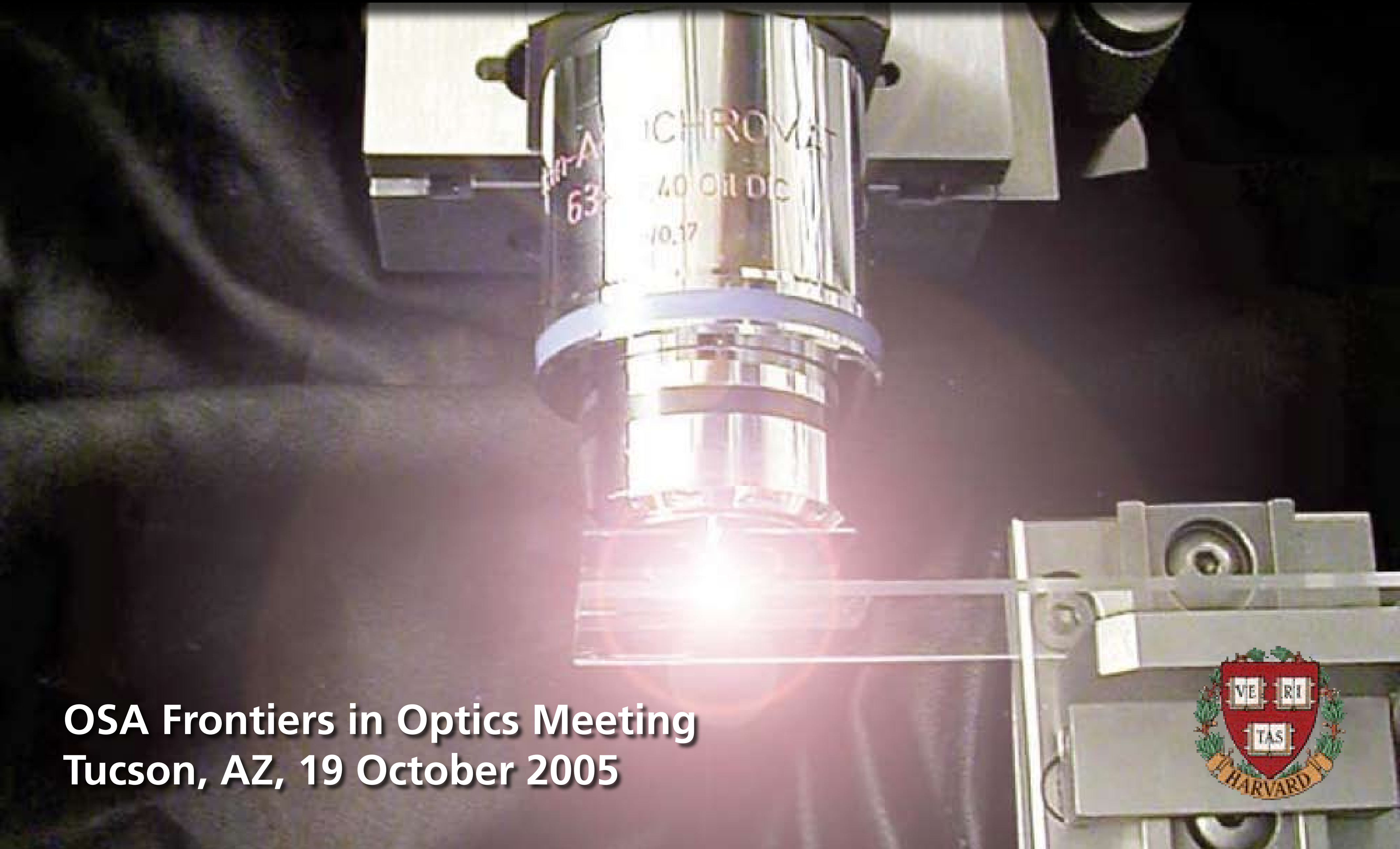
Materials Processing Using Ultrashort Laser Pulses



OSA Frontiers in Optics Meeting
Tucson, AZ, 19 October 2005


Rafael Gattass


Loren Cerami


Tina Shih


Masanao Kamata

and also....

Iva Maxwell
Eli Glezer
Chris Schaffer
Nozomi Nishimura
Jonathan Ashcom
Jeremy Hwang
Nan Shen
Dr. André Brodeur
Dr. Sanjoy Kumar
Dr. Limin Tong
Dr. Prissana Thamboon

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Prof. Denise Krol (UC Davis)
Dr. Yossi Chay (Sagitta, Inc.)
Dr. S.K. Sundaram (PNNL)
Prof. Minoru Obara (Keio University)
Prof. Don Ingber (Harvard Medical School)
Prof. Aravi Samuel (Harvard)

My message

fs micromachining: great technique for manipulating matter

Introduction

ASTM

STP 1141

22nd ANNUAL BOULDER DAMAGE SYMPOSIUM
Proceedings

LASER-INDUCED DAMAGE IN OPTICAL MATERIALS: 1990

24–26 OCTOBER 1990
BOULDER, COLORADO

Introduction

216 J. Opt. Soc. Am. B/Vol. 13, No. 1/January 1996

Breakdown threshold and plasma formation in femtosecond laser–solid interaction

D. von der Linde and H. Schüler

Institut für Laser- und Plasmaphysik, Universität Essen, D-45117 Essen, Germany

Received March 6, 1995; revised manuscript received June 15, 1995

Combining femtosecond pump–probe techniques with optical microscopy, we have studied laser-induced optical breakdown in optically transparent solids with high temporal and spatial resolution. The threshold of plasma formation has been determined from measurements of the changes of the optical reflectivity associated with the developing plasma. It is shown that plasma generation occurs at the surface. We have observed a remarkable resistance to optical breakdown and material damage in the interaction of femtosecond laser pulses with bulk optical materials.

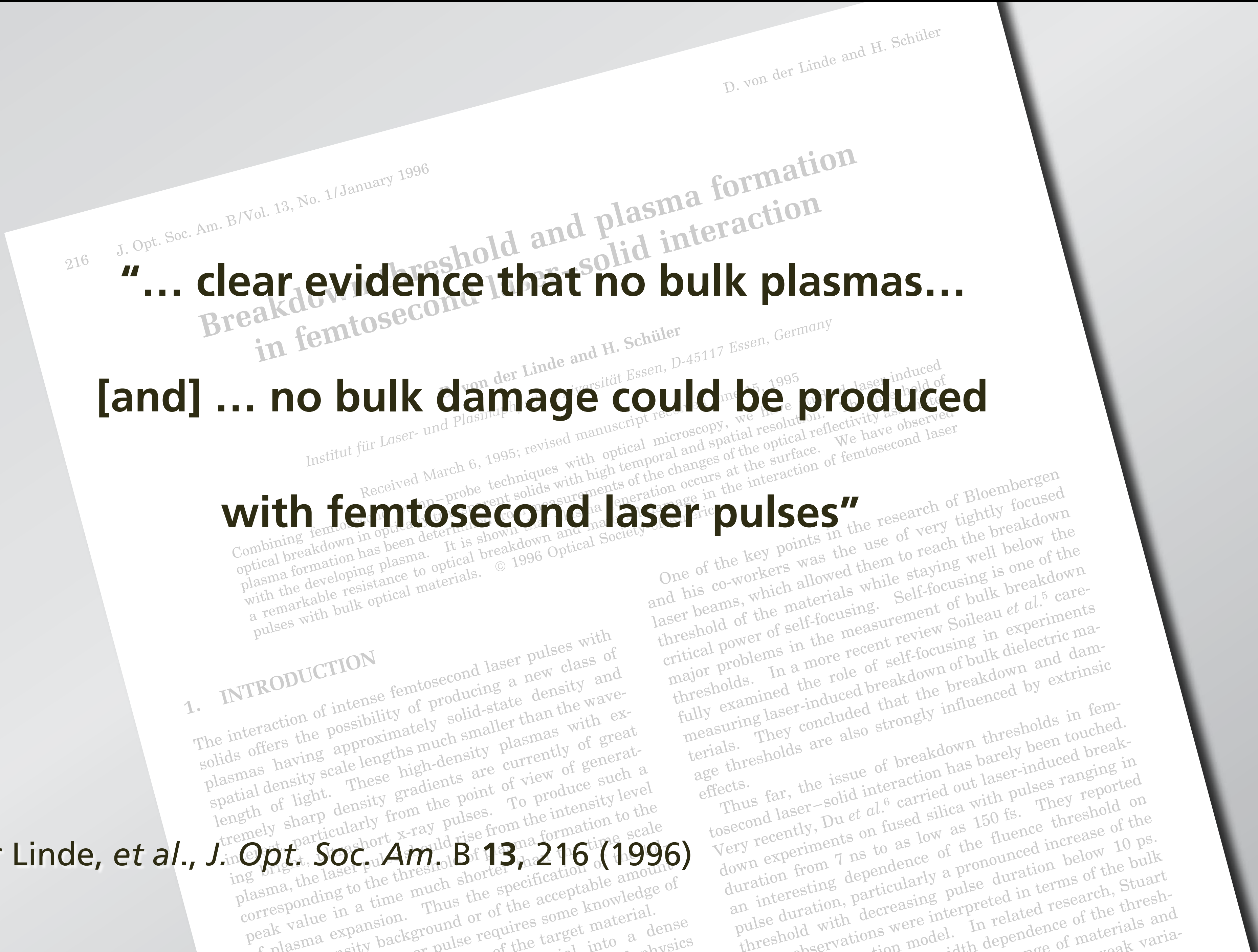
1. INTRODUCTION

The interaction of intense femtosecond laser pulses with solids offers the possibility of producing a new class of plasmas having approximately solid-state density and spatial density scale lengths much smaller than the wavelength of light. These high-density plasmas with extremely sharp density gradients are currently of great interest, particularly from the point of view of generating bright, ultrashort x-ray pulses. To produce such a plasma, the laser pulse should rise from the intensity level corresponding to the threshold of plasma formation to the peak value in a time much shorter than the time scale of plasma expansion. Thus the specification of the tol- nsity background or of the acceptable amount er pulse requires some knowledge of of the target material. ial into a dense physics

One of the key points in the research of Bloembergen and his co-workers was the use of very tightly focused laser beams, which allowed them to reach the breakdown threshold of the materials while staying well below the critical power of self-focusing. Self-focusing is one of the major problems in the measurement of bulk breakdown thresholds. In a more recent review Soileau *et al.*[5] carefully examined the role of self-focusing in experiments measuring laser-induced breakdown of bulk dielectric materials. They concluded that the breakdown and damage thresholds are also strongly influenced by extrinsic effects.

Thus far, the issue of breakdown thresholds in femtosecond laser–solid interaction has barely been touched. Very recently, Du *et al.*[6] carried out laser-induced breakdown experiments on fused silica with pulses ranging in duration from 7 ns to as low as 150 fs. They reported an interesting dependence of the fluence threshold on pulse duration, particularly a pronounced increase of the threshold with decreasing pulse duration below 10 ps. observations were interpreted in terms of the bulk tion model. In related research, Stuart idth dependence of the thresh- nge of materials and weak varia-

Introduction



"… clear evidence that no bulk plasmas…

[and] … no bulk damage could be produced

with femtosecond laser pulses"

von der Linde, *et al*., *J. Opt. Soc. Am*. B **13**, 216 (1996)

216 J. Opt. Soc. Am. B/Vol. 13, No. 1/January 1996

D. von der Linde and H. Schüler

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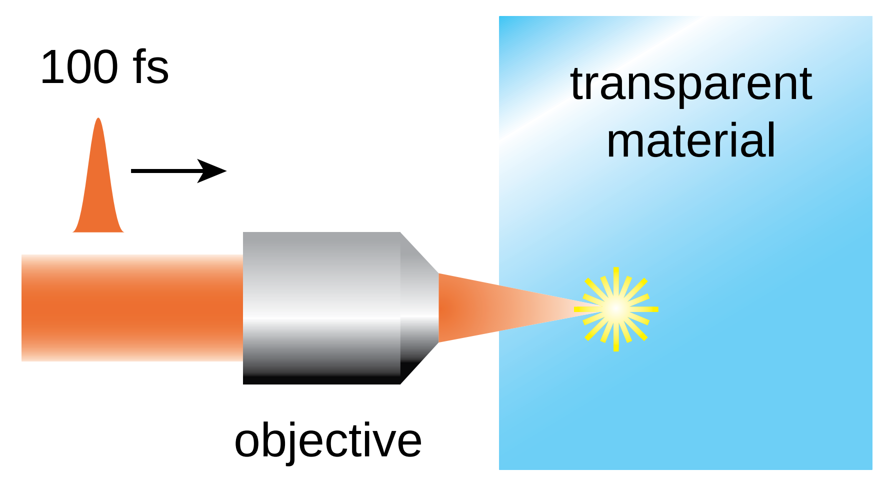
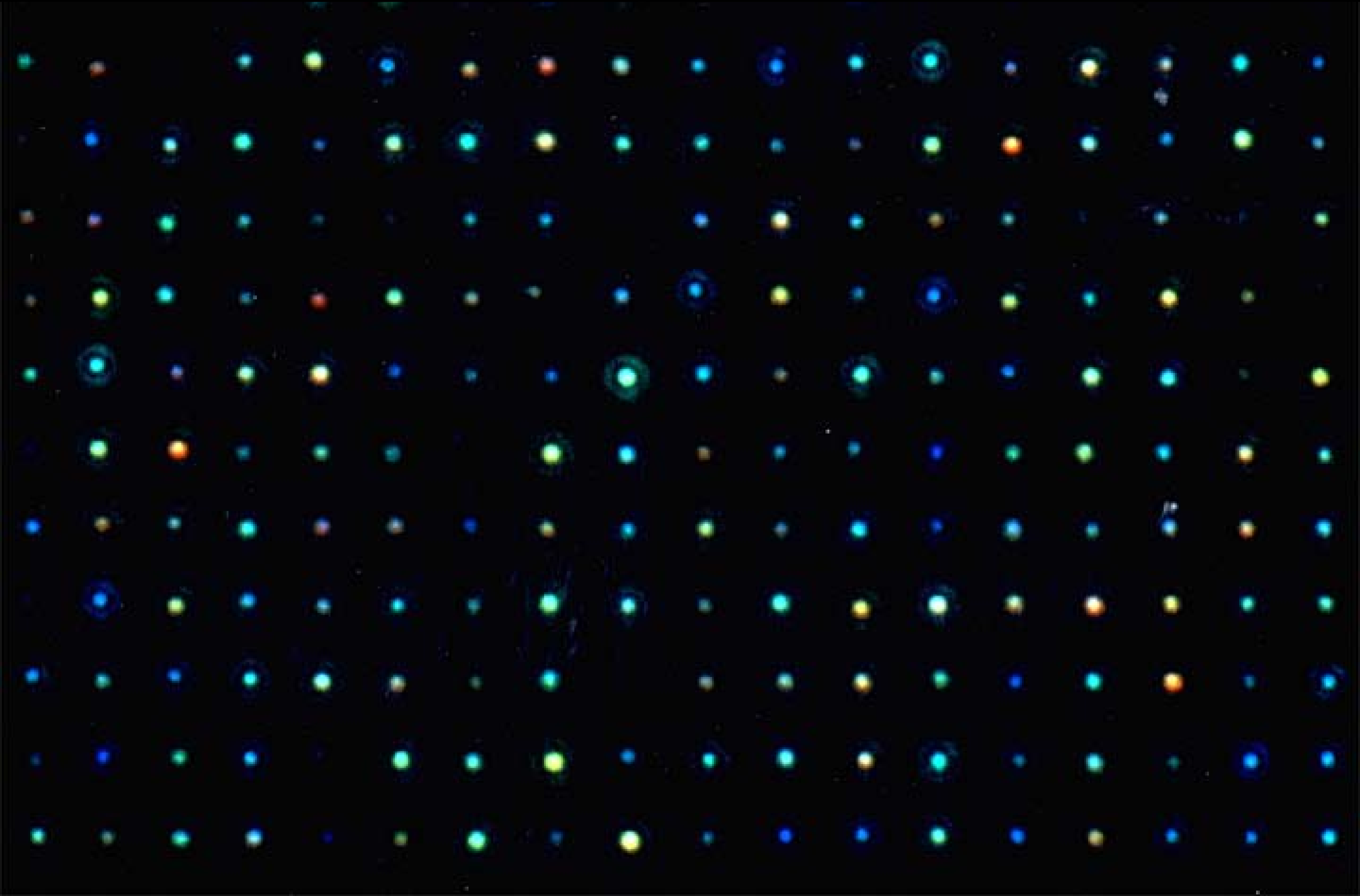
Introduction

focus laser beam inside material



Opt. Lett. **21**, 2023 (1996)

Introduction

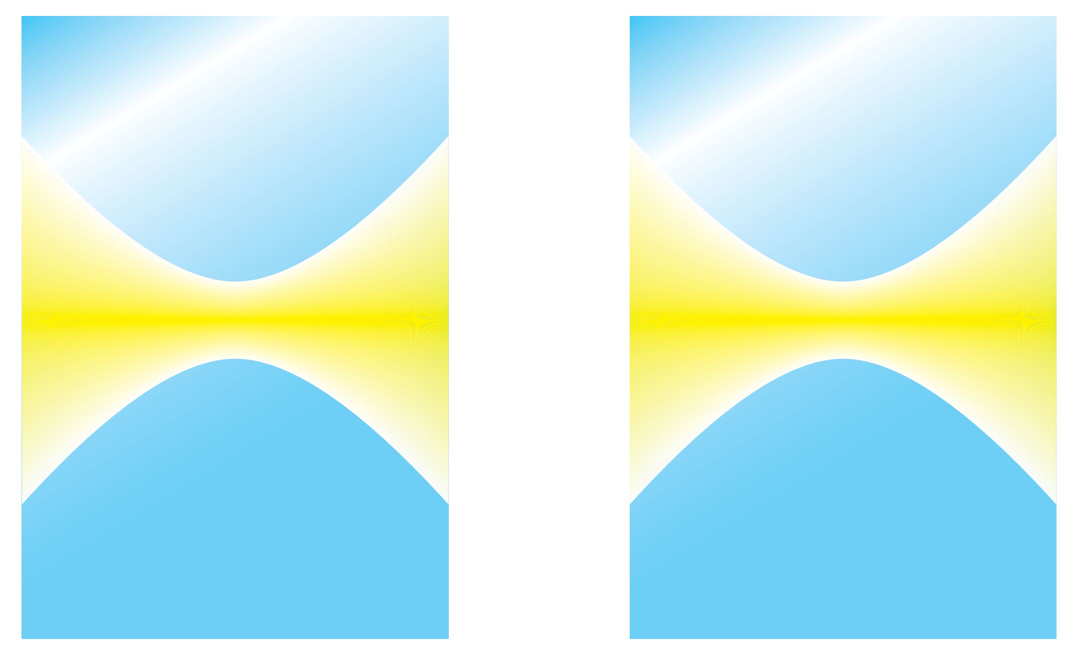


Introduction

photon energy < bandgap ⟶ nonlinear interaction

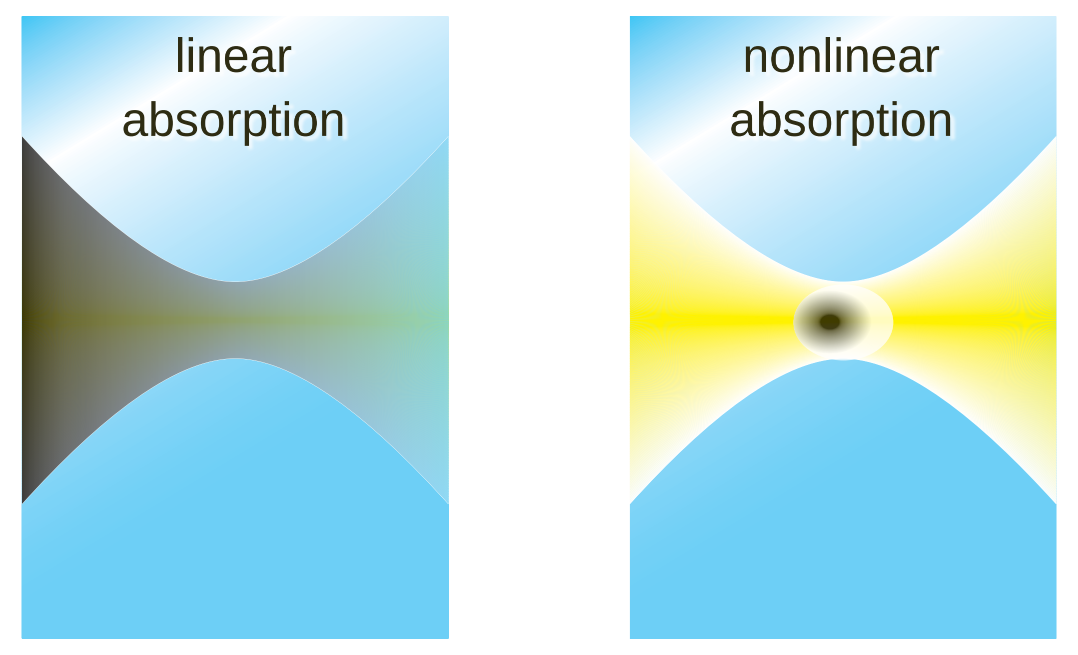
Introduction

nonlinear interaction provides bulk confinement



Introduction

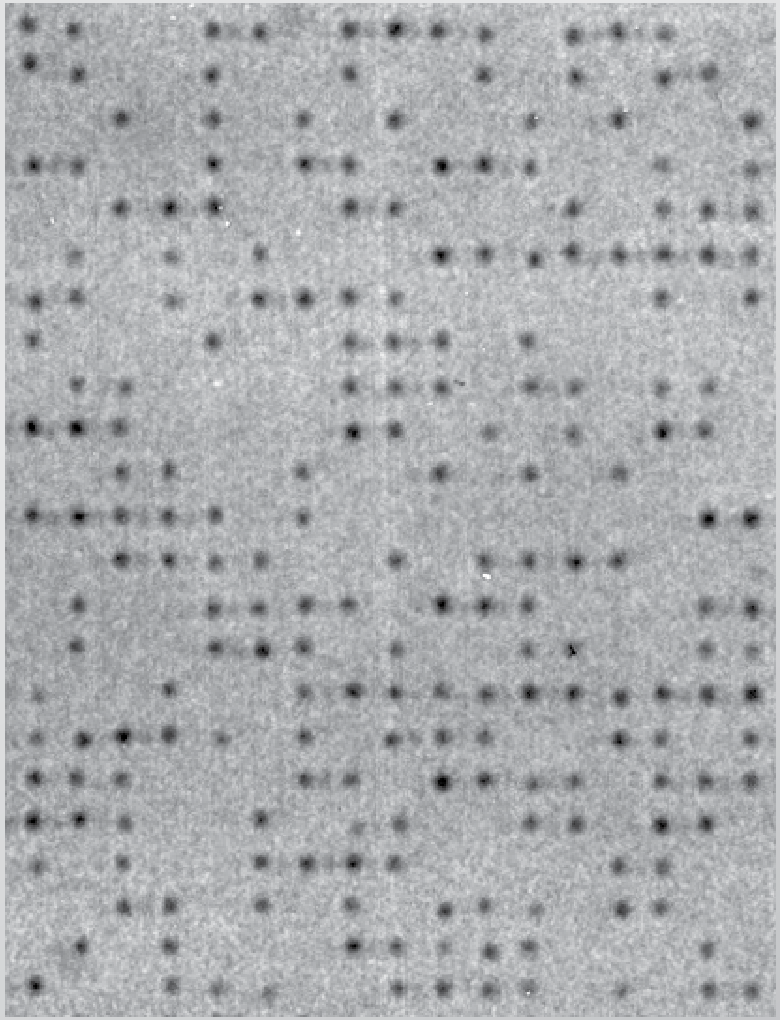
nonlinear interaction provides bulk confinement



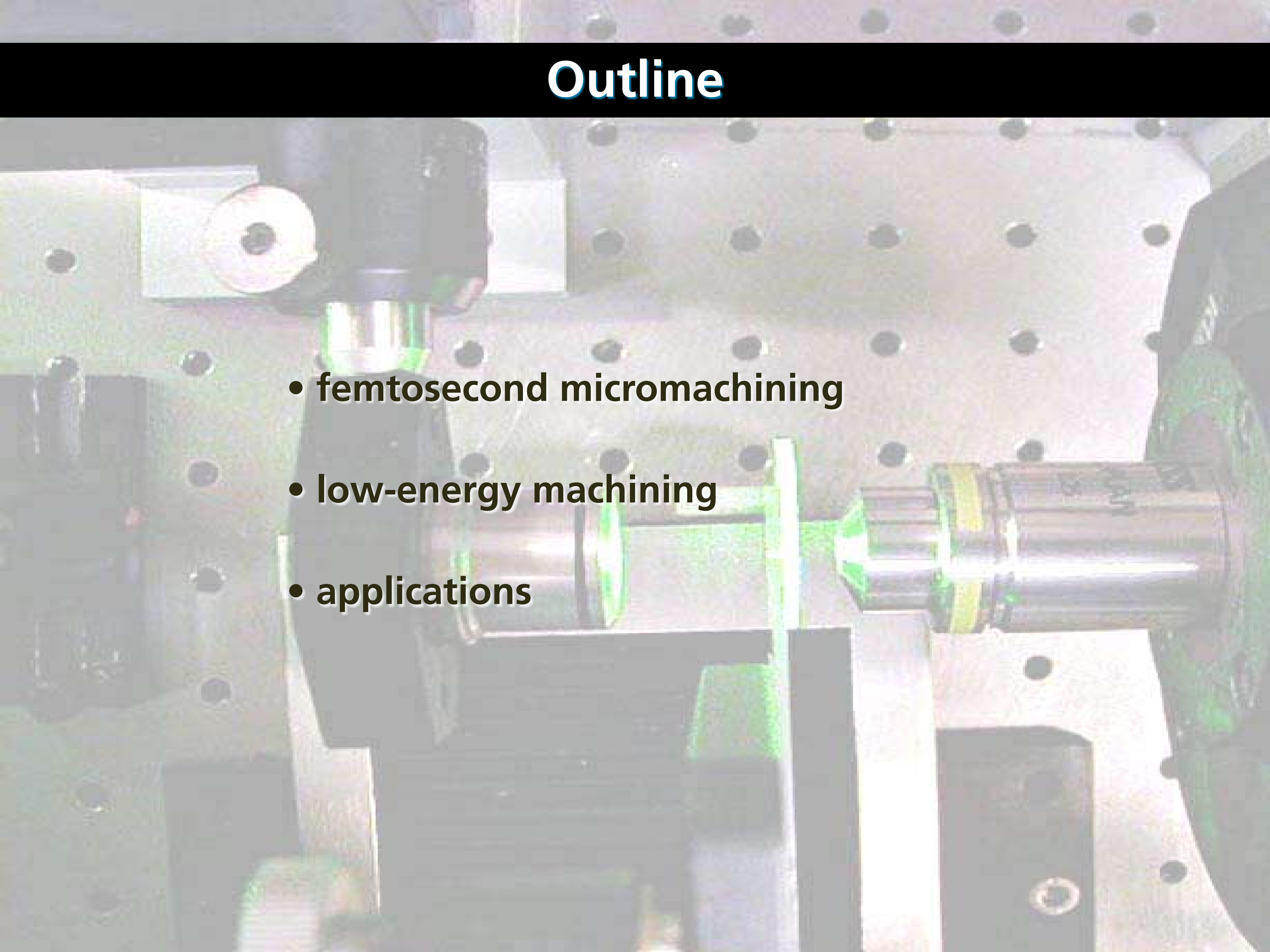
Femtosecond micromachining

Some applications:

- data storage
- waveguides
- microfluidics



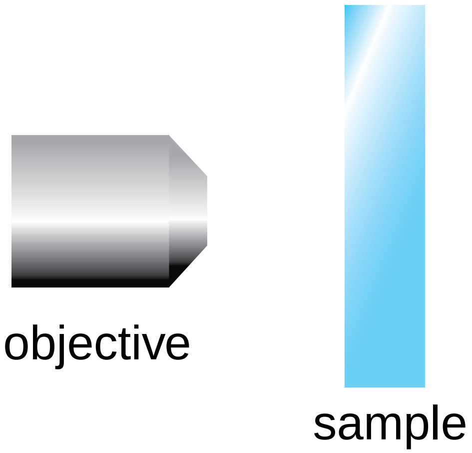
Outline



- femtosecond micromachining
- low-energy machining
- applications

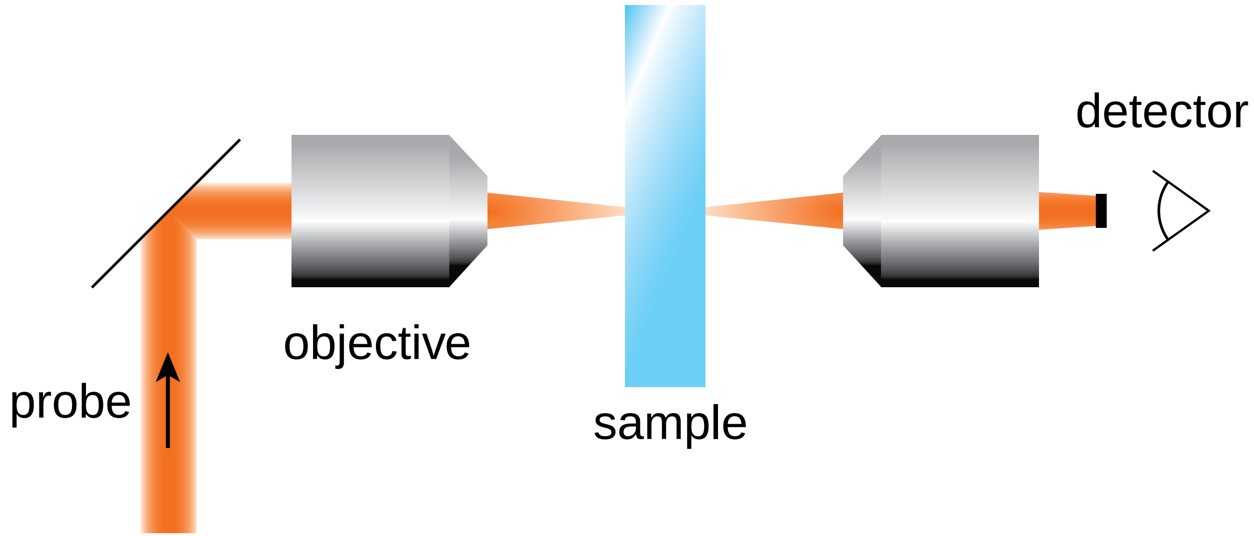
Femtosecond micromachining

Dark-field scattering



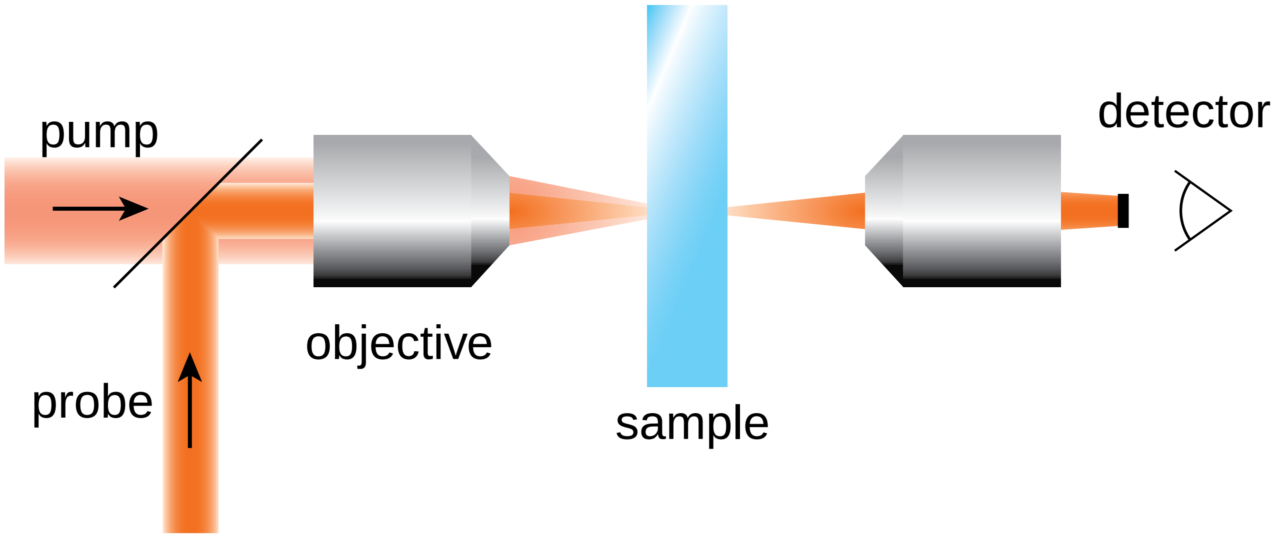
Femtosecond micromachining

block probe beam…



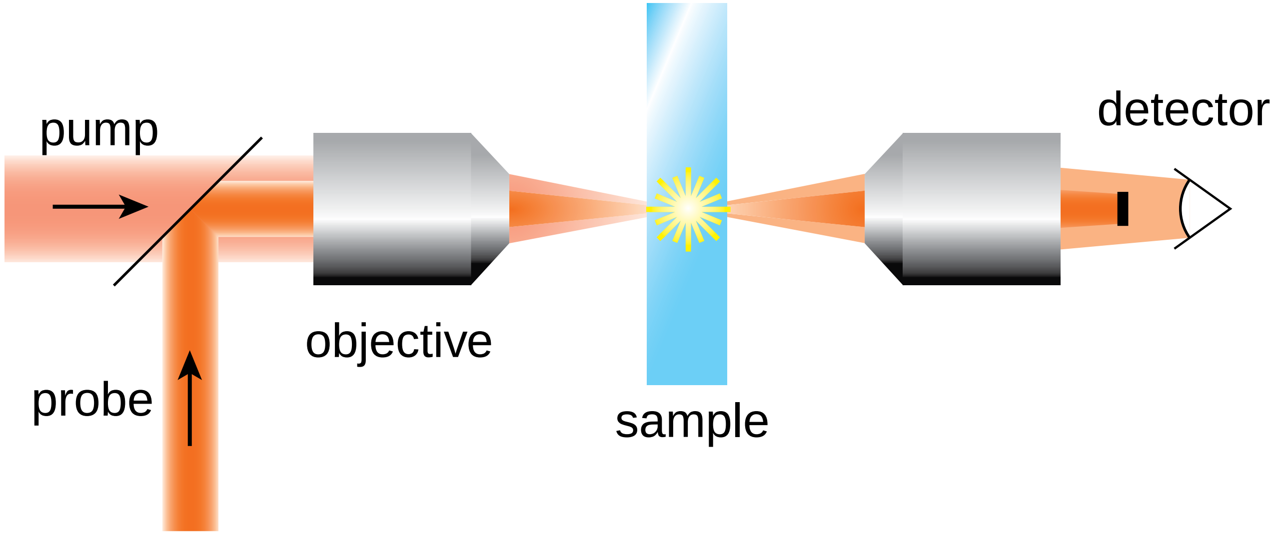
Femtosecond micromachining

… bring in pump beam…



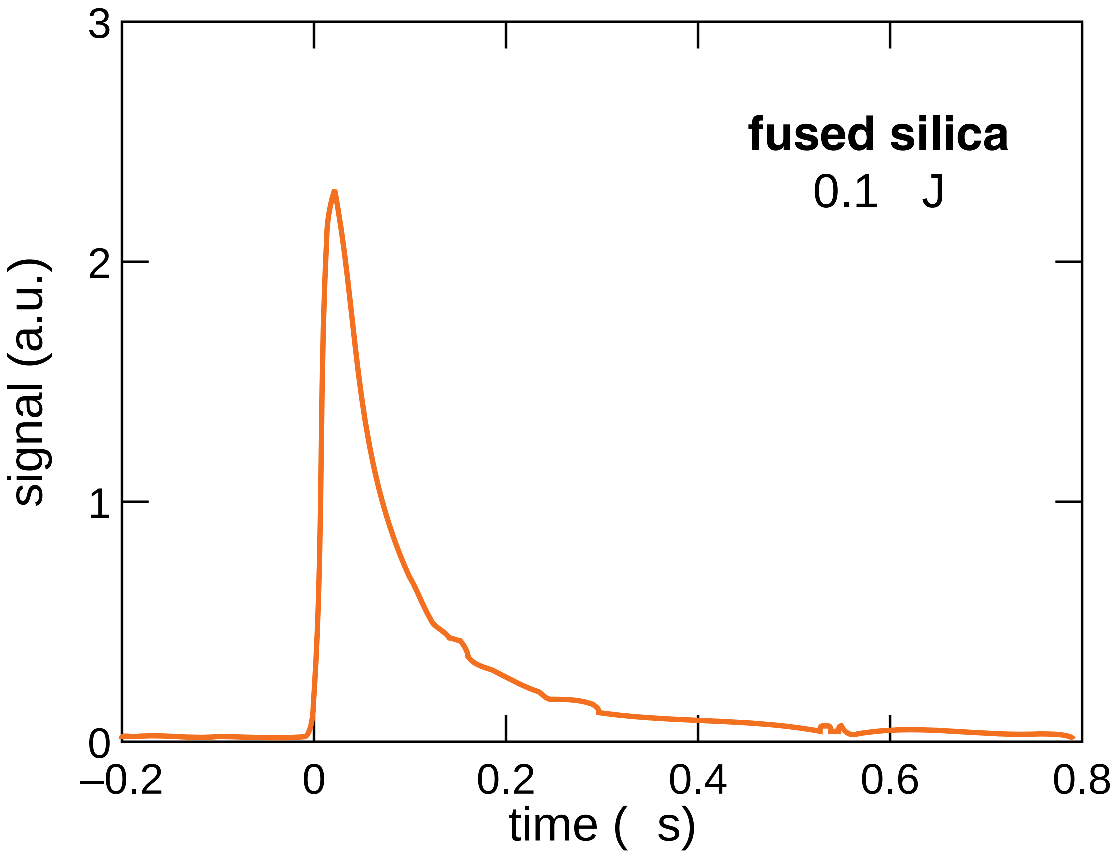
Femtosecond micromachining

… damage scatters probe beam



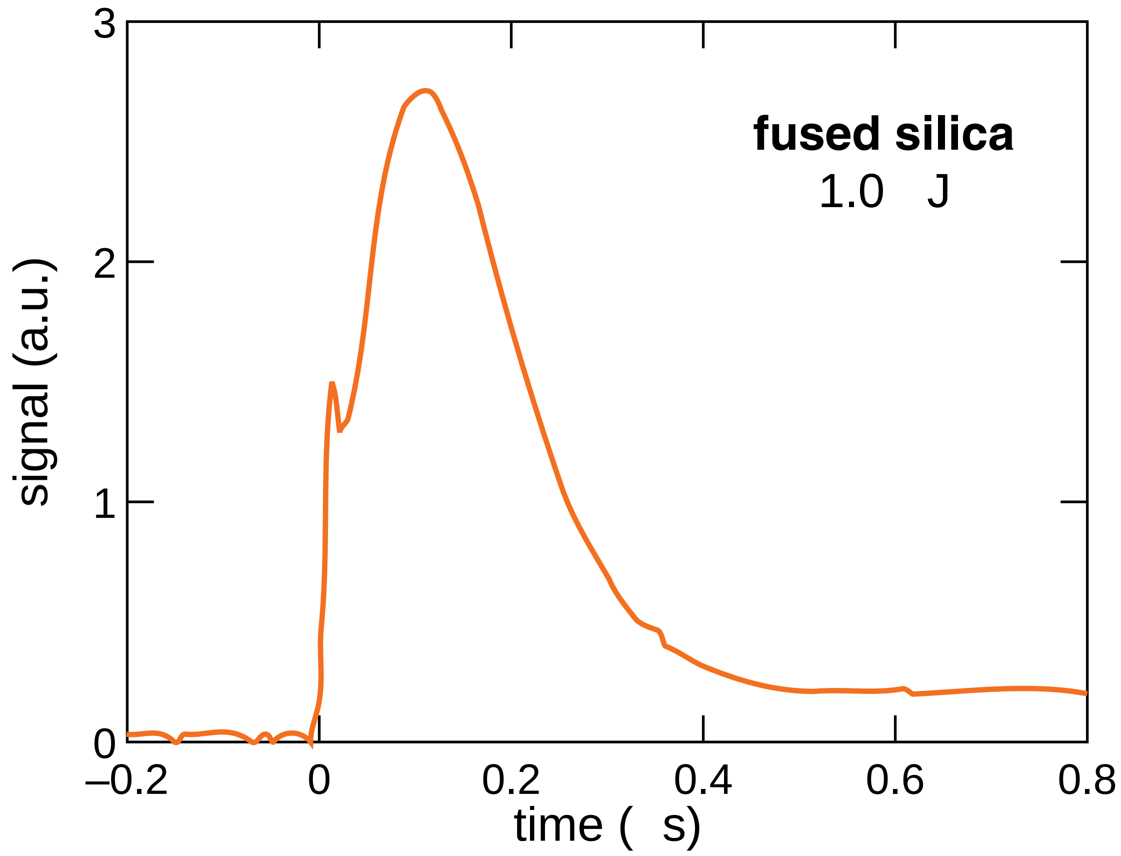
Femtosecond micromachining

scattered signal



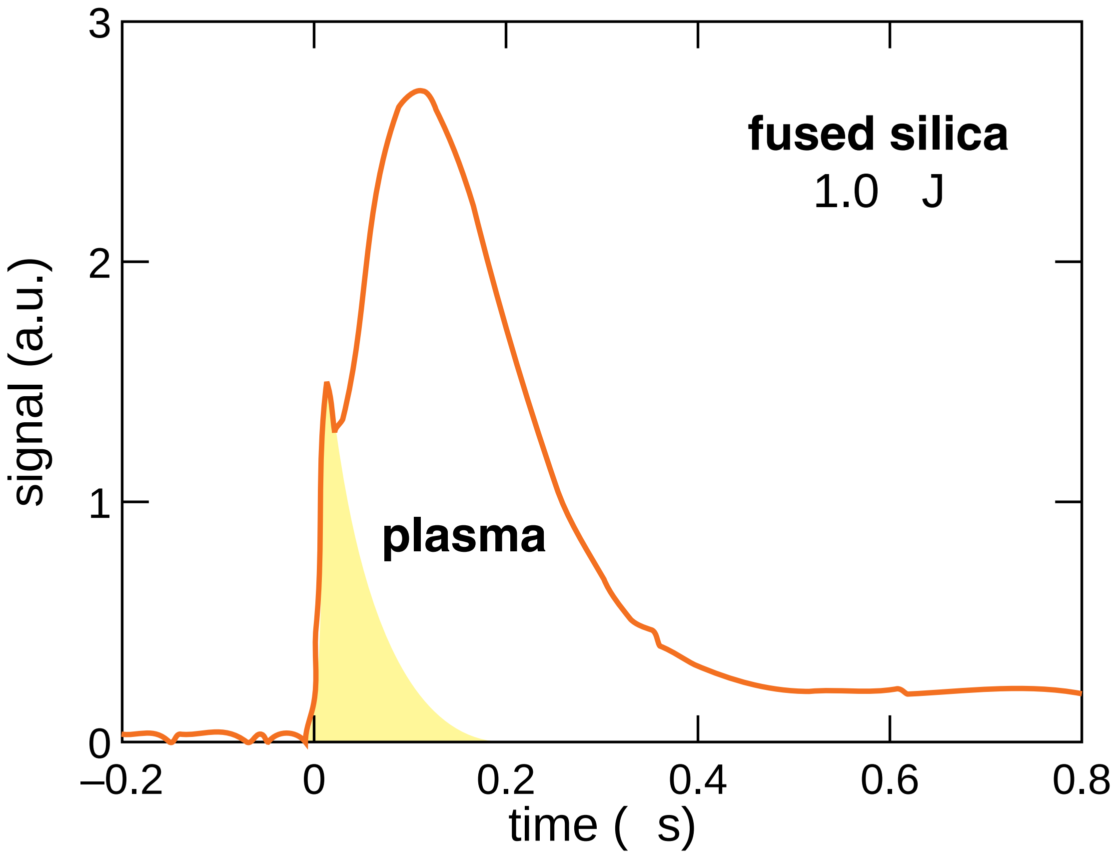
Femtosecond micromachining

scattered signal



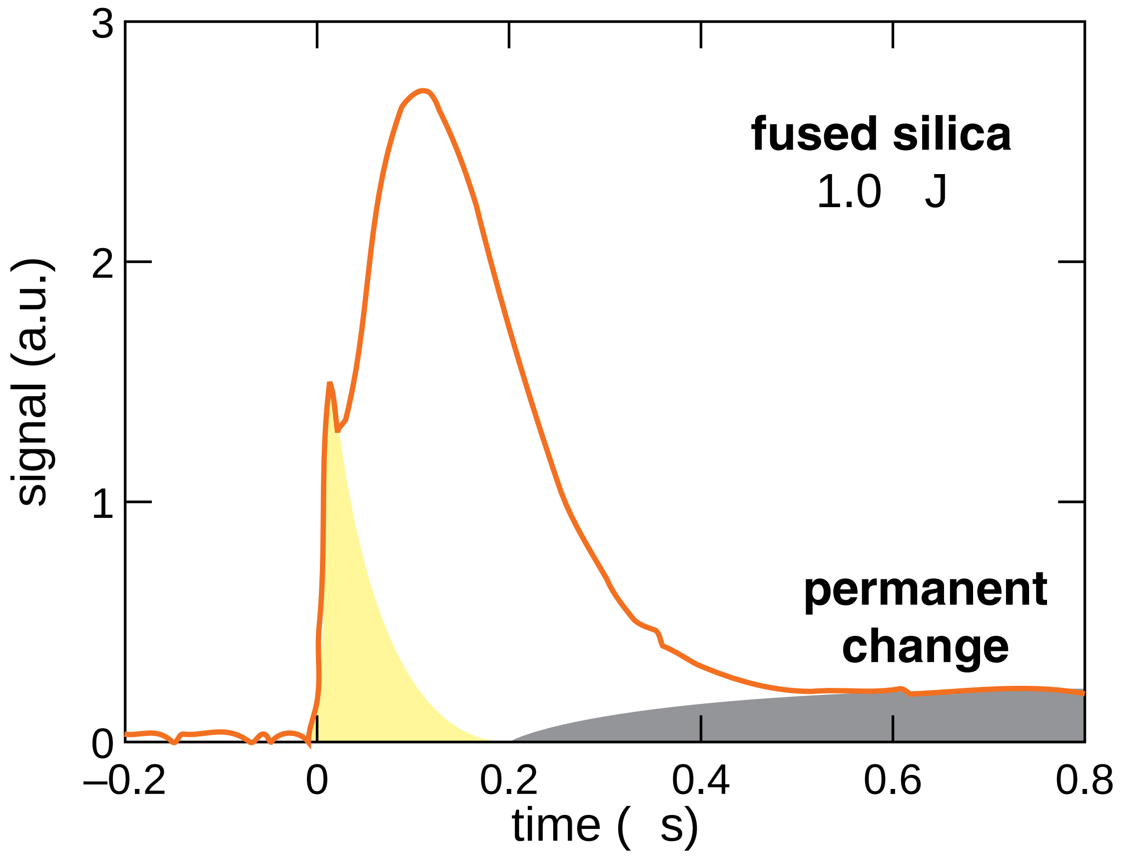
Femtosecond micromachining

scattered signal



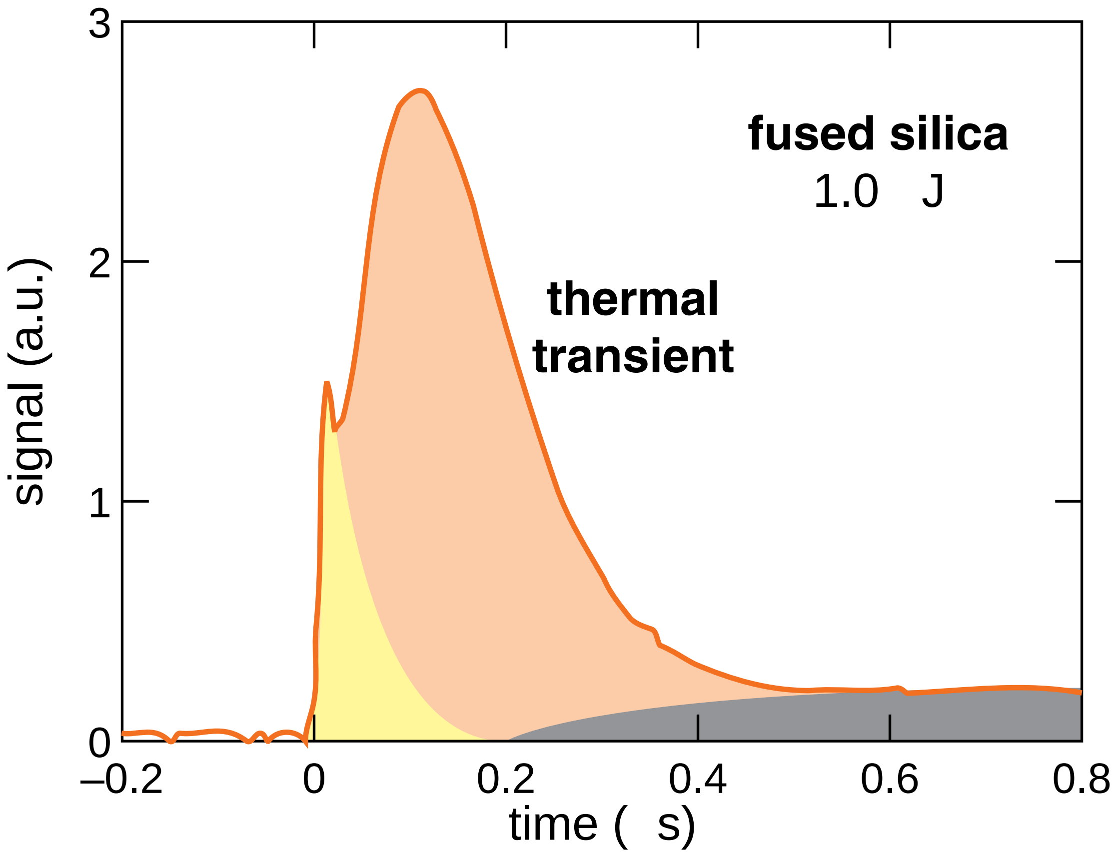
Femtosecond micromachining

scattered signal



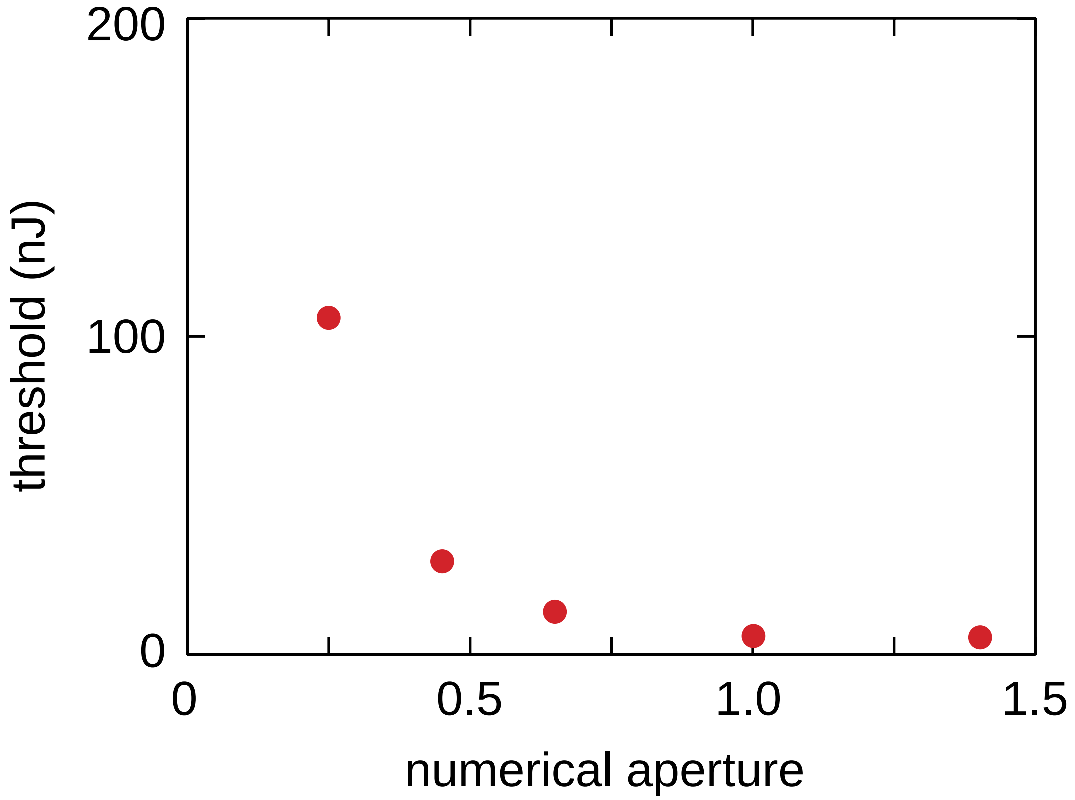
Femtosecond micromachining

scattered signal



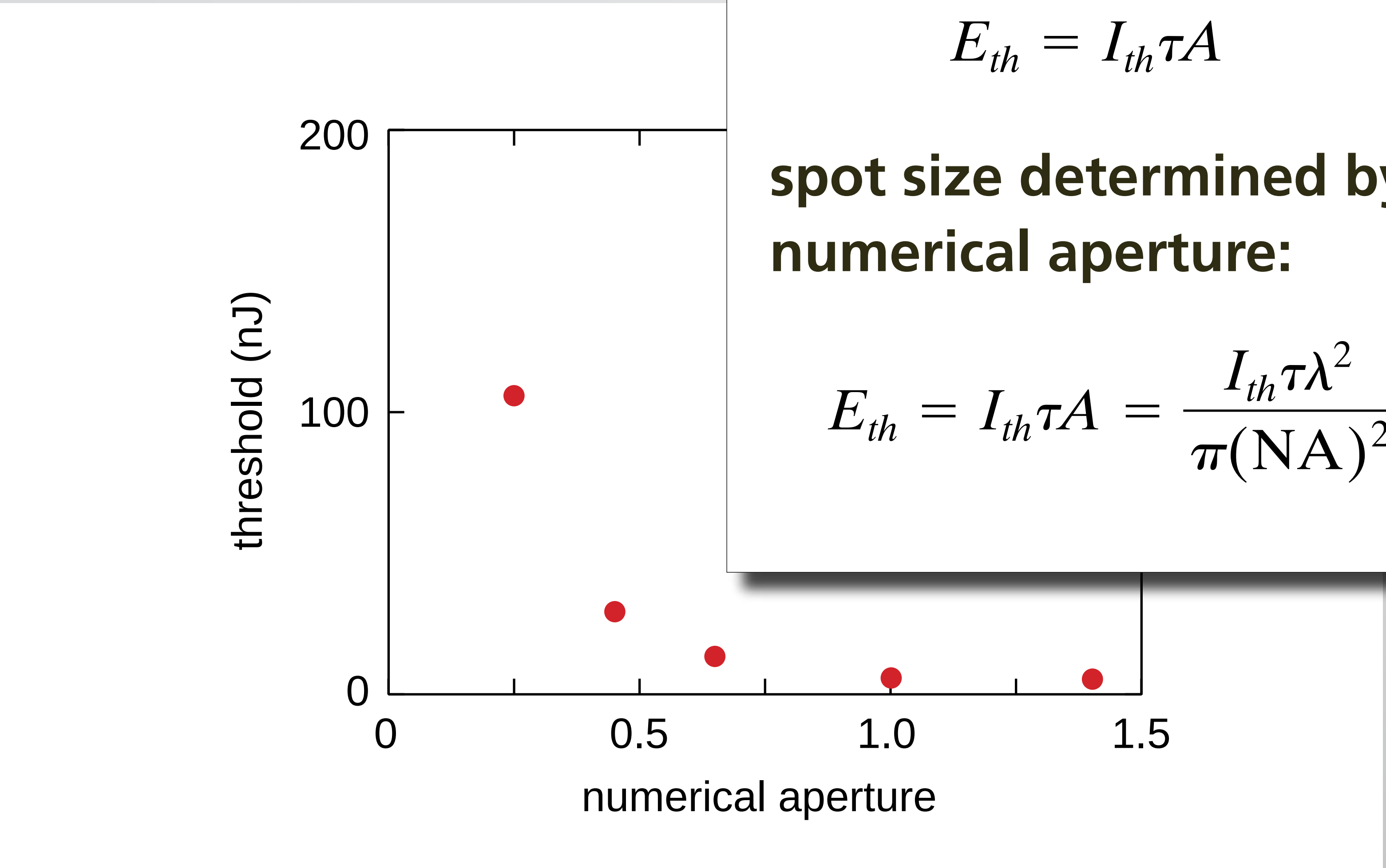
Femtosecond micromachining

vary numerical aperture



Femtosecond micromachining

vary numeric



intensity threshold:

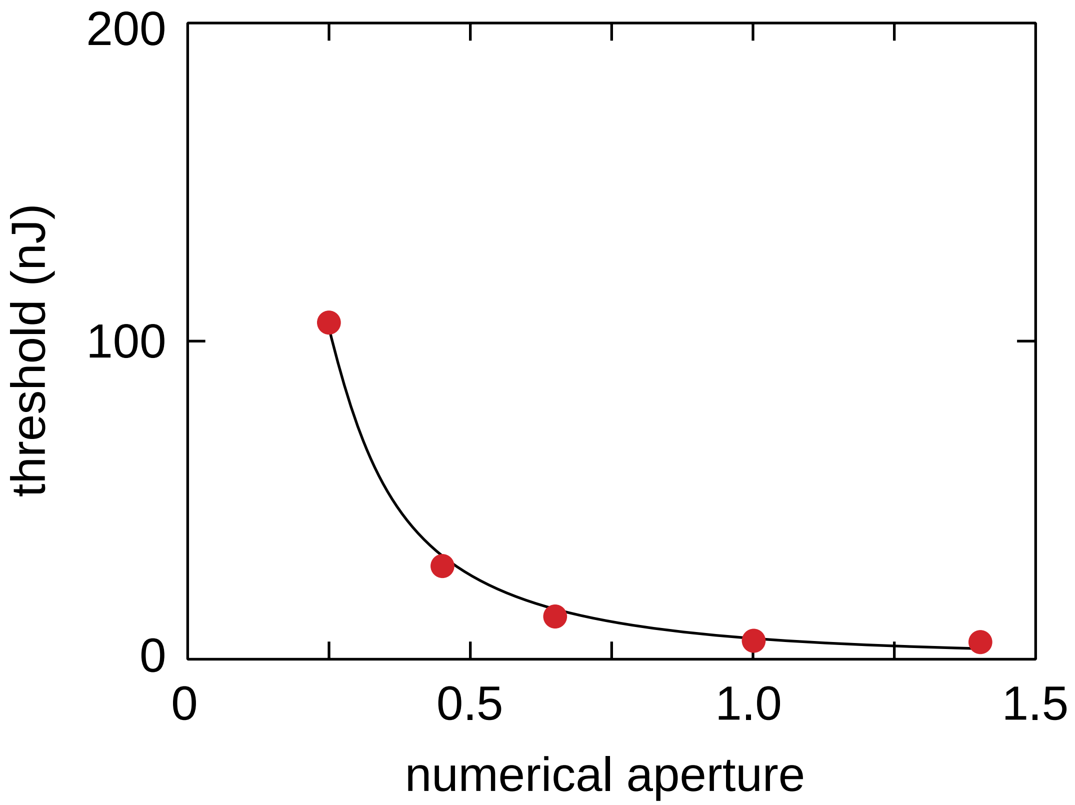
$$E_{th} = I_{th}\tau A$$

spot size determined by numerical aperture:

$$E_{th} = I_{th}\tau A = \frac{I_{th}\tau\lambda^2}{\pi(\mathrm{NA})^2}$$

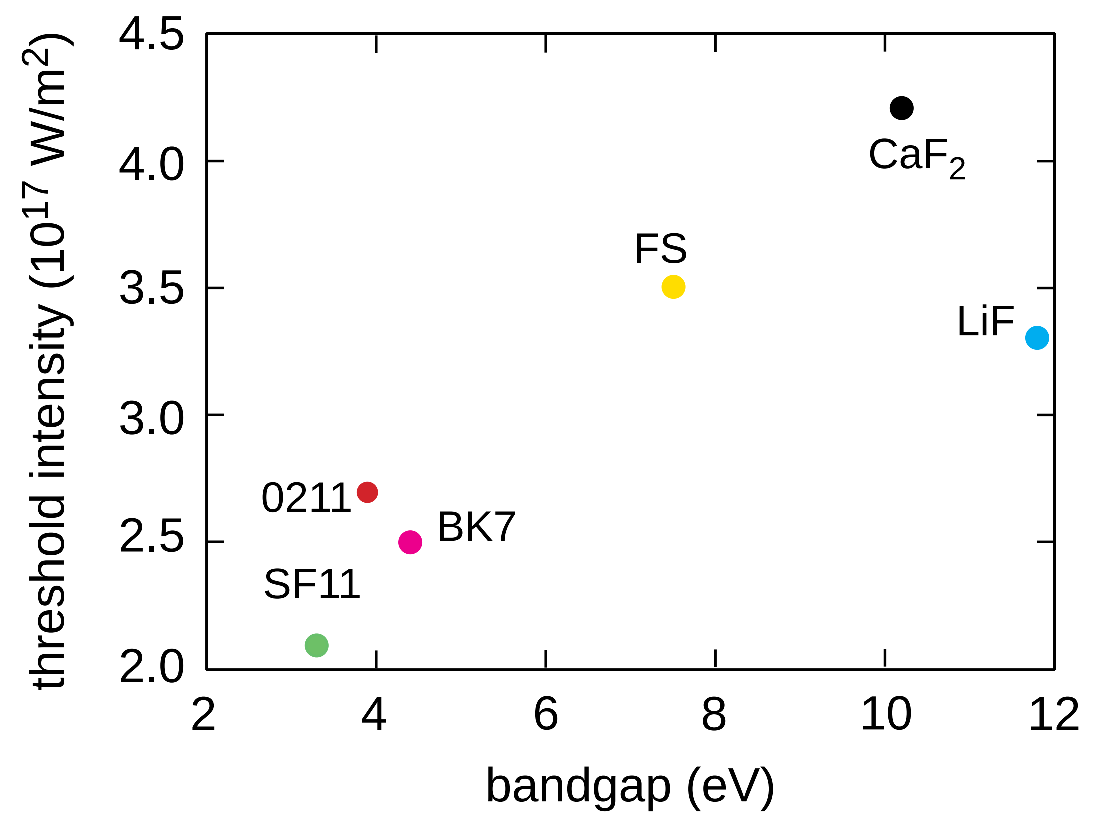
Femtosecond micromachining

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



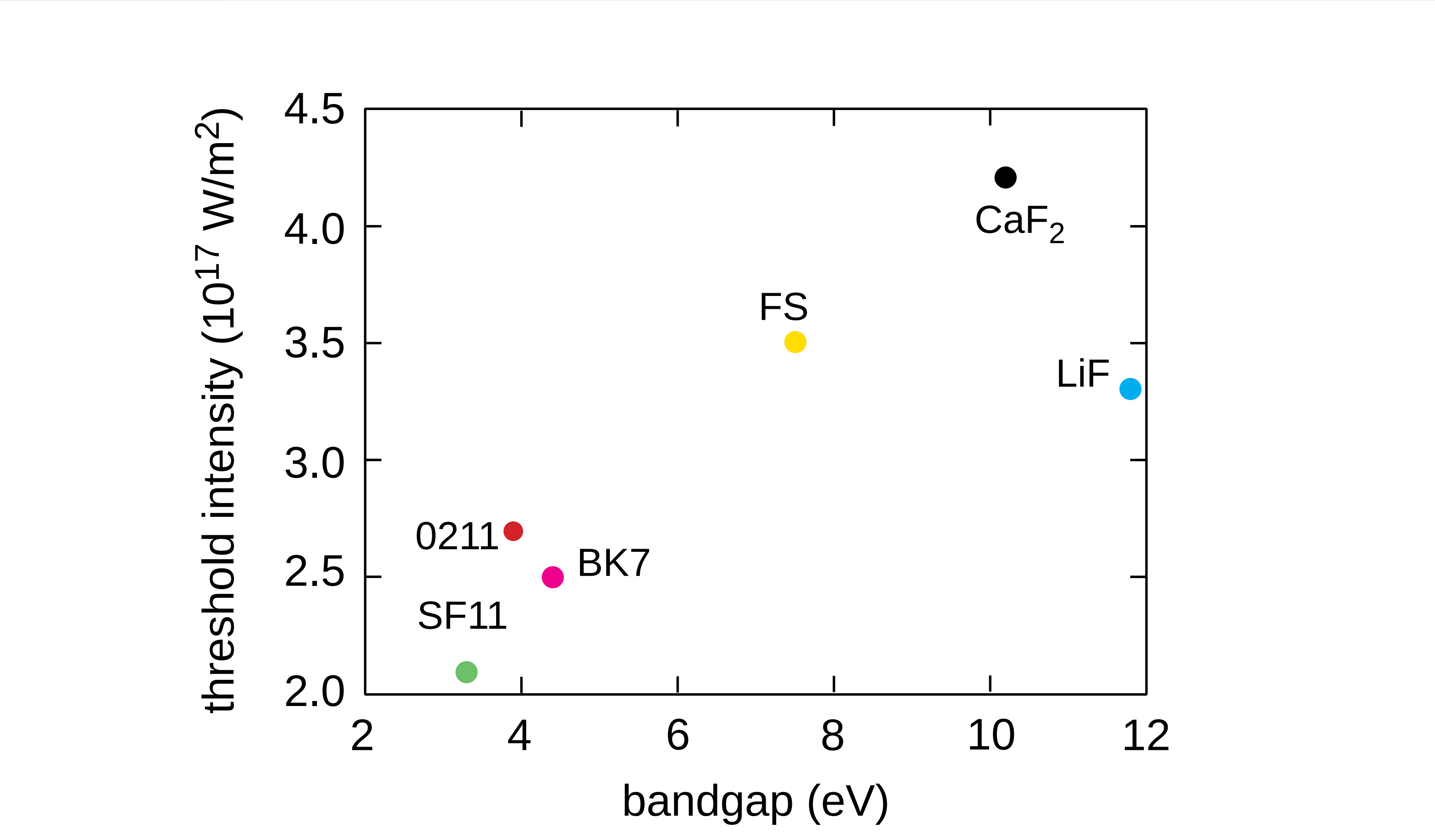
Femtosecond micromachining

vary material…



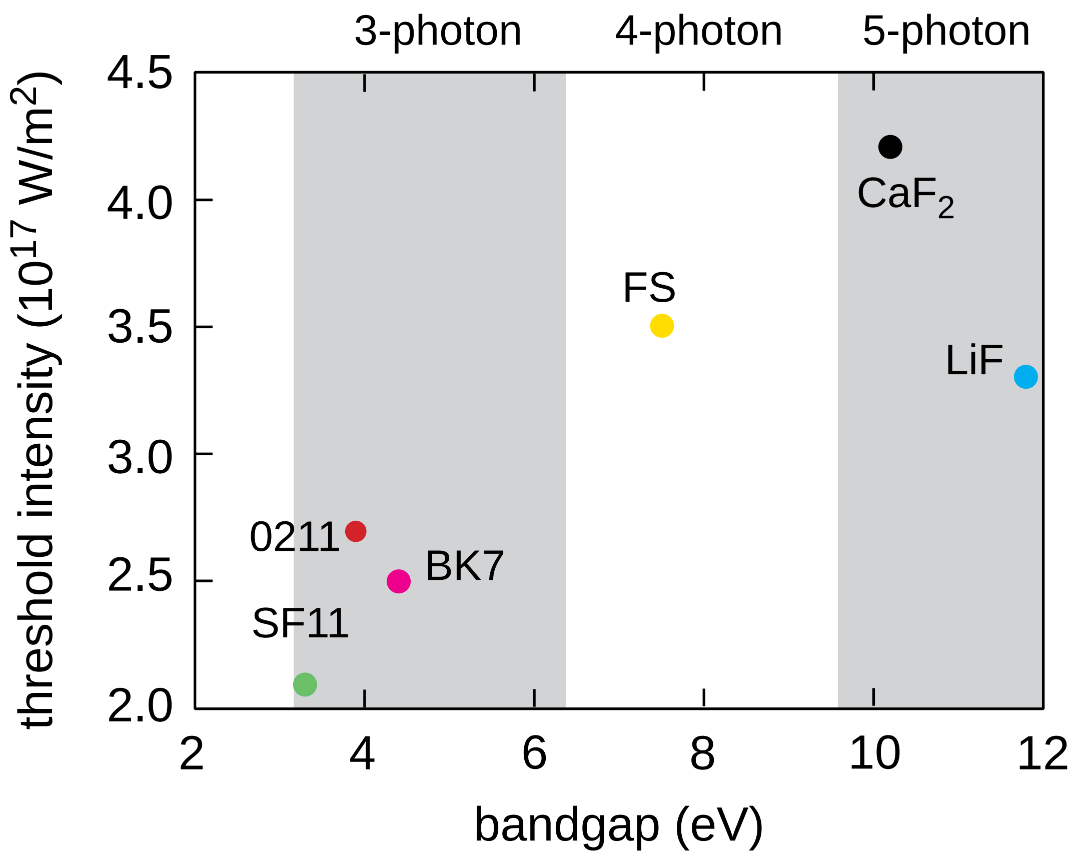
Femtosecond micromachining

…threshold varies with band gap (but not much!)



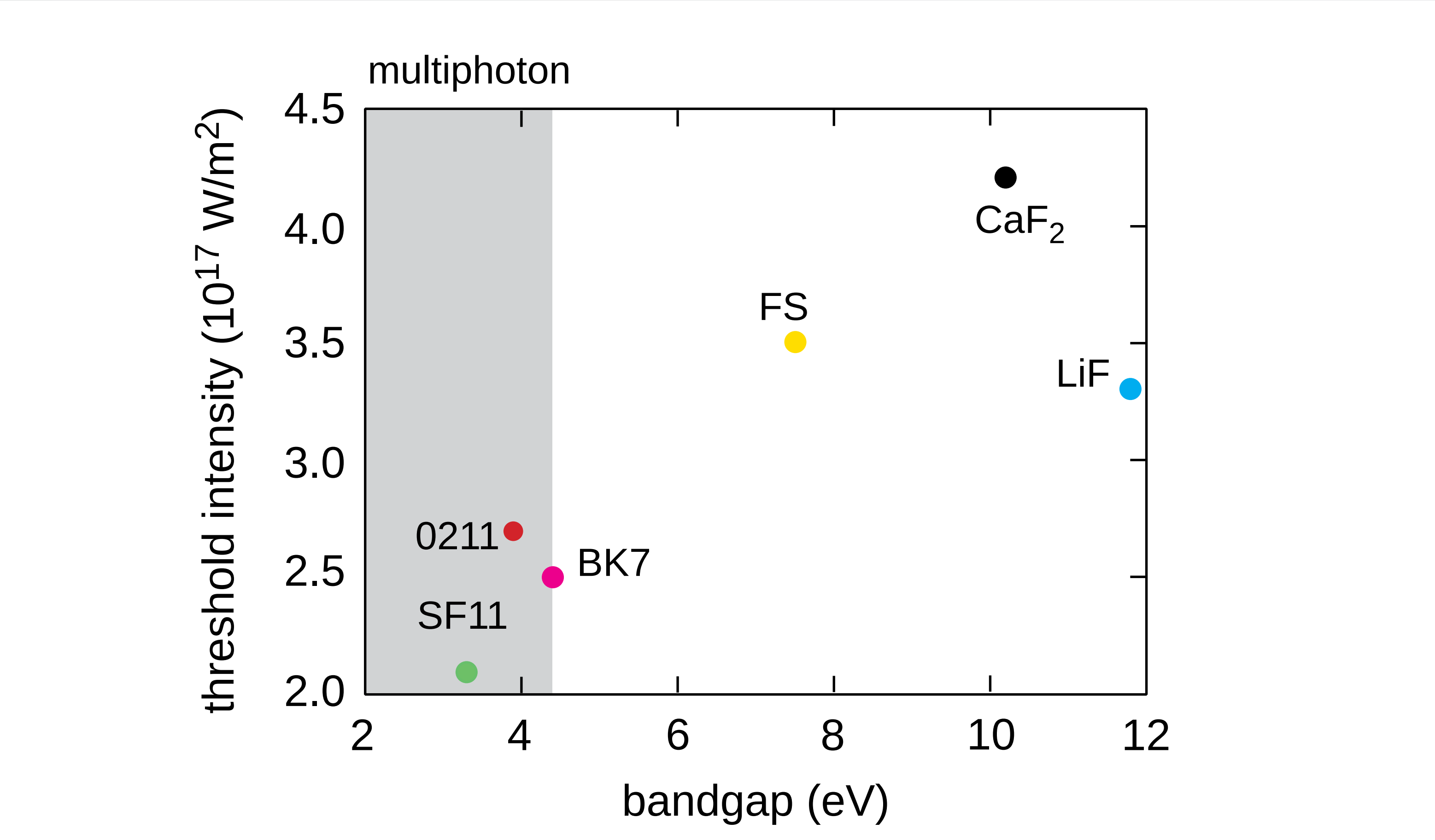
Femtosecond micromachining

would expect much more than a factor of 2



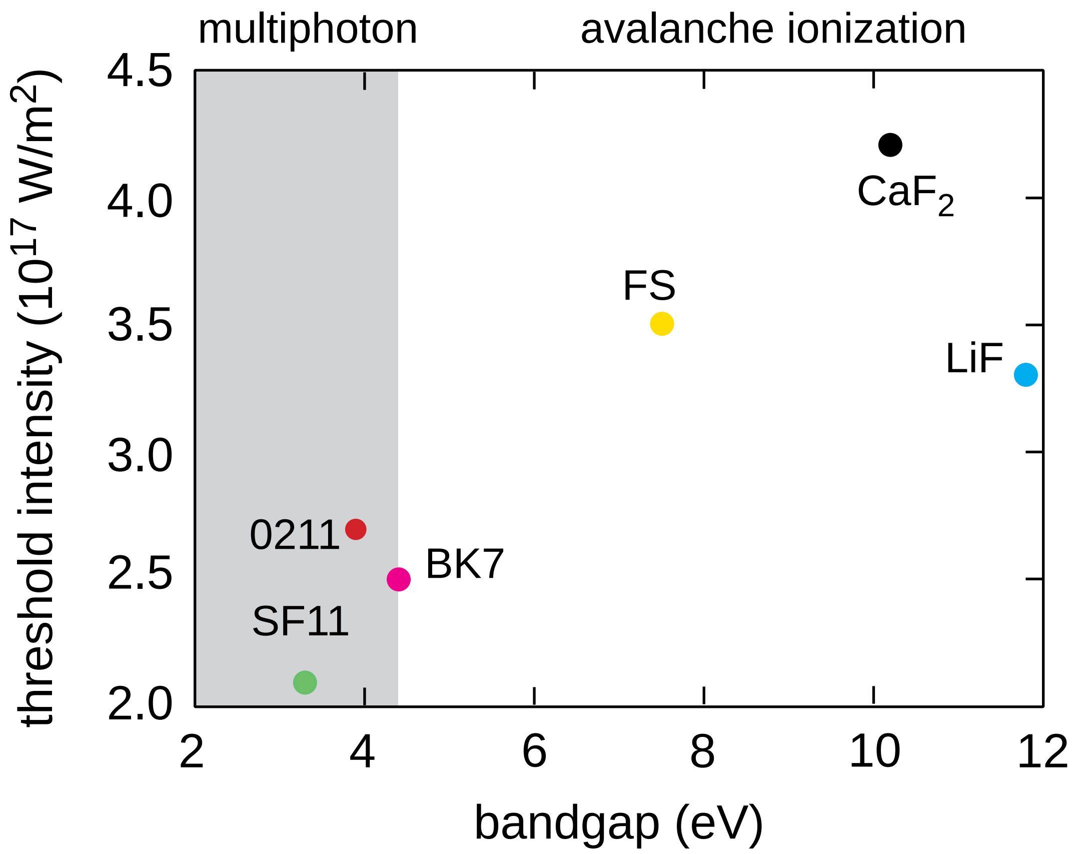
Femtosecond micromachining

critical density reached by multiphoton for low gap only



Femtosecond micromachining

avalanche ionization important at high gap



Femtosecond micromachining

what prevents damage at low NA?

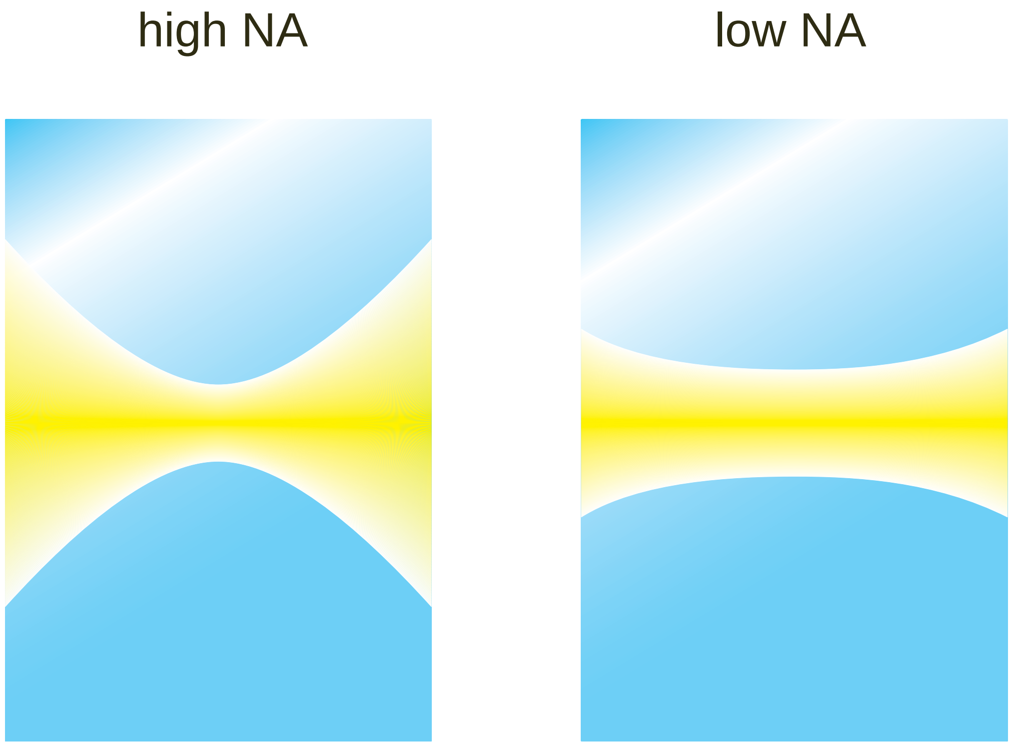
Femtosecond micromachining

Competing nonlinear effects:

- multiphoton absorption
- supercontinuum generation
- self-focusing

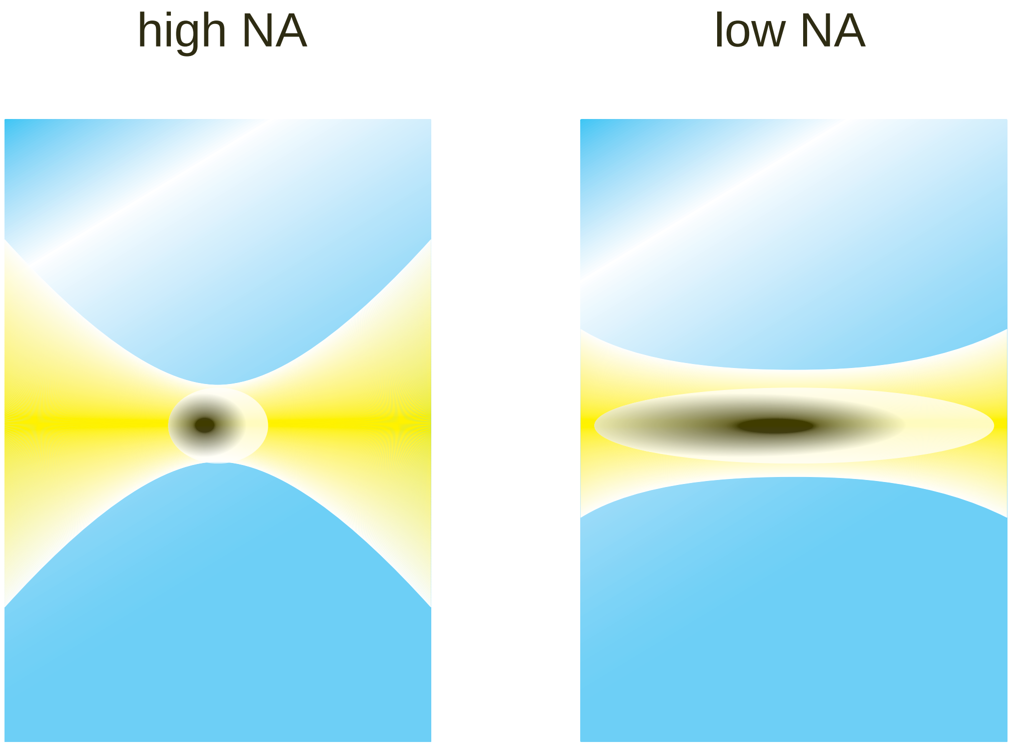
Femtosecond micromachining

why the difference?



Femtosecond micromachining

very different confocal length/interaction length

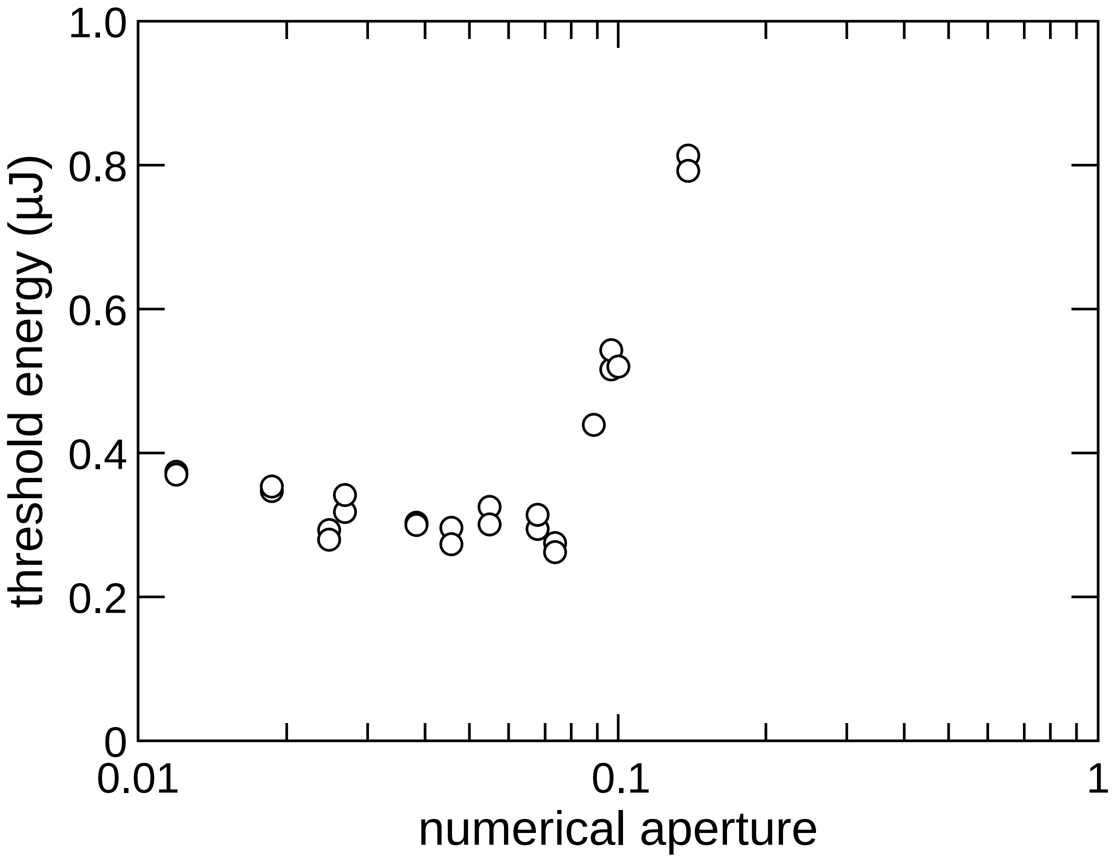


Femtosecond micromachining

high NA: interaction length too short for self-focusing

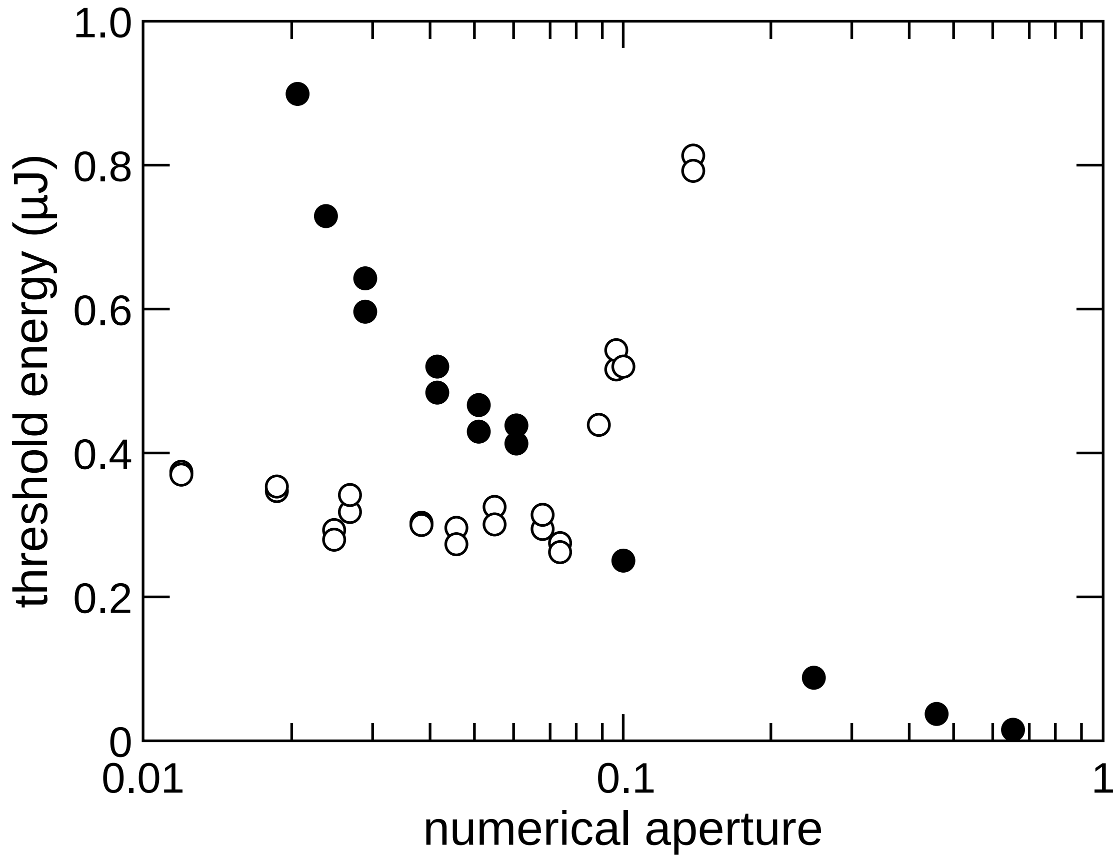
Femtosecond micromachining

threshold for supercontinuum generation



Femtosecond micromachining

threshold for damage

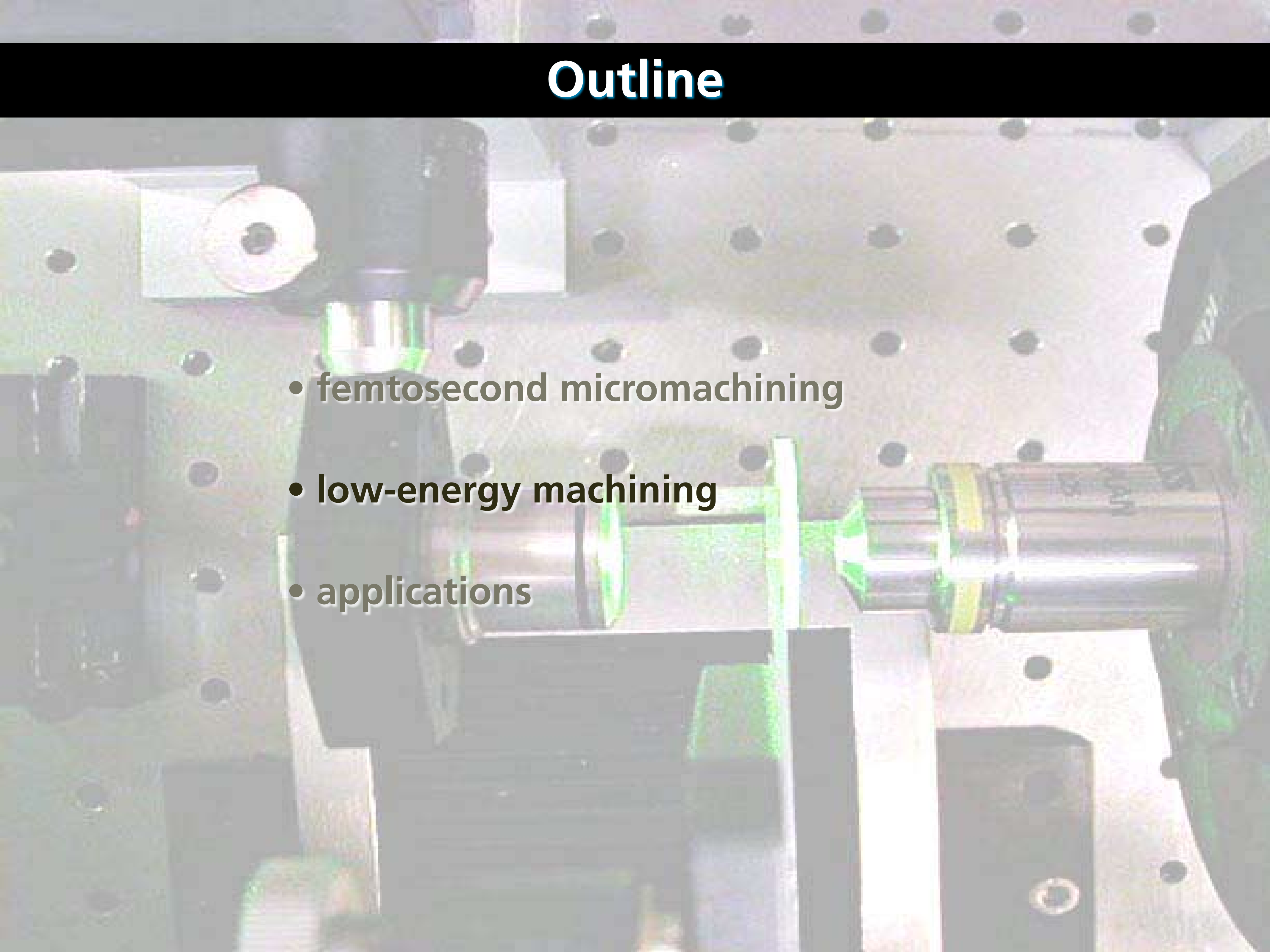


Femtosecond micromachining

Points to keep in mind:

- threshold critically dependent on NA
- surprisingly little material dependence
- avalanche ionization important

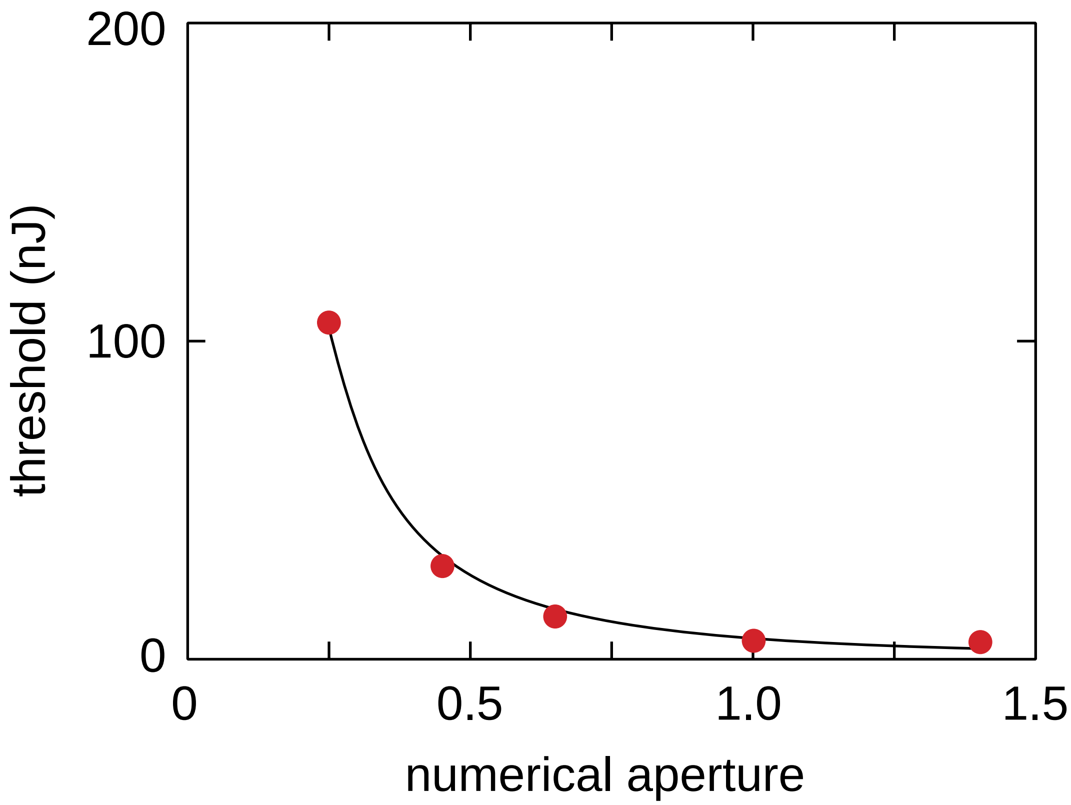
Outline



- femtosecond micromachining
- **low-energy machining**
- applications

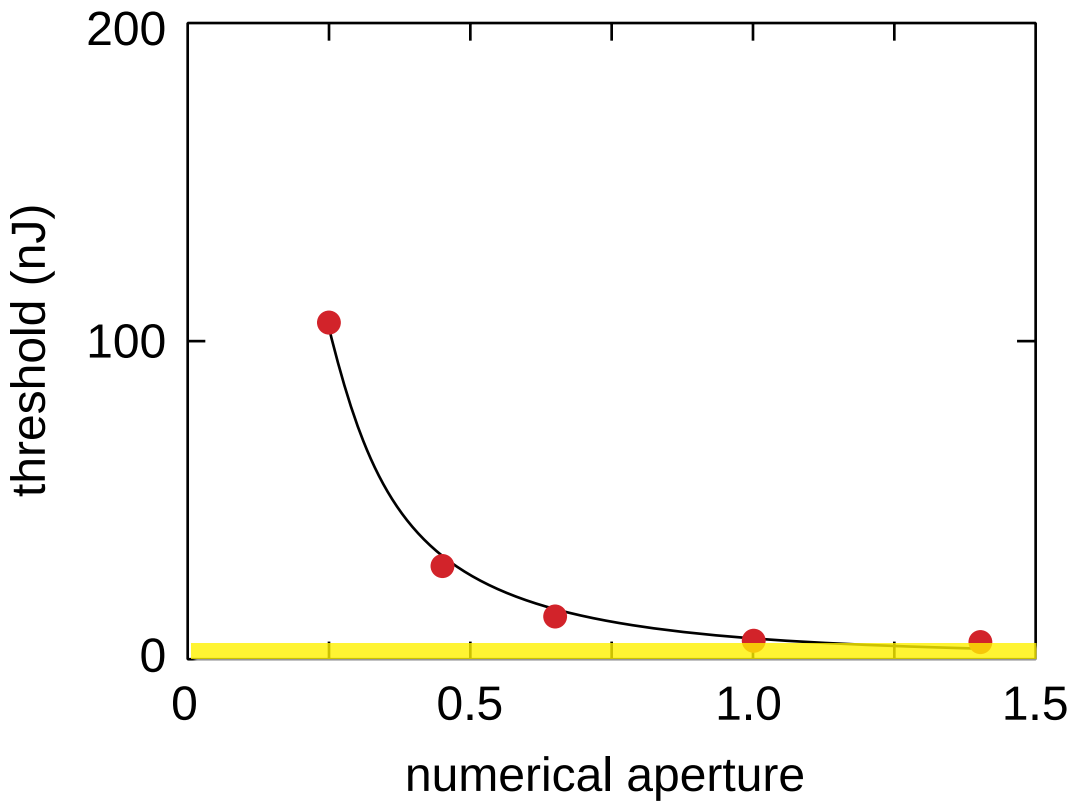
Low-energy machining

threshold decreases with increasing numerical aperture



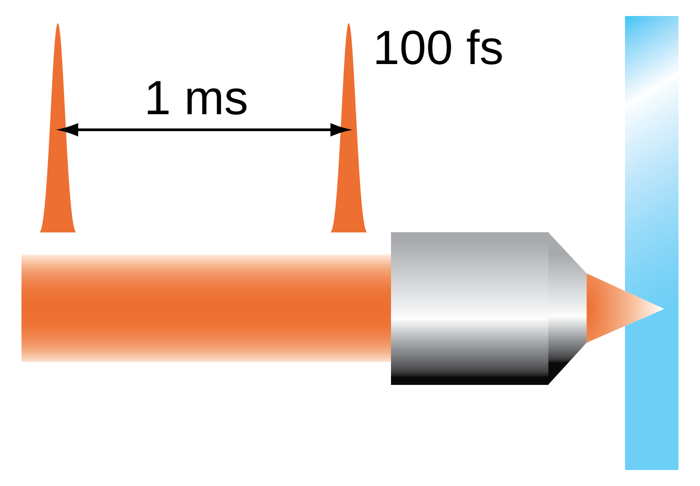
Low-energy machining

less than 10 nJ at high numerical aperture!



Low-energy machining

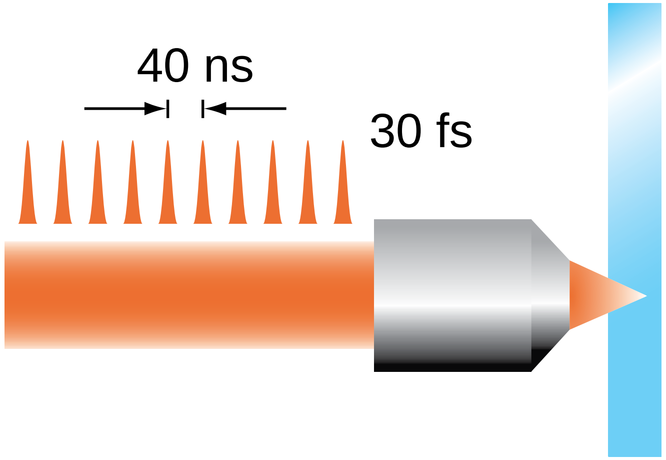
amplified laser: 1 kHz, 1 mJ



heat diffusion time: $\tau_{diff} \approx 1\ \mu s$

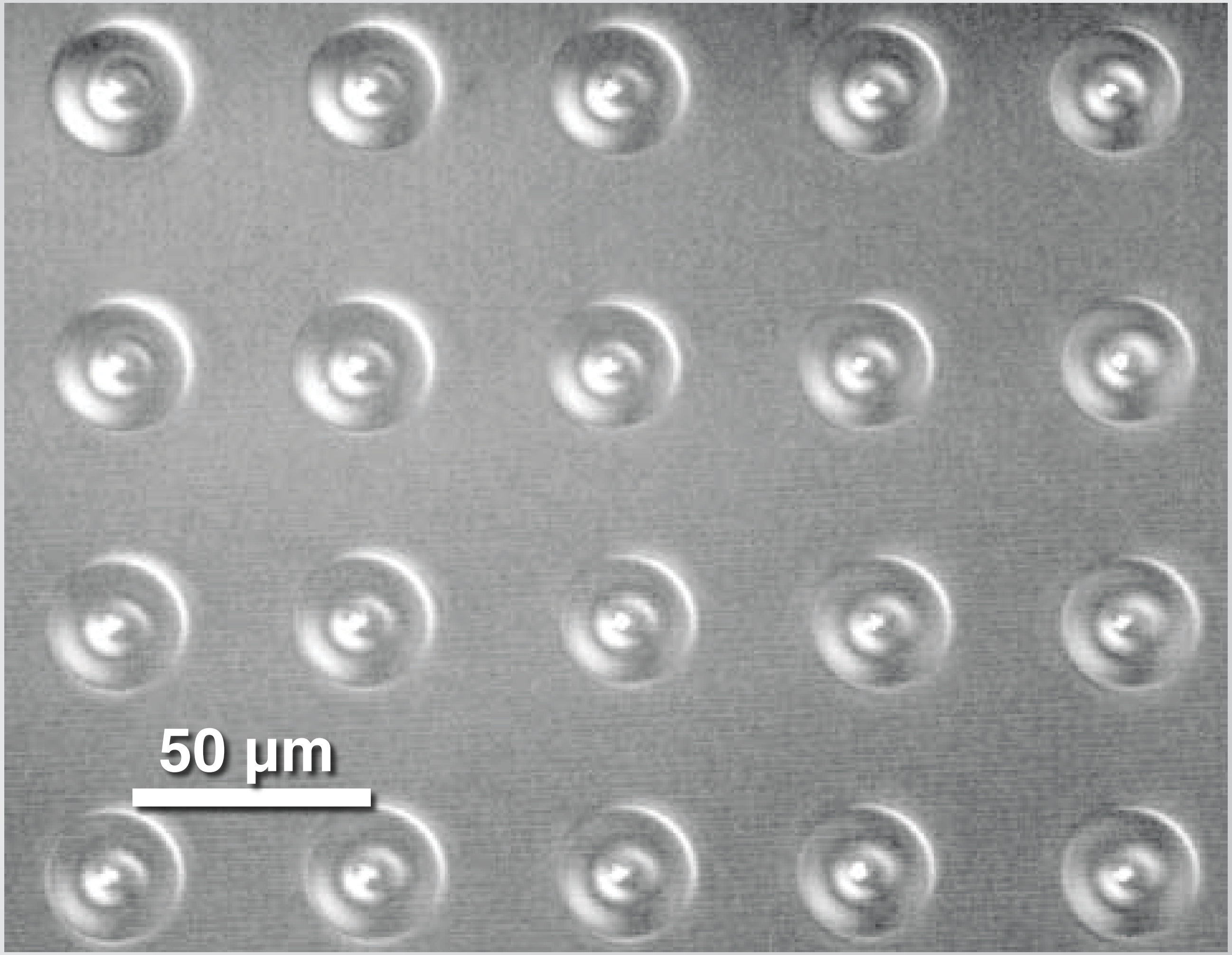
Low-energy machining

long cavity oscillator: 25 MHz, 25 nJ



heat diffusion time: $\tau_{diff} \approx 1\ \mu s$

Low-energy machining



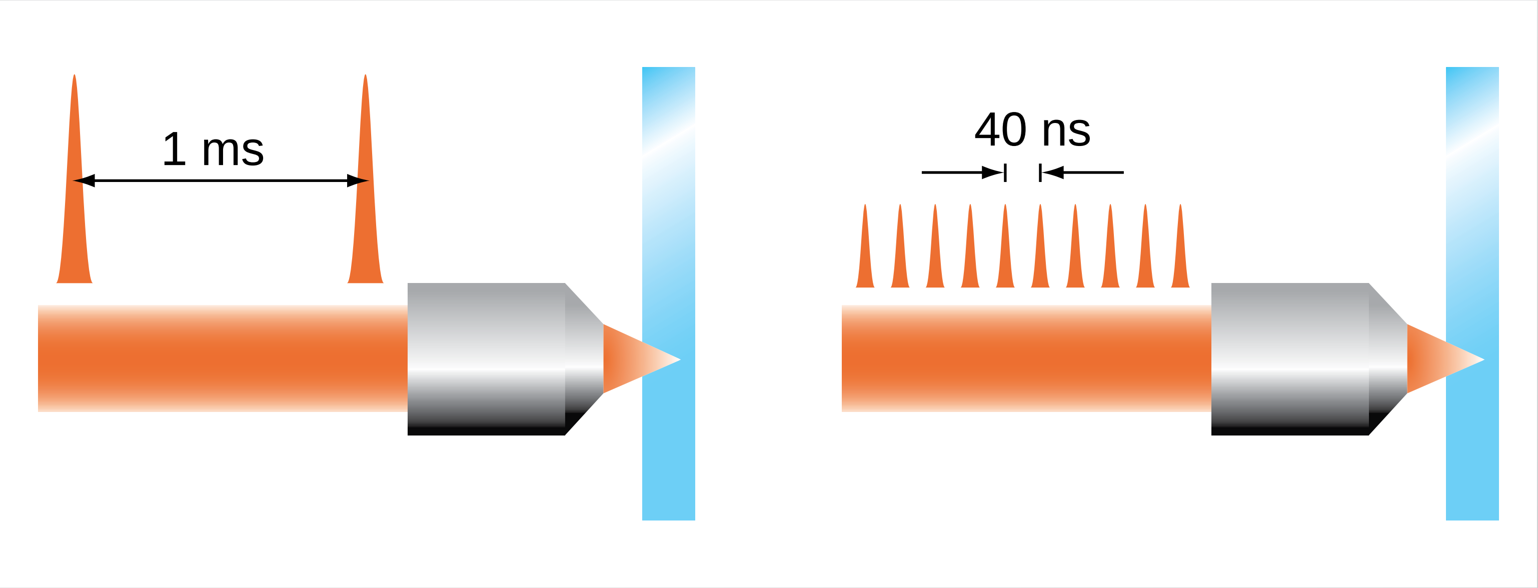
Low-energy machining

High repetition-rate micromachining:

- structural changes exceed focal volume
- spherical structures
- density change caused by melting

Low-energy machining

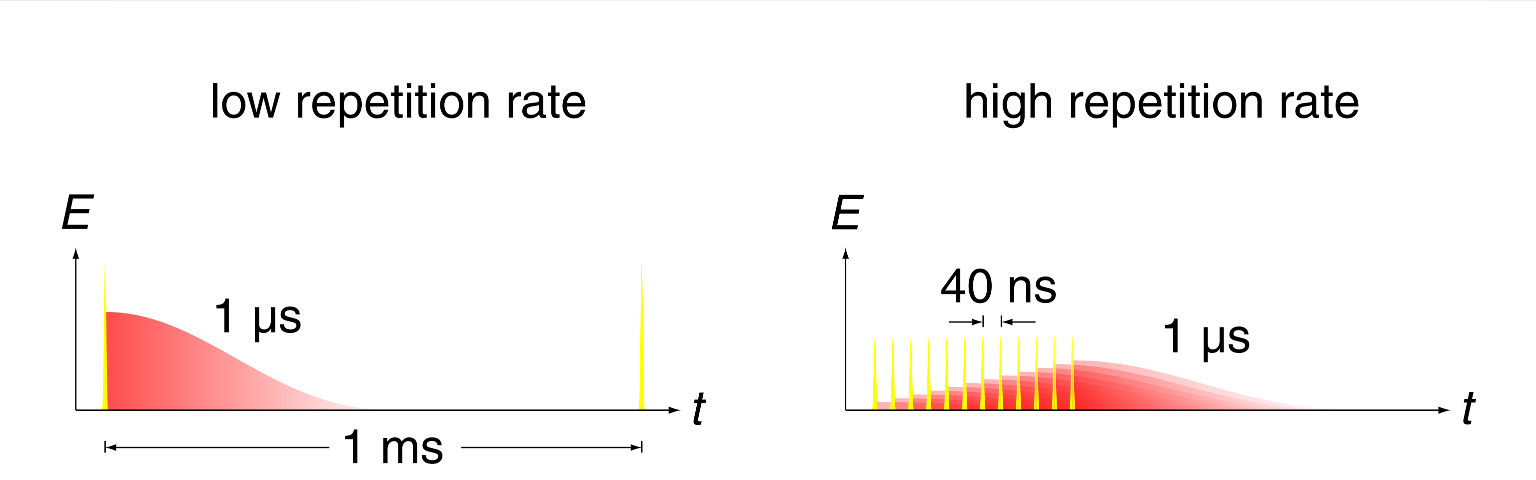
amplified laser **oscillator**



repetitive **cumulative**

Low-energy machining

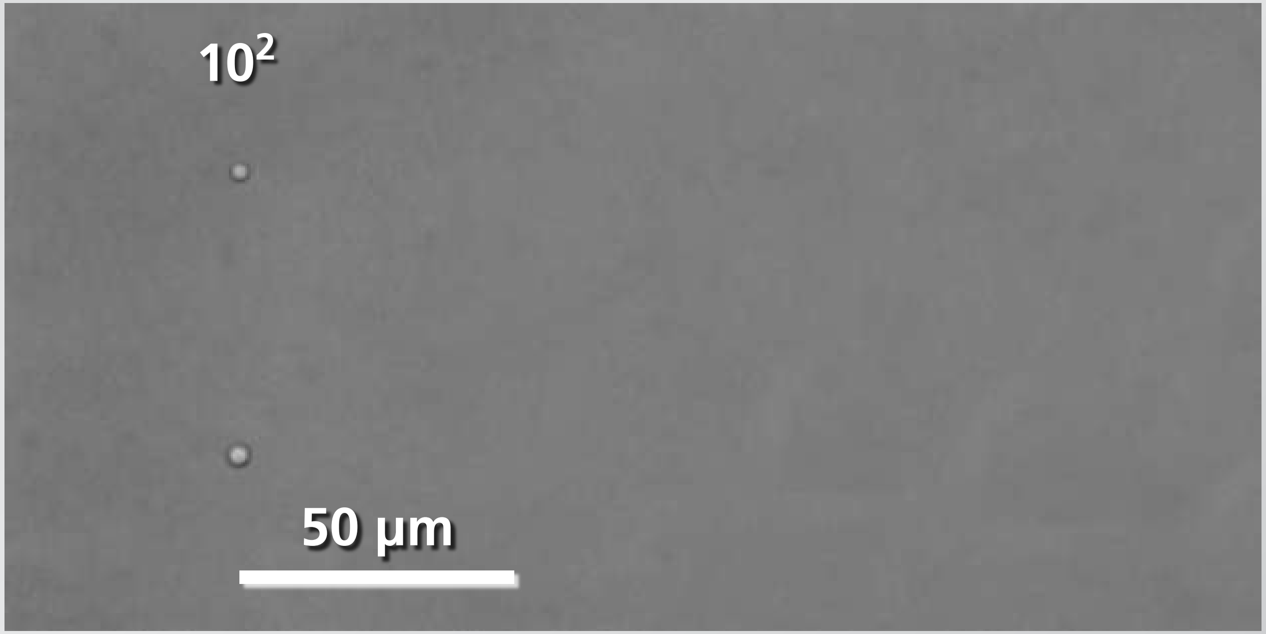
amplified laser **oscillator**



repetitive **cumulative**

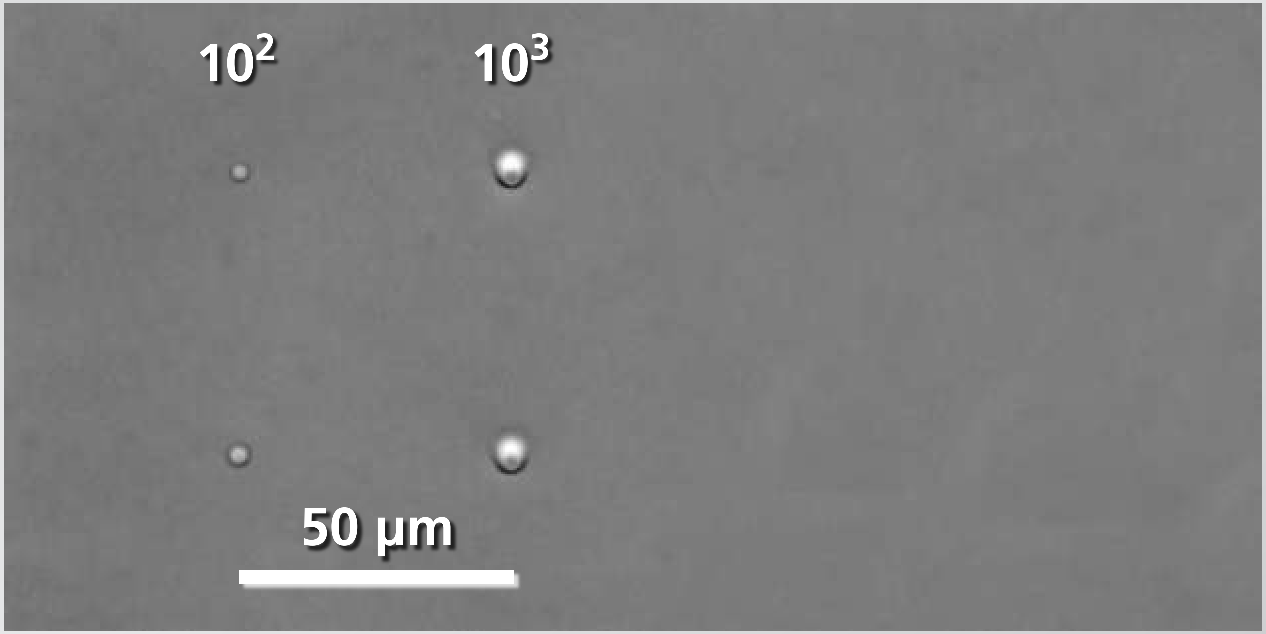
Low-energy machining

the longer the irradiation…



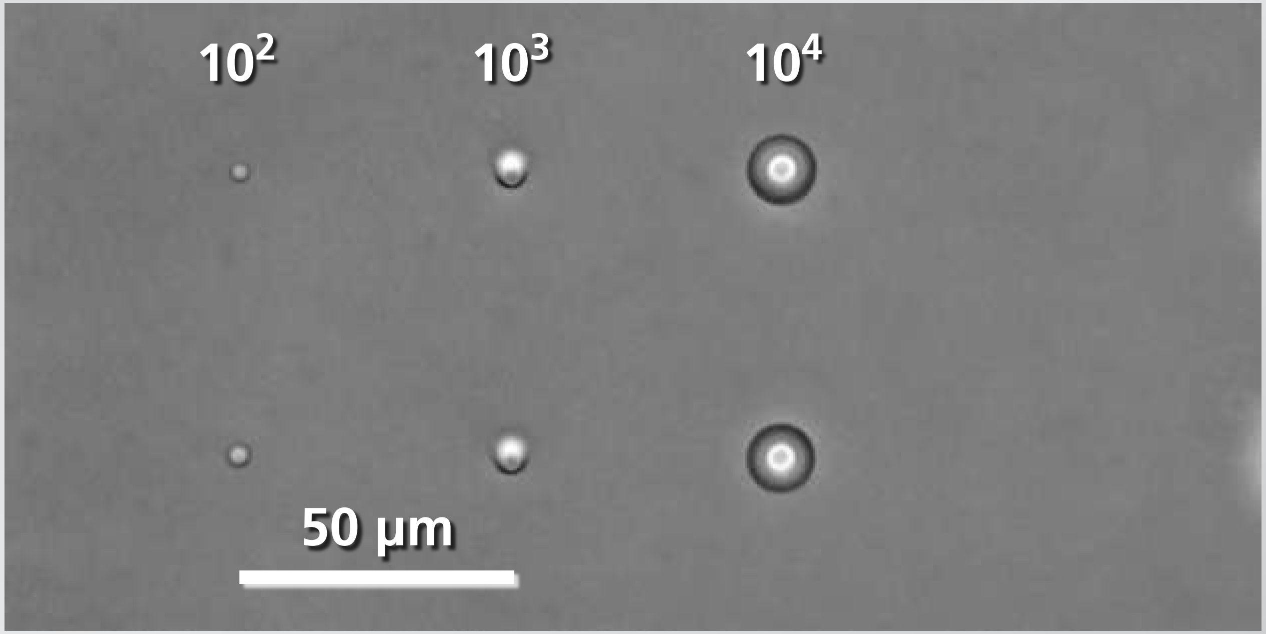
Low-energy machining

the longer the irradiation…



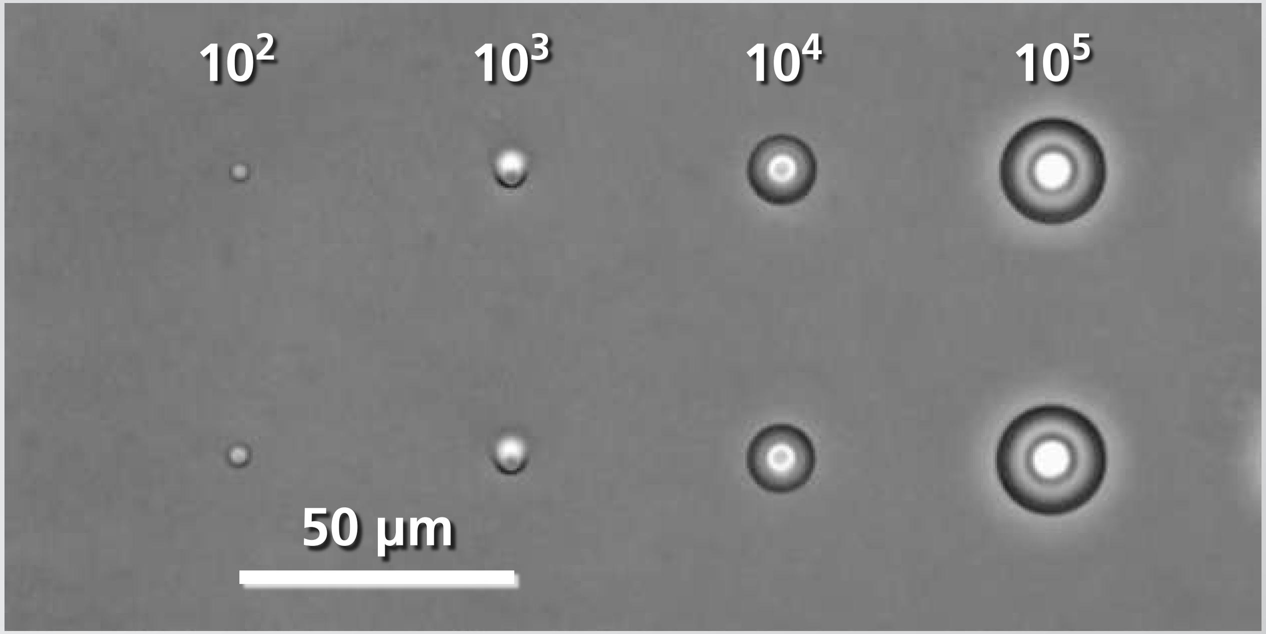
Low-energy machining

the longer the irradiation…



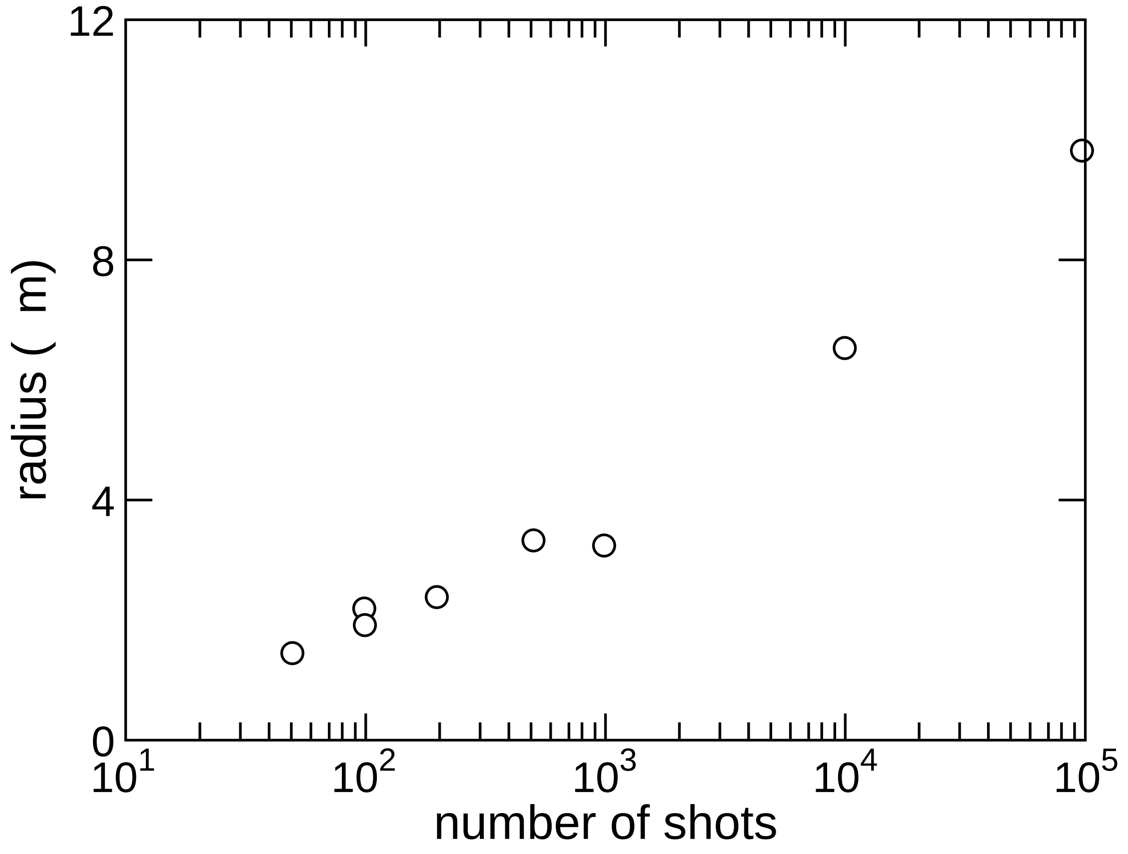
Low-energy machining

the longer the irradiation…



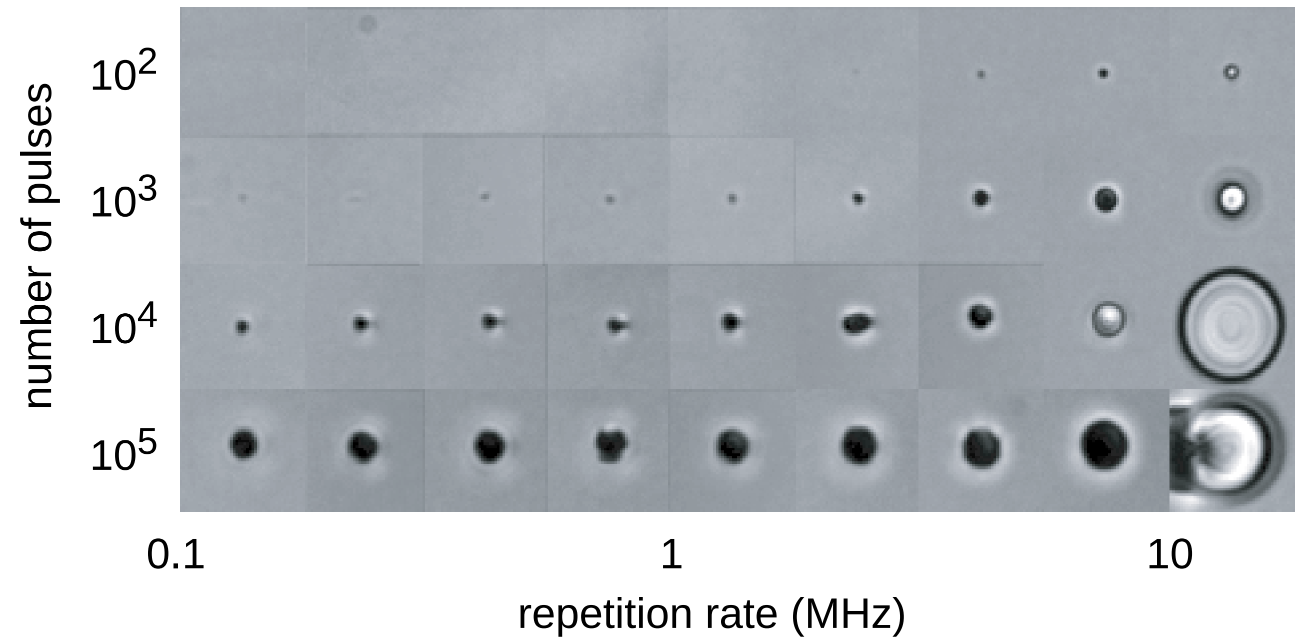
… the larger the radius

Low-energy machining



Low-energy machining

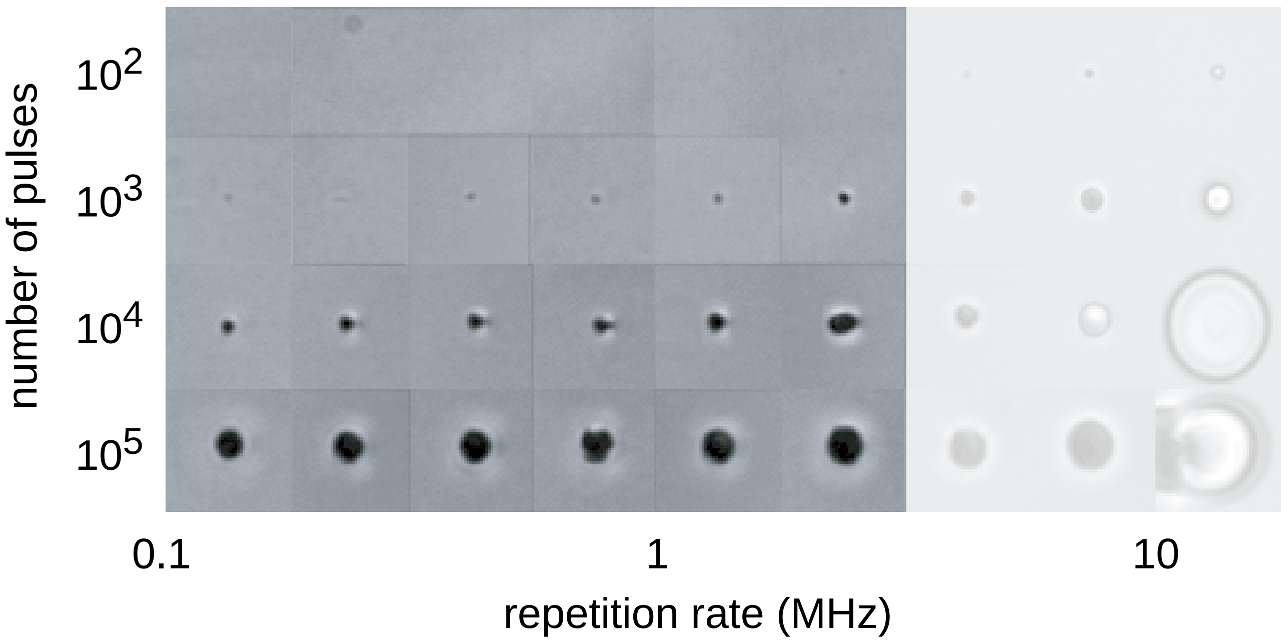
repetition-rate dependence



As_2S_3, 100 fs, 7 nJ

Low-energy machining

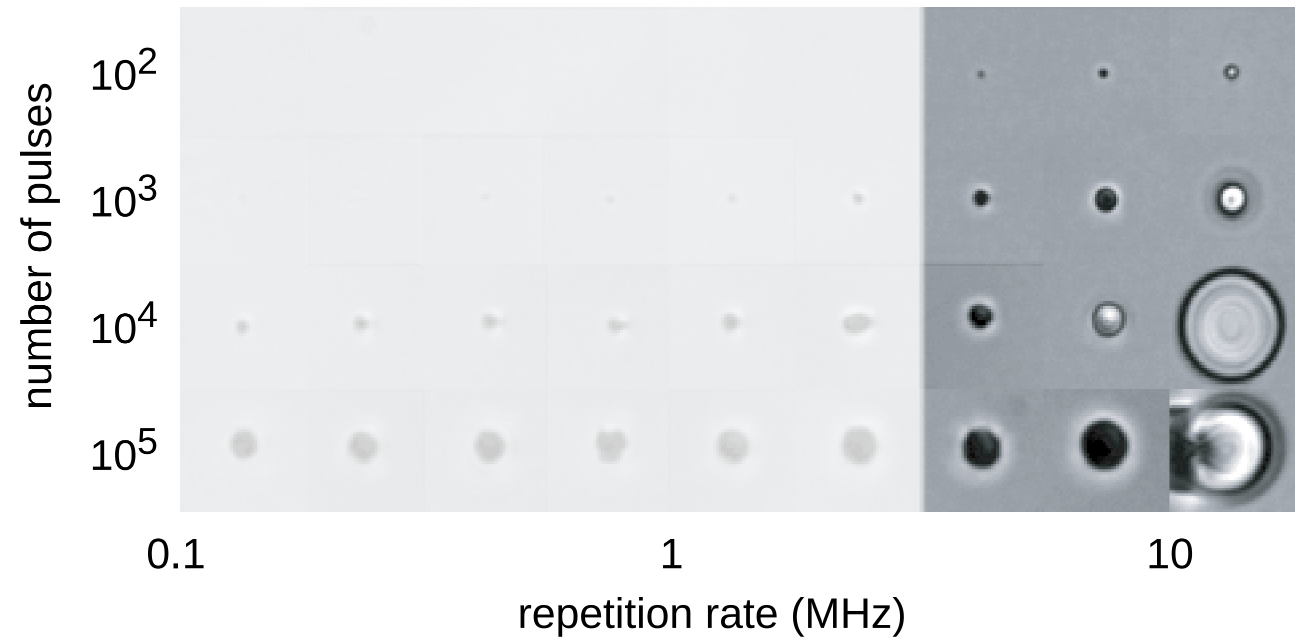
repetition-rate dependence



As_2S_3, 100 fs, 7 nJ

Low-energy machining

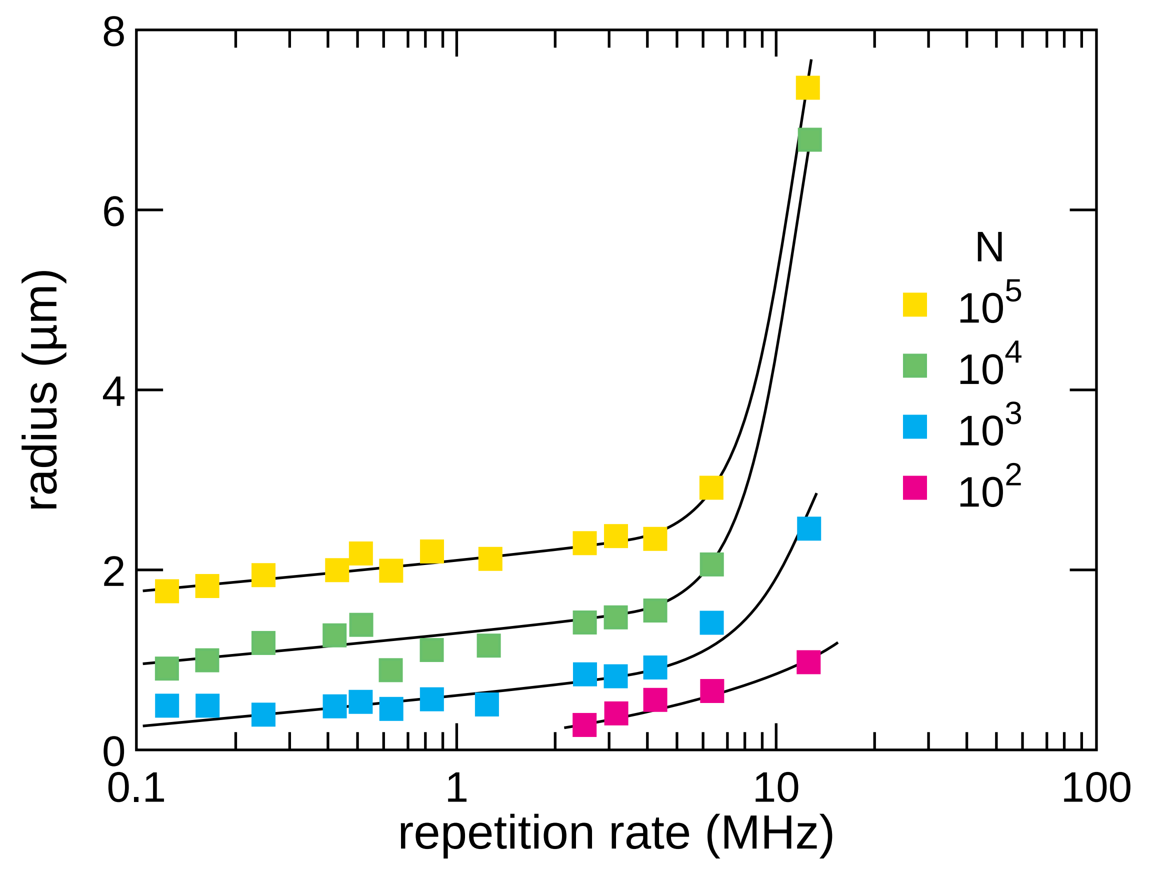
repetition-rate dependence



As_2S_3, 100 fs, 7 nJ

Low-energy machining

repetition-rate dependence

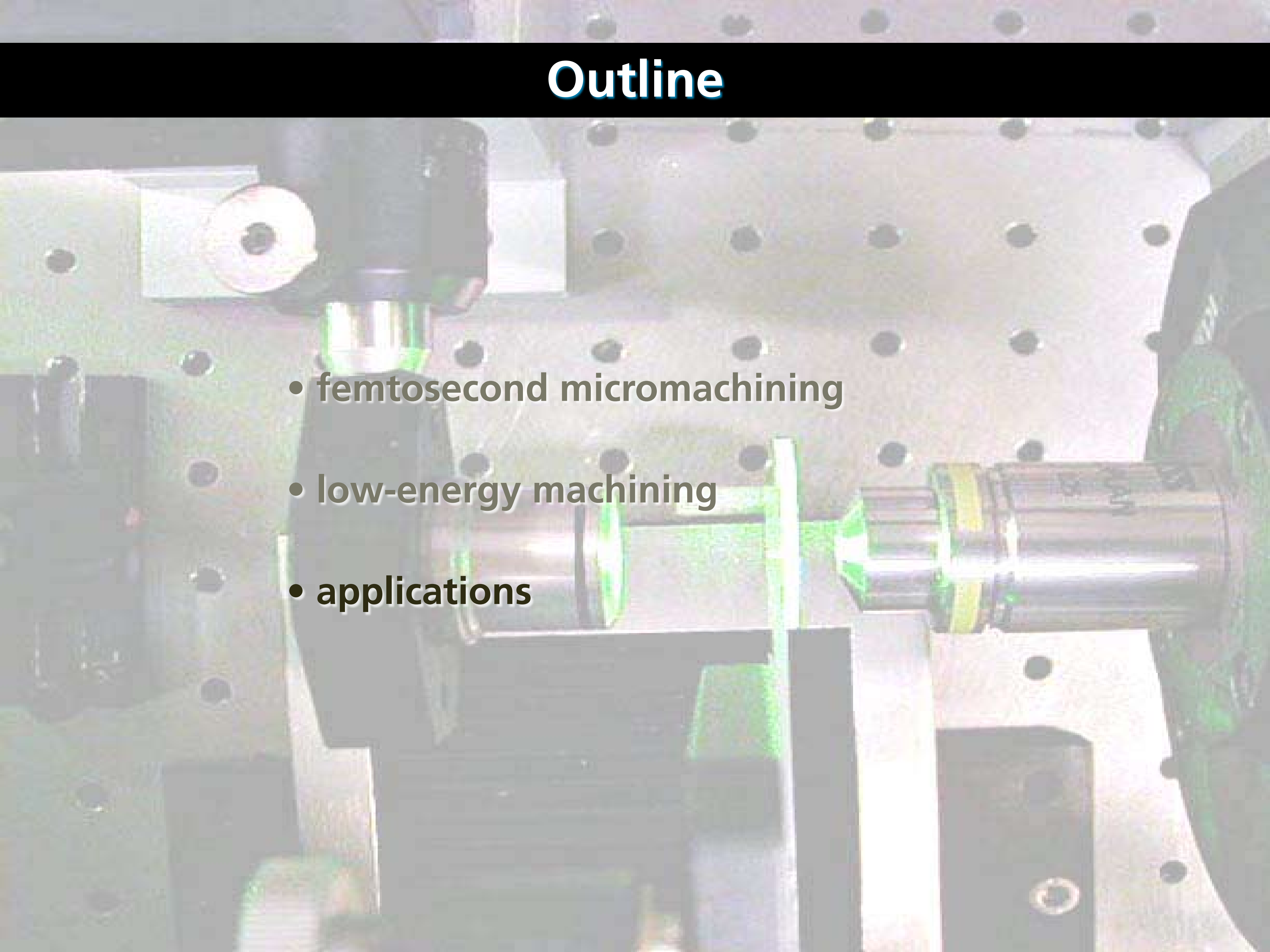


As_2S_3, 100 fs, 7 nJ

Low-energy machining

above 5 MHz: internal “point-source of heat”

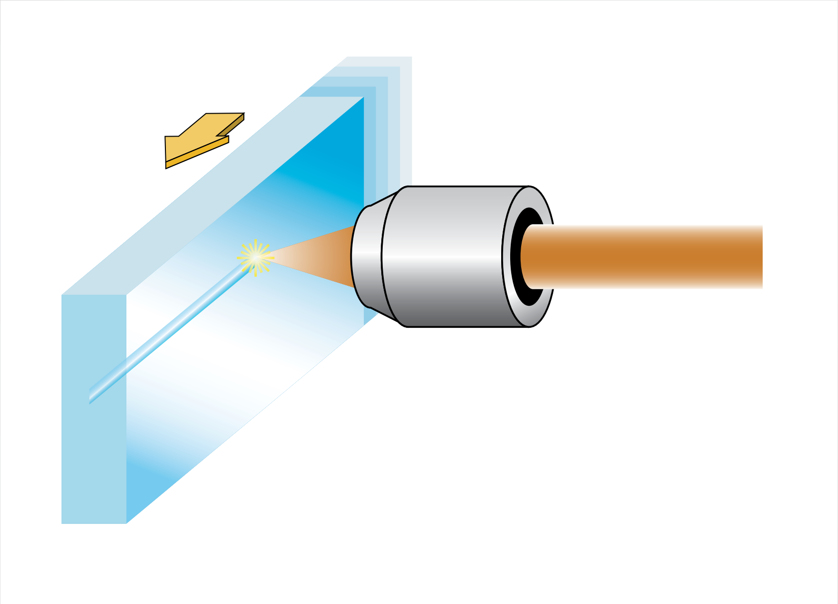
Outline



- femtosecond micromachining
- low-energy machining
- **applications**

Low-energy machining

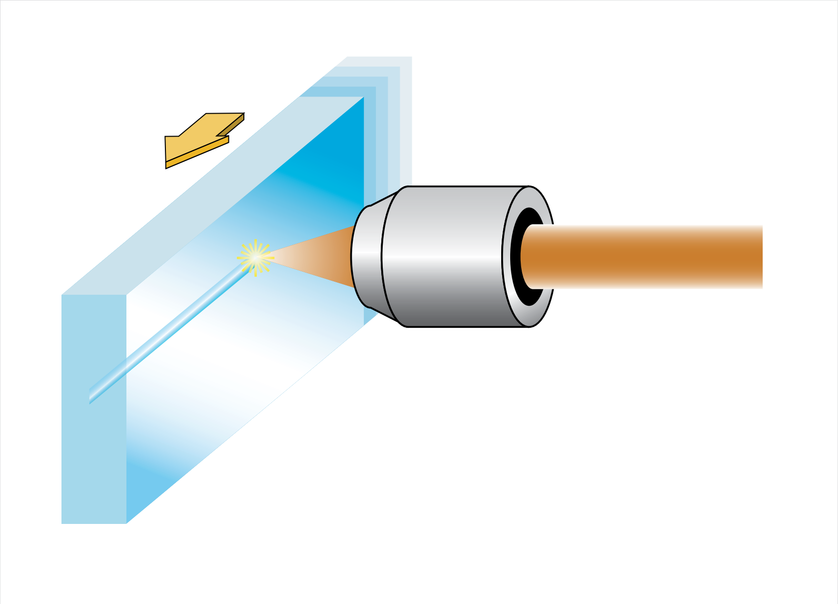
waveguide micromachining

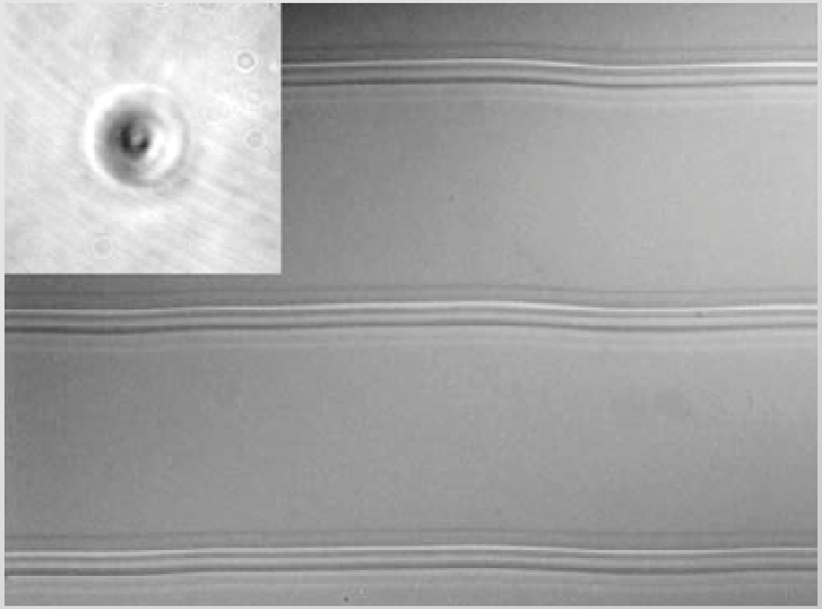


Opt. Lett. **26**, 93 (2001)

Low-energy machining

waveguide micromachining

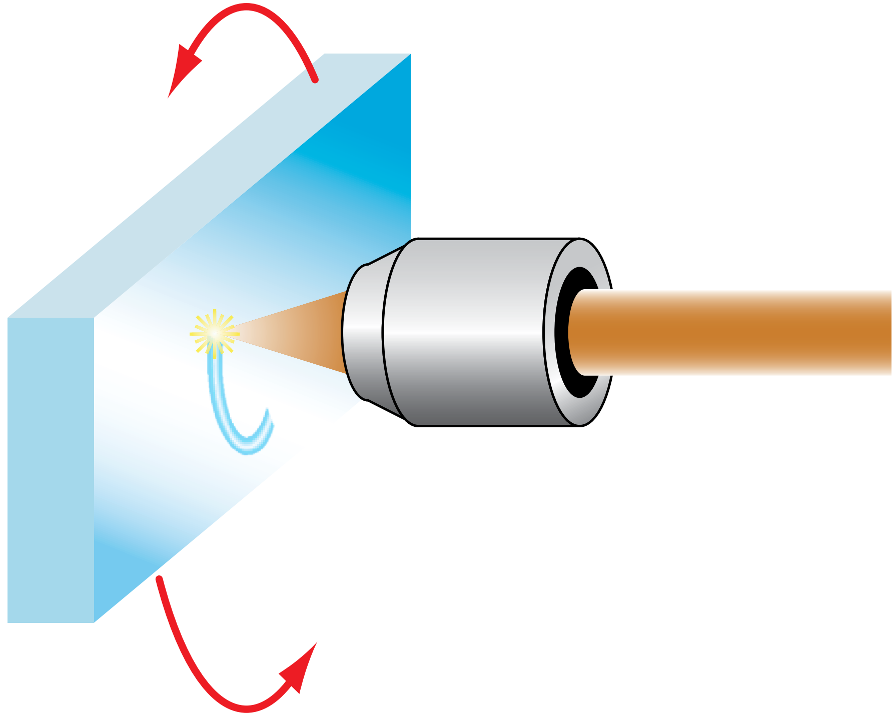




Opt. Lett. **26**, 93 (2001)

Applications

curved waveguides

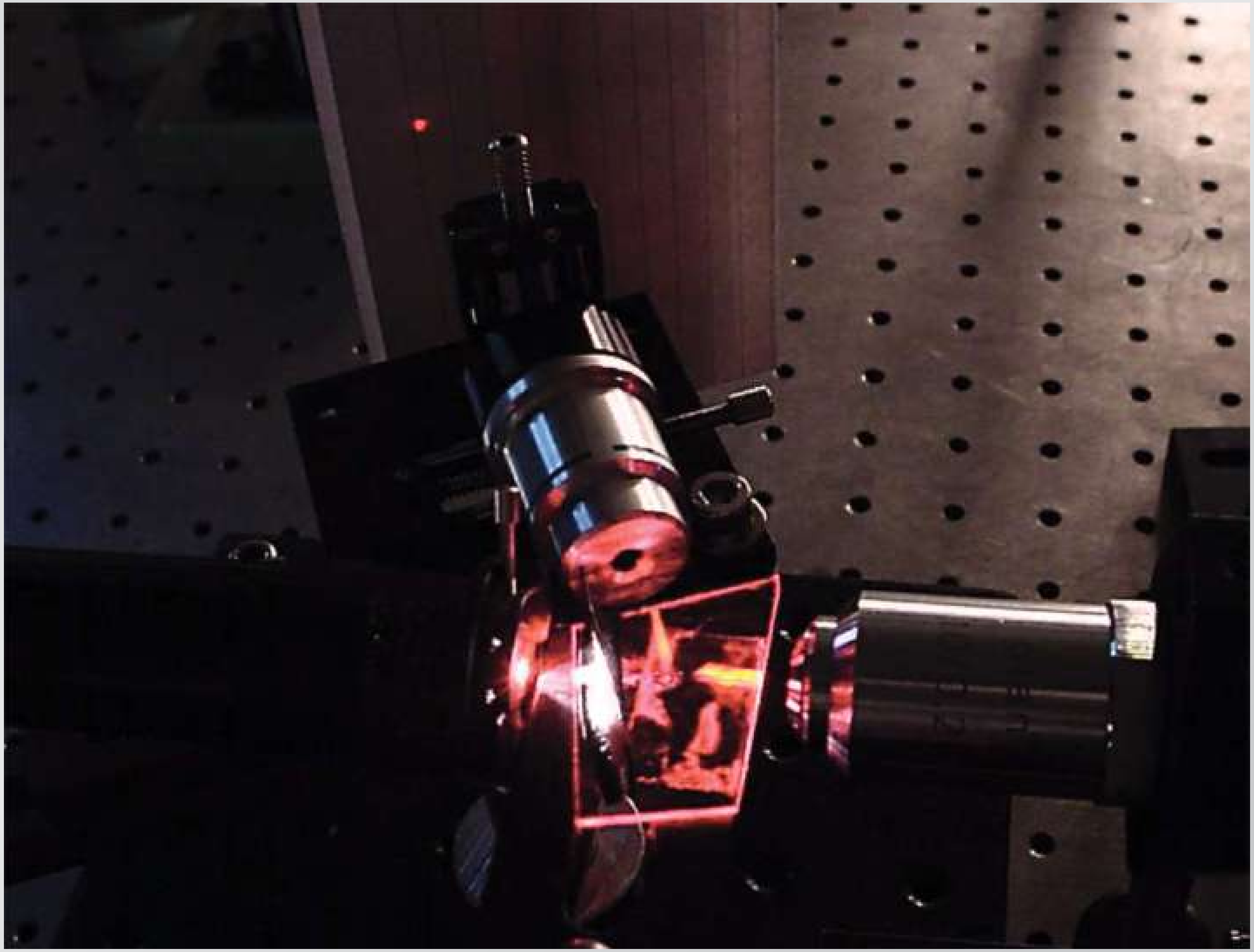


Applications

curved waveguides

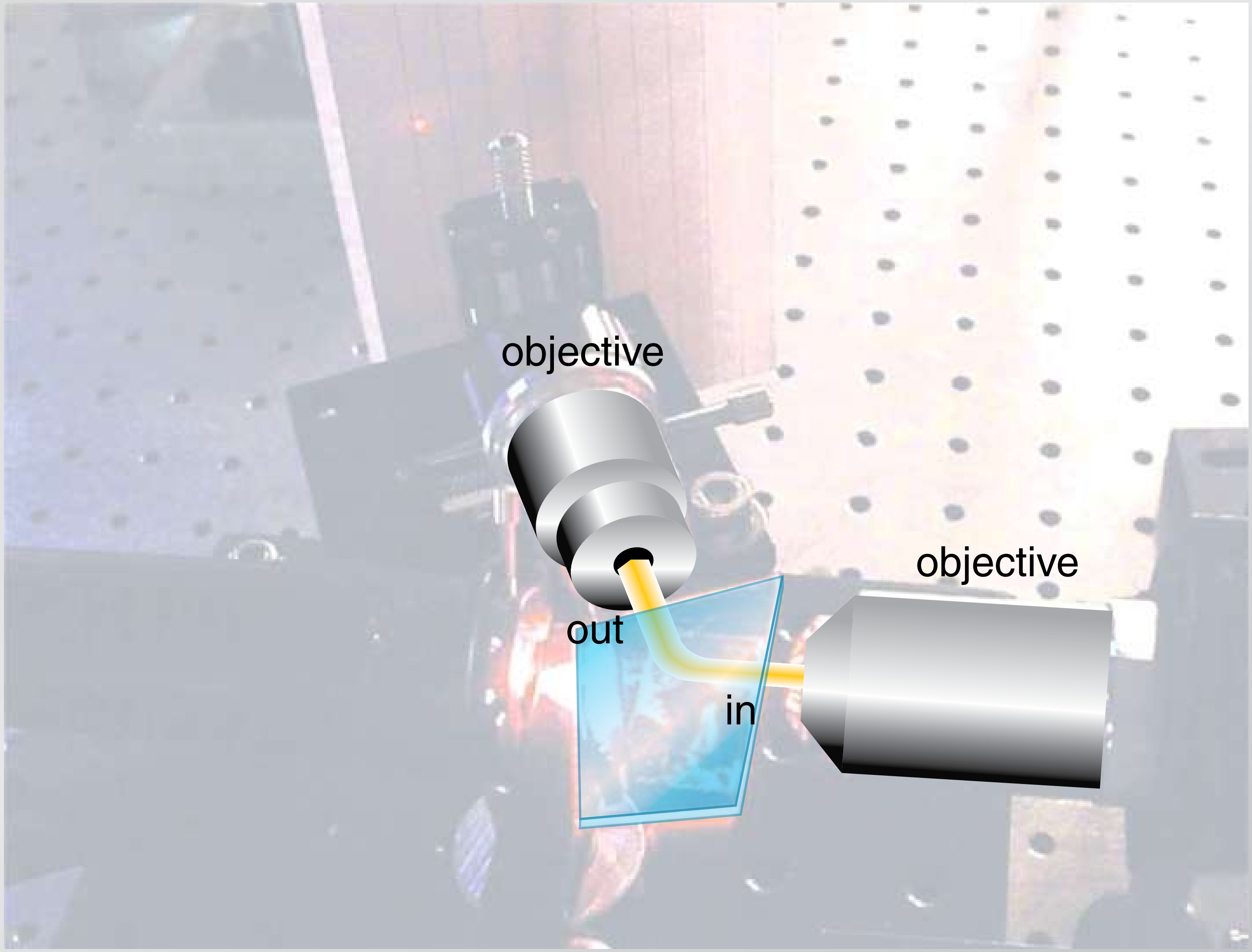
Applications

curved waveguides



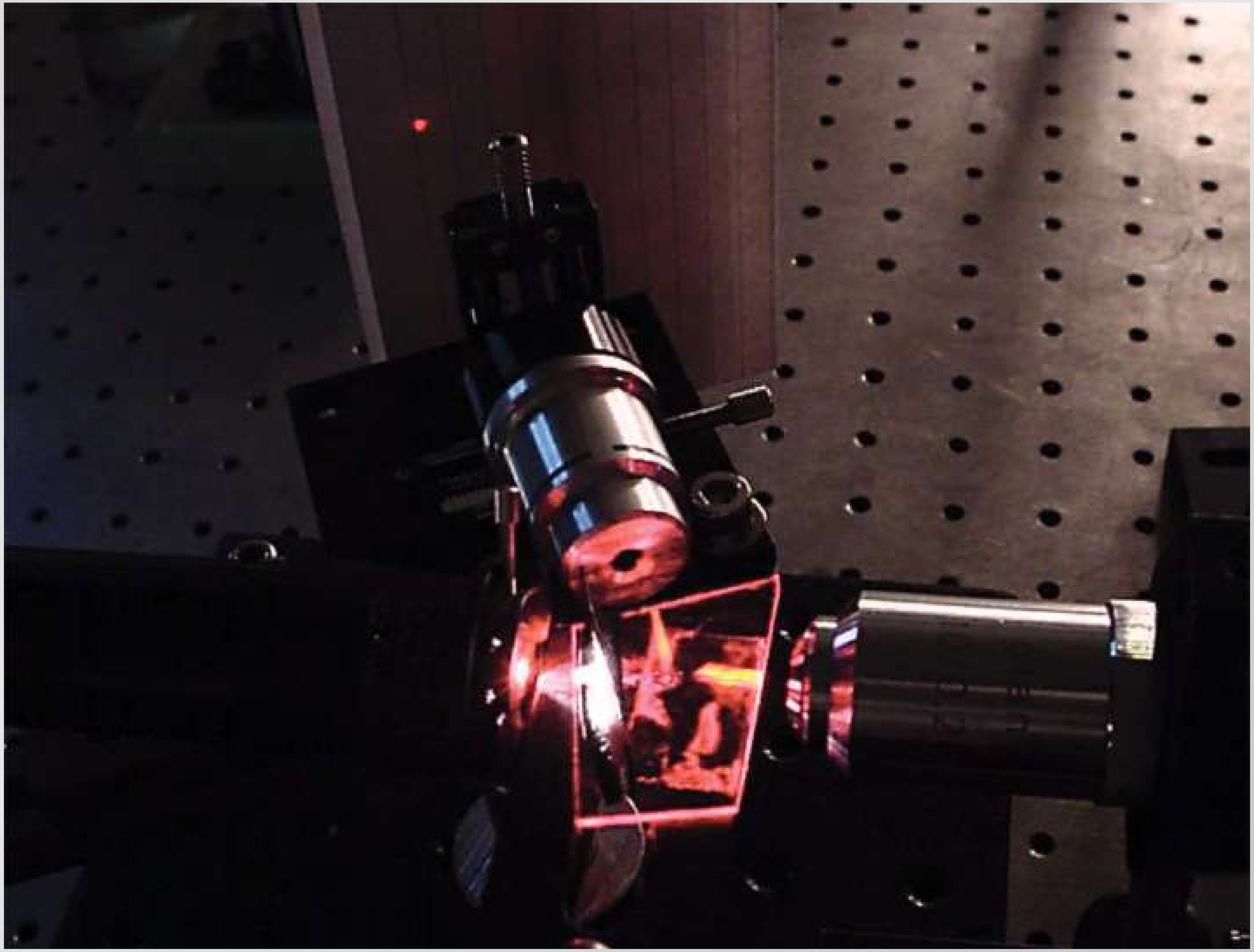
Applications

curved waveguides



Applications

curved waveguides



Applications

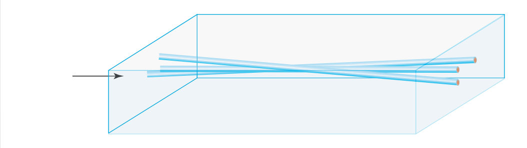
photonic fabrication techniques

	fs micromachining	other
loss (dB/cm)	< 3	0.1–3
bending radius	36 mm	30–40 mm
Δn	2×10^{-3}	$10^{-4} - 0.5$
3D integration	Y	N

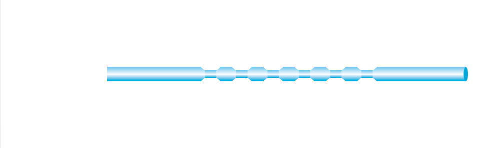
Applications

photonic devices

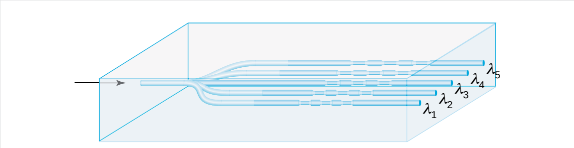
3D splitter



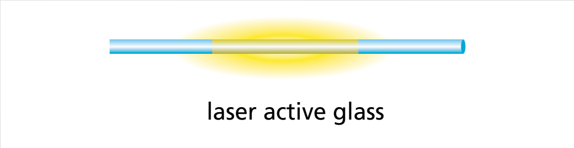
Bragg grating



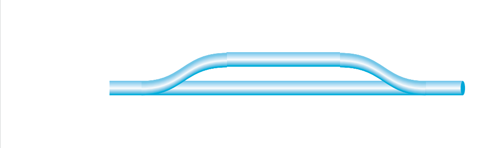
demultiplexer



amplifier

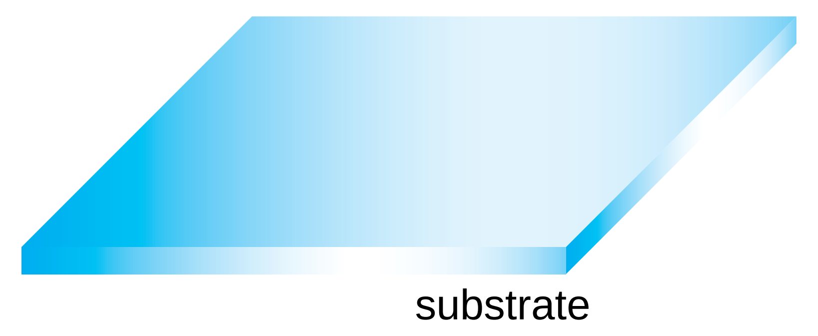


interferometer



Applications

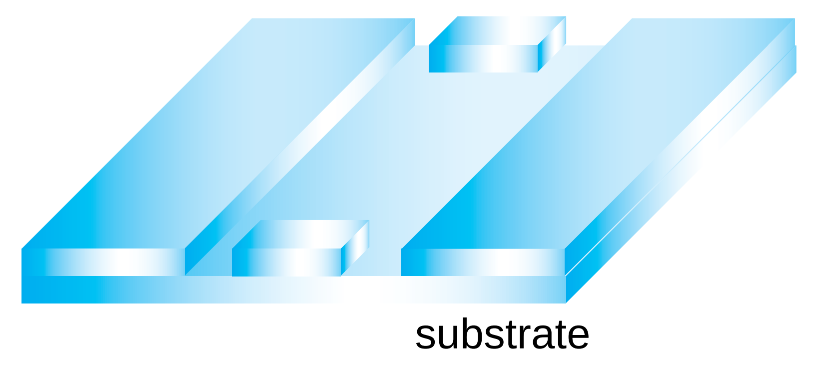
all-optical sensor



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

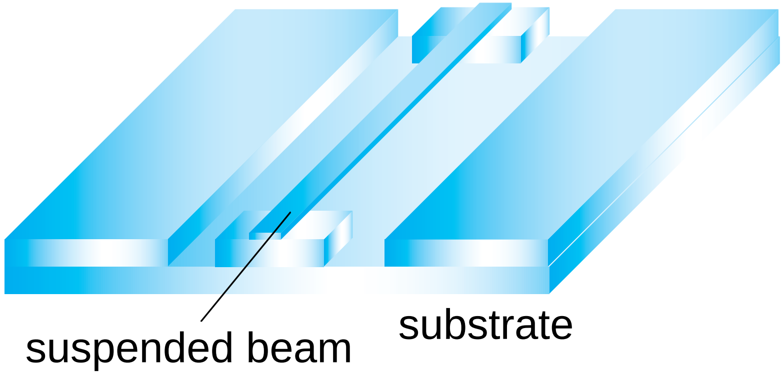
all-optical sensor



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

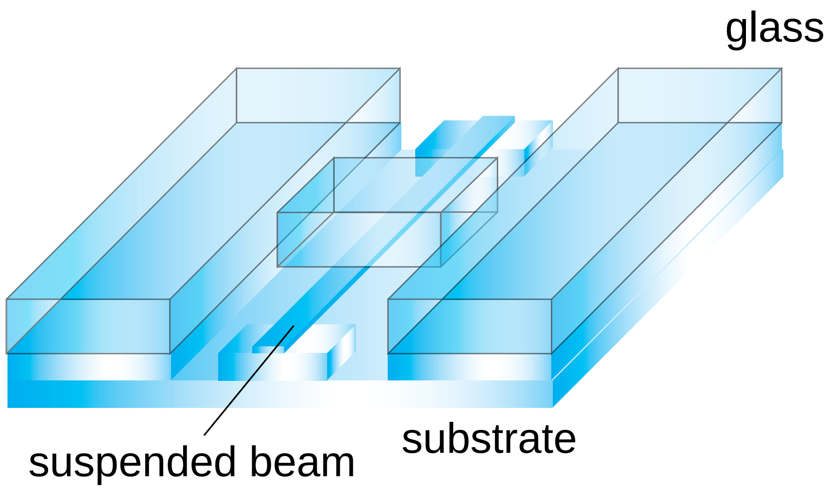
all-optical sensor



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

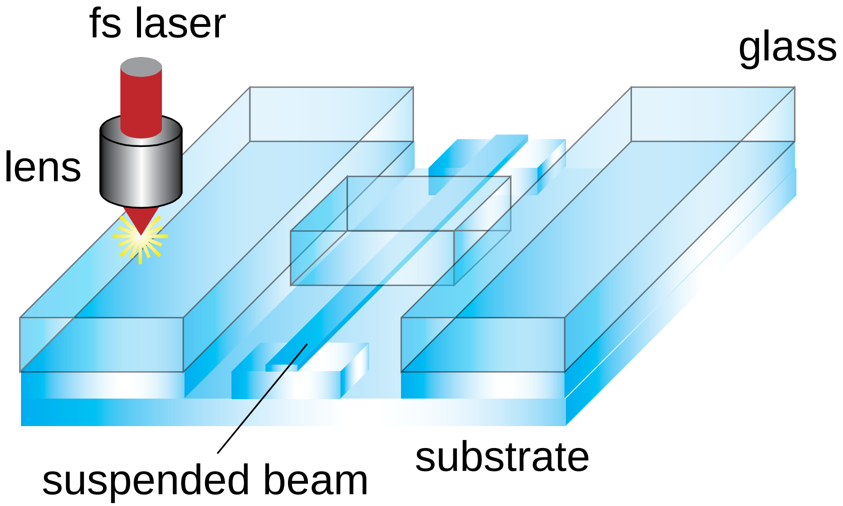
all-optical sensor



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

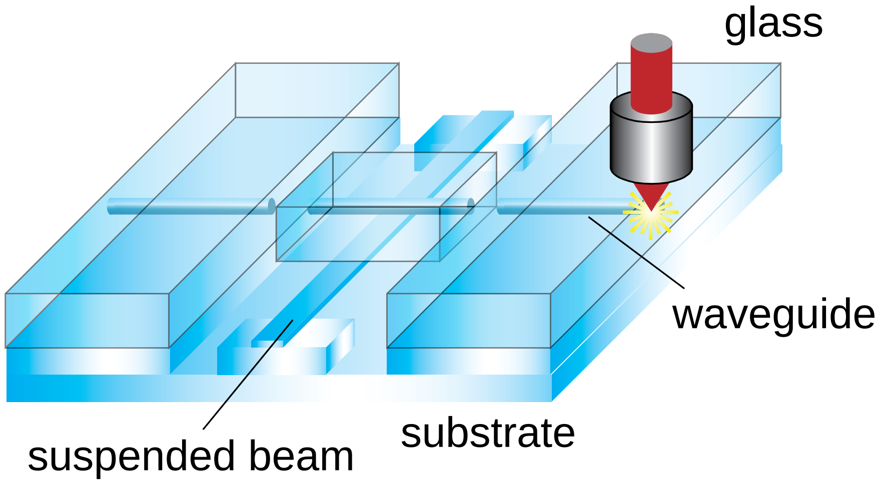
all-optical sensor



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

all-optical sensor



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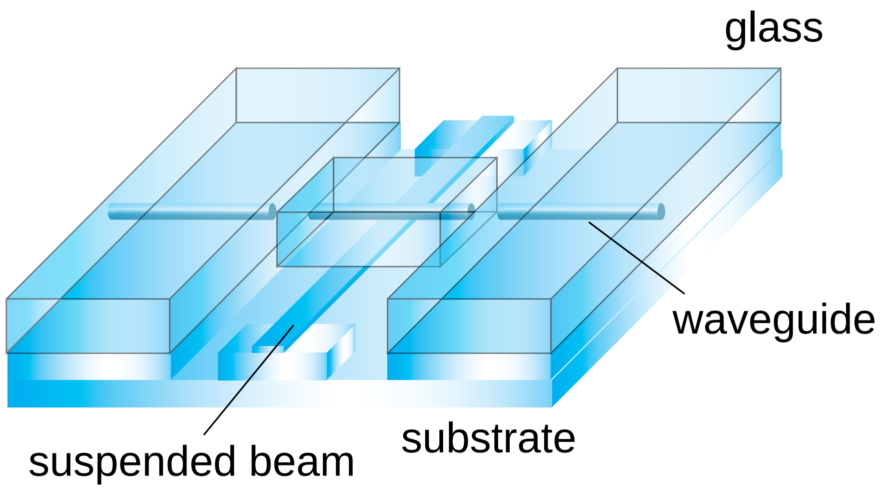
Applications

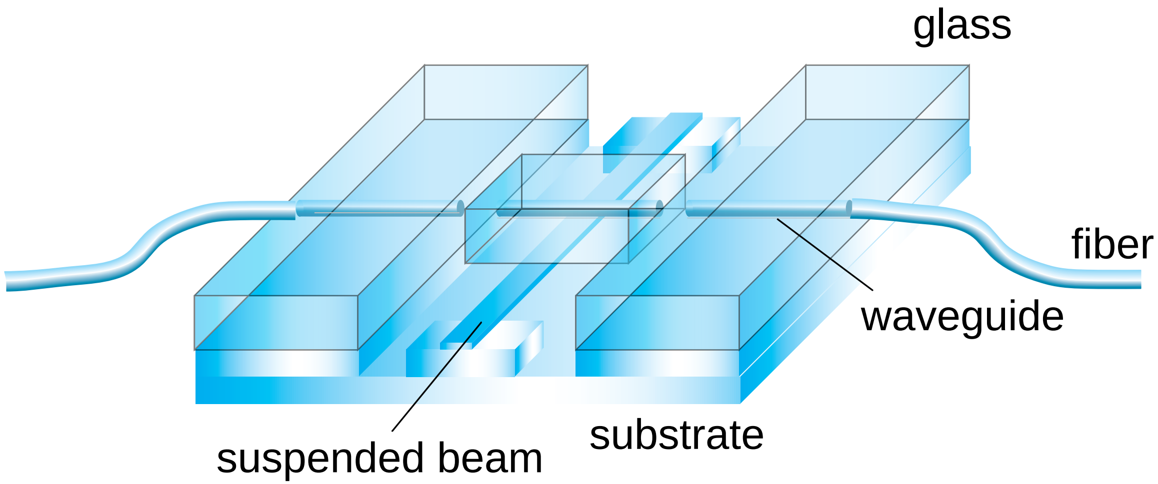
all-optical sensor



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

all-optical sensor



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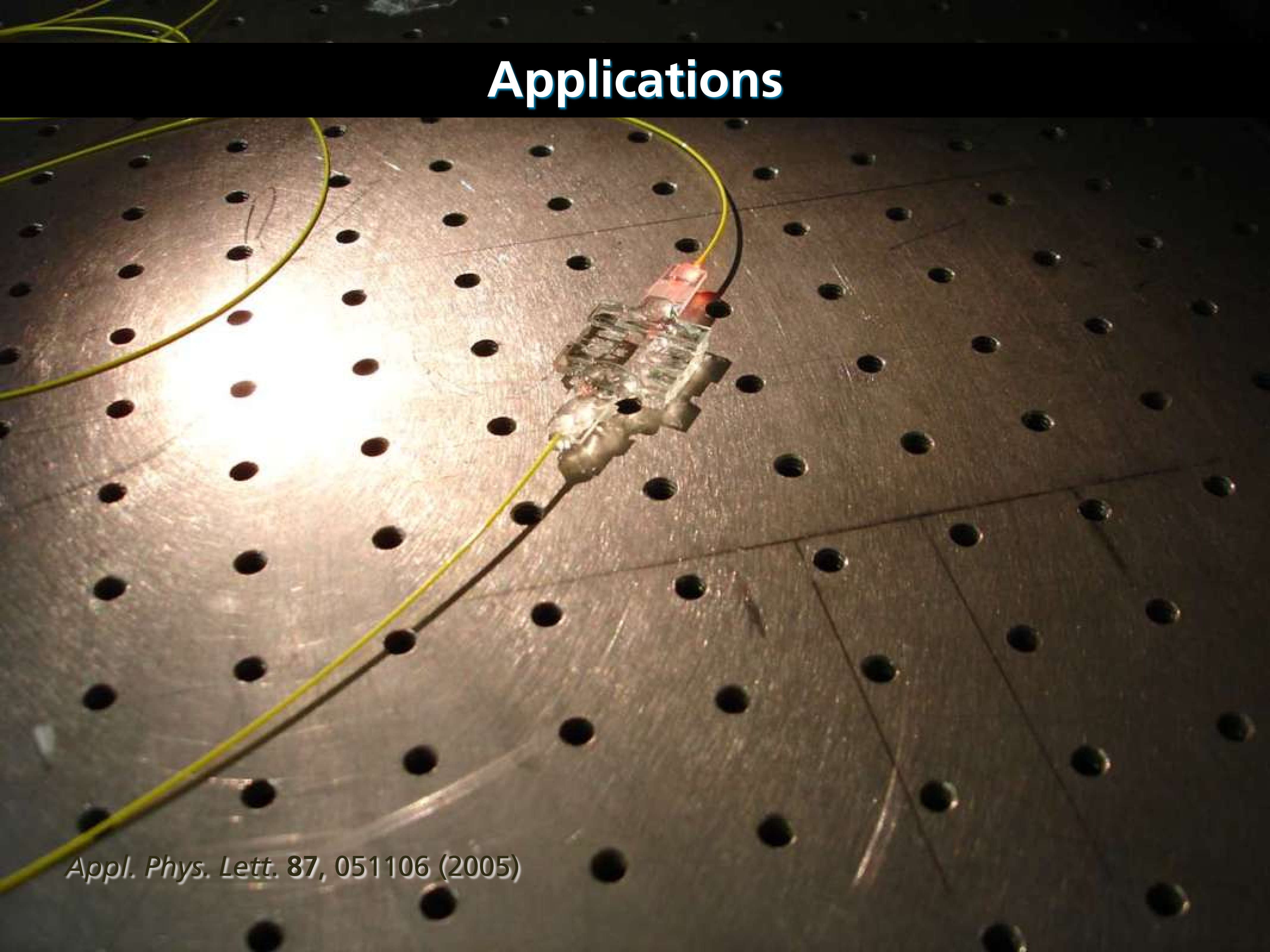
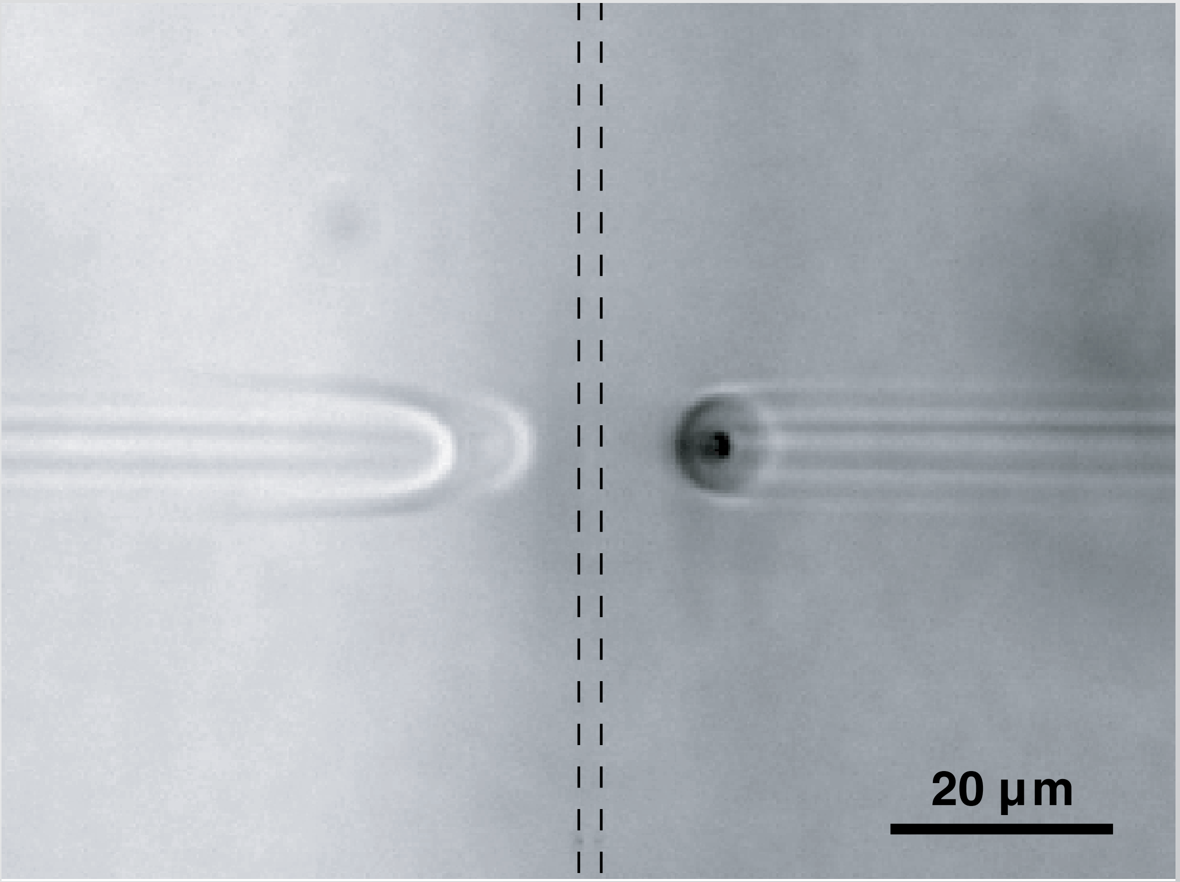
Applications



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

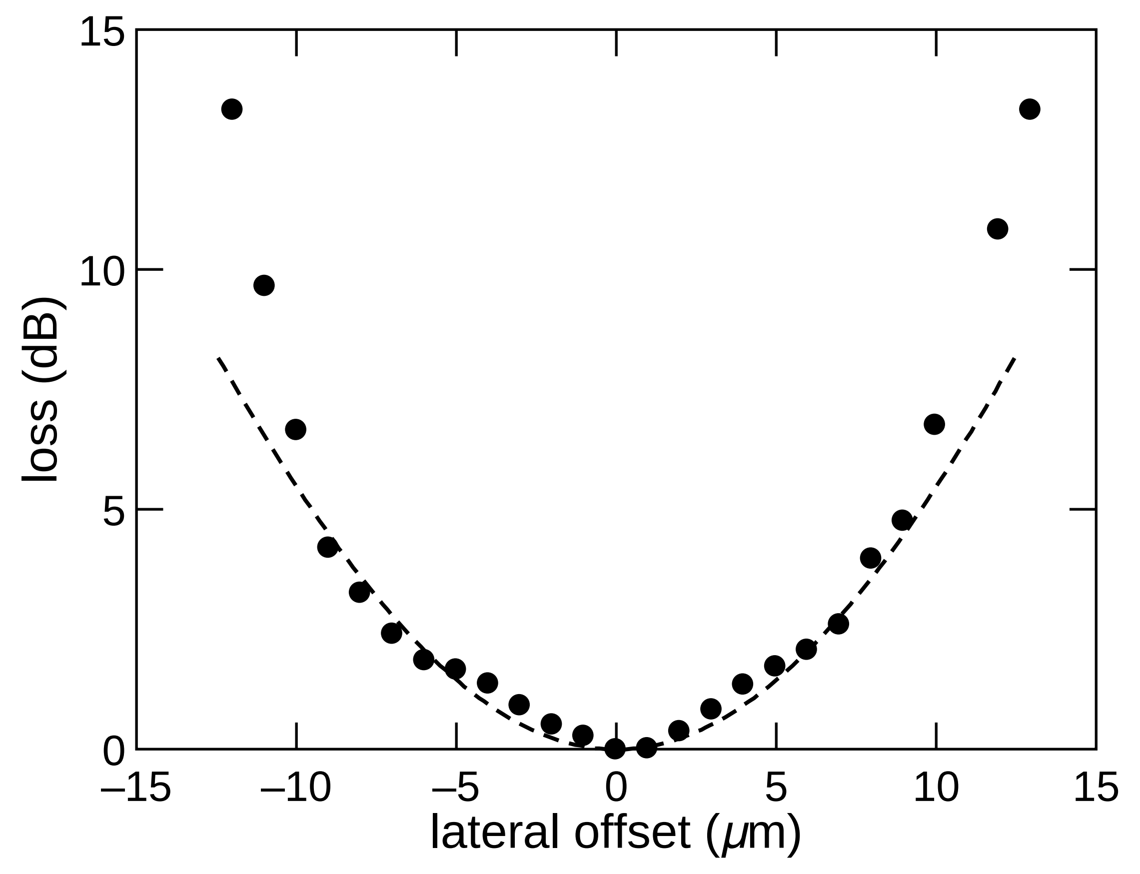
sensor gap



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

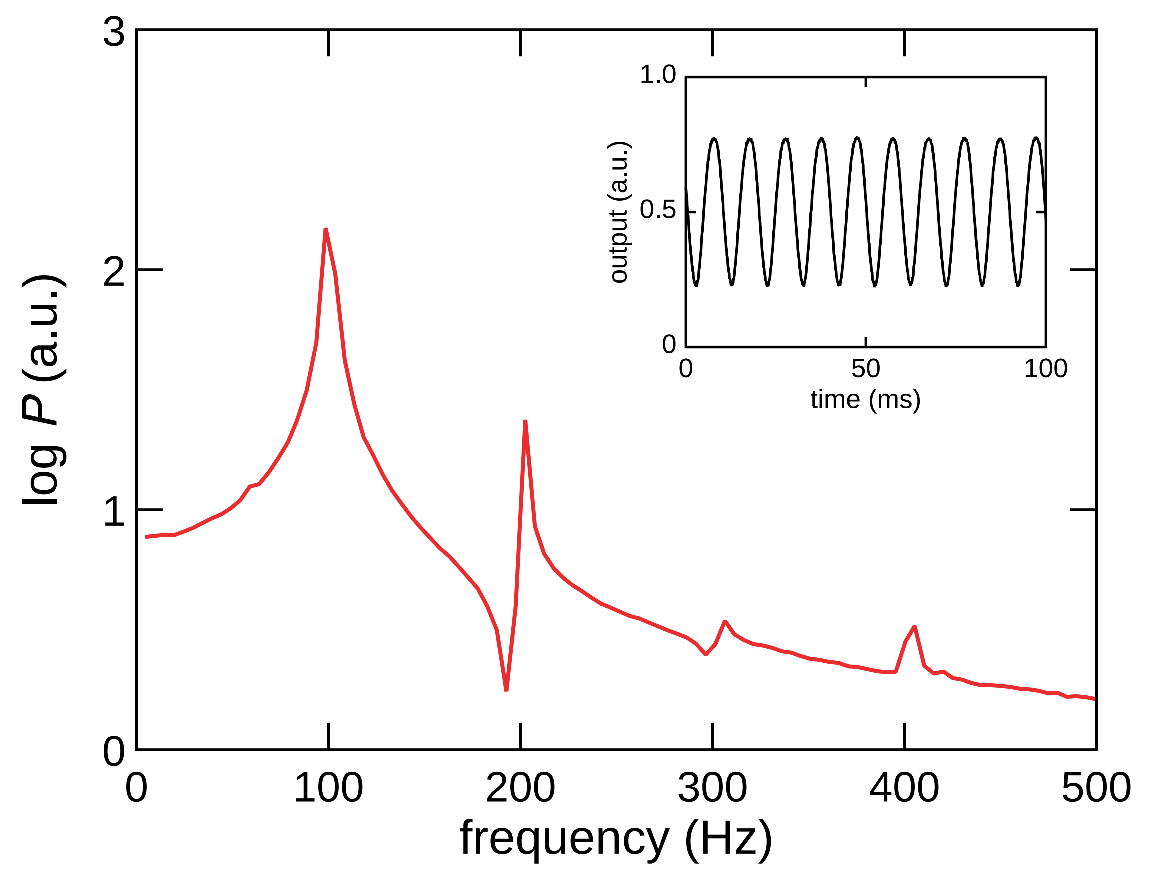
calibration



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

sensor response to 100 Hz acoustic wave



Appl. Phys. Lett. **87**, 051106 (2005)

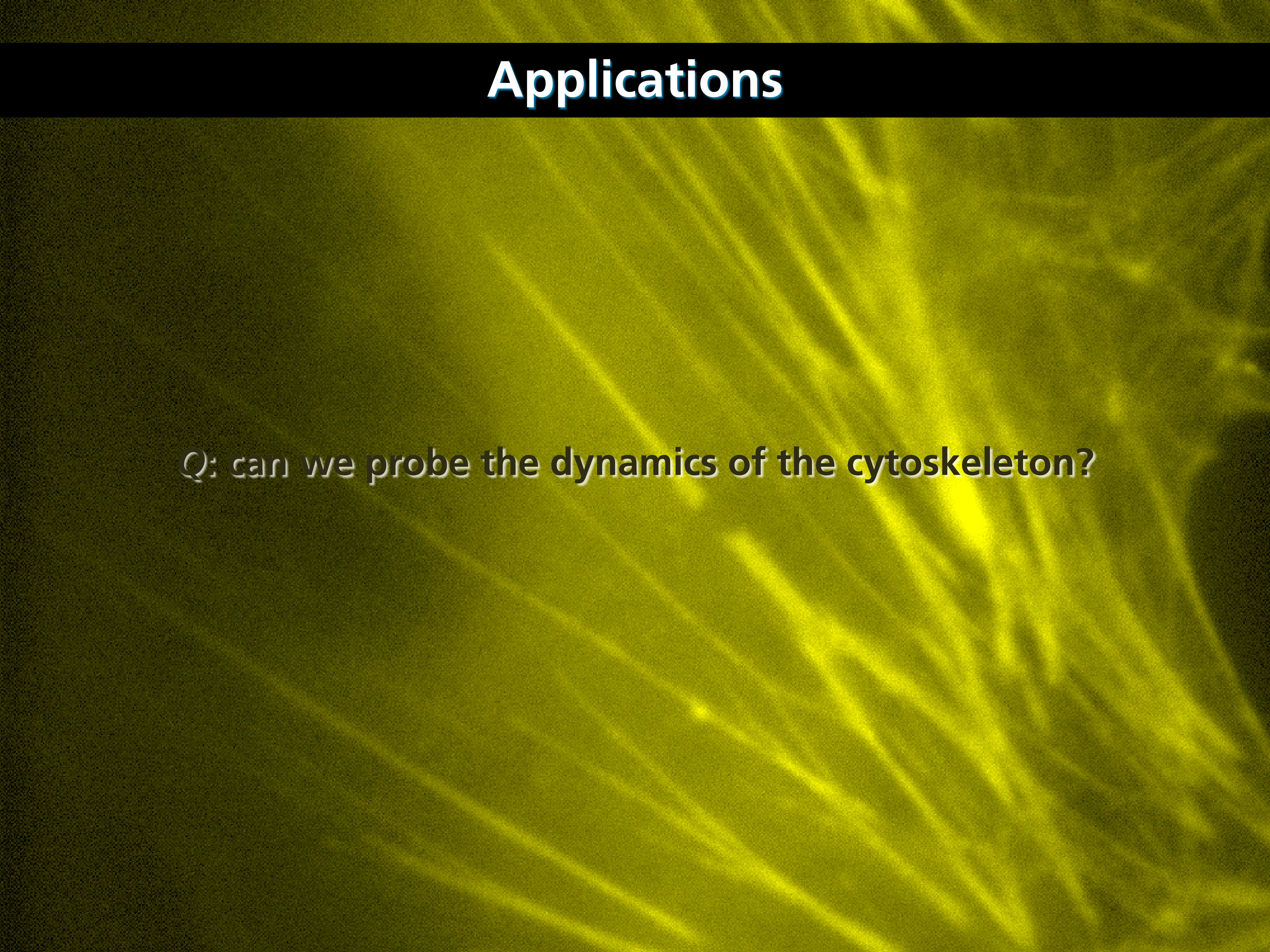
Applications

ideal tool for ablating (living) tissue

Applications

- standard biochemical tools: species selective
- fs laser “nanosurgery”: site specific

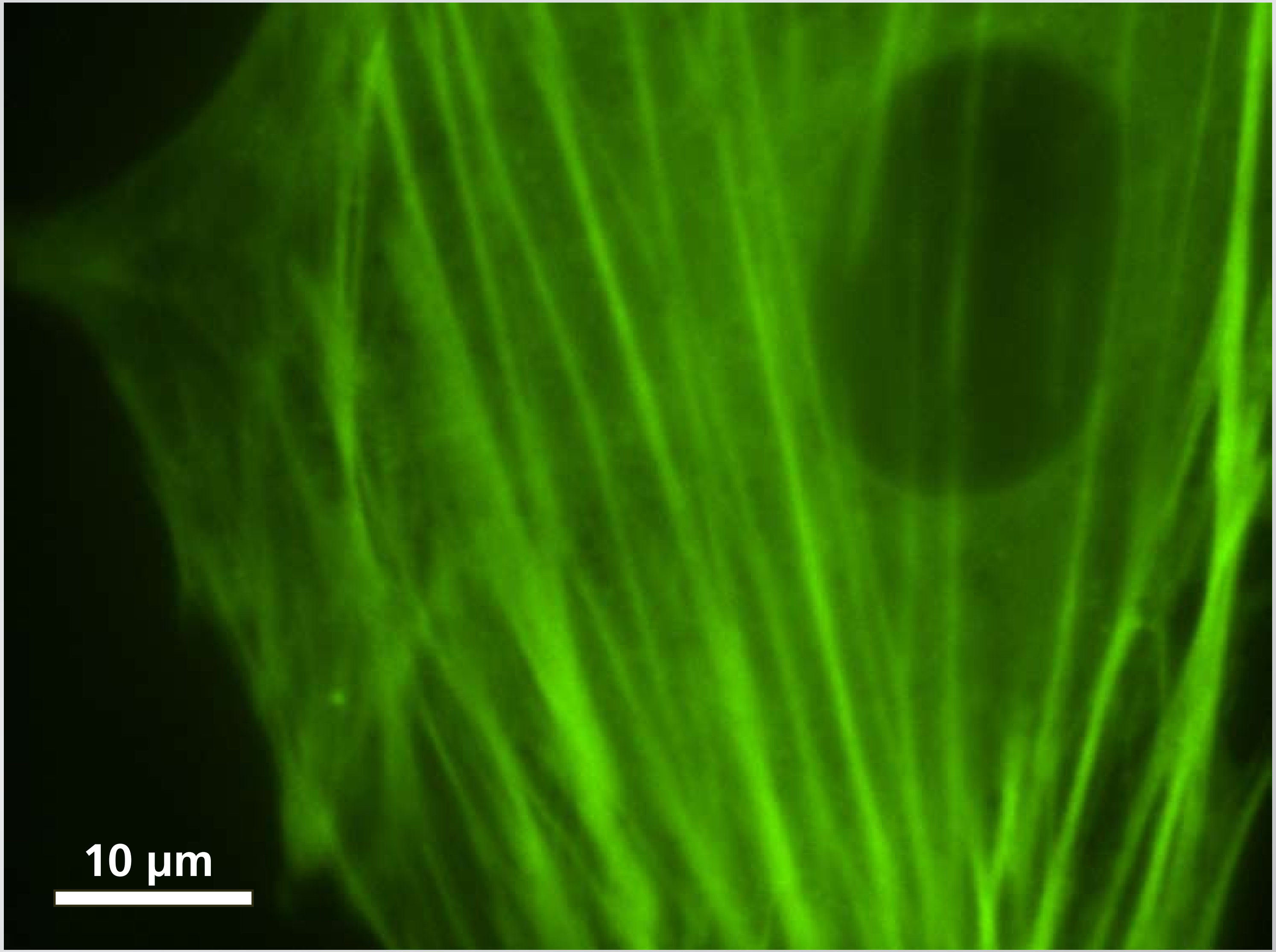
Applications



Q: can we probe the dynamics of the cytoskeleton?

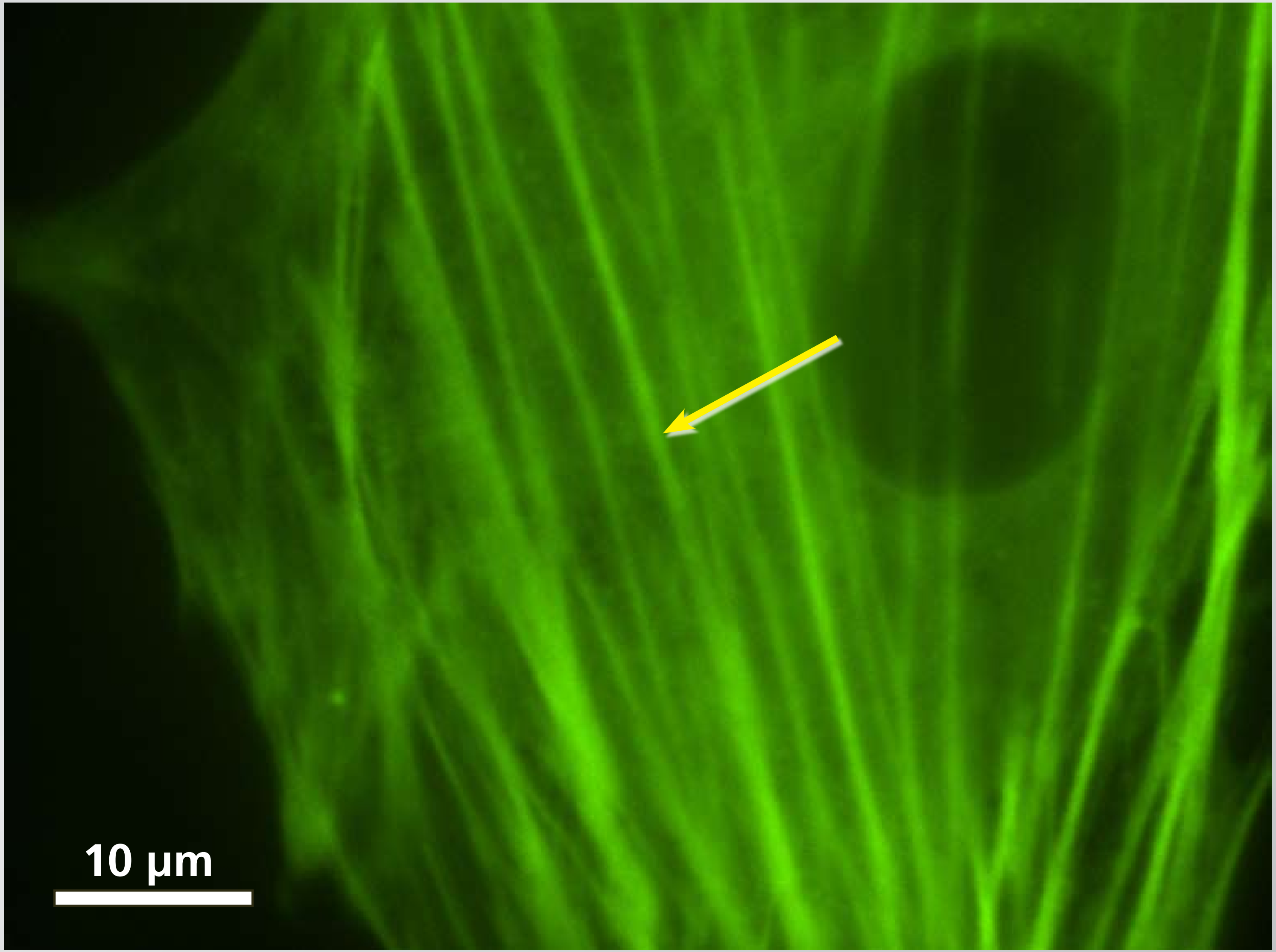
Applications

actin fiber network of a live cell



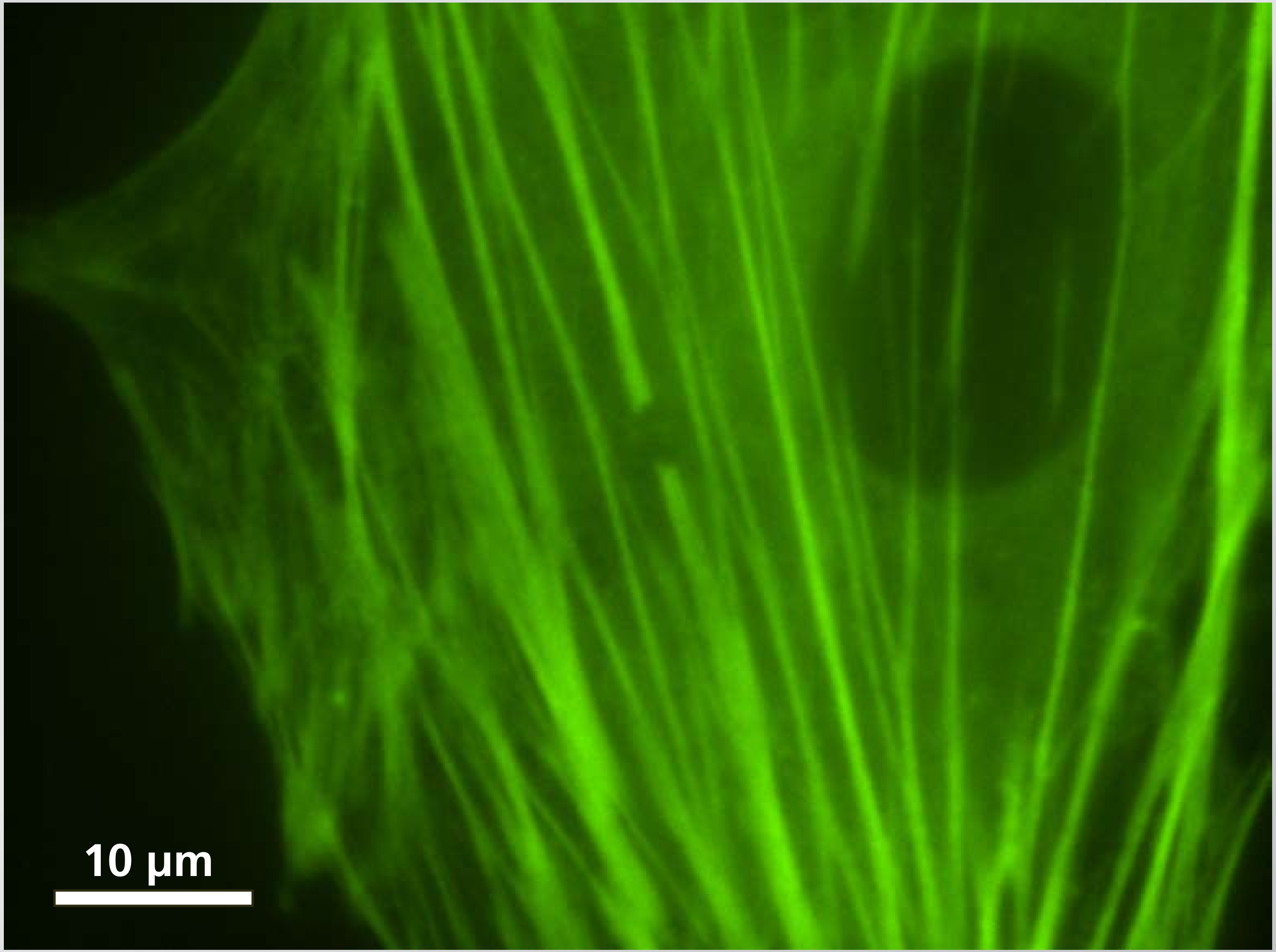
Applications

cut a single fiber bundle



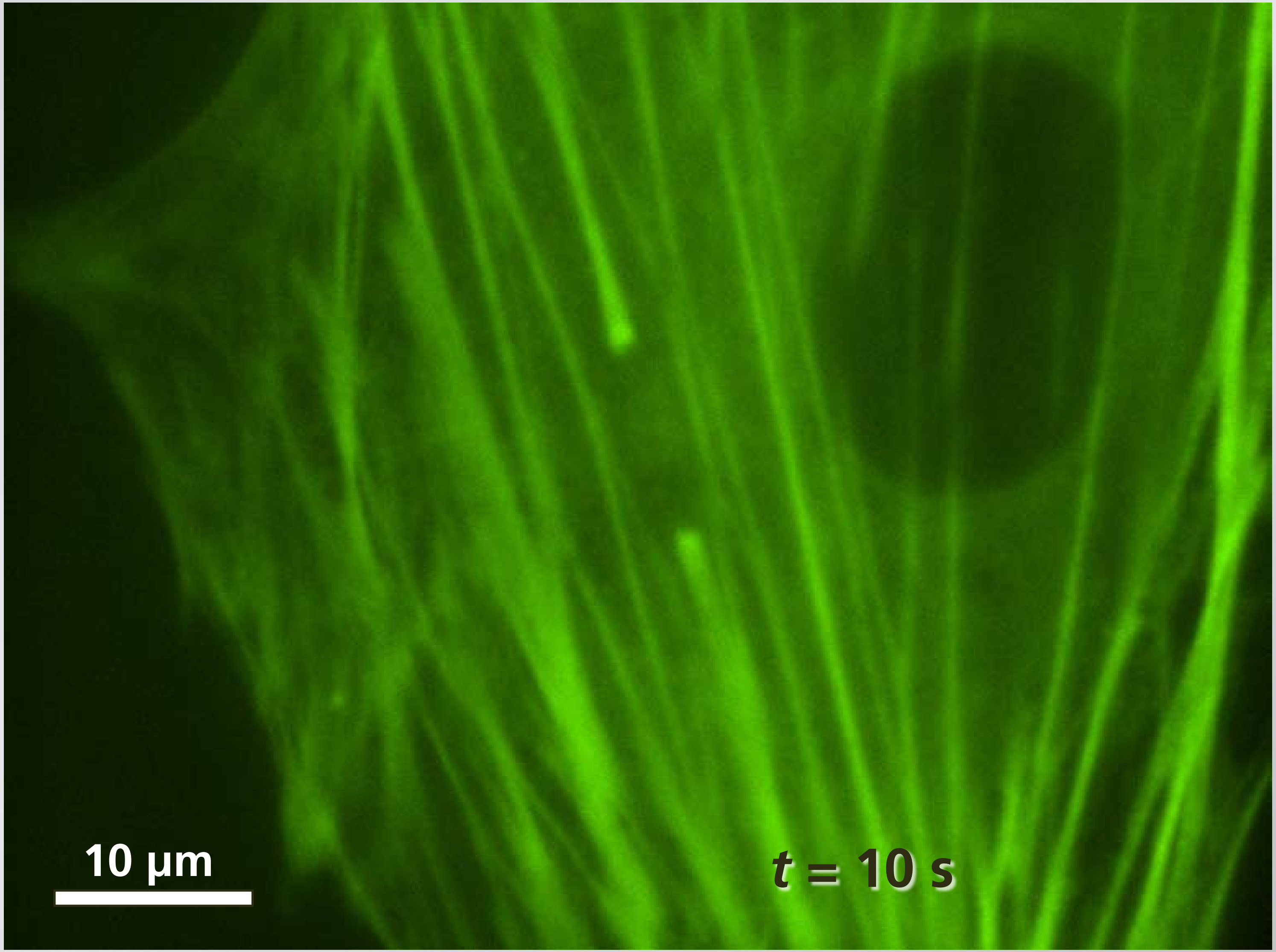
Applications

cut a single fiber bundle



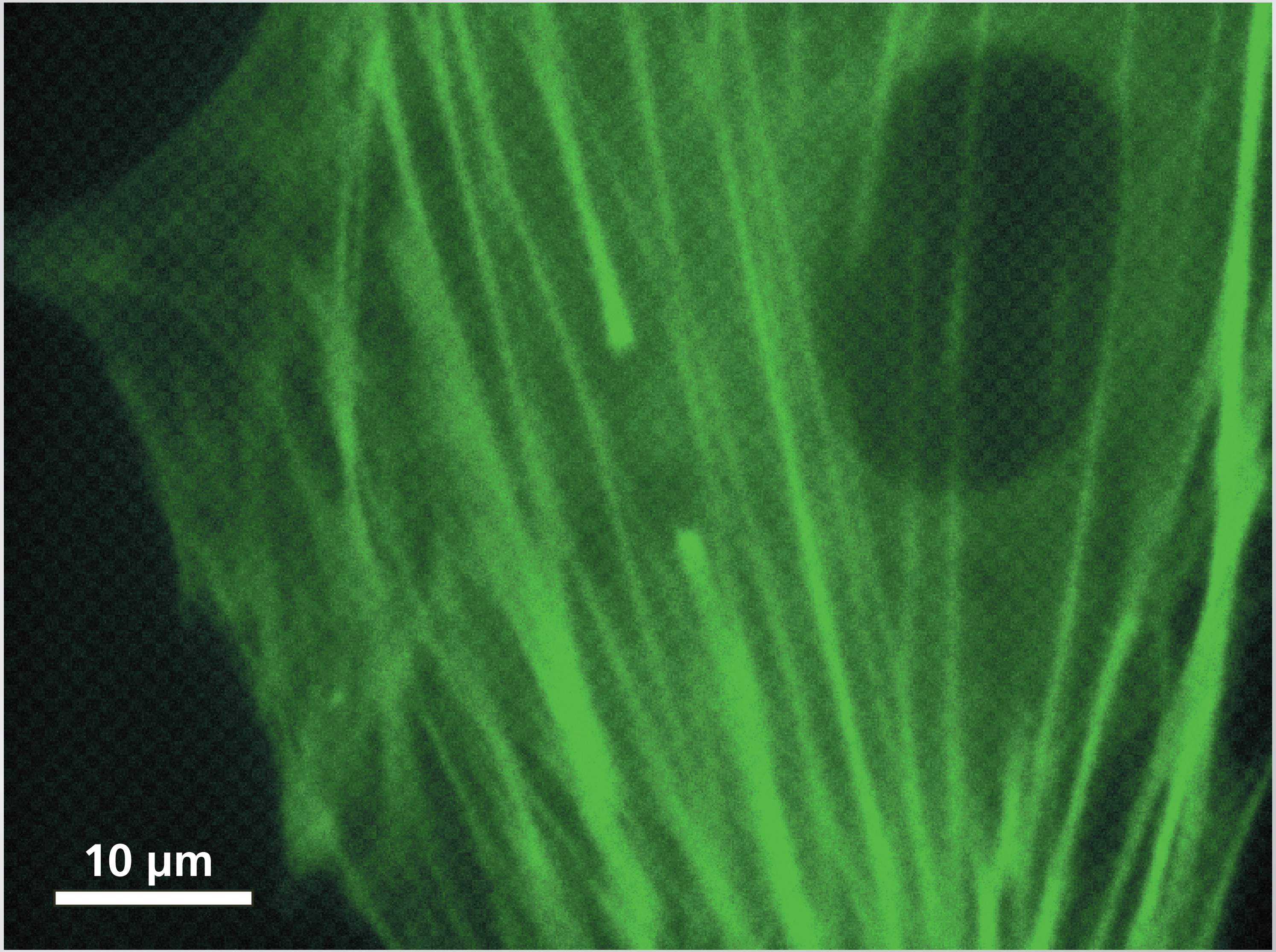
Applications

gap widens with time

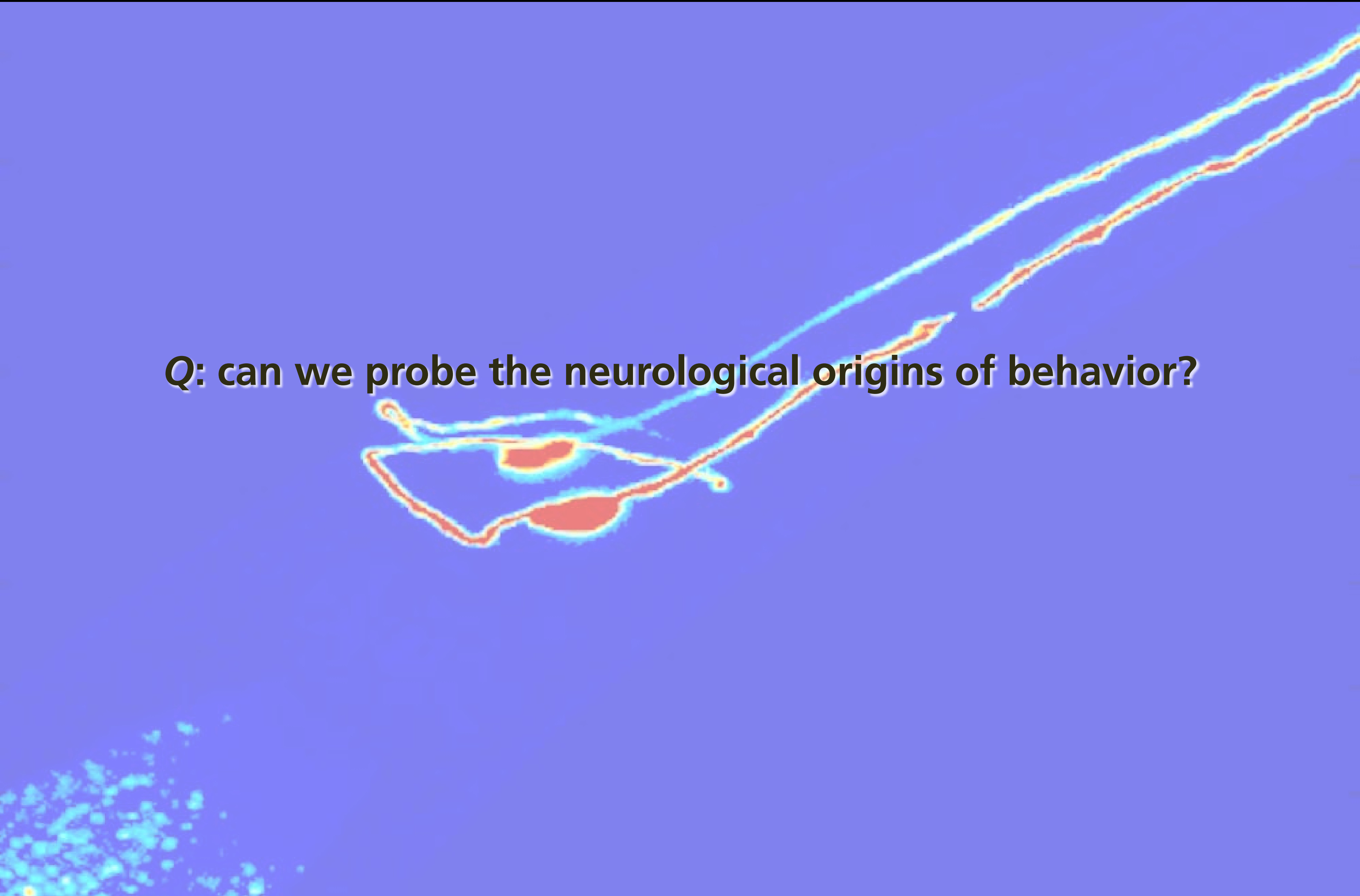


Applications

dynamics provides information on *in vivo* mechanics



Applications



Q: can we probe the neurological origins of behavior?

Applications

Caenorhabditis Elegans

Juergen Berger & Ralph Sommer
Max-Planck Institute for Developmental Biology

Applications

Caenorhabditis Elegans

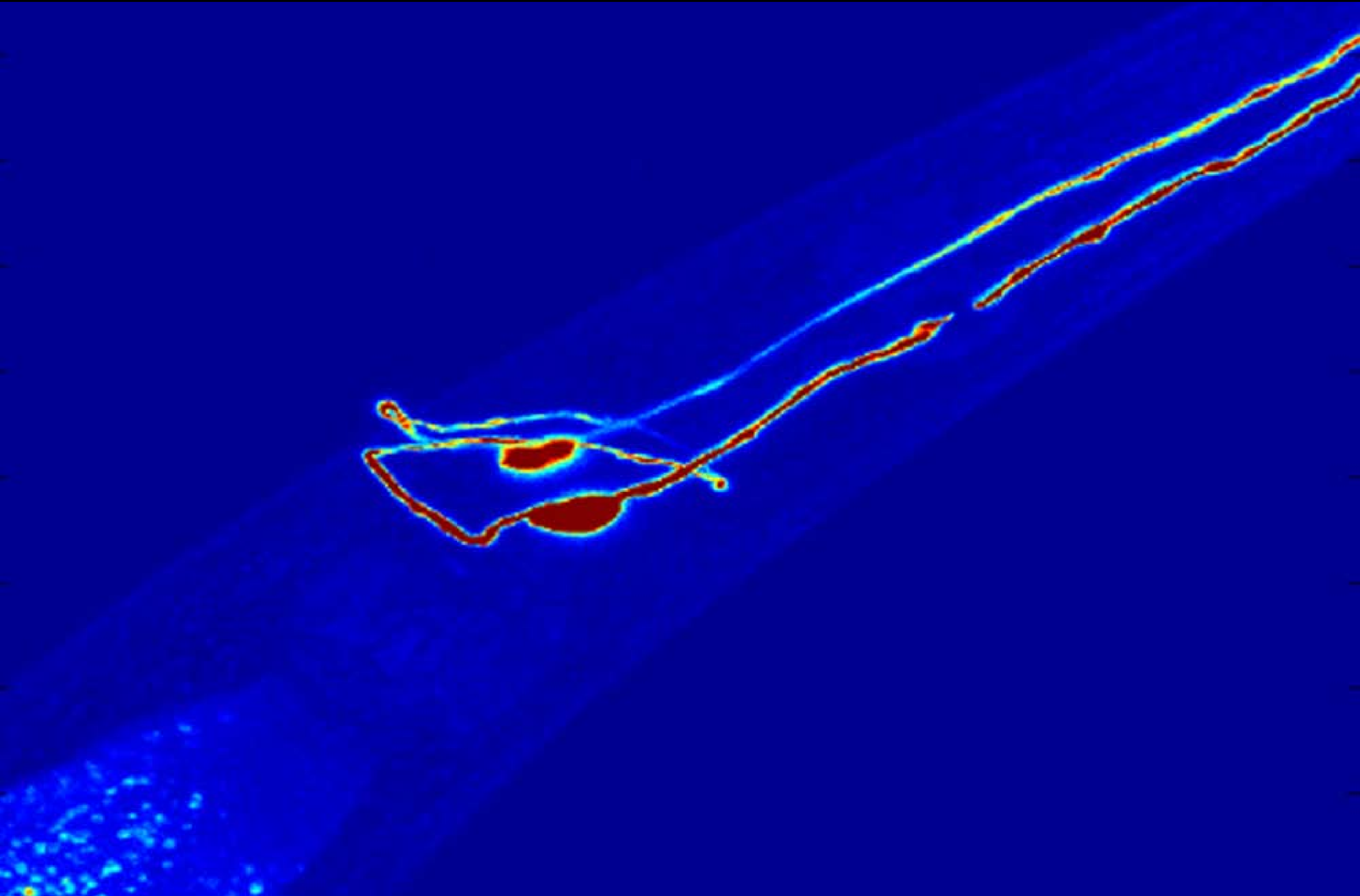
- simple model organism
- similarities to higher organisms
- genome fully sequenced
- easy to handle

Applications

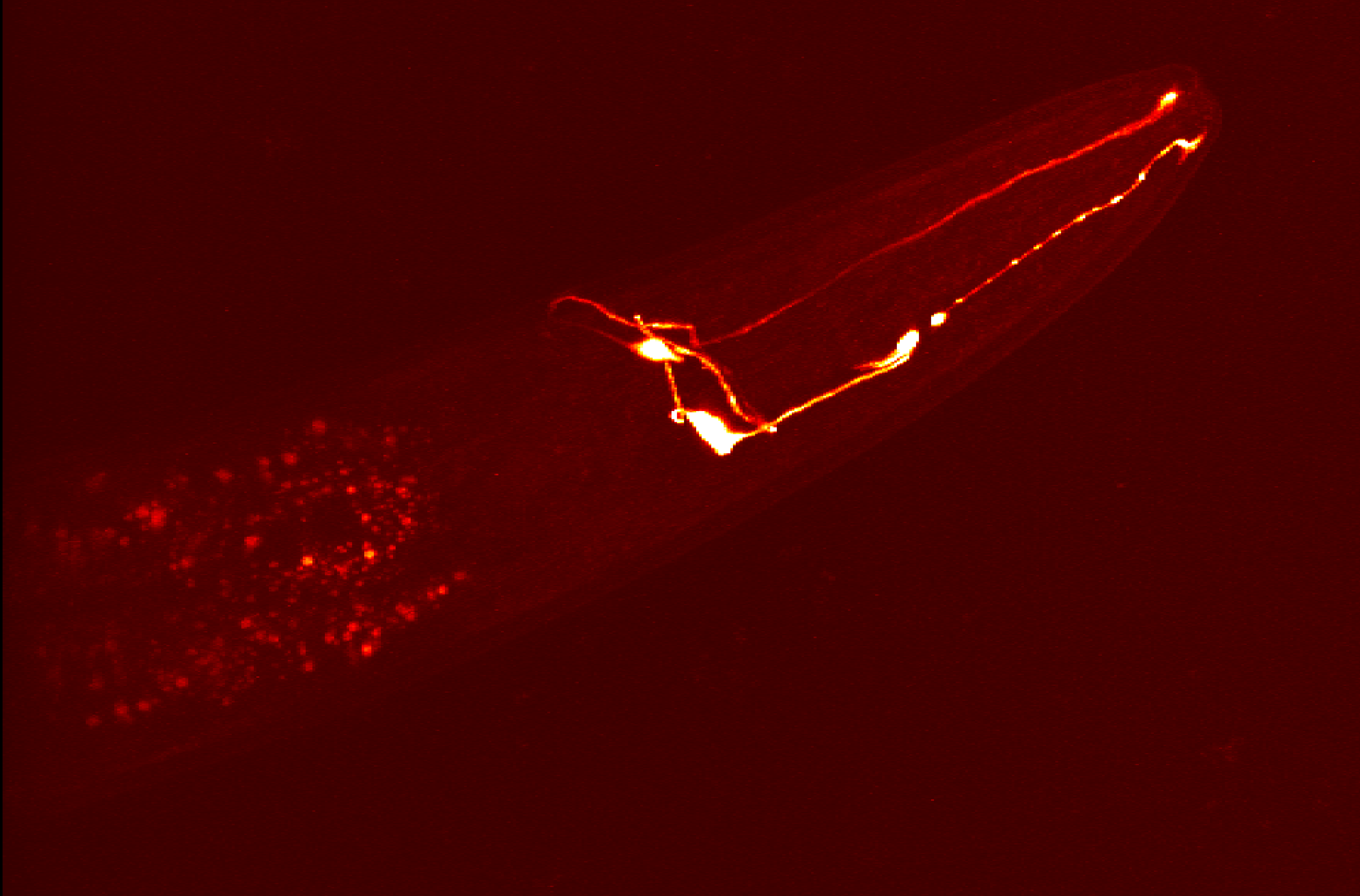
Caenorhabditis Elegans

- 80 µm x 1 mm
- about 1300 cells
- 302 neurons
- invariant wiring diagram
- neuronal system completely encodes behavior

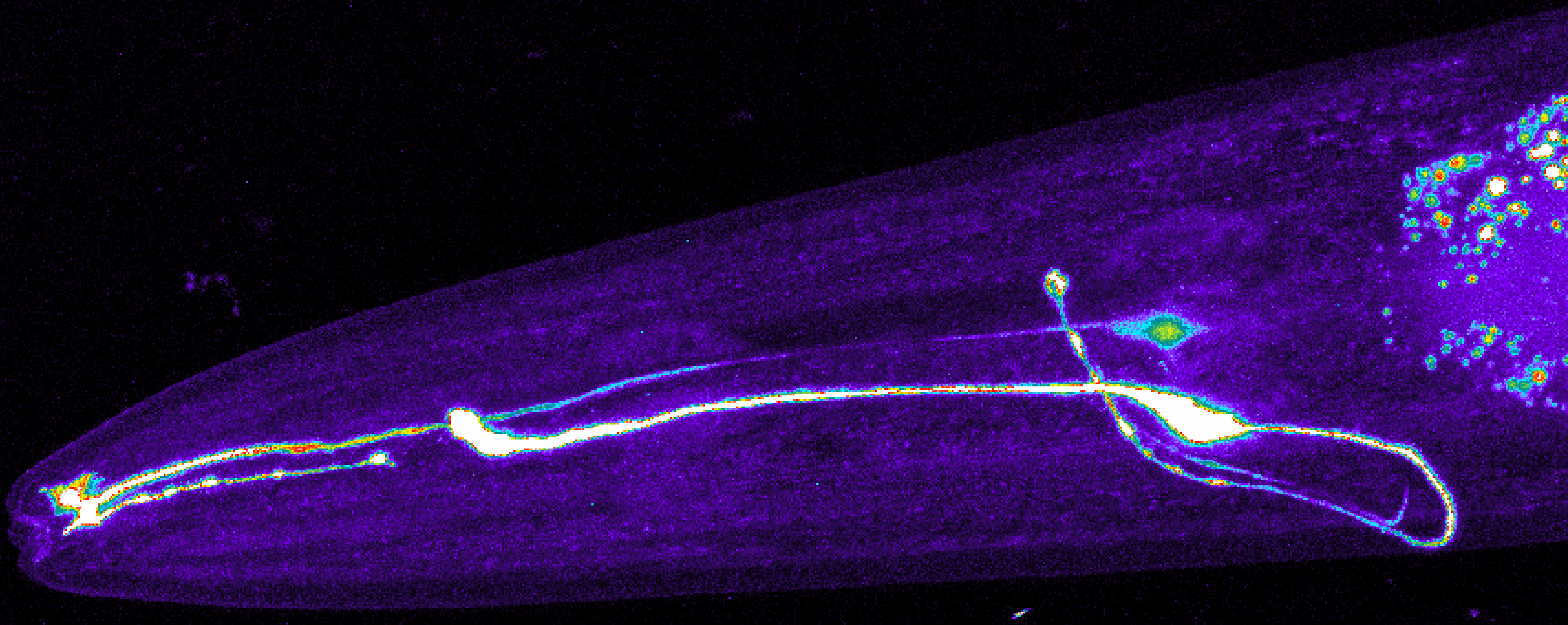
Applications



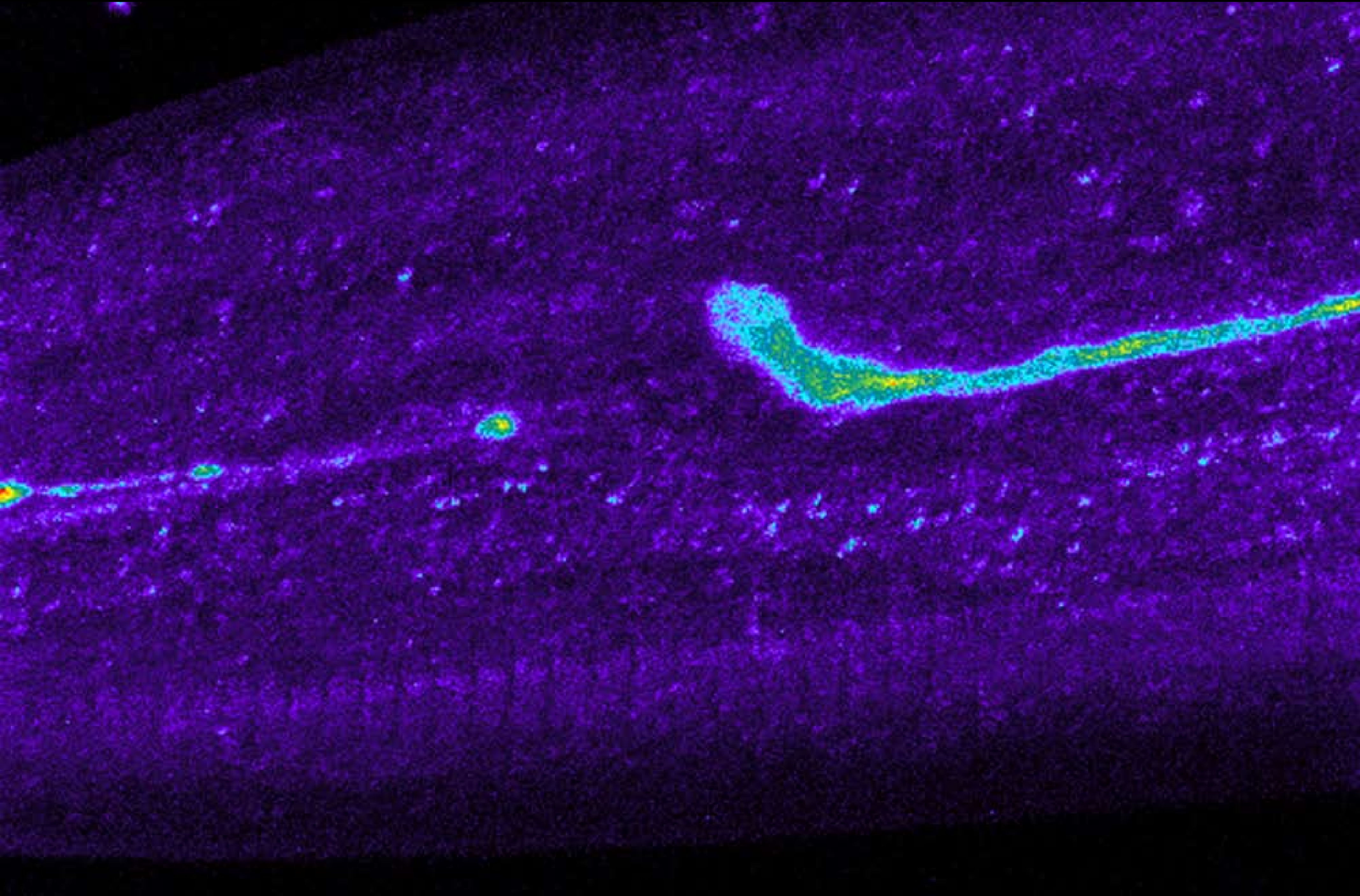
Applications



Applications

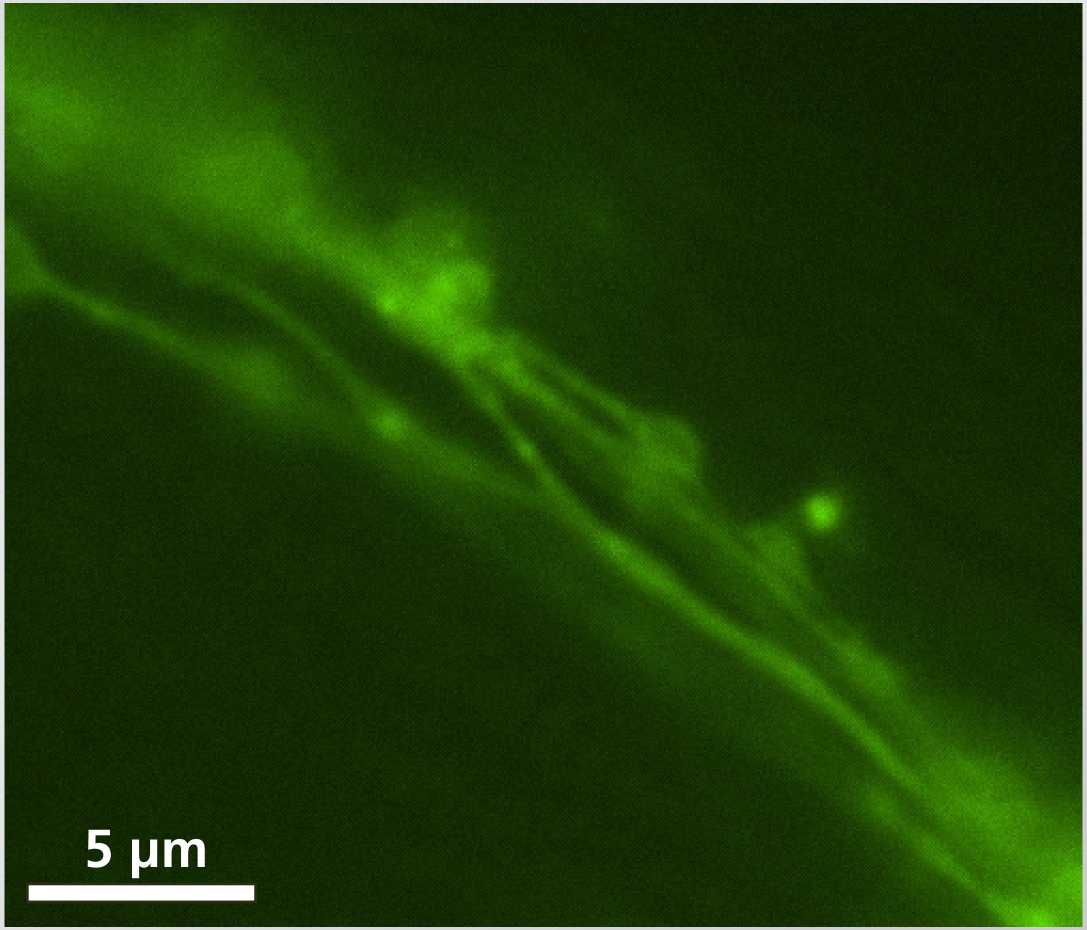


Applications



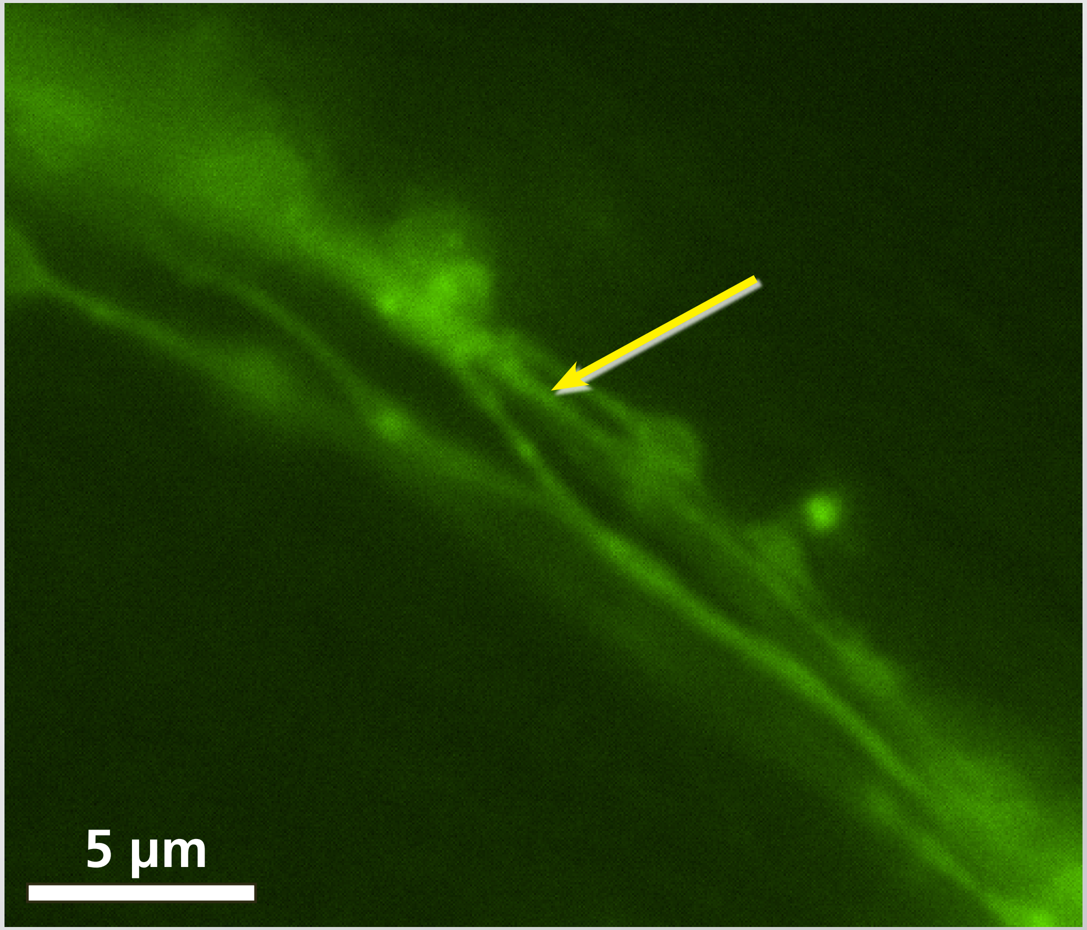
Applications

cut single dendrite in amphid bundle



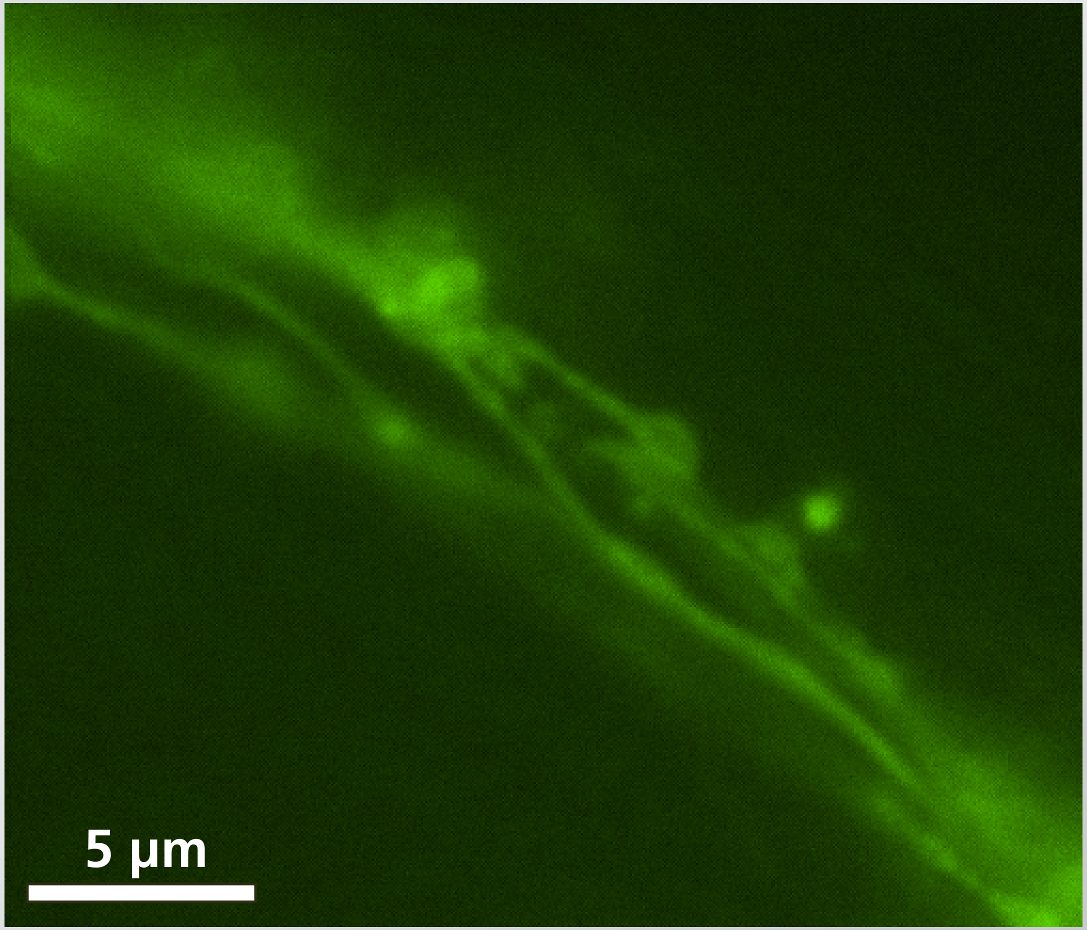
Applications

cut single dendrite in amphid bundle



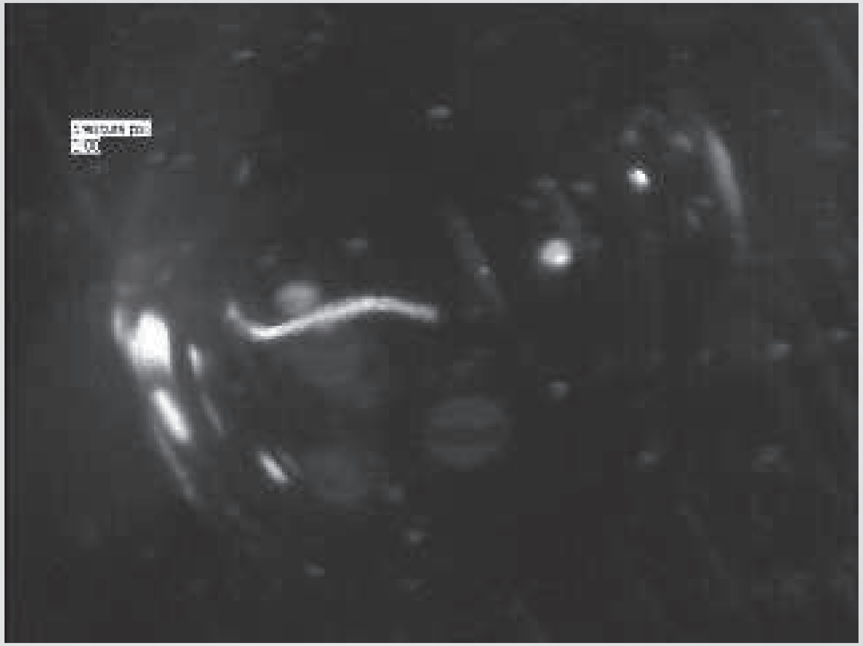
Applications

cut single dendrite in amphid bundle



Applications

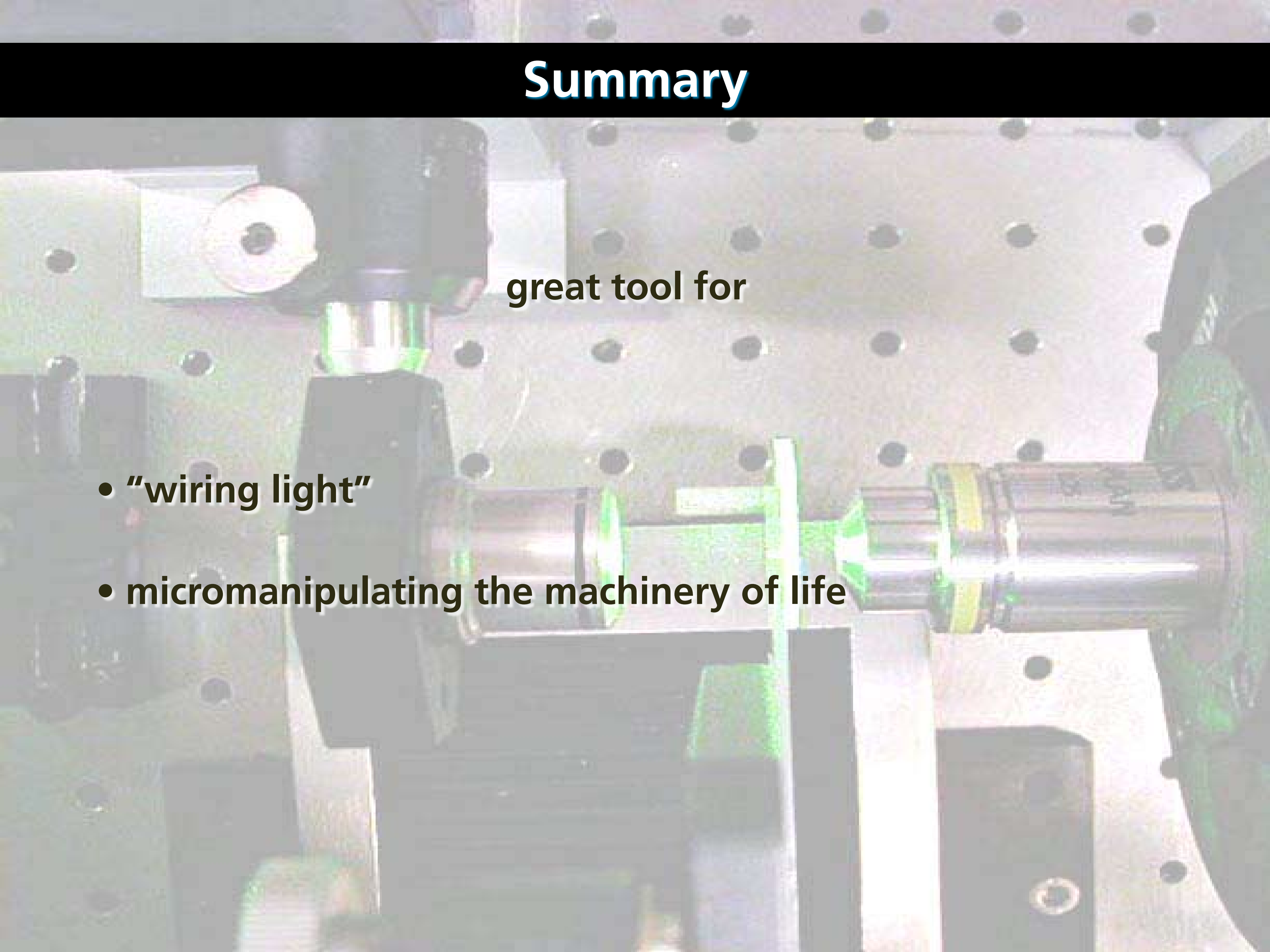
surgery results in quantifiable behavior changes



before

after

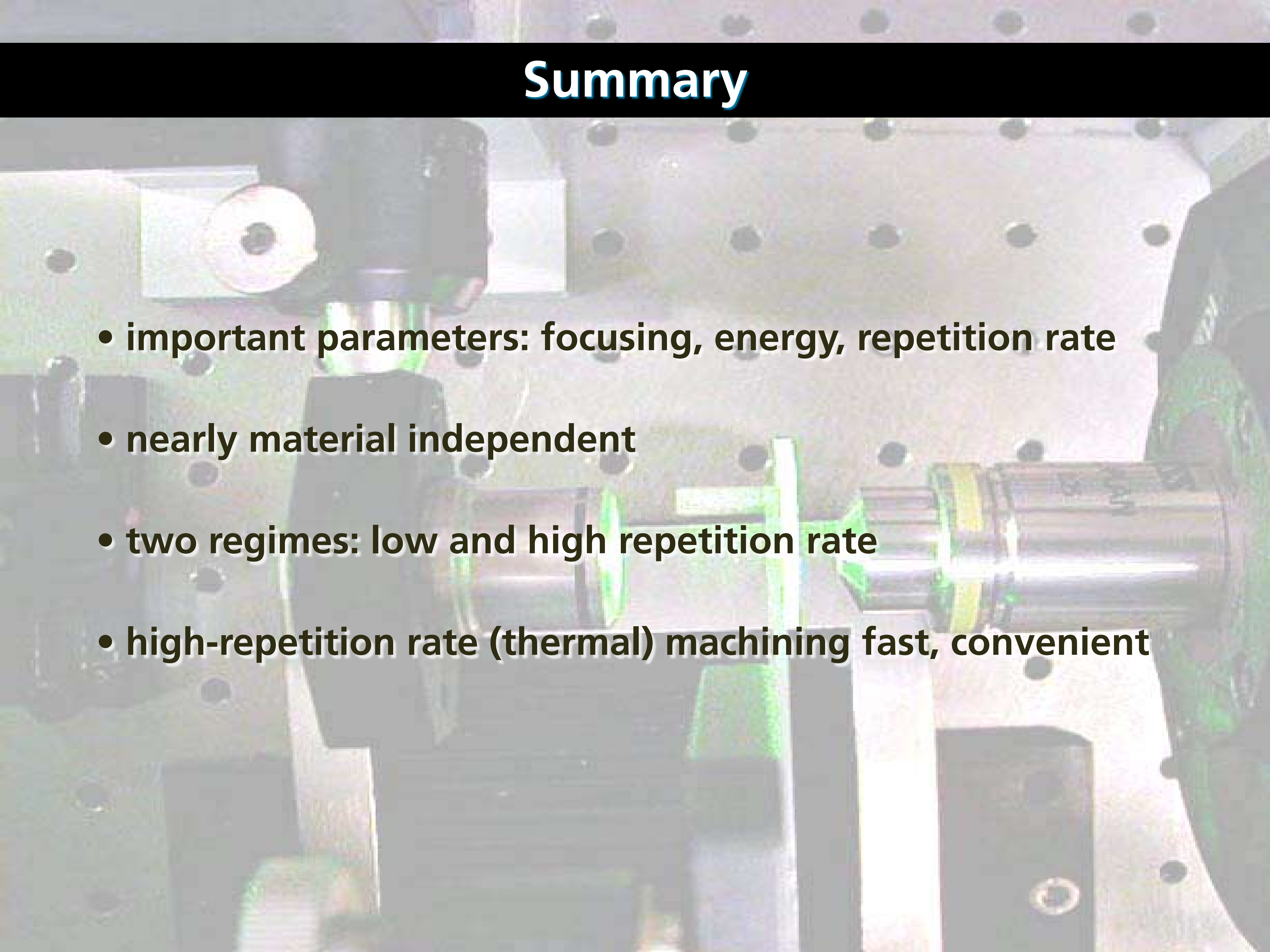
Summary



great tool for

- “wiring light”
- micromanipulating the machinery of life

Summary



- important parameters: focusing, energy, repetition rate
- nearly material independent
- two regimes: low and high repetition rate
- high-repetition rate (thermal) machining fast, convenient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LABORATORY OF
APPLIED SCIENCE

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National Science Foundation

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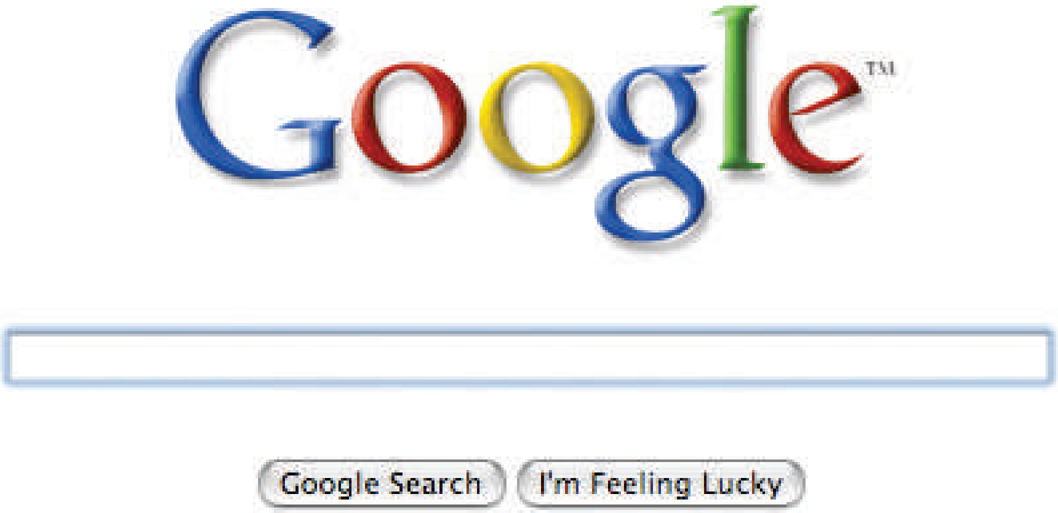
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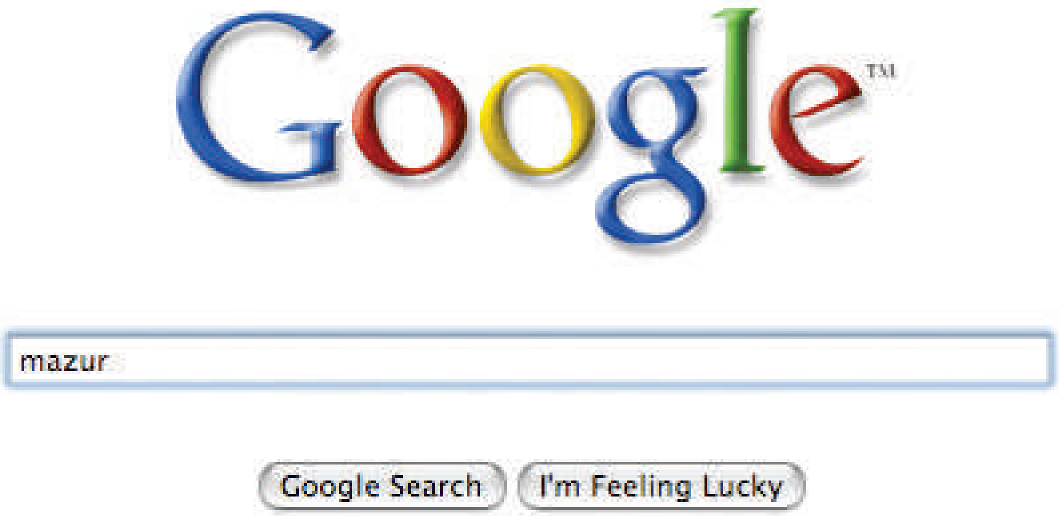
Google Search
I'm Feeling Lucky



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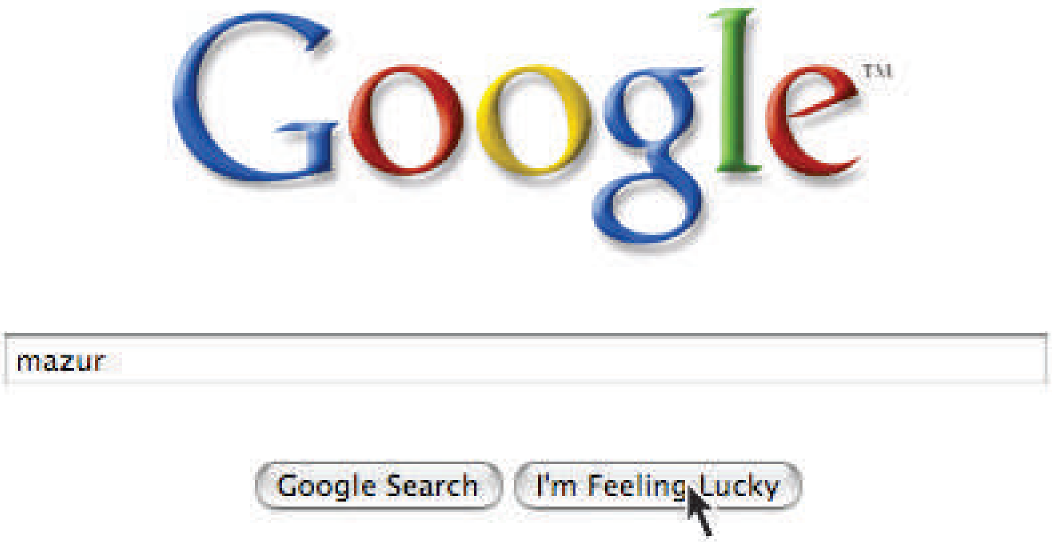

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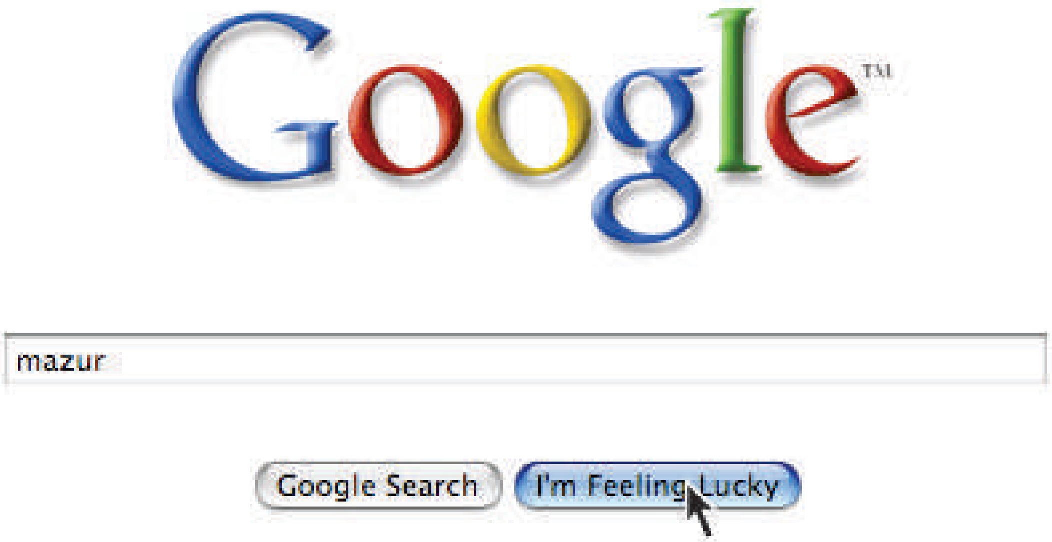

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