

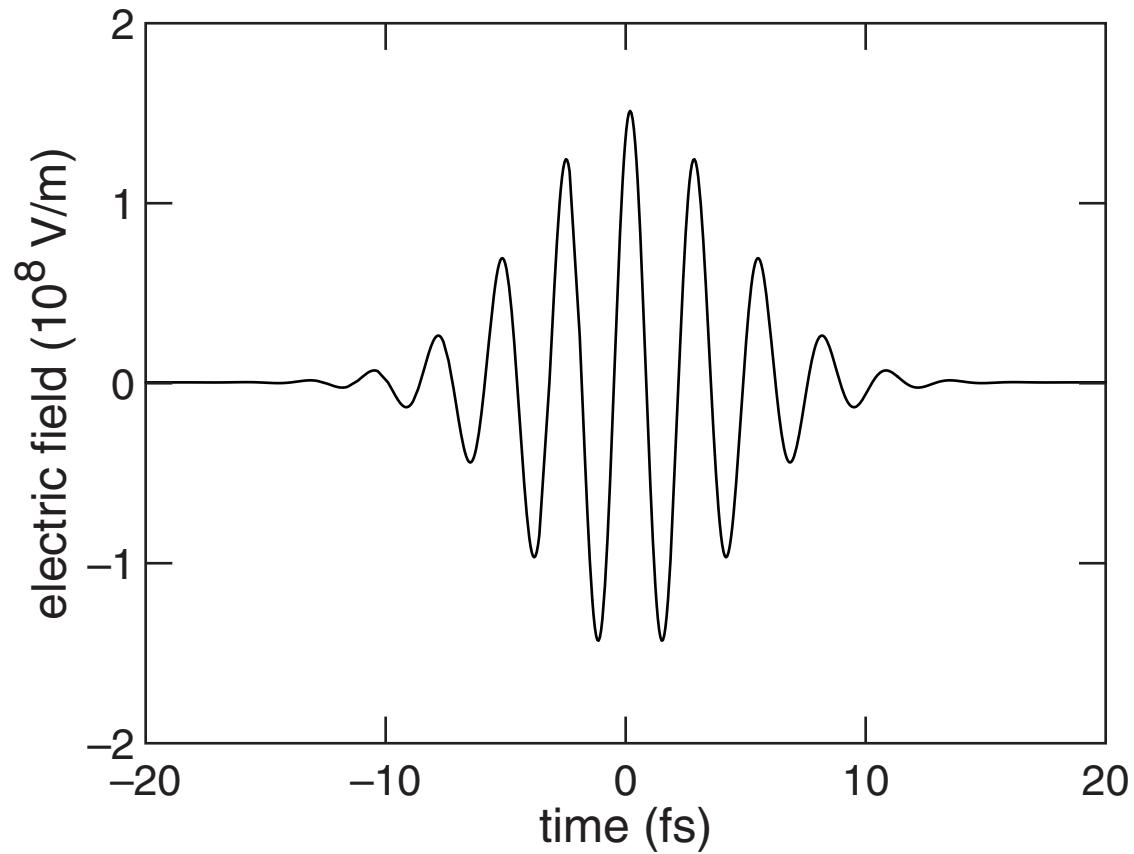
# **LIGHT-MATTER INTERACTIONS IN THE EXTREME NONLINEAR REGIME**

**Eric Mazur**

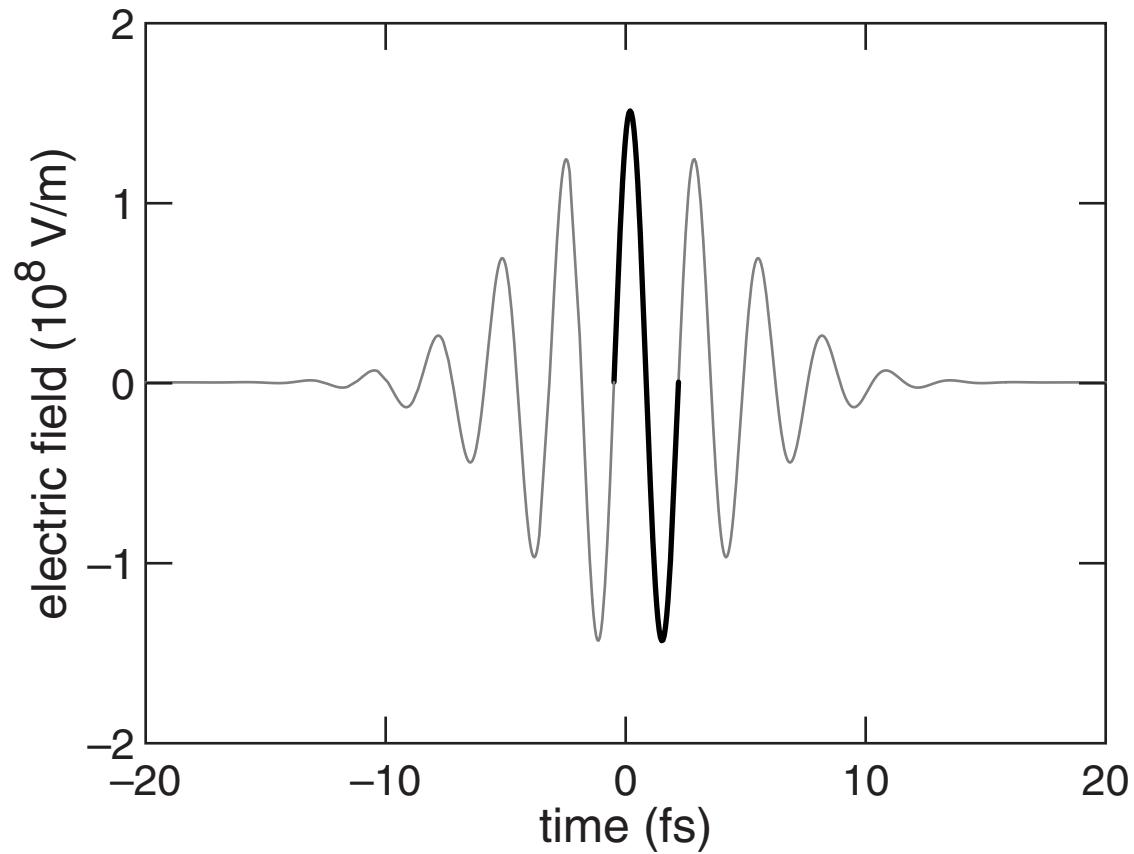
GK-12 Seminar  
10 March 2003



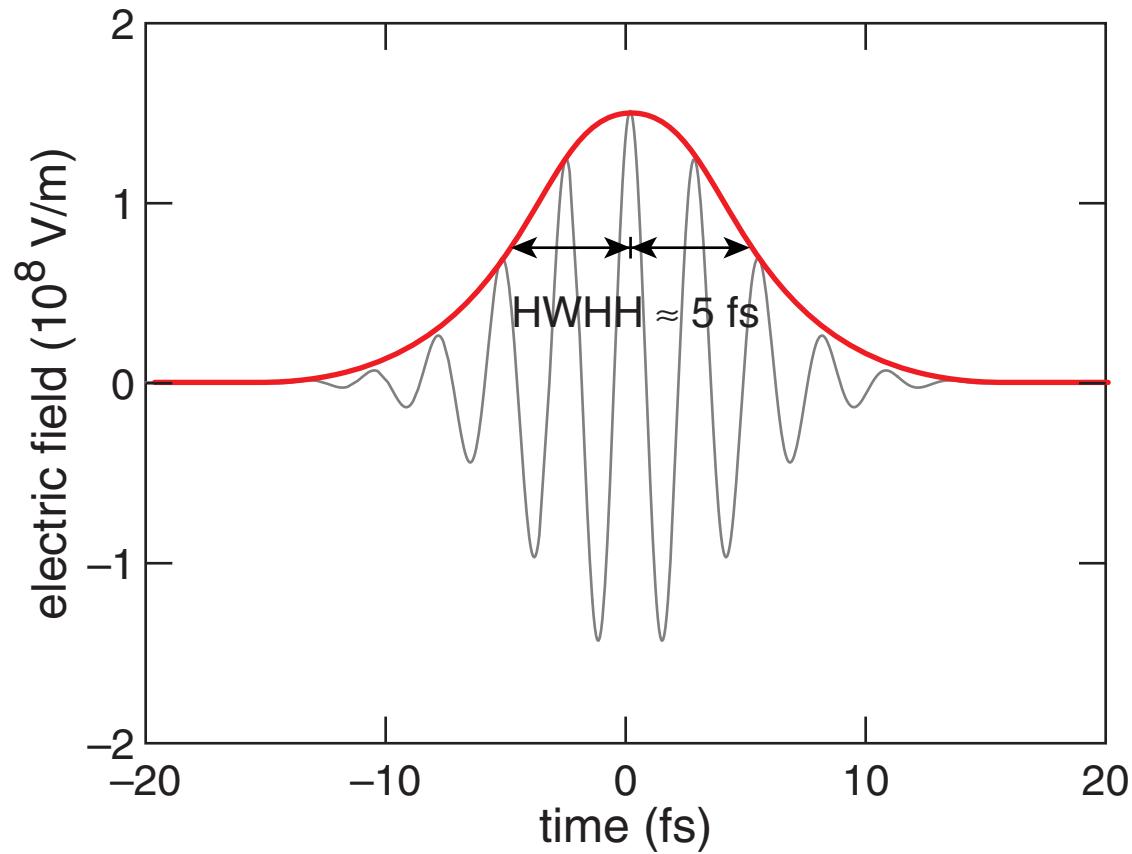
# *Introduction*



# *Introduction*



# *Introduction*

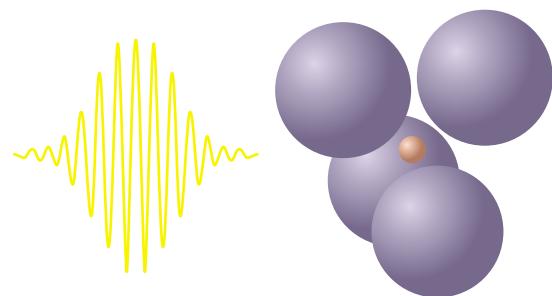


# *Introduction*

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

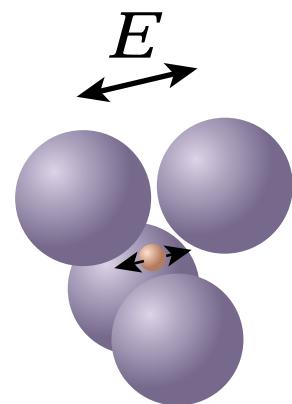
# *Introduction*

## light-matter interactions



# *Introduction*

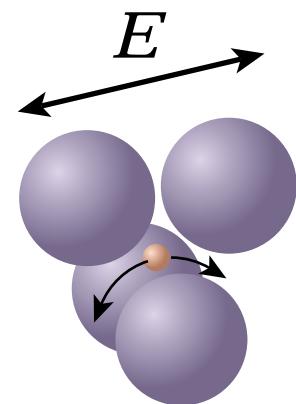
## linear response



“stiffness” determines index of refraction

# *Introduction*

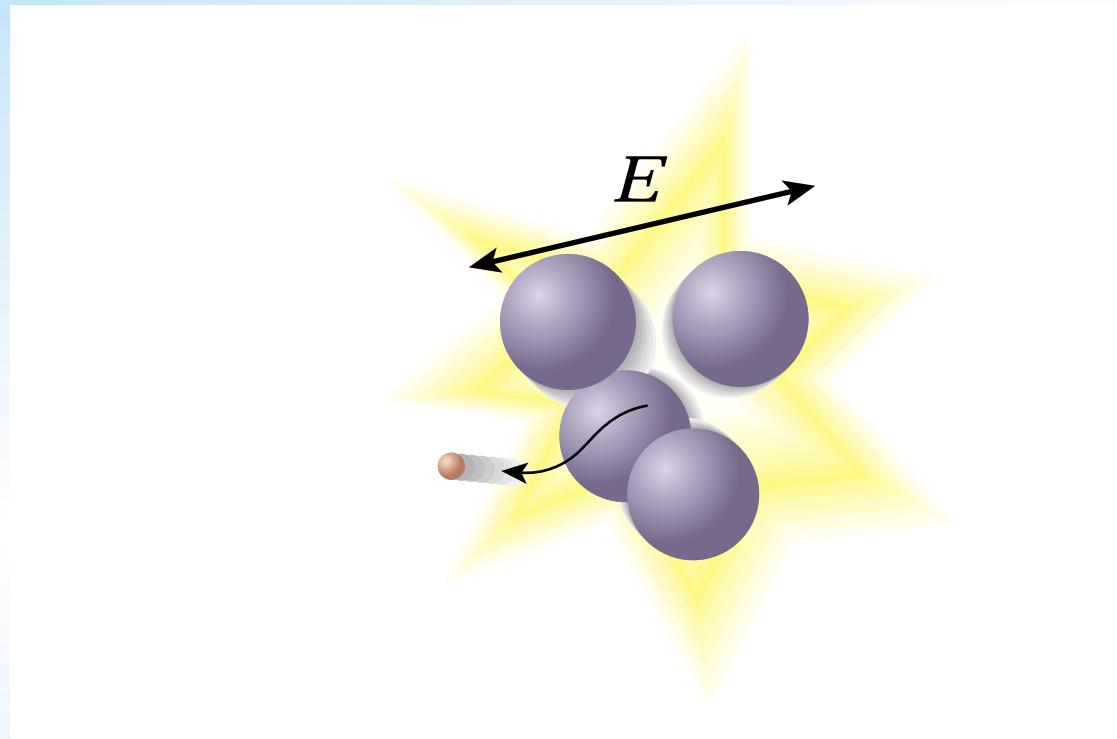
## nonlinear response



second harmonic generation

# *Introduction*

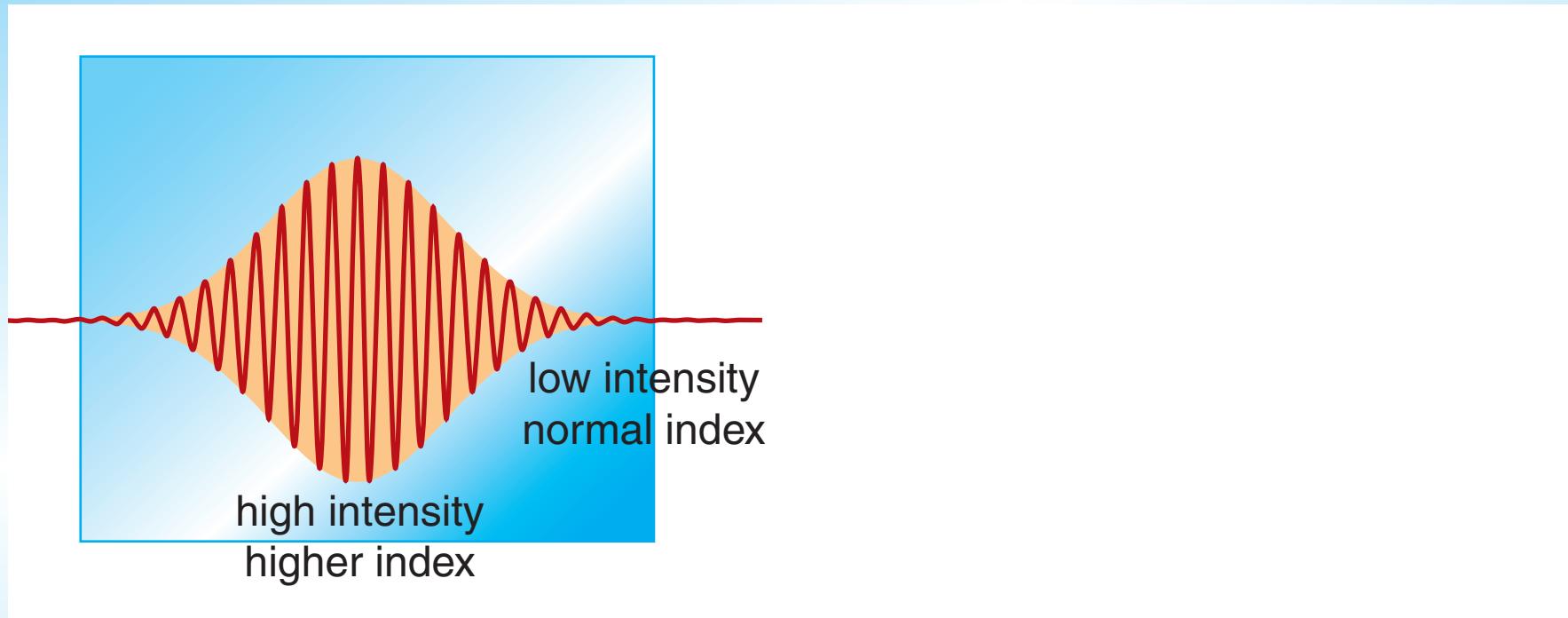
“extremely” nonlinear response



# *Nonlinear optics*

**Intensity dependent index of refraction:**

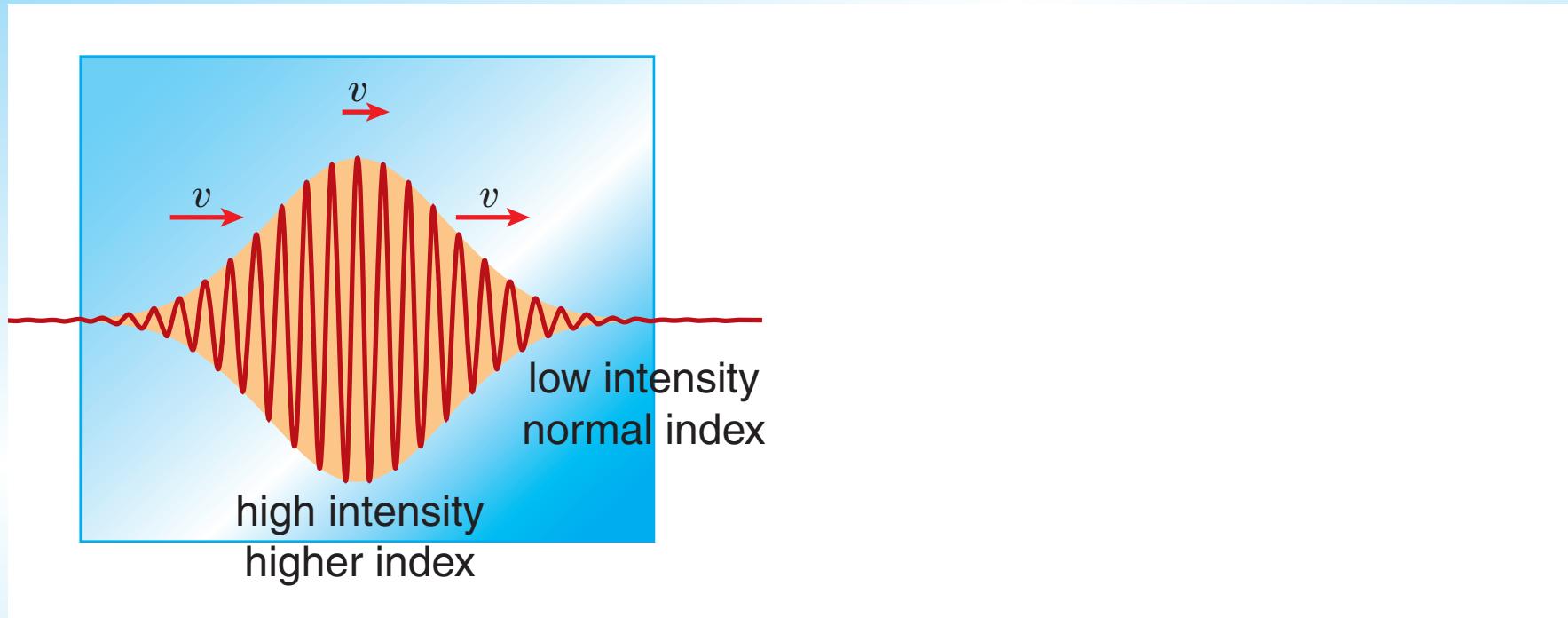
$$n = n_o + n_2 I$$



# *Nonlinear optics*

**Intensity dependent index of refraction:**

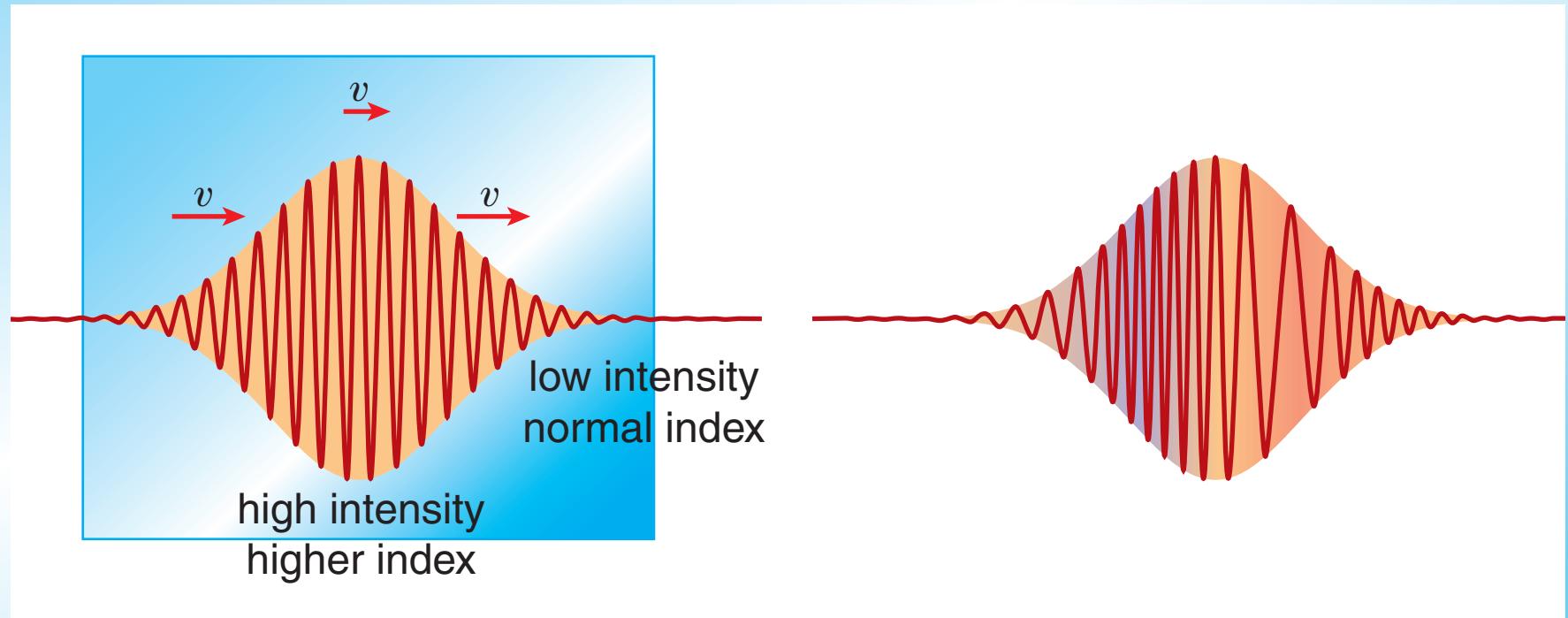
$$n = n_o + n_2 I$$



# *Nonlinear optics*

**Intensity dependent index of refraction:**

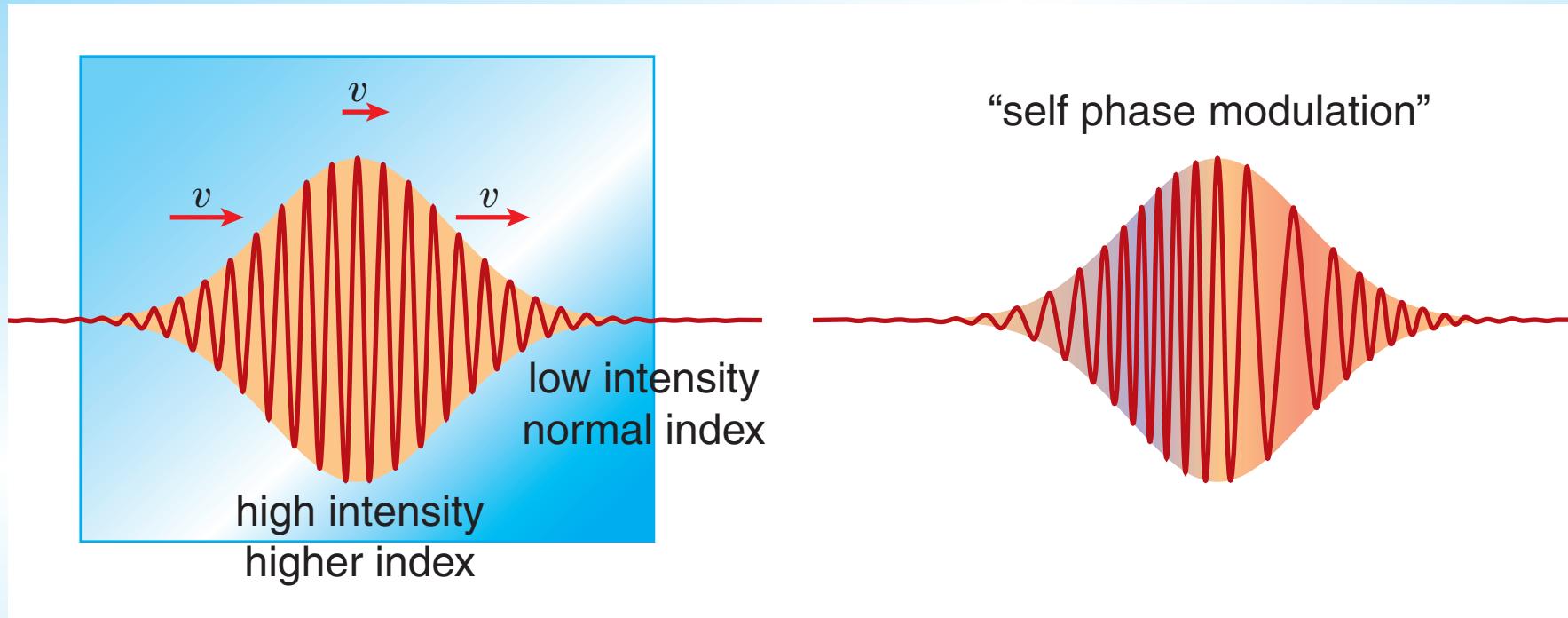
$$n = n_o + n_2 I$$



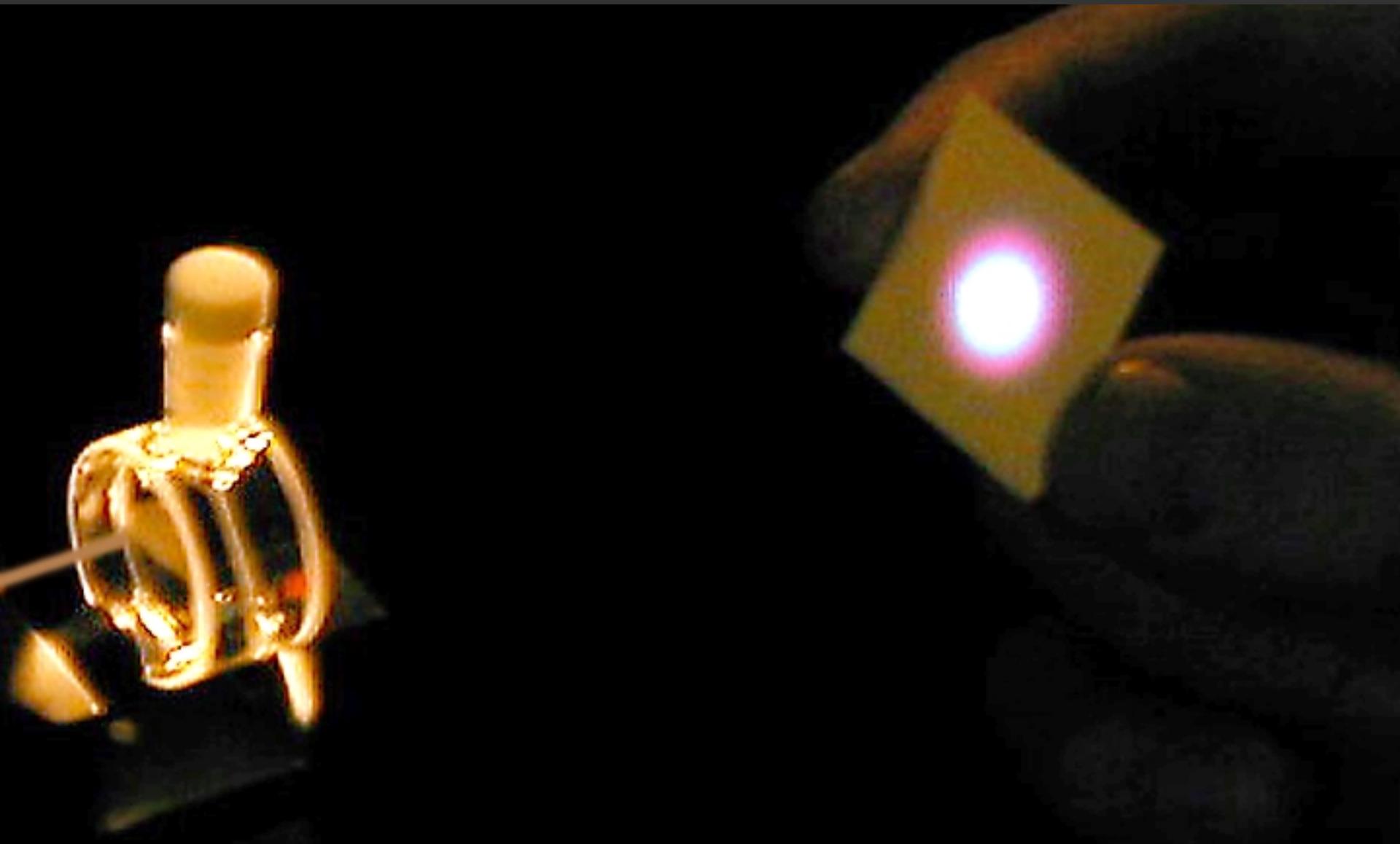
# *Nonlinear optics*

## Intensity dependent index of refraction:

$$n = n_o + n_2 I$$

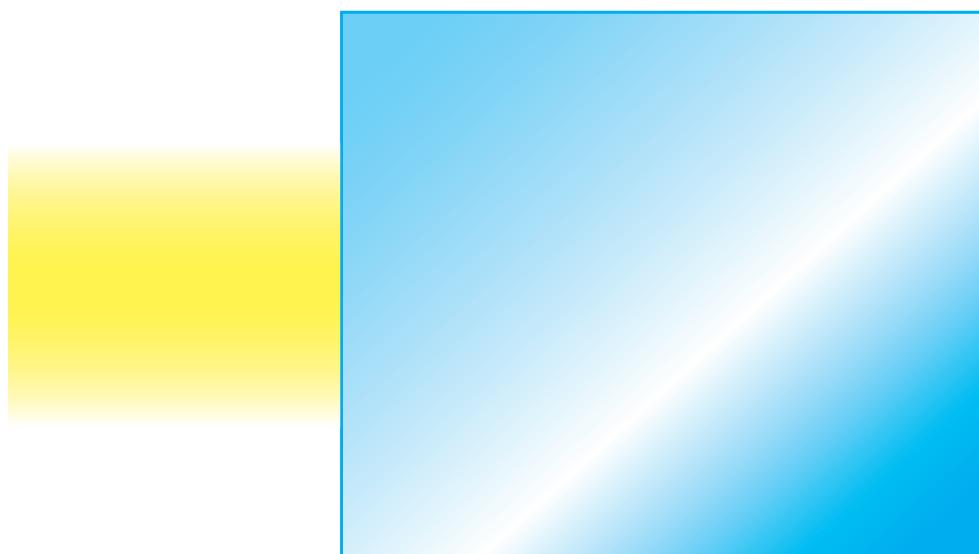


# *Introduction*



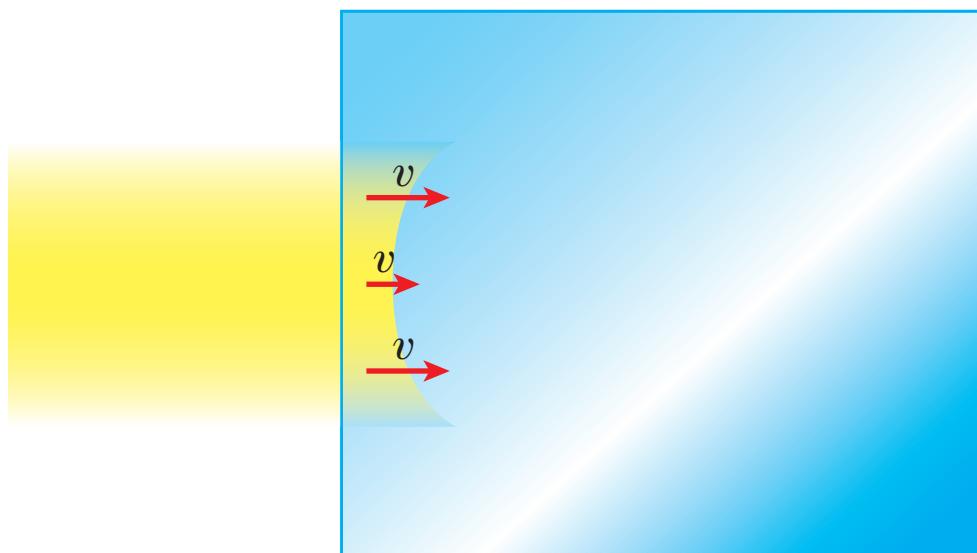
# *Nonlinear optics*

Spatial intensity profile...



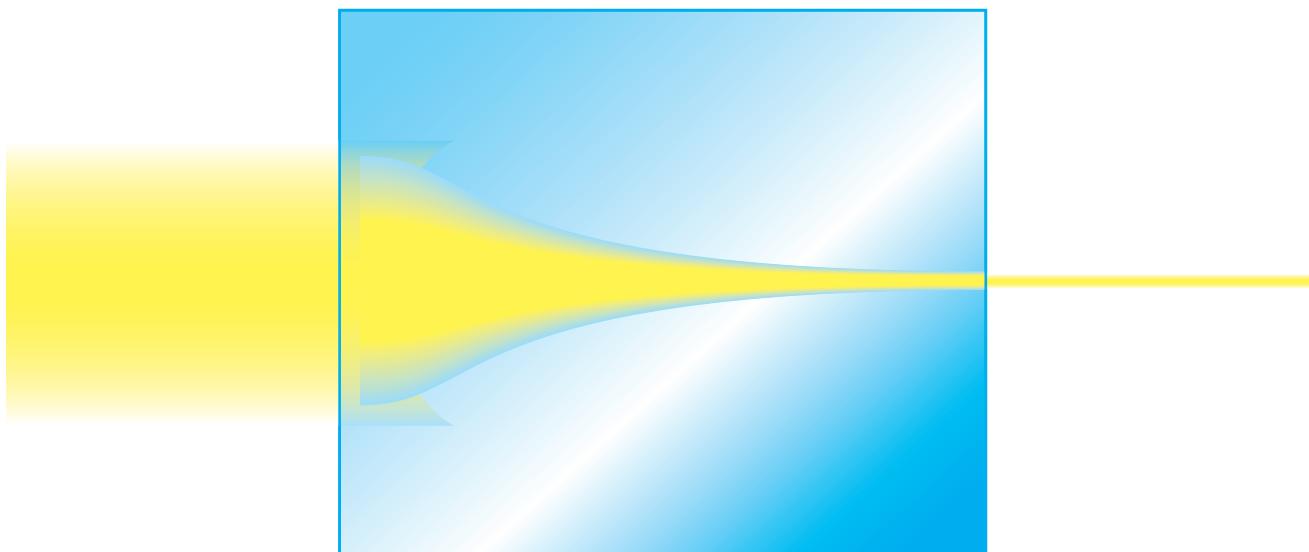
# *Nonlinear optics*

## Spatial intensity profile...



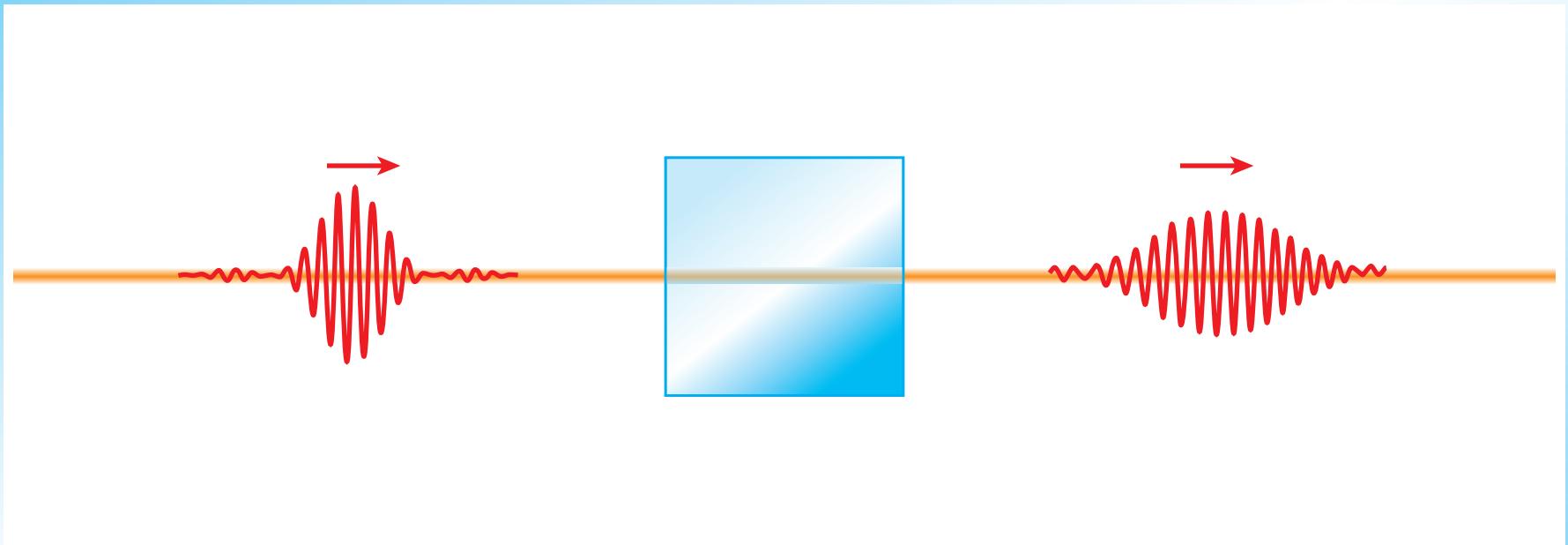
# *Nonlinear optics*

**...causes self-focusing**



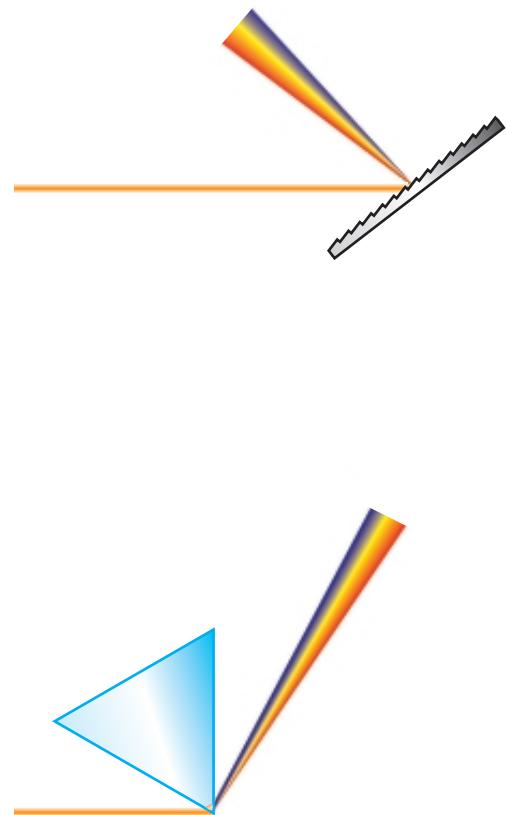
# *Dispersion compensation*

**Dispersion stretches the pulse**

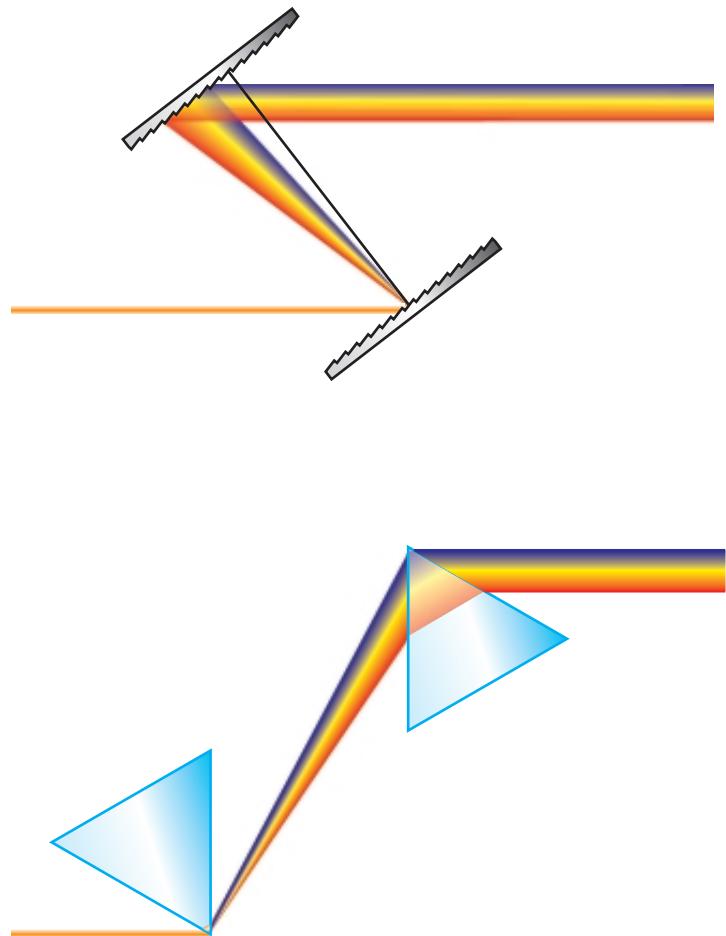


**Compensate by rearranging spectral components!**

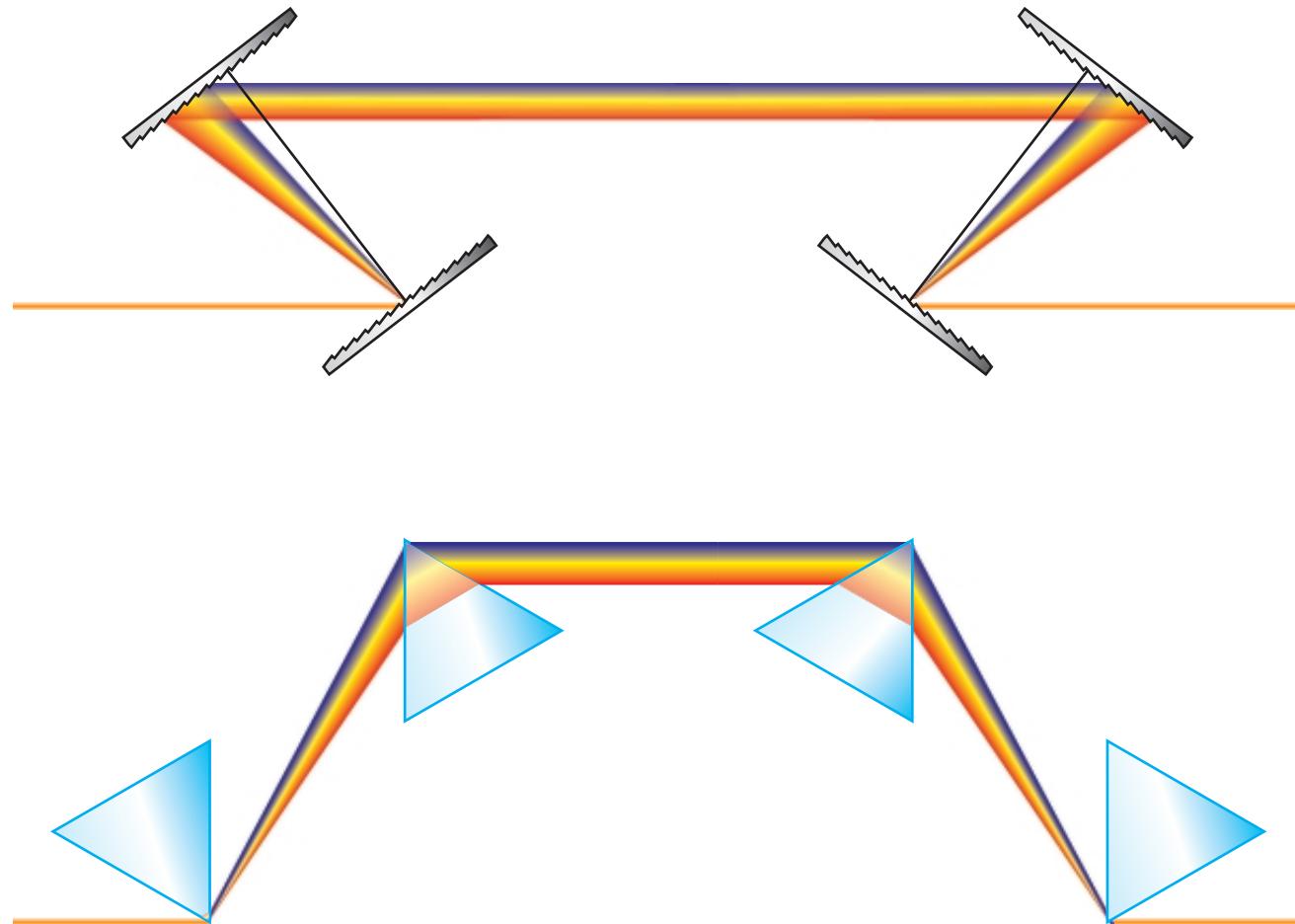
# *Dispersion compensation*



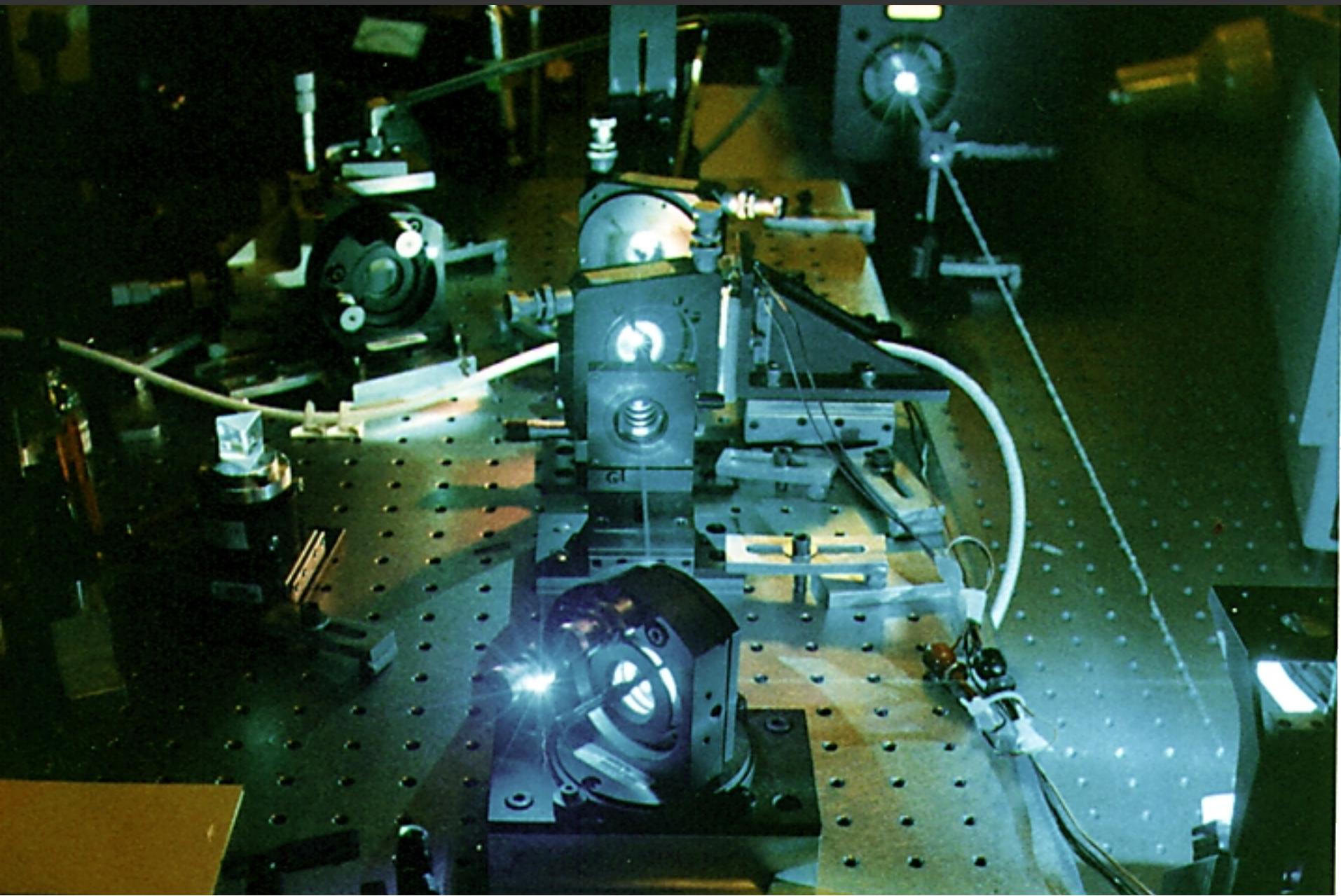
# *Dispersion compensation*



# *Dispersion compensation*

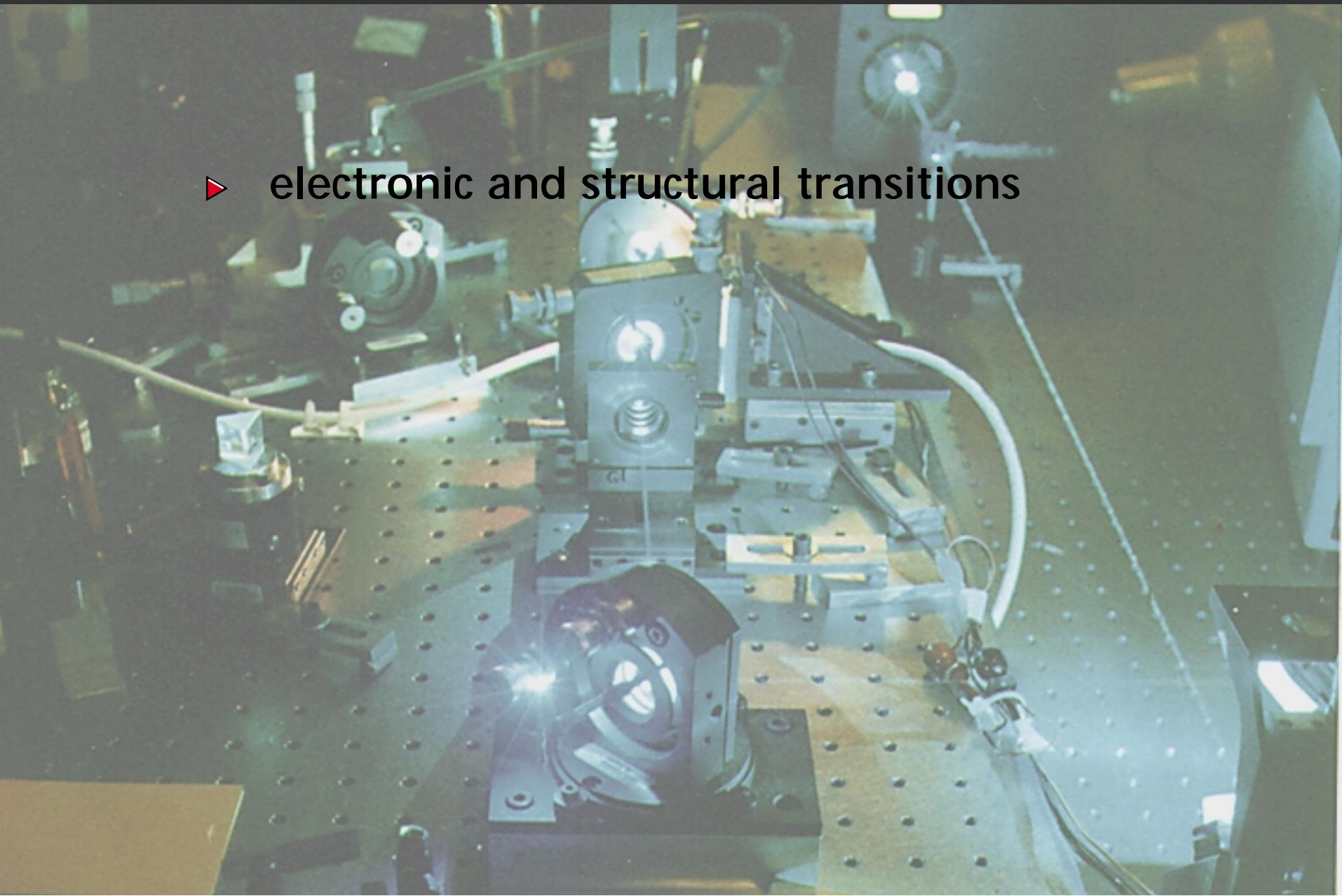


# *Overview*



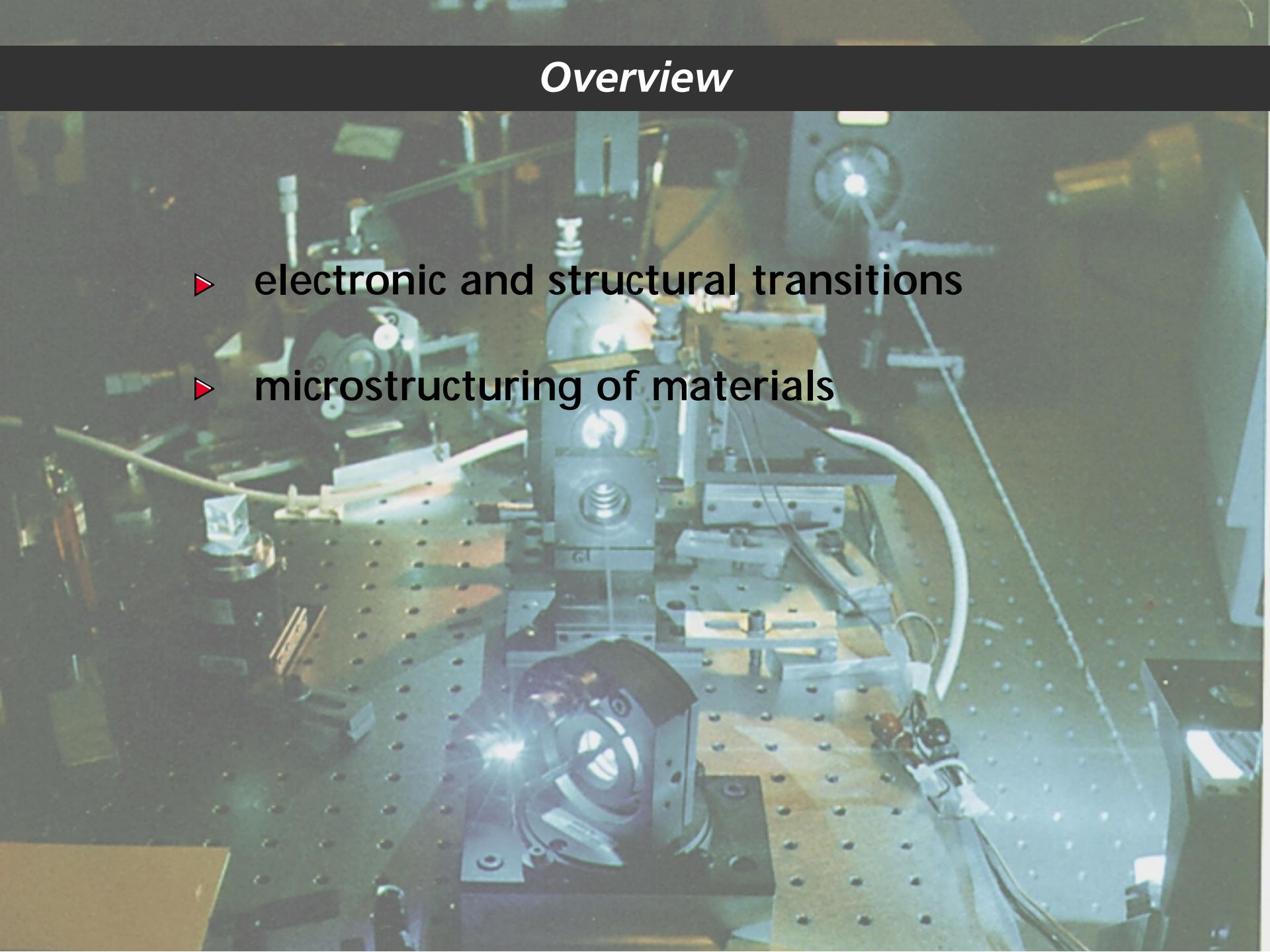
# *Overview*

- ▶ electronic and structural transitions



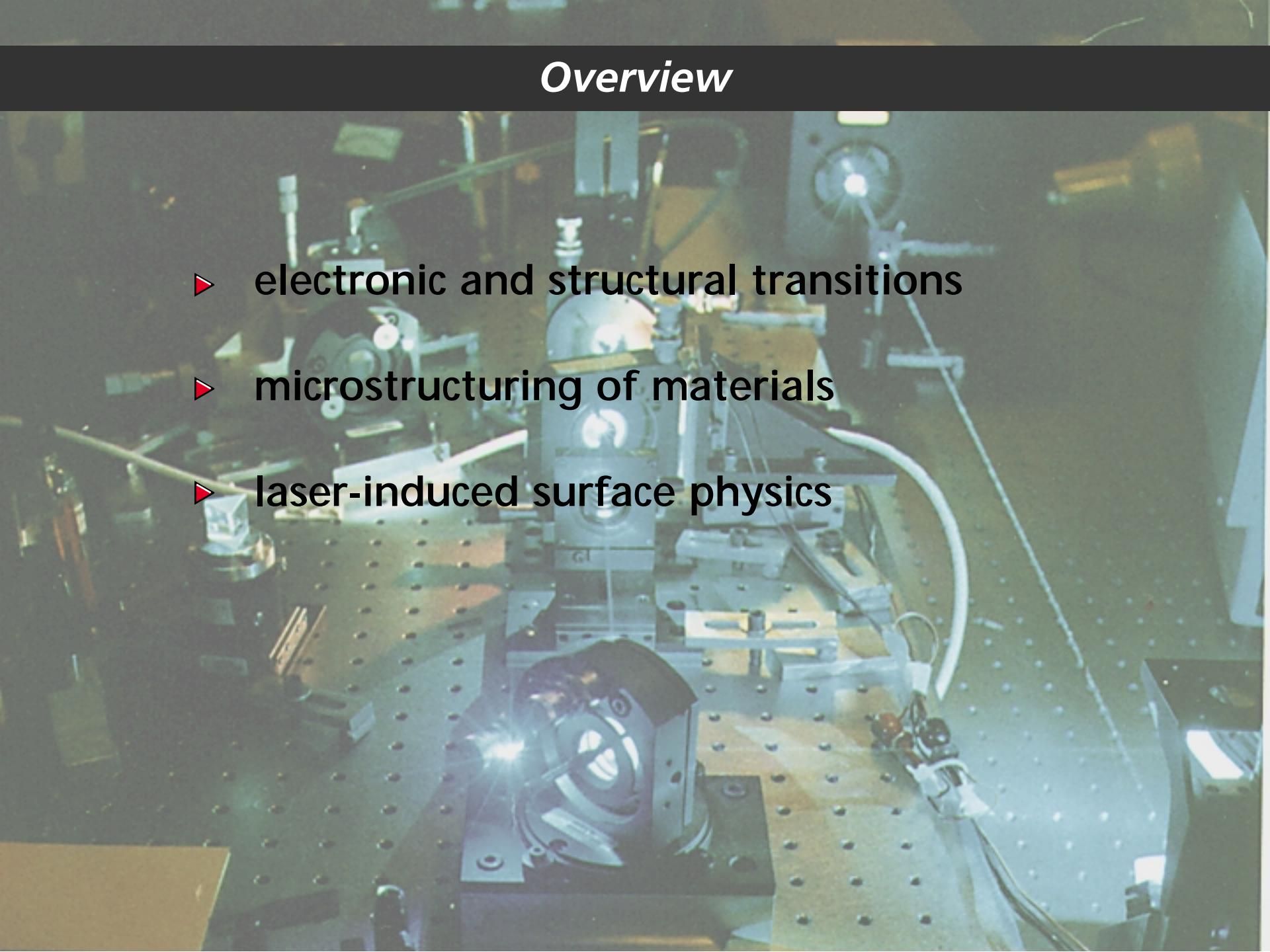
# *Overview*

- ▶ electronic and structural transitions
- ▶ microstructuring of materials



# *Overview*

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

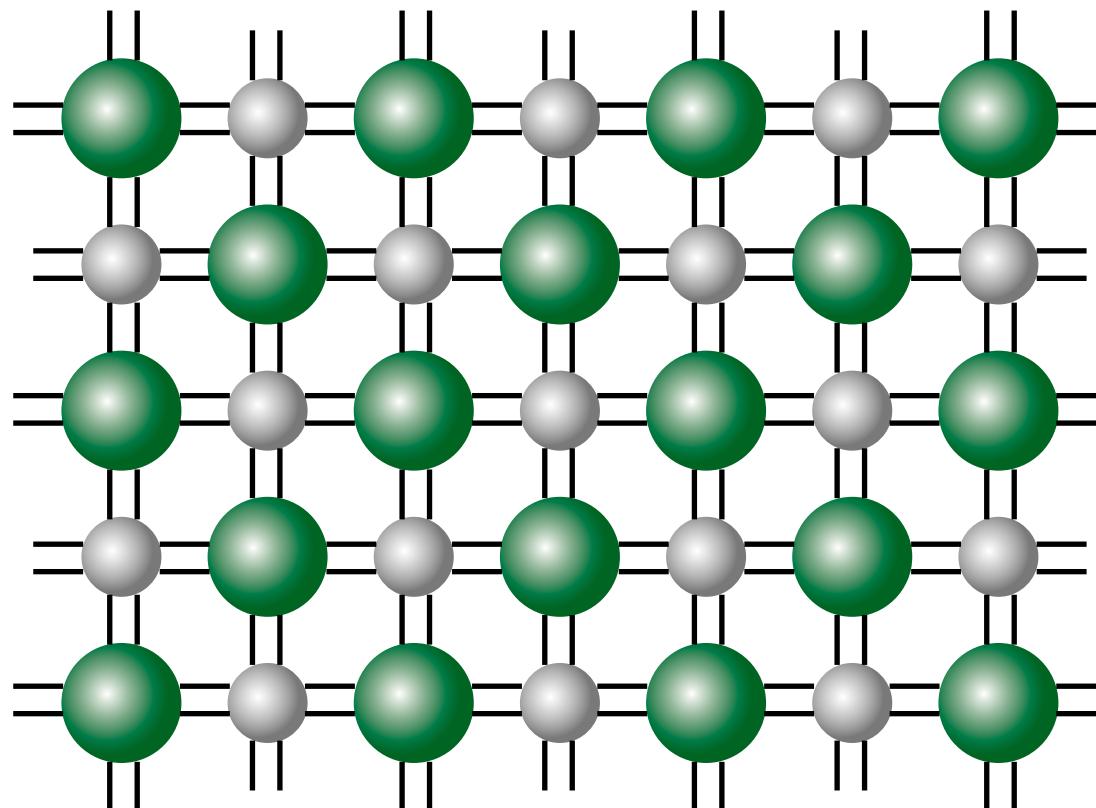


# *Overview*

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

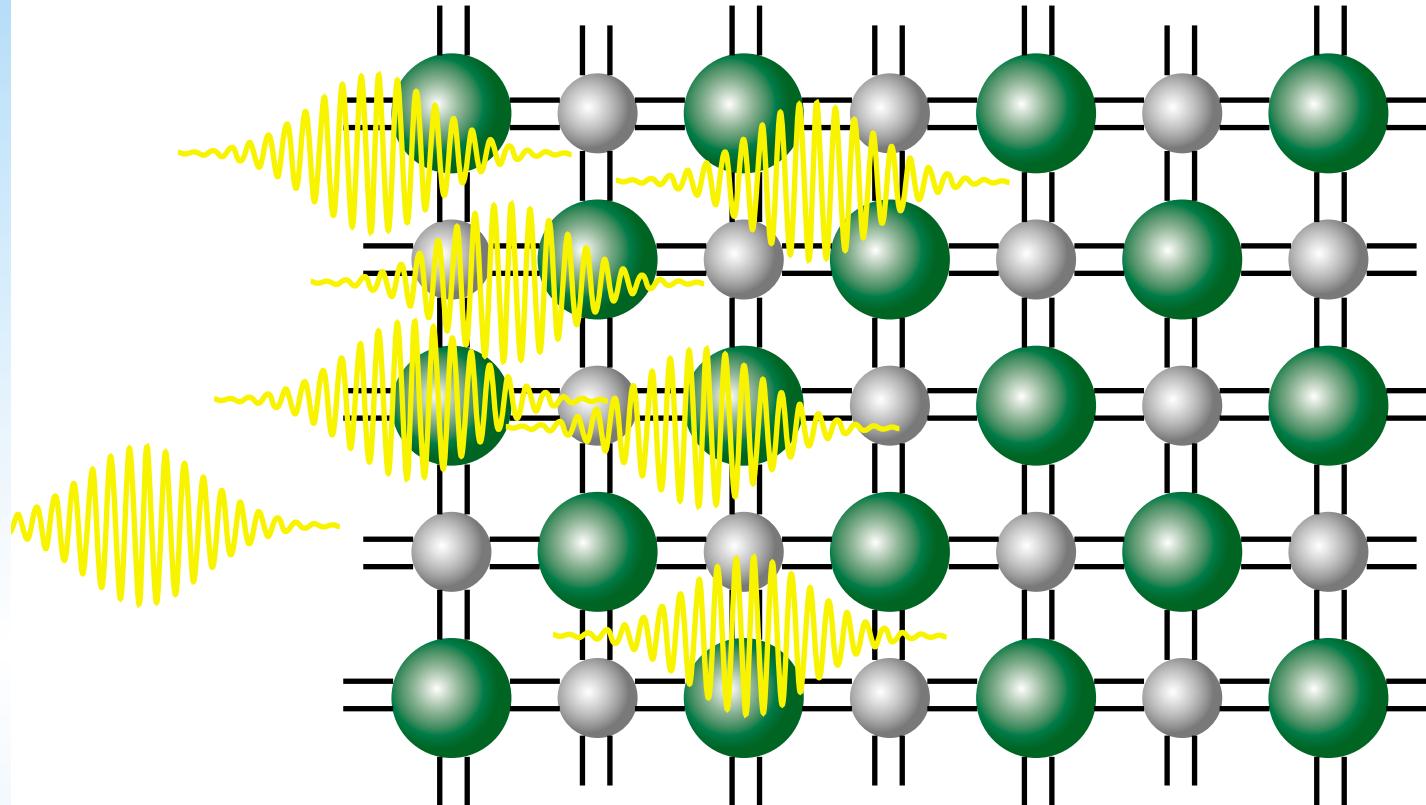
# *Electronic and structural transitions*

how do femtosecond laser pulses alter a solid?



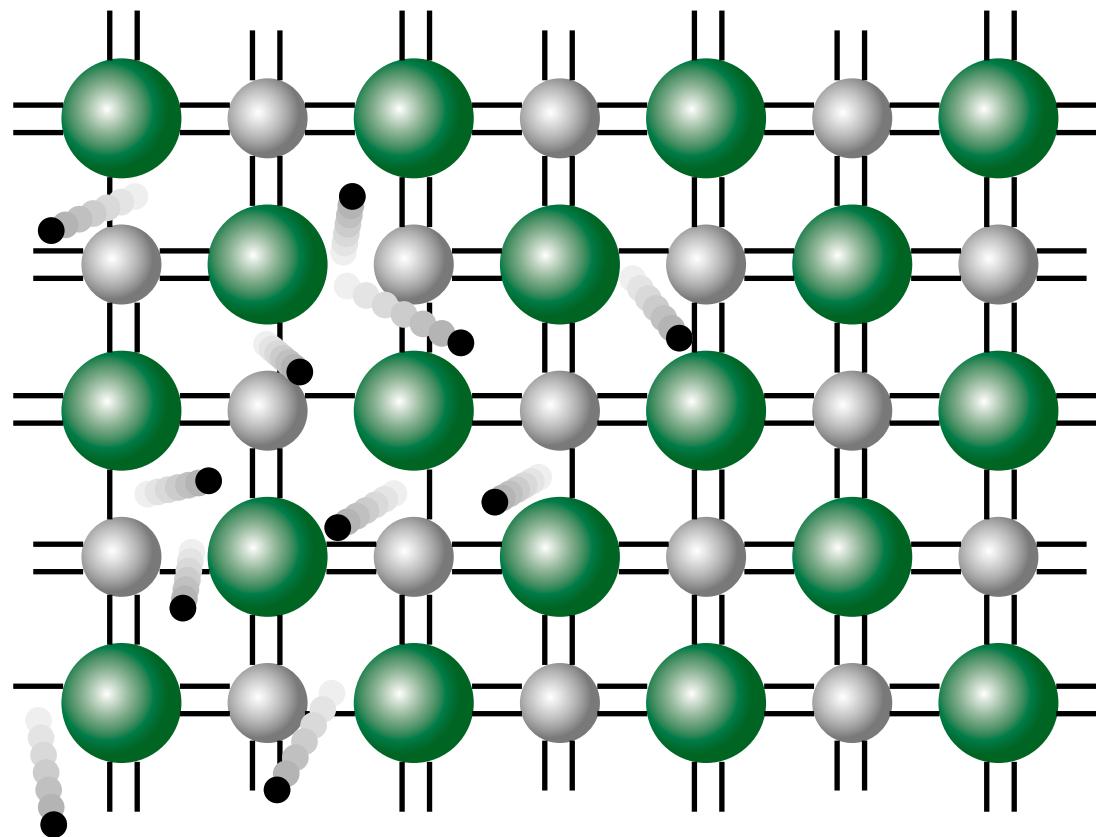
## *Electronic and structural transitions*

photons excite valence electrons...



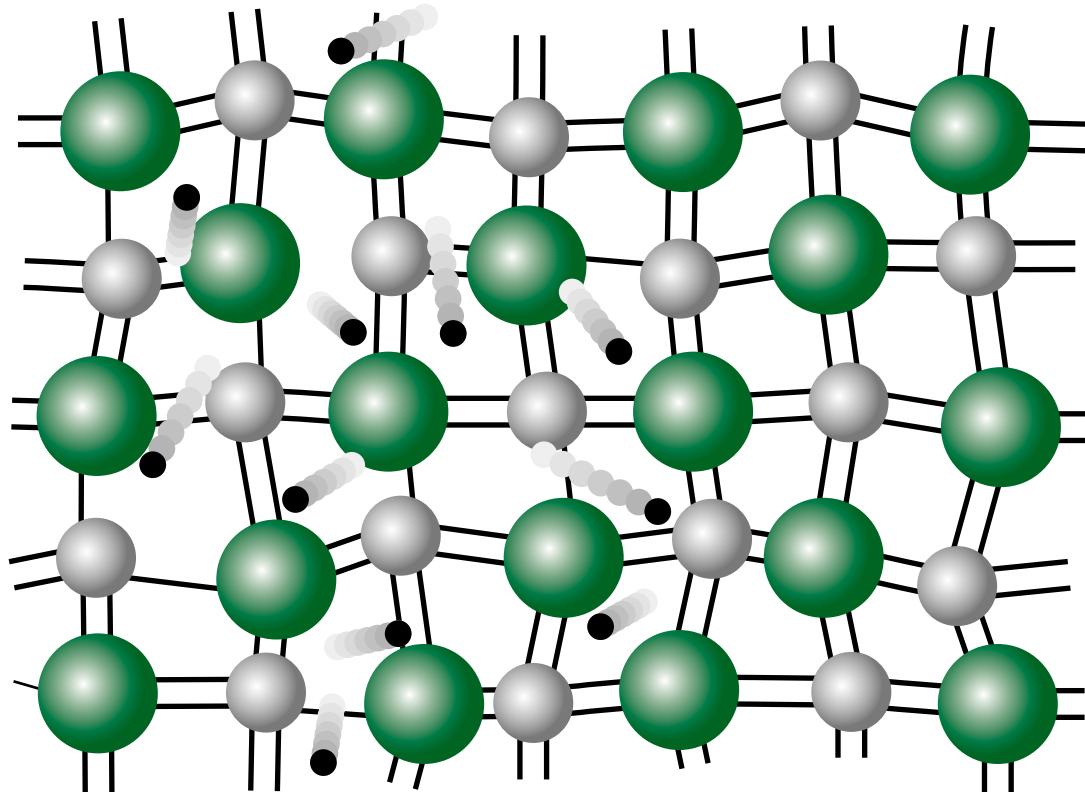
# *Electronic and structural transitions*

...and create free electrons...



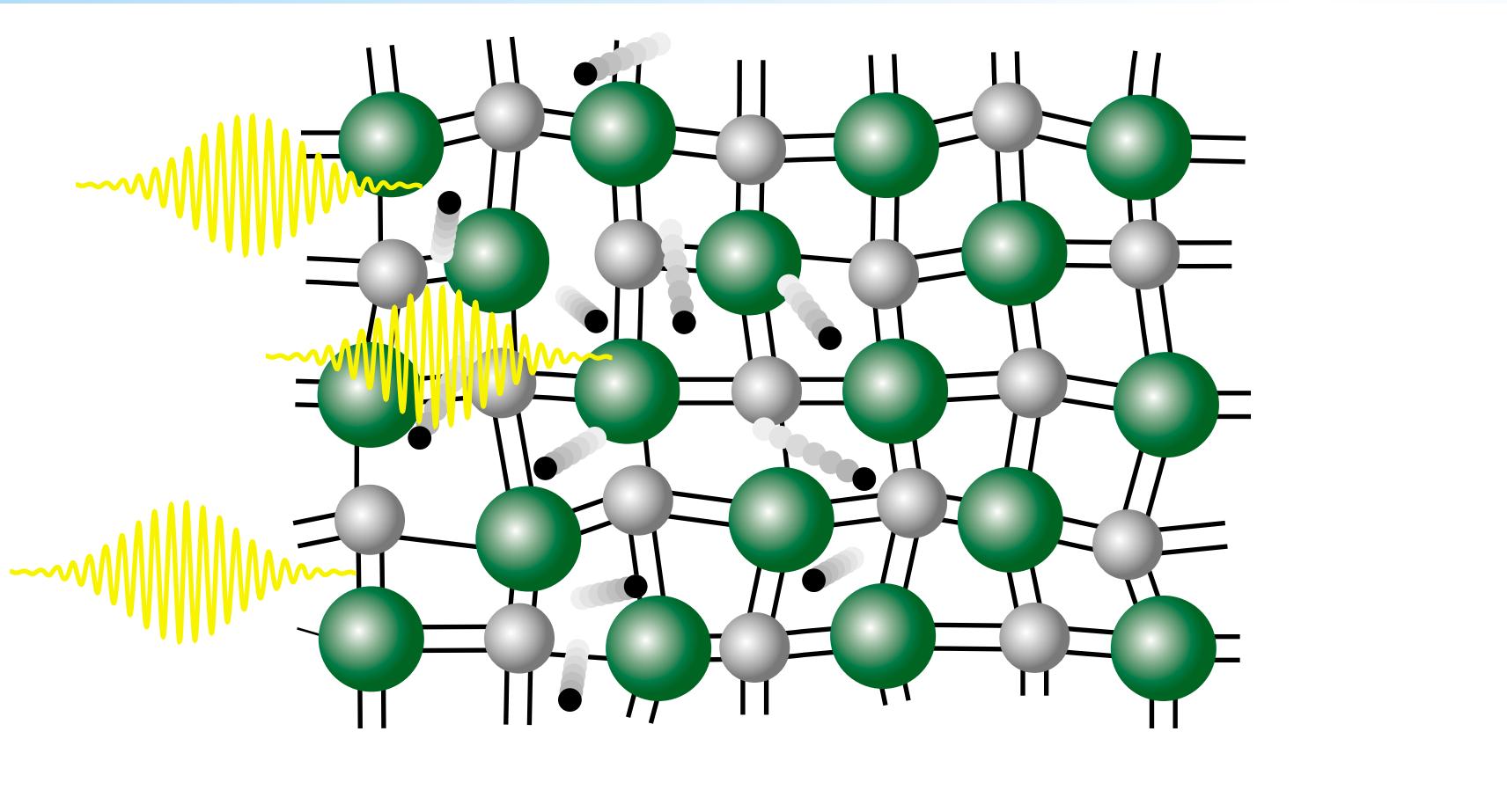
## *Electronic and structural transitions*

...causing electronic and structural changes...



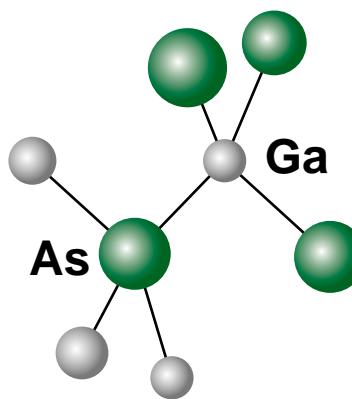
## *Electronic and structural transitions*

...which we measure with another pulse

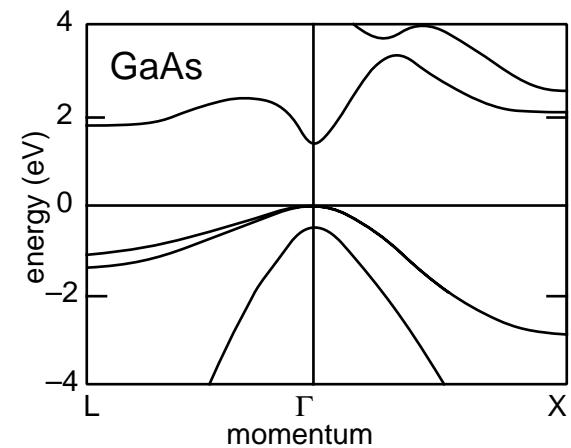


# *Electronic and structural transitions*

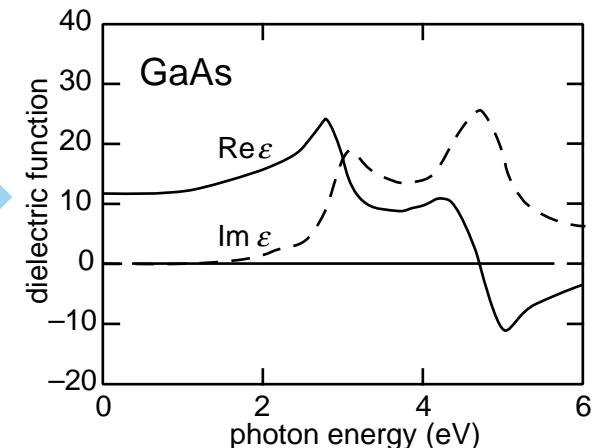
**structure**



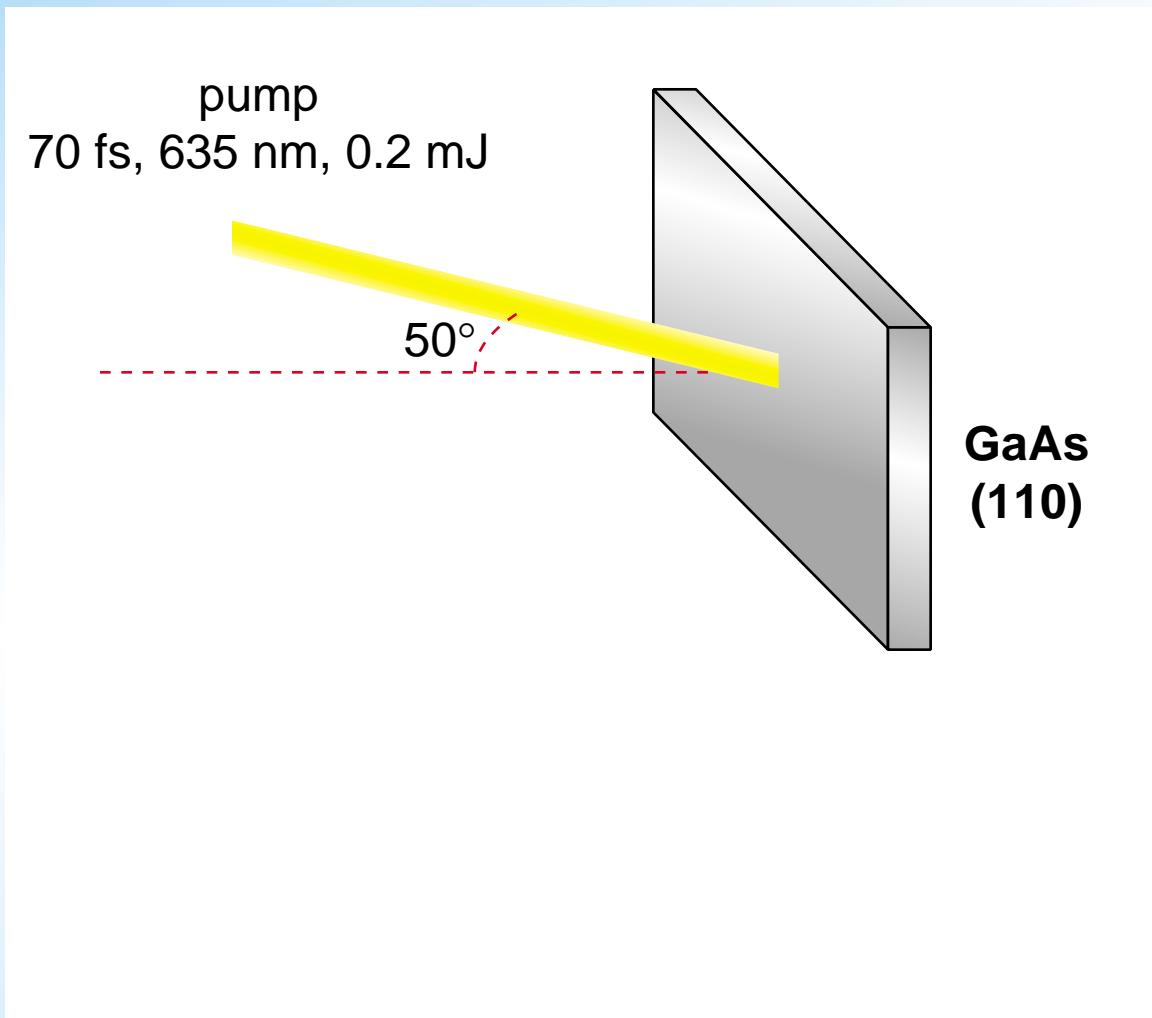
**bandstructure**



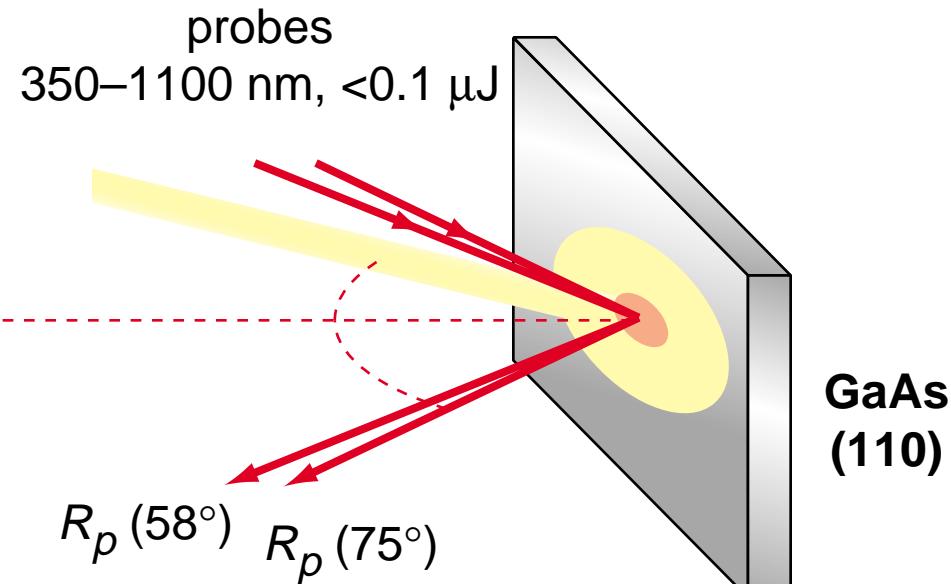
**dielectric function**



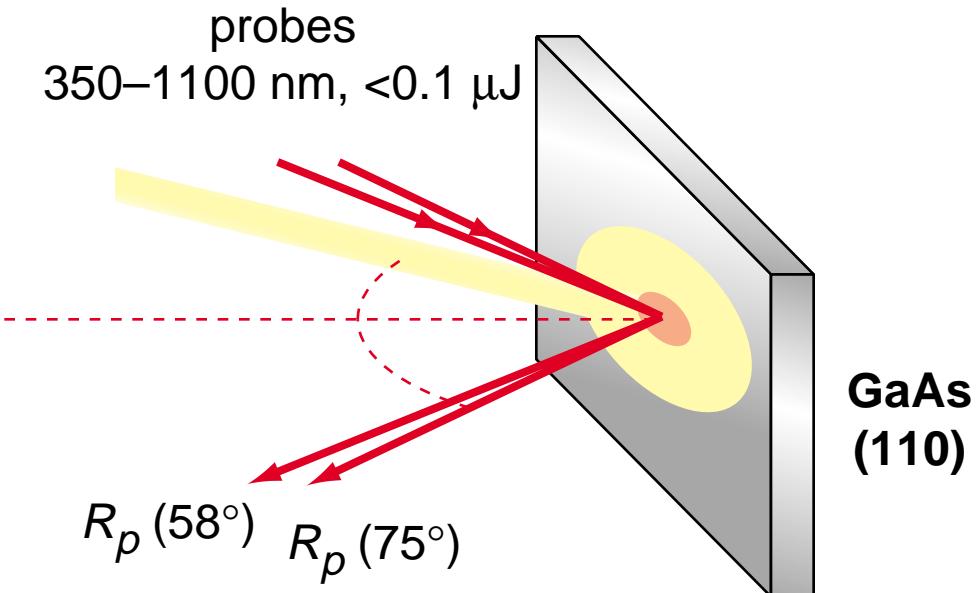
# *Electronic and structural transitions*



# *Electronic and structural transitions*



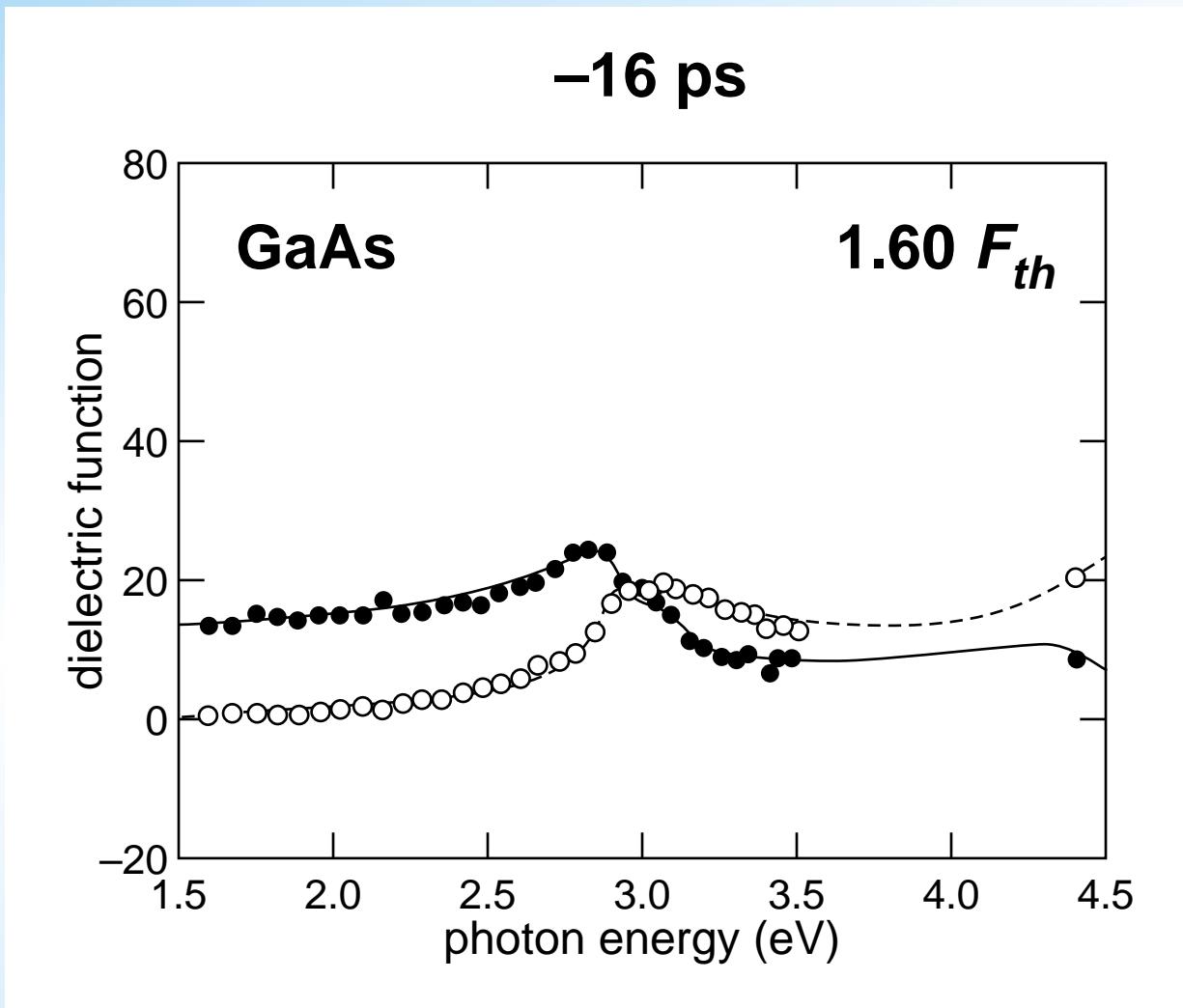
# *Electronic and structural transitions*



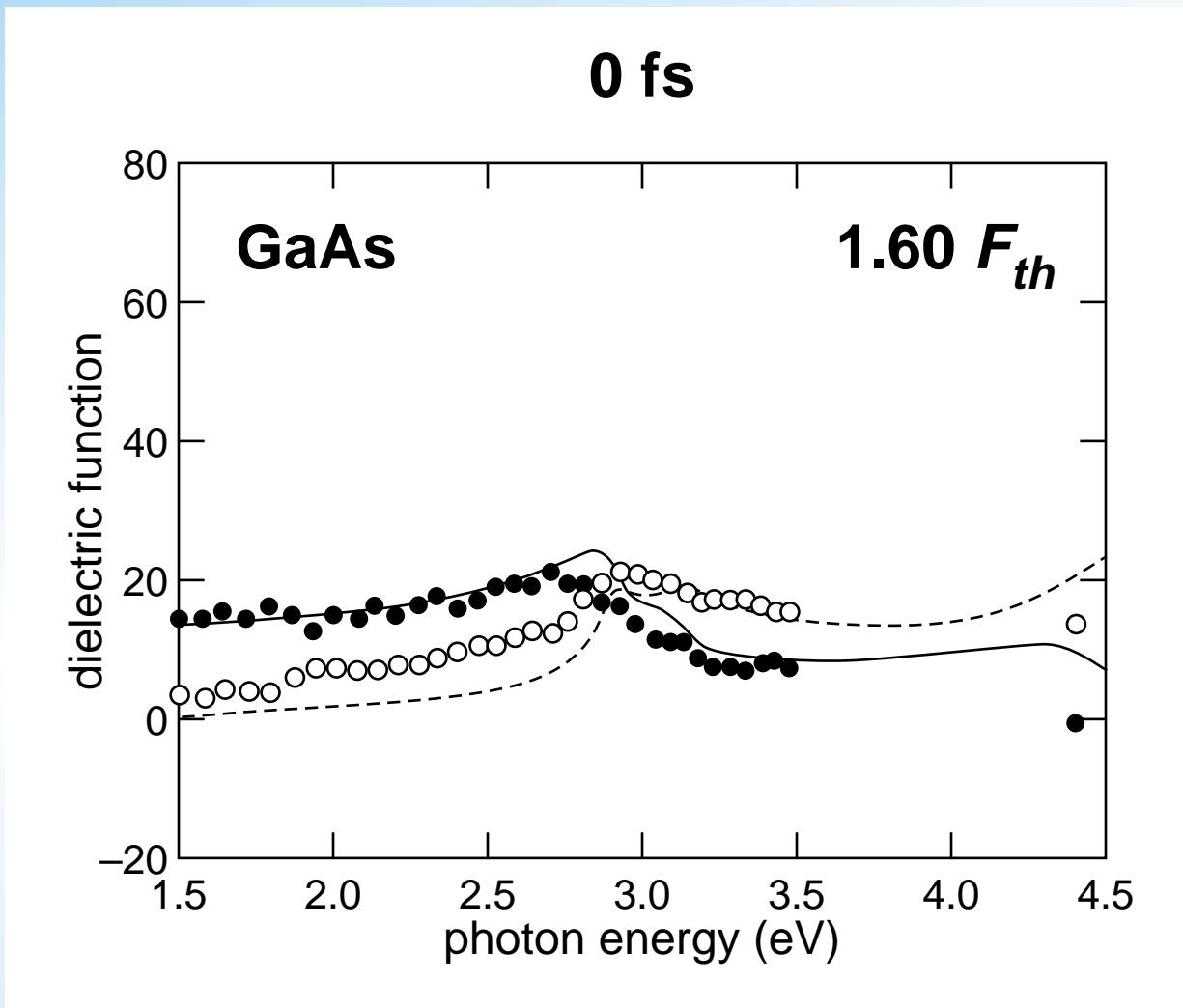
↓      →

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

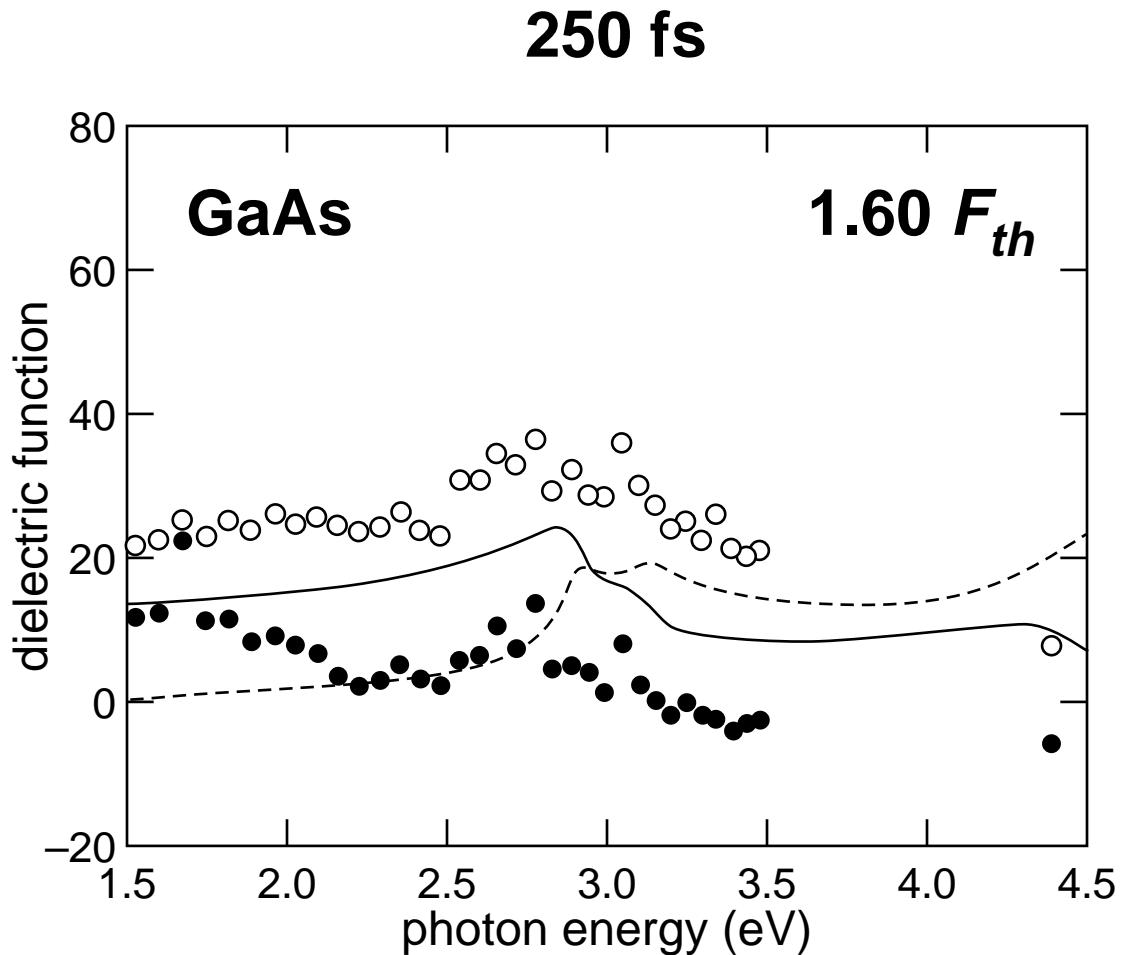
# *Electronic and structural transitions*



# *Electronic and structural transitions*

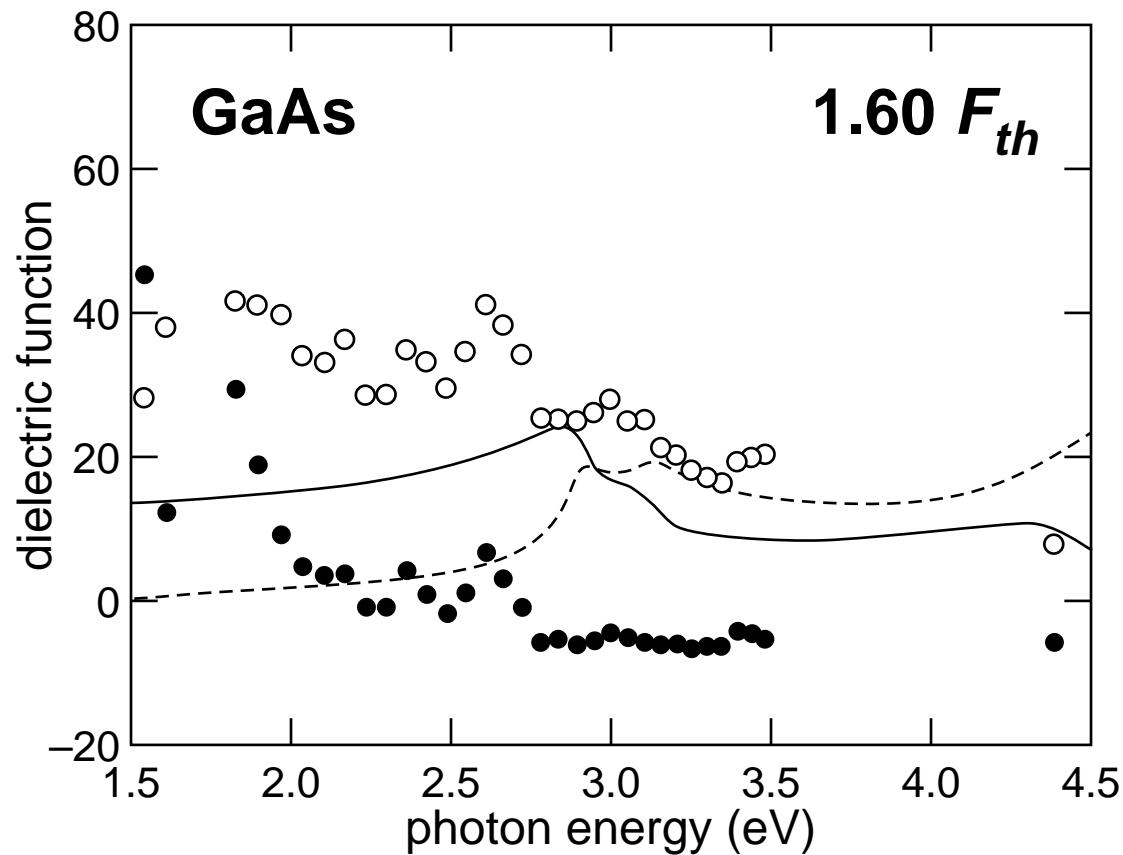


# *Electronic and structural transitions*

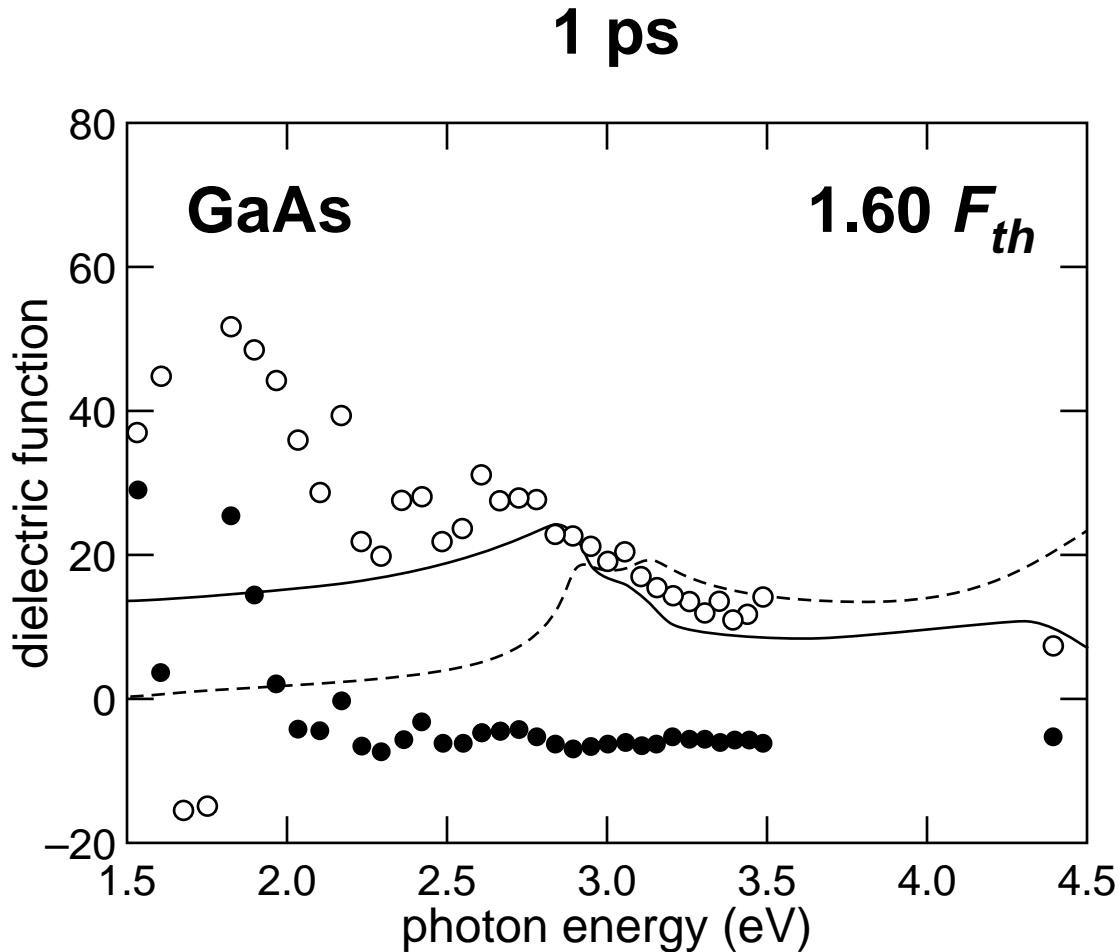


# *Electronic and structural transitions*

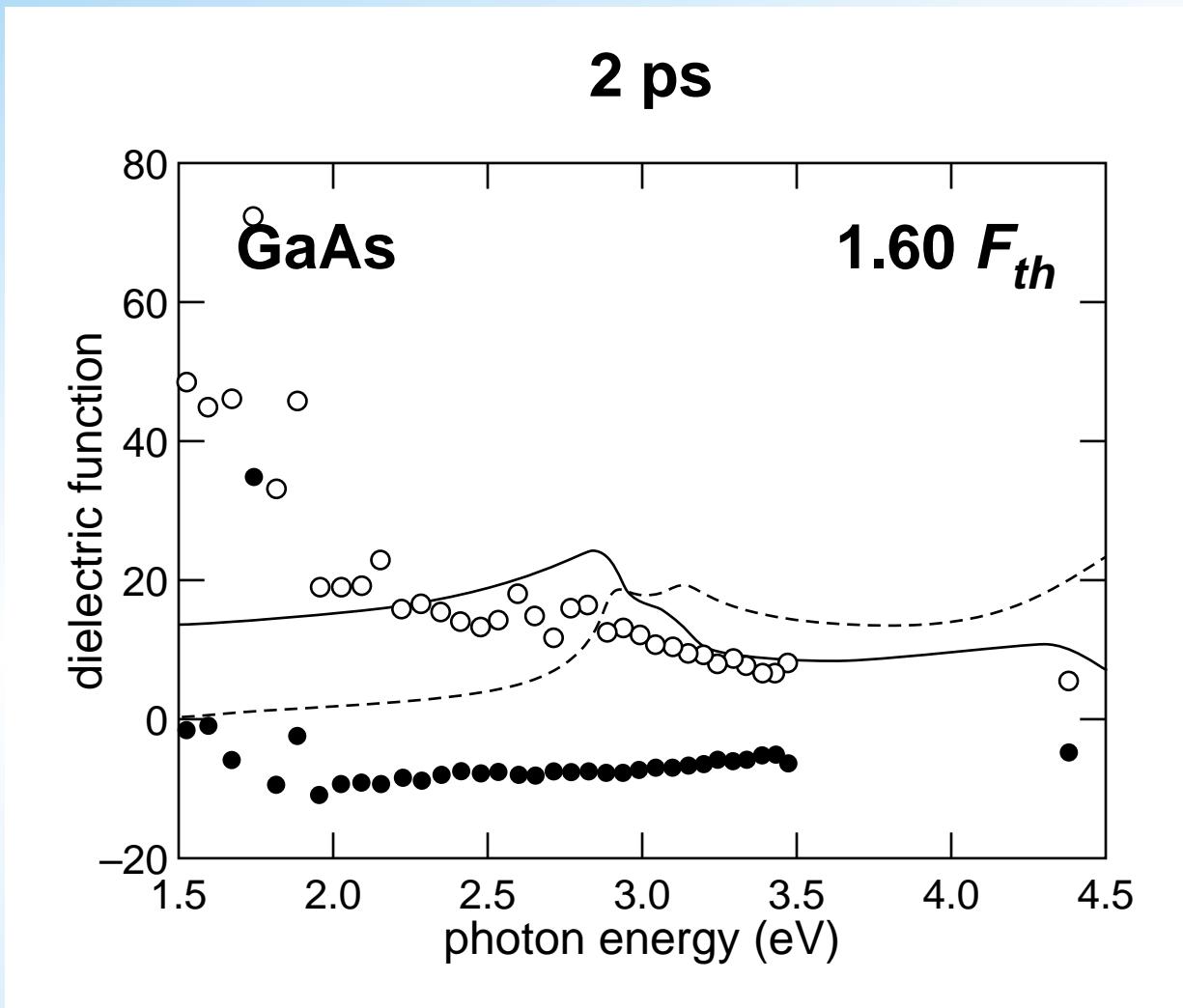
**500 fs**



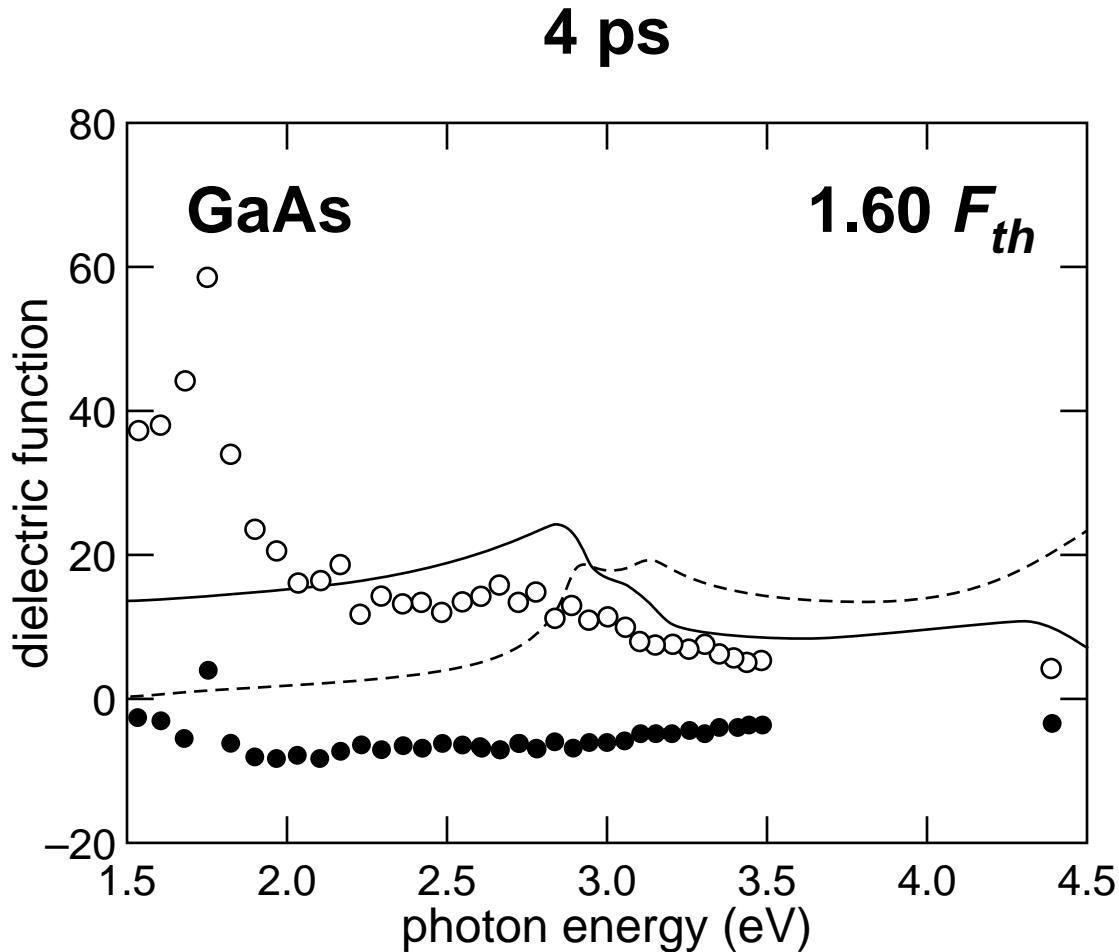
# *Electronic and structural transitions*



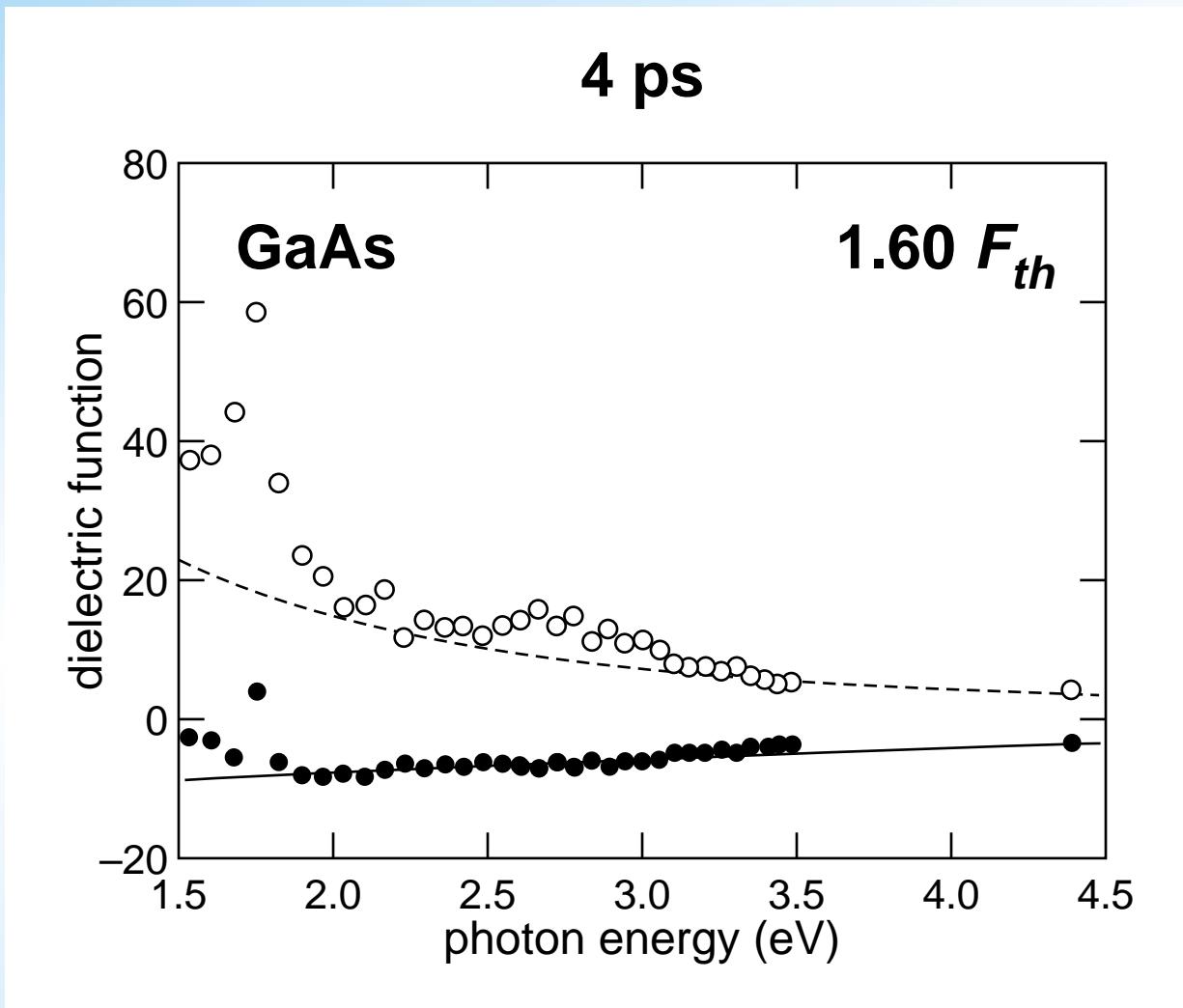
# *Electronic and structural transitions*



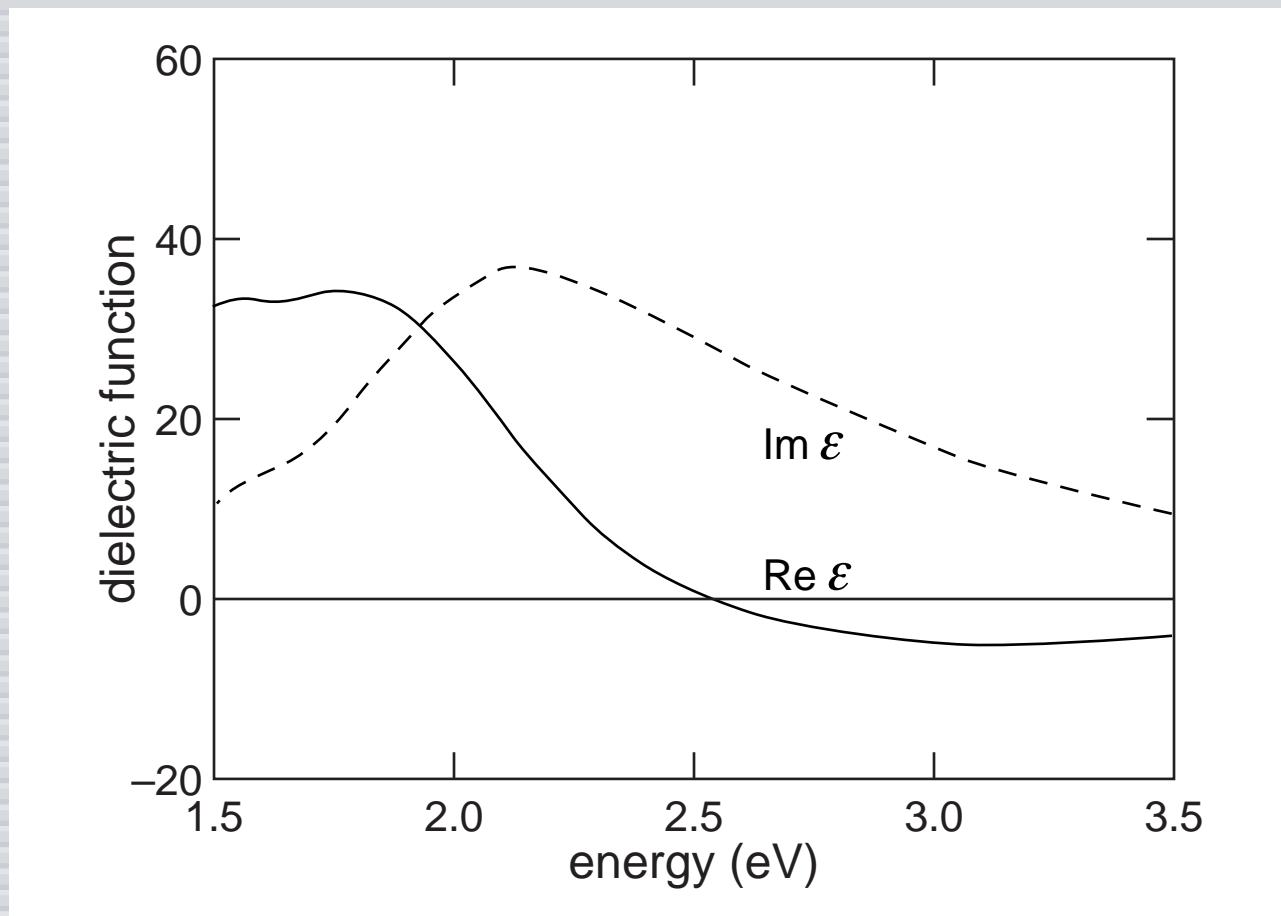
# *Electronic and structural transitions*



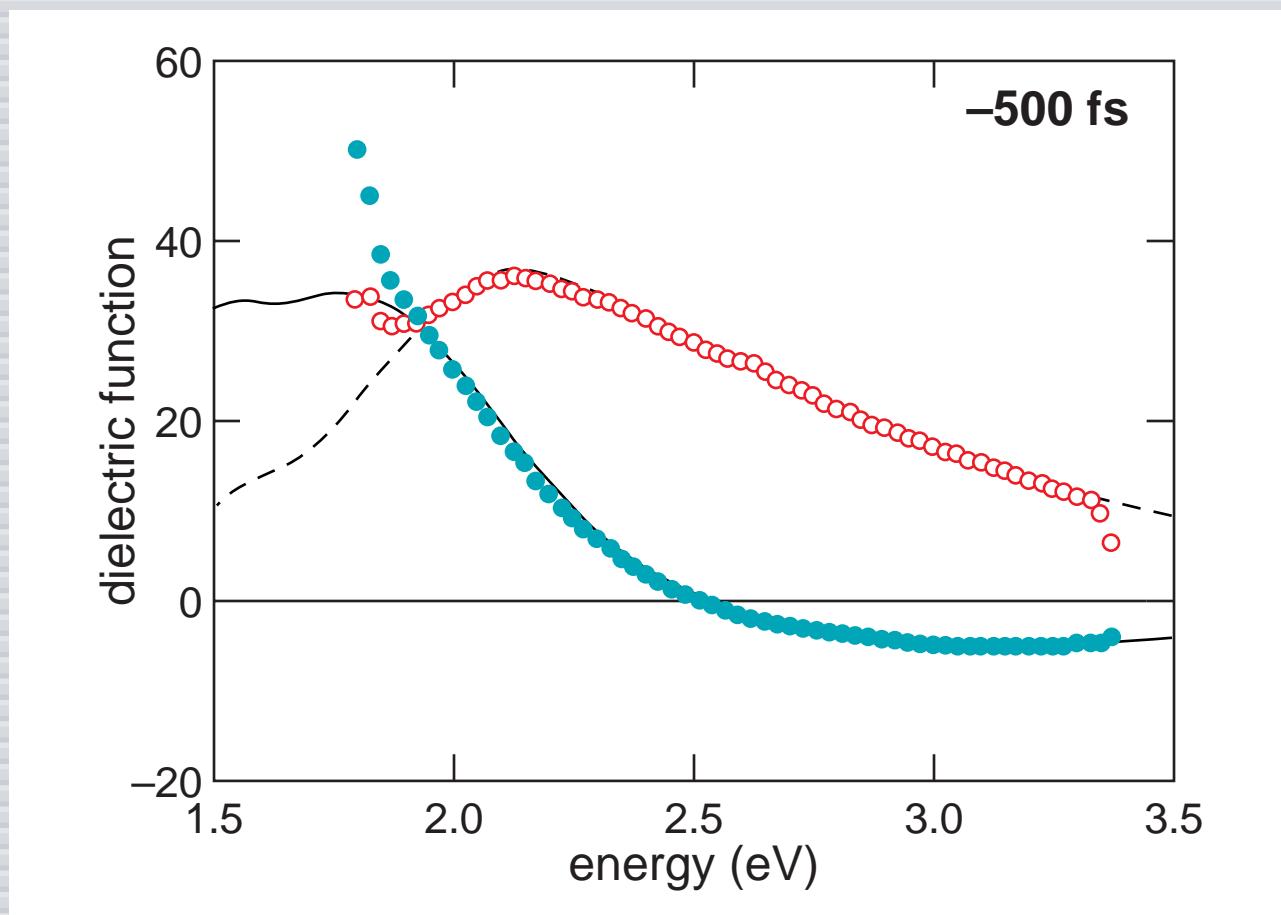
# *Electronic and structural transitions*



# *Results*

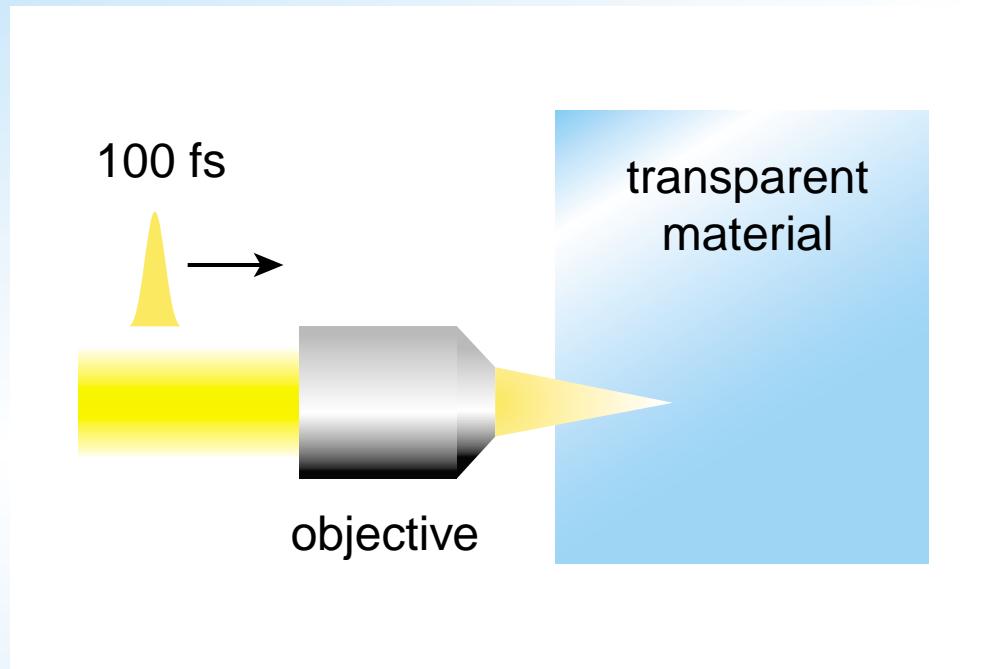


# *Results*



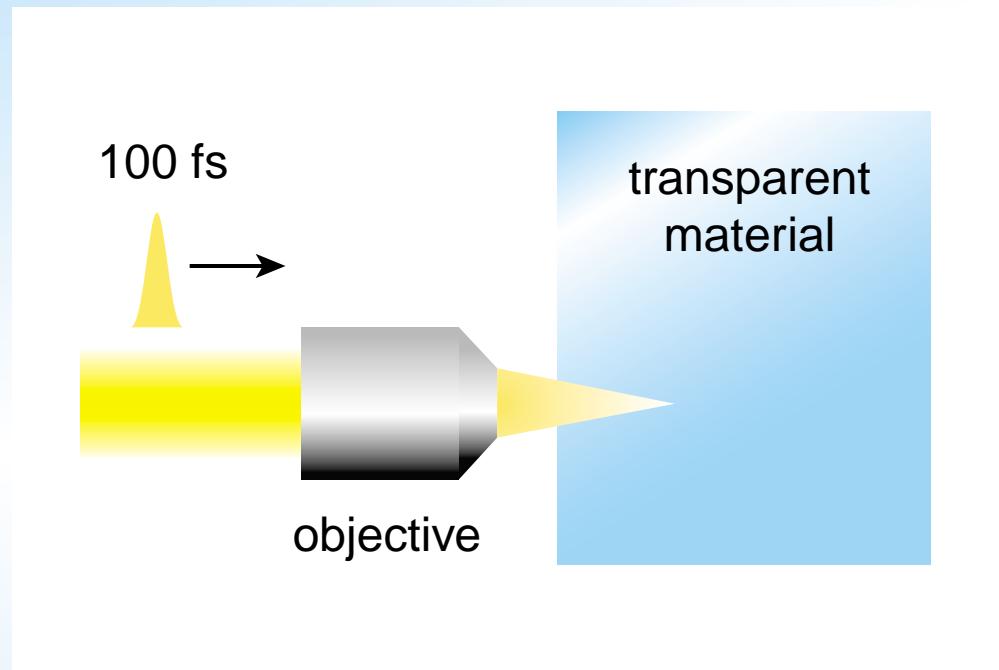
# *Microstructuring*

focus laser beam inside material...



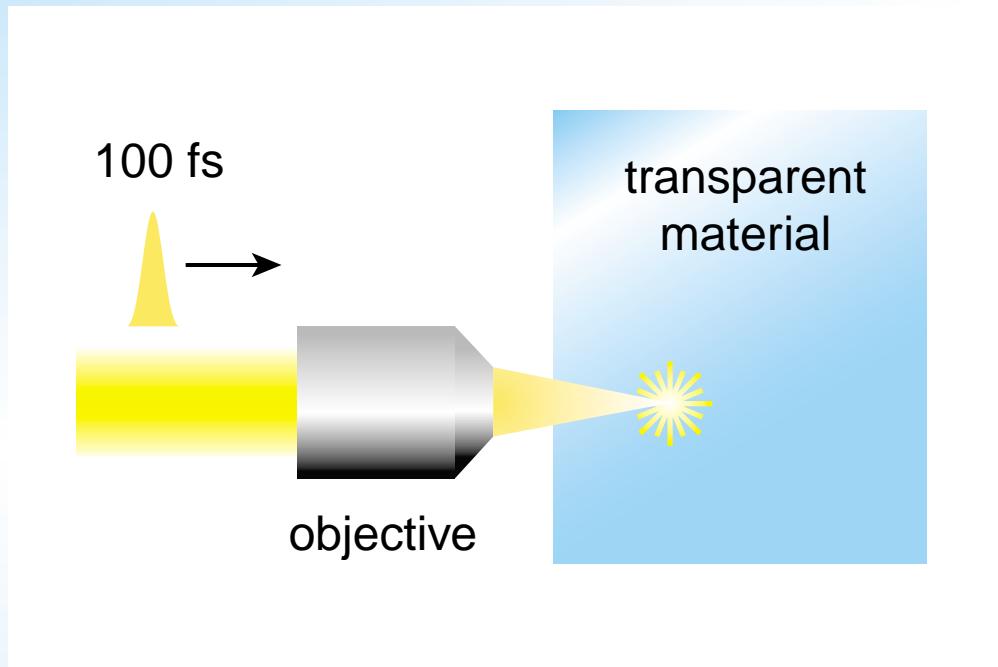
# *Microstructuring*

high intensity at focus...



# *Microstructuring*

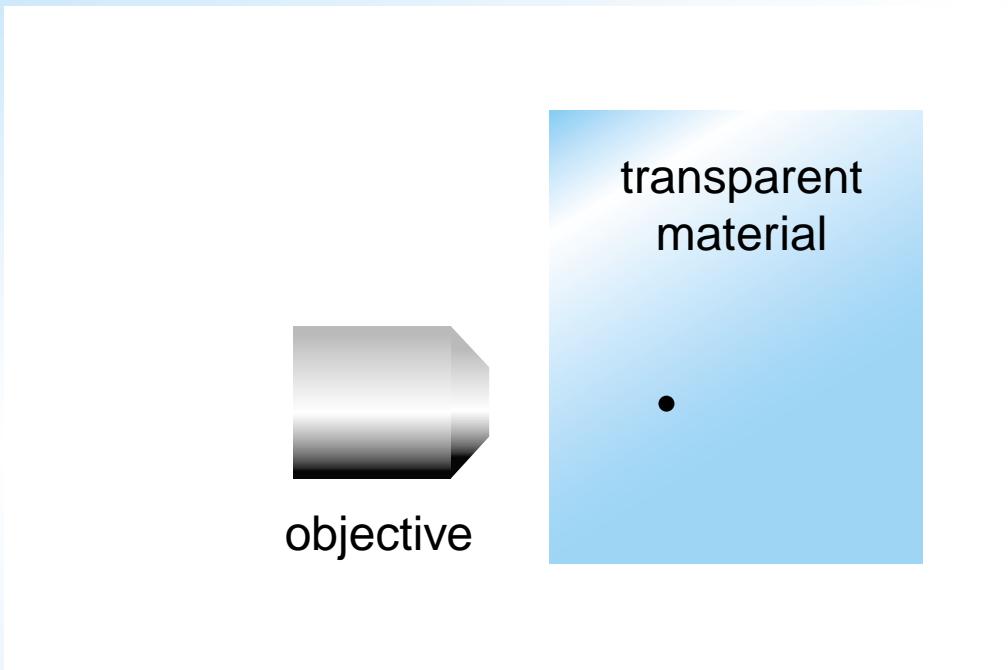
... causes nonlinear ionization...



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

# *Microstructuring*

## and microscopic bulk damage



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

# *Microstructuring*

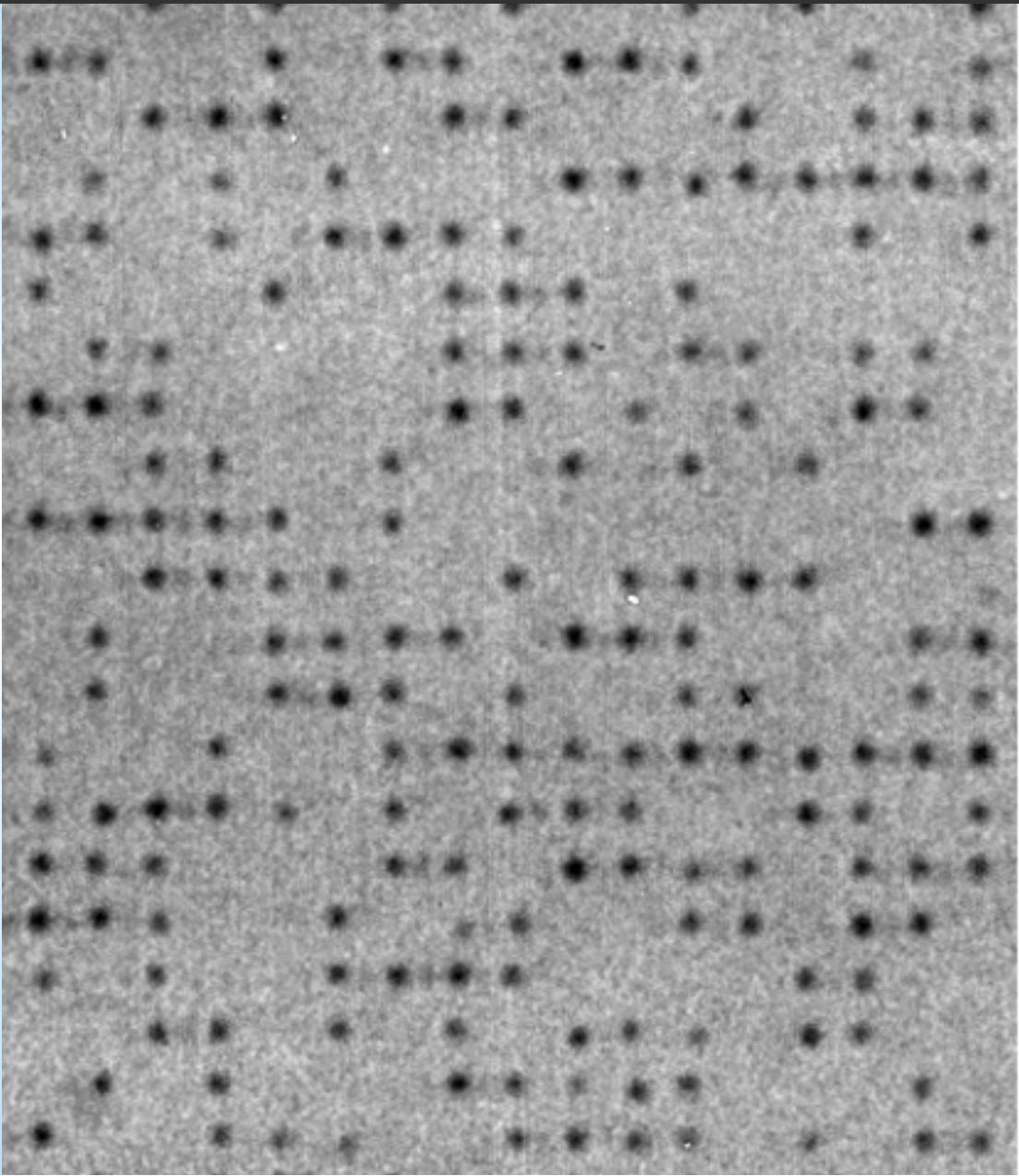
optical microscopy

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

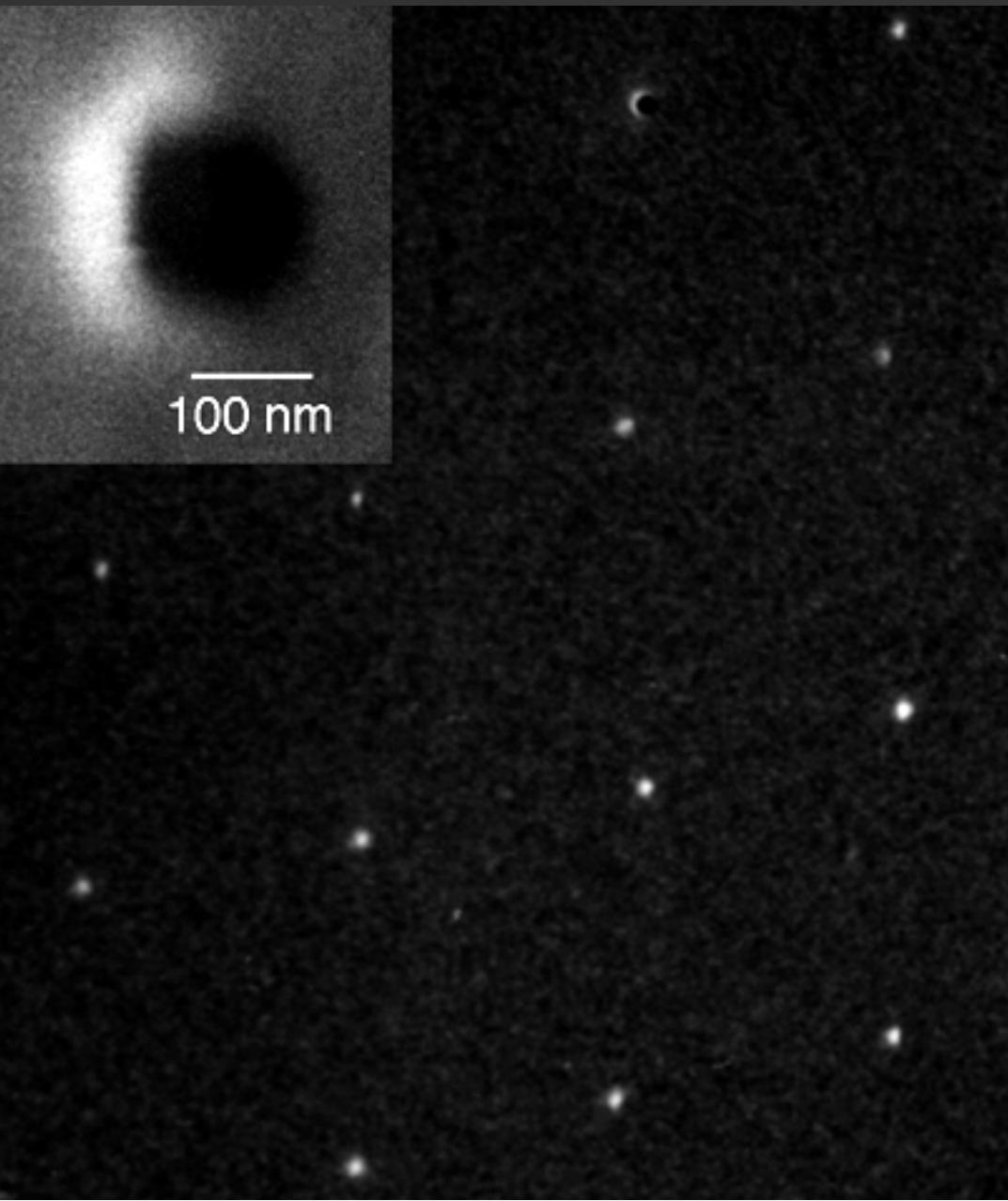
fused silica

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

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



# *Microstructuring*

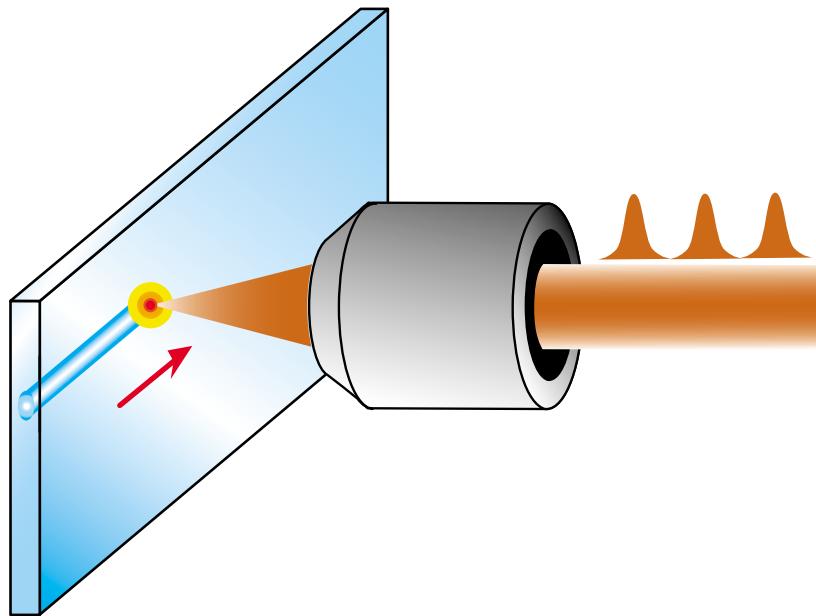


SEM:

bumps & pits!

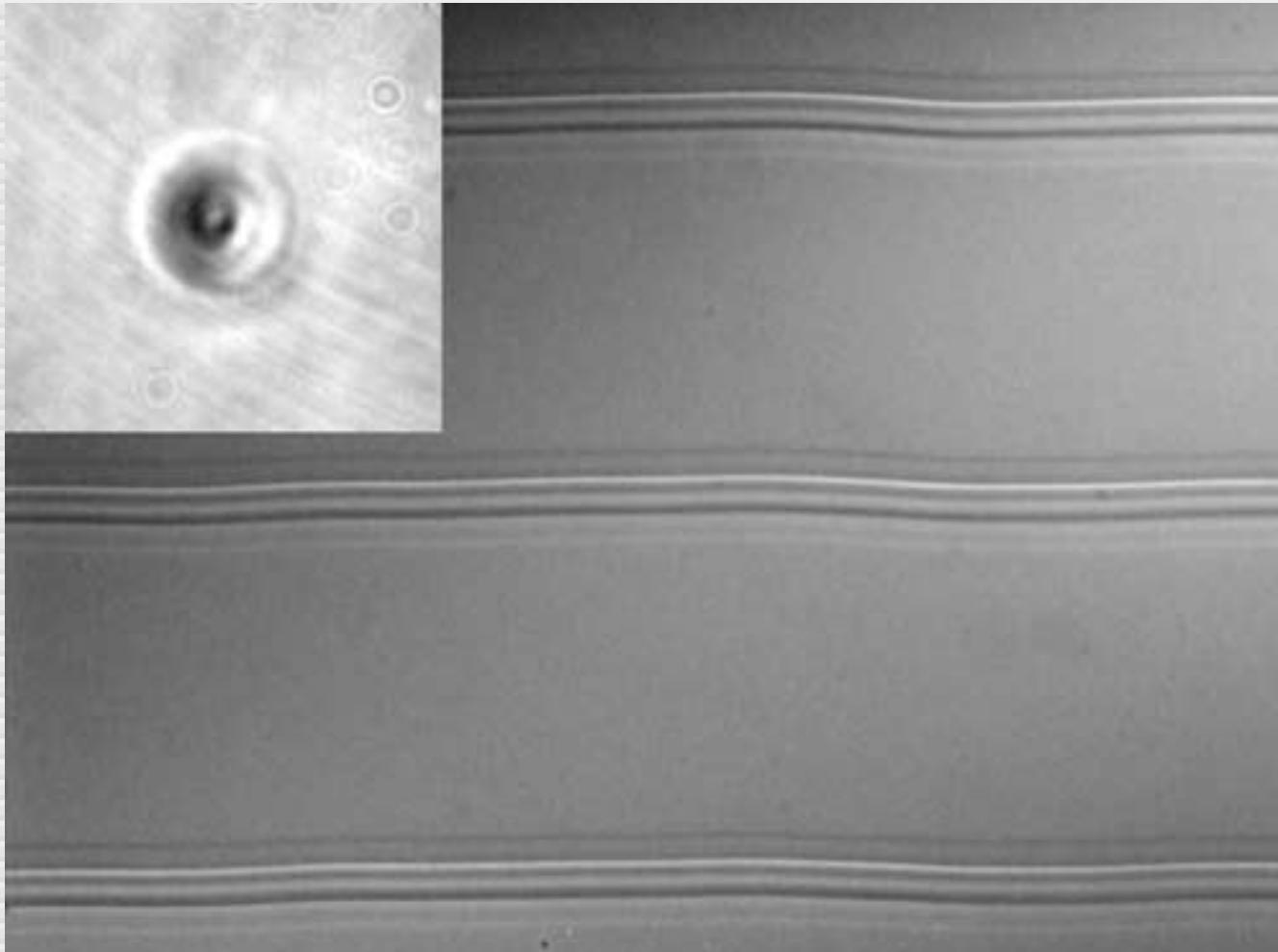
*Low-energy processing*

## waveguide machining



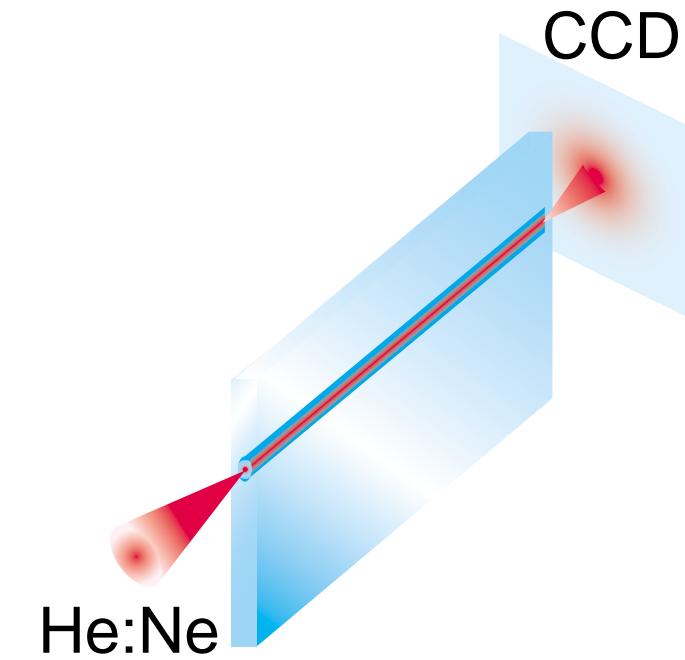
*Low-energy processing*

## waveguide machining



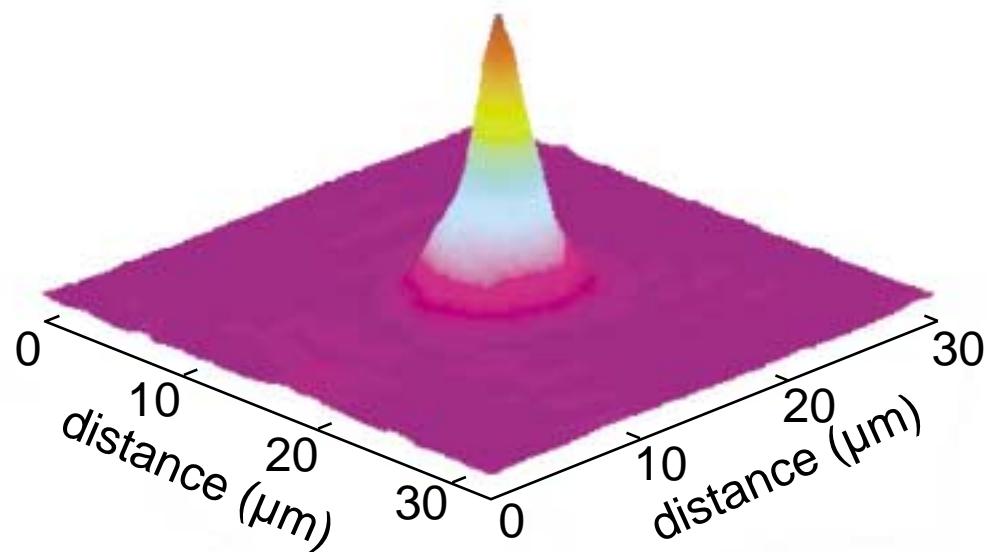
*Low-energy processing*

## waveguide mode analysis



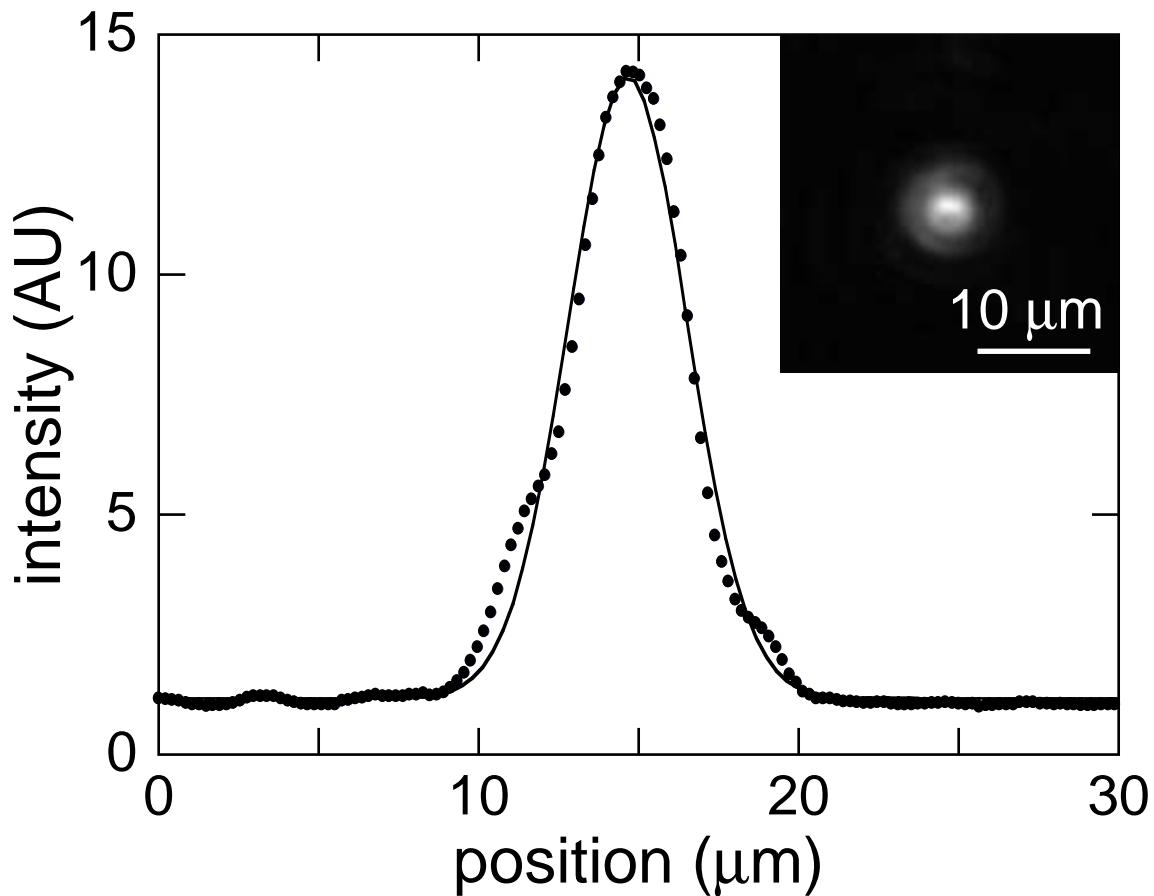
# *Low-energy processing*

## **near field mode**



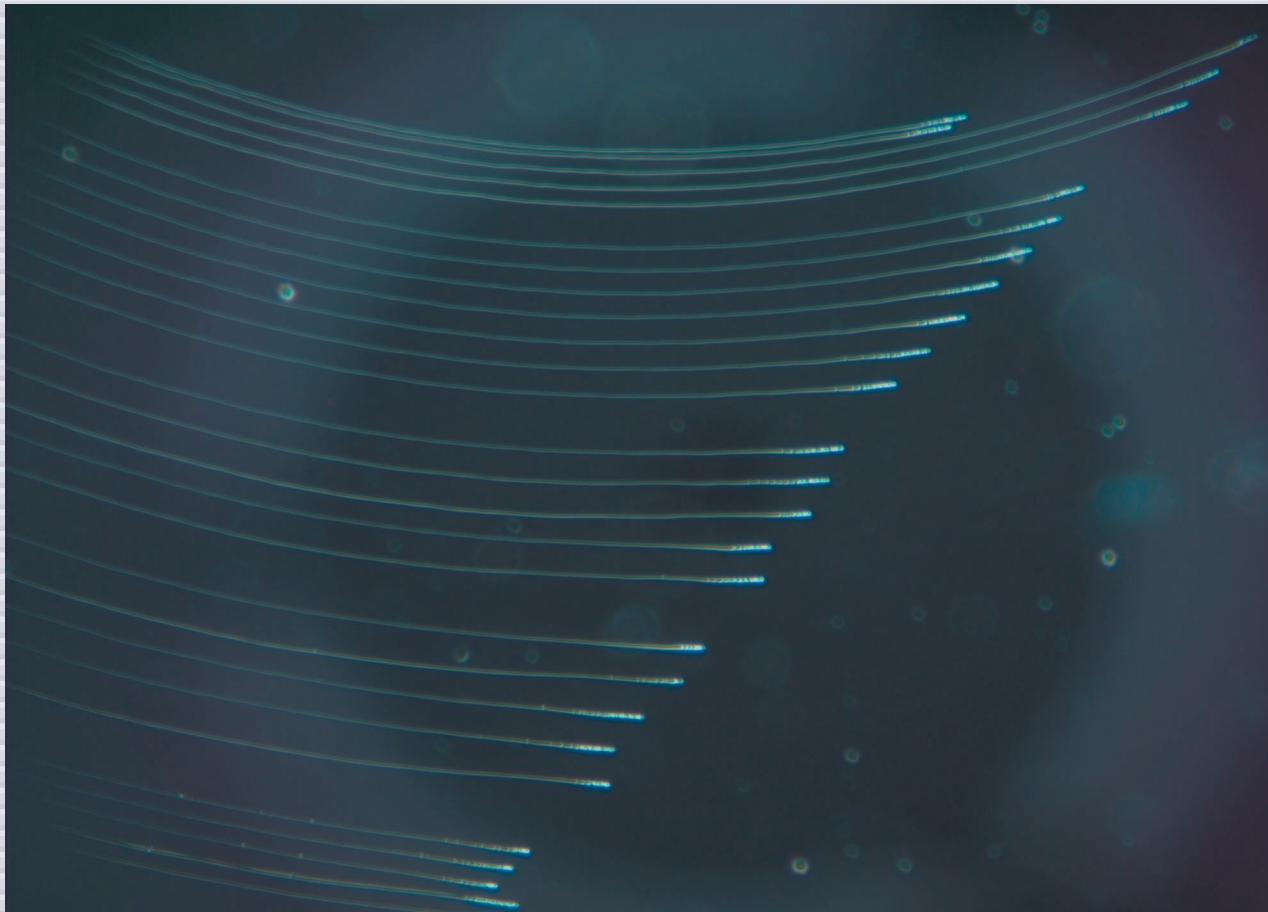
# *Low-energy processing*

## **near field mode**



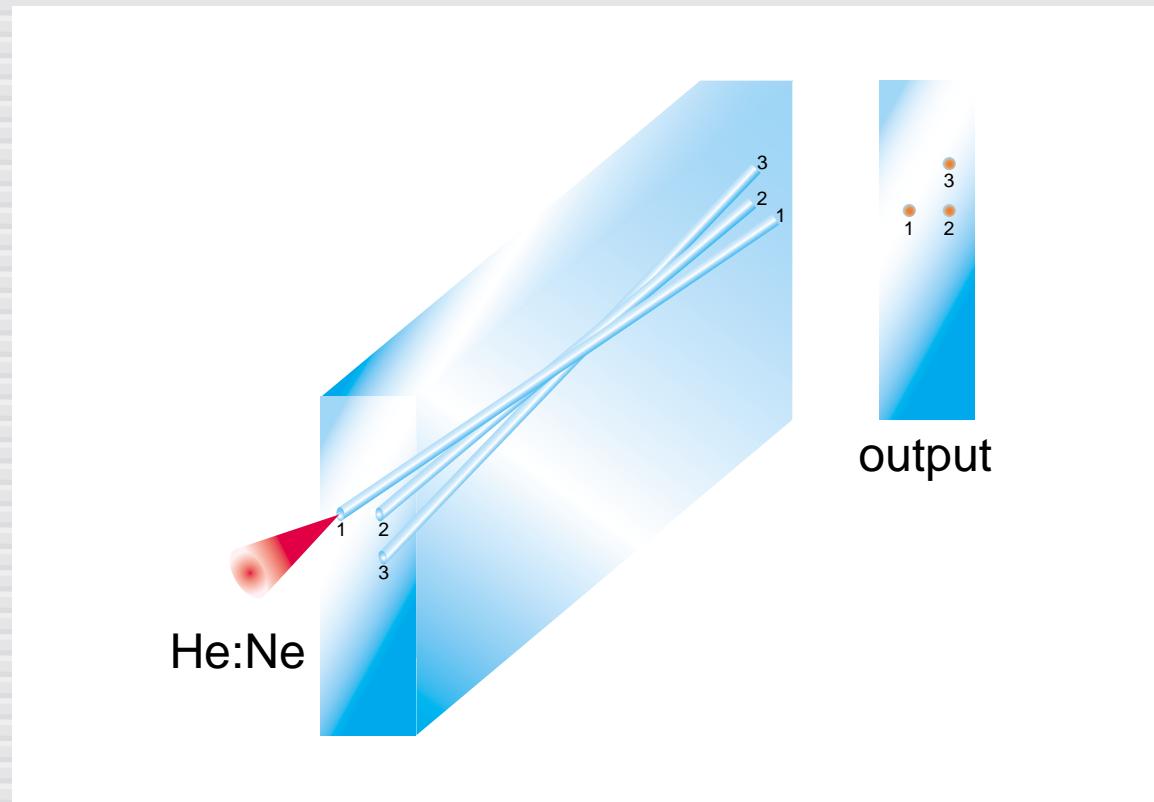
*Low-energy processing*

**curved waveguides**



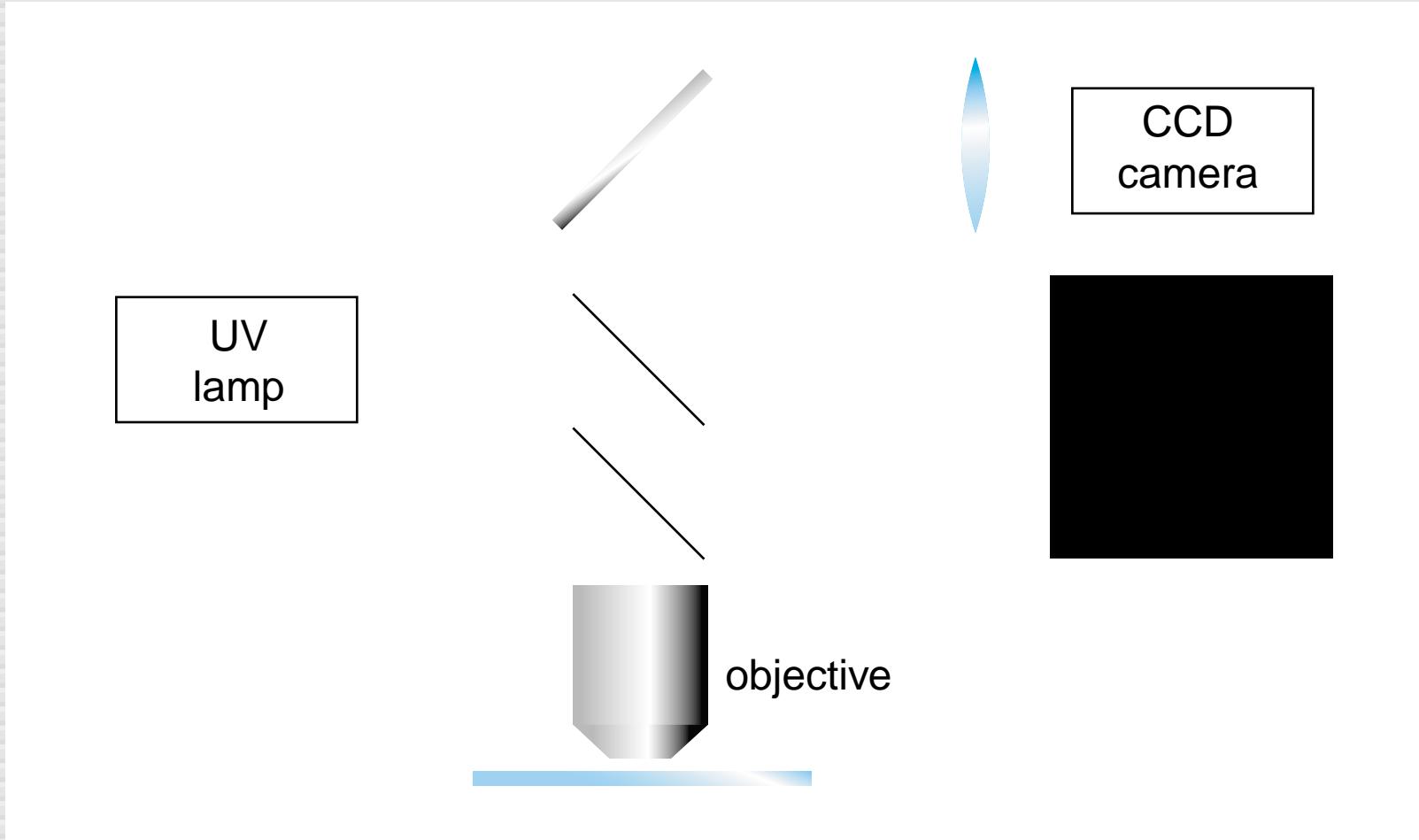
# *Low-energy processing*

## 3D wave splitter



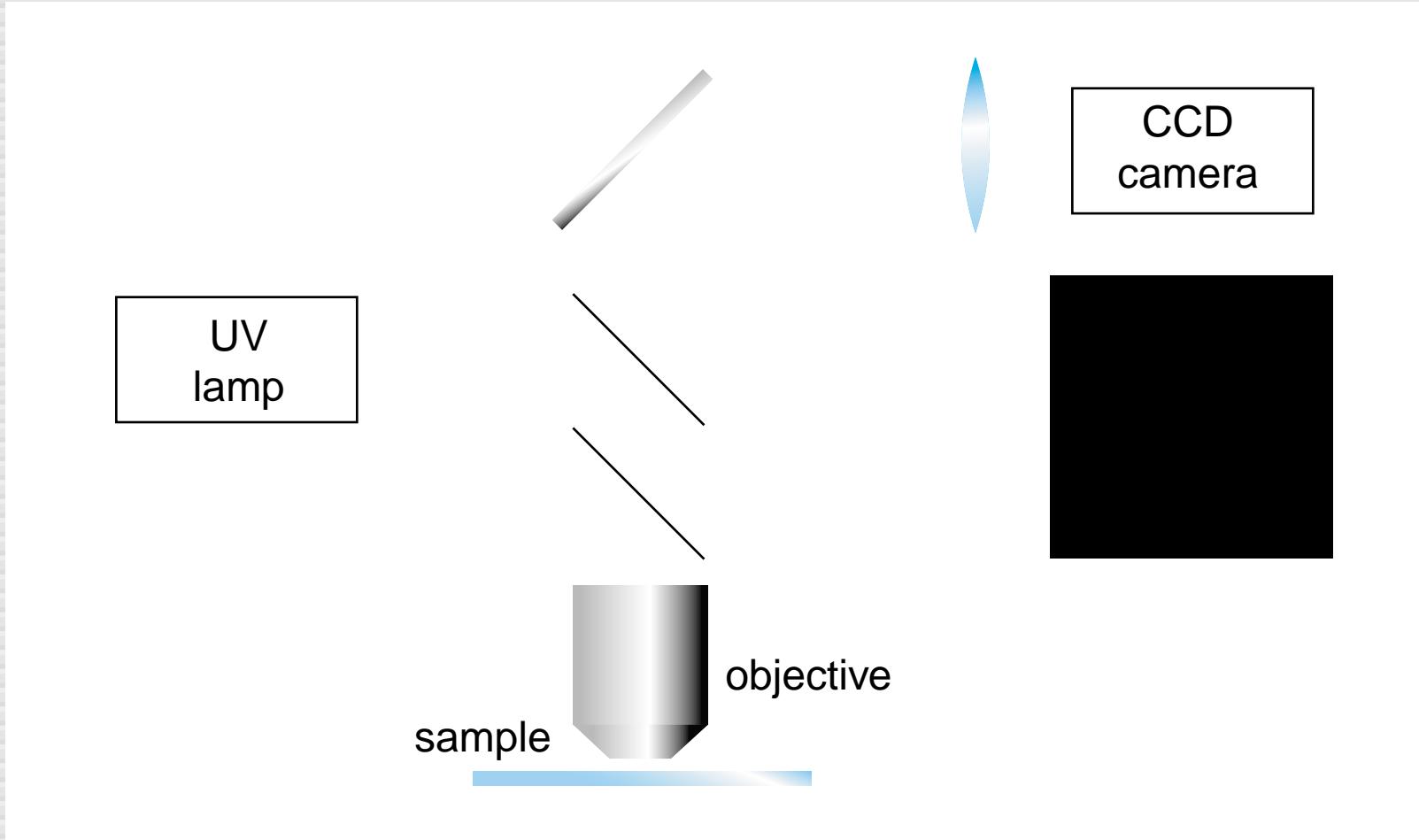
# *Low-energy processing*

## epi-fluorescence microscope



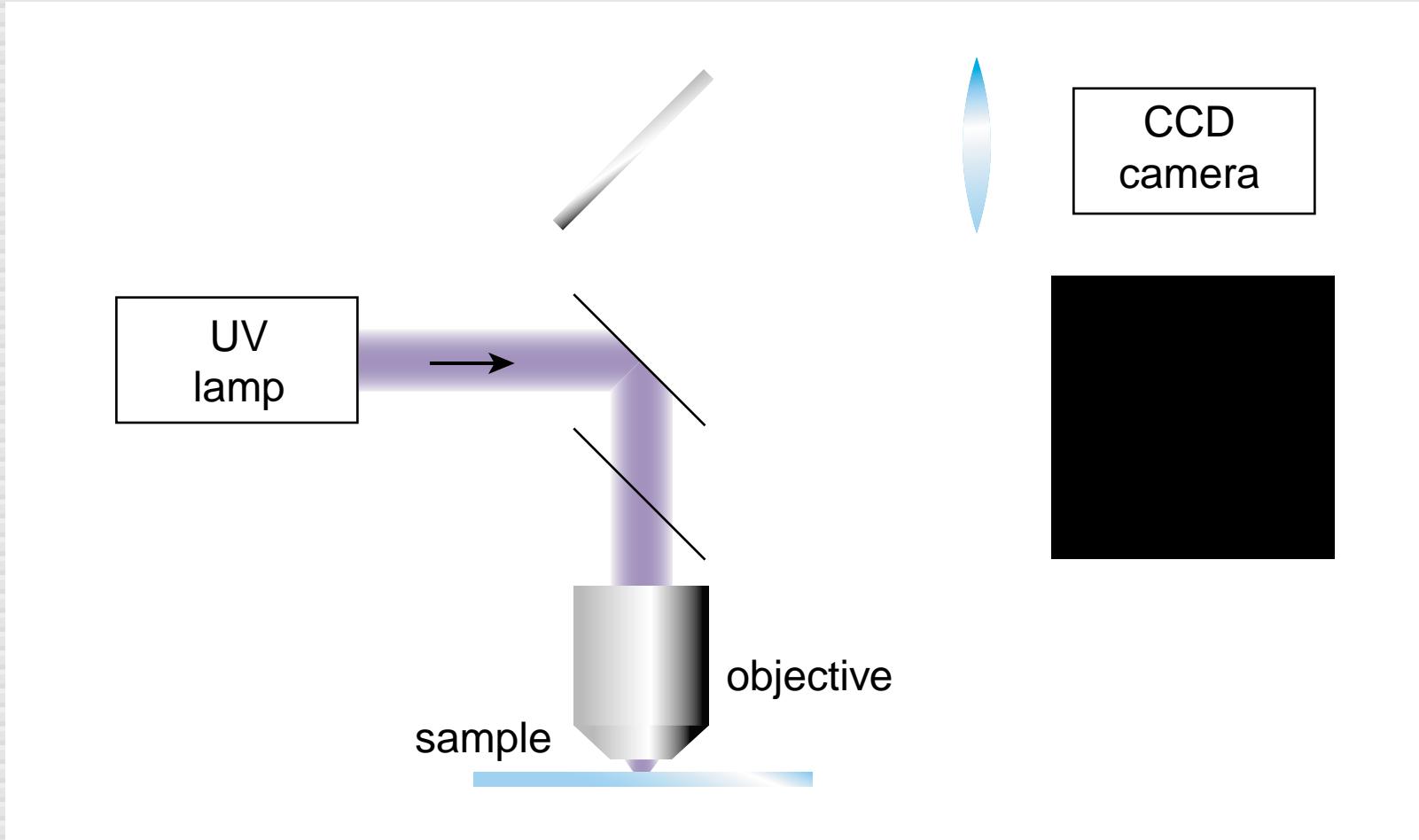
# *Biology and medicine*

## mount fluorescently tagged sample



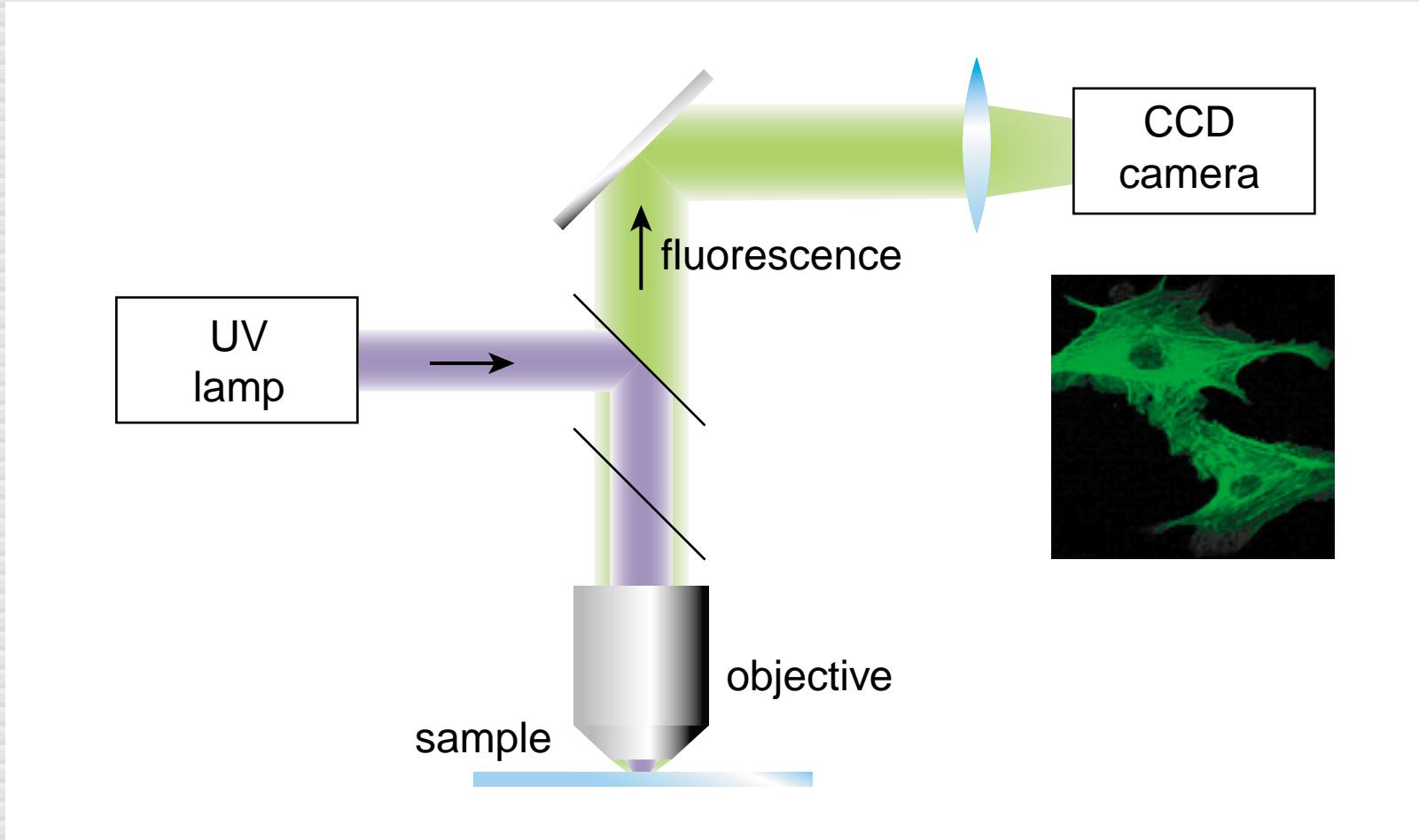
# *Biology and medicine*

## UV illumination...



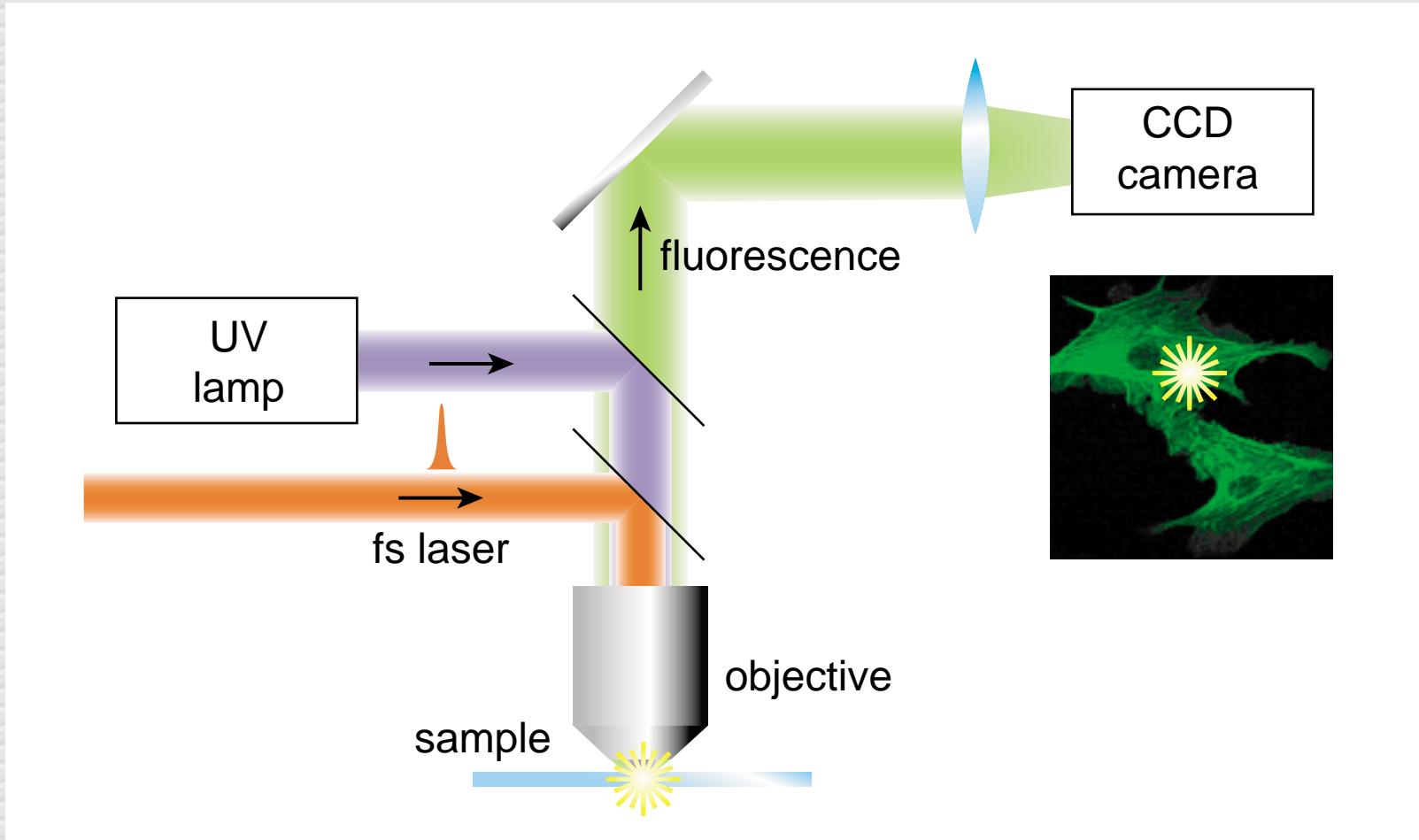
# *Biology and medicine*

... causes fluorescence

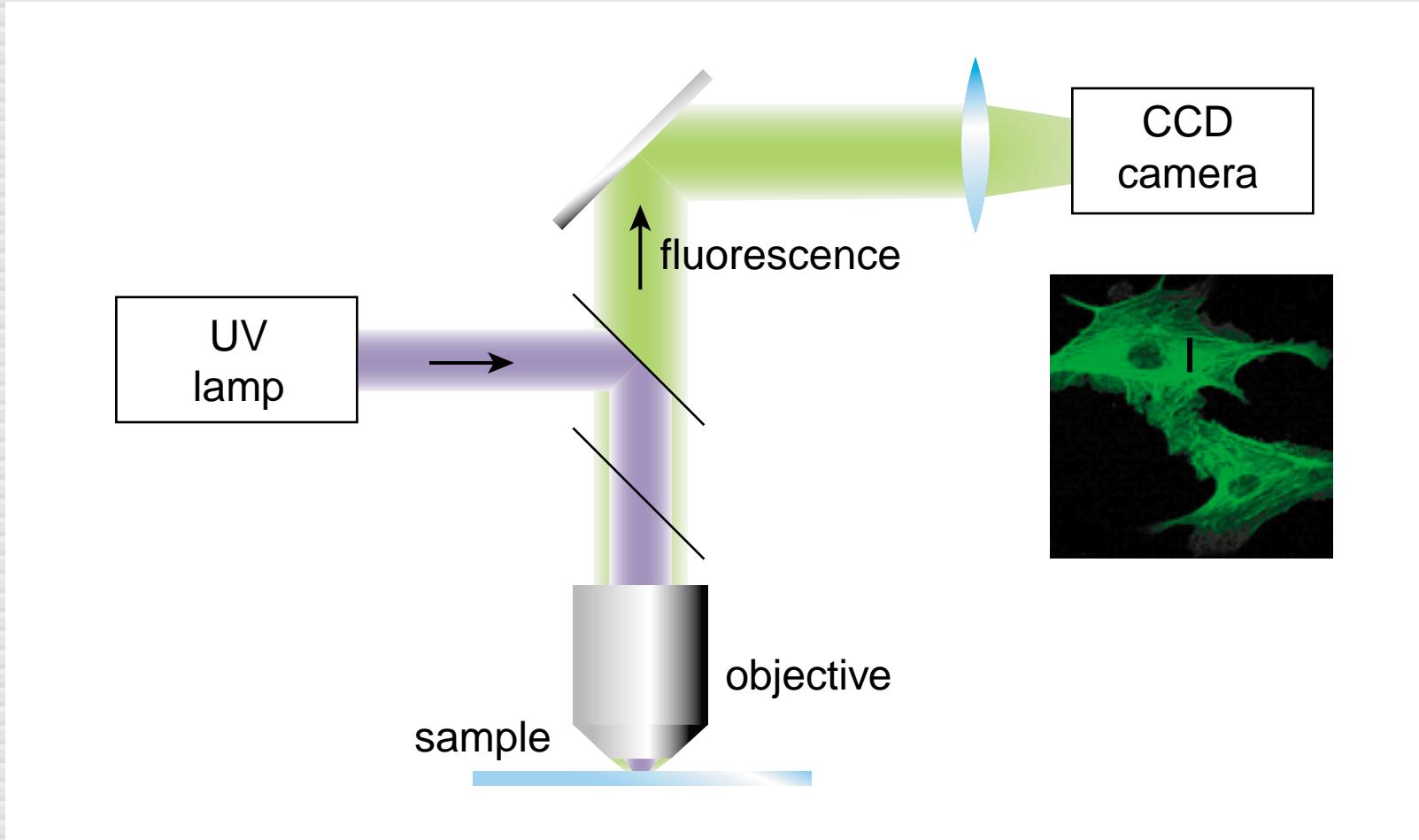


# *Biology and medicine*

## process with fs laser beam



# *Biology and medicine*



# *Biology and medicine*

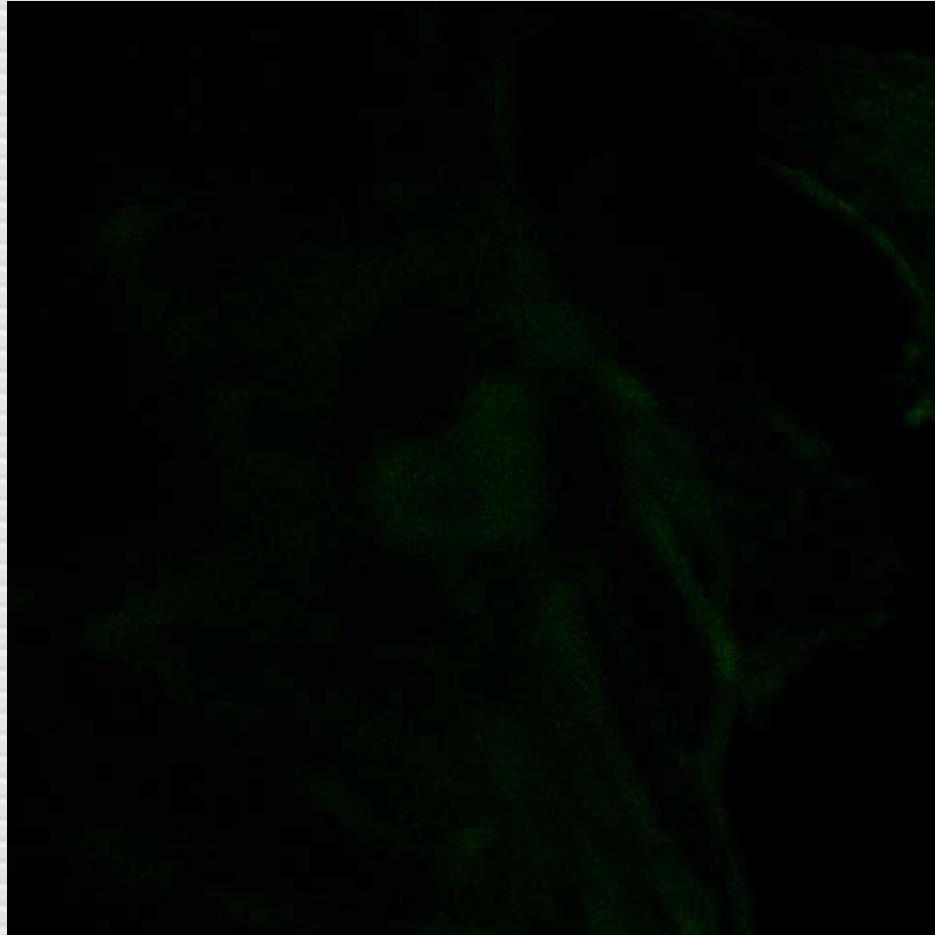
**before**

**after**

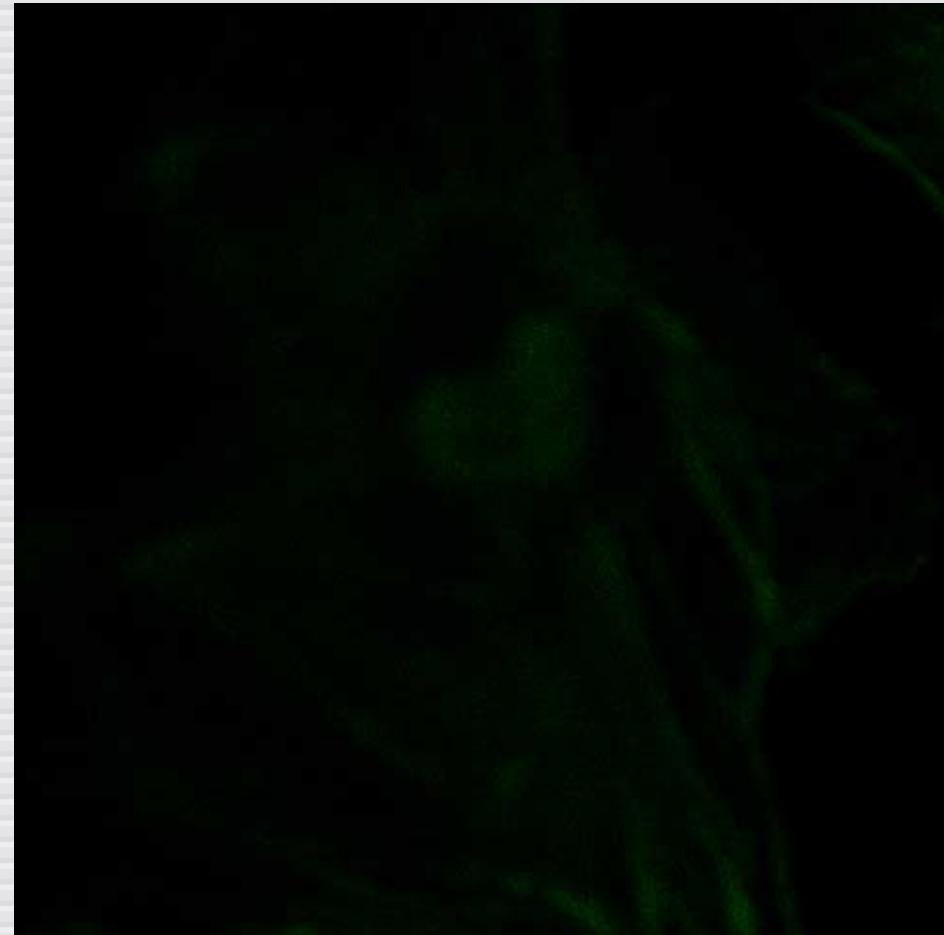
**examine in confocal microscope**

# *Biology and medicine*

**before**

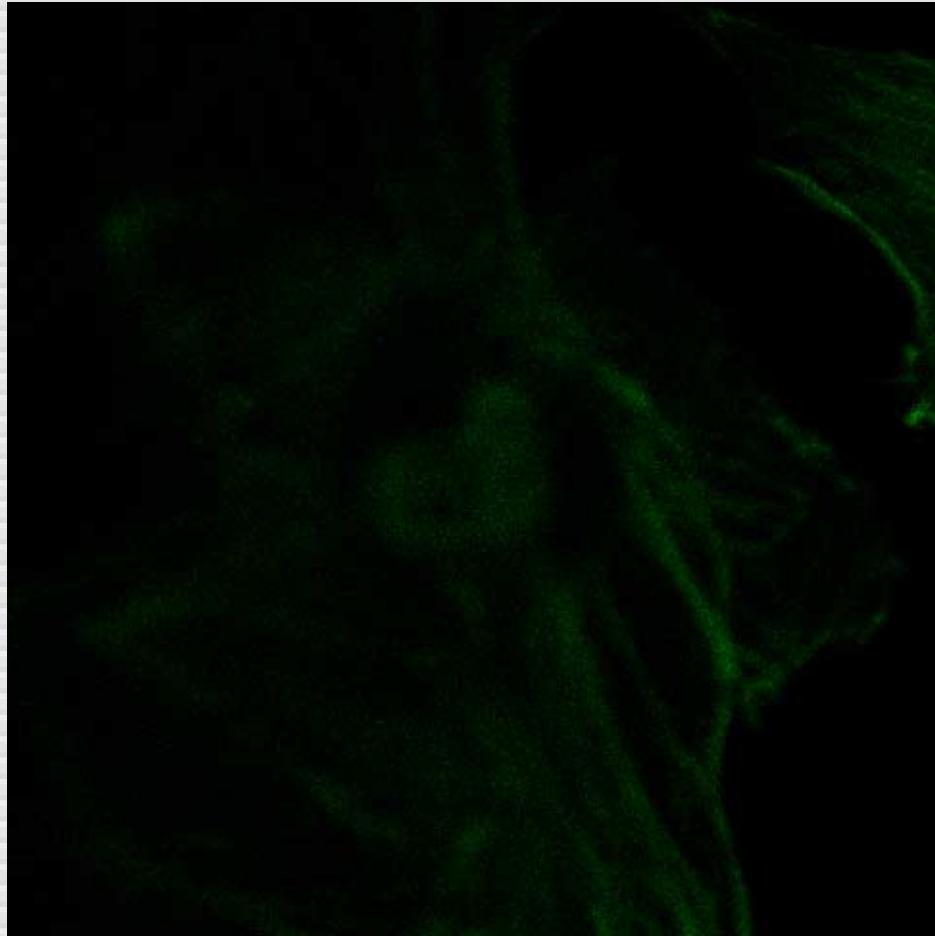


**after**

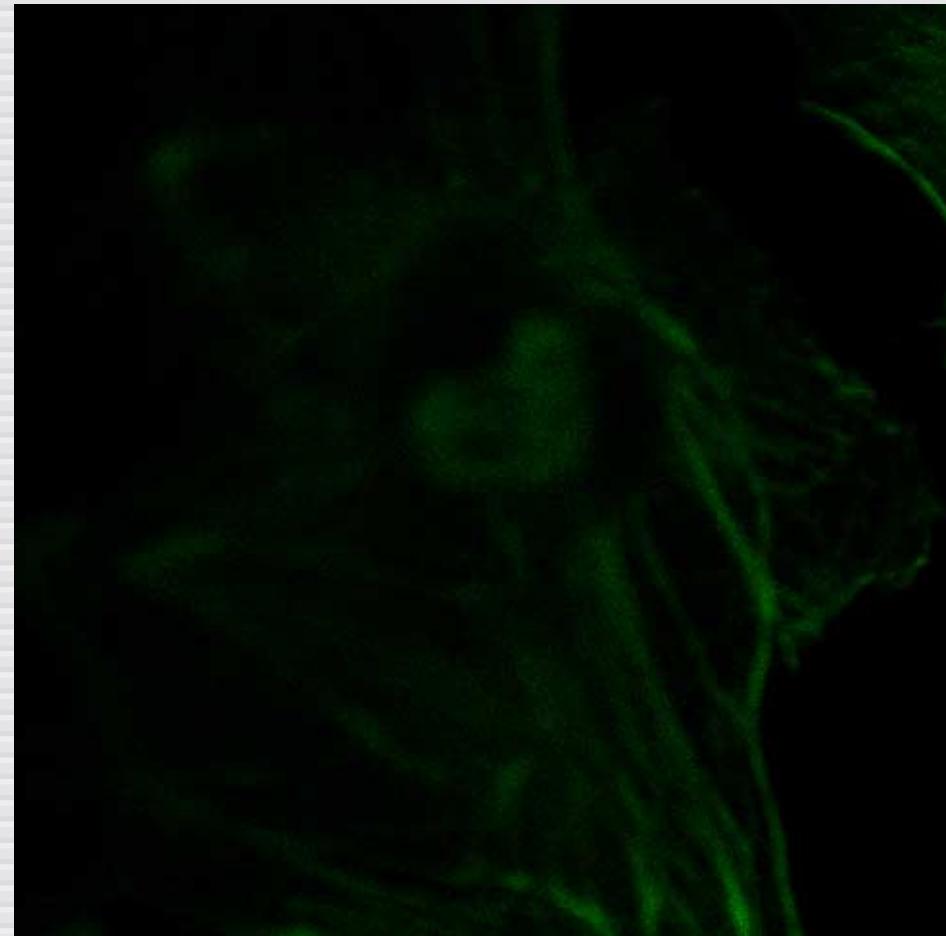


# *Biology and medicine*

**before**

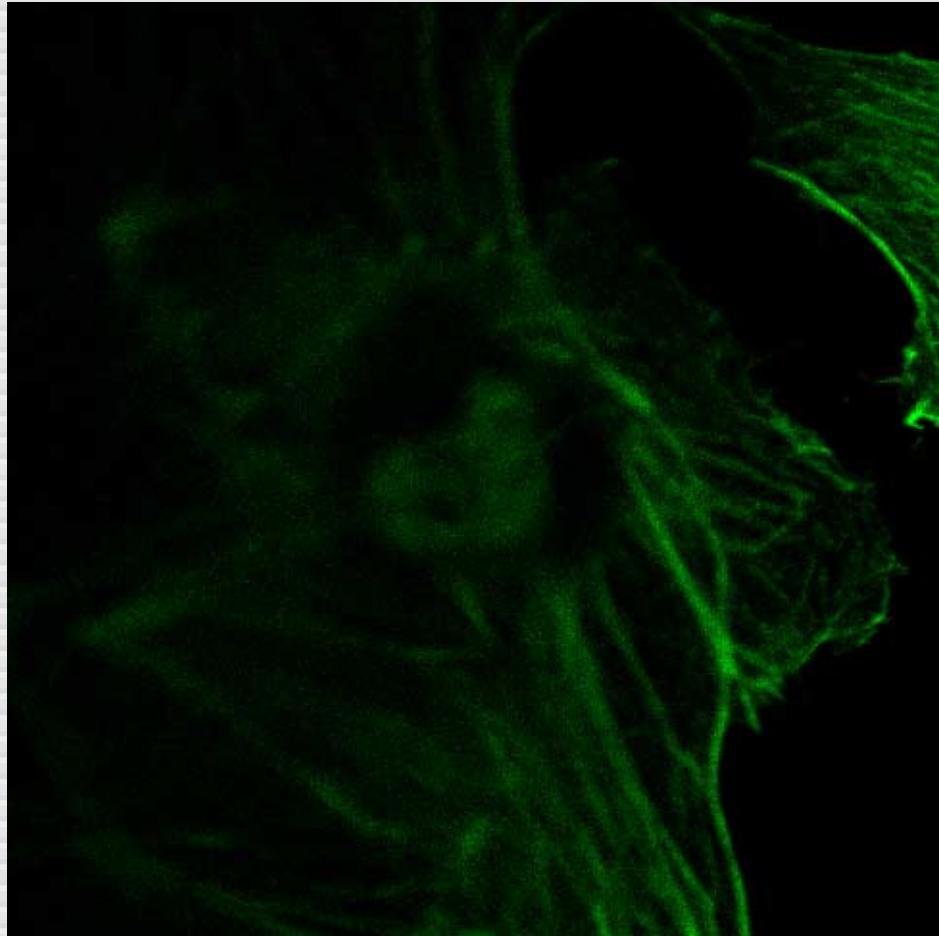


**after**

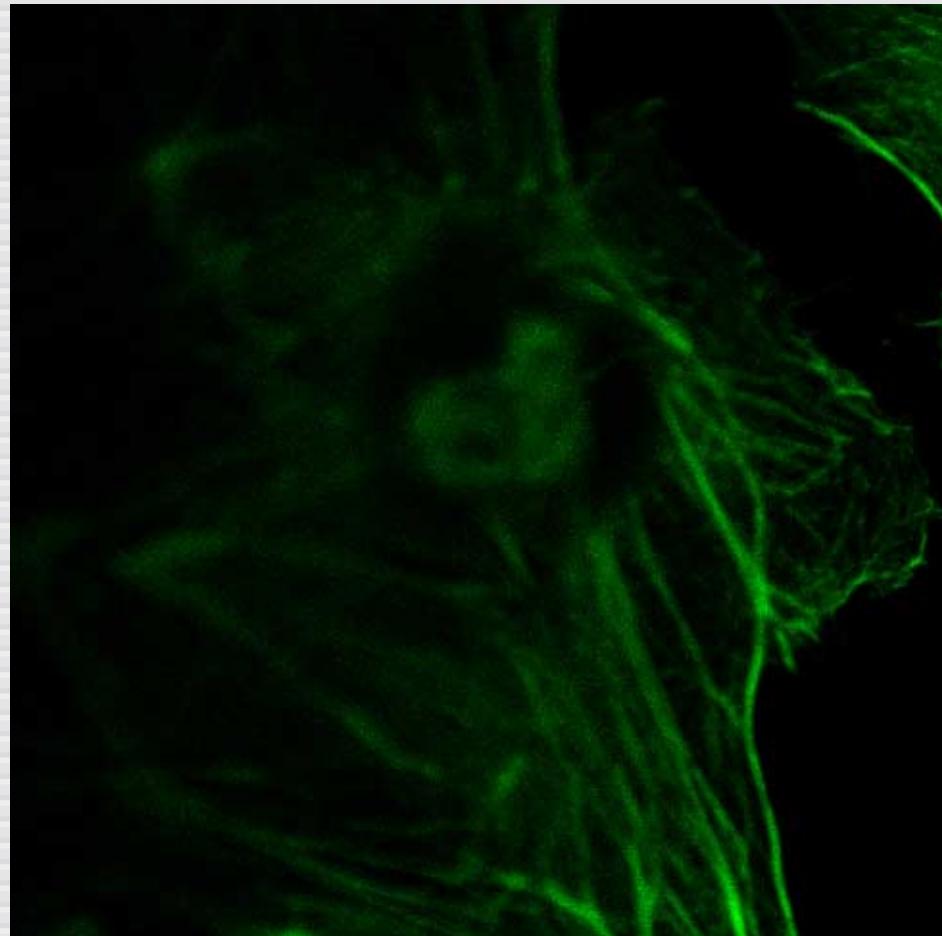


# *Biology and medicine*

**before**

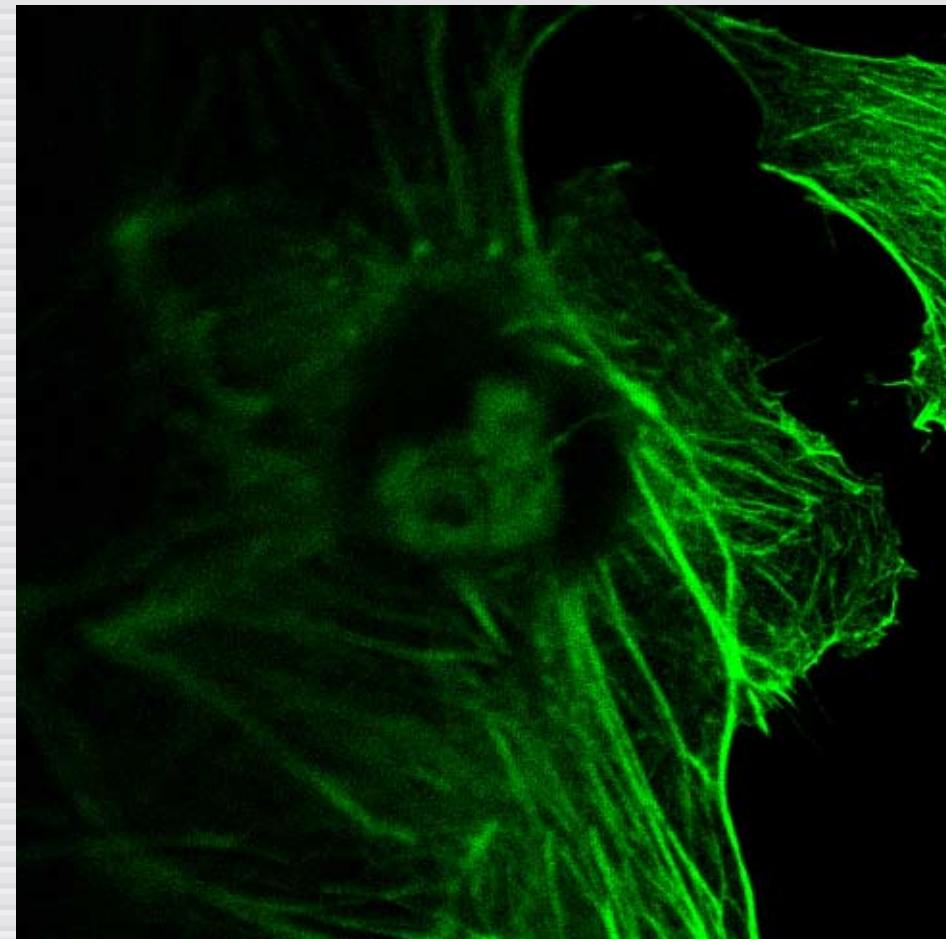


**after**

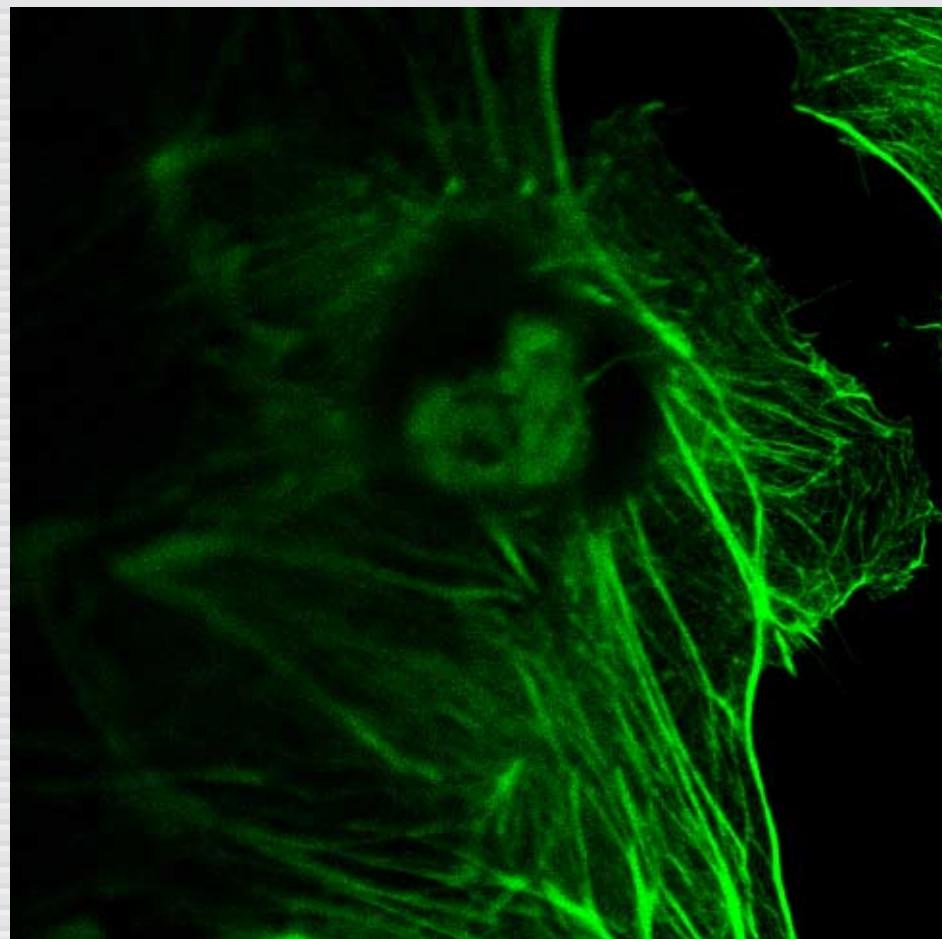


# *Biology and medicine*

**before**

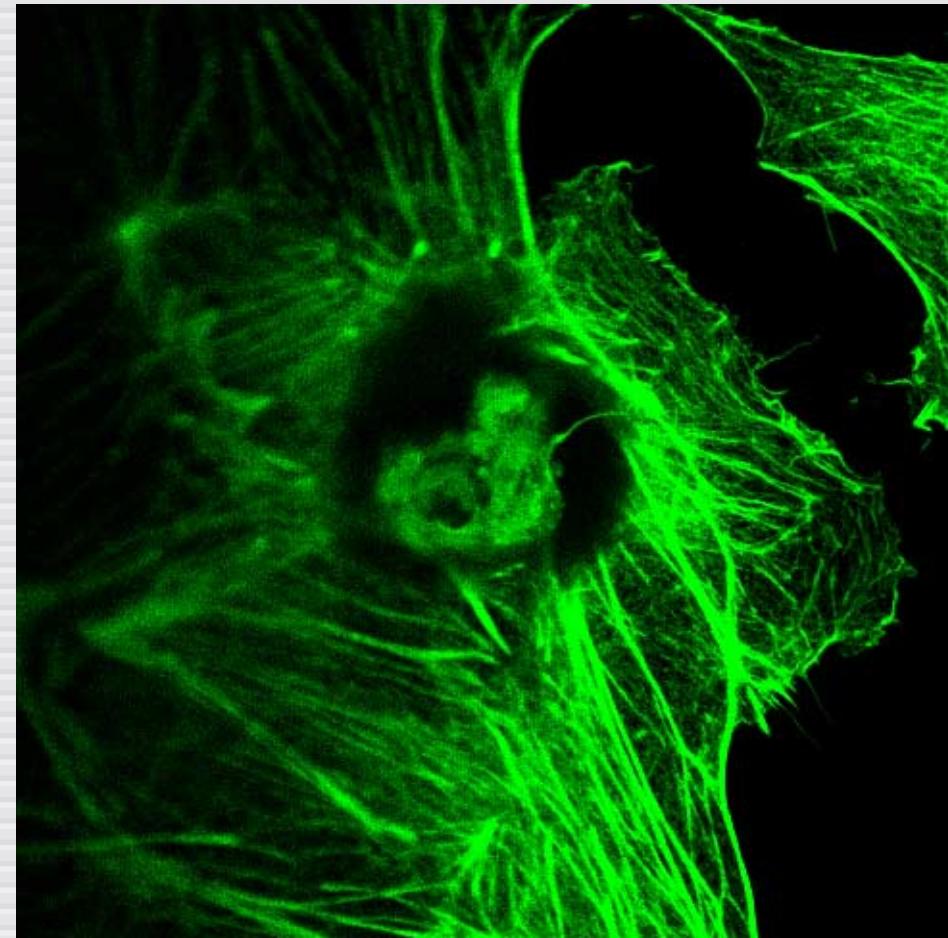


**after**

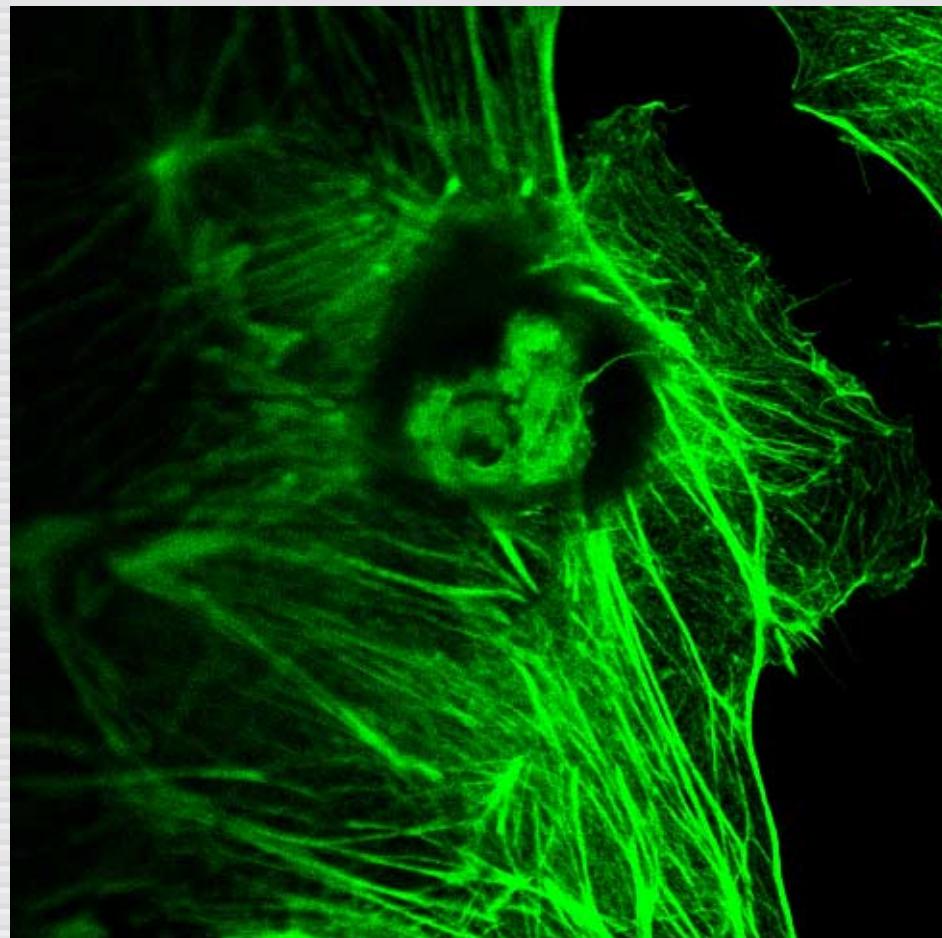


# *Biology and medicine*

**before**

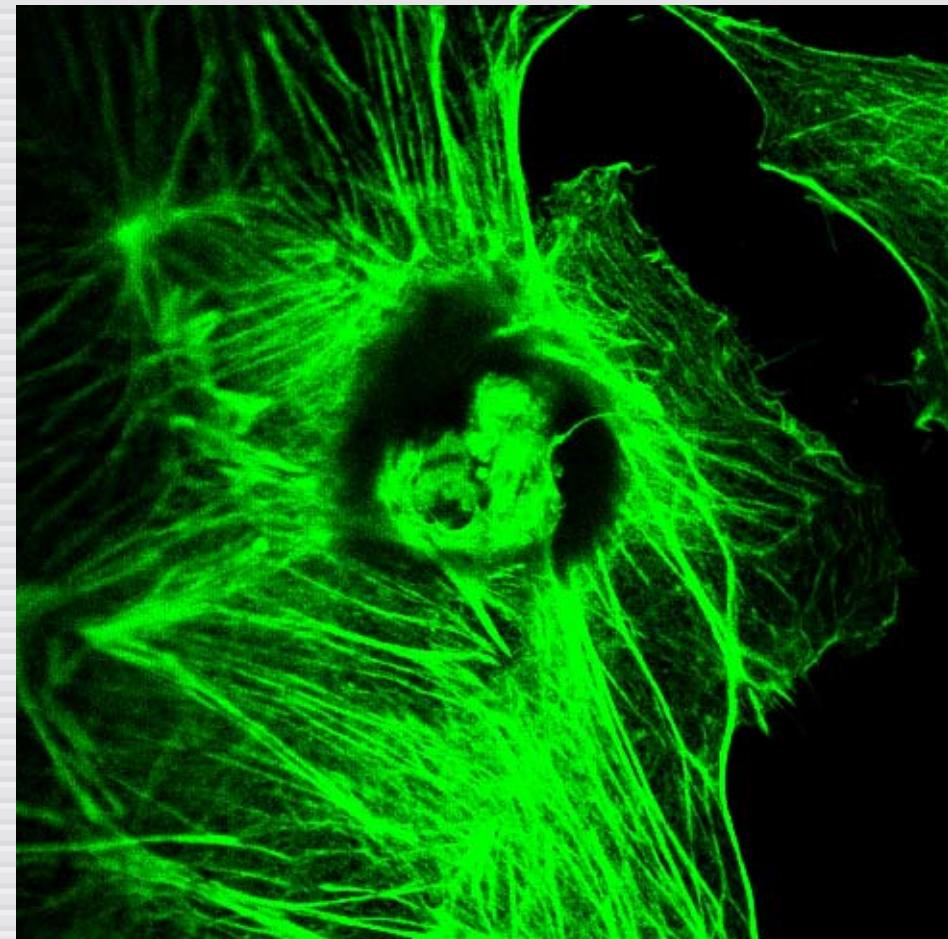


**after**

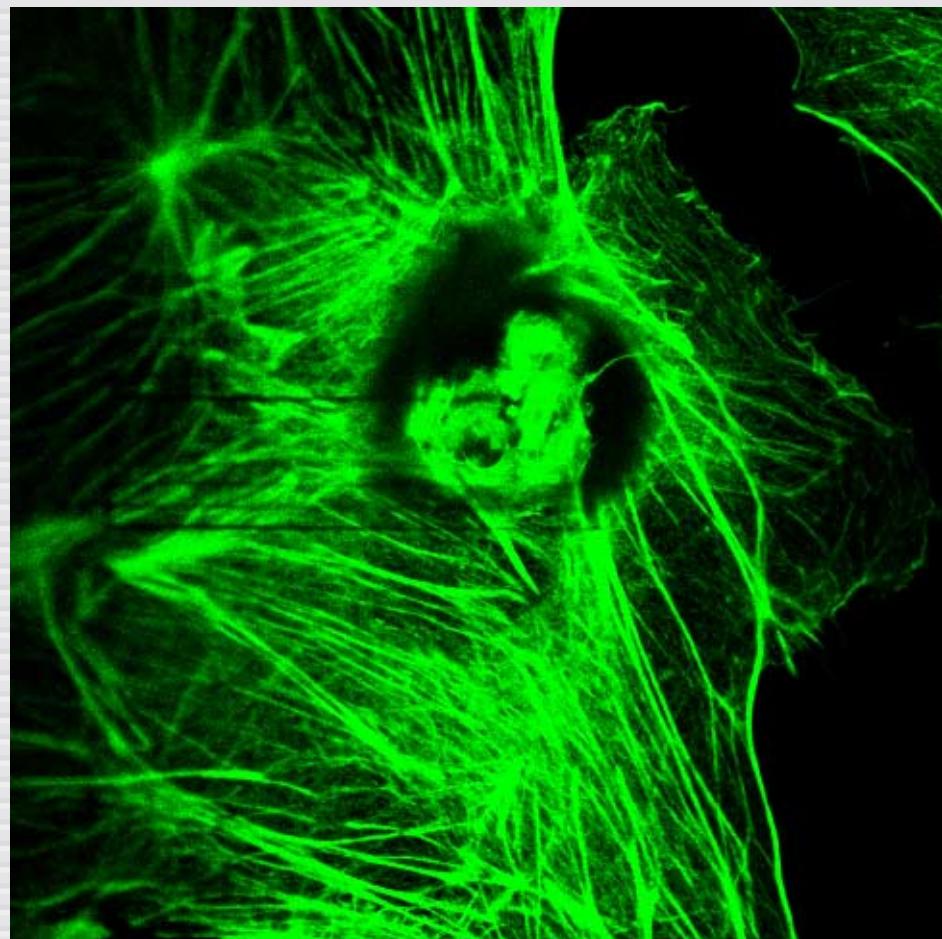


# *Biology and medicine*

**before**

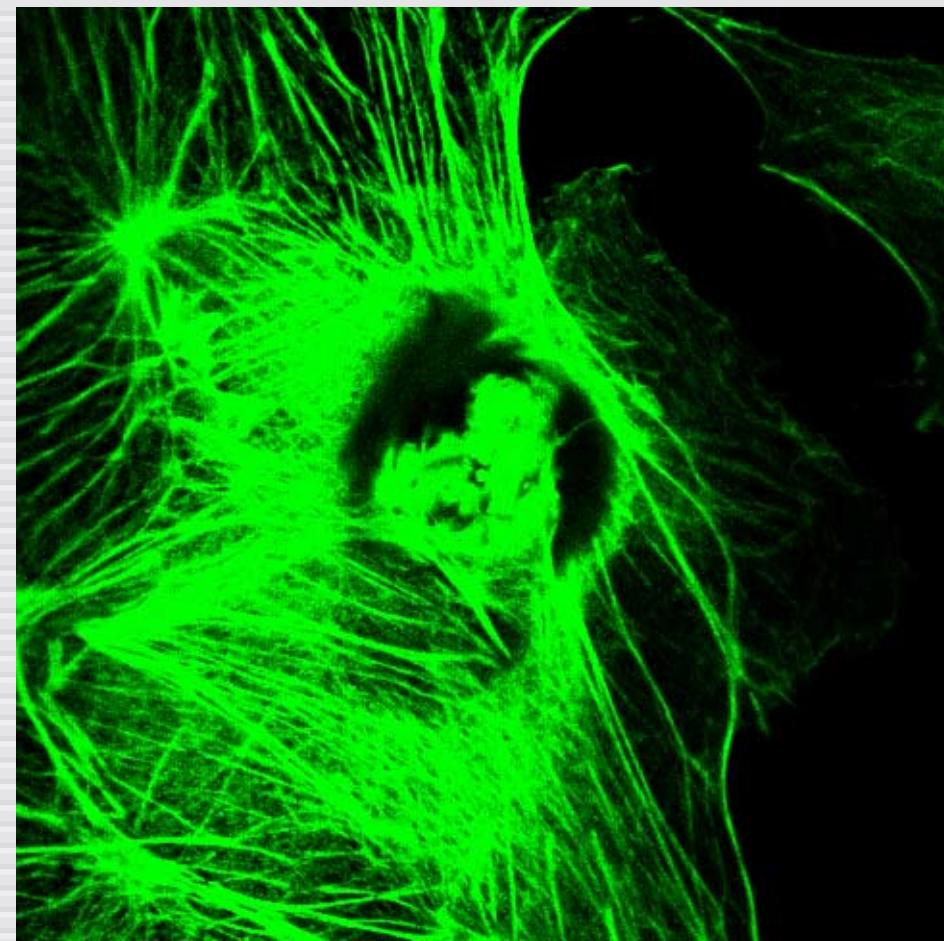


**after**

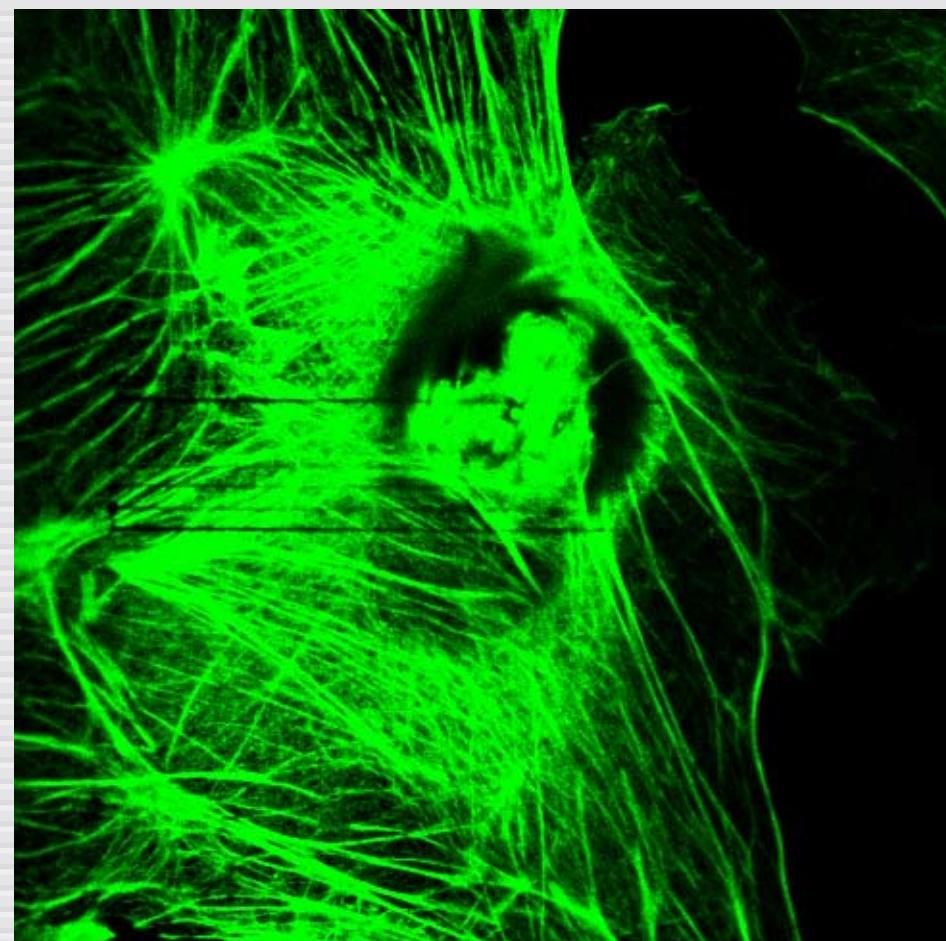


# *Biology and medicine*

**before**

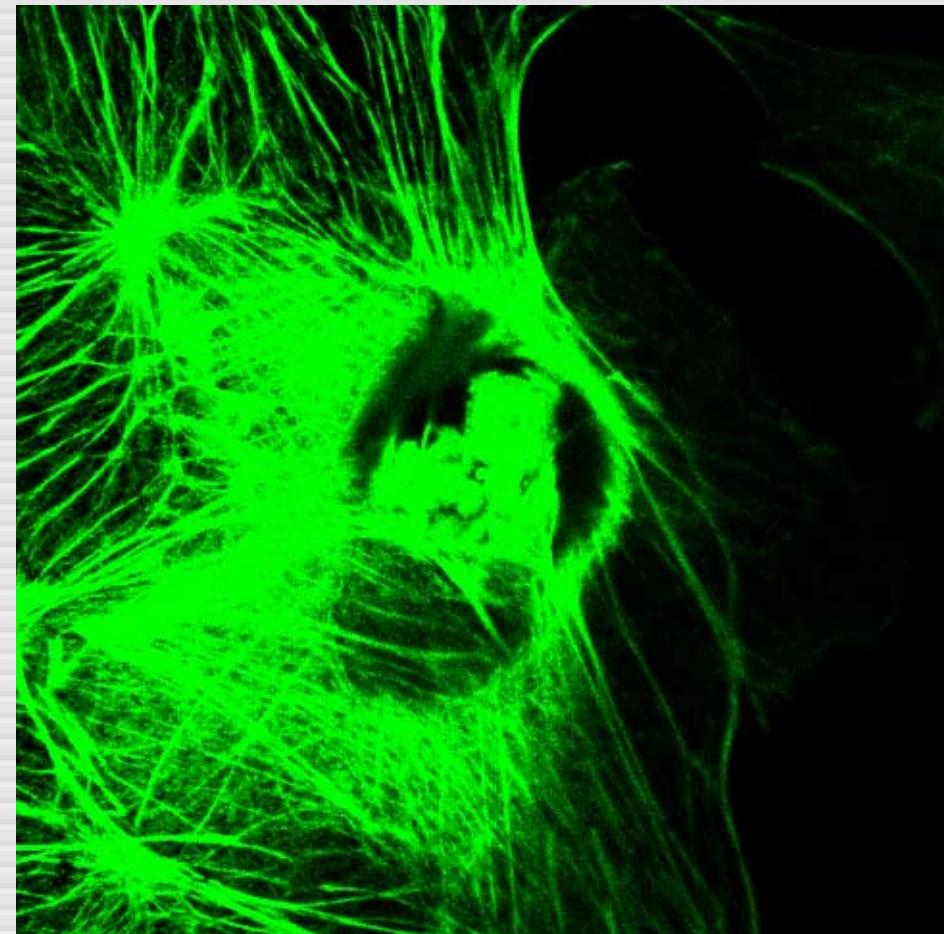


**after**

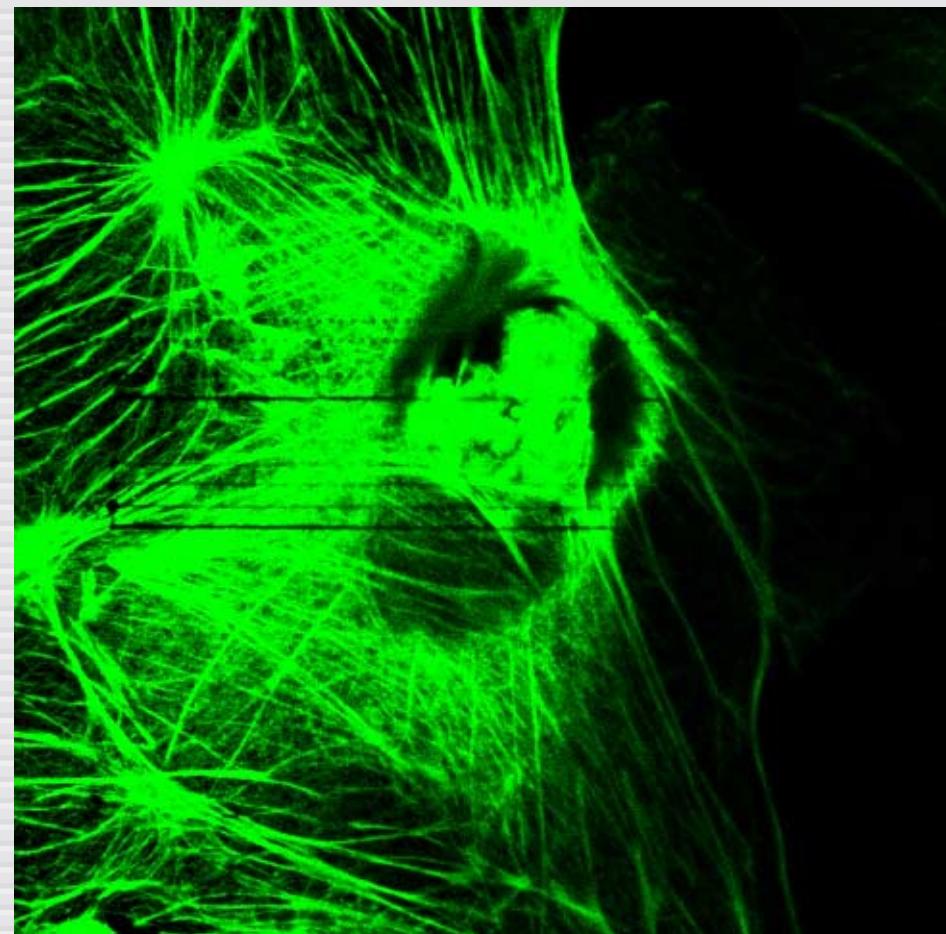


# *Biology and medicine*

**before**

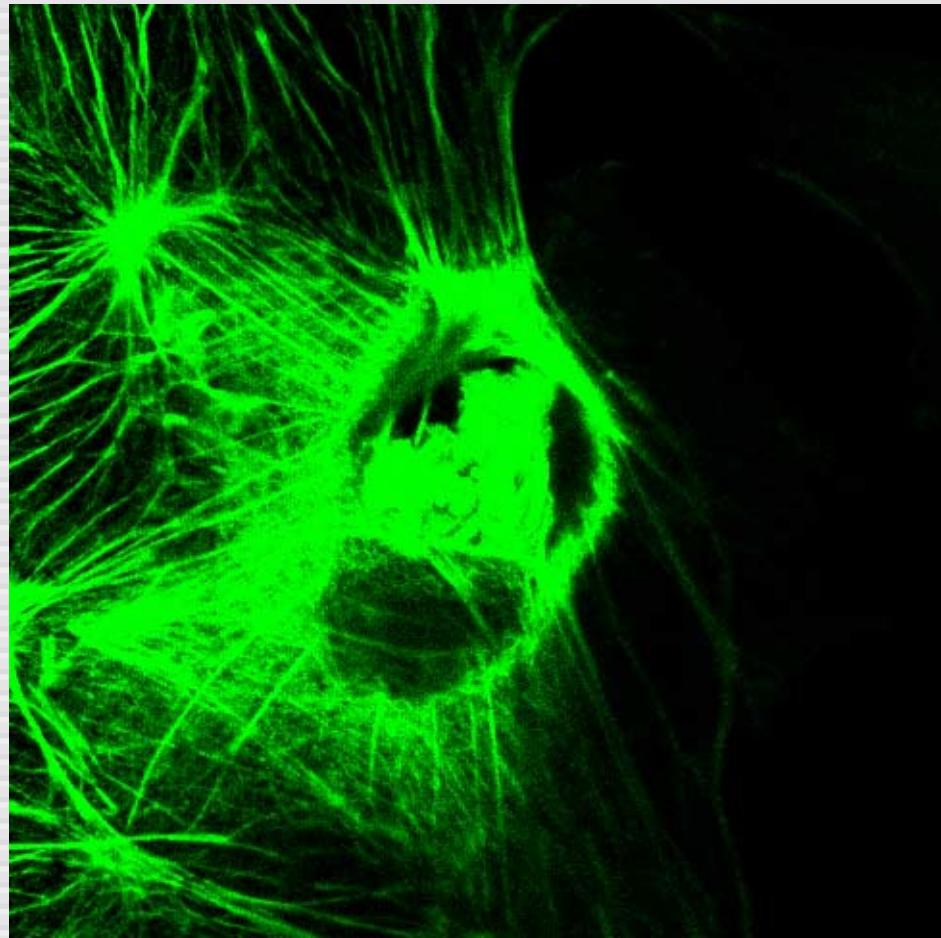


**after**

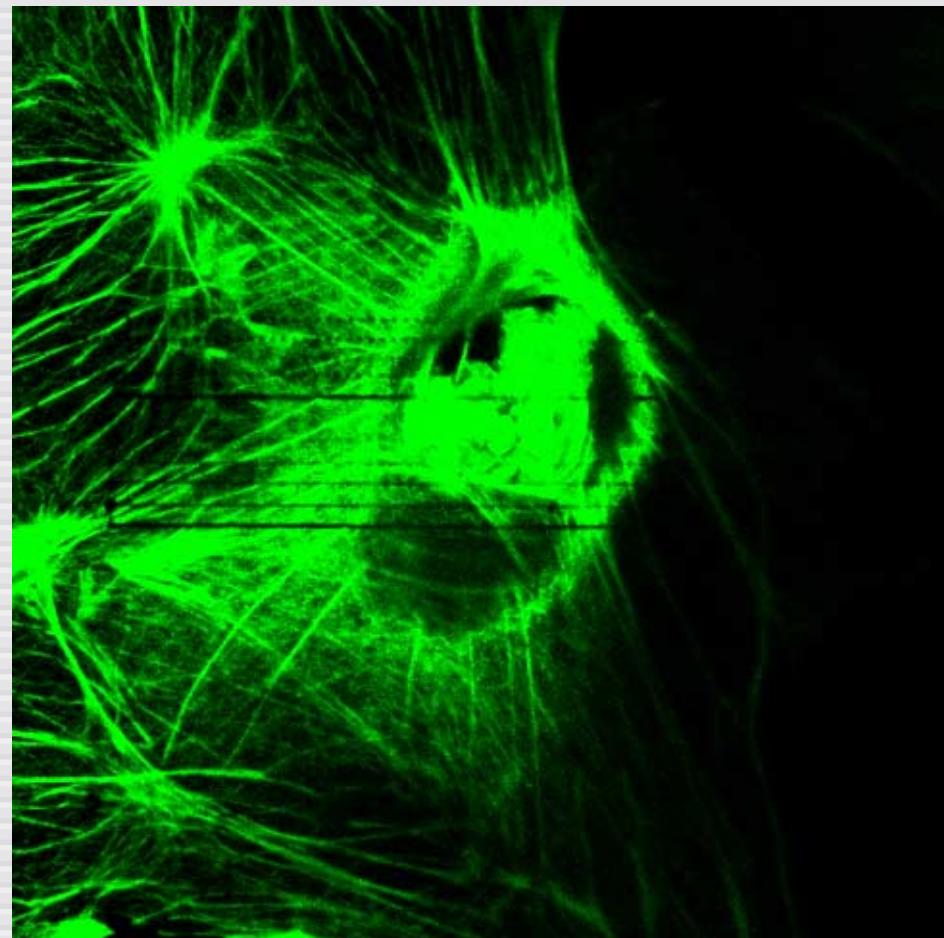


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**before**

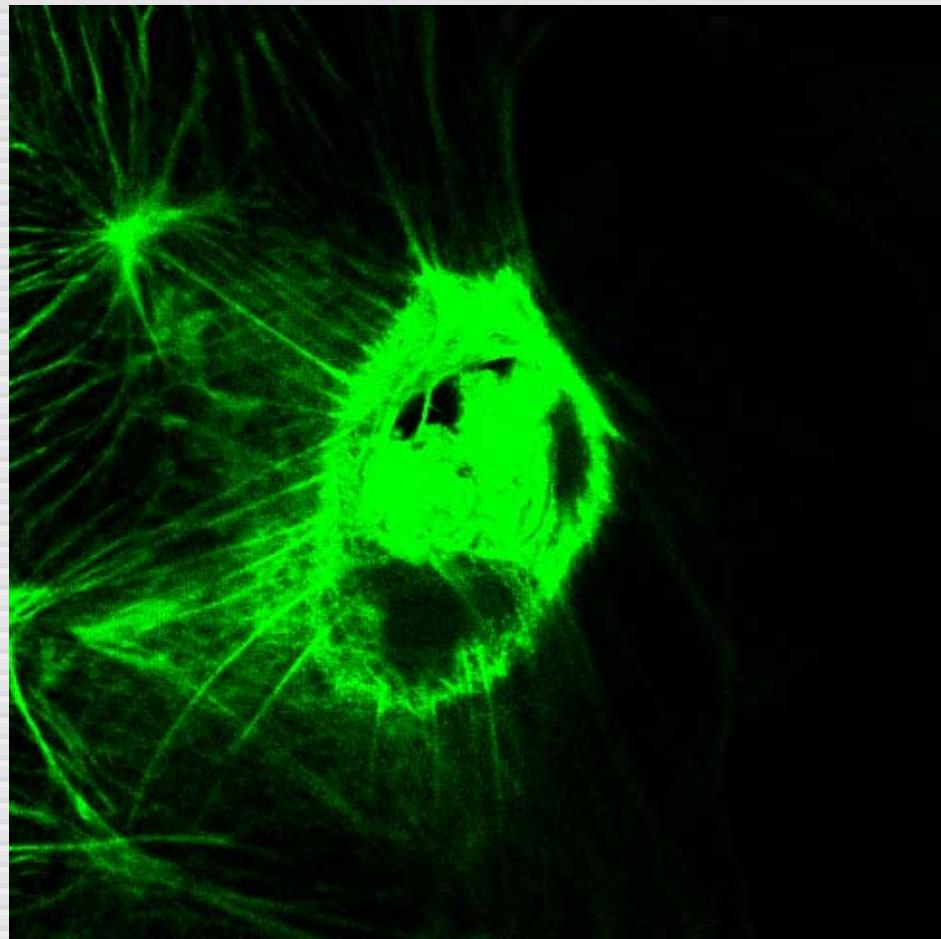


**after**

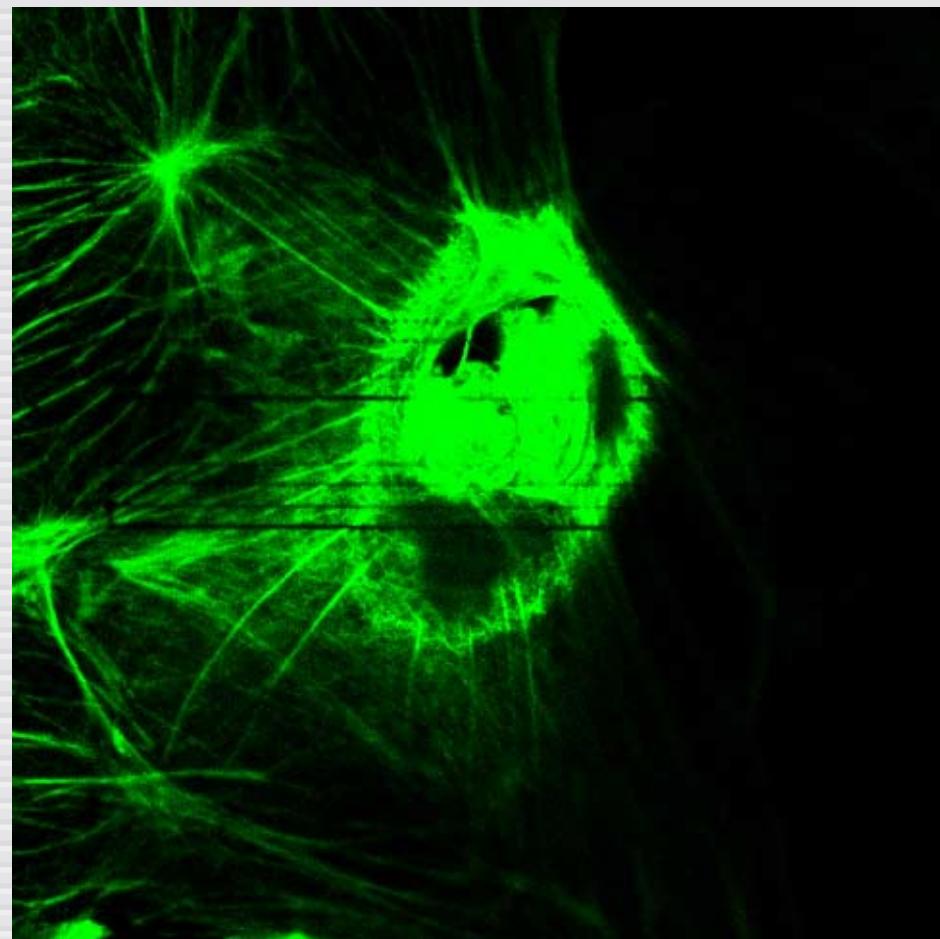


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**before**

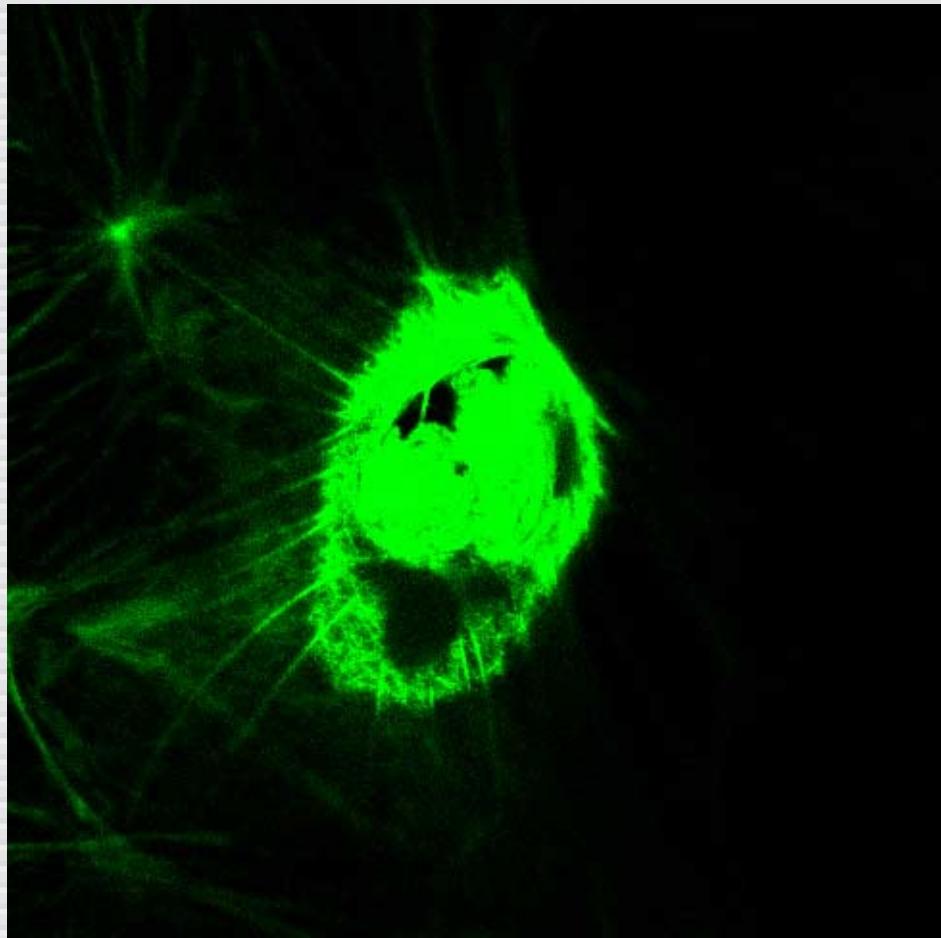


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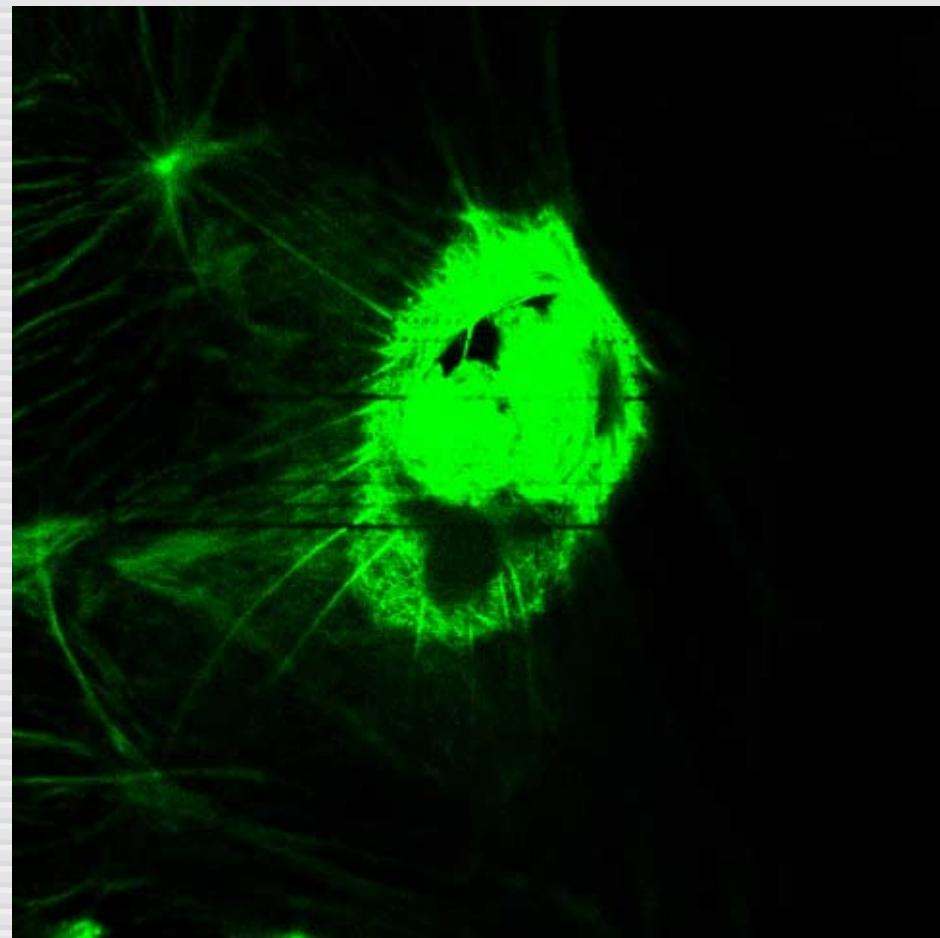


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**before**

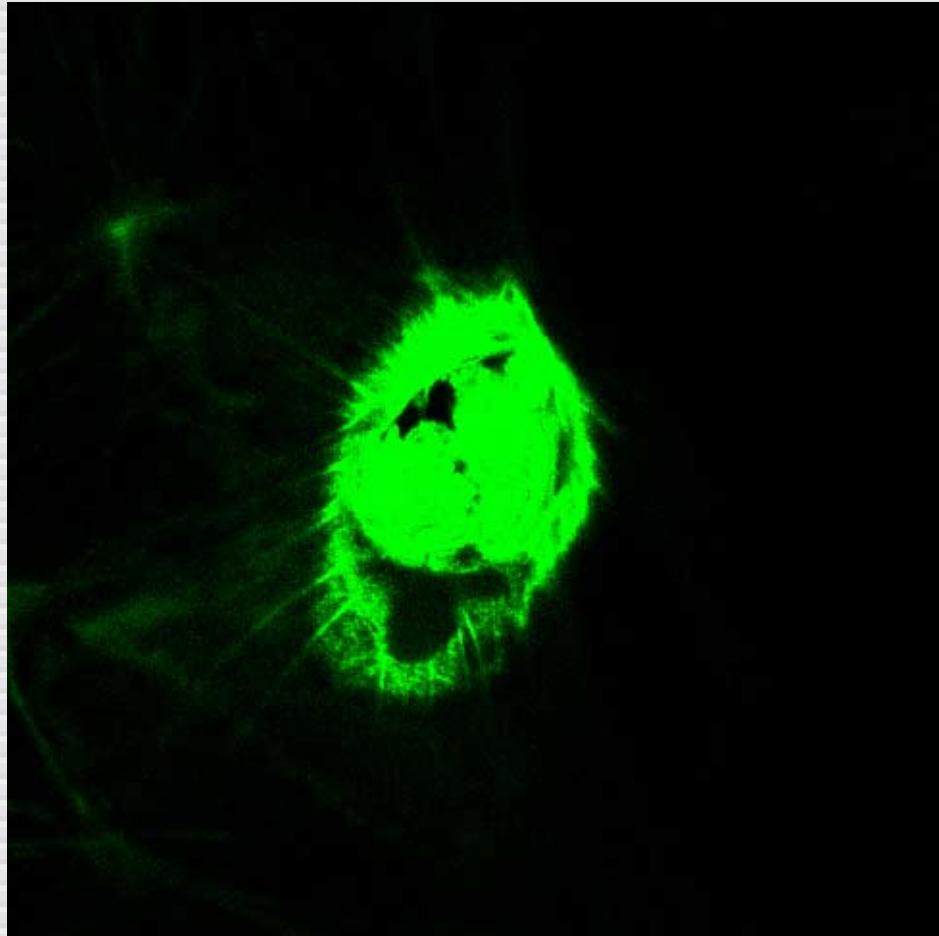


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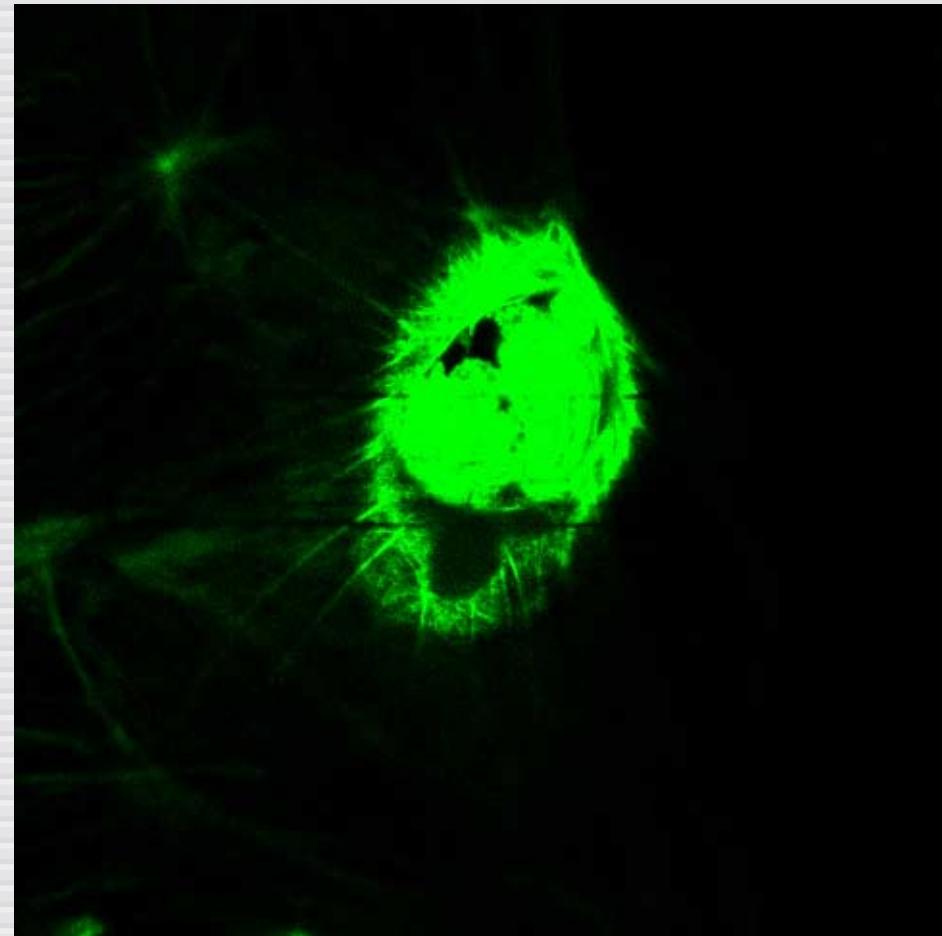


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**before**

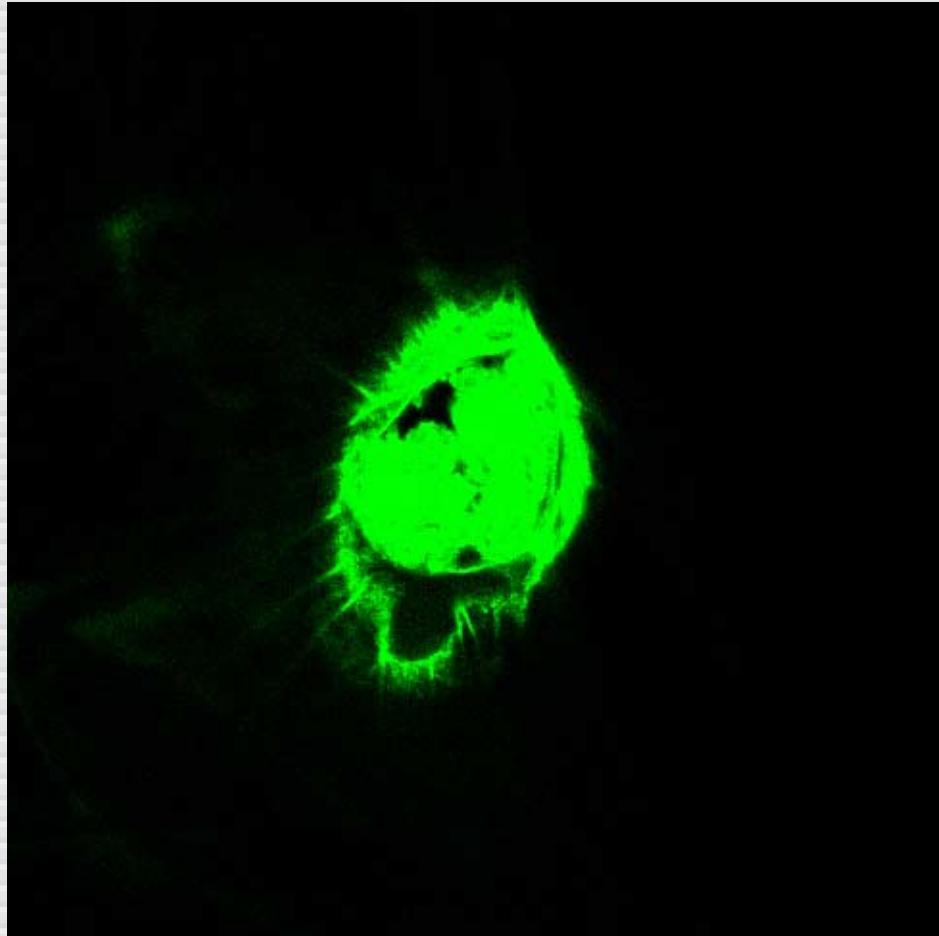


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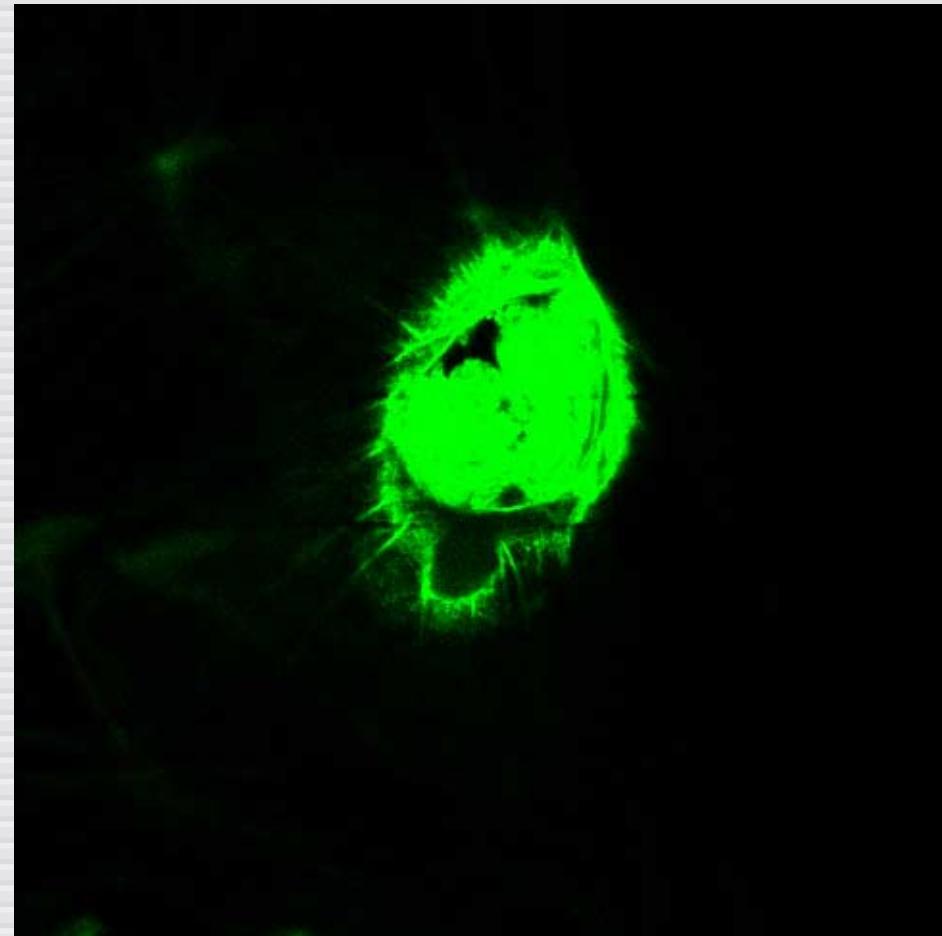


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**before**

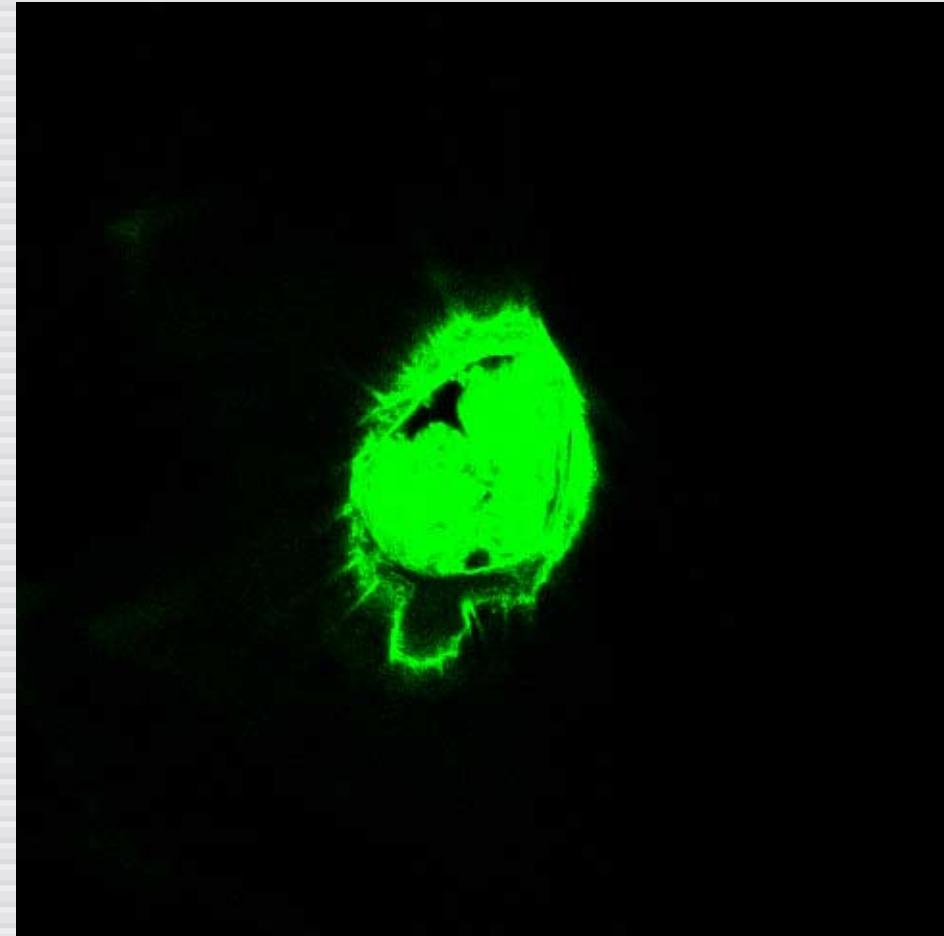


**after**

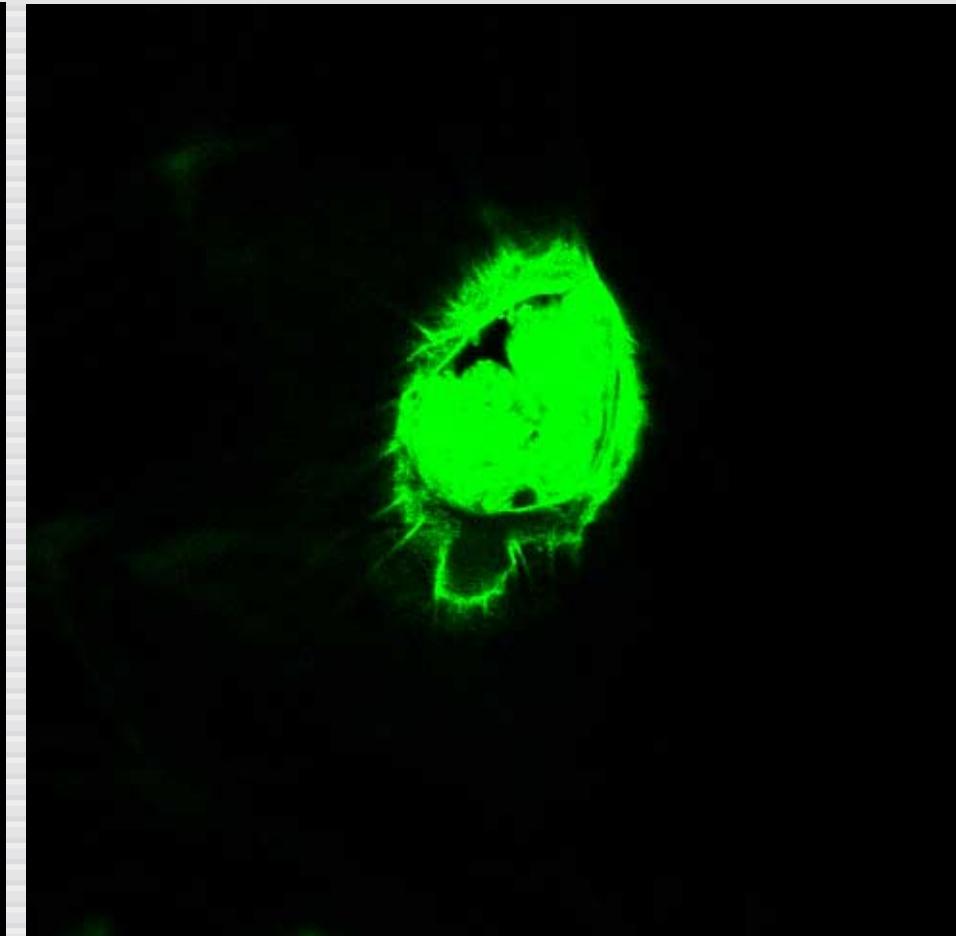


# *Biology and medicine*

**before**

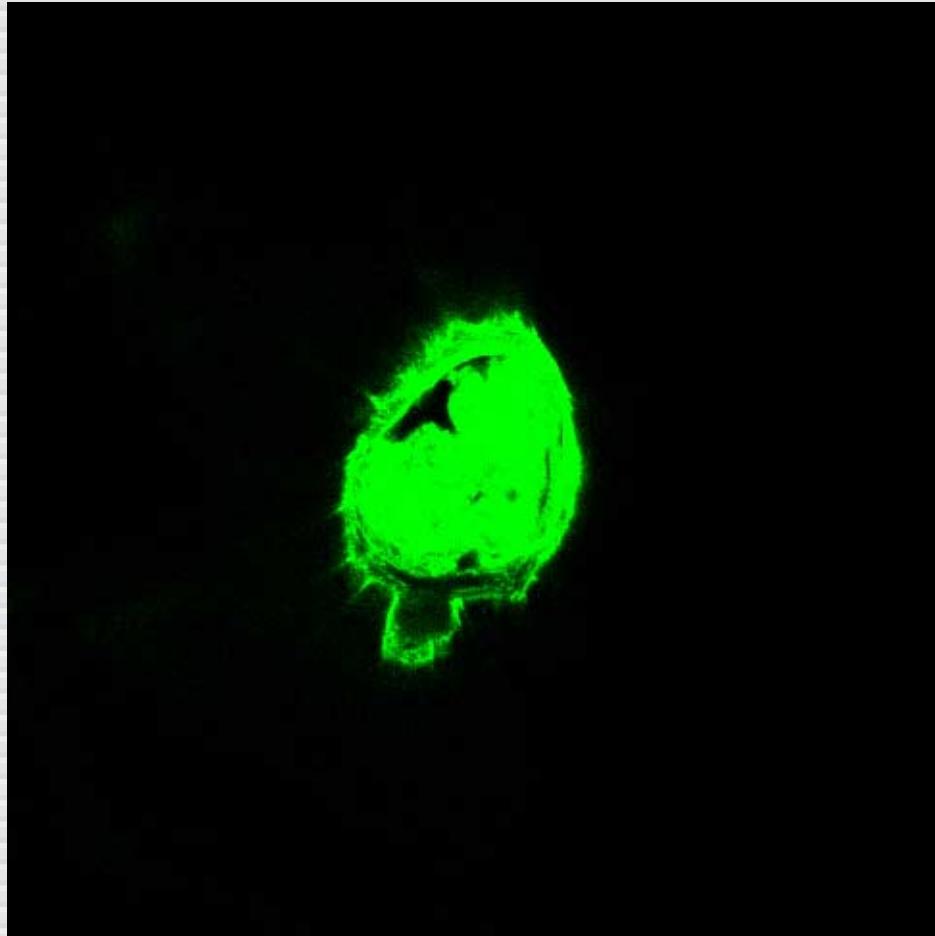


**after**

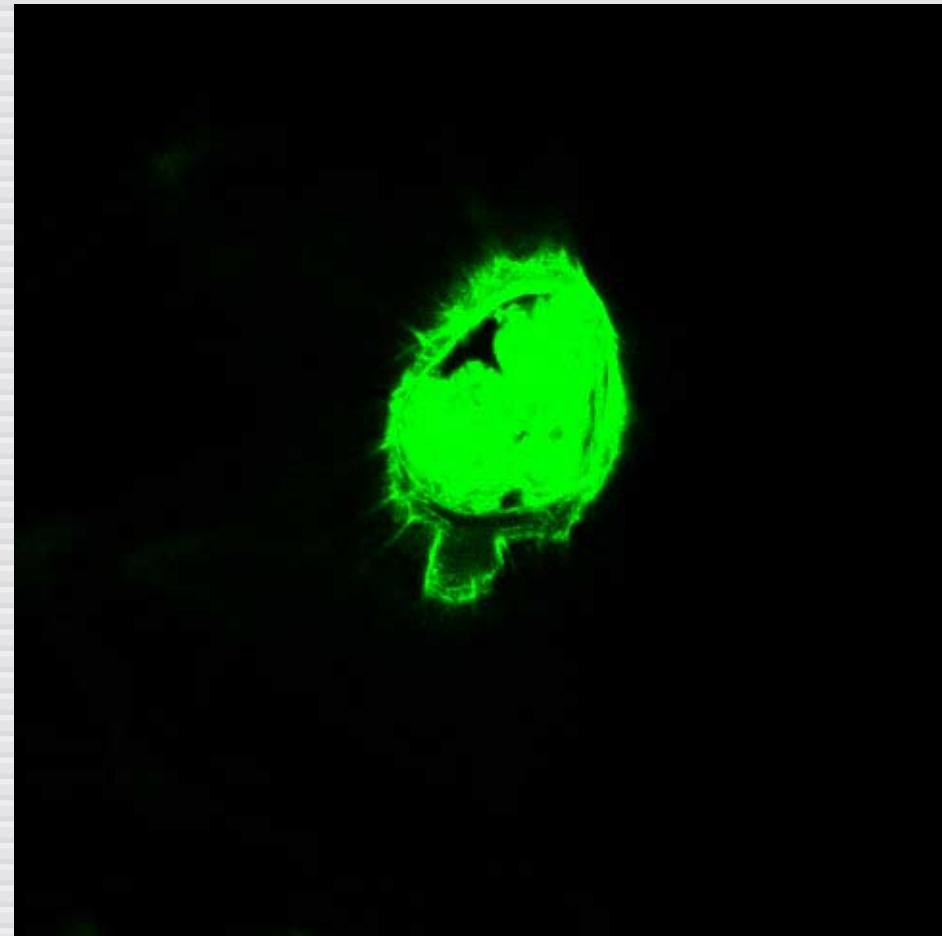


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**before**

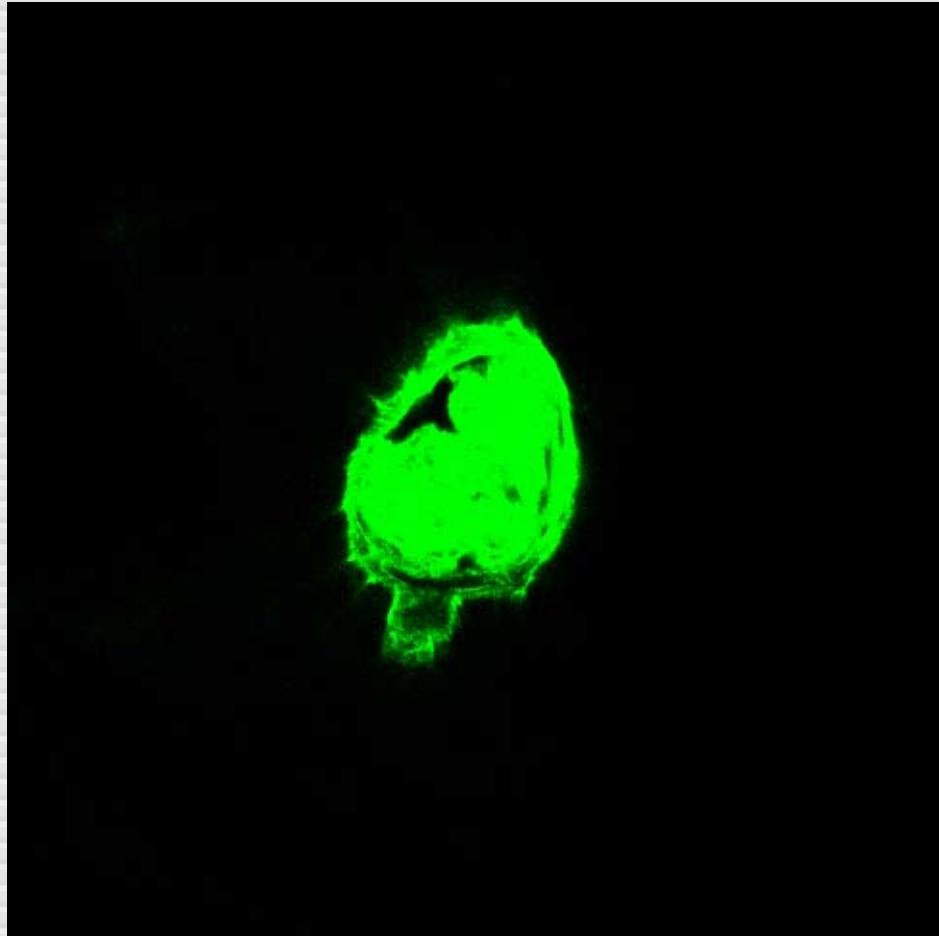


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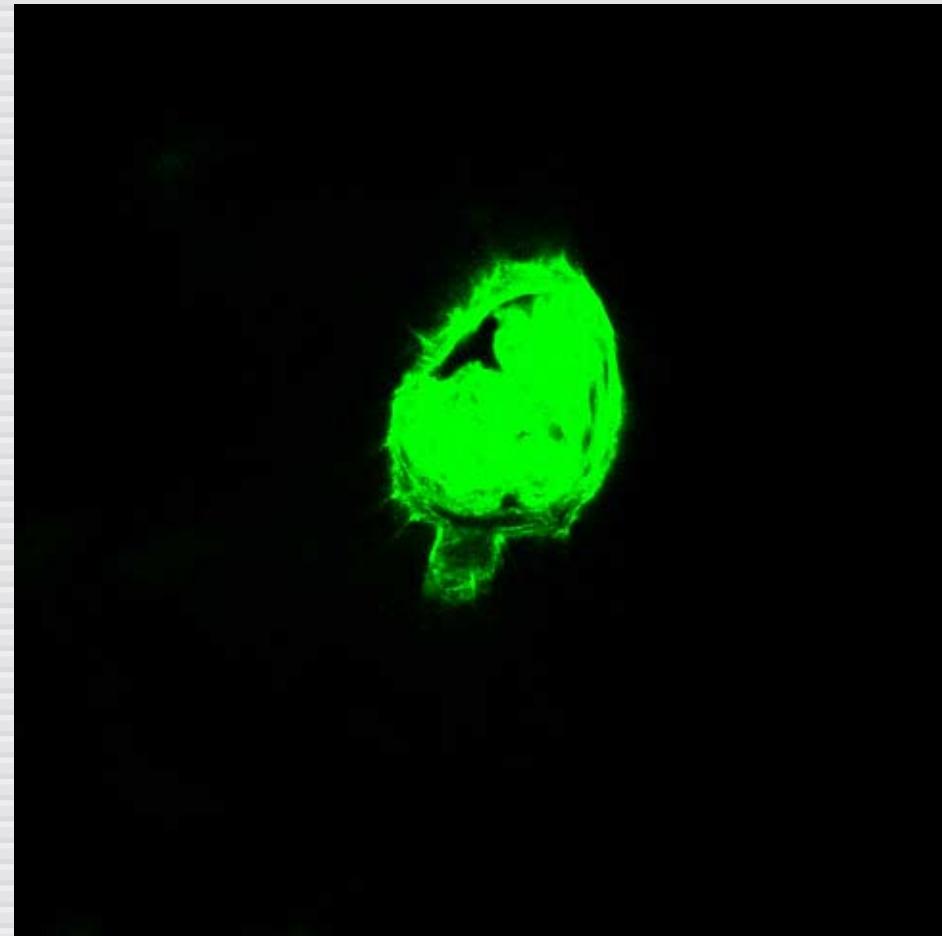


# *Biology and medicine*

**before**

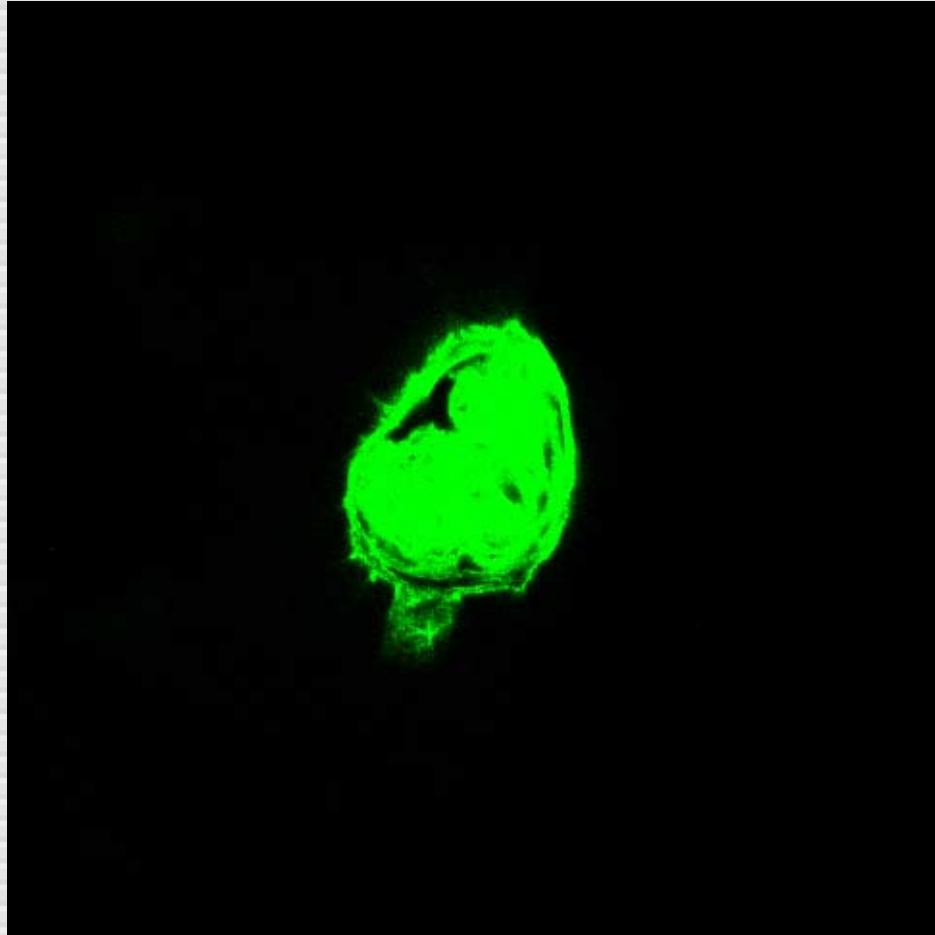


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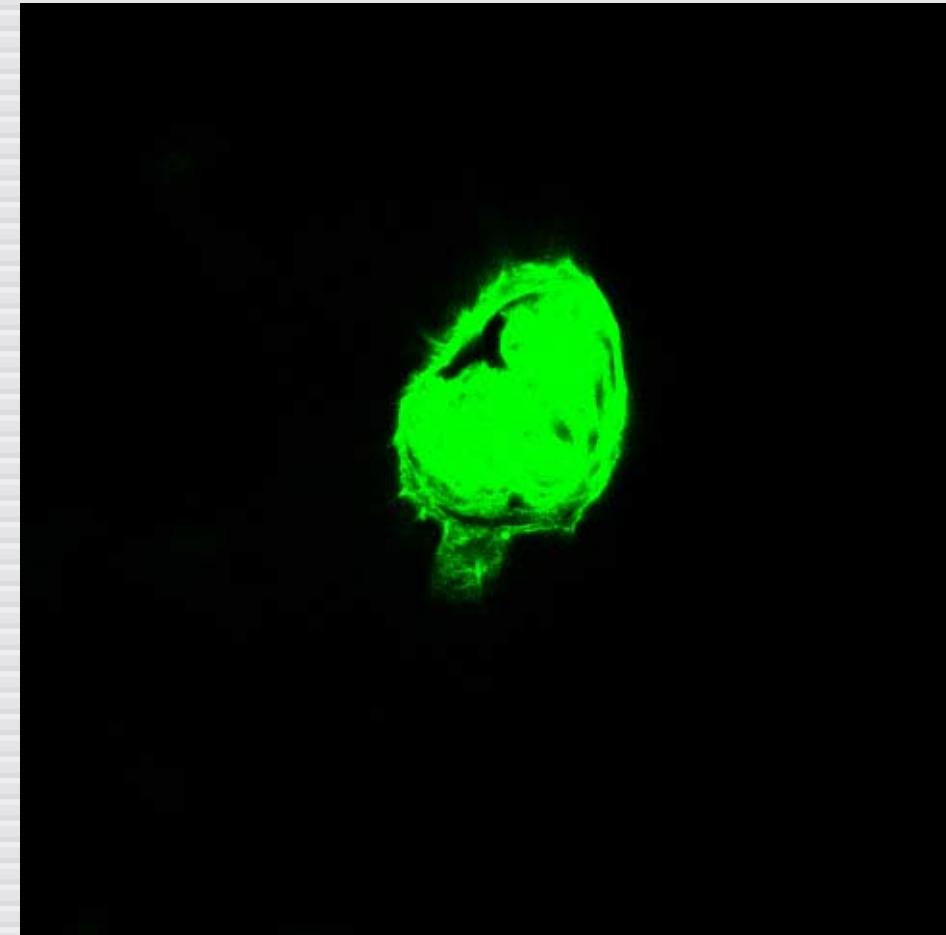


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**before**

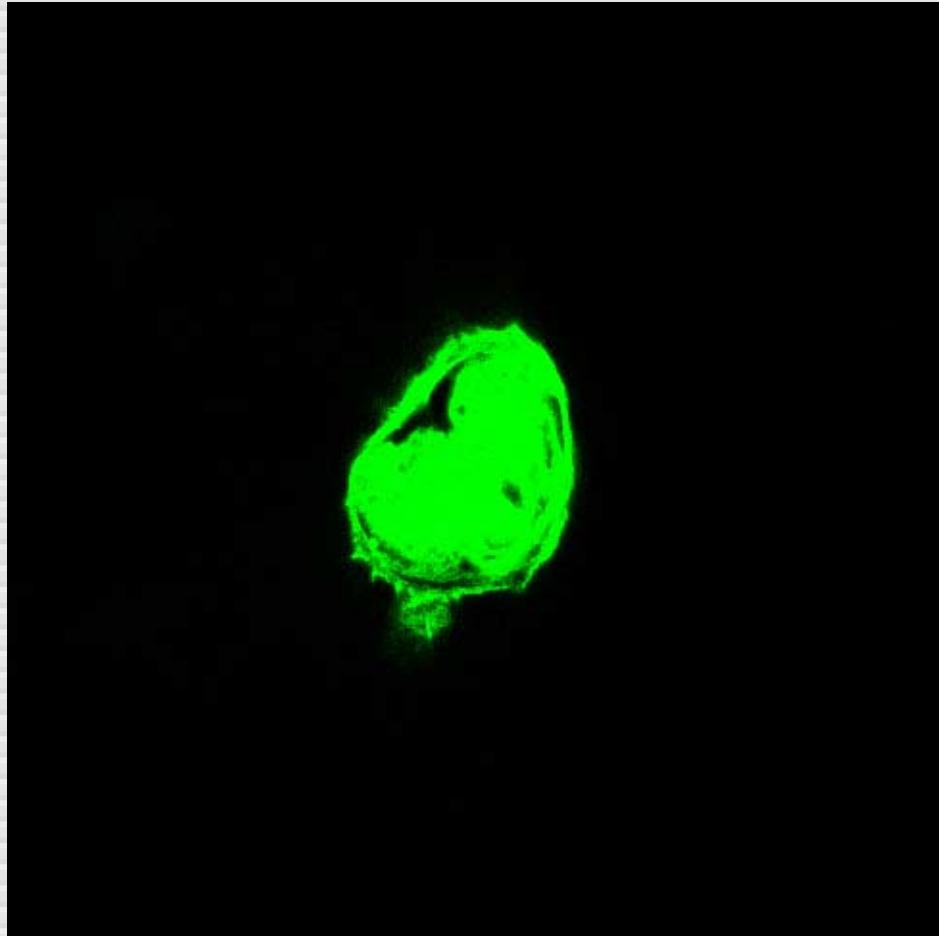


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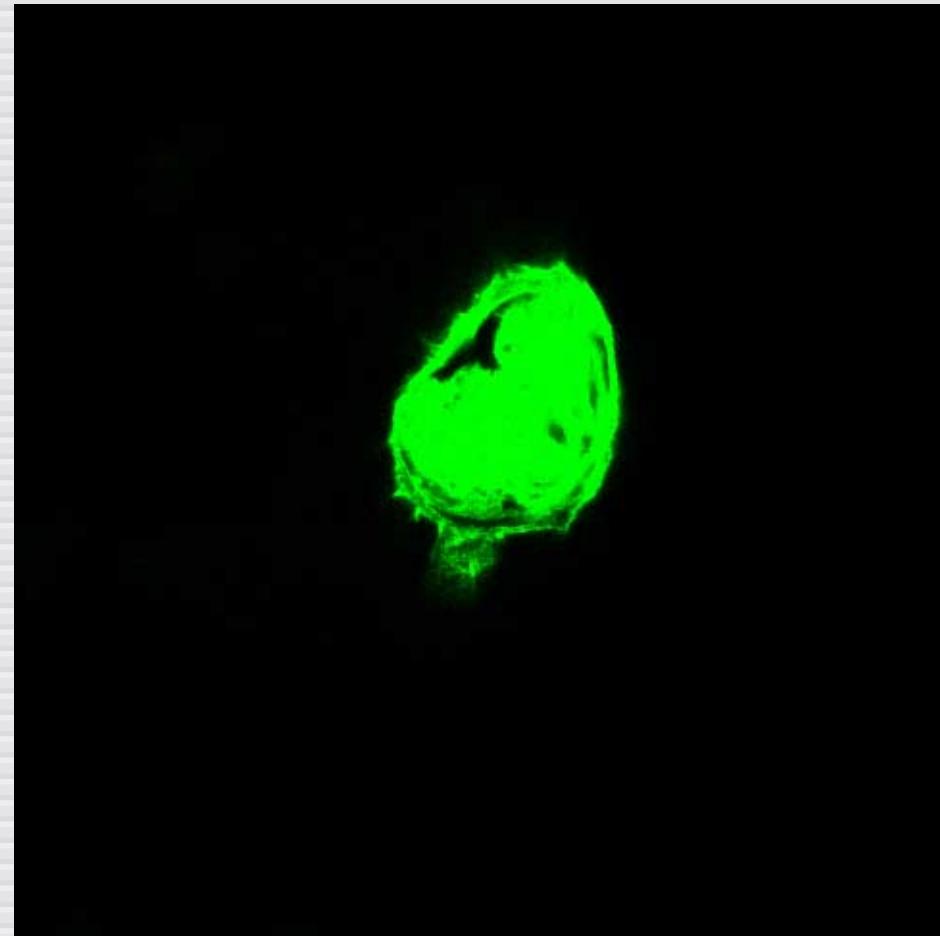


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**before**

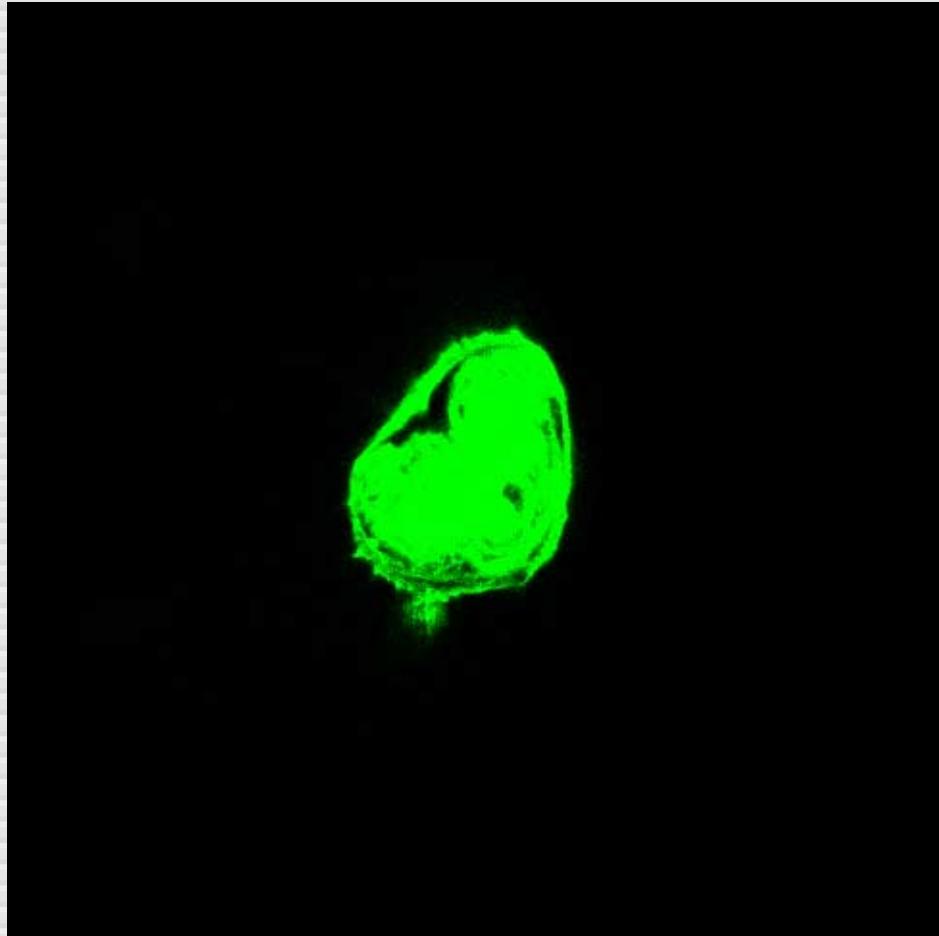


**after**

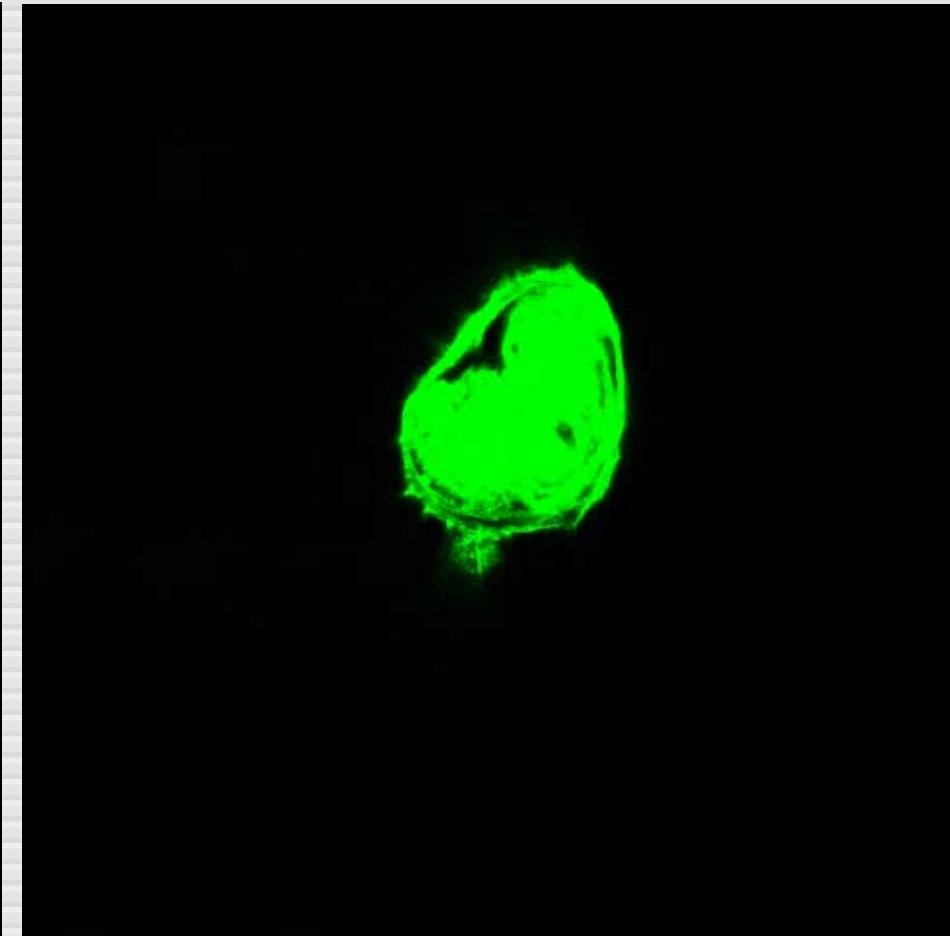


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**before**

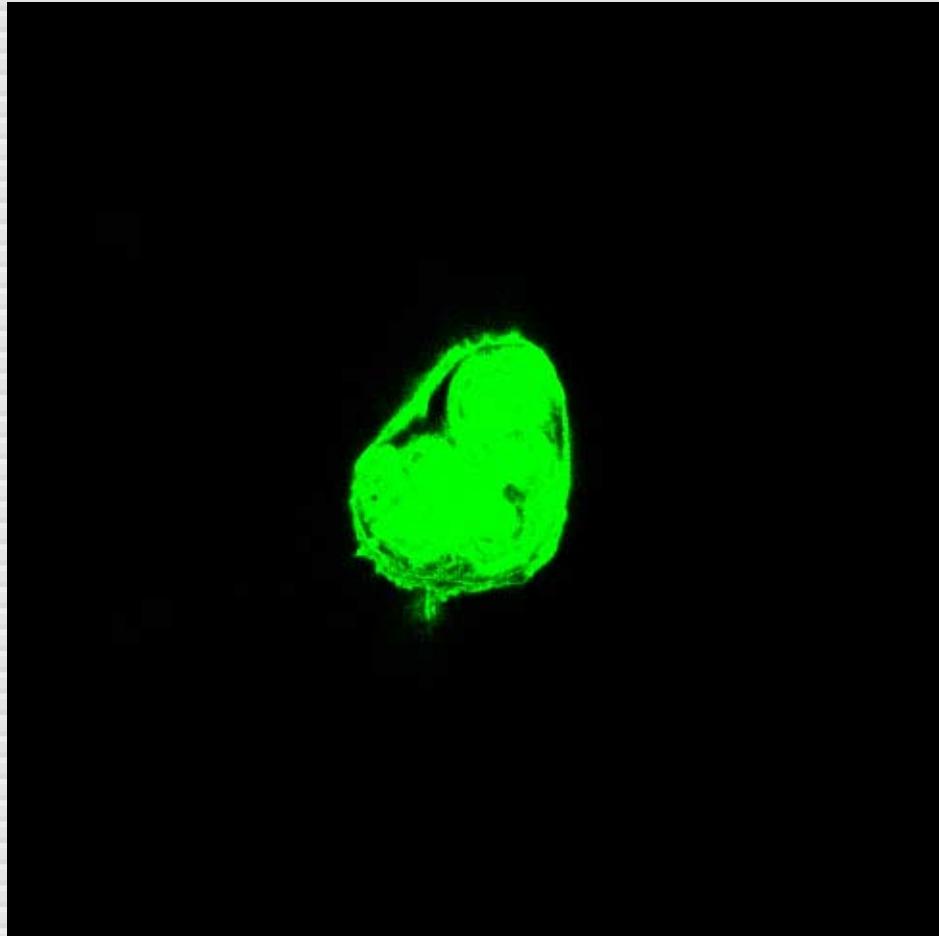


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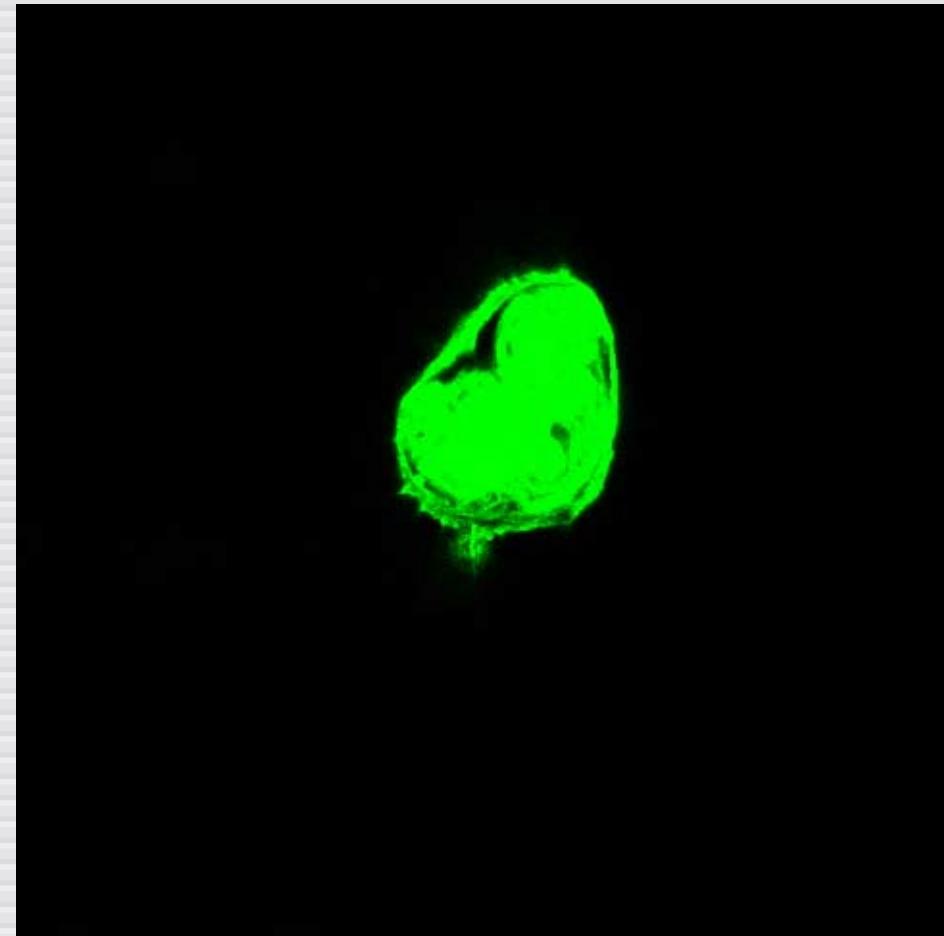


# *Biology and medicine*

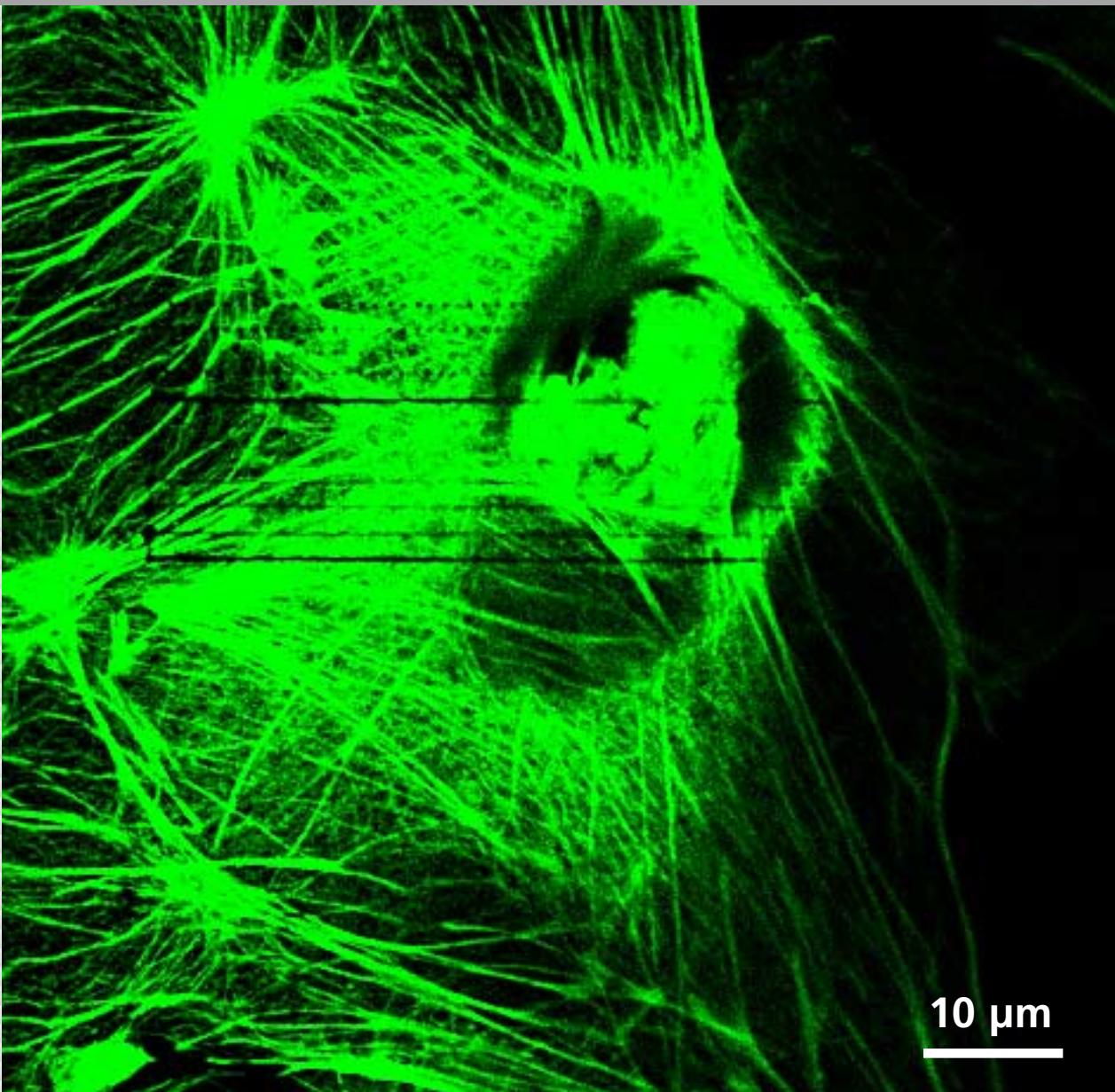
**before**



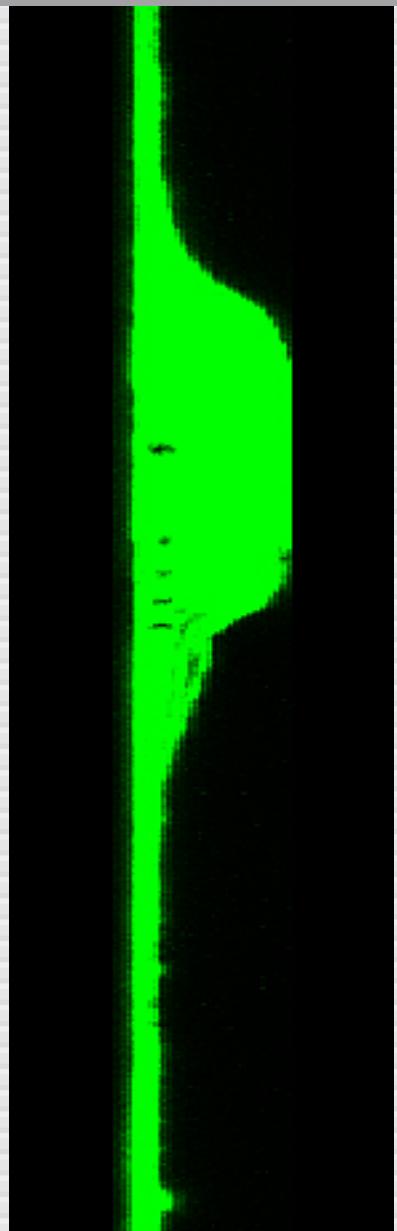
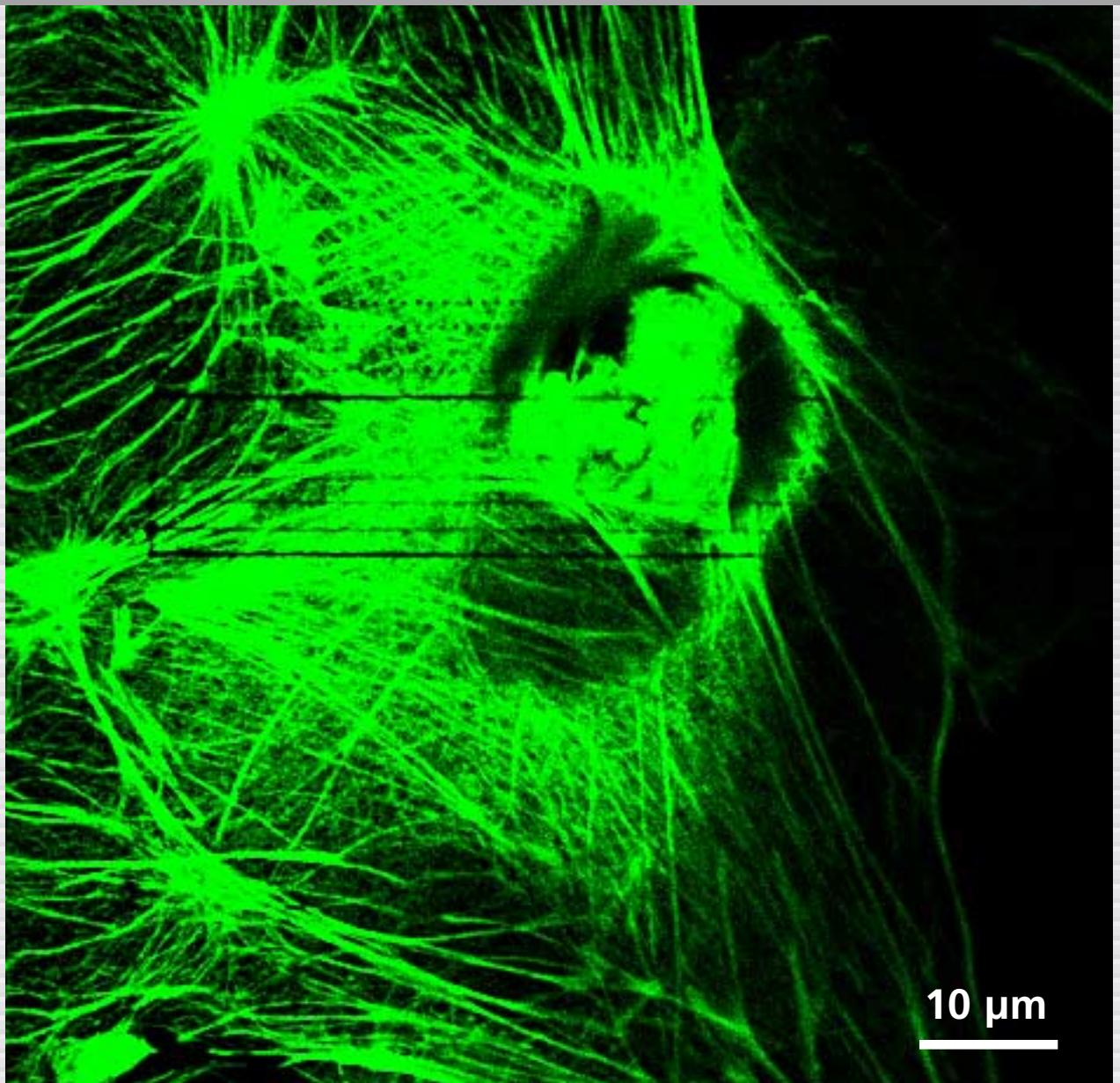
**after**



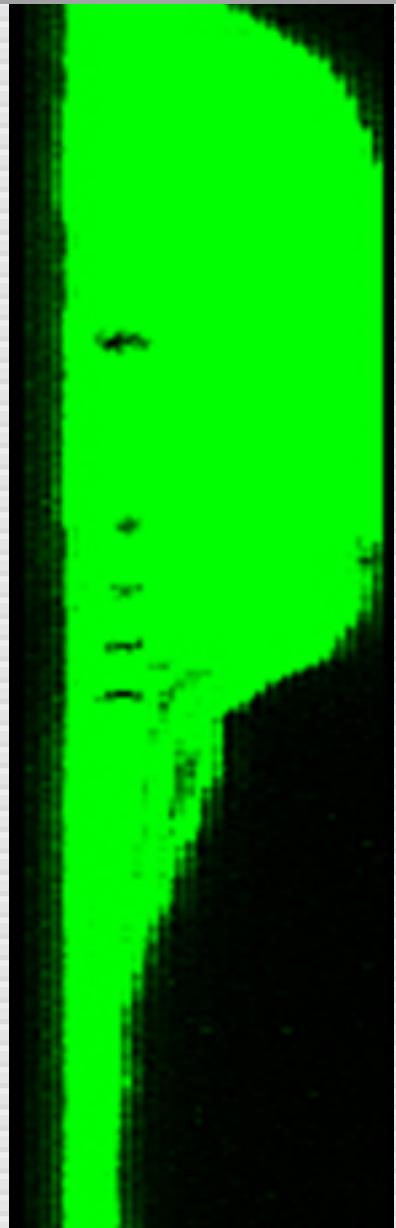
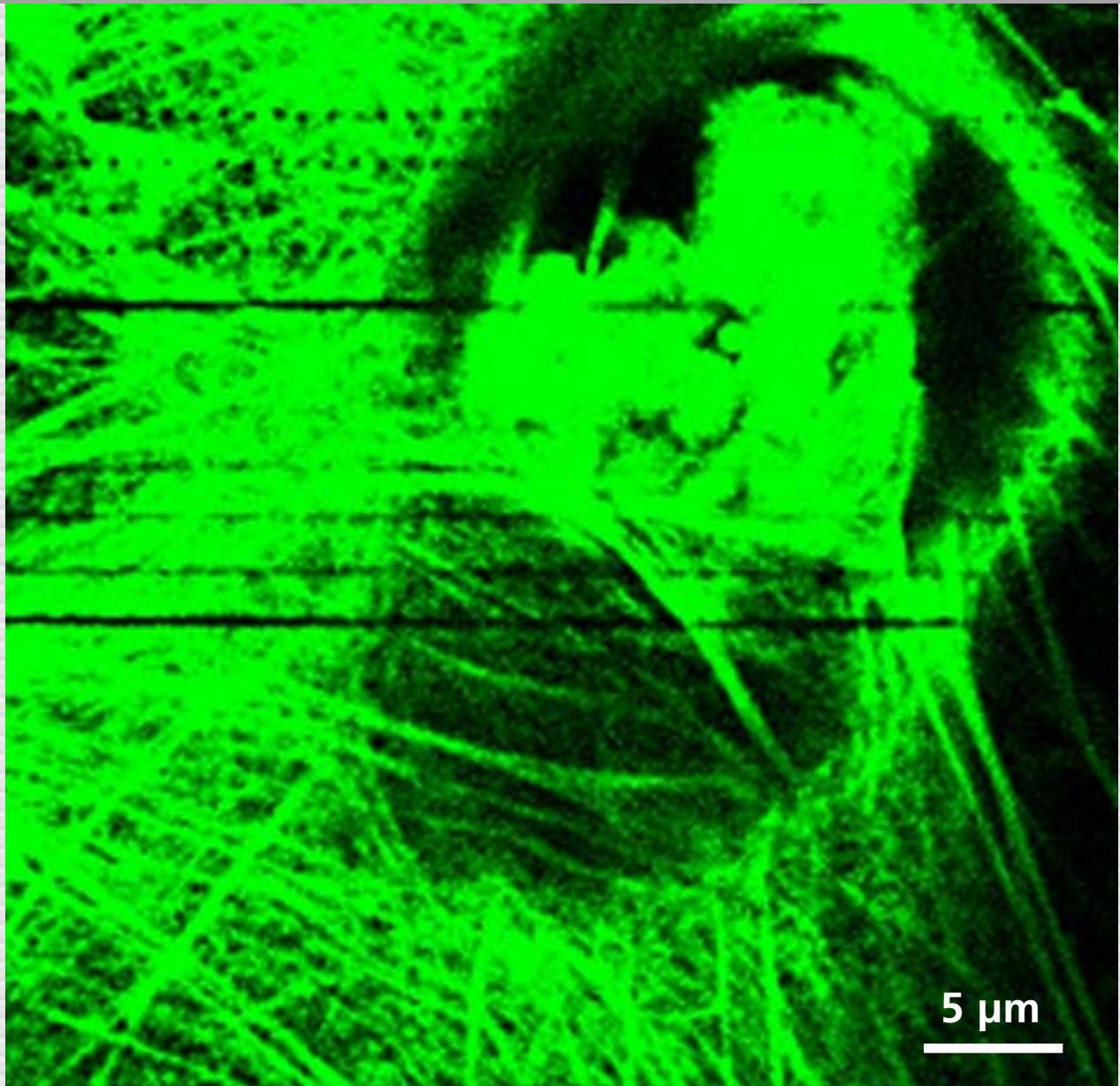
# *Biology and medicine*



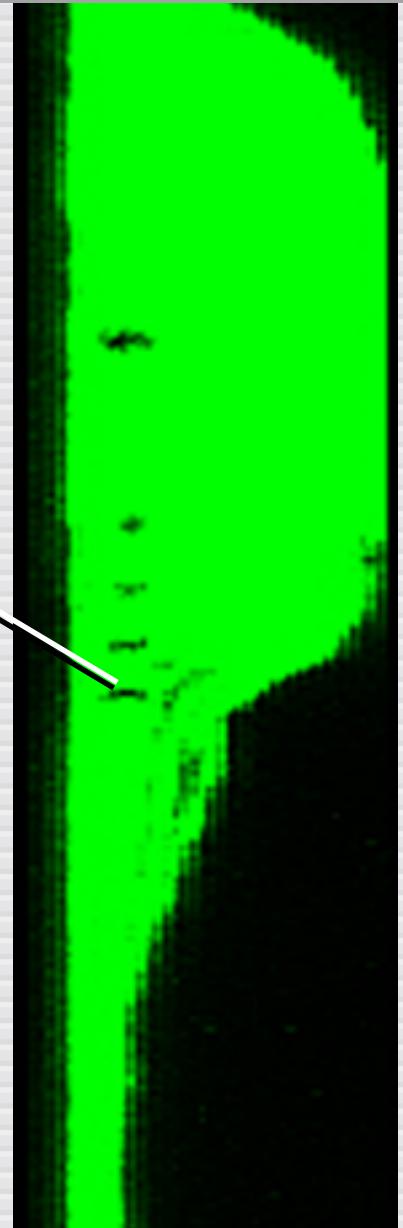
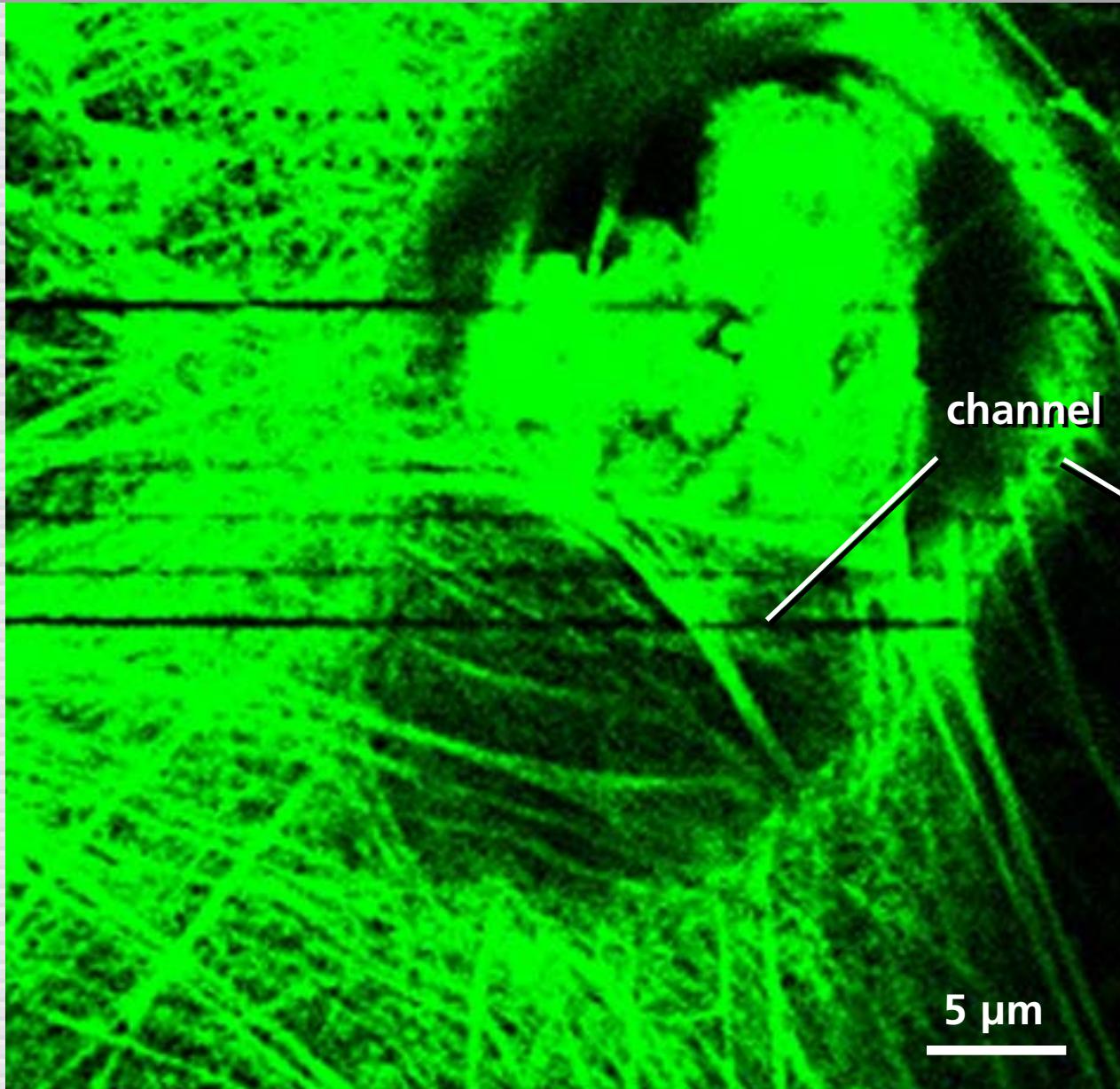
# *Biology and medicine*



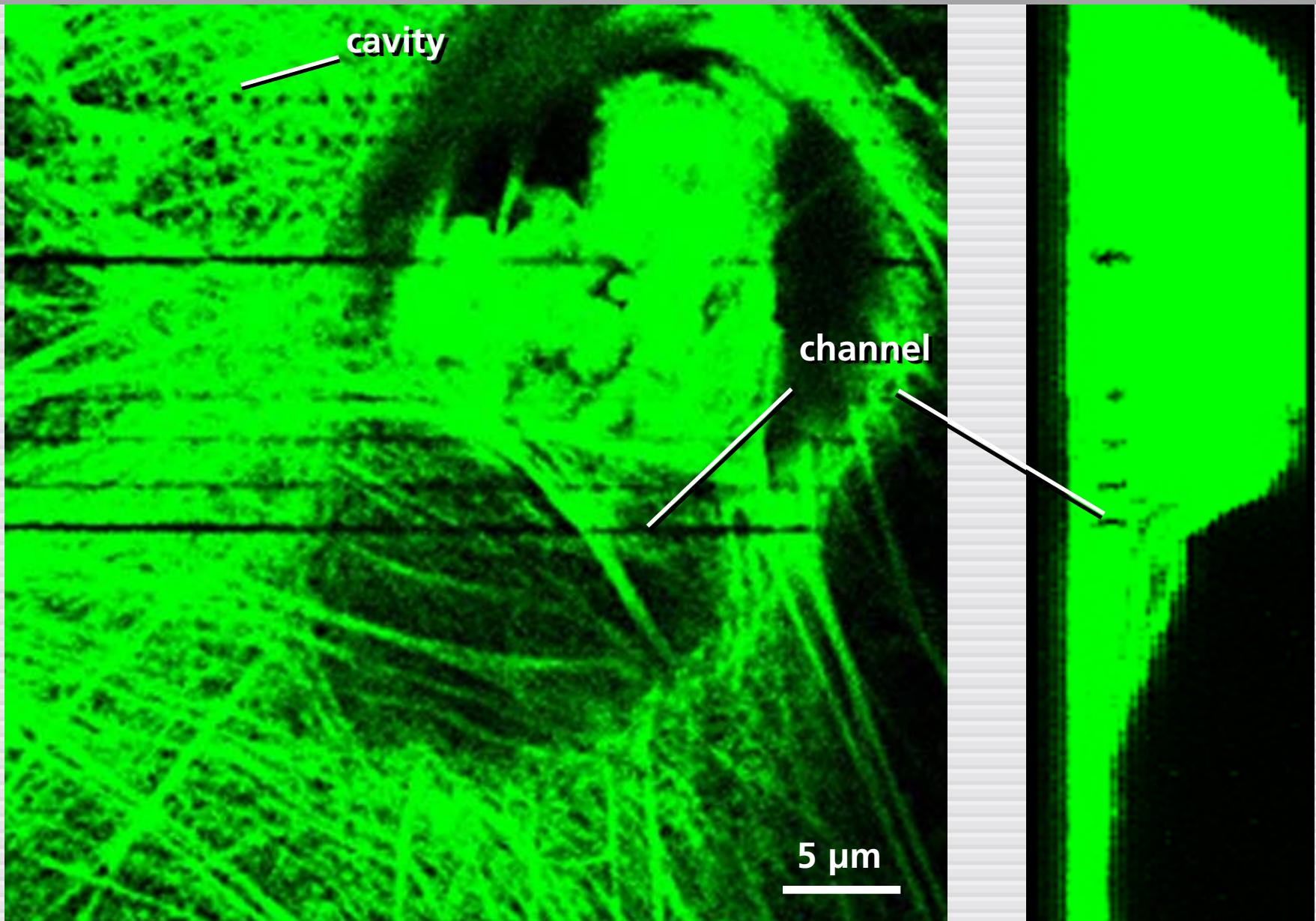
# *Biology and medicine*



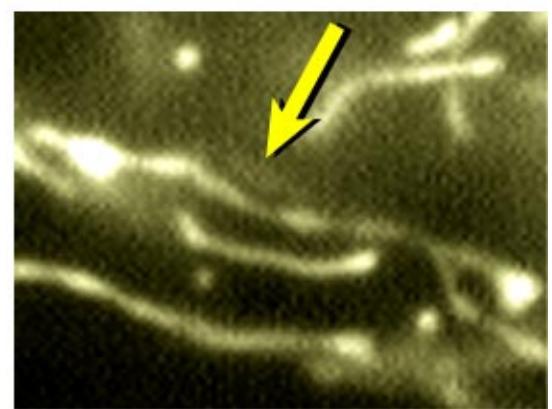
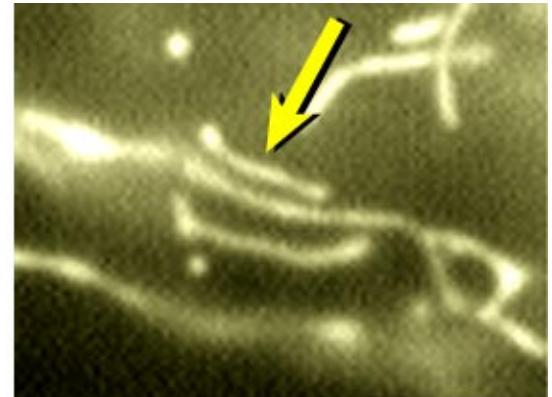
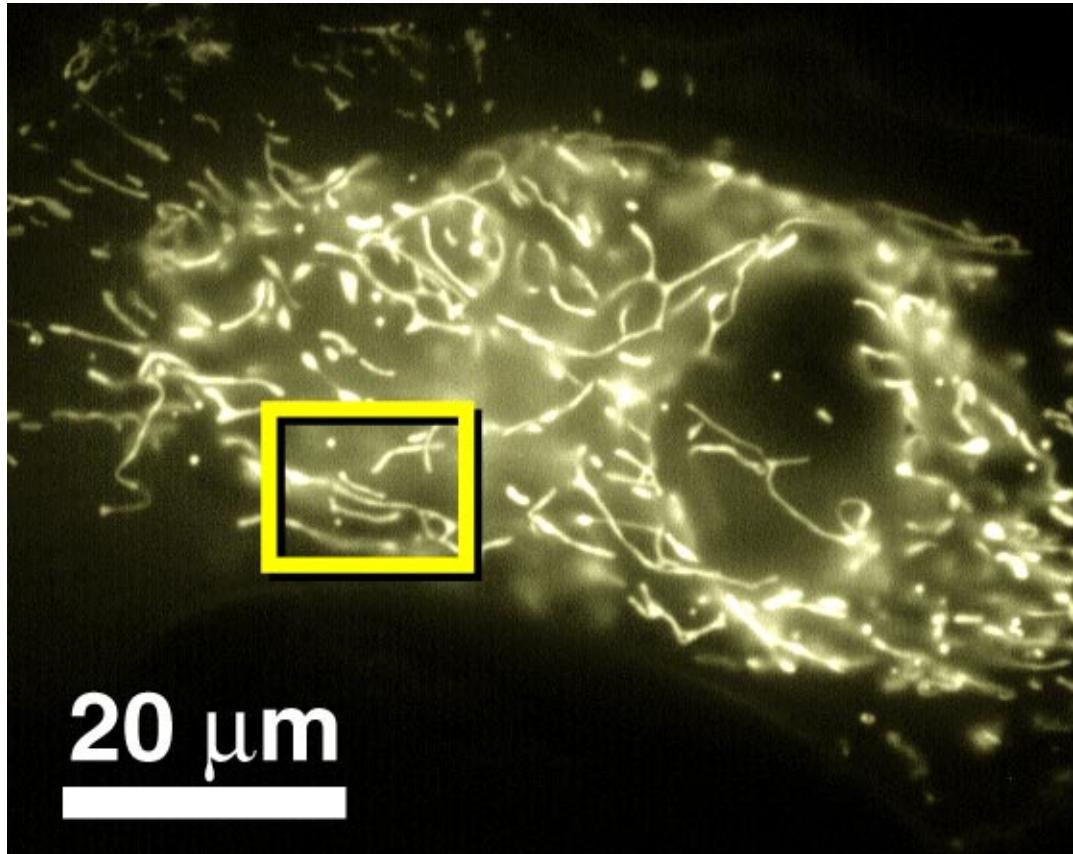
# Biology and medicine



# Biology and medicine

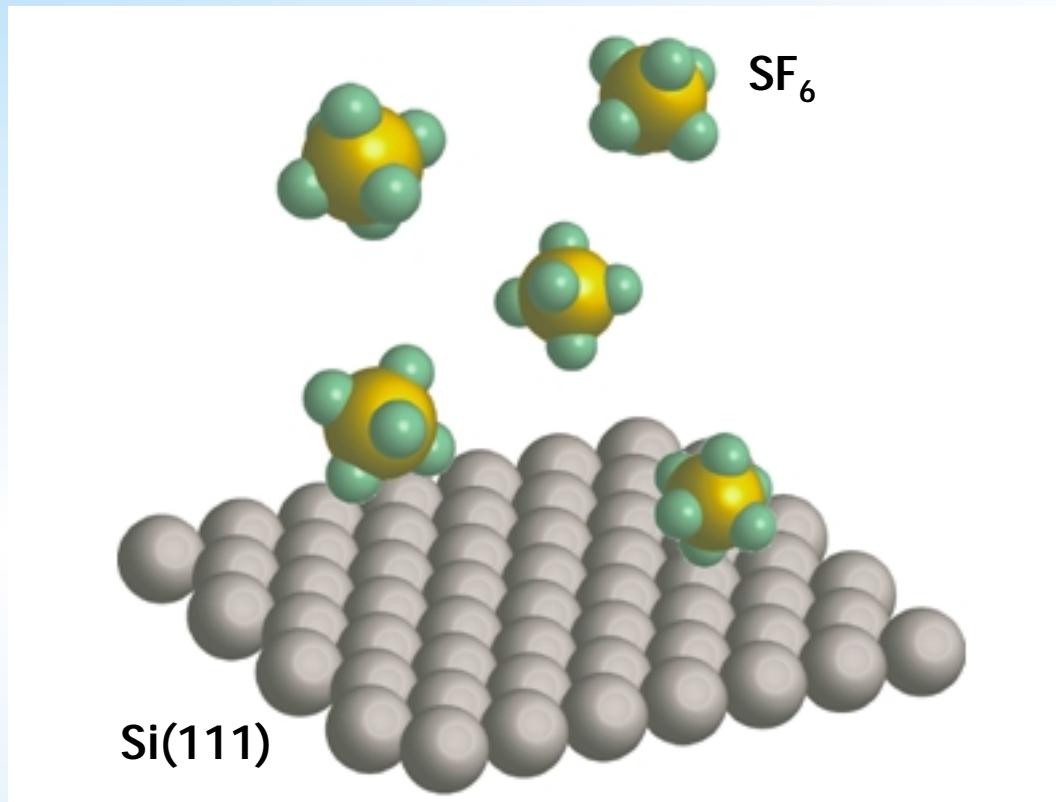


## *Low-energy processing*



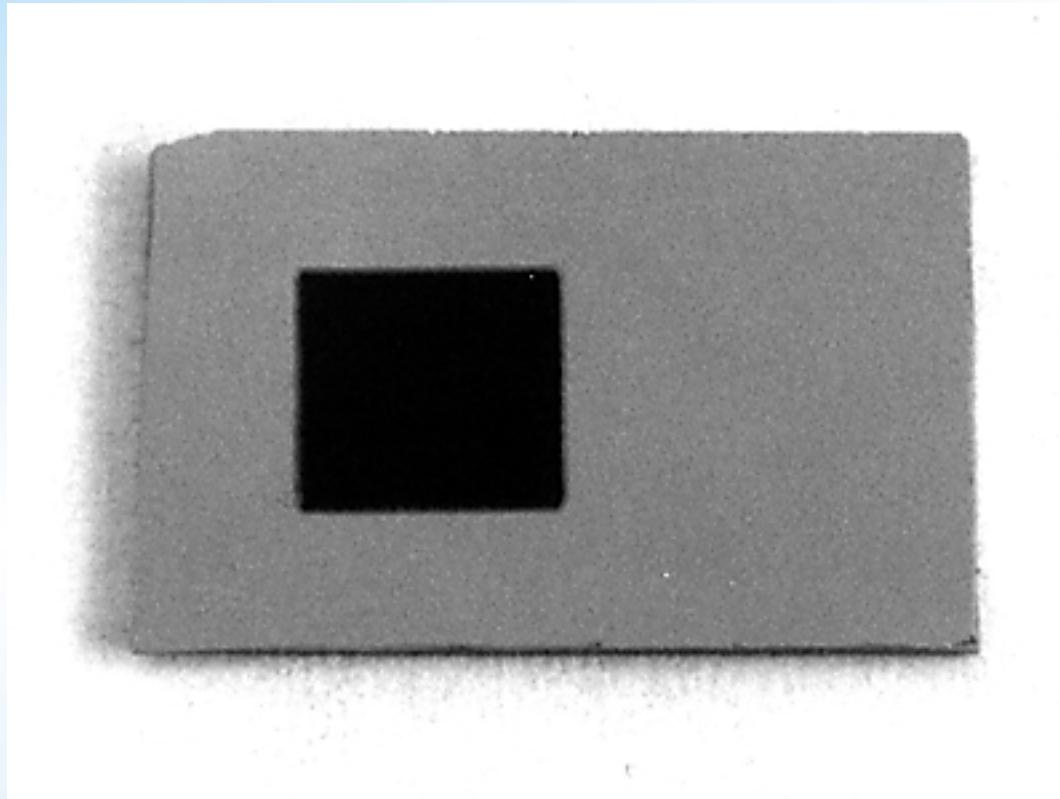


# *Microstructuring*



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

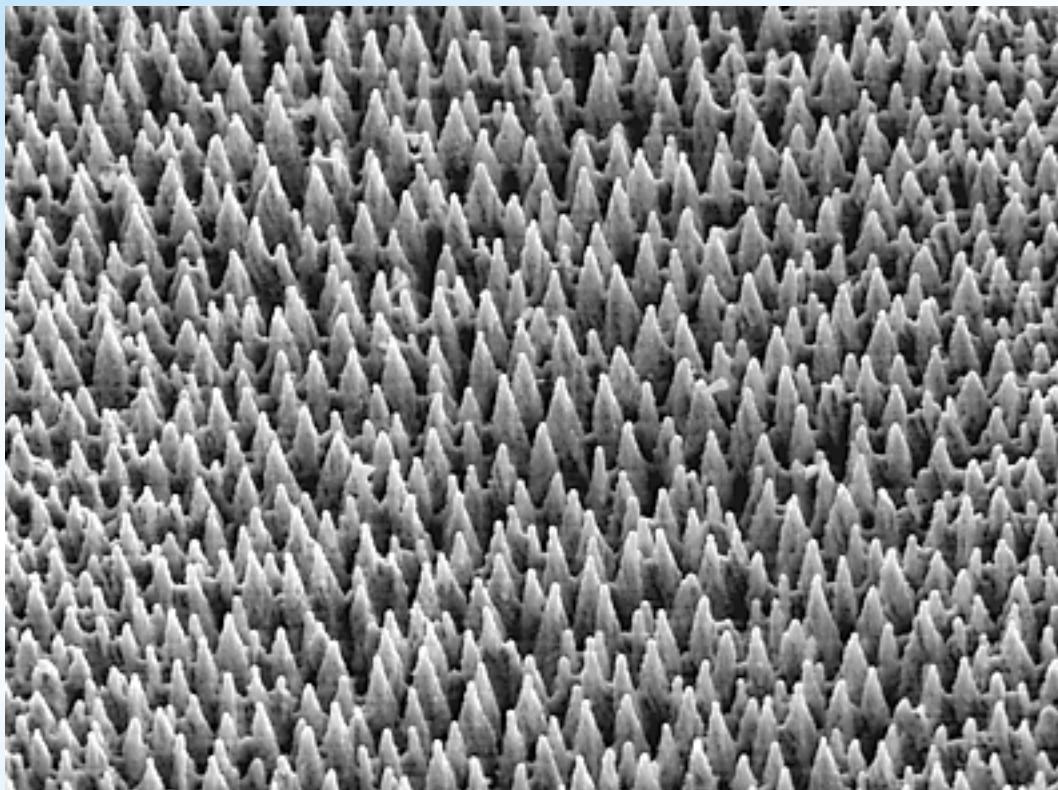
# *Microstructuring*



—

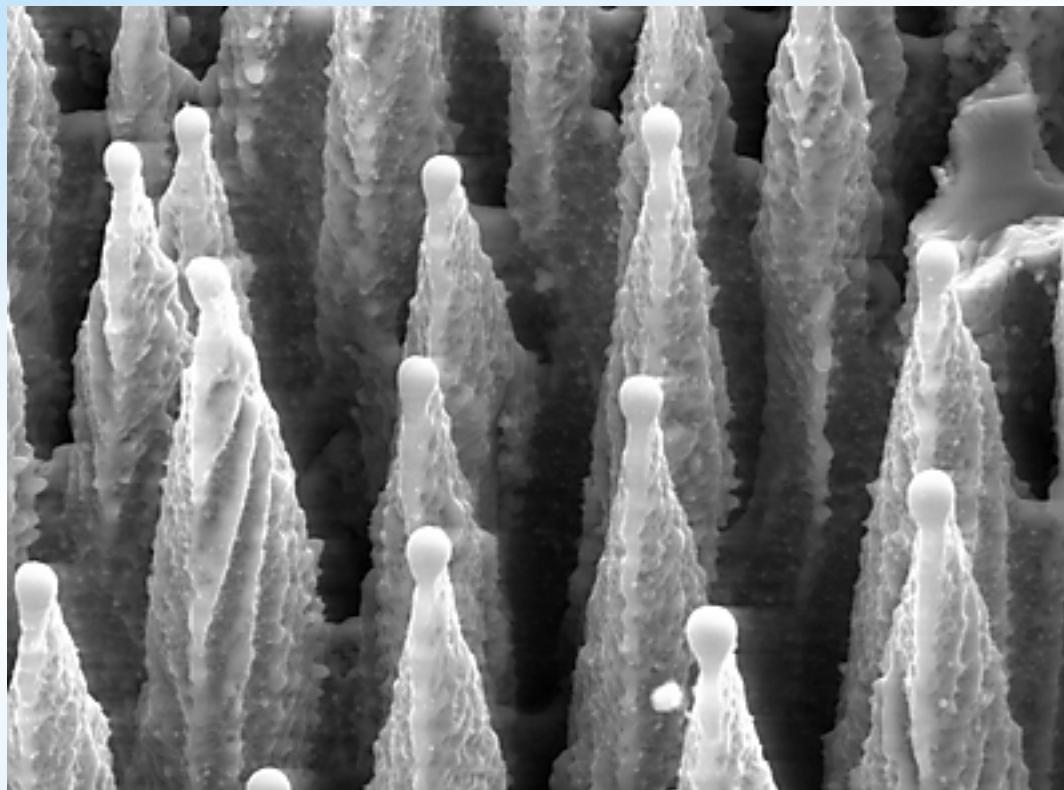
5 mm

# *Microstructuring*



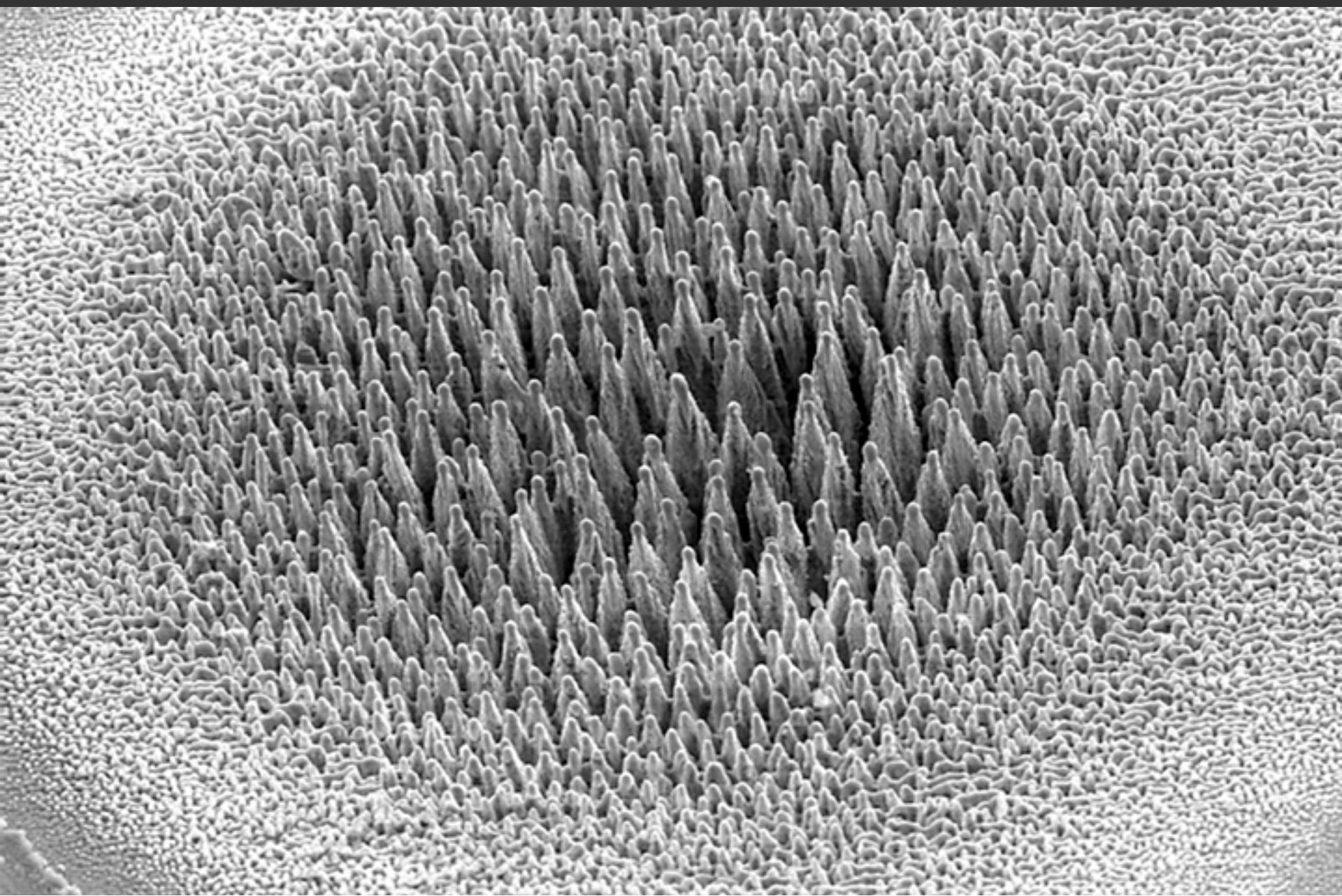
20  $\mu\text{m}$

# *Microstructuring*



4  $\mu\text{m}$

# *Microstructuring*



## *Summary*

- ▶ diversified use of femtosecond lasers

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For additional information, see:

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