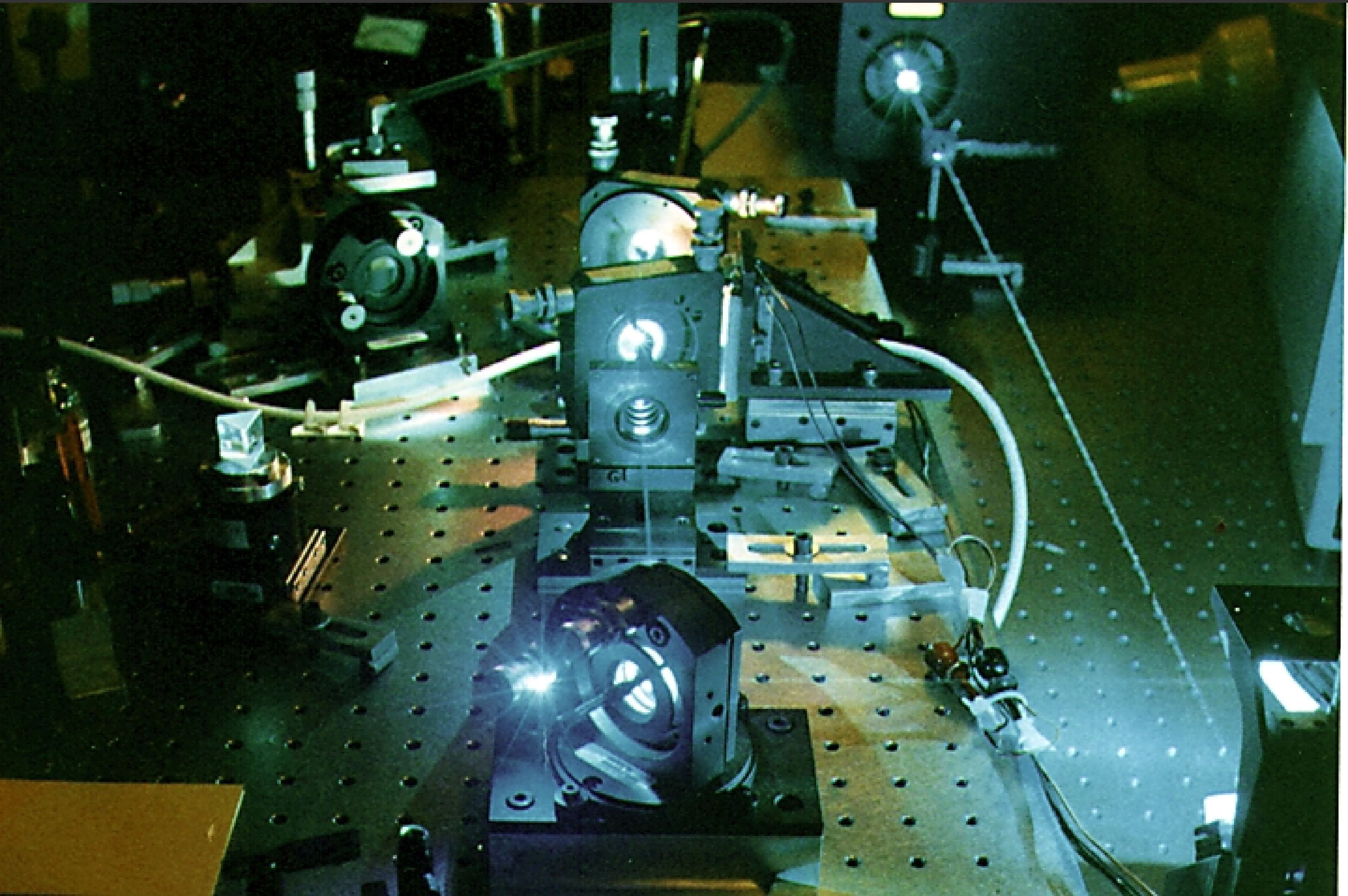
Micromachining of bulk glass with tightly-focused femtosecond laser pulses

Chris B. Schaffer
André Brodeur
José Garcia
Eric Mazur

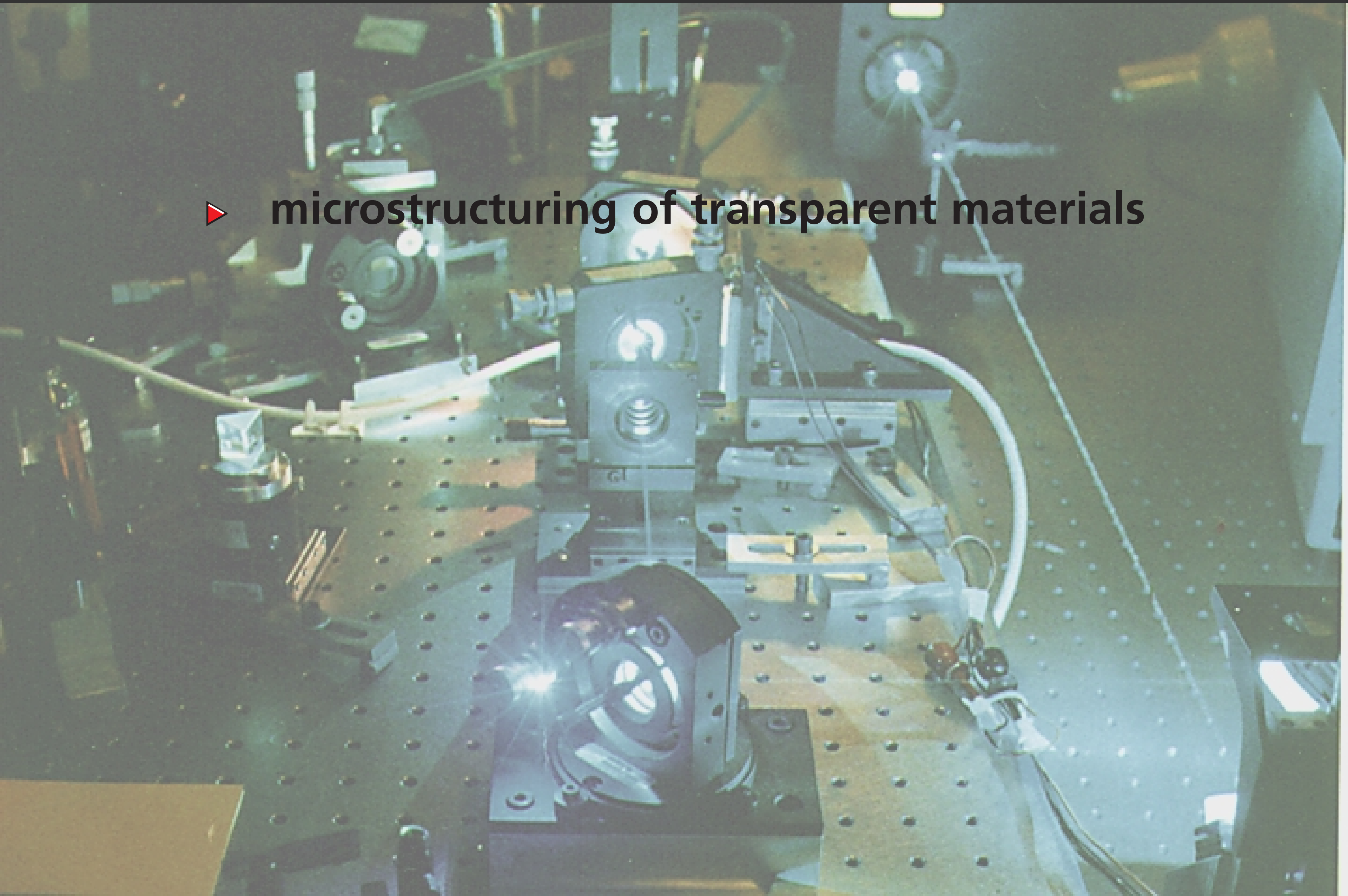
UPS ‘99, Taipei
26 October 1999

Introduction

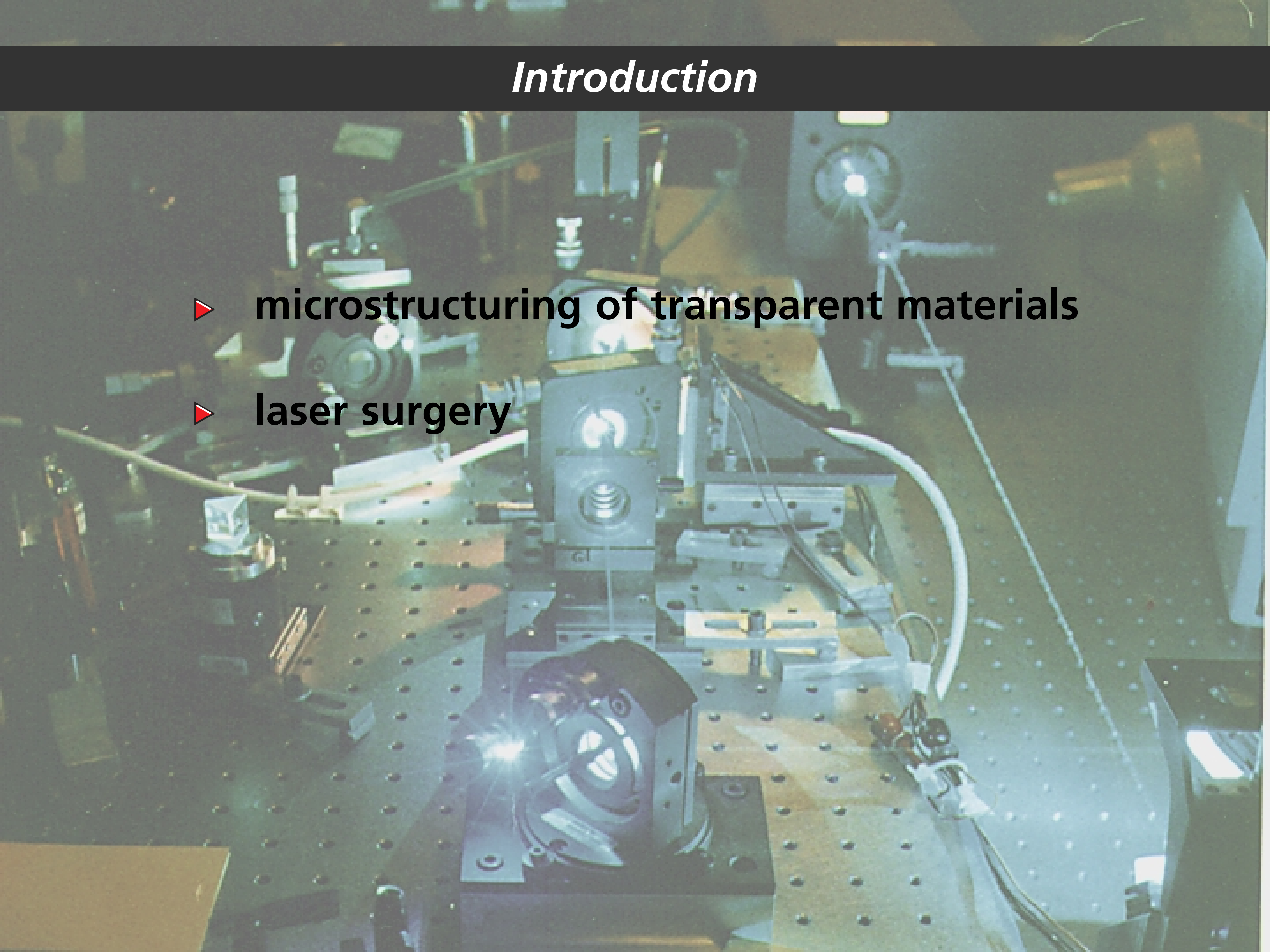


Introduction

- microstructuring of transparent materials



Introduction



- microstructuring of transparent materials
- laser surgery

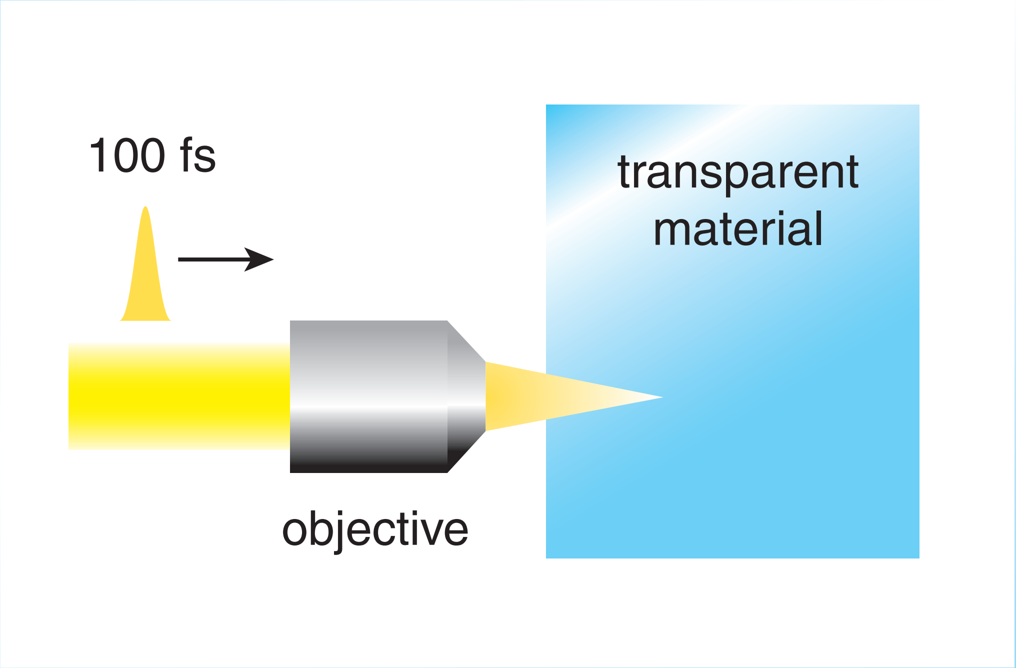
Introduction

- microstructuring of transparent materials
- laser surgery
- electronic and structural transitions

Introduction

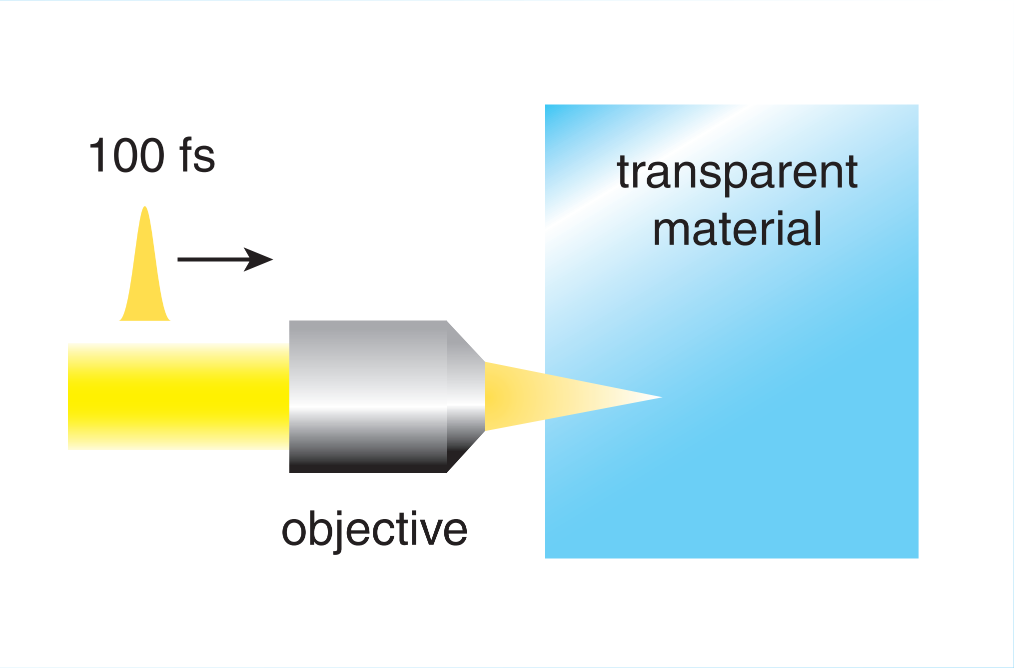
- **microstructuring of transparent materials**
- **laser surgery**
- **electronic and structural transitions**
- **laser assisted chemistry**

focus laser beam inside material…



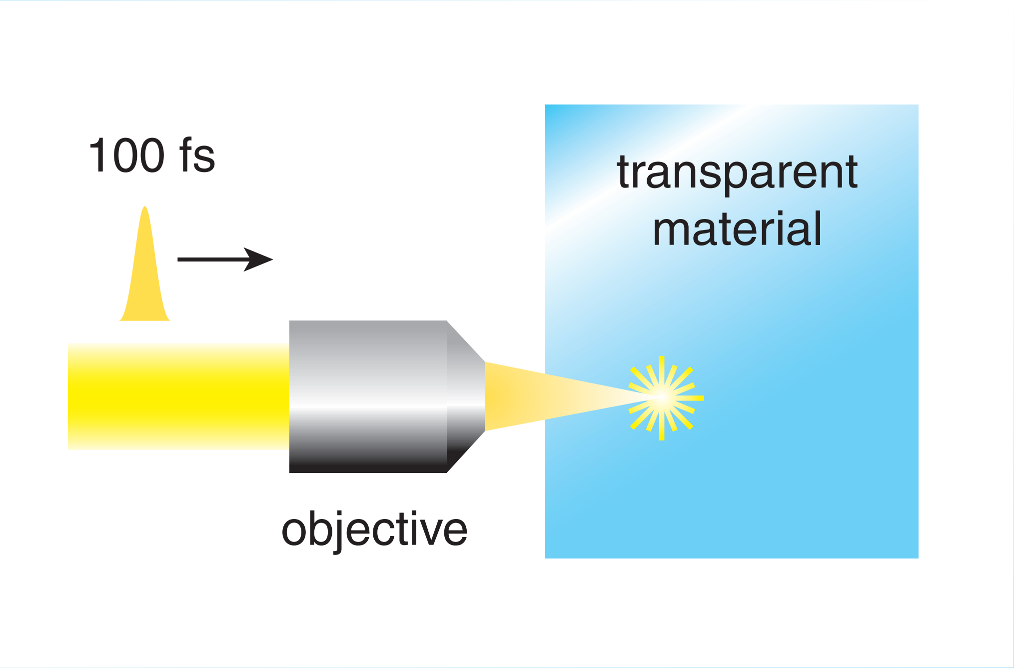
Introduction

high intensity at focus…

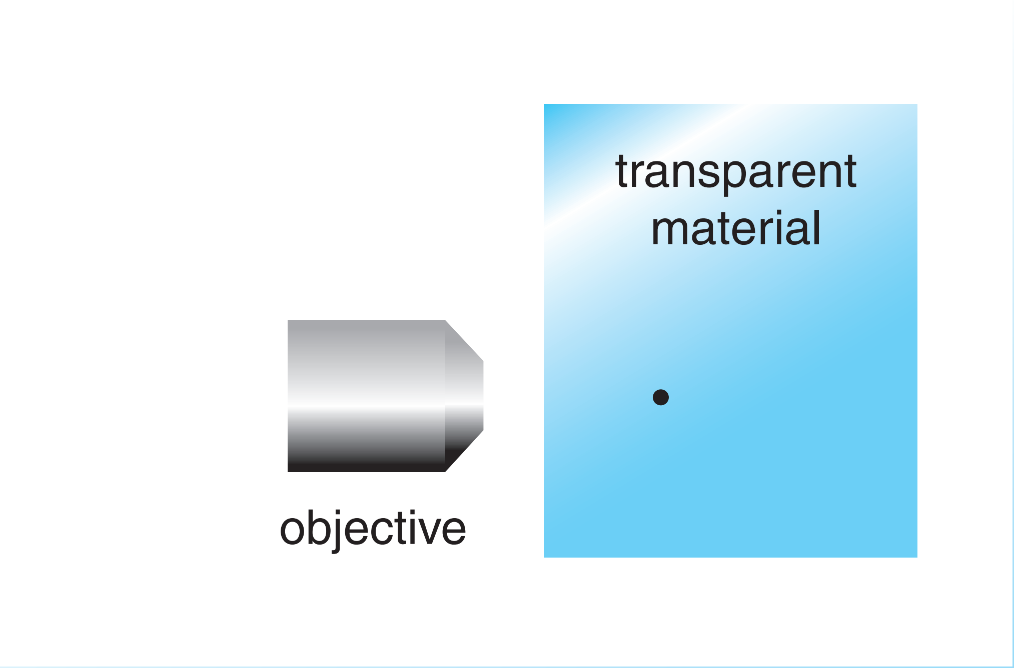


Introduction

… causes nonlinear ionization…



and microscopic bulk damage



Introduction

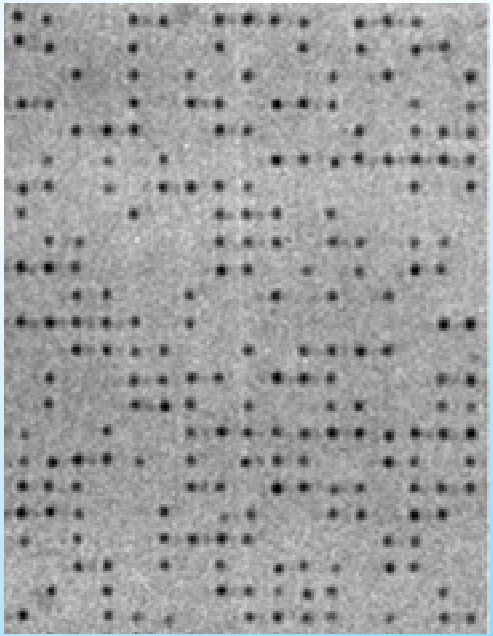
Applications:

- **data storage**

Introduction

Applications:

- **data storage**



Introduction

Applications:

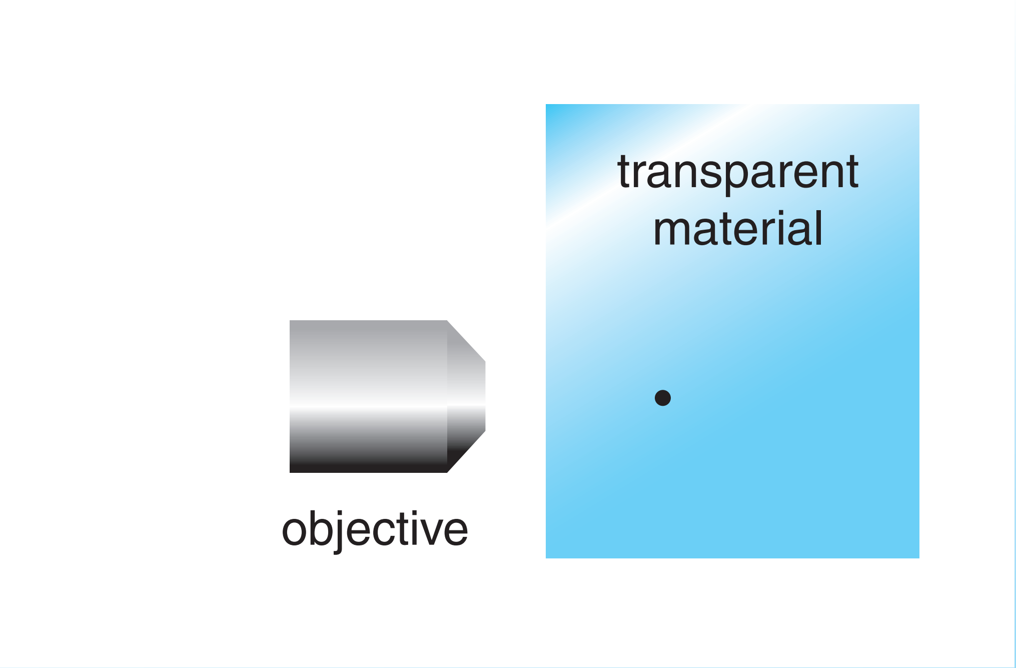
- **data storage**
- **photonic devices**

Introduction

Applications:

- **data storage**
- **photonic devices**
- **internal micromachining**

What are the conditions at focus?



laser deposits energy in ~1 μm^3

Introduction

What temperature?

What temperature?

$$\Delta E = C_V \rho V \, \Delta T$$

Introduction

What temperature?

$$\Delta E = C_V \rho V \, \Delta T$$

$$C_V = 0.75 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$$

$$\rho = 2.2 \times 10^3 \text{ kg/m}^3$$

Introduction

What temperature?

$$\Delta E = C_V \rho V \, \Delta T$$

$$C_V = 0.75 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$$

$$\rho = 2.2 \times 10^3 \text{ kg/m}^3$$

So, 1 μJ in 1 μm^3 gives

~1,000,000 K!

What pressure?

Introduction

What pressure?

Treat ionized material as an ideal gas:

$$pV = nRT$$

Introduction

What pressure?

Treat ionized material as an ideal gas:

$$pV = nRT$$

Gives

$$p = 10\ \mathrm{MBar!}$$

So:

	microexplosion
T	≈ 1 MK
p	≈ 10 MBar
ρ	2.2×10^3 kg/m^3

So:

	microexplosion	sun
T	≈1 MK	2–15 MK
p	≈10 MBar	
ρ	2.2×10^3 kg/m^3	$0.15\text{–}150 \times 10^3$ kg/m^3

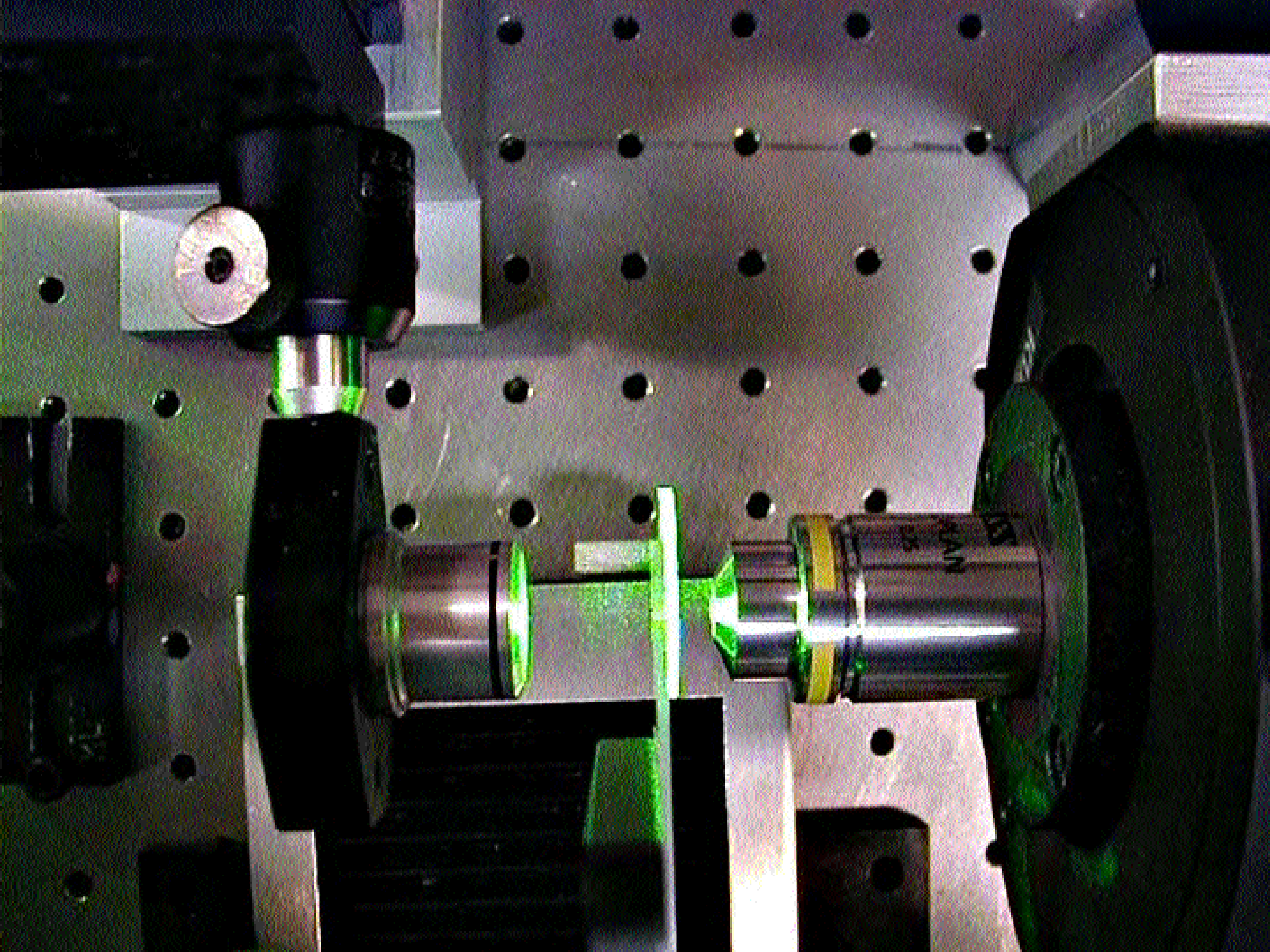
So:

	microexplosion	sun
T	≈ 1 MK	2–15 MK
p	≈ 10 MBar	
ρ	2.2×10^3 kg/m^3	0.15–150×10^3 kg/m^3

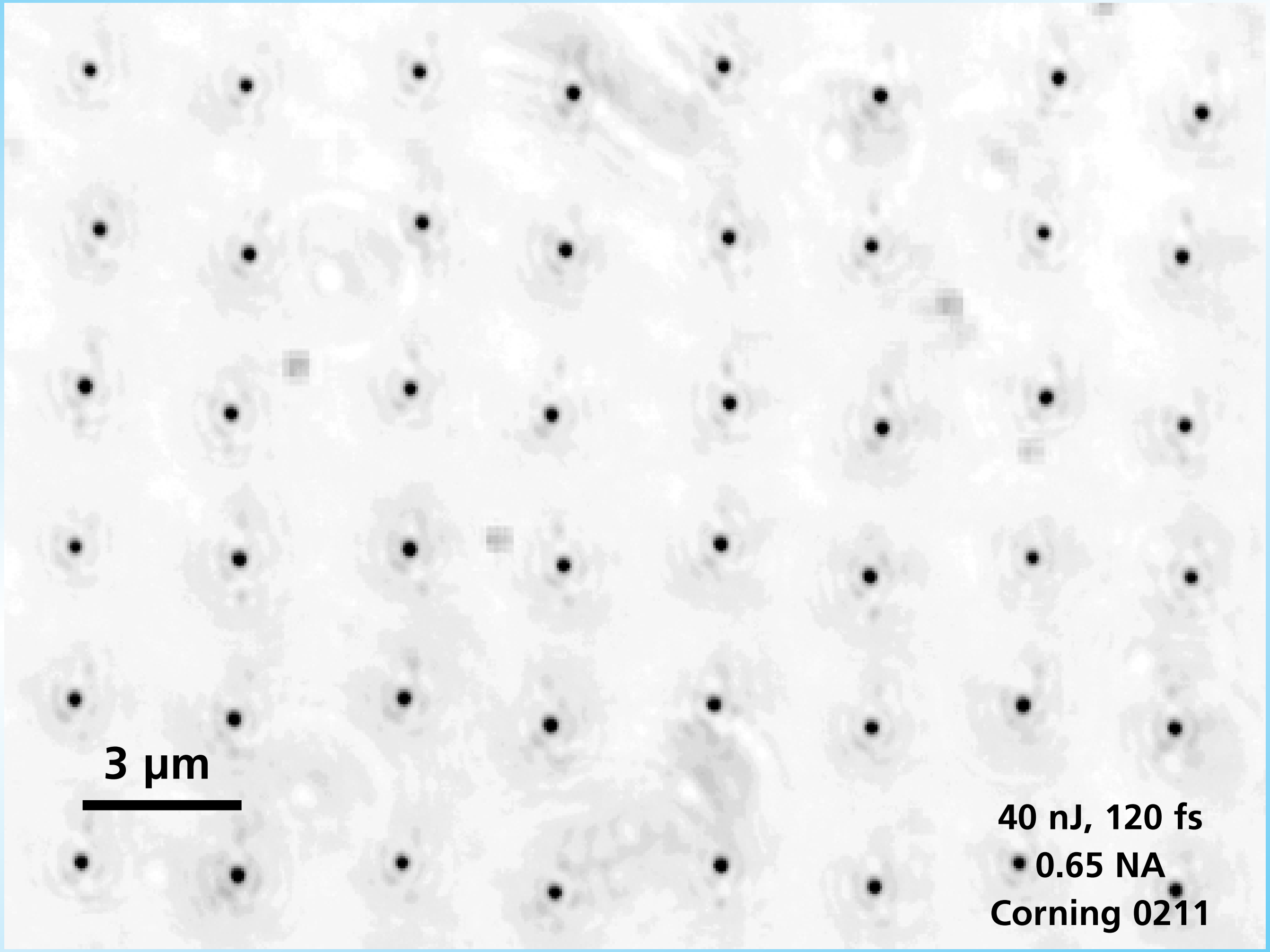
creating stellar conditions in lab!

Outline

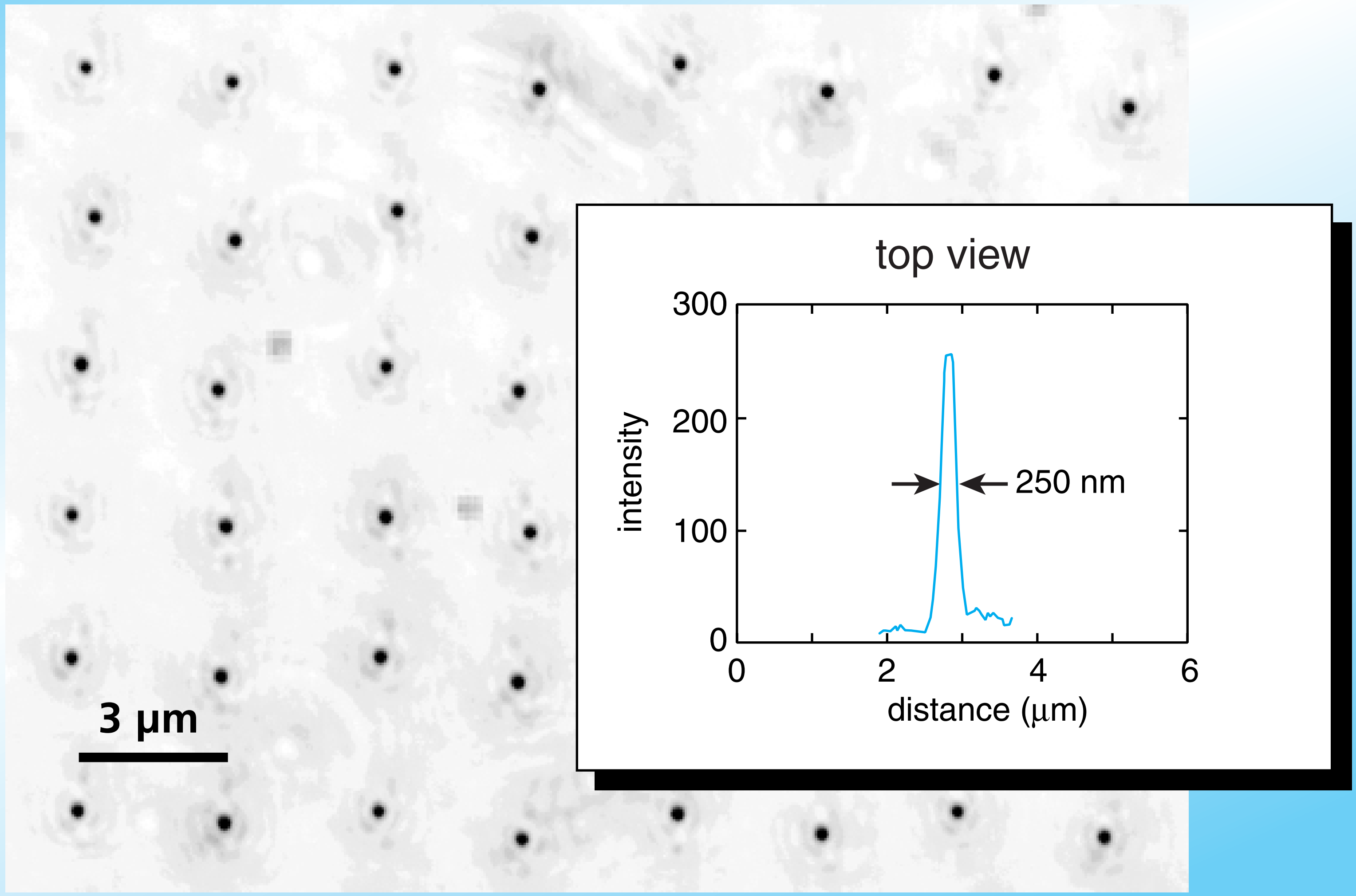
- Damage morphology
- Energy deposition
- Dynamics



Damage morphology

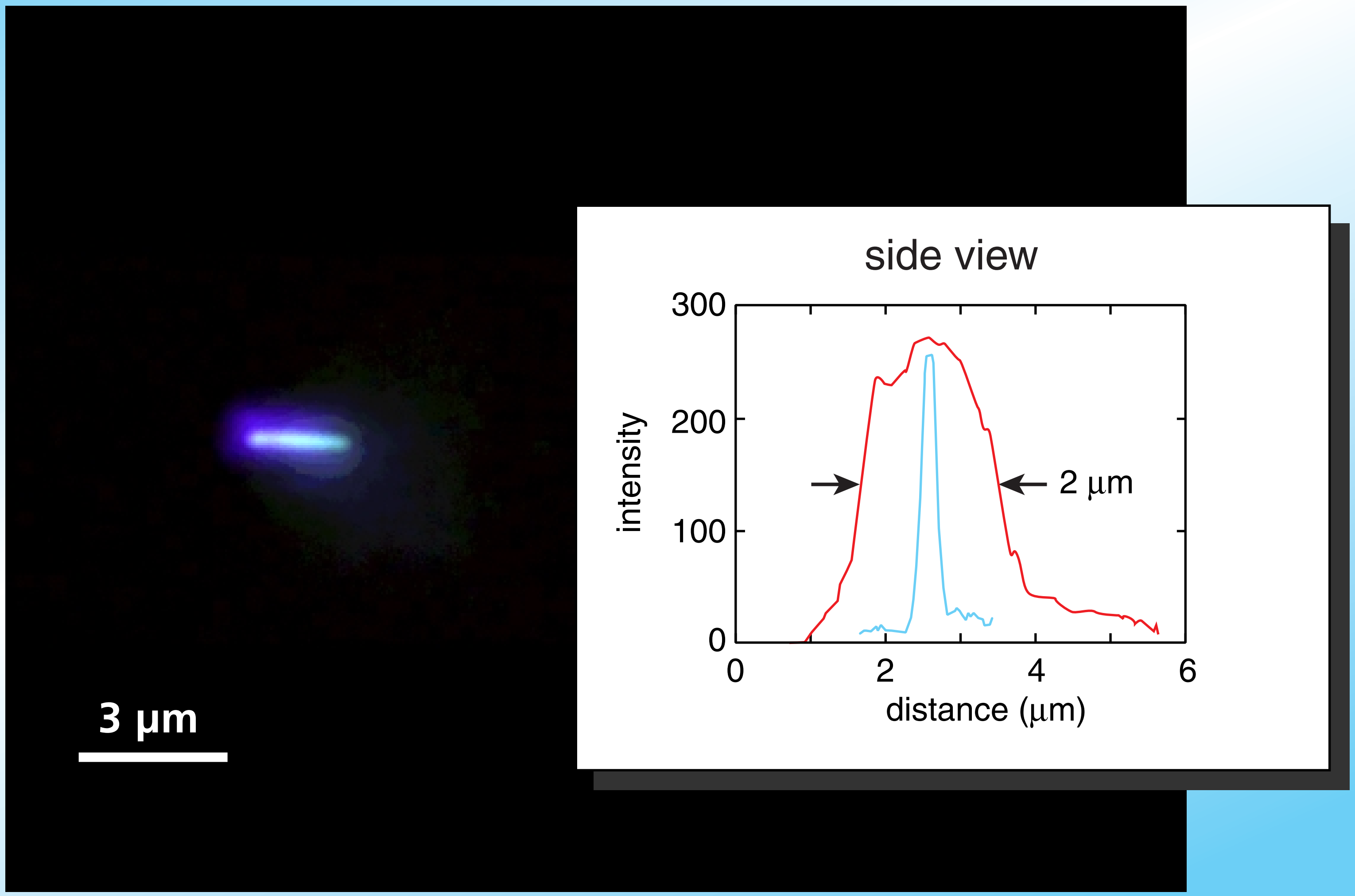


Damage morphology

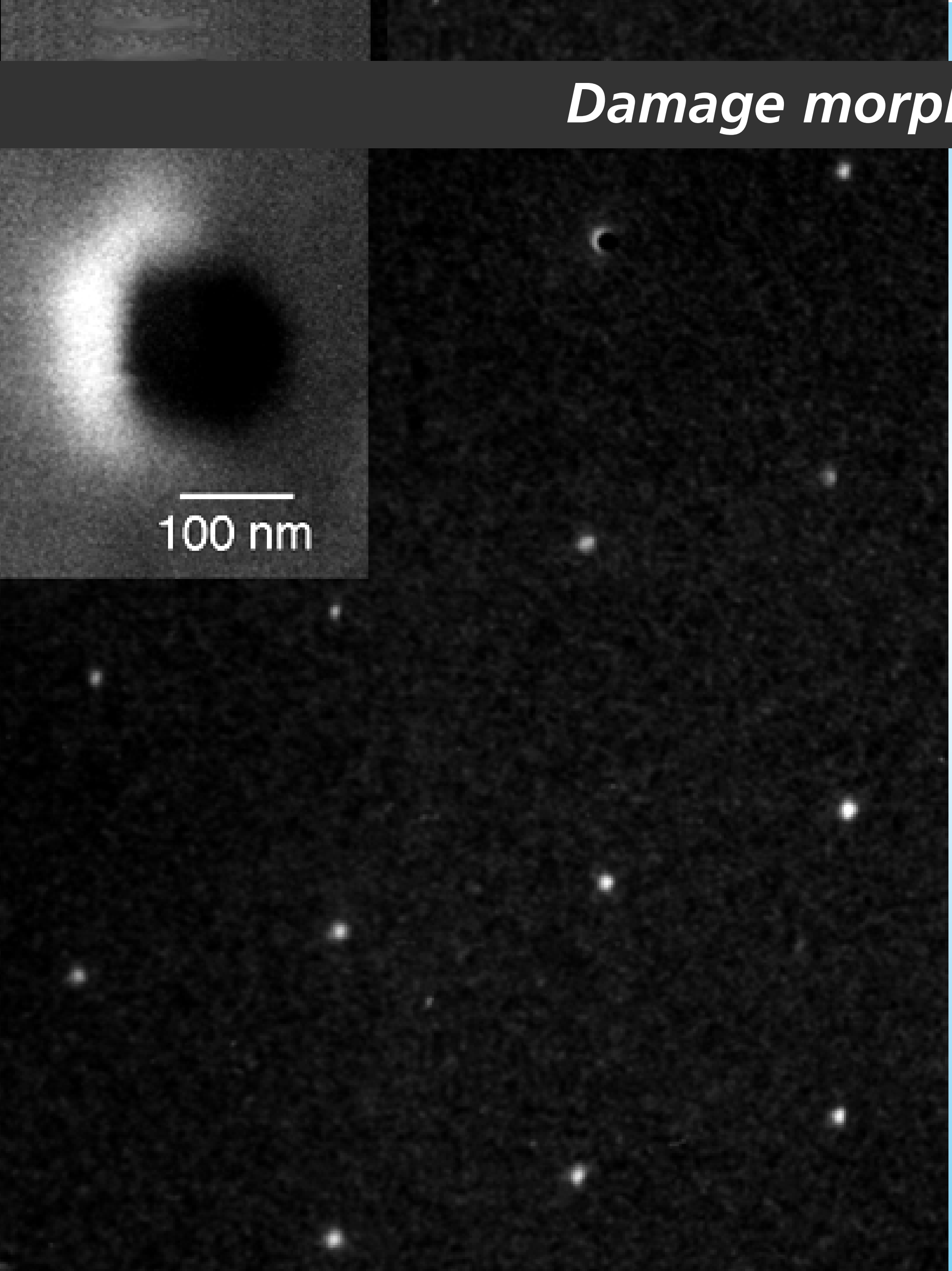


Damage morphology

Damage morphology



Damage morphology

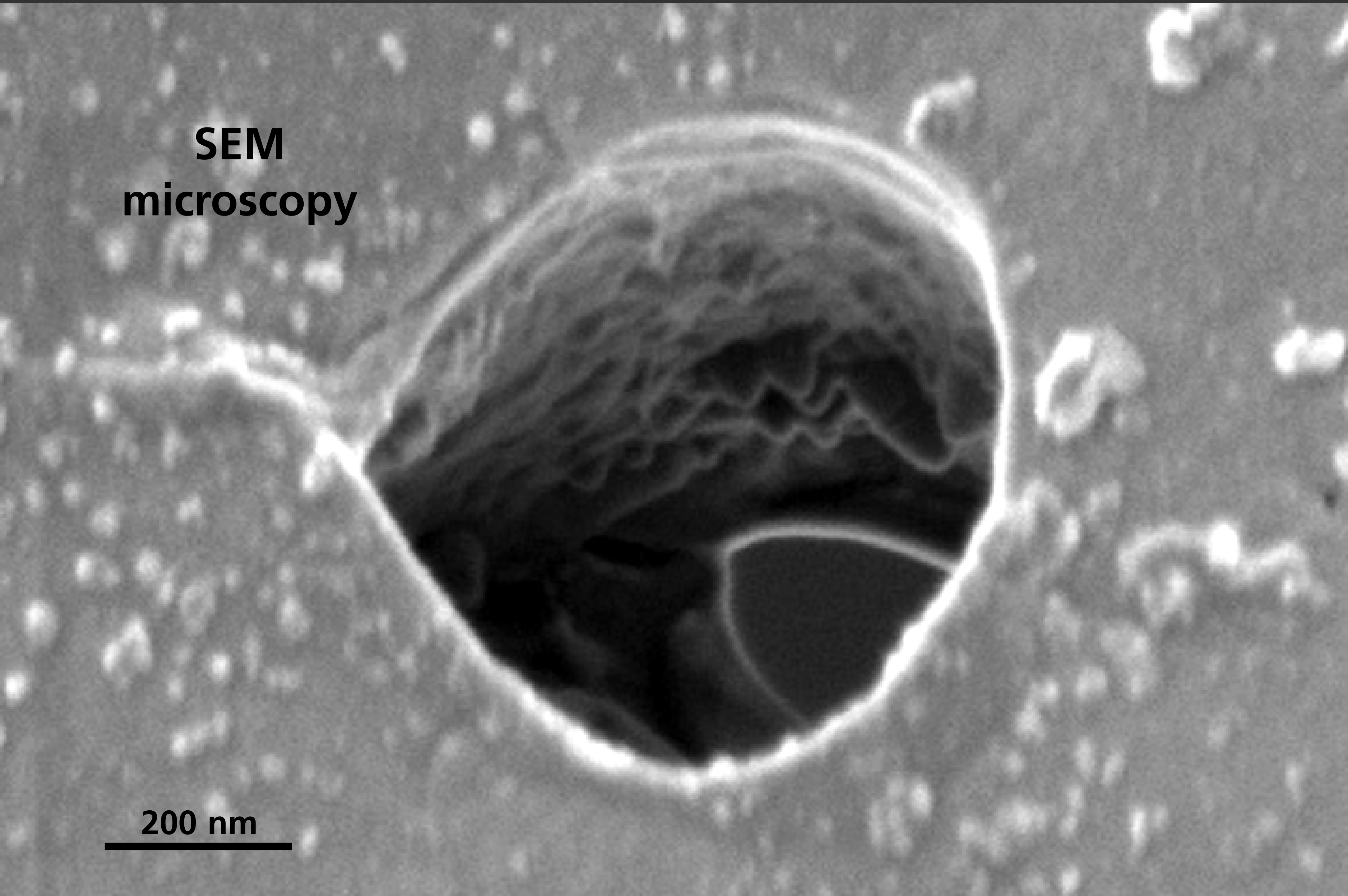


Electron Microscopy:

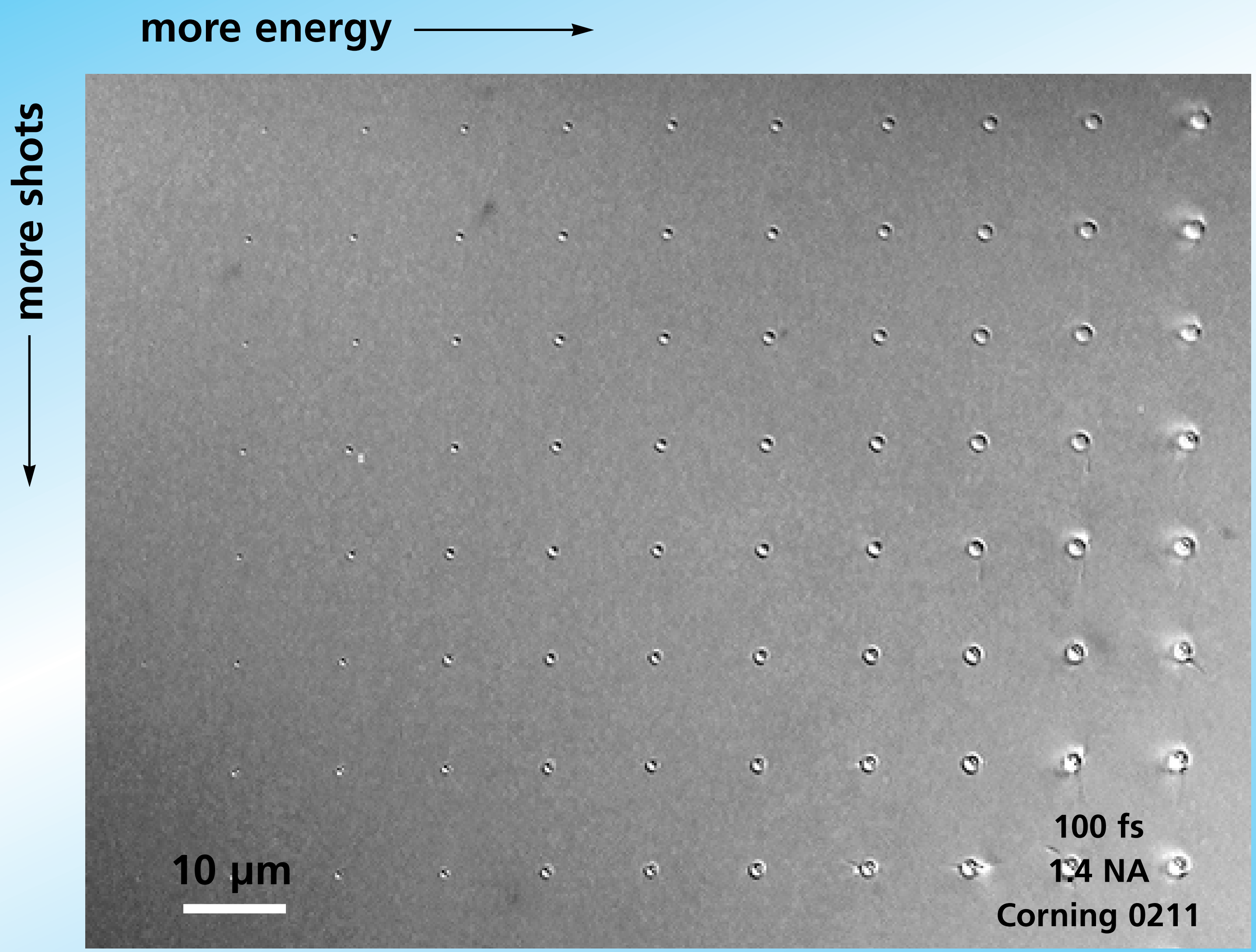
explosive damage forms voids

100 fs, 500 nJ
0.65 NA
fused silica

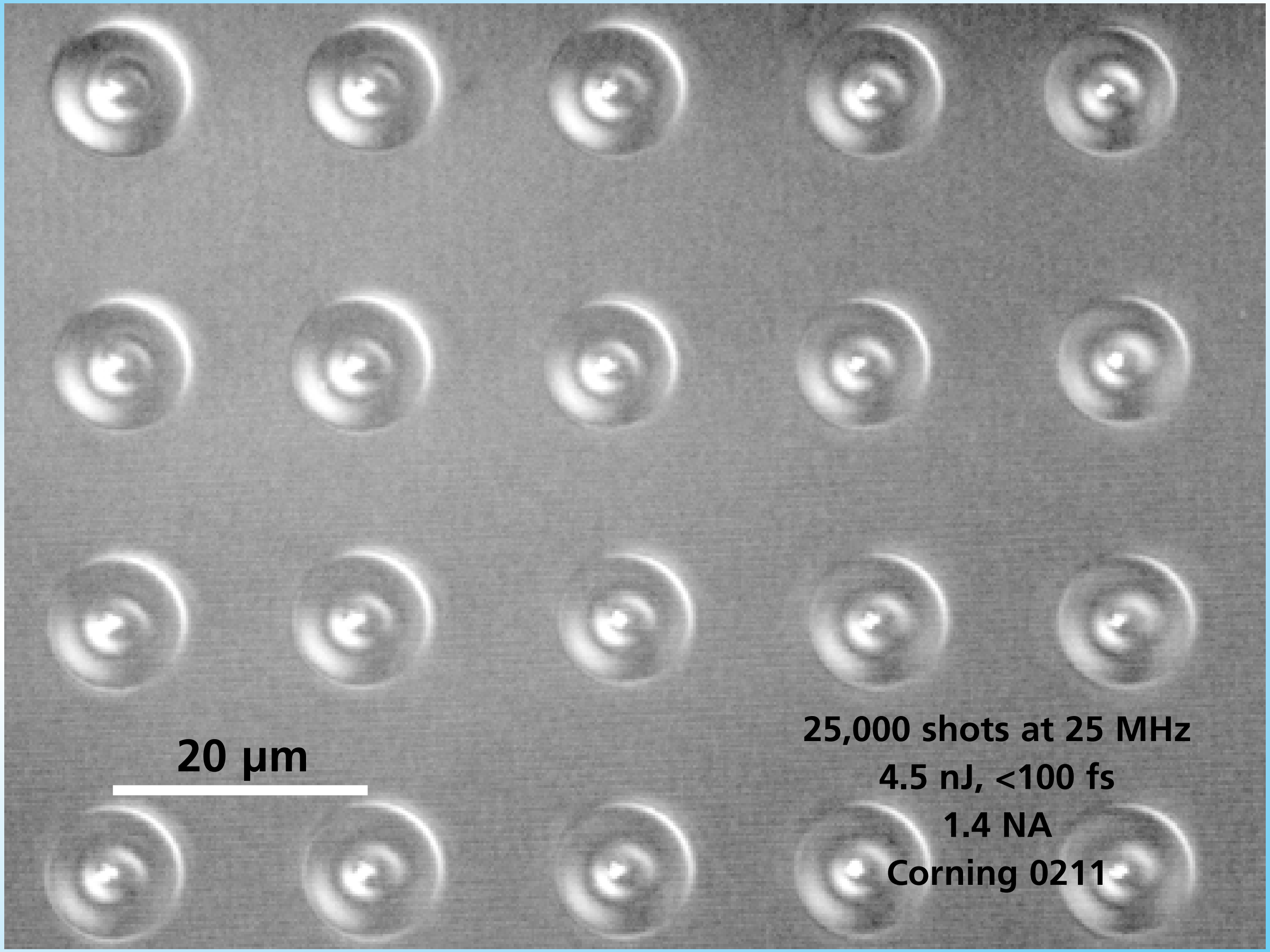
Damage morphology



Damage morphology



Damage morphology



Damage morphology

summary of damage mechanisms

	single shot	multiple shot (25 MHz)
low energy		
high energy		

Damage morphology

summary of damage mechanisms

	single shot	multiple shot (25 MHz)
low energy		
high energy	explosive	

Damage morphology

summary of damage mechanisms

	single shot	multiple shot (25 MHz)
low energy		thermal
high energy	explosive	

Damage morphology

summary of damage mechanisms

	single shot	multiple shot (25 MHz)
low energy	?	thermal
high energy	explosive	

Outline

- Damage morphology
- **Energy deposition**
- Dynamics

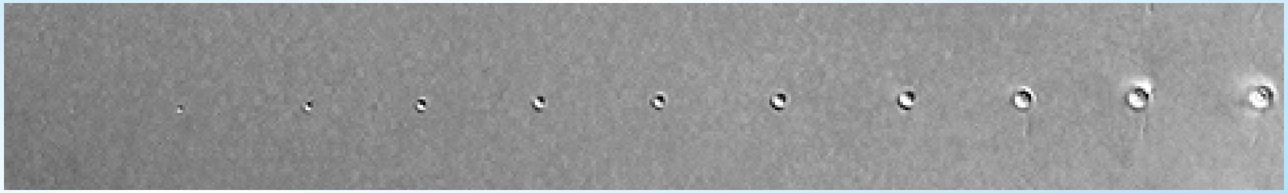
Energy deposition

Determine threshold for damage:

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

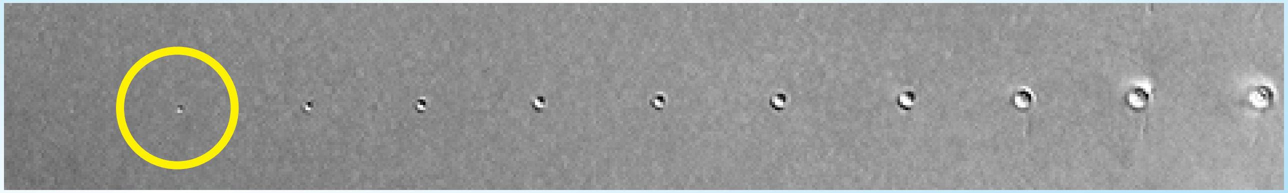
Energy deposition

optical microscopy



Energy deposition

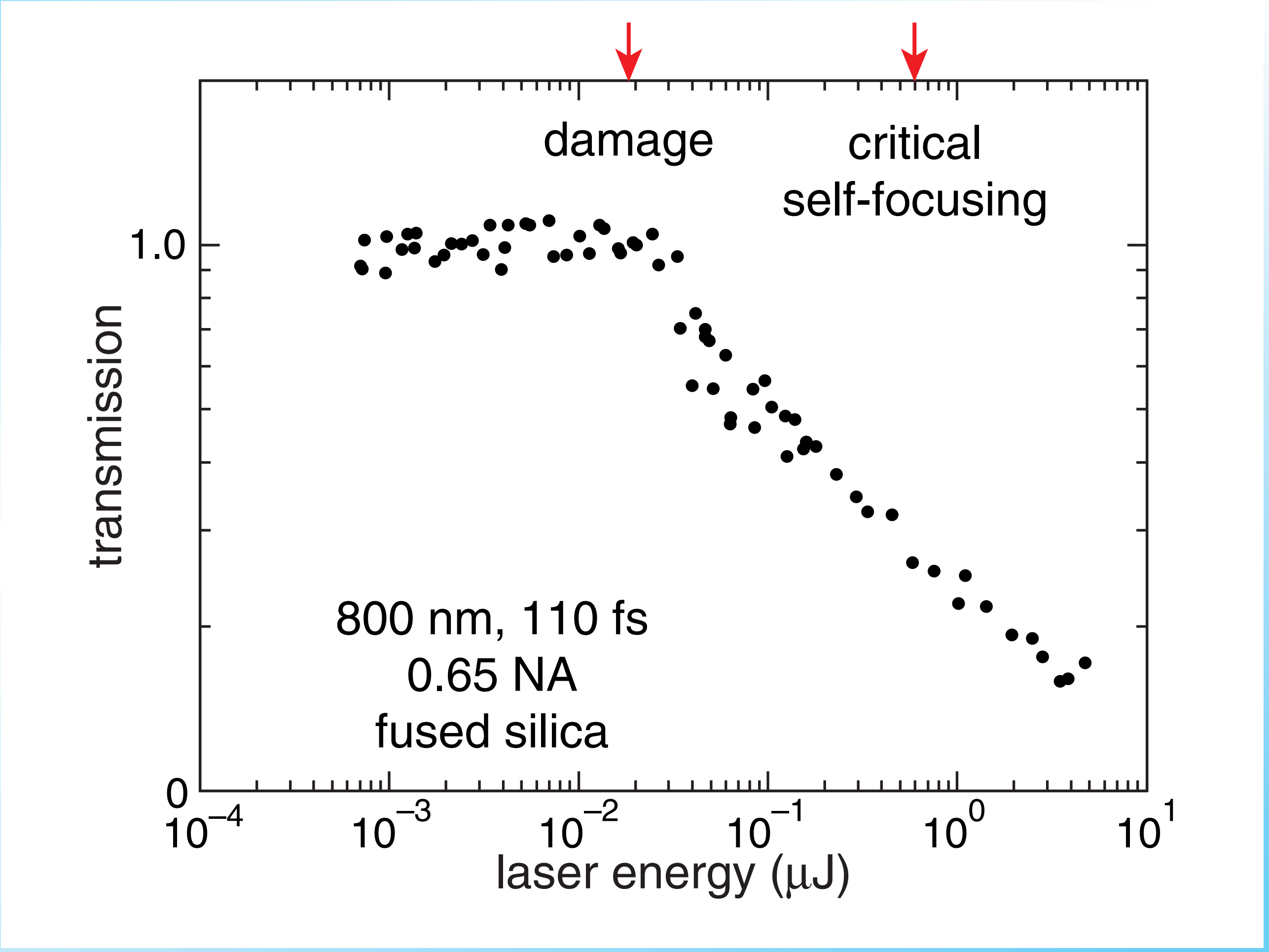
optical microscopy



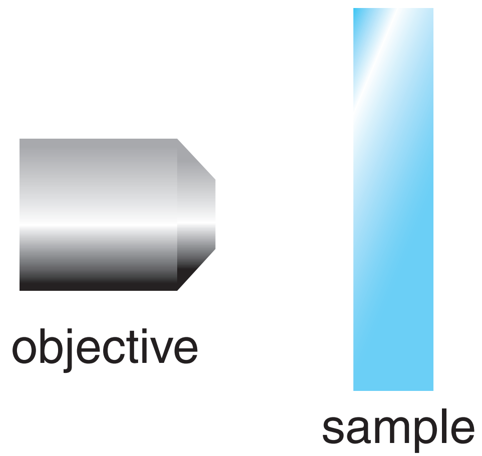
6.6 nJ

Energy deposition

transmission of pump beam in fused silica

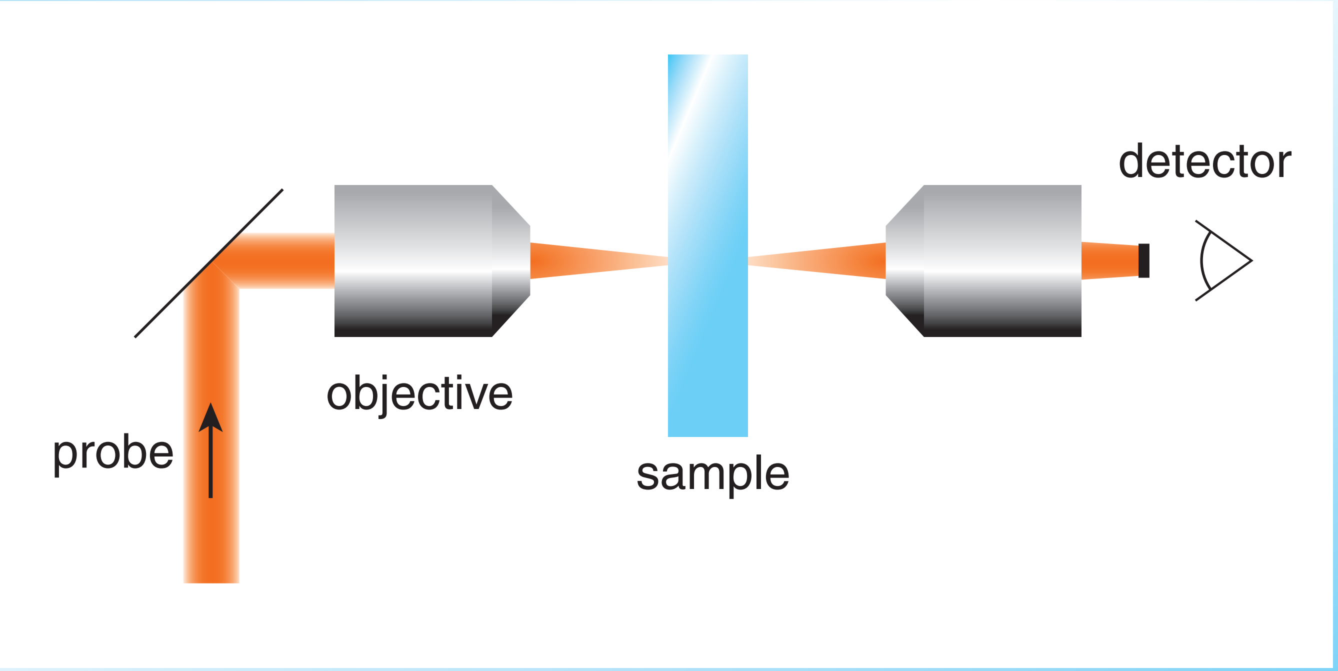


Dark-field scattering



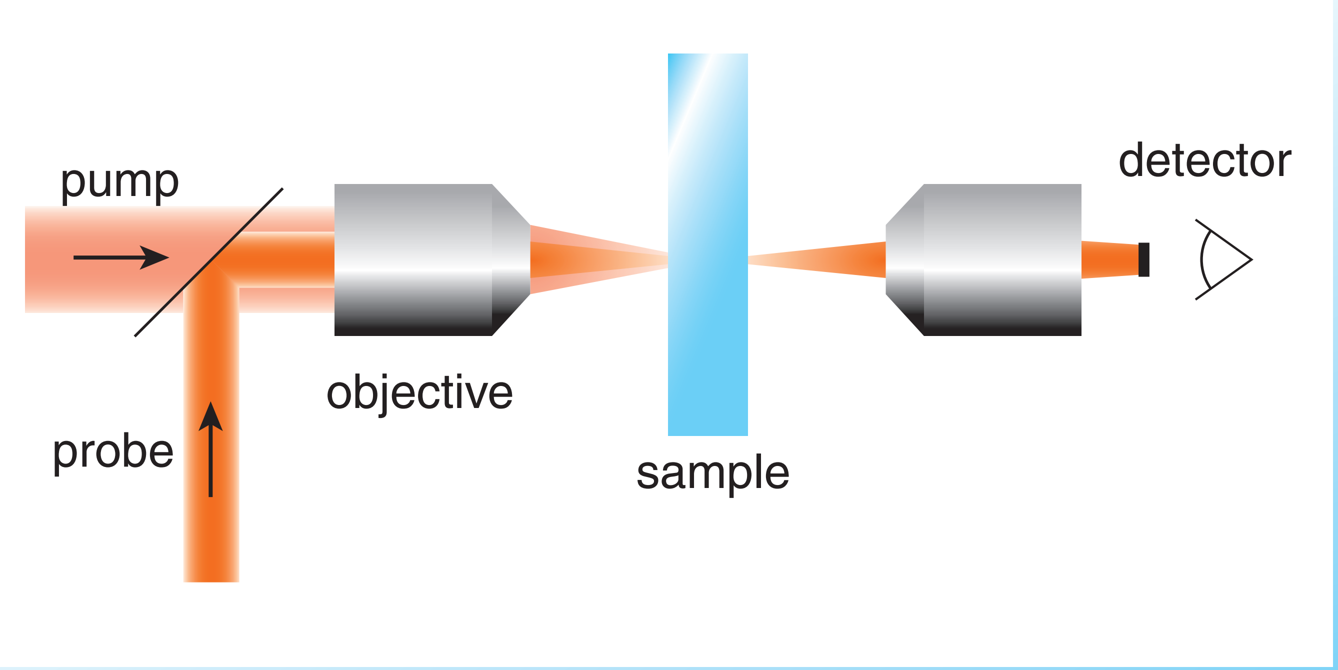
Energy deposition

block probe beam…



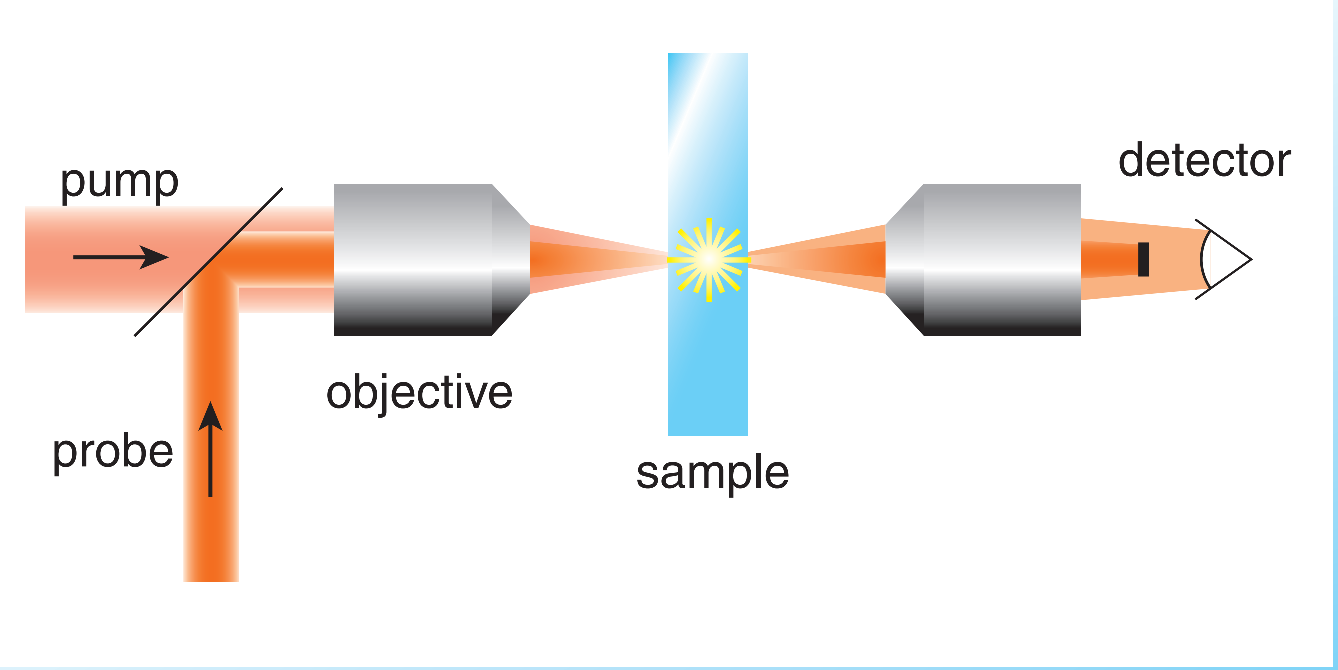
Energy deposition

…bring in pump beam…

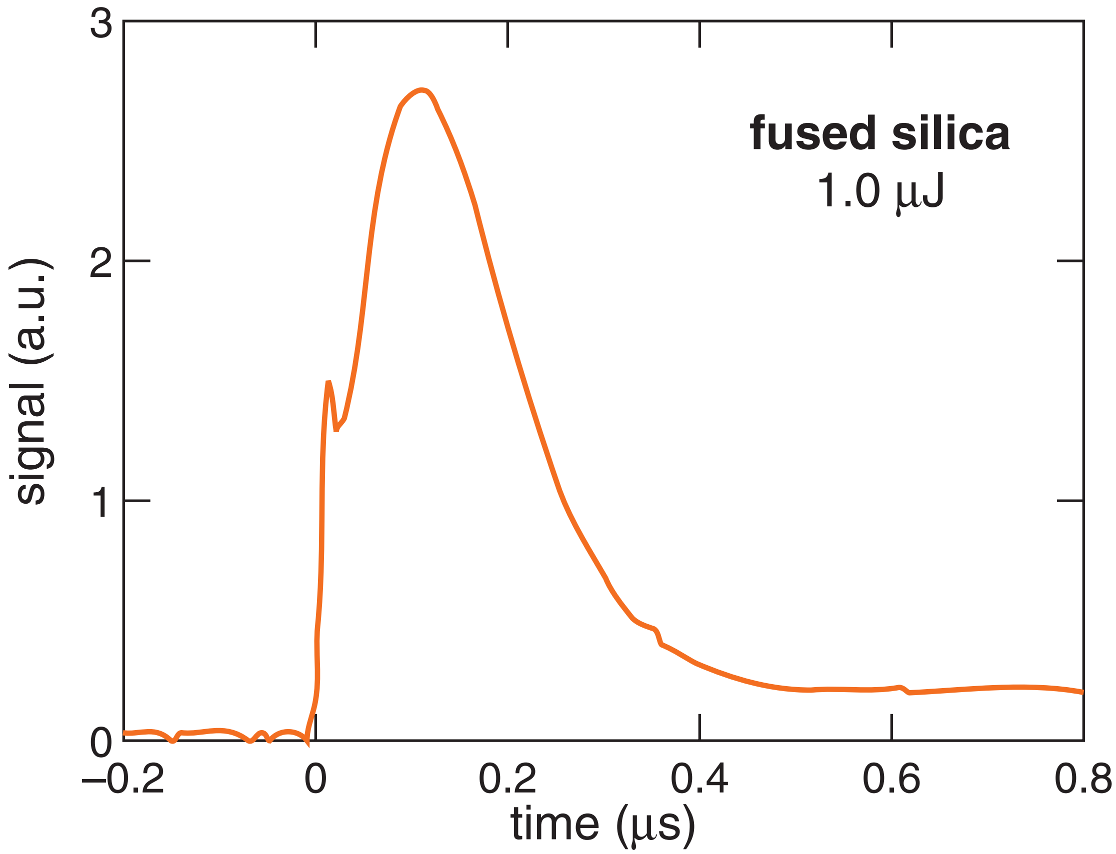


Energy deposition

…damage scatters probe beam

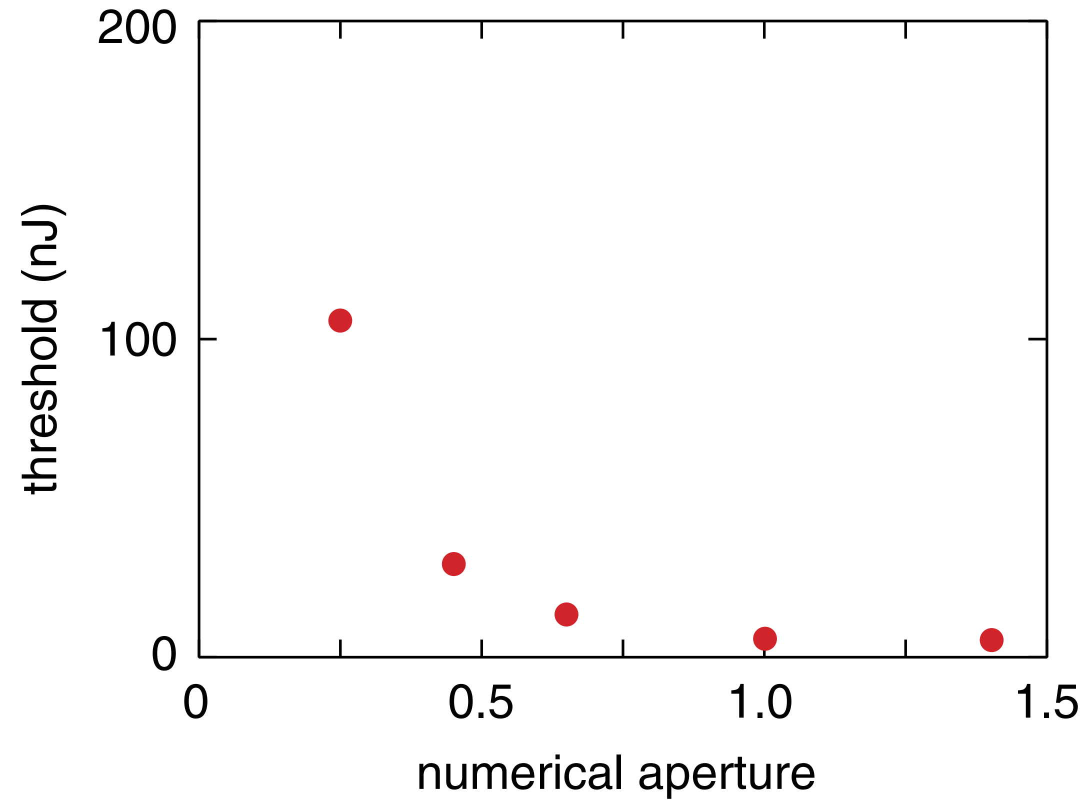


Energy deposition

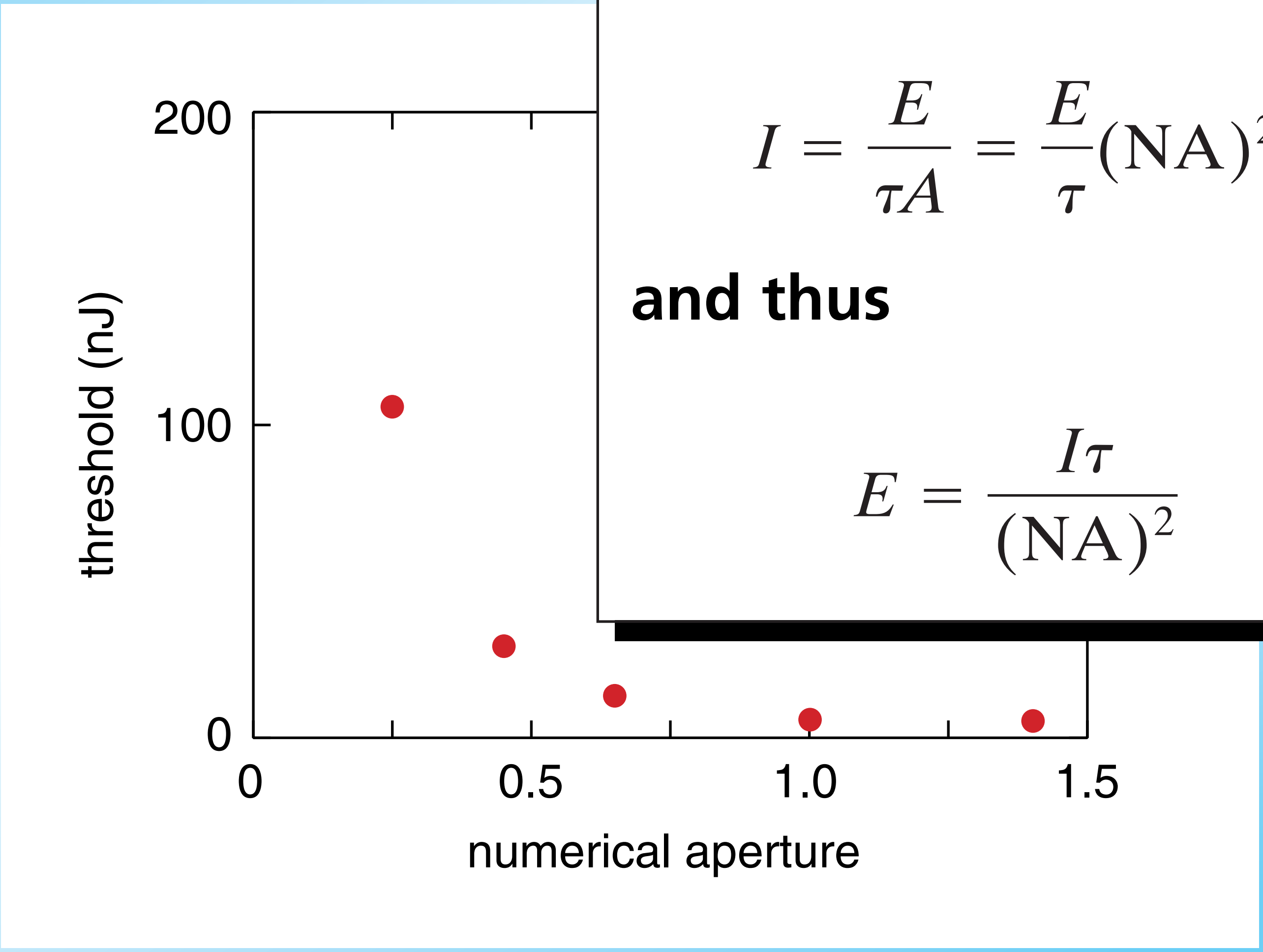


Energy deposition

vary numerical aperture in Corning 0211



Energy deposition



minimal self focusing, so spot size determined by:

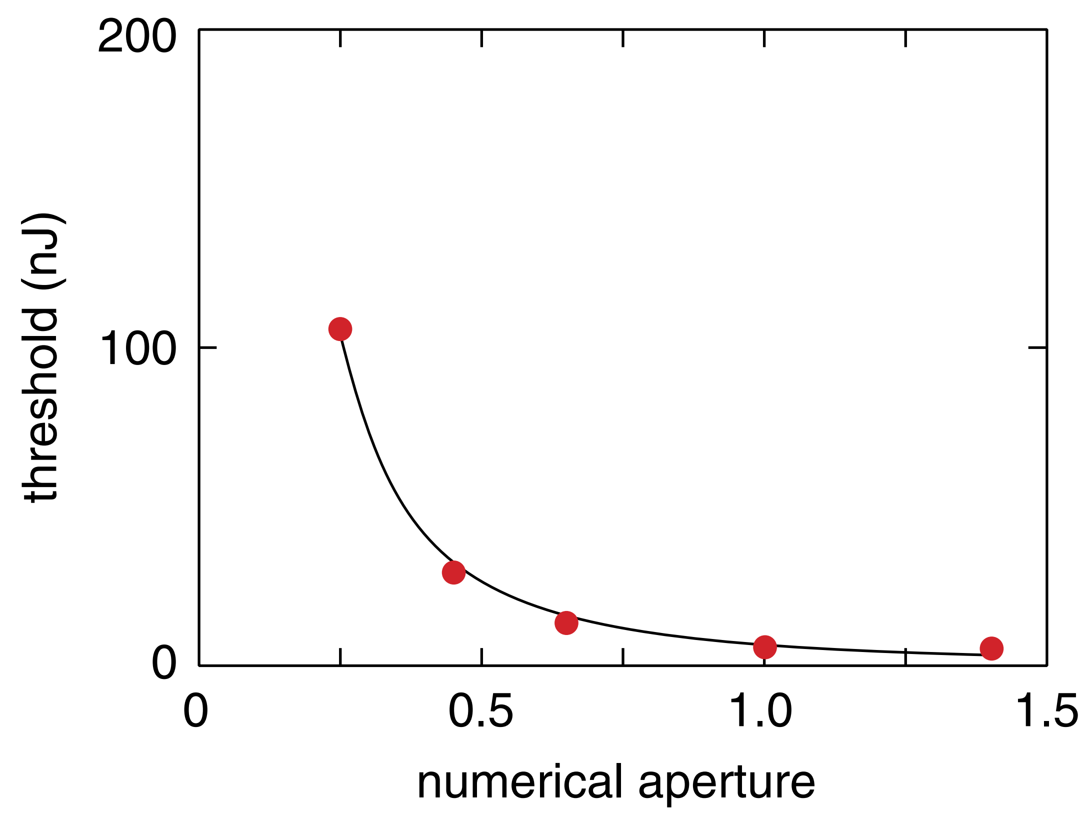
$$I = \frac{E}{\tau A} = \frac{E}{\tau}(\mathrm{NA})^2$$

and thus

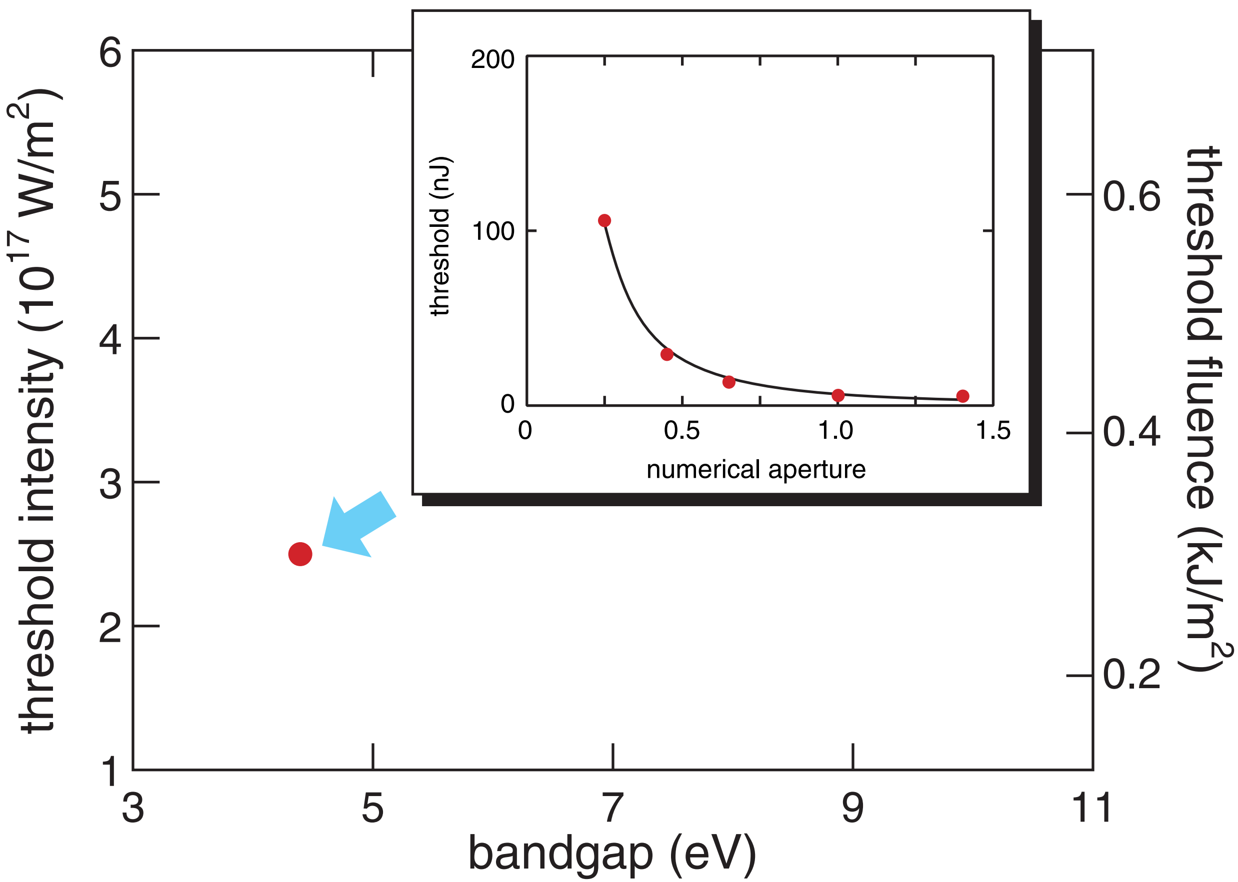
$$E = \frac{I\tau}{(\mathrm{NA})^2}$$

Energy deposition

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

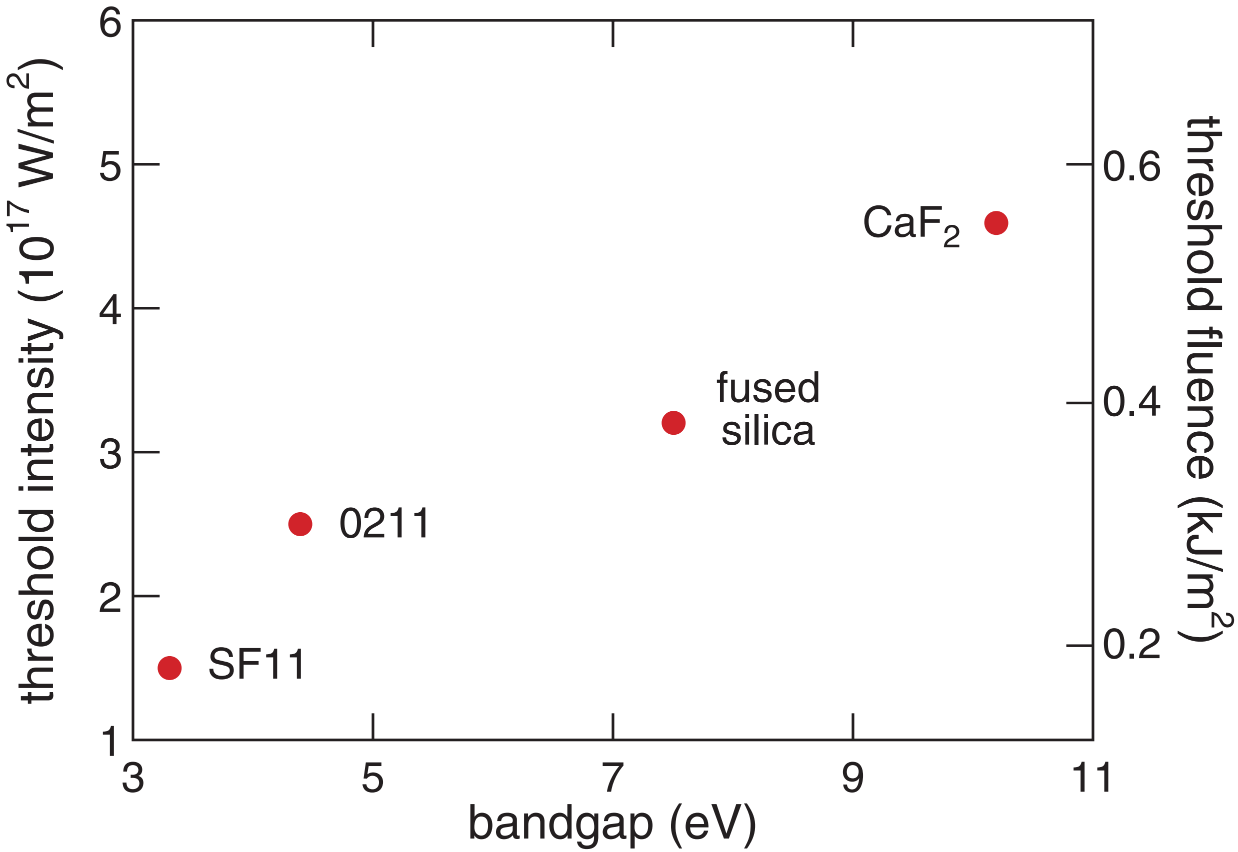


Energy deposition



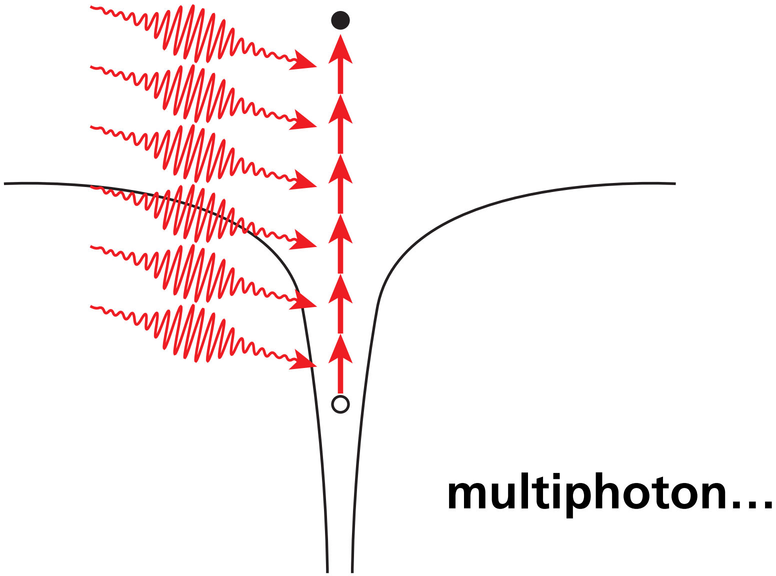
Energy deposition

vary material…



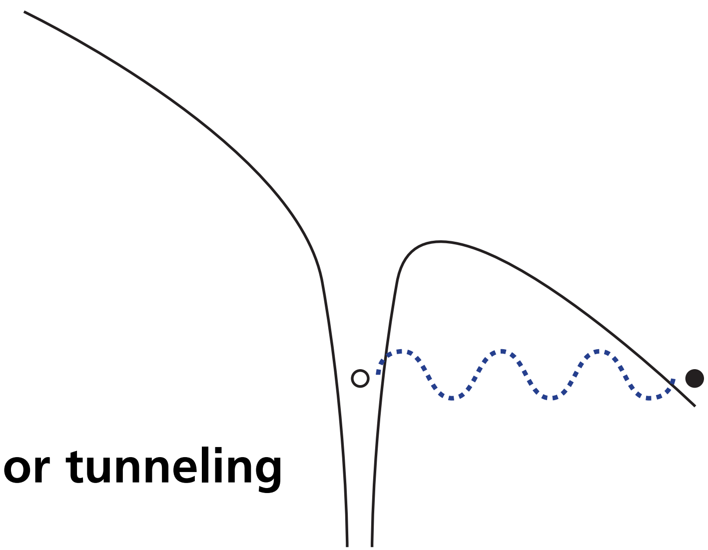
Energy deposition

laser field ionization



Energy deposition

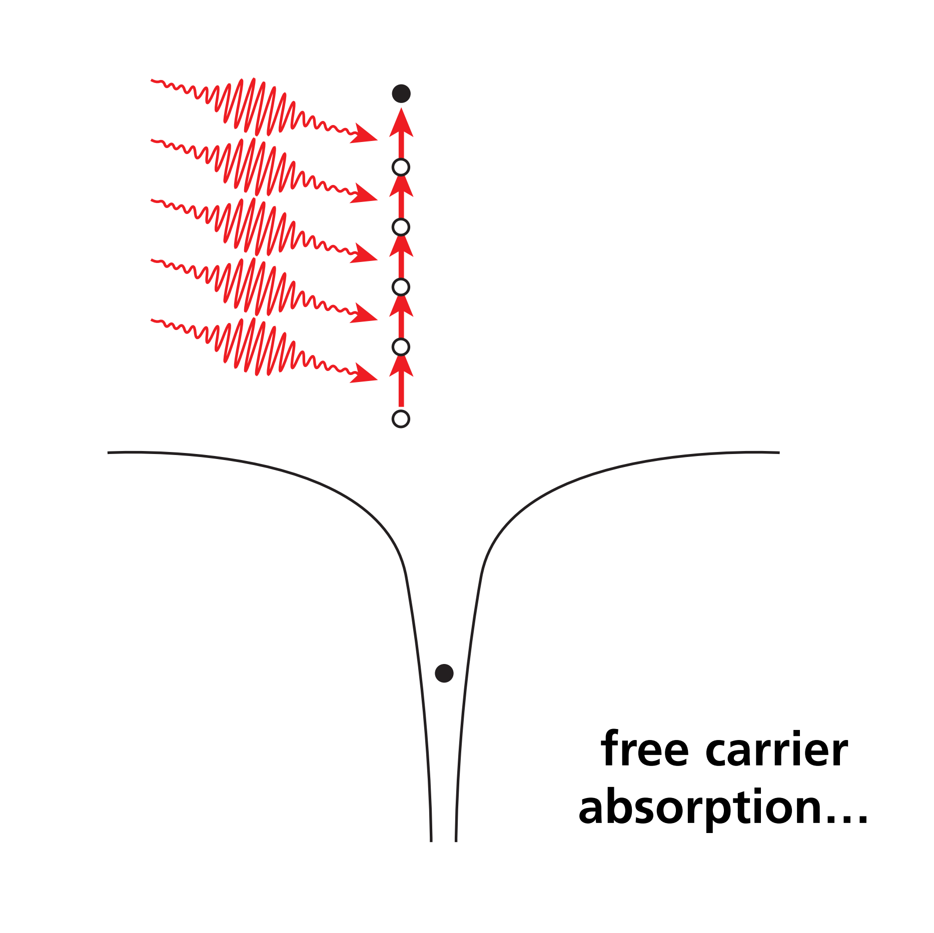
laser field ionization



...or tunneling

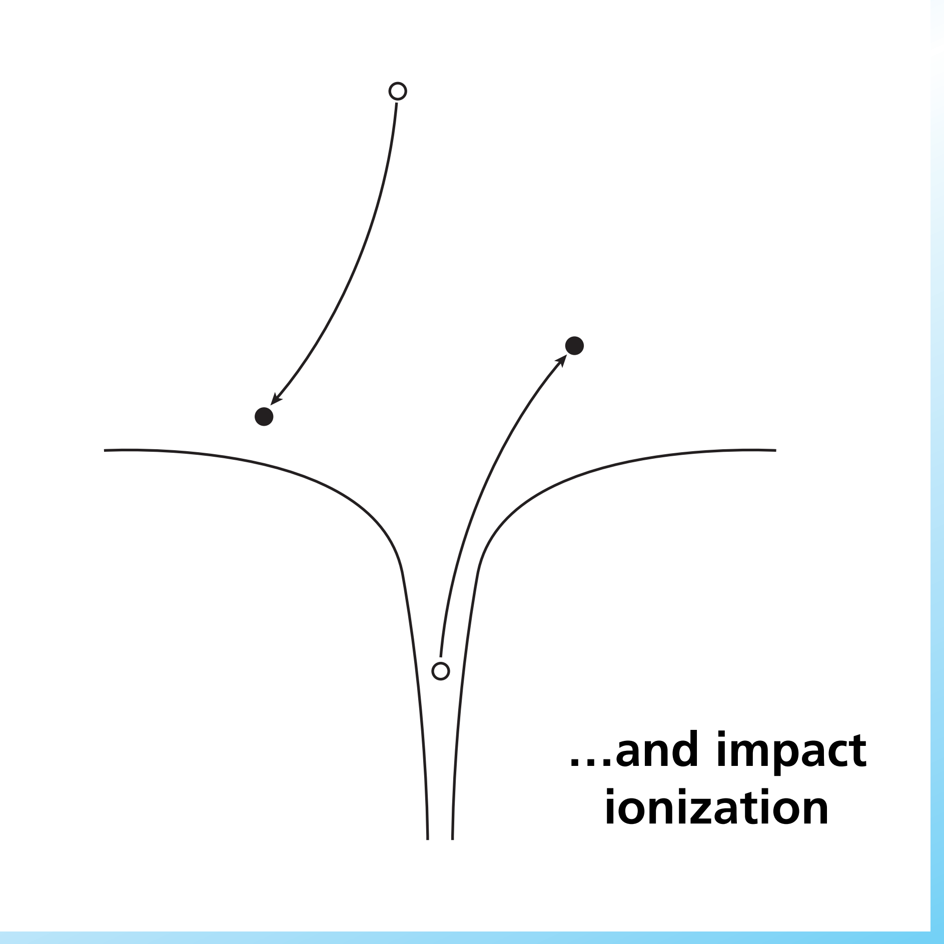
Energy deposition

avalanche ionization



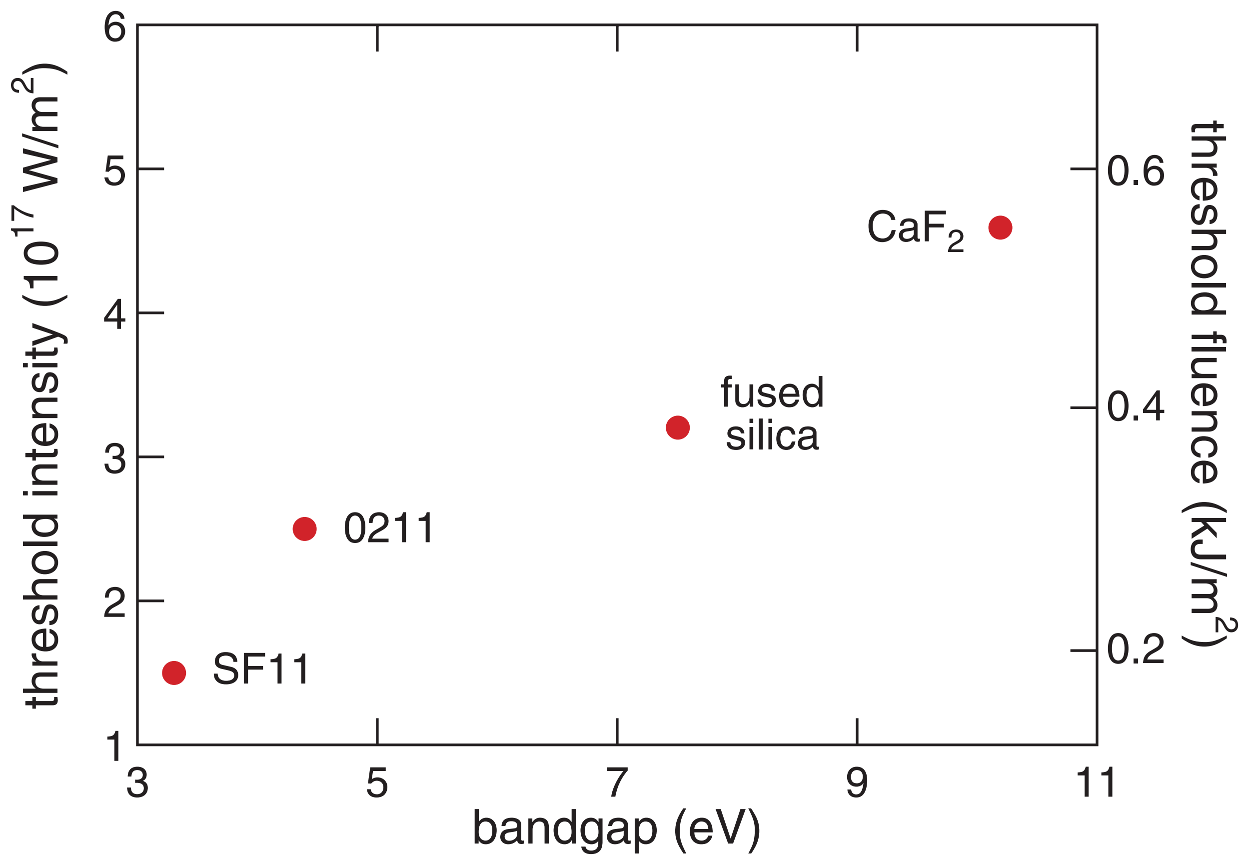
Energy deposition

avalanche ionization



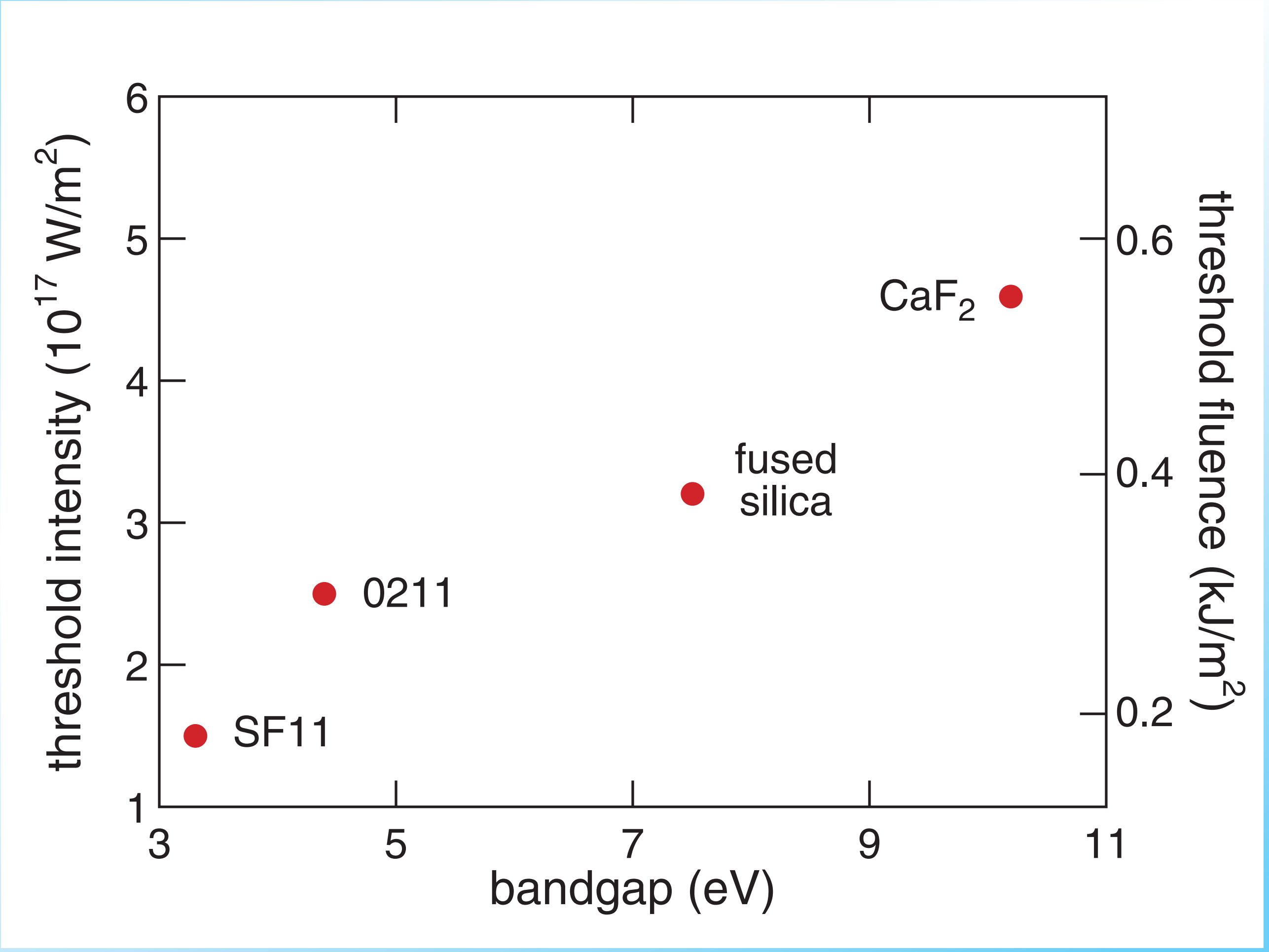
Energy deposition

threshold increases with bandgap...



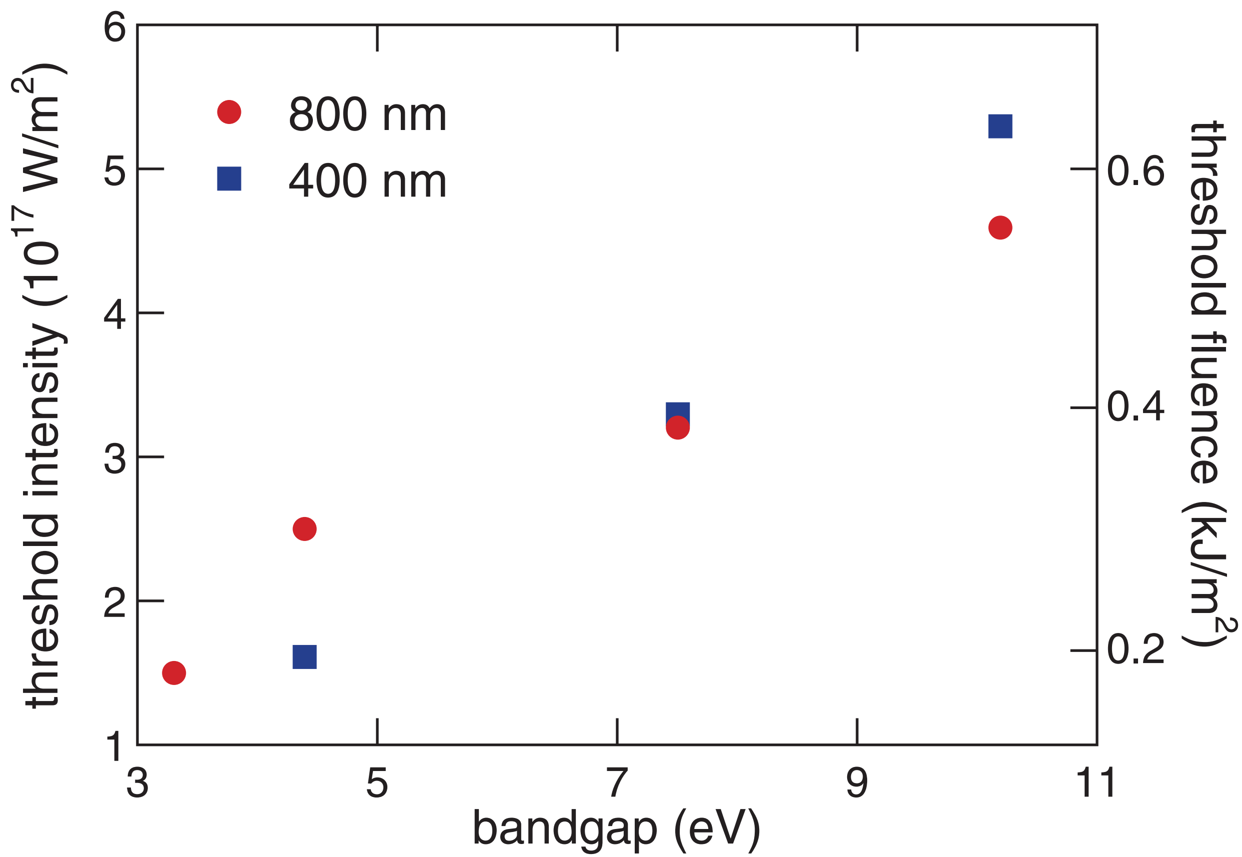
Energy deposition

…but not very much



Energy deposition

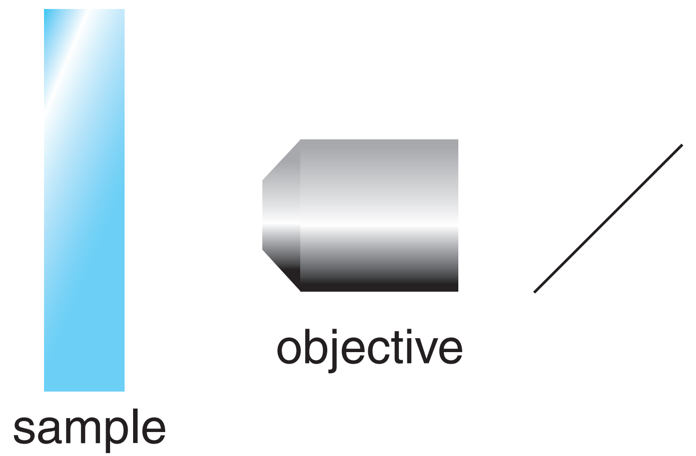
same trend at 400 nm



Outline

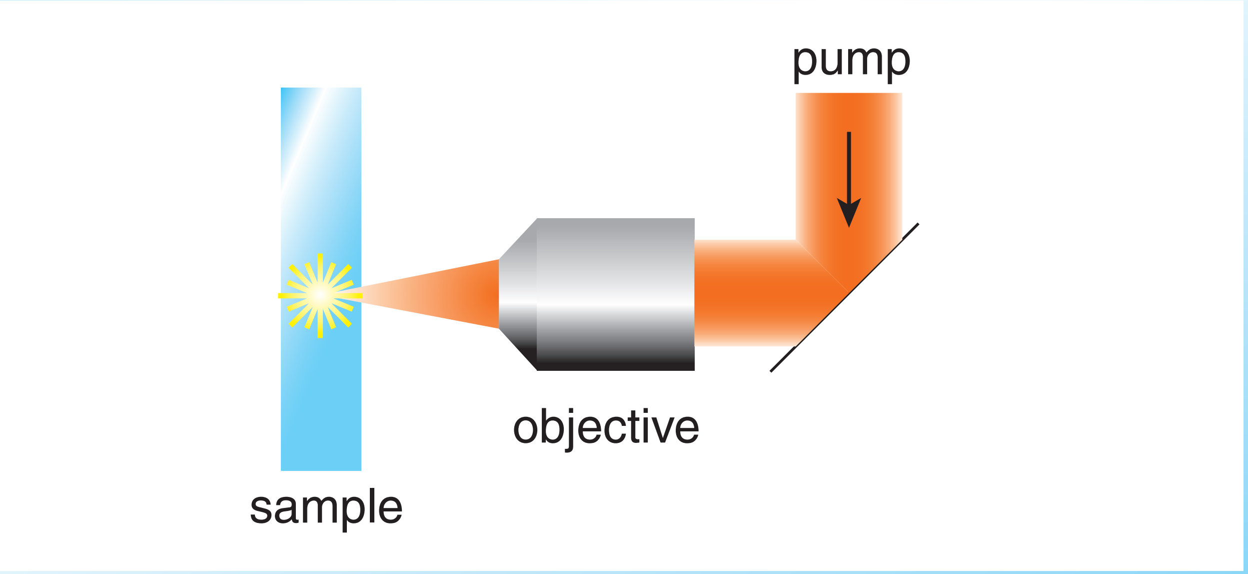
- Damage morphology
- Energy deposition
- **Dynamics**

imaging setup

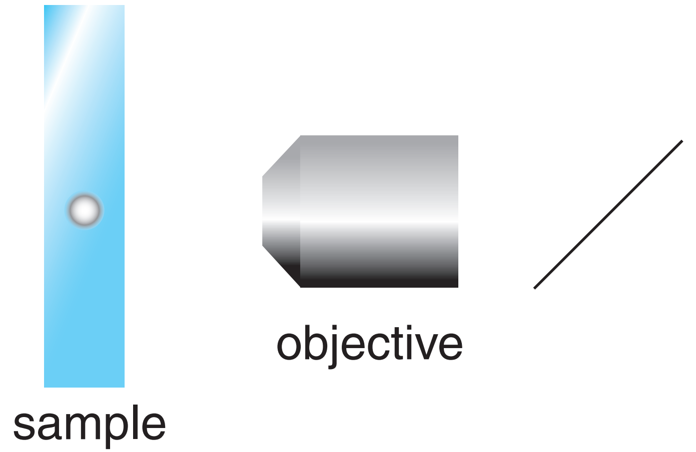


Dynamics

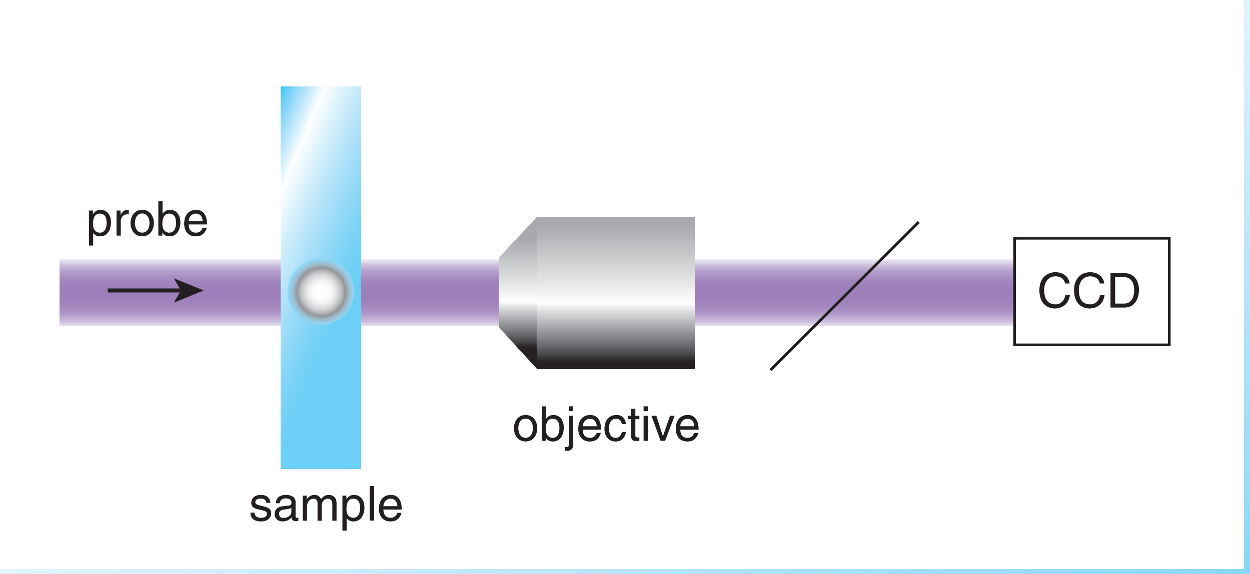
imaging setup



imaging setup



imaging setup



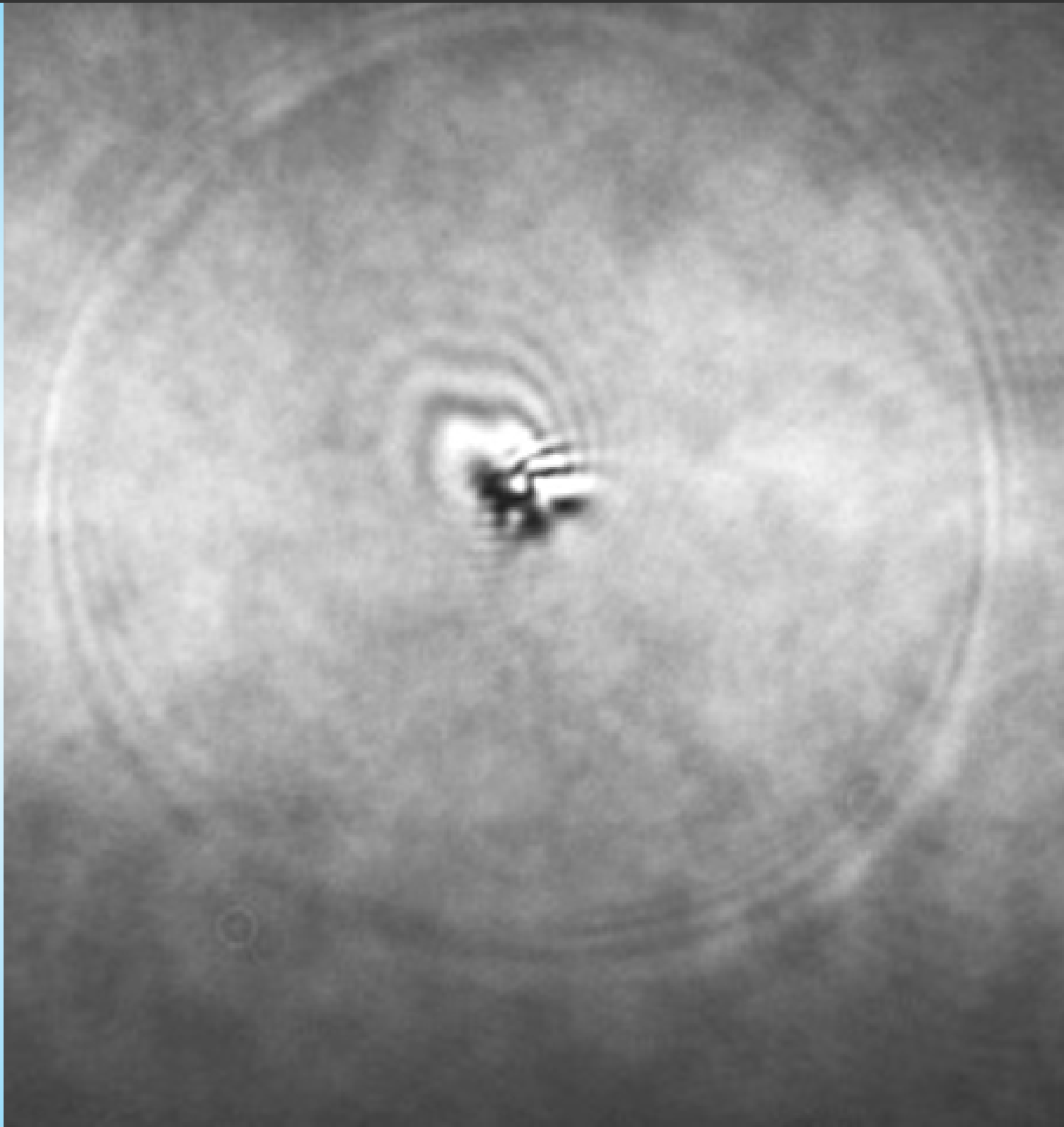
Dynamics

sapphire

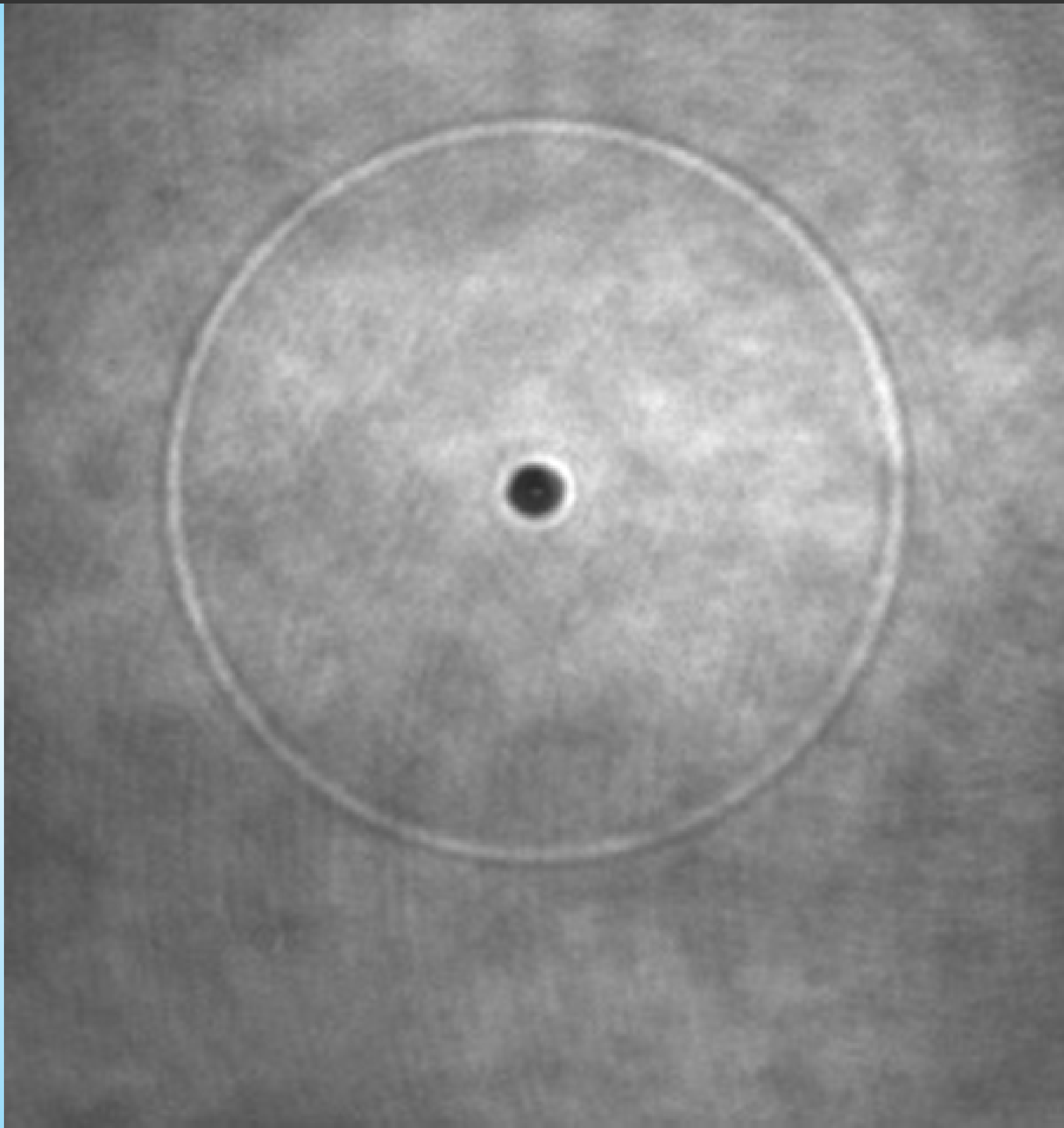
3 μJ pulse

3.8 ns delay

40 μm radius



Dynamics



water ("self-healing")

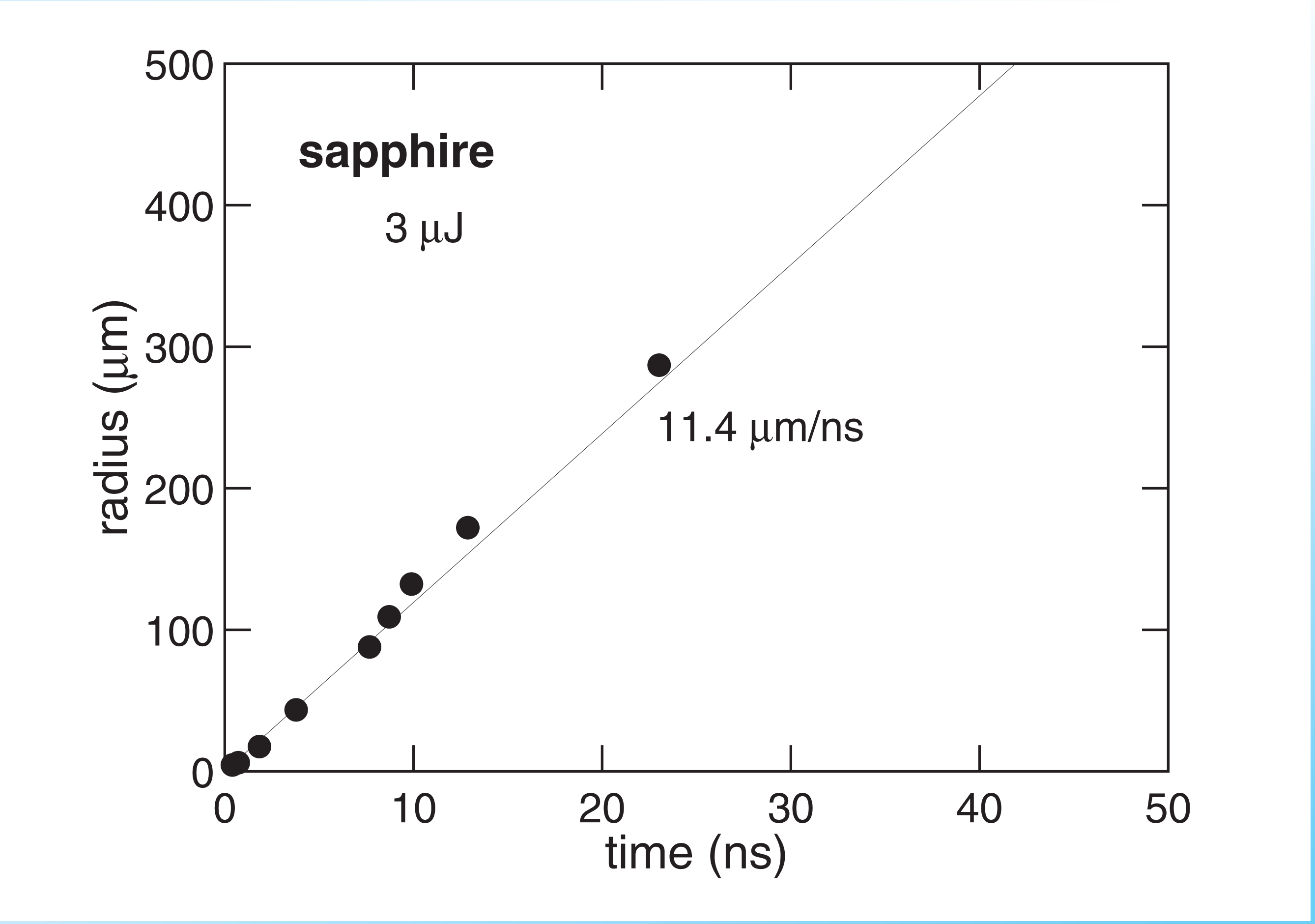
1.0 µJ pulse

35 ns delay

58 µm radius

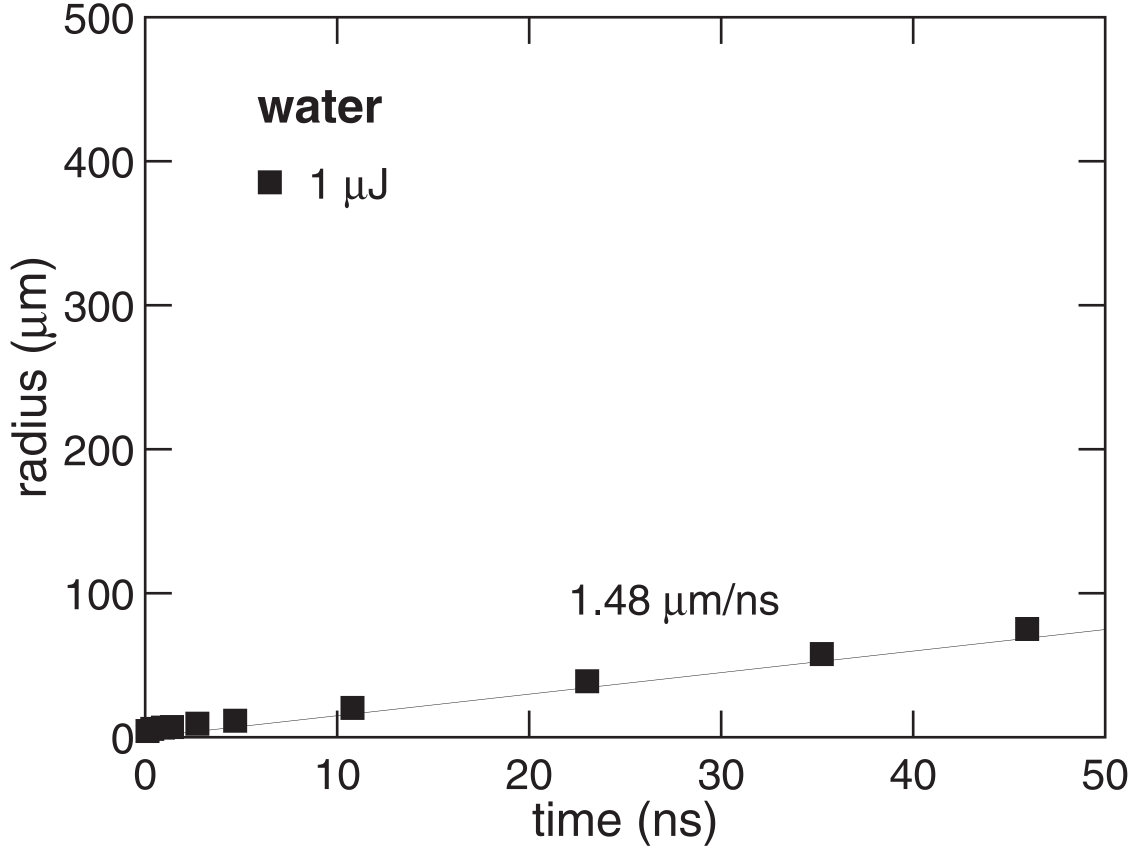
Dynamics

Dynamics



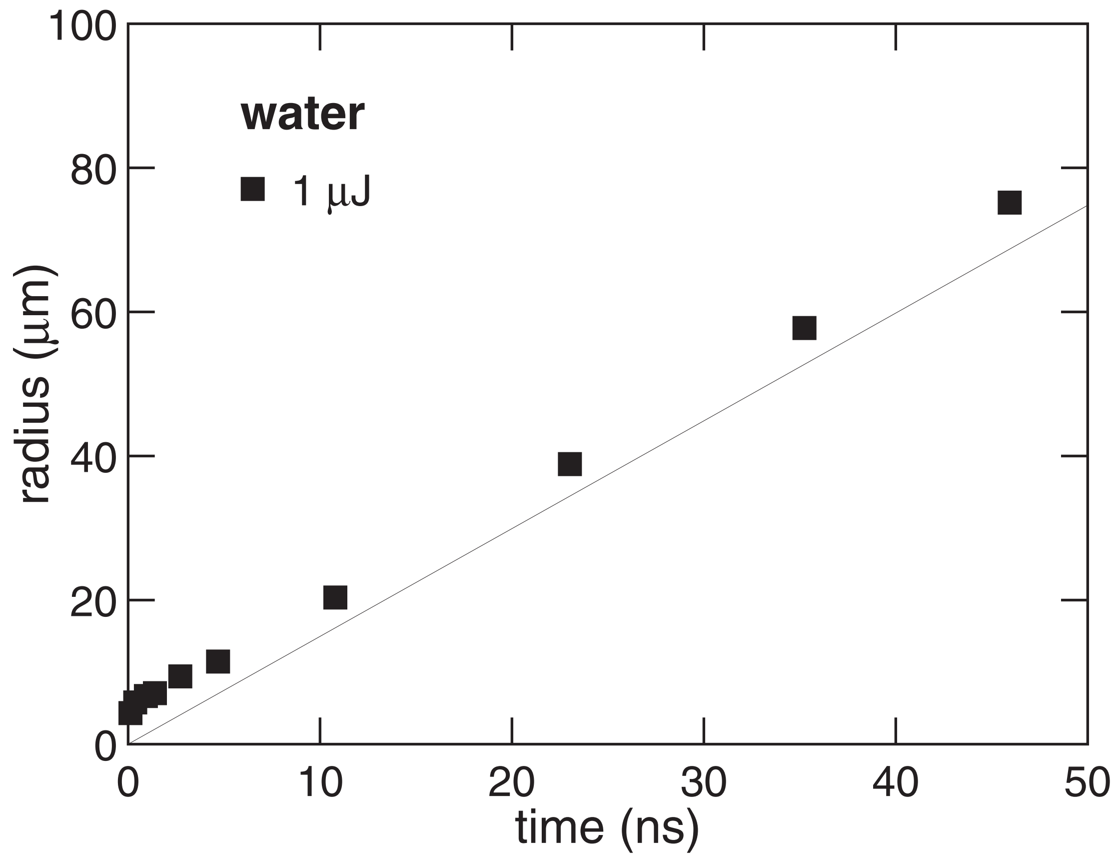
sapphire
3 μJ
11.4 μm/ns
radius (μm)
time (ns)
0
100
200
300
400
500
0
10
20
30
40
50

Dynamics

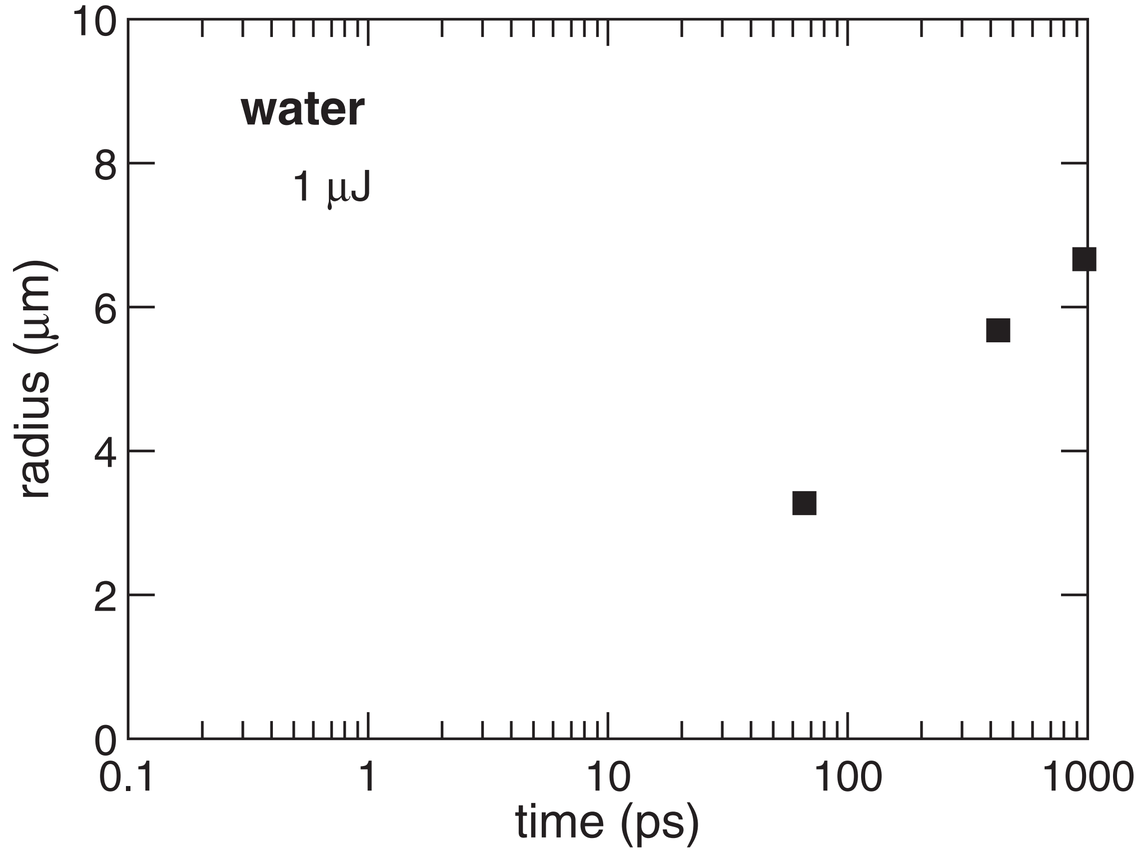


water
1 μJ
1.48 μm/ns
radius (μm)
time (ns)
0
100
200
300
400
500
0
10
20
30
40
50

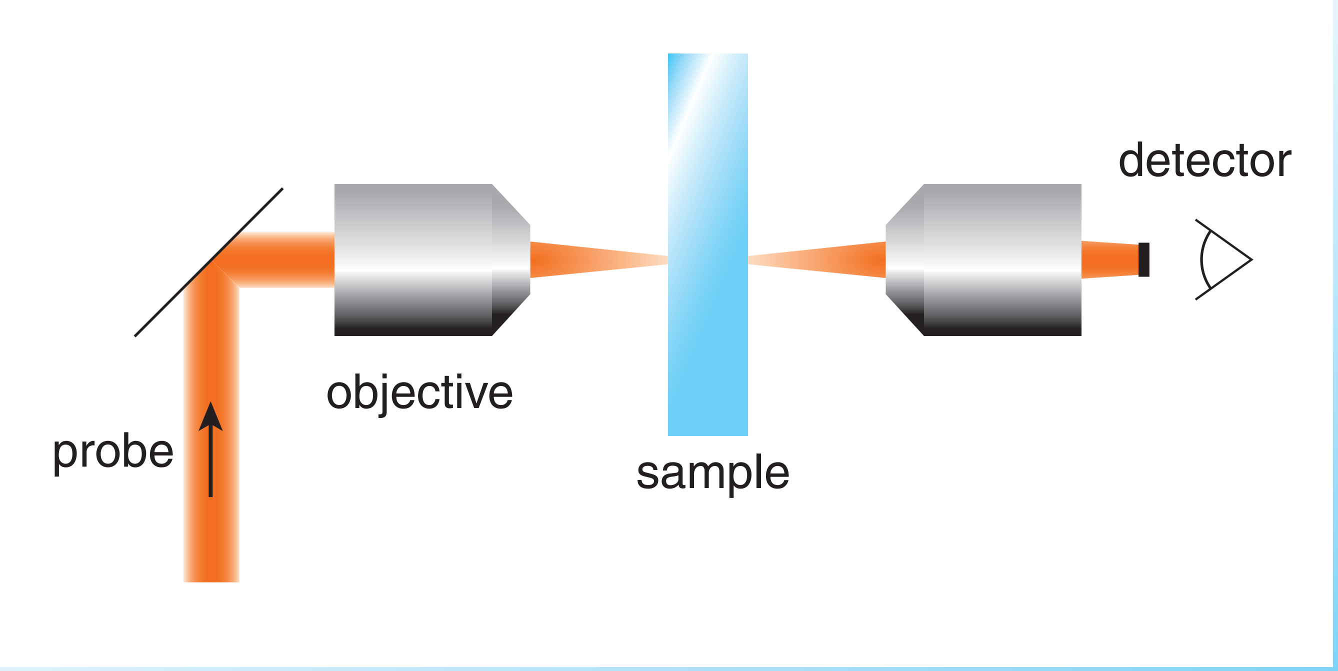
Dynamics



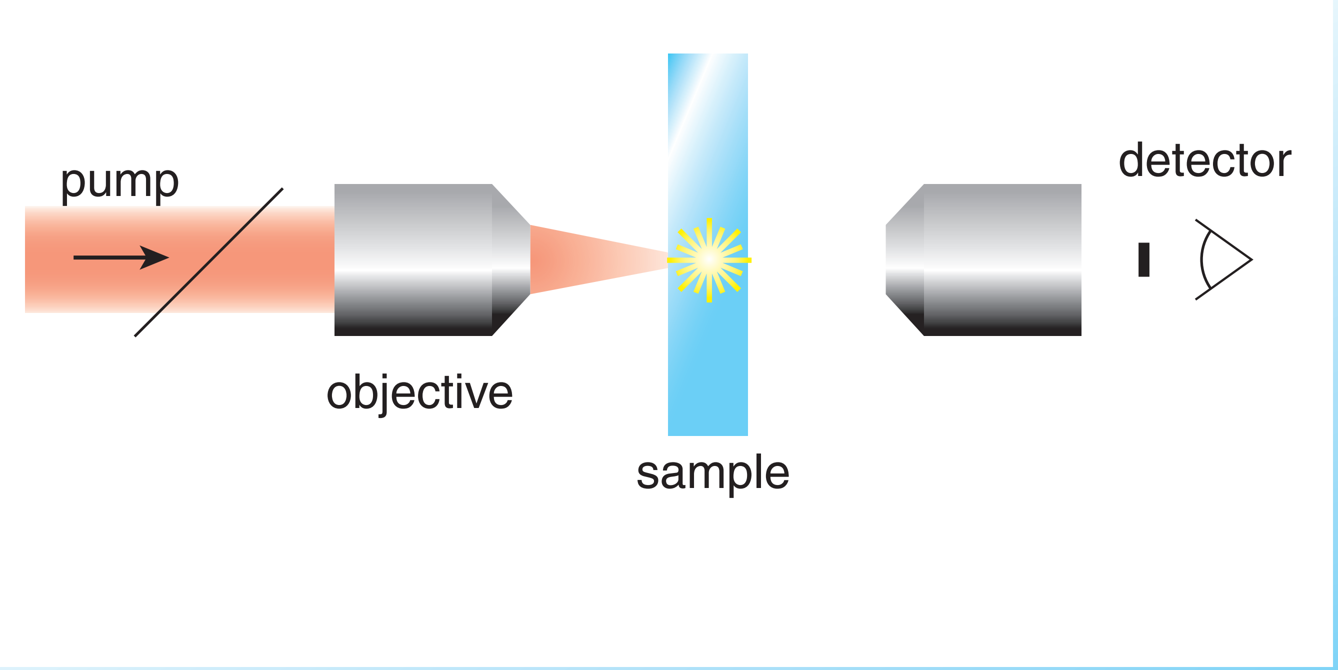
Dynamics



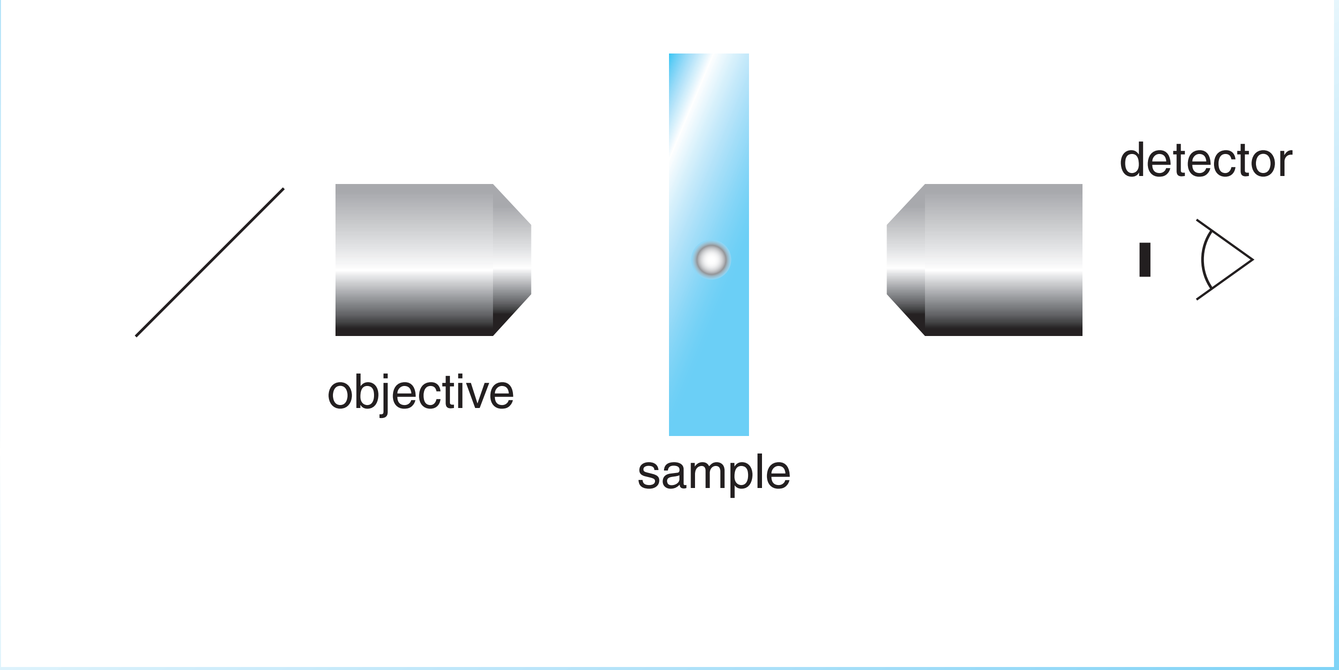
time-resolved scattering setup



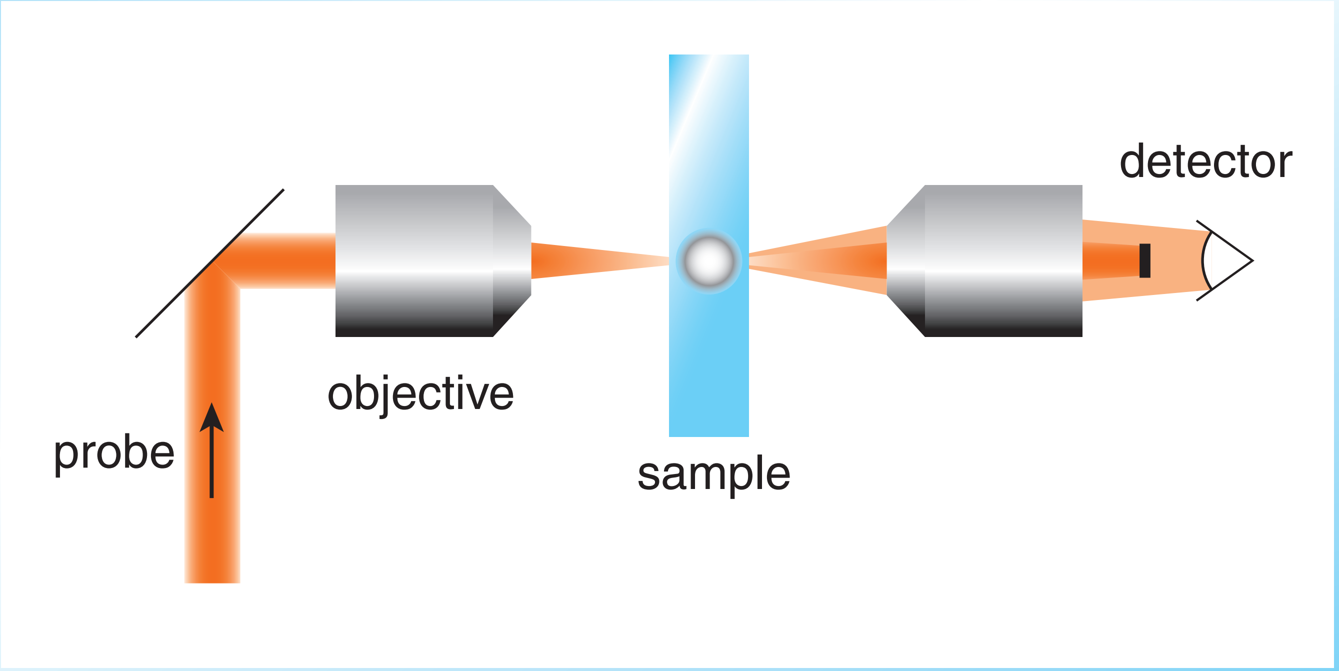
time-resolved scattering setup



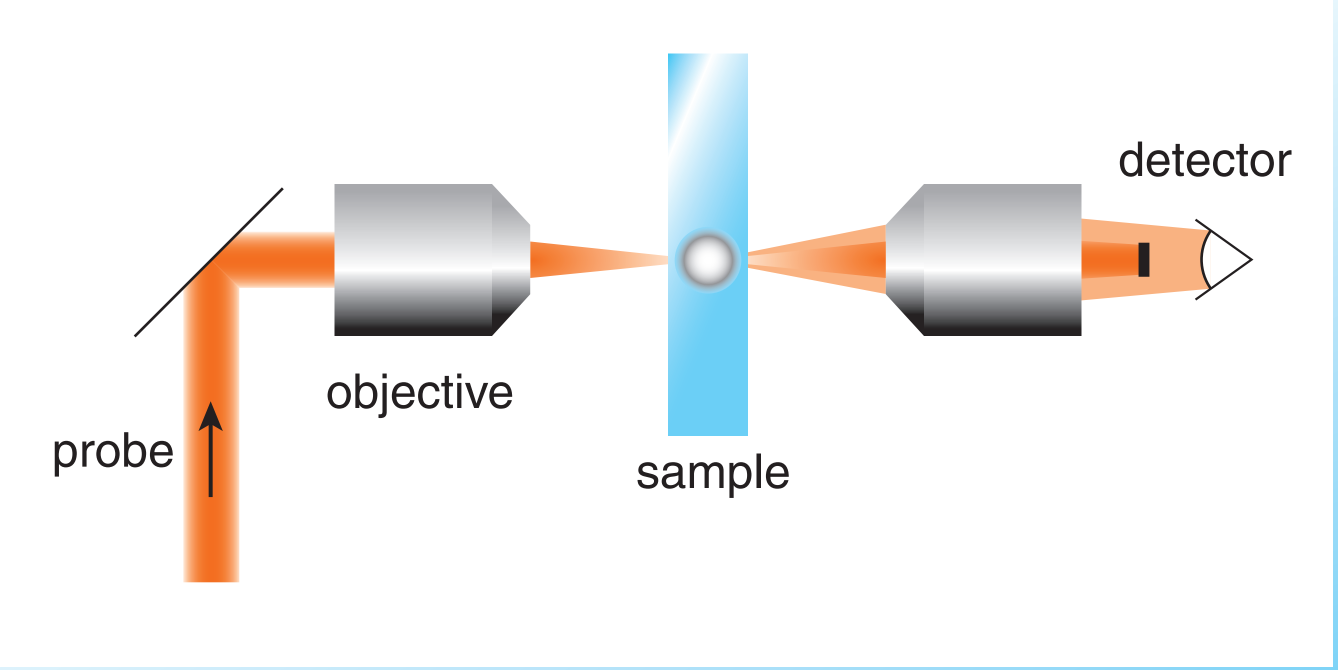
time-resolved scattering setup



time-resolved scattering setup

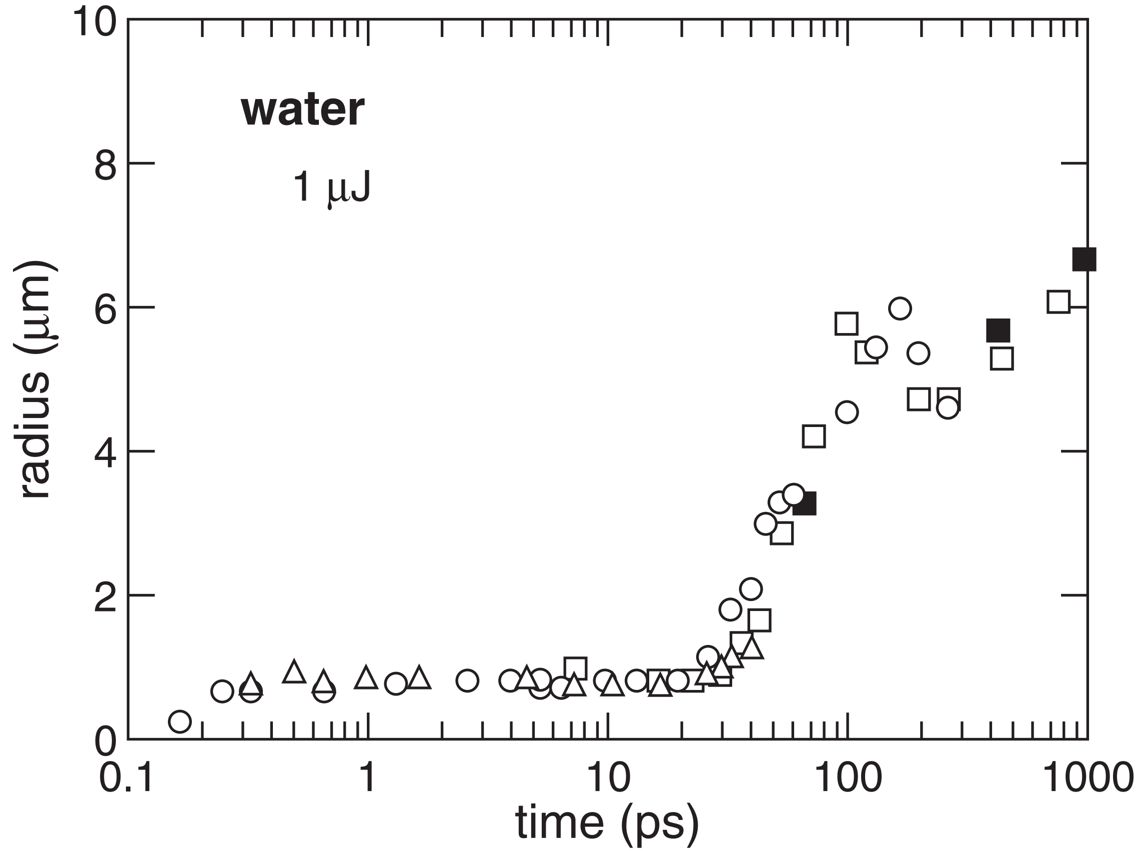


time-resolved scattering setup

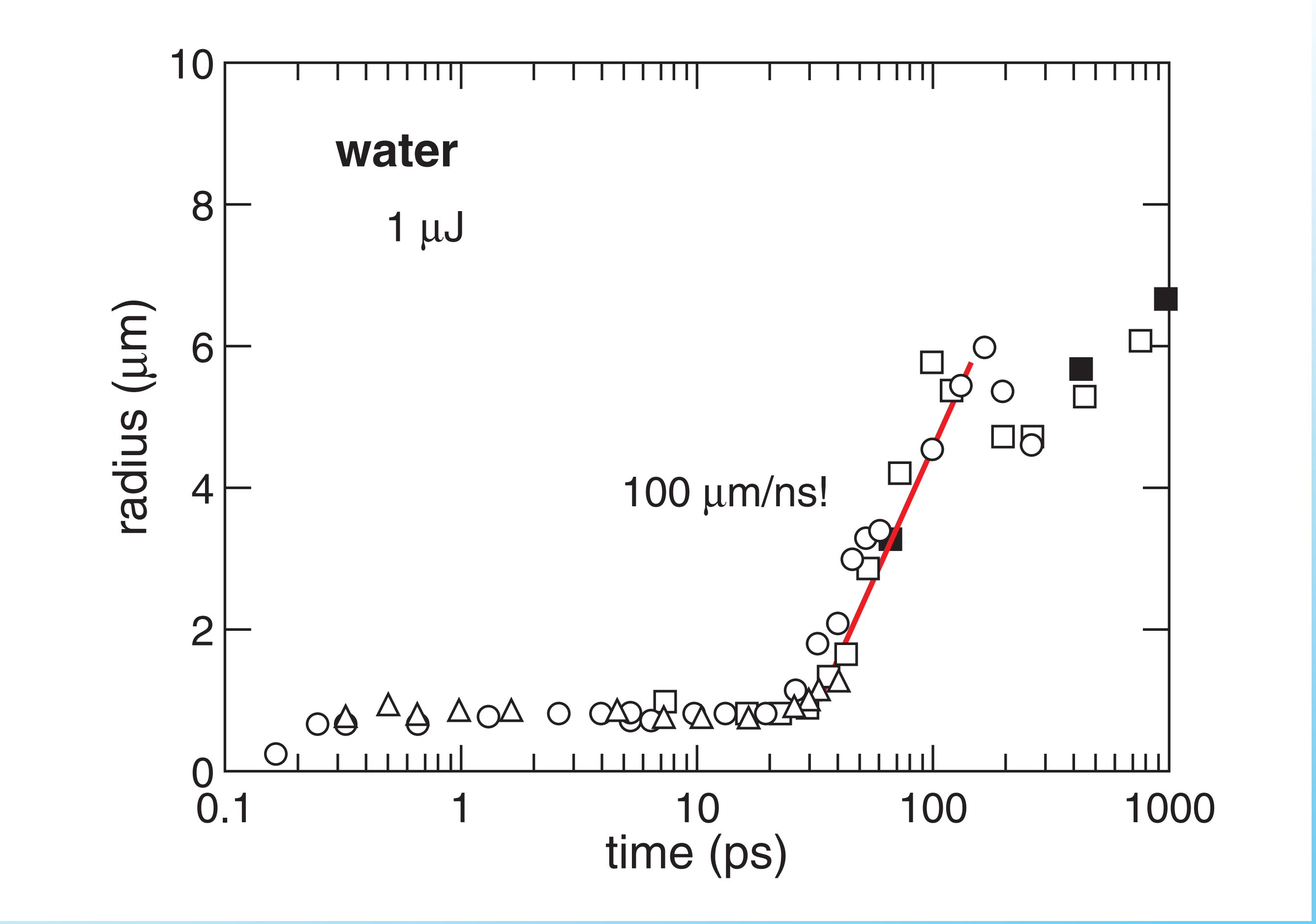


signal proportional to area of scatterer

Dynamics



Dynamics

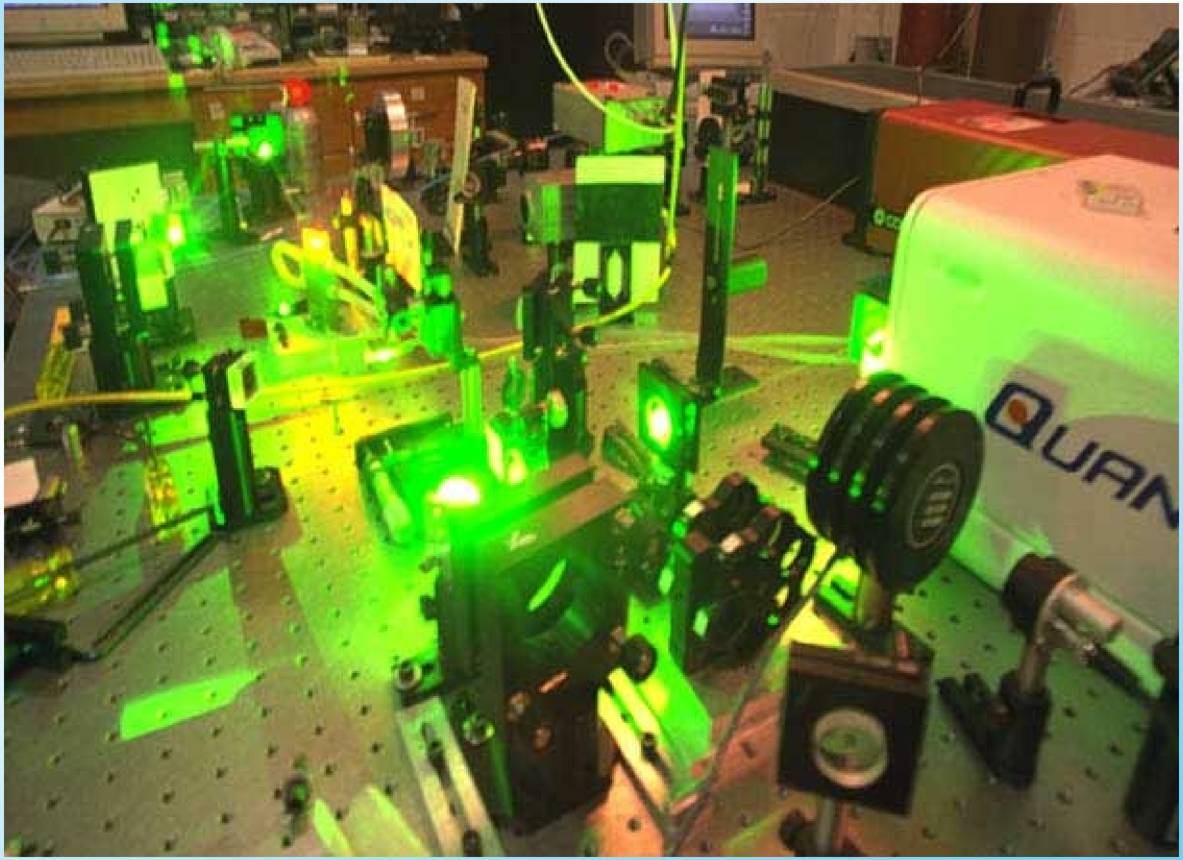


Conclusions

- submicron-scale bulk micromachining
- weak bandgap and wavelength dependence
- only a few nanojoules required

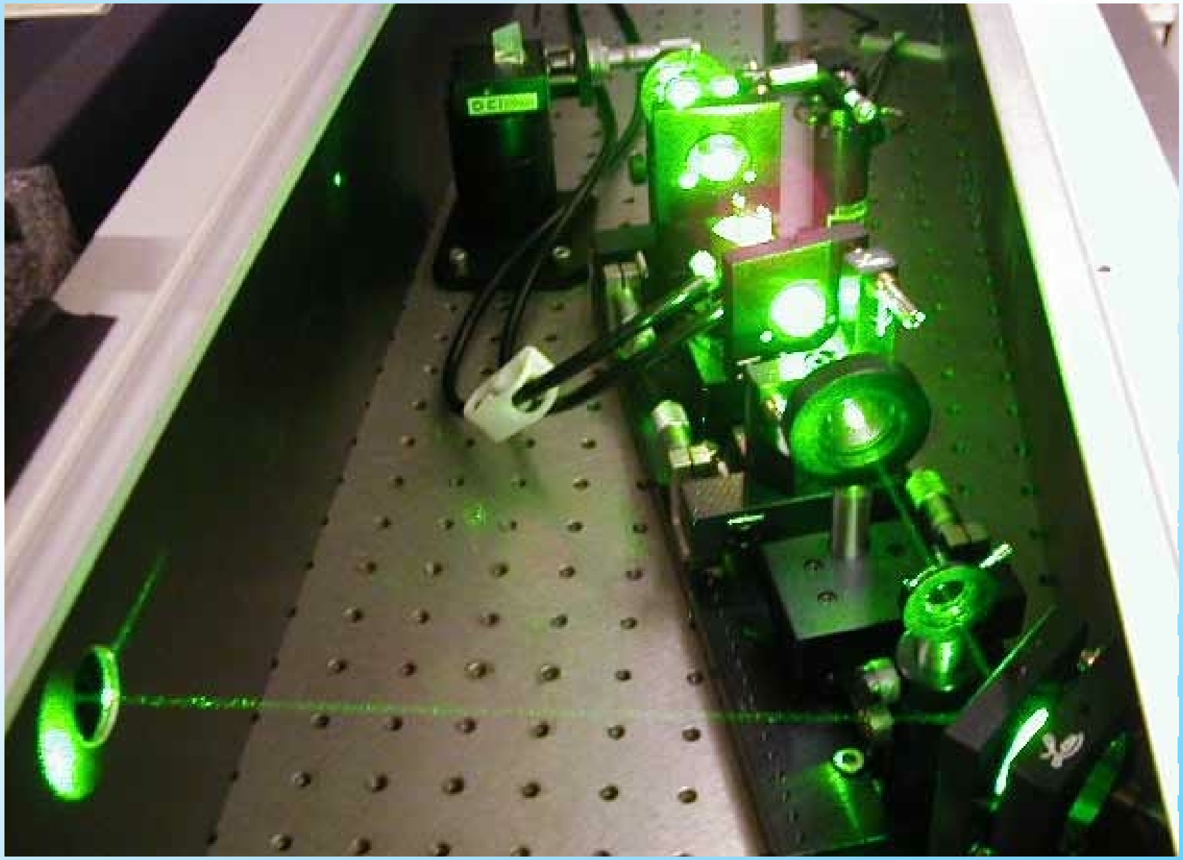
Laser micromachining simplified

5-nJ threshold: unamplified micromachining



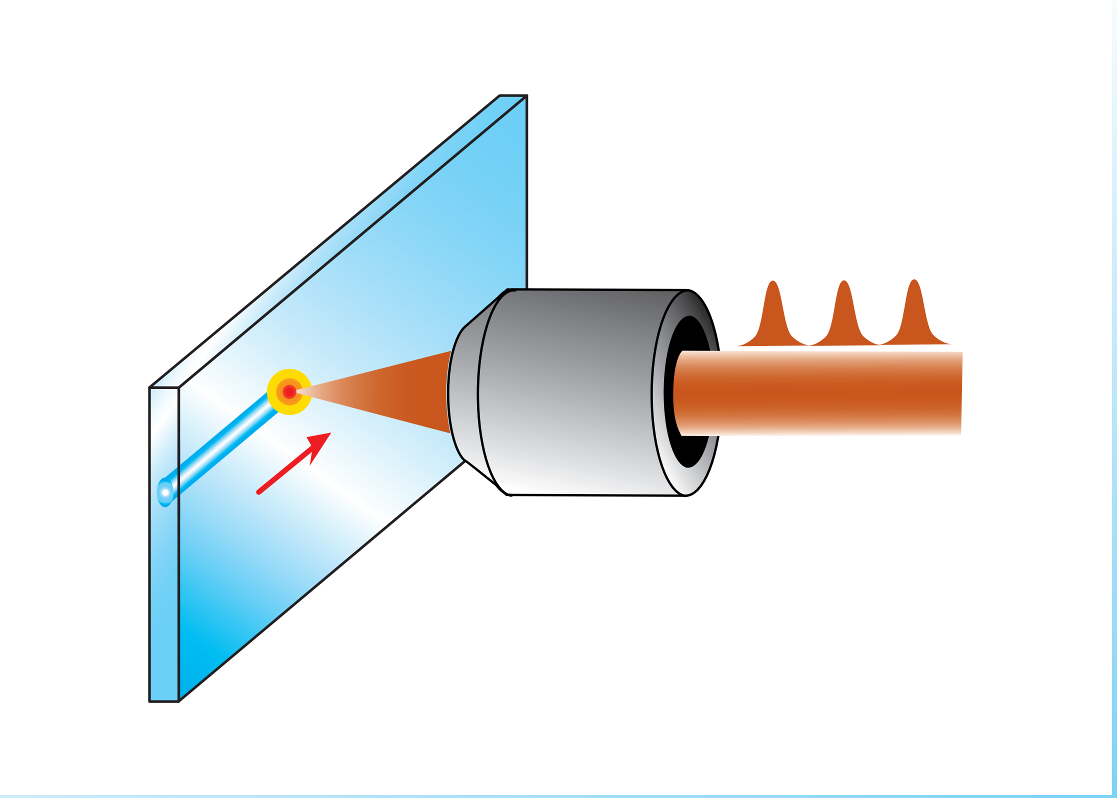
Laser micromachining simplified

5-nJ threshold: unamplified micromachining



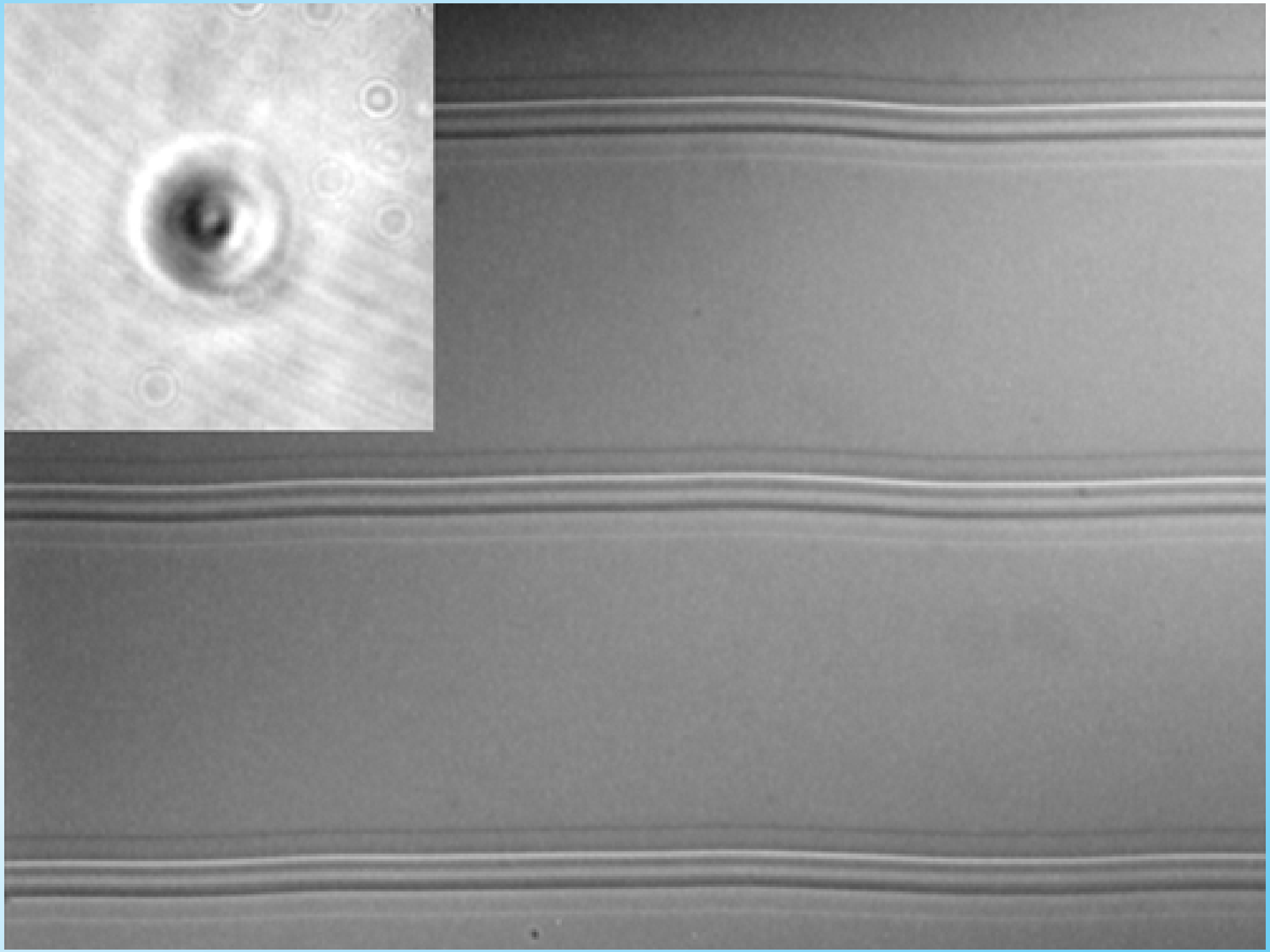
Laser micromachining simplified

waveguide machining



Laser micromachining simplified

waveguide machining



Future applications

- **Photonic devices**

Future applications

- **Photonic devices**
- **Wavelength-selective splitter**

Future applications

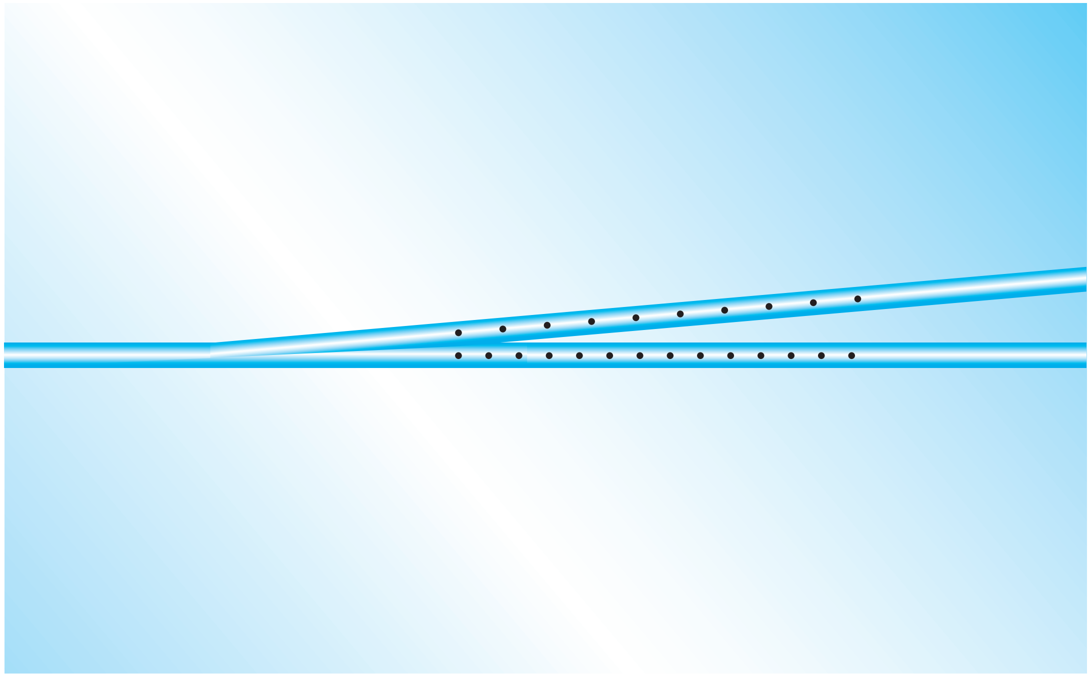
wavelength selective splitter

Future applications

wavelength selective splitter

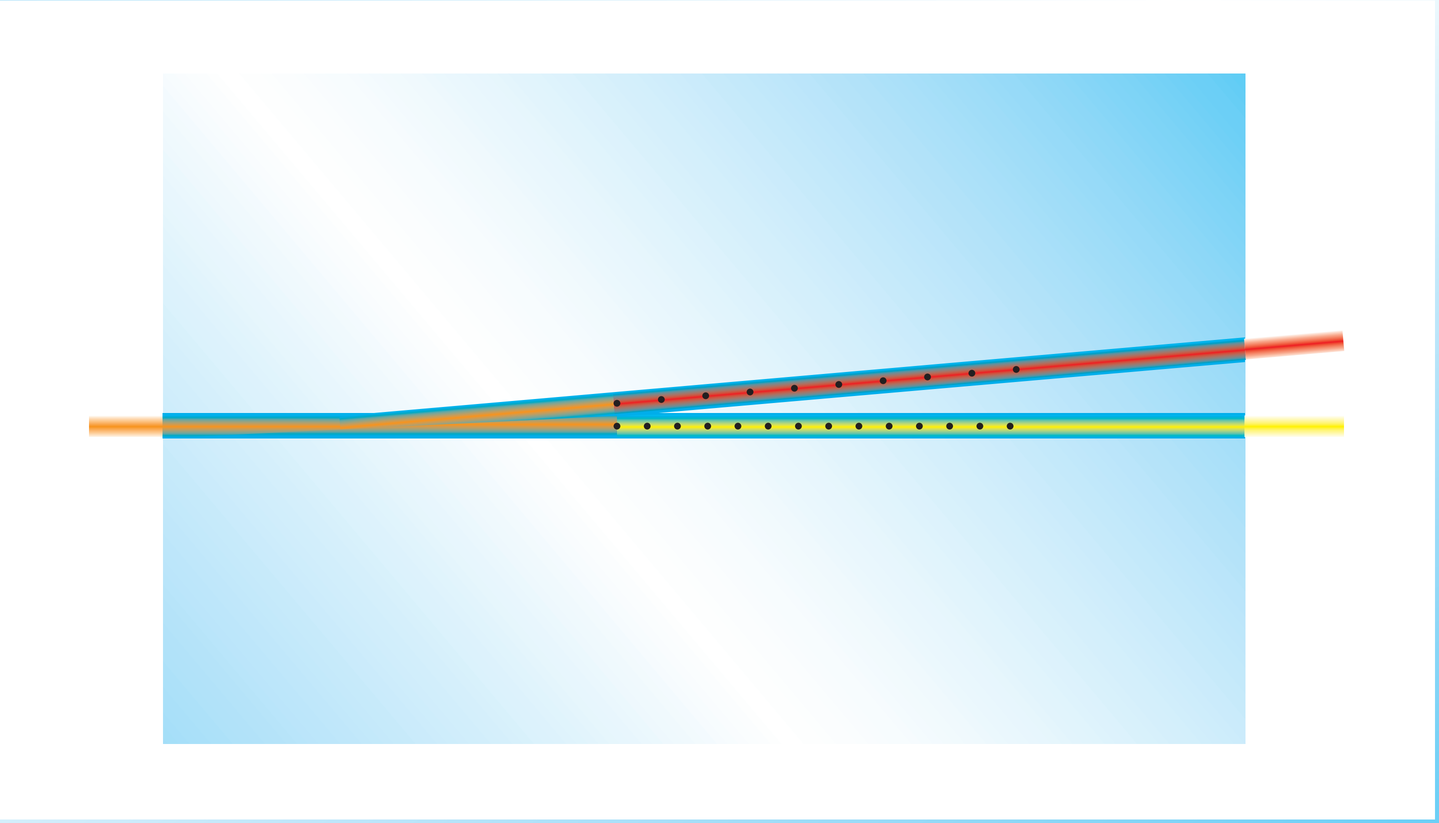
Future applications

wavelength selective splitter



Future applications

wavelength selective splitter



Future applications

- **Photonic devices**
- **Wavelength-selective splitter**
- **Photonic bandgap materials**


GORDON McKAY
LABORATORY OF
APPLIED SCIENCE

Funding: National Science Foundation

Acknowledgments:
Prof. Alex Gaeta (Cornell)
Prof. Nico Bloembergen (Harvard)
Carl Zeiss, Inc.

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

http://mazur-www.harvard.edu