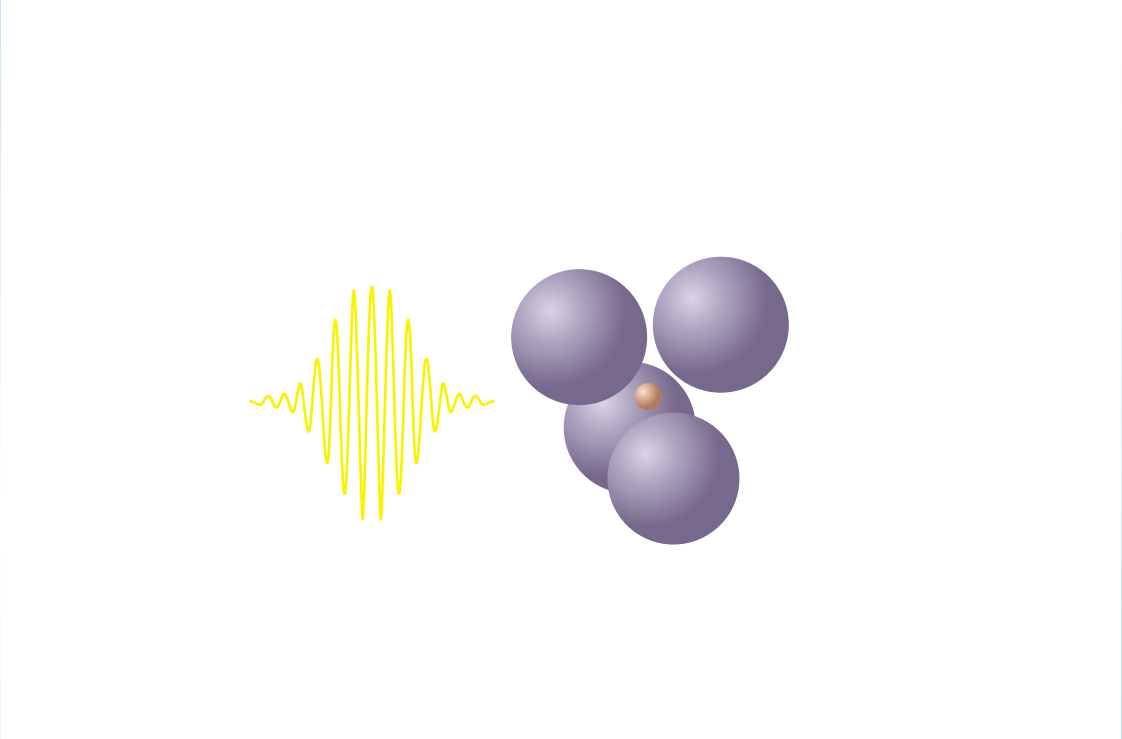
Interactions of Femtosecond Laser Pulses with Transparent Materials

André Brodeur
José Garcia
Nan Shen
Chris B. Schaffer
Eric Mazur

University of Massachusetts at Lowell
12 April 2000

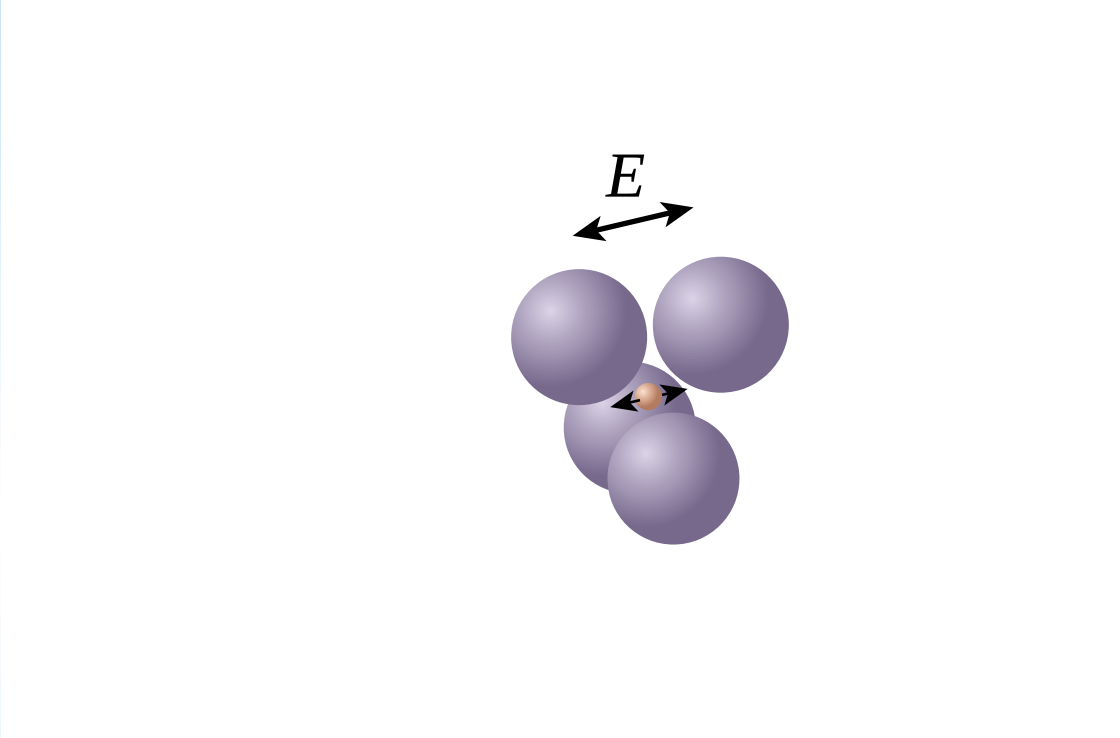
Introduction

light-matter interactions



Introduction

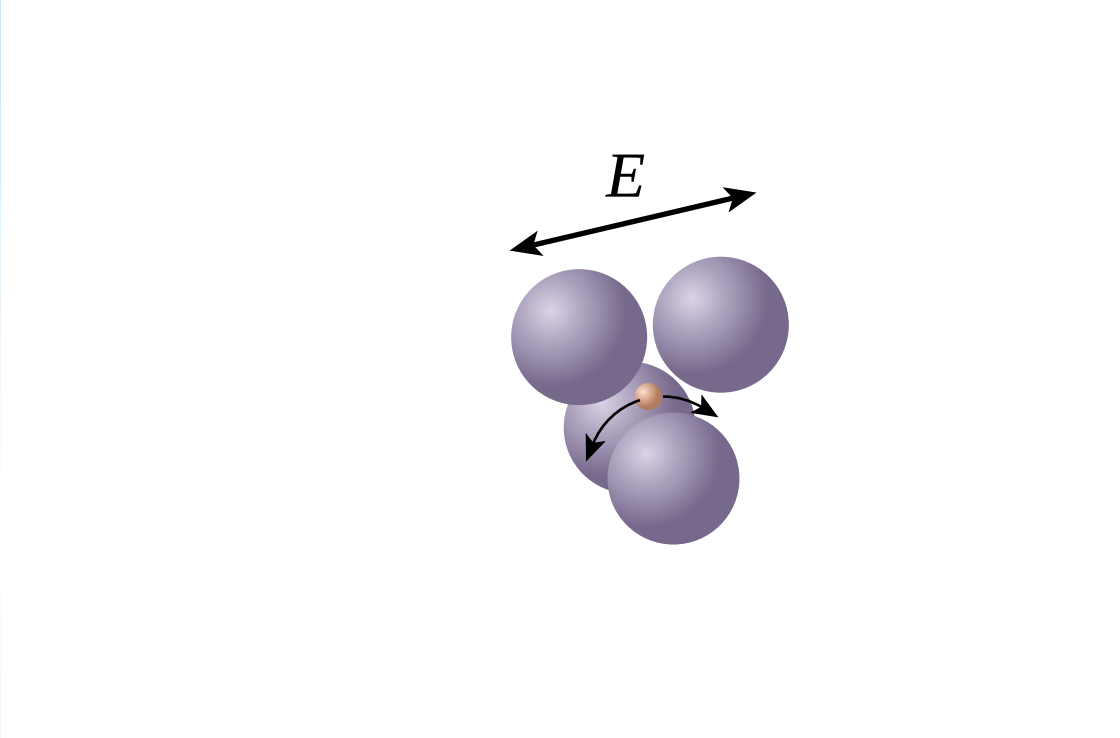
linear response



“stiffness” determines index of refraction

Introduction

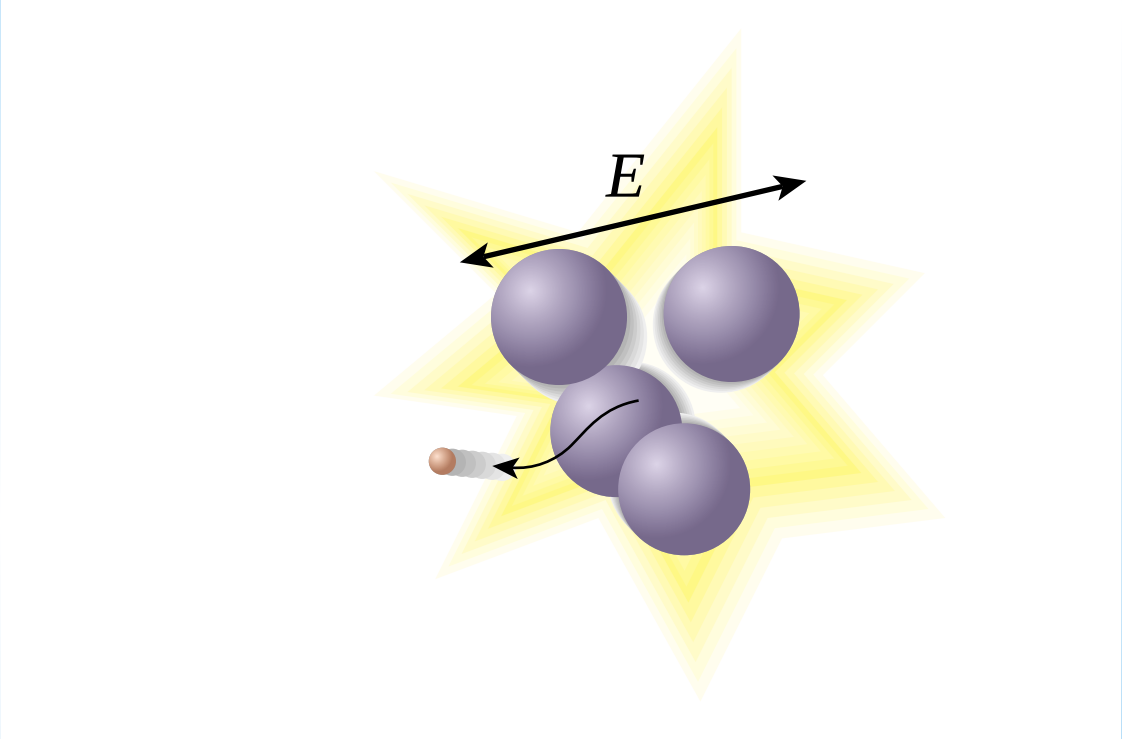
nonlinear response



second harmonic generation

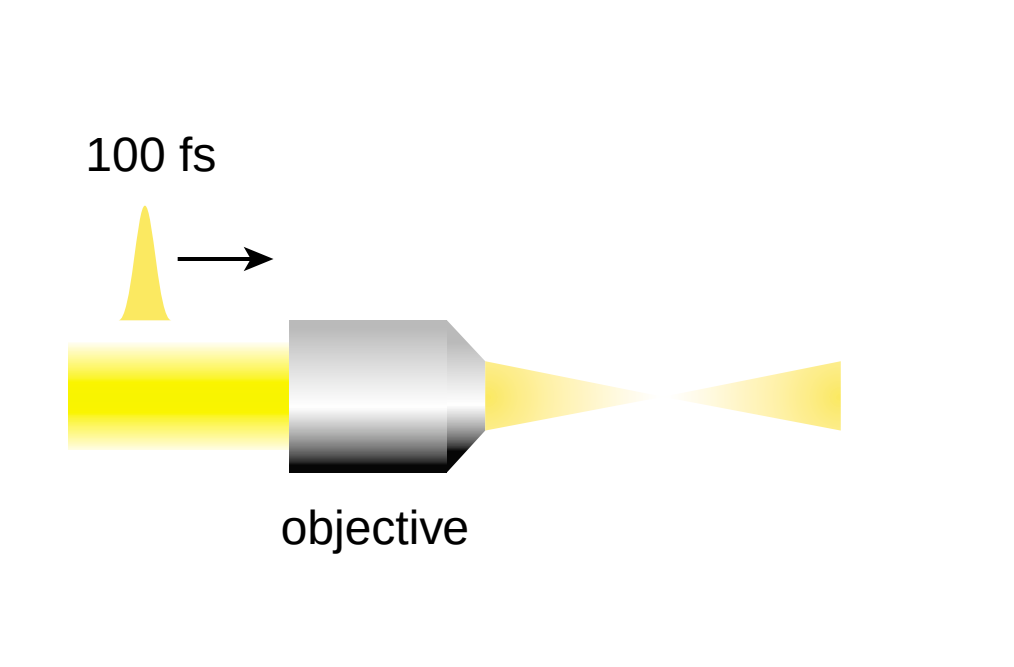
Introduction

“extremely” nonlinear response



Introduction

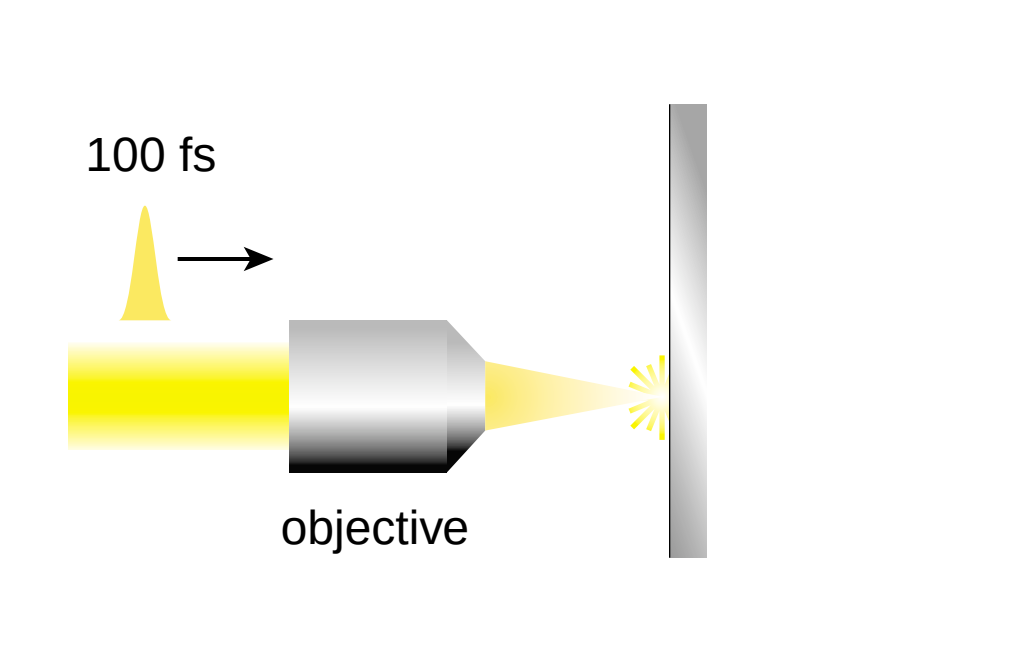
tightly focus laser beam



field at focus 10^{11} V/m!

Introduction

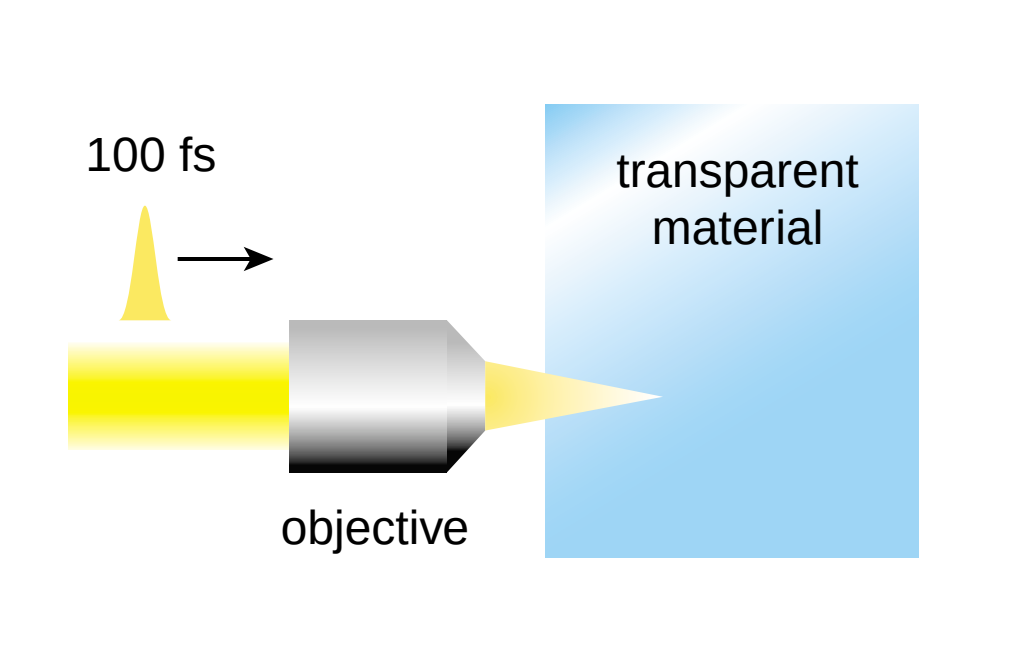
focus laser beam at surface



(works for all materials)

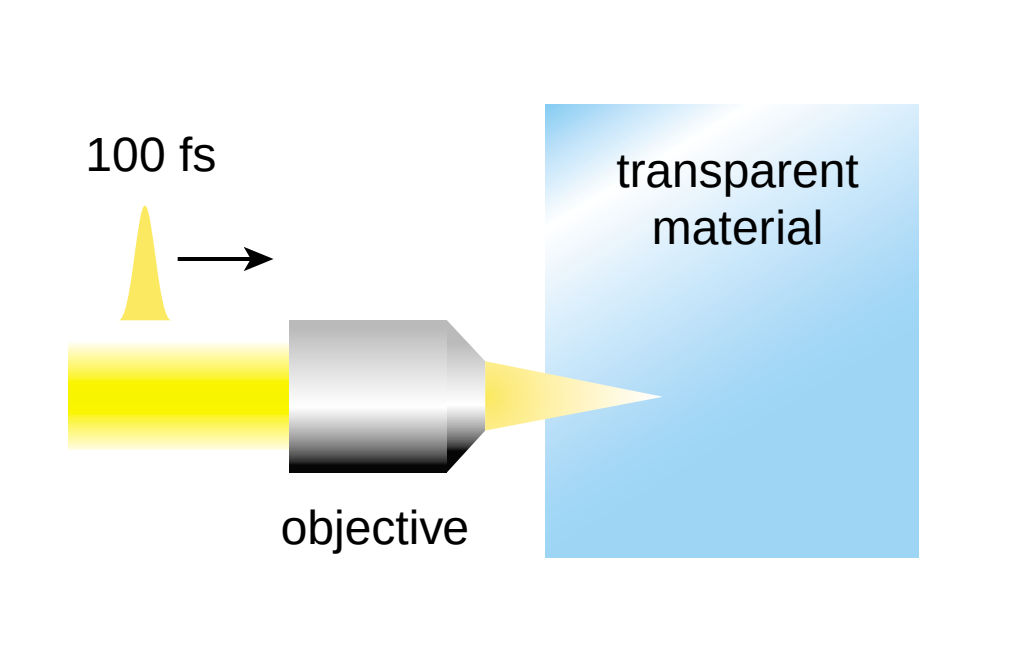
Introduction

focus beam inside transparent material…



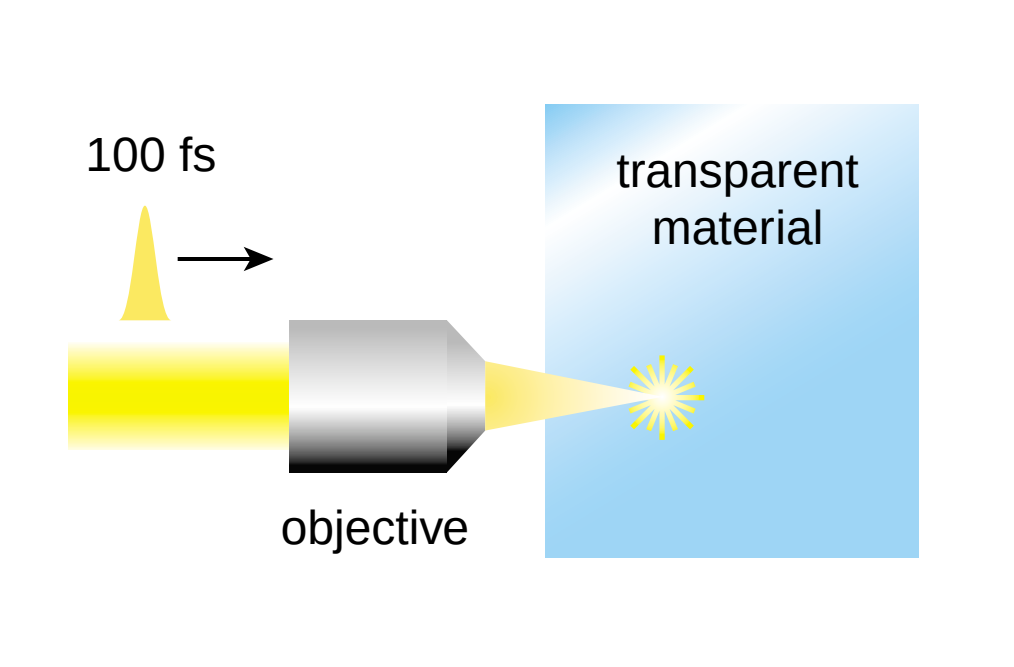
Introduction

high intensity at focus…



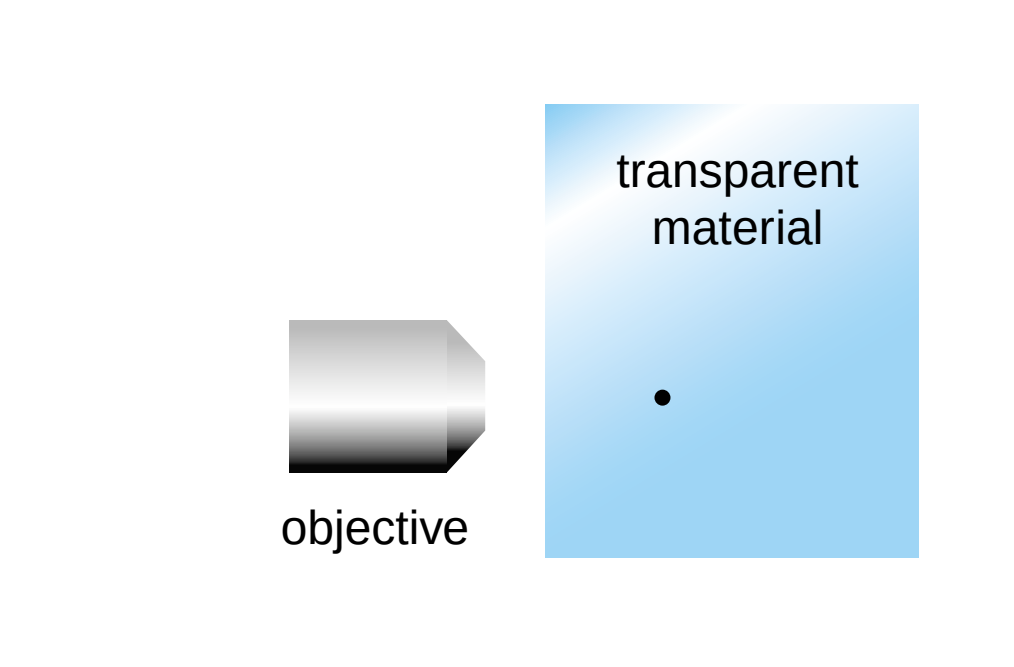
Introduction

… causes nonlinear ionization…

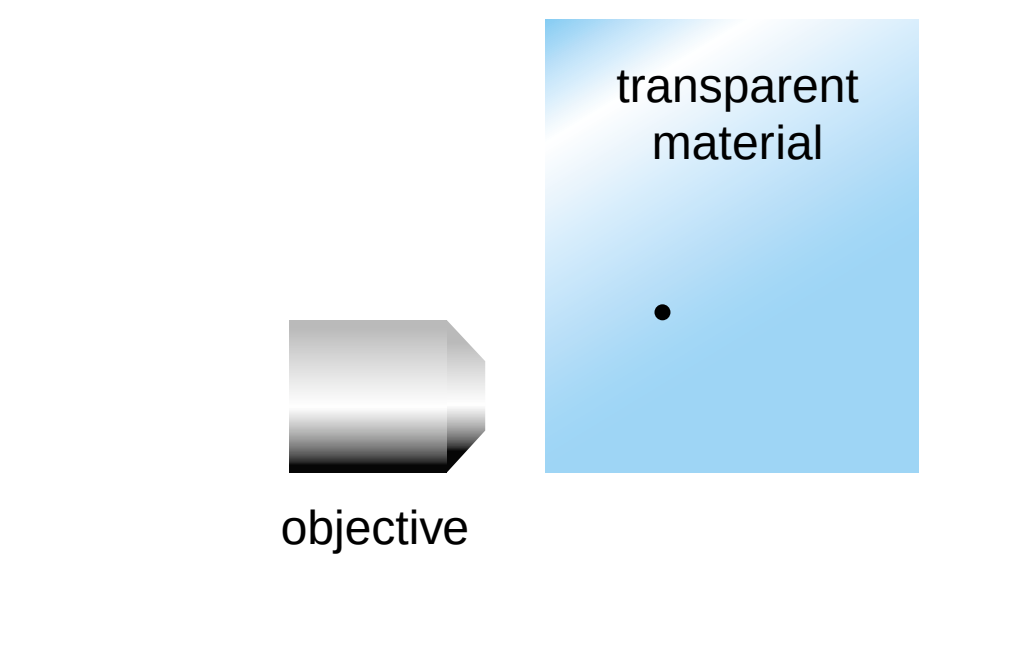


Introduction

and irreversible structural changes on microscopic scale

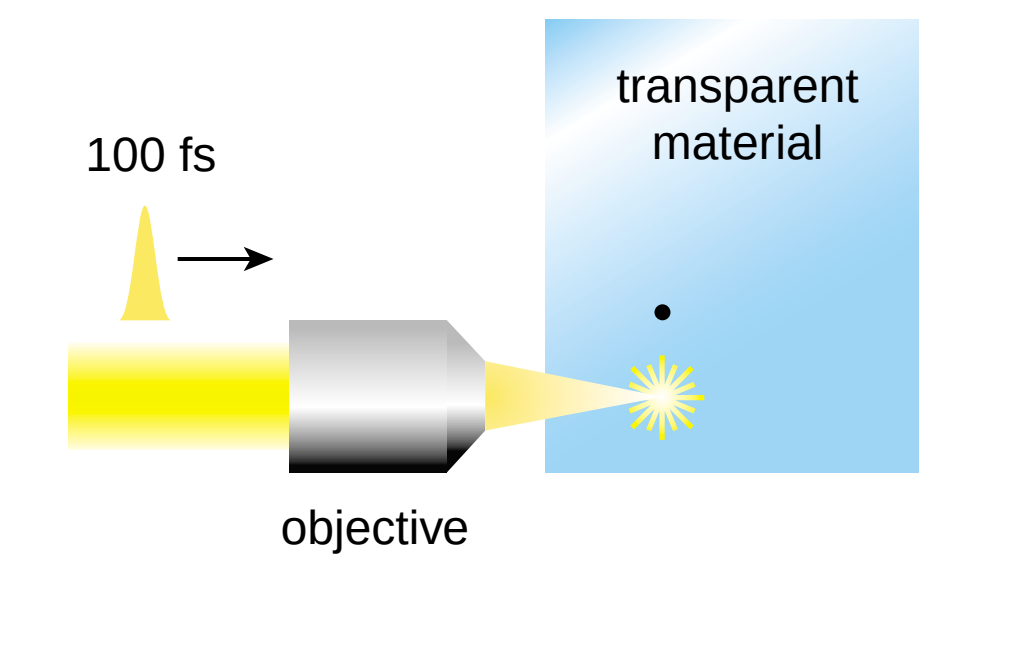


Introduction



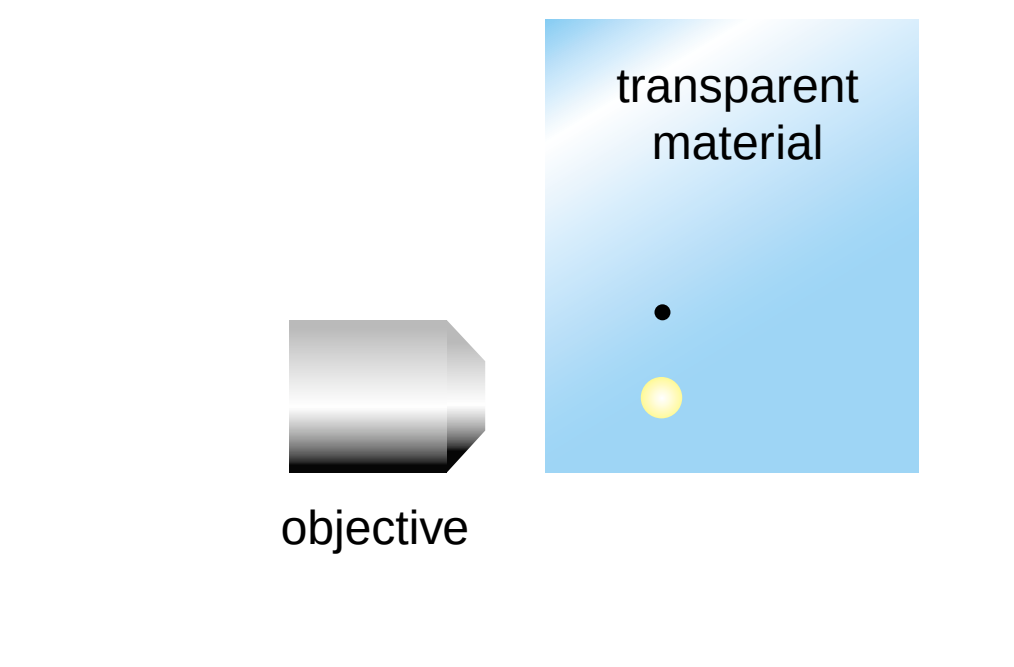
Introduction

100 fs: laser energy transferred to electrons

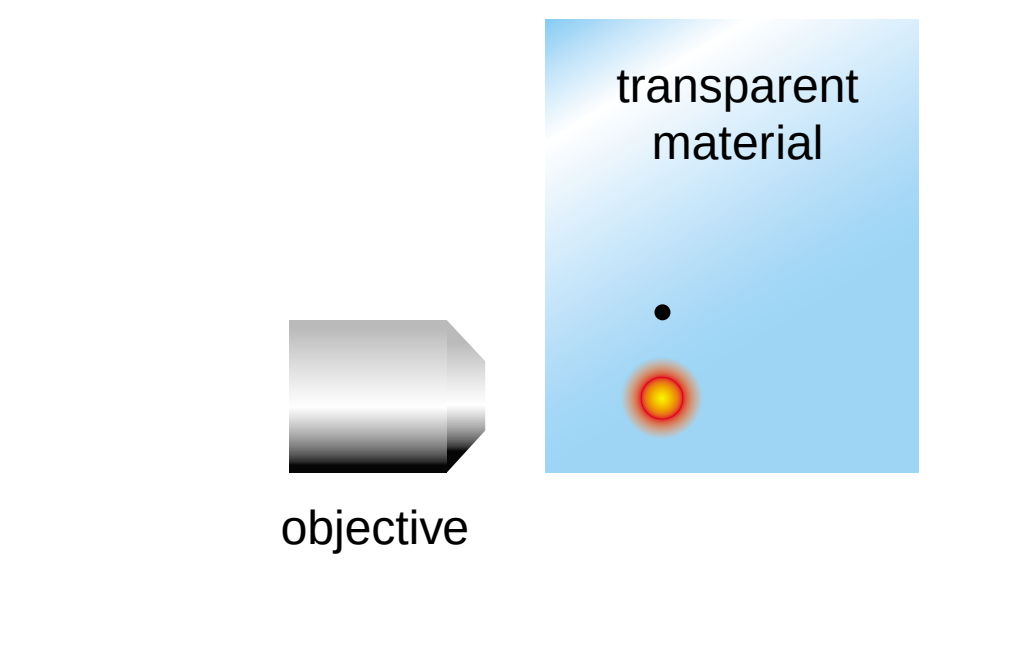


Introduction

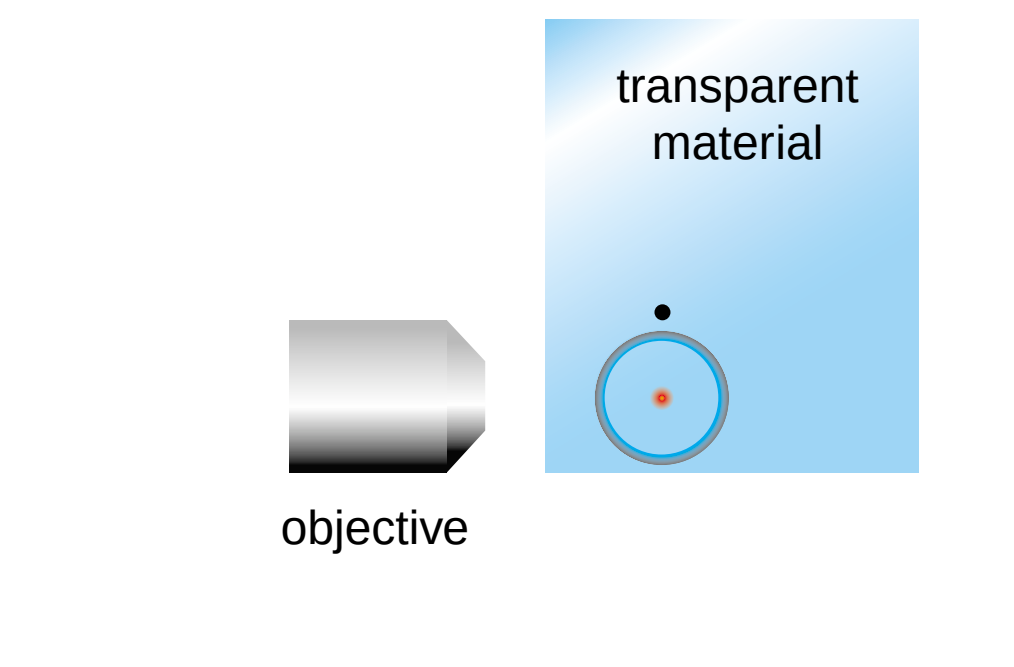
10 ps: energy transfer to ions



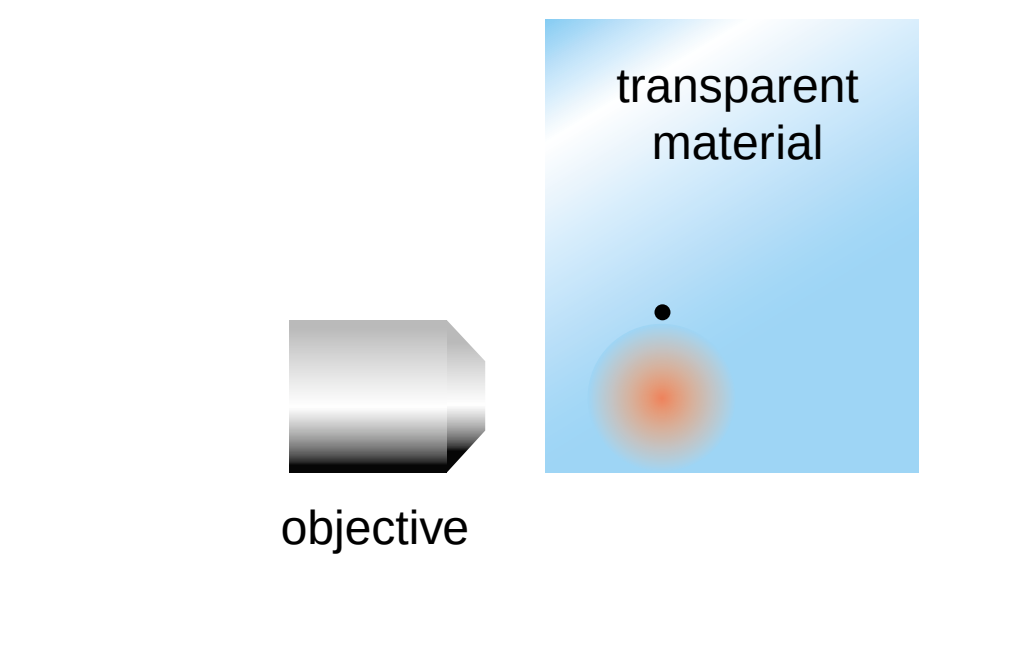
100 ps: plasma expansion



10–100 ns: shock propagation

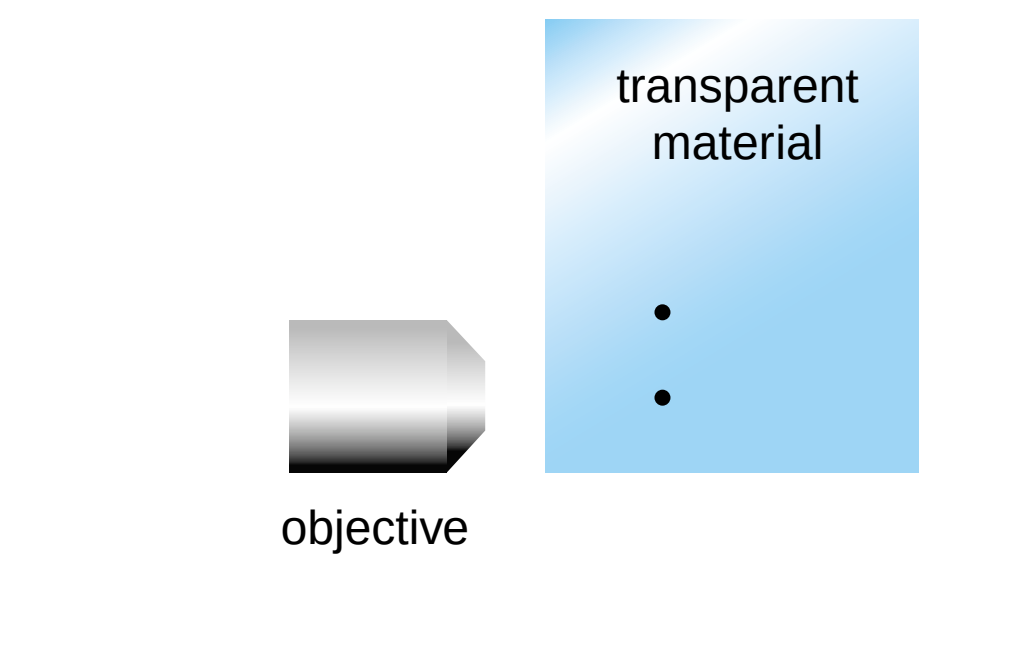


1 µs: thermal diffusion



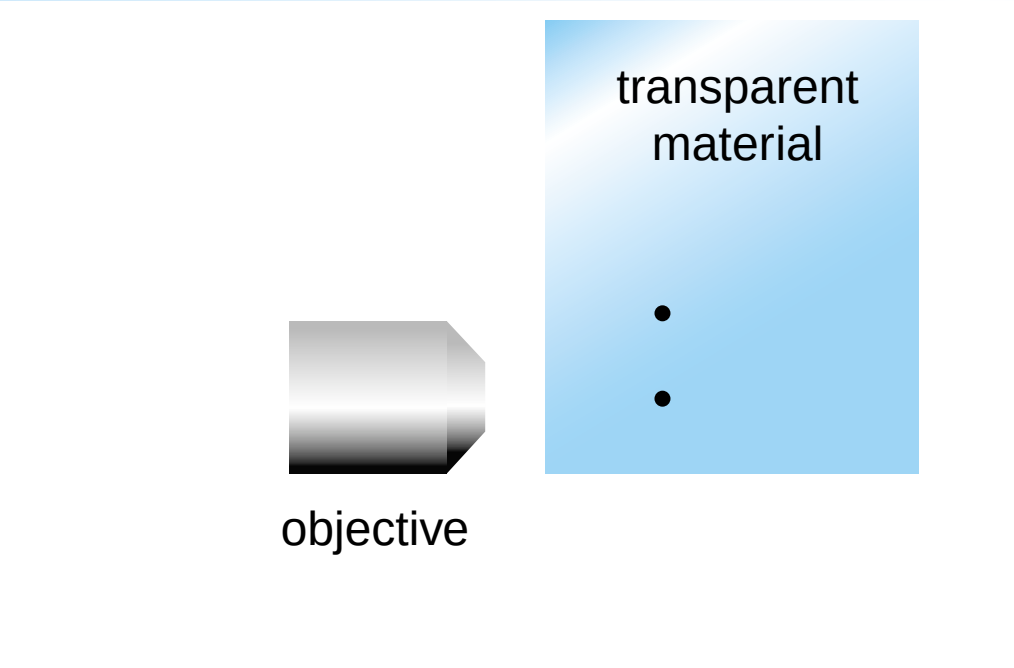
Introduction

1 ms: permanent structural change



Introduction

What are the conditions at the focus?



laser deposits energy in ~0.1 μm^3

Introduction

Electric field at focus is about 10^{11} V/m

Introduction

Electric field at focus is about 10^{11} V/m

Compare to atomic field of 10^{9} V/m

Introduction

Electric field at focus is about 10^{11} V/m

Compare to atomic field of 10^{9} V/m

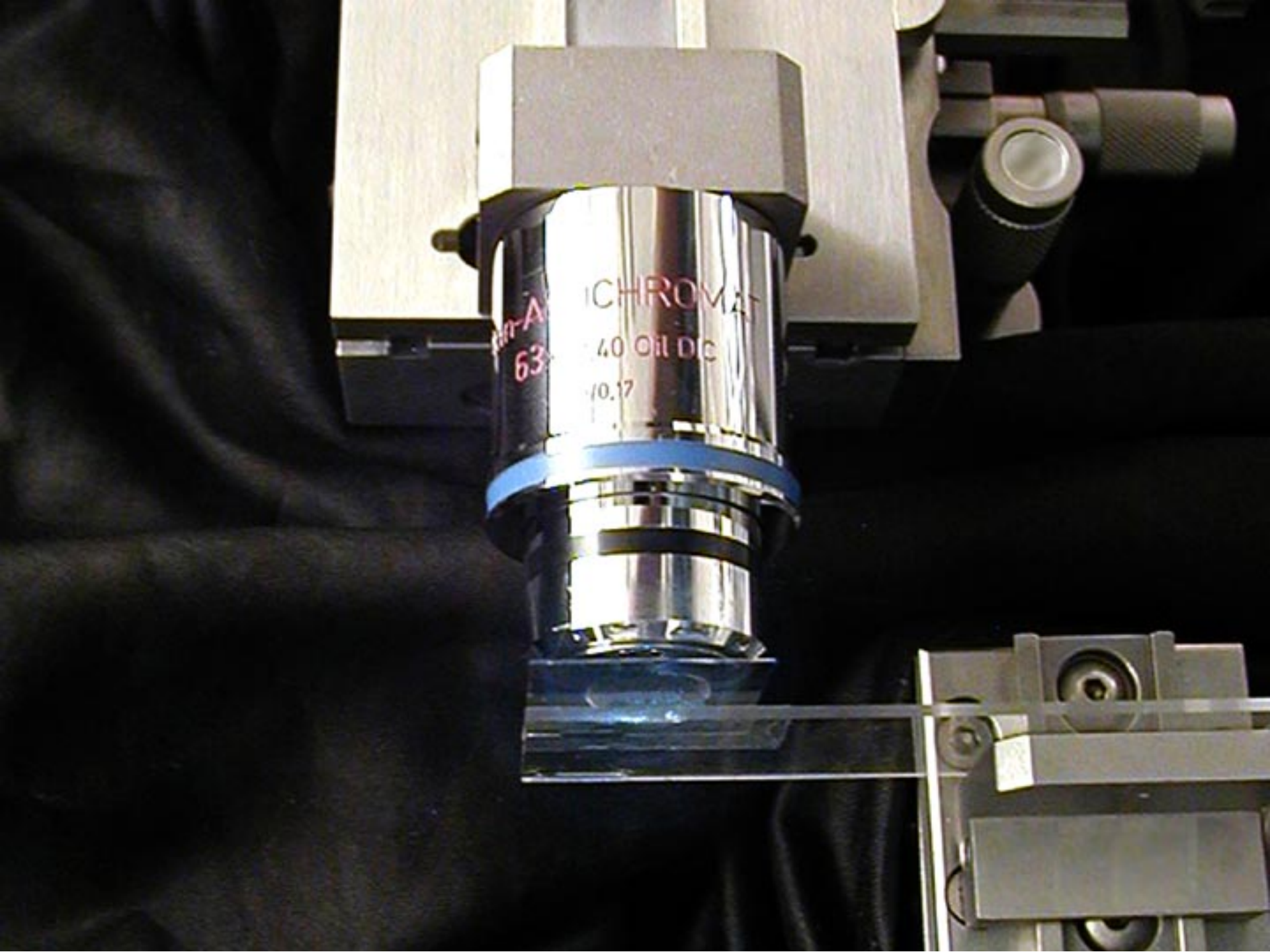
Material is a perturbation to the light!

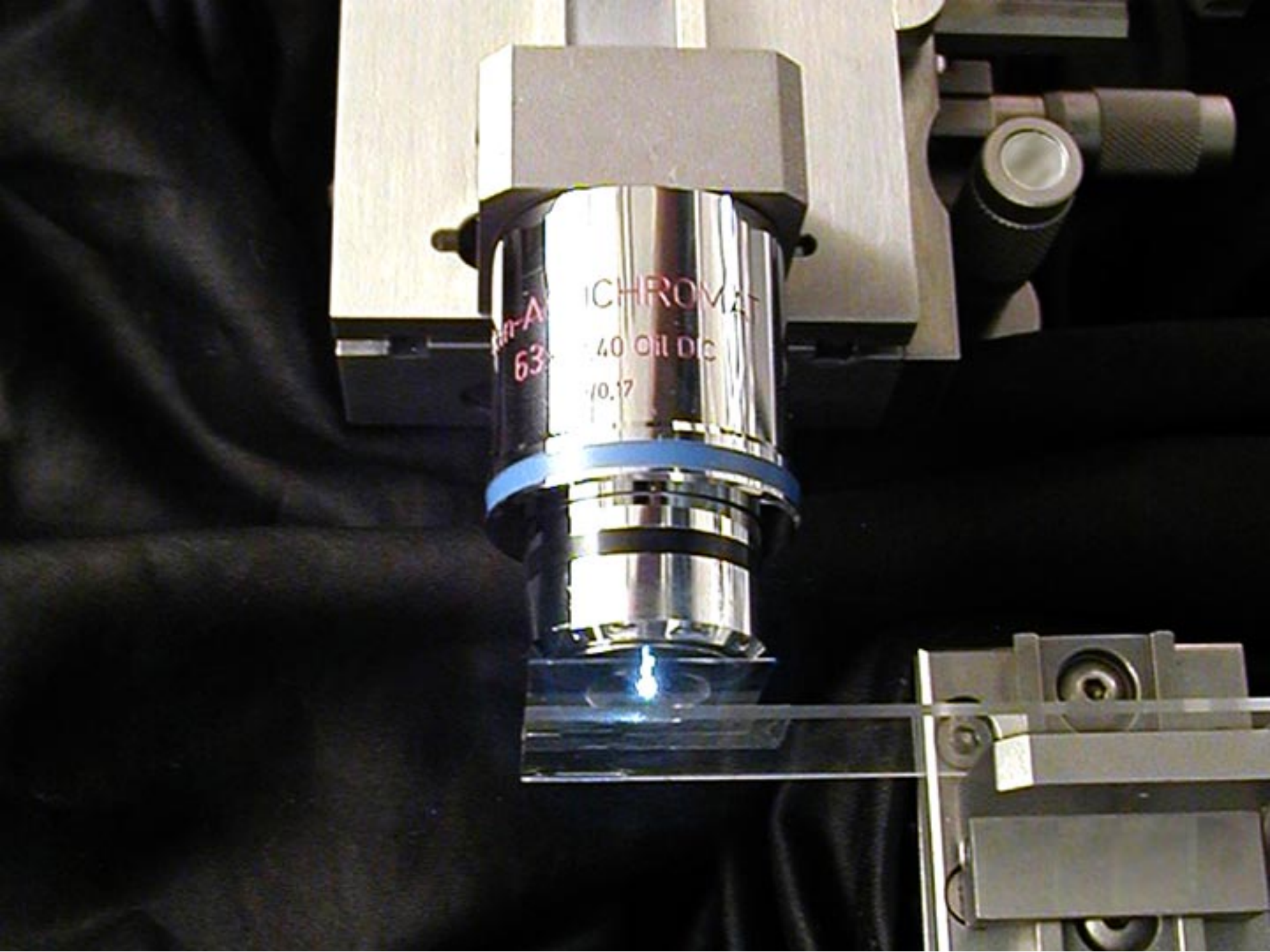
Introduction

How do materials behave under these extreme conditions?

Outline

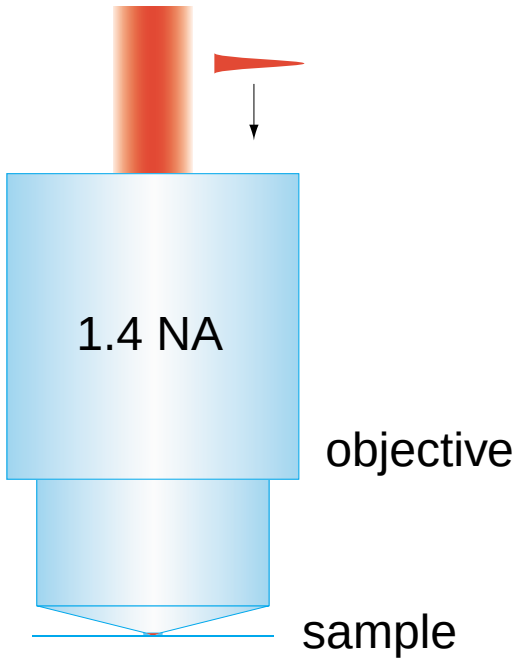
- Setup
- Morphology
- Energy deposition
- Dynamics


ICHROMAT
40 Oil DC
0.17


CHROMAT
40 Oil DC
0.17

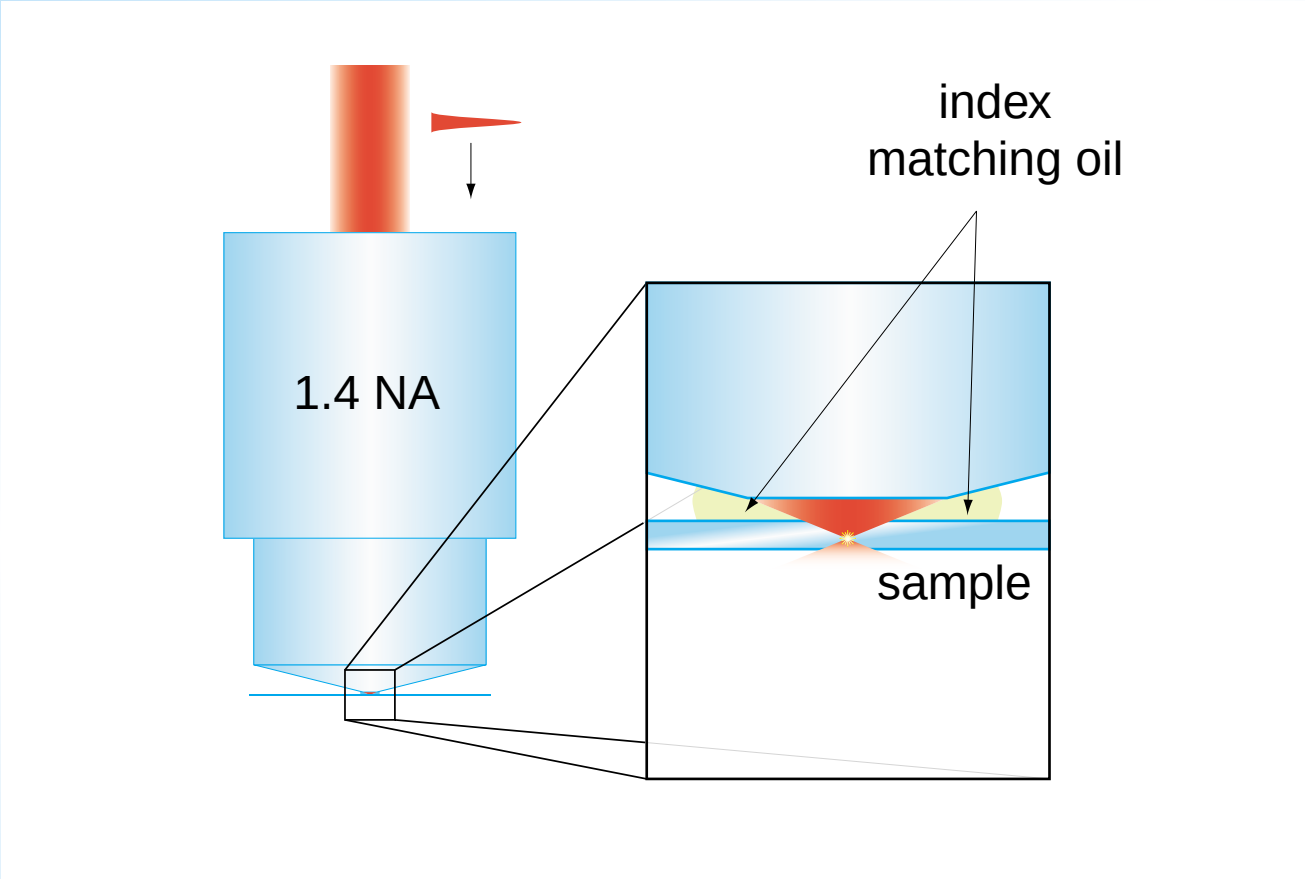
Setup

1.4 numerical aperture (NA) focusing geometry



Setup

1.4 numerical aperture (NA) focusing geometry

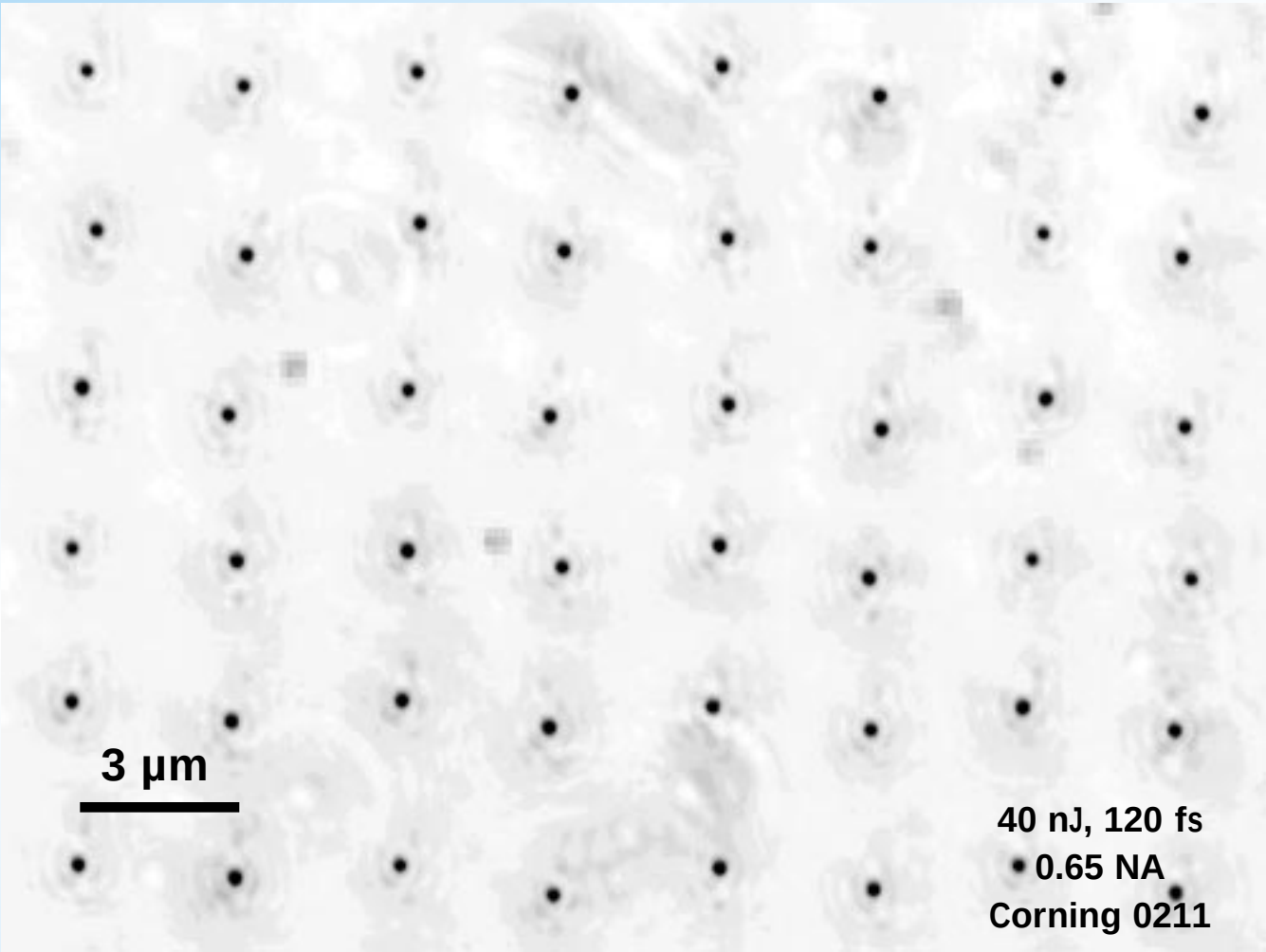


Outline

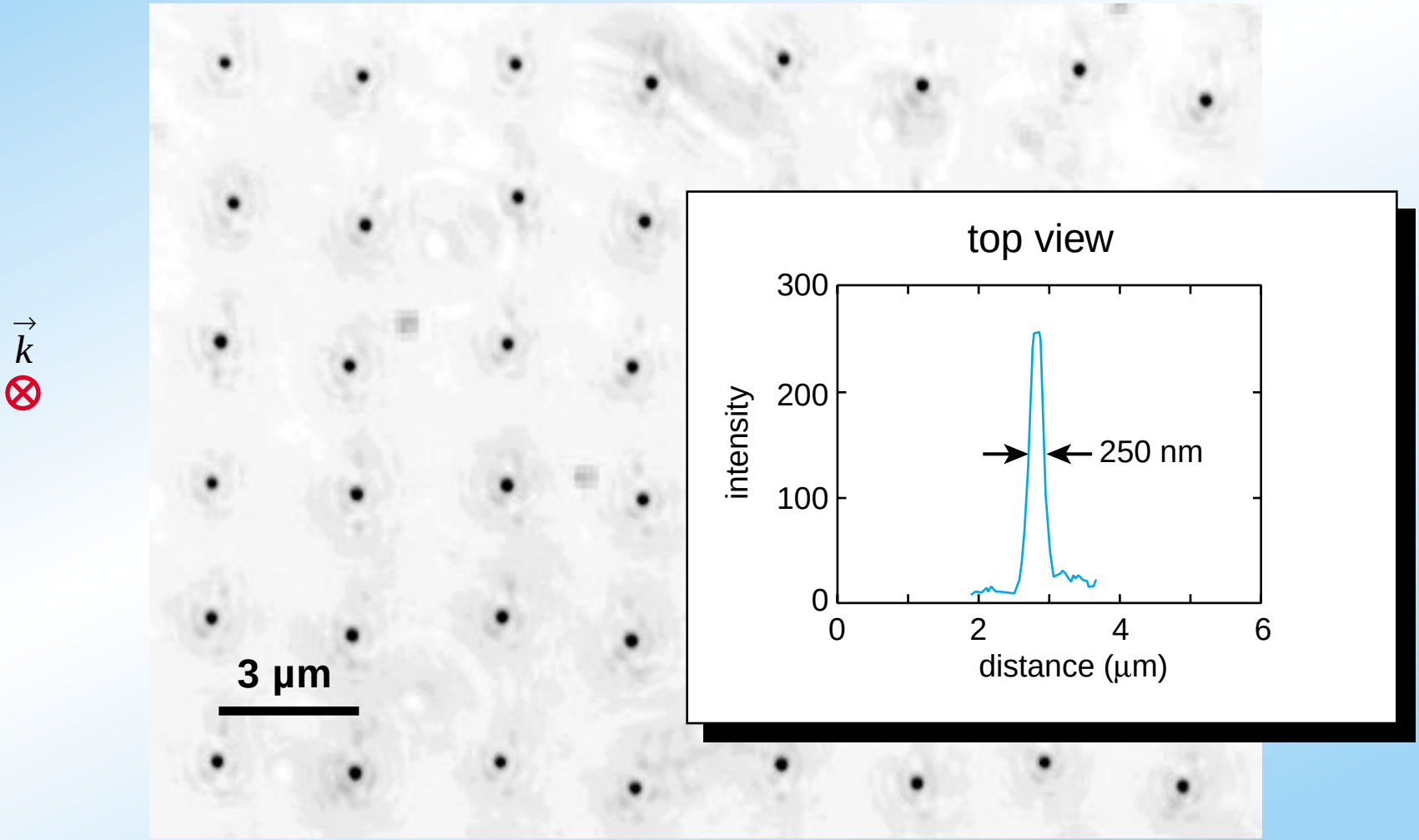
- Setup
- **Morphology**
- Energy deposition
- Dynamics

Morphology

$\vec{k}$



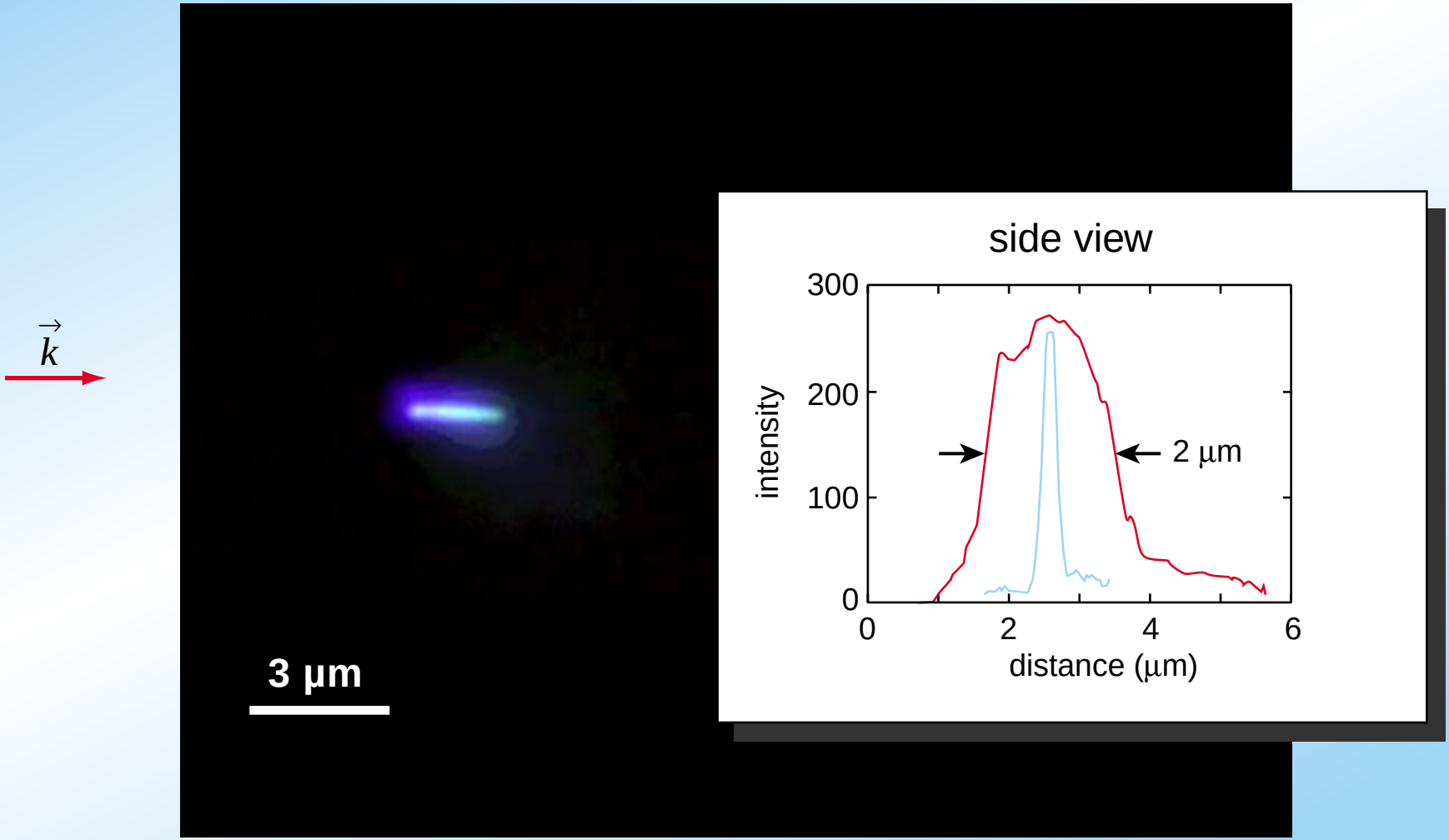
Morphology


$\vec{k}$
3 µm
top view
300
200
100
0
intensity
250 nm
0
2
4
6
distance (µm)

Morphology

$\vec{k}$

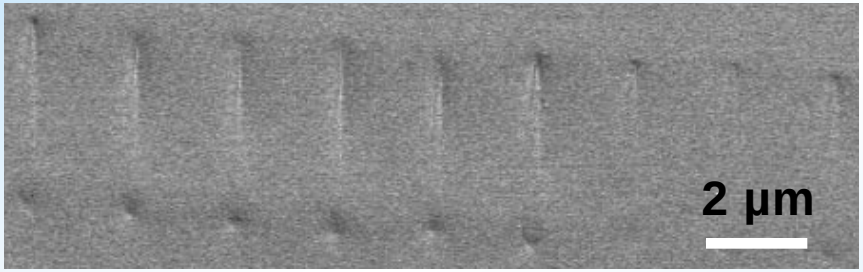
Morphology


$\vec{k}$
3 µm
side view
300
200
100
0
intensity
0
2
4
6
distance (µm)
2 µm

Morphology

SEM pictures of single-shot structures

140 nJ



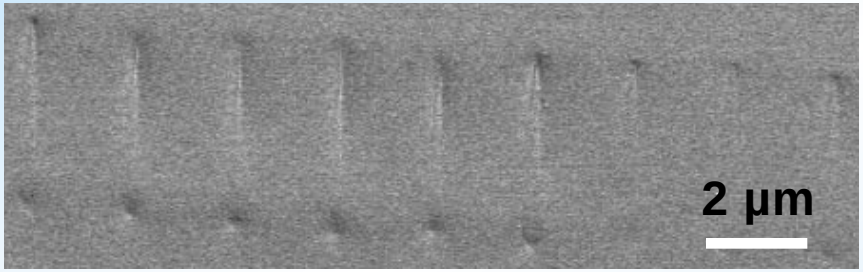
$\vec{k}$

100 fs
800 nm
0.45 NA
Corning 0211

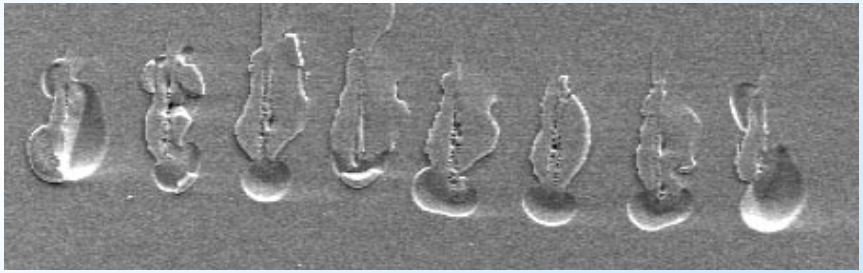
Morphology

SEM pictures of single-shot structures

140 nJ



250 nJ



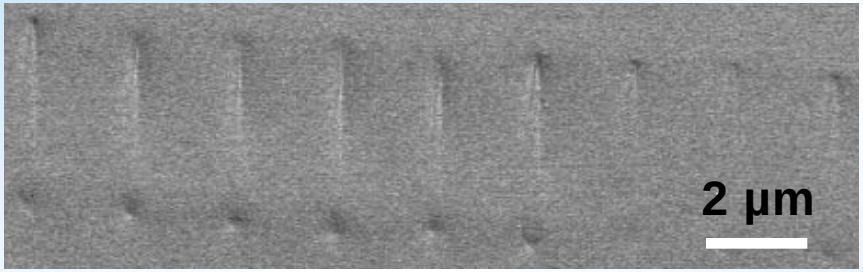
$\vec{k}$

100 fs
800 nm
0.45 NA
Corning 0211

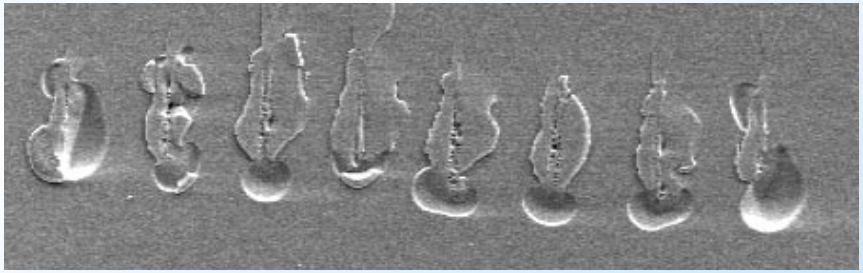
Morphology

SEM pictures of single-shot structures

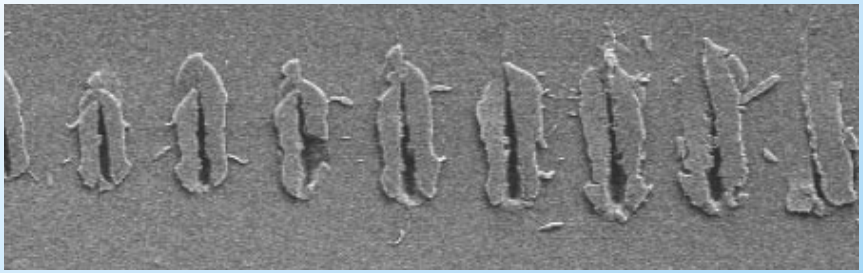
140 nJ



250 nJ



540 nJ



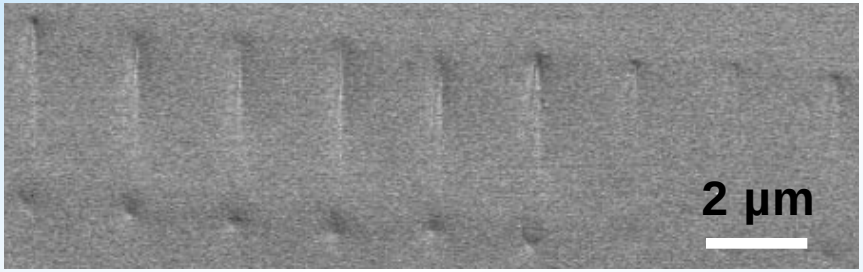
$\vec{k}$

100 fs
800 nm
0.45 NA
Corning 0211

Morphology

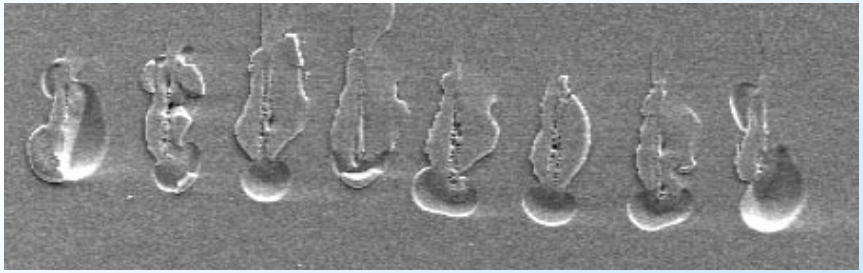
SEM pictures of single-shot structures

140 nJ

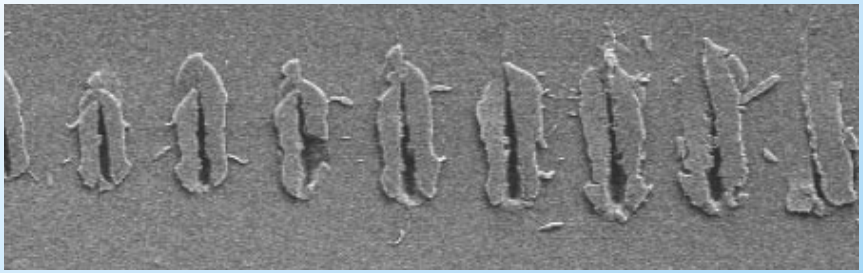


thermal

250 nJ



540 nJ



explosive

Morphology

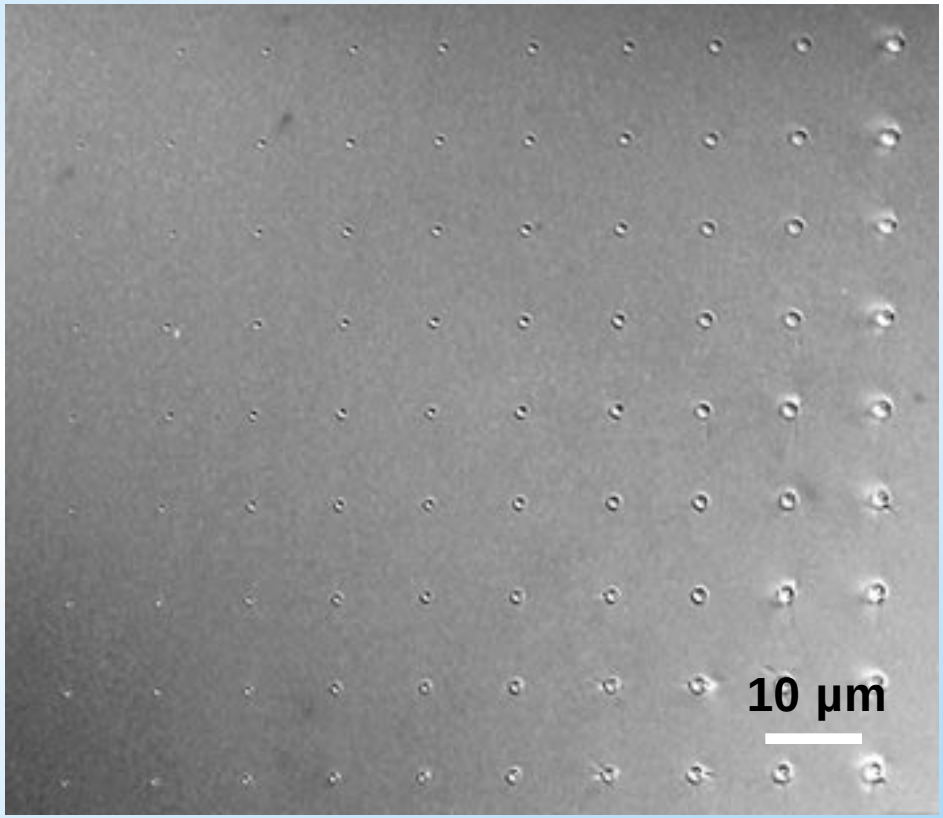
What happens when several pulses strike the same spot?

Morphology

multiple-shot structures (1 kHz)

more energy →

more shots ↓

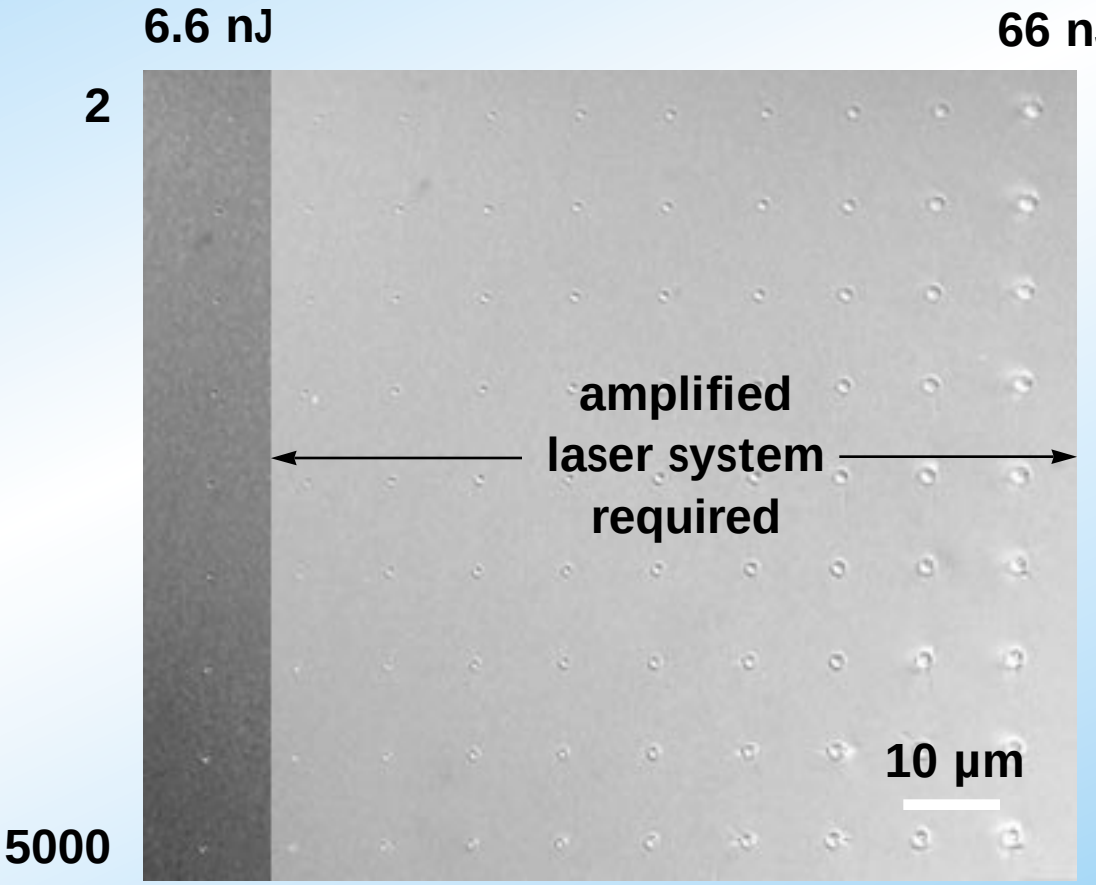


$\vec{k}$ ⊗

100 fs
1.4 NA
Corning 0211

Morphology

multiple-shot structures (1 kHz)

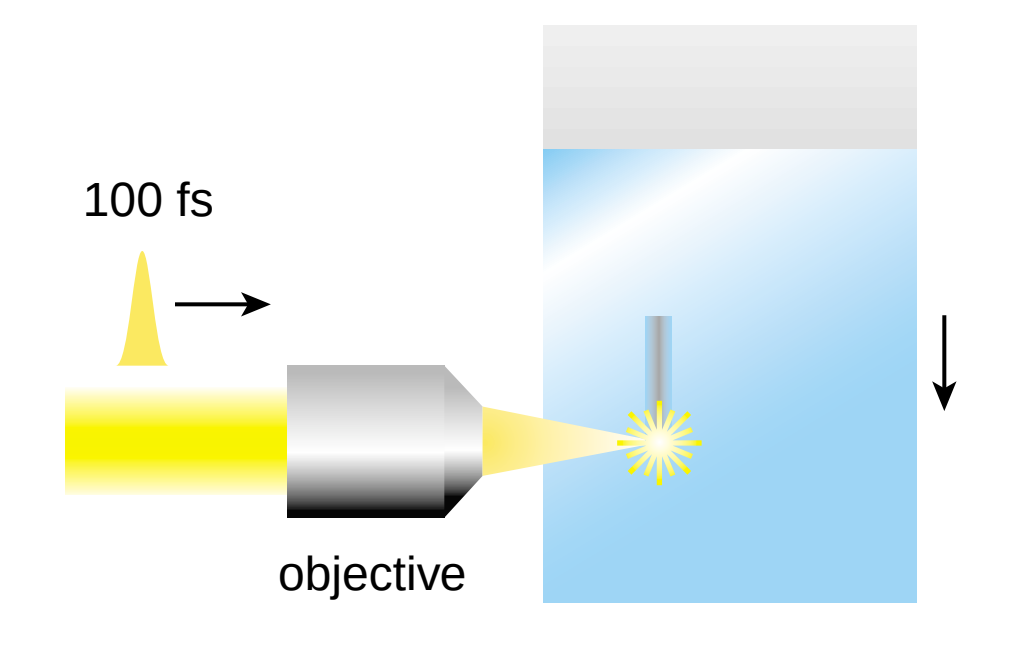


$\vec{k}$ ⊗

100 fs
1.4 NA
Corning 0211

Morphology

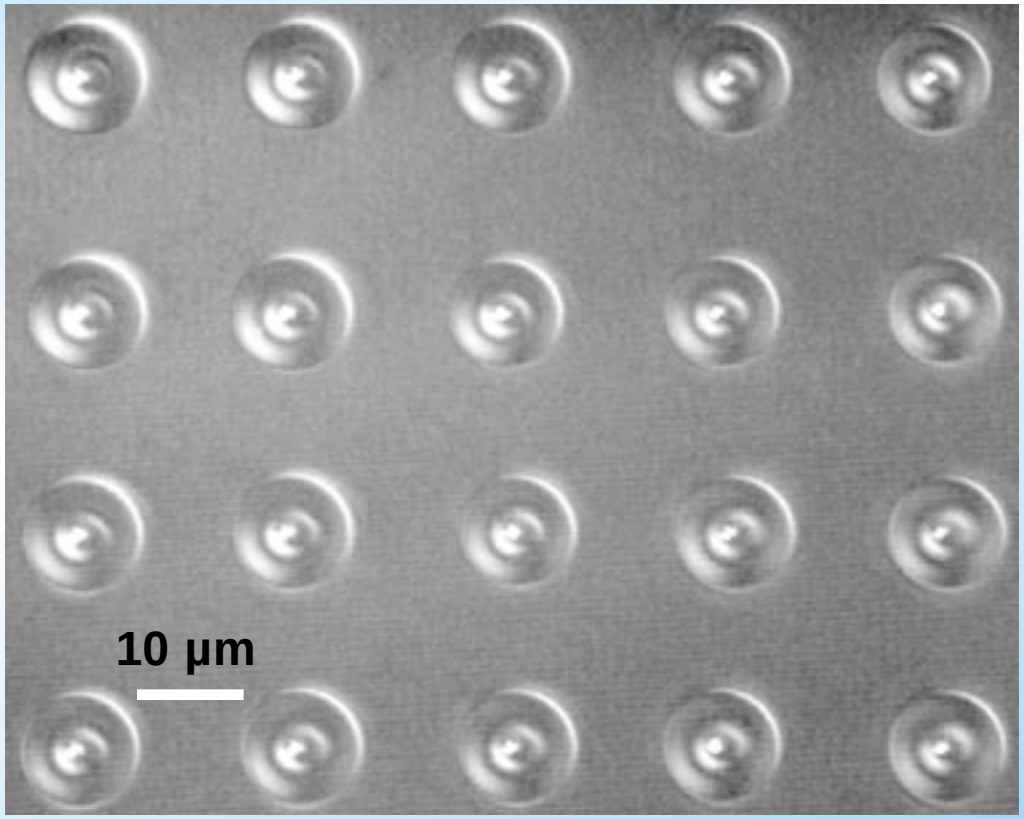
oscillator-only “micromachining”



25 MHz: point source of heat inside material!

Morphology

cumulative heating structures (25 MHz)

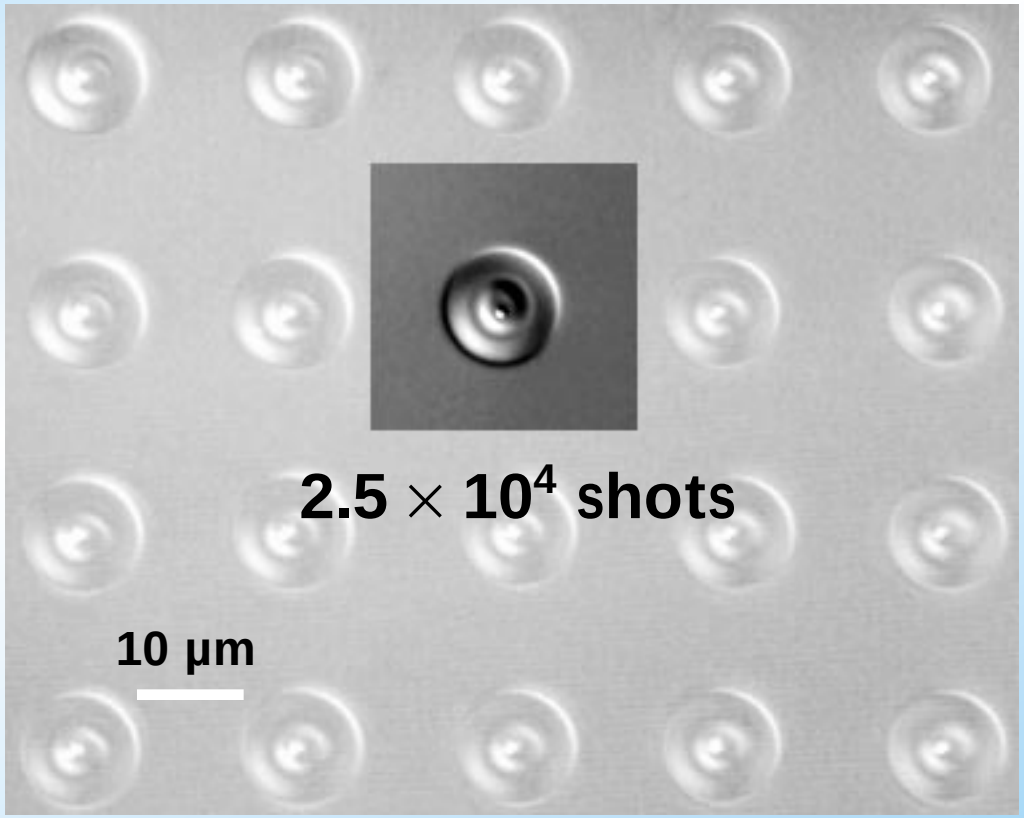


$\vec{k}$ ⊗

25,000 shots
4.5 nJ, <100 fs
1.4 NA
Corning 0211

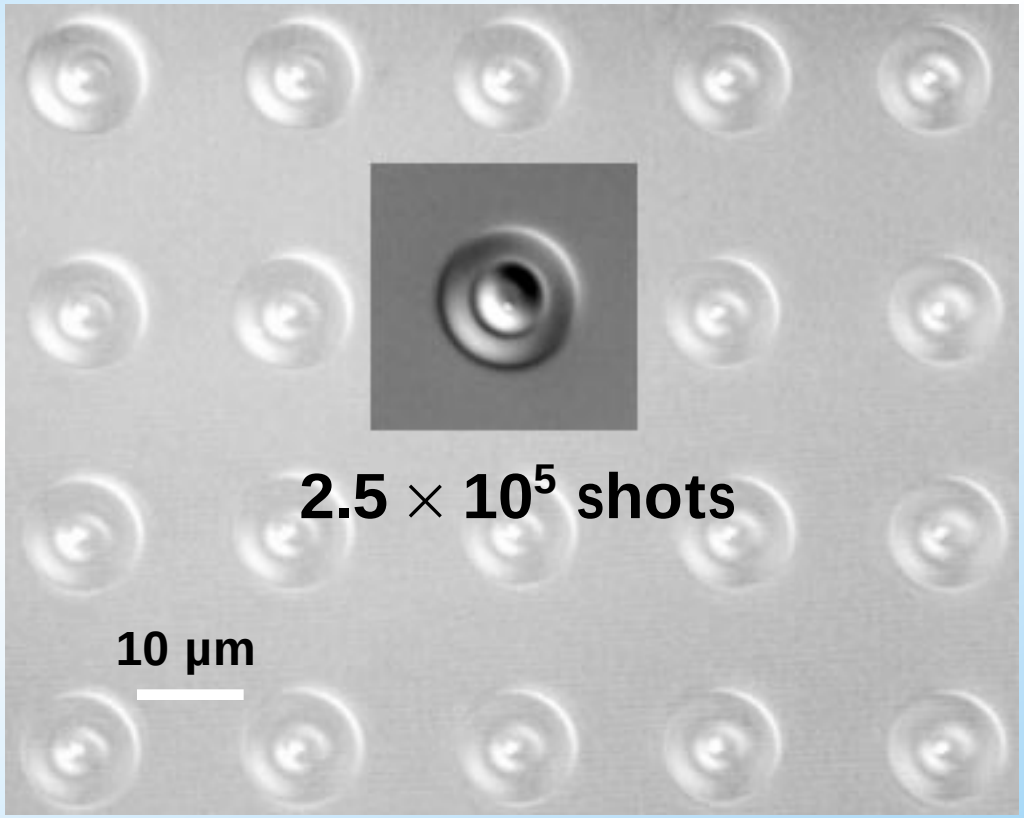
Morphology

cumulative heating structures (25 MHz)



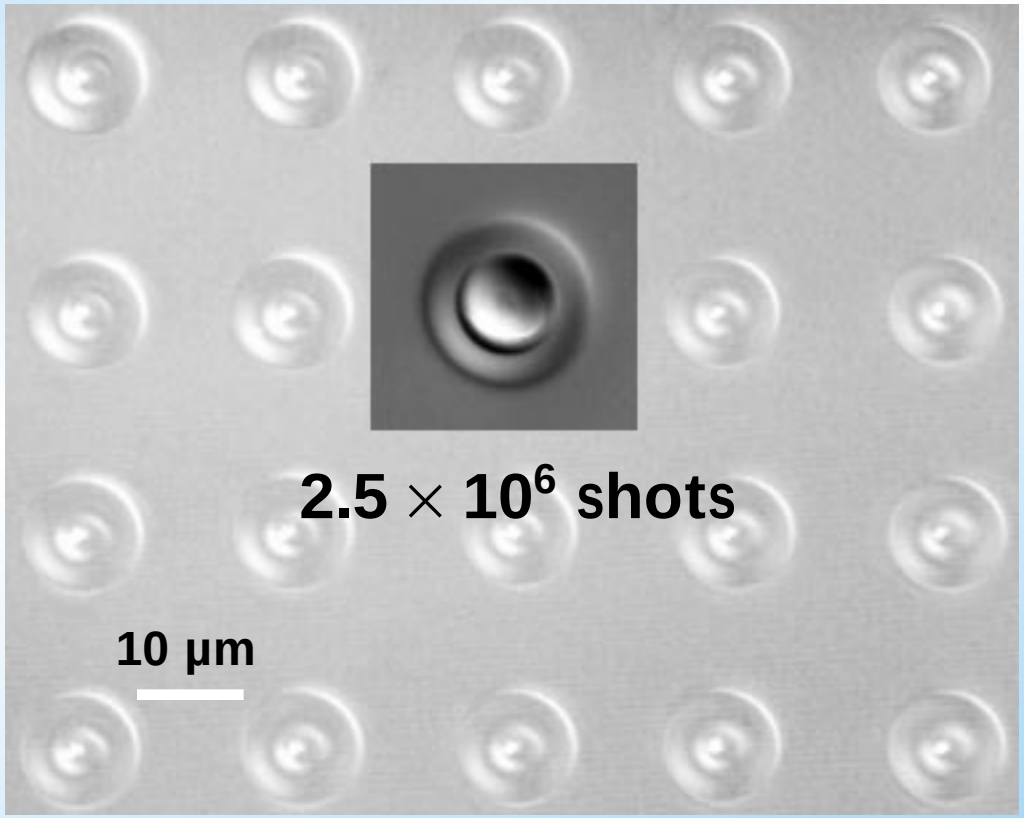
Morphology

cumulative heating structures (25 MHz)



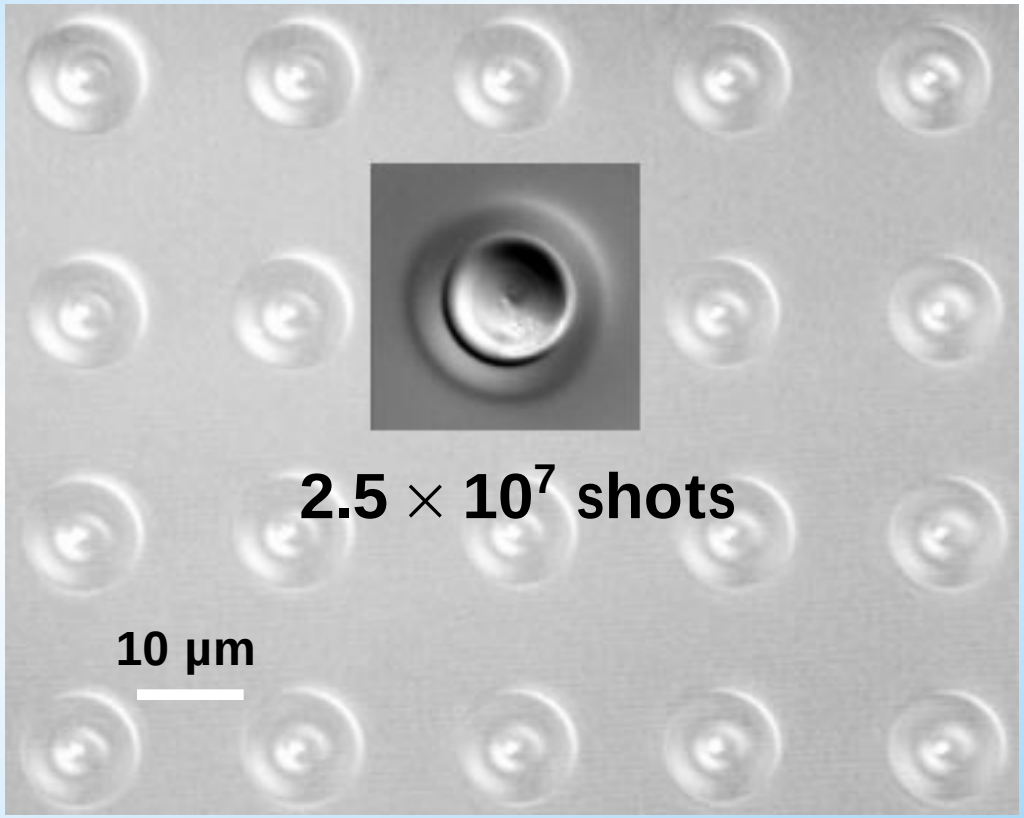
Morphology

cumulative heating structures (25 MHz)

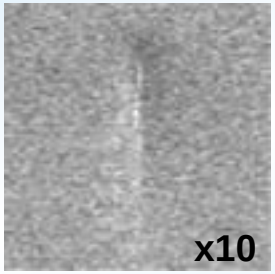
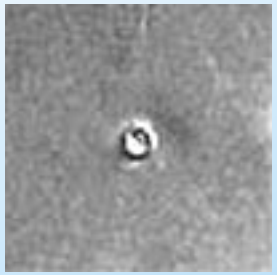
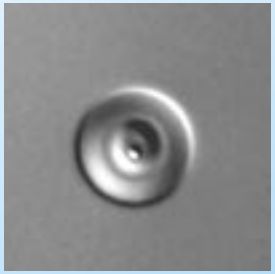


Morphology

cumulative heating structures (25 MHz)



Morphology

	low energy	high energy
single shot		
multiple shot 1 kHz		
multiple shot 25 MHz		

Outline

- Setup
- Morphology
- **Energy deposition**
- Dynamics

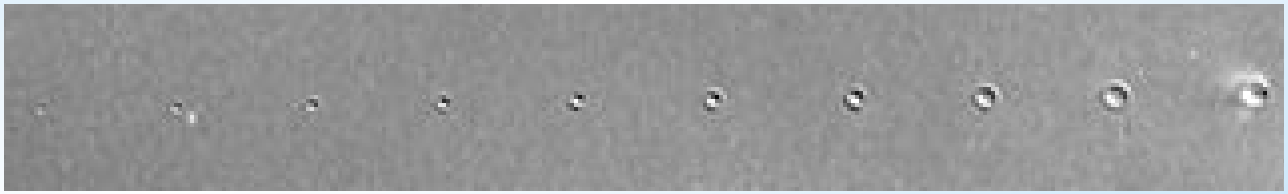
Energy deposition

Determine threshold for structural change:

- **Optical microscopy**
- **Transmission**
- **Dark field scattering**

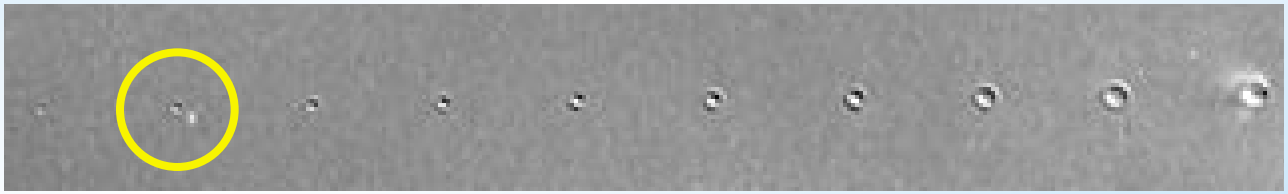
Energy deposition

optical microscopy



Energy deposition

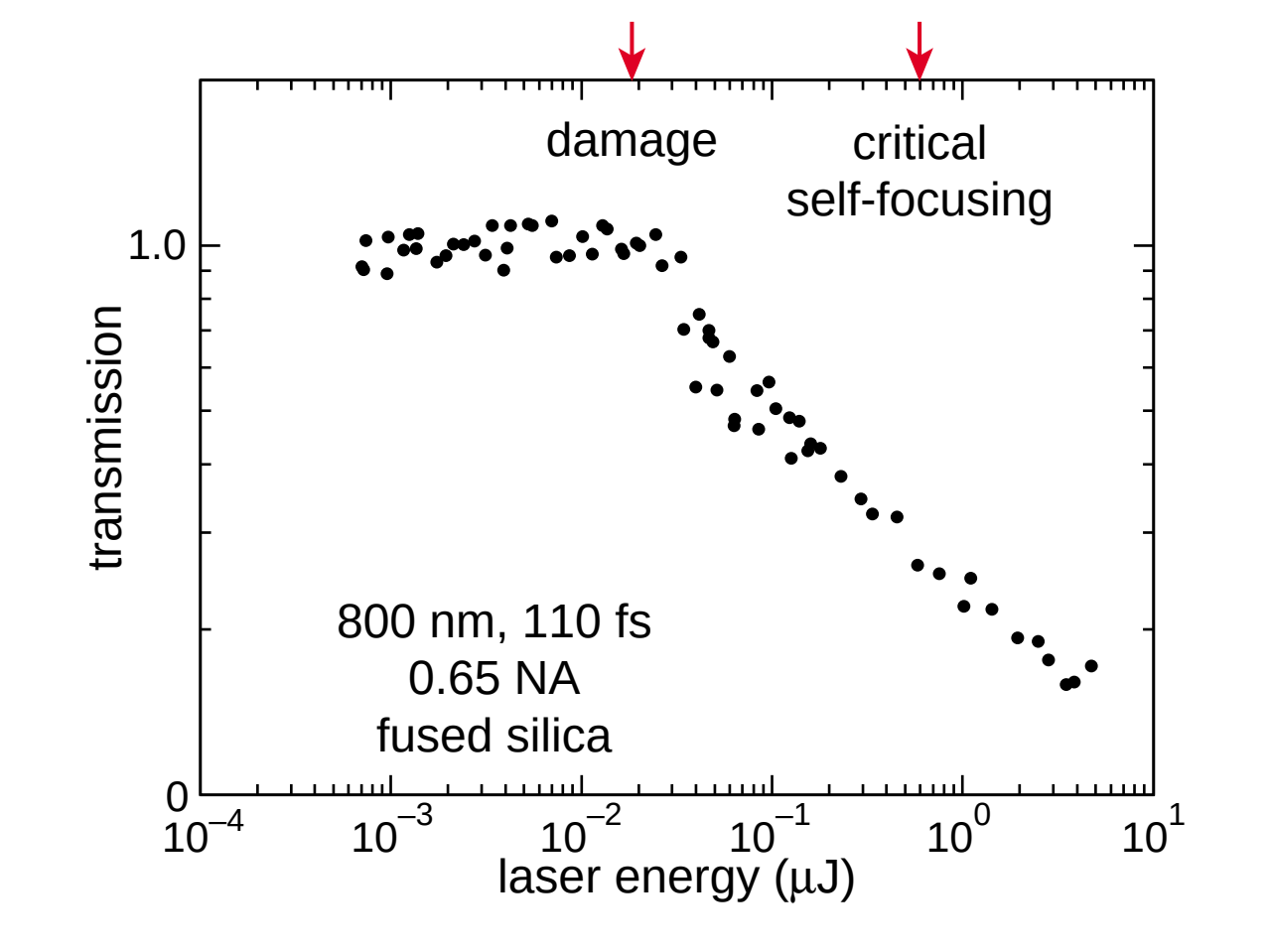
optical microscopy



6.6 nJ

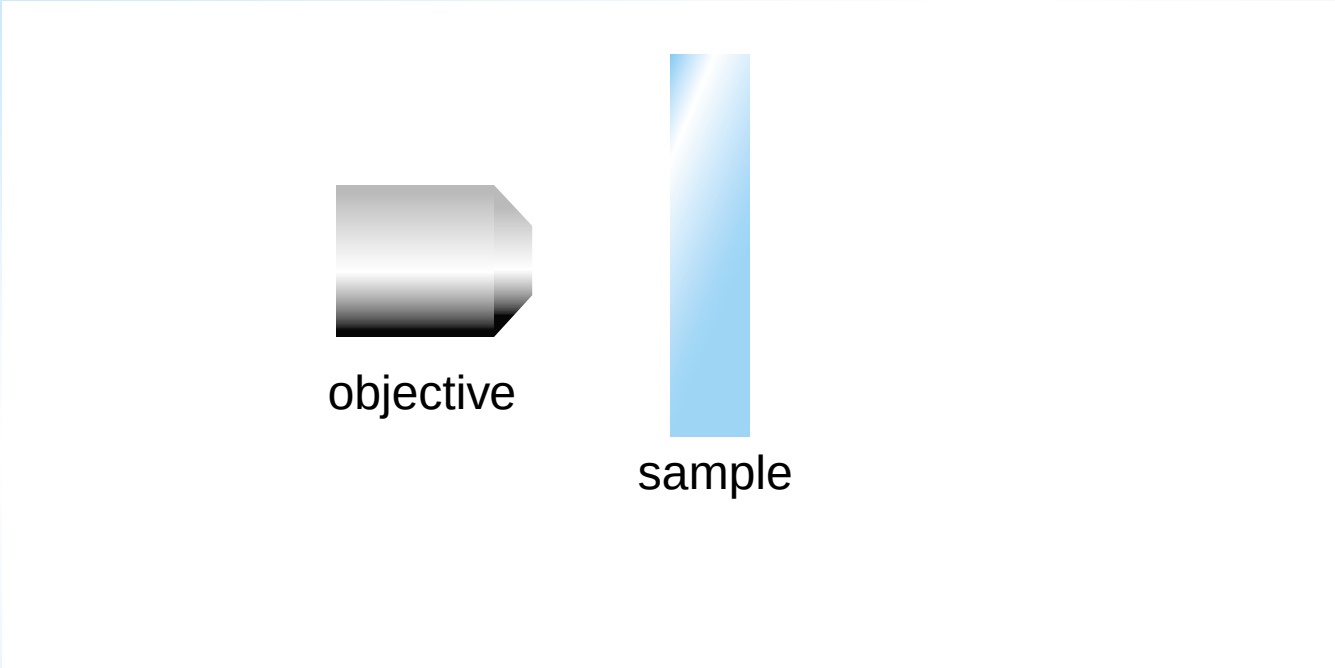
Energy deposition

transmission of pump beam in fused silica



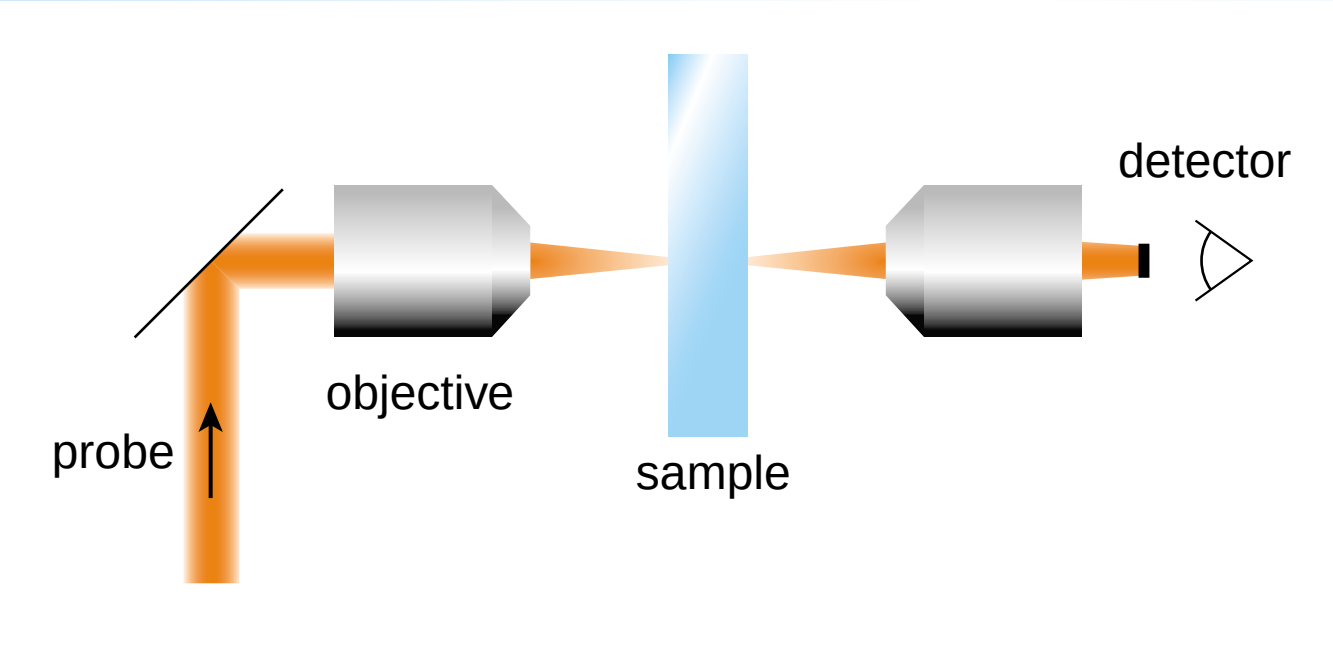
Energy deposition

Dark-field scattering



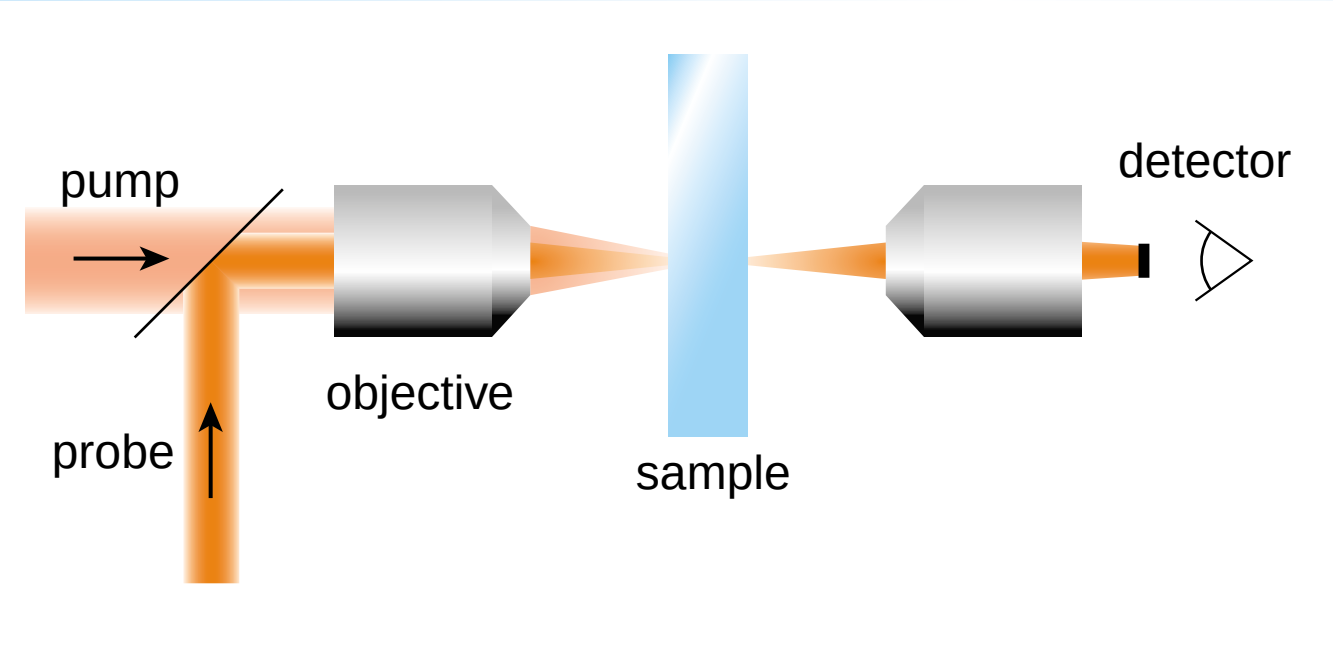
Energy deposition

block probe beam…



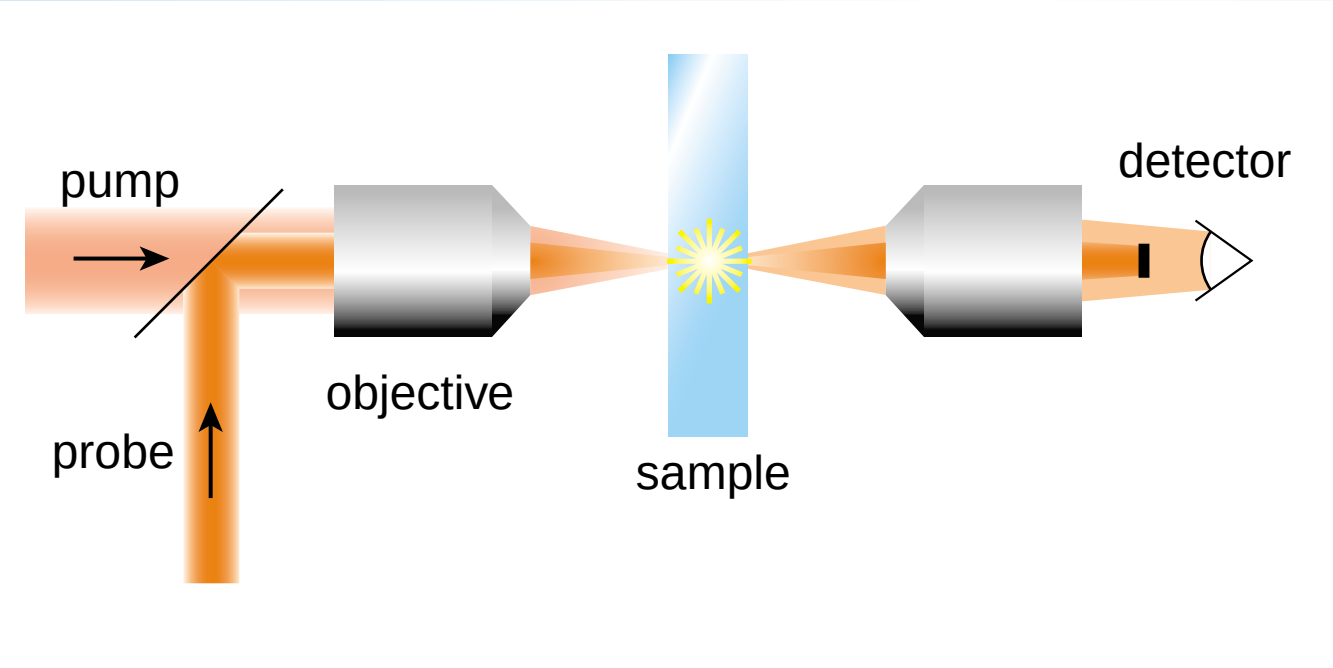
Energy deposition

…bring in pump beam…

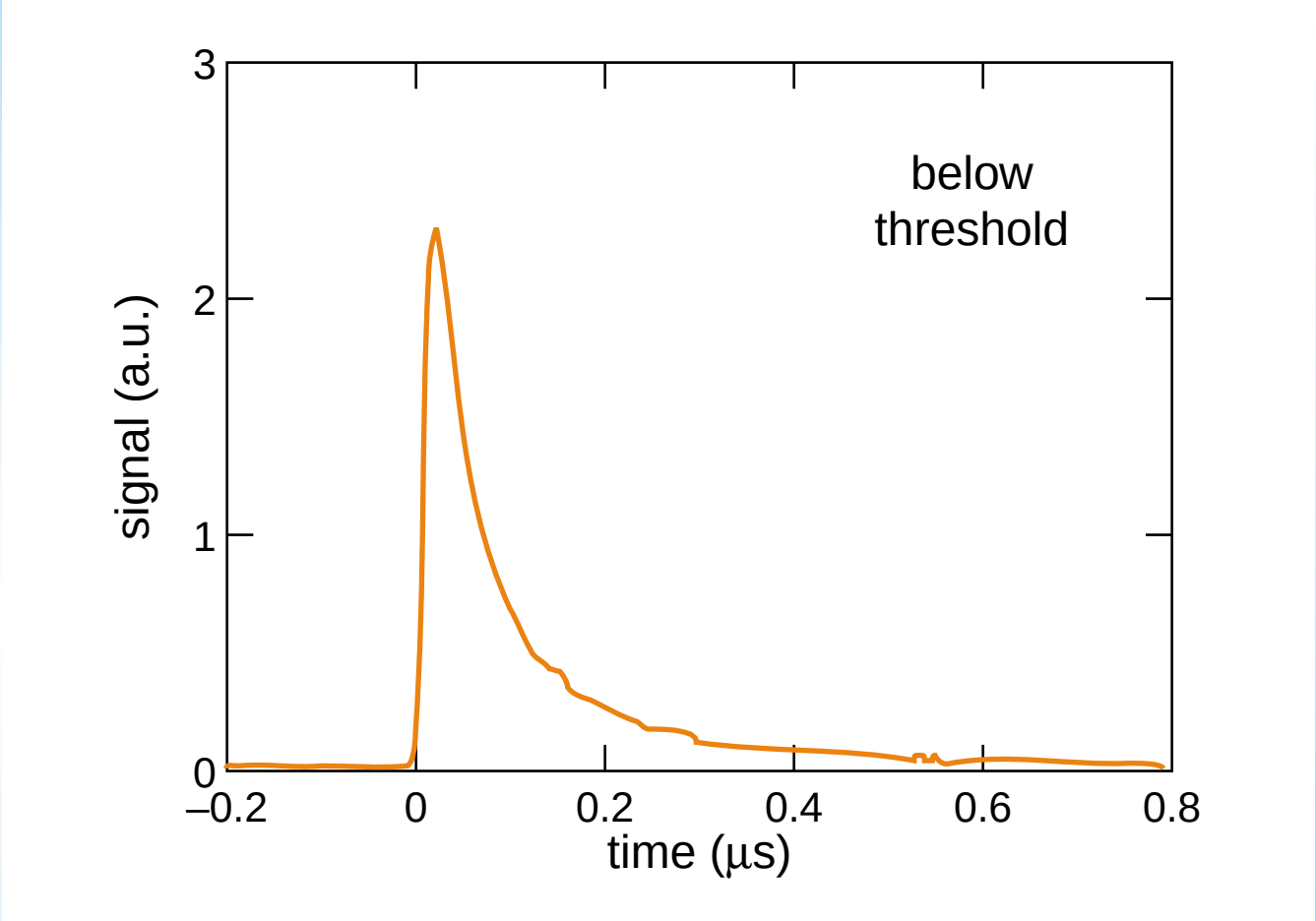


Energy deposition

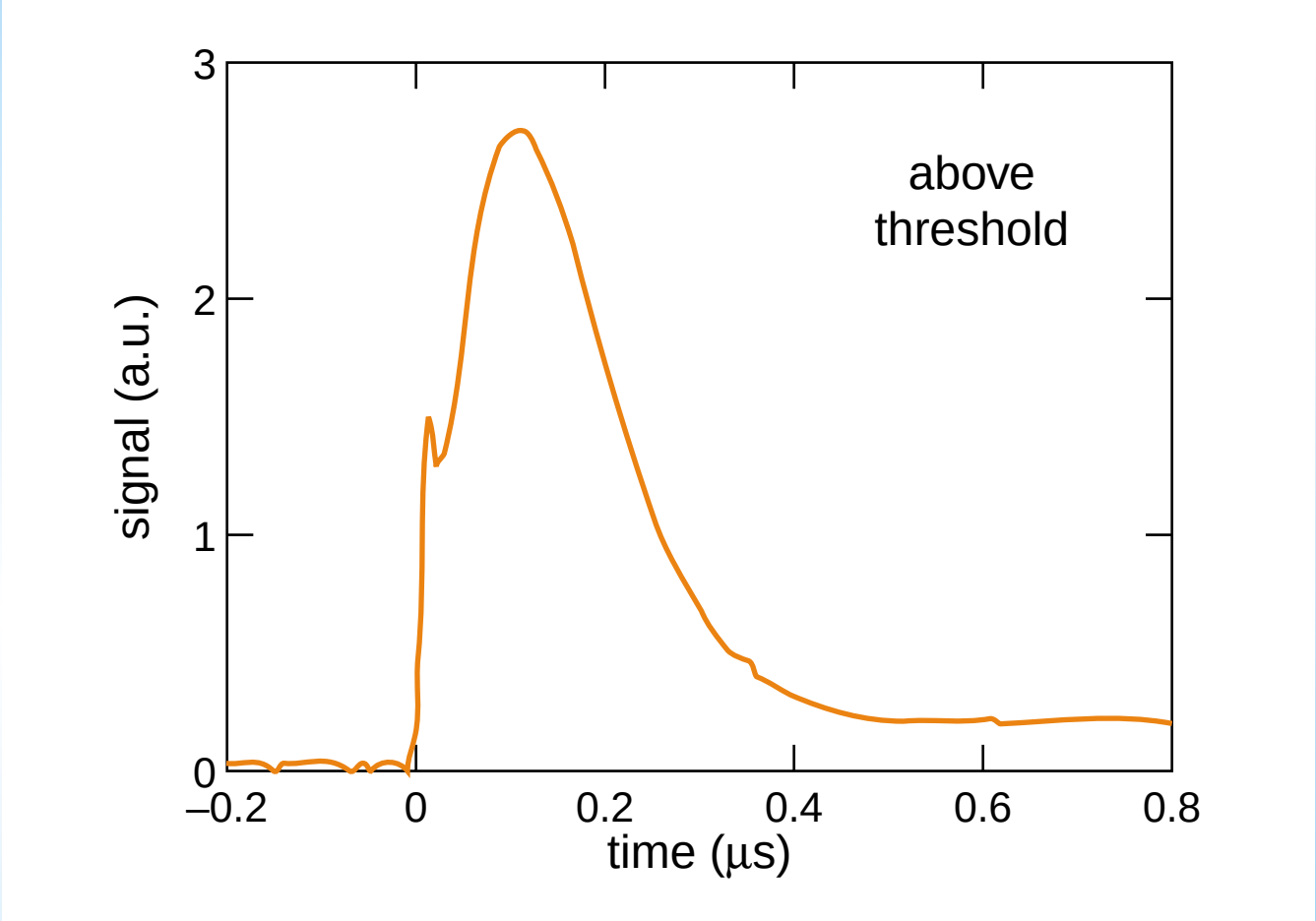
…structural change scatters probe beam



Energy deposition

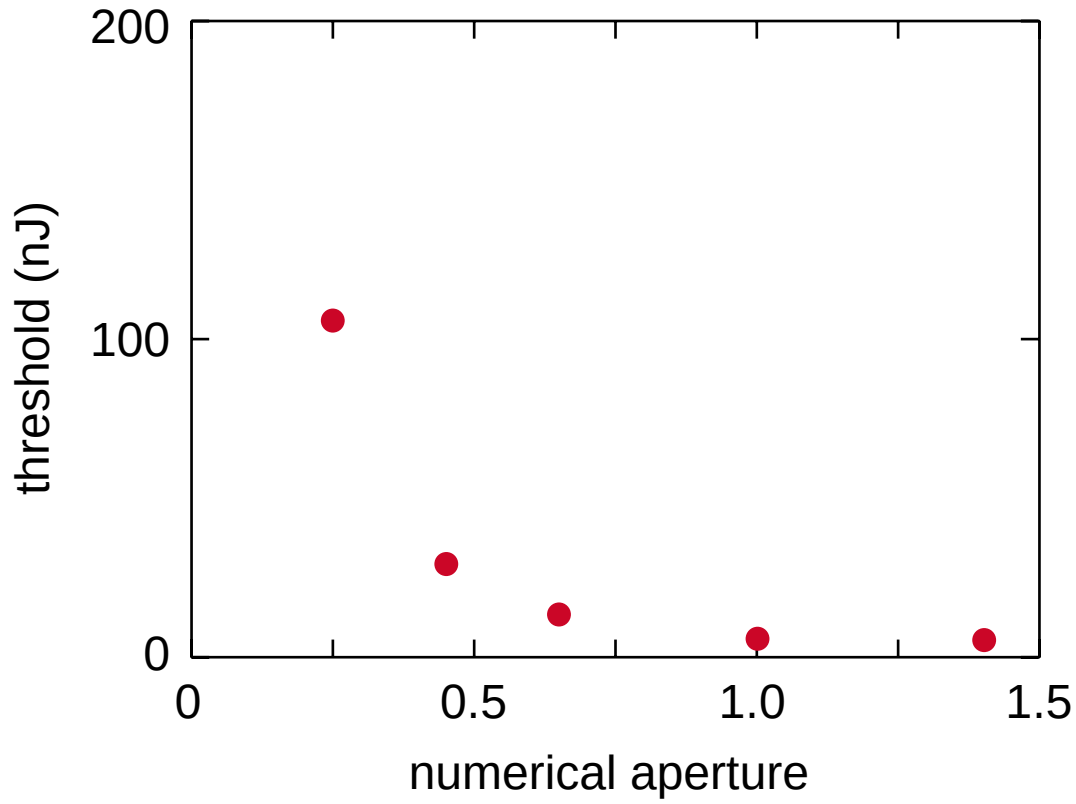


Energy deposition

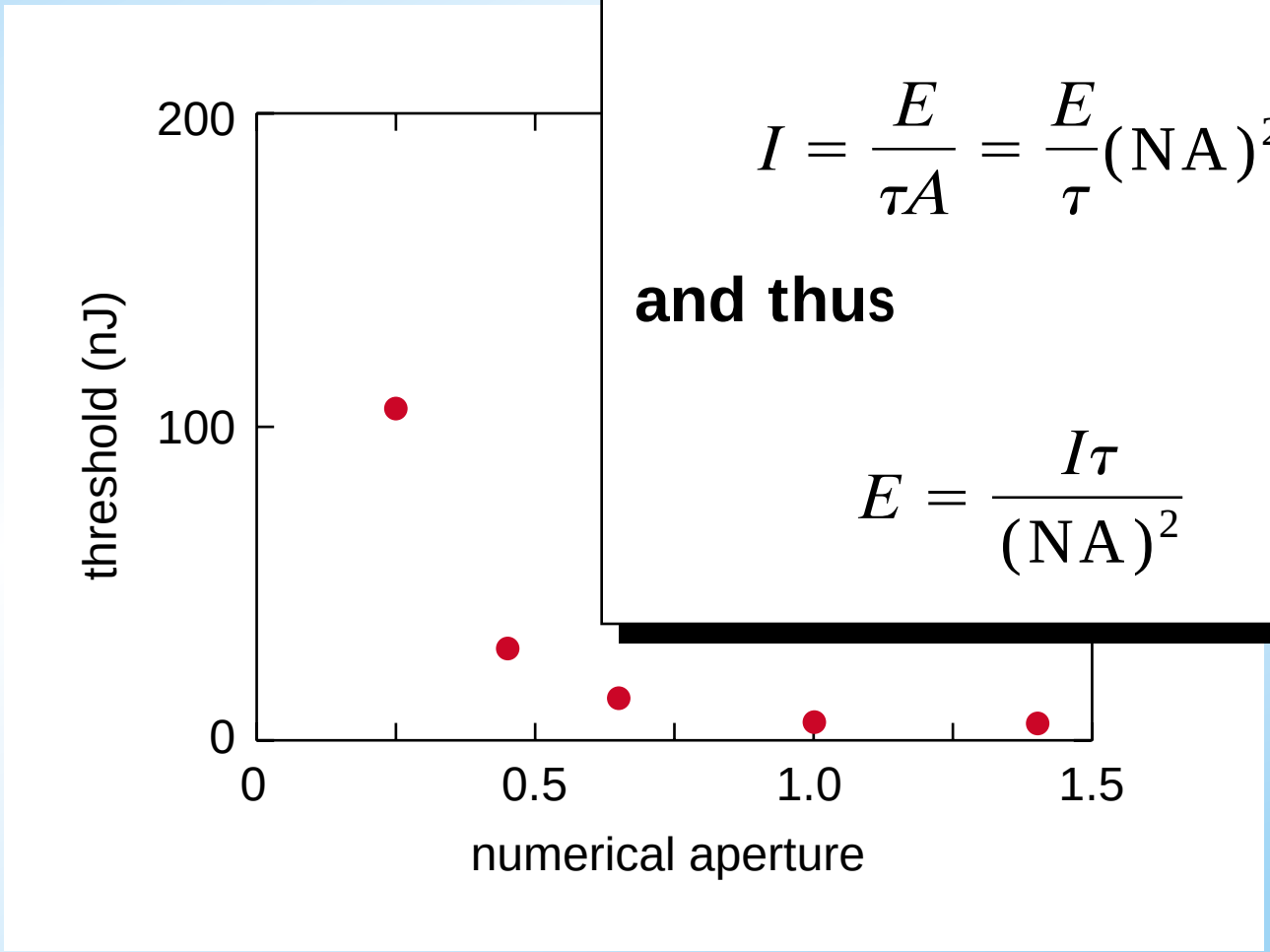


Energy deposition

vary numerical aperture in Corning 0211



Energy deposition



minimal self focusing, so spot size determined by:

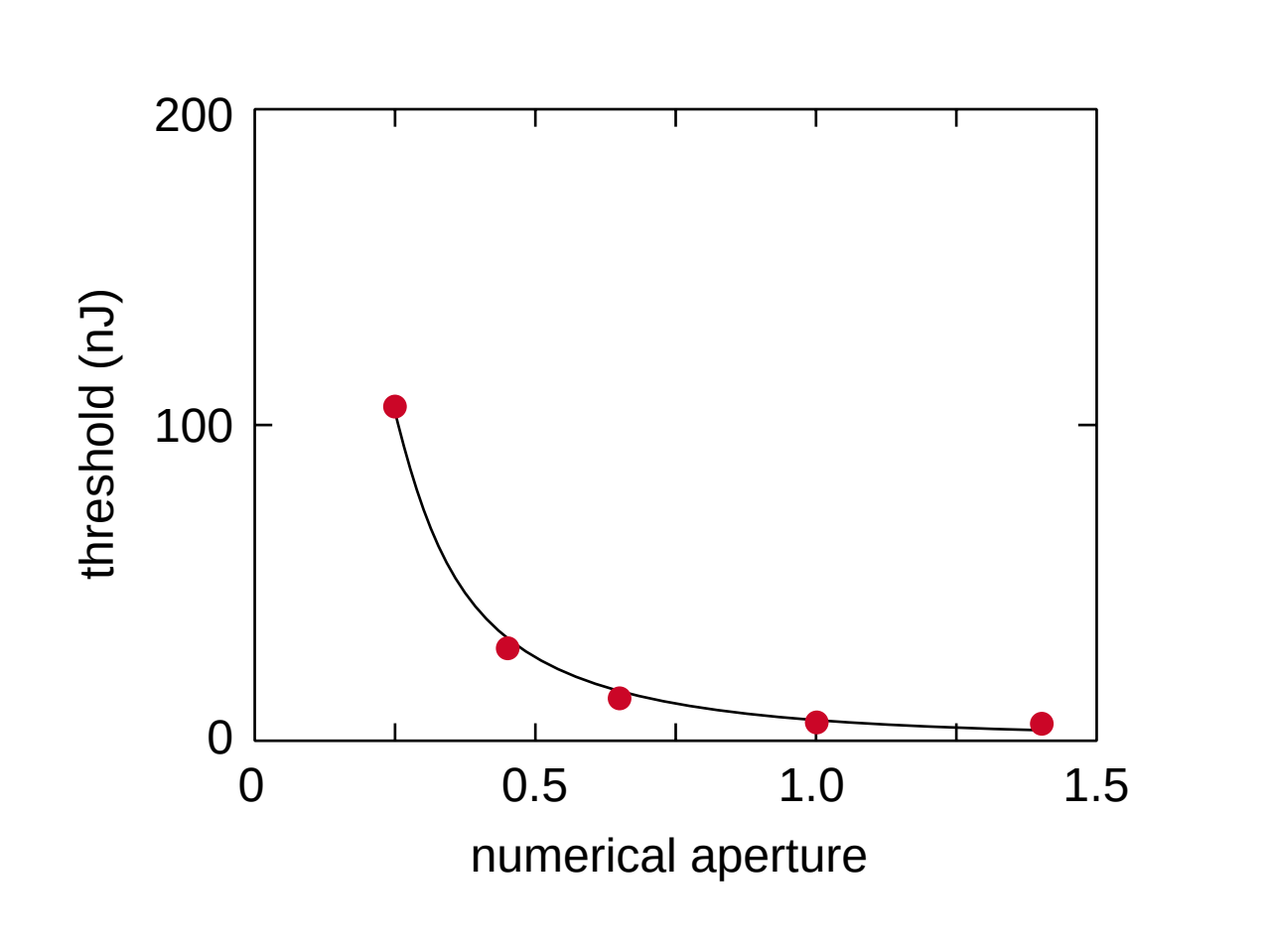
$$I = \frac{E}{\tau A} = \frac{E}{\tau}(\mathrm{NA})^2$$

and thus

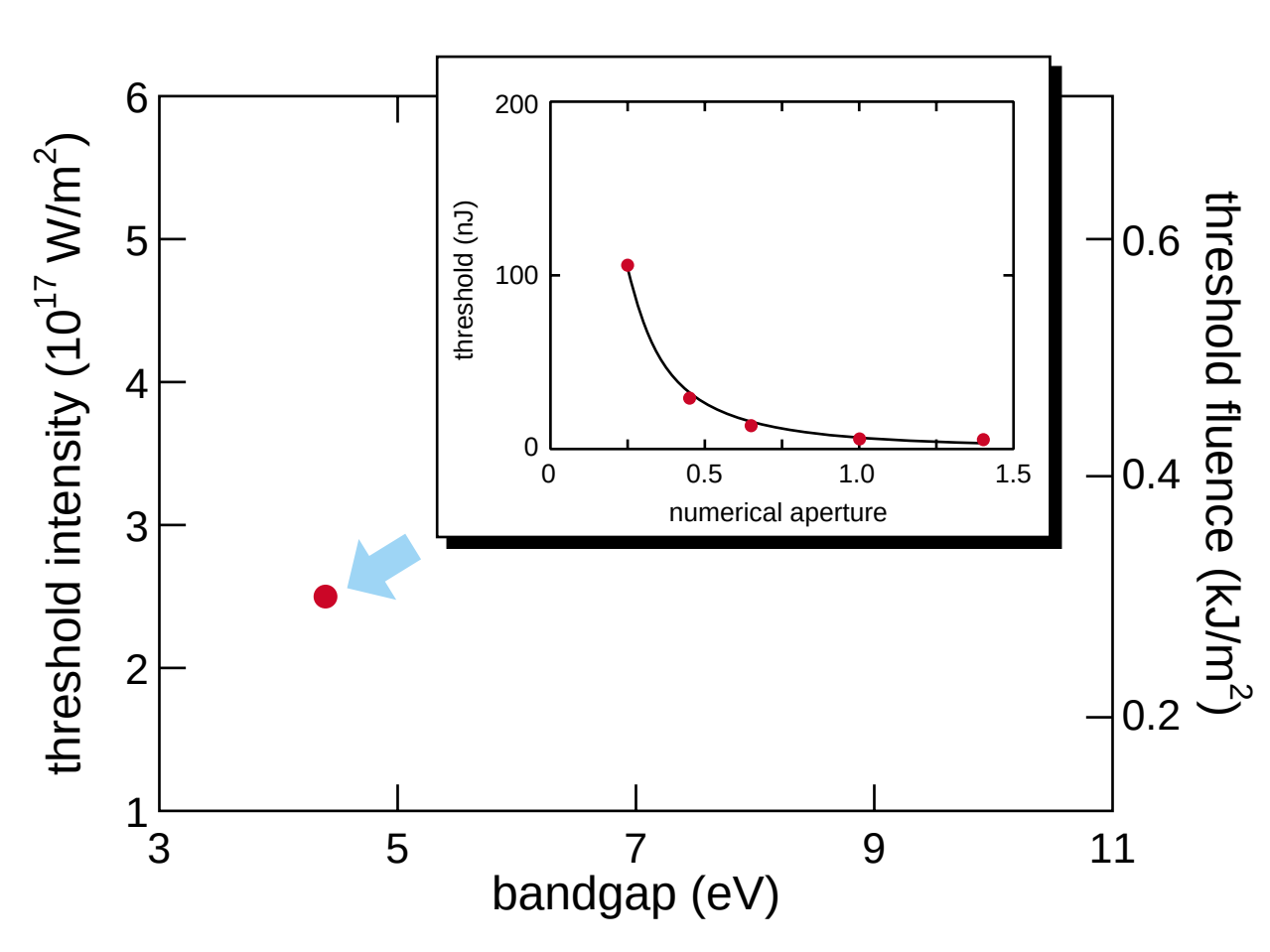
$$E = \frac{I\tau}{(\mathrm{NA})^2}$$

Energy deposition

fit gives threshold intensity: I_{th} = 2.5 x 10^{17} W/m^2

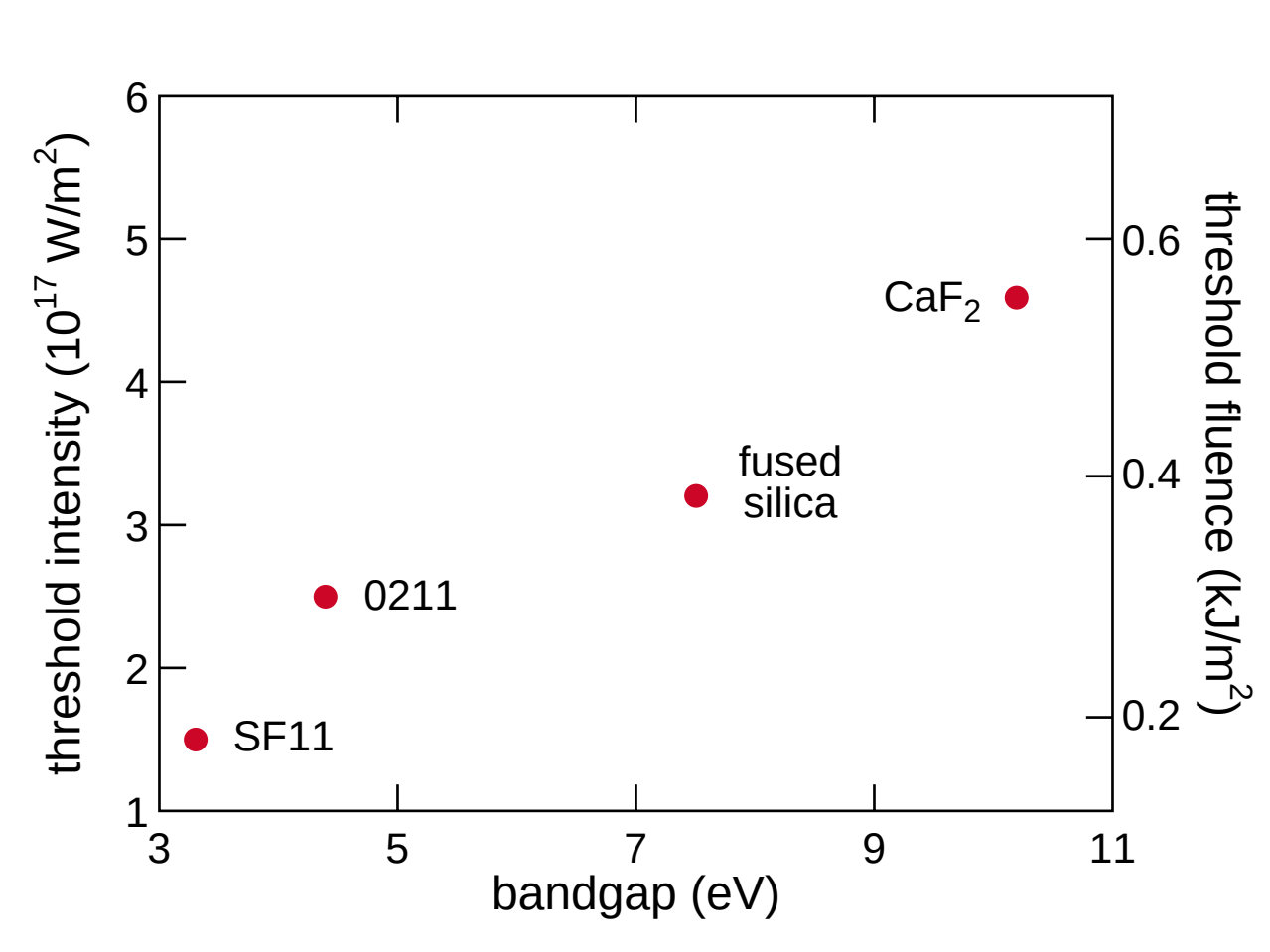


Energy deposition



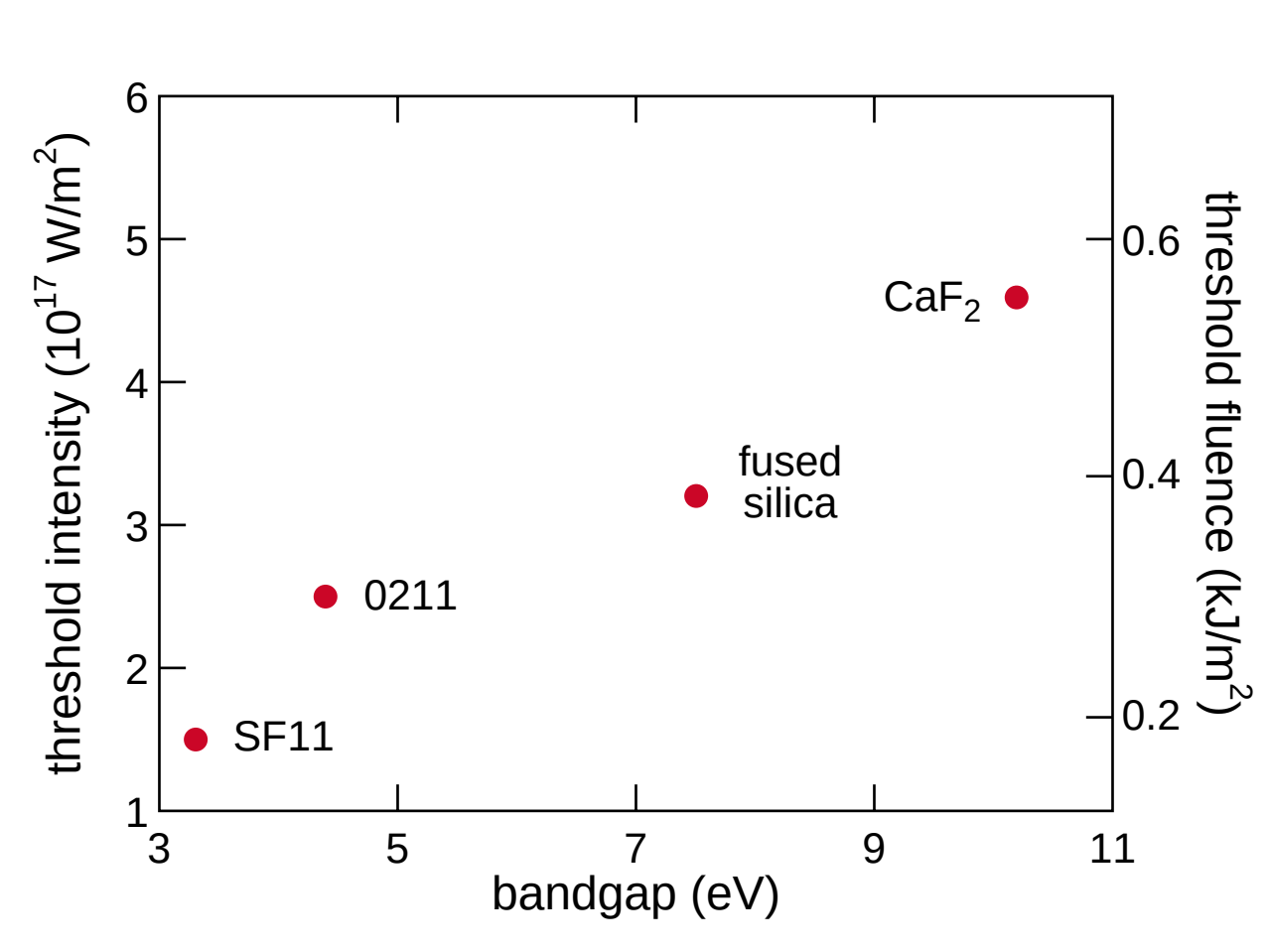
Energy deposition

vary material…



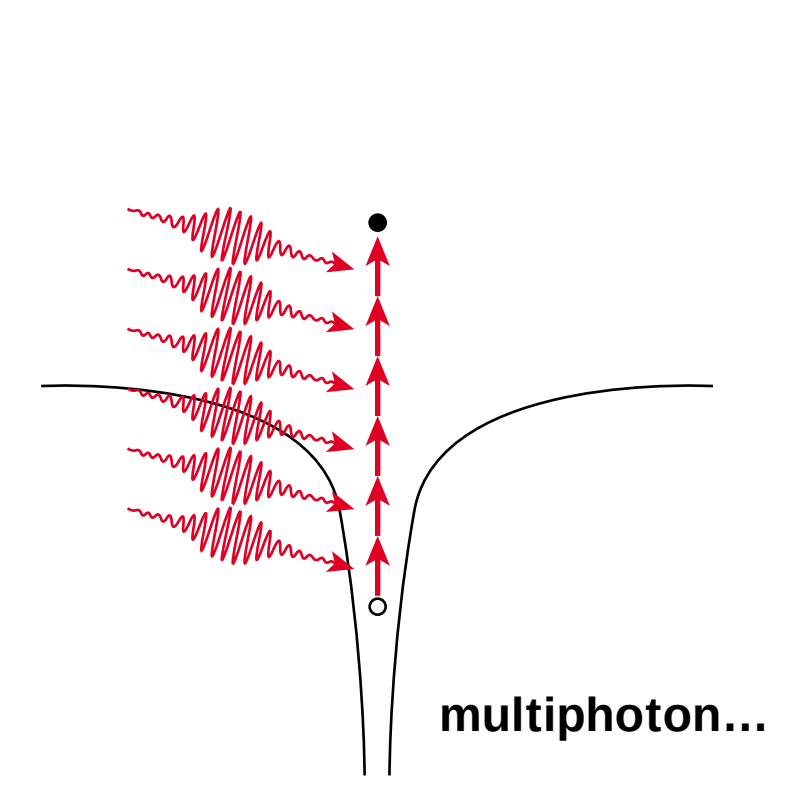
Energy deposition

threshold increases with bandgap



Energy deposition

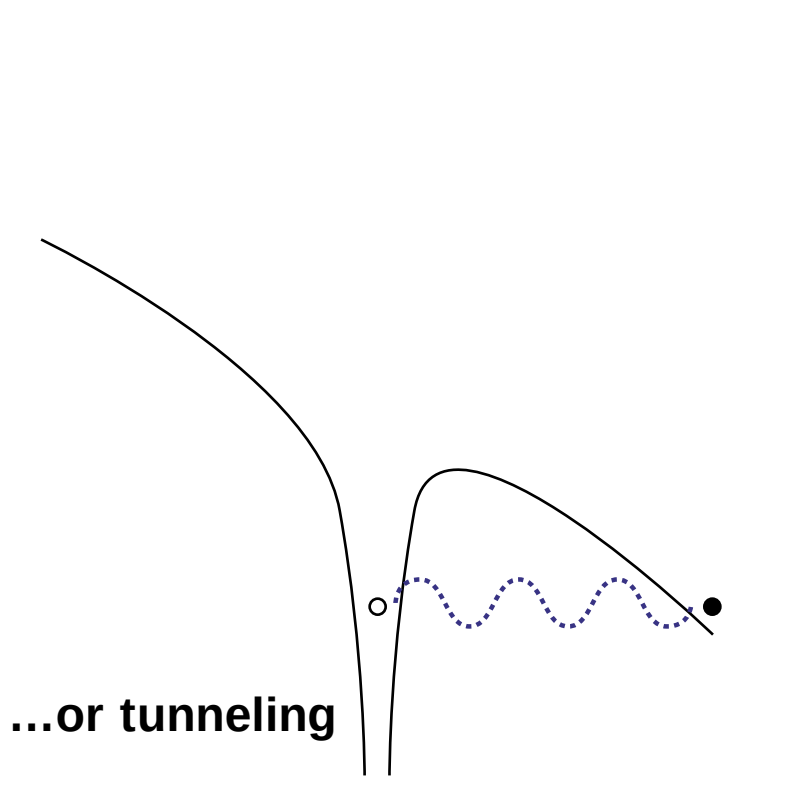
laser field ionization



nonlinear: I^n

Energy deposition

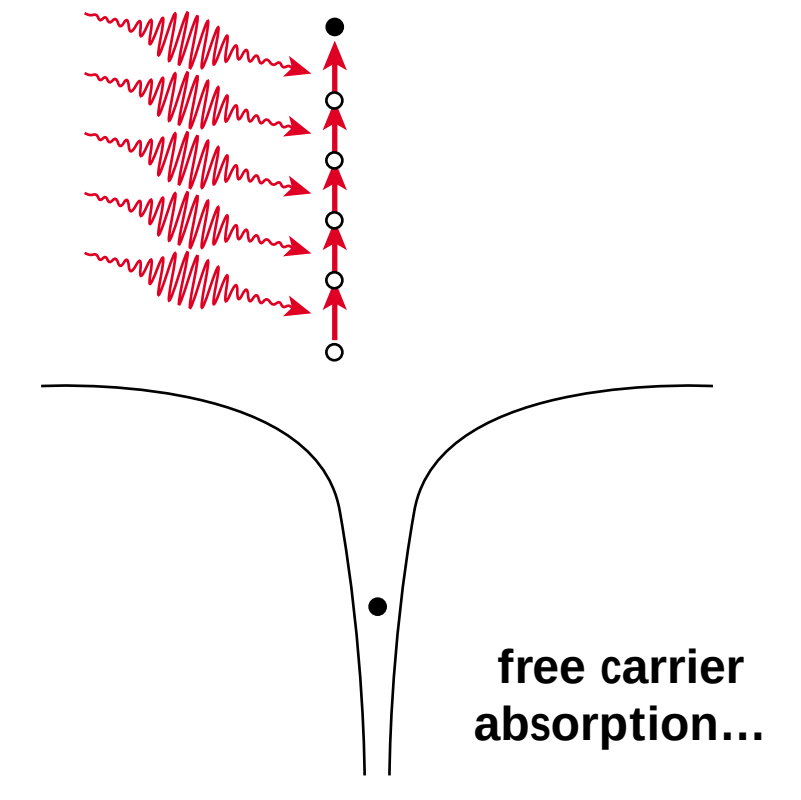
laser field ionization



also nonlinear: $I^{-\frac{1}{2}}\exp(I^{-\frac{1}{2}})$

Energy deposition

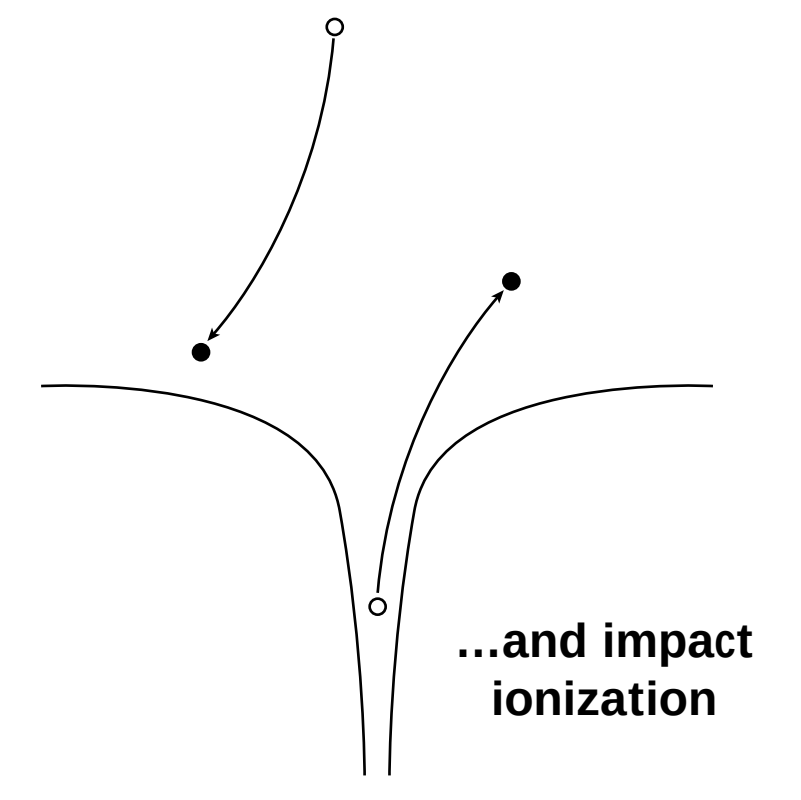
avalanche ionization



linear: nI

Energy deposition

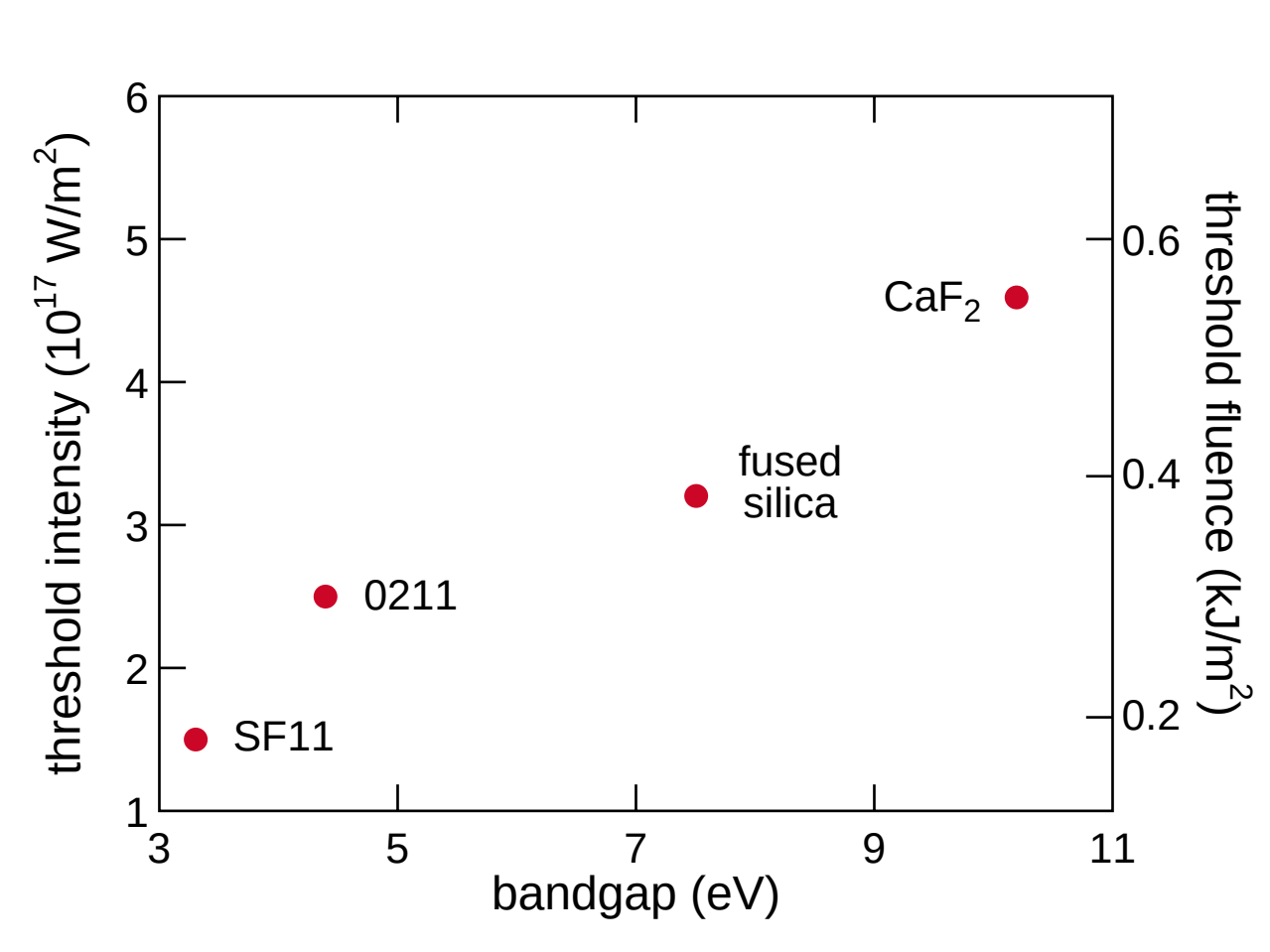
laser field ionization



linear: nI

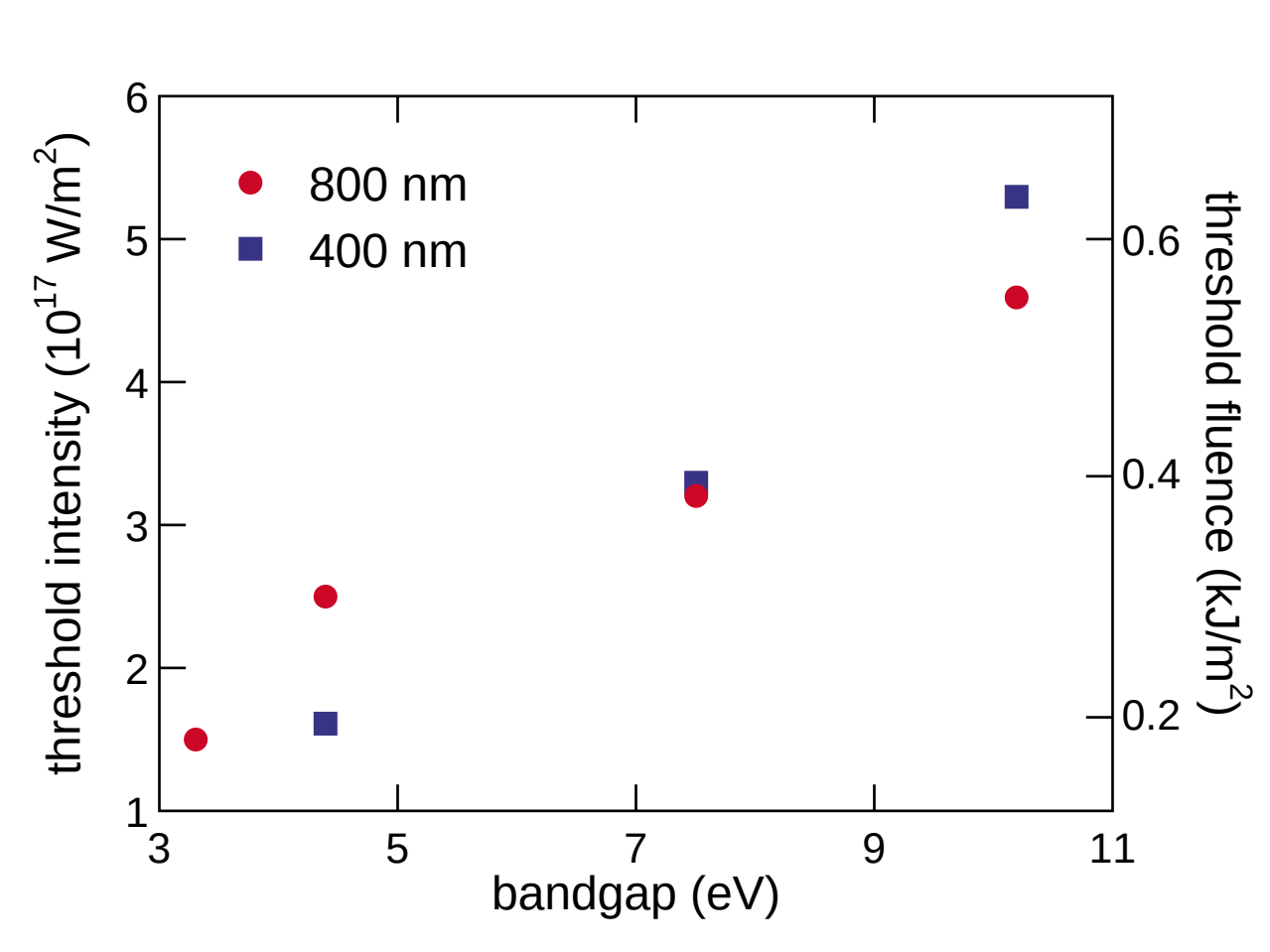
Energy deposition

large bandgap: avalanche ionization dominates



Energy deposition

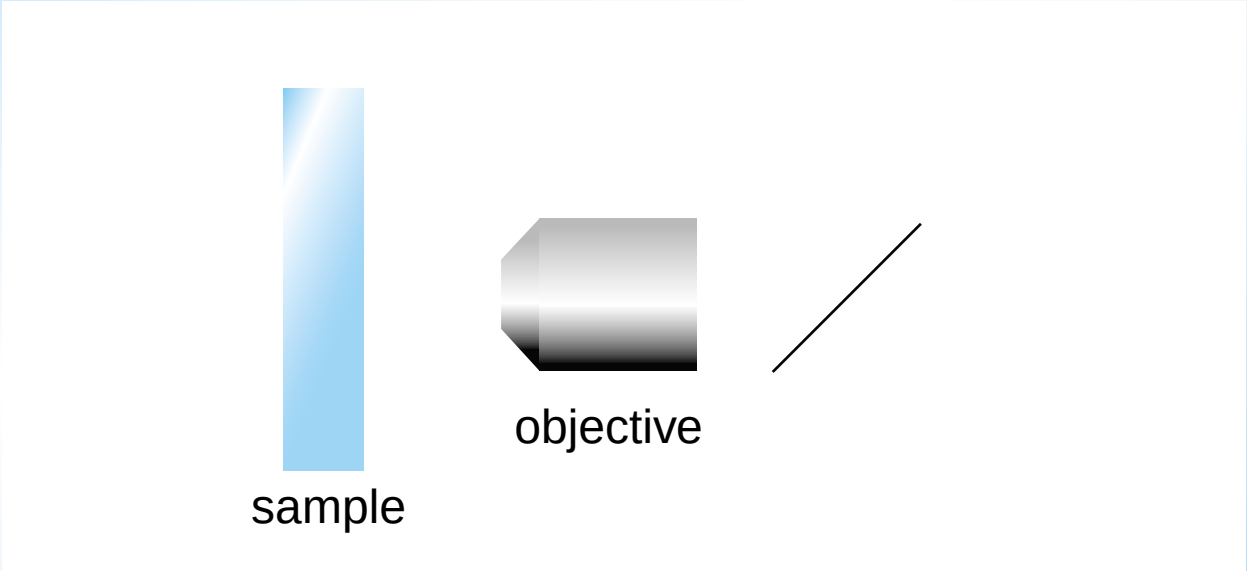
same trend at 400 nm



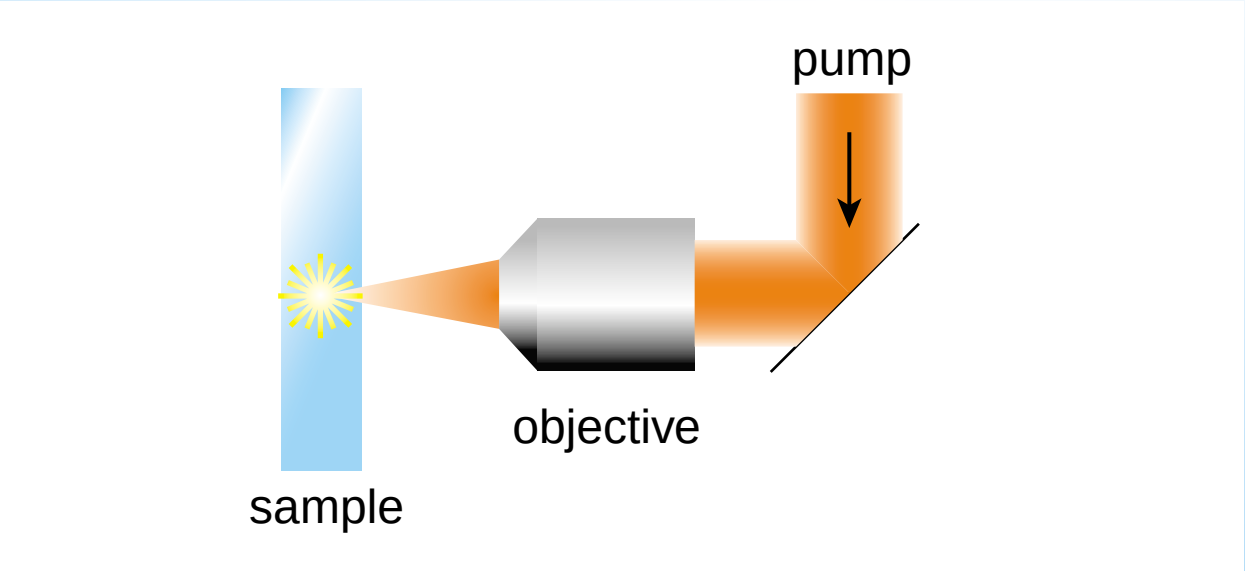
Outline

- Setup
- Morphology
- Energy deposition
- **Dynamics**

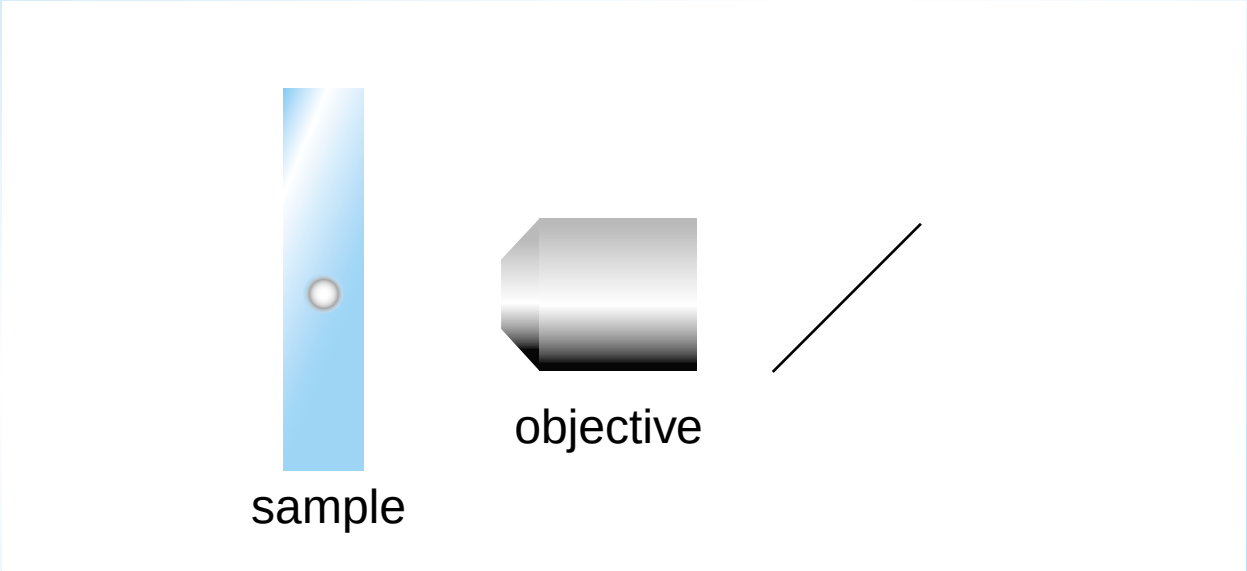
imaging setup



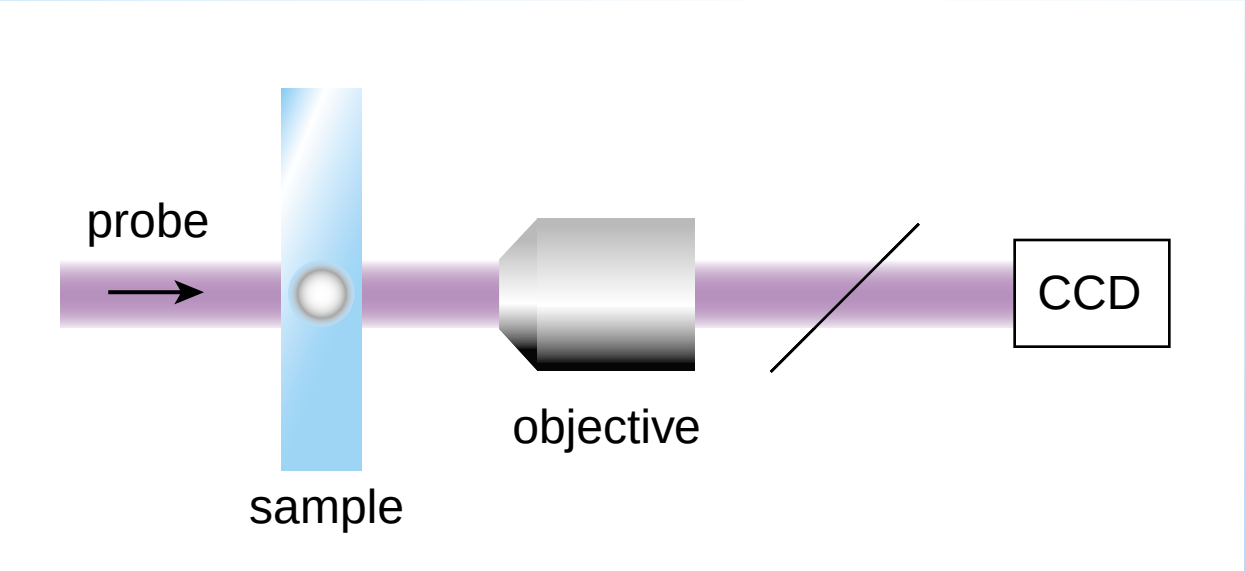
imaging setup



imaging setup



imaging setup



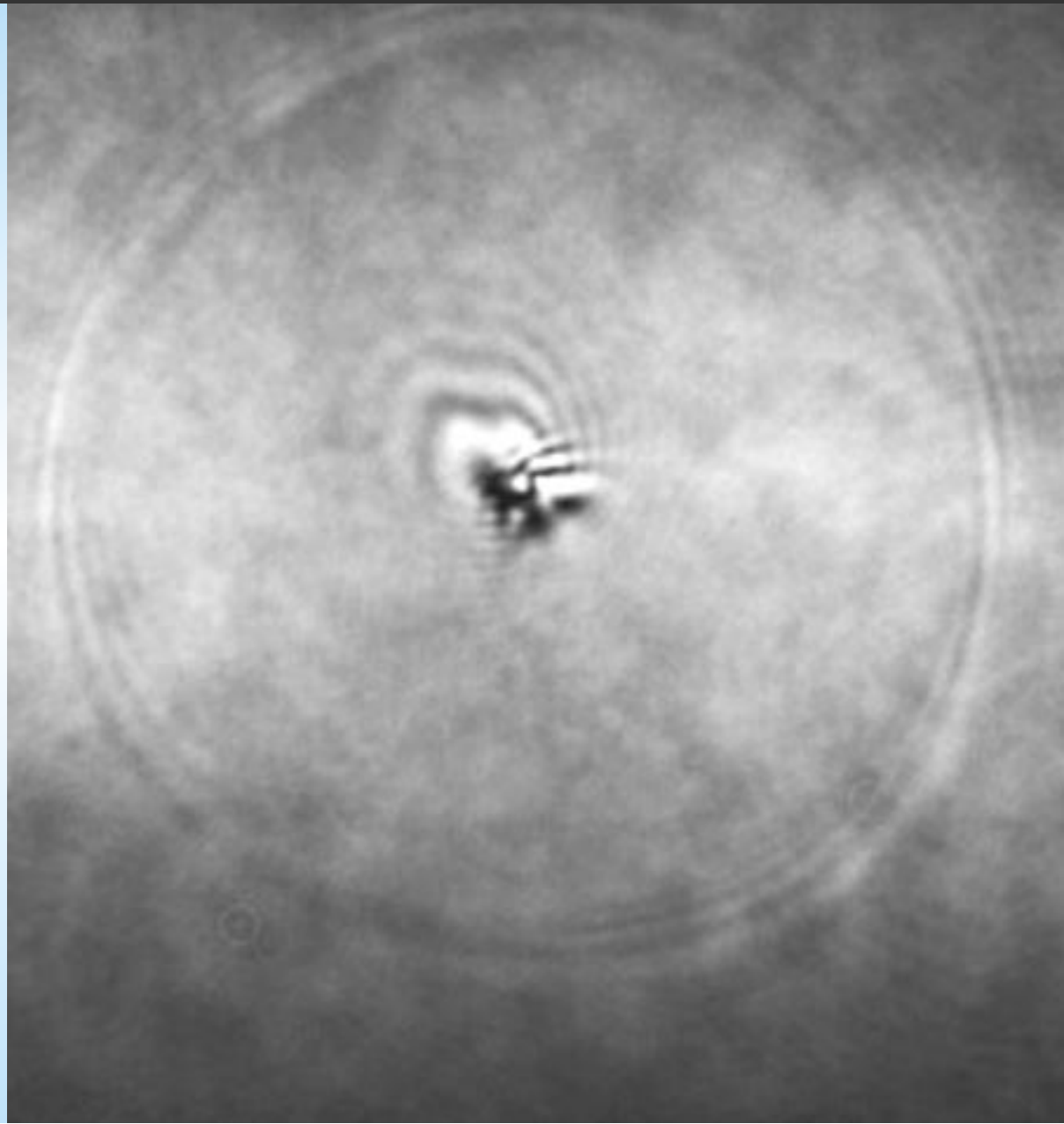
Dynamics

sapphire

3 μJ pulse

3.8 ns delay

40 μm radius



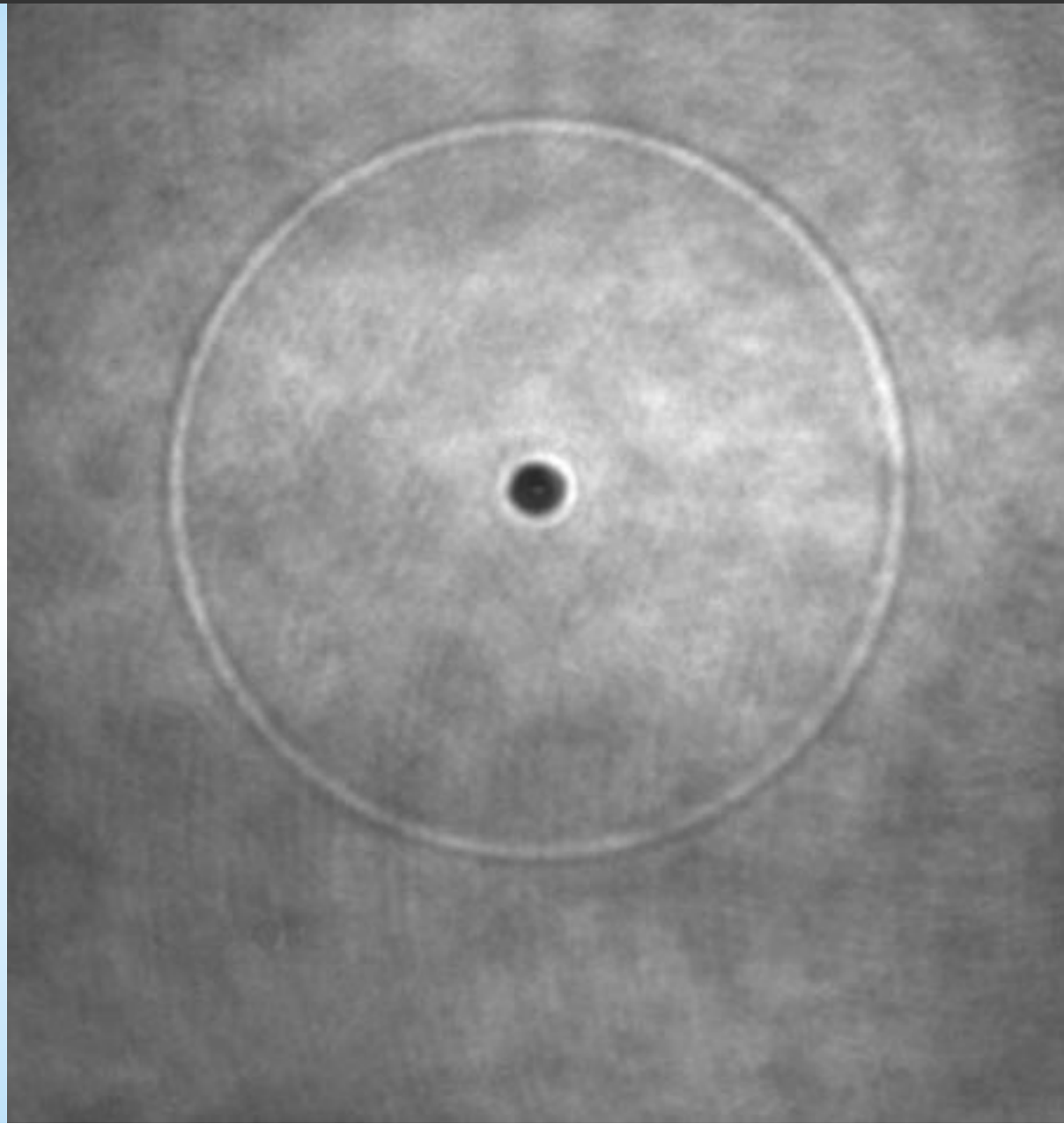
Dynamics

water (“self-healing”)

1.0 μJ pulse

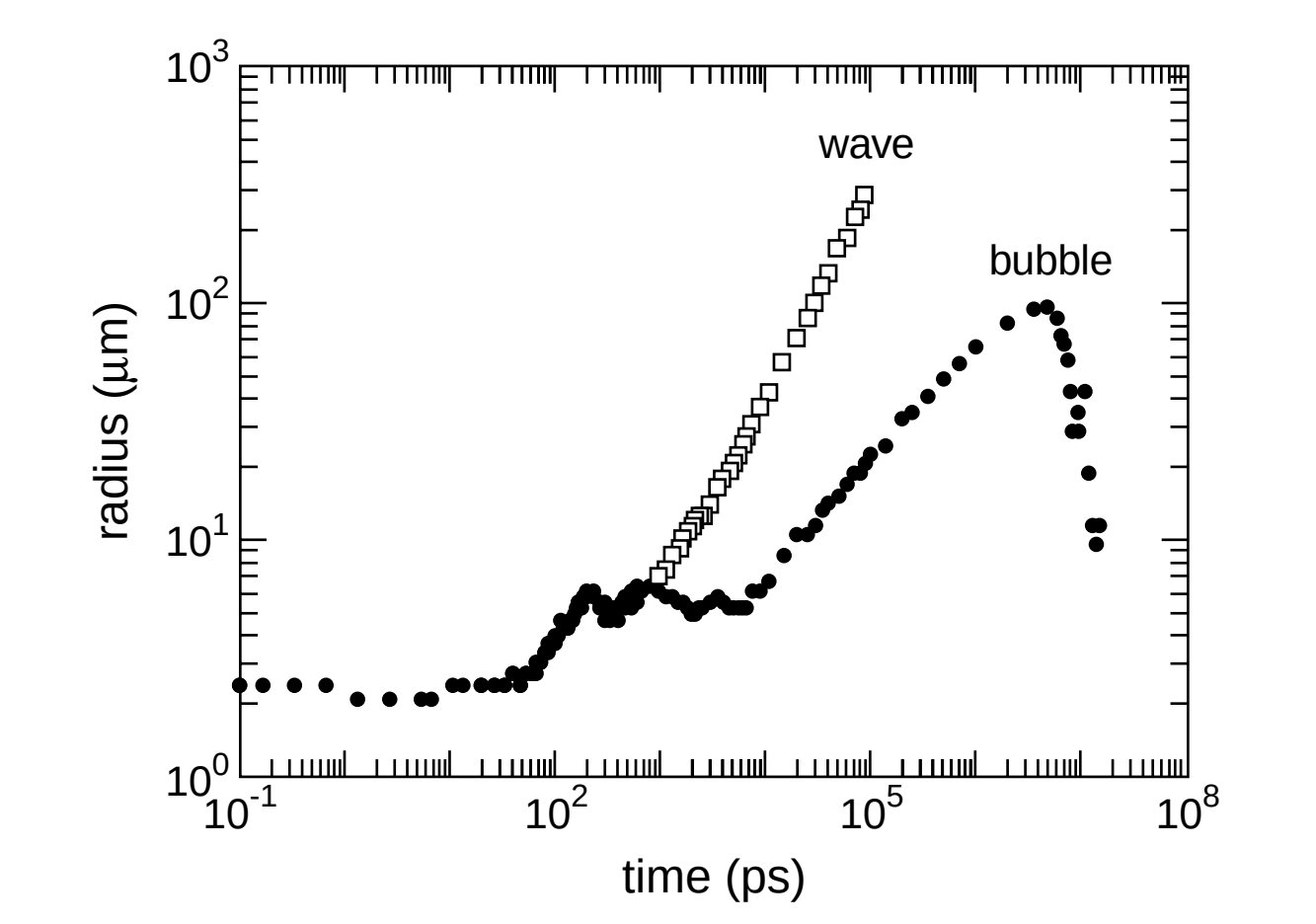
35 ns delay

58 μm radius

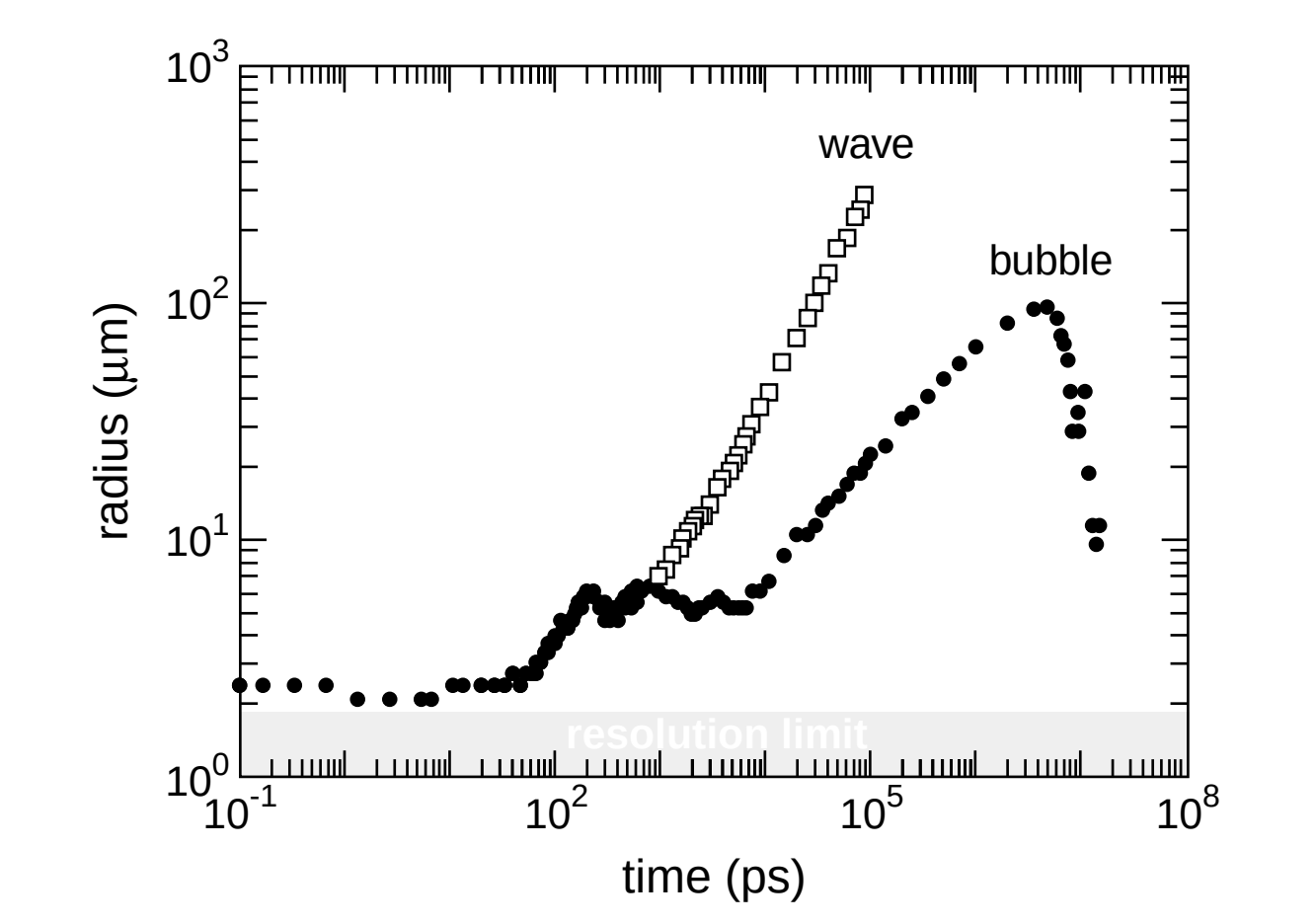


Dynamics

Dynamics

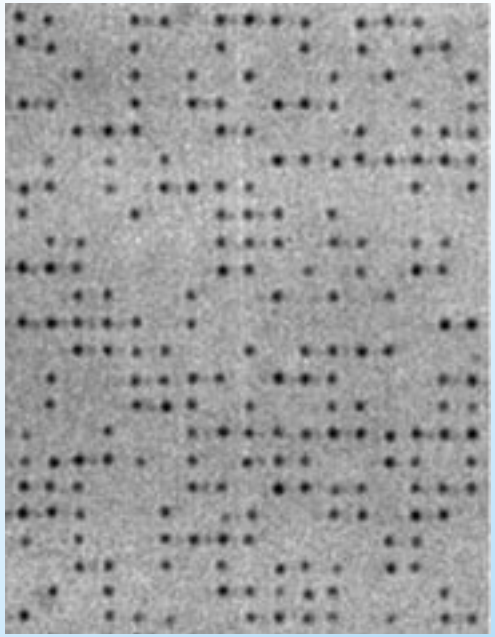


Dynamics


wave
bubble
resolution limit
radius (µm)
time (ps)
10^3
10^2
10^1
10^0
10^{-1}
10^2
10^5
10^8

Applications

- **data storage**



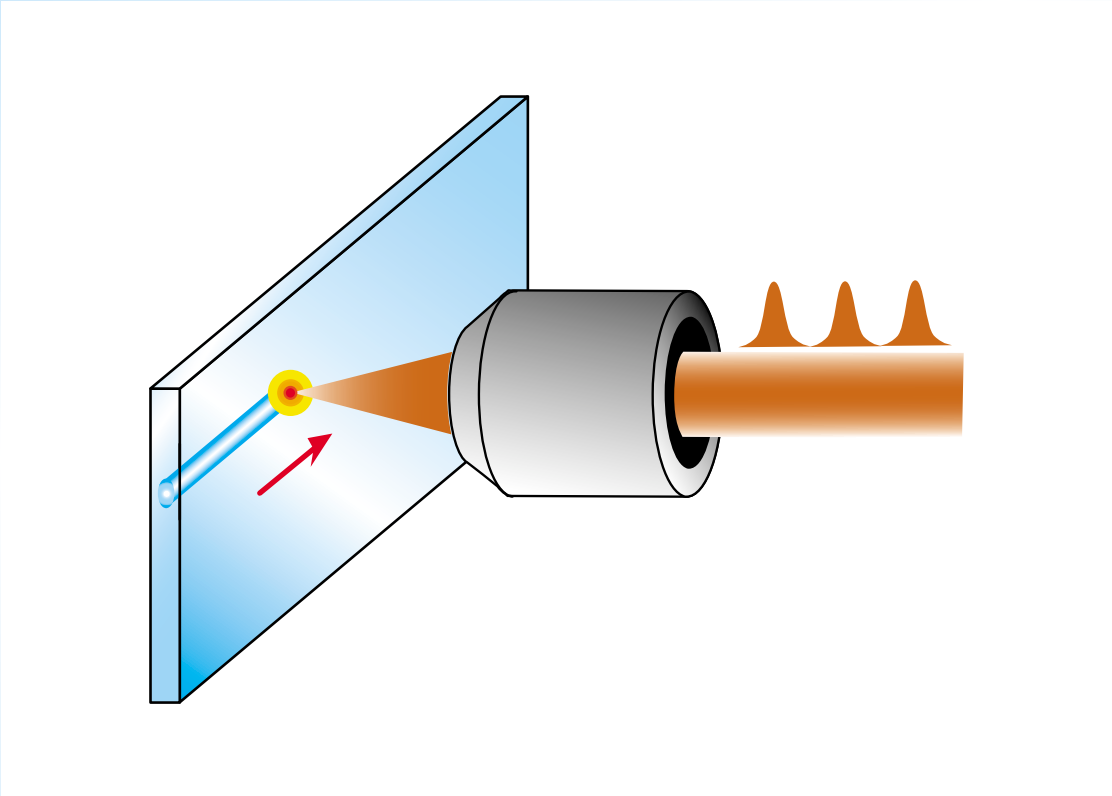
100 GB multilayer CD

Applications

- **data storage**
- **photonic devices**

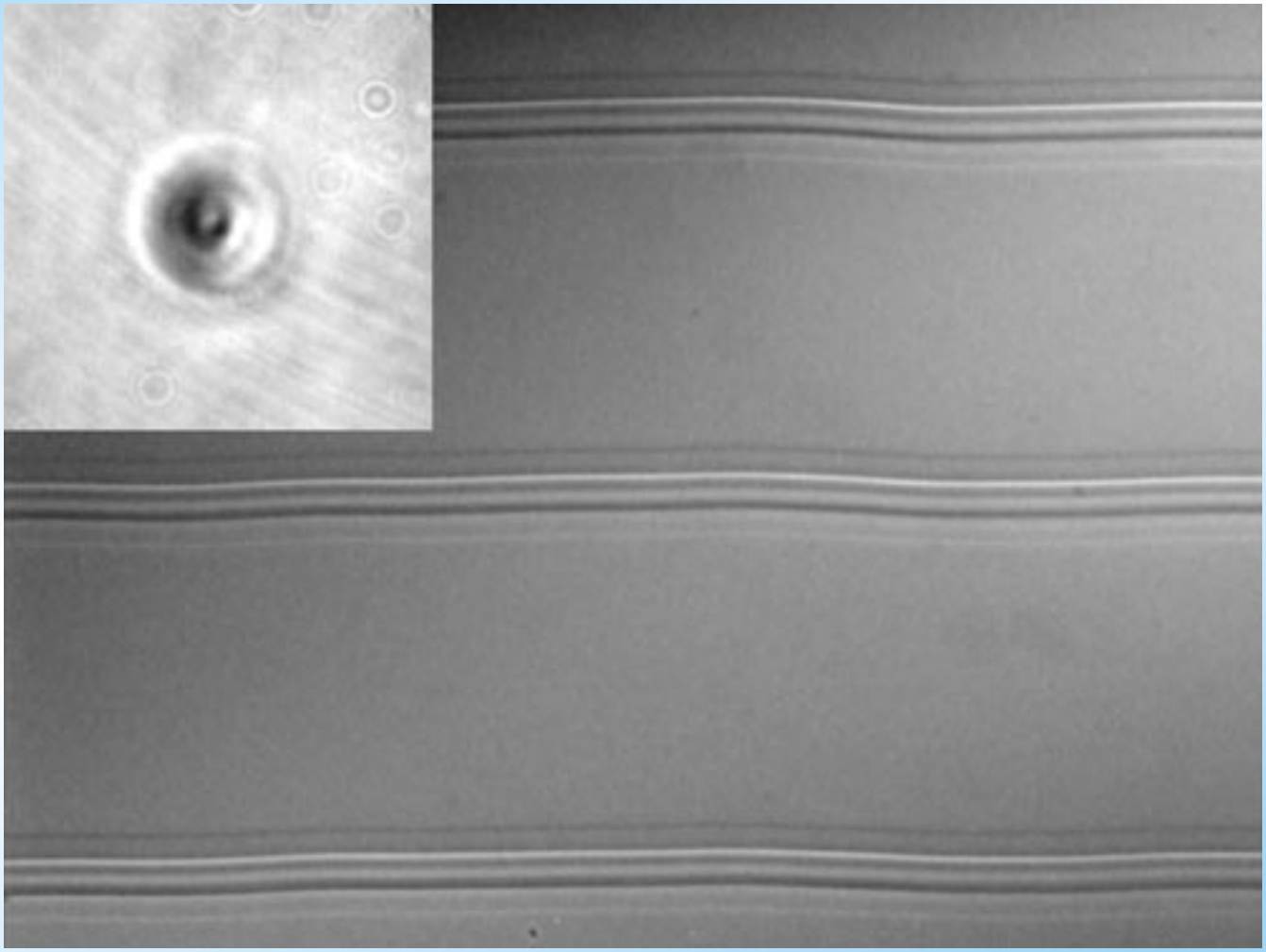
Applications

waveguide machining



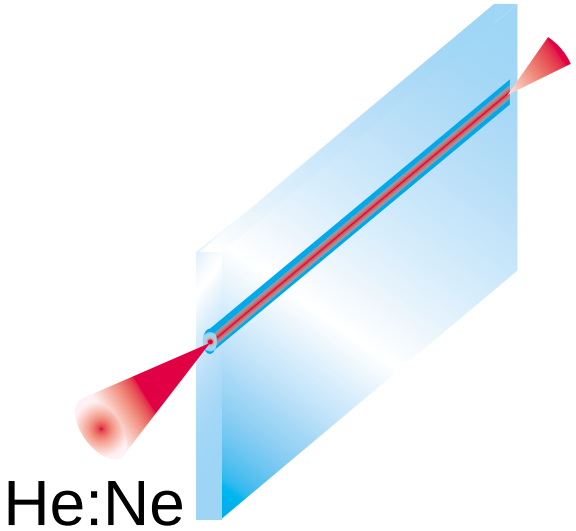
Applications

waveguide machining



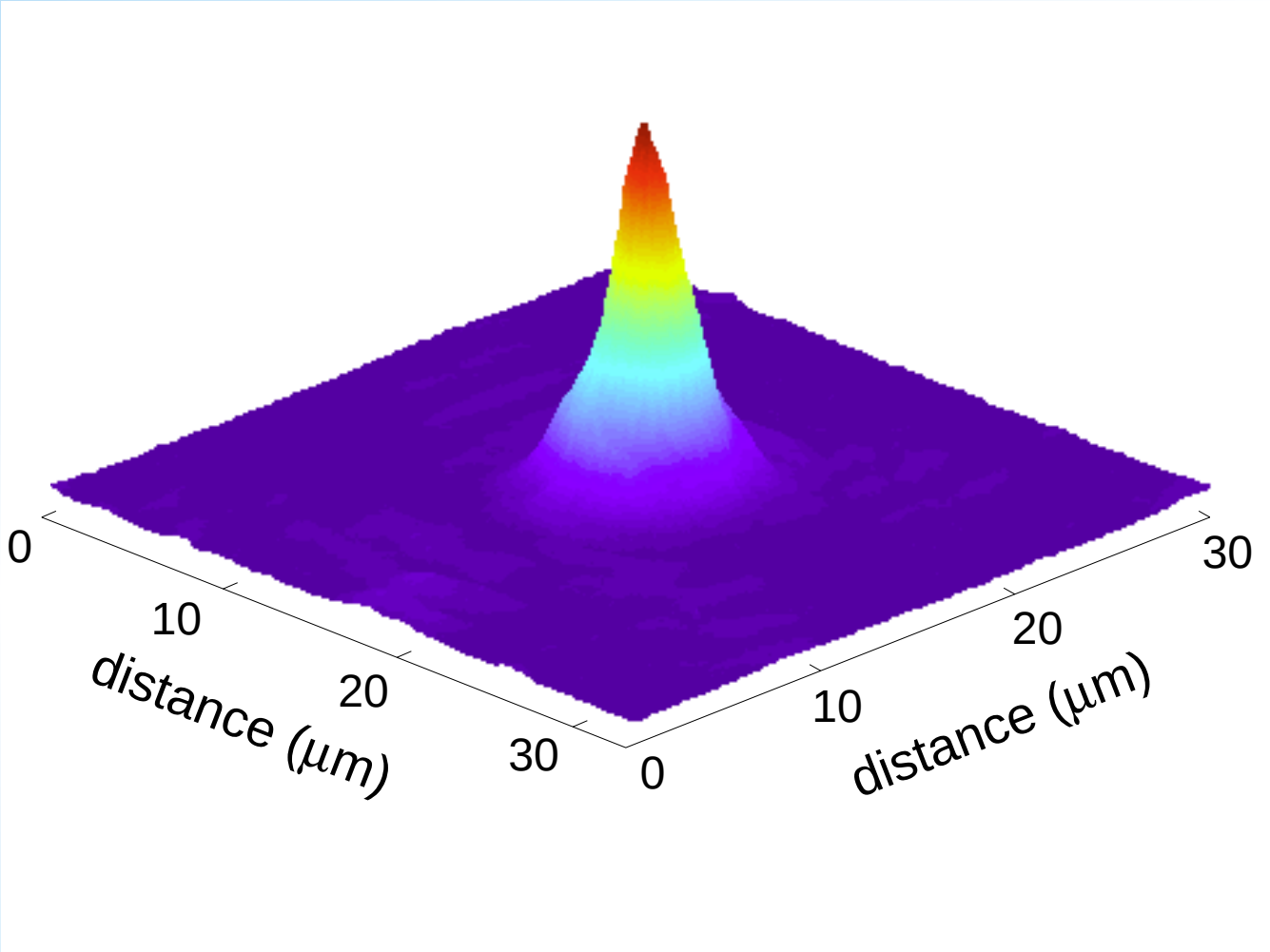
Applications

waveguide mode analysis



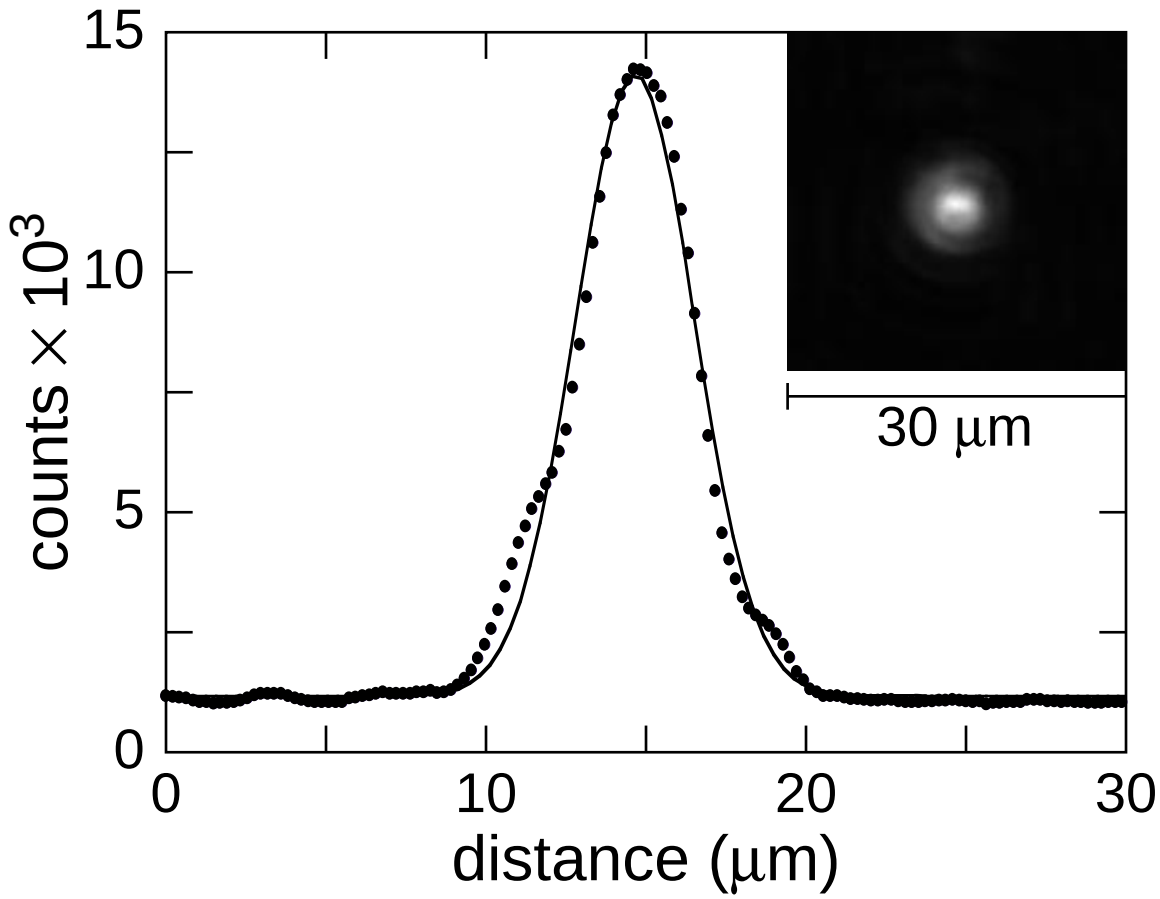
Applications

near field mode



Applications

near field mode



Future applications

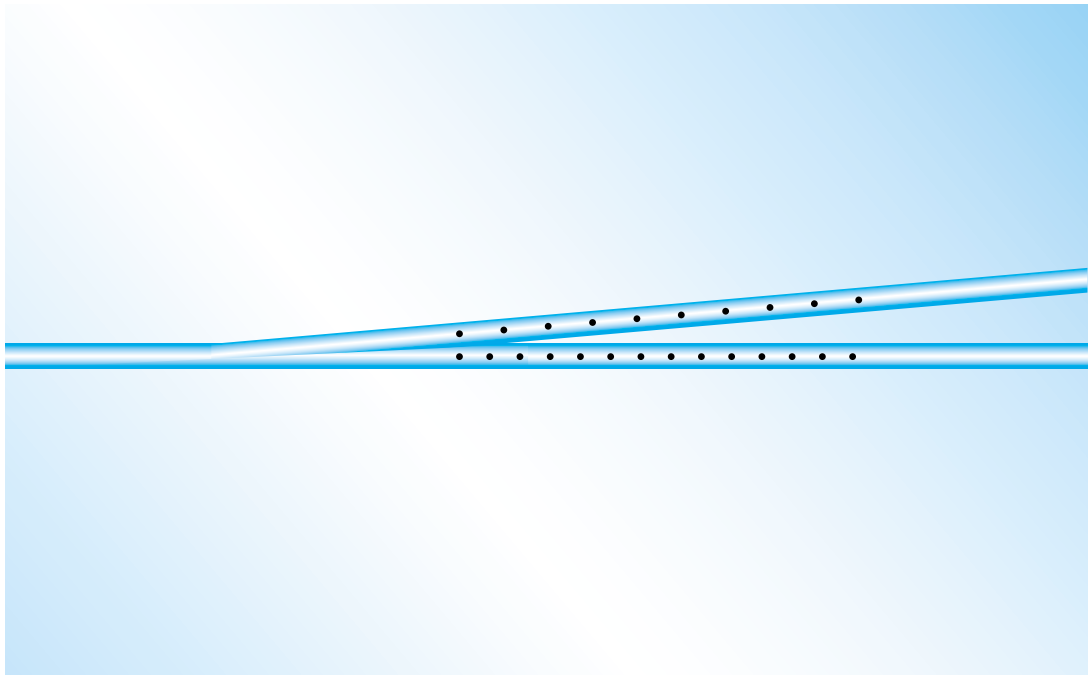
wavelength selective splitter

Future applications

wavelength selective splitter

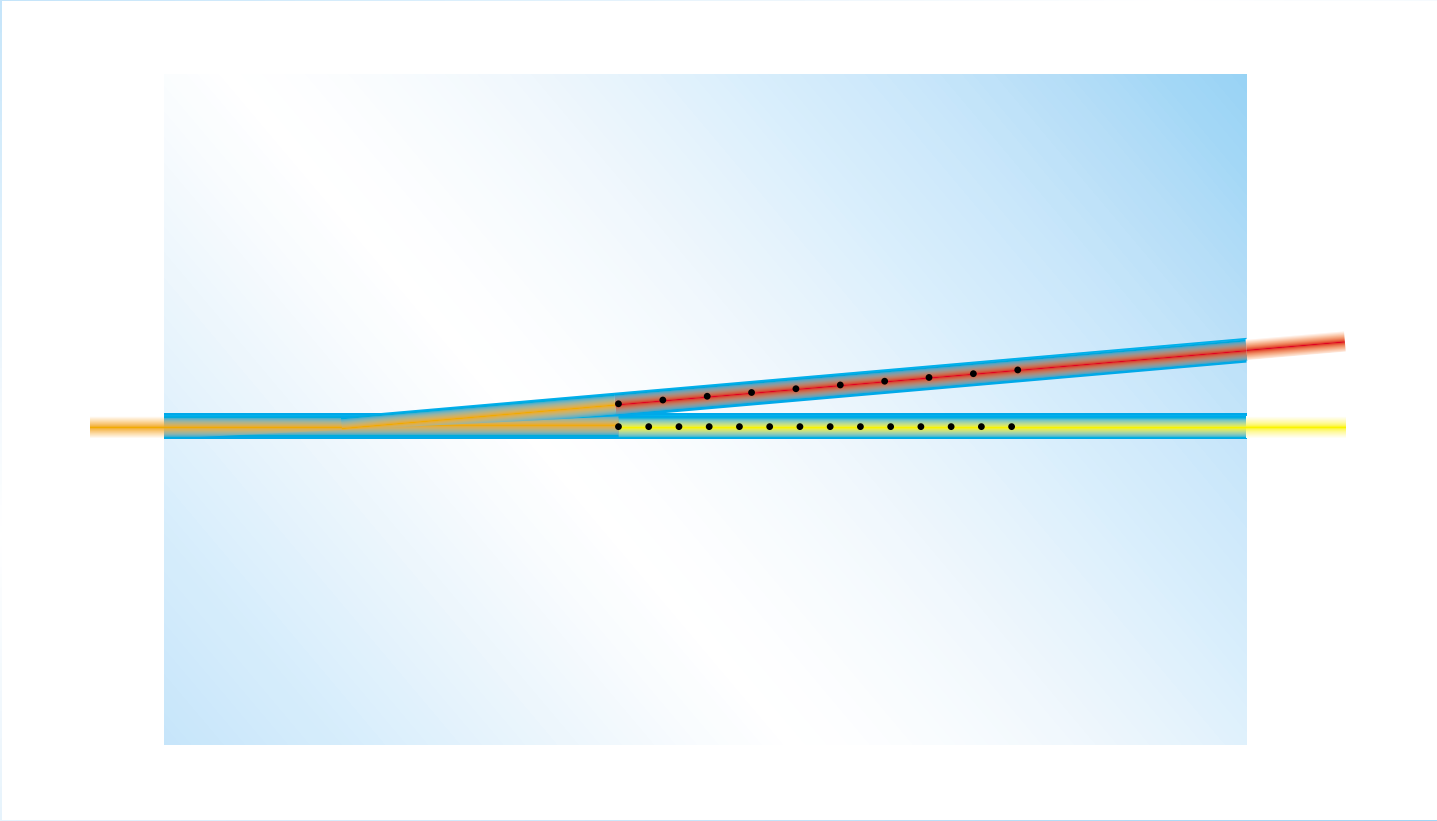
Future applications

wavelength selective splitter



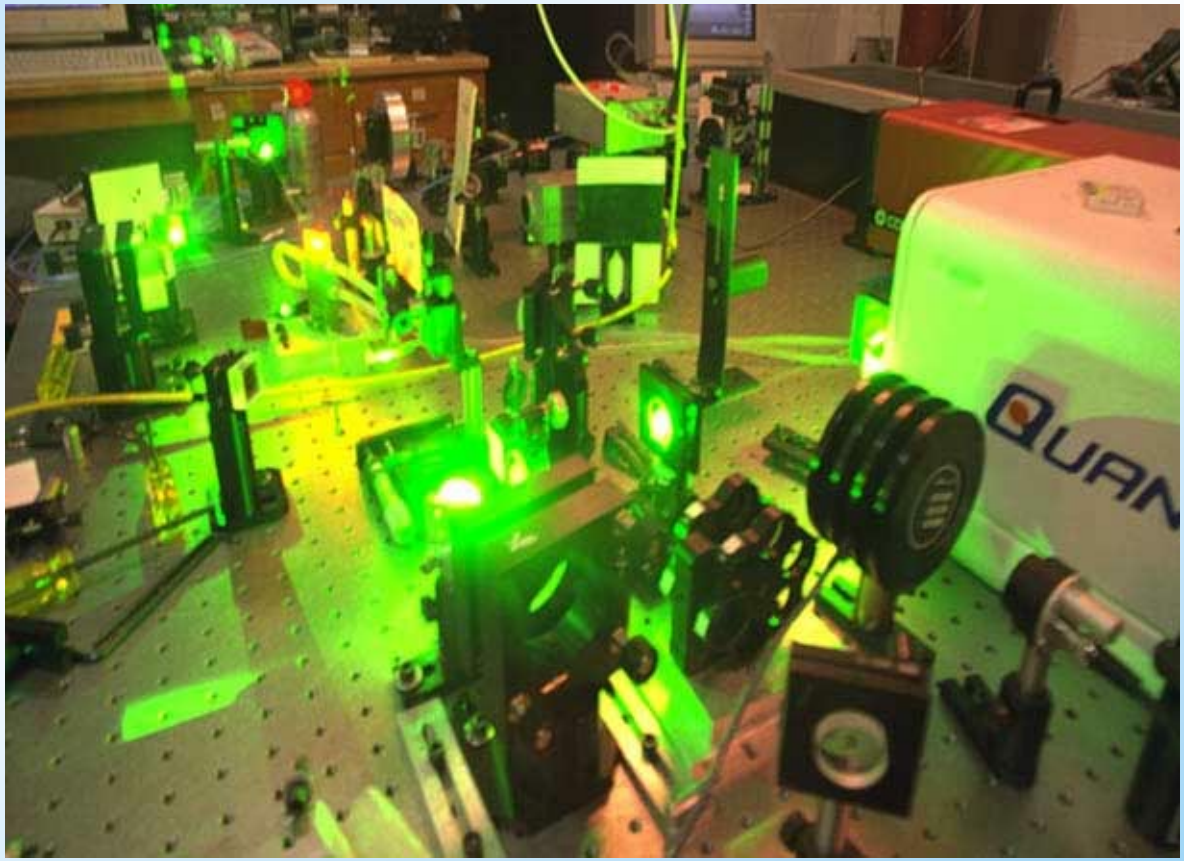
Future applications

wavelength selective splitter



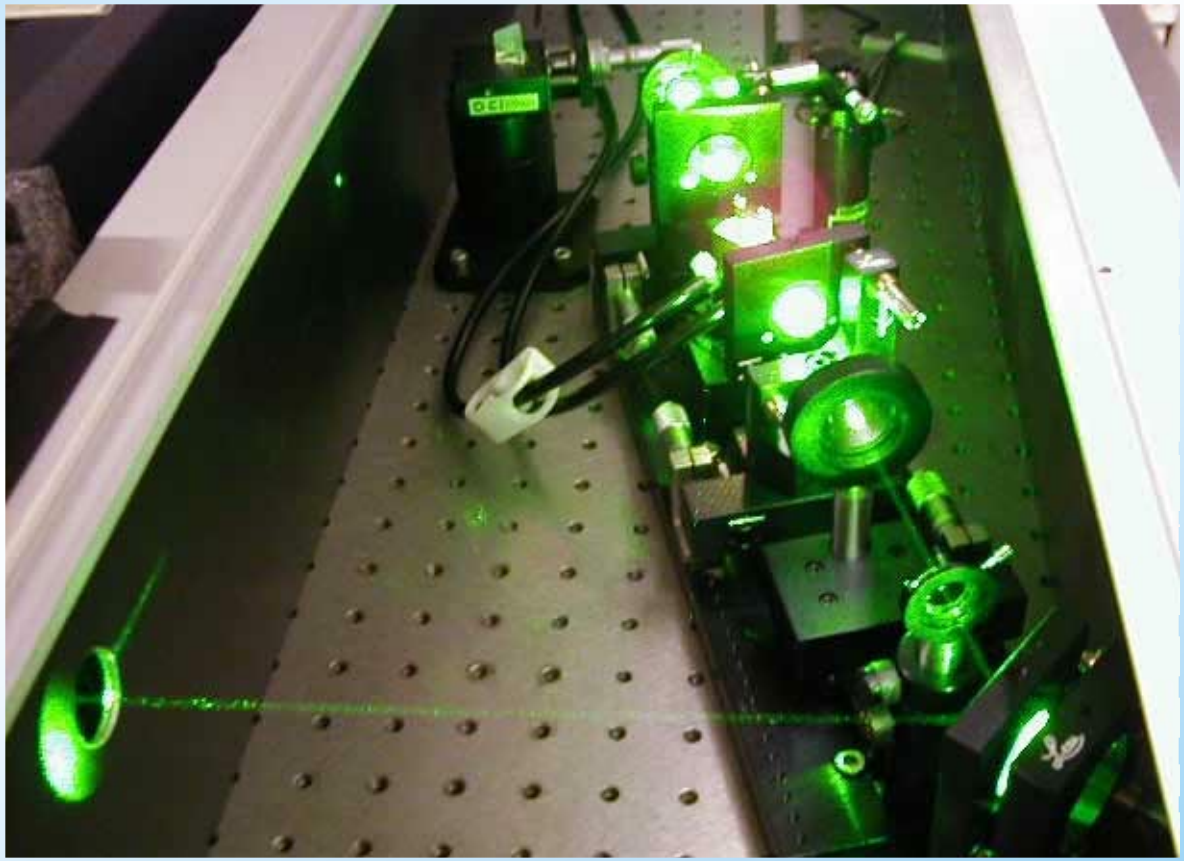
Applications

5-nJ threshold: unamplified micromachining



Applications

5-nJ threshold: unamplified micromachining



Applications

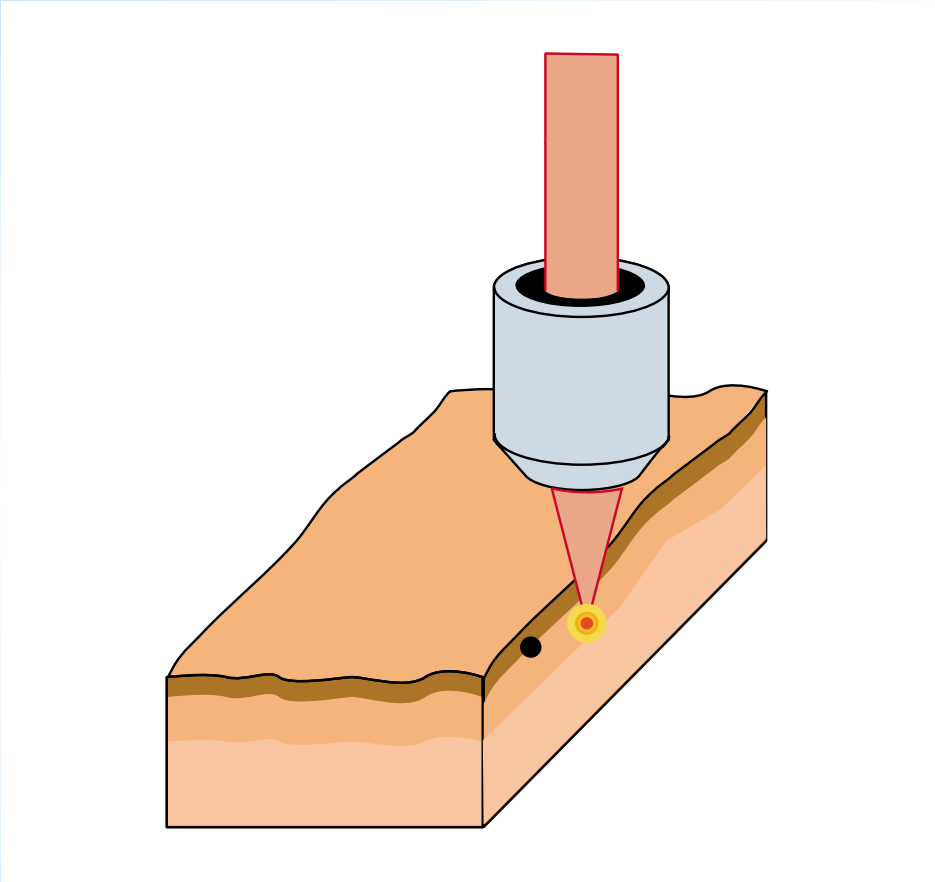
- **data storage**
- **photonic devices**
- **photonic bandgap materials**

Applications

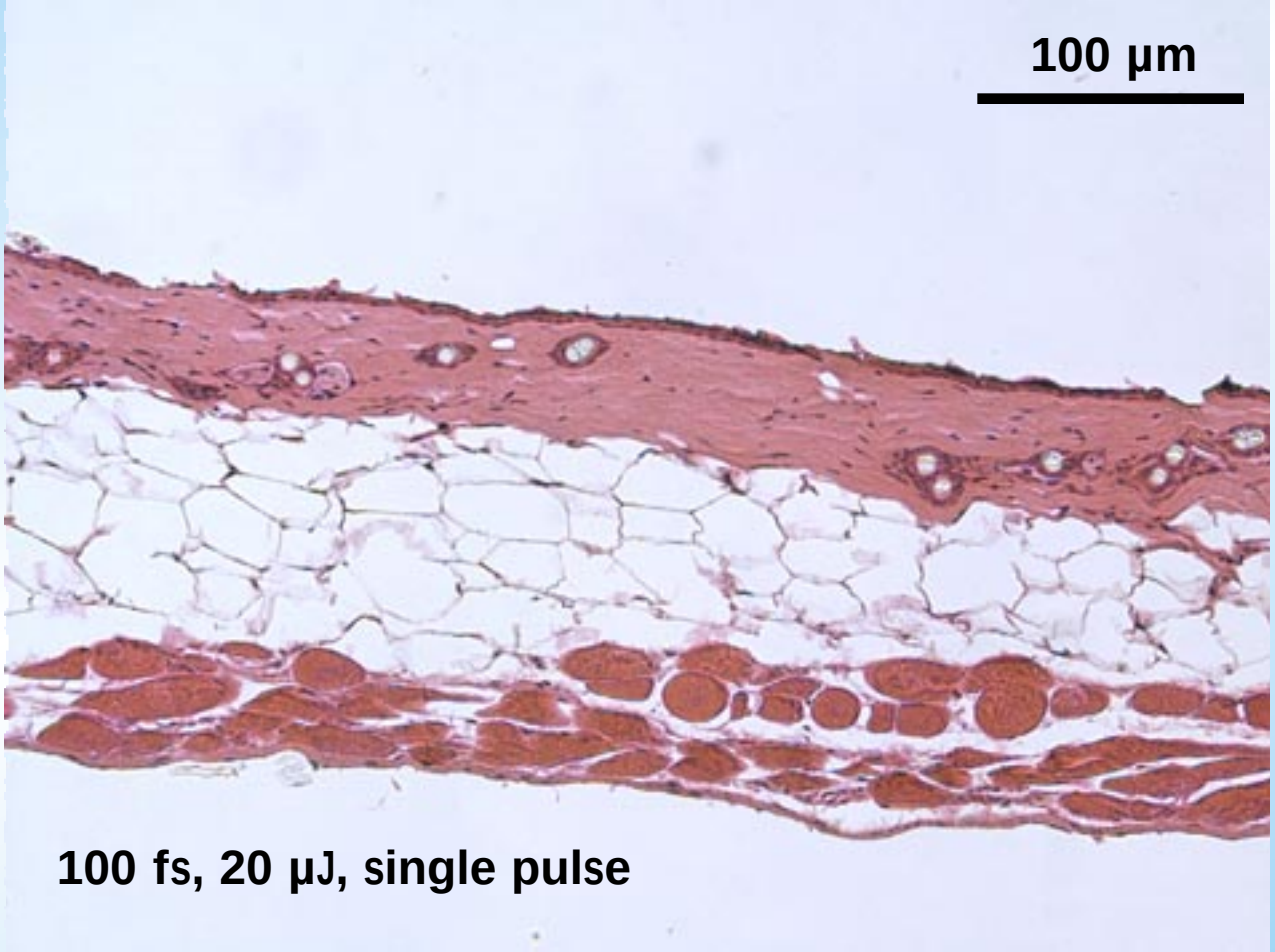
- **data storage**
- **photonic devices**
- **photonic bandgap materials**
- **biology/medicine**

Applications

subsurface surgery

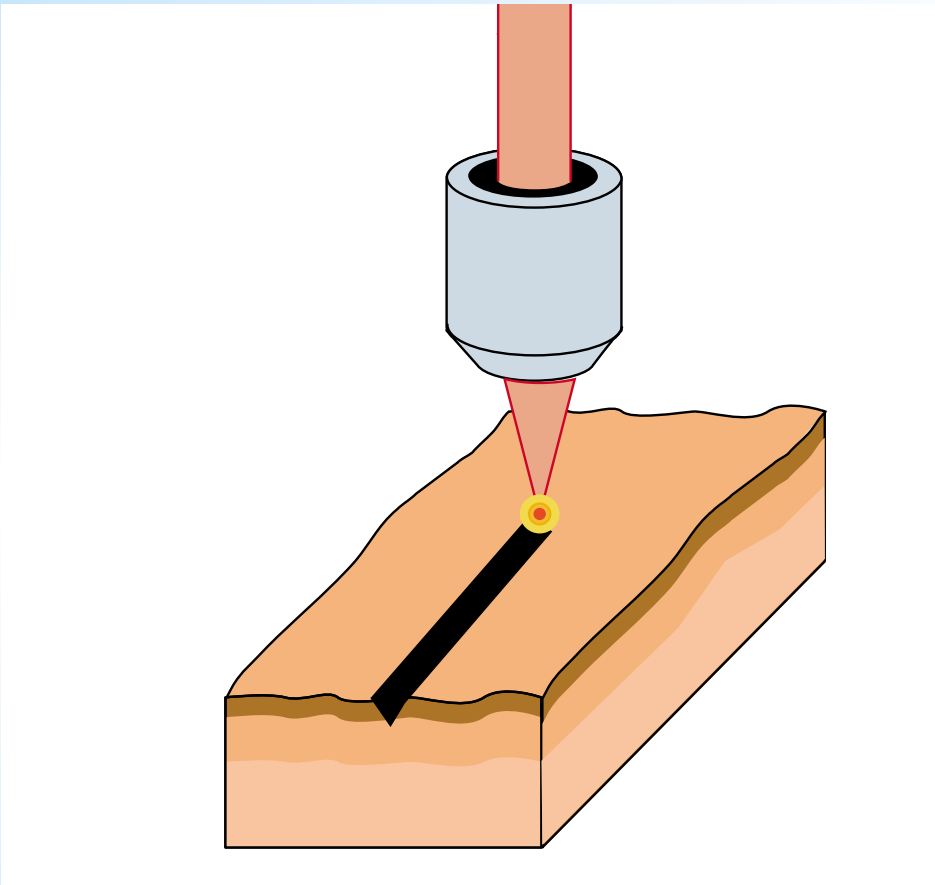


Applications

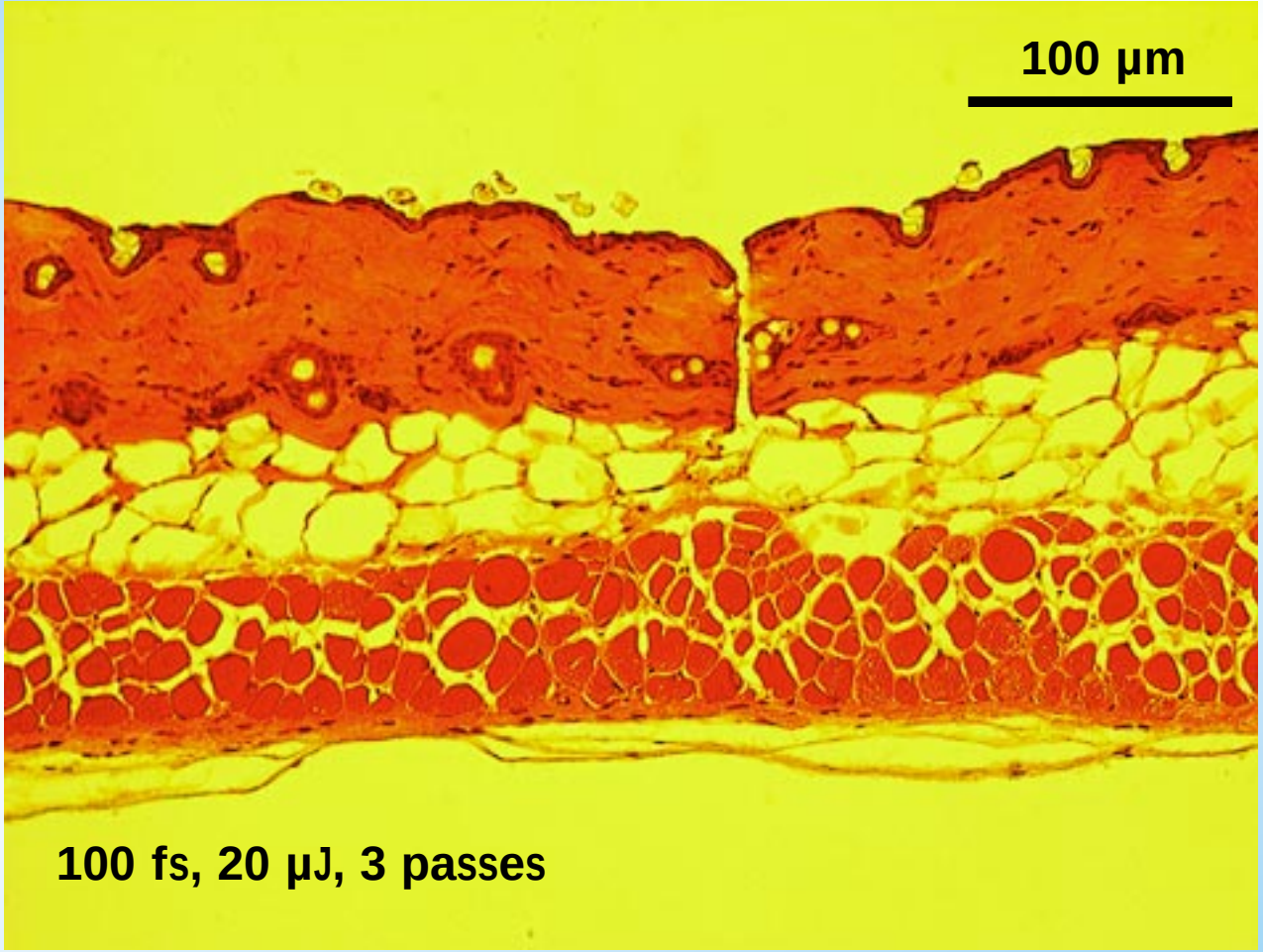


Applications

incision setup



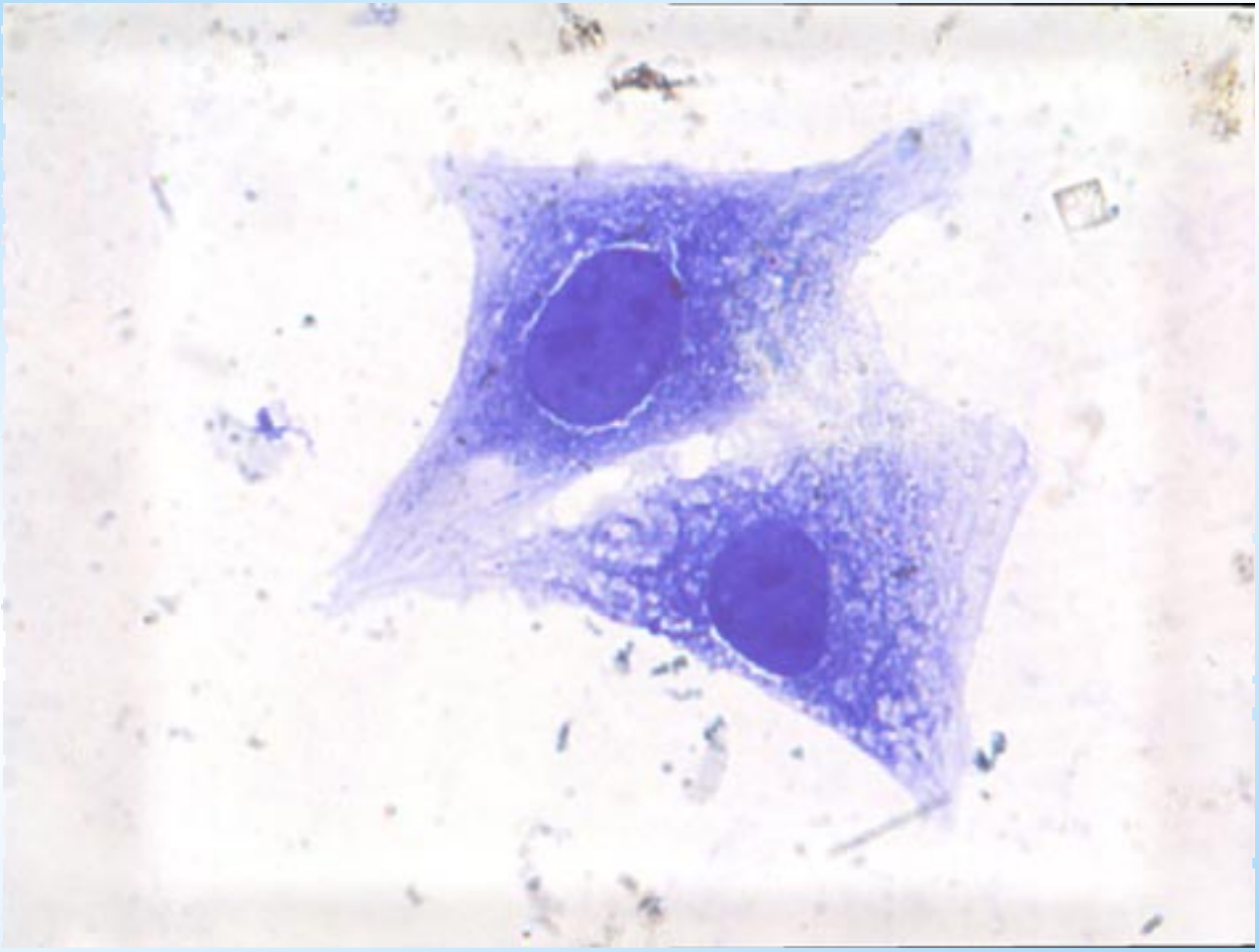
Applications



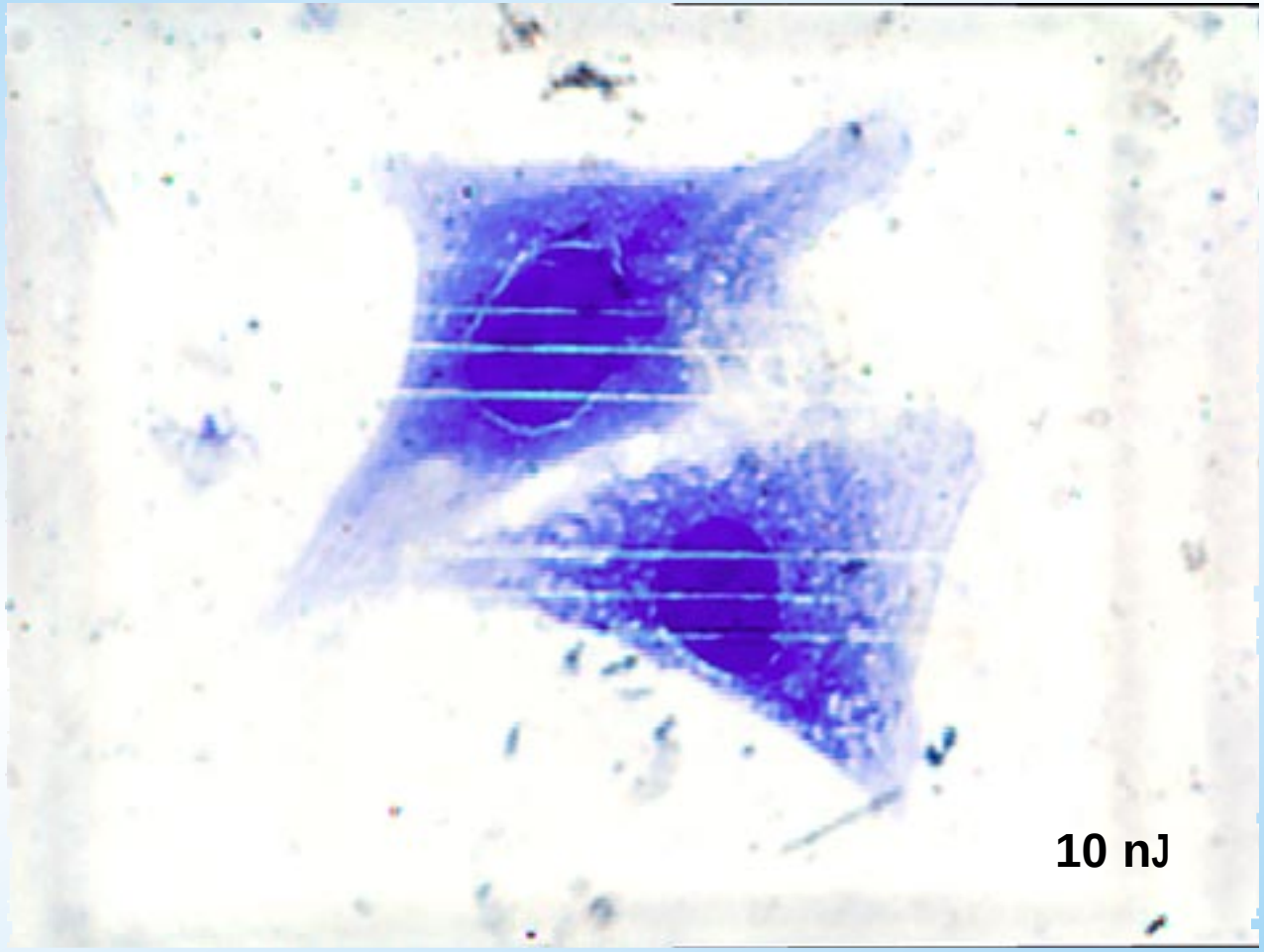
Conclusions

- **determined mechanism from morphology**
- **role of ionization mechanisms**
- **oscillator-only micromachining**
- **biological applications**

Subcellular micromachining



Subcellular micromachining




GORDON McKAY
LABORATORY OF
APPLIED SCIENCE

Funding: National Science Foundation

Acknowledgments:
Prof. Alex Gaeta (Cornell)
Prof. Nico Bloembergen (Harvard)
Prof. Doug Melton (Harvard, biology)
Prof. Don Ingber (Harvard Medical School)
Dr. Joop Grevelink (MGH)
W. Leight
Alan Jamieson

For a copy of this talk and additional information, see:

http://mazur-www.harvard.edu