Application of ultrashort pulses

allery.com

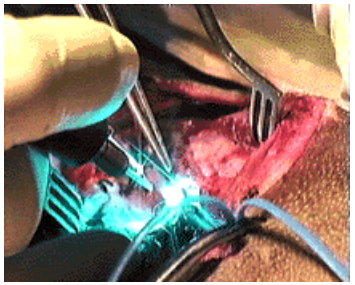
Nobel price in Physics (2005)
Theodor W. Hänsch (optical comb technology)

Nonlinear optics

- Optical frequency converter
- Self focusing and Nonlinear absorption
- Optical metrology

High energy physics

- X-ray laser
- Electron accelerator



Ultrashort laser

Material processing

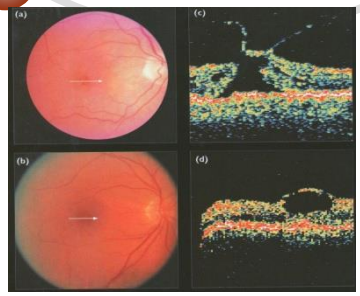
- Micromachining
- Laser annealing

Medical

- vision-correction surgery
- Laser Tissue Welding

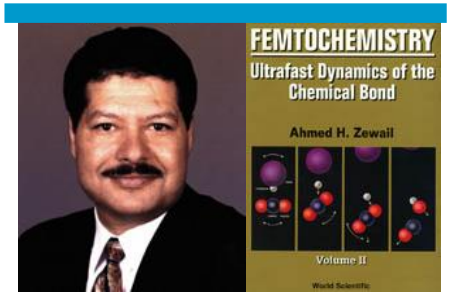
Biology/ Environment sensing

- Coherent tomography
- Higher harmonic optical microscopy



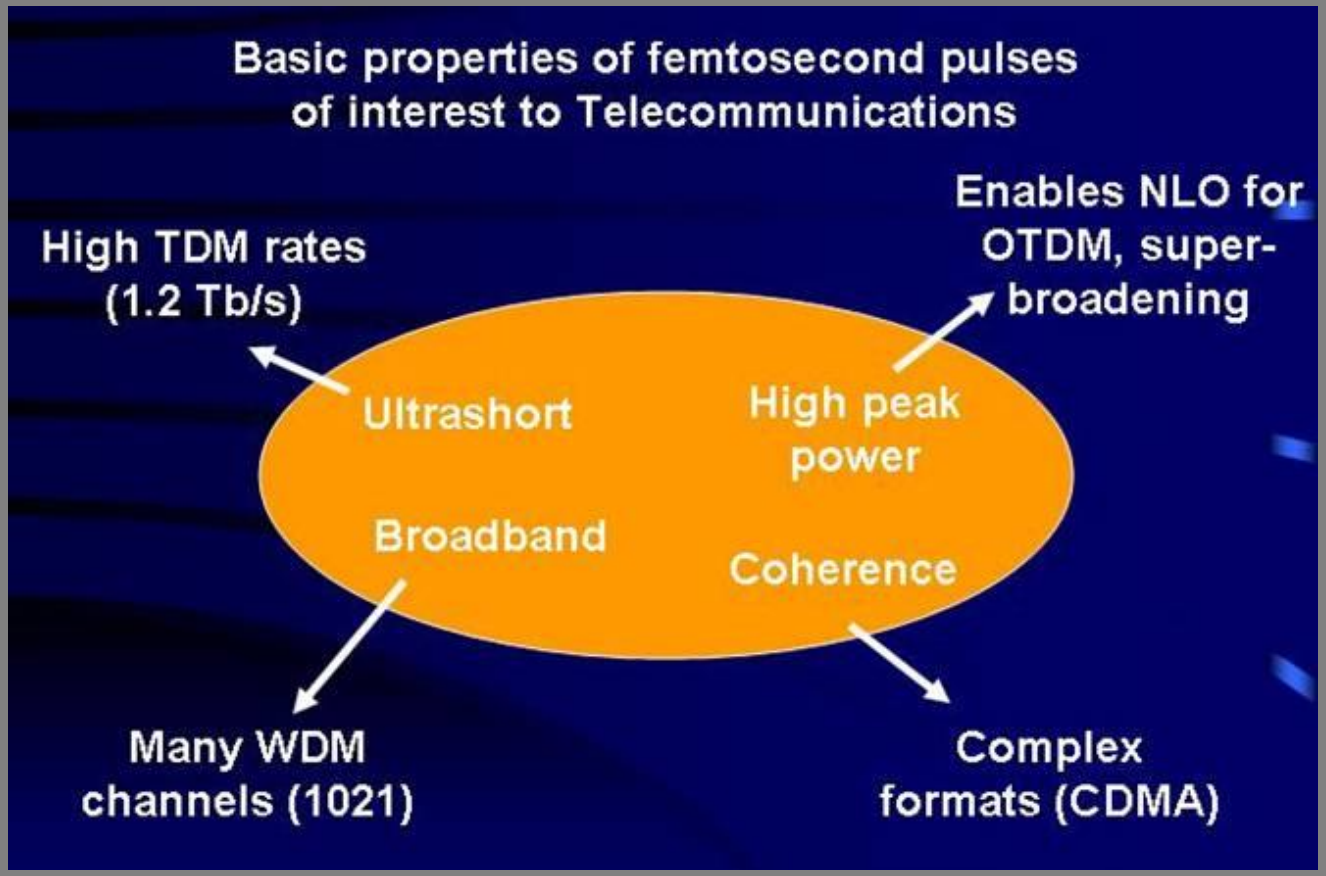
Optical Chemistry

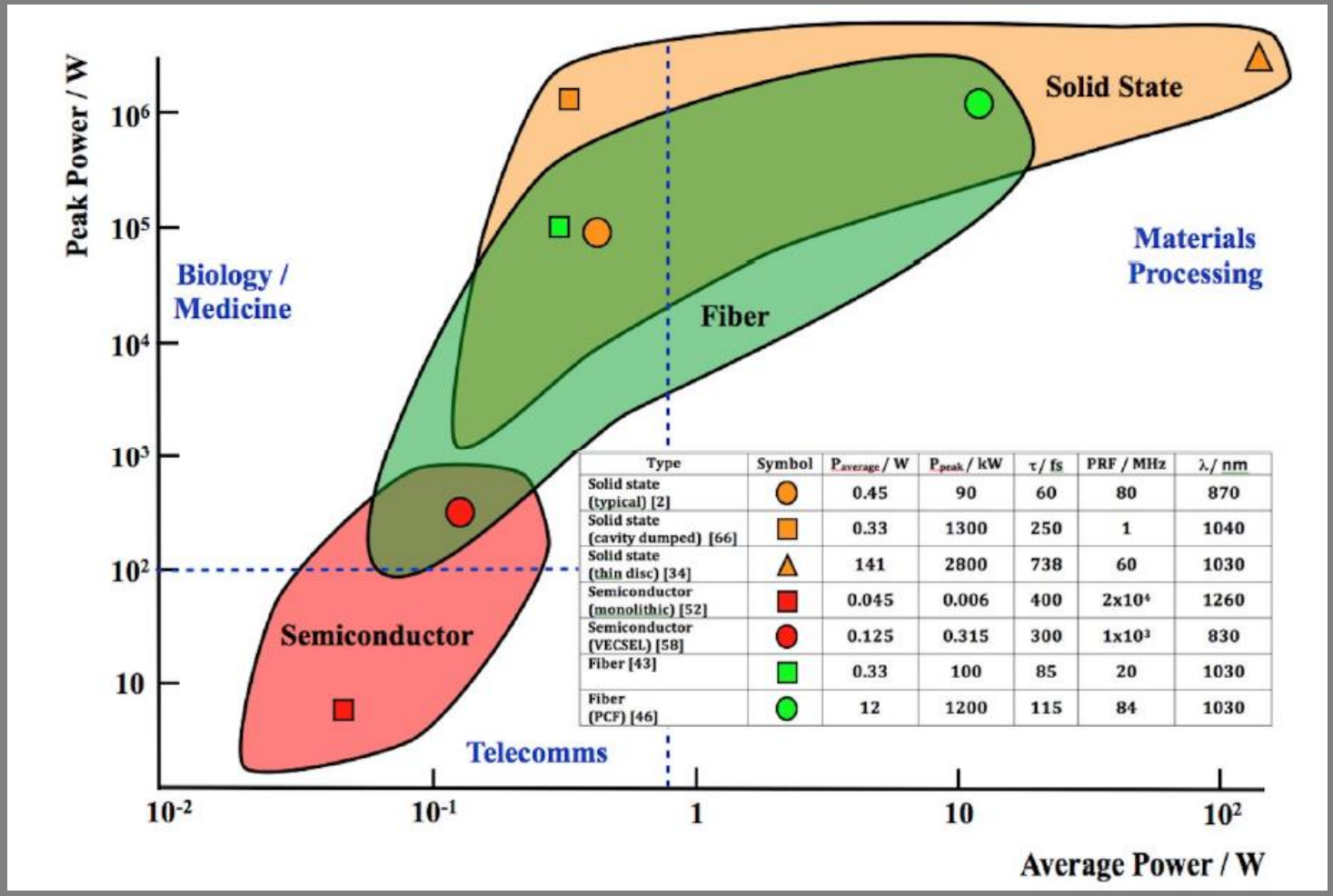
- Optical spectroscopy



Nobel price in chemistry (1999)
Ahmed Zewail

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





Type	Symbol	$P_{average}$ / W	P_{peak} / kW	τ / fs	PRF / MHz	λ / nm
Solid state (typical) [2]		0.45	90	60	80	870
Solid state (cavity dumped) [66]		0.33	1300	250	1	1040
Solid state (thin disc) [34]		141	2800	738	60	1030
Semiconductor (monolithic) [52]		0.045	0.006	400	$2x10^4$	1260
Semiconductor (VECSEL) [58]		0.125	0.315	300	$1x10^3$	830
Fiber [43]		0.33	100	85	20	1030
Fiber (PCF) [46]		12	1200	115	84	1030

A plot of peak power versus average power for a range of ultrashort pulse laseroscillator technologies. Also included are indicative application areas placed in appropriate regions of laser performance.

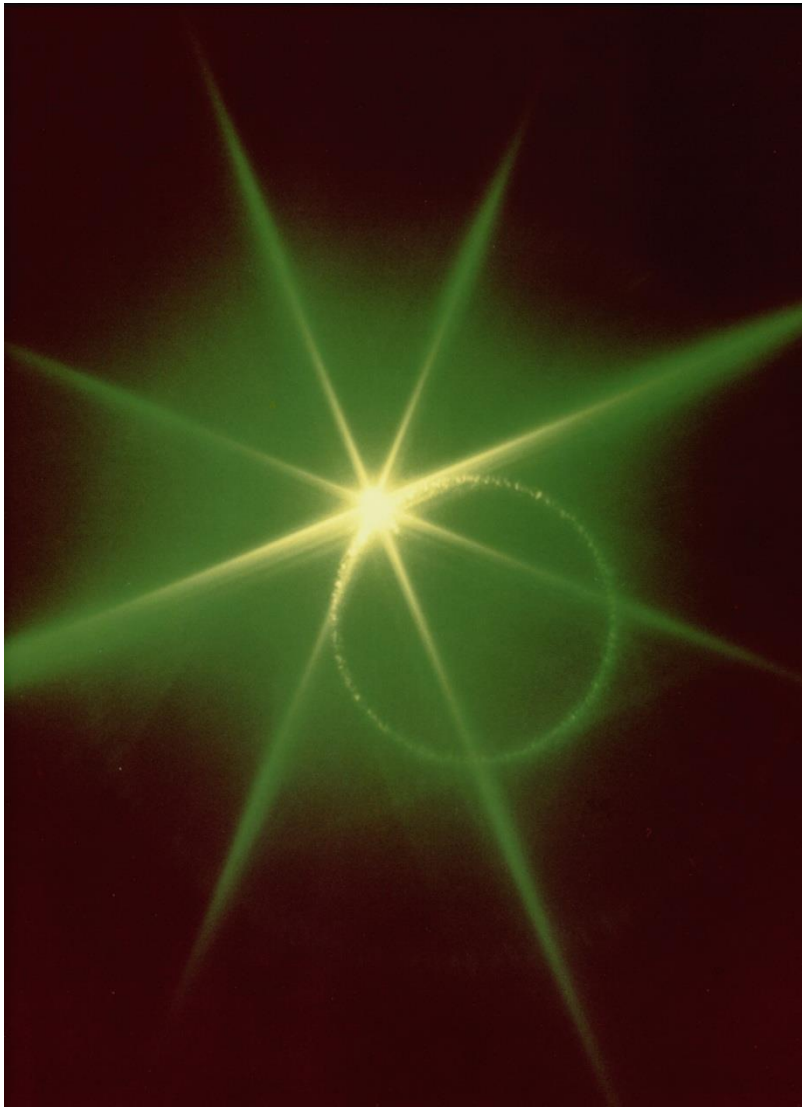
Opt. express-20-6994-2012

Ultrafast optics is nonlinear optics.

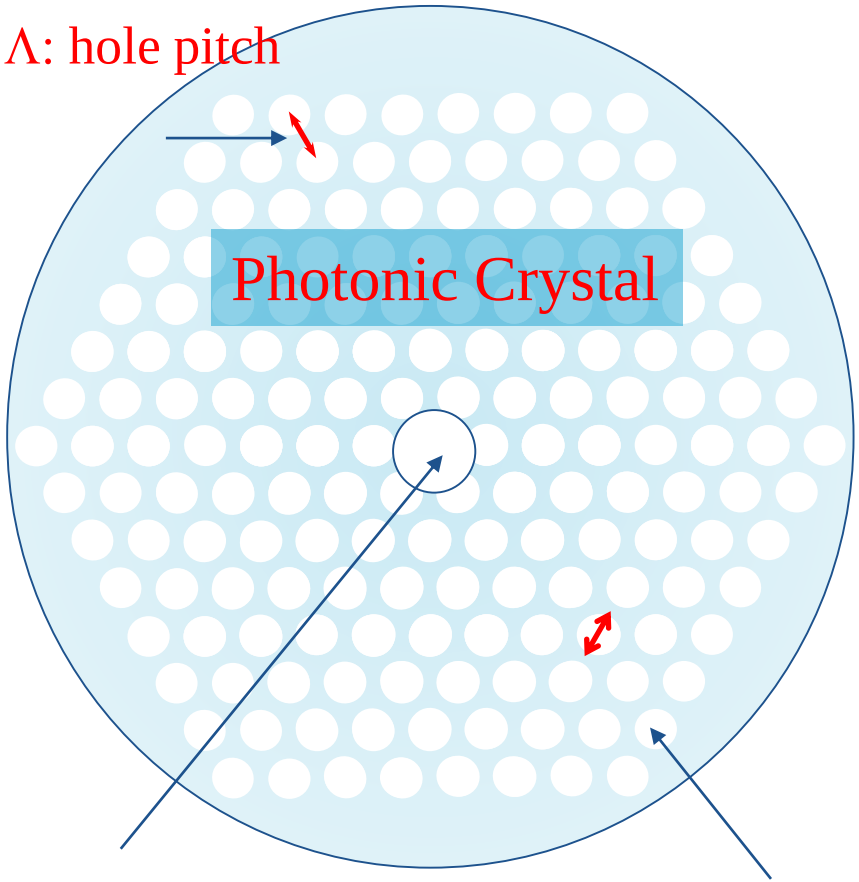
At high intensities, nonlinear-optical effects occur.

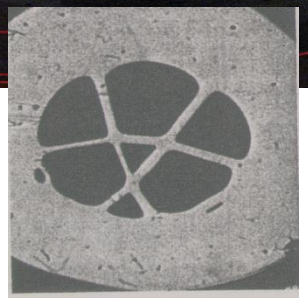
All mode-locking techniques are nonlinear-optical.

Creating new colors of laser light requires nonlinear optics.

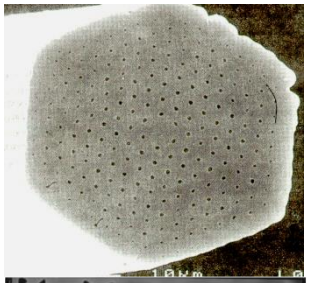


Photonic Crystal fibers

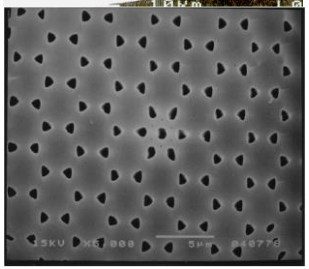




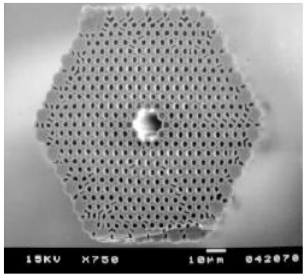
1974
Kaiser *et al.*
Air-silica fibers



1996
Knight, Birks,
Russell, Atkin,
Photonic crystal fiber



1998
Knight, Broeng,
Birks, Russell
Photonic bandgap
fiber (PGB)

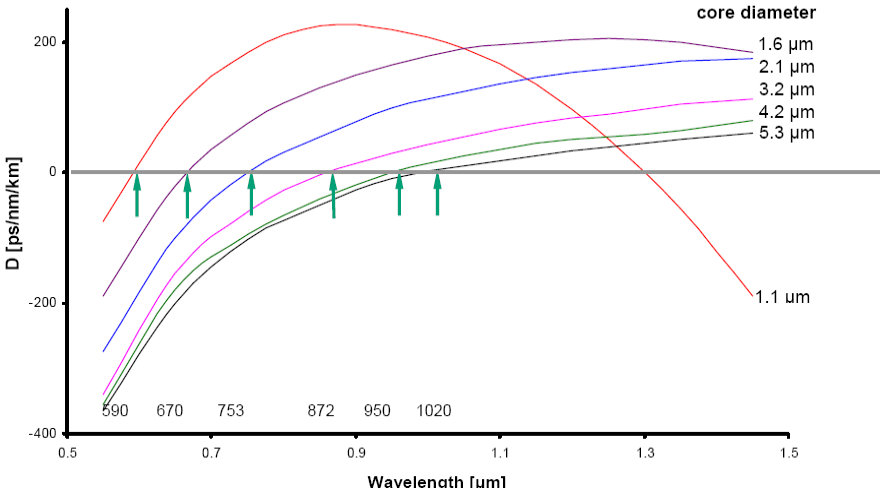


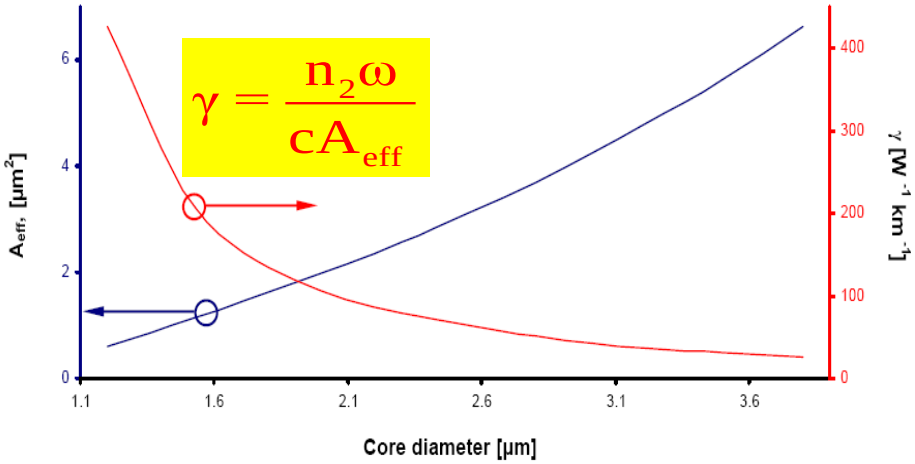
1999
Cregan, Mangan, Knight,
Birks,
Russell, Roberts, Allan
SM PGB

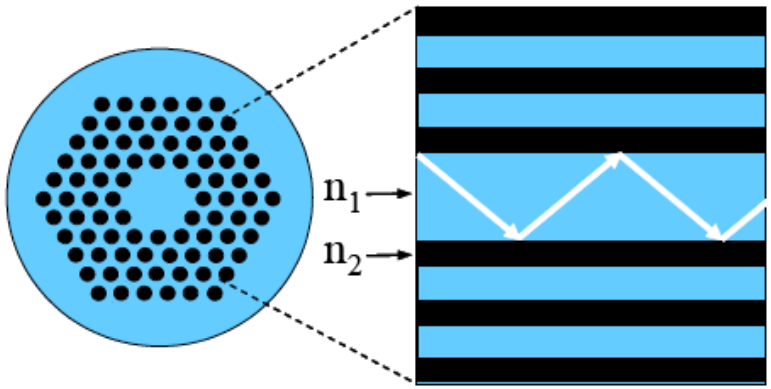
T.K. Birks, P.J. Roberts,P.S.J. Russel, Atkin, Shepherd, Electron. Lett. **31**, 1941-1942 (1995)

Nonlinear PCF (microstructure fiber)

- **Feature**
  - pure silica core surrounded by regular array of air holes
- **Property**
  - **Dispersion properties** can be tailored in broad range
    - **from 1.3 mm to visible**
  - Small mode area
    - Highly nonlinearity

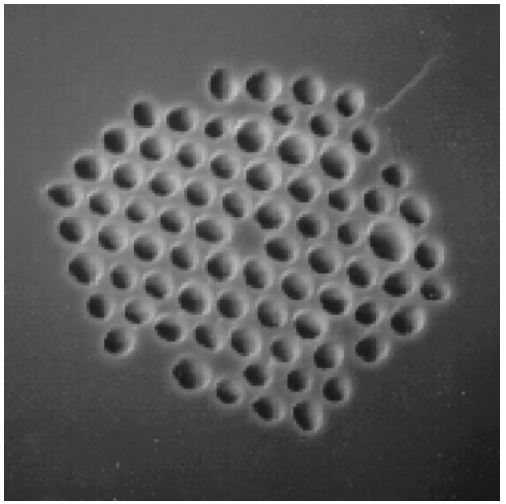


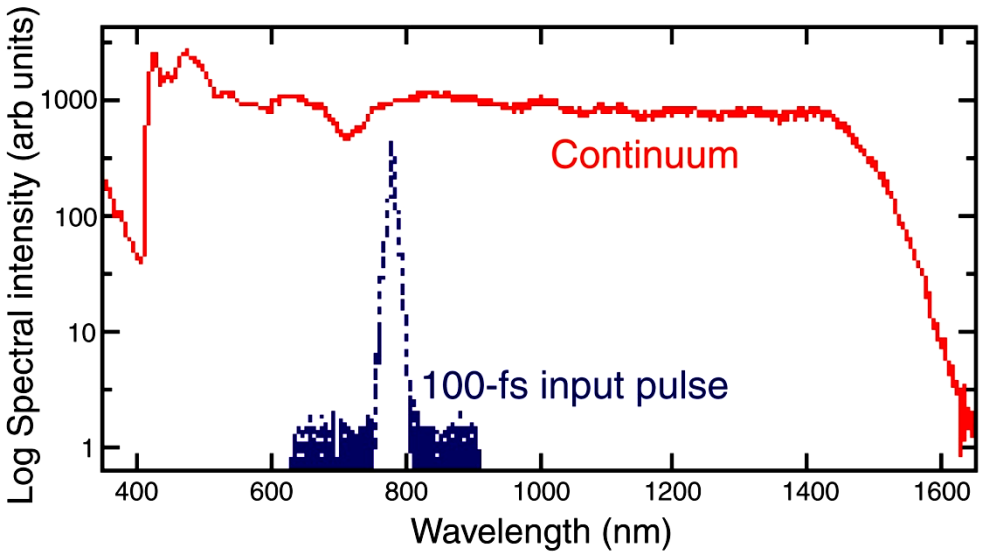




Blaze Photonics Crystal Fibre. Inc

The continuum from microstructure optical fiber is ultrabroadband.

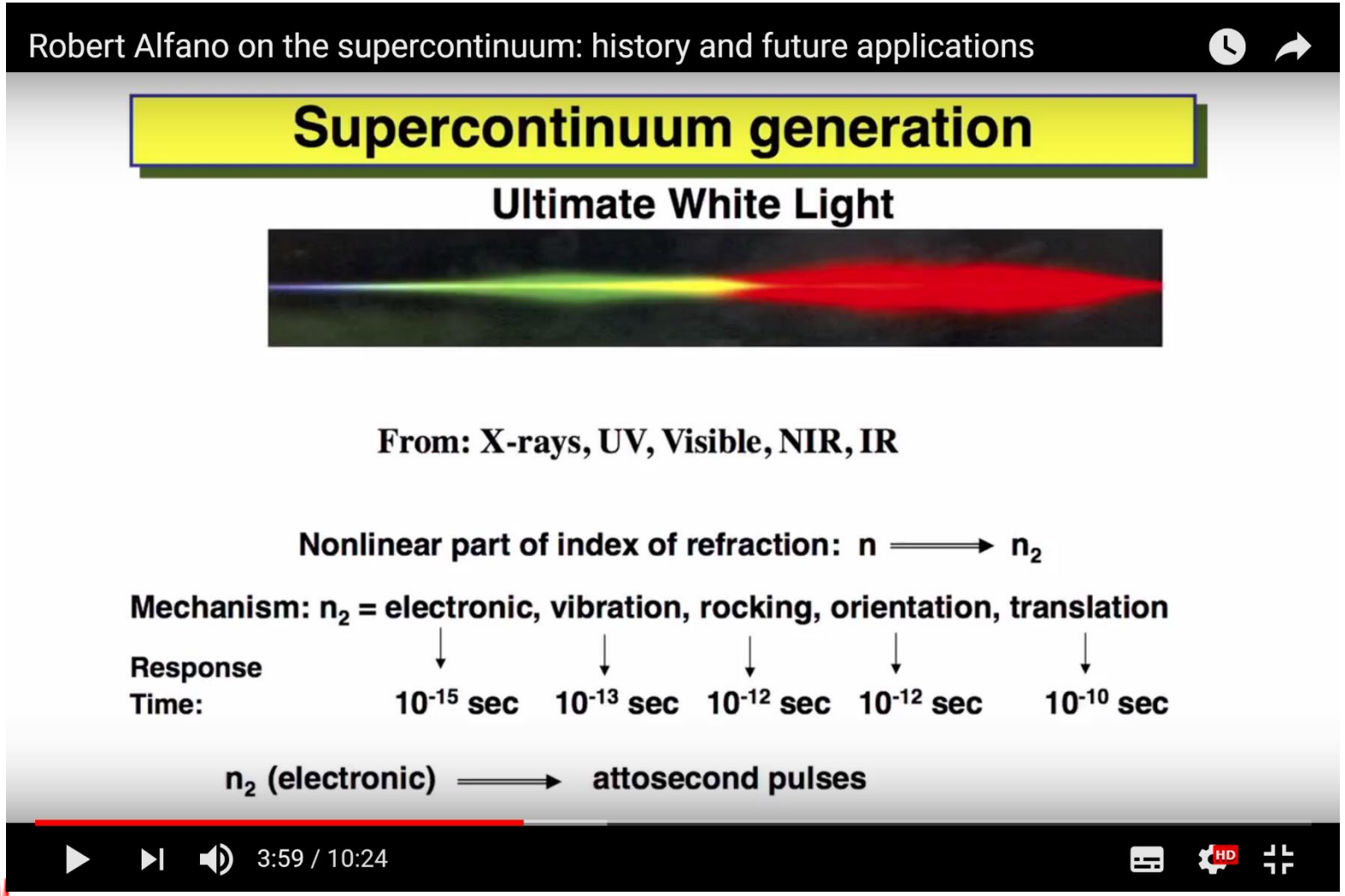


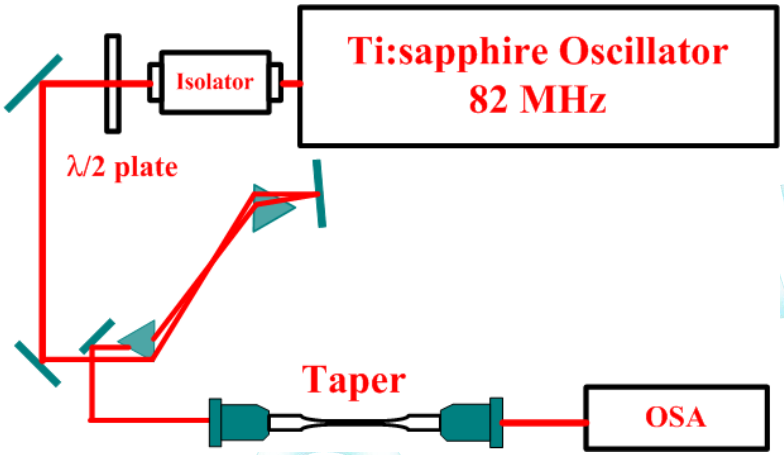


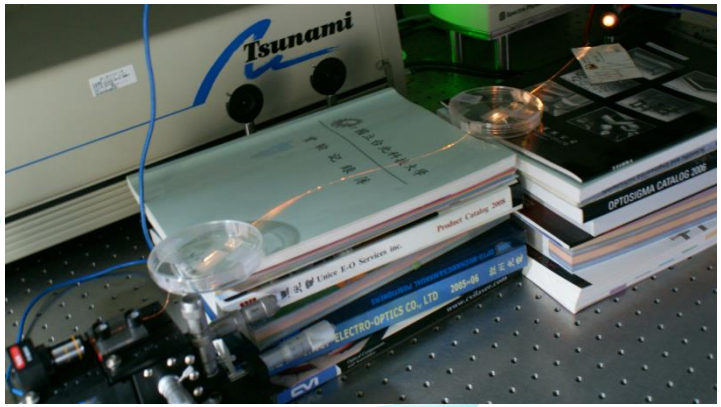
The spectrum extends from ~400 to ~1500 nm and is relatively flat (when averaged over time).

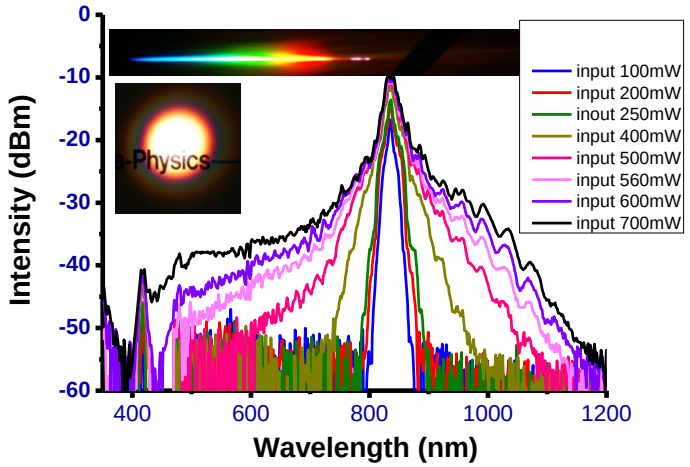
Superconintuum generation (history and application)

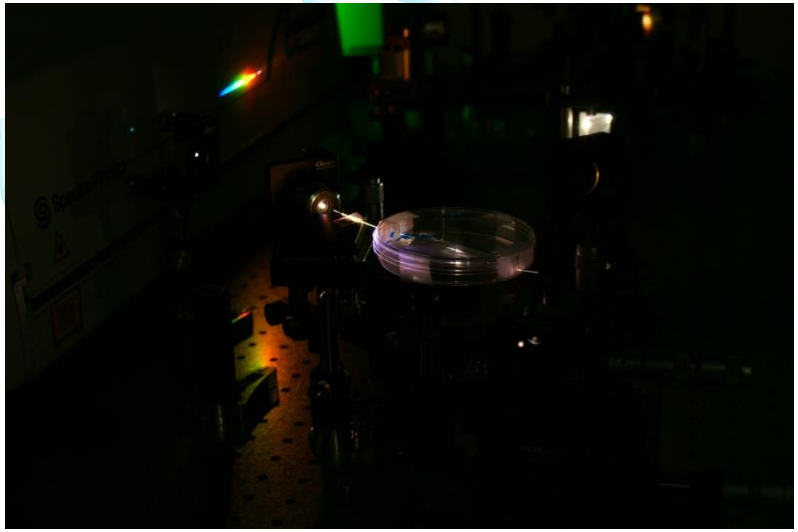
- https://www.youtube.com/watch?v=j5-vBxnt2kI&t=360s




Ti:sapphire Oscillator
82 MHz
Isolator
λ/2 plate
Taper
OSA

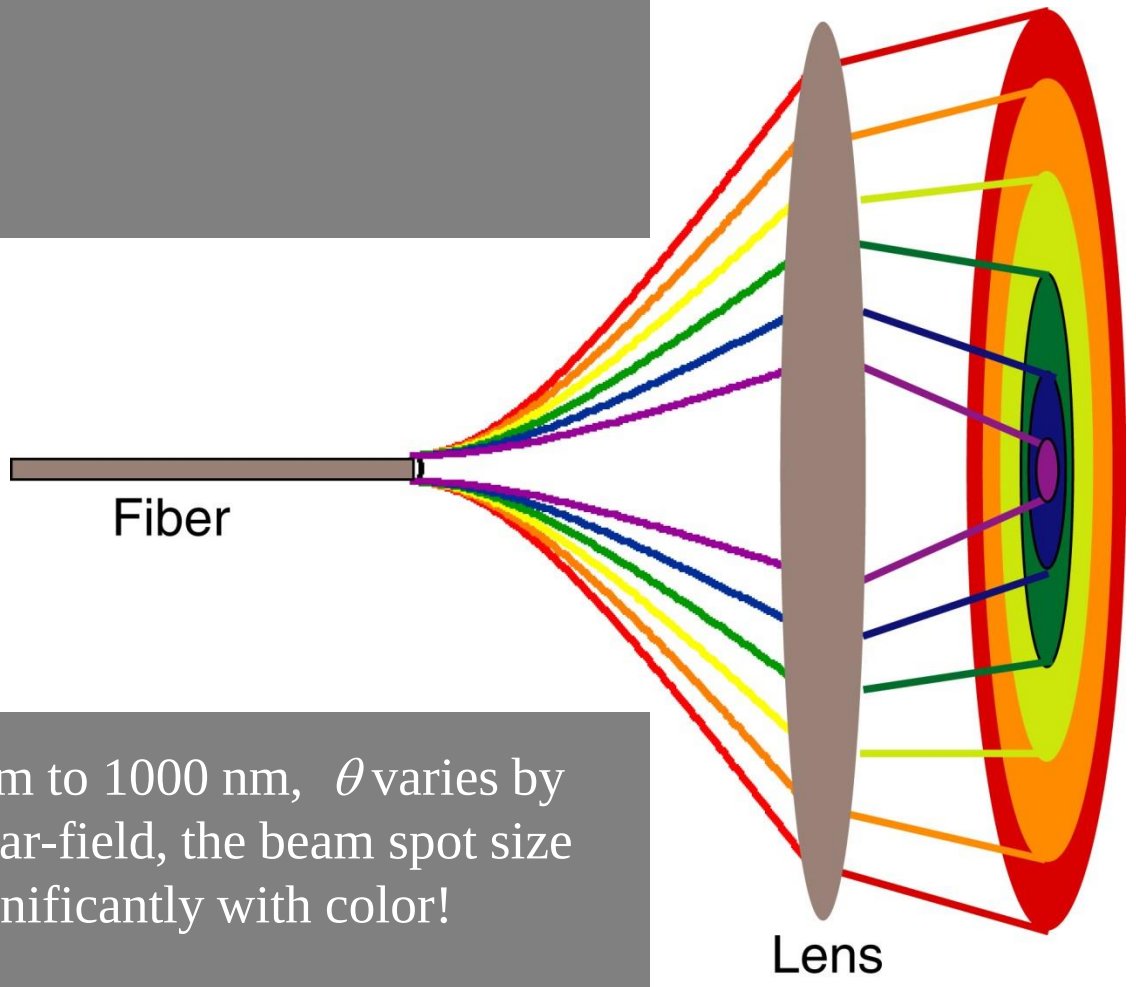

Tsunami


Intensity (dBm)
0
-10
-20
-30
-40
-50
-60
400
600
800
1000
1200
Wavelength (nm)
input 100mW
input 200mW
inout 250mW
input 400mW
input 500mW
input 560mW
input 600mW
input 700mW
Physics



Spatio-temporal characteristics of ultrashort laser pulses

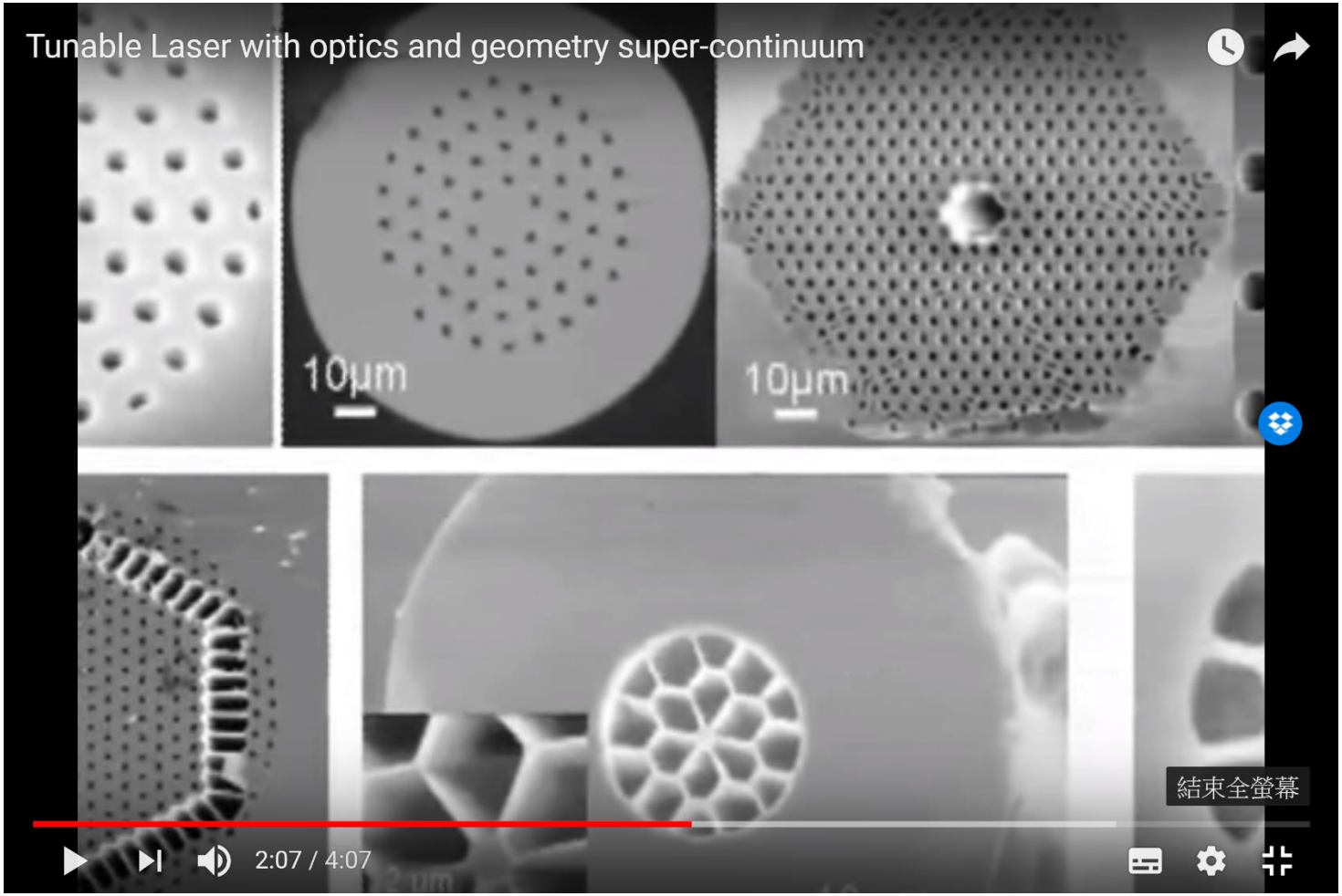
Beam divergence angle θ depends on λ: $\theta = 2\lambda/\pi\omega$, where ω = beam spot size



500 nm to 1000 nm, θ varies by
n the far-field, the beam spot size
ry significantly with color!

SCG from tunable laser

- https://www.youtube.com/watch?v=Pqw_Q4rT9_I



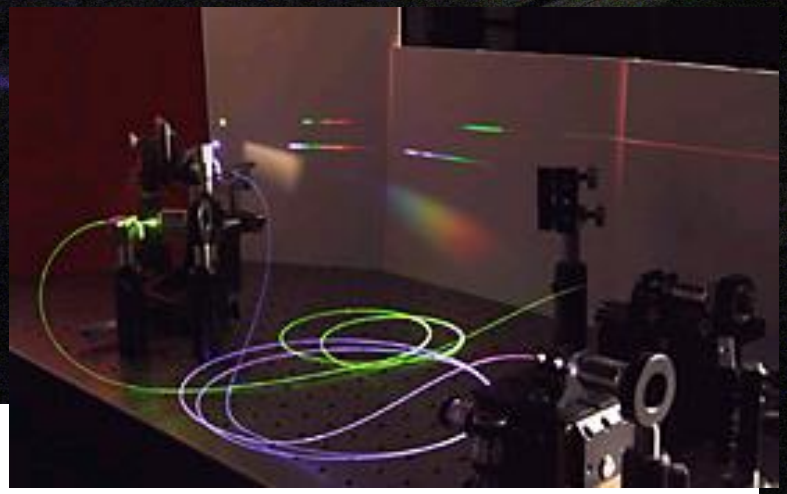
Light matter interaction in PCF

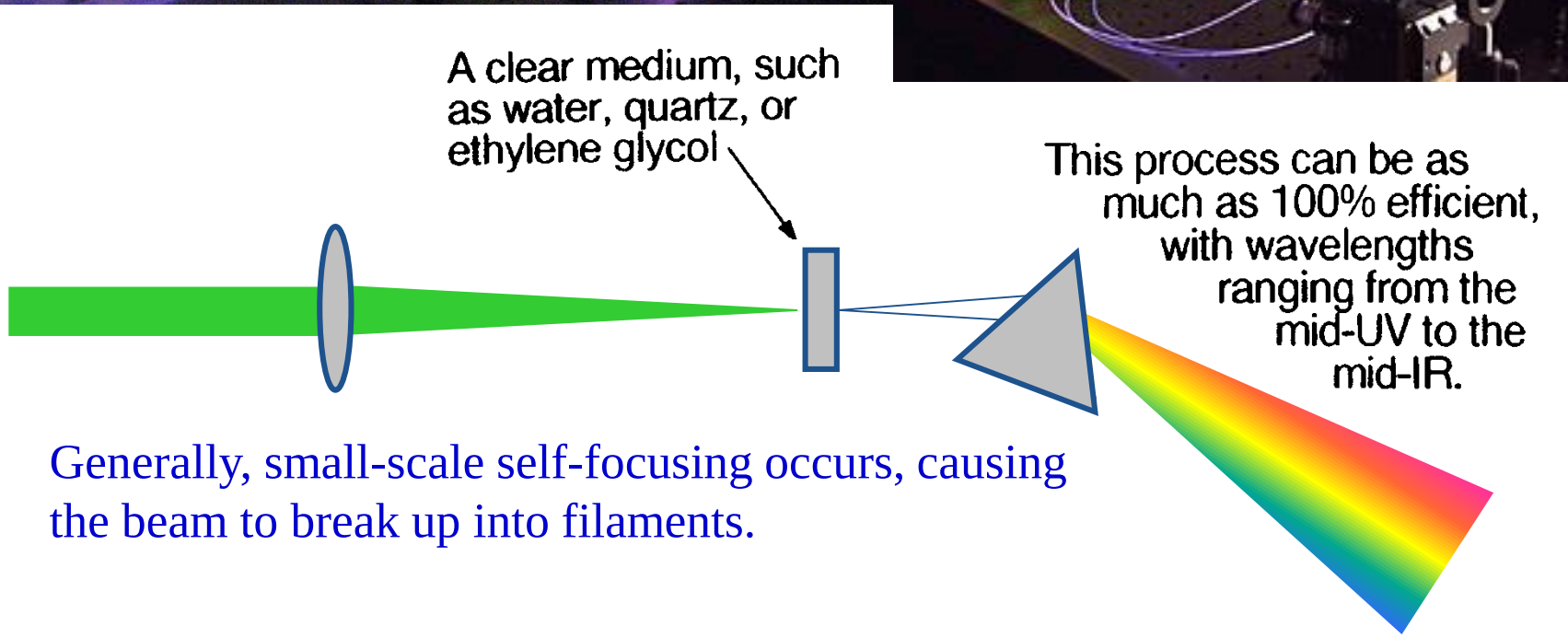
- https://www.youtube.com/watch?v=WAp_UjsMx90

光子技術實驗室

Continuum Generation

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





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!


•Applied to i
and coupled

The "stack and draw" technique

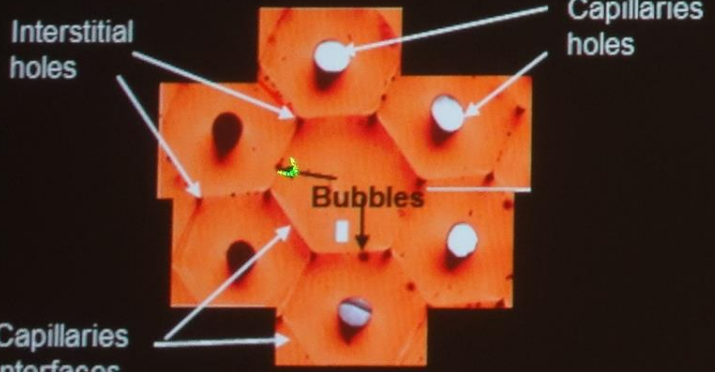
UNIVERSITÉ DE RENNES

❑ **The first Glass studied : S-Sb-Ge-(Ga) Glass**

- Tg = 250 °C, n = 2,25, n_2 = 130 x n_2 SiO_2

❑ **Elaboration of the preform**

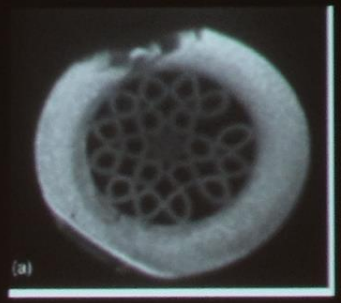
❑ **stack and draw limits**

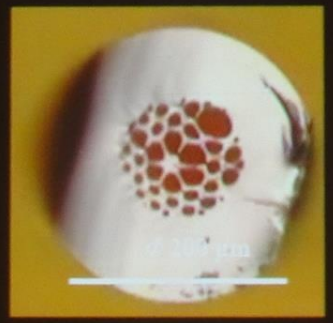


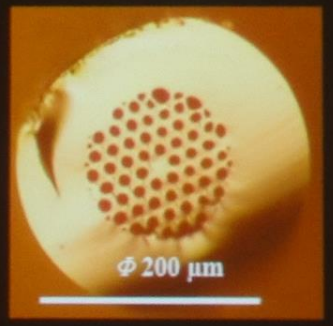
❑ **Strong optical losses**

❑ 5 – 15 d/m at 1,55 µm

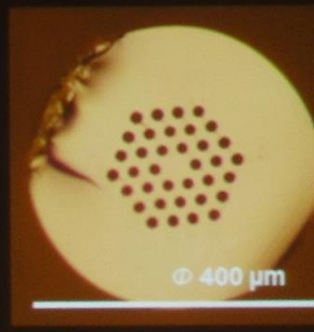
❑ **The first fibers**

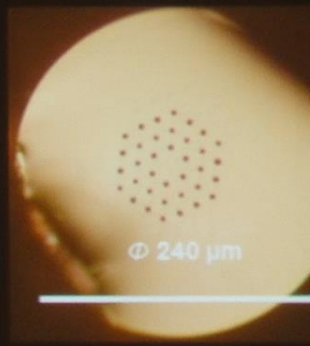


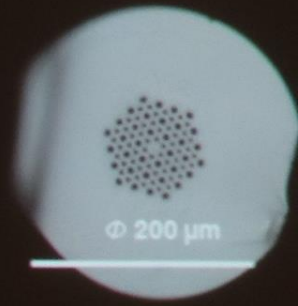




❑ **and..**



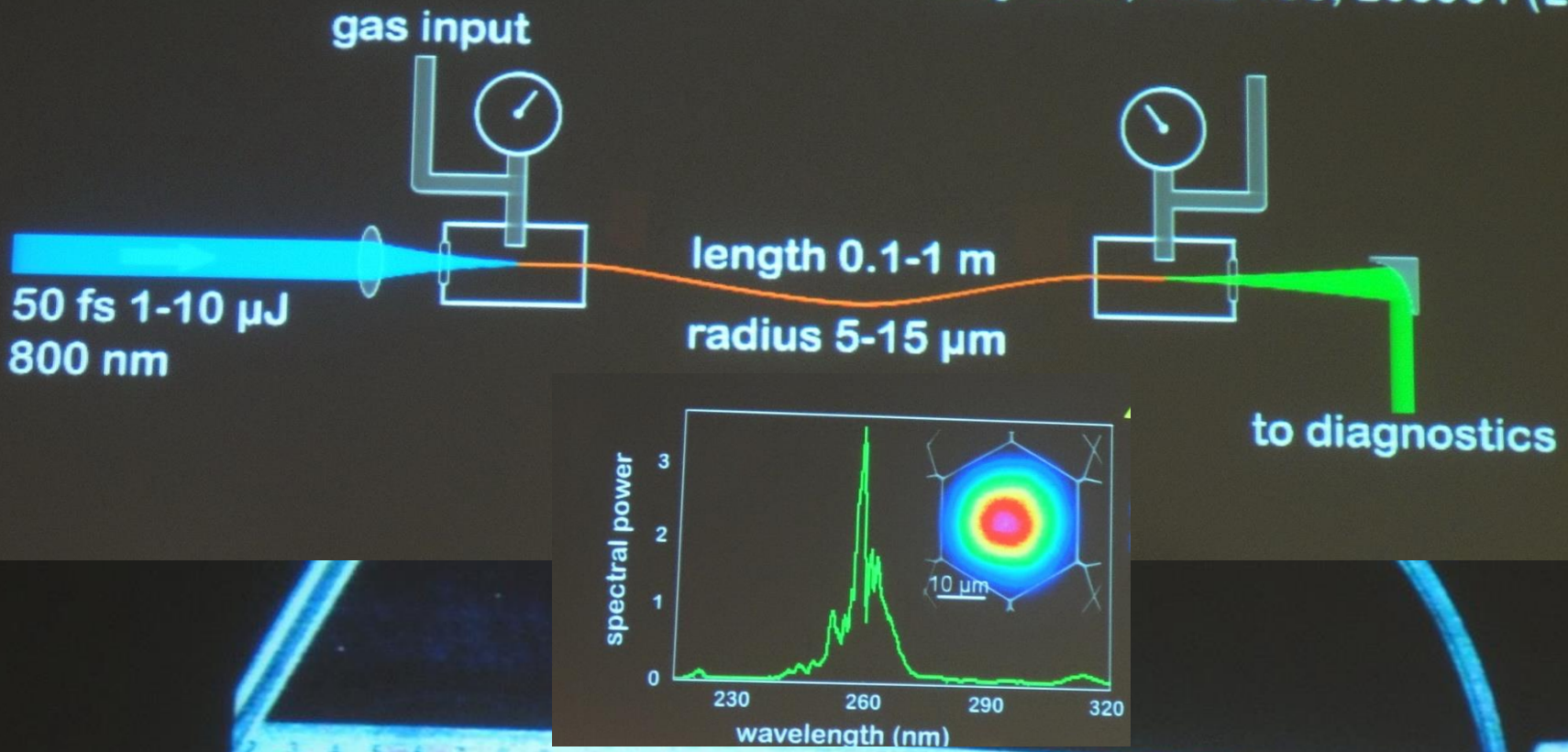


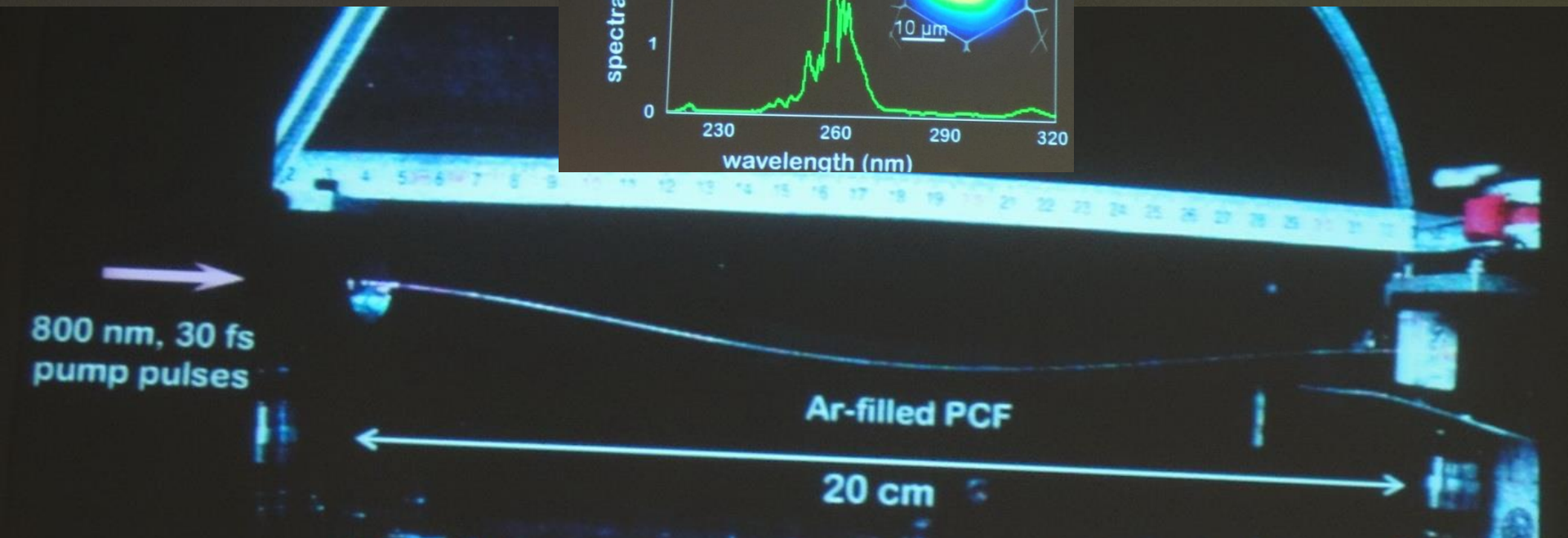


PERFOS

Efficient tunable deep-UV

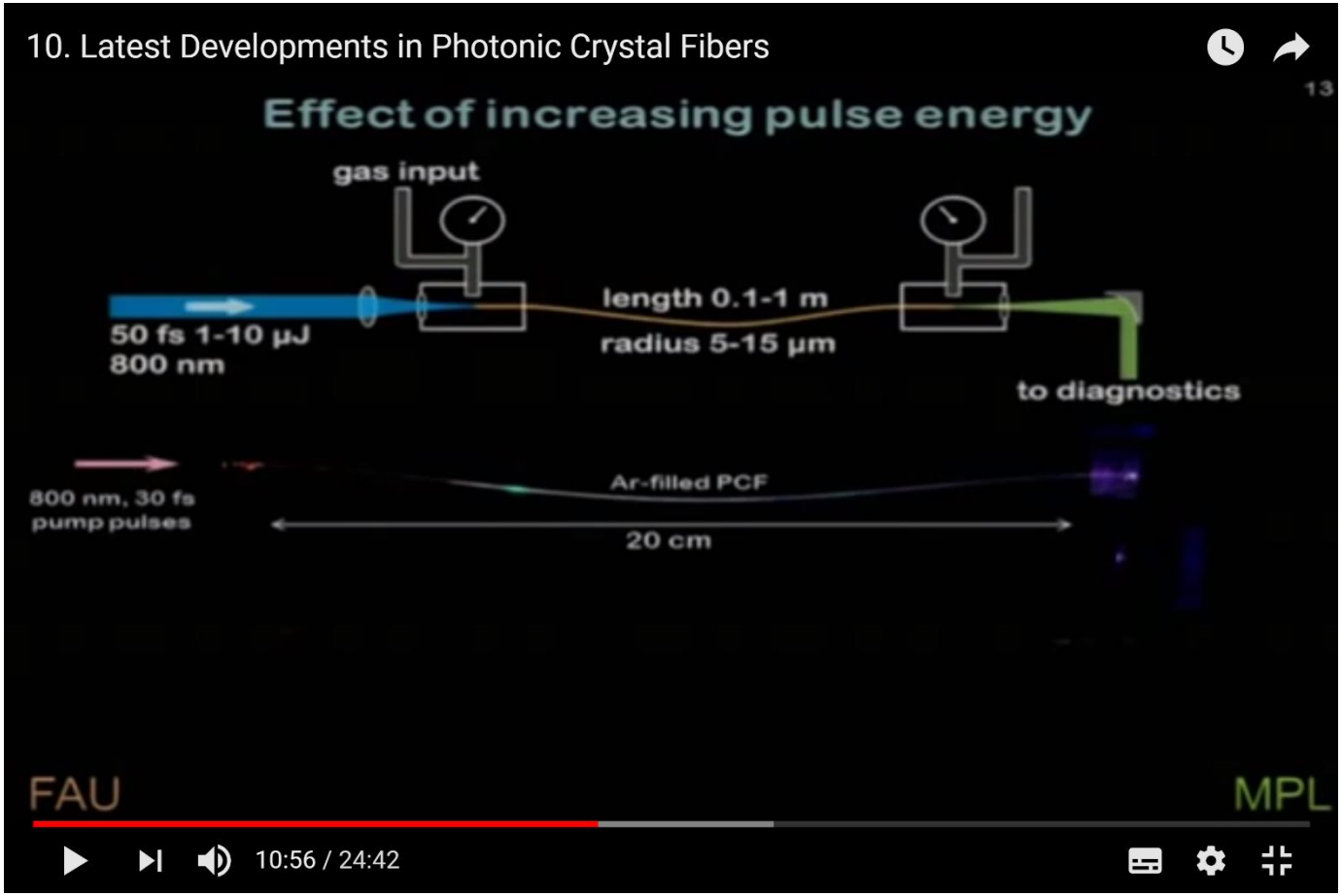
Joly et al, PRL 106, 203901 (2011)





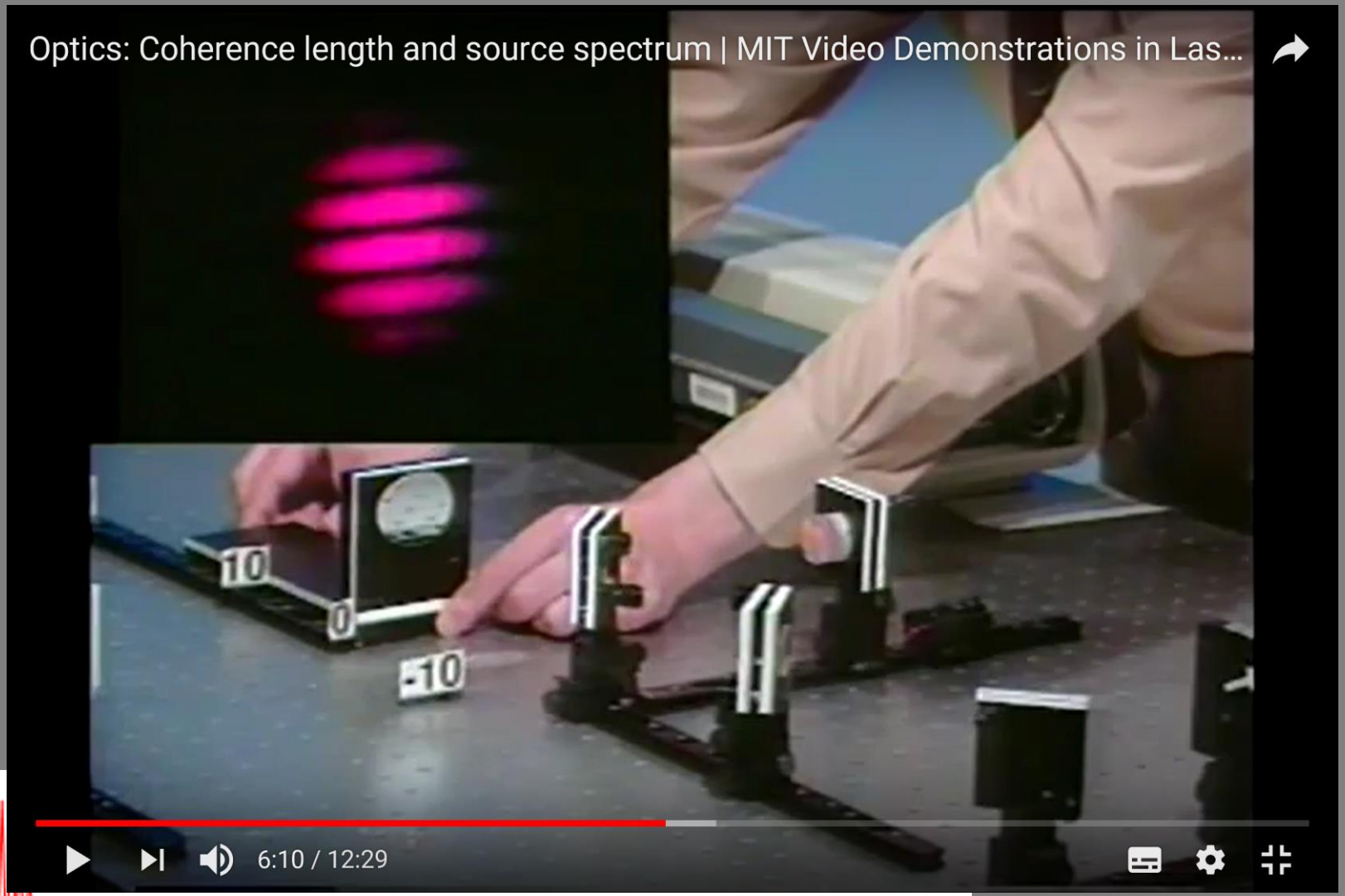
Latest Developments in Photonic Crystal Fibers

- https://www.youtube.com/watch?v=IgoWPW0aC80&t=1s



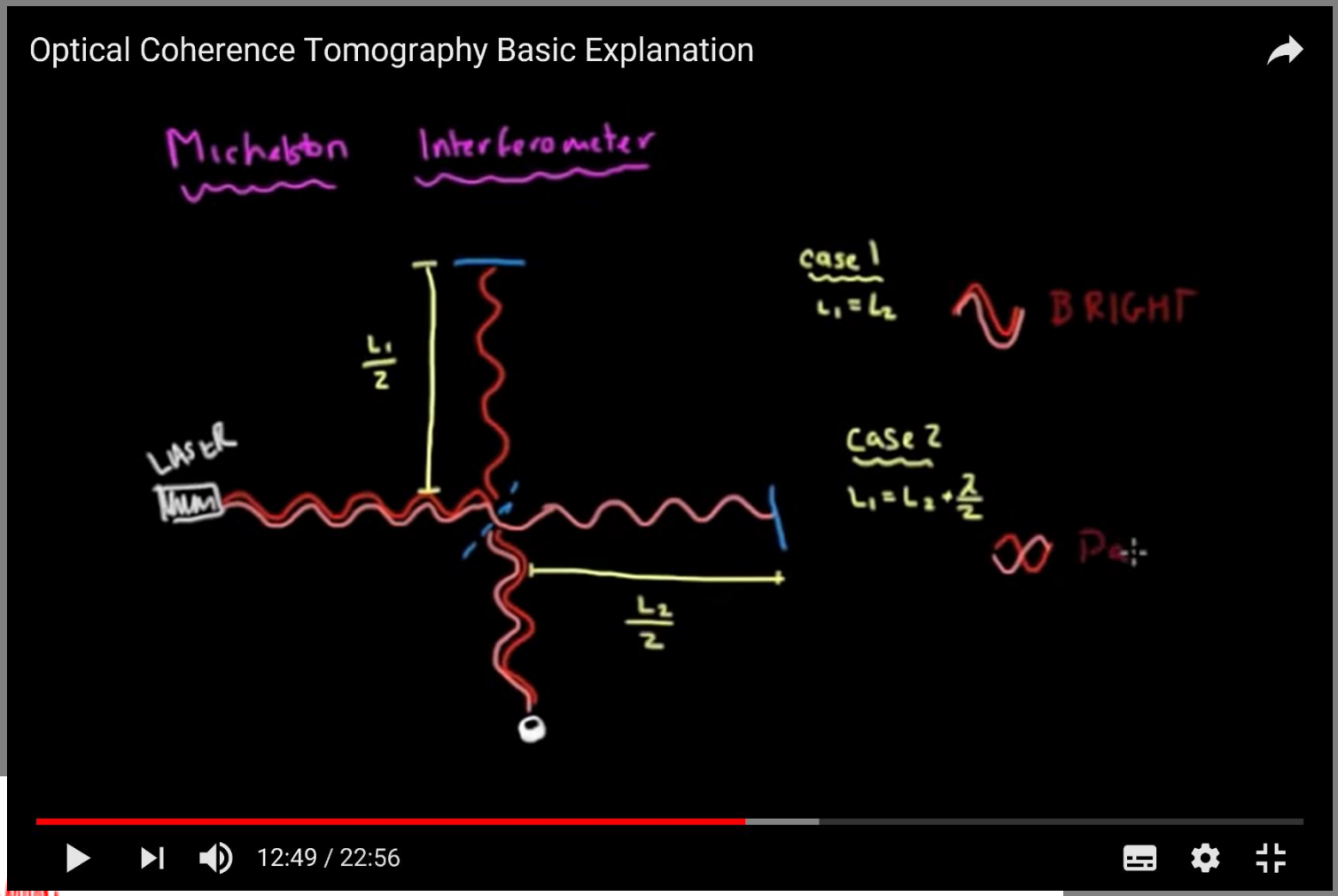
Coherence length

- https://www.youtube.com/watch?v=LixwAXsN8vg



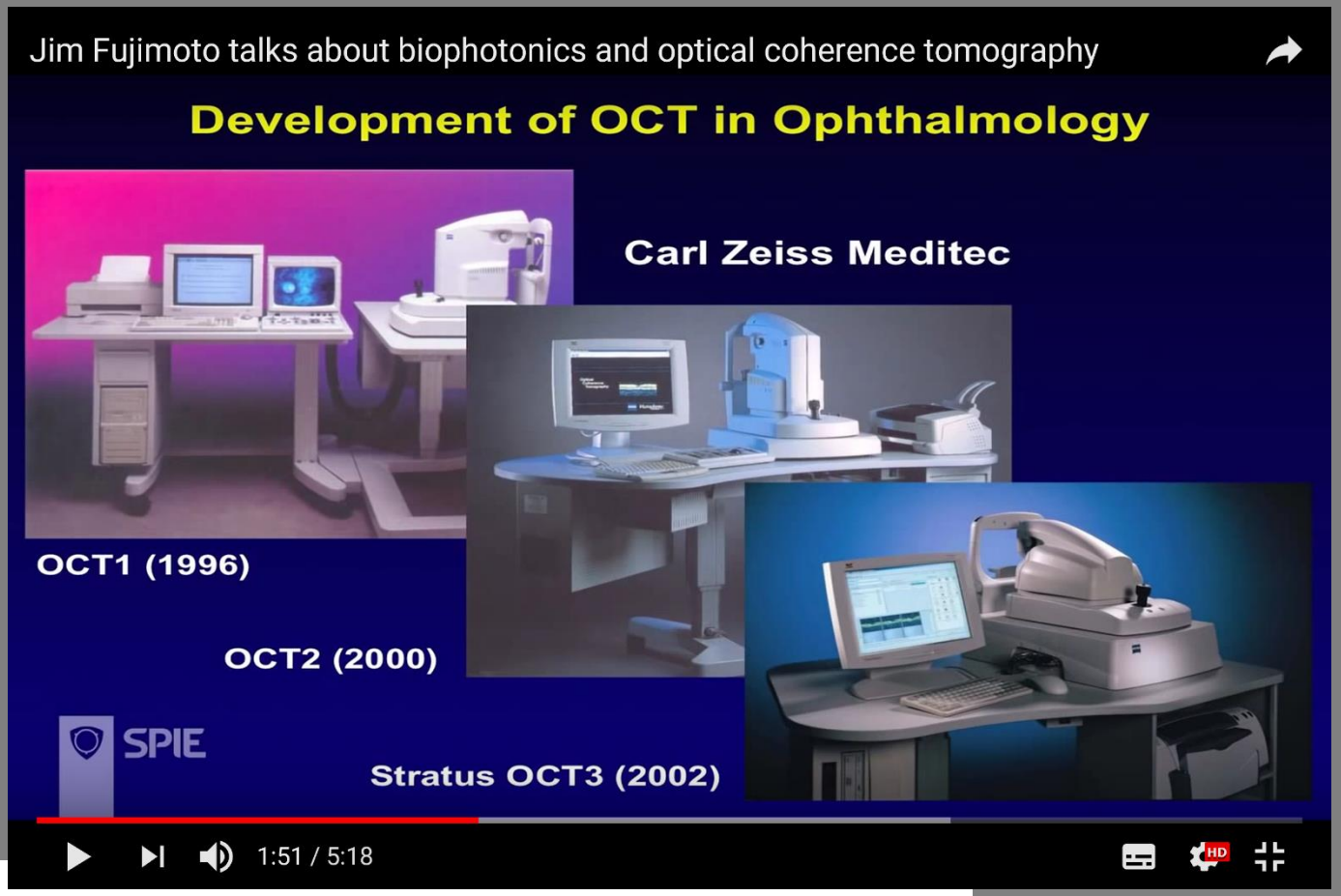
Optical coherence tomography (Principle)

- https://www.youtube.com/watch?v=HJnNJIUPm4s



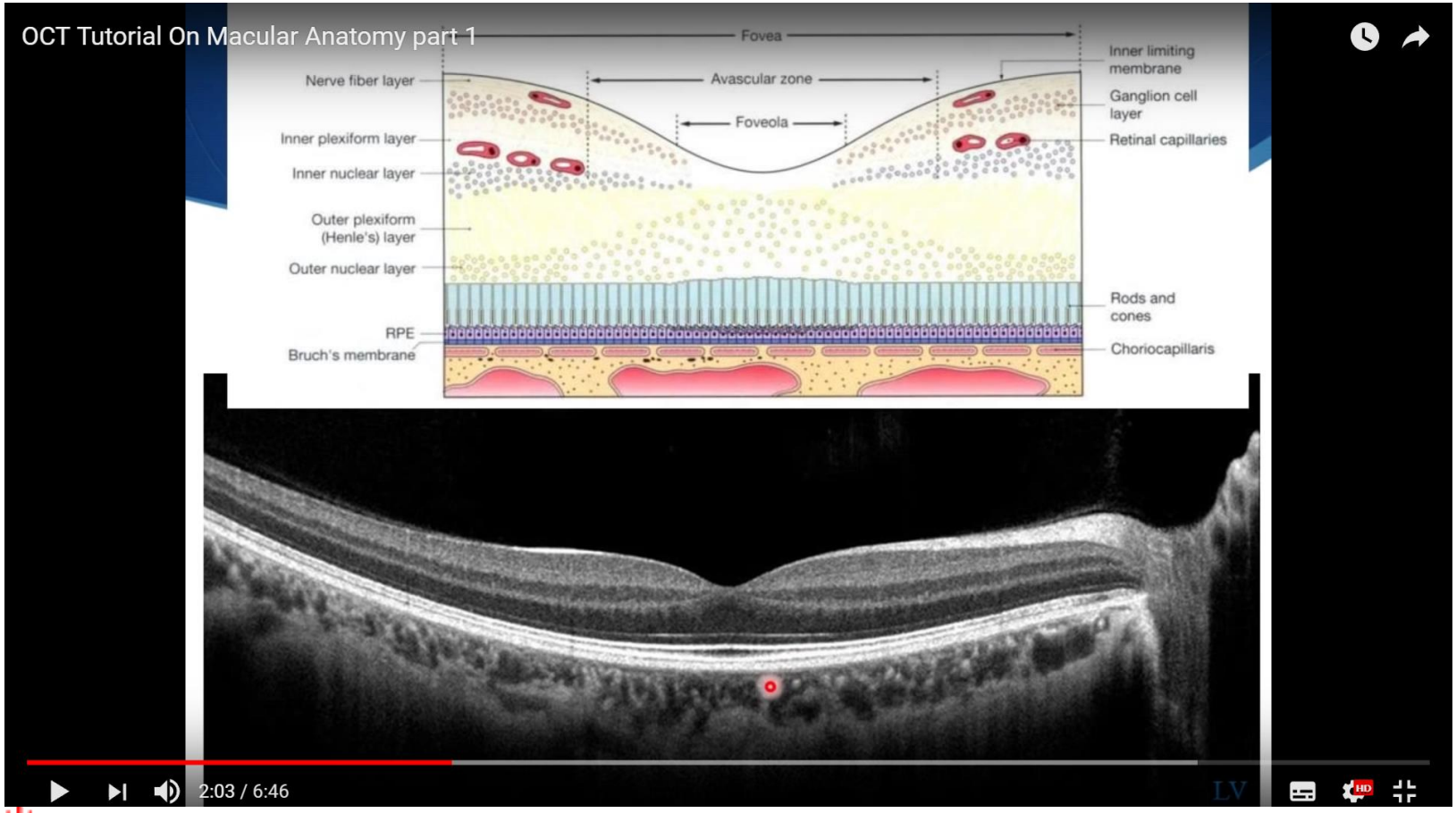
Optical coherence tomography (Inventor)

- https://www.youtube.com/watch?v=JyCmzEO4RDw



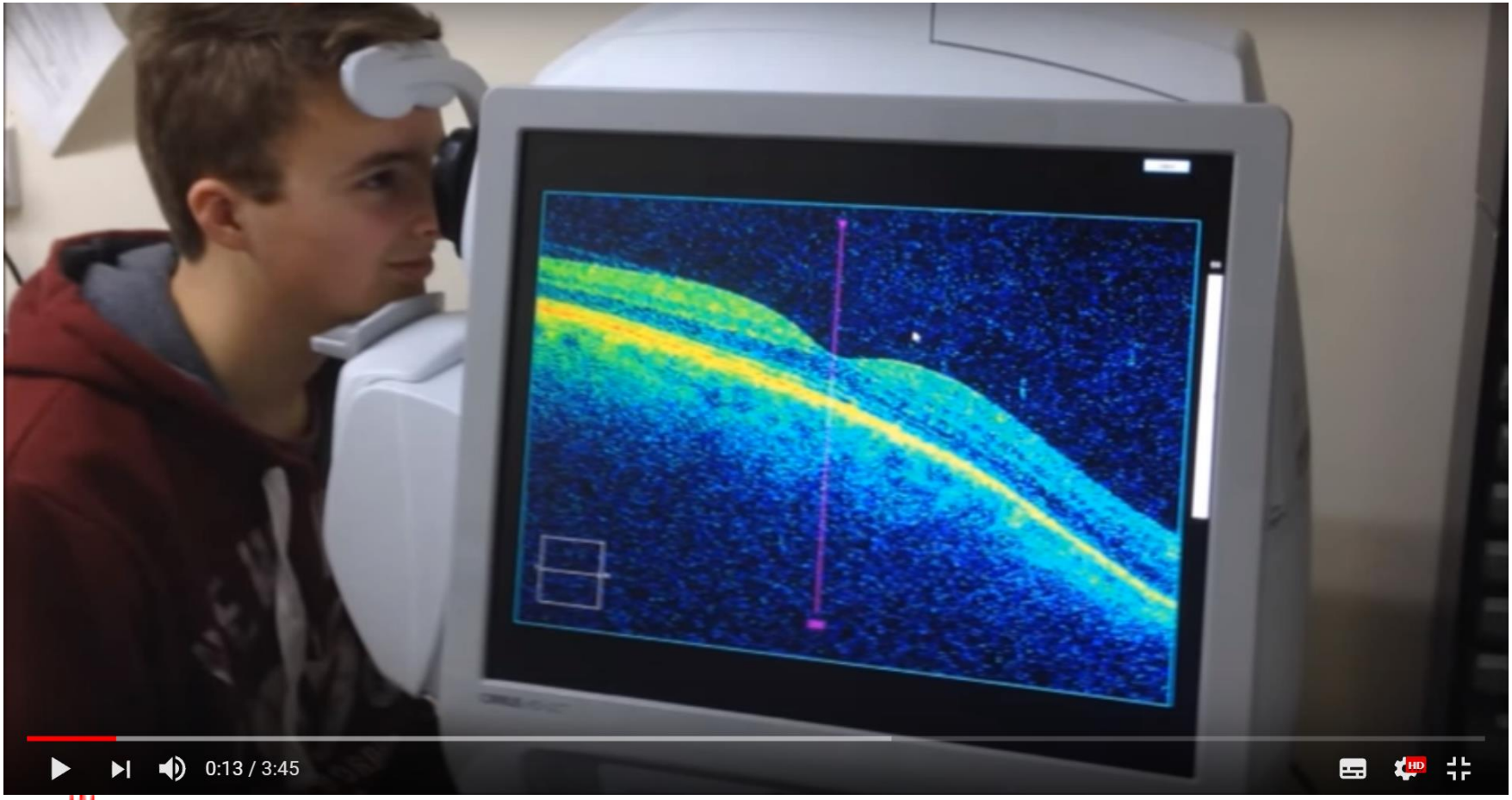
OCT Tutoria

- https://www.youtube.com/watch?v=H43ccvAEYEk



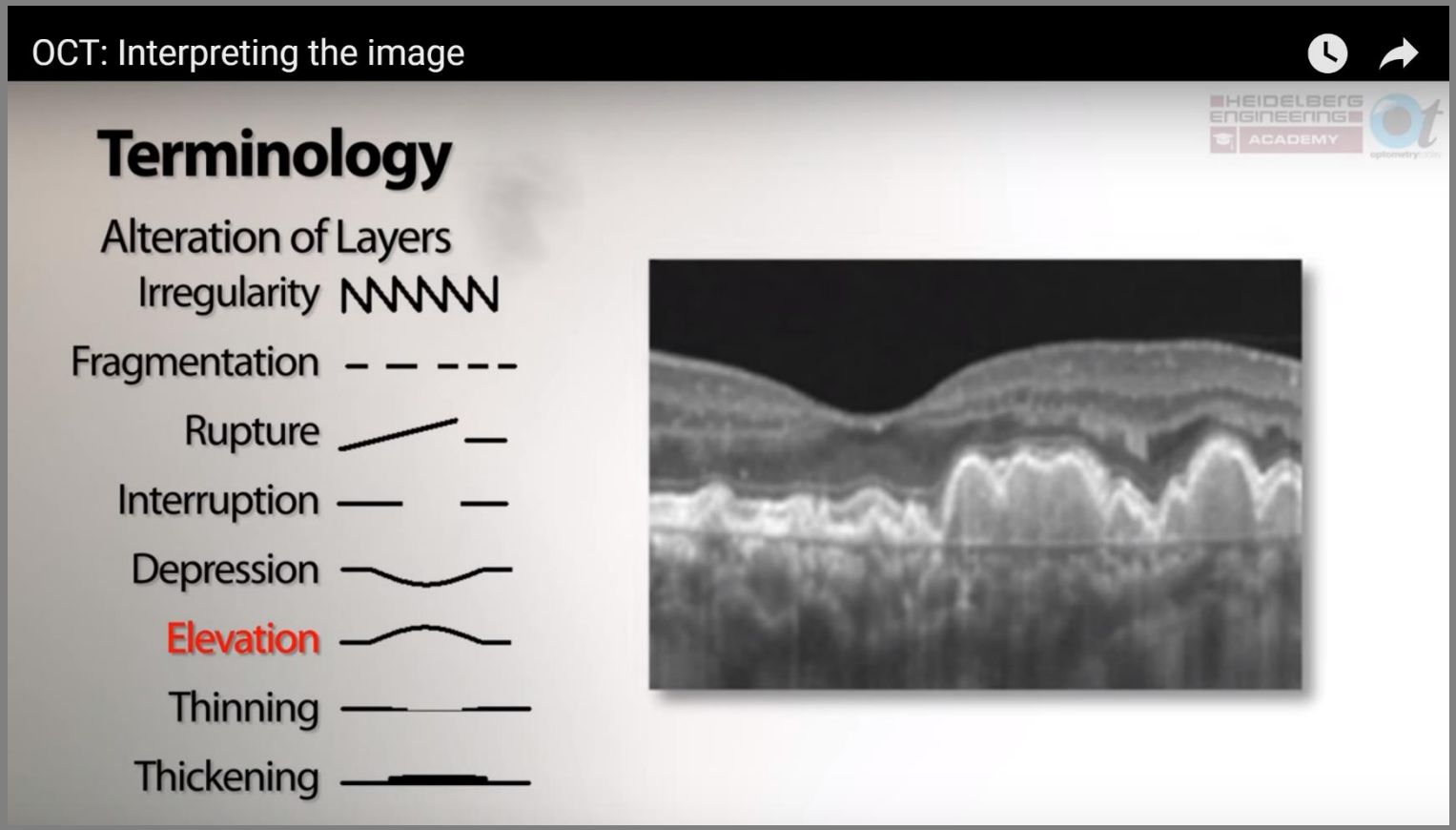
What is OCT?

- https://www.youtube.com/watch?v=BxRAAVr7oA8

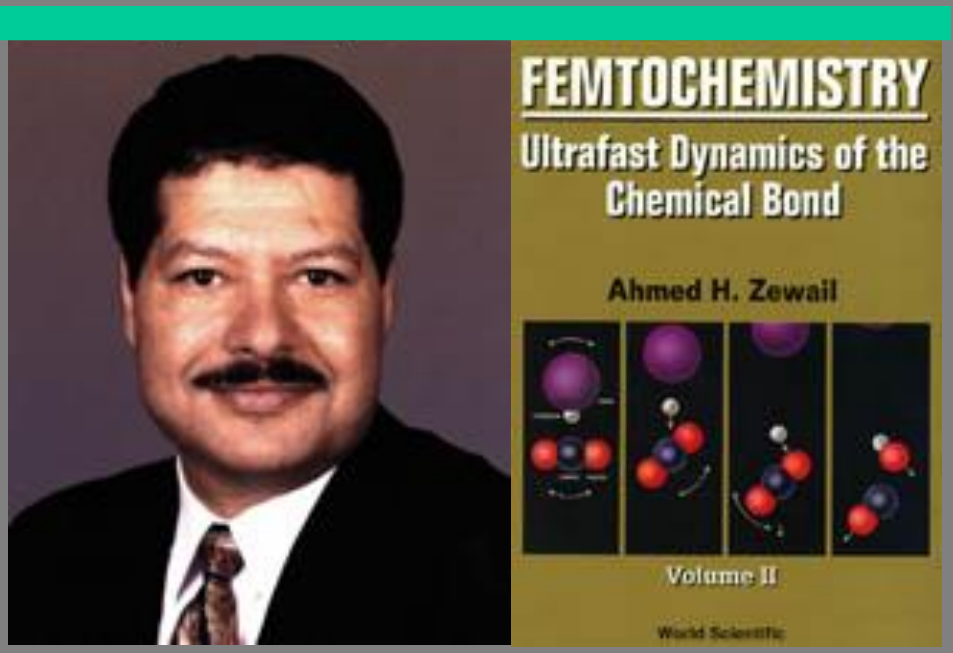


OCT image

- https://www.youtube.com/watch?v=m932i-c_-4Y



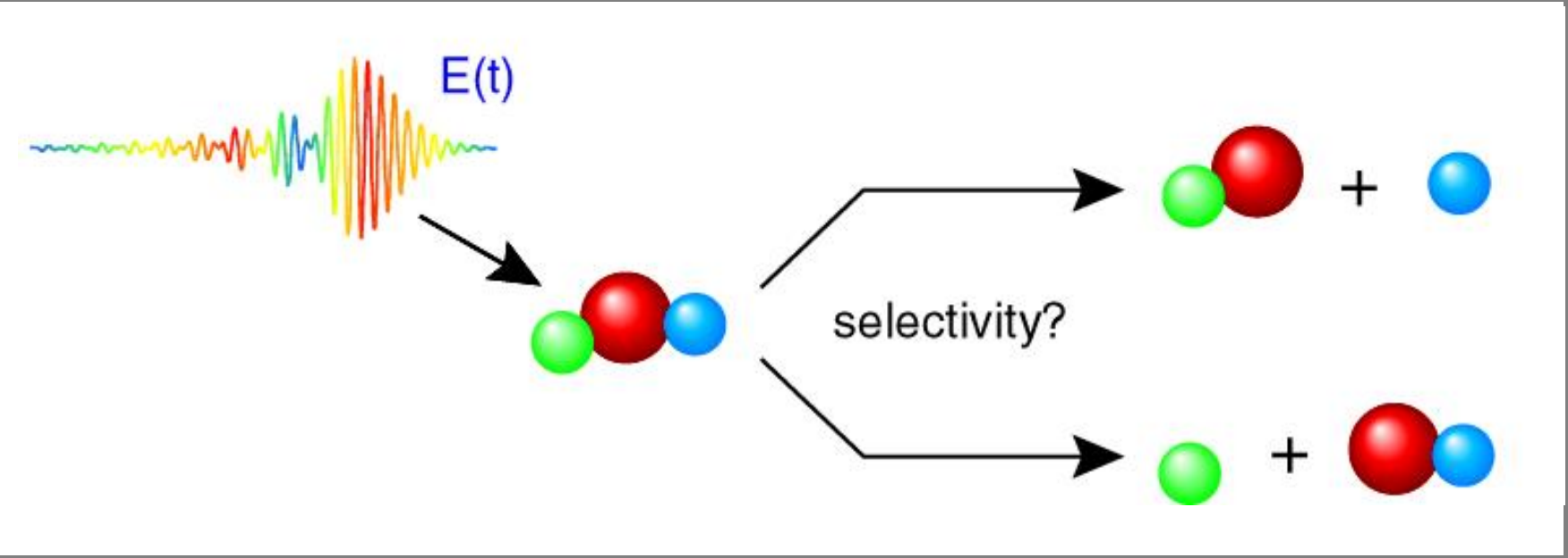
The 1999 Nobel Prize in Chemistry went to Professor Ahmed Zewail of Cal Tech for ultrafast spectroscopy.



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

Beyond ultrafast spectroscopy: controlling chemical reactions with ultrashort pulses

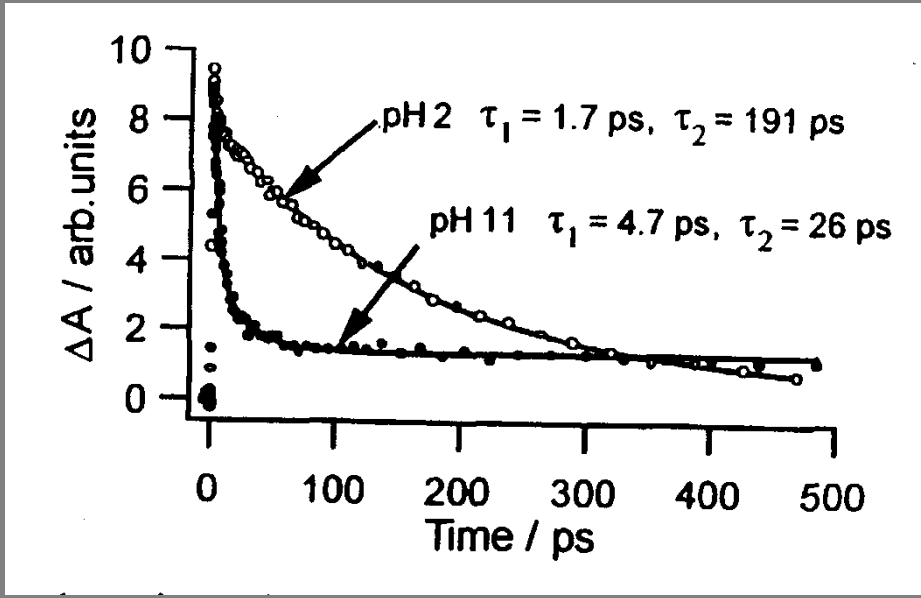
You can excite a chemical bond with the right wavelength, but the energy redistributes all around the molecule rapidly ("IVR").



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

Ultrafast Excite-Probe Measurements in DNA

DNA bases undergo photo-oxidative damage, which can yield mutations. Understanding the photo-physics of these important molecules may help to understand this process.



Transient absorption at 600 nm of protonated guanosine in acidic (pH 2) and basic (pH 11) aqueous solution.

Pecourt, et al., Ultrafast Phenomena XII, p.566(2000)

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.
- Fluorescence occurs on a ns time scale, but competing non-radiative processes only speed things up because relaxation rates add:

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

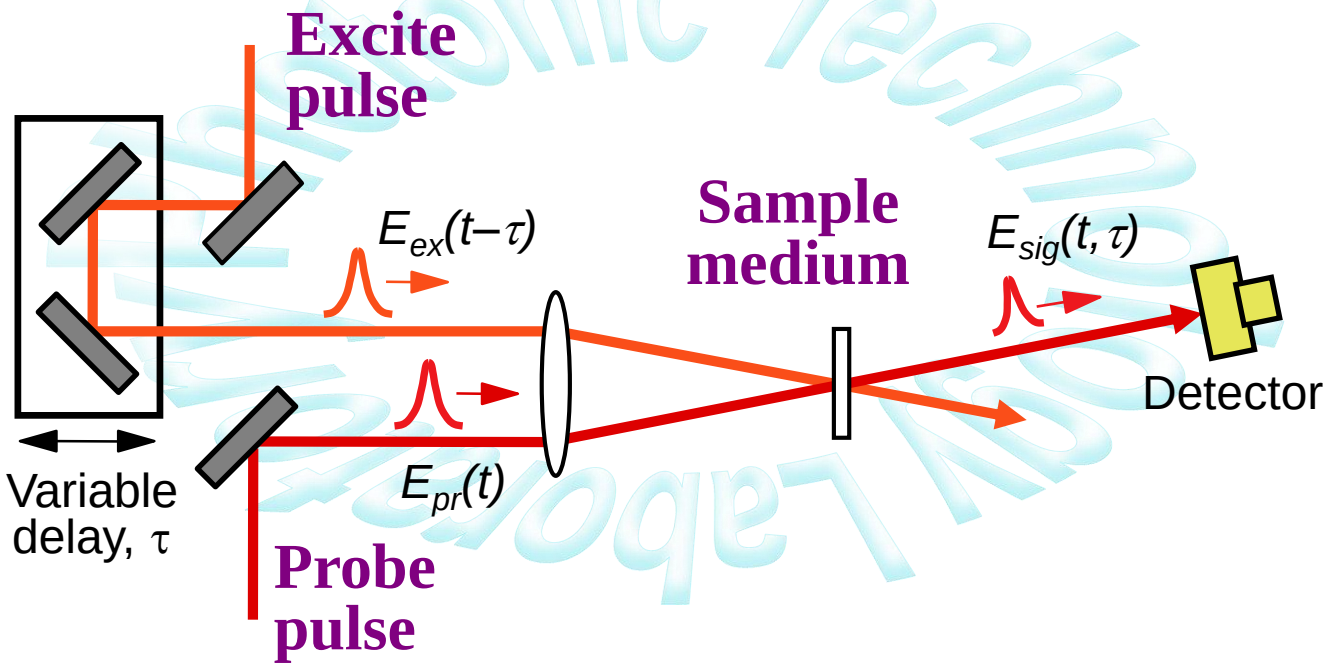
Biologically important processes utilize excitation energy for purposes other than fluorescence and hence must be very fast.

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 simplest ultrafast spectroscopy method is the Pump-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:

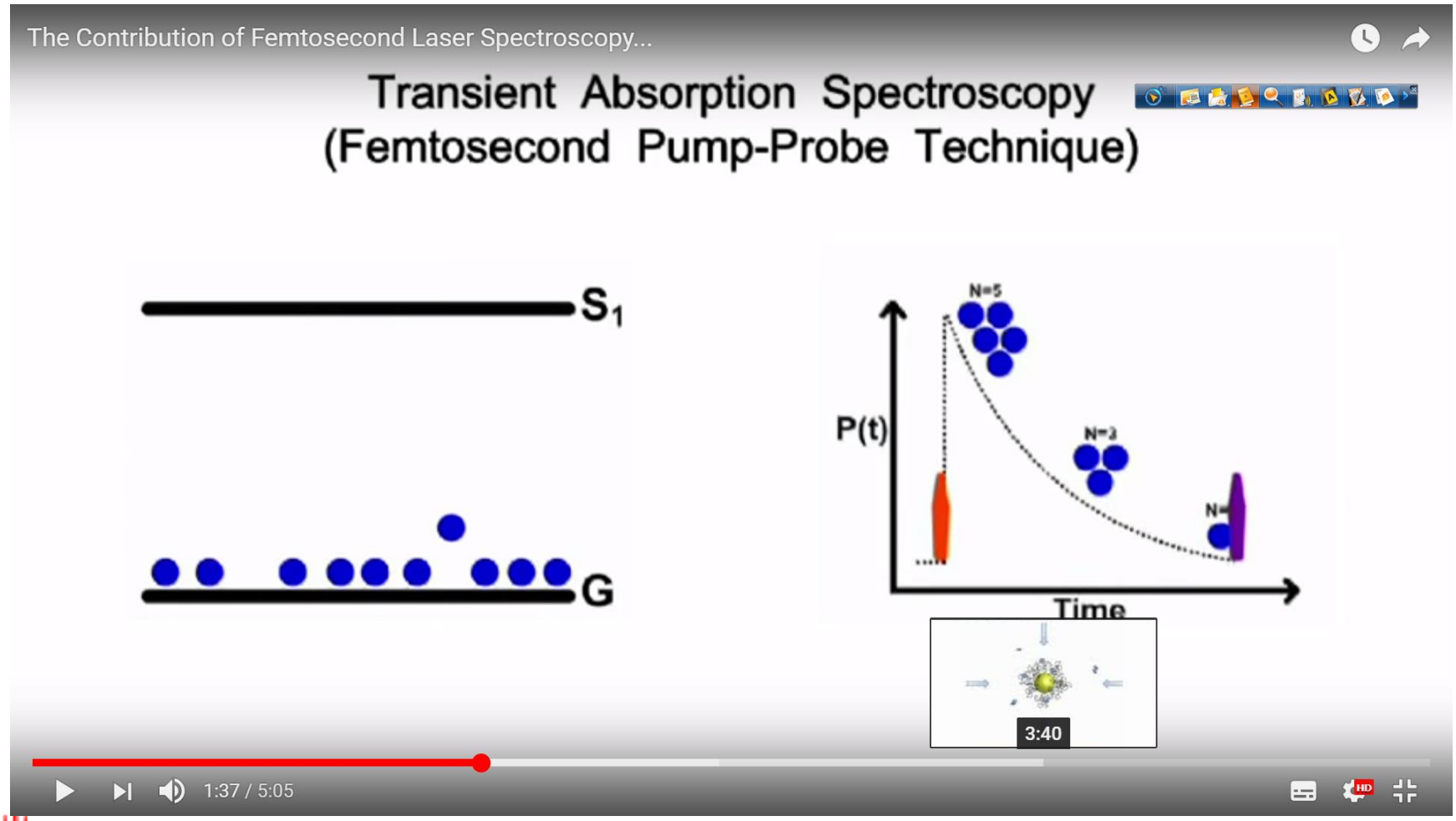


The excite and probe pulses can be different colors.

This technique is also called the "Pump-Probe" Technique.

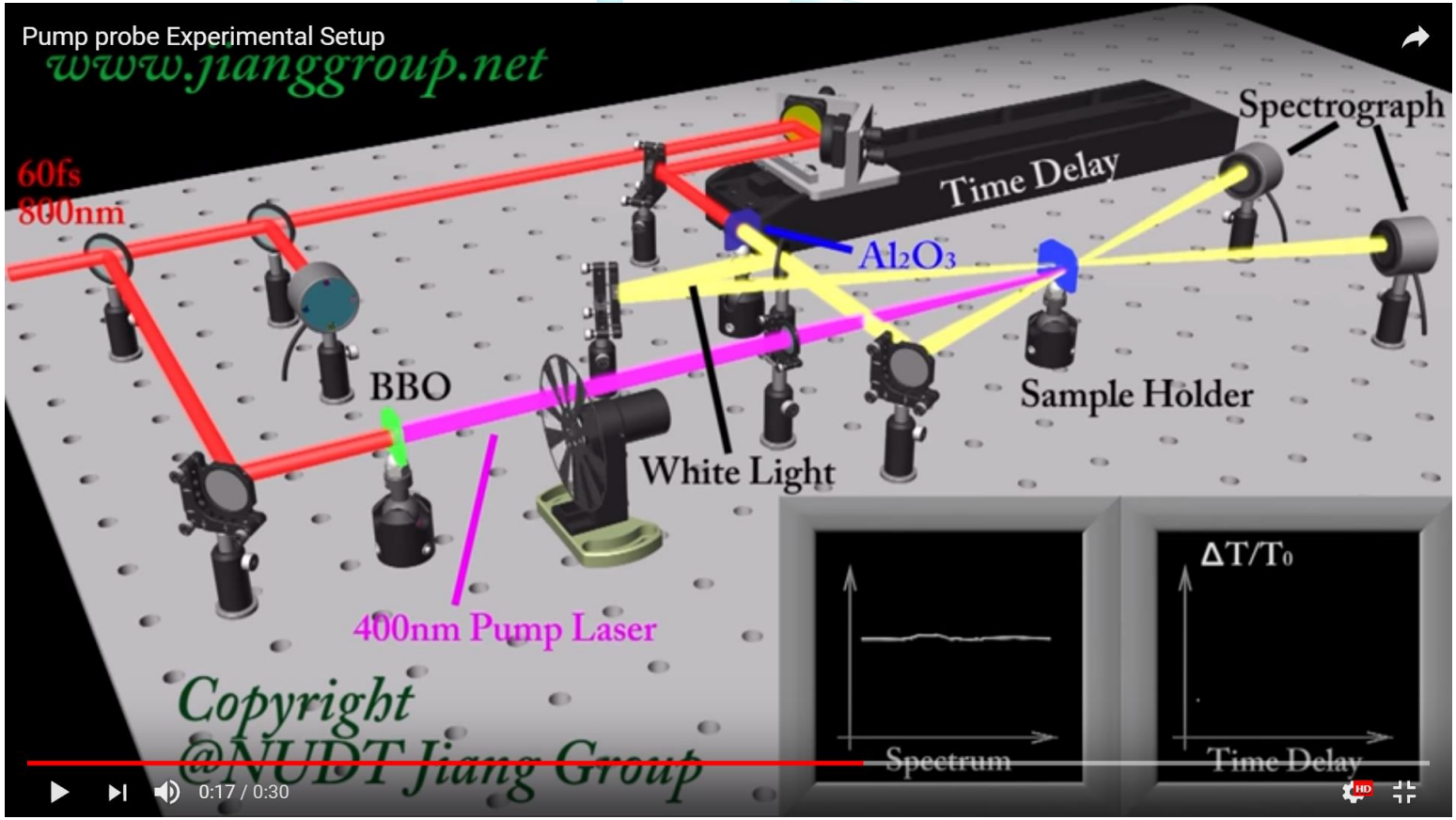
Contribution of Femtosecond Laser Spectroscopy

- https://www.youtube.com/watch?v=4hx_TfLabOs



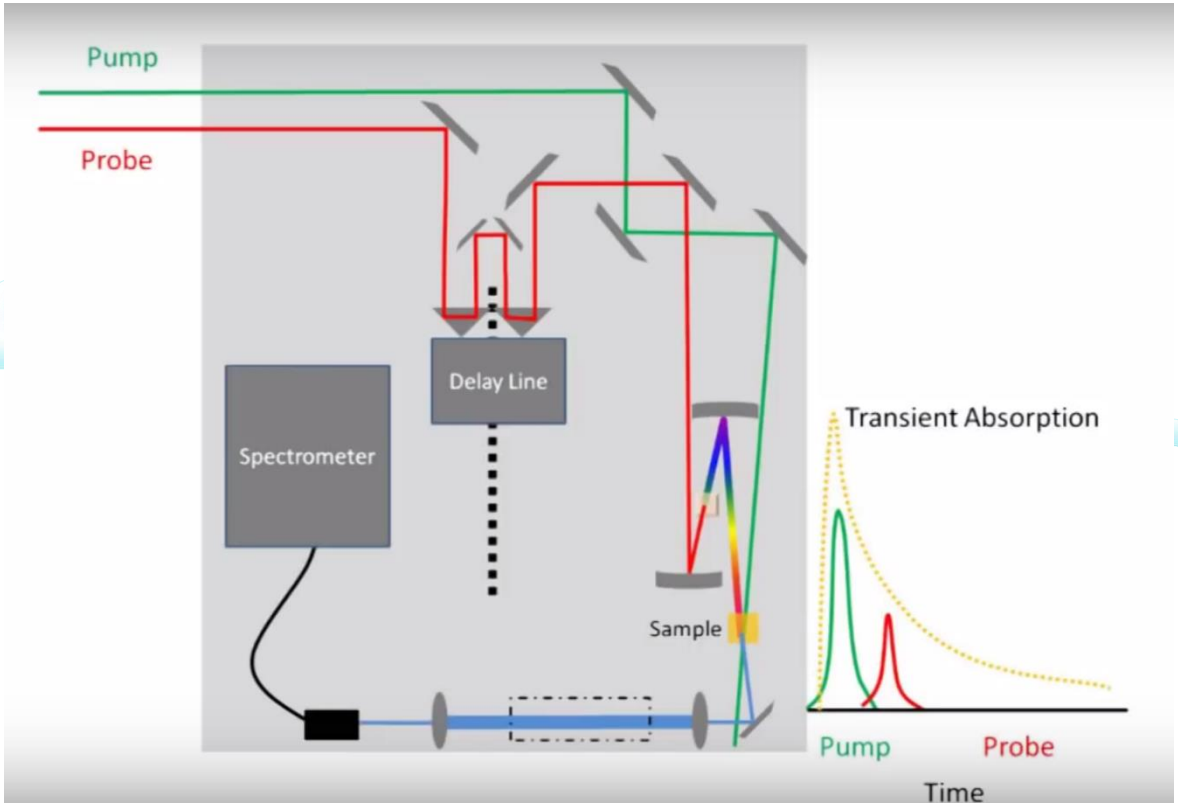
Pump-probe Setup

- https://www.youtube.com/watch?v=BZBgPanGuEI



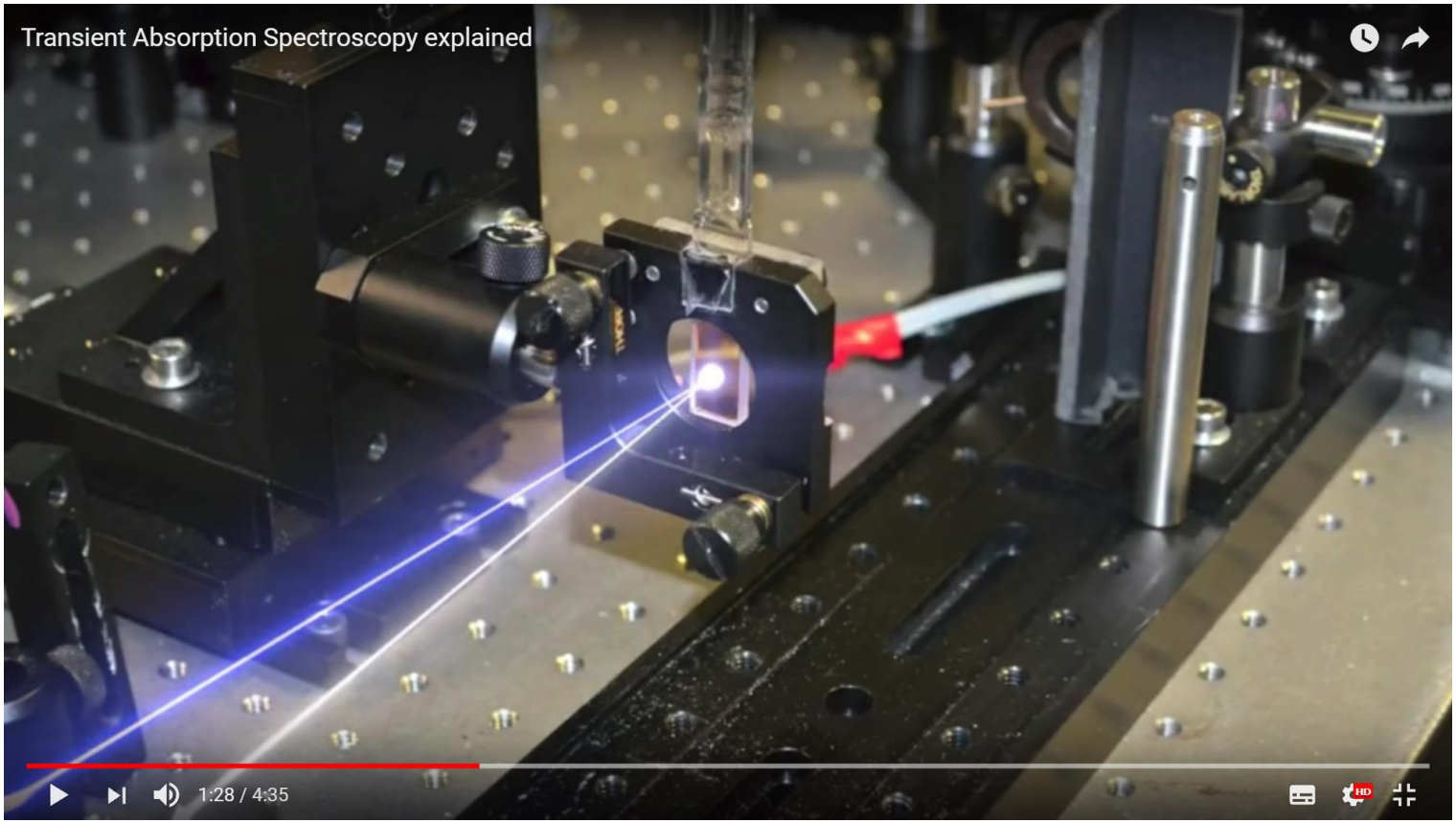
Pump-Probe technique

- https://www.youtube.com/watch?v=mdNr6eVBJqk



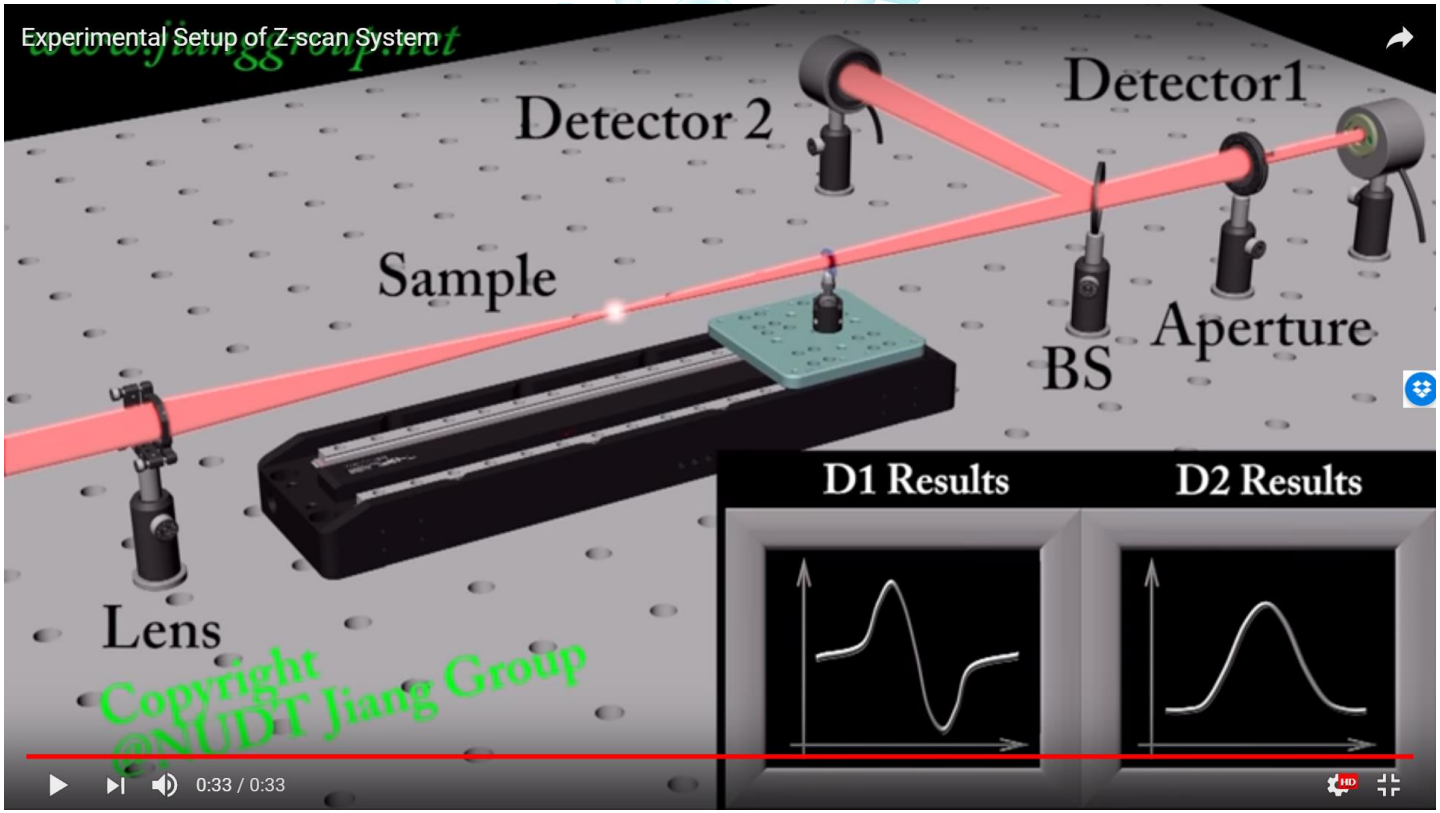
Transient absorption spectroscopy

- https://www.youtube.com/watch?v=RFFfYlq3oEo&t=44s



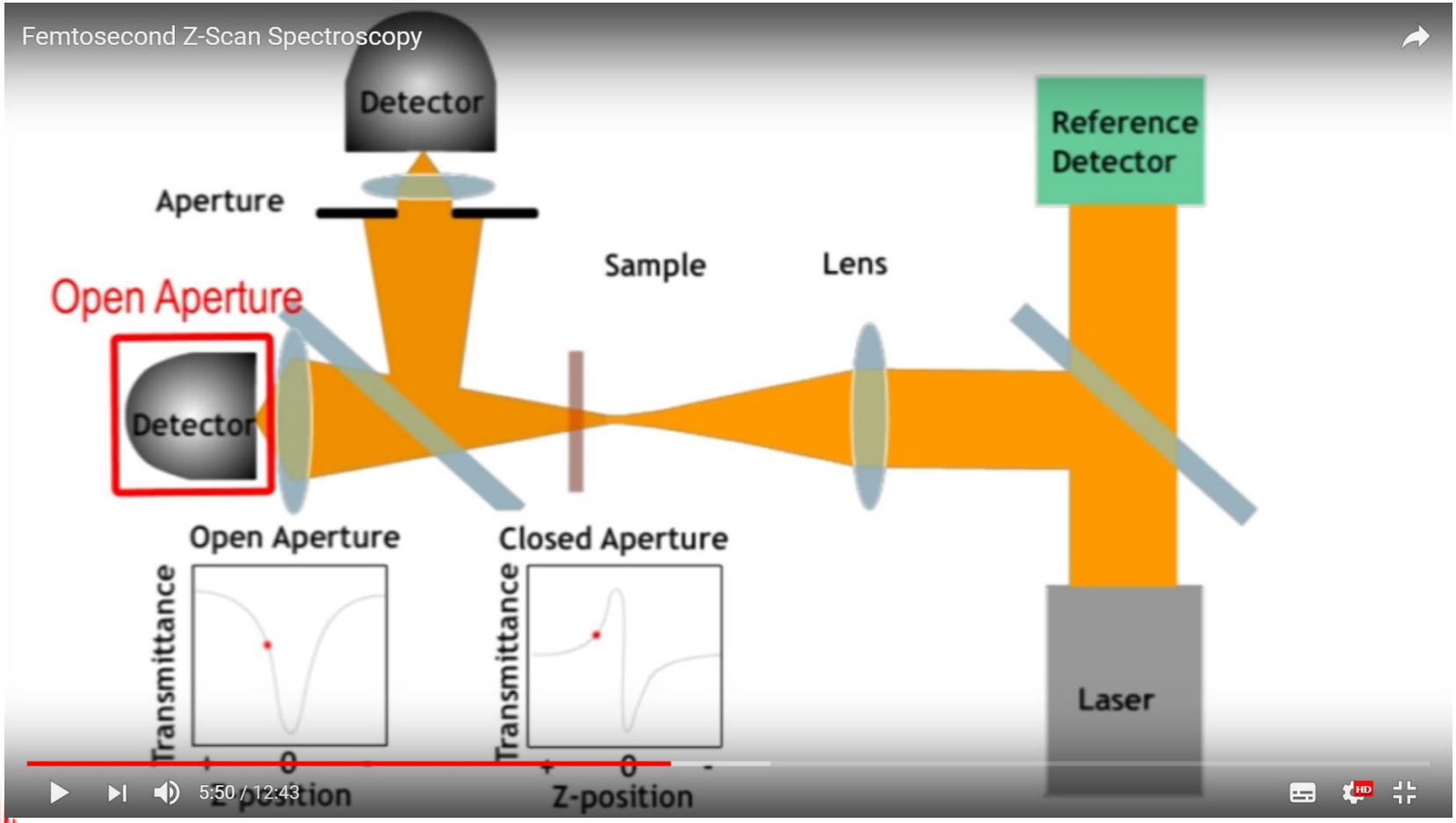
Z-scan

- https://www.youtube.com/watch?v=lSJl3cNkq74



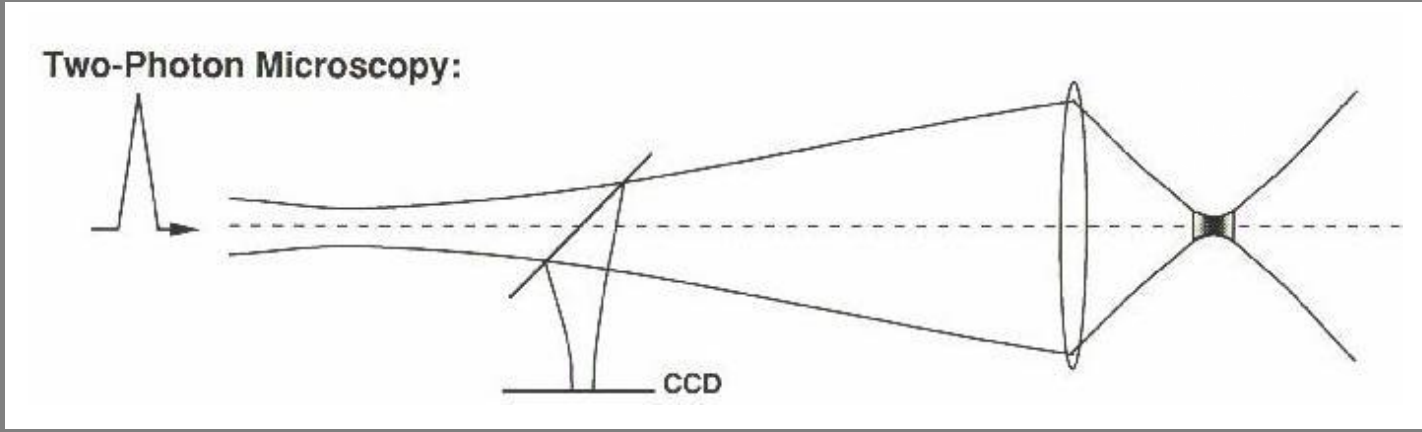
Z-scan principle

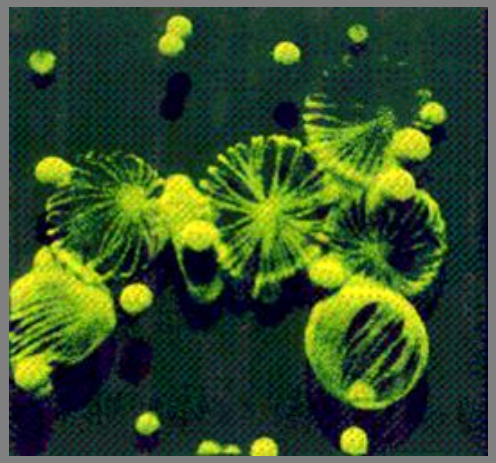
- https://www.youtube.com/watch?v=yMhNLLIYb5w&t=204s



High intensity allows nonlinear imaging.

Novel imaging techniques yield ~1-μm resolution, emphasizing edges of objects. They include optical coherence tomography and multi-photon imaging.



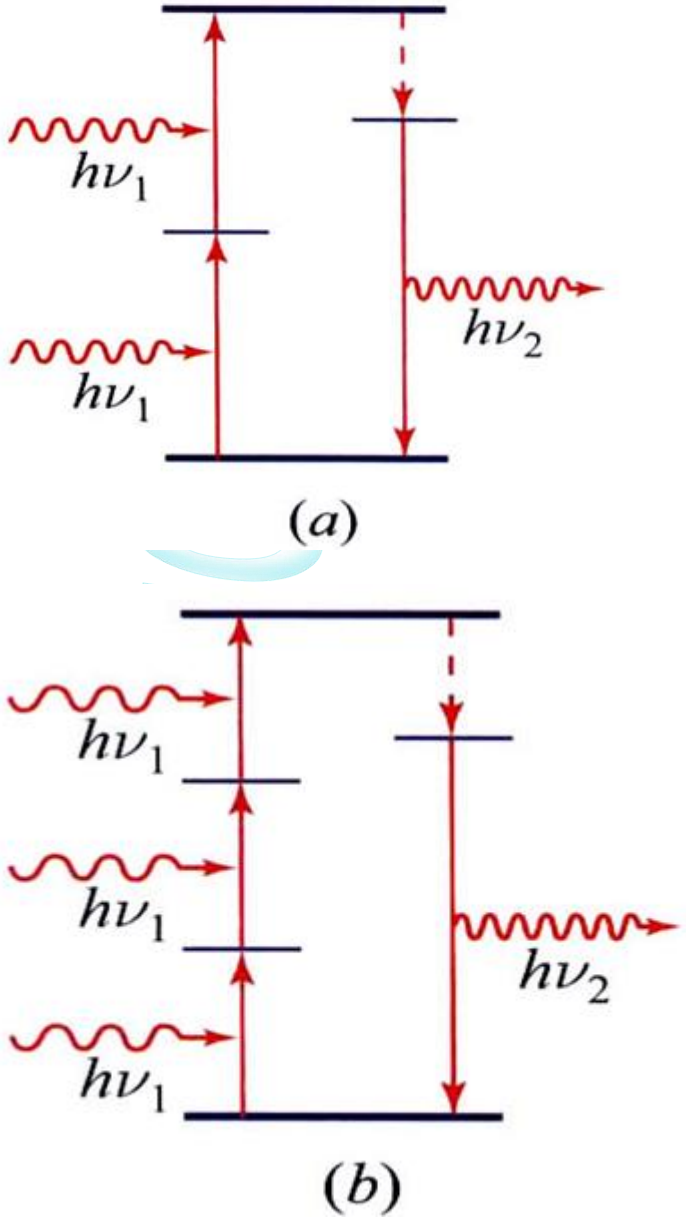


2-photon microscopy
of pollen grains using an ultrashort pulse

University of Michigan
Center for Ultrafast Optical Sciences

Multiphoton fluorescence

- Two or more photons of the same energy may conspire to raise the system to a higher energy level, where it undergoes photoluminescence (**fluorescence (a) and (b)**).
- Two-photon fluorescence in (a) is the basis of an imaging technique known as **two-photon laser scanning fluorescence microscopy (TPLSM)**.
- A fluorescent probe (**fluorophore**), absorbs **a pair of photons** that arrive in its vicinity, each with energy $h\nu_1$, and then emits **a single fluorescence photon** with energy $h\nu_2$ ($> h\nu_1$), which is detected.

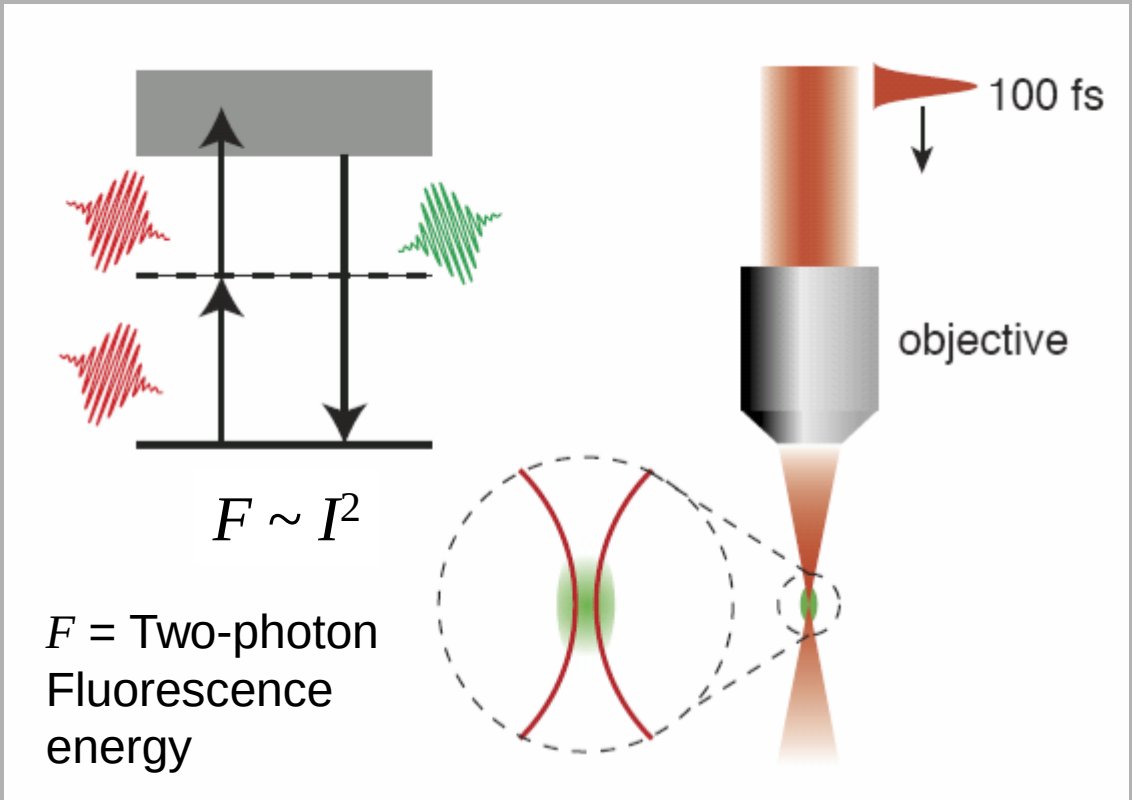


- The advantage of TPLSM in the domain of **biology** is the **double wavelength** of the excitation
  - since **longer wavelengths** penetrate more deeply into **biological tissue**.
  - The **peak intensity** is sufficiently high to engender **two-photon absorption**,
  - The average power is sufficiently low to avoid damage to delicate tissue,
  - The excitation is often provided by a **mode-locked *laser*** that generates ultrashort (femtosecond) optical pulses.

- **Multiphoton laser scanning fluorescence microscopy** operates in much the same way,
  - Except that *k* independent photons, rather than two, conspire to effect each absorption
  - The **emitted fluorescence-photon rate** varies as $I^k(\boldsymbol{r},\boldsymbol{t})$.

Multi-photon imaging

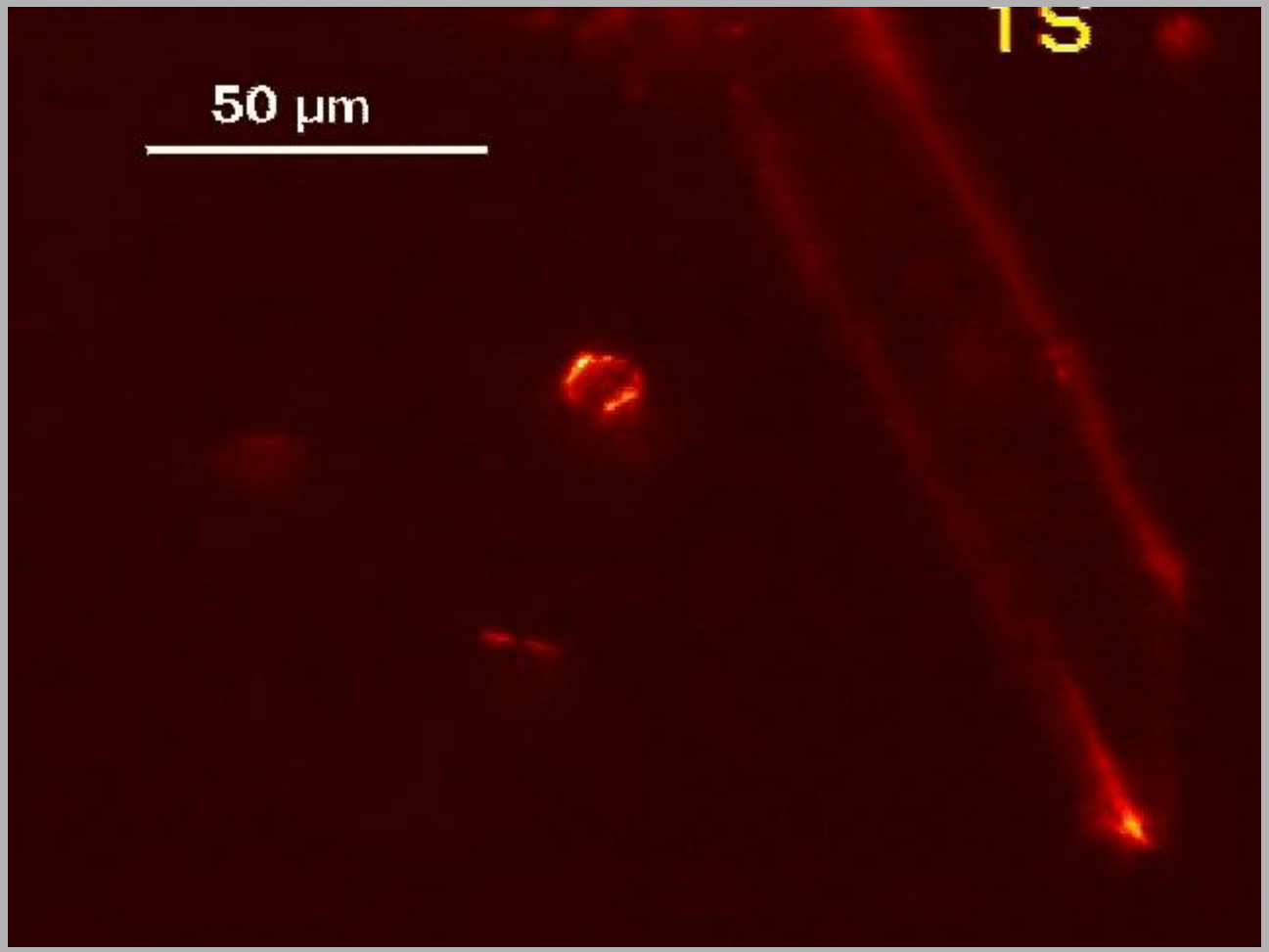
In multi-photon imaging, we focus an ultrashort pulse tightly into an object and observe the multi-photon signal light.



Images due to Chris Schaffer, UCSD

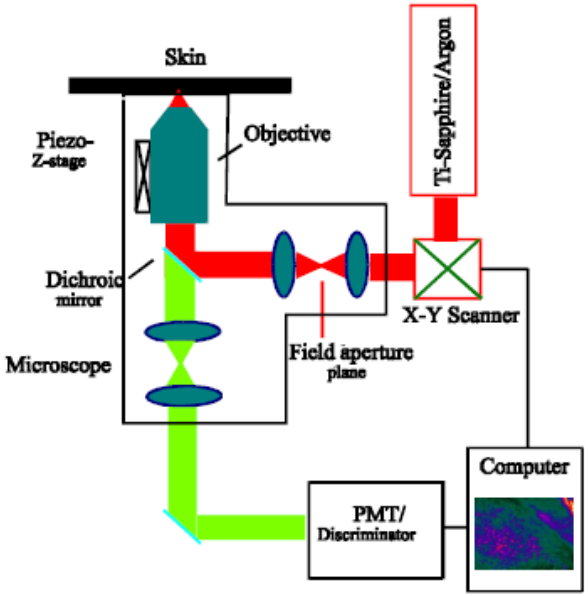
Real-Time THG Images

Anonymous microbes in Amsterdam canal water
(阿姆斯特丹運河不知名微生物)



Images due to Jeff Squier, Colorado School of Mines

Confocal microscopy and multi-photon excitation microscopy of human skin in vivo

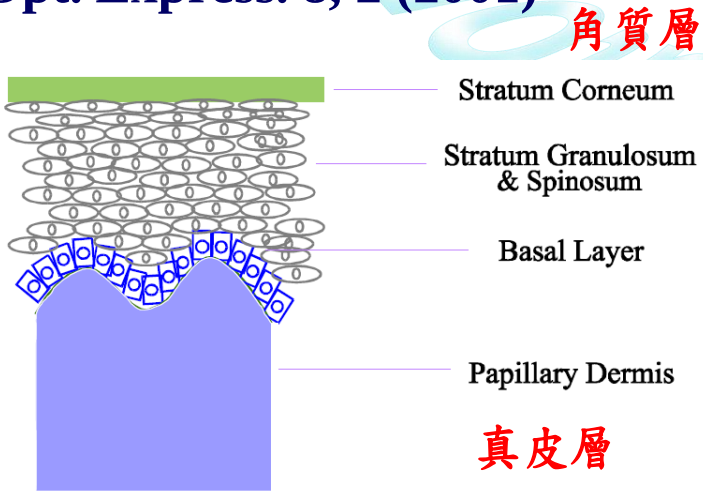


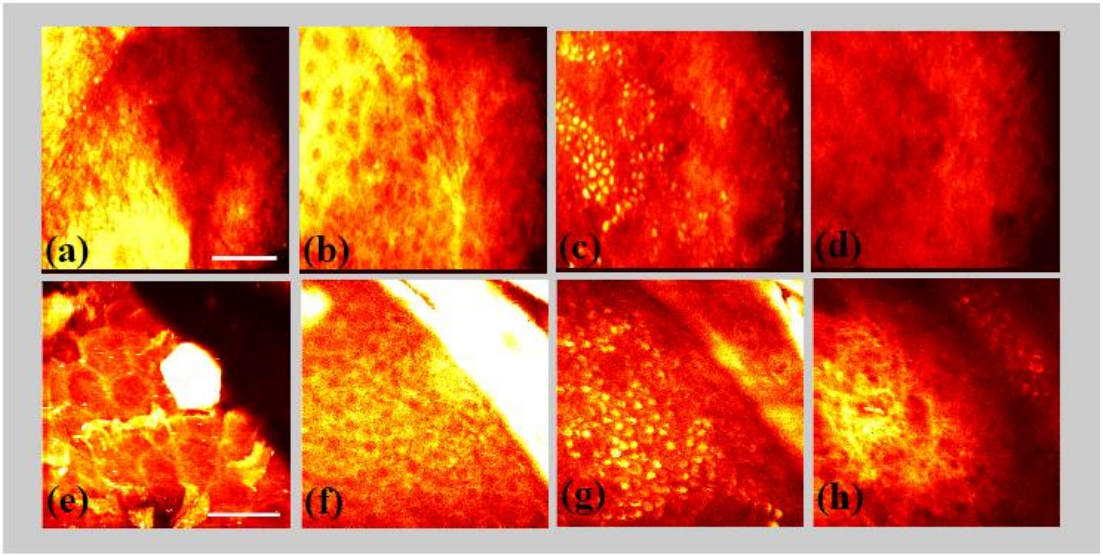
Opt. Express. 8, 2 (2001)

Frontal sections of human skin in vivo acquired with reflected light **confocal microscopy** (a-d) and acquired from **multi-photon excitation microscopy** with excitation at 780nm (e-h).

Images were acquired at the regions: 10 microns below surface in stratum corneum (a and e), cells of stratum spinosum (b and f), cells of basal layer (c and g), and within the **dermis** (d and h).

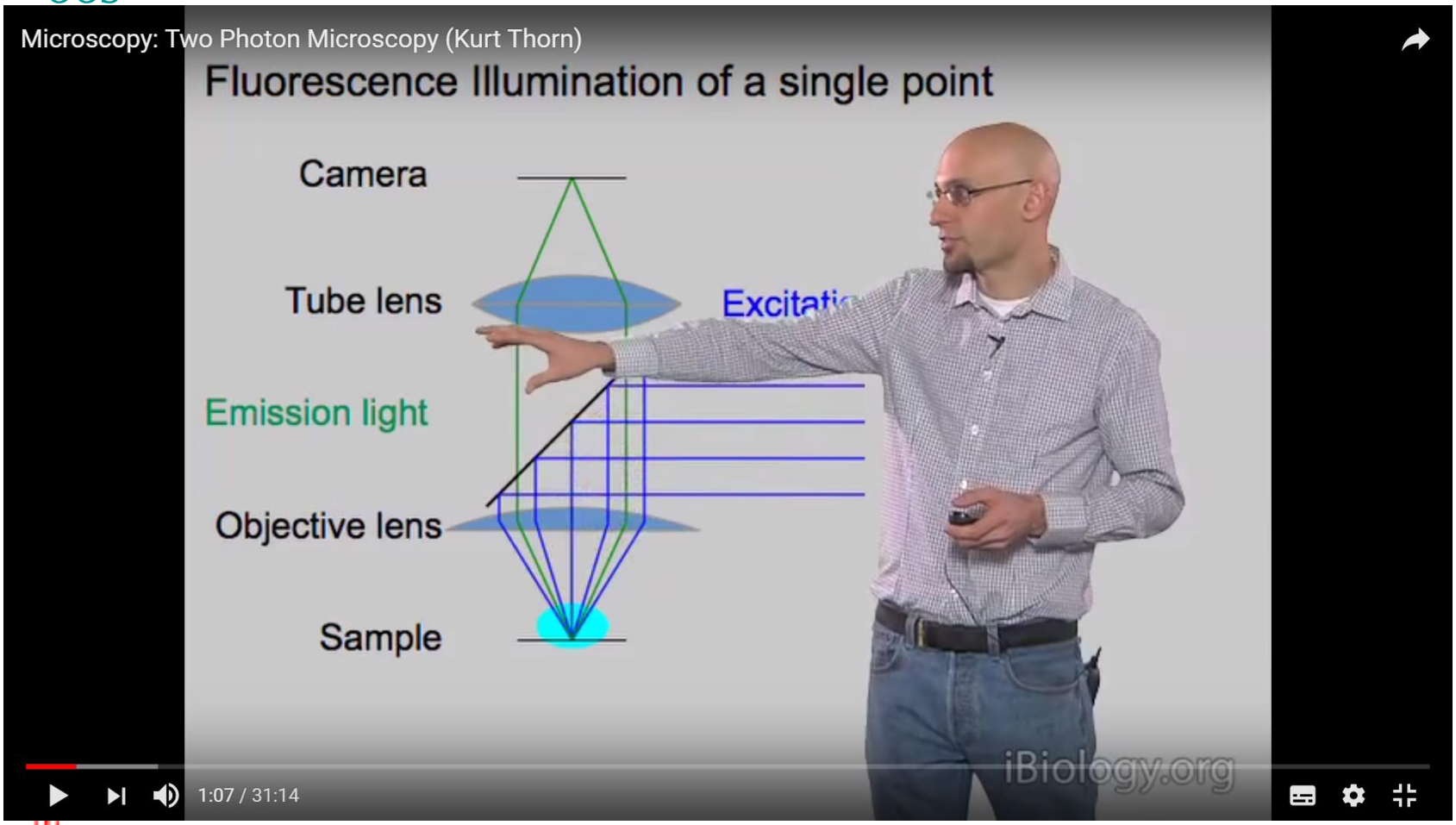
Scale bars show 50 microns.





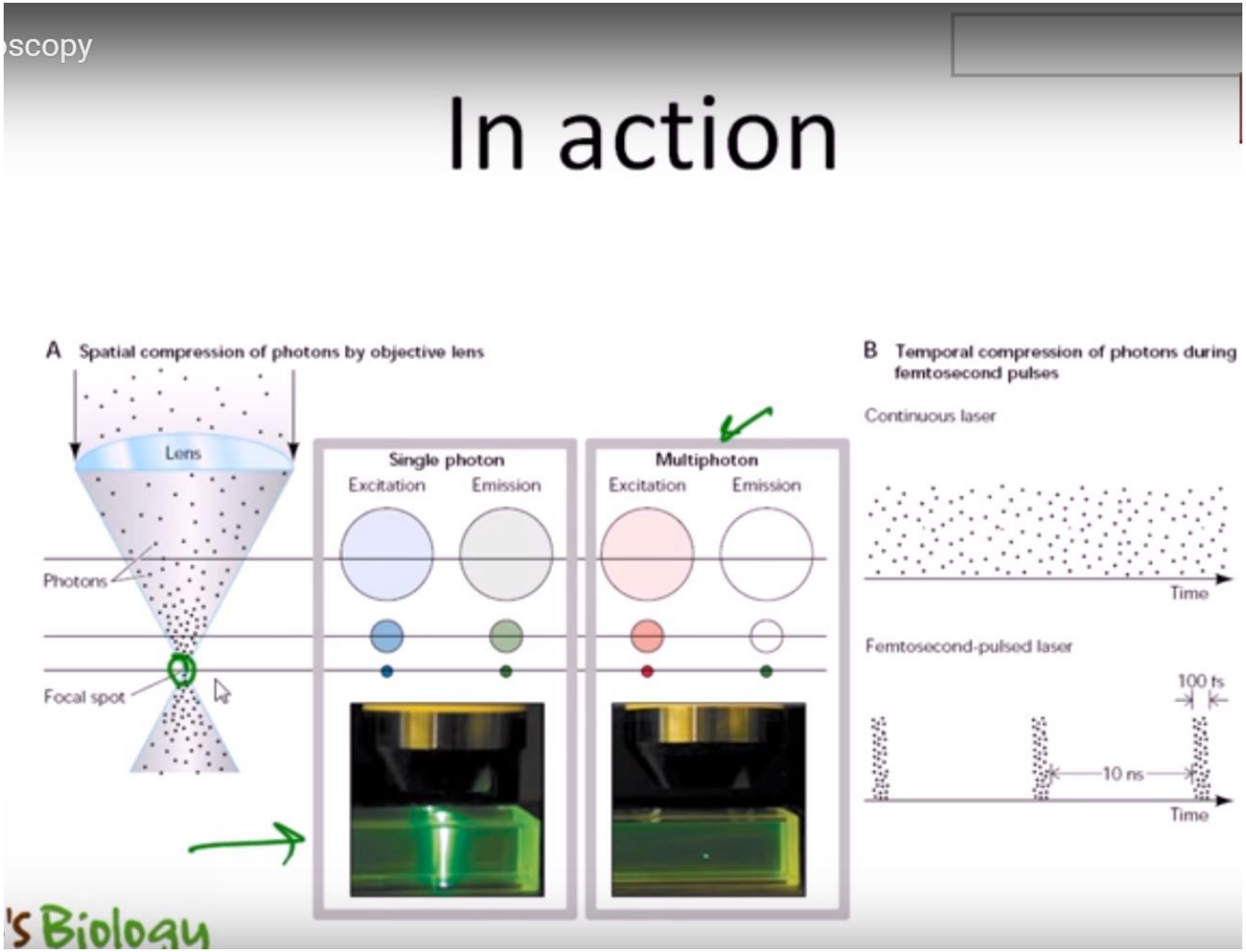
Two photon microscopy

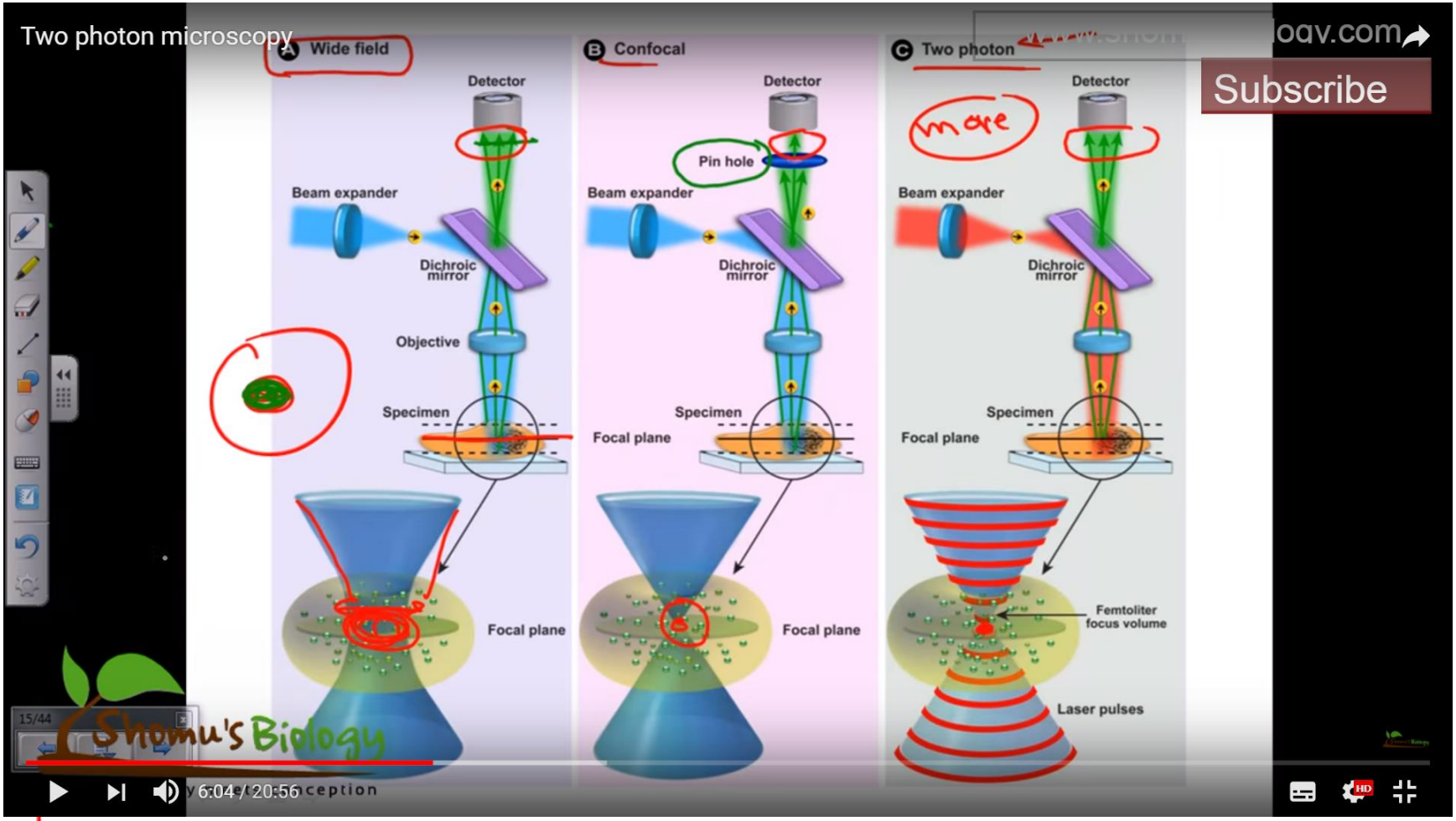
- https://www.youtube.com/watch?v=CZifB2aQDDM&t=1266s



Two photon microscopy

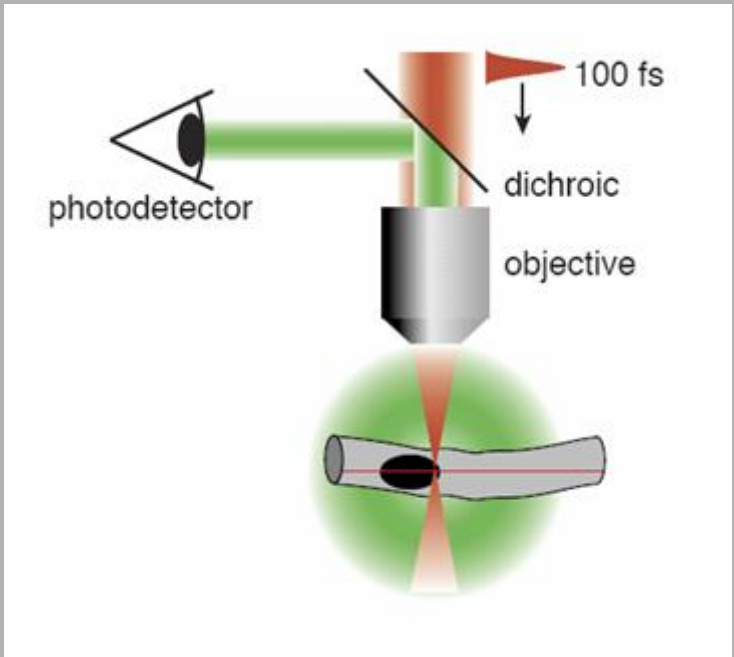
- https://www.youtube.com/watch?v=f9Bj7oe7k8w

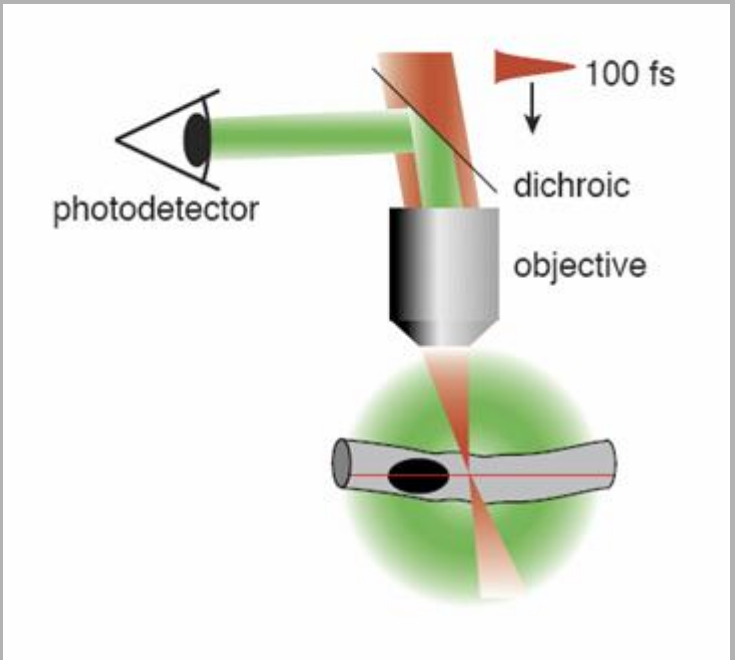



Two photon microscopy
A Wide field
B Confocal
C Two photon
Detector
Pin hole
Beam expander
Dichroic mirror
Objective
Specimen
Focal plane
Femtoliter focus volume
Laser pulses
Subscribe
Shomu's Biology
6:04 / 20:56

Multi-photon imaging

We do this as we raster-scan the focus throughout the medium.



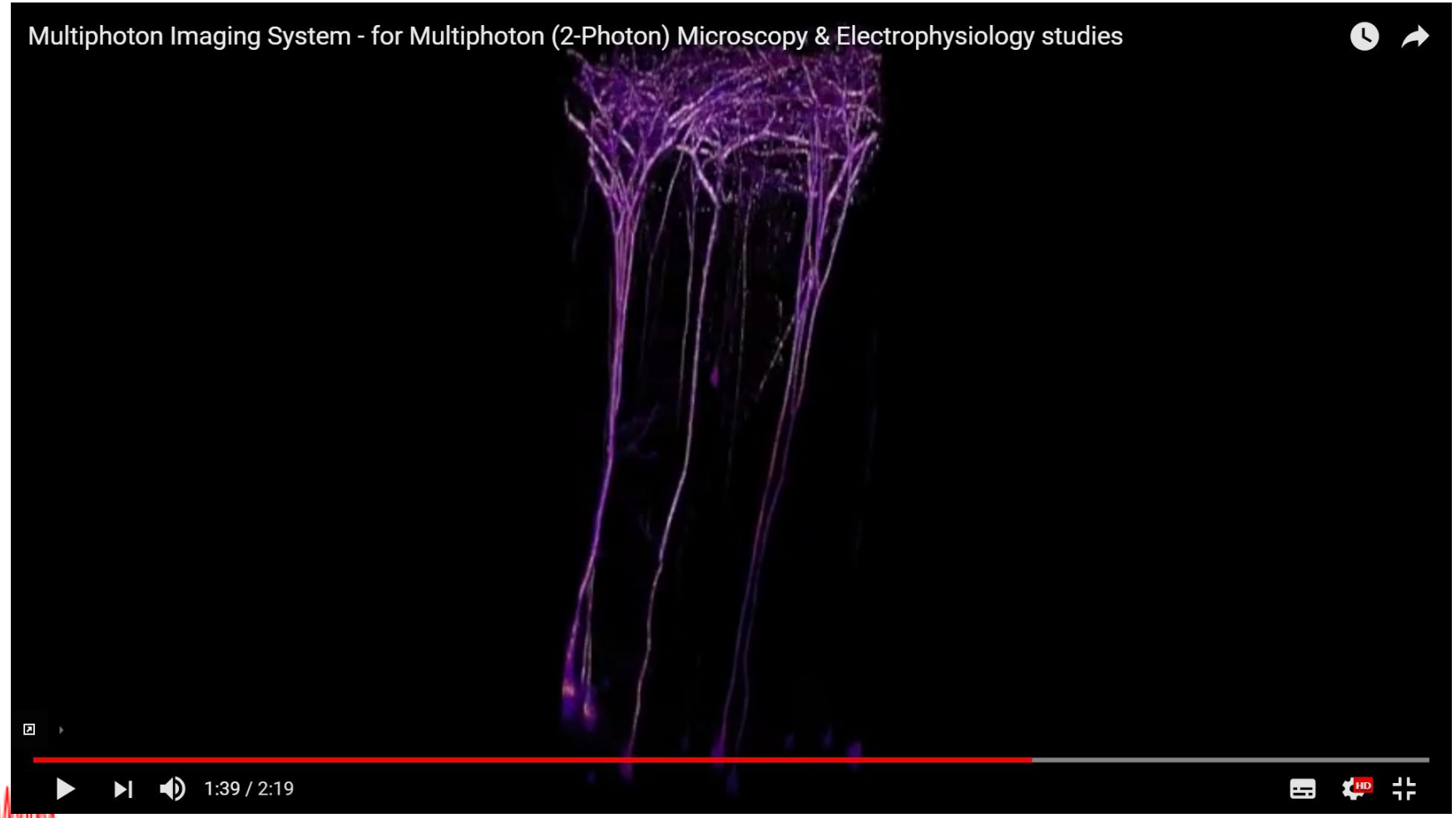


Multi-photon microscopy is responsible for more sales of ultrafast lasers than all other applications combined!

Images due to Chris Schaffer, UCSD

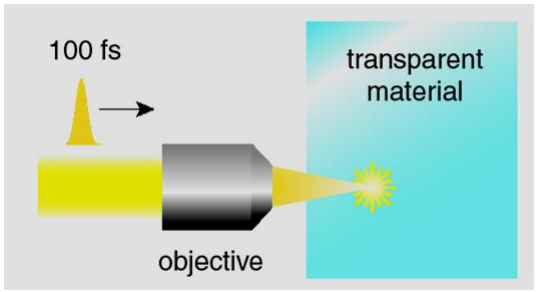
Multiphoton Imaging System

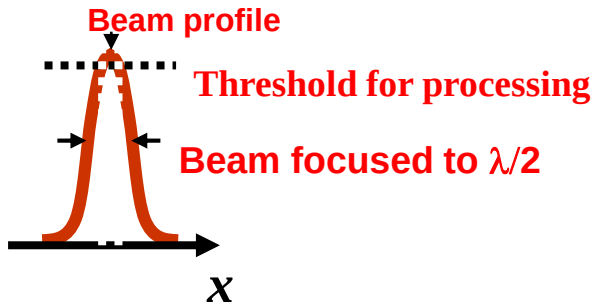
- https://www.youtube.com/watch?v=cl6sPHCI-oQ



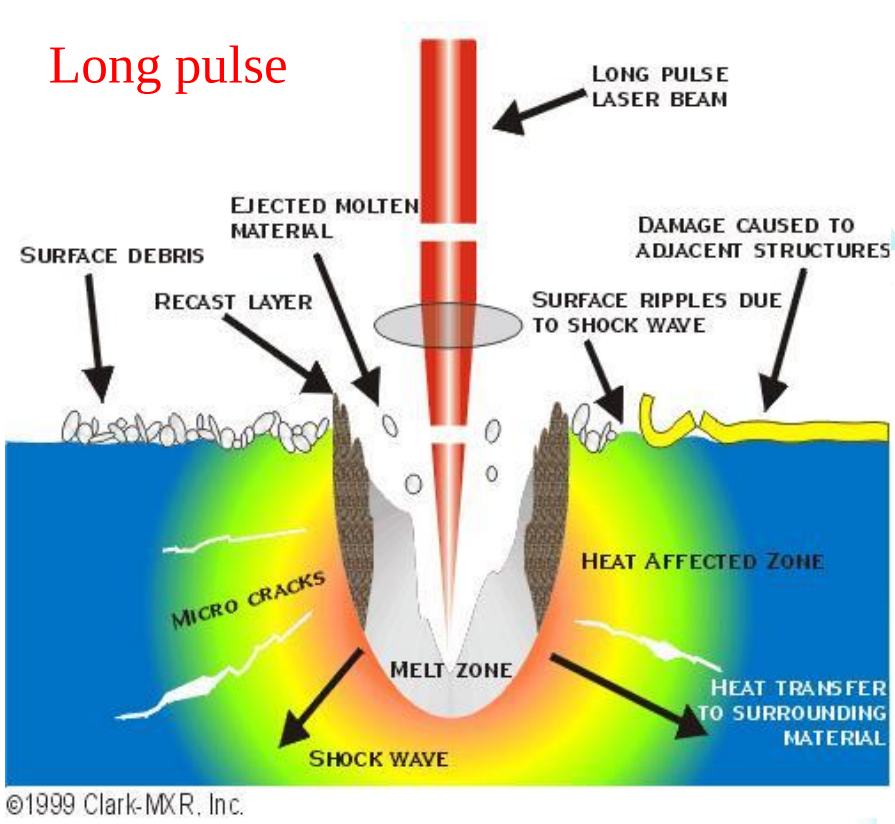
Three-dimensional multiphoton microlithography

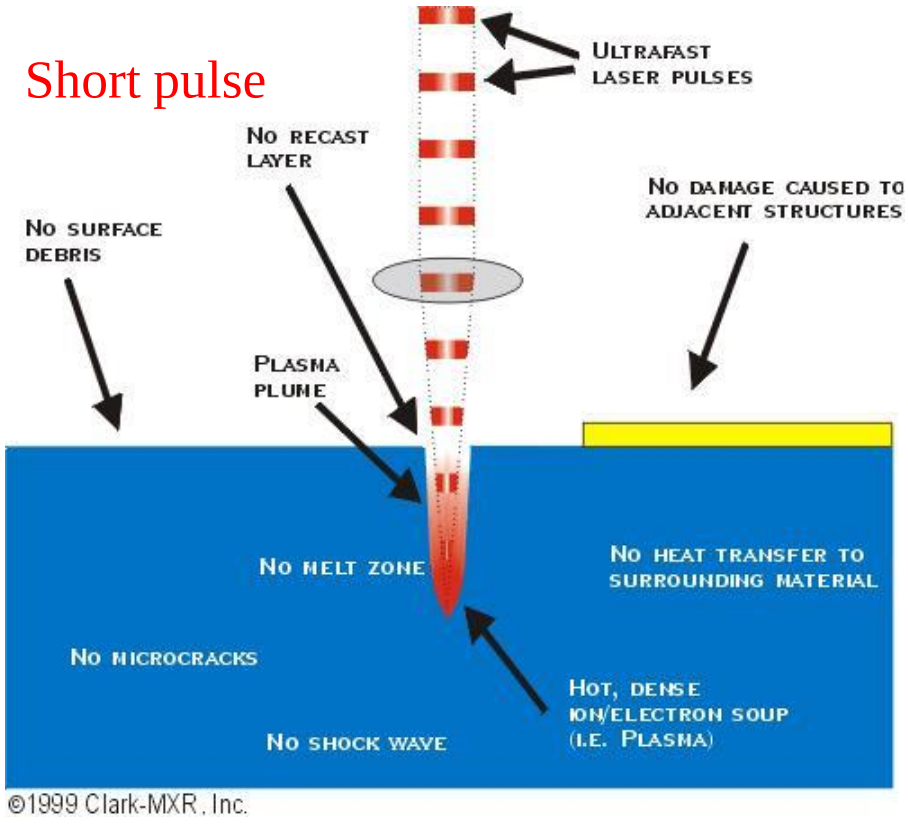
- A similar approach is used to fabricate **micro-objects**.
- A lens delivers **high-power optical pulses** to a particular location in a specially designed transparent **polymeric material**.
- The light has **sufficient intensity** to **effect multiphoton polymerization** only in the vicinity of the focal region;
  - it reaches that region without affecting the **intervening material**.
- Moving the **focal point** of the lens about allows any desired **three-dimensional microstructure** to be written.





Long- vs. short-pulse micromachining



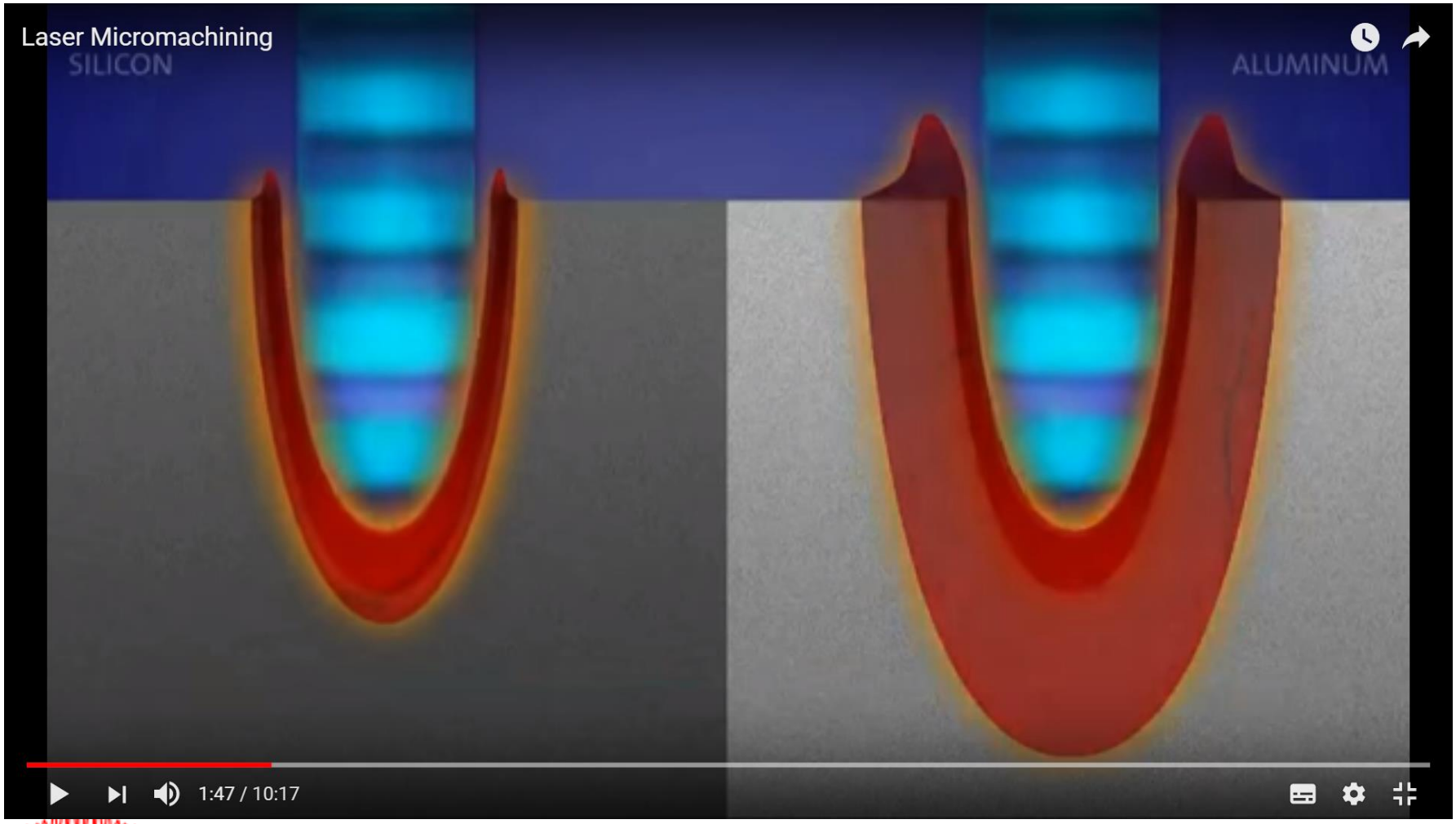


Energy-deposition time is short compared to the **electron-phonon time** (a few ps), so thermal conduction and **hydrodynamic motion** are generally negligible, and ejecta carry away most of the deposited energy.

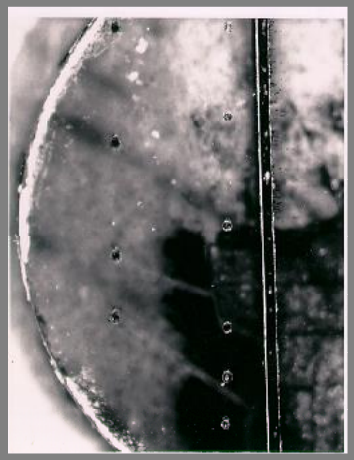
As a result, there's minimal **collateral damage** to remaining material.

Micromachining with pico- or nano-second pulses

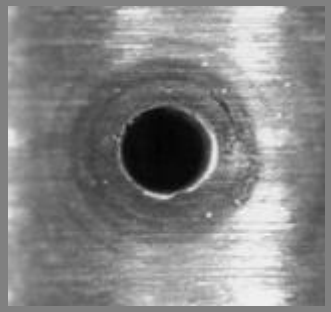
- https://www.youtube.com/watch?v=TmuXT3QR2mg&t=164s



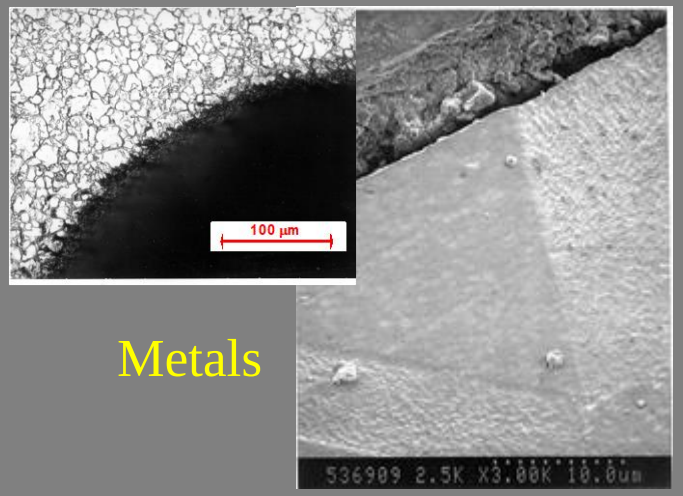
Ultrashort pulse lasers can precision machine many materials.



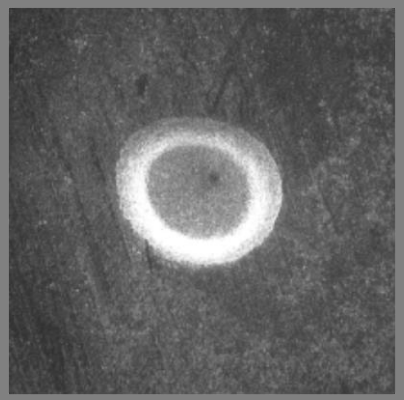
Diamond



Ceramics



Metals



Teeth

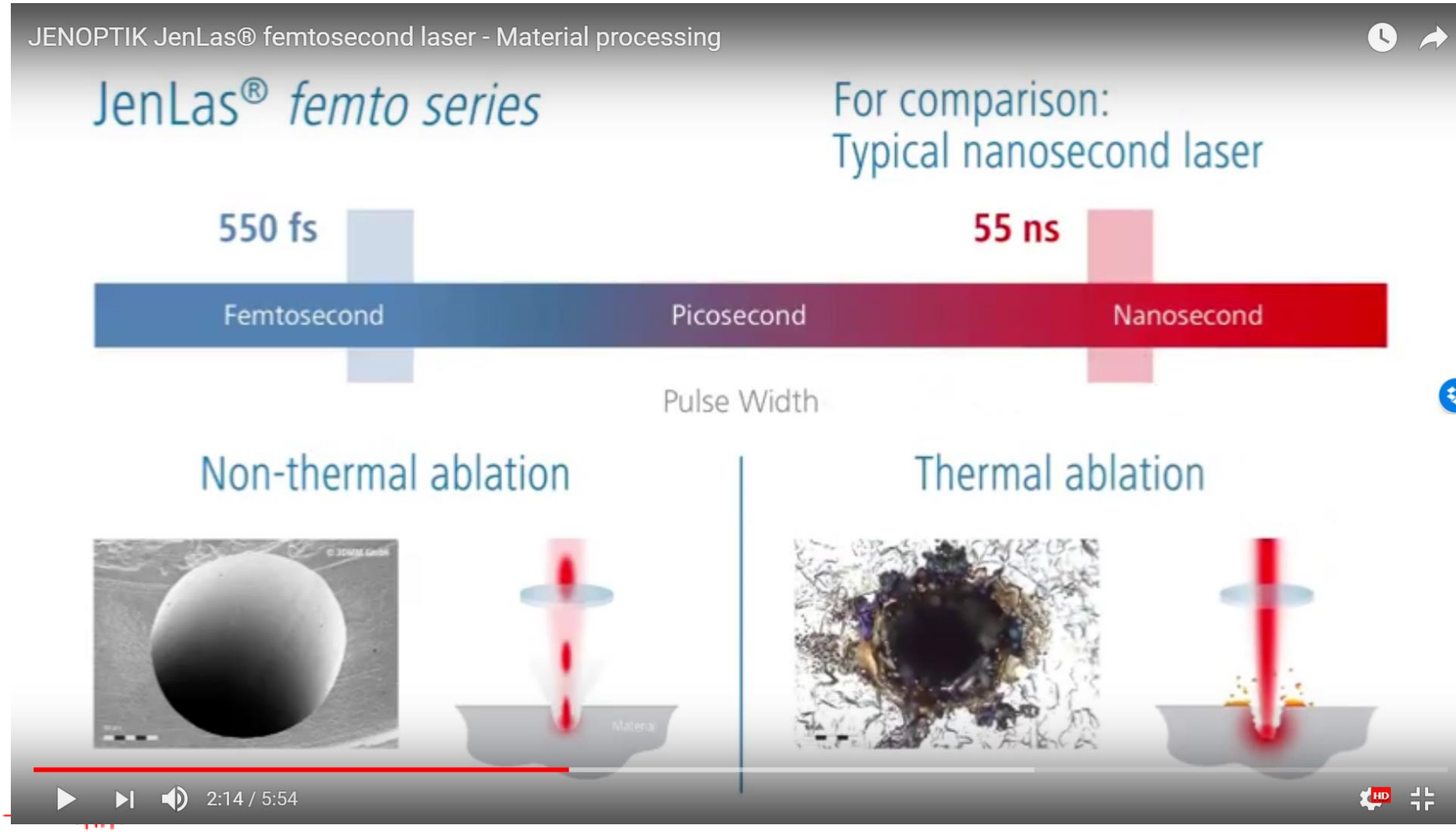
Polymers

High Explosives

M.D. Feit, A.M. Komashko, A.M. Rubenchik, *Lawrence Livermore National Laboratory*

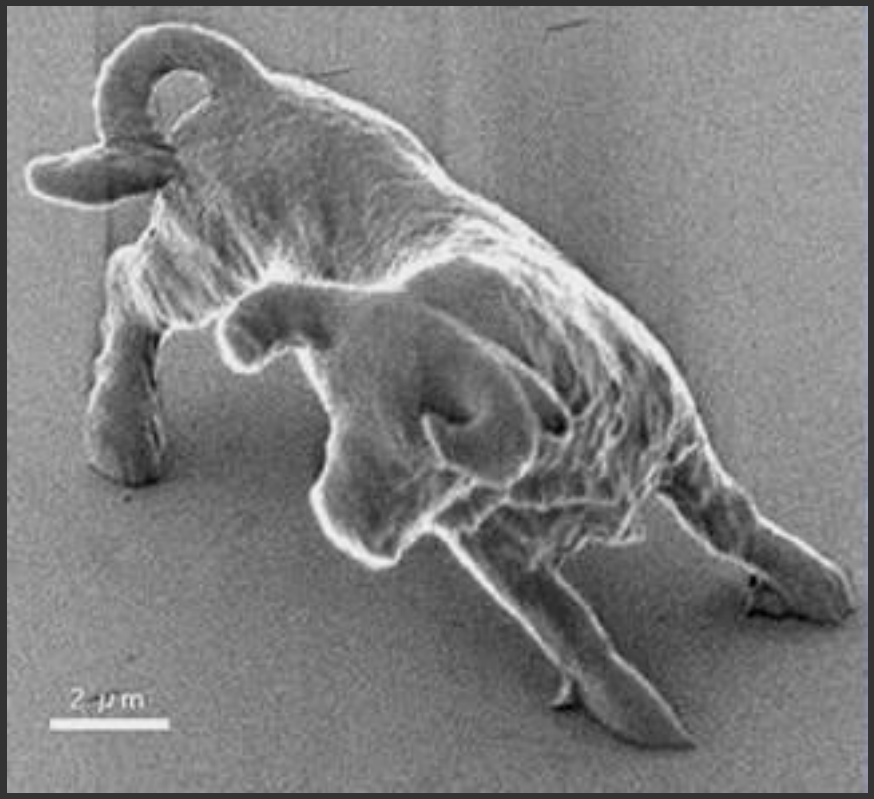
Femotosecond material processing

- https://www.youtube.com/watch?v=wNhGXAR1drw



Sub-micron sculpting

Photo-polymerization: light causes a polymer to solidify. Structural details of 120 nm (due to two-photon photo-polymerization).



S. Kawata, et al., Osaka Univ. Nature 412, 697, 2001.

Nano-dissection of human chromosomes with fs pulses

K. König, I. Riemann
Laser Microscopy Division, Institute of Anatomy II, Jena, Germany
W. Fritzsche
Institute for Physical High Technology Jena, Jena, Germany

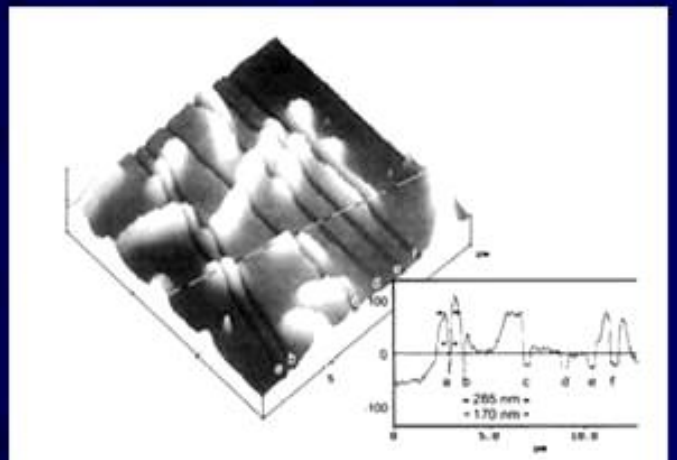


Fig. 1. Complete dissection of human chromosomes with 800-nm subnanojoule femtosecond laser pulses. The depth profile of cut a indicates a FWHM cut size below 200 nm. The other cuts (b–f) are in the range

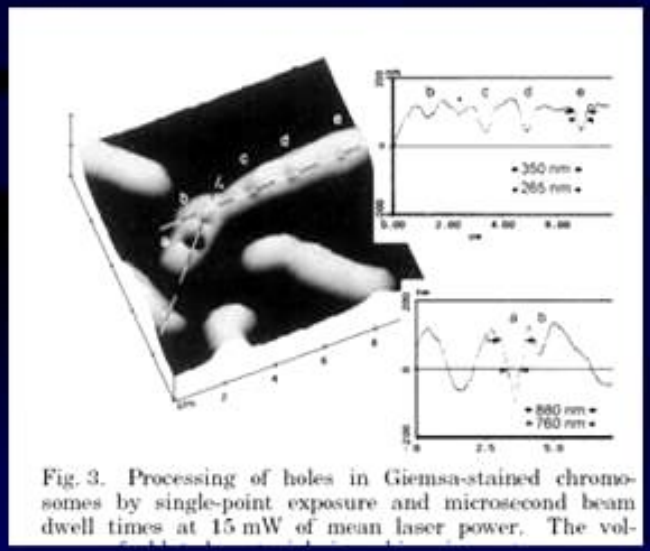
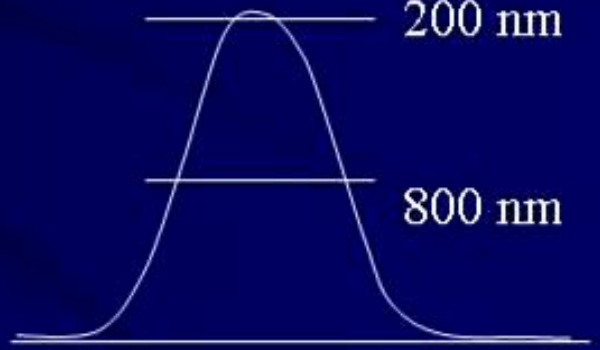
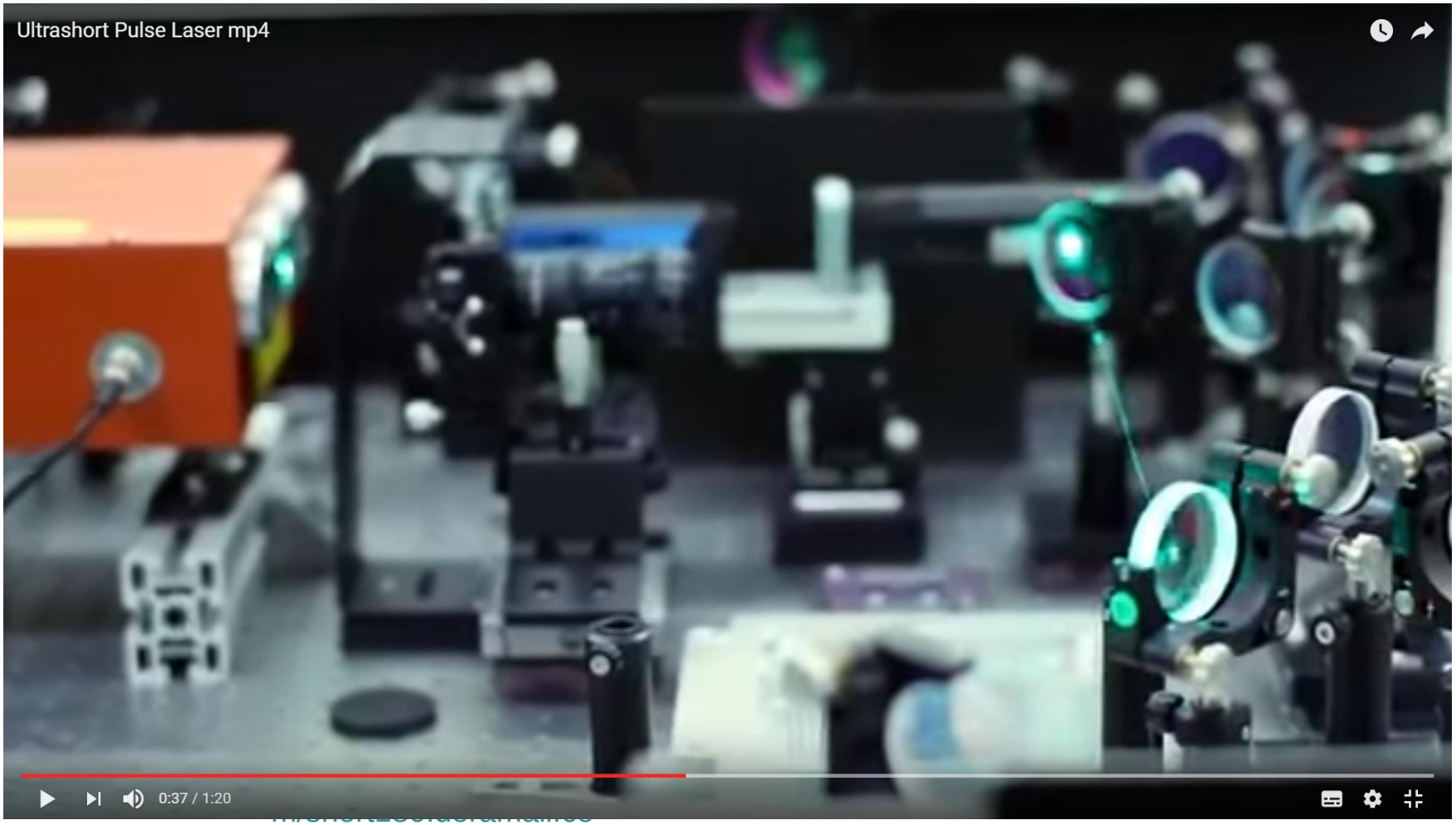


Fig. 3. Processing of holes in Giemsa-stained chromosomes by single-point exposure and microsecond beam dwell times at 15 mW of mean laser power. The vol-



Marking with fs pulses

https://www.youtube.com/watch?v=ciyxPgiEjIk

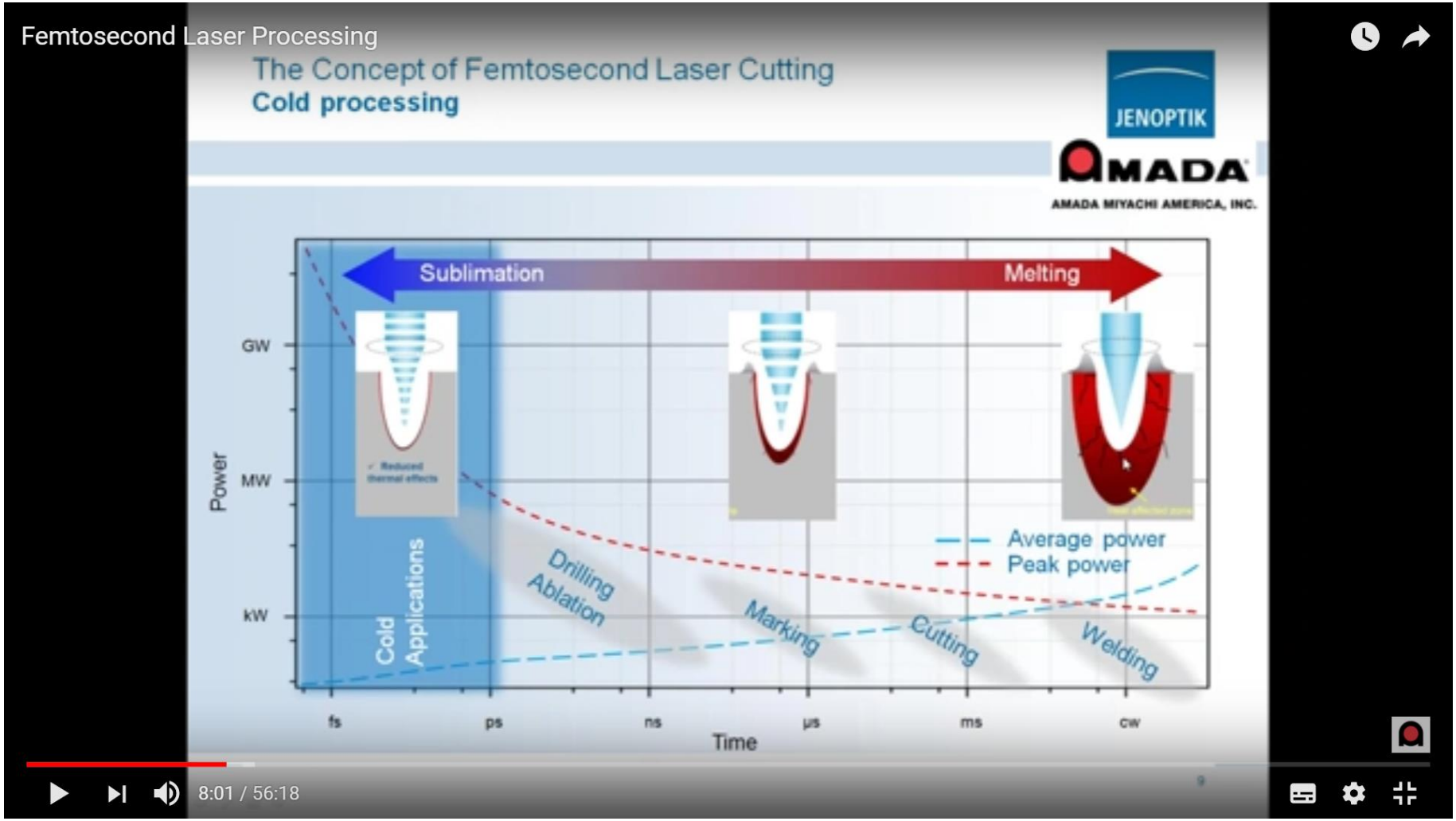


m/b4.htm

Company Logo

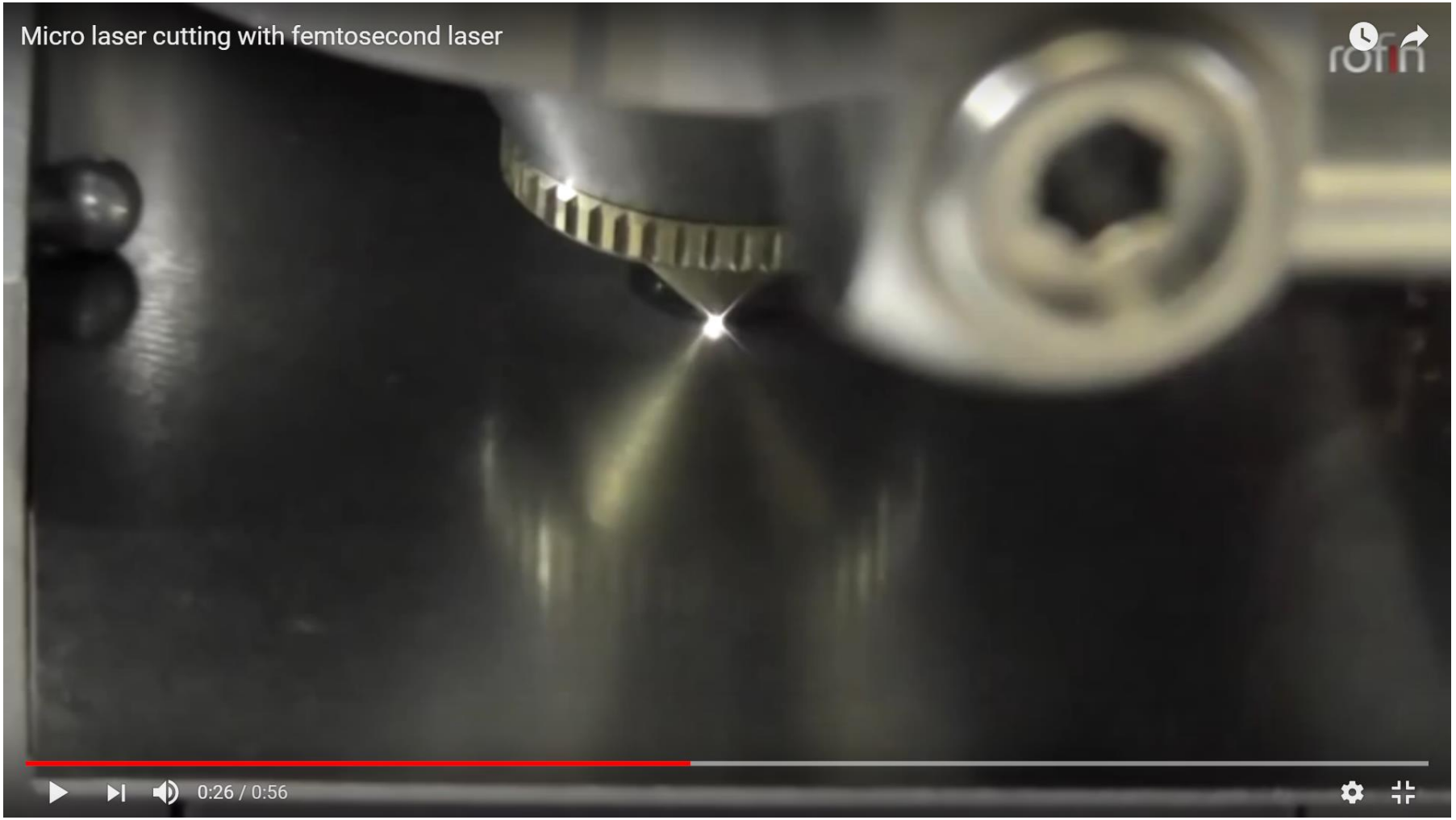
Femtosecond laser processing

- https://www.youtube.com/watch?v=G1kSeFphMds



Cutting with fs laser

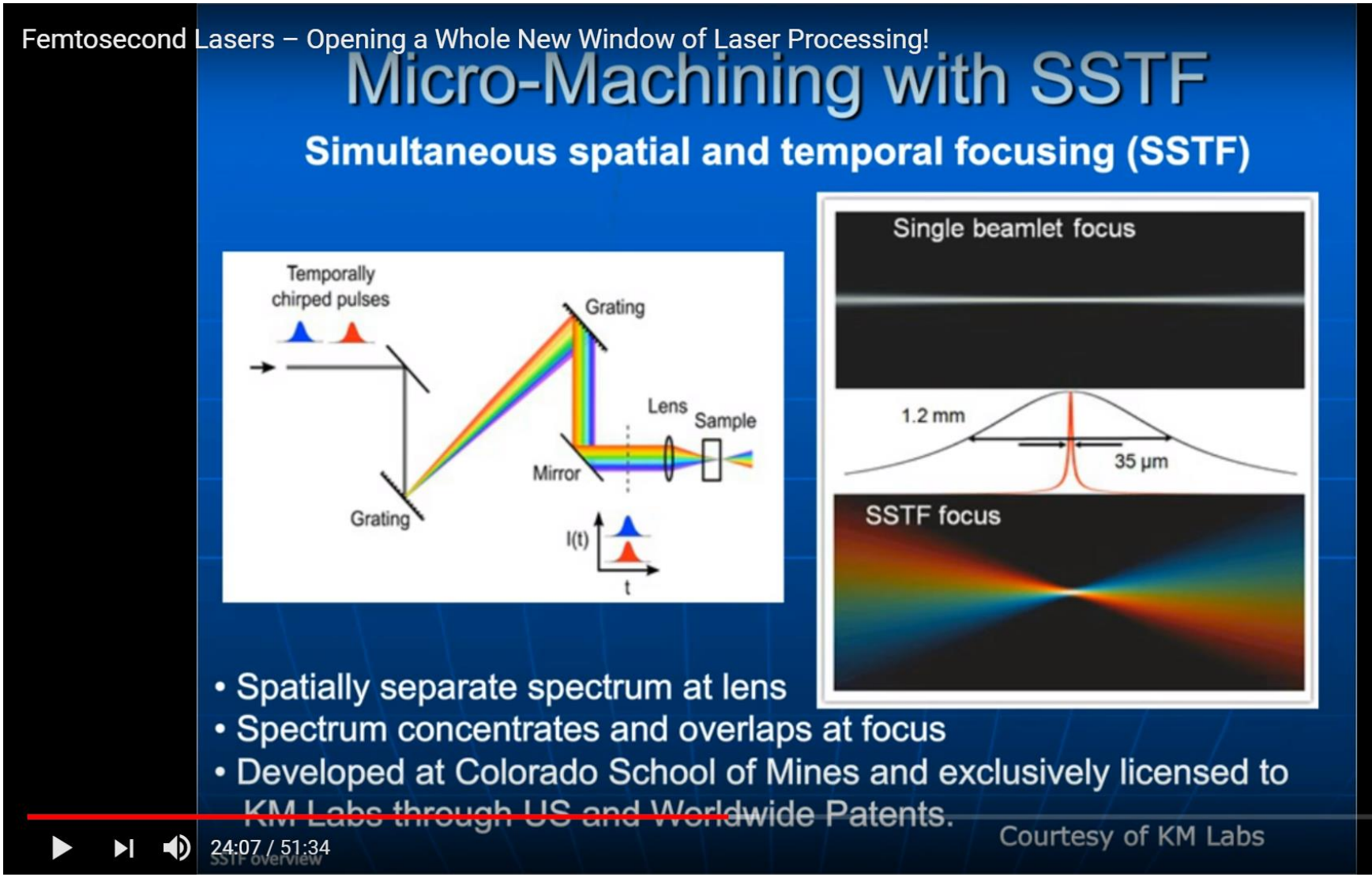
- https://www.youtube.com/watch?v=i9u4XQYVSt4



Other fs-processing

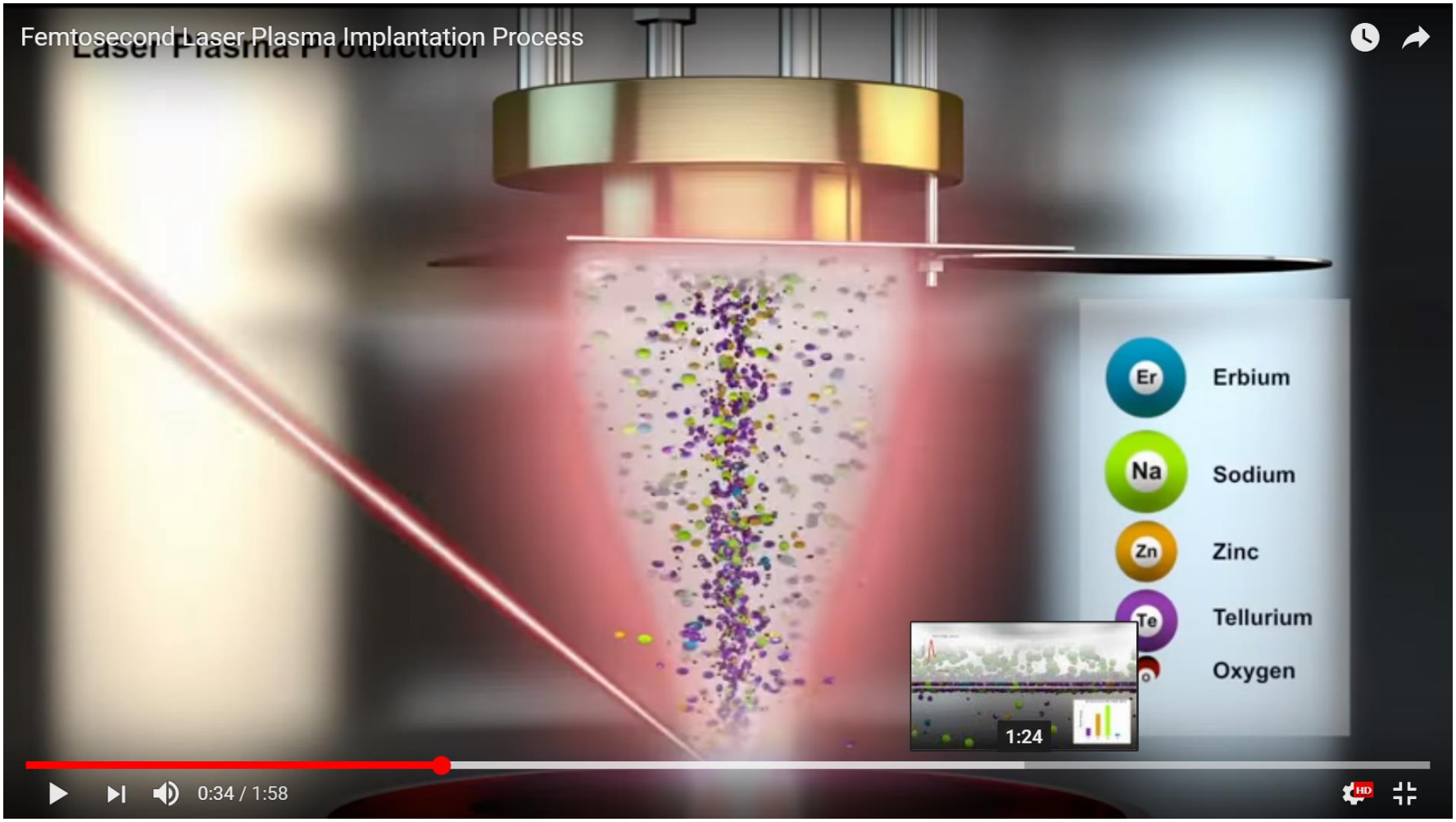
fs processing

- https://www.youtube.com/watch?v=N72hpENywLs



Femtosecond Laser Plasma Implantation Process

- https://www.youtube.com/watch?v=MEUTukv3e7M



Intralase performs vision-correction surgery using fs lasers.

FDA approval is already in hand.

https://www.youtube.com/watch?v=ZpYlZoJHbHE

Eye surgery

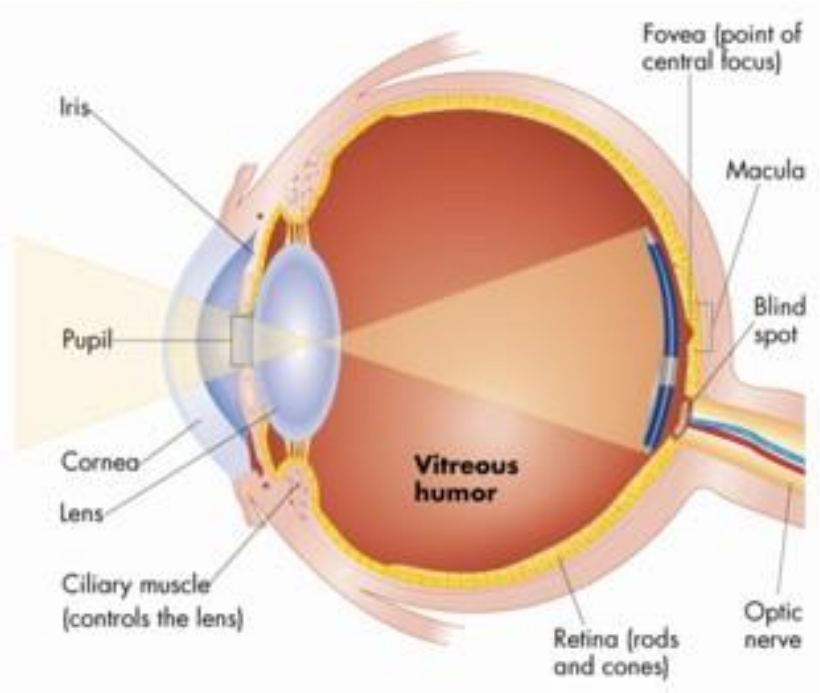
http://home.doramail.com/short180:doramail.com/b4.htm

Link1

- https://www.youtube.com/watch?v=dKANhIU7Sxk

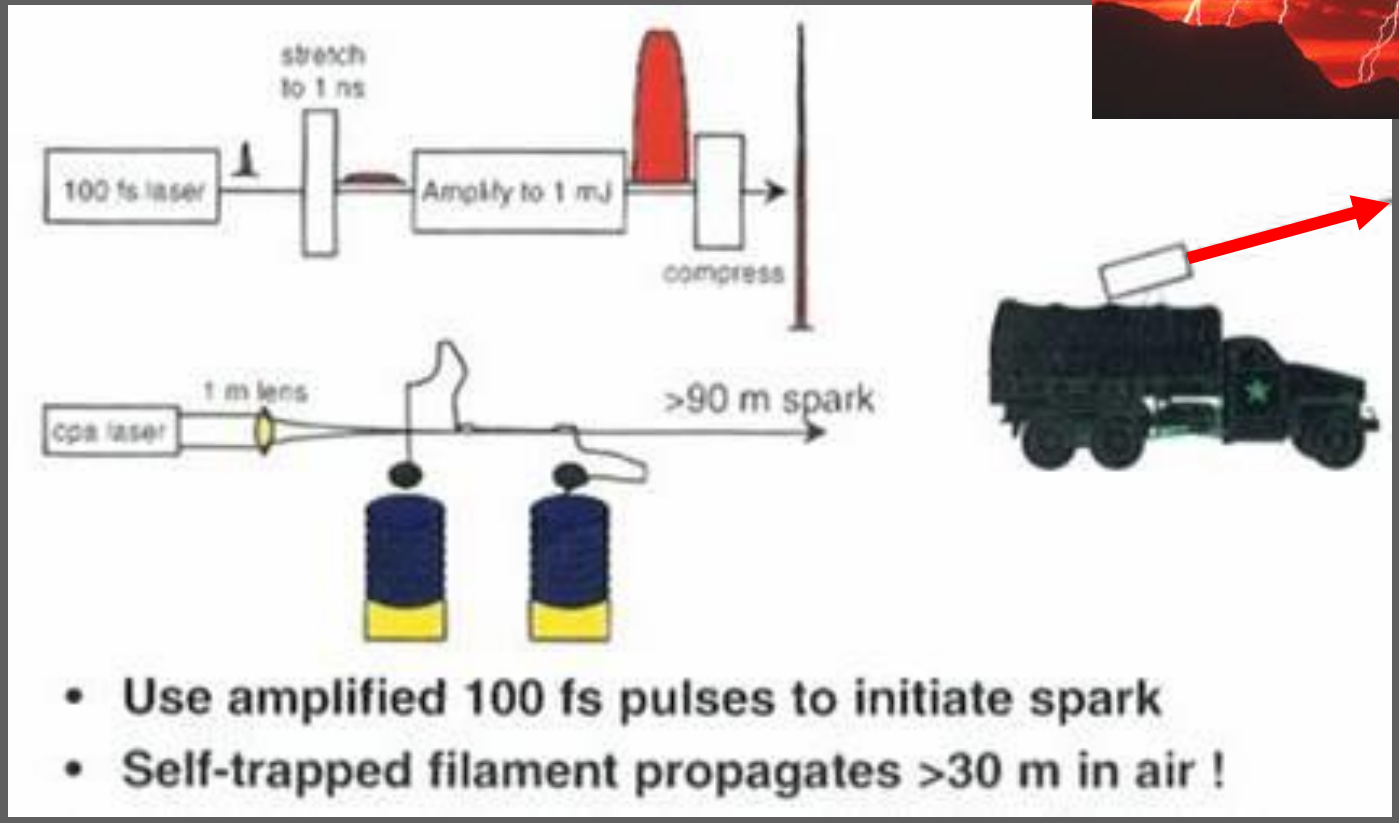
Link2

- https://www.youtube.com/watch?v=rrks9qchLXA



Protection from lightning using amplified fs pulses

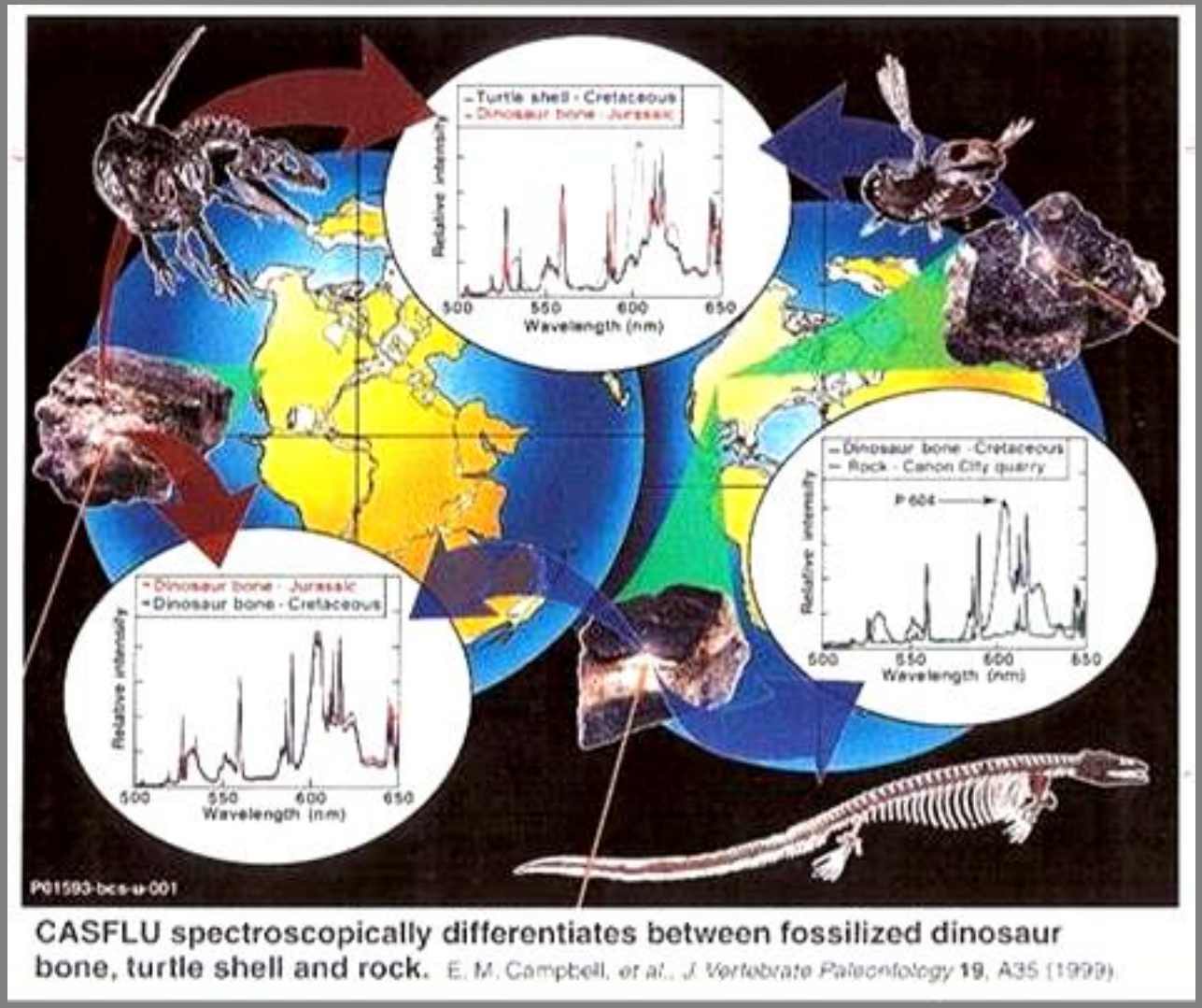
National Geographic



Diels and Mourou

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

Compositional Analysis by Scanned fs Laser Probing



CASFLU spectroscopically differentiates between fossilized dinosaur bone, turtle shell and rock. E. M. Campbell, *et al.*, *J. Vertebrate Paleontology* **19**, A35 (1999).

This technique takes advantage of the broadband nature of ultrashort pulses.

LLNL

All that needs to be said about telecom