Institute of Applied Physics
Friedrich-Schiller-Universität Jena

# Metrology and Sensing

Lecture 13-2: Confocal sensors

2020-02-09

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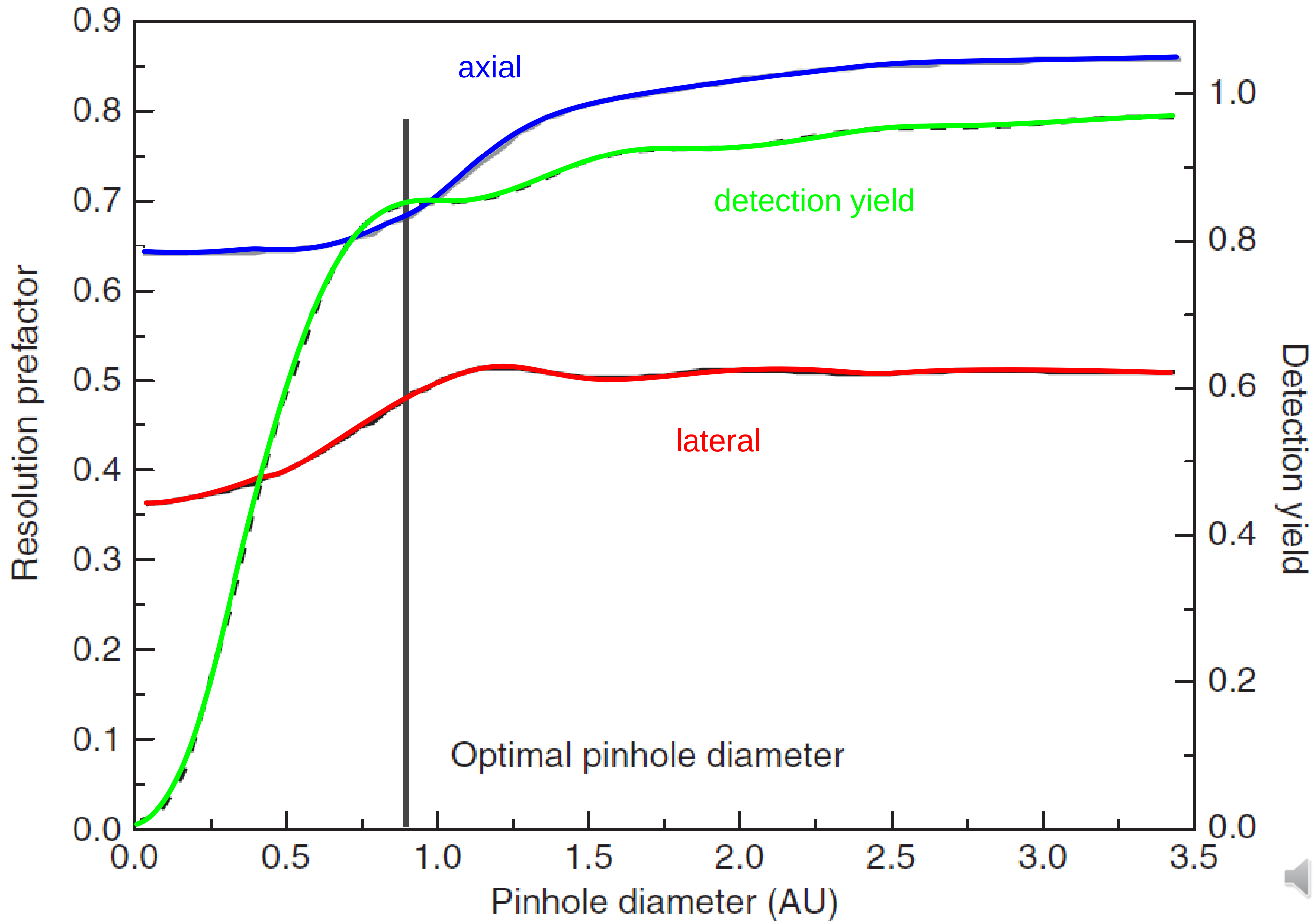
# Content

- Resolution
- Pinhole size
- Impact of aberrations
- Chromatical confocal method

# Lateral and Axial Resolution



- Tradeoff between:
  1. lateral resolution
  2. axial resolution
  3. signal to noise ratio (detection yield)




Ref: U. Kubitschek

# Confocal Microscopy: PSF and Lateral Resolution

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- Normalized transverse coordinate v

$$v = \frac{2\pi}{\lambda} \cdot x' \cdot \sin\alpha$$

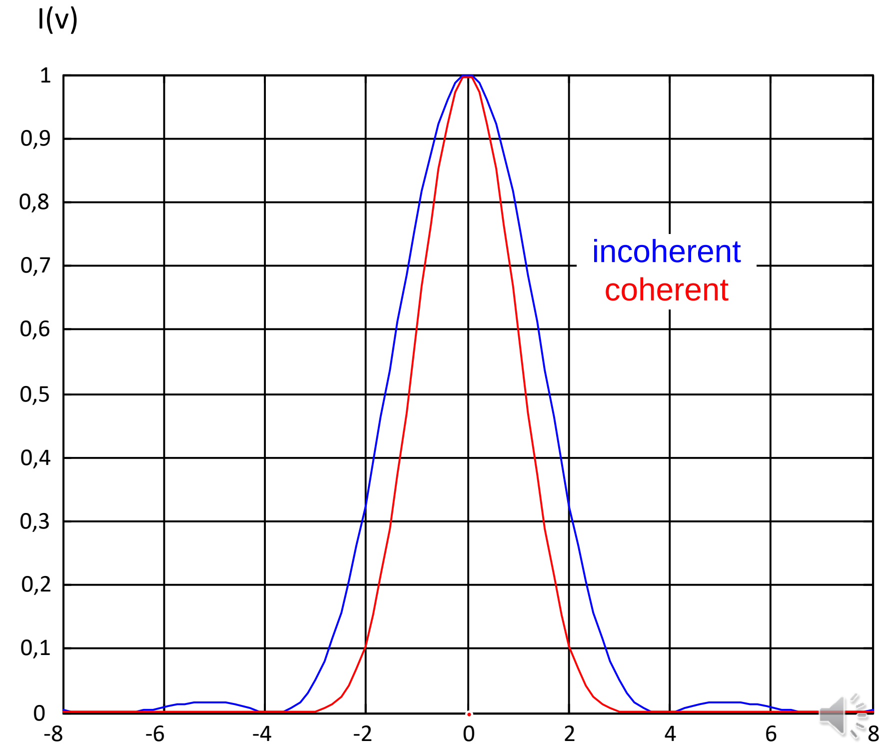
- Usual PSF: Airy

$$I(v) = \left[ \frac{2J_1(v)}{v} \right]^2$$

- Confocal imaging:
  Identical PSF for illumination and observation assumed

$$I(v) = \left[ \frac{2J_1(v)}{v} \right]^4$$

Resolution improvement be factor 1.4 for FWhM



# Confocal Microscopy: Axial Sectioning

- Normalized axial coordinate

$$u = \frac{8\pi}{\lambda} \cdot z \cdot \sin^2(\alpha/2)$$

- Conventional wide field imaging:
  Intensity on axis

$$I(u) = \left[\frac{\sin(u/2)}{u/2}\right]^2$$

  Axial resolution

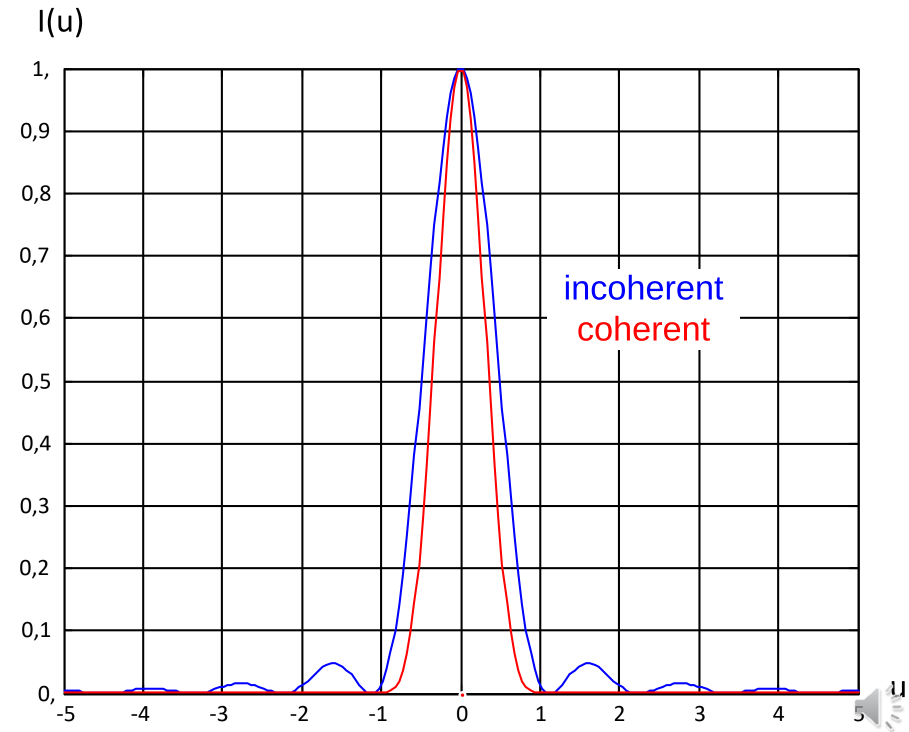
$$\Delta z_{wide}^{(approx)} = \frac{0.45 \cdot \lambda}{n' \cdot (1 - \cos\theta)}$$

- Confocal imaging:
  Intensity on axis

$$I(u) = \left[\frac{\sin(u/2)}{u/2}\right]^4$$

  Axial resolution improved by factor 1.41 for FWhM

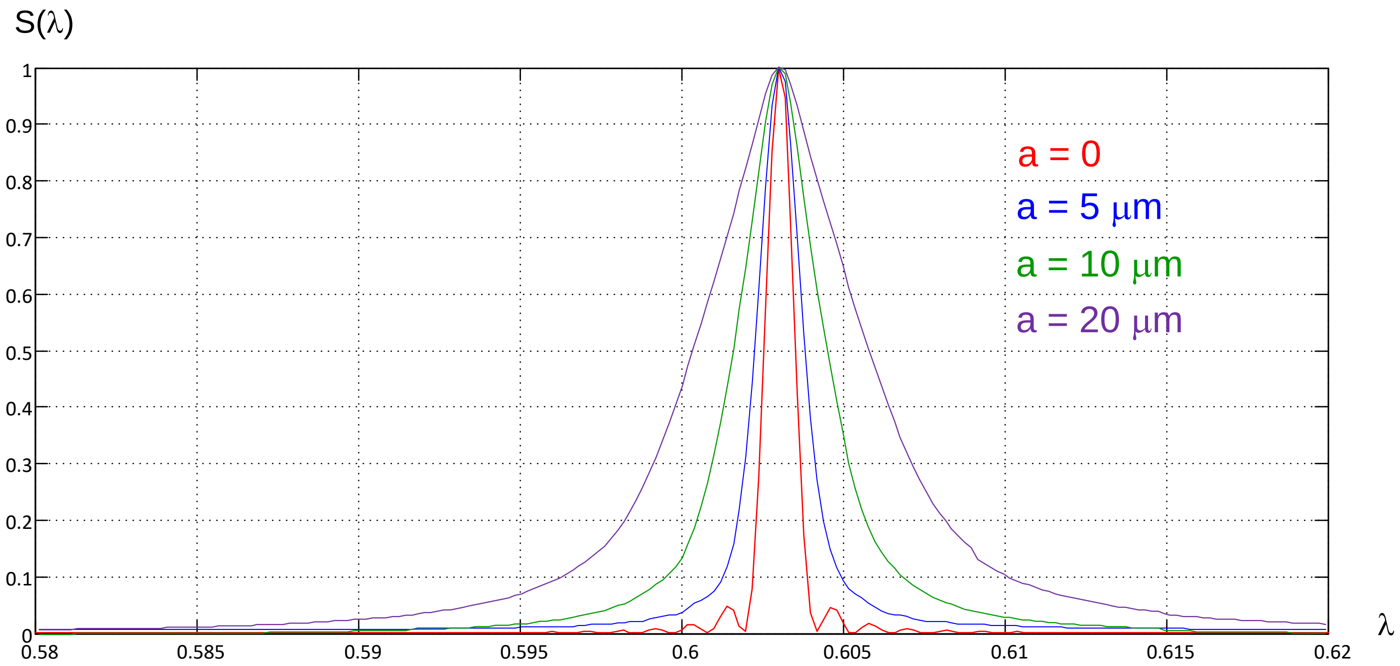
$$\Delta z_{confo} = \frac{0.319 \cdot \lambda}{n' \cdot (1 - \cos\theta)}$$



# Confocal Signal for Different Pinhole Sizes



- Numerical result for different sizes a of the fiber radius
- The width increases with the fiber diameter
- The diffraction fine structure disappears with growing a



# Size of Pinhole and Confocality

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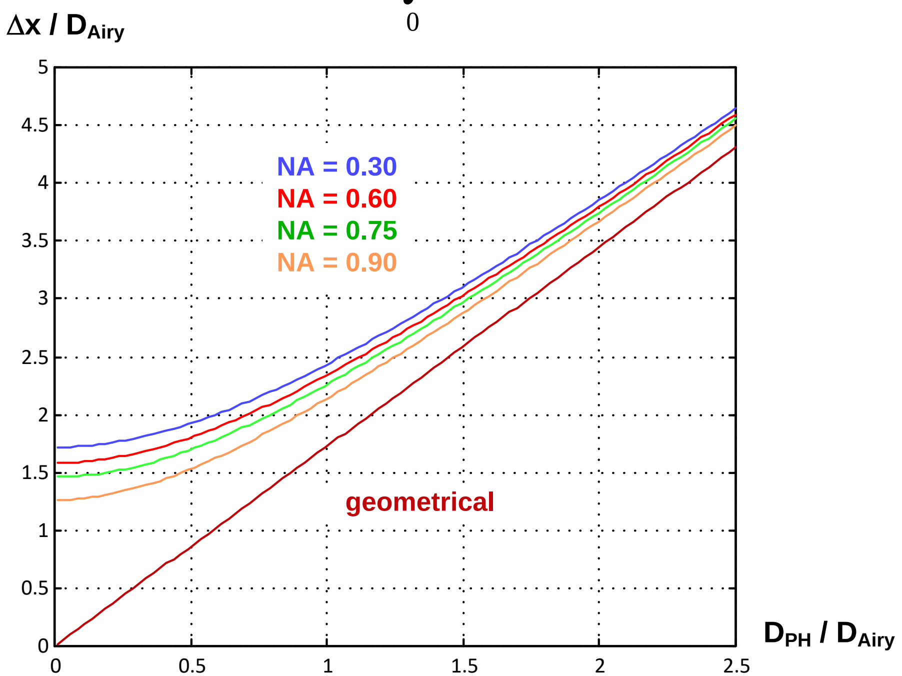
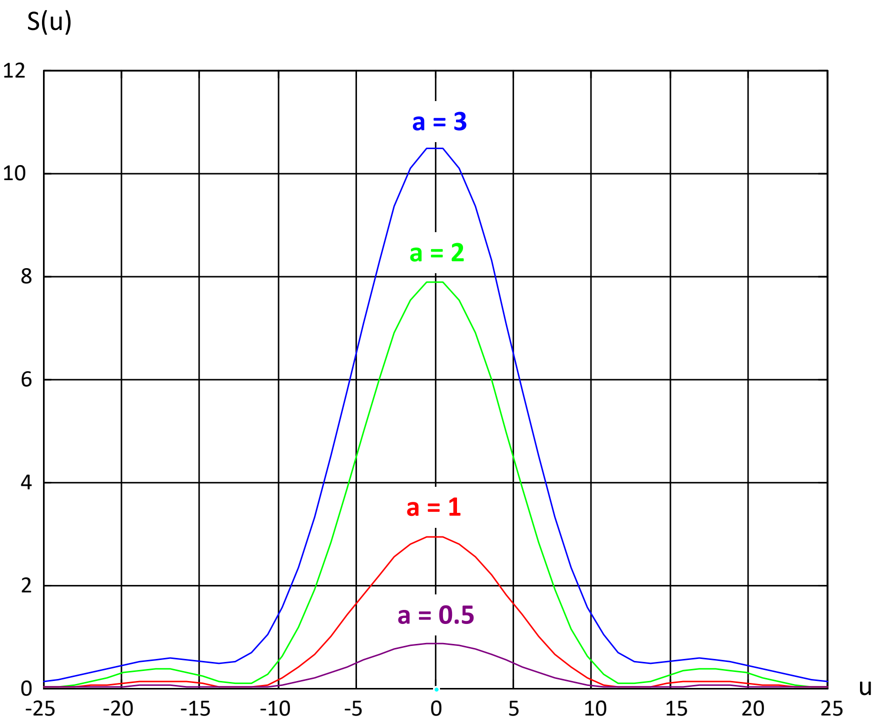
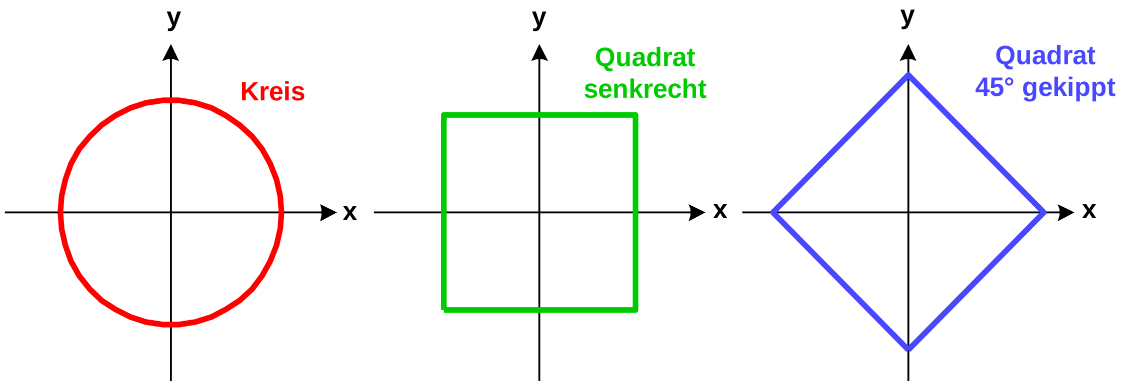
- Large pinhole: geometrical optic
- Small pinhole:
  - Diffraction dominates
  - Scaling by Airy diameter $a = D/D_{Airy}$
  - diffraction relevant for pinholes $D < D_{airy}$
- Confocal signal:
  Integral over pinhole size

$$S(u) = \int_0^a \left|U(u,v)\right|^2 2\pi v\,dv$$

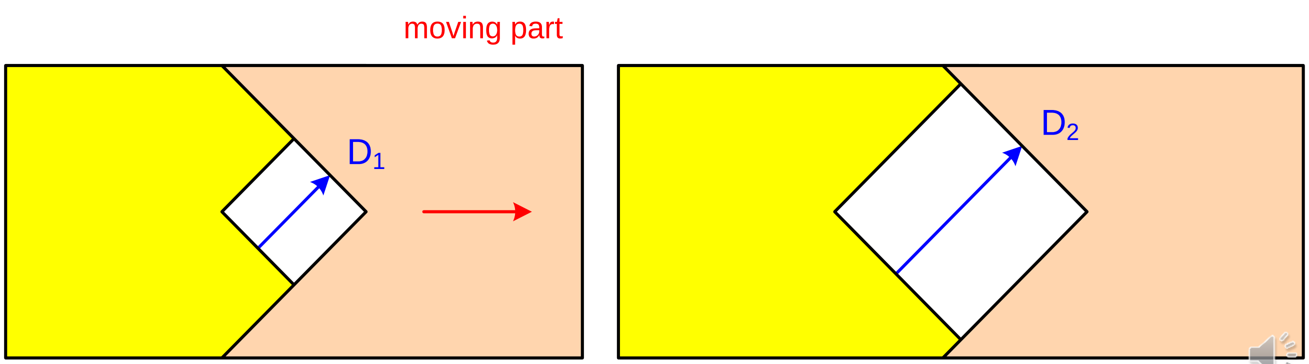


# Variable Pinhole Diaphragm



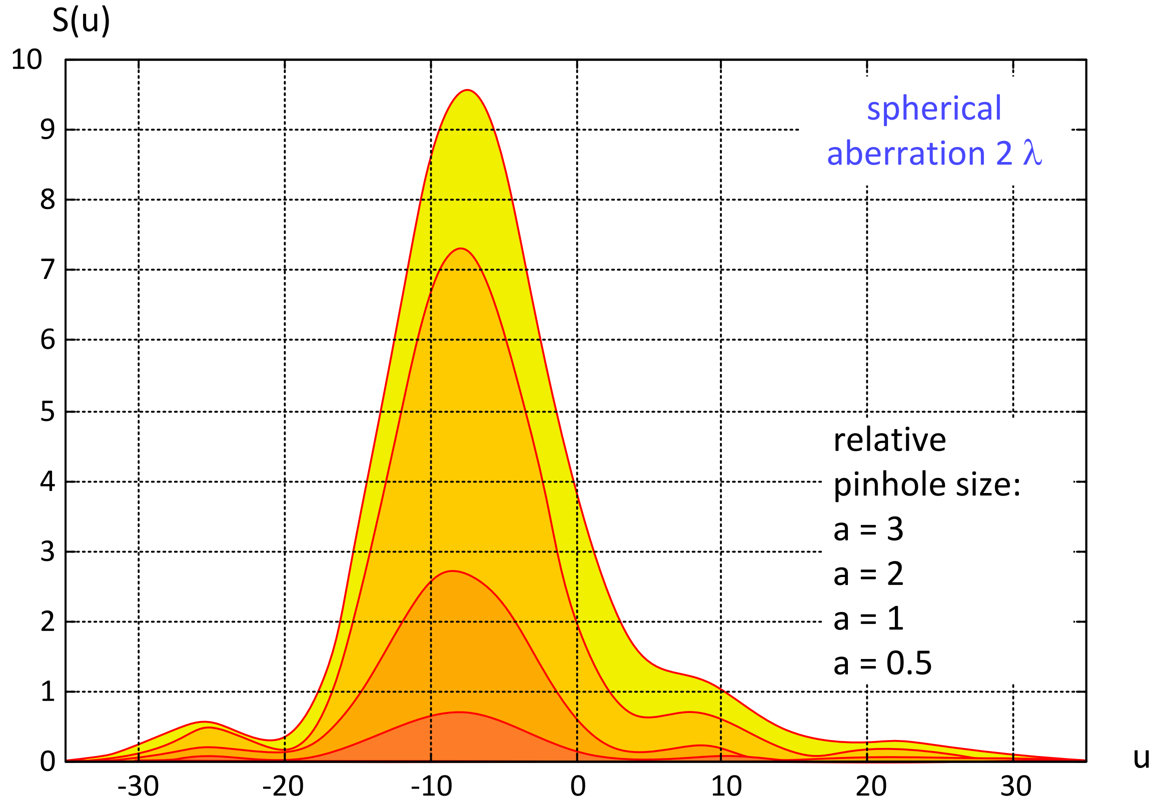

- Real shape of pinhole:
  quadratic or circular
  signal depends on shape
- Variable pinhole easy to realy
  quadratic
- Typical size:
  $D_{pinhole} = 0.5...2\ D_{airy}$
- Easy to fabricate: approx. 30 mm
  very small numerical aperture in pinhole objective lens helps



# Confocal Signal with Spherical Aberration

- Spherical aberration:
  - PSF broadened
  - PSF no longer symmetrical around image plane during defocus

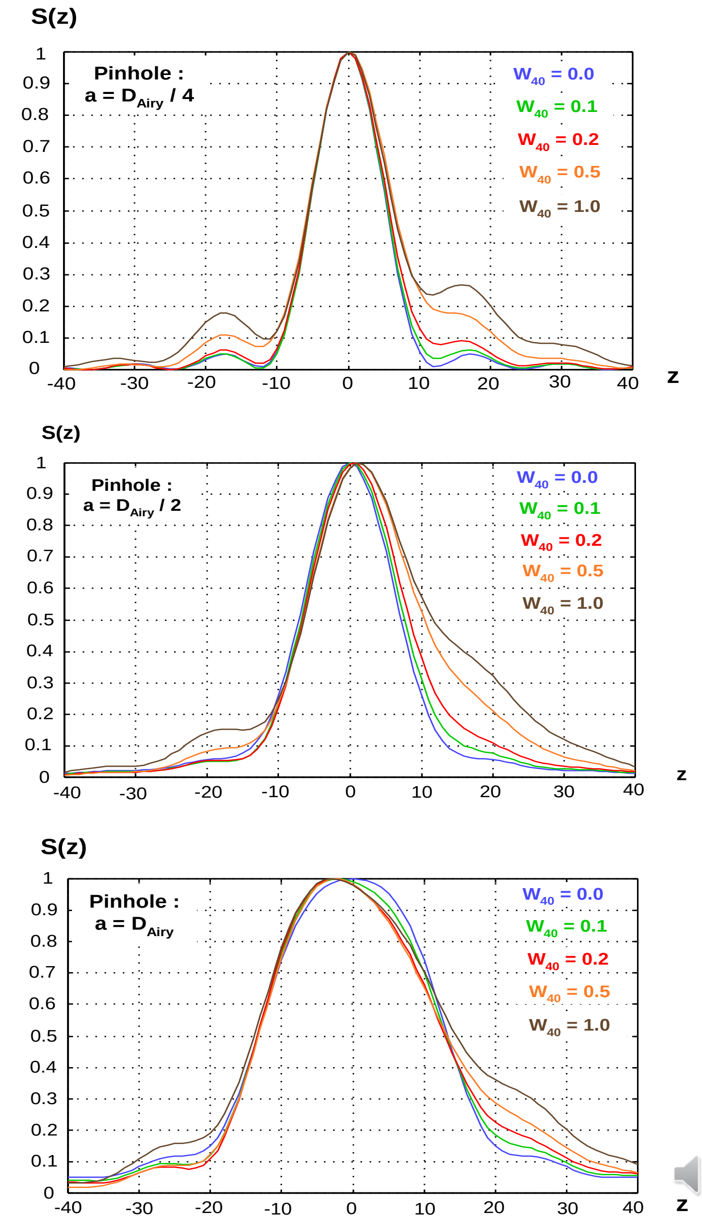
- Confocal signal:
  - loss in contrast
  - decreased resolution



# Confocal Signal with Spherical Aberration

- Spherical aberration with Zernike coefficient $W_{40}$
- Integration over finite size pinhole with radius a
- Asymmetry and width depends on a and $W_{40}$
- Large pinhole:
  - depth discrimination decreased
  - fine structure disappears

• Sphärische Aberration mit Koeffizient $W_{40}$



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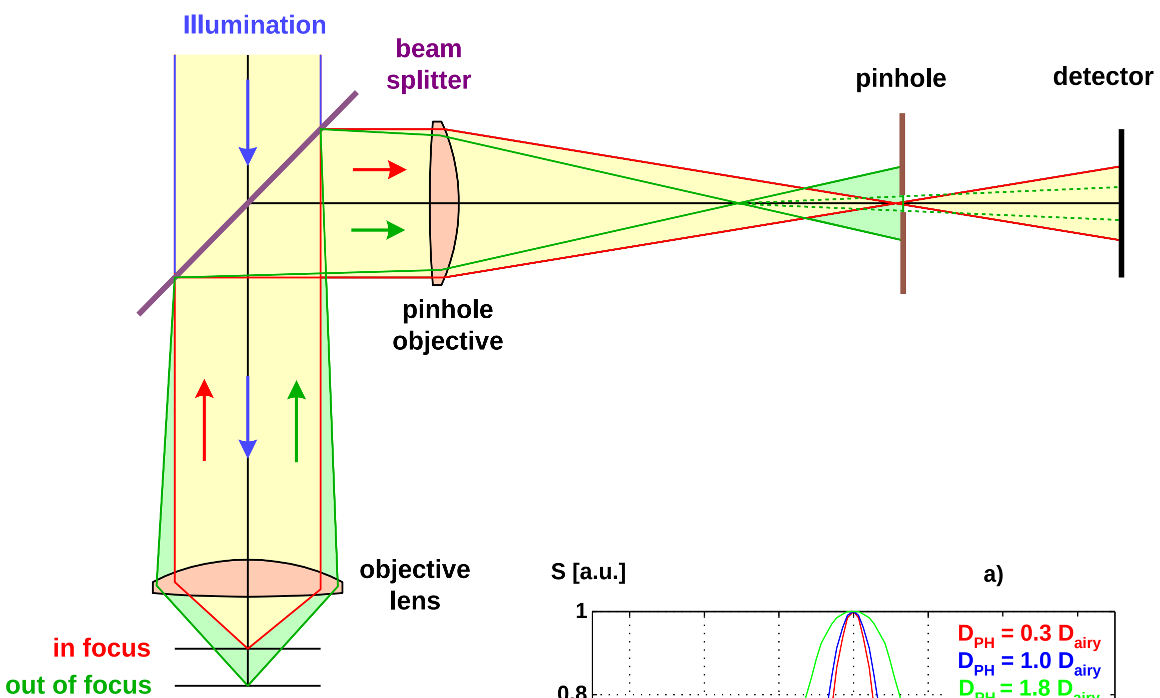
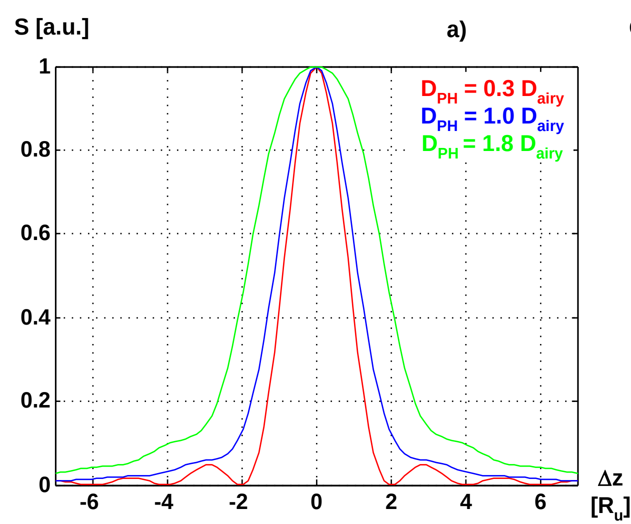
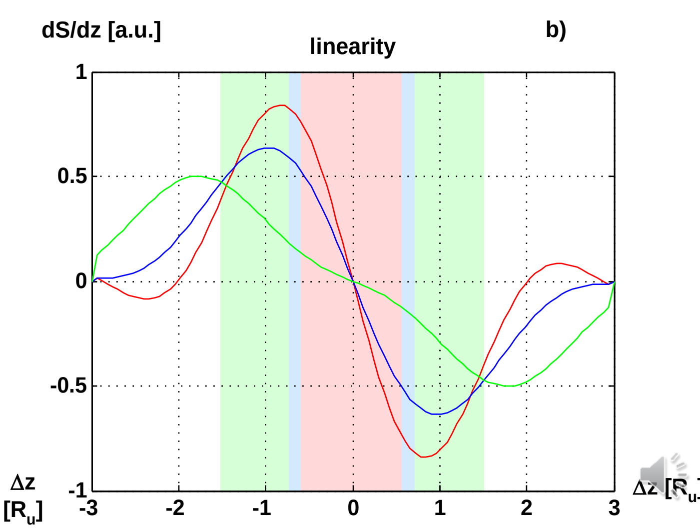
# Confocal Distance Sensor

- Principle of the confocal distance sensor



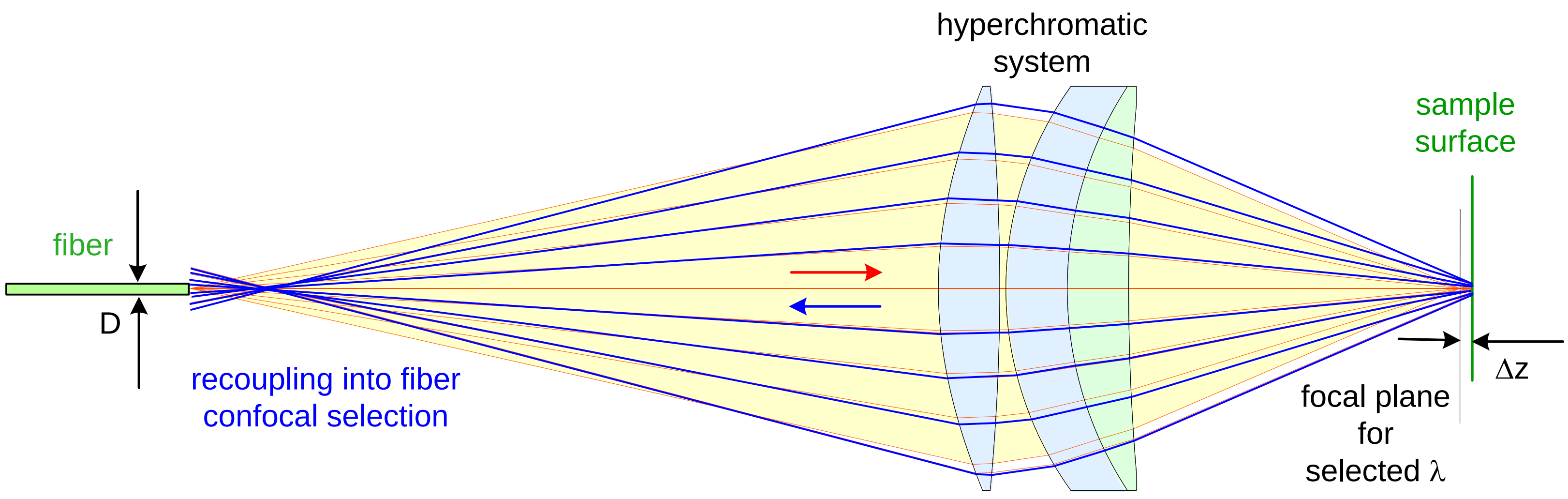
# Confocal Depth Measuring System

- Fourier optical model:
  - object/sample to be assumed as a plane mirror
  - fiber source incoherent, diameter $D_{fib}$, uniformly radiating
  - optical system with point spread function $h_{psf}$
  - confocal detection by fiber (pinhole) size $D_{fib}$
- Incoherent imaging model to get the intensity of at the fiber

$$I_{ima}(a,\Delta z) = I_{fib}(a) \otimes \left| h_{psf}(\Delta z) \right|^2$$

- Calculation of the confocal signal by integration over the pinhole

$$S_{conf}(a,\Delta z) = \iint_{r<a} I_{ima}(a,\Delta z)\, dx\, dy$$



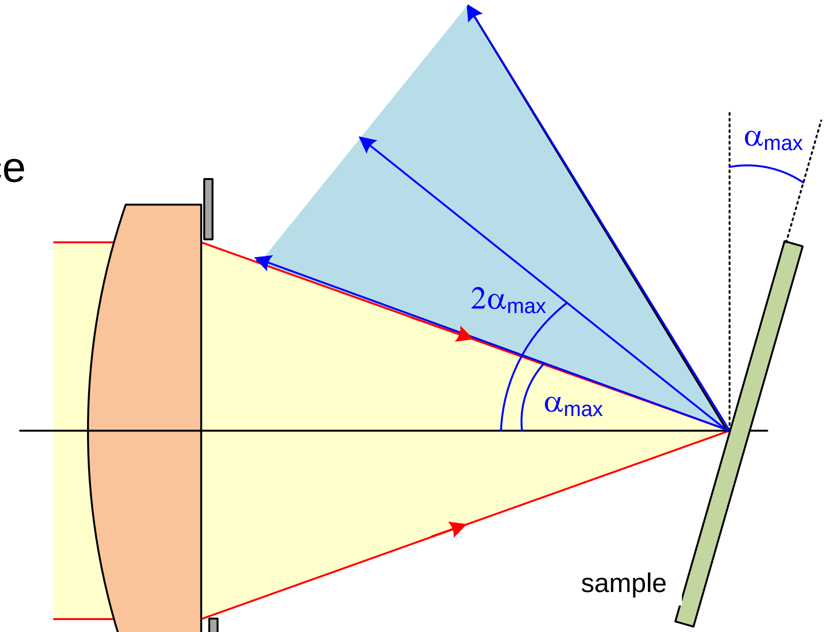
# Surface Smoothness



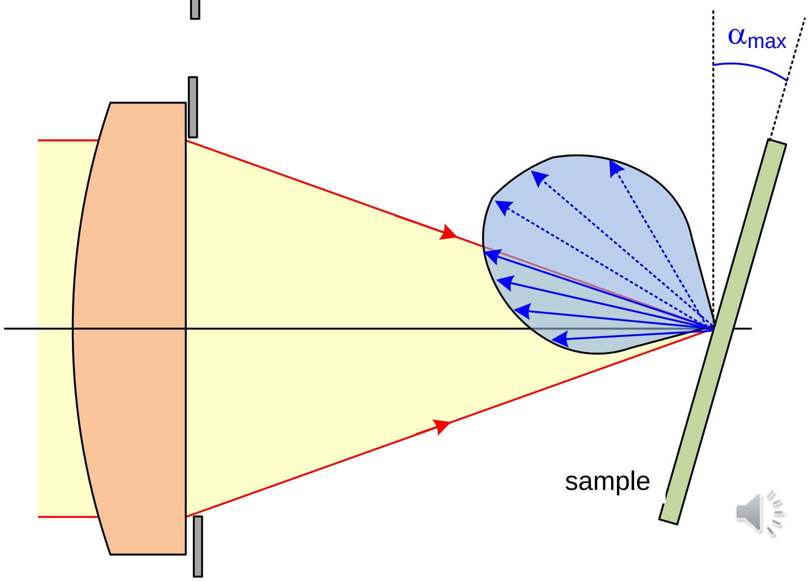
- Smooth / polished surface:
  - only reflected light is measured
  - maximum acceptable slope of the sampe surface

$$\alpha_{\max} = arc\sin(NA)$$

| NA | maximum angle $\alpha$ |
|---|---|
| 0.3 | 18° |
| 0.4 | 24° |
| 0.5 | 30° |
| 0.6 | 37° |
| 0.7 | 44° |



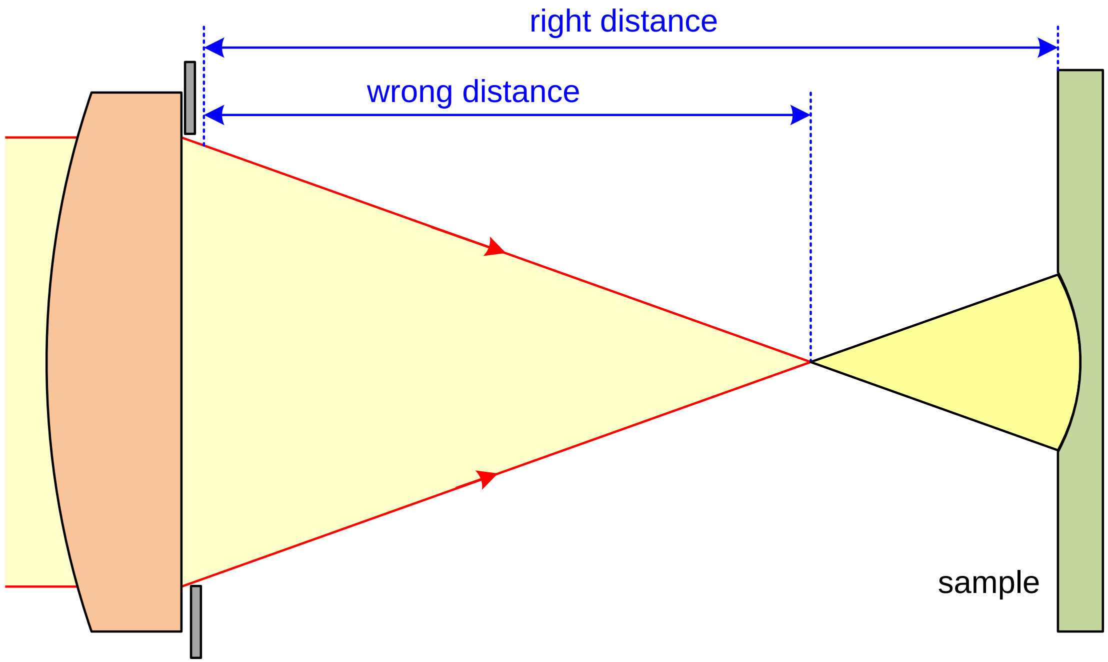

- Diffuse surface:
  - larger slopes can be measured
  - quantitatively the BRDF determines the limit



# Ghost Foci



- If parts of a polished sample are spherical in shape:
  - ghost foci with high intensity
  - wrong interpretation of the depth out of the signal



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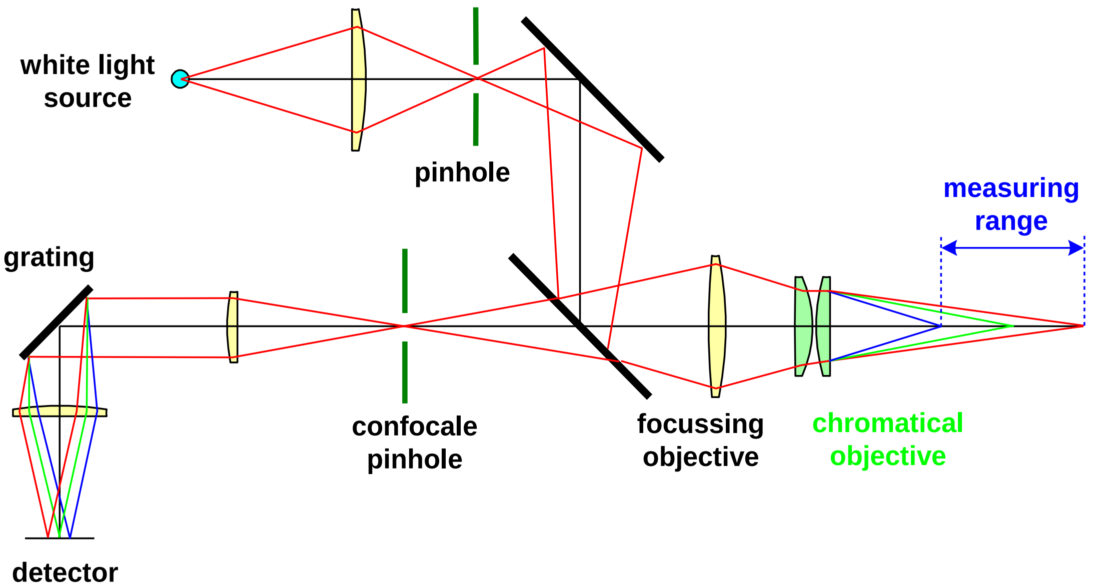
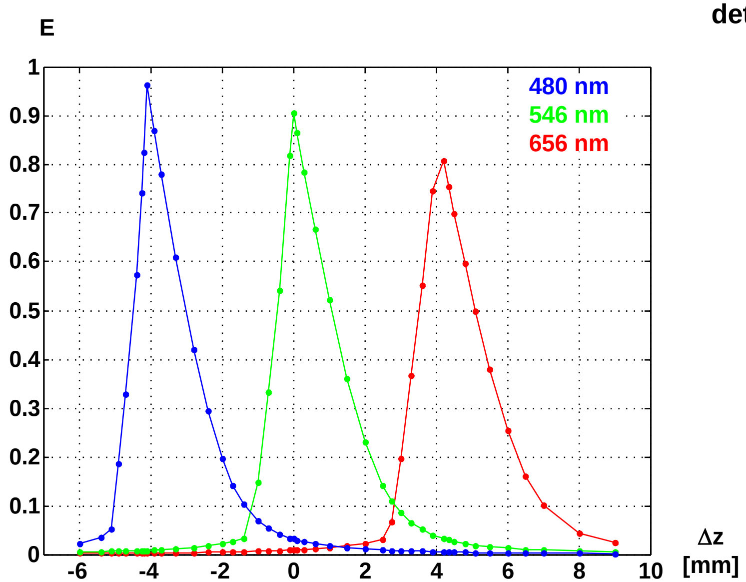
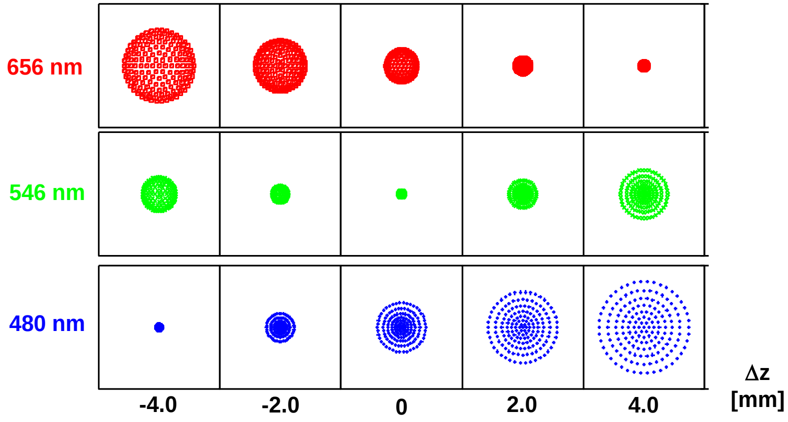
# Chromatical Confocal Sensor

- Spectral sensitive sensor
- Objective lens with large axial chromatical aberration



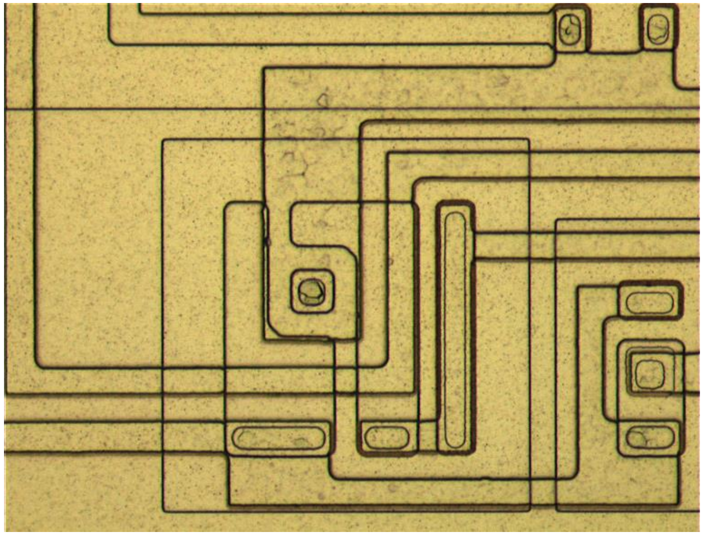



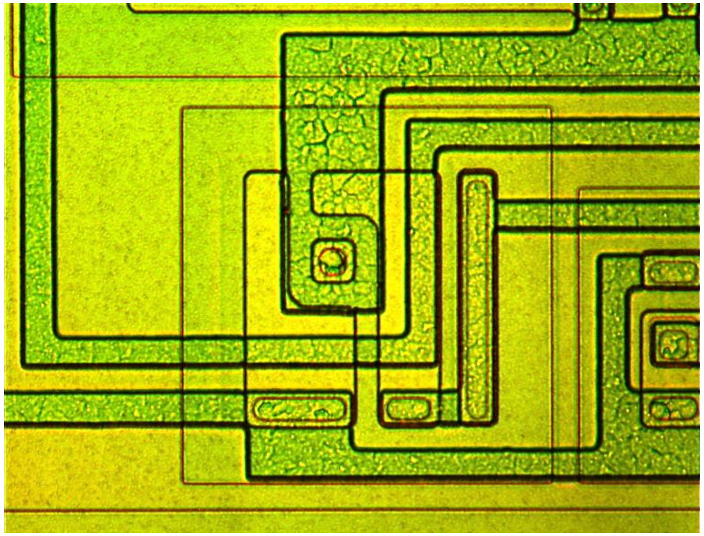



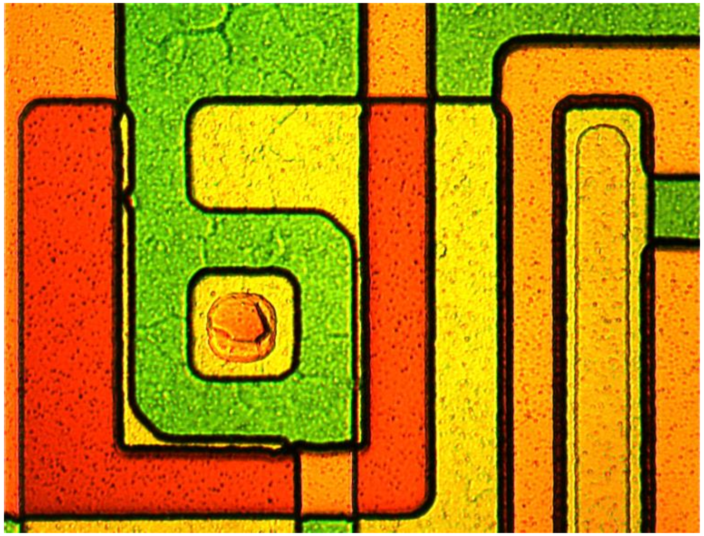
# Confocal Imaging with Hyper Chromate



- Wide field 20x0.5
- Confocal with chromate at low aperture 20x0.5
- Confocal with chromate at high aperture 50x0.9







Ref: R. Semmler

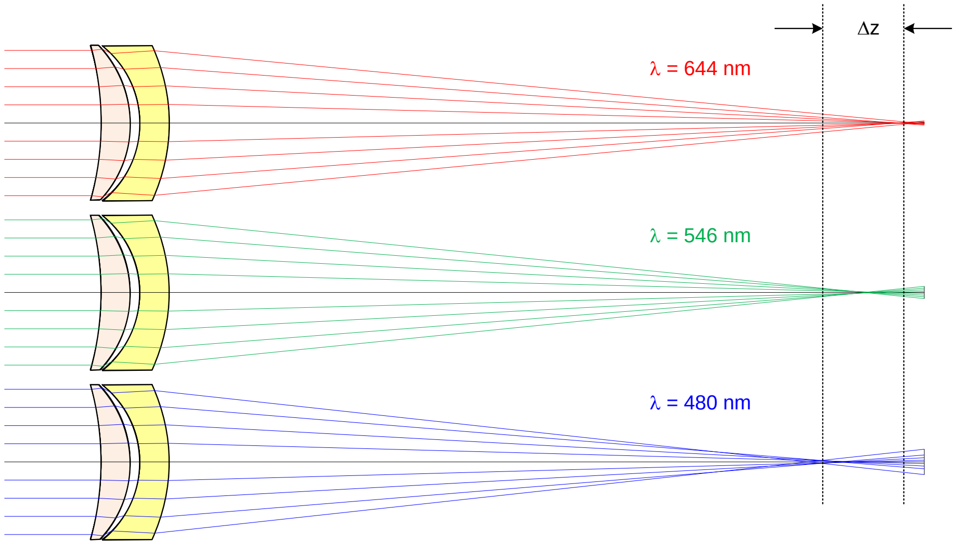
# Principle



- Goal:
  1. large chromatical spreading (large CHL) $\Delta z$
  2. large numerical aperture
  3. corrected spherochromatism

- In the case of a large ratio $\Delta z$ / f, the numerical aperture shows a considerable change in the measuring interval

- Design approach:
  1. Achromate with positive flint and negative crown
  2. Achromates cascaded
  3. Improved spherochromatism by asphere
  4. monochromatic lens with buried surface adapter



## Case 1-1

$NA_{image} = 0.3$, $NA_{object} = 0.22$
$\Delta z = 3$ mm, $f = 13$ mm
$z_{free} = 16.3$ mm

1st surface: aspherical