LASER INDUCED MICROEXPLOSIONS: ULTRAFAST PHYSICS WITH CLINICAL APPLICATIONS

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Chemical Center Seminar
Lund University
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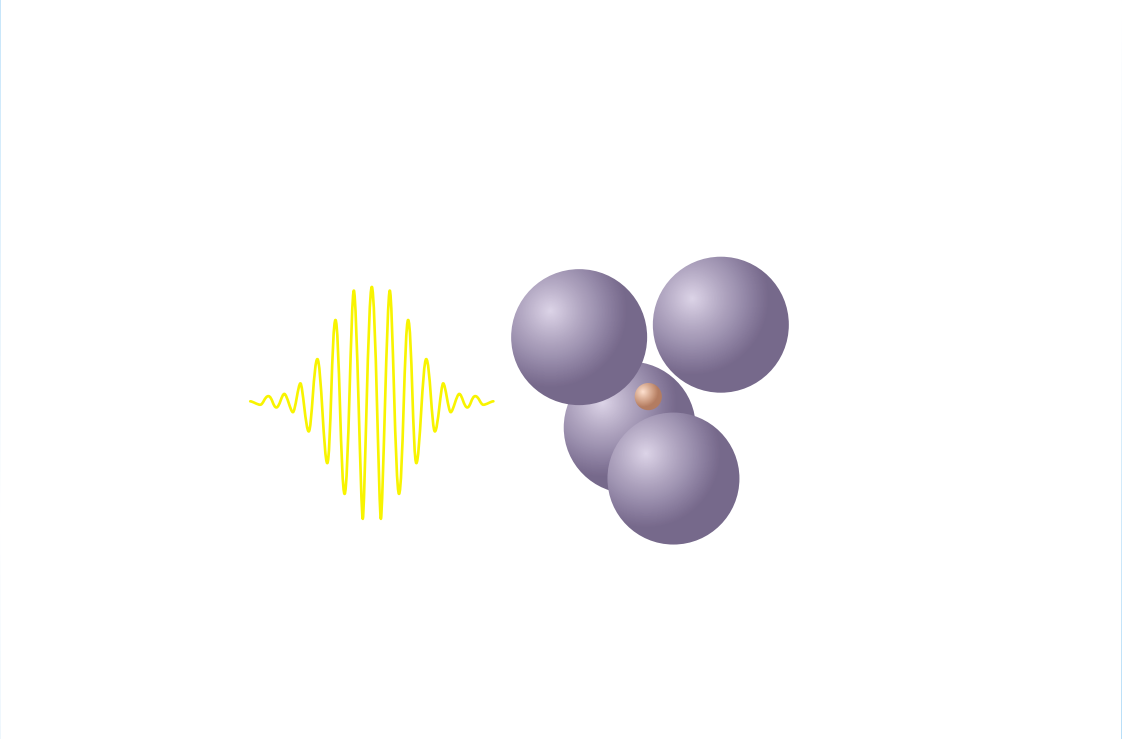
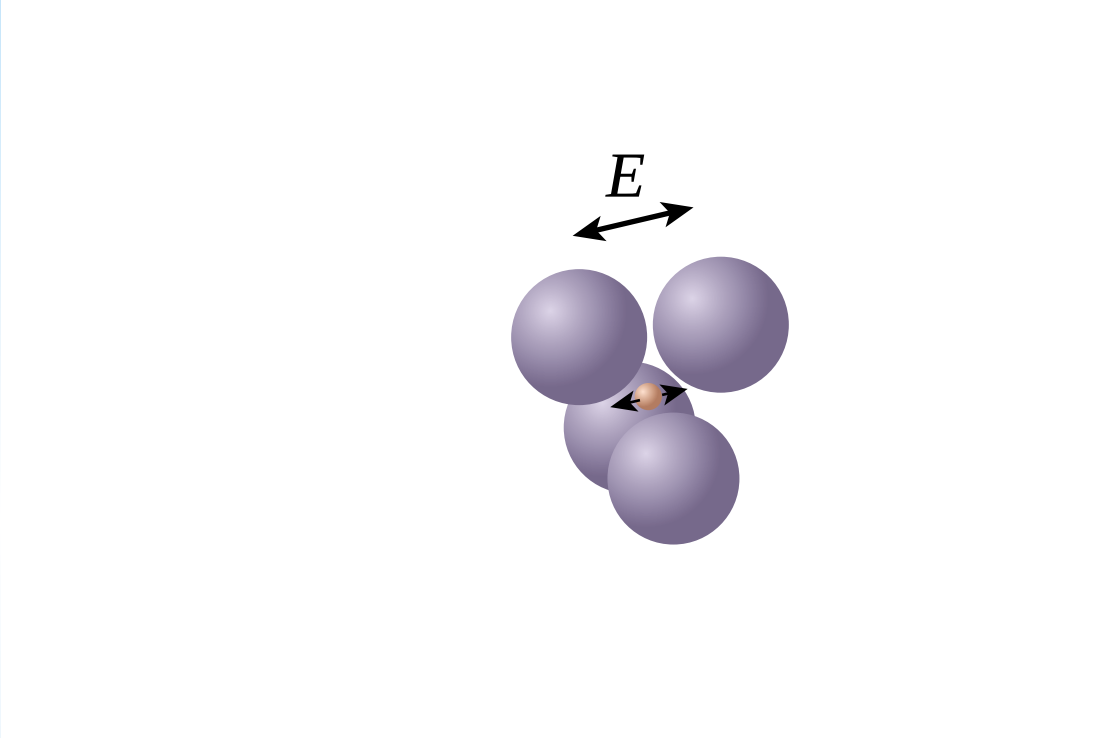
Introduction

light-matter interactions



Introduction

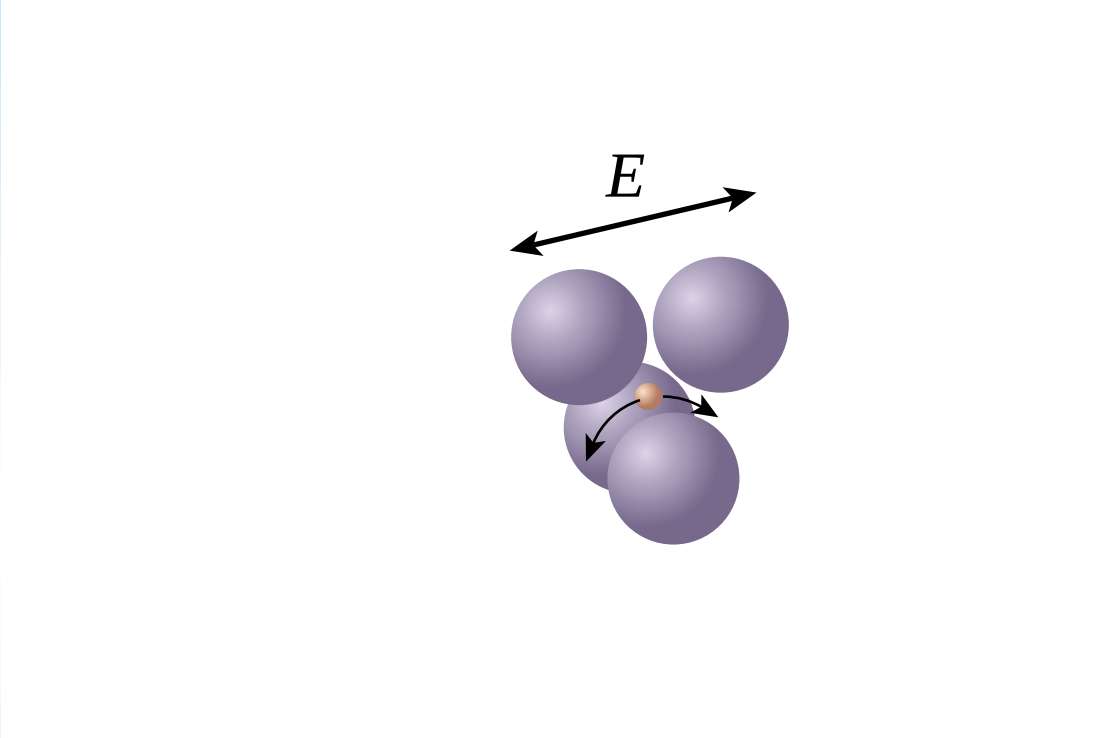
linear response



“stiffness” determines index of refraction

Introduction

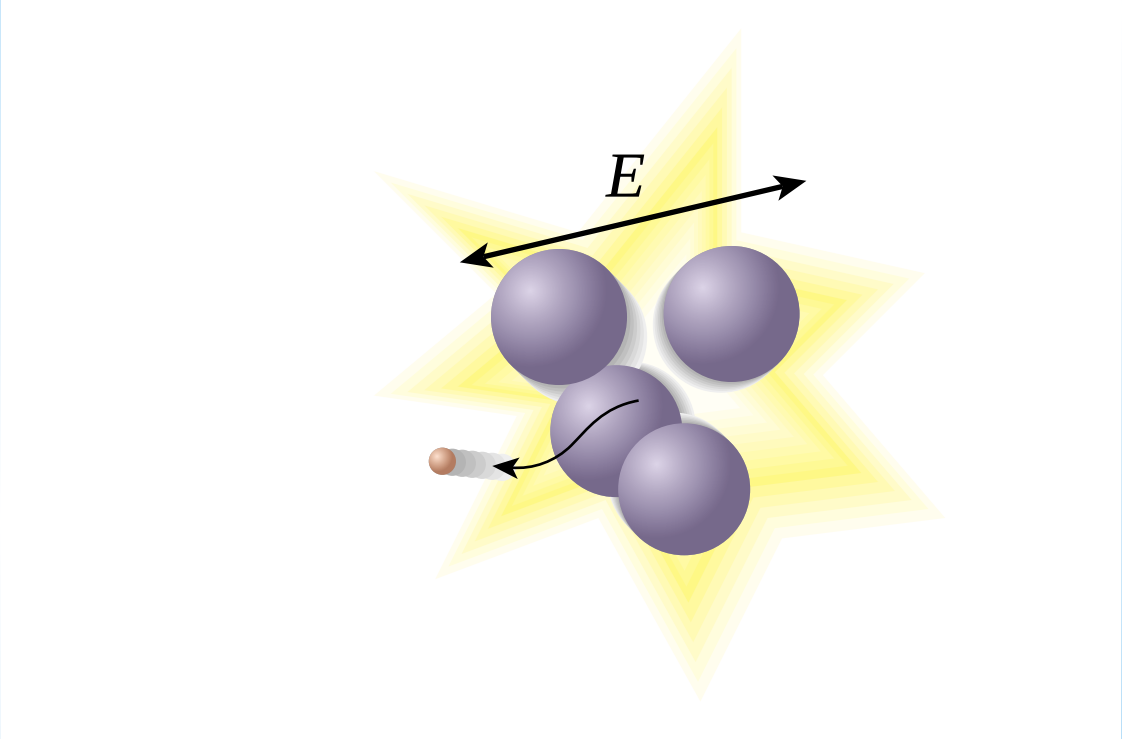
nonlinear response



second harmonic generation

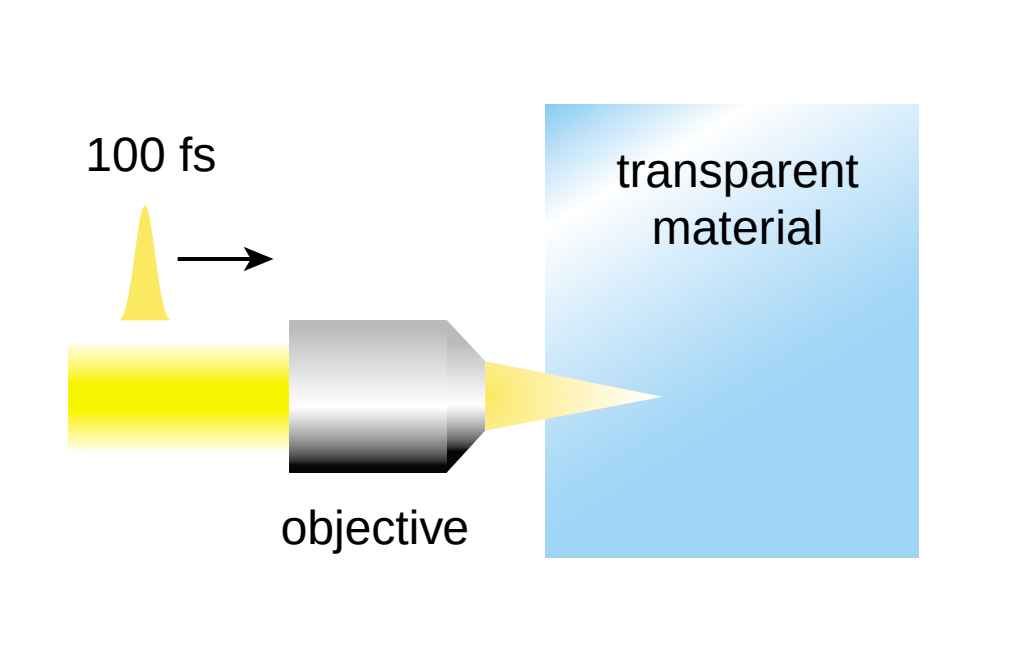
Introduction

“extremely” nonlinear response



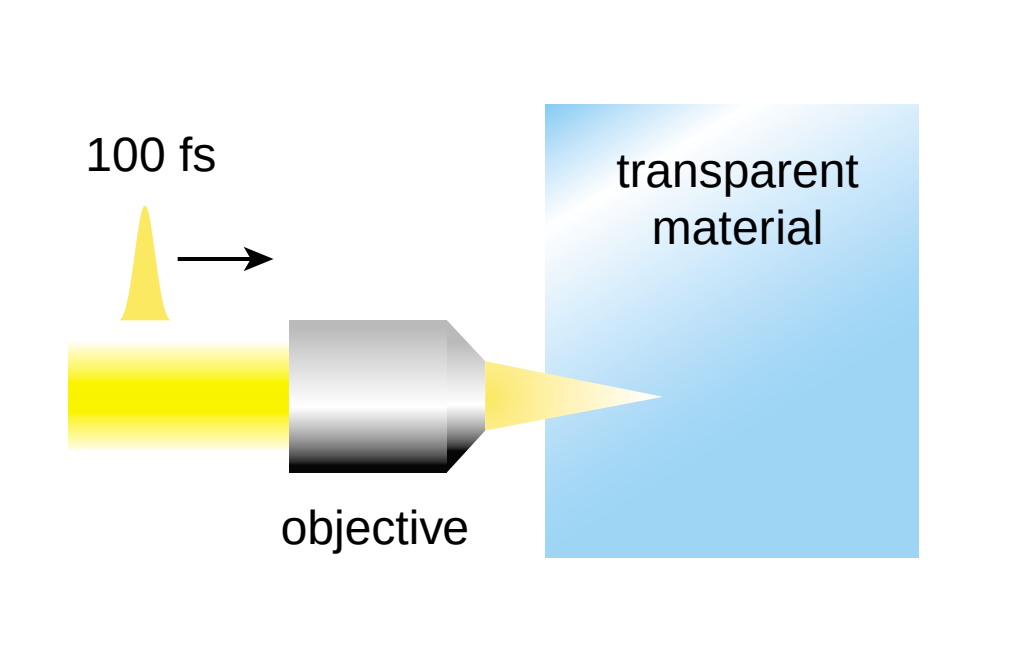
Introduction

focus beam inside transparent material…



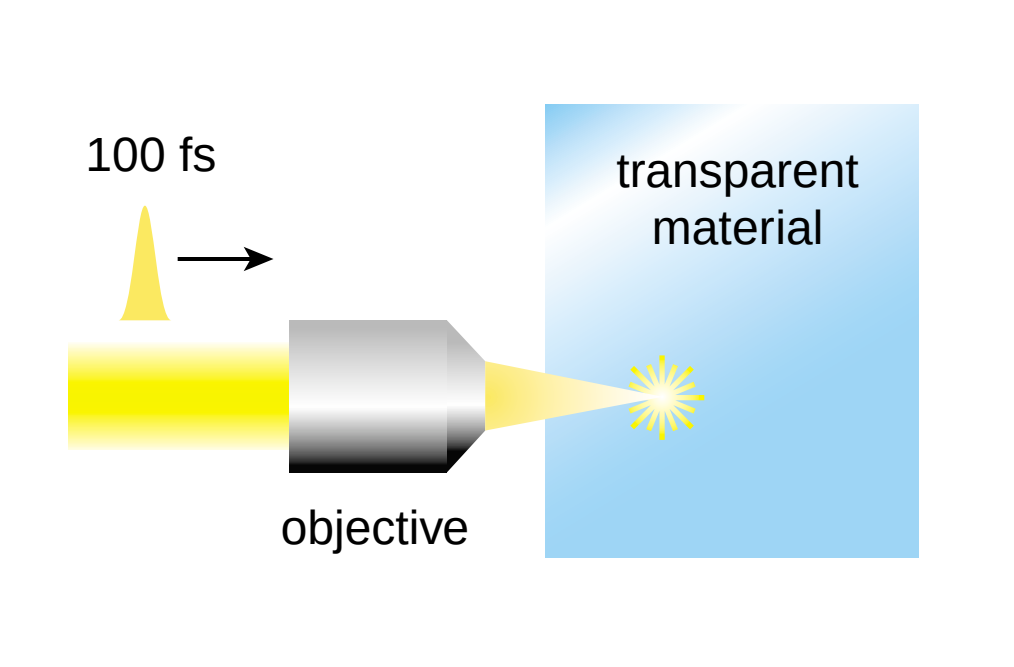
Introduction

high intensity at focus…



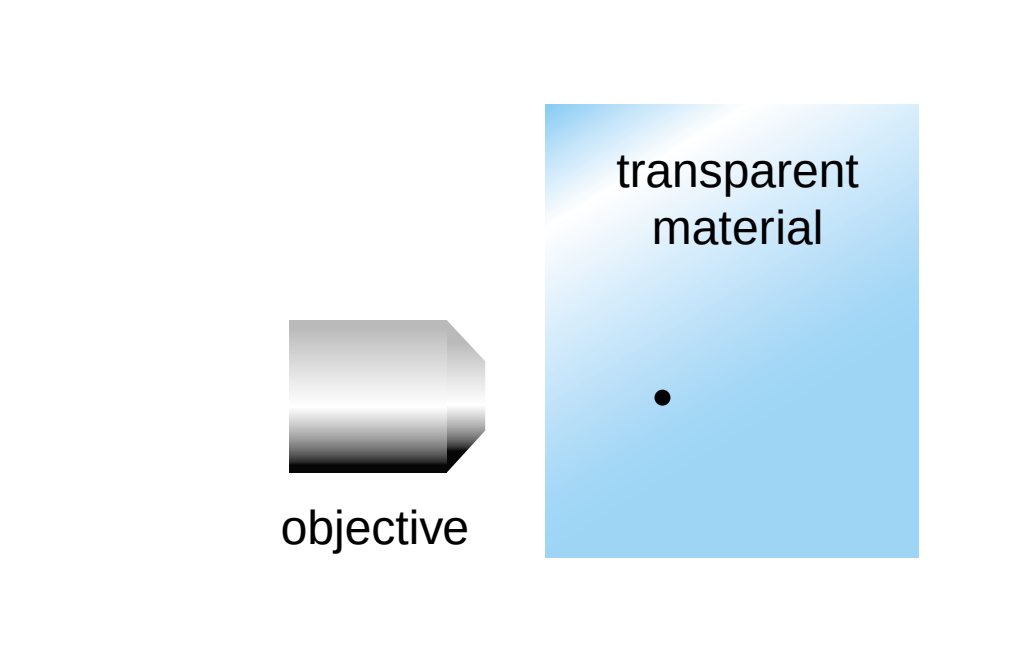
Introduction

… causes nonlinear ionization…

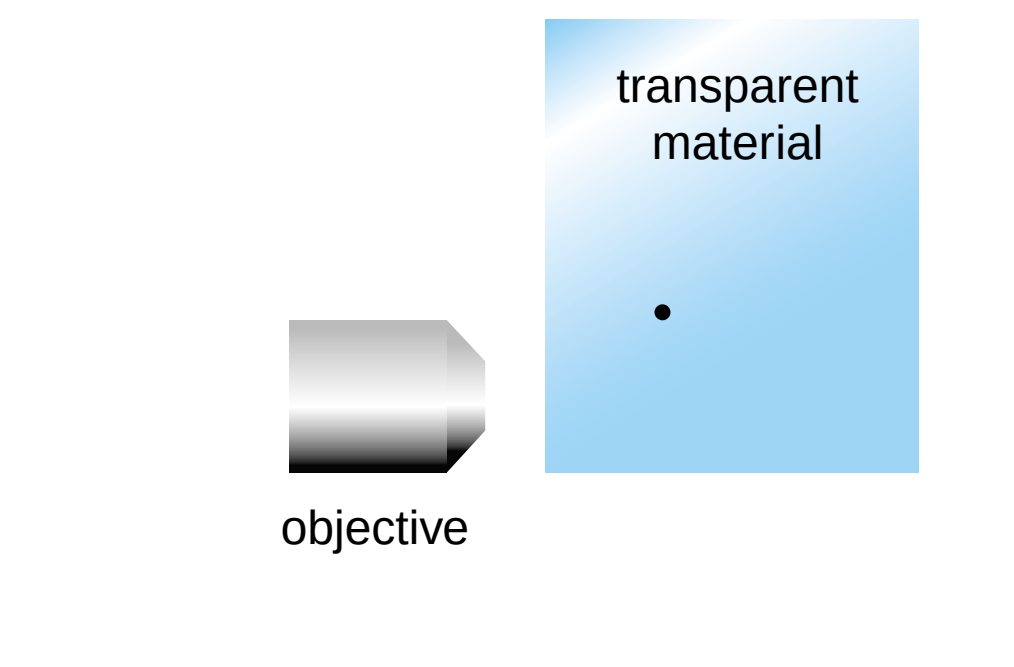


Introduction

and irreversible structural changes on microscopic scale

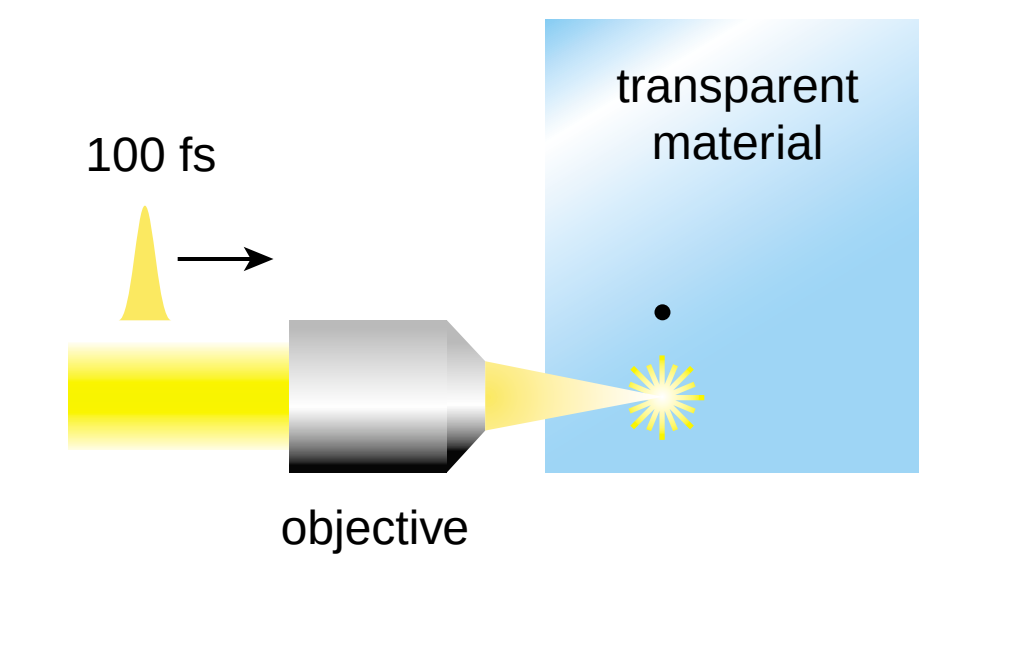


Introduction



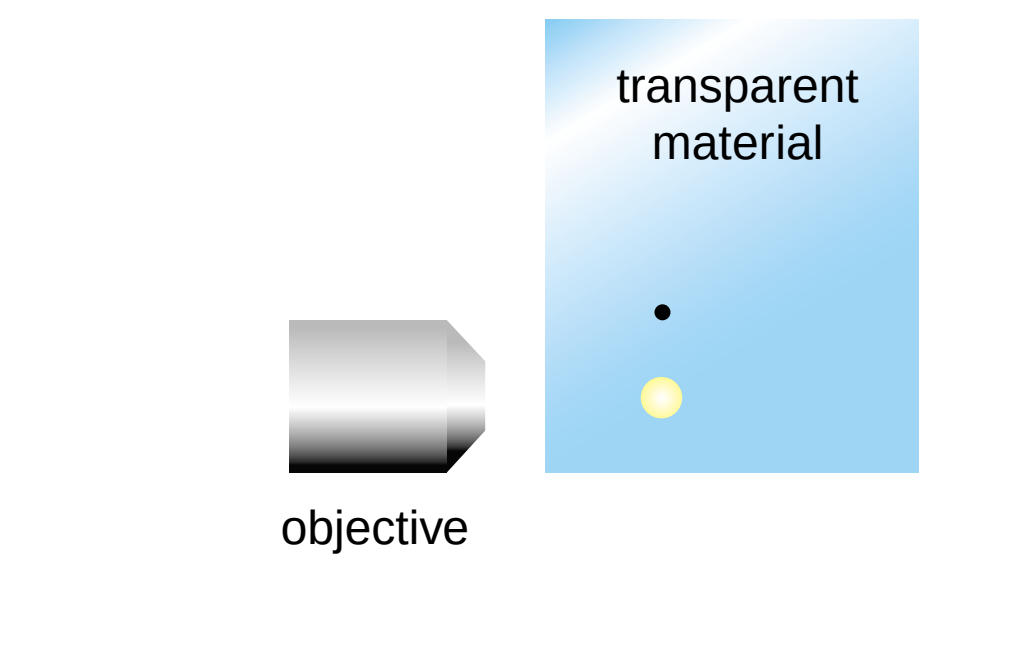
Introduction

100 fs: laser energy transferred to electrons

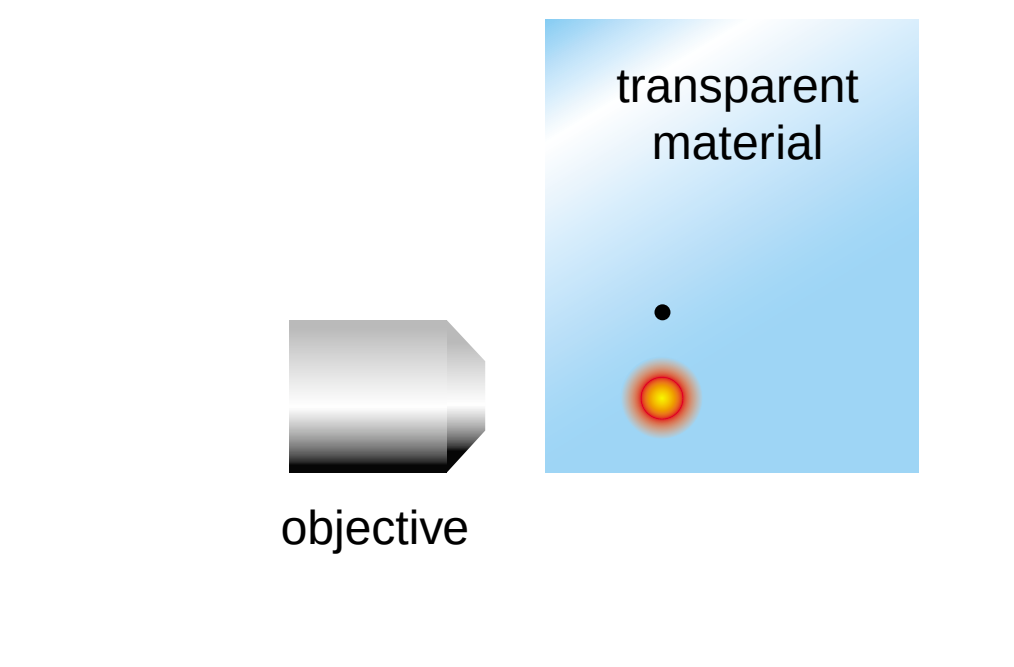


Introduction

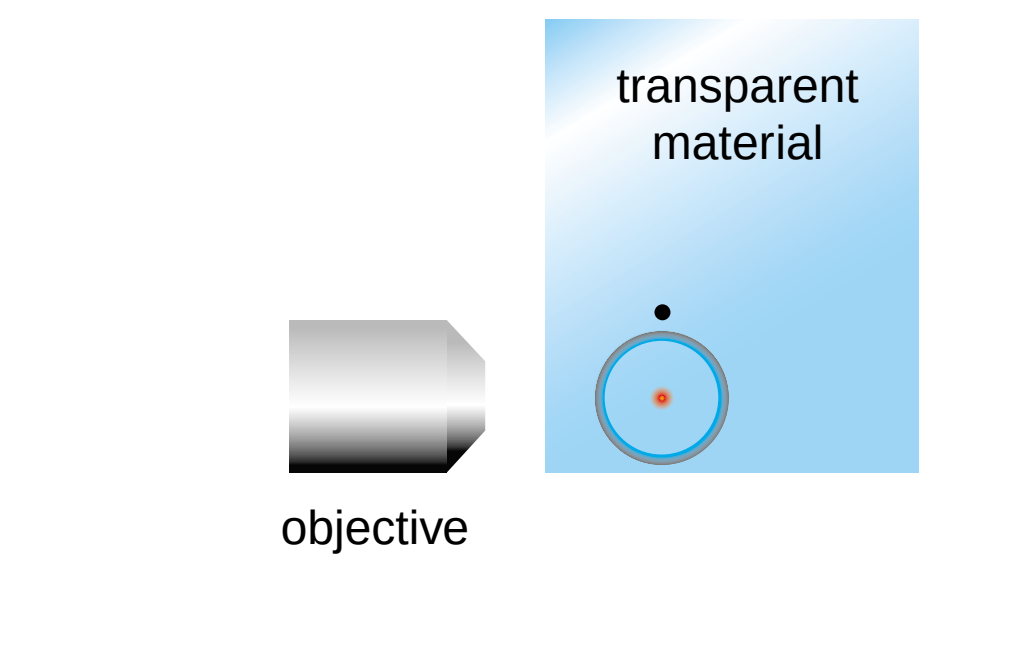
10 ps: energy transfer to ions



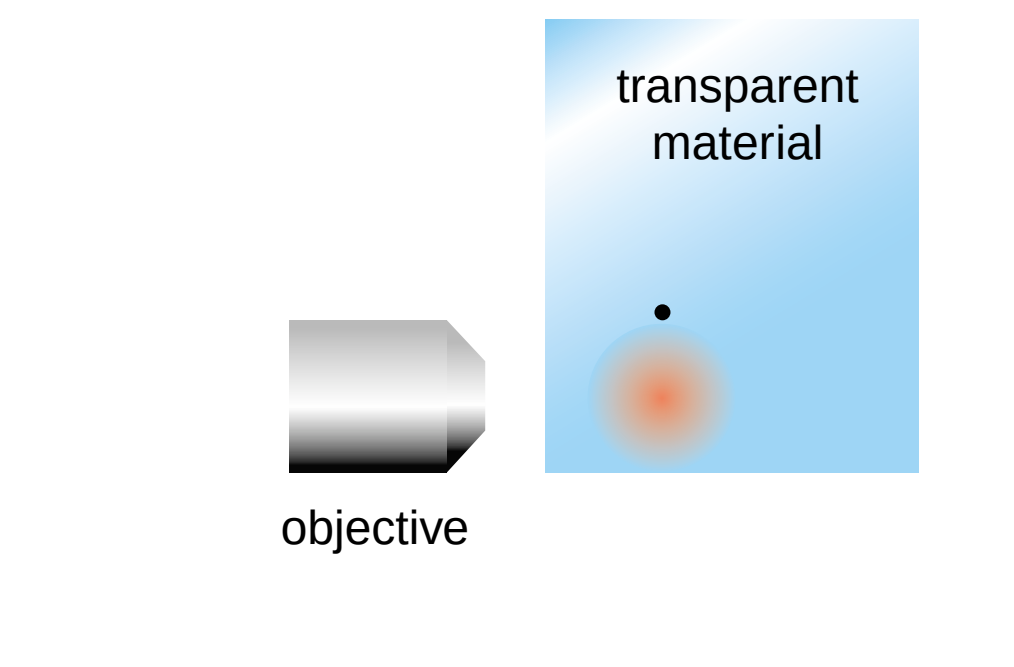
100 ps: plasma expansion



10–100 ns: shock propagation

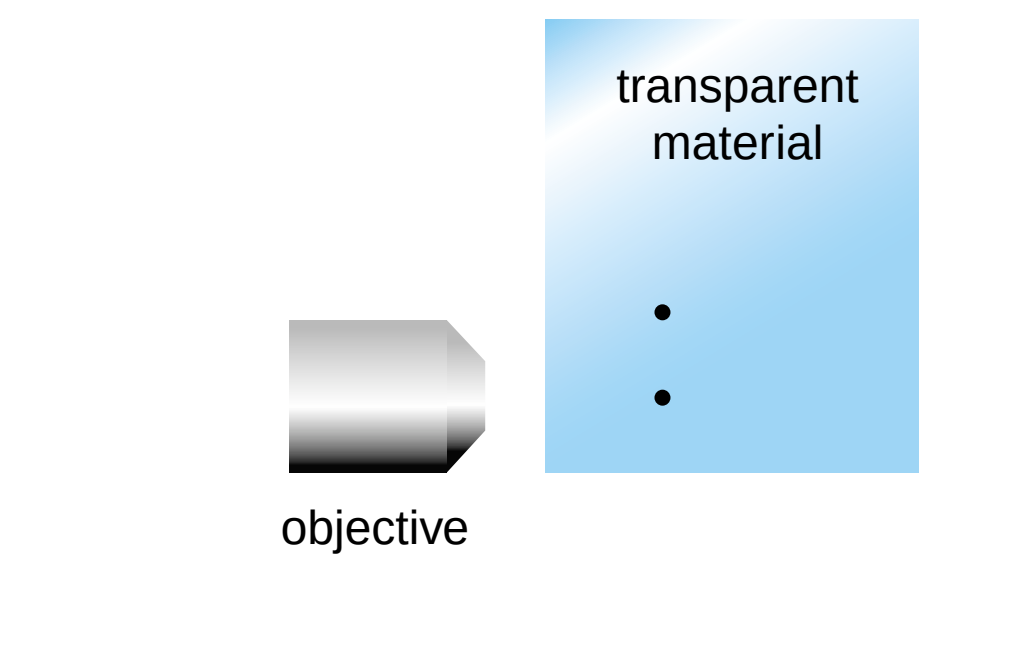


1 µs: thermal diffusion



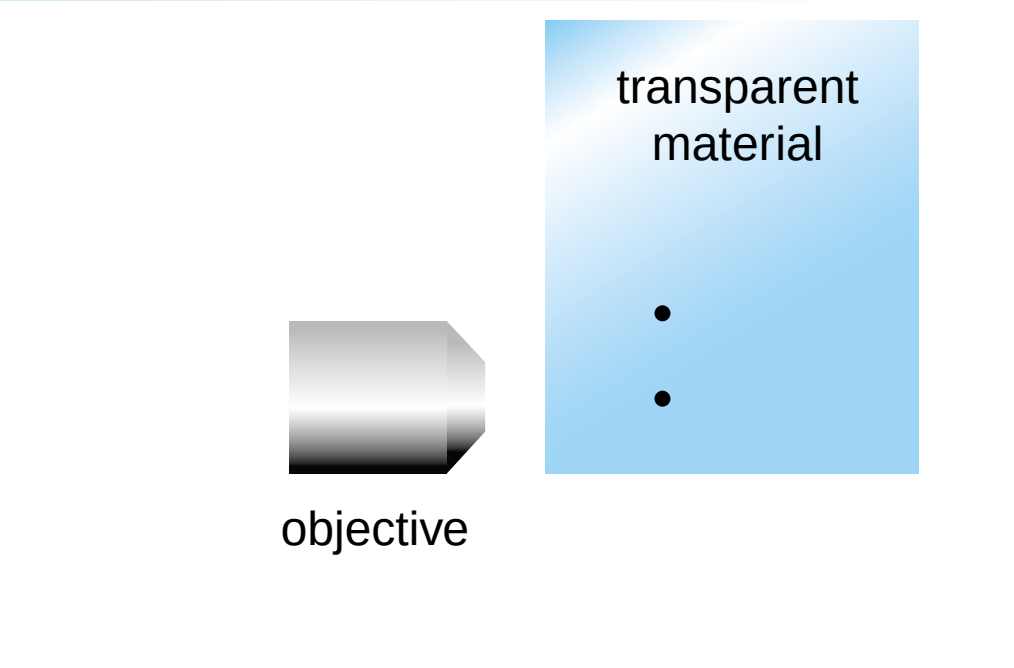
Introduction

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

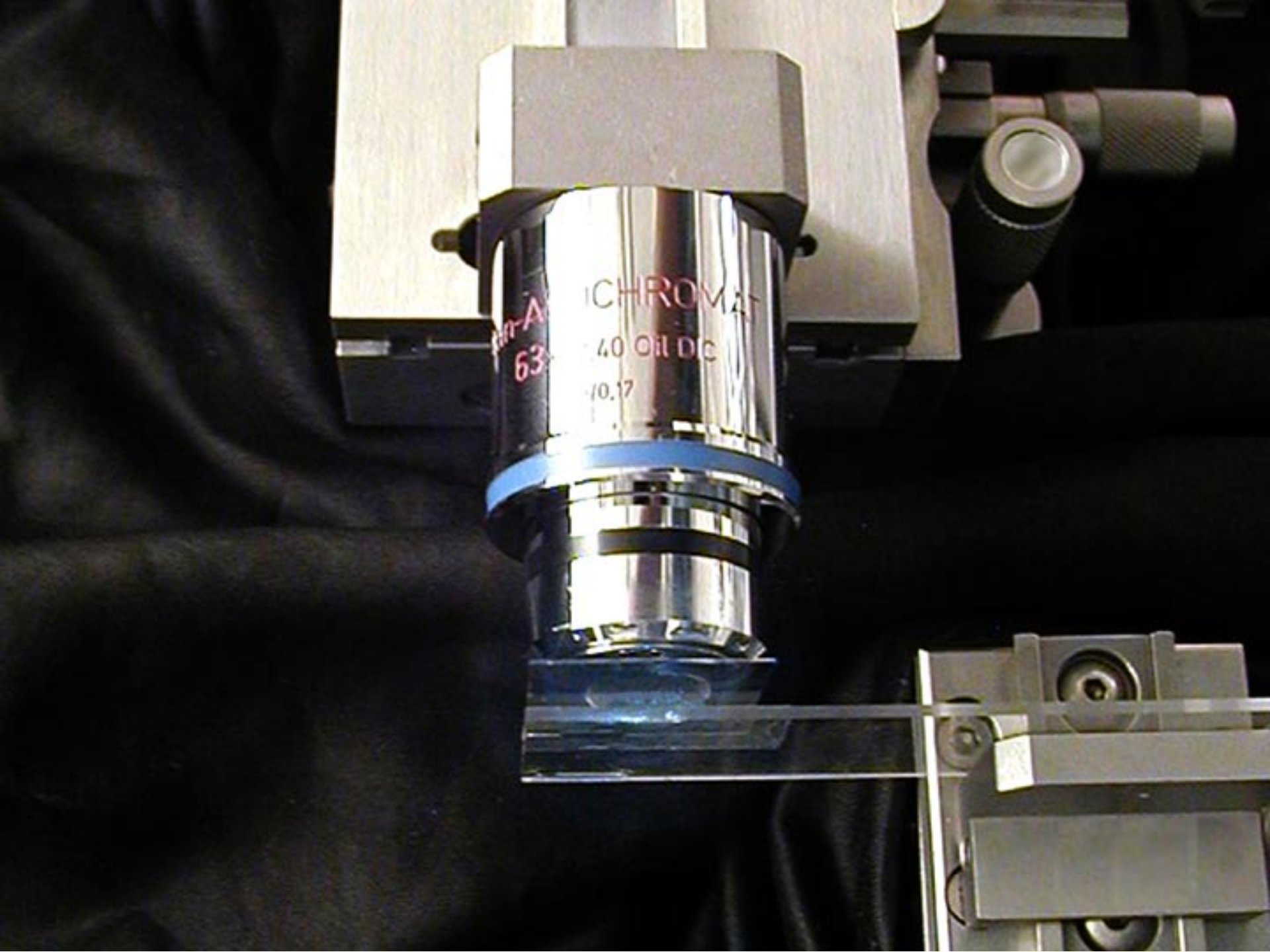
Material is a perturbation to the light!

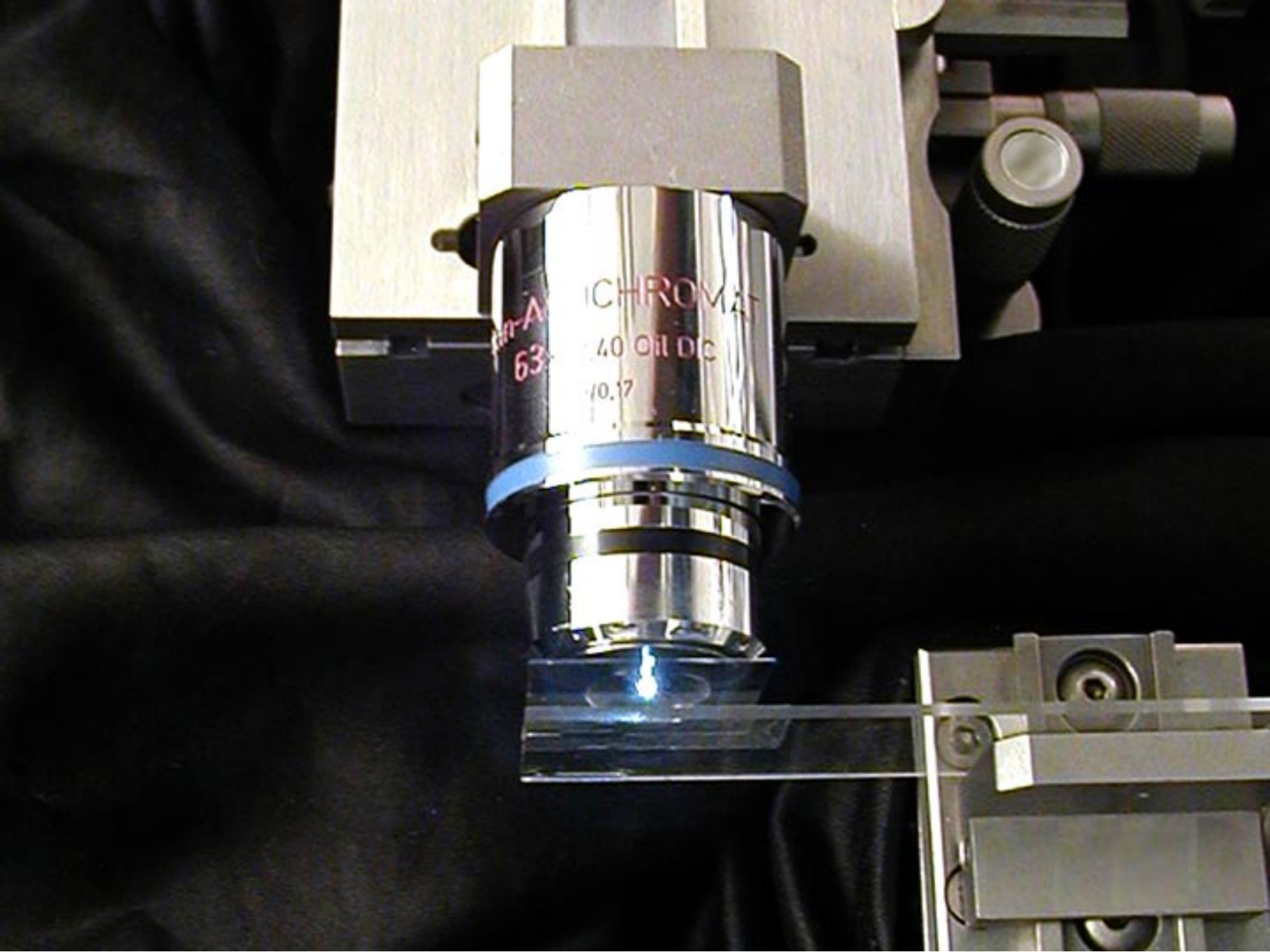
Introduction

How do materials behave under these extreme conditions?

Outline

- Setup
- Morphology
- Energy deposition
- Dynamics


ICHROMAT
40 Oil DC
0.17

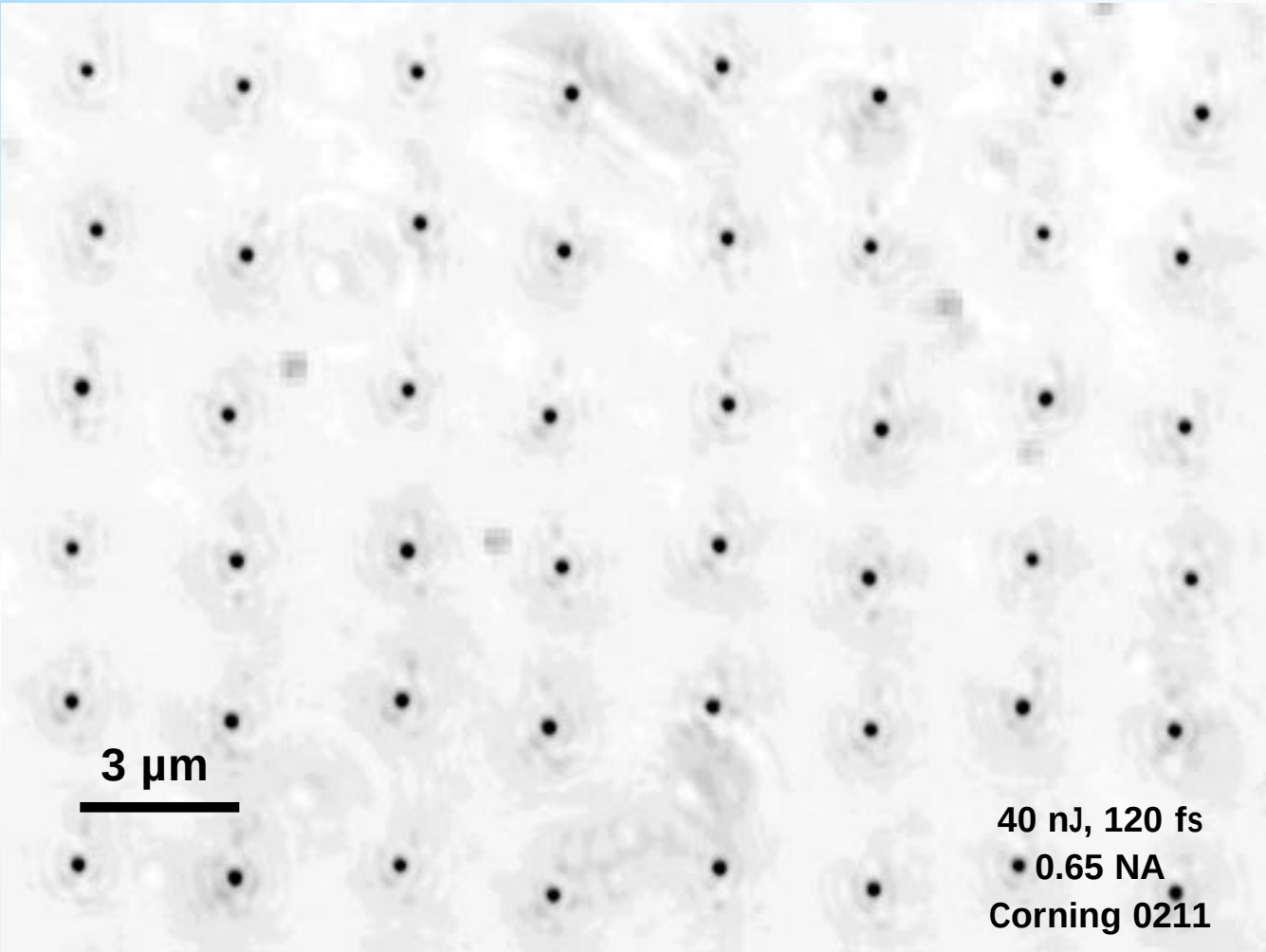

CHROMAT
40 Oil DC
0.17

Outline

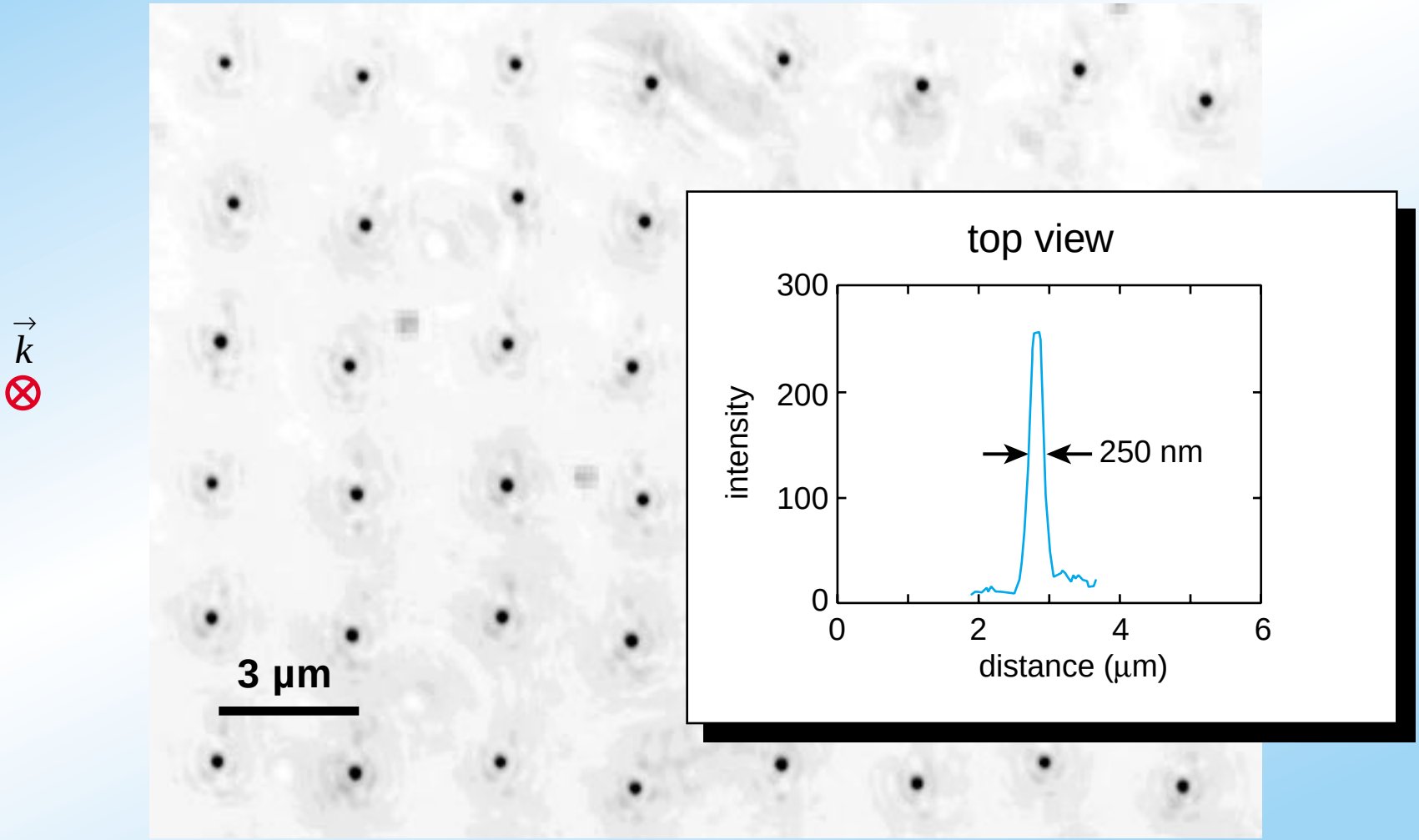
- Setup
- **Morphology**
- Energy deposition
- Dynamics

Morphology

$\vec{k}$



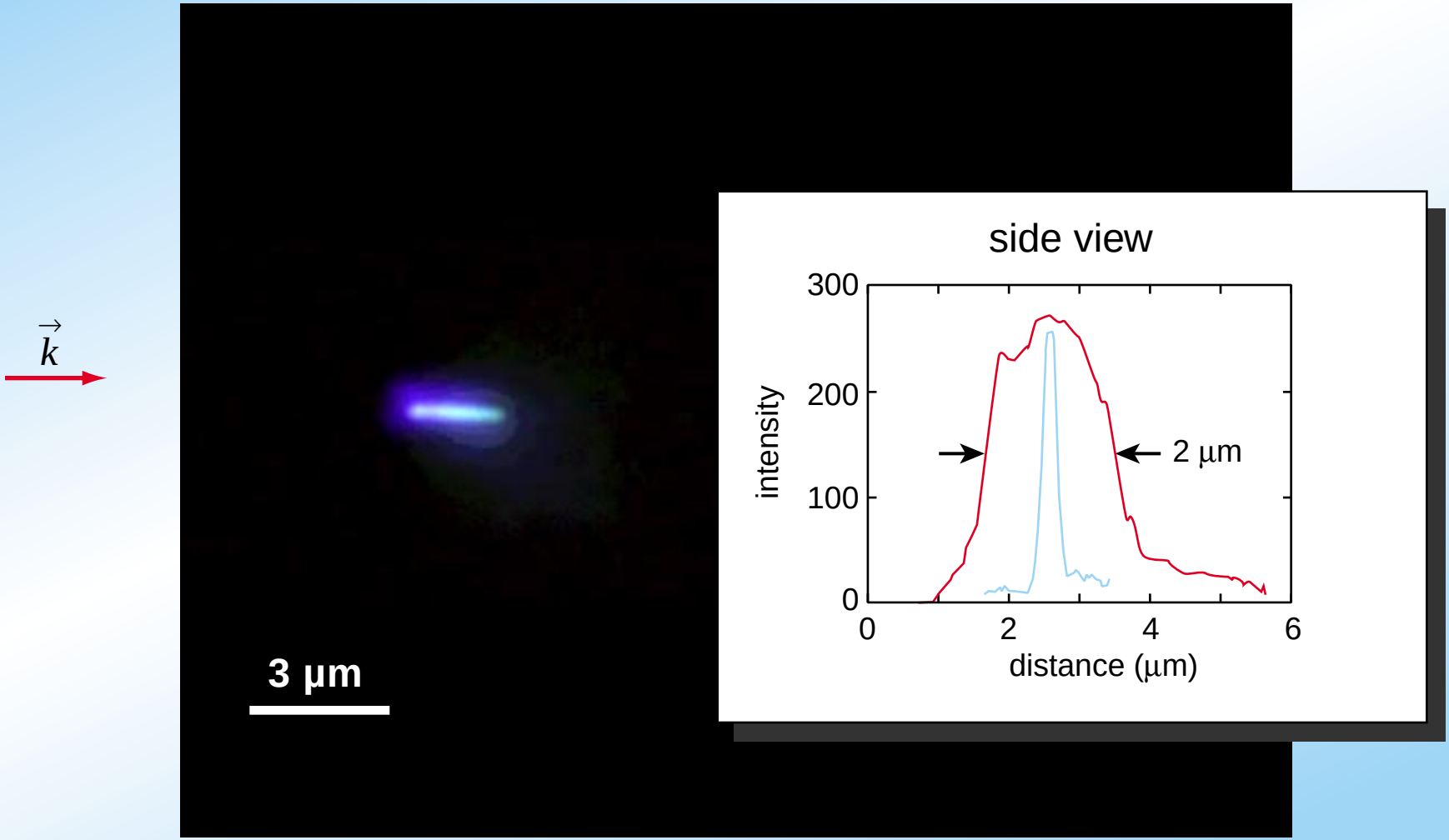
Morphology


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

Morphology

$\vec{k}$

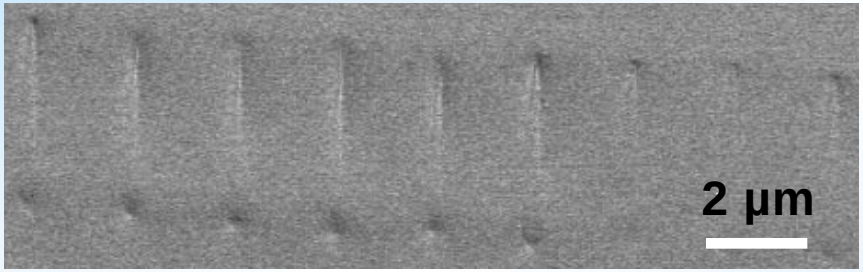
Morphology


$\vec{k}$
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



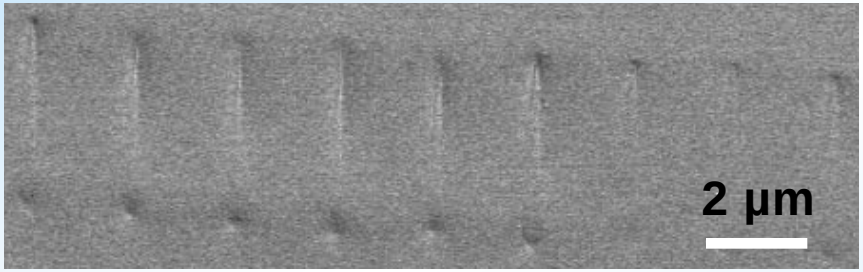
$\vec{k}$

100 fs
800 nm
0.45 NA
Corning 0211

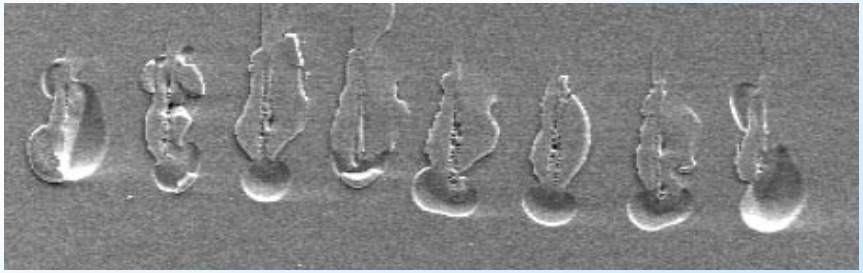
Morphology

SEM pictures of single-shot structures

140 nJ



250 nJ



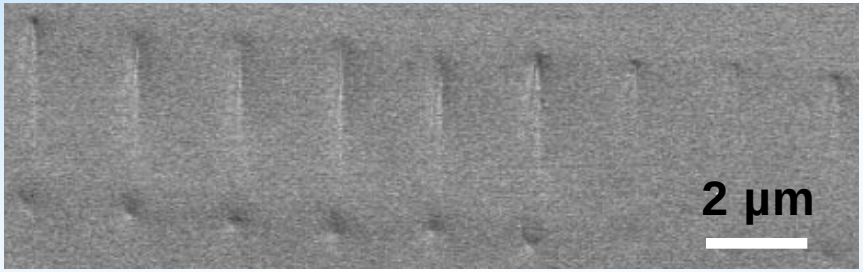
$\vec{k}$

100 fs
800 nm
0.45 NA
Corning 0211

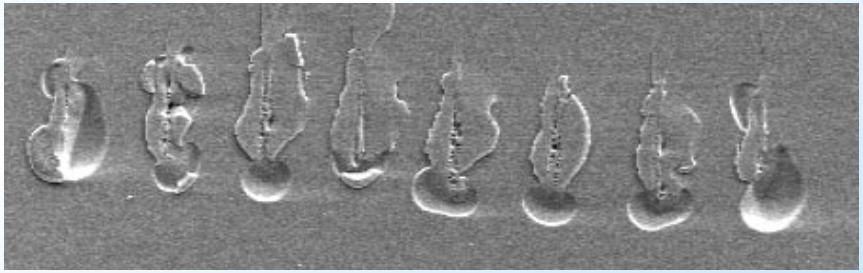
Morphology

SEM pictures of single-shot structures

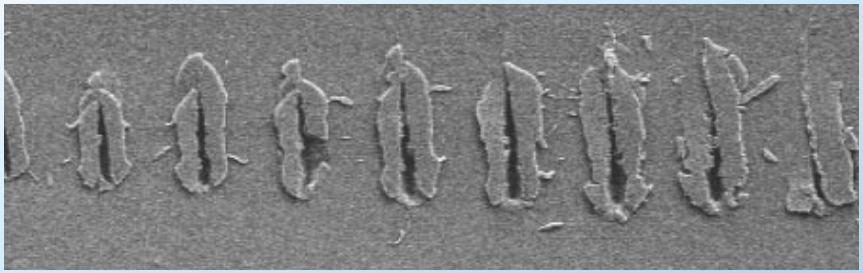
140 nJ



250 nJ



540 nJ



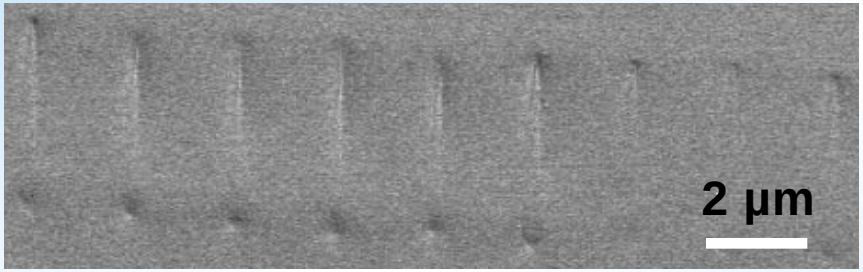
$\vec{k}$

100 fs
800 nm
0.45 NA
Corning 0211

Morphology

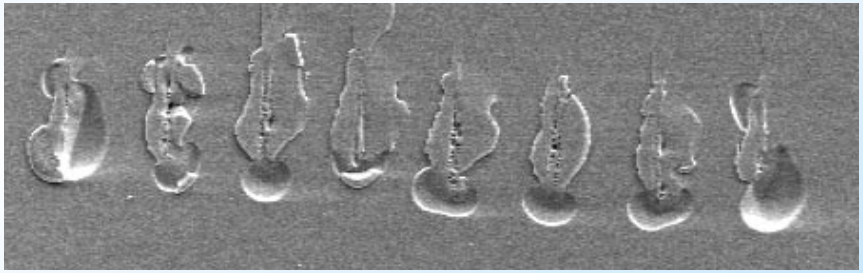
SEM pictures of single-shot structures

140 nJ

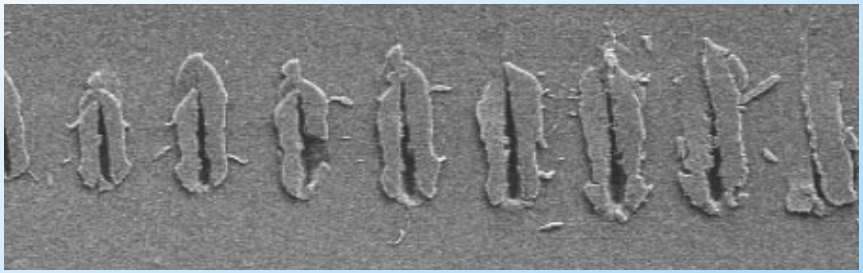


thermal

250 nJ



540 nJ



explosive

Morphology

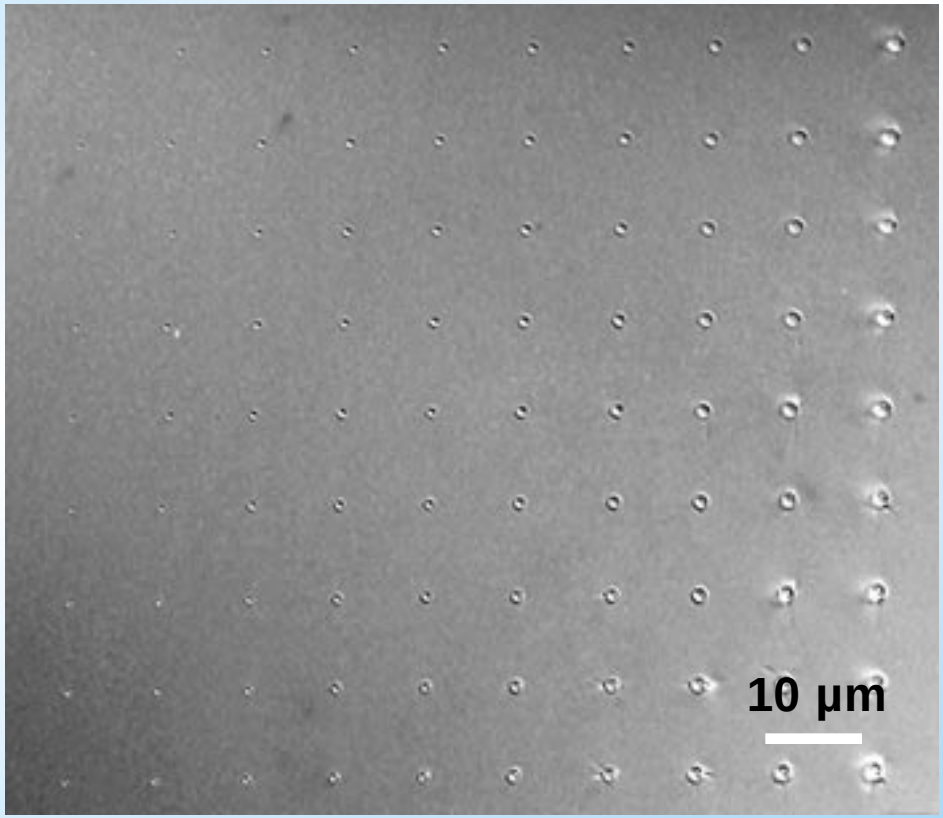
What happens when several pulses strike the same spot?

Morphology

multiple-shot structures (1 kHz)

more energy →

more shots ↓

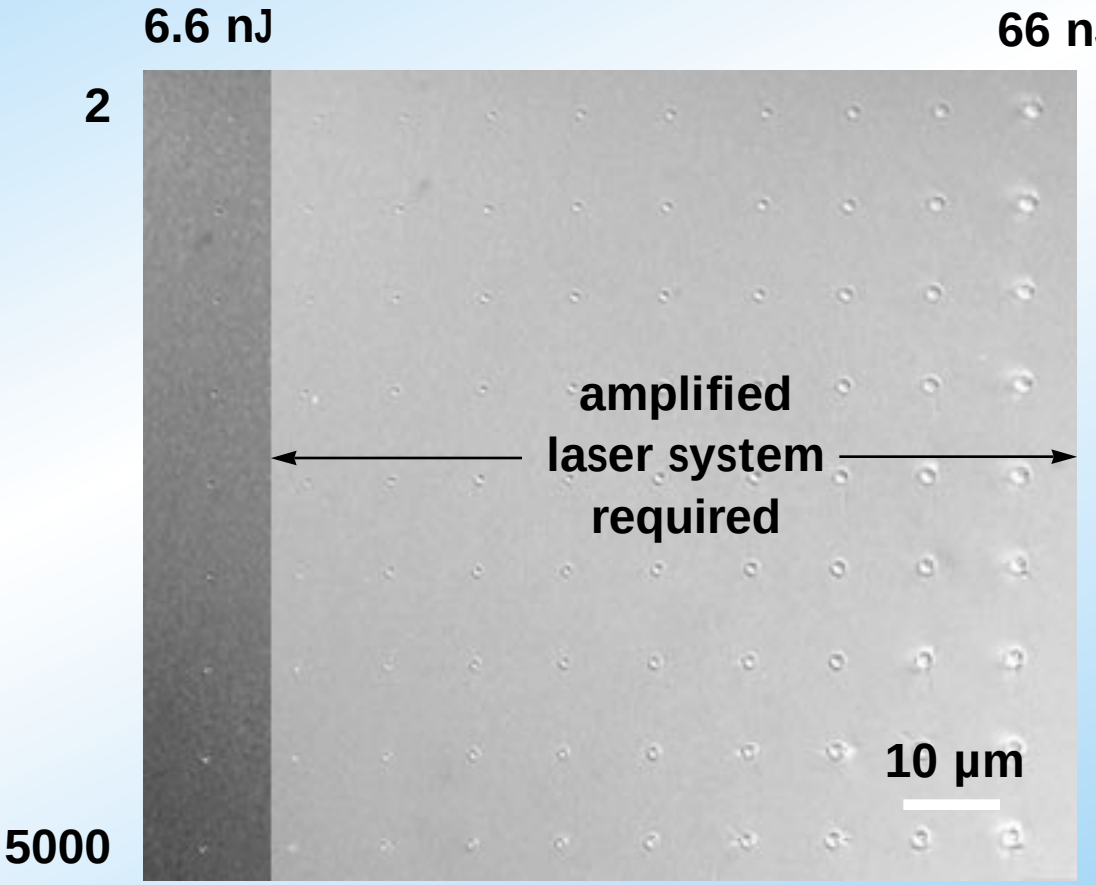


$\vec{k}$ ⊗

100 fs
1.4 NA
Corning 0211

Morphology

multiple-shot structures (1 kHz)

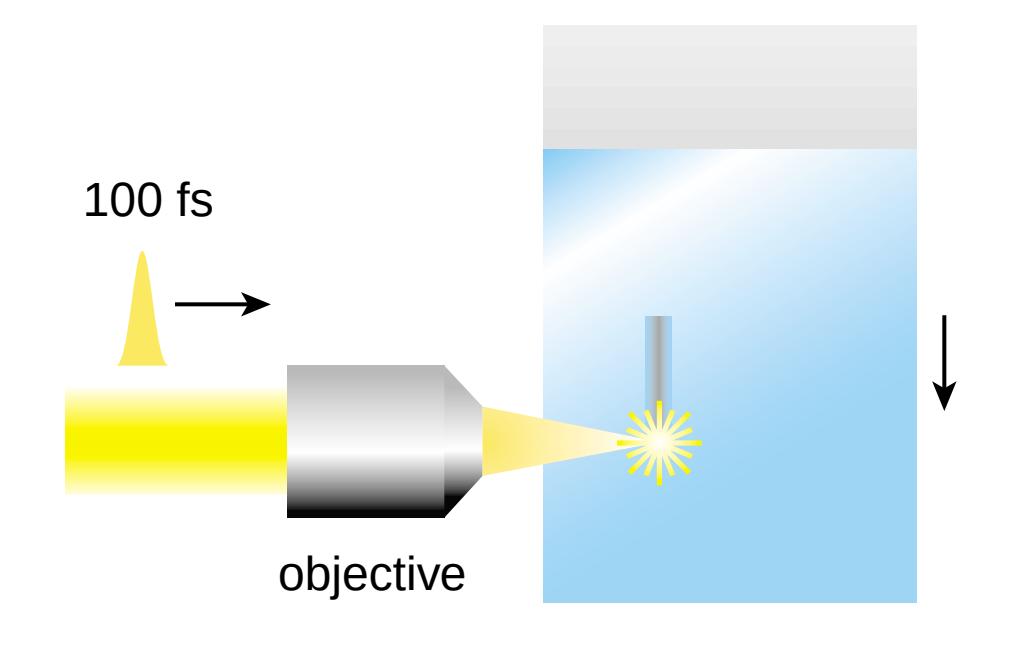


$\vec{k}$ ⊗

100 fs
1.4 NA
Corning 0211

Morphology

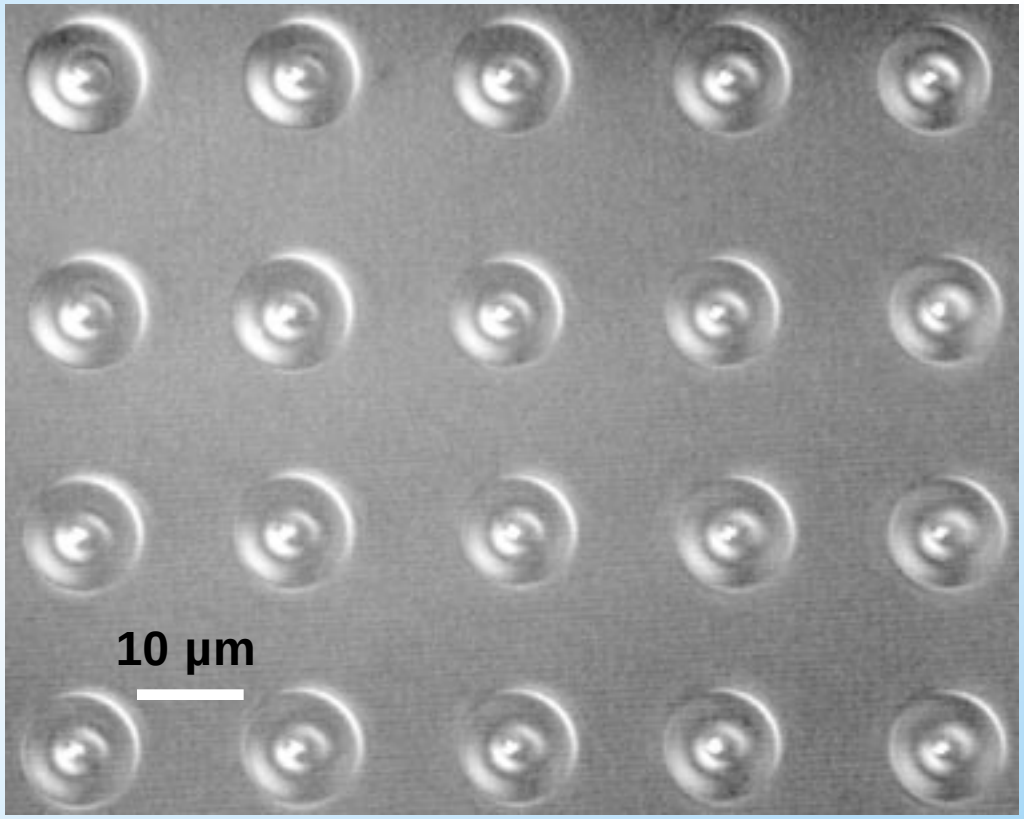
oscillator-only “micromachining”



25 MHz: point source of heat inside material!

Morphology

cumulative heating structures (25 MHz)

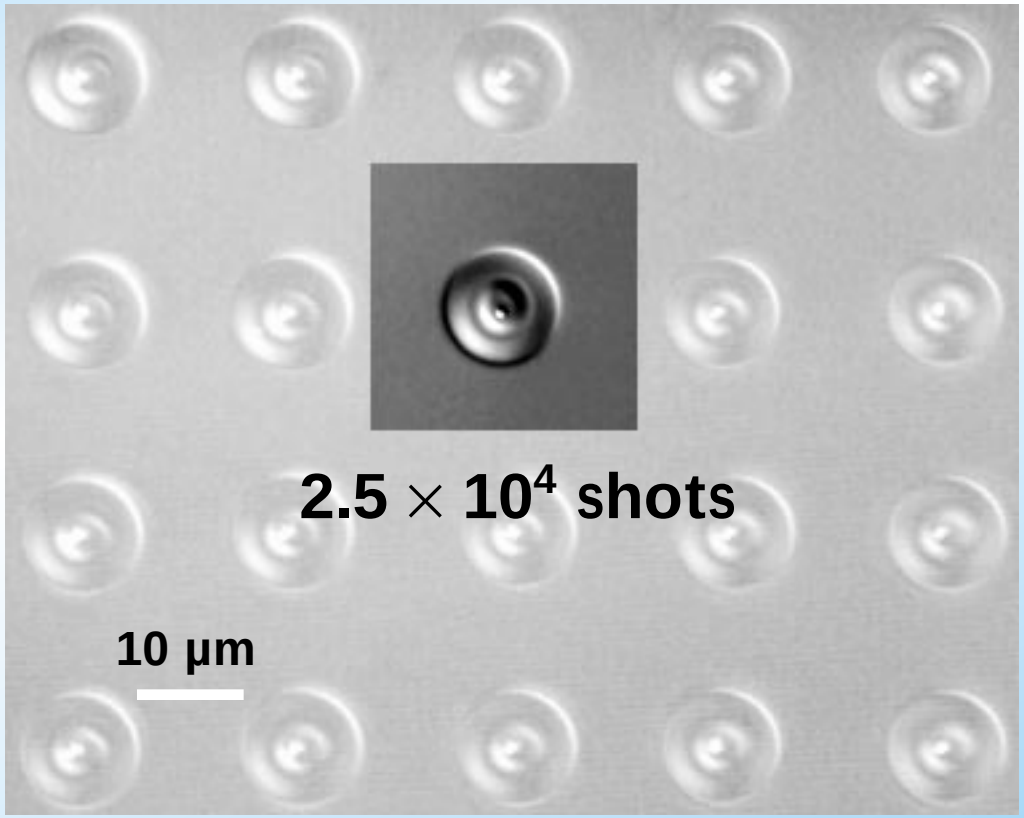


$\vec{k}$ ⊗

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

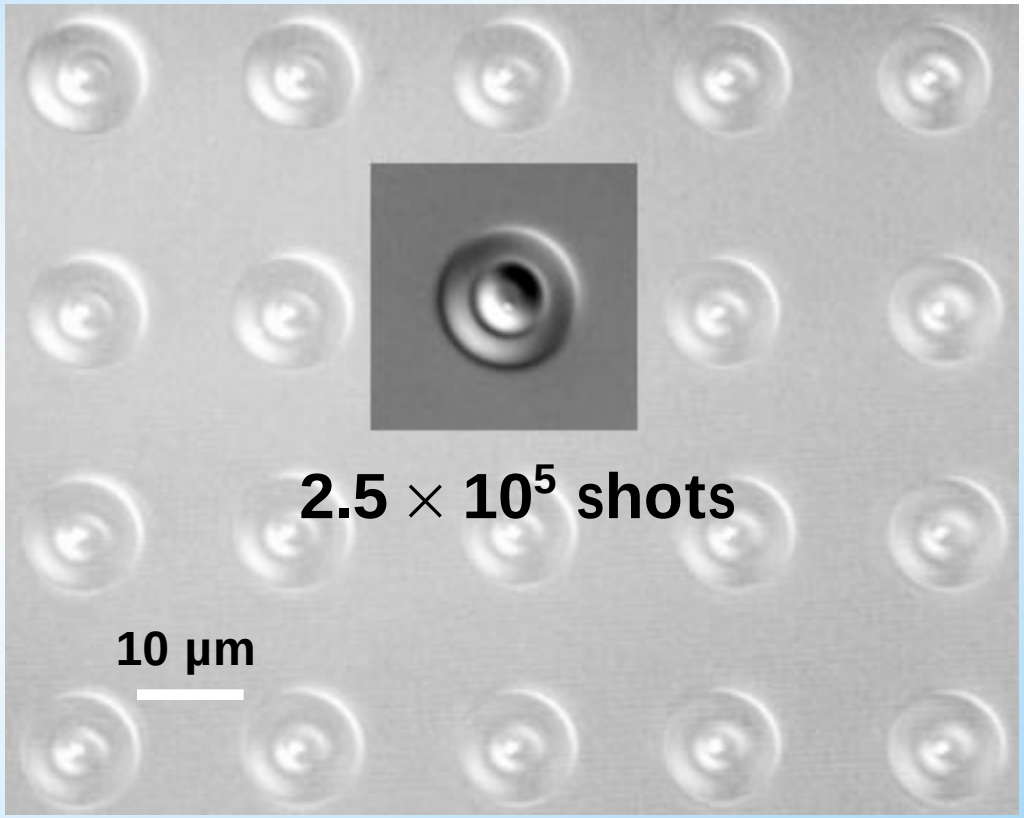
Morphology

cumulative heating structures (25 MHz)



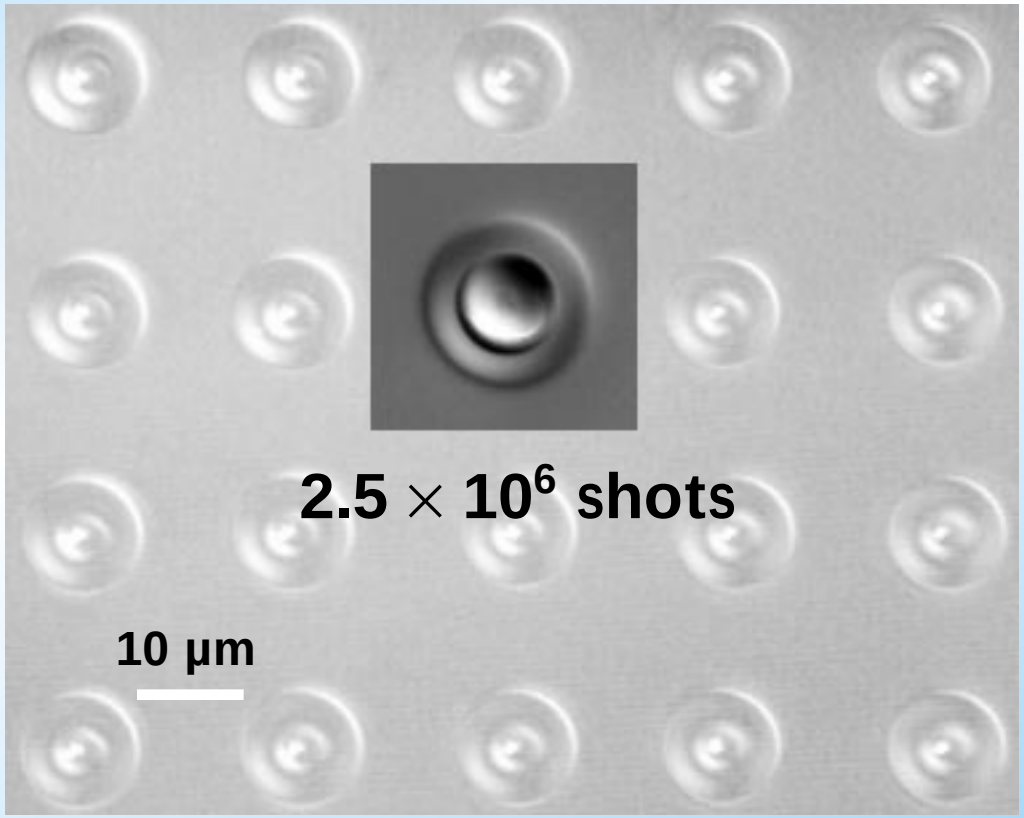
Morphology

cumulative heating structures (25 MHz)



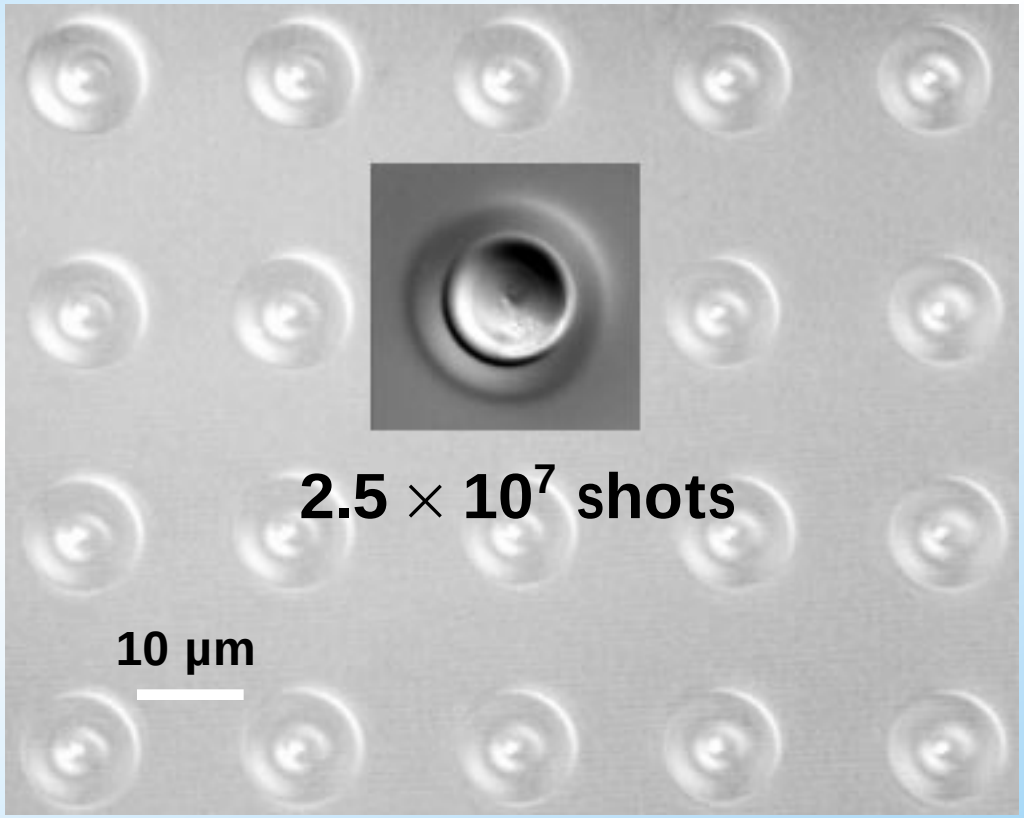
Morphology

cumulative heating structures (25 MHz)

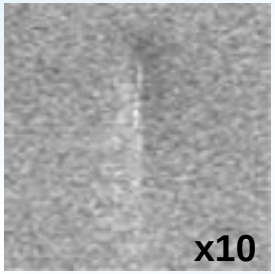
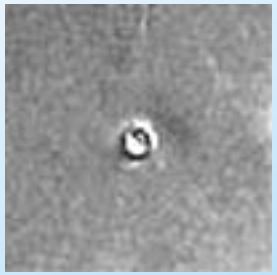
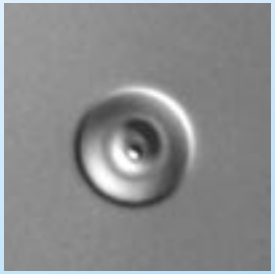


Morphology

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

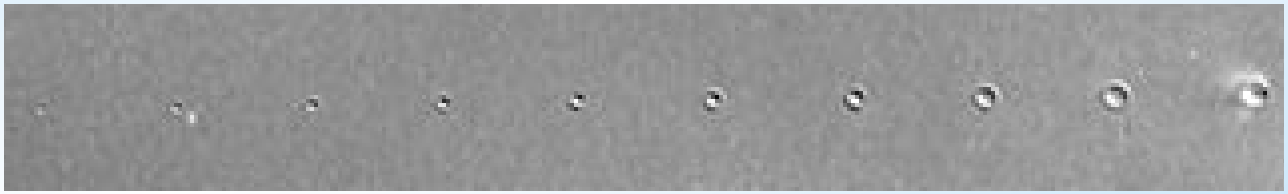
Energy deposition

Determine threshold for structural change:

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

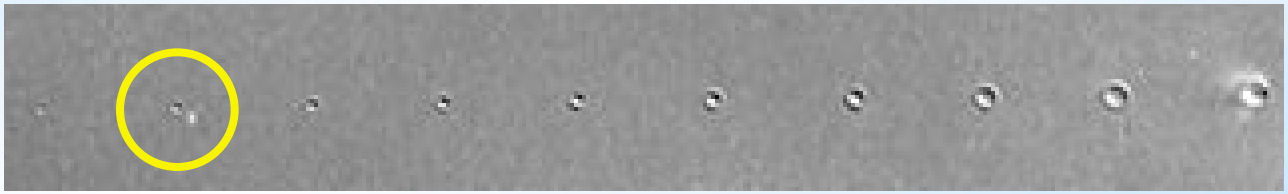
Energy deposition

optical microscopy



Energy deposition

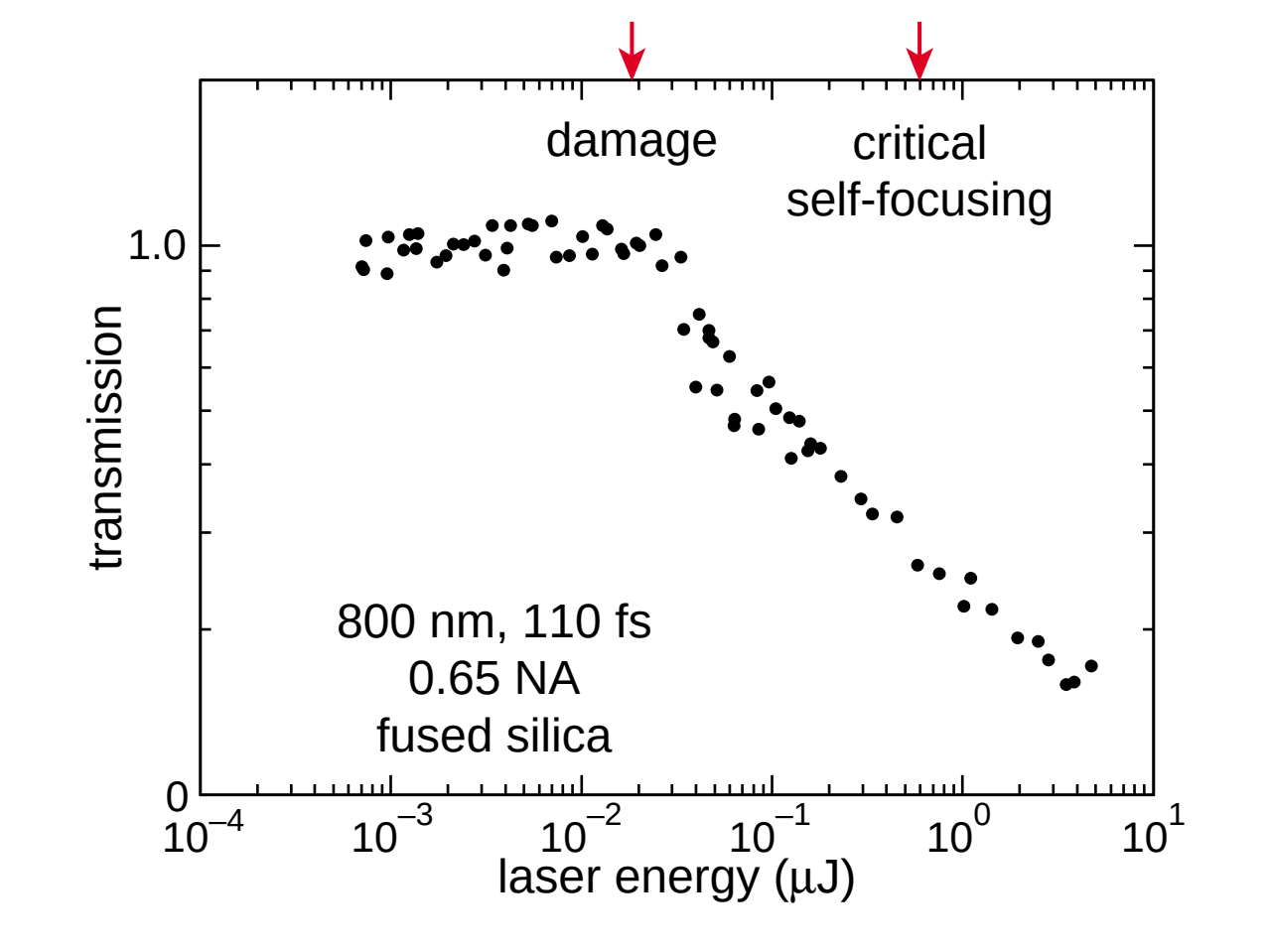
optical microscopy



6.6 nJ

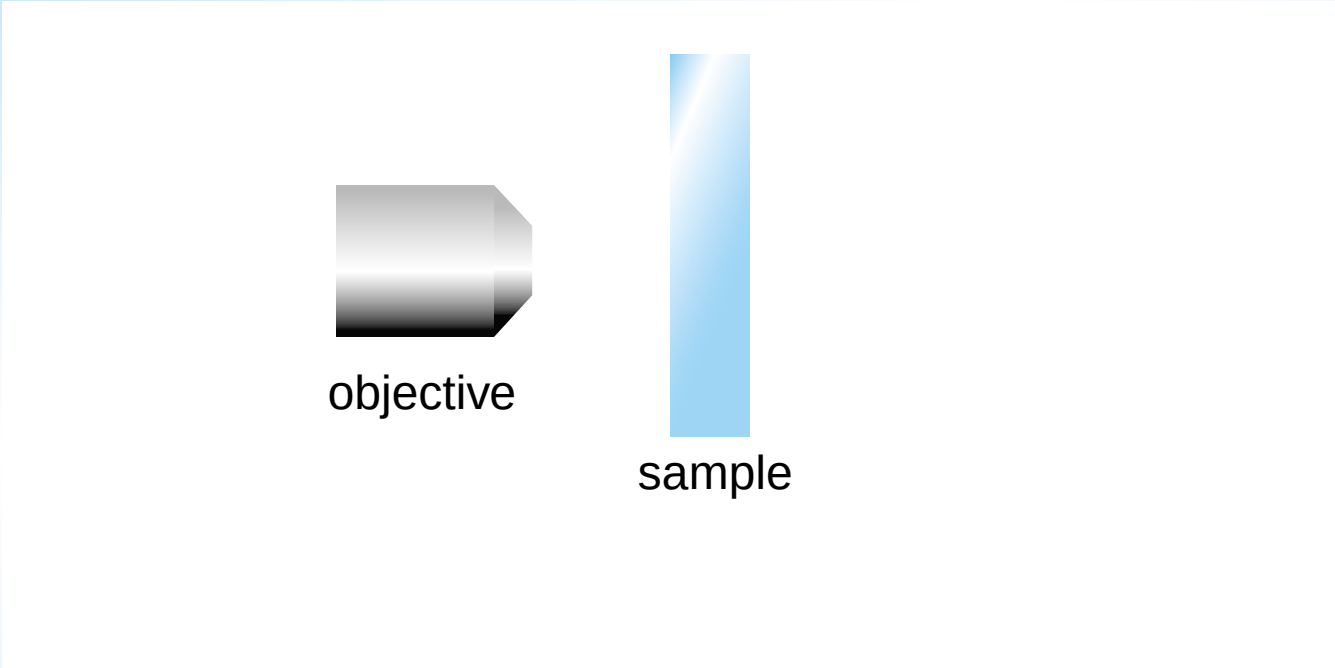
Energy deposition

transmission of pump beam in fused silica



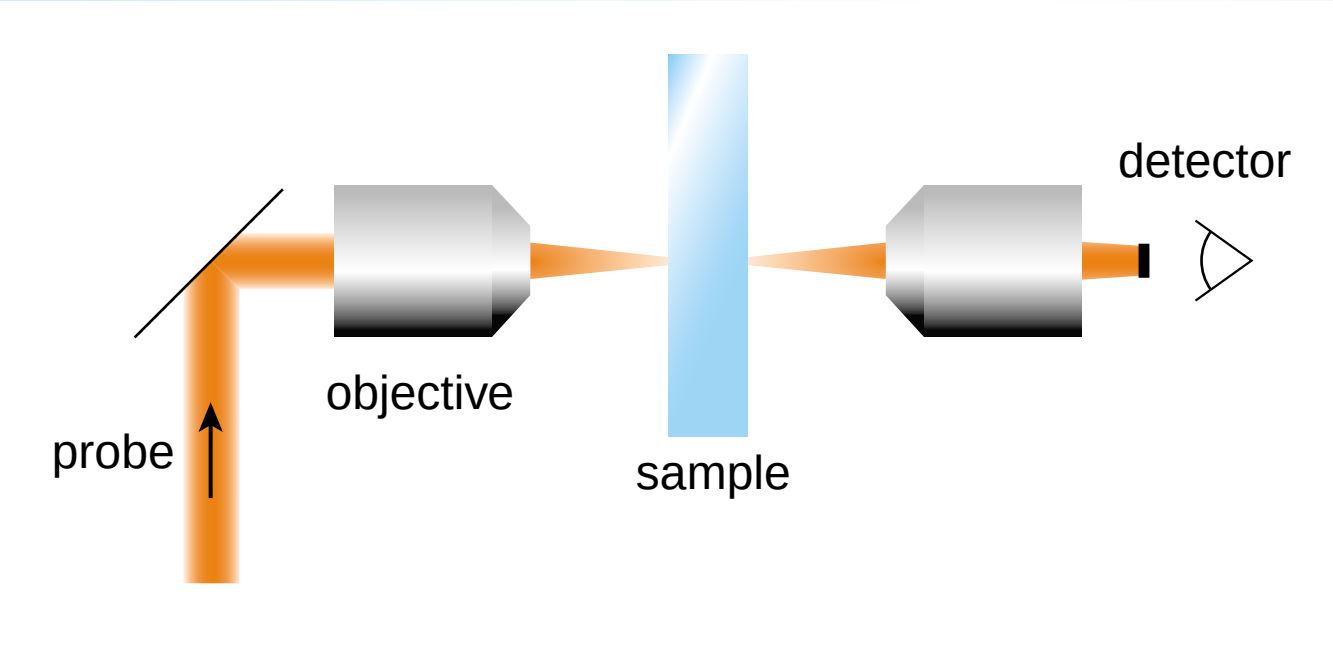
Energy deposition

Dark-field scattering



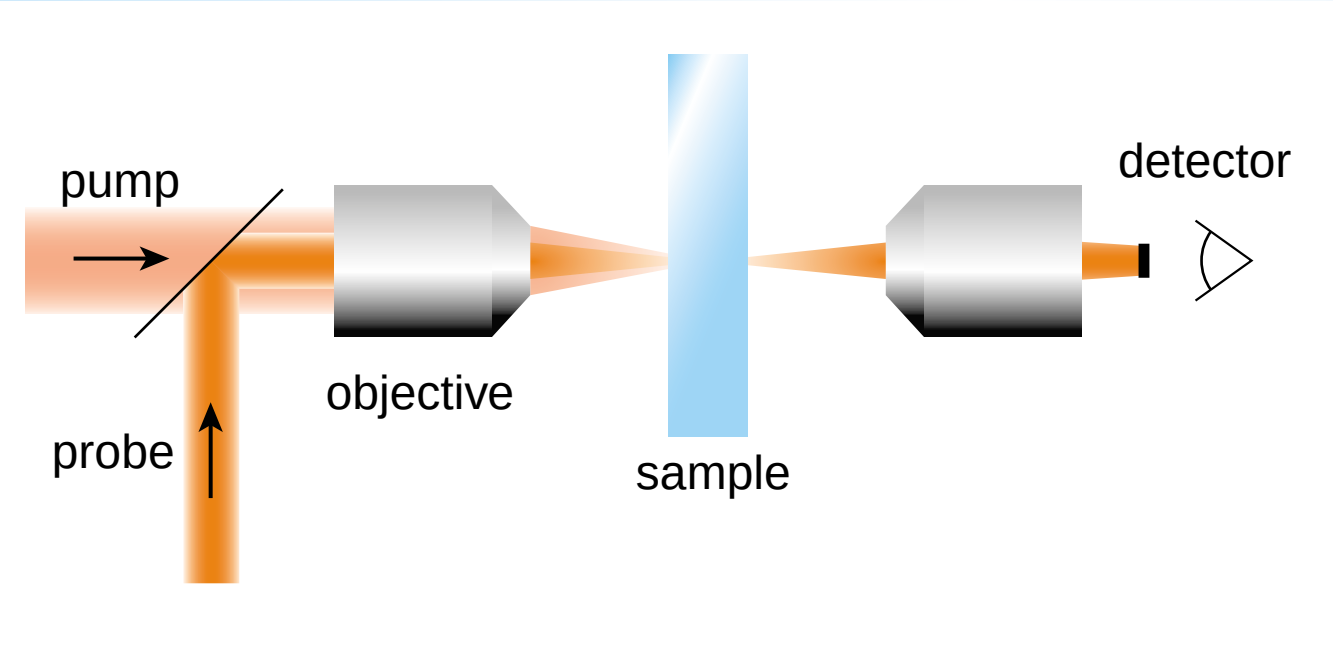
Energy deposition

block probe beam…



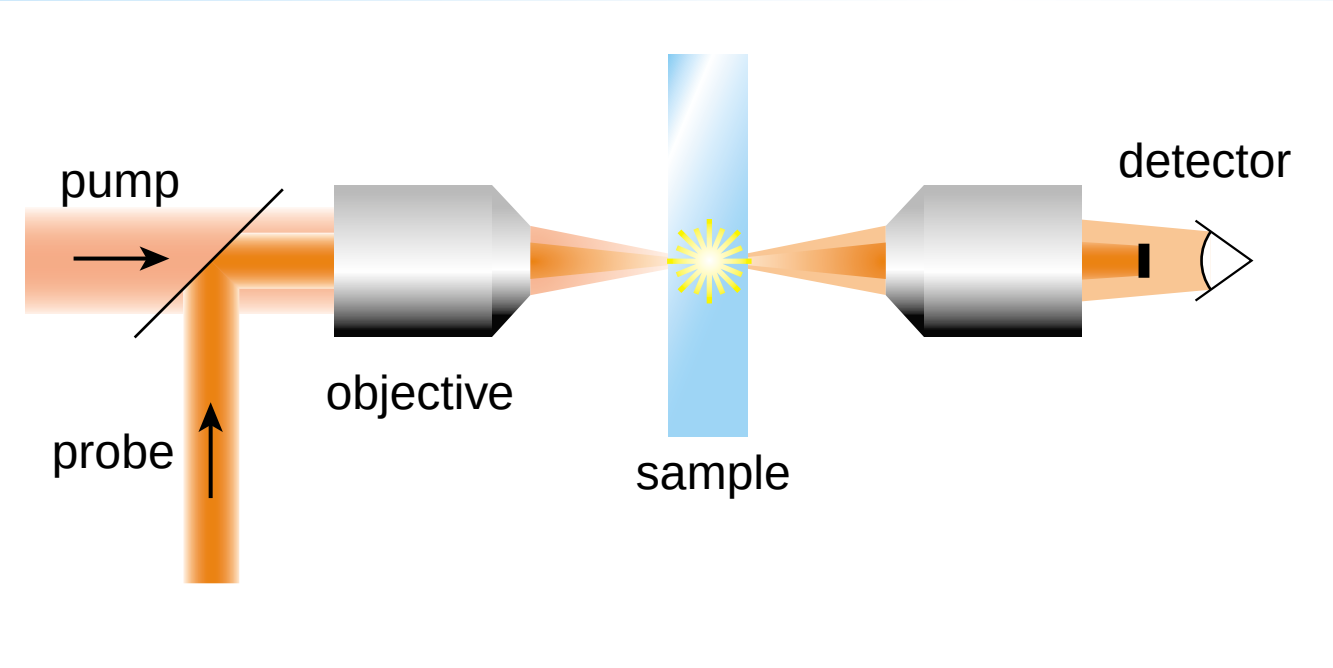
Energy deposition

…bring in pump beam…

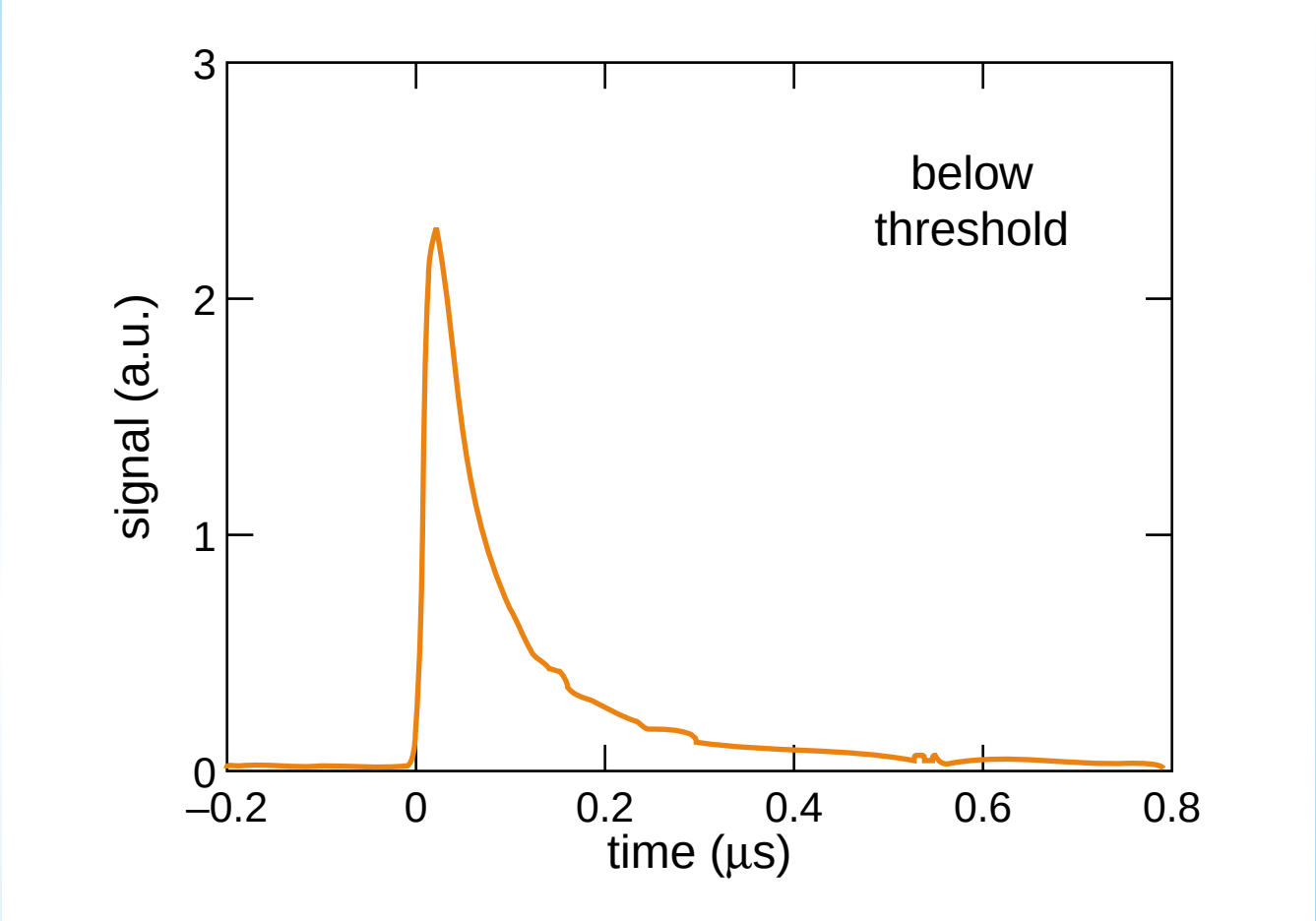


Energy deposition

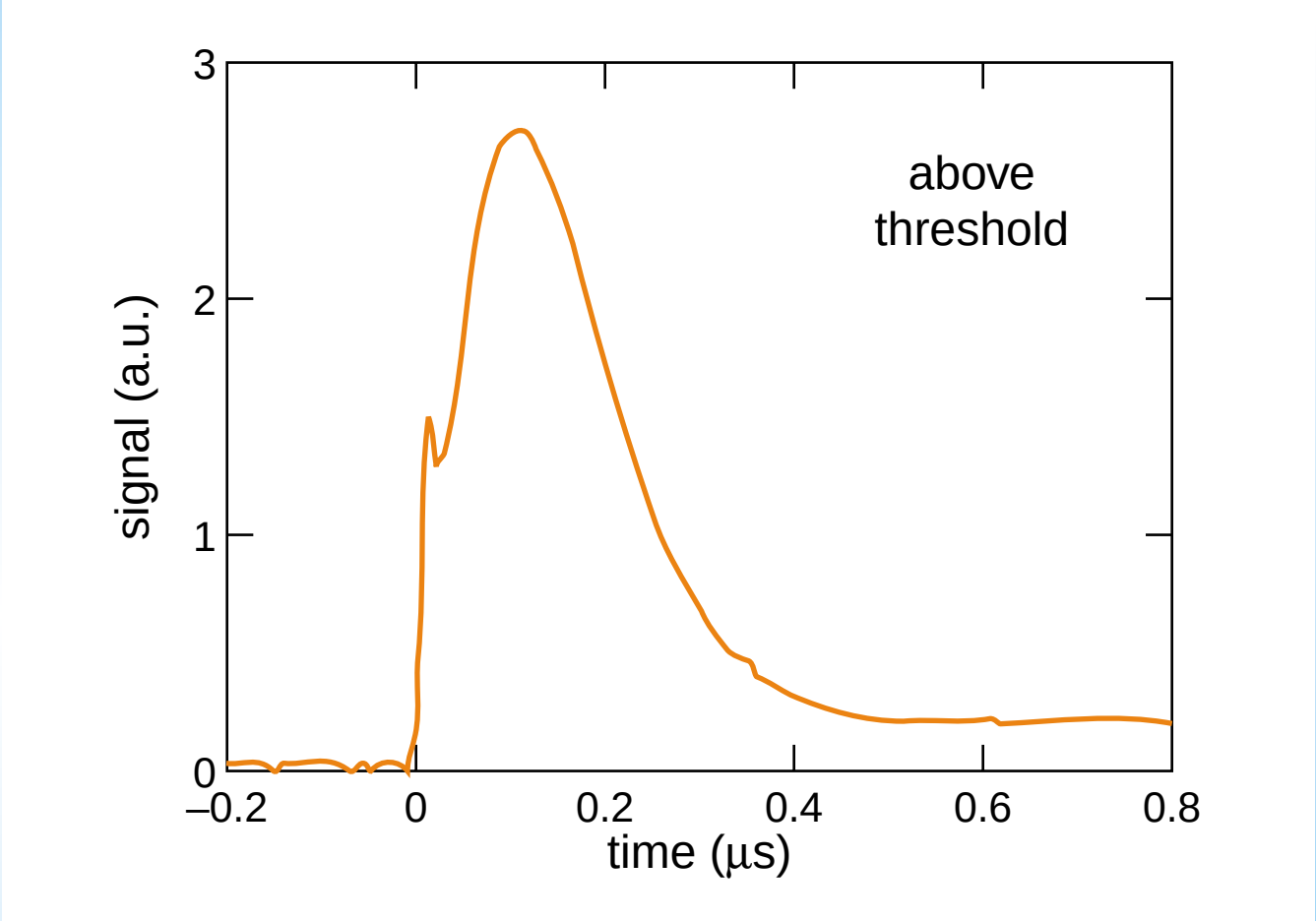
…structural change scatters probe beam



Energy deposition

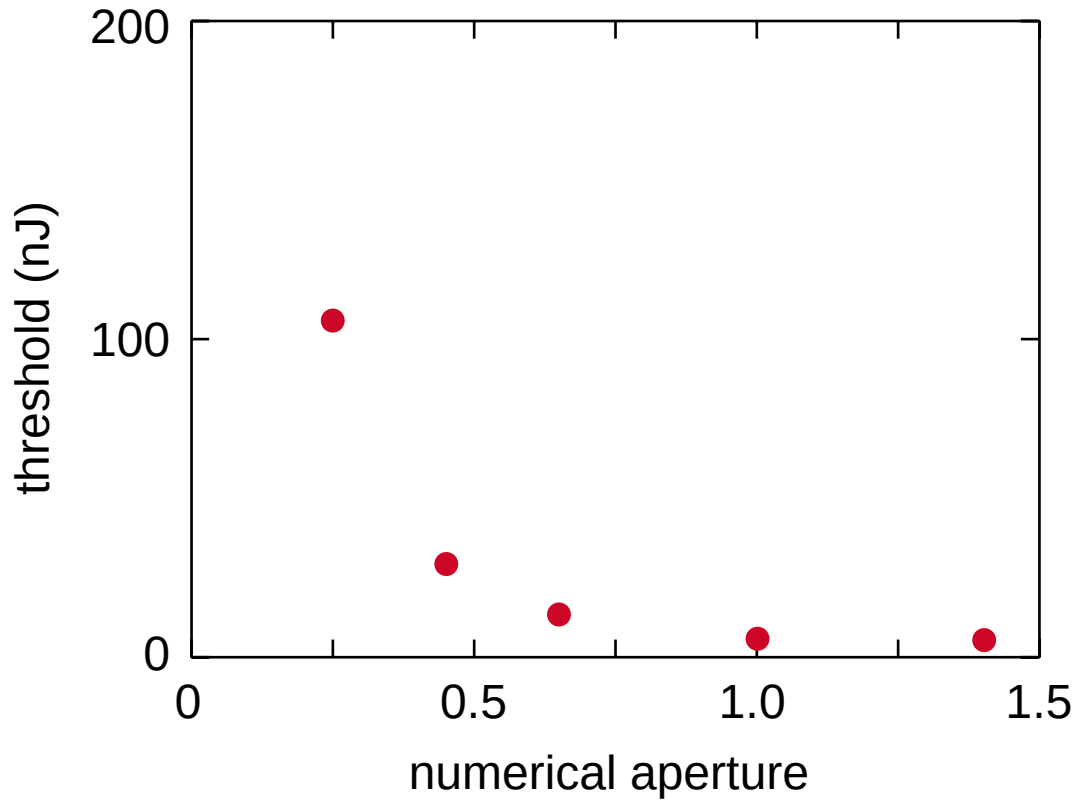


Energy deposition

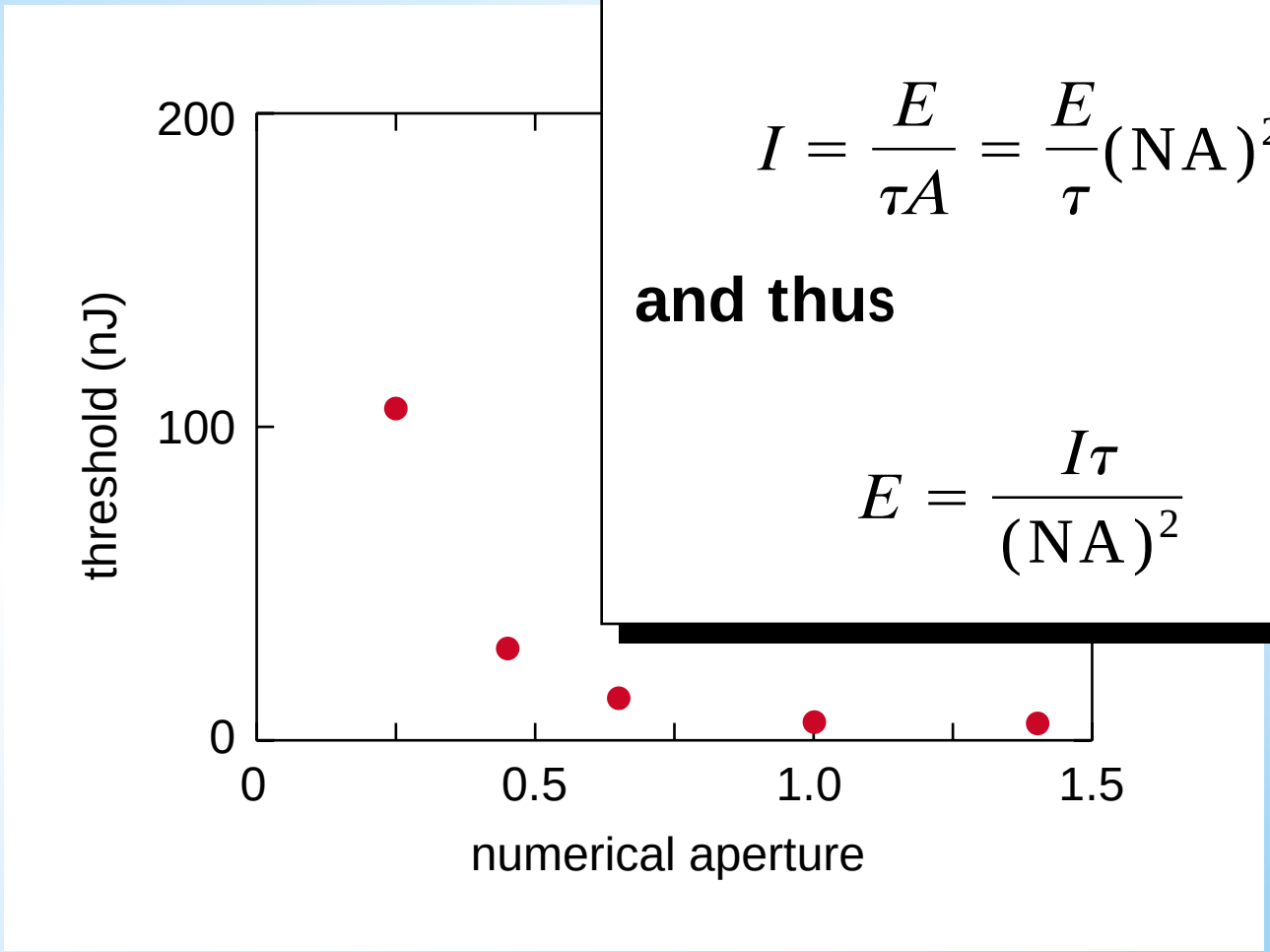


Energy deposition

vary numerical aperture in Corning 0211



Energy deposition



minimal self focusing, so spot size determined by:

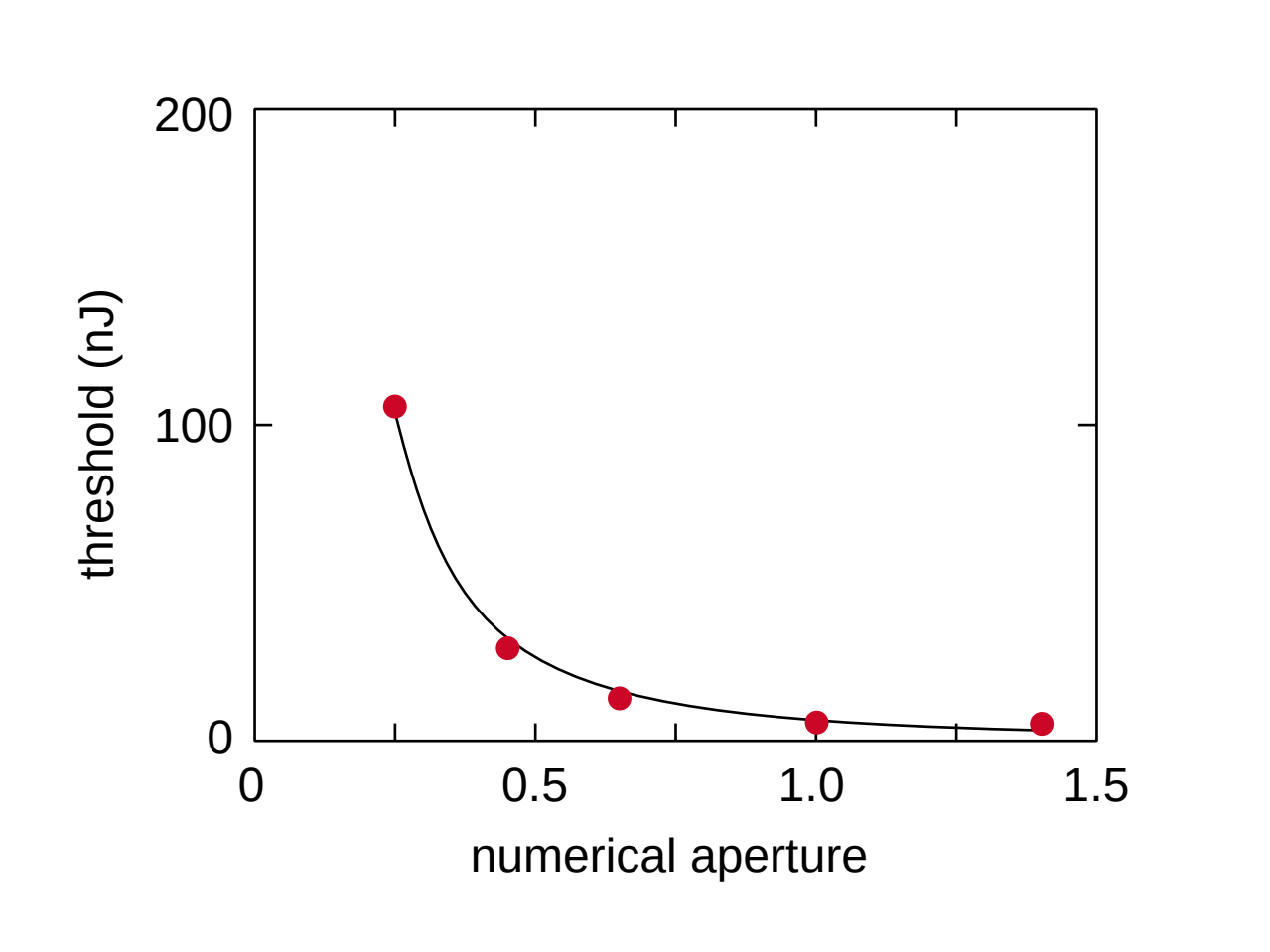
$$I = \frac{E}{\tau A} = \frac{E}{\tau}(\mathrm{NA})^2$$

and thus

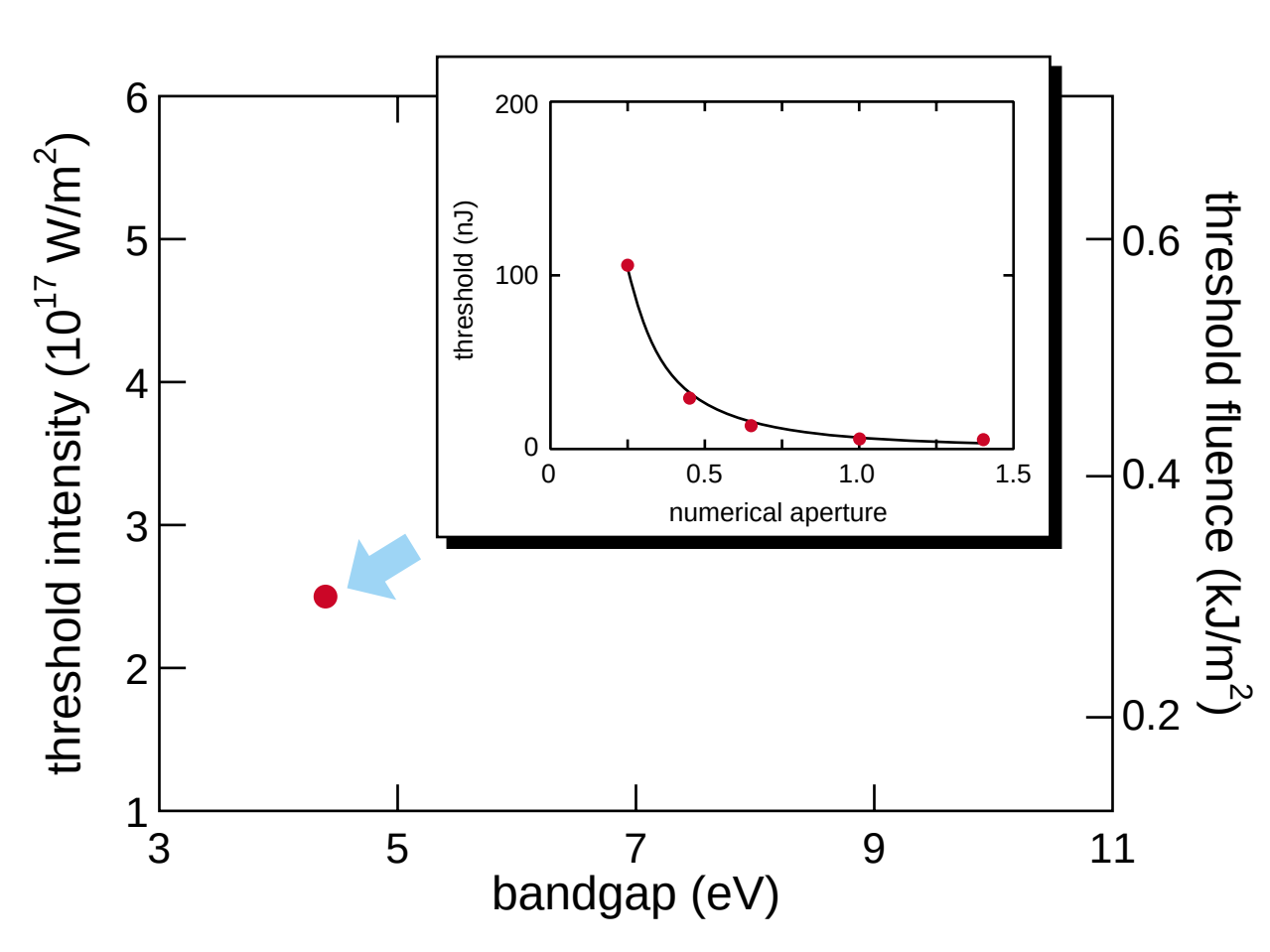
$$E = \frac{I\tau}{(\mathrm{NA})^2}$$

Energy deposition

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

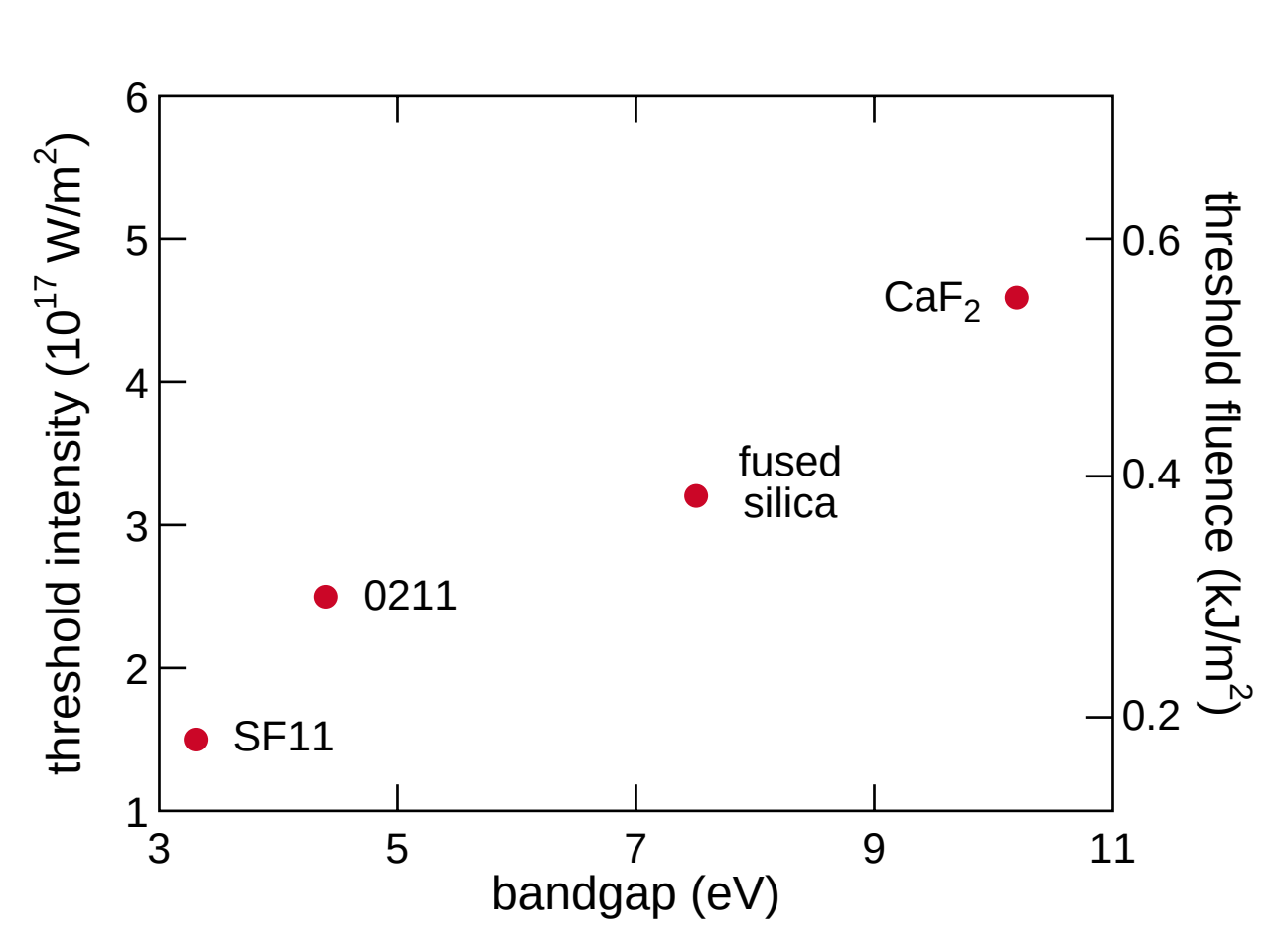


Energy deposition



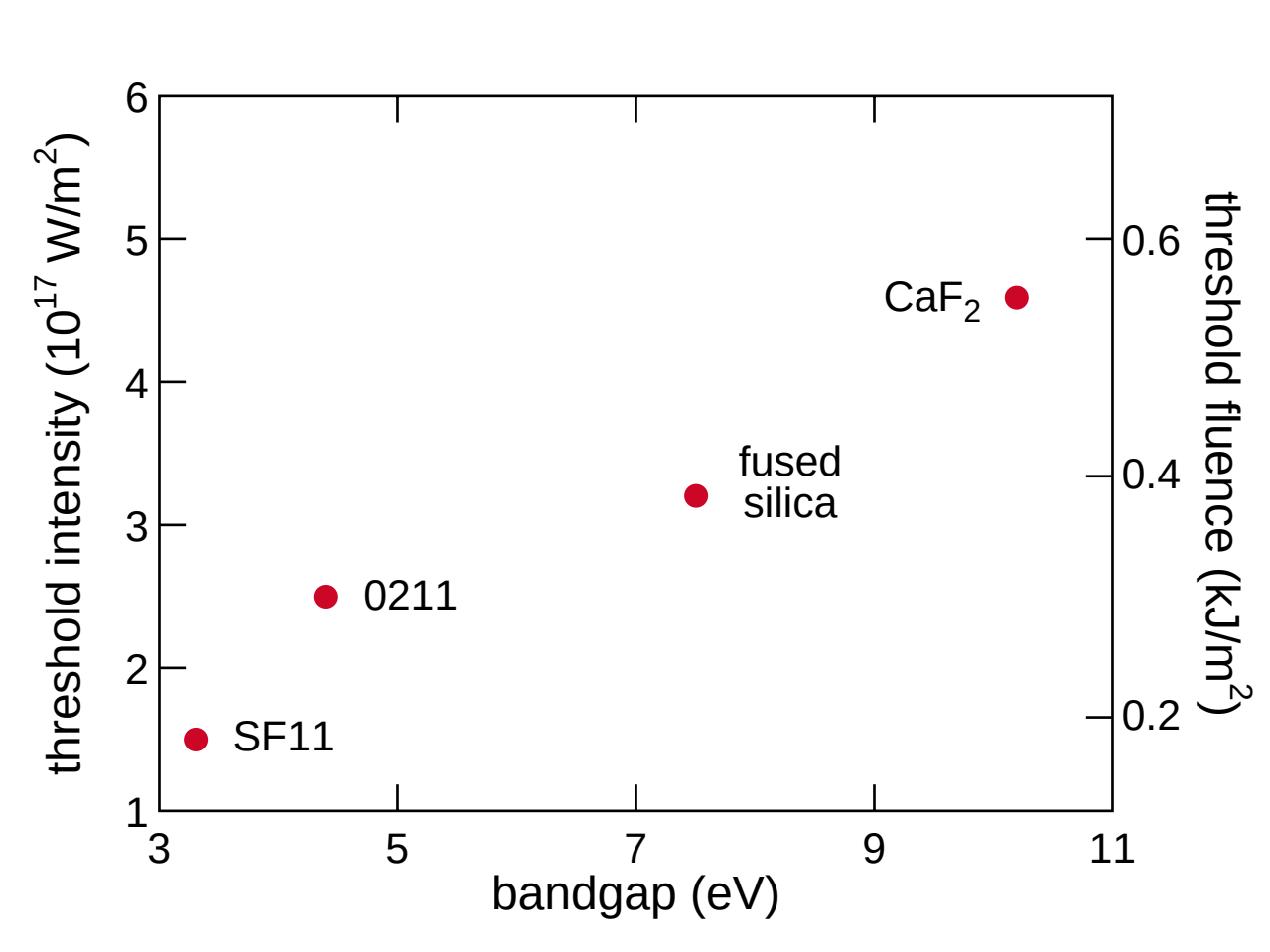
Energy deposition

vary material…



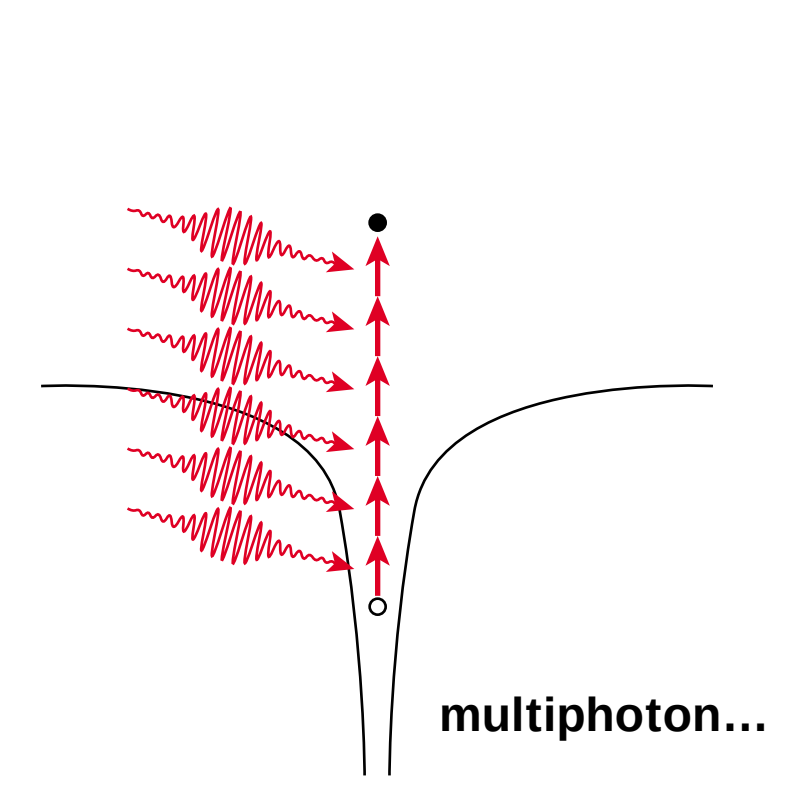
Energy deposition

threshold increases with bandgap



Energy deposition

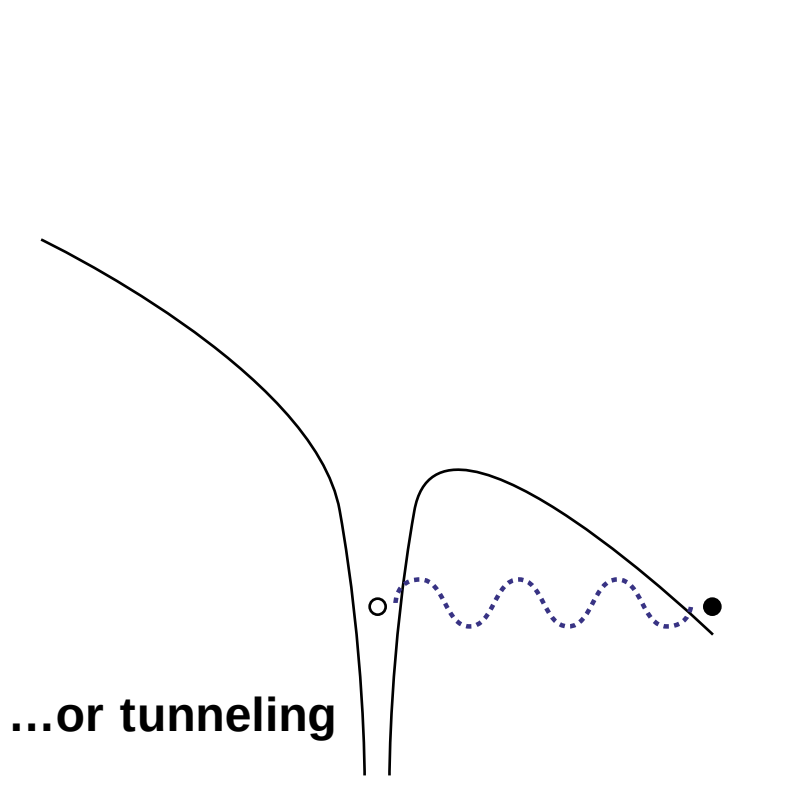
laser field ionization



nonlinear: I^n

Energy deposition

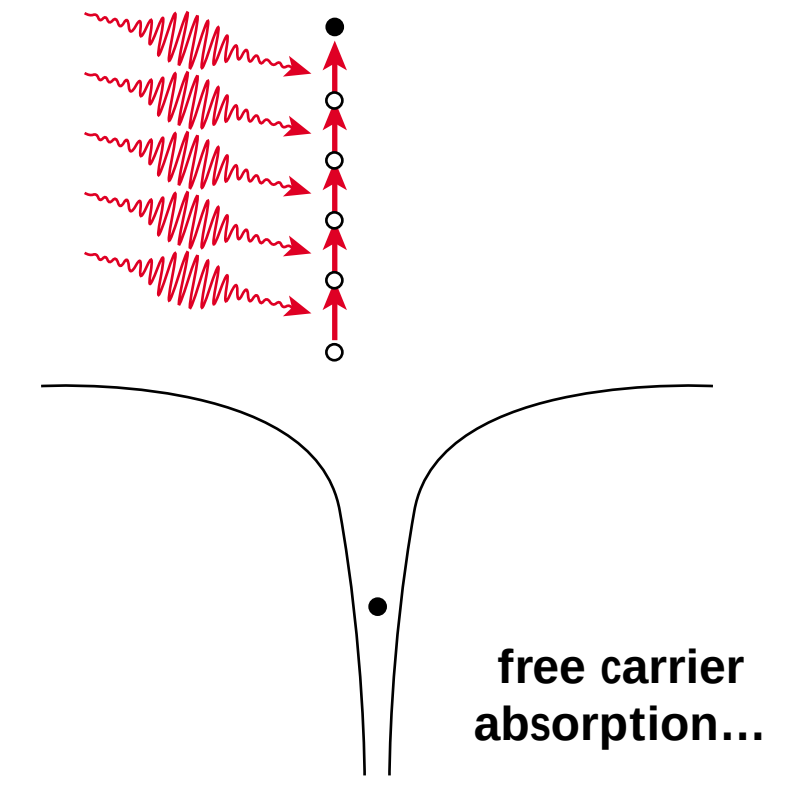
laser field ionization



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

Energy deposition

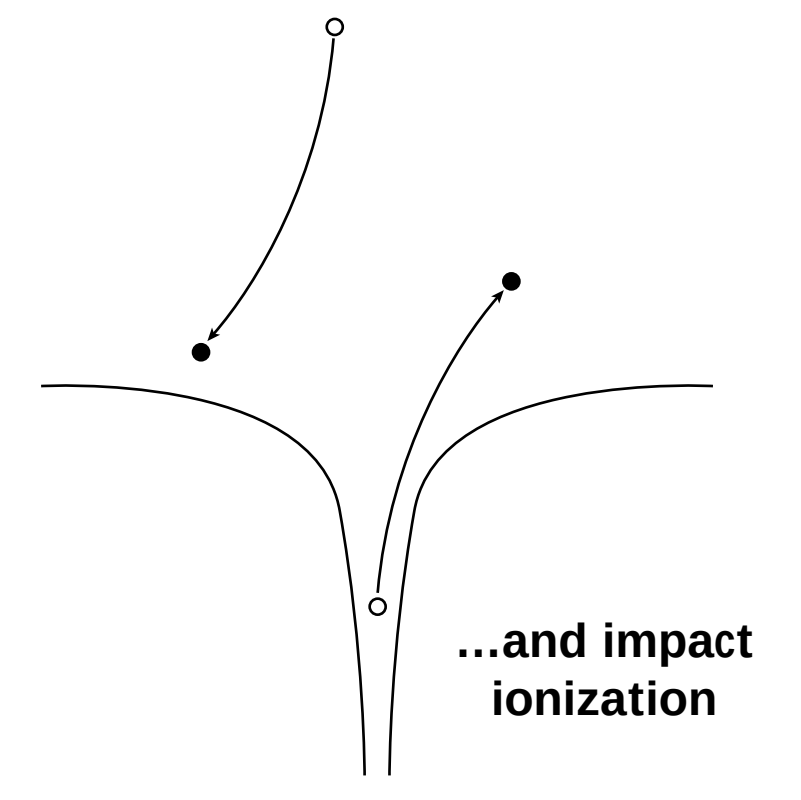
avalanche ionization



linear: nI

Energy deposition

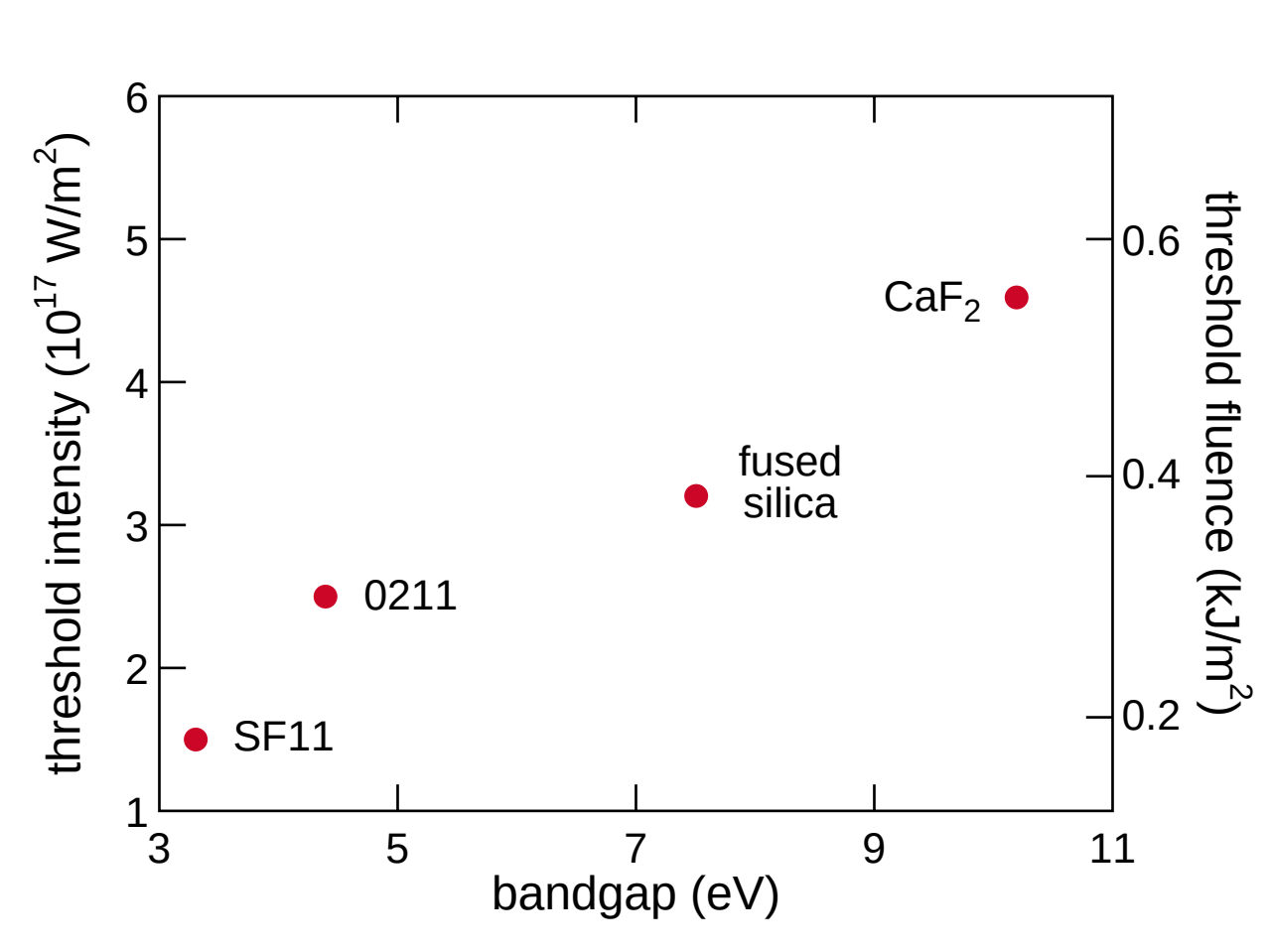
avalanche ionization



linear: nI

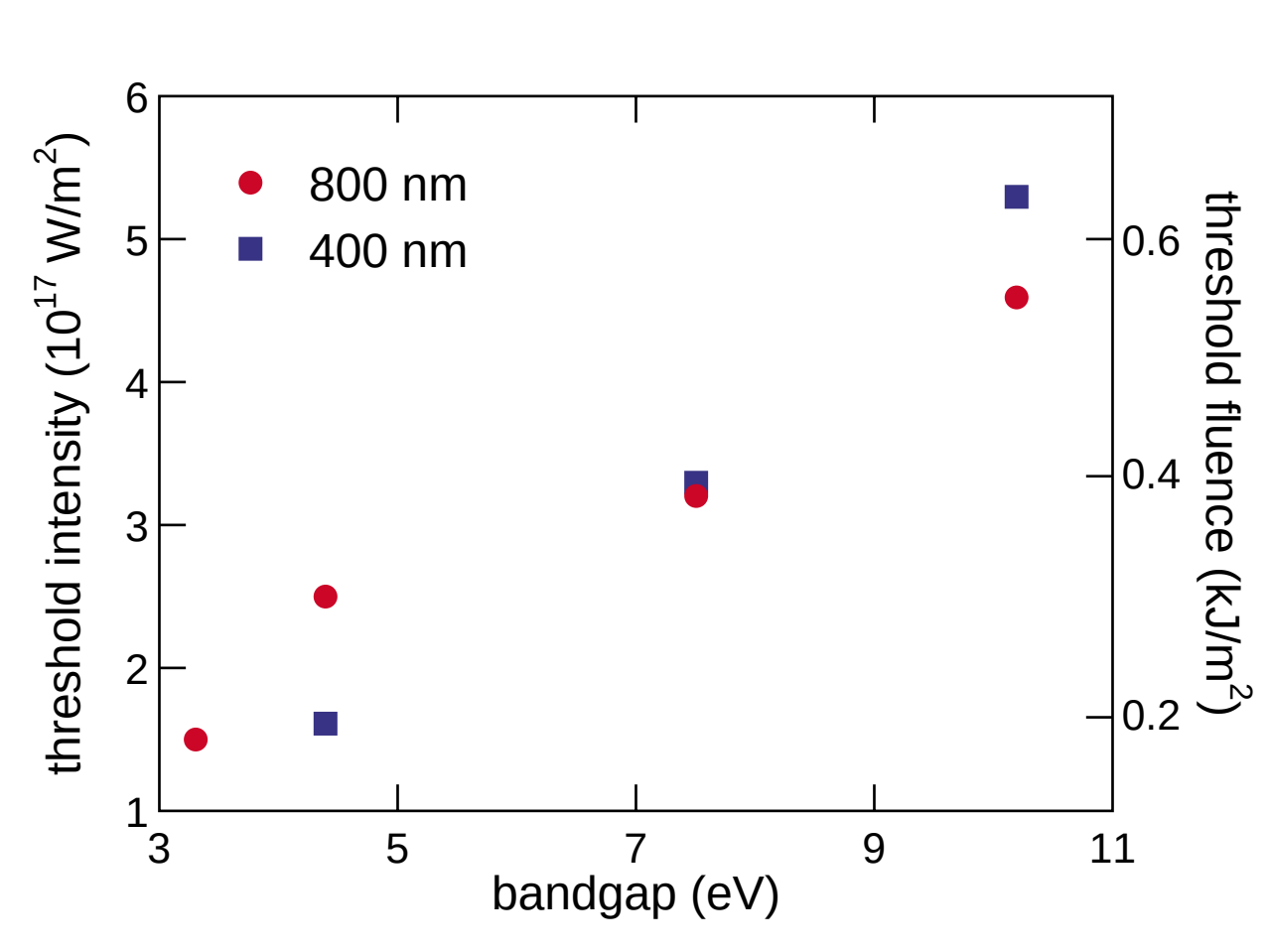
Energy deposition

large bandgap: avalanche ionization dominates



Energy deposition

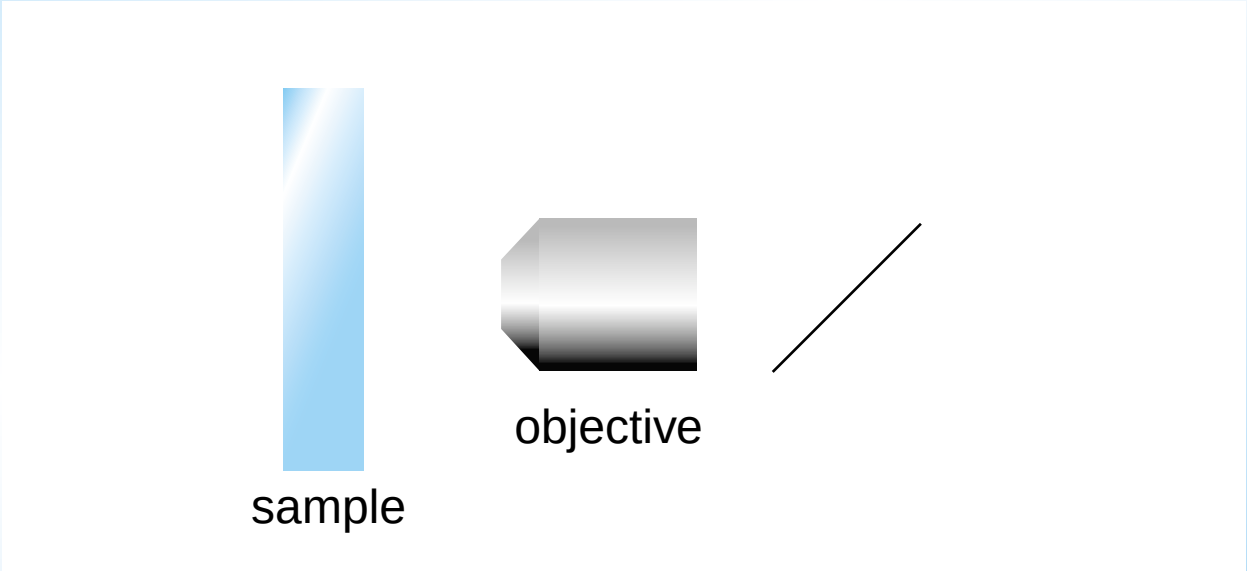
same trend at 400 nm



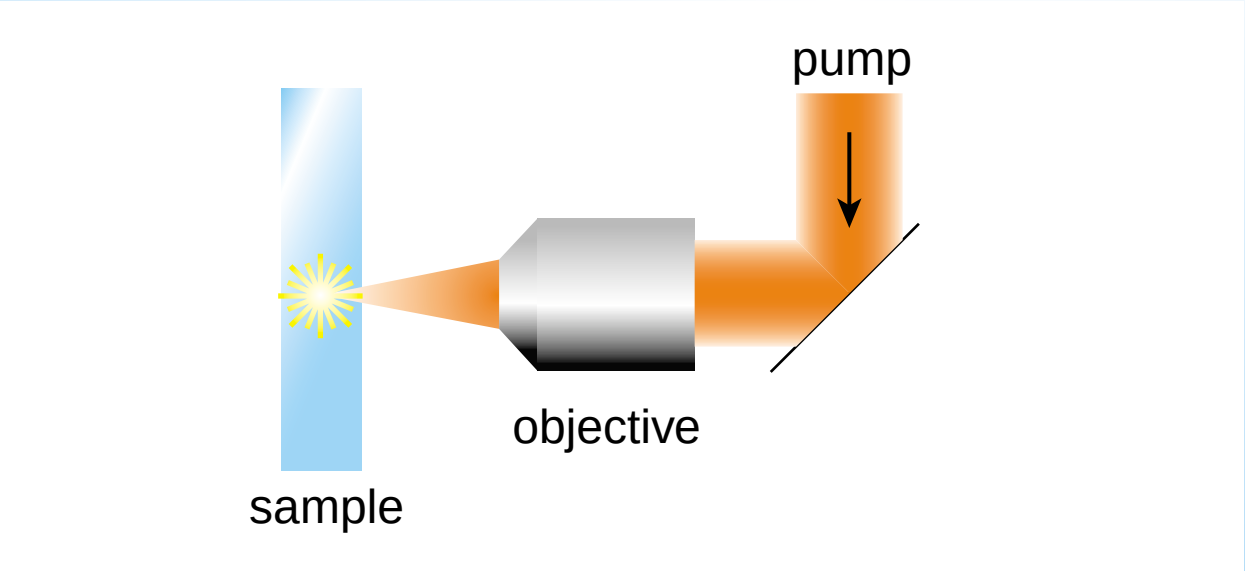
Outline

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

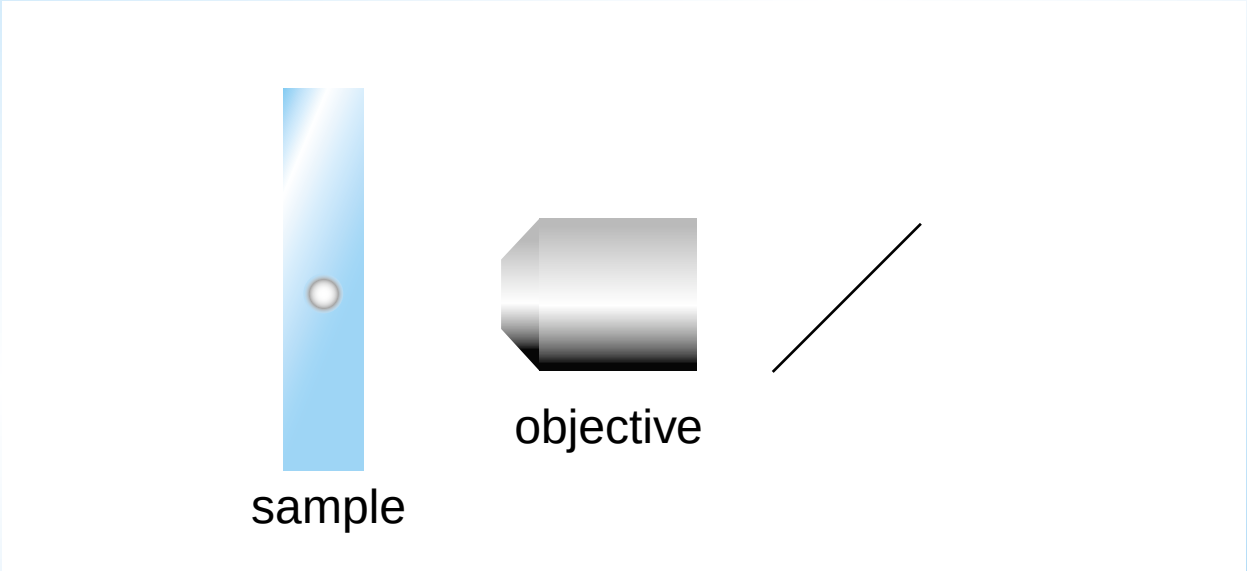
imaging setup



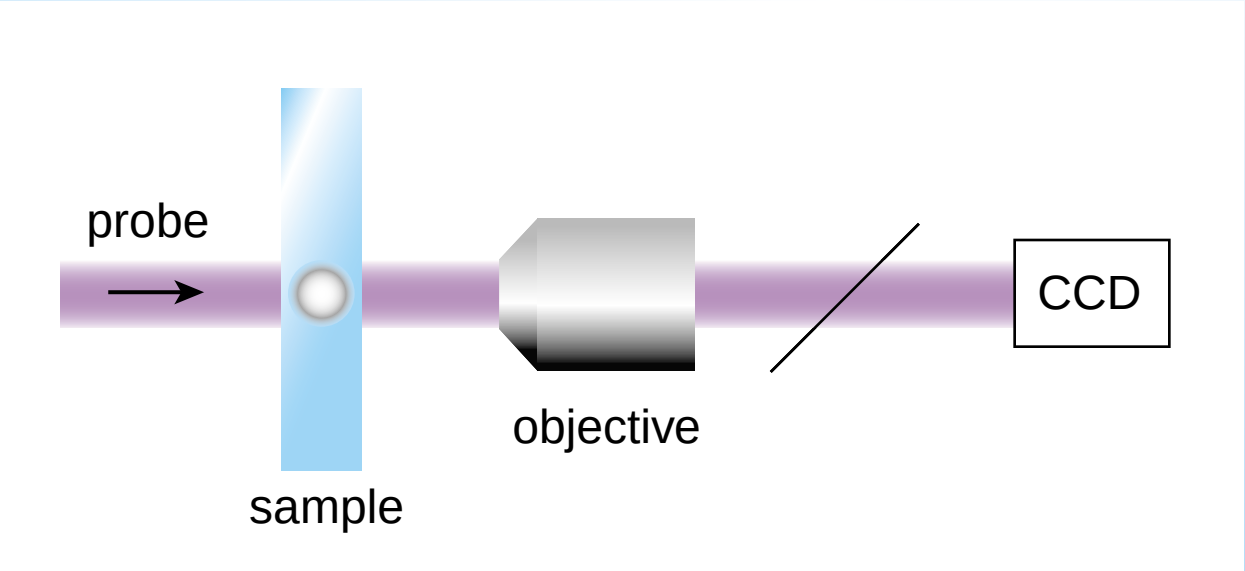
imaging setup



imaging setup



imaging setup



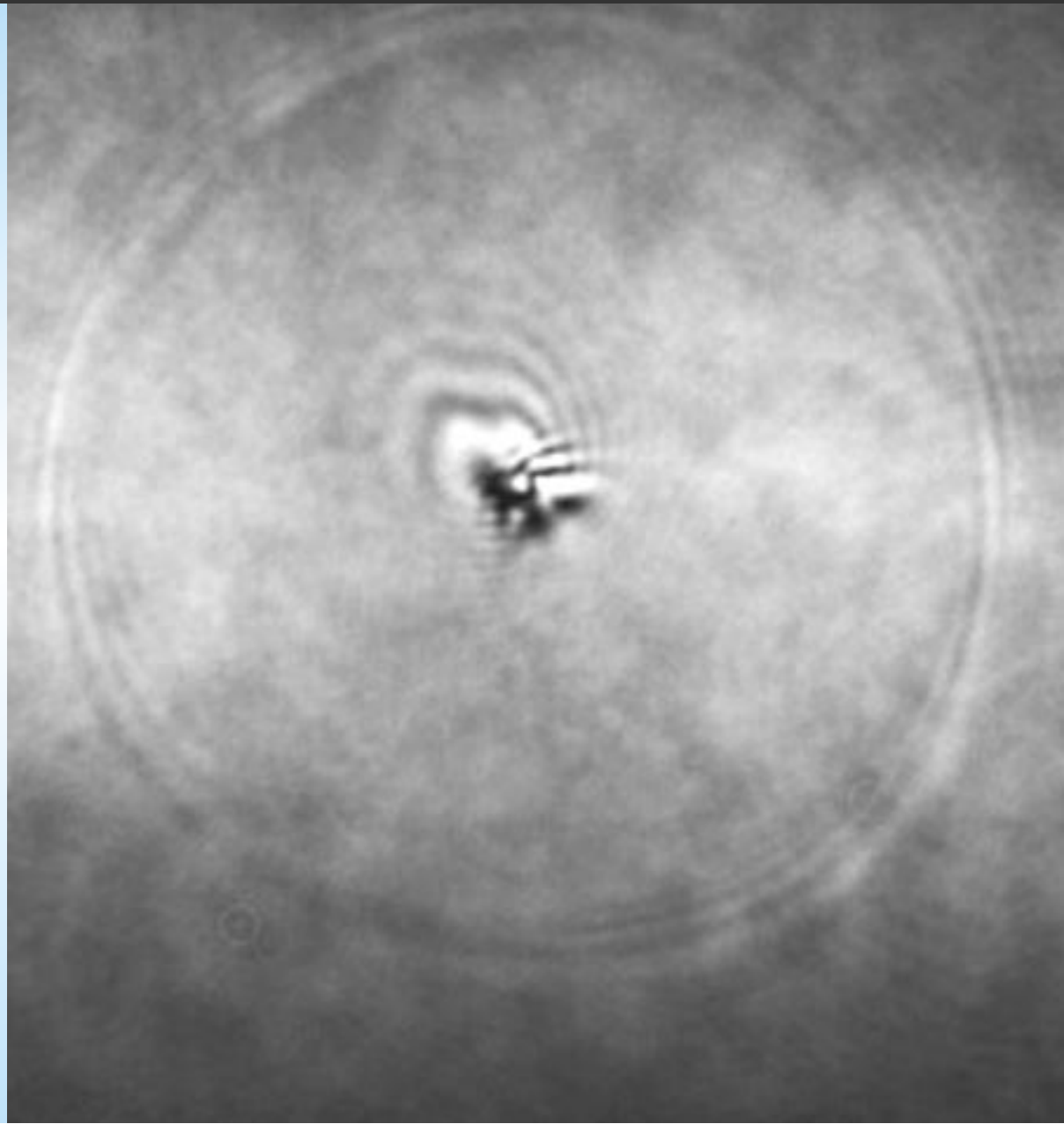
Dynamics

sapphire

3 μJ pulse

3.8 ns delay

40 μm radius



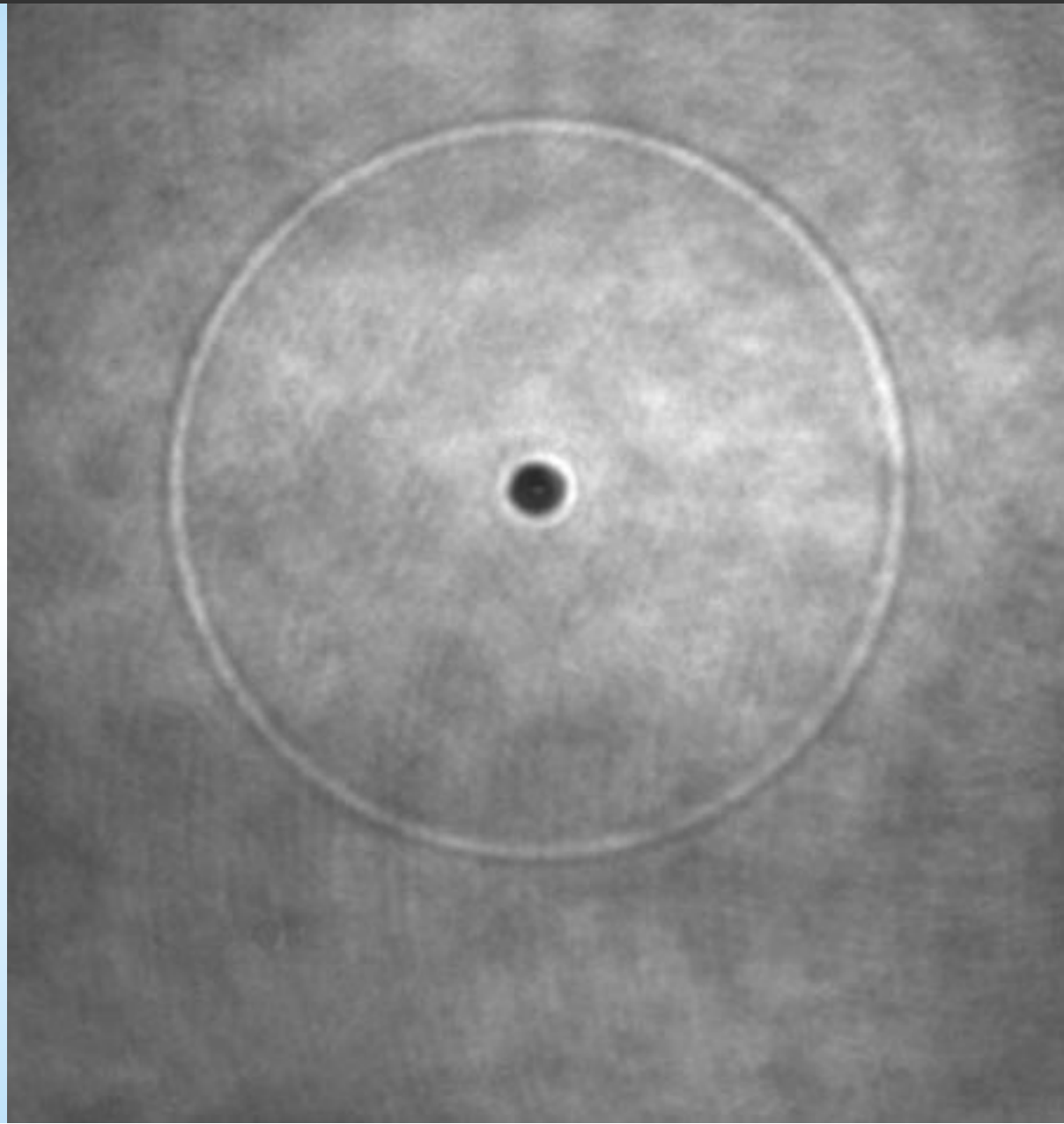
Dynamics

water (“self-healing”)

1.0 μJ pulse

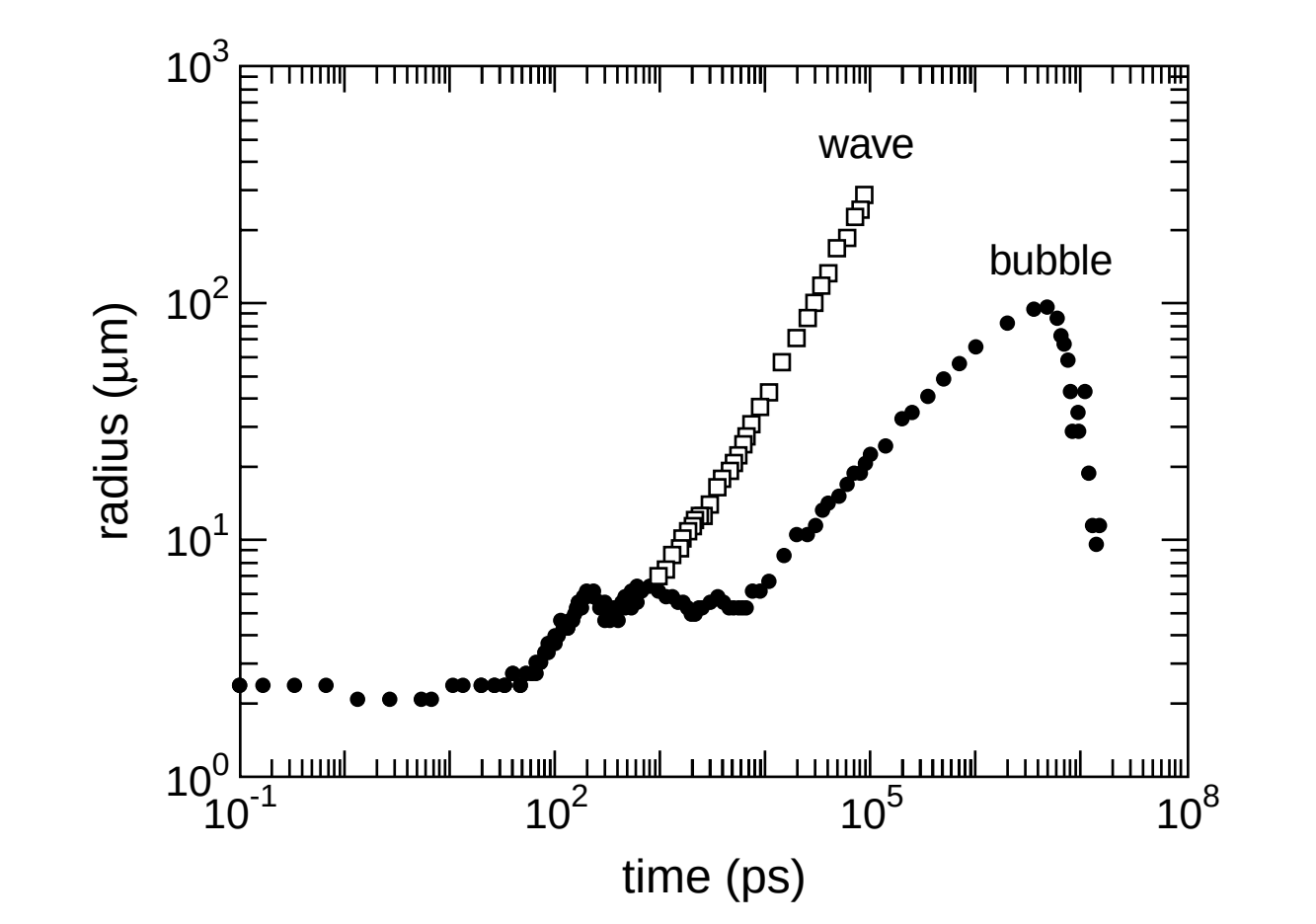
35 ns delay

58 μm radius



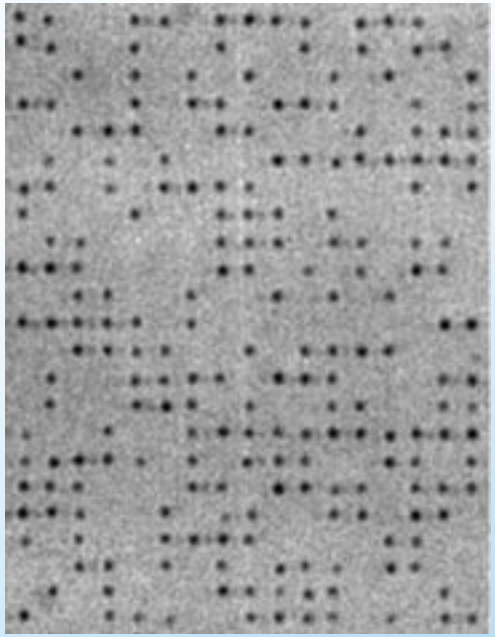
Dynamics

Dynamics



Applications

- **data storage**



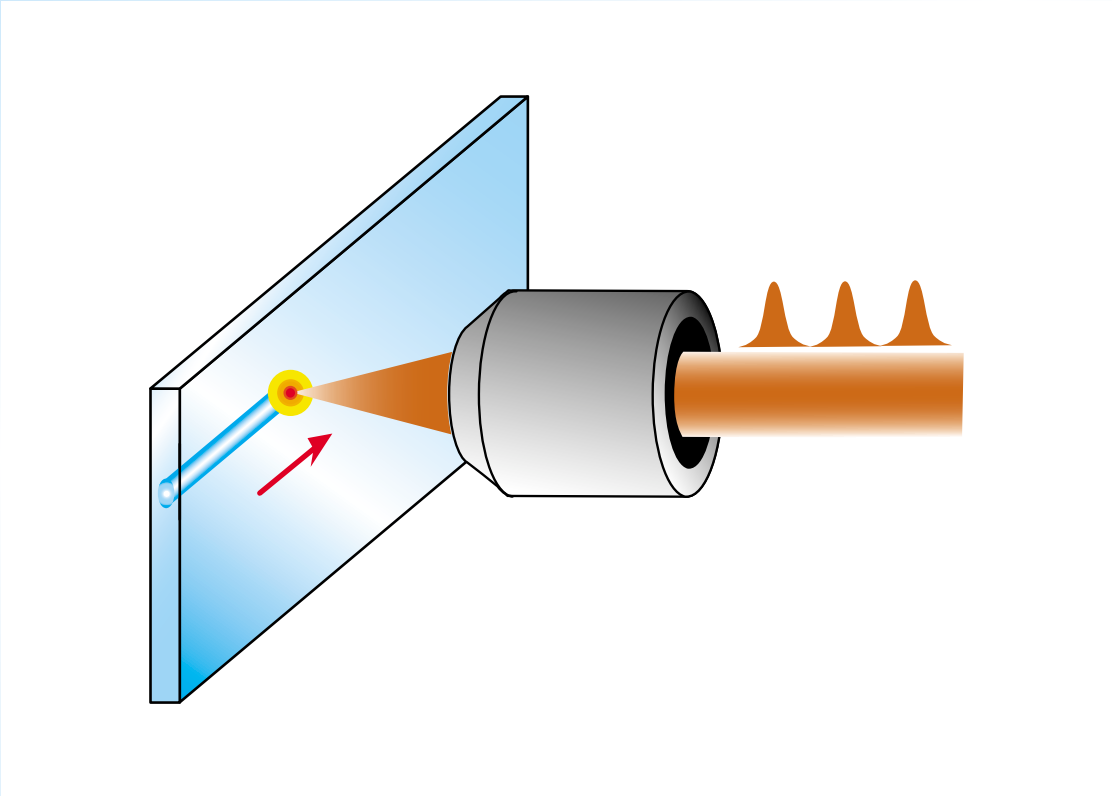
100 GB multilayer CD

Applications

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

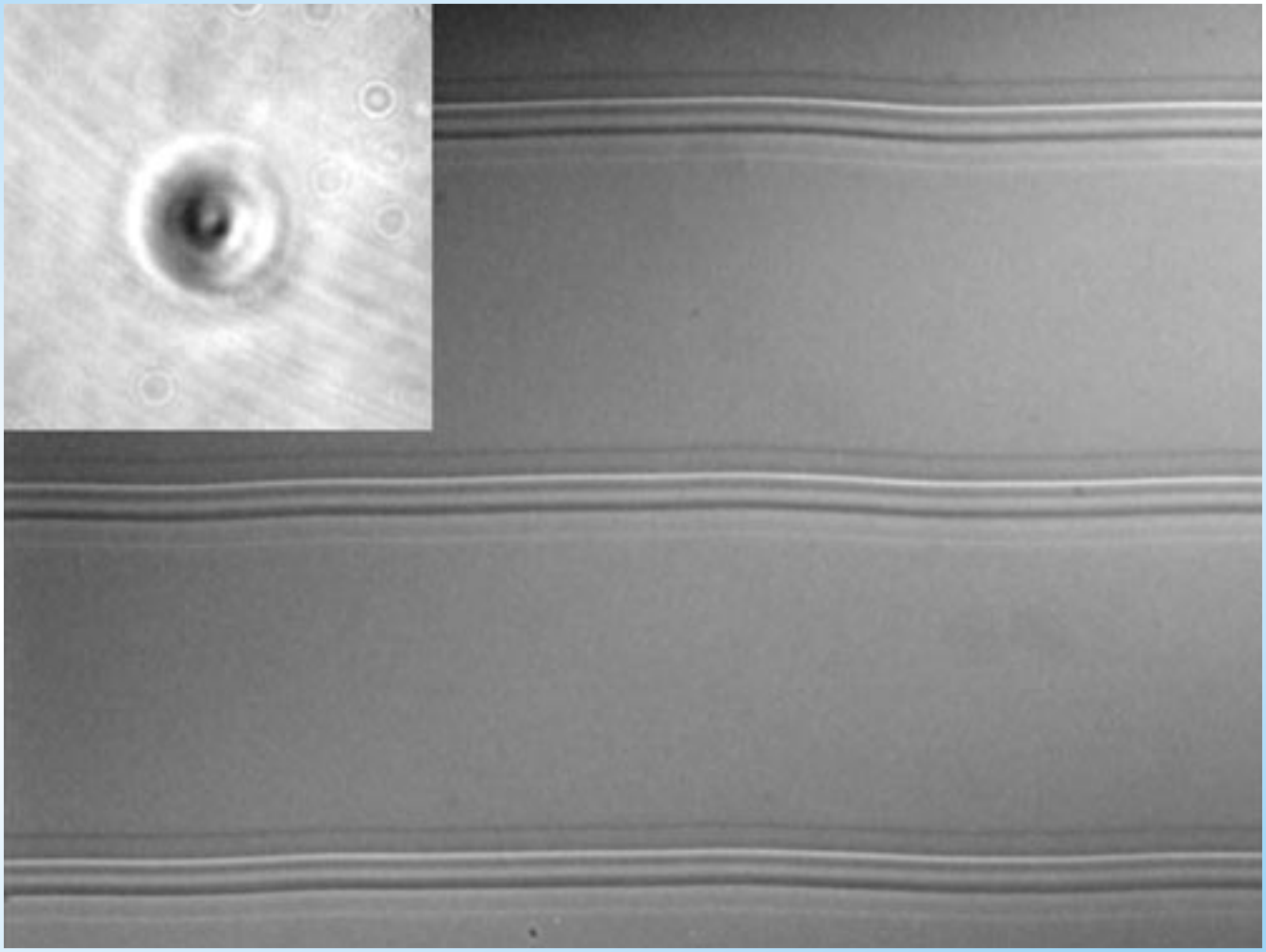
Applications

waveguide machining



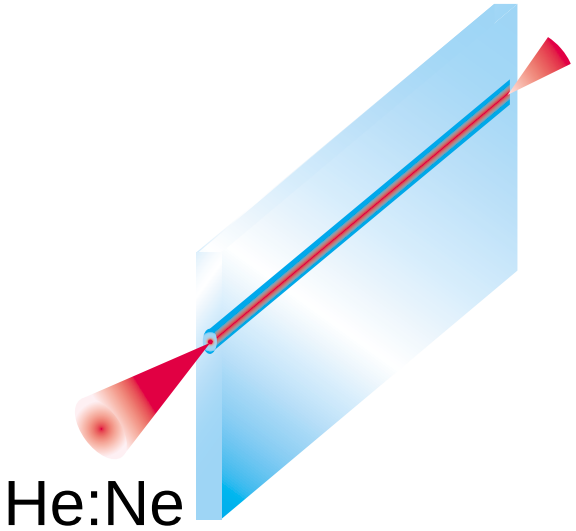
Applications

waveguide machining



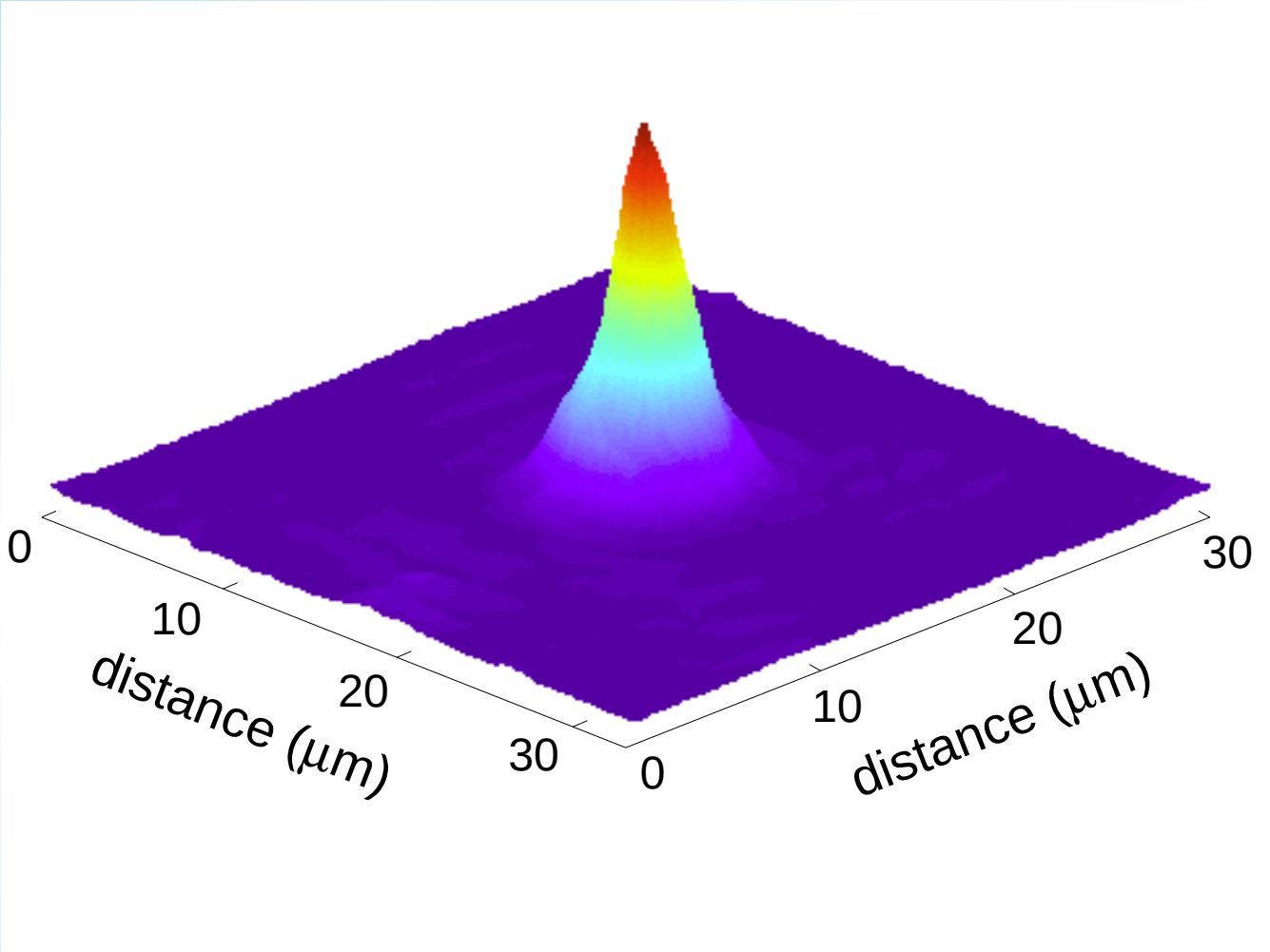
Applications

waveguide mode analysis



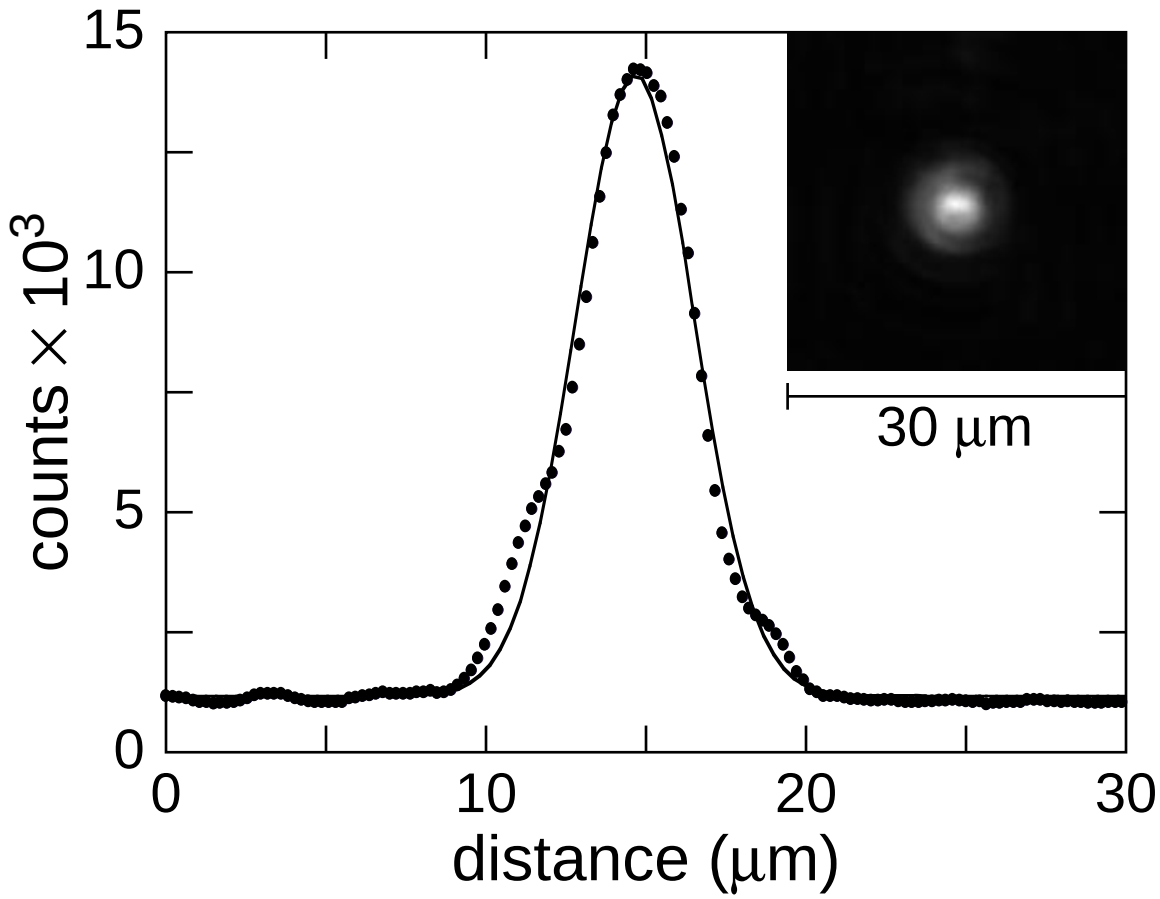
Applications

near field mode



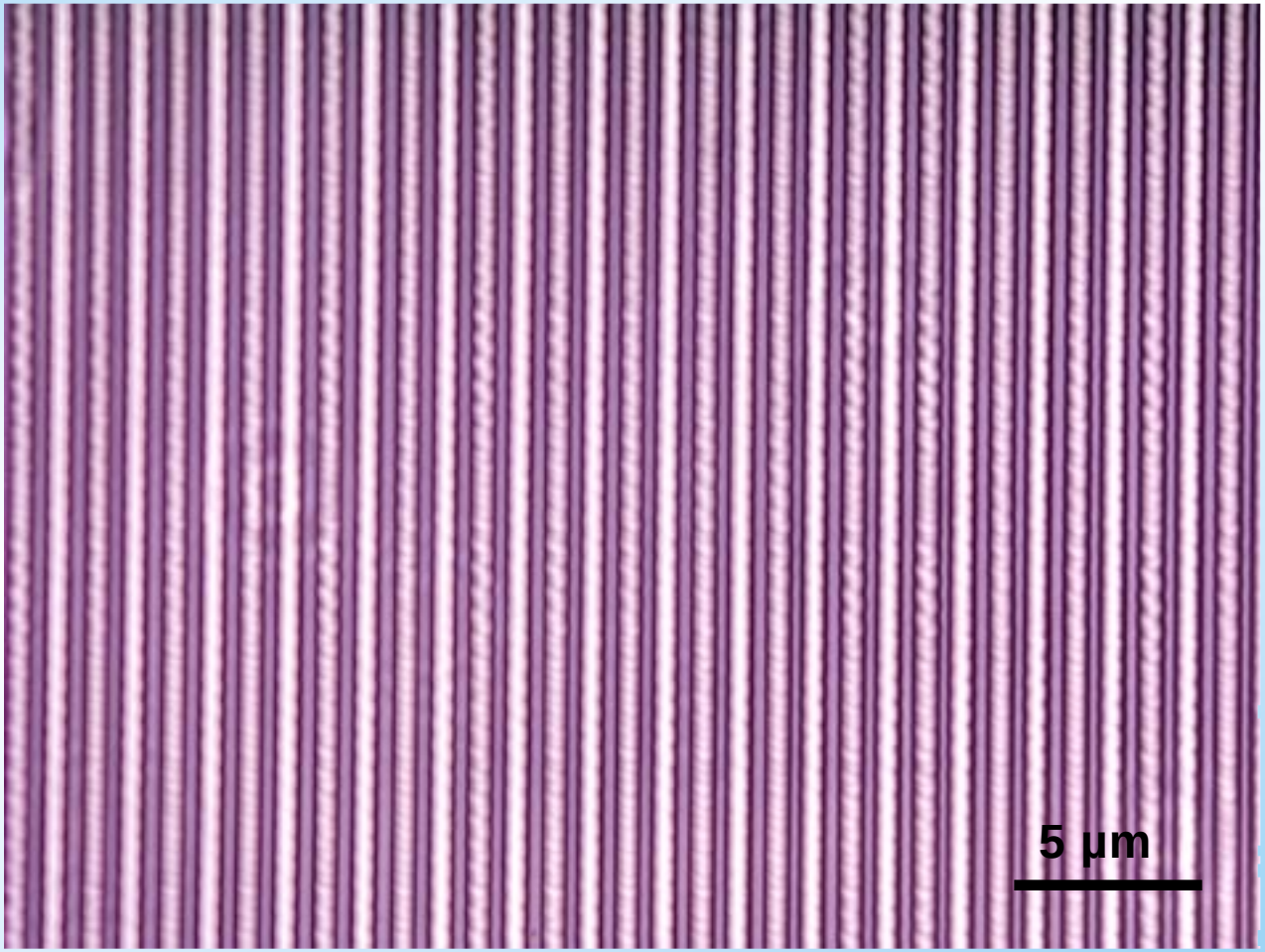
Applications

near field mode



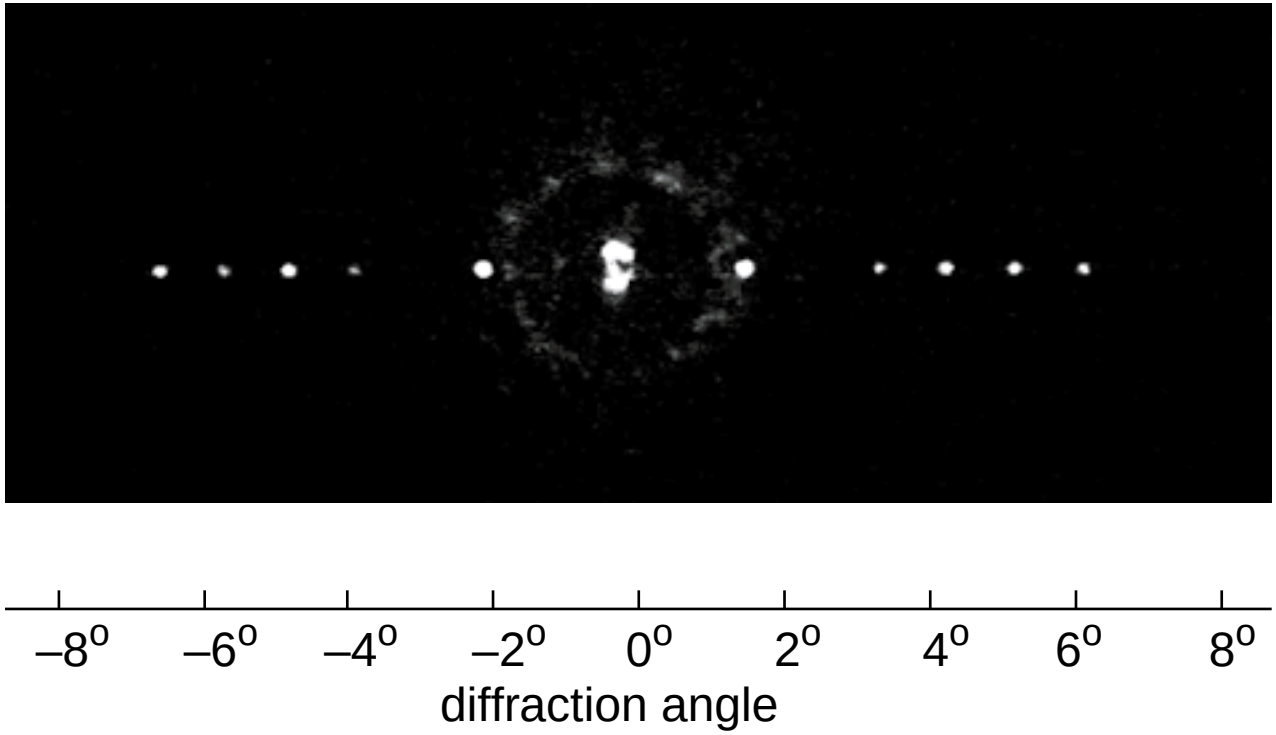
Applications

diffraction grating



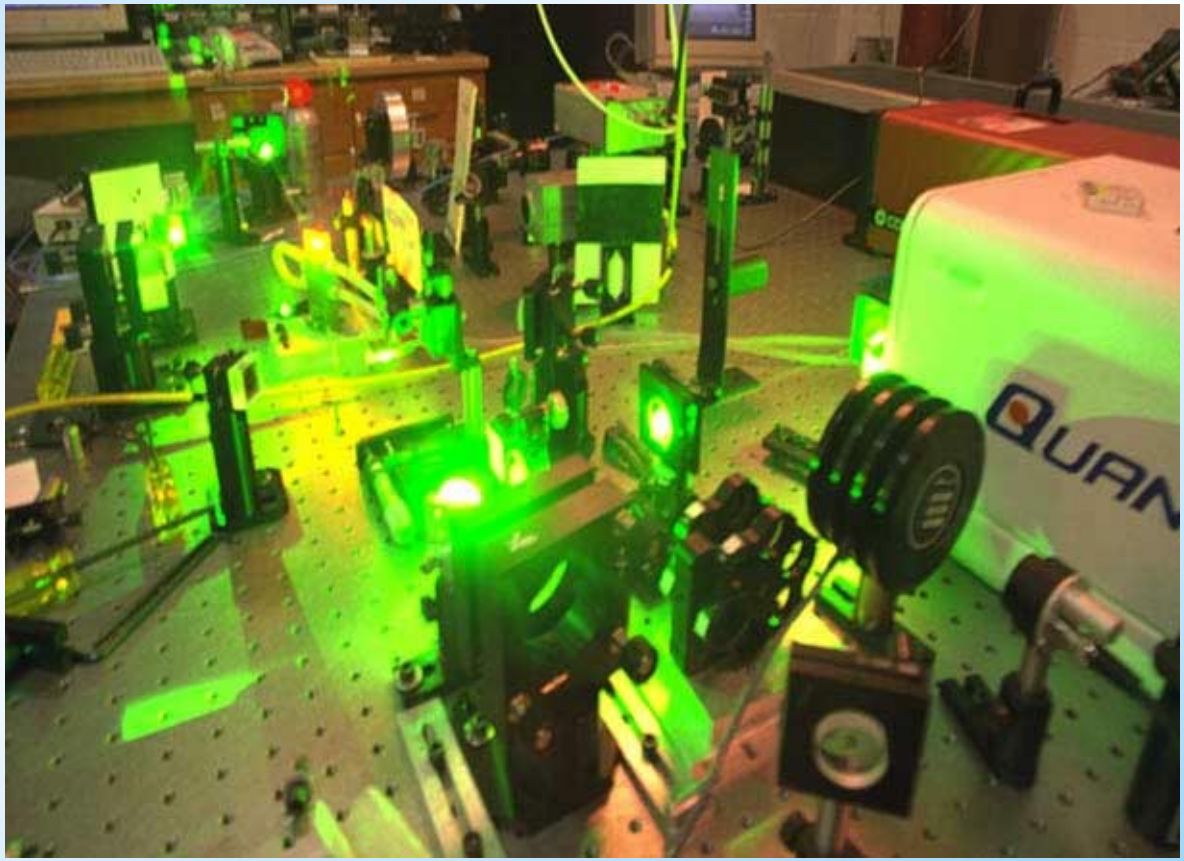
Applications

diffraction pattern



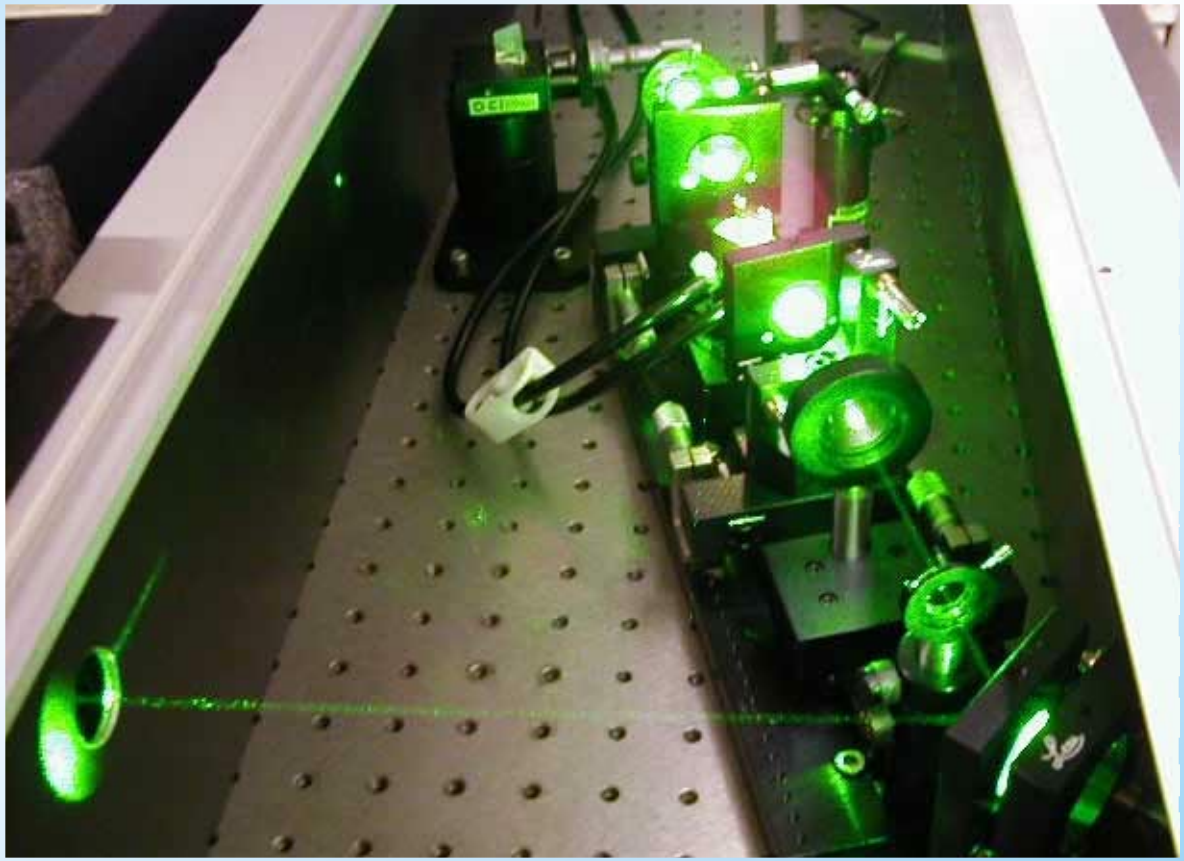
Applications

5-nJ threshold: unamplified micromachining



Applications

5-nJ threshold: unamplified micromachining



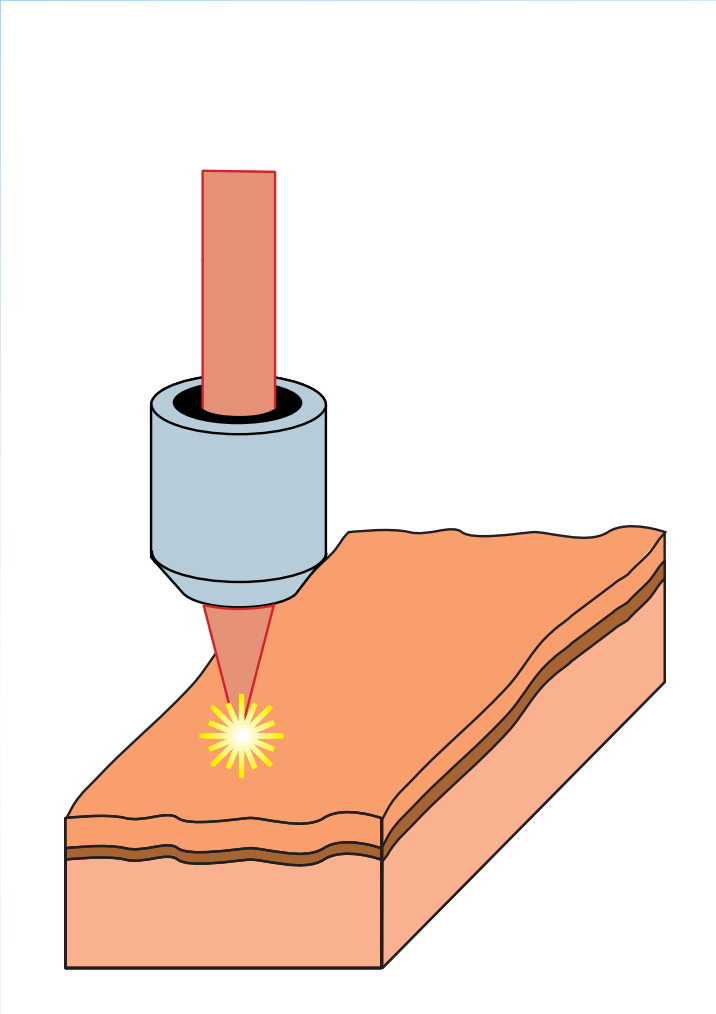
Applications

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

Applications

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

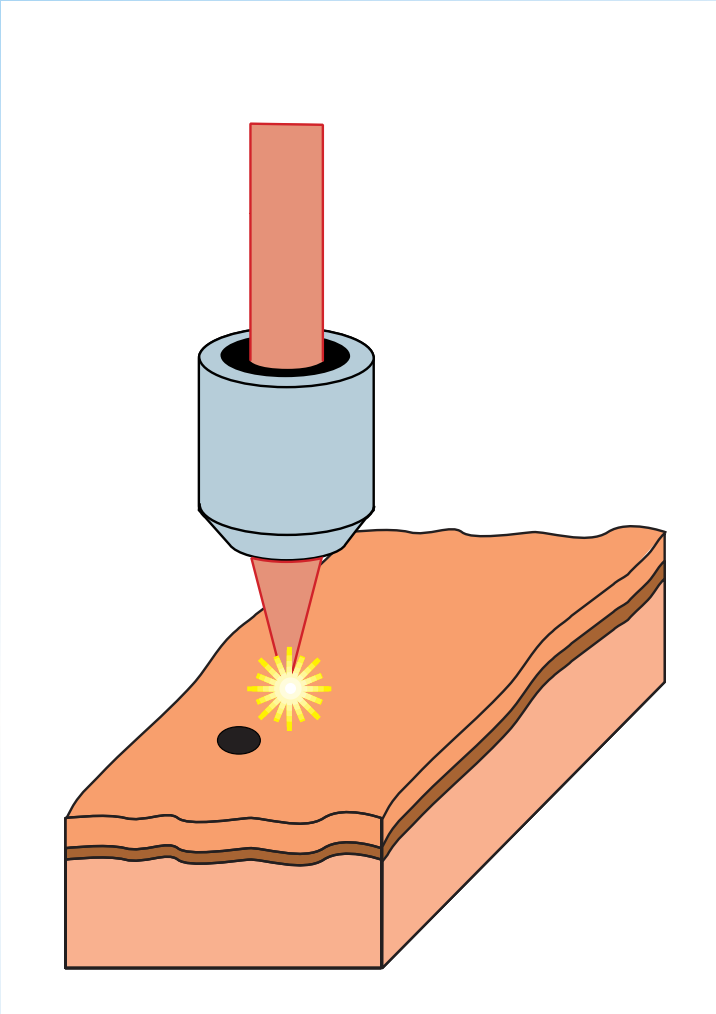
Applications



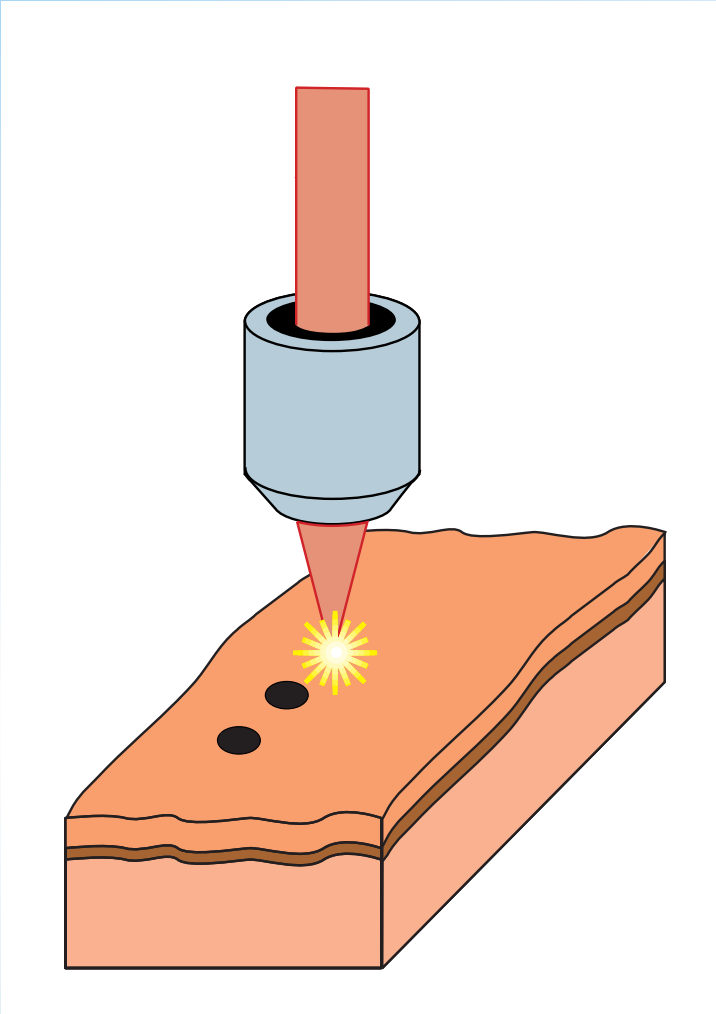
EpiDerm from MatTek Corp.

stratified skin model

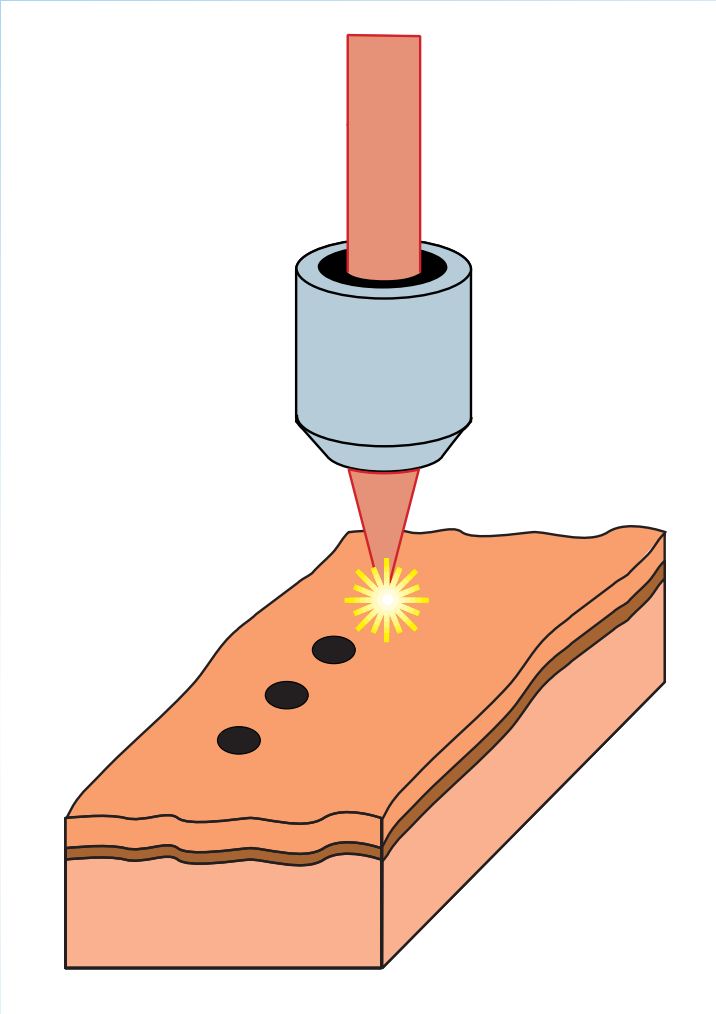
Applications



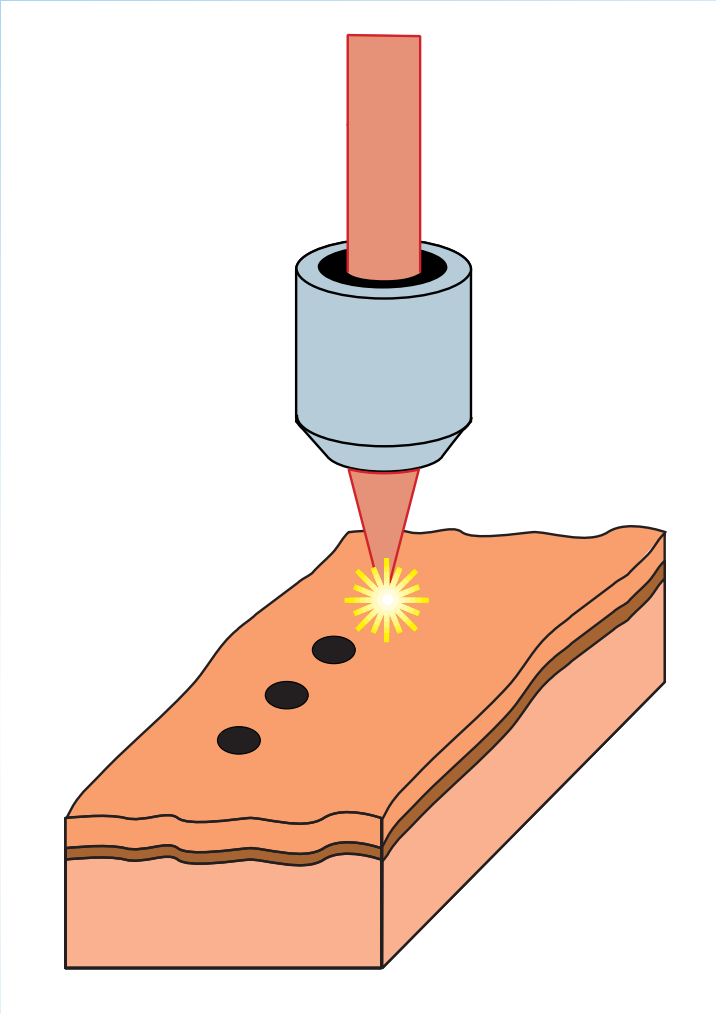
Applications



Applications



Applications

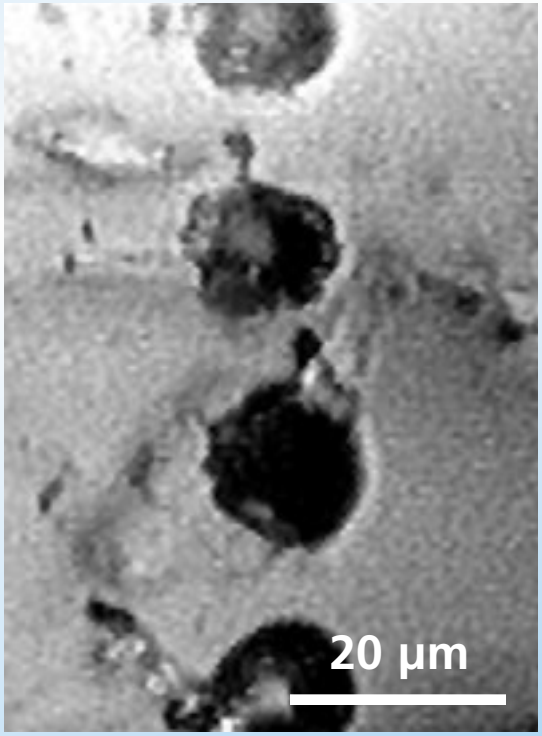


	damage threshold
100 fs	2 μJ
200 ps	5 μJ

Applications

200 ps, 40 µJ

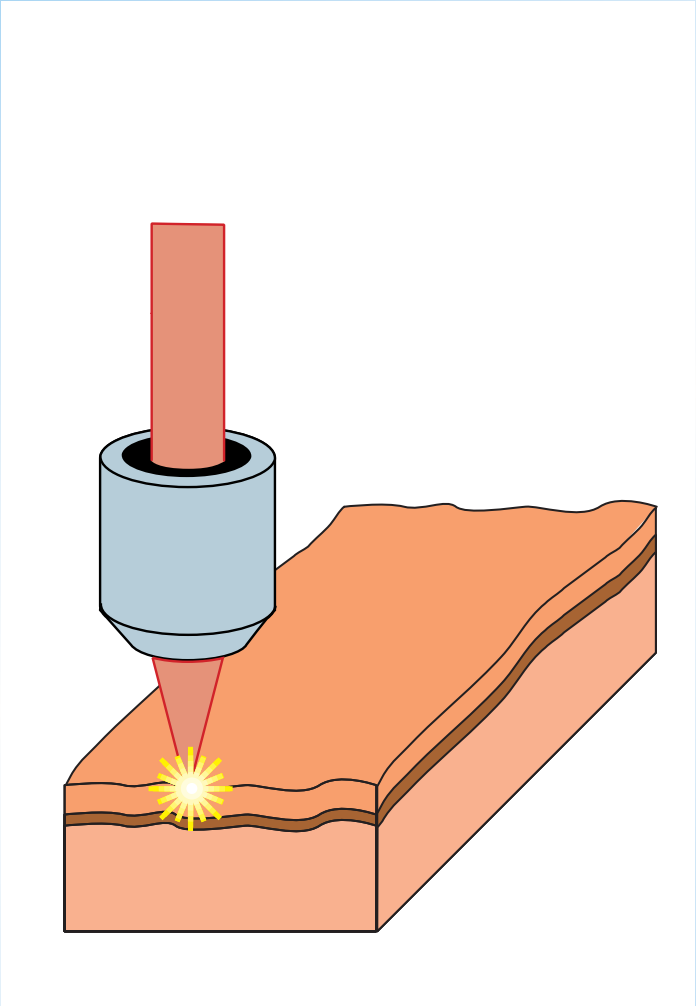
100 fs, 40 µJ



fs pulses reduce collateral damage

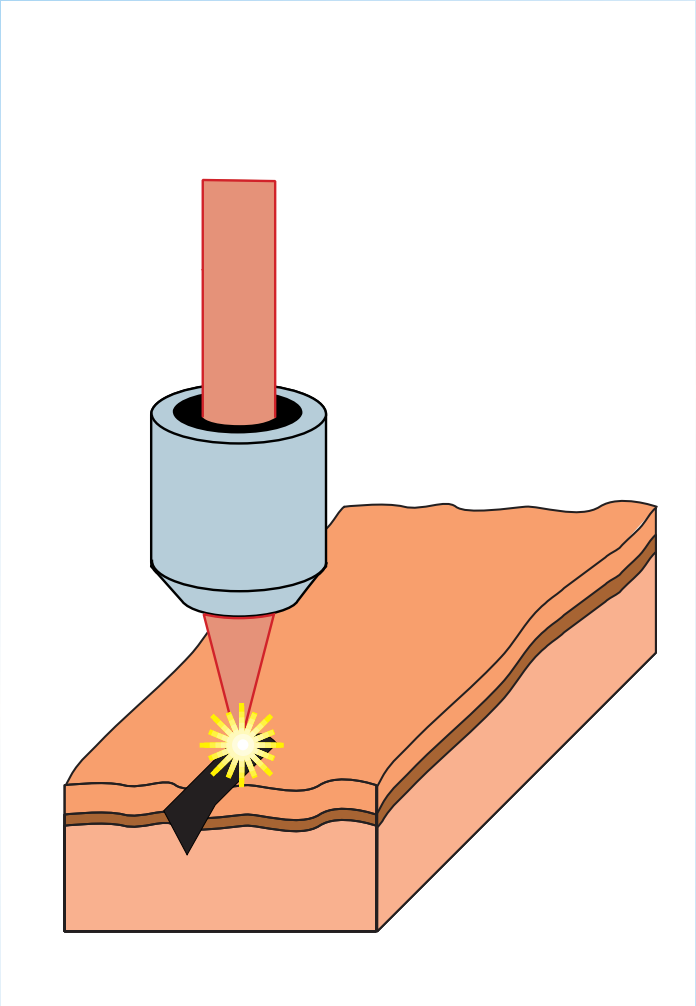
Applications

incision setup



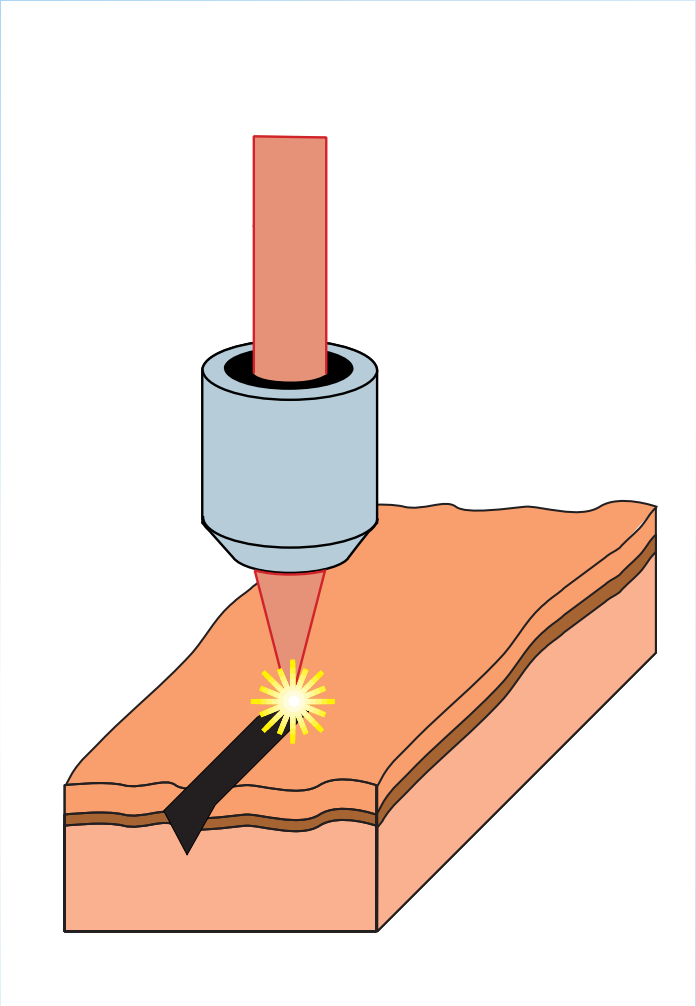
Applications

incision setup



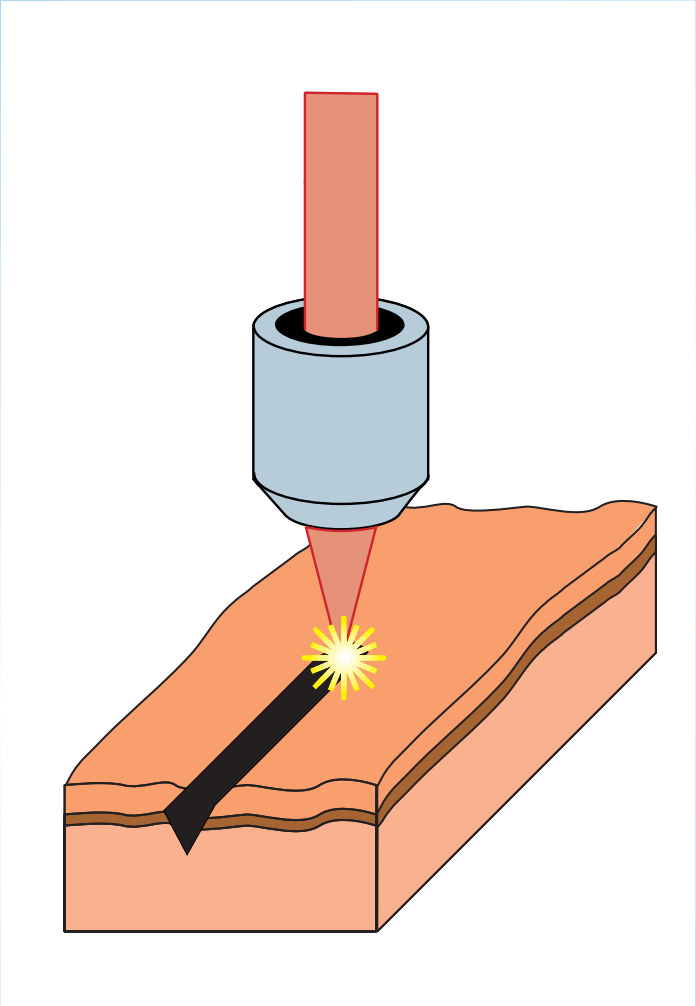
Applications

incision setup

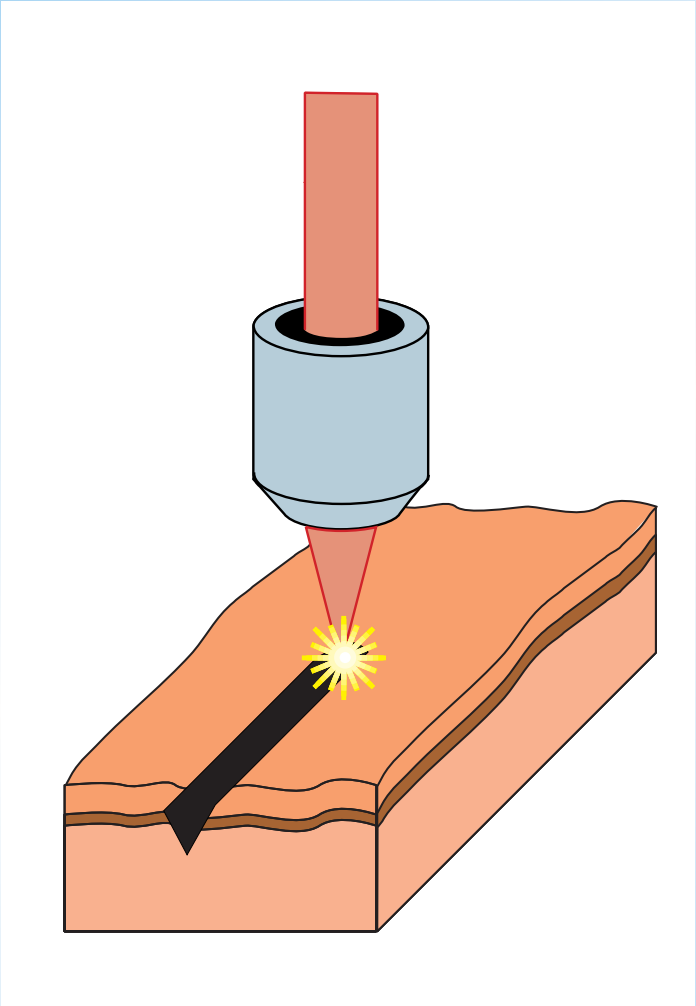


Applications

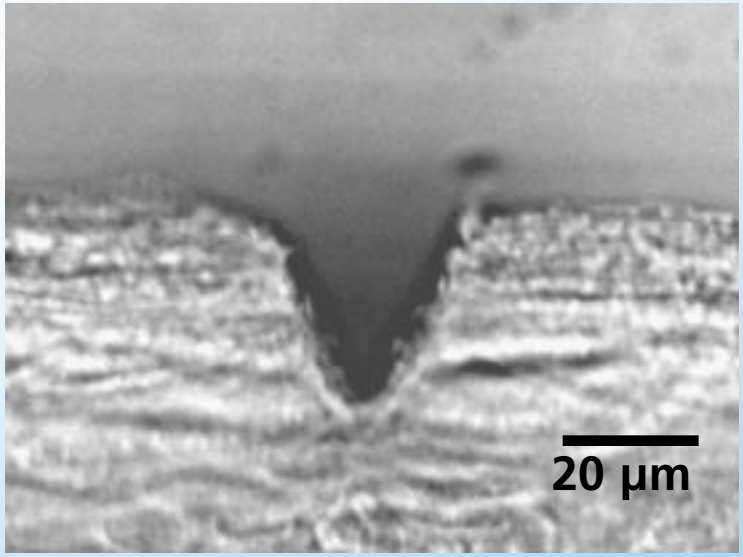
incision setup



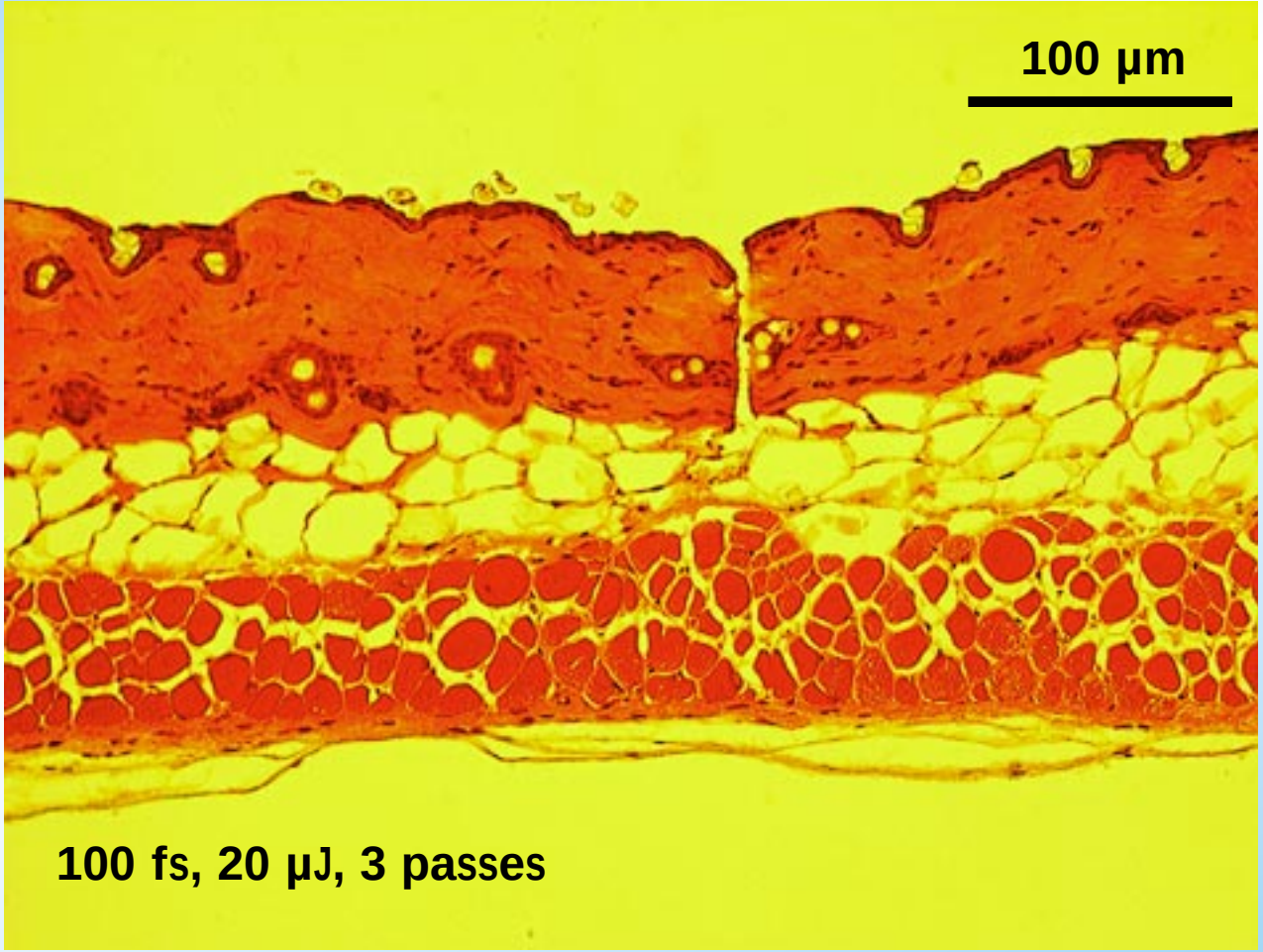
Applications



100 fs, 4 μJ

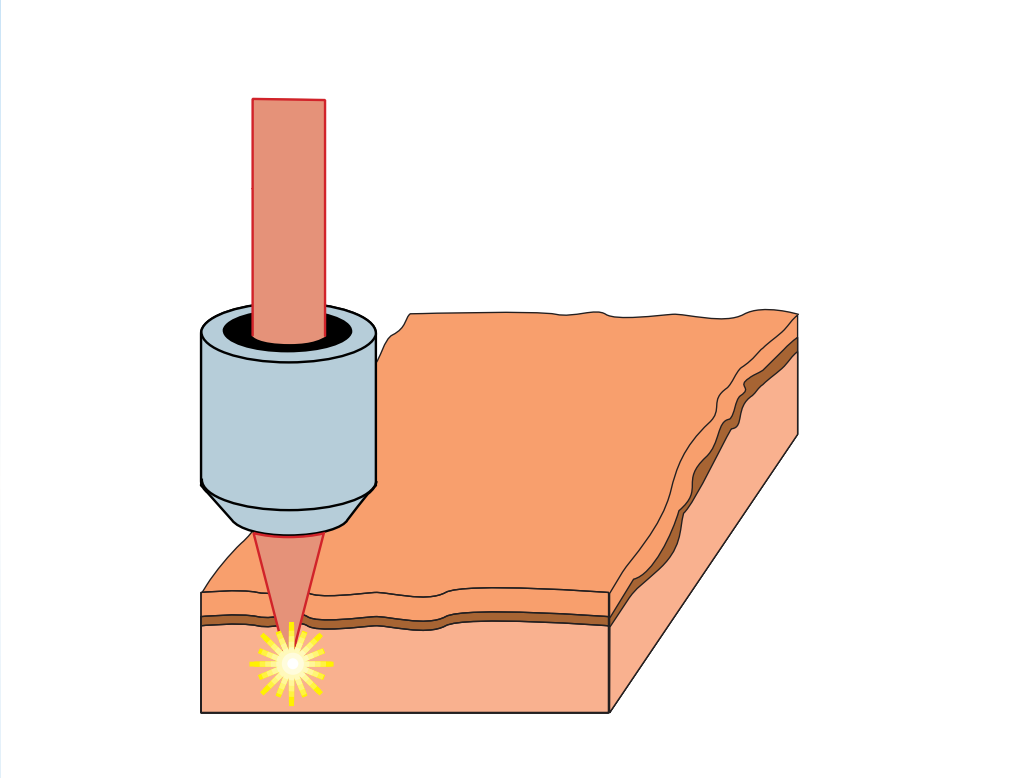


Applications



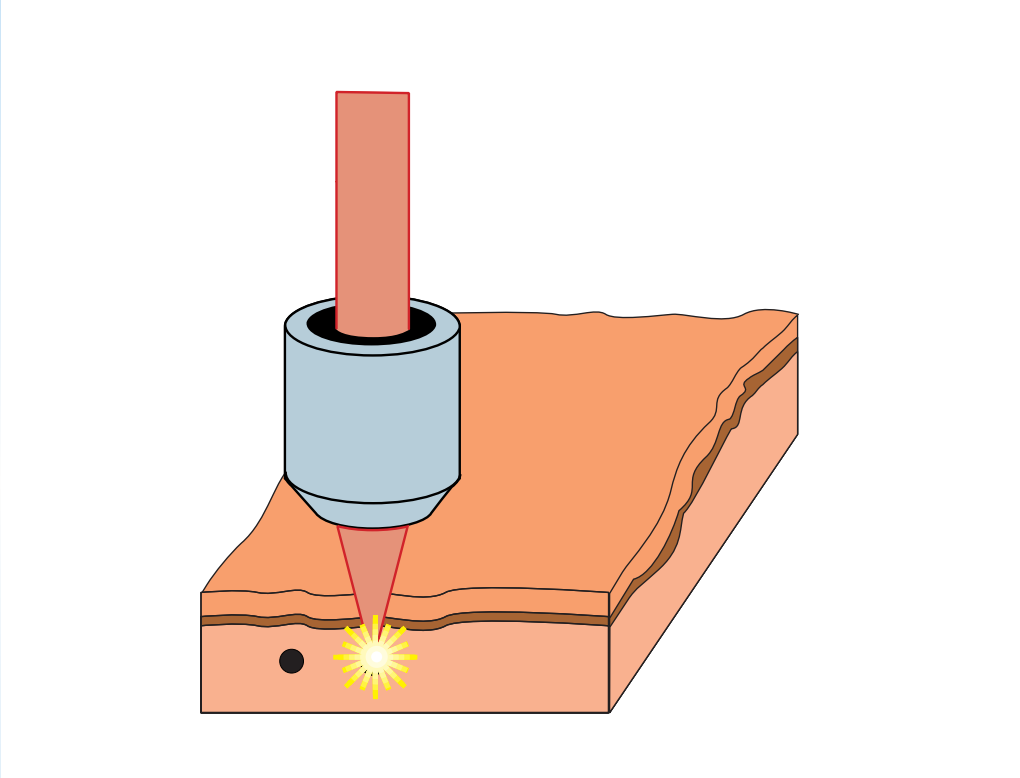
Applications

focus below surface…



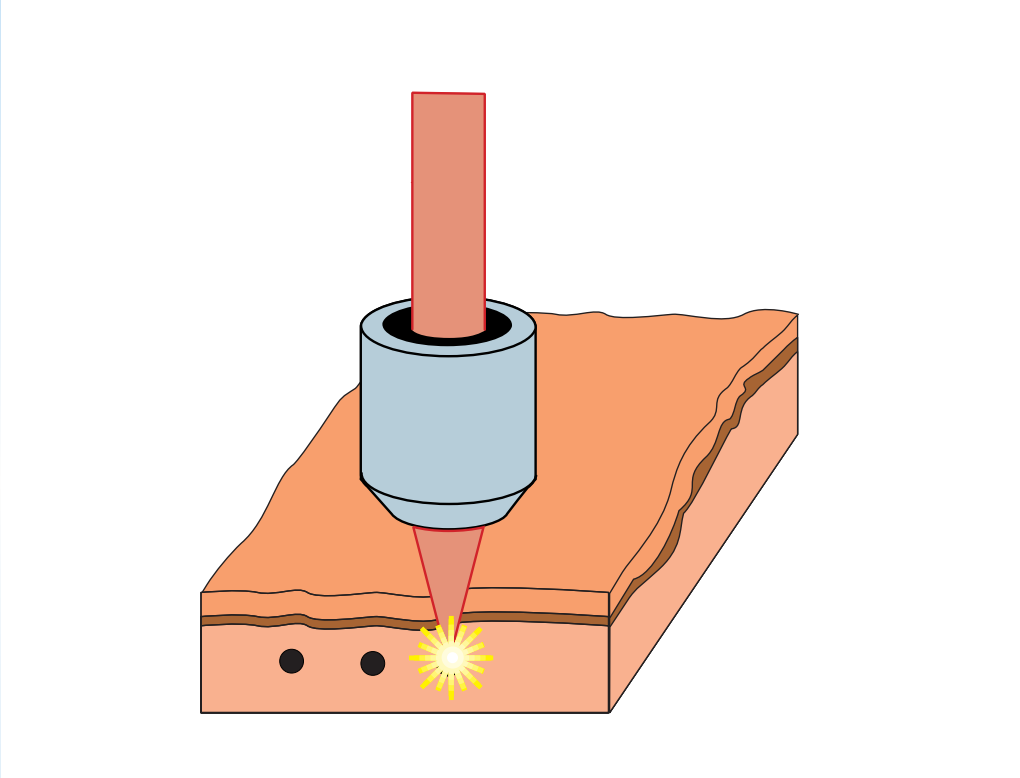
Applications

… and translate beam



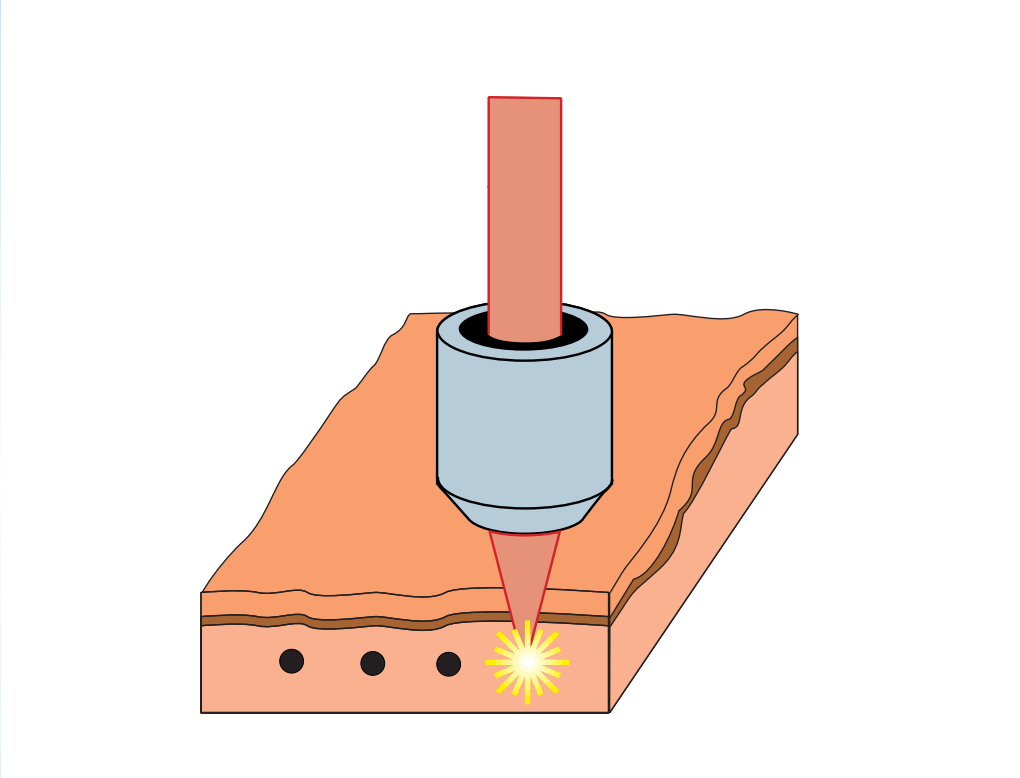
Photodisruption in epidermis

… and translate beam

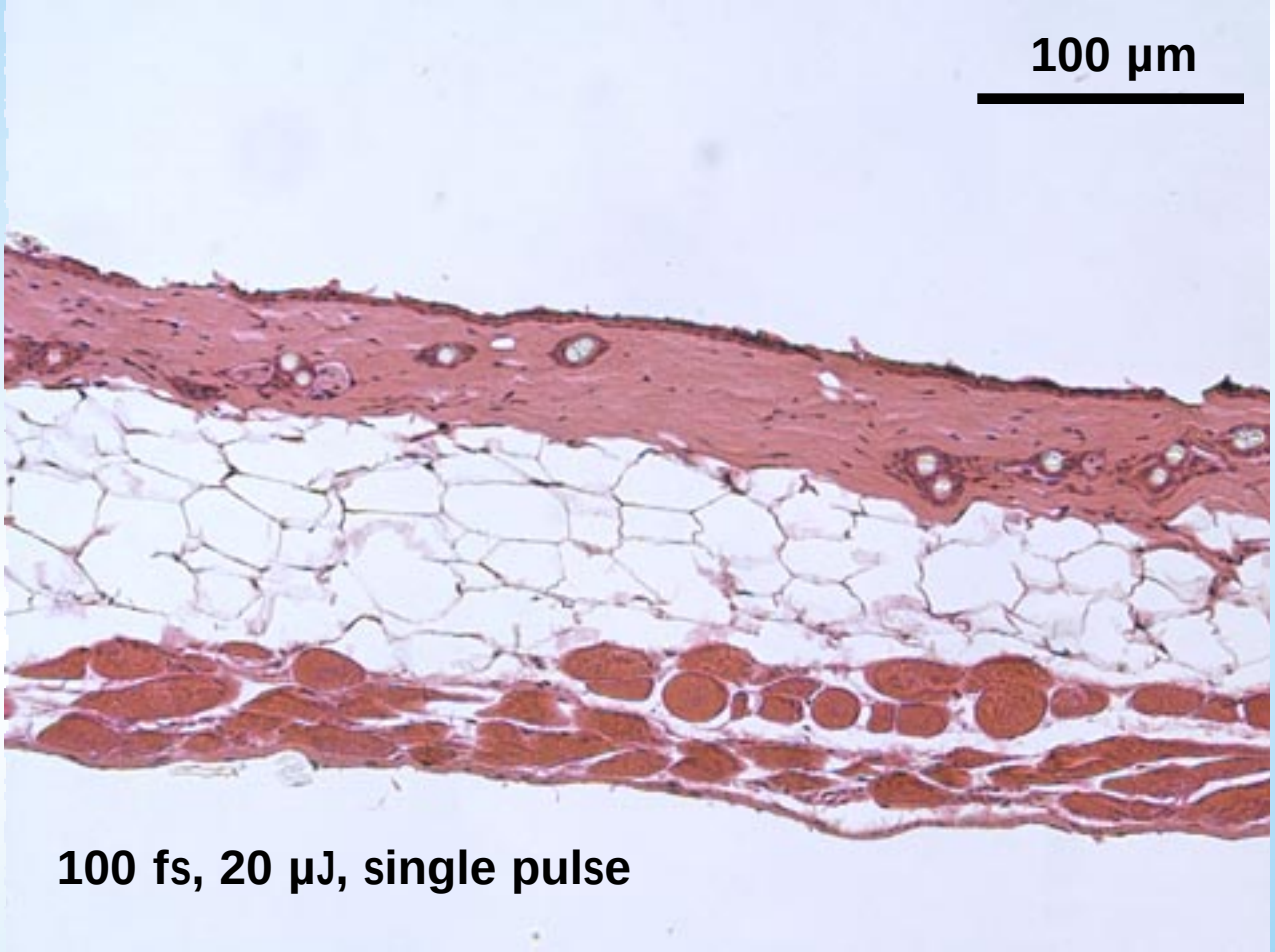


Photodisruption in epidermis

… and translate beam

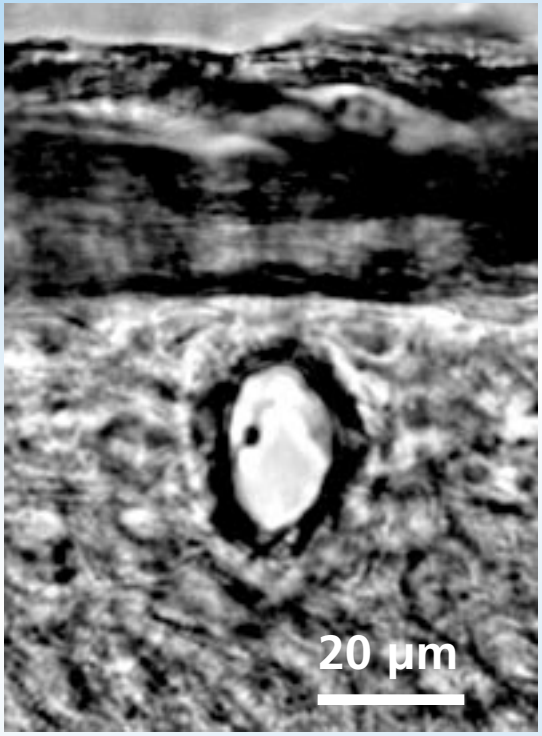


Applications

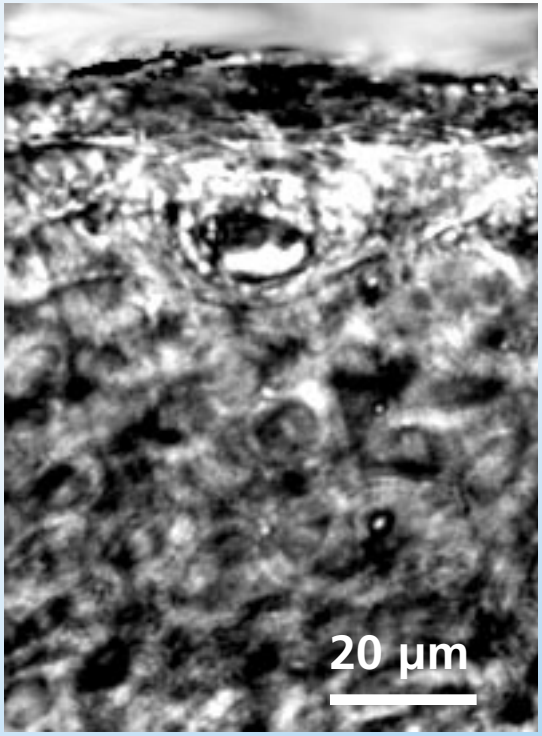


Applications

200 ps, 20 µJ



100 fs, 20 µJ

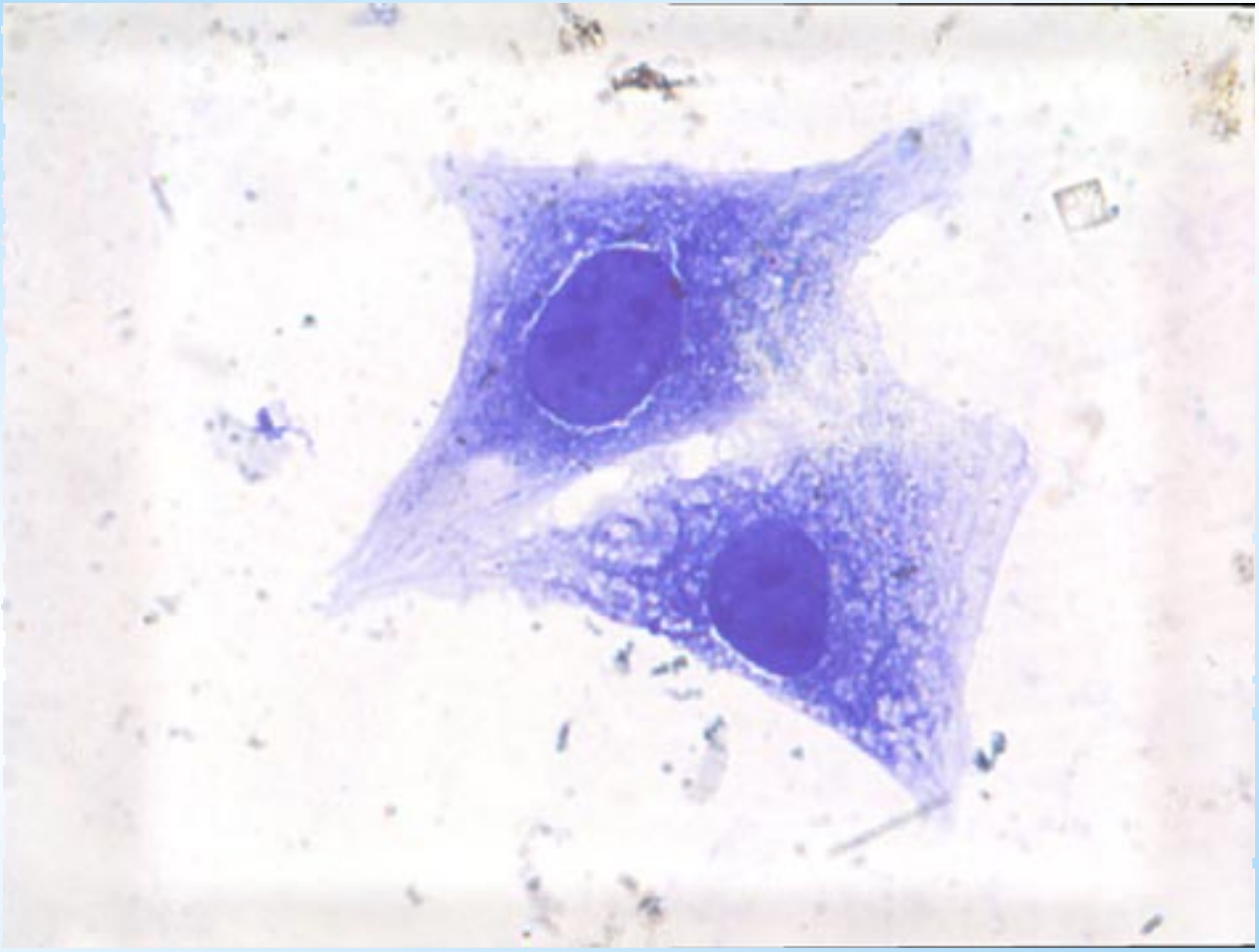


undamaged surface

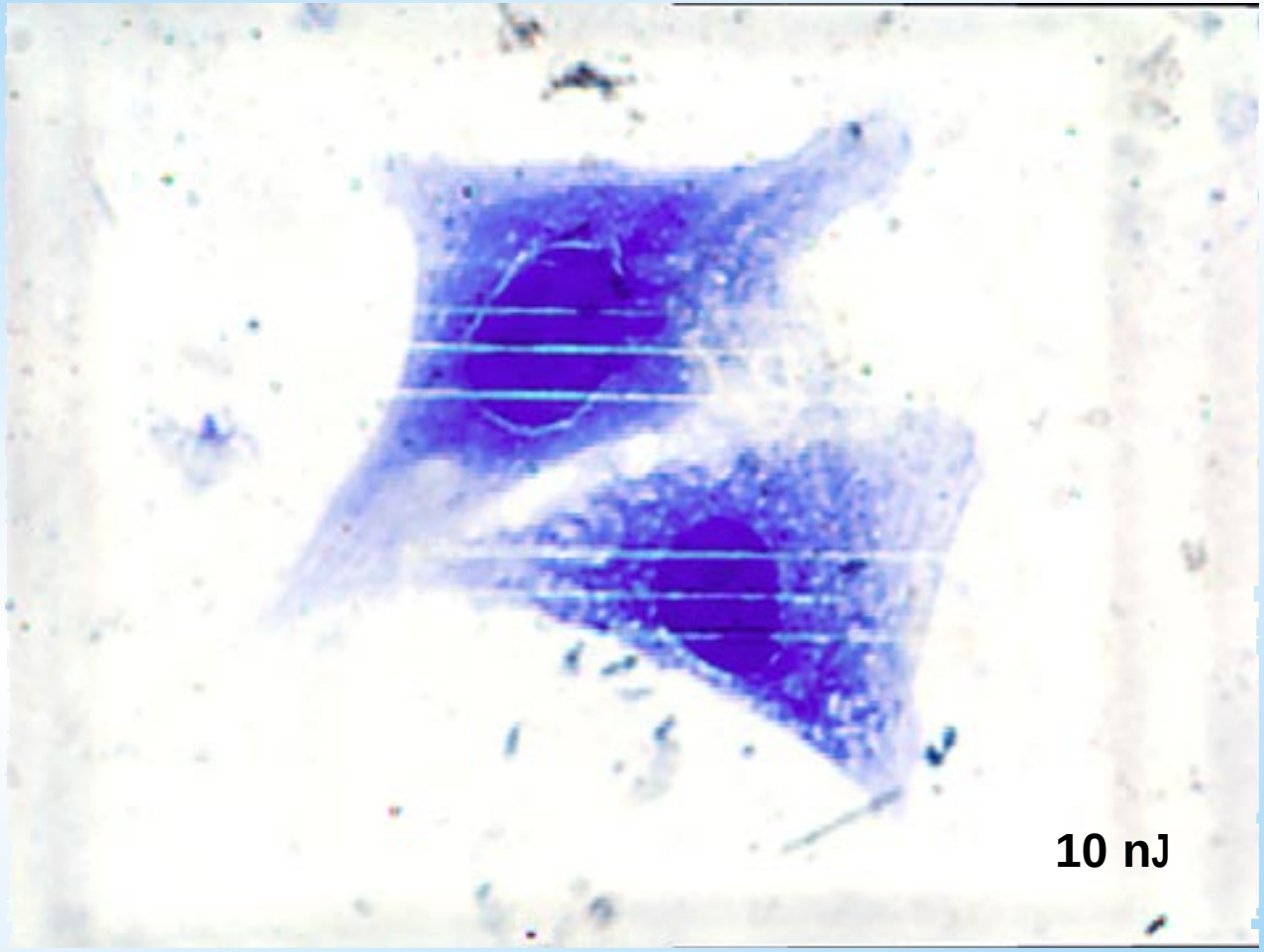
Conclusions

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

Subcellular micromachining



Subcellular micromachining

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LABORATORY OF
APPLIED SCIENCE

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W. Leight
Alan Jamieson

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