Laser-Induced Microexplosions: creating stellar conditions on an optical bench

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André Brodeur
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Hong Kong University
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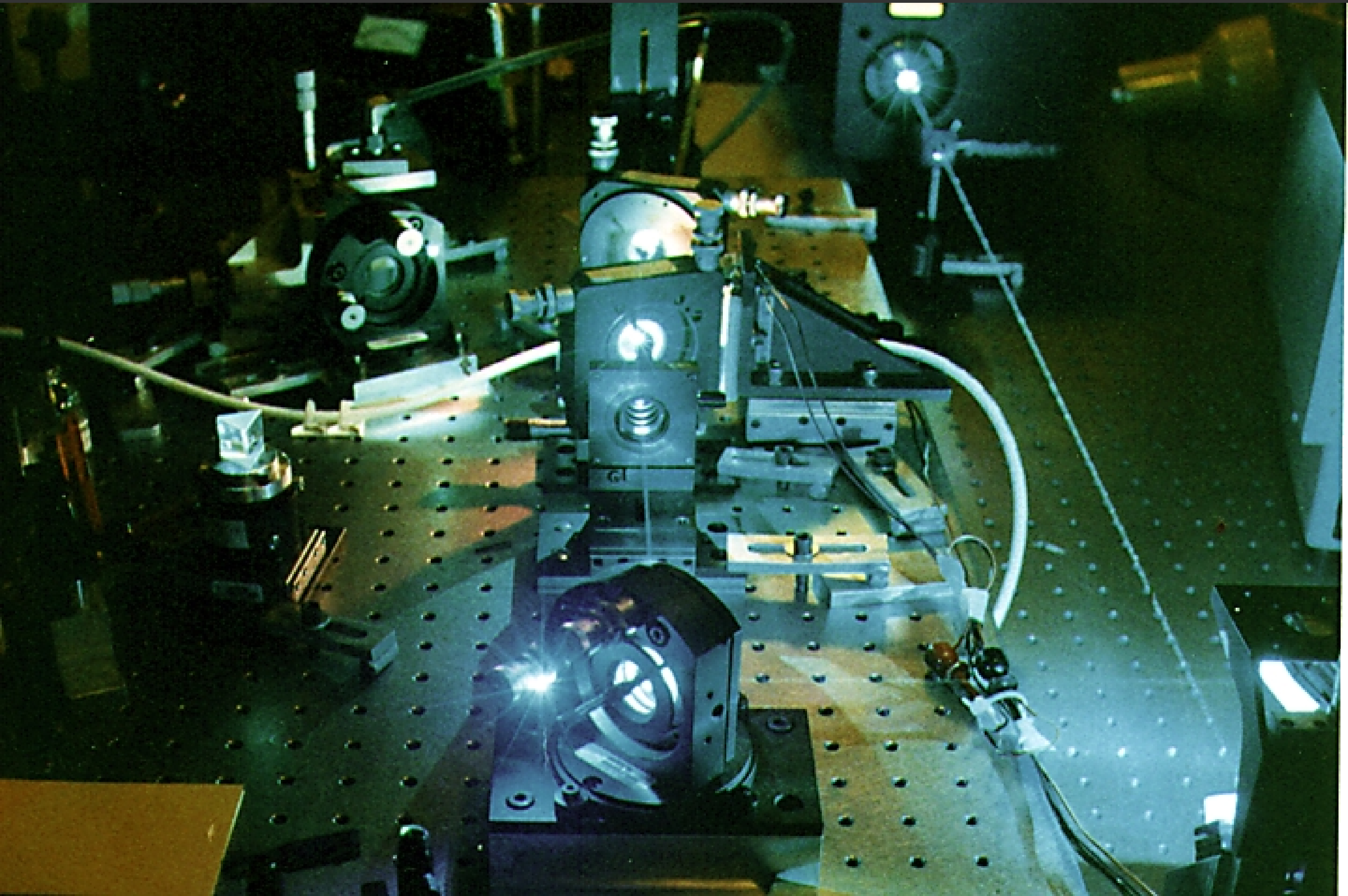
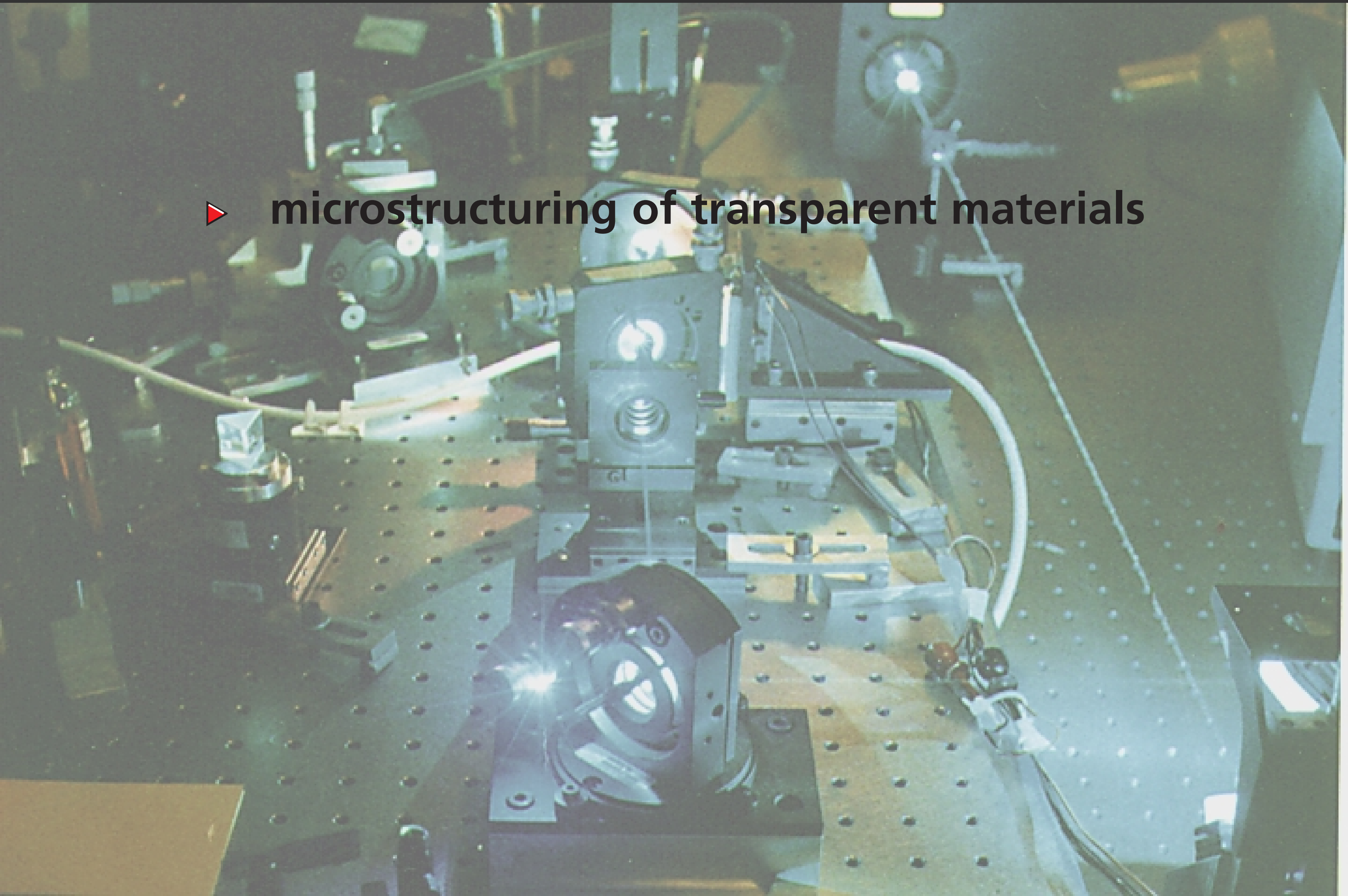
Introduction

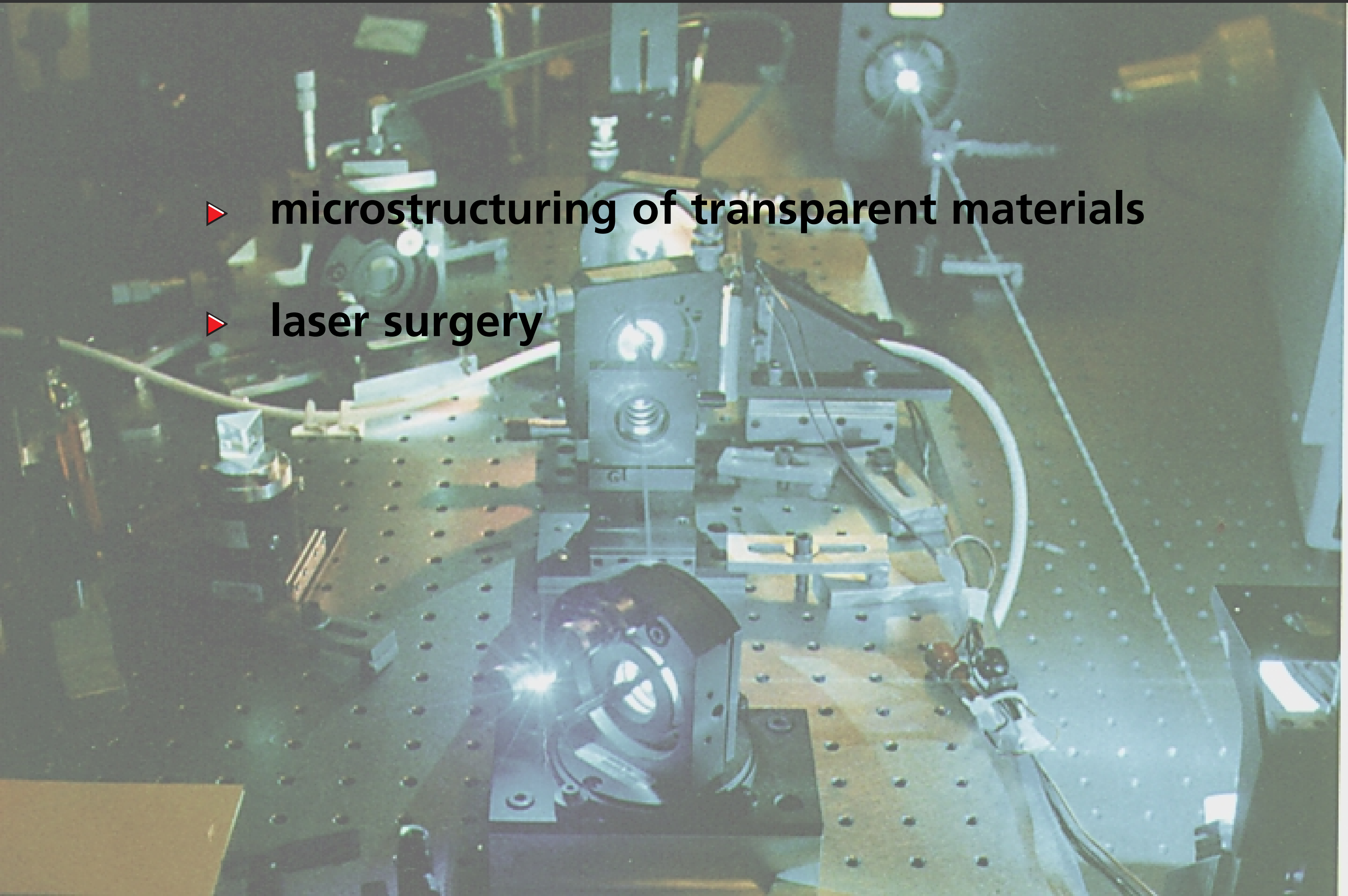


Introduction

- microstructuring of transparent materials



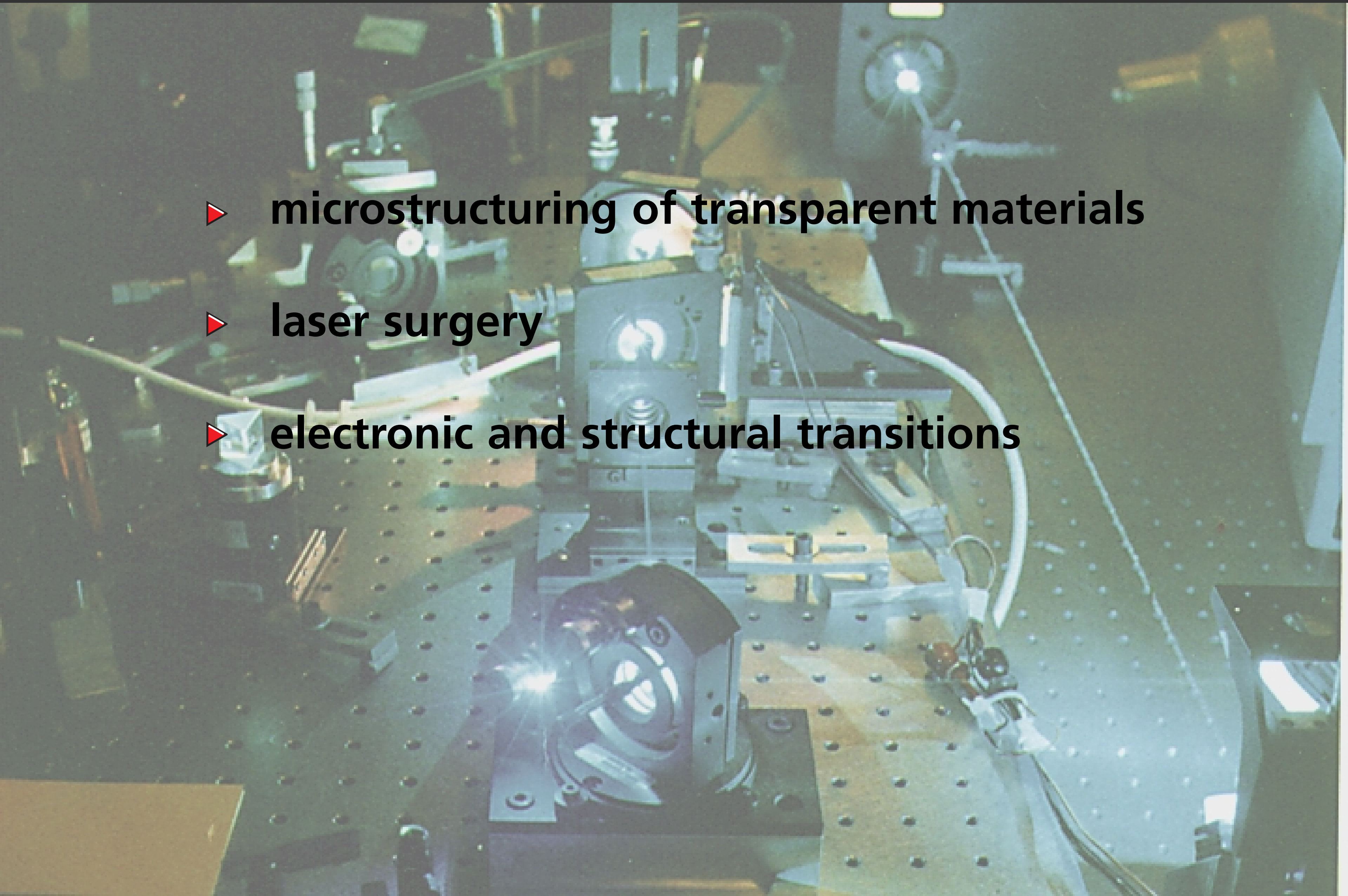
Introduction



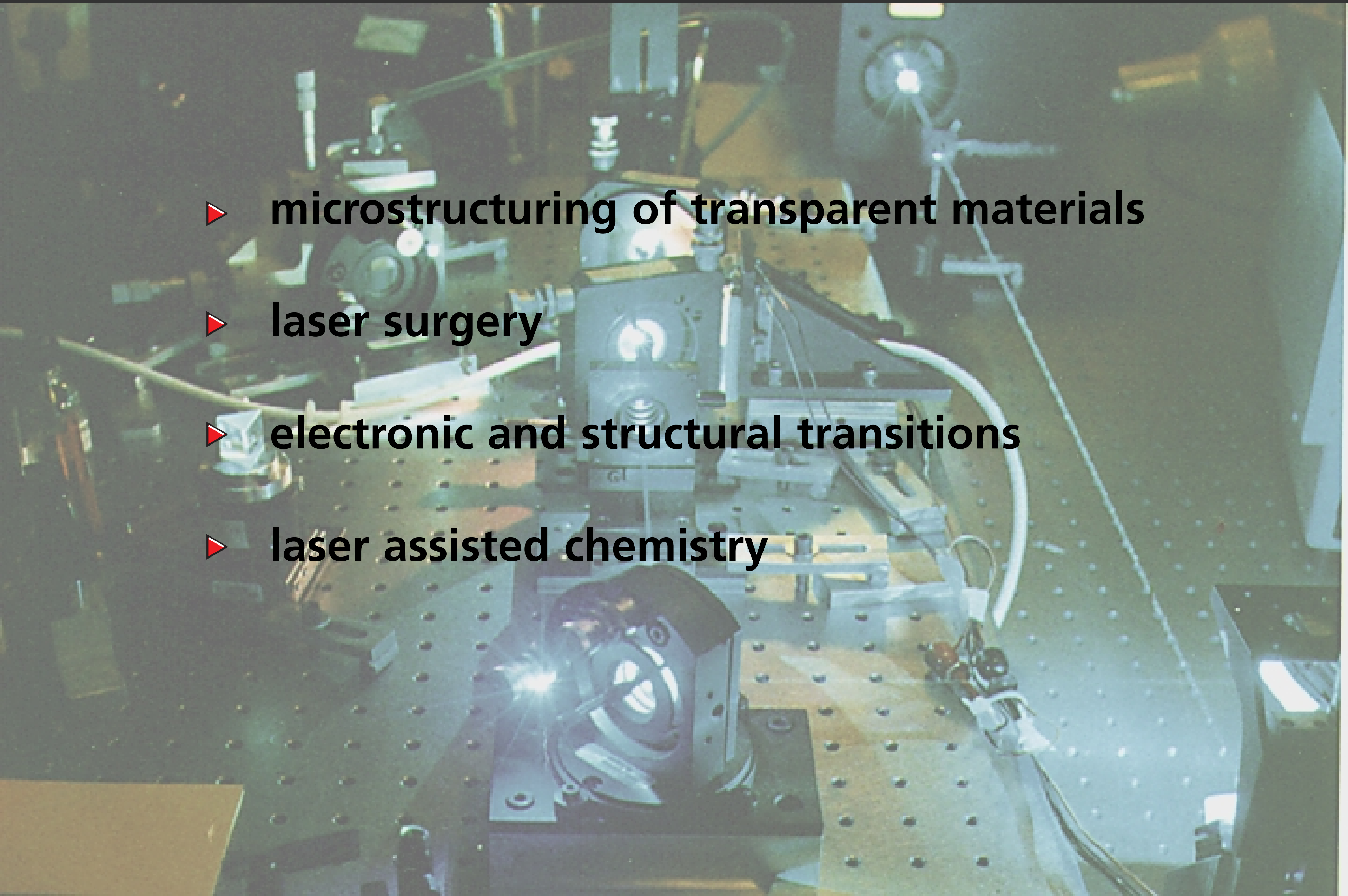
- microstructuring of transparent materials
- laser surgery

Introduction

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

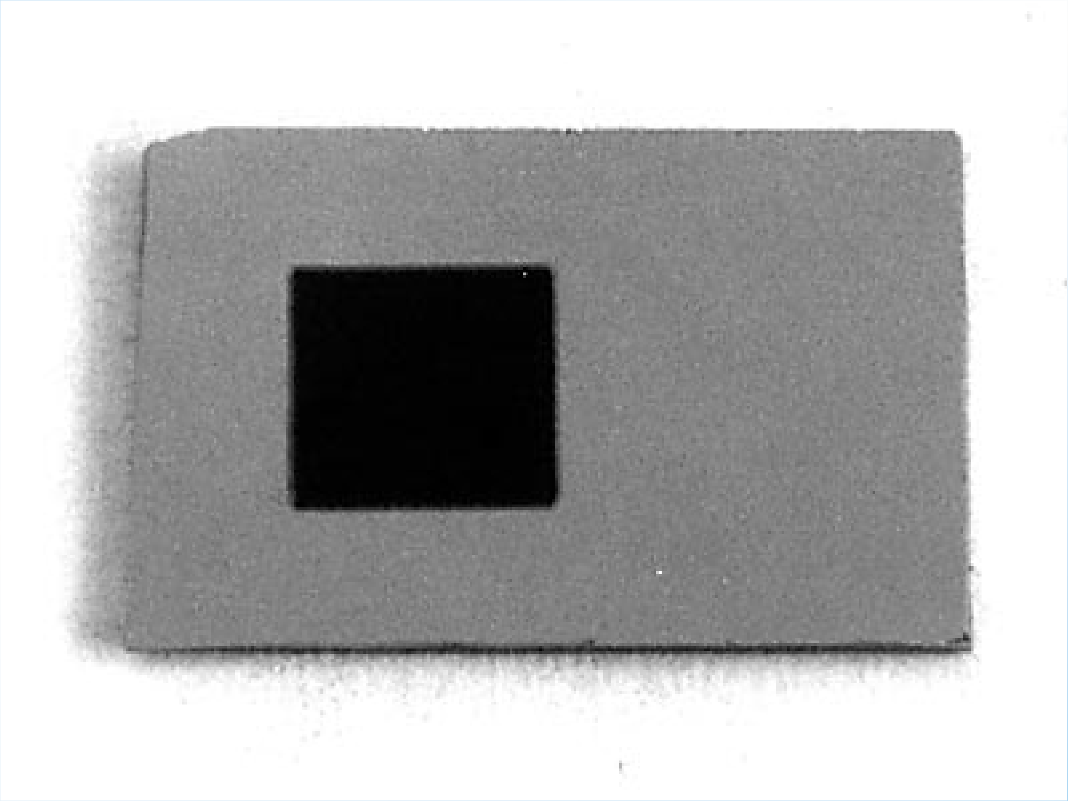


Introduction



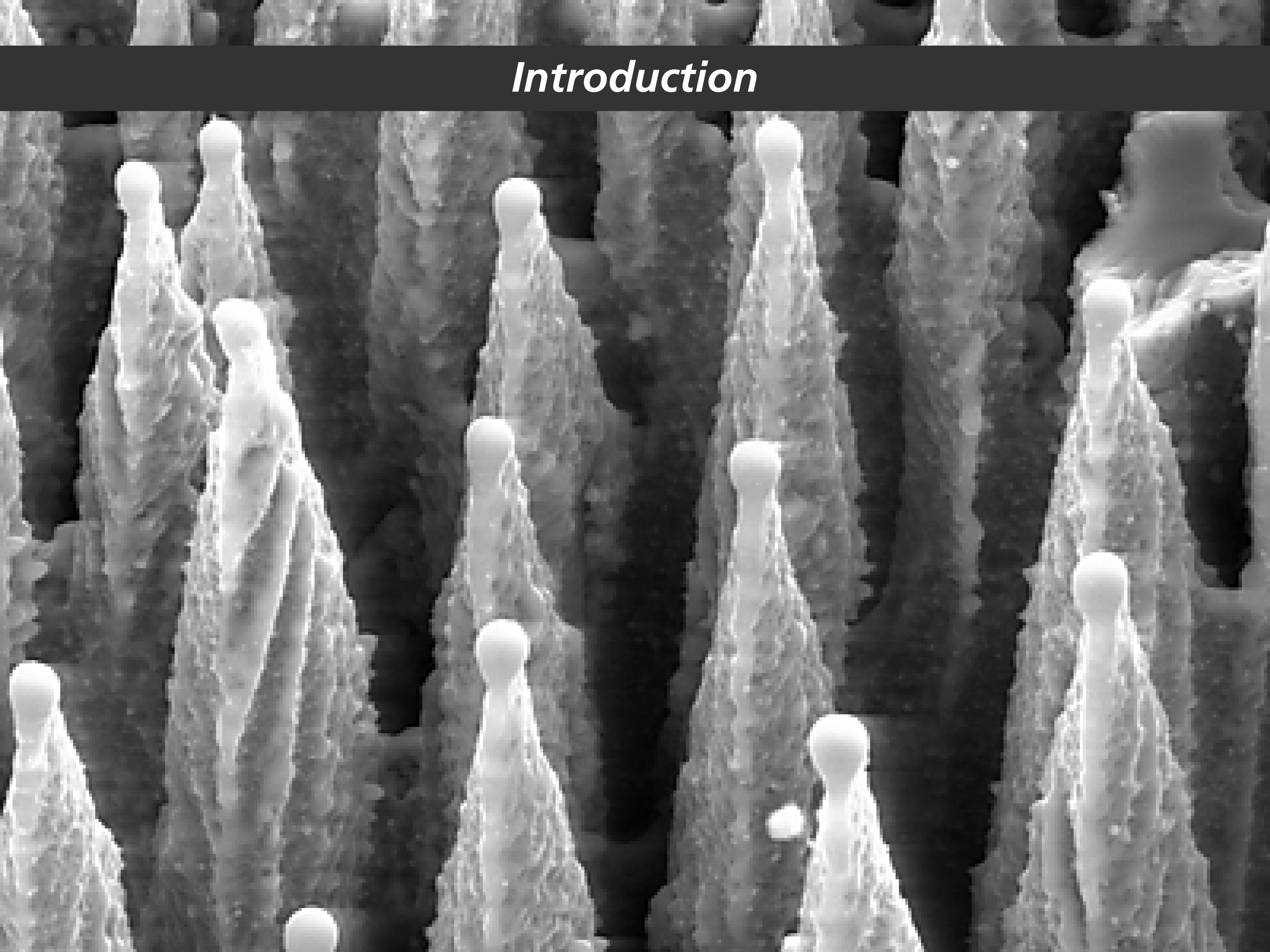
- **microstructuring of transparent materials**
- **laser surgery**
- **electronic and structural transitions**
- **laser assisted chemistry**

Introduction

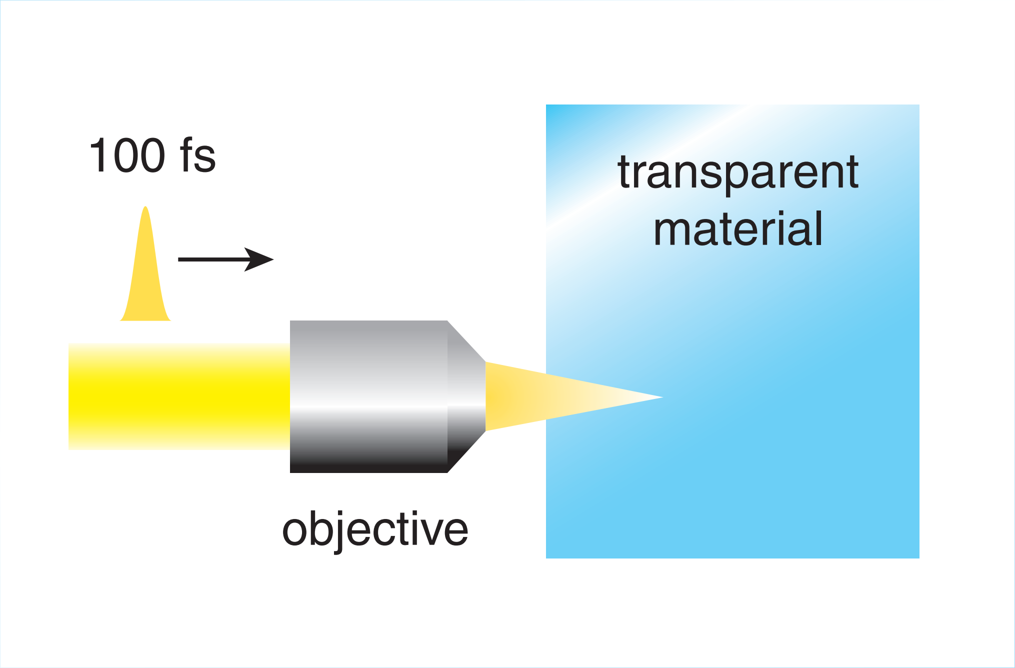


5 mm

Introduction

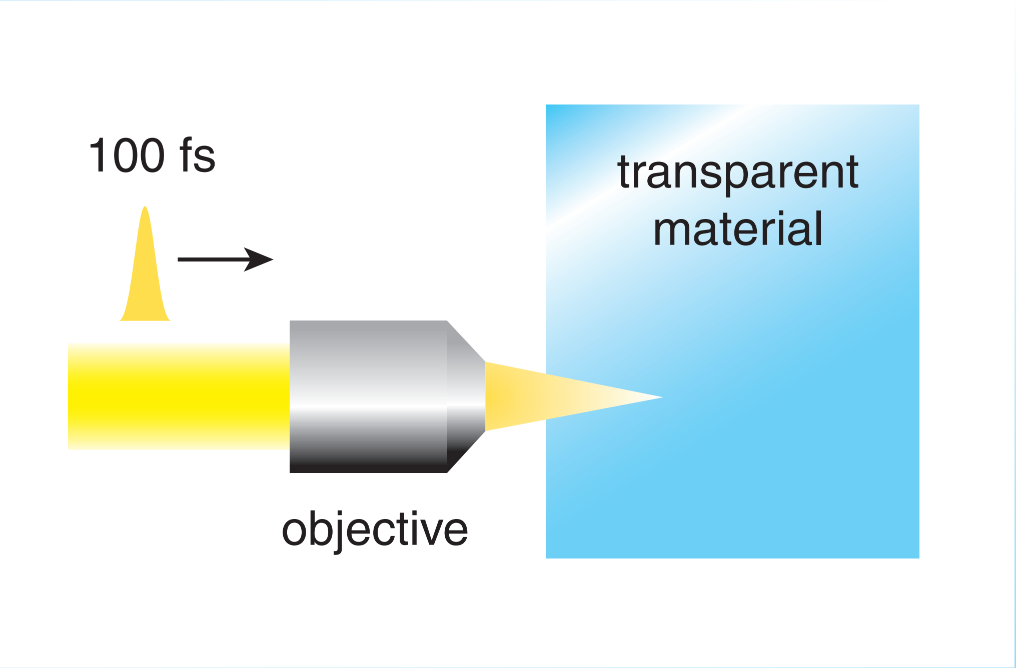


focus laser beam inside material…

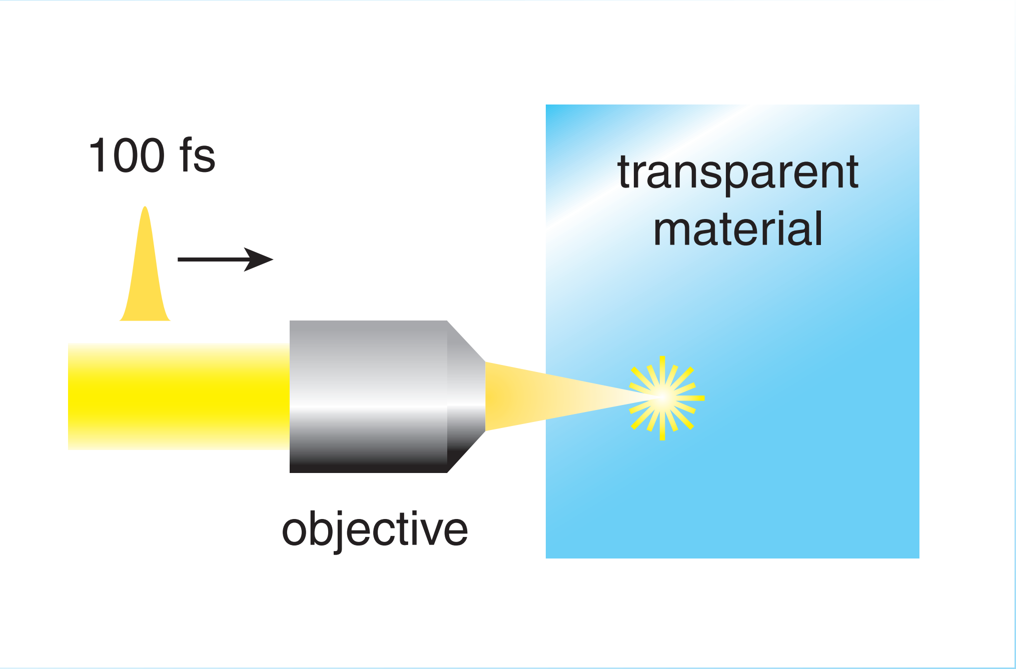


Introduction

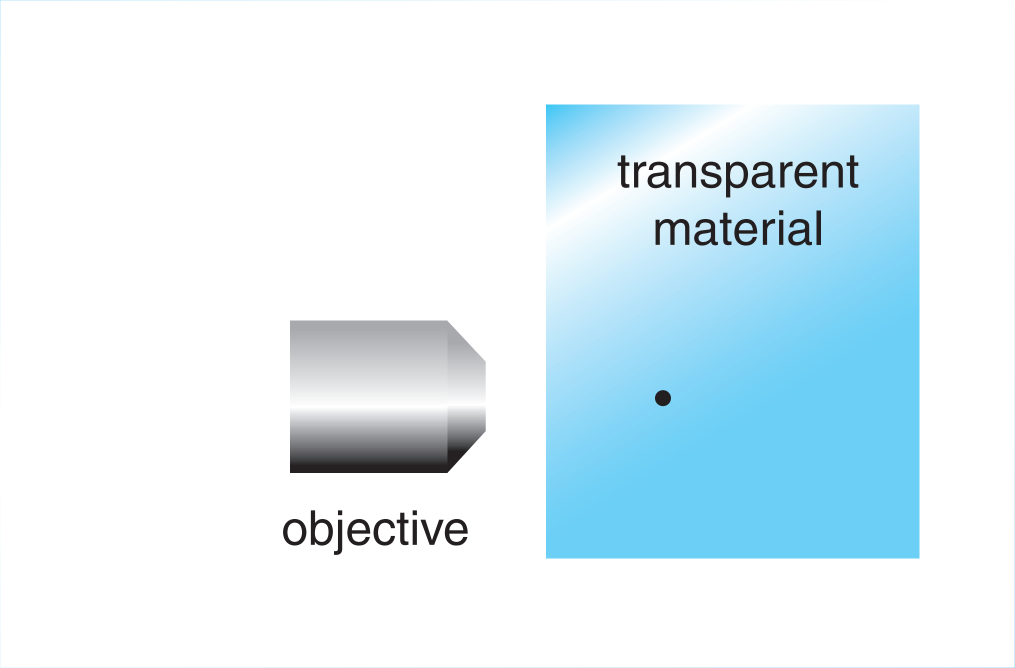
high intensity at focus…



… causes nonlinear ionization…

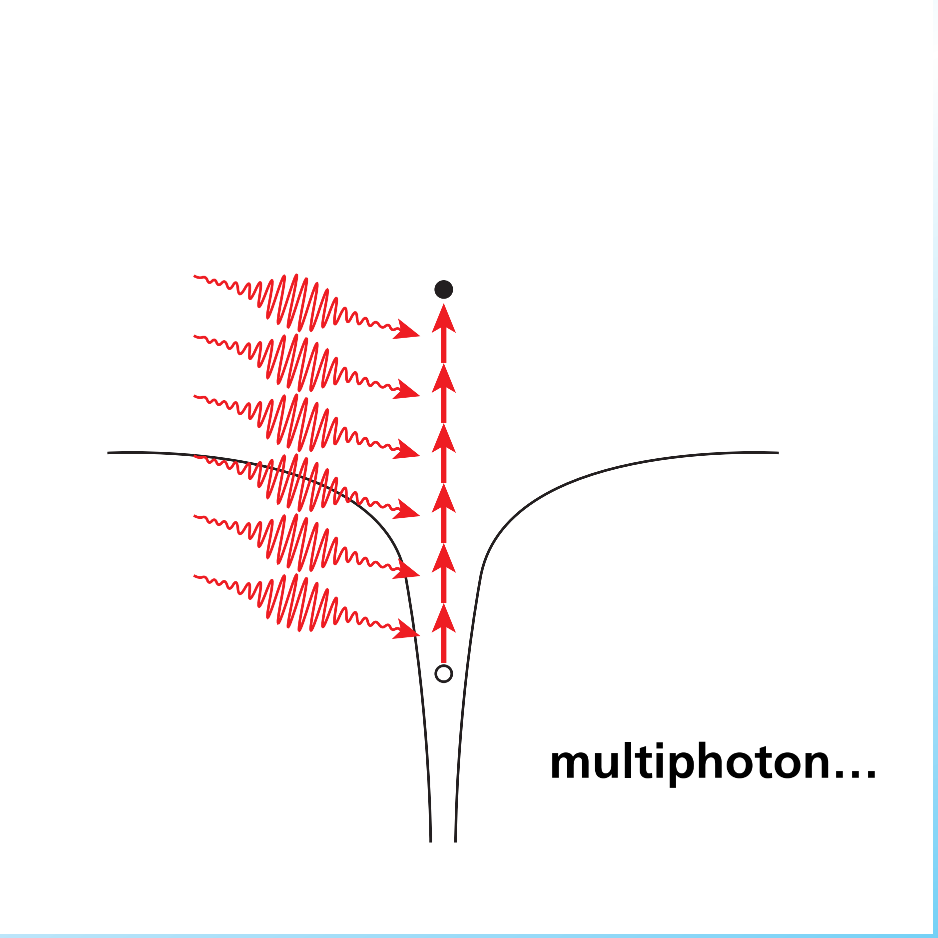


and microscopic bulk damage



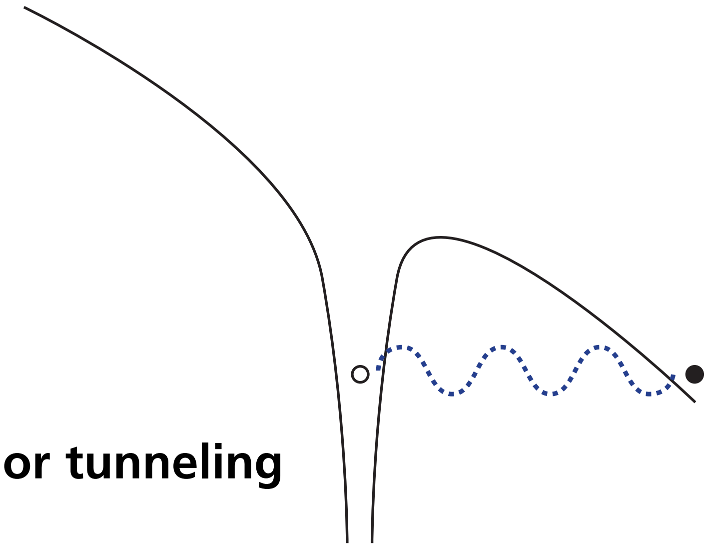
Introduction

laser field ionization



Introduction

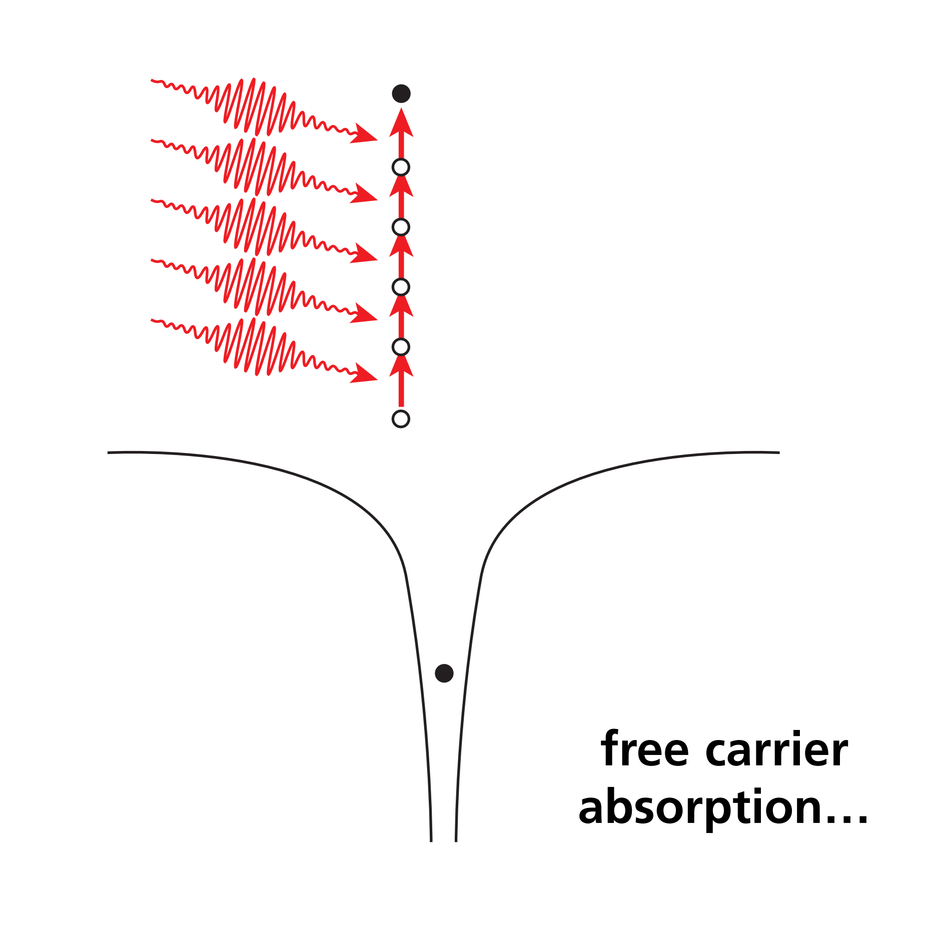
laser field ionization



...or tunneling

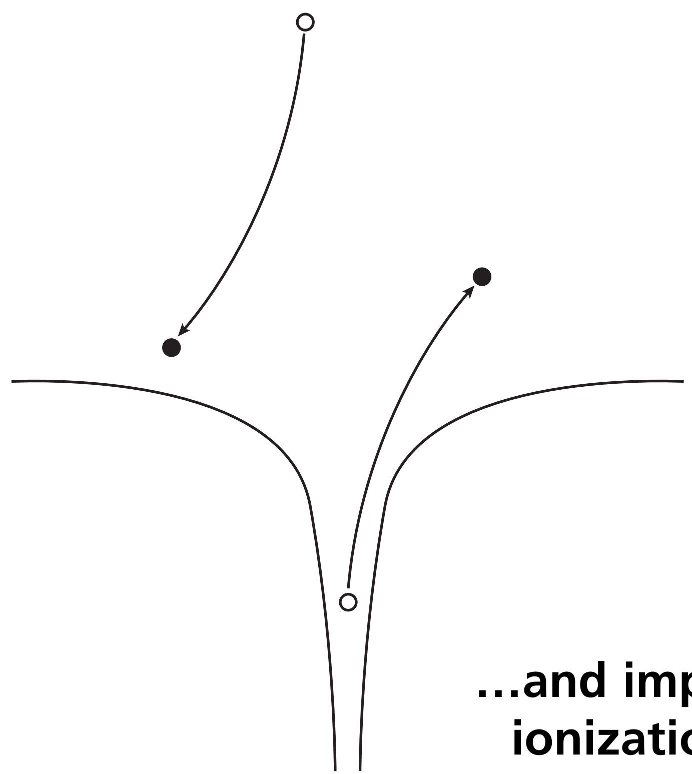
Introduction

avalanche ionization



Introduction

avalanche ionization



…and impact ionization

Introduction

Damage mechanisms:

- **explosive**
- **thermal**
- **defect forming**

Introduction

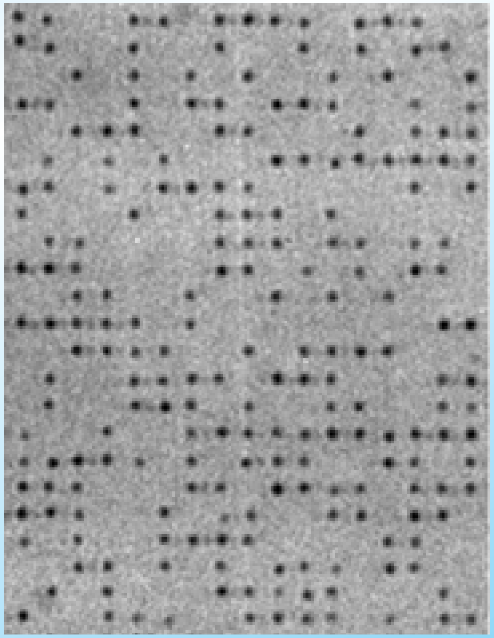
Applications:

- **data storage**

Introduction

Applications:

- **data storage**



Introduction

Applications:

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

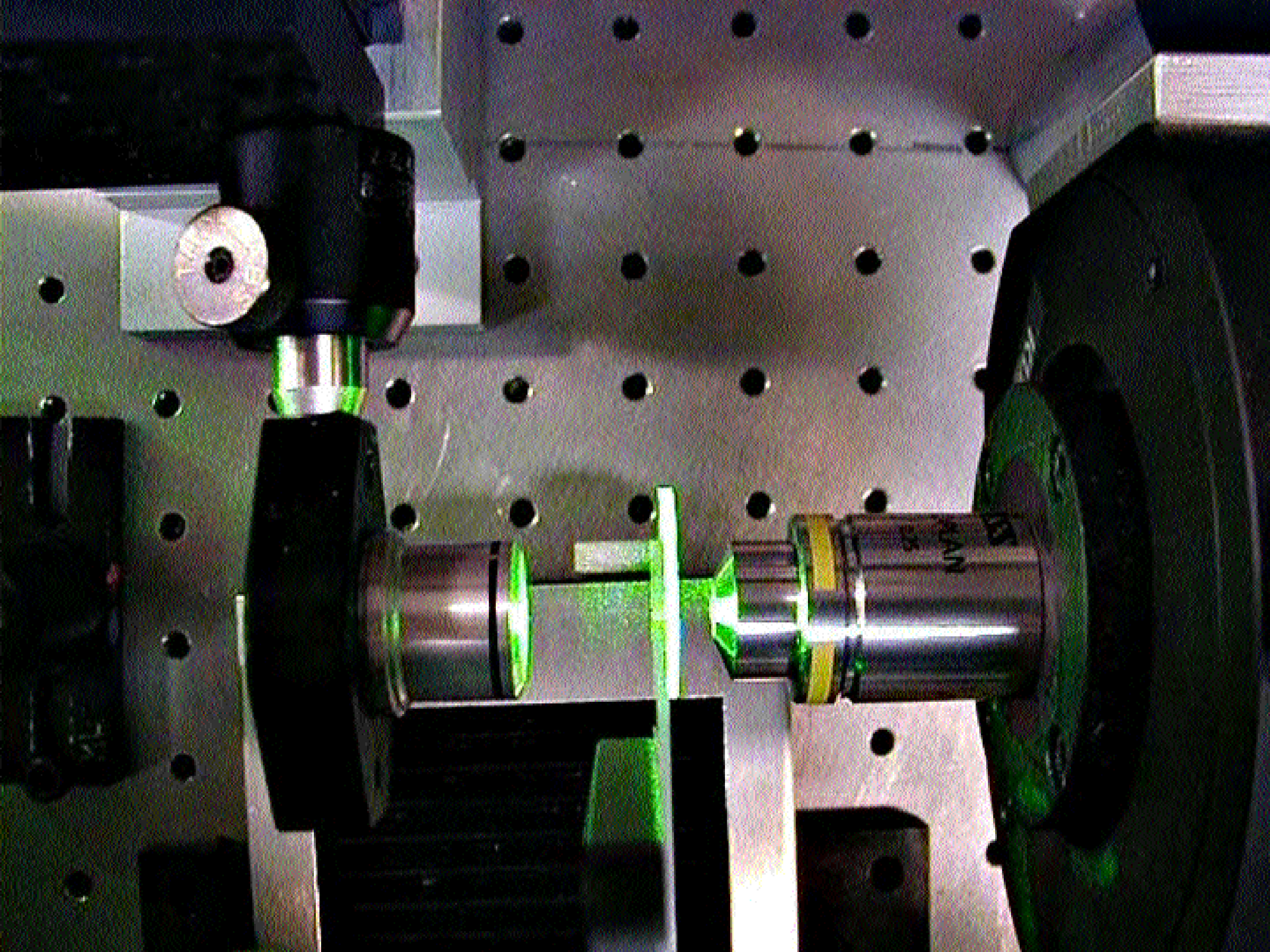
Introduction

Applications:

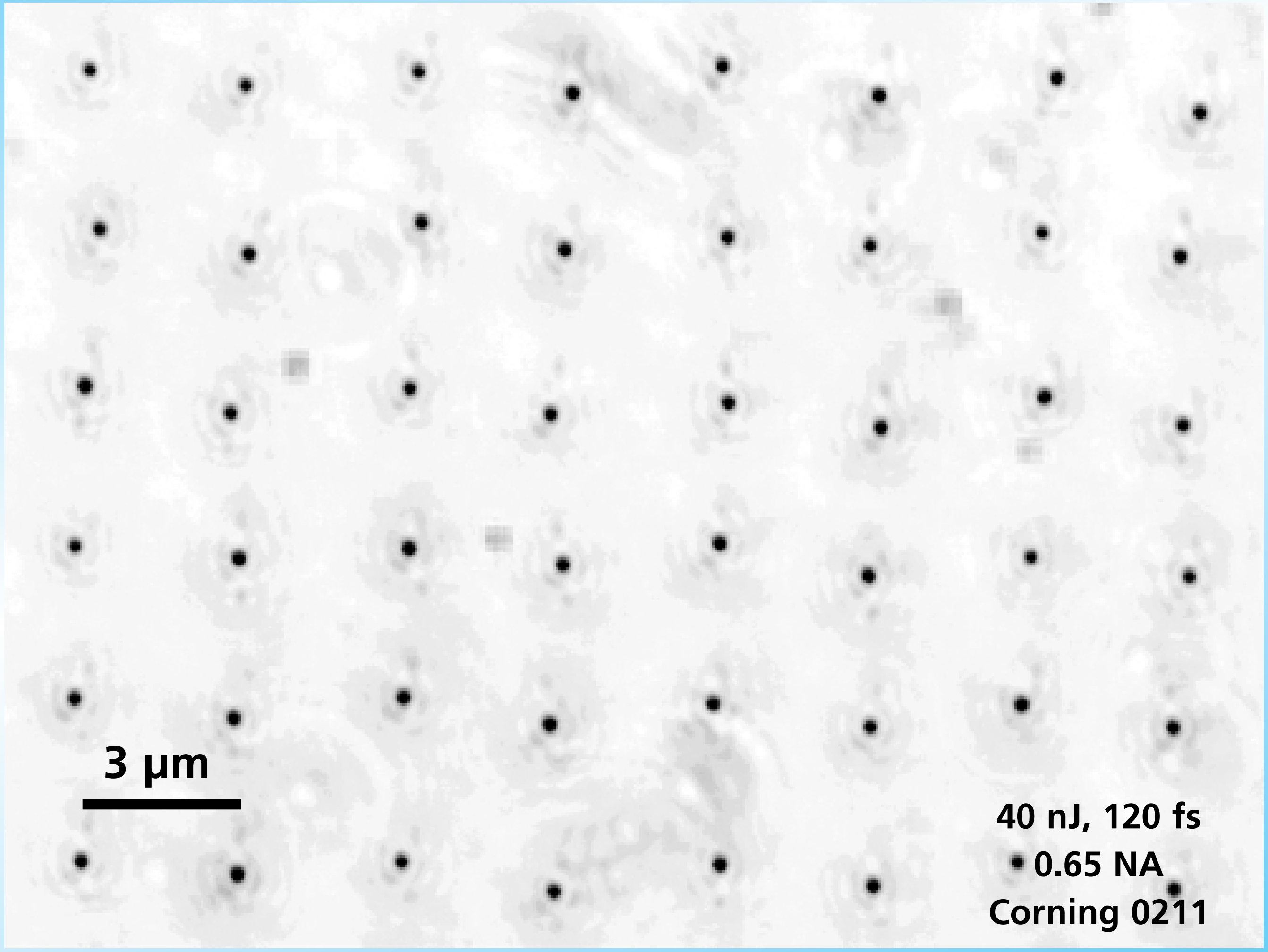
- **data storage**
- **photonic devices**
- **internal micromachining**

Outline

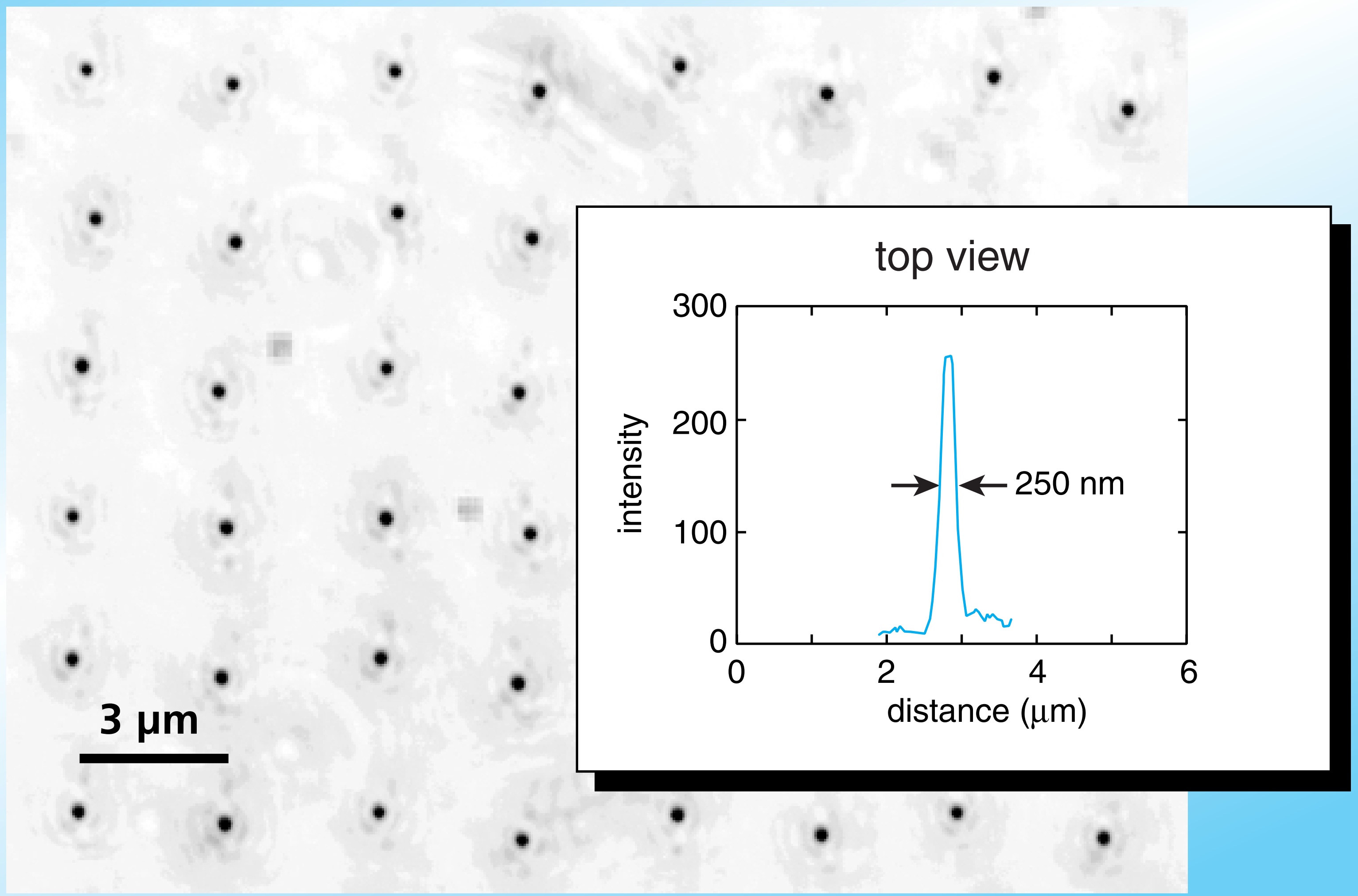
- Damage morphology
- Energy deposition
- Dynamics



Damage morphology

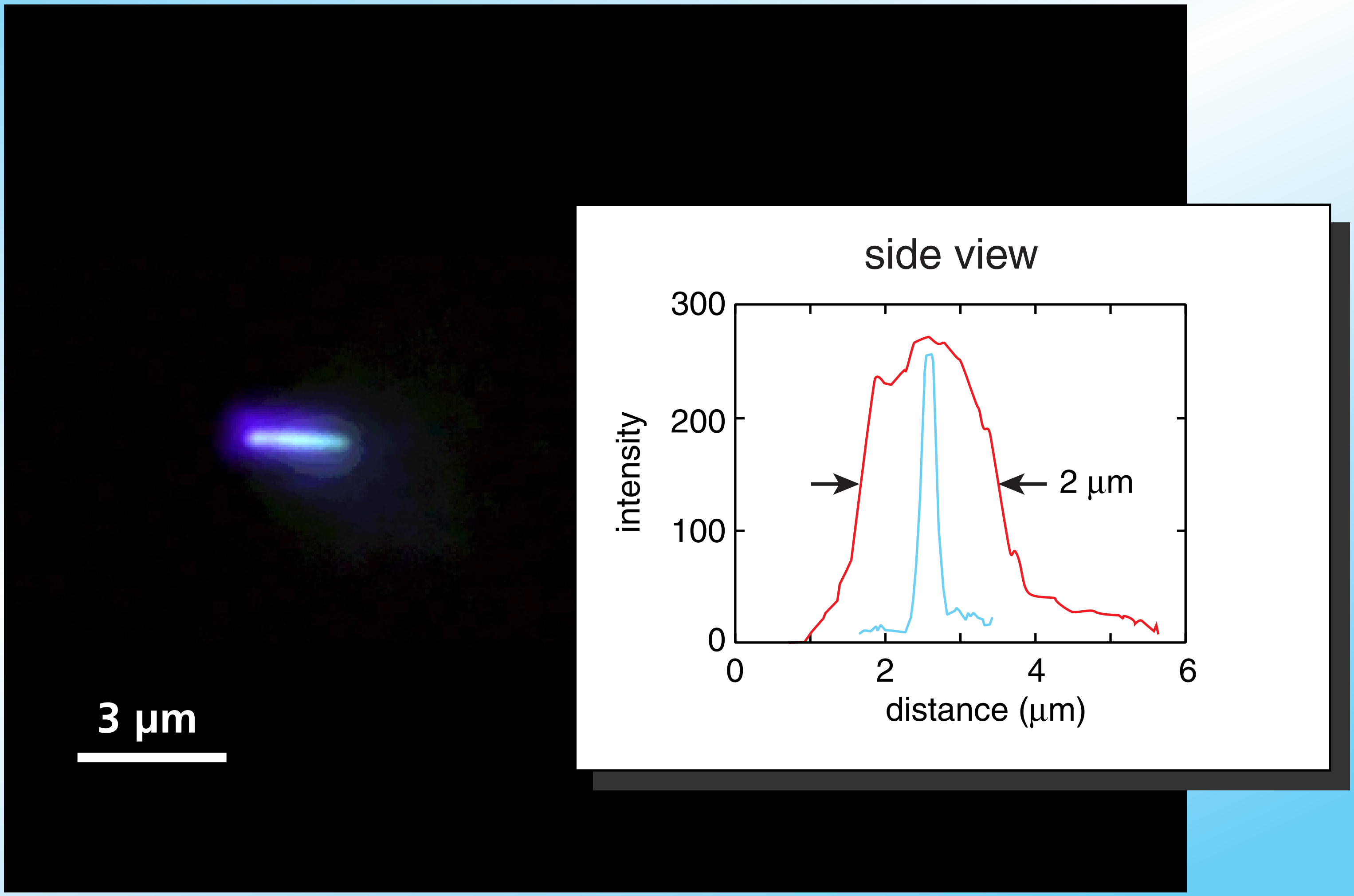


Damage morphology

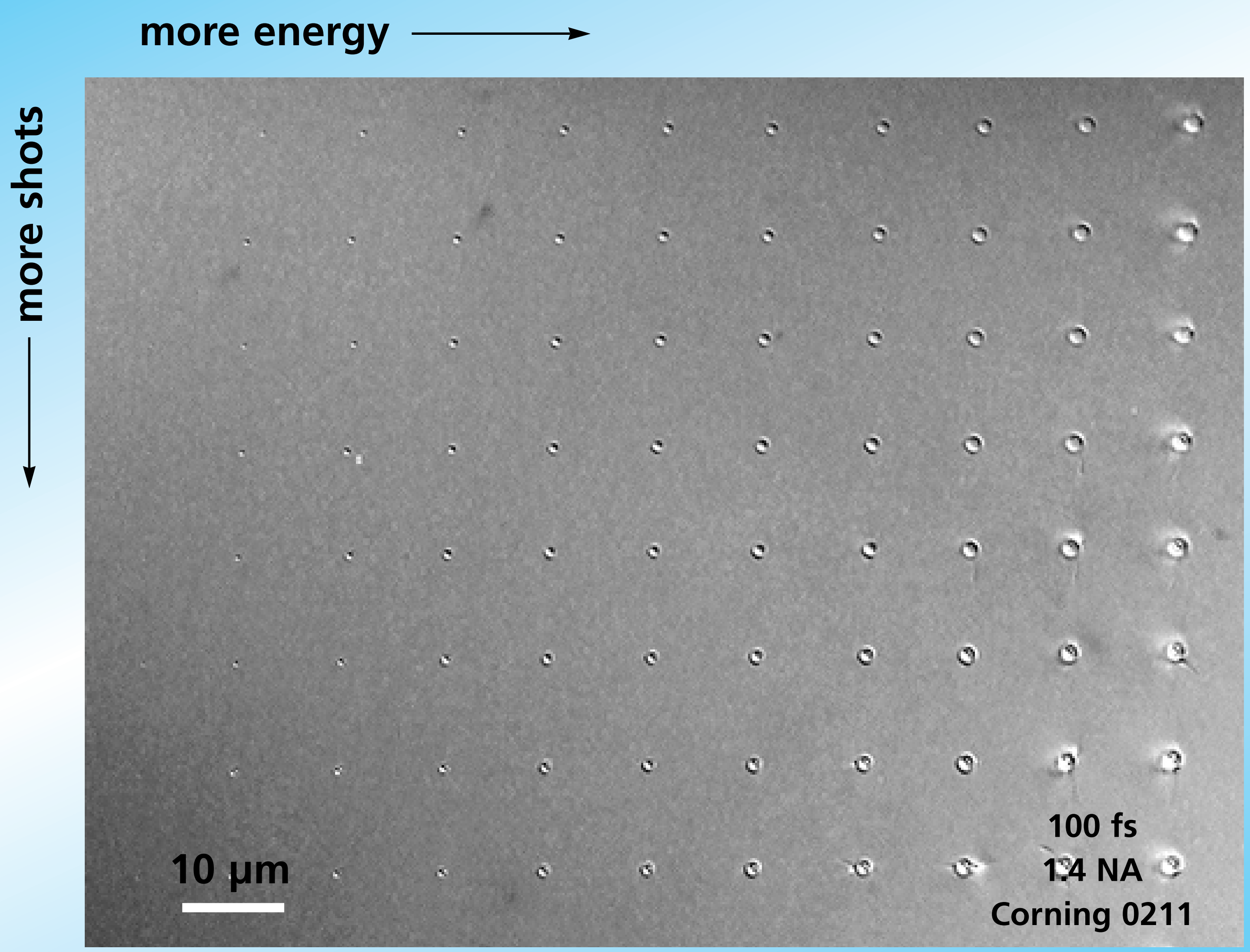


Damage morphology

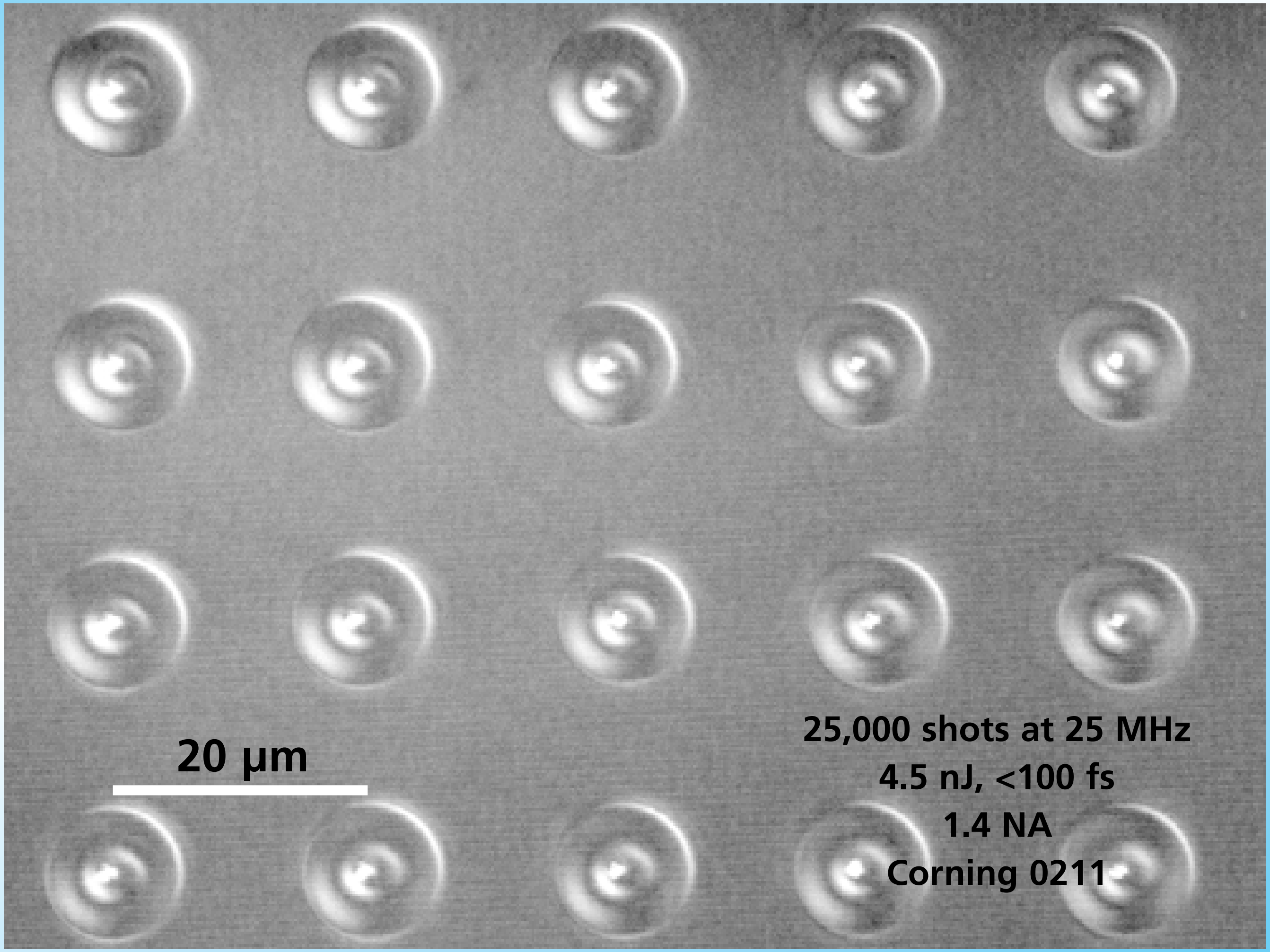
Damage morphology



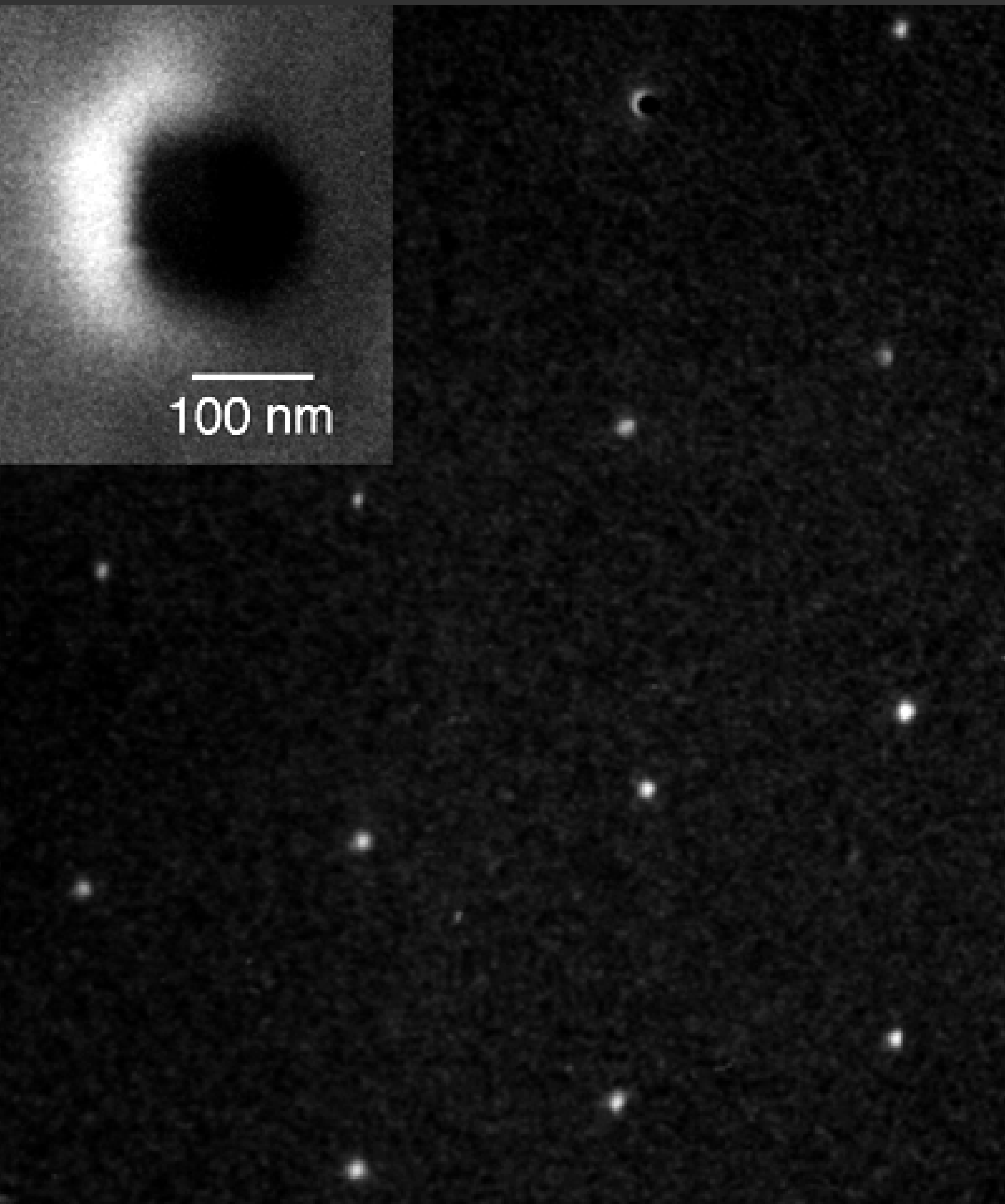
Damage morphology



Damage morphology



Damage morphology



Electron Microscopy:

explosive damage forms voids

100 fs, 500 nJ
0.65 NA
fused silica

Damage morphology

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

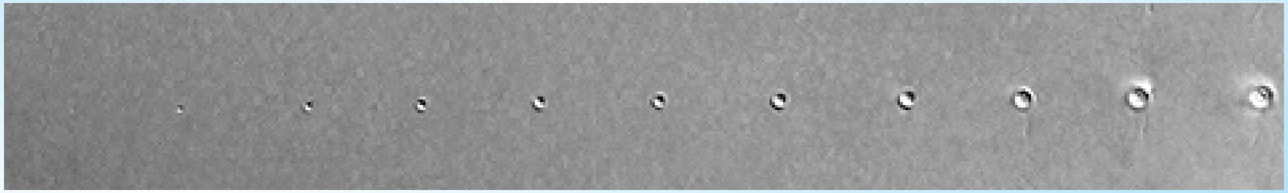
Energy deposition

Determine threshold for damage:

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

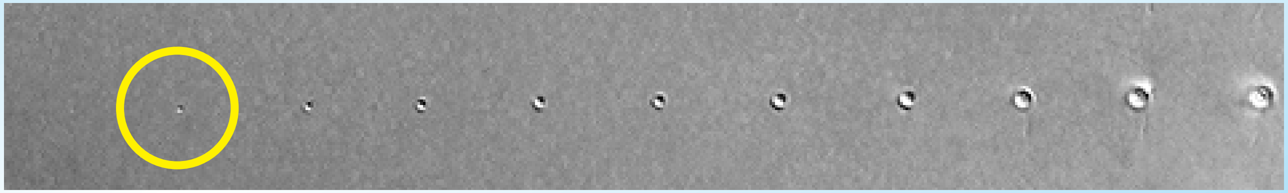
Energy deposition

optical microscopy



Energy deposition

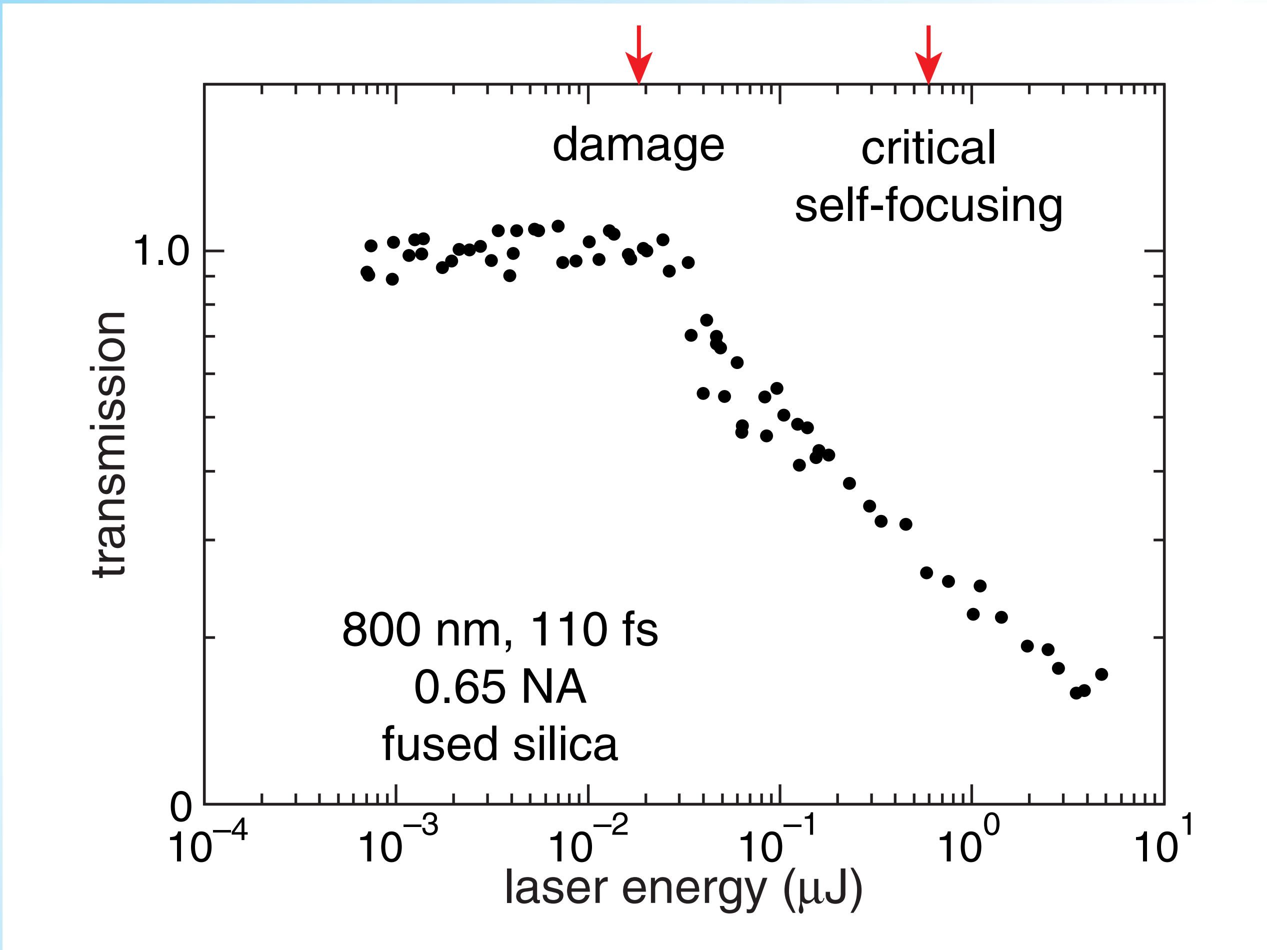
optical microscopy



6.6 nJ

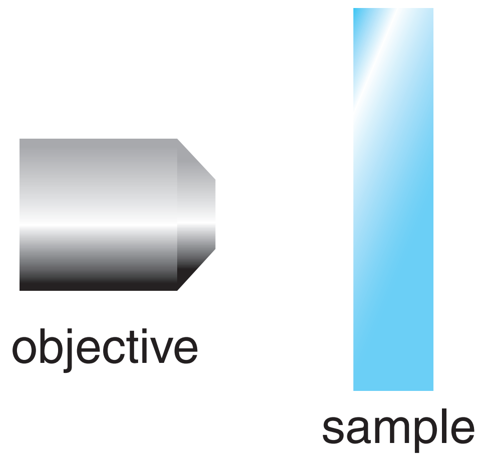
Energy deposition

transmission of pump beam in fused silica



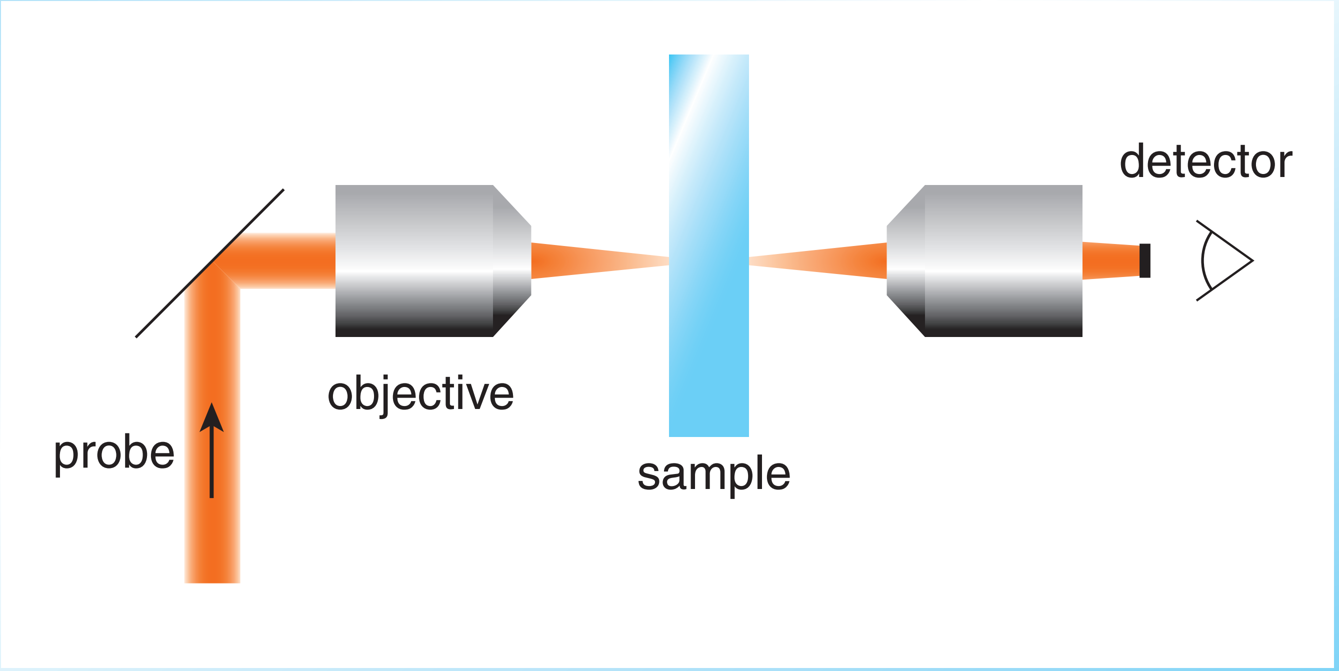
Energy deposition

Dark-field scattering



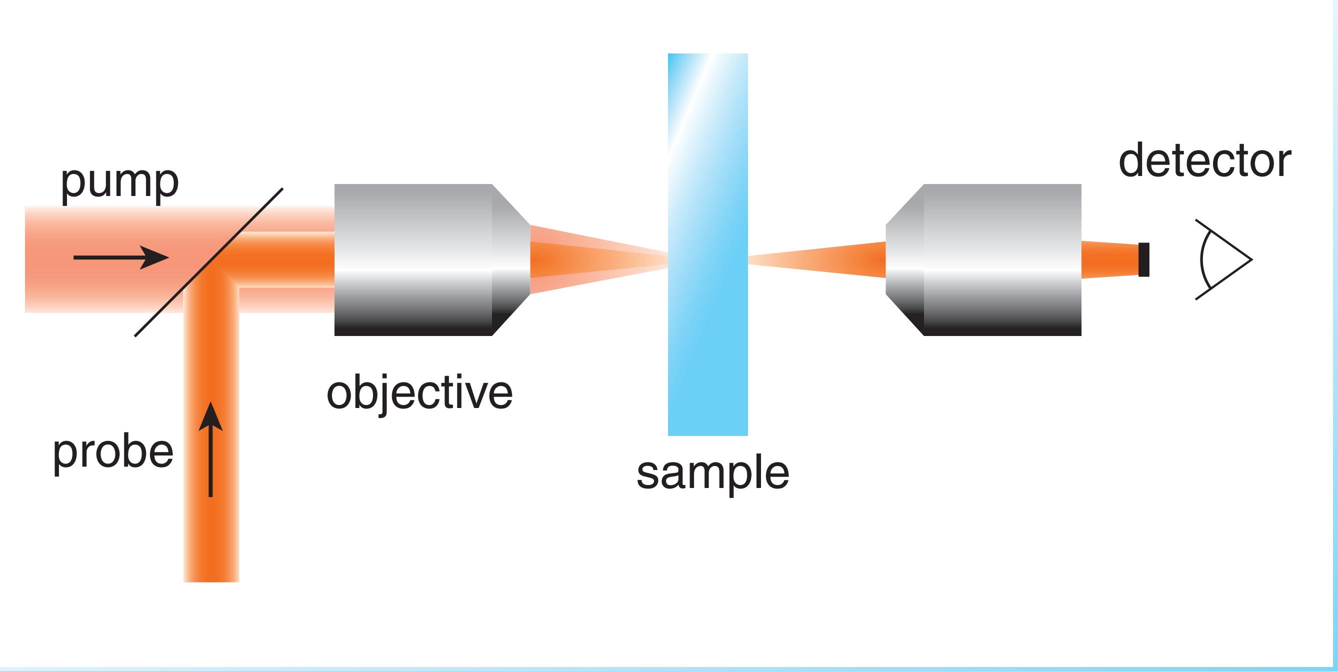
Energy deposition

block probe beam…



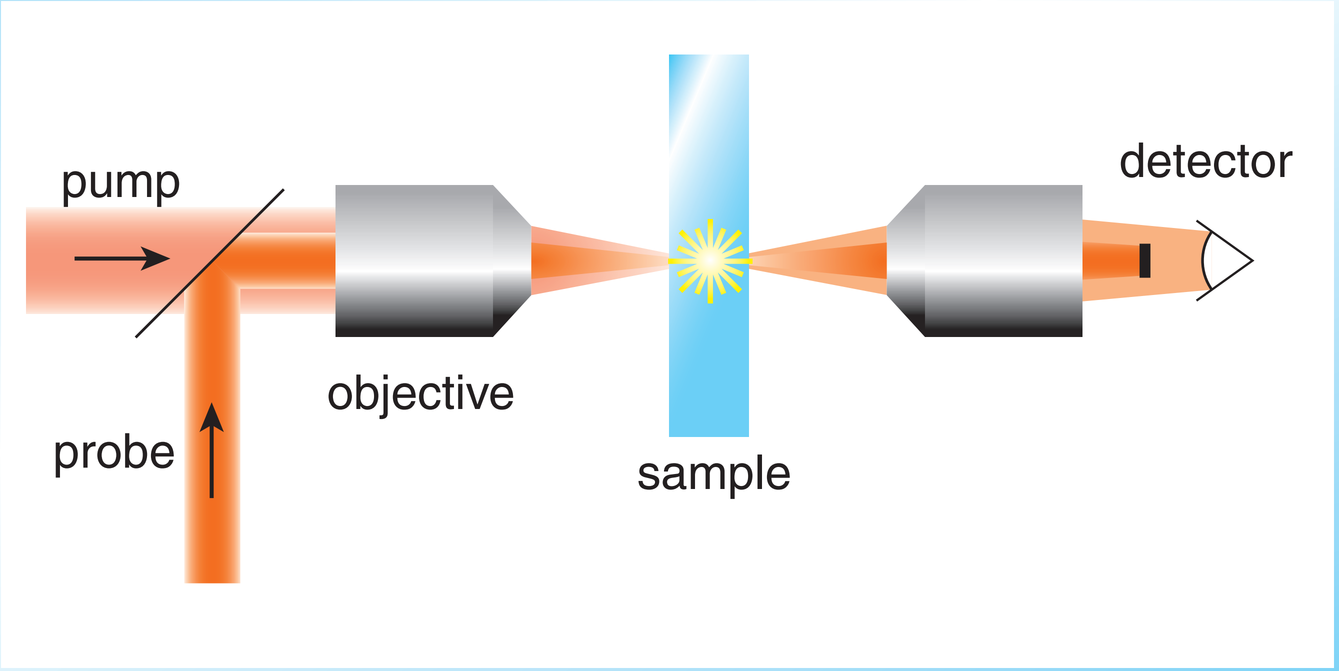
Energy deposition

…bring in pump beam…

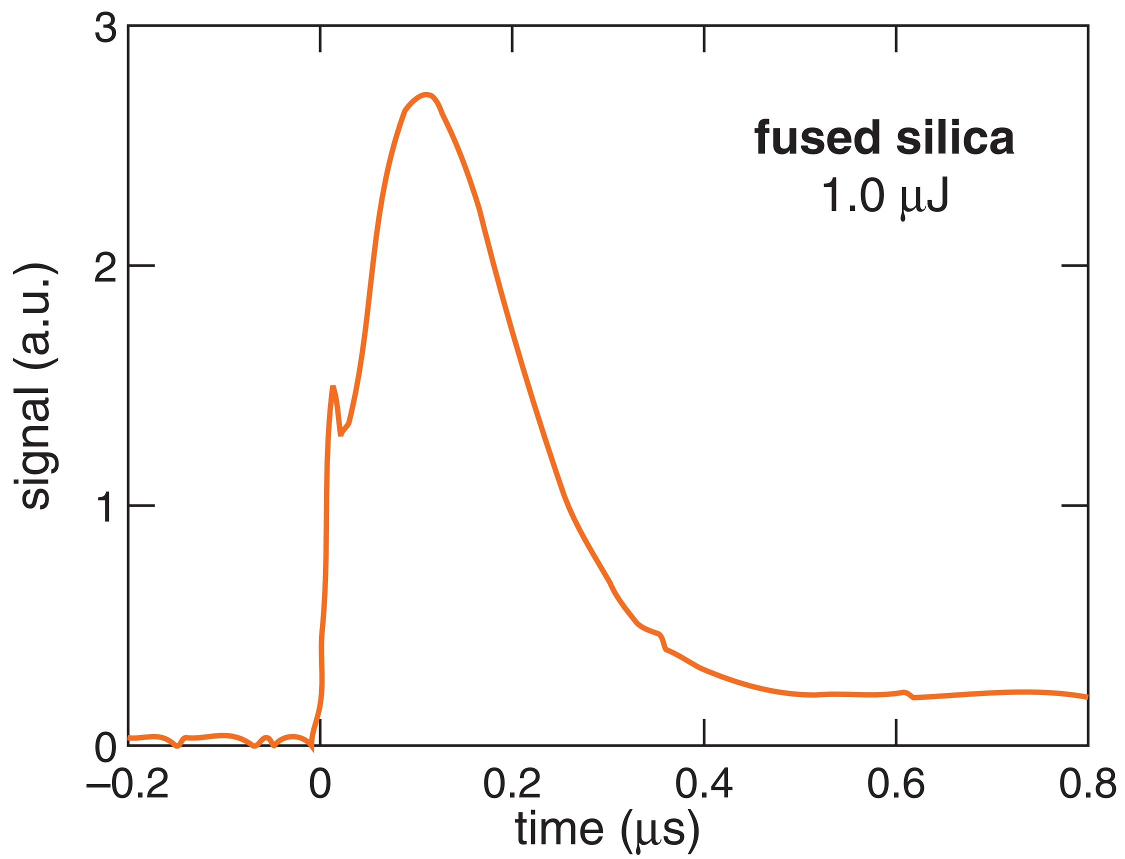


Energy deposition

…damage scatters probe beam

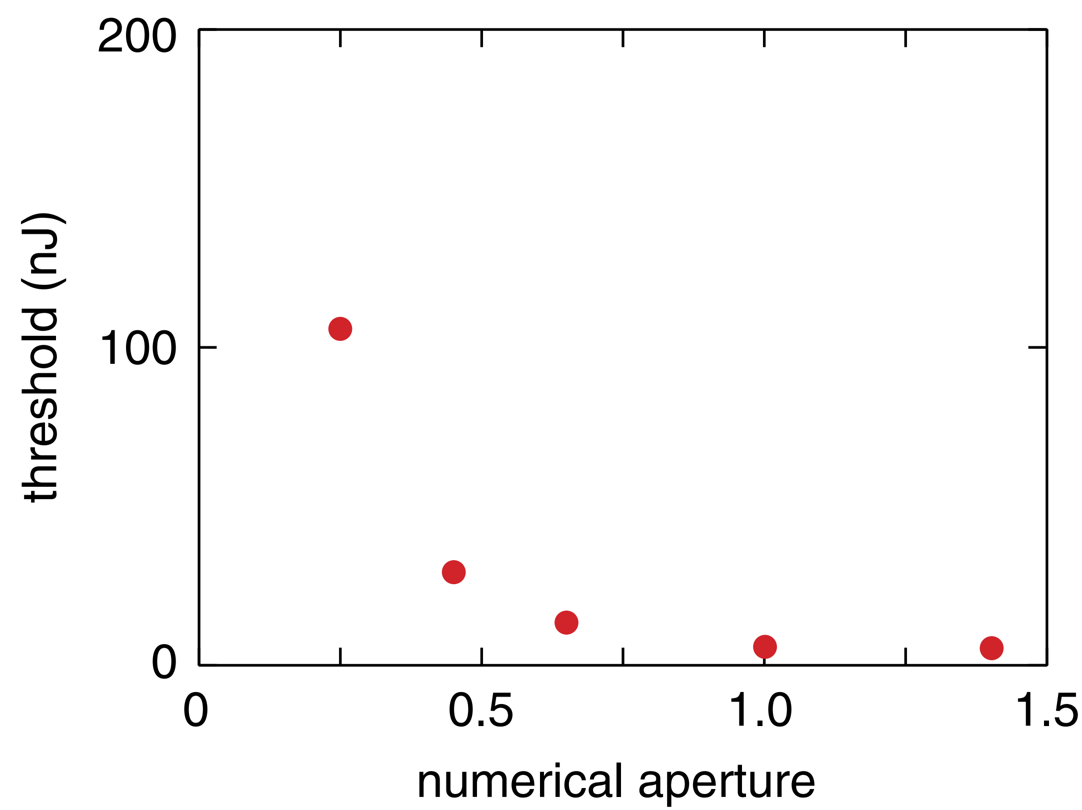


Energy deposition

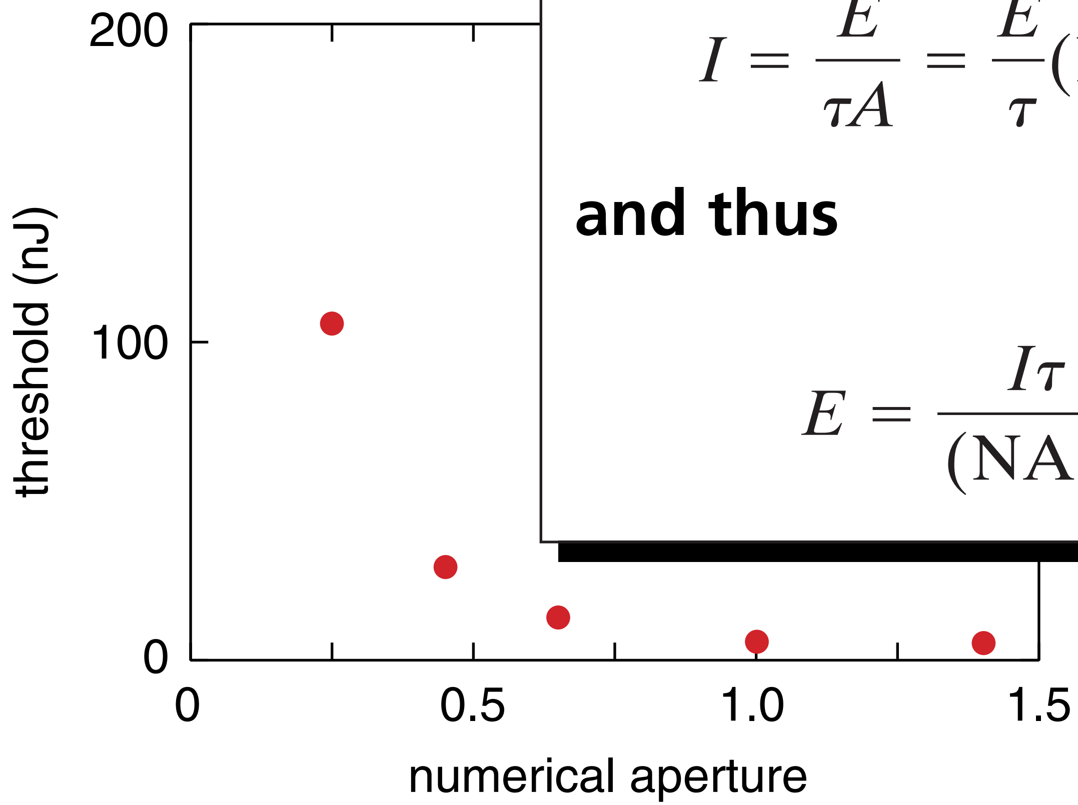


Energy deposition

vary numerical aperture in Corning 0211



Energy deposition



minimal self focusing, so spot size determined by:

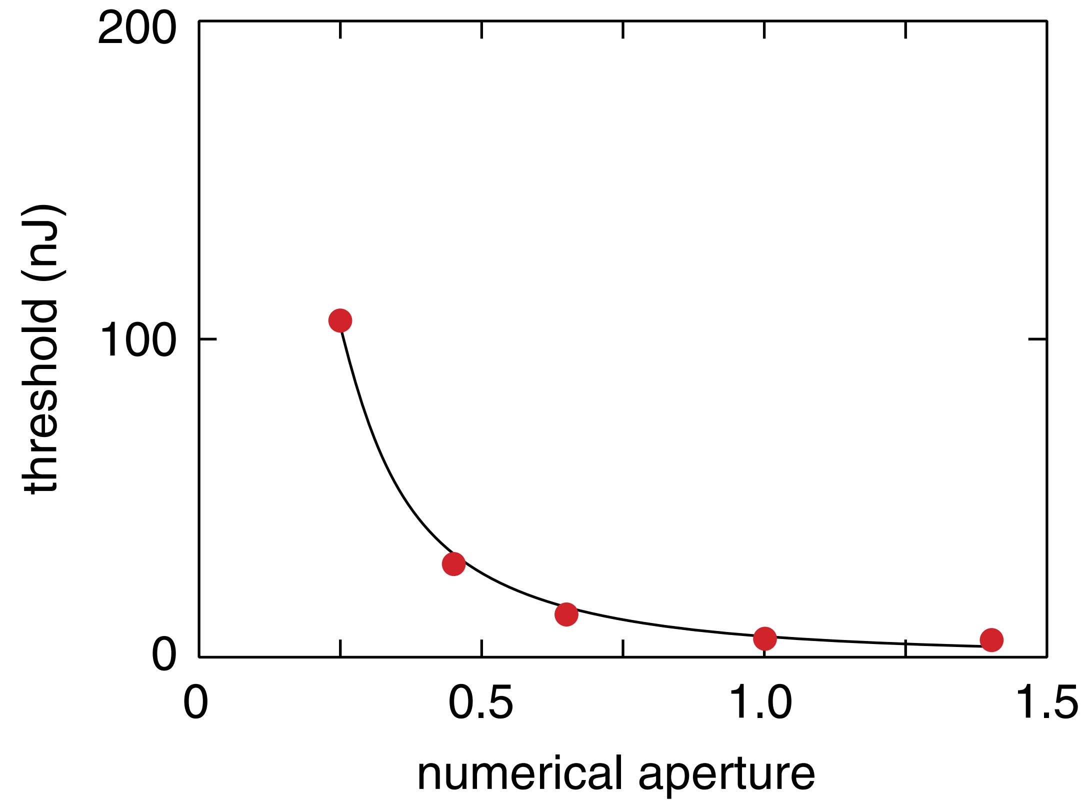
$$I = \frac{E}{\tau A} = \frac{E}{\tau}(\mathrm{NA})^2$$

and thus

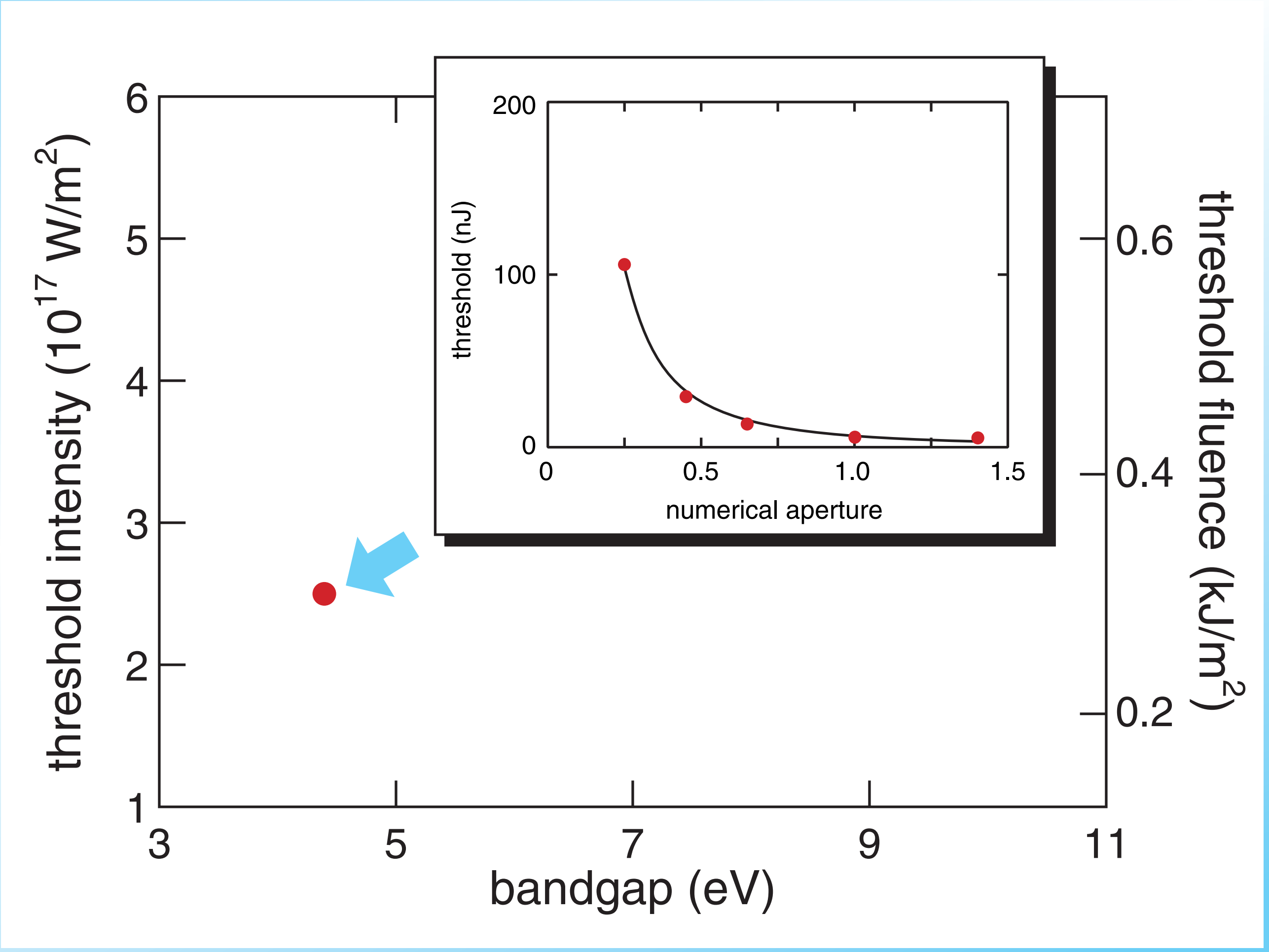
$$E = \frac{I\tau}{(\mathrm{NA})^2}$$

Energy deposition

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

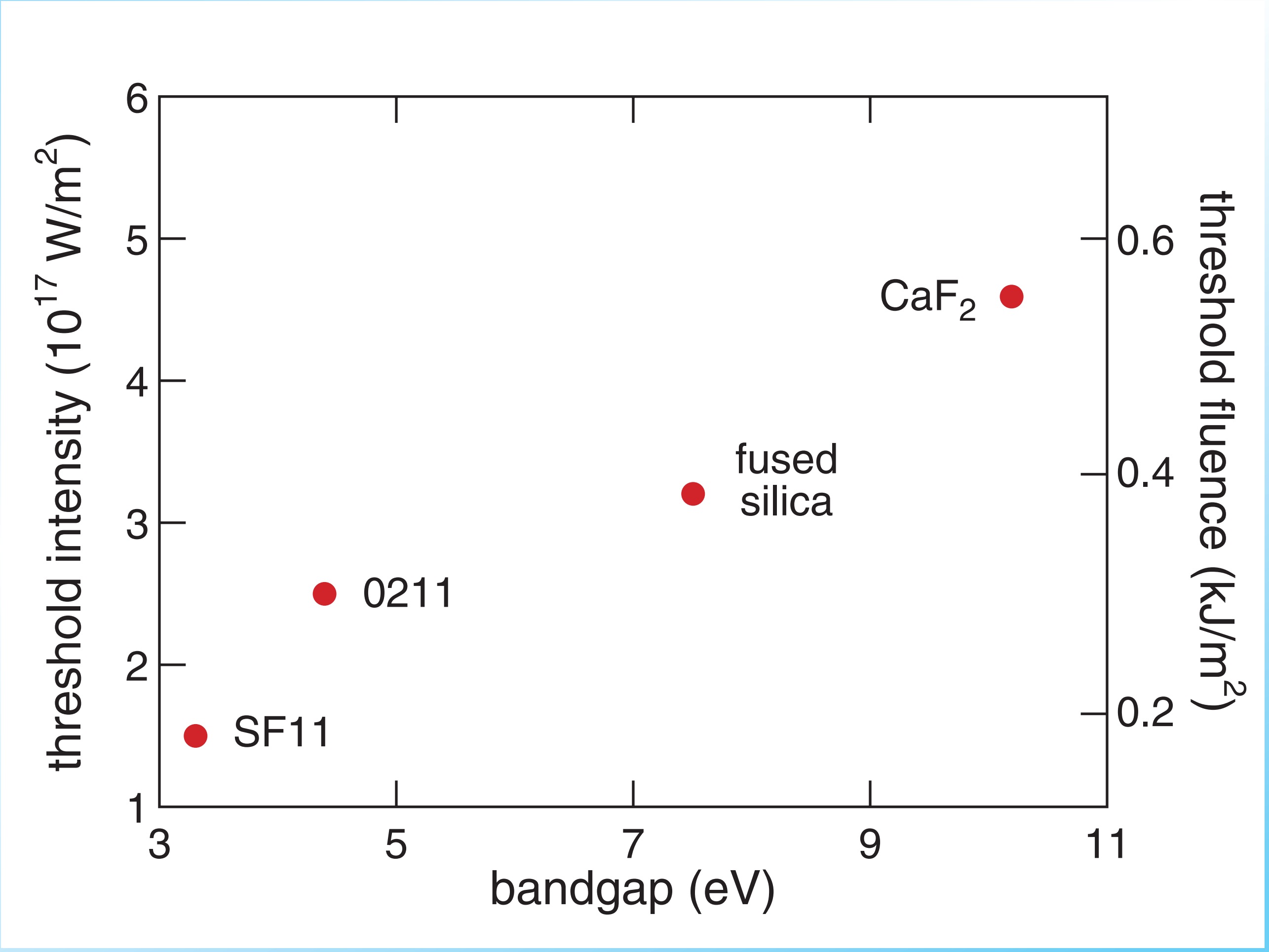


Energy deposition



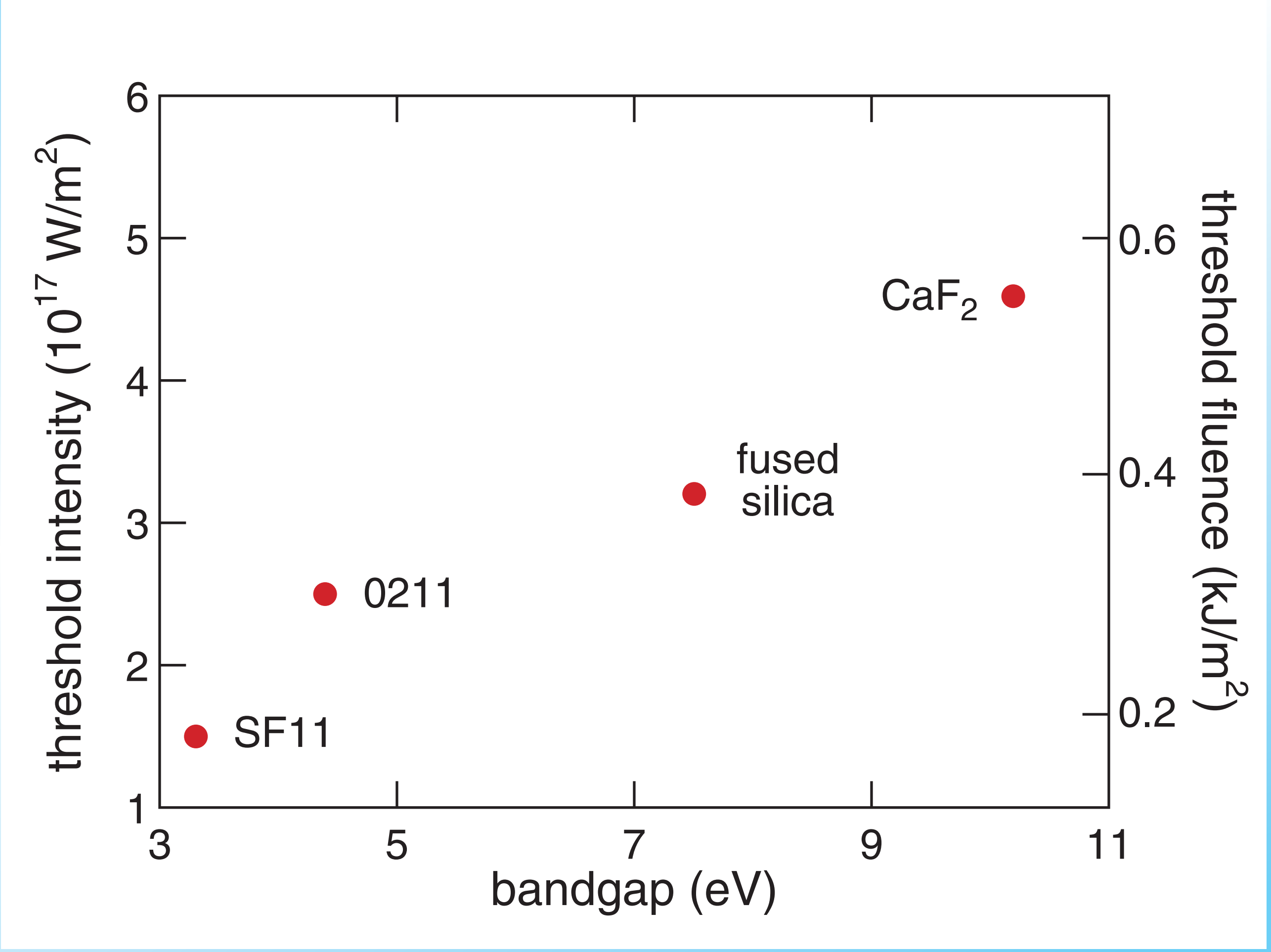
Energy deposition

vary material…



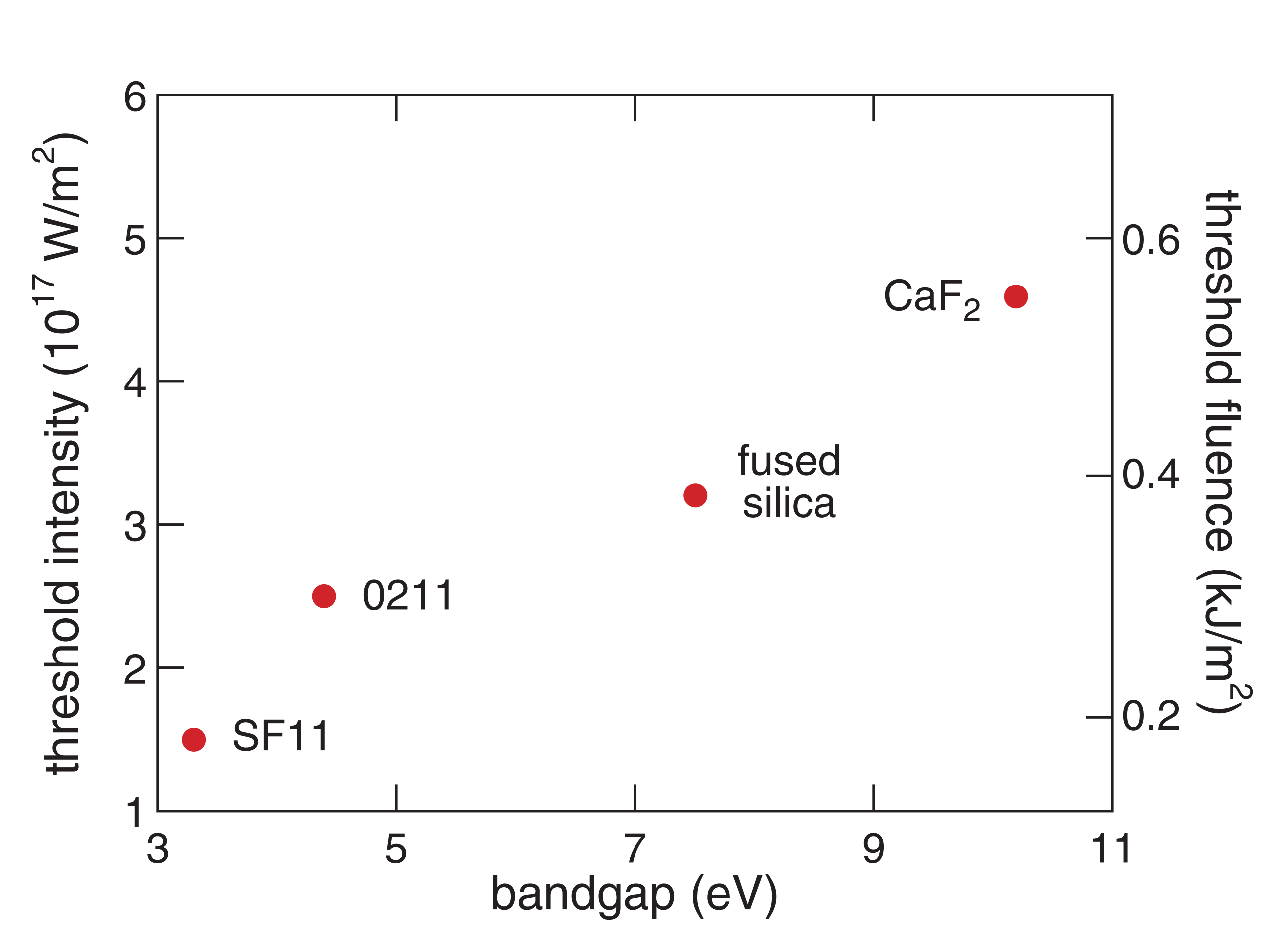
Energy deposition

threshold increases with bandgap...



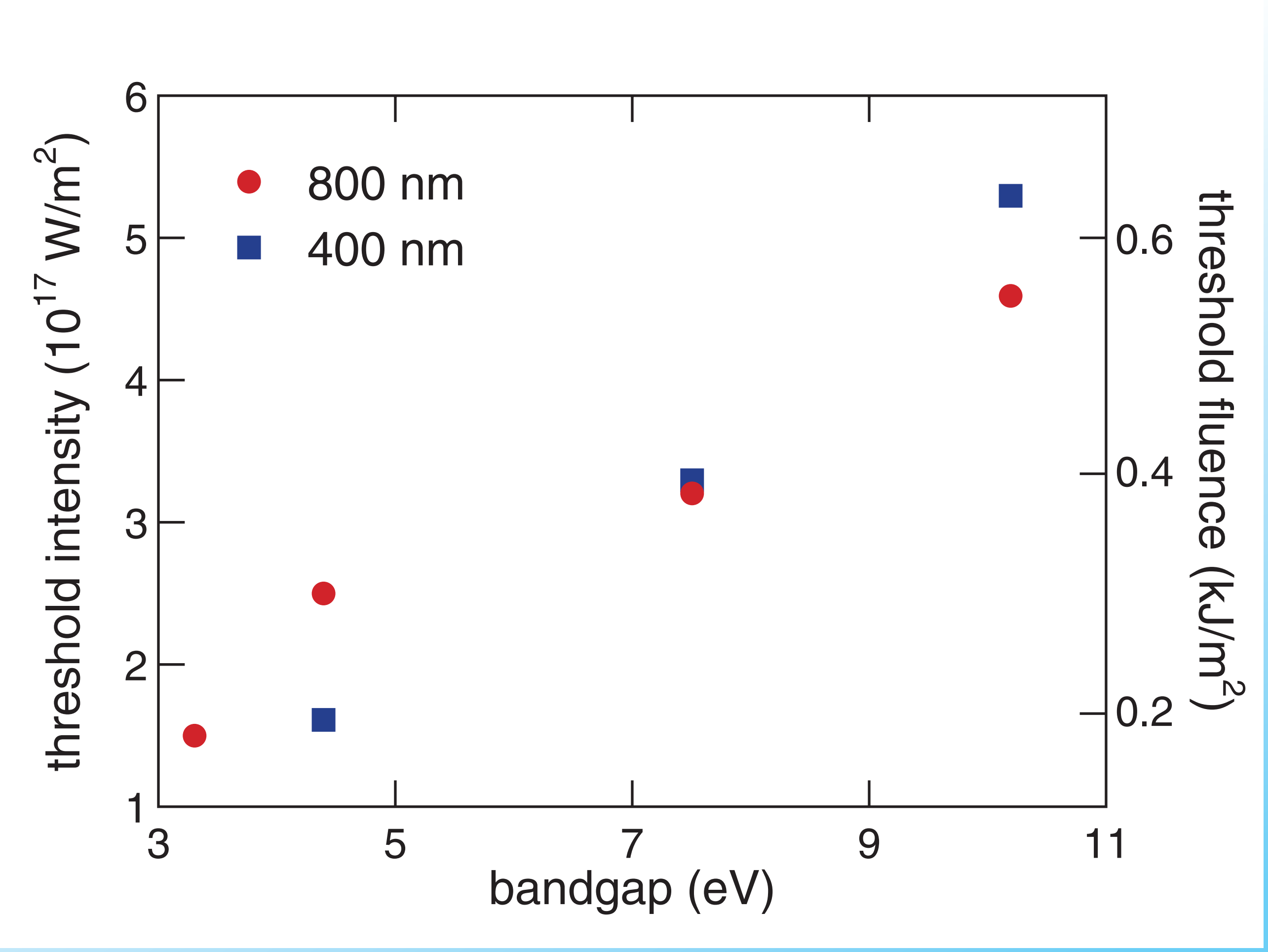
Energy deposition

…but not very much



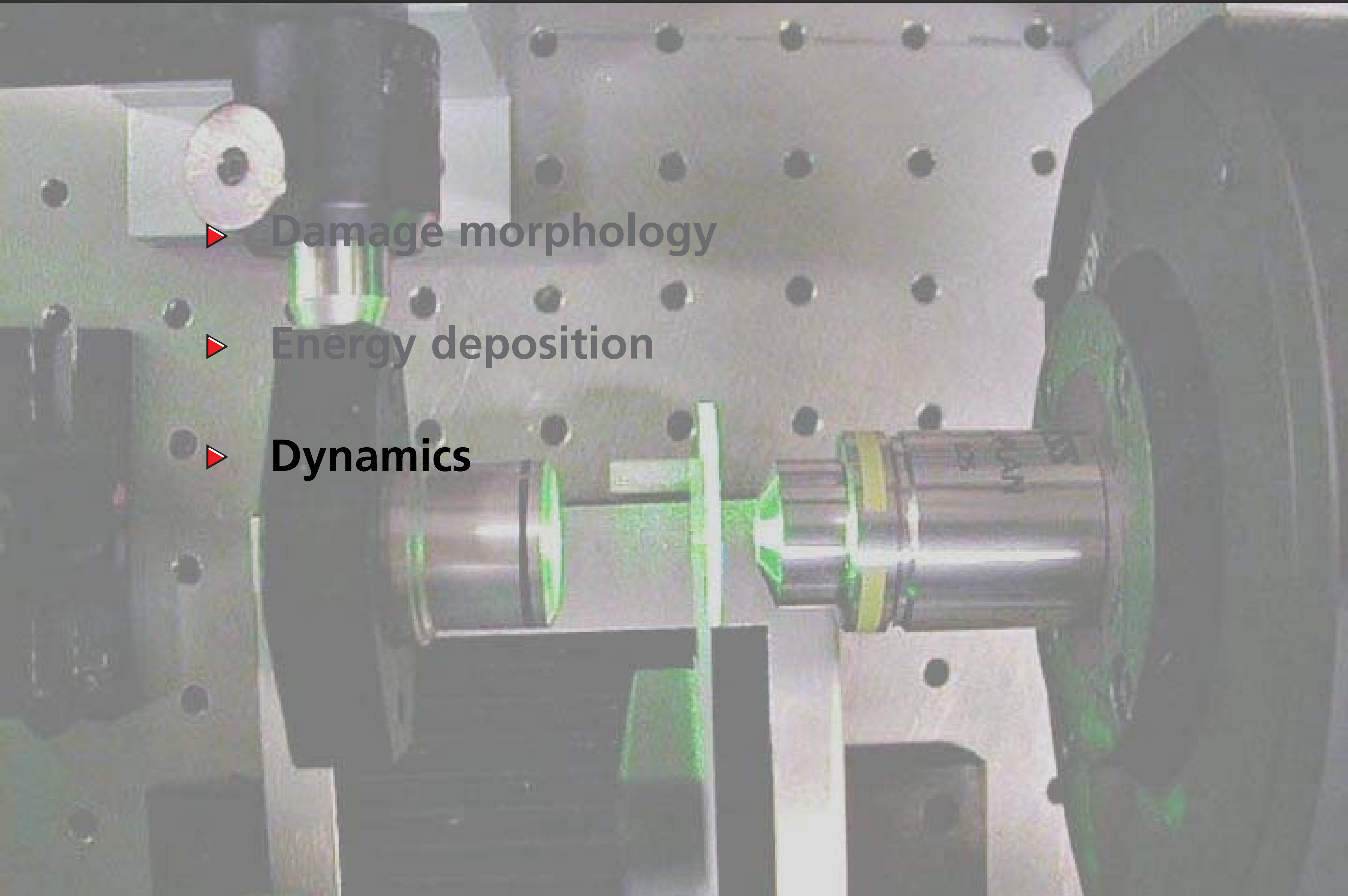
Energy deposition

same trend at 400 nm

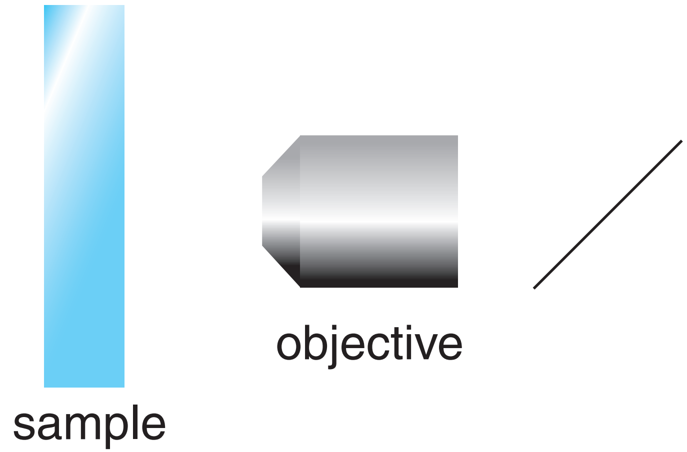


Outline

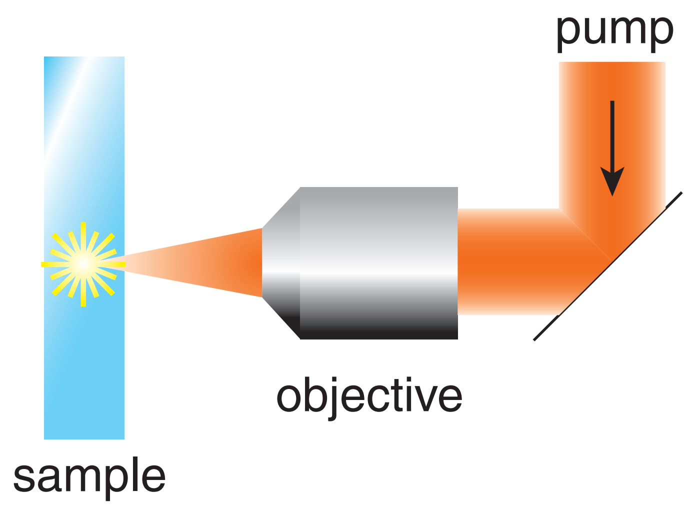
- Damage morphology
- Energy deposition
- **Dynamics**



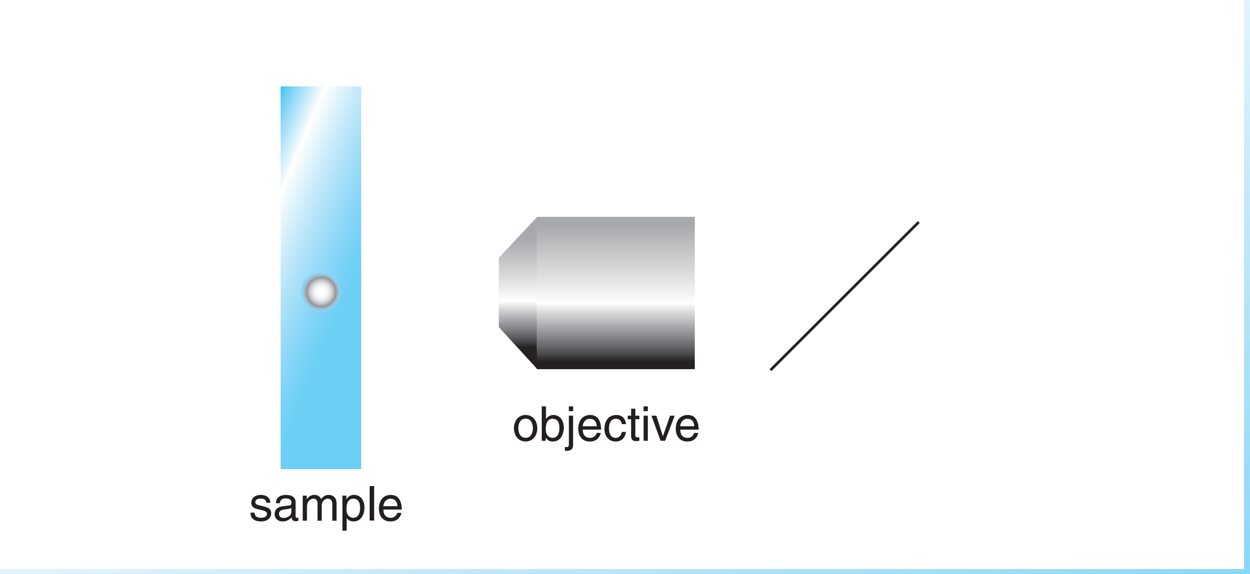
imaging setup



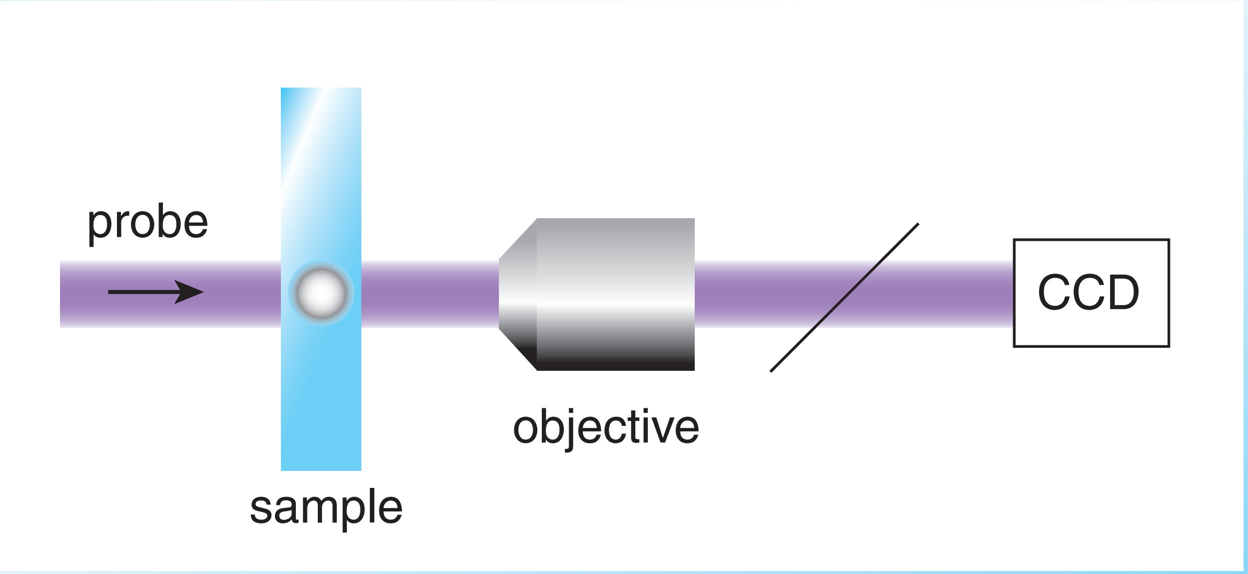
imaging setup



imaging setup



imaging setup



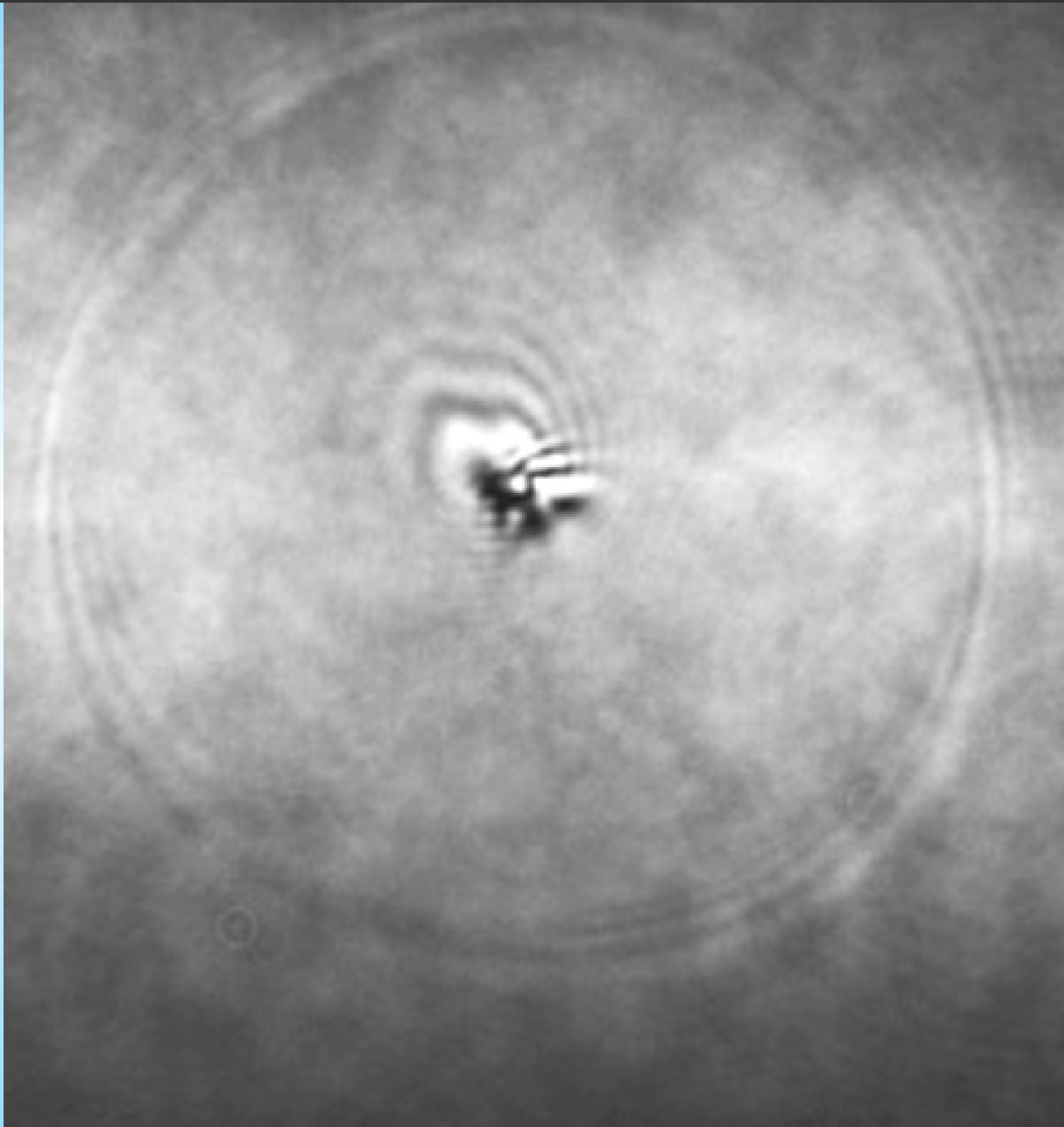
Dynamics

sapphire

3 μJ pulse

3.8 ns delay

40 μm radius



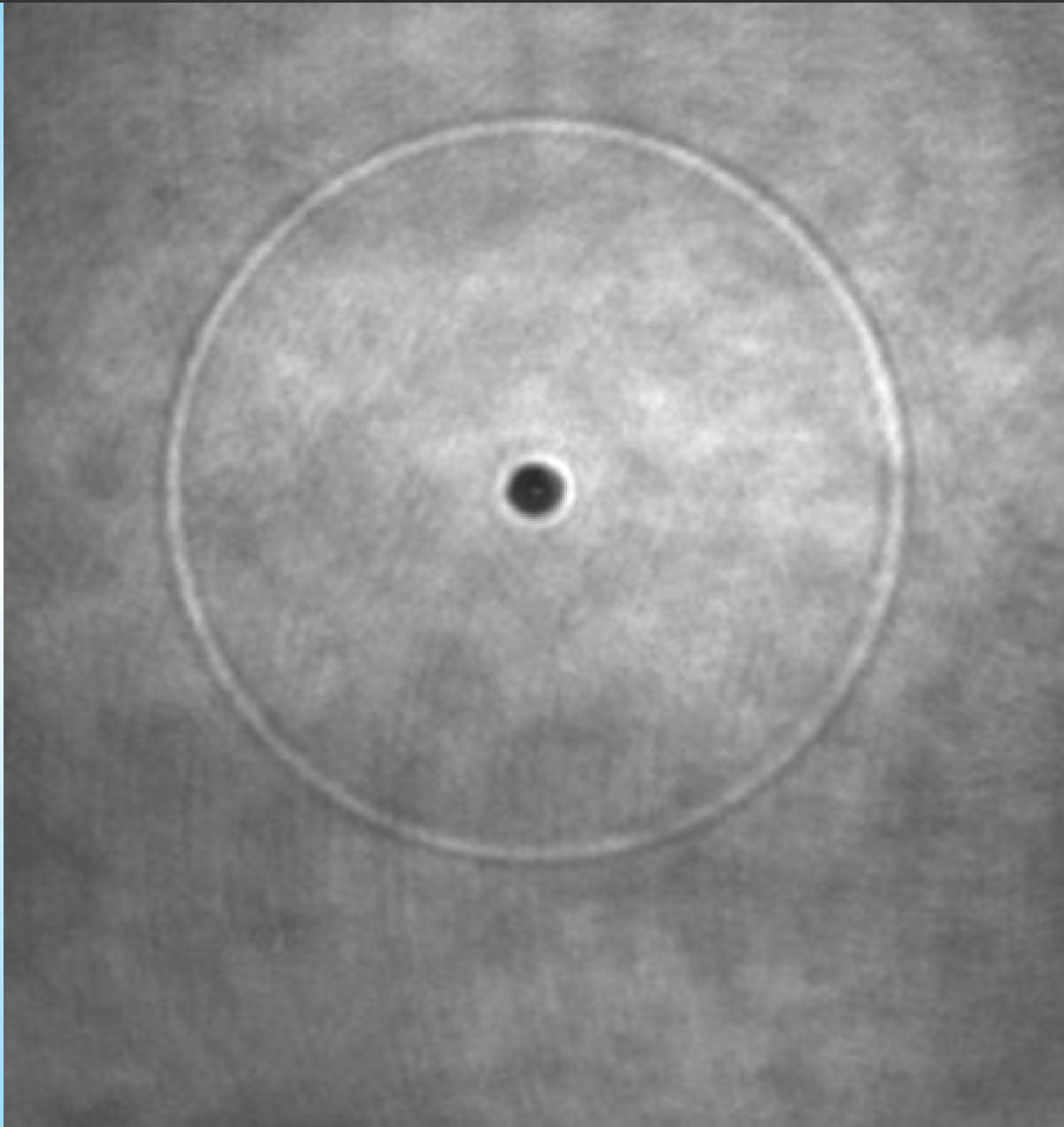
Dynamics

water ("self-healing")

1.0 μJ pulse

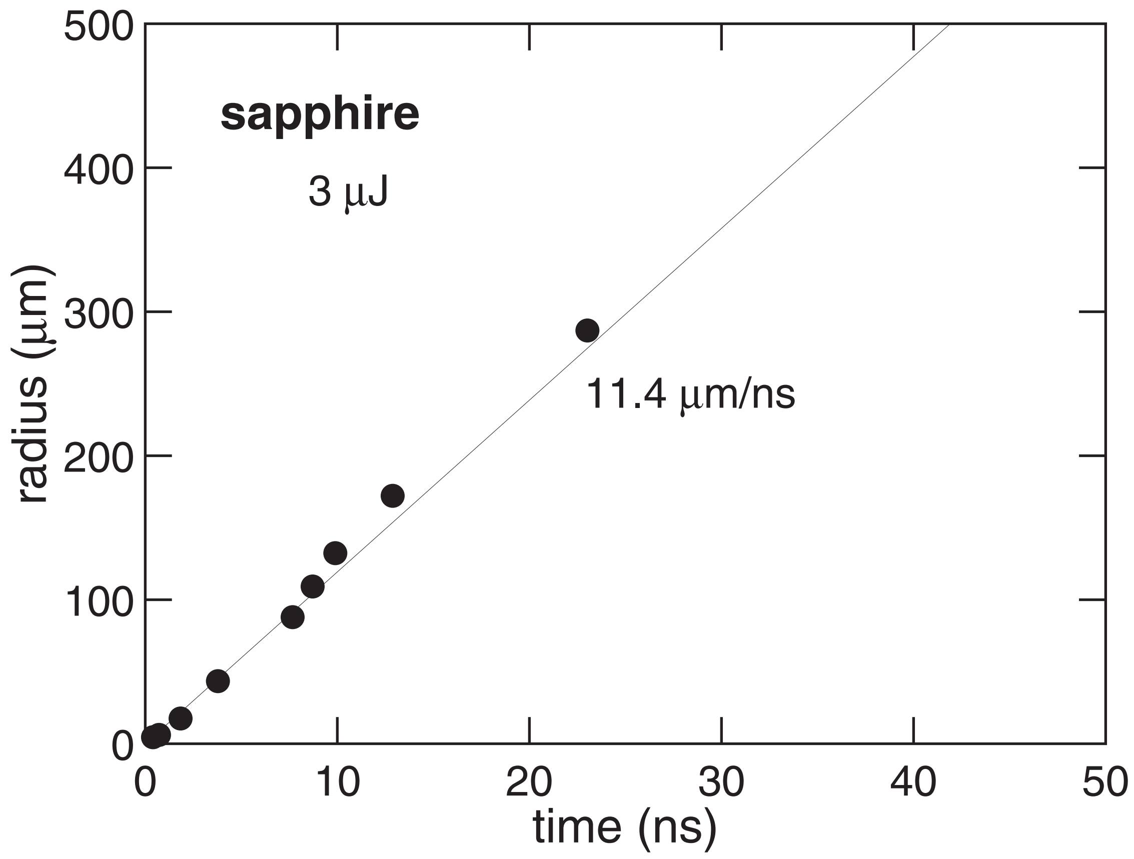
35 ns delay

58 μm radius



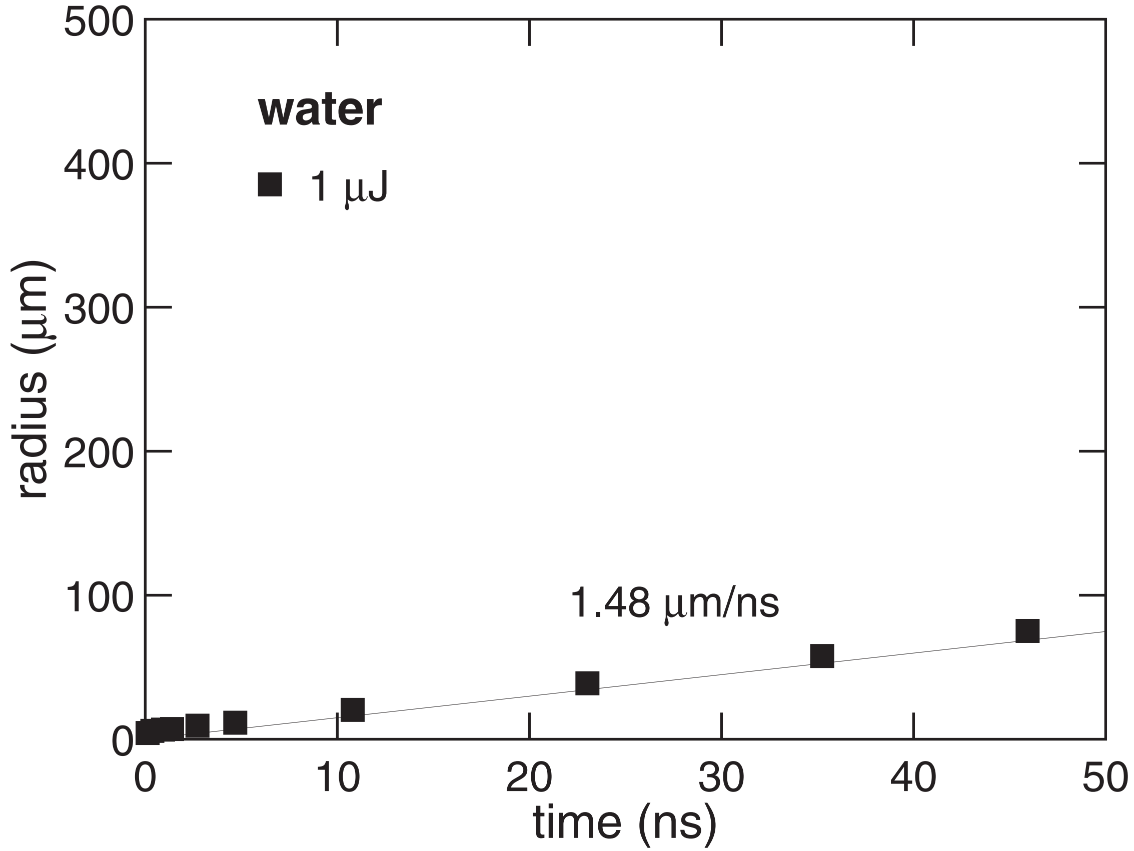
Dynamics

Dynamics

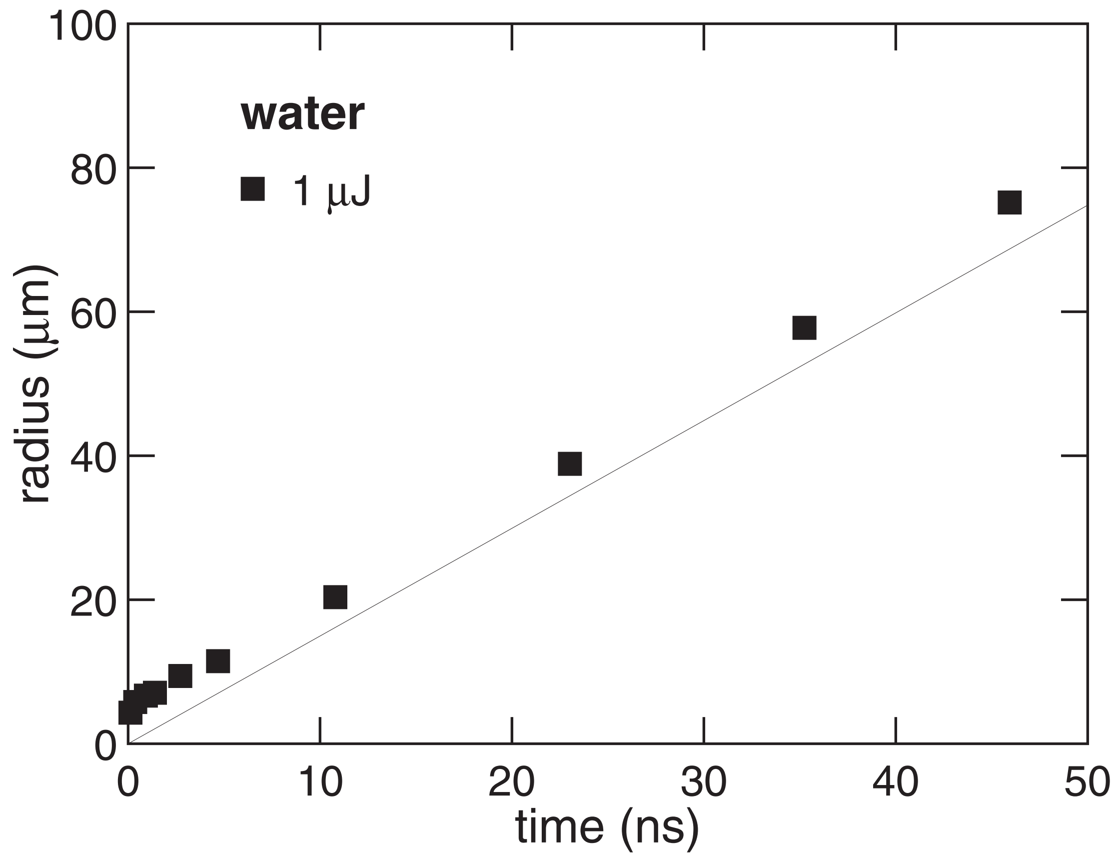


sapphire
3 µJ
11.4 µm/ns
radius (µm)
time (ns)
0
100
200
300
400
500
0
10
20
30
40
50

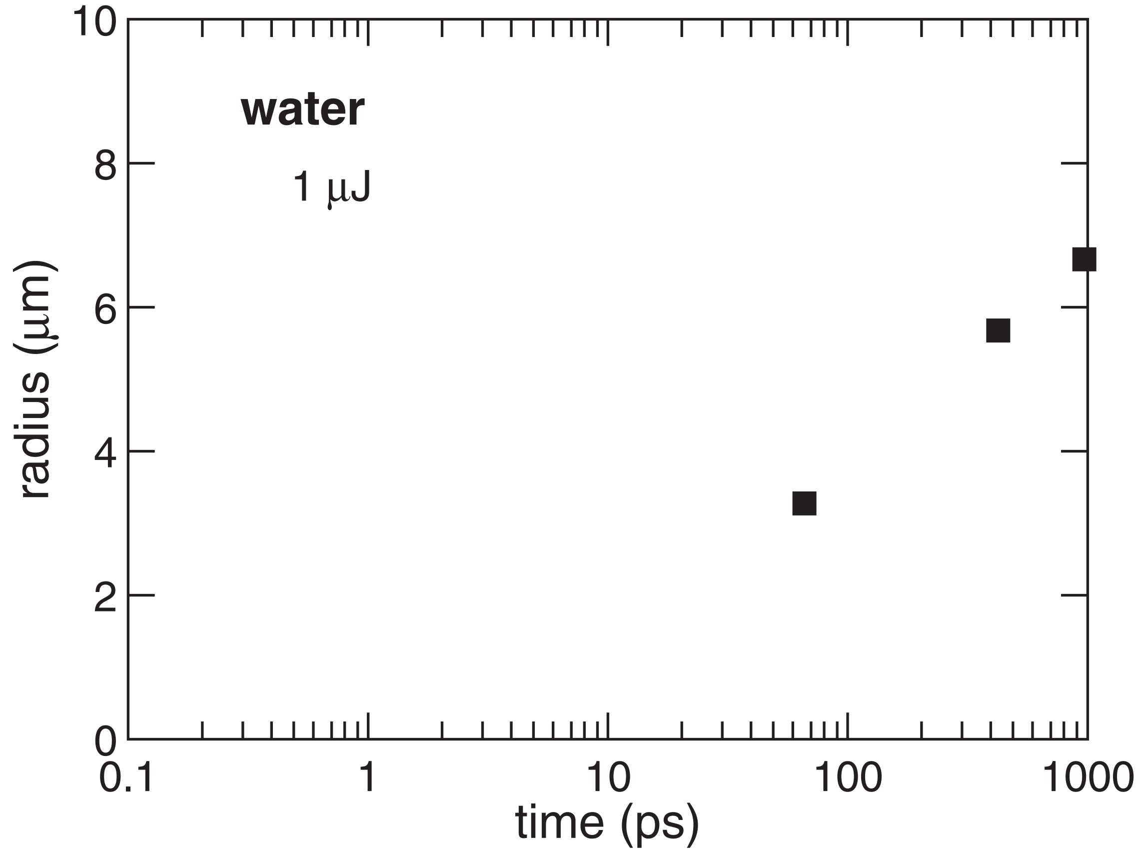
Dynamics


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

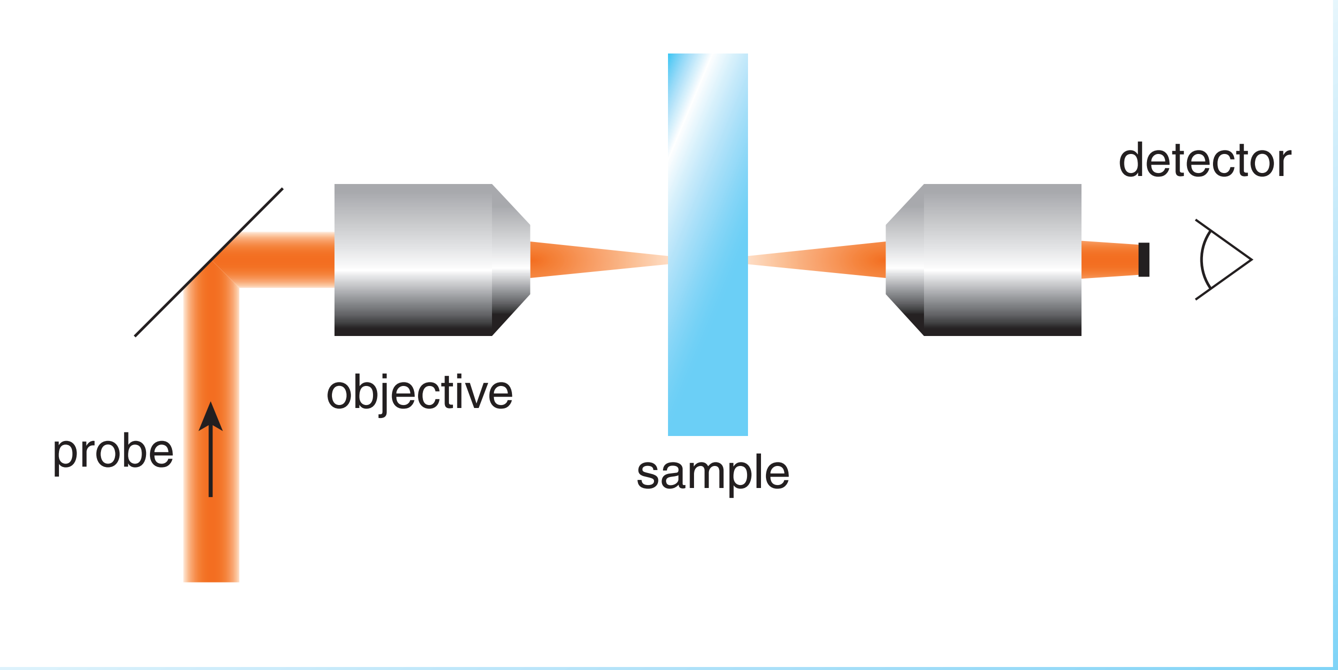
Dynamics



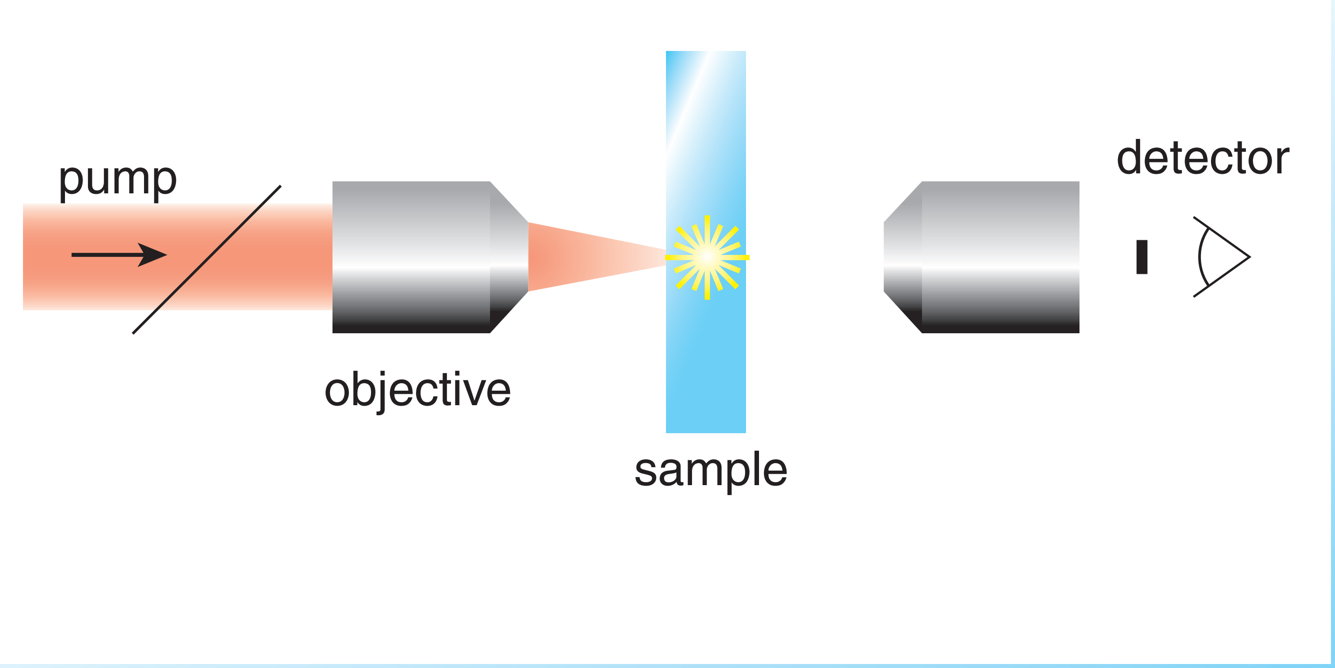
Dynamics



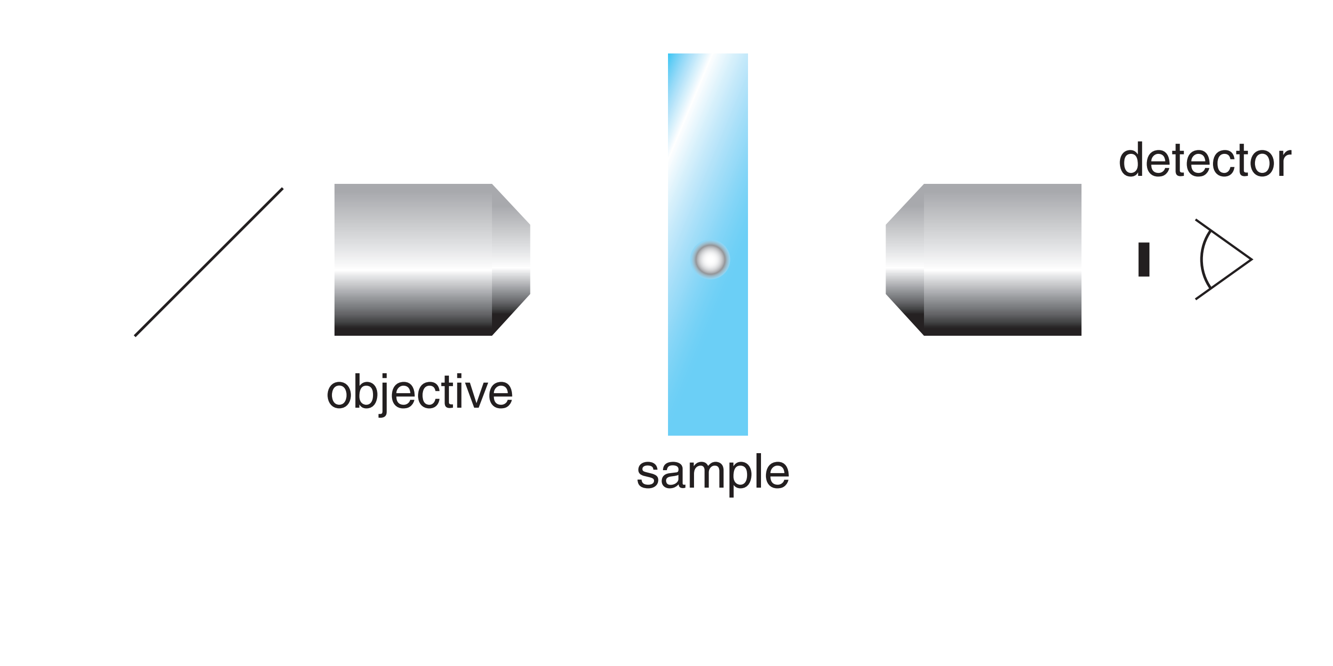
time-resolved scattering setup



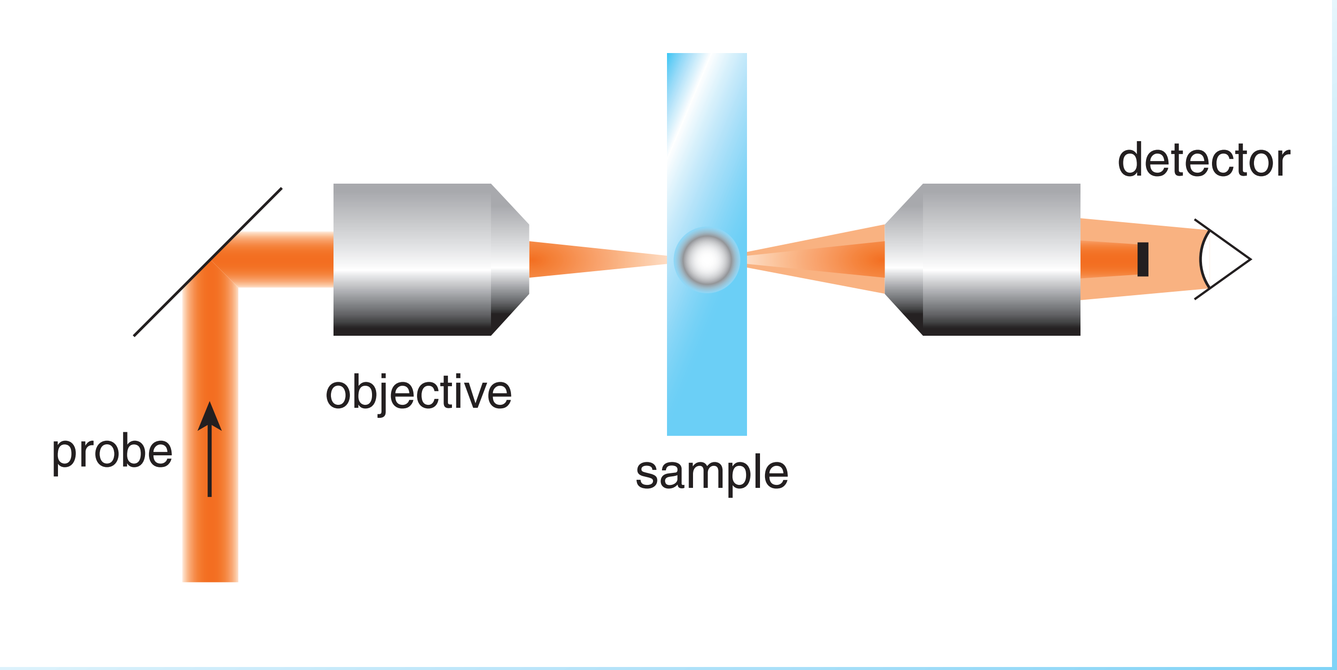
time-resolved scattering setup



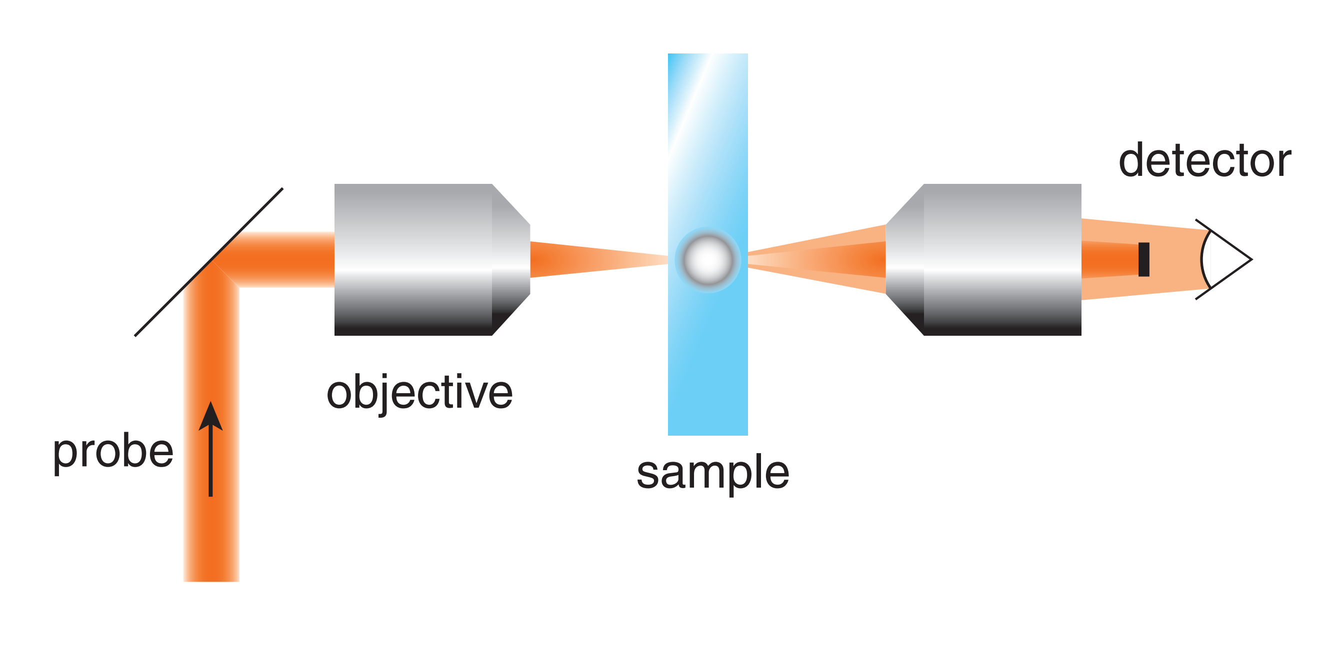
time-resolved scattering setup



time-resolved scattering setup

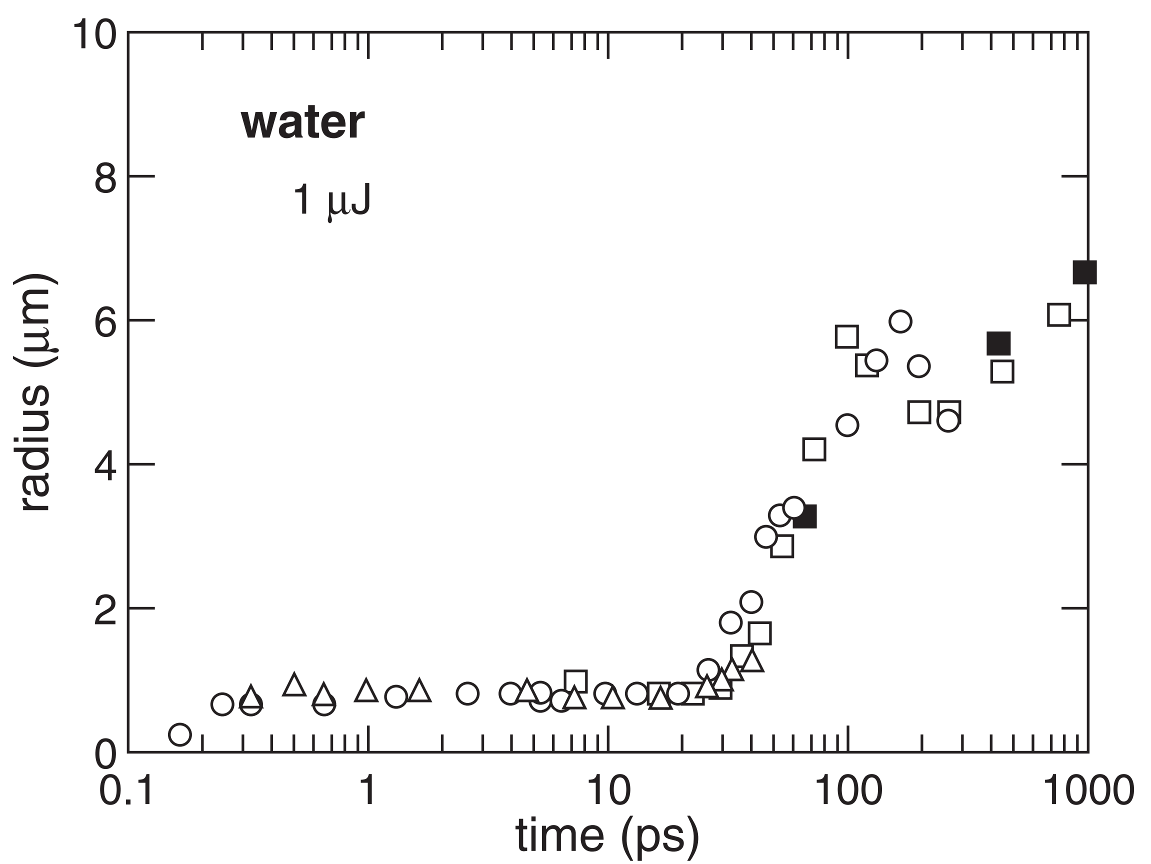


time-resolved scattering setup

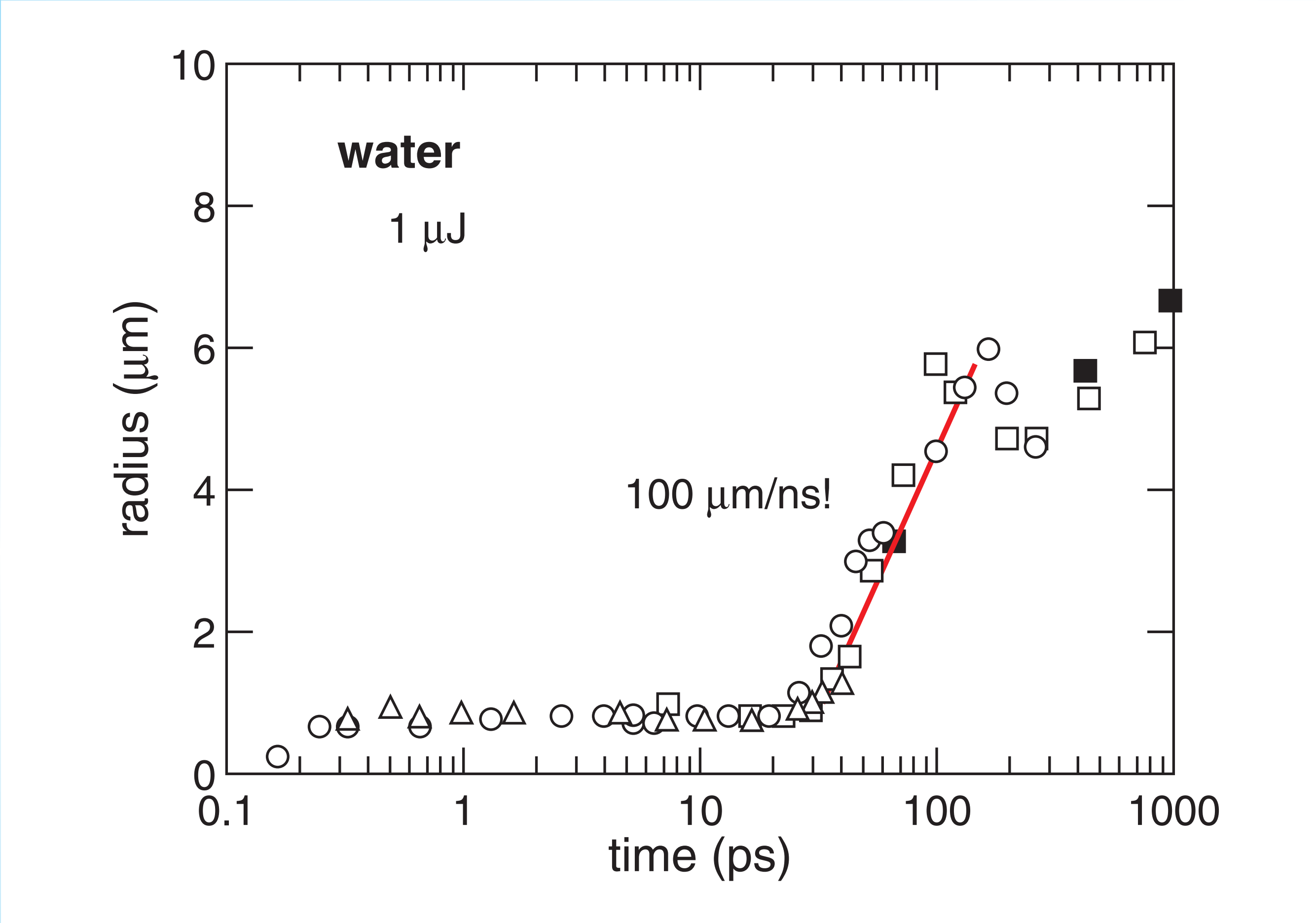


signal proportional to area of scatterer

Dynamics



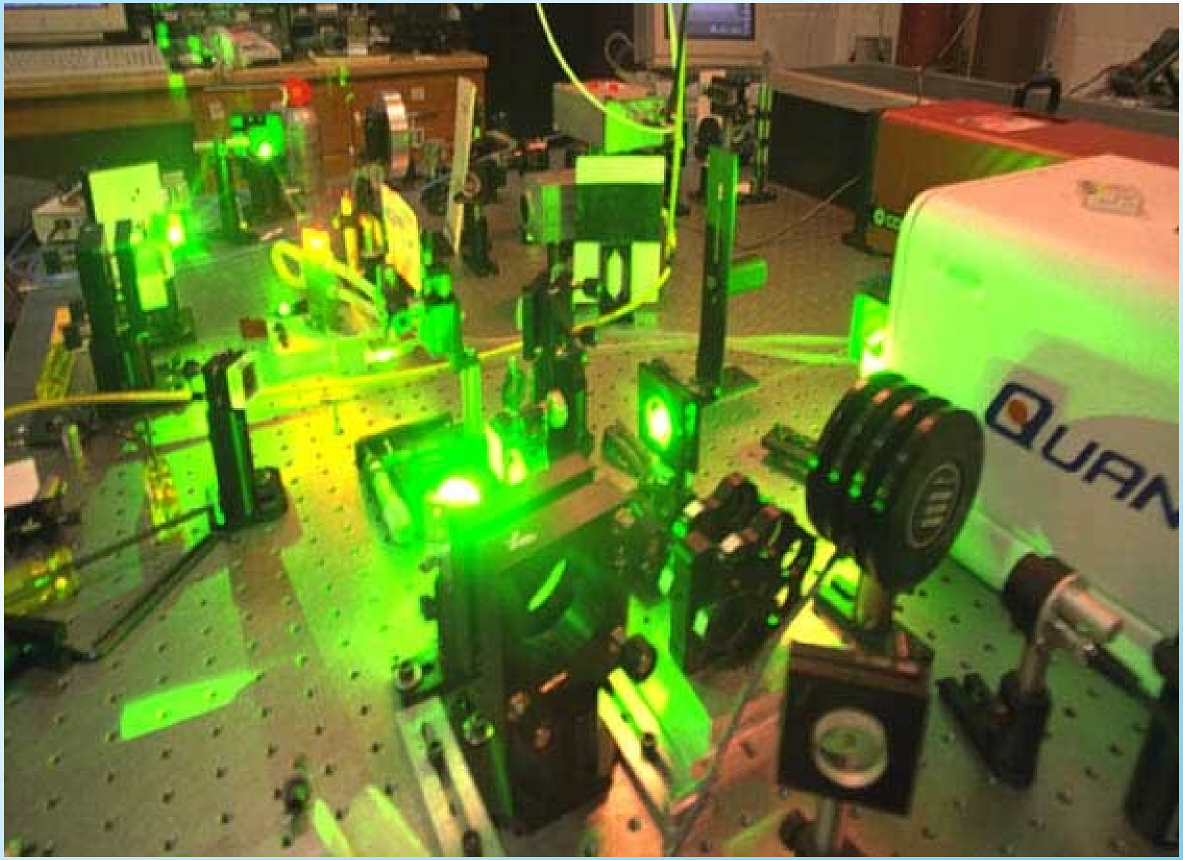
Dynamics



Conclusions

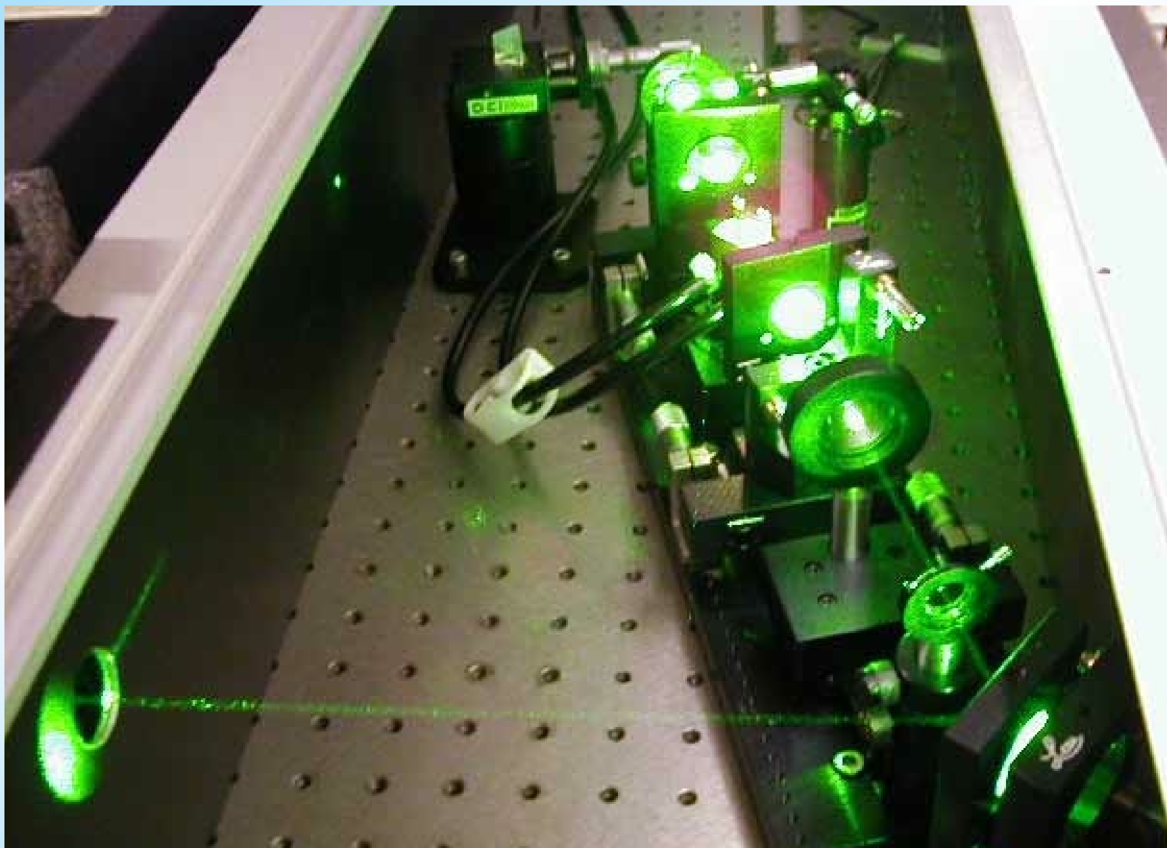
- submicron-scale bulk micromachining
- weak bandgap and wavelength dependence
- only a few nanojoules required

5-nJ threshold: unamplified micromachining



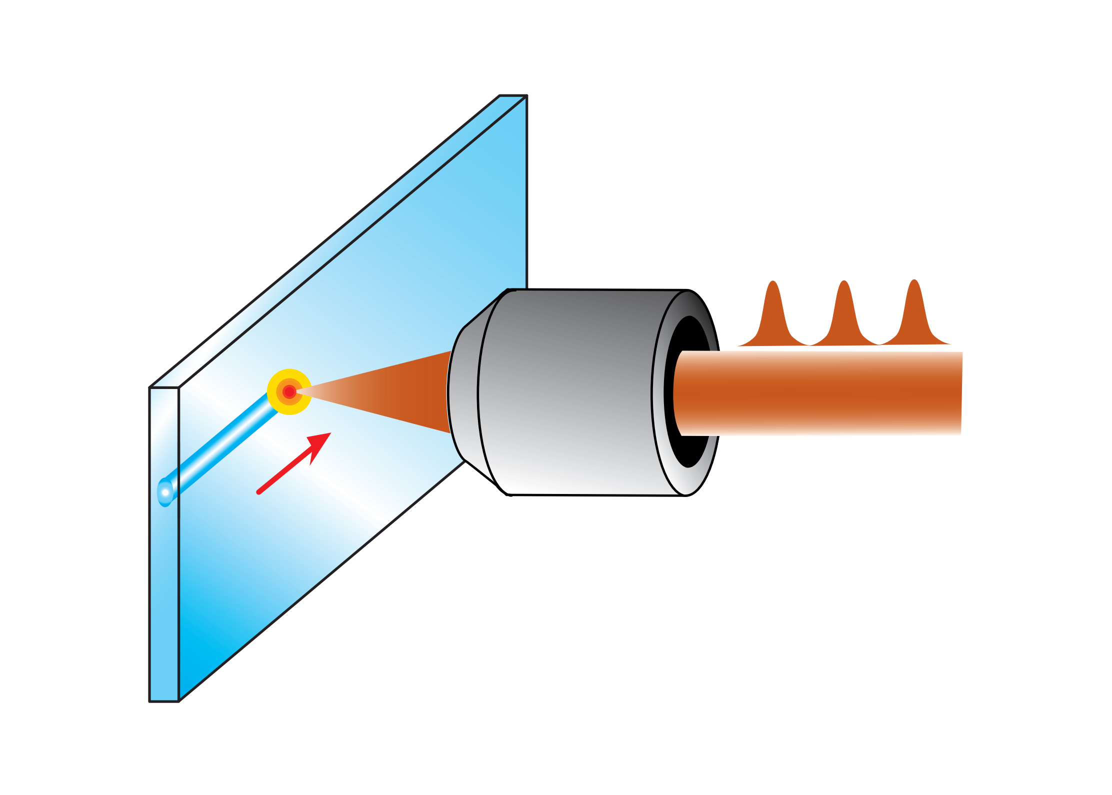
Laser micromachining simplified

5-nJ threshold: unamplified micromachining

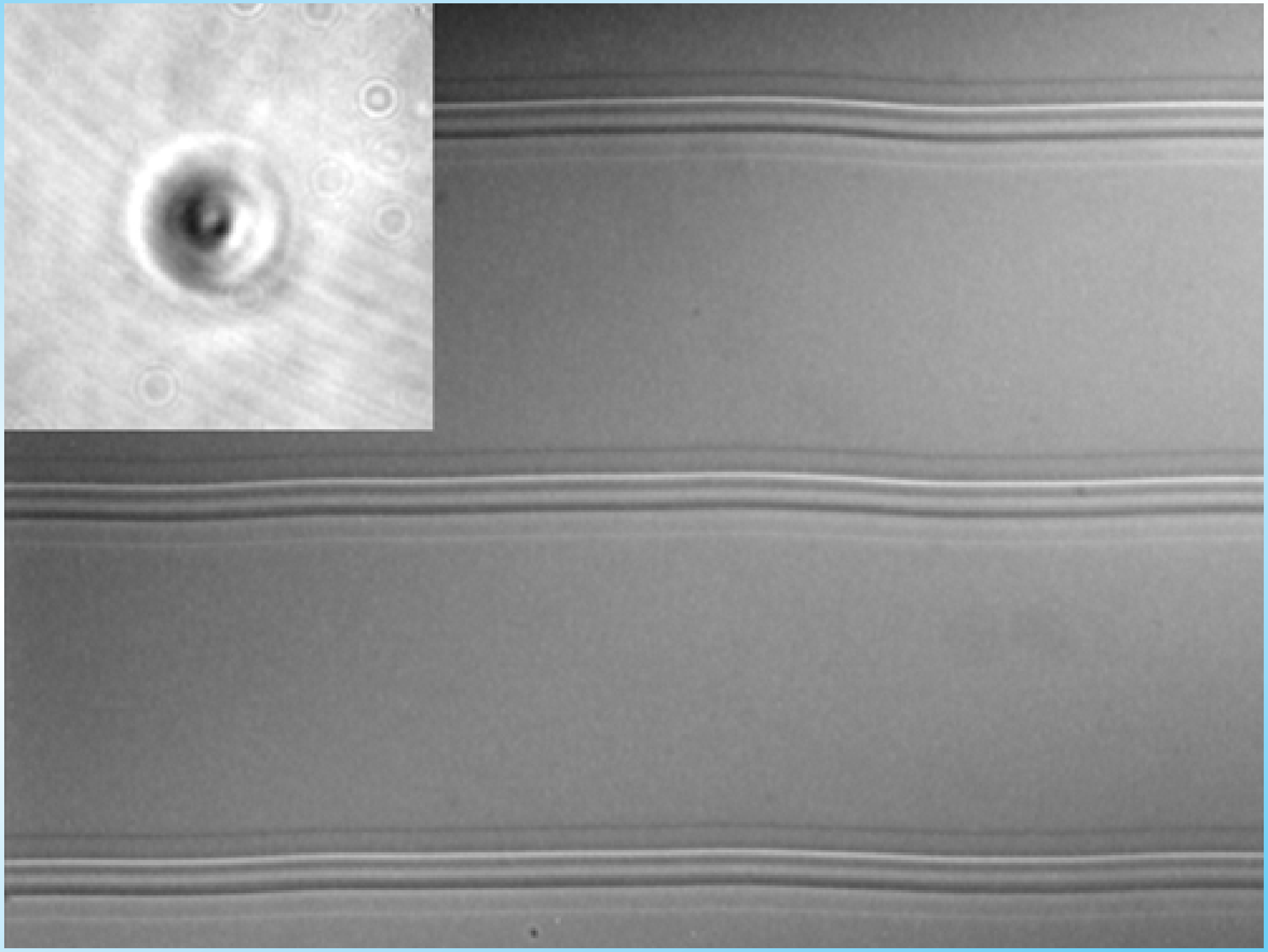


Laser micromachining simplified

waveguide machining



waveguide machining



Future applications

- **Photonic devices**

Future applications

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

Future applications

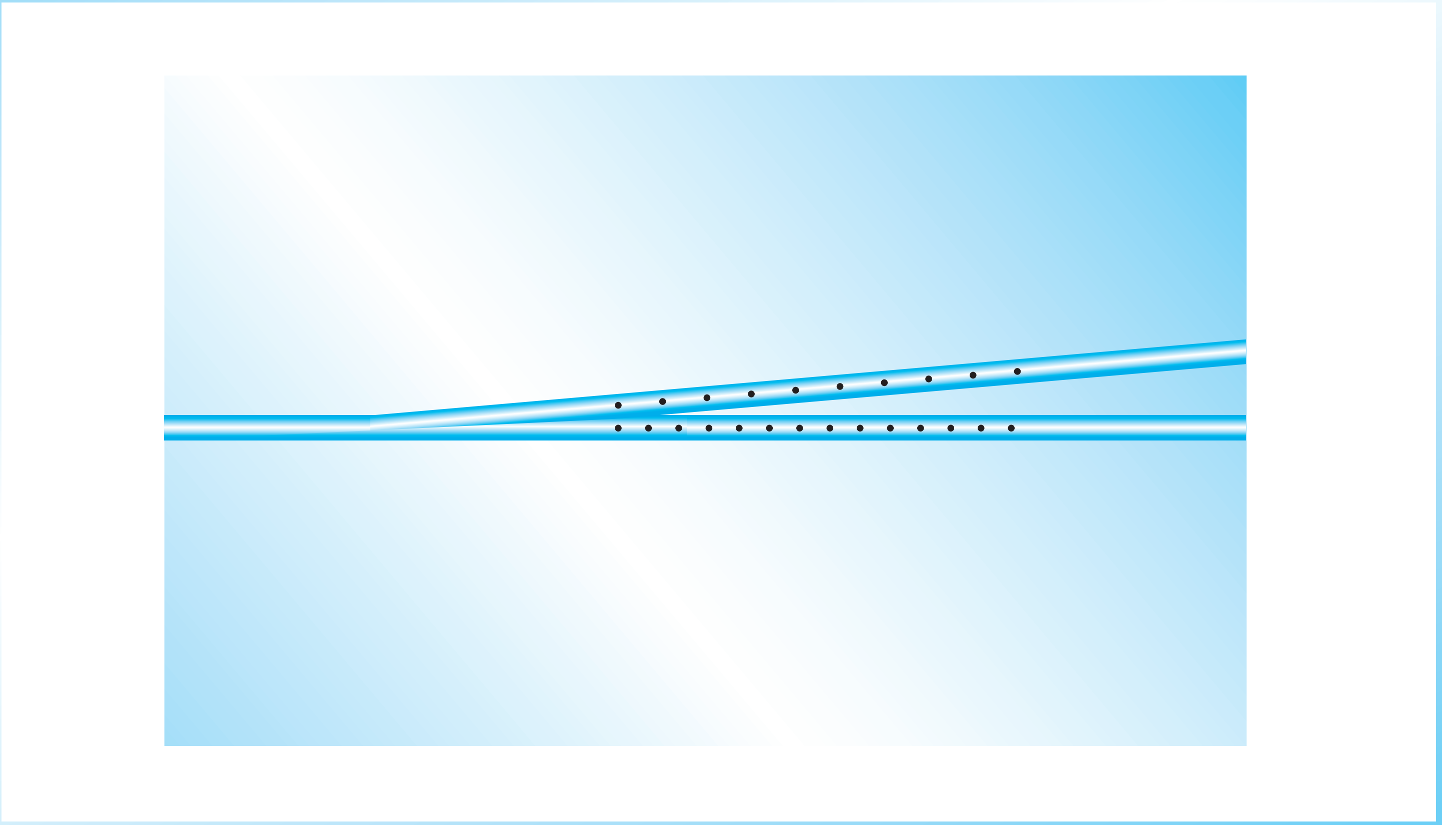
wavelength selective splitter

Future applications

wavelength selective splitter

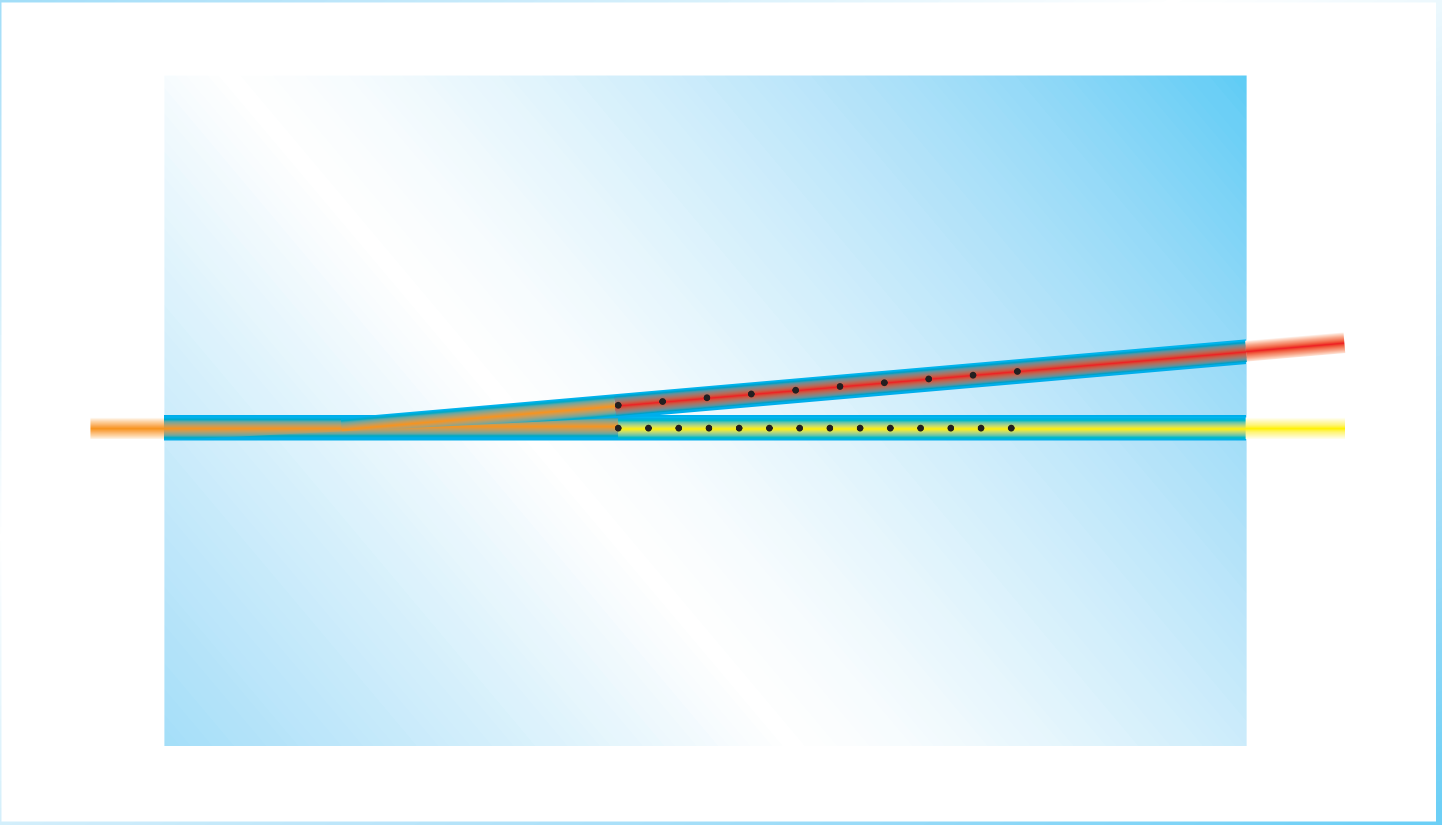
Future applications

wavelength selective splitter



Future applications

wavelength selective splitter



Future applications

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

Open questions

- **Propagation of pulses**
- **Mechanisms**

Funding: National Science Foundation

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Prof. Alex Gaeta (Cornell)
Prof. Nico Bloembergen (Harvard)
W. Leight
Carl Zeiss, Inc

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