ULTRAFAST OPTICS

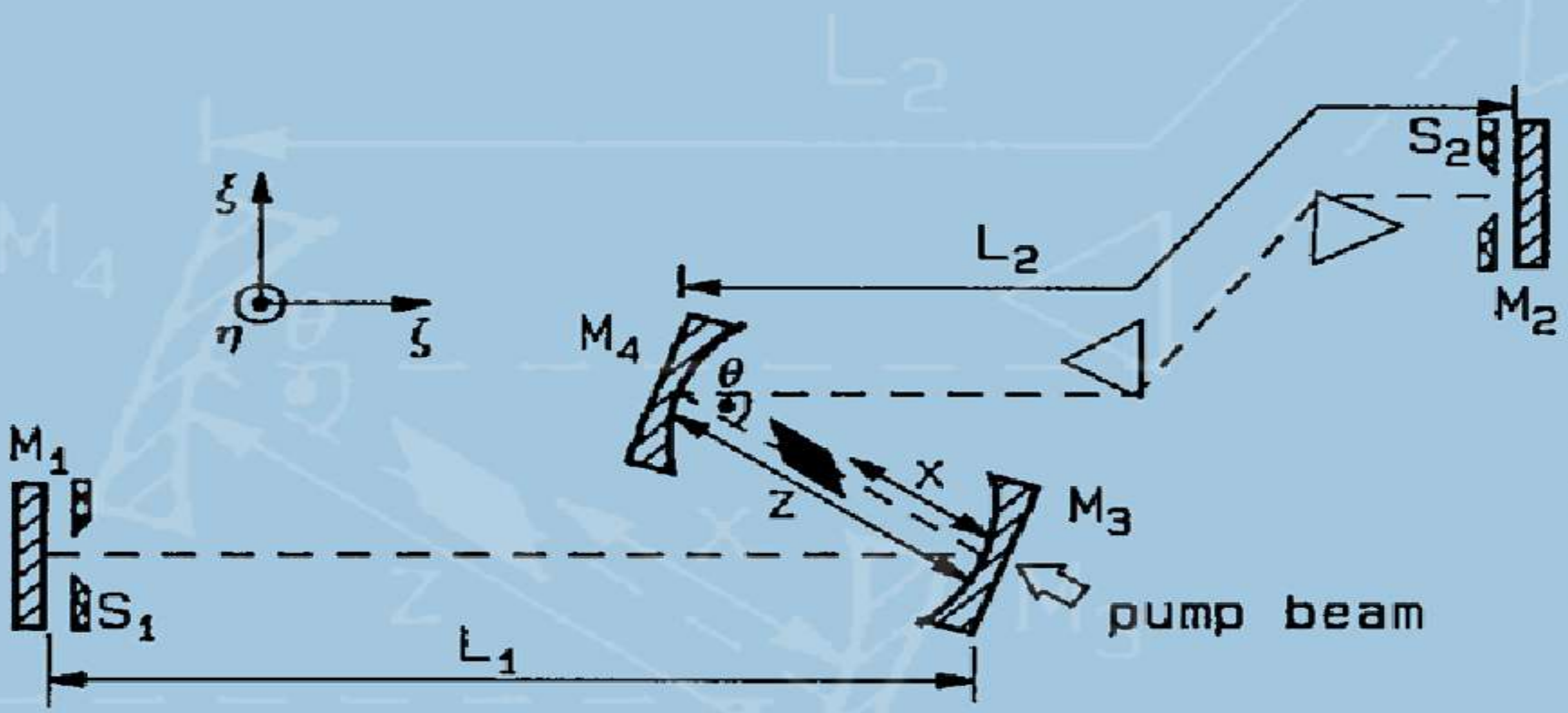


image from G. Cerullo et al., Opt. Lett. 19, 807 (1994), © OSA

by PIOTR WASYLCZYK

Ultrafast Optics /ˈʌl.trəfɑːst ˈɒp.tɪks /

The lecture concept and most slides prepared by Rick Trebino

(Pre)recorded lectures, problems and questions (and more) available at

http://www.optics.fuw.edu.pl/ultrafast-optics

No	Date (Wednesdays 12:00)	topic	type
1	21/10	Introduction to femtosecond optics	Live on-line
2	28/10	Short light pulses	Pre-recorded
3	4/11	Generation, modelocking	Pre-recorded
4	12/11	Amplification (laser, parametric)	Pre-recorded
5	18/11 – this is „Wednesday”!	**Summary,** ultrafast spectroscopy	Live on-line
6	25/11	Dispersion, pulse propagation	Pre-recorded
7	2/12	Pulse shaping	Pre-recorded
8	9/12	Nonlinear optics	Pre-recorded
9	16/12	**Summary,** coherent control	Live on-line
10	8/1 – this is „Wednesday”!	2nd/3rd order effects, Phase matching	Pre-recorded
11	13/1	Autocorrelation, FROG	Pre-recorded
12	20/1	SPIDER	Pre-recorded
13	27/1	**Summary,** atto pulses, material processing	Live on-line
14			

Ultrafast Optics—Introduction

The birth of ultrafast optics

Ultrahigh intensity

The uncertainty principle and long vs. short pulses

Generic ultrashort-pulse laser

Mode-locking and mode-locking techniques

Group-velocity dispersion (GVD)

Compensating GVD with a pulse compressor

Continuum generation

Measuring ultrashort pulses

The shortest event ever created

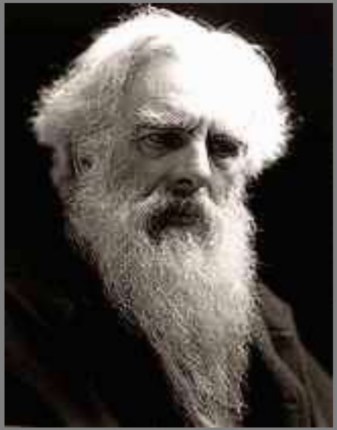
Ultrafast spectroscopy

Medical imaging

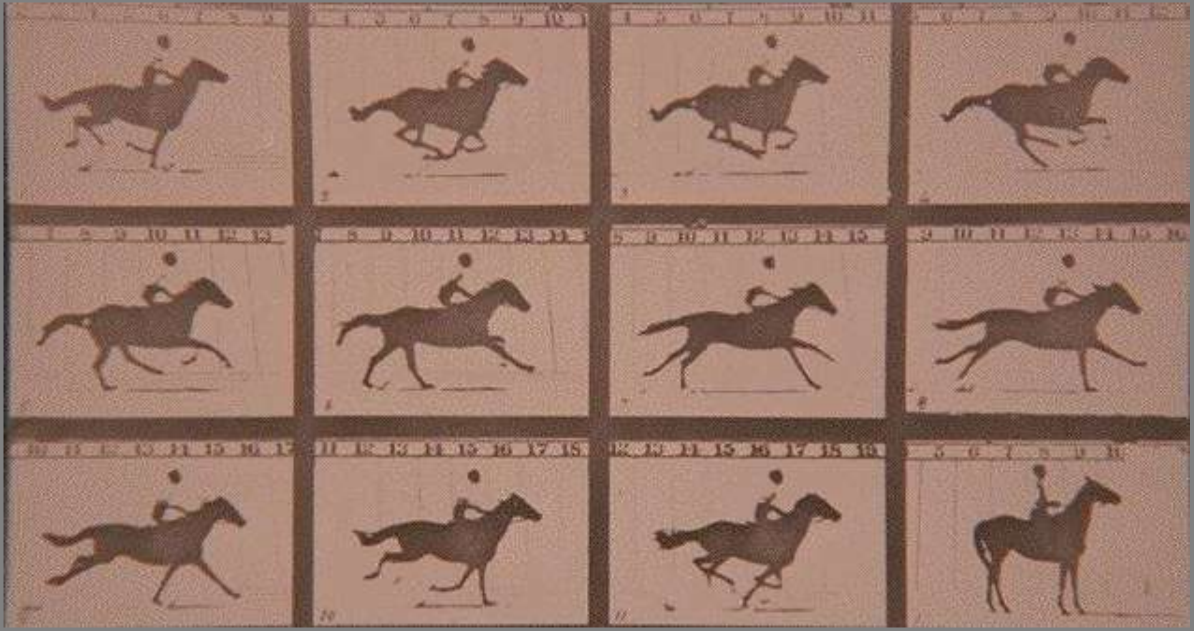
The birth of ultrafast technology

Bar bet: Do all four hooves of a galloping horse ever simultaneously leave the ground?

Leland Stanford



Eadweard Muybridge



The “Galloping Horse” Controversy

Palo Alto, CA 1872

Time resolution:
1/60th of a second

If you think you know fast, think again.

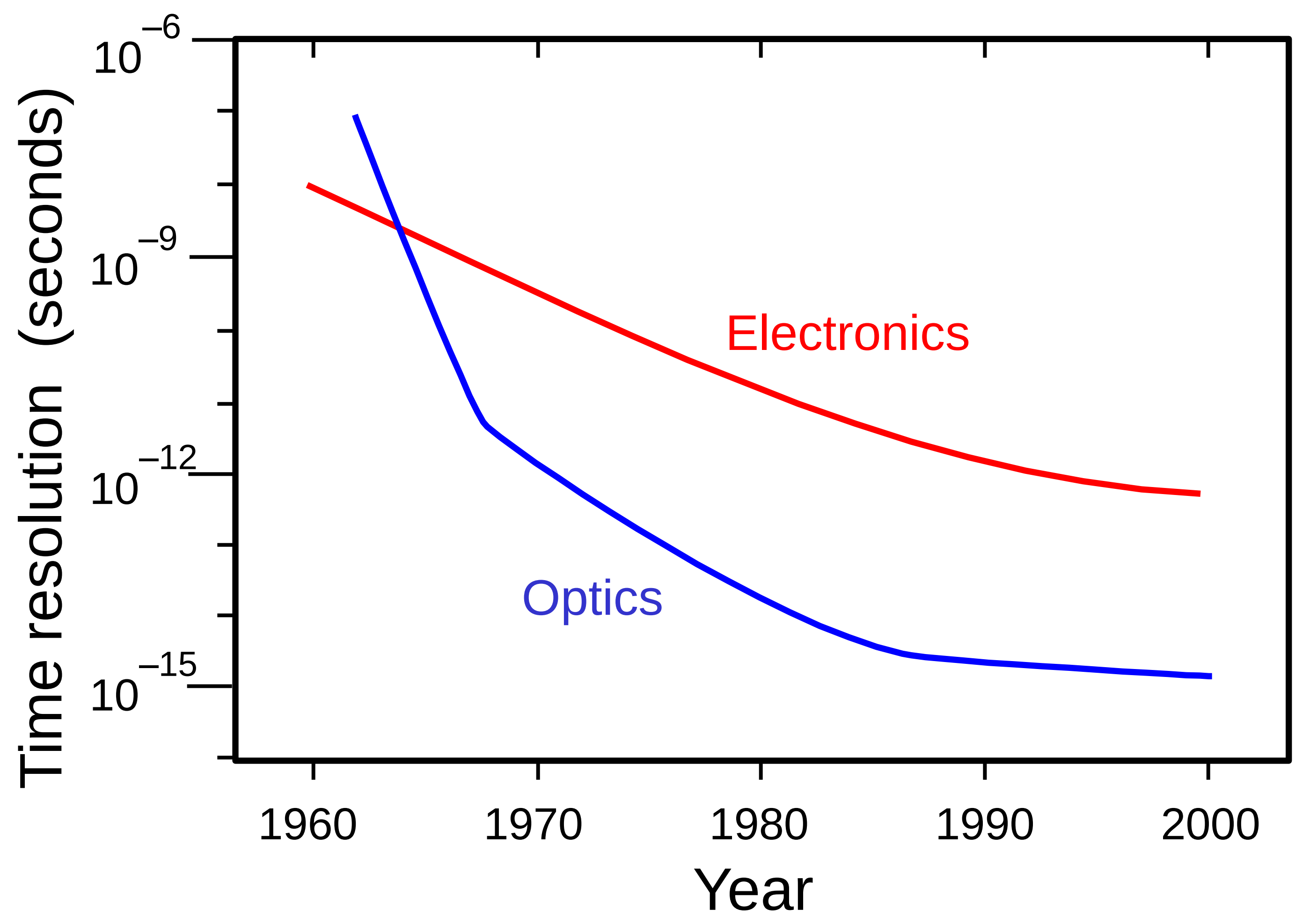
Ultrashort laser pulses are the shortest events ever created.

The current record (in the far UV) is

below 100 as

(attoseconds).

Ultrafast optics vs. electronics



No one expects electronics to ever catch up.

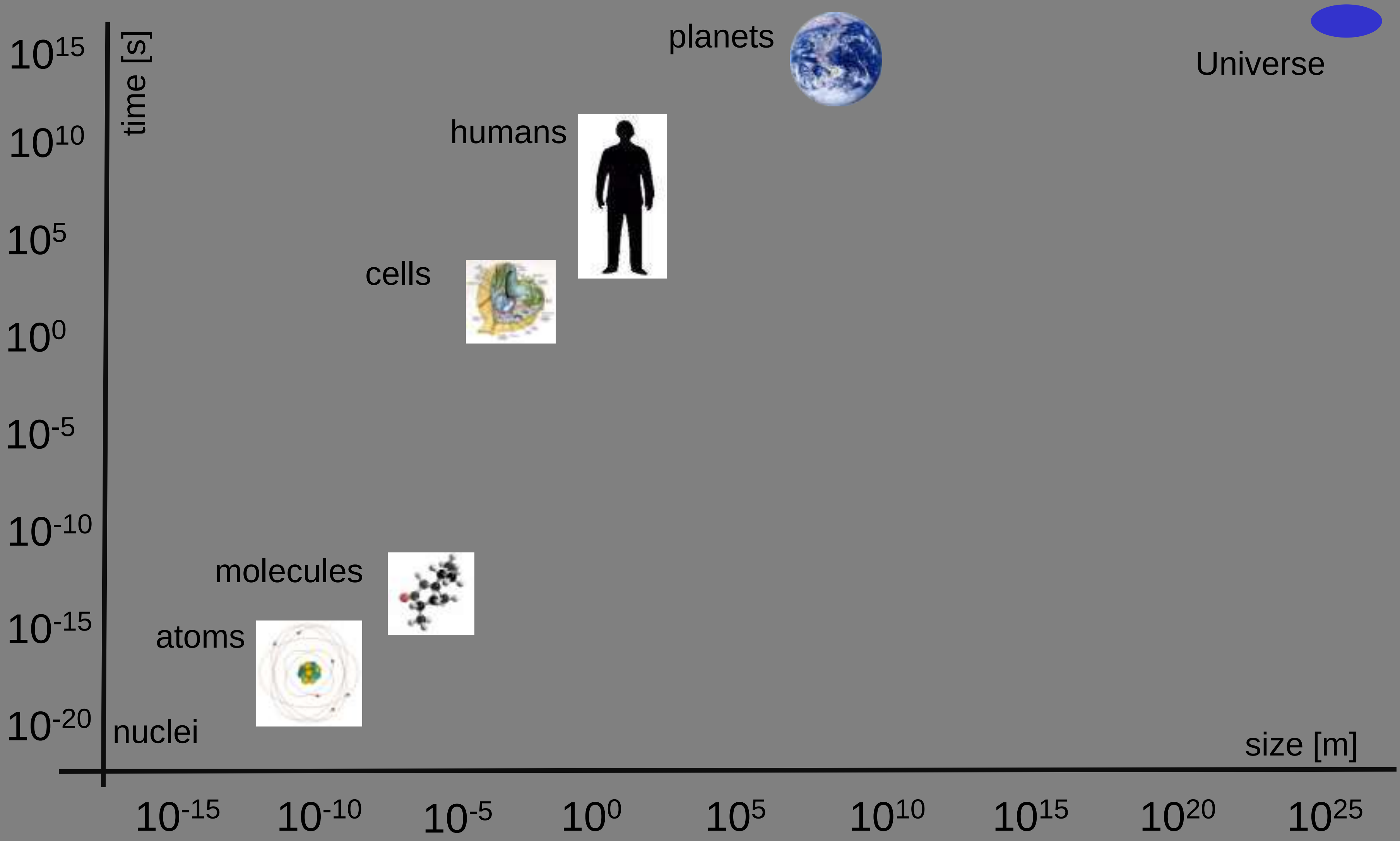
The metric system

We'll need to really know the metric system because the pulses are incredibly short and the powers and intensities can be incredibly high.

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}

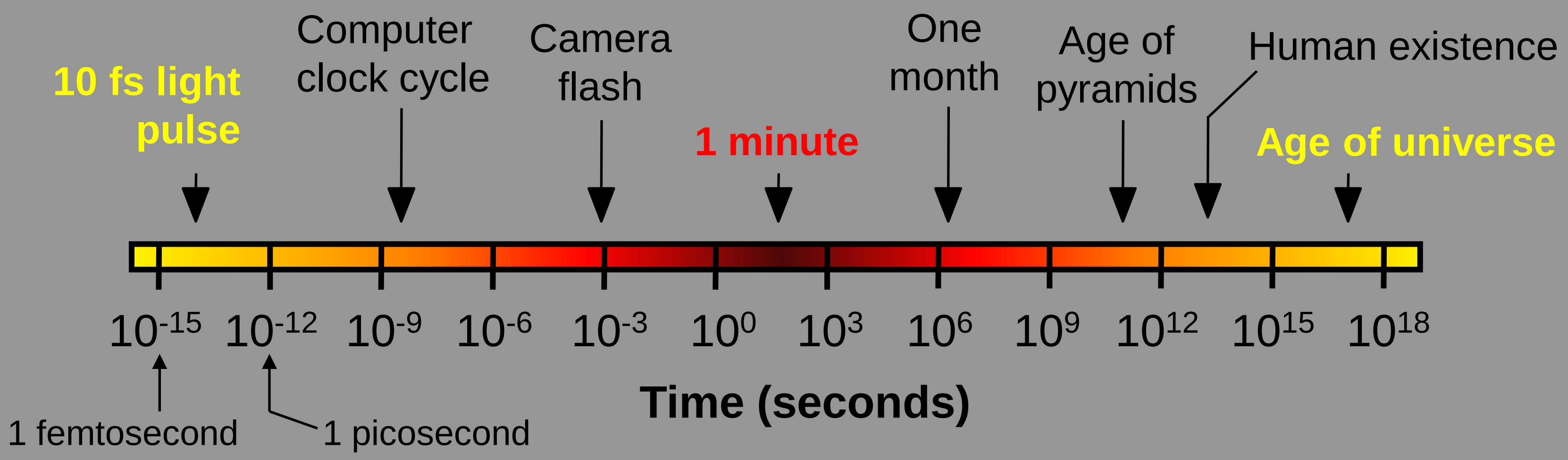
Time and space in the Universe



Timescales

It’s routine to generate pulses well below 1 picosecond (10^{-12} s).

Researchers generate pulses a few femtoseconds (10^{-15} s) long.



10 fs light pulse

Computer clock cycle

Camera flash

1 minute

One month

Age of pyramids

Human existence

Age of universe

10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 10^{0} 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18}

1 femtosecond

1 picosecond

Time (seconds)

Such a pulse is to one minute as one minute is to the age of the universe.

Strobe photography

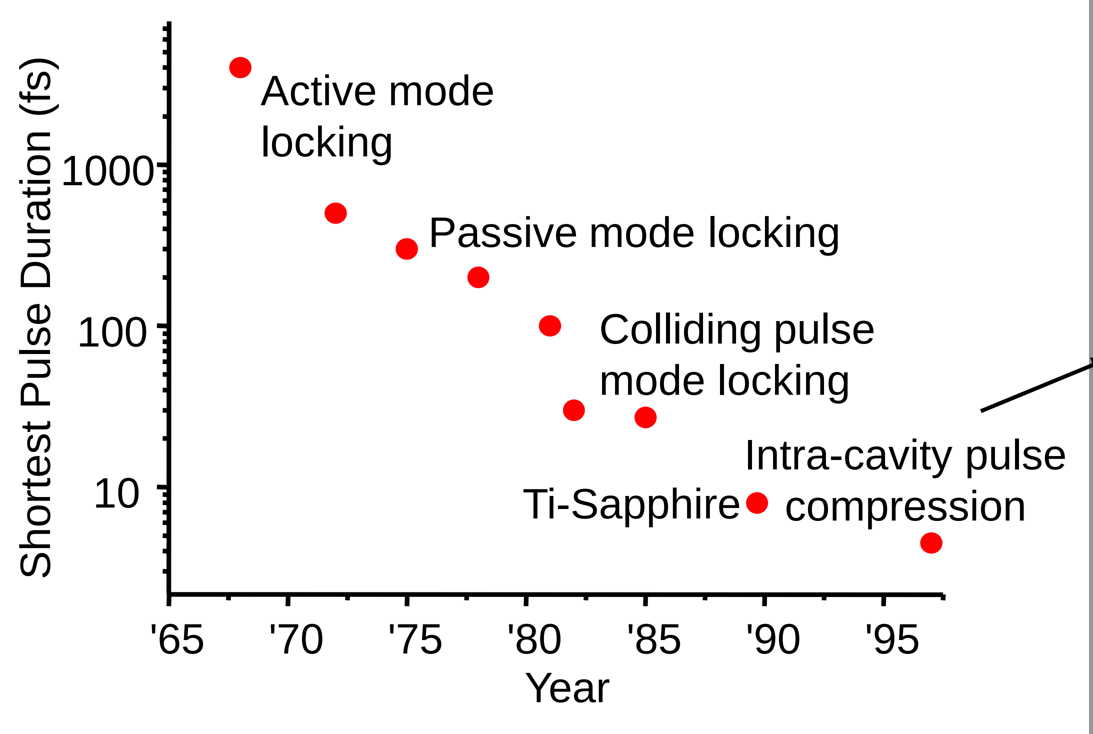
Harold
Edgerton
MIT, 1942

“How to Make
Apple sauce
at MIT”
1964

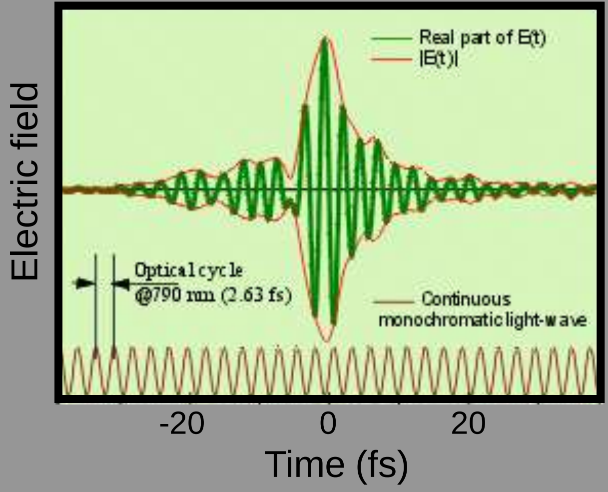
“Splash on a
Glass”
Junior High
School
student
1996

Time resolution: a few microseconds

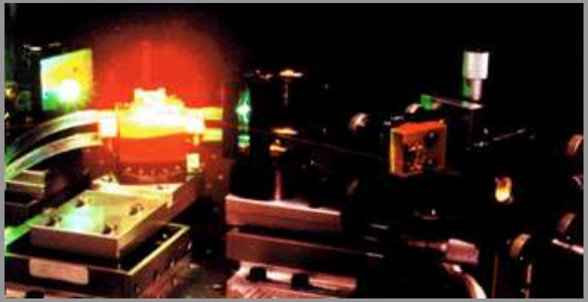
Ultrafast lasers



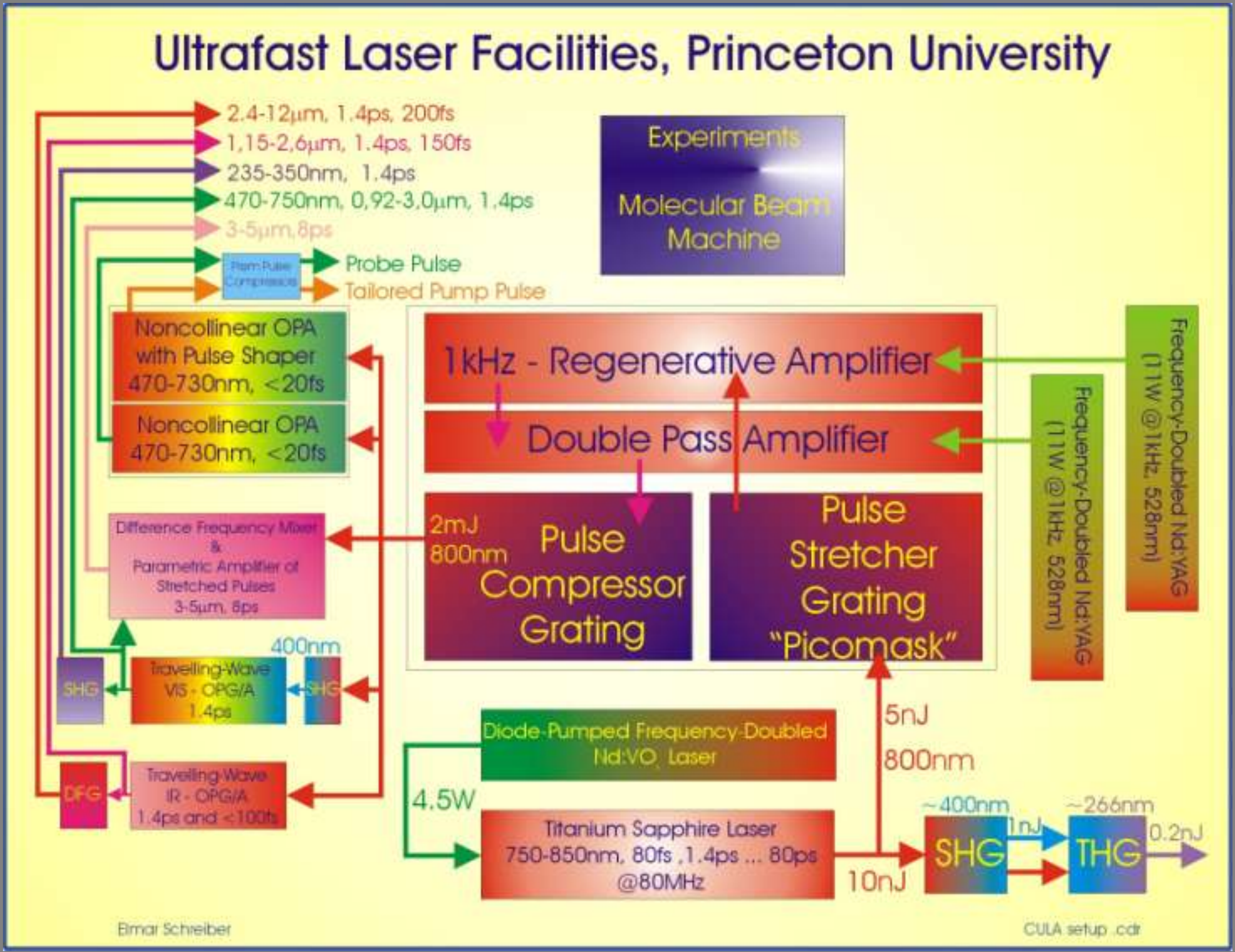
The electric field of a 4.5-fs pulse



Ultrafast Ti:sapphire laser

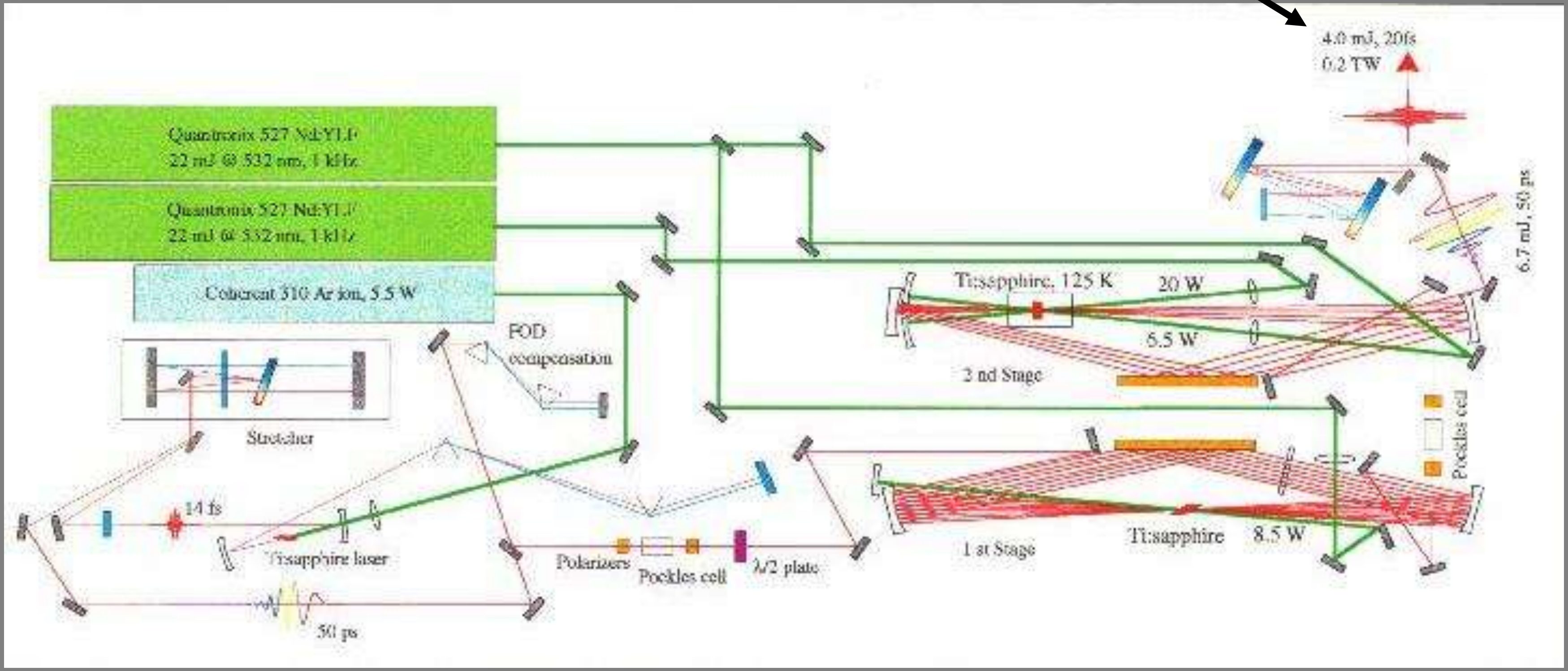


Ultrafast set-ups can be very sophisticated



The highest intensities imaginable

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



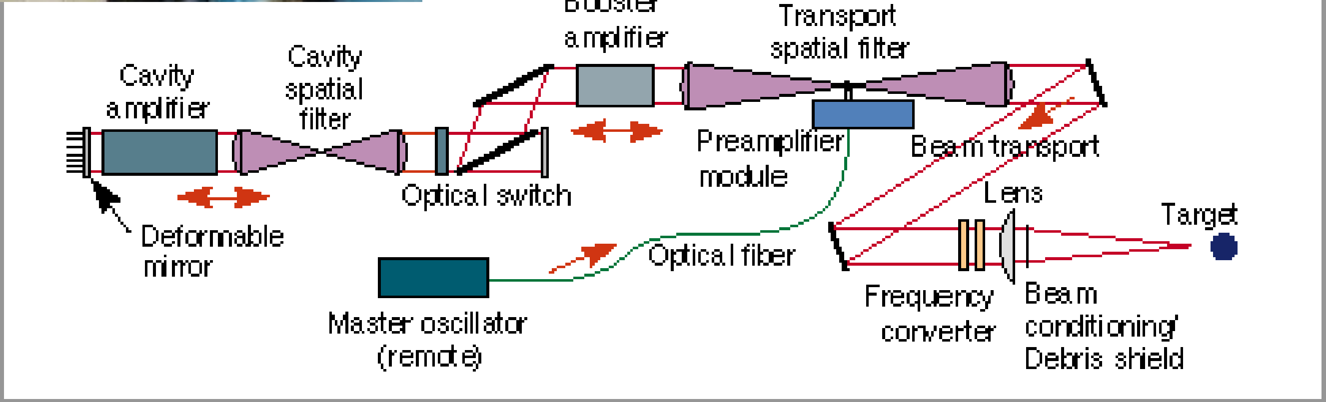
1 kHz “Chirped-Pulse Amplification (CPA)” system at the University of Colorado (Murnane and Kapteyn)

Even higher intensities!

Nova

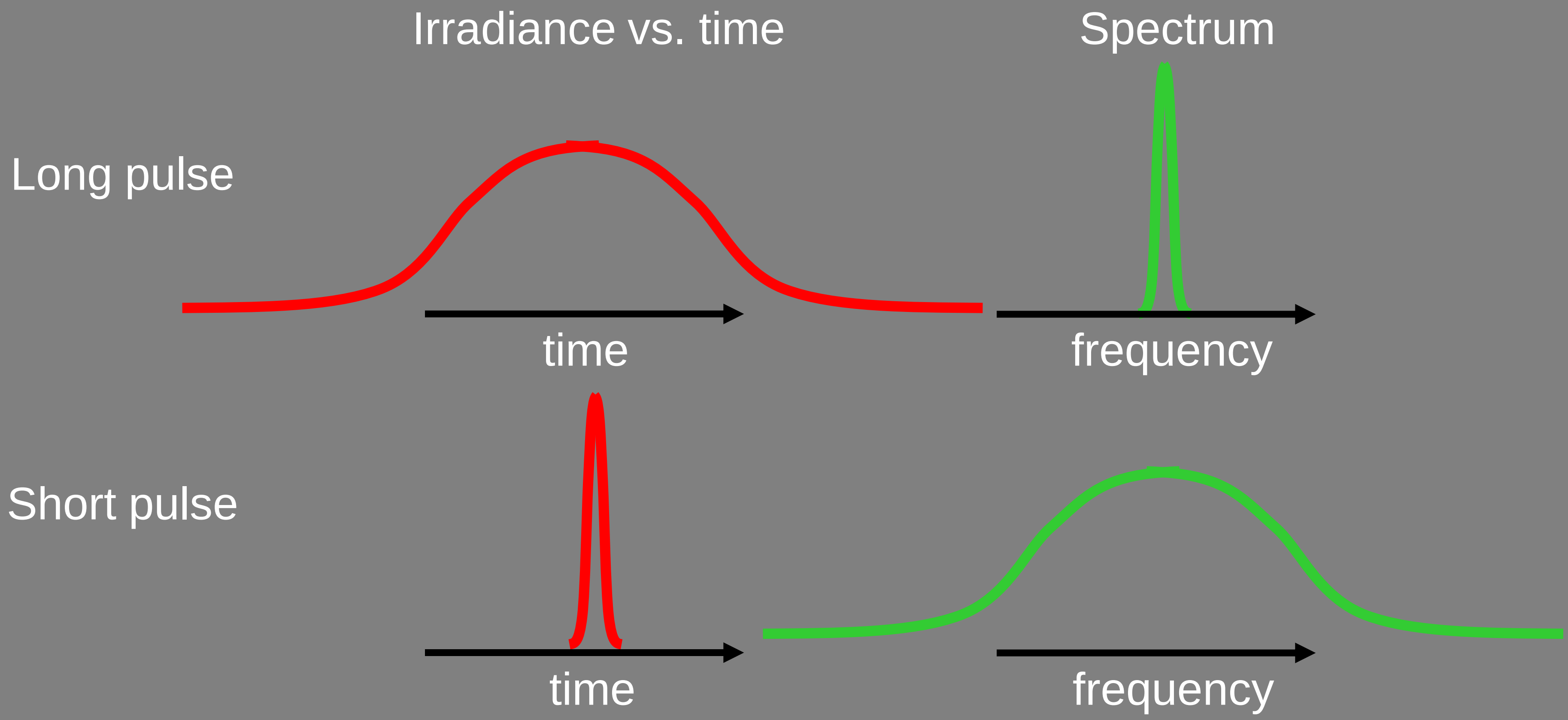
National Ignition Facility (under construction)

192 shaped pulses; 1.8 MJ total energy



Long vs. short pulses of light

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



Irradiance vs. time

Spectrum

Long pulse

time

frequency

Short pulse

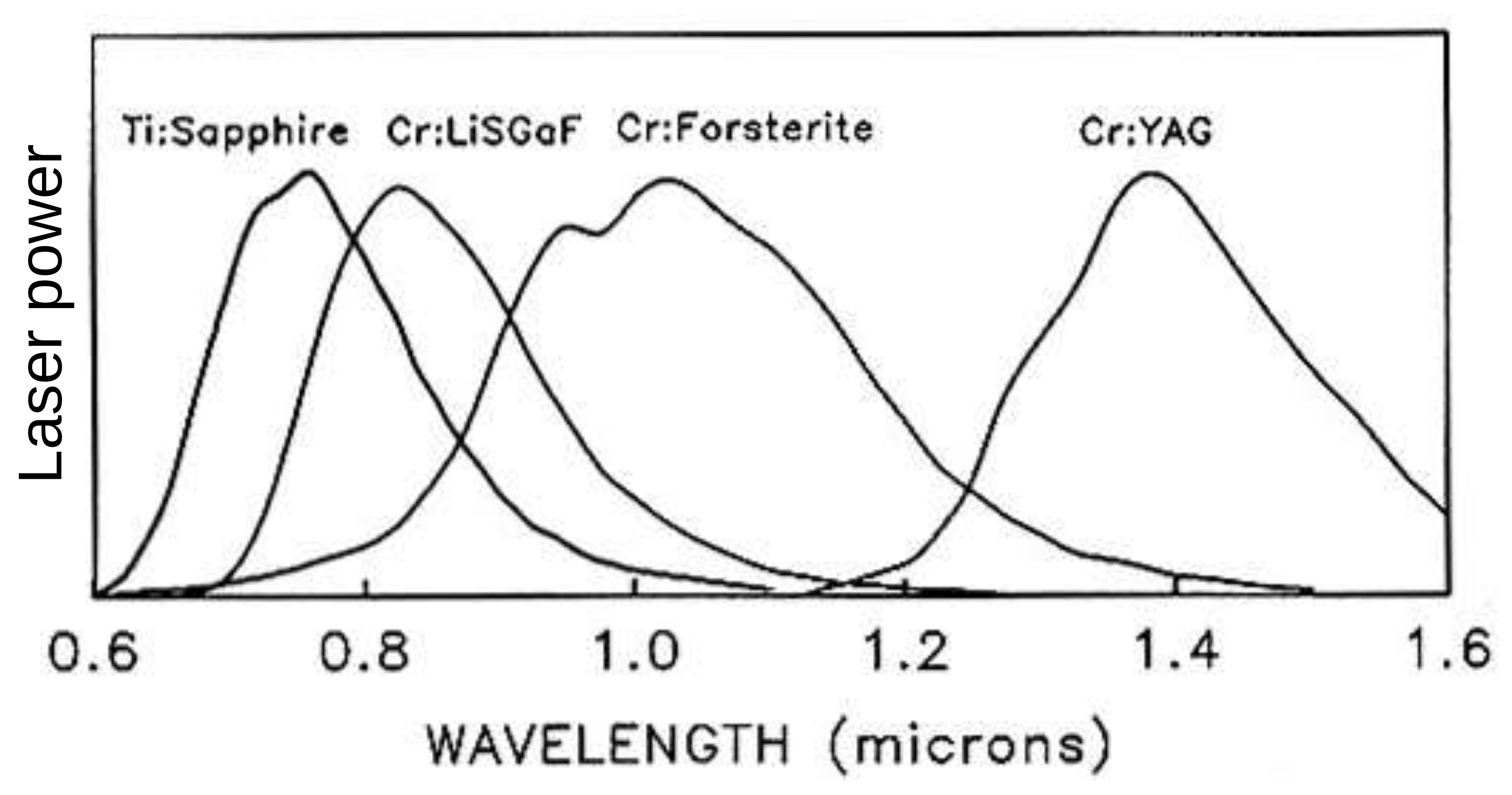
time

frequency

Rule of thumb: for 100 fs (NIR) you need 10 nm of bandwidth

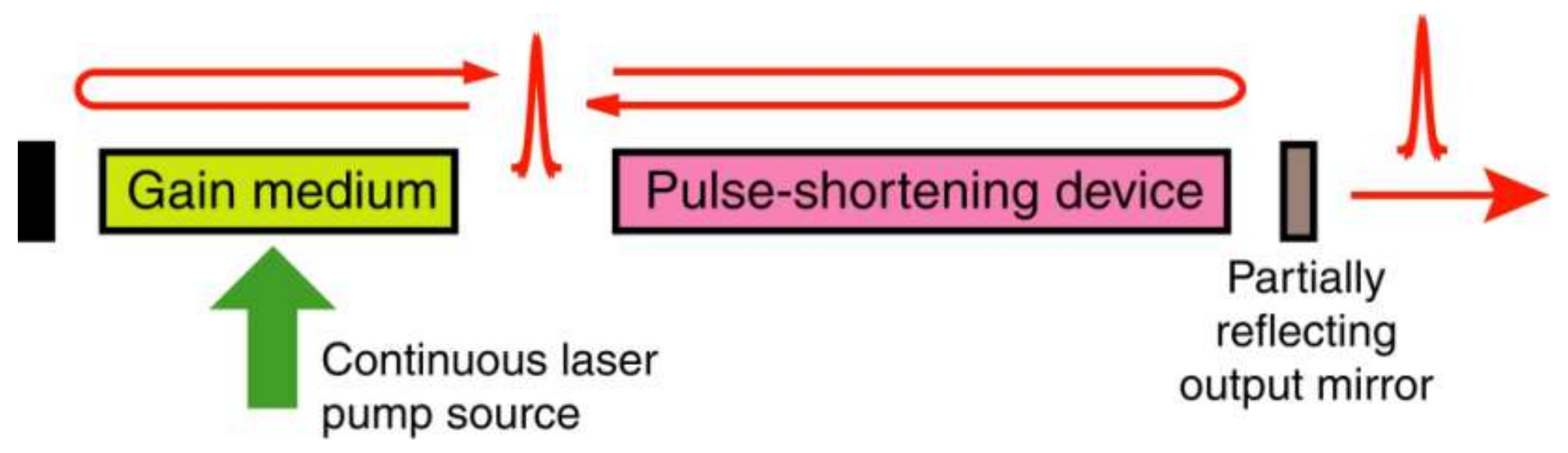
Ultrafast laser media

Solid-state laser media have broad bandwidths and are convenient.



A generic ultrashort-pulse laser

A generic ultrafast laser has a broadband gain medium, a pulse-shortening device, and two or more mirrors:

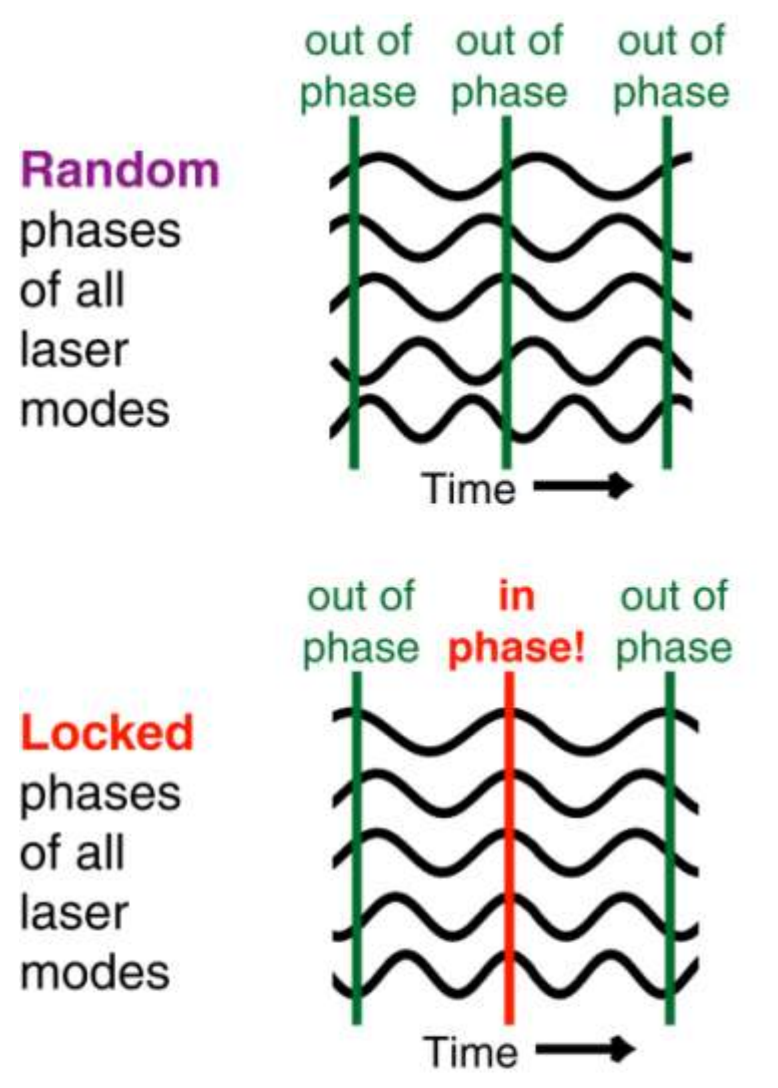


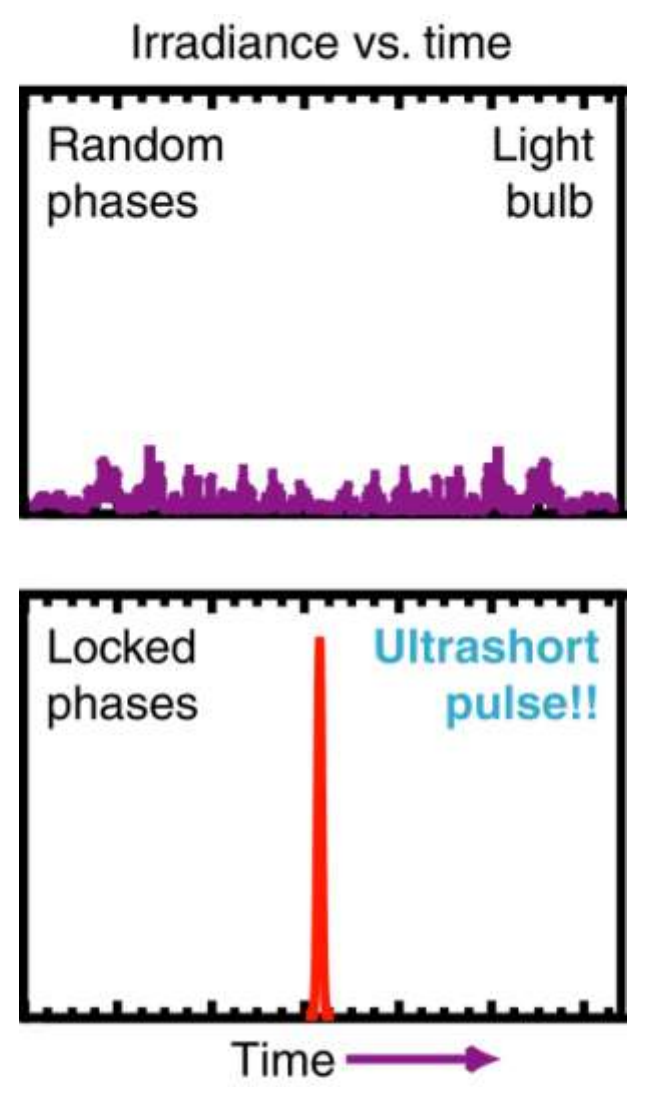
Pulse-shortening devices include:

- Saturable absorbers
- Phase modulators
- Dispersion compensators
- Optical-Kerr media

Generating short pulses = “mode-locking”

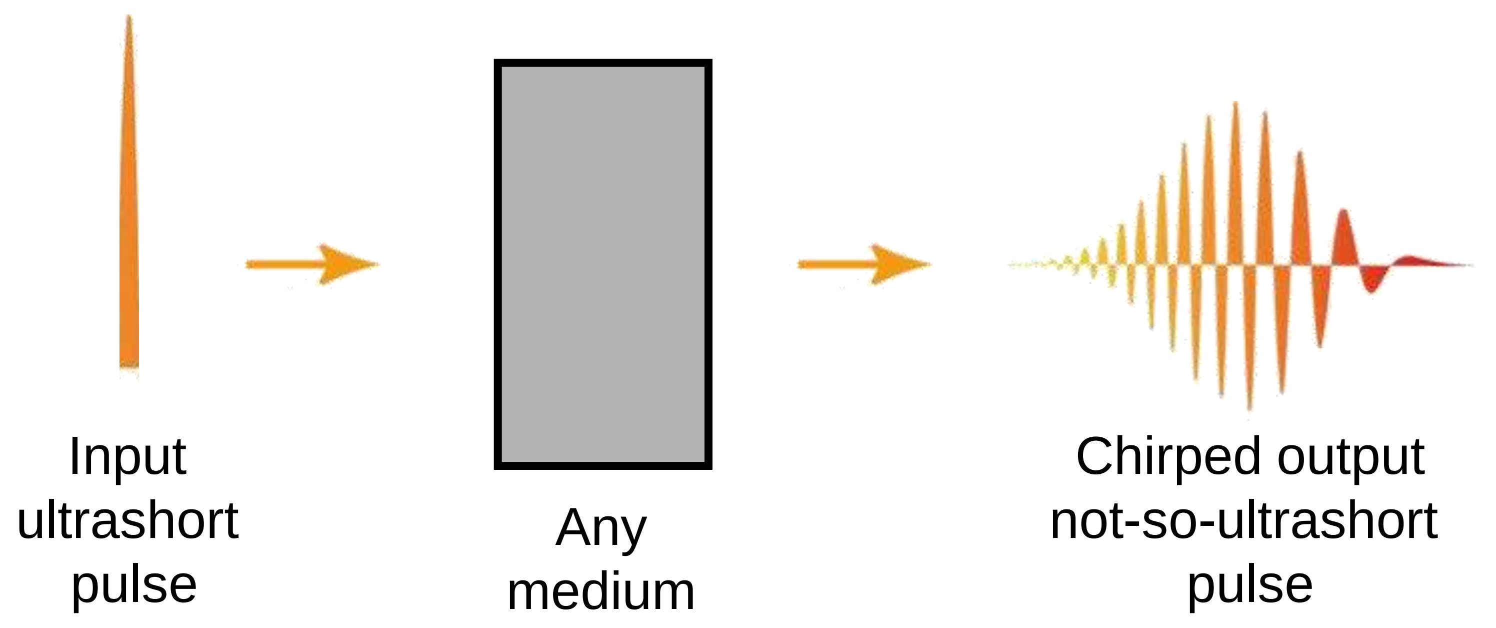
Locking the phases of the laser frequencies yields an ultrashort pulse.





Group velocity dispersion (GVD) broadens ultrashort laser pulses

Different frequencies travel at different group velocities in materials, causing pulses to expand to highly "chirped" (frequency-swept) pulses.



Input ultrashort pulse

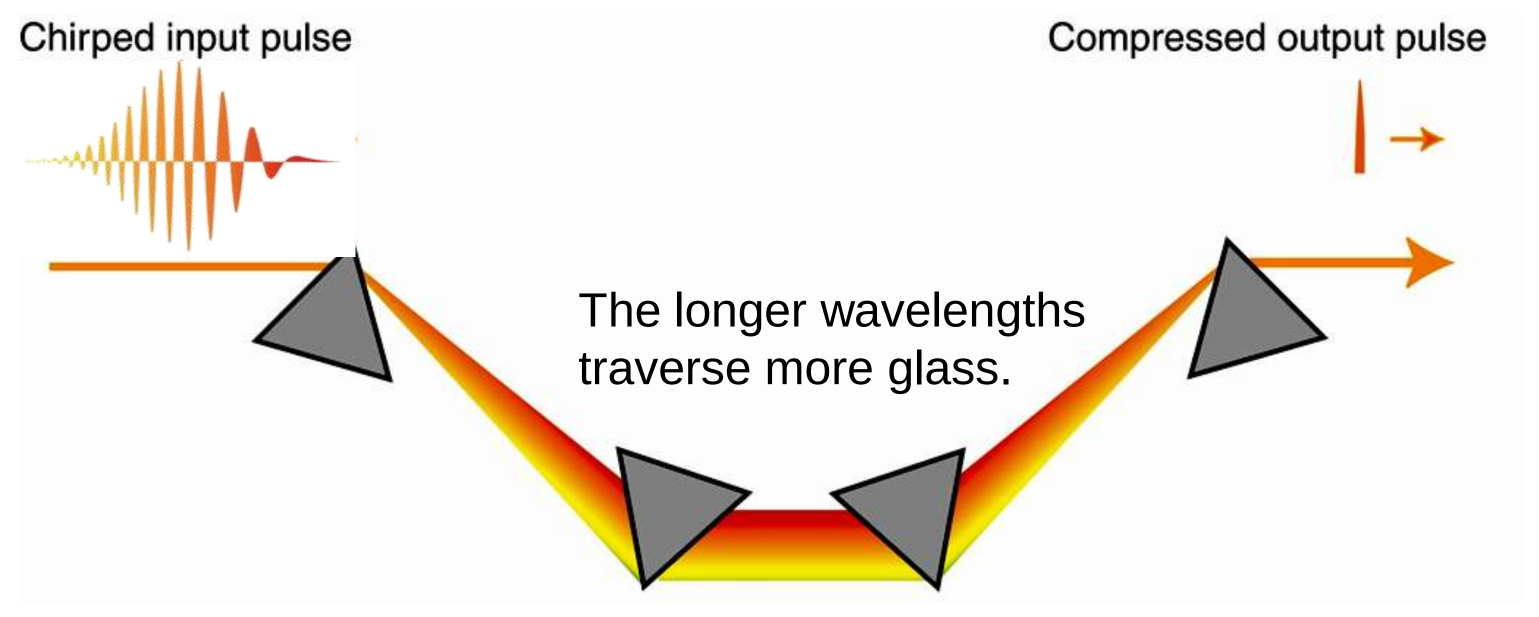
Any medium

Chirped output not-so-ultrashort pulse

Longer wavelengths almost always travel faster than shorter ones.

Pulse compressor

This device has negative group-velocity dispersion and hence can compensate for propagation through materials (i.e., for positive chirp).



The longer wavelengths traverse more glass.

It’s routine to stretch and then compress ultrashort pulses by factors of >1000.

Ultrafast optics is nonlinear optics.

At high intensities, nonlinear-optical effects occur.

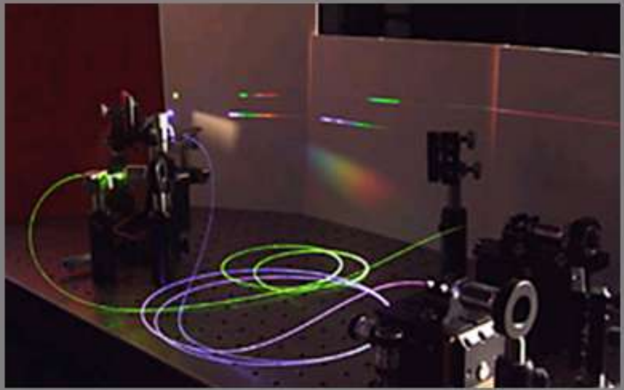
All mode-locking techniques are nonlinear-optical.

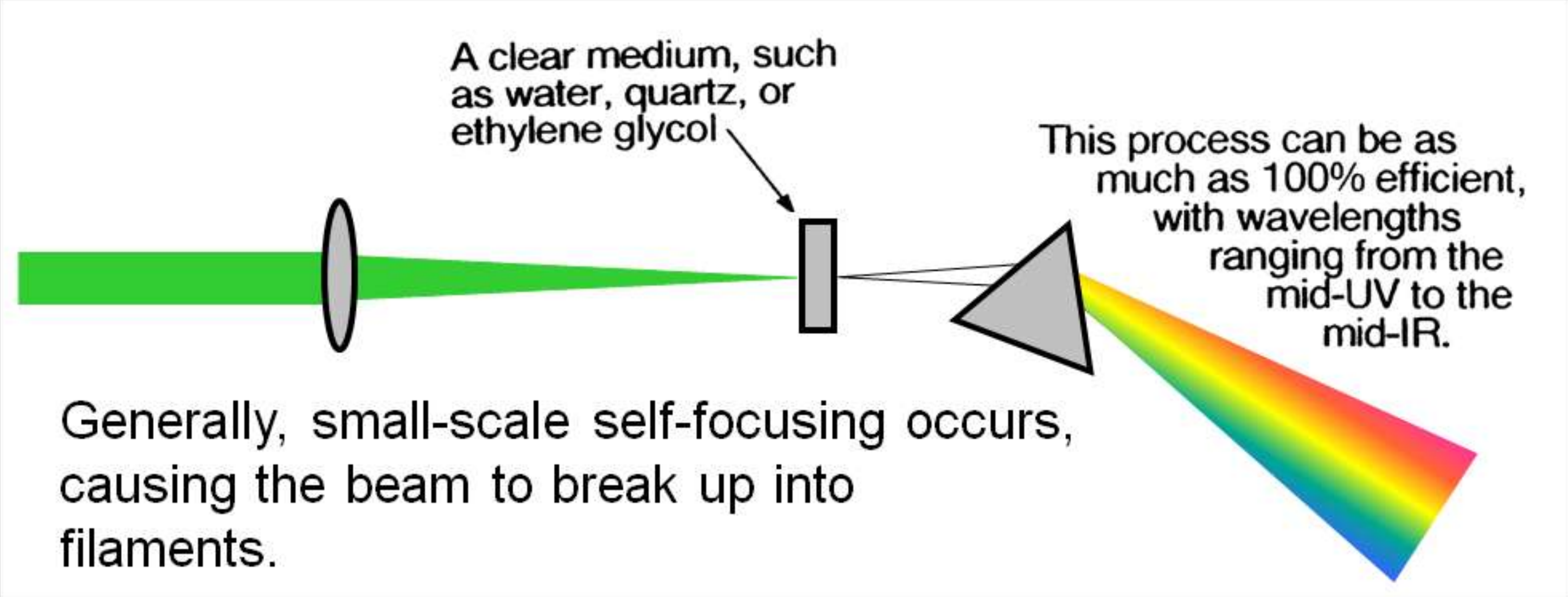
Creating new colors of laser light requires nonlinear optics.

Second-harmonic-generation of infrared light yields this beautiful display of intense green light.

Continuum generation

Continuum Generation: focusing a femtosecond pulse into a clear medium turns the pulse white.





A clear medium, such as water, quartz, or ethylene glycol

This process can be as much as 100% efficient, with wavelengths ranging from the mid-UV to the mid-IR.

Generally, small-scale self-focusing occurs, causing the beam to break up into filaments.

Recently developed techniques involving optical fibers, hollow fibers, and microstructure fibers produce very broadband continuum, over 500 THz (1000 nm) in spectral width!

The Dilemma

In order to measure an event in time, you need a *shorter* one.

To study this event, you need a strobe light pulse that's shorter.

But then, to measure the strobe light pulse, you need a detector whose response time is even shorter.

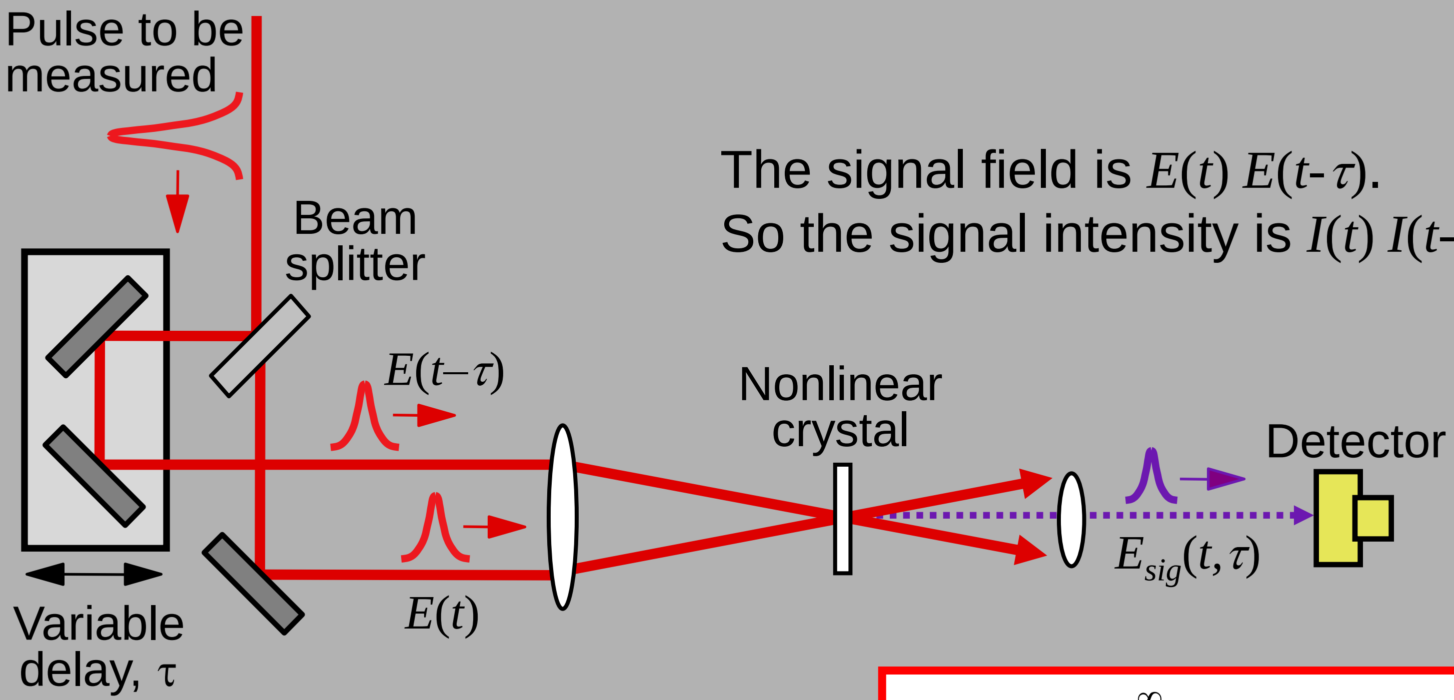
And so on…

So, now, how do you measure the *shortest* event?

Using the pulse to measure itself: The Intensity Autocorrelator

Crossing beams in a nonlinear-optical crystal, varying the delay between them, and measuring the signal pulse energy vs. delay, yields the **Intensity Autocorrelation, $A^{(2)}(\tau)$**.

The signal field is $E(t)\,E(t\text{-}\tau)$.
So the signal intensity is $I(t)\,I(t\text{-}\tau)$



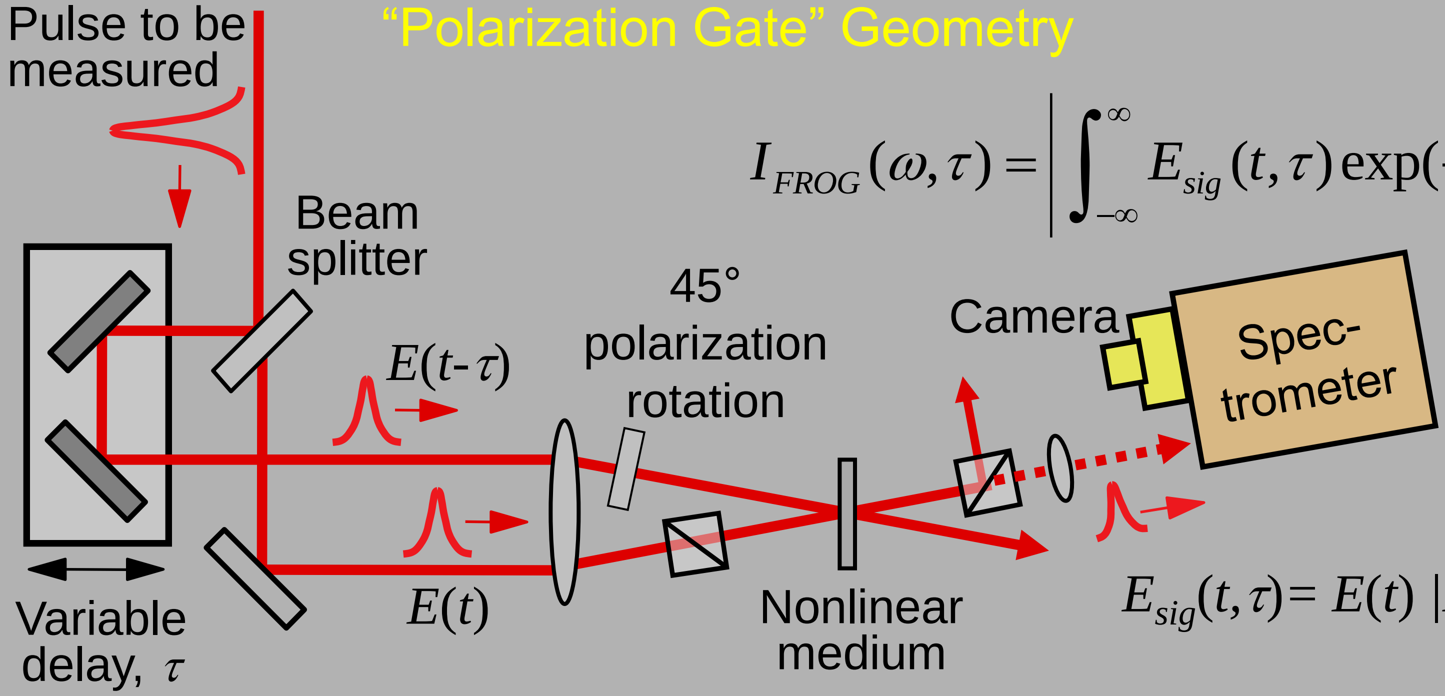
The Intensity Autocorrelation:

$$\boxed{A^{(2)}(\tau) \equiv \int_{-\infty}^{\infty} I(t)\,I(t-\tau)\,dt}$$

Frequency-Resolved Optical Gating (FROG)

FROG involves gating the pulse with a variably delayed replica of itself in an instantaneous nonlinear-optical medium and then spectrally resolving the gated pulse vs. delay.

"Polarization Gate" Geometry



Pulse to be measured

Beam splitter

Variable delay, τ

$E(t-\tau)$

$E(t)$

45° polarization rotation

Nonlinear medium

Camera

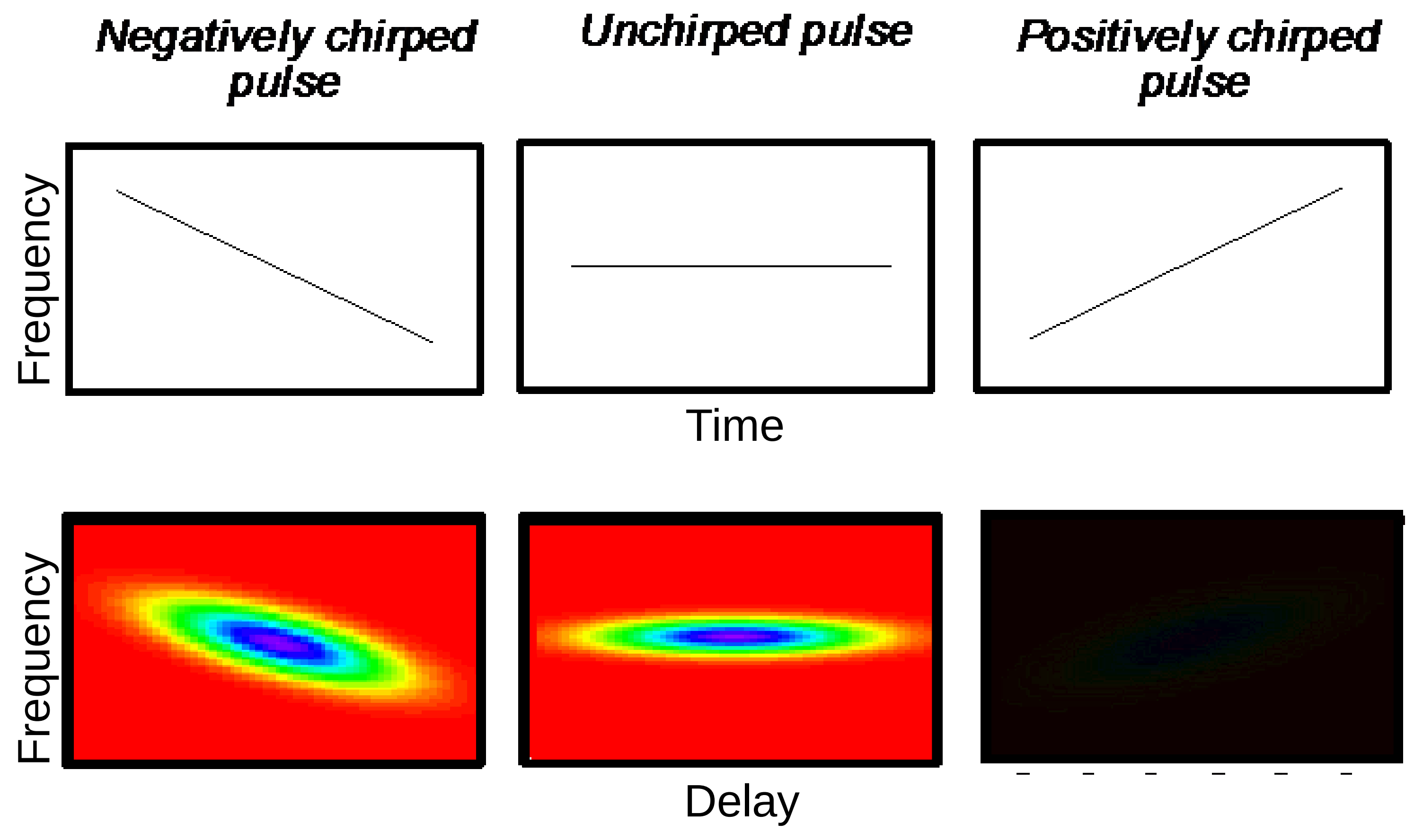
Spec-trometer

$$I_{FROG}(\omega,\tau) = \left| \int_{-\infty}^{\infty} E_{sig}(t,\tau)\exp(-i\omega t)\,dt \right|^2$$

$$E_{sig}(t,\tau) = E(t)\,|E(t-\tau)|^2$$

Use any ultrafast nonlinearity: Second-harmonic generation, etc.

FROG traces for linearly chirped pulses

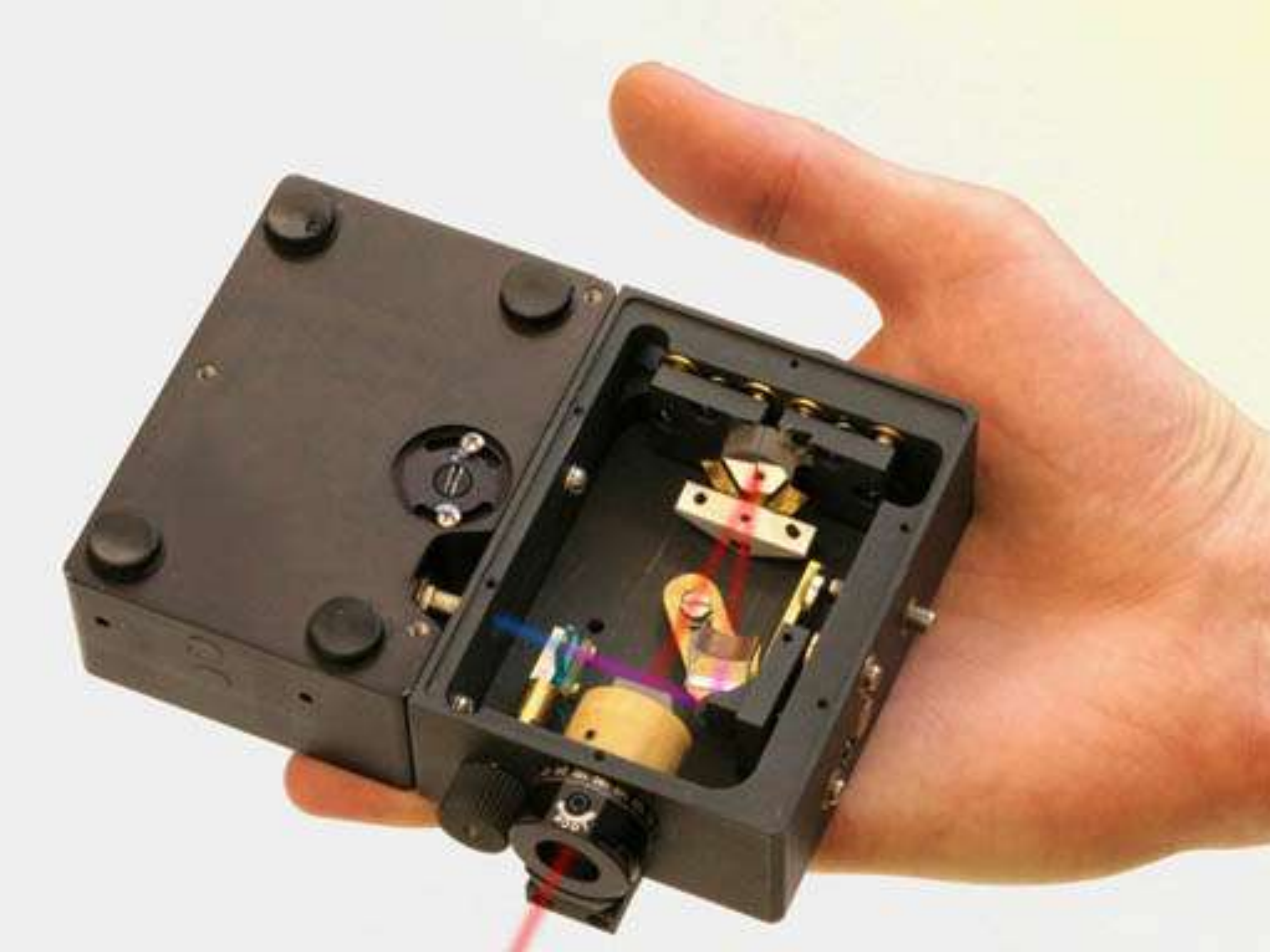


Negatively chirped pulse

Unchirped pulse

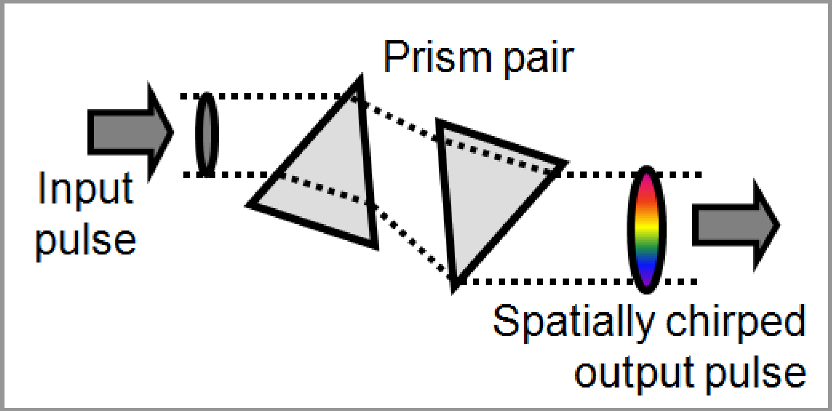
Positively chirped pulse

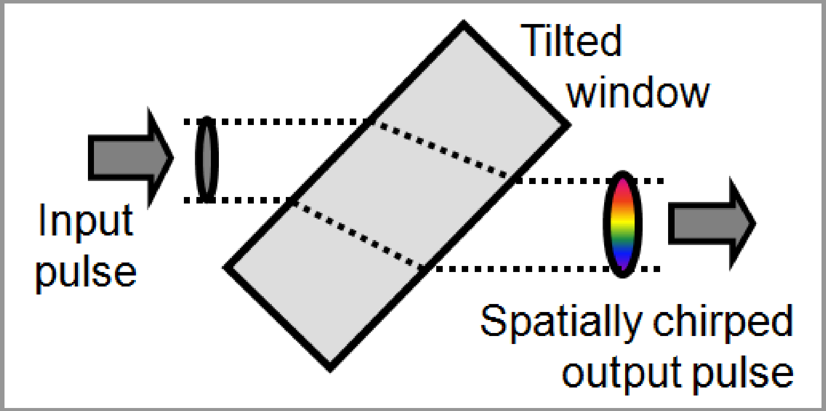
The FROG trace visually displays the pulse frequency vs. time.



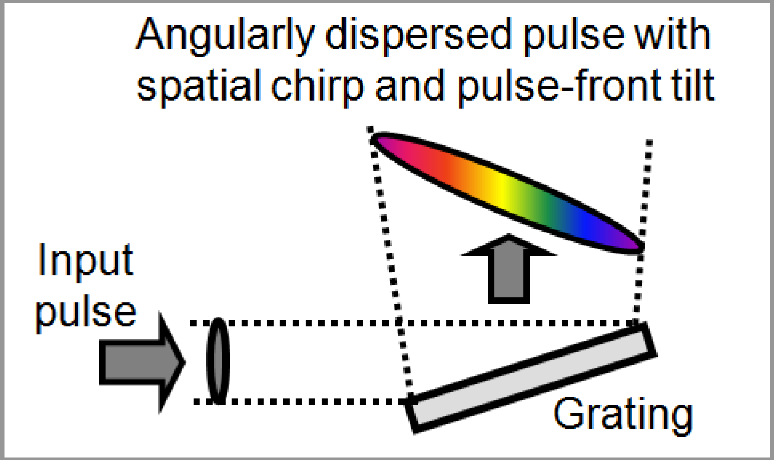
Spatio-temporal distortions in pulses

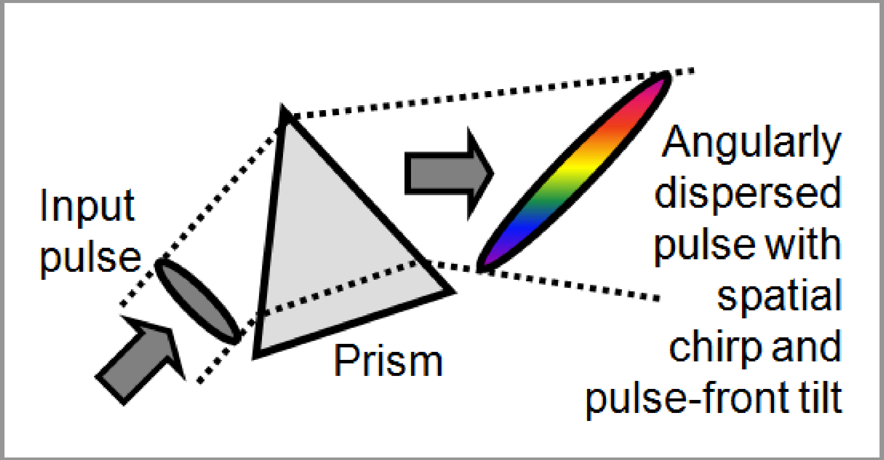
Prism pairs and simple tilted windows cause “spatial chirp.”



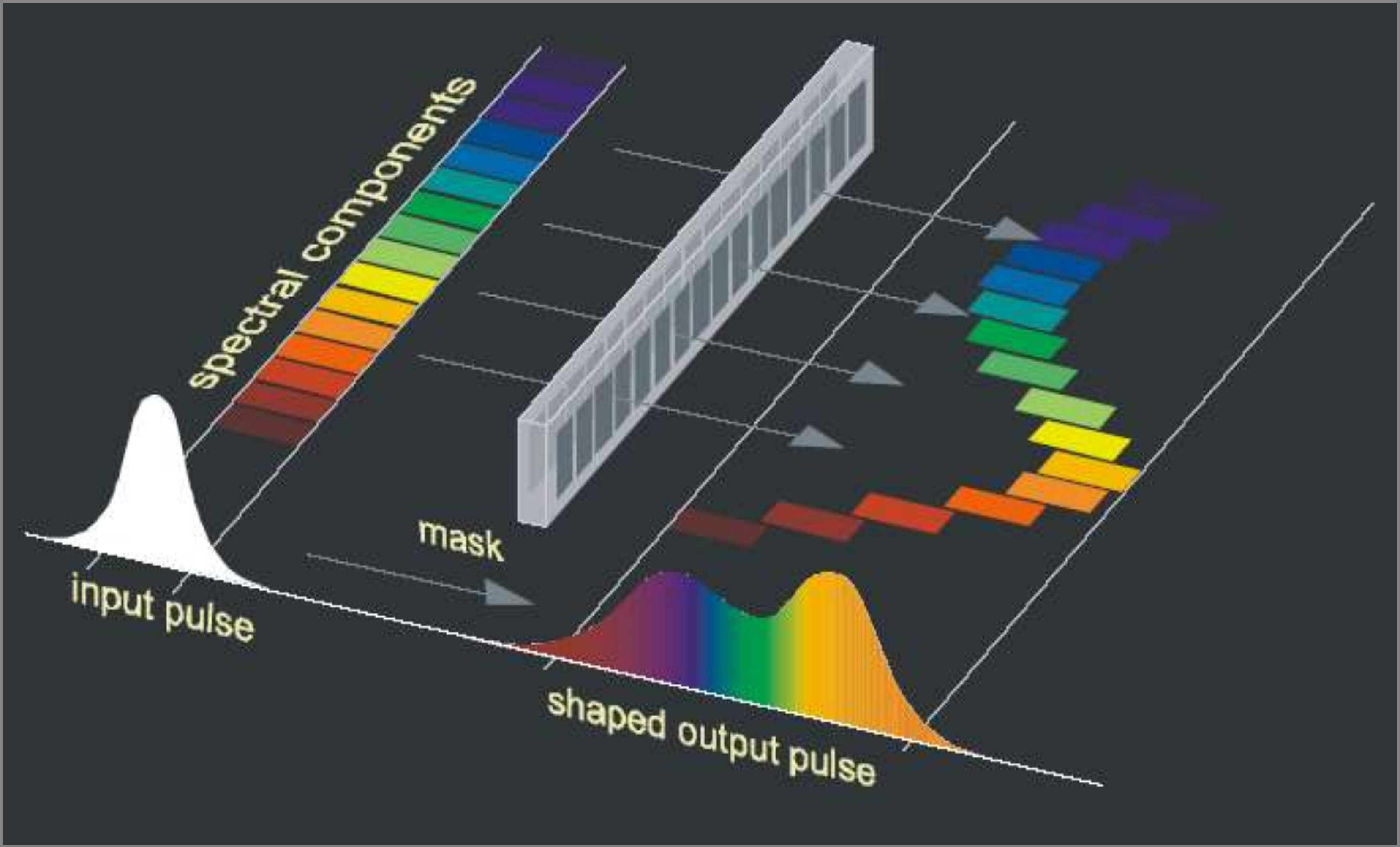


Gratings and prisms cause both spatial chirp and “pulse-front tilt.”

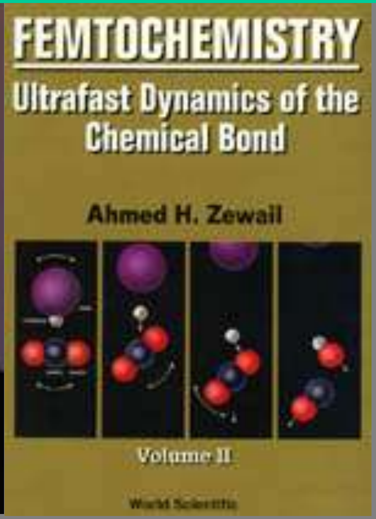




We can shape ultrashort pulses.



The 1999 Nobel Prize in Chemistry went to Professor Ahmed Zewail of Cal Tech for ultrafast spectroscopy.



FEMTOCHEMISTRY

Ultrafast Dynamics of the Chemical Bond

Ahmed H. Zewail

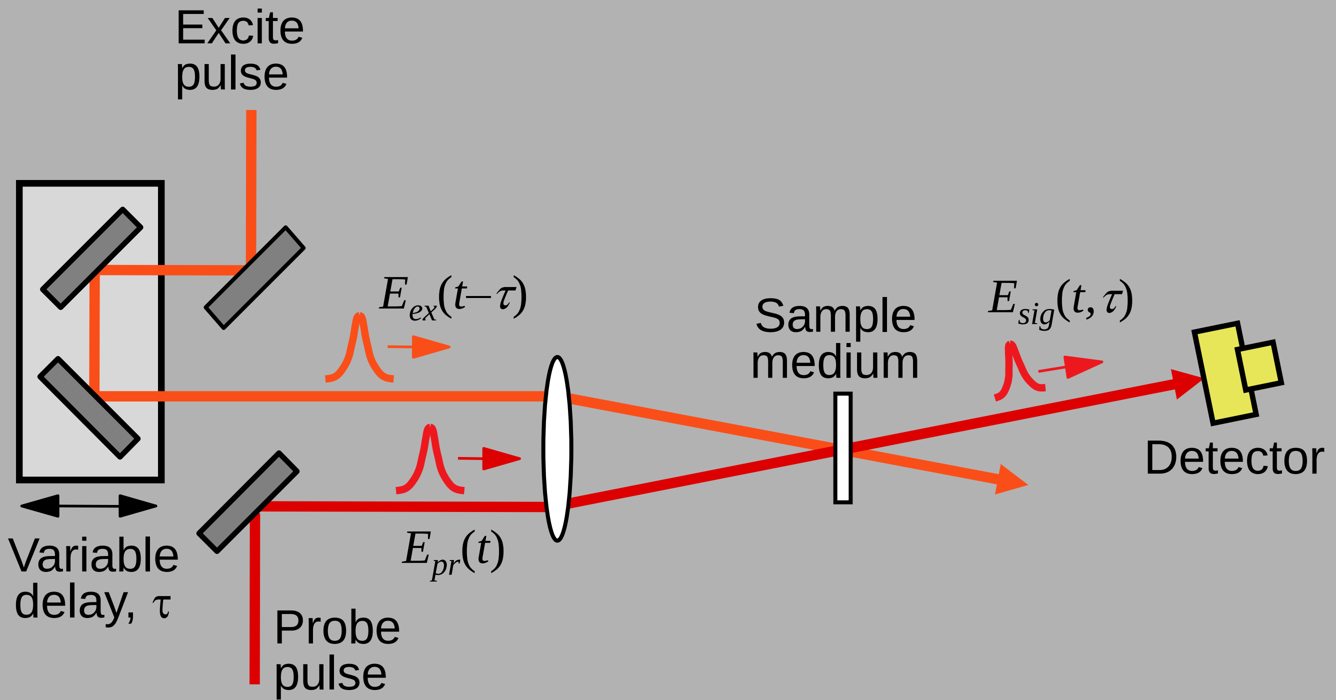
Volume II

World Scientific

Zewail used ultrafast-laser techniques to study how atoms in a molecule move during chemical reactions.

The simplest ultrafast spectroscopy method is the Excite-Probe Technique.

This involves exciting the sample with one pulse, probing it with another a variable delay later, and measuring the change in the transmitted probe pulse average power vs. delay:

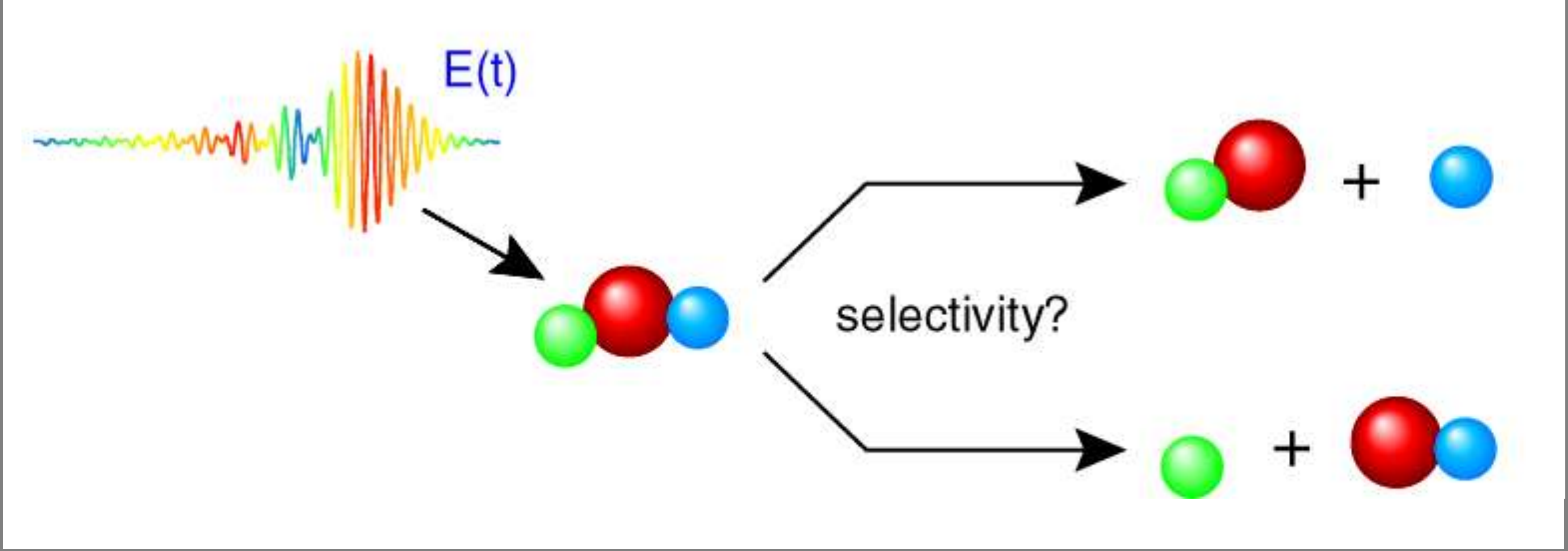


The excite and probe pulses can be different colors.

This technique is also called the “Pump-Probe” Technique.

Beyond ultrafast spectroscopy: controlling chemical reactions with ultrashort pulses

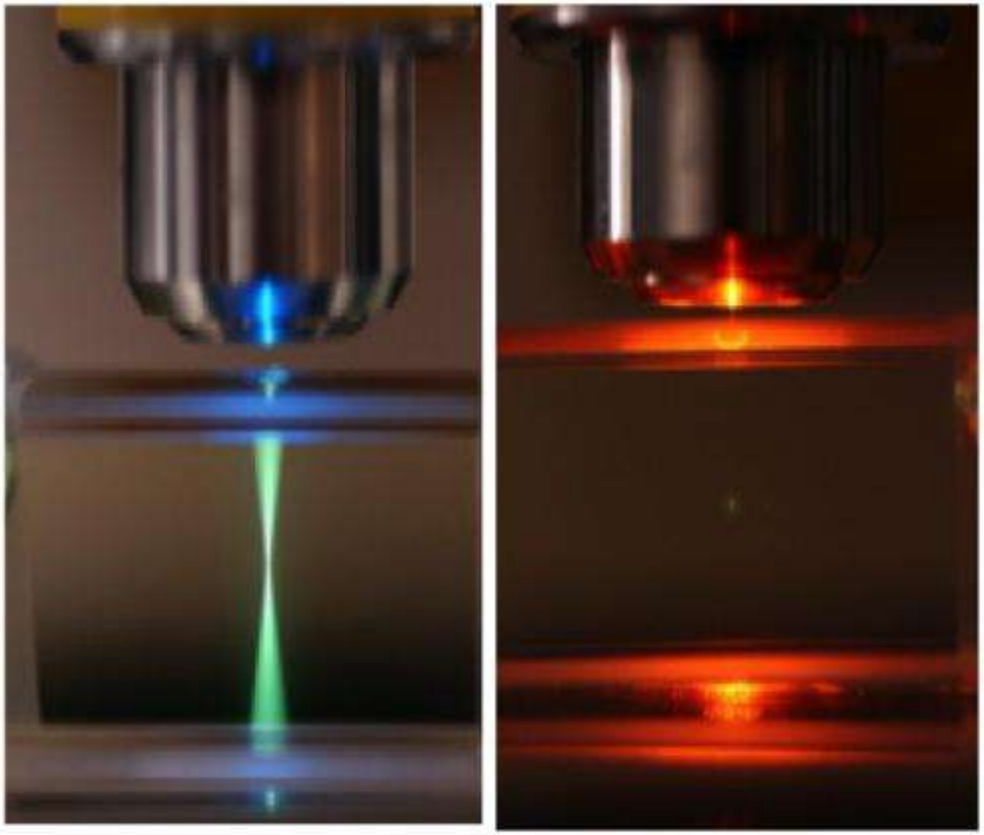
You can excite a chemical bond with the right wavelength, but the energy redistributes all around the molecule rapidly (“IVR”).



But exciting with an intense, shaped ultrashort pulse can control the molecule’s vibrations and produce the desired products.

Multi-photon imaging

1-photon vs. 2-photon



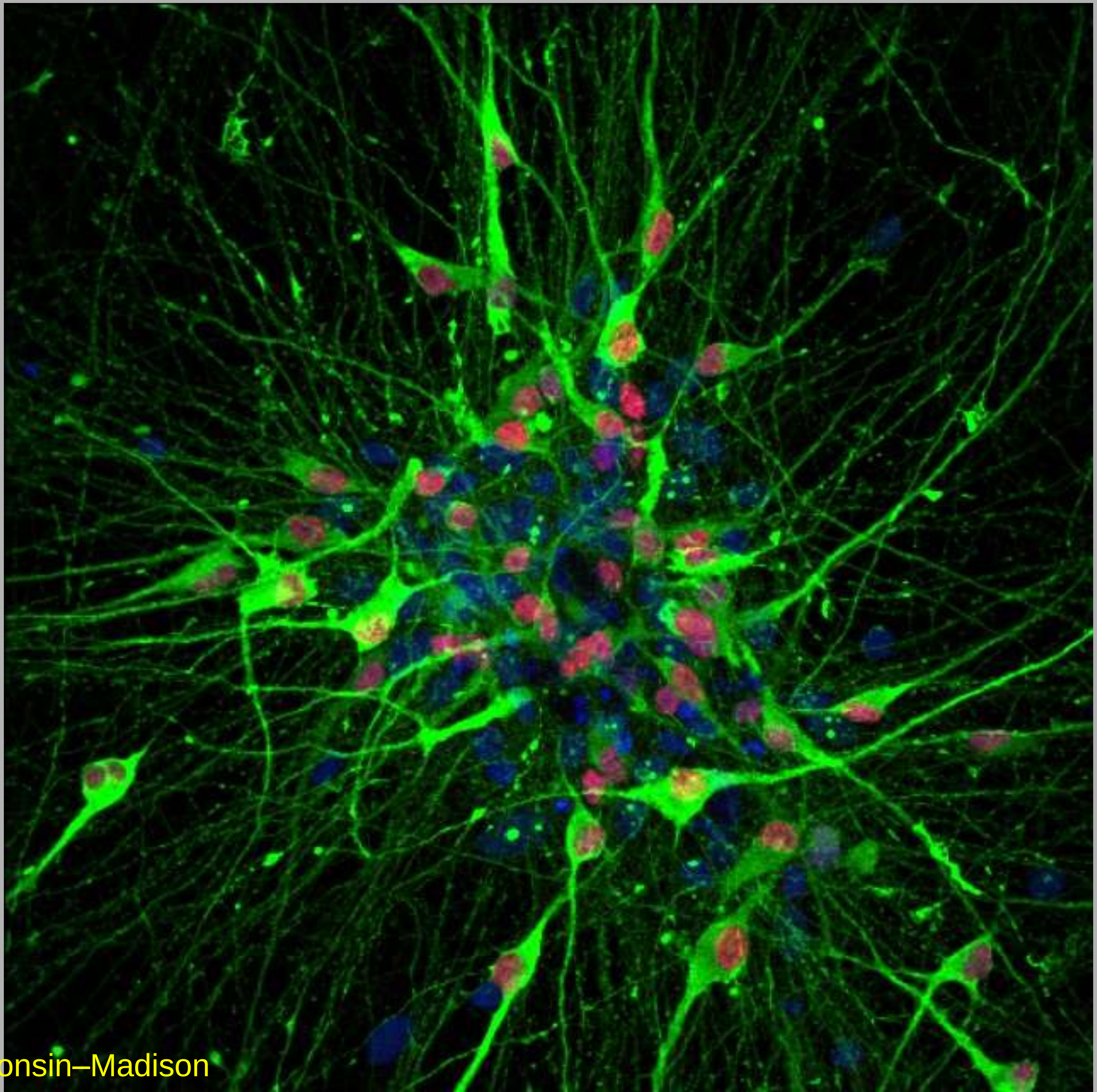
Photos by Steve Ruzin

Fluorescence from out of focus planes

Fluorescence from focal spot only

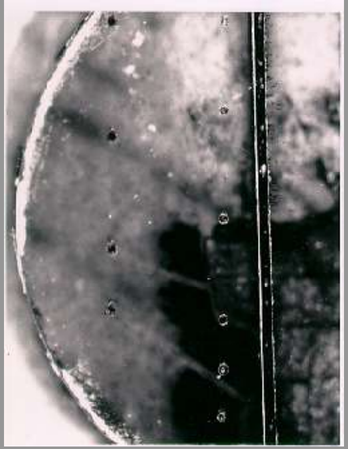
The Robey Lab, Berkeley

Two-photon fluorescence imaging



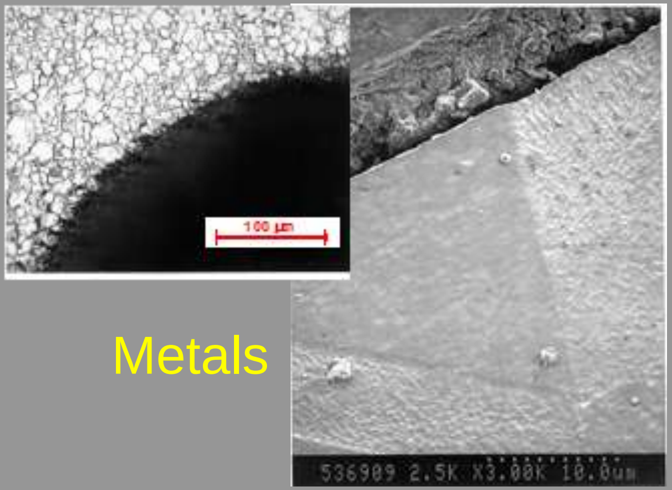
University of Wisconsin–Madison

Ultrashort pulse lasers can precision machine many materials.

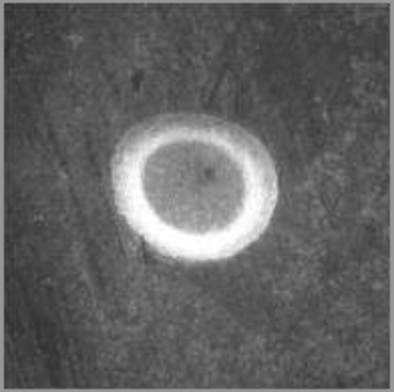


Diamond

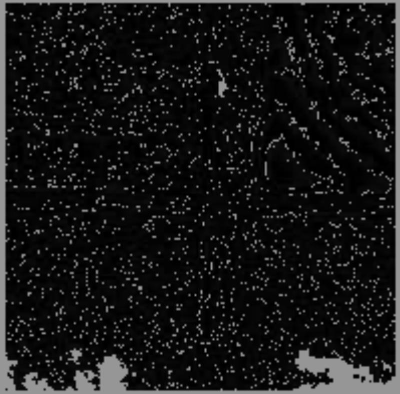
Ceramics



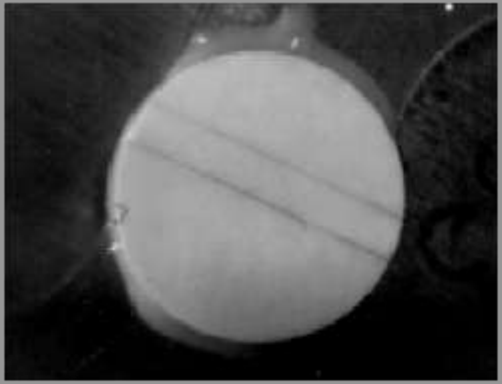
Metals



Teeth

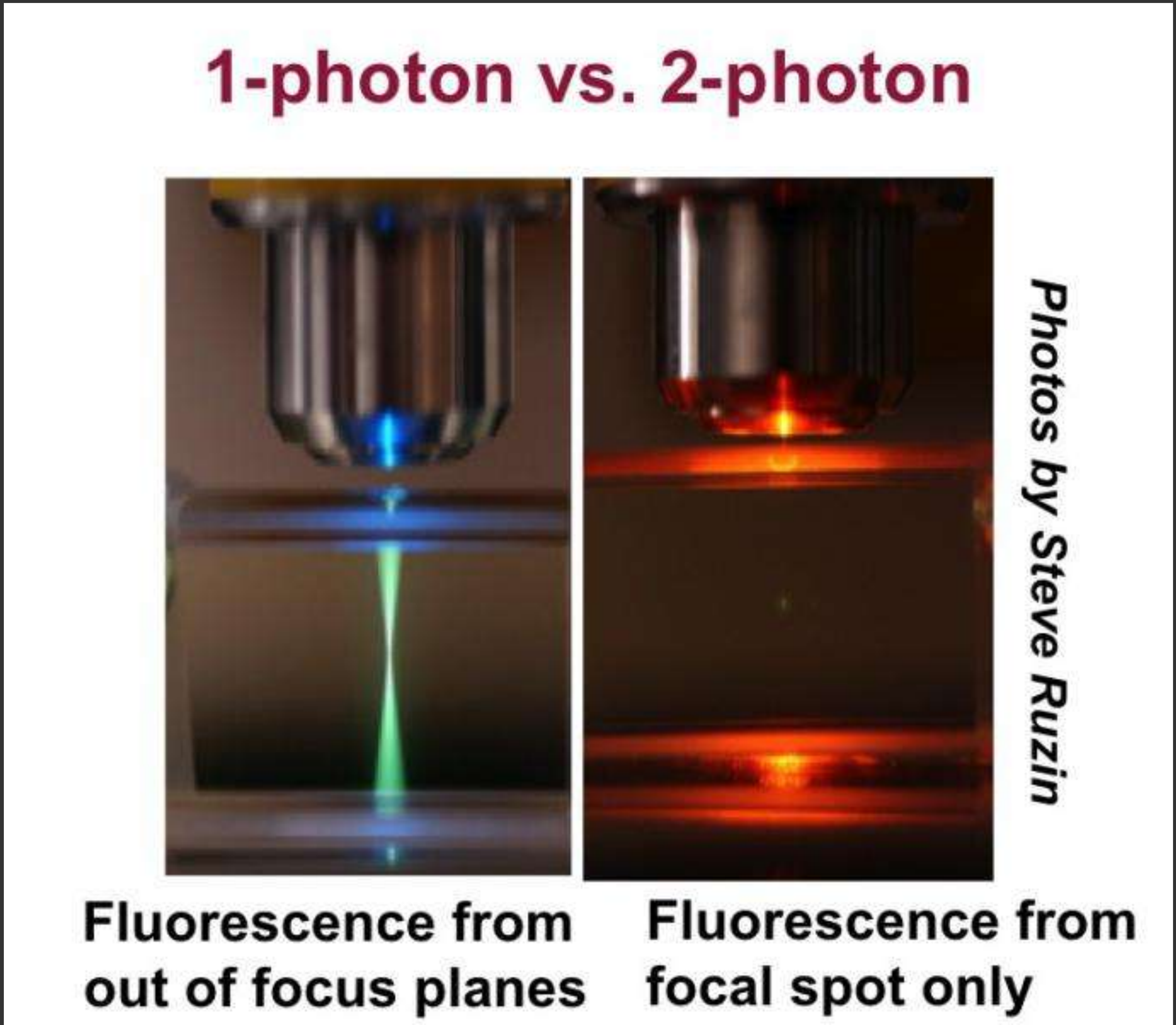


Polymers



High Explosives

Sub-micron 3D printing



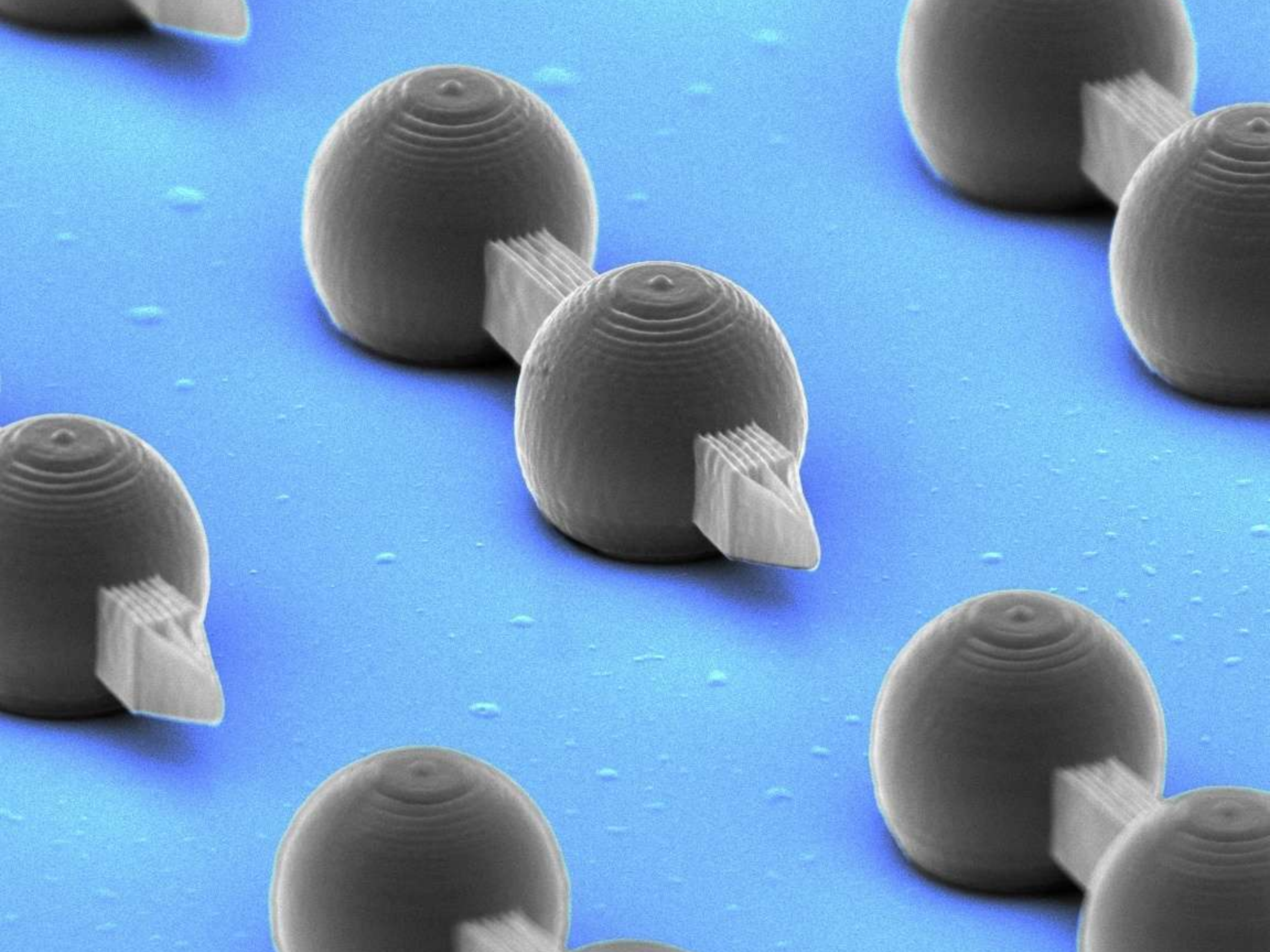
1-photon vs. 2-photon

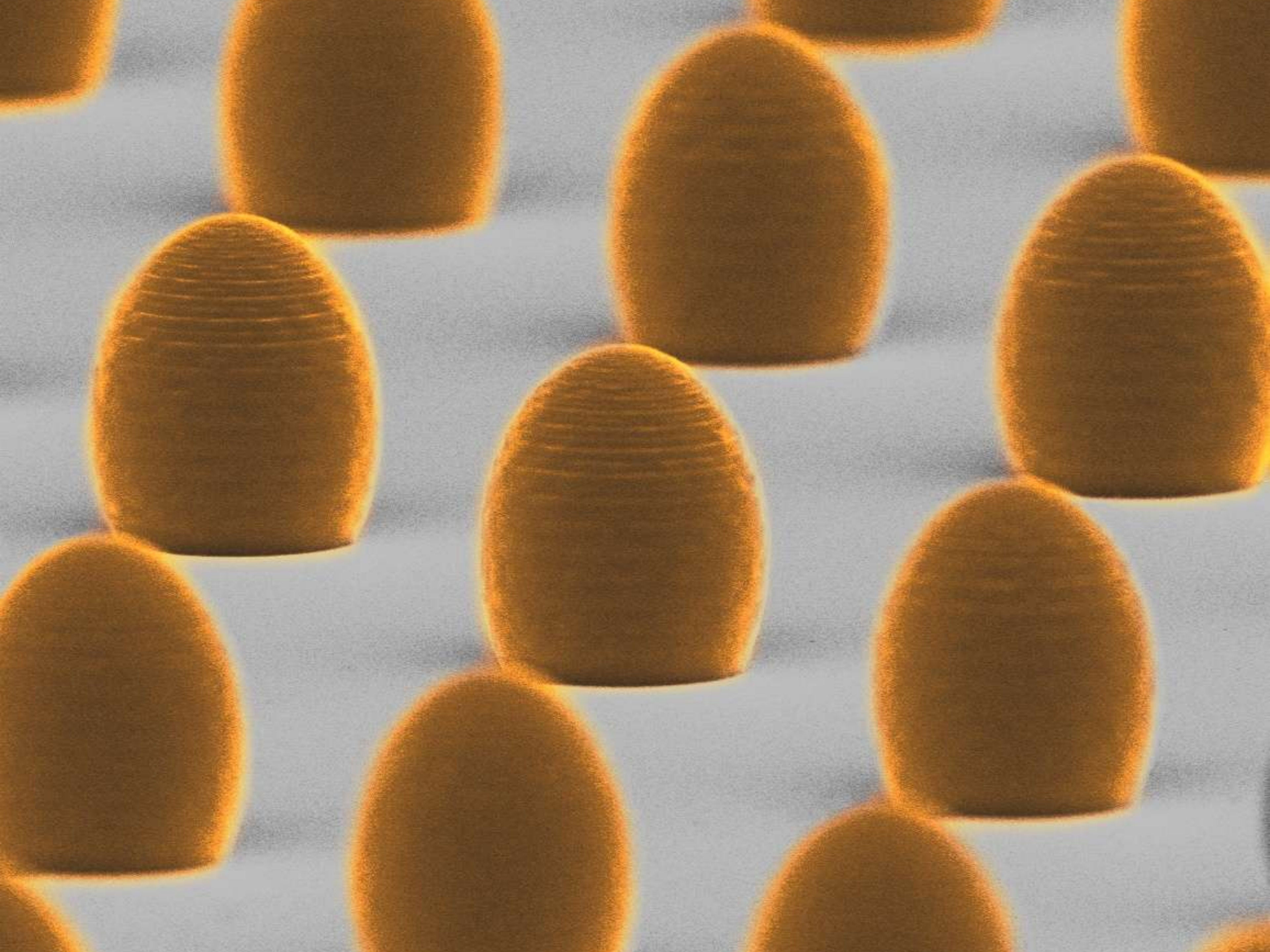
Fluorescence from out of focus planes

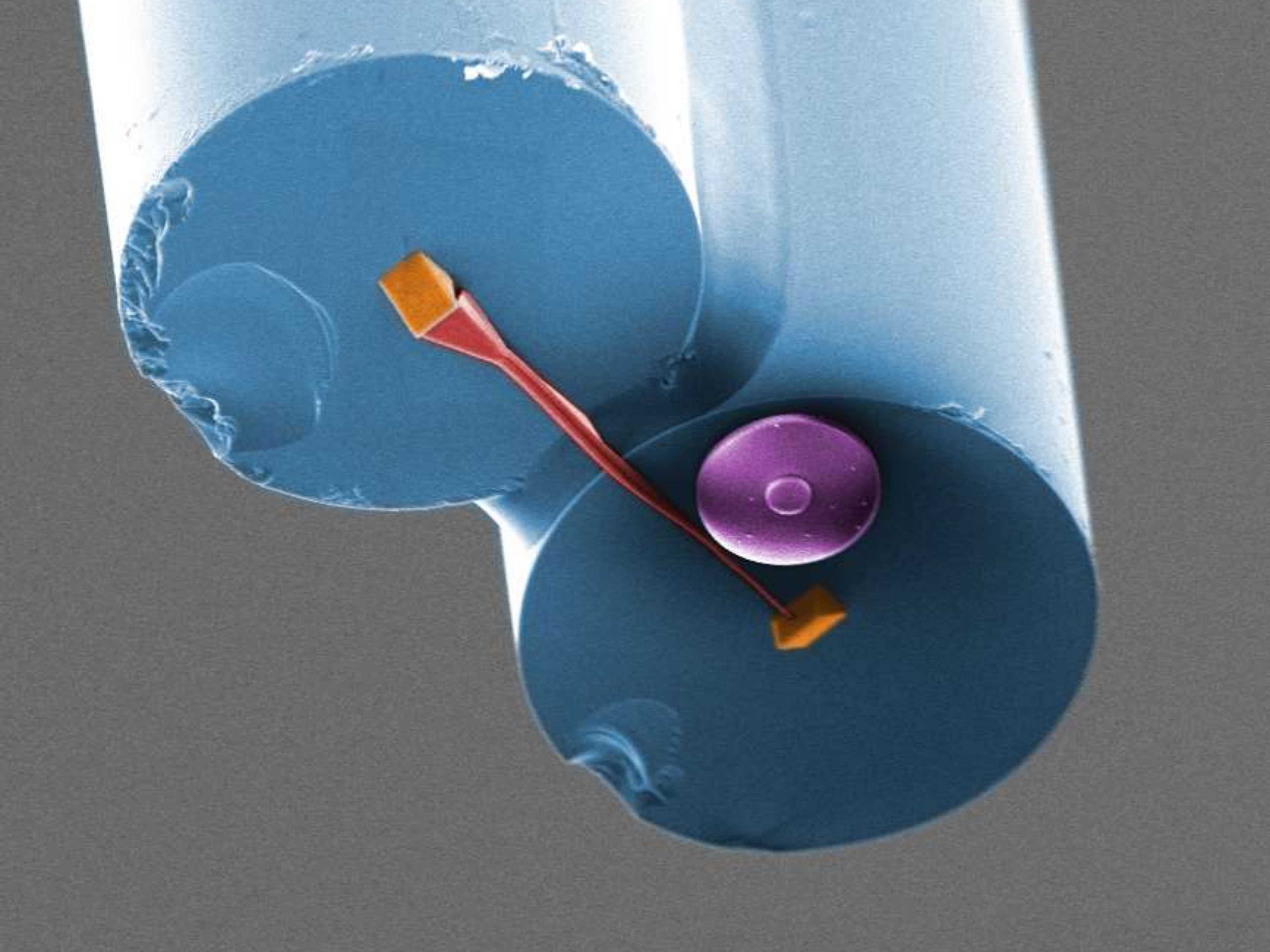
Fluorescence from focal spot only

Photos by Steve Ruzin

The Robey Lab, Berkeley



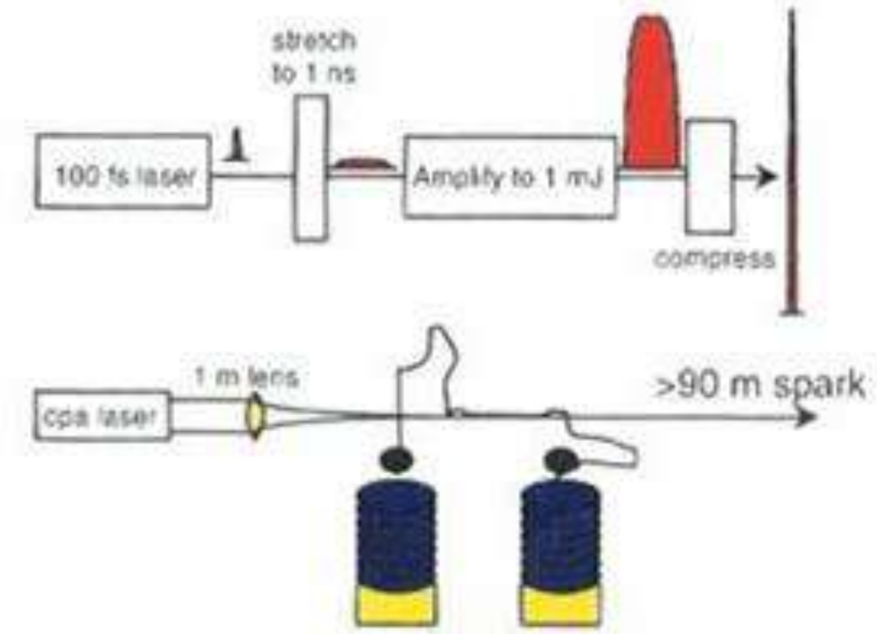




Intralase performs vision-correction surgery using fs lasers.

FDA approval is already in hand.

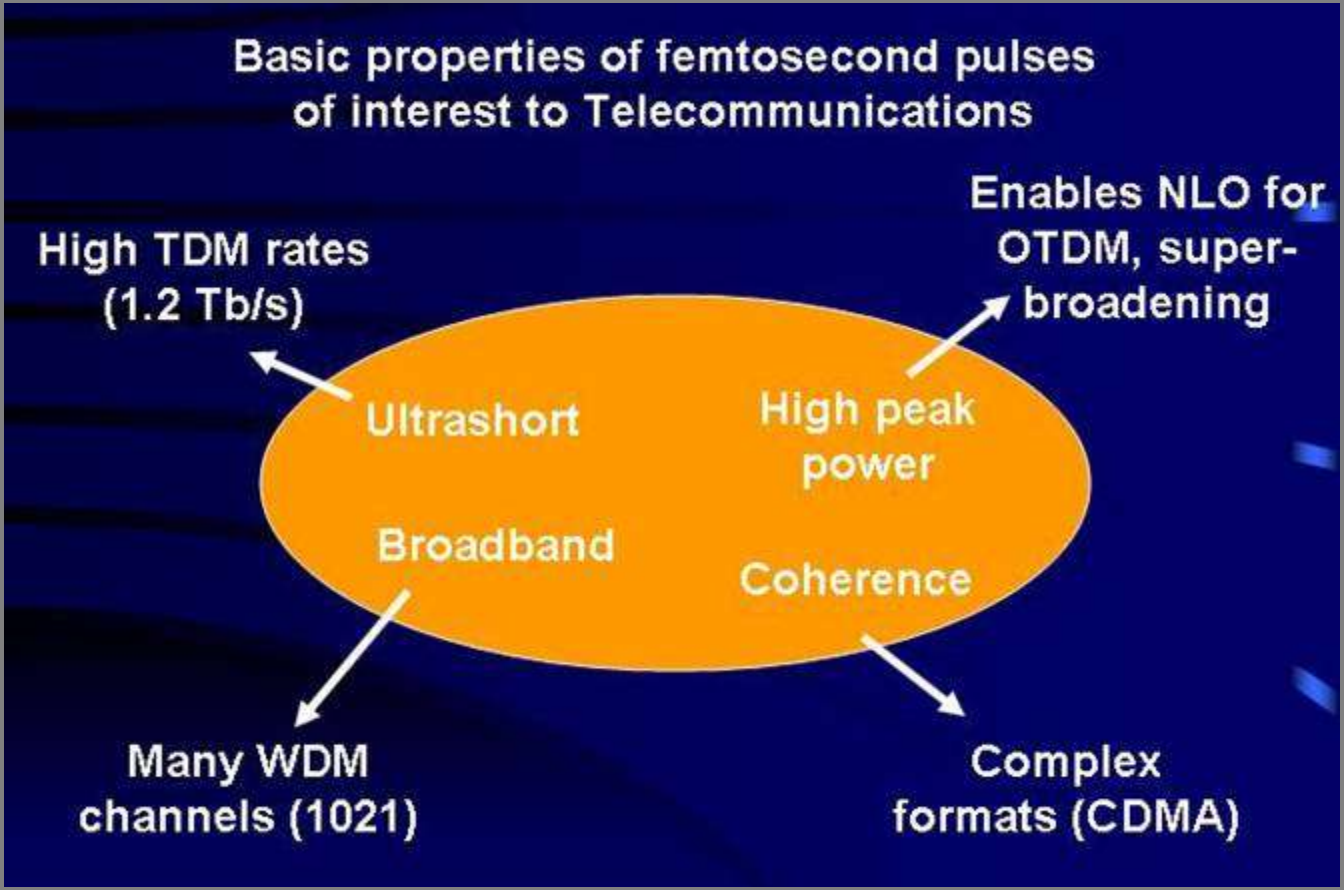
Protection from lightning using amplified fs pulses



- 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 charge before lightning can occur.

Actually, from the ruins, a new, more realistic telecom industry will emerge, and it will be ultrafast.



Basic properties of femtosecond pulses of interest to Telecommunications

Ultrashort

High peak power

Broadband

Coherence

High TDM rates (1.2 Tb/s)

Enables NLO for OTDM, super-broadening

Many WDM channels (1021)

Complex formats (CDMA)

Well… Maybe…