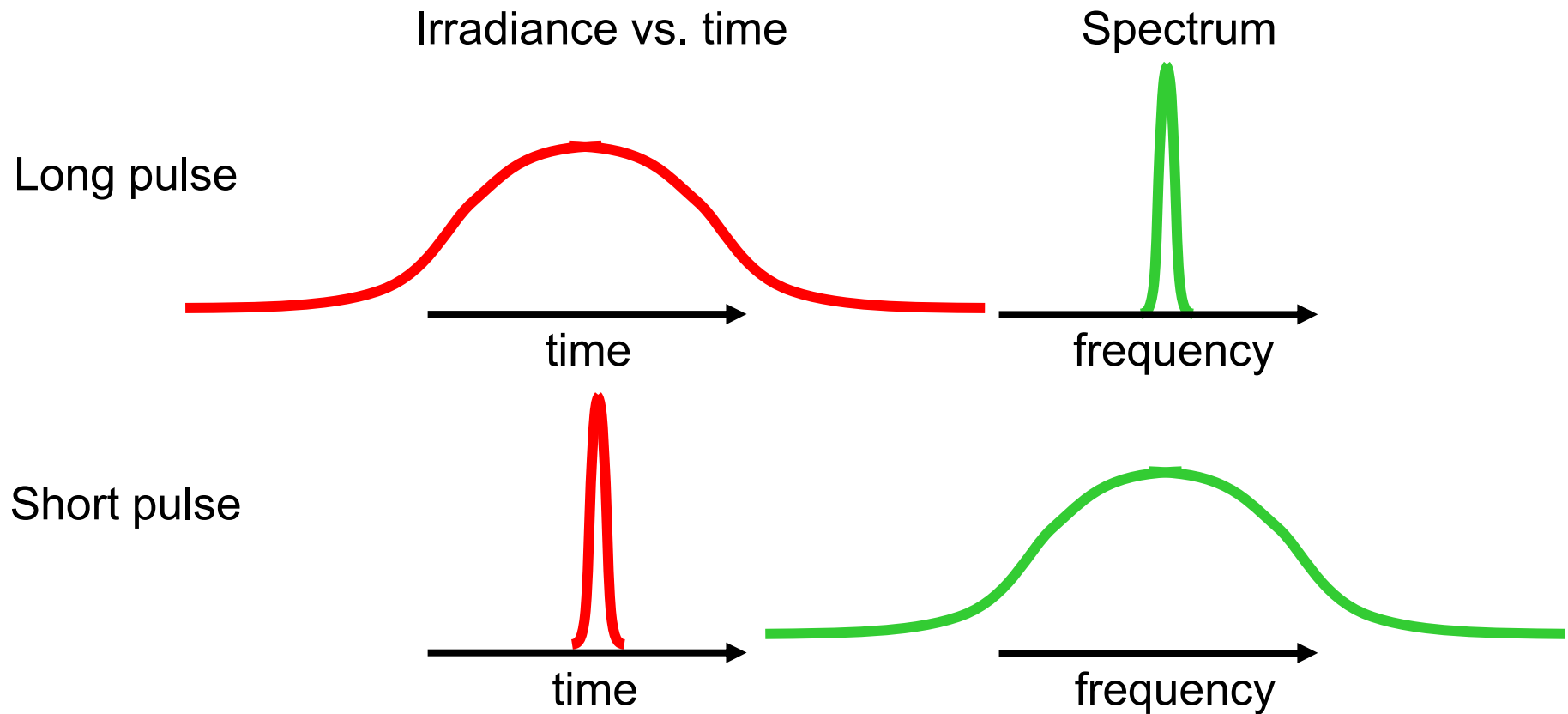


**Locked**  
phases  
of all  
laser  
modes



# Long vs. Short light pulses

The uncertainty principle says that the product of the temporal and spectral pulse widths is greater than  $\sim 1$ .



To make a short pulse, you need a lot of spectral bandwidth.

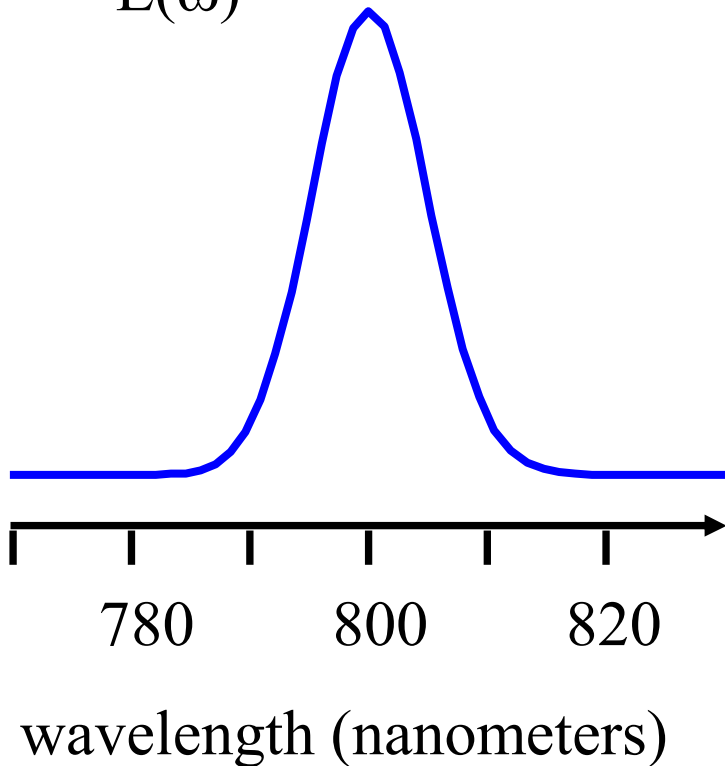
# A typical pulse

Consider a pulse:

duration = 100 femtoseconds  
wavelength = 800 nanometers

frequency domain:

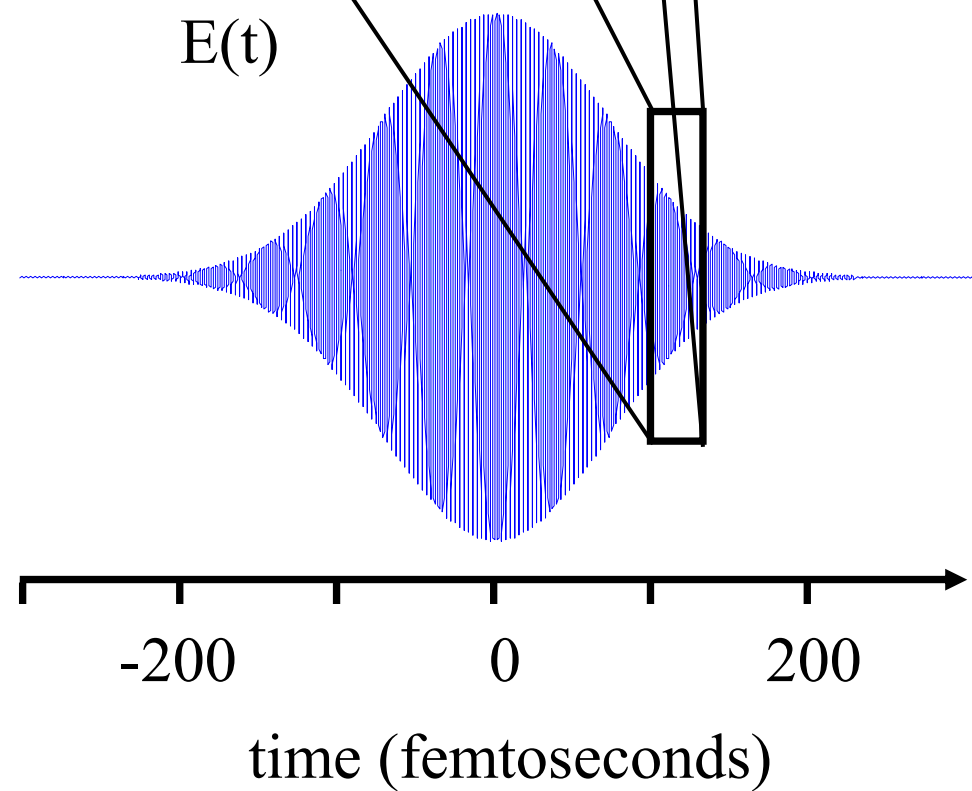
$E(\omega)$



Fourier transform

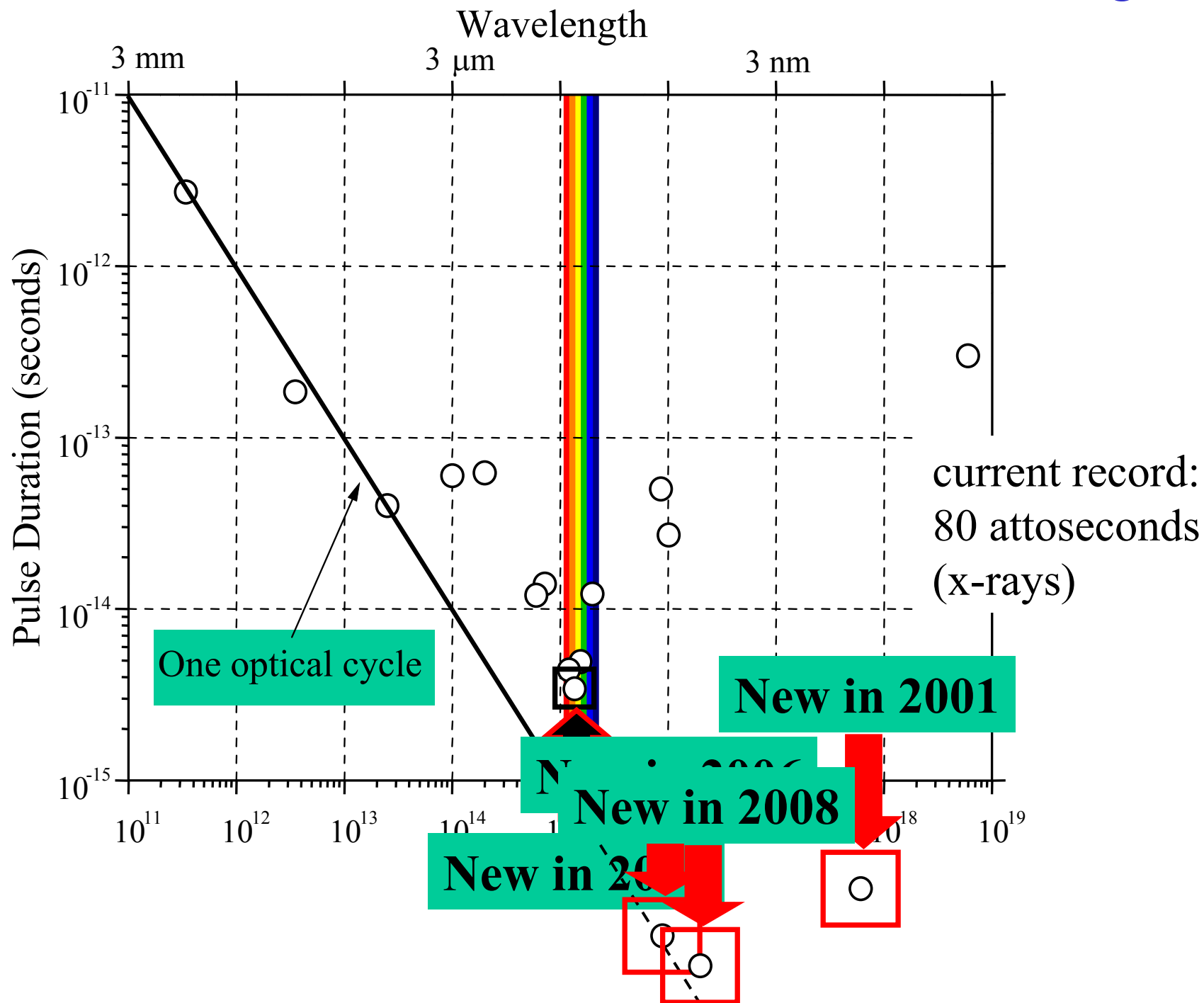
time domain:

$E(t)$

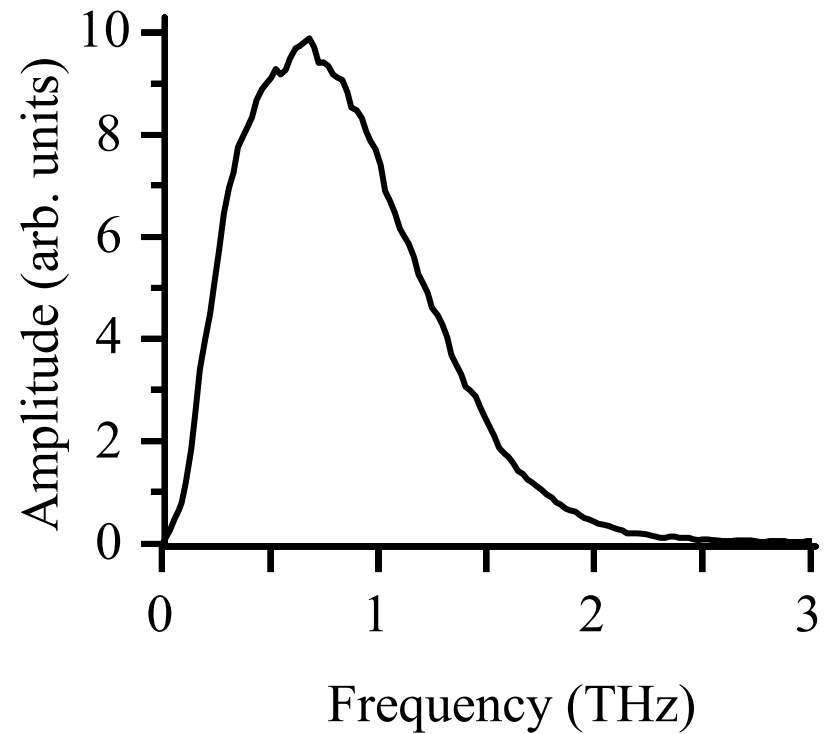
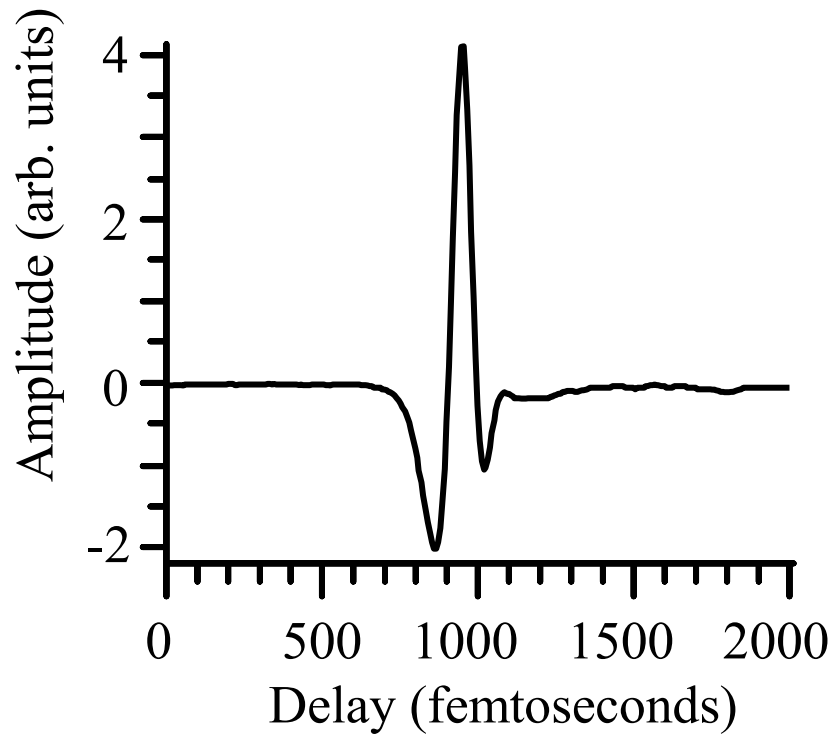


number of cycles  $\sim$  (duration of one cycle) / (duration of pulse)

# The Shortest Pulses at Different Wavelengths

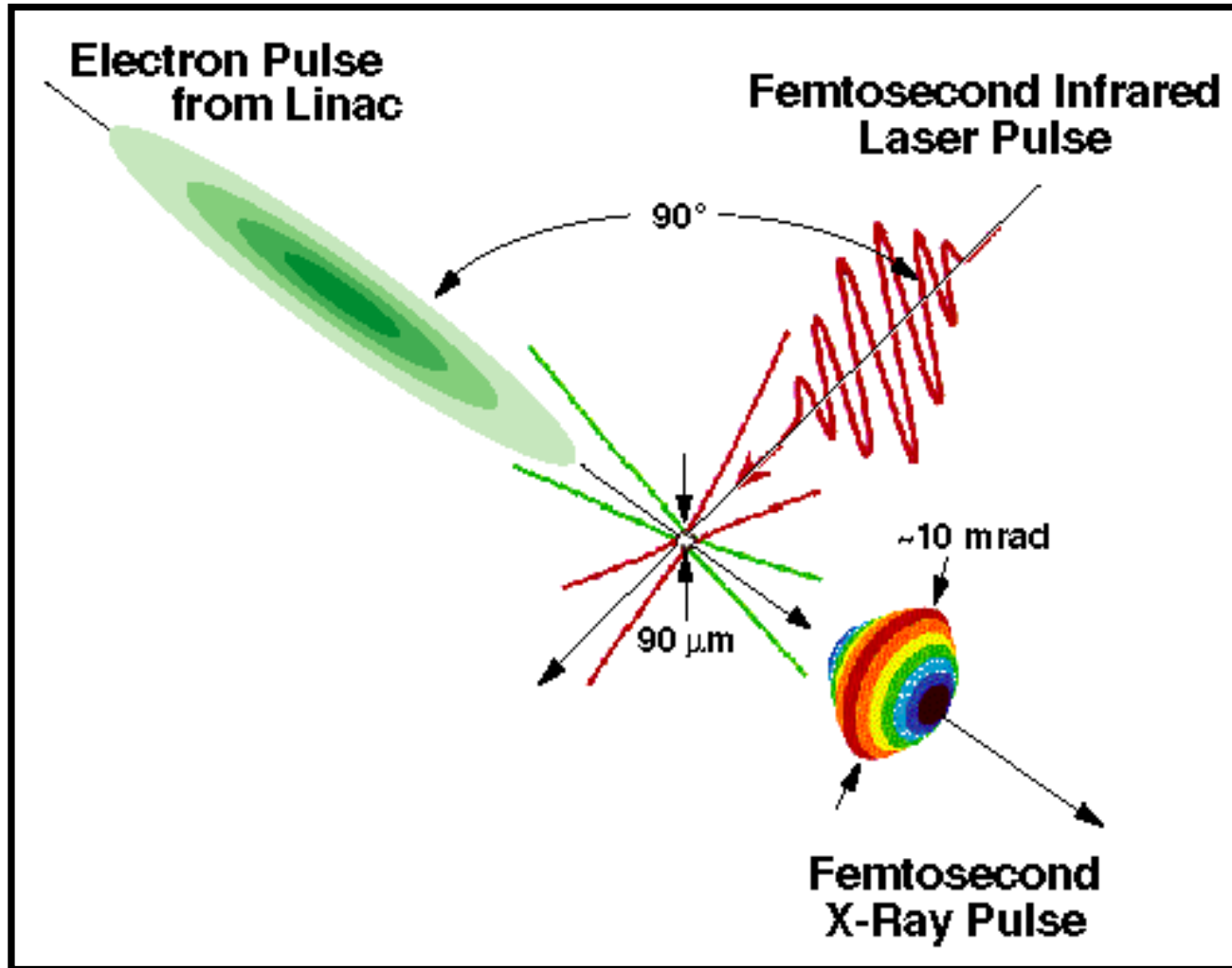


# The Shortest Pulses at Long Wavelengths



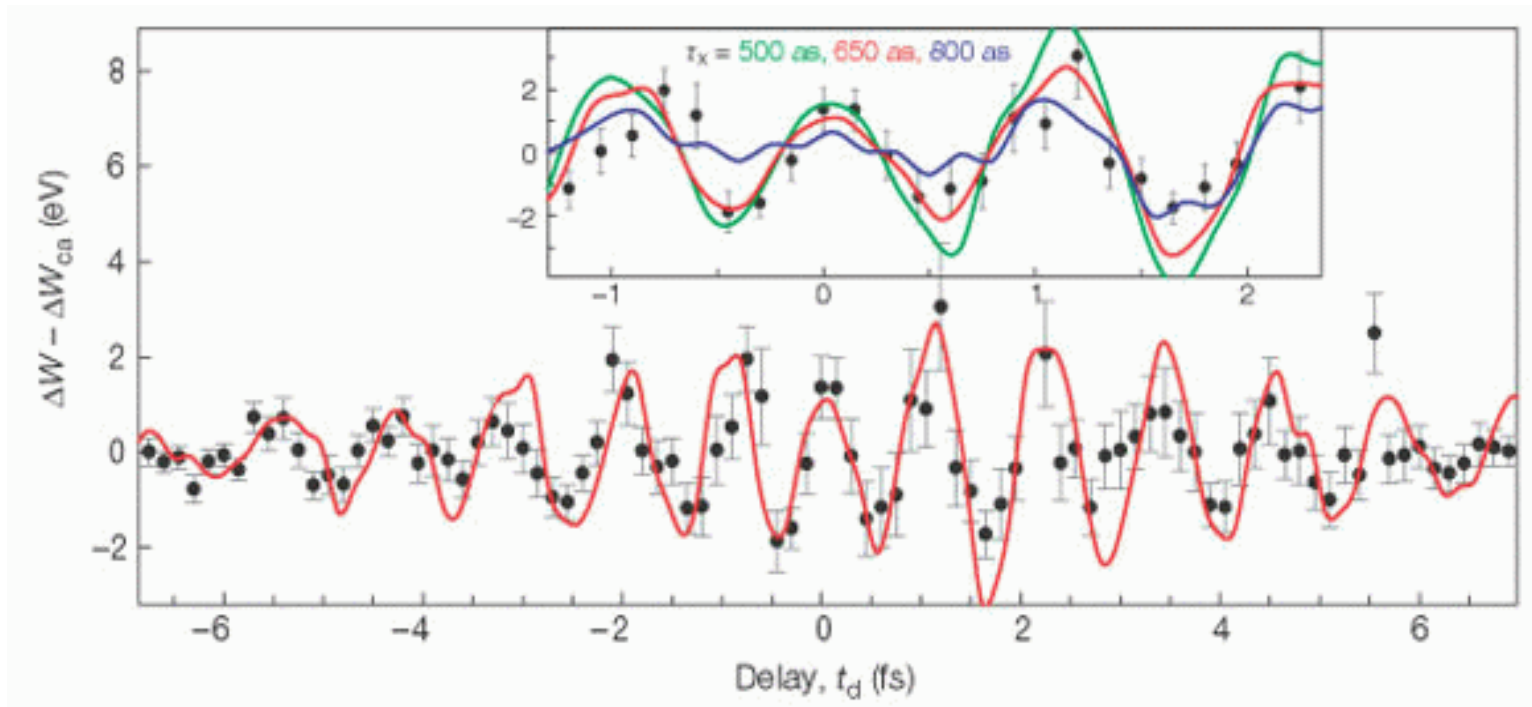


# Short Pulses at Short Wavelengths



90 degree relativistic Thomson scattering  
Lawrence Berkeley National Laboratory

# Breaking the attosecond barrier



F. Krausz and co-workers, TU Vienna, 2001

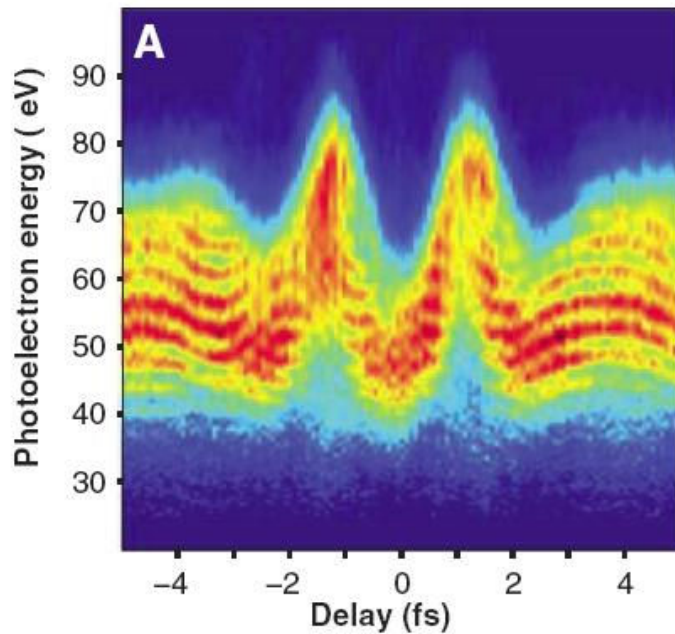
A cross-correlation of a 650 attosecond x-ray pulse with a 7.5 femtosecond infrared pulse

$\lambda = 13.8 \text{ nm}$

measured signal: spectral width of a photoelectron spectrum

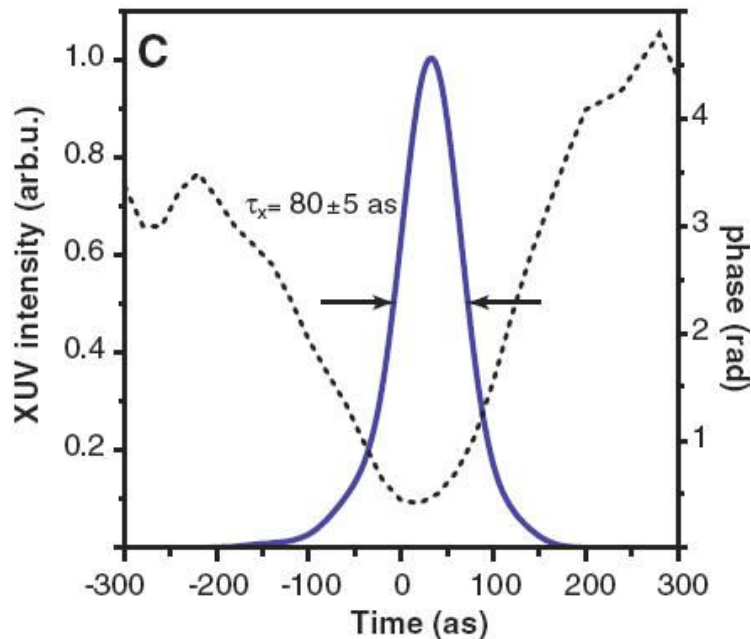
Required infrared pulse intensity:  $5 \times 10^{13} \text{ W/cm}^2$

# The shortest pulses ever (so far)



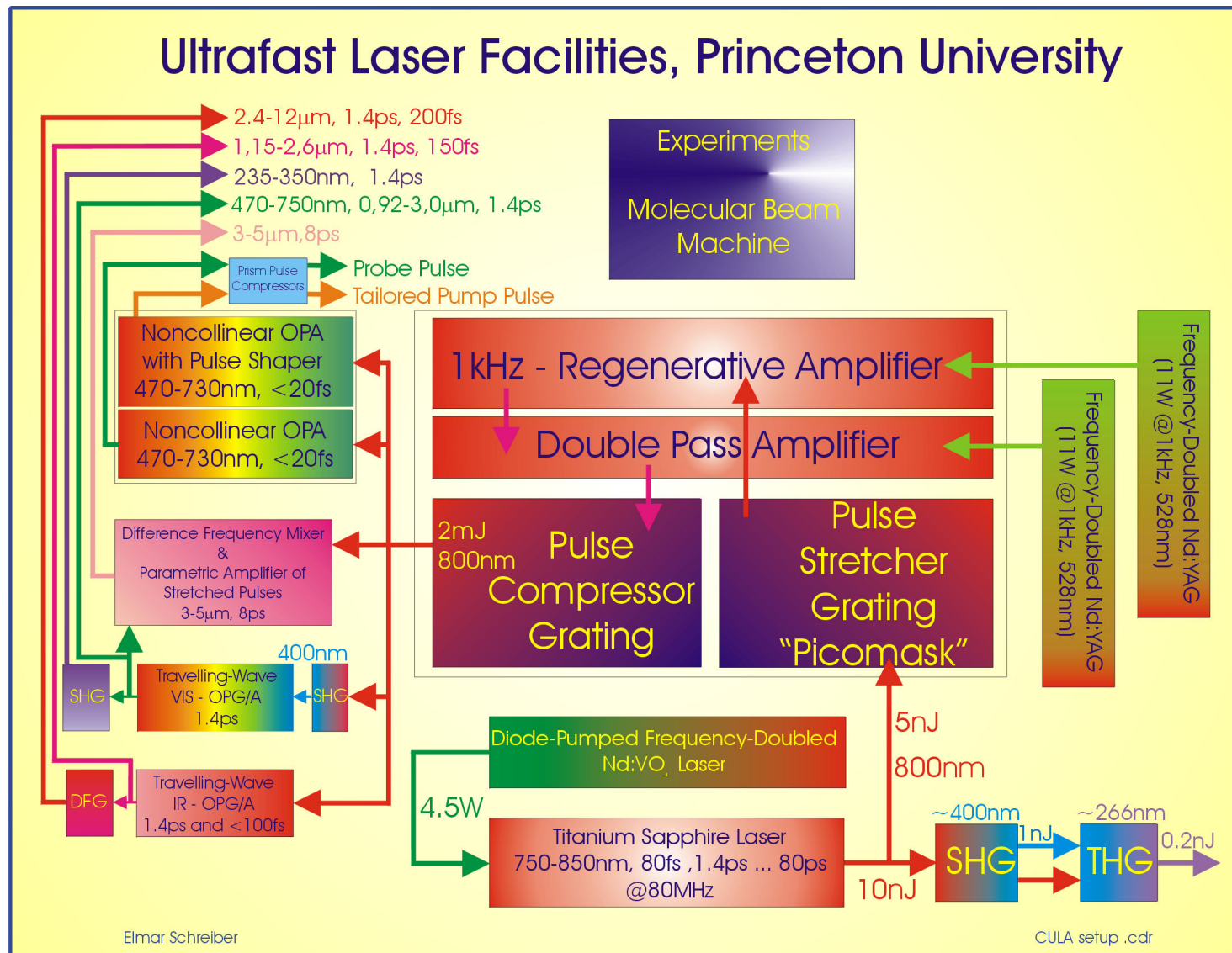
measured  
photoelectron  
spectrum

Goulielmakis, et al., *Science*, June 2008



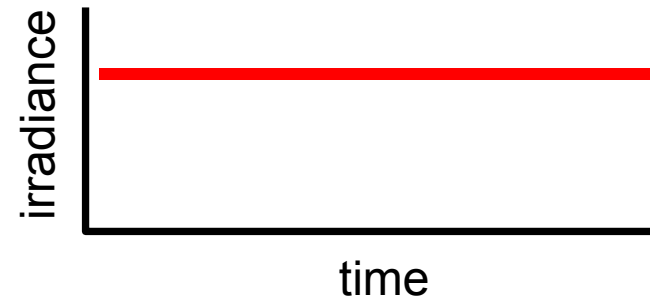
reconstructed  
attosecond pulse

# Ultrafast set-ups can be very sophisticated.



# Why does ultrashort usually mean ultra-intense?

A continuous-wave (cw) laser:

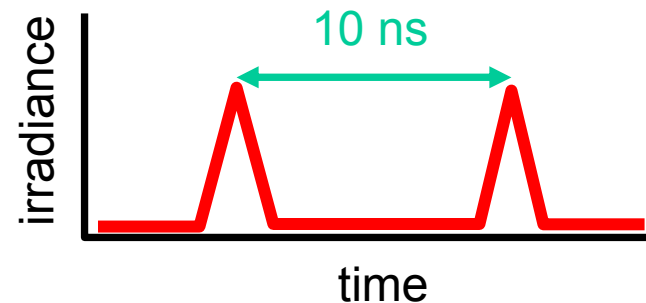


average energy = power/time = joules per second = Watts

Example: 1 Watt at  $\lambda = 800$  nm is  $4 \times 10^{18}$  photons per second. So, in a 100 fs window, we have only  $4 \times 10^5$  photons.

A pulsed laser:

pulse duration = 100 fs  
pulse rate = 100 MHz



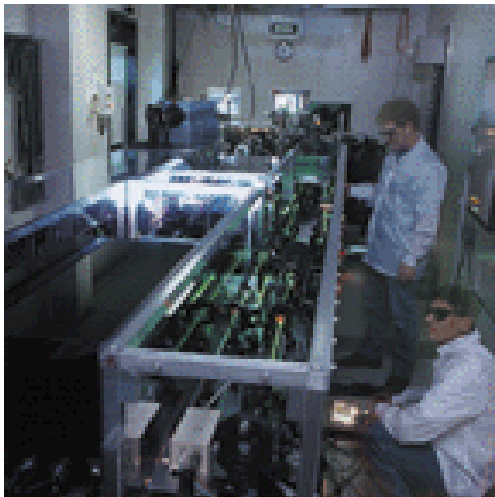
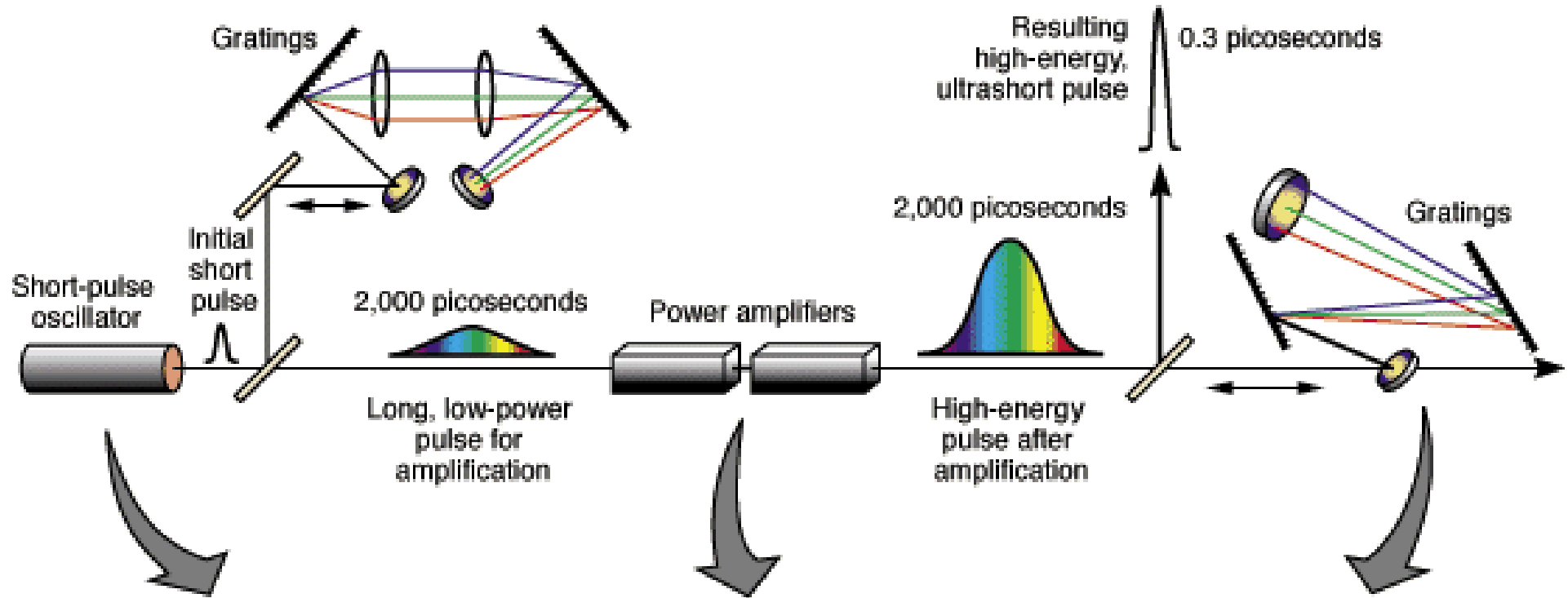
Example: 1 Watt at  $\lambda = 800$  nm is  $4 \times 10^{10}$  photons per pulse.

Energy per pulse =  $4 \times 10^{10}$  photons per pulse  $\times$  energy/photon = 10 nJ/pulse

*Peak* energy = energy per pulse / pulse duration =  $10^5$  W

Focus this to a 10  $\mu$ m diameter spot: *Peak* irradiance =  $10^{15}$  W/m<sup>2</sup>

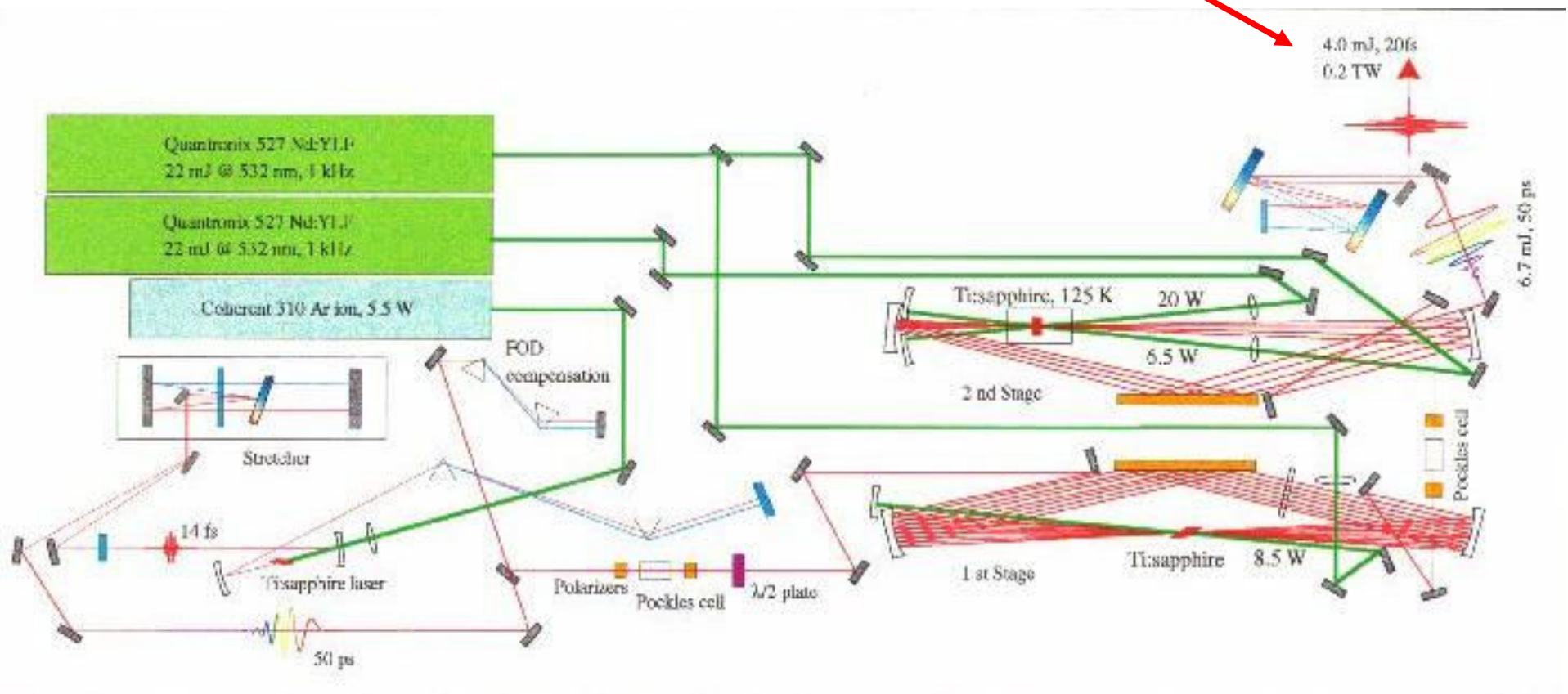
# Chirped pulse amplification





# The Highest Intensities You Can Possibly Imagine

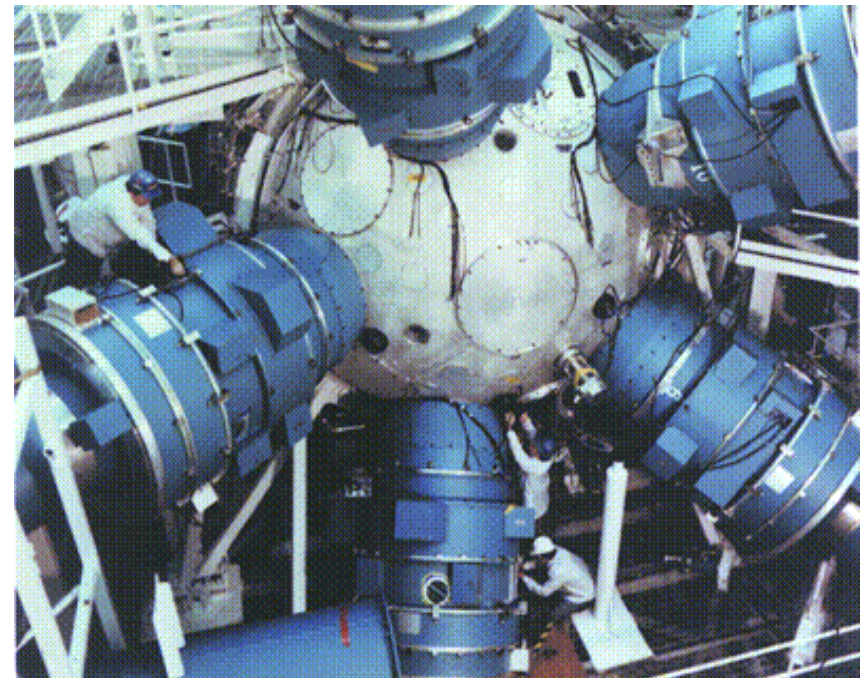
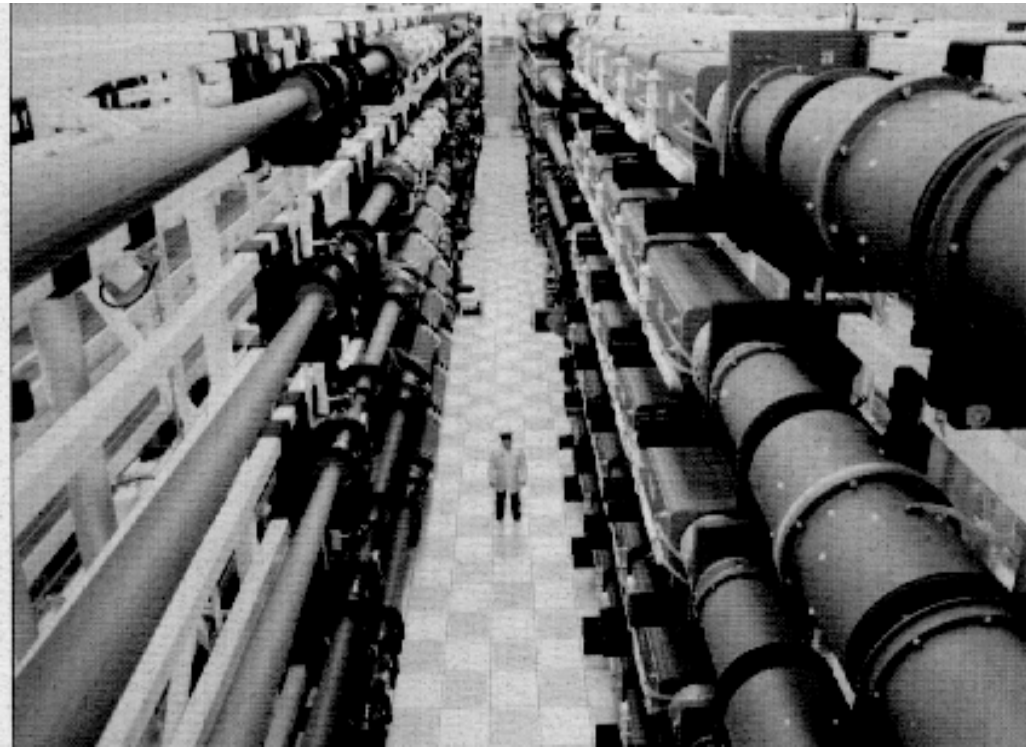
0.2 TW = 200,000,000,000 watts!



1 kHz CPA system at the University of California, Santa Barbara

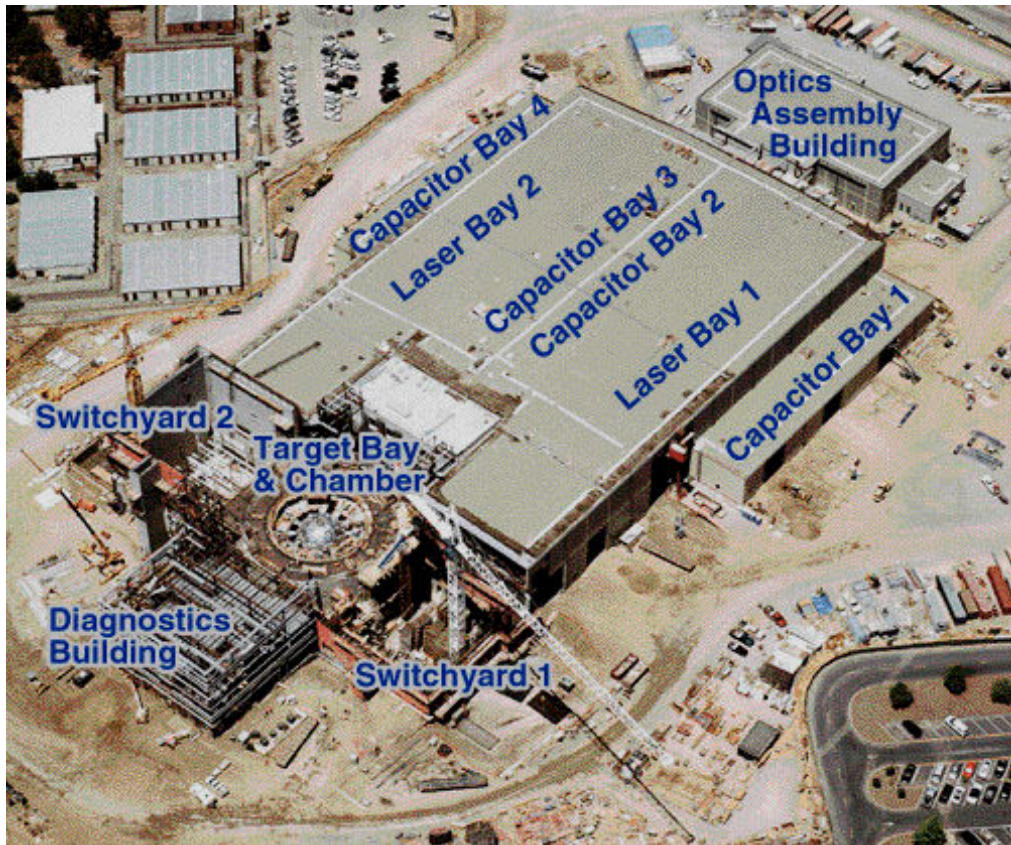
# (used to be) The world's biggest laser

Nova - Lawrence Livermore National Laboratory



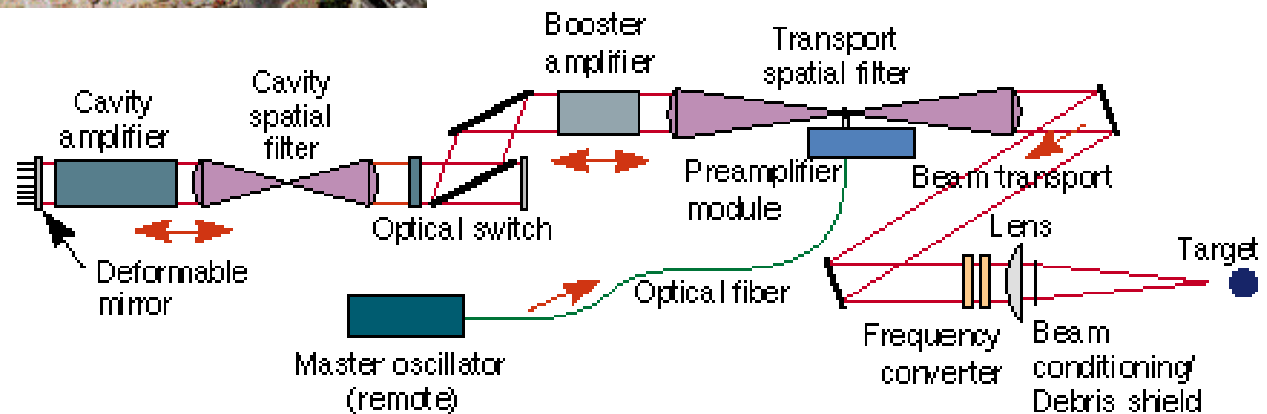


# (currently) The world's biggest laser

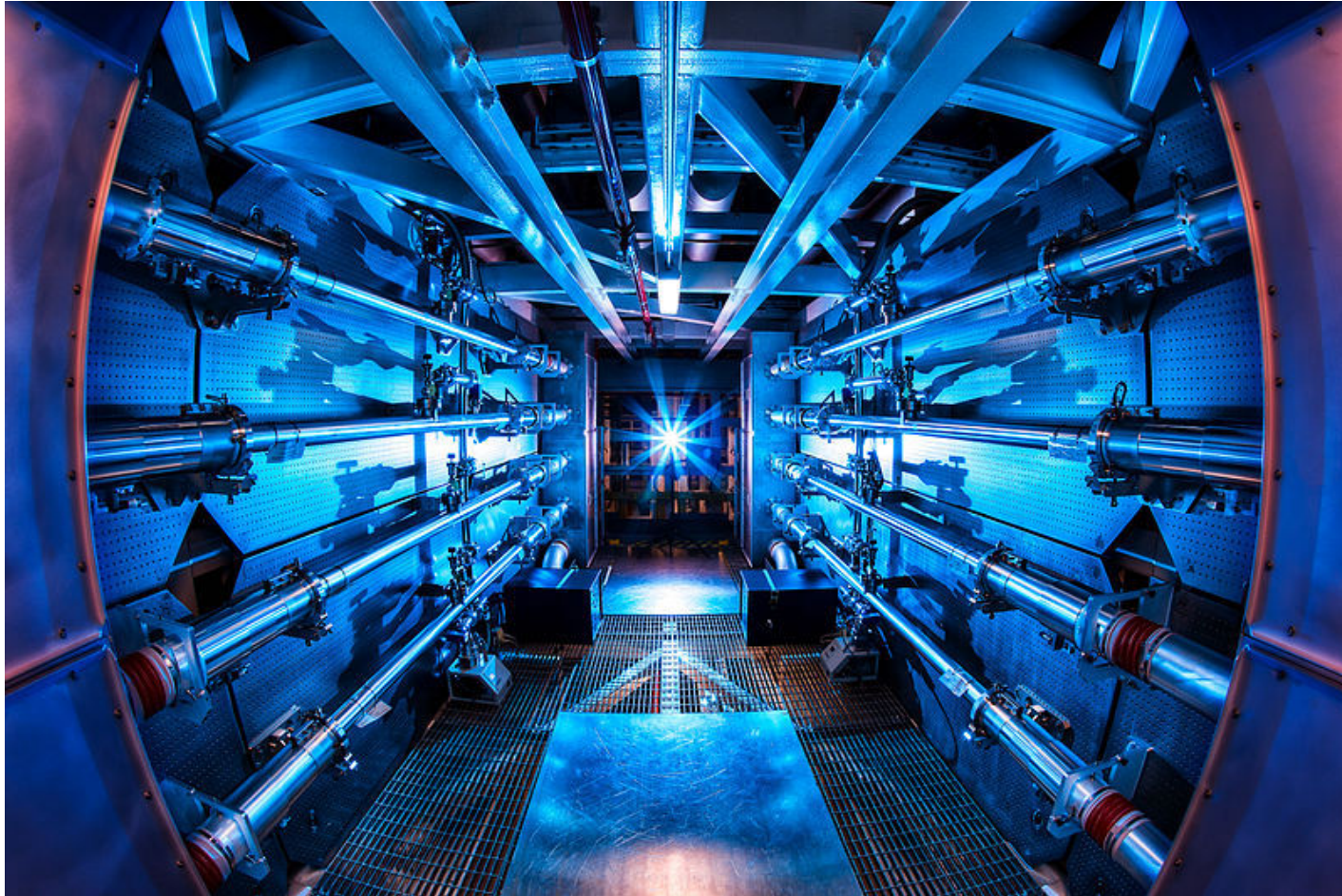


National Ignition Facility  
(commissioned in 2009)

192 shaped pulses  
1.8 MJ total energy



# National Ignition Facility



In 2012: generated a peak power of 500 terawatts (2 megajoules in 4 nanoseconds)

For that brief instant, NIF produced 1000 times as much power as the entire US electrical grid.



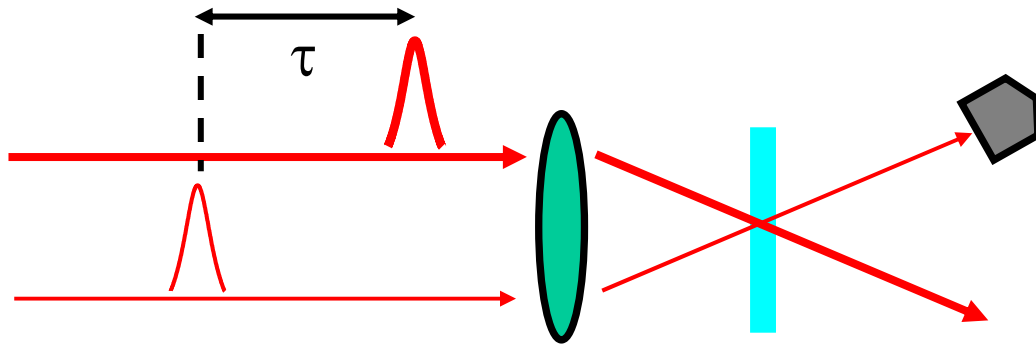
# Ultrafast Laser Spectroscopy: Why?

- Most events that occur in atoms and molecules occur on fs and ps time scales. The length scales are very small, so very little time is required for the relevant motion.
- Excited state decay via fluorescence occurs on a ns time scale, but competing non-radiative processes only speed things up because relaxation rates add:

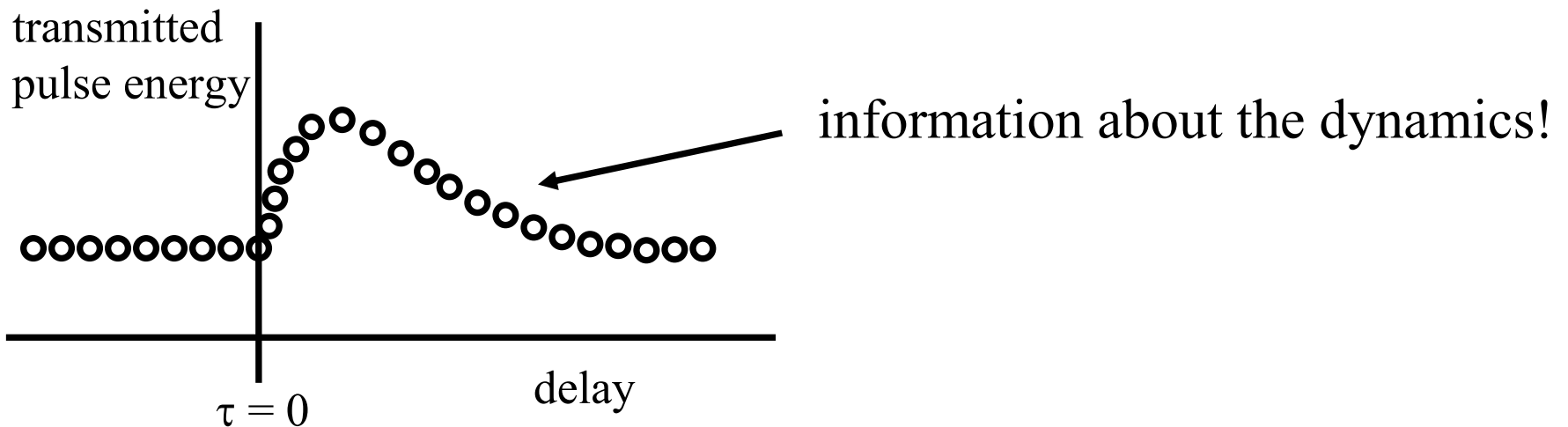
$$\frac{1}{\tau_{ex}} = \frac{1}{\tau_{fl}} + \frac{1}{\tau_{nr}}$$

- Biologically important processes utilize excitation energy for purposes other than fluorescence and hence must be very fast.
- Collisions in room-temperature liquids occur on a few-fs time scale, so nearly all processes in liquids are ultrafast.
- Semiconductor processes of technological interest are necessarily ultrafast or we wouldn't be interested.

## The most common type of ultrafast measurement



- Strong pump pulse perturbs the sample at  $t = 0$ .
- A time  $\tau$  later, a weak probe pulse interrogates the sample.
- Measure the transmission of the probe pulse at each delay  $\tau$ .





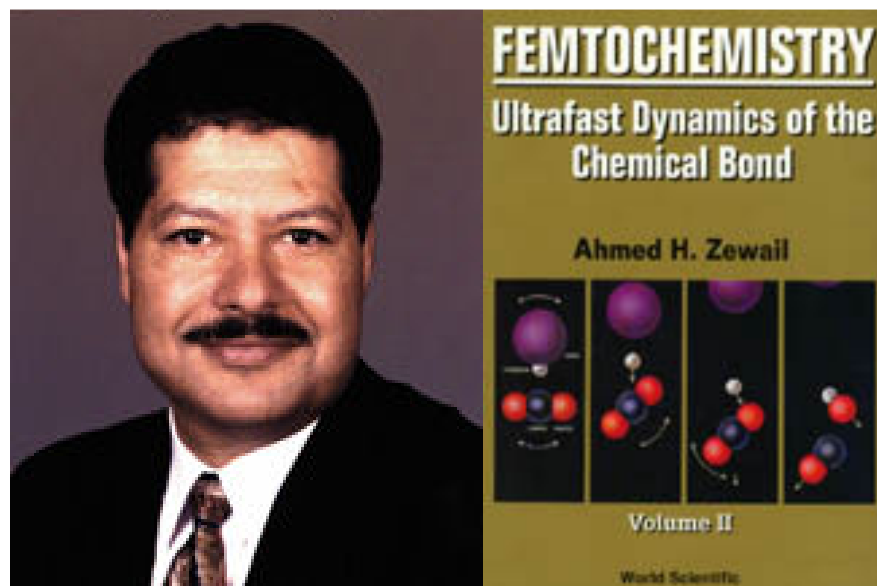
# PRESS RELEASE 12 OCTOBER 1999

The Royal Swedish Academy of Sciences has awarded the 1999 Nobel Prize in Chemistry to Professor Ahmed H. Zewail, California Institute of Technology, Pasadena, USA for showing that it is possible with rapid laser technique to see how atoms in a molecule move during a chemical reaction.

## *The Academy's citation:*

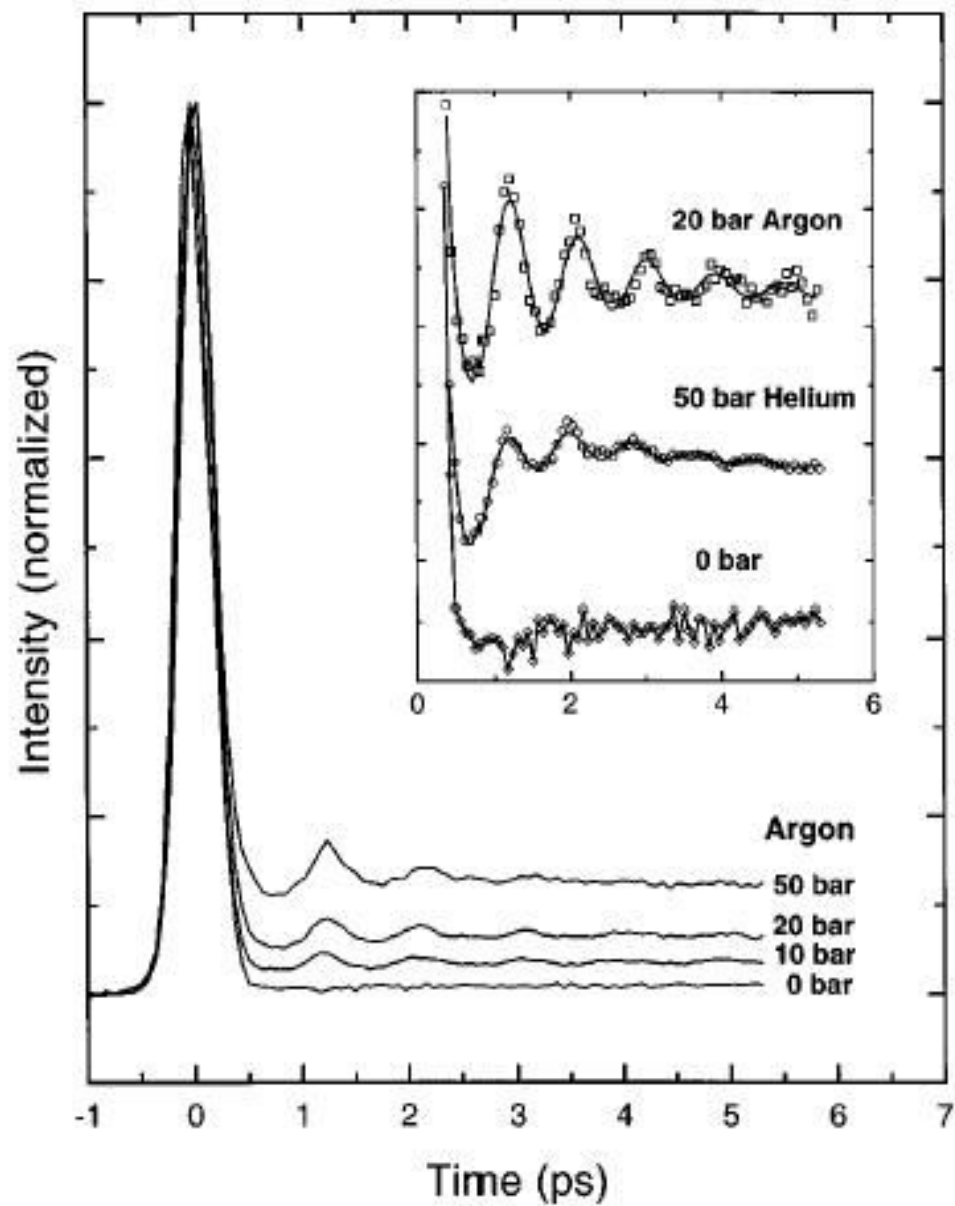
For his studies of the transition states of chemical reactions using femtosecond spectroscopy.

This year's laureate in Chemistry is being rewarded for his pioneering investigation of fundamental chemical reactions, using ultra-short laser flashes, on the time scale on which the reactions actually occur. Professor Zewail's contributions have brought about a revolution in chemistry and adjacent sciences, since this type of investigation allows us to understand and predict important reactions.



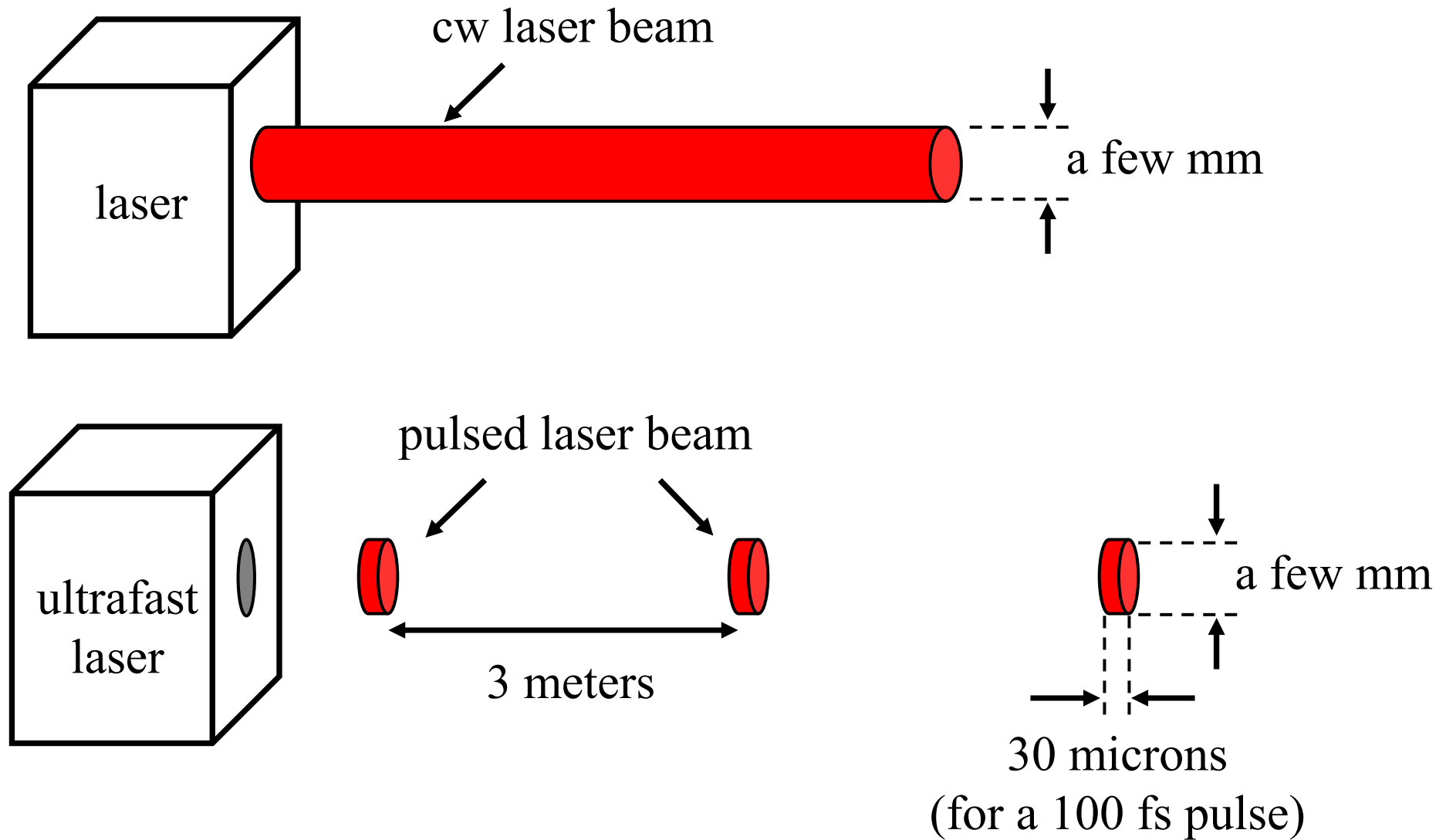
# What is "Femtochemistry"?

Example:  
Pump-probe fluorescence of  
iodine in the gas phase

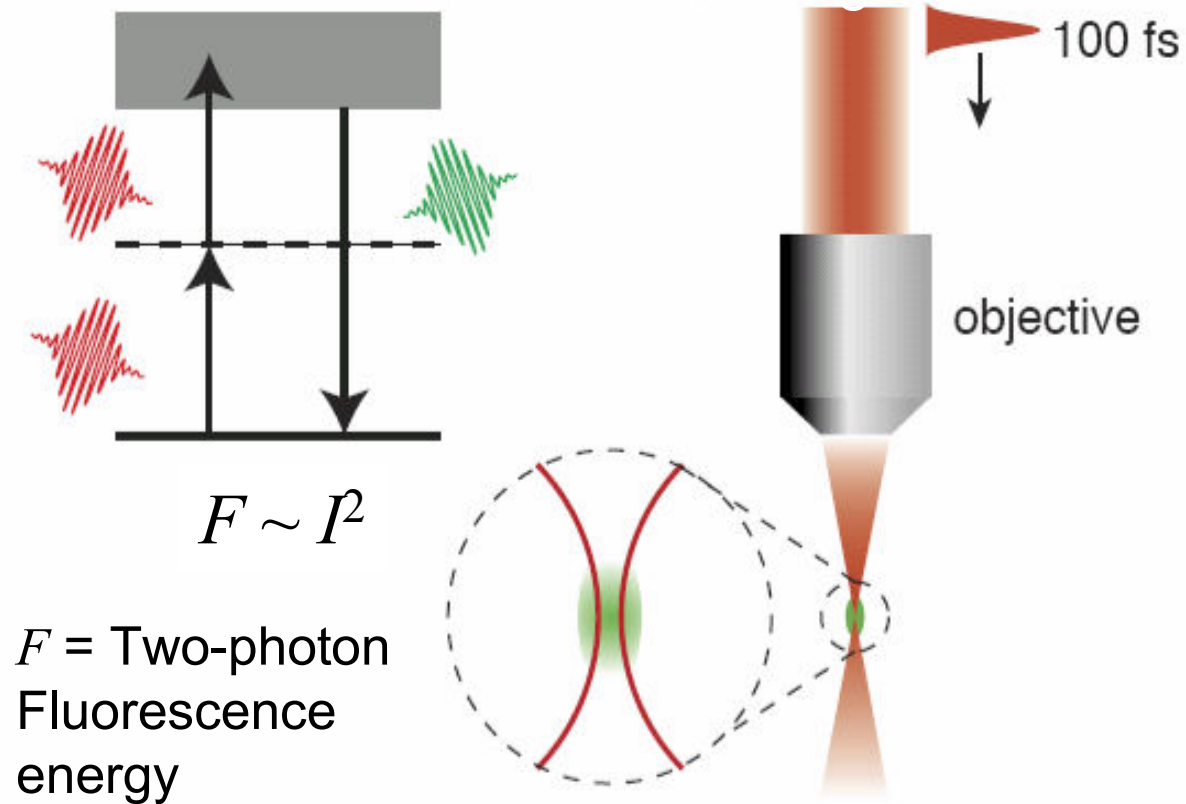


Zewail, et al., *J. Chem. Phys.*, **106**, 4353 (1997)

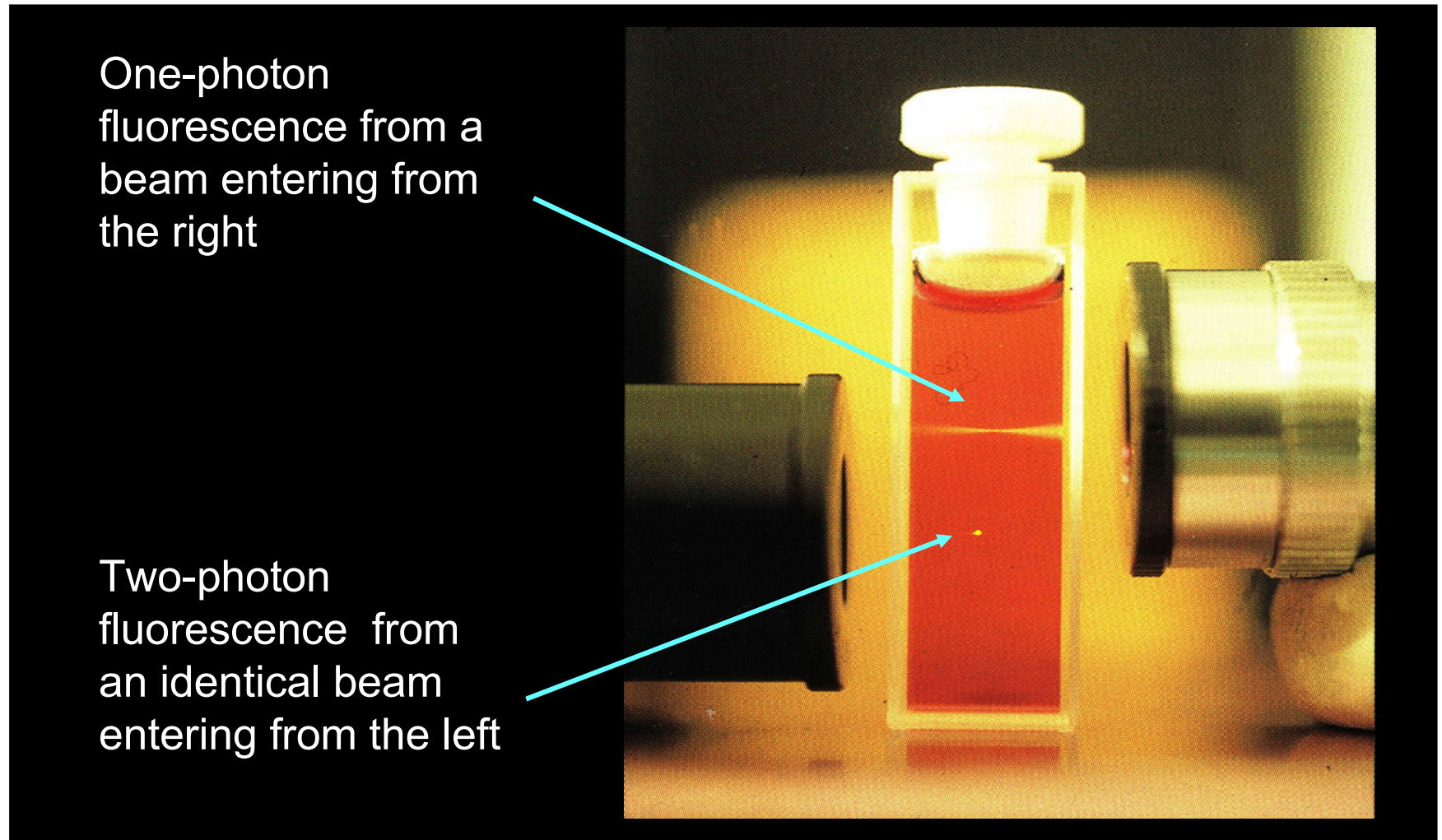
# Ultrashort in time is also ultrashort in **space**



# Ultrashort in time is also ultrashort in **space**, part II

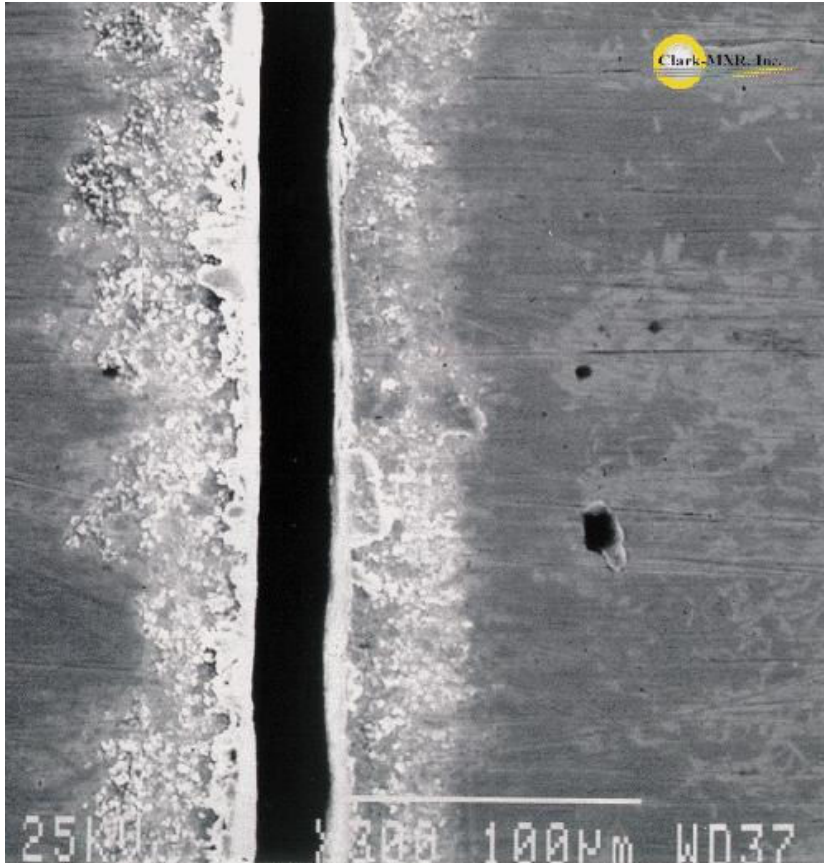


# Ultrashort in time is also ultrashort in **space**, part III

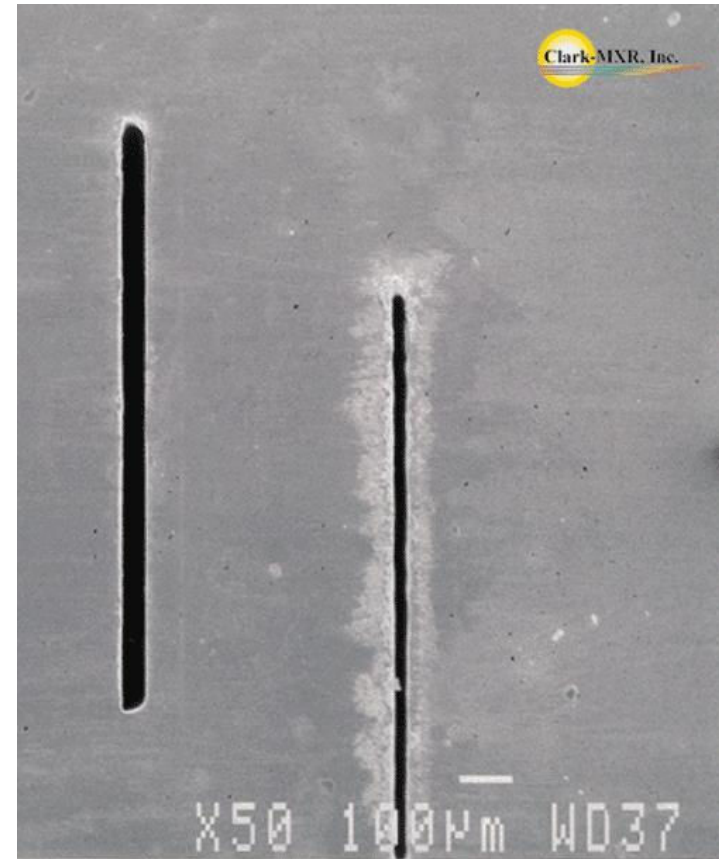




# Ultrashort pulses interact with materials differently



groove machined with nanosecond pulse



...and with femtosecond pulse



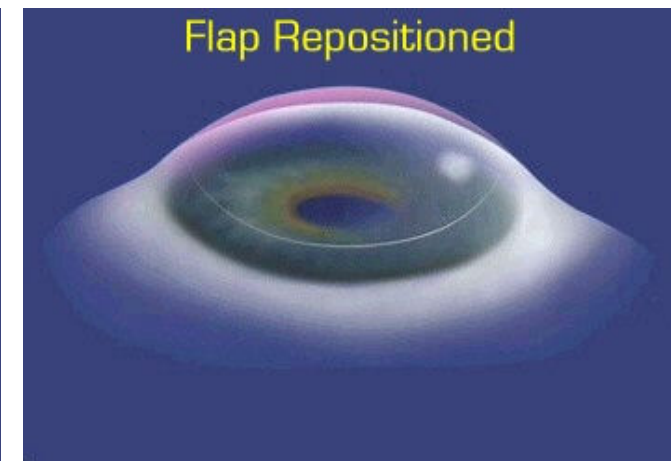
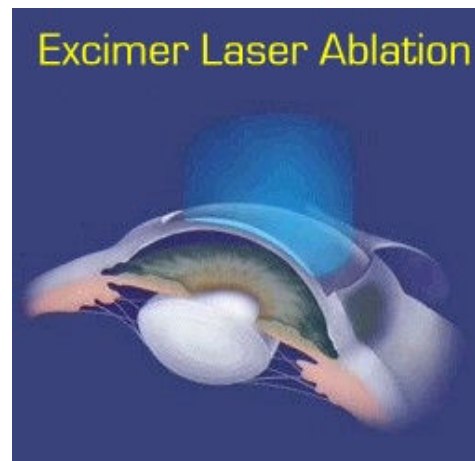
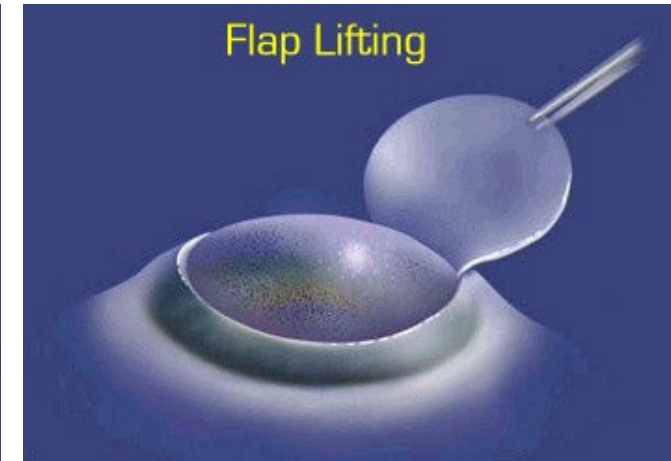
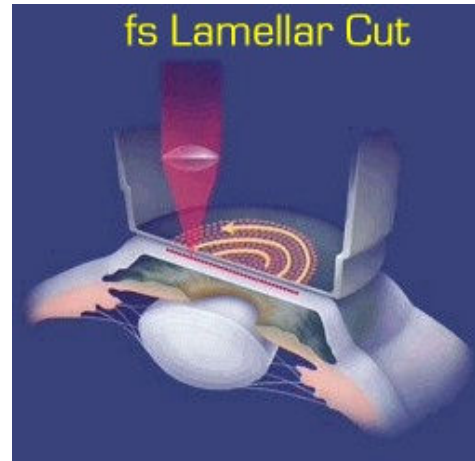
# Ultrafast lasers make great scalpels!

## Introducing... The INTRALASE FS Laser

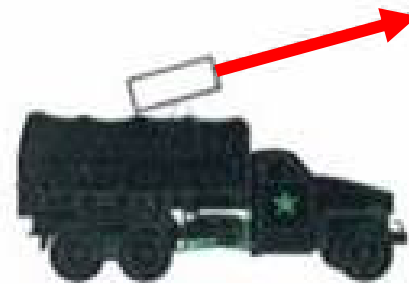
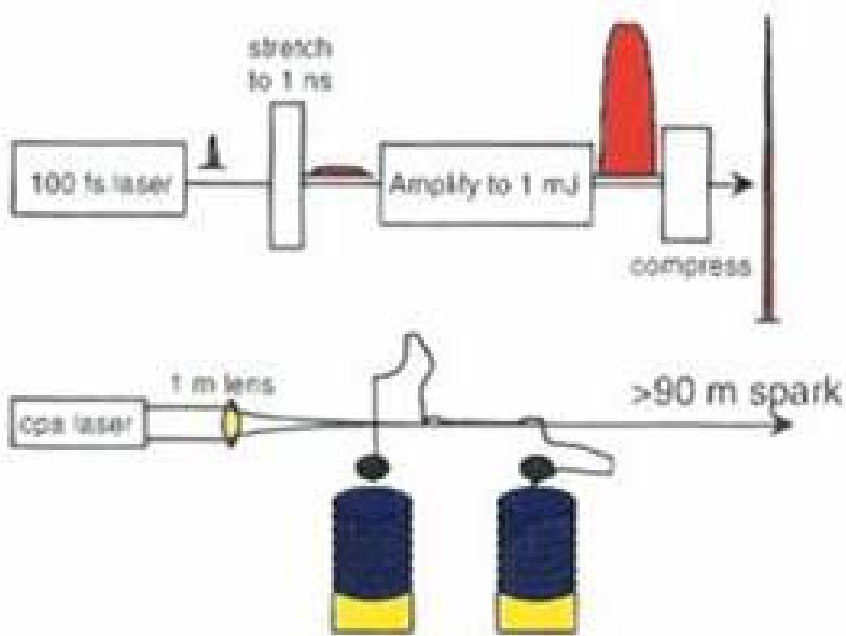


[www.intralase.com](http://www.intralase.com)

New eye surgery technique developed at CUOS (Center for Ultrafast Optical Sciences), at the University of Michigan



# Lightning protection using amplified short pulses



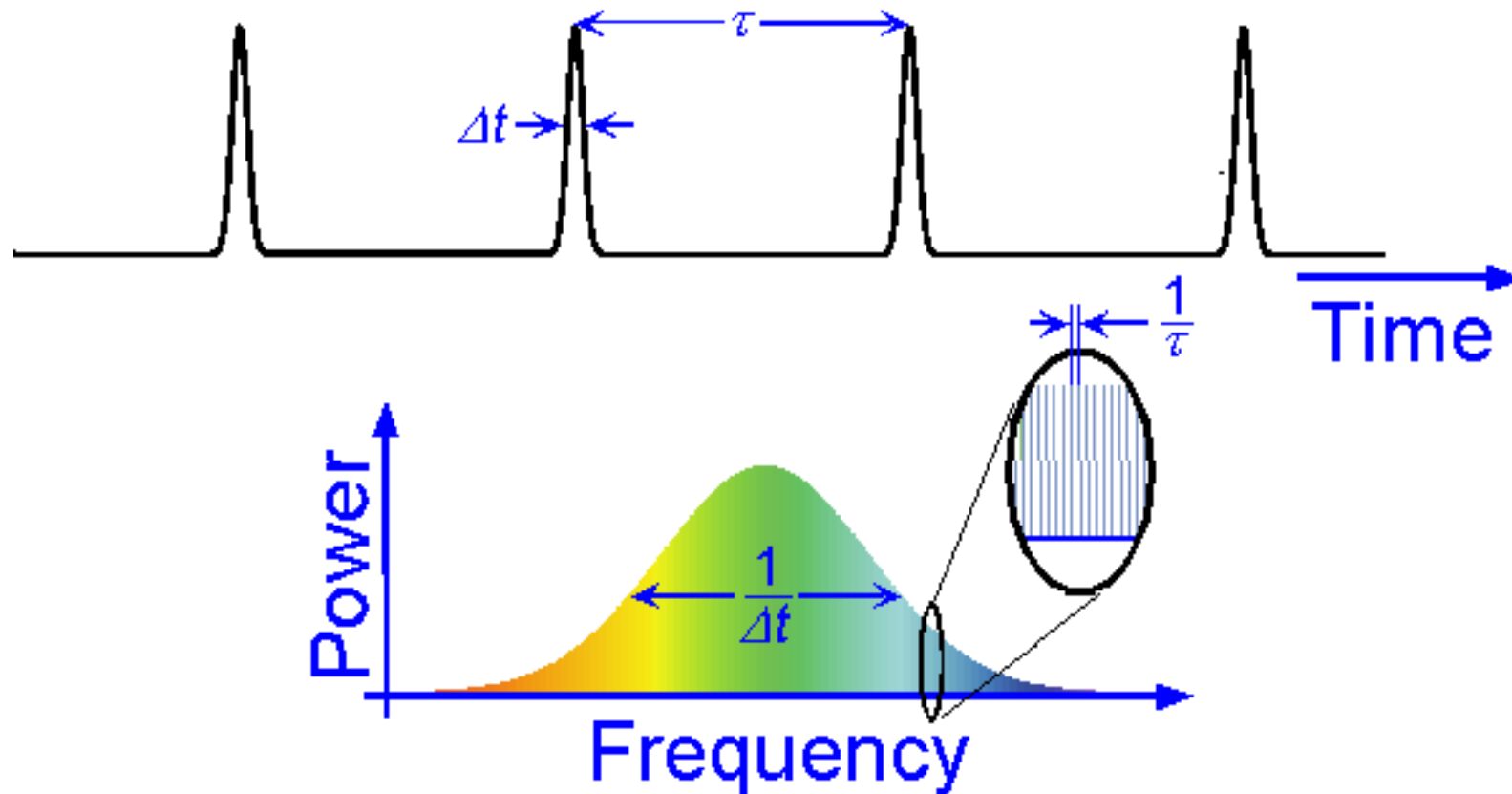
guided and unguided lightning



- Use amplified 100 fs pulses to initiate spark
- Self-trapped filament propagates >30 m in air !

The pulse induces a conducting path, discharging the cloud before lightning can occur.

# Ultrafast lasers make great clocks!



- Temporal spacing of pulses translates to frequency spacing of the comb
- Temporal spacing can be stabilized to much better than one part in  $10^{11}$

# PRESS RELEASE 4 OCTOBER 2005

The Royal Swedish Academy of Sciences has awarded the 2005 Nobel Prize in Physics for 2005 with one half to

## Roy J. Glauber

Harvard University, Cambridge, MA, USA

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

and one half jointly to

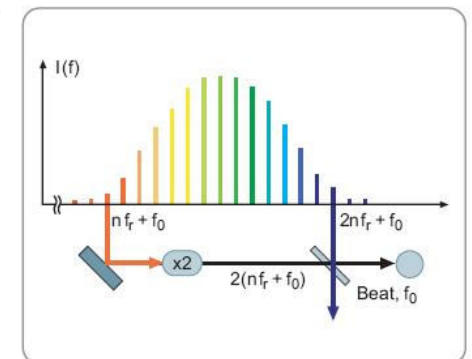
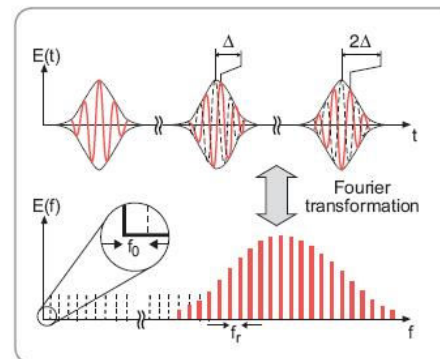
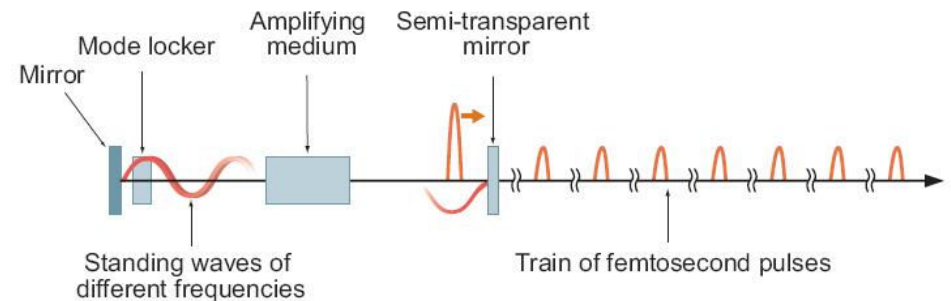
## John L. Hall

National Institute of Standards and Technology, Boulder, CO, USA and

## Theodor W. Hänsch

Max-Planck-Institut für Quantenoptik,  
Garching, Germany

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



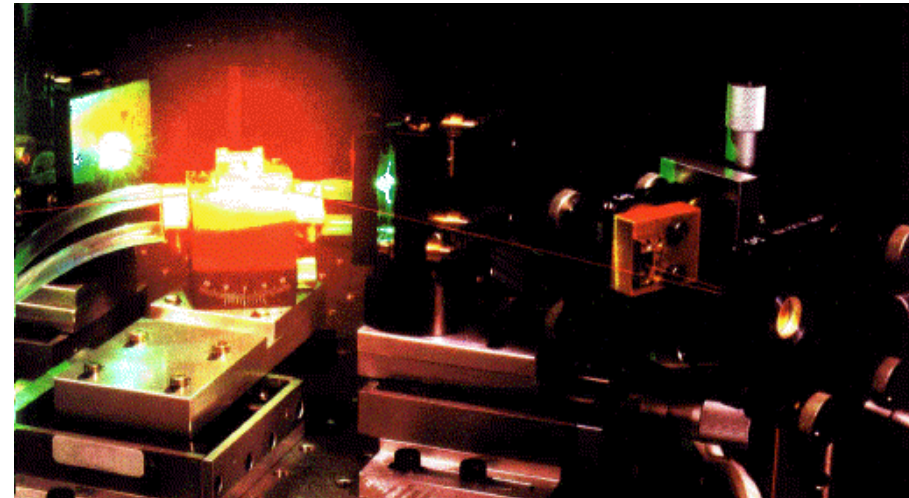
# How does it work?

In order to understand the formation of femtosecond pulses, we need to know about:

- how a cw (continuous wave) laser works.
- how a short pulse propagates through materials at low intensities,
- ...and at high intensities.
- mode locking.

Our model system to learn all of this:

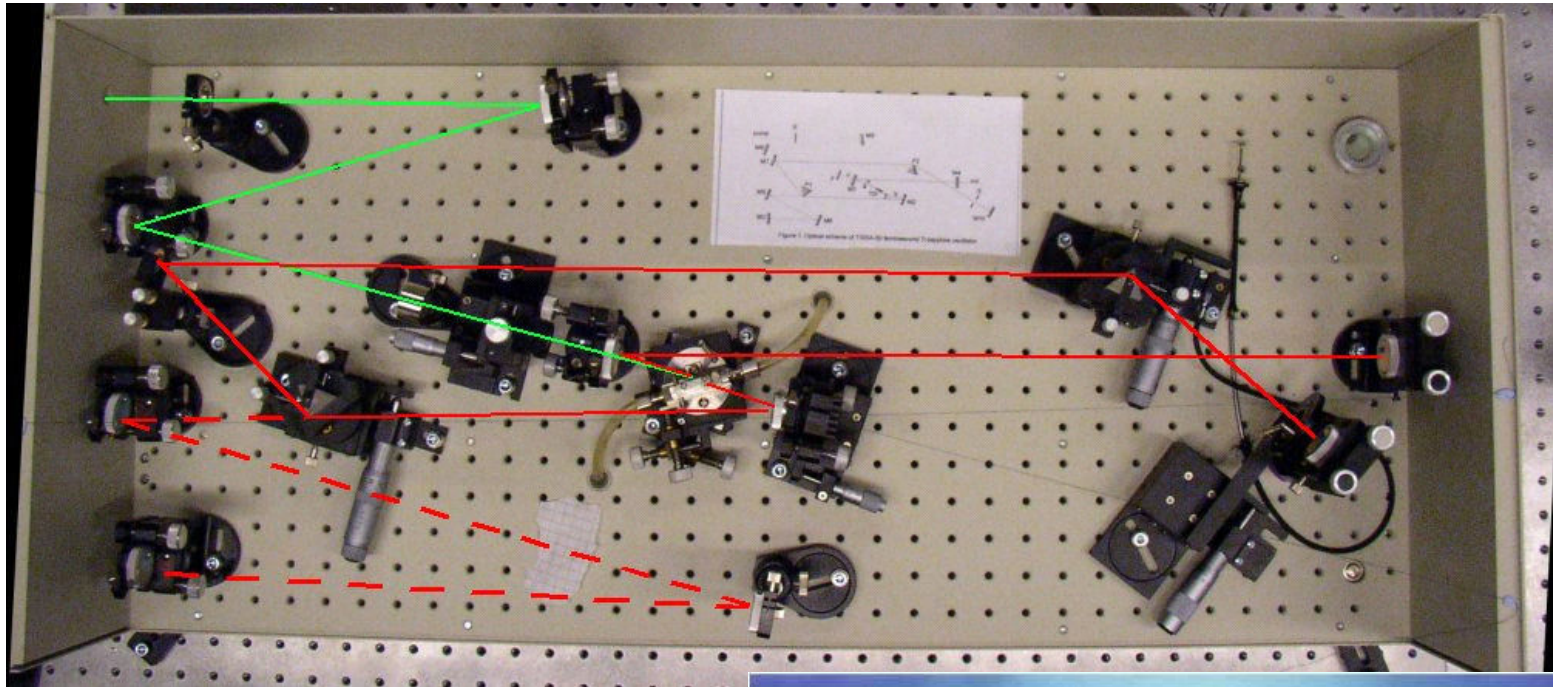
Titanium-doped sapphire laser  
(Ti:sapphire)





# The Ti:sapphire laser

A typical optical layout, if you want to build your own:



or you can buy one:





# Reminders

This class has:

- mandatory lecture attendance
- no text book
- oral presentations by all students in March/April
- weekly office hours (Tuesday 1:00-2:30 in Brockman 351)