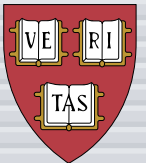


# **Femtosecond laser micromachining of transparent materials for photonics and biology**

**Eric Mazur  
Eli Glezer  
Chris Schaffer  
Jon Ashcom  
Raffael Gattass  
Iva Maxwell  
Limin Tong  
Harvard University**



# 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

## I. 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 with unambiguous theoretical interpretations 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

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### 1. Introduction

THE history of laser-induced electric breakdown is important in the history of lasers itself. Early in 1961 Mink et al. [1] reported the first laser-induced electric breakdown in transparent dielectrics and the production of a spark in an extremely focused ruby laser beam. The importance of these results for the production of laser-induced surface

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, and gases and other optical components, remained, and 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, quantitatively 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 our understanding of the problem of dielectric breakdown 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 its experiments were mainly the influence of the occurrence of space charge, the effects of heating and

# Introduction

**DAMAGED**

STP 1141

22nd ANNUAL BOULDER DAMAGE SYMPOSIUM  
Proceedings

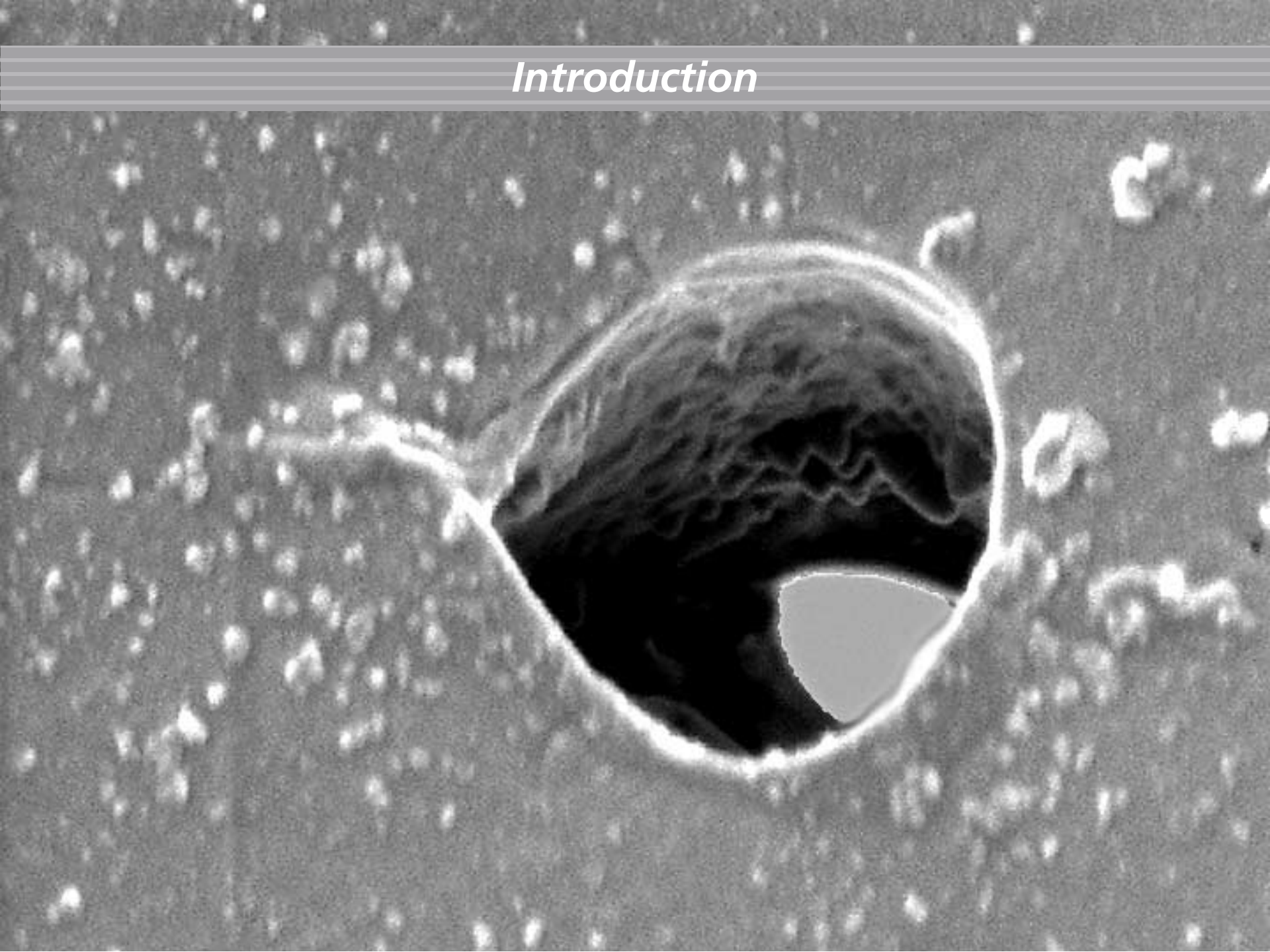


LASER-INDUCED DAMAGE  
IN OPTICAL MATERIALS: 1990

24-26 OCTOBER 1990  
BOULDER, COLORADO



# *Introduction*



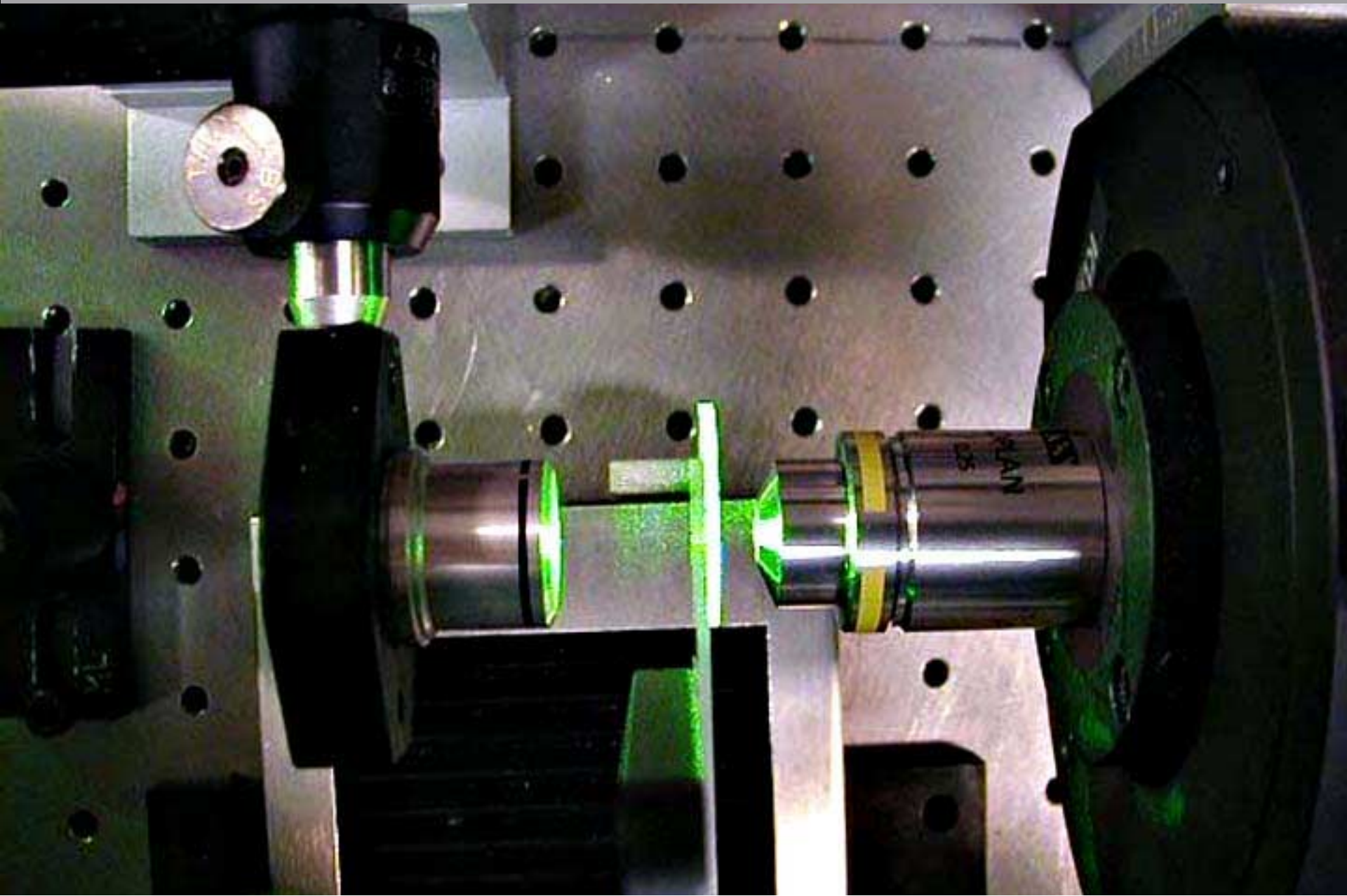
# *Introduction*



**use damage for processing!**



# *Outline*

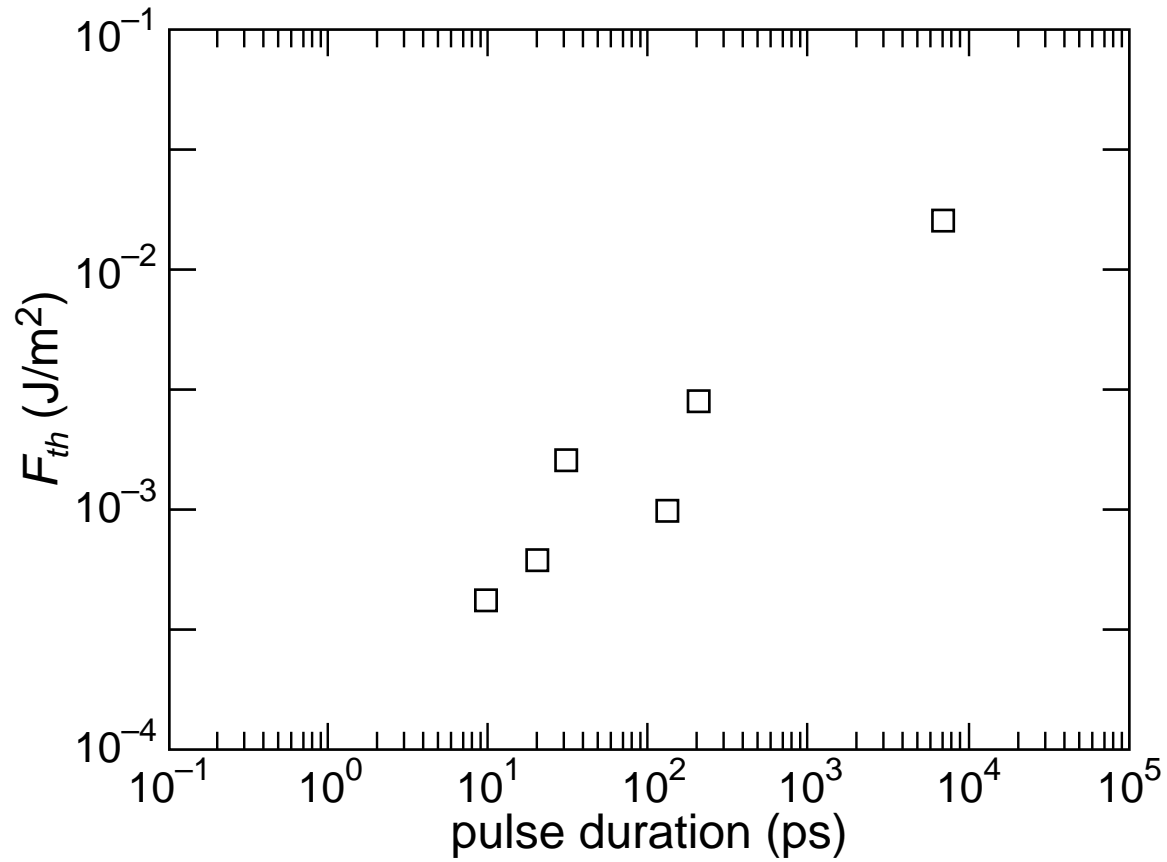


# Outline

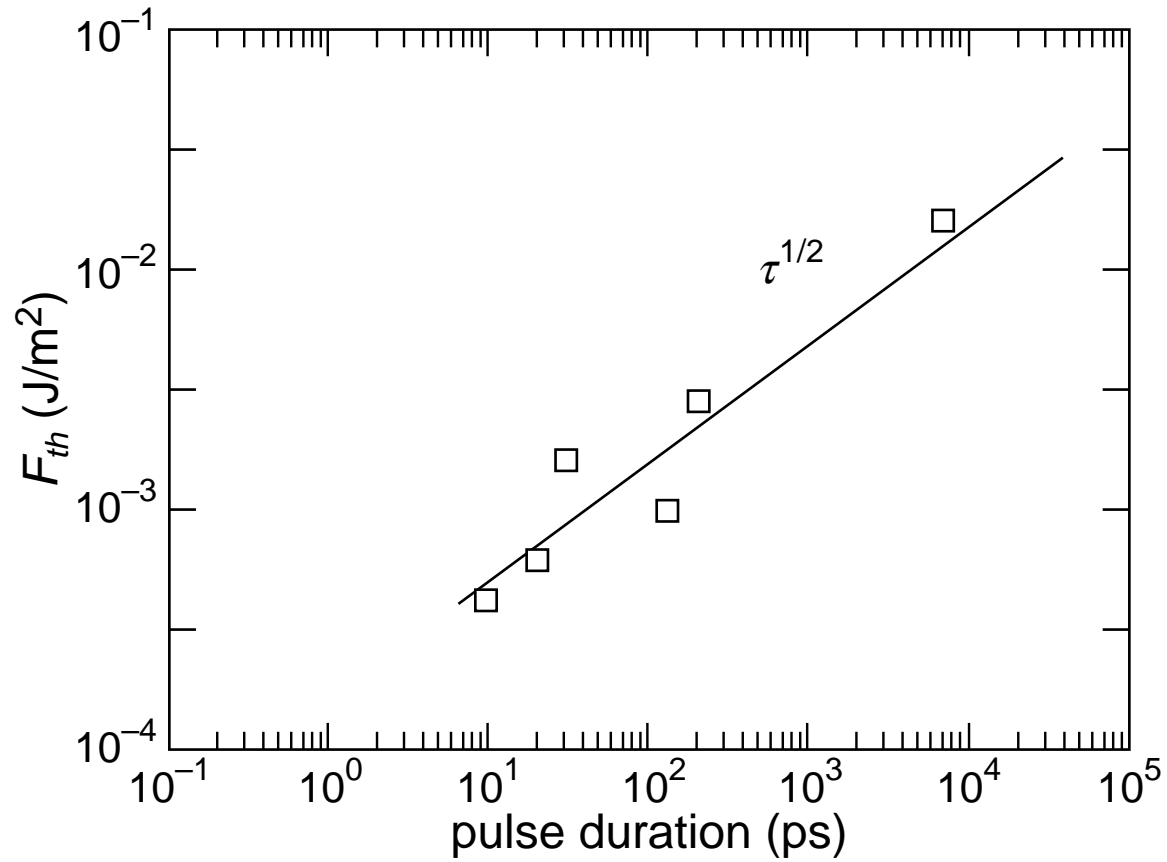
- ▶ Processing with fs pulses
- ▶ Role of focusing
- ▶ Low-energy processing



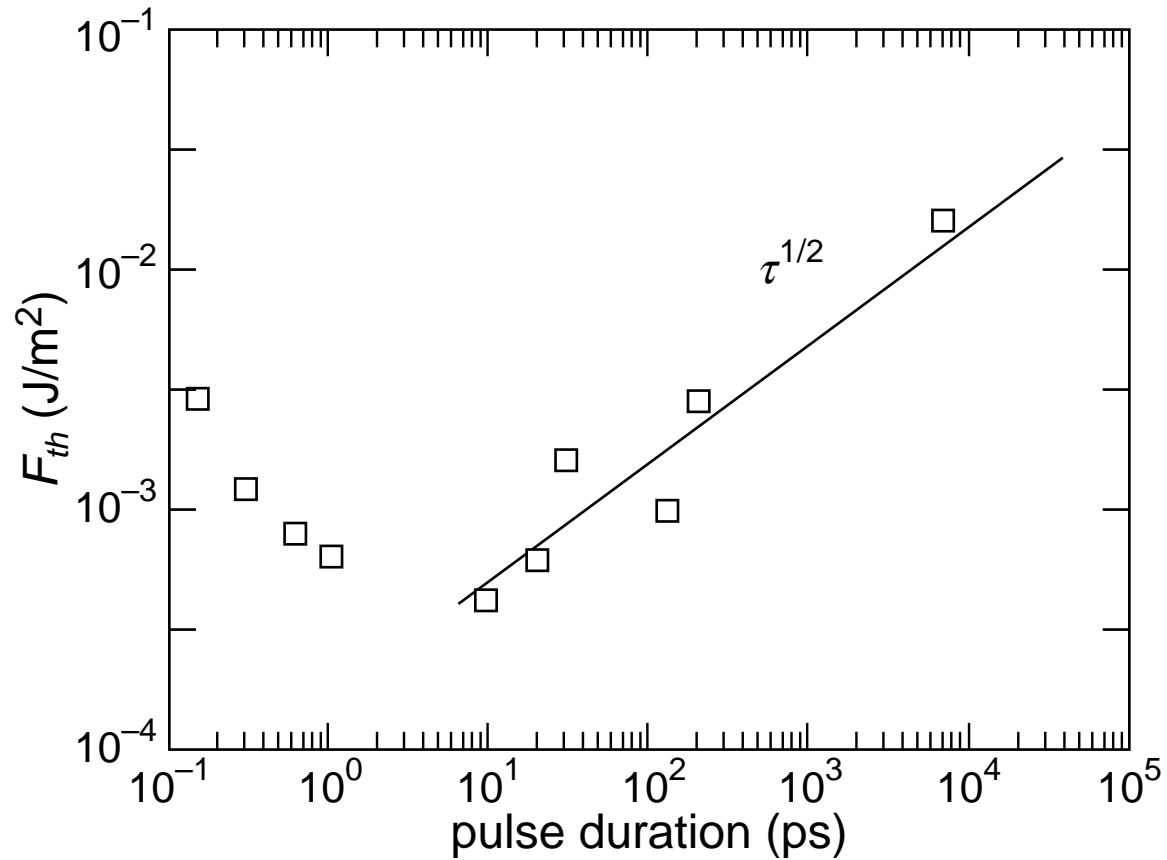
## *Processing with fs pulses*



# *Processing with fs pulses*



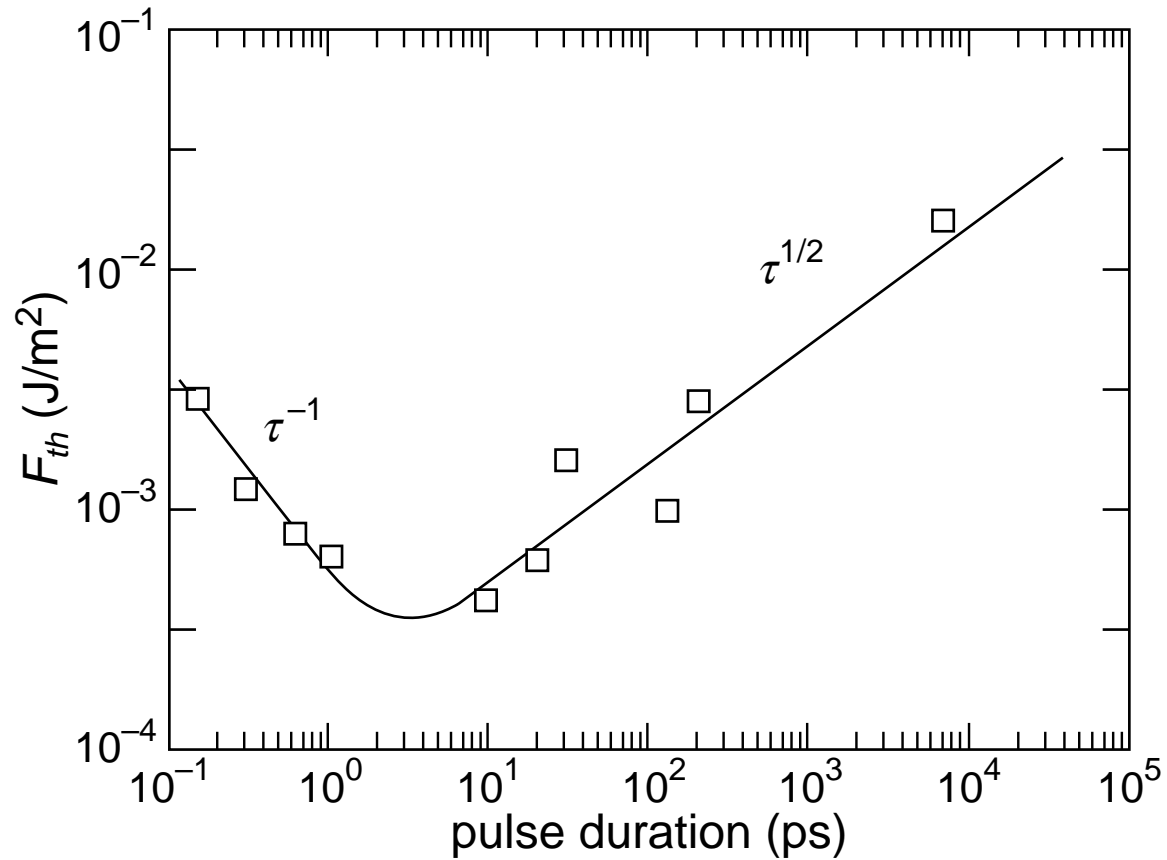
## Processing with fs pulses



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

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. © 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.*<sup>5</sup> 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.*<sup>6</sup> 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/cm<sup>2</sup> for 100-fs pulses and  $10^{13}$  W/cm<sup>2</sup> for 150-fs pulses.

# Processing with fs pulses

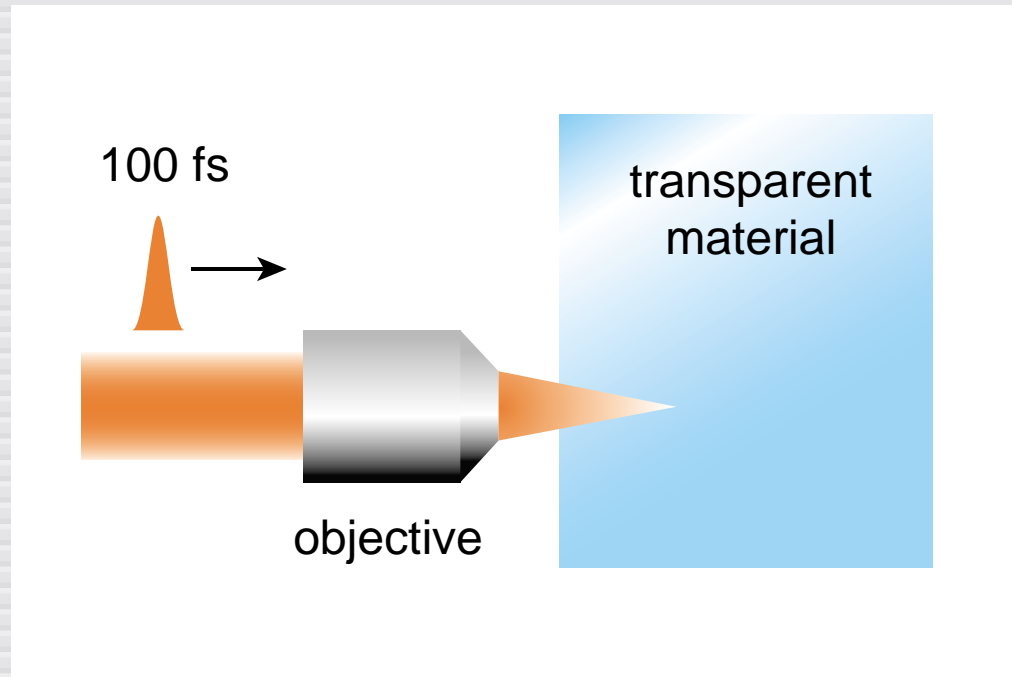
**"... clear evidence that no bulk plasmas ...  
[and] ... no bulk damage could be produced  
with femtosecond laser pulses."**

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

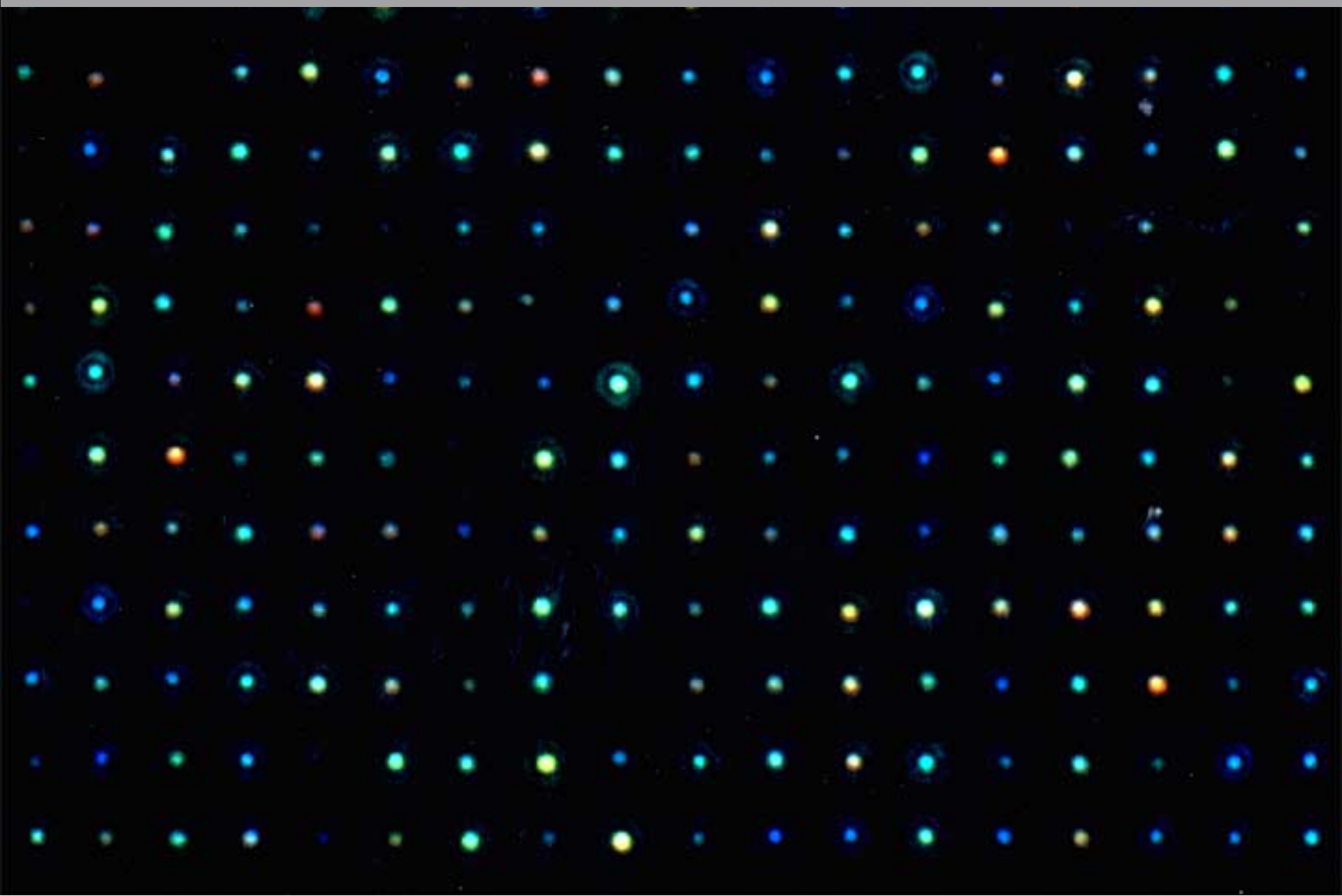


## *Processing with fs pulses*

**focus laser beam inside material**



# *Processing with fs pulses*

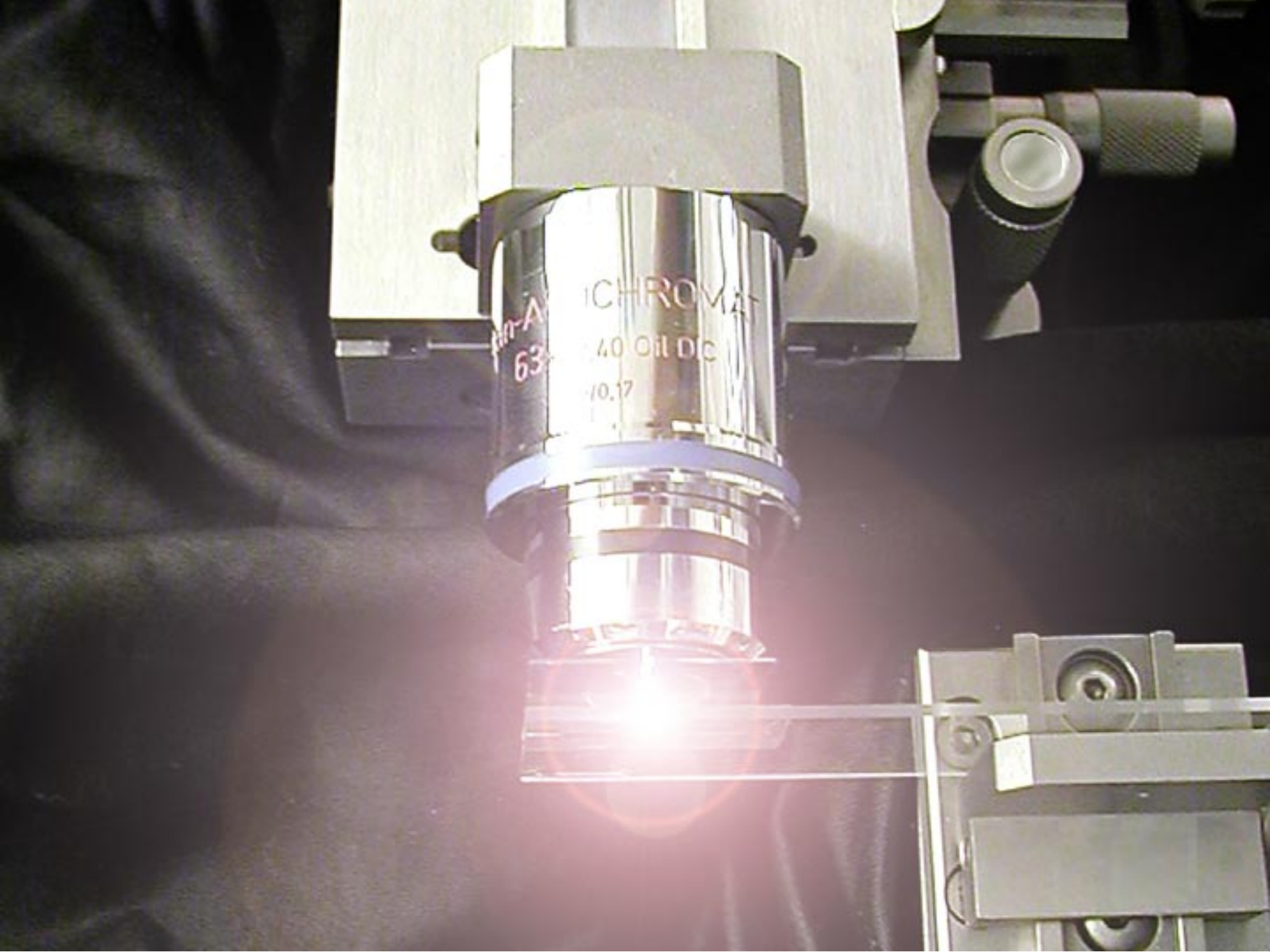






CHROMAT  
40 Oil DC  
0.17

63



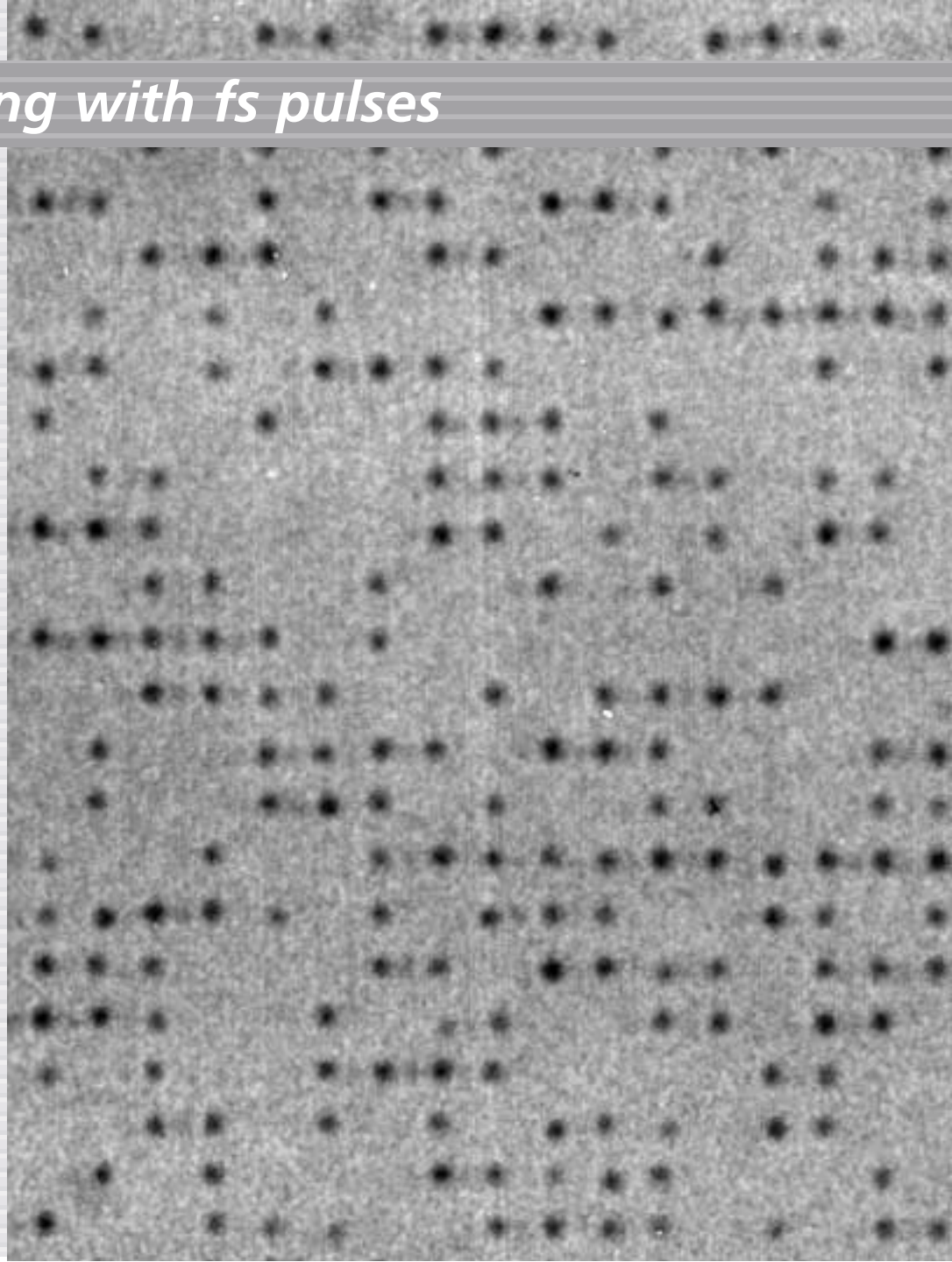


## *Processing with fs pulses*

**2 x 2  $\mu\text{m}$  array**

**fused silica, 0.65 NA**

**0.5  $\mu\text{J}$ , 100 fs, 800 nm**



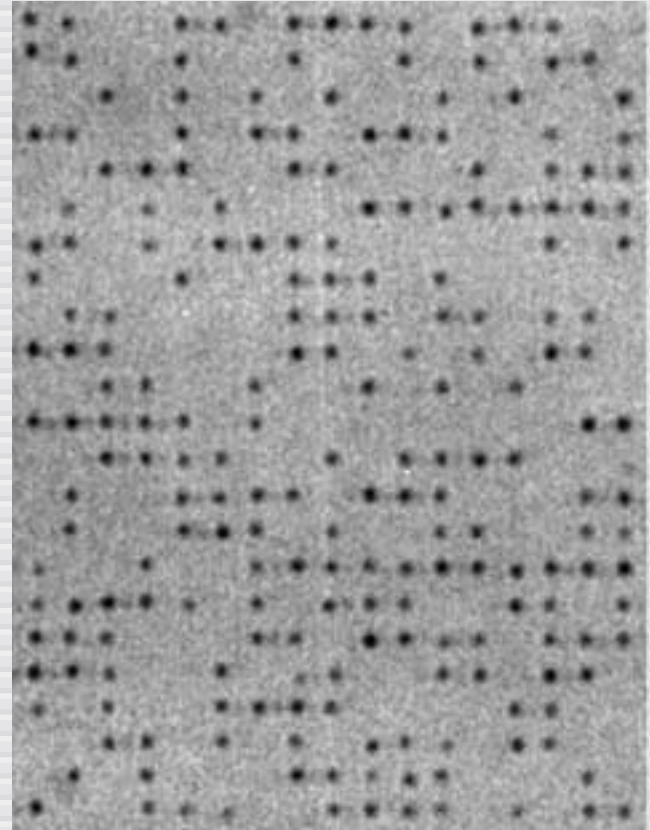
***Opt. Lett.* 21, 2023 (1996)**

## *Processing with fs pulses*

**2 x 2  $\mu\text{m}$  array**

**fused silica, 0.65 NA**

**0.5  $\mu\text{J}$ , 100 fs, 800 nm**

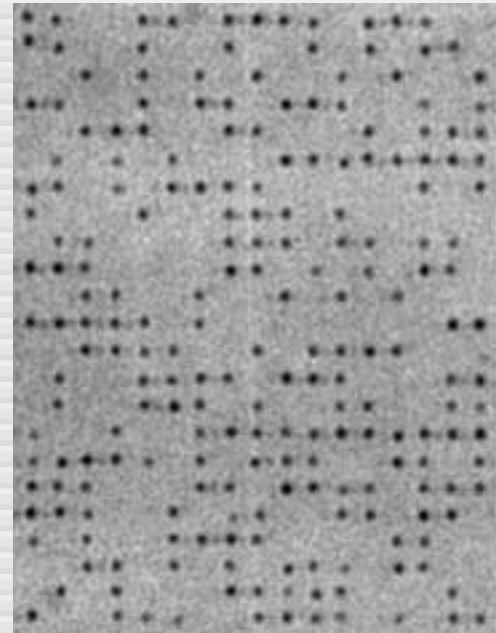


## *Processing with fs pulses*

**2 x 2  $\mu\text{m}$  array**

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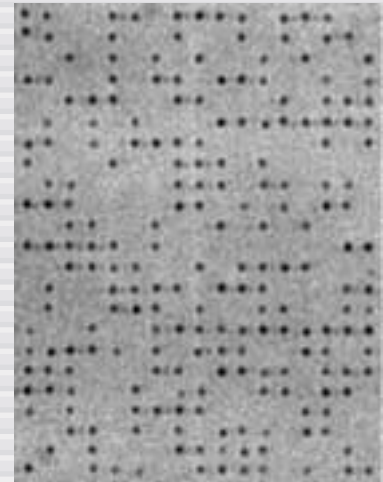


## *Processing with fs pulses*

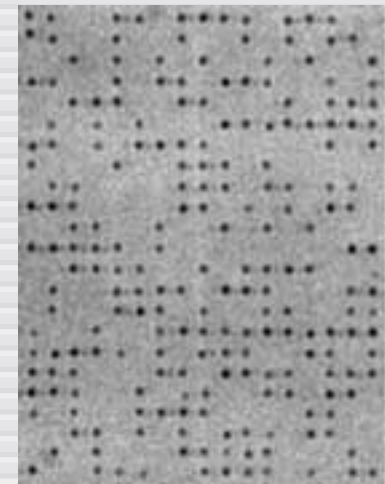
**2 x 2  $\mu\text{m}$  array**

**fused silica, 0.65 NA**

**0.5  $\mu\text{J}$ , 100 fs, 800 nm**



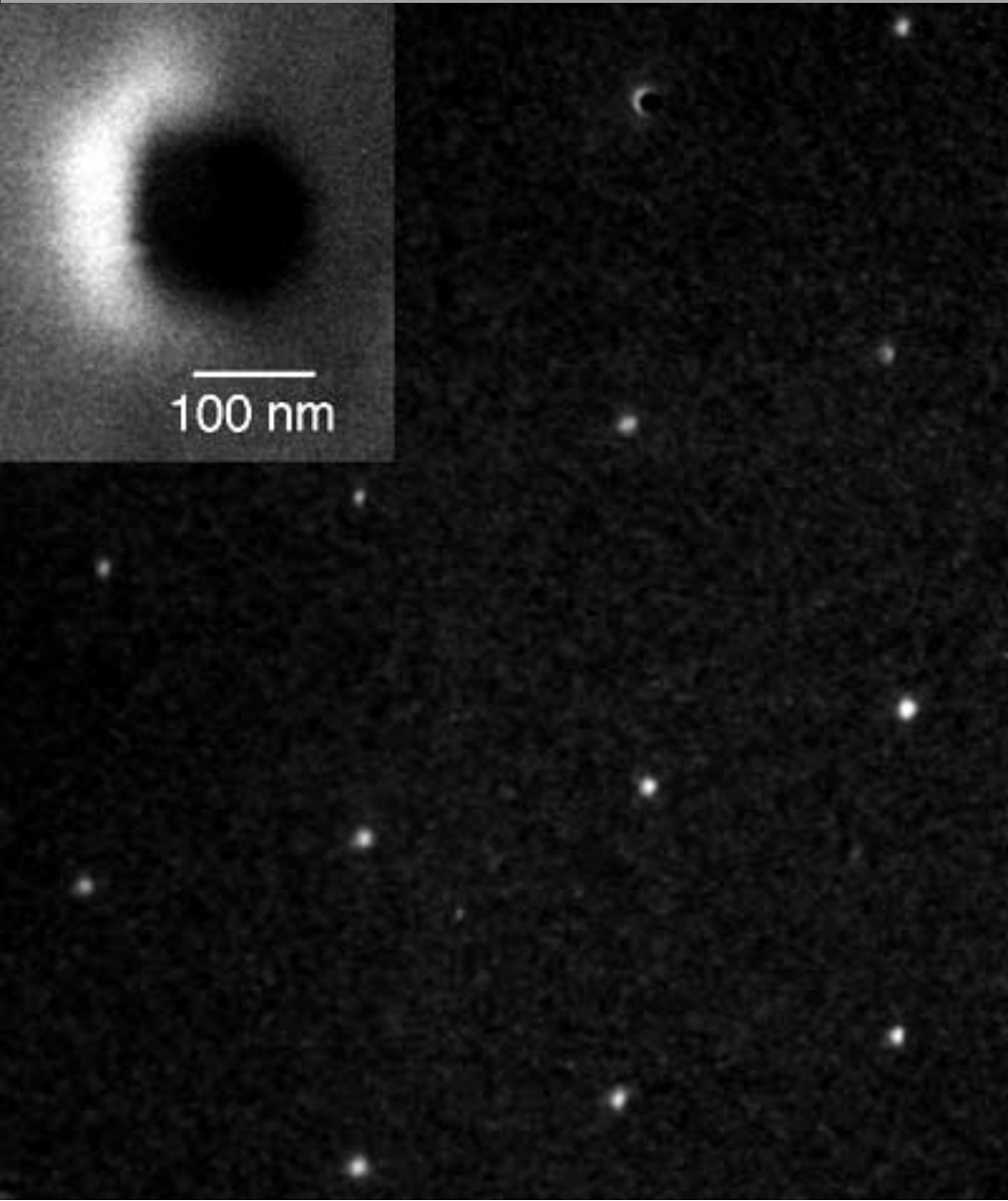
## *Processing with fs pulses*



**100 fs**  
**0.5  $\mu$ J**

**200 ps**  
**9  $\mu$ J**

## *Processing with fs pulses*



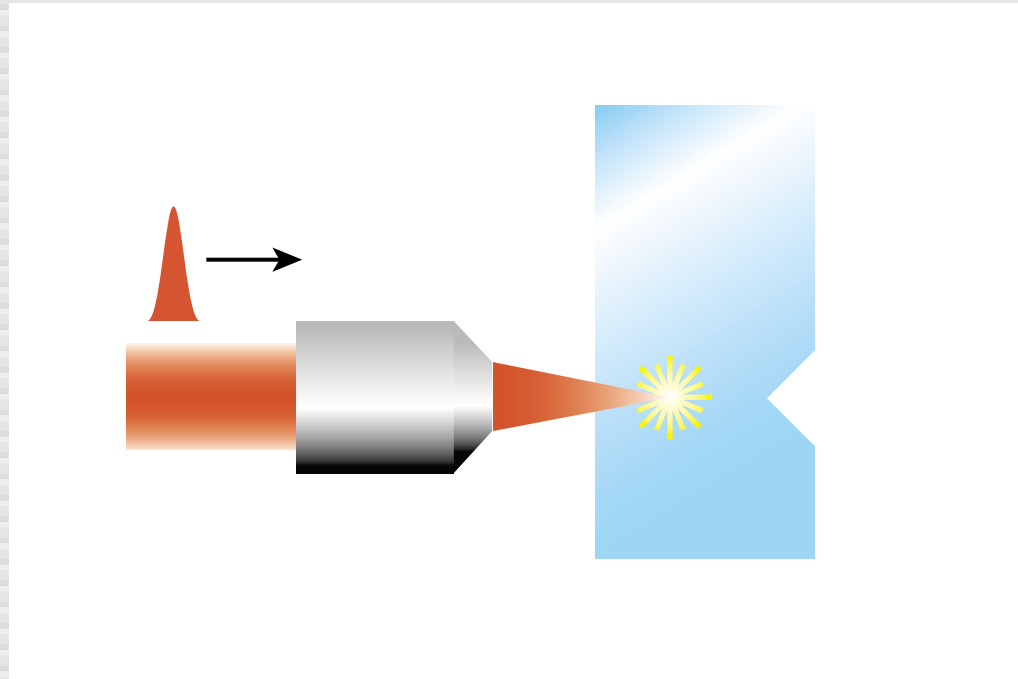
**5 x 5  $\mu\text{m}$  array**

**fused silica, 0.65 NA**

**0.5  $\mu\text{J}$ , 100 fs, 800 nm**

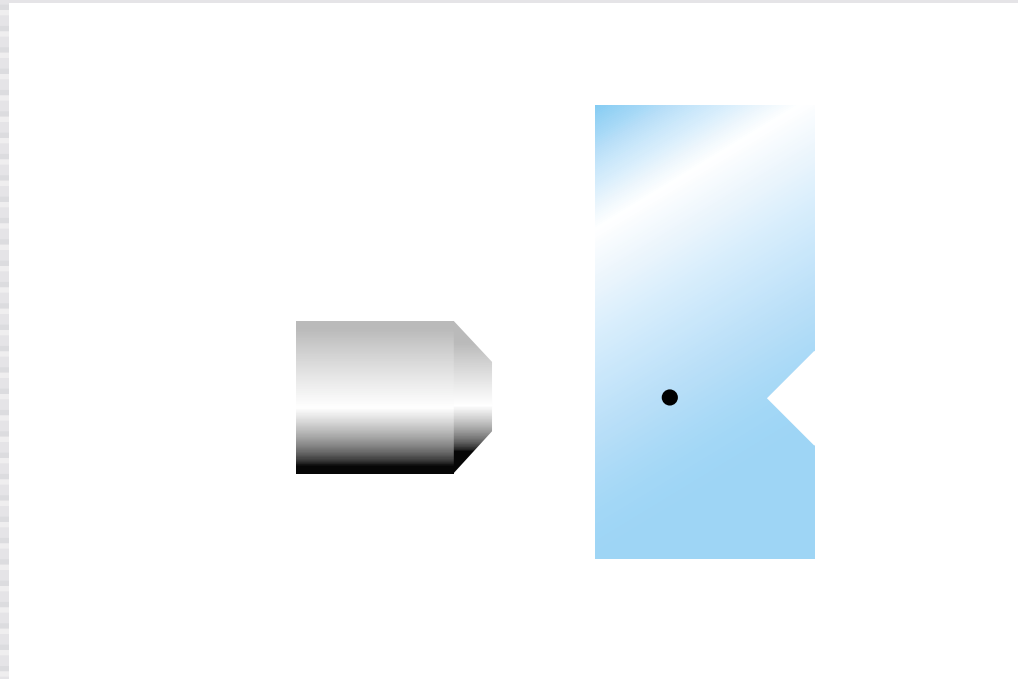
*Opt. Lett.* 21, 2023 (1996)

## *Processing with fs pulses*



**microstructure scribed sample**

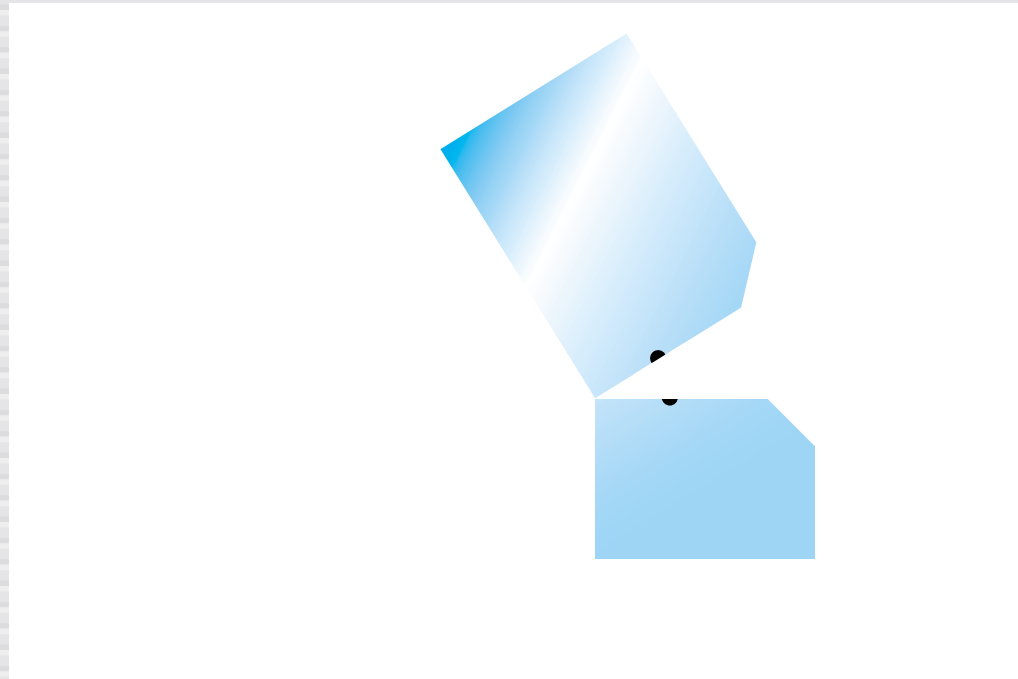
## *Processing with fs pulses*



**microstructure scribed sample**

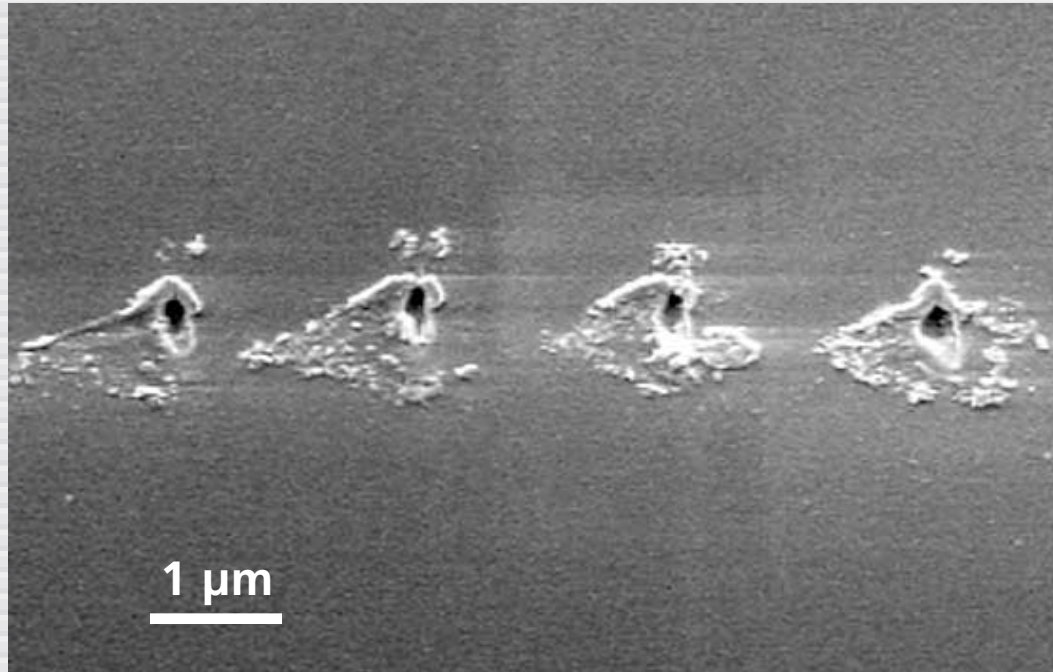


## *Processing with fs pulses*



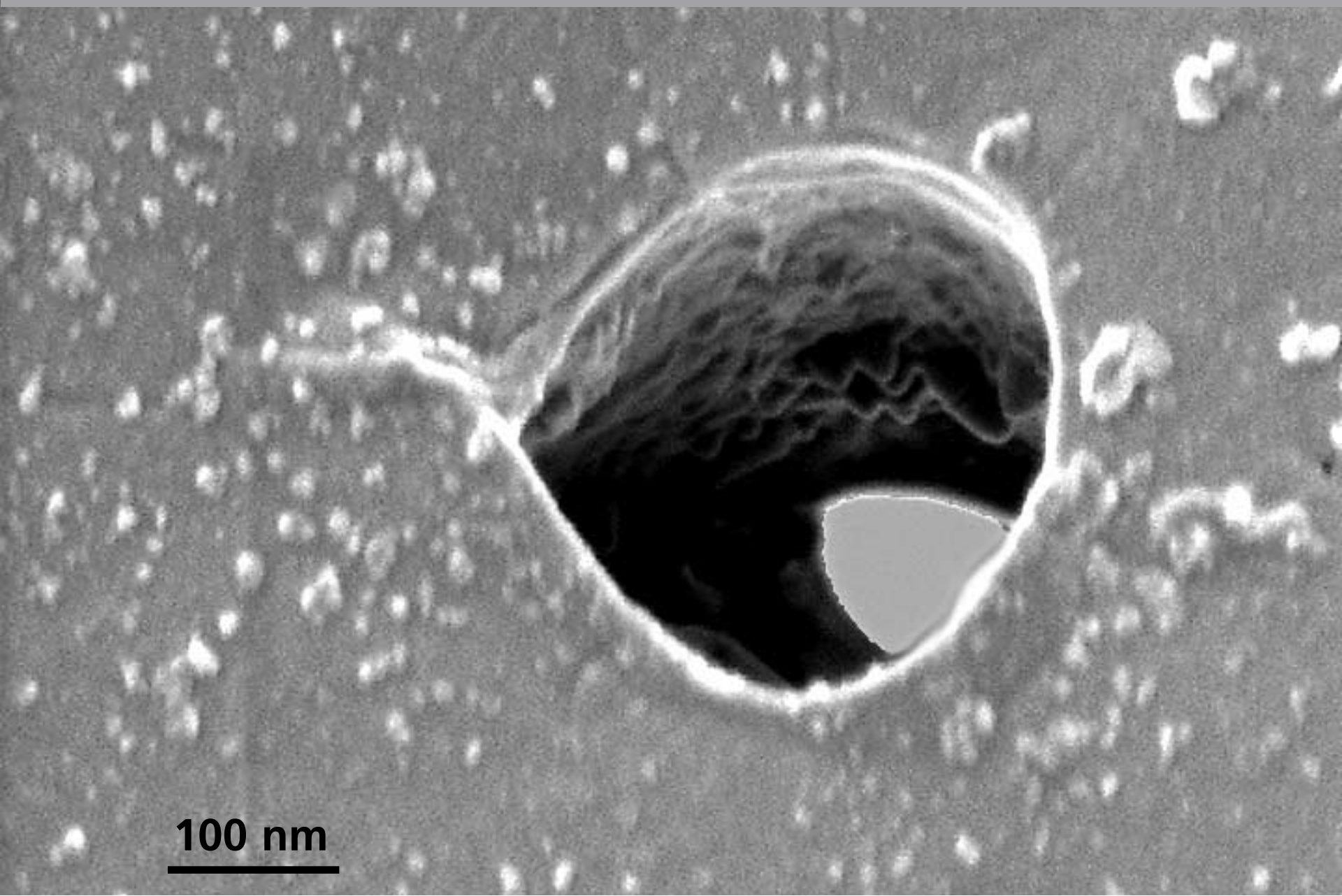
**fracture along scribe line**

## *Processing with fs pulses*



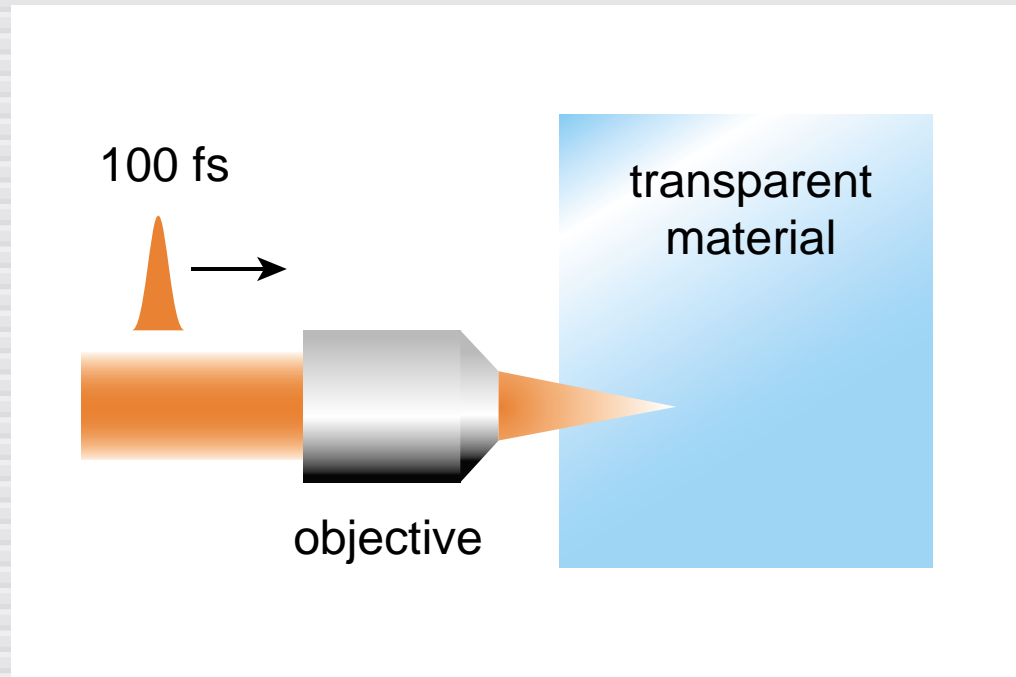
**Corning 0211**  
**1.4 NA, 140 nJ**

## *Processing with fs pulses*



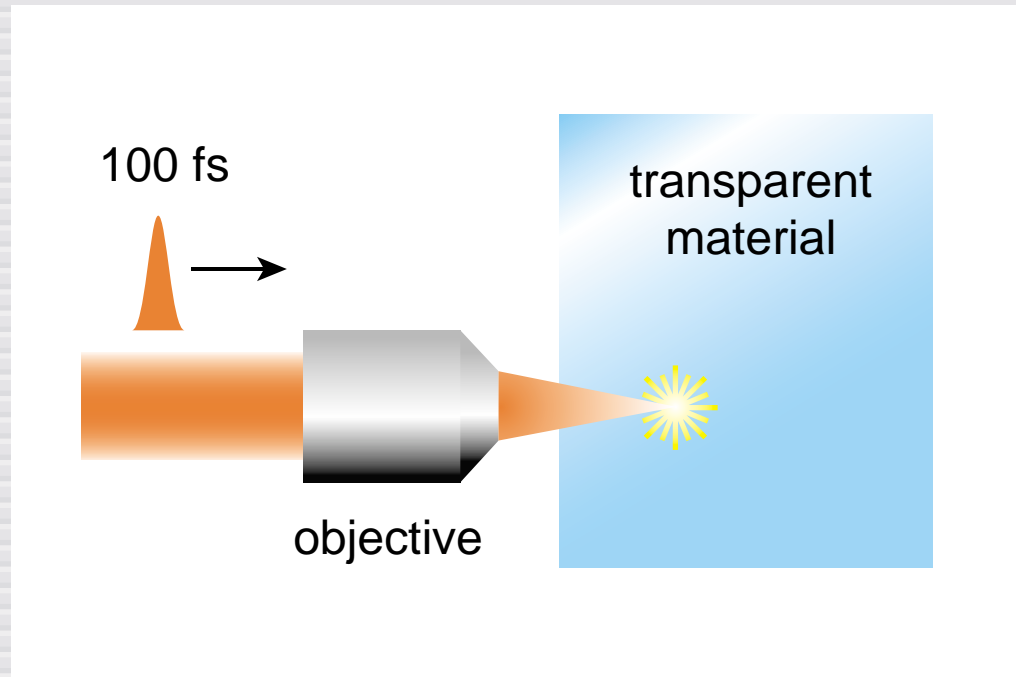
100 nm

## *Processing with fs pulses*



**high intensity at focus...**

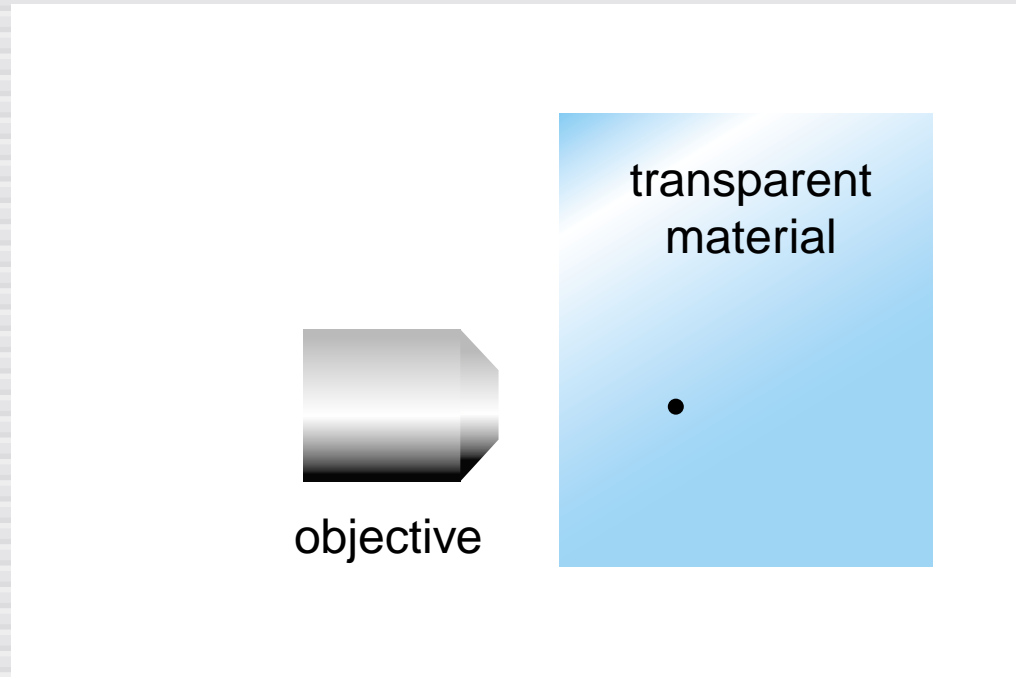
## *Processing with fs pulses*



**... causes nonlinear ionization...**



## *Processing with fs pulses*



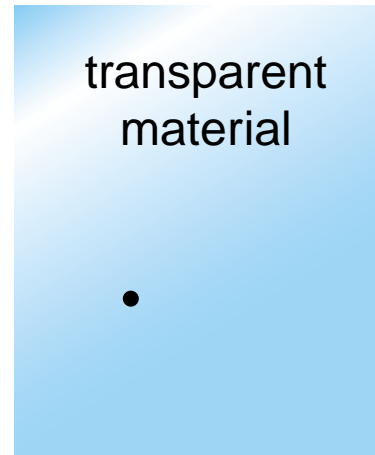
**and 'microexplosion' causes microscopic damage**

## *Processing with fs pulses*

**What are the conditions at focus?**



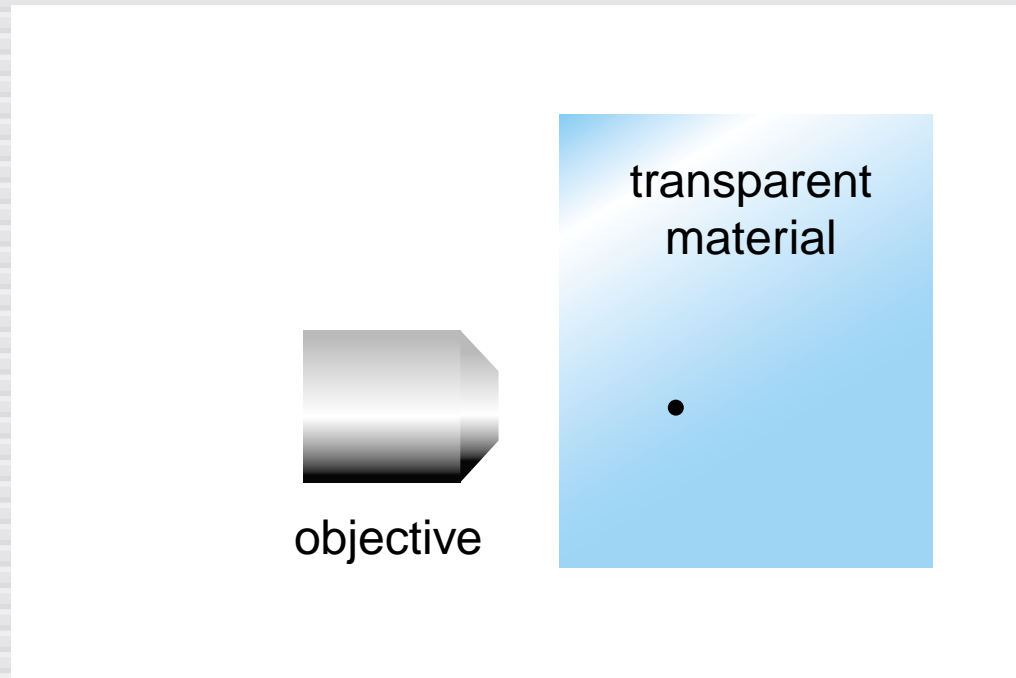
objective



transparent  
material

## *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  $\mu\text{J}$  in 1  $\mu\text{m}^3$  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:**

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

## *Processing with fs pulses*

**So:**

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

**creating stellar conditions in lab!**

## *Processing with fs pulses*

### **Points to keep in mind:**

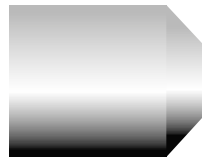
- ▶ **fs laser processing works**
- ▶ **focusing very important**
- ▶ **no collateral damage**

# Outline

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

## *Role of focusing*

### **Dark-field scattering**



objective

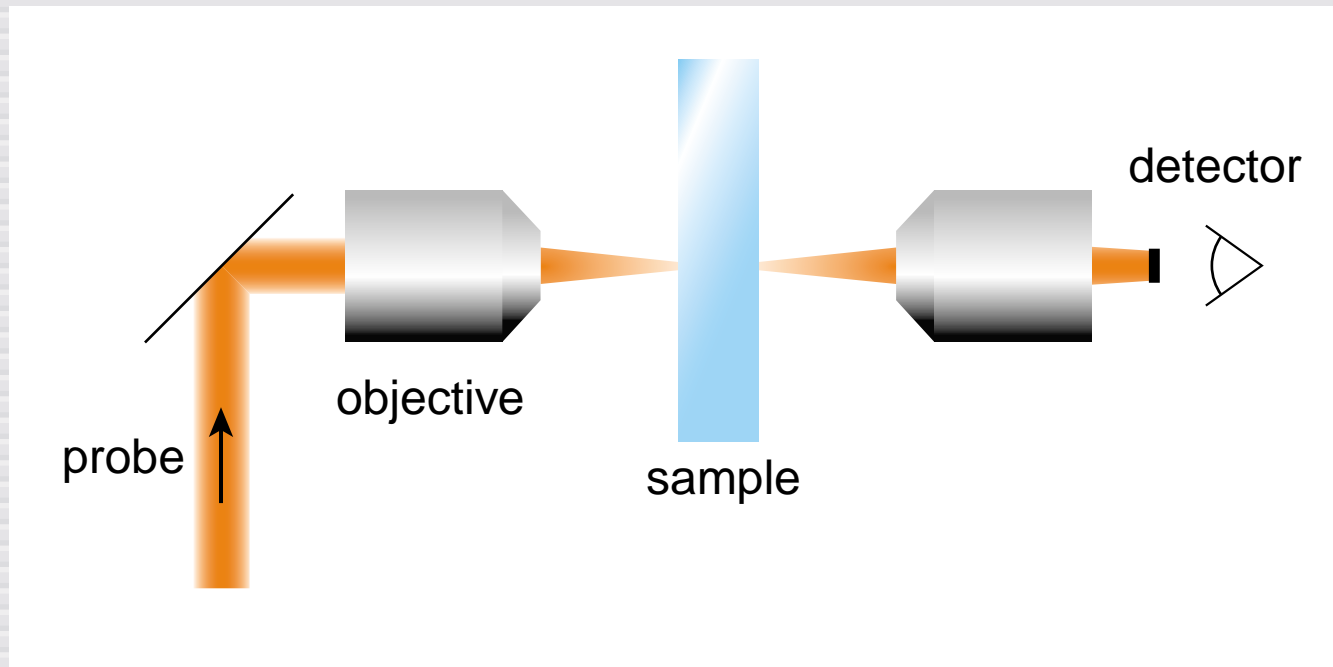


sample



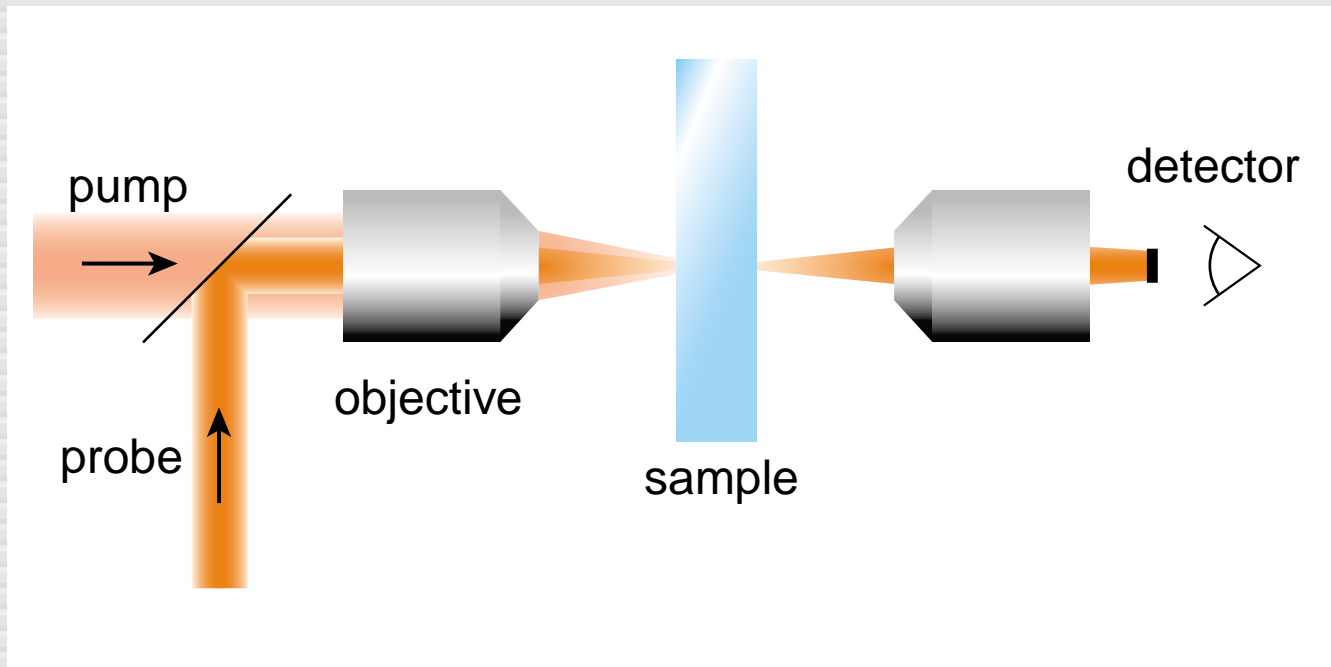
## *Role of focusing*

**block probe beam...**



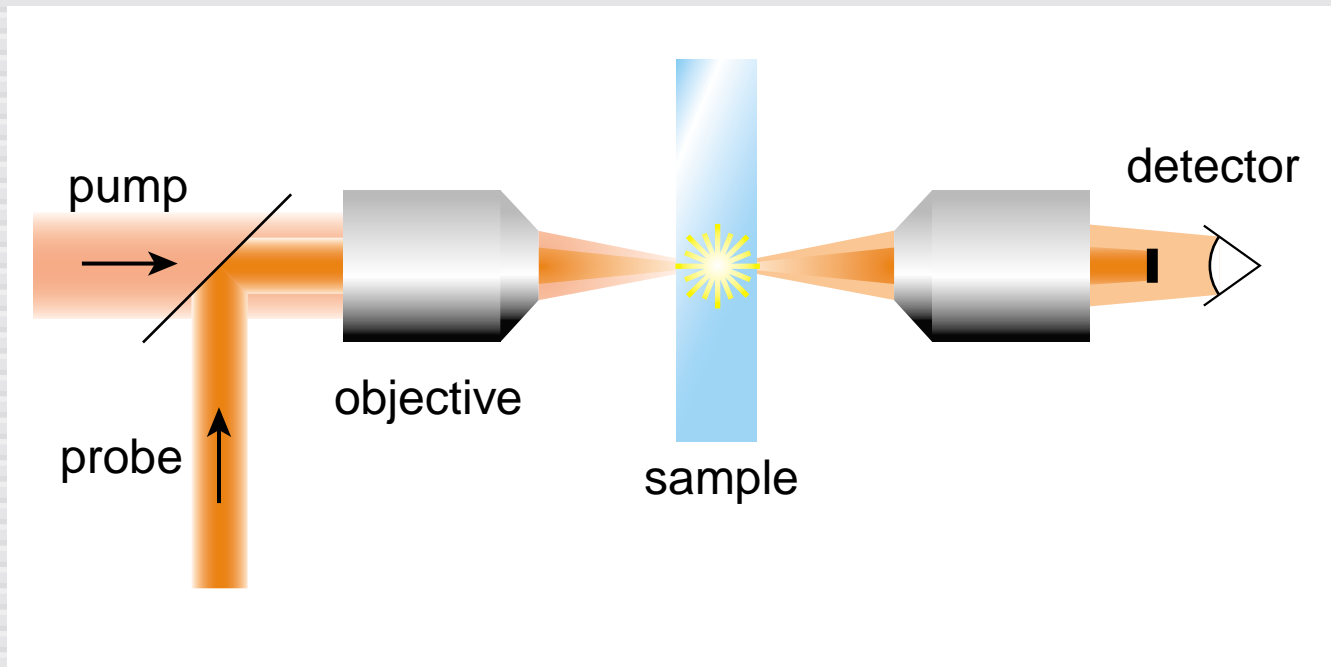
## *Role of focusing*

**... bring in pump beam...**

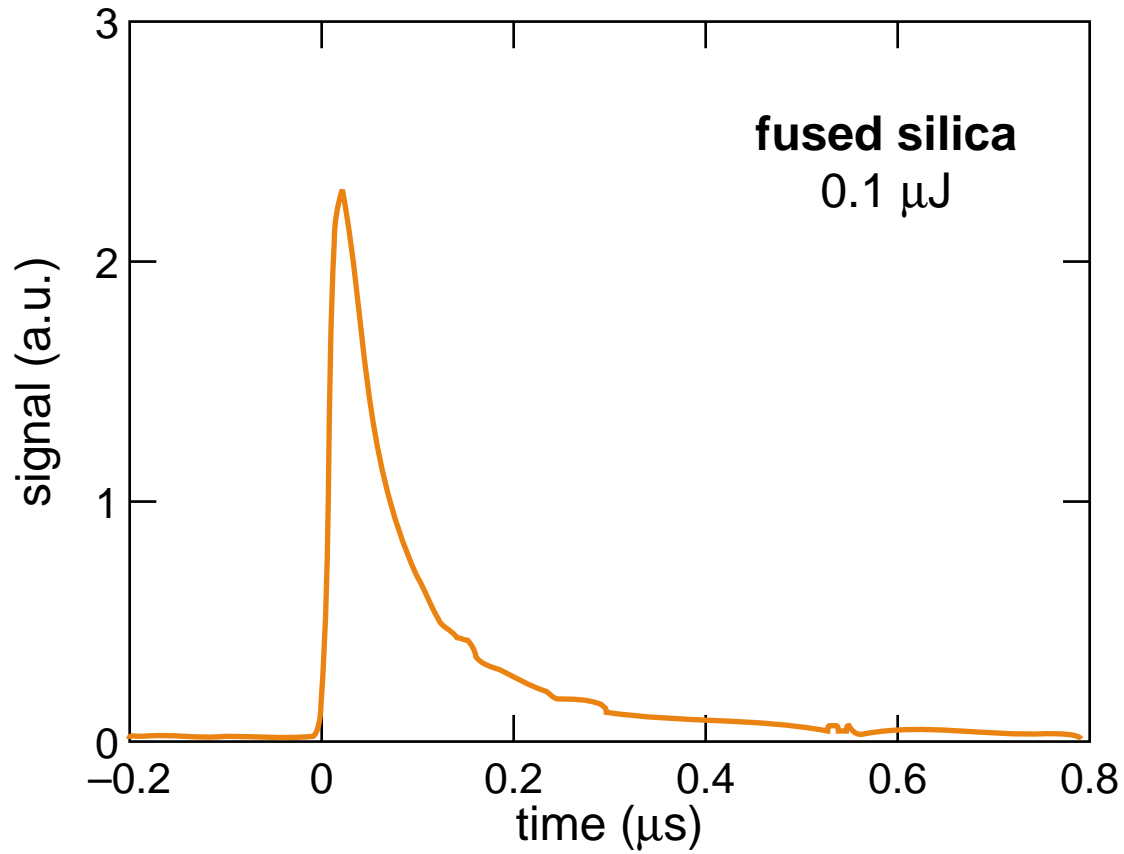


## *Role of focusing*

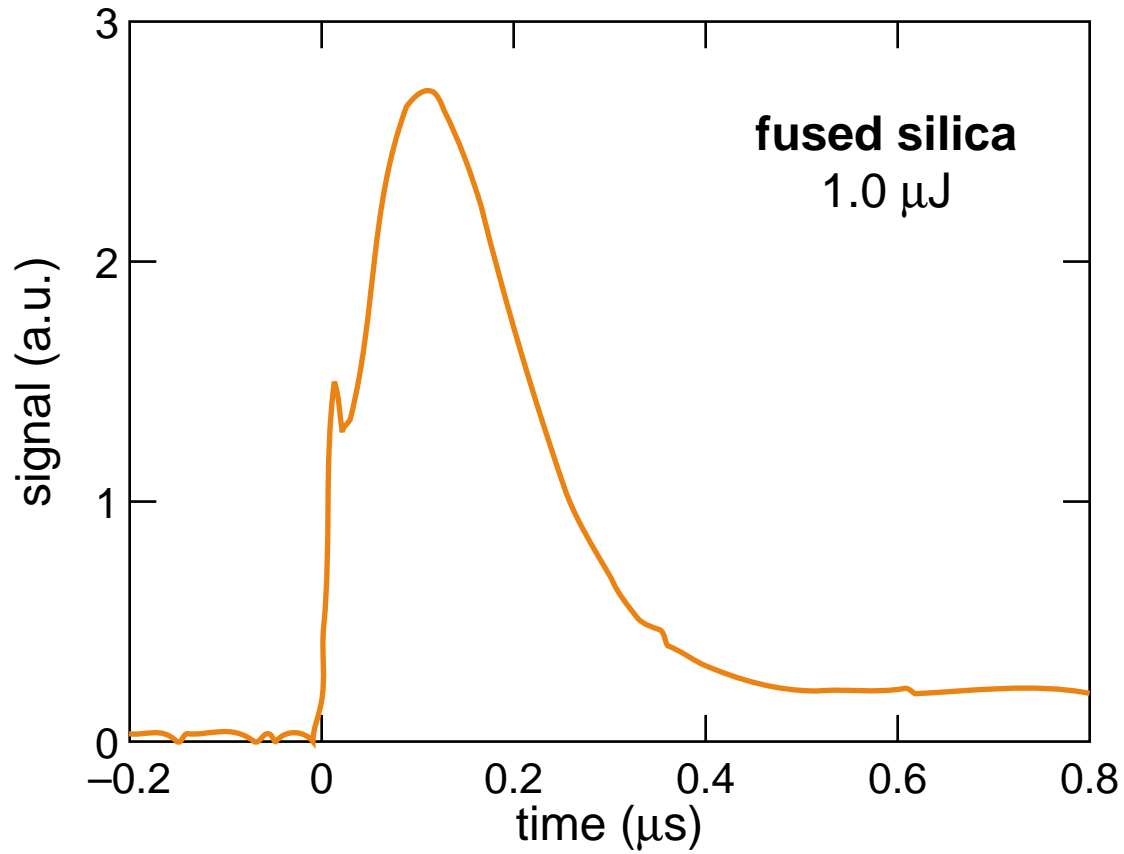
**... damage scatters probe beam**



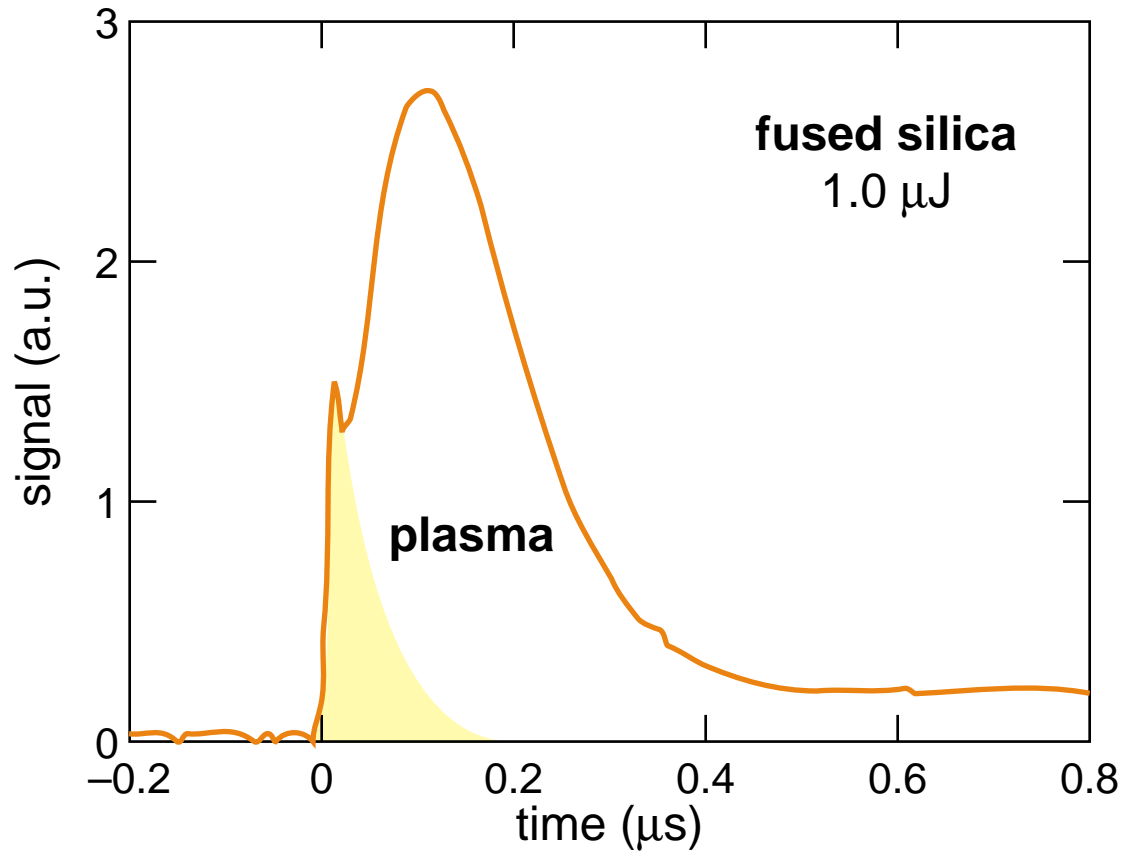
## *Role of focusing*



## *Role of focusing*

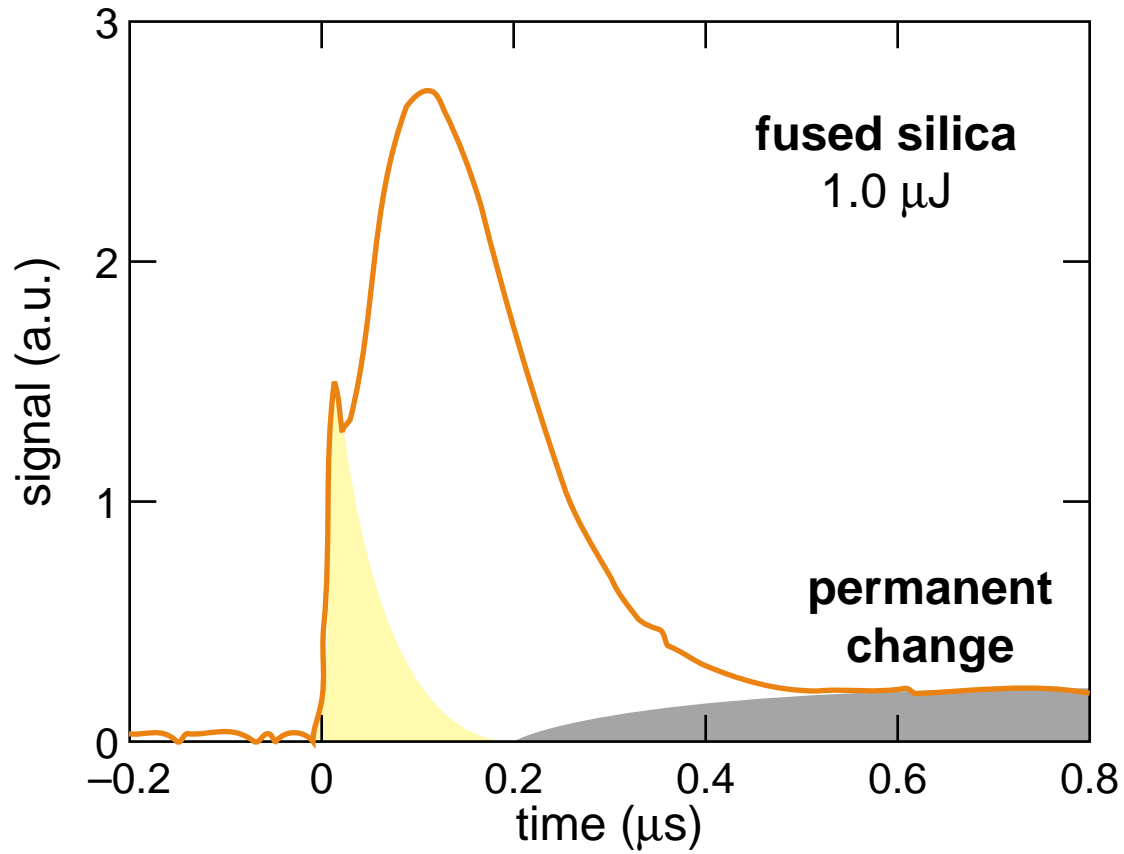


## *Role of focusing*

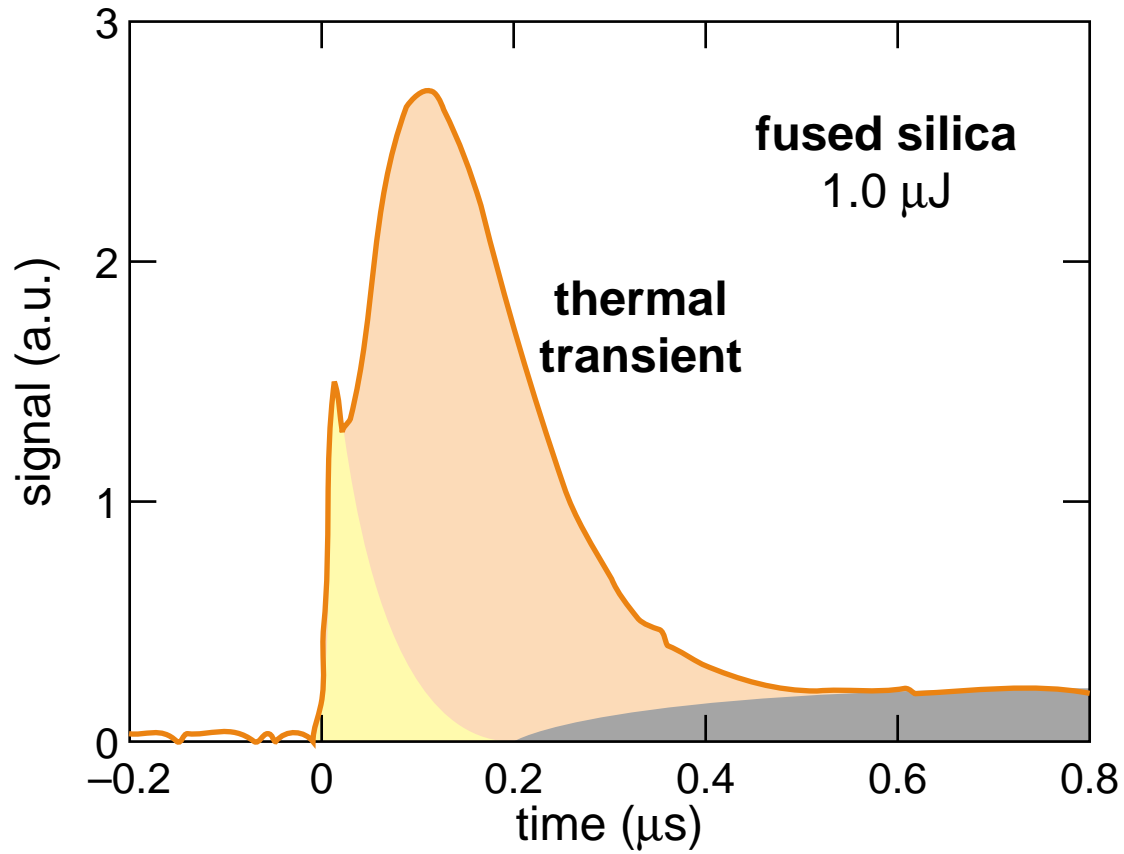




## *Role of focusing*

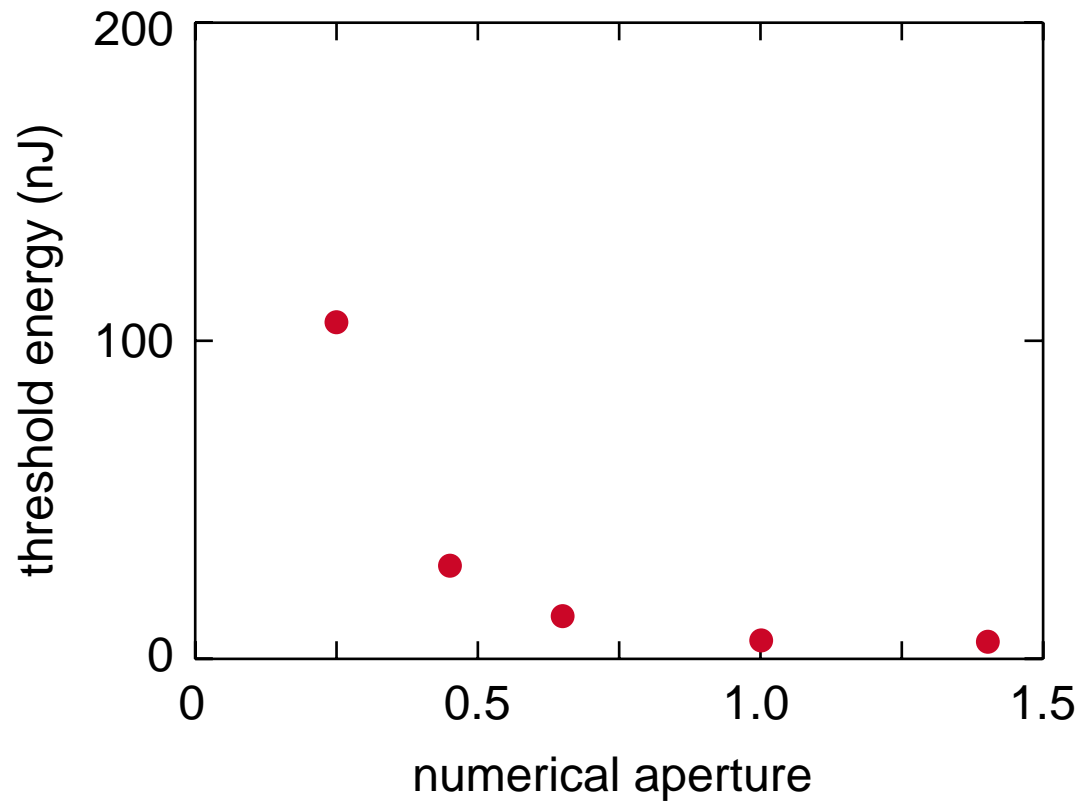


## *Role of focusing*

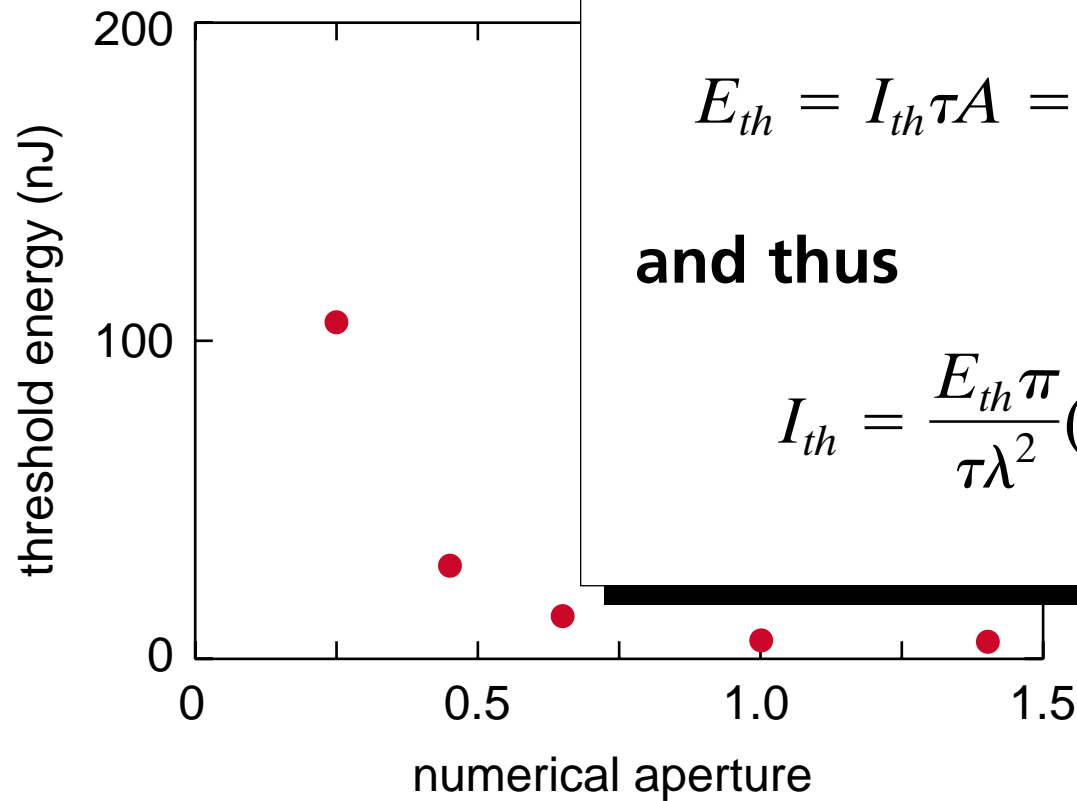


## *Role of focusing*

**vary numerical aperture in Corning 0211**



## Role of focusing



**spot size determined by  
numerical aperture:**

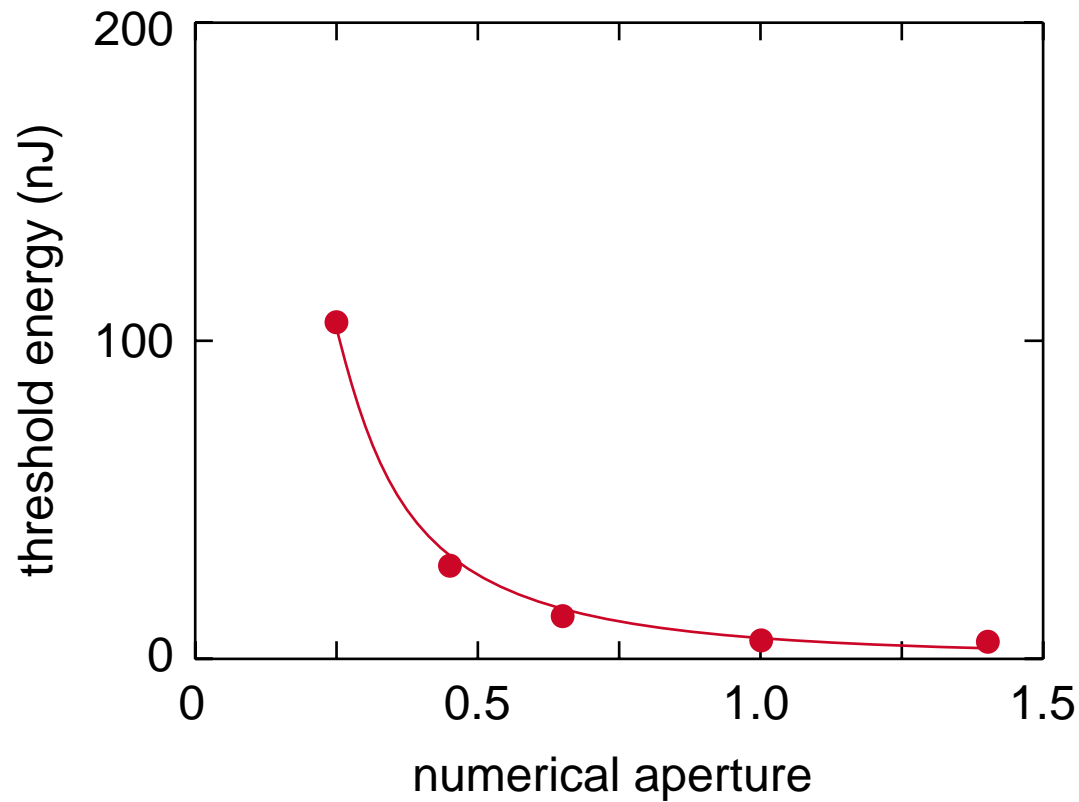
$$E_{th} = I_{th} \tau A = \frac{I_{th} \tau \lambda^2}{\pi (\text{NA})^2}$$

**and thus**

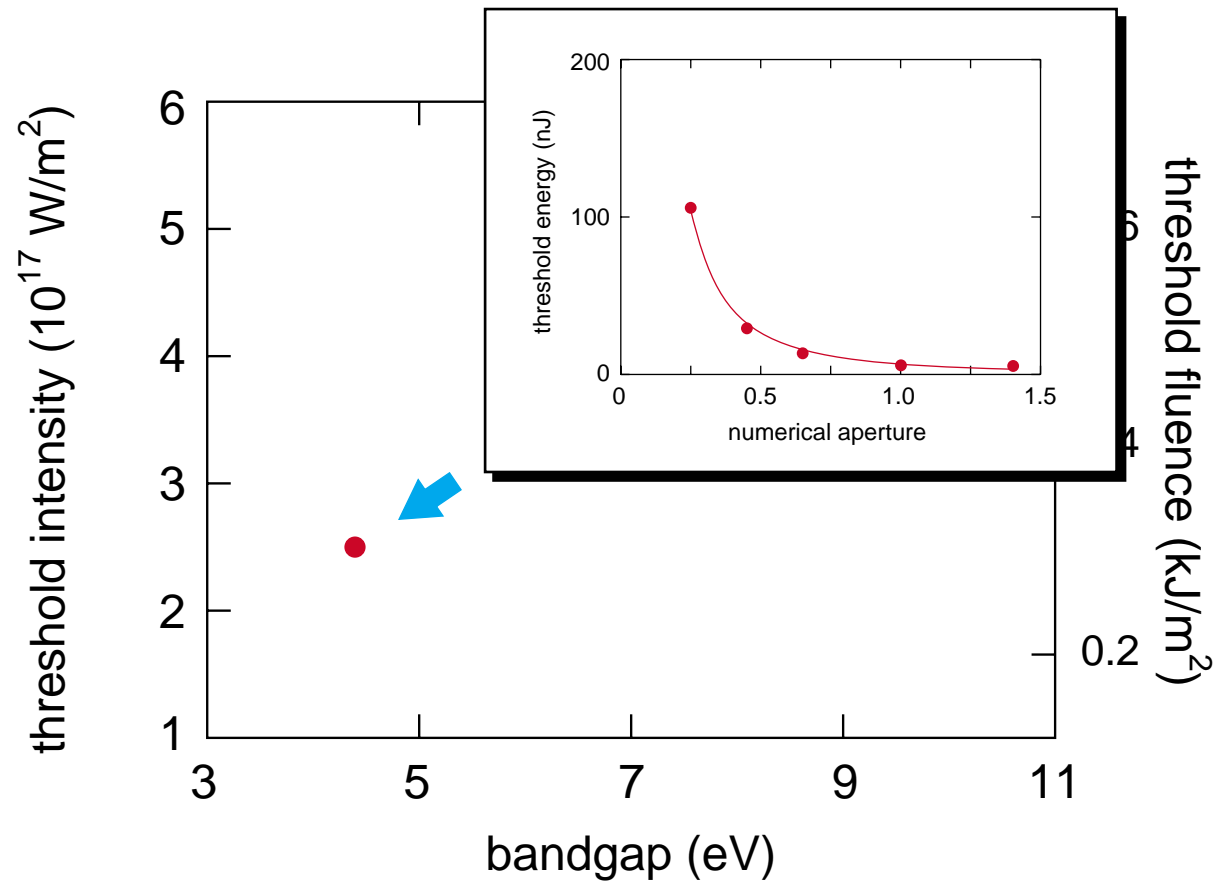
$$I_{th} = \frac{E_{th} \pi}{\tau \lambda^2} (\text{NA})^2$$

## *Role of focusing*

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



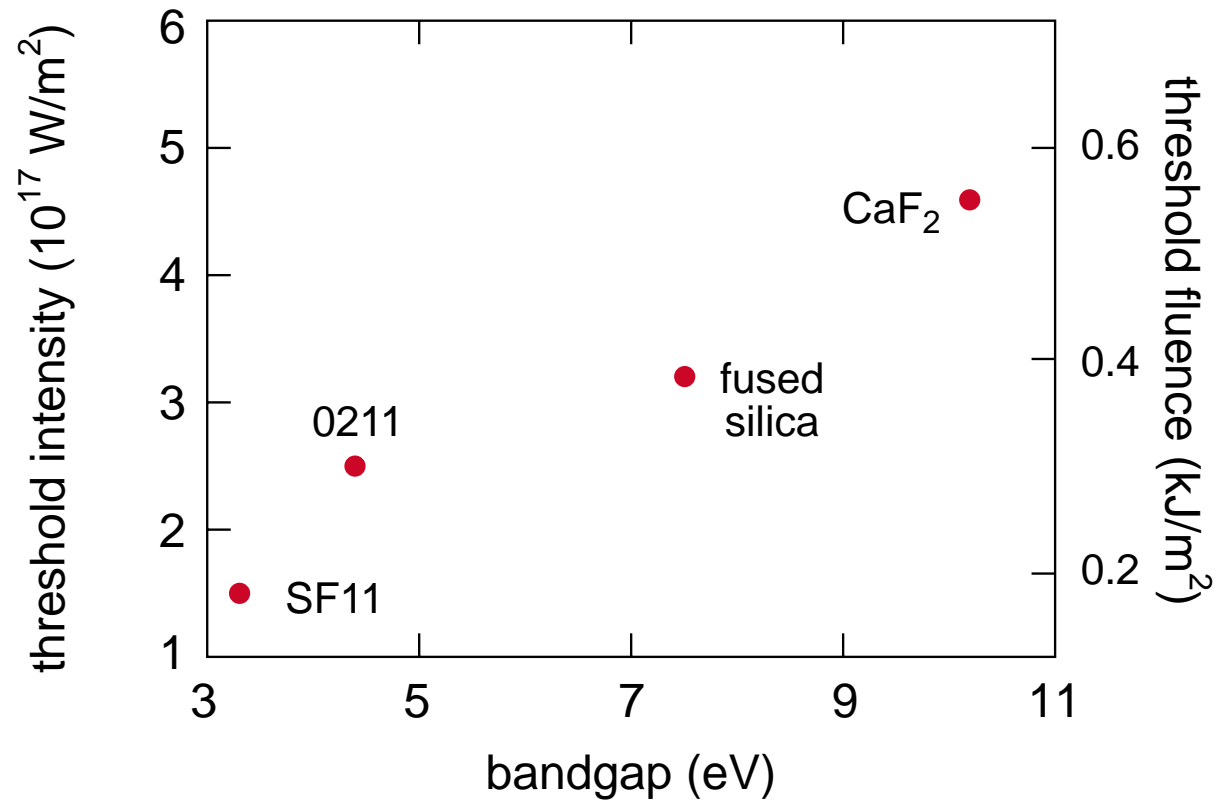
# Role of focusing





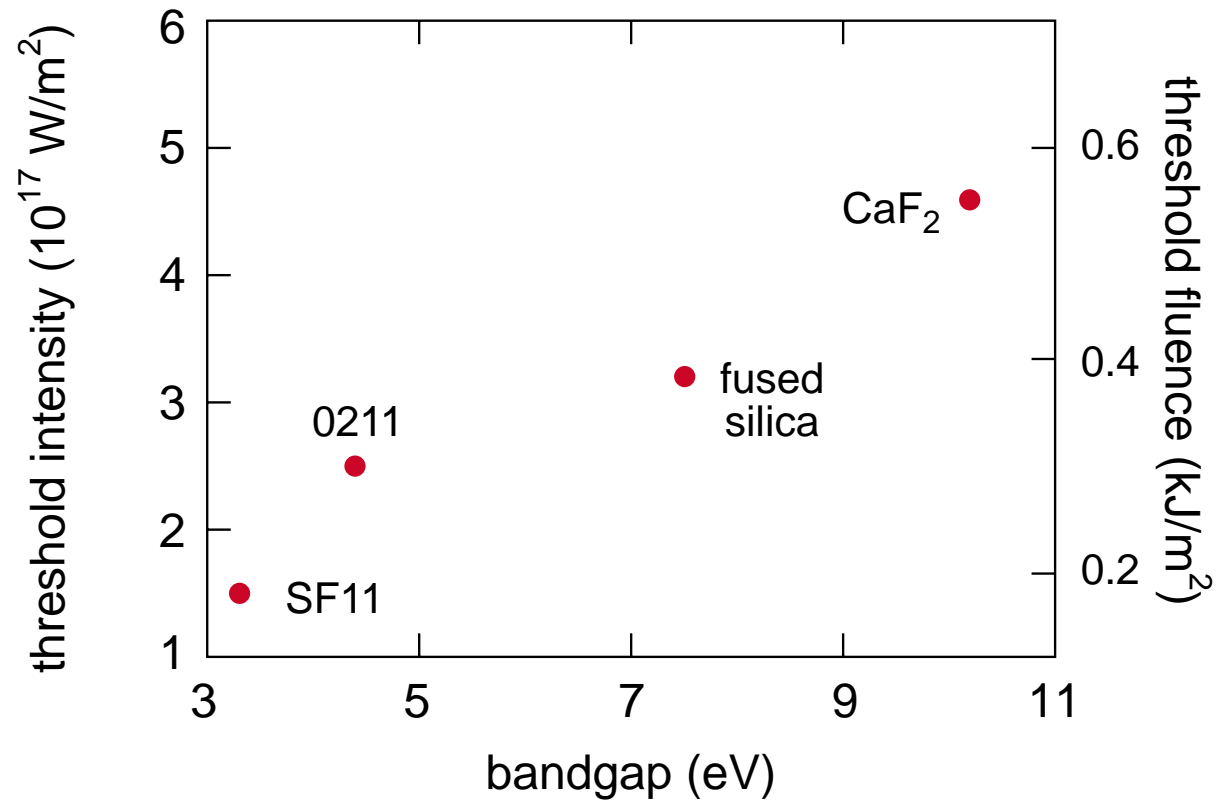
## *Role of focusing*

**vary material...**



## *Role of focusing*

**threshold varies with bandgap**



## *Role of focusing*

### **Points to keep in mind:**

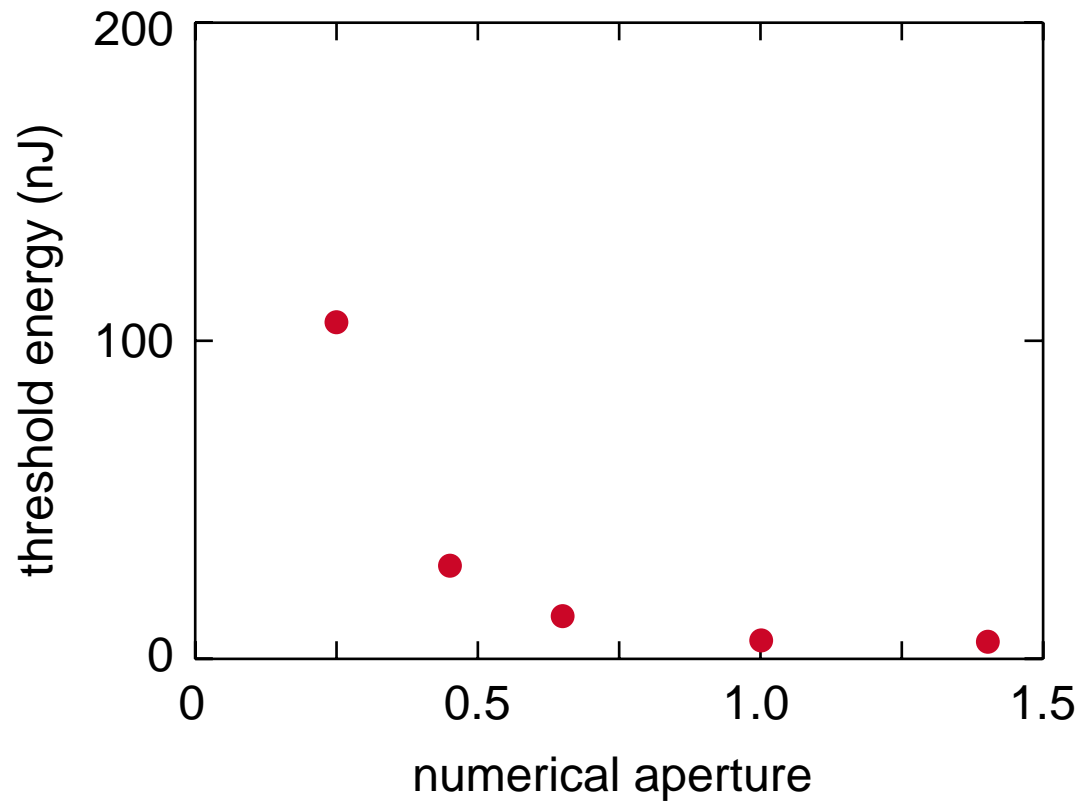
- ▶ **threshold critically dependent on NA**
- ▶ **surprisingly little material dependence**
- ▶ **avalanche ionization important**

# Outline

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

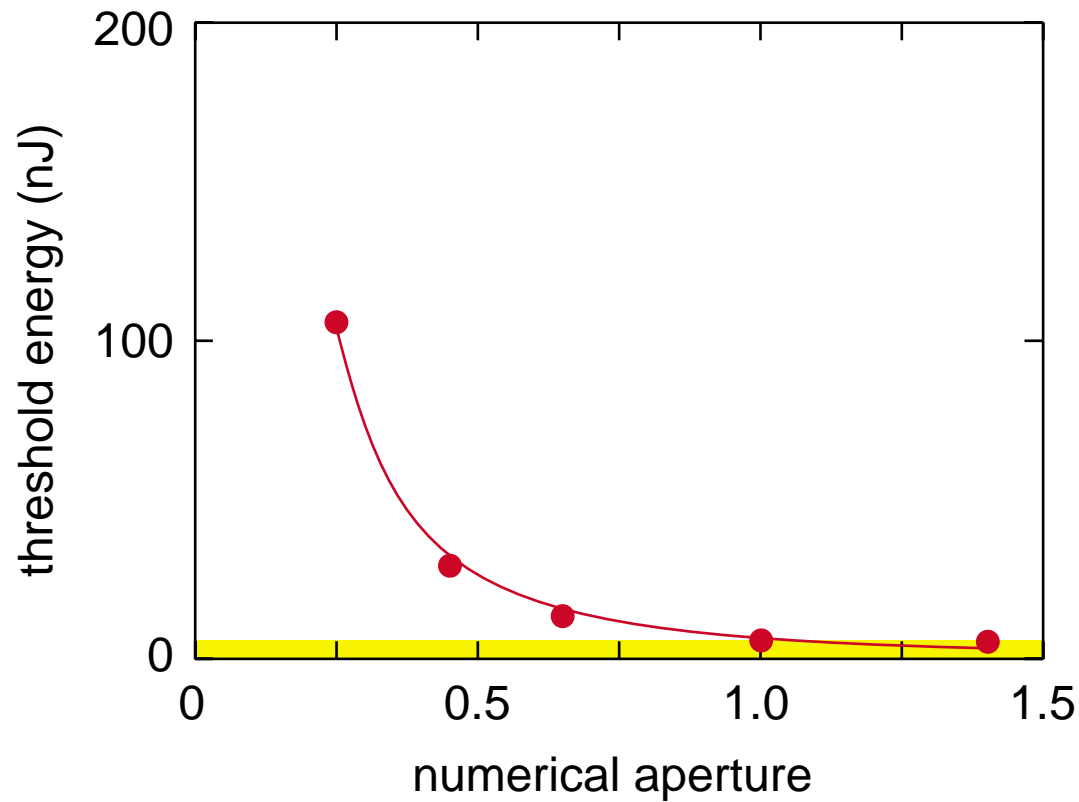
## *Low-energy processing*

**threshold decreases with increasing numerical aperture**



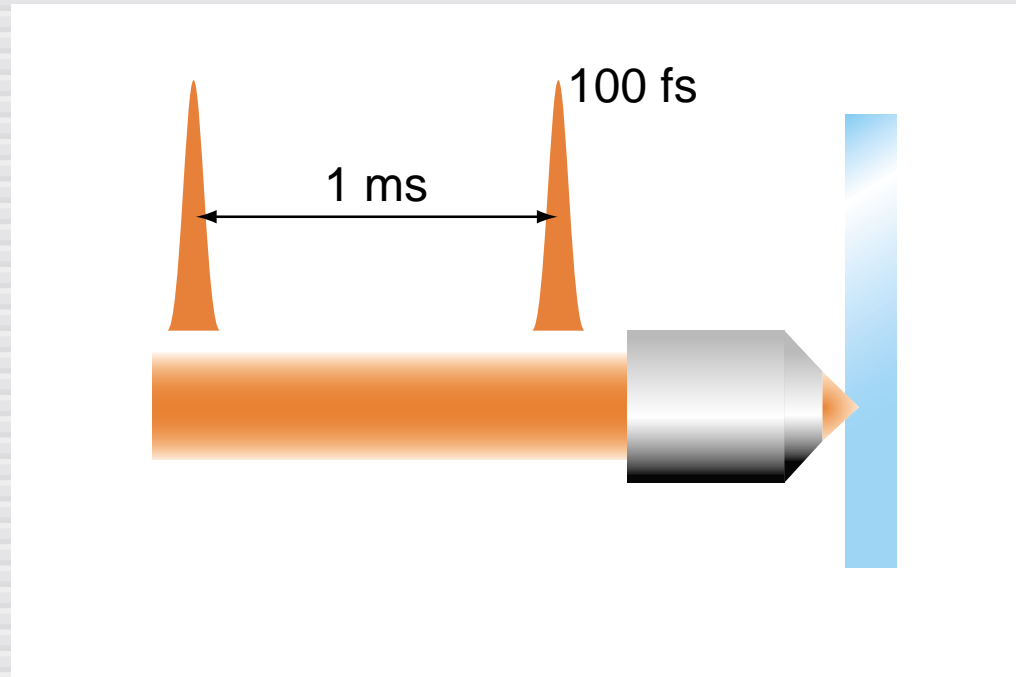
## *Low-energy processing*

**less than 10 nJ at high numerical aperture!**



# *Low-energy processing*

## **amplified laser**

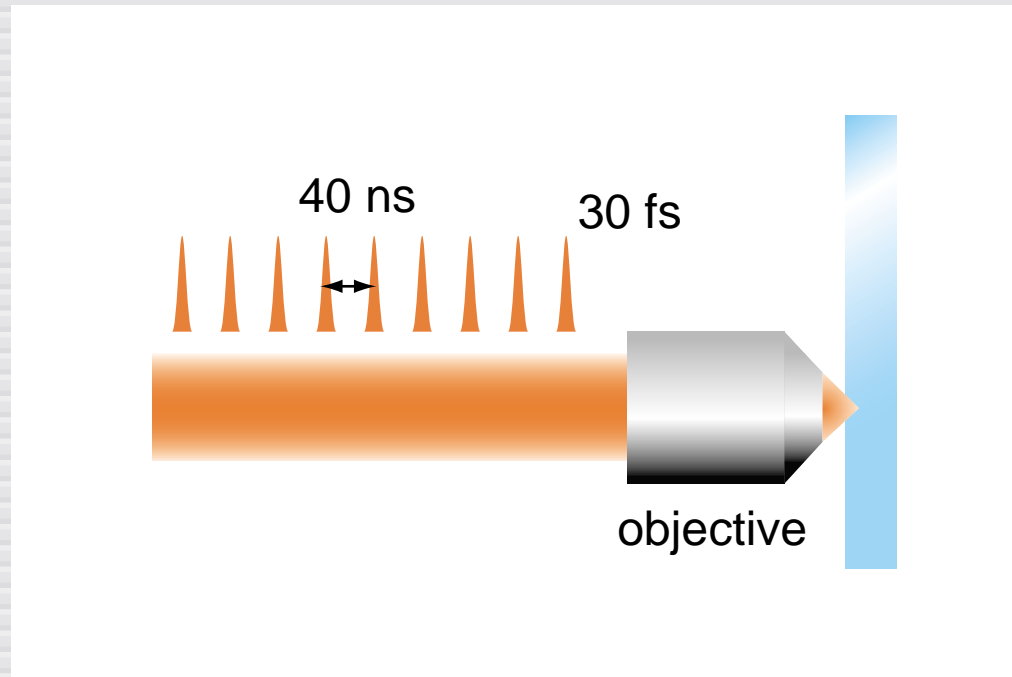


**heat-diffusion time:**  $\tau_{diff} \approx 1 \mu s$



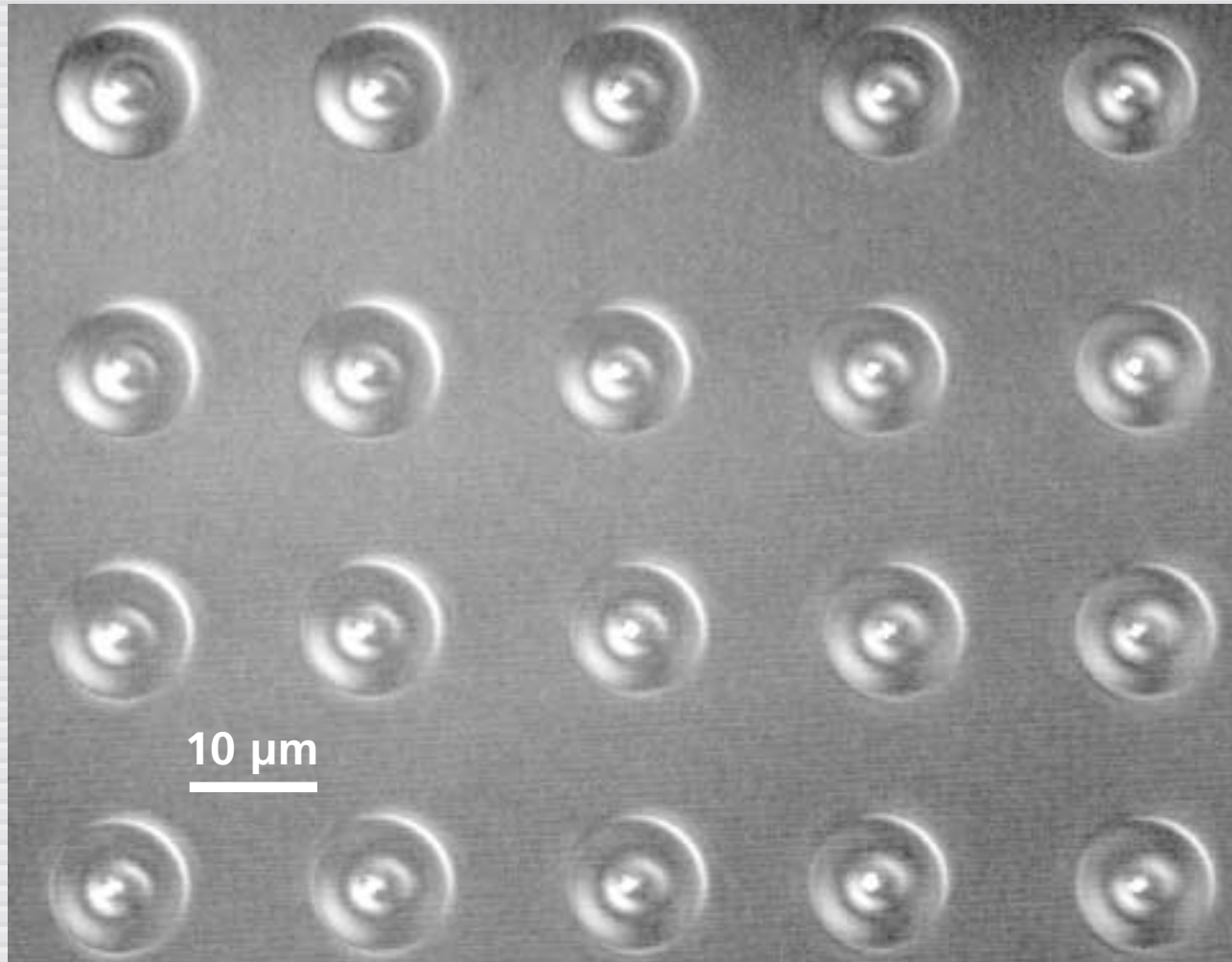
## *Low-energy processing*

### **long-cavity Ti:sapphire oscillator**

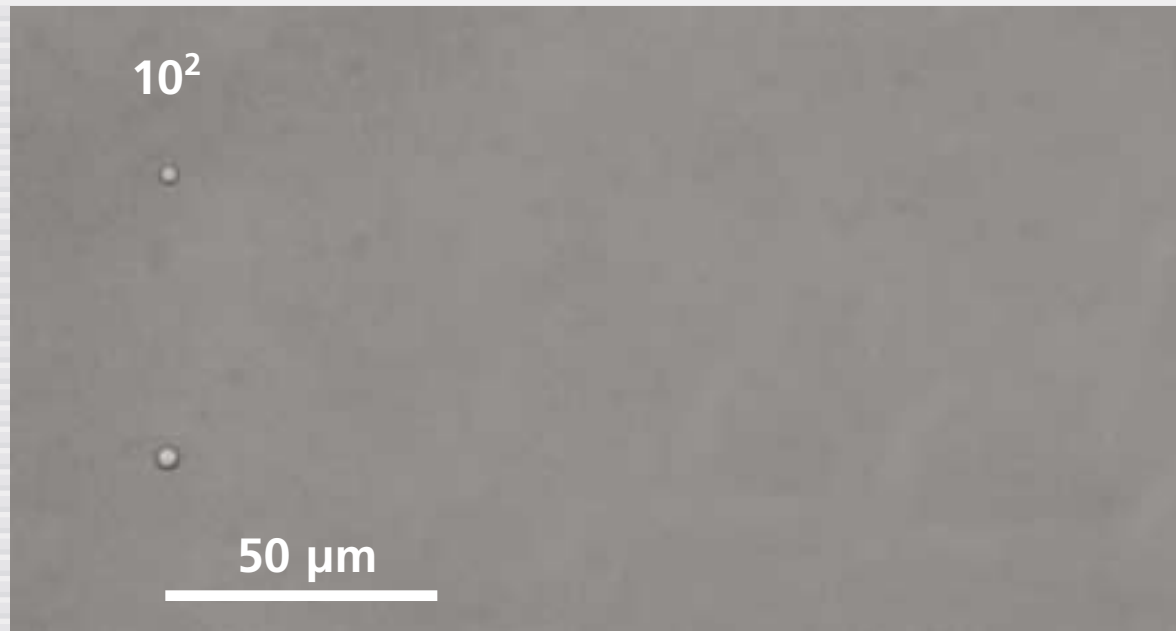


**heat-diffusion time:**  $\tau_{diff} \approx 1 \mu s$

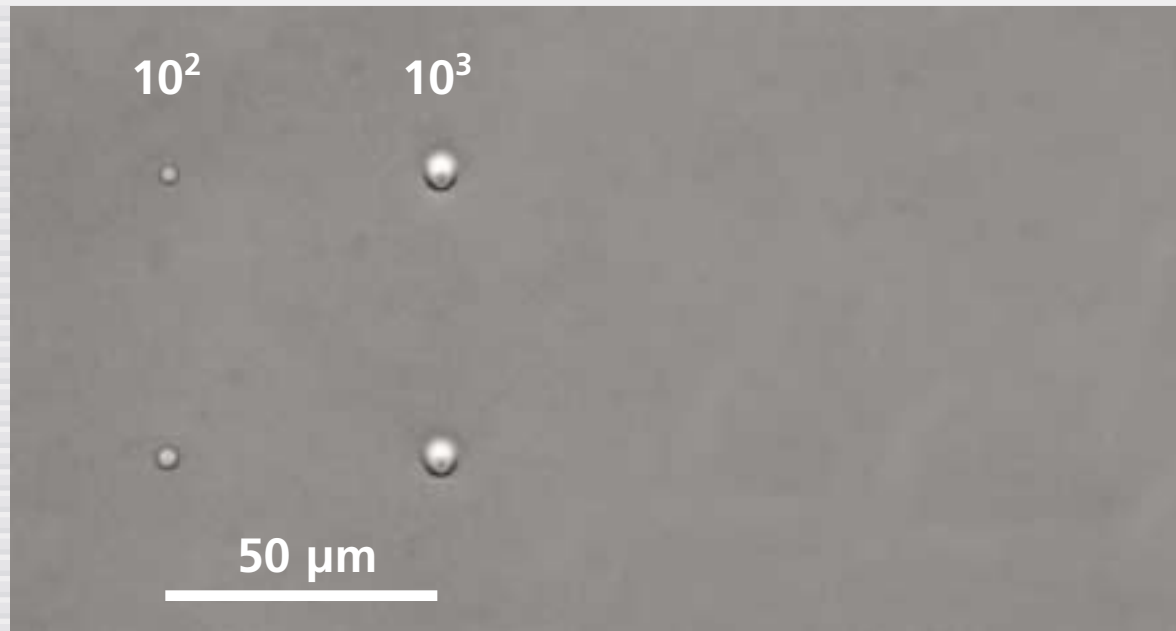
## *Low-energy processing*



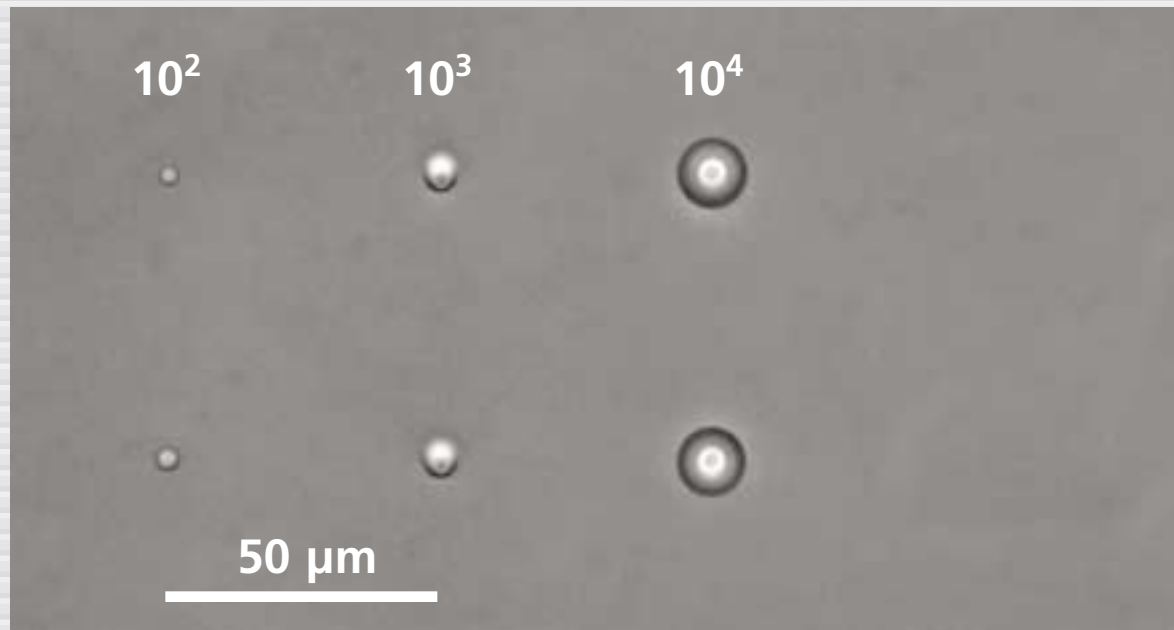
## *Low-energy processing*



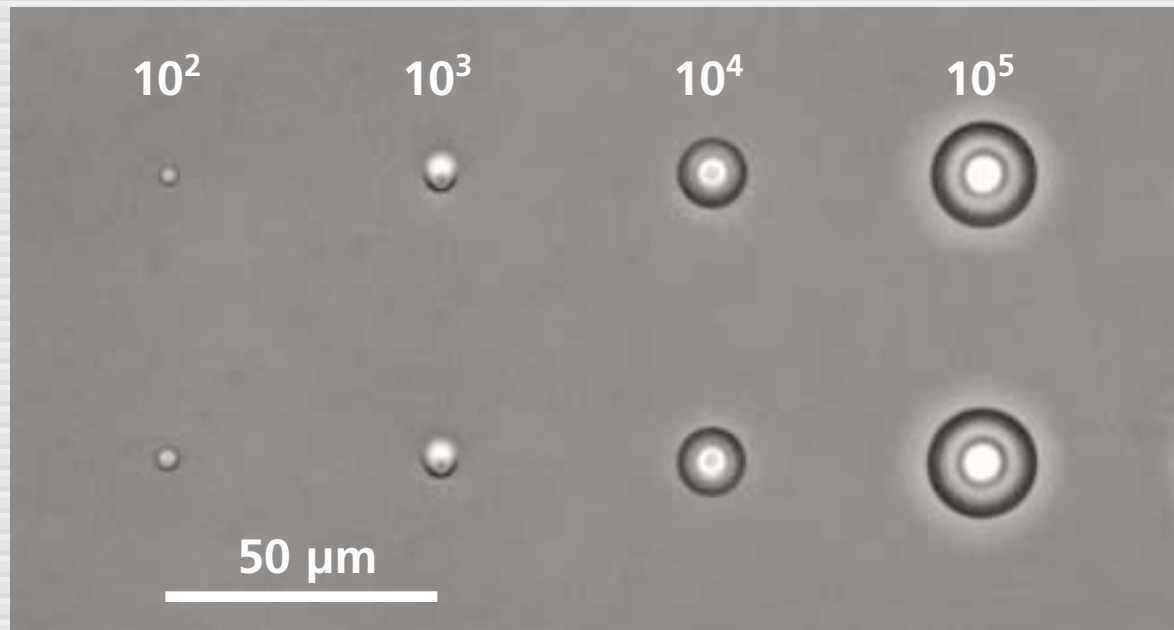
## *Low-energy processing*



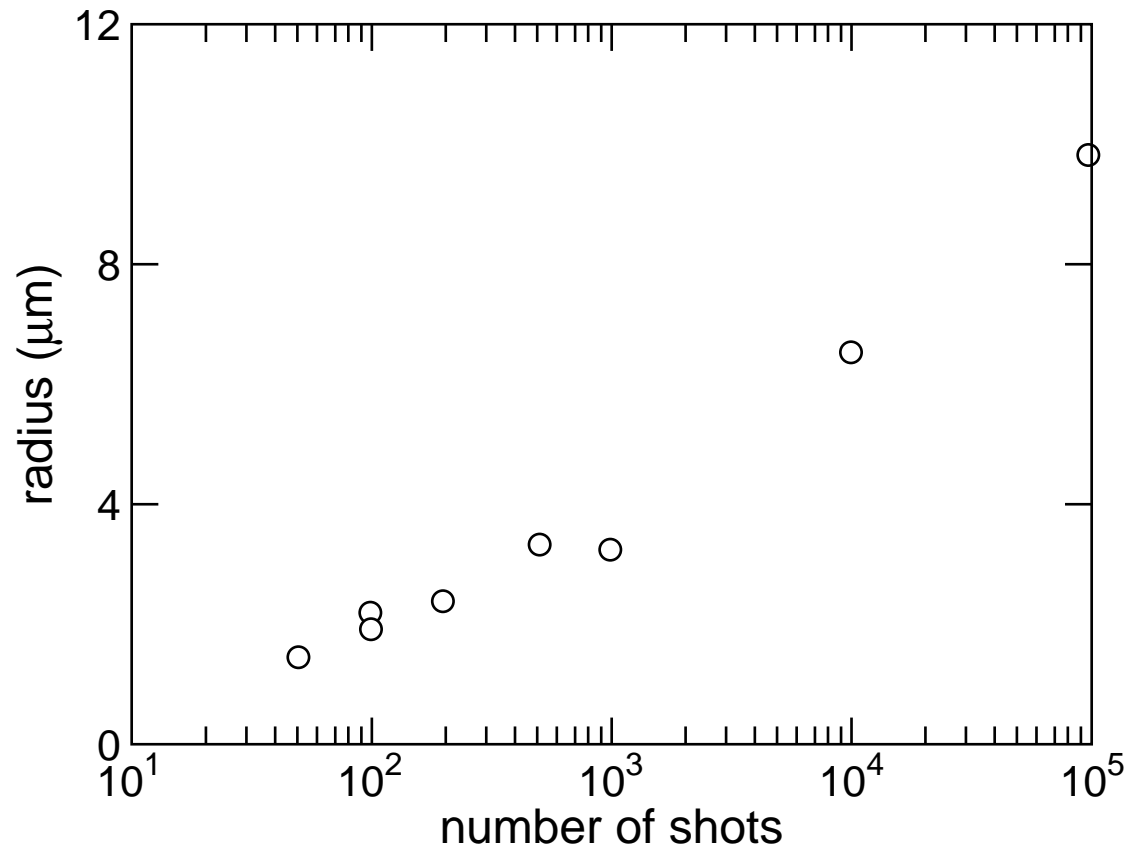
## *Low-energy processing*



## *Low-energy processing*

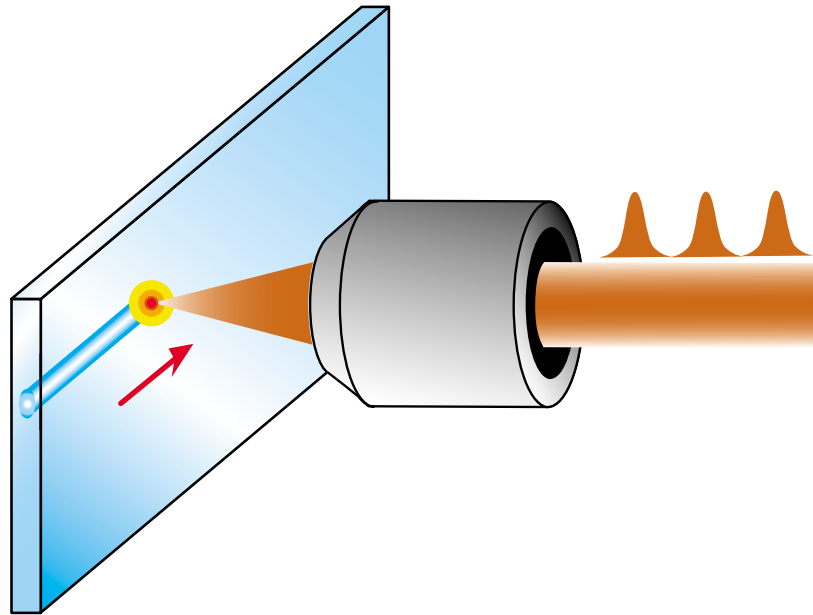


## *Low-energy processing*



# *Low-energy processing*

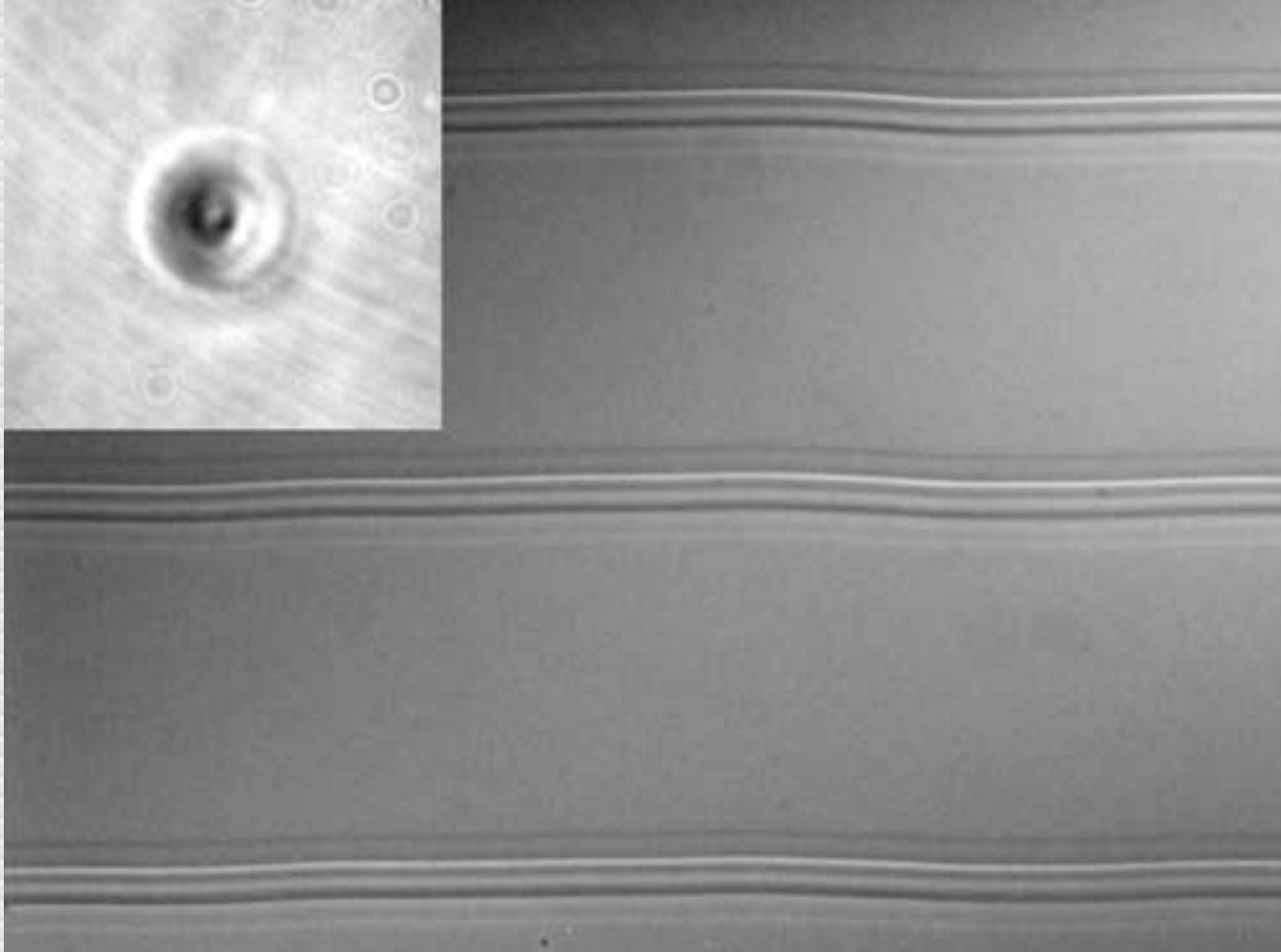
## **waveguide machining**





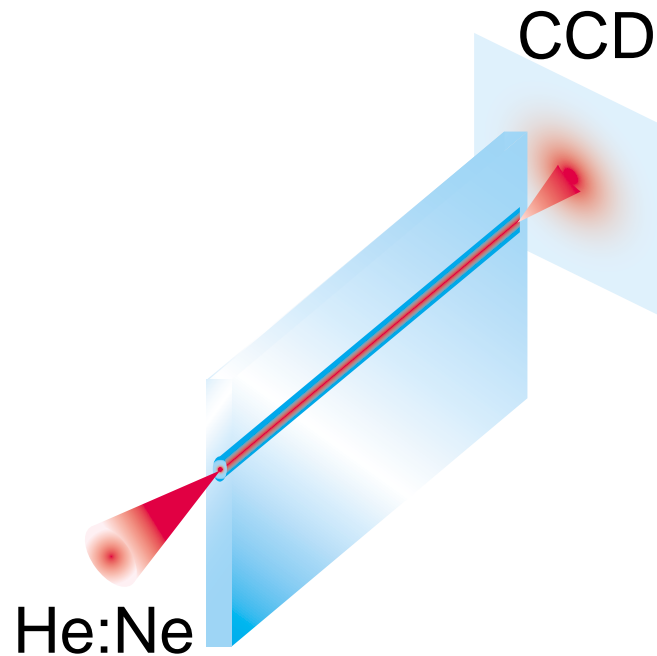
# *Low-energy processing*

## **waveguide machining**



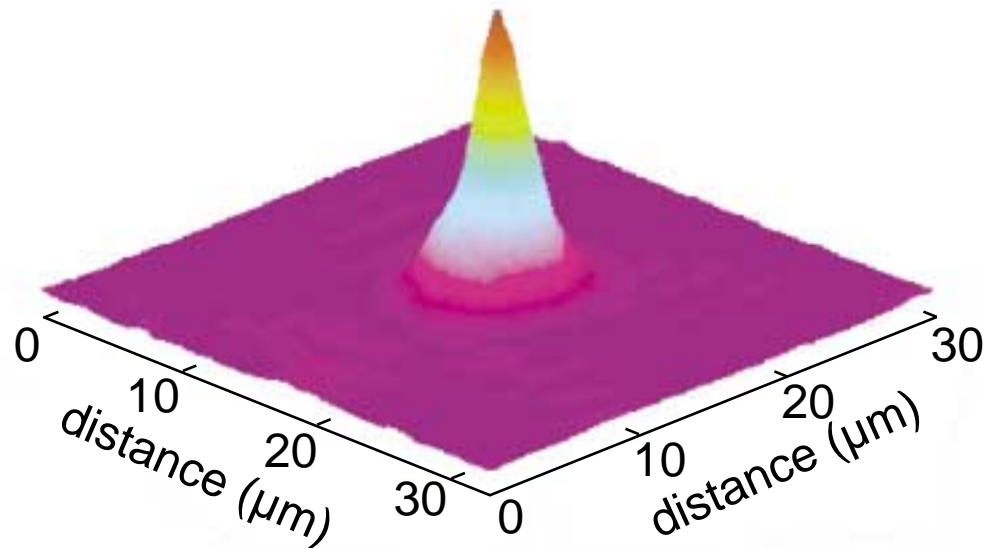
# *Low-energy processing*

## **waveguide mode analysis**



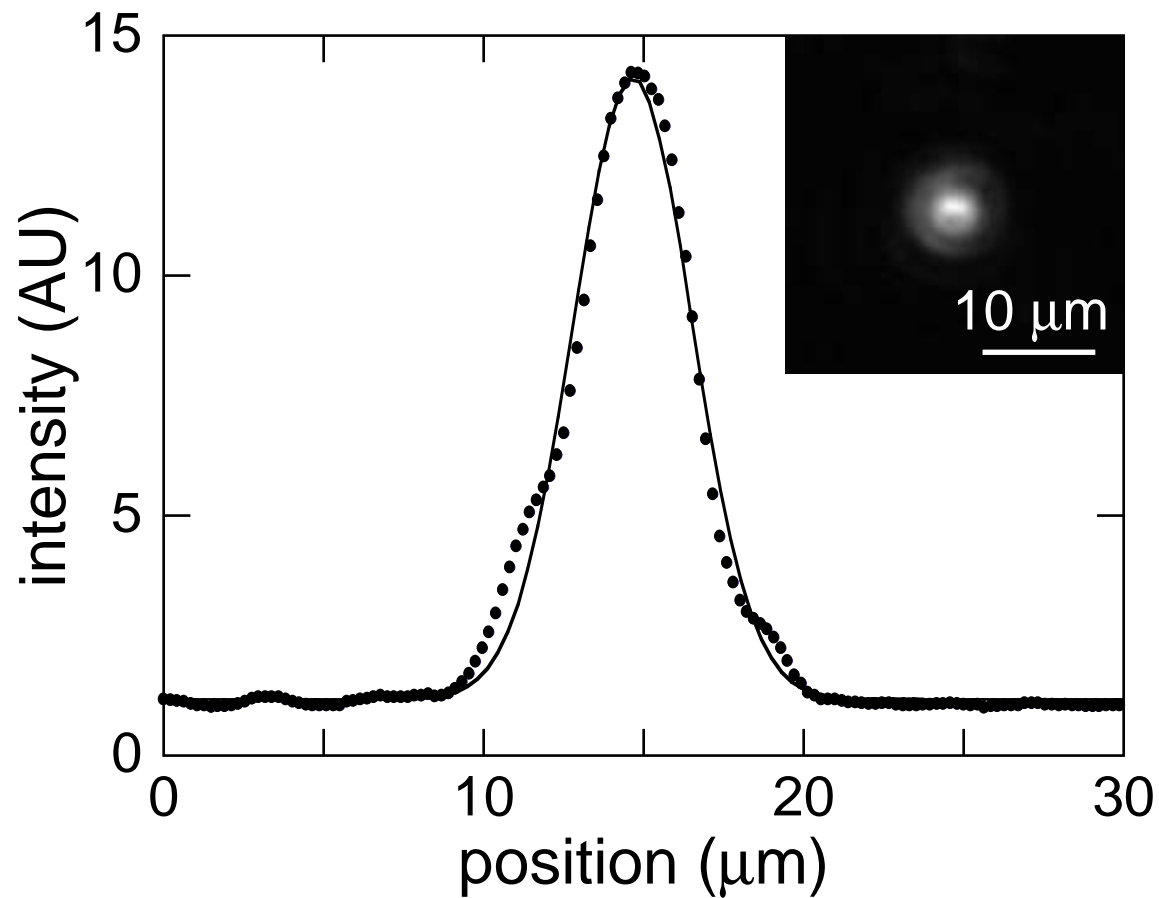
# *Low-energy processing*

## **near field mode**



# *Low-energy processing*

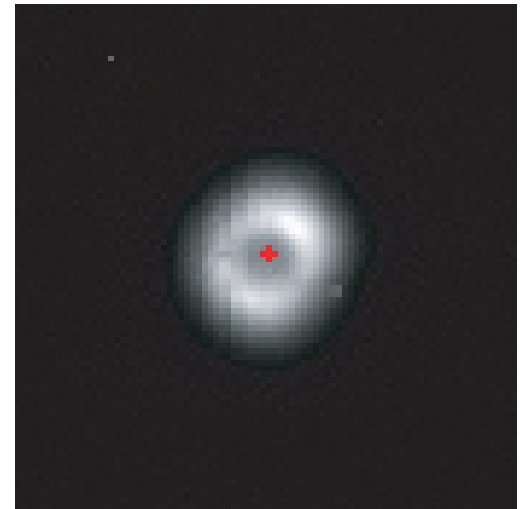
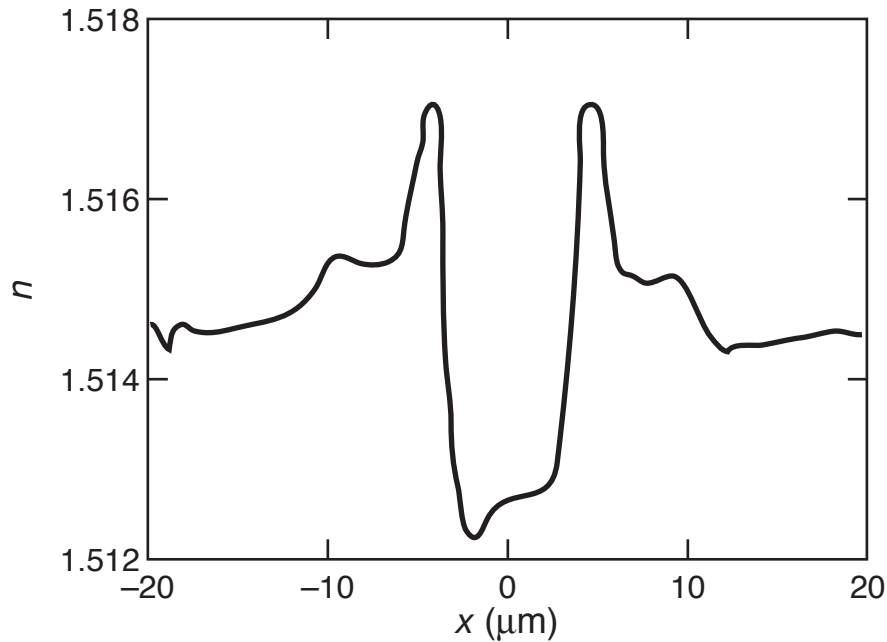
## **near field mode**



## *Low-energy processing*

### refractive index profiles and near field mode at 1550 nm

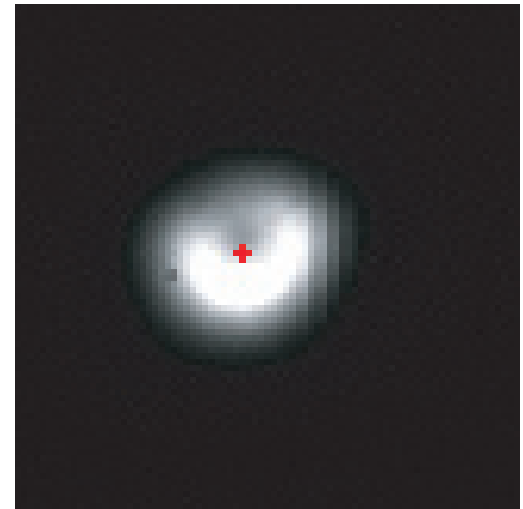
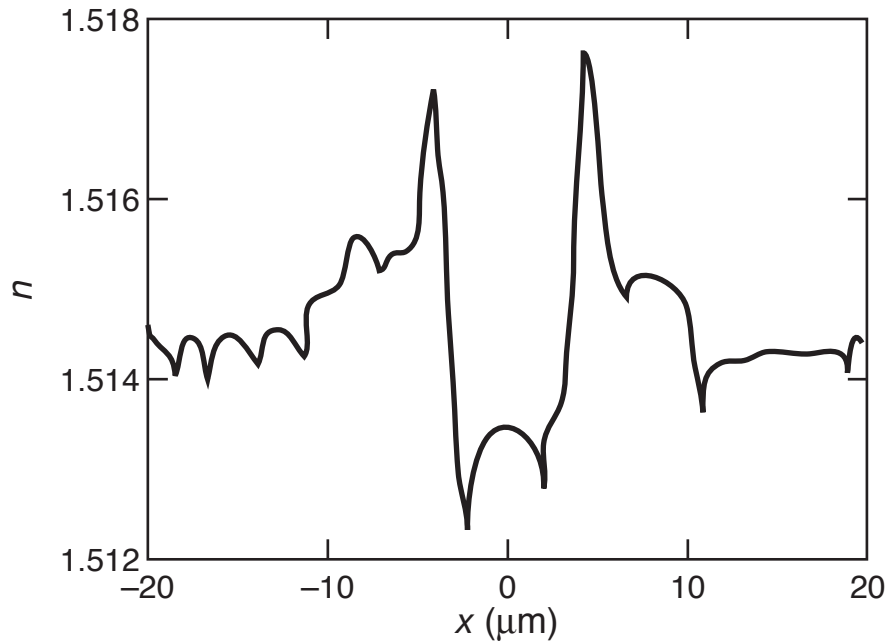
10 mm/s



## *Low-energy processing*

### refractive index profiles and near field mode at 1550 nm

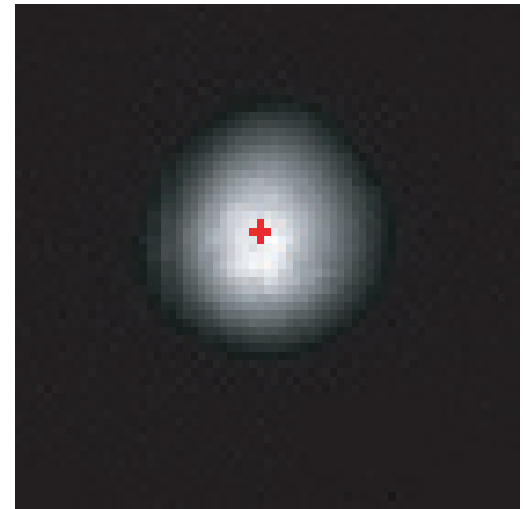
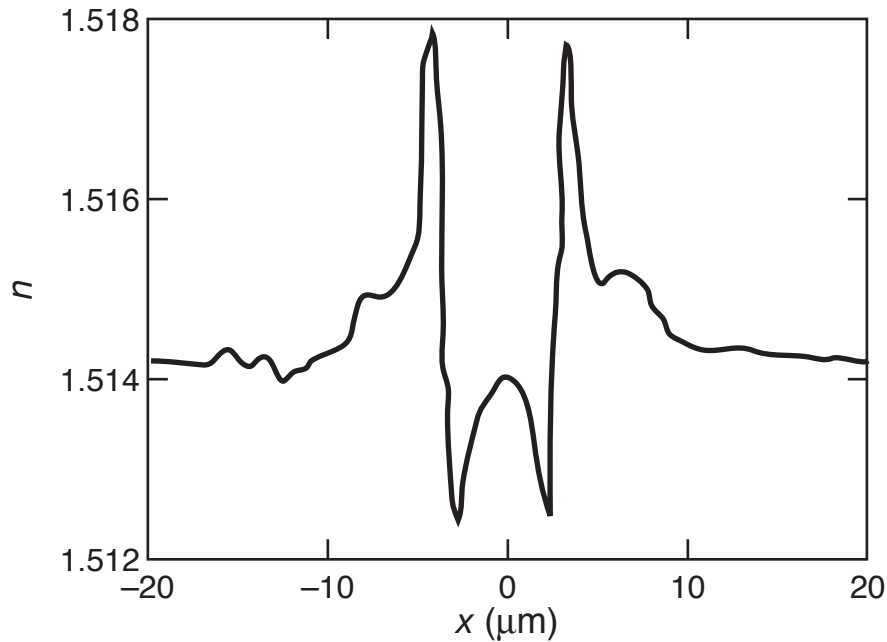
15 mm/s



## *Low-energy processing*

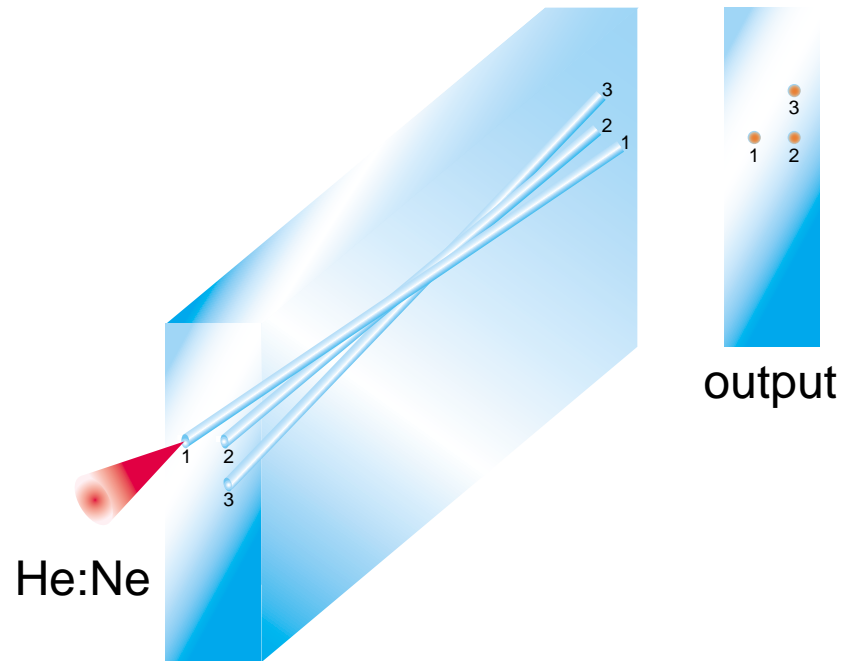
### refractive index profiles and near field mode at 1550 nm

20 mm/s



# *Low-energy processing*

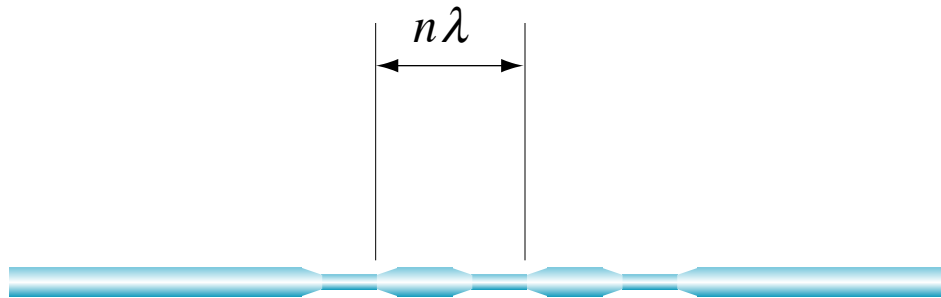
## **3D wave splitter**





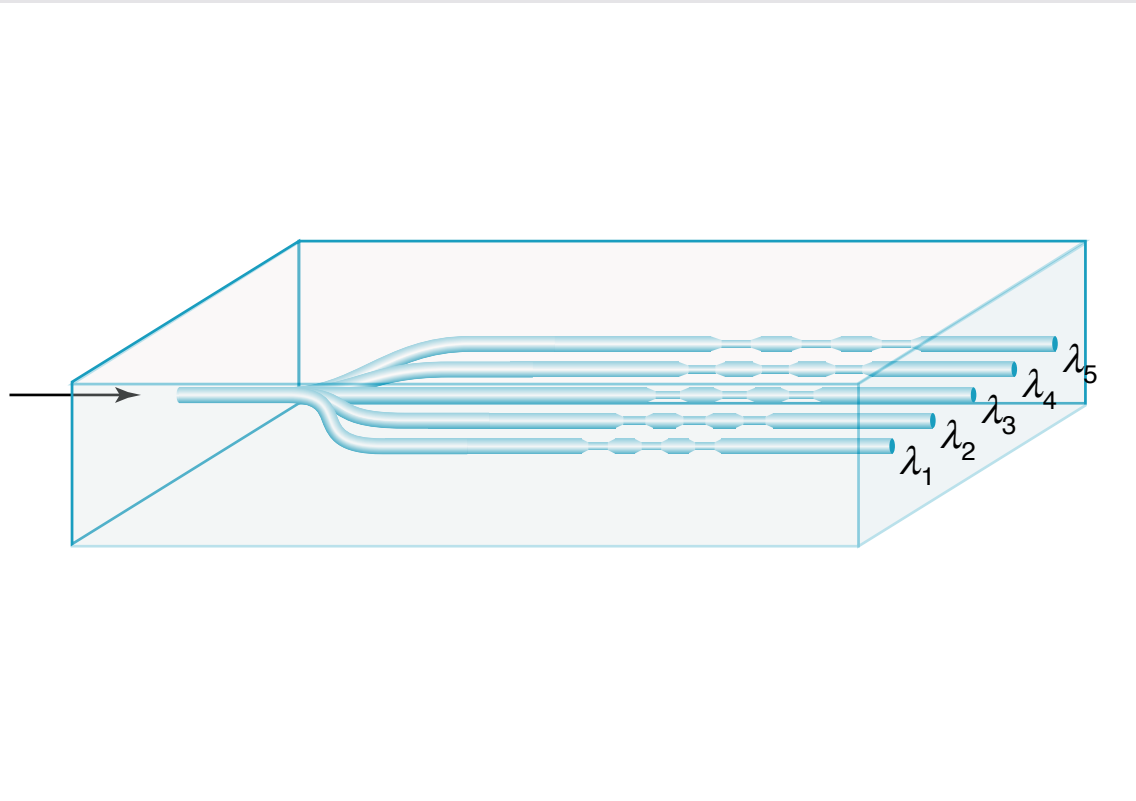
# *Low-energy processing*

## **Bragg grating**



# *Low-energy processing*

## **Bragg grating**



# *Low-energy processing*

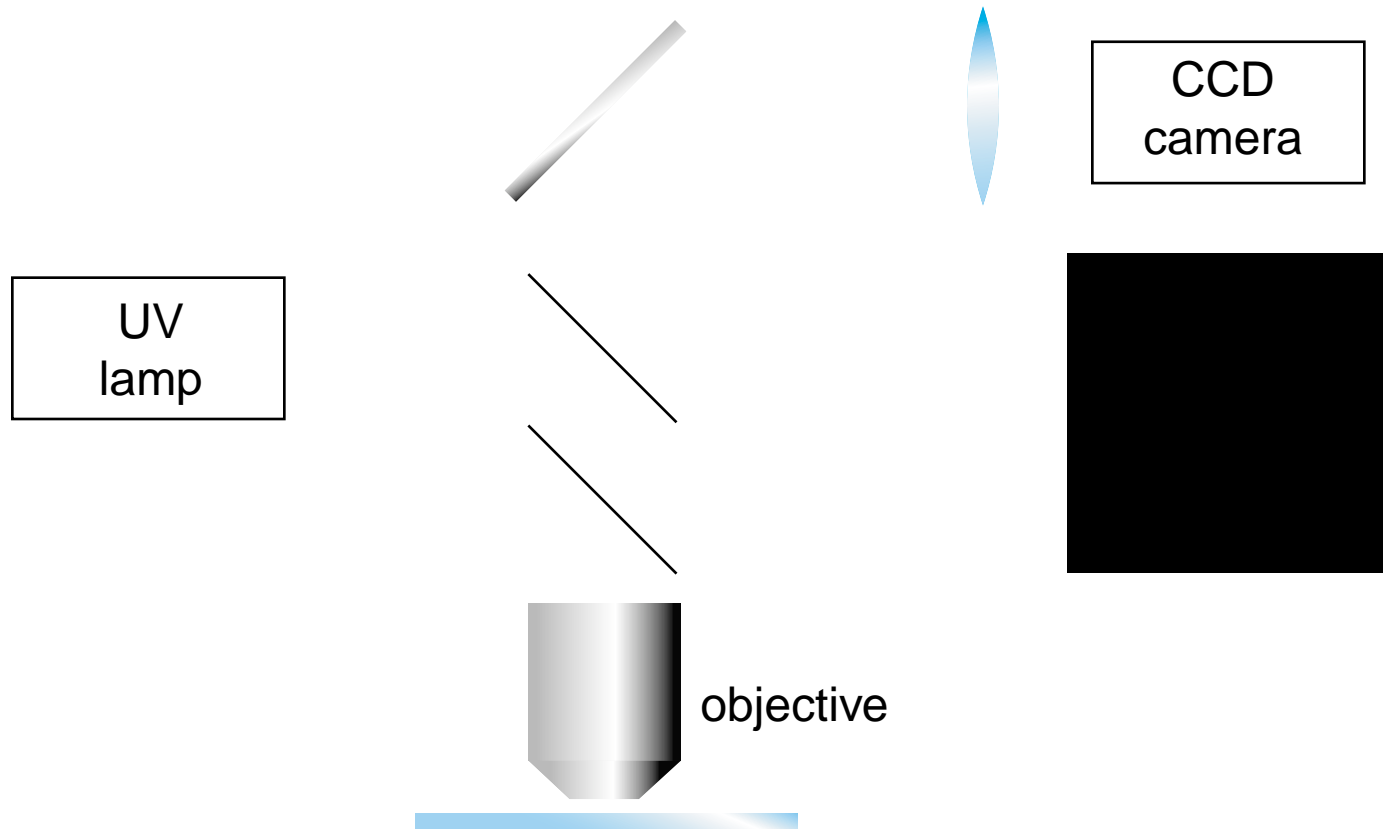
## **monolithic amplifier**



laser active glass

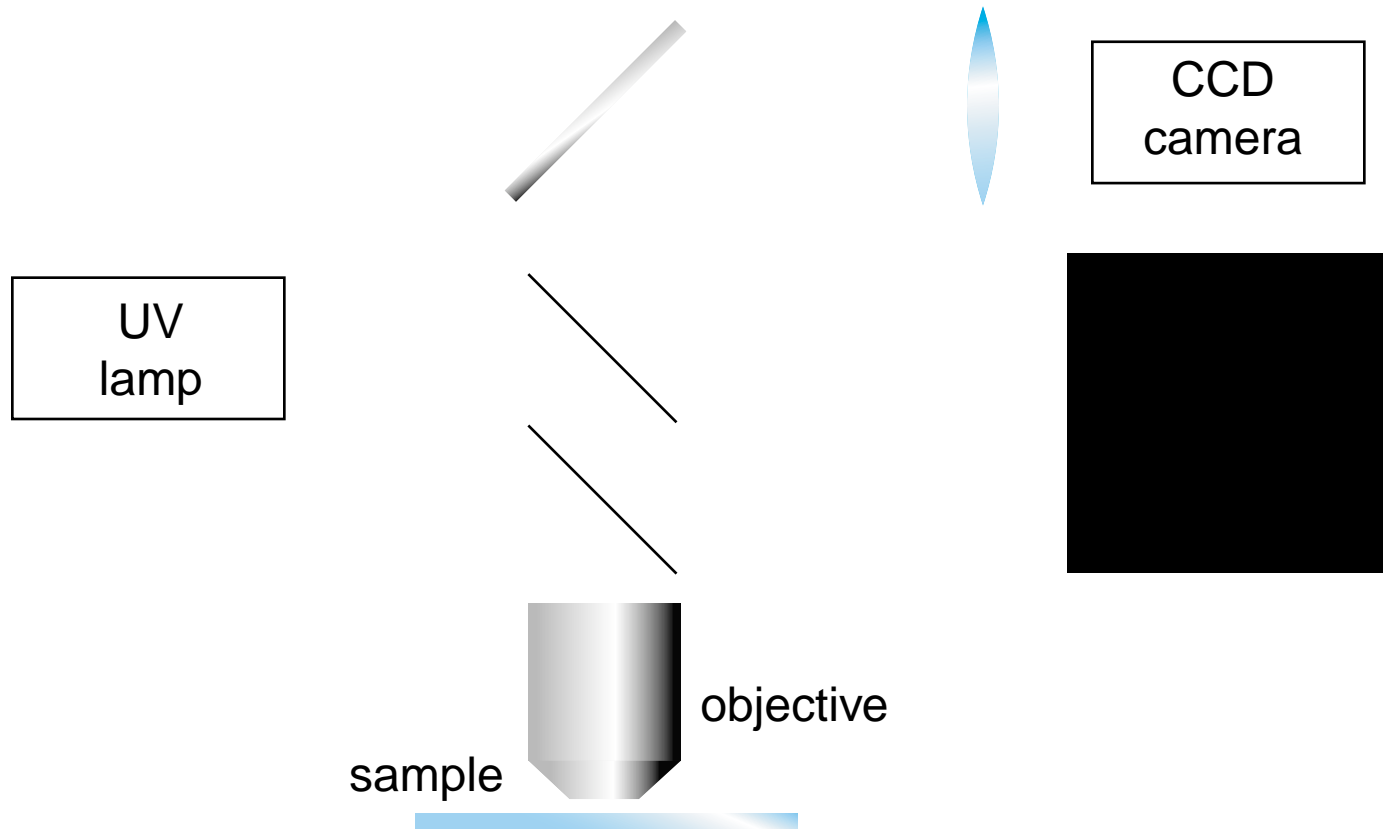
# *Low-energy processing*

## **epi-fluorescence microscope**



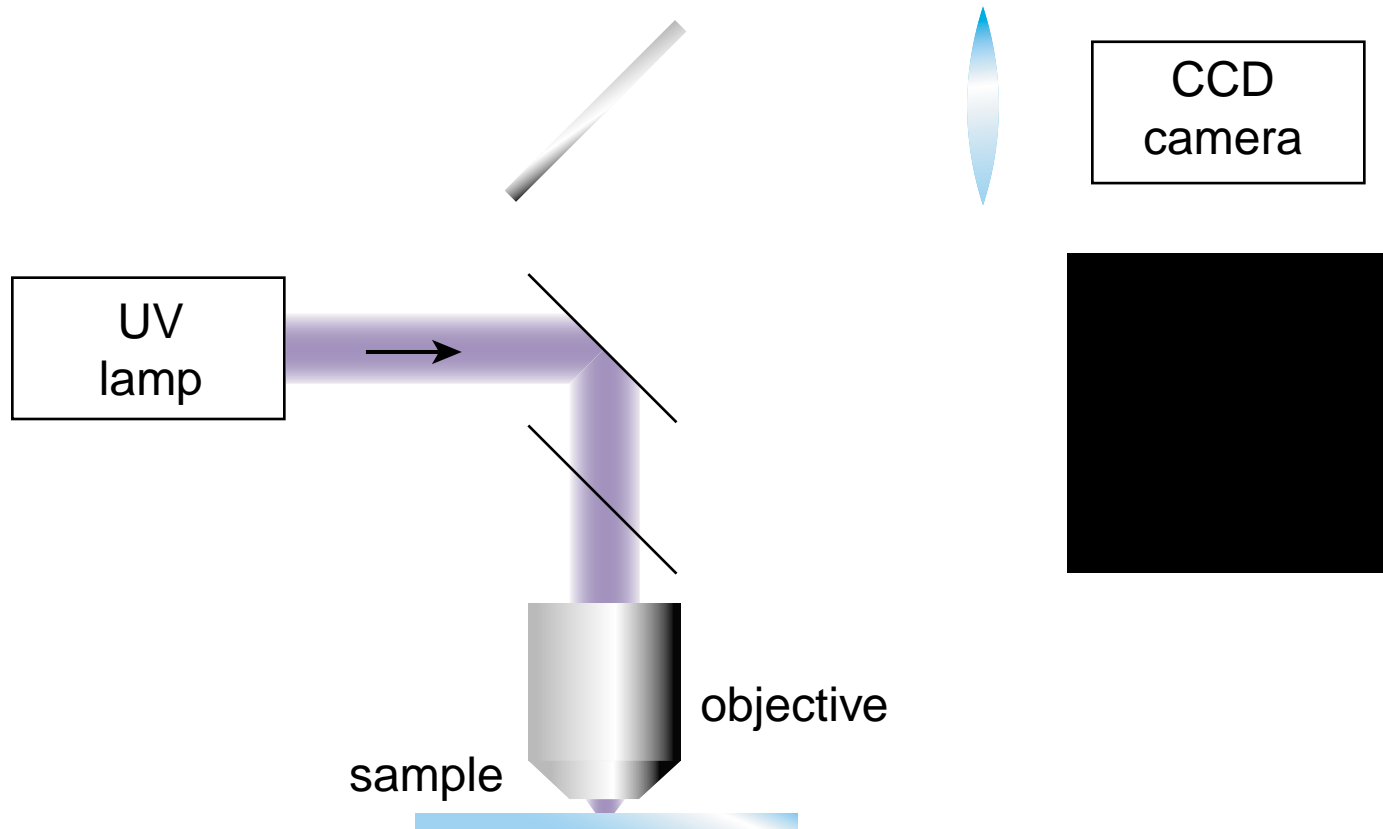
# *Low-energy processing*

**mount fluorescently tagged sample**



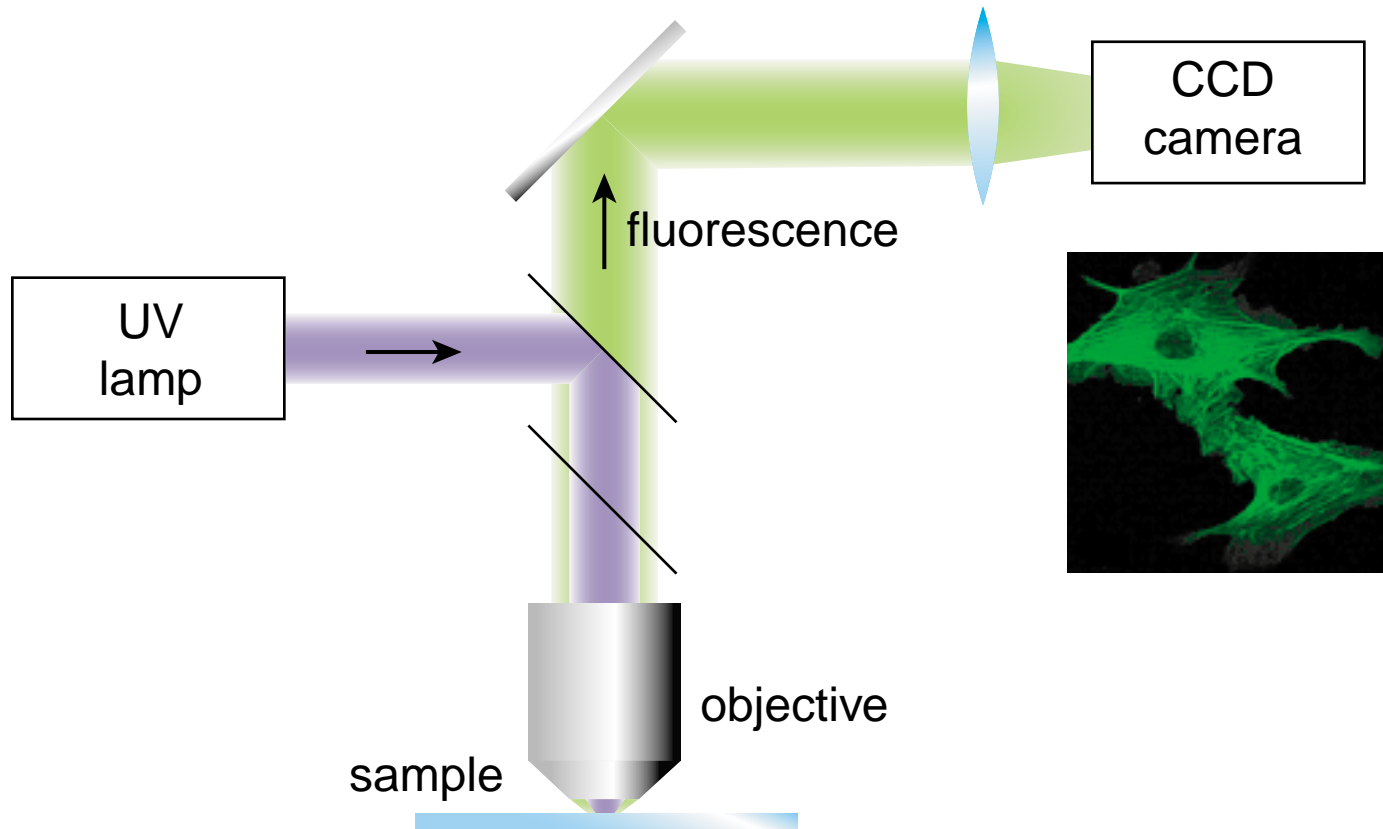
# *Low-energy processing*

## **UV illumination...**



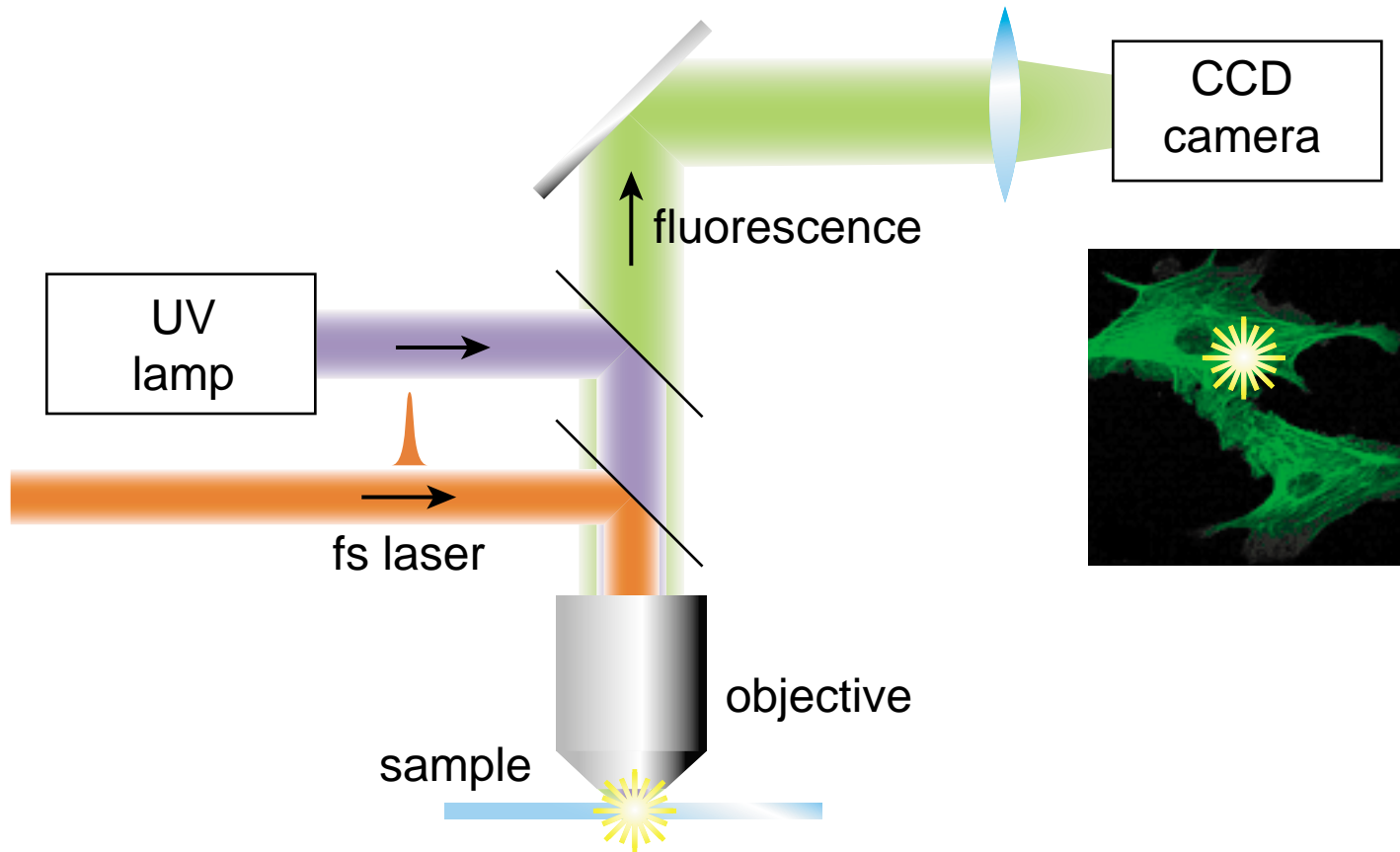
# *Low-energy processing*

**... causes fluorescence**



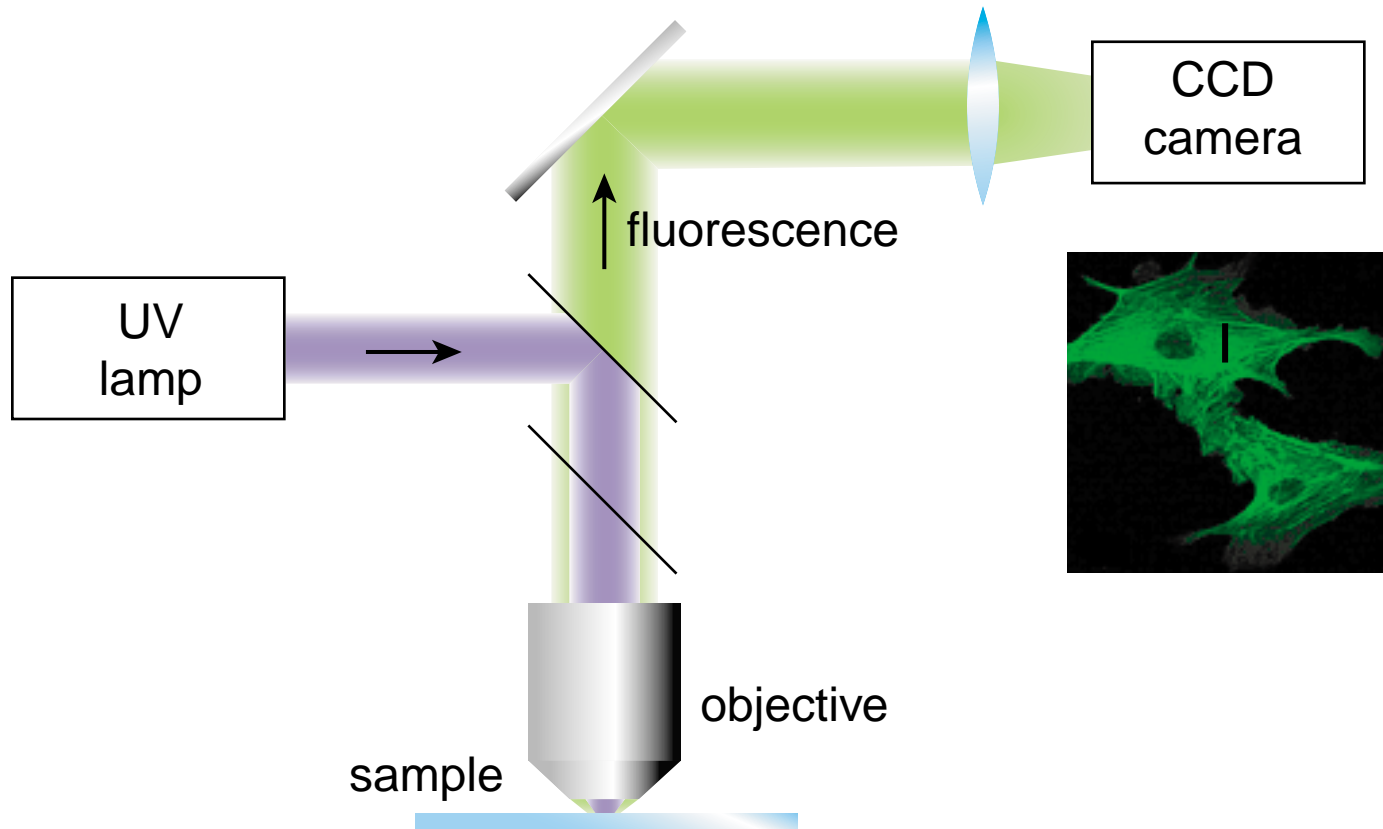
# *Low-energy processing*

## **process with fs laser beam**





# *Low-energy processing*



## *Low-energy processing*

**before**

**after**

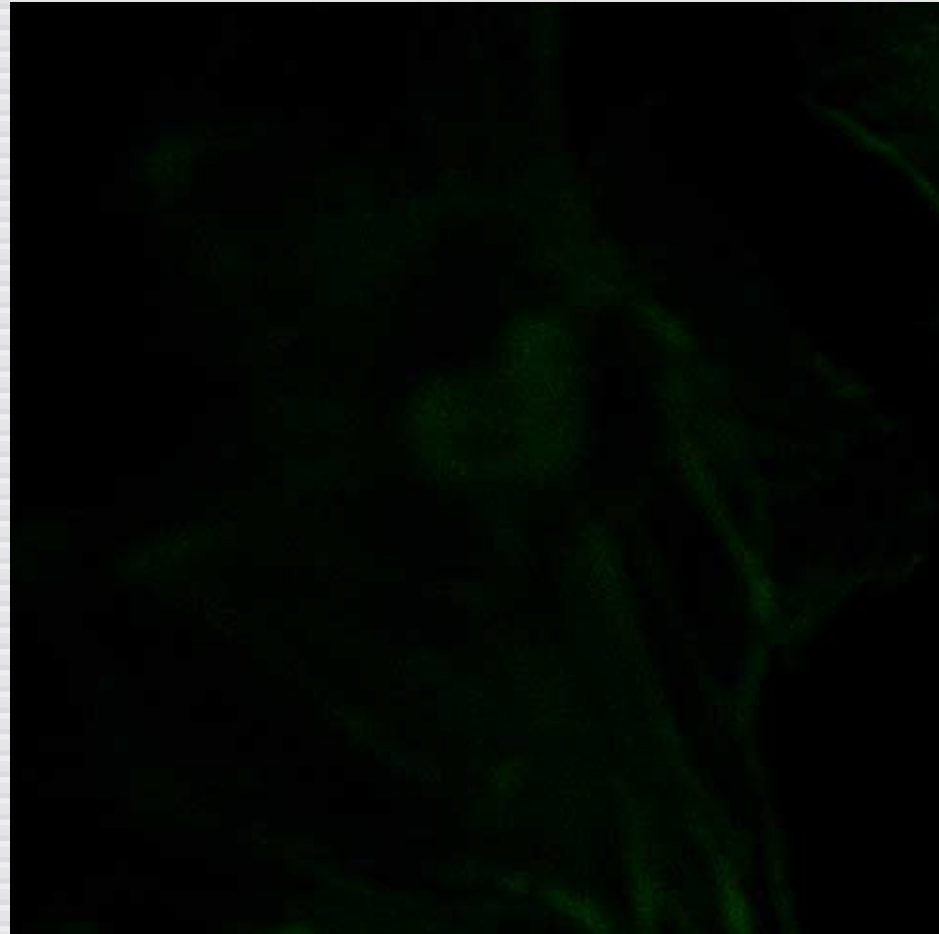
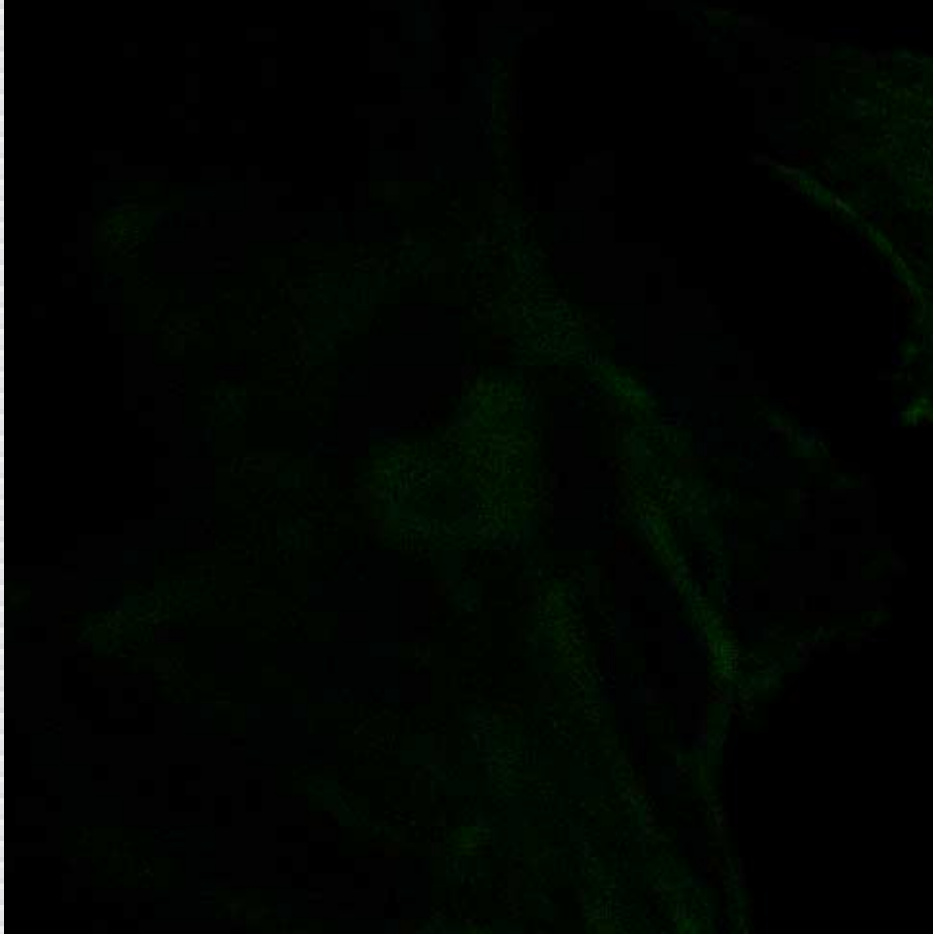


**examine in confocal microscope**

## *Low-energy processing*

**before**

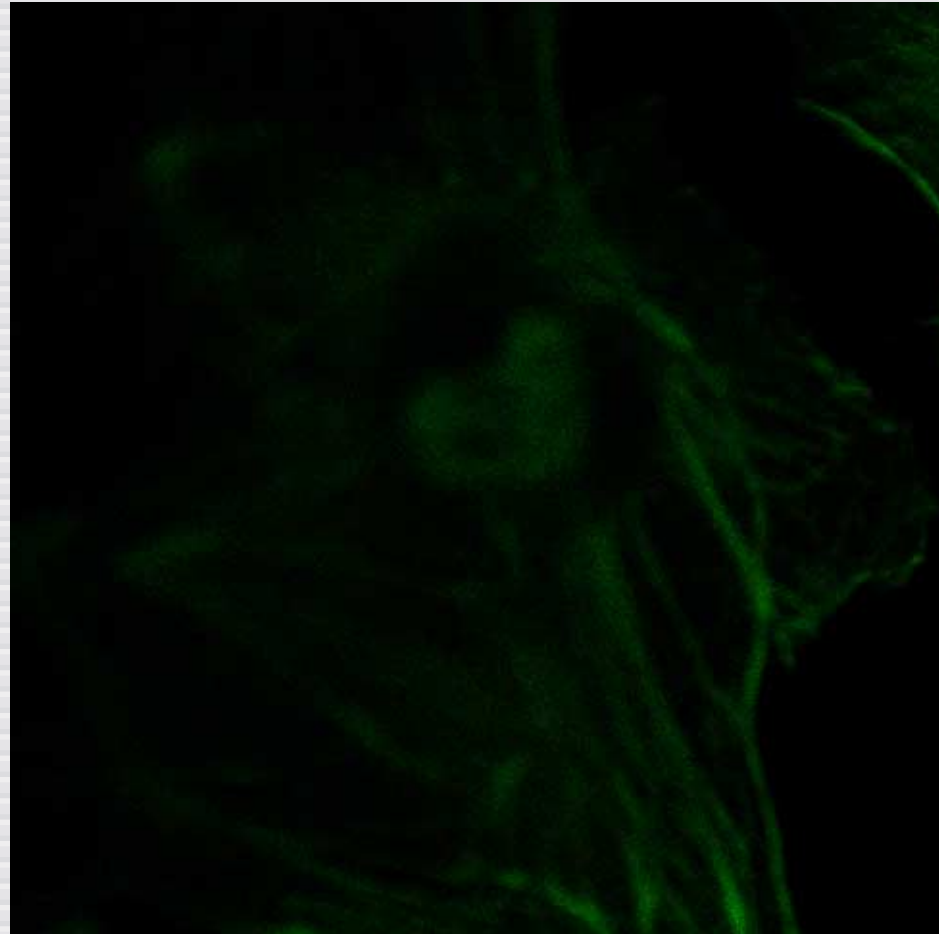
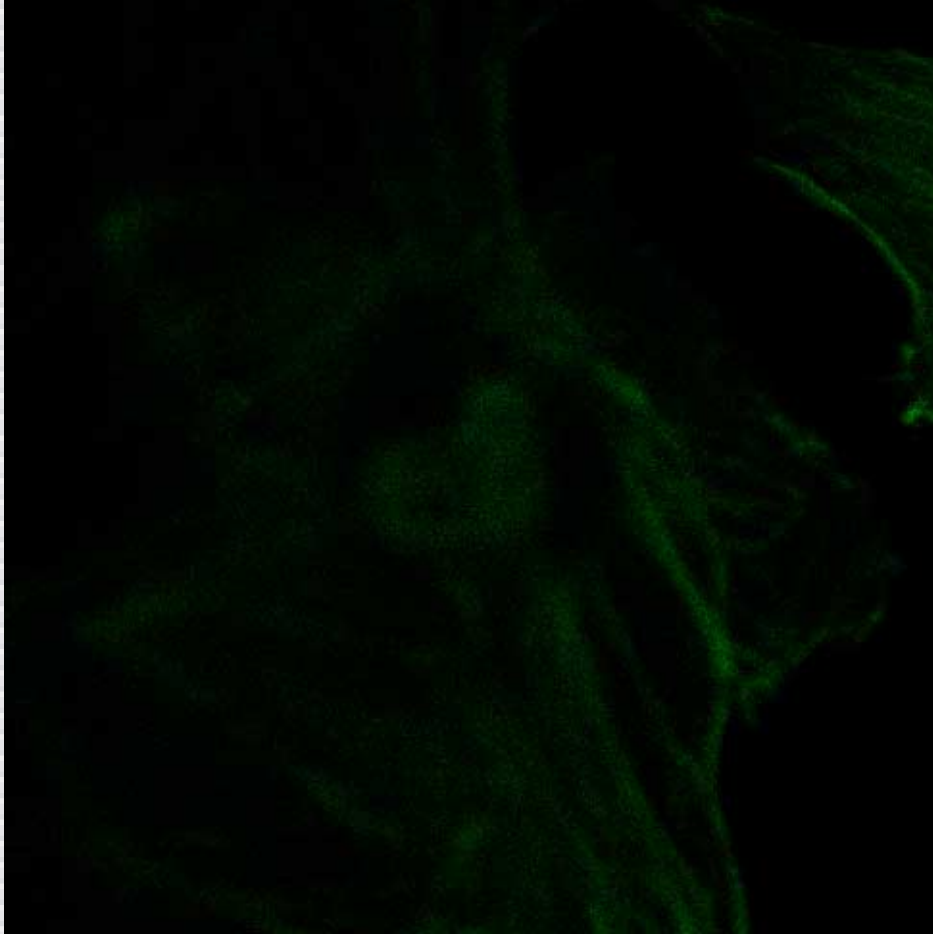
**after**



## *Low-energy processing*

before

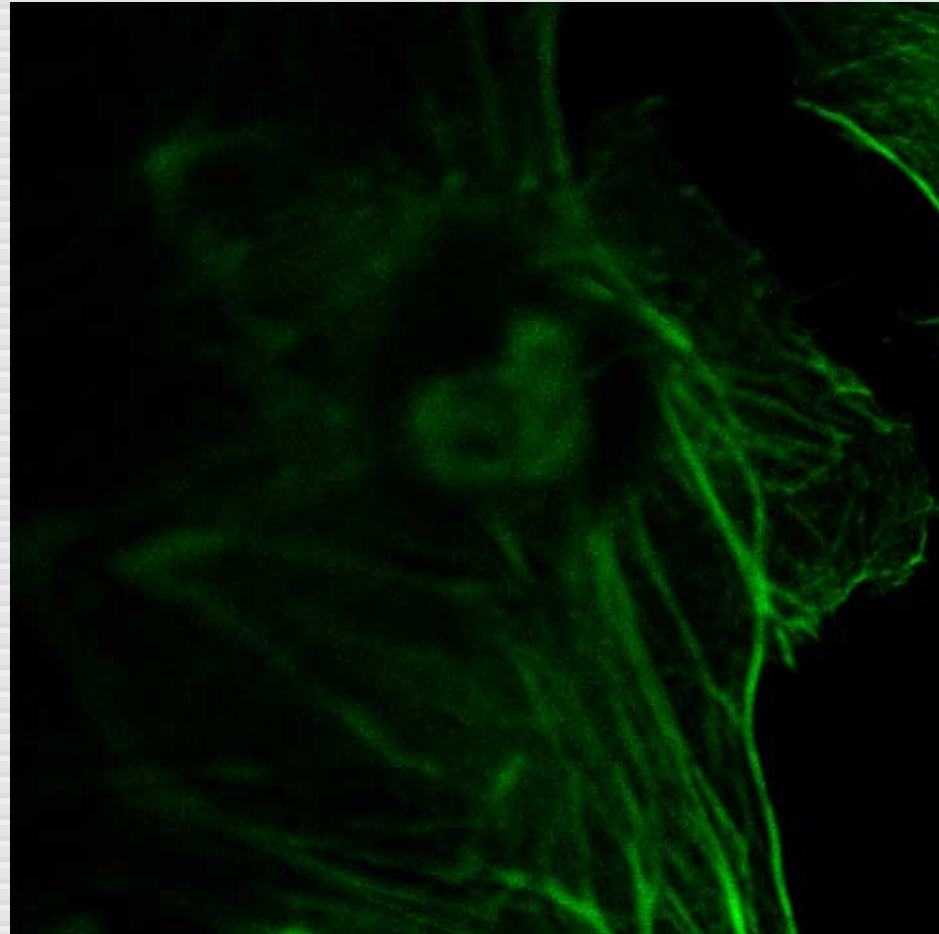
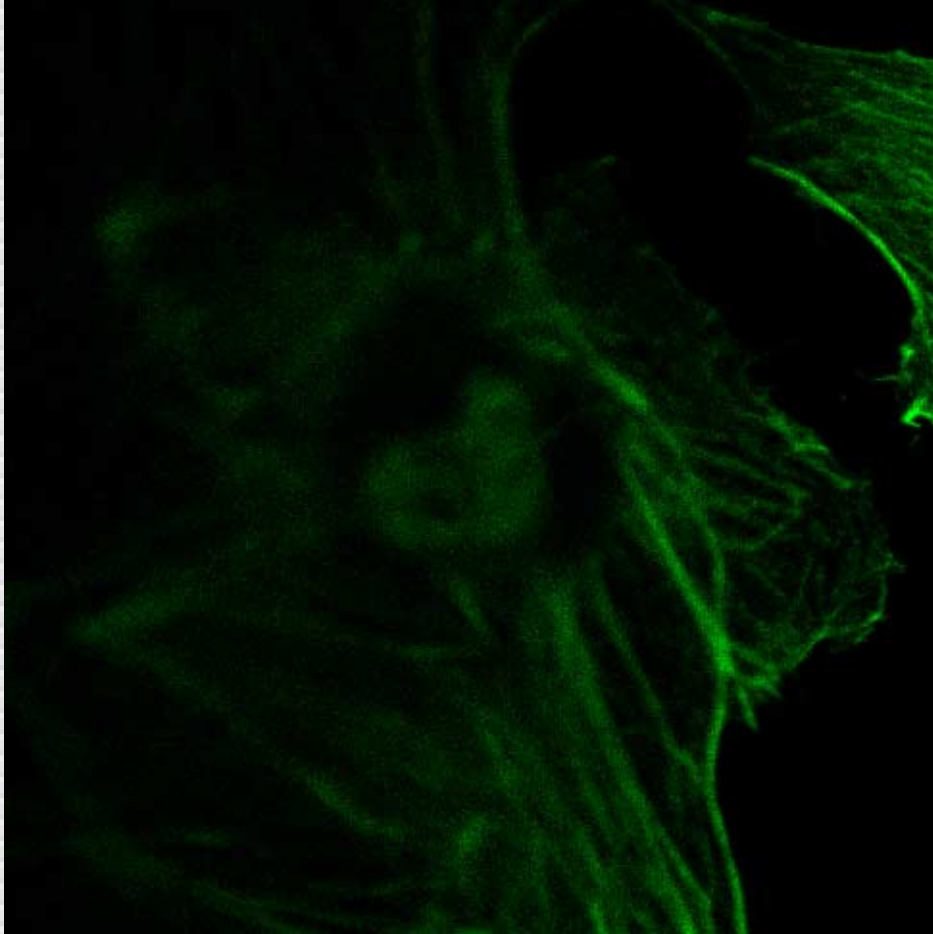
after



## *Low-energy processing*

**before**

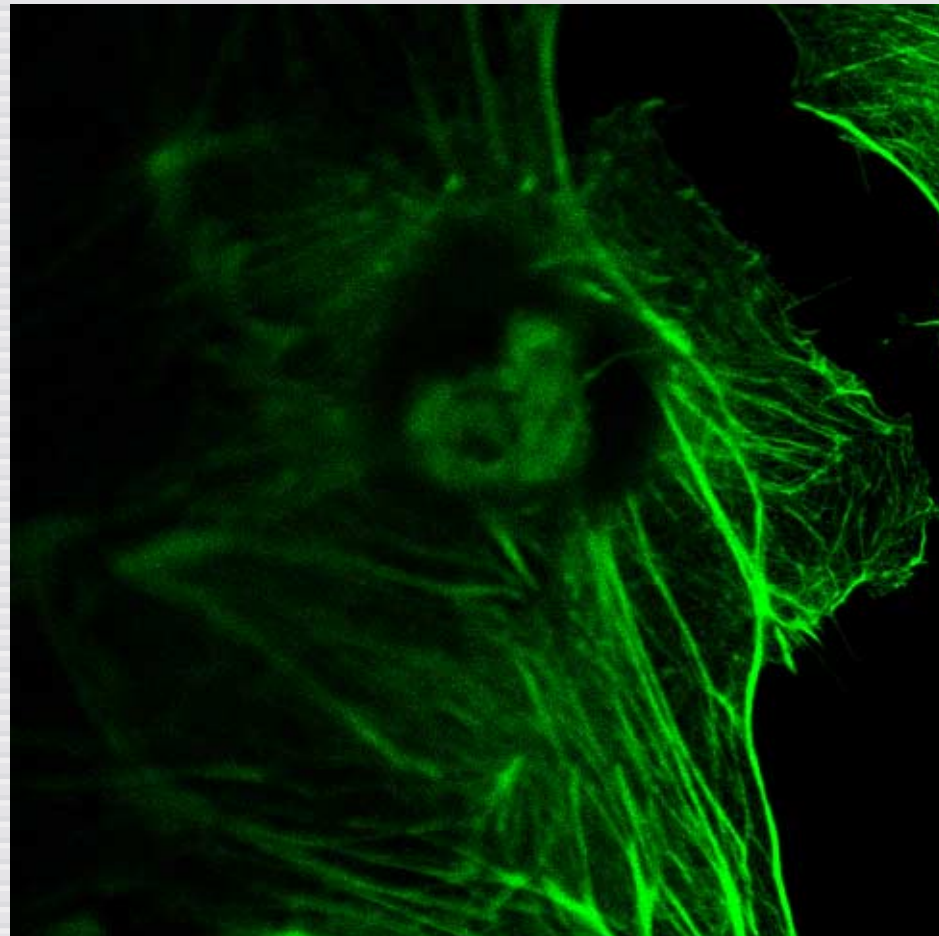
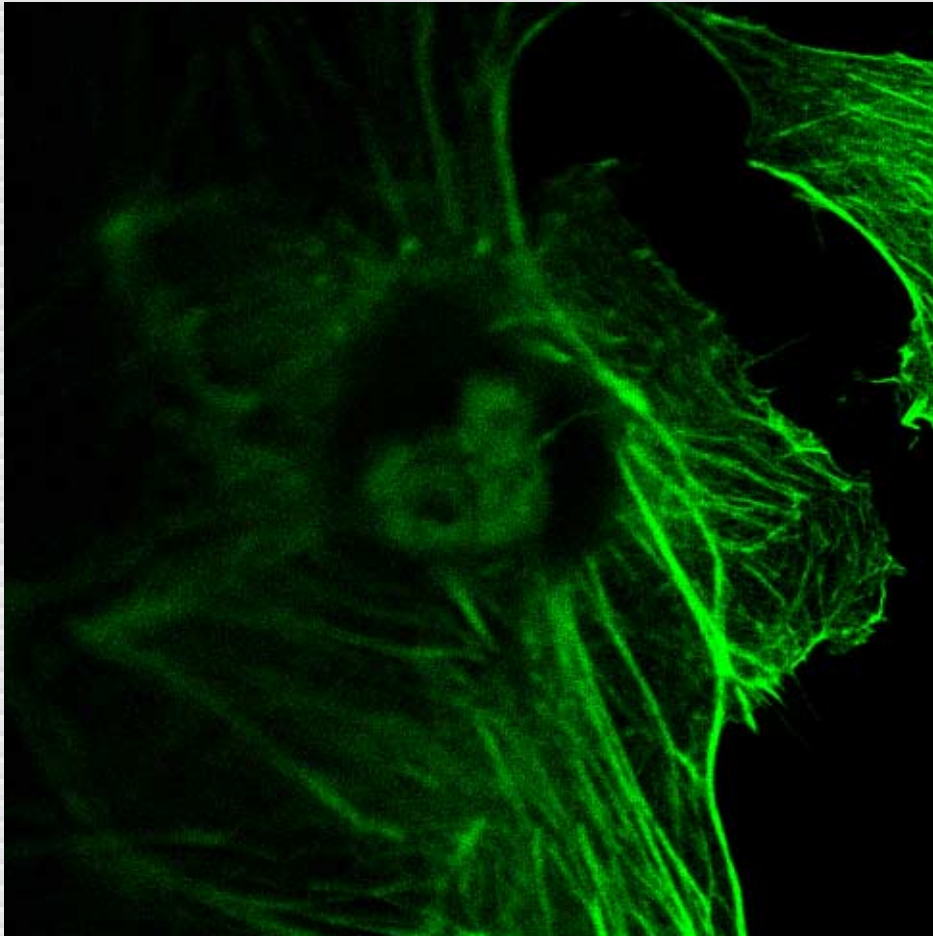
**after**



## *Low-energy processing*

**before**

**after**

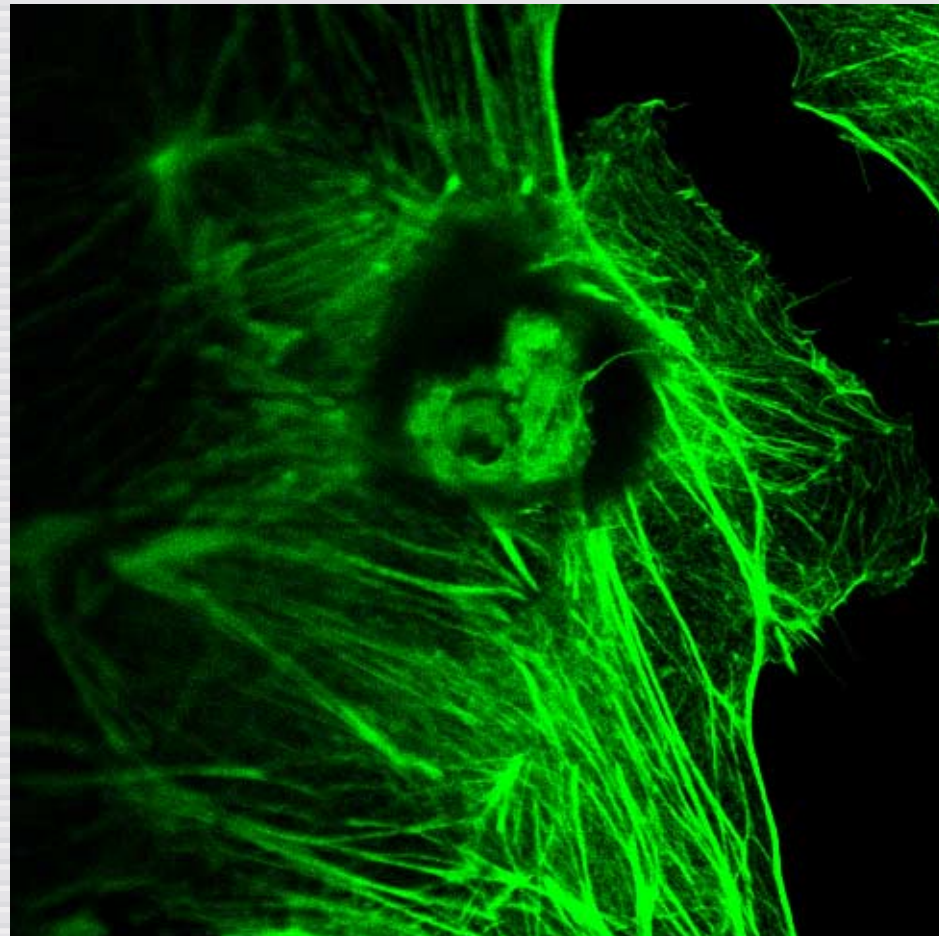
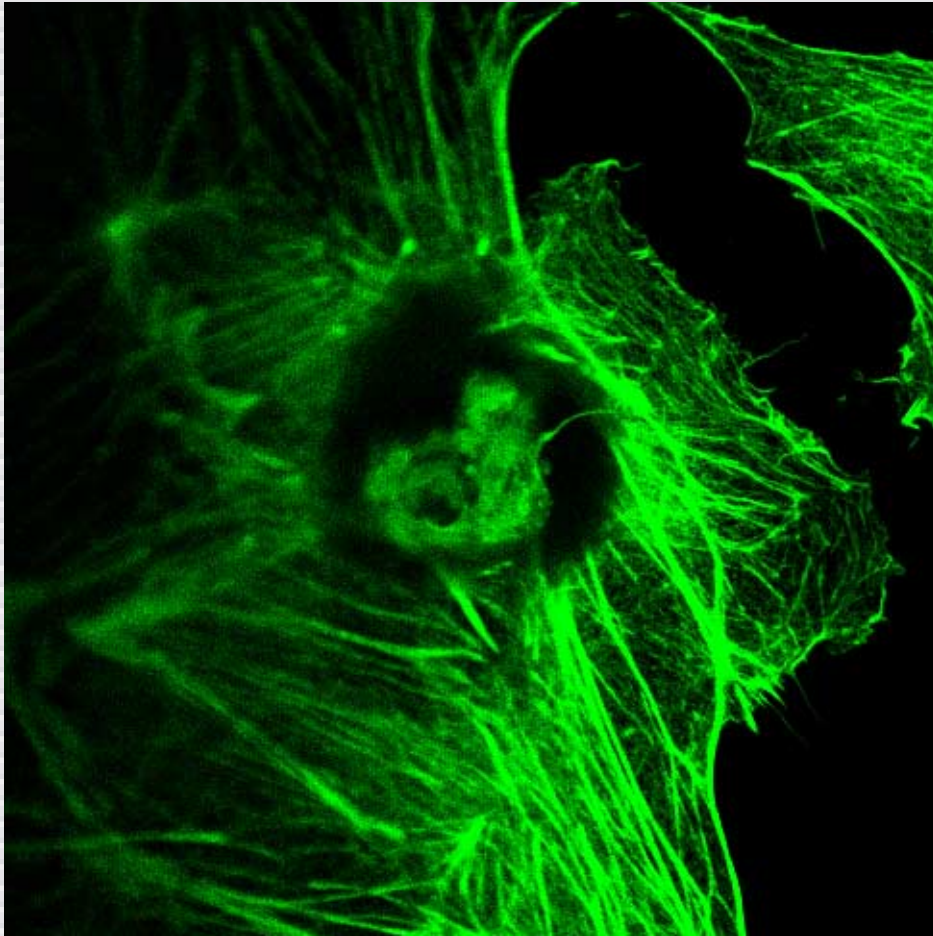




## *Low-energy processing*

before

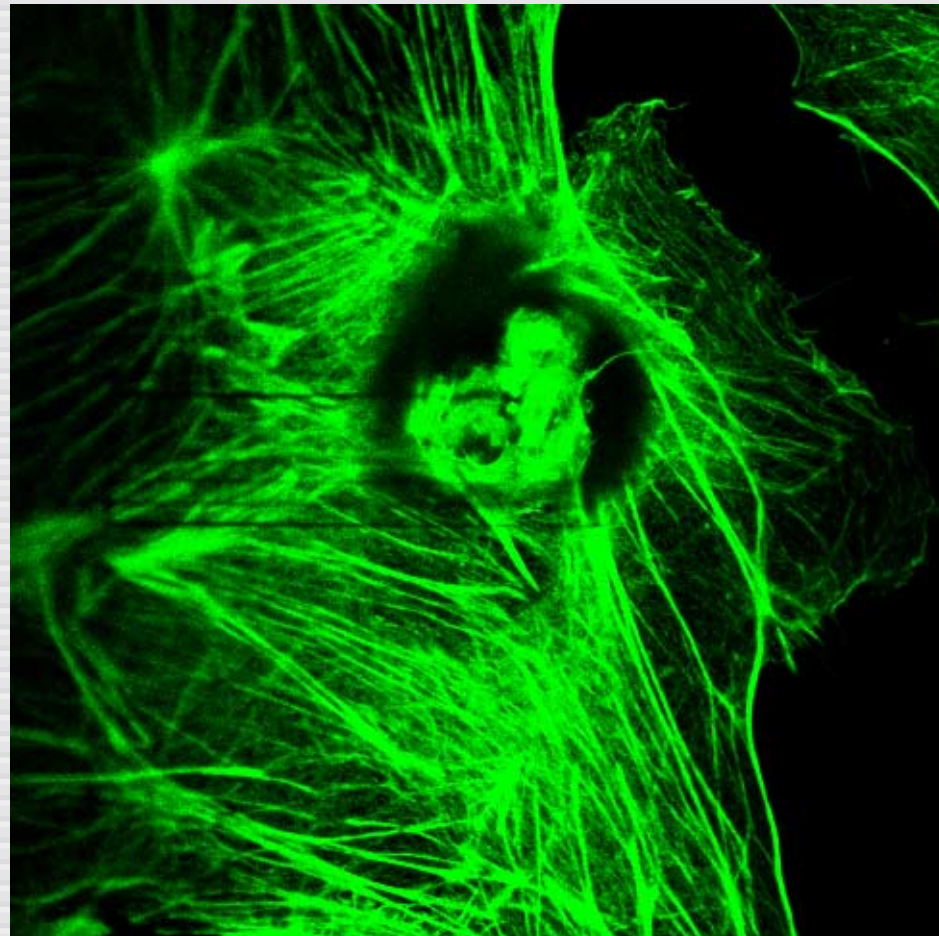
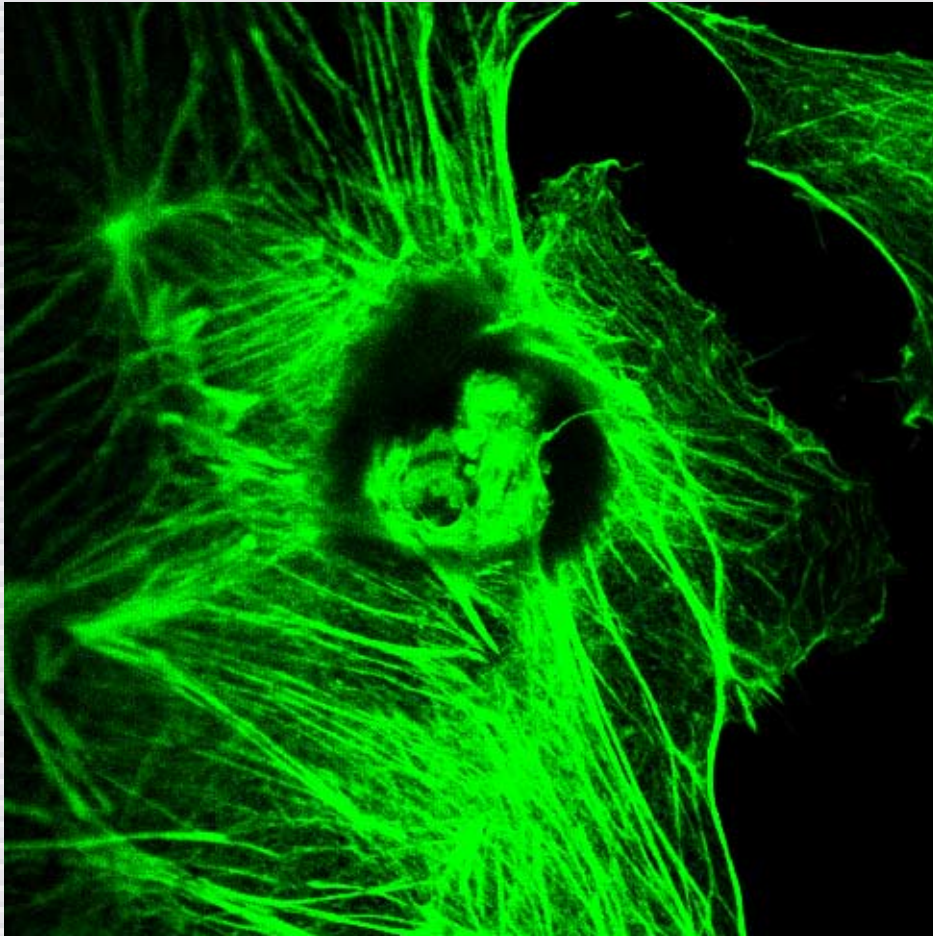
after



## *Low-energy processing*

before

after

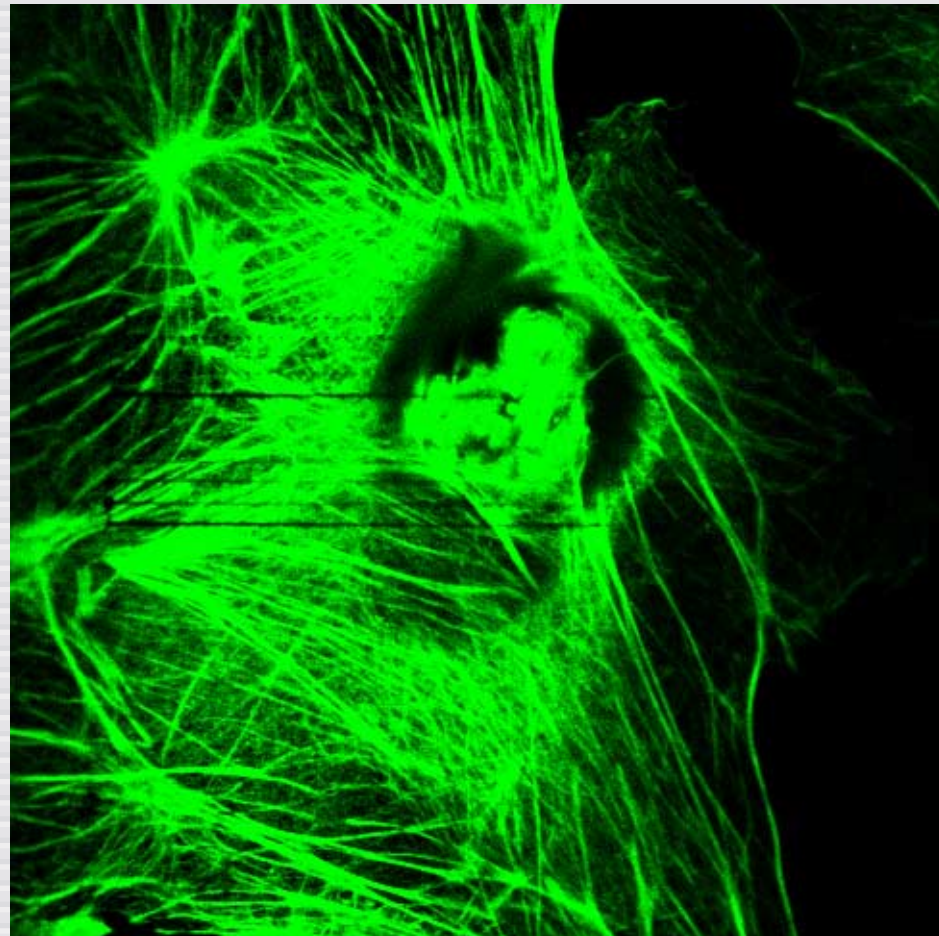
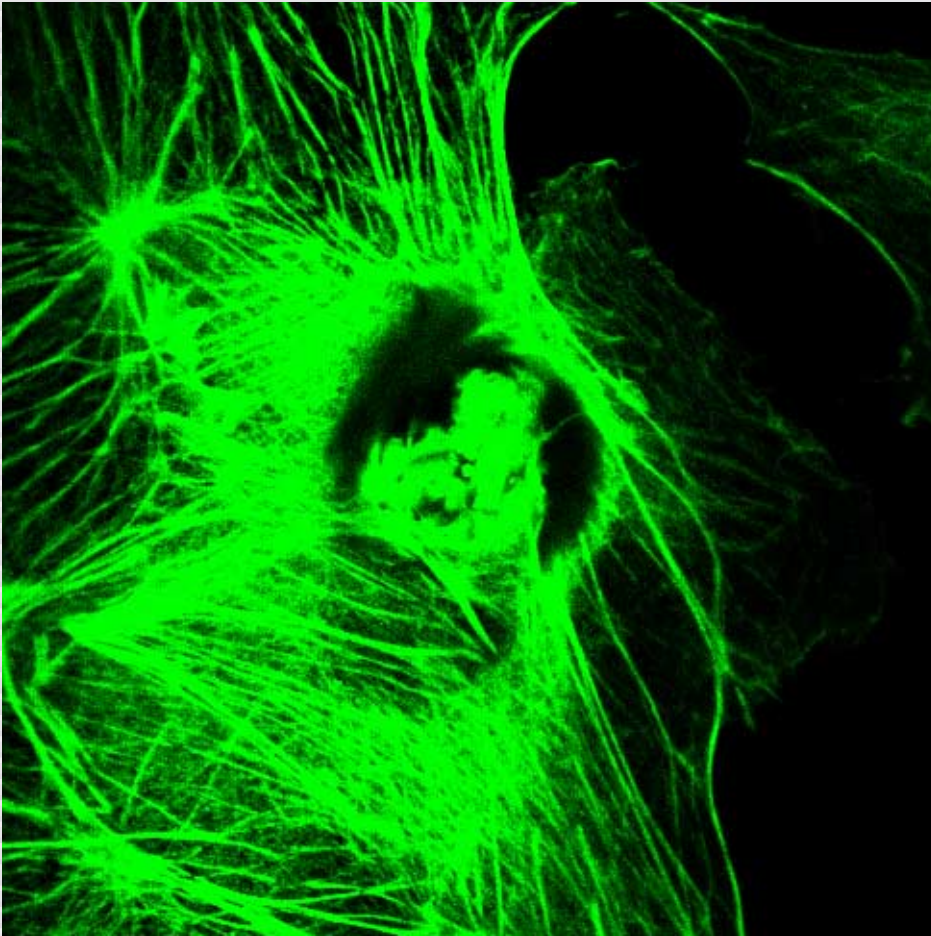




## *Low-energy processing*

**before**

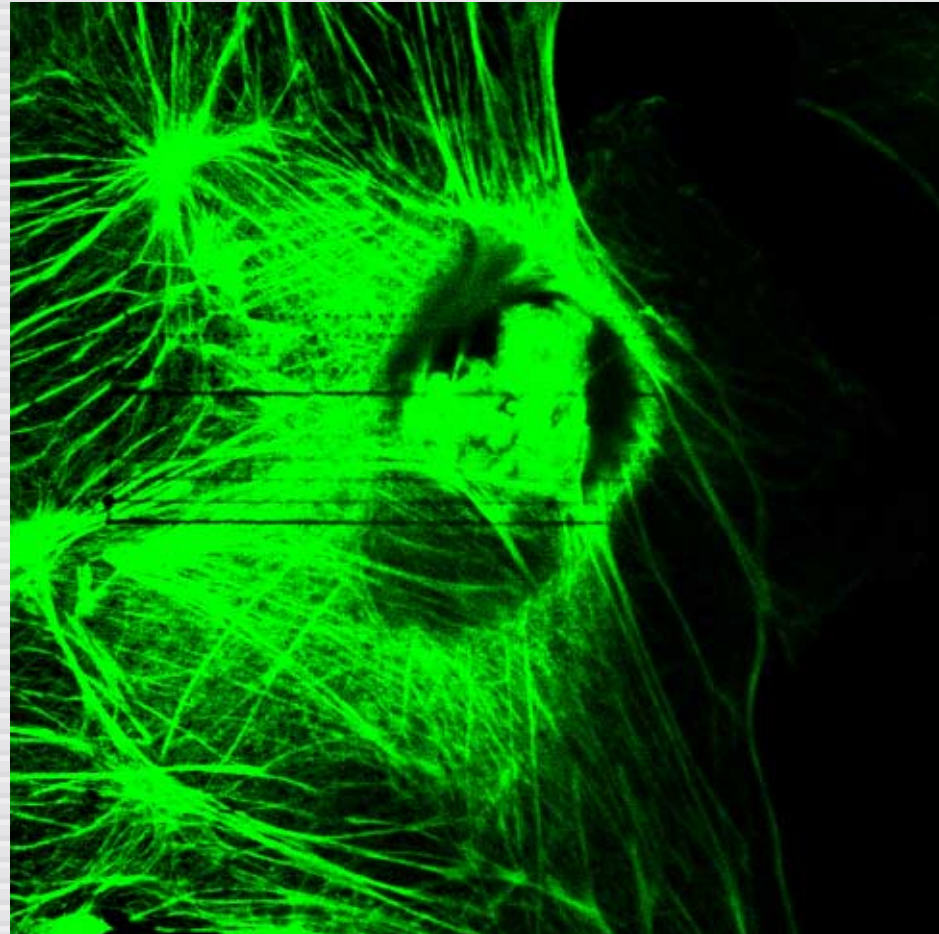
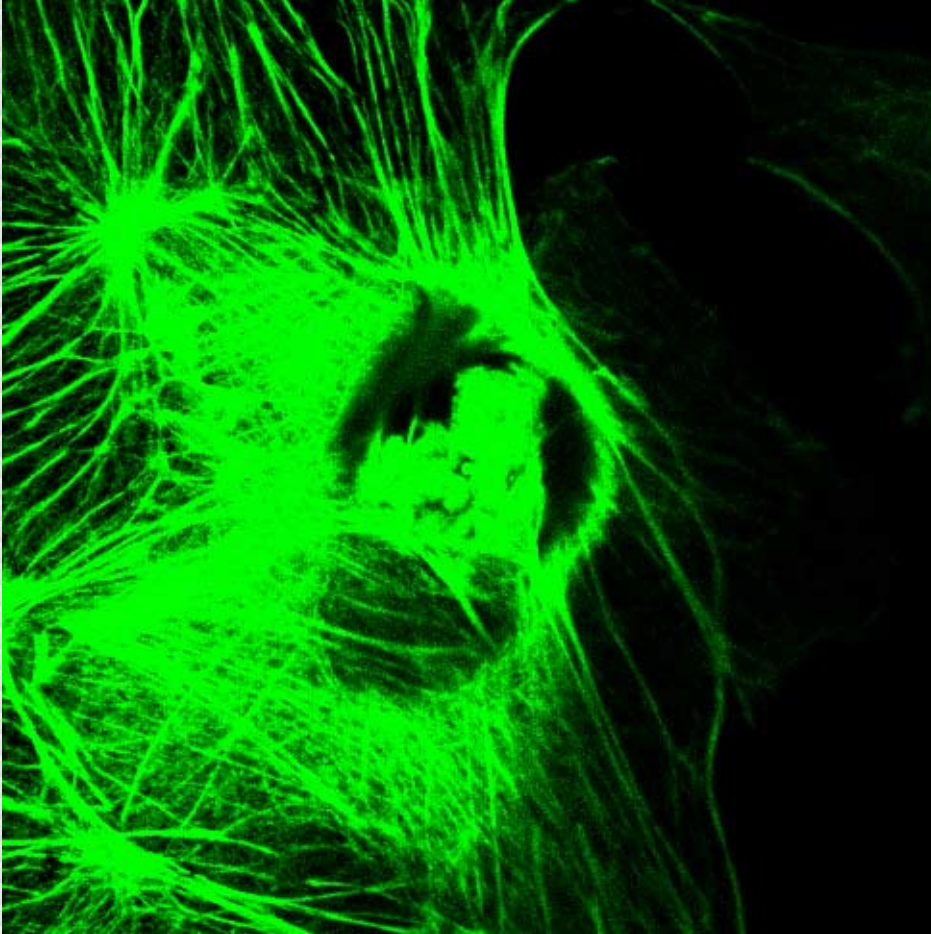
**after**



## *Low-energy processing*

before

after

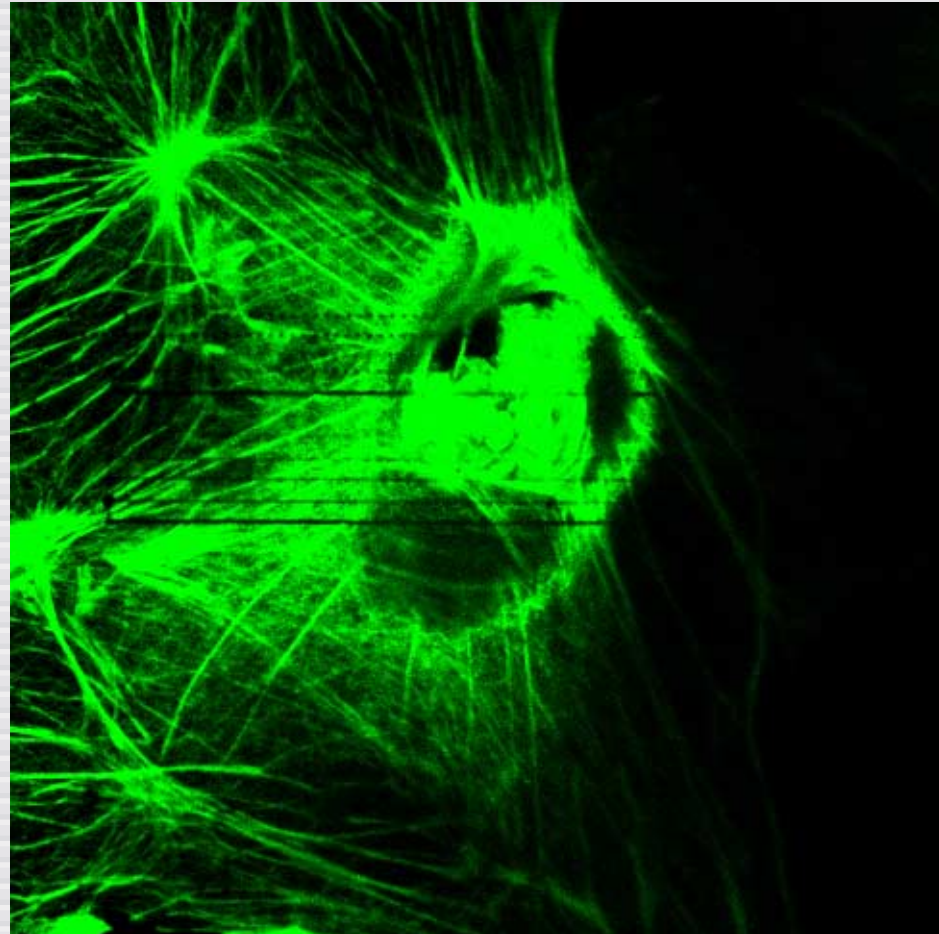
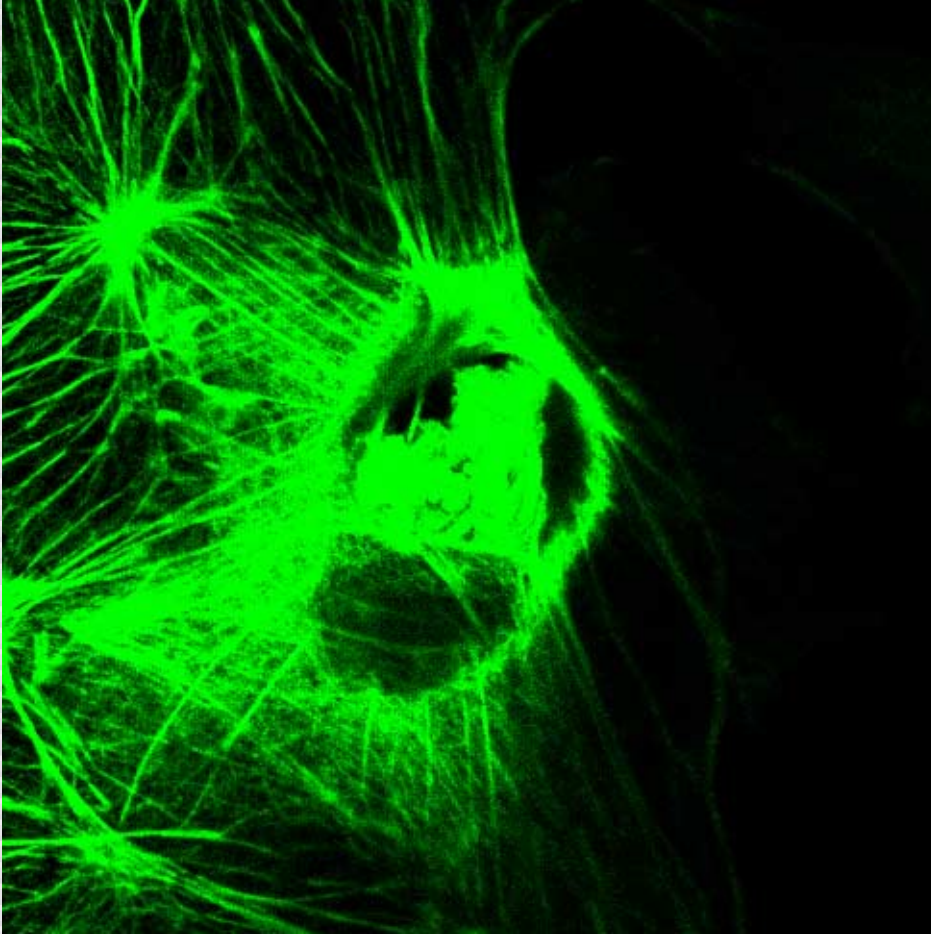




## *Low-energy processing*

**before**

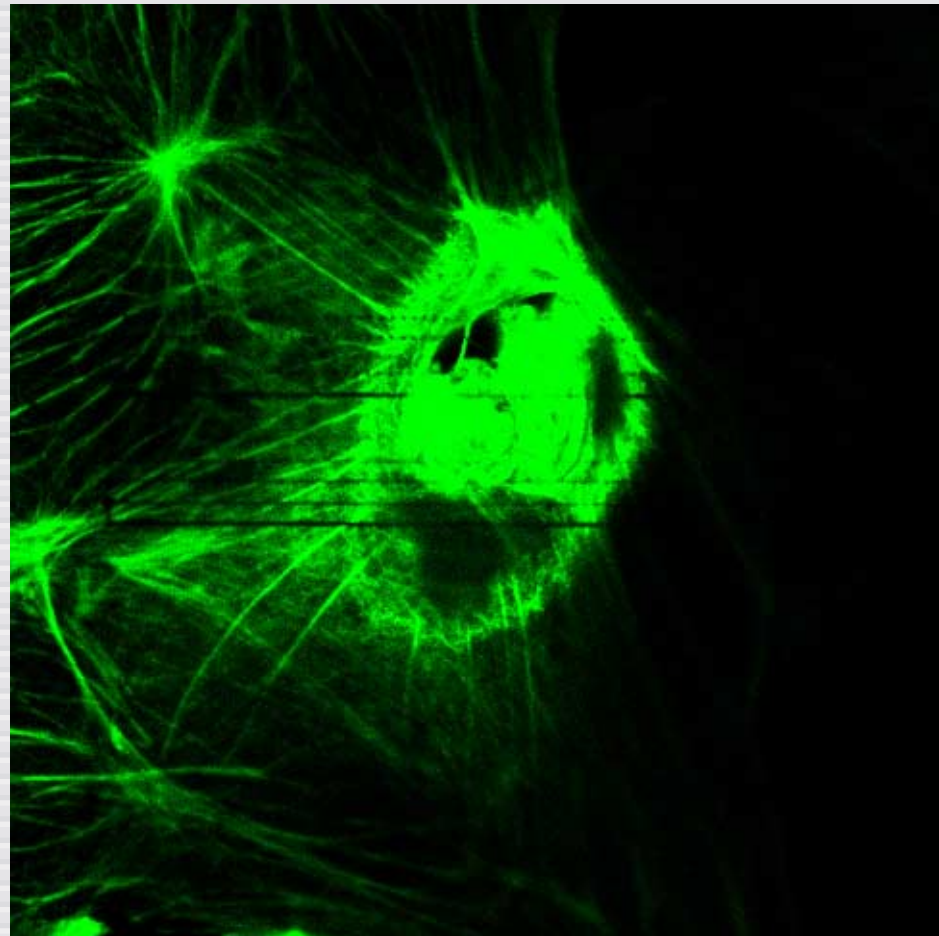
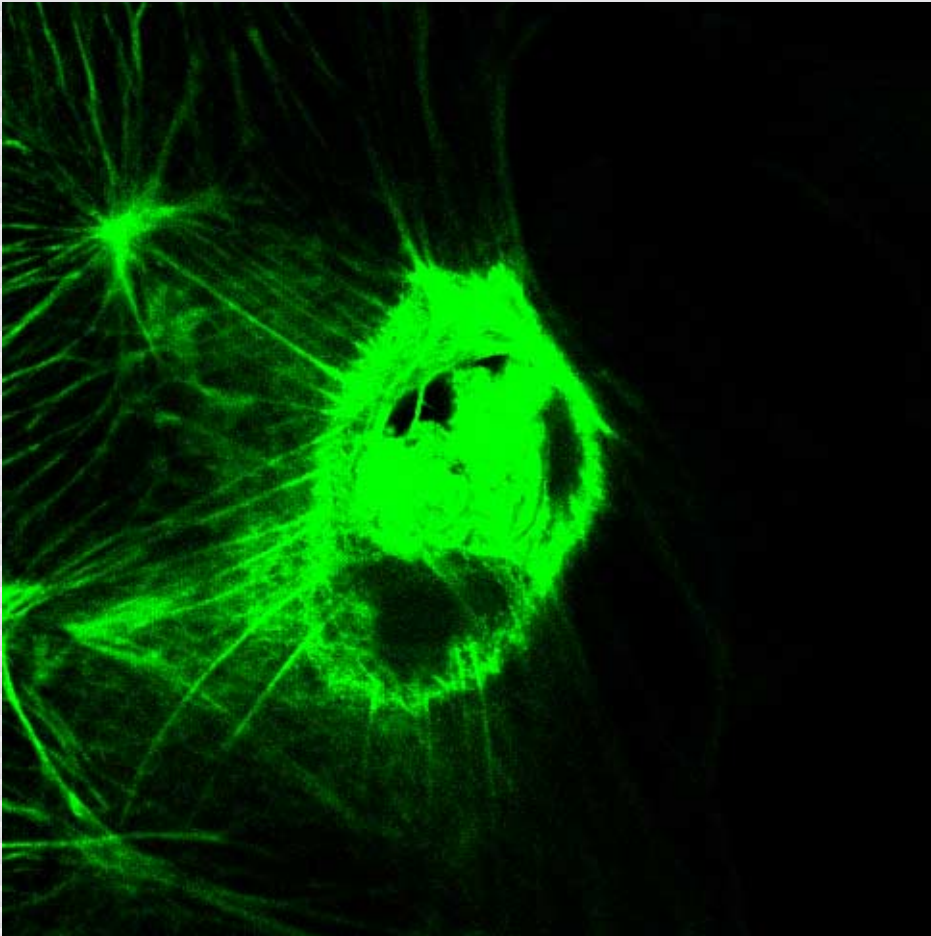
**after**



## *Low-energy processing*

before

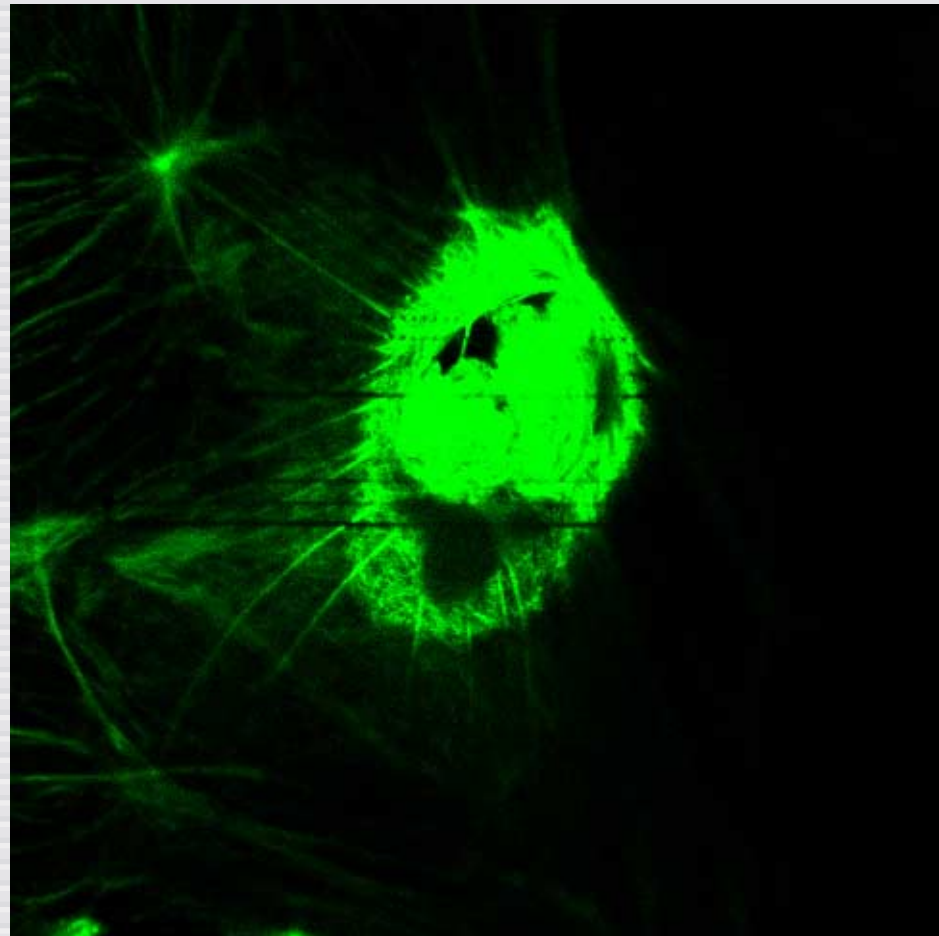
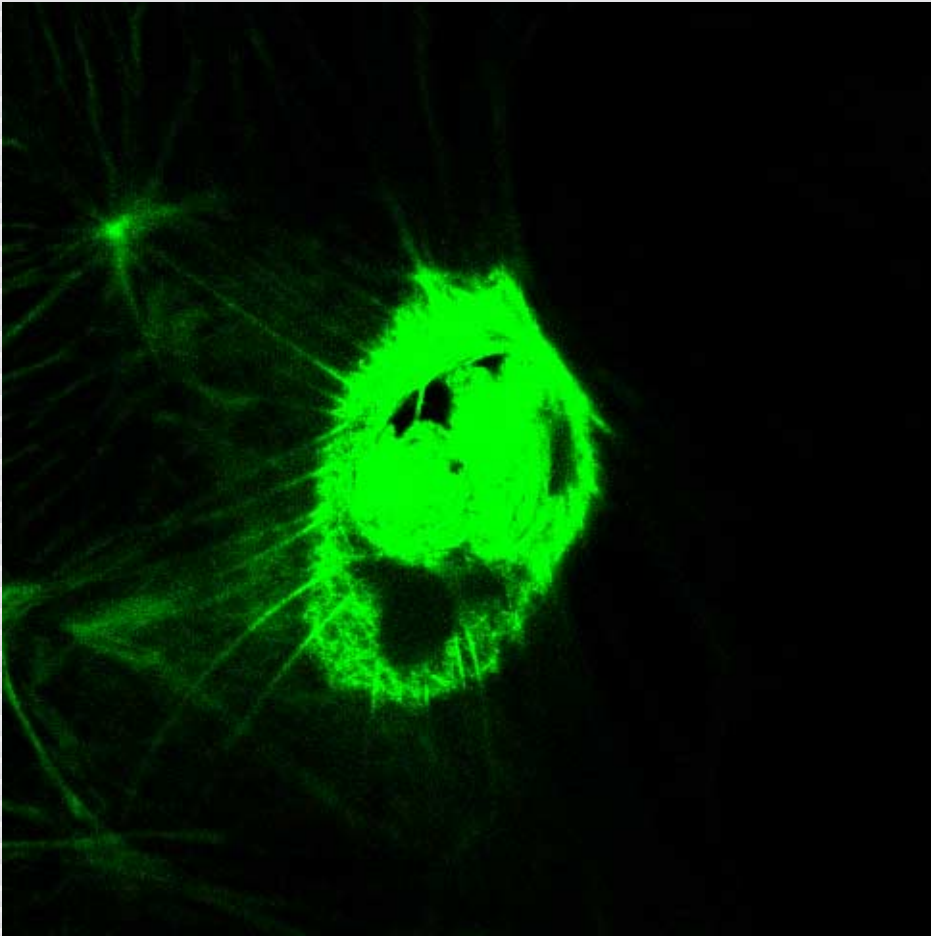
after



## *Low-energy processing*

before

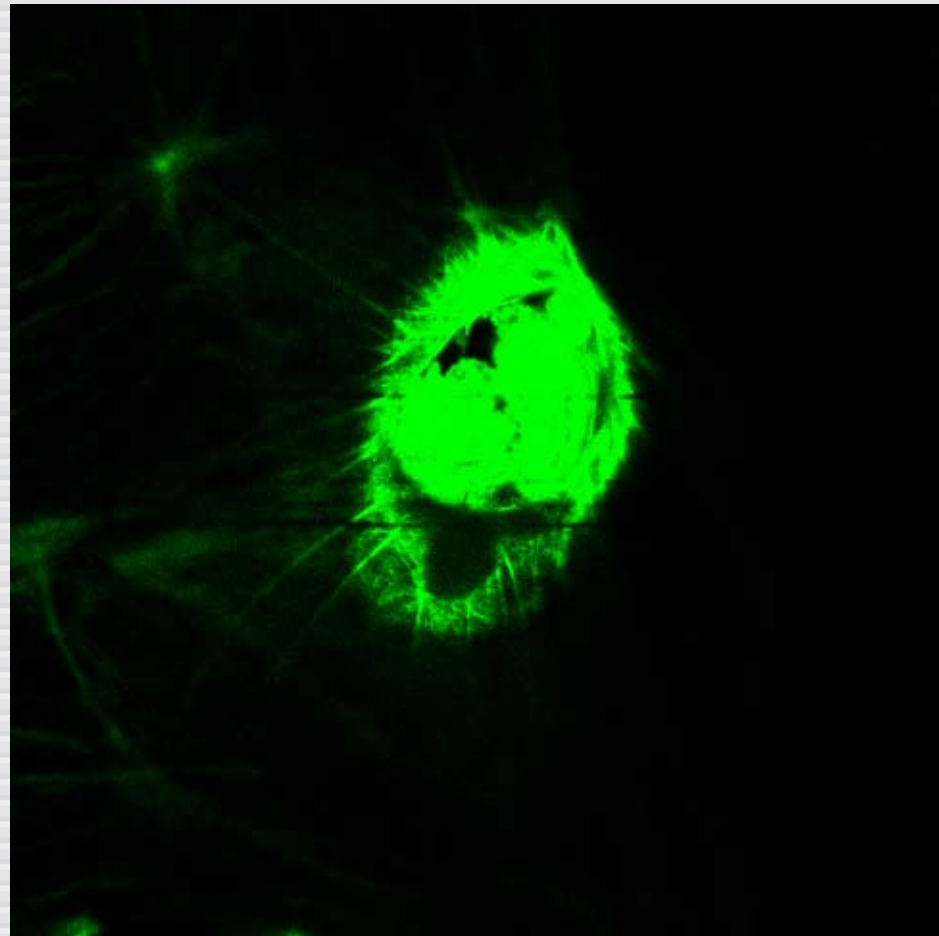
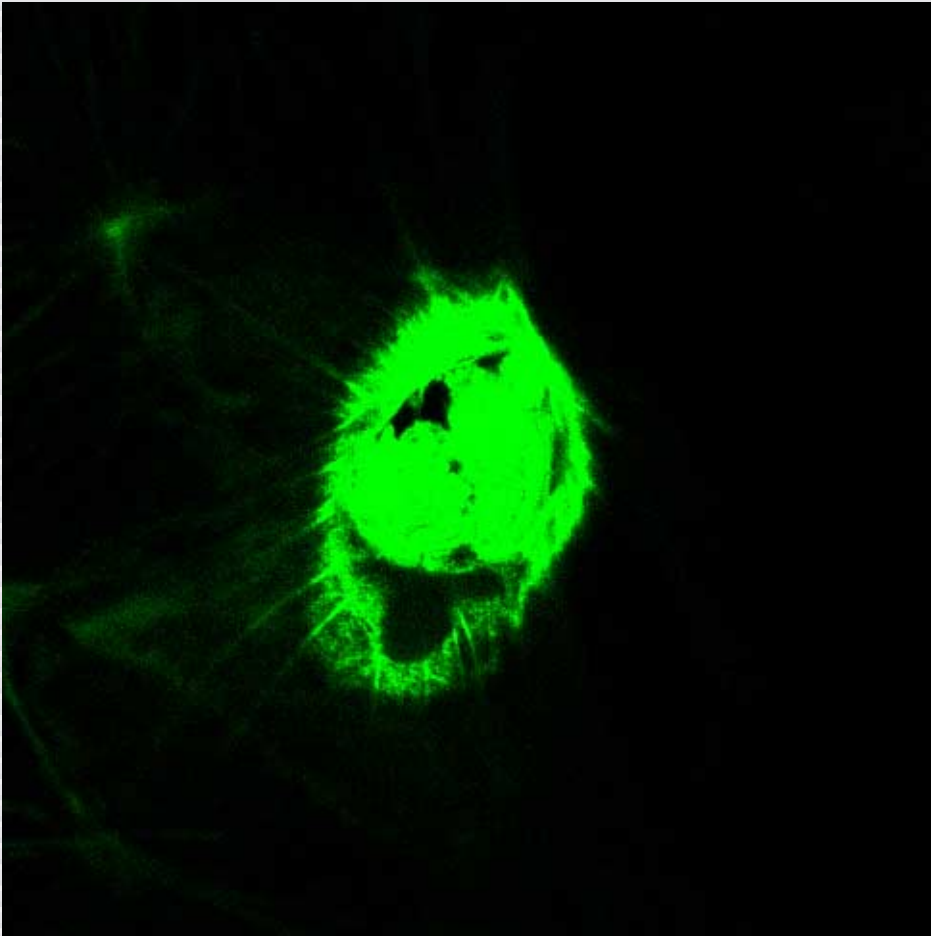
after



## *Low-energy processing*

before

after

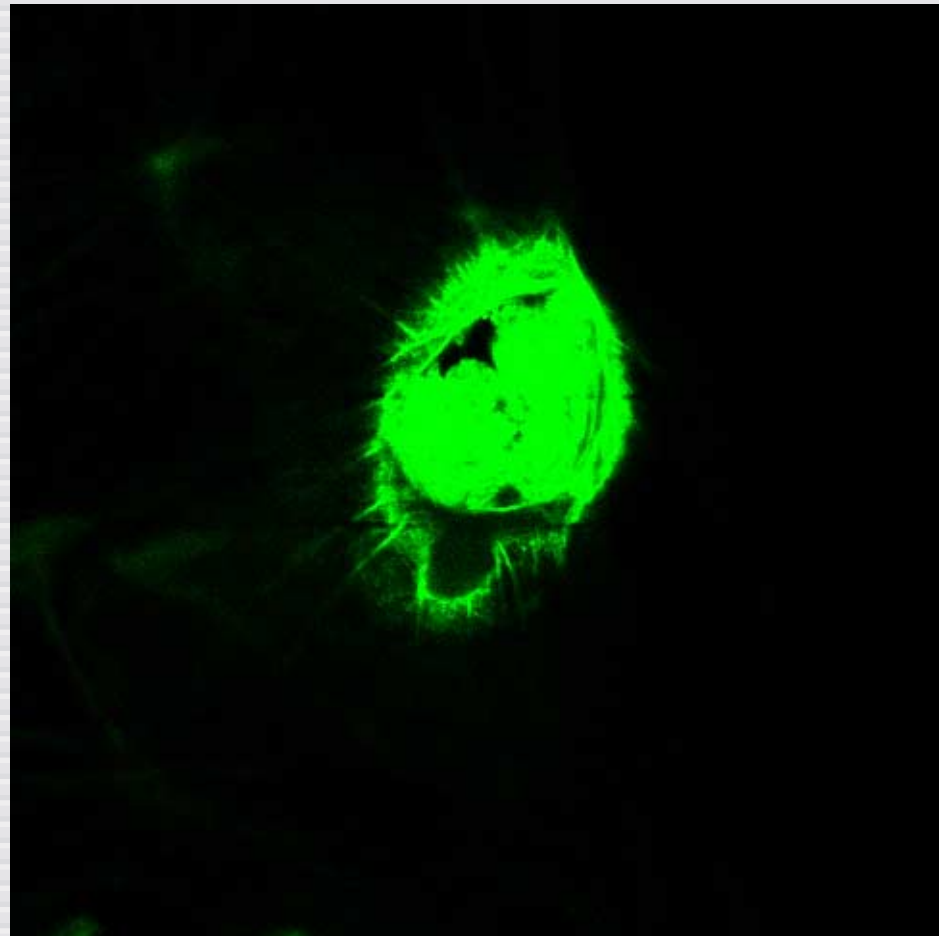
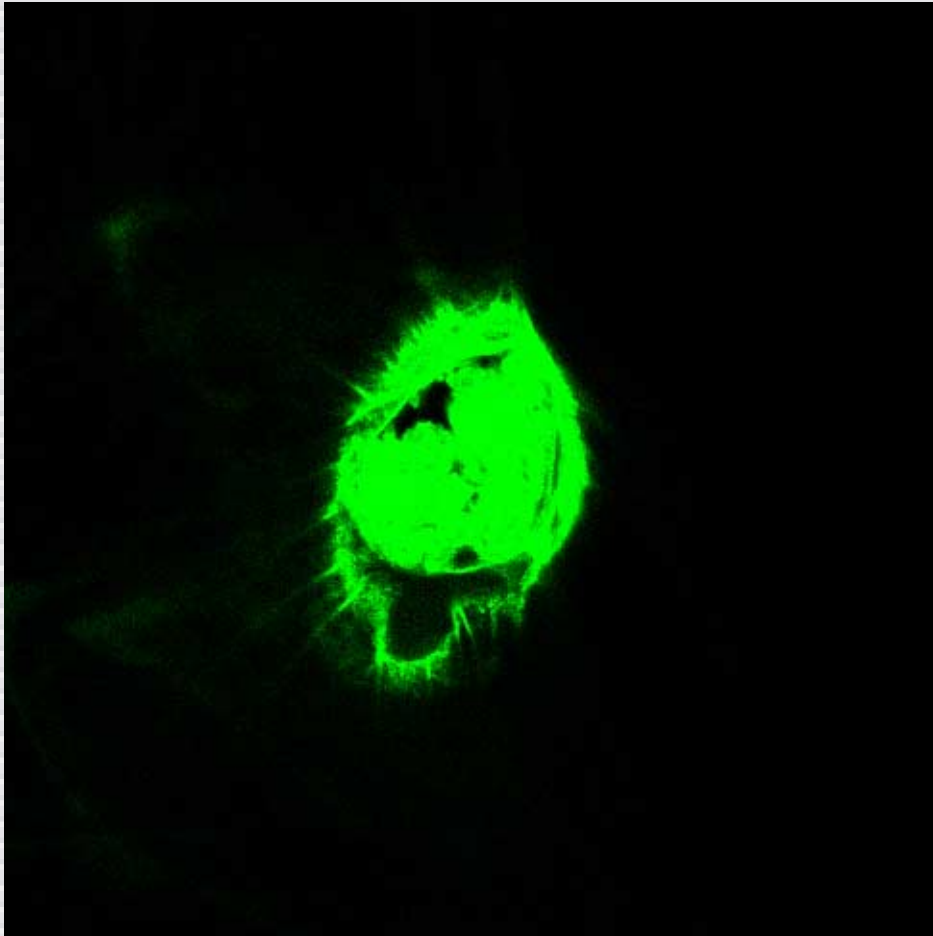




## *Low-energy processing*

before

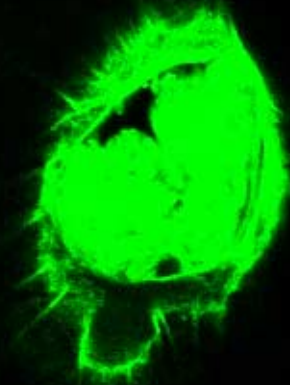
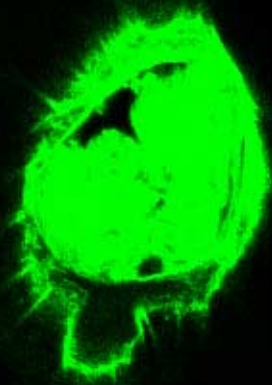
after



## *Low-energy processing*

before

after

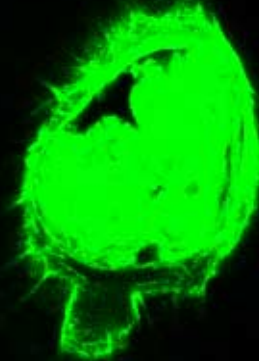
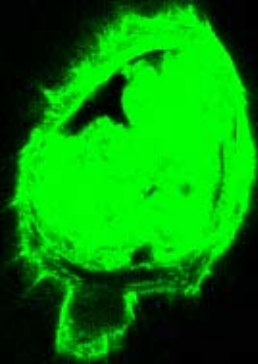




## *Low-energy processing*

before

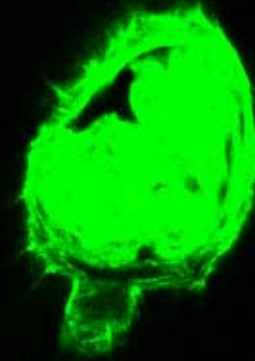
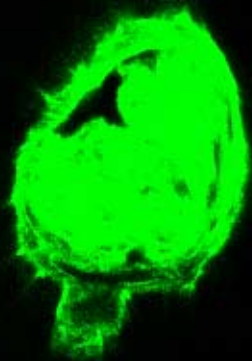
after



## *Low-energy processing*

**before**

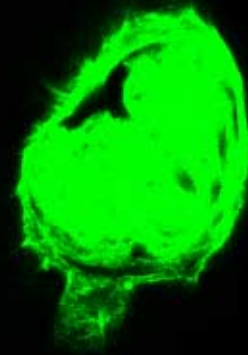
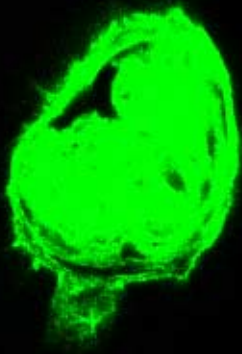
**after**



## *Low-energy processing*

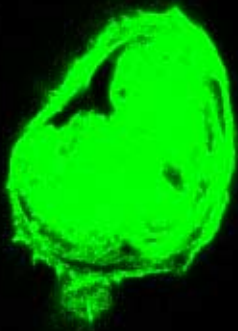
**before**

**after**

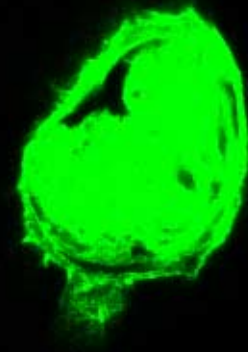


## *Low-energy processing*

before

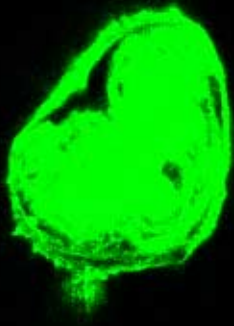


after

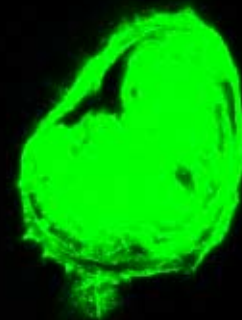


## *Low-energy processing*

**before**

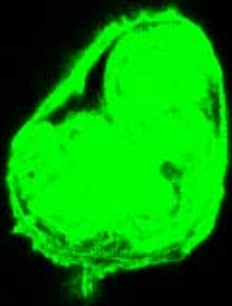


**after**

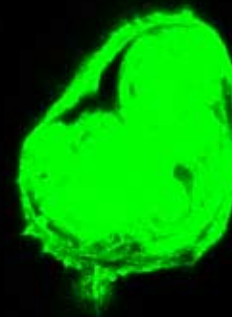


## *Low-energy processing*

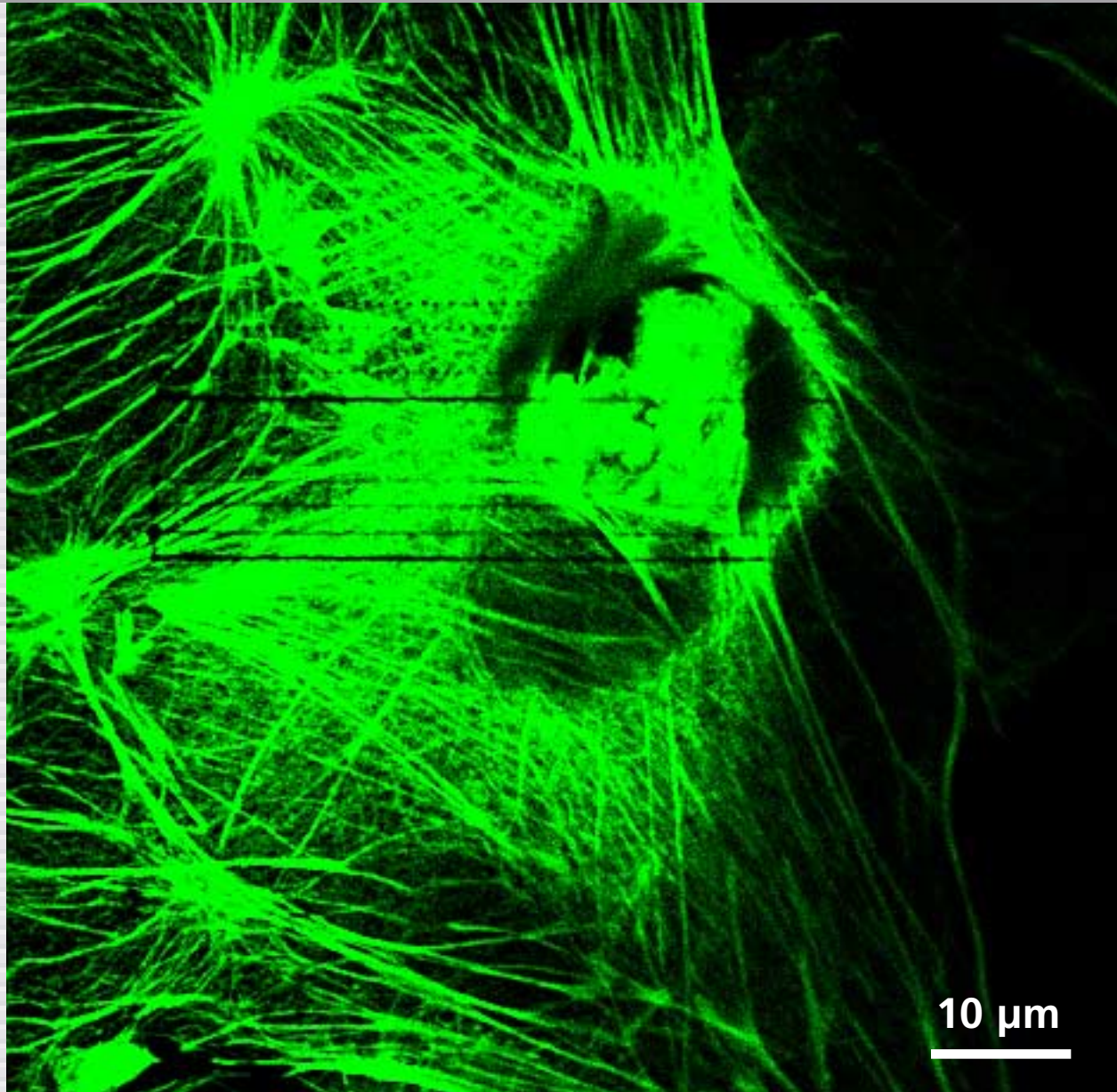
**before**



**after**

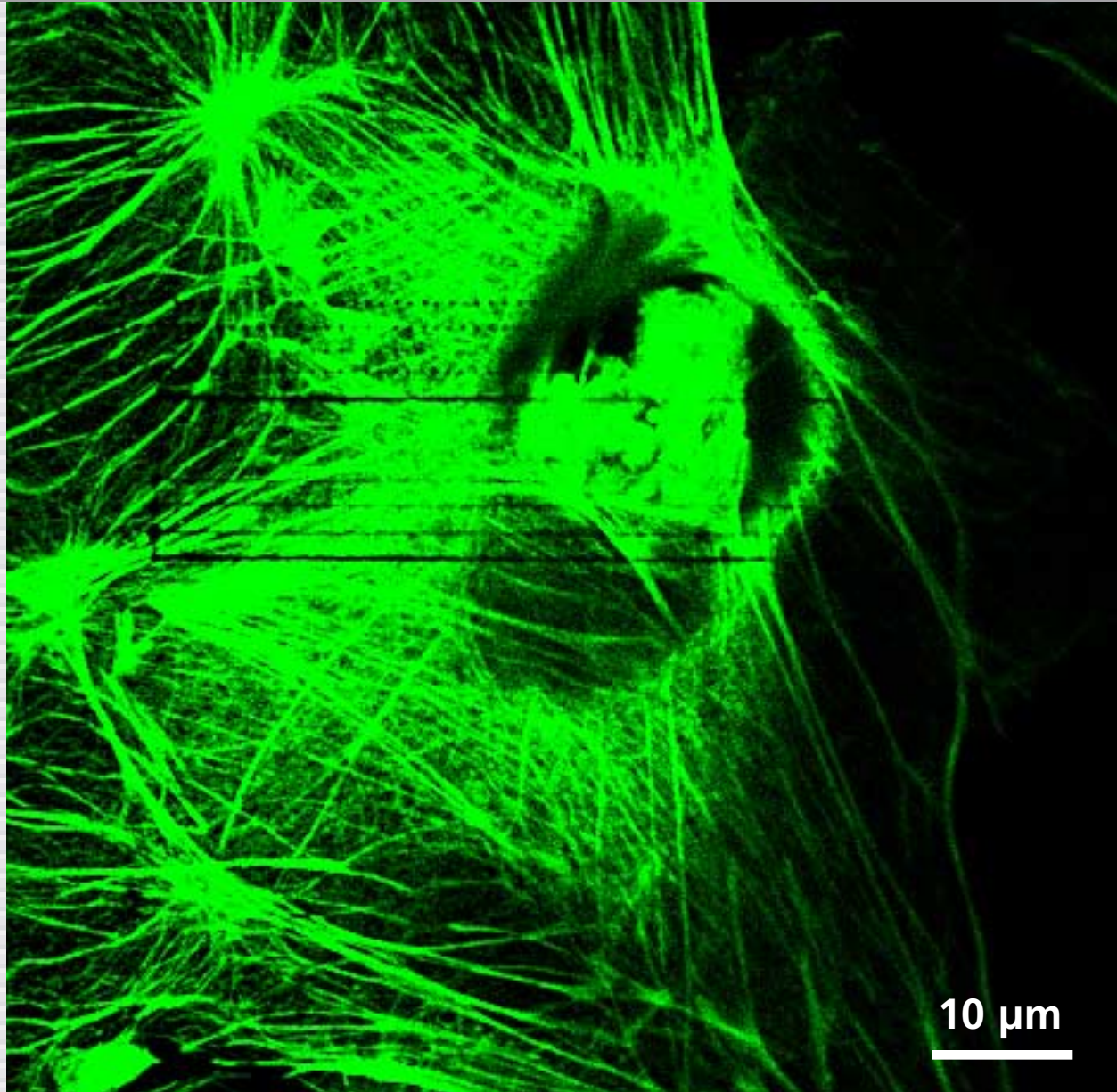


## *Low-energy processing*



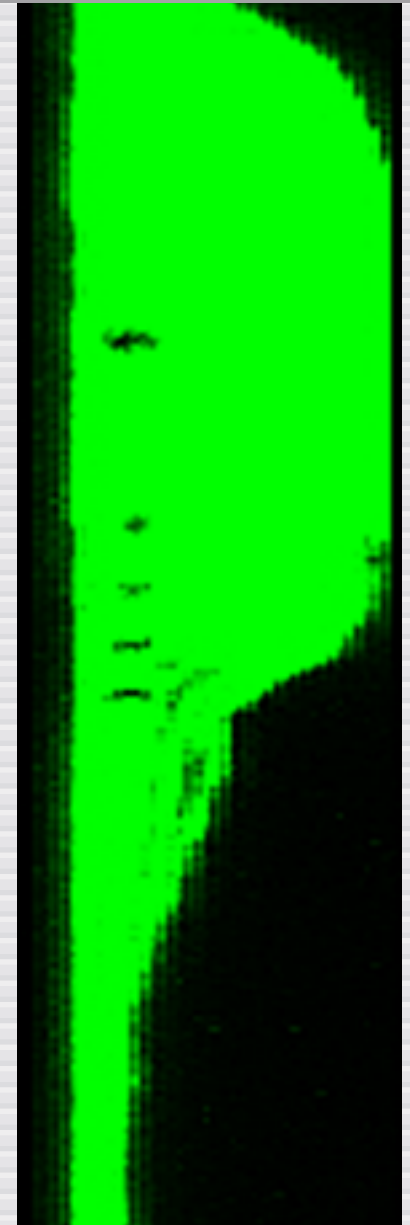
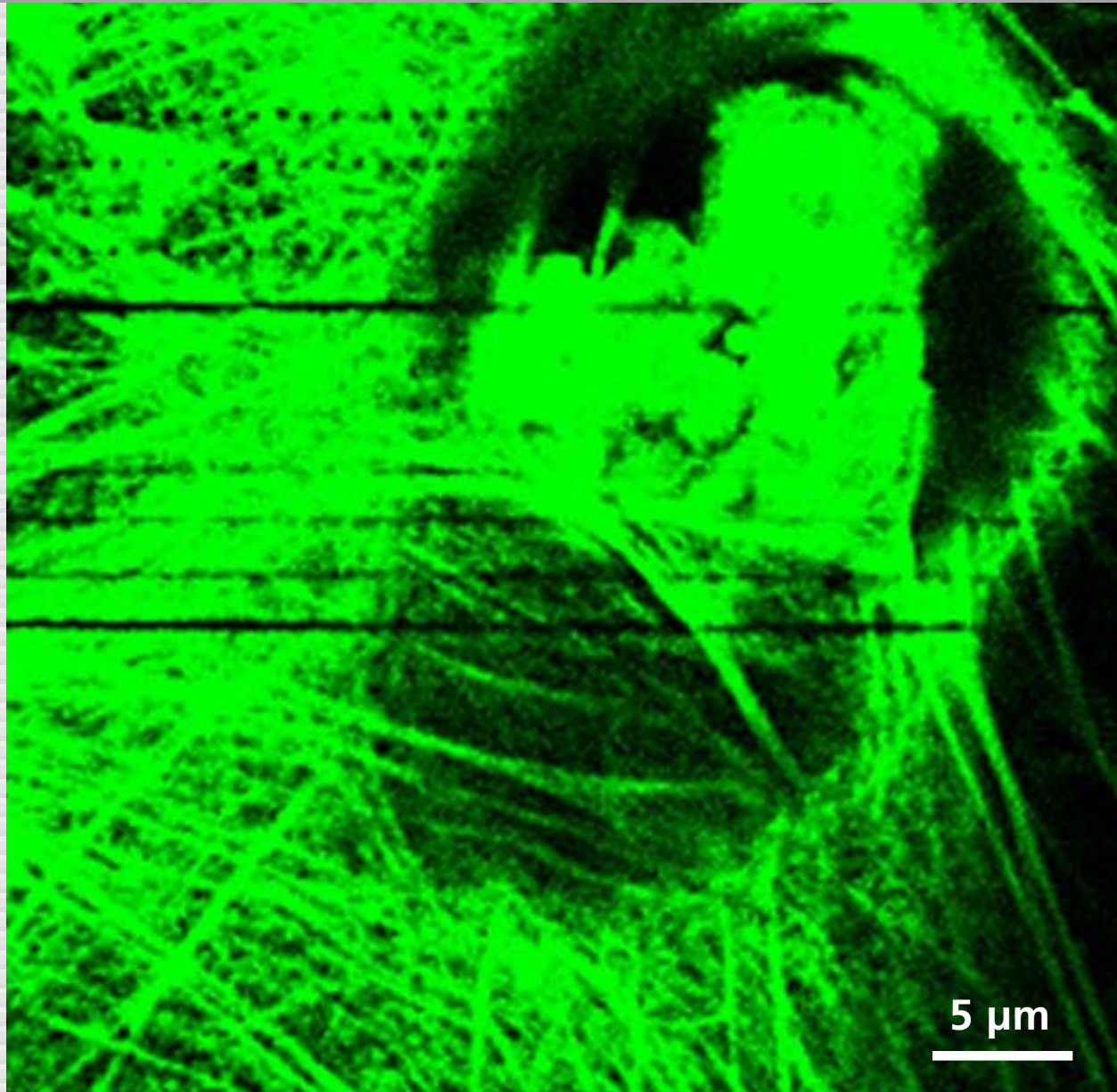


## *Low-energy processing*

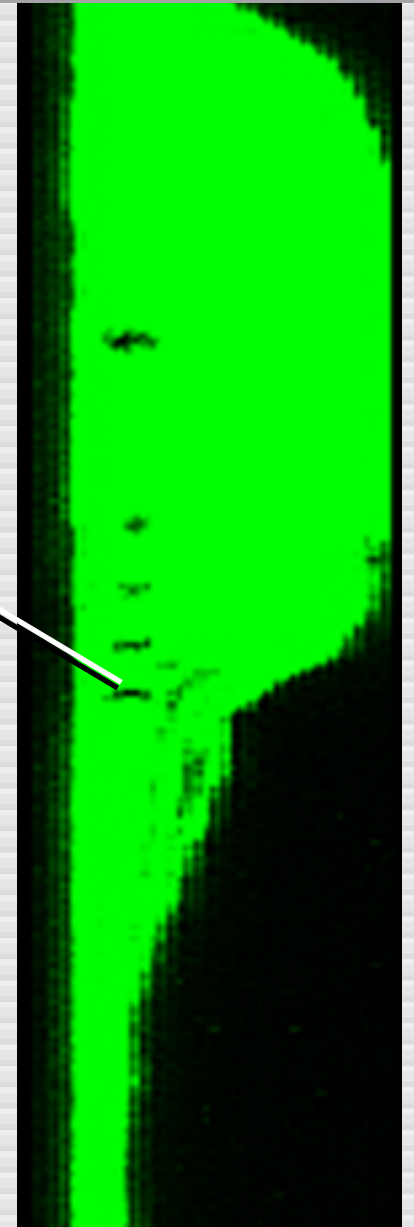
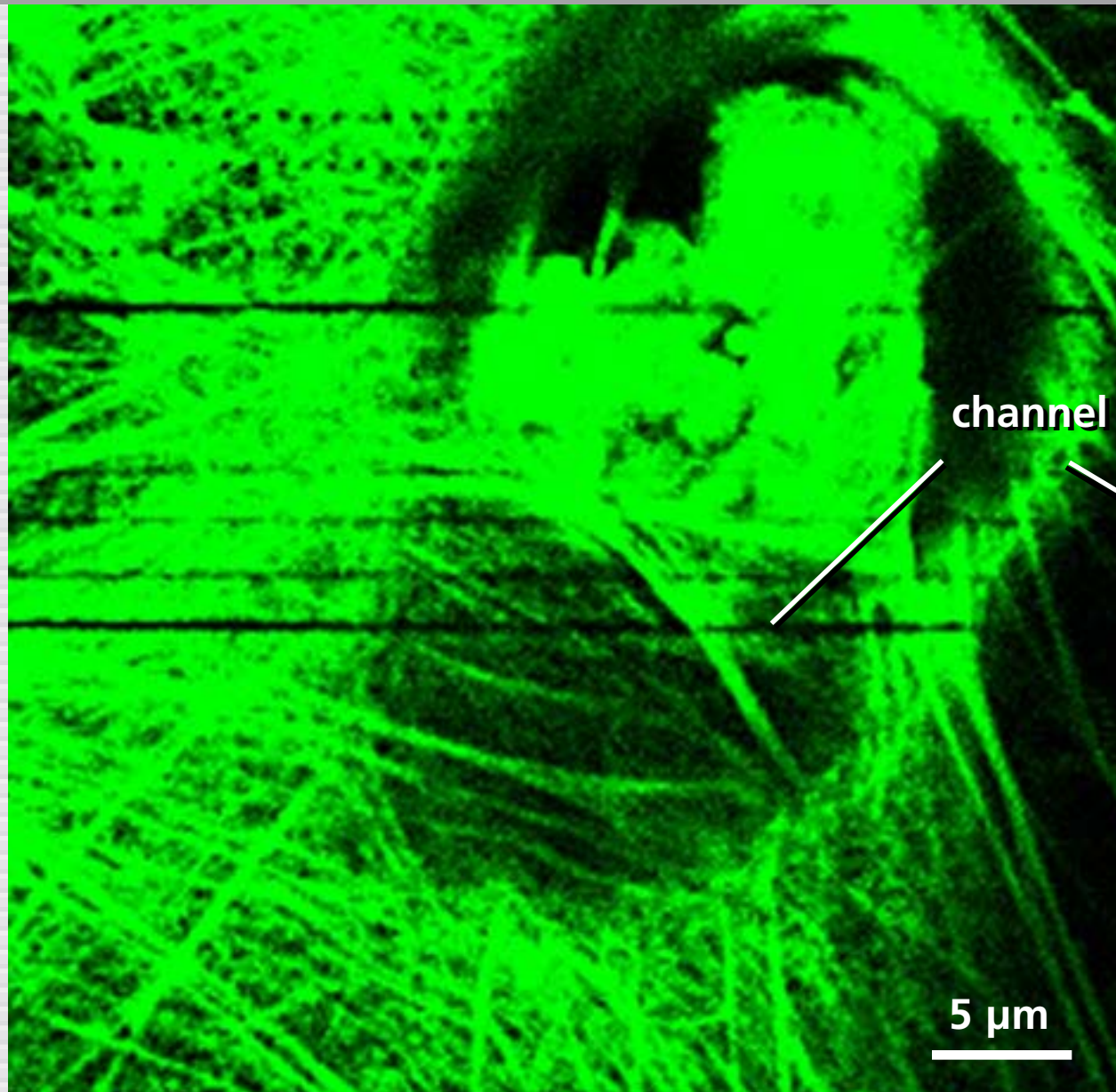




## *Low-energy processing*

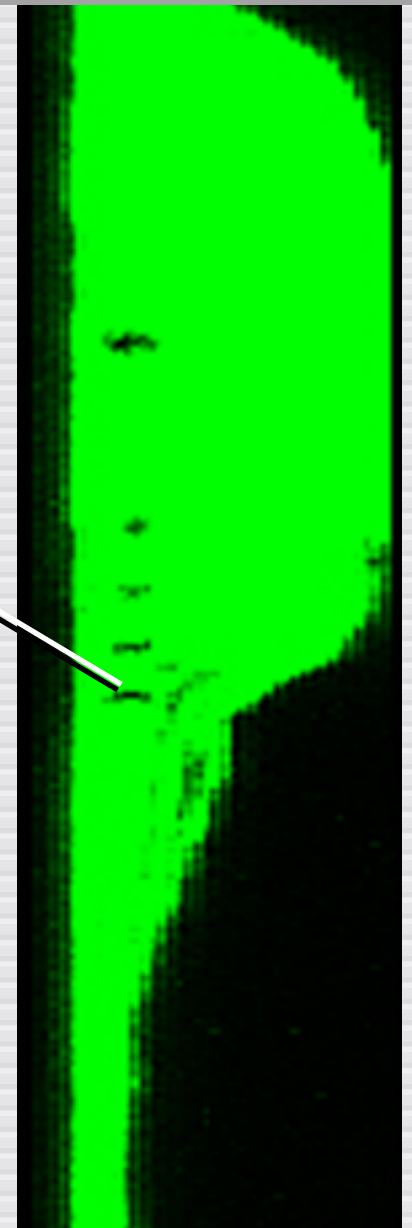
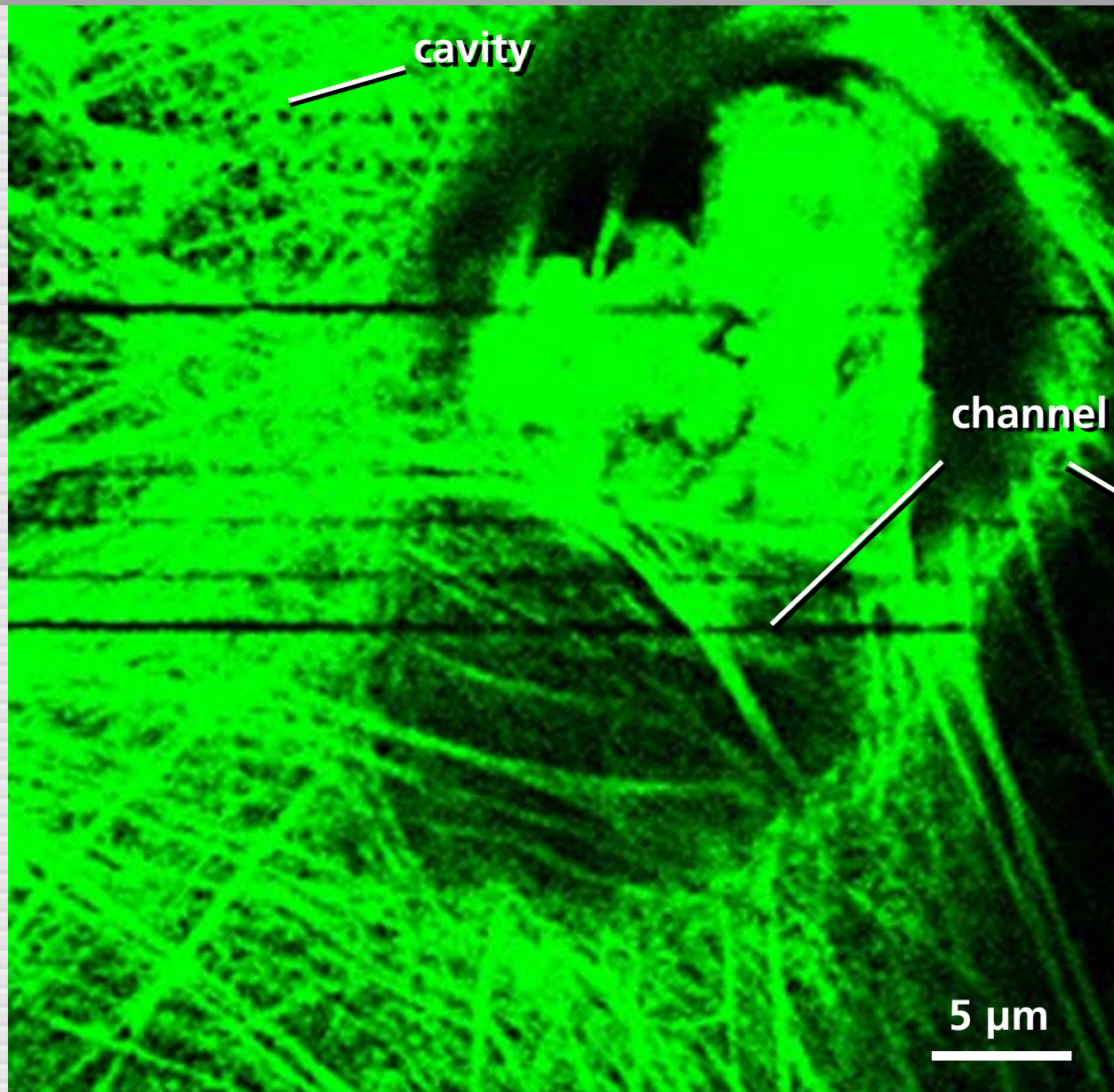


## *Low-energy processing*

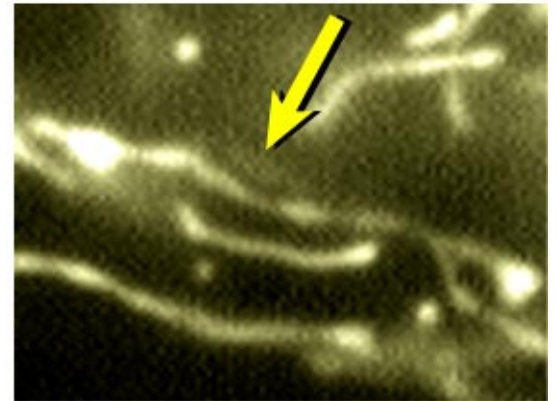
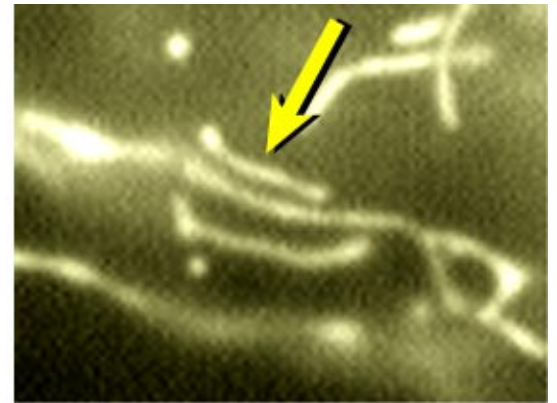
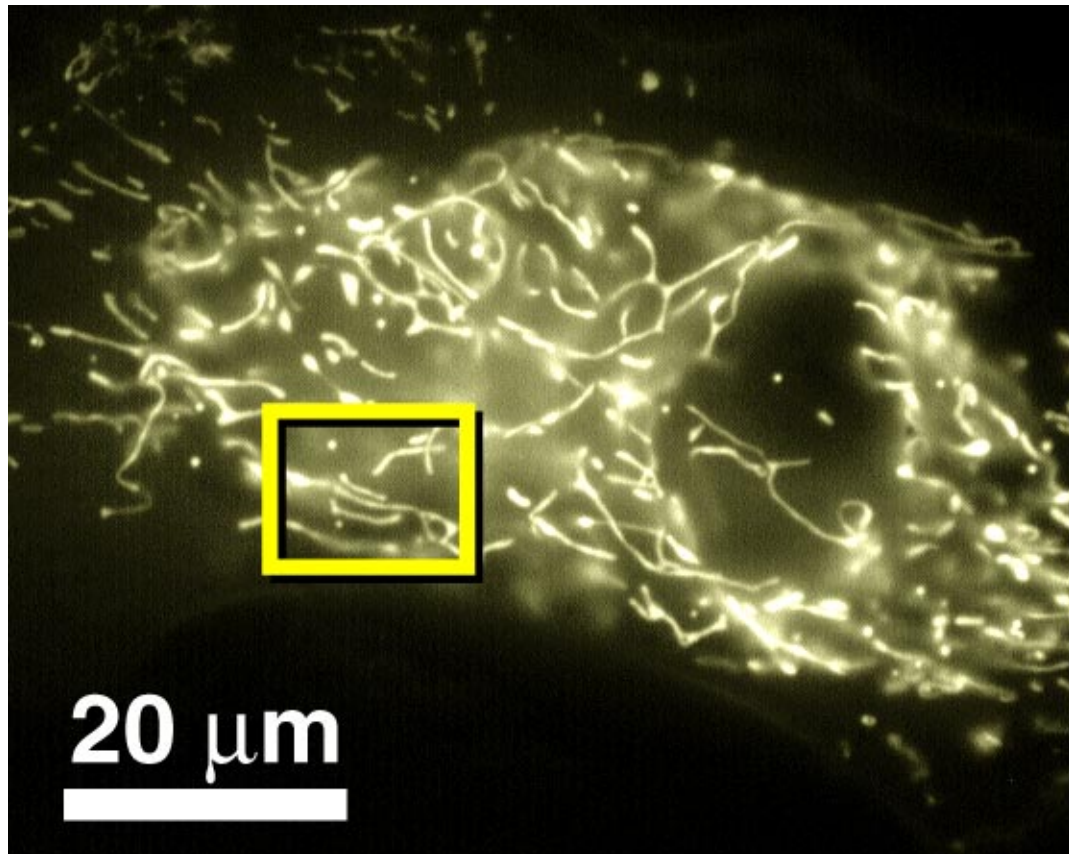




## *Low-energy processing*

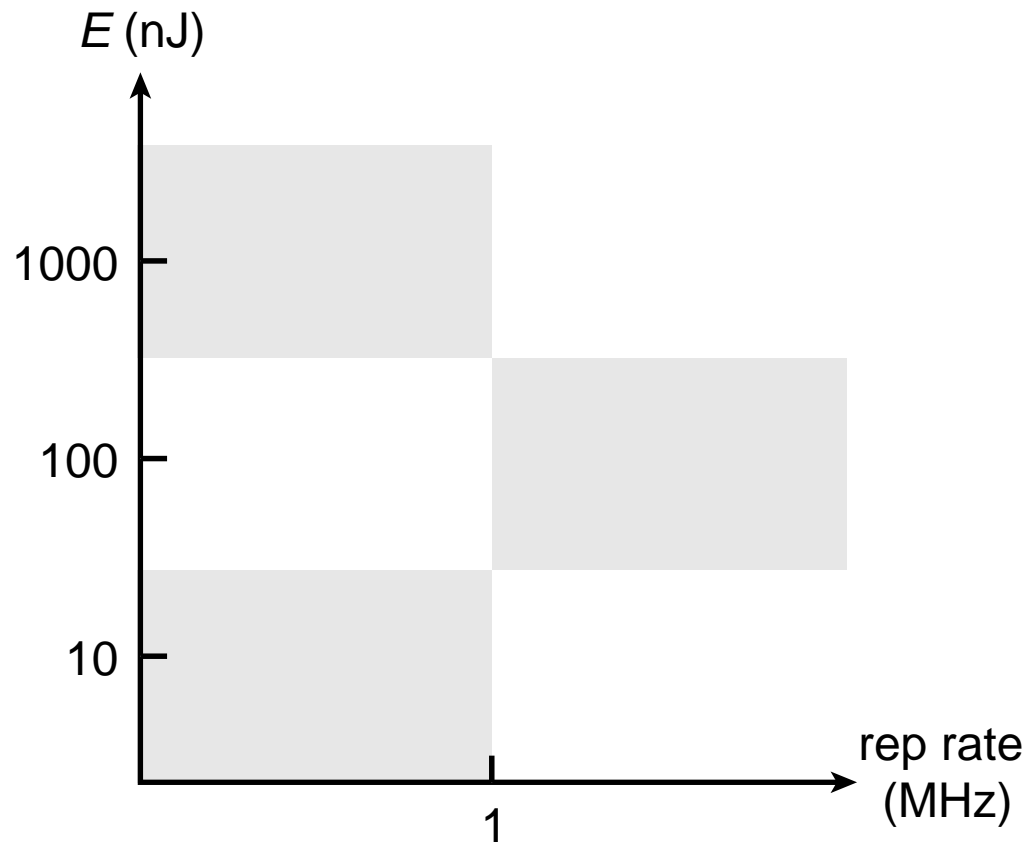


## *Low-energy processing*

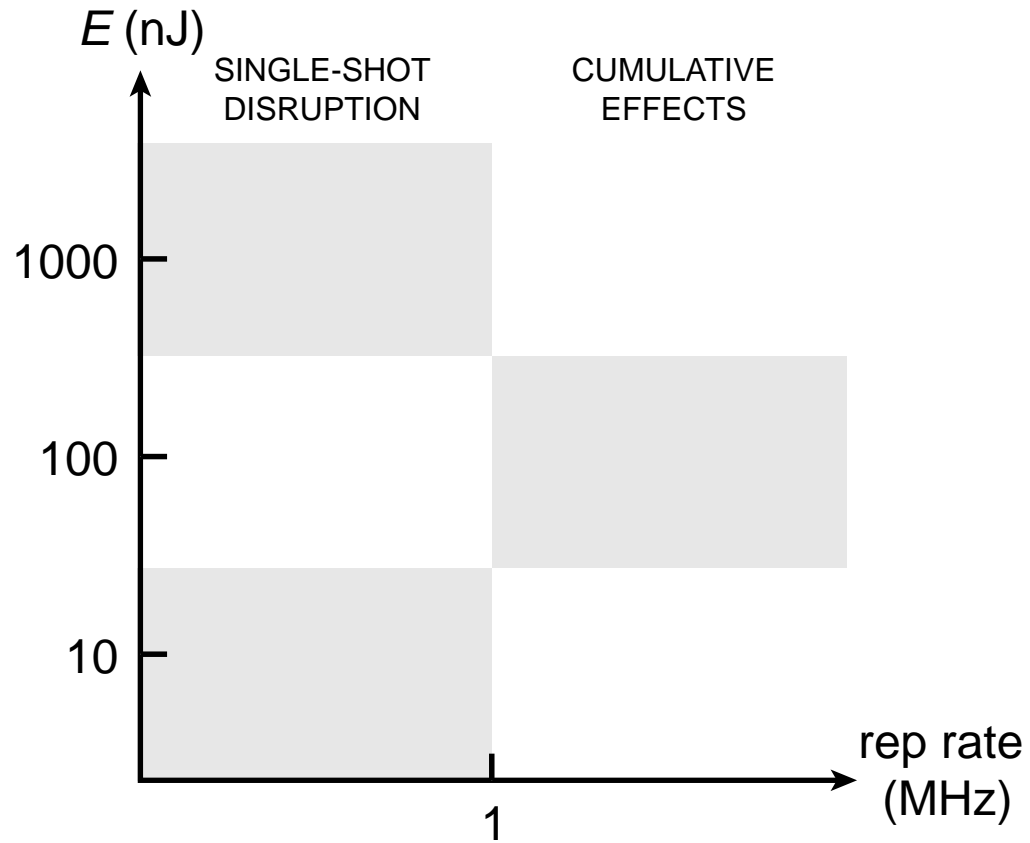




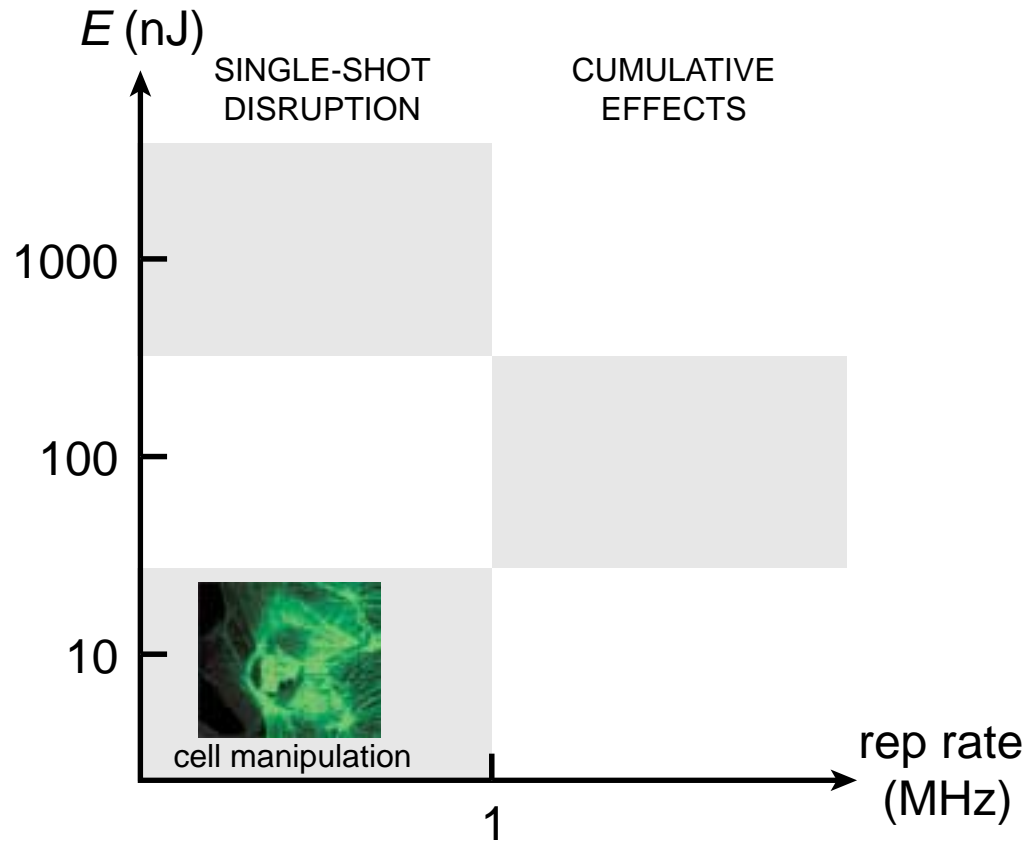
# Summary



# Summary

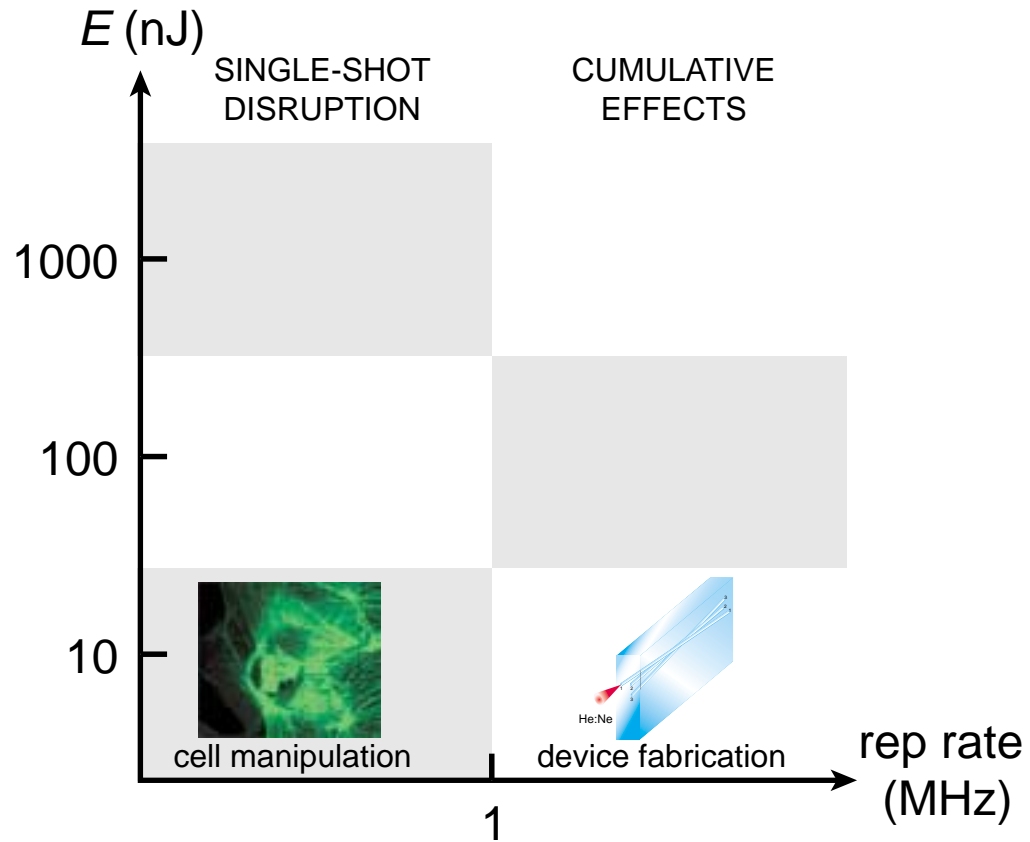


# Summary

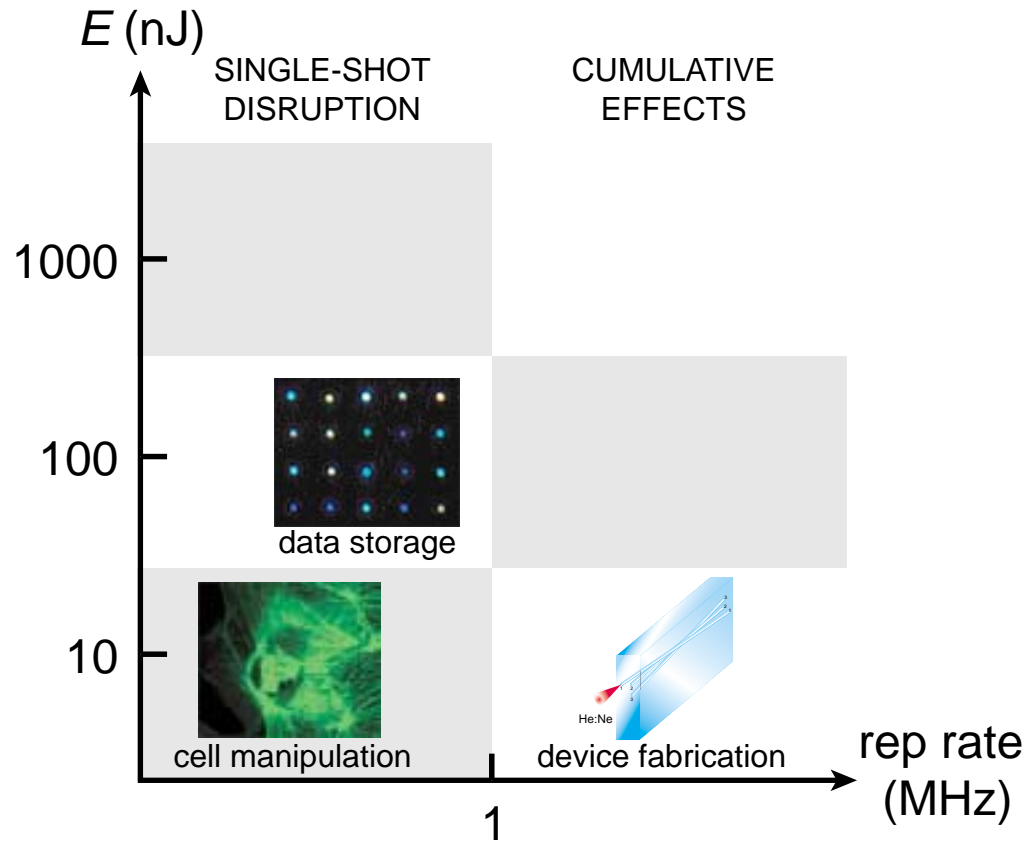




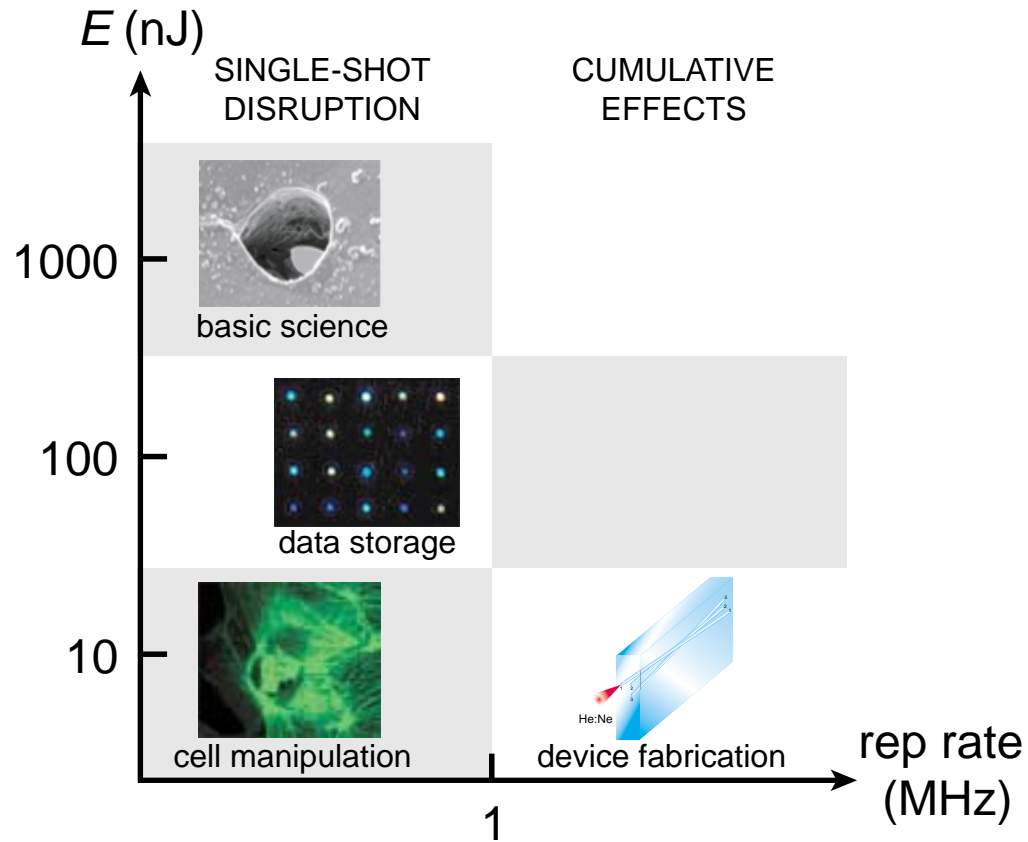
# Summary



# Summary



# Summary



# *Conclusions*

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

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