



Super-resolution imaging through microspheres

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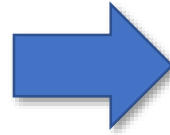


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Performance in optical imaging

Diffraction of light → Resolution limit in optical microscopy

Abbe criterion



$$d = \frac{\lambda}{2n \sin \alpha}$$

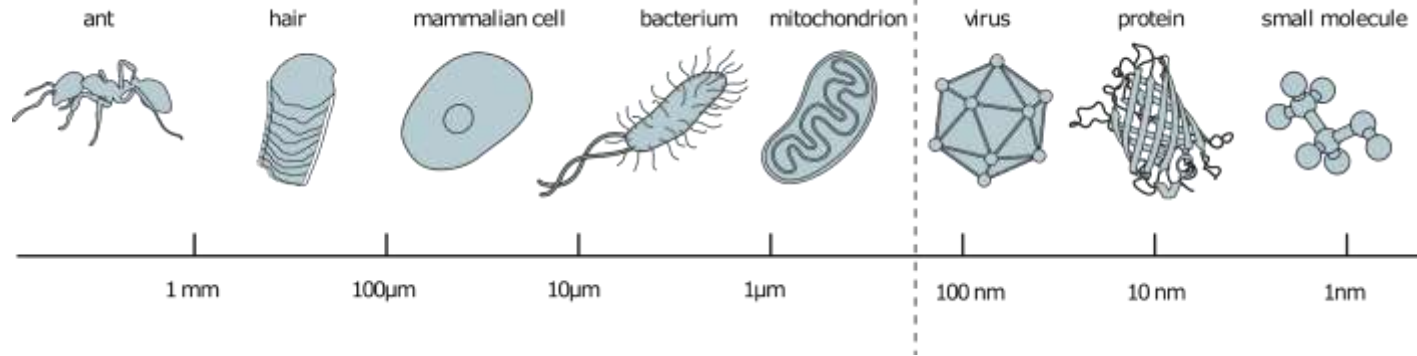


Illustration: Press release, The Royal Swedish Academy of Sciences, nobelprize.org (2014)

Aberration-free imaging system → $\delta > 200$ nm in air (theory)

Real imaging system → $\delta > 500$ nm

Overcome the diffraction limit

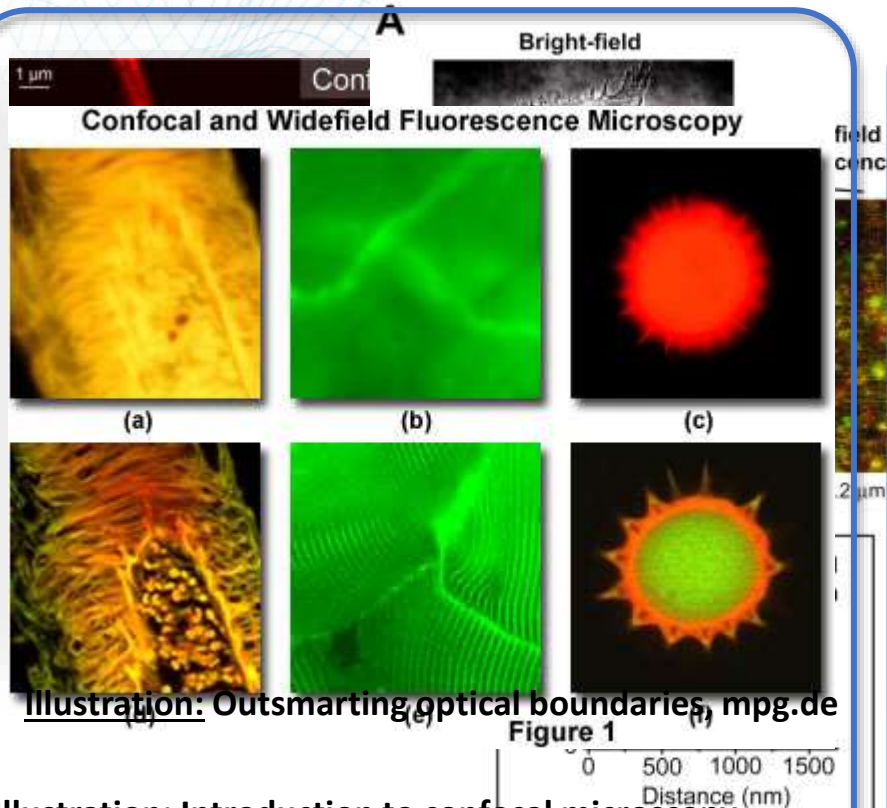


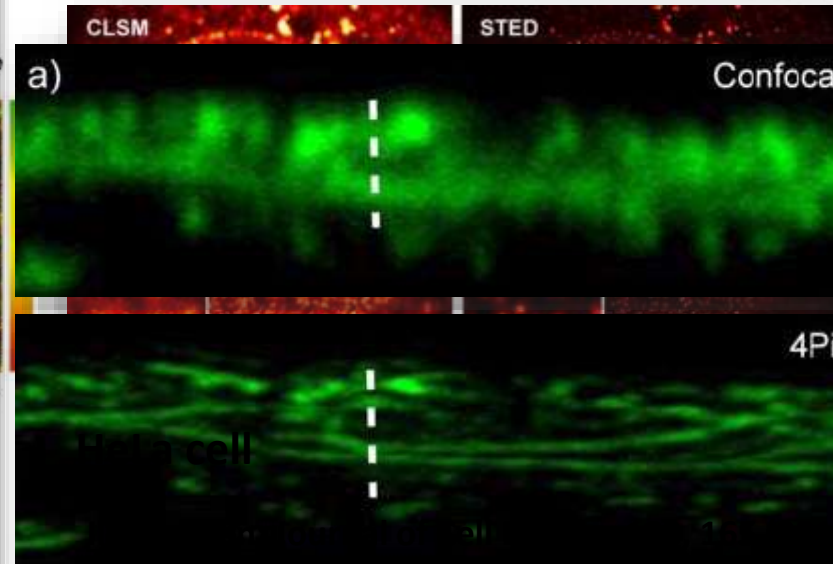
Illustration: Outsmarting optical boundaries, mpg.de

Illustration: Introduction to confocal microscopy,
olympus-lifescience.com

Fibroblast (expressing LFA-1-GFP) Illustration: New J. Phys. 10, 043041 (2008)

Illustration: Journal of Cell Science 114, 4153 (2001)

Enhancement: 4Pi microscopy



Microtubular network in a PtK-2 cell
stained with Rhodamine

Resolution $\approx 40\text{ nm}$ $\gg 200\text{ nm}$

es - fluorophores
scanning
working distance
High optical intensity

ng Photo toxic

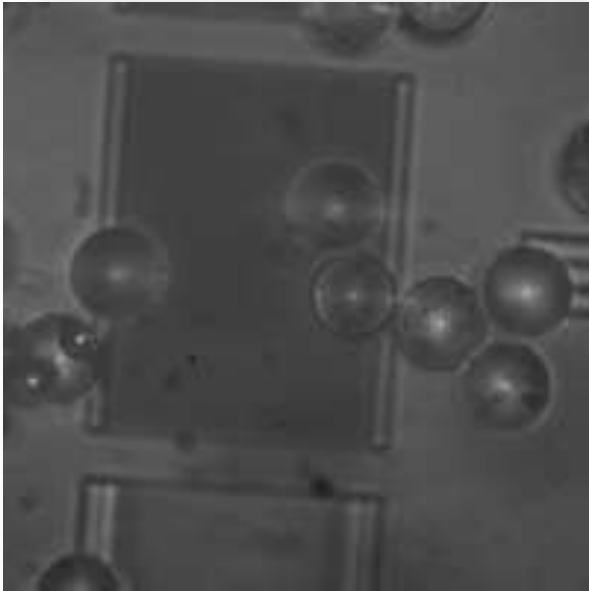
- Scanning
- Alignment complex



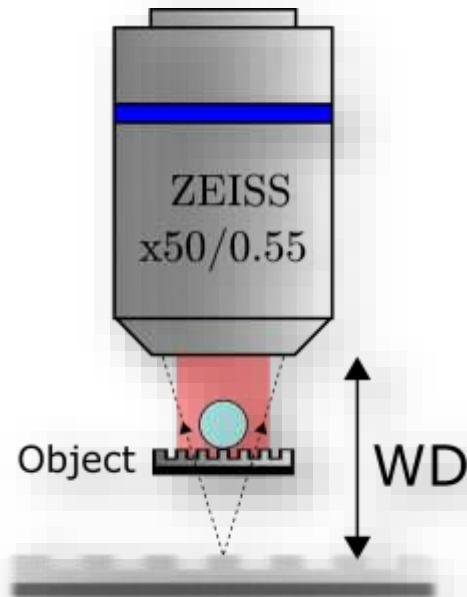
Microsphere-assisted microscopy

Principle of microsphere-assisted microscopy

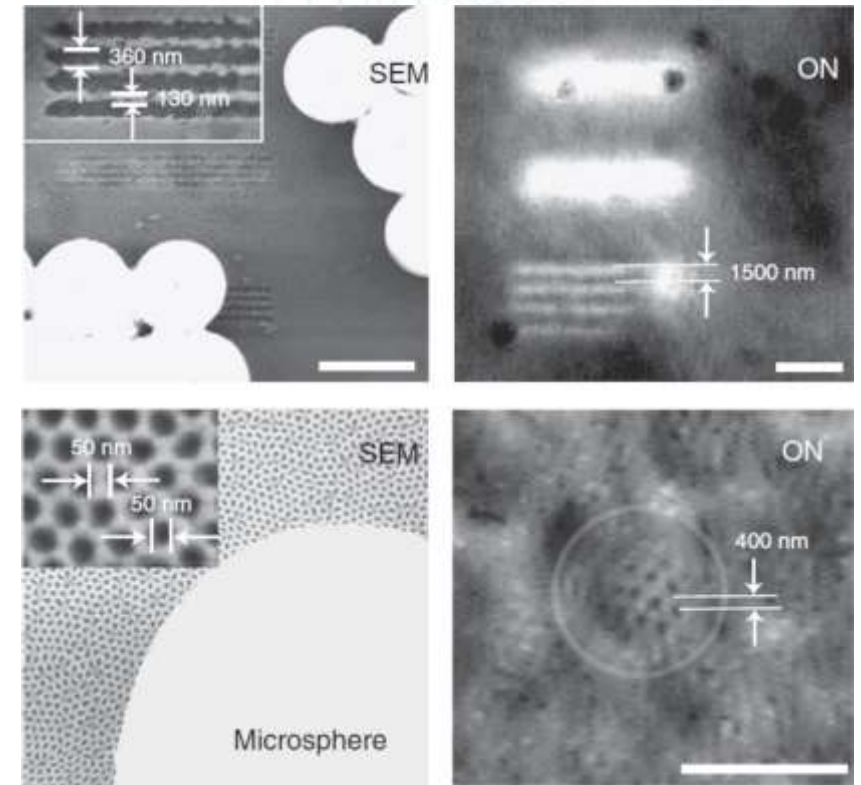
- White-light illumination
- Glass microsphere
- $2\text{ }\mu\text{m} < \text{diameter} < 50\text{ }\mu\text{m}$



- Easy-to-implement
- Full-field acquisition



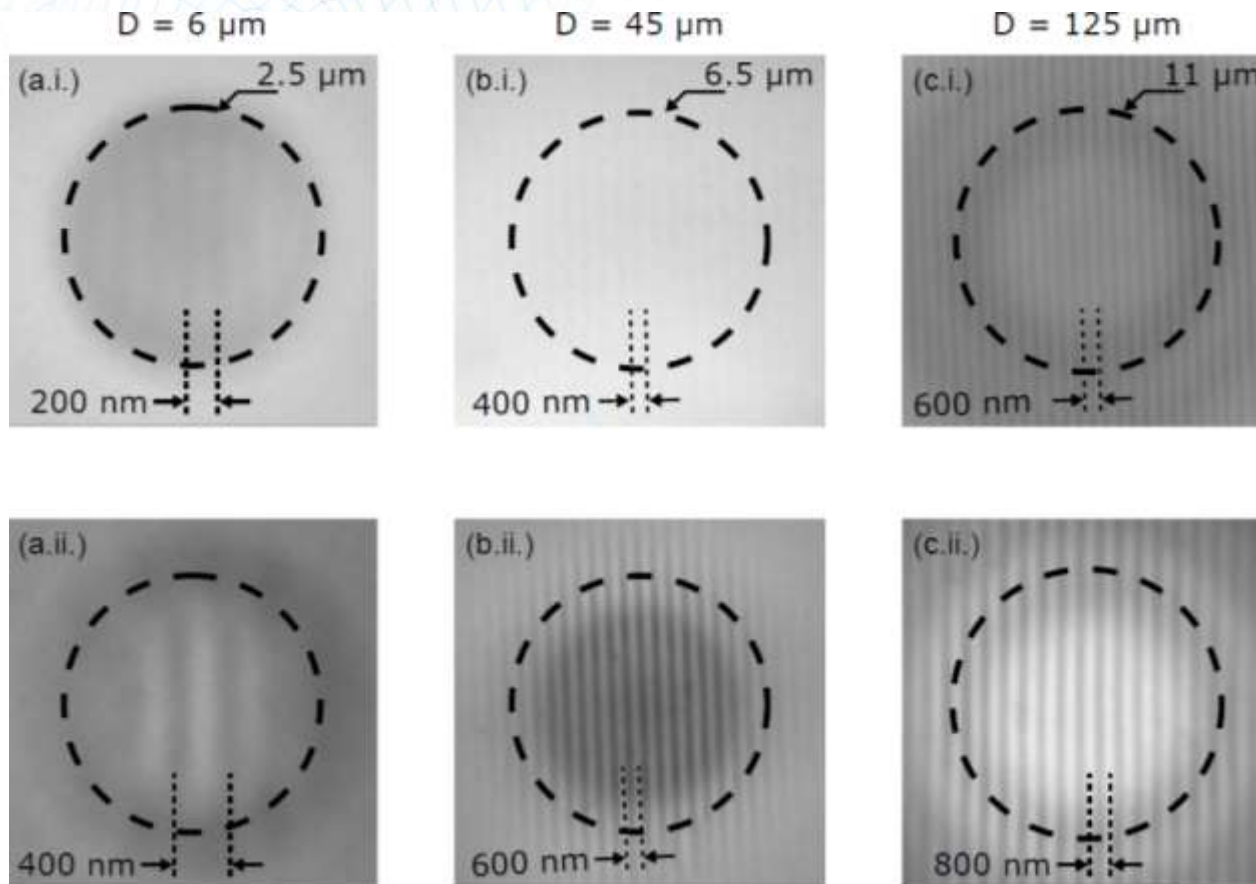
- Far-field acquisition
- Near-field collection



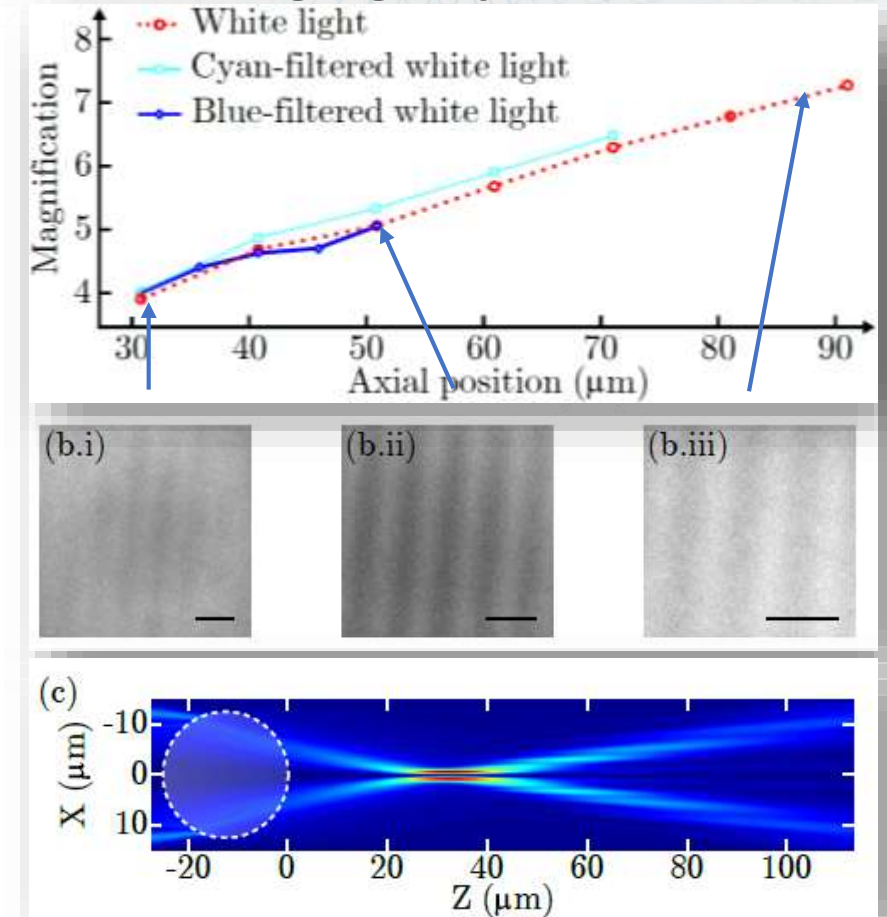
Resolution limit = $100\text{ nm} (\lambda / 7)$ in air

Performance in microsphere-assisted microscopy

Sphere diameter \rightarrow FOV and resolution



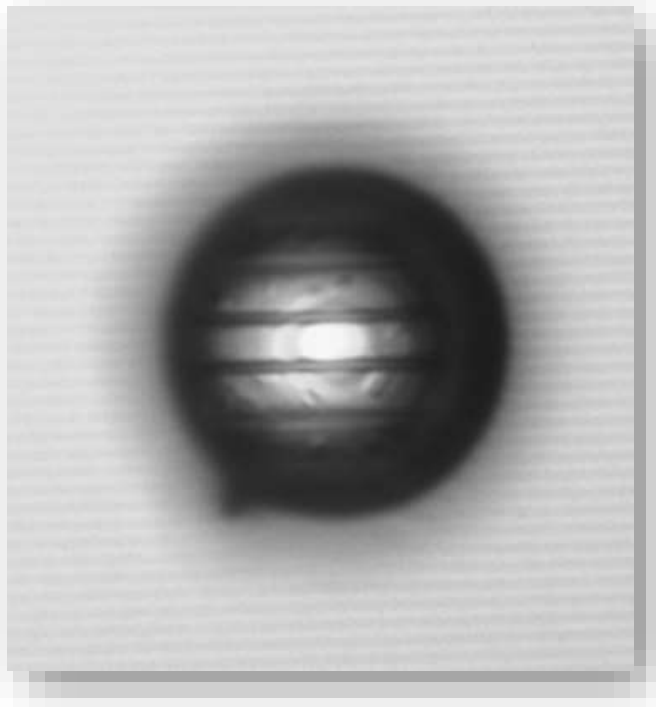
$\Delta\lambda \rightarrow$ imaging depth and contrast



Performance in microsphere-assisted microscopy

Refractive index ratio \rightarrow imaging contrast, magnification, FOV and resolution

Imaging through a barium-titanate-glass microsphere immersed in water (Formation of a virtual image)



Imaging through a barium-titanate-glass microsphere immersed in air (Formation of a real image)

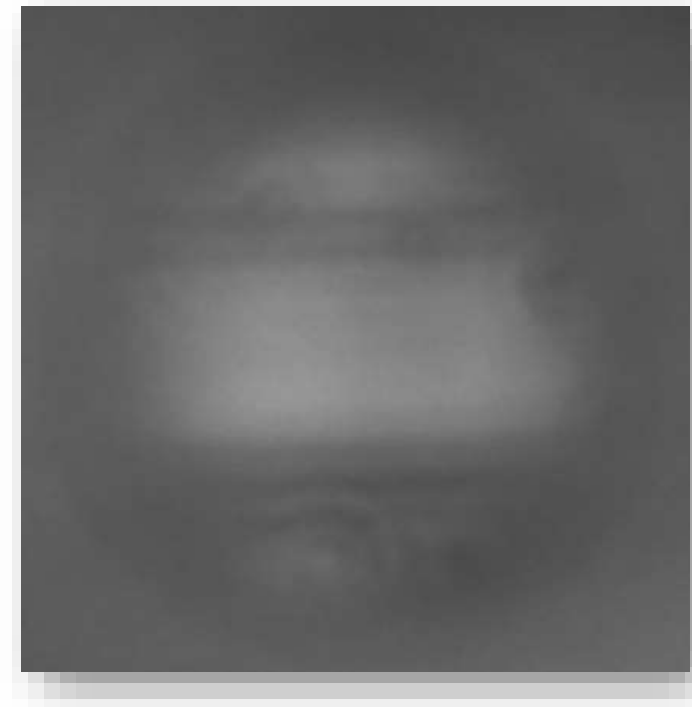


Image formation through microspheres

Refractive index and axial image position → nature of image

Photonic jet → focal point of the microsphere

Image formation through microspheres with different refractive index ratio

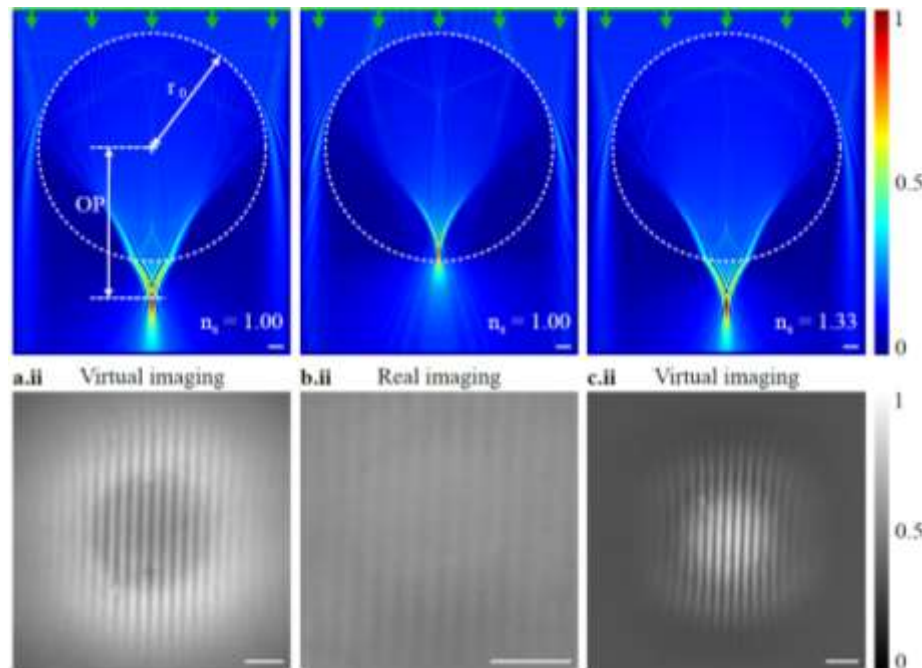
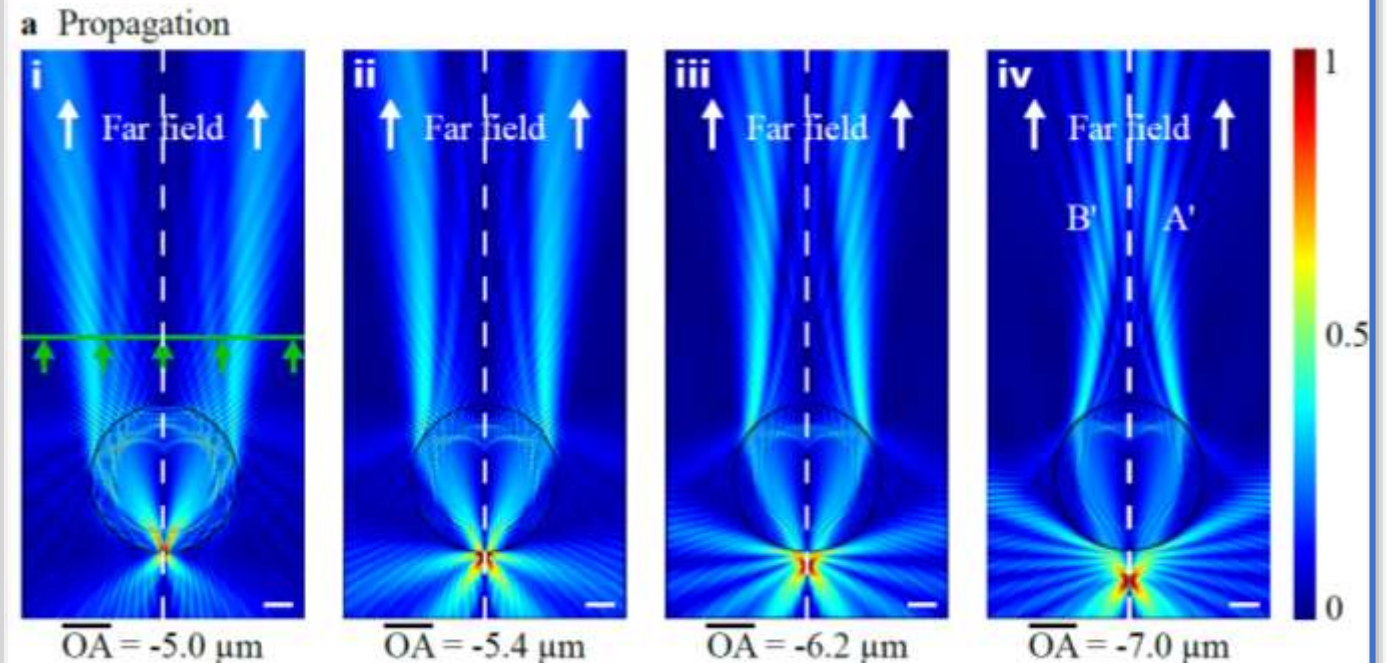


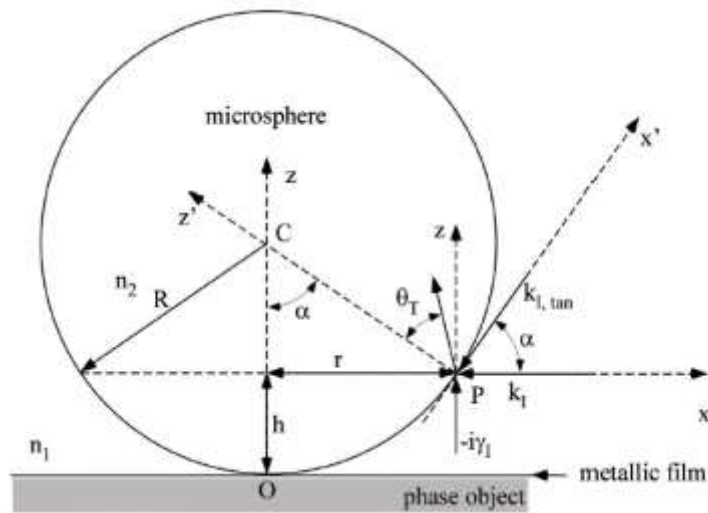
Image formation through microspheres at different axial position of the object



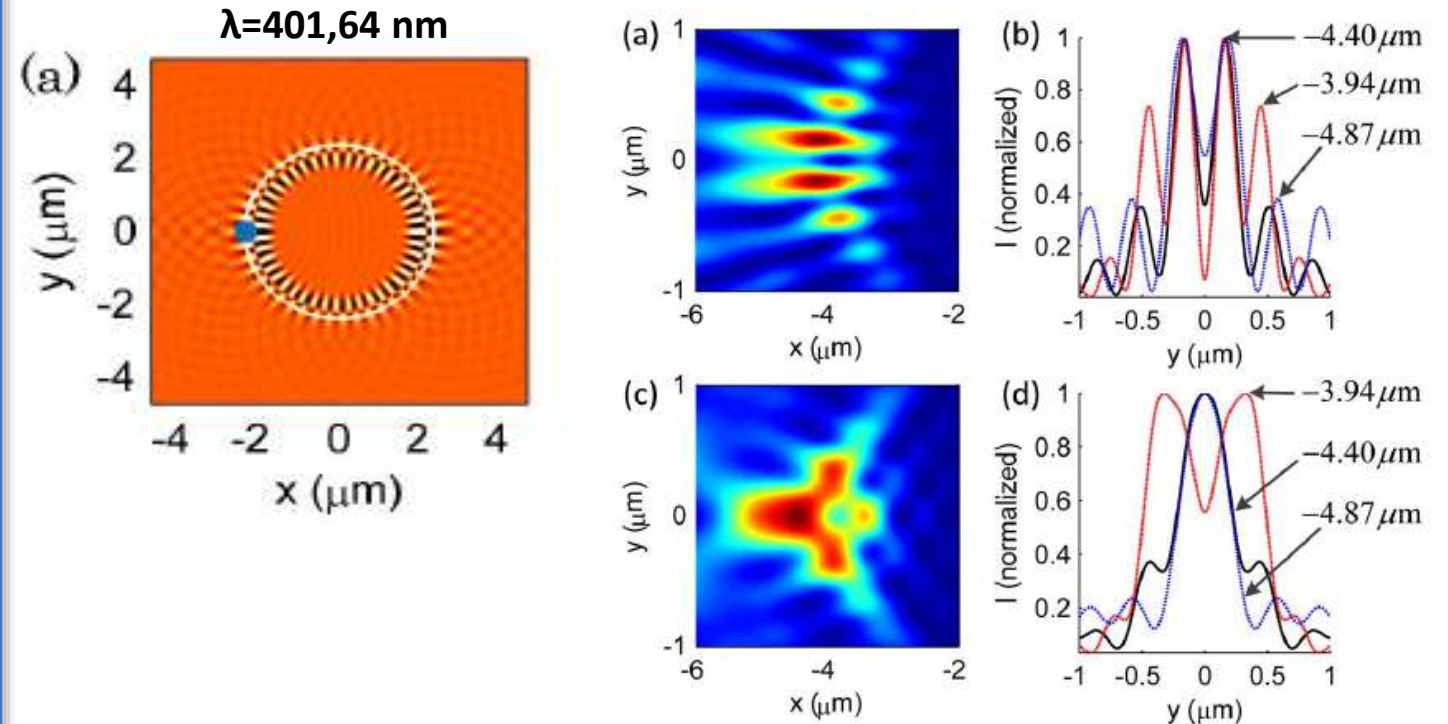
Towards an explanation of the super-resolution phenomenon

Collection of evanescent waves
by microsphere

→ Complex Snell-Descartes law

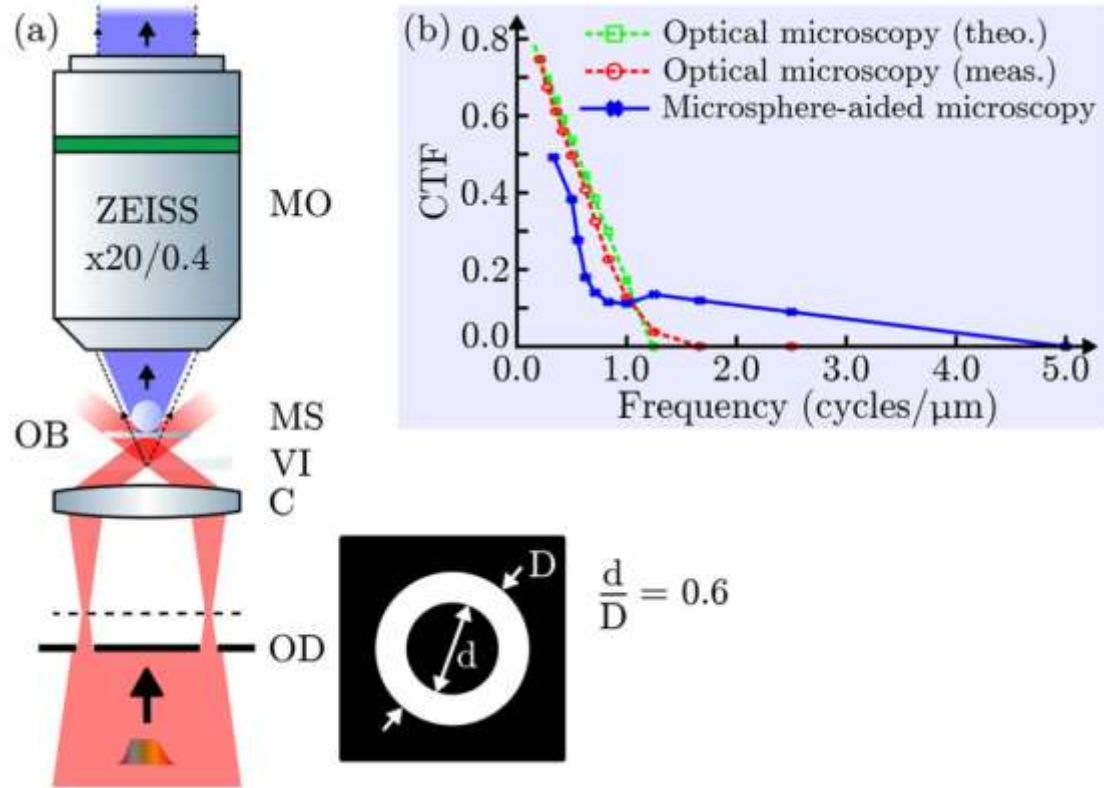


Generation of whispering gallery modes
→ Resonant phenomenon



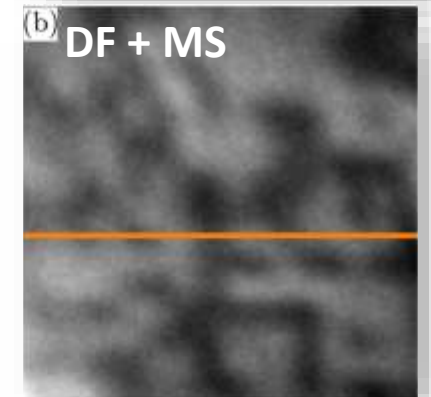
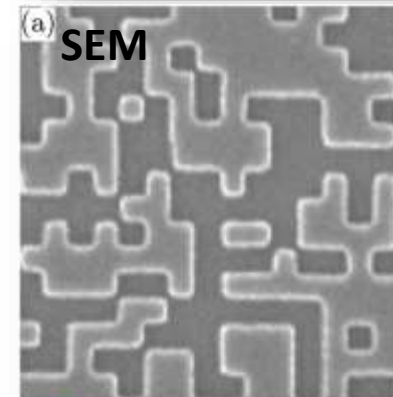
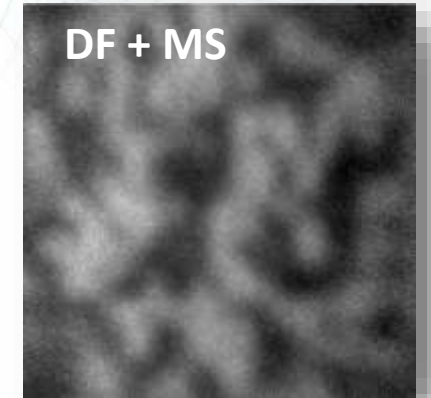
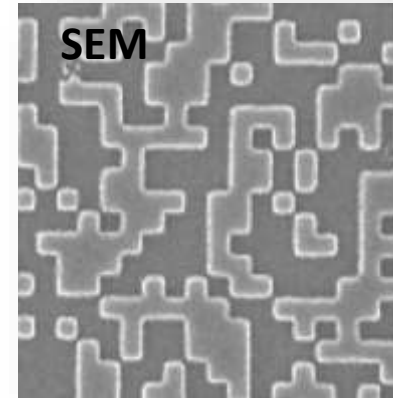
Paper 11368-4, April 10th, 11:00 AM - 12:30 PM

Dark-field microsphere-assisted microscopy



White light, $D = 25 \mu\text{m}$, $n = 1.52$, x20 / 0.4

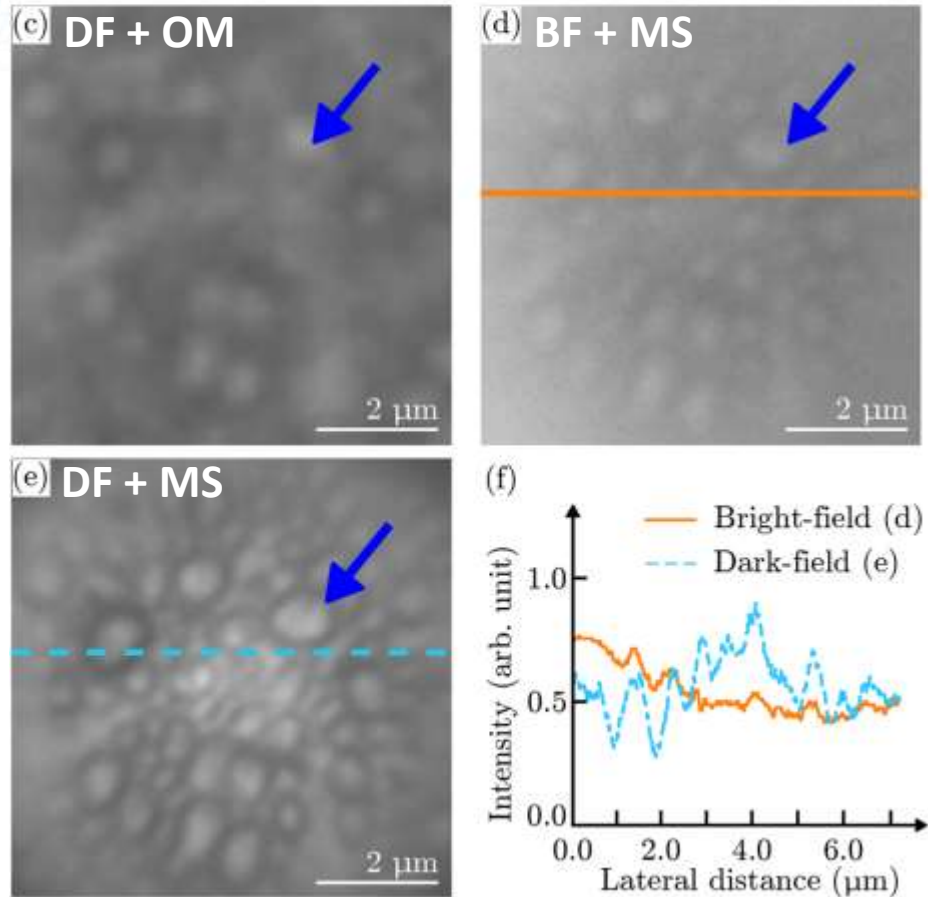
Direct imaging of glass squares (250 nm of side)



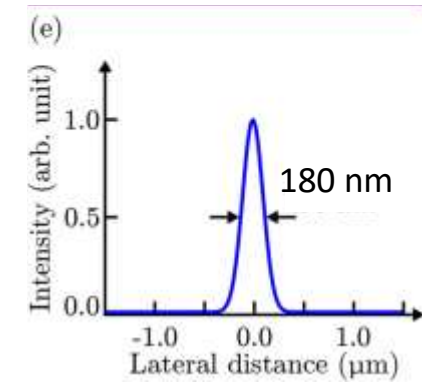
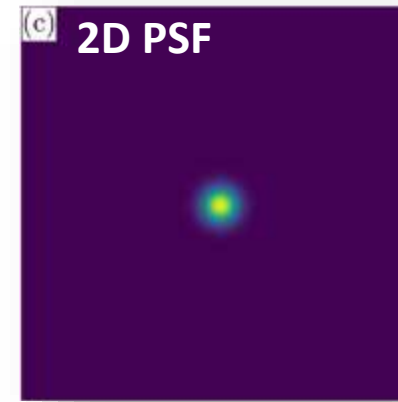
SEM: Scanning electron microscopy
DF + MS: Dark-field + Microsphere

Dark-field microsphere-assisted microscopy

Direct imaging of myelinated nerve fibres



- Resolution = 180 nm (in air)



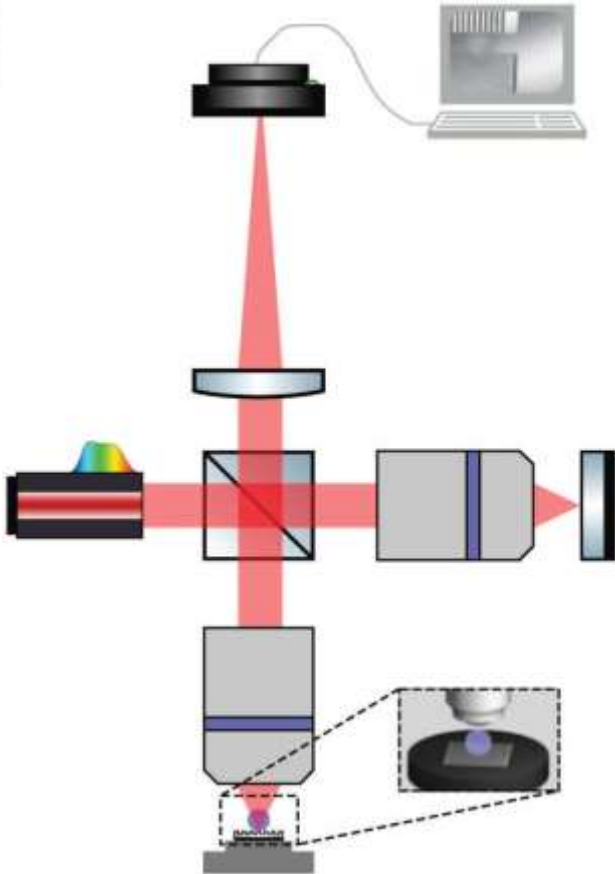
- Full-field
- Label-free imaging of translucent object



Microsphere-assisted interference microscopy

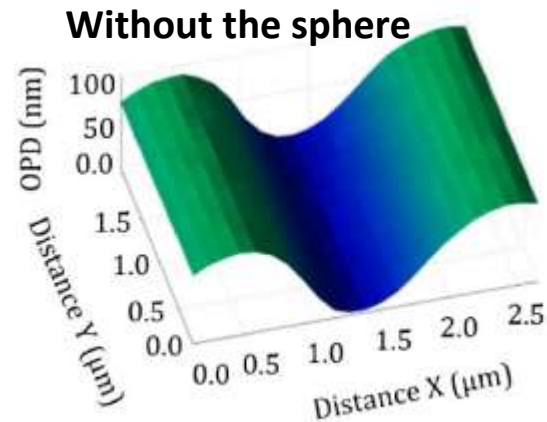
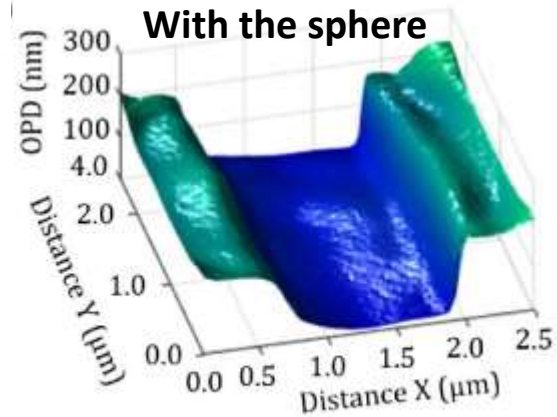
Microsphere-assisted interference microscopy (MAIM)

Linnik interferometer

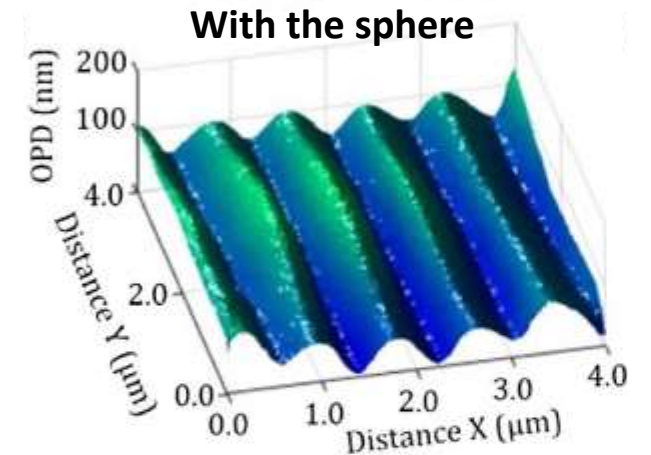


White light, $D = 25\ \mu\text{m}$, $n = 1.52$, $\times 50 / 0.3$
Phase shifting interferometry

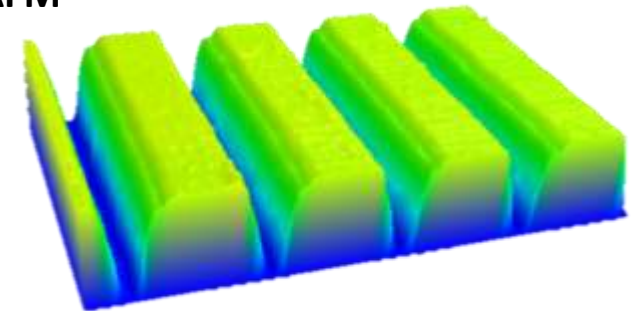
1- μm -groove grating
→ Perfectly resolved



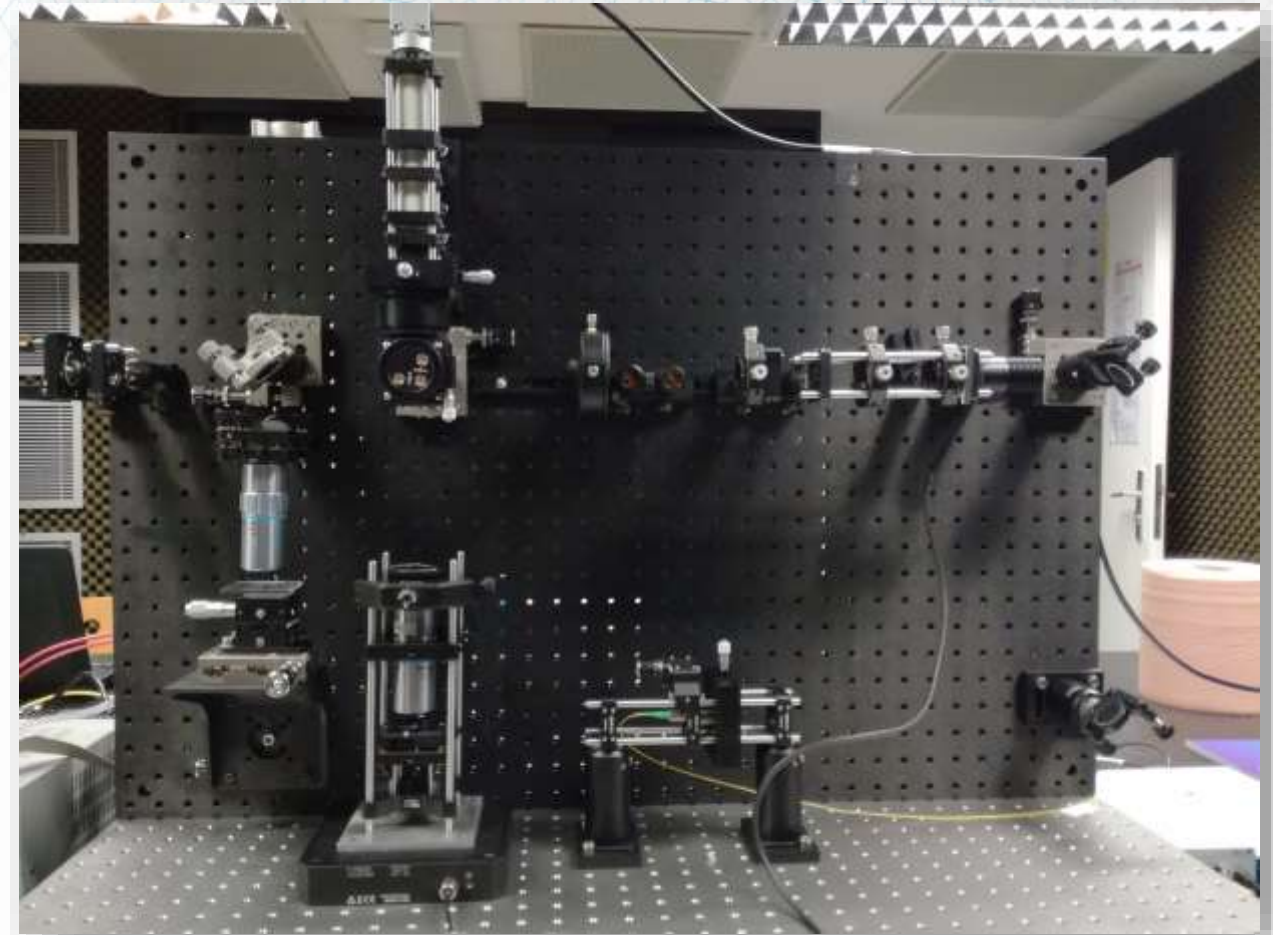
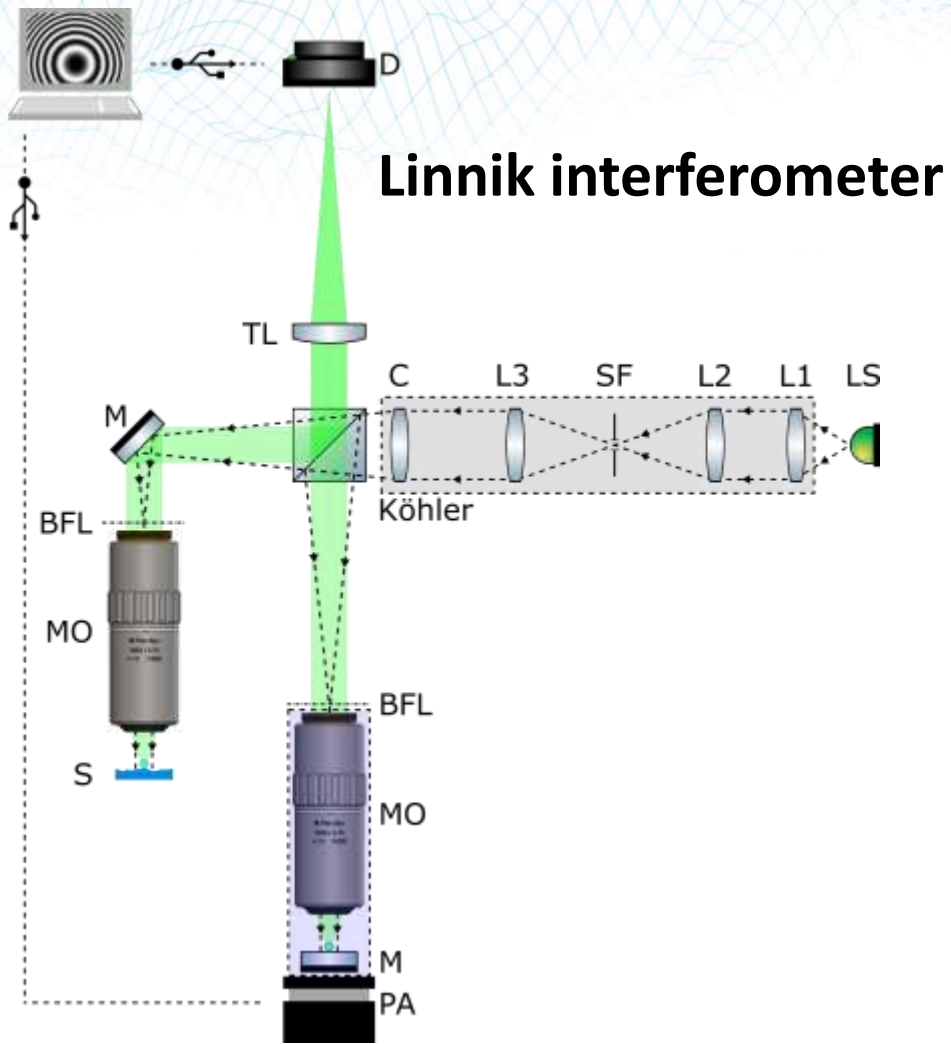
400-nm-groove grating
→ Perfectly resolved



AFM



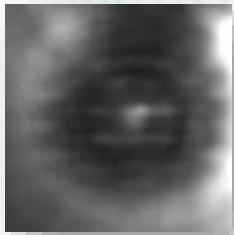
Compensated microsphere-assisted interference microscopy (cMAIM)



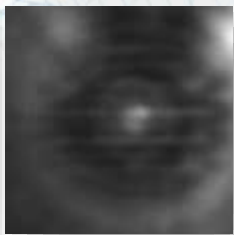
LED light @ 530 nm, $D = 30 \mu\text{m}$, $n = 1.52$, $\times 50 / 0.55$
Phase shifting interferometry (four-steps algorithm)

Compensated microsphere-assisted interference microscopy (cMAIM)

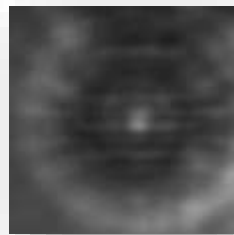
Stack of interferograms



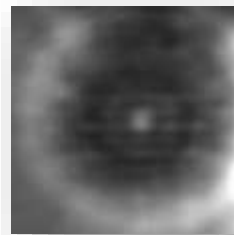
$\Delta\phi = 0 \text{ rad}$



$\Delta\phi = \pi/2 \text{ rad}$

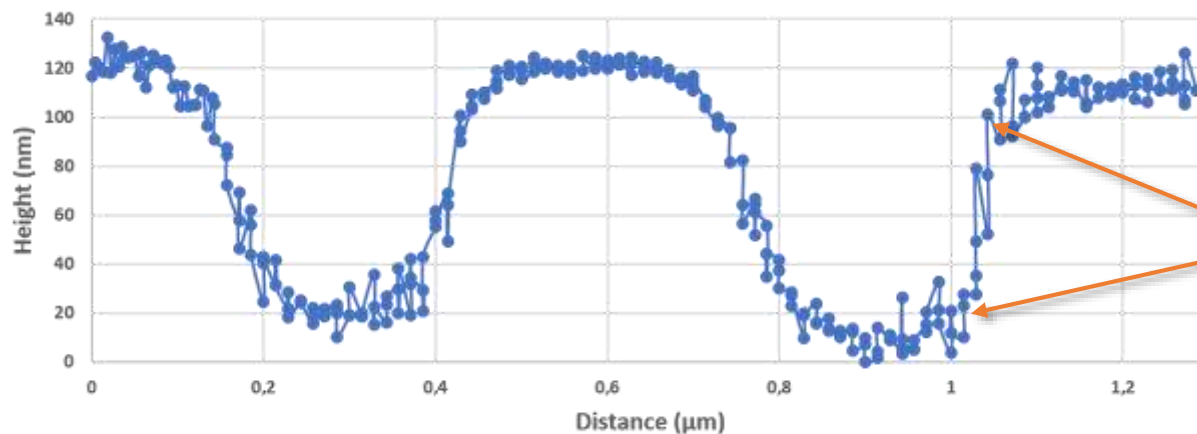


$\Delta\phi = \pi \text{ rad}$

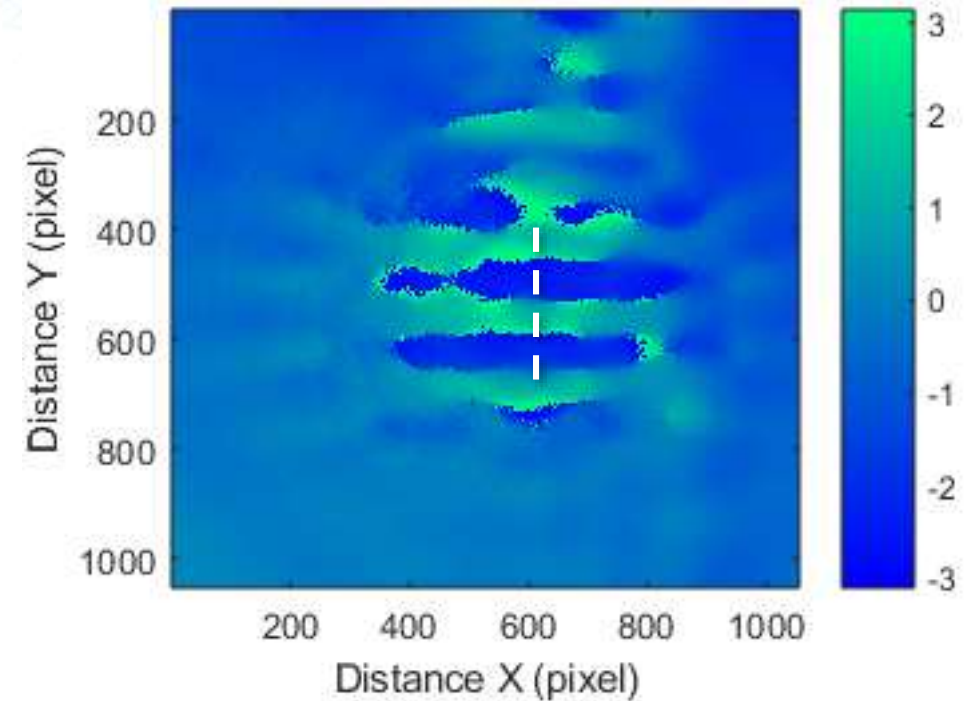


$\Delta\phi = 3\pi/2 \text{ rad}$

period = 600 nm, h = 170 nm



Wrapped phase

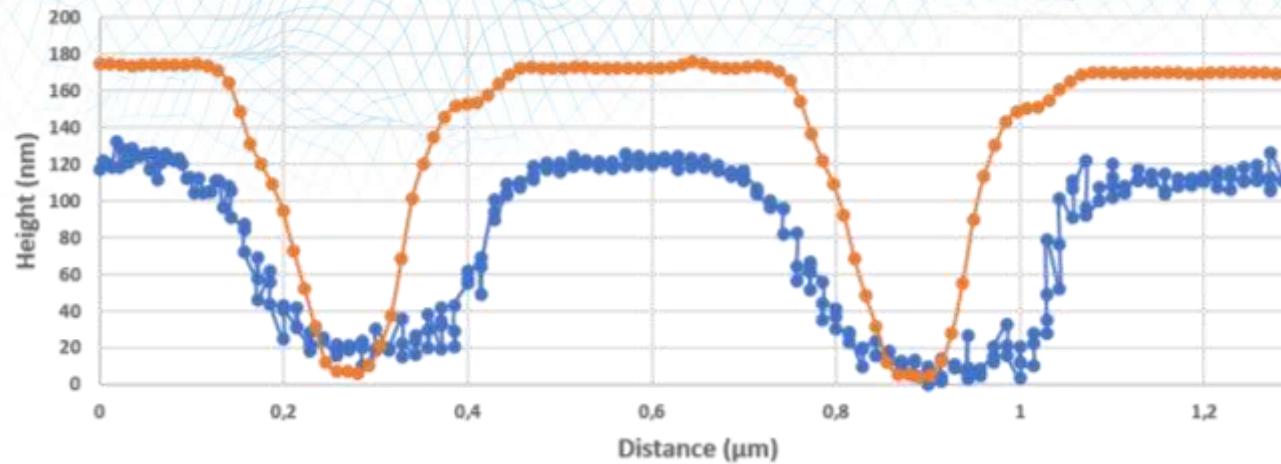


No data processing

→ Fringe contrast = 60%

→ Axial sensitivity $\sigma = 5.6 \text{ nm}$

Measurement errors in cMAIM



$h = 170$ nm (AFM \rightarrow V-like shape of profile)

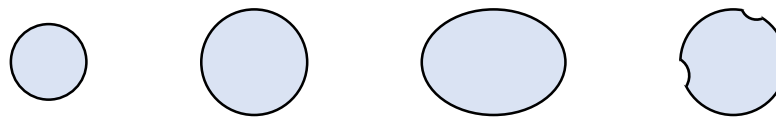
$h = 120$ nm (cMAIM \rightarrow microsphere quality)



\rightarrow Diameter ($\Delta D \approx 2$ μm)

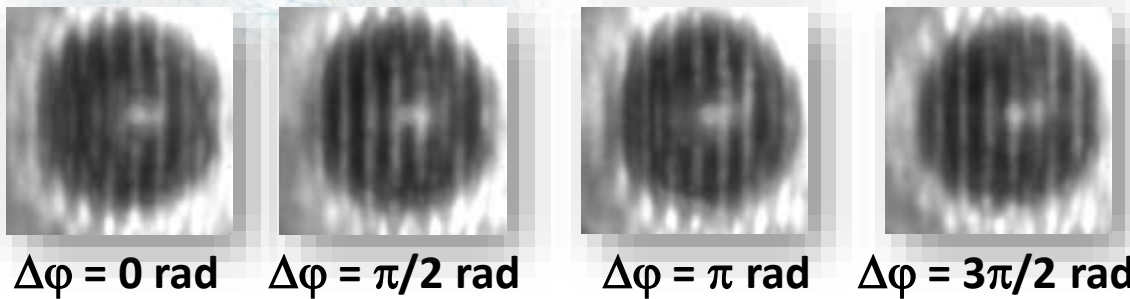
\rightarrow Sphericity

\rightarrow Surface chips

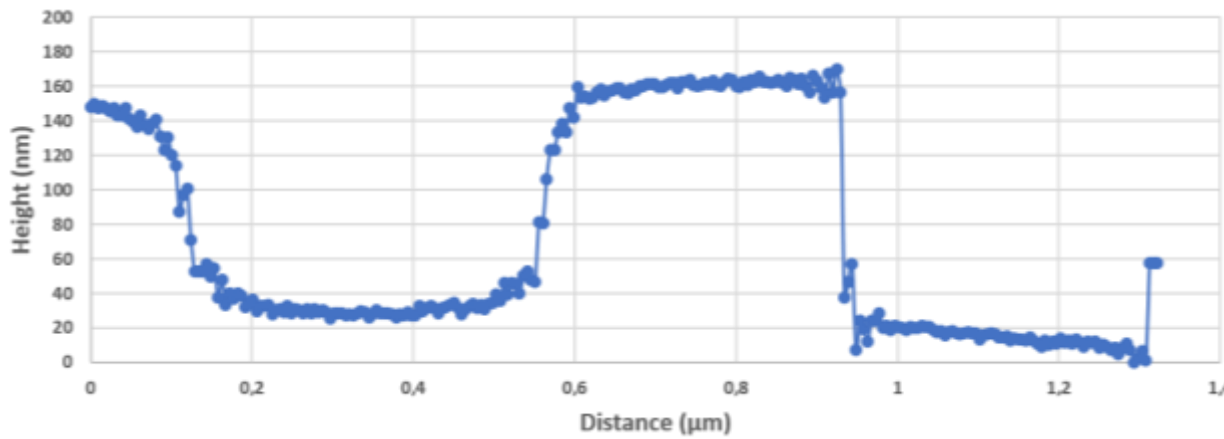


Compensated microsphere-assisted interference microscopy (cMAIM)

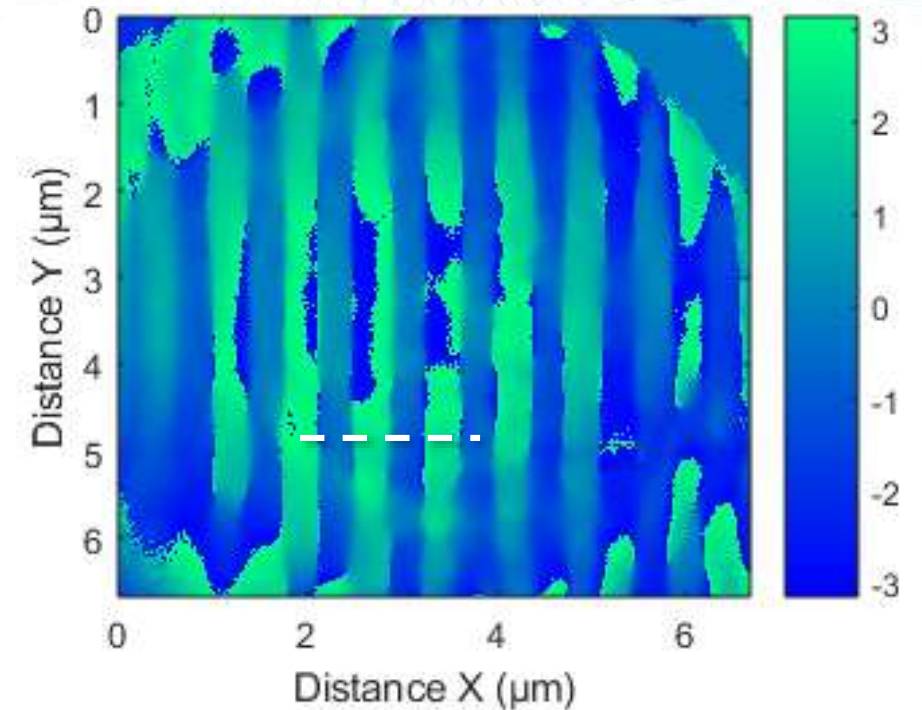
Stack of interferograms ($D = 50 \mu\text{m}$)



period = 800 nm, $h = 160 \text{ nm}$



Wrapped phase

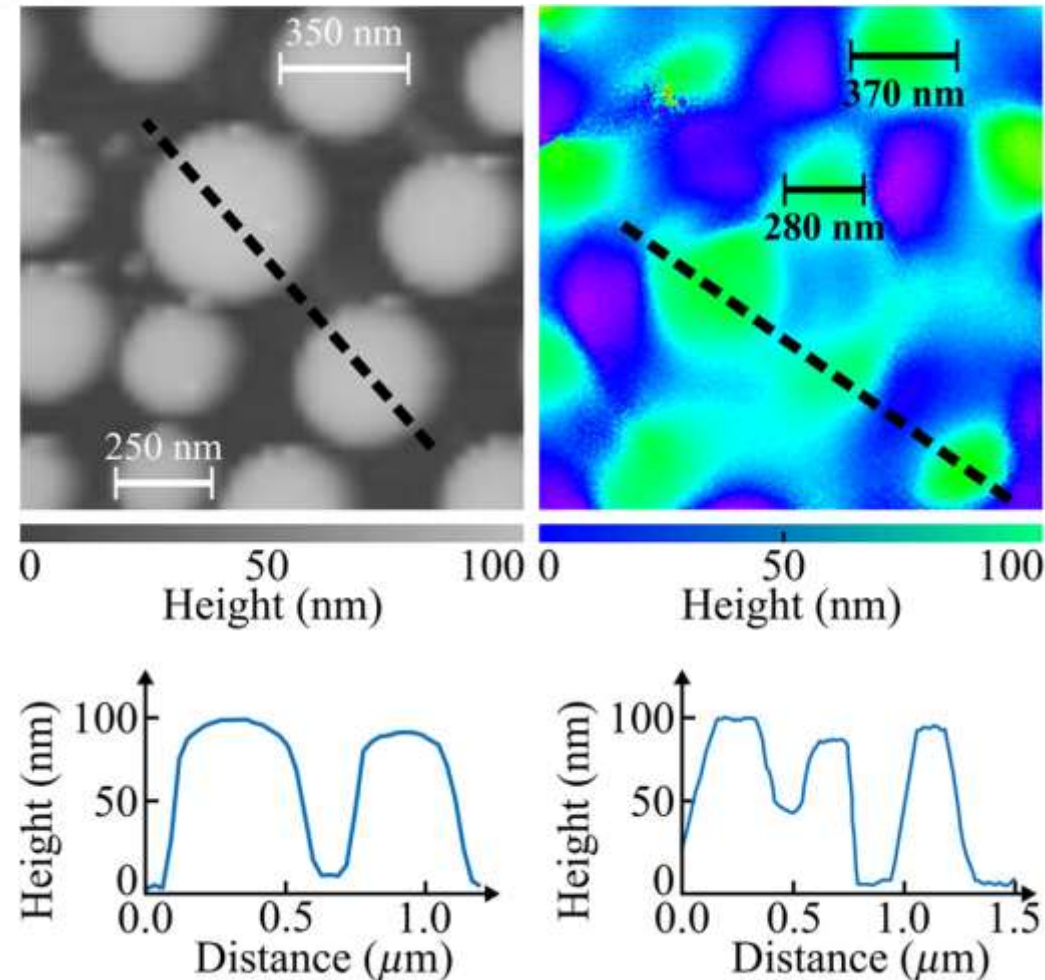


→ Fringe contrast = 65%

→ Axial sensitivity $\sigma = 3.6 \text{ nm}$

Compensated microsphere-assisted interference microscopy (cMAIM)

Disordered array of poly(methyl methacrylate)-based nanopillars ($D = 30\ \mu\text{m}$)



Discussion

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Château de Chambord (France) through a ball lens, Photography [@monvoisinsappellemickjagger](https://www.instagram.com/monvoisinsappellemickjagger)

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