

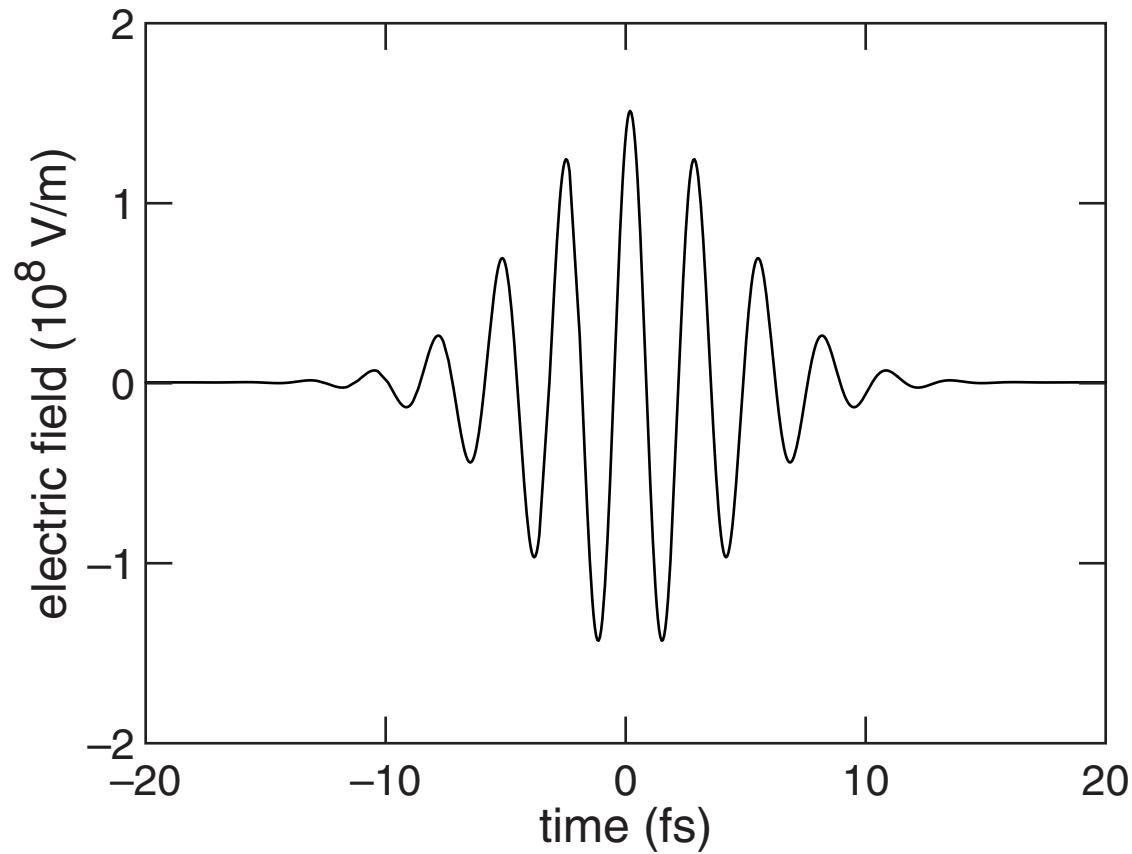
# **SHAPING MATTER WITH LIGHT**

**Eric Mazur**

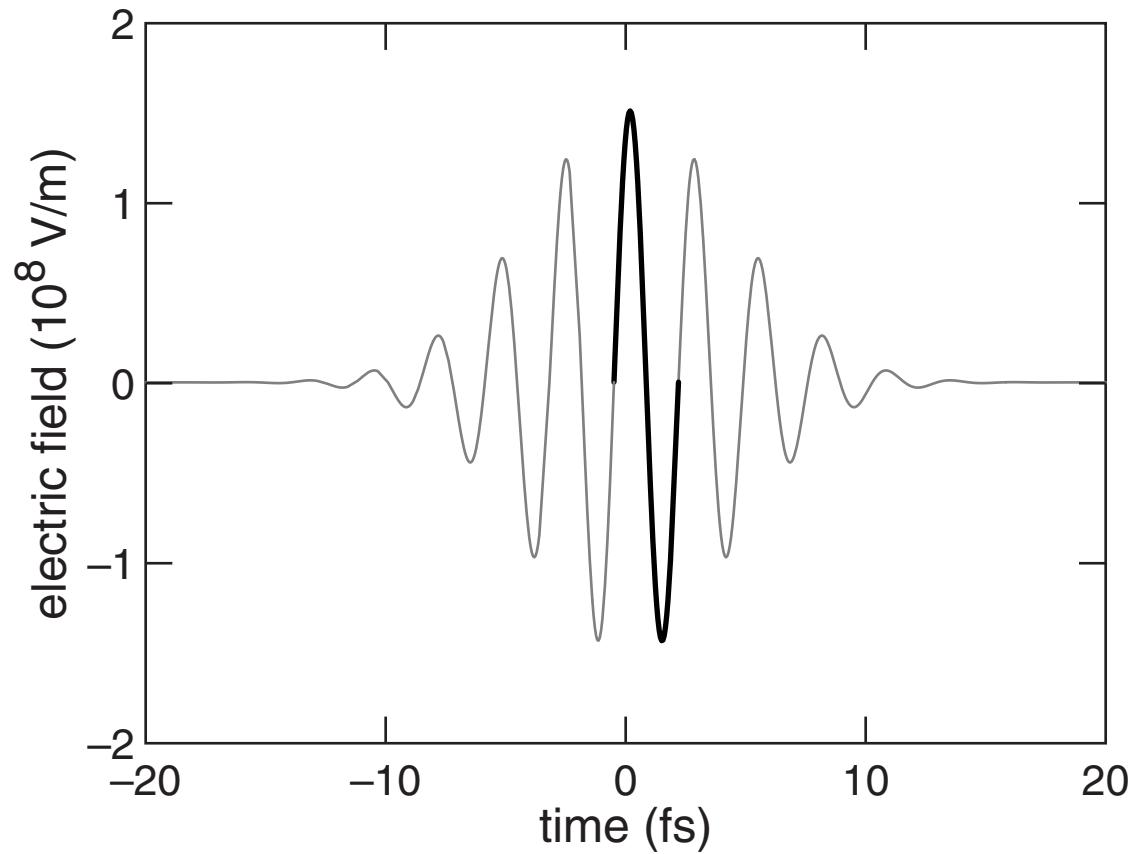
**REU/RET Seminar  
11 June 2003**



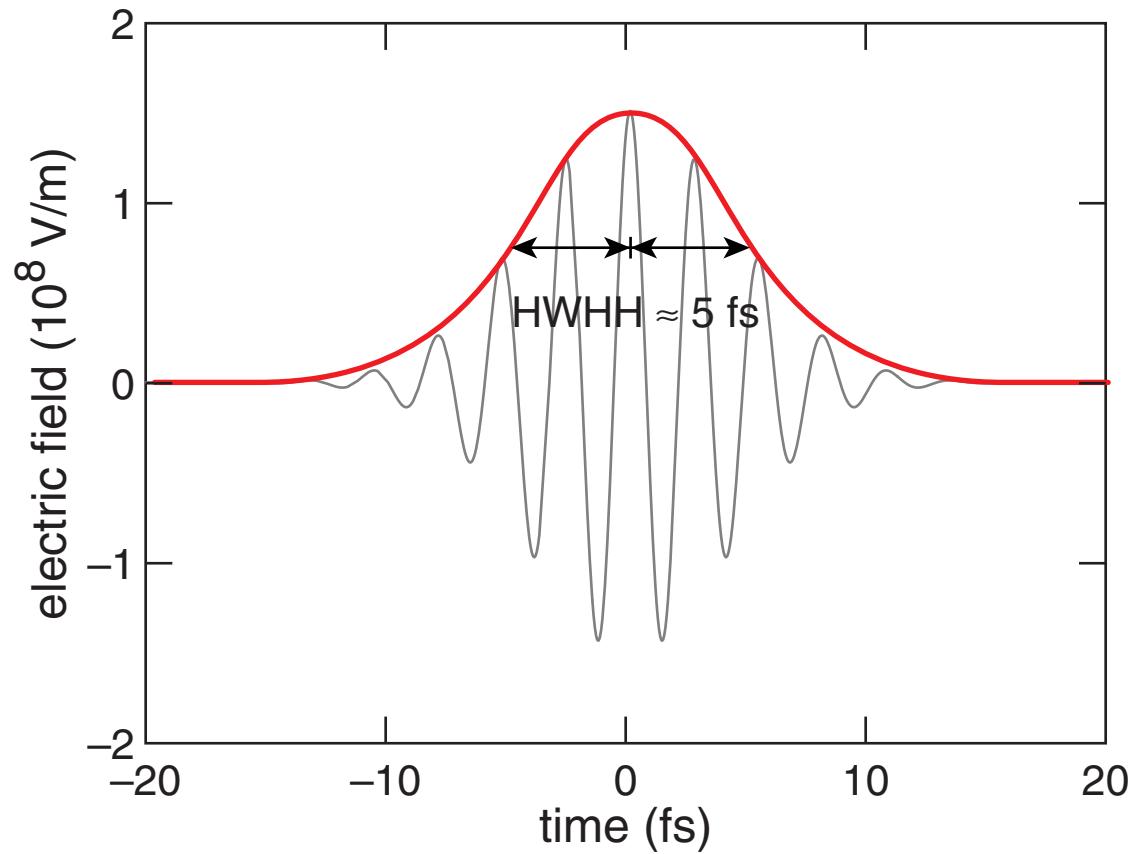
# *Introduction*



# *Introduction*



# *Introduction*

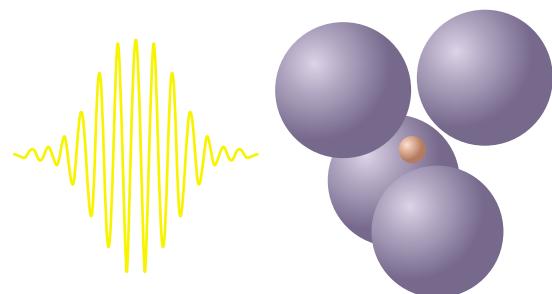


# *Introduction*

- ▶ time resolution
- ▶ high intensity
- ▶ nonlinear optics
- ▶ new physics

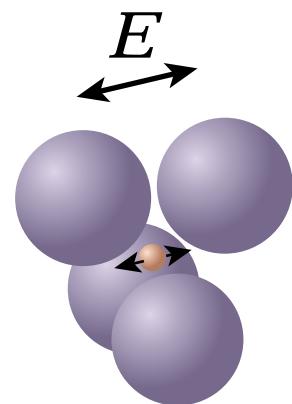
# *Introduction*

## light-matter interactions



# *Introduction*

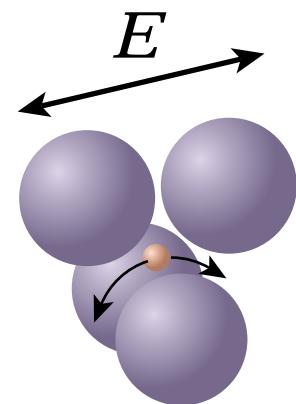
## linear response



“stiffness” determines index of refraction

# *Introduction*

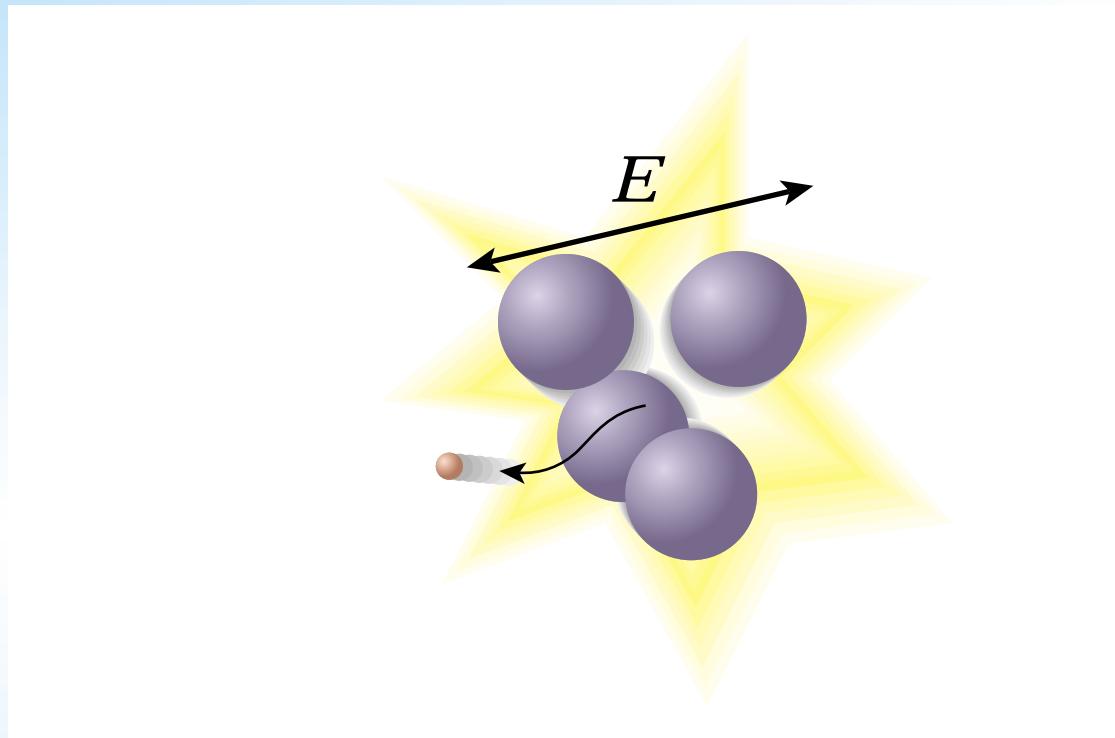
## nonlinear response



second harmonic generation

# *Introduction*

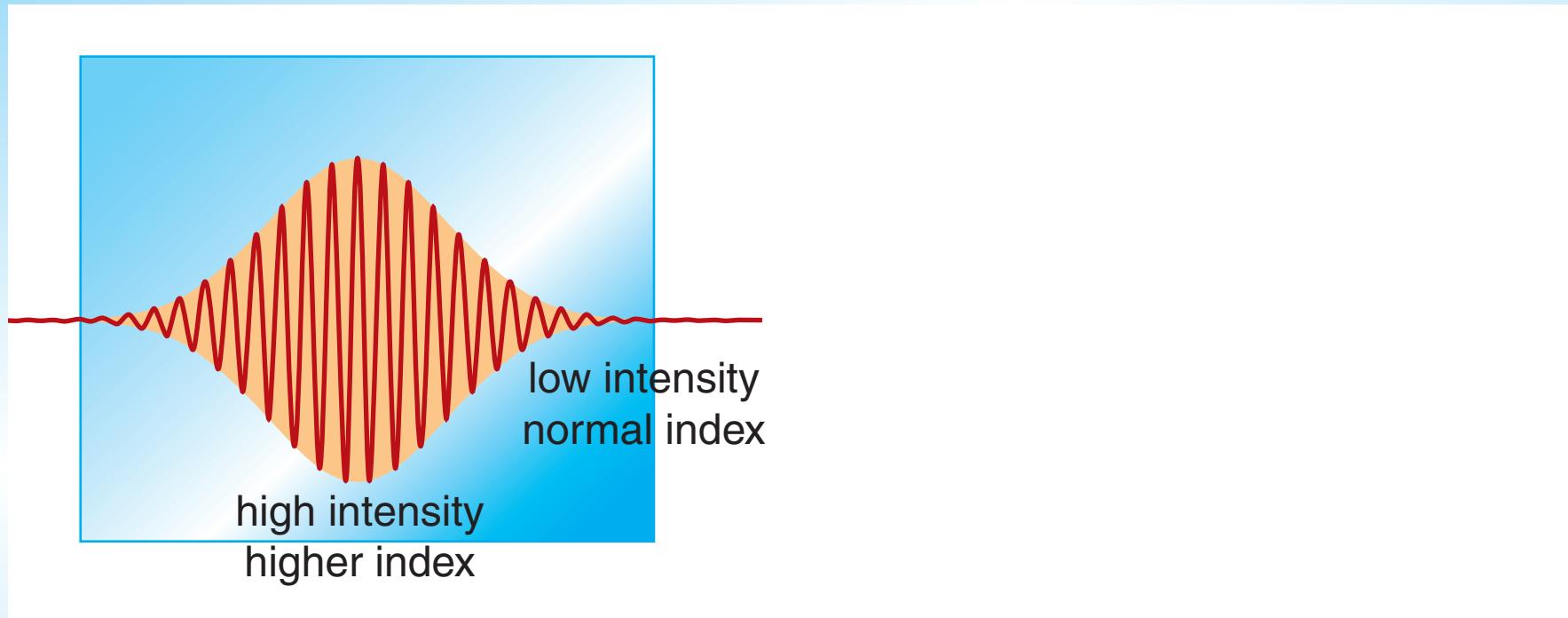
“extremely” nonlinear response



# *Nonlinear optics*

**Intensity dependent index of refraction:**

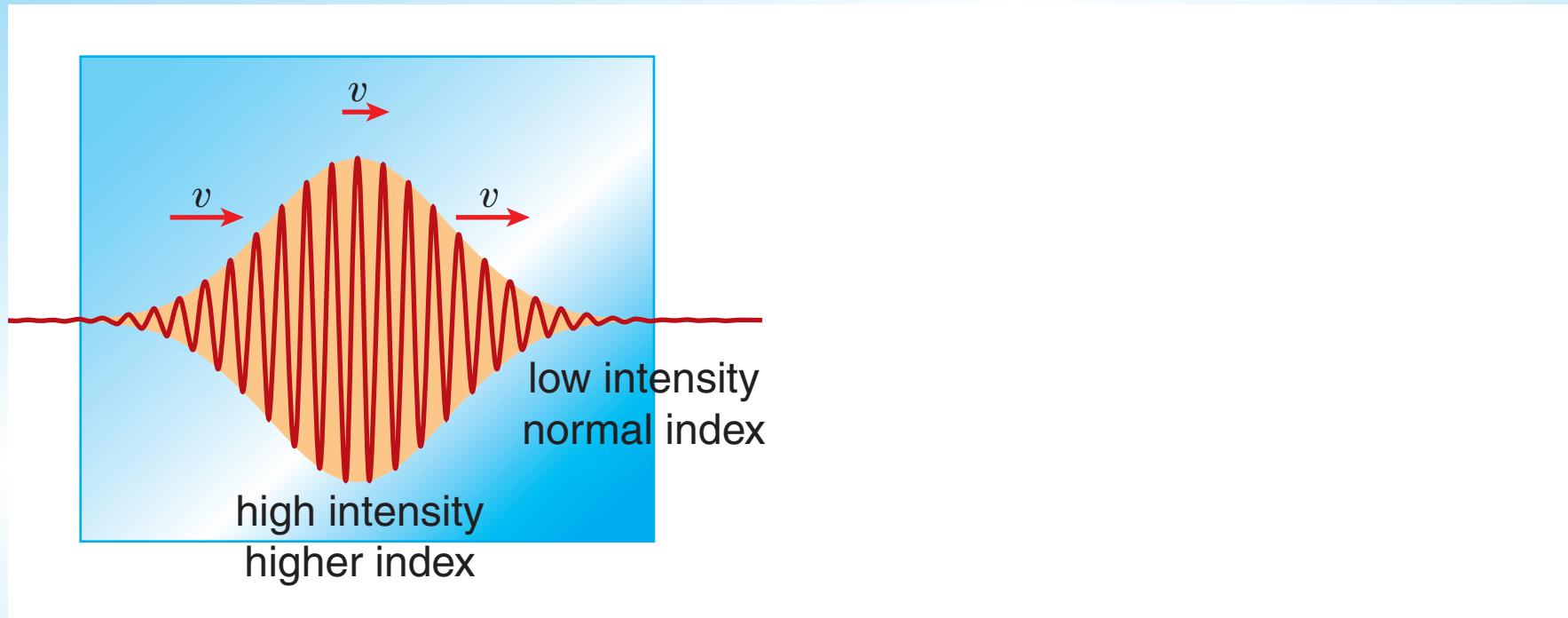
$$n = n_o + n_2 I$$



# *Nonlinear optics*

**Intensity dependent index of refraction:**

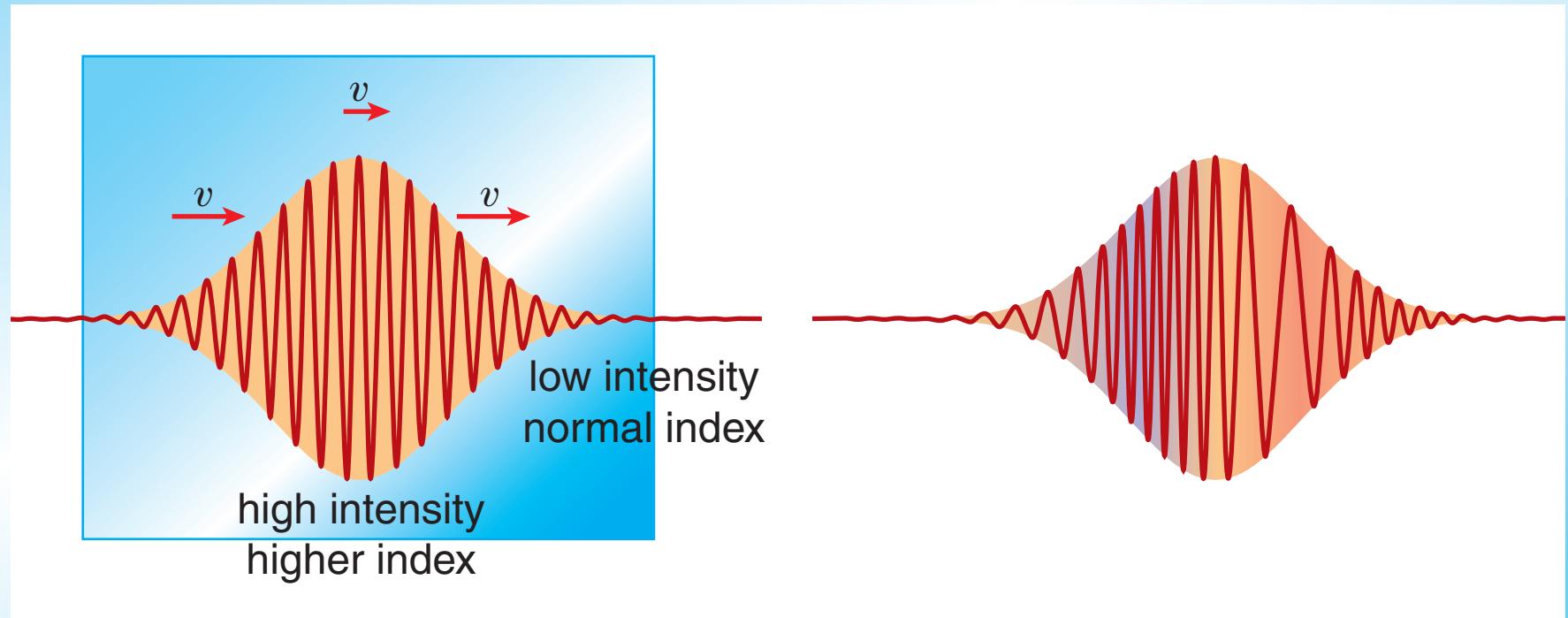
$$n = n_o + n_2 I$$



# *Nonlinear optics*

**Intensity dependent index of refraction:**

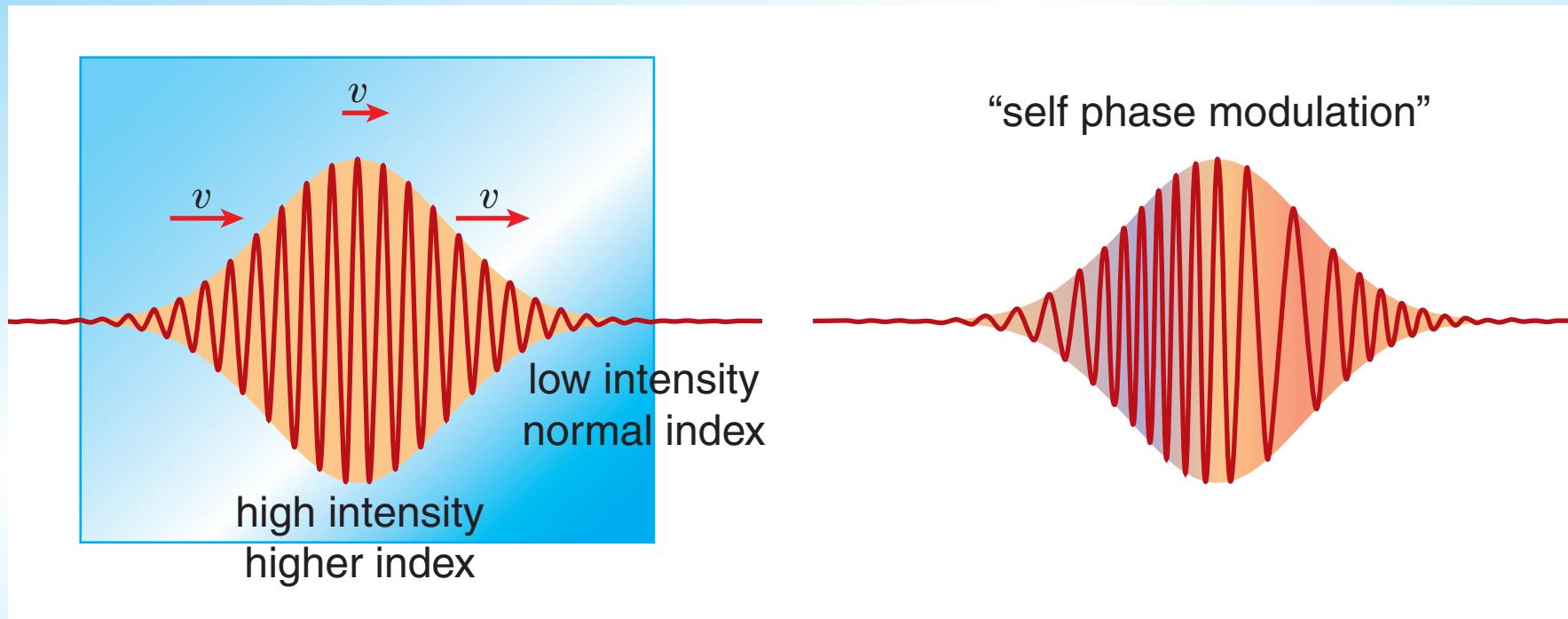
$$n = n_o + n_2 I$$



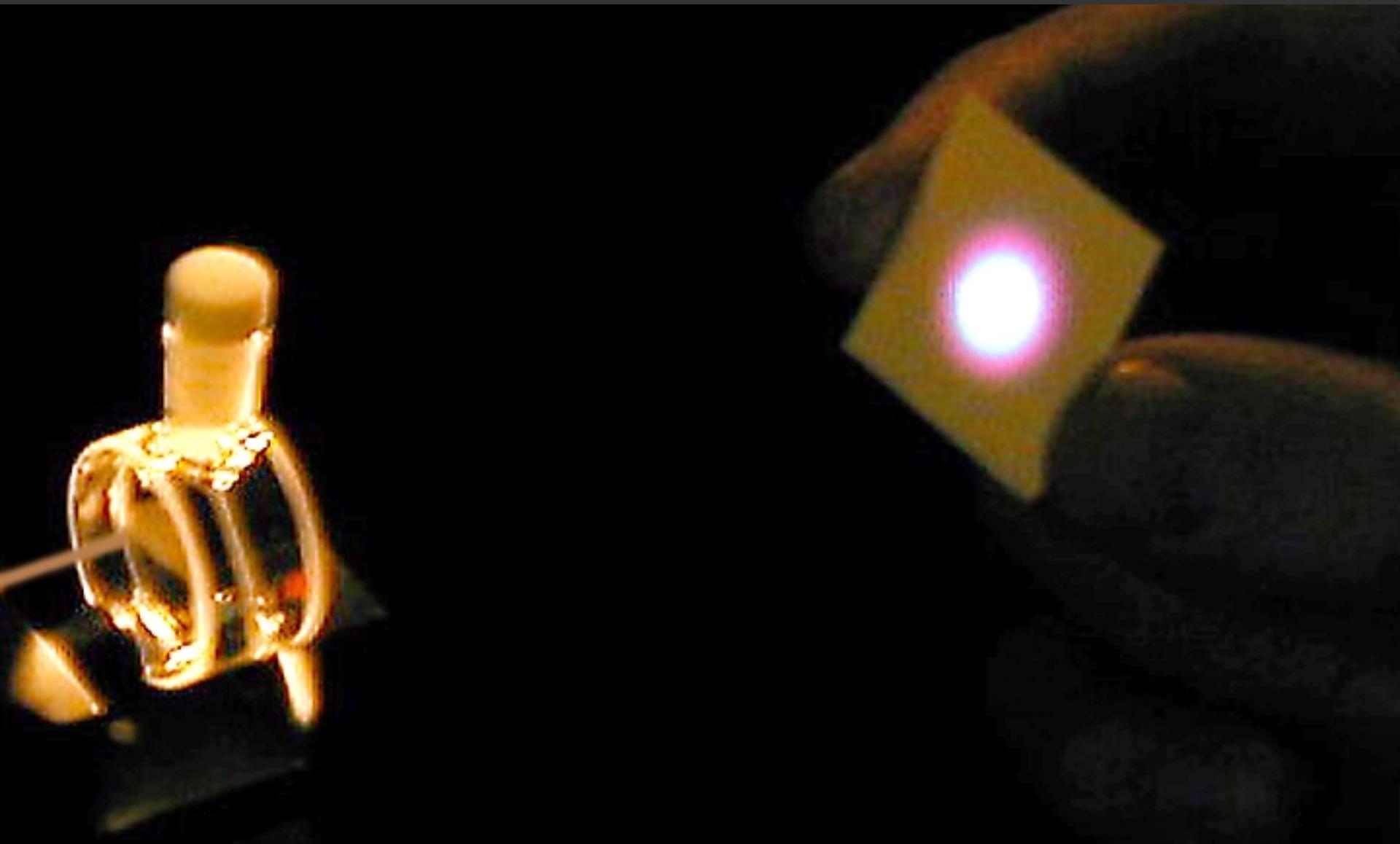
# *Nonlinear optics*

## Intensity dependent index of refraction:

$$n = n_o + n_2 I$$

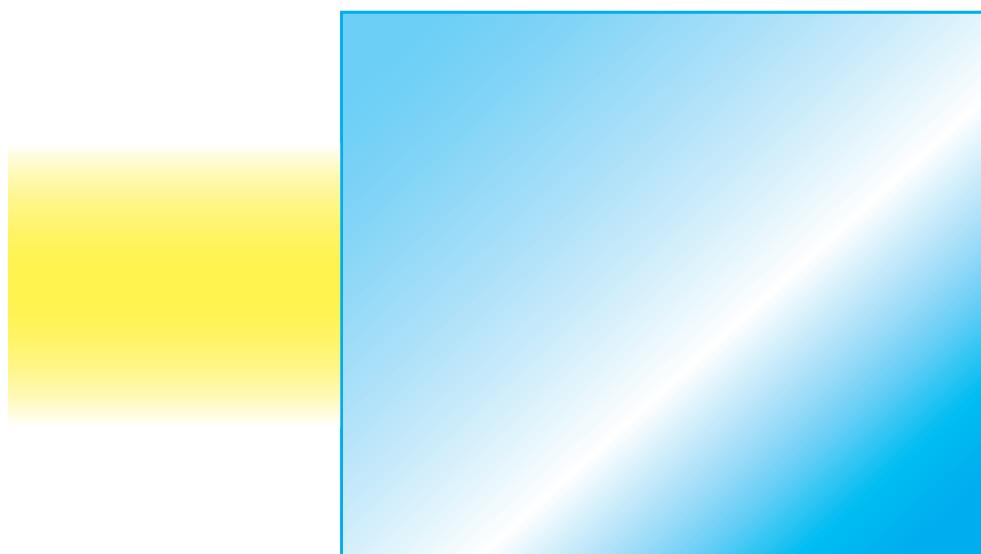


# *Introduction*



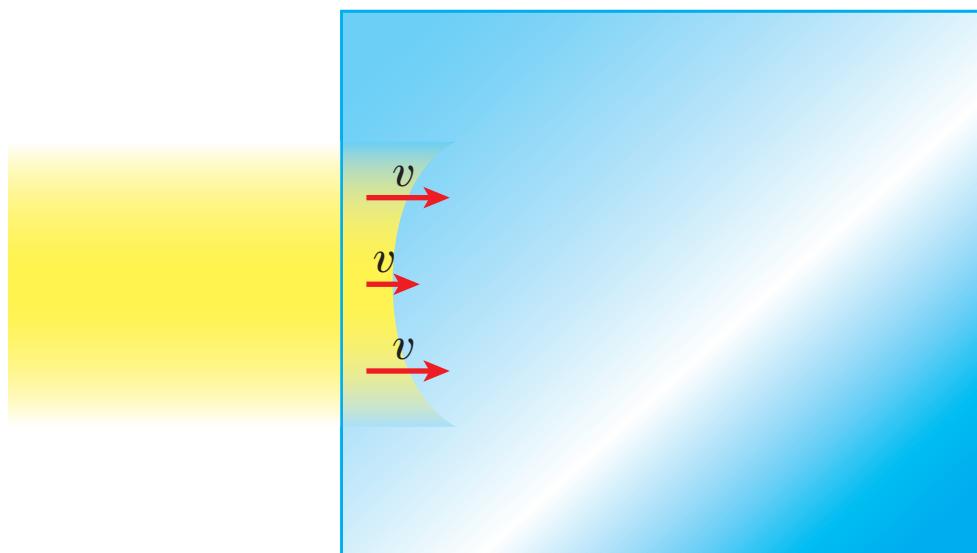
# *Nonlinear optics*

Spatial intensity profile...



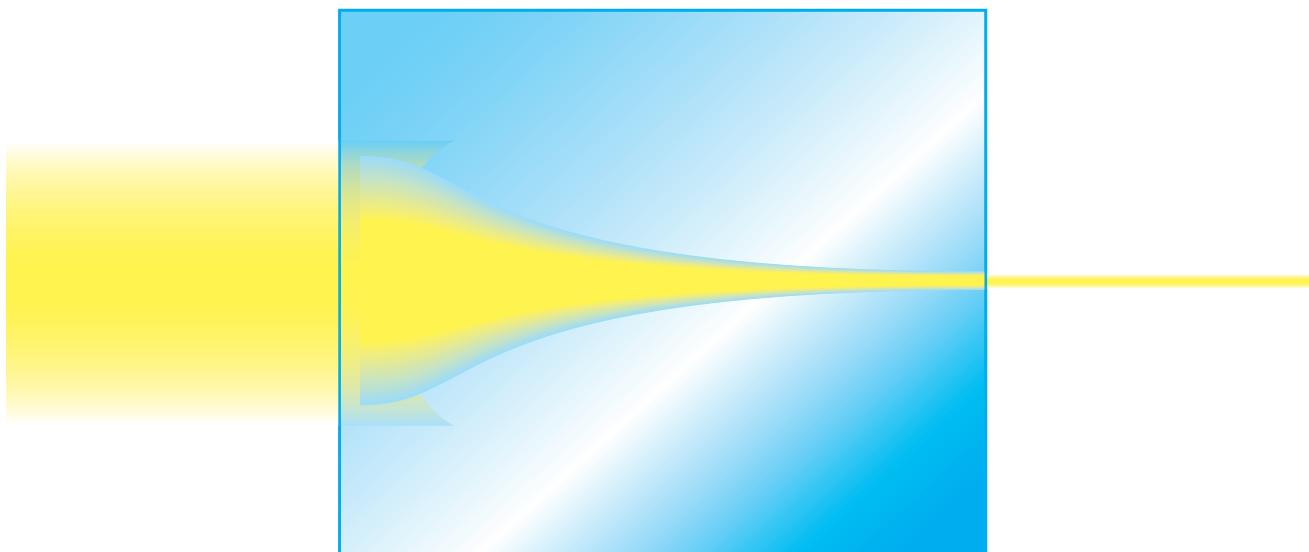
# *Nonlinear optics*

## Spatial intensity profile...



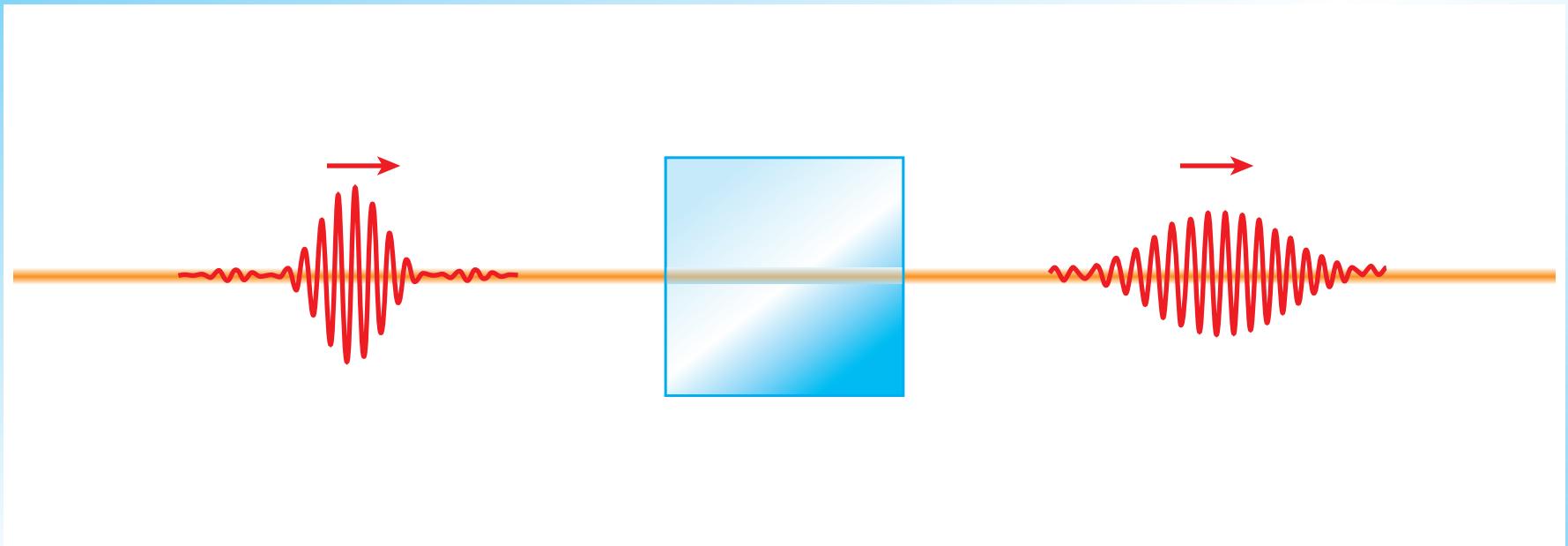
# *Nonlinear optics*

**...causes self-focusing**



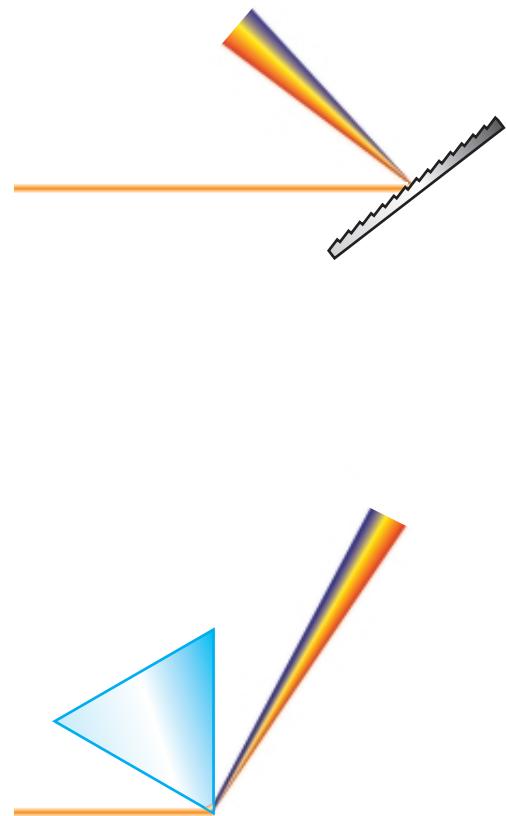
# *Dispersion compensation*

**Dispersion stretches the pulse**

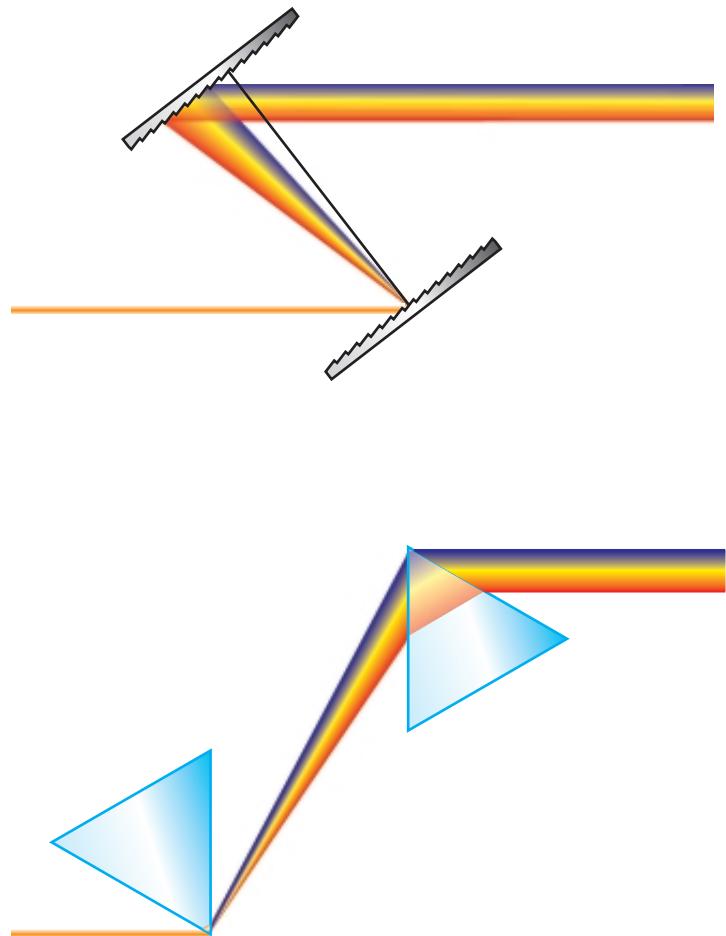


**Compensate by rearranging spectral components!**

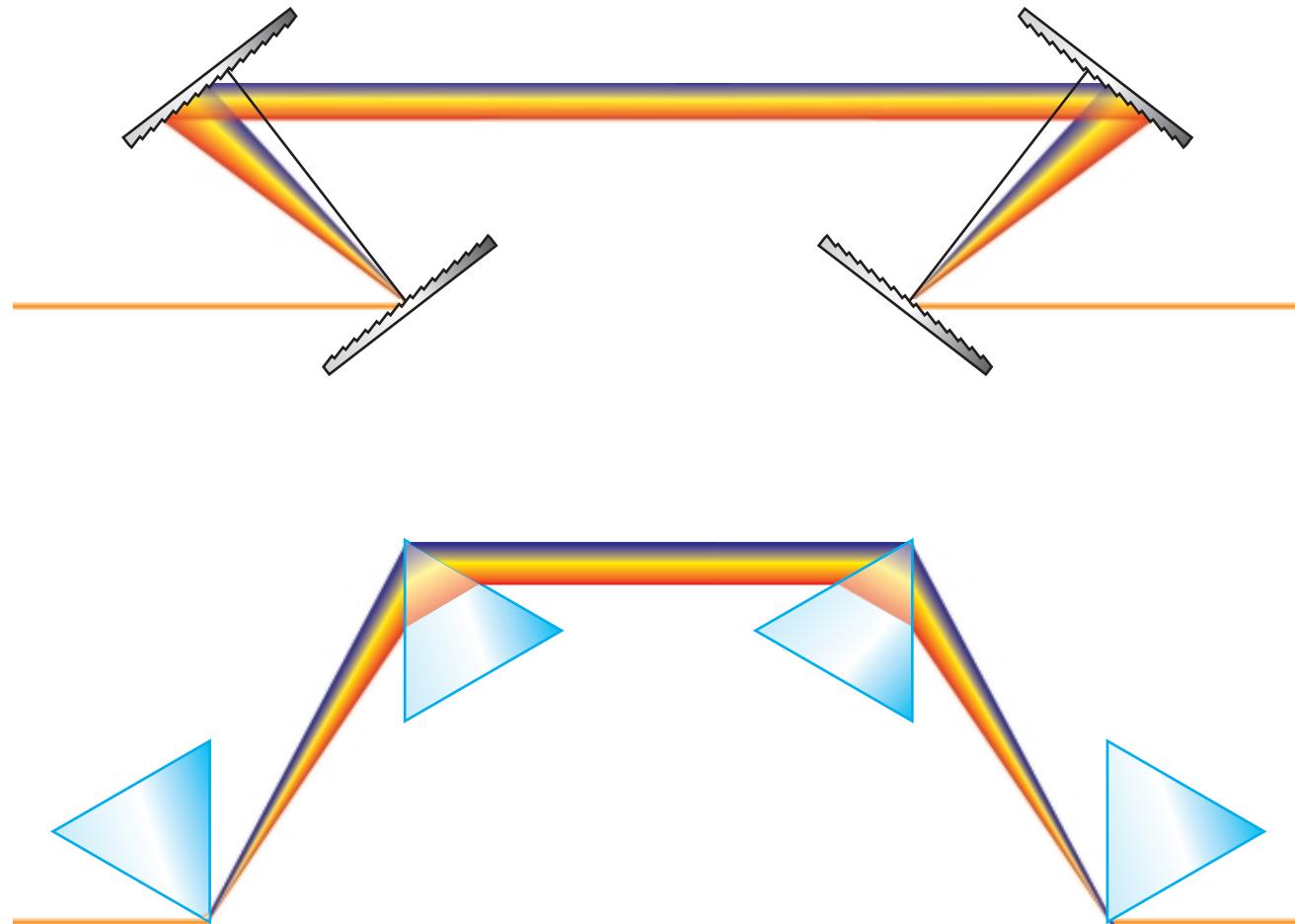
# *Dispersion compensation*



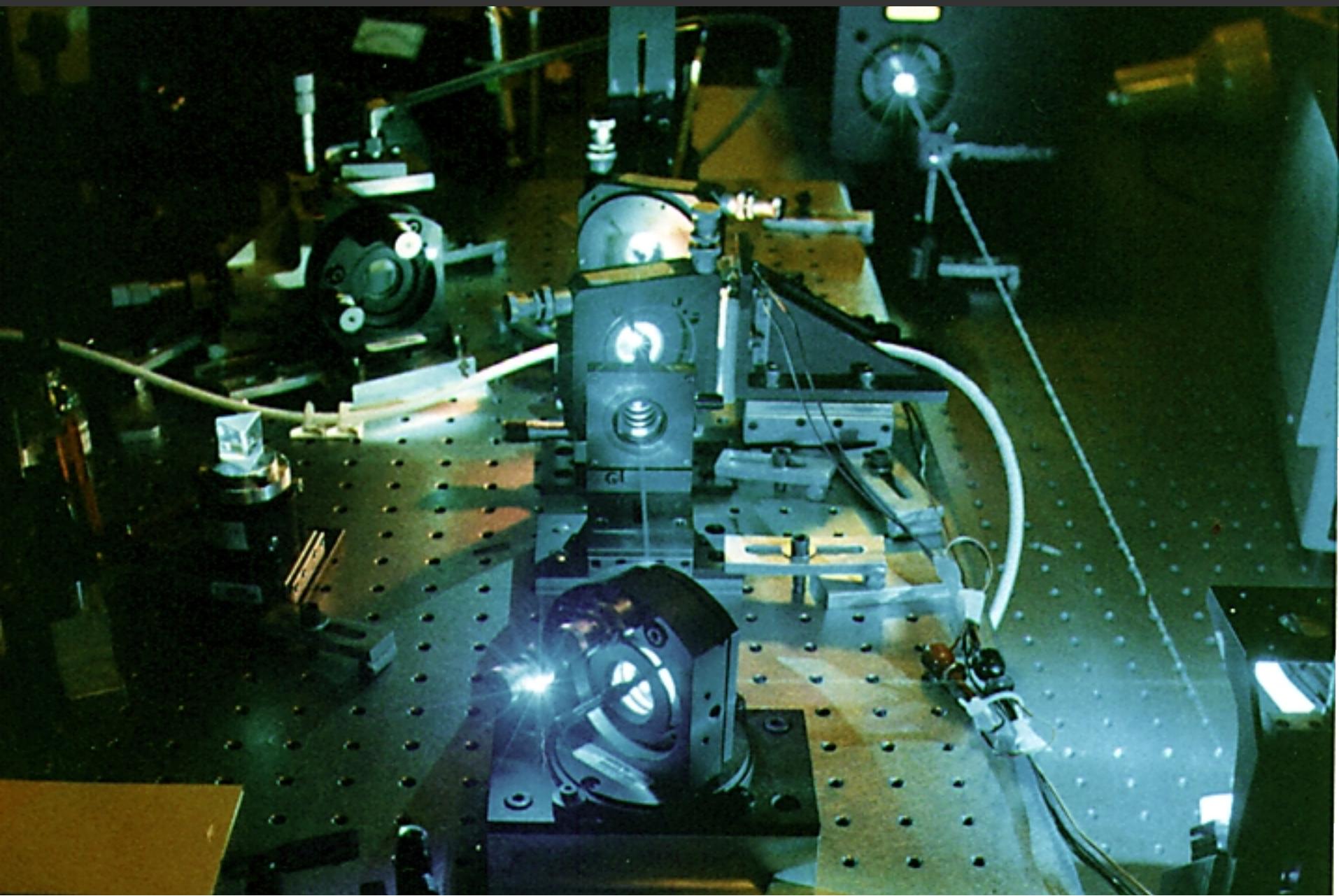
# *Dispersion compensation*



# *Dispersion compensation*

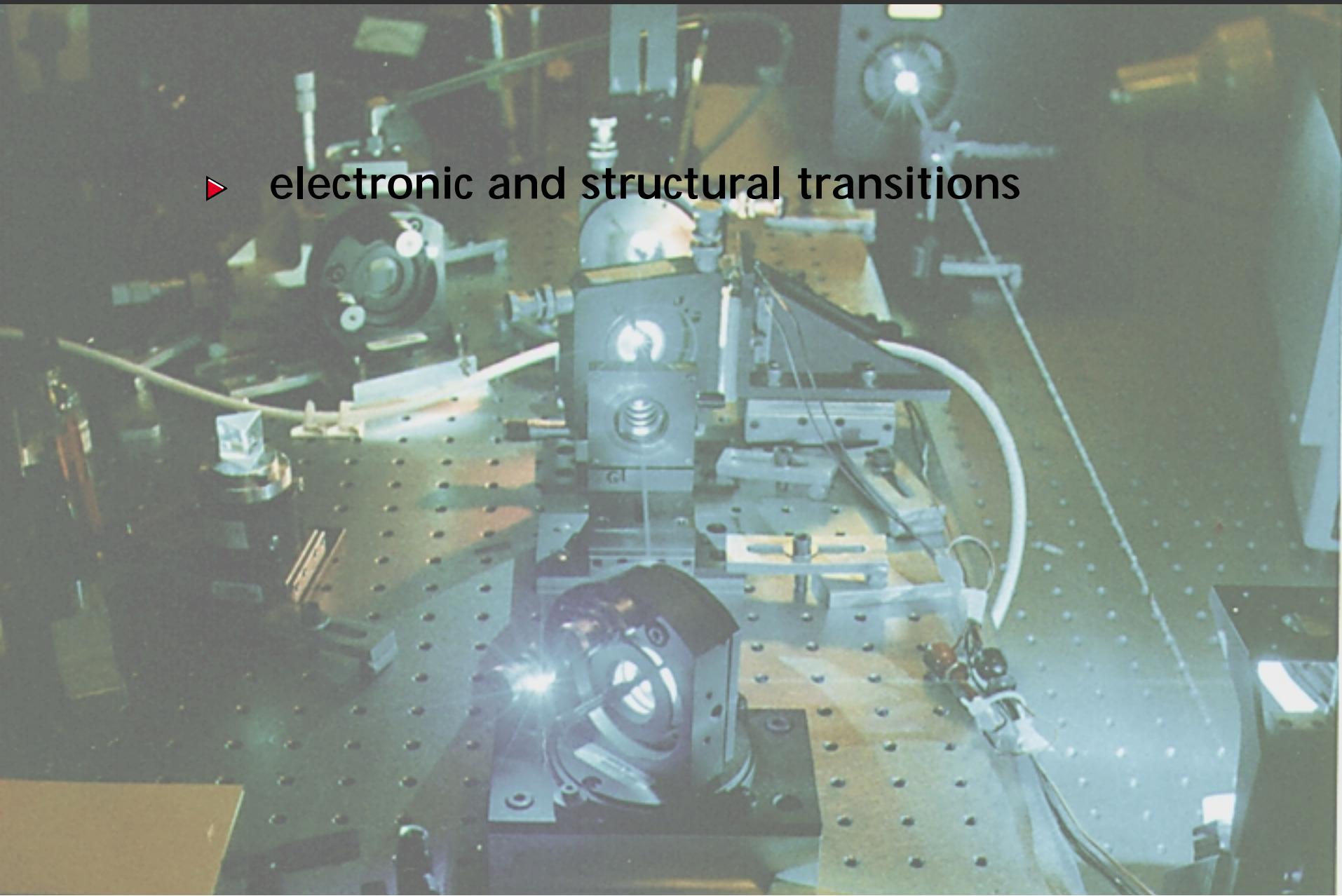


# *Overview*



# *Overview*

- ▶ electronic and structural transitions



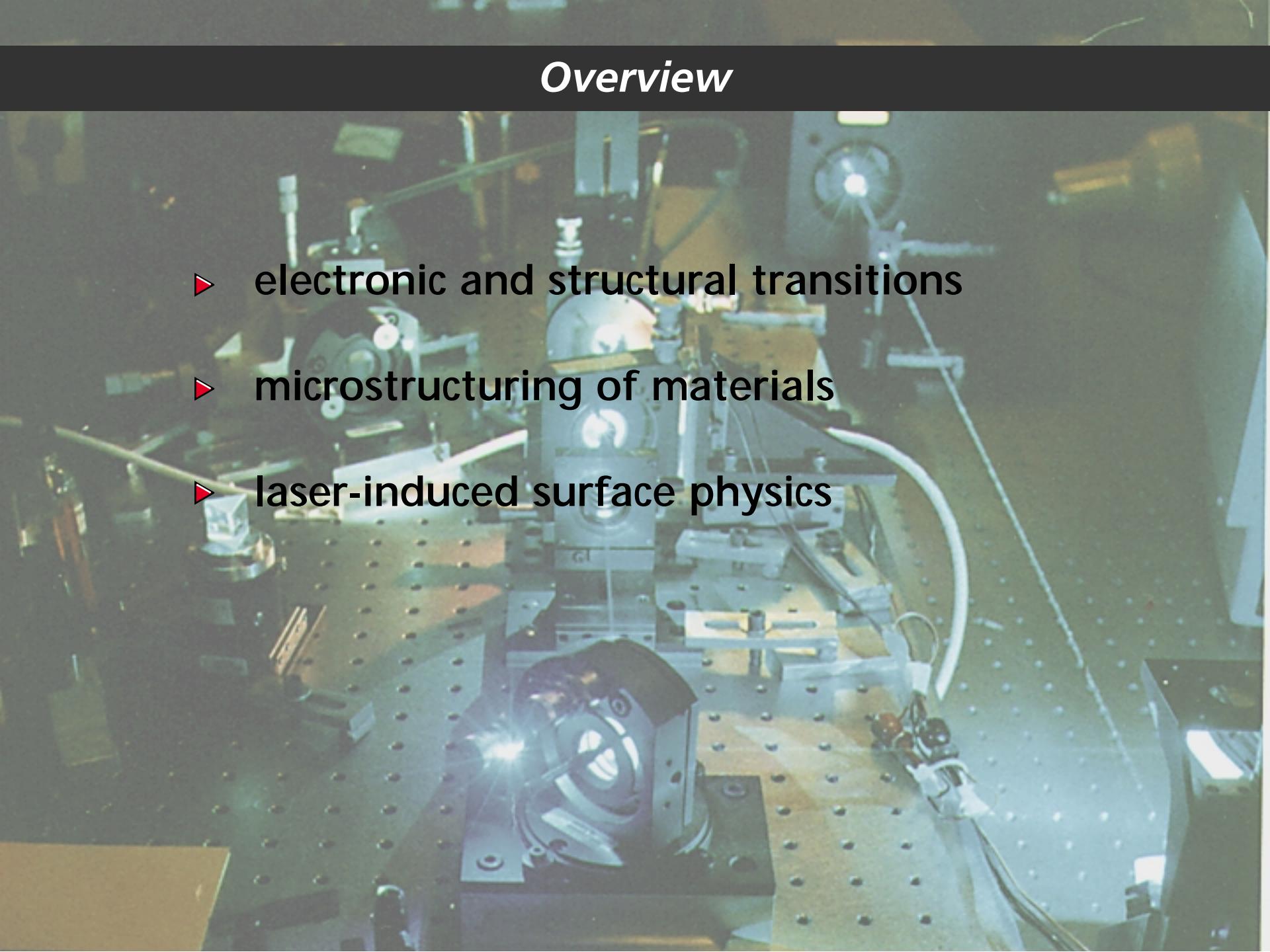
# *Overview*

- ▶ electronic and structural transitions
- ▶ microstructuring of materials



# *Overview*

- ▶ electronic and structural transitions
- ▶ microstructuring of materials
- ▶ laser-induced surface physics

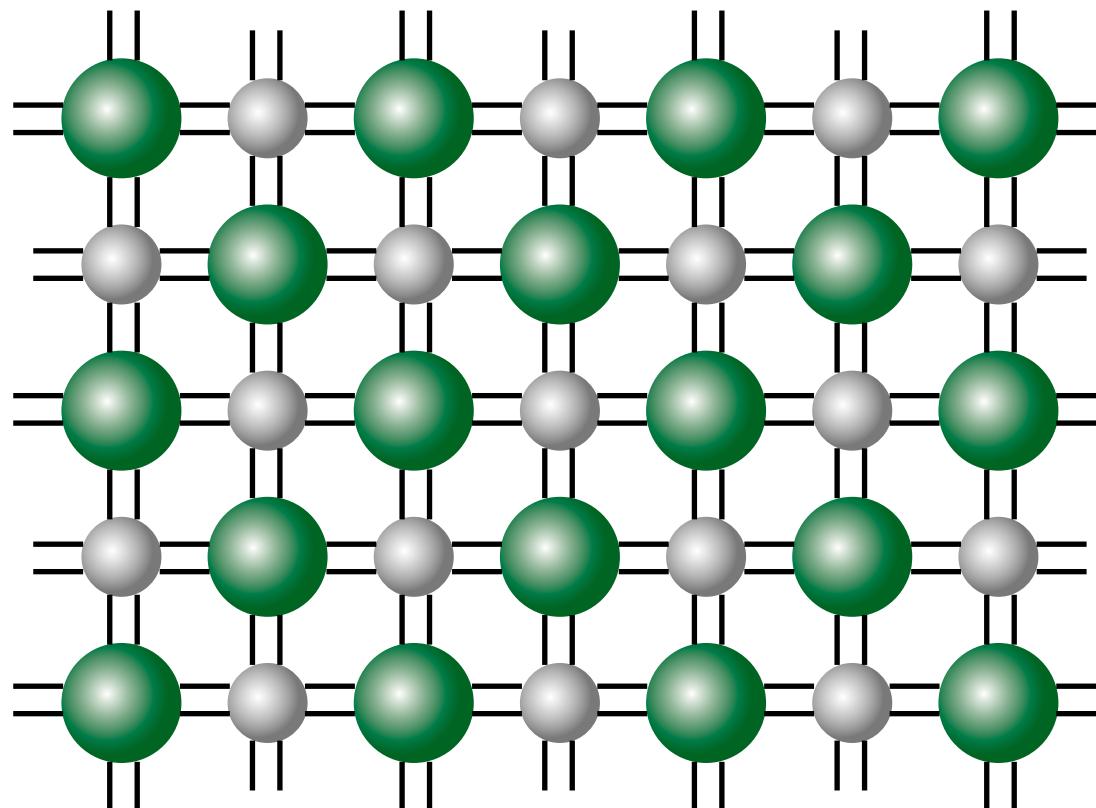


# *Overview*

- ▶ electronic and structural transitions
- ▶ microstructuring of materials
- ▶ laser-induced surface physics
- ▶ biology and medicine

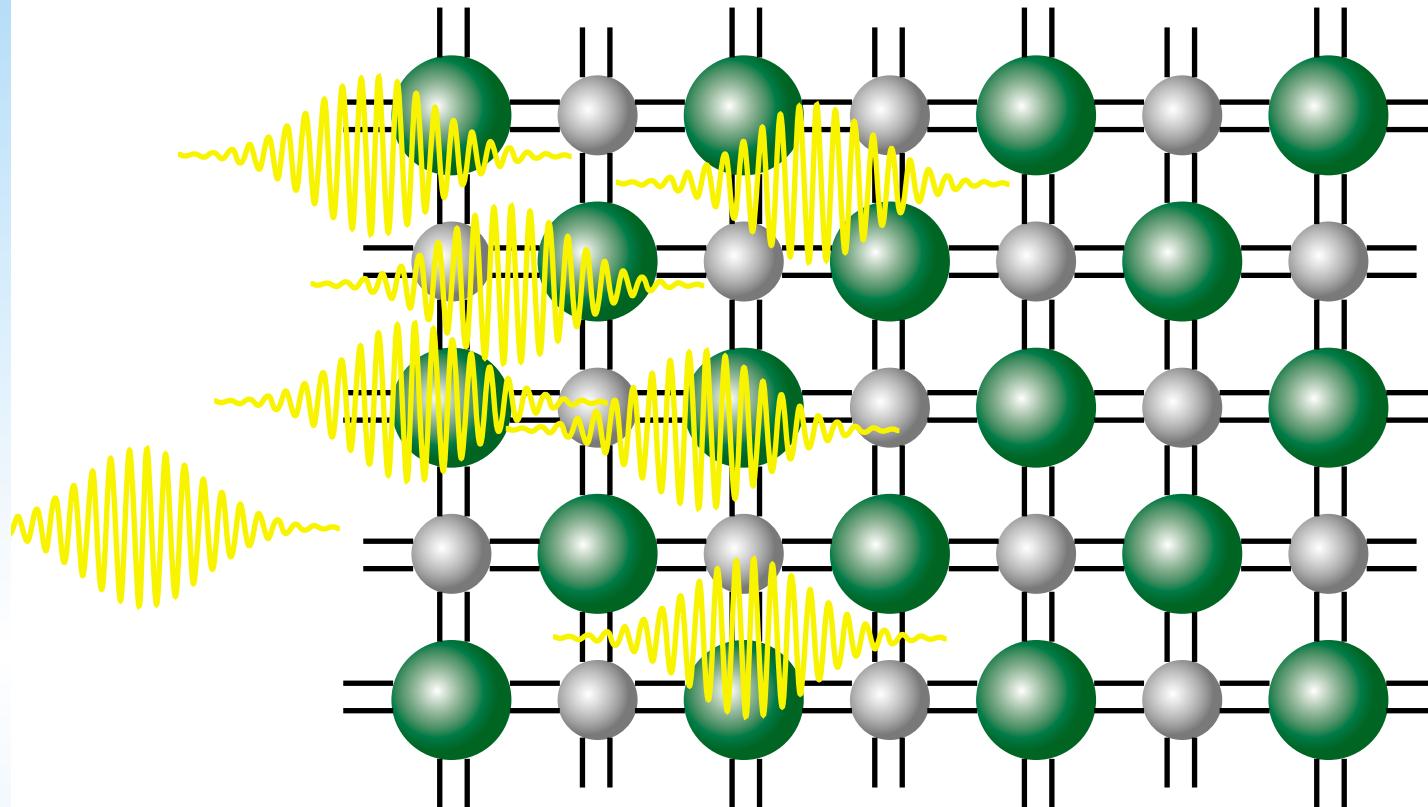
# *Electronic and structural transitions*

how do femtosecond laser pulses alter a solid?



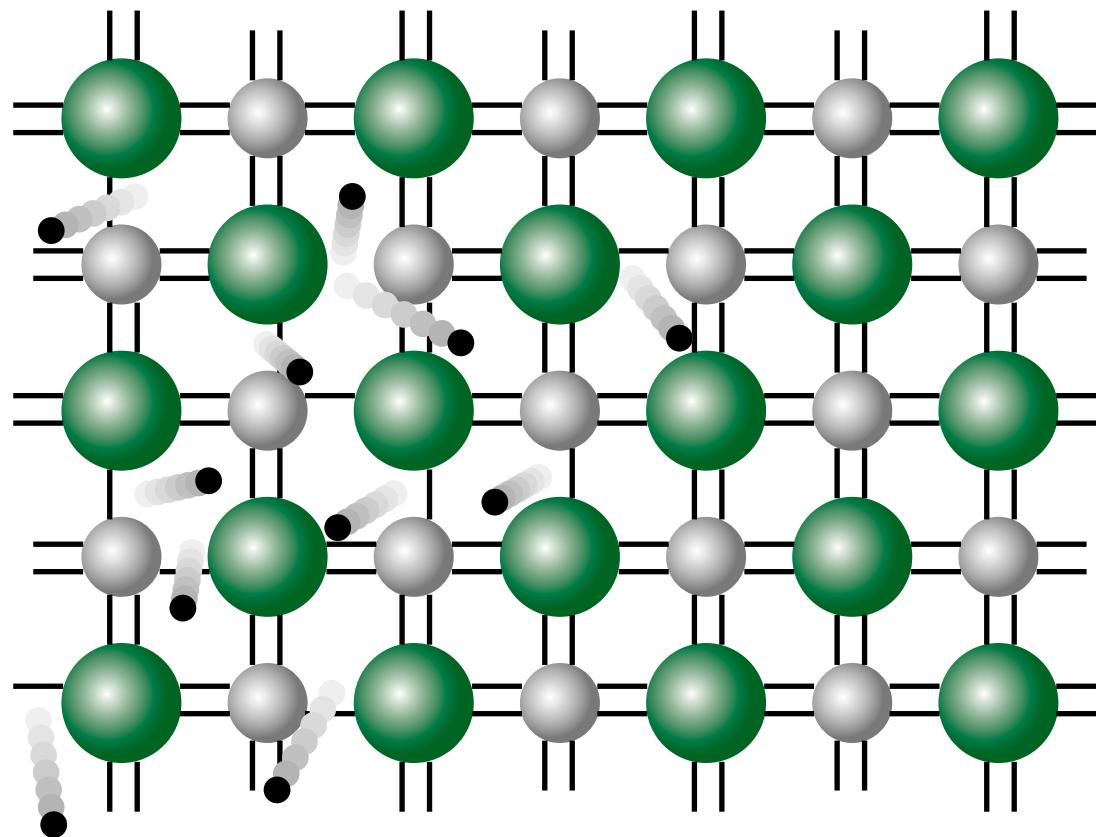
## *Electronic and structural transitions*

photons excite valence electrons...



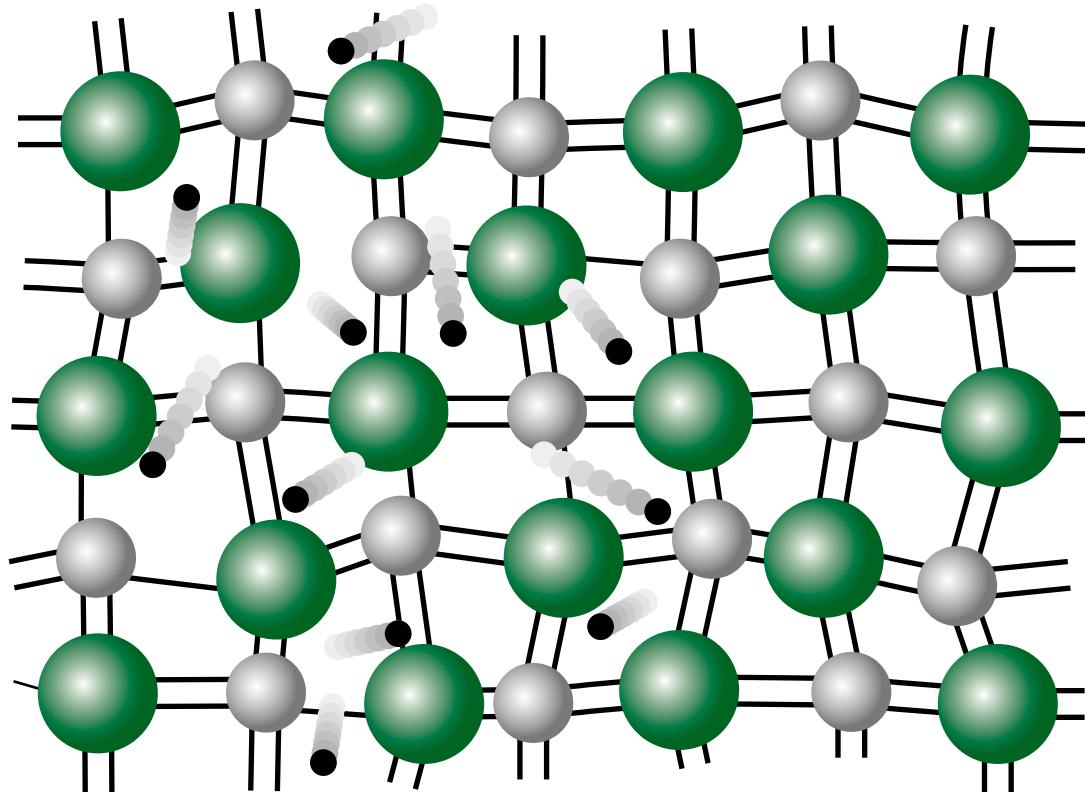
# *Electronic and structural transitions*

...and create free electrons...



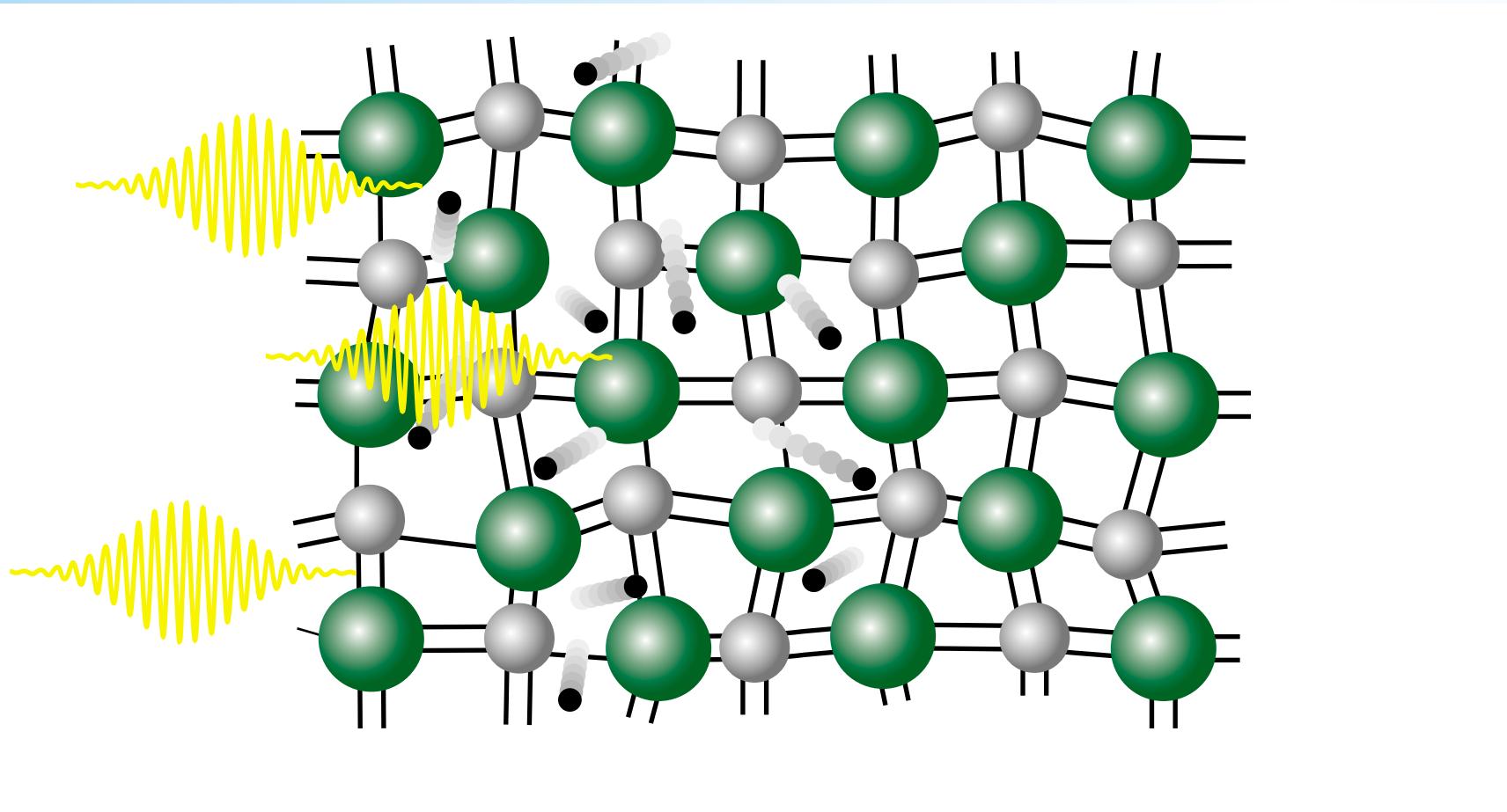
## *Electronic and structural transitions*

...causing electronic and structural changes...



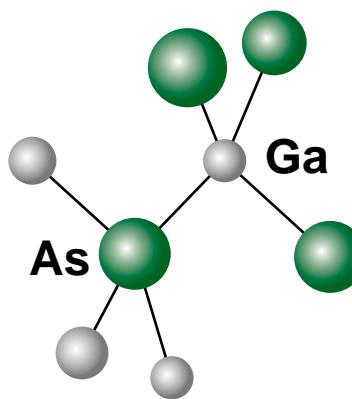
## *Electronic and structural transitions*

...which we measure with another pulse

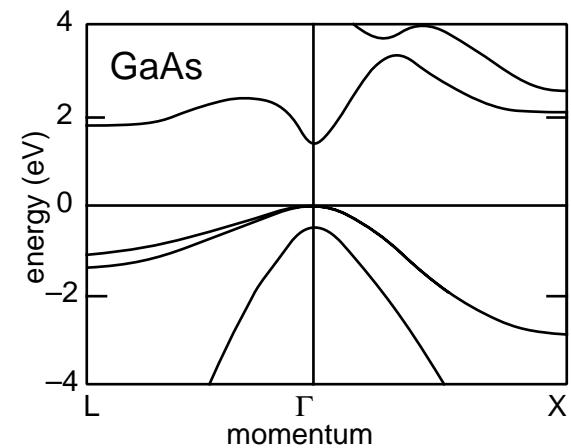


# *Electronic and structural transitions*

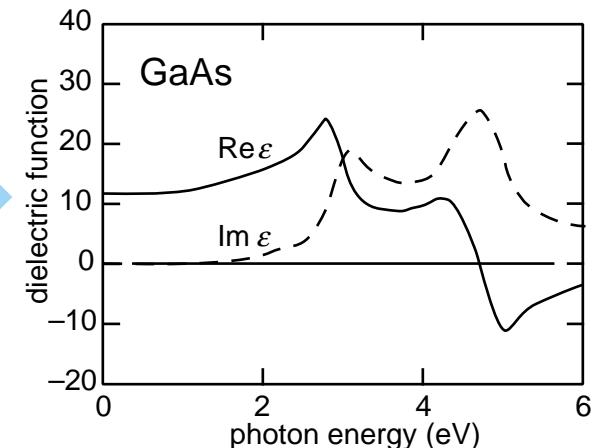
**structure**



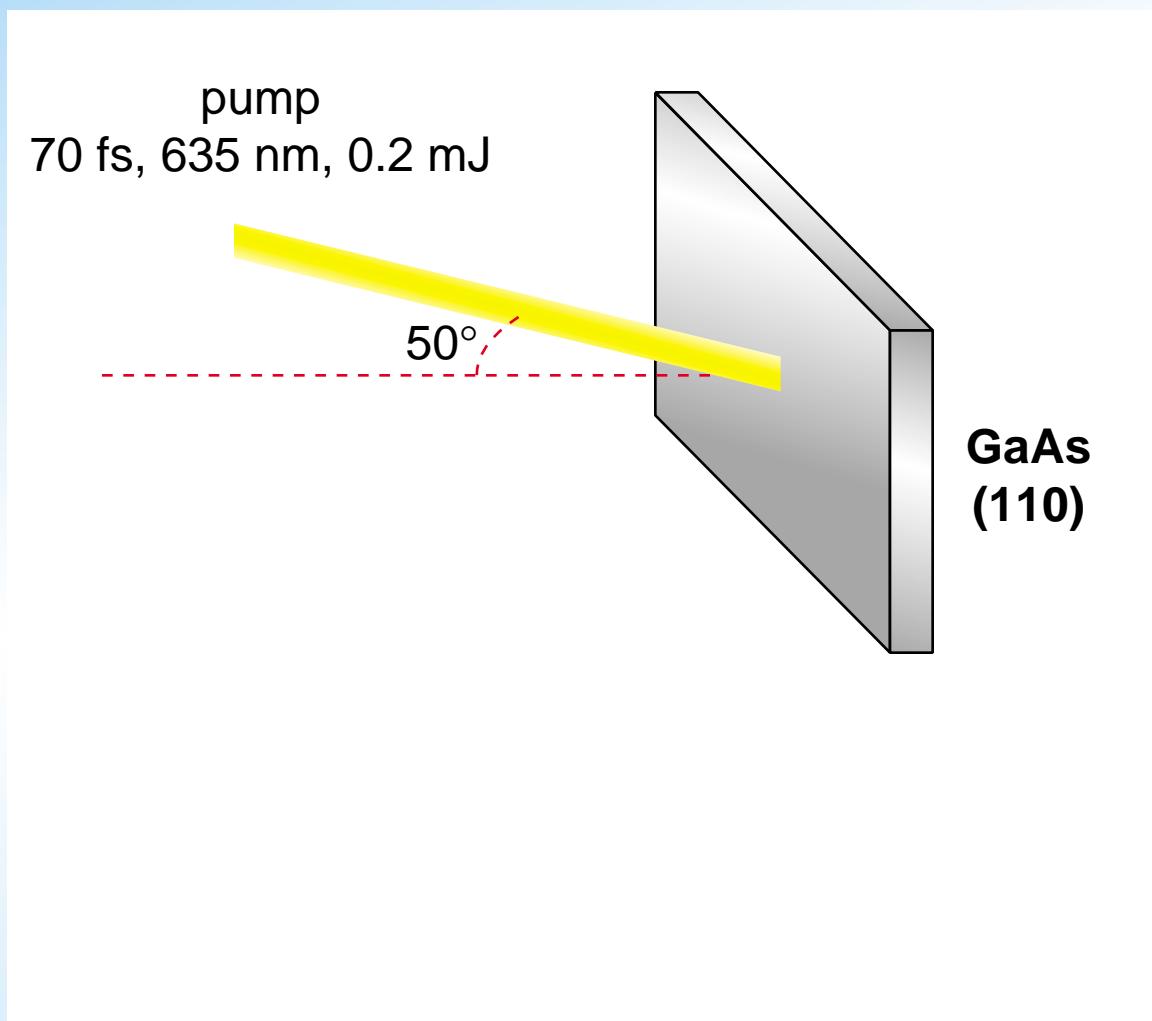
**bandstructure**



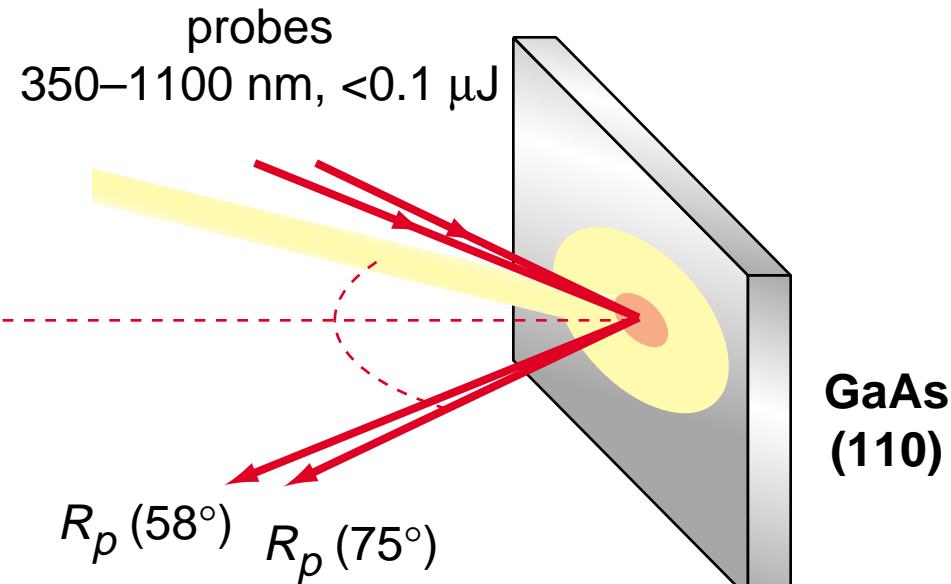
**dielectric function**



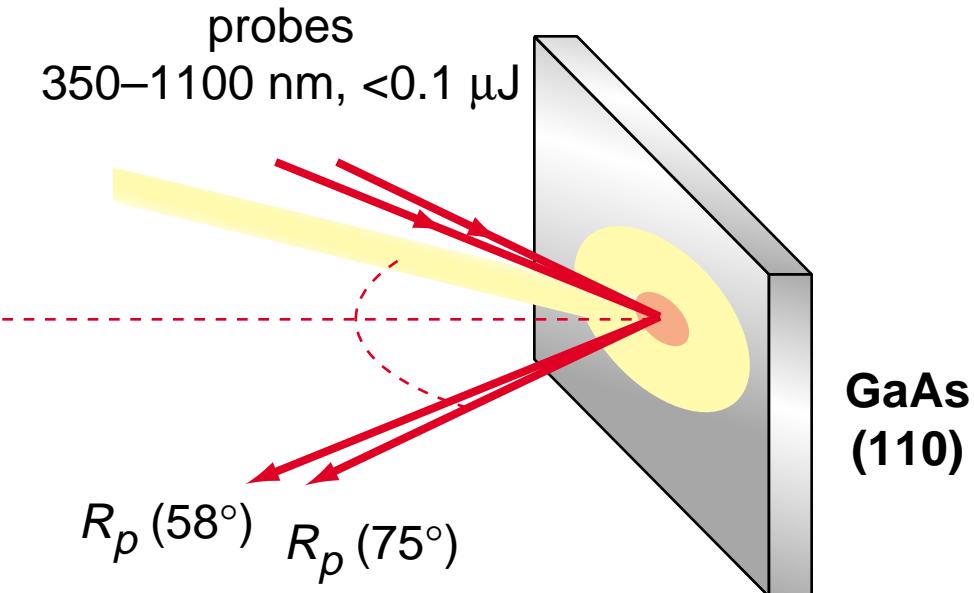
# *Electronic and structural transitions*



# *Electronic and structural transitions*



# *Electronic and structural transitions*

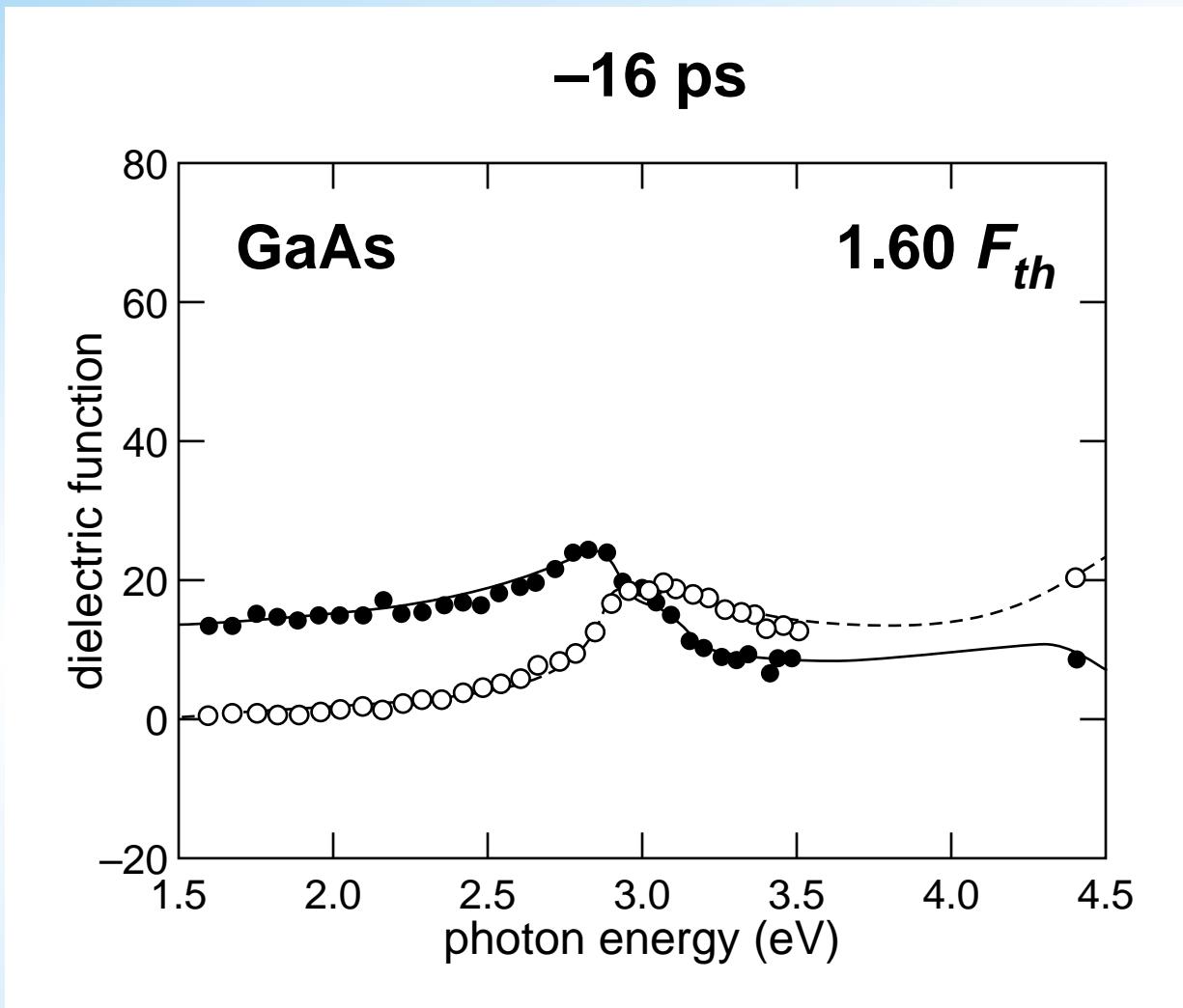


Fresnel  
equations

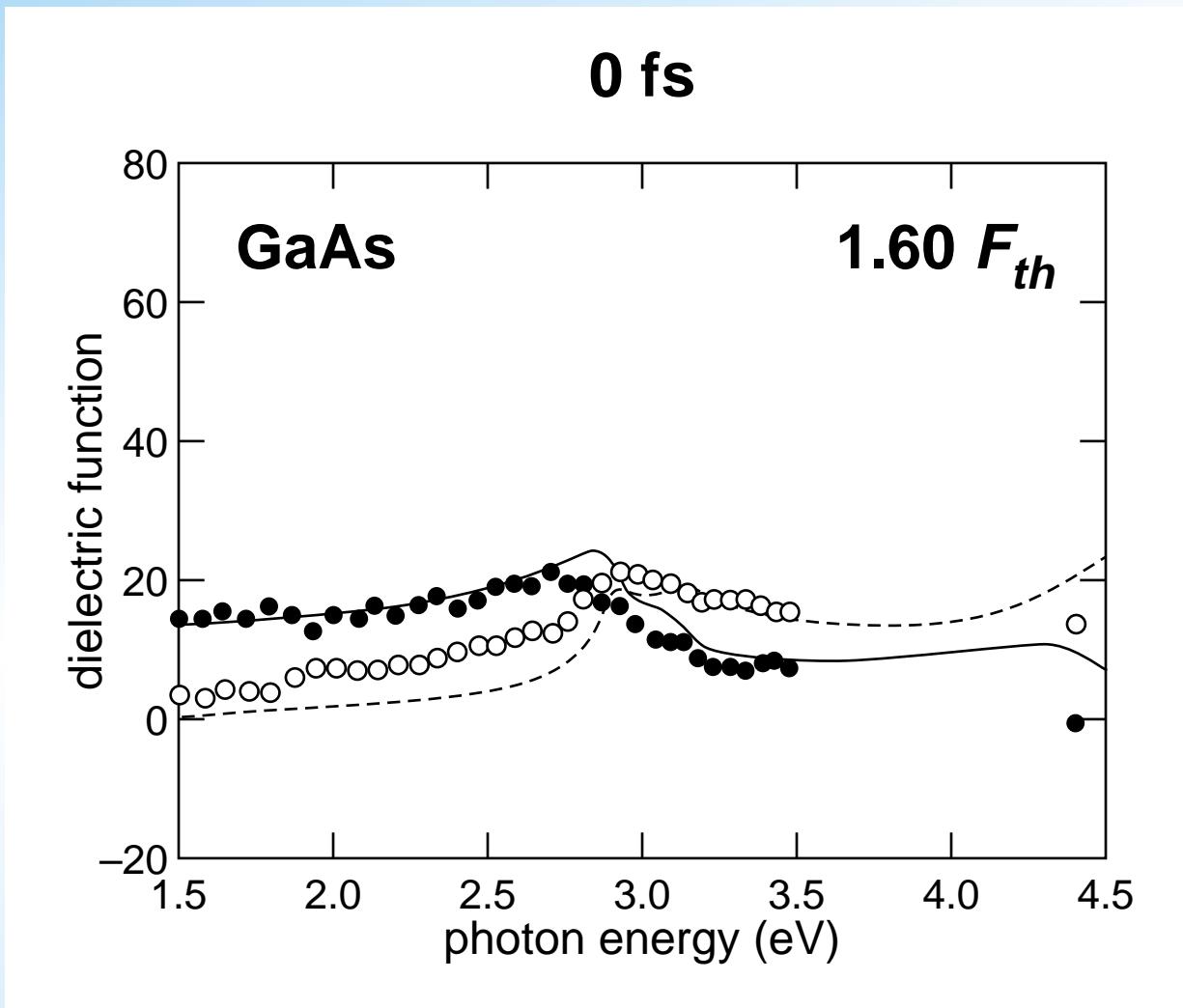


$\text{Re } \varepsilon(\omega)$   
 $\text{Im } \varepsilon(\omega)$

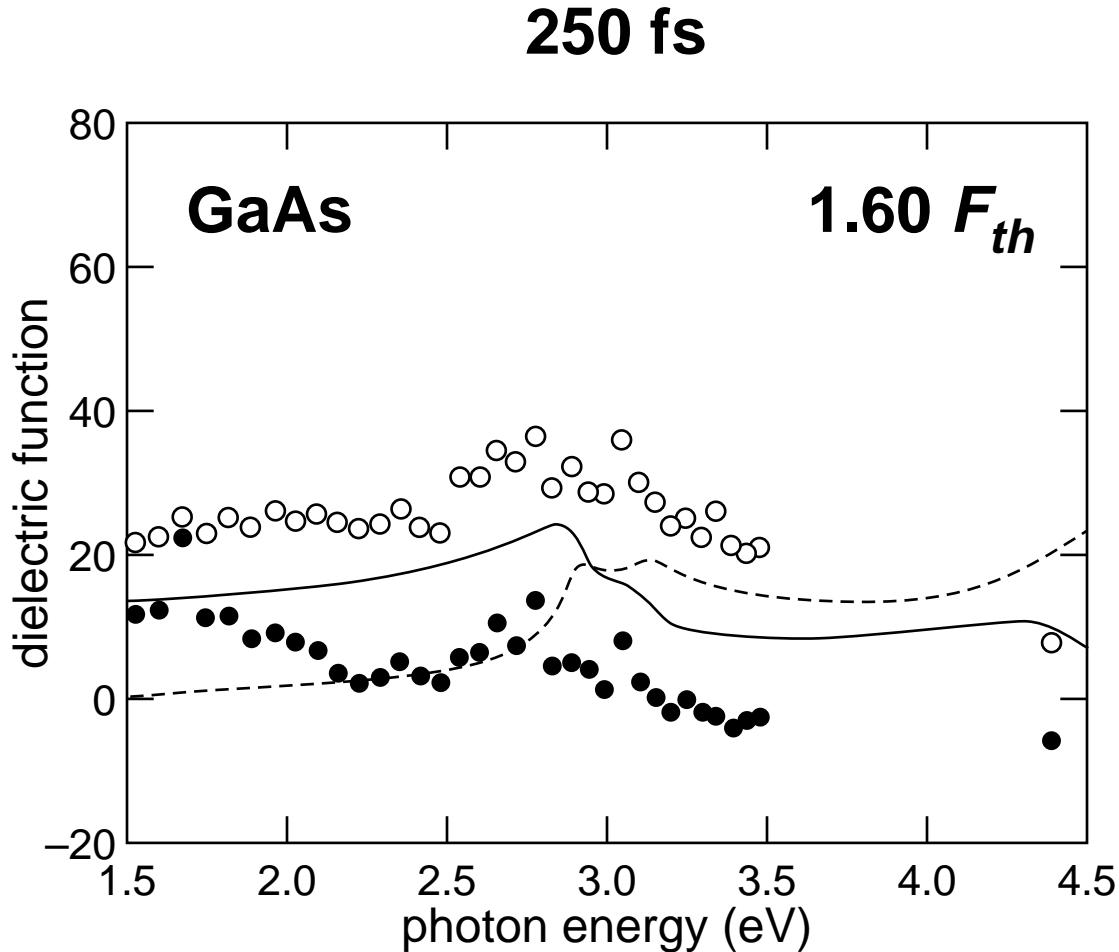
# *Electronic and structural transitions*



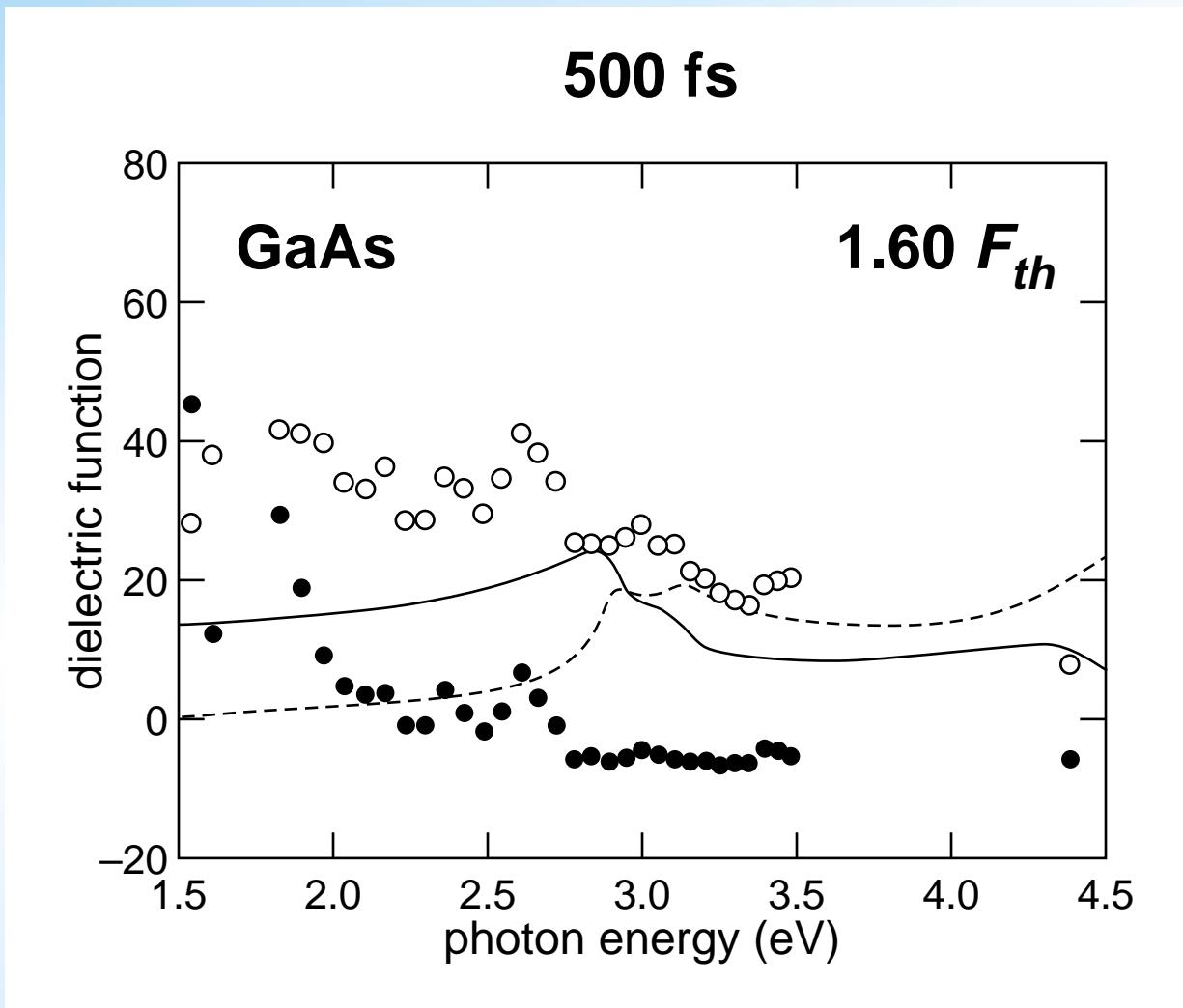
# *Electronic and structural transitions*



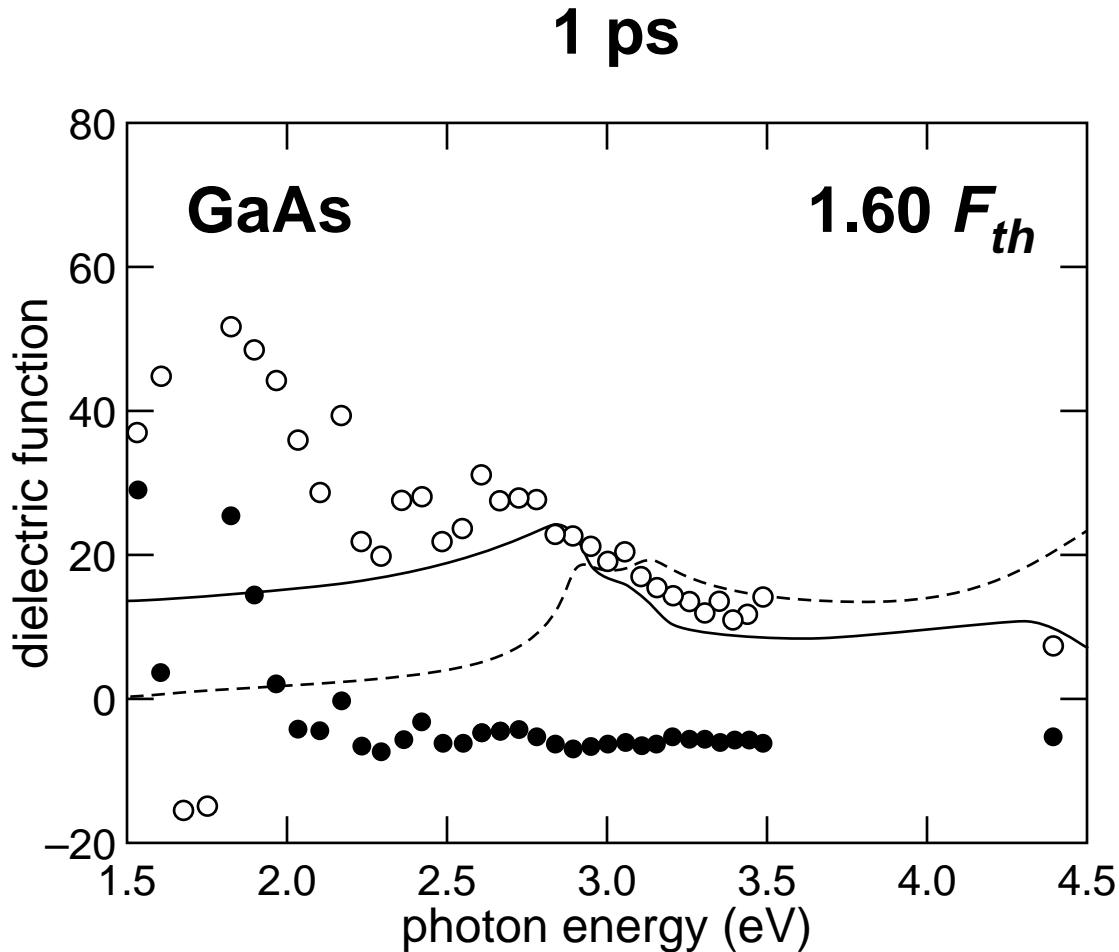
# *Electronic and structural transitions*



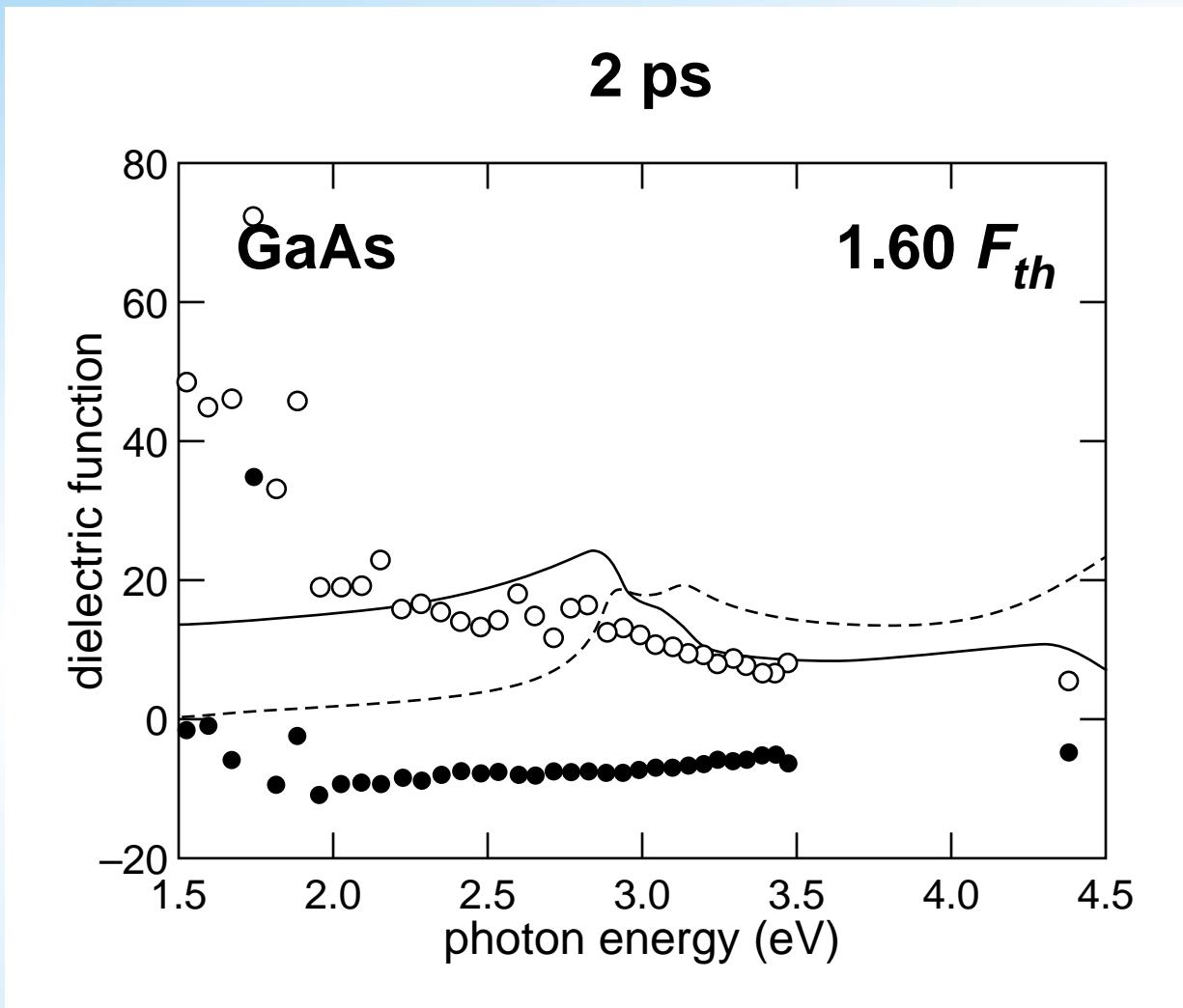
# *Electronic and structural transitions*



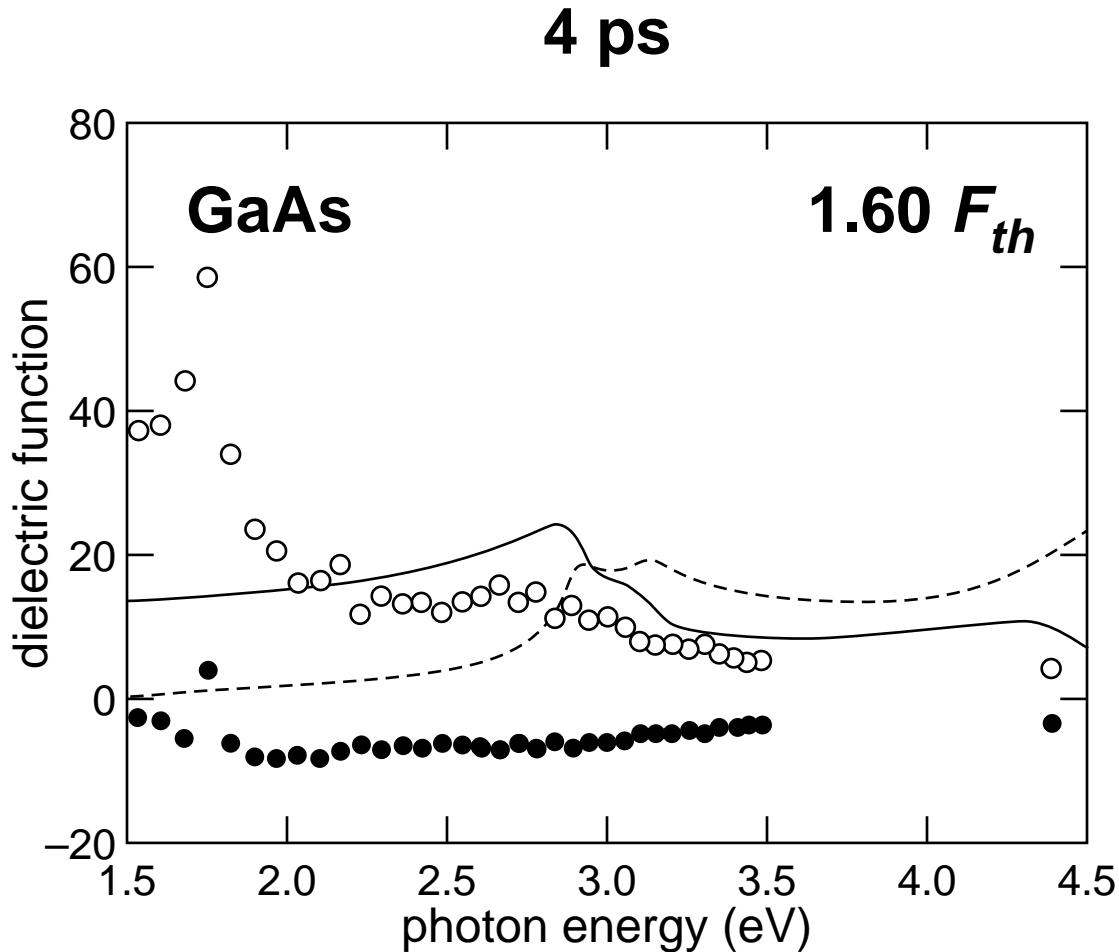
# *Electronic and structural transitions*



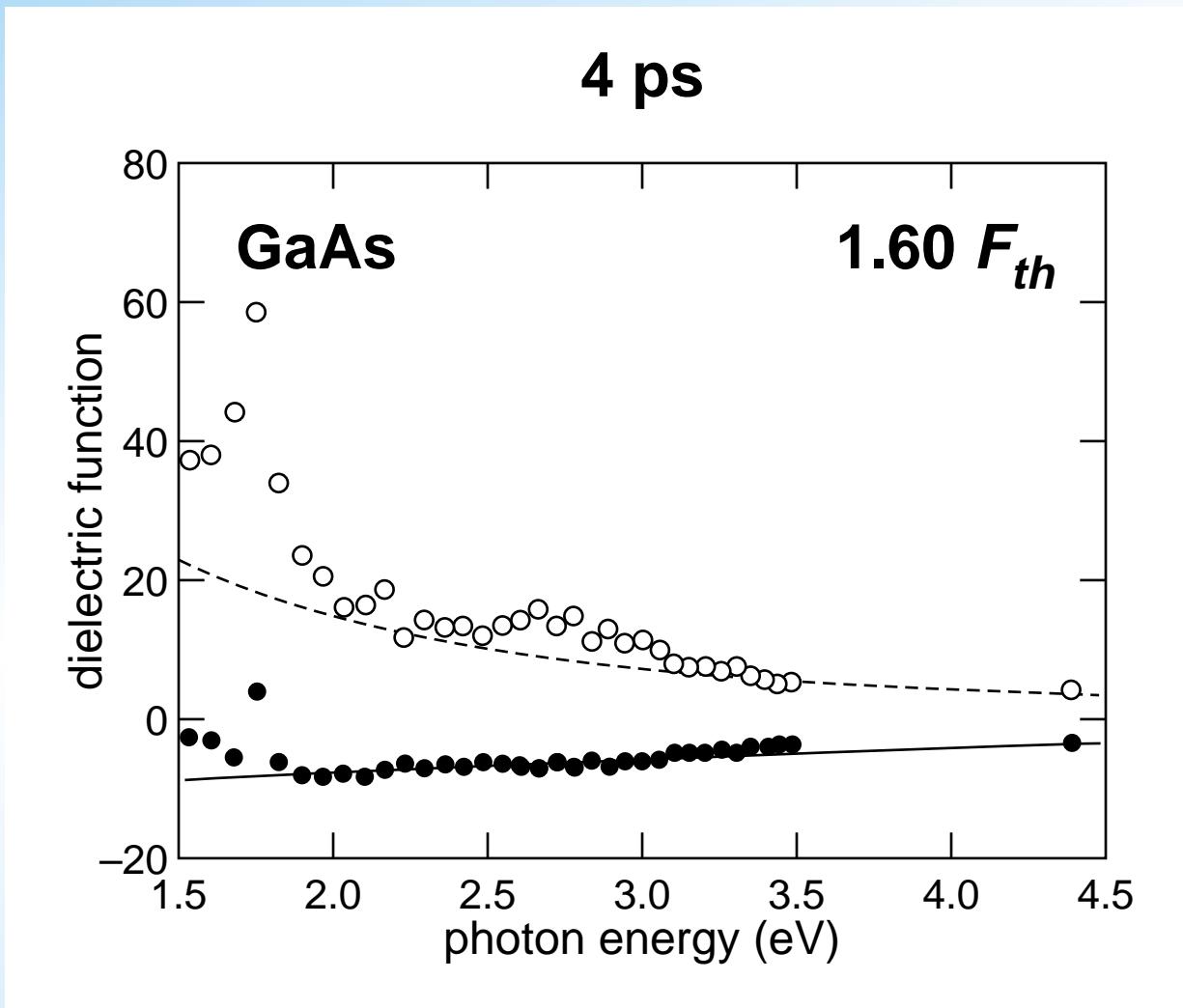
# *Electronic and structural transitions*



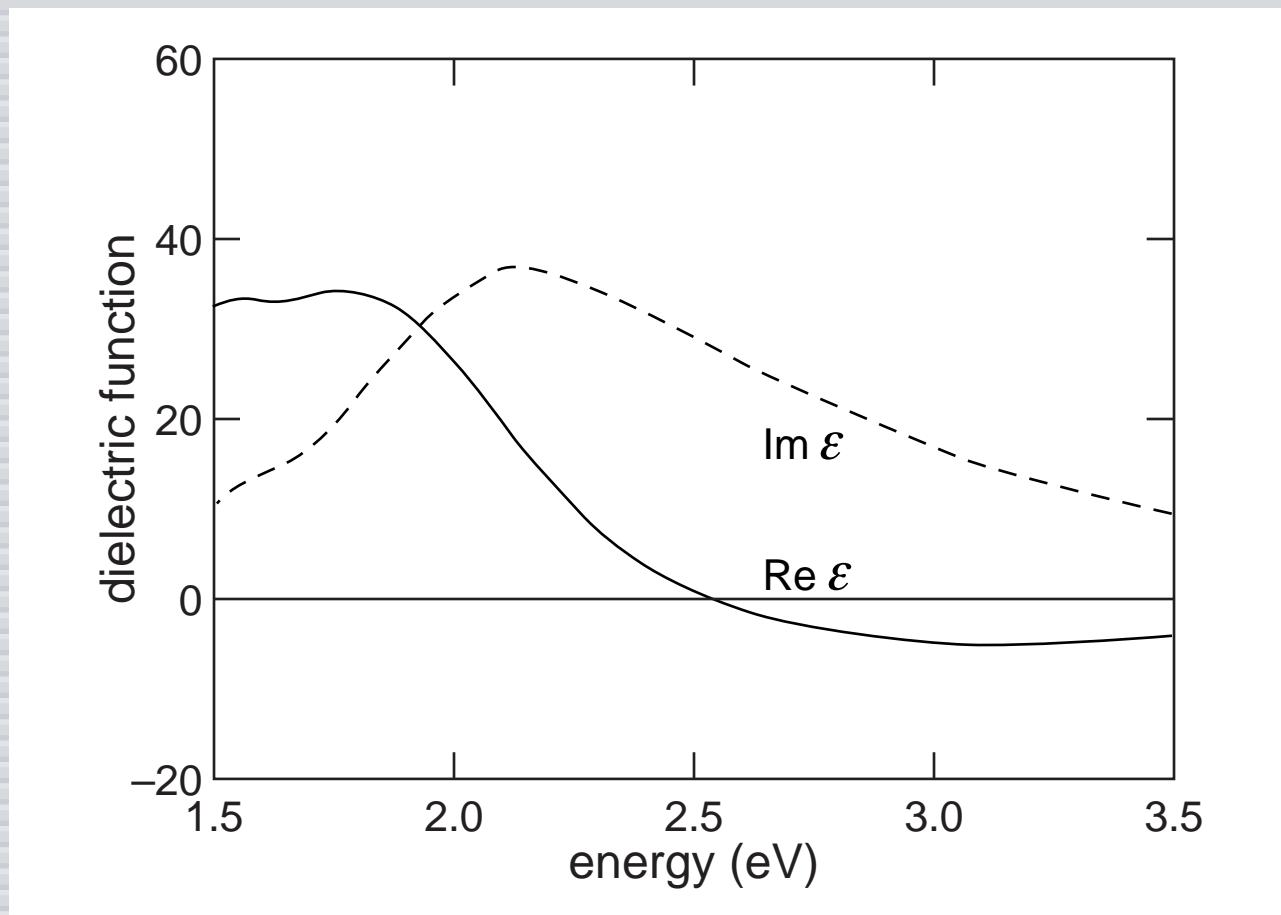
# *Electronic and structural transitions*



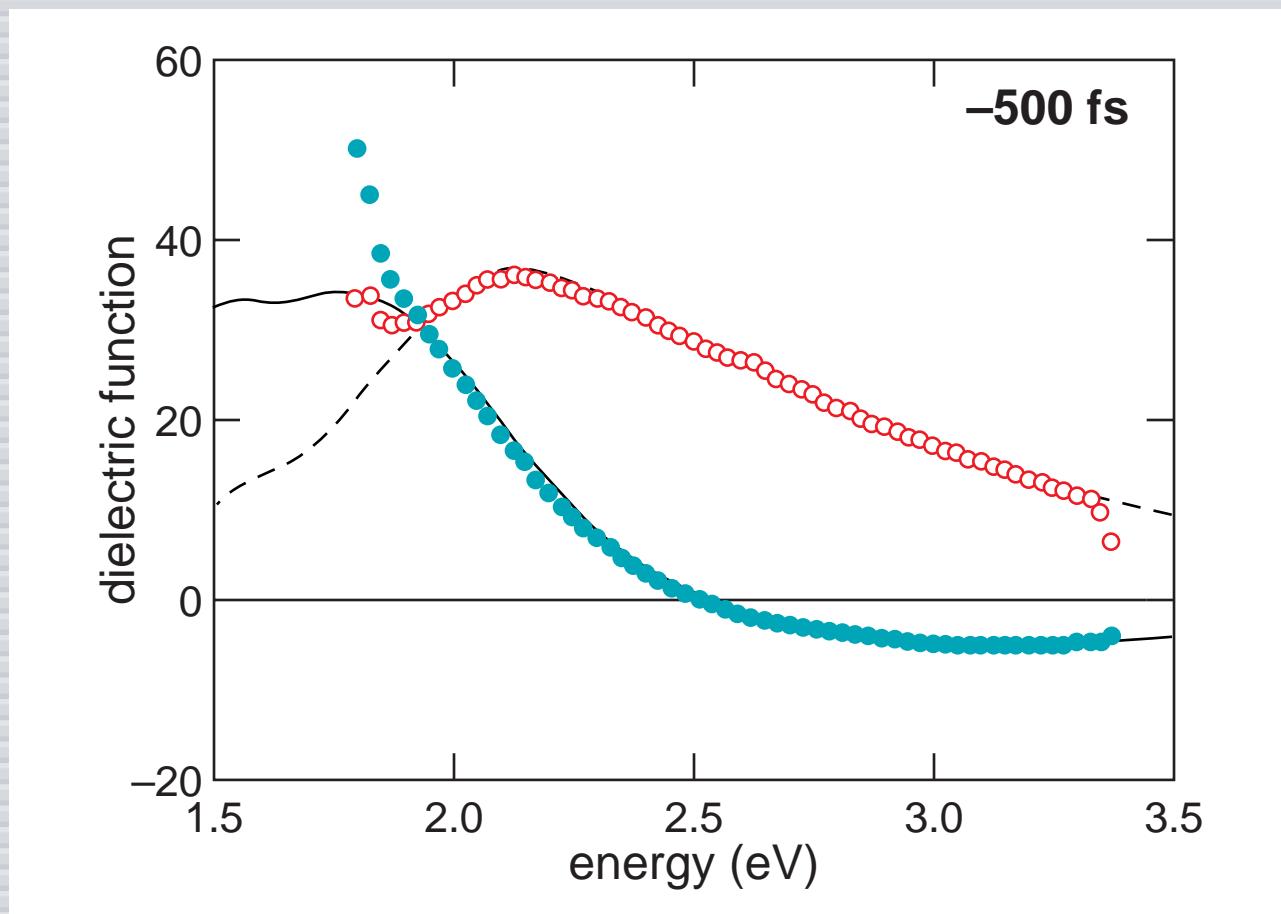
# *Electronic and structural transitions*



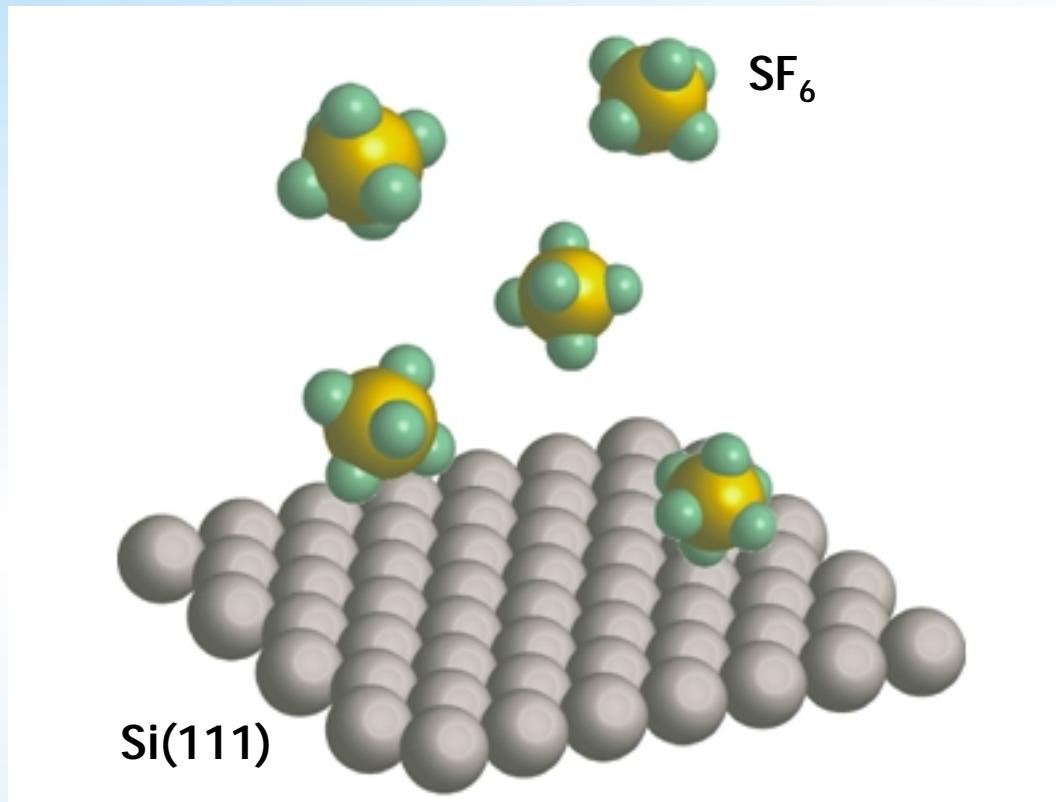
# Results



# *Results*

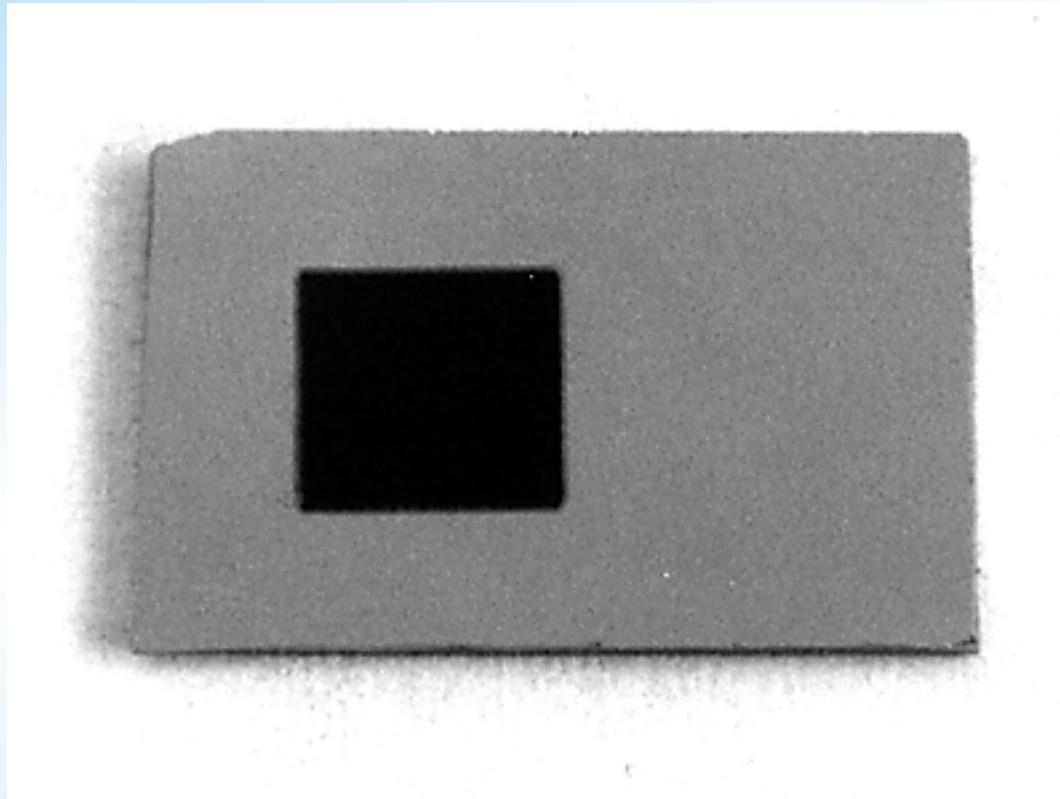


# *Microstructuring*



irradiate with 100 fs 10 kJ/m<sup>2</sup> laser pulses

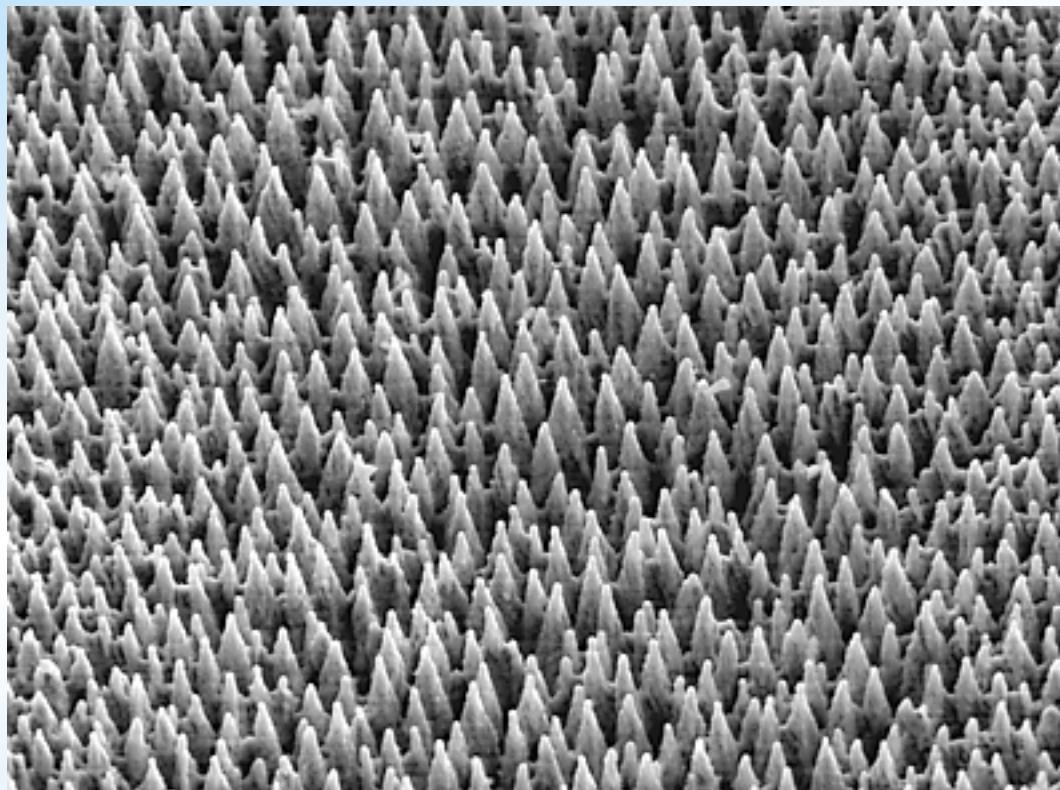
# *Microstructuring*



—

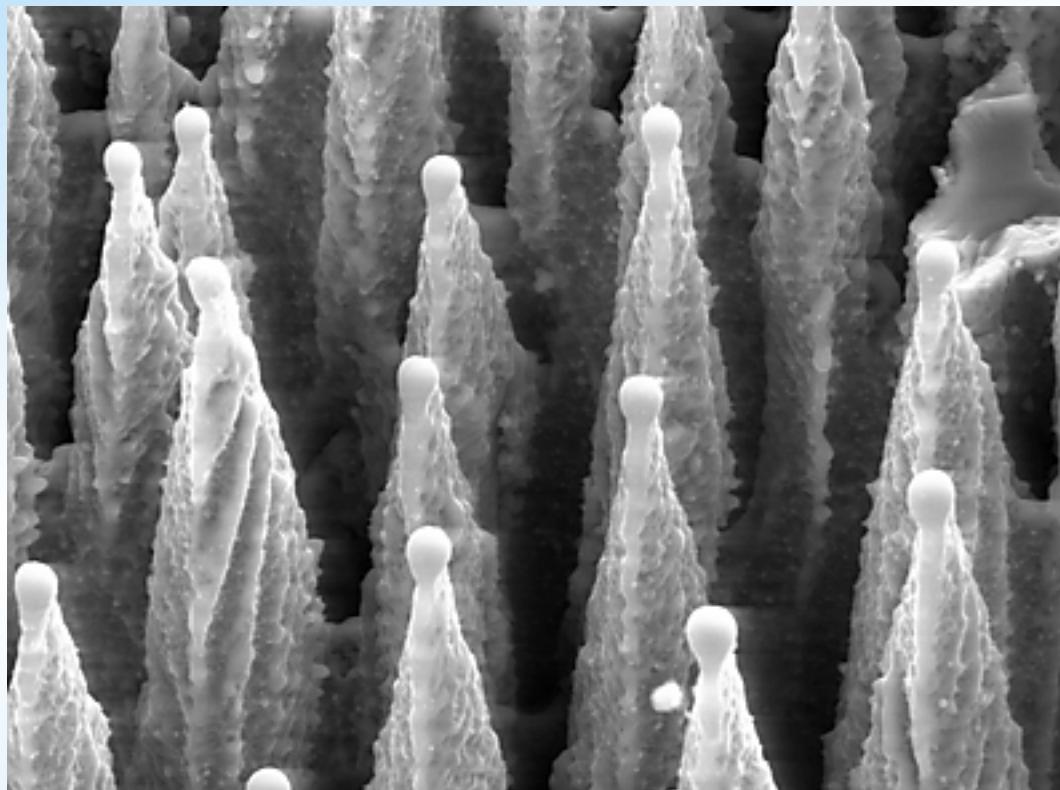
5 mm

# *Microstructuring*



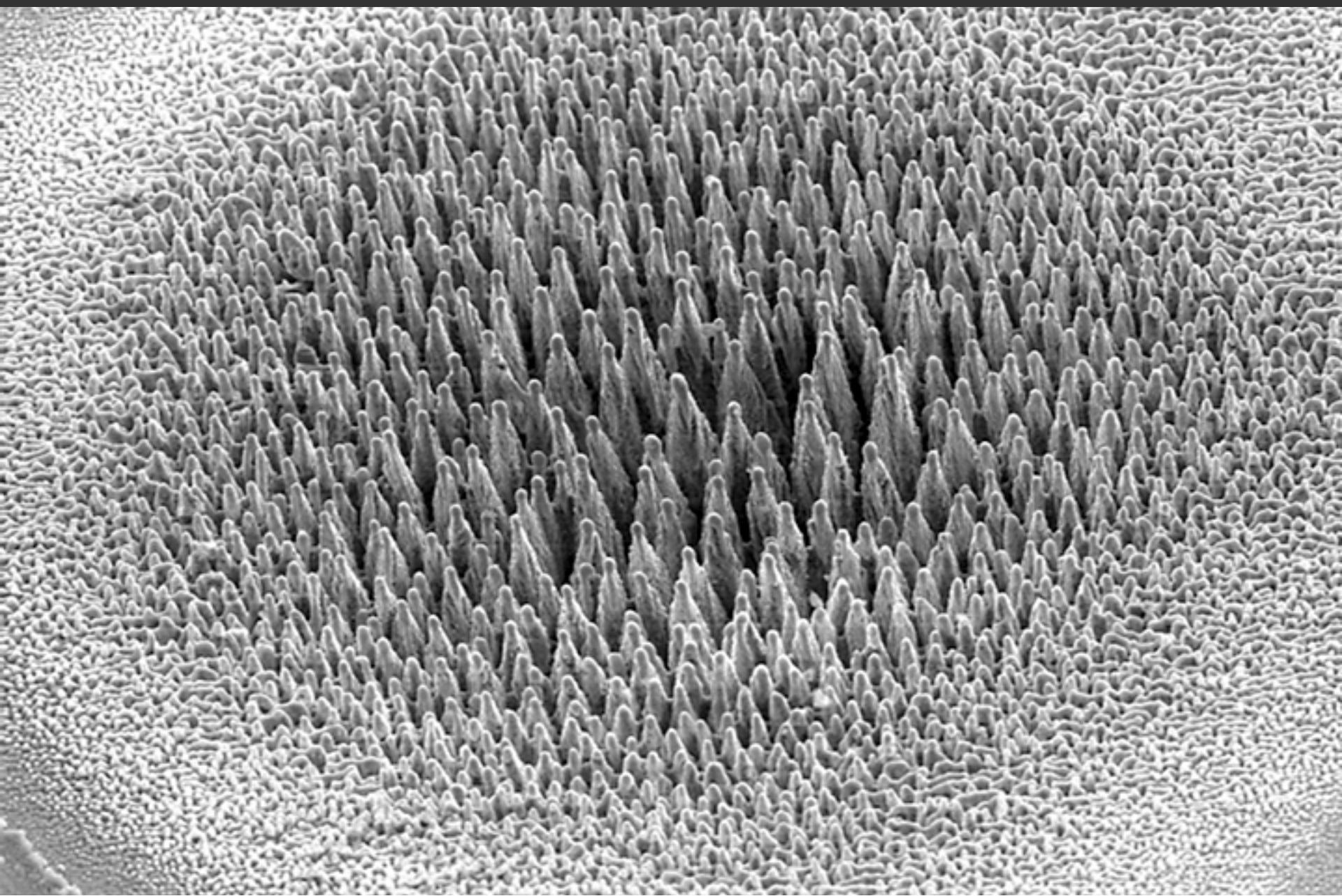
20  $\mu\text{m}$

# *Microstructuring*



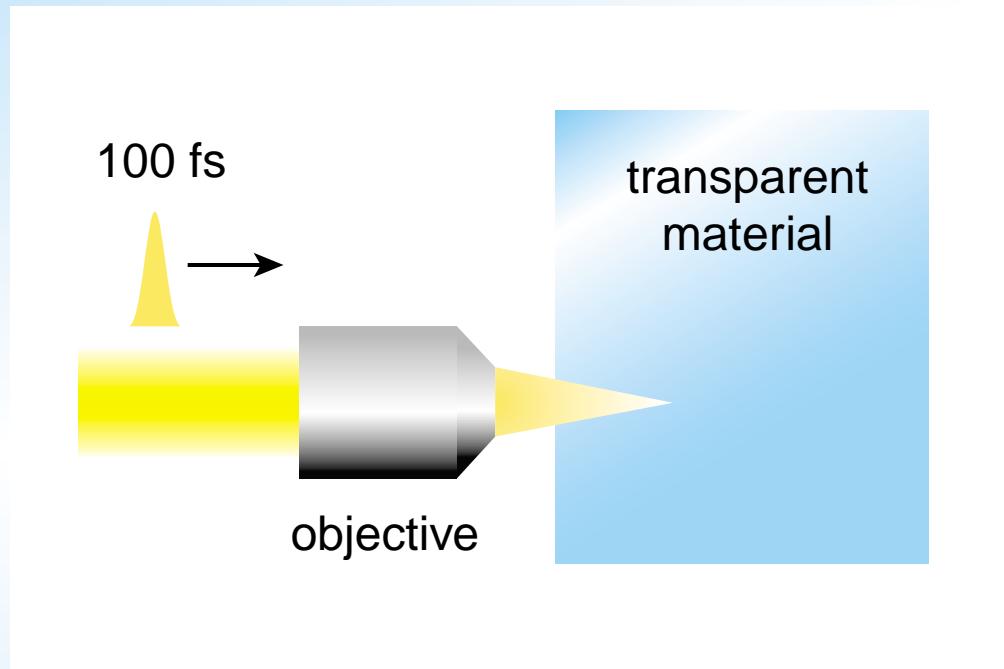
4  $\mu\text{m}$

# *Microstructuring*



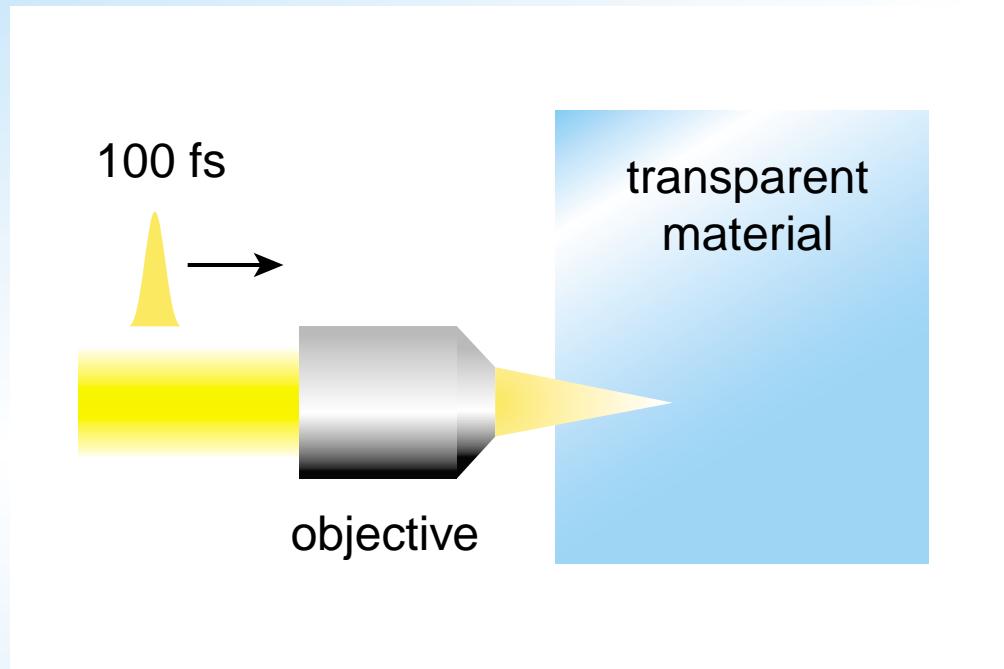
# *Microstructuring*

focus laser beam inside material...



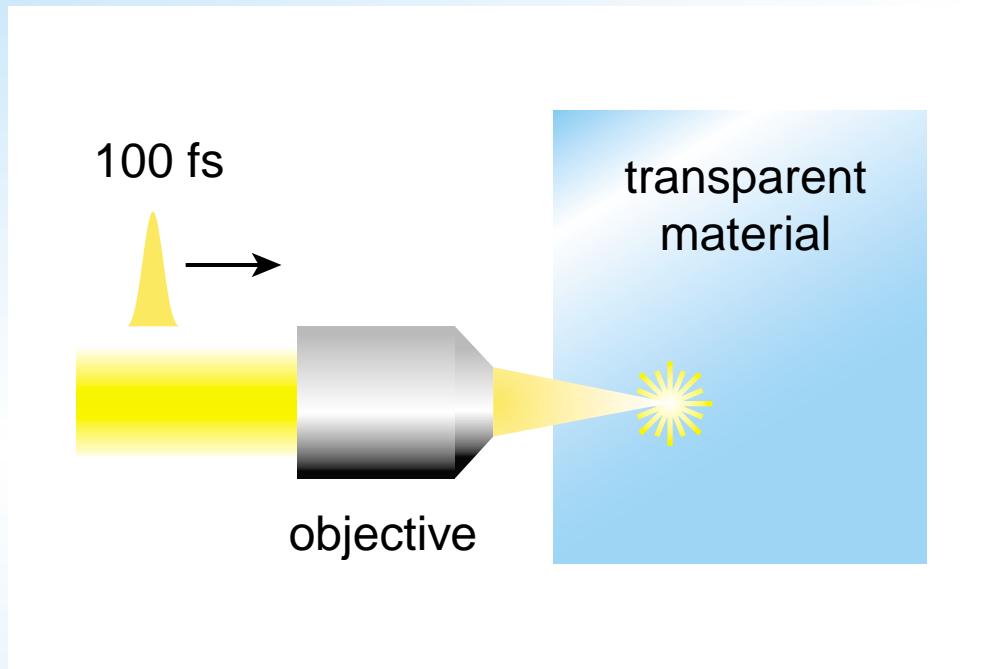
# *Microstructuring*

high intensity at focus...



# *Microstructuring*

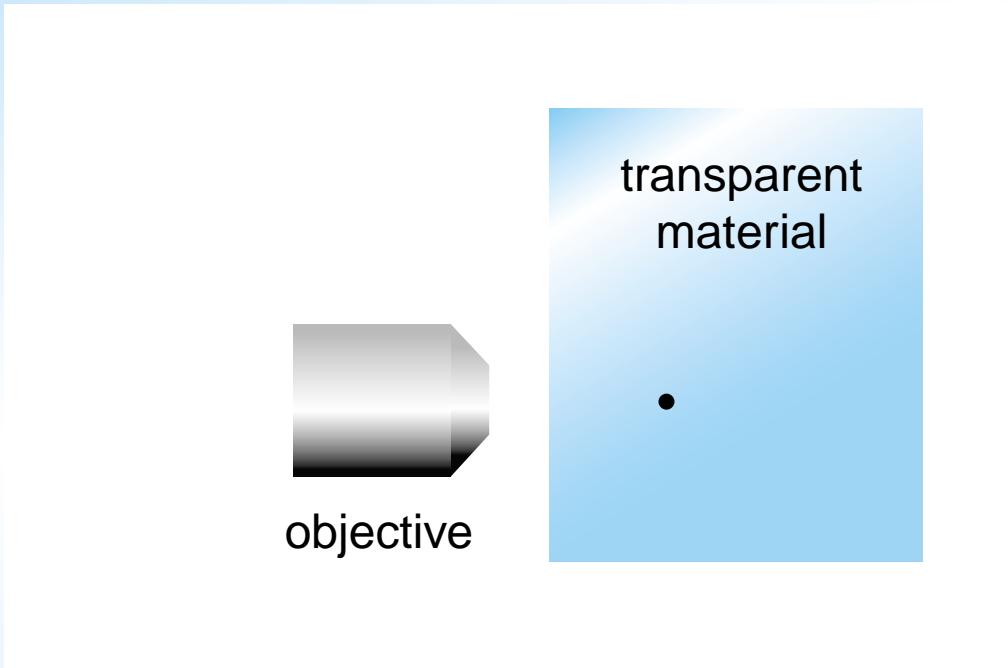
... causes nonlinear ionization...



Glezer, et al., *Opt. Lett.* 21, 2023 (1996)

# *Microstructuring*

## and microscopic bulk damage



Glezer, et al., *Opt. Lett.* 21, 2023 (1996)

# *Microstructuring*

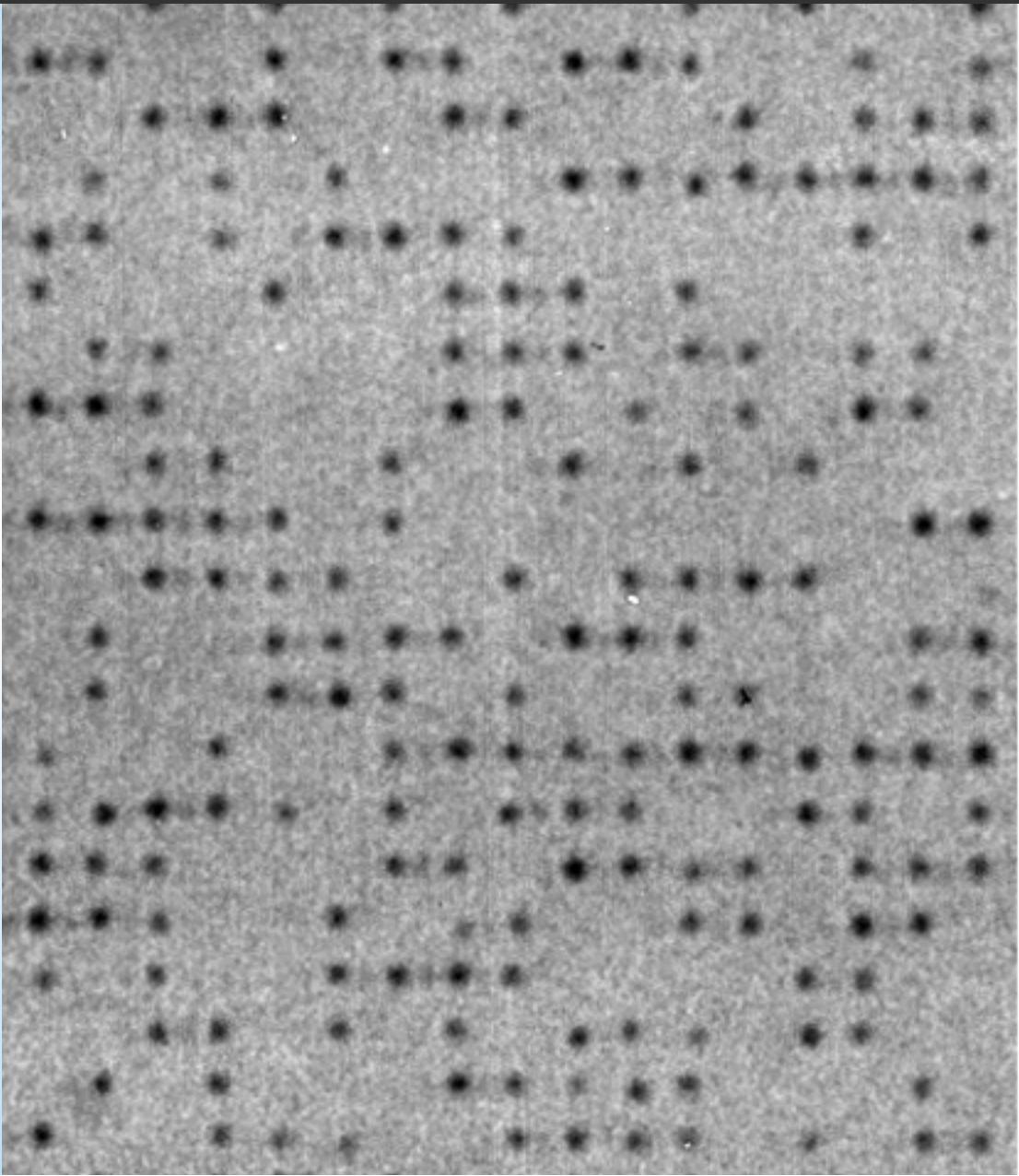
optical microscopy

$2 \times 2 \mu\text{m}$  array

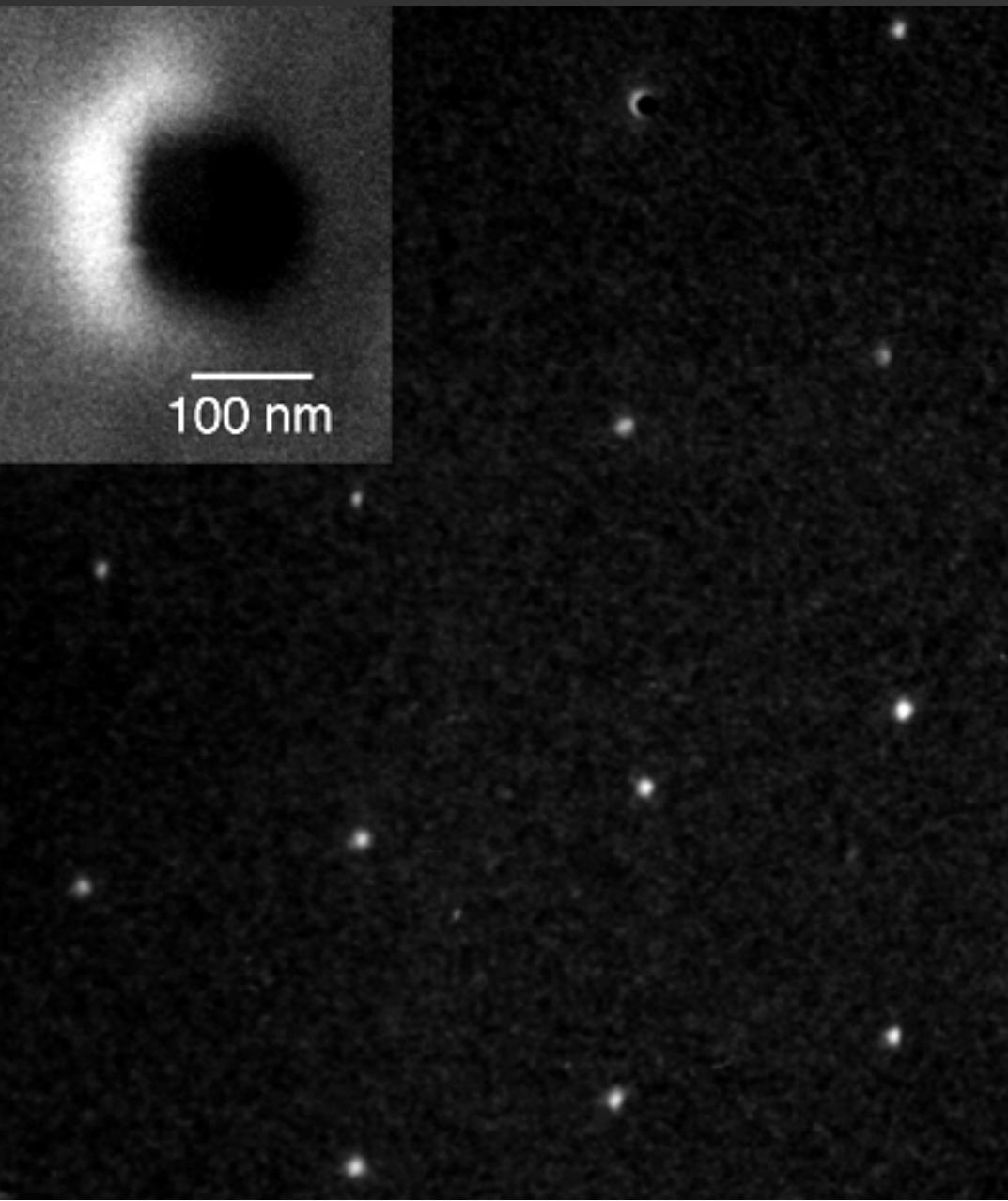
fused silica

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

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



# *Microstructuring*

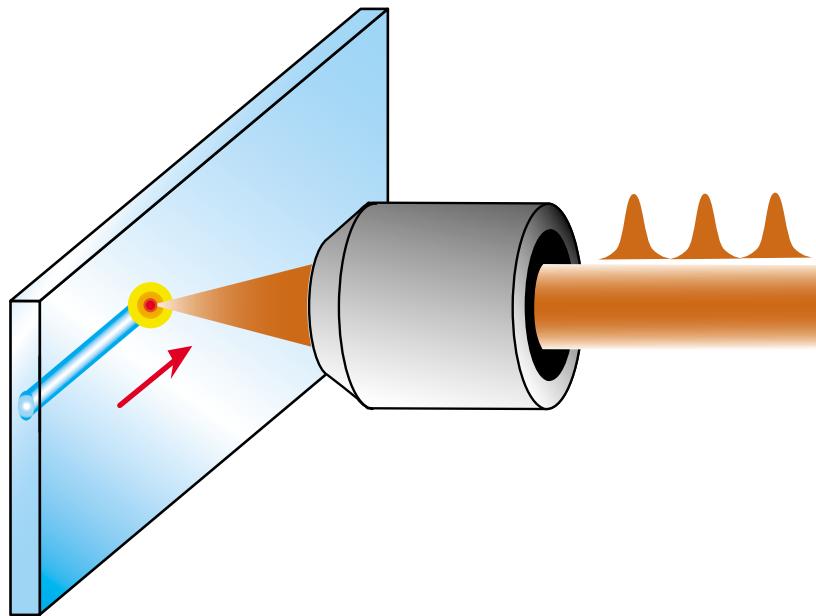


SEM:

bumps & pits!

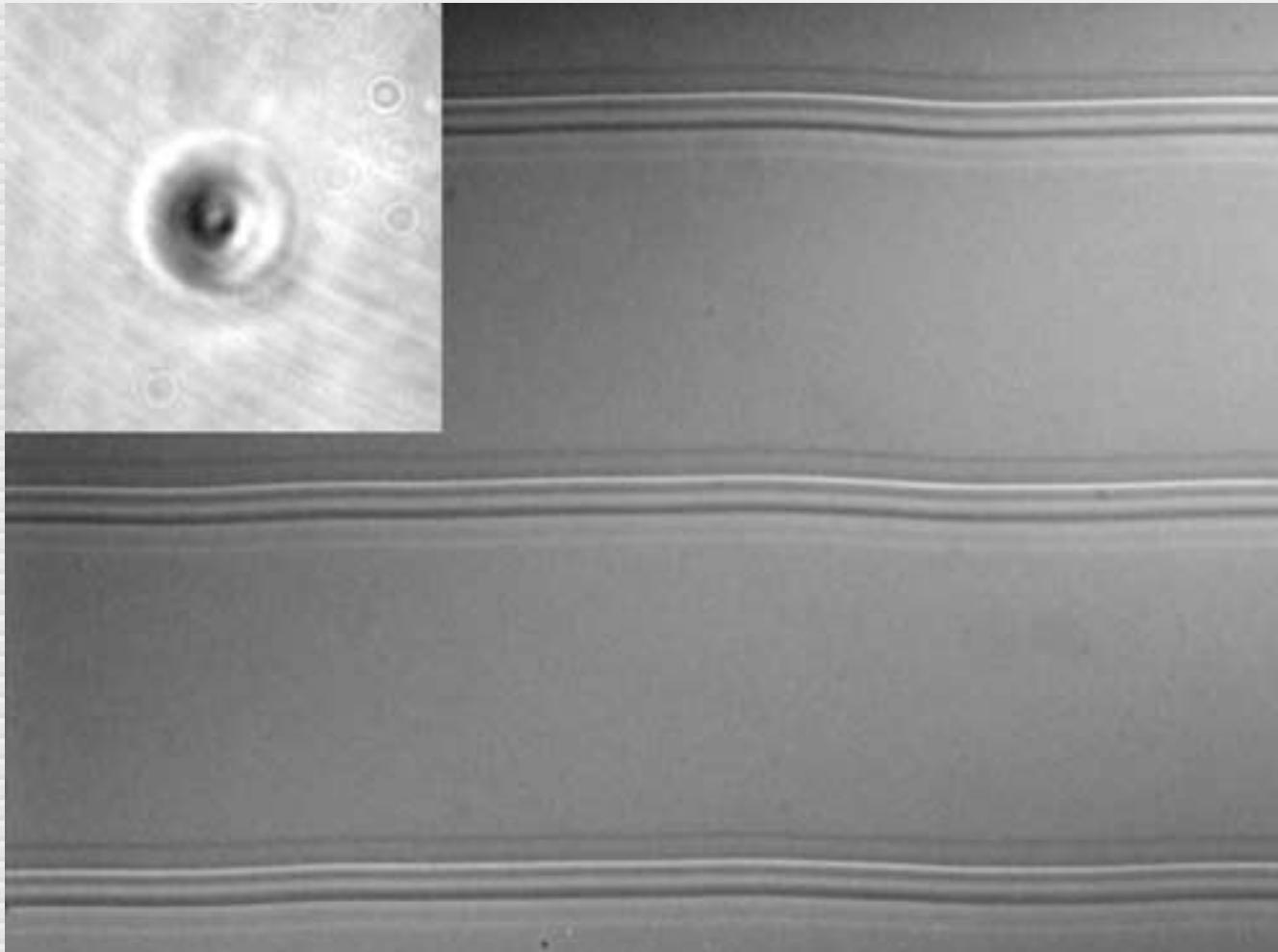
*Low-energy processing*

## waveguide machining



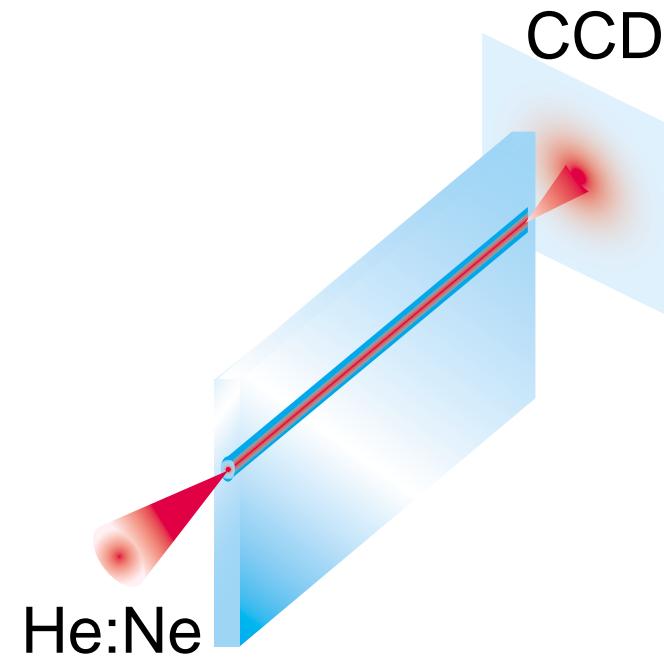
*Low-energy processing*

## waveguide machining



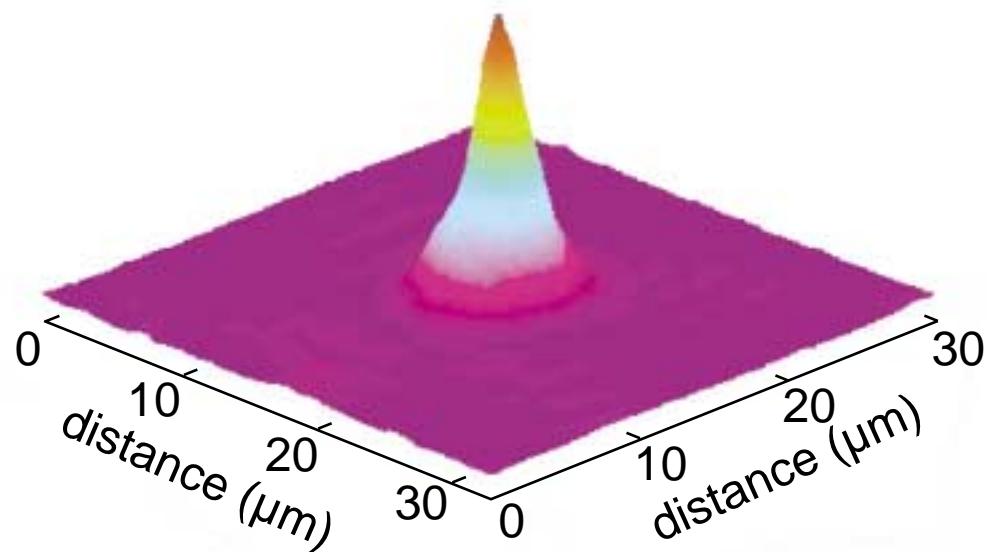
*Low-energy processing*

## waveguide mode analysis



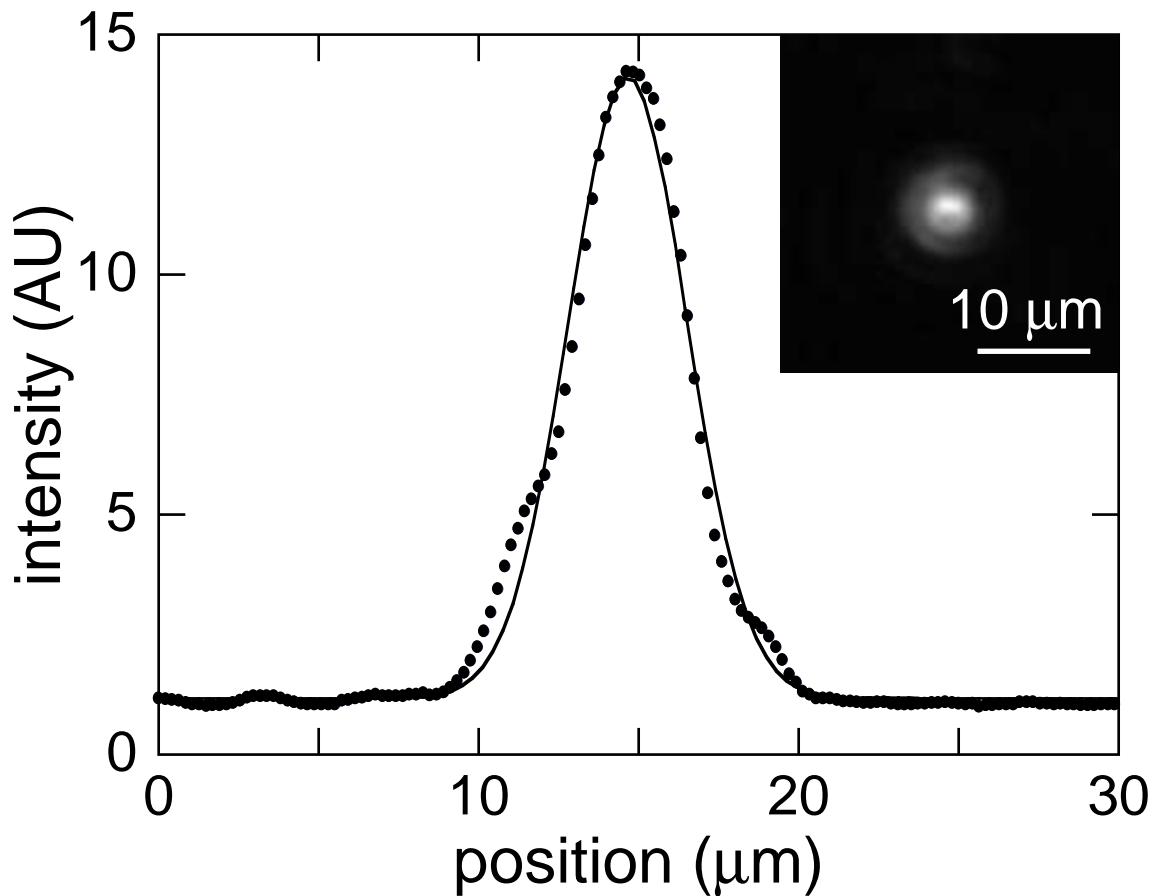
# *Low-energy processing*

## **near field mode**



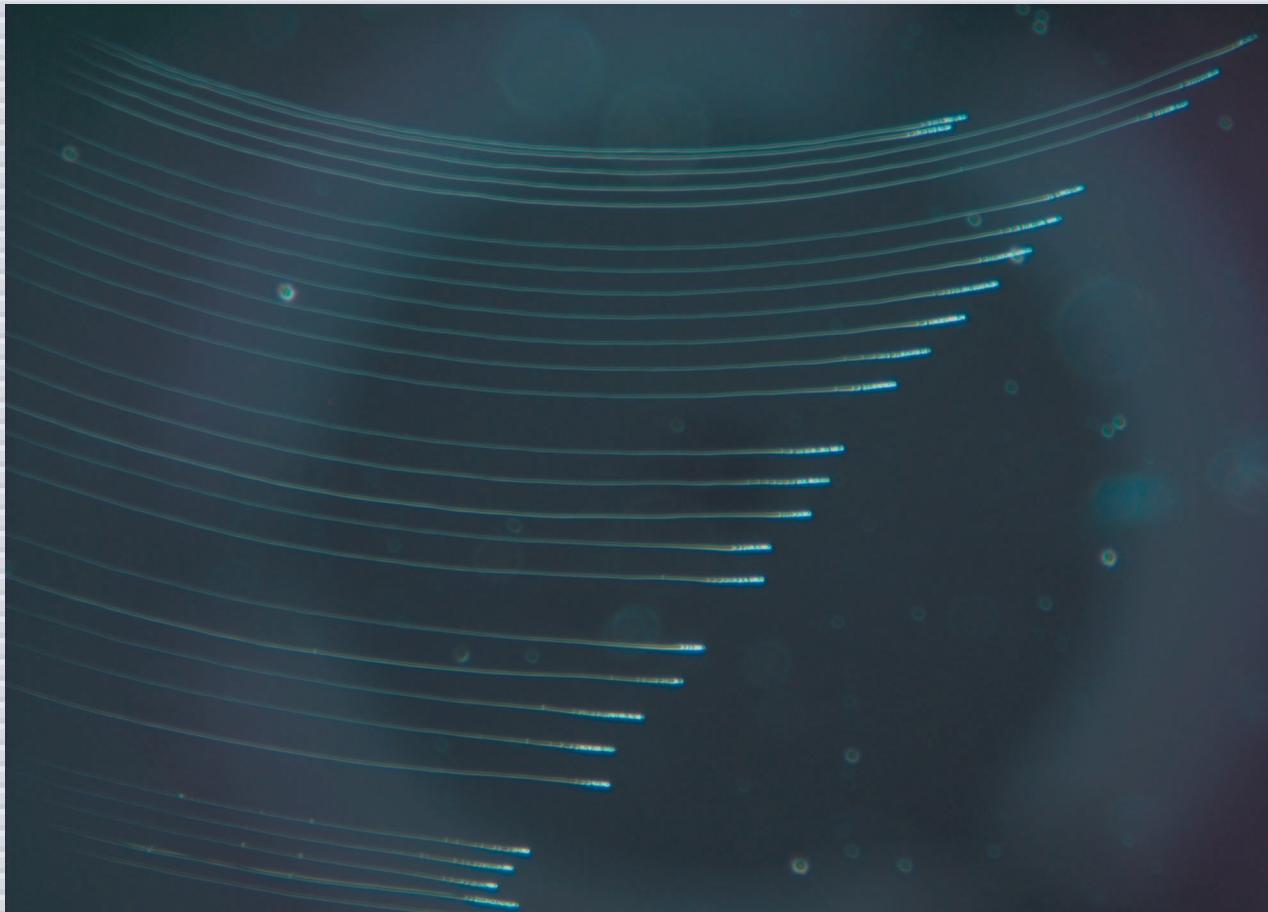
# *Low-energy processing*

## **near field mode**



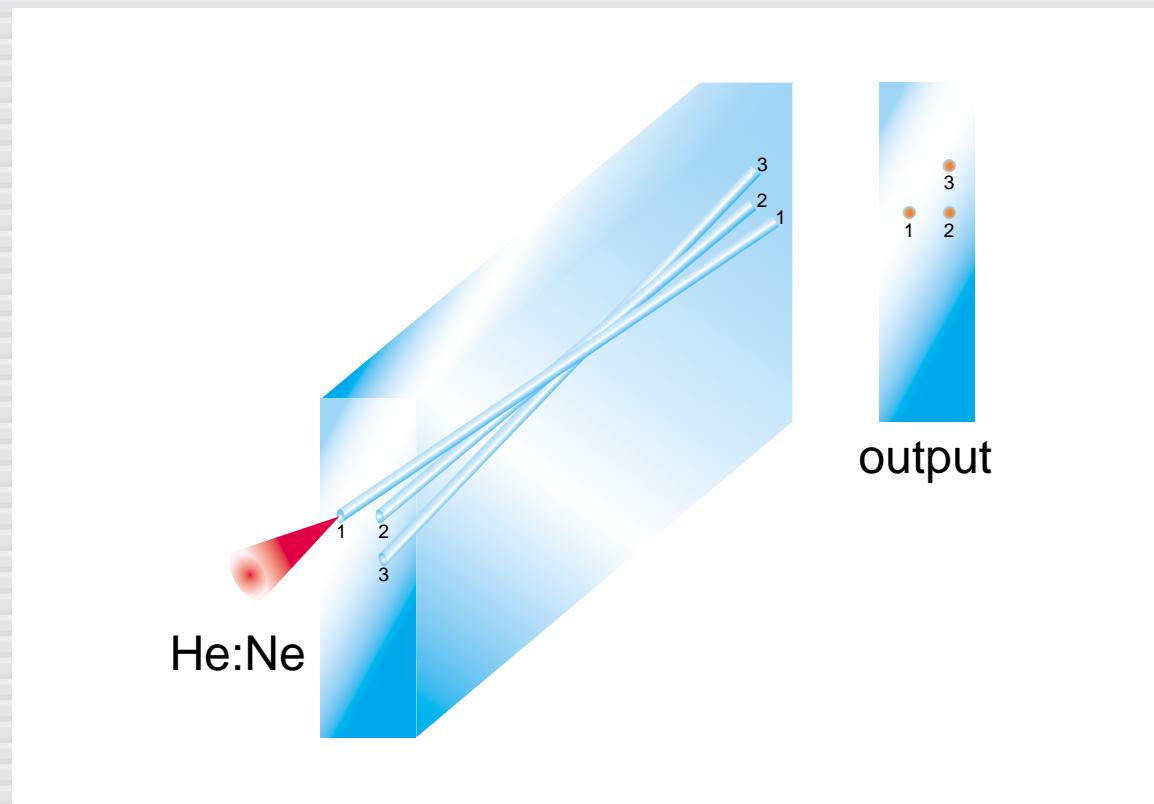
*Low-energy processing*

**curved waveguides**



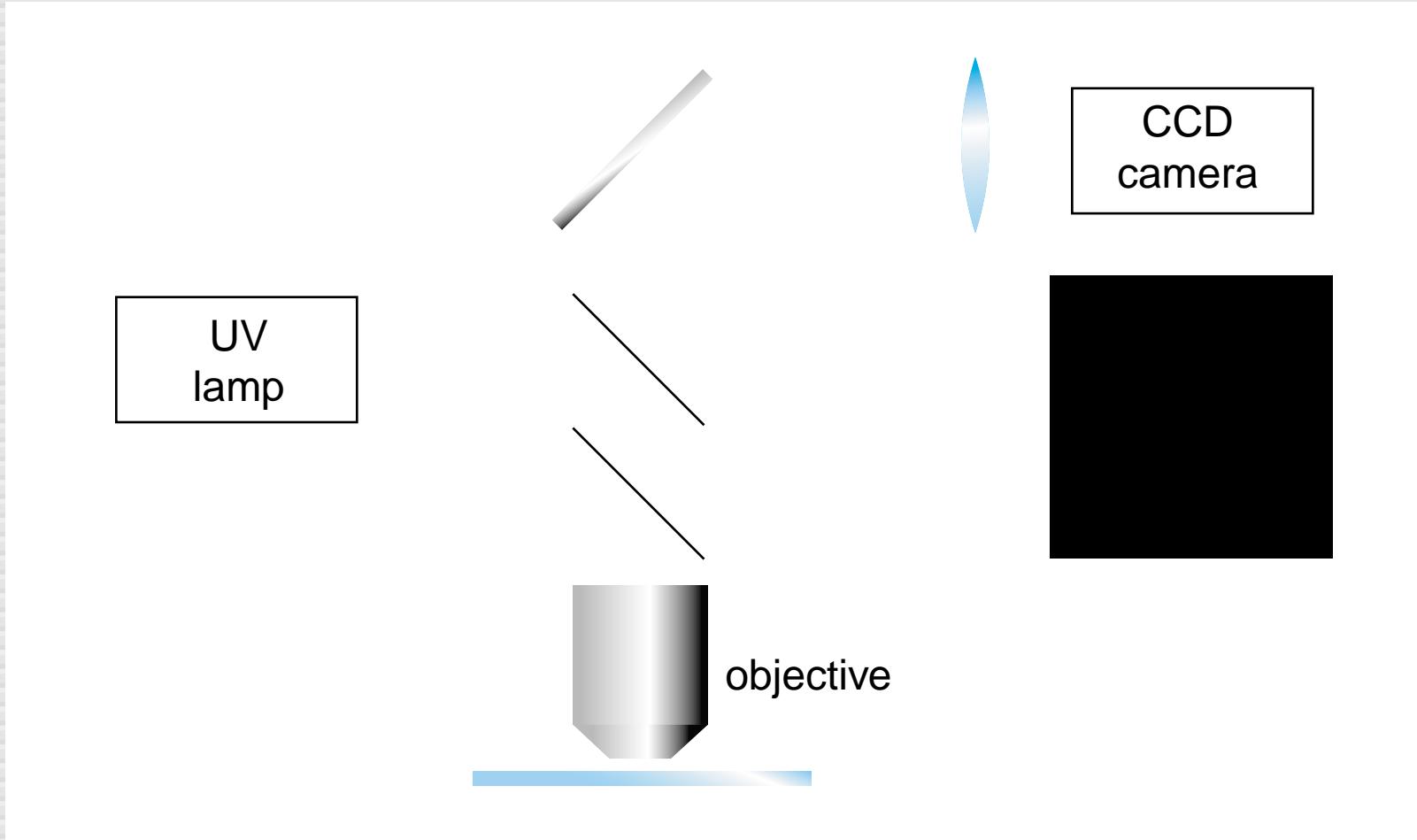
# *Low-energy processing*

## 3D wave splitter



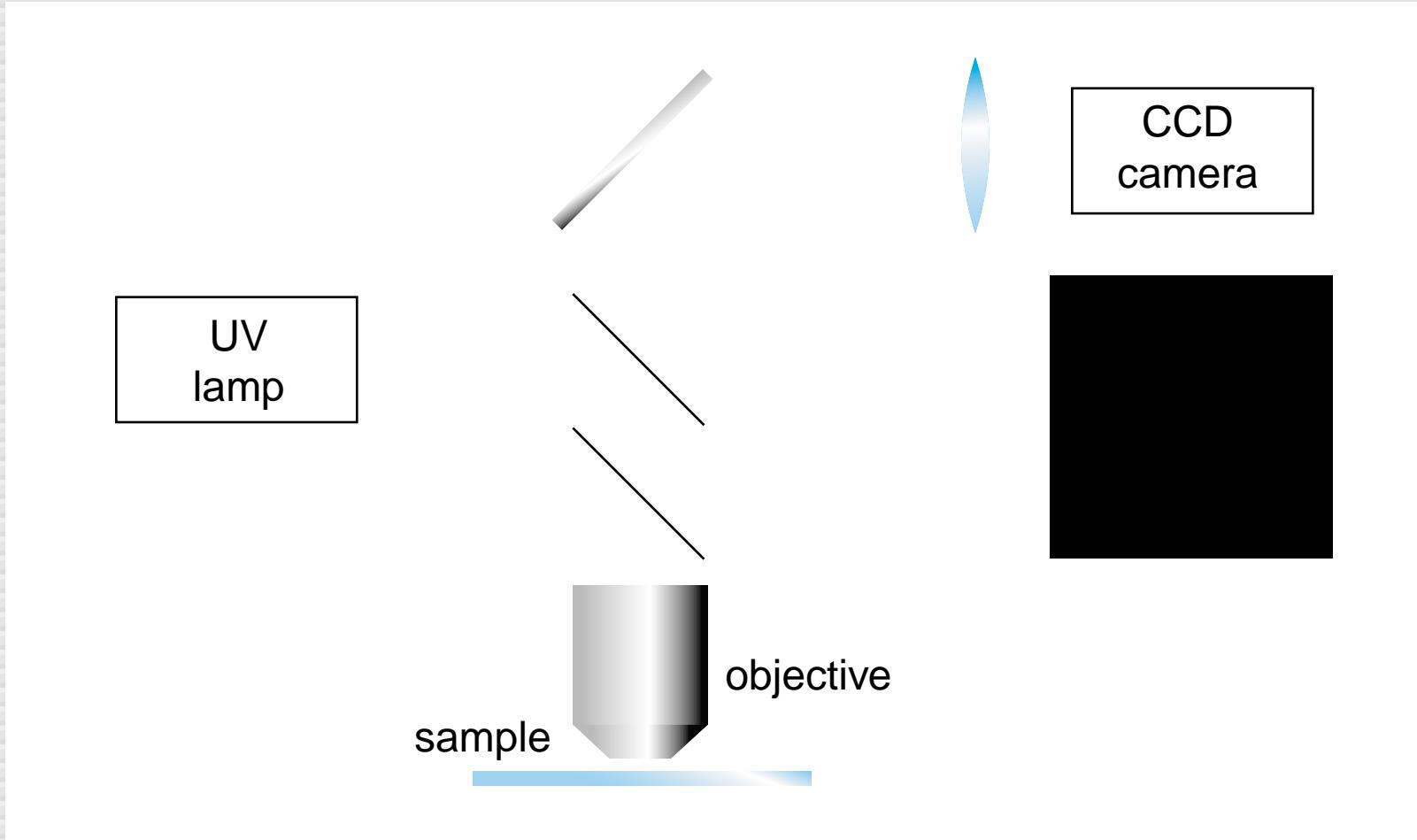
# *Low-energy processing*

## epi-fluorescence microscope



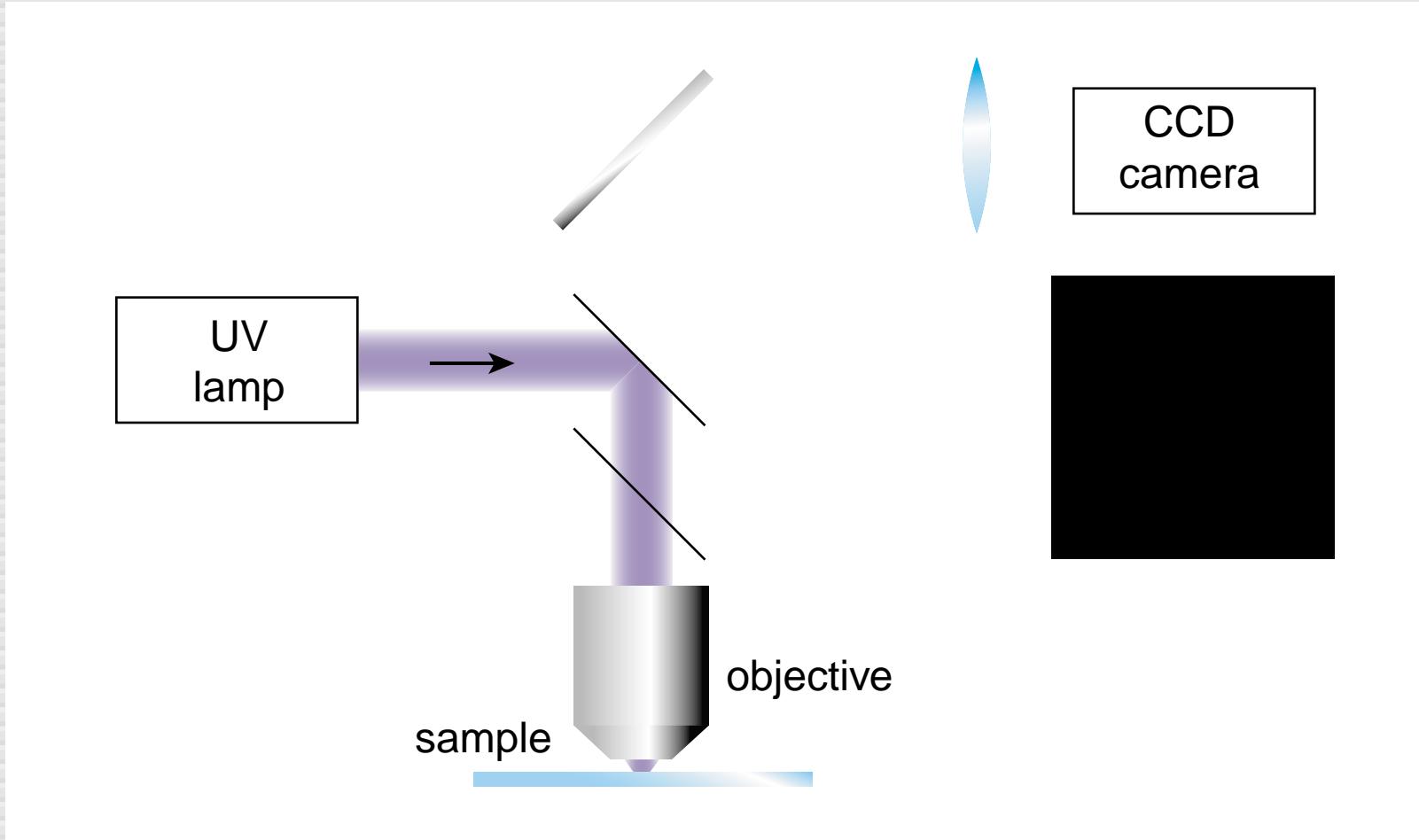
# *Biology and medicine*

## mount fluorescently tagged sample



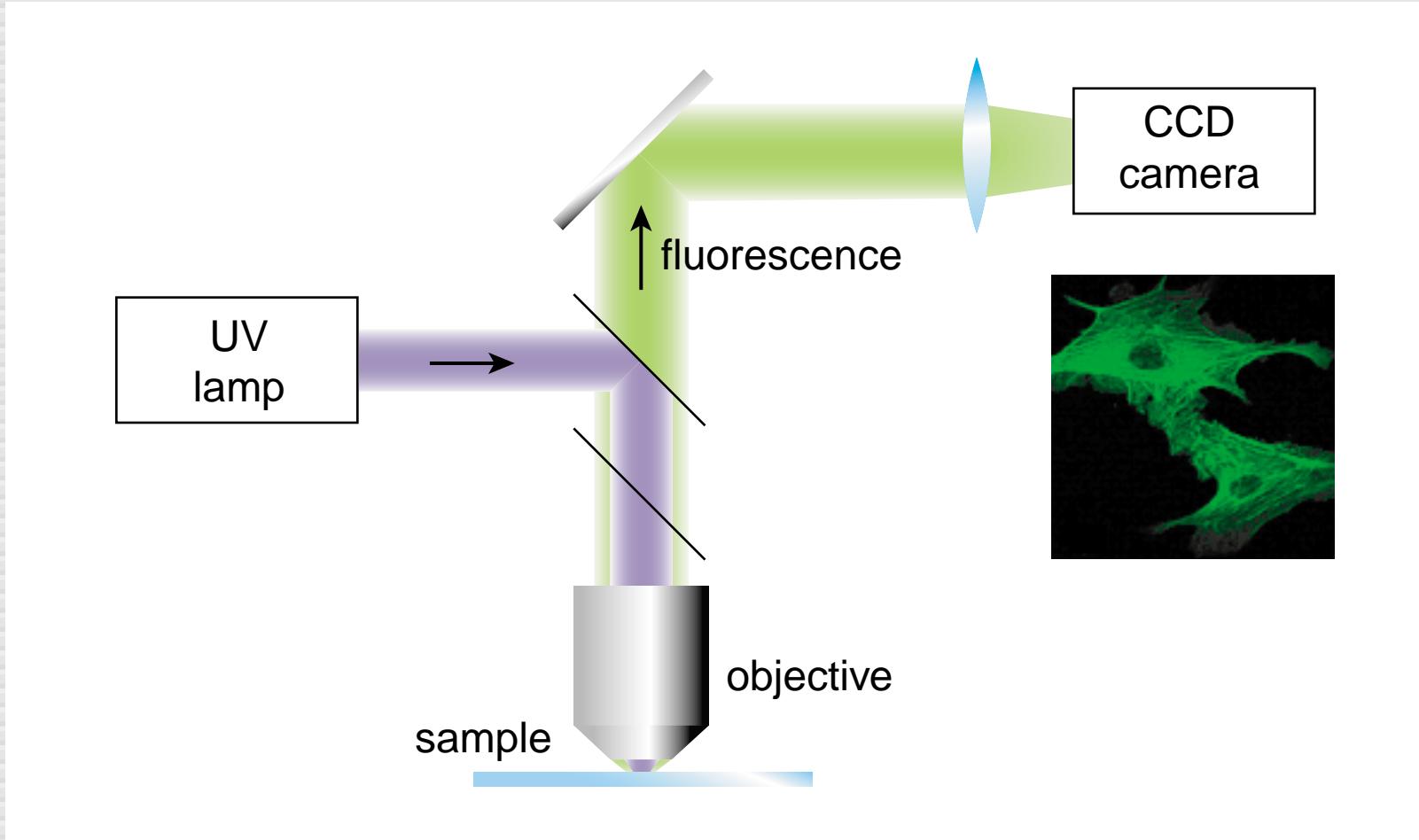
# *Biology and medicine*

## UV illumination...



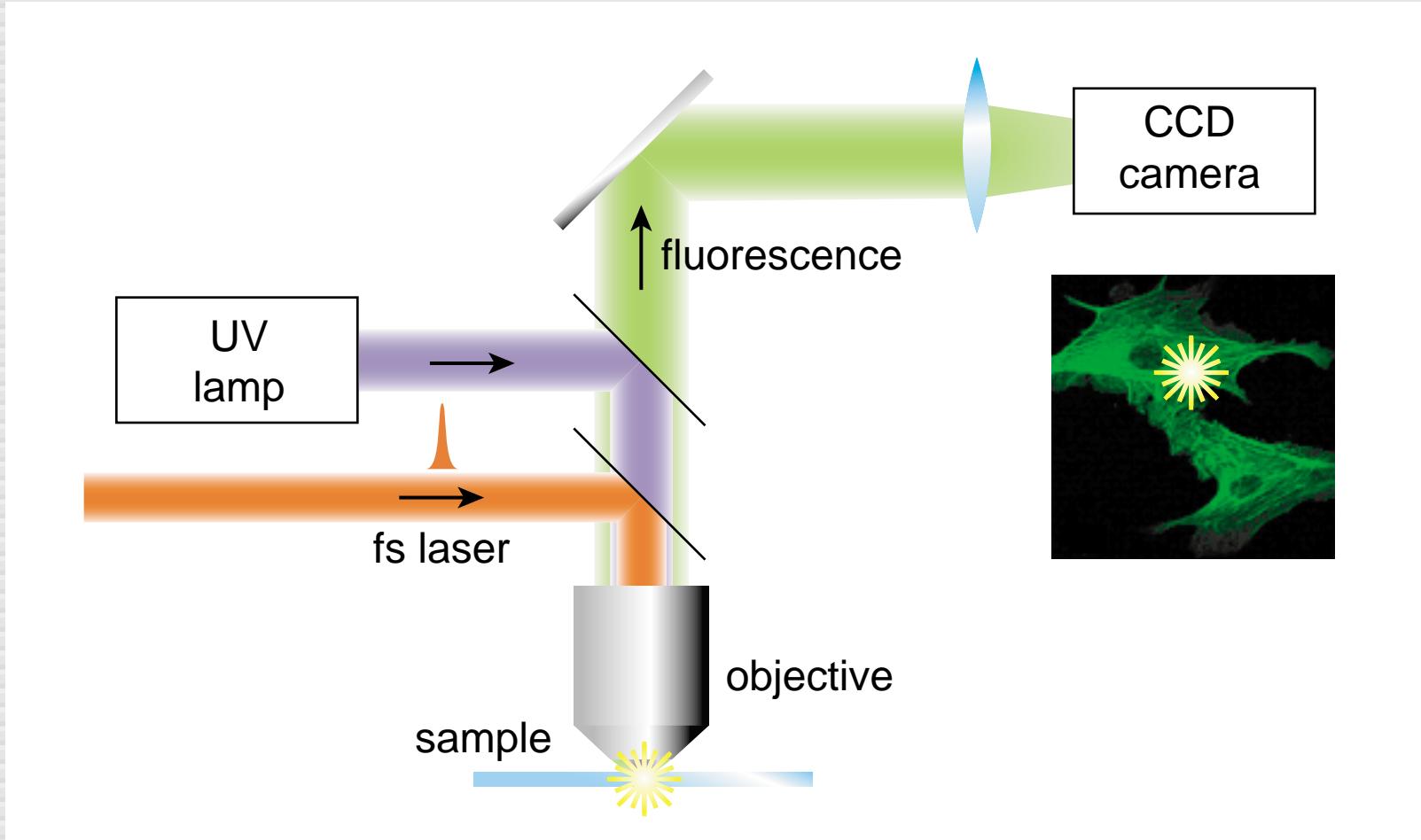
# *Biology and medicine*

... causes fluorescence

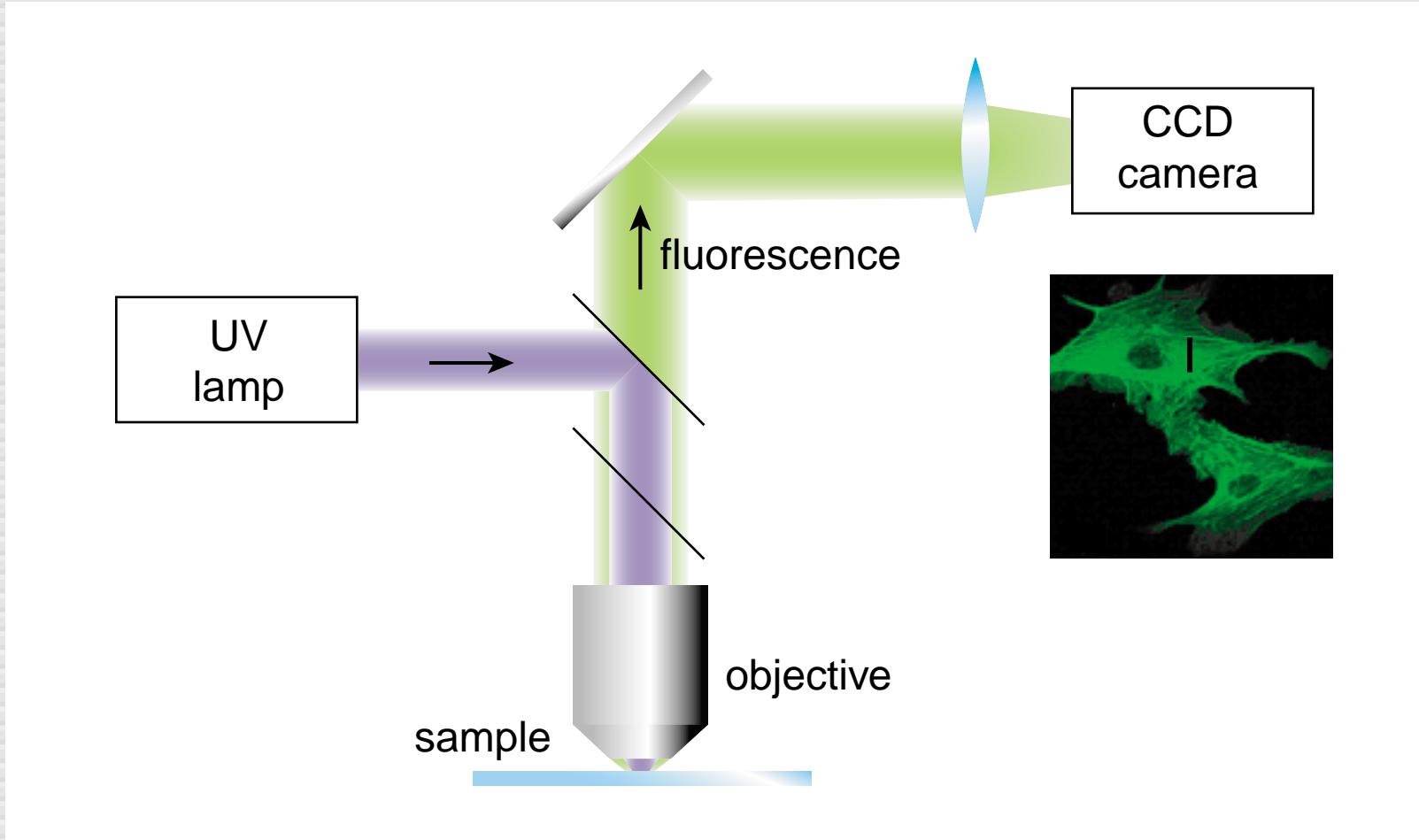


# *Biology and medicine*

## process with fs laser beam



# *Biology and medicine*

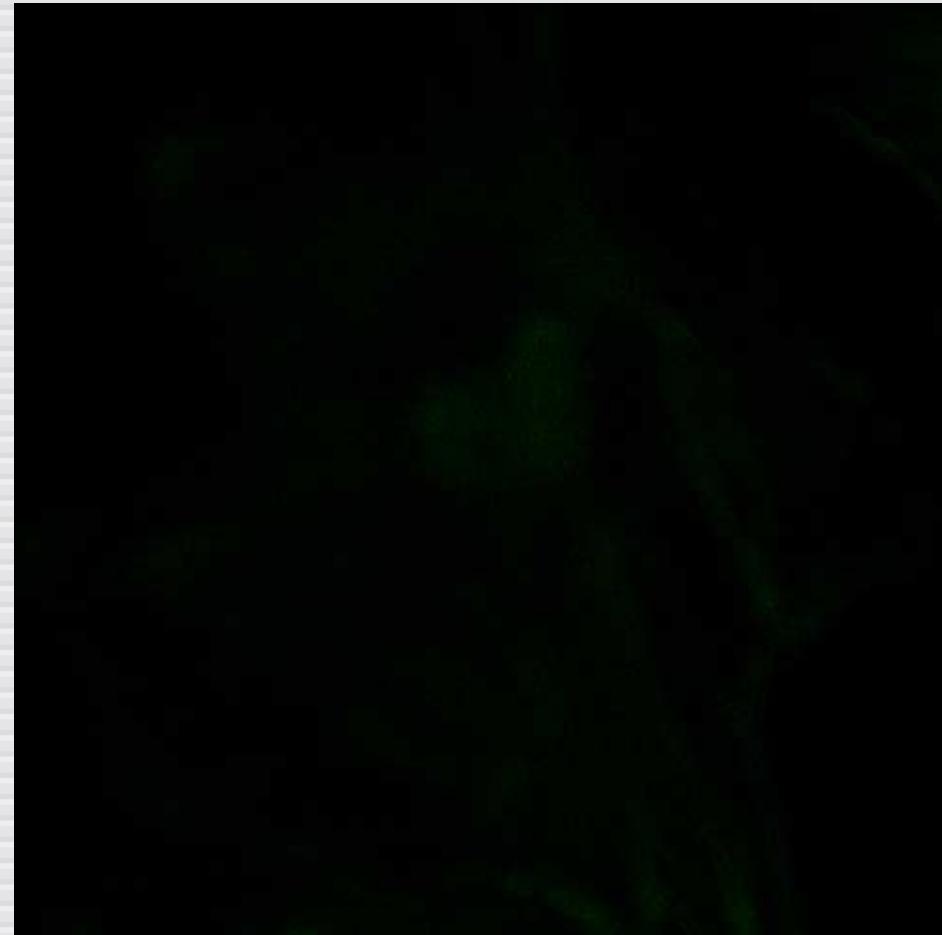


# *Biology and medicine*

**before**



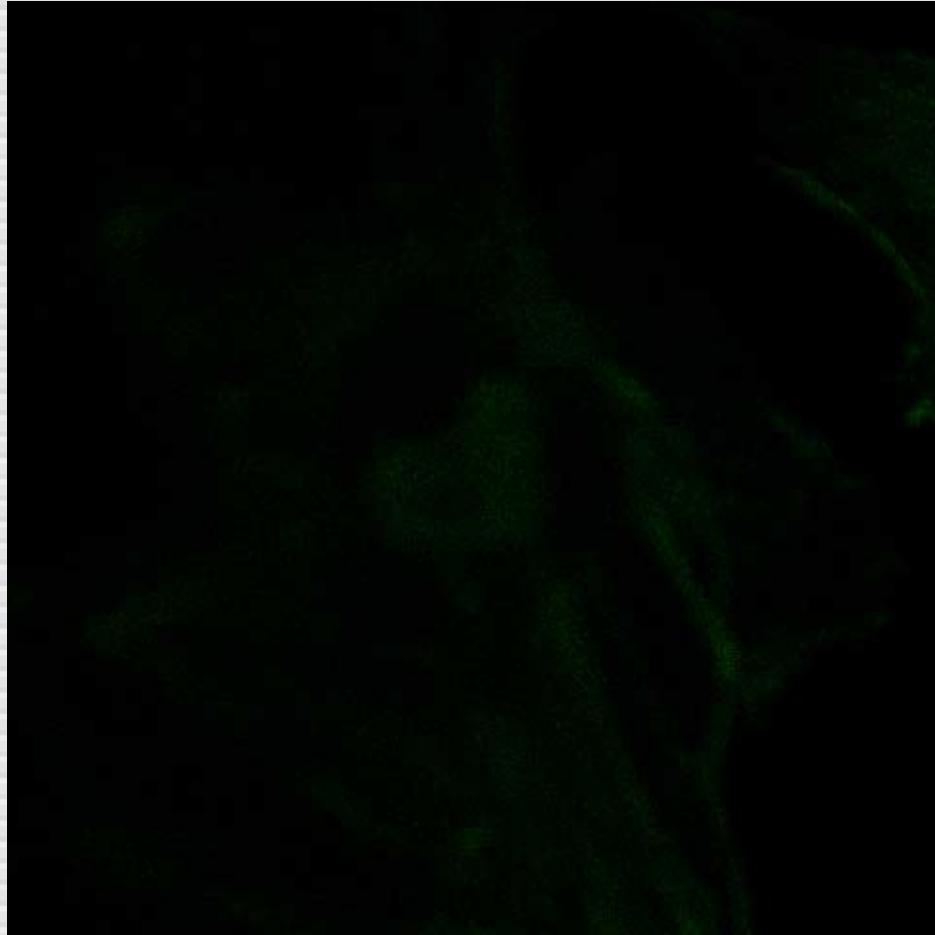
**after**



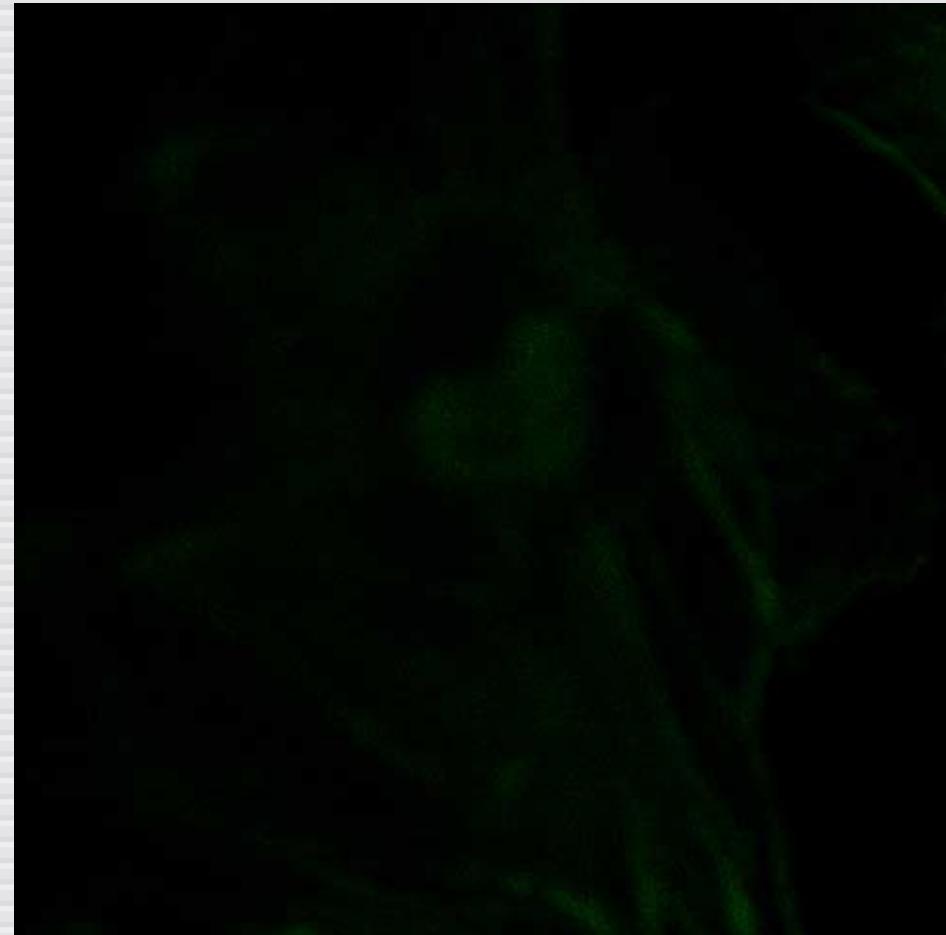
**examine in confocal microscope**

# *Biology and medicine*

**before**

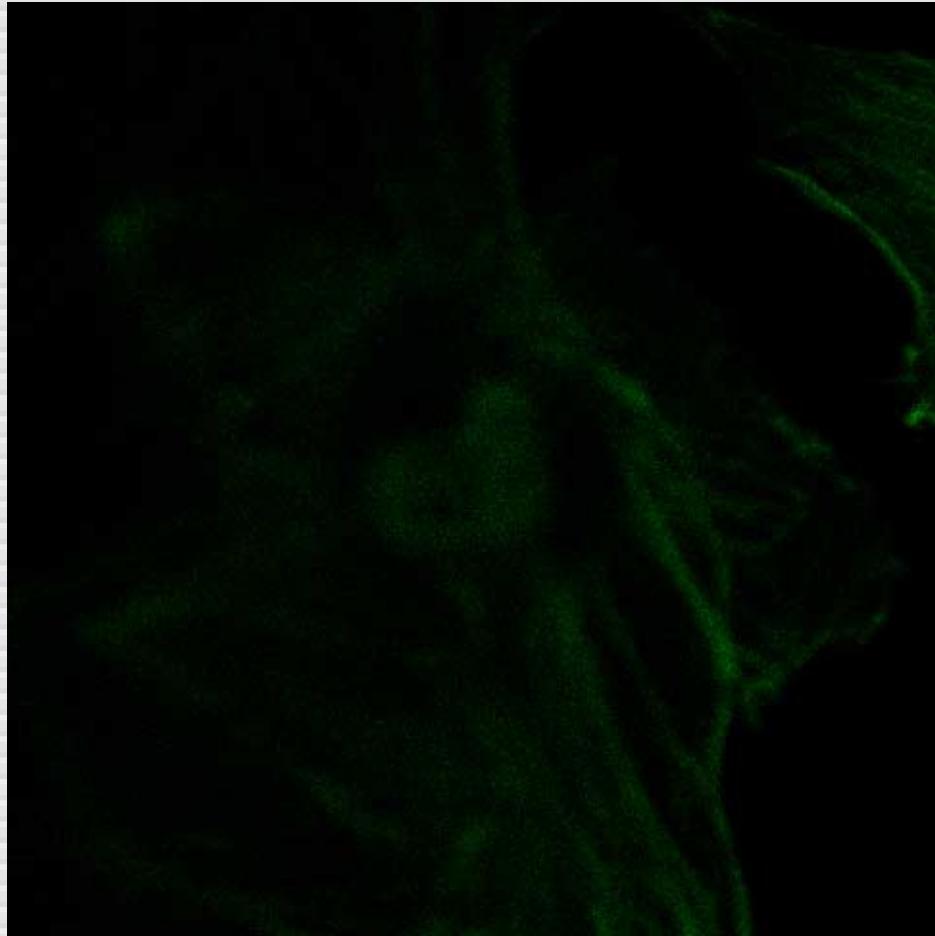


**after**

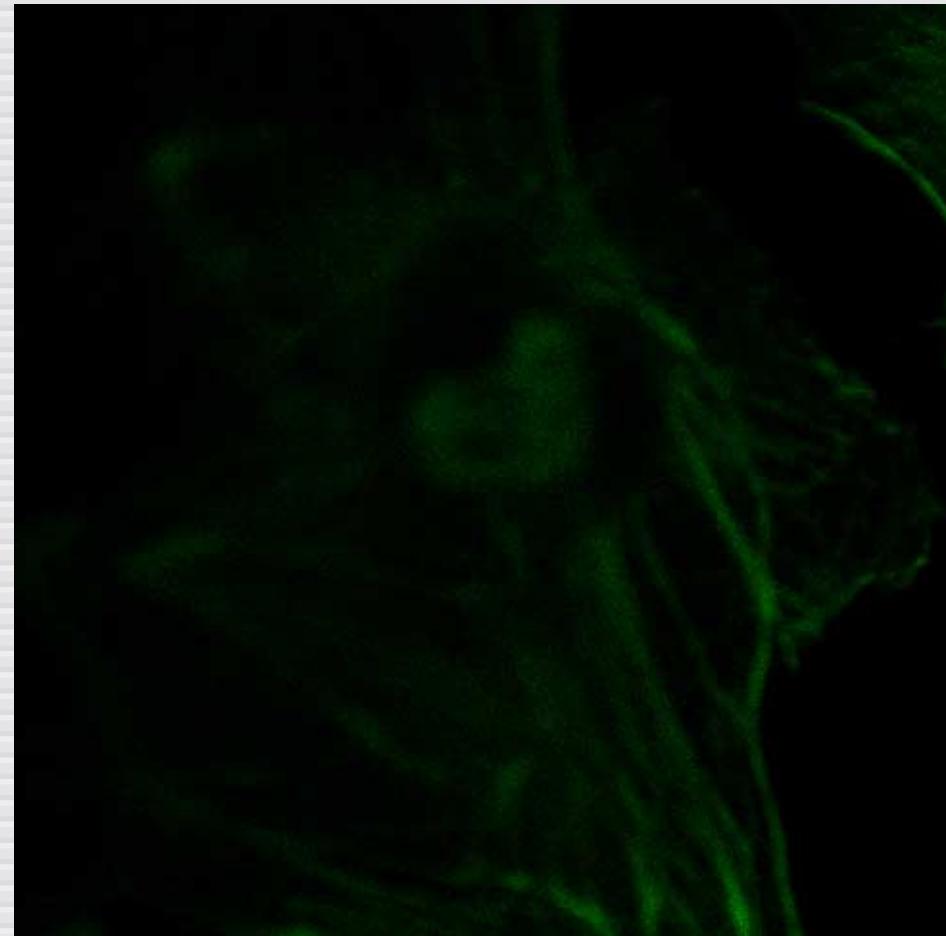


# *Biology and medicine*

**before**

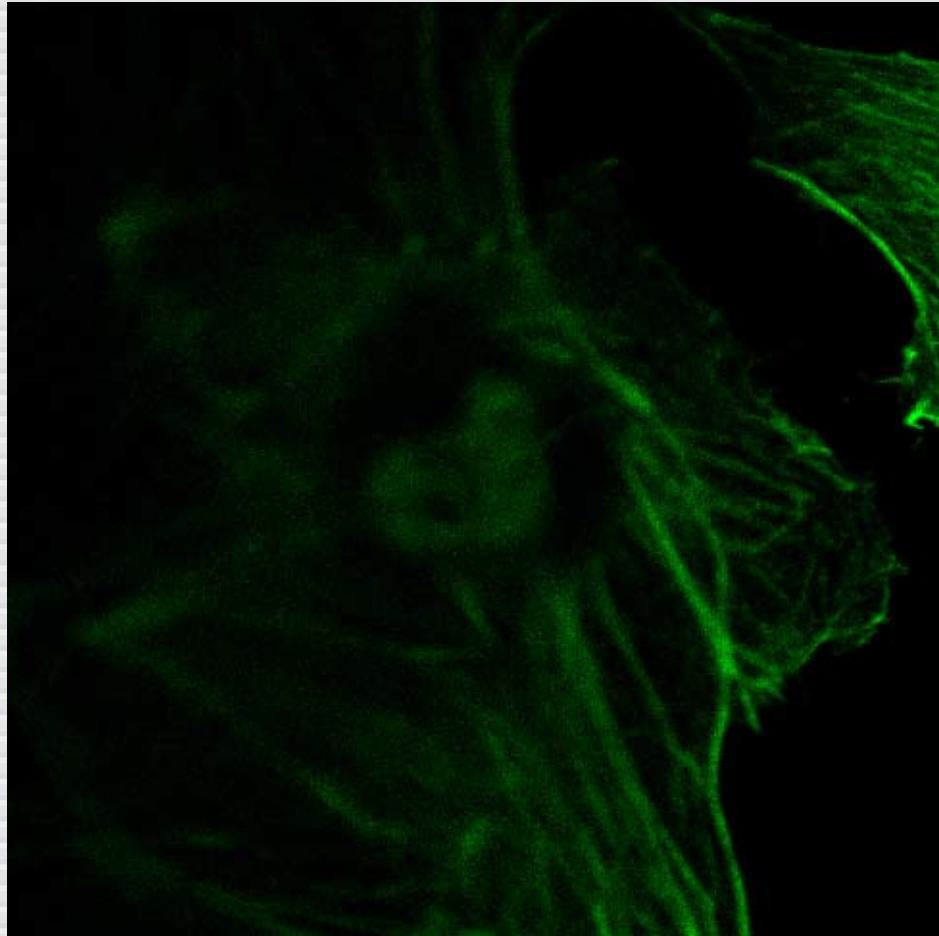


**after**

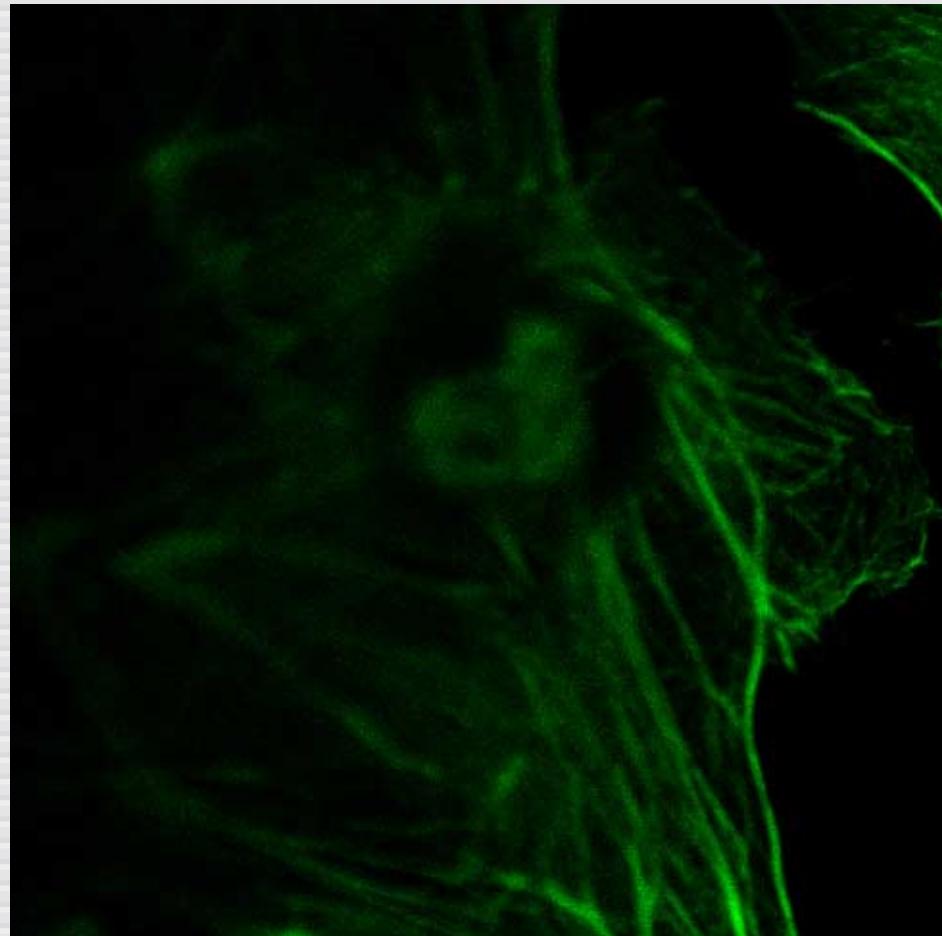


# *Biology and medicine*

**before**

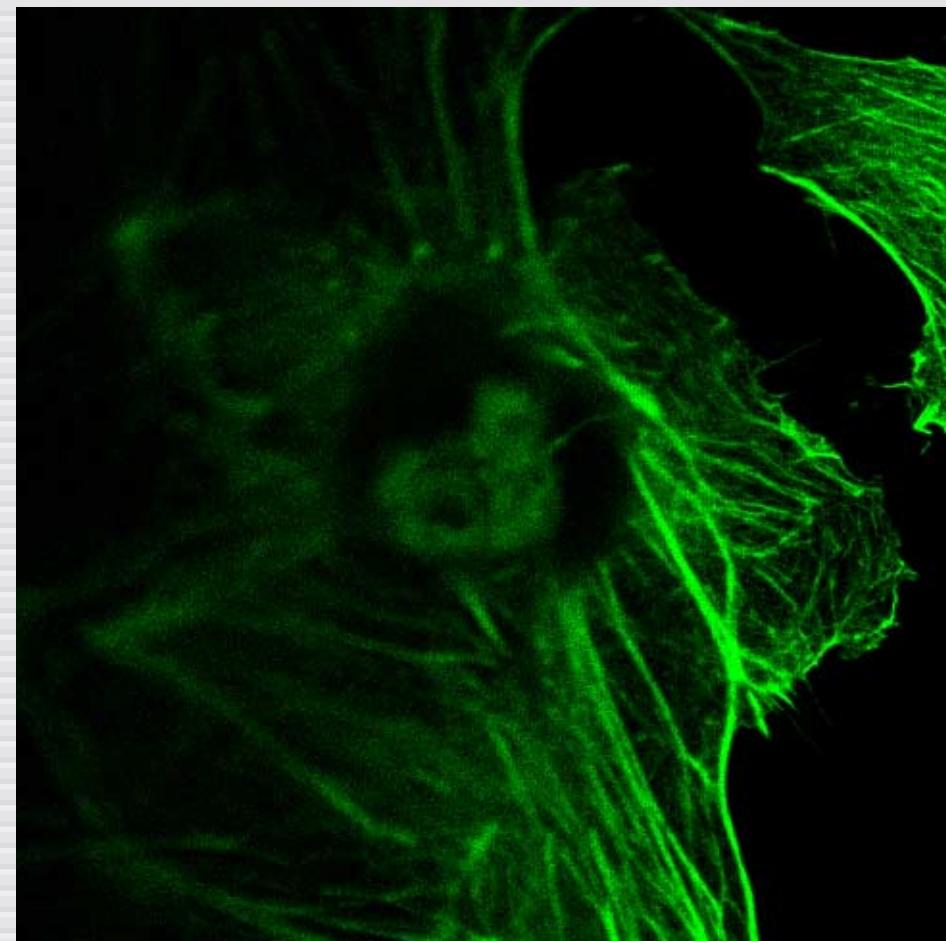


**after**

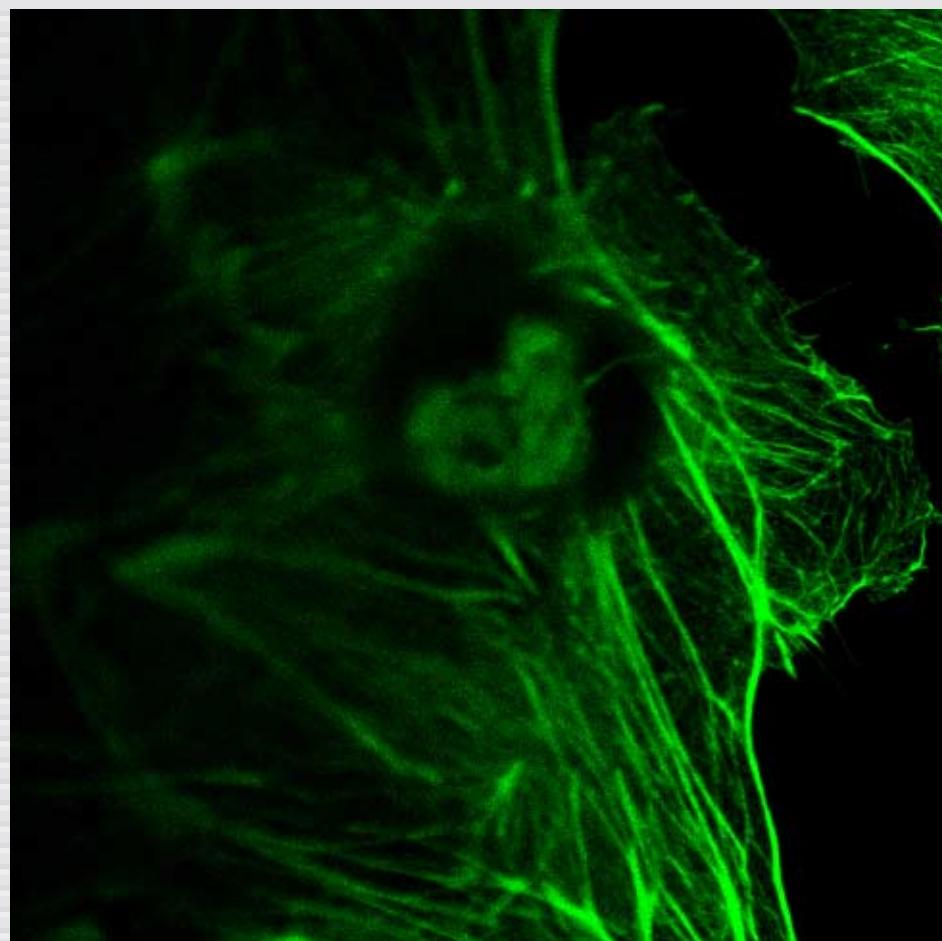


# *Biology and medicine*

**before**

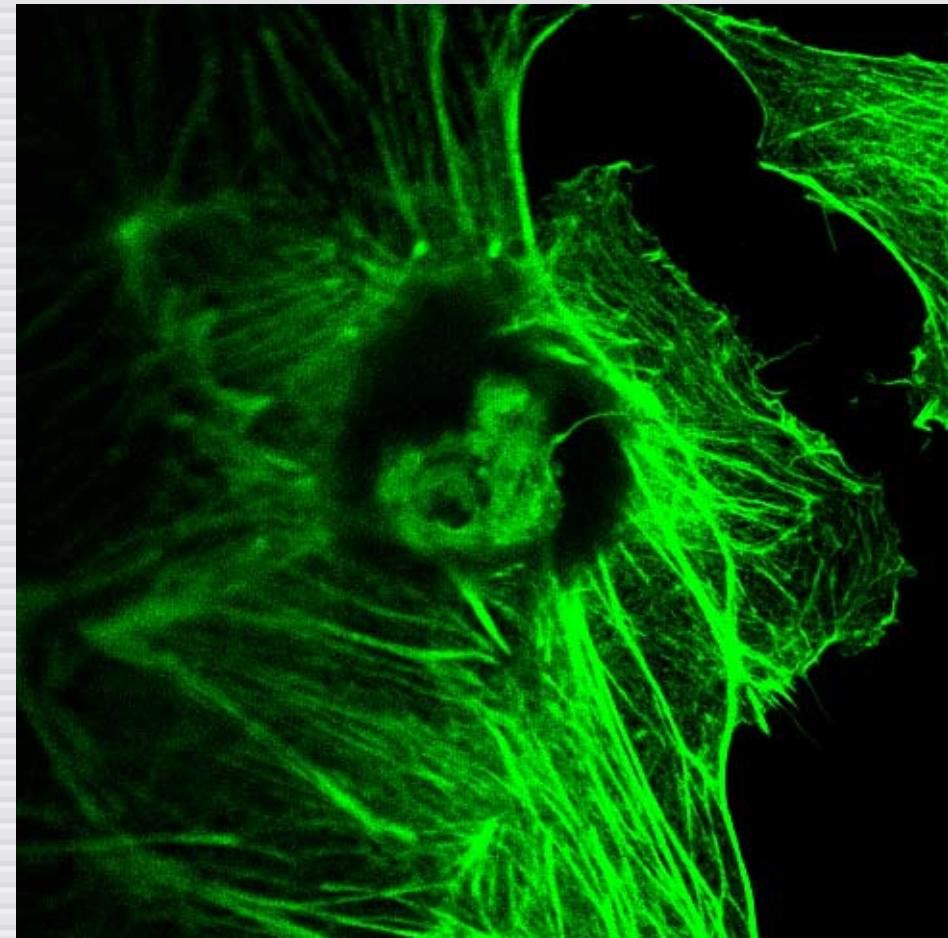


**after**

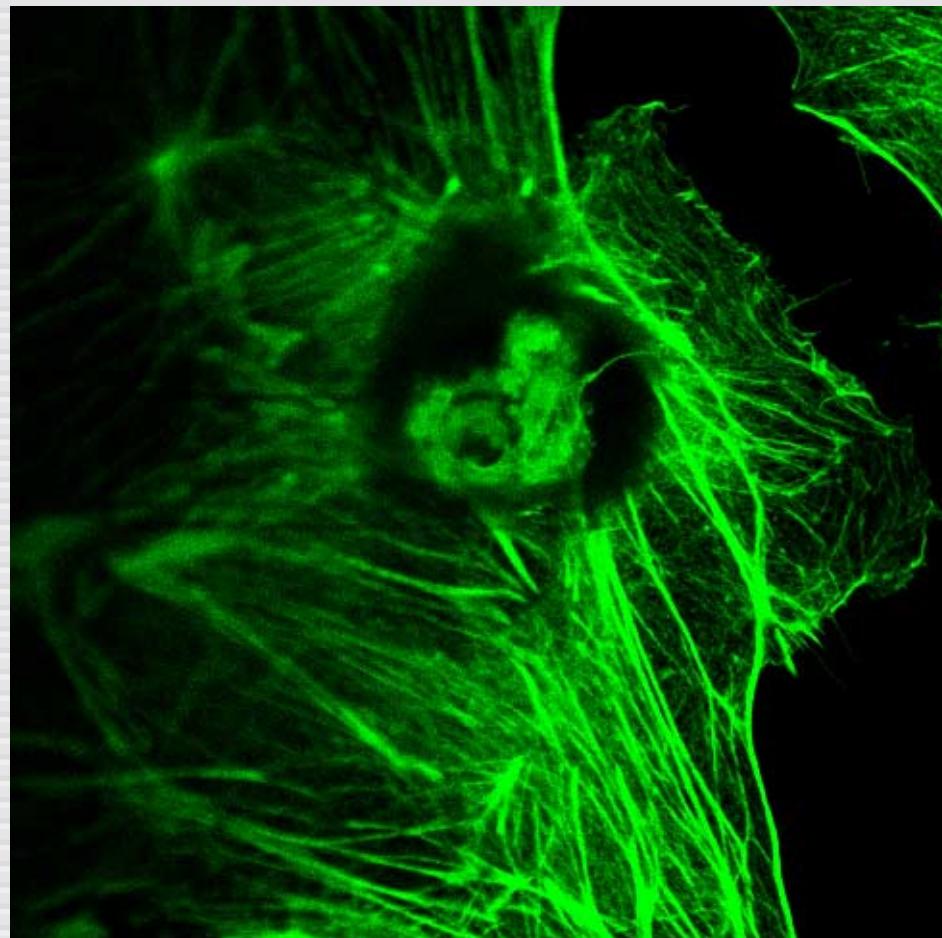


# *Biology and medicine*

**before**

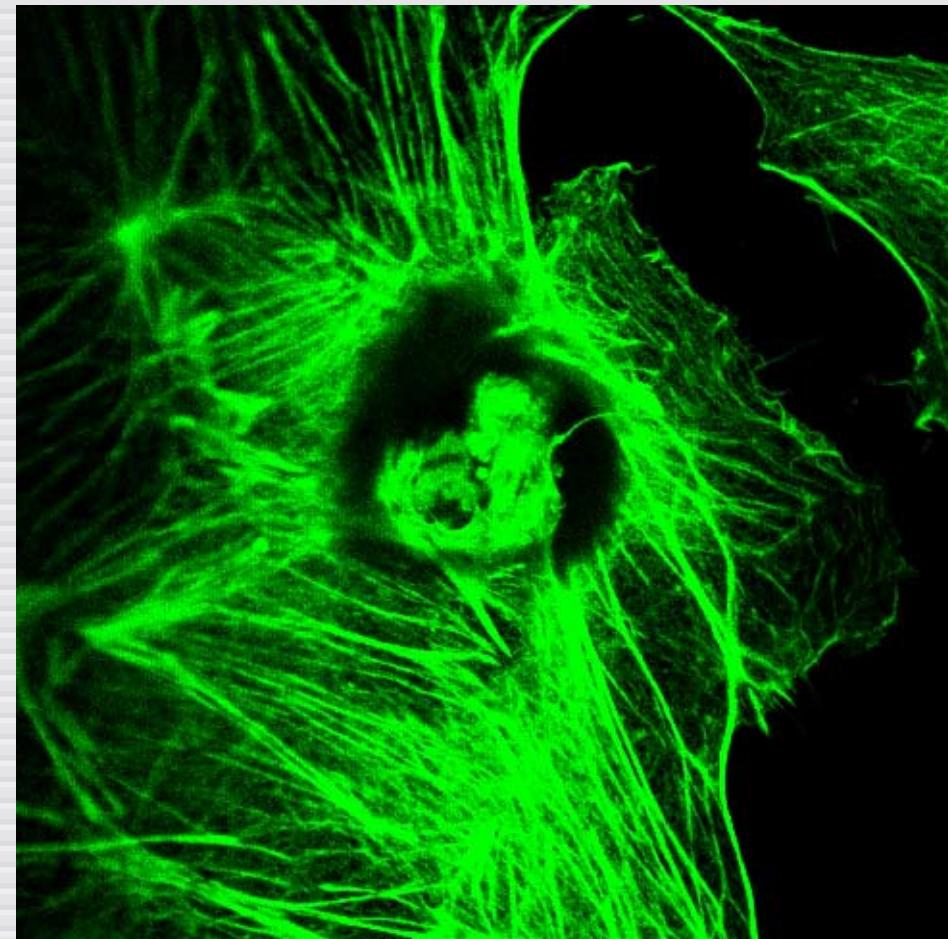


**after**

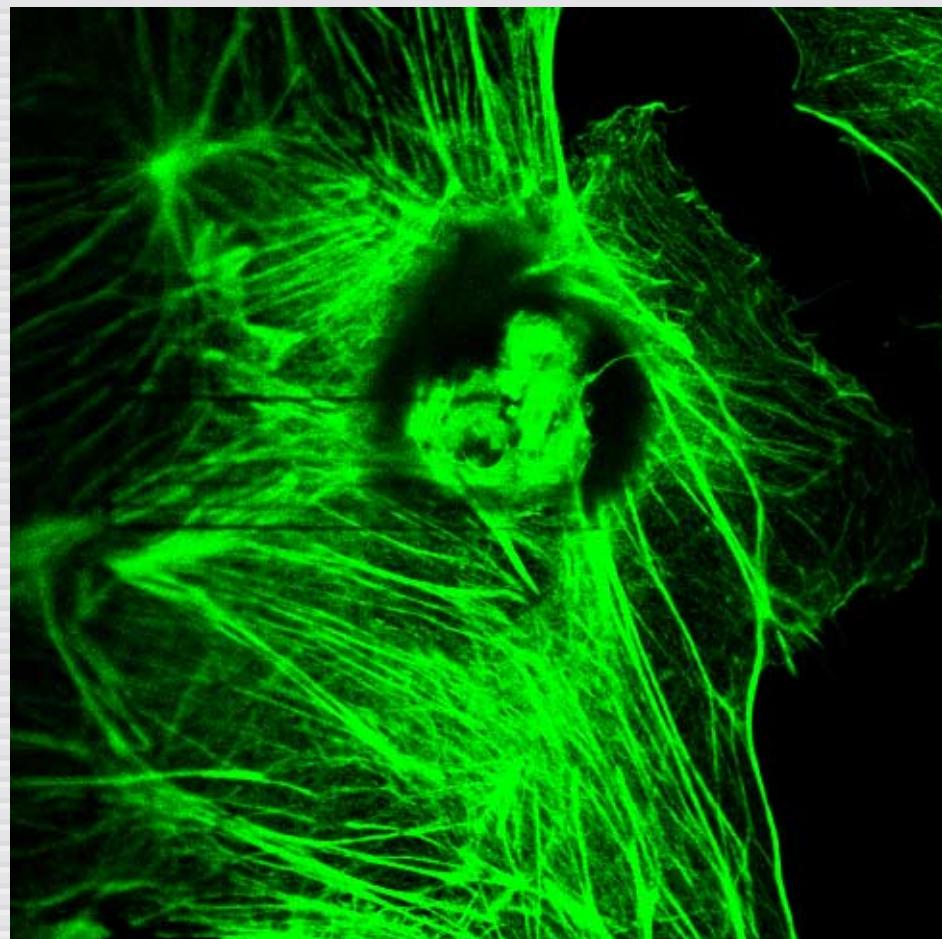


# *Biology and medicine*

**before**

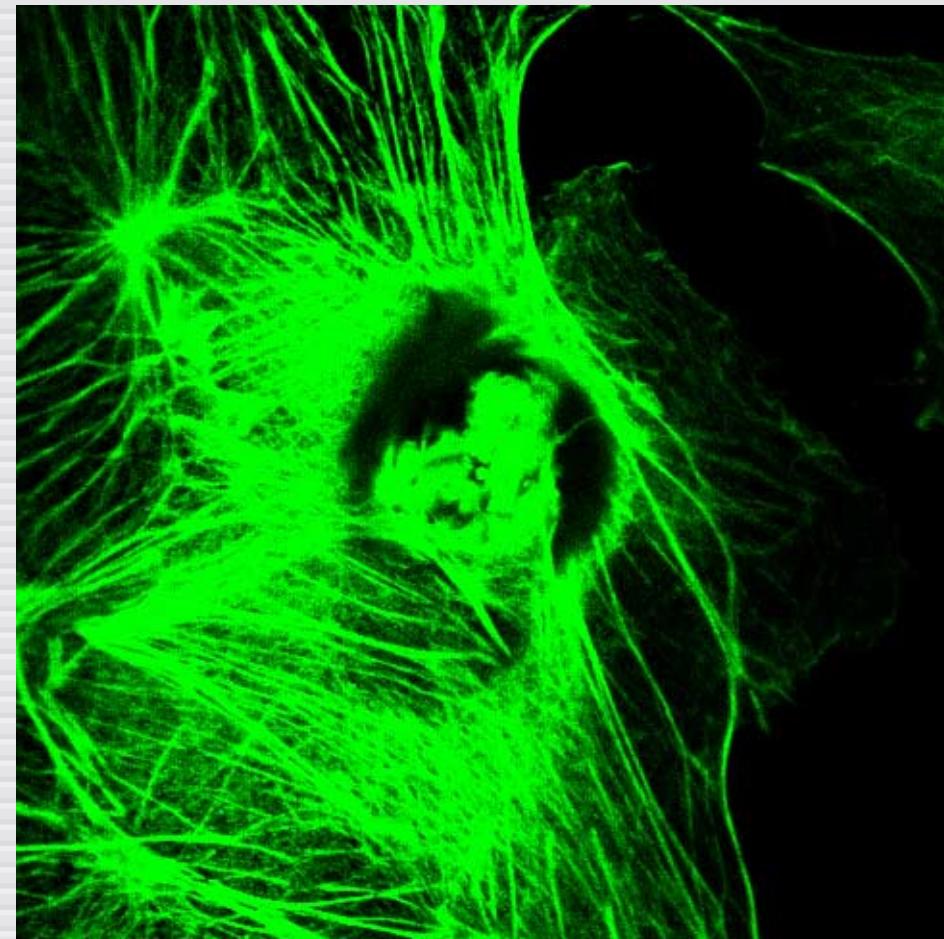


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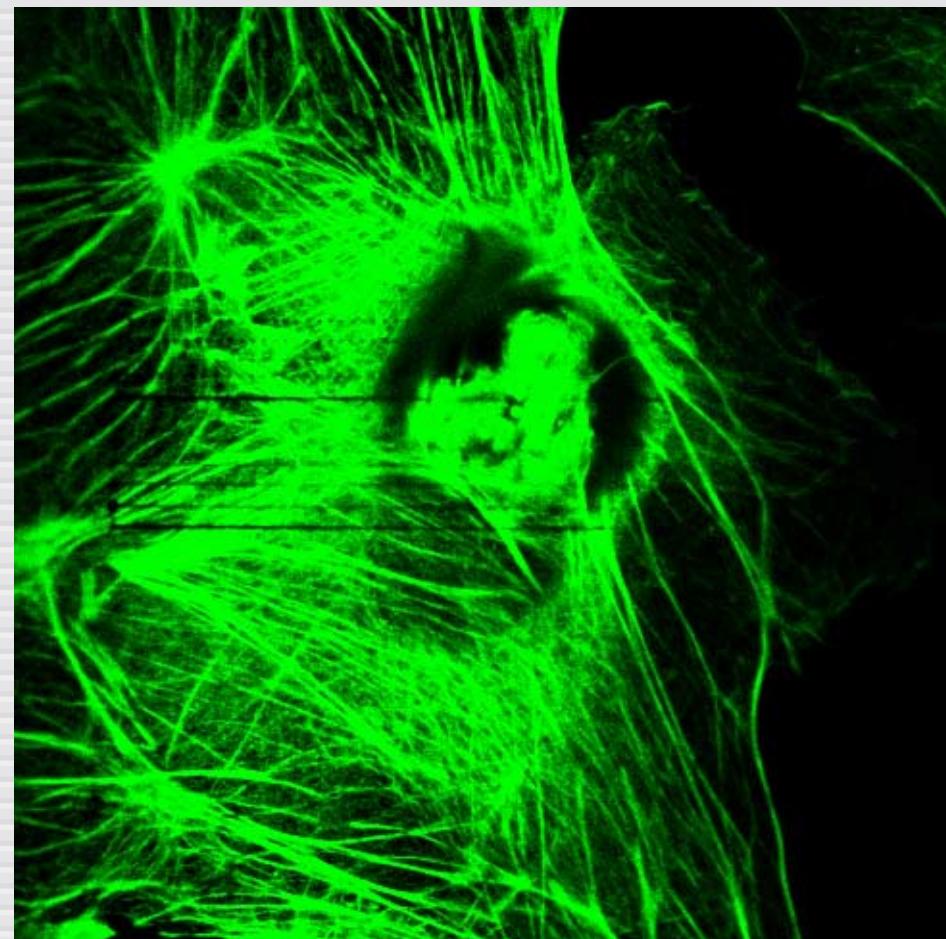


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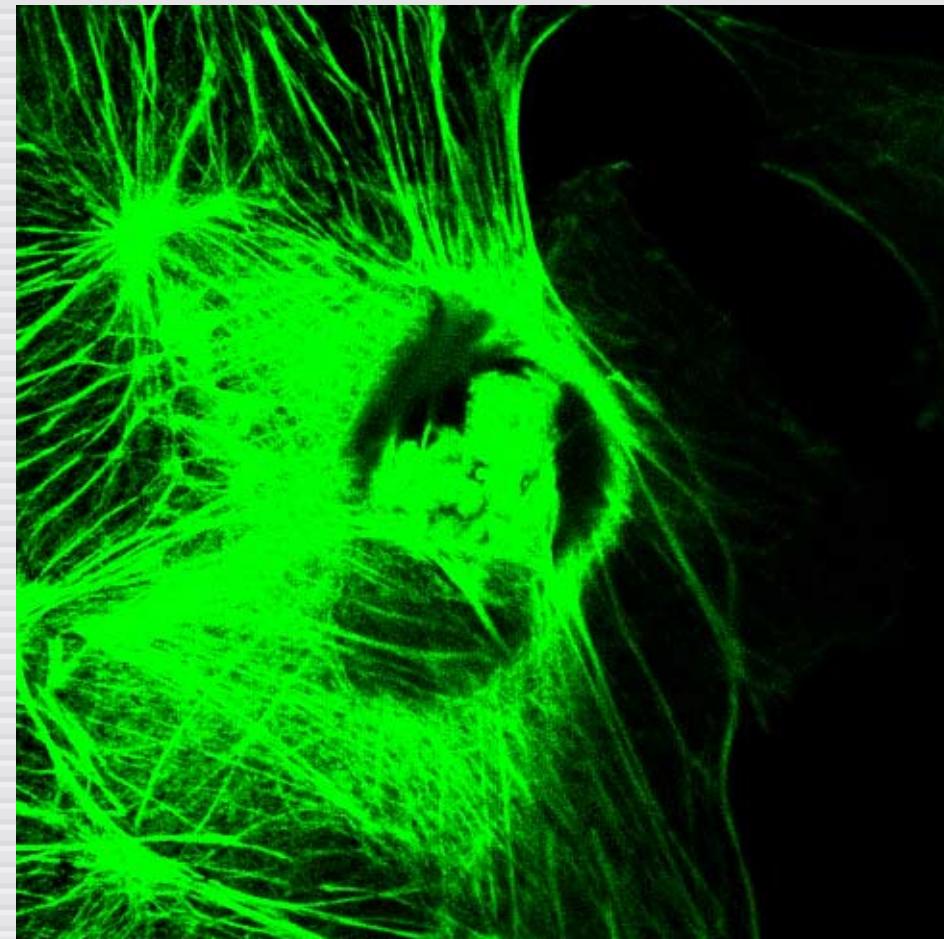


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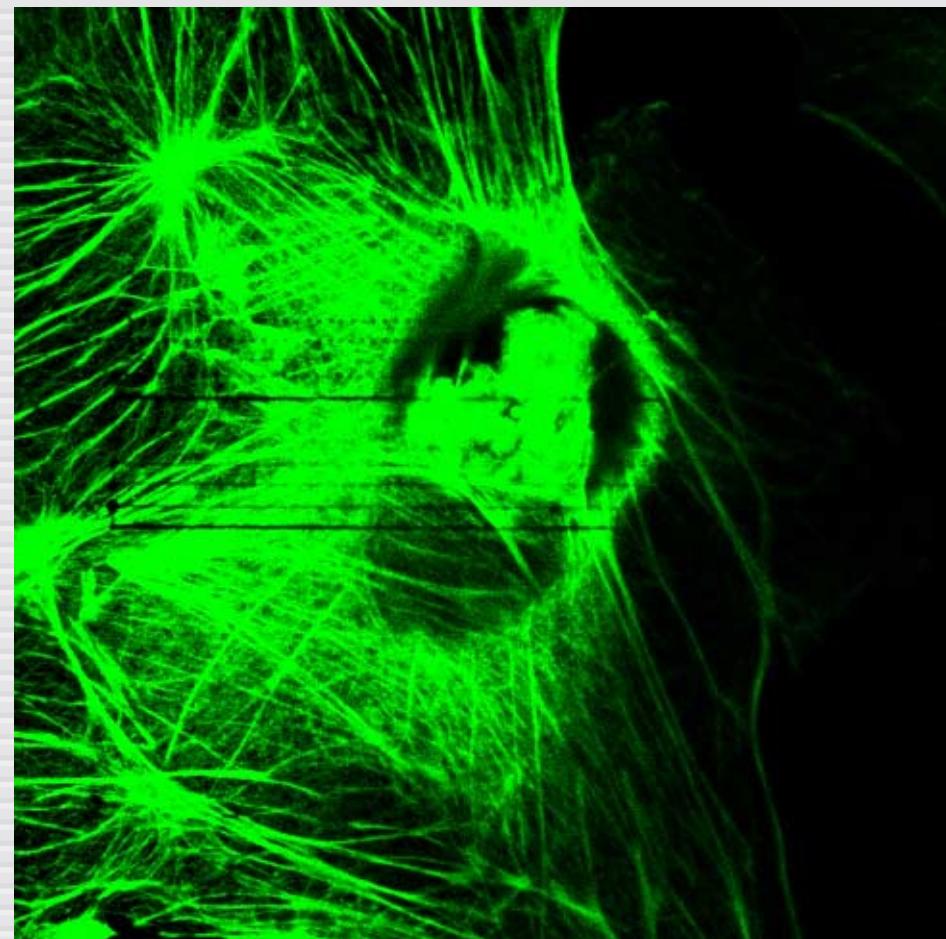


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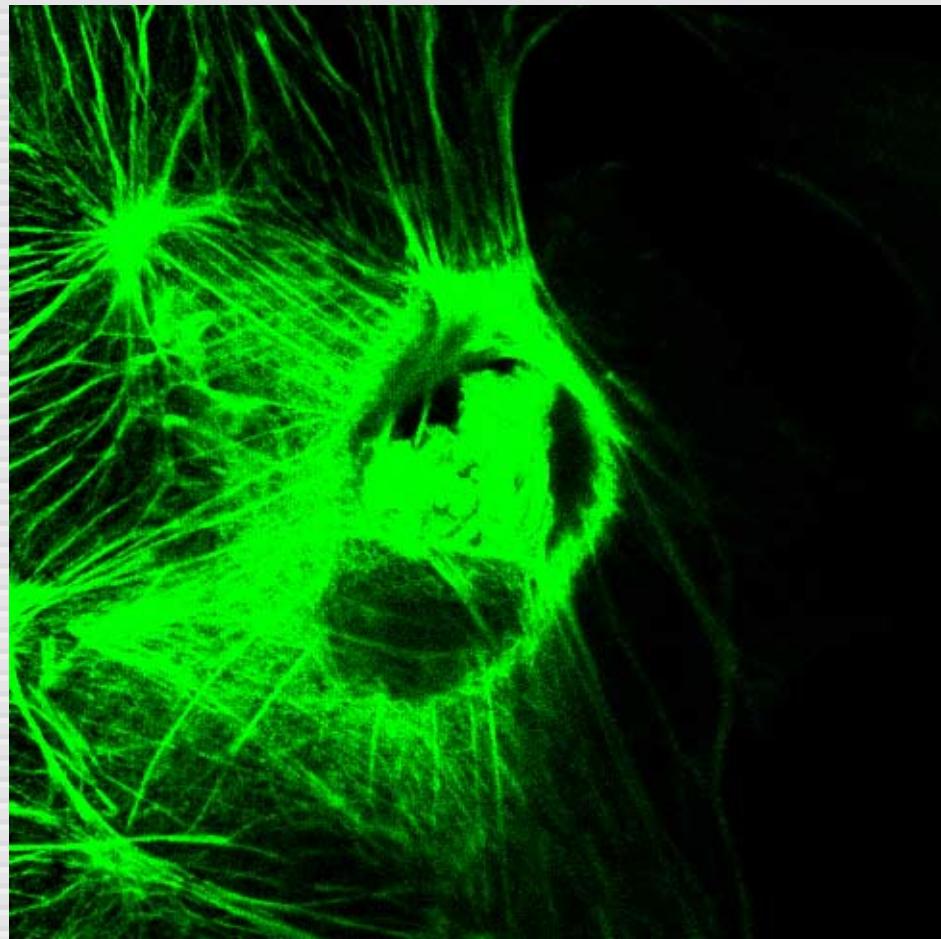


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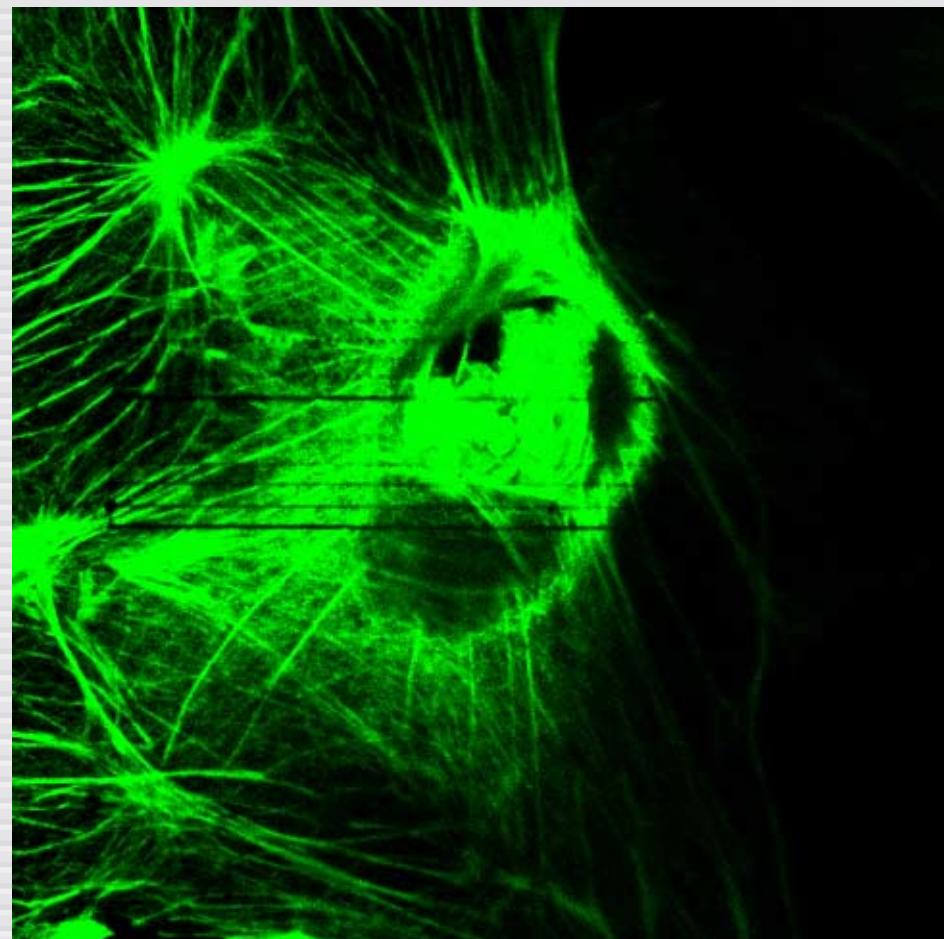


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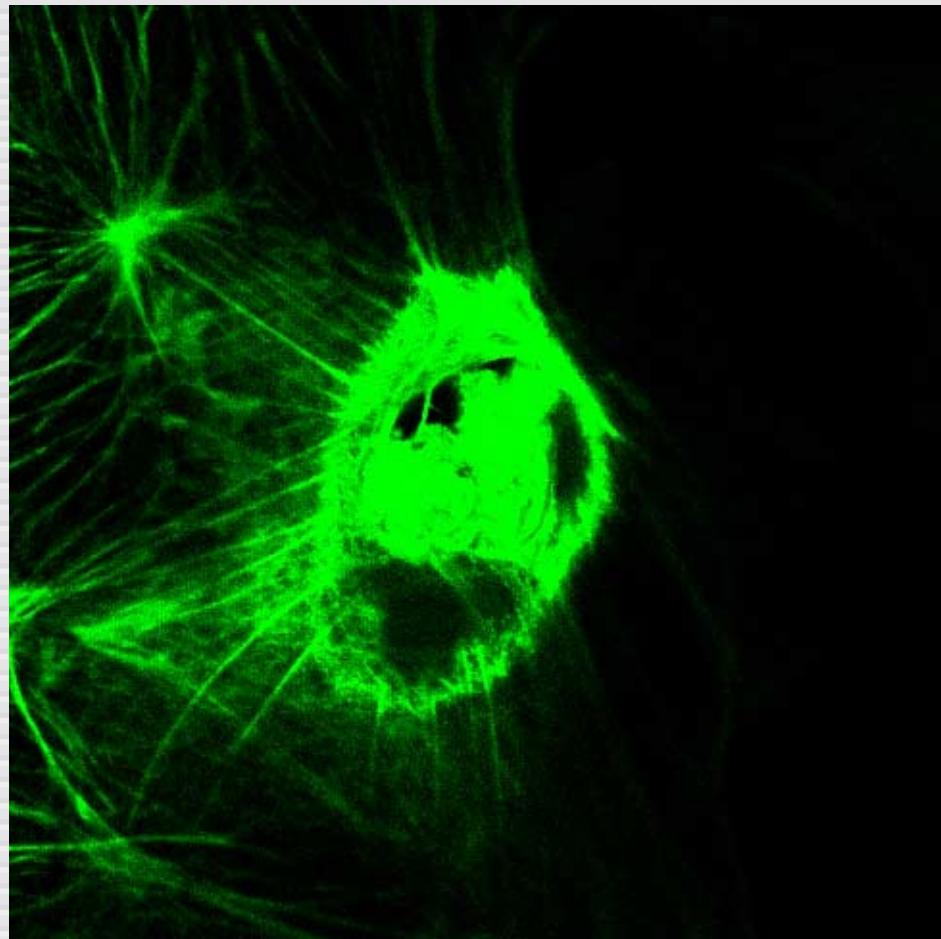


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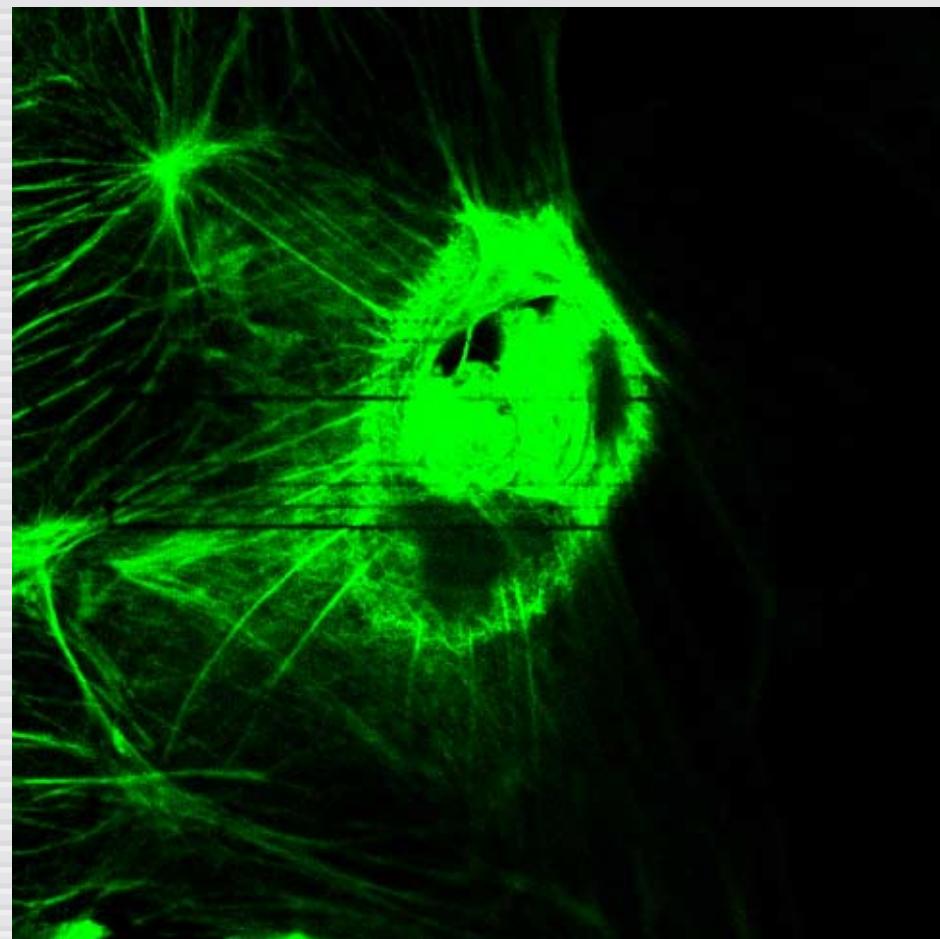


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**before**

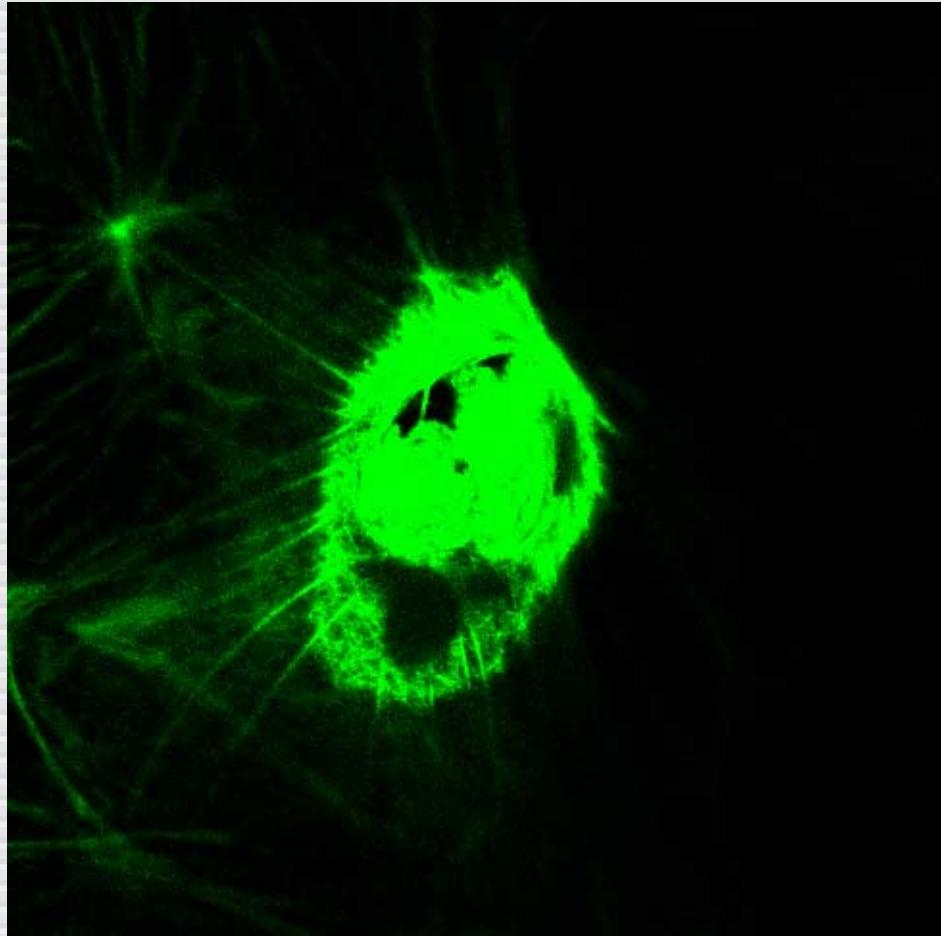


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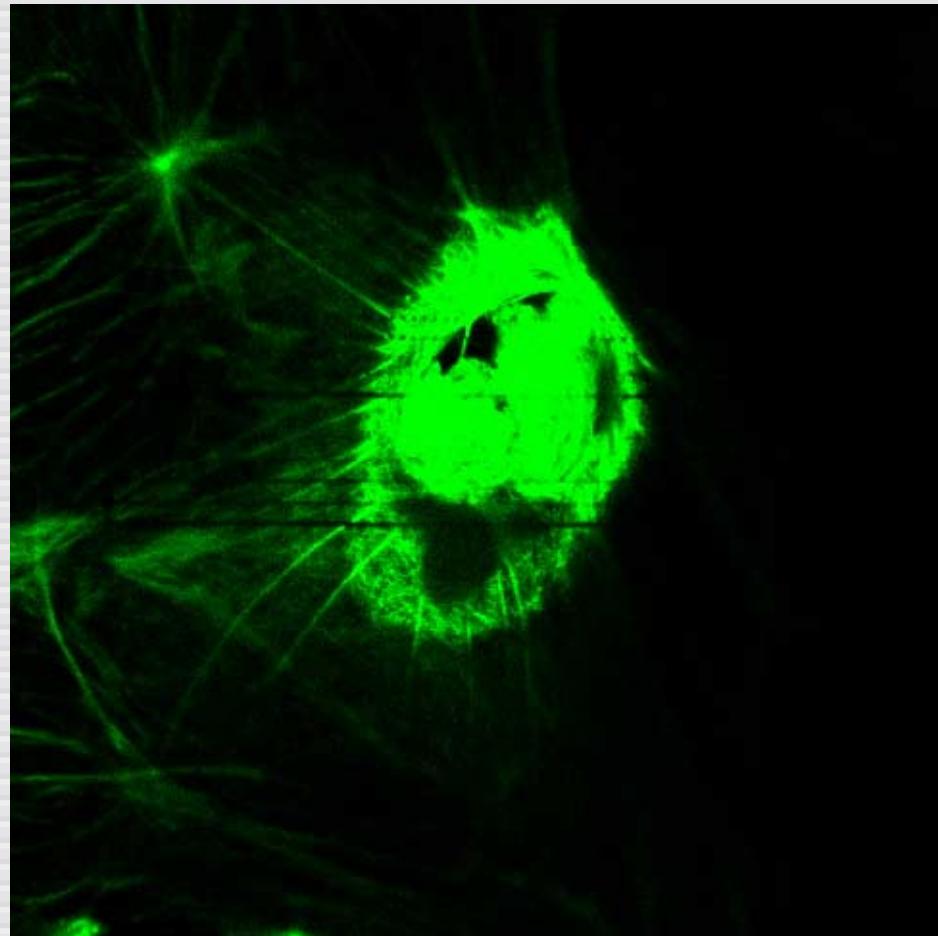


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**before**

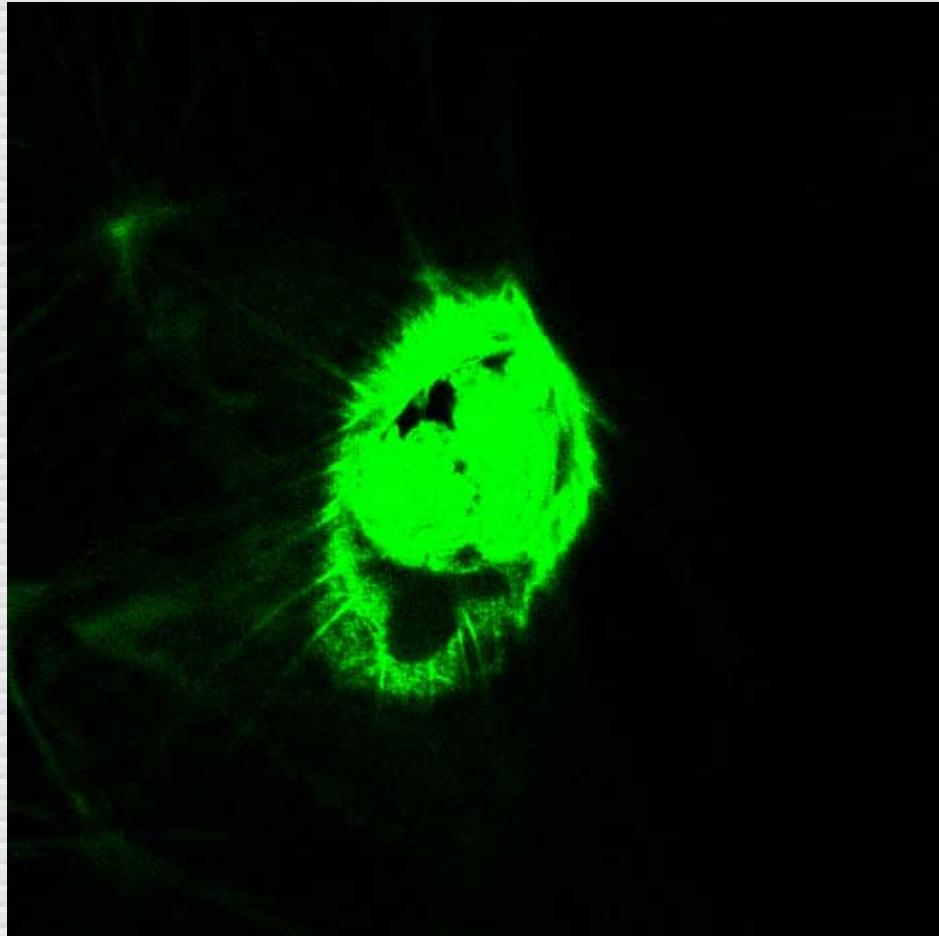


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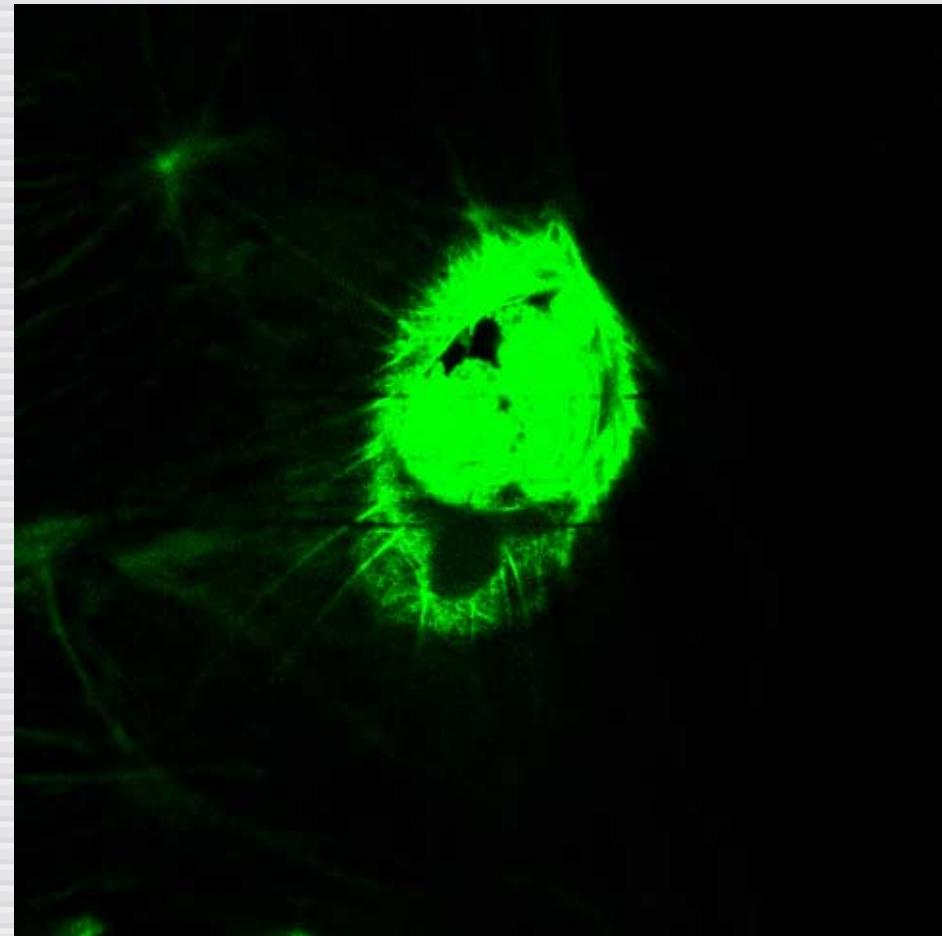


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**before**

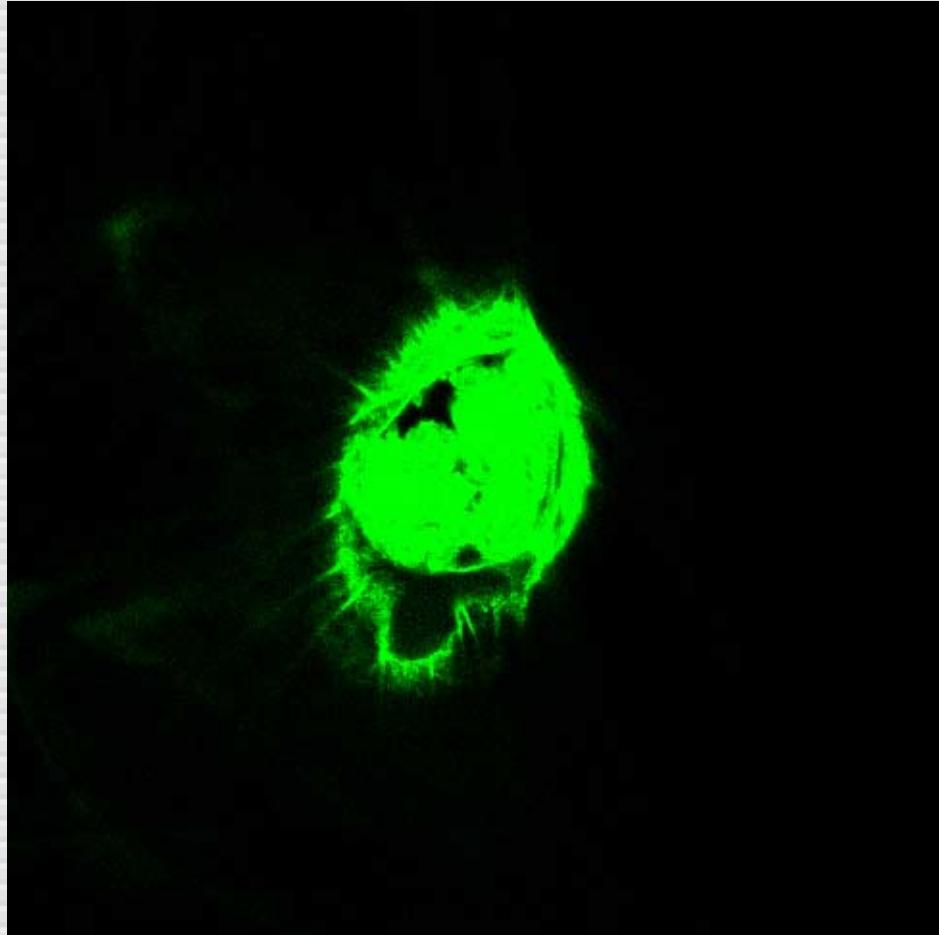


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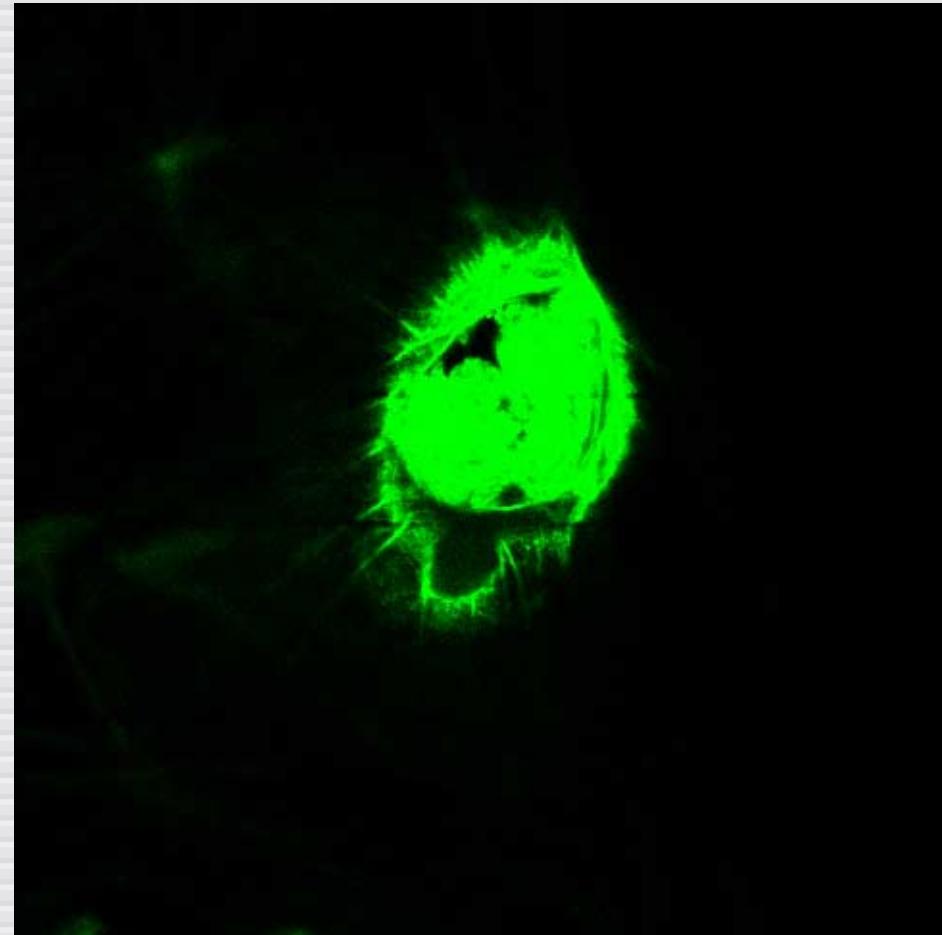


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**before**

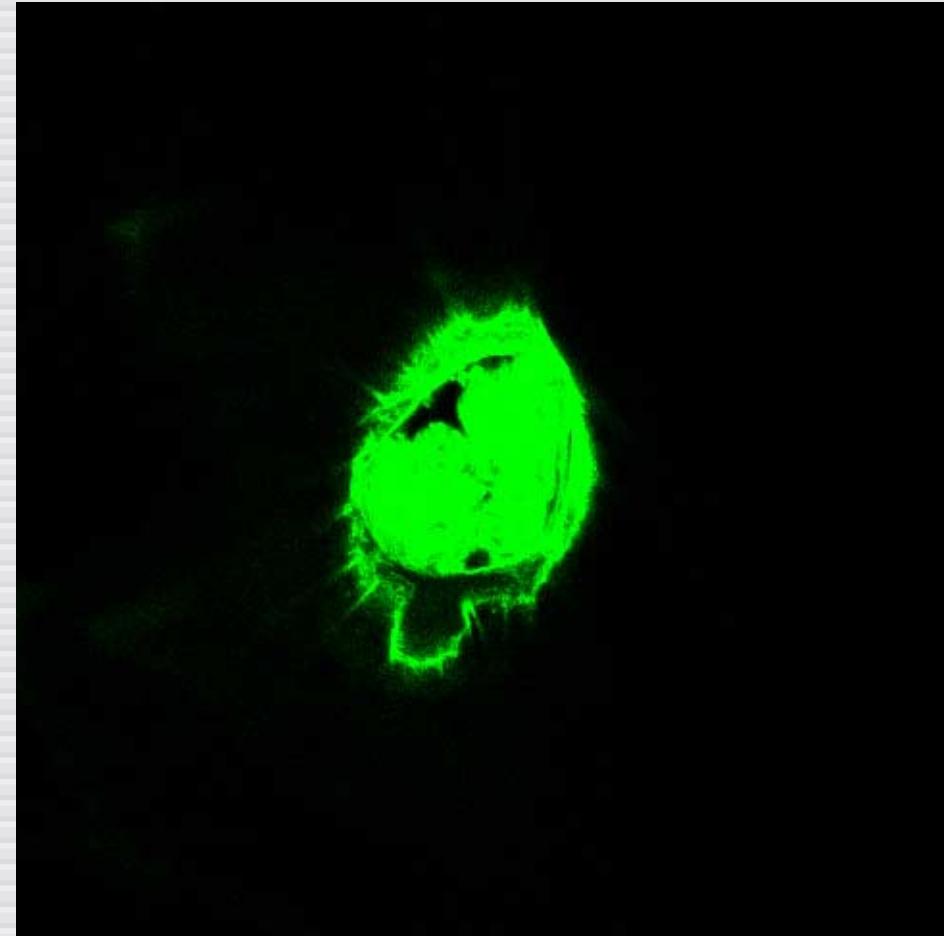


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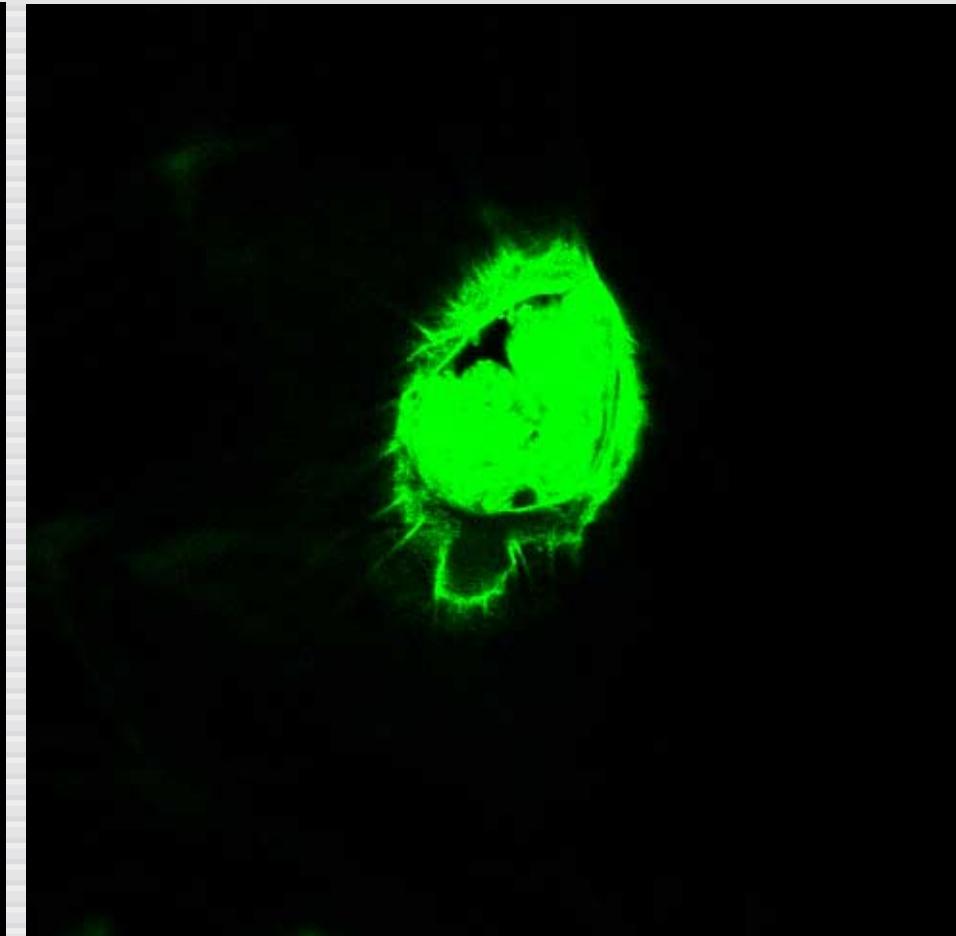


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**before**

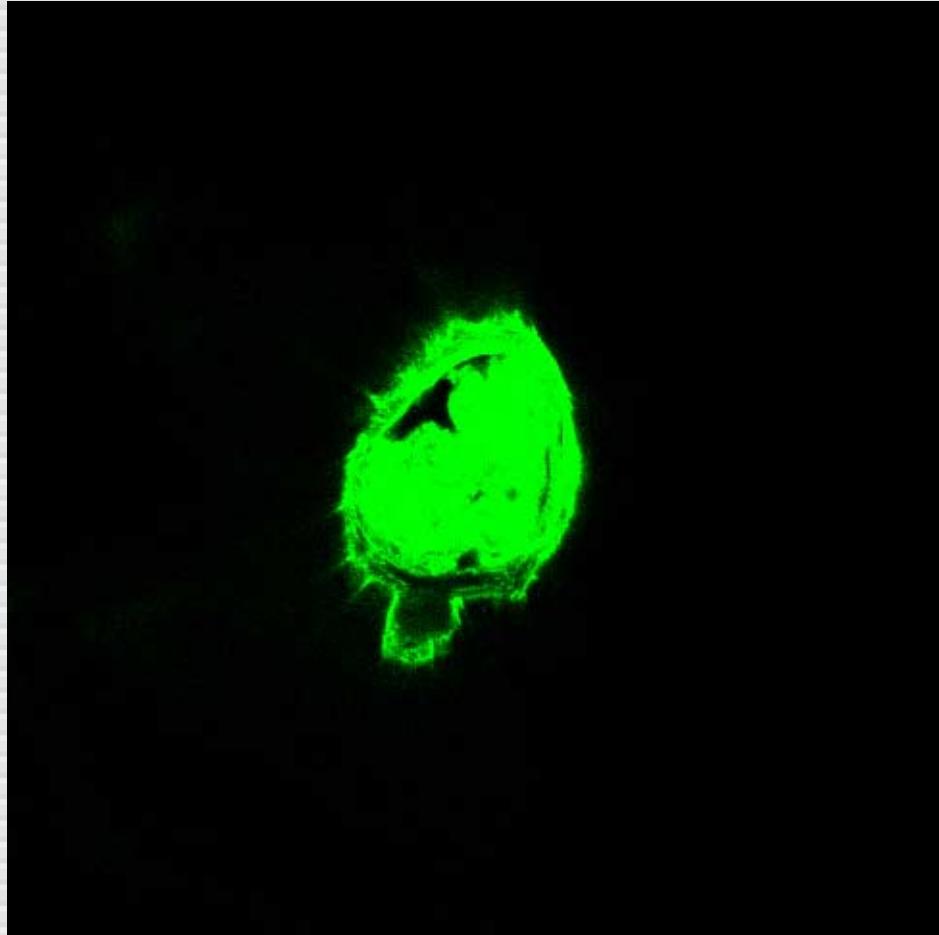


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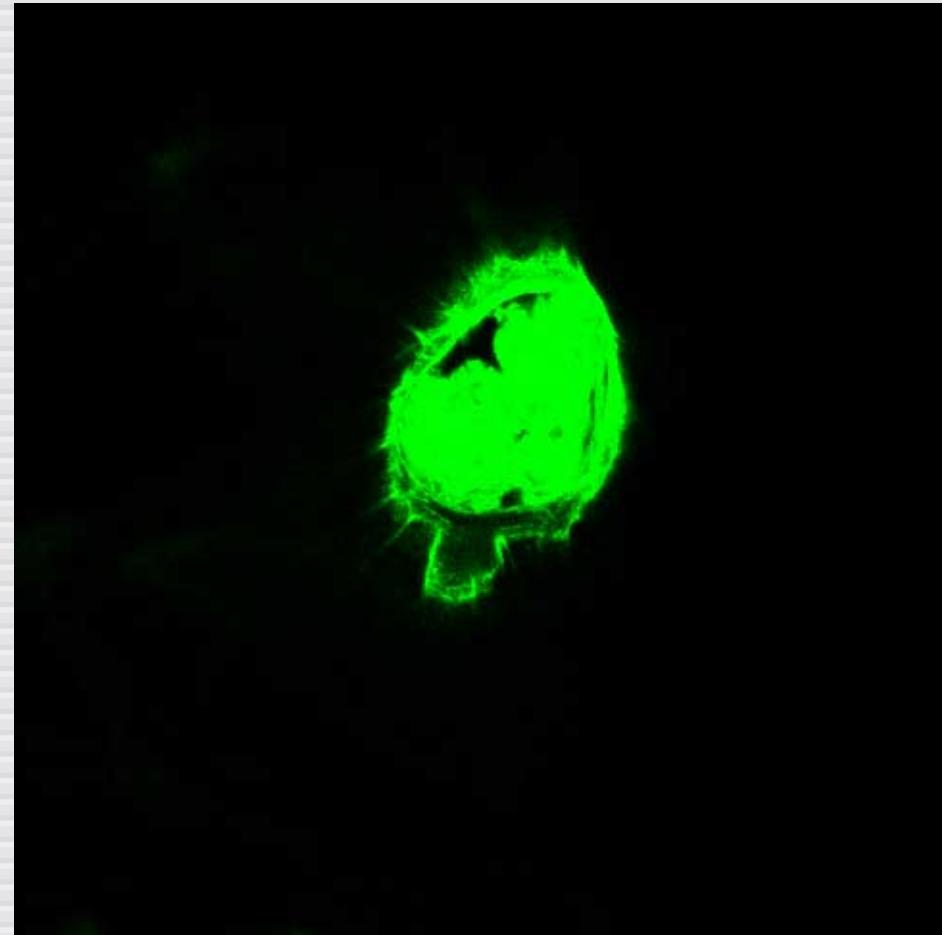


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**before**

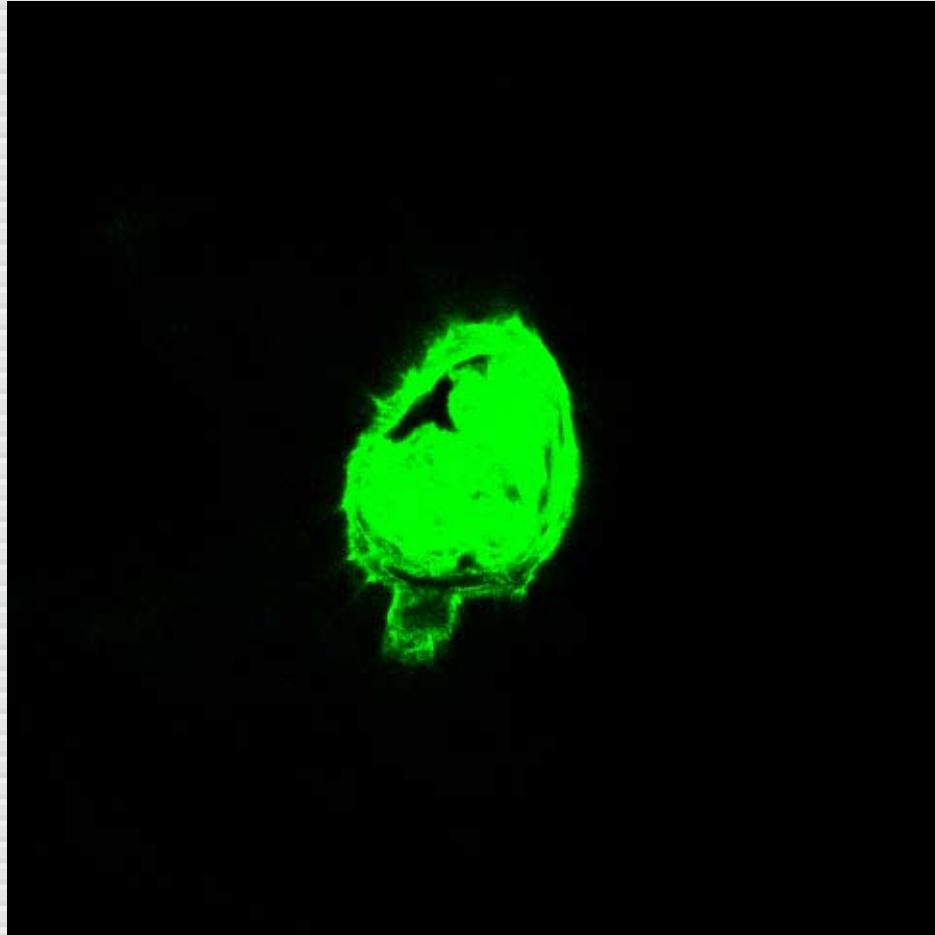


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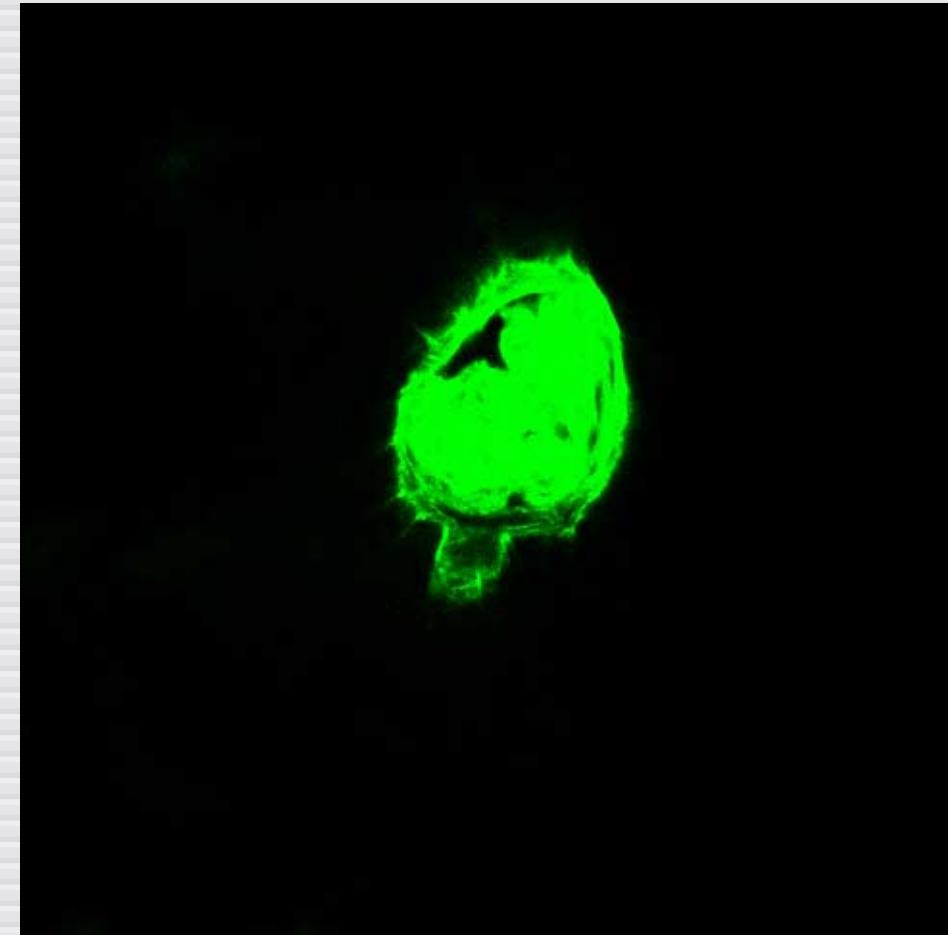


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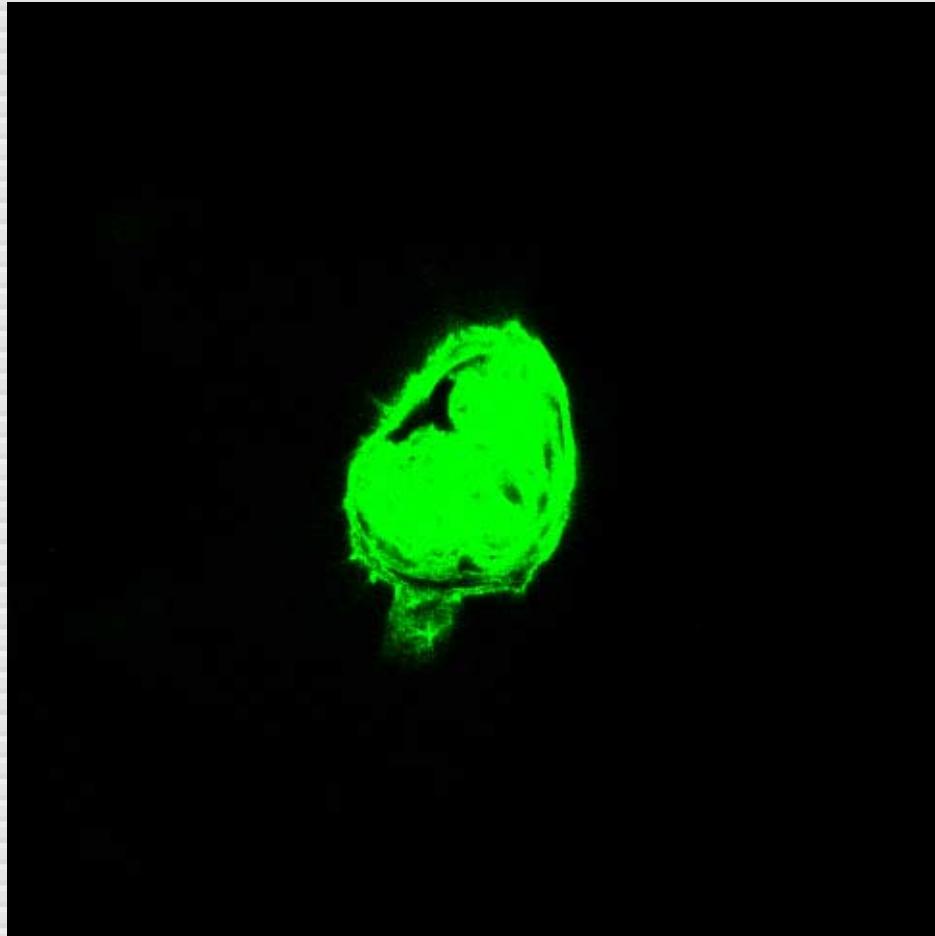


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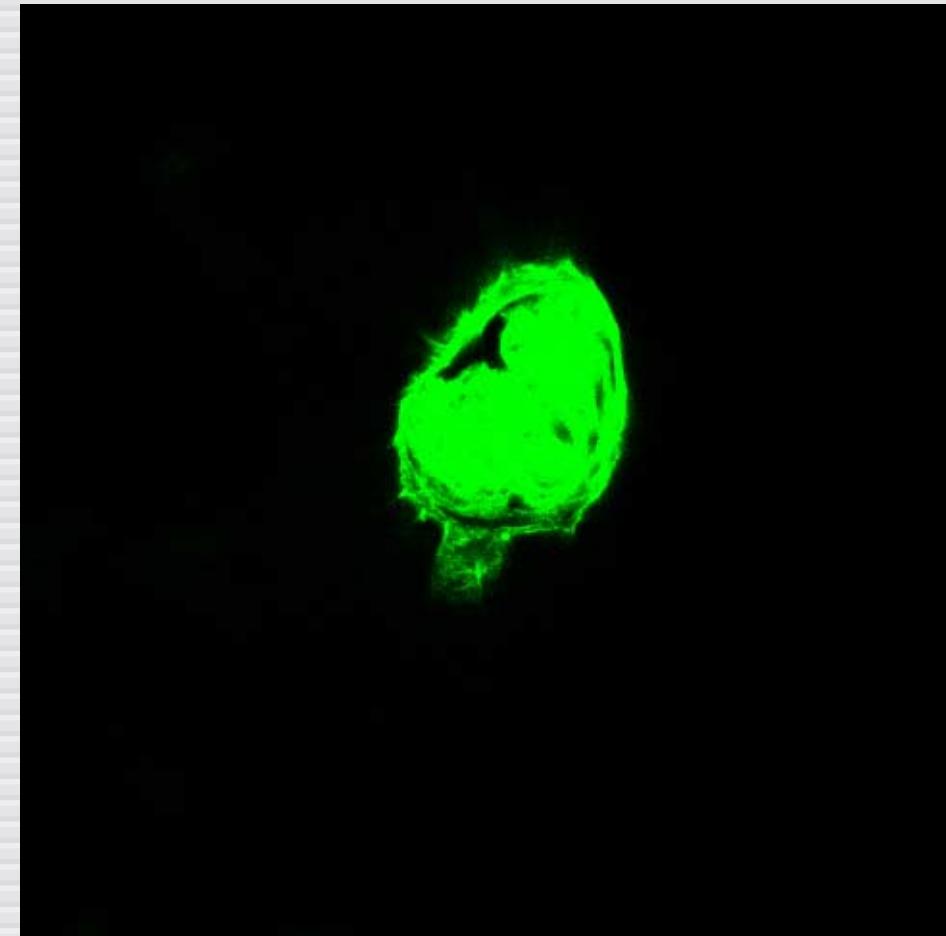


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**before**

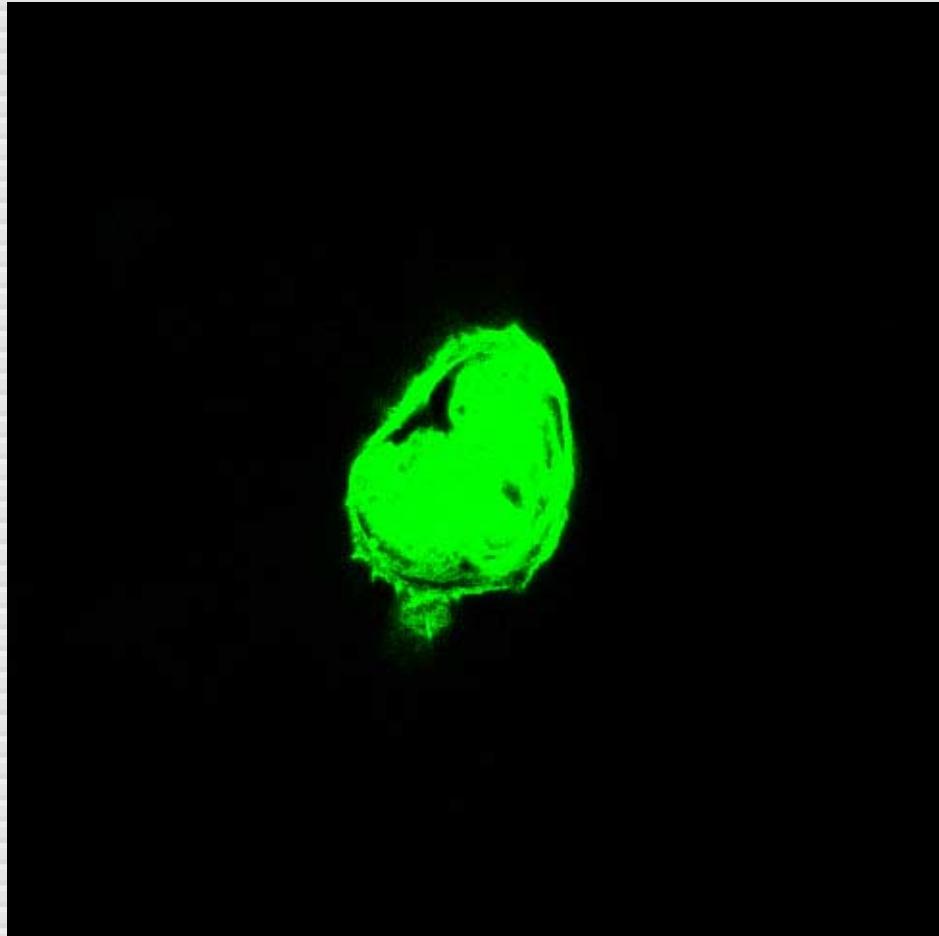


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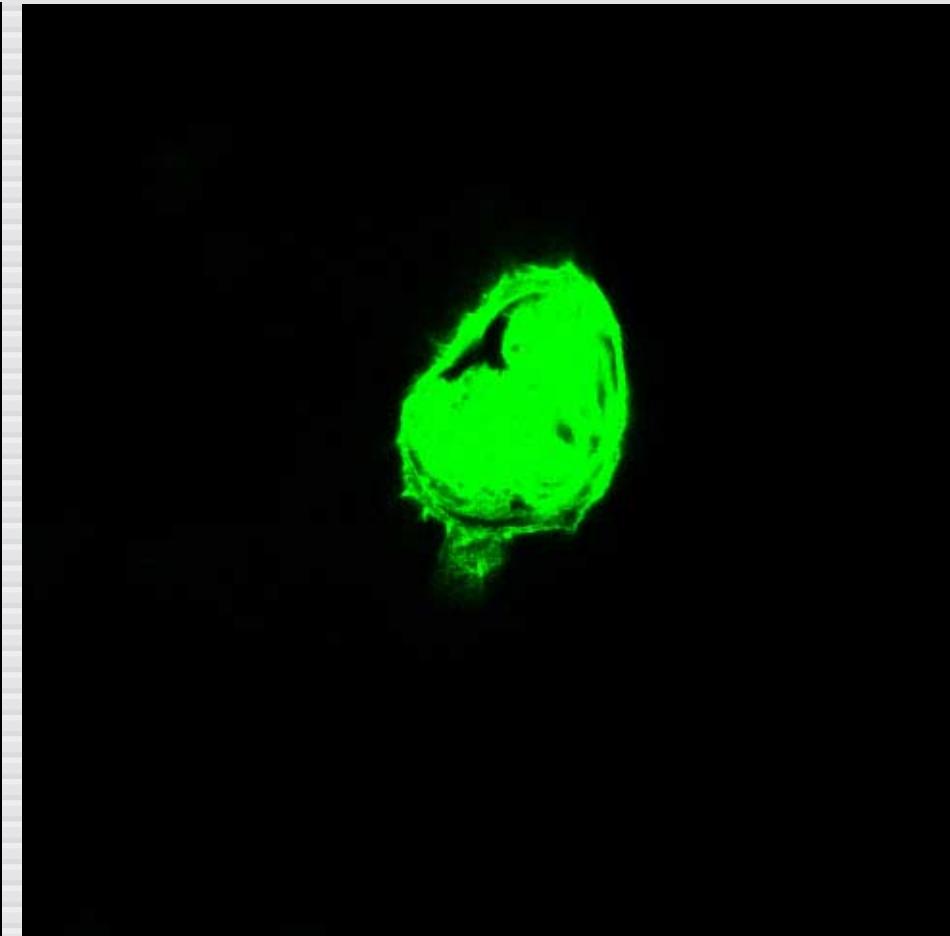


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**before**

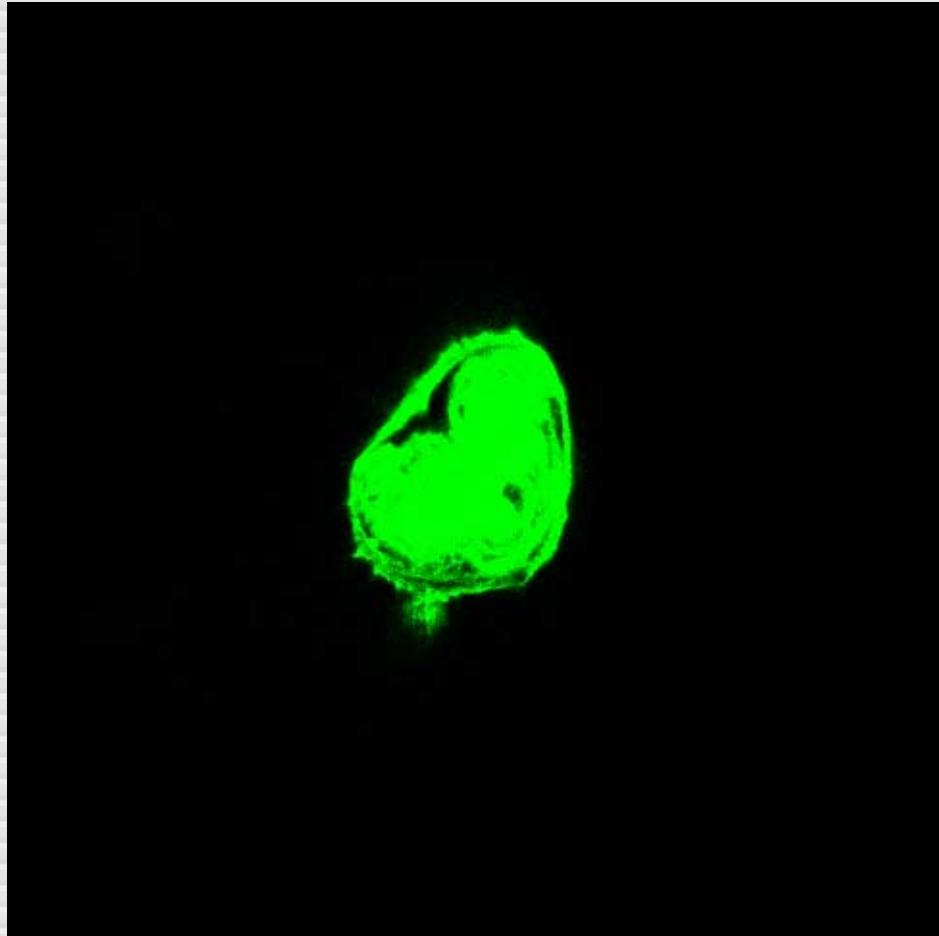


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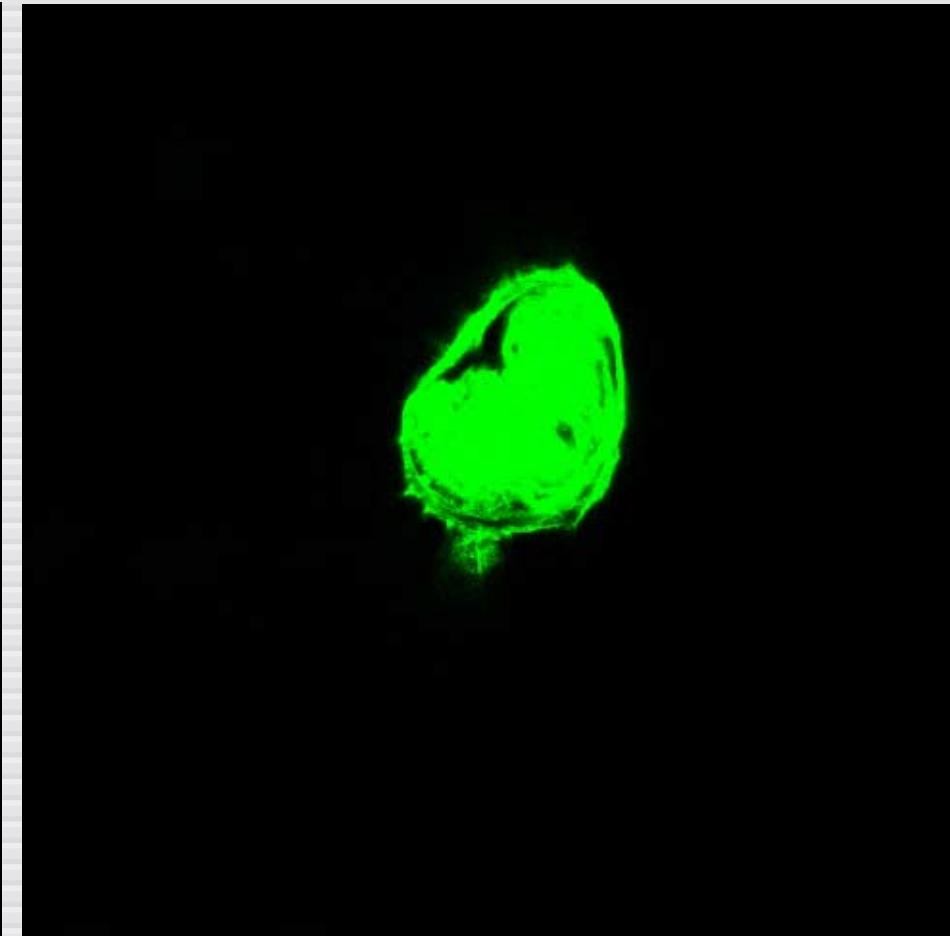


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**before**

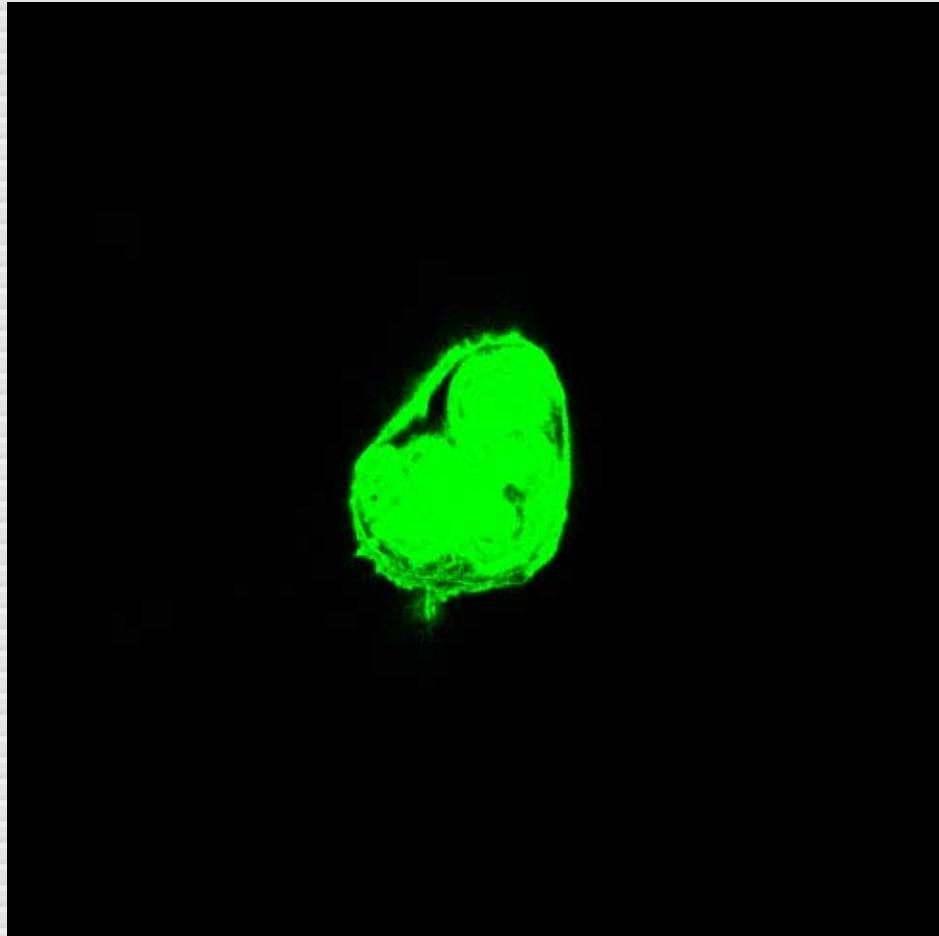


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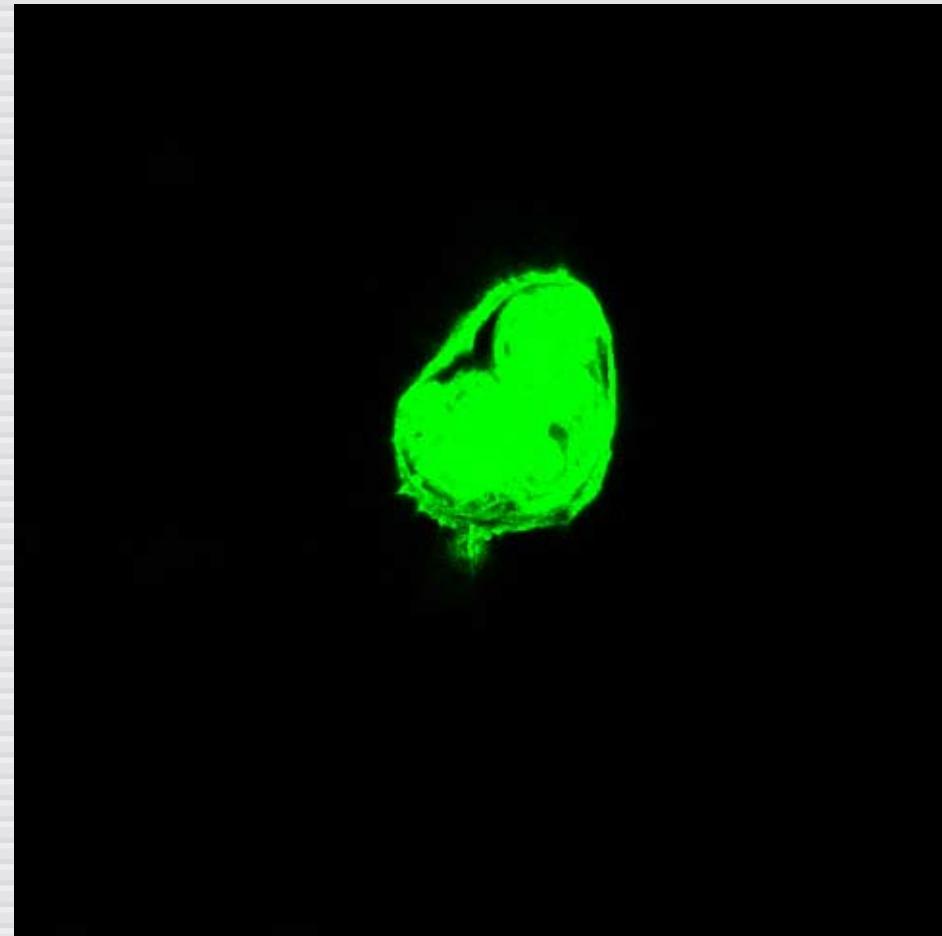


# *Biology and medicine*

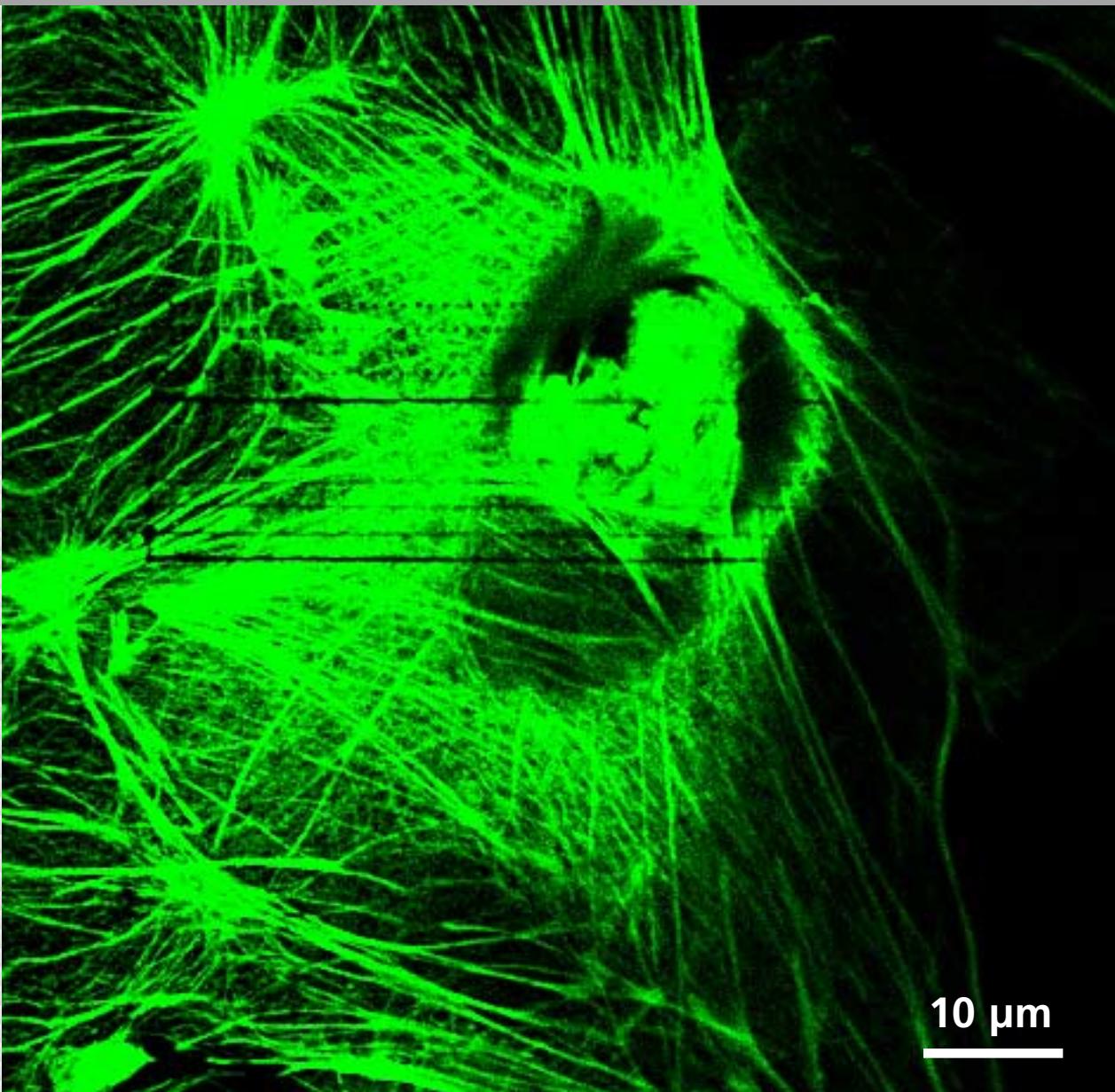
**before**



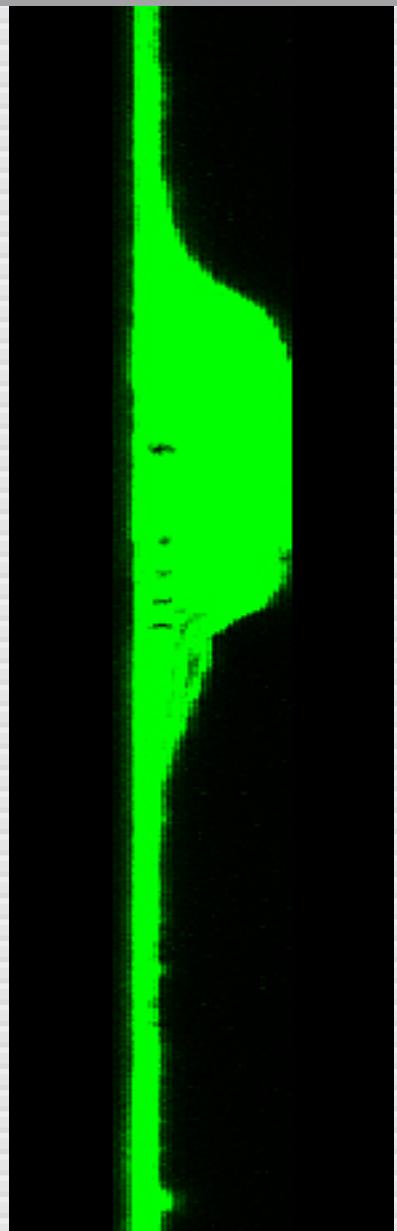
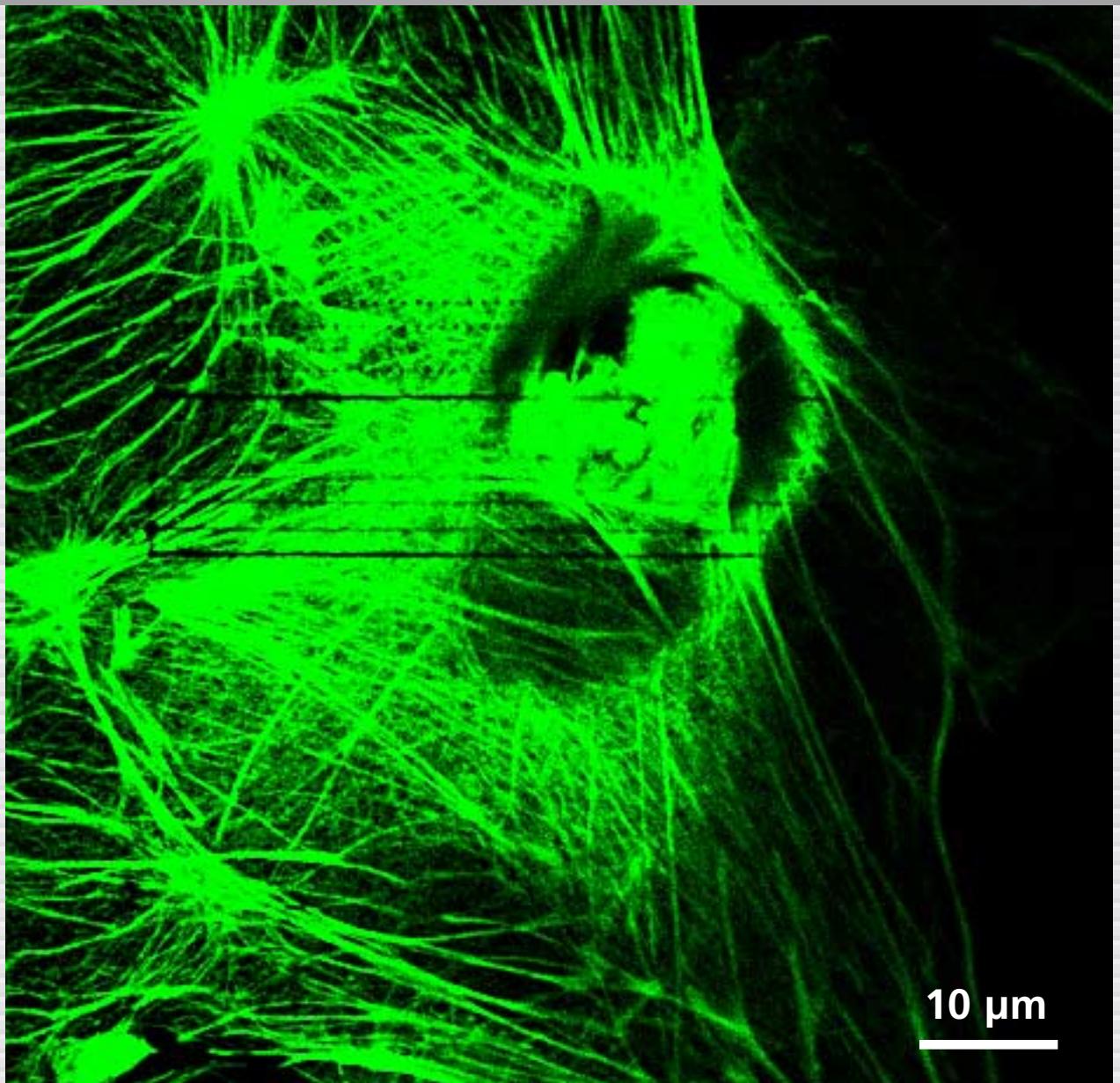
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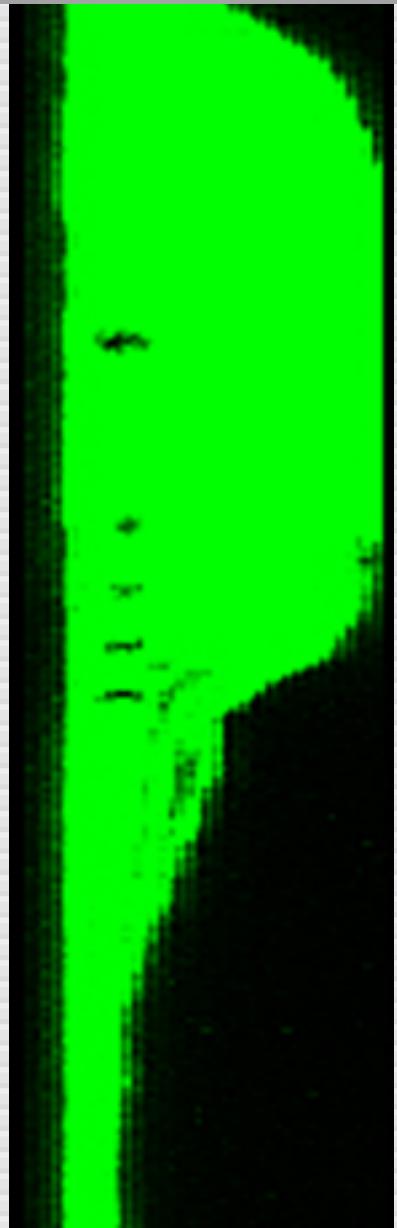
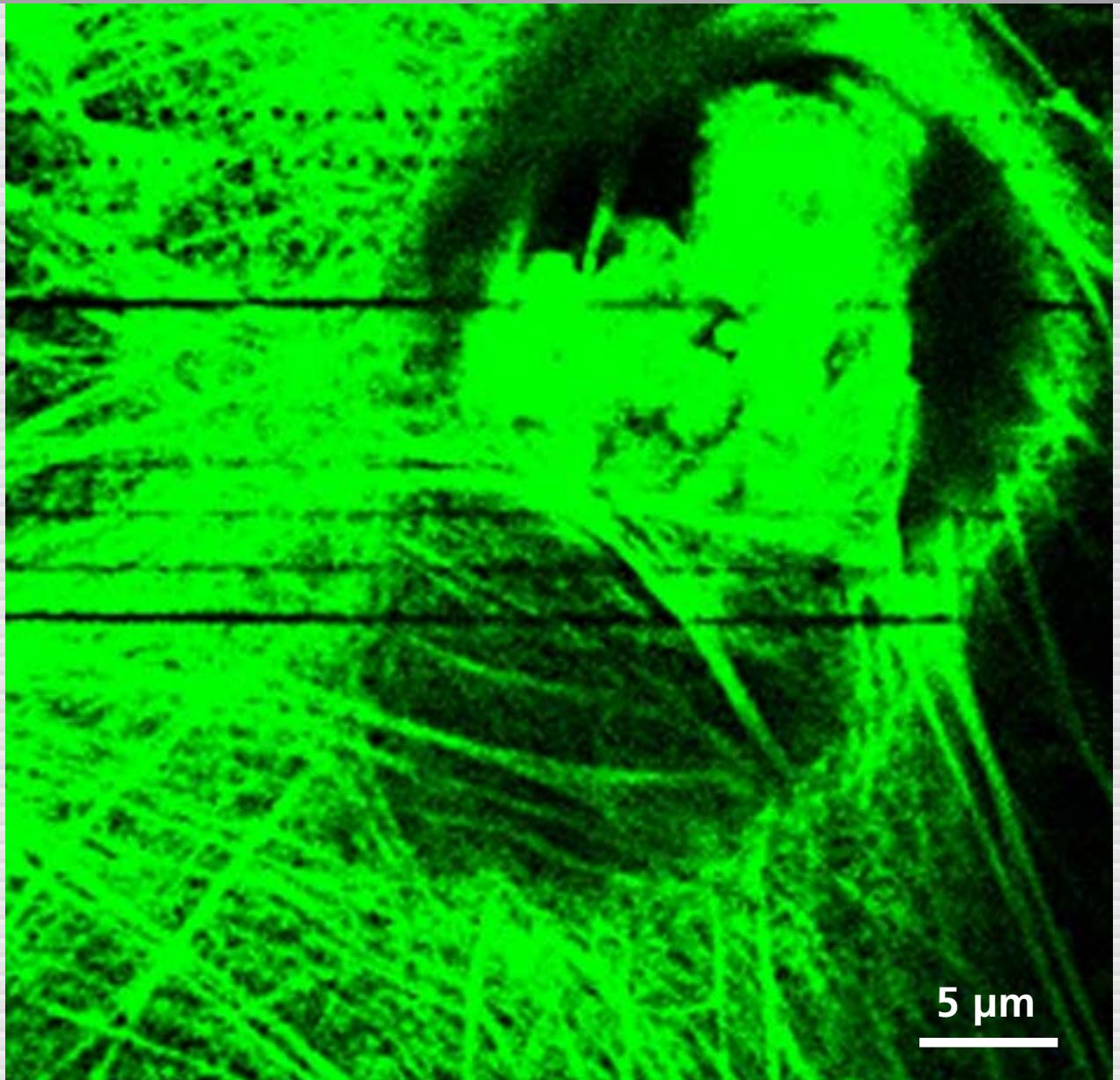
# *Biology and medicine*



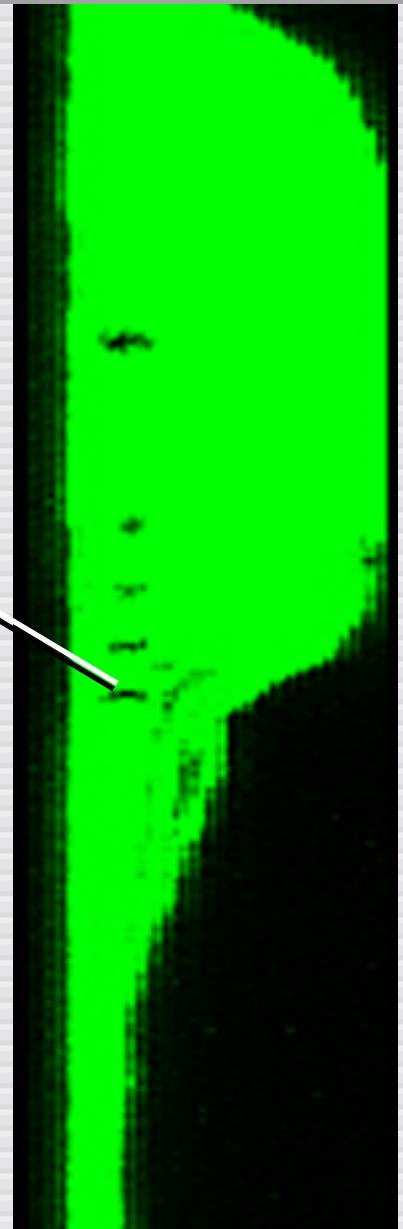
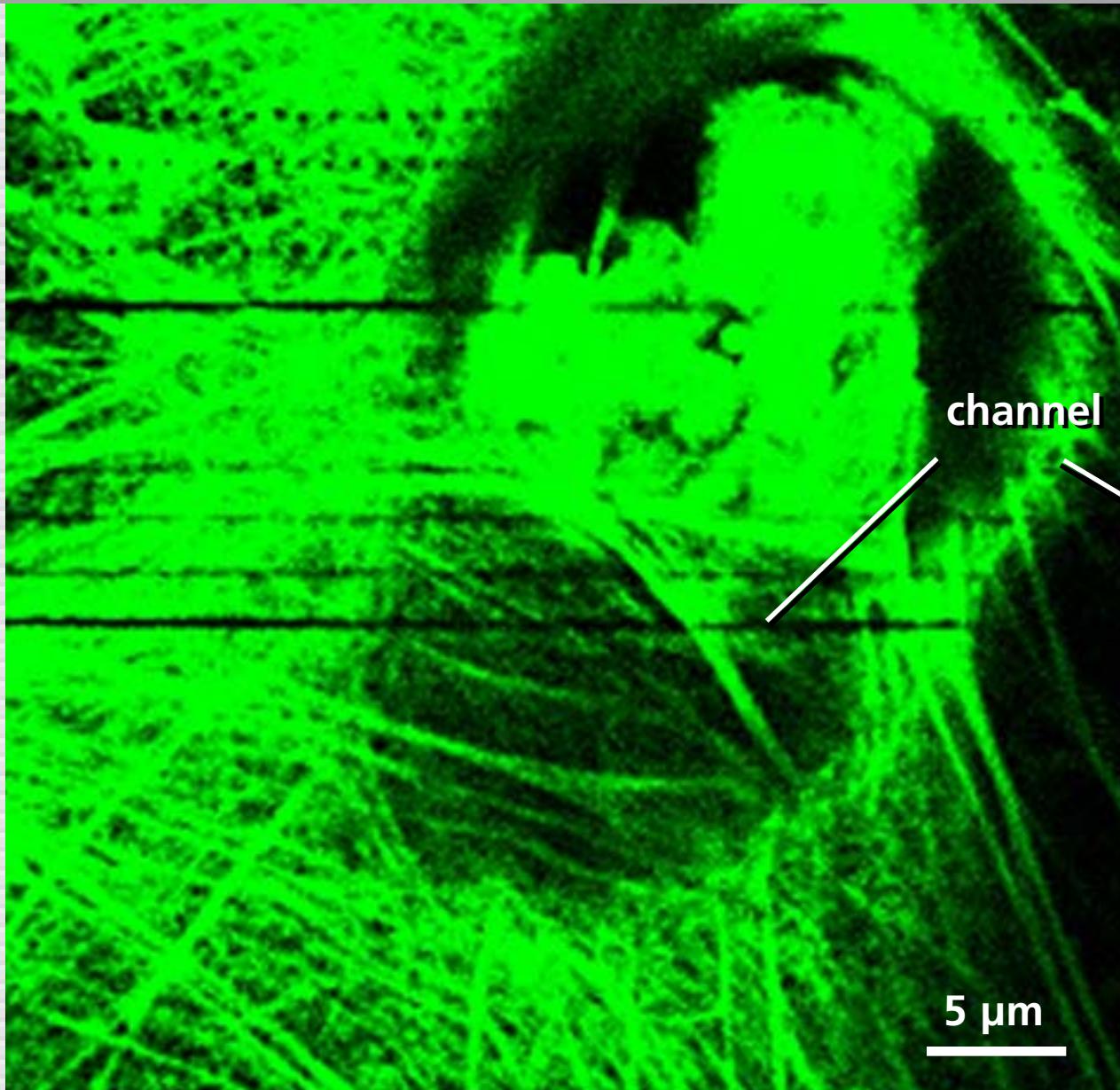
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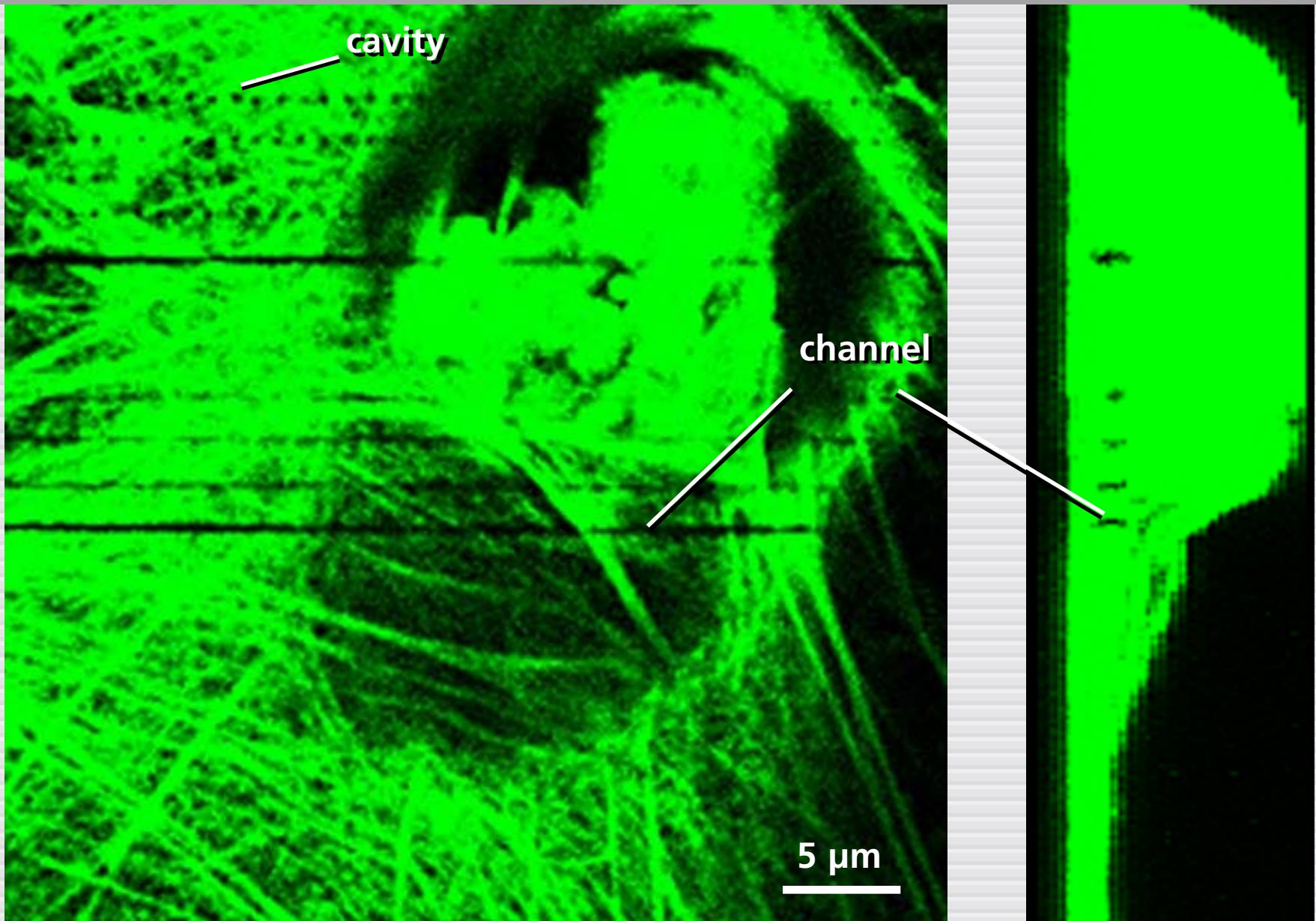
# *Biology and medicine*



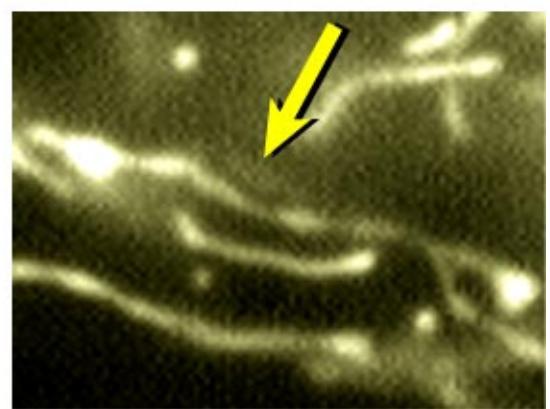
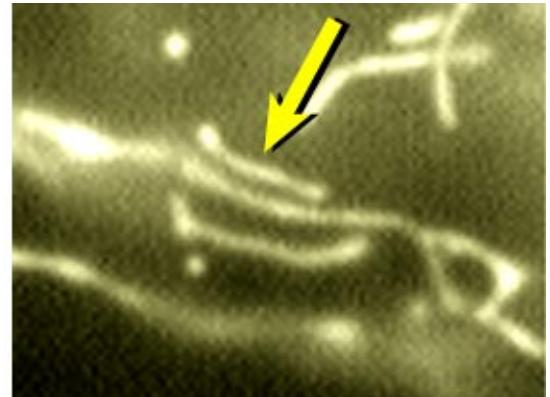
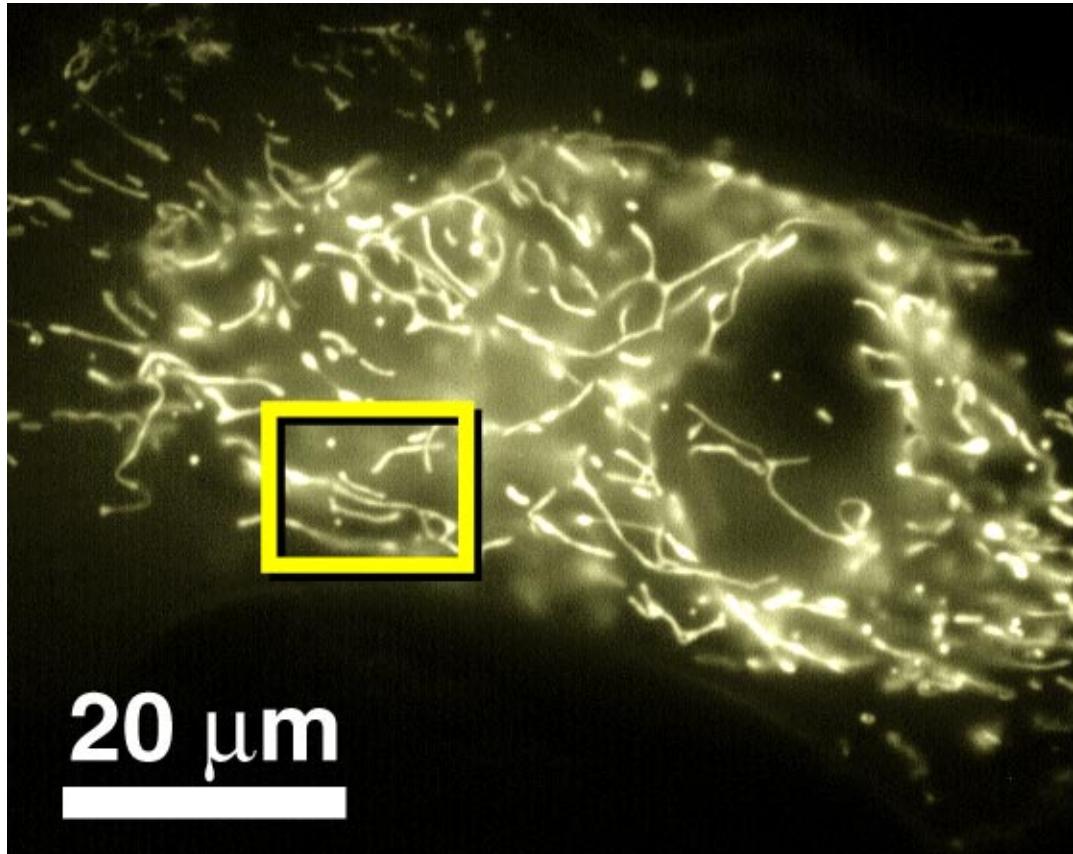
# Biology and medicine



# Biology and medicine



## *Low-energy processing*





# *Nanoneurosurgery*

## *Caenorhabditis Elegans*



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

# *Nanoneurosurgery*

## *Caenorhabditis Elegans*

- ▶ simple model organism

# *Nanoneurosurgery*

## *Caenorhabditis Elegans*

- ▶ simple model organism
- ▶ similarities to higher organism

# *Nanoneurosurgery*

## *Caenorhabditis Elegans*

- ▶ **simple model organism**
- ▶ **similarities to higher organism**
- ▶ **genome fully sequenced**

# *Nanoneurosurgery*

## *Caenorhabditis Elegans*

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

# *Nanoneurosurgery*

## *Caenorhabditis Elegans*

- ▶ 80 µm x 1 mm

# *Nanoneurosurgery*

## *Caenorhabditis Elegans*

- ▶ **80 µm x 1 mm**
- ▶ **about 1300 cells**

# *Nanoneurosurgery*

## *Caenorhabditis Elegans*

- ▶ **80 µm x 1 mm**
- ▶ **about 1300 cells**
- ▶ **302 neurons**

# *Nanoneurosurgery*

## *Caenorhabditis Elegans*

- ▶ **80 µm x 1 mm**
- ▶ **about 1300 cells**
- ▶ **302 neurons**
- ▶ **invariant wiring diagram**

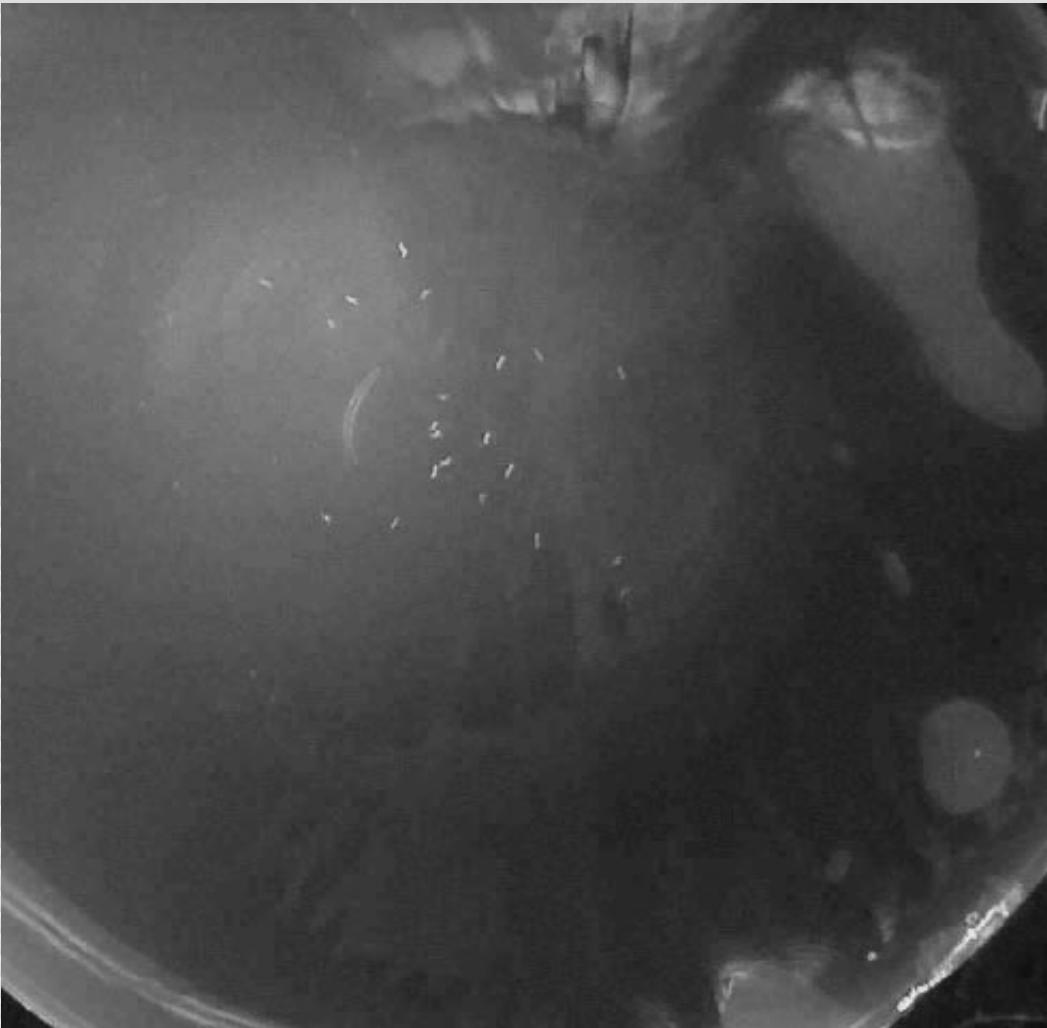
# *Nanoneurosurgery*

## *Caenorhabditis Elegans*

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

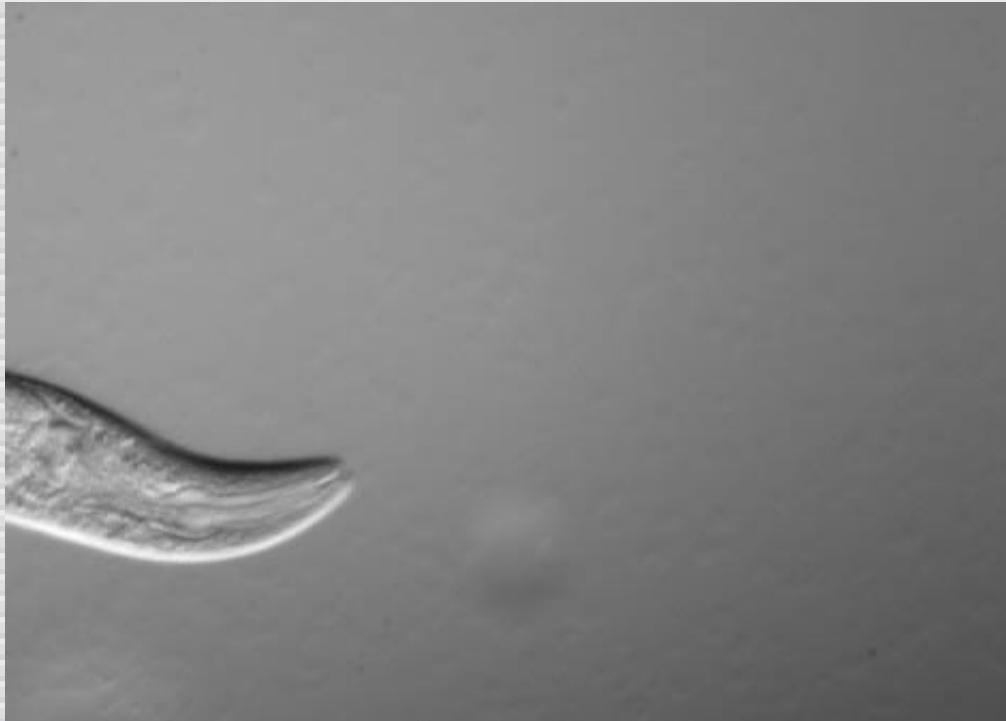
*Nanoneurosurgery*

*Caenorhabditis Elegans*



*Nanoneurosurgery*

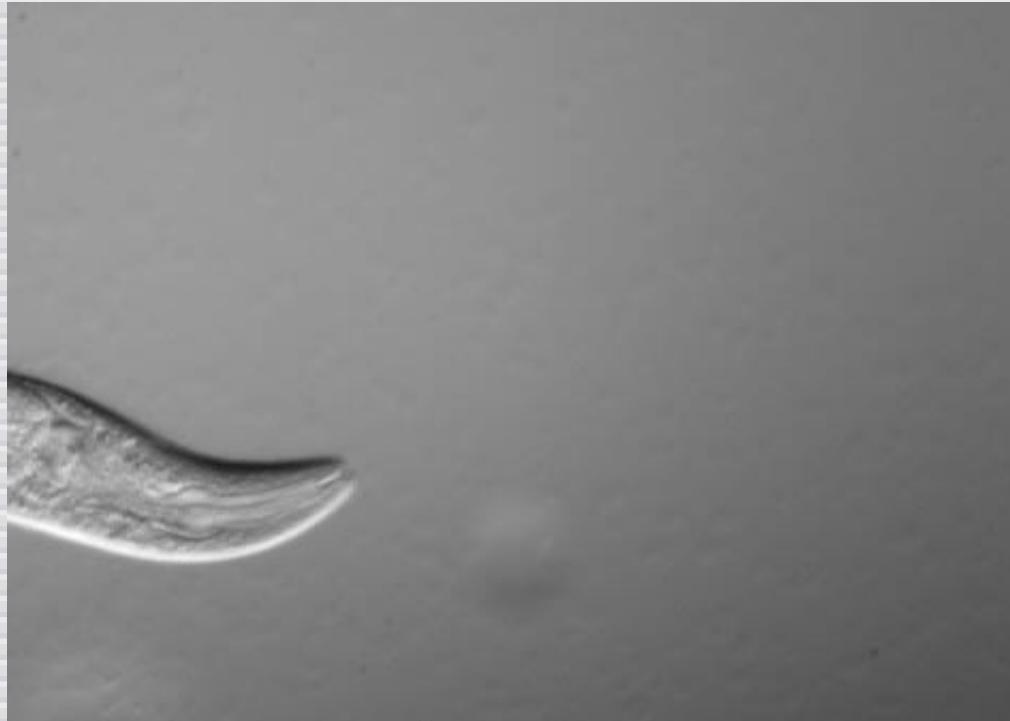
*Caenorhabditis Elegans*



**Bob Goldstein, UNC Chapel Hill**

*Nanoneurosurgery*

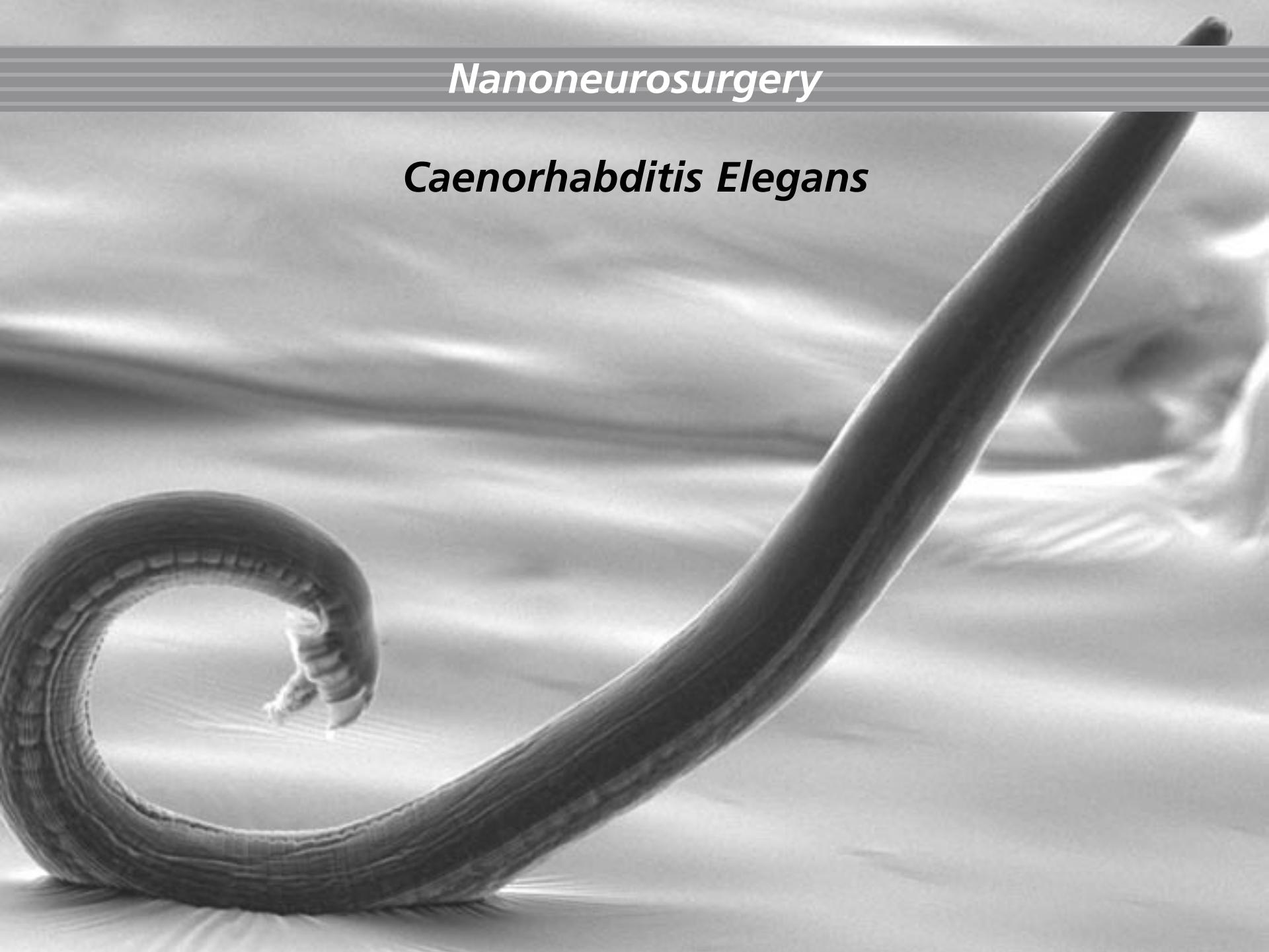
*Caenorhabditis Elegans*



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*Nanoneurosurgery*

***Caenorhabditis Elegans***





# *Nanoneurosurgery*



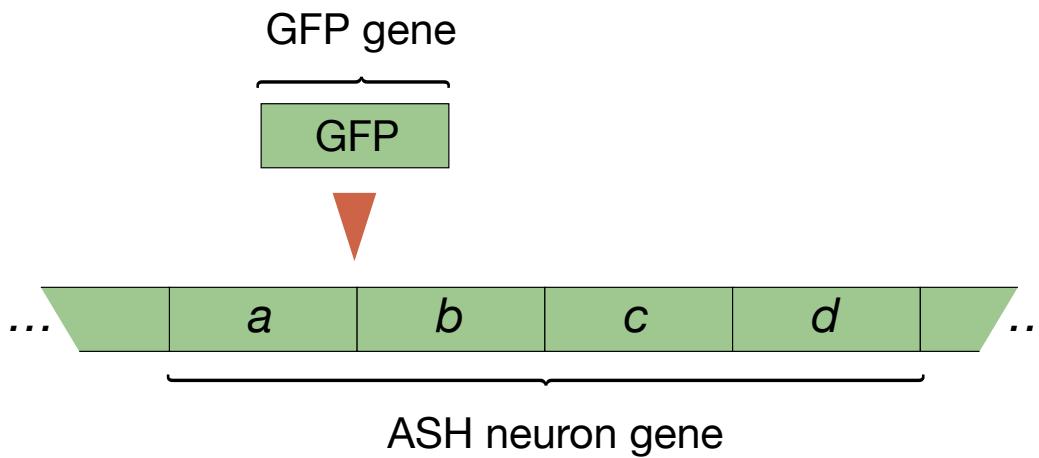
# *Nanoneurosurgery*

## ASH neurons

- ▶ **responsible for osmotic avoidance**
- ▶ **ciliary projections extend through skin**
- ▶ **one on each side**

# *Nanoneurosurgery*

**make ASH neurons express GFP**



# *Nanoneurosurgery*

**GFP: absorbs UV, emits green**

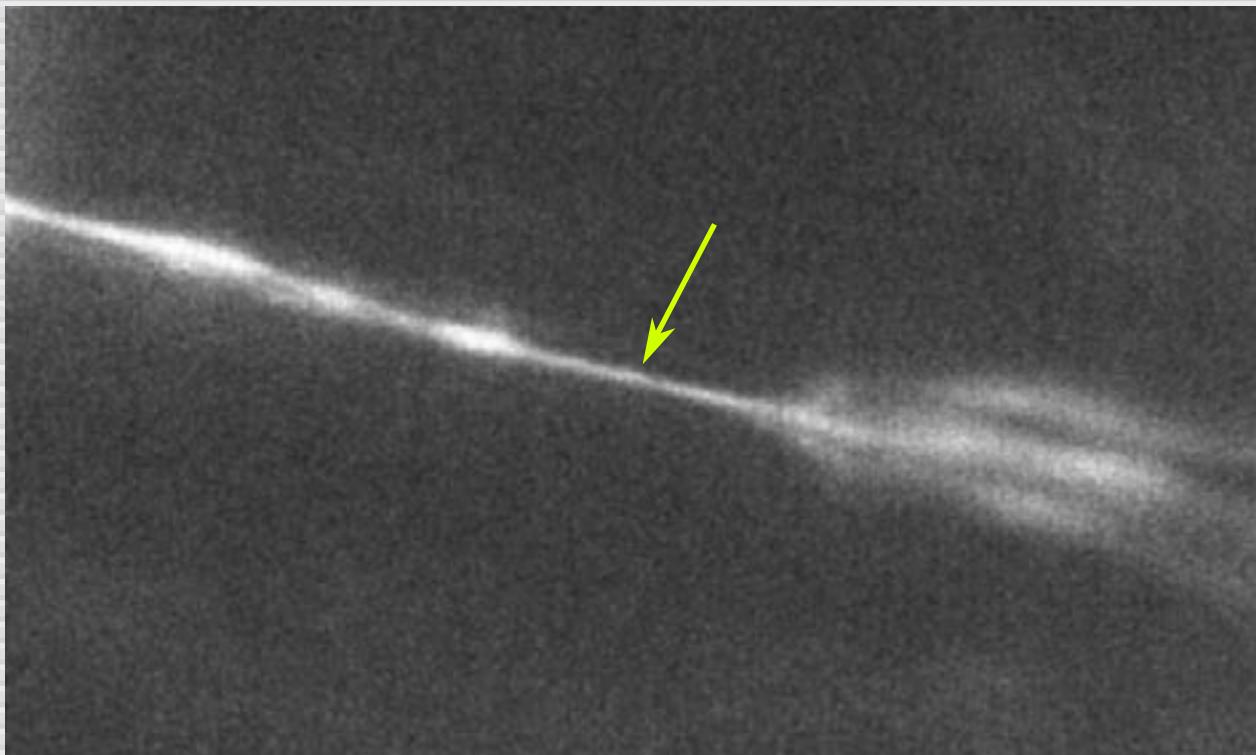


**Manual**

**1-10-00      2H  
16:42:28      1/60**

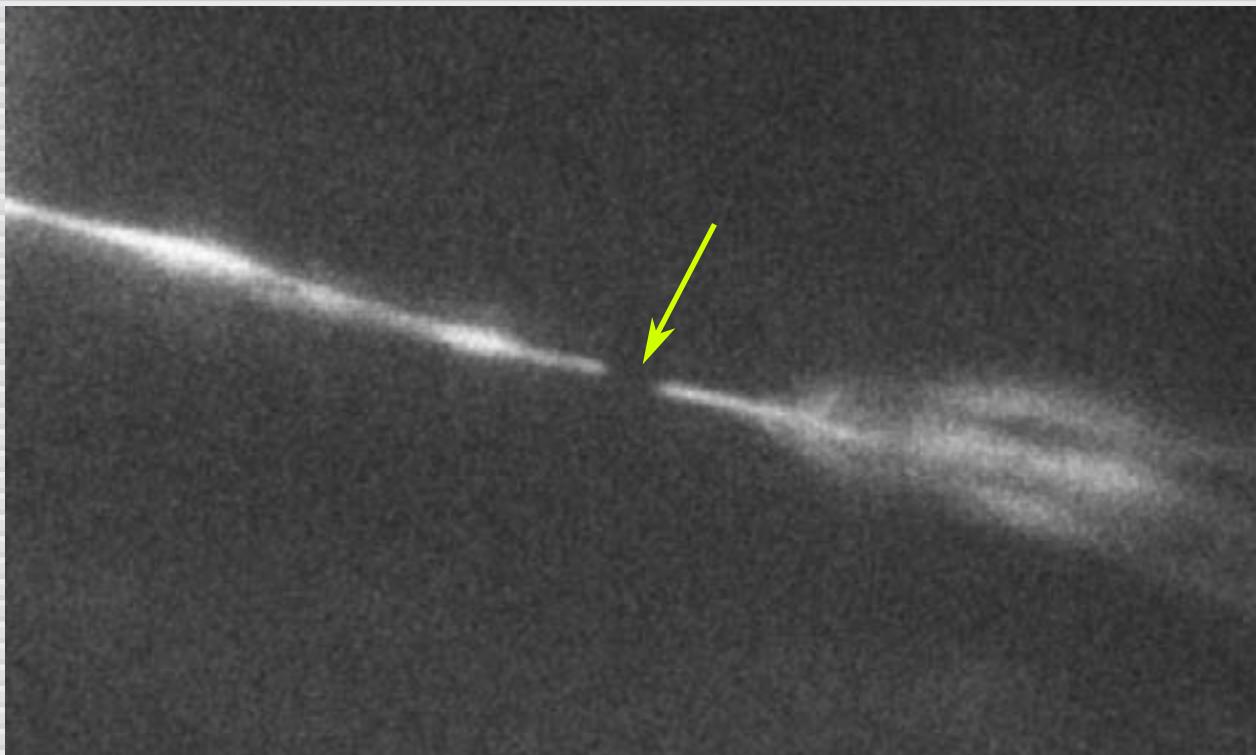
# *Nanoneurosurgery*

**cutting an axon**



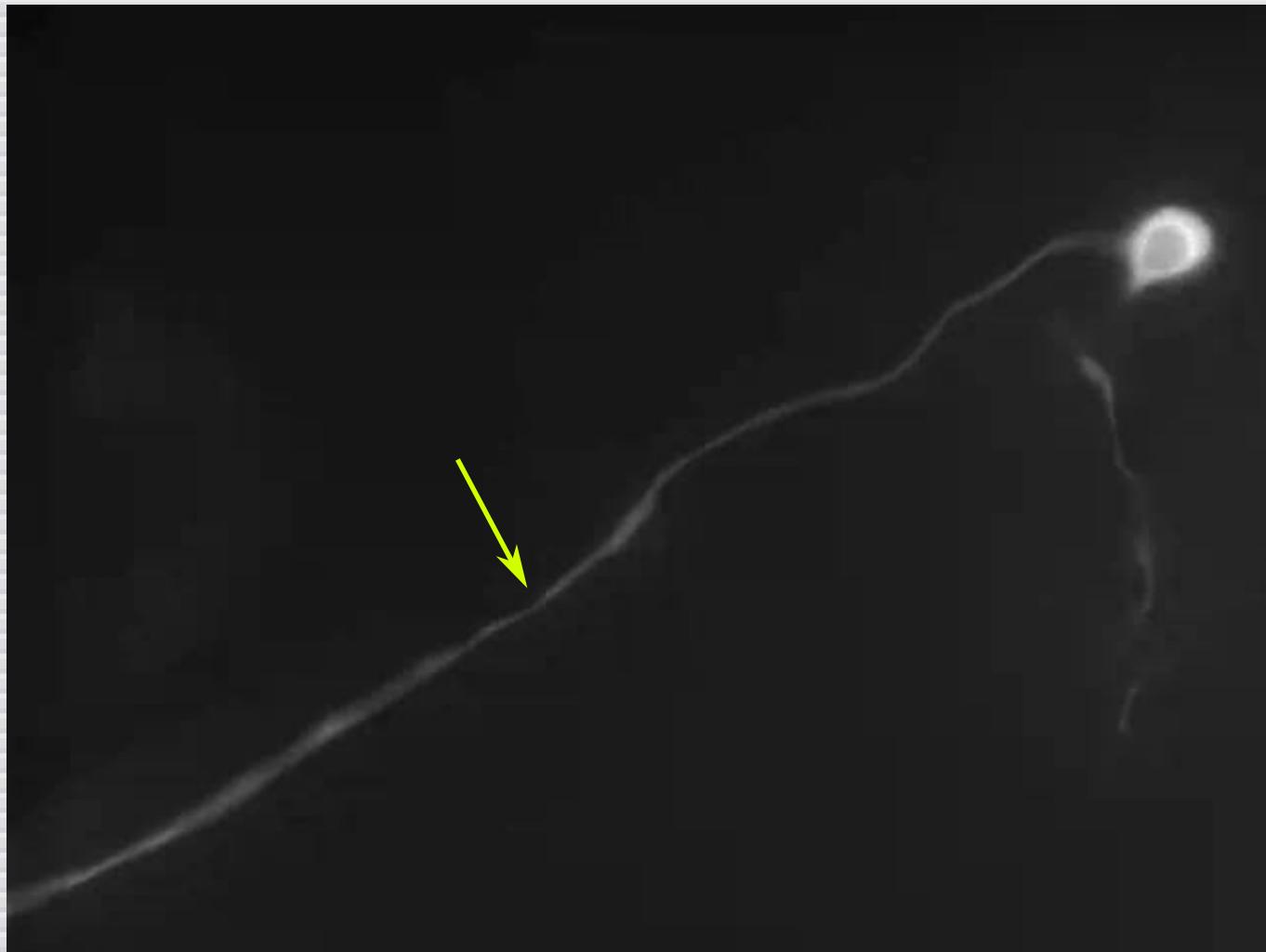
# *Nanoneurosurgery*

**cutting an axon**



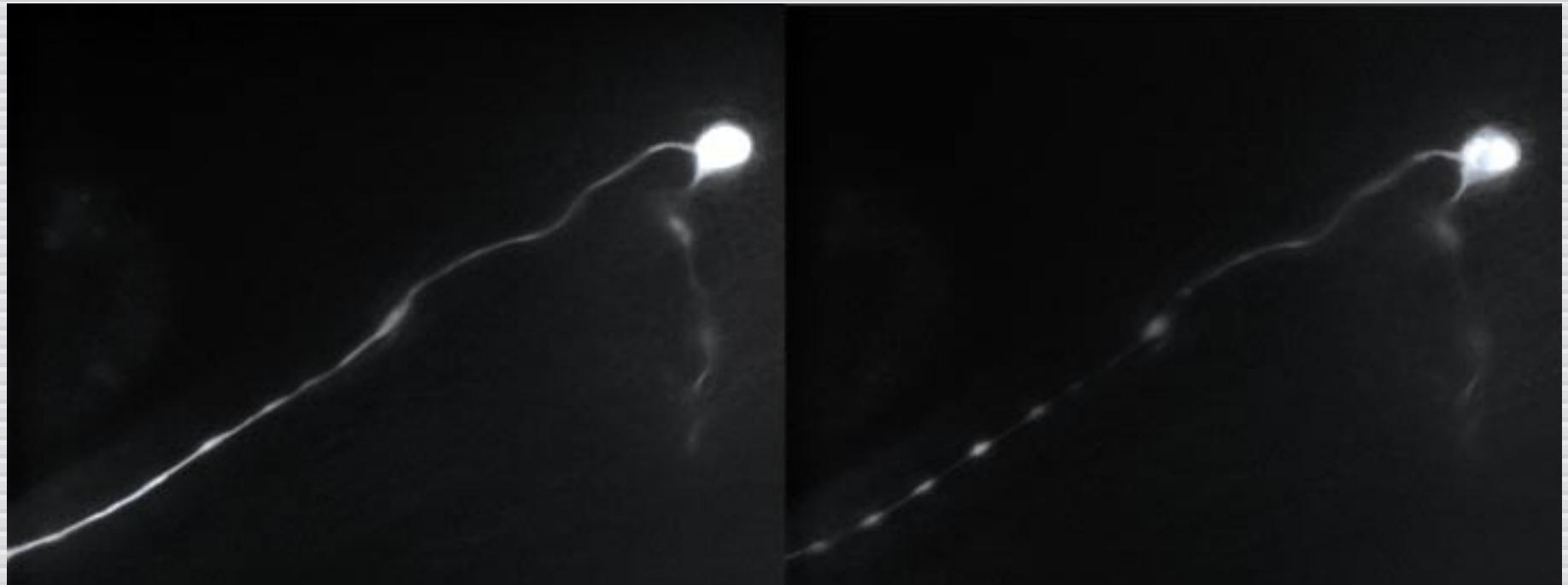
*Nanoneurosurgery*

**pearling instability**



*Nanoneurosurgery*

**pearling instability**



## *Summary*

- ▶ diversified use of femtosecond lasers

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- ▶ unprecedented view into dynamics

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- ▶ diversified use of femtosecond lasers
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For additional information, see:

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