

MICROEXPLOSIONS: CONTROLLING MATTER WITH LIGHT

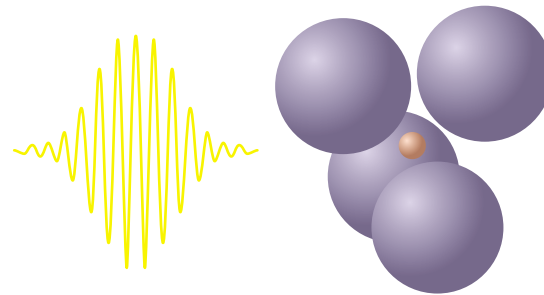
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Alan Jamieson
Nan Shen
Chris B. Schaffer
Eric Mazur**

University of Missouri-Rolla
13 April 2001



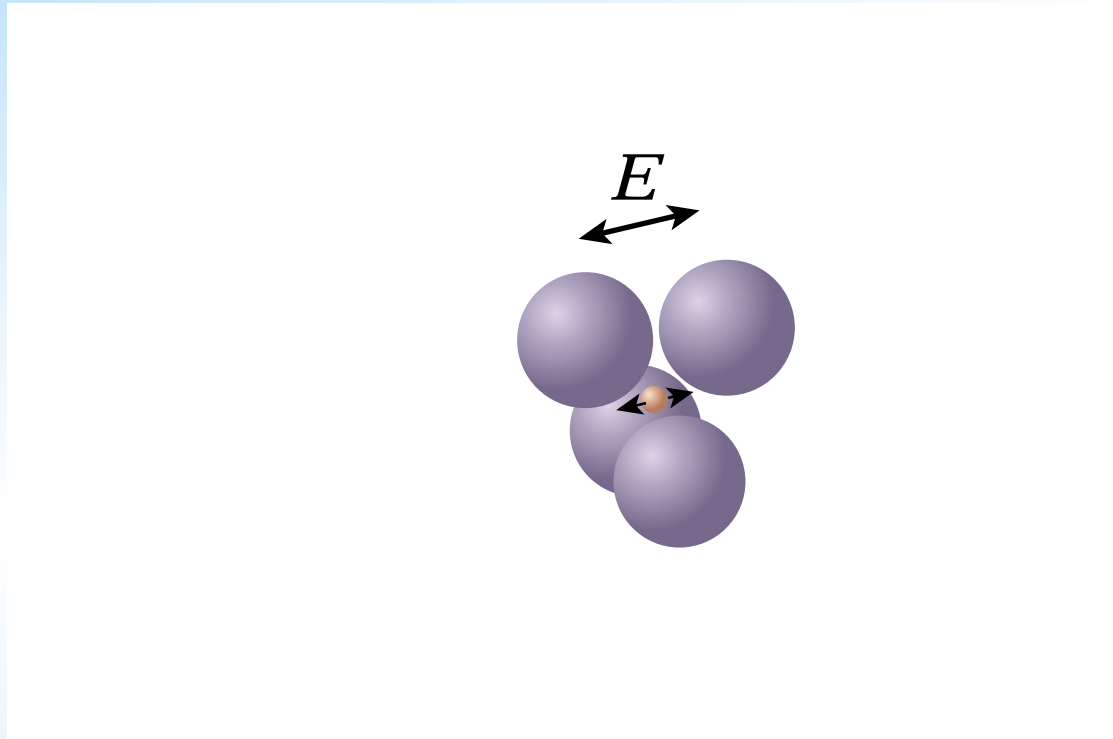
Introduction

light-matter interactions



Introduction

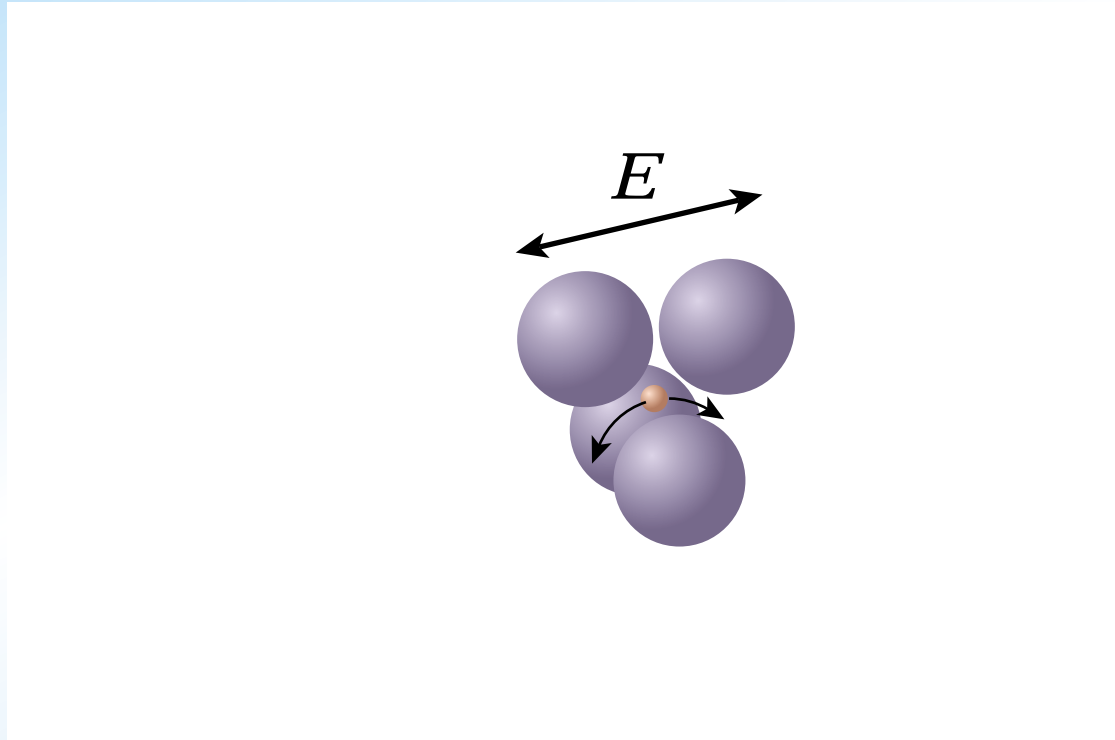
linear response



“stiffness” determines index of refraction

Introduction

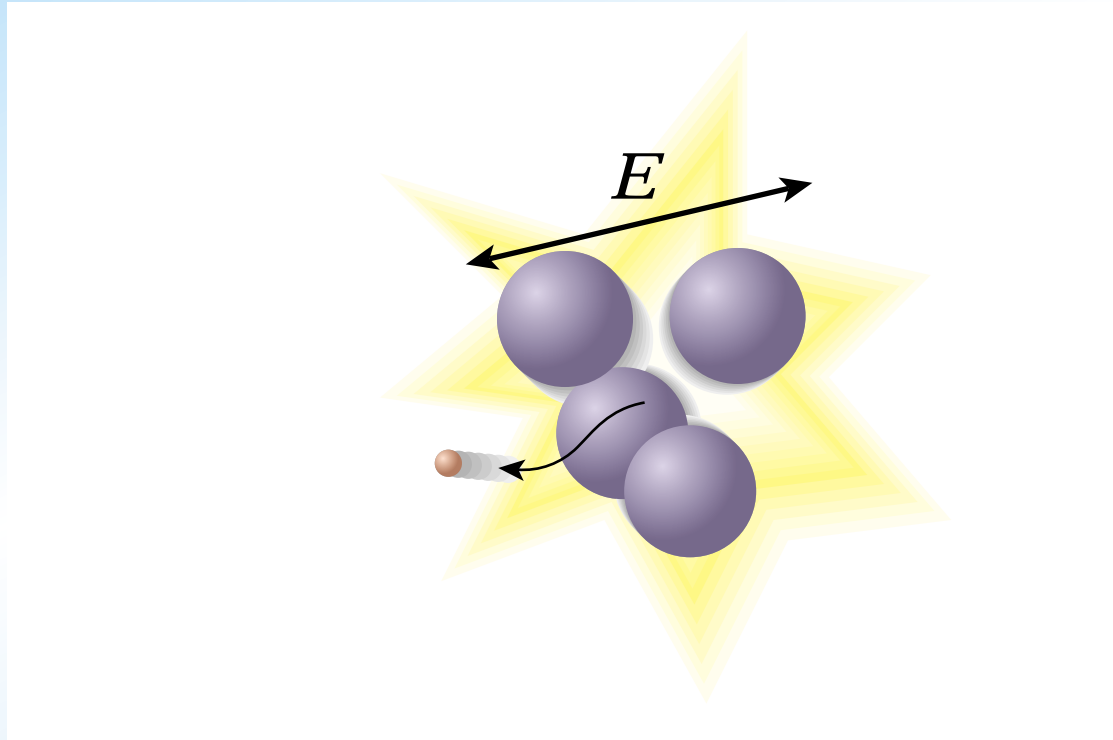
nonlinear response



second harmonic generation

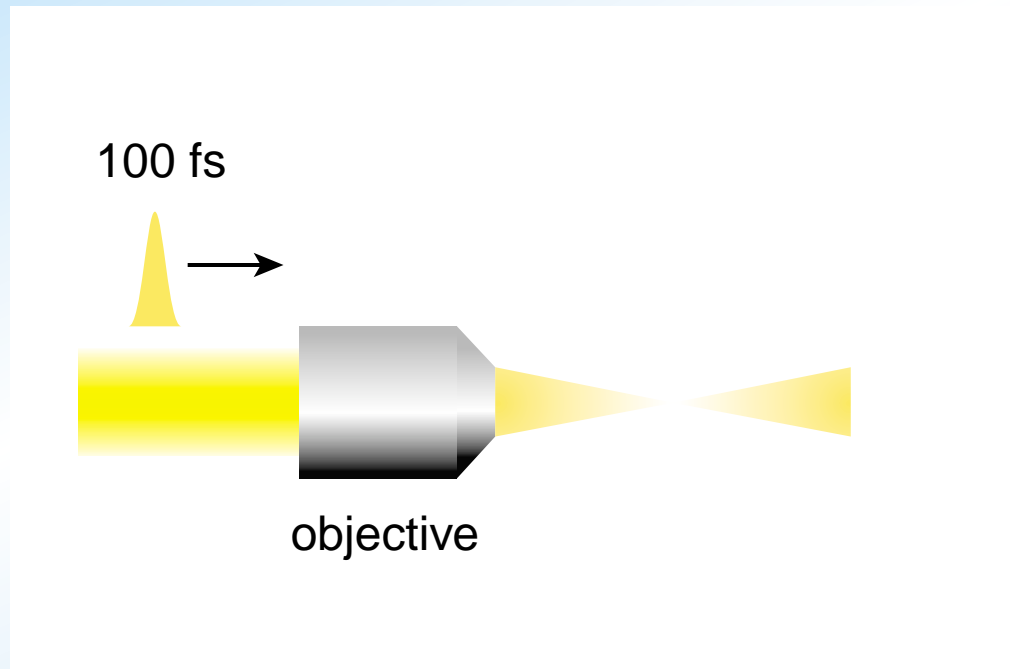
Introduction

“extremely” nonlinear response



Introduction

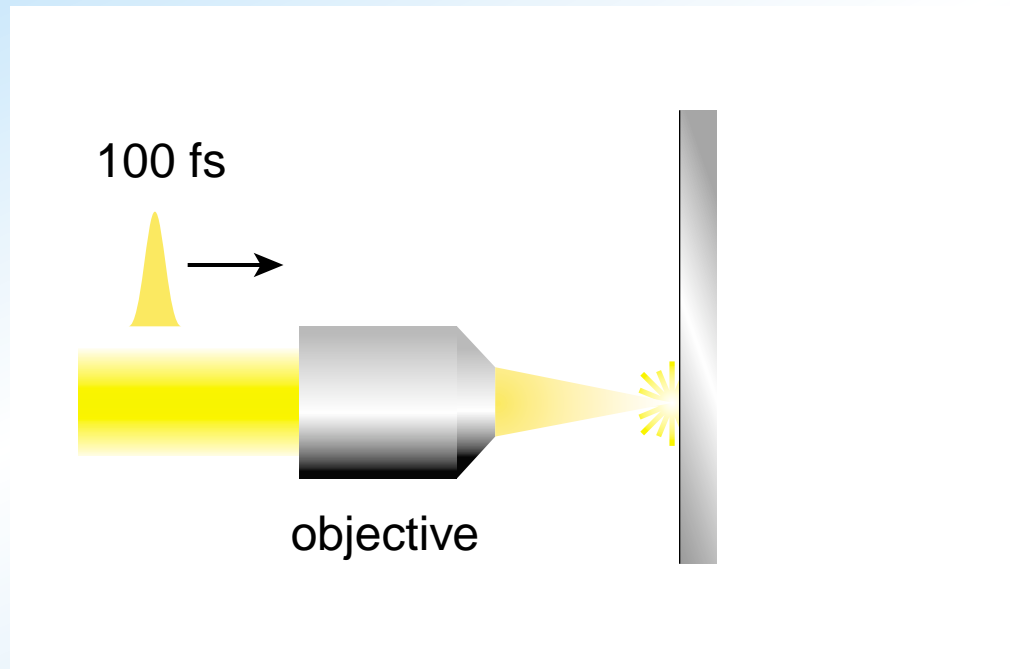
tightly focus laser beam



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

Introduction

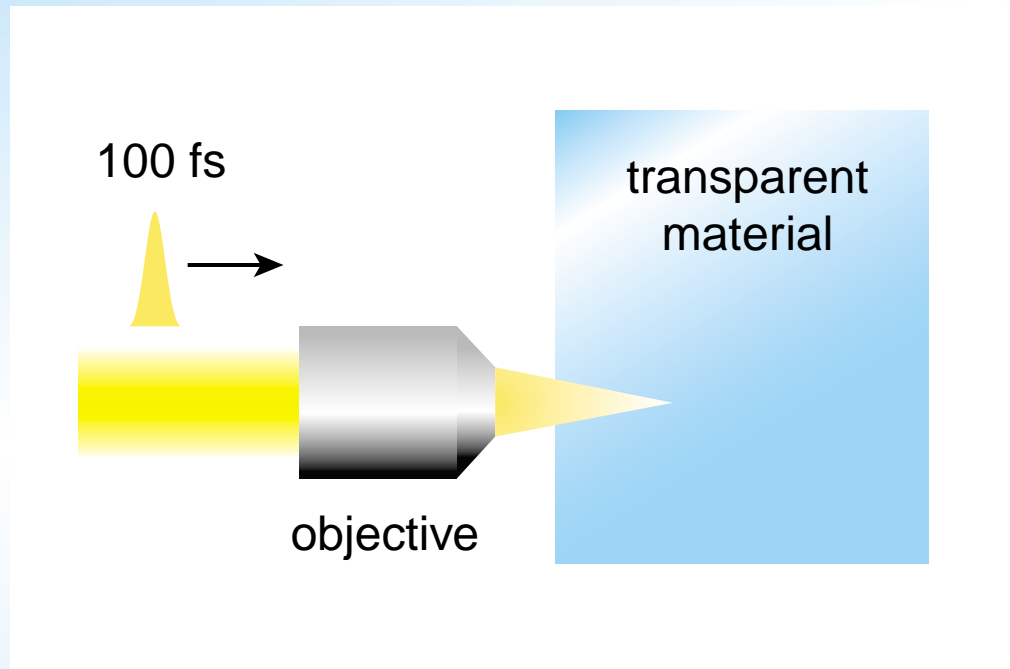
focus laser beam at surface



(works for all materials)

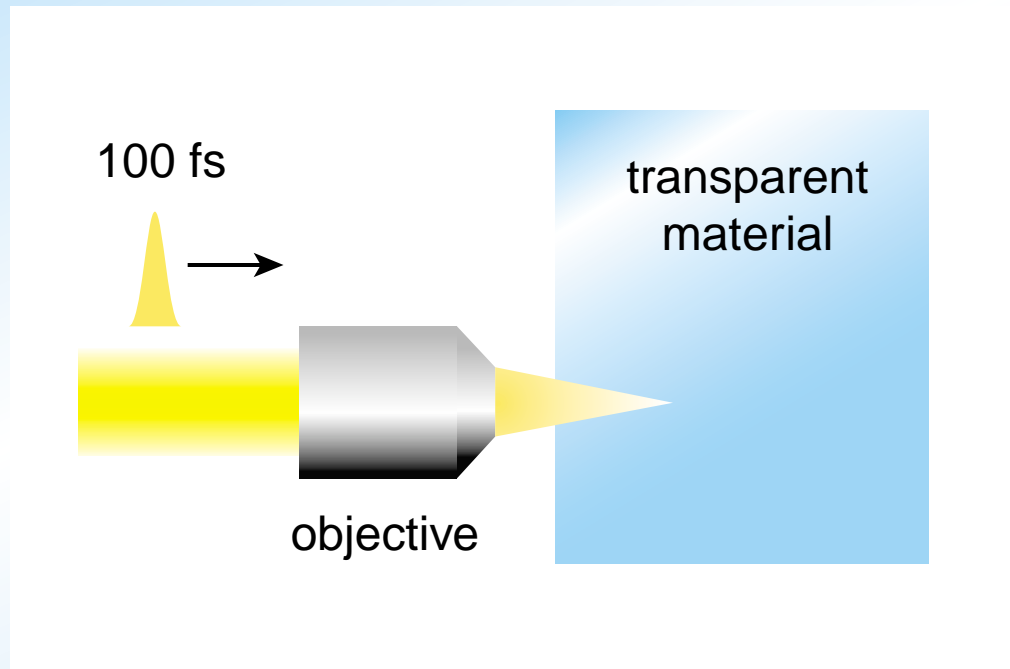
Introduction

focus beam inside transparent material...



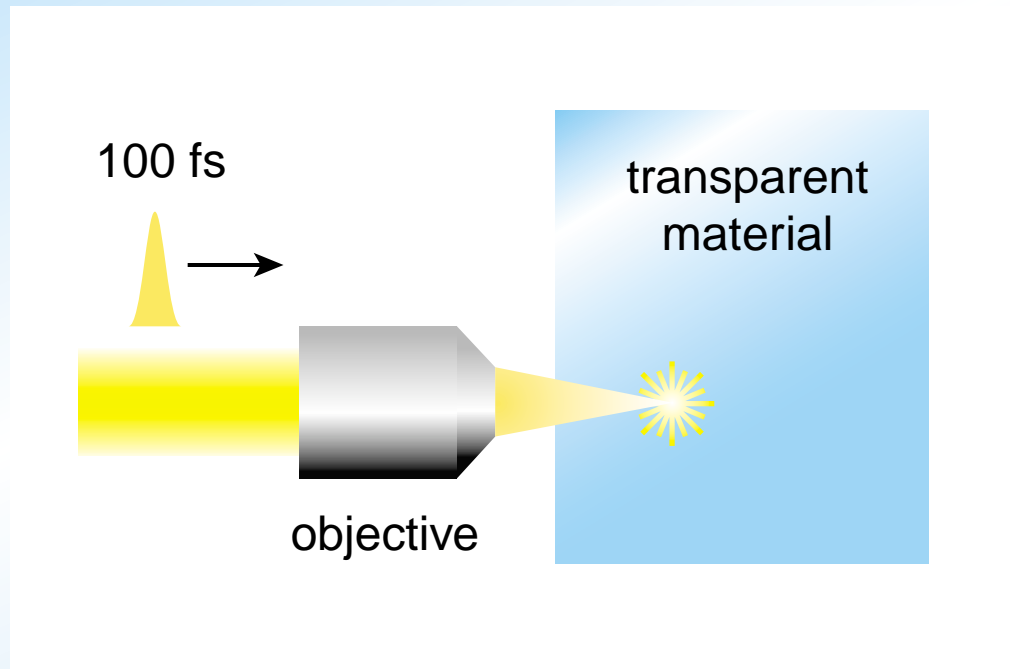
Introduction

high intensity at focus...



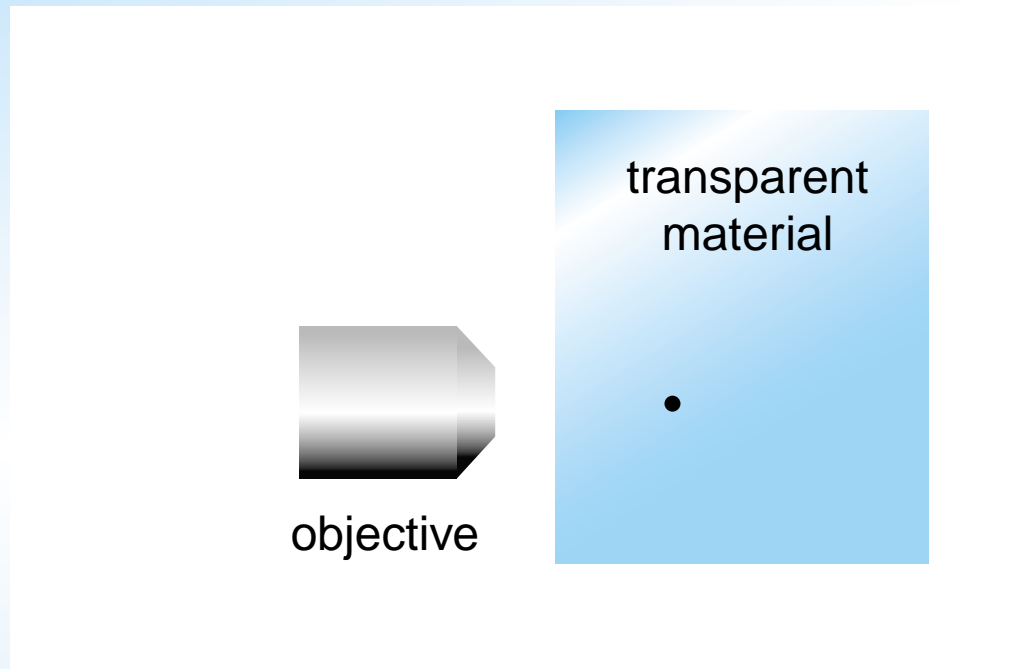
Introduction

... causes nonlinear ionization...

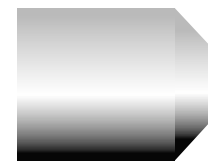


Introduction

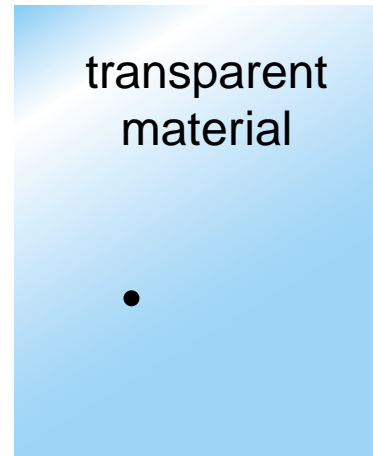
and irreversible structural changes on microscopic scale



Introduction



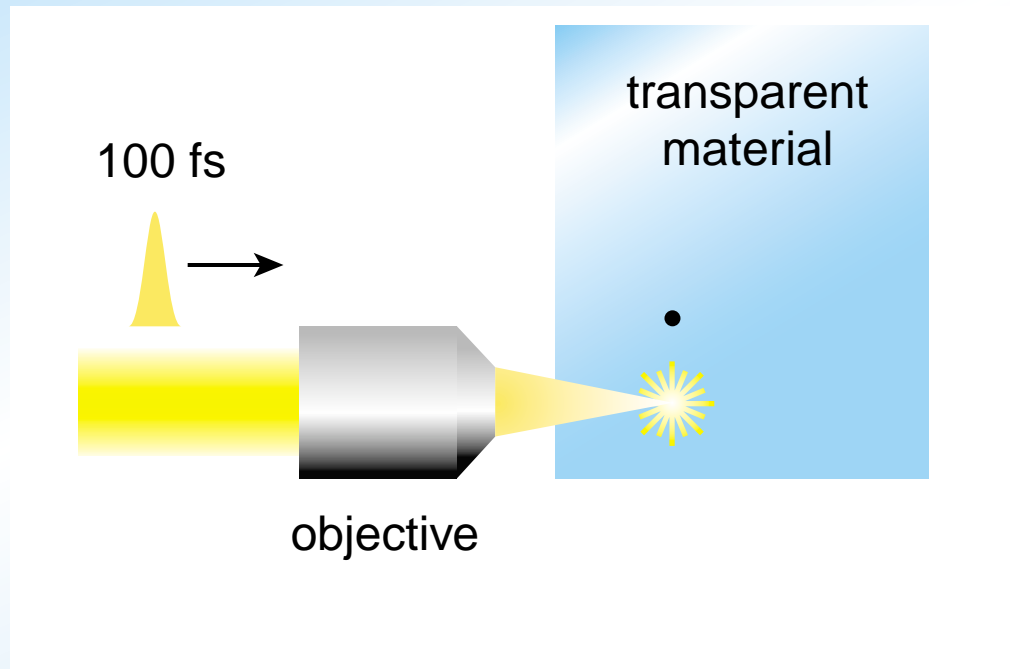
objective



transparent
material

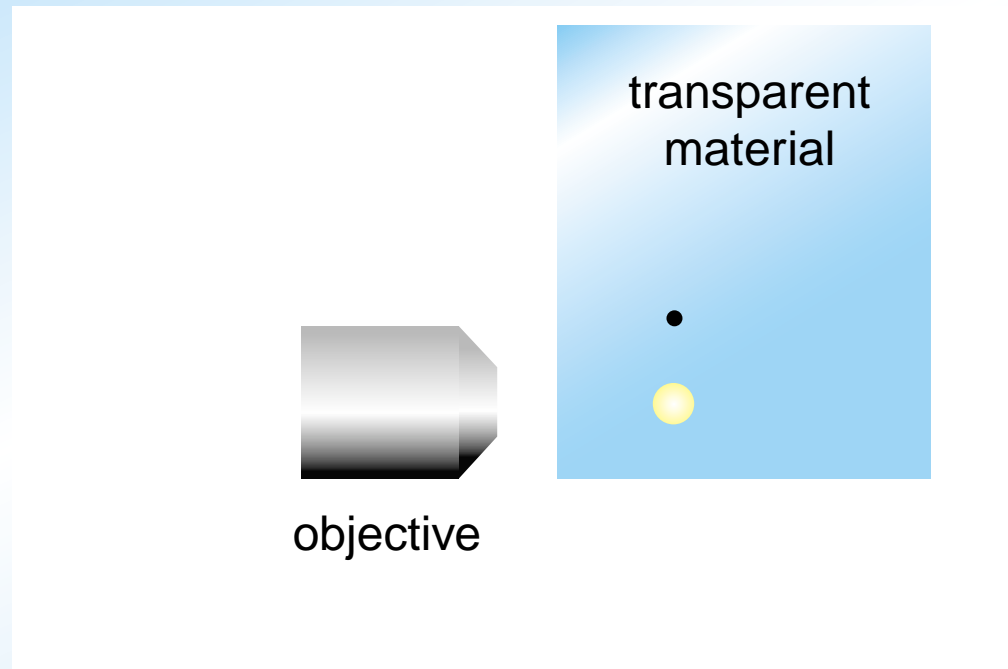
Introduction

100 fs: laser energy transferred to electrons



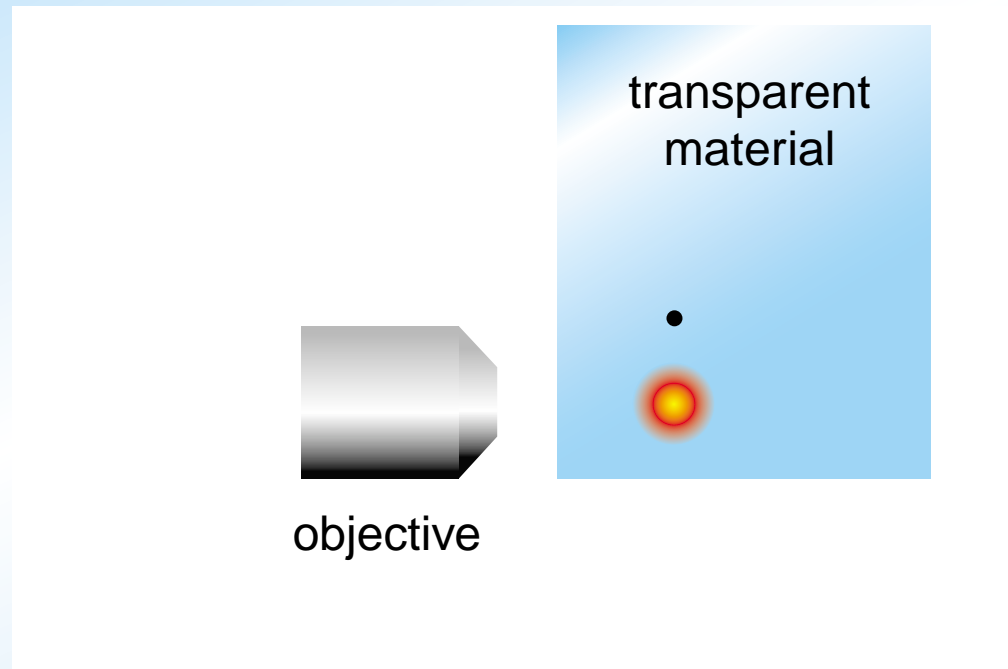
Introduction

10 ps: energy transfer to ions



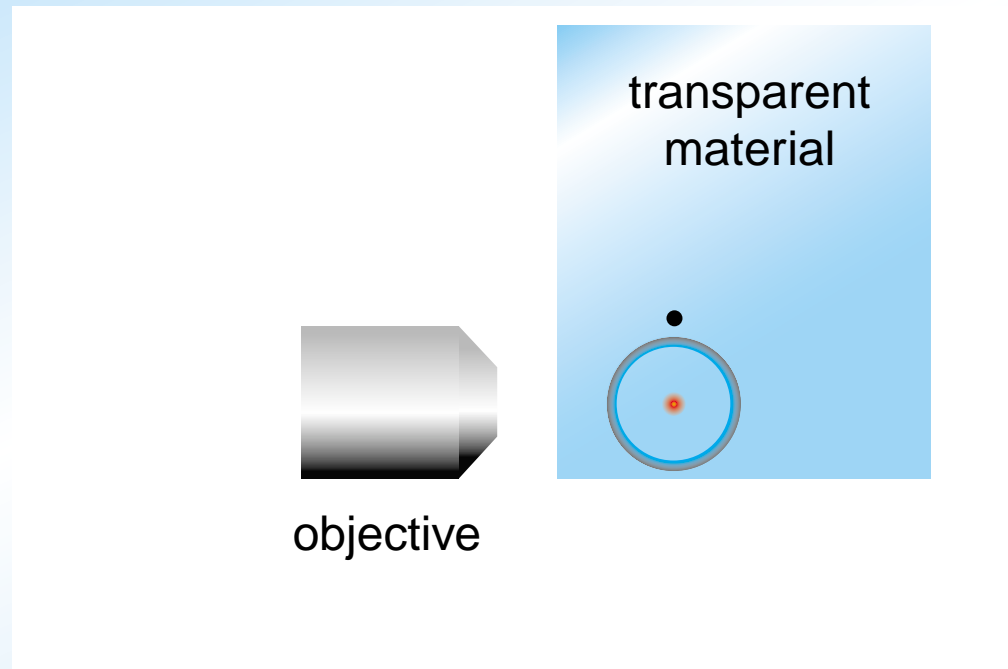
Introduction

100 ps: plasma expansion



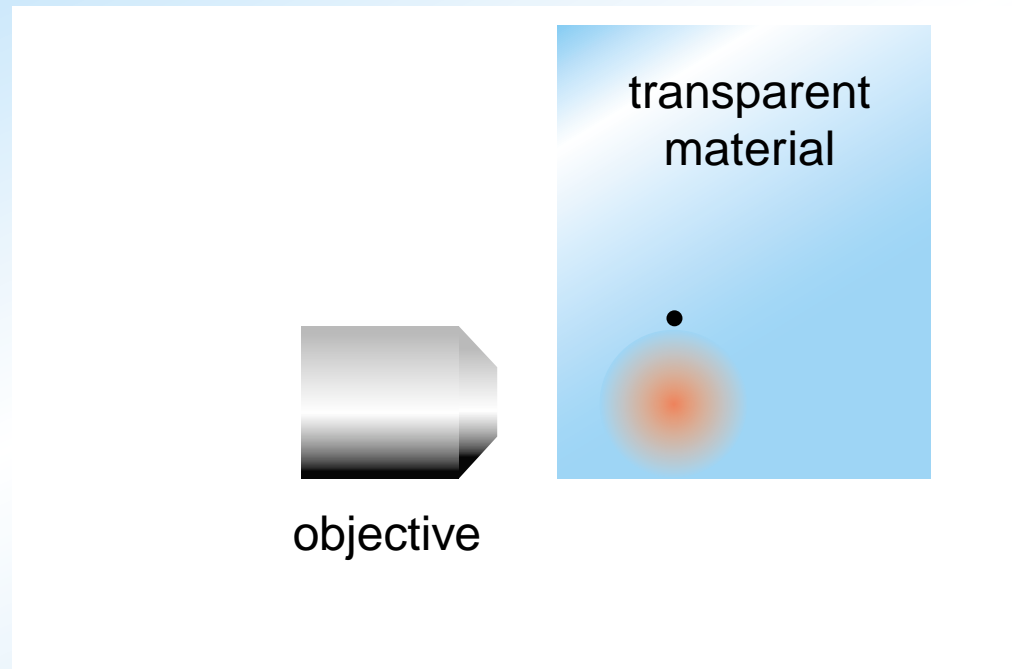
Introduction

10–100 ns: shock propagation



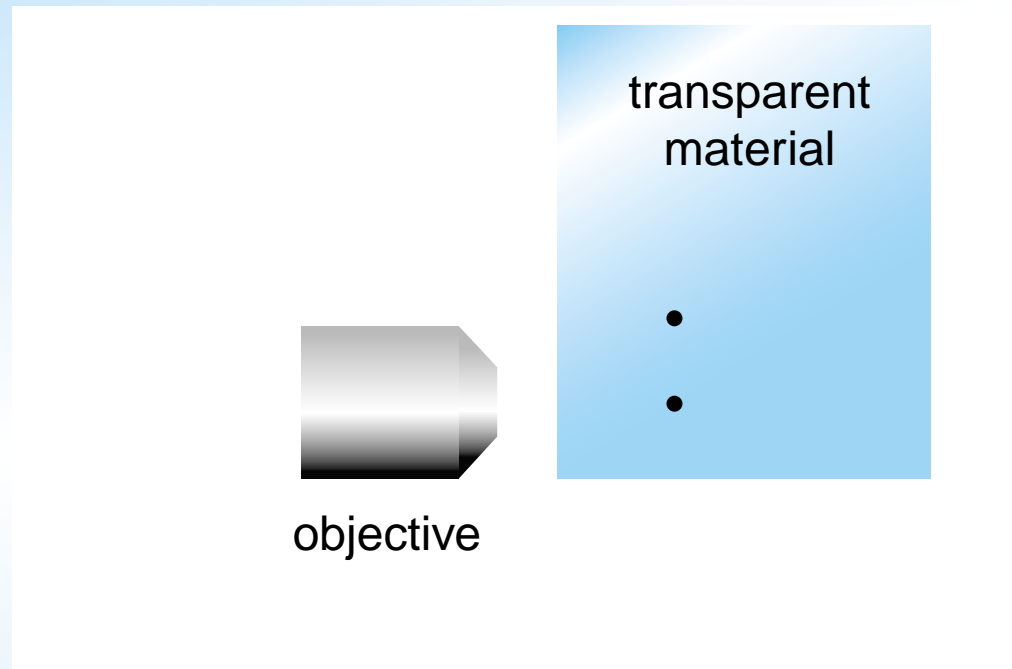
Introduction

1 μ s: thermal diffusion



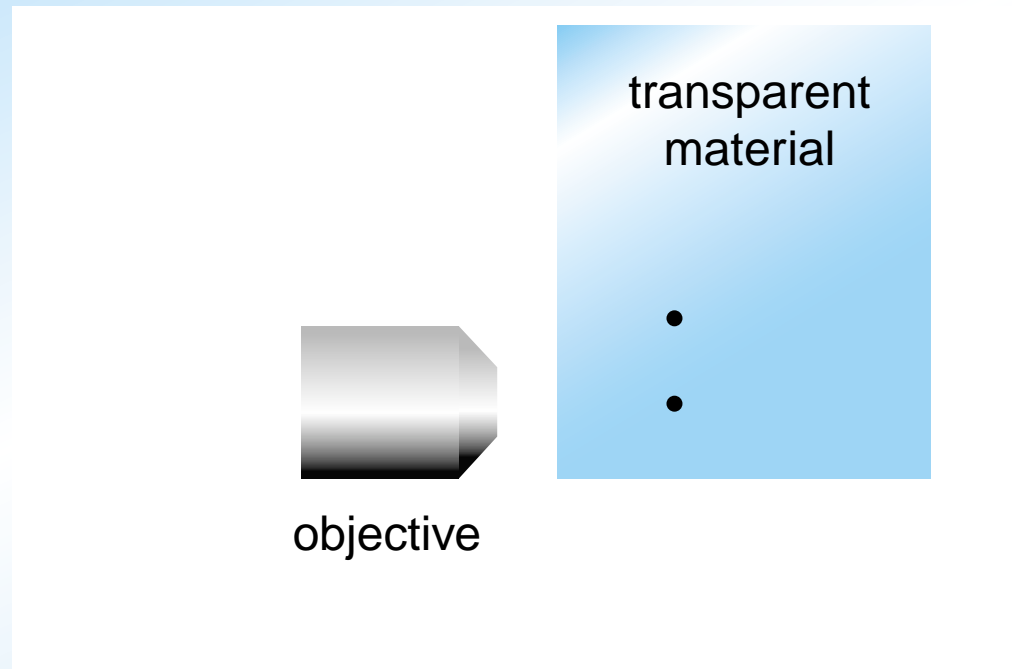
Introduction

1 ms: permanent structural change



Introduction

What are the conditions at the focus?



laser deposits energy in $\sim 0.1 \mu\text{m}^3$

Introduction

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

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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

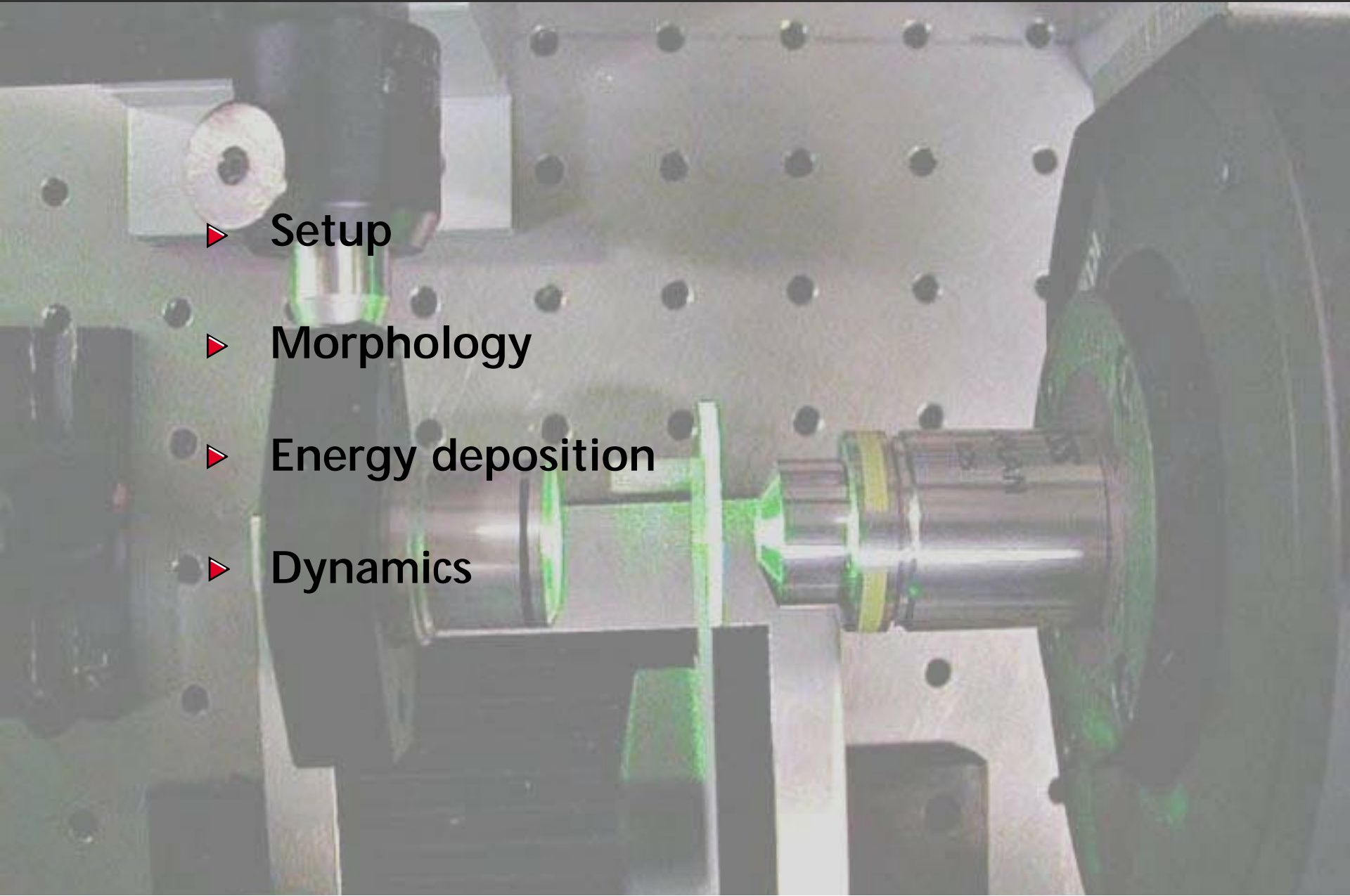
Material is a perturbation to the light!

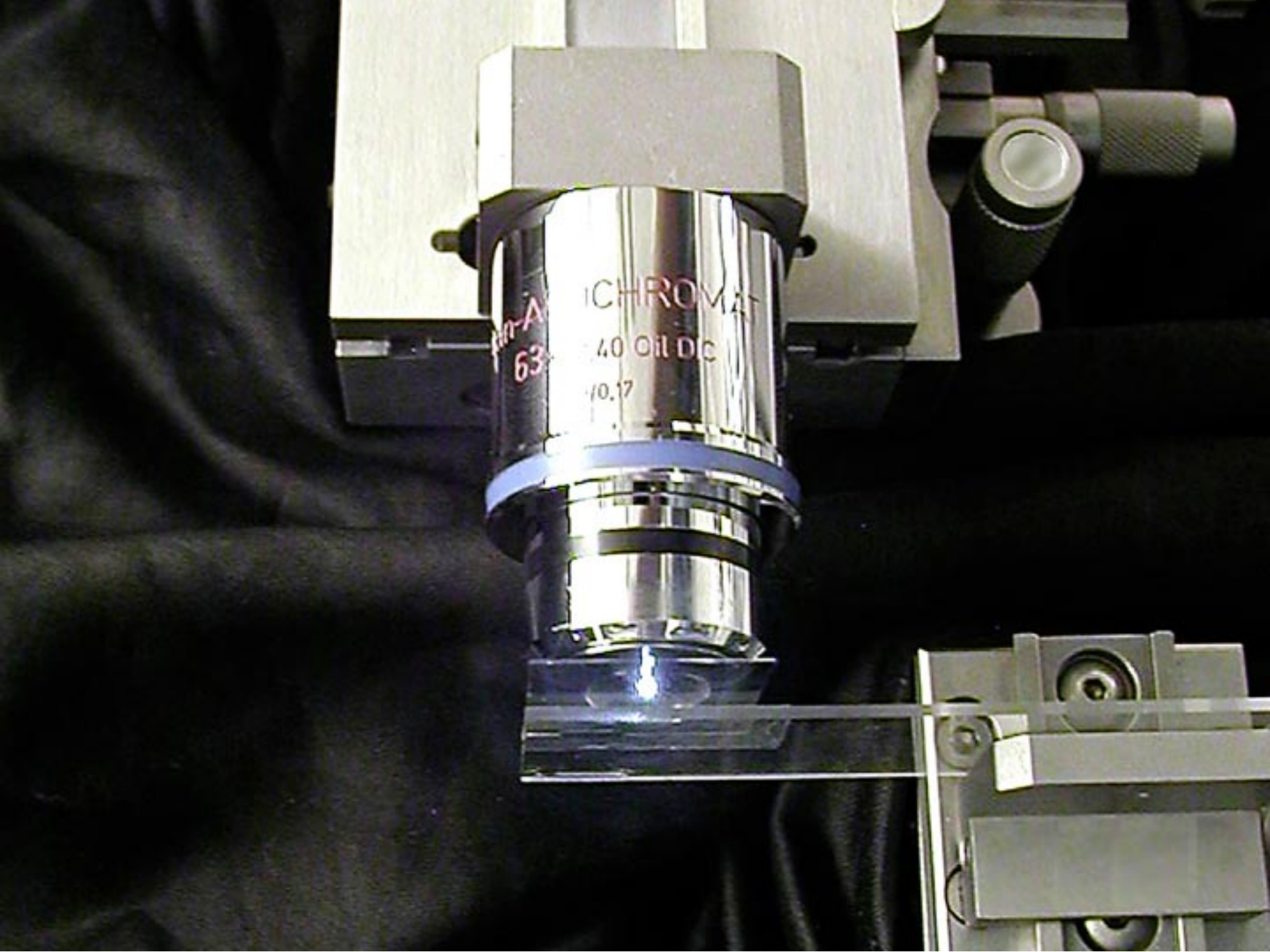
Introduction

How do materials behave under these extreme conditions?

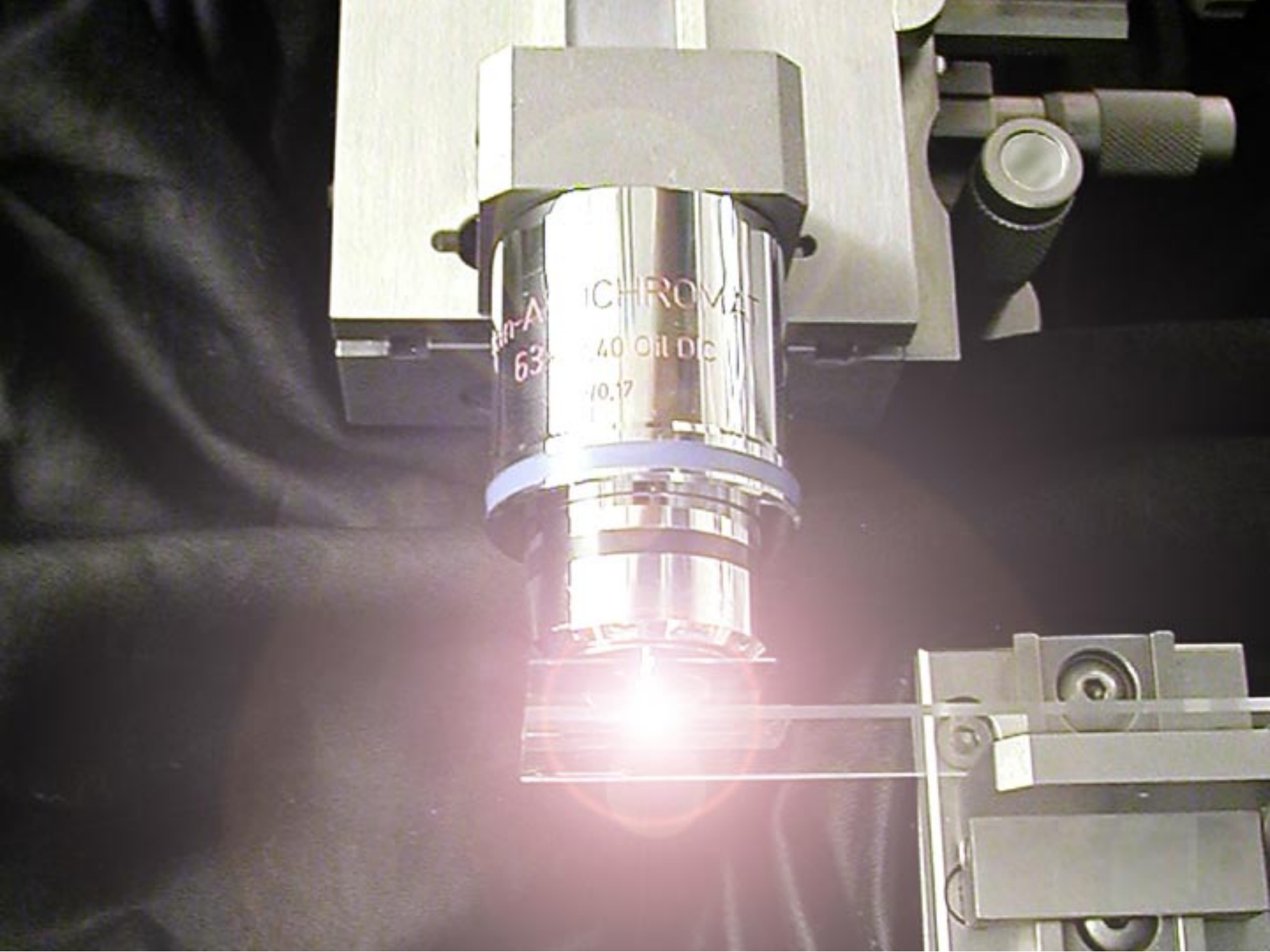
Outline

- ▶ Setup
- ▶ Morphology
- ▶ Energy deposition
- ▶ Dynamics





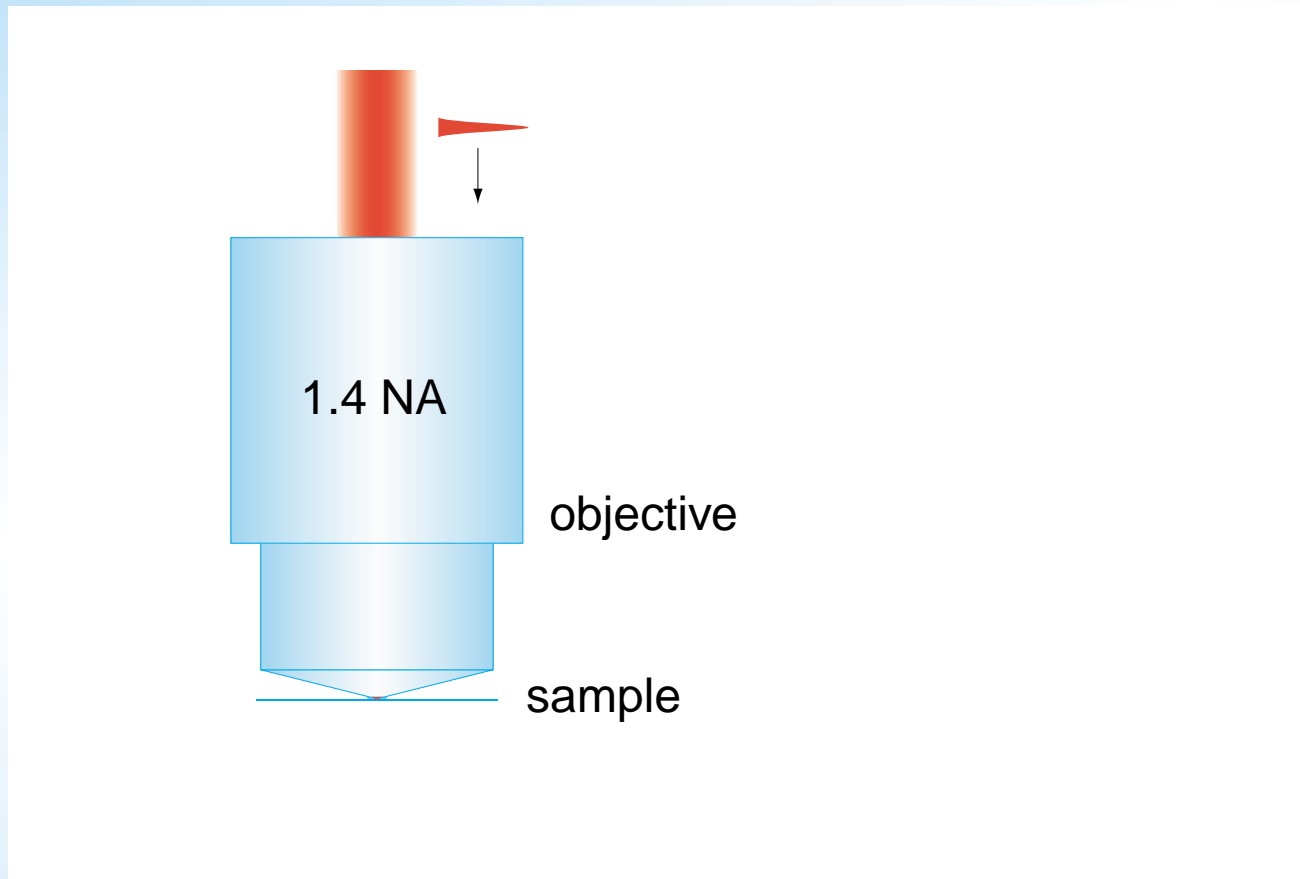
Mikro-A
63x
ACHROMAT
40 Oil DC
10.17



10x
10.17
40 Oil DC
ACHROMAT

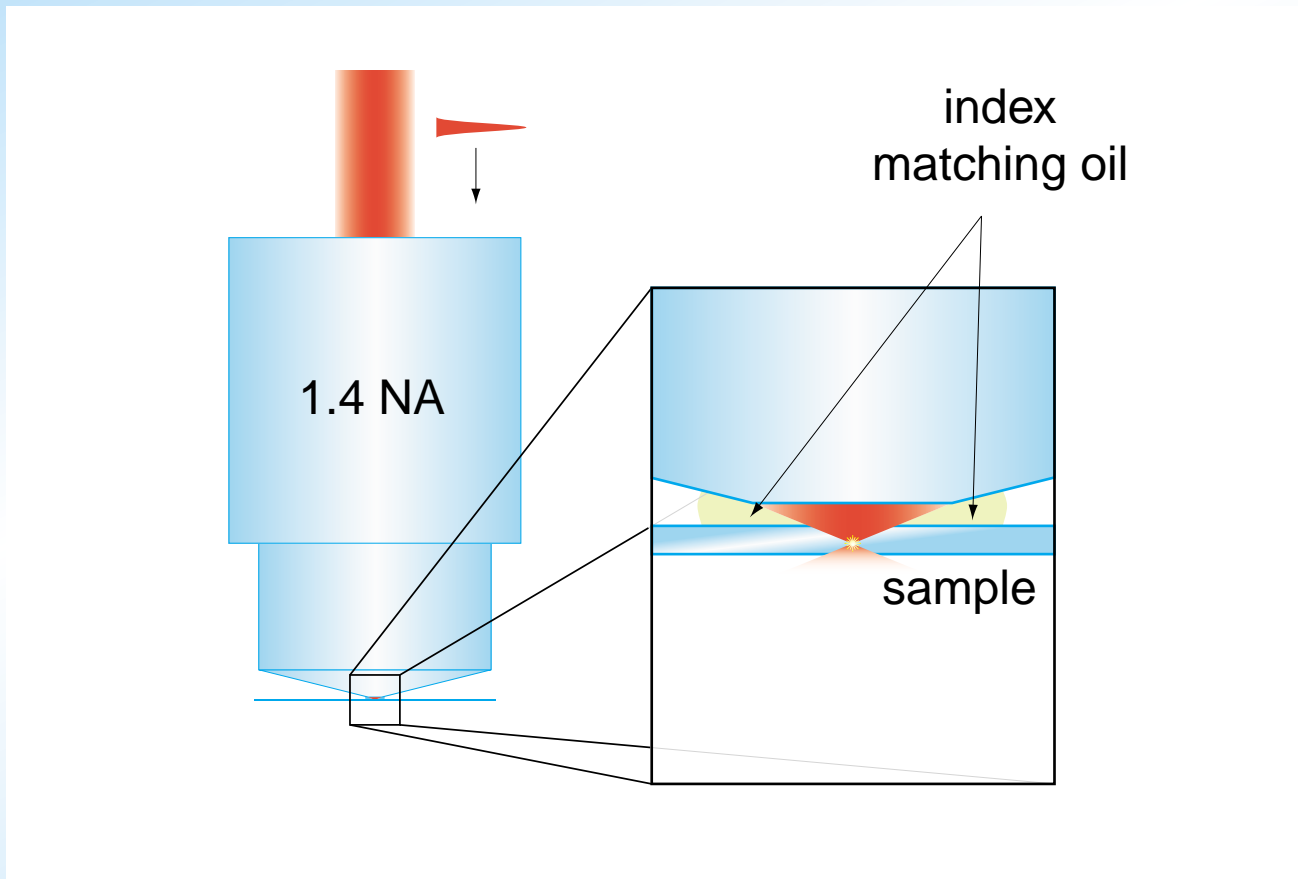
Setup

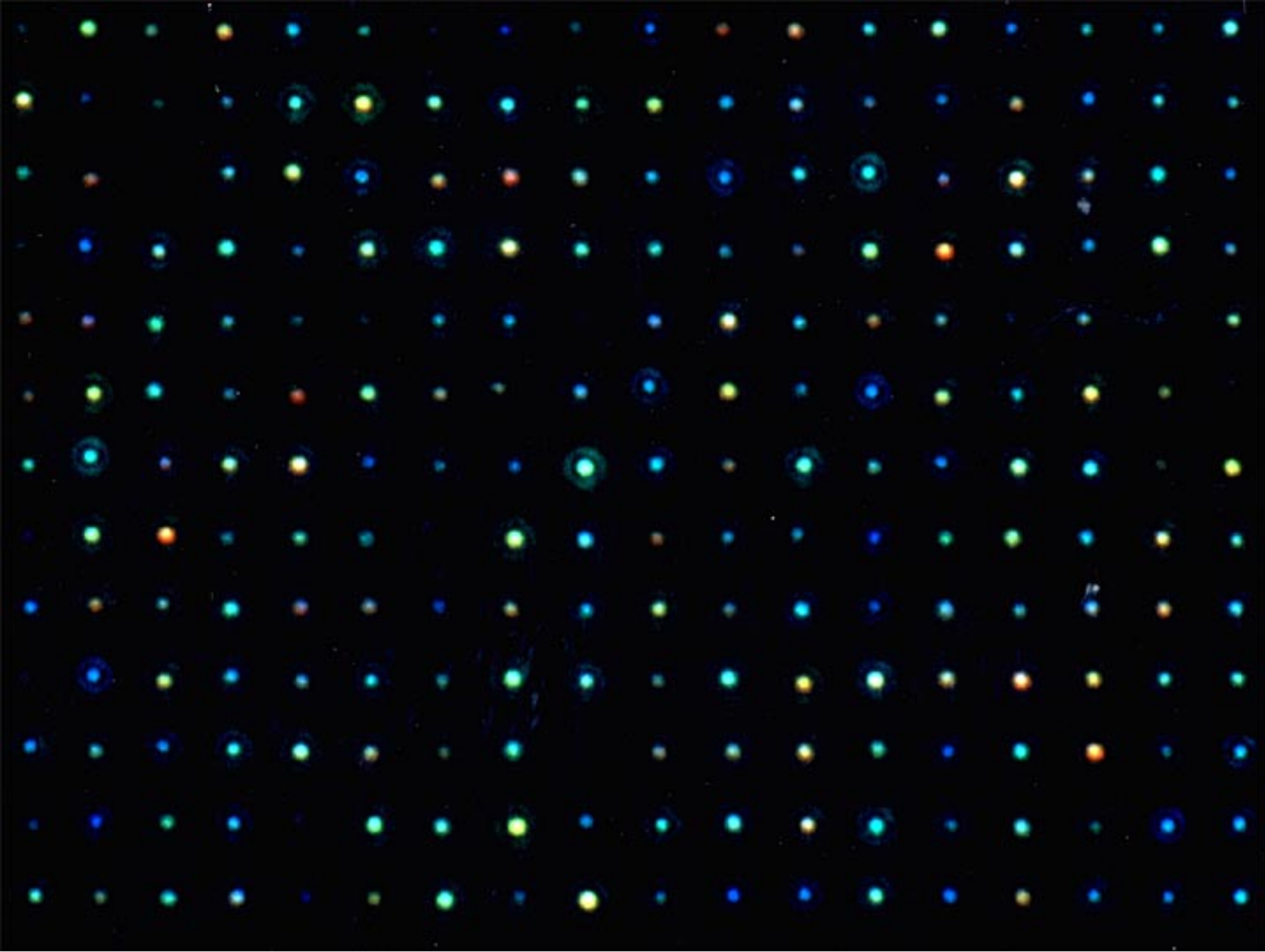
1.4 numerical aperture (NA) focusing geometry



Setup

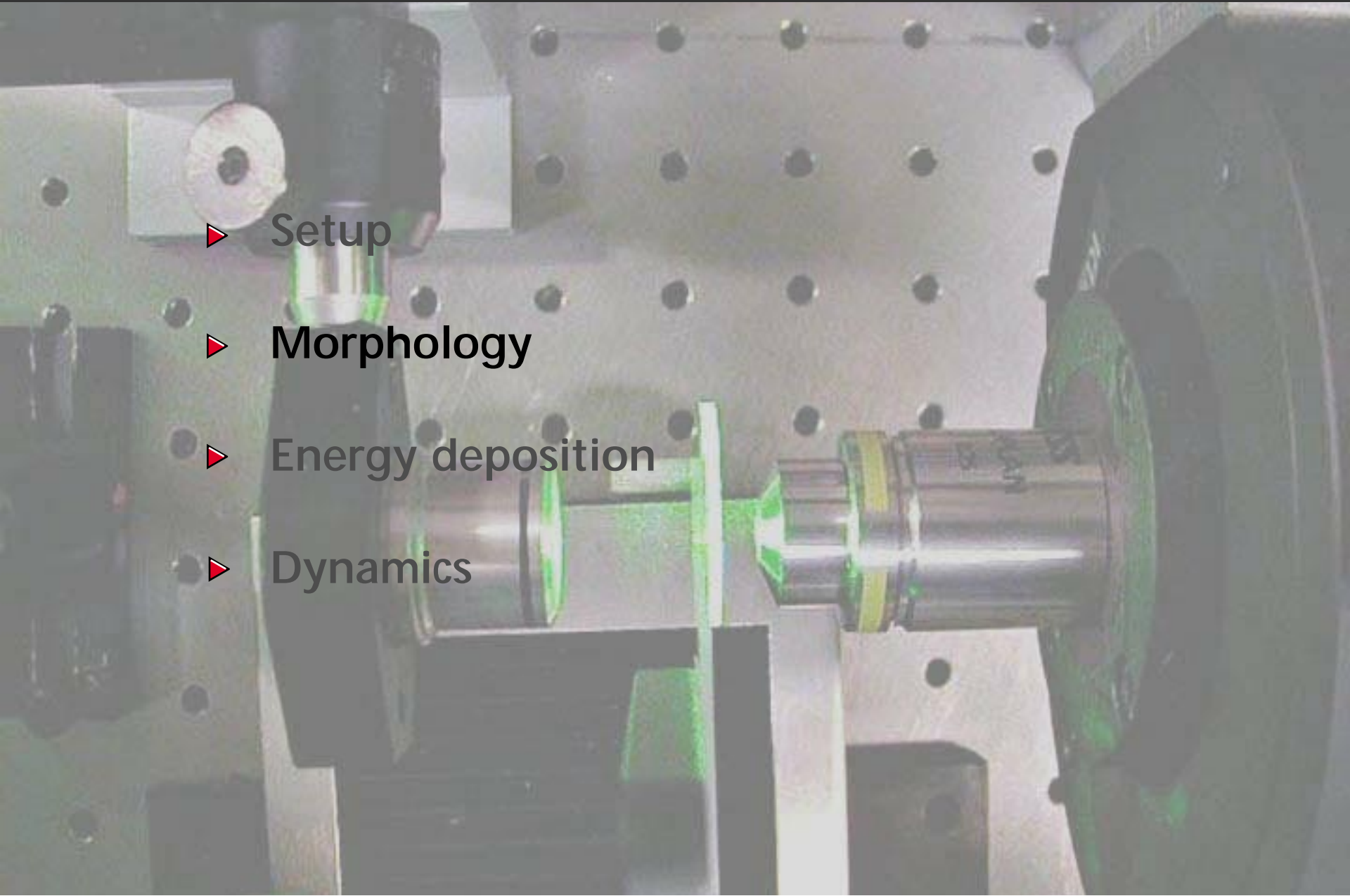
1.4 numerical aperture (NA) focusing geometry





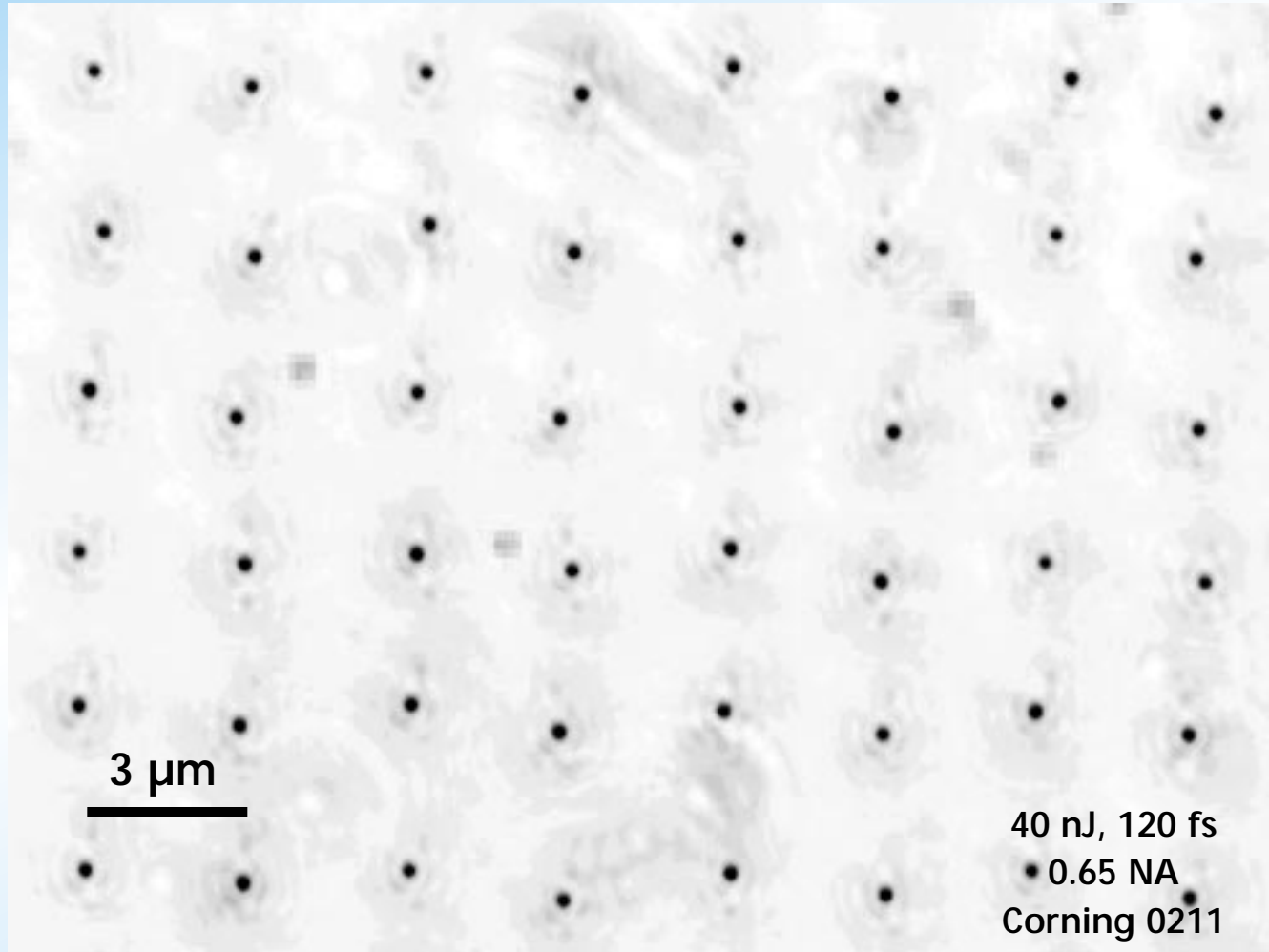
Outline

- ▶ Setup
- ▶ Morphology
- ▶ Energy deposition
- ▶ Dynamics



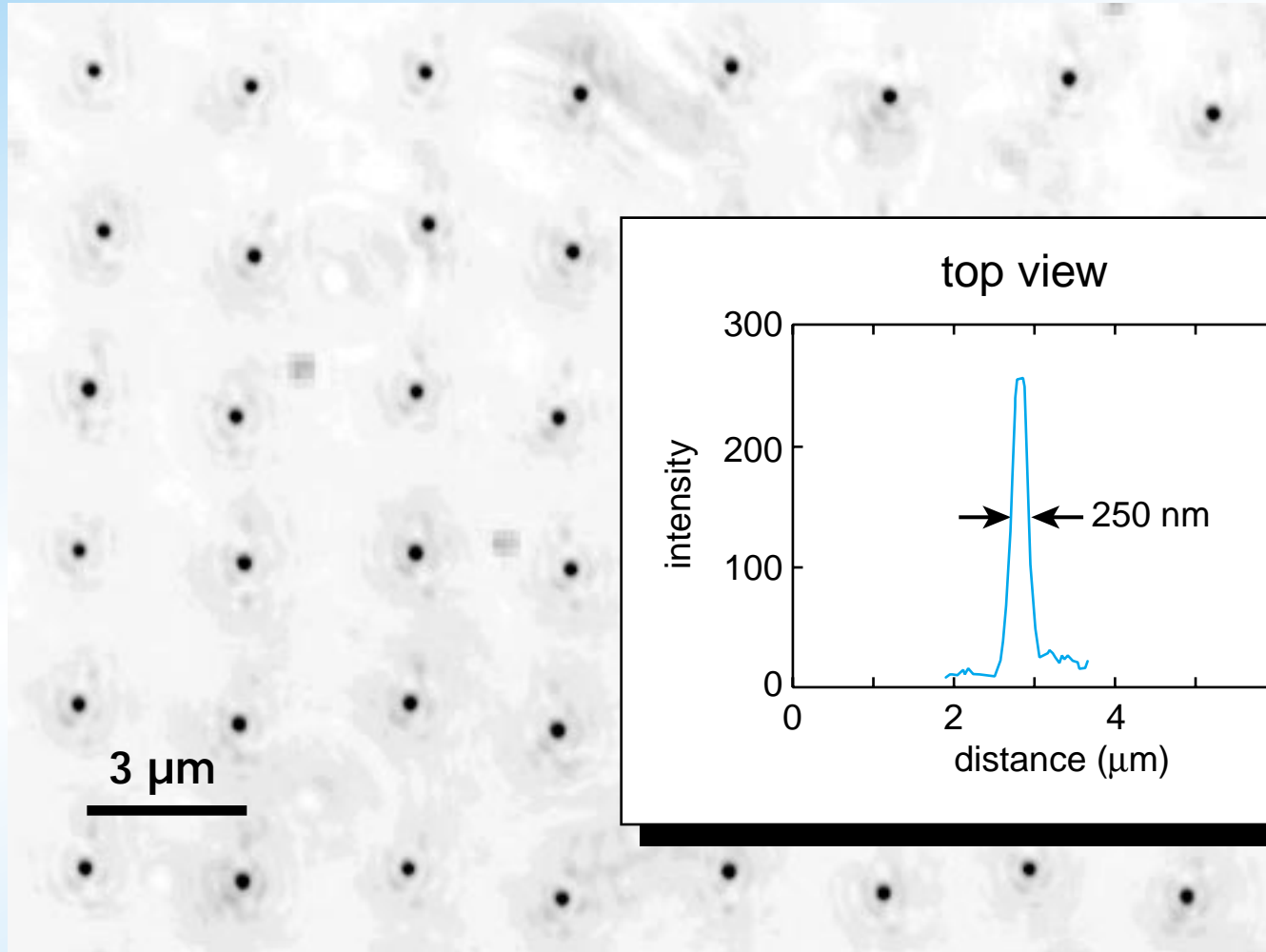
Morphology

\vec{k}
⊗

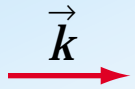


Morphology

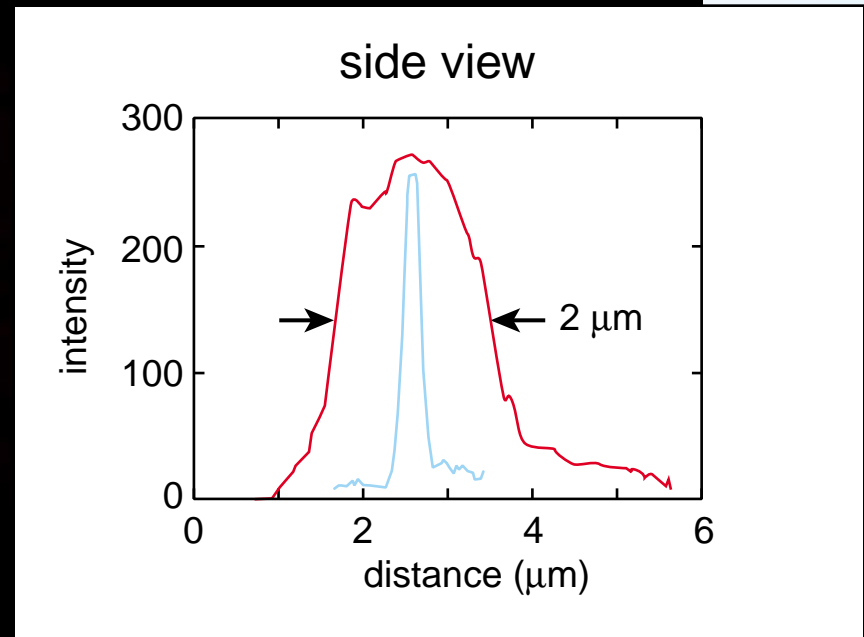
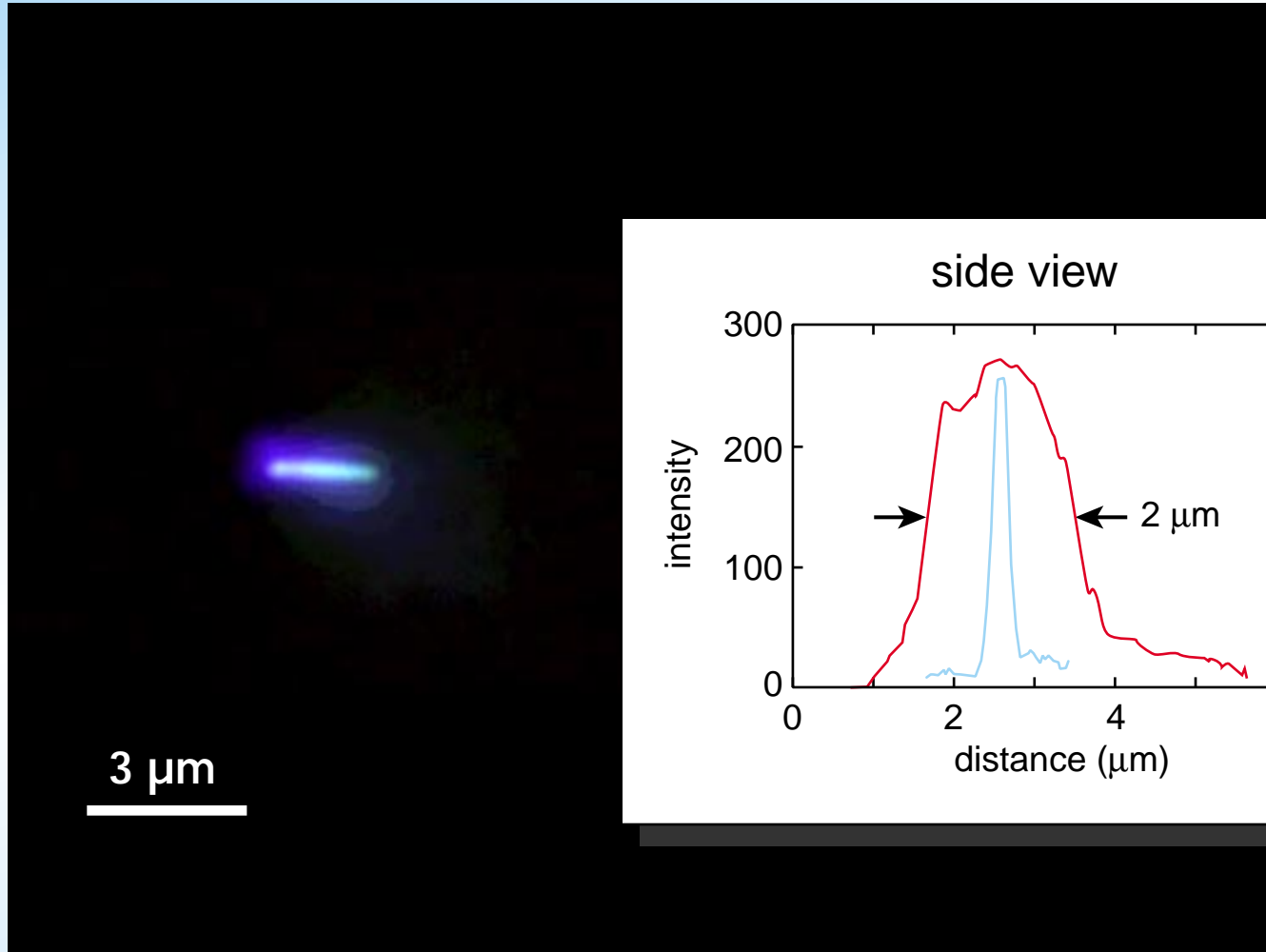
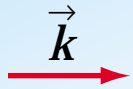
\vec{k}
 \otimes



Morphology



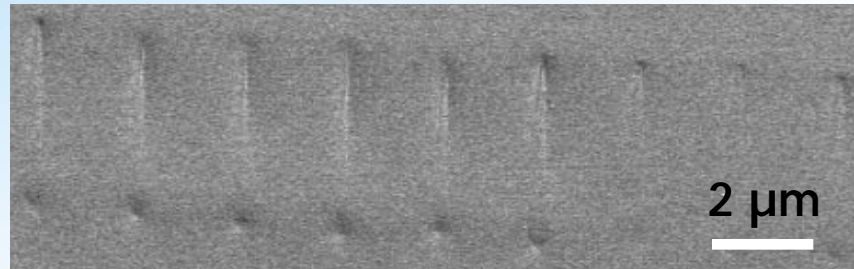
Morphology



Morphology

SEM pictures of single-shot structures

140 nJ



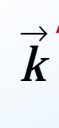
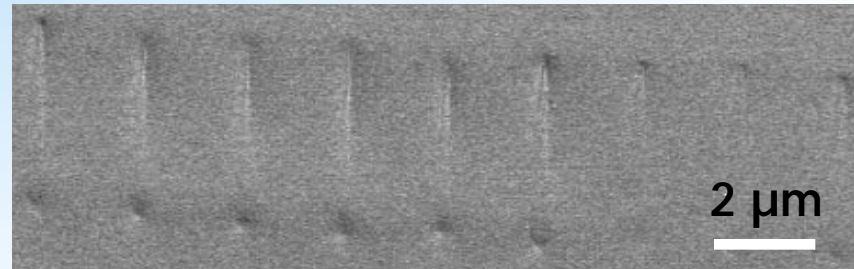
\vec{k}

100 fs
800 nm
0.45 NA
Corning 0211

Morphology

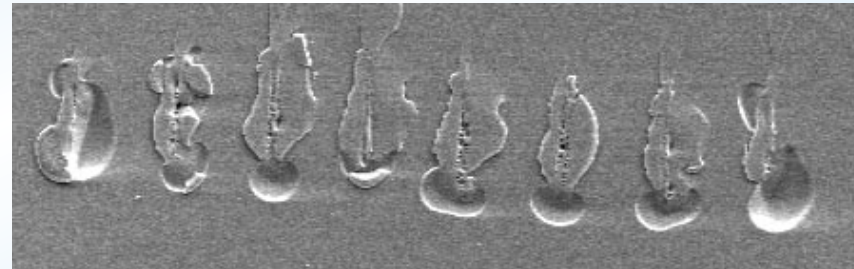
SEM pictures of single-shot structures

140 nJ



100 fs
800 nm
0.45 NA
Corning 0211

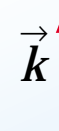
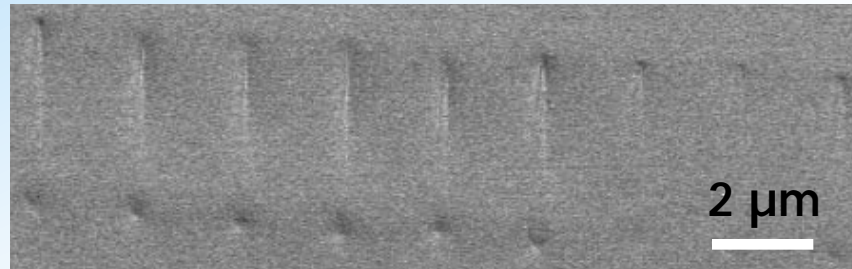
250 nJ



Morphology

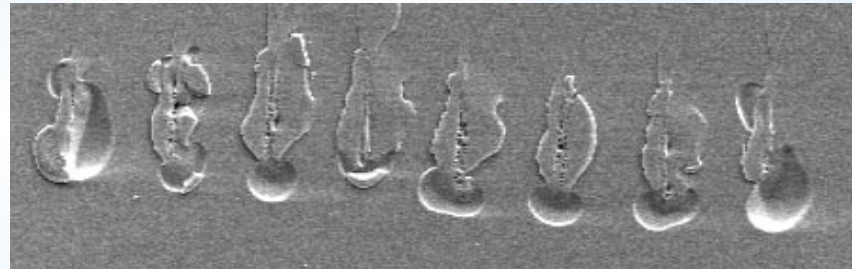
SEM pictures of single-shot structures

140 nJ

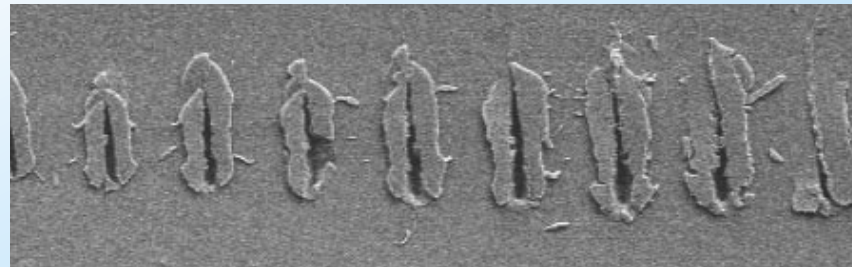


100 fs
800 nm
0.45 NA
Corning 0211

250 nJ



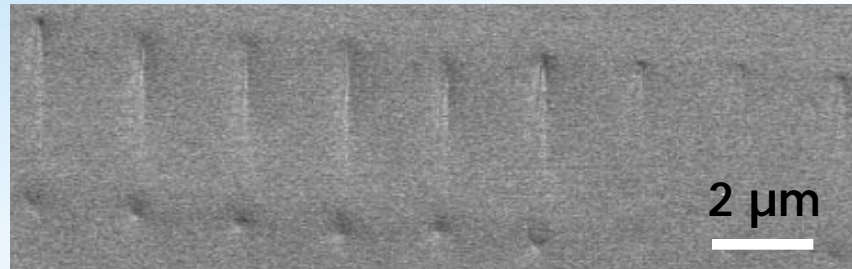
540 nJ



Morphology

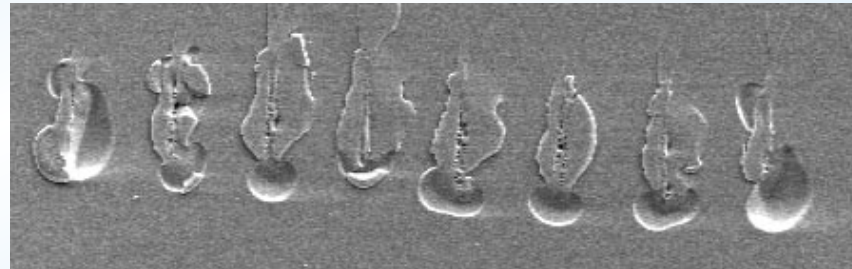
SEM pictures of single-shot structures

140 nJ

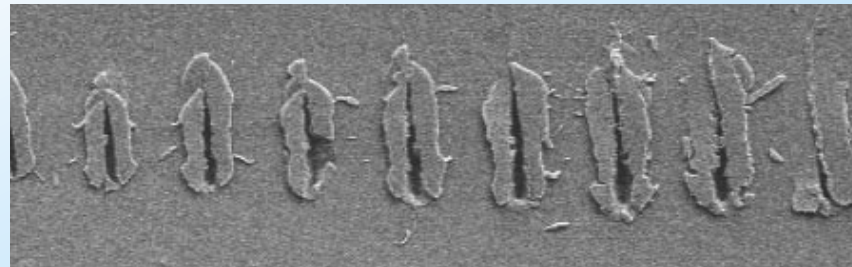


thermal

250 nJ



540 nJ



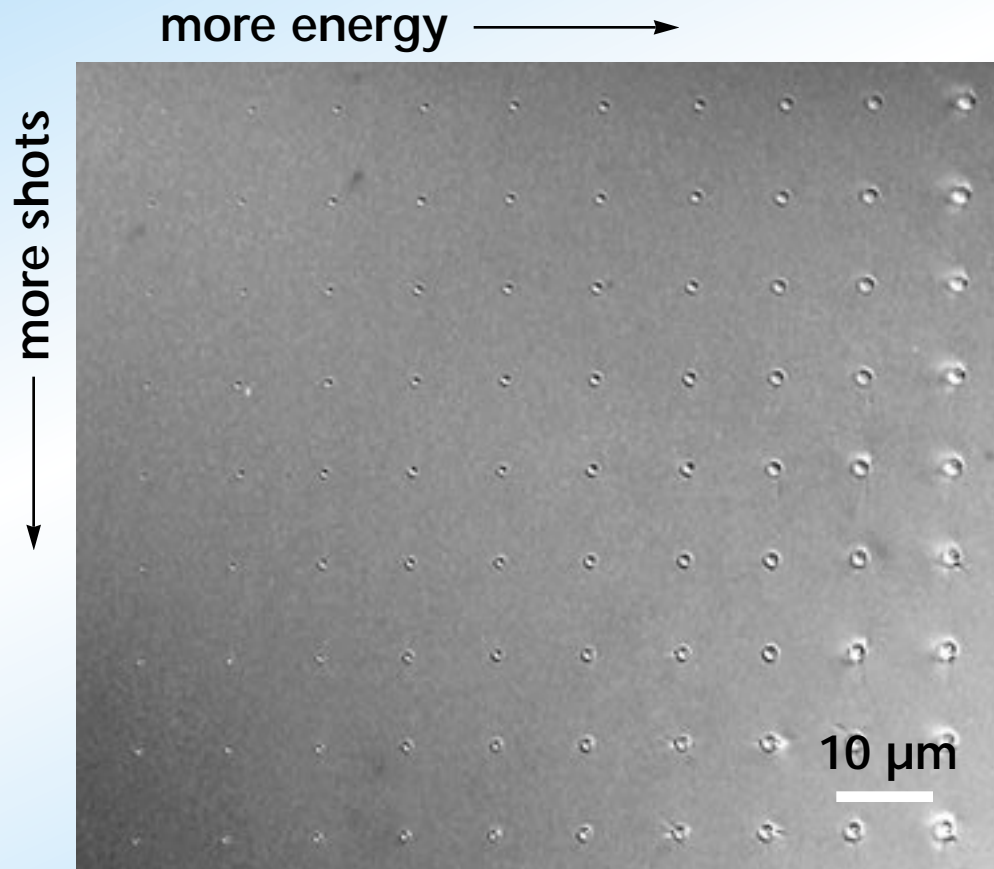
explosive

Morphology

What happens when several pulses strike the same spot?

Morphology

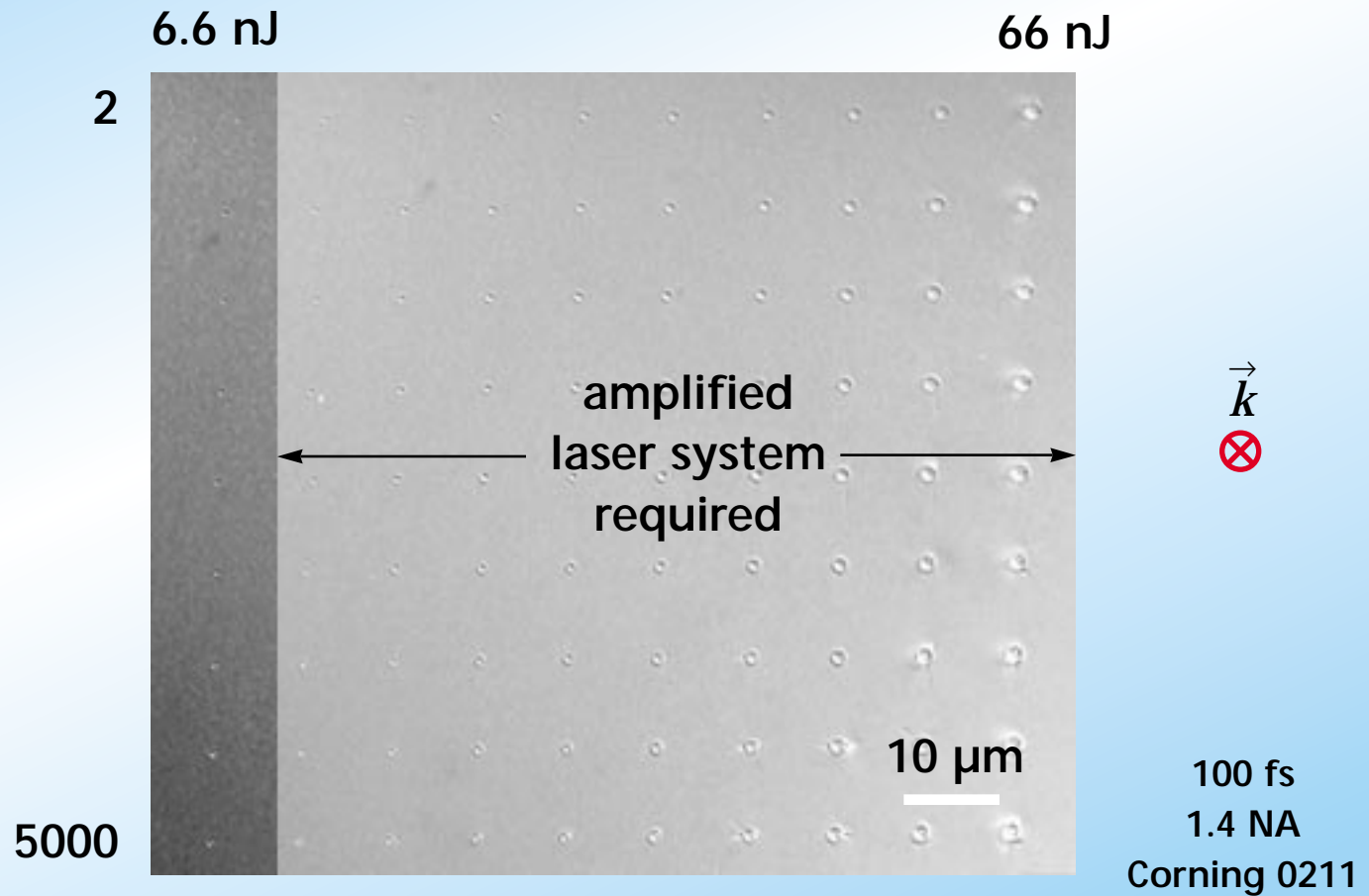
multiple-shot structures (1 kHz)



100 fs
1.4 NA
Corning 0211

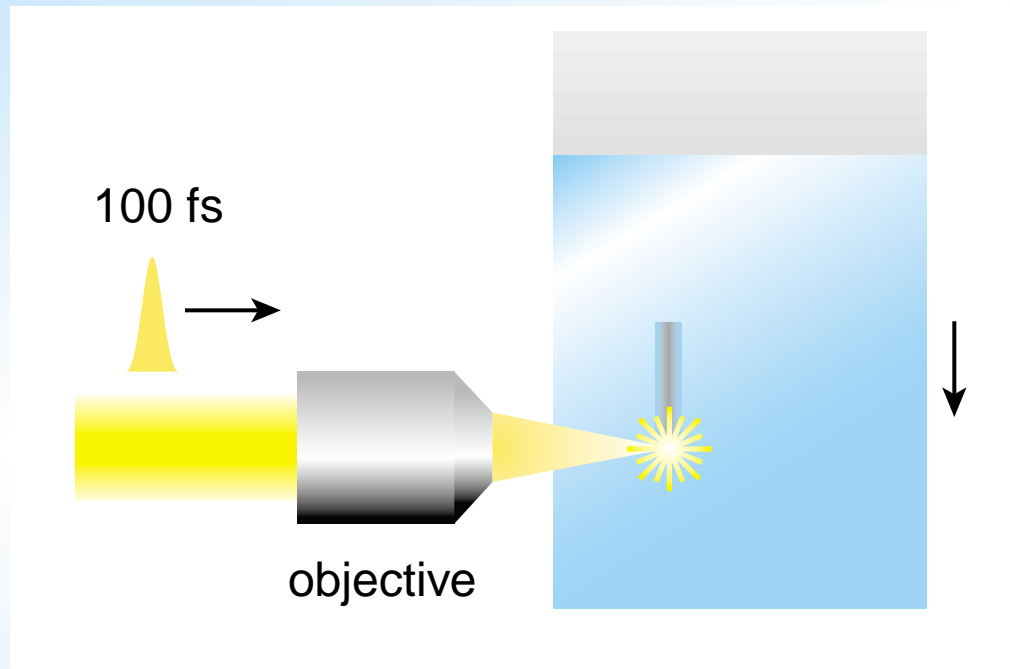
Morphology

multiple-shot structures (1 kHz)



Morphology

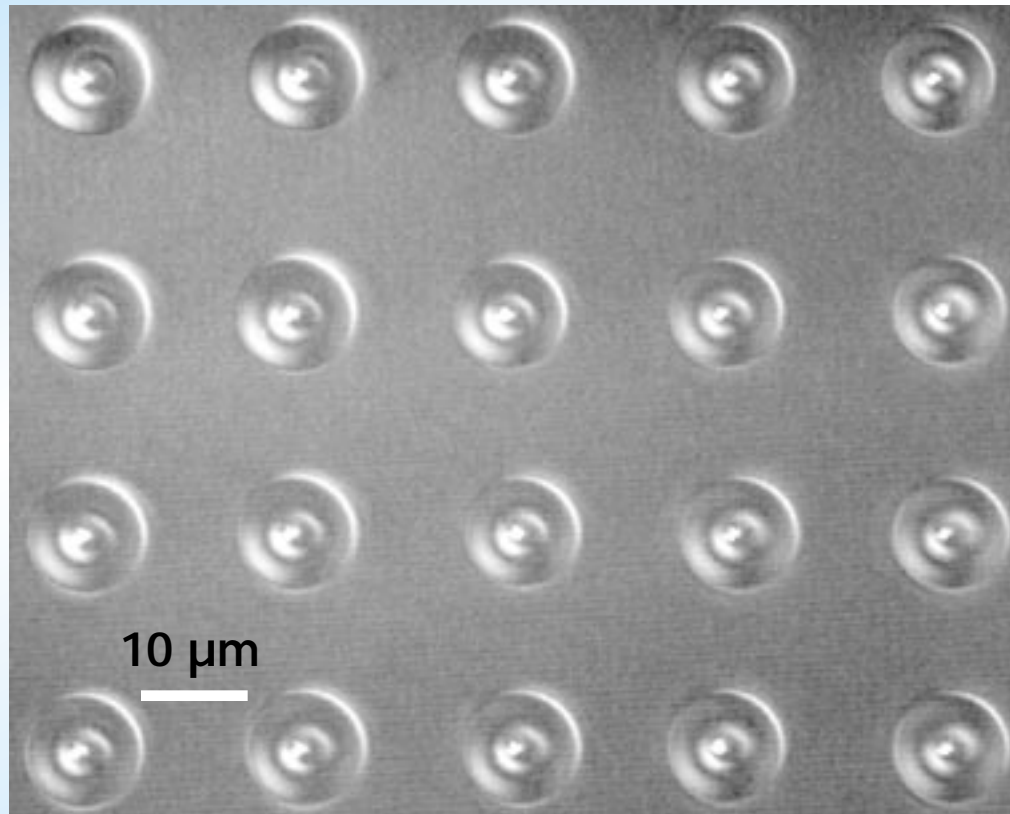
oscillator-only “micromachining”



25 MHz: point source of heat inside material!

Morphology

cumulative heating structures (25 MHz)

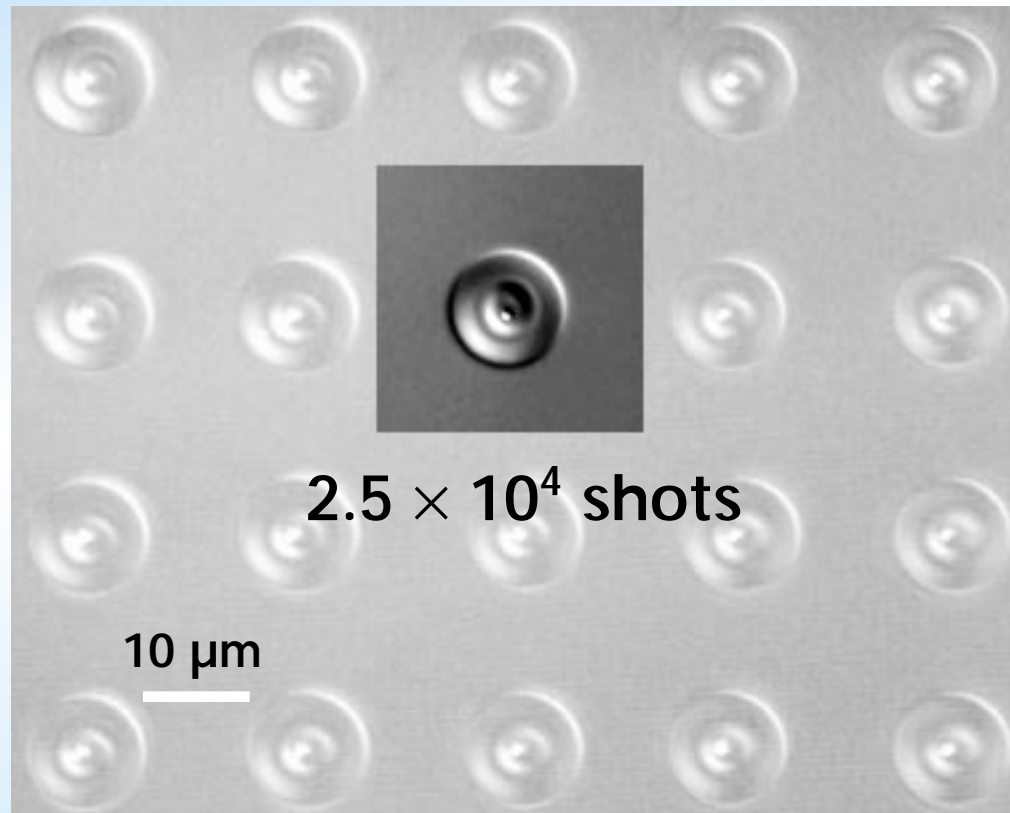


\vec{k}
⊗

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

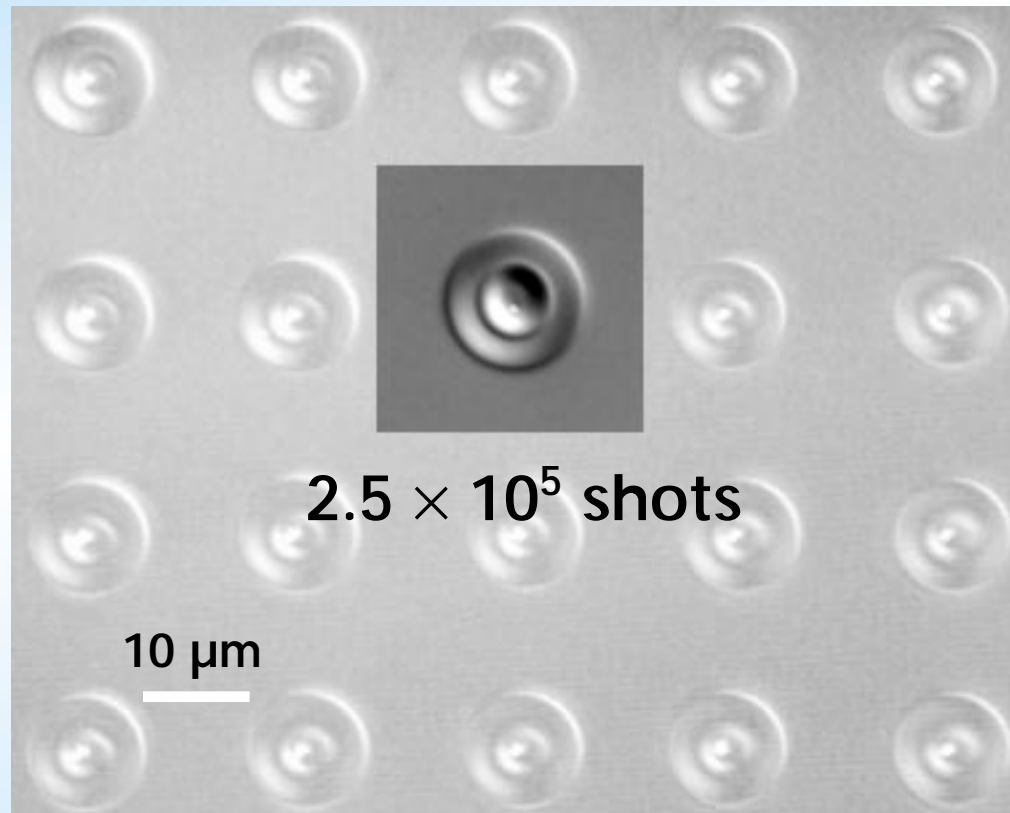
Morphology

cumulative heating structures (25 MHz)



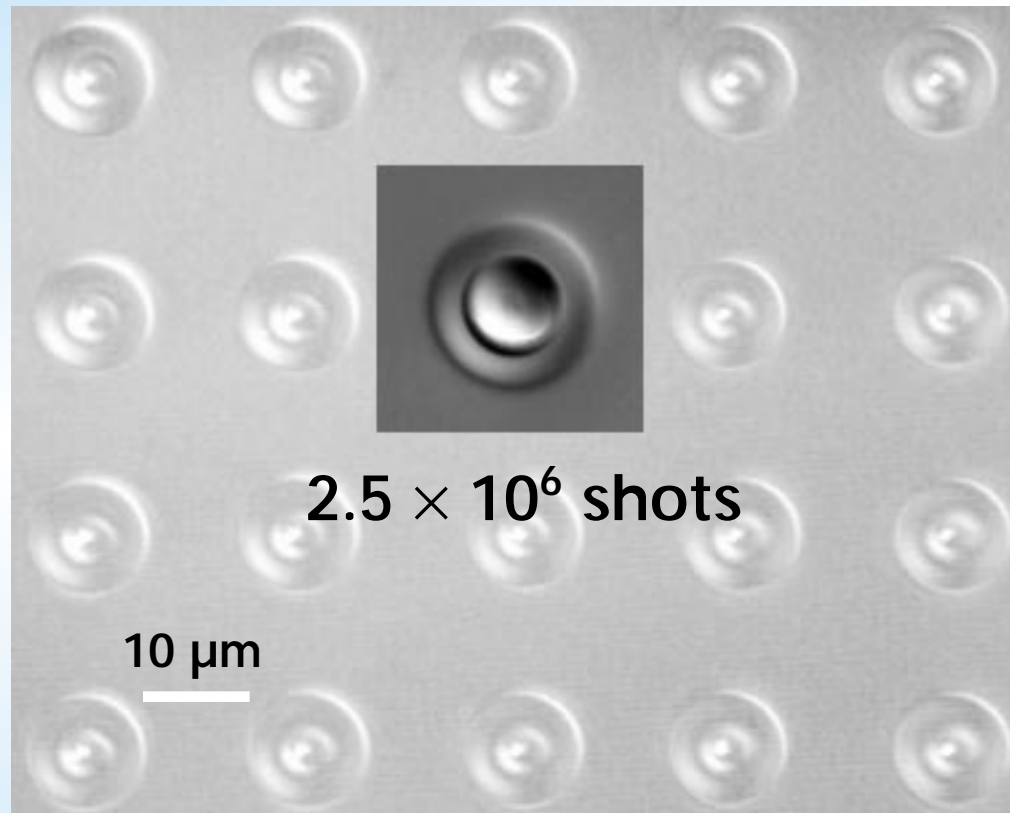
Morphology

cumulative heating structures (25 MHz)



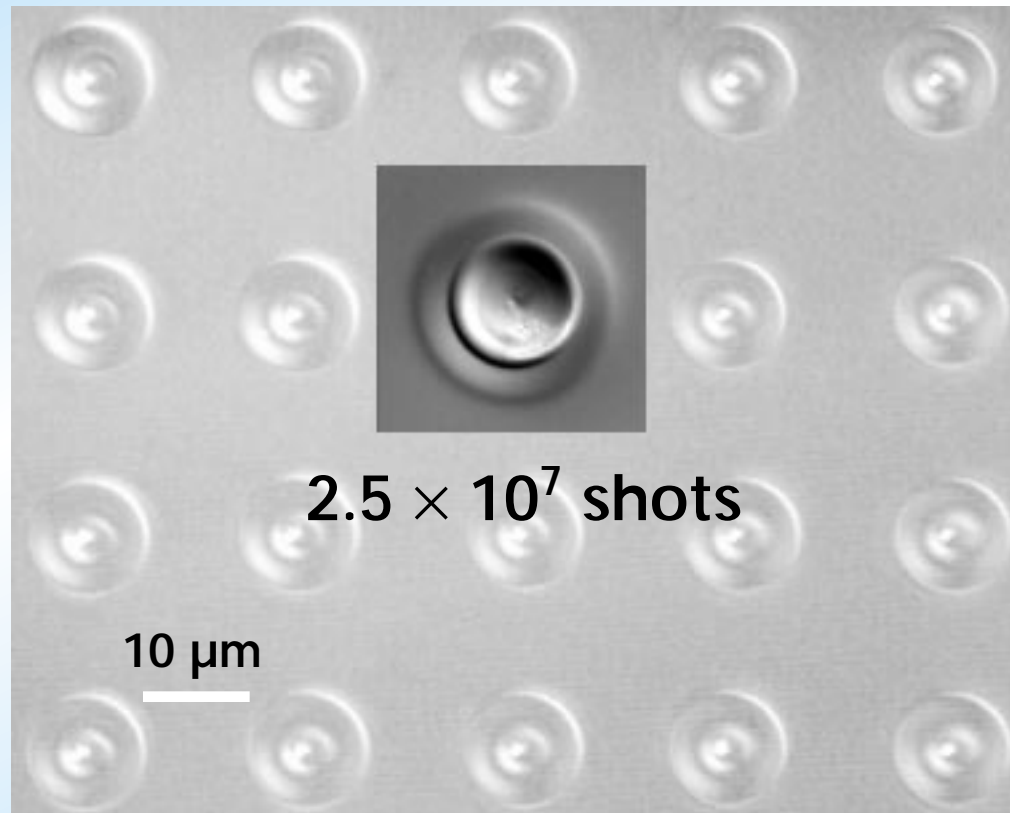
Morphology

cumulative heating structures (25 MHz)



Morphology

cumulative heating structures (25 MHz)

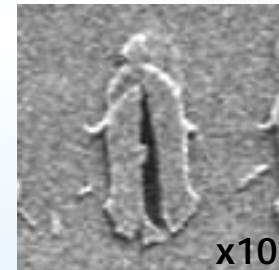
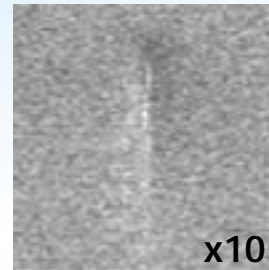


Morphology

low energy

high energy

single shot

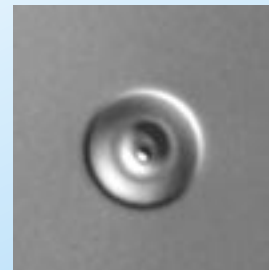


1 kHz



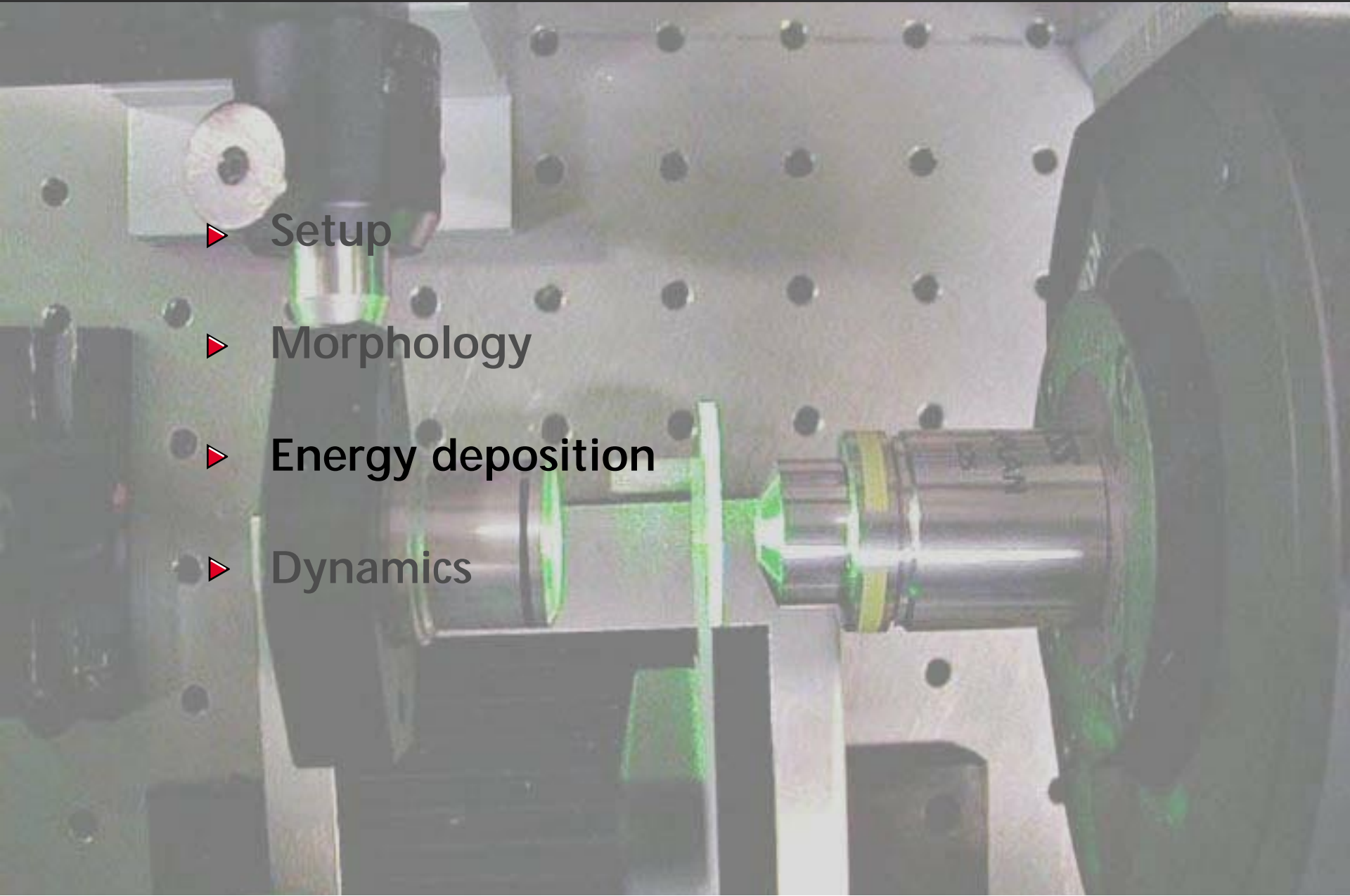
multiple shot

25 MHz



Outline

- ▶ Setup
- ▶ Morphology
- ▶ Energy deposition
- ▶ Dynamics



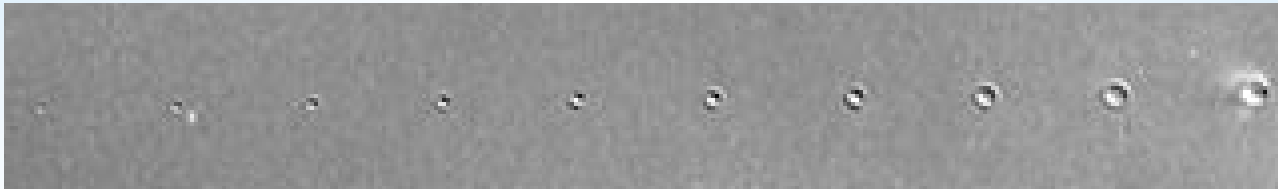
Energy deposition

Determine threshold for structural change:

- ▶ Optical microscopy
- ▶ Transmission
- ▶ Dark field scattering

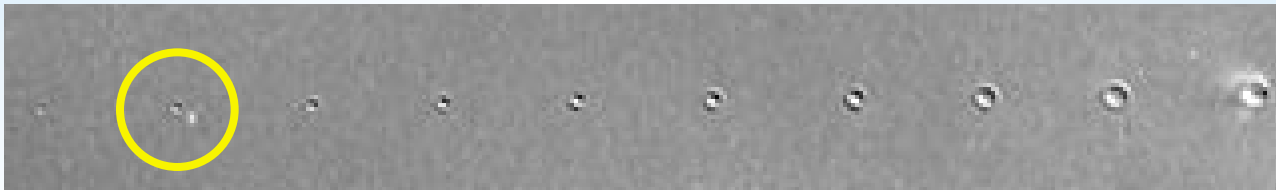
Energy deposition

optical microscopy



Energy deposition

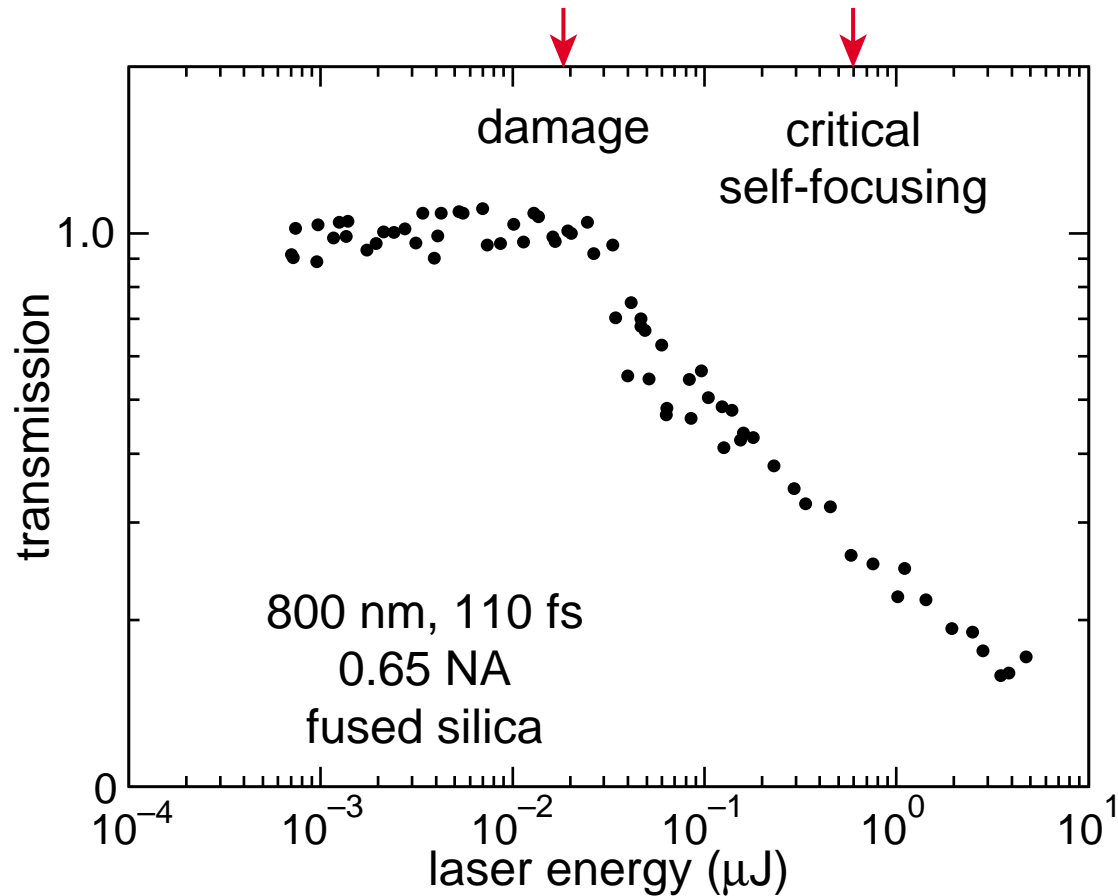
optical microscopy



6.6 nJ

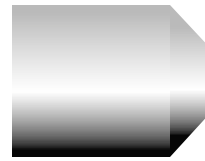
Energy deposition

transmission of pump beam in fused silica



Energy deposition

Dark-field scattering



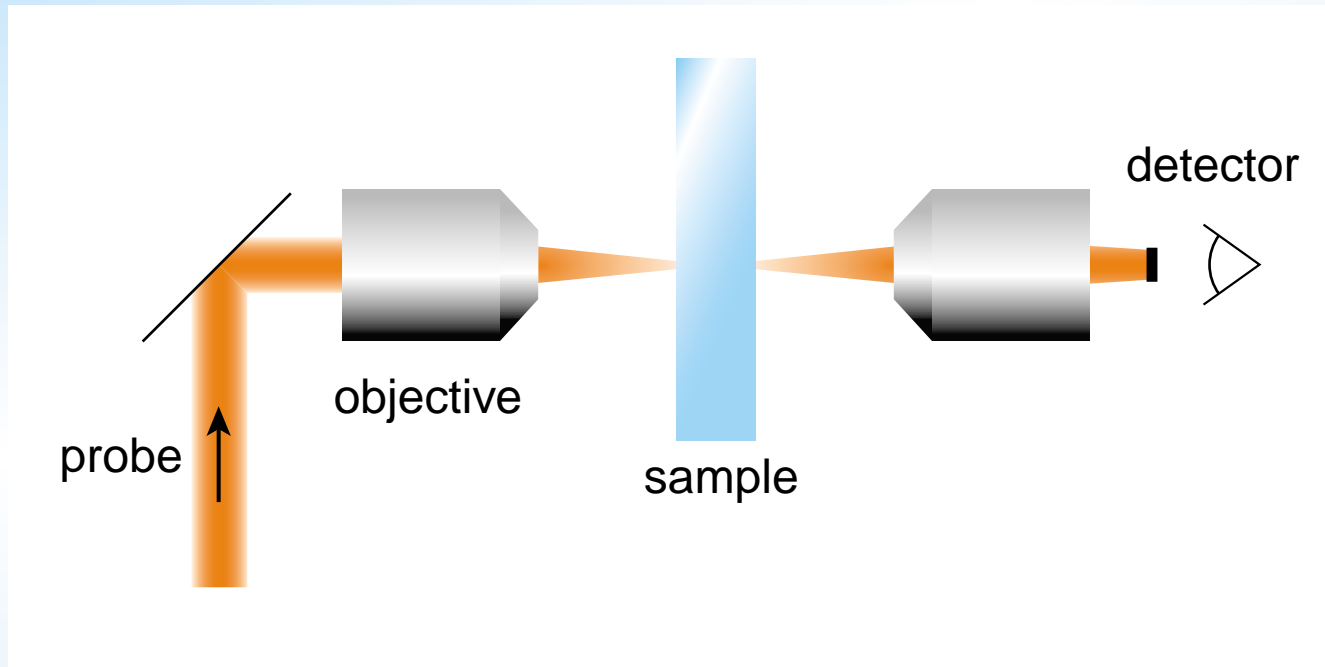
objective



sample

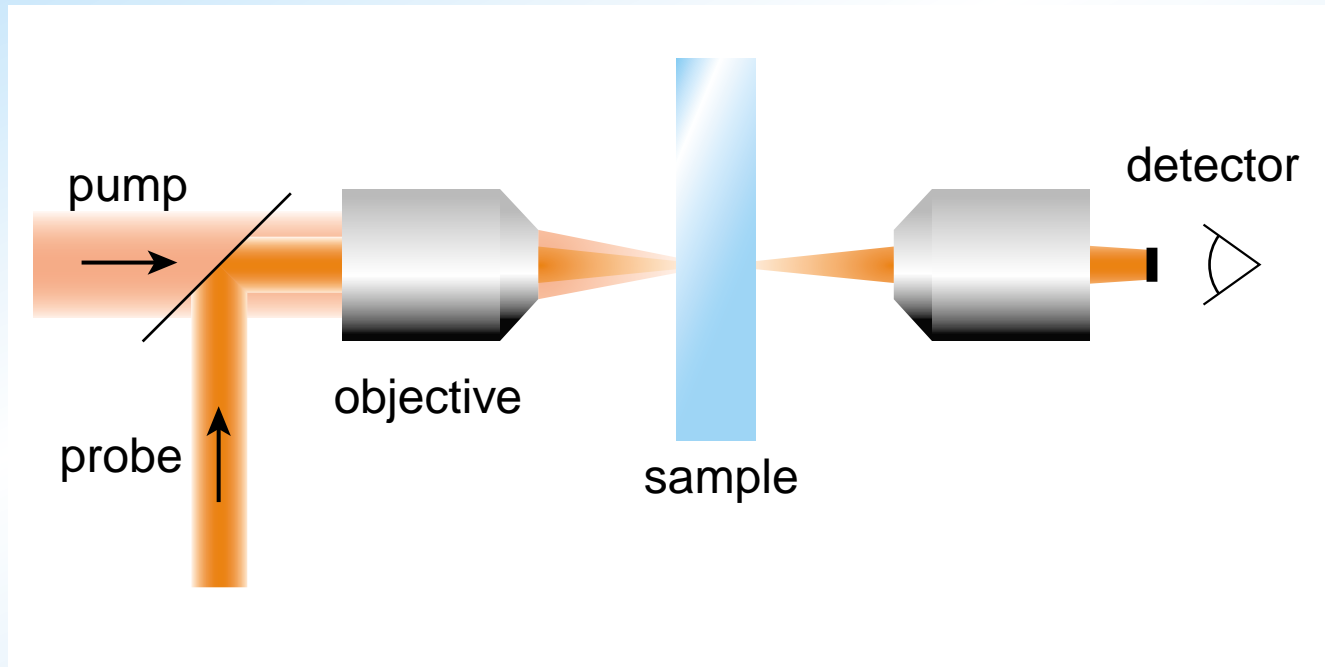
Energy deposition

block probe beam...



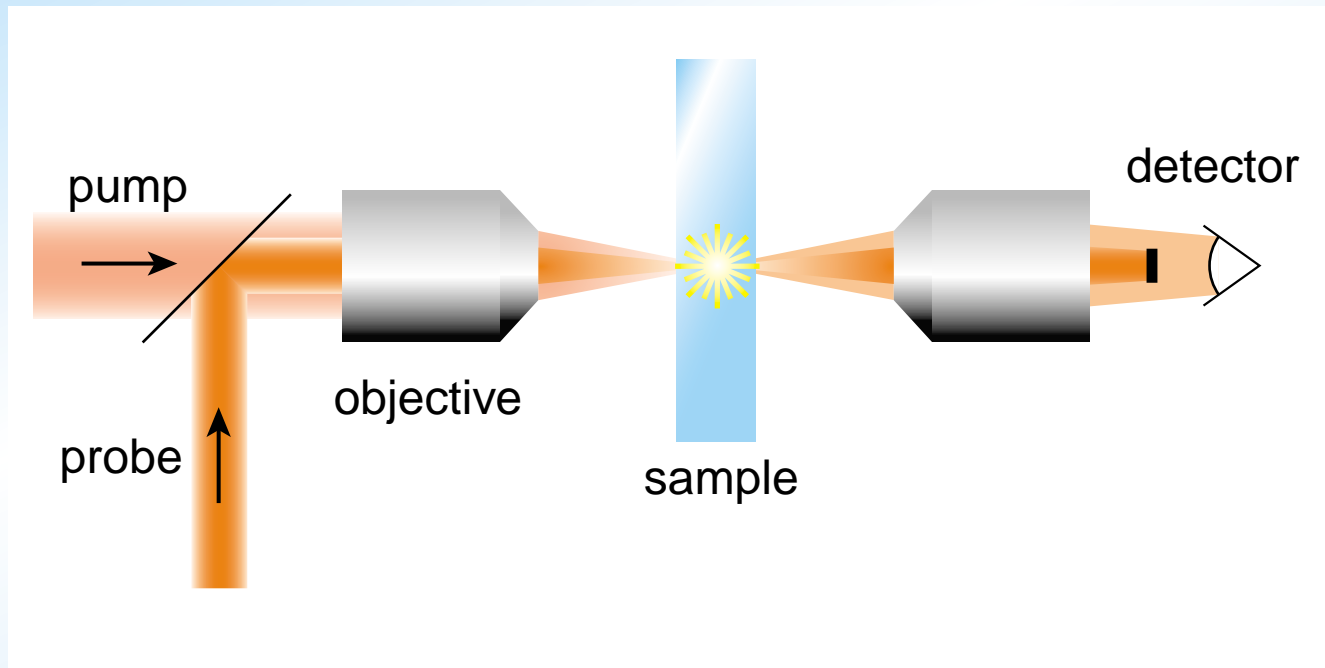
Energy deposition

...bring in pump beam...

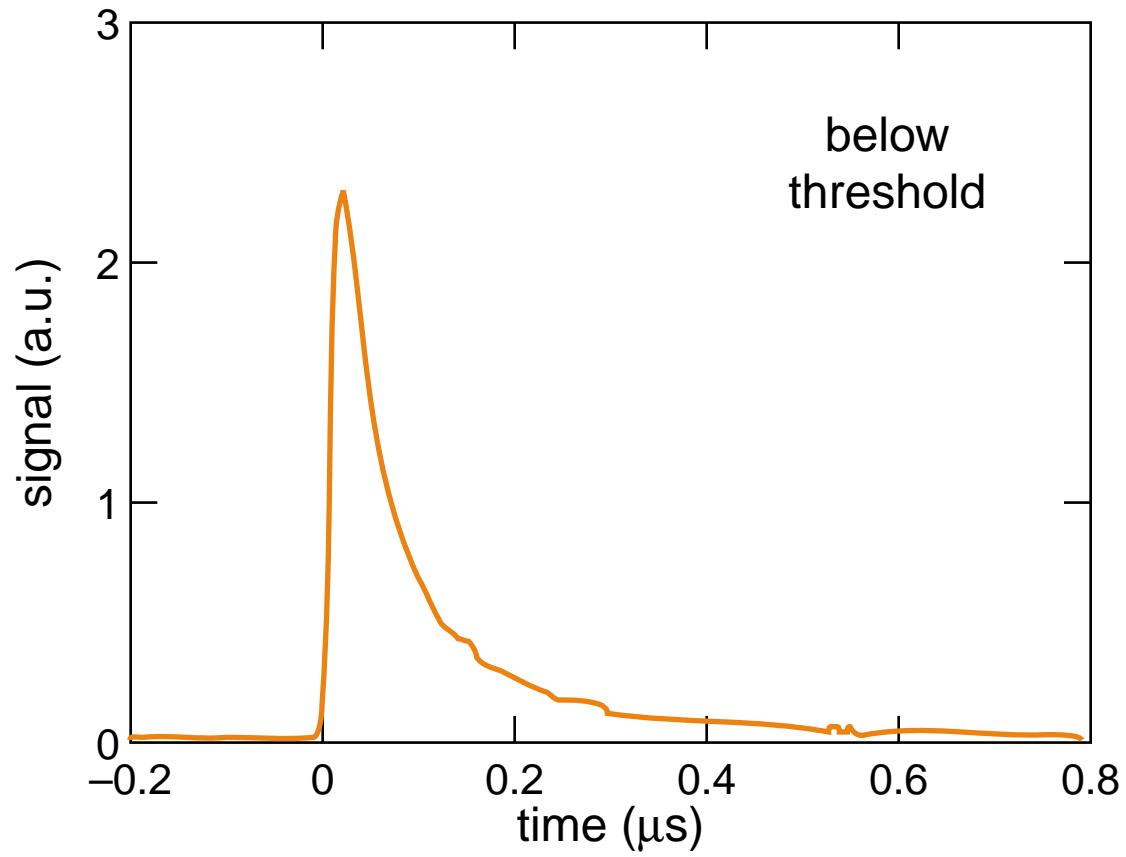


Energy deposition

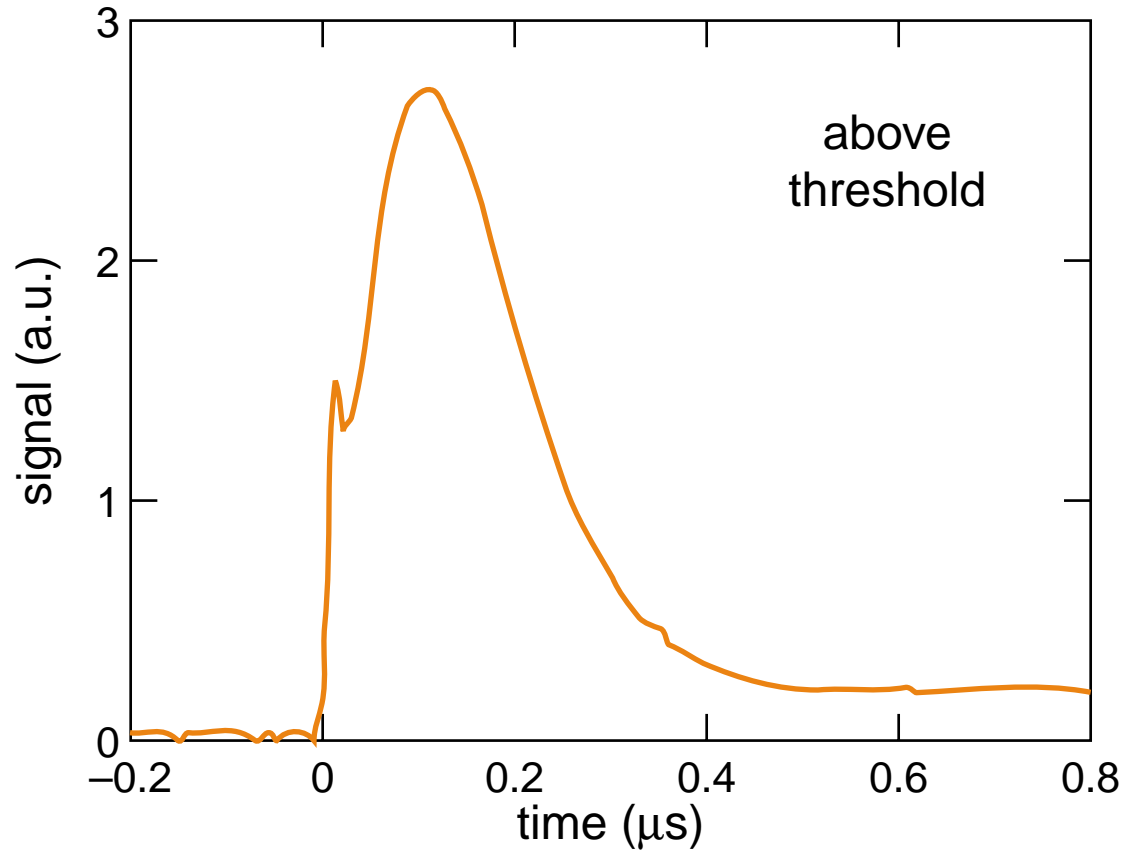
...structural change scatters probe beam



Energy deposition

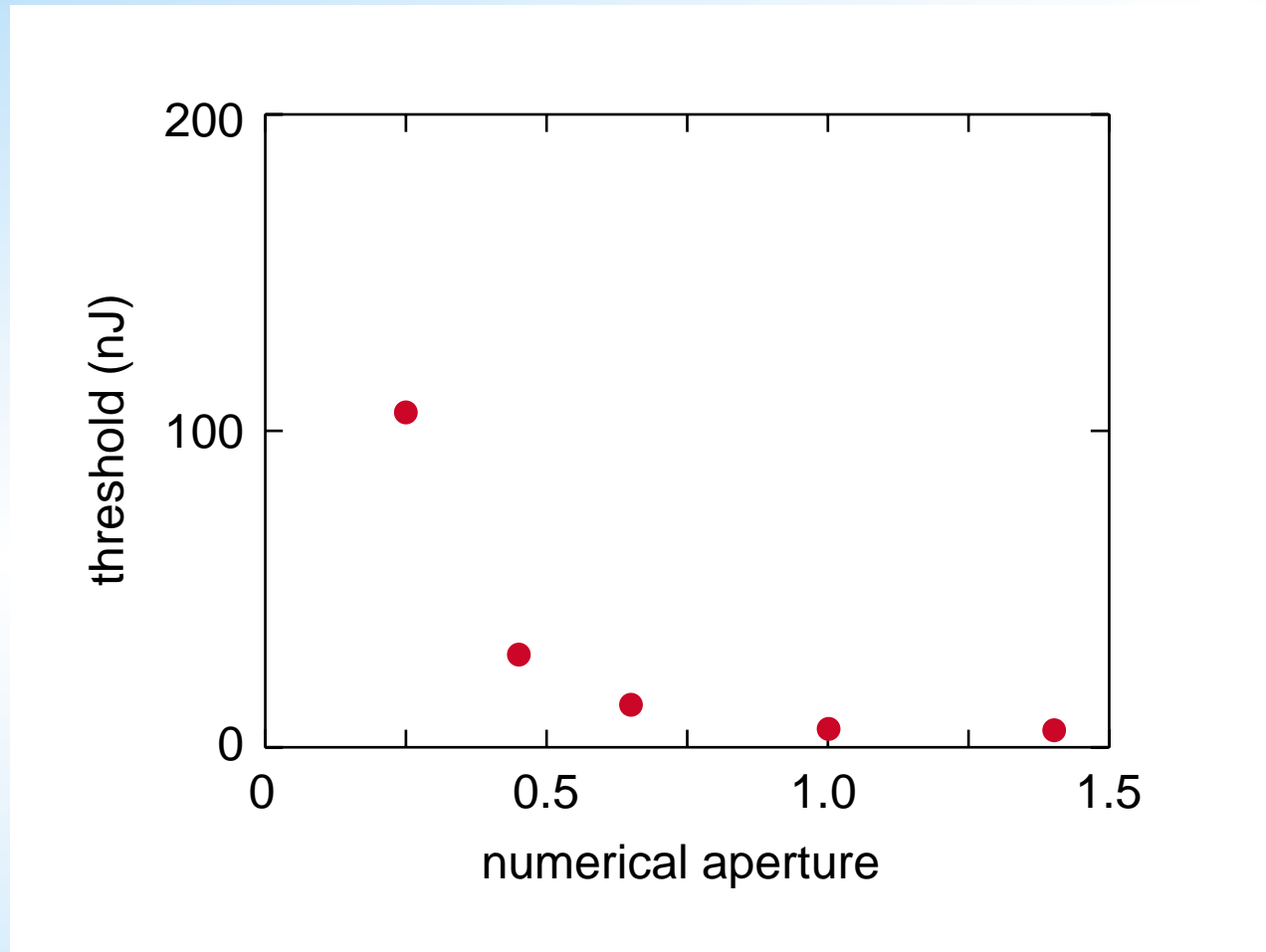


Energy deposition



Energy deposition

vary numerical aperture in Corning 0211



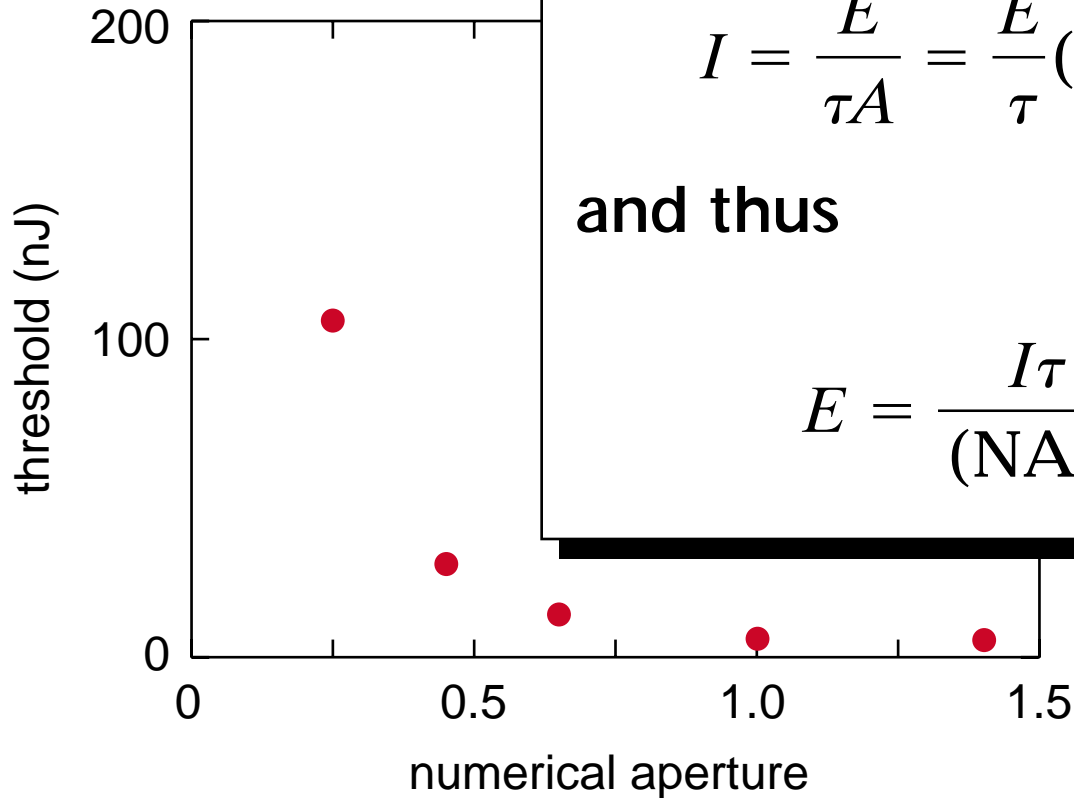
Energy deposition

minimal self focusing, so
spot size determined by:

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

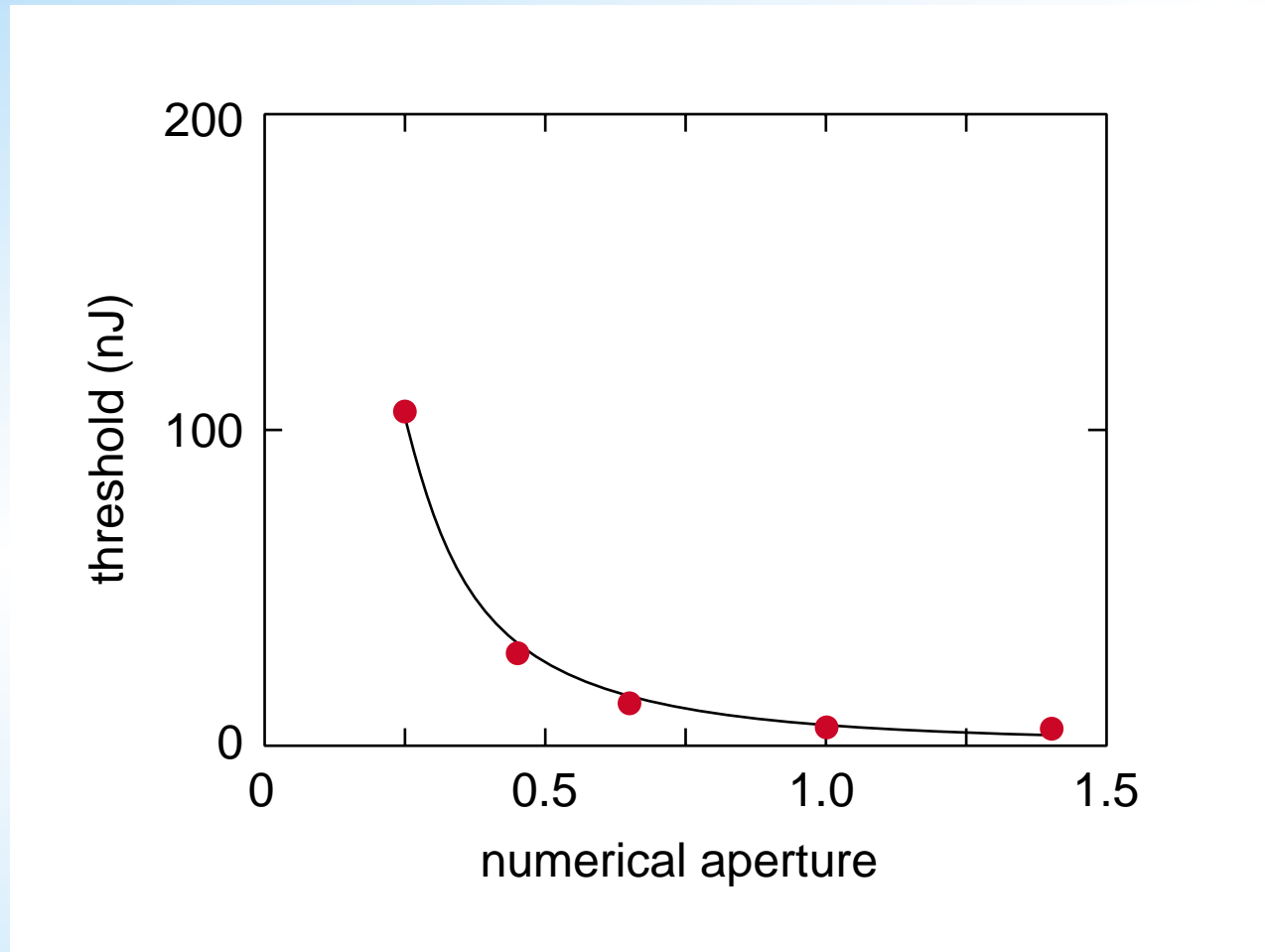
and thus

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

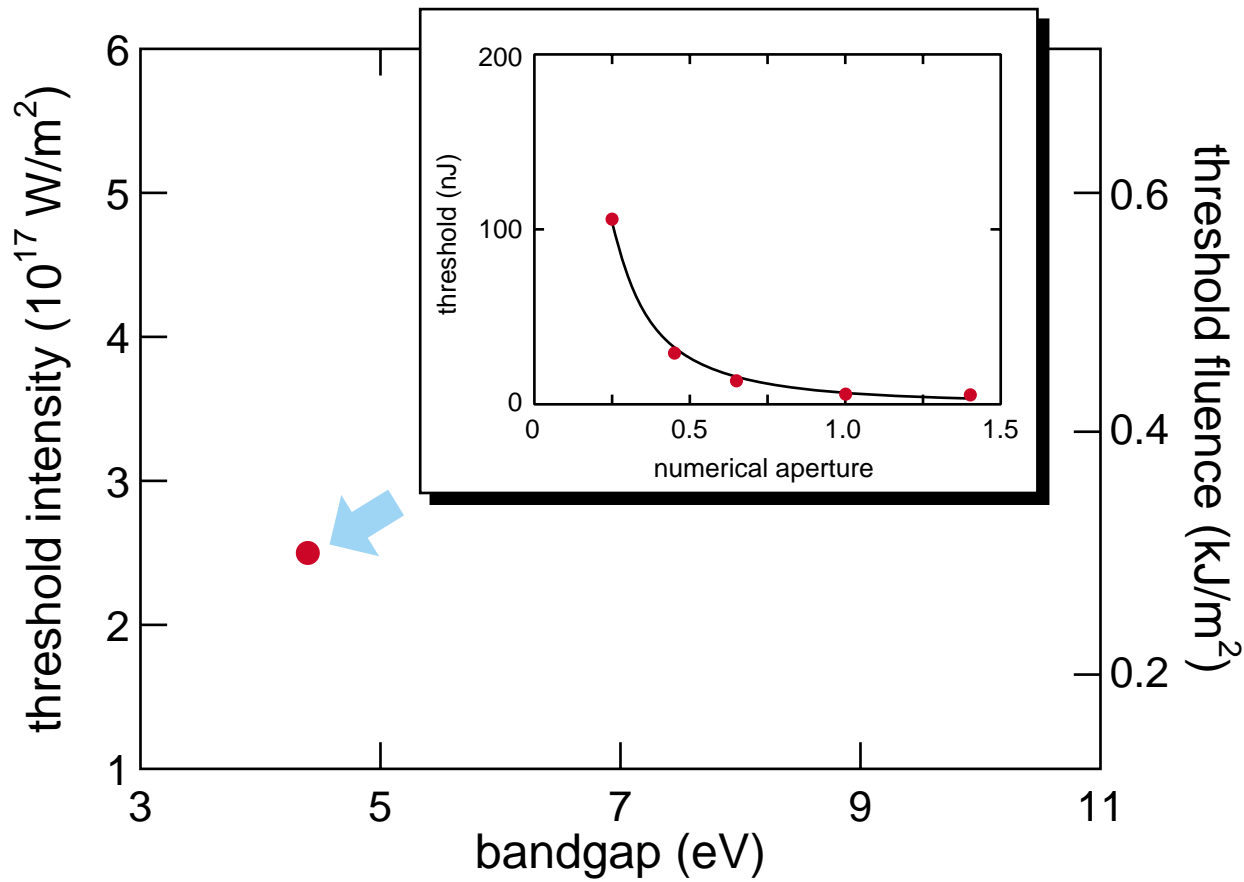


Energy deposition

fit gives threshold intensity: $I_{th} = 2.5 \times 10^{17} \text{ W/m}^2$

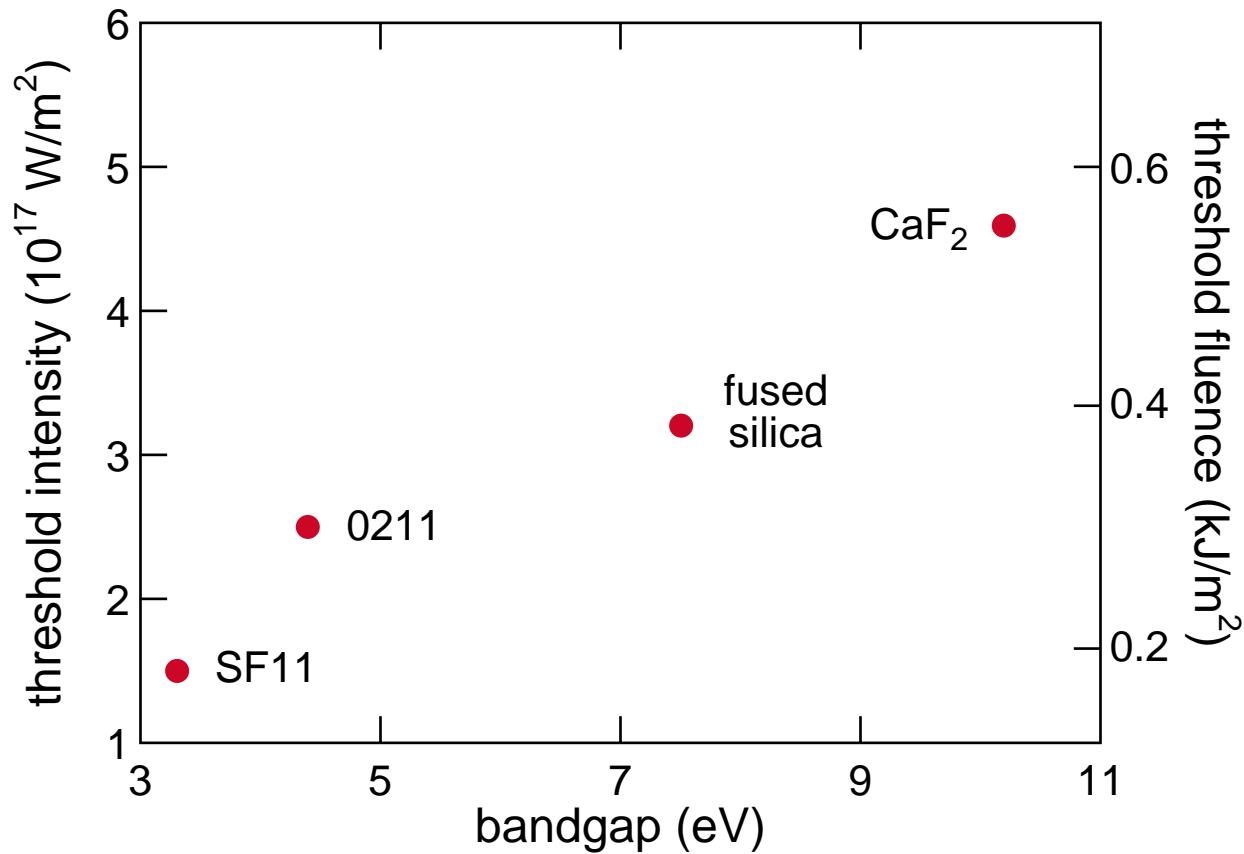


Energy deposition



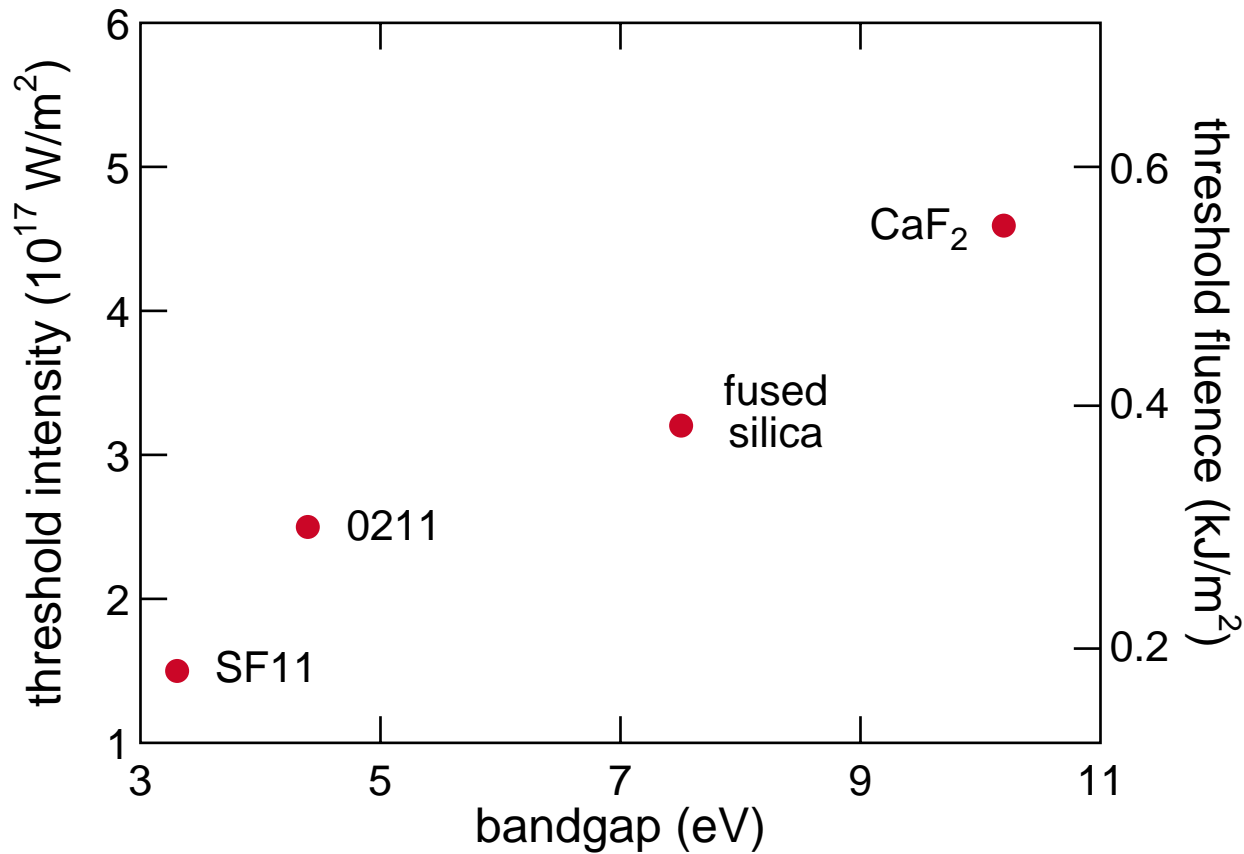
Energy deposition

vary material...



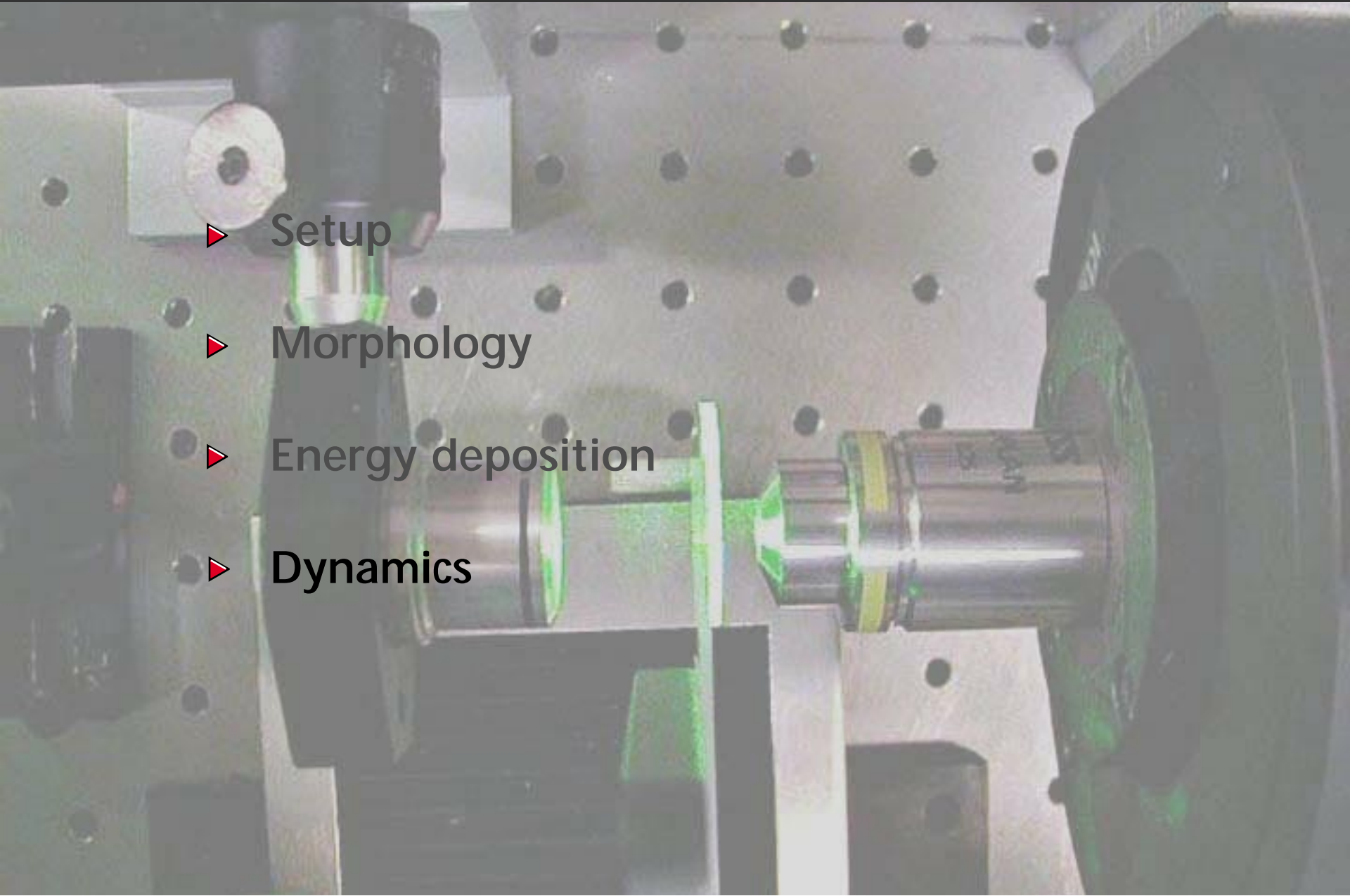
Energy deposition

threshold increases with bandgap



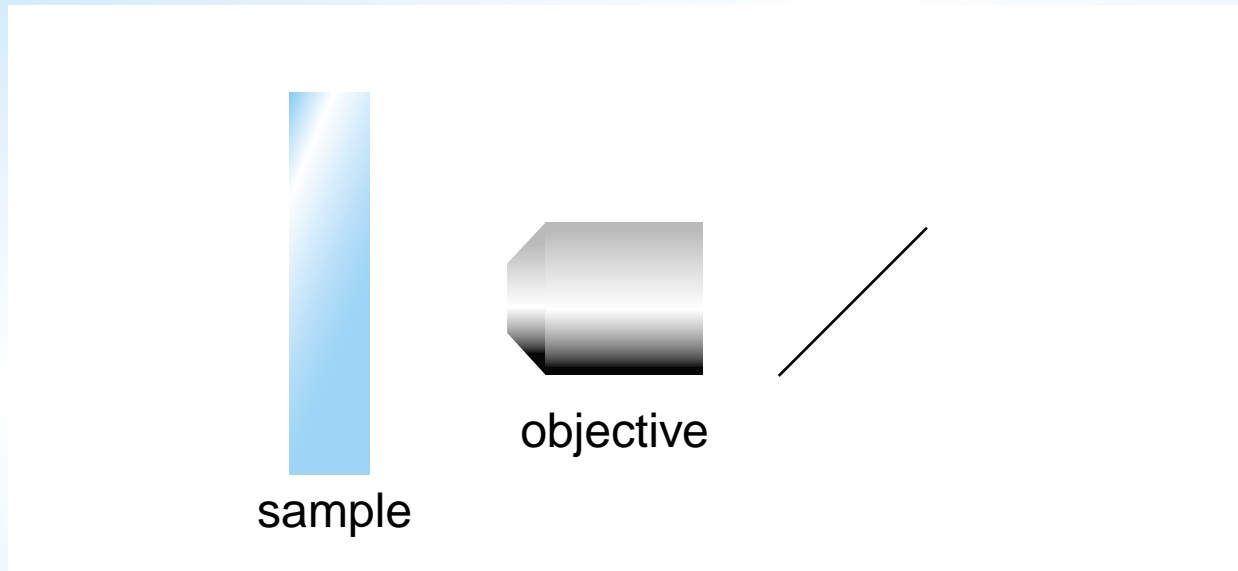
Outline

- ▶ Setup
- ▶ Morphology
- ▶ Energy deposition
- ▶ Dynamics



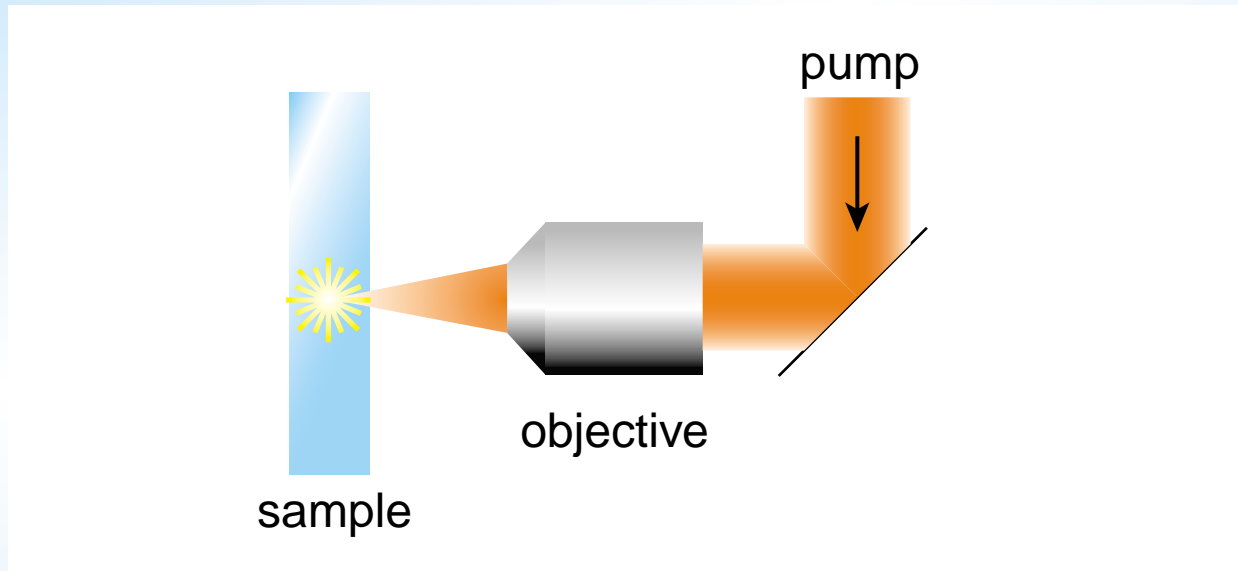
Dynamics

imaging setup



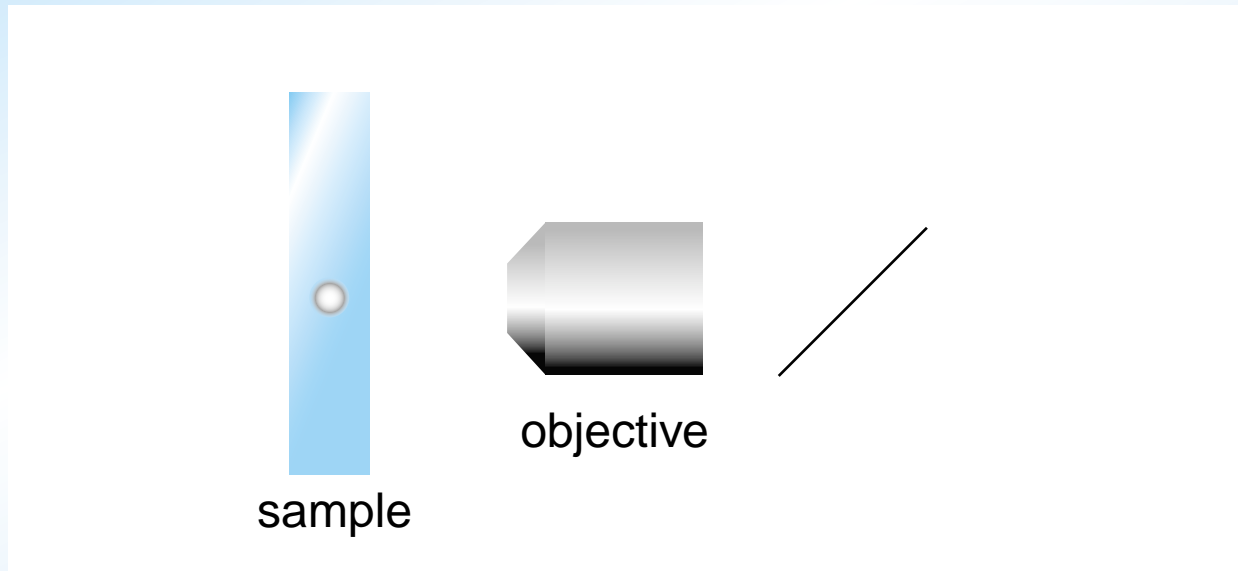
Dynamics

imaging setup



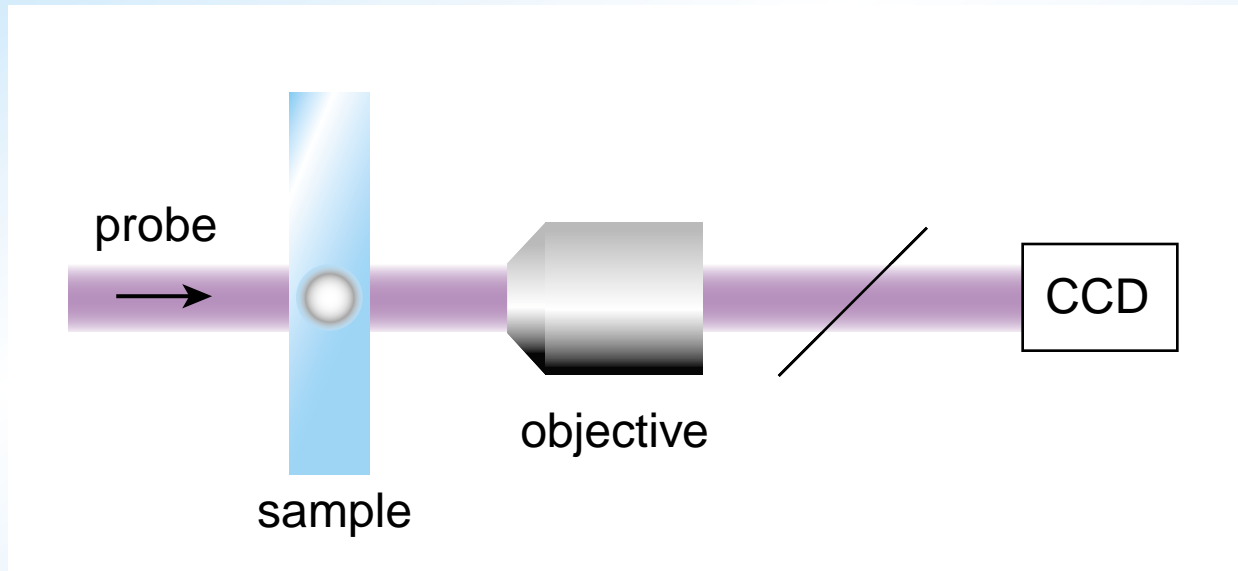
Dynamics

imaging setup



Dynamics

imaging setup



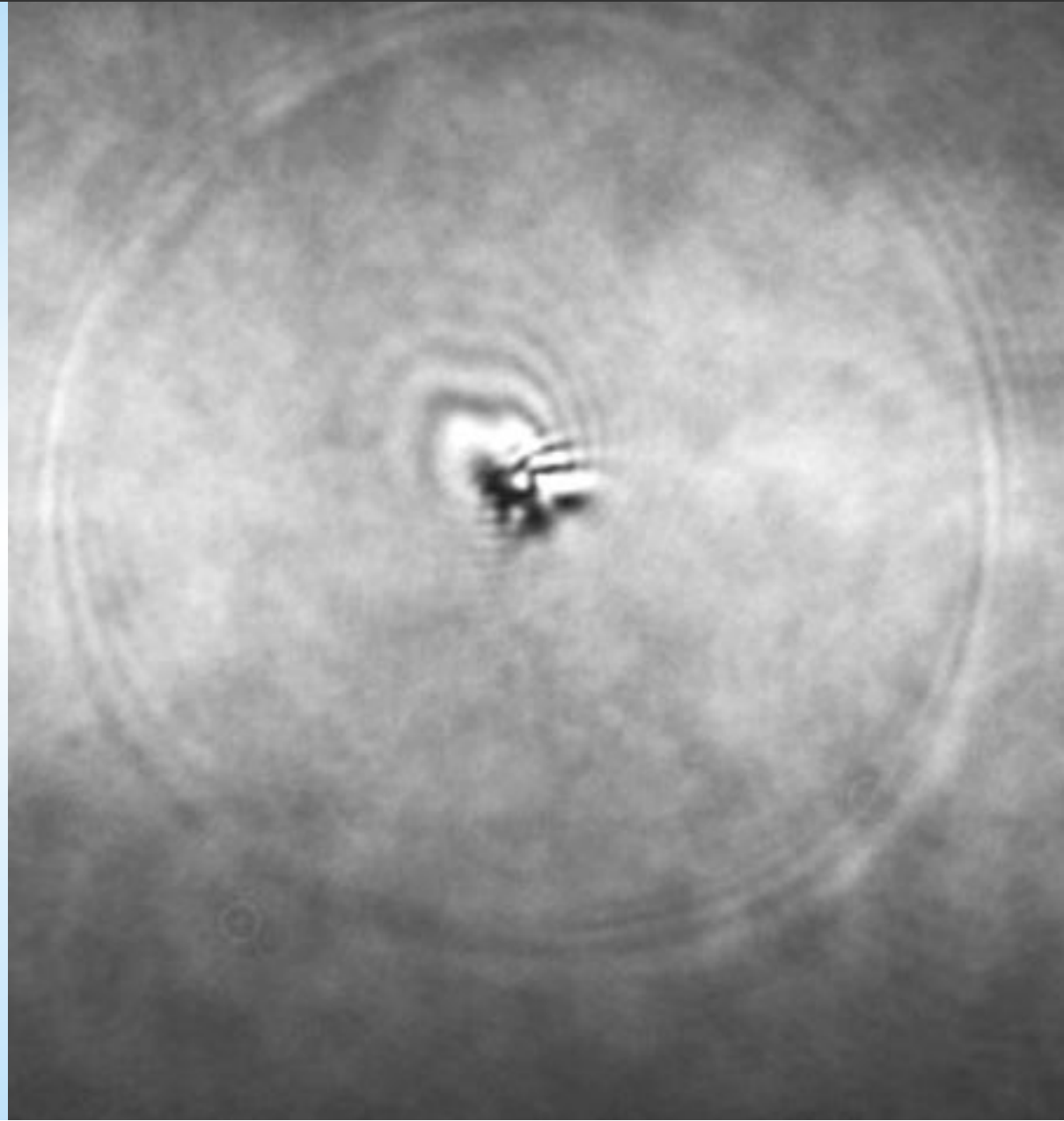
Dynamics

sapphire

3 μJ pulse

3.8 ns delay

40 μm radius



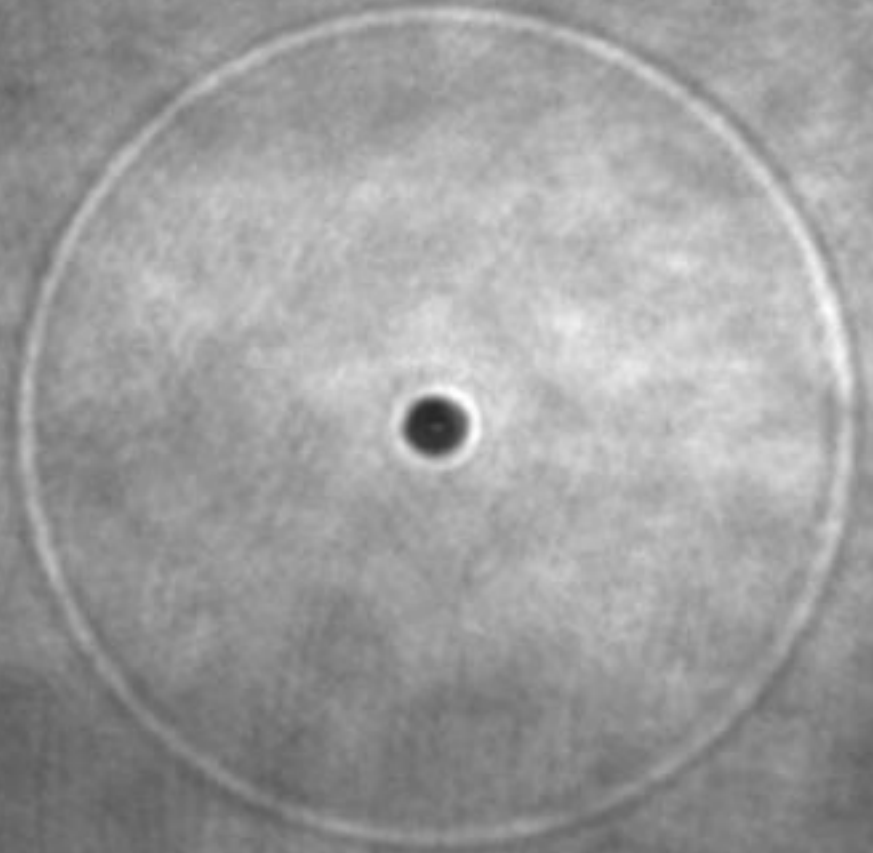
Dynamics

water ("self-healing")

1.0 μJ pulse

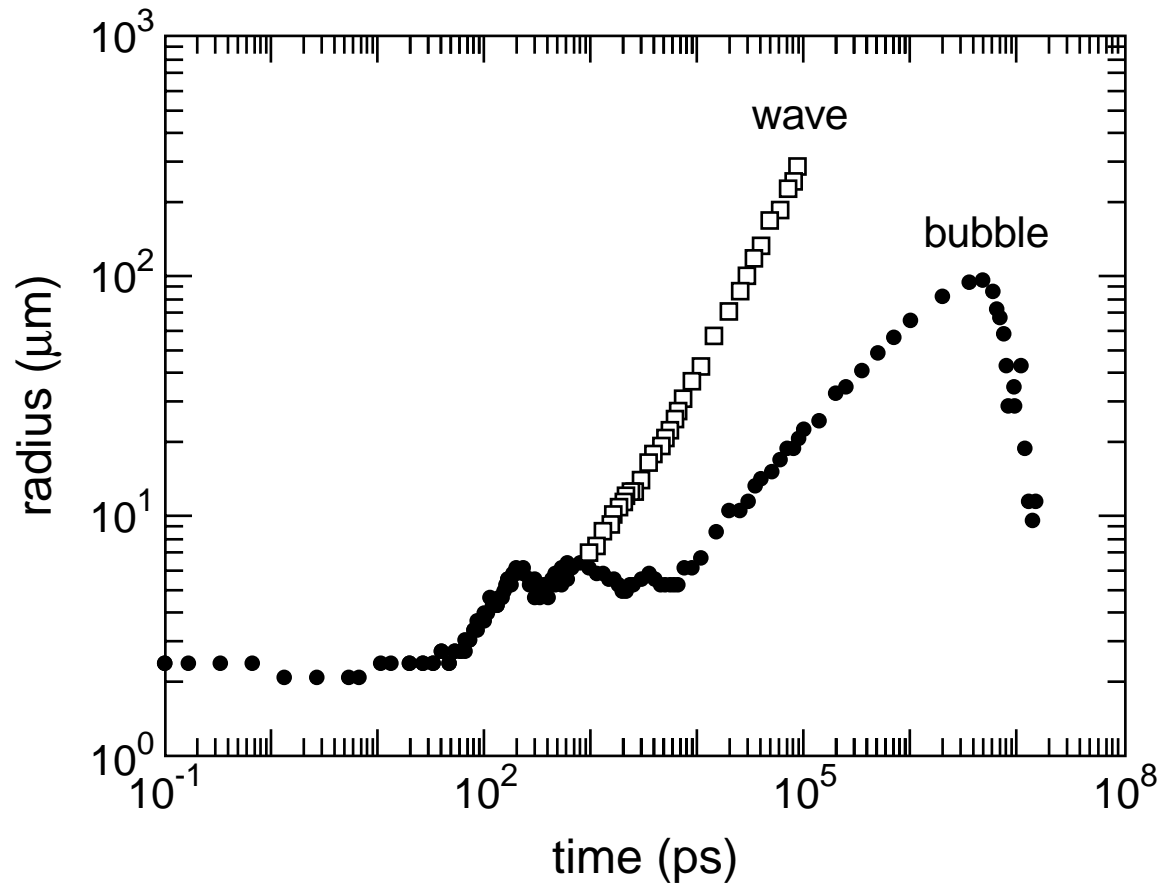
35 ns delay

58 μm radius



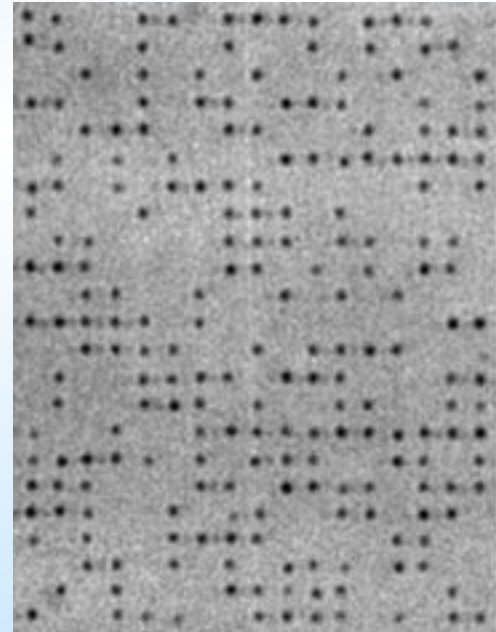
Dynamics

Dynamics



Applications

- ▶ data storage



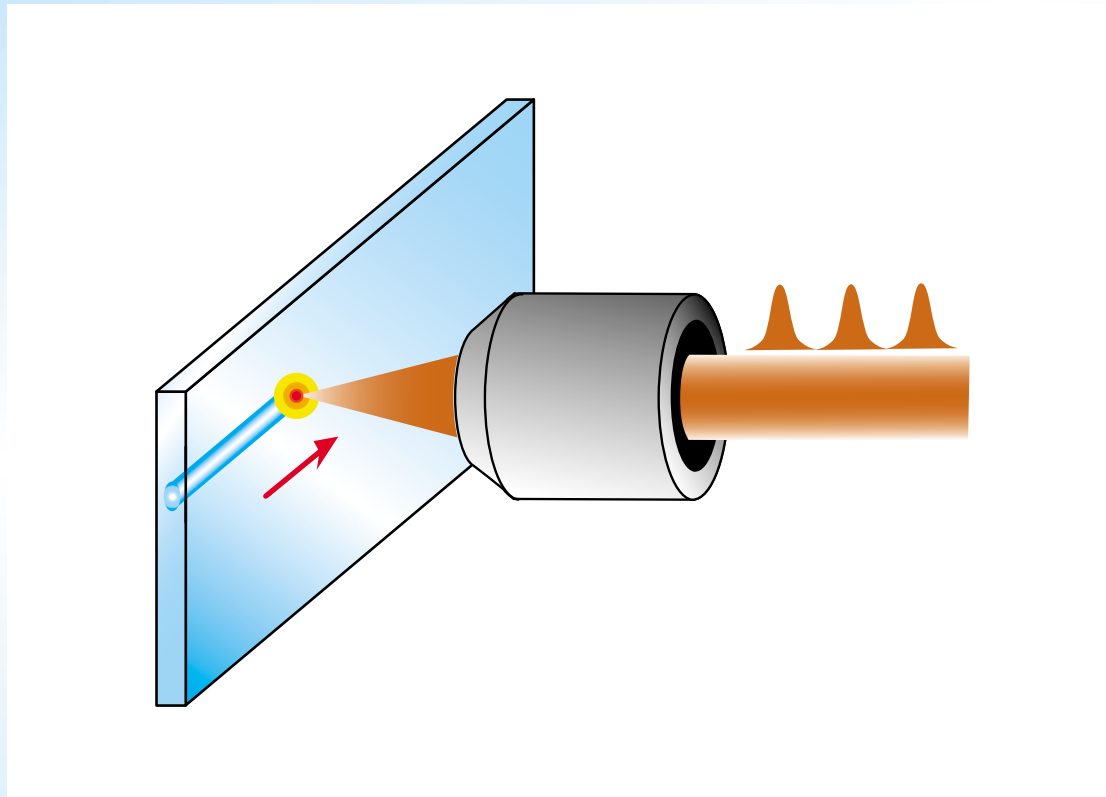
100 GB multilayer CD

Applications

- ▶ data storage
- ▶ photonic devices

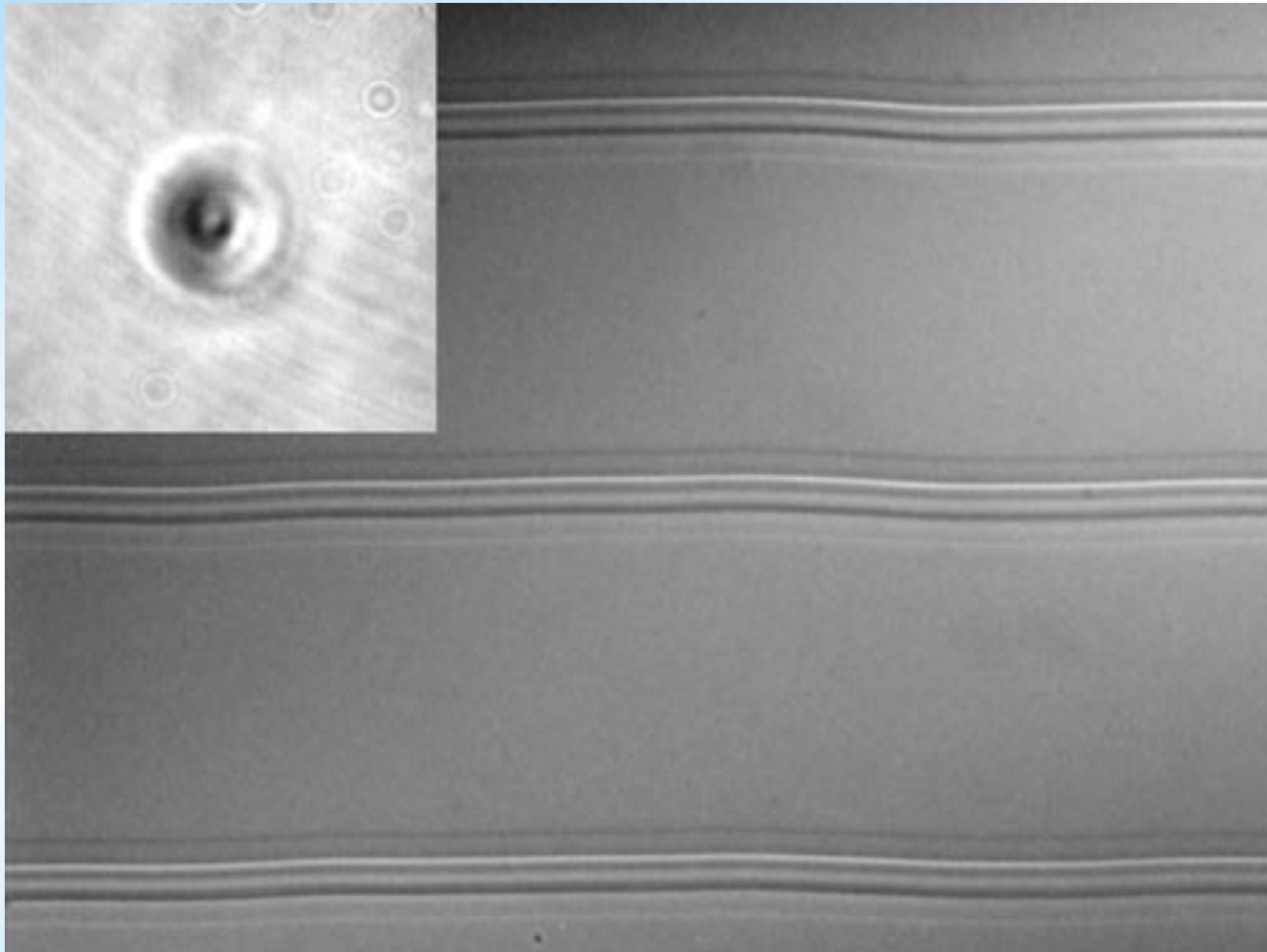
Applications

waveguide machining



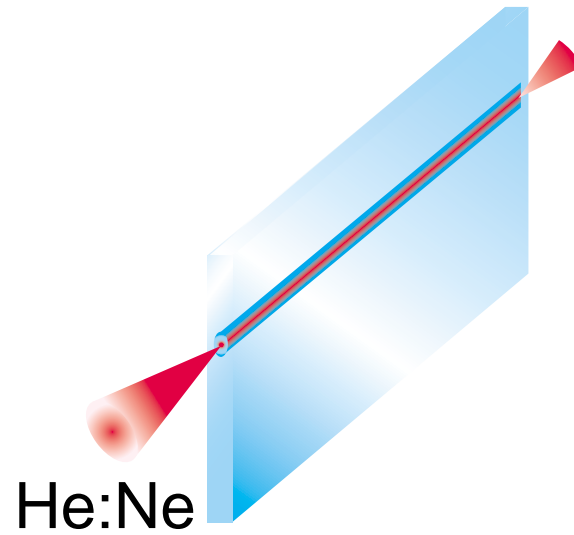
Applications

waveguide machining



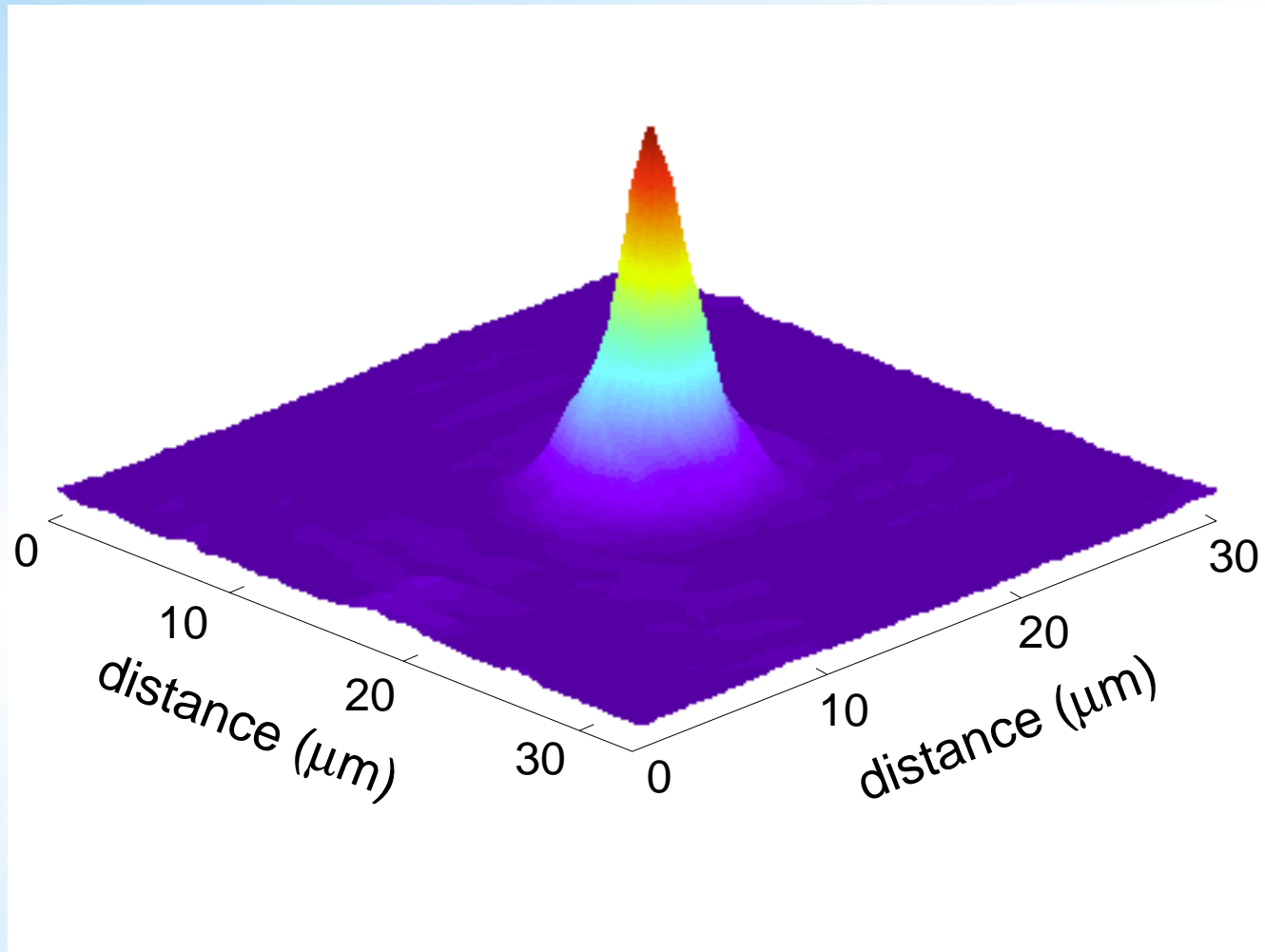
Applications

waveguide mode analysis



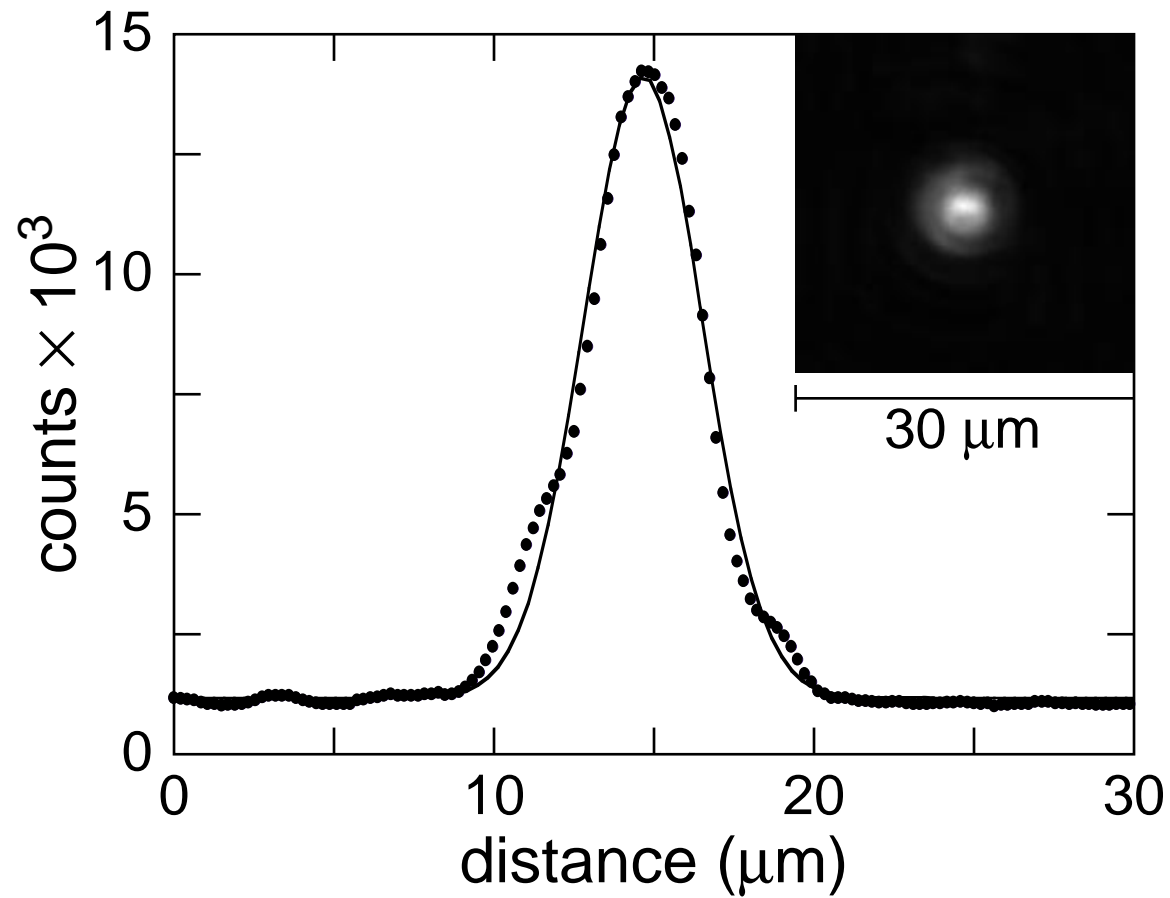
Applications

near field mode



Applications

near field mode



Future applications

wavelength selective splitter



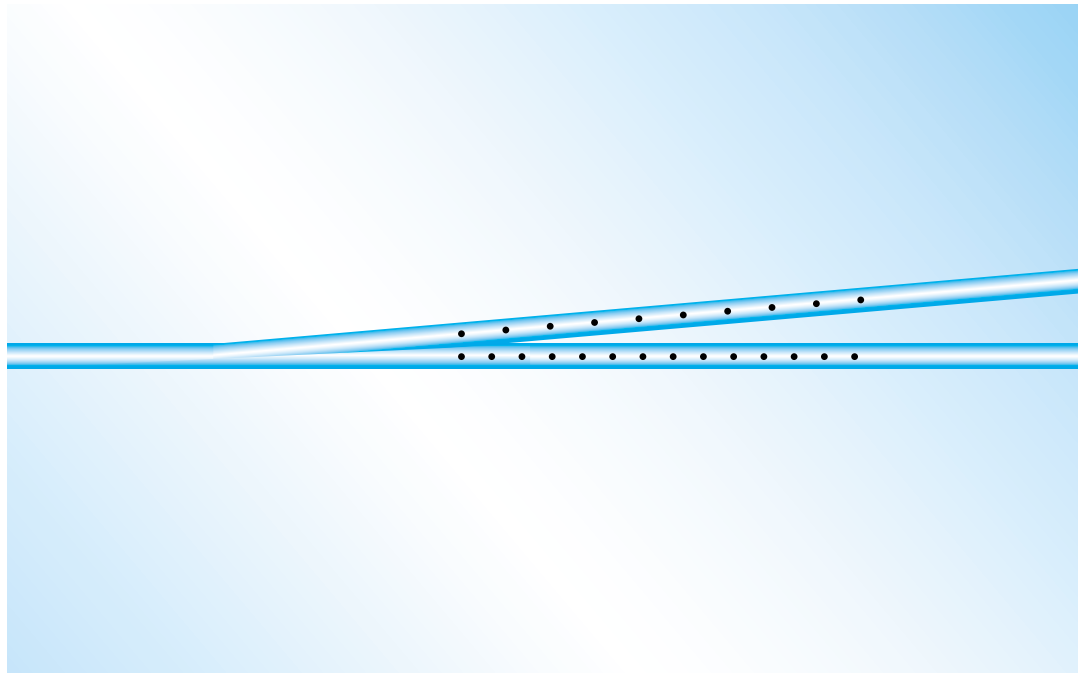
Future applications

wavelength selective splitter



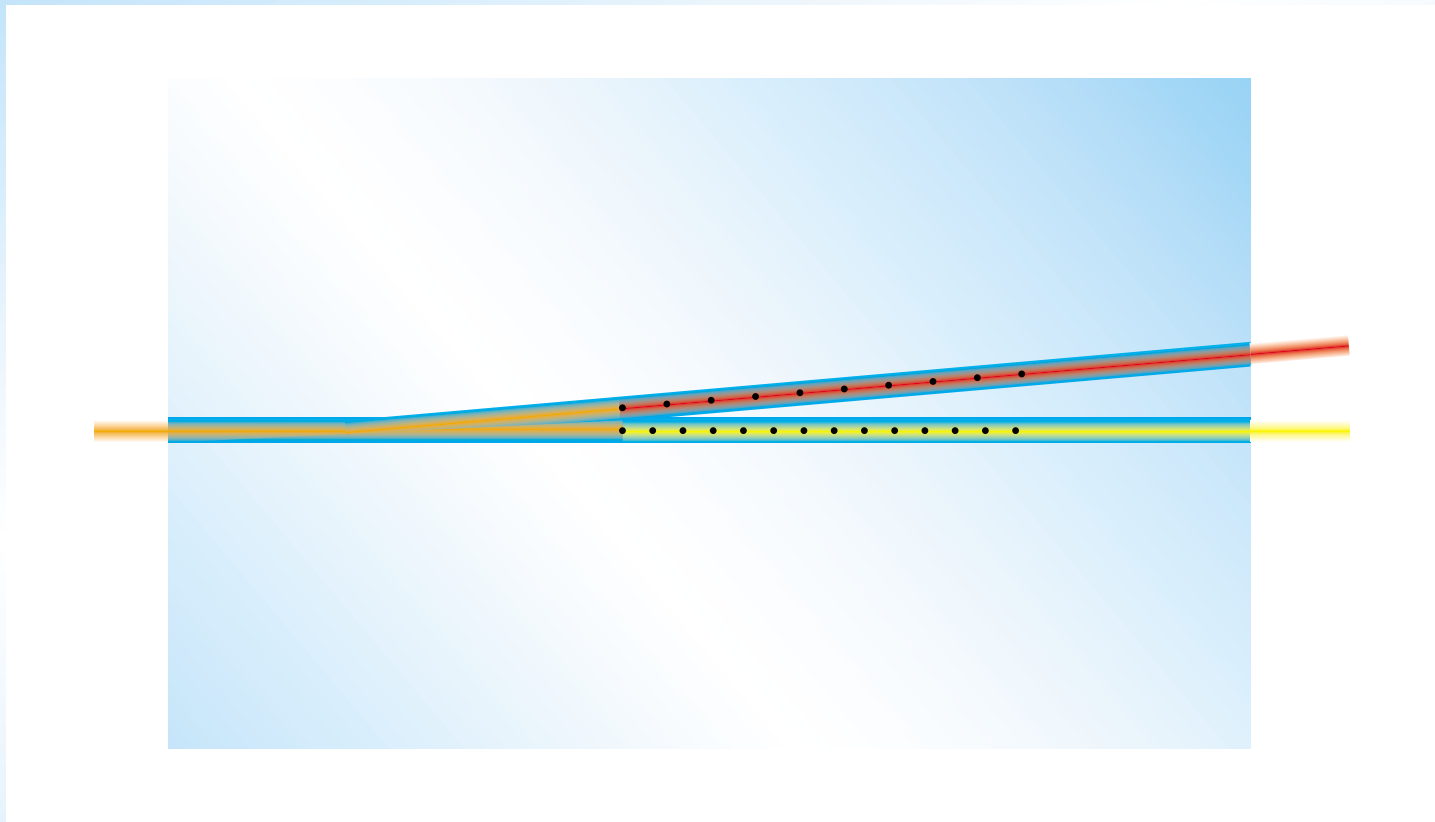
Future applications

wavelength selective splitter



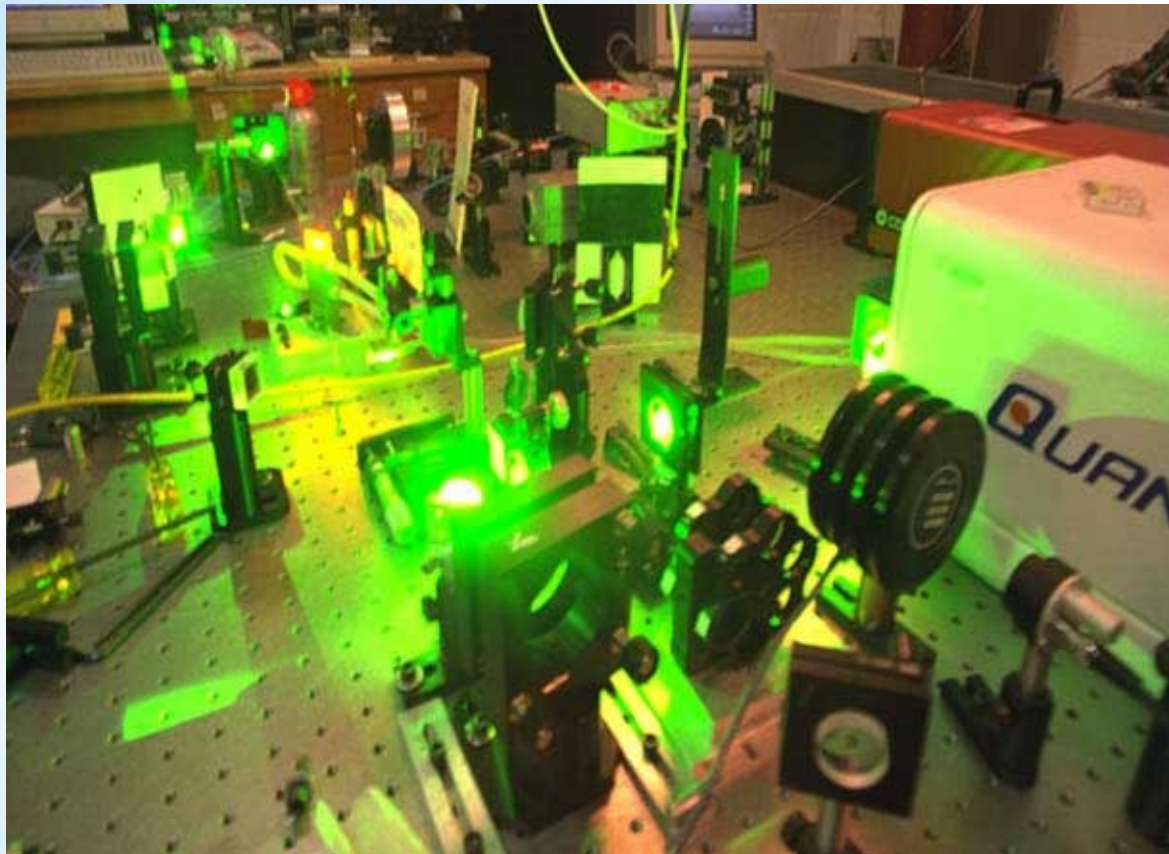
Future applications

wavelength selective splitter



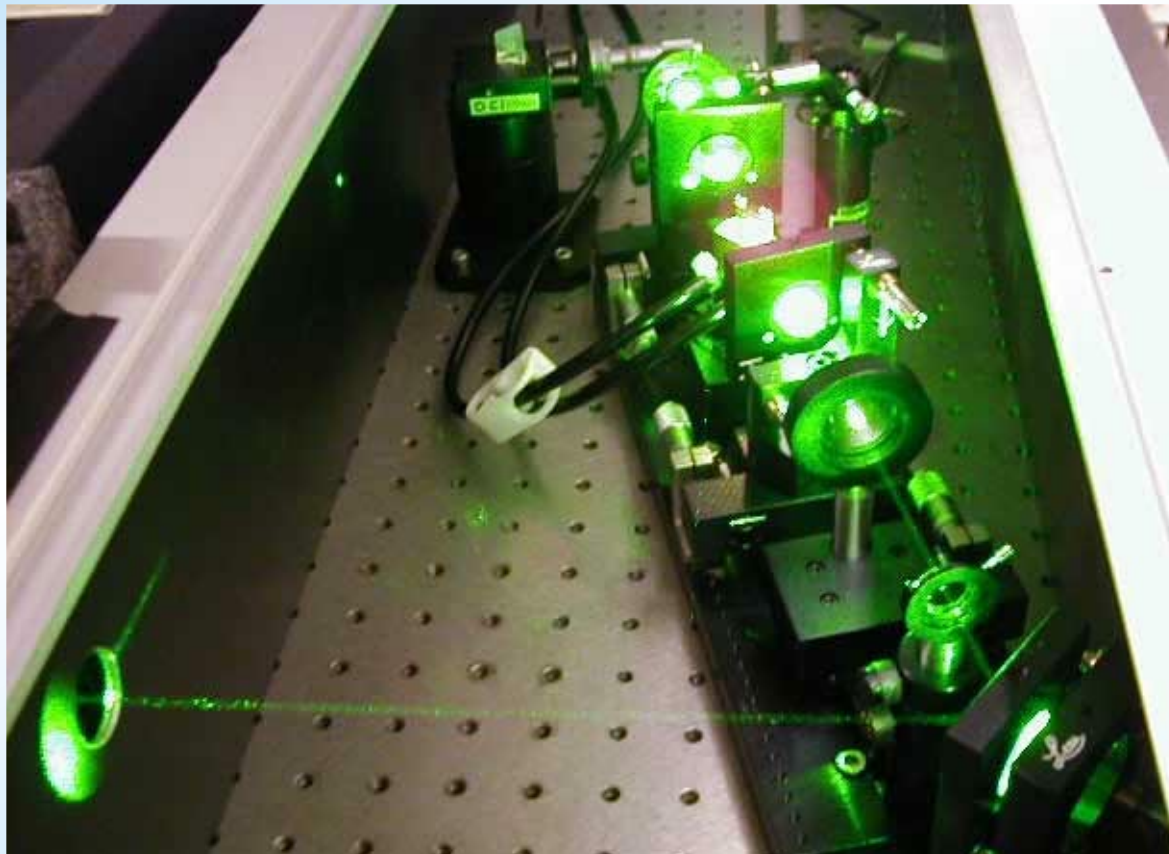
Applications

5-nJ threshold: unamplified micromachining



Applications

5-nJ threshold: unamplified micromachining



Applications

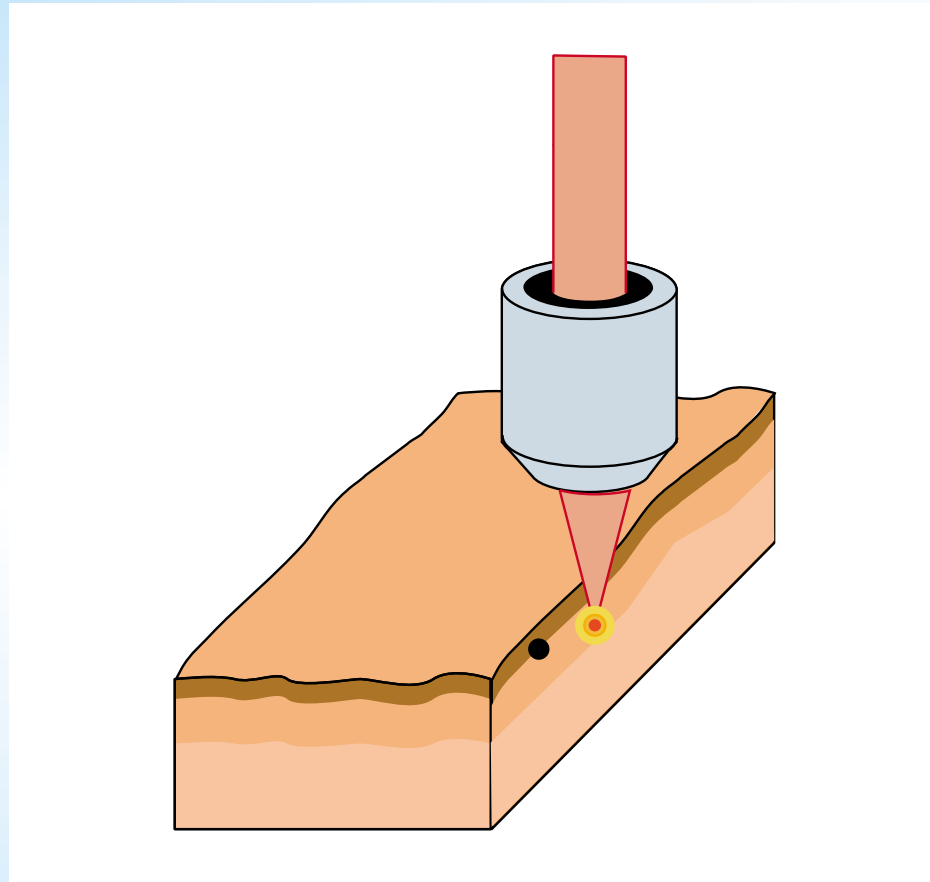
- ▶ **data storage**
- ▶ **photonic devices**
- ▶ **photonic bandgap materials**

Applications

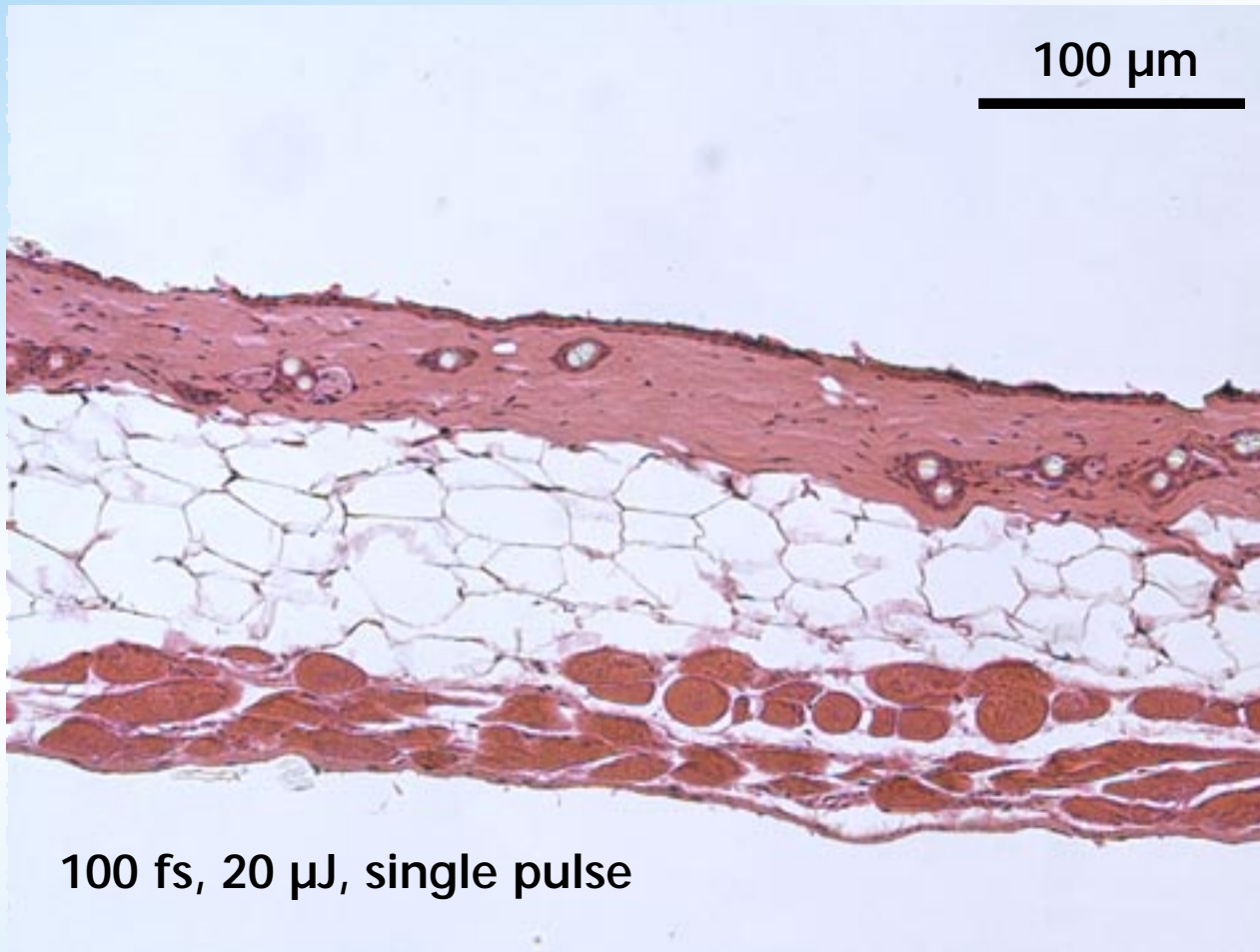
- ▶ **data storage**
- ▶ **photonic devices**
- ▶ **photonic bandgap materials**
- ▶ **biology/medicine**

Applications

subsurface surgery

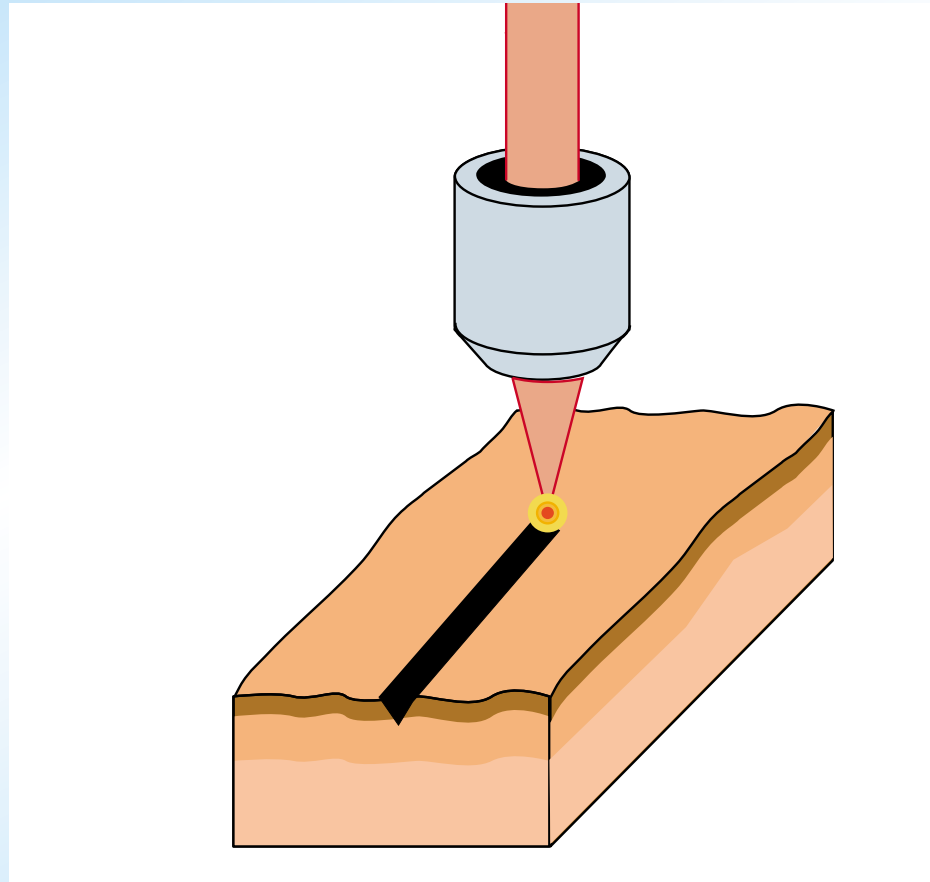


Applications

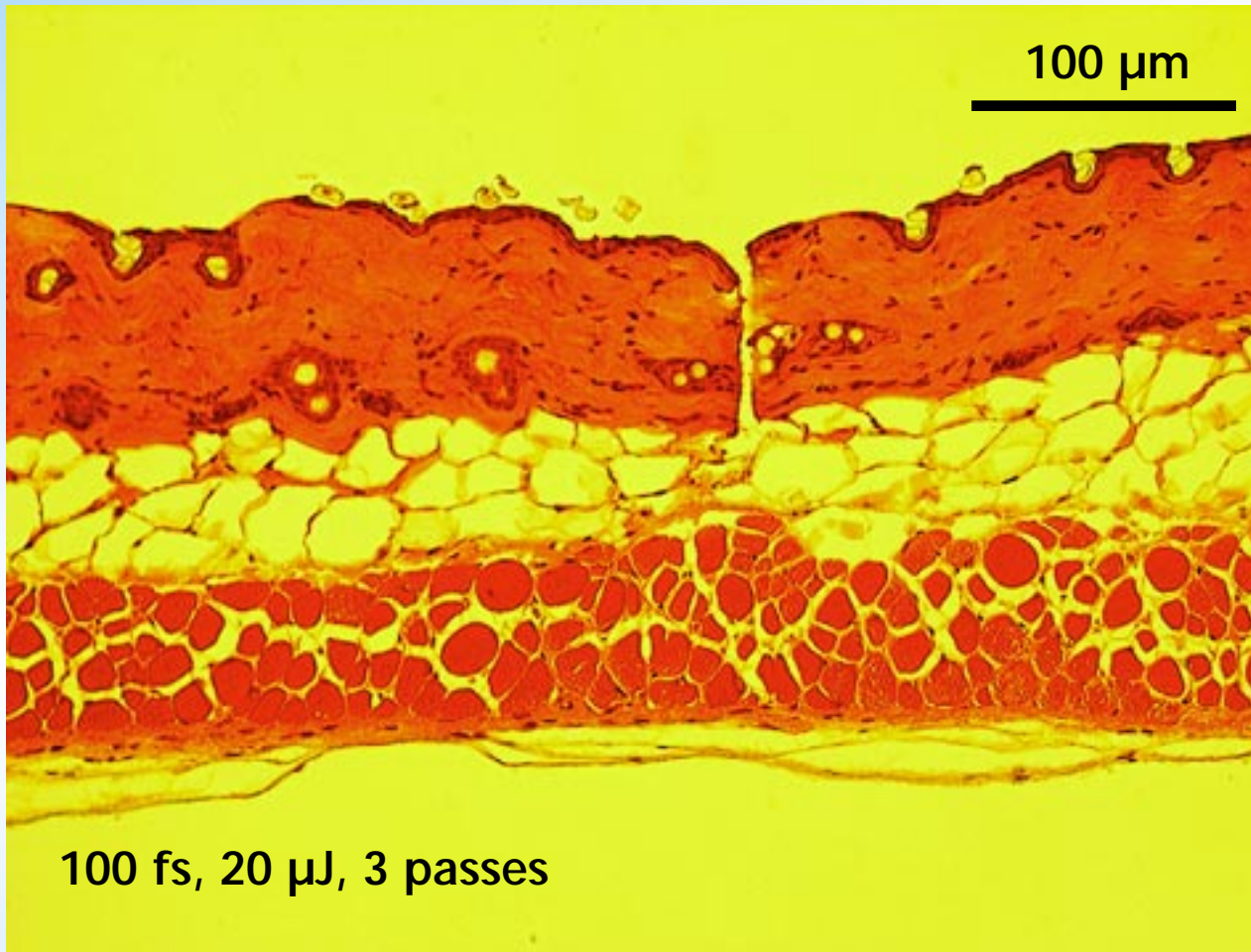


Applications

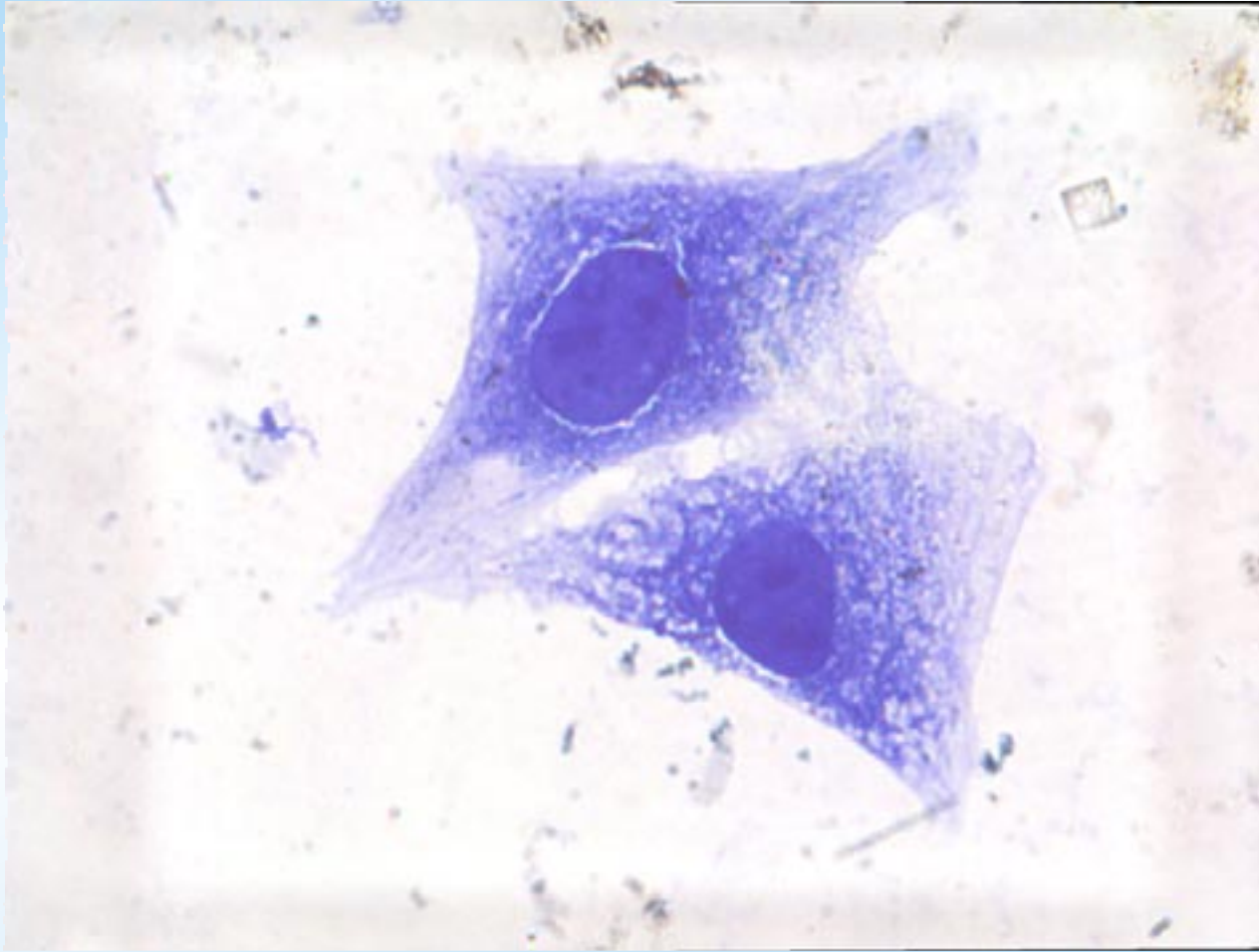
incision setup



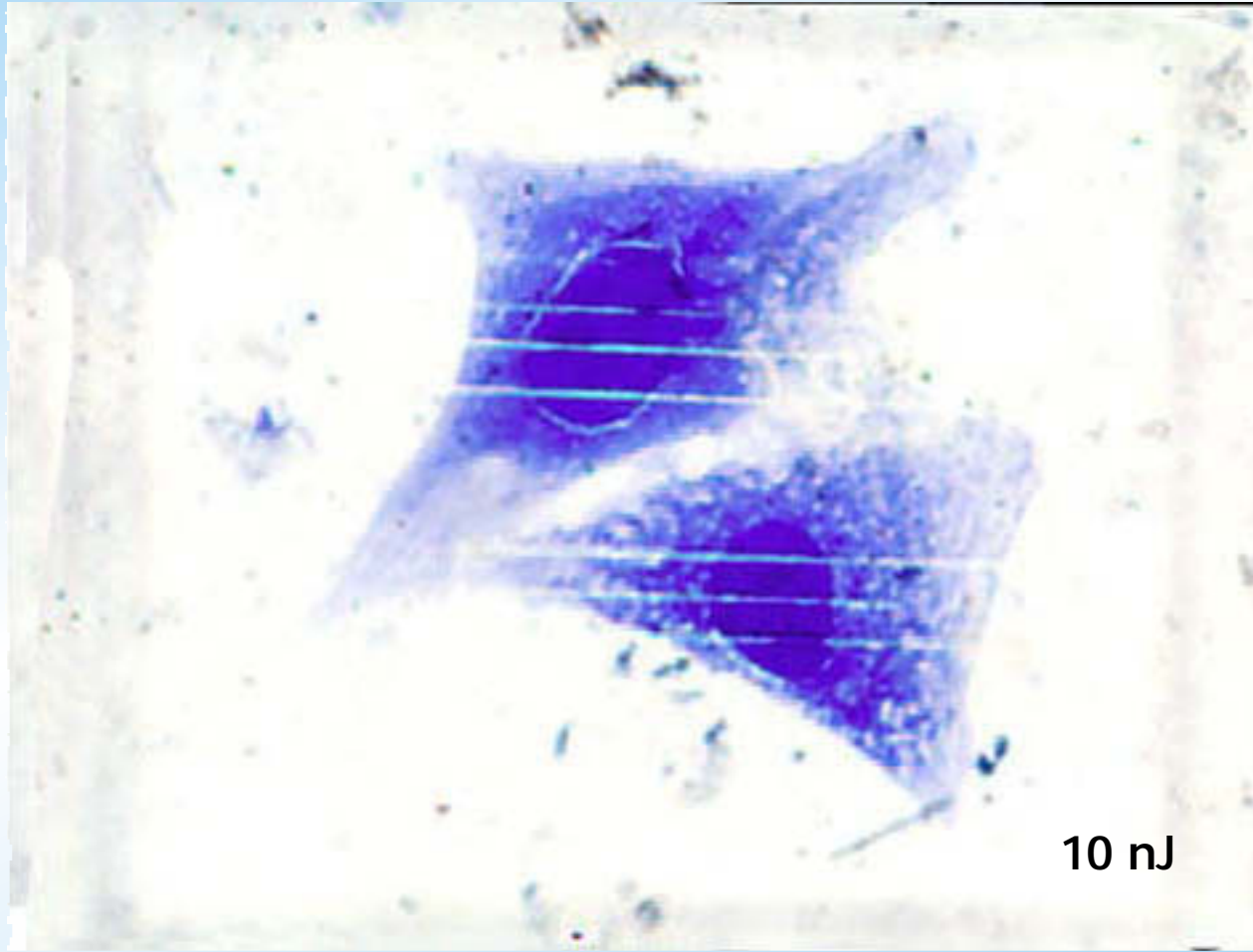
Applications

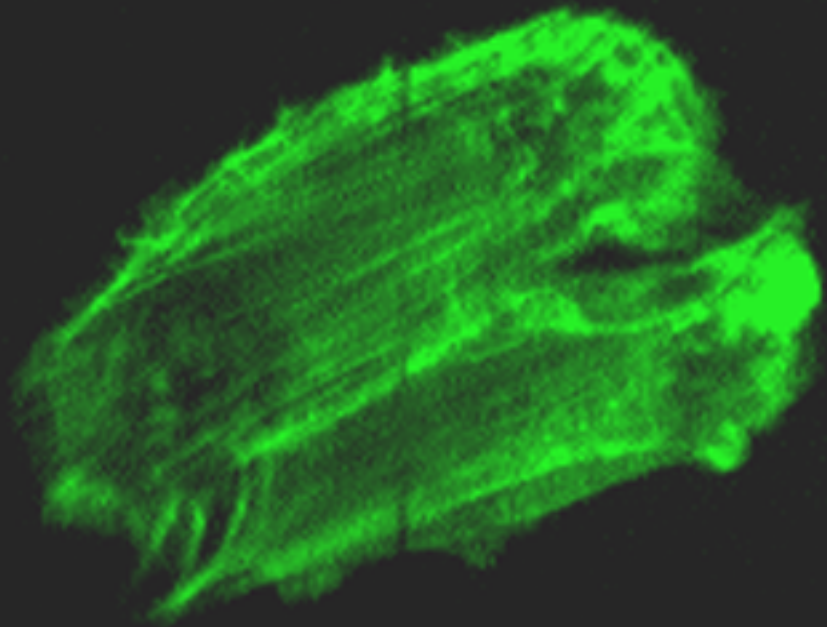


Subcellular micromachining



Subcellular micromachining

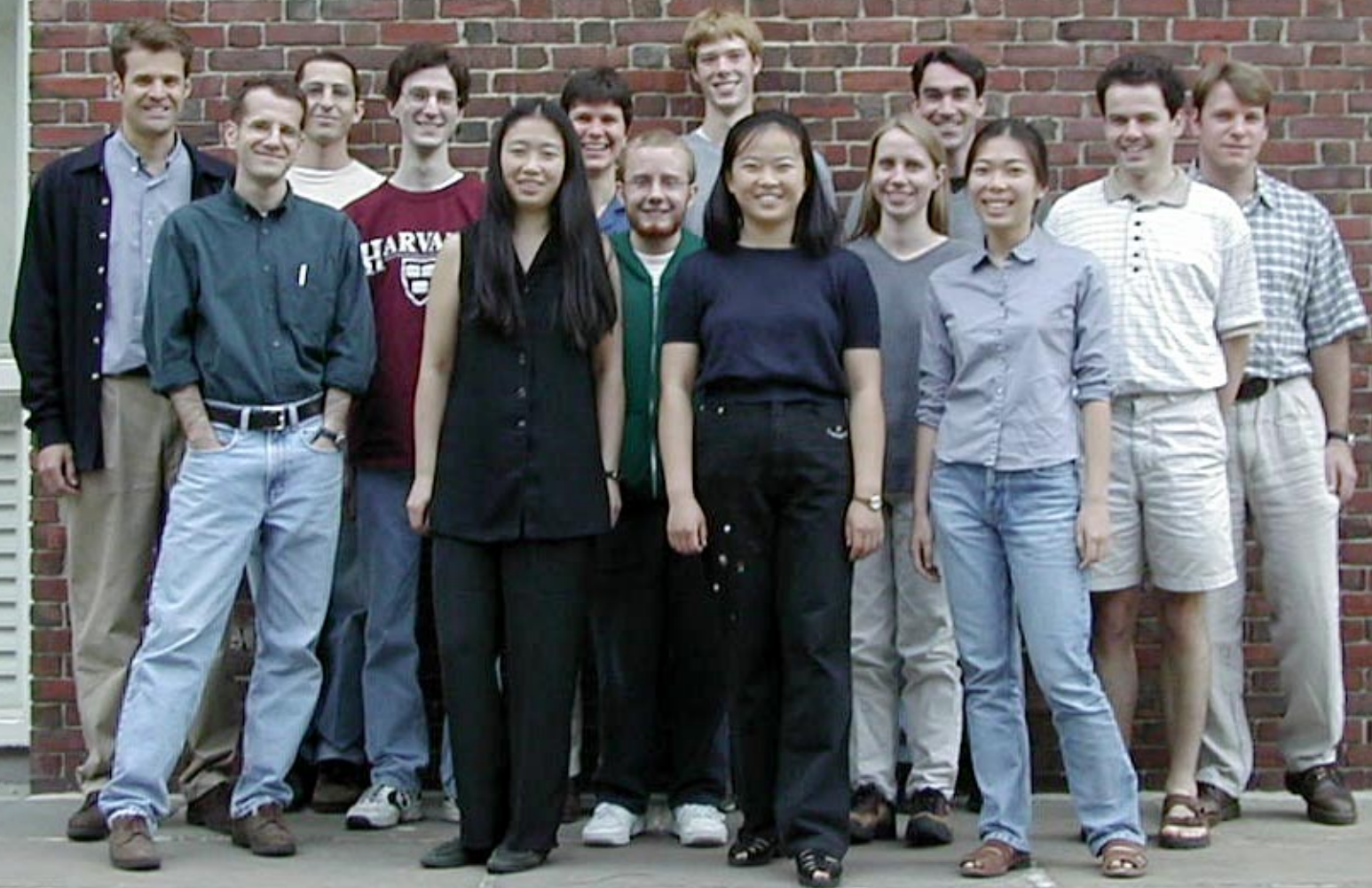




Conclusions

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

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LABORATORY OF
APPLIED SCIENCE



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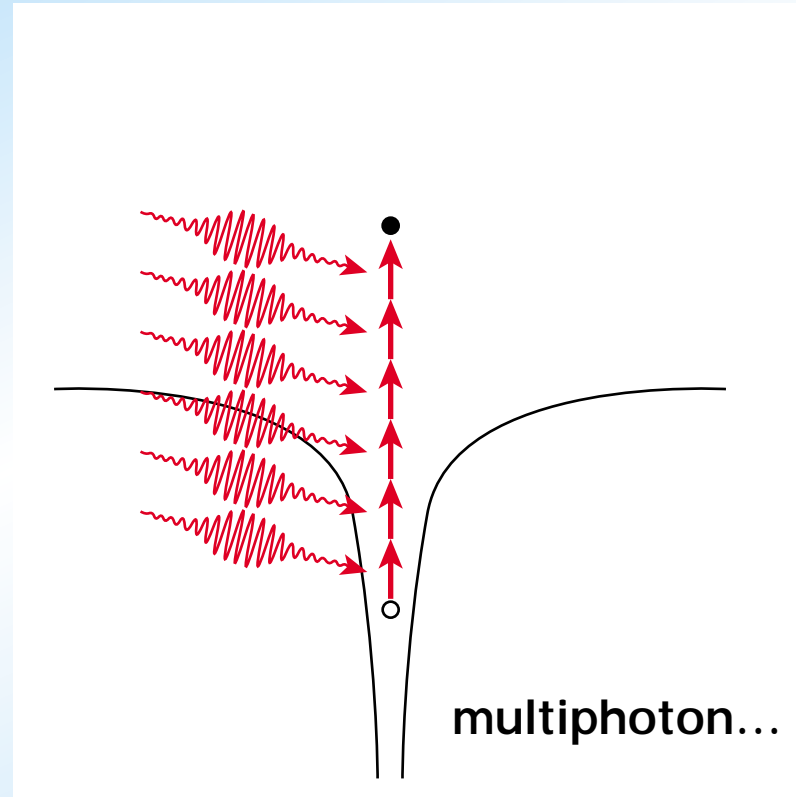
W. Leight

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

<http://mazur-www.harvard.edu>

Energy deposition

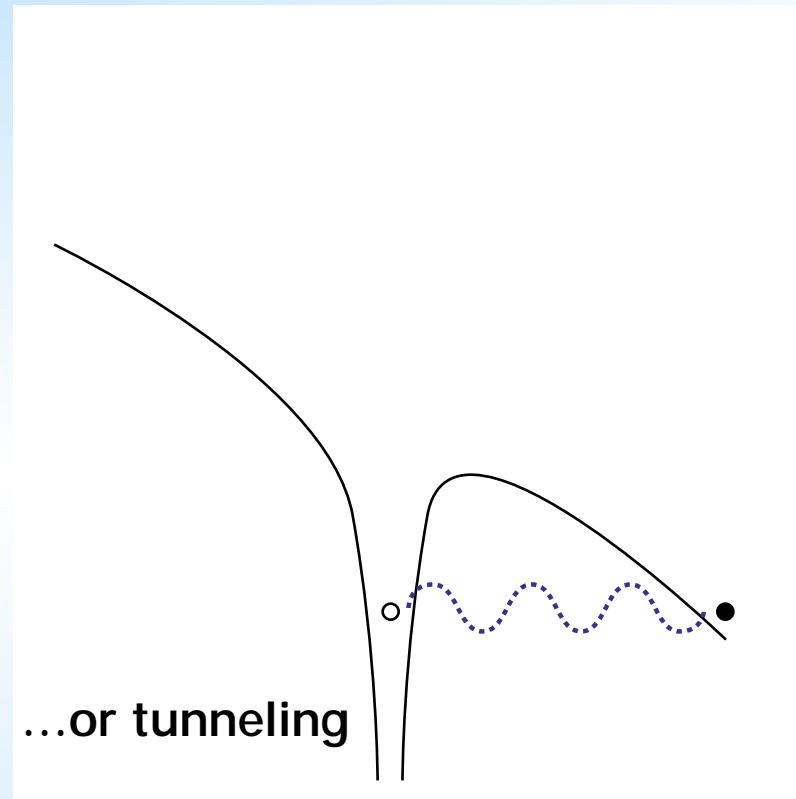
laser field ionization



nonlinear: I^n

Energy deposition

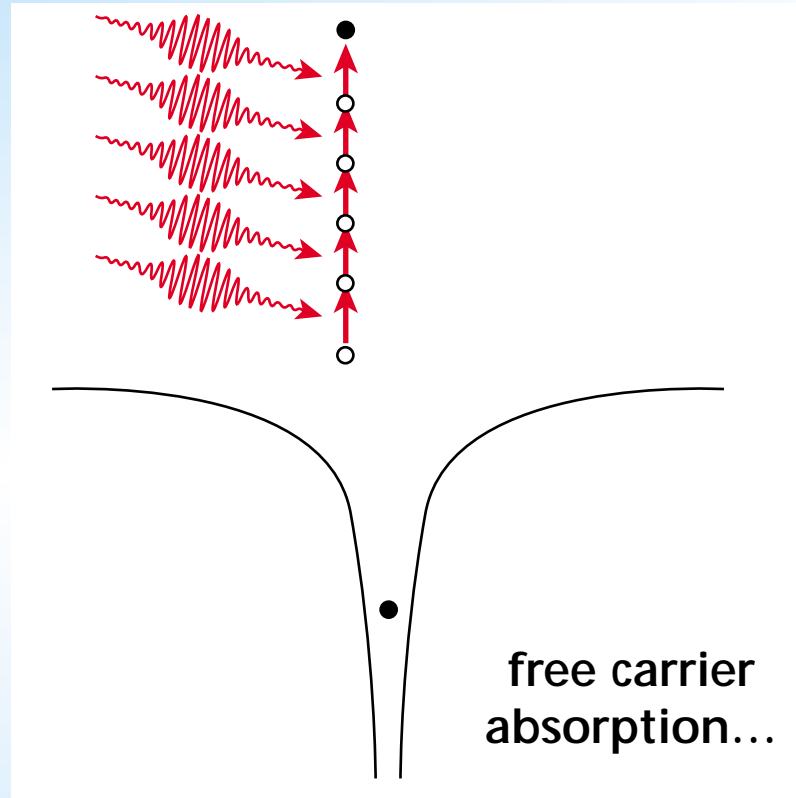
laser field ionization



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

Energy deposition

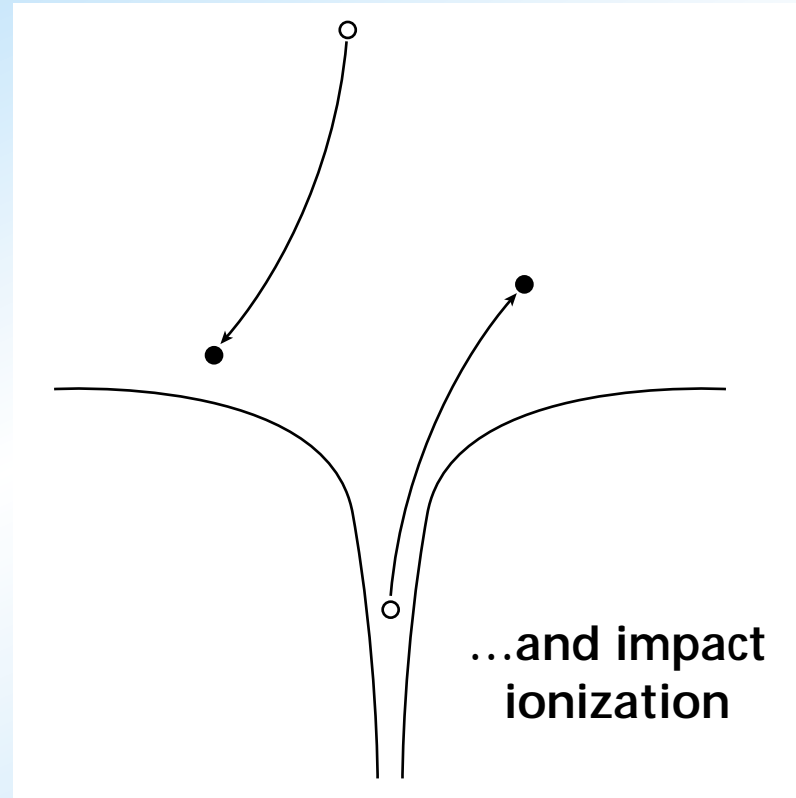
avalanche ionization



linear: nI

Energy deposition

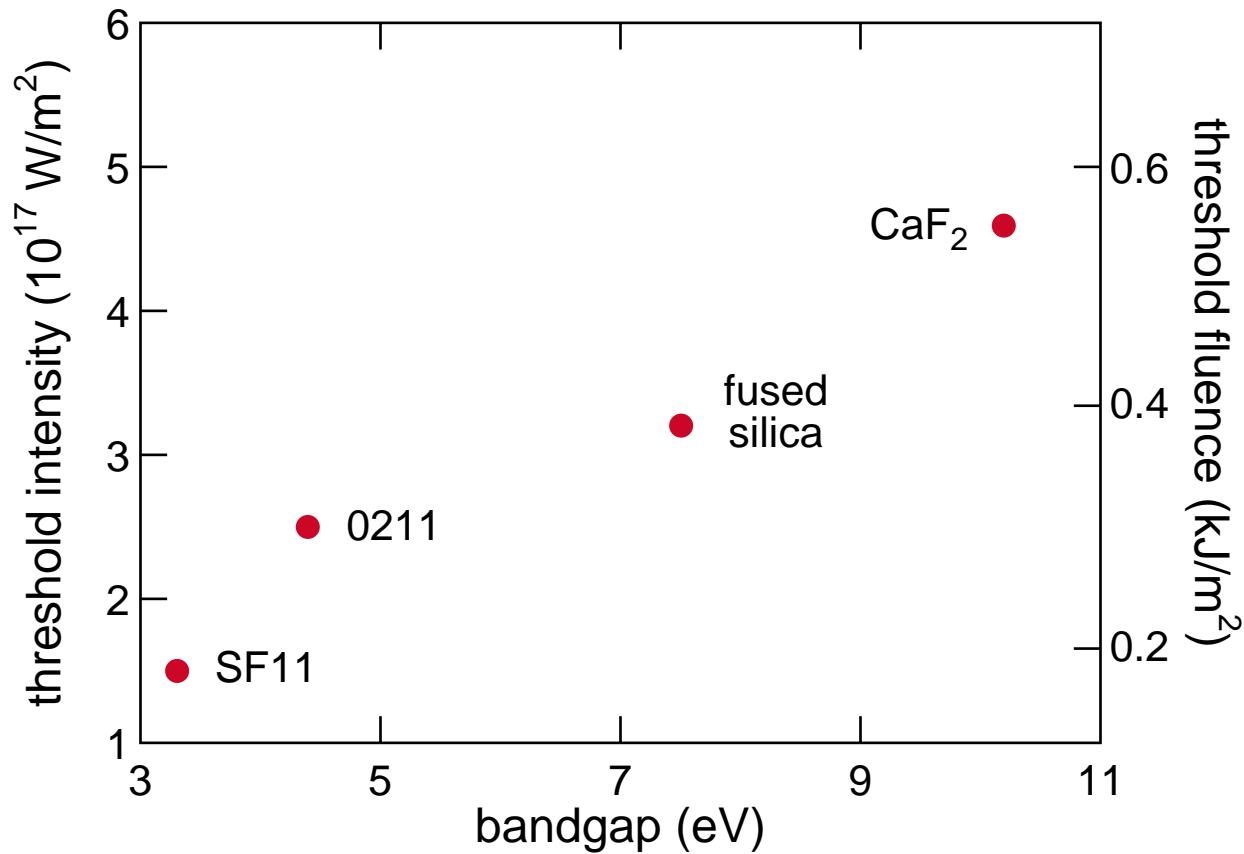
laser field ionization



linear: nI

Energy deposition

large bandgap: avalanche ionization dominates



Energy deposition

same trend at 400 nm

