Welcome to Ultrafast Optics

Who am I: Daniel Mittleman (office hours: Thurs. 1:00-2:30)

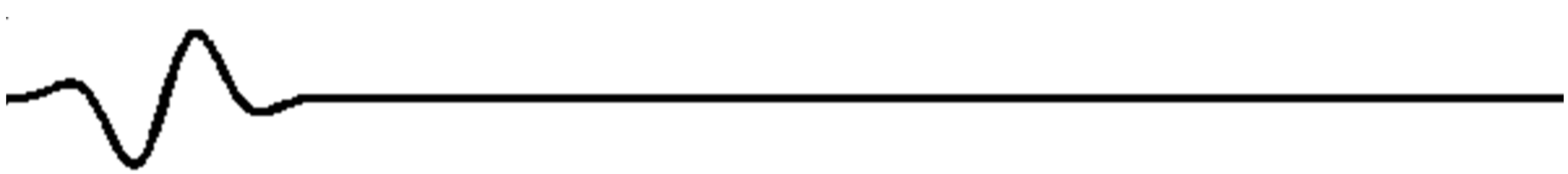
When, where: Tues / Thurs @ 9am. BH163

Web page:

https://www.brown.edu/research/labs/mittleman/engn-2911T-fall-2021

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 (stay tuned for more info)



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)

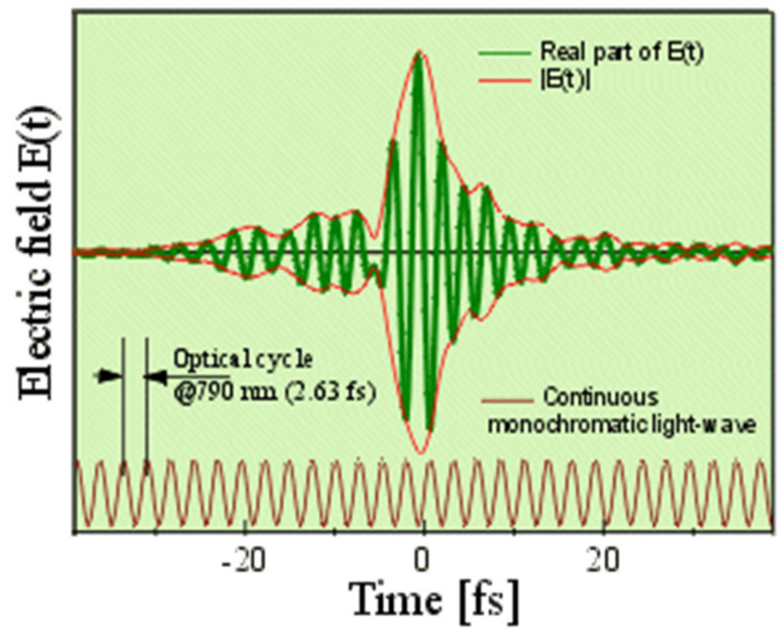
Recommended reading - ultrafast phenomena:

- *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
- Making short pulses

How do they do this? (and why)



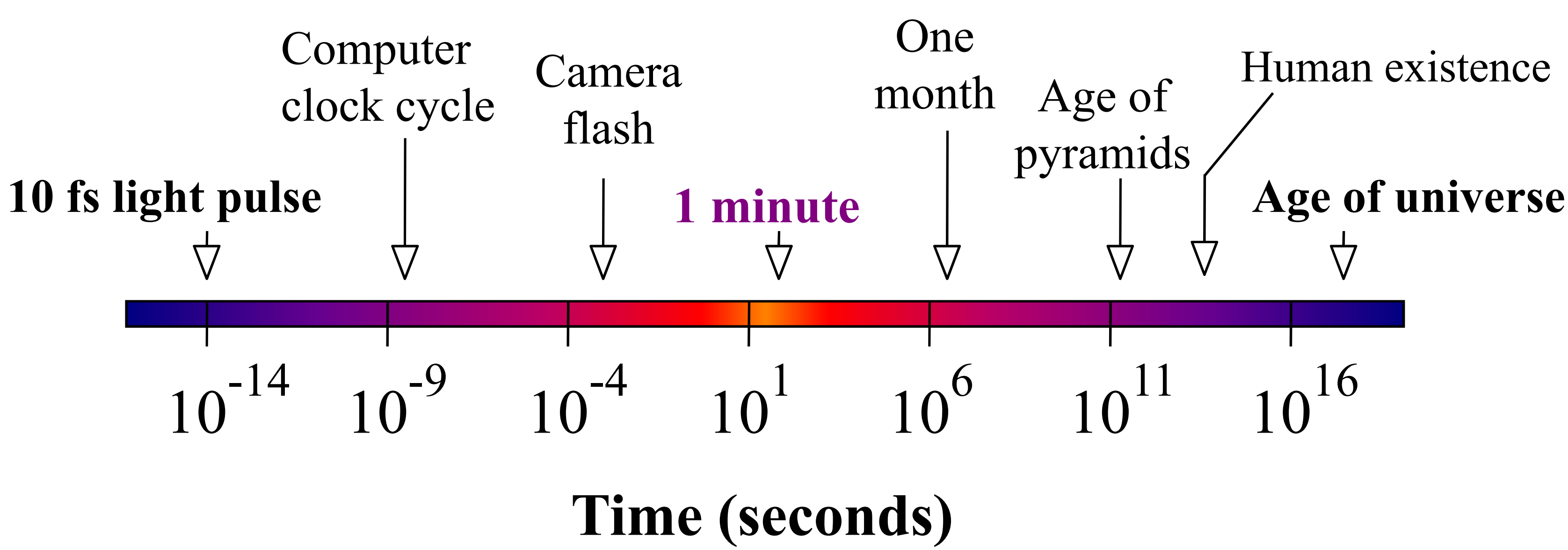
www.chem.rug.nl/spectro/projects/laser.html

Other topics pending…

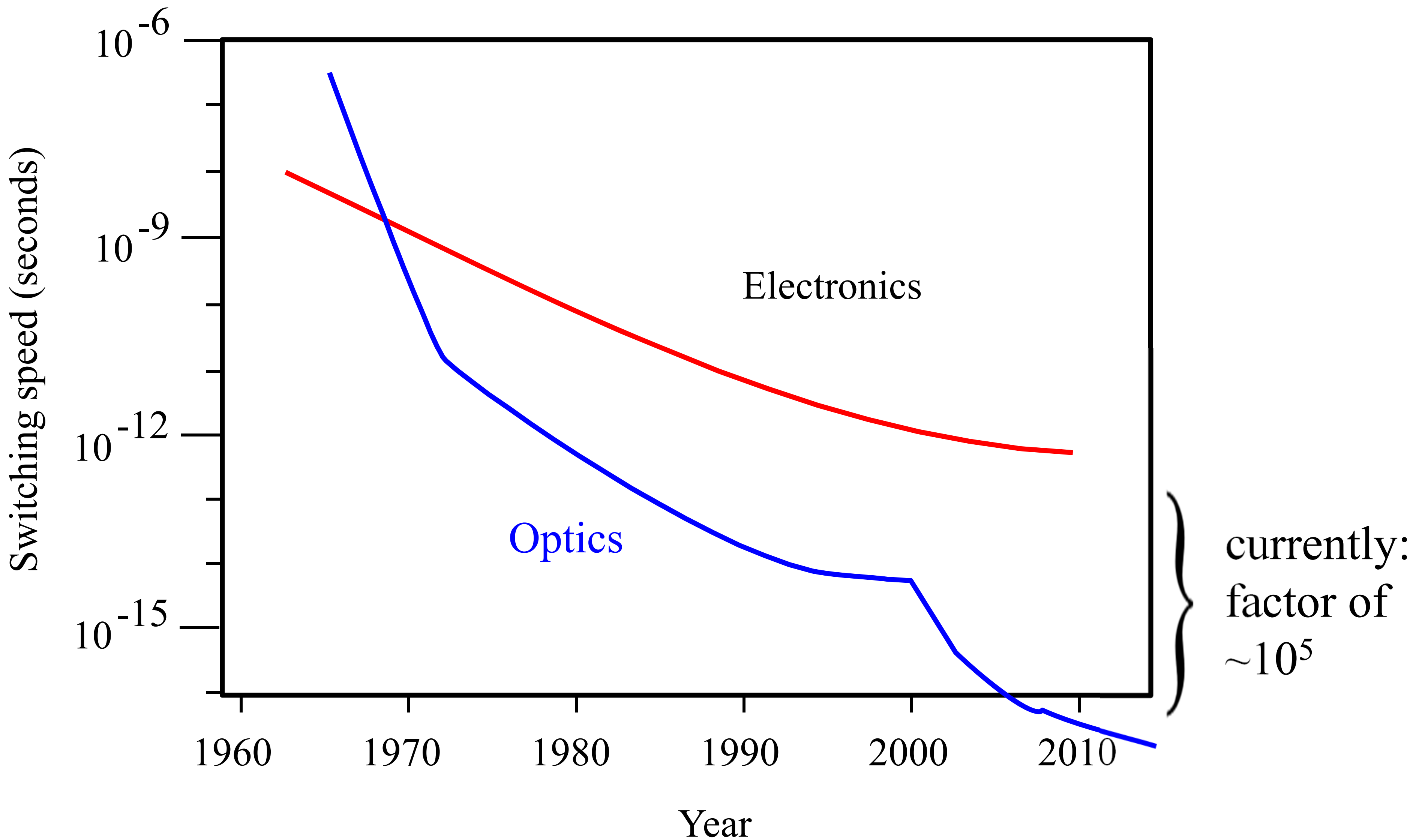
How big and how small?

Prefixes:

Small		Big	
Milli (m)	10^{-3}	Kilo (k)	10^{+3}
Micro (μ)	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}



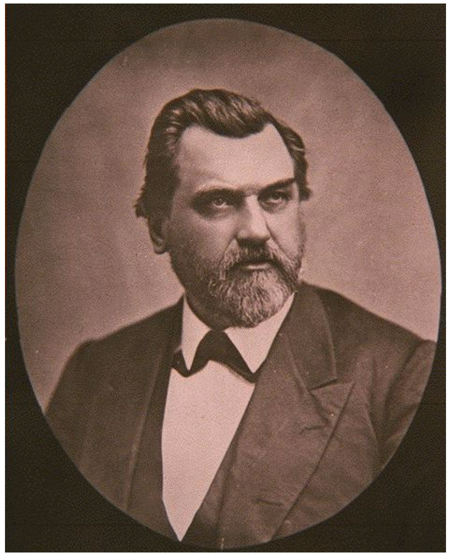
Ultrafast Phenomena - The Evolution of Speed

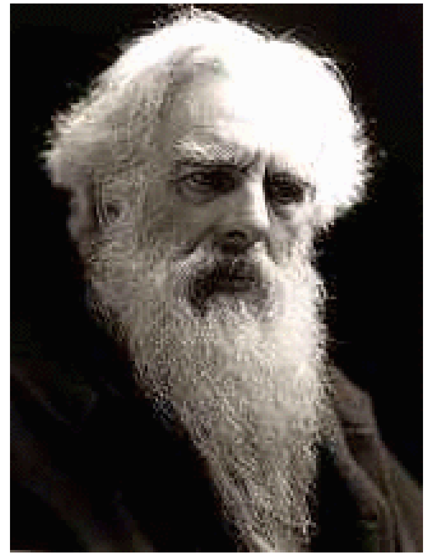


From the earliest days of the laser, optics has been faster than electronics.
And it always will be.

A brief history of time resolution

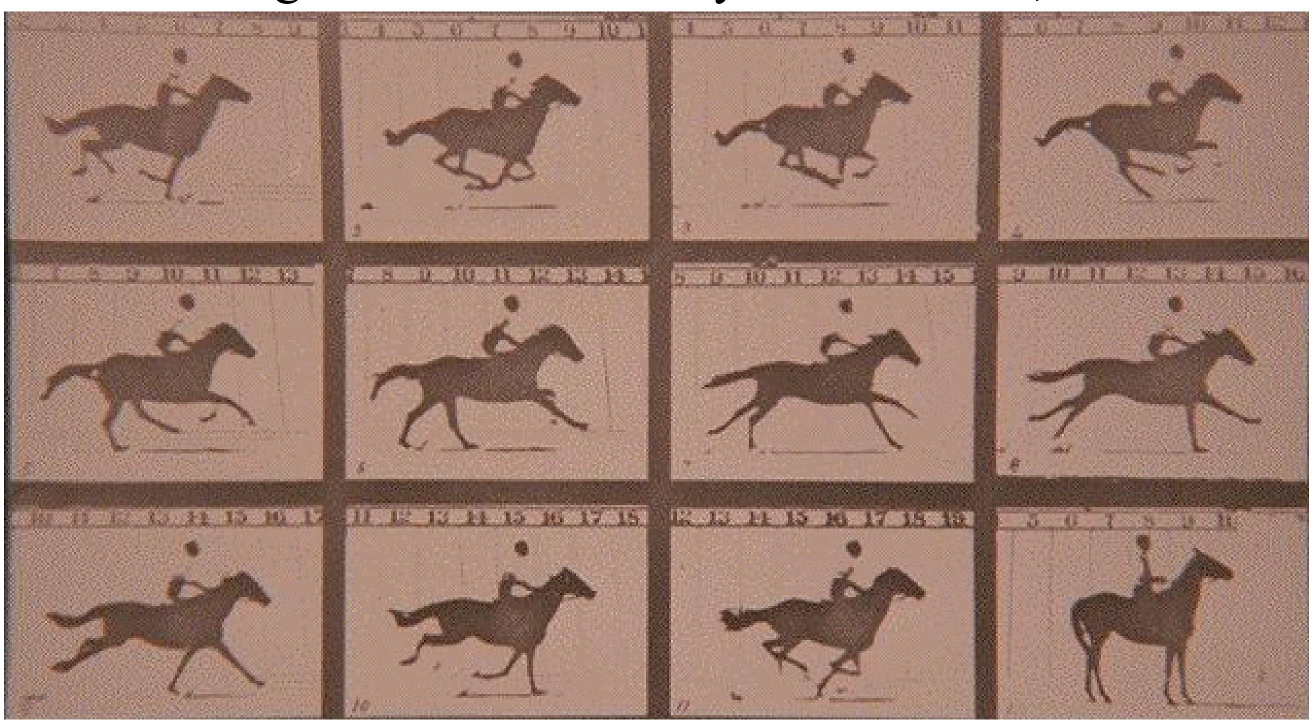
Leland Stanford





Eadweard Muybridge

The "Trotting Horse" Controversy   Palo Alto, CA   1872

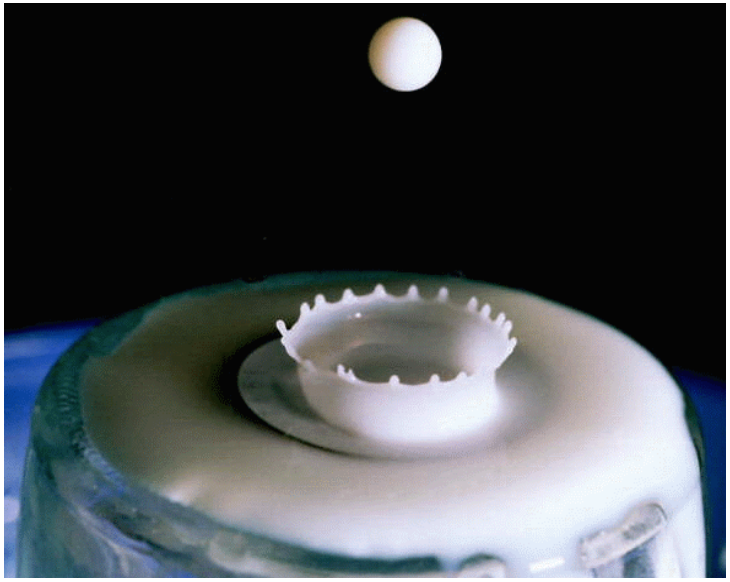


Time Resolution:
1/60th of a second

'Doc' Edgerton - Strobe Photography

Harold Edgerton 1942
MIT Research Laboratory for Electronics

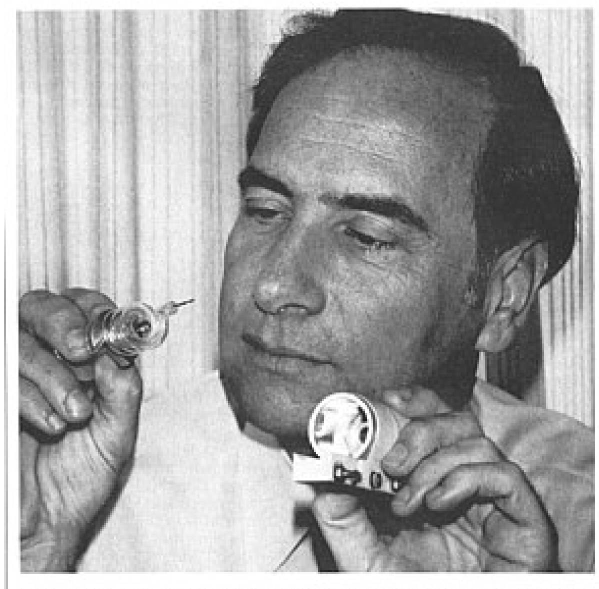
"How to Make Apple sauce at MIT"
H. Edgerton, 1964

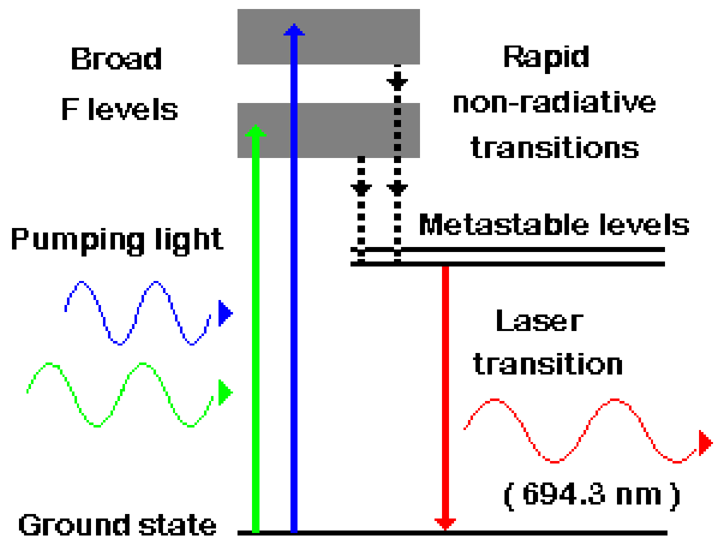


"Splash on a Glass"
Curtis Hurley
Junior High
School student
1996

Time Resolution: a few microseconds

REAL progress started with the invention of the laser…

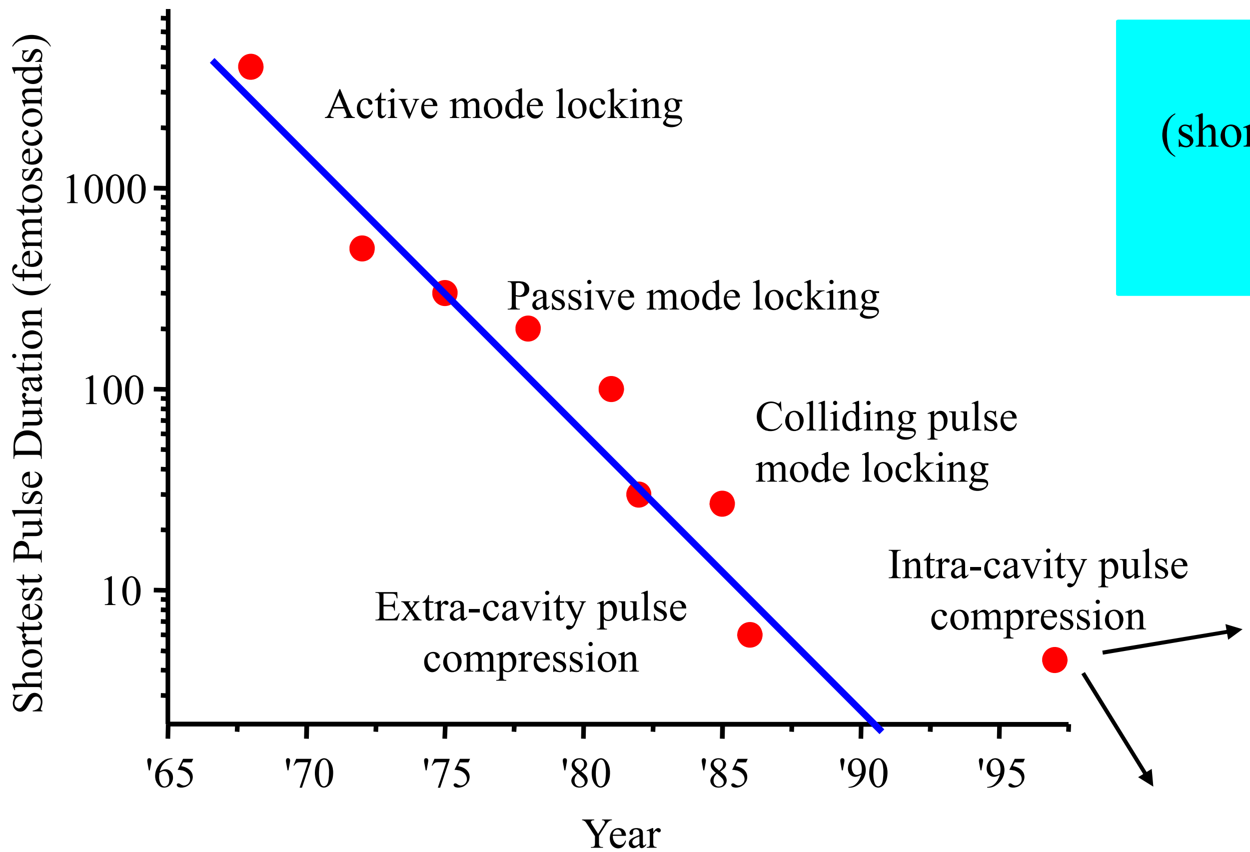

Maiman examines first ruby laser built at Hughes Research Laboratories. (circa 1960)



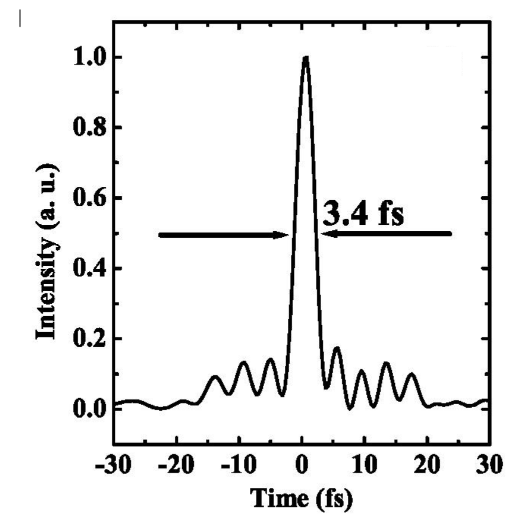
Energy levels of chromium ions in ruby

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

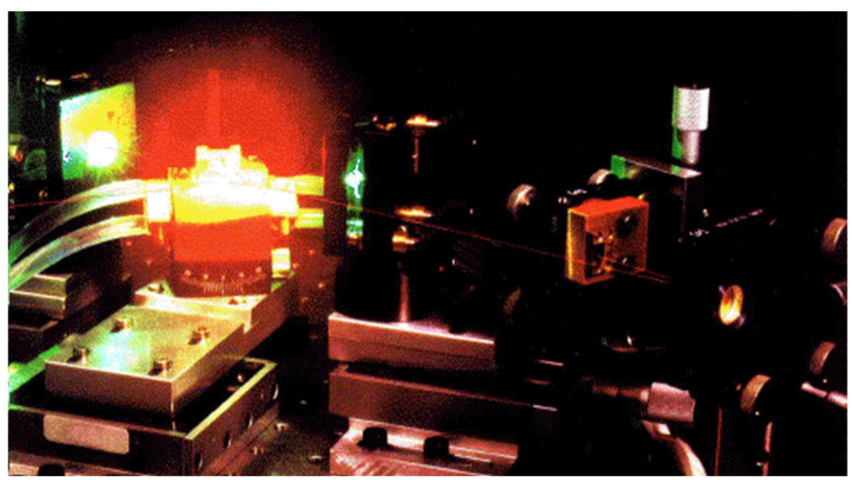
The Laser - Mode Locking



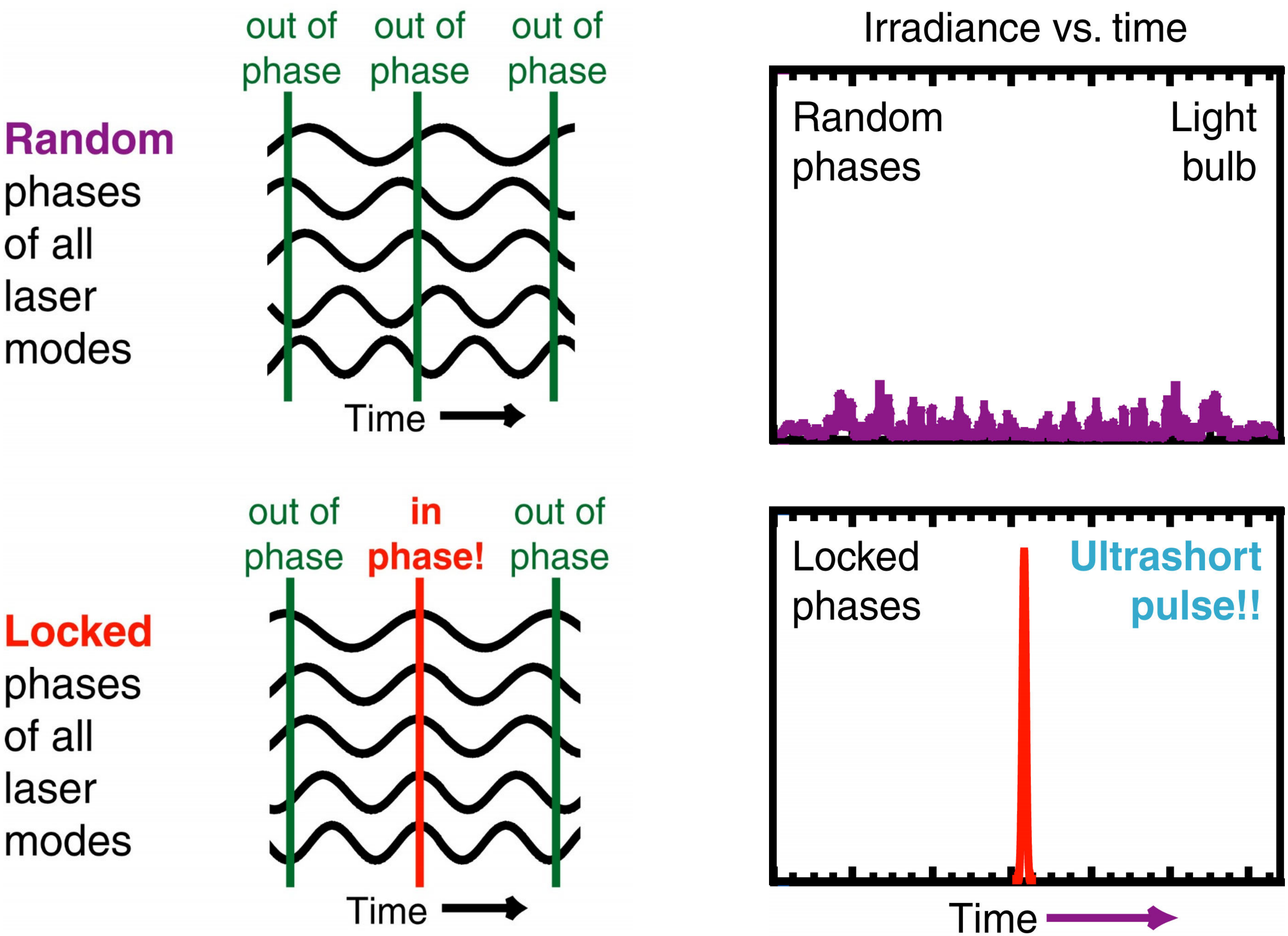
Current record
(shortest pulse straight out of the laser):
3.4 fsec
Yamane, et al. Nov. 2003



Mode-locked
Ti:sapphire laser

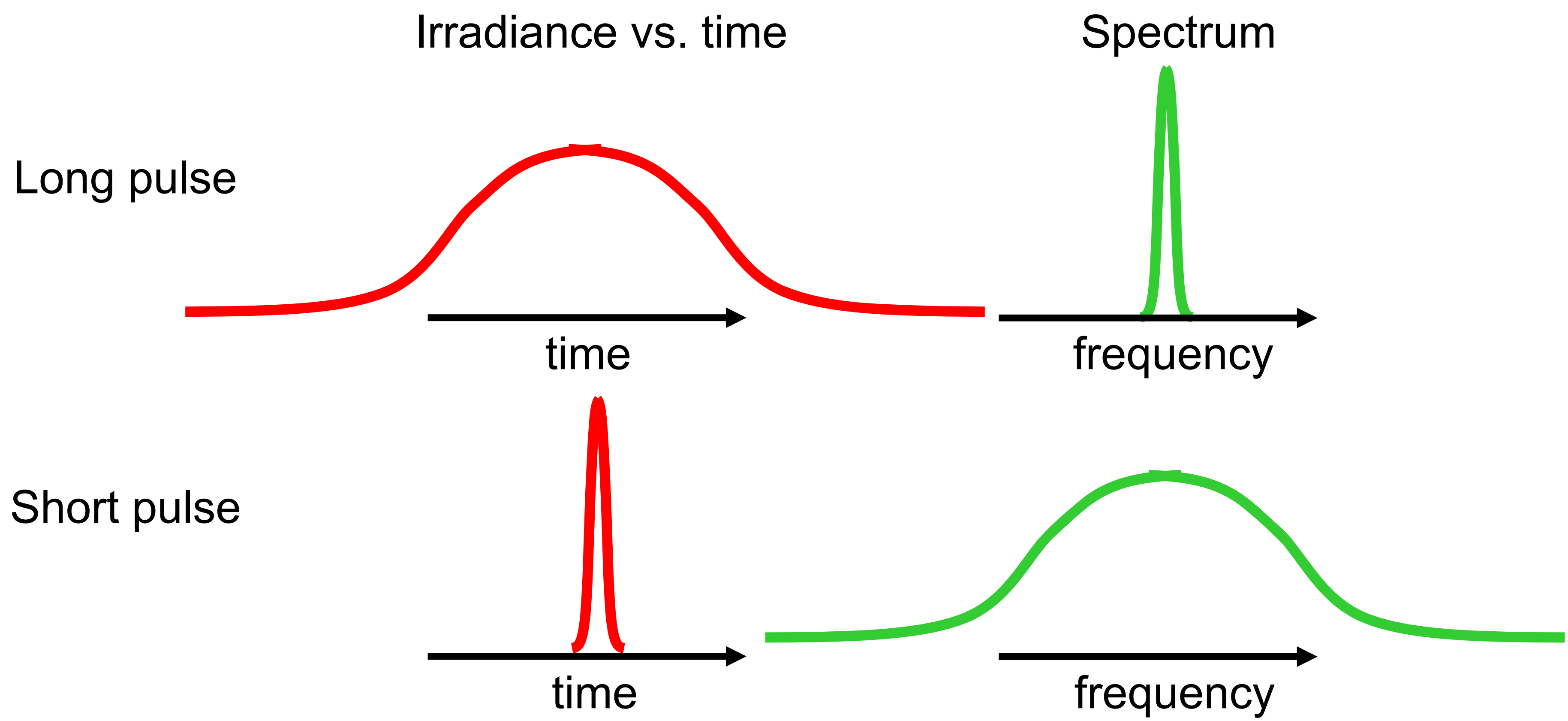


Generating ultrashort pulses: mode locking



Long vs. Short light pulses

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



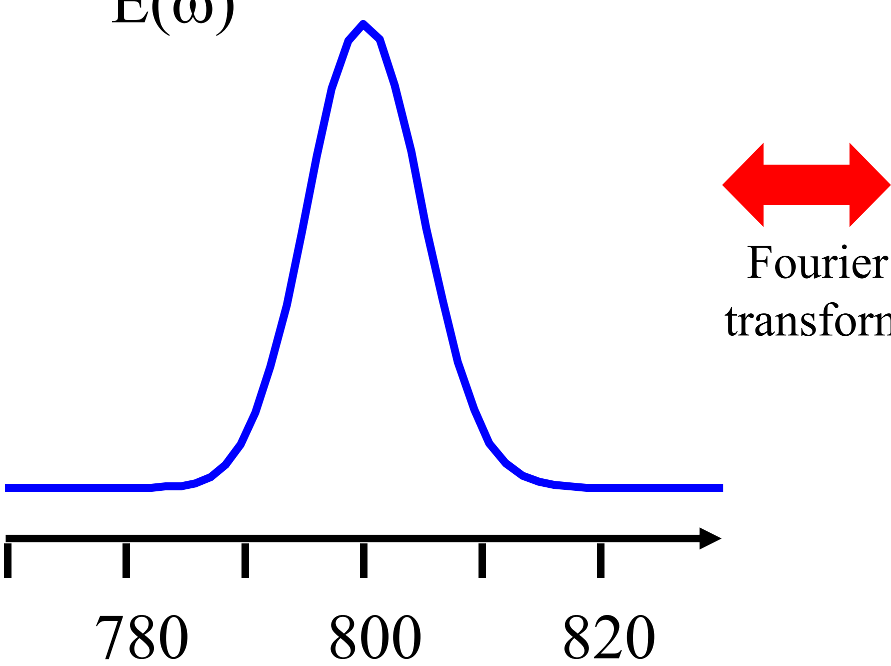
To make a short pulse, you need a lot of spectral bandwidth.

A typical pulse

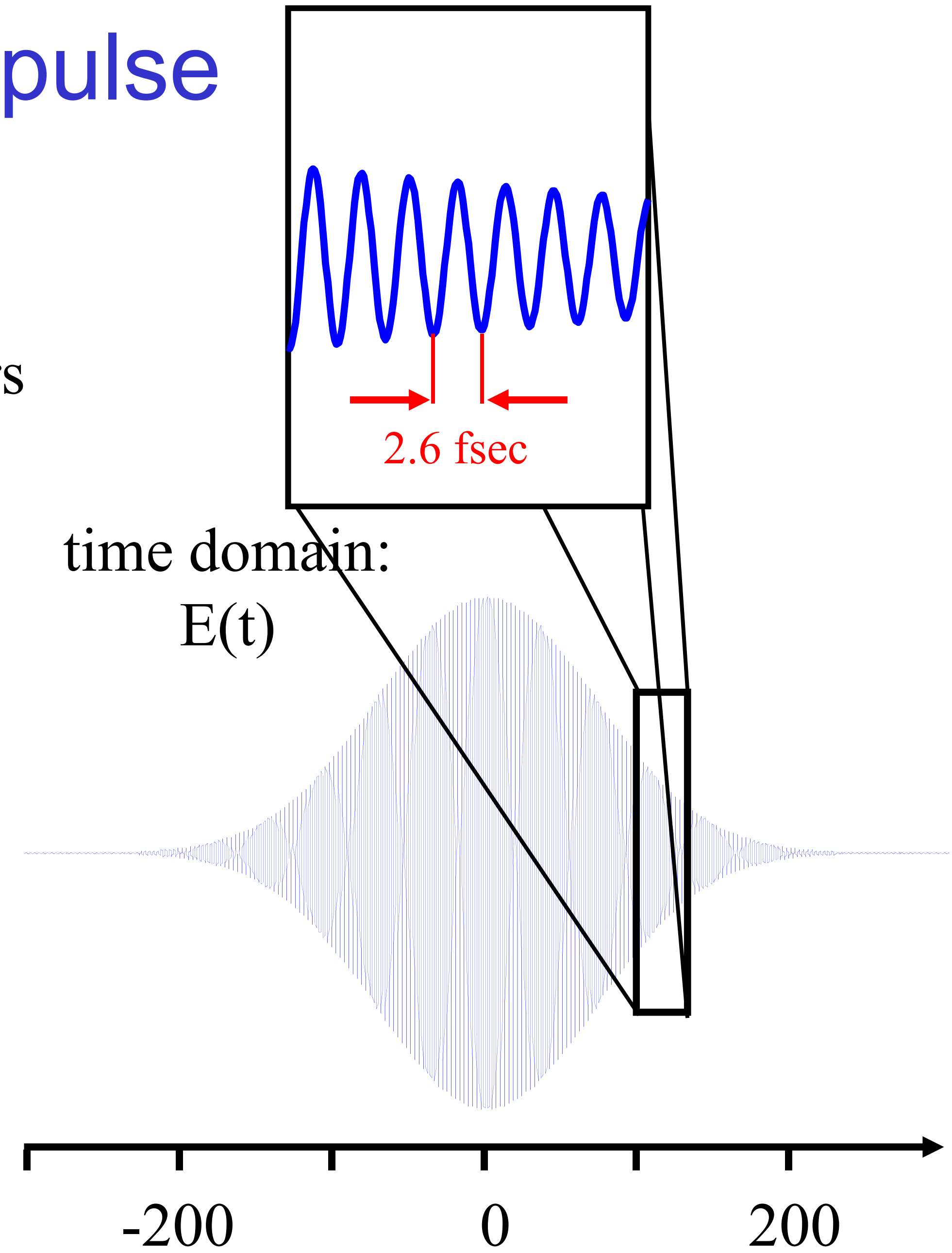
Consider a pulse:

duration = 100 femtoseconds
wavelength = 800 nanometers

frequency domain:
E(ω)

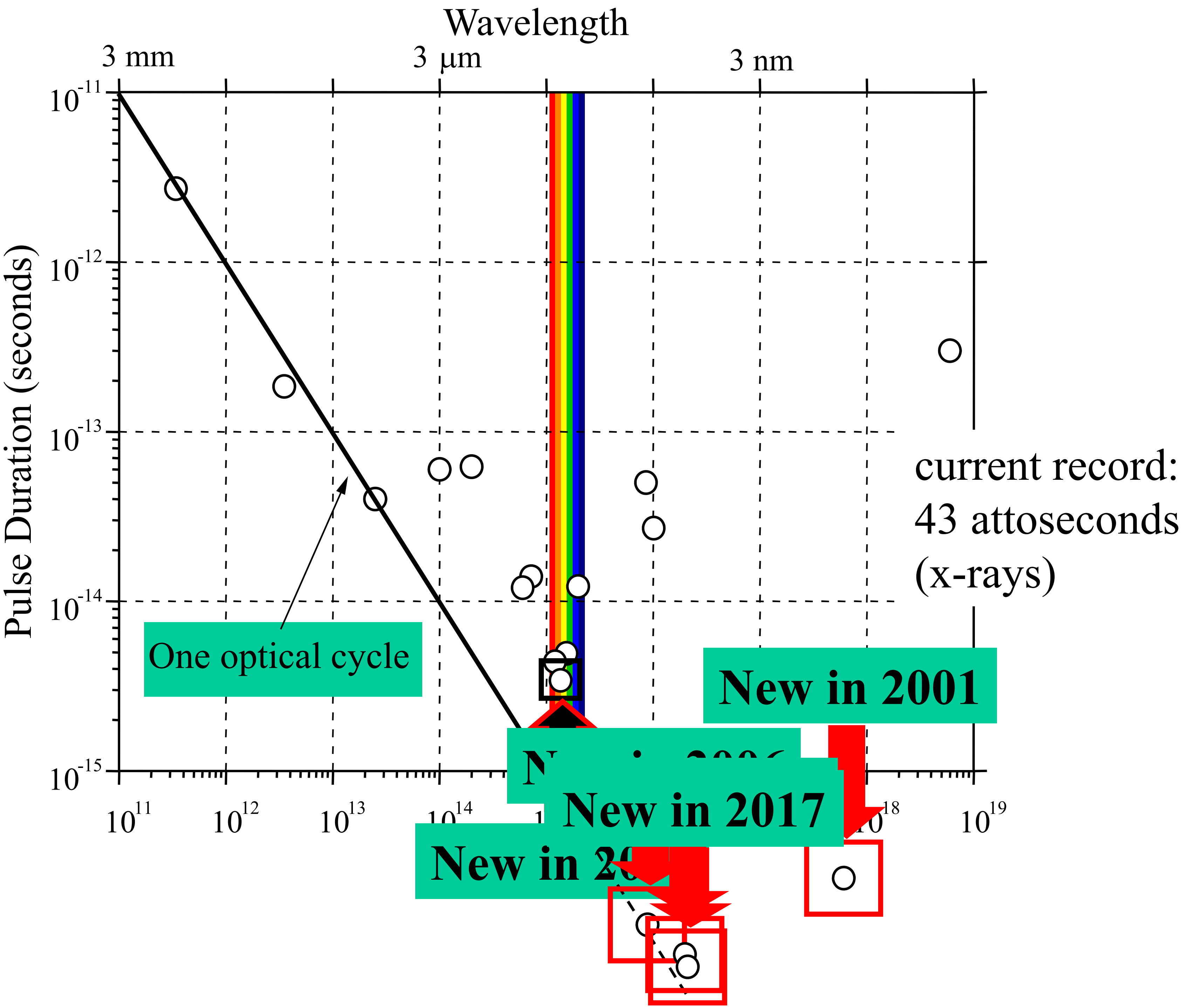


time domain:
E(t)



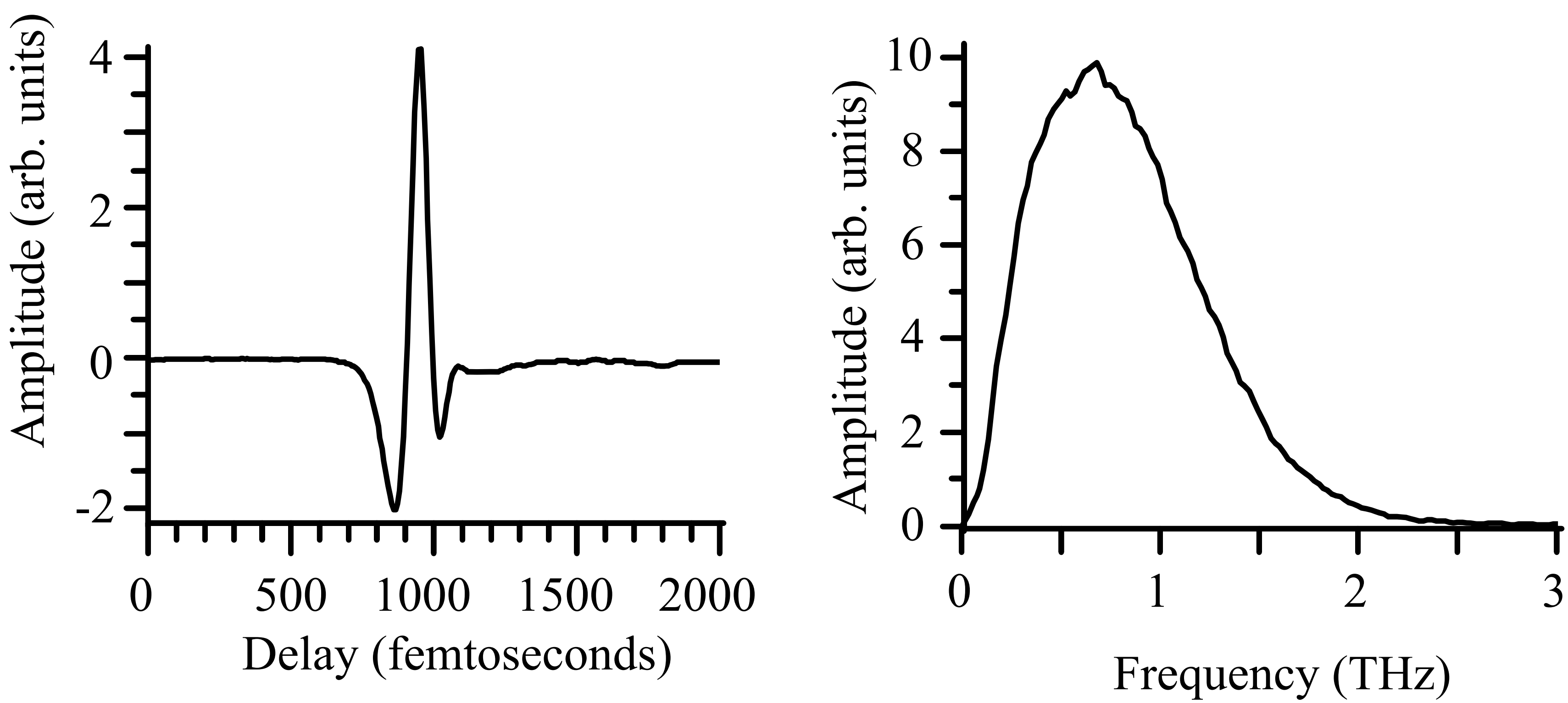
number of cycles ~ (duration of one cycle) / (duration of pulse)

The Shortest Pulses at Different Wavelengths



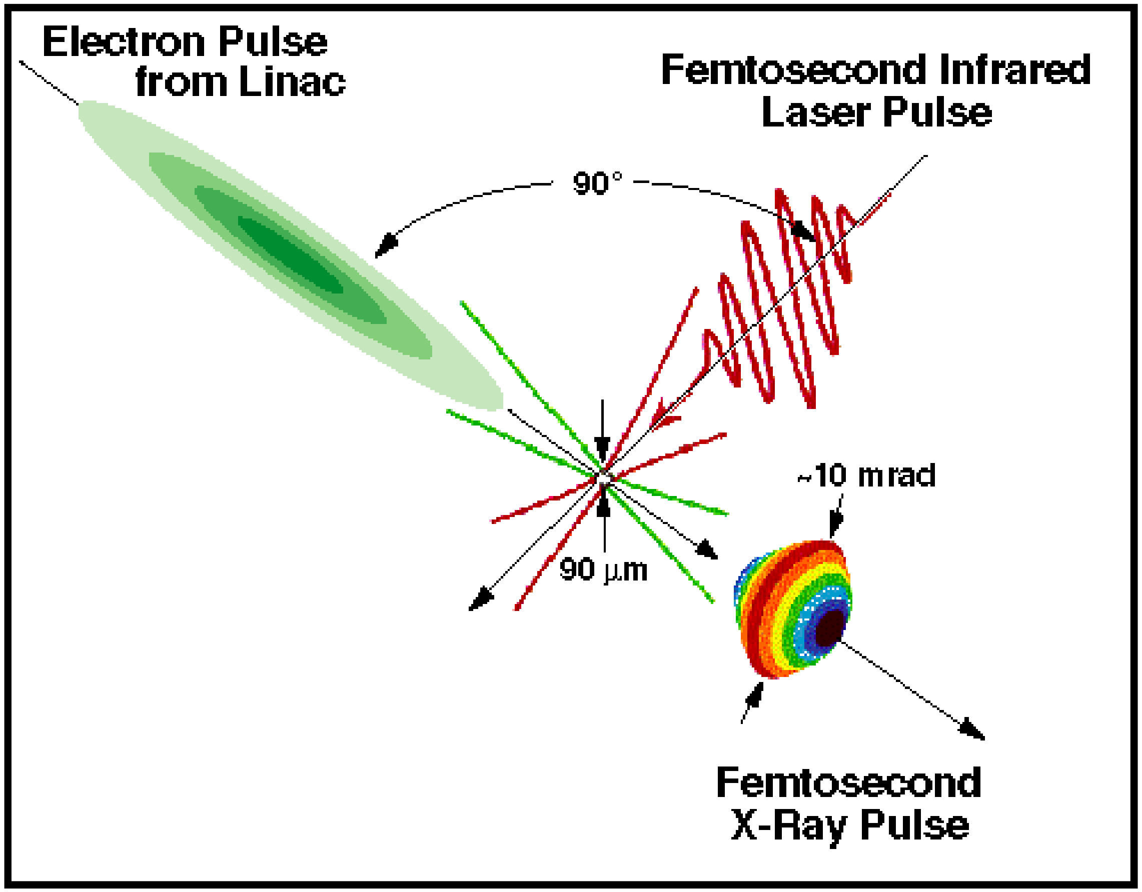
The Shortest Pulses at Long Wavelengths

Approximately one cycle



Short Pulses at Short Wavelengths

The first attempt to make short x-ray pulses:

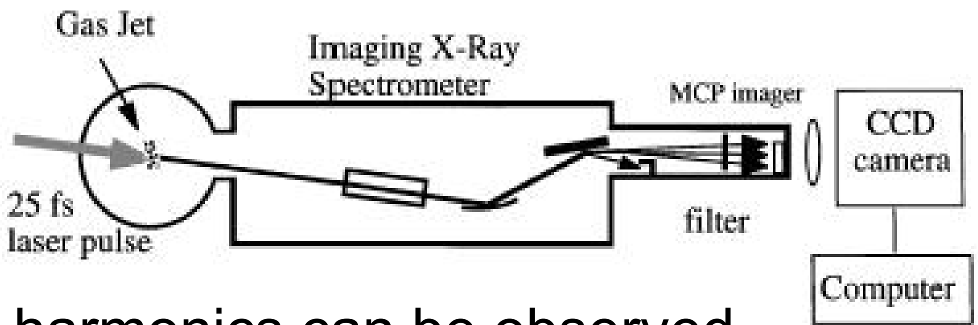


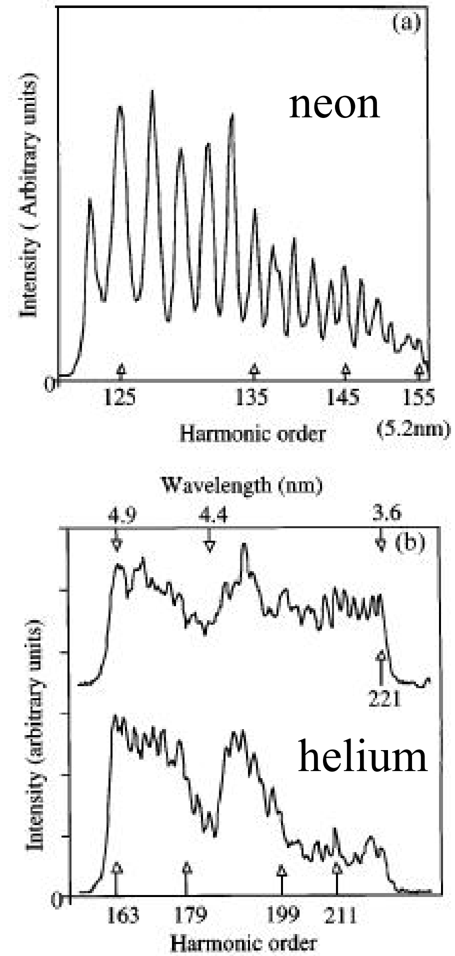
90 degree relativistic Thompson scattering
Lawrence Berkeley National Laboratory

More modern methods

Very high harmonic generation.

First report:
Kapteyn and Murnane, *Phys. Rev. Lett.*, **79**, 2967 (1997)



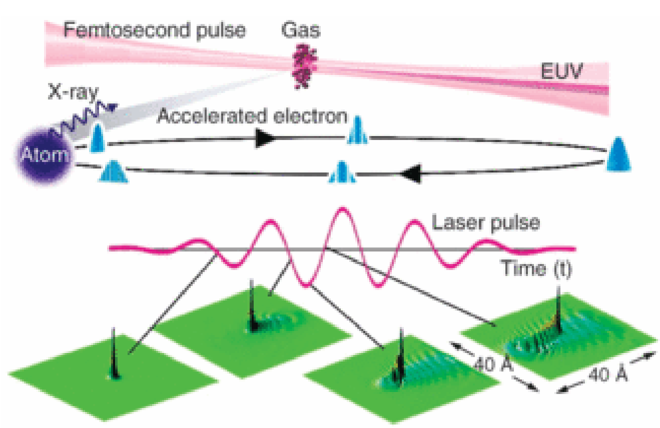


Very high-order harmonics can be observed.

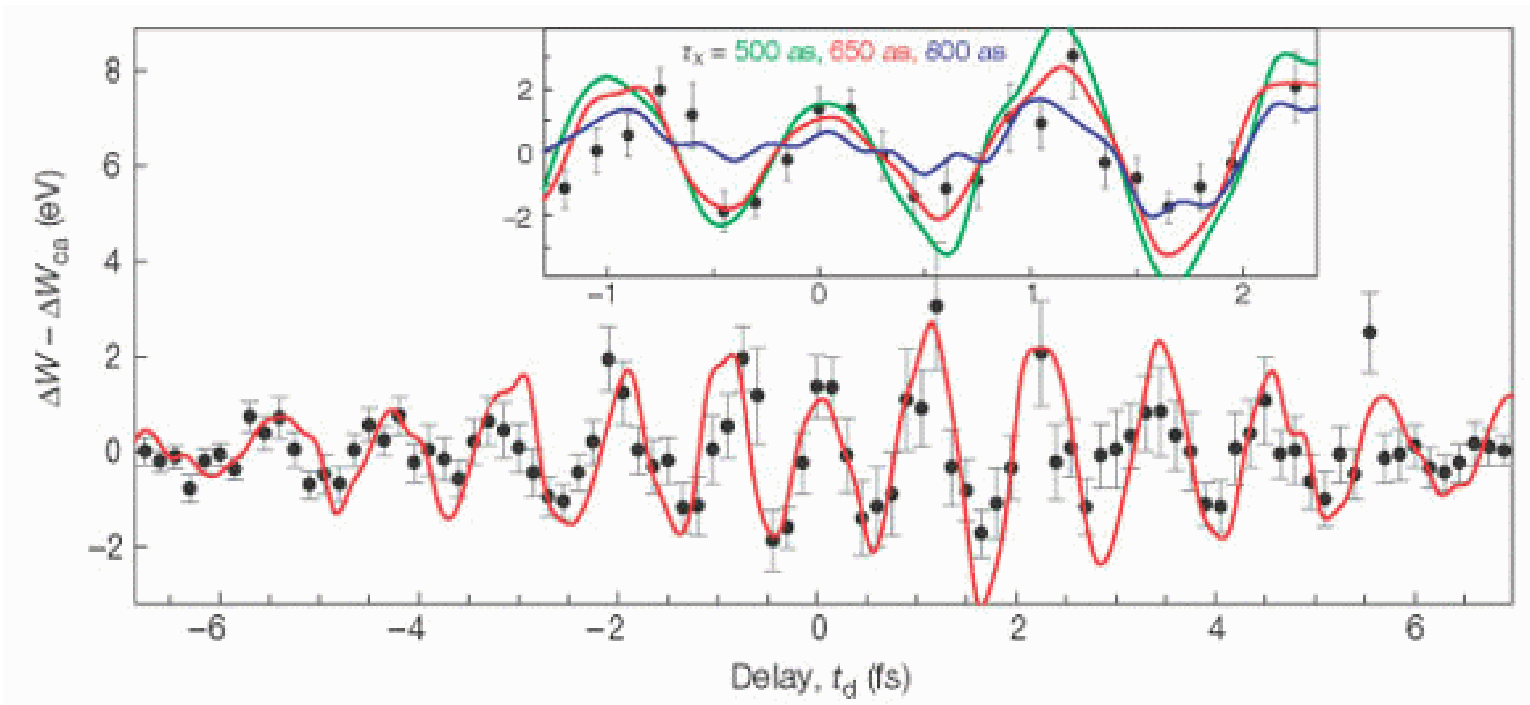
This gives a very broadband spectrum that spans from UV to x-ray.

Other challenges:

- Making sure that all the spectral components are in phase
- Measuring what you've made



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

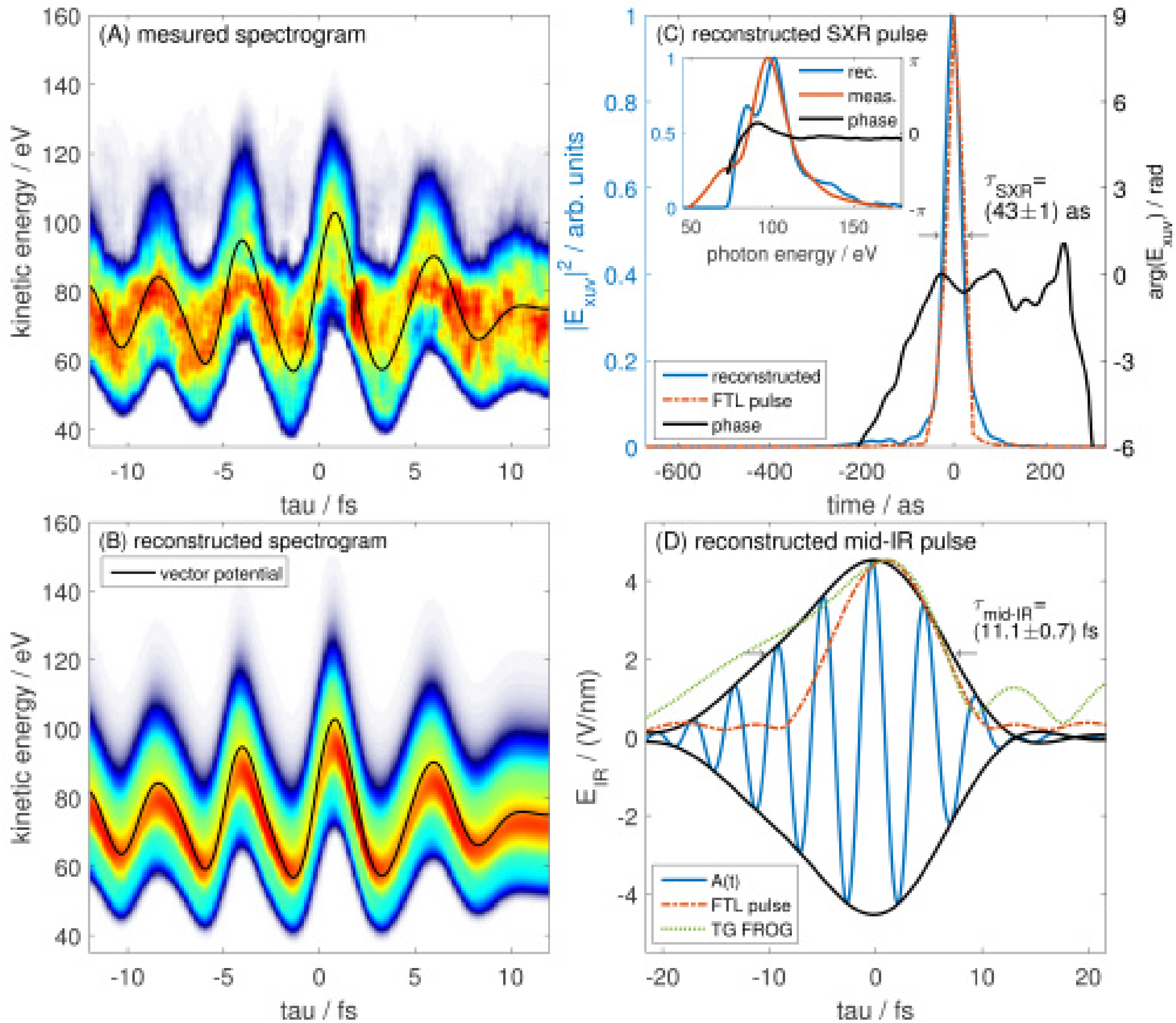
λ = 13.8 nm

measured signal: spectral width of a photoelectron spectrum

Required infrared pulse intensity: 5×10^{13} W/cm^2

The shortest pulses ever (so far)

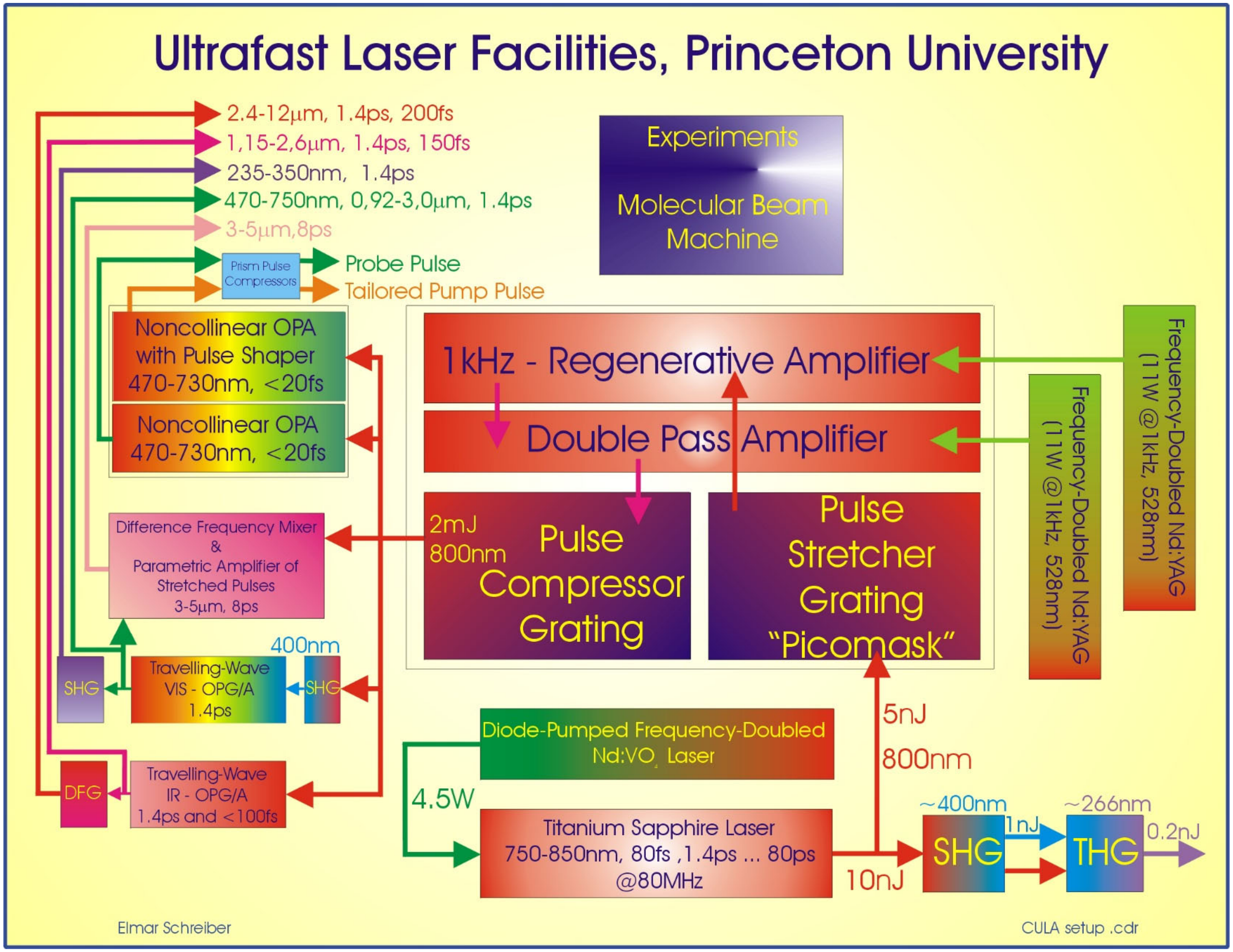
Measured and reconstructed photoelectron spectrum



from T. Gaumnitz et al., Optics Express (2017)

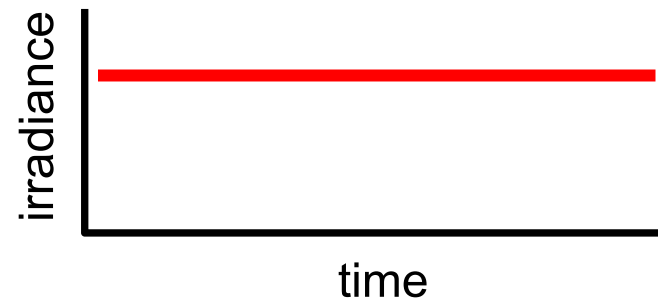
43 attoseconds!

Ultrafast set-ups can be very sophisticated.



Why does ultrashort often mean ultra-intense?

A continuous-wave (cw) laser:

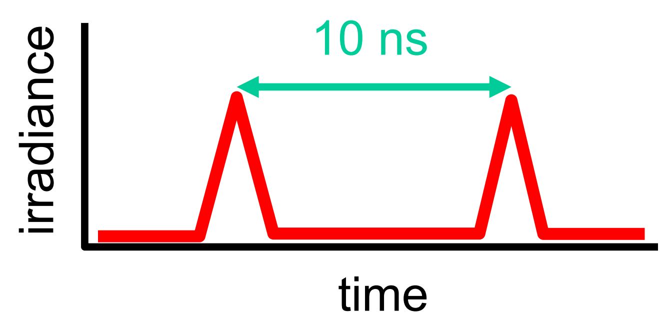


average energy = power/time = joules per second = Watts

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

A pulsed laser:

pulse duration = 100 fs
pulse rate = 100 MHz



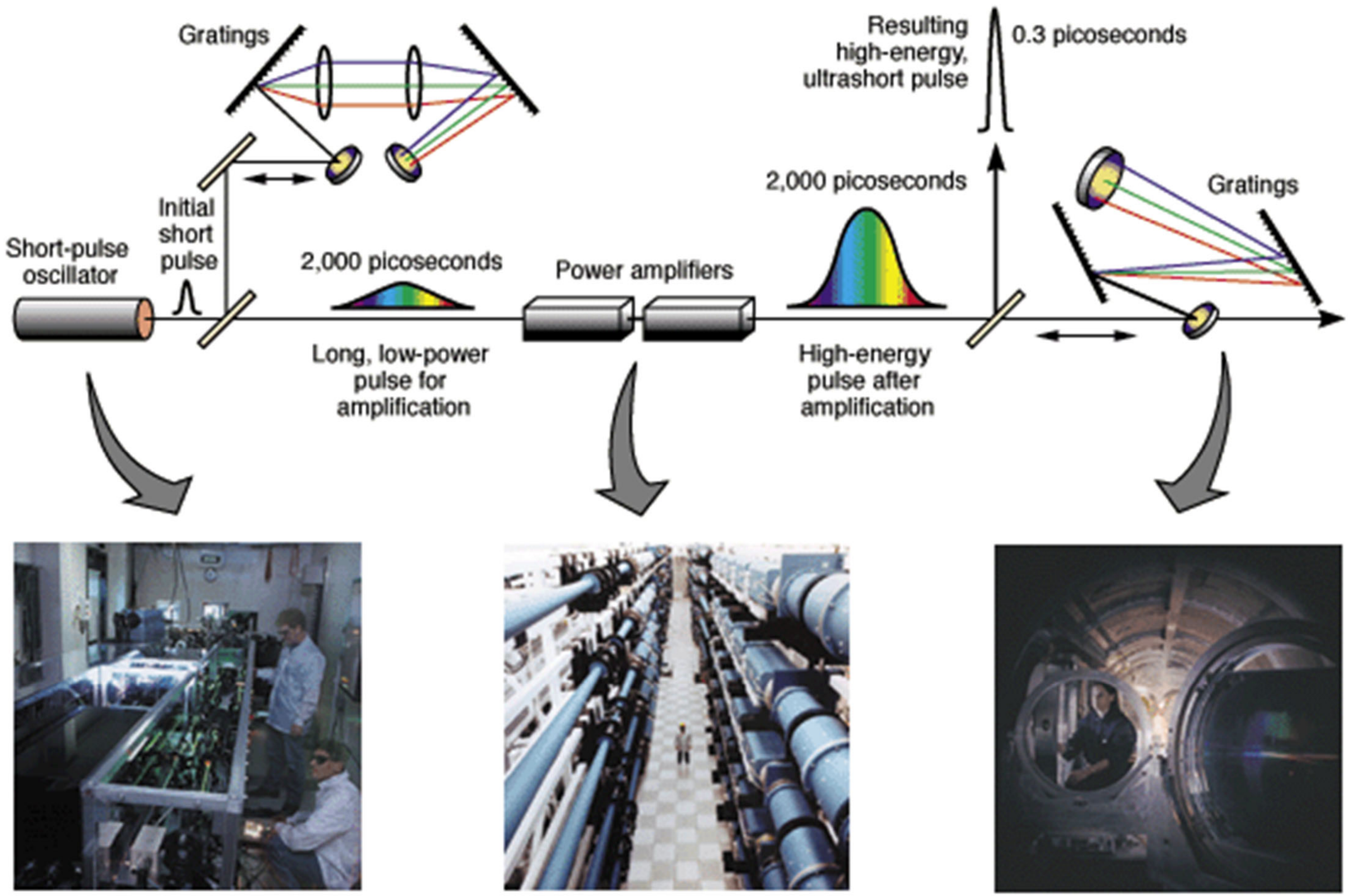
Example: 1 Watt at λ = 800 nm is **4×10^{10}** photons per pulse.

Energy per pulse = 4×10^{10} photons per pulse × energy/photon = 10 nJ/pulse

Peak energy = energy per pulse / pulse duration = 10^{5} W

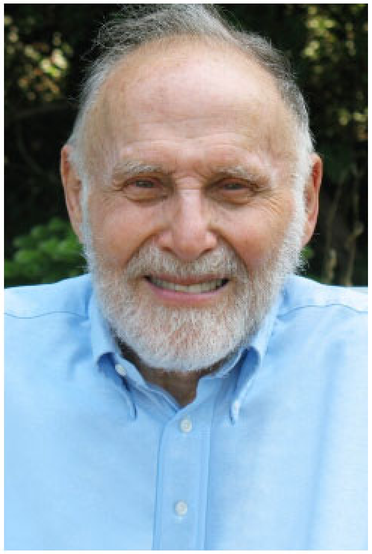
Focus this to a 10 μm diameter spot: *Peak* irradiance = 10^{15} W/m^{2}

Chirped pulse amplification



Chirped pulse amplification: The Prize

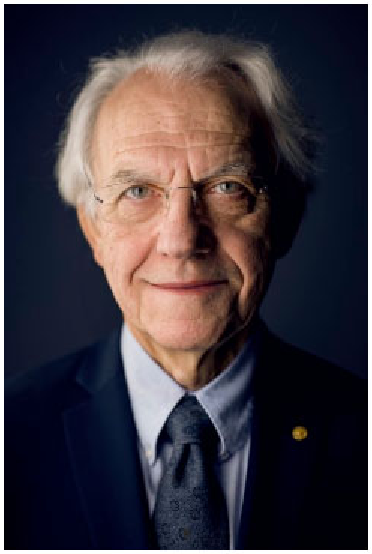
The Nobel Prize in Physics 2018



© Arthur Ashkin

Arthur Ashkin

Prize share: 1/2



© Nobel Media AB. Photo: A. Mahmoud

Gérard Mourou

Prize share: 1/4

© Nobel Media AB. Photo: A. Mahmoud

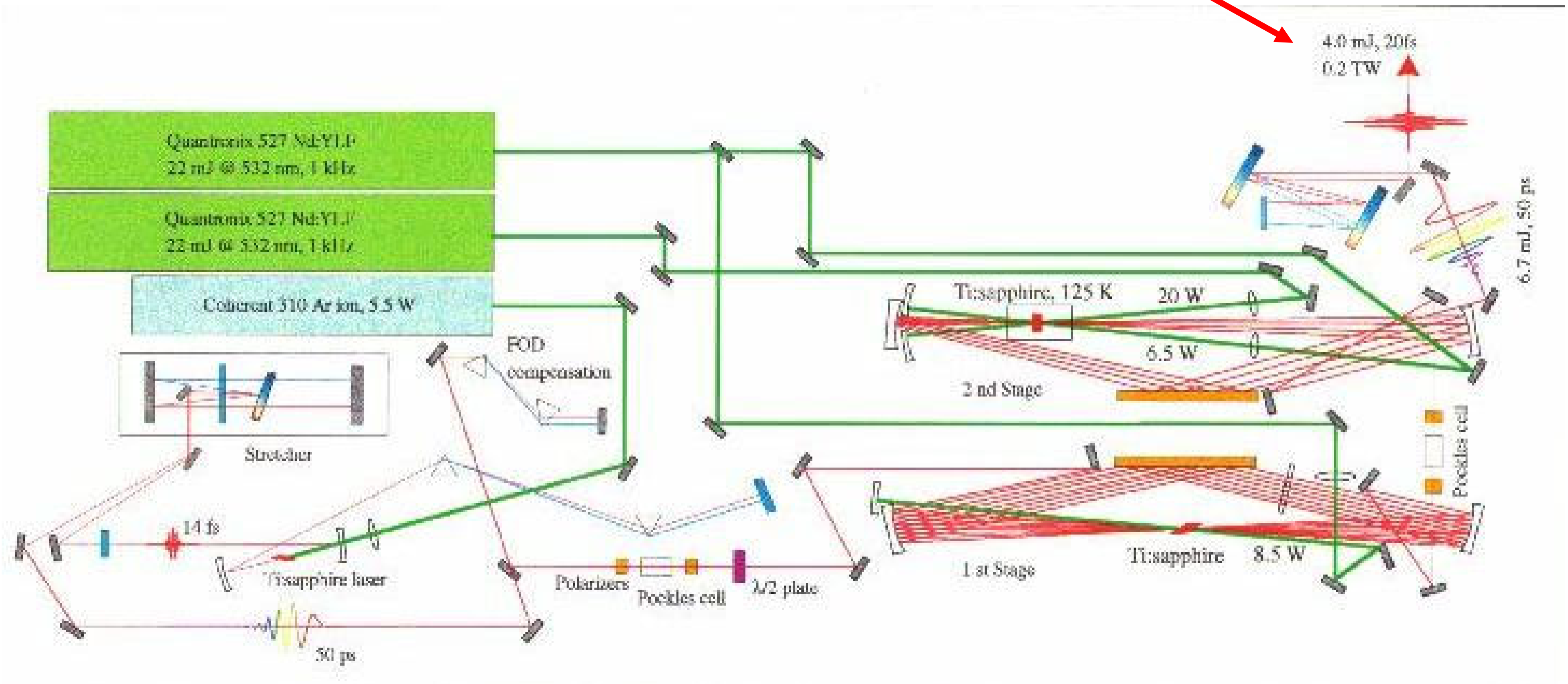
Donna Strickland

Prize share: 1/4

The Nobel Prize in Physics 2018 was awarded "for groundbreaking inventions in the field of laser physics" with one half to Arthur Ashkin "for the optical tweezers and their application to biological systems", the other half jointly to Gérard Mourou and Donna Strickland "for their method of generating high-intensity, ultra-short optical pulses."

The Highest Intensities You Can Possibly Imagine

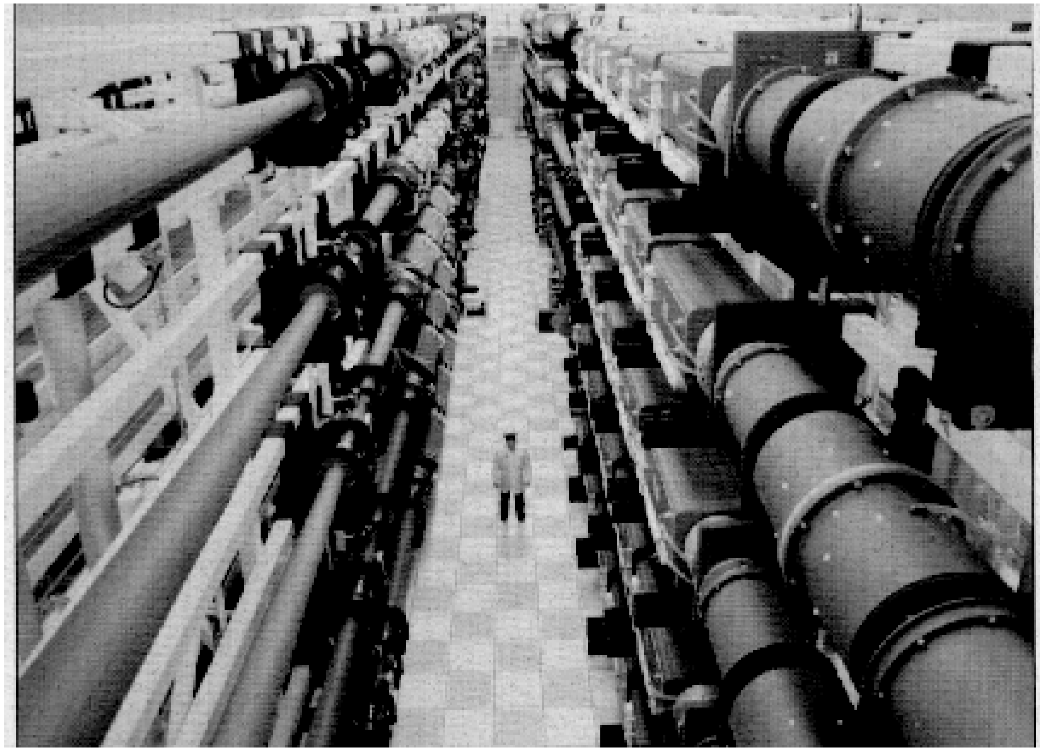
0.2 TW = 200,000,000,000 watts!

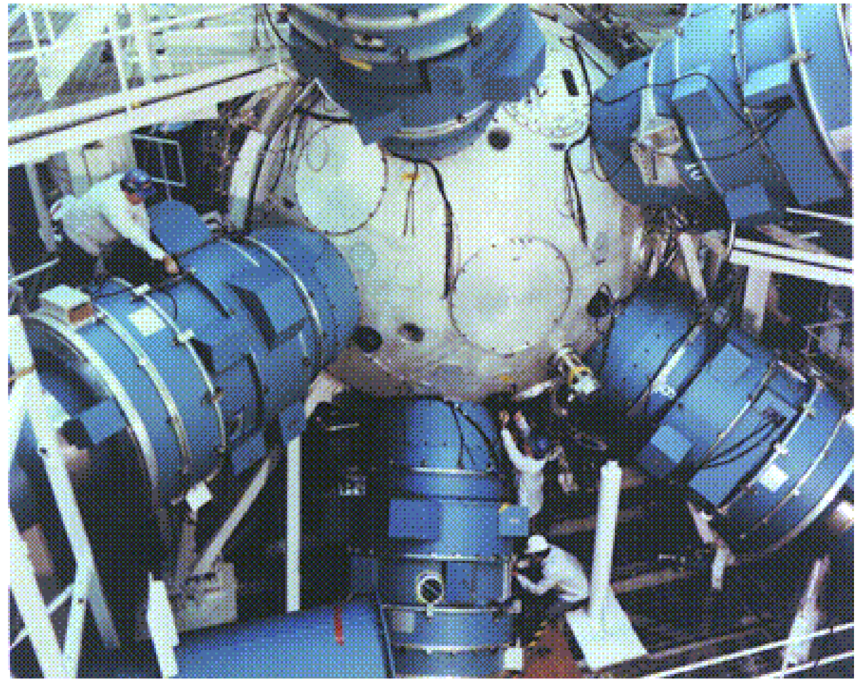


1 kHz CPA system at the University of California, Santa Barbara

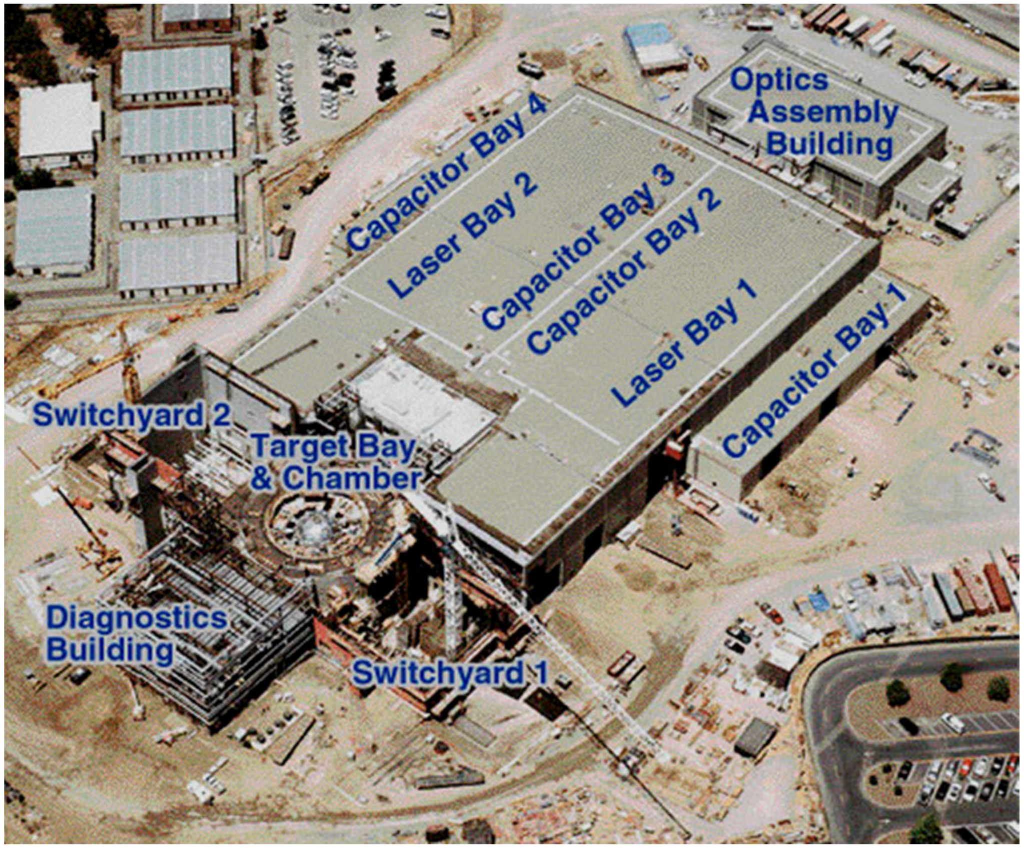
(used to be) The world's biggest laser

Nova - Lawrence Livermore National Laboratory



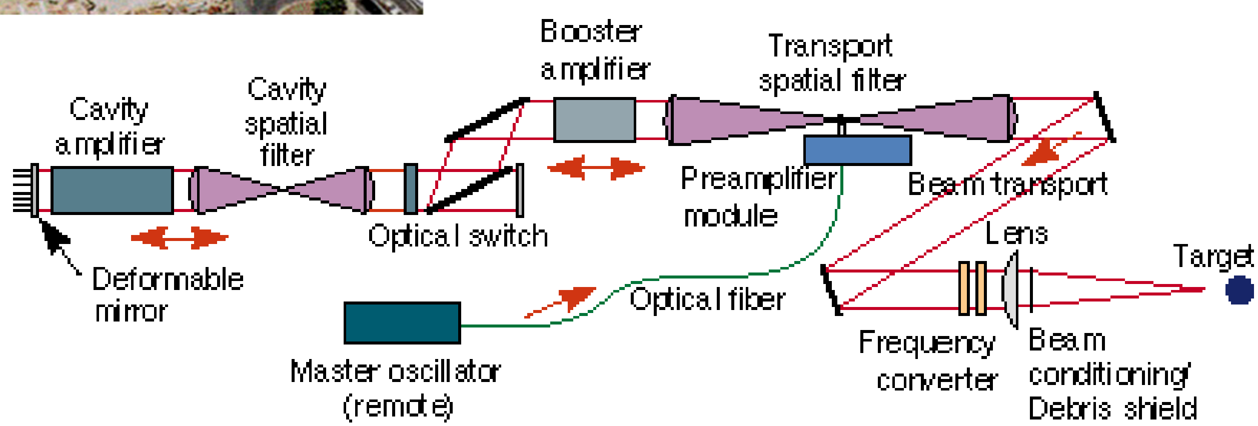


(currently) The world's biggest laser

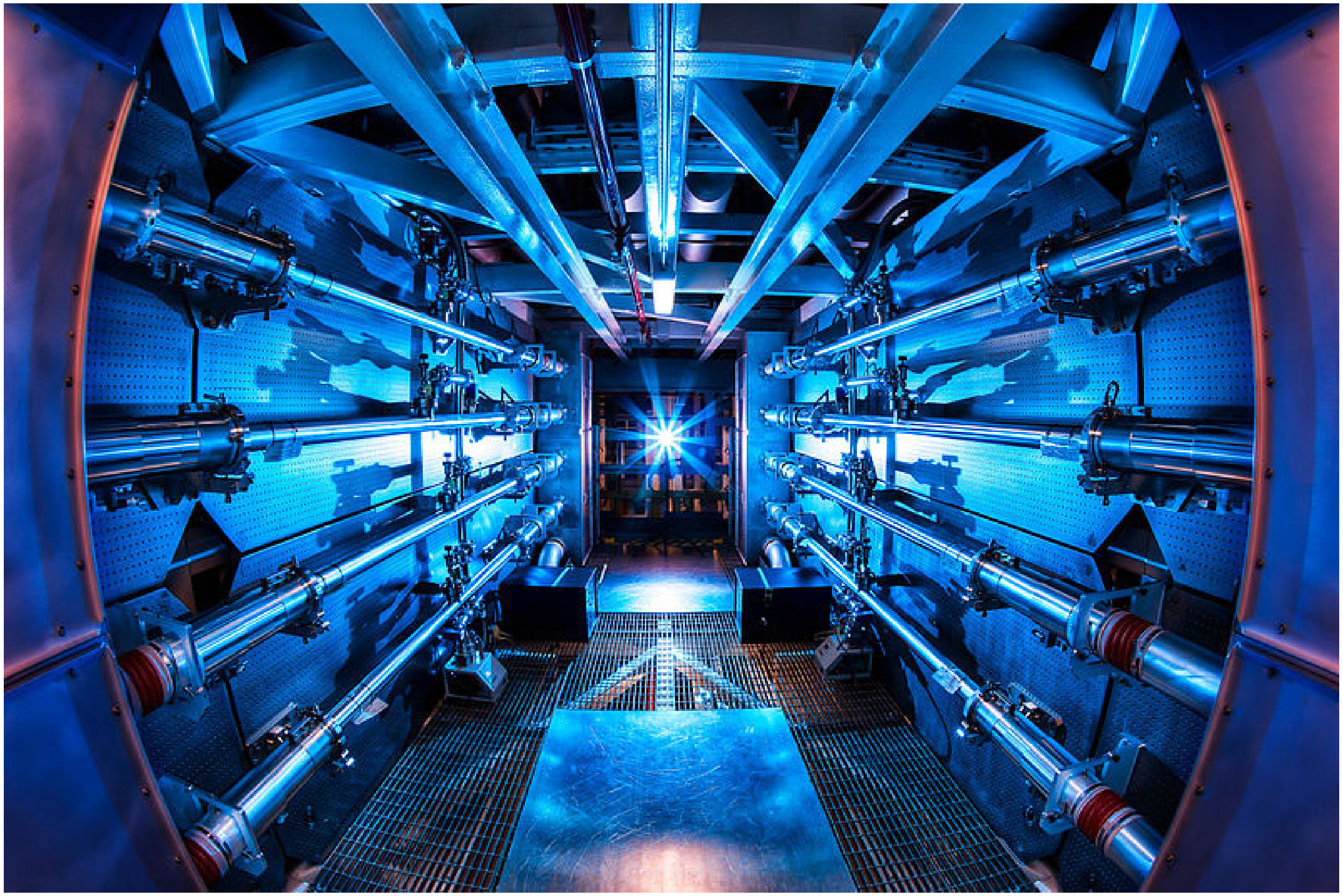


National Ignition Facility
(commissioned in 2009)

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:

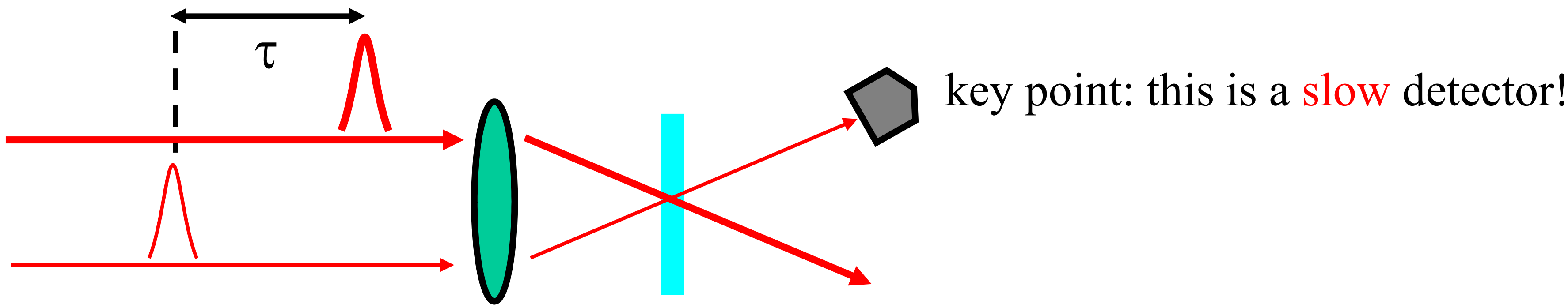
$$\frac{1}{\tau_{ex}} = \frac{1}{\tau_{fl}} + \frac{1}{\tau_{nr}}$$

• Biologically important processes utilize excitation energy for purposes other than fluorescence and hence must be very fast.

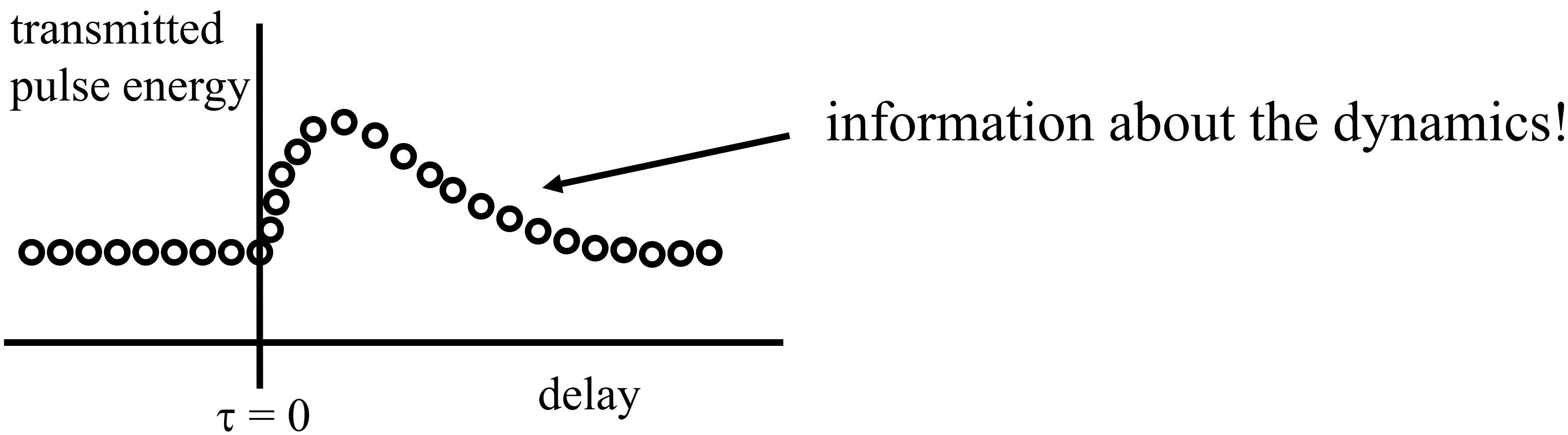
• Collisions in room-temperature liquids occur on a few-fs time scale, so nearly all processes in liquids are ultrafast.

• 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 τ later, a weak probe pulse interrogates the sample.
• Measure the transmission of the probe pulse at each delay τ.



PRESS RELEASE 12 OCTOBER 1999

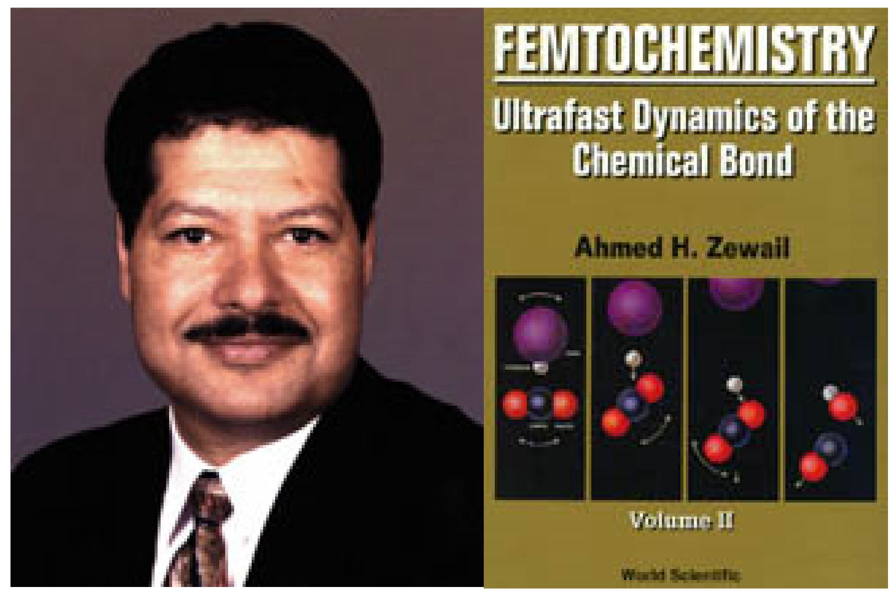
The Royal Swedish Academy of Sciences has awarded the 1999 Nobel Prize in Chemistry to

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.

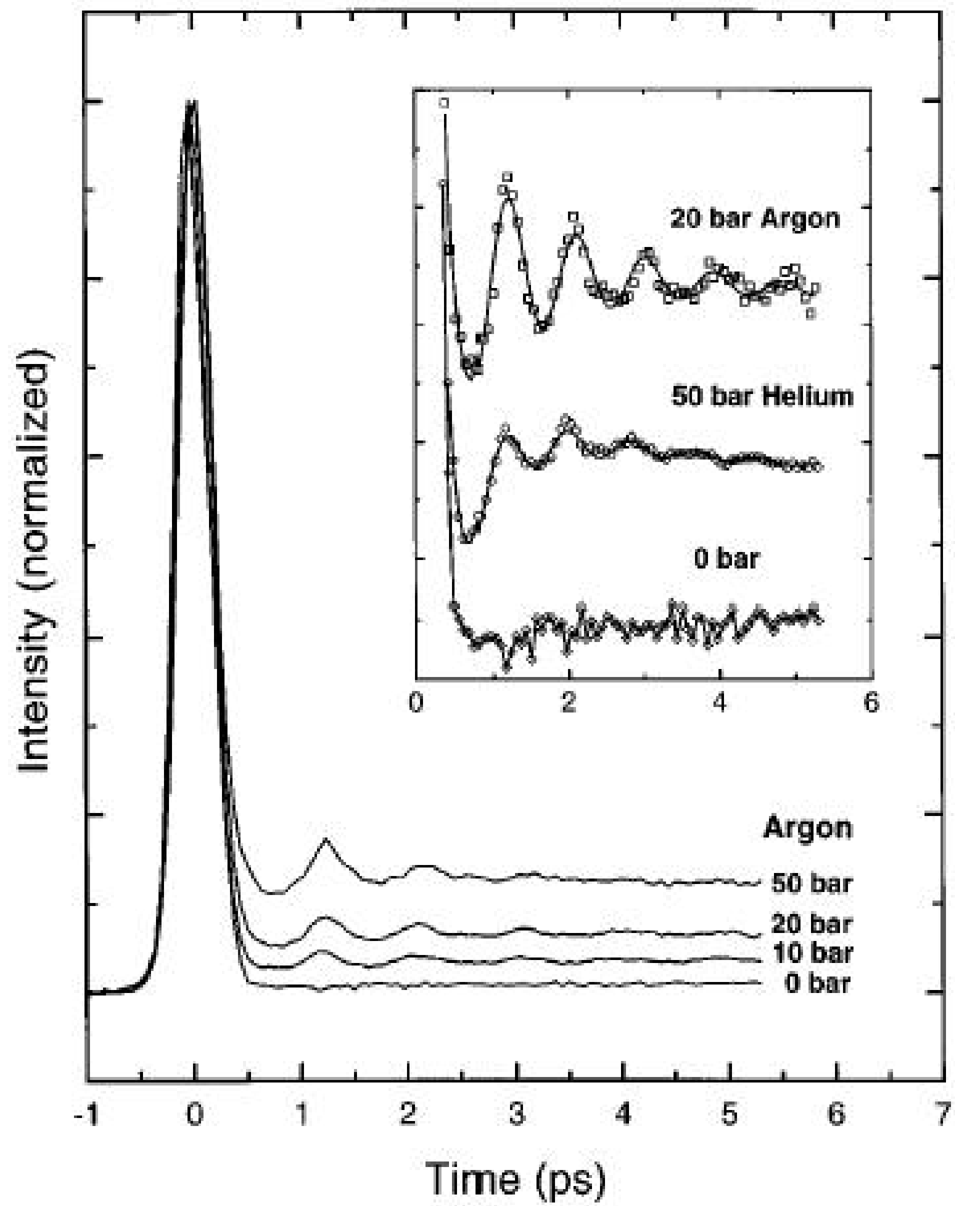
The Academy's citation:
For his studies of the transition states of chemical reactions using femtosecond spectroscopy.

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.



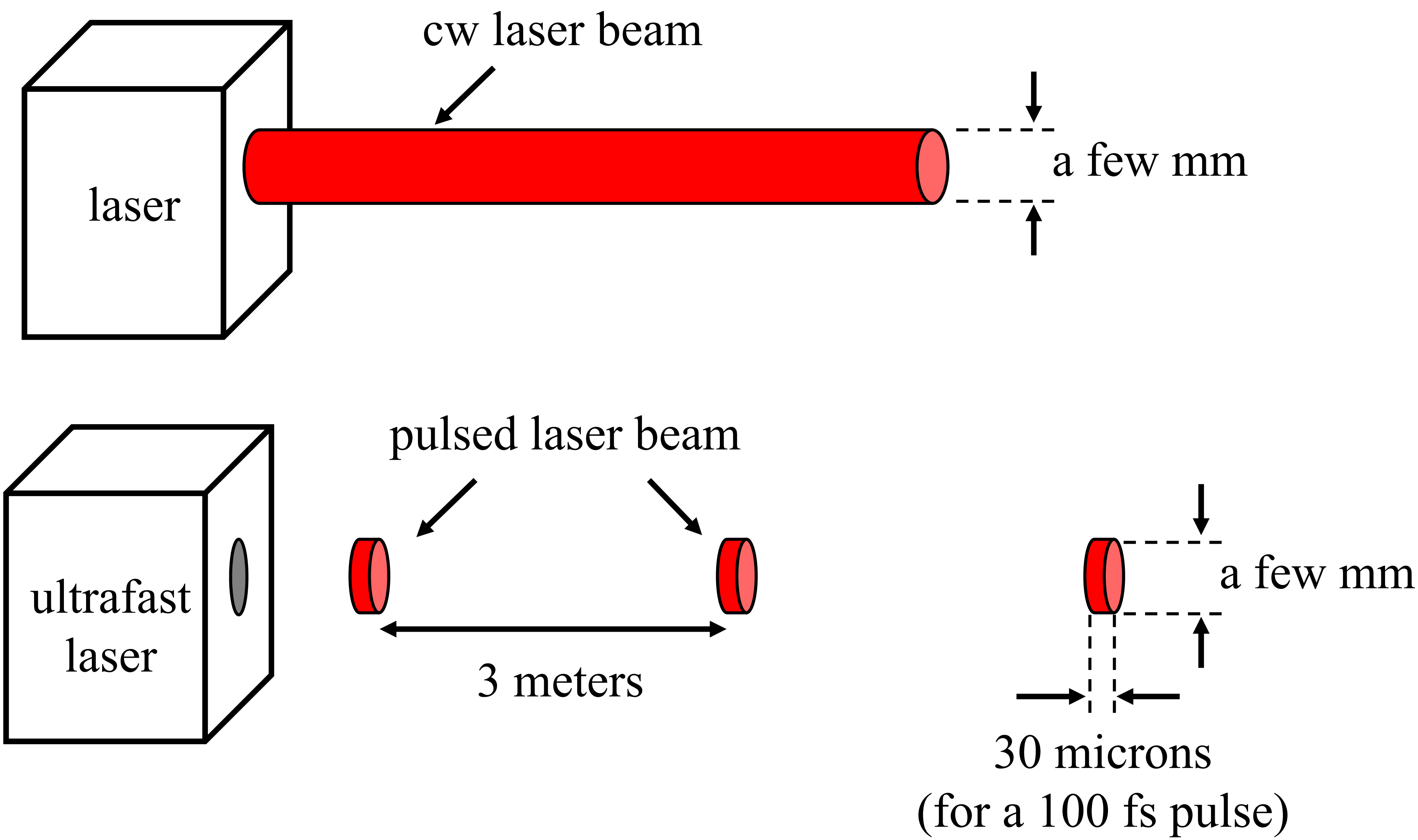
What is "Femtochemistry"?

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

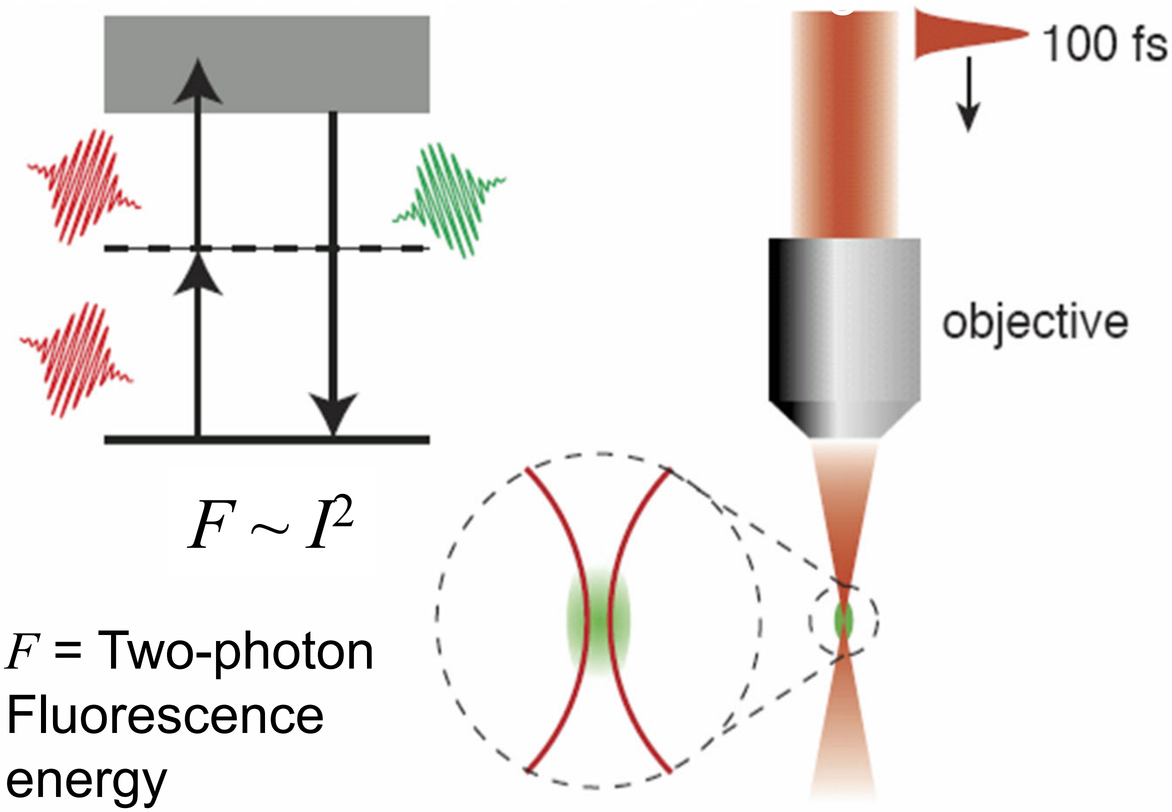


Zewail, et al., *J. Chem. Phys.*, **106**, 4353 (1997)

Ultrashort in time is also ultrashort in space



Ultrashort in time is also ultrashort in space, part II



$$F \sim I^2$$

F = Two-photon Fluorescence energy

Ultrashort in time is also ultrashort in space, part III

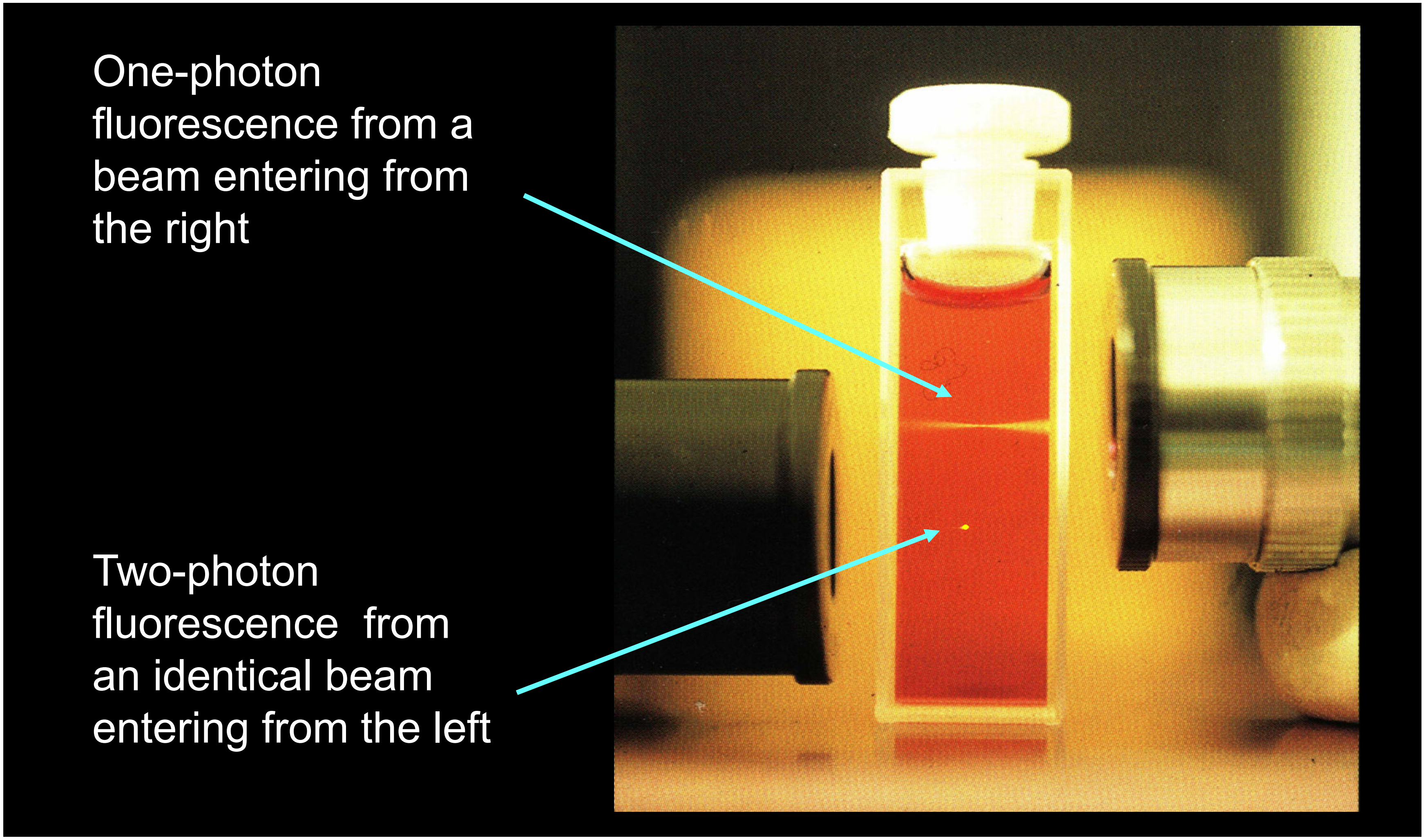
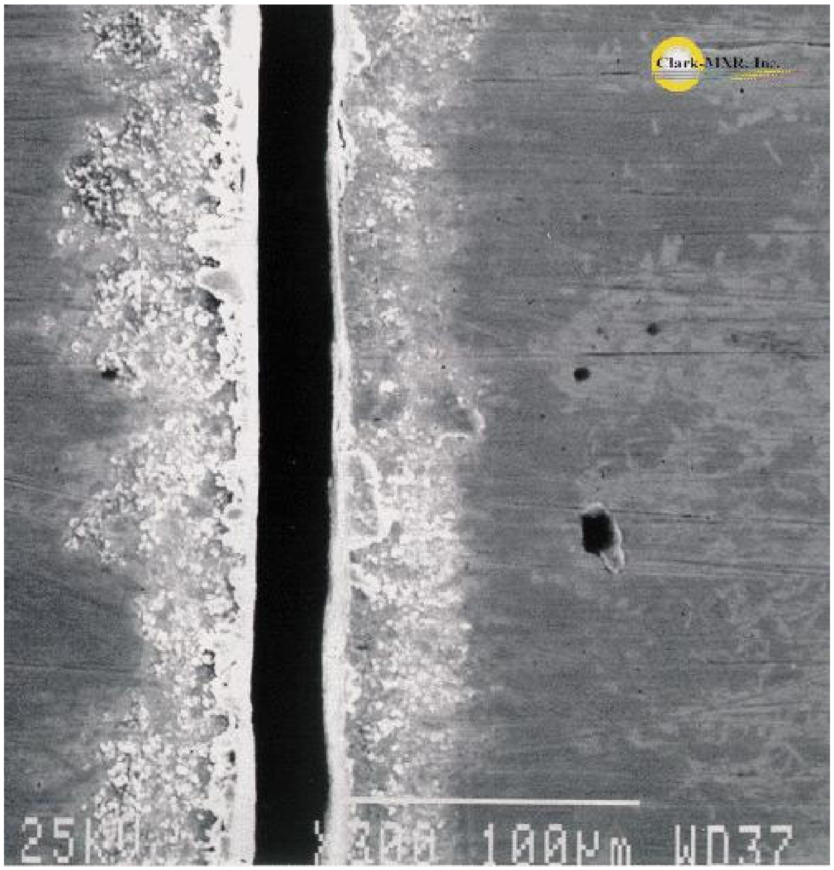
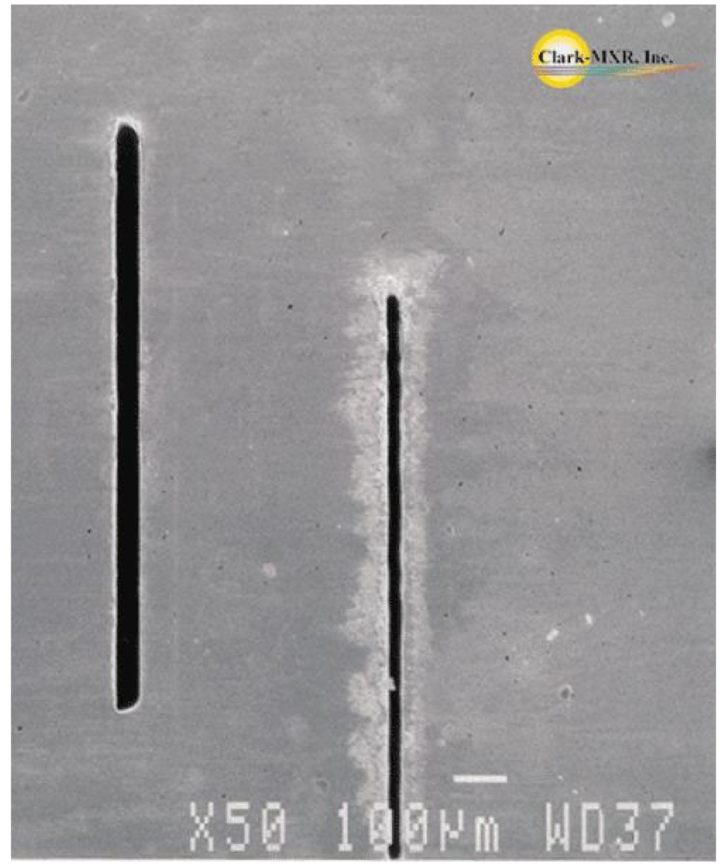


Image from Chris Schaffer, UCSD

Ultrashort pulses interact with materials differently



groove machined with nanosecond pulse



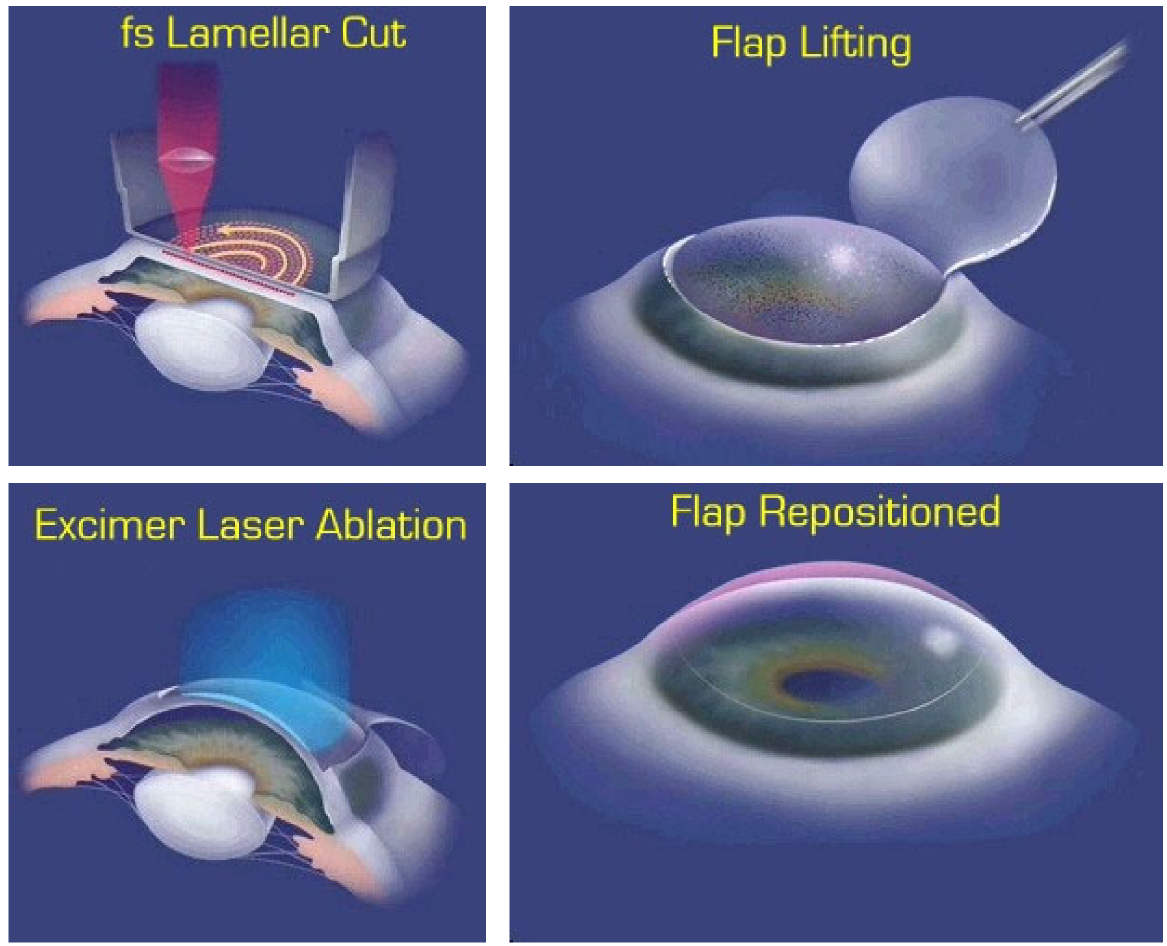
…and with femtosecond pulse

Clark MXR, Inc., Ann Arbor, MI

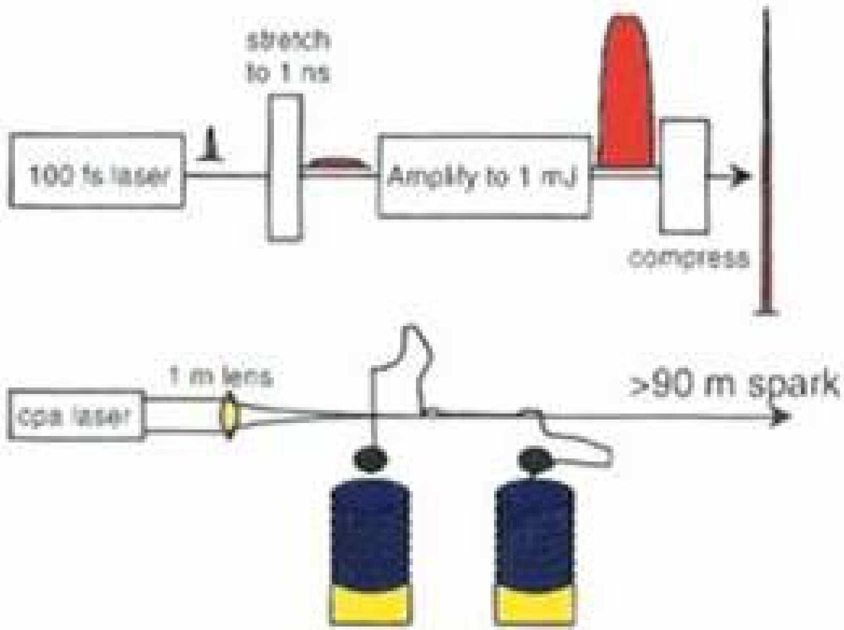
Ultrafast lasers make great scalpels!

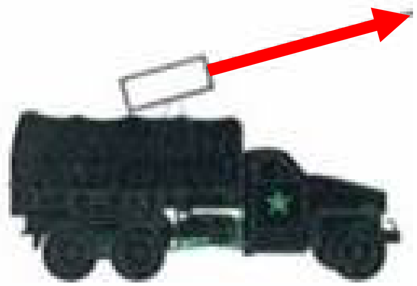
www.intralase.com

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



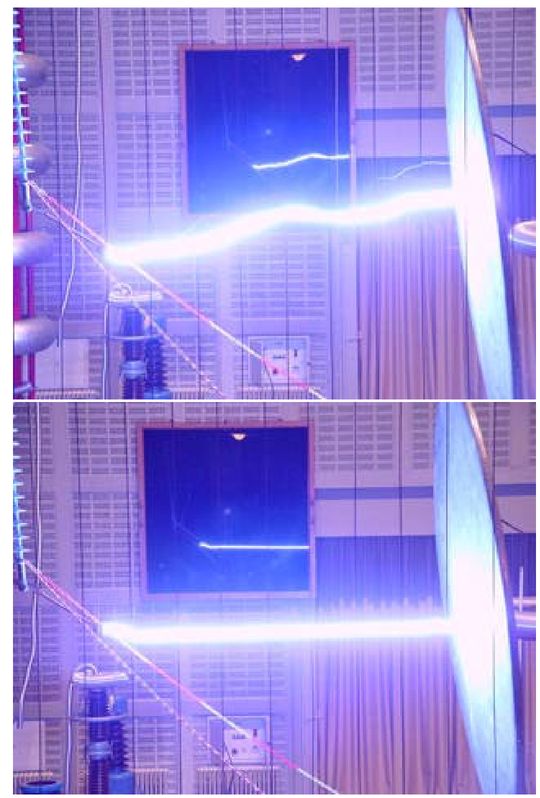
Lightning protection using amplified short pulses





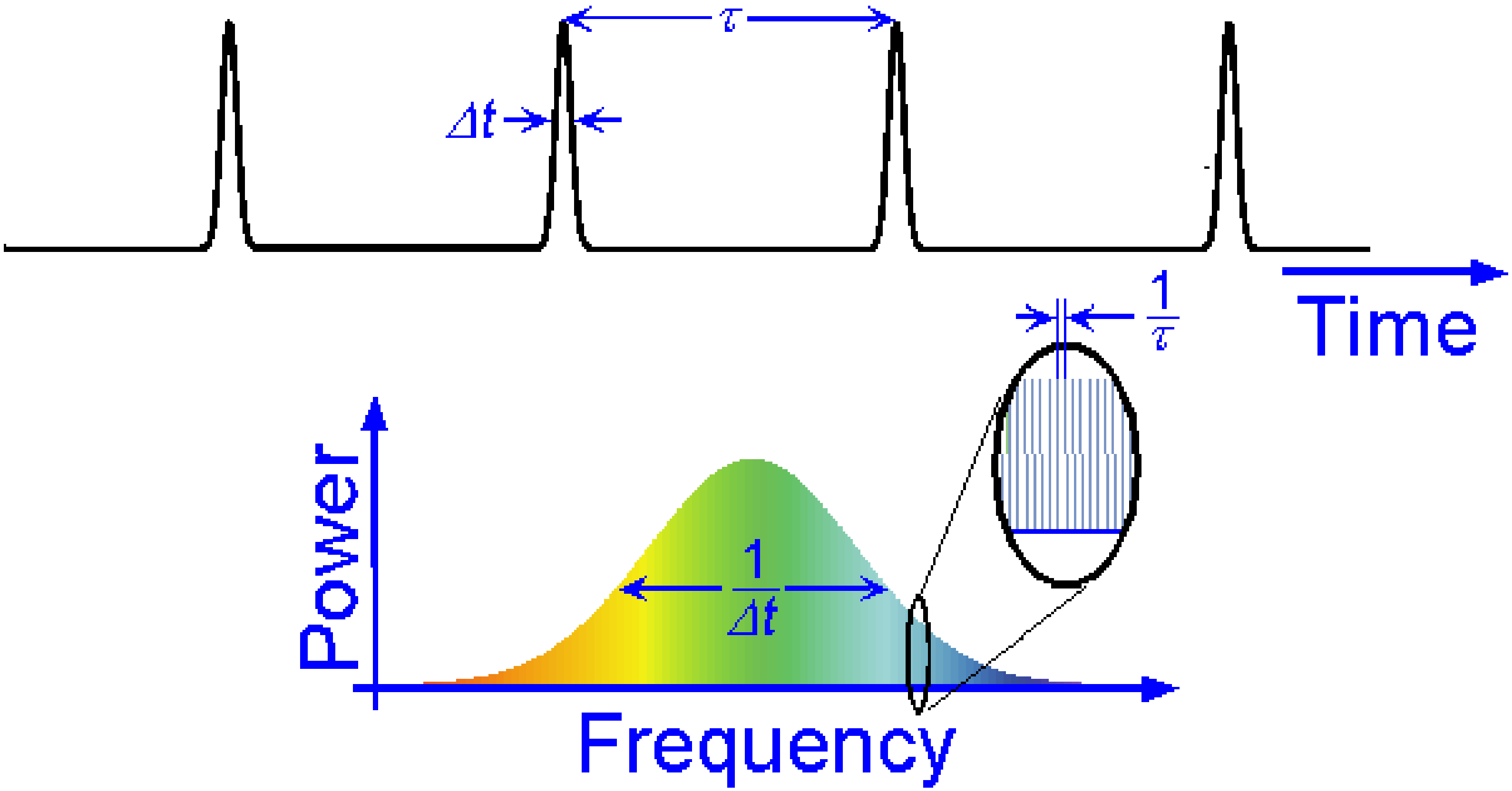
- Use amplified 100 fs pulses to initiate spark
- Self-trapped filament propagates >30 m in air !

guided and
unguided lightning



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}

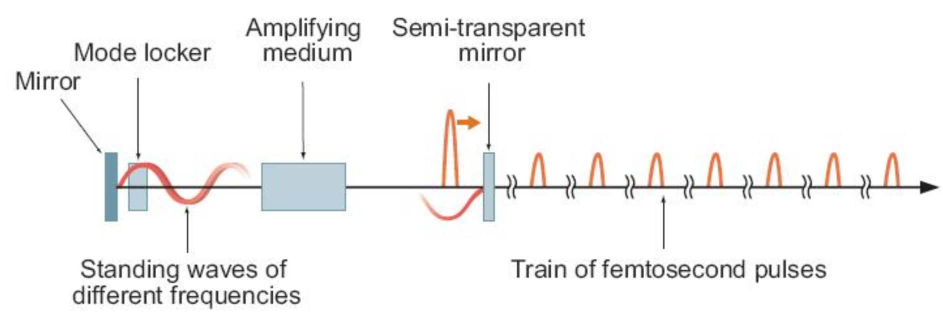
PRESS RELEASE 4 OCTOBER 2005

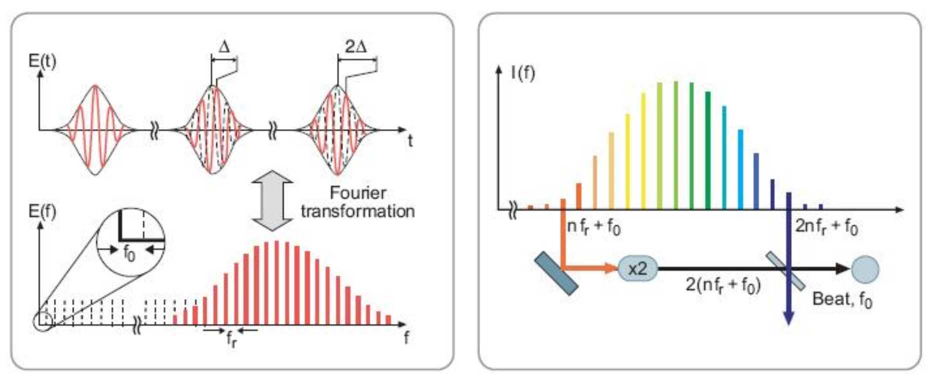
The Royal Swedish Academy of Sciences has awarded the 2005 Nobel Prize in Physics for 2005 with one half to

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*".





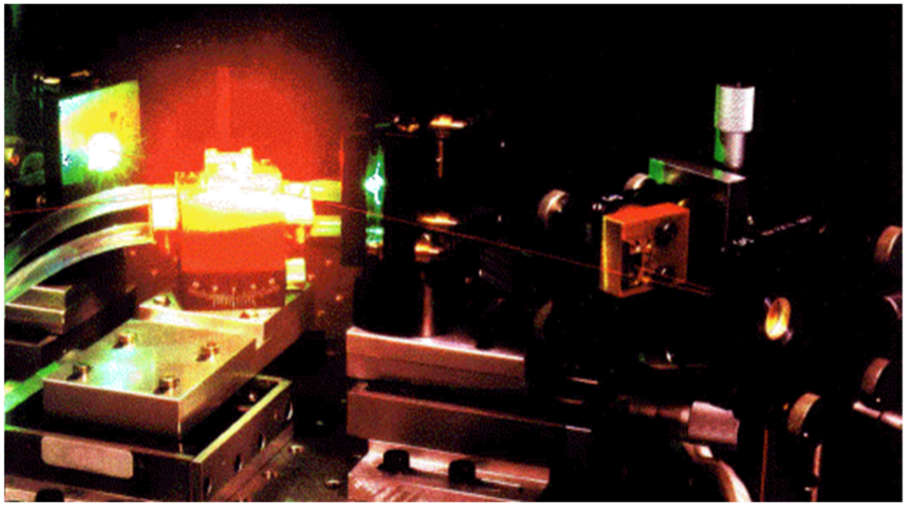
How does it work?

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.

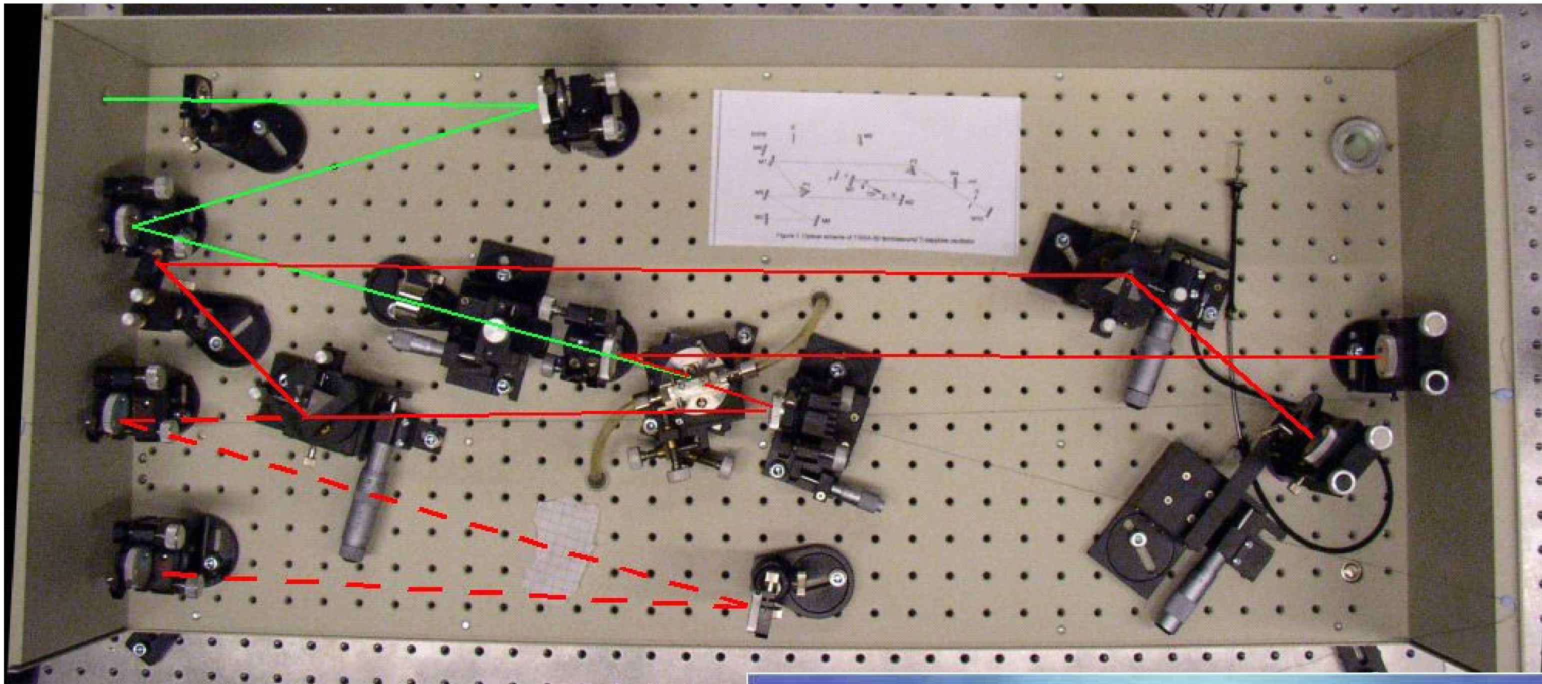
Our model system to learn all of this:

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: