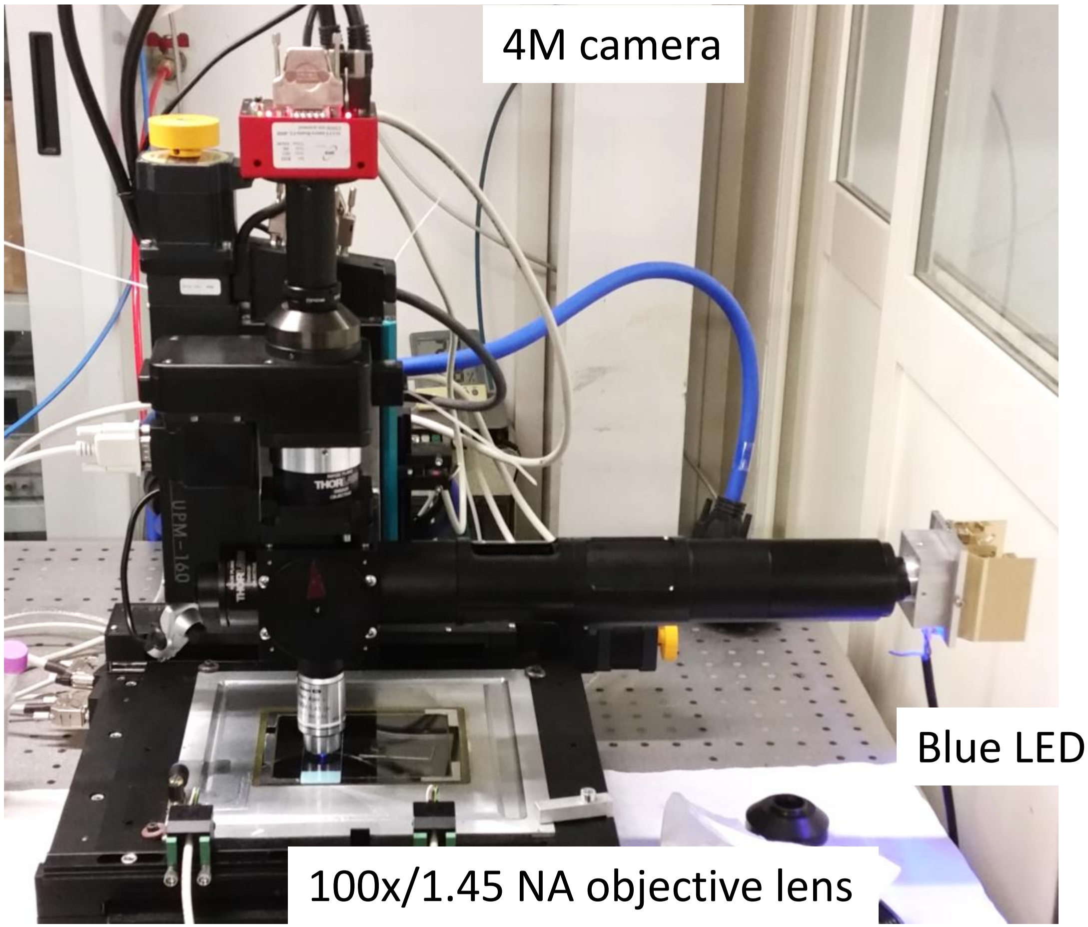
# Readout System

Andrey Alexandrov

# Outline

- Current status
- EPI-illuminator R&D
  - Motivation
  - Design guidelines
- Resolution Measurements
  - PSF method
  - ESF method

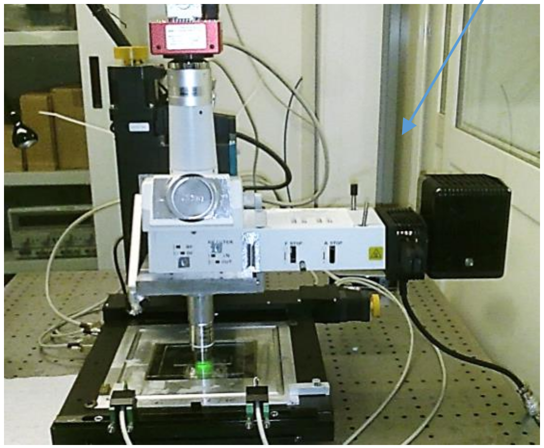
# Current Readout System



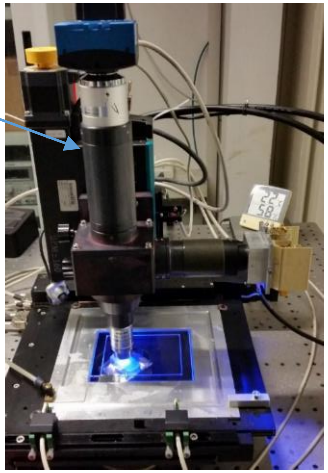

- Same as ESS mechanics
- Custom EPI-illuminator
- 2x Magnification lens
- Motorized polarizer
- 4M camera (563 fps)
- Blue LED (465 nm)
- Pixel size ~ 30 nm
- Scanning speed ~20 $mm^2/h$

# EPI-illuminator R&D

# EPI-illuminator R&D



- Nikon EPI:
  - Big and heavy
  - 100W halogen lamp
  - Green filter
  - Diaphragms
  - Diffuser
  - Insufficient light to see particles < 100 nm
- Custom EPI:
  - Compact
  - LED (green, blue, violet)
  - No color filter needed
  - Diffuser
  - No diaphragms
  - Low image contrast
  - Image artifacts



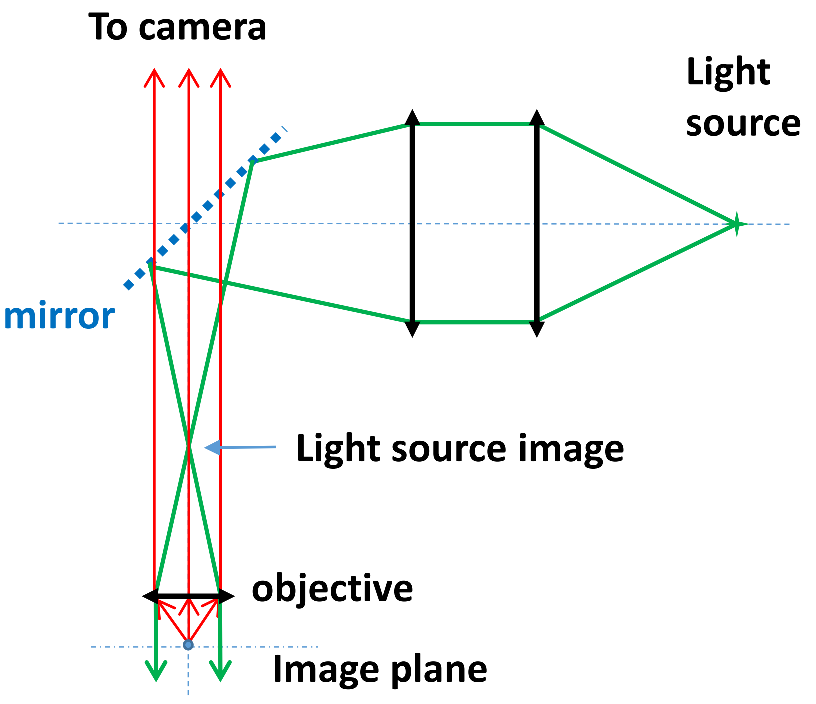
- **<u>Performance of existing illumination systems was not good enough to measure small grains</u>**

# Goals

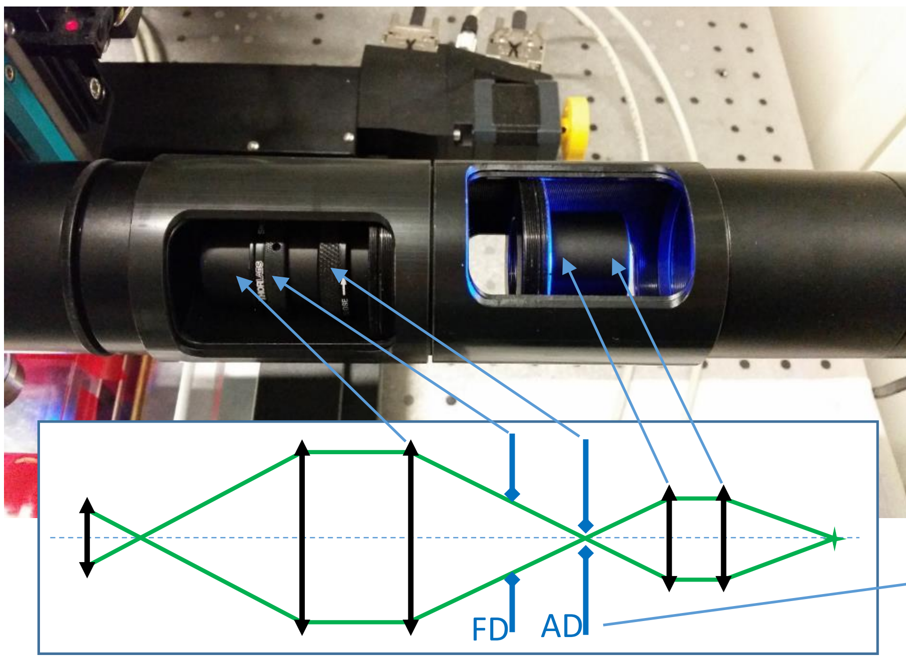
- Build a custom build a custom illumination system <u>optimized for our needs</u>
  - Brighter illumination
  - Efficient light collection
  - Compact and lightweight
  - LED
  - No filters or diffusors (if possible)
  - Diaphragms (improve contrast and resolution)

# EPI-illumination Principle

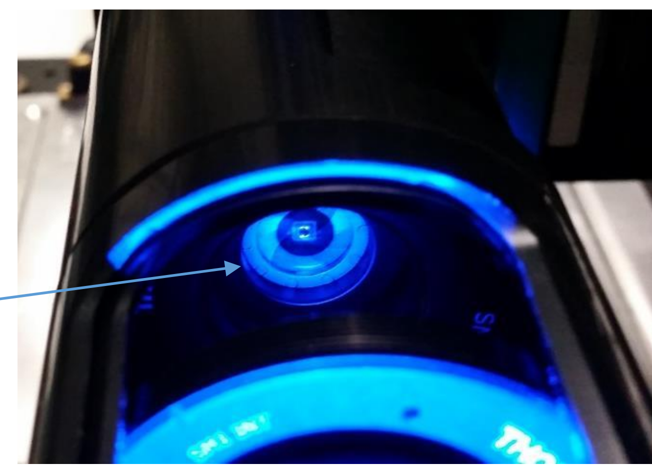
- A point-like illumination source placed in the back focus of the objective lens
- A sample is illuminated with a parallel light beam
- Reflected light is collected by the objective within its entire NA



# Optimized Illumination System (ver.1)




- 12 times more powerful than Nikon EPI with 100W halogen lamp and green filter
- Max output light power reaching objective (mW):
  - EPI v.1 – 18 @ 435 nm (LED)
  - Nikon – 1.4 @ 550 nm (halogen)



# Optimized Illumination System (ver.1)

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| 1 | | LC6W- ( WEIGHT (Total)):0.33 Kgs<br>60 mm Cage Cube | Today | 1 | 118,80 € | 118,80 € | |
| 2 | | LB3C/M- ( WEIGHT (Total)):0.09 Kgs<br>Mounting Platform for 60 mm Cage Cube, Metric Taps | Today | 1 | 40,95 € | 40,95 € | |
| 3 | | SM2CP2- ( WEIGHT (Total)):0.03 Kgs<br>Externally SM2-Threaded End Cap | Today | 1 | 16,20 € | 16,20 € | |
| 4 | | SM2A6- ( WEIGHT (Total)):0.02 Kgs<br>Adapter with External SM2 Threads and Internal SM1 Threads | Today | 1 | 21,60 € | 21,60 € | |
| 5 | | SM1A12- ( WEIGHT (Total)):0.00 Kgs<br>Adapter with External SM1 Threads and Internal M25 x 0.75 Threads | Today | 1 | 17,78 € | 17,78 € | |
| 6 | | SM2A20- ( WEIGHT (Total)):0.05 Kgs<br>Adapter with External SM2 Threads and Internal M38 x 0.5 Threads | Today | 1 | 40,50 € | 40,50 € | |
| 7 | | ITL200- ( WEIGHT (Total)):0.04 Kgs<br>Infinity-Corrected Tube Lens for Plan Fluorite Objectives | Today | 1 | 405,00 € | 405,00 € | |
| 8 | | SM2V15- ( WEIGHT (Total)):0.05 Kgs<br>Ø2" Adjustable Lens Tube, 1.31" Travel | Today | 1 | 45,00 € | 45,00 € | |
| 9 | | SM2L30- ( WEIGHT (Total)):0.09 Kgs<br>SM2 Lens Tube, 3" Thread Depth, One Retaining Ring Included | Today | 1 | 31,95 € | 31,95 € | |
| 10 | | SM1A2- ( WEIGHT (Total)):0.01 Kgs<br>Adapter with External SM1 Threads and Internal SM2 Threads | Today | 1 | 21,60 € | 21,60 € | |
| 11 | | SM1A9- ( WEIGHT (Total)):0.00 Kgs<br>Adapter with External C-Mount Threads and Internal SM1 Threads | Today | 1 | 16,88 € | 16,88 € | |
| 12 | | SM1V05- ( WEIGHT (Total)):0.01 Kgs<br>Ø1" Adjustable Lens Tube, 0.31" Travel Range | Today | 1 | 26,64 € | 26,64 € | |
| WEIGHT (Total): 0.73 Kgs | | | | | TOTAL: | 802,90 € | |

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| 1 | | SM1S01- ( WEIGHT (Total)):0.01 Kgs<br>Plastic Optic Spacer, 0.015" (0.381 mm) Thick, 10 Pack | Today | 1 | 4,73 € | 4,73 € | |
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| 3 | | SM2L20- ( WEIGHT (Total)):0.12 Kgs<br>SM2 Lens Tube, 2" Thread Depth, One Retaining Ring Included | Today | 2 | 27,00 € | 54,00 € | |
| 4 | | SM2L30C- ( WEIGHT (Total)):0.14 Kgs<br>SM2 Slotted Lens Tube, 3" Thread Depth, 2 Retaining Rings Included | Today | 2 | 79,20 € | 158,40 € | |
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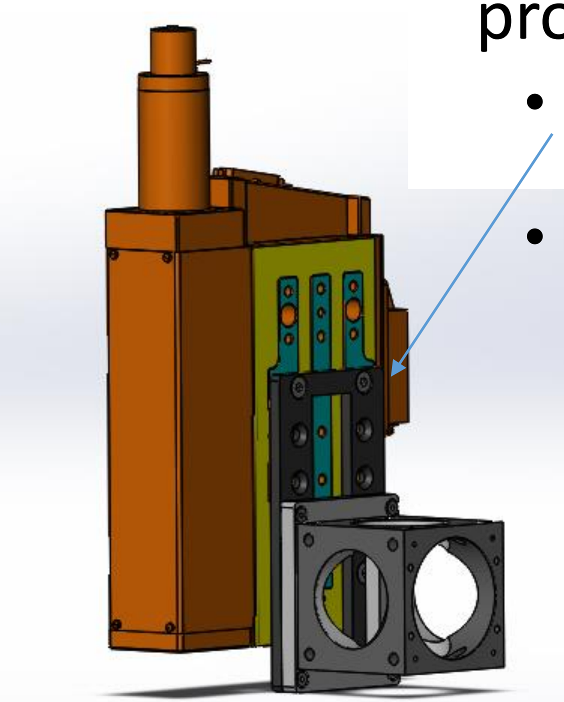
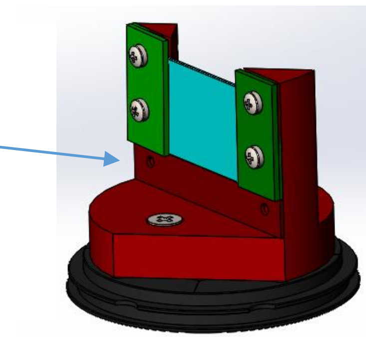
| 6 | | SM2A6- ( WEIGHT (Total)):0.07 Kgs<br>Adapter with External SM2 Threads and Internal SM1 Threads | Today | 3 | 21,60 € | 64,80 € | |
| 7 | | SM2A21- ( WEIGHT (Total)):0.04 Kgs<br>Externally SM2-Threaded Mounting Adapter with Ø1.2" Bore and 2" Outer Diameter | Today | 1 | 39,78 € | 39,78 € | |
| 8 | | SM1L03- ( WEIGHT (Total)):0.02 Kgs<br>SM1 Lens Tube, 0.30" Thread Depth, One Retaining Ring Included | Today | 3 | 10,94 € | 32,82 € | |
| 9 | | SM1L05- ( WEIGHT (Total)):0.01 Kgs<br>SM1 Lens Tube, 0.50" Thread Depth, One Retaining Ring Included | Today | 1 | 11,33 € | 11,33 € | |
| 10 | | SM1L10- ( WEIGHT (Total)):0.02 Kgs<br>SM1 Lens Tube, 1.00" Thread Depth, One Retaining Ring Included | Today | 1 | 12,83 € | 12,83 € | |
| 11 | | SM1D12D- ( WEIGHT (Total)):0.05 Kgs<br>Ring-Actuated SM1 Iris Diaphragm | Today | 2 | 57,87 € | 115,74 € | |
| 12 | | LA1050-A- ( WEIGHT (Total)):0.06 Kgs<br>N-BK7 Plano-Convex Lens, Ø50.8 mm, f = 100.0 mm, AR Coating: 350-700 nm | Today | 1 | 34,29 € | 34,29 € | |
| 13 | | LA1027-A- ( WEIGHT (Total)):0.03 Kgs<br>N-BK7 Plano-Convex Lens, Ø1", f = 35.0 mm, AR Coating: 350-700 nm | 2-3 Days | 1 | 29,07 € | 29,07 € | |
| 14 | | LA1134-A- ( WEIGHT (Total)):0.02 Kgs<br>N-BK7 Plano-Convex Lens, Ø1", f = 60.0 mm, AR Coating: 350-700 nm | Today | 1 | 27,99 € | 27,99 € | |
| 15 | | LA1708-A- ( WEIGHT (Total)):0.02 Kgs<br>N-BK7 Plano-Convex Lens, Ø1", f = 200.0 mm, AR Coating: 350-700 nm | Today | 1 | 26,37 € | 26,37 € | |
| 16 | | SM1L35- ( WEIGHT (Total)):0.05 Kgs<br>SM1 Lens Tube, 3.50" Thread Depth, One Retaining Ring Included | Today | 1 | 32,32 € | 32,32 € | |
| 17 | | BSW10R- ( WEIGHT (Total)):0.03 Kgs<br>25 x 36 mm 50:50 UVFS Plate Beamsplitter, Coating: 400 - 700 nm, t = 1 mm | Today | 1 | 99,00 € | 99,00 € | |
| WEIGHT (Total): 0.82 Kgs | | | | | TOTAL: | 820,42 € | |

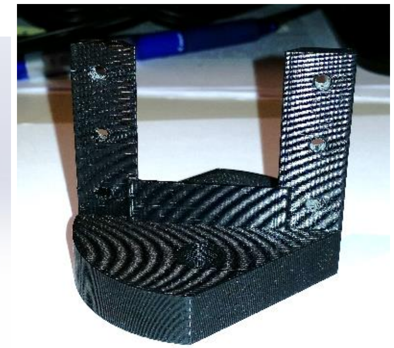
- Microscope cost ~800 euro
- EPI ver.1 cost ~820 euro

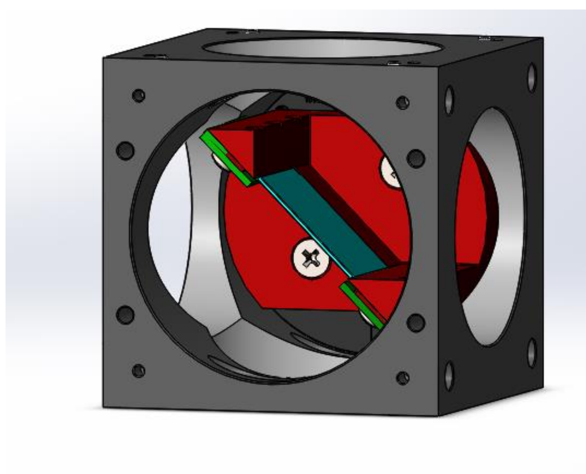
# Optimized Illumination System (ver.1)

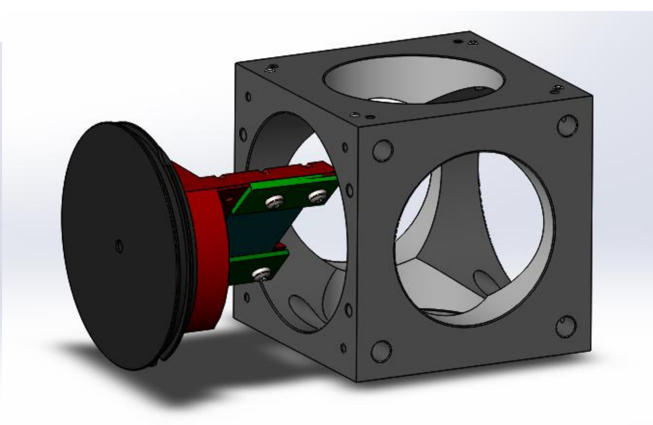


- Custom parts to be produced:
  - Beamsplitter holder
    - Produced at a 3D-printer
  - Cube-to-stage mounting plates
    - In production









# Resolution Measurements

# Image Formation

- The objective and tube lens do not image a point in the object (for example, a minute hole in a metal foil) as a bright disk with sharply defined edges, but as a slightly blurred spot surrounded by diffraction rings, called Airy pattern

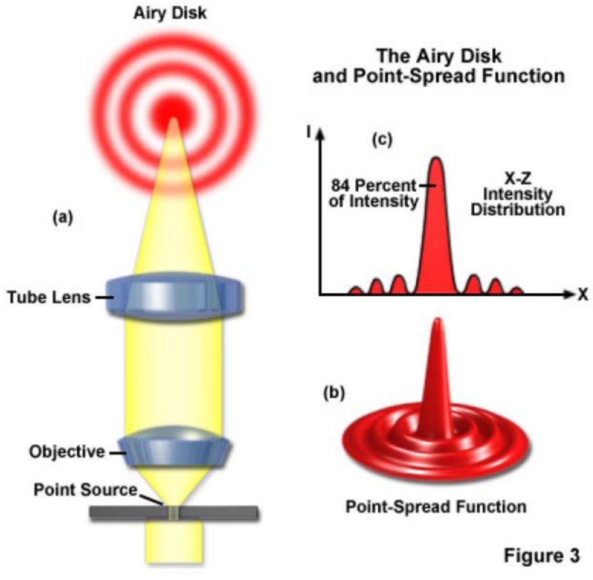
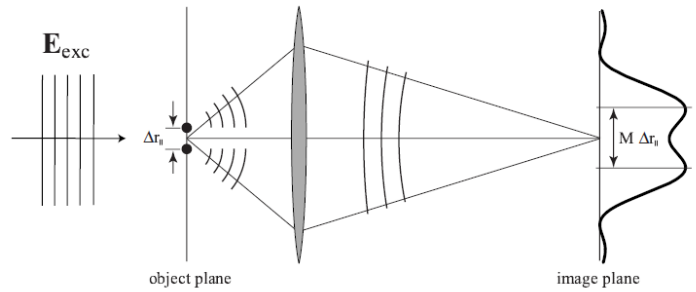



Figure 3

# Resolution definition

- The limit up to which two small objects are still seen as separate entities is used as a measure of the resolving power of a microscope. The distance where this limit is reached is known as the effective resolution of the microscope ($\mathbf{d_0}$)
- **The Rayleigh Criterion:** The principal maximum of the second Airy disk coincides with the first minimum of the first Airy disk
- The definition is independent of SW!



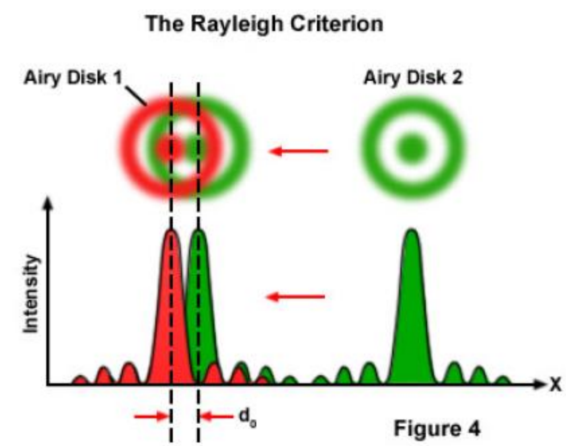
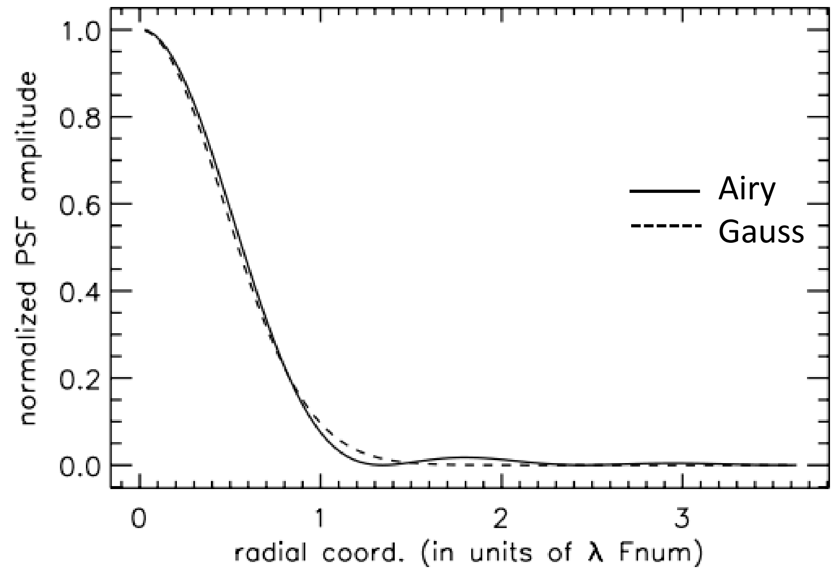



Figure 4

# Approximation of an Airy disk with Gaussian

$$I(q) \approx I_0' \exp\left(\frac{-q^2}{2\sigma^2}\right) \ ,$$

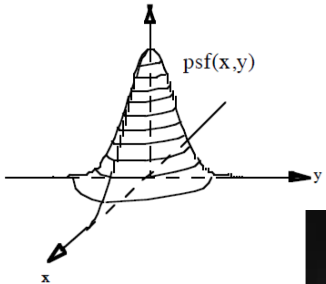



- $\sigma \approx 0.42\lambda F$, if normalized by amplitude
- $\sigma \approx 0.45\lambda F$, if normalized by volume
- $Resolution = \ d_0 = 1.22\lambda F \approx 2.9\sigma$
- It is possible to measure the resolution by fitting the central peak of the Airy pattern with the Gaussian
- But one still needs a point source!

# PSF Resolution Measurement Algorithm

- Put a sample with nanoparticles onto stage
- Scan some area
- Reconstruct clusters and grains
- Select the most focused cluster in each grain
- For each selected cluster find minor (= $2\sigma$) by elliptical fitting
- Plot all minors and find the mean $\mu$ of the distribution
- Get the resolution as 1.45 $\mu$

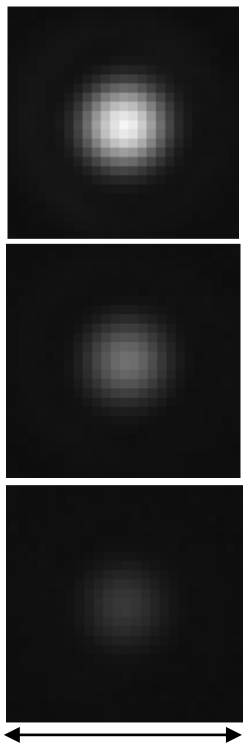
# Resolution Measurement with the PSF method




60 nm
Contrast: 245/12

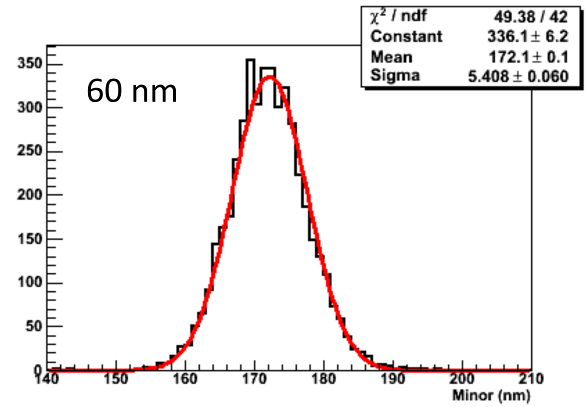
40 nm
Contrast: 112/13

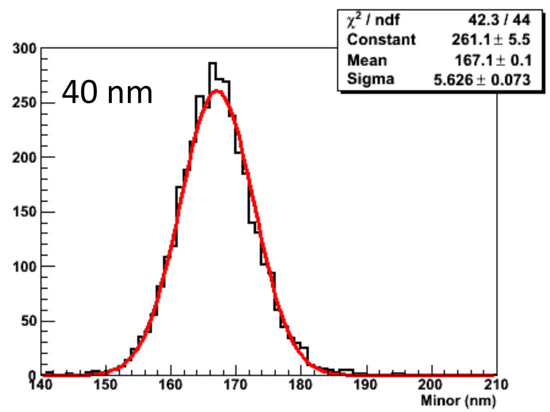
20 nm
Contrast: 56/13

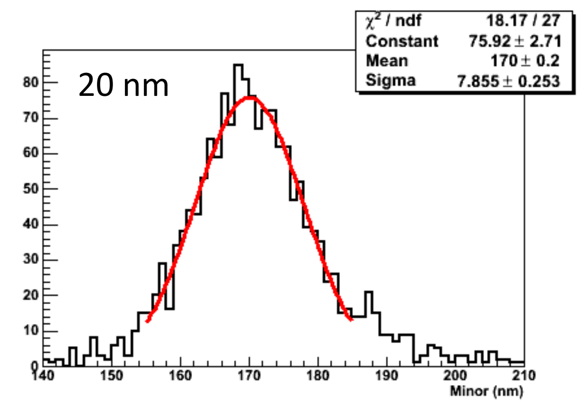


750 nm

- All samples give similar result
- Minor = 170 ± 4 nm
- Resolution = 1.45*Minor = 246 ± 6 nm



# PSF, LSF and ESF

*Point Spread Function (PSF):*

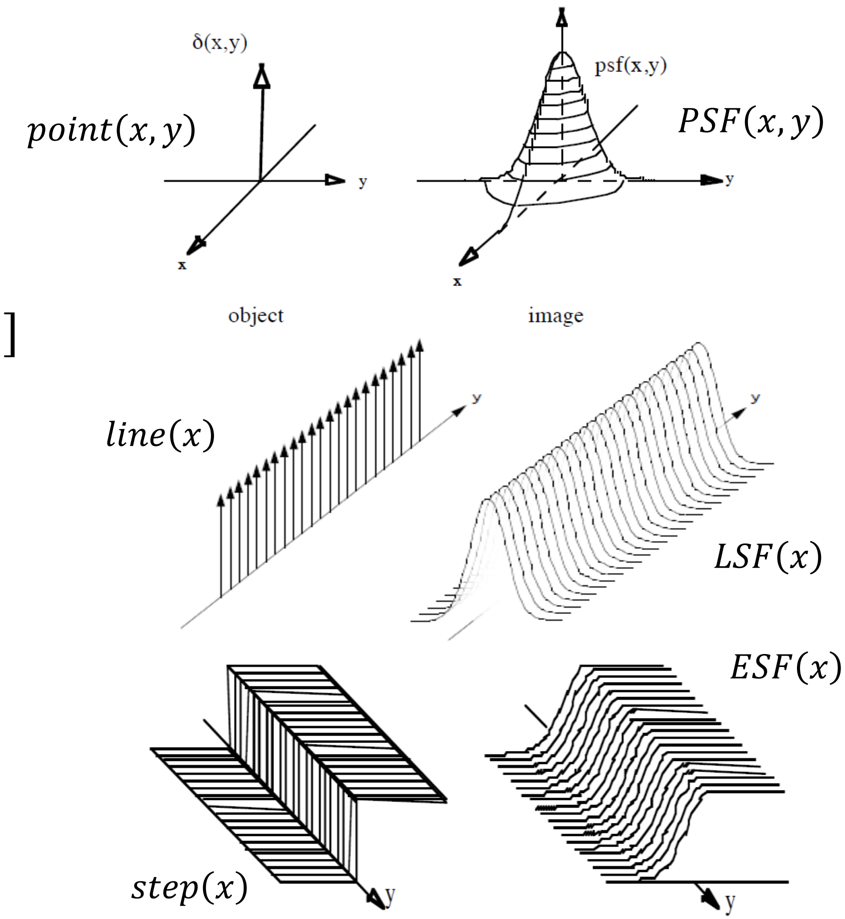
- $point(x,y) = \delta(x)\delta(y)$
- $PSF(x,y) = T[point(x,y)] = T[\delta(x)\delta(y)]$

*Line Spread Function (LSF):*

- $line(x) = \delta(x) = \int_{-\infty}^{+\infty} \delta(x)\delta(y)dy$
- $LSF(x) = T[line(x)] = \int_{-\infty}^{+\infty} PSF(x,y)dy$

*Edge Spread Function (ESF):*

- $step(x) = \int_{-\infty}^{x} \delta(x')dx' = \int_{-\infty}^{x} line(x')dx'$
- $ESF(x) = T[step(x)] = \int_{-\infty}^{x} LSF(x')dx'$



# Resolution Measurement Method

- $LSF(x) = \frac{d}{dx}[ESF(x)]$
- It is possible to obtain LSF profile by differentiating ESF profile!

But also:

- $LSF(x) = \int_{-\infty}^{+\infty} PSF(x,y)dy = \int_{-\infty}^{+\infty} A\exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right)dy =$

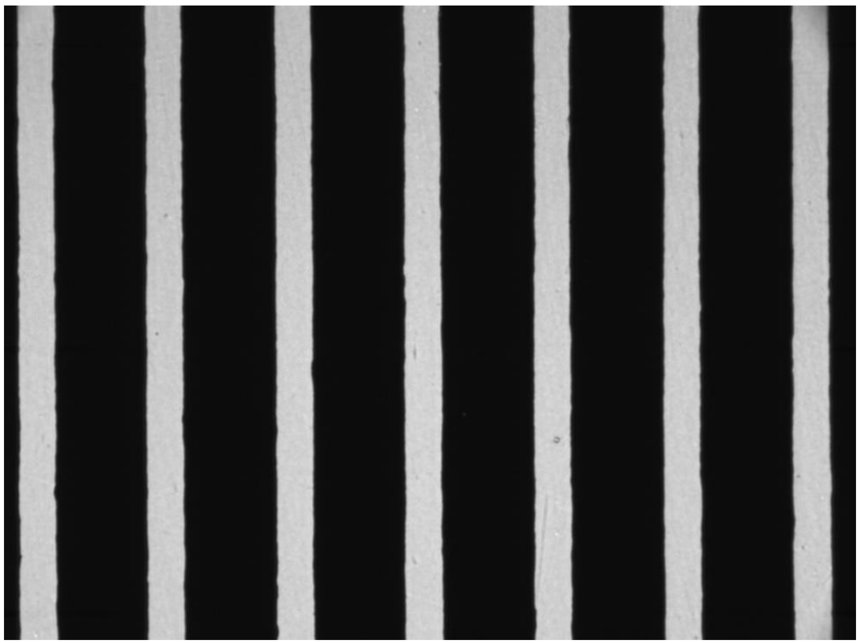
$$= \mathrm{A}\exp\left(-\frac{x^2}{2\sigma_x^2}\right)\int_{-\infty}^{+\infty}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)dy = \sqrt{2\pi}\sigma_y A\exp\left(-\frac{x^2}{2\sigma_x^2}\right)$$

- It is possible to measure $\sigma_x$ by fitting the LSF profile with Gaussian!
- $Resolution \approx 2.9\sigma$

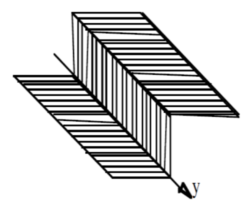
# ESF Resolution Measurement Algorithm

- Put an object micrometer onto stage with the ticks perpendicular to the X axis
- Take an image of the object's edge
- Get the ESF profile by averaging profiles for every line of pixels
- Get the LSF profile by differentiating numerically the ESF profile
- Get $\sigma_x$ by fitting the LSF profile
- Get the resolution as $2.9\ \sigma_x$

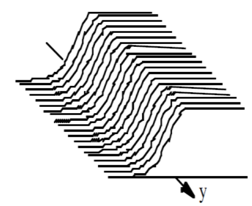
# Resolution Measurement with the Edge method



- Use an object micrometer as a sample
- Uses the ESF of a sharp edge to measure the resolution
- Resolution = 221 ± 6 nm
- The resolution is similar to that of the PSF method



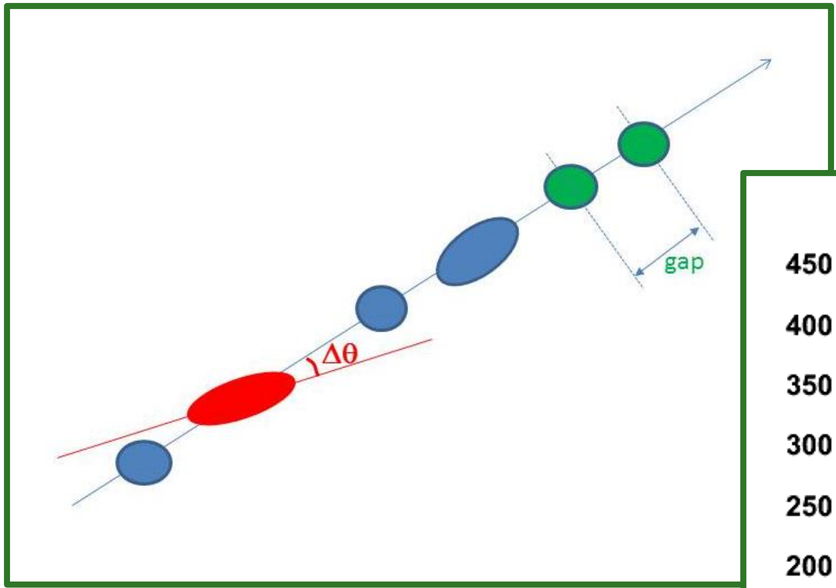

$Edge(x)$



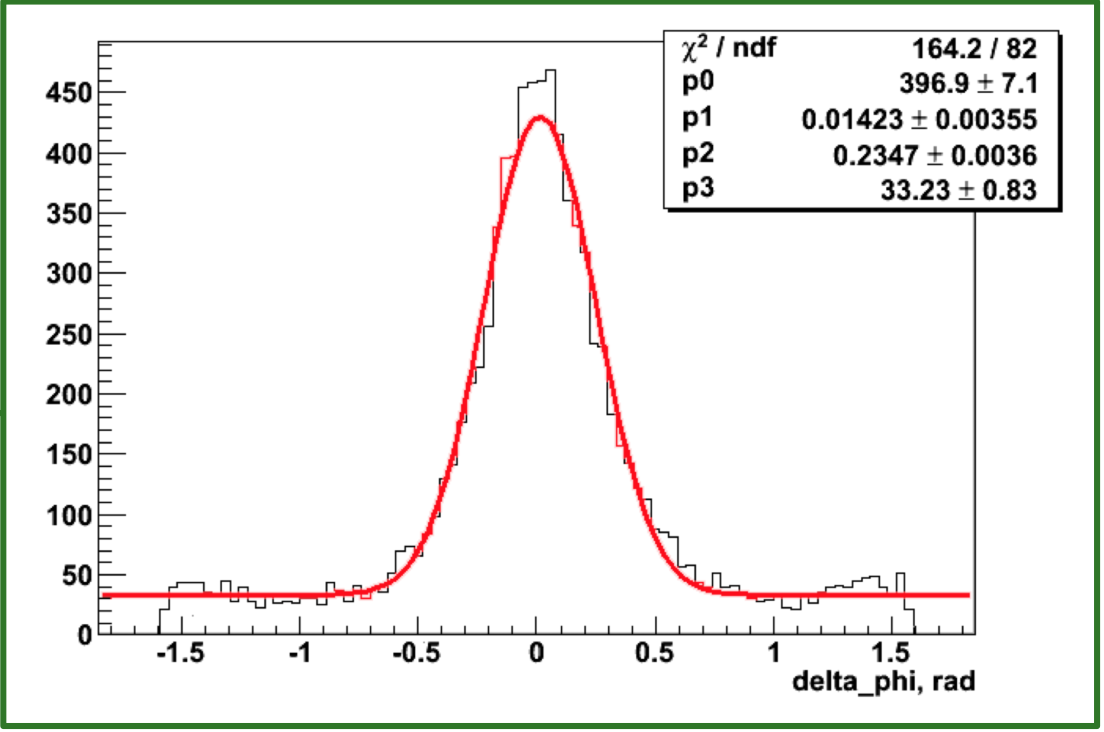

$ESF(x)$

# Intrinsic Angular Resolution

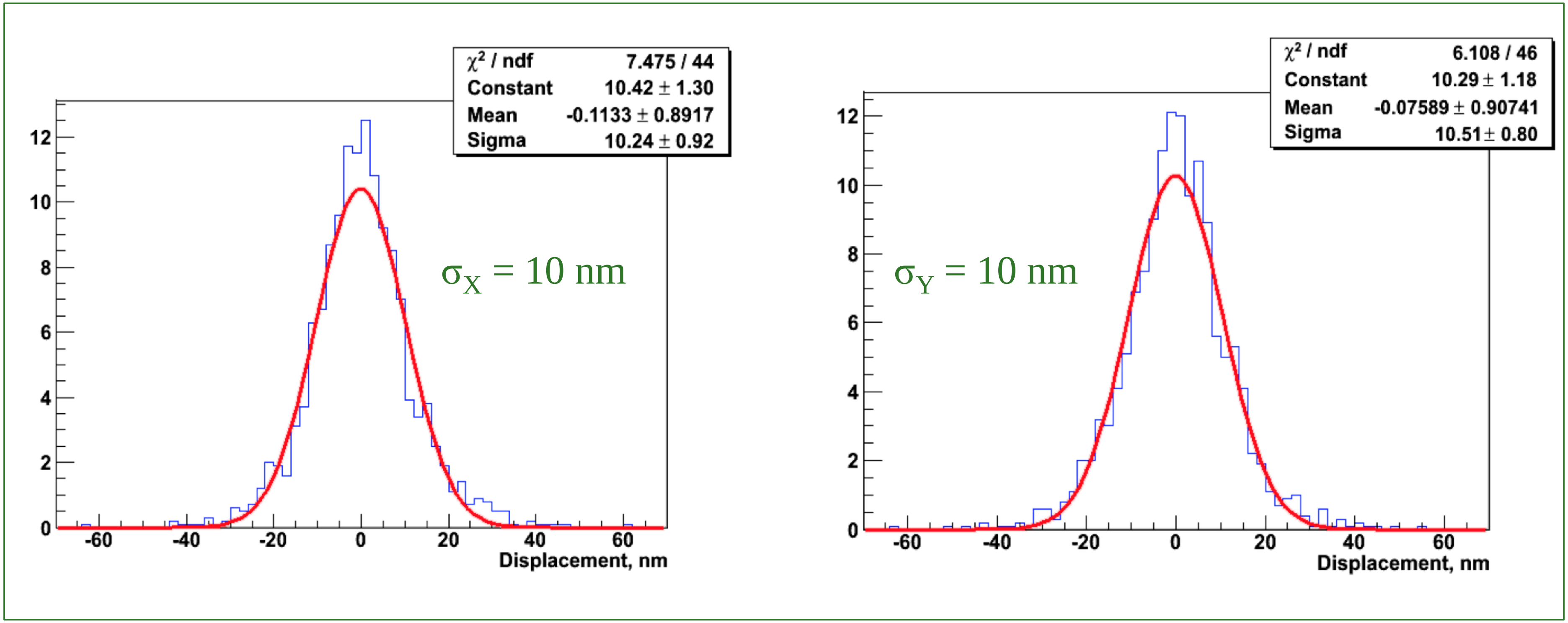
- Neutron test Beam sample (FNS exposure)
- Compare clusters with elliptical (e > 1.1) shape with the proton recoil direction
- Scattering contribution negligible




$\sigma = 235$ mrad $= 13°$



# POSITION ACCURACY




(pixel size 28 nm)

Accuracy of 10 nm on both coordinates

# Planned Improvements

- Revise optical design to improve light collection and make the EPI shorter
- Use a beam-splitter cube instead of the mirror
  - Does not polarize transmitted/reflected light -> better for plasmon analysis
  - Does not shift transmitted light -> easier to align
  - Strong back reflection from sides -> worse contrast
- Use a smaller size LED
  - Produces less heat
  - Can render the aperture diaphragm unnecessary -> more compact design
- Replace the mechanical polarization rotator with a one based on liquid crystals
  - Reduce vibrations

# Thank You!