

Femtosecond laser-induced microexplosions in transparent materials

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Chris Schaffer
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Introduction

Laser-Induced Electric Breakdown in Solids

NICOLAAS BLOEMBERGEN, FELLOW, IEEE

Abstract—A review is given of recent experimental results on laser-induced electric breakdown in transparent optical solid materials. A fundamental breakdown threshold exists characteristic for each material. The threshold is determined by the same physical process as dc breakdown, namely, avalanche ionization. The dependence of the threshold on laser pulse duration and frequency is consistent with this process. The implication of this breakdown mechanism for laser bulk and surface damage to optical components is discussed. It also determines physical properties of self-focused filaments.

1. INTRODUCTION

THE history of laser-induced electric breakdown is almost as old as the history of lasers itself. Early in 1963 Maker *et al.* [1] reported damage to transparent dielectrics and the production of a spark in air by focusing pulsed ruby laser beam. The importance of these results for the production of laser-induced dense

plasmas and for the propagation characteristics of high-power laser beams through solids, liquids, and gases was quickly recognized. The subject of electric breakdown in transparent optical solids, including laser materials, windows, and other optical components, remained, until recently, largely an empirical or engineering science. Although a vast amount of theoretical and experimental effort was expended in the economically and technically important problem of optical damage, quantitative reproducible breakdown thresholds have been obtained only during the last two years. The situation was somewhat analogous to the development of our understanding of the problem of dc breakdown in electrical insulators. There, too, the field developed largely by engineering trial and error. Basic quantitative understanding was not achieved until reproducible experimental results on well-defined materials were obtained [2]. The difficulties in dc breakdown experiments were manifold: the influence of the occurrence of space charges, the effects of heating due to the few elec-

Introduction

Laser-Induced Electric Breakdown in Solids

NICOLAS BLOEMBERGEN, MITCHELL WEISS

Abstract: A review is given of recent experimental results on laser-induced electric breakdown in transparent optical solid materials. A fundamental breakdown threshold exists characteristic for each material. The threshold is determined by the same physical process as dielectric breakdown, avalanche ionization. The dependence of the threshold on laser pulse duration and frequency is consistent with this process. The implication of this breakdown mechanism for laser bulk and surface damage components is discussed. It also determines physical properties of self-focused beams.

1. INTRODUCTION

THE history of laser-induced electric breakdown is important in the history of lasers itself. Early in 1961 Maker et al. (1) reported the first observation of laser-induced electric breakdown in the production of a spark in an insulating material by a laser beam. The importance of these results for the production of laser-induced electric

breakdown in transparent solids, liquids, and gases was quickly recognized. The subject of electric breakdown in transparent optical solids, including laser materials, and other optical components, remained quiet until recently, largely an empirical or engineering science. Although a lot of work in theoretical and experimental studies was expended in the economically and technically important problem of optical damage, quantitative reproducible breakdown thresholds with unambiguous theoretical interpretations have been obtained only during the last two years. The situation was somewhat analogous to the development of an understanding of the problem of dielectric breakdown by engineering first and then by basic quantitative understanding was not achieved until reproducible experimental results on well-defined materials were obtained (2). The difficulties in obtaining experiments were mainly the influence of the occurrence of space charge, the effects of heating and

Introduction

DAMAGED

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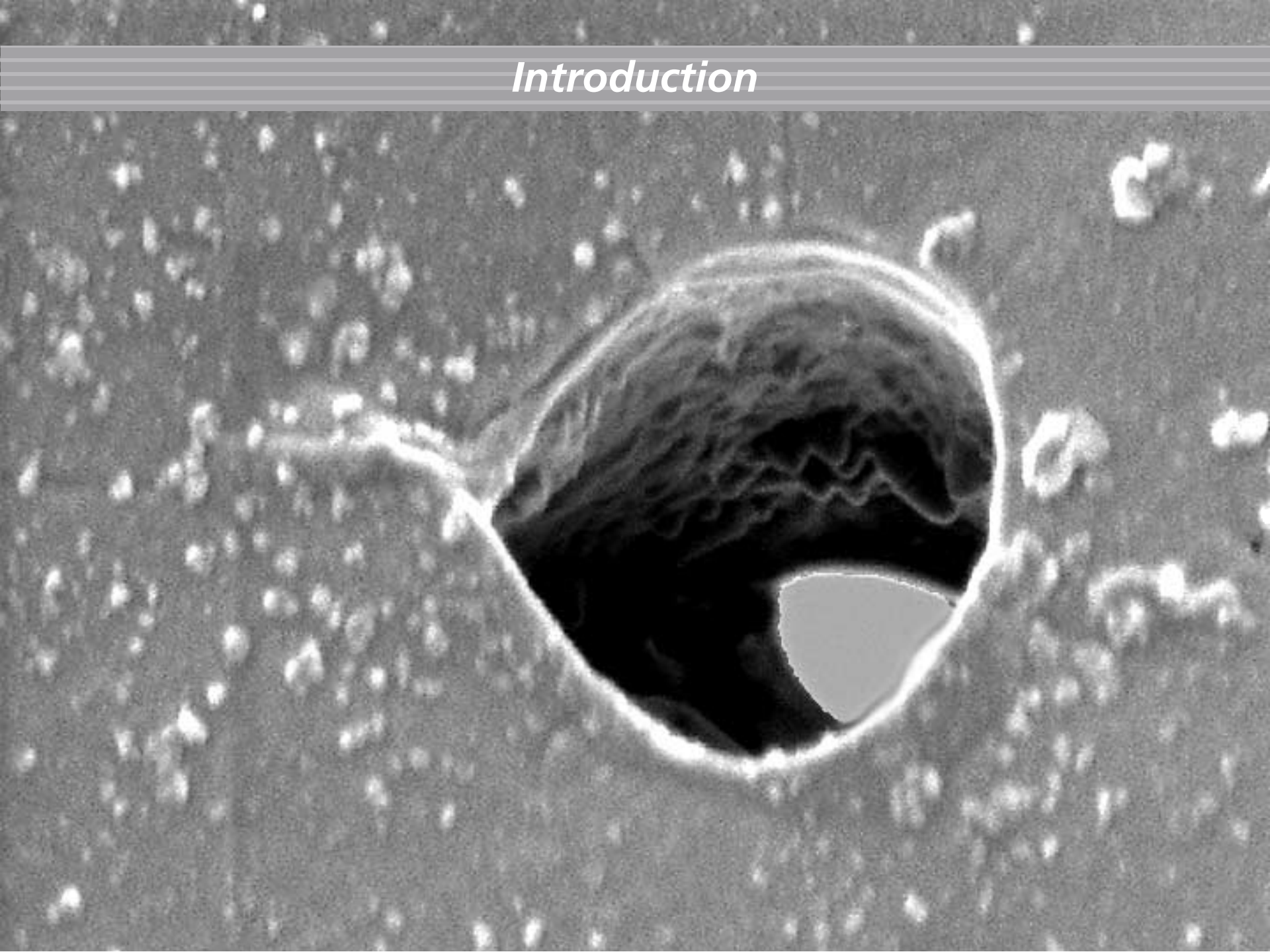
22nd ANNUAL BOULDER DAMAGE SYMPOSIUM
Proceedings



LASER-INDUCED DAMAGE
IN OPTICAL MATERIALS: 1990

24-26 OCTOBER 1990
BOULDER, COLORADO

Introduction

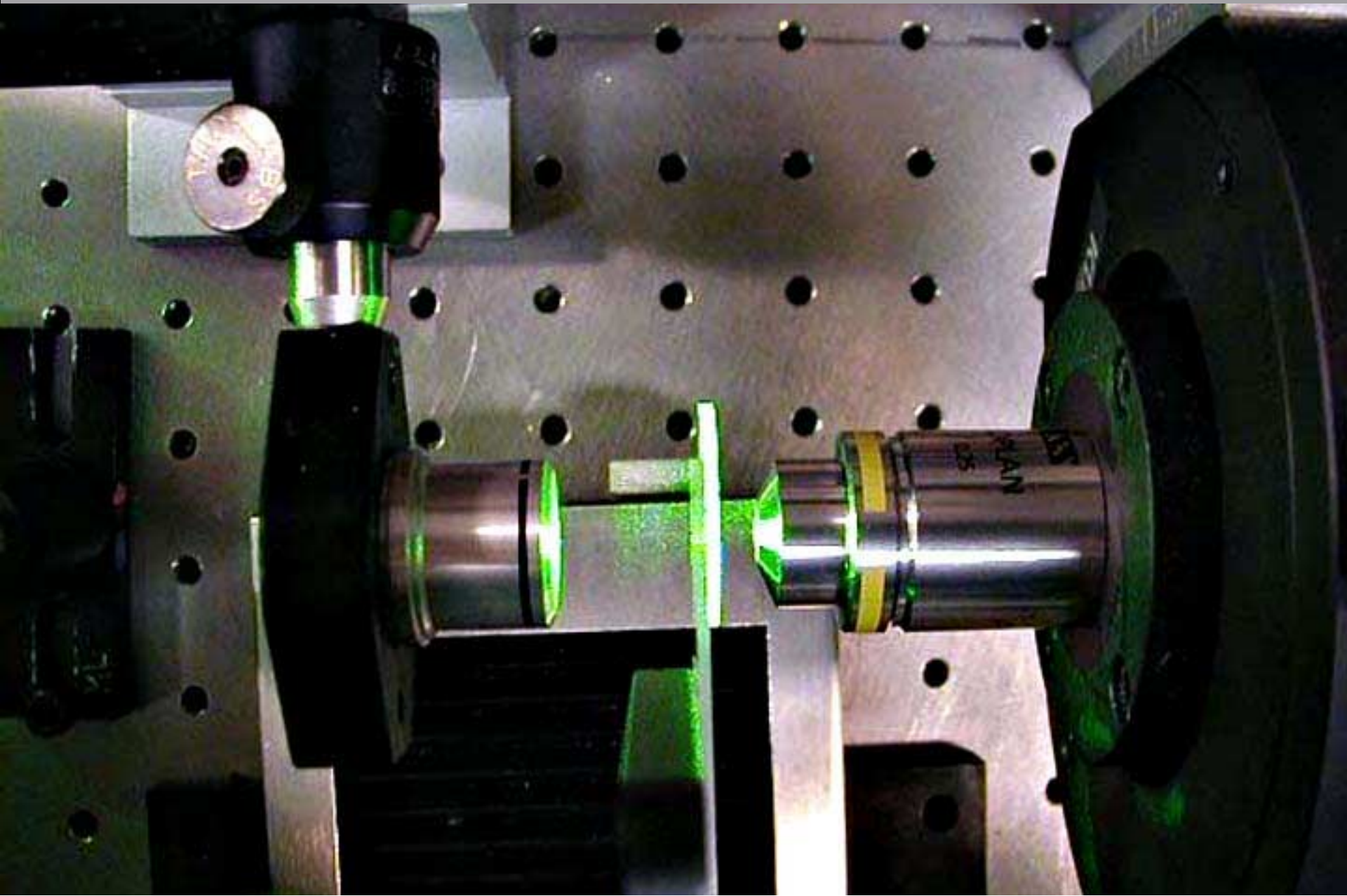


Introduction



use damage for processing!

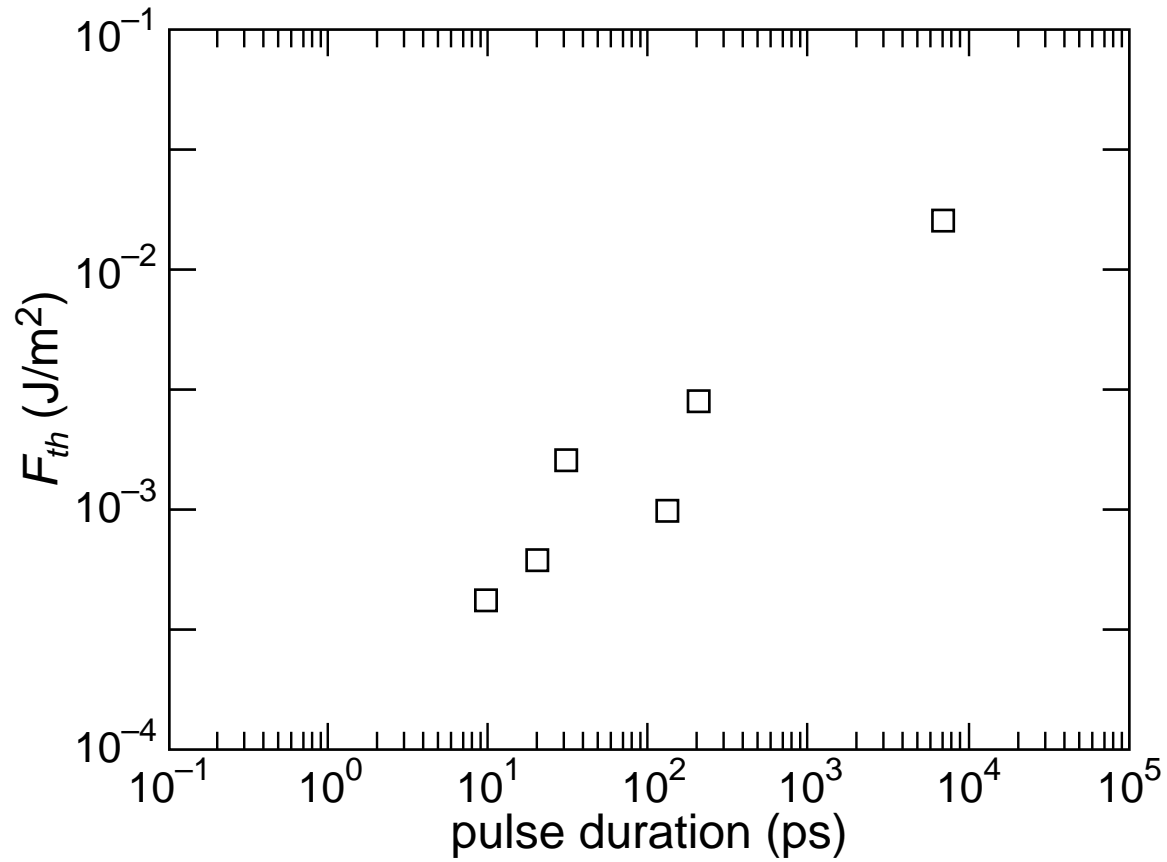
Outline



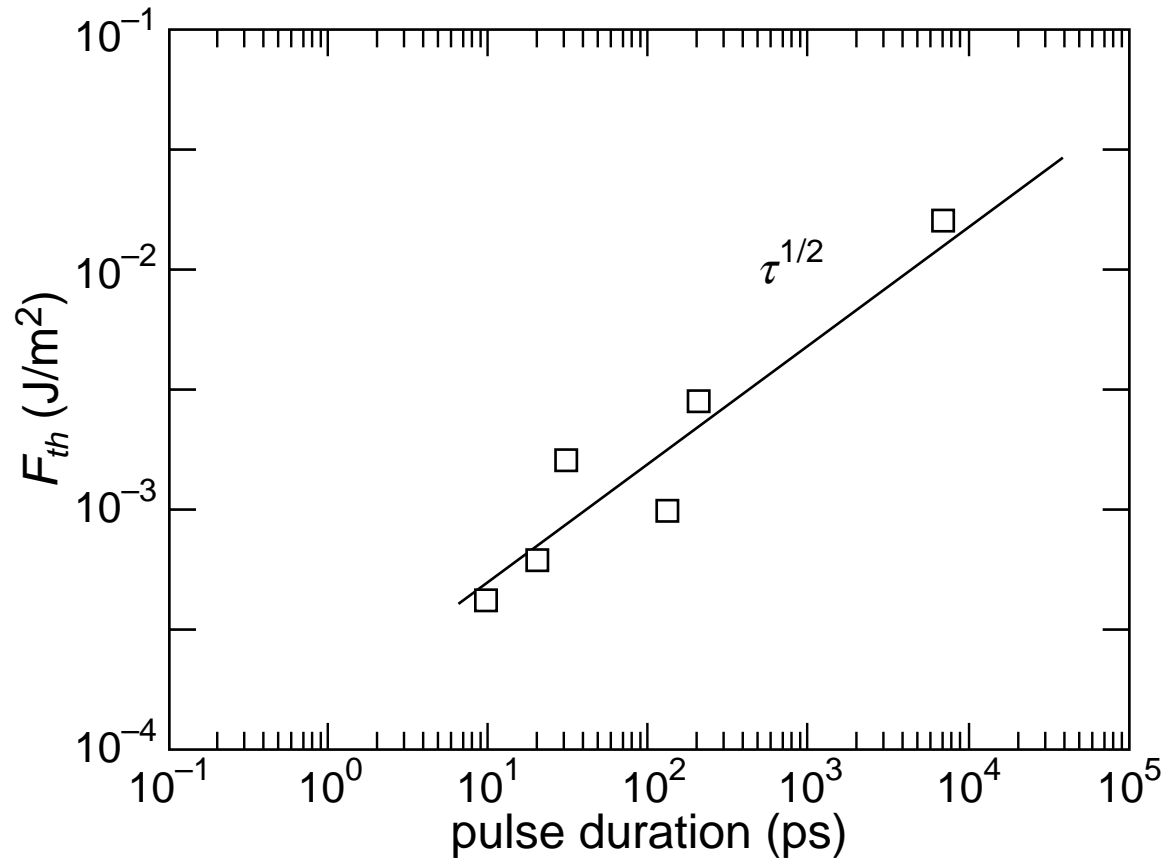
Outline

- ▶ **Processing with fs pulses**
- ▶ **Role of focusing**
- ▶ **Low-energy processing**

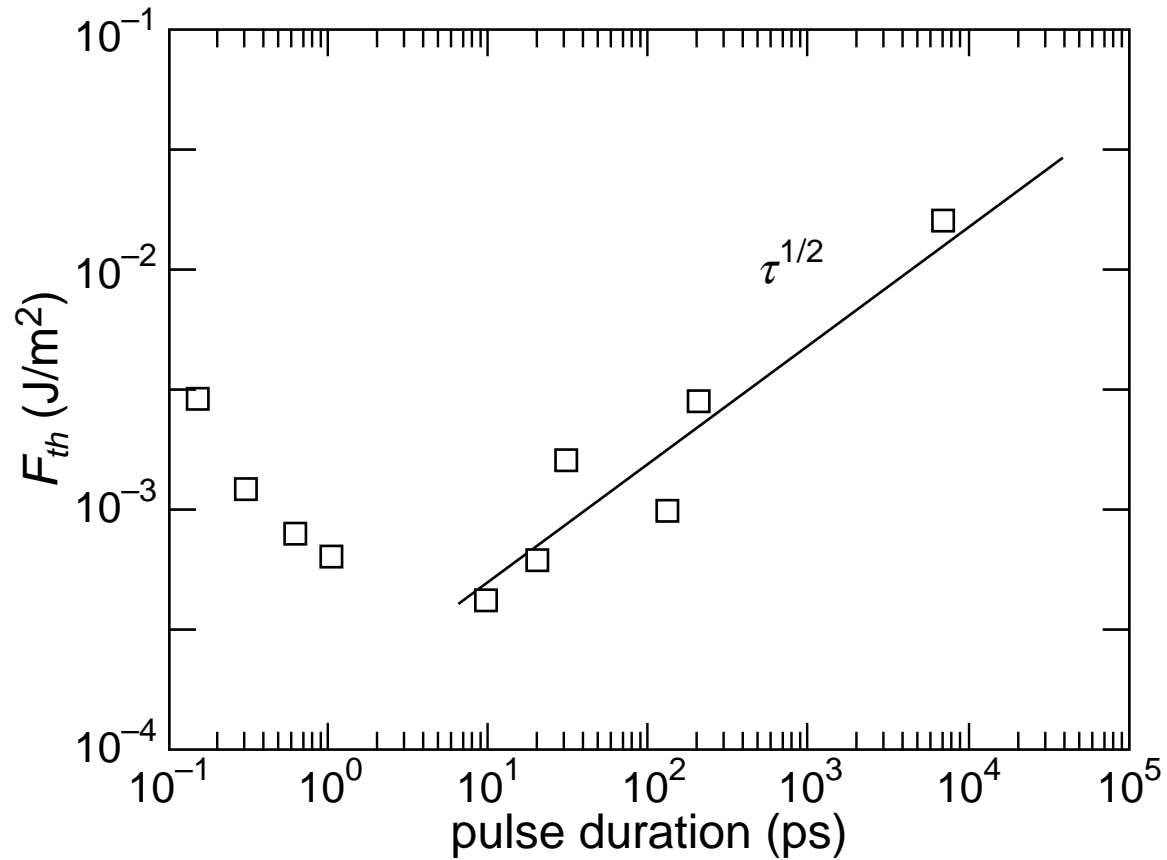
Processing with fs pulses



Processing with fs pulses

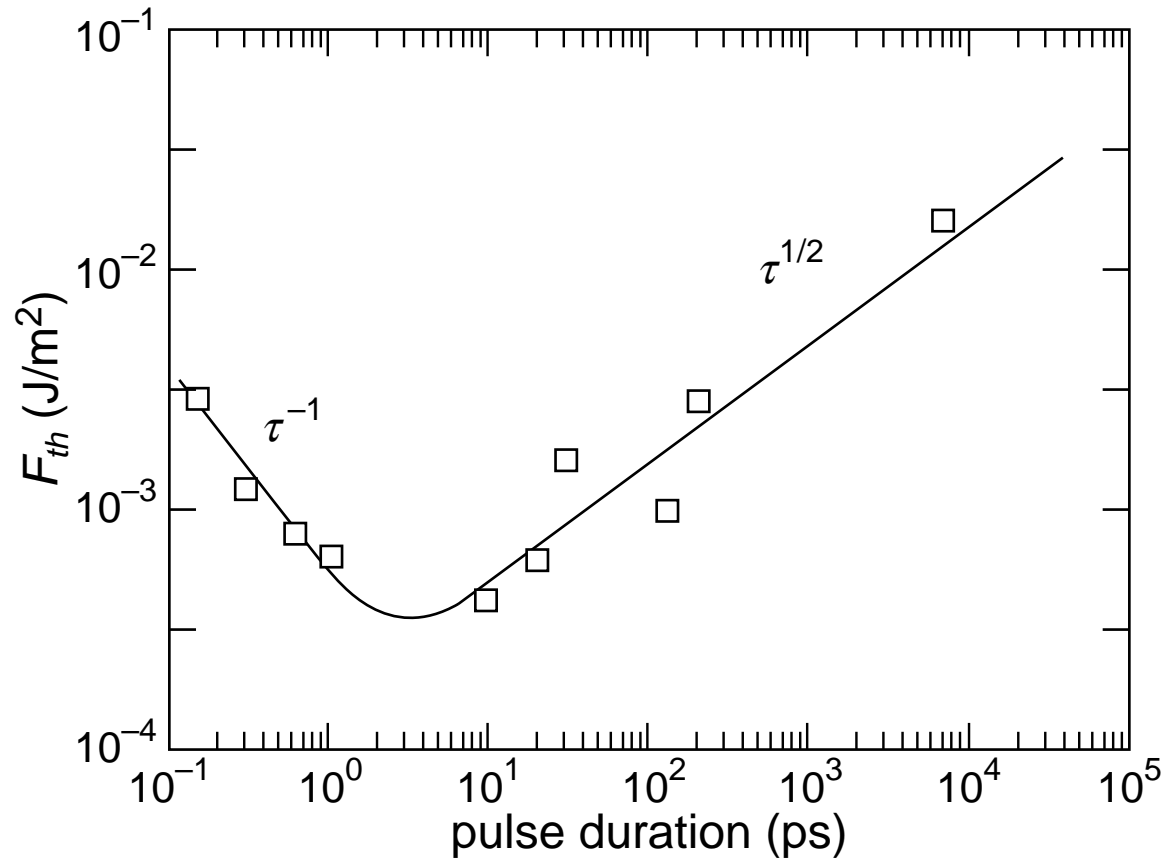


Processing with fs pulses



Du et al., *Appl. Phys. Lett.* 64, 3071 (1994)

Processing with fs pulses



Du et al., *Appl. Phys. Lett.* 64, 3071 (1994)

Processing with fs pulses

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

D. von der Linde and H. Schöler

Breakdown threshold and plasma formation in femtosecond laser–solid interaction

D. von der Linde and H. Schöler

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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. © 1996 Optical Society of America

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 short x-ray pulses. To produce such a plasma, the intensity must rise from the intensity level of the incident laser pulse to a threshold value on a time scale

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. Recently, Du *et al.*⁶ carried out laser-induced breakdown experiments on fused silica with pulses ranging in duration from 100 to 150 fs. They reported a breakdown threshold of the order of 10^{14} W/cm² for 100-fs pulses and of the order of 10^{13} W/cm² for 150-fs pulses.

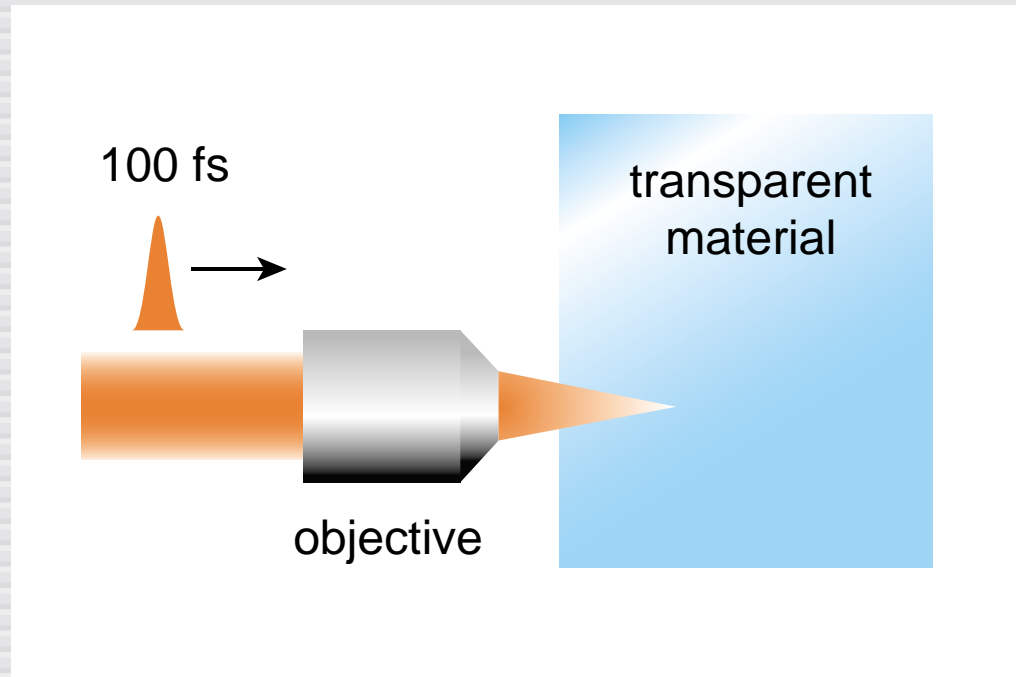
Processing with fs pulses

**"... clear evidence that no bulk plasmas ...
[and] ... no bulk damage could be produced
with femtosecond laser pulses."**

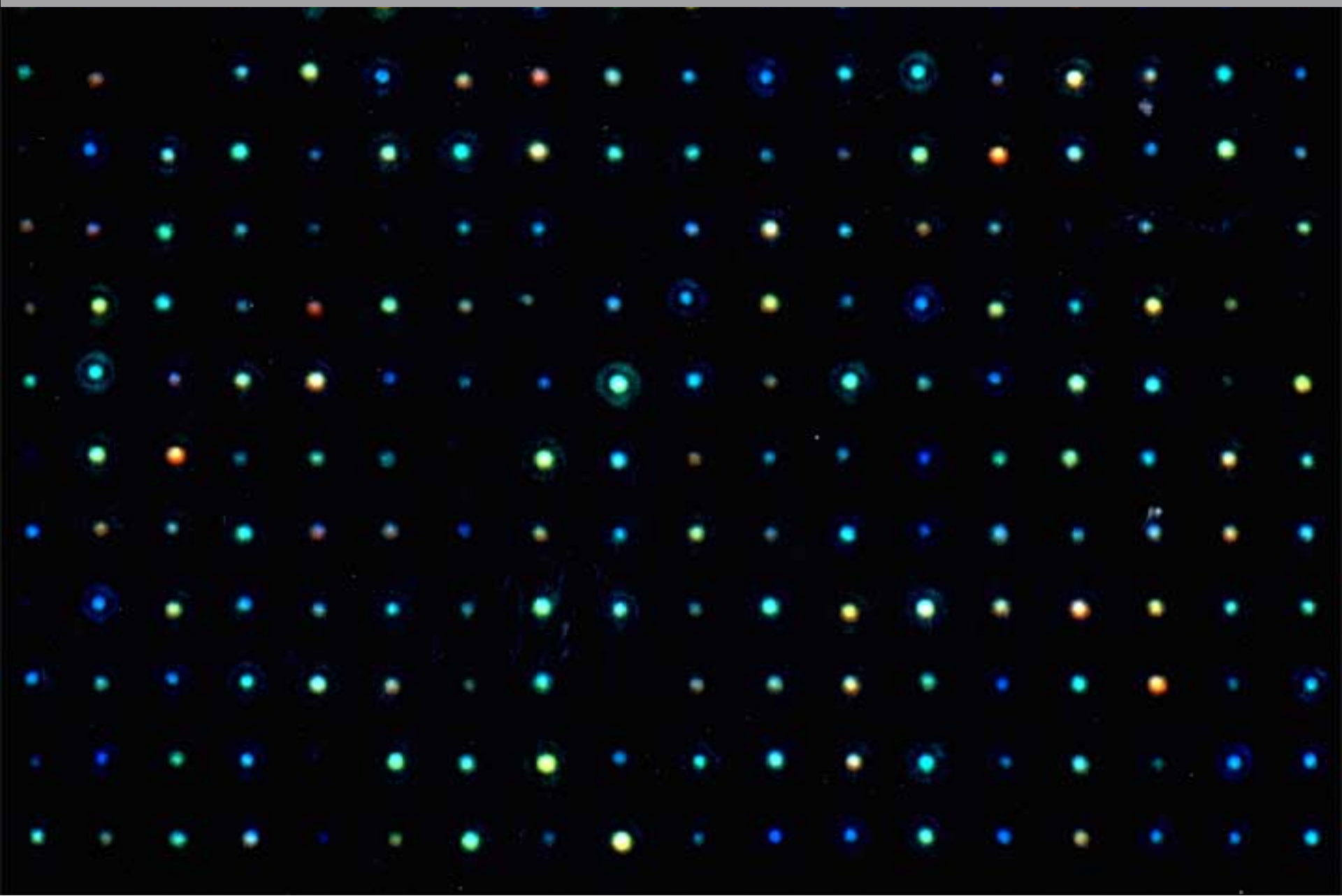
von der Linde, et al., *J. Opt. Soc. Am.* 13, 216 (1996)

Processing with fs pulses

focus laser beam inside material



Processing with fs pulses

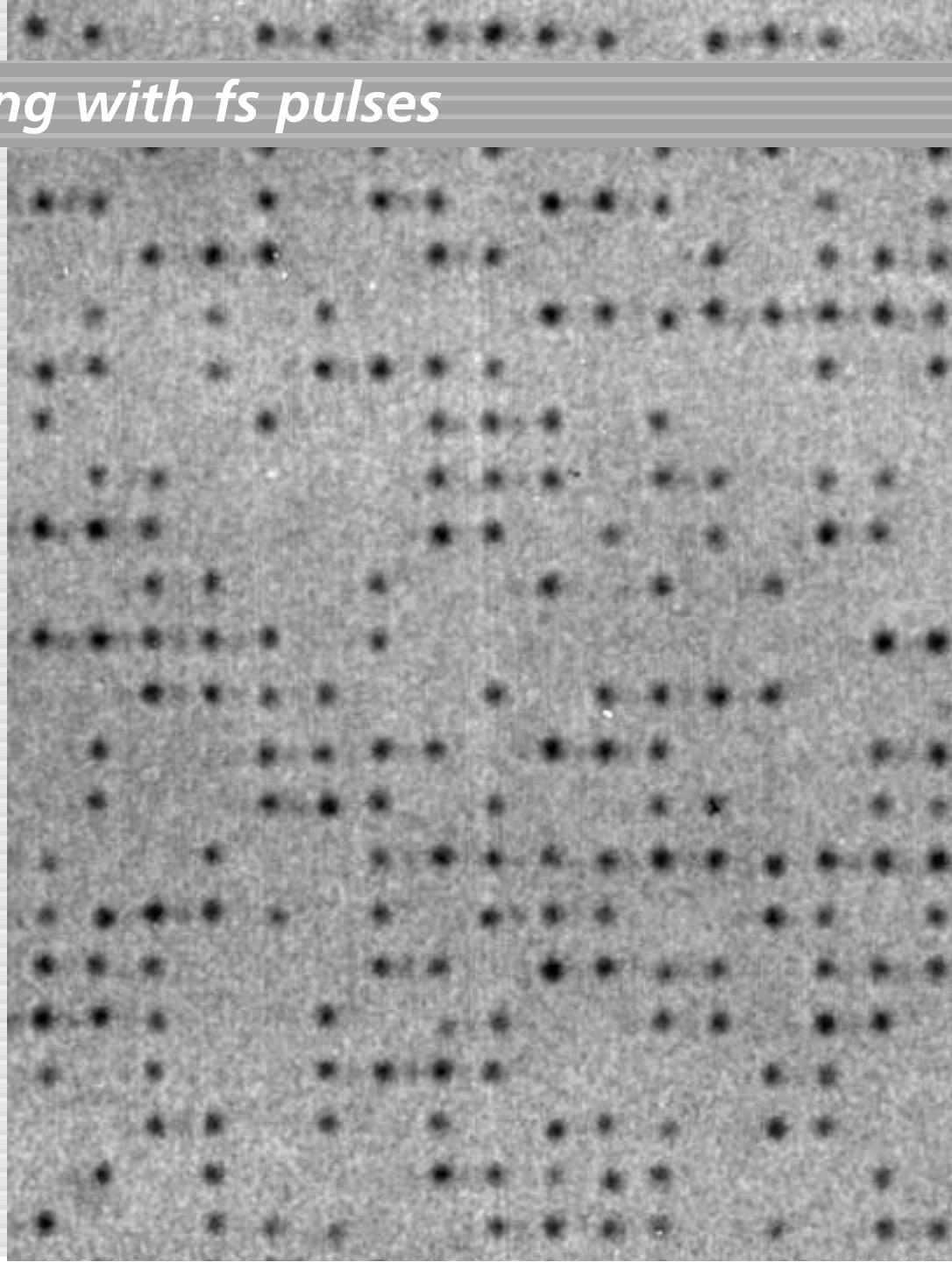


Processing with fs pulses

2 x 2 μm array

fused silica, 0.65 NA

0.5 μJ , 100 fs, 800 nm



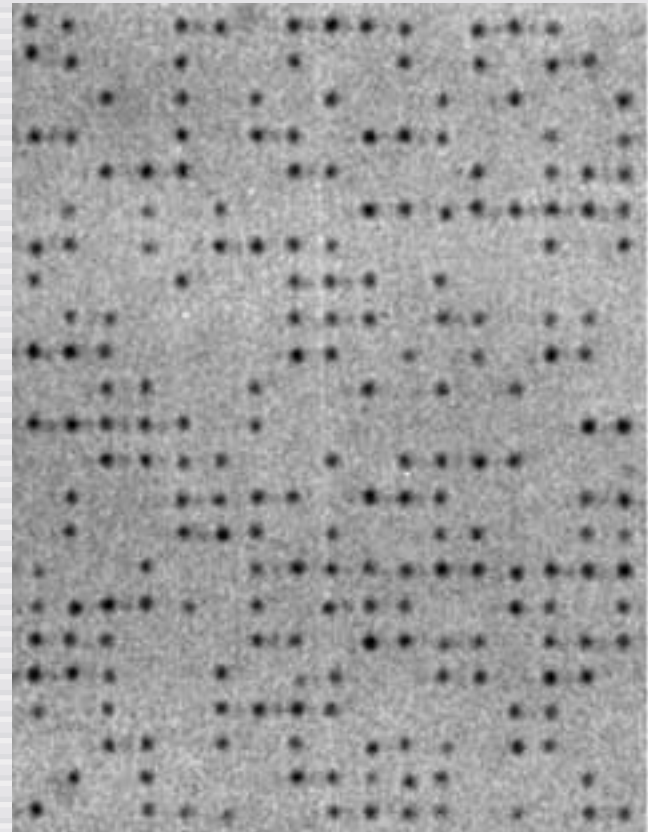
***Opt. Lett.* 21, 2023 (1996)**

Processing with fs pulses

2 x 2 μm array

fused silica, 0.65 NA

0.5 μJ , 100 fs, 800 nm

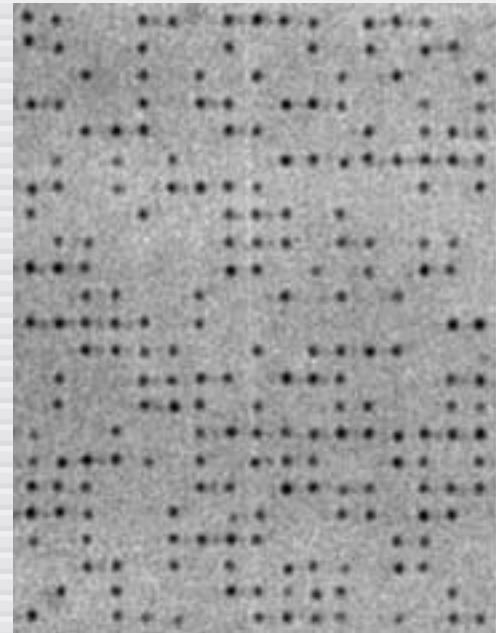


Processing with fs pulses

2 x 2 μm array

fused silica, 0.65 NA

0.5 μJ , 100 fs, 800 nm

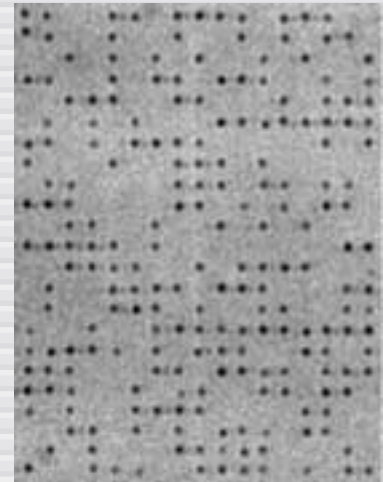


Processing with fs pulses

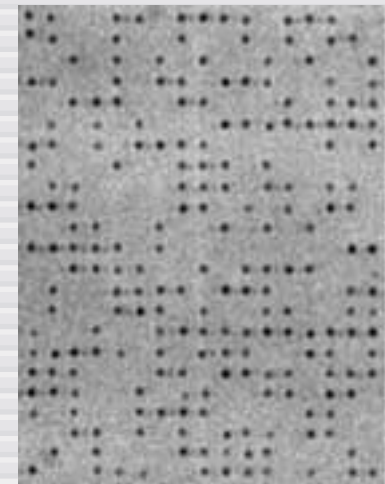
2 x 2 μm array

fused silica, 0.65 NA

0.5 μJ , 100 fs, 800 nm



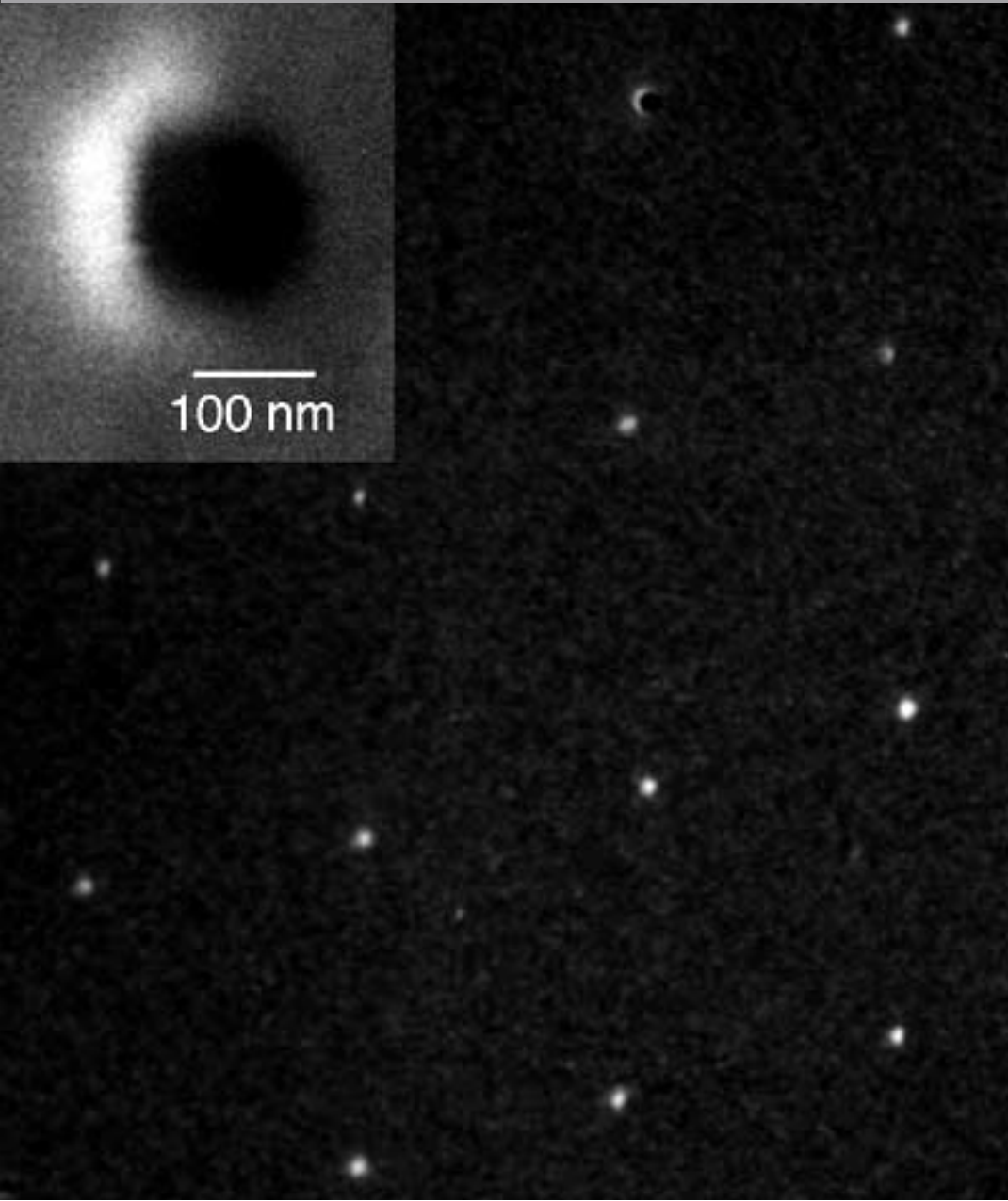
Processing with fs pulses



100 fs
0.5 μ J

200 ps
9 μ J

Processing with fs pulses



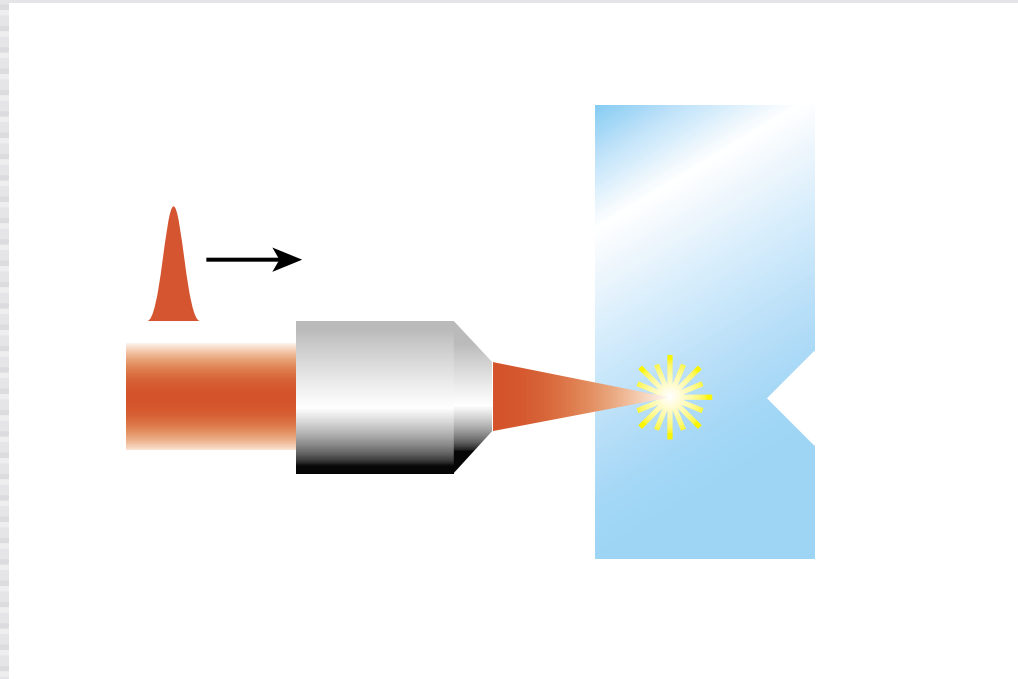
5 x 5 μm array

fused silica, 0.65 NA

0.5 μJ , 100 fs, 800 nm

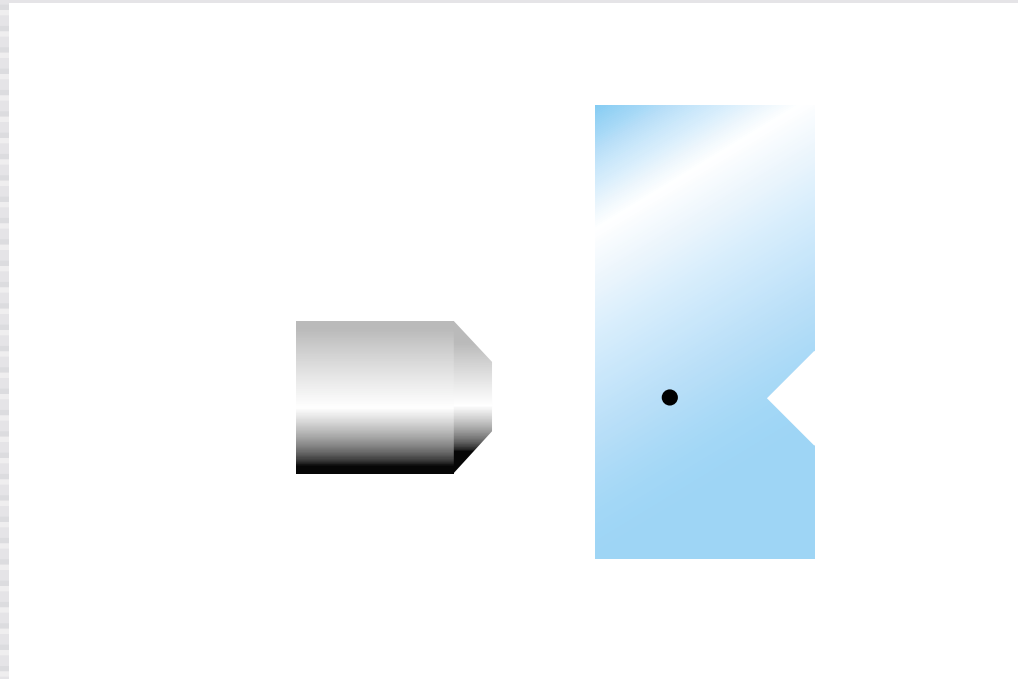
Opt. Lett. 21, 2023 (1996)

Processing with fs pulses



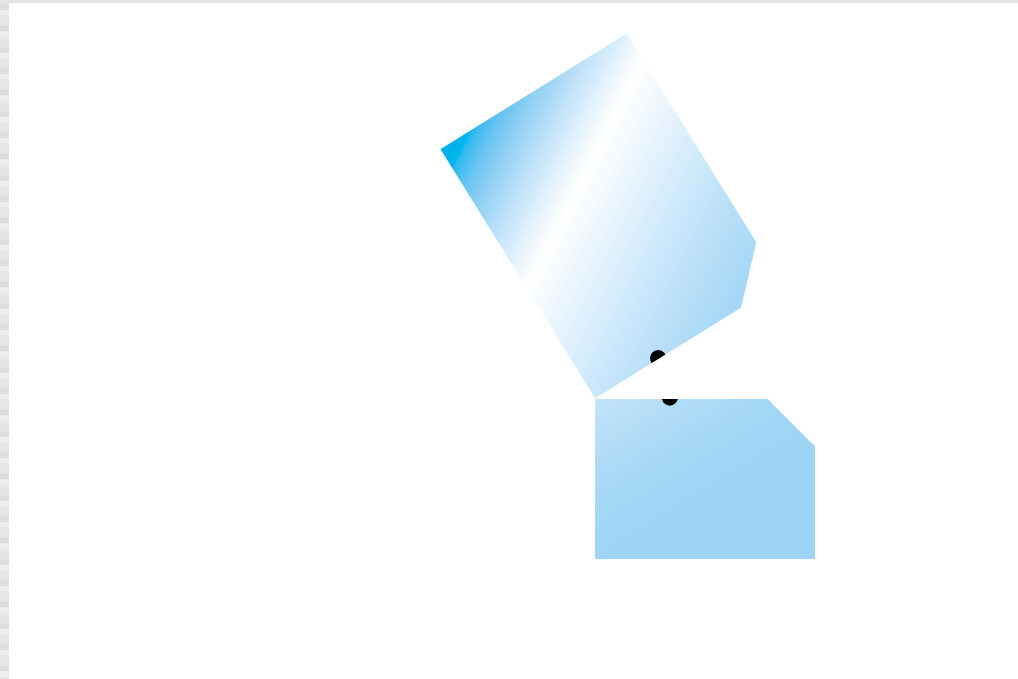
microstructure scribed sample

Processing with fs pulses



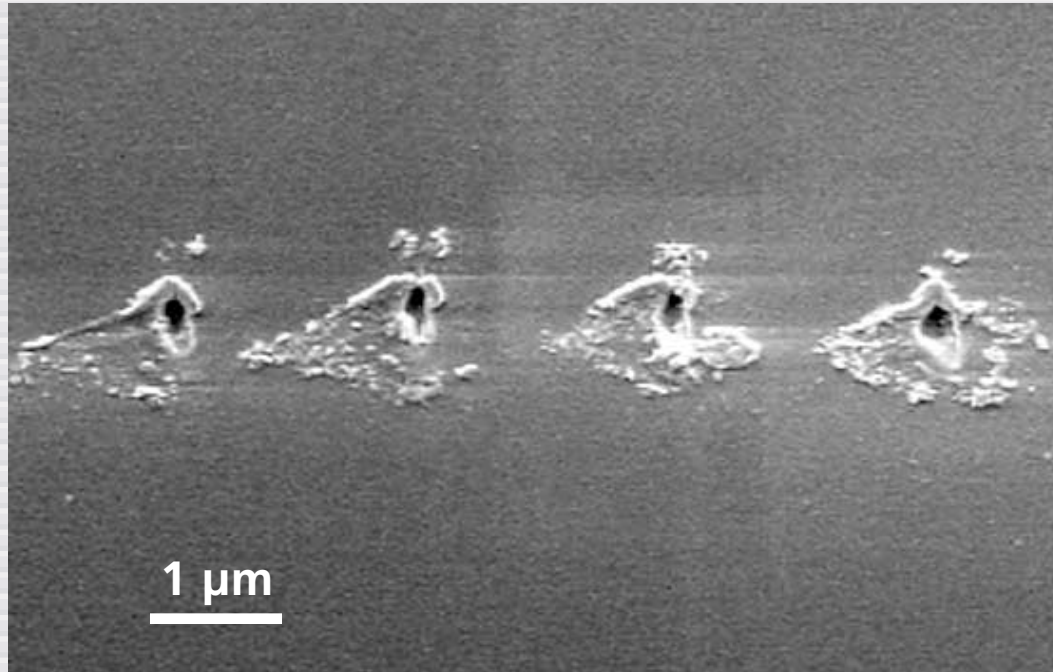
microstructure scribed sample

Processing with fs pulses



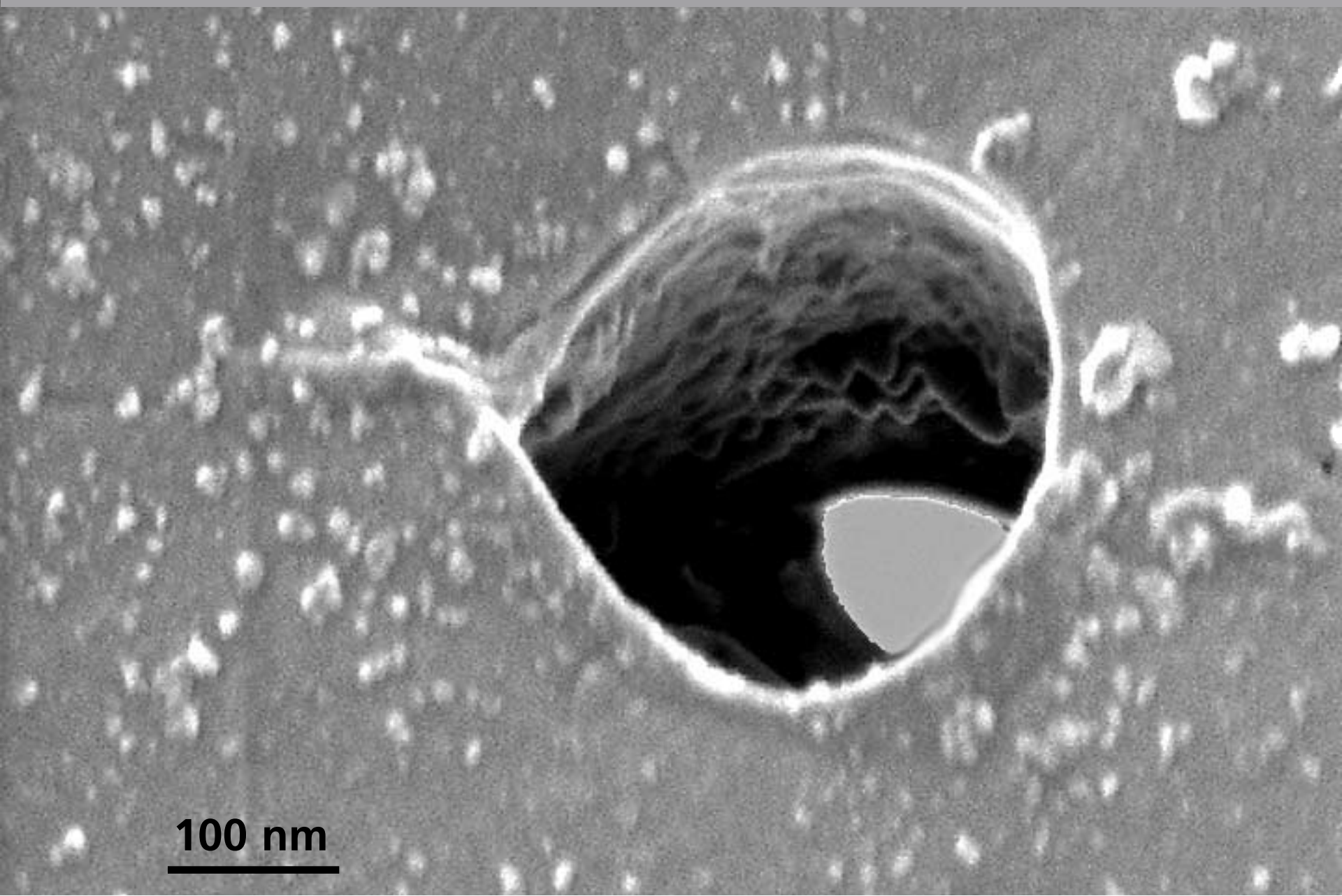
fracture along scribe line

Processing with fs pulses



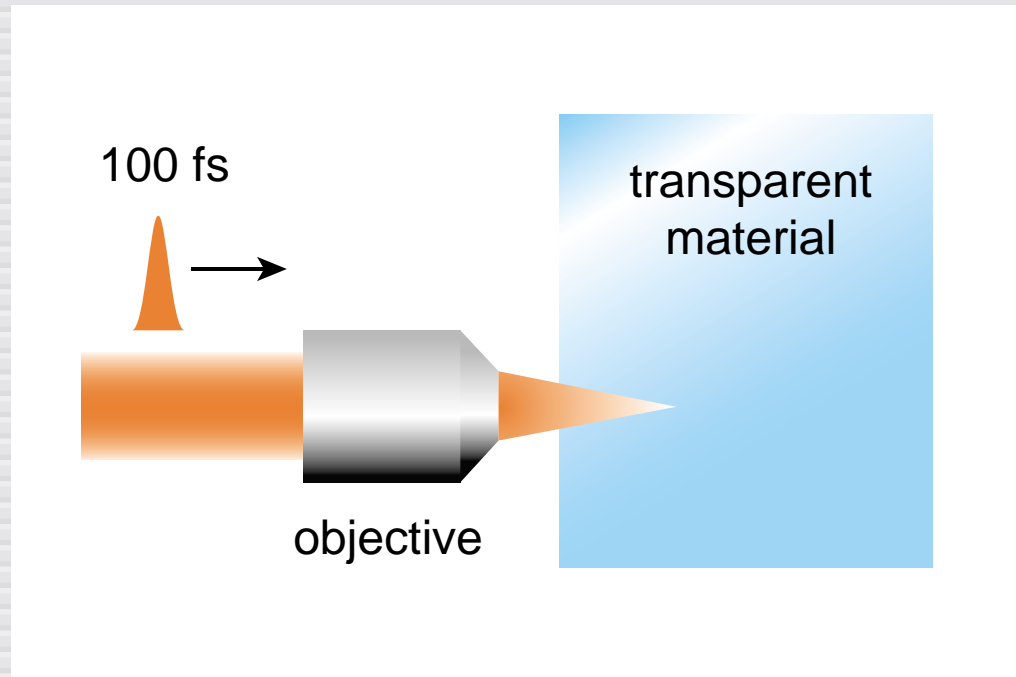
Corning 0211
1.4 NA, 140 nJ

Processing with fs pulses



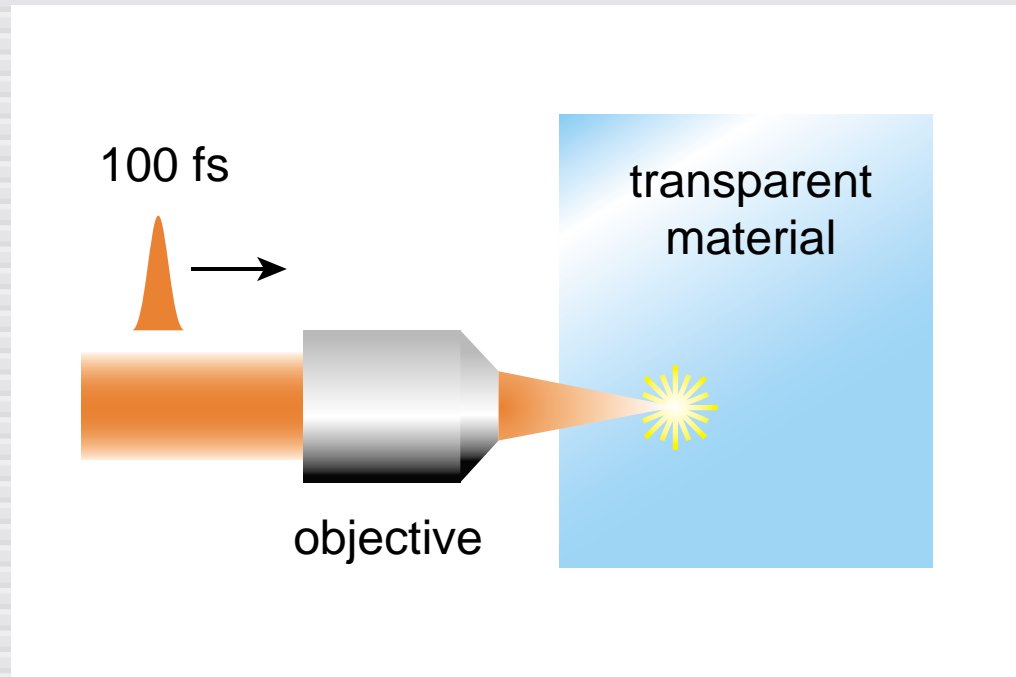
100 nm

Processing with fs pulses



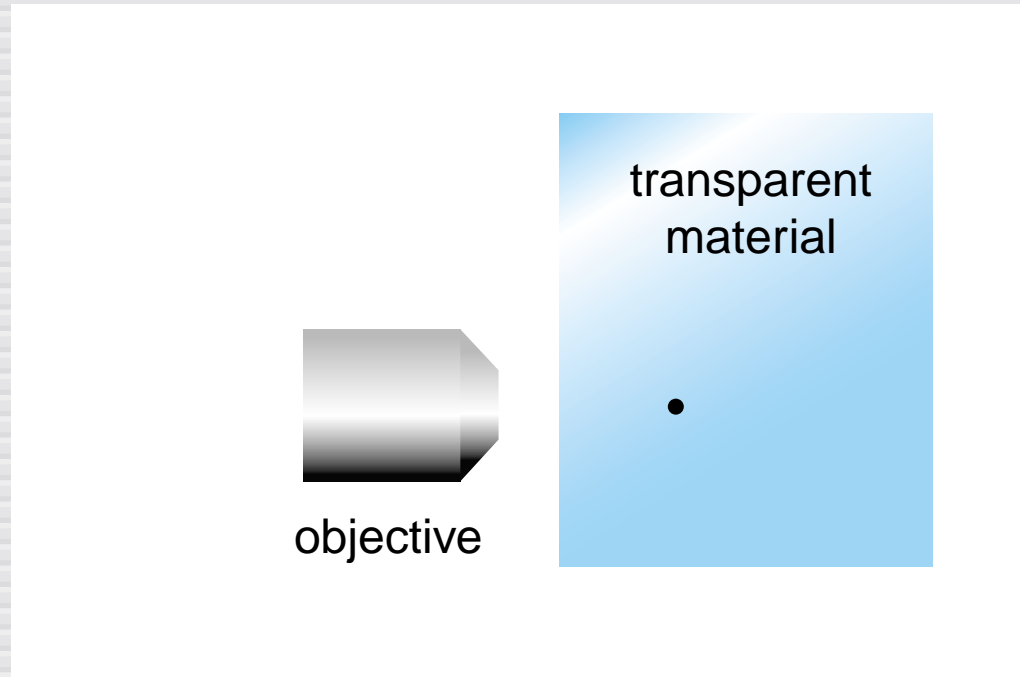
high intensity at focus...

Processing with fs pulses



... causes nonlinear ionization...

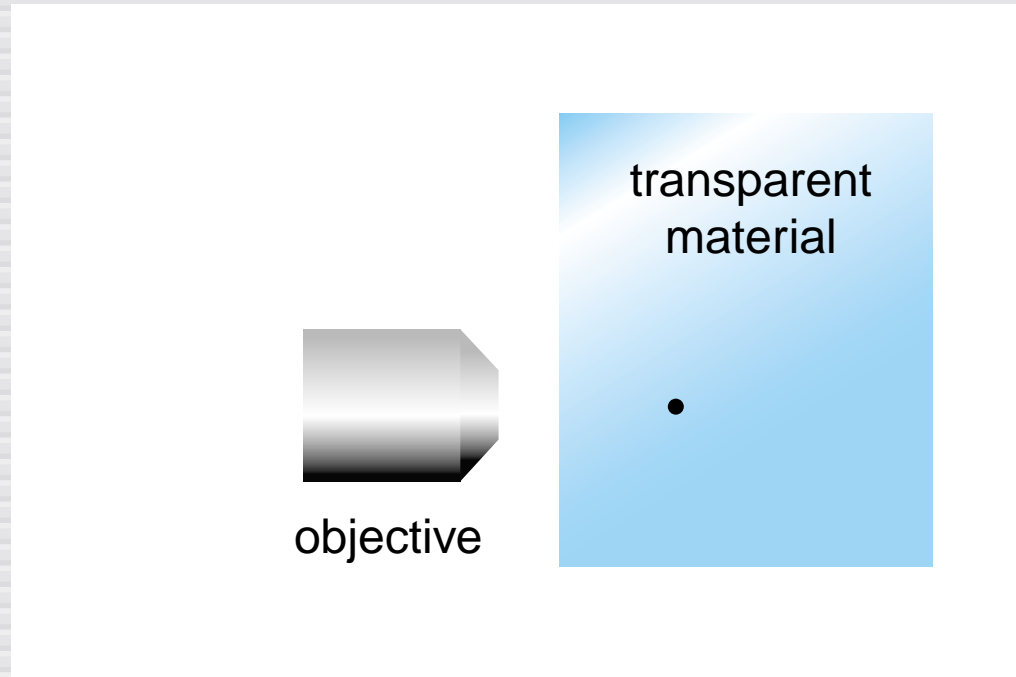
Processing with fs pulses



and 'microexplosion' causes microscopic damage

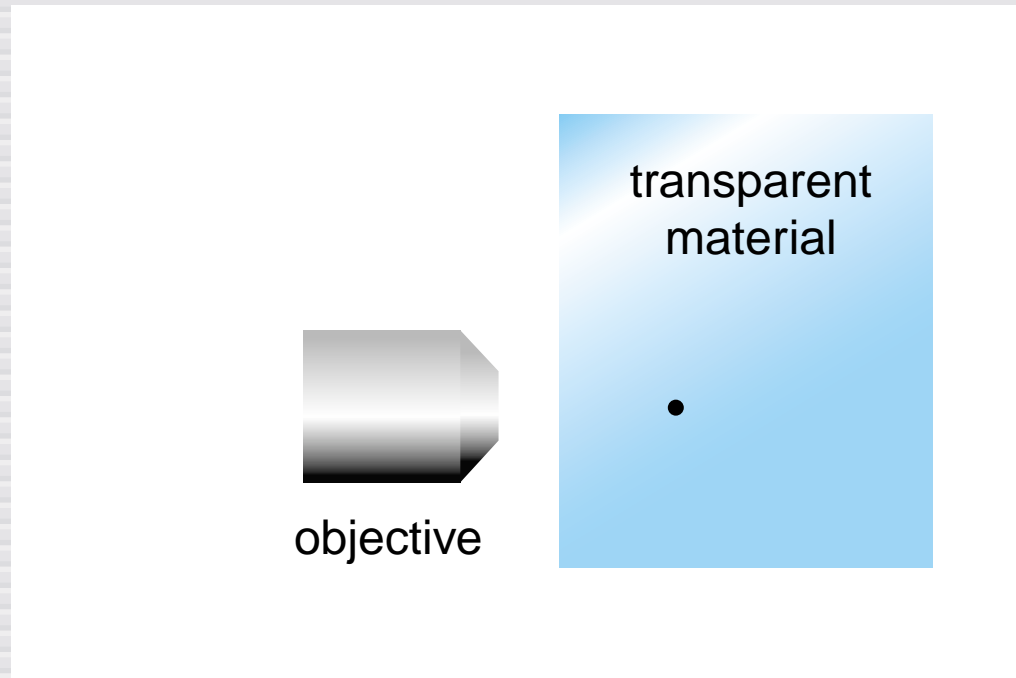
Processing with fs pulses

What are the conditions at focus?



Processing with fs pulses

What are the conditions at focus?



laser deposits energy in $\sim 1 \mu\text{m}^3$

Processing with fs pulses

What temperature?

Processing with fs pulses

What temperature?

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

Processing with fs pulses

What temperature?

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

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

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

Processing with fs pulses

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

$\sim 1,000,000 \text{ K!}$

Processing with fs pulses

What pressure?

Processing with fs pulses

What pressure?

Treat ionized material as an ideal gas:

$$pV = nRT$$

Processing with fs pulses

What pressure?

Treat ionized material as an ideal gas:

$$pV = nRT$$

Gives

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

Processing with fs pulses

So:

microexplosion

$T \approx 1 \text{ MK}$

$p \approx 10 \text{ MBar}$

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

Processing with fs pulses

So:

	microexplosion	sun
T	$\approx 1 \text{ MK}$	$2 - 5 \text{ MK}$
p	$\approx 10 \text{ MBar}$	
ρ	$2.2 \times 10^3 \text{ kg/m}^3$	$0.15 - 150 \times 10^3 \text{ kg/m}^3$

Processing with fs pulses

So:

	microexplosion	sun
T	$\approx 1 \text{ MK}$	$2 - 5 \text{ MK}$
p	$\approx 10 \text{ MBar}$	
ρ	$2.2 \times 10^3 \text{ kg/m}^3$	$0.15 - 150 \times 10^3 \text{ kg/m}^3$

creating stellar conditions in lab!

Processing with fs pulses

Points to keep in mind:

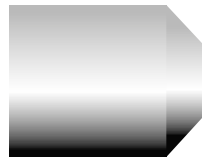
- ▶ **fs laser processing works**
- ▶ **focusing very important**
- ▶ **no collateral damage**

Outline

- ▶ Processing with fs pulses
- ▶ Role of focusing
- ▶ Low-energy processing

Role of focusing

Dark-field scattering



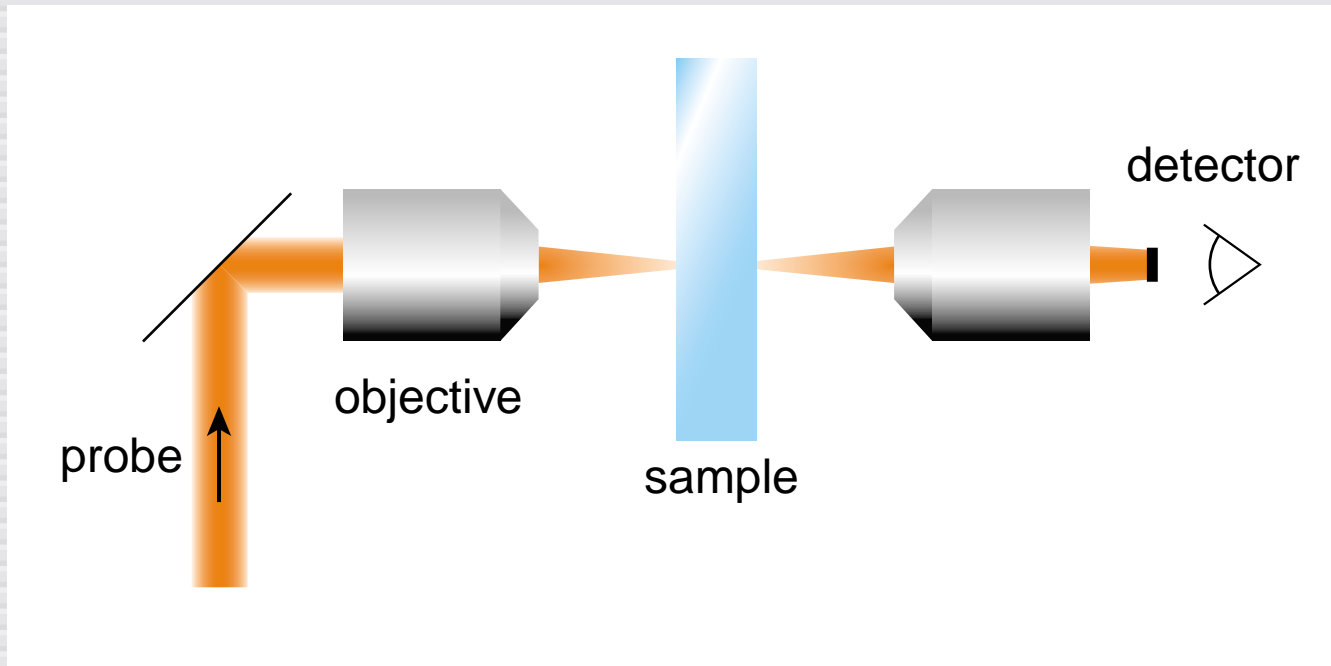
objective



sample

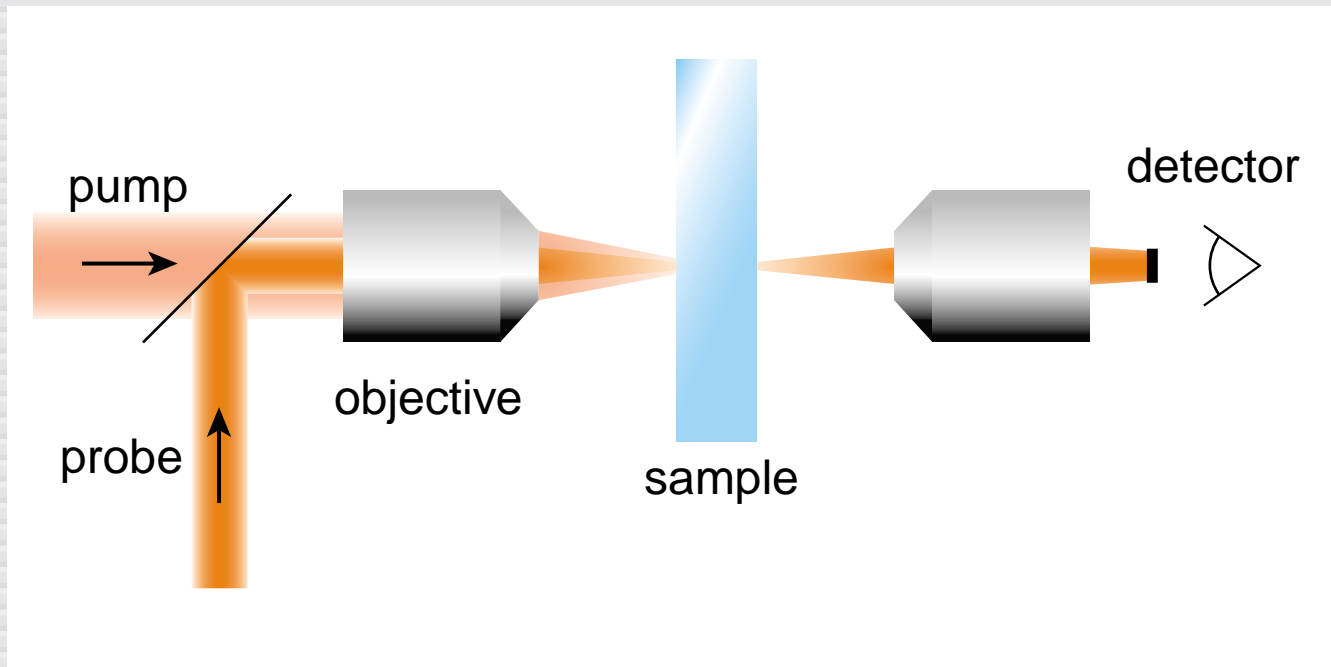
Role of focusing

block probe beam...



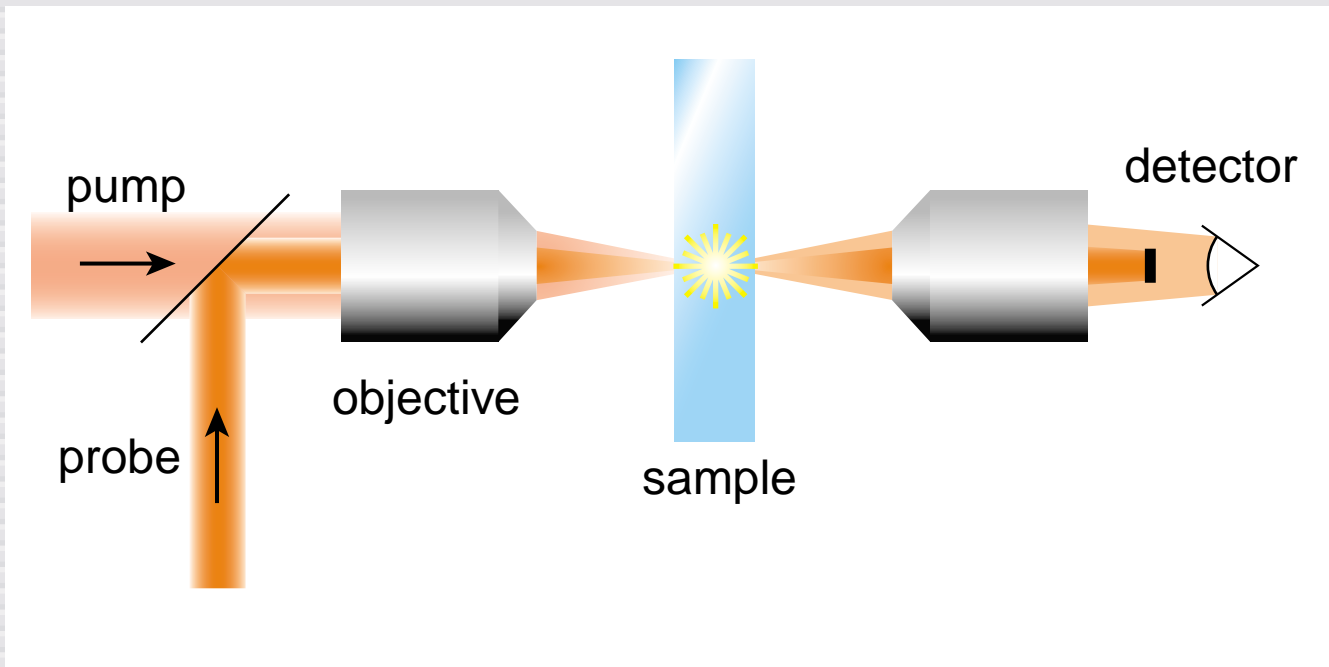
Role of focusing

... bring in pump beam...

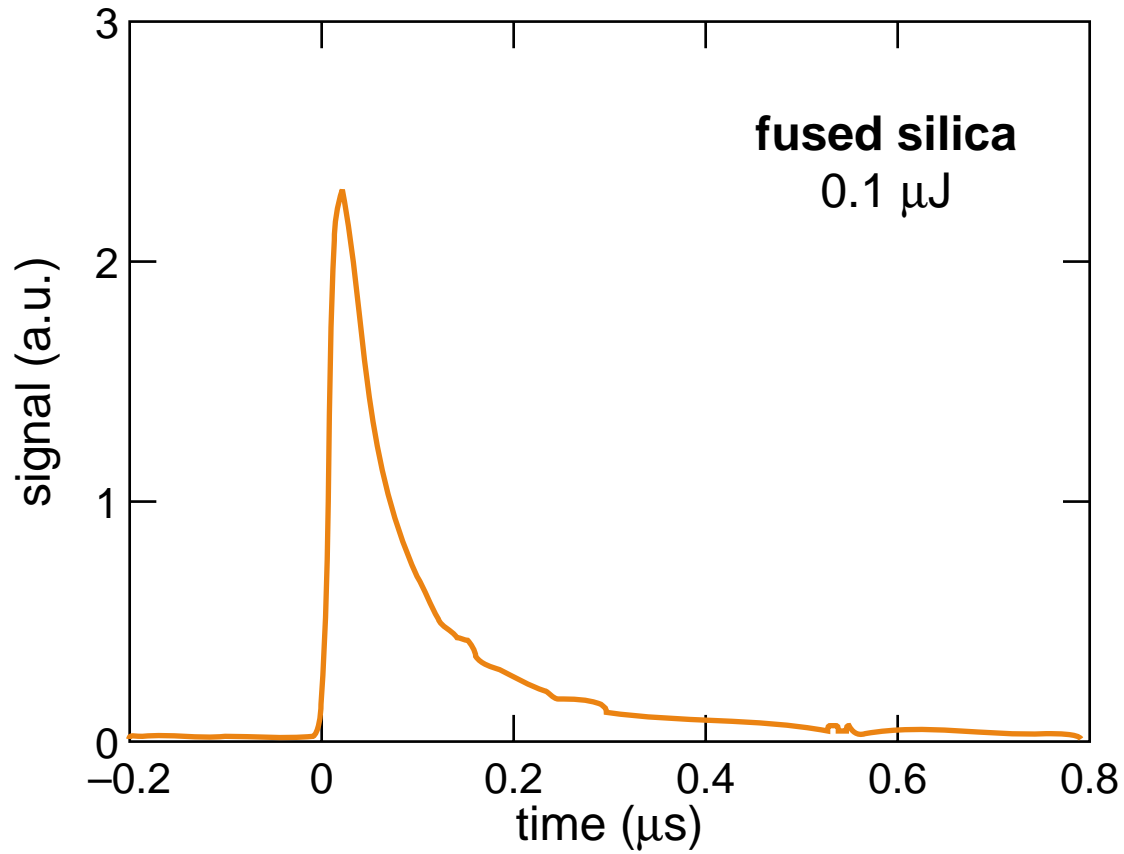


Role of focusing

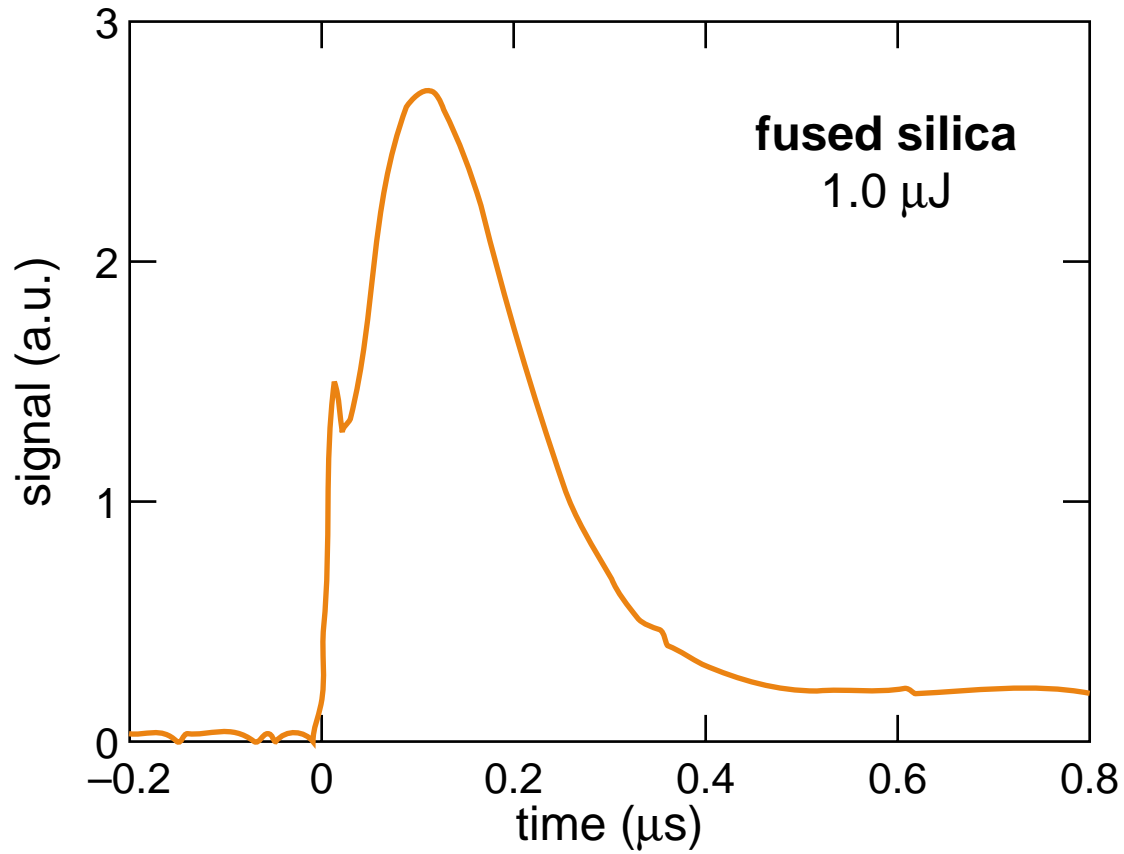
... damage scatters probe beam



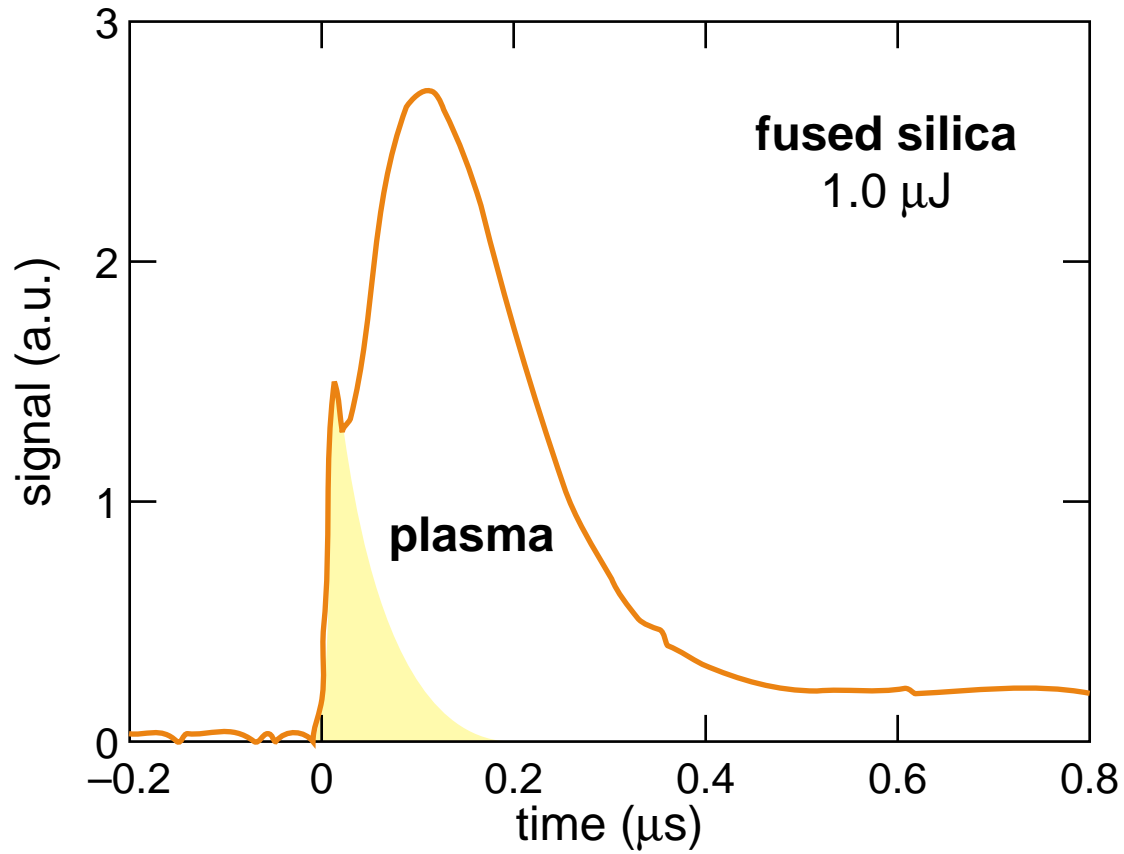
Role of focusing



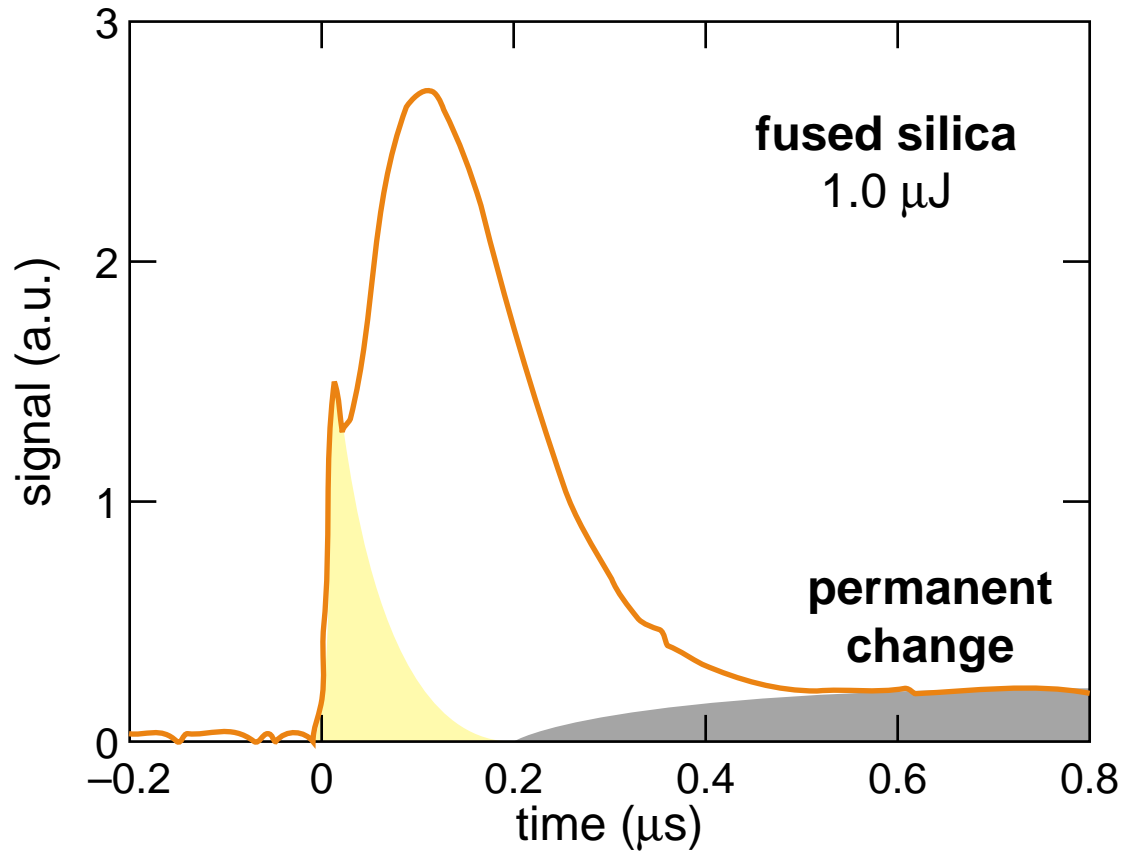
Role of focusing



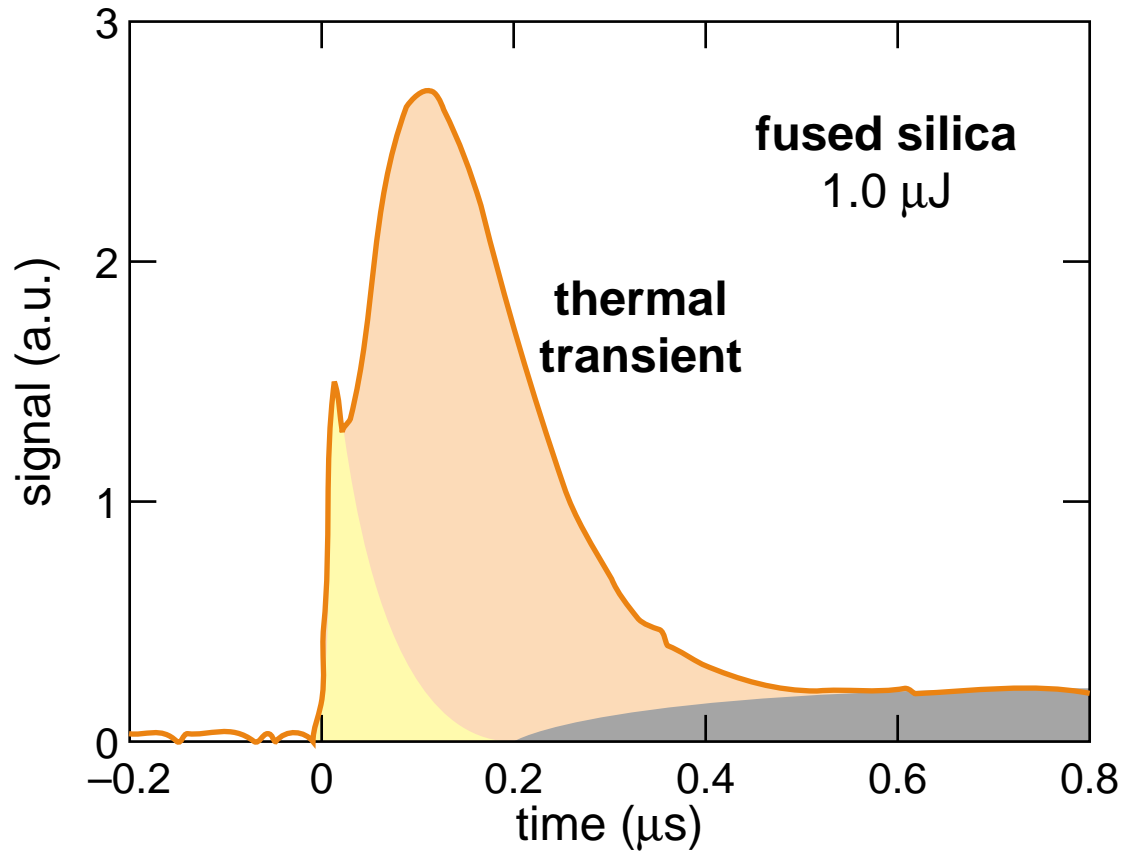
Role of focusing



Role of focusing

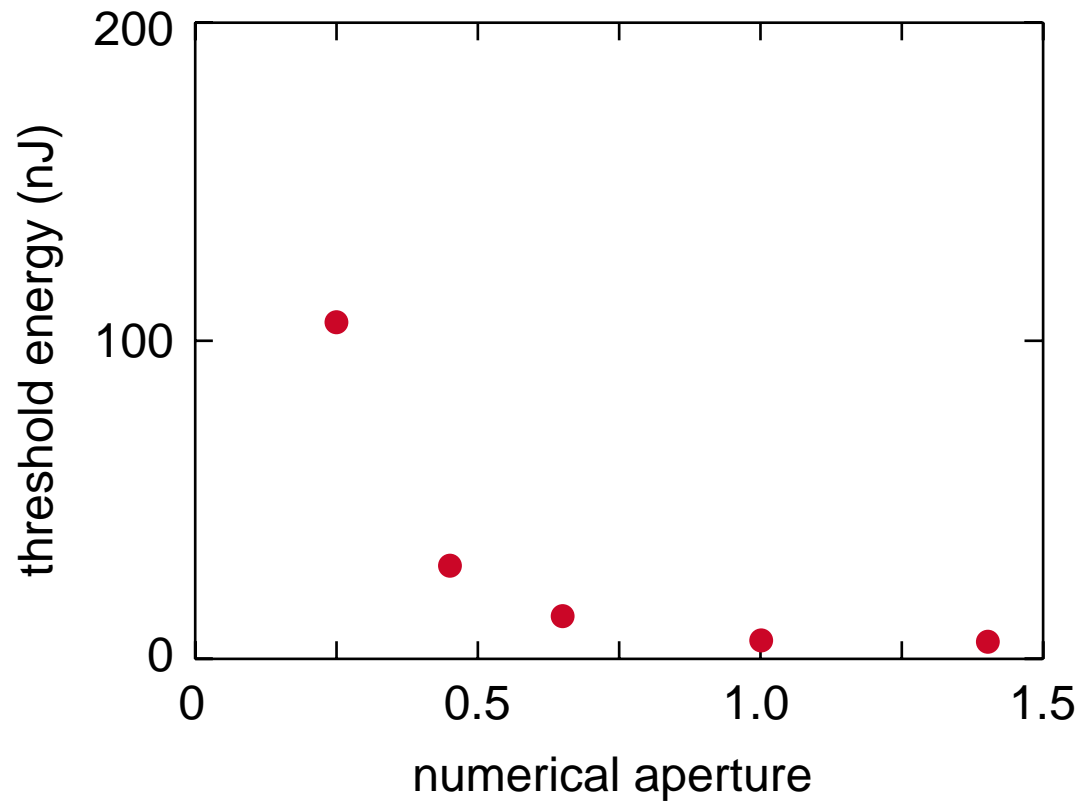


Role of focusing

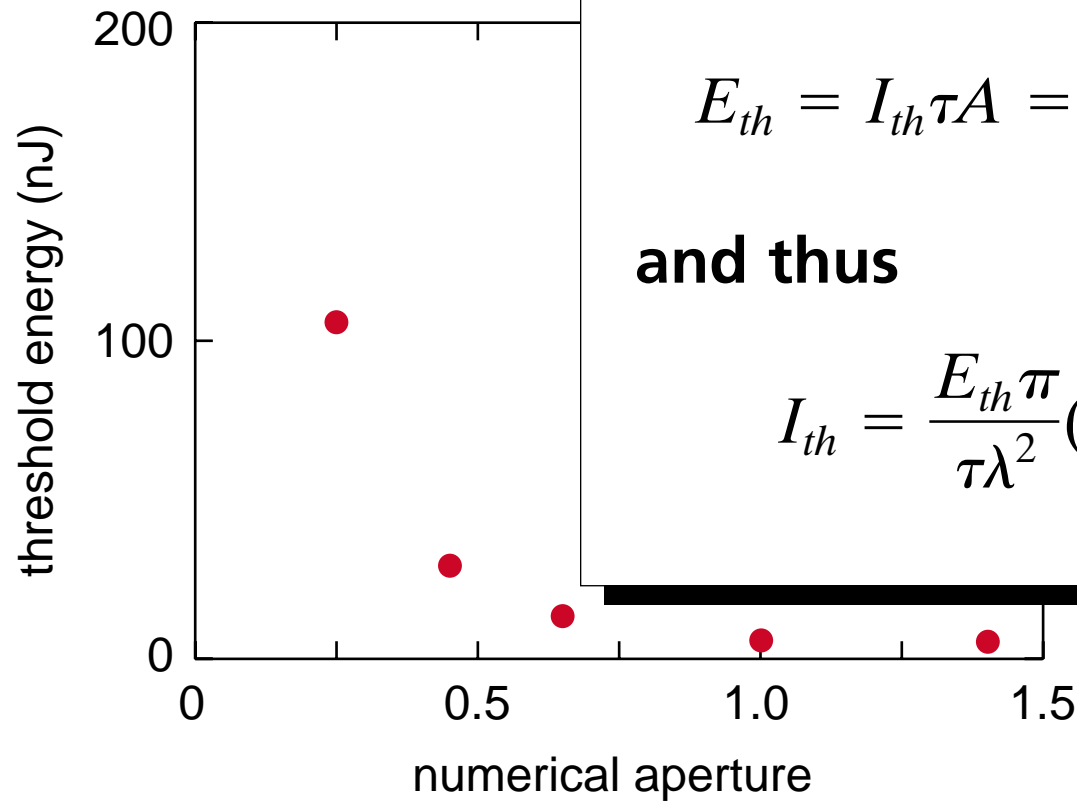


Role of focusing

vary numerical aperture in Corning 0211



Role of focusing



spot size determined by numerical aperture:

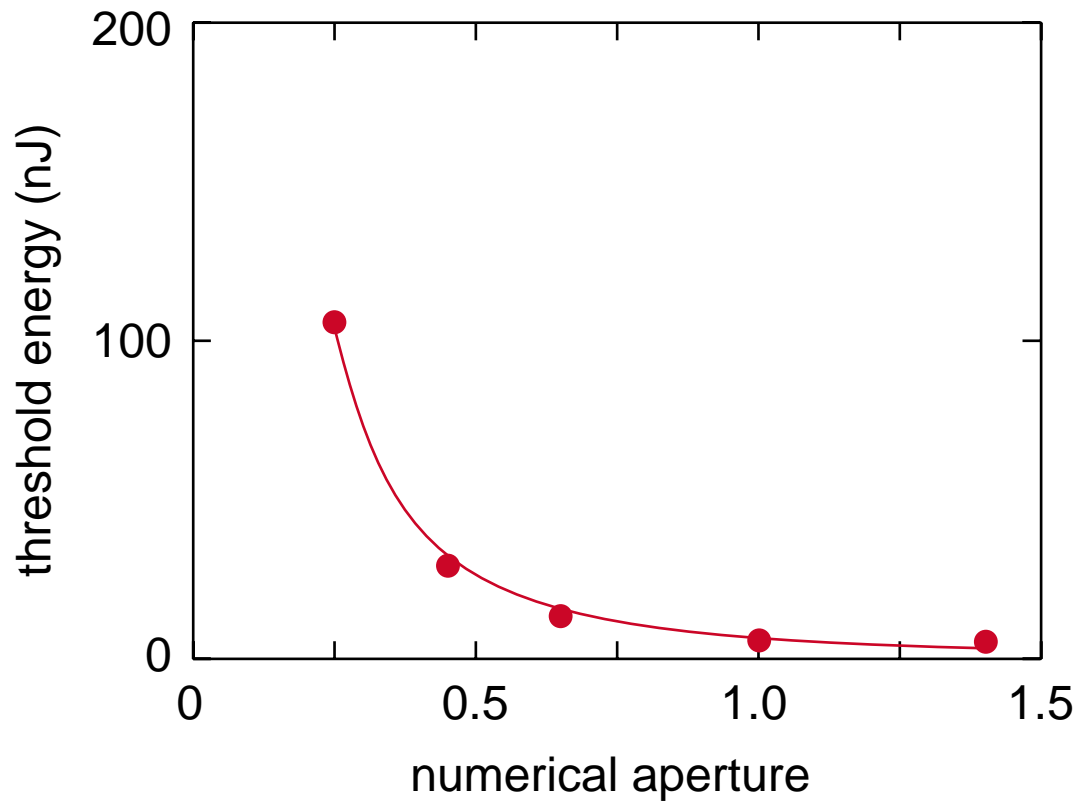
$$E_{th} = I_{th} \tau A = \frac{I_{th} \tau \lambda^2}{\pi (\text{NA})^2}$$

and thus

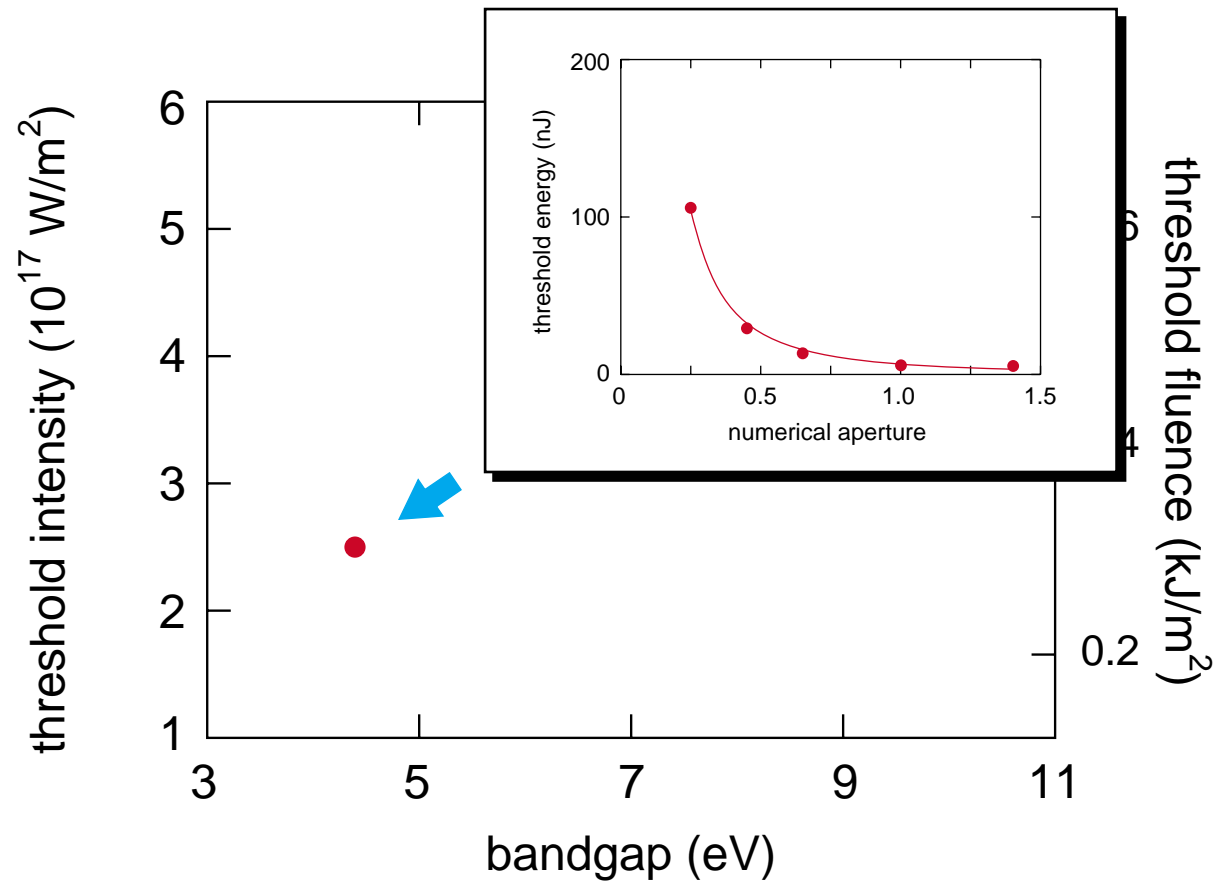
$$I_{th} = \frac{E_{th} \pi}{\tau \lambda^2} (\text{NA})^2$$

Role of focusing

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

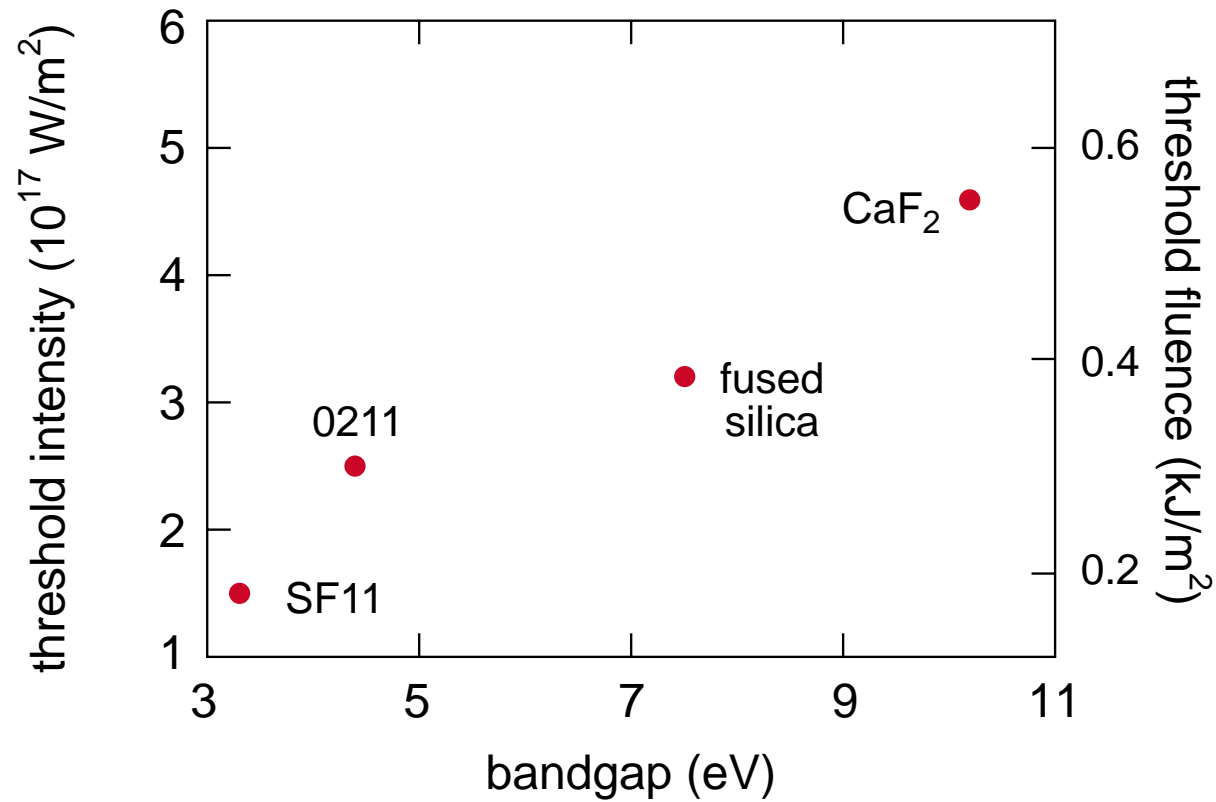


Role of focusing



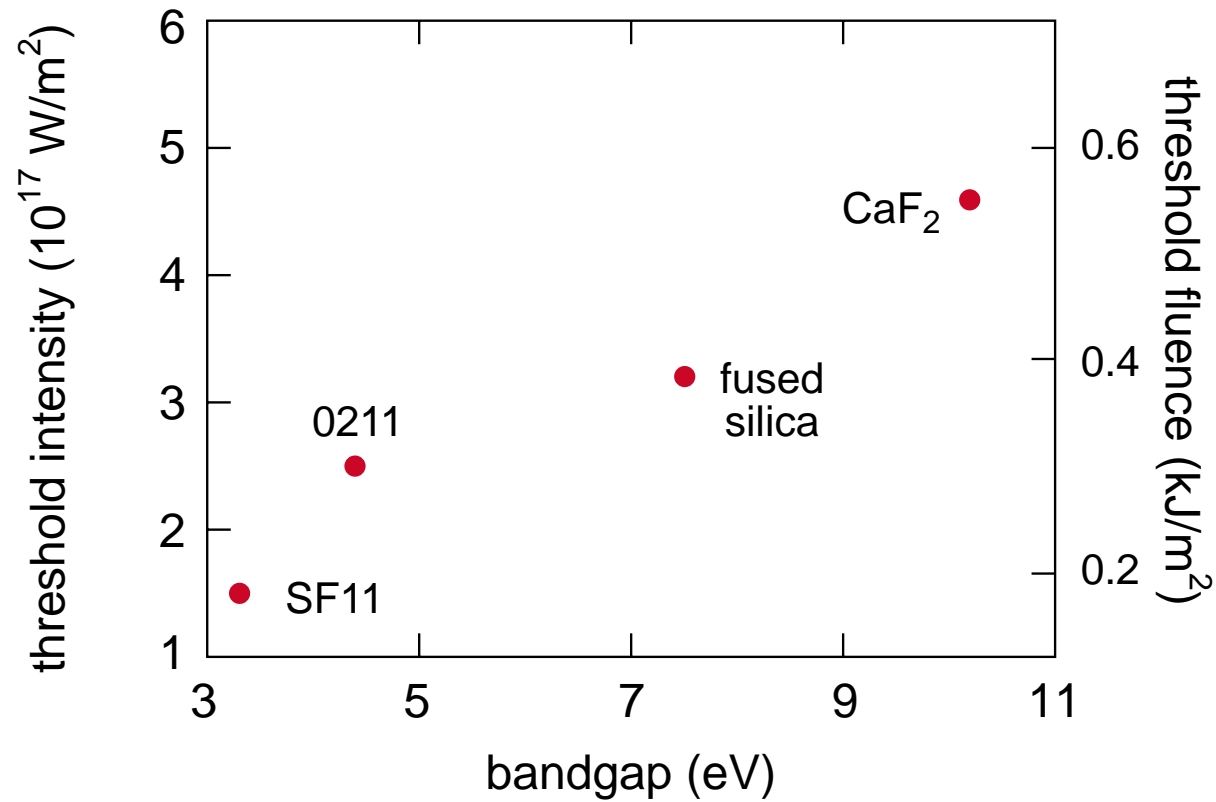
Role of focusing

vary material...



Role of focusing

threshold varies with bandgap



Role of focusing

Points to keep in mind:

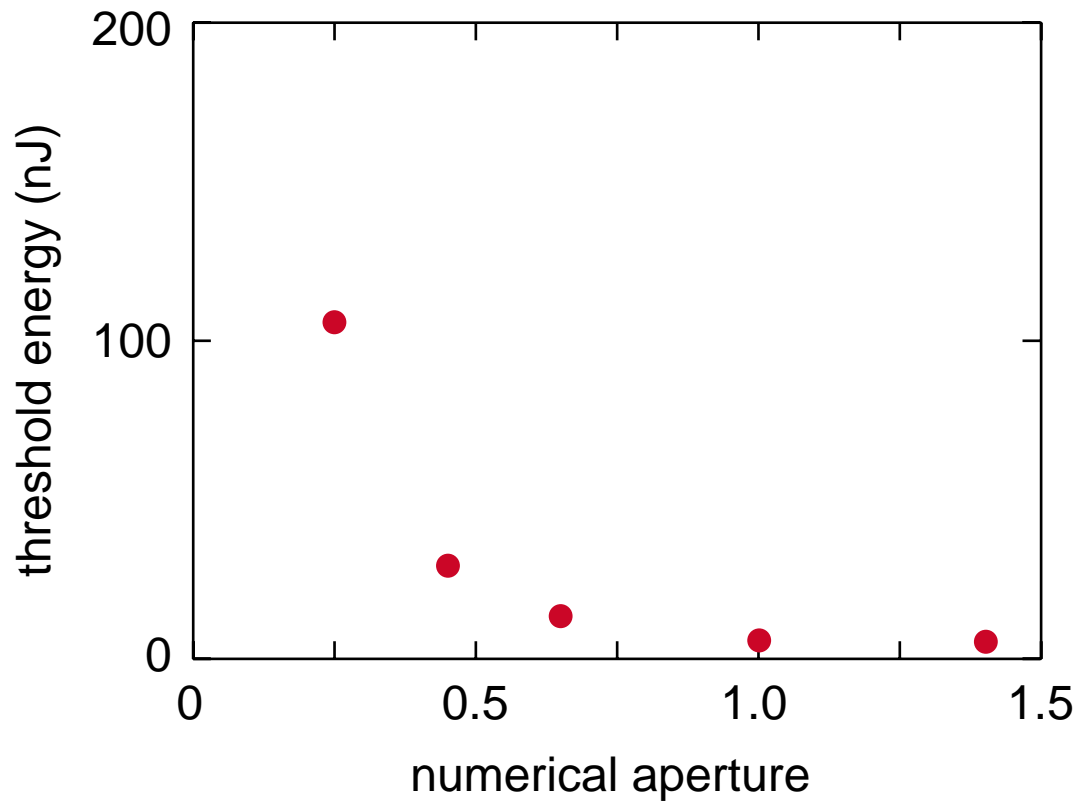
- ▶ **threshold critically dependent of NA**
- ▶ **surprisingly little material dependence**
- ▶ **avalanche ionization important**

Outline

- ▶ Processing with fs pulses
- ▶ Role of focusing
- ▶ **Low-energy processing**

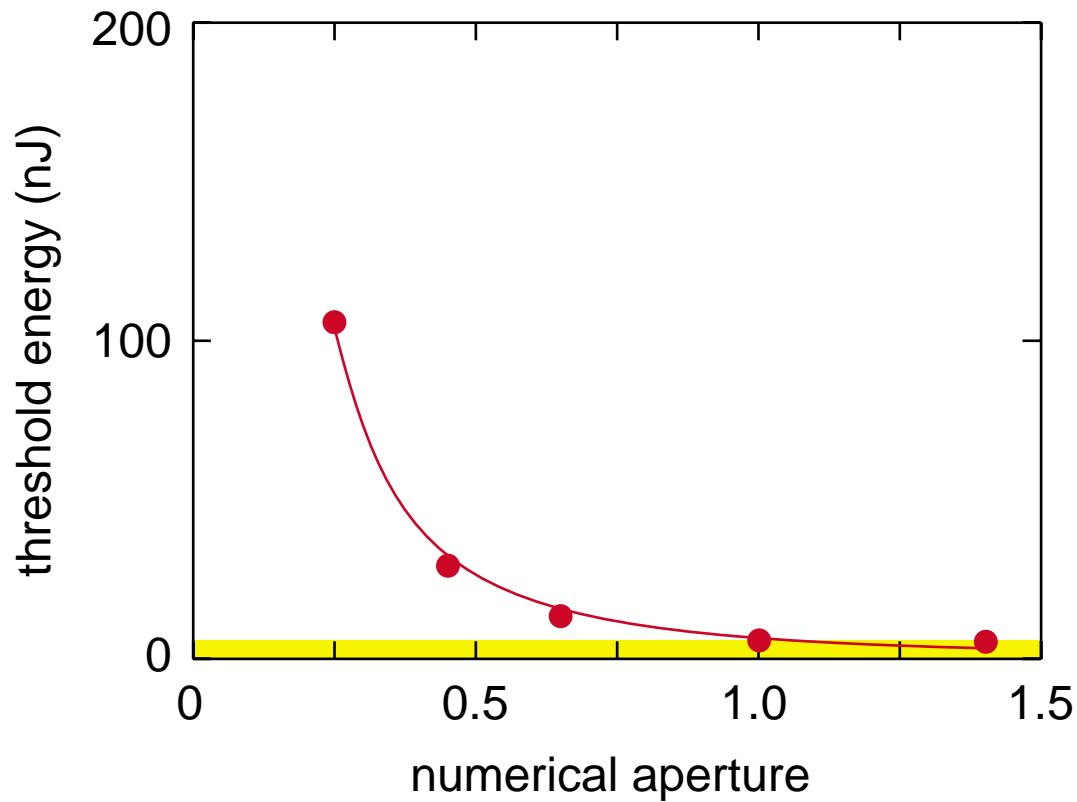
Low-energy processing

threshold decreases with increasing numerical aperture



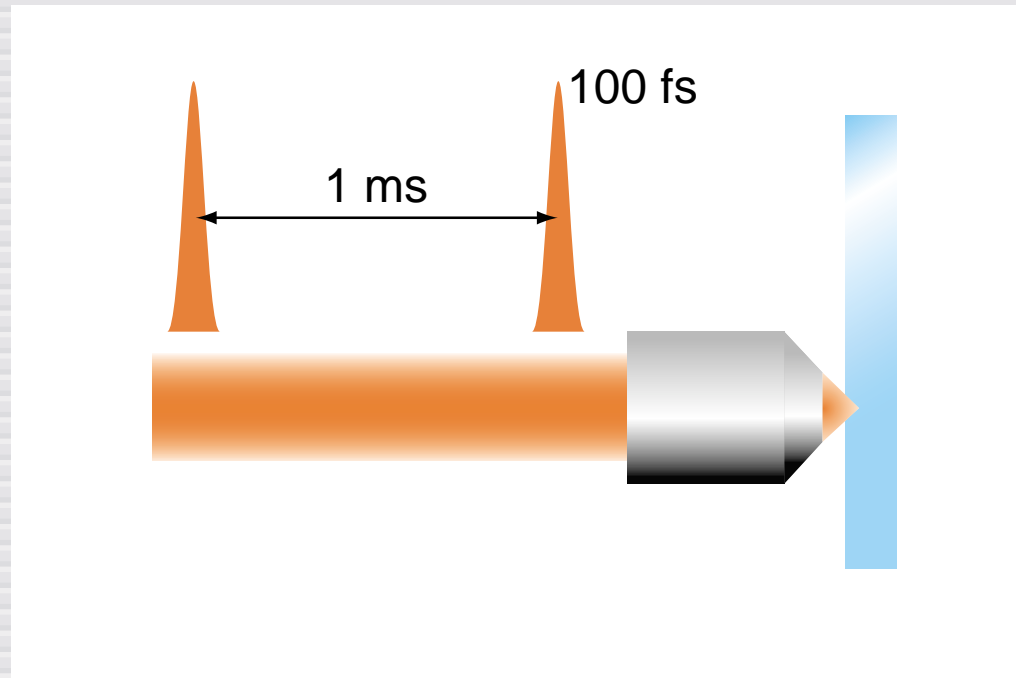
Low-energy processing

less than 10 nJ at high numerical aperture!



Low-energy processing

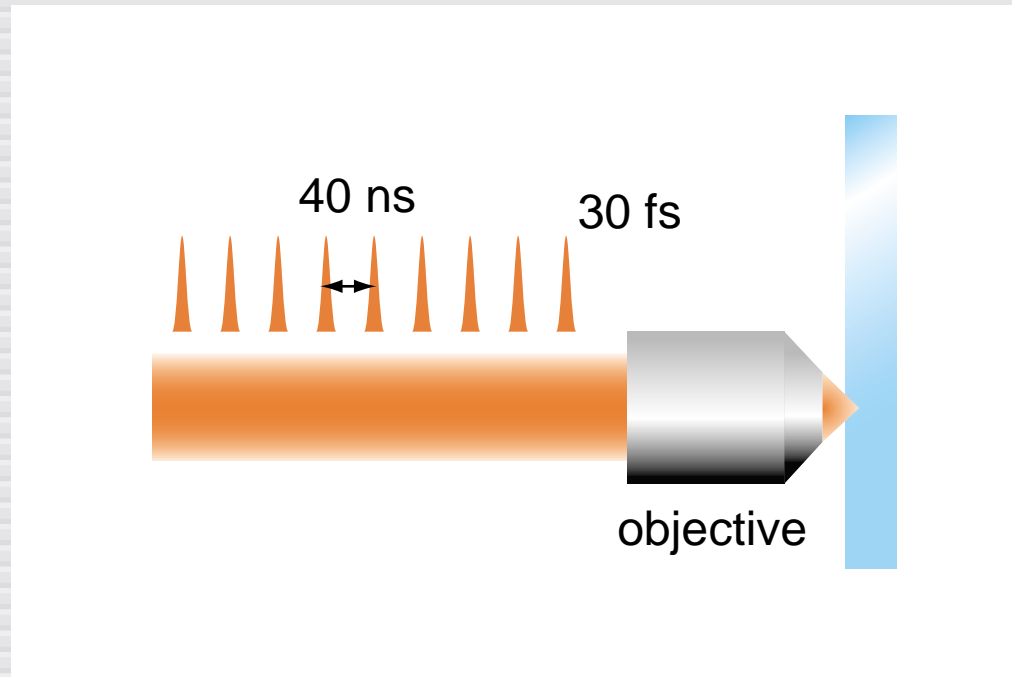
amplified laser



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

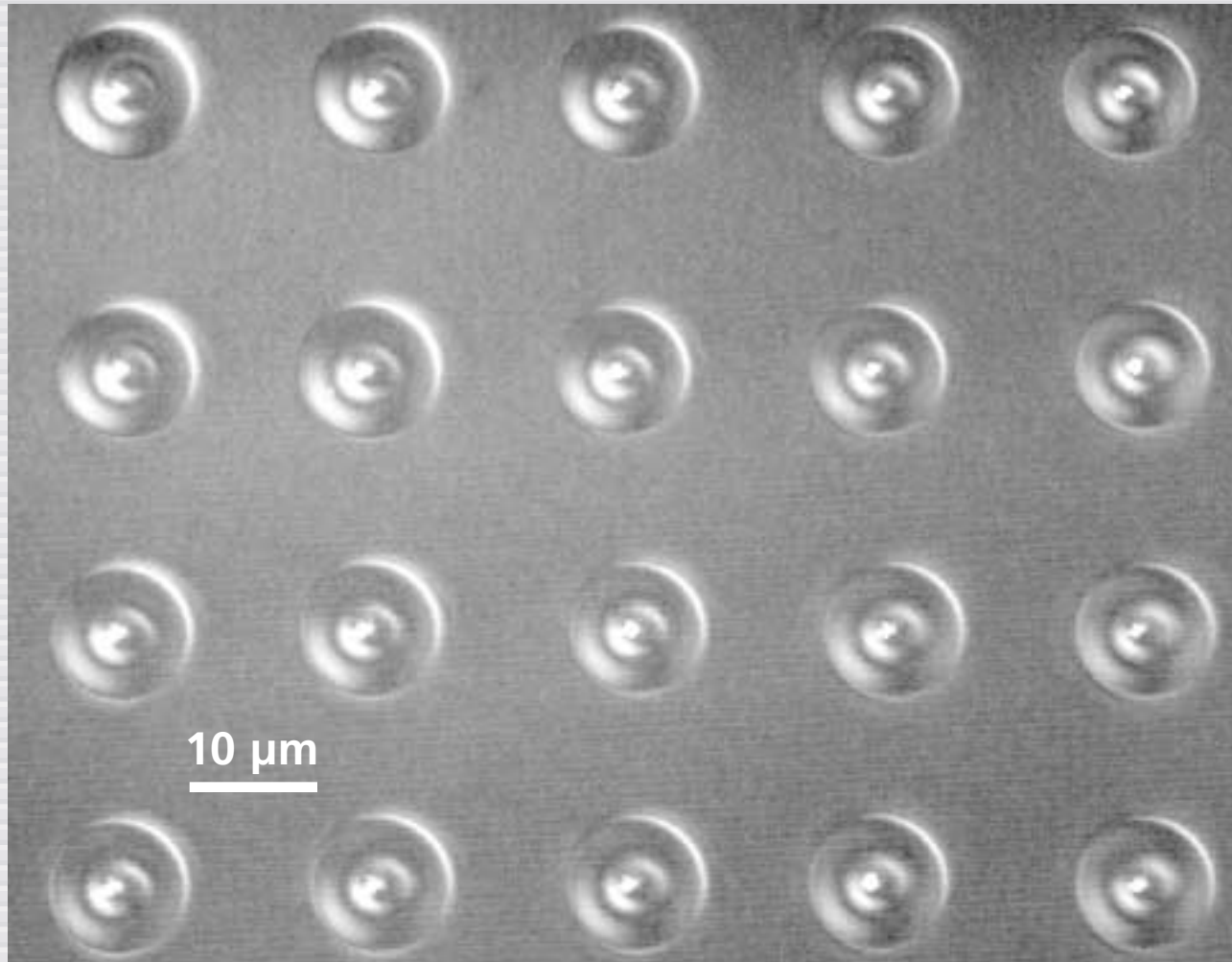
Low-energy processing

long-cavity Ti:sapphire oscillator

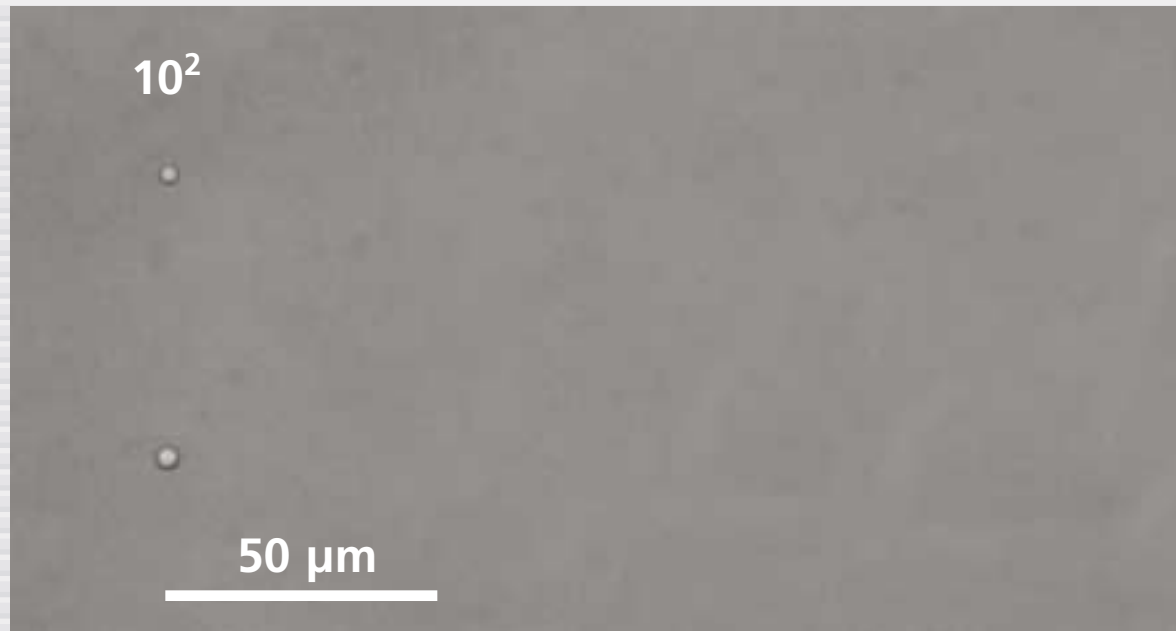


heat-diffusion time: $\tau_{diff} \approx 1 \mu s$

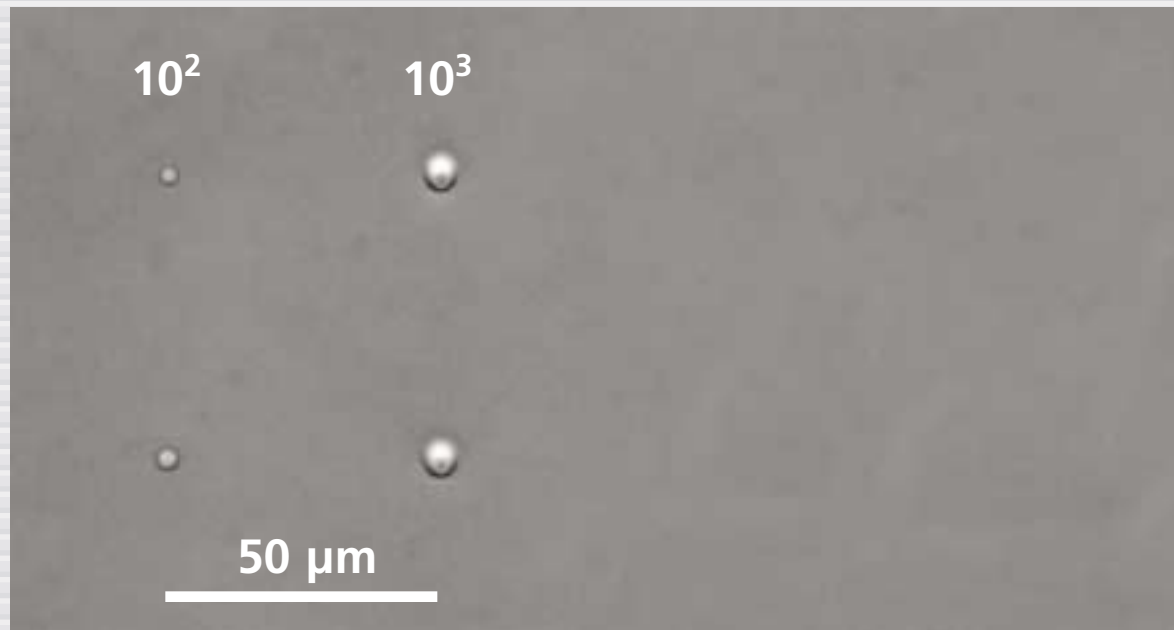
Low-energy processing



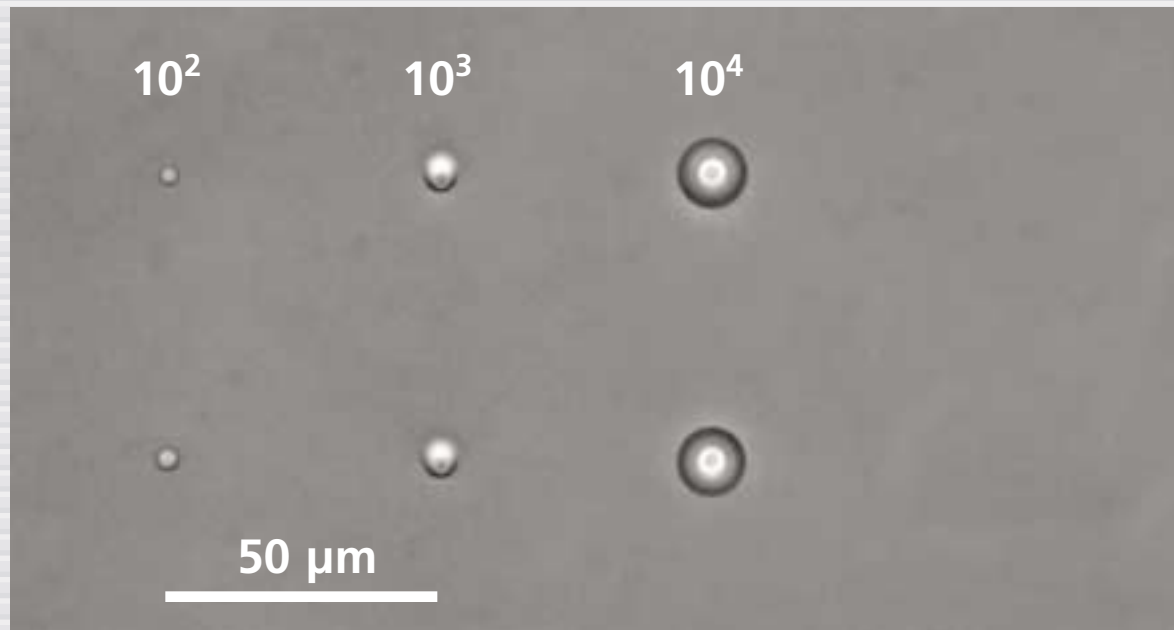
Low-energy processing



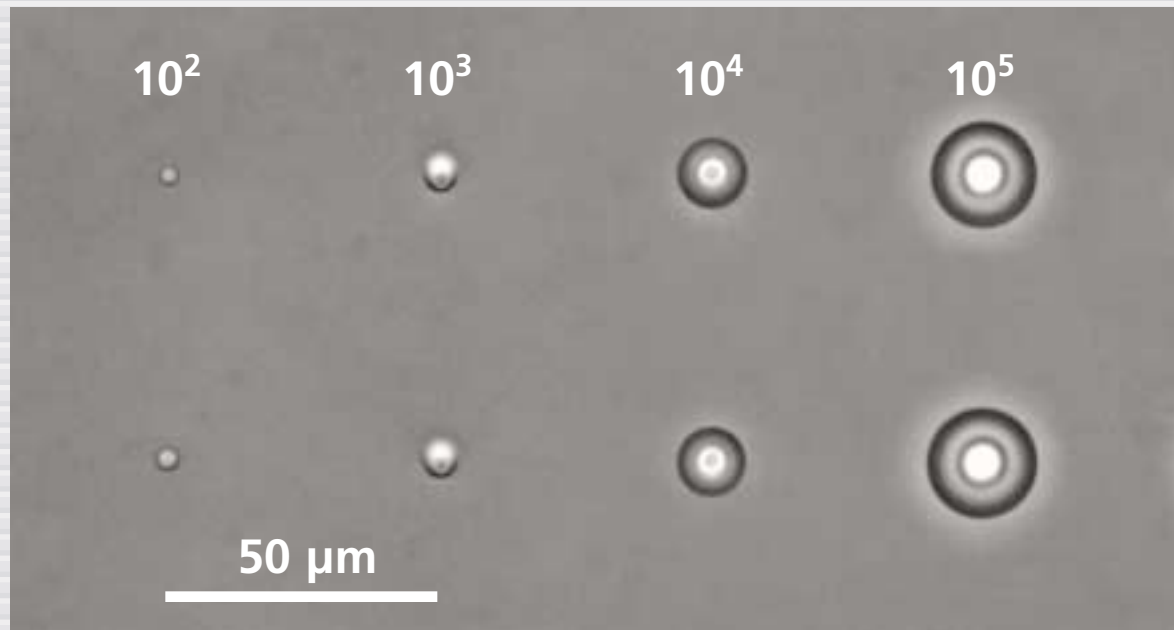
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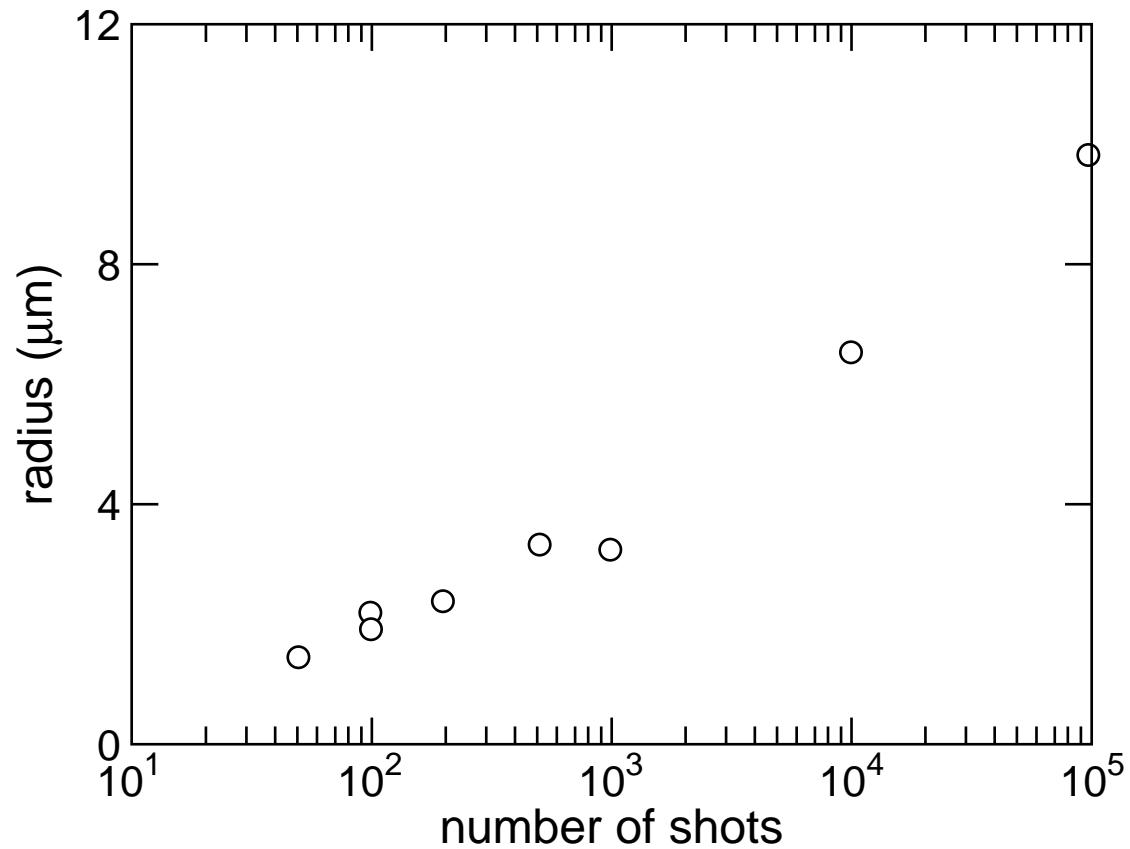
Low-energy processing



Low-energy processing

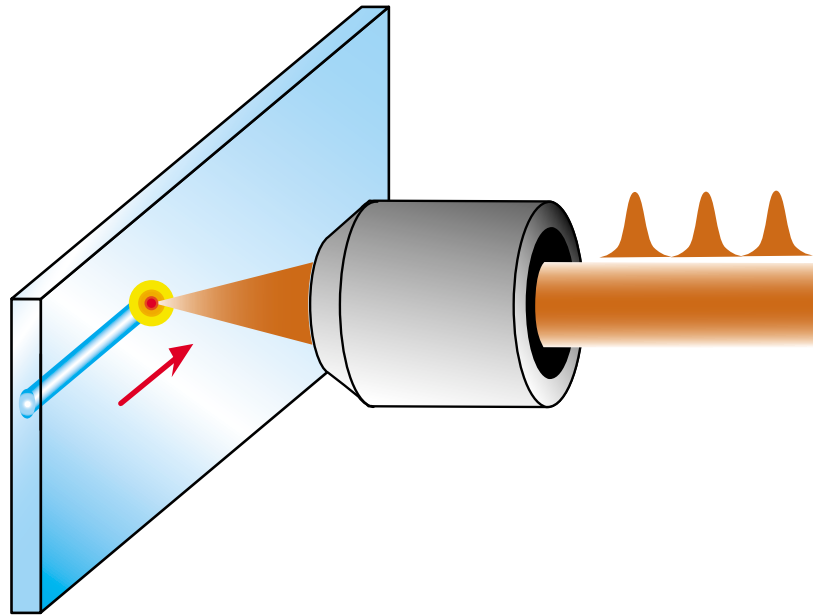


Low-energy processing



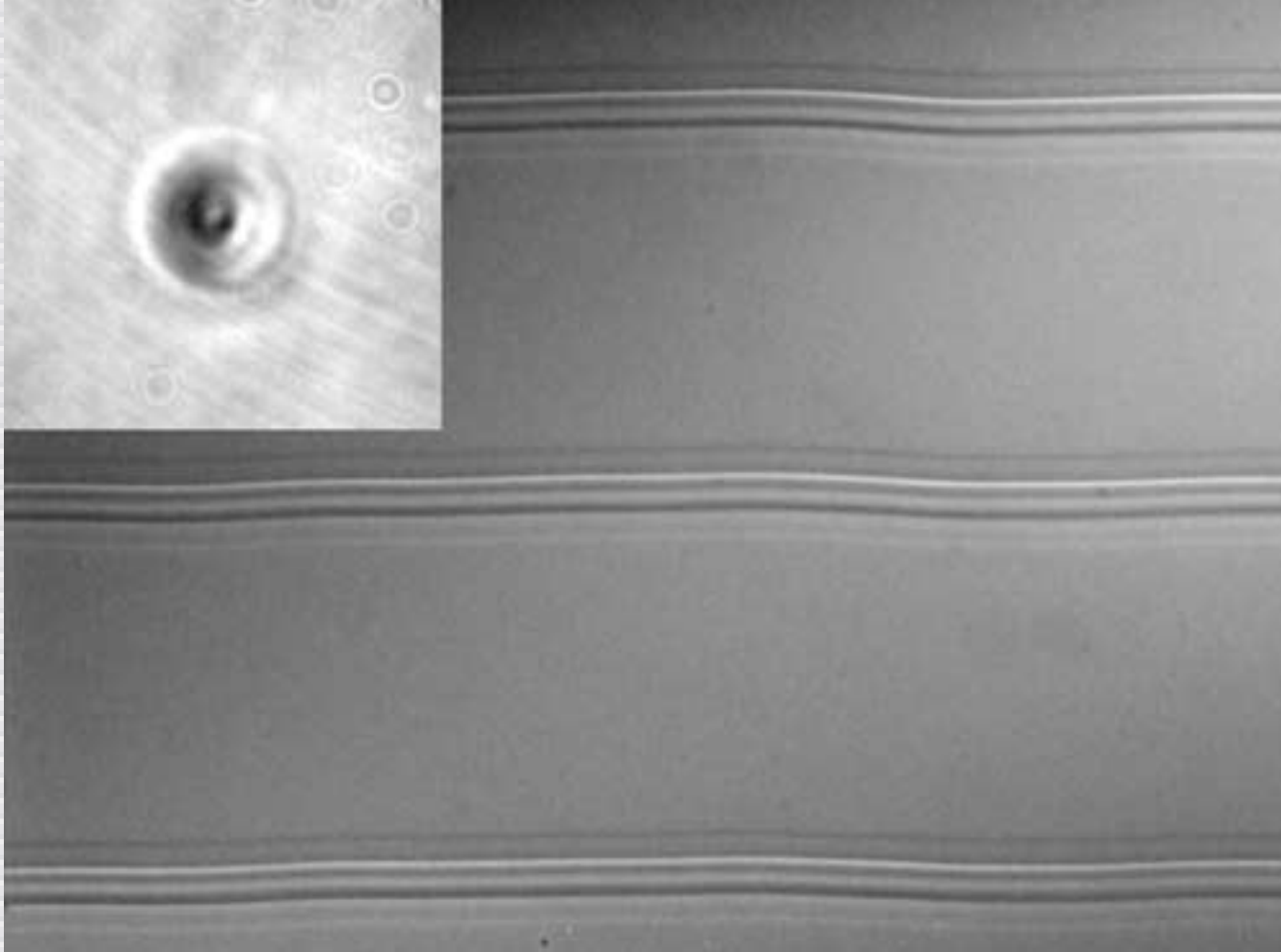
Low-energy processing

waveguide machining



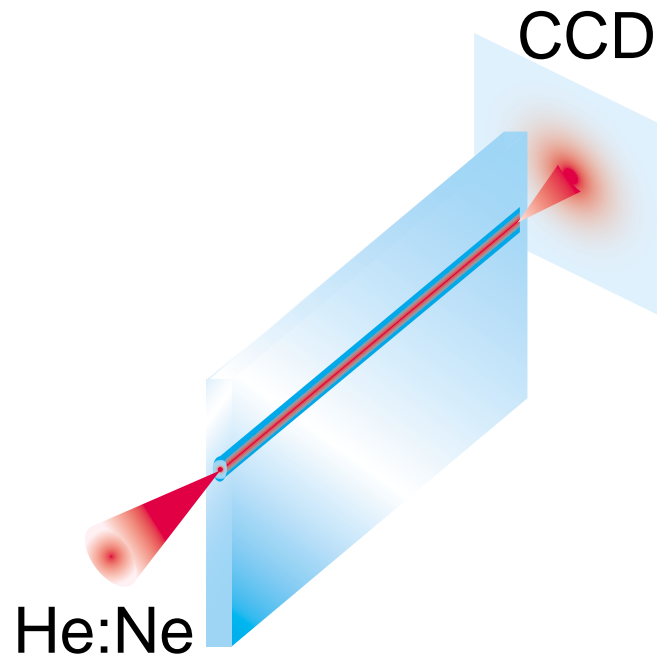
Low-energy processing

waveguide machining



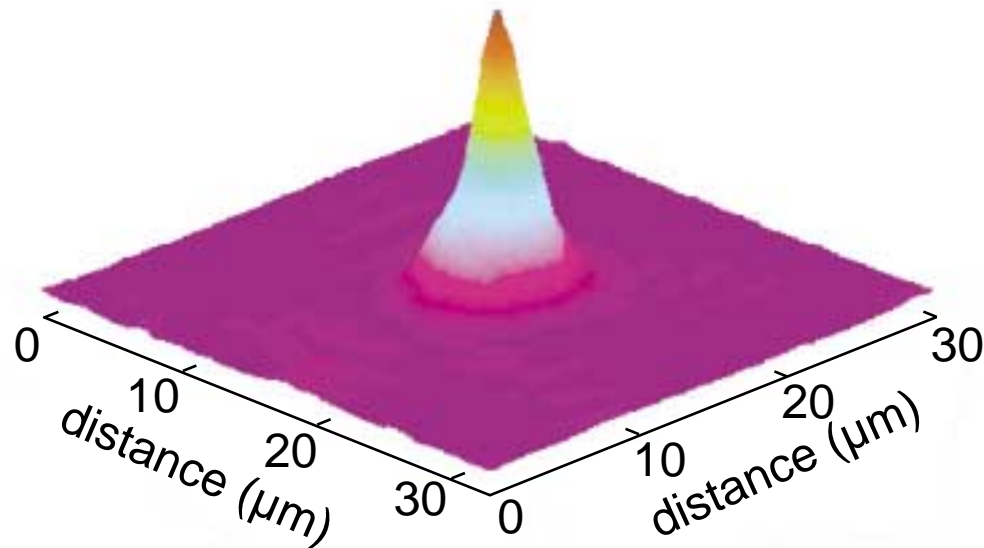
Low-energy processing

waveguide mode analysis



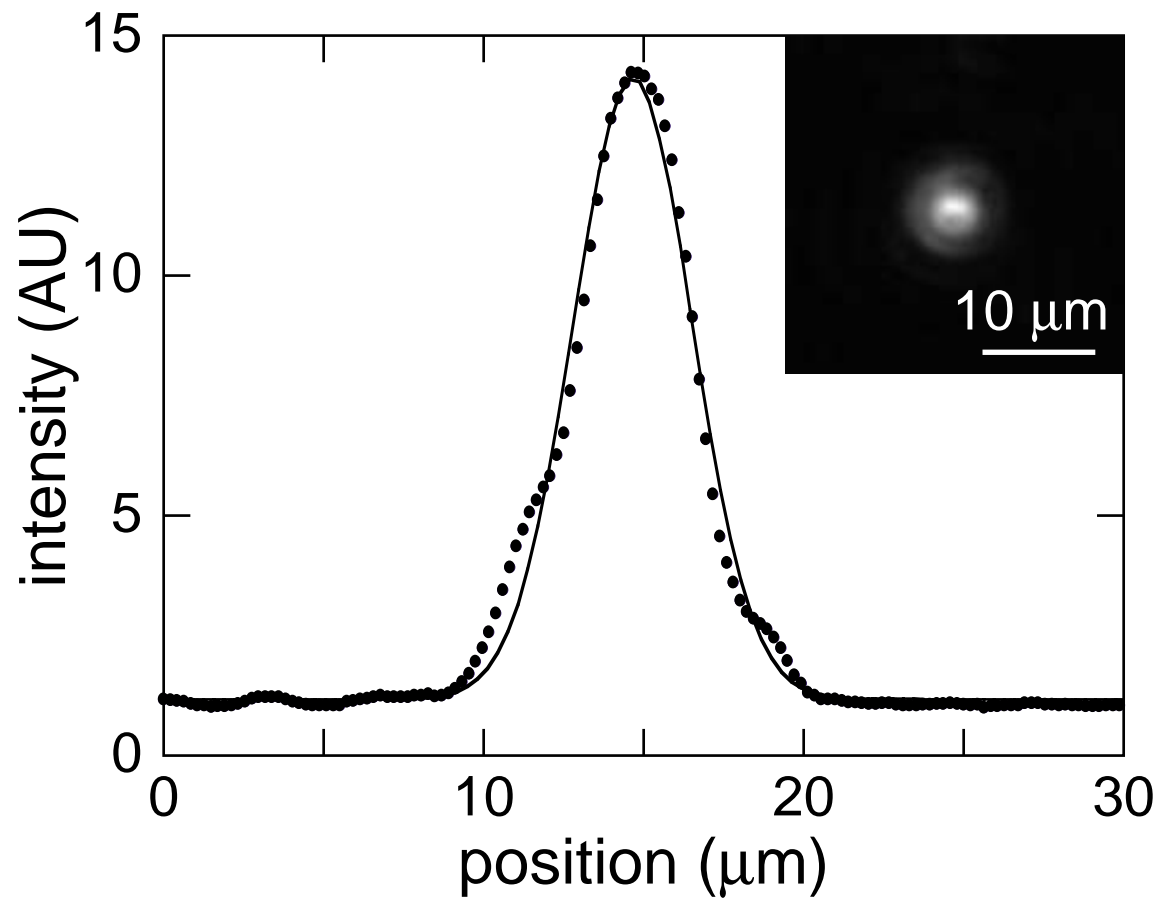
Low-energy processing

near field mode



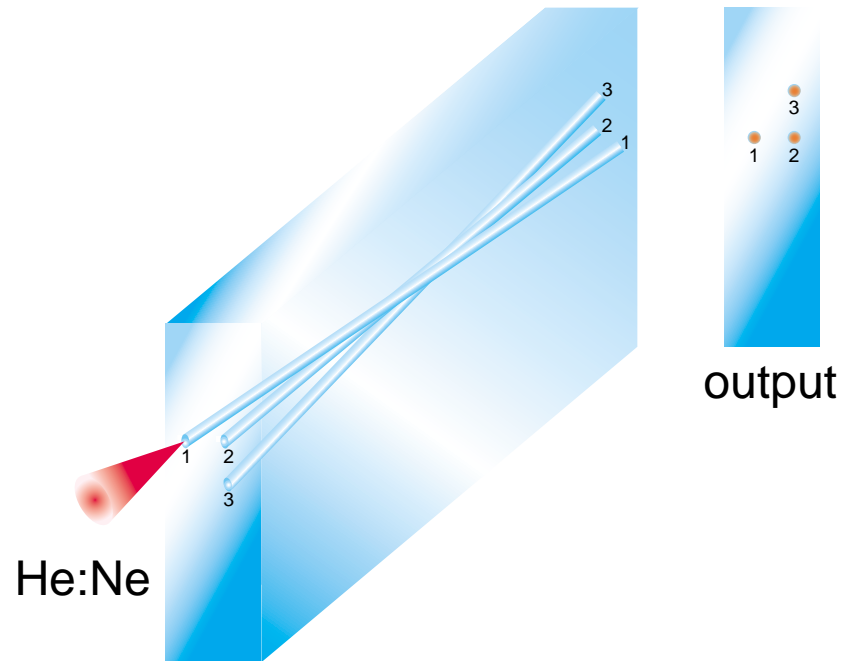
Low-energy processing

near field mode



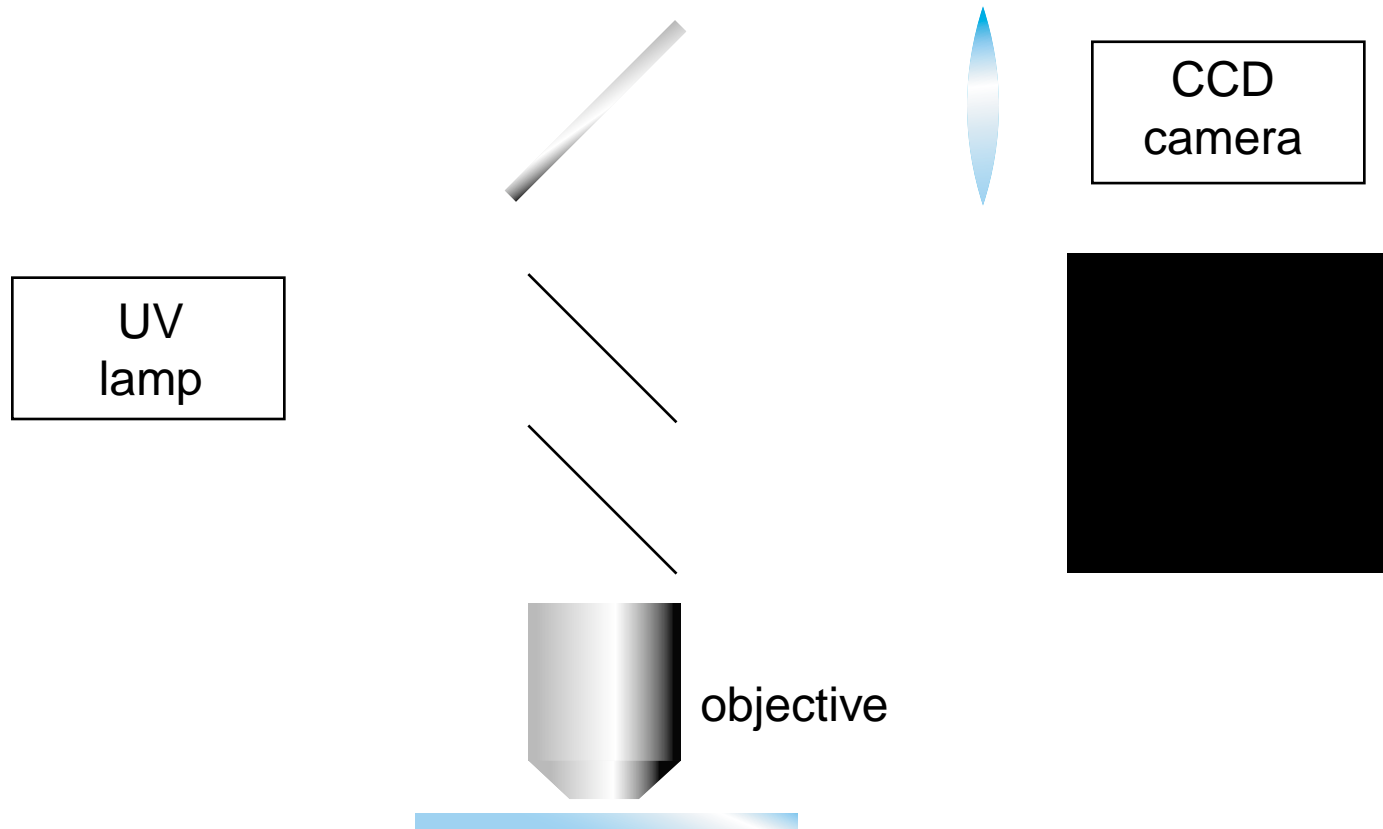
Low-energy processing

3D wave splitter



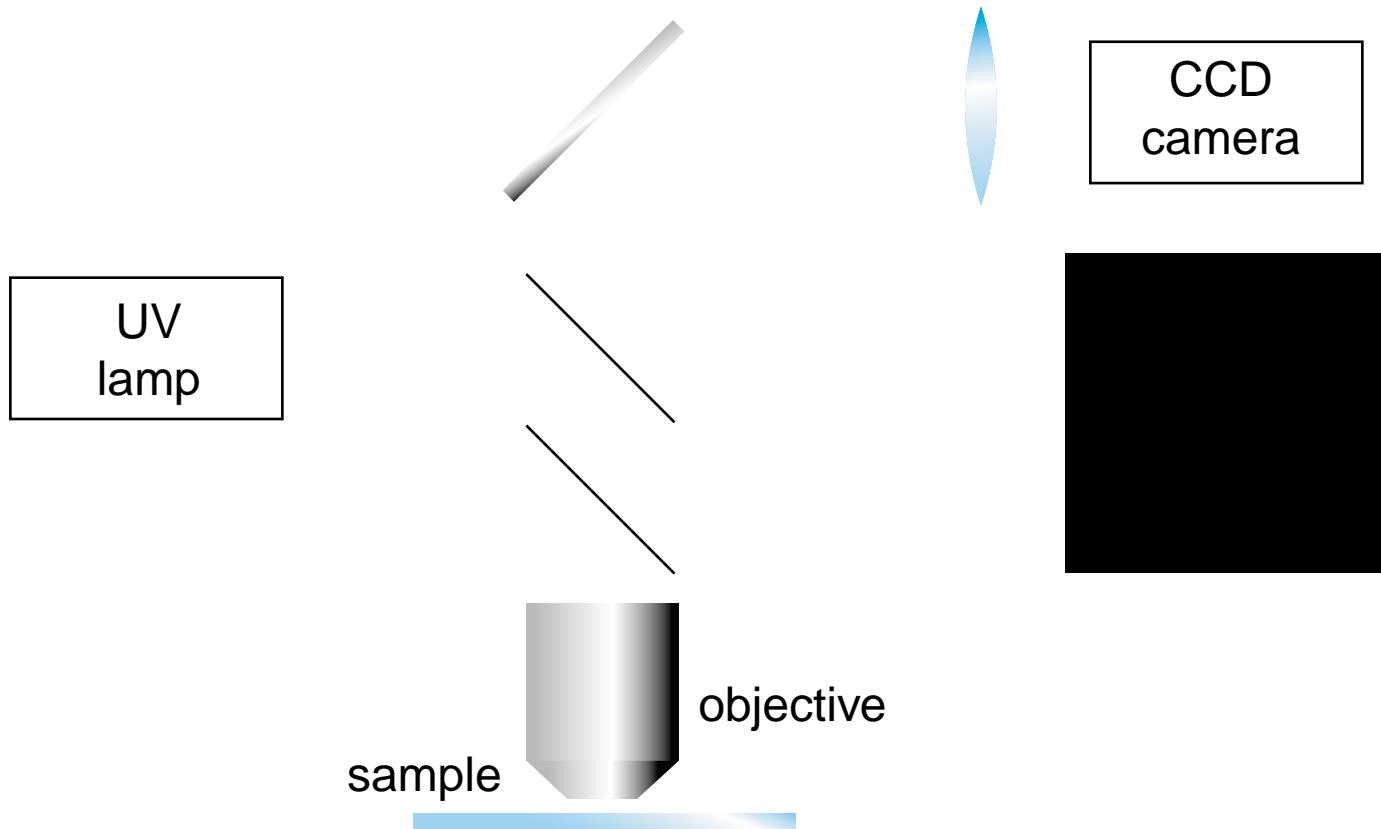
Low-energy processing

epi-fluorescence microscope



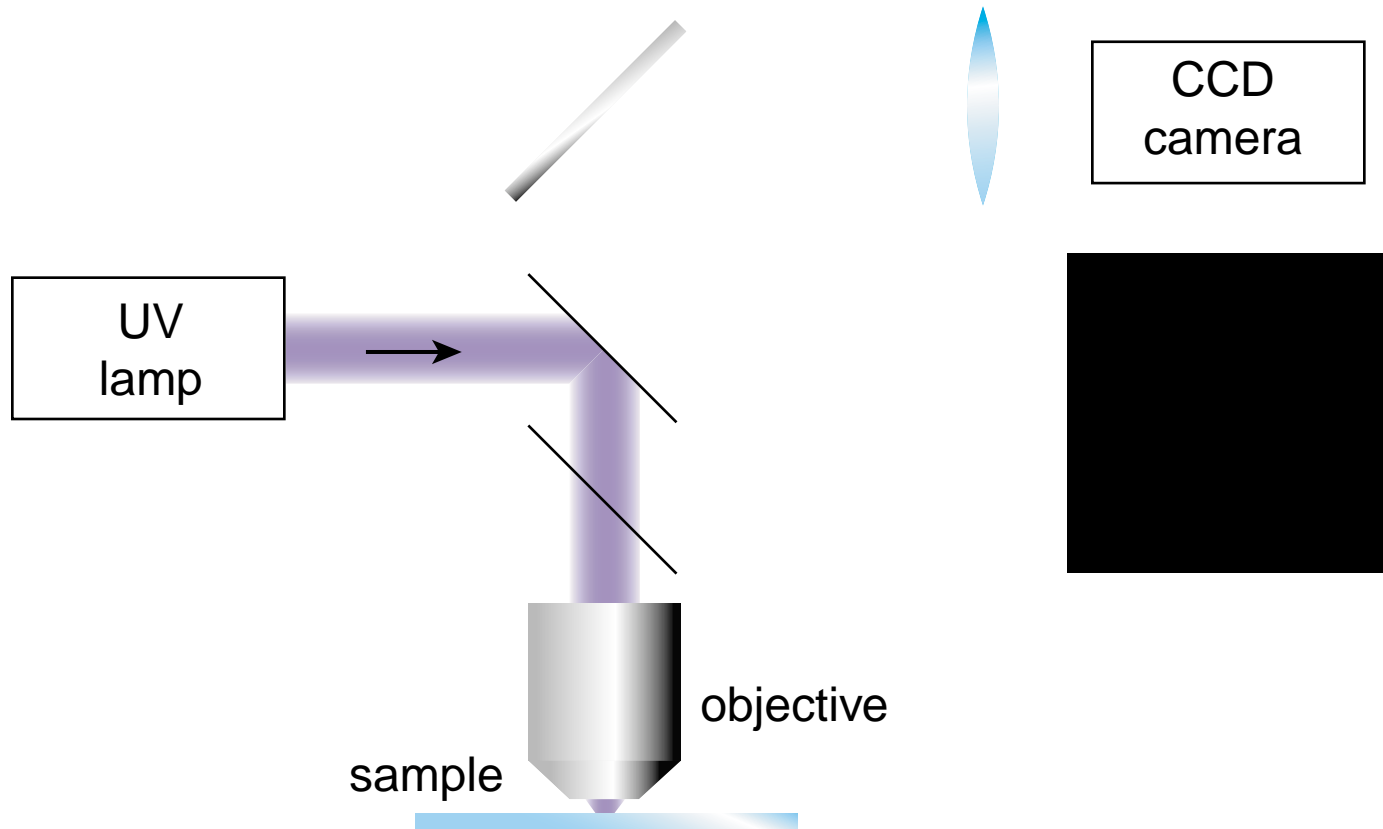
Low-energy processing

mount fluorescently tagged sample



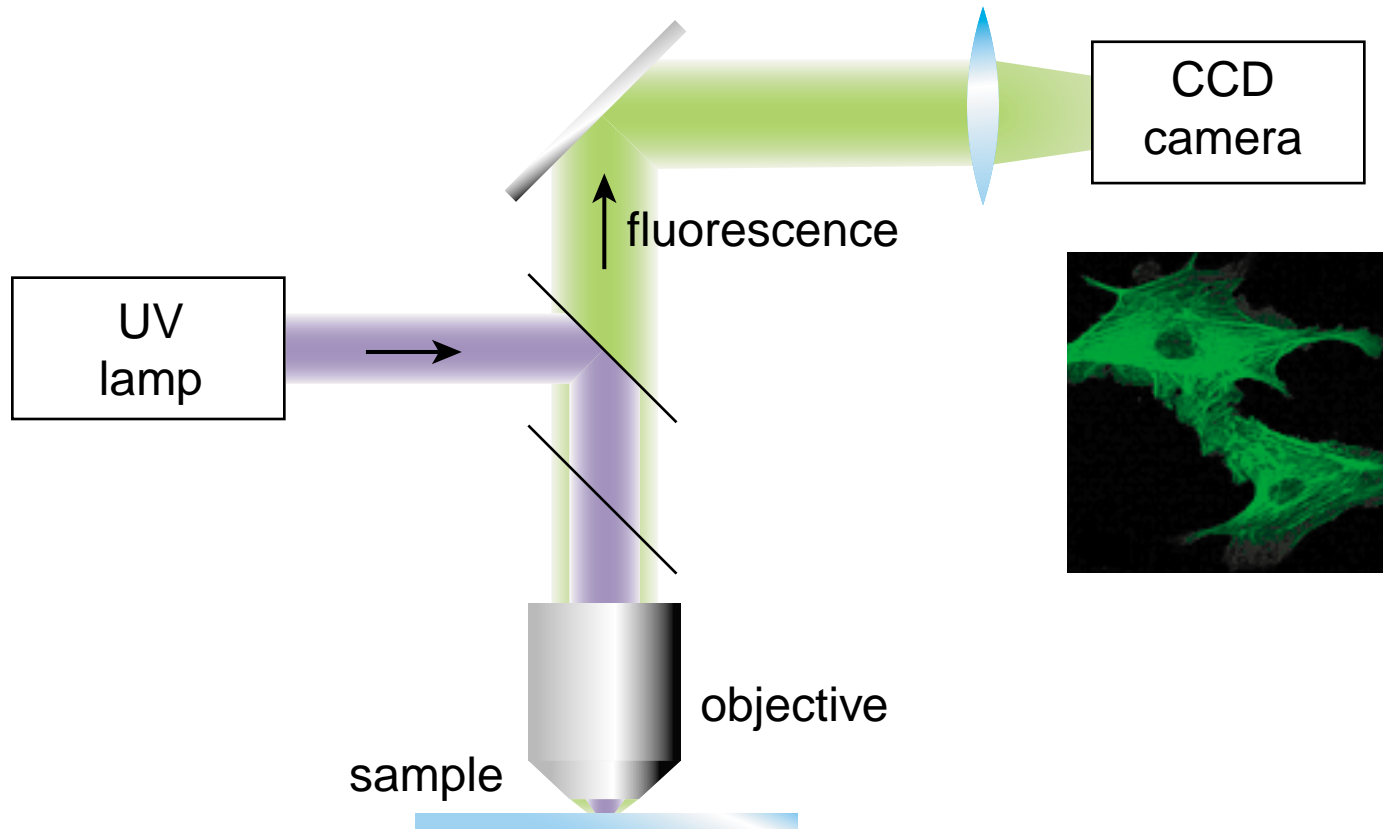
Low-energy processing

UV illumination...



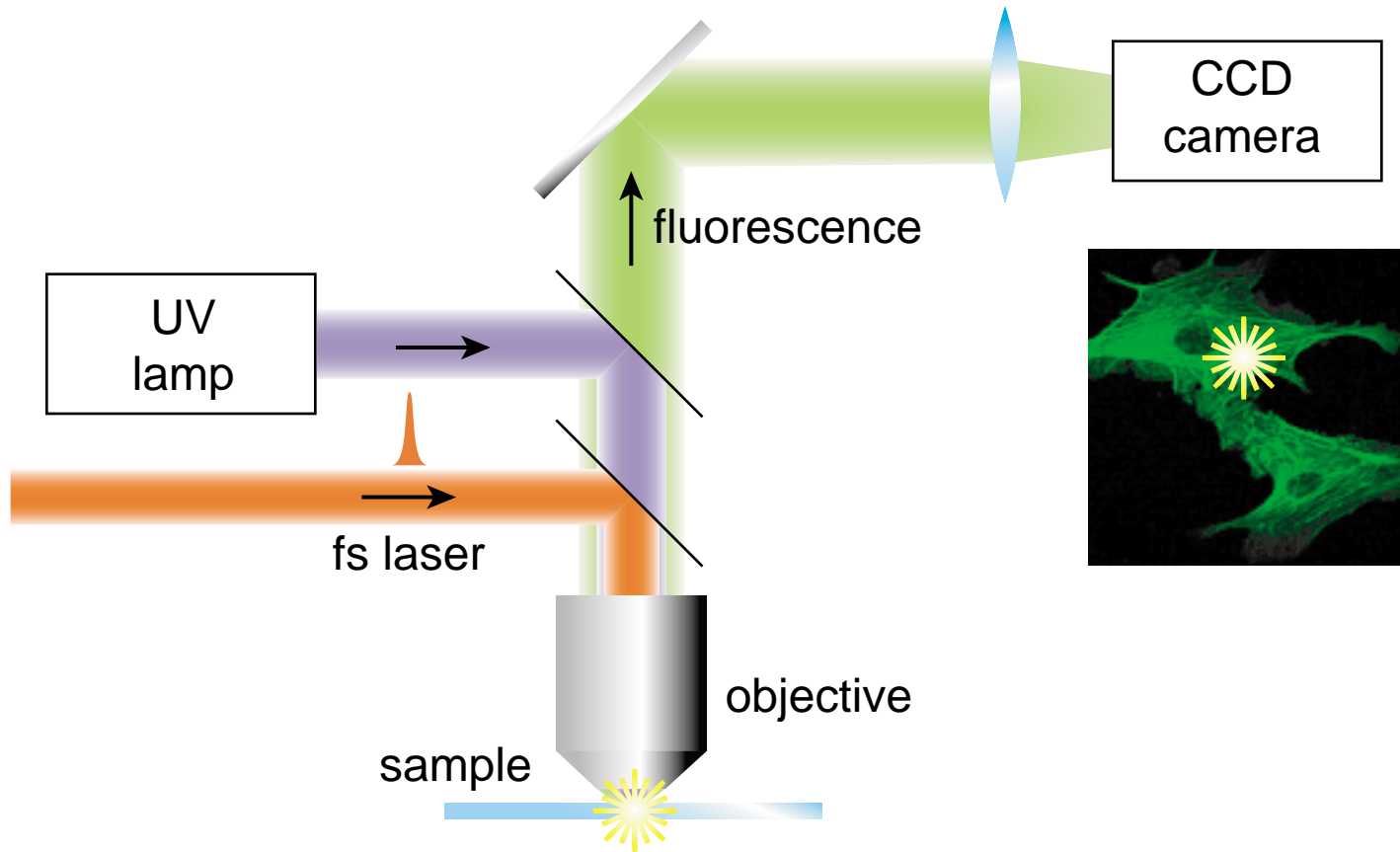
Low-energy processing

... causes fluorescence

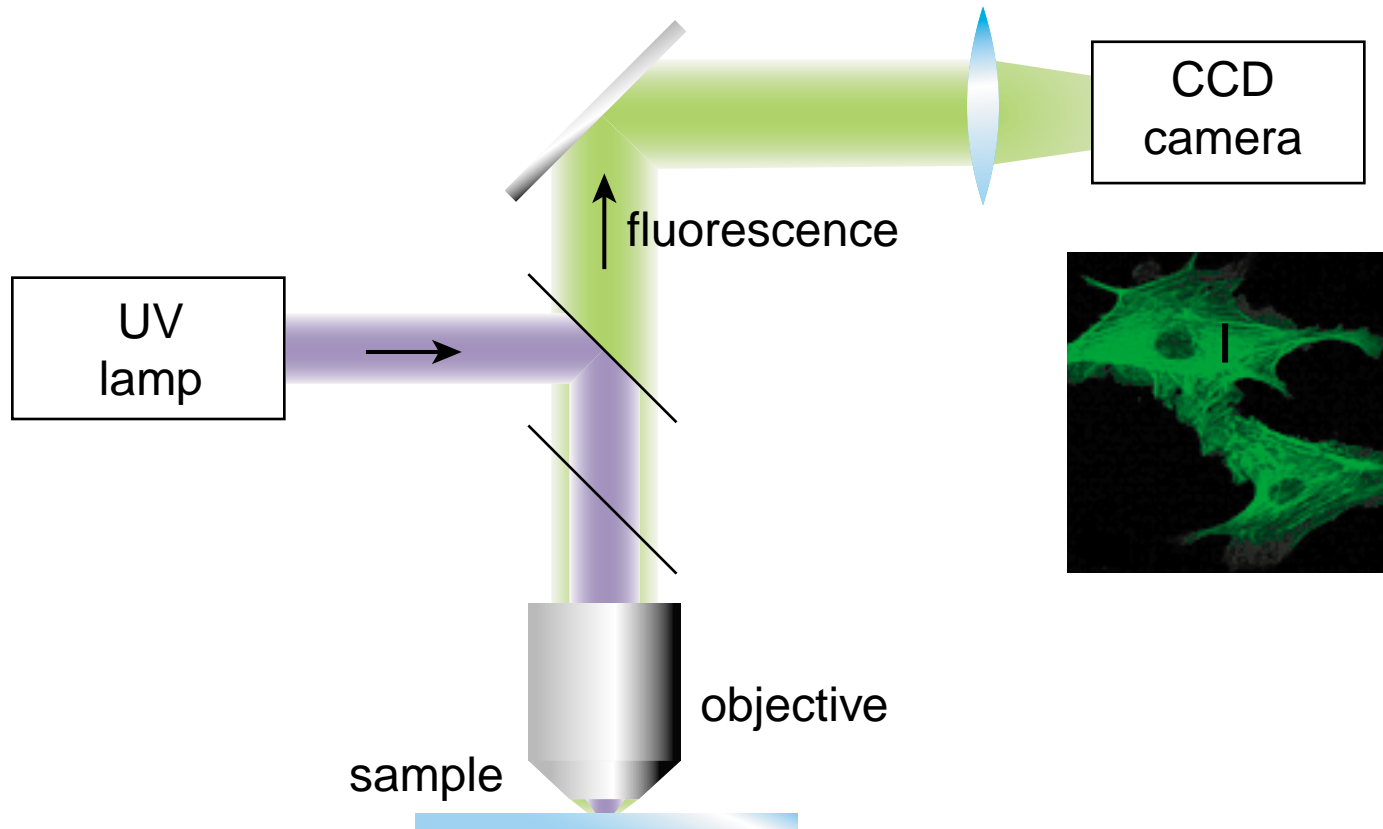


Low-energy processing

process with fs laser beam



Low-energy processing



Low-energy processing

before

after

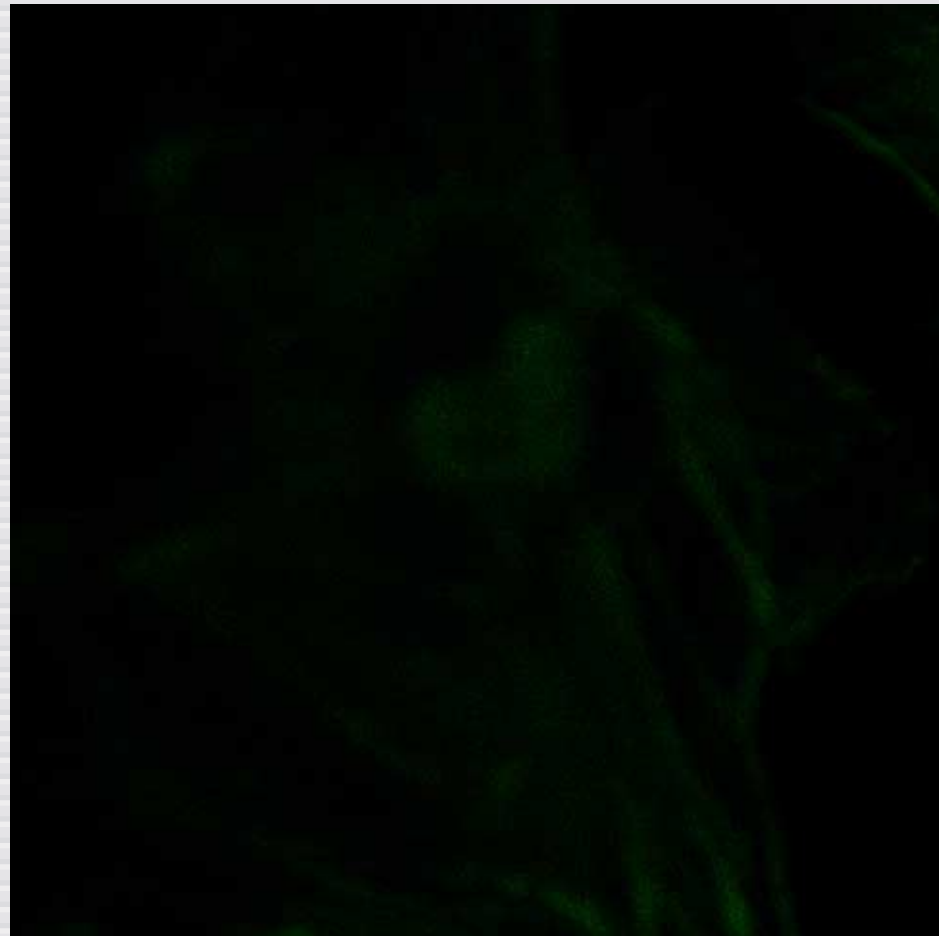


examine in confocal microscope

Low-energy processing

before

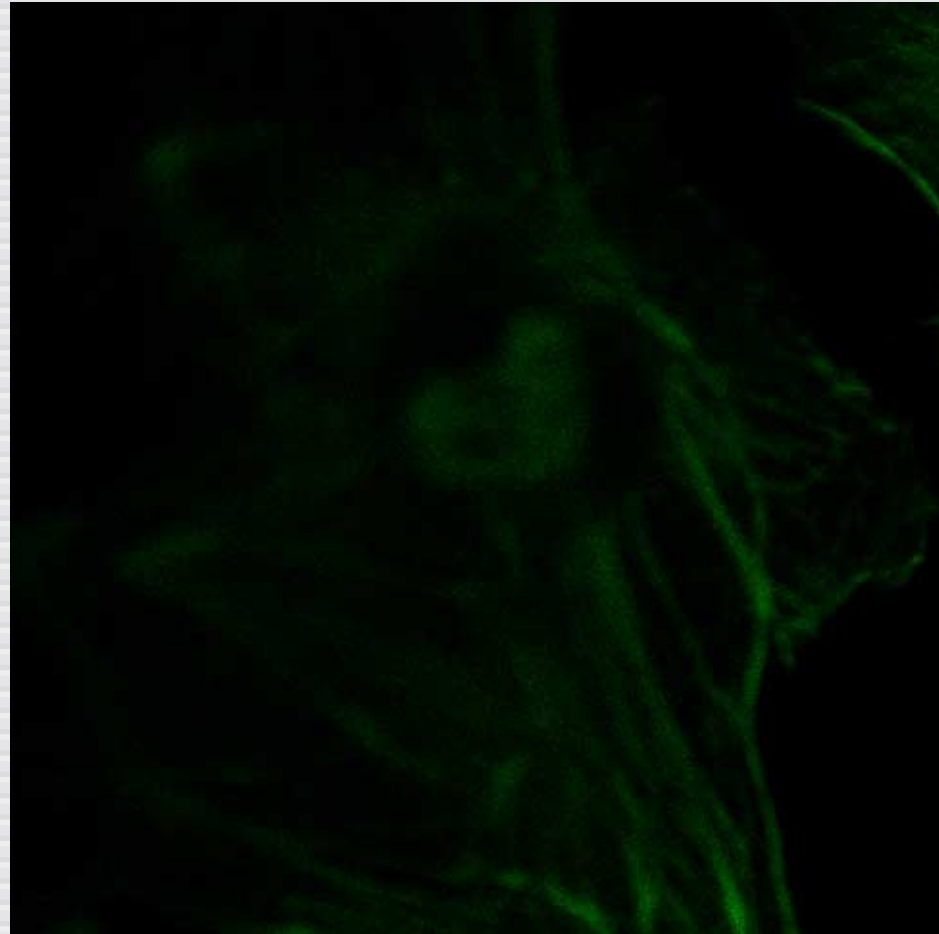
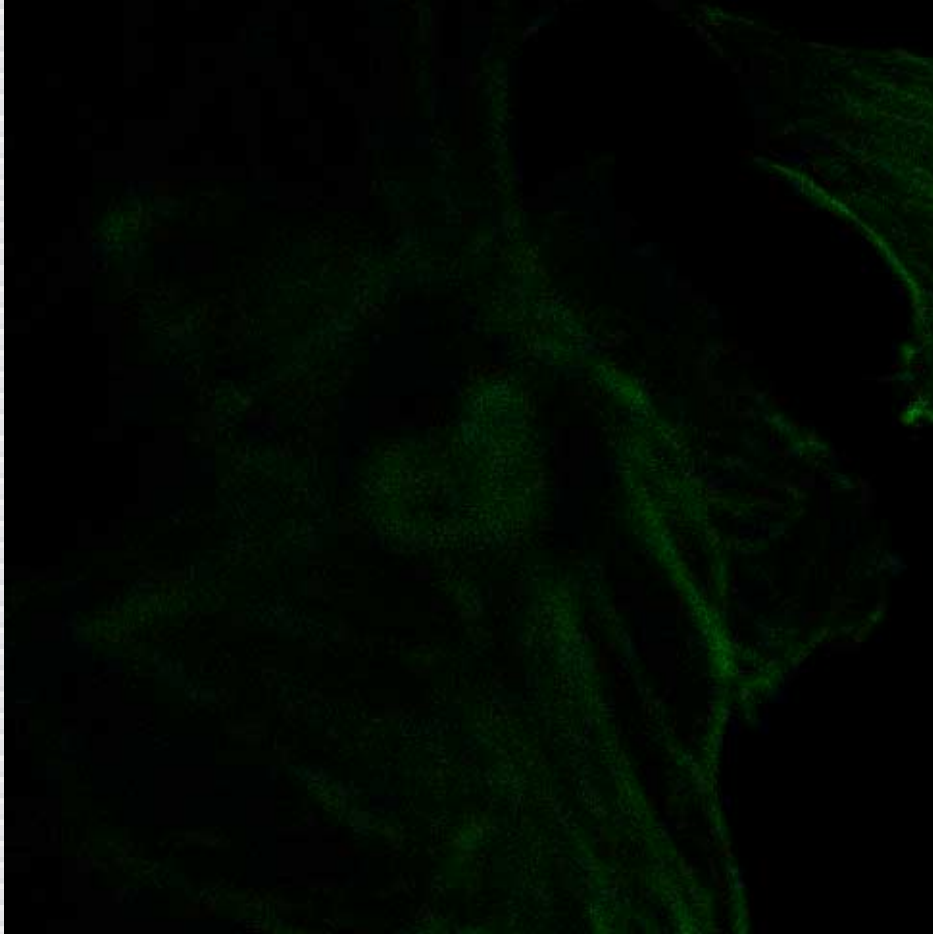
after



Low-energy processing

before

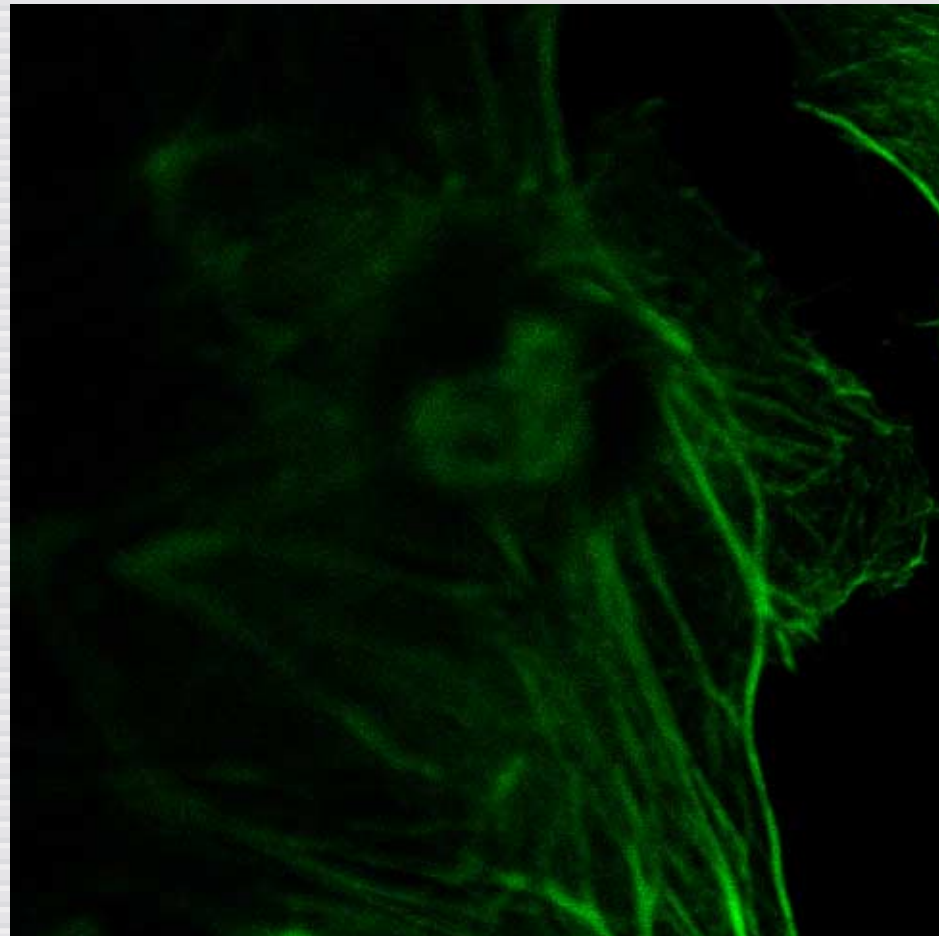
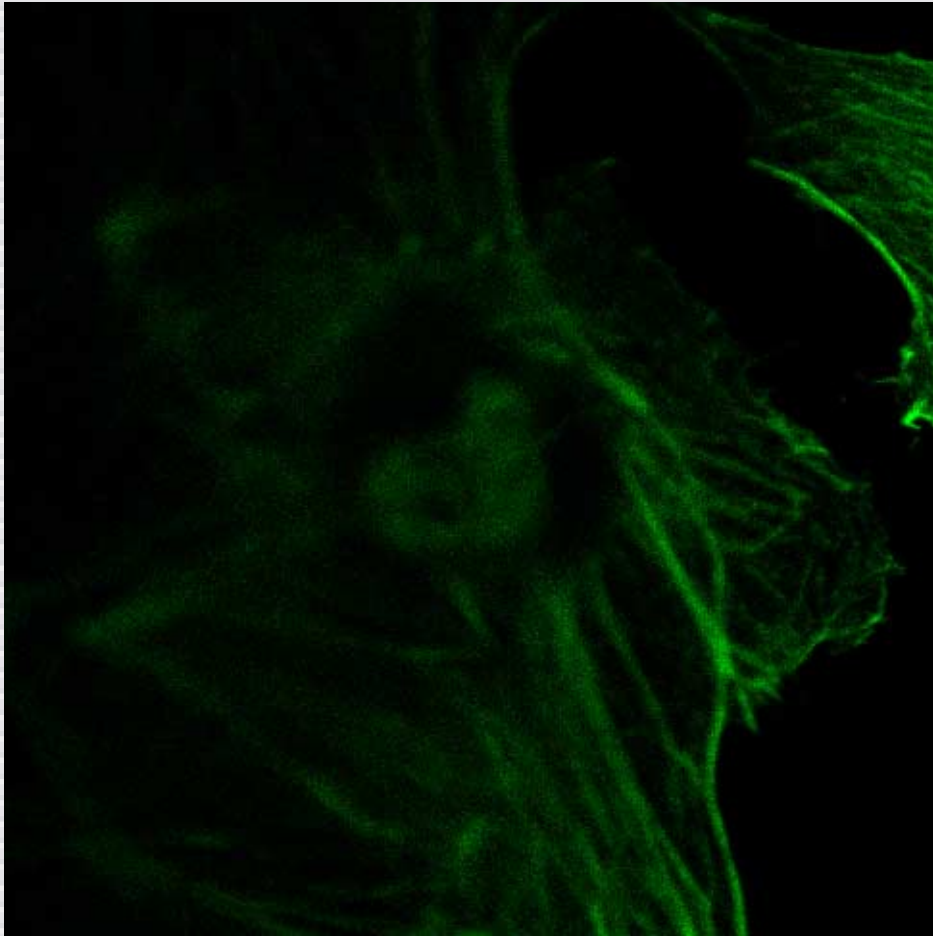
after



Low-energy processing

before

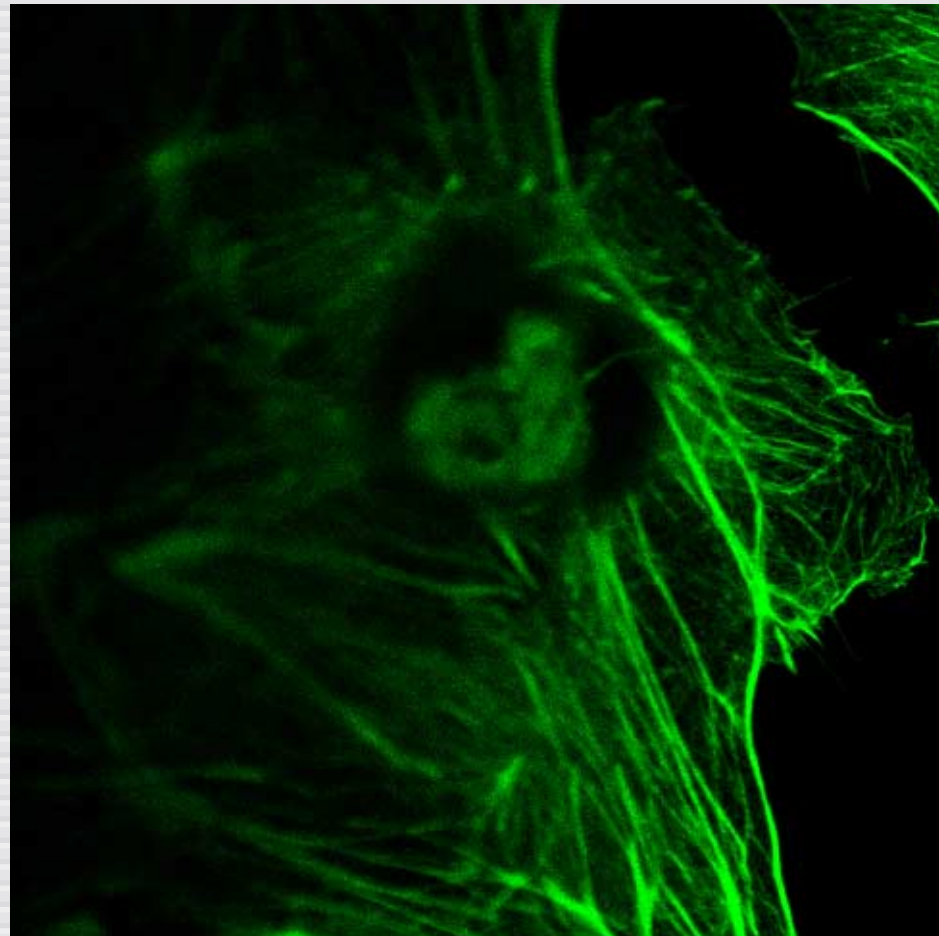
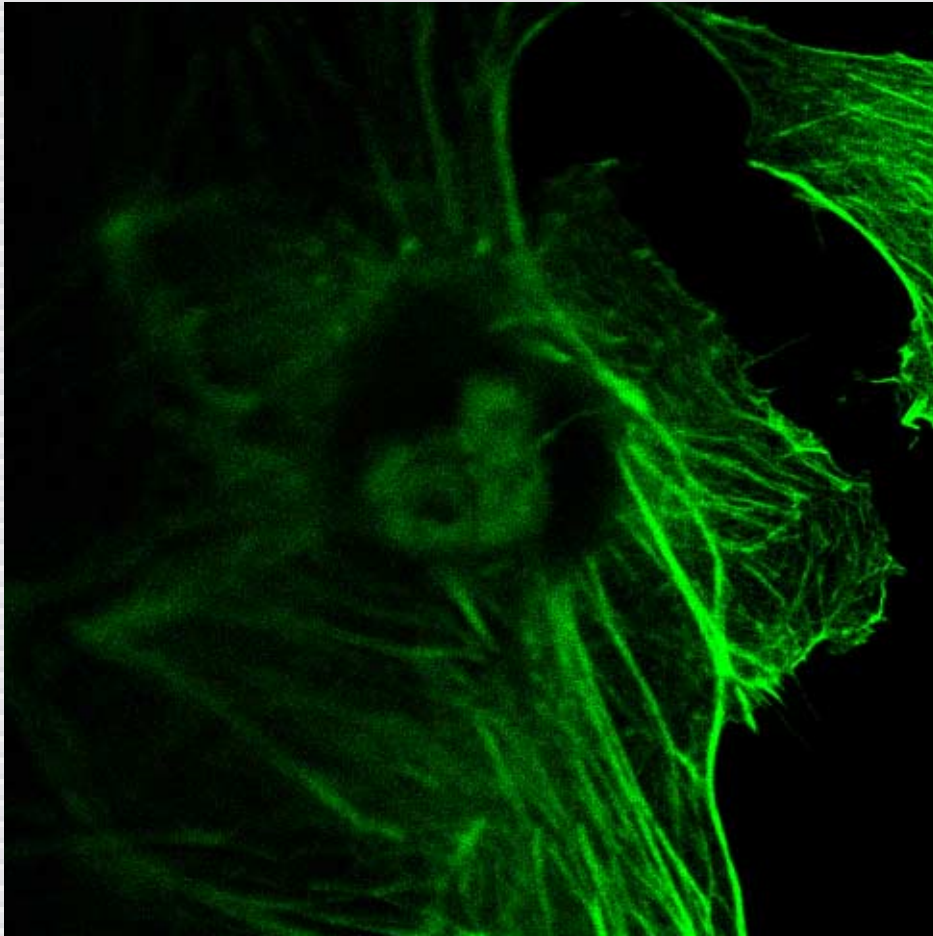
after



Low-energy processing

before

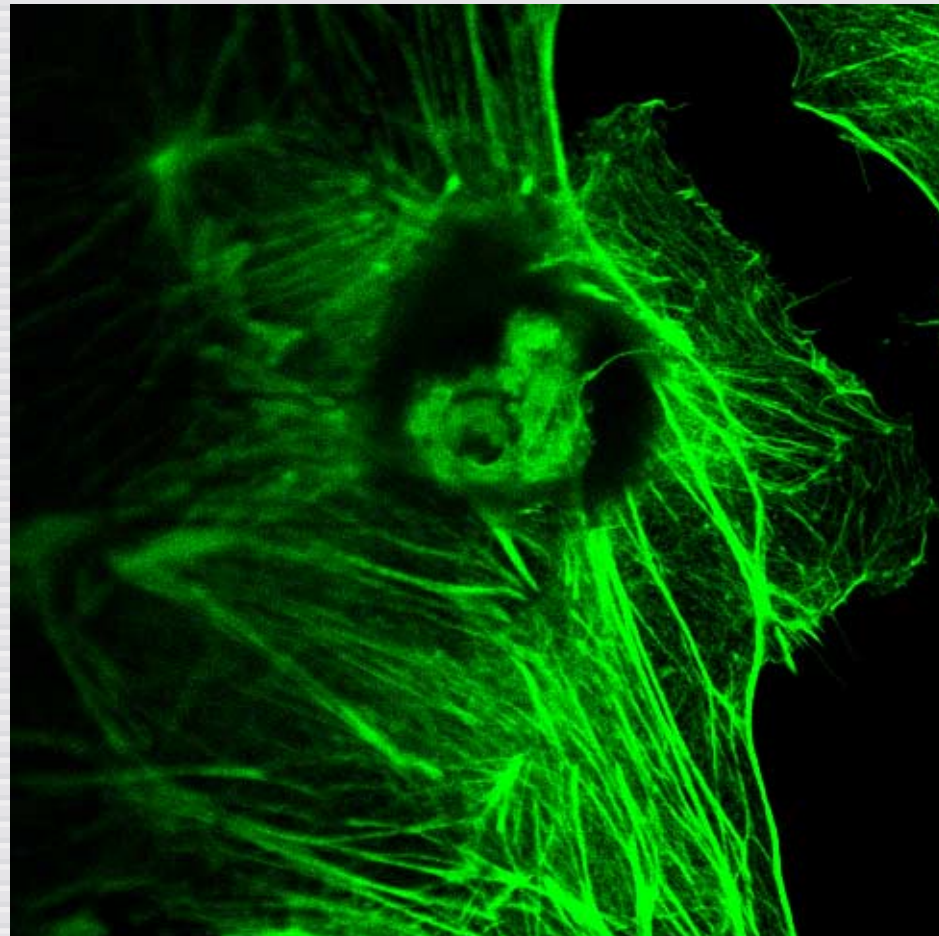
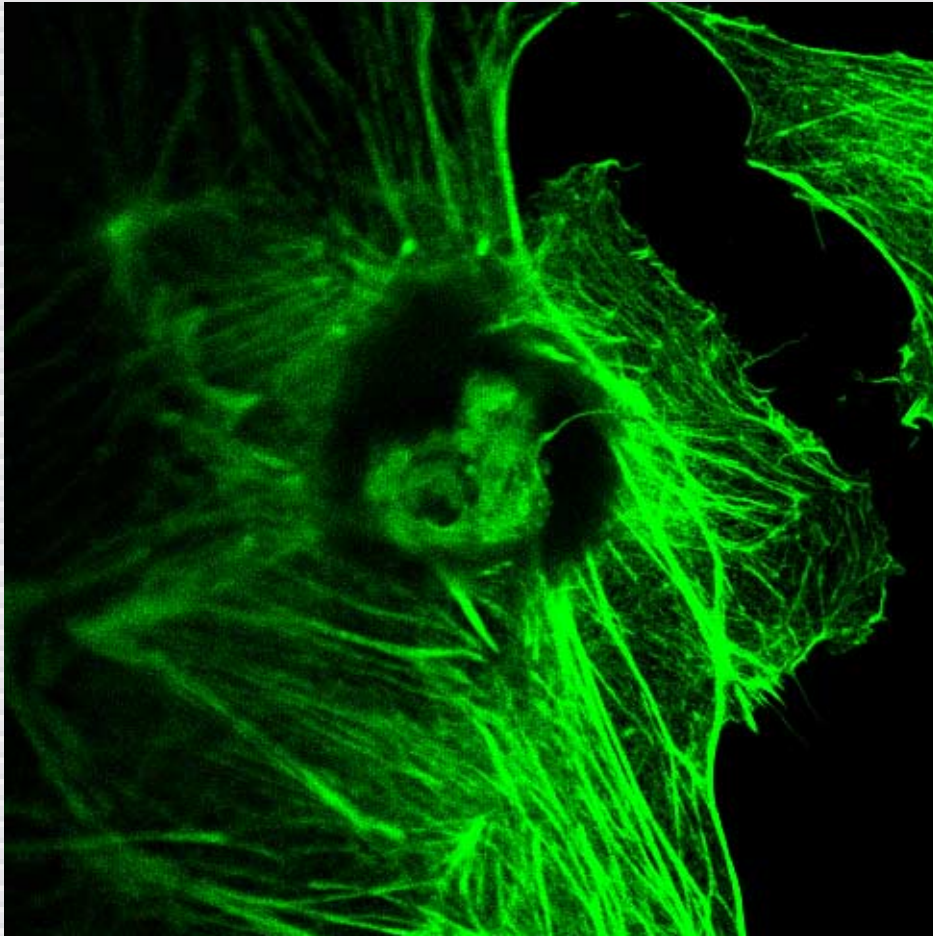
after



Low-energy processing

before

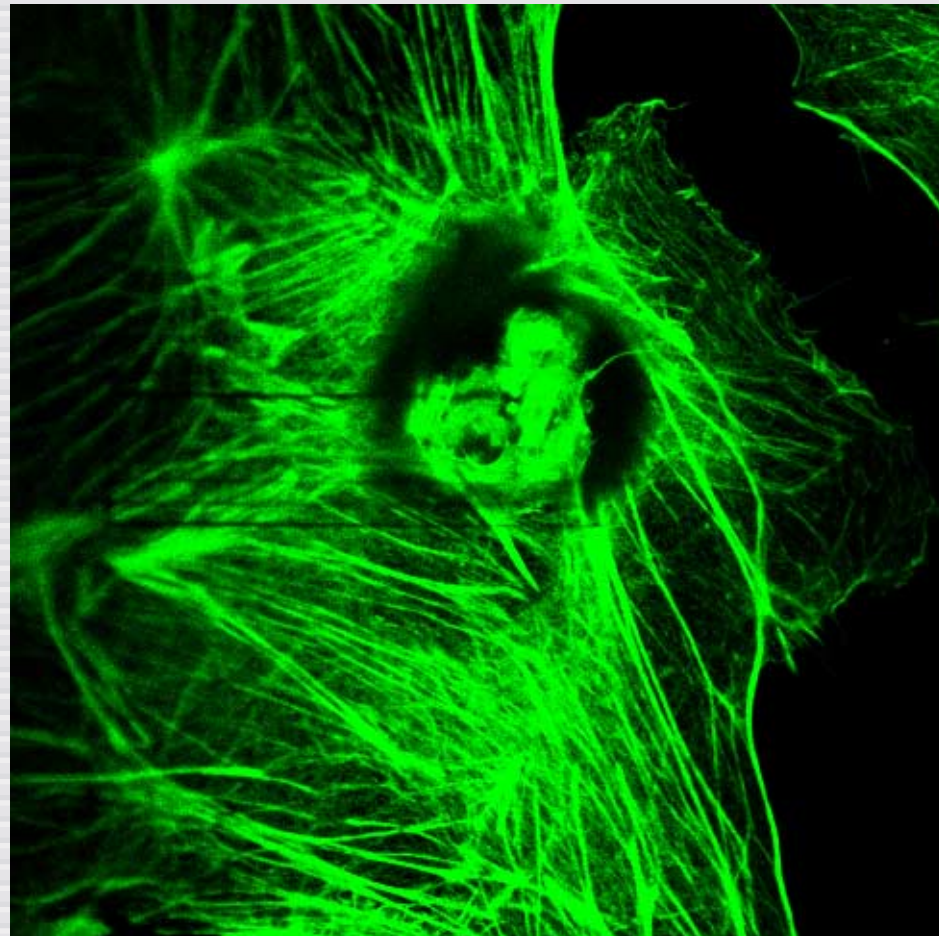
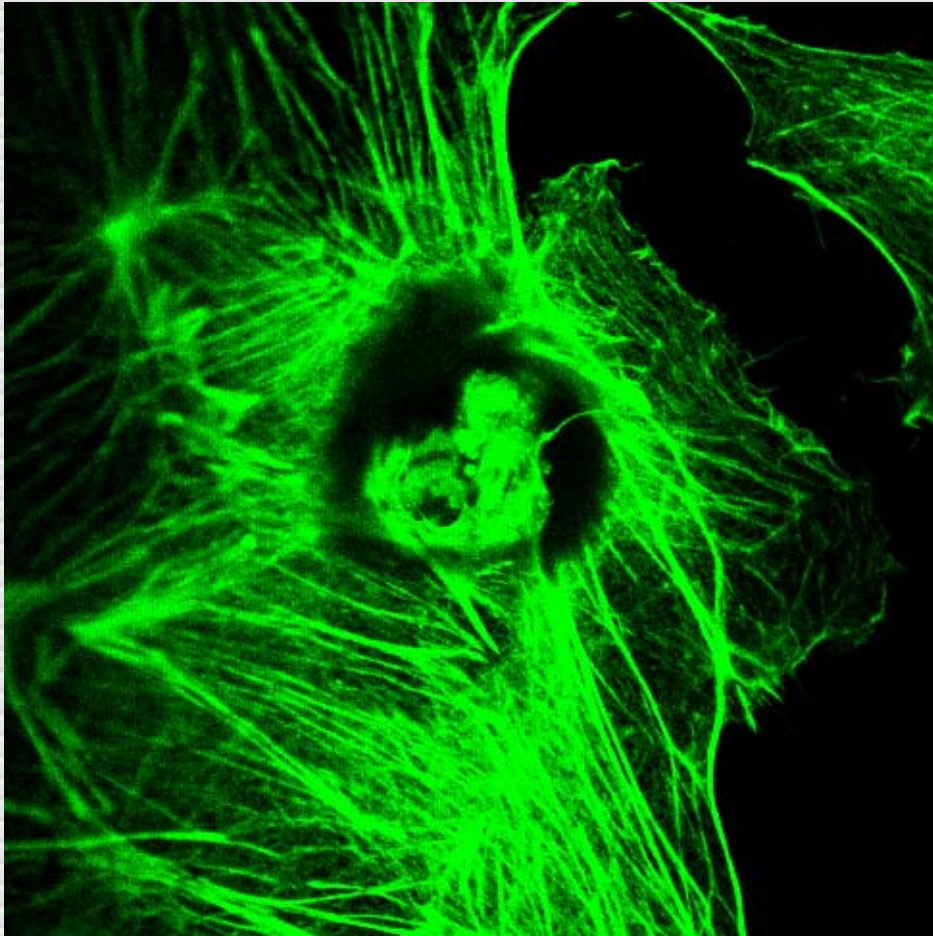
after



Low-energy processing

before

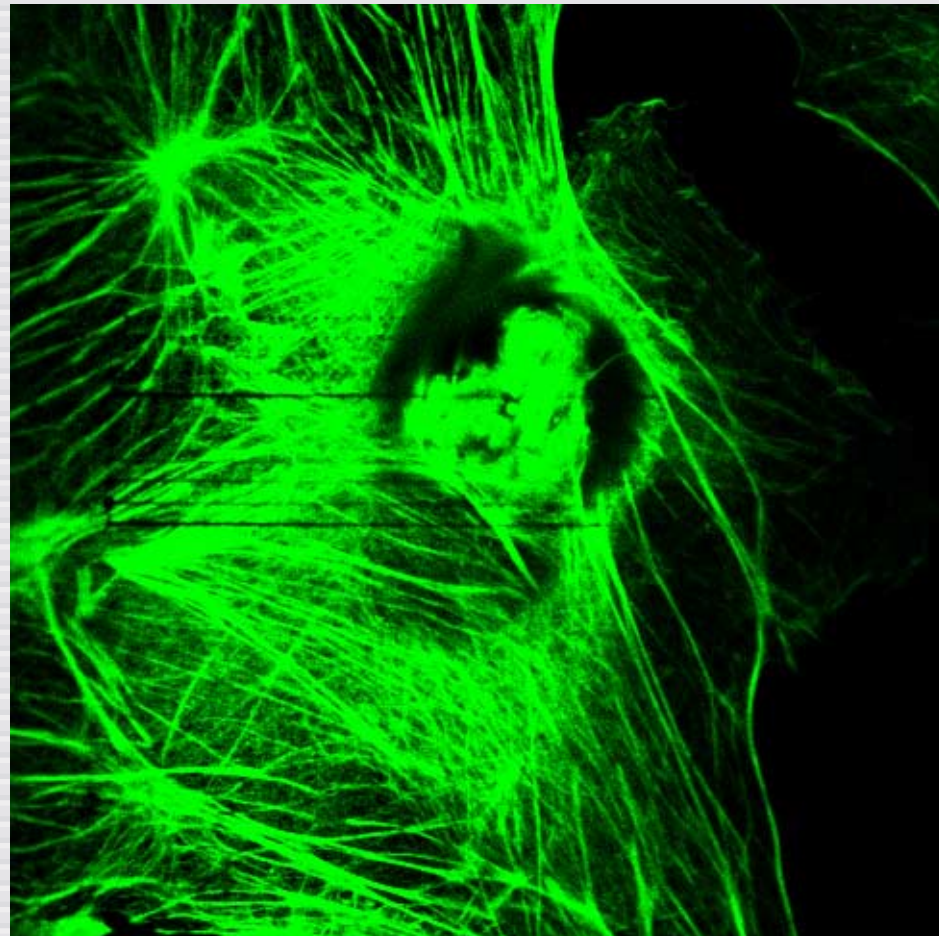
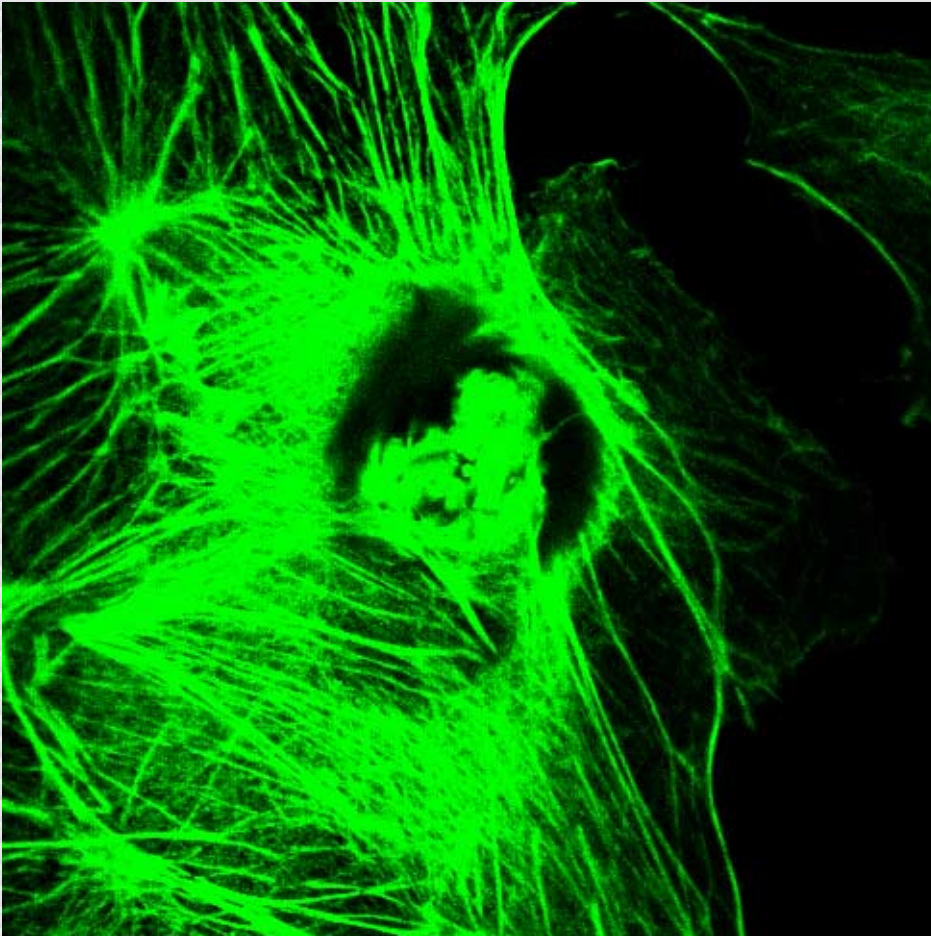
after



Low-energy processing

before

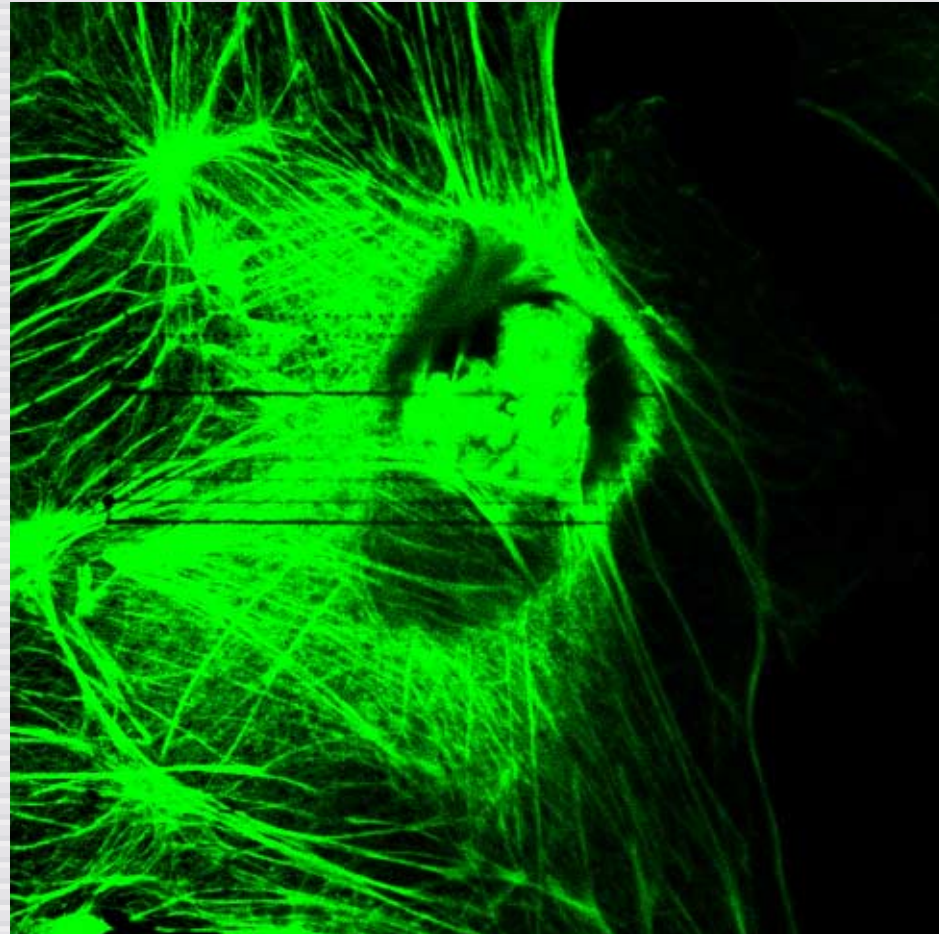
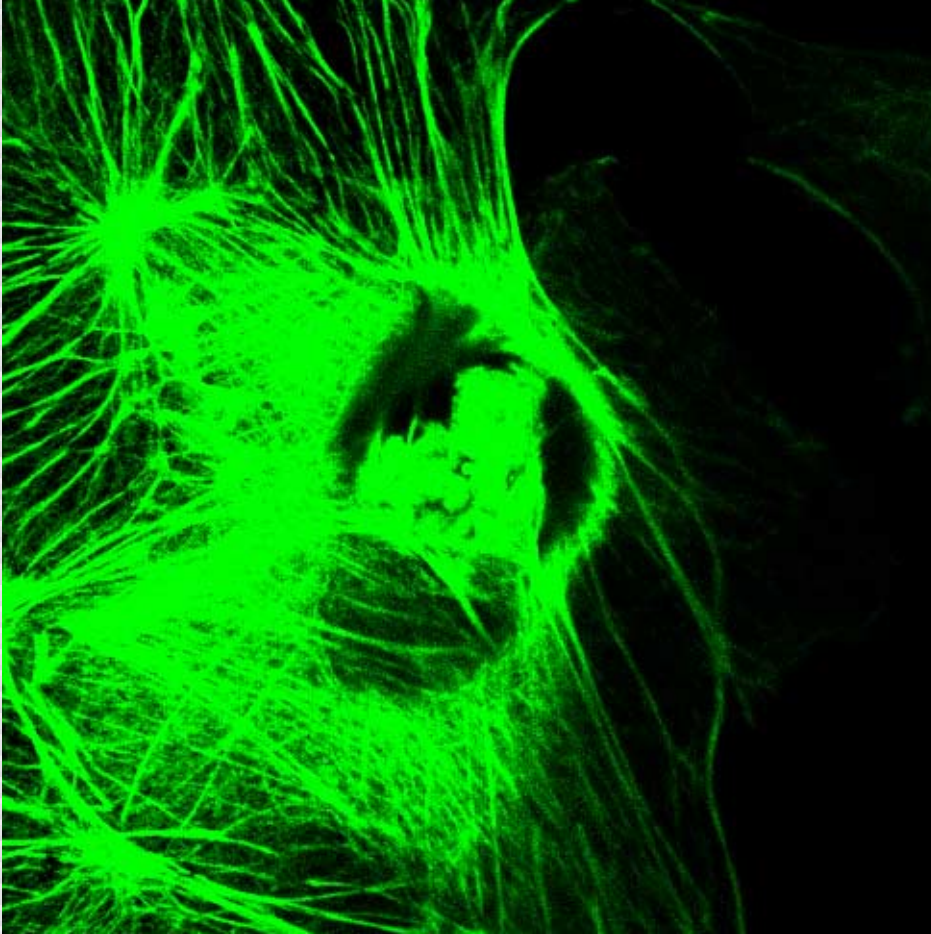
after



Low-energy processing

before

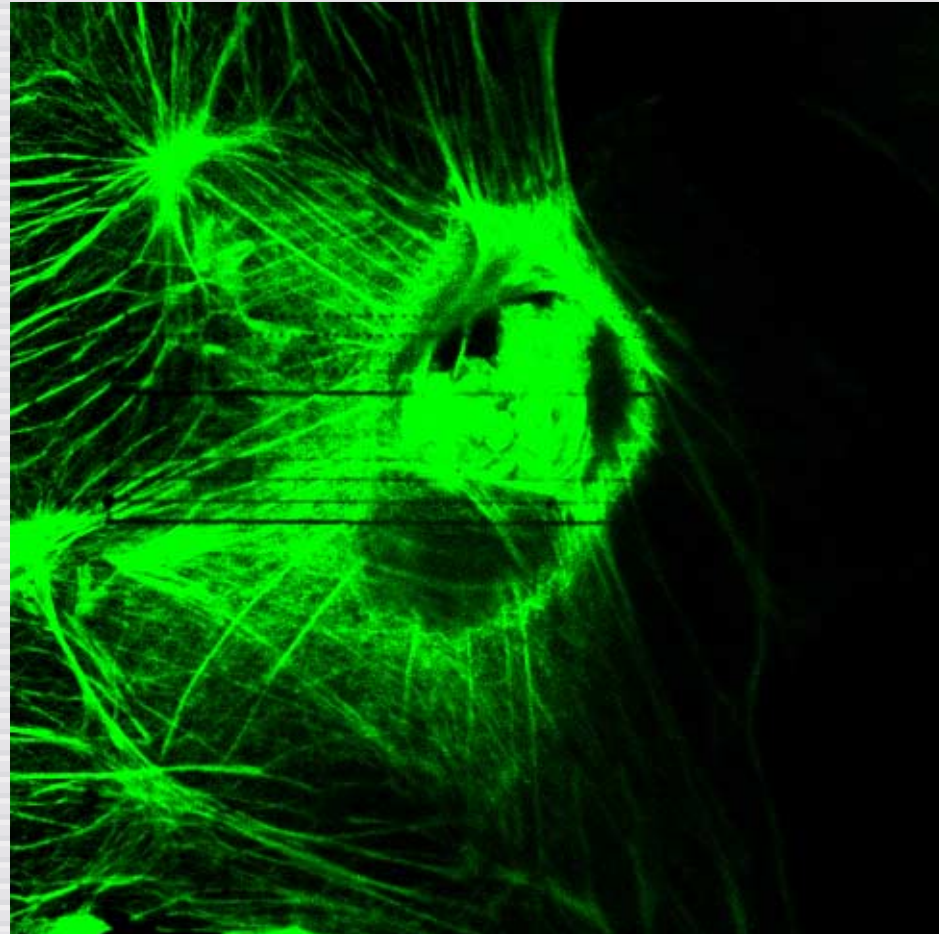
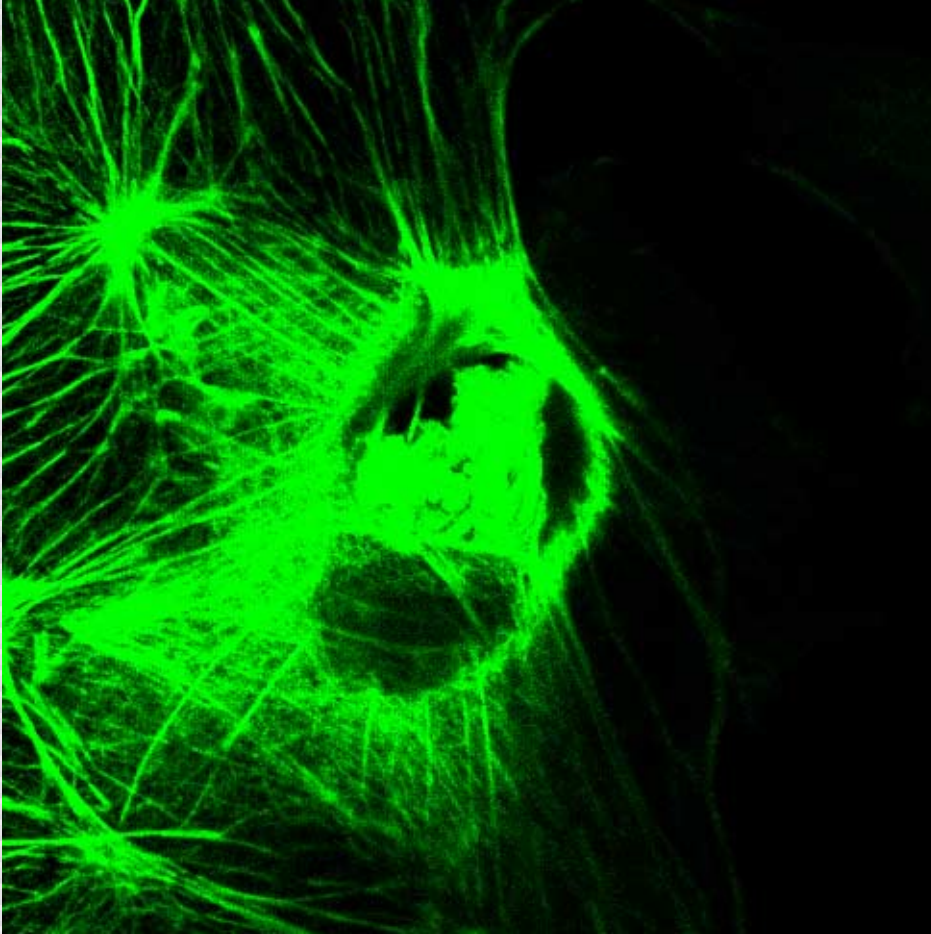
after



Low-energy processing

before

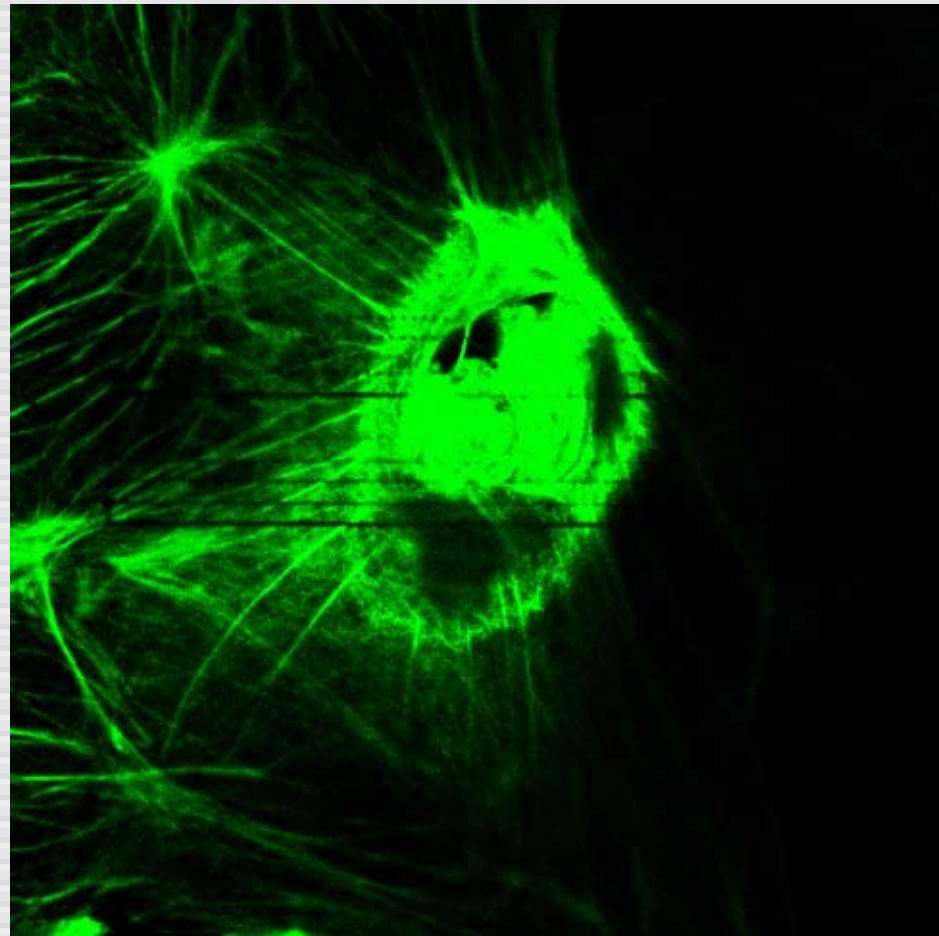
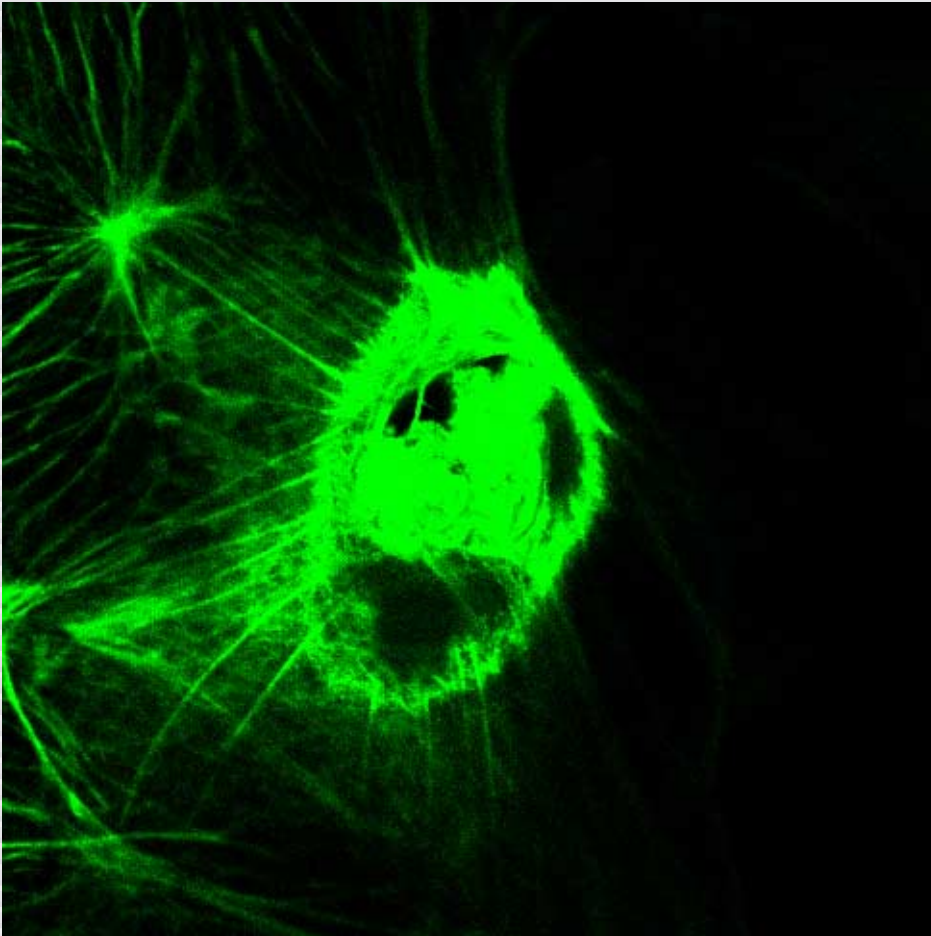
after



Low-energy processing

before

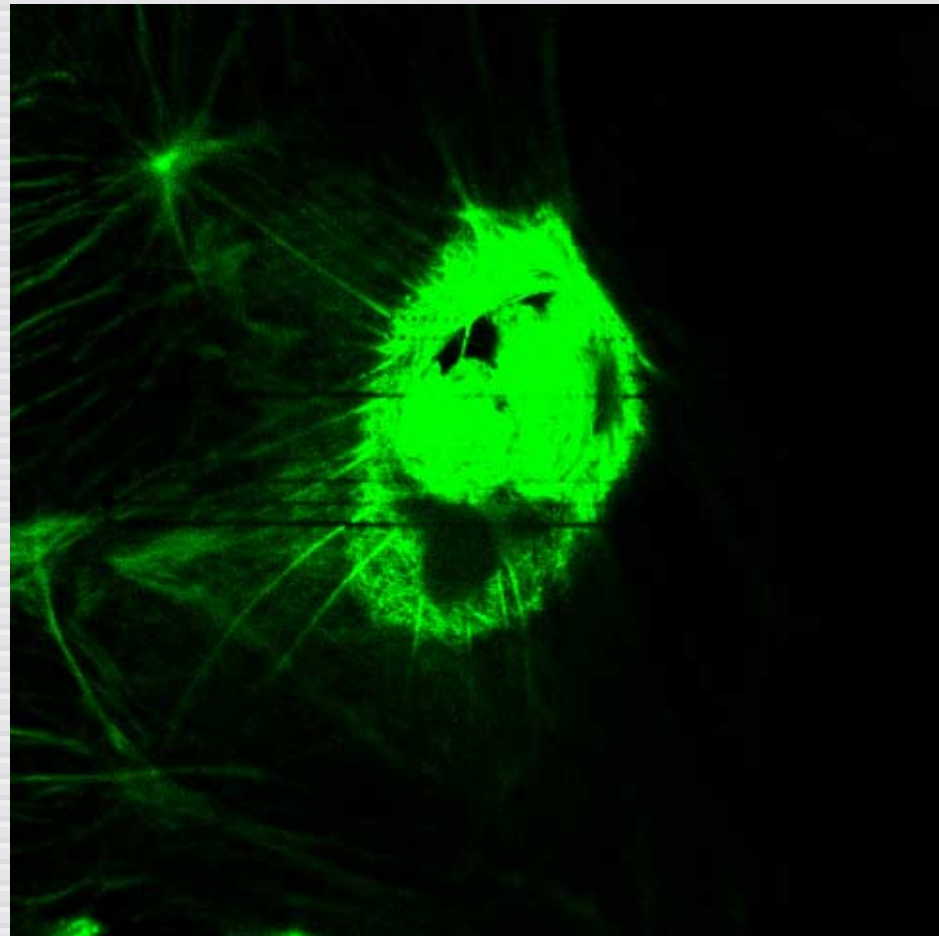
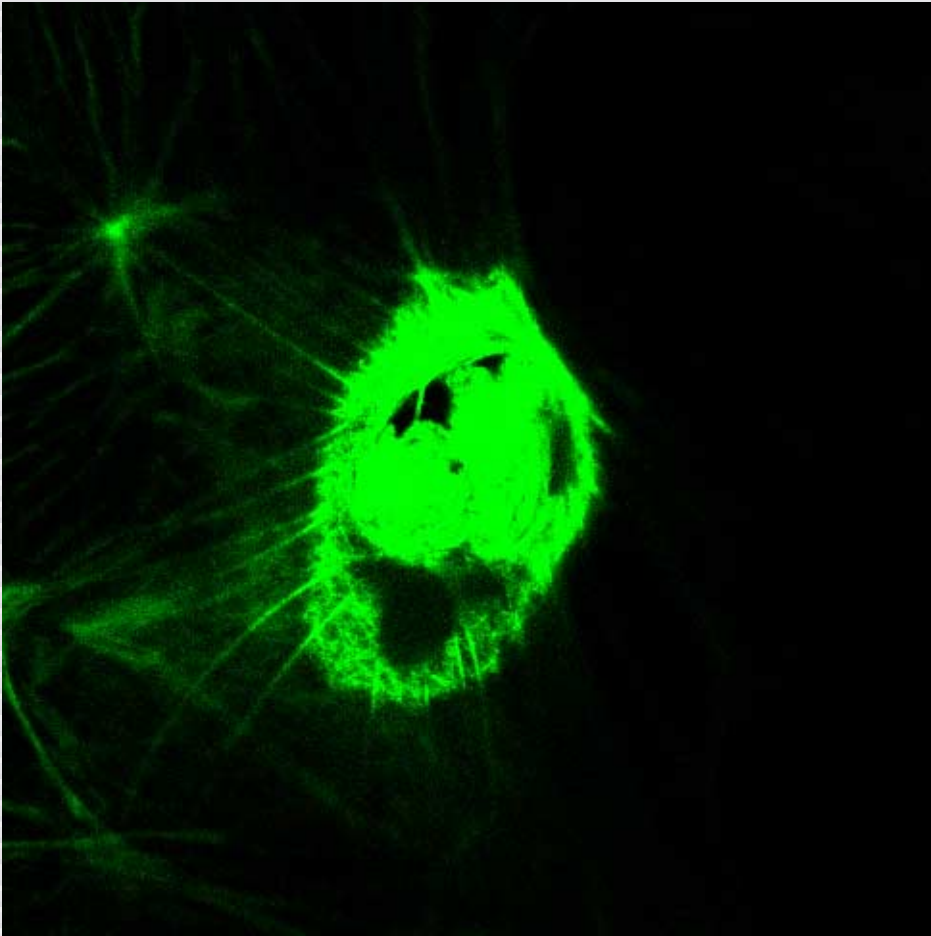
after



Low-energy processing

before

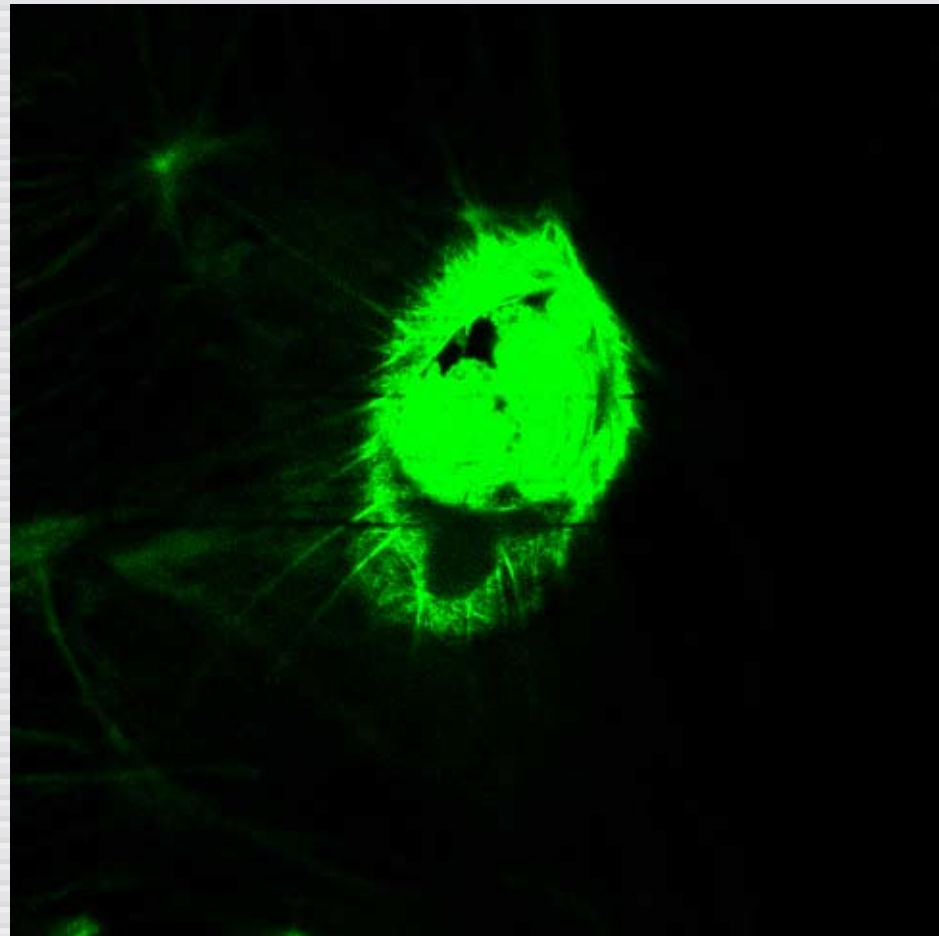
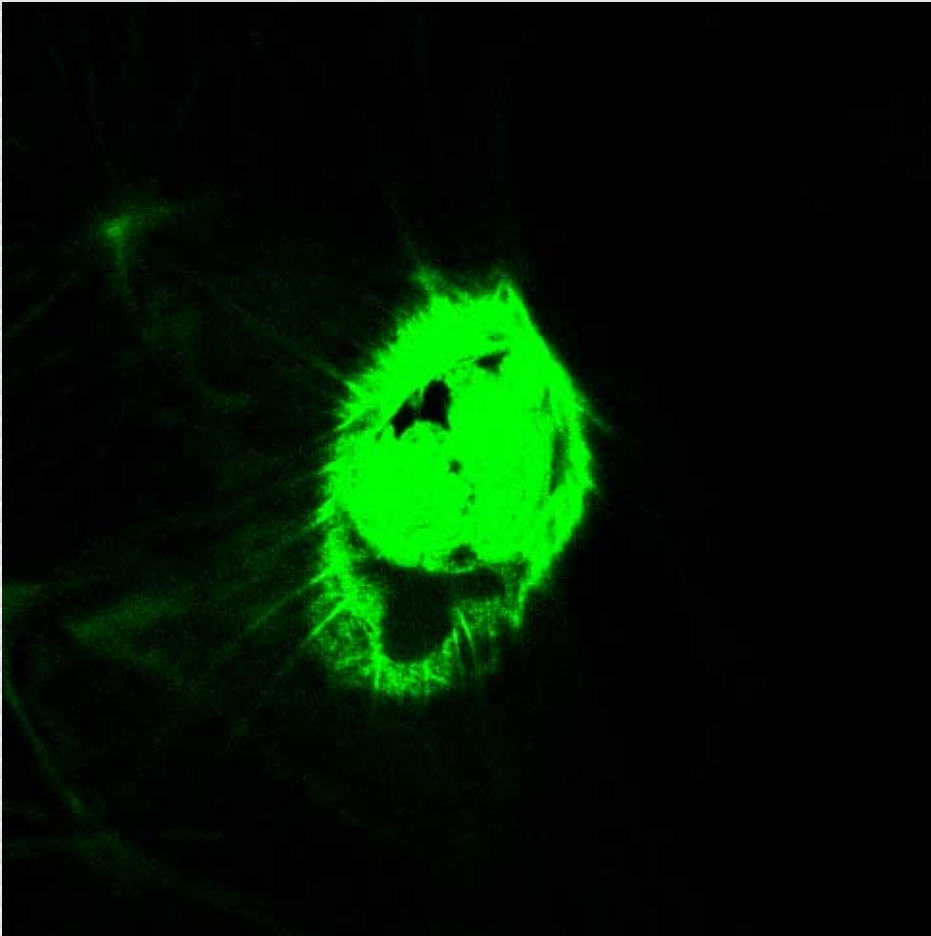
after



Low-energy processing

before

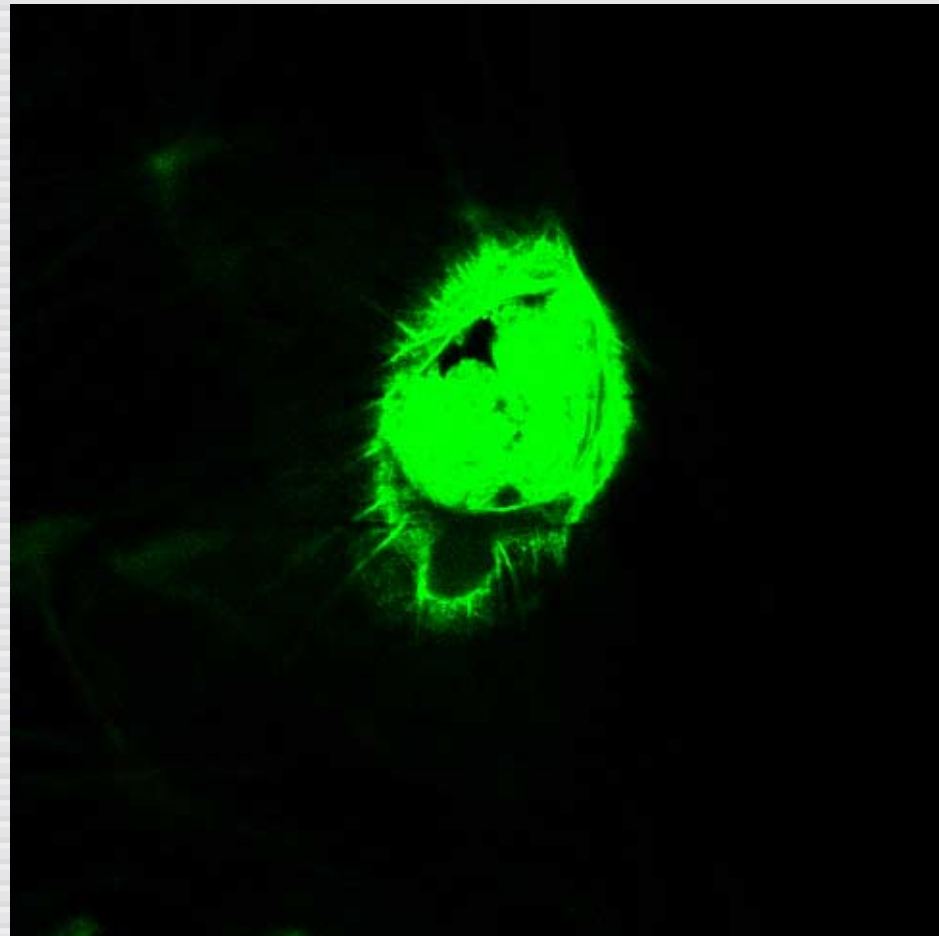
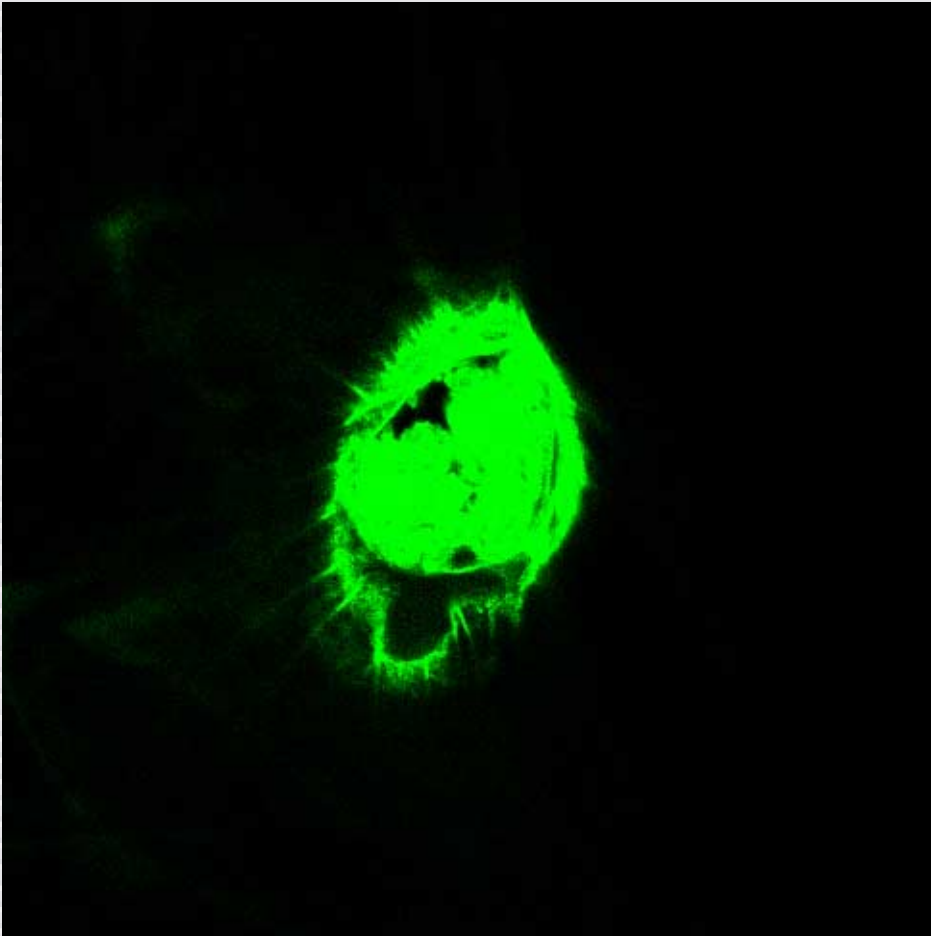
after



Low-energy processing

before

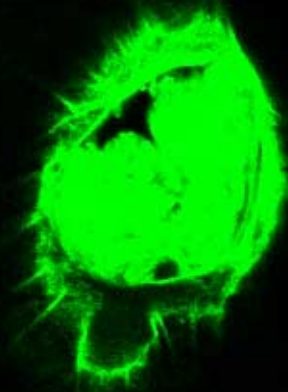
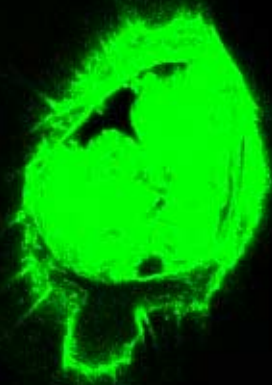
after



Low-energy processing

before

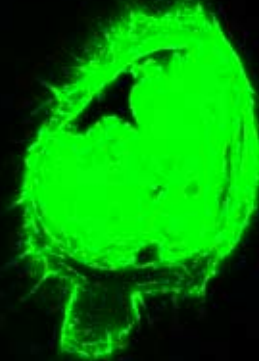
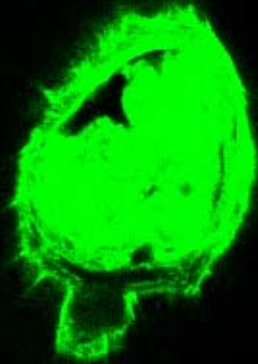
after



Low-energy processing

before

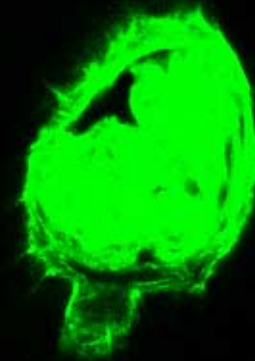
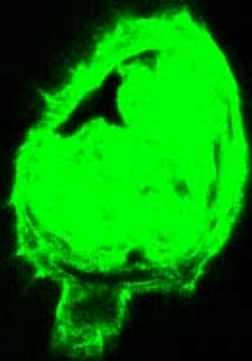
after



Low-energy processing

before

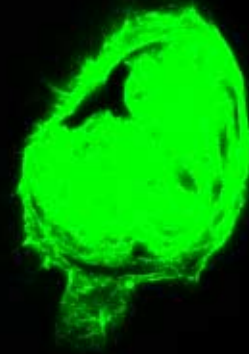
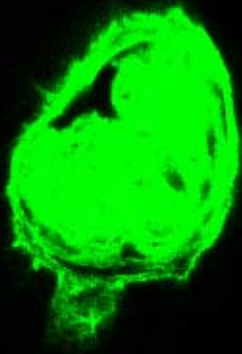
after



Low-energy processing

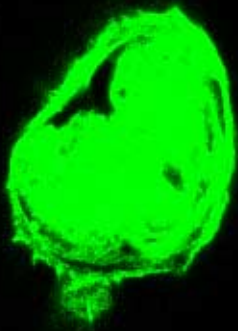
before

after

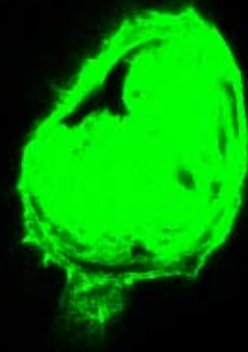


Low-energy processing

before

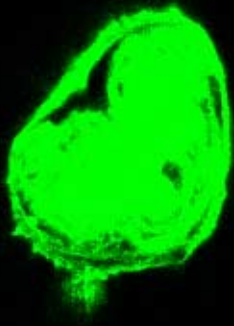


after

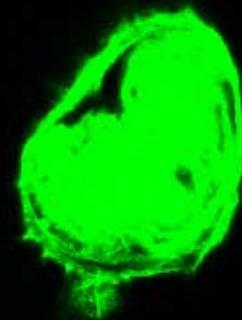


Low-energy processing

before

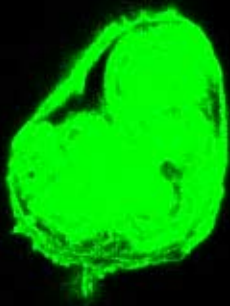


after

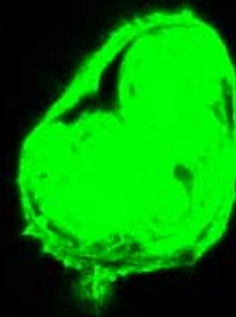


Low-energy processing

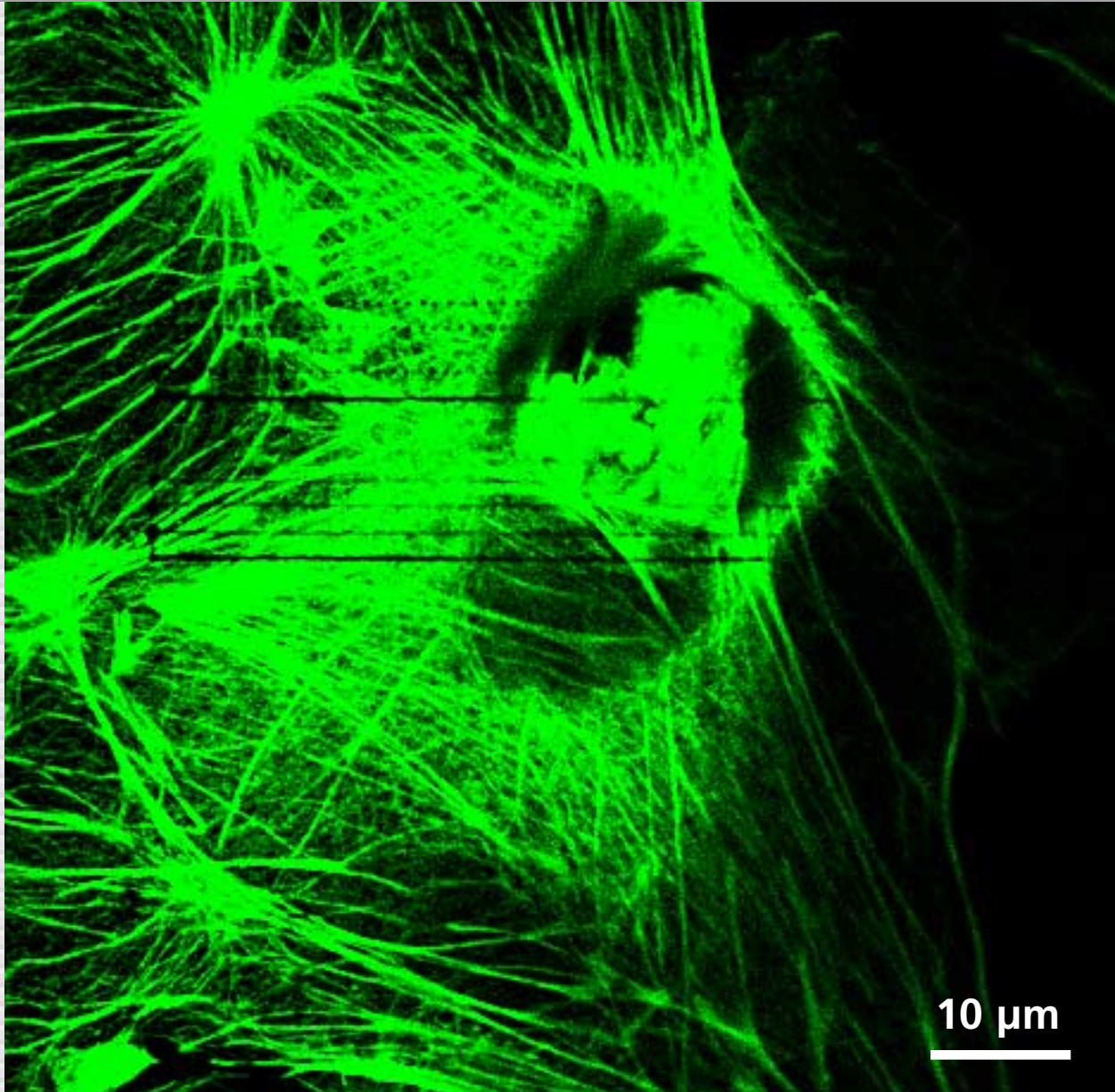
before



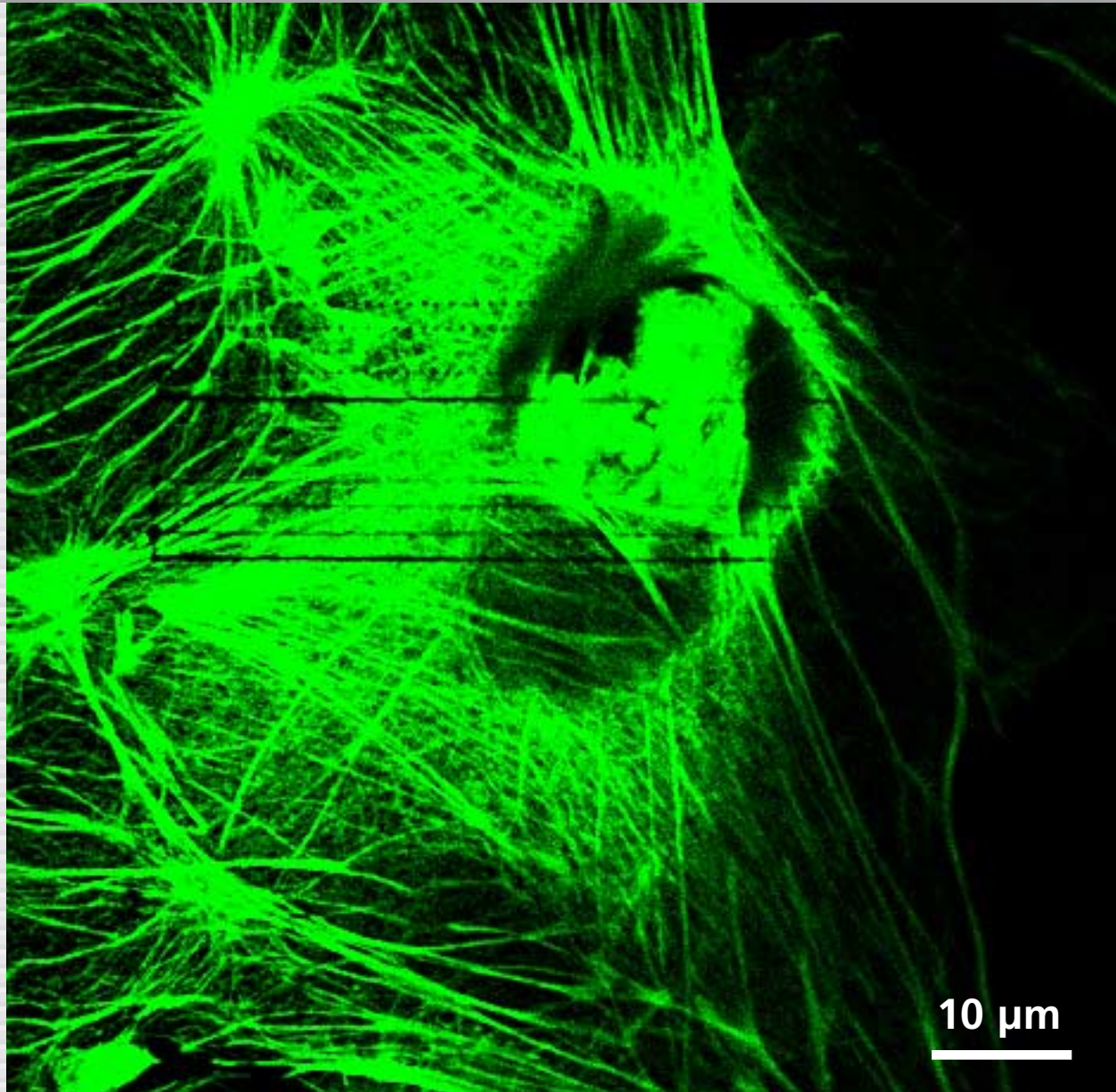
after



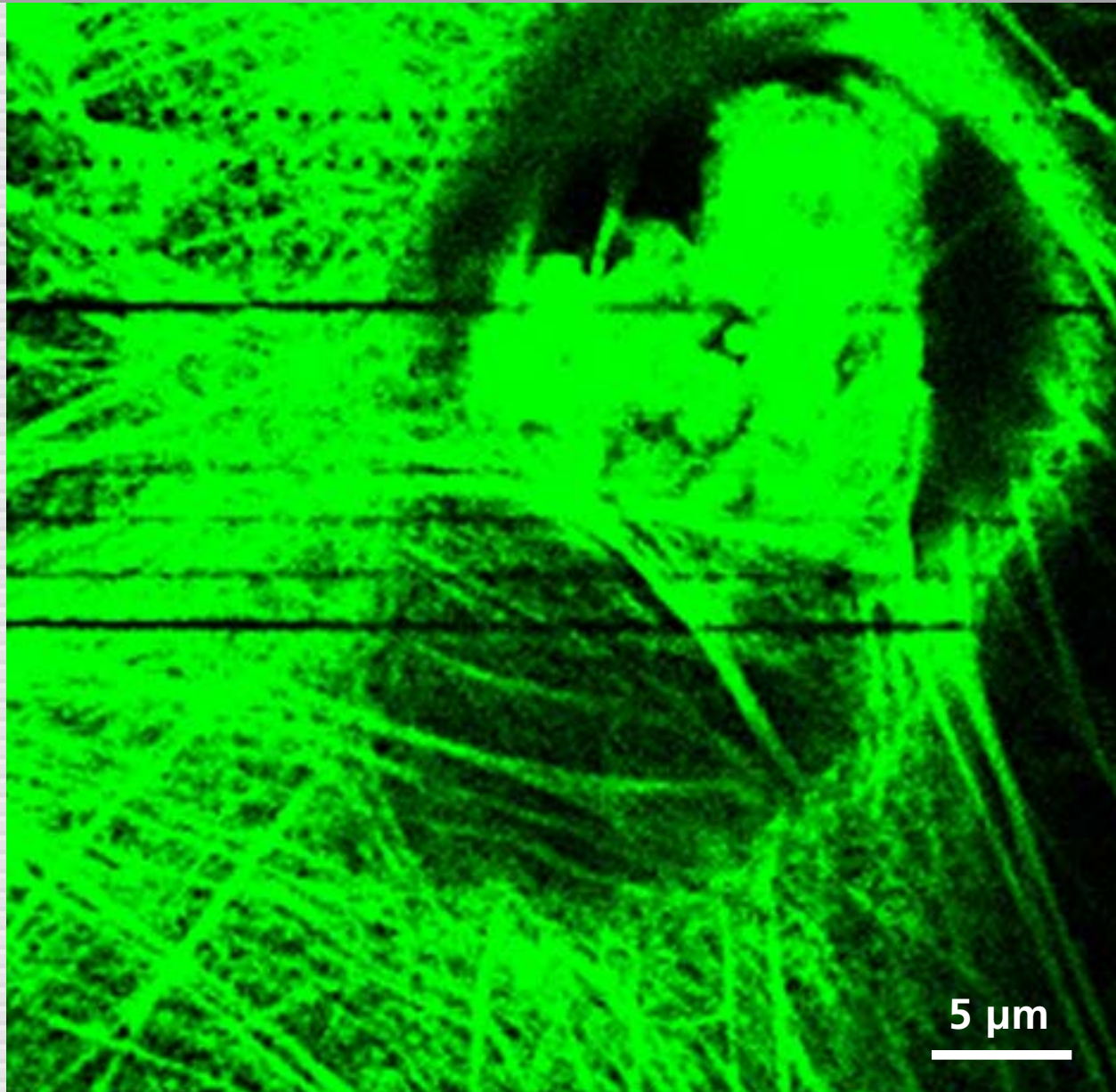
Low-energy processing



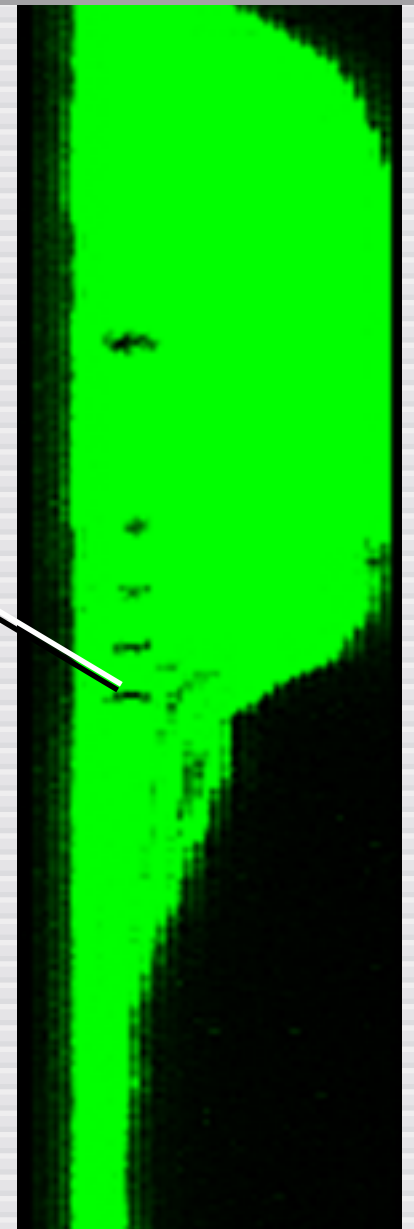
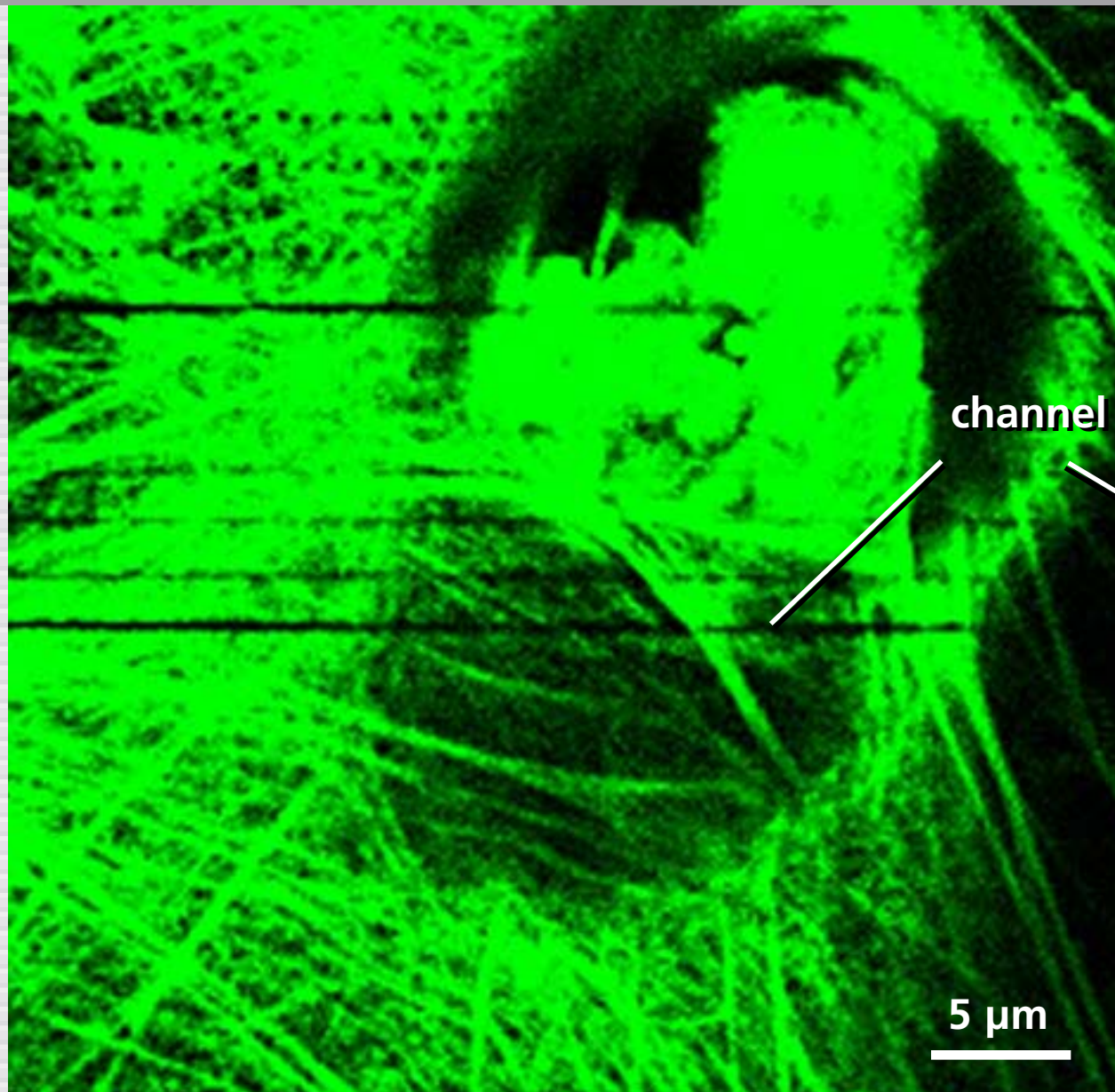
Low-energy processing



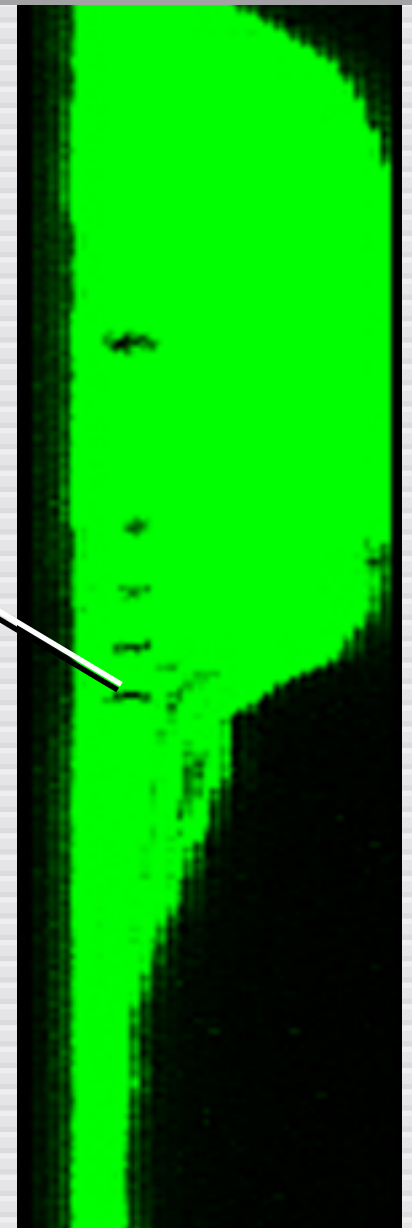
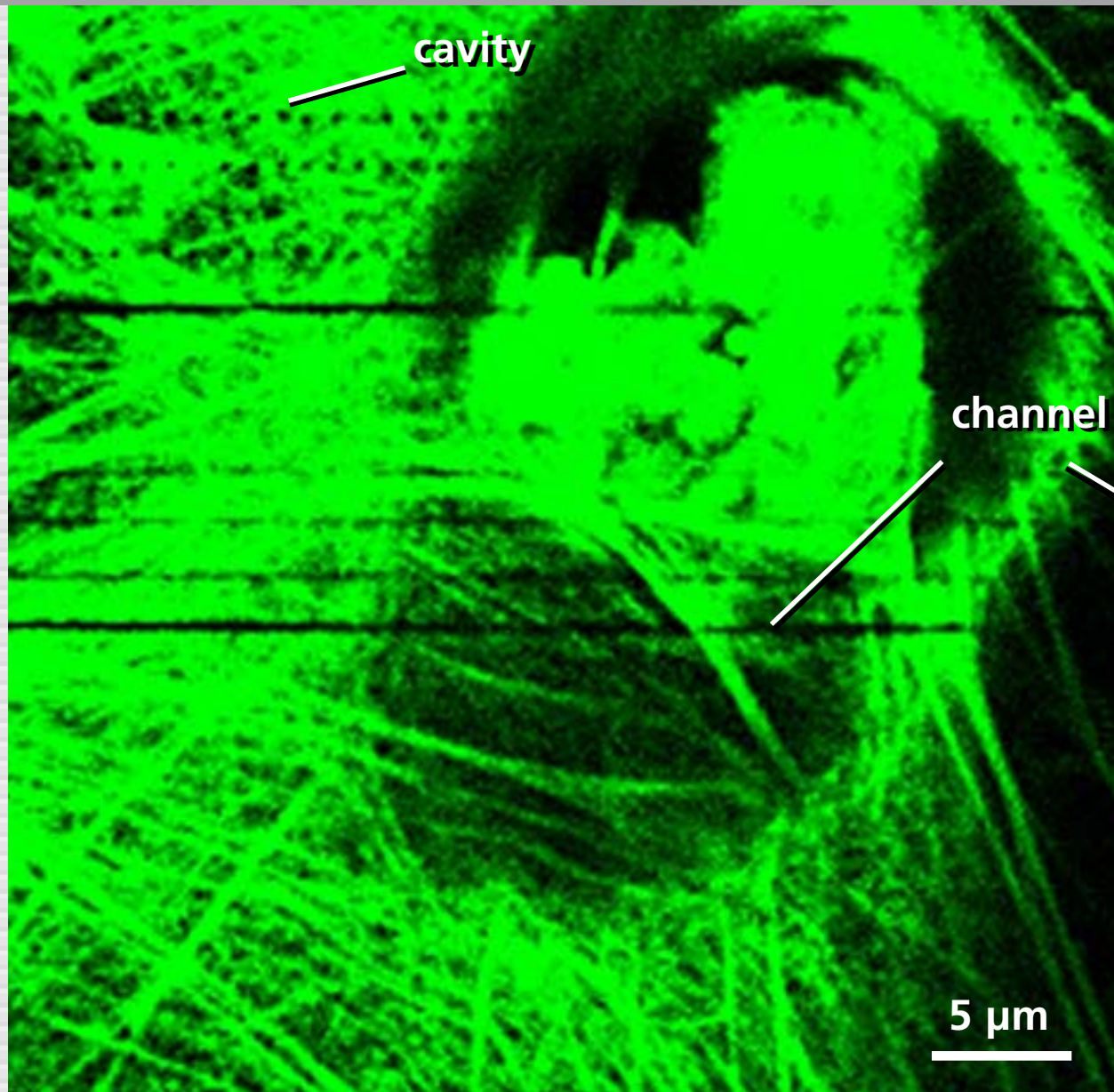
Low-energy processing



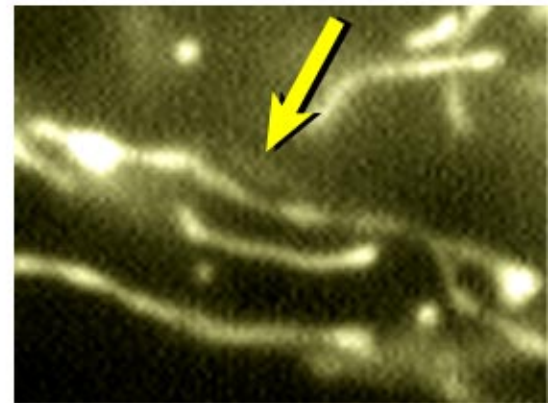
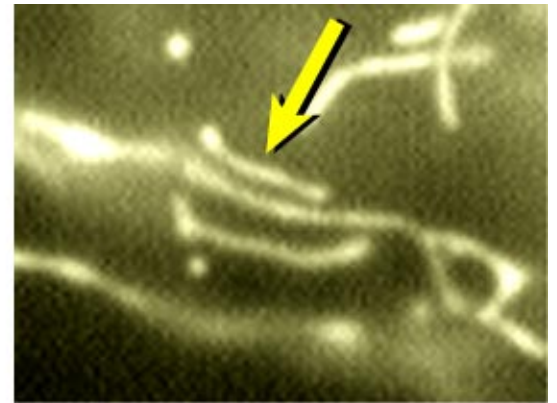
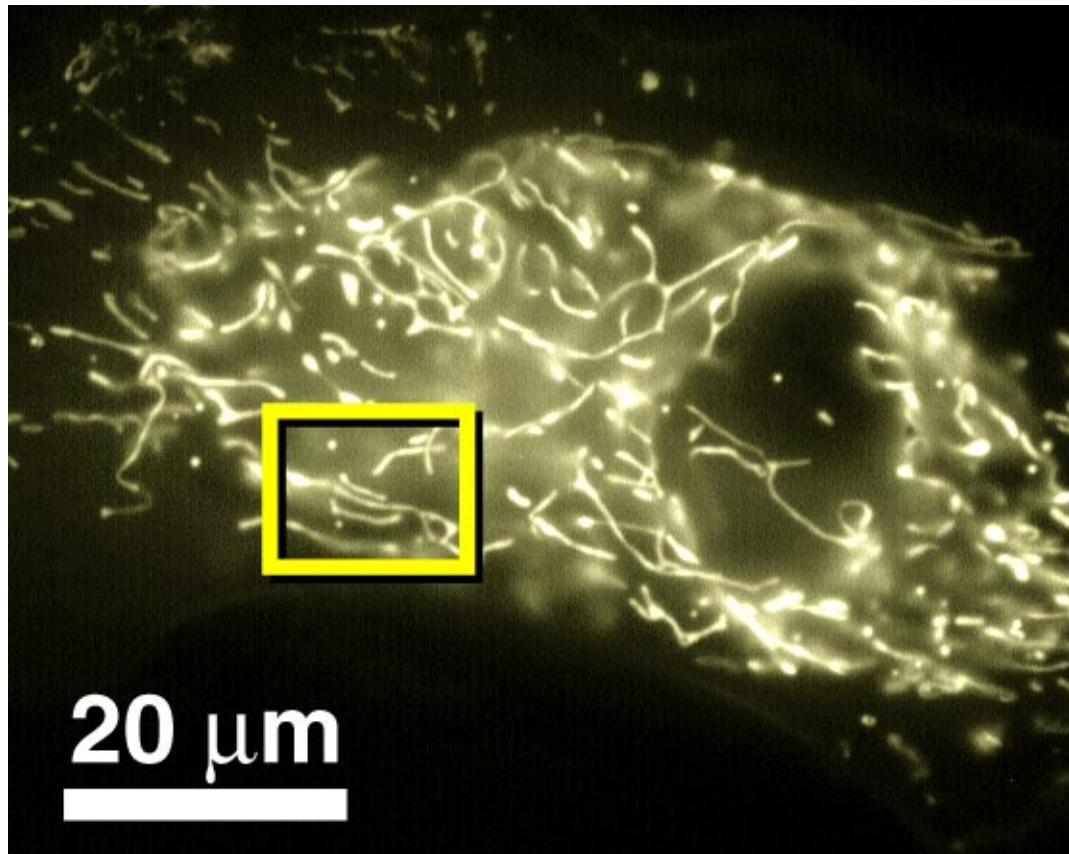
Low-energy processing



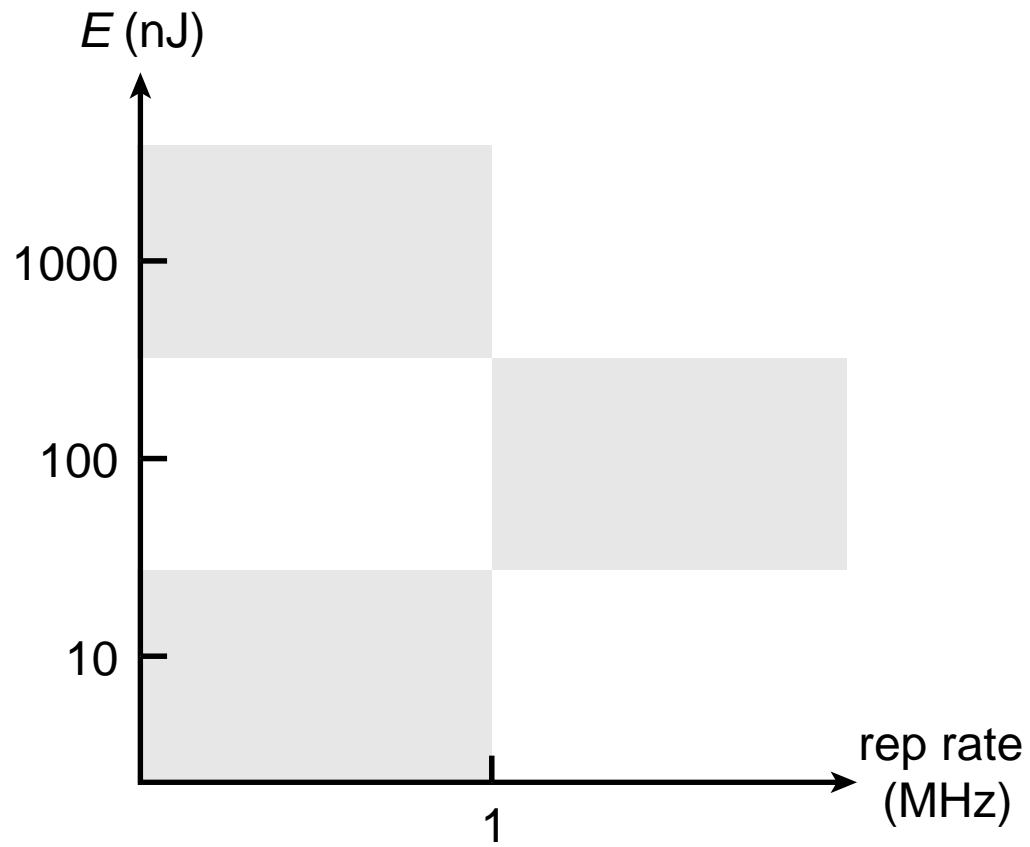
Low-energy processing



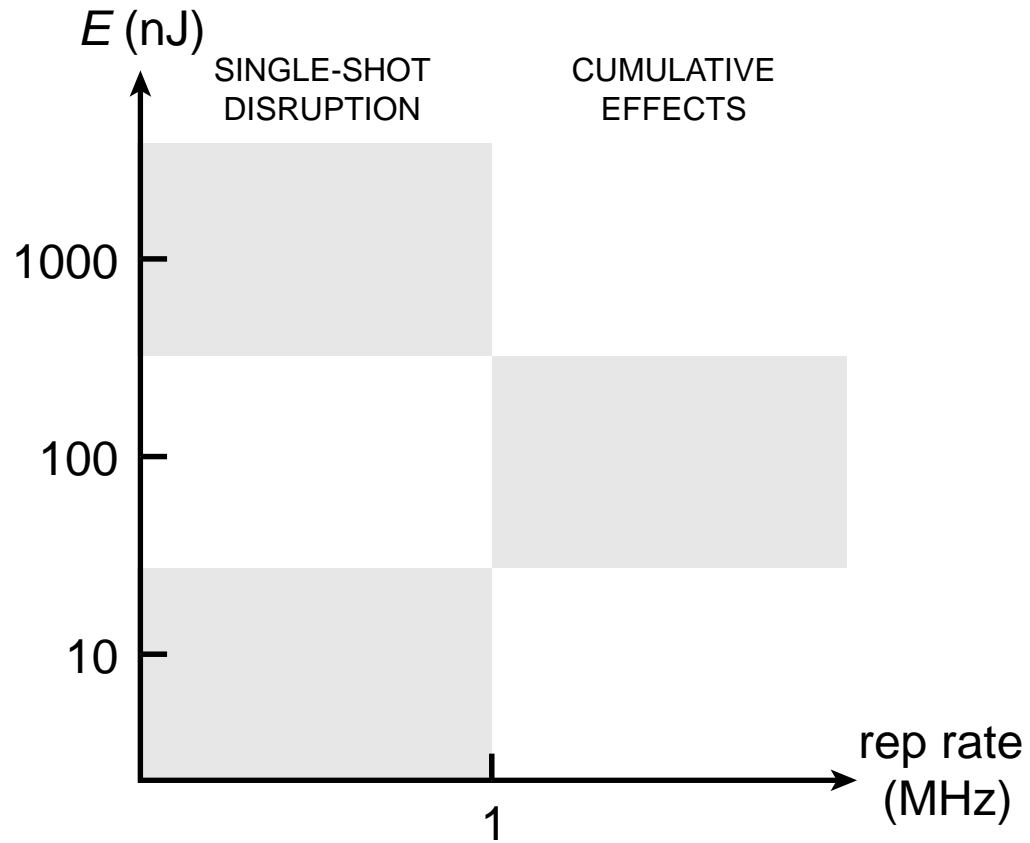
Low-energy processing



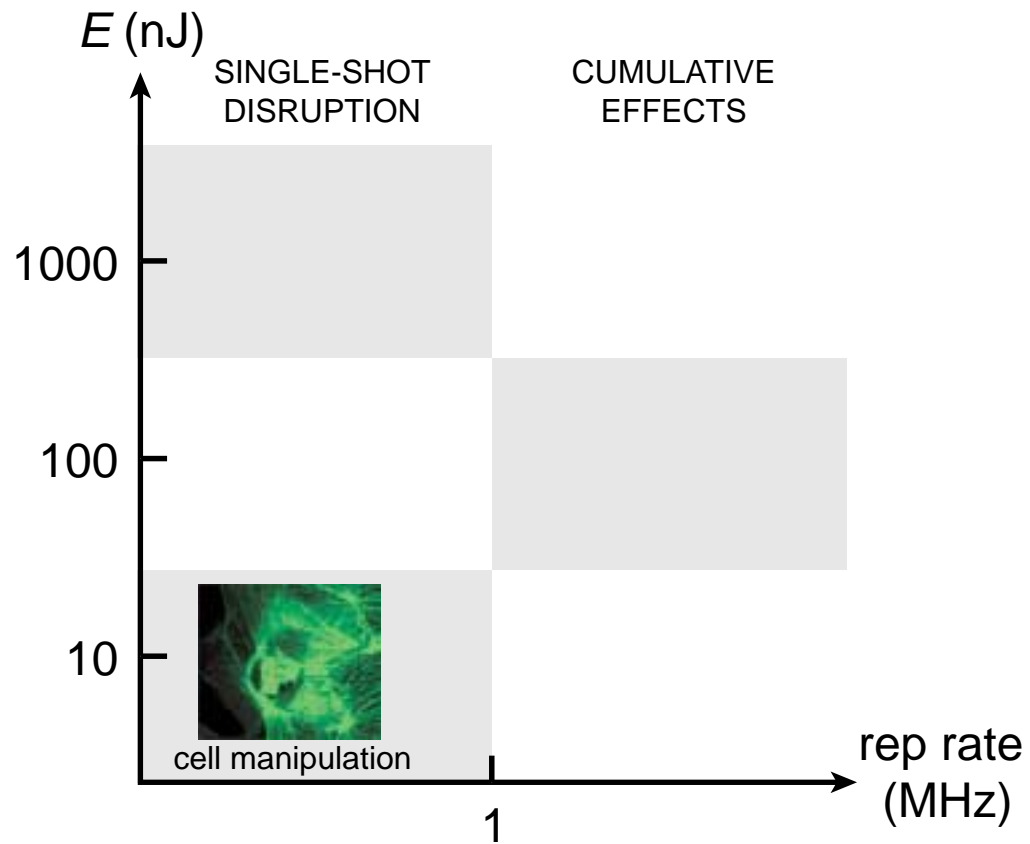
Summary



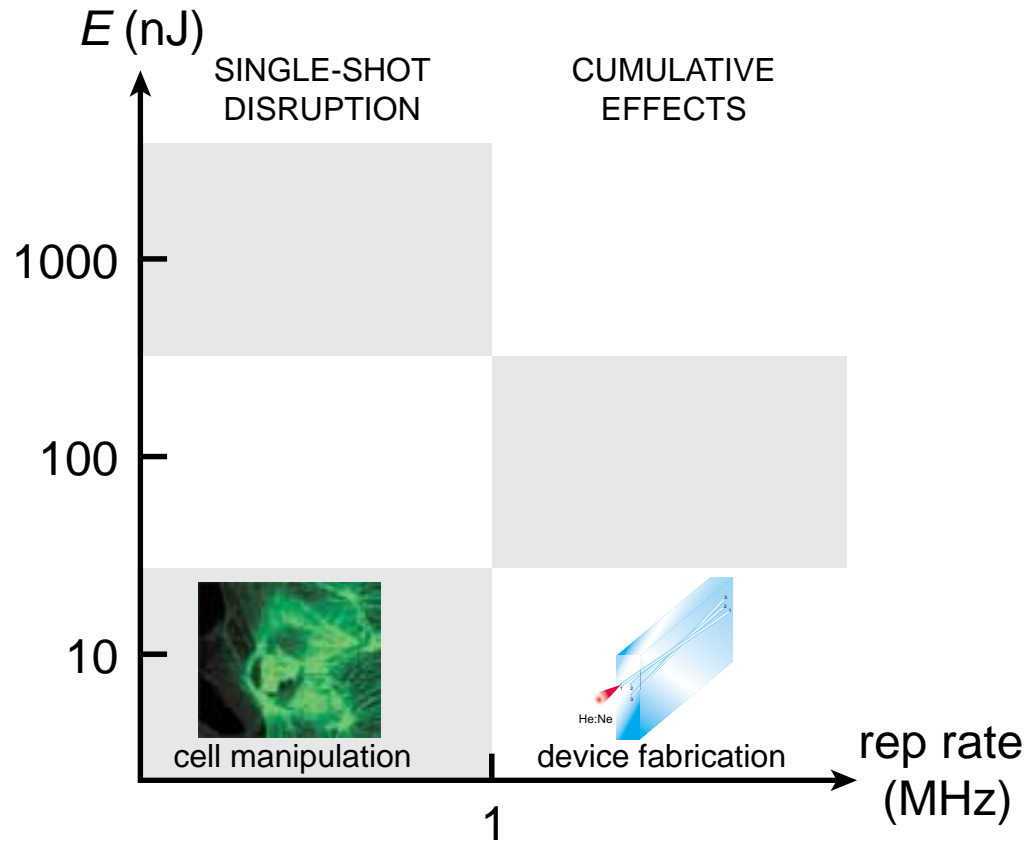
Summary



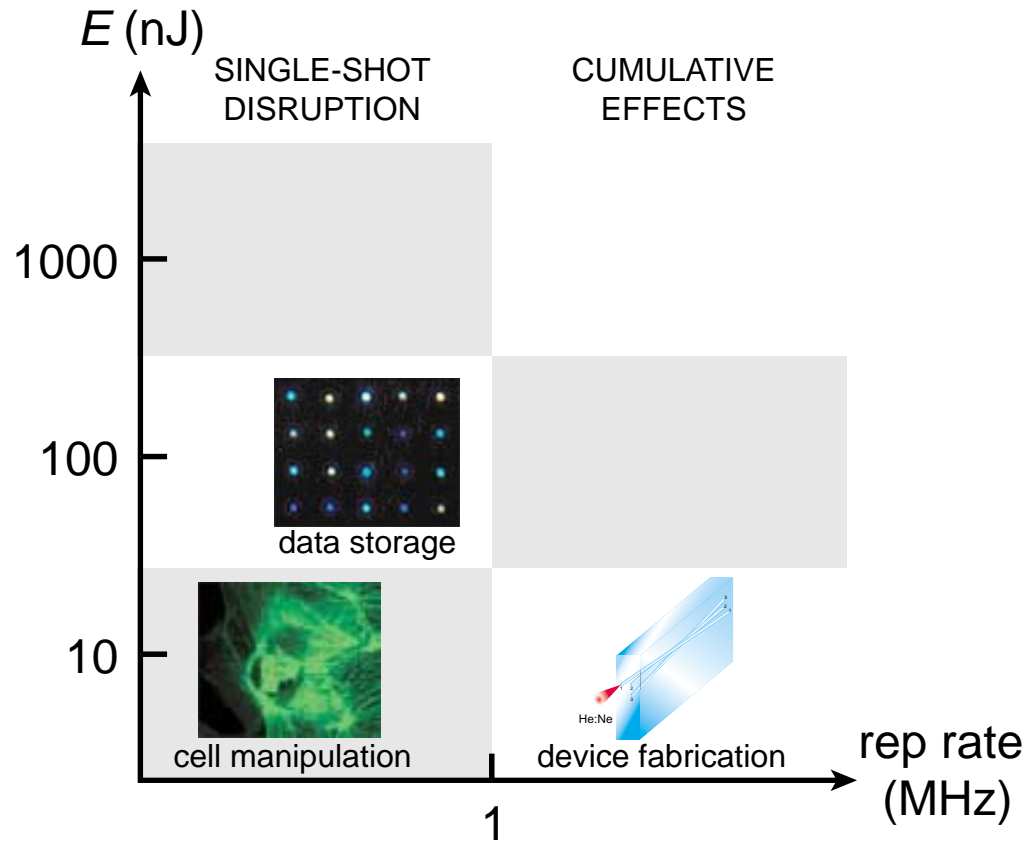
Summary



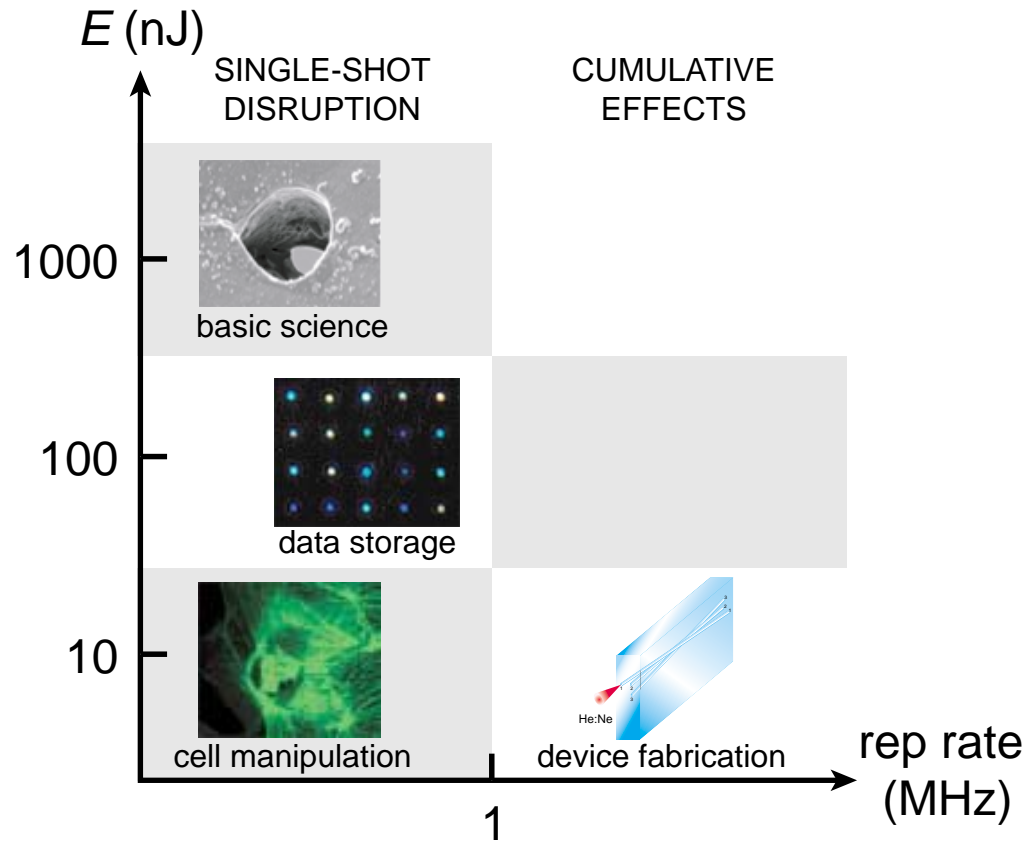
Summary



Summary



Summary



Conclusions

- ▶ **stellar conditions**
- ▶ **precision micromachining**
- ▶ **exciting new applications**

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