COMPUTATIONAL IMAGING BEYOND THE ABBE AND NYQUIST LIMITS

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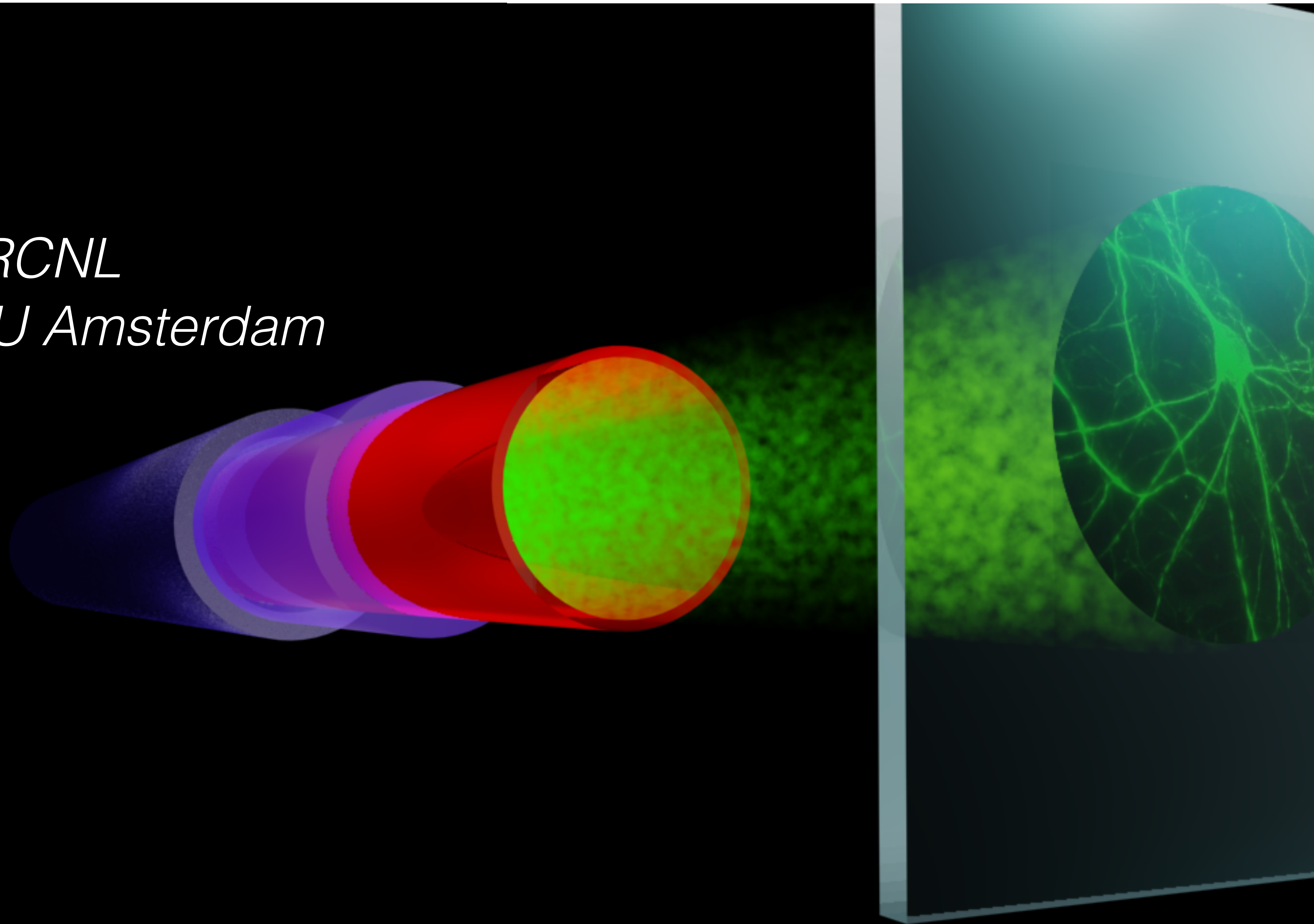

April 2021

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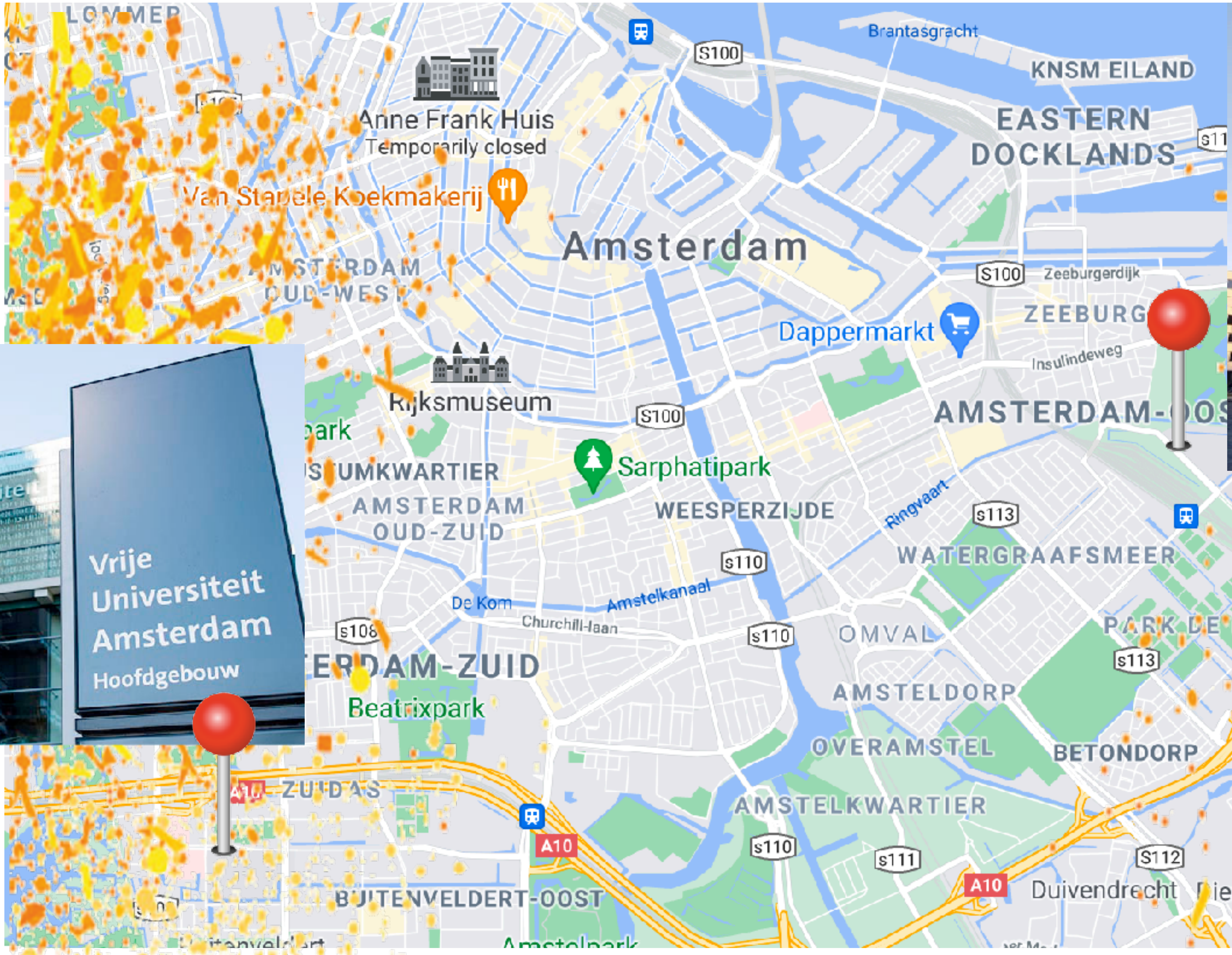

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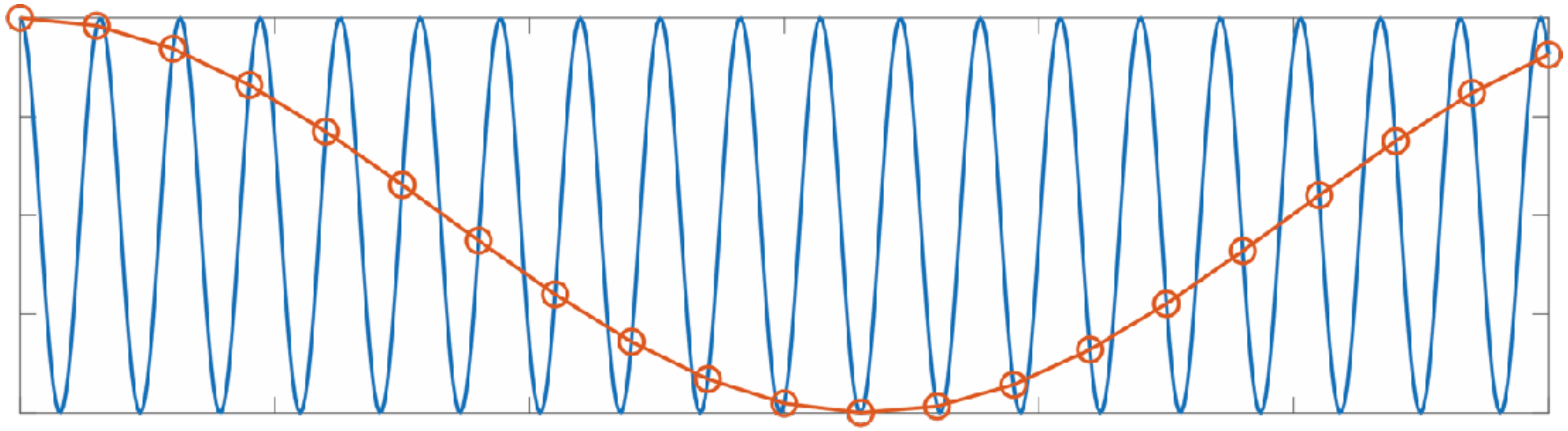
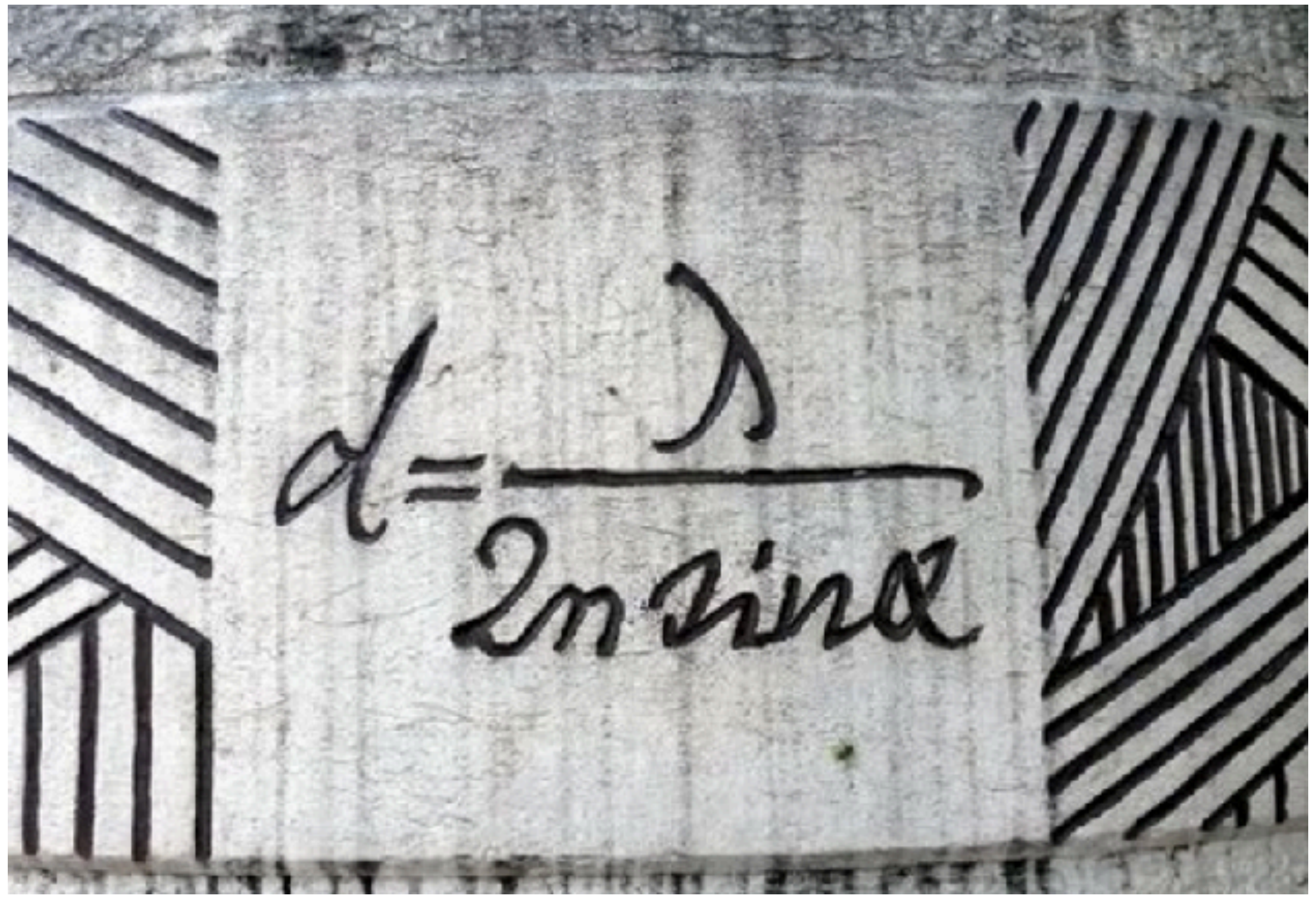
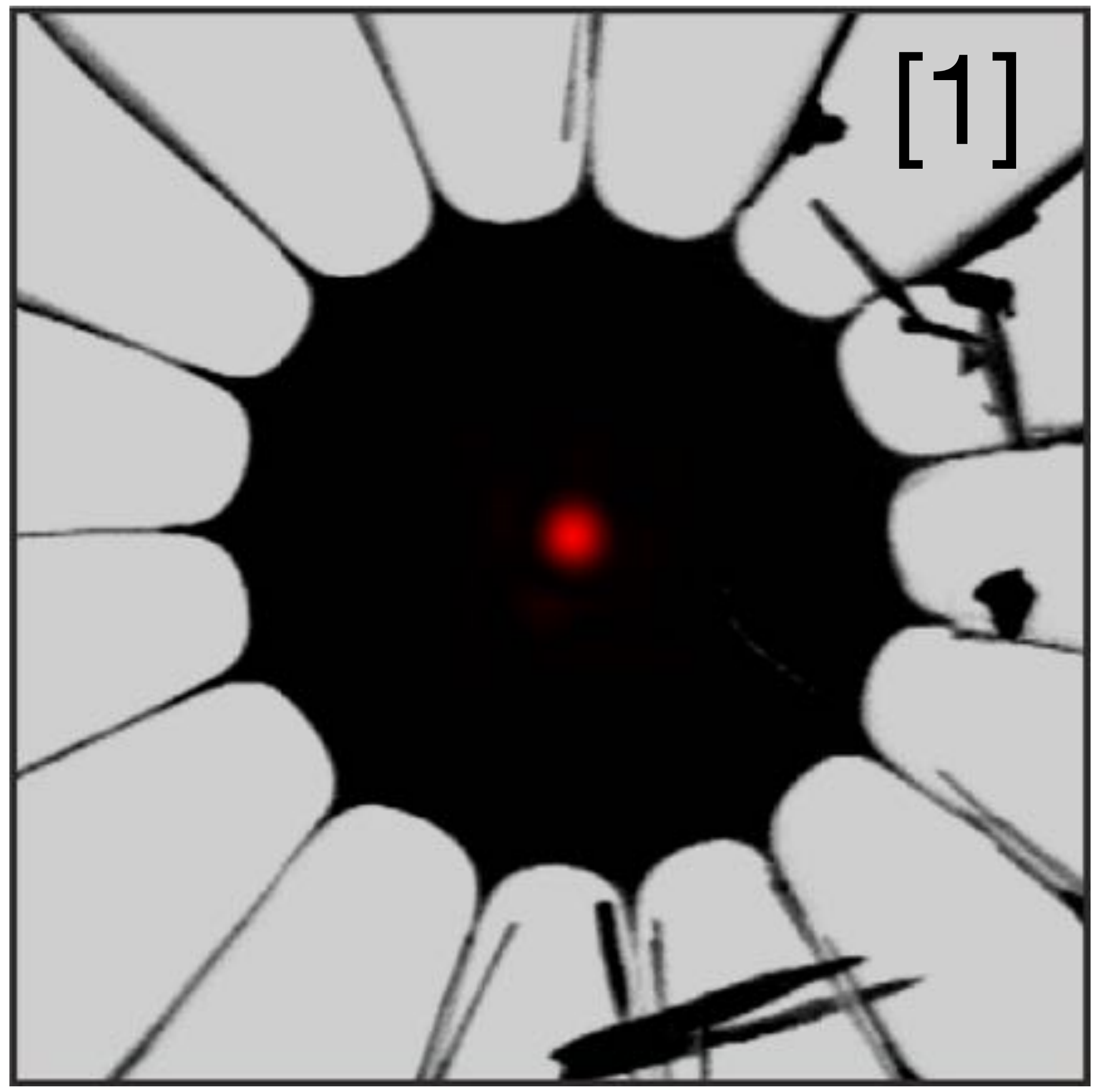
Far-field optical imaging

State-of-the-art
‘fundamental’ limits

- Imaging speed:
  Nyquist limit
- Spatial resolution:
  Abbe diffraction limit
- Penetration depth





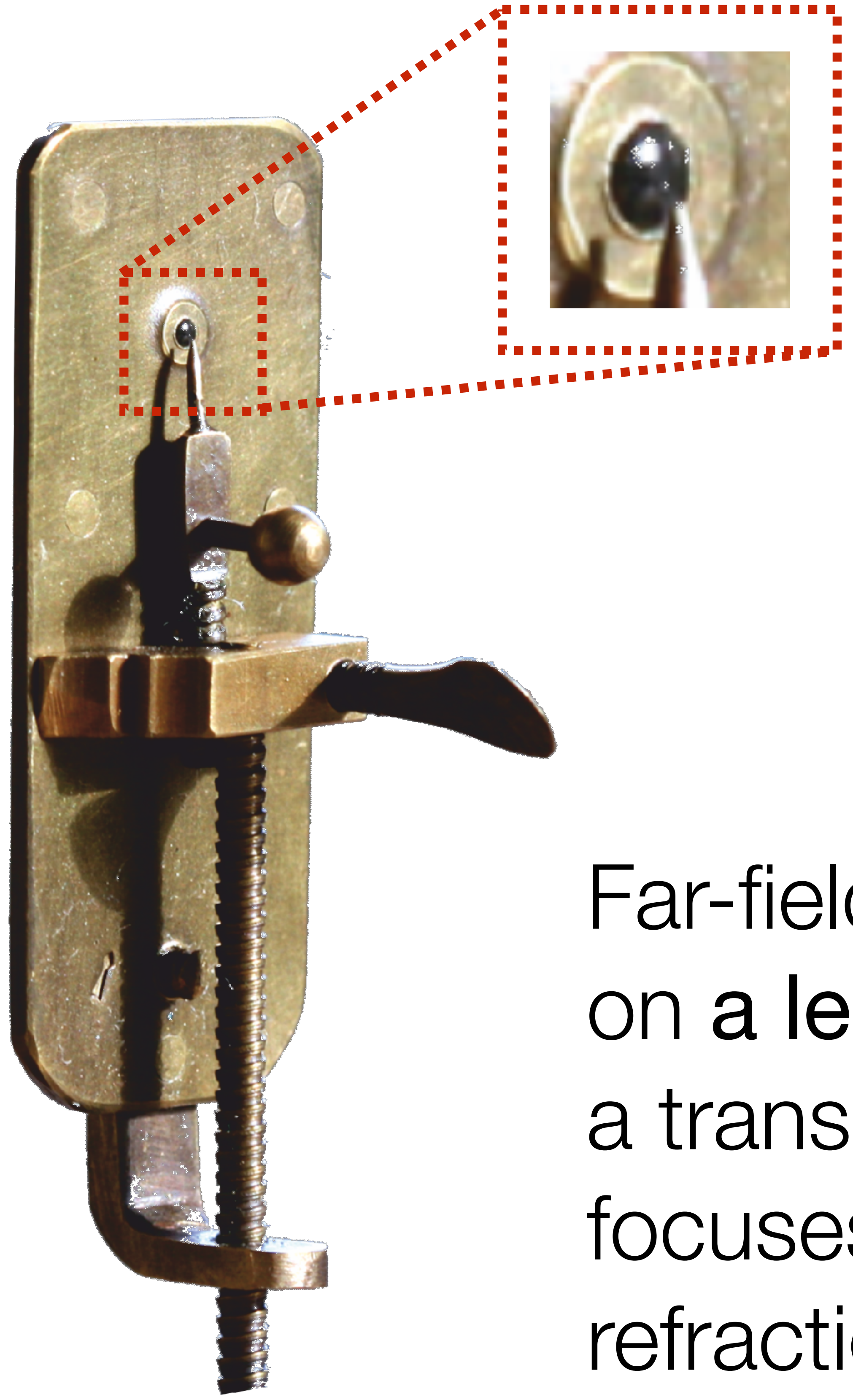


[1] Amitonova, L. V. *et al. Optics Letters* **41**, 497 (2016)

Far-field optical microscopy

17th | 19th | 21st | centuries

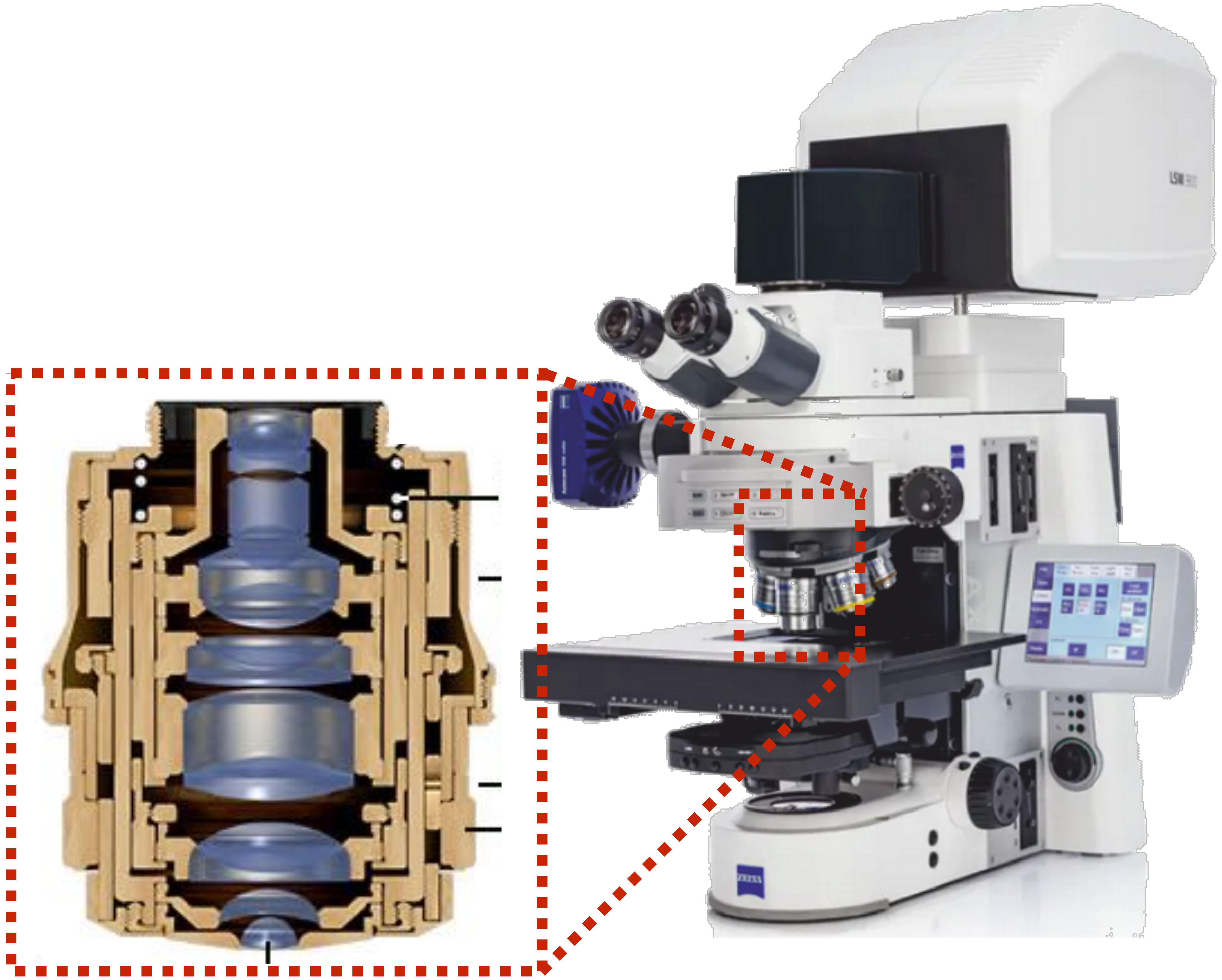
van Leeuwenhoek | Abbe | Zeiss



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

The main principle is not changing!

Far-field optical microscopy is based on **a lens**:
a transmissive optical element that focuses a light beam by means of refraction



New paradigm

Exploiting disorder!

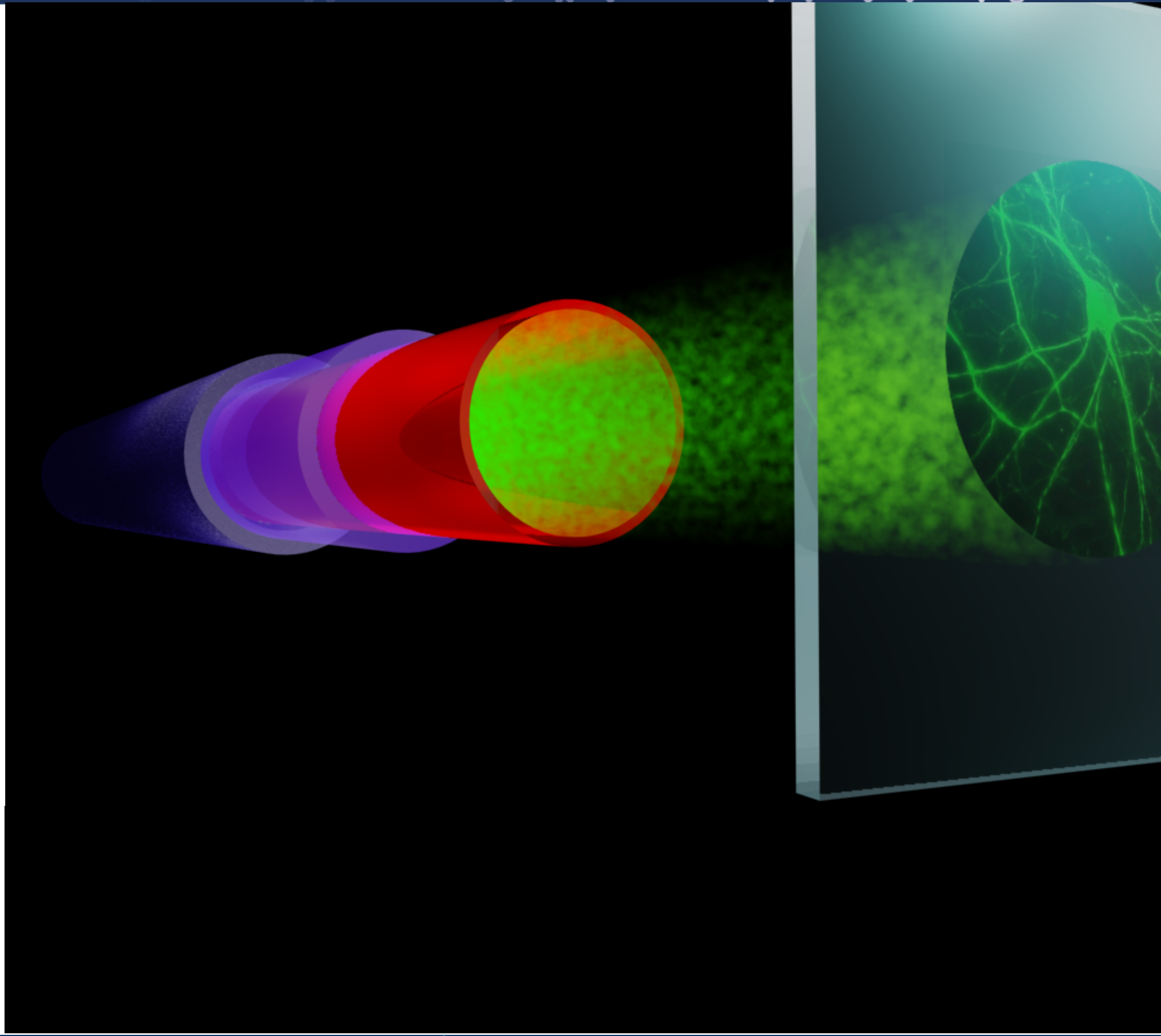
I aimed to change the concept: **disorder helps to see better!**

Exploiting disorder!

I aimed to change the concept: **disorder helps to see better!**

Outline

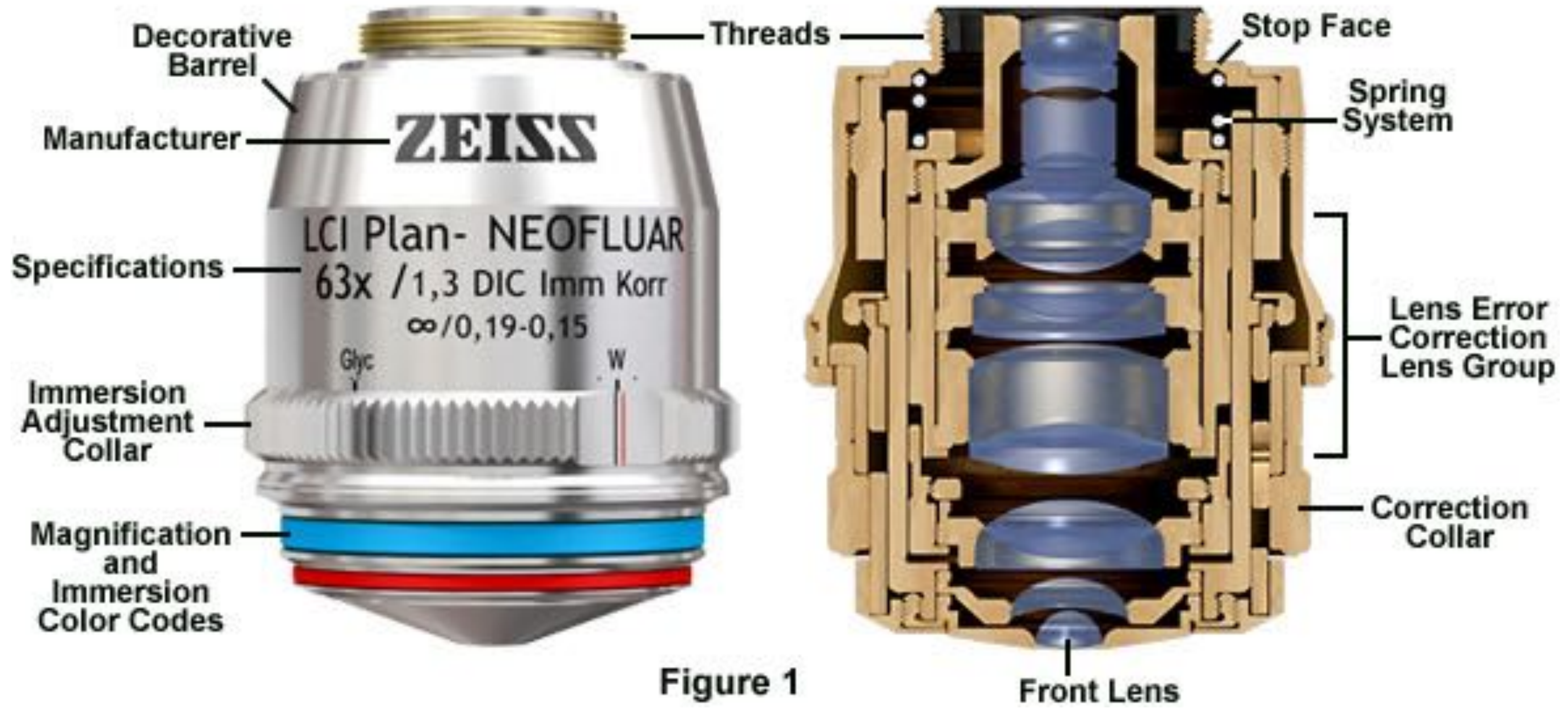
- New concept of far-field computational imaging beyond the limits
- Fluorescent super-resolution imaging:
  - simulations
  - experimental results
  - theoretical analysis
- Label-free super-resolution imaging:
  - experimental results
- Summary

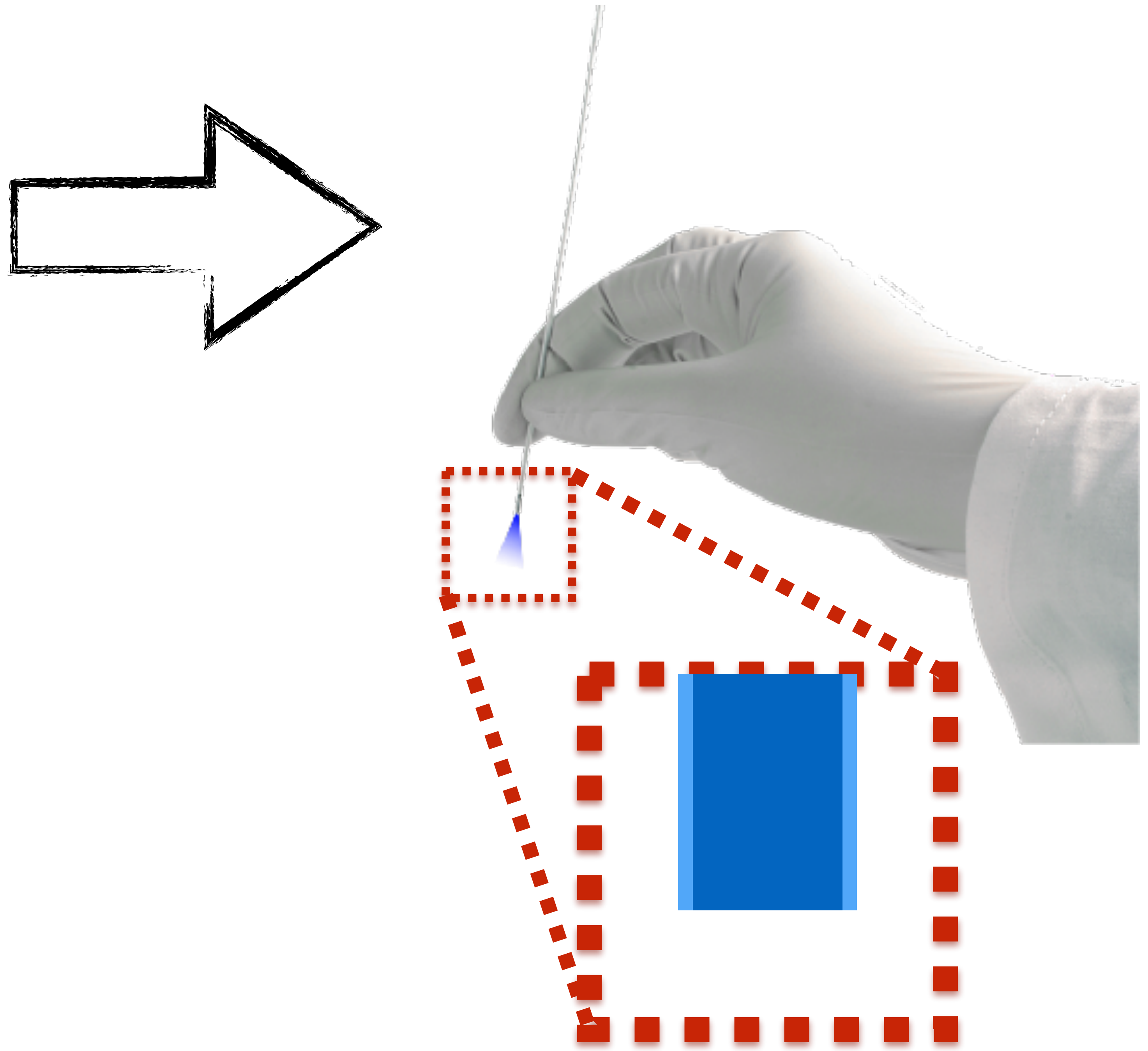


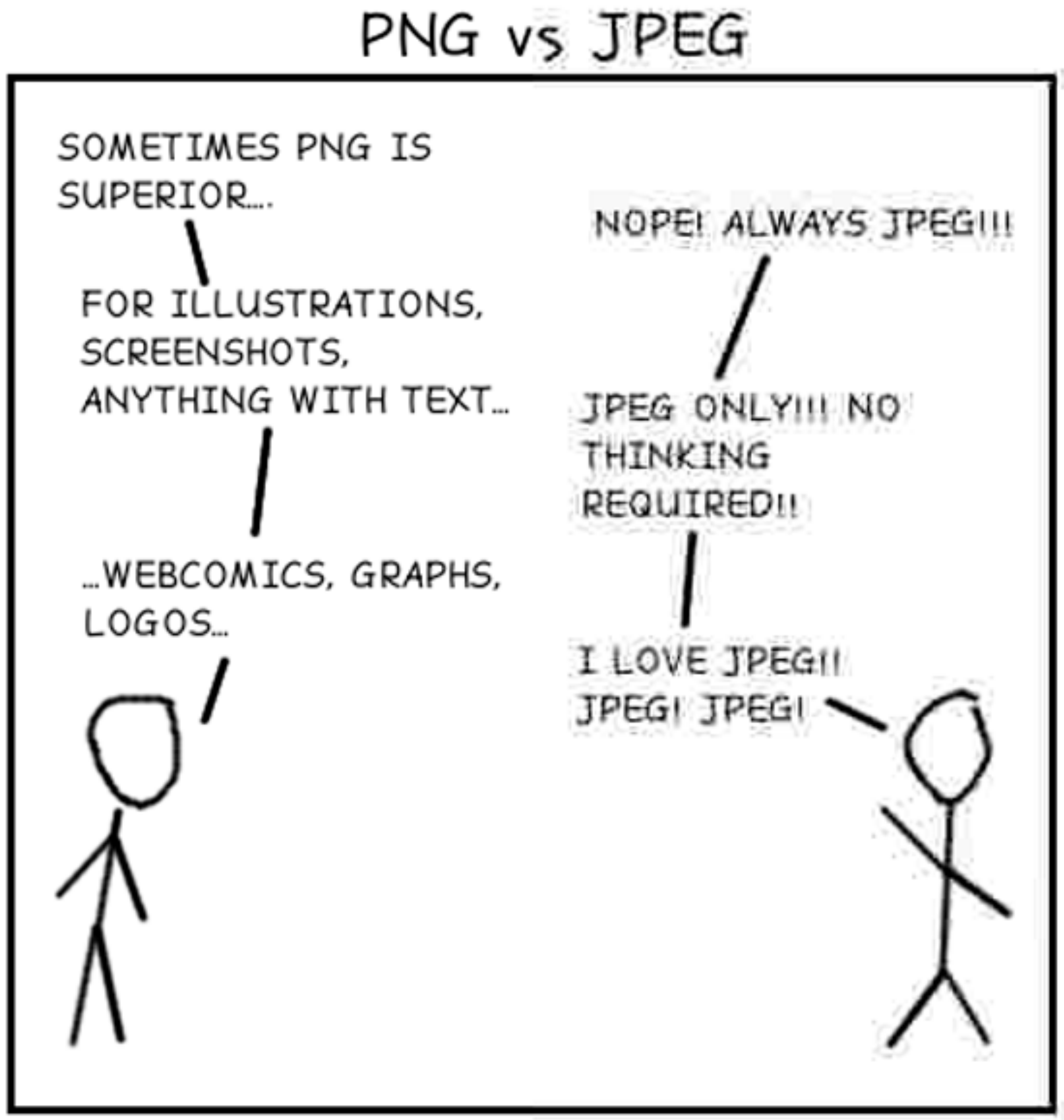
New concept of imaging

Components:

- Light scrambling → maximise information content
- Multimode fiber → ultra-compact probe
- Compressive sensing → optimal reconstruction







Standard microscope objective

- Complicated design and large price
- Large size
- Coupling between field of view and resolution: high resolution leads to low FOV

New concept of imaging

100% of information

100% of information

< 10% of information

Overcoming the Nyquist limit

Sparsity constraint allows to reconstruct the data from *incomplete* measurement set

→ Imaging beyond **the Nyquist limit**

Problem:
To recover a vector $x \in \mathbb{R}^n$
from data *y:*

$$y = Ax,$$

where A is an m×n 'sensing matrix'
n — number of pixels
m — number of 'measurements'
m << n

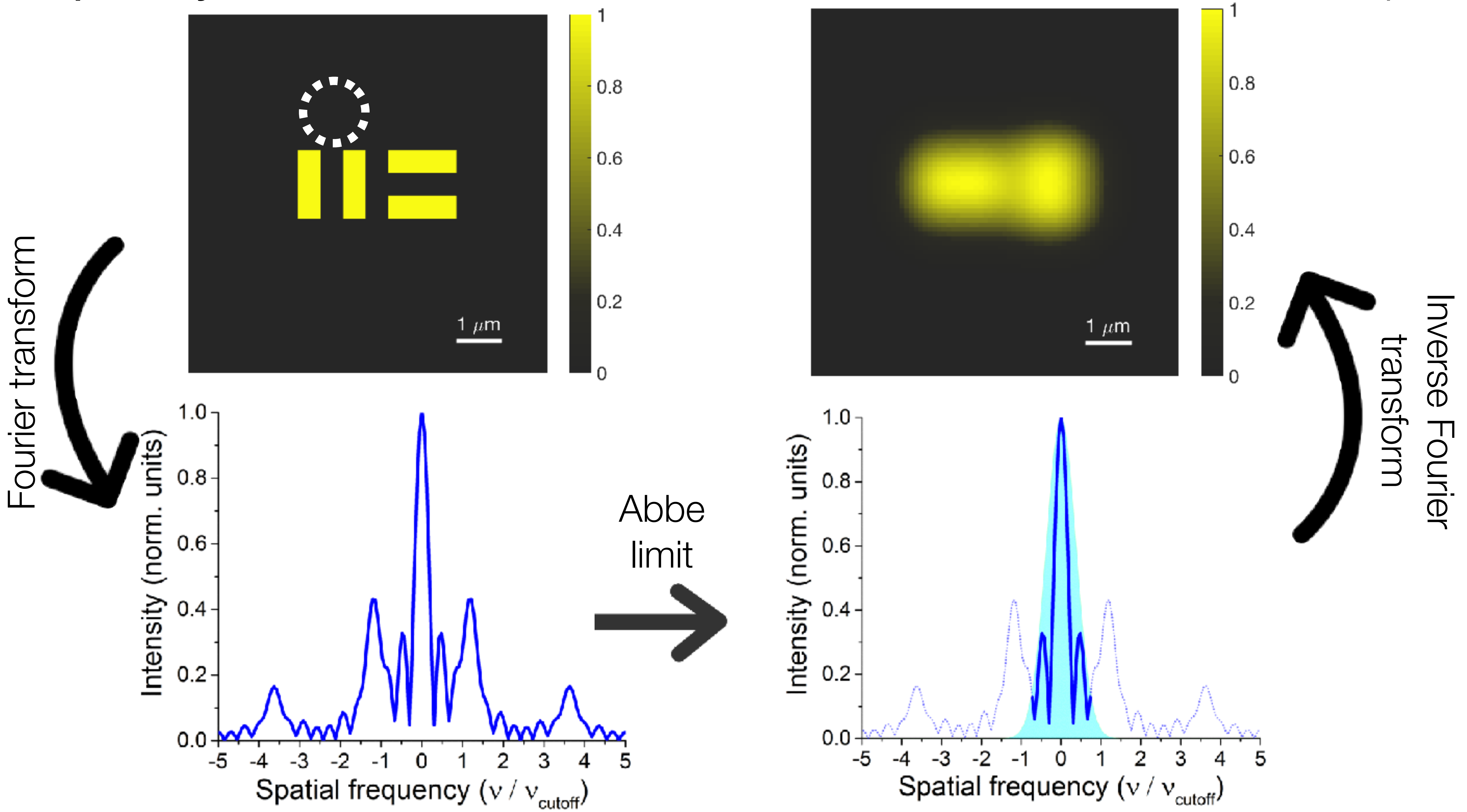
Solution:
The following linear program gives an accurate reconstruction:

$$\min_{\tilde{x} \in \mathbb{R}^n} \|\tilde{x}\|_{\ell_1} \quad \text{subject to} \quad A\tilde{x} = y (= Ax)$$

Among all objects consistent with the data, we pick that whose coefficient sequence has minimal l_1 norm.

Overcoming the Abbe limit

Sparsity constraint allows to reconstruct the data from *incomplete* measurement set



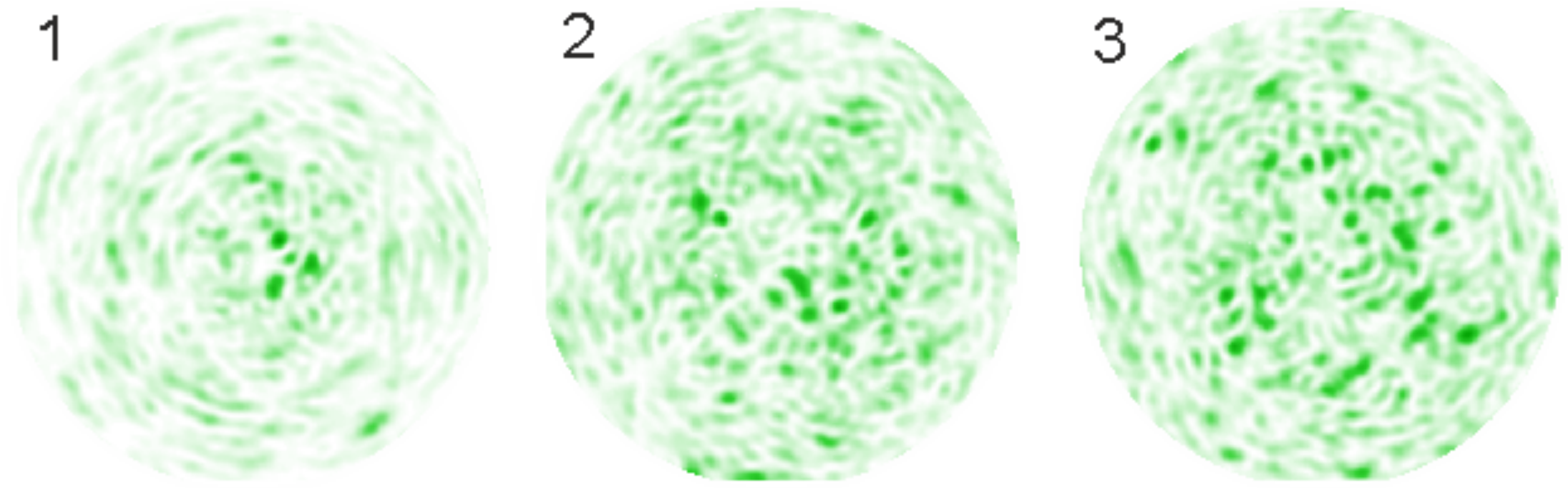
Overcoming the Abbe limit

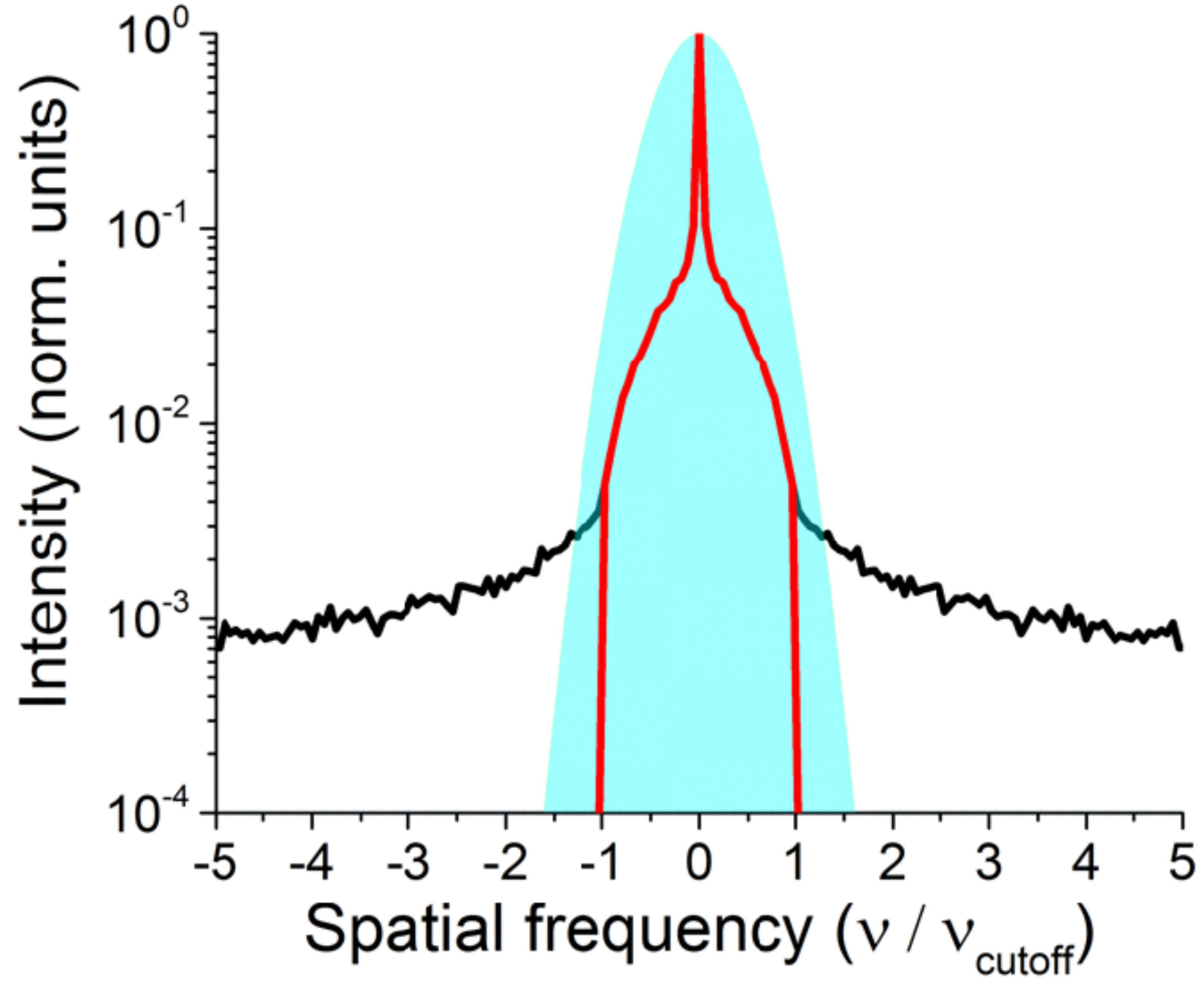
Sparsity constraint allows to reconstruct the data from *incomplete* measurement set

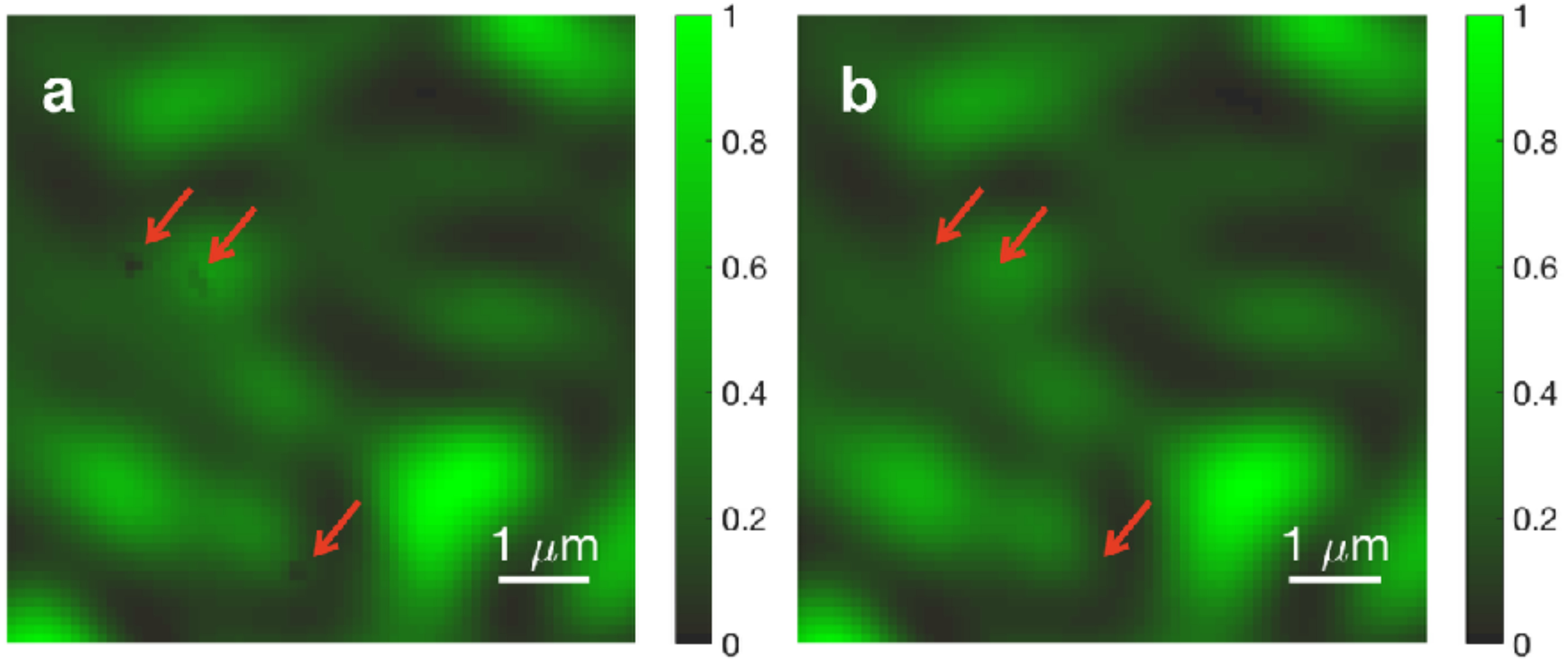
Simulations

Parameters

- Experimentally measured set of speckle patterns
- NA = 0.22 (Spatial frequency profile of each speckle pattern was filtered to remove any accidental high frequency component)
- Poisson noise
- ℓ1-magic [from Stanford.edu]

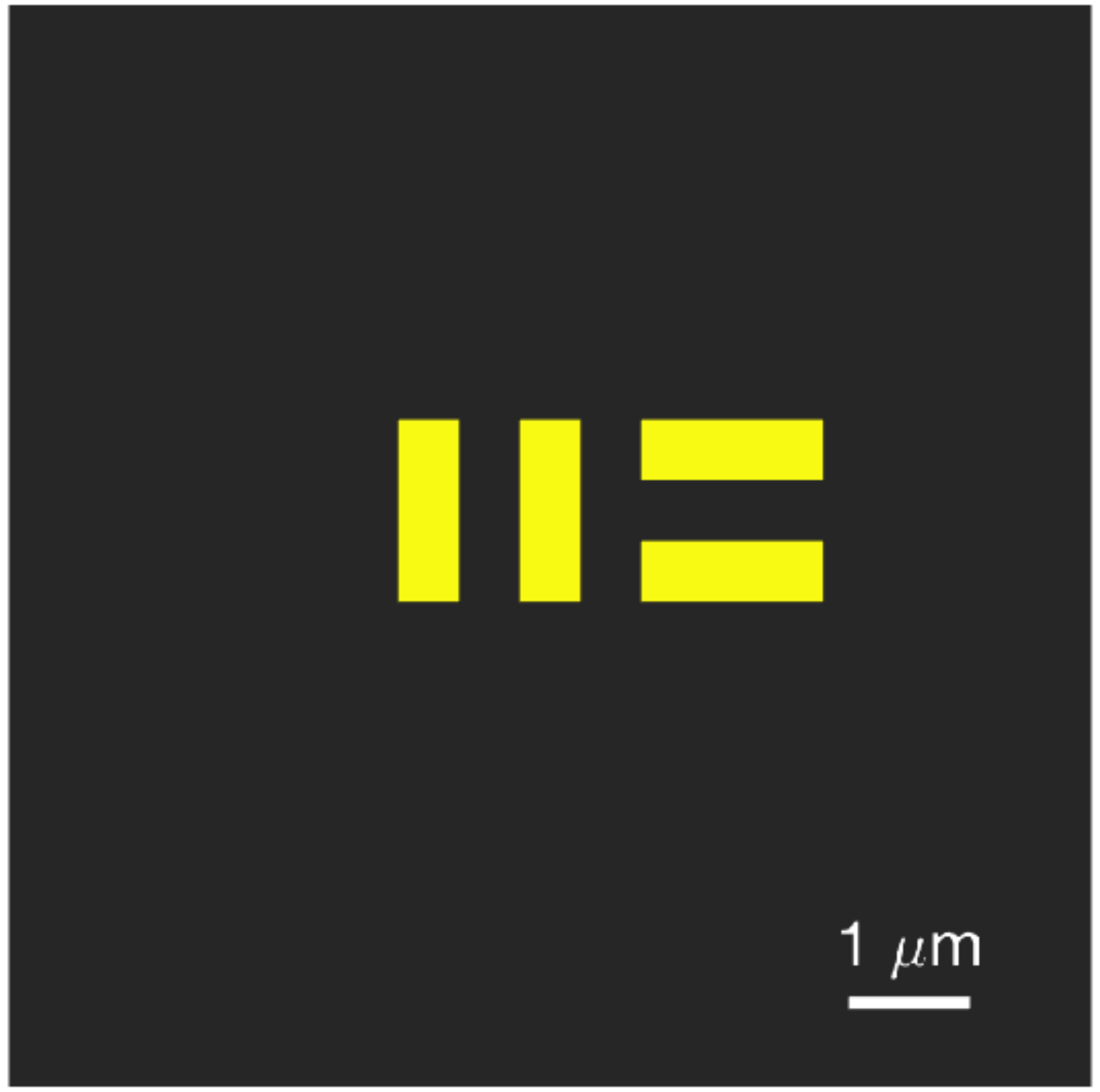




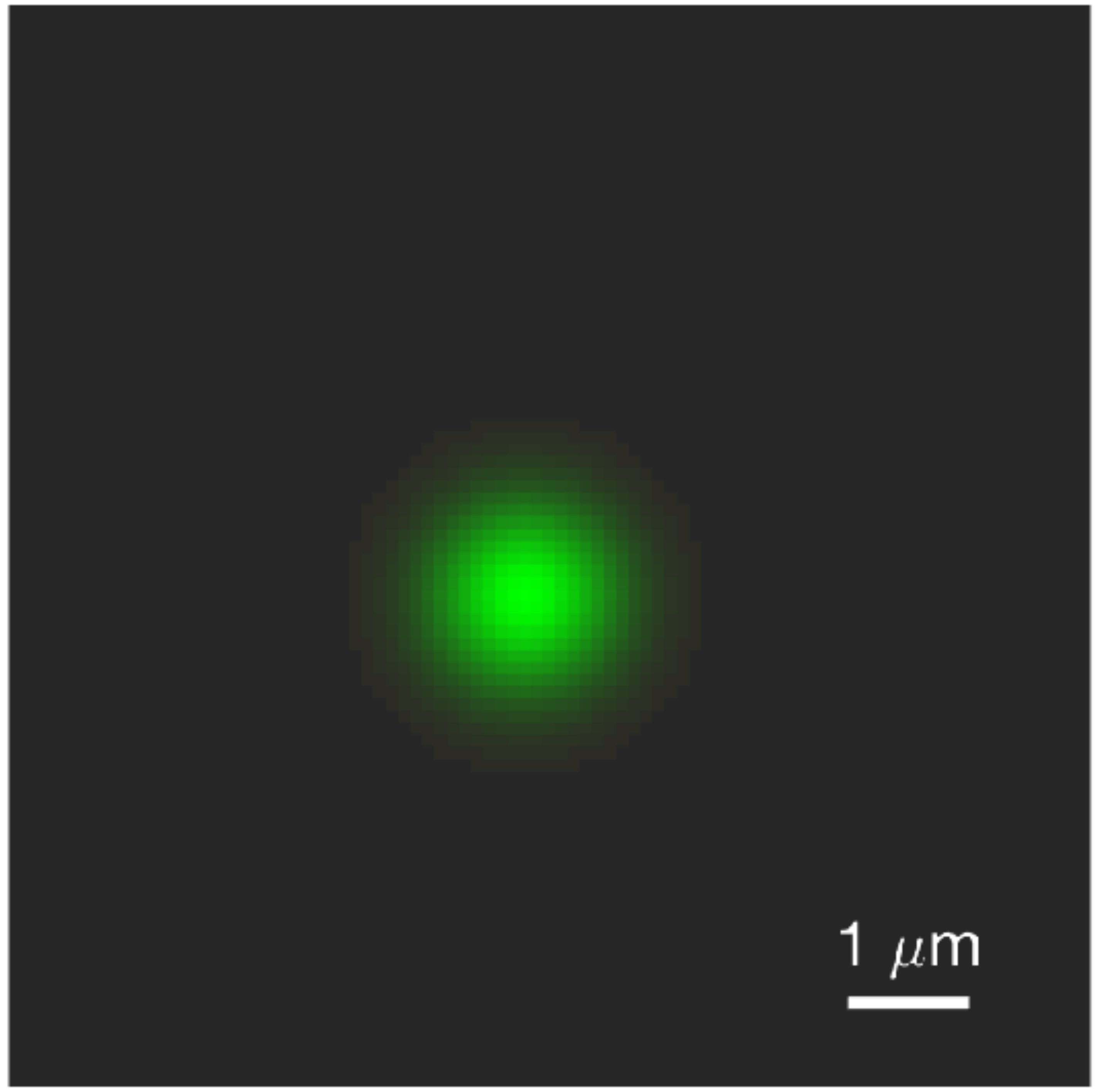


Simulations

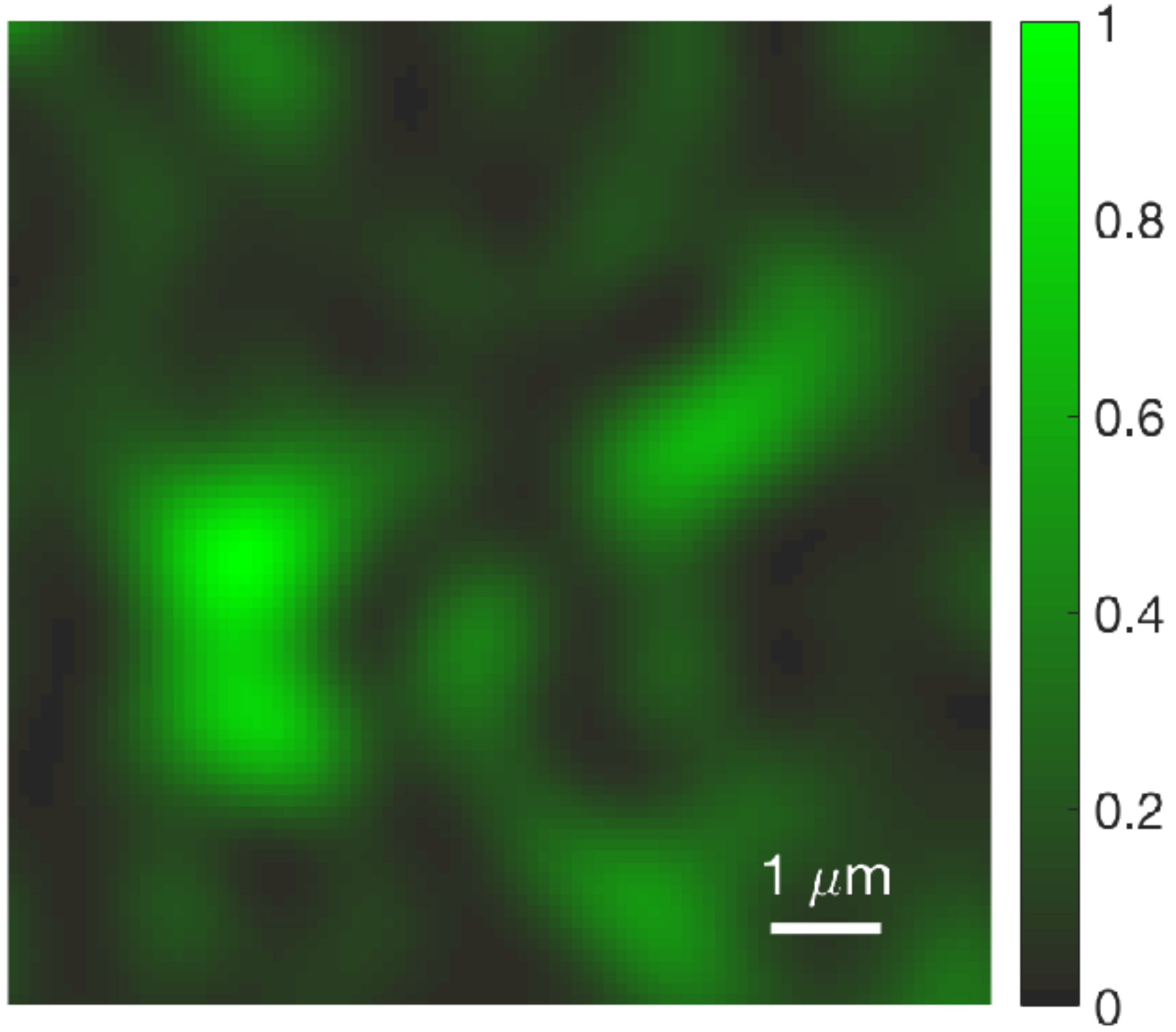
Sample



Gauss illumination

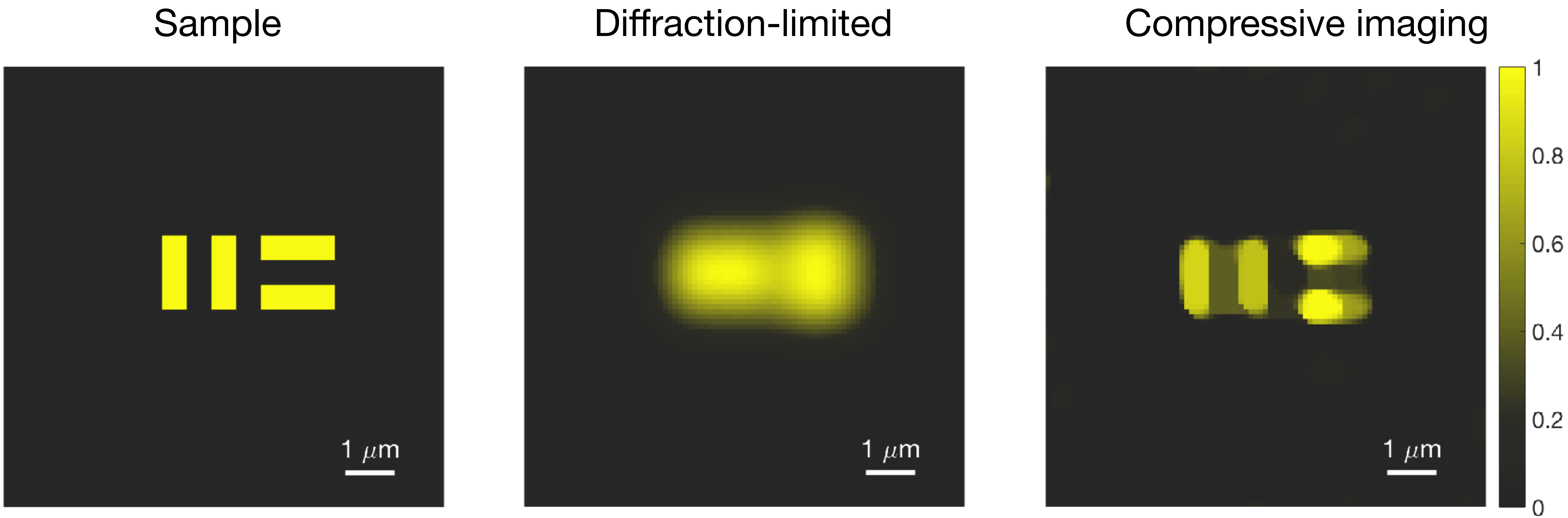


Speckle pattern



- NA = 0.22

Simulations



- NA = 0.22
- 3E6 photons per ‘measurement’ in average
- 256 ‘measurements’ to reconstruct 8100 pxls
- > 30 times speed improvements
- 2.4 times resolution improvements

Experimental setup

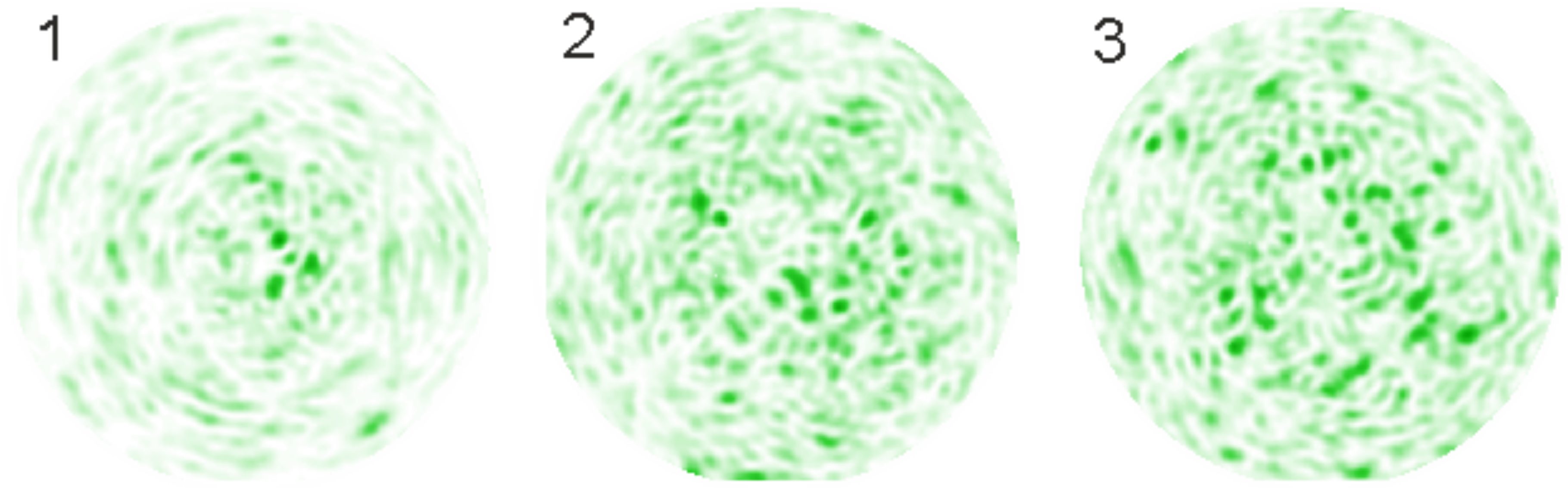
Fiber core radius a

Numerical aperture $NA = \sqrt{n_{core}^2 - n_{clad}^2}$

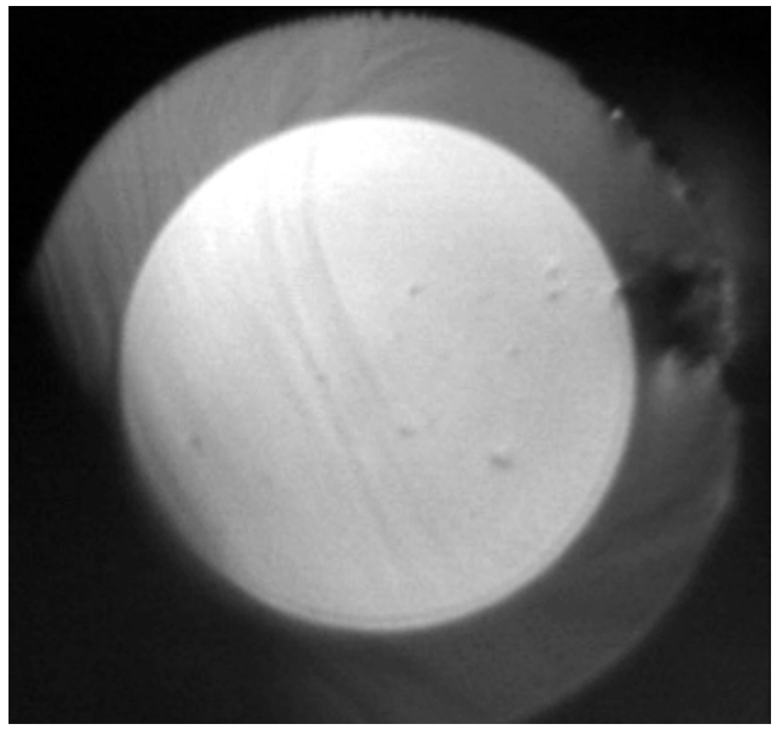
V parameter (normalized frequency): $V = \frac{2\pi}{\lambda} a NA$

Number of modes

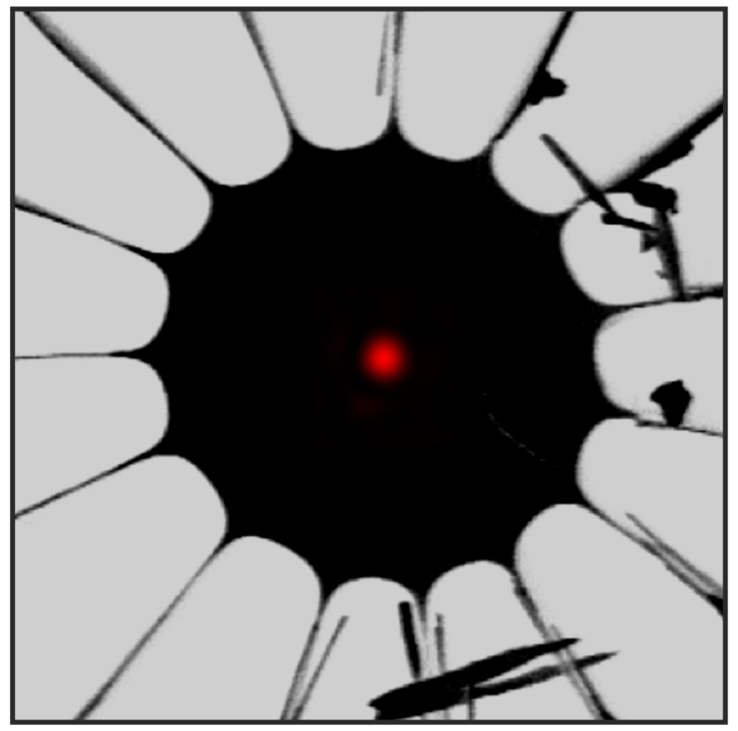
$$N_{modes} = \frac{V^2}{2}$$

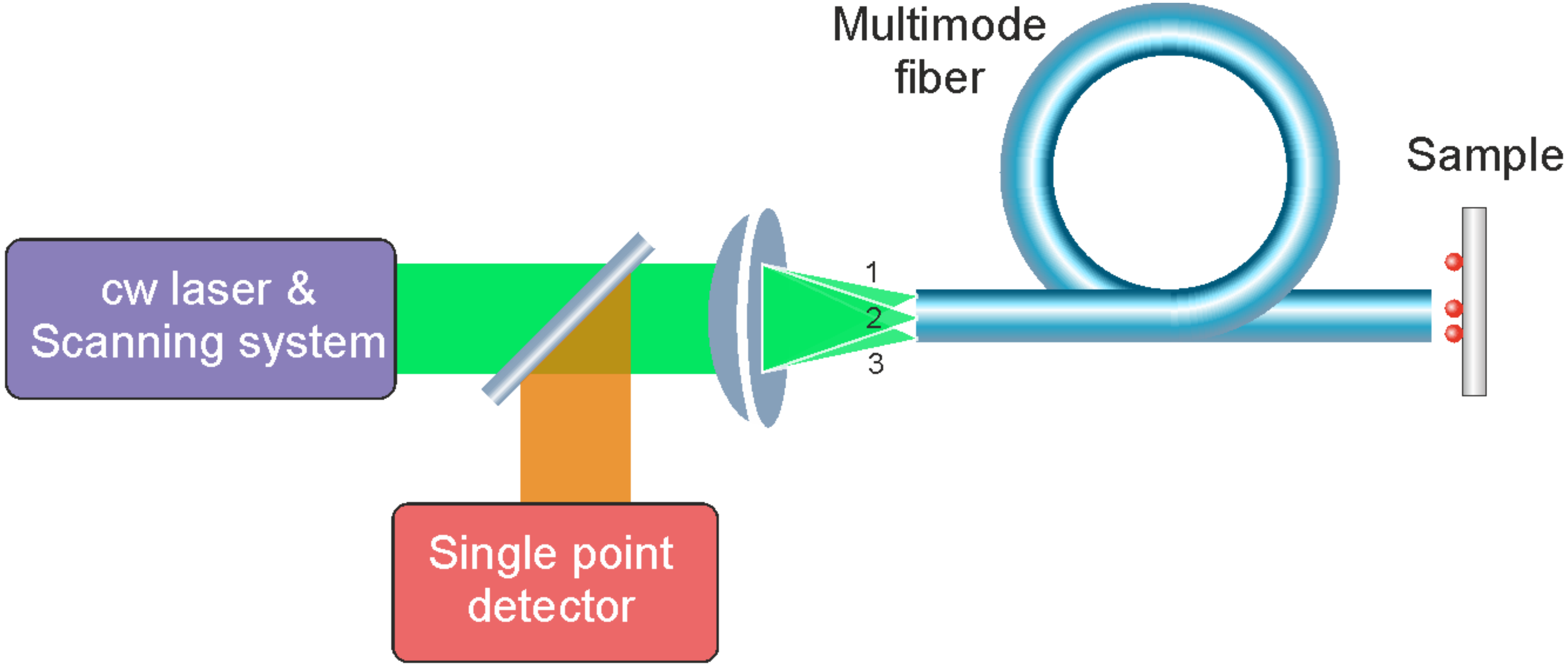


NA ~ 0.22



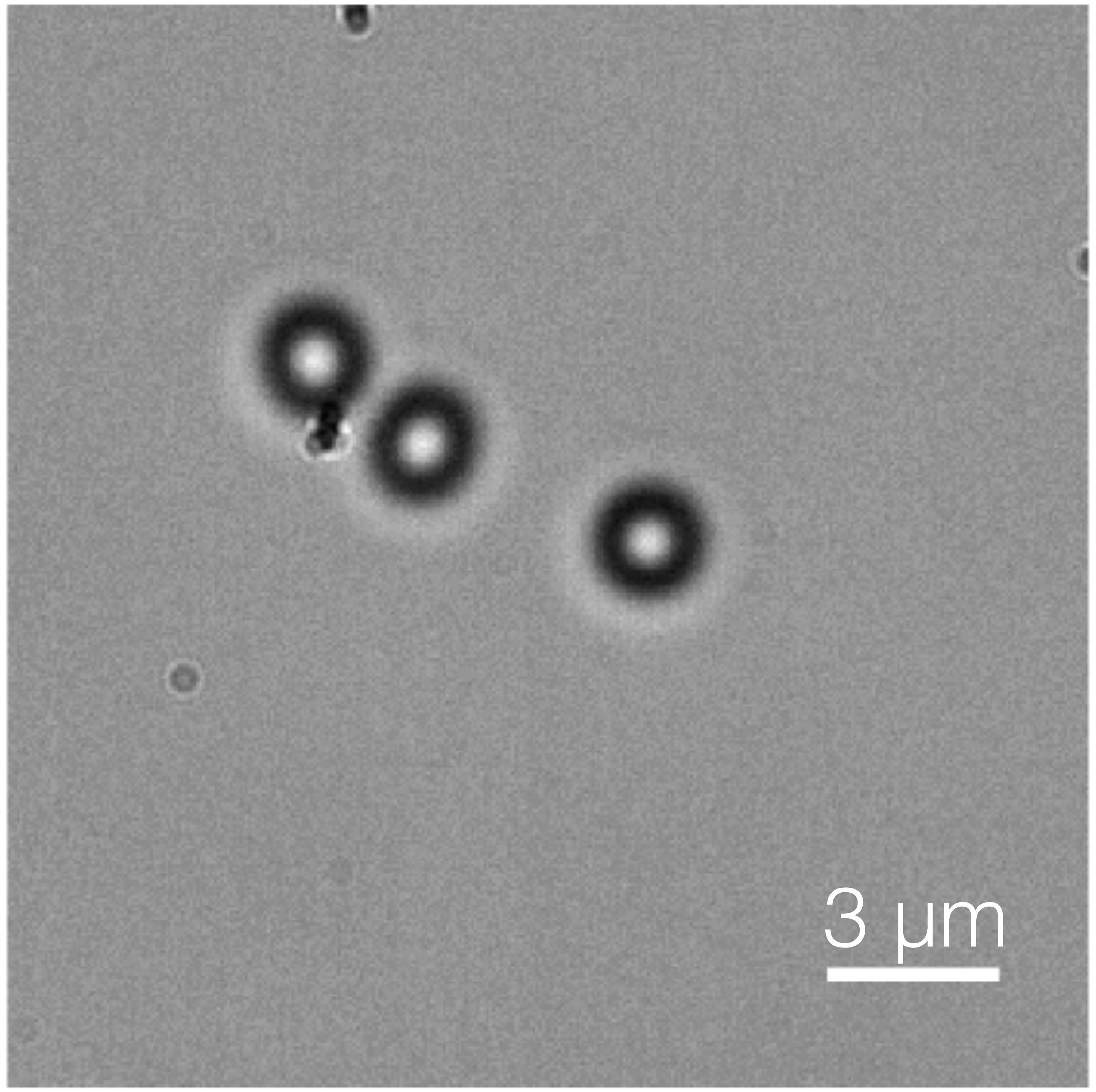
NA > 0.6



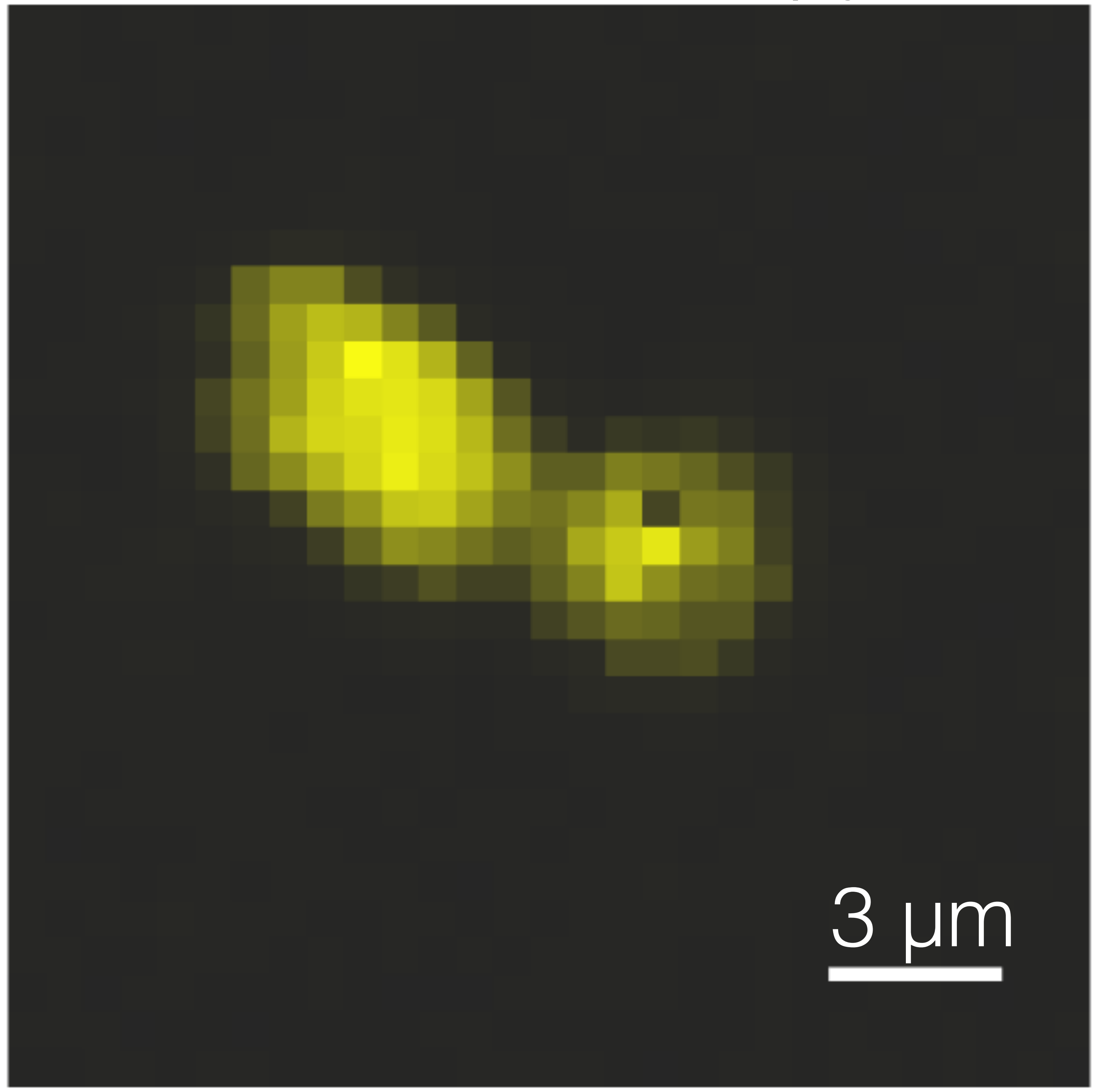


Experimental results

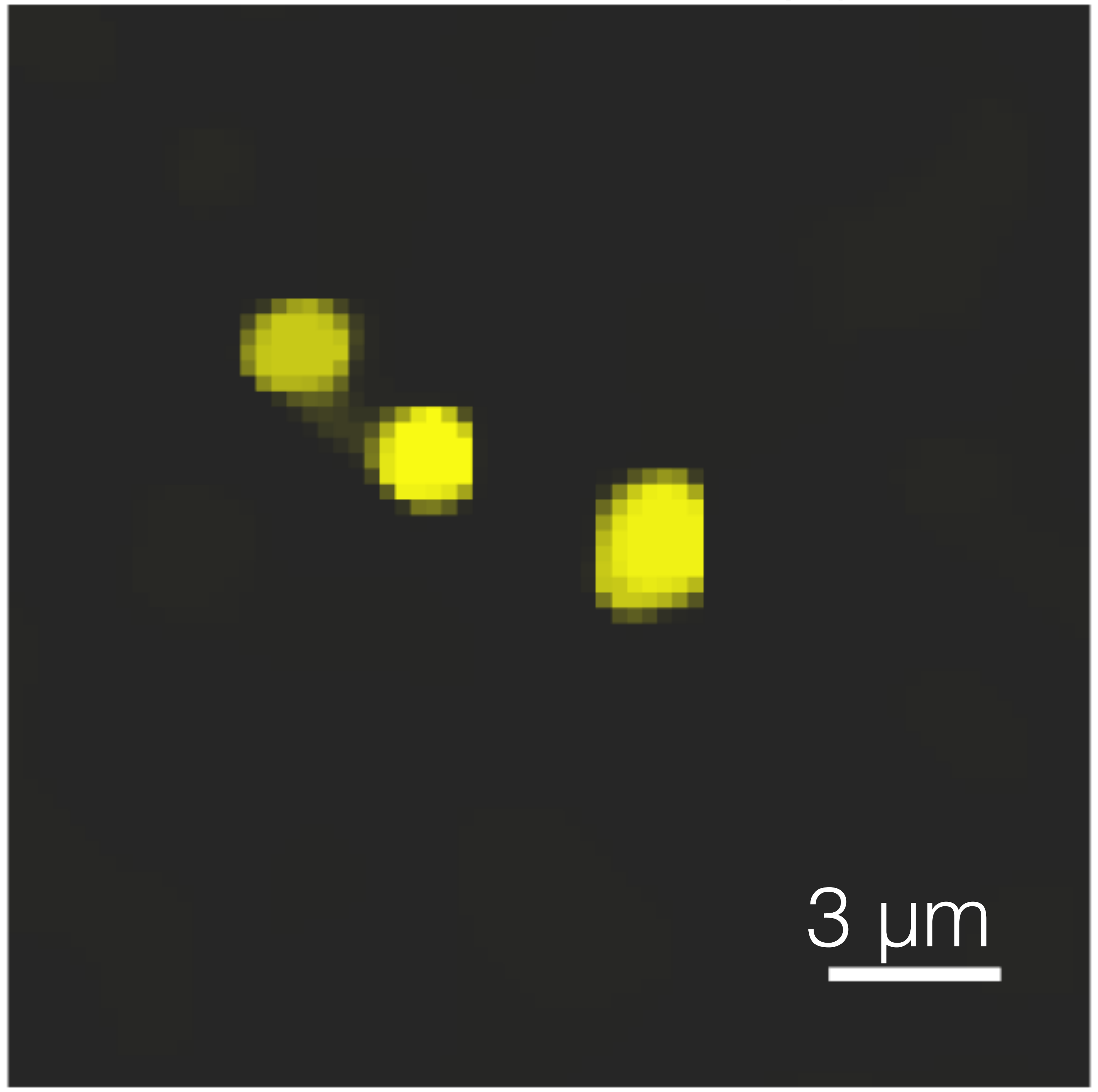
Sample



Diffraction-limited endo-microscopy



Super-resolution endo-microscopy



NA	0.1
Diffraction limit	2.66 µm
Area	30x30 µm^2

Resolution	> 2.5 times below the Abbe limit
Imaging speed	> 15 times better than Nyquist limit

L. V. Amitonova and J. F. de Boer, Light Sci Appl **9**, 1–12 (2020)

Ultimate limits

We investigated *fundamental resolution limits* of compressive imaging via sparsity constraint, speckle illumination and single-pixel detection

$$RIF = l_{dl}/l$$

l_{dl} – diffraction limit

l – pixel size resolved

$$RIF \leq \sqrt{\frac{2N^2}{K}}$$

Dr. Benjamin Lochocki

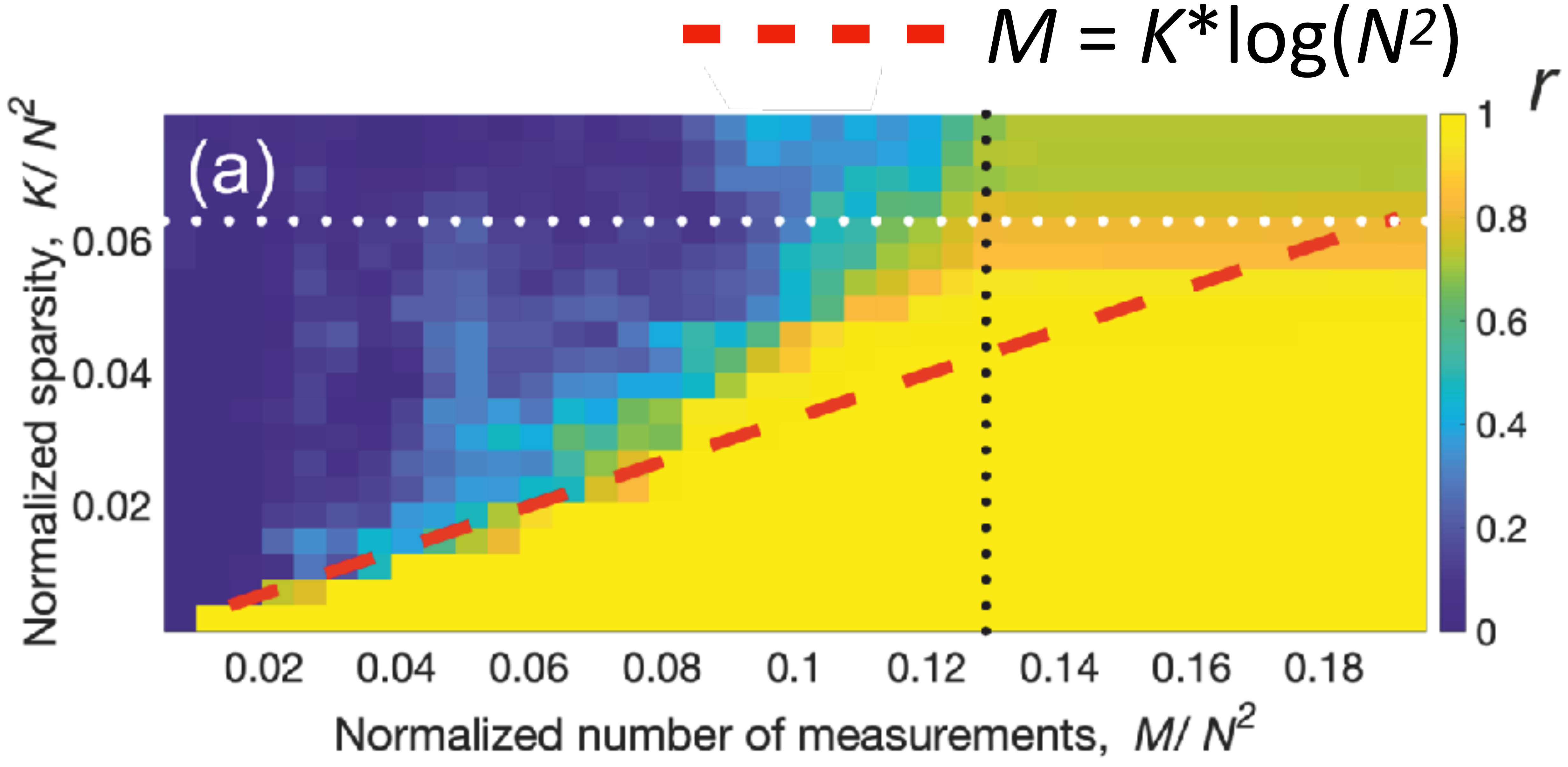
Pixel size 200 nm

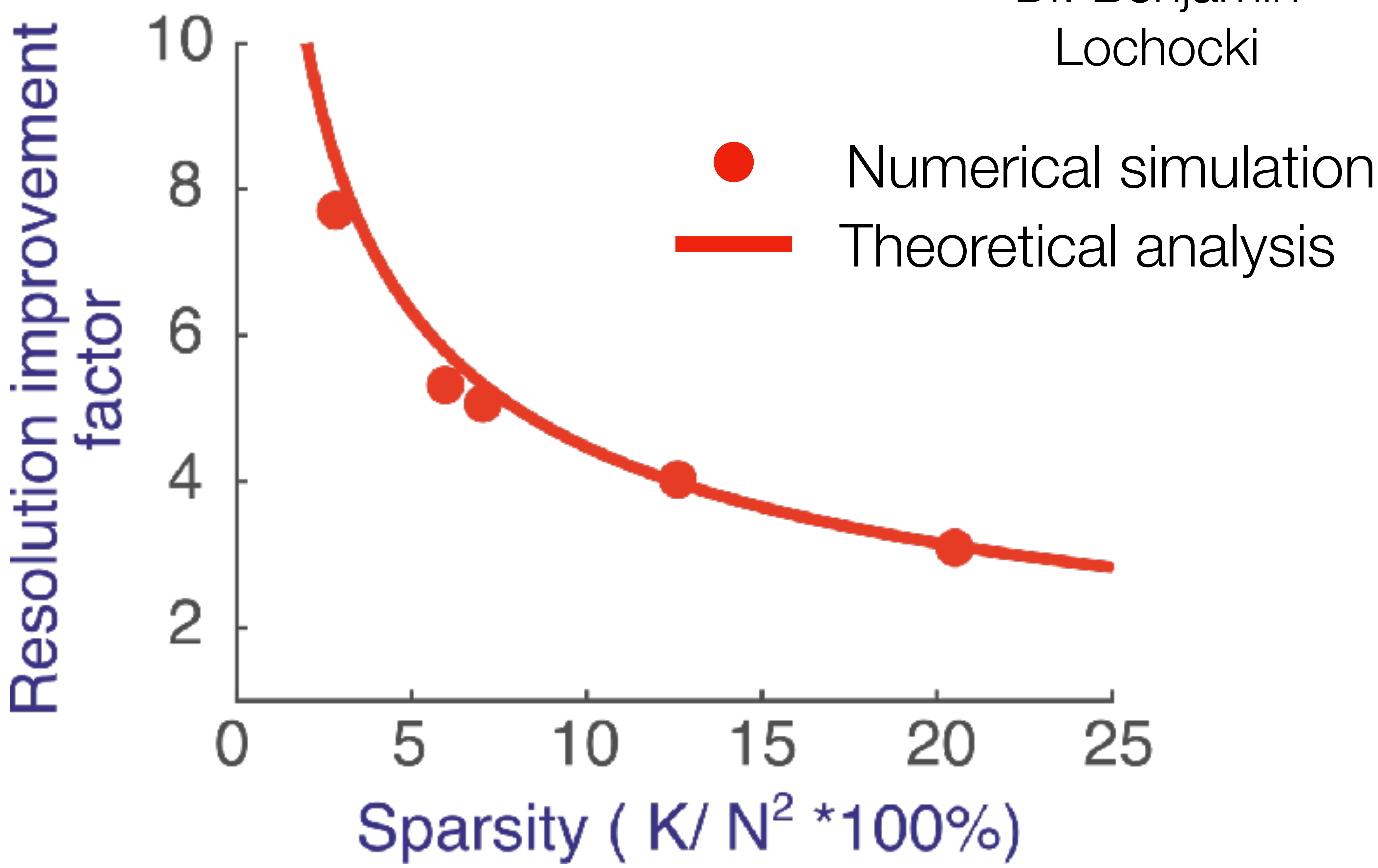
NA = 0.25

Diffraction limit 1060 nm

K – number of nonzero pixels

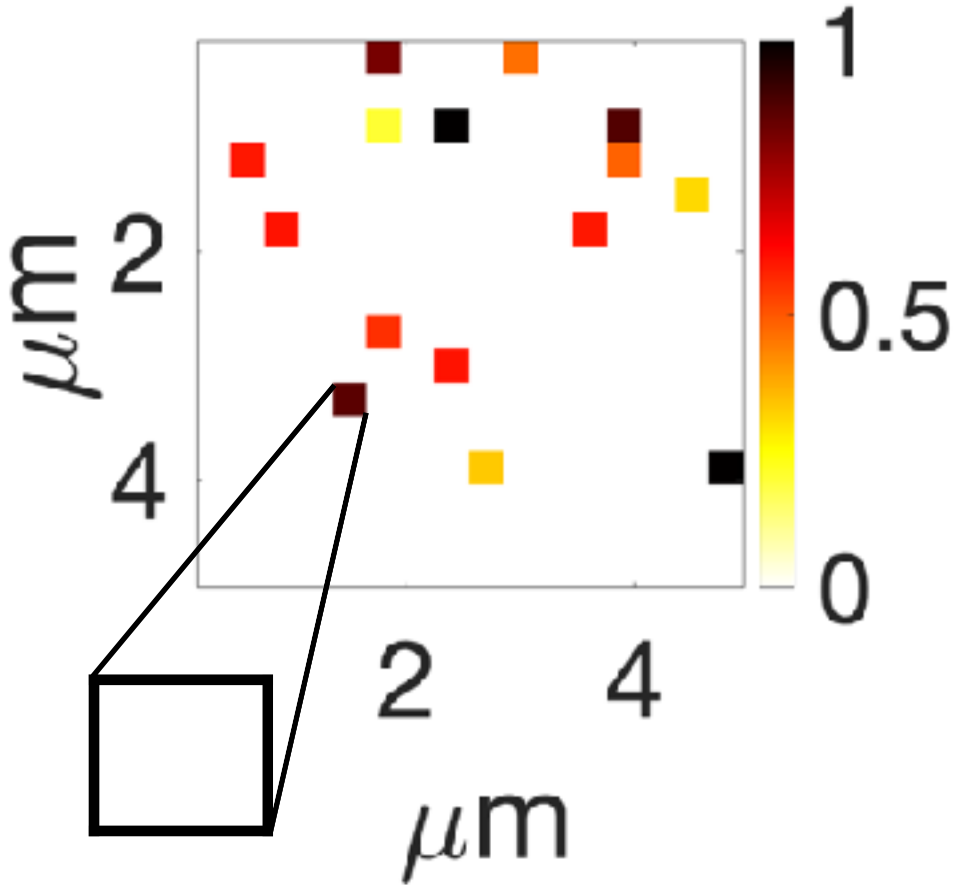
N^2 – total number of pixels





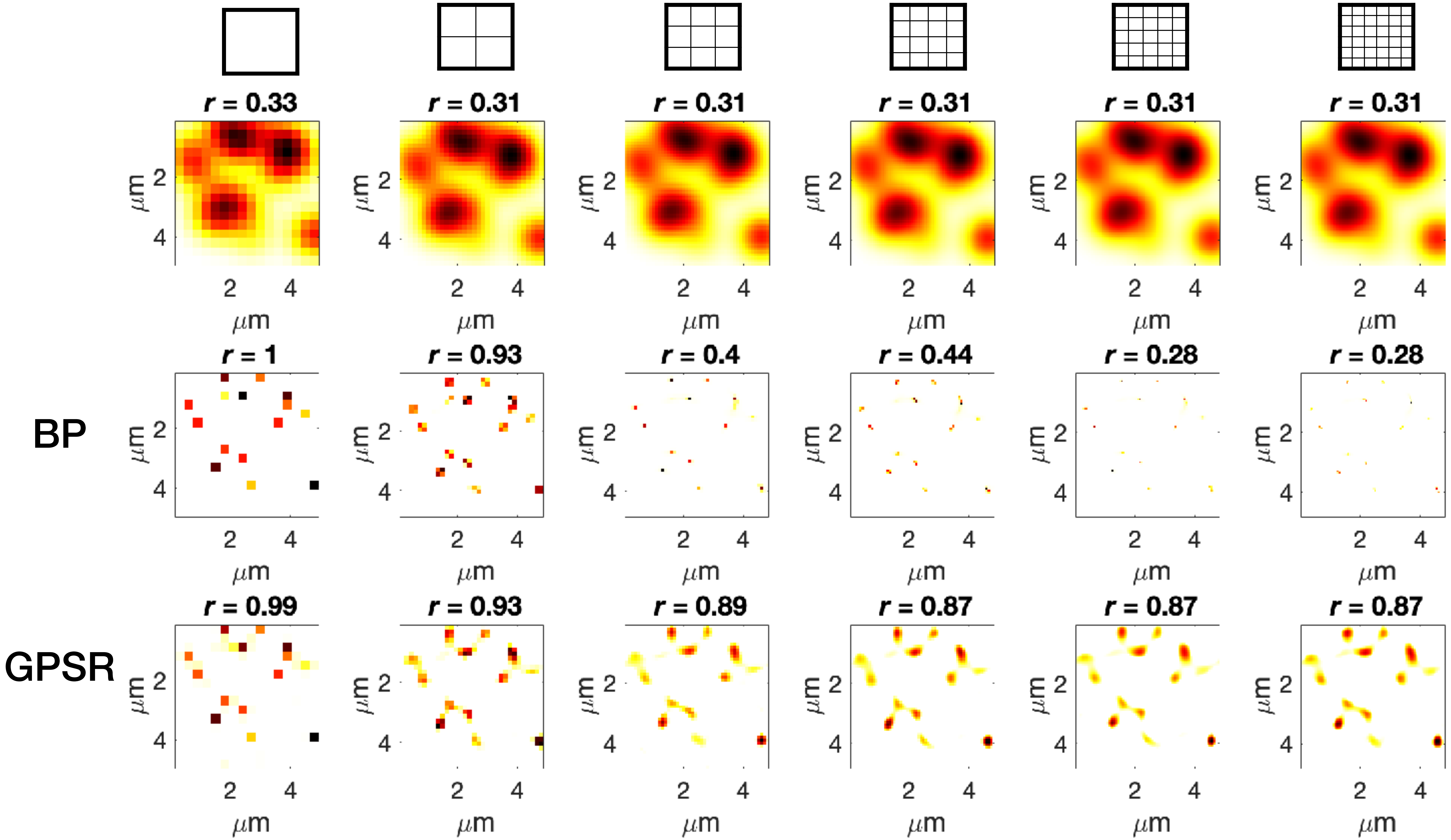
B. Lochocki, K. Abrashitova, J. F. de Boer, and L. V. Amitonova, Optics Express **29**, 3943–3955 (2021)

Ultimate limits



Feature size 300 nm;
Diffraction limit 1200 nm

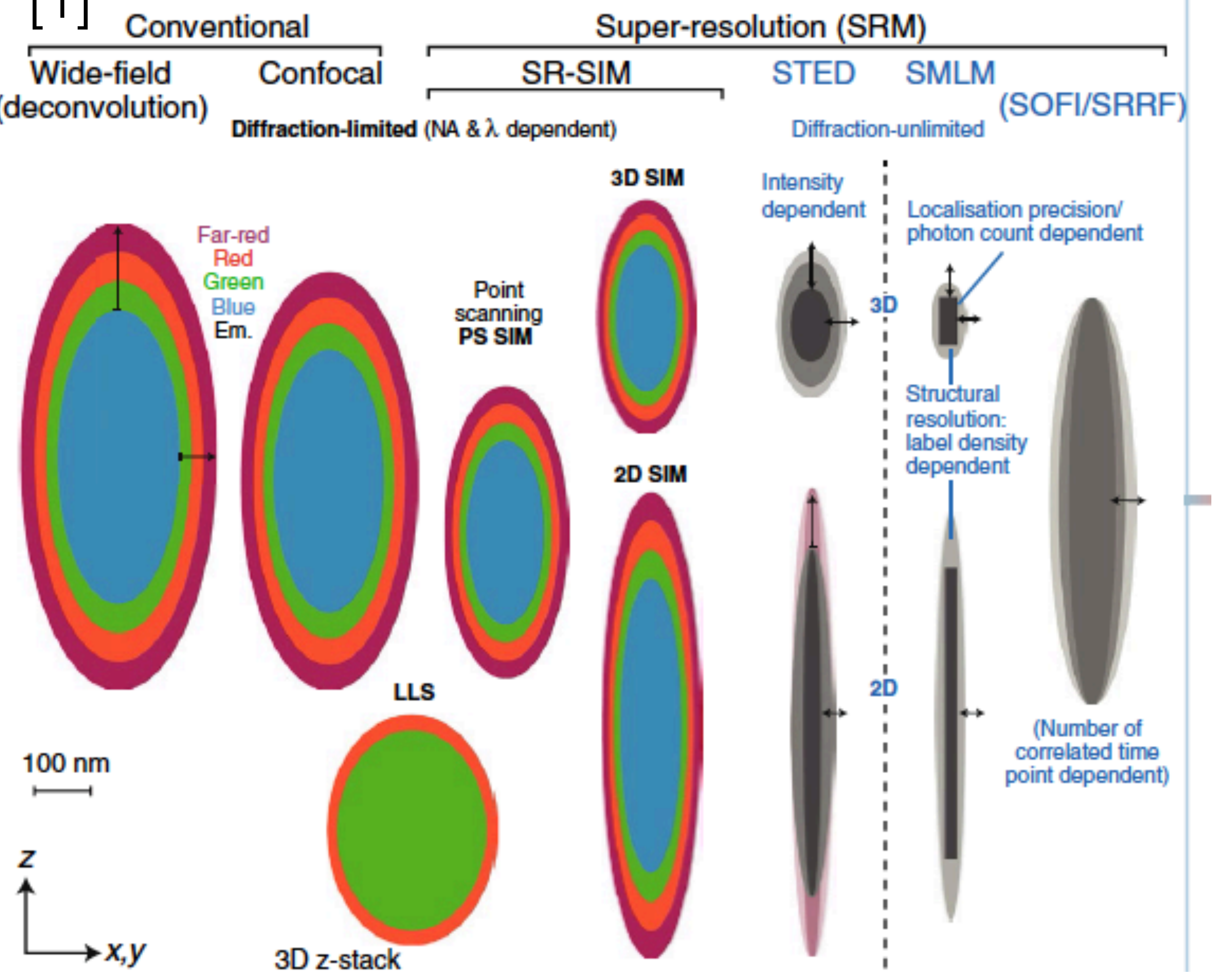
Sparsity is constant

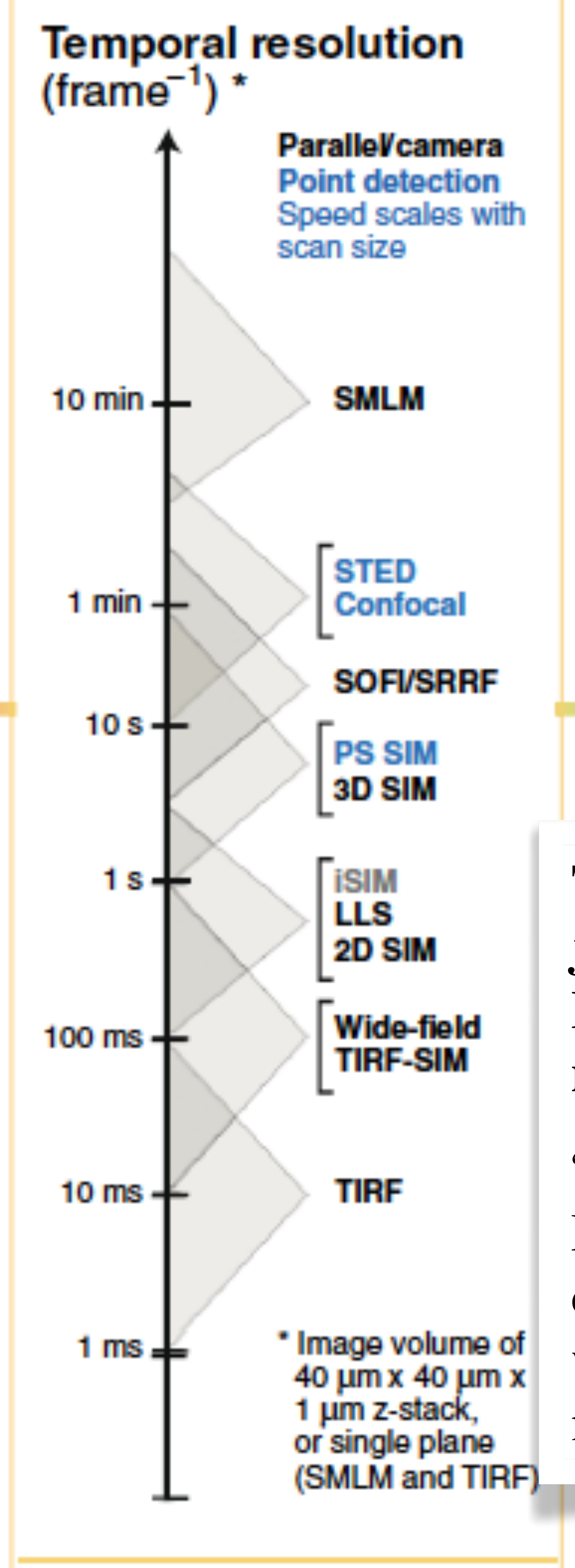


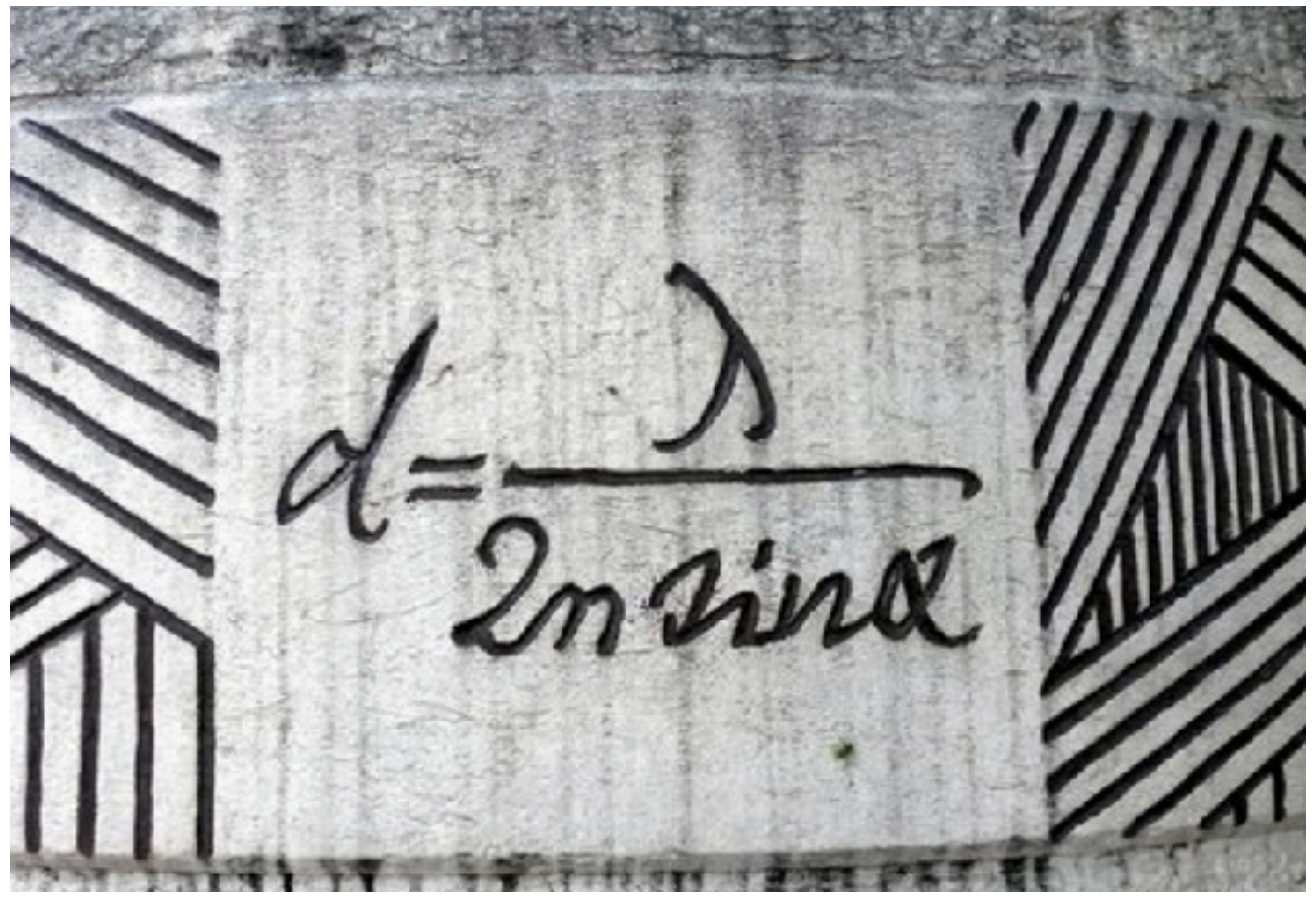
B. Lochocki, K. Abrashitova, J. F. de Boer, and L. V. Amitonova, Optics Express **29**, 3943–3955 (2021).

Super-resolution microscopy

[1]





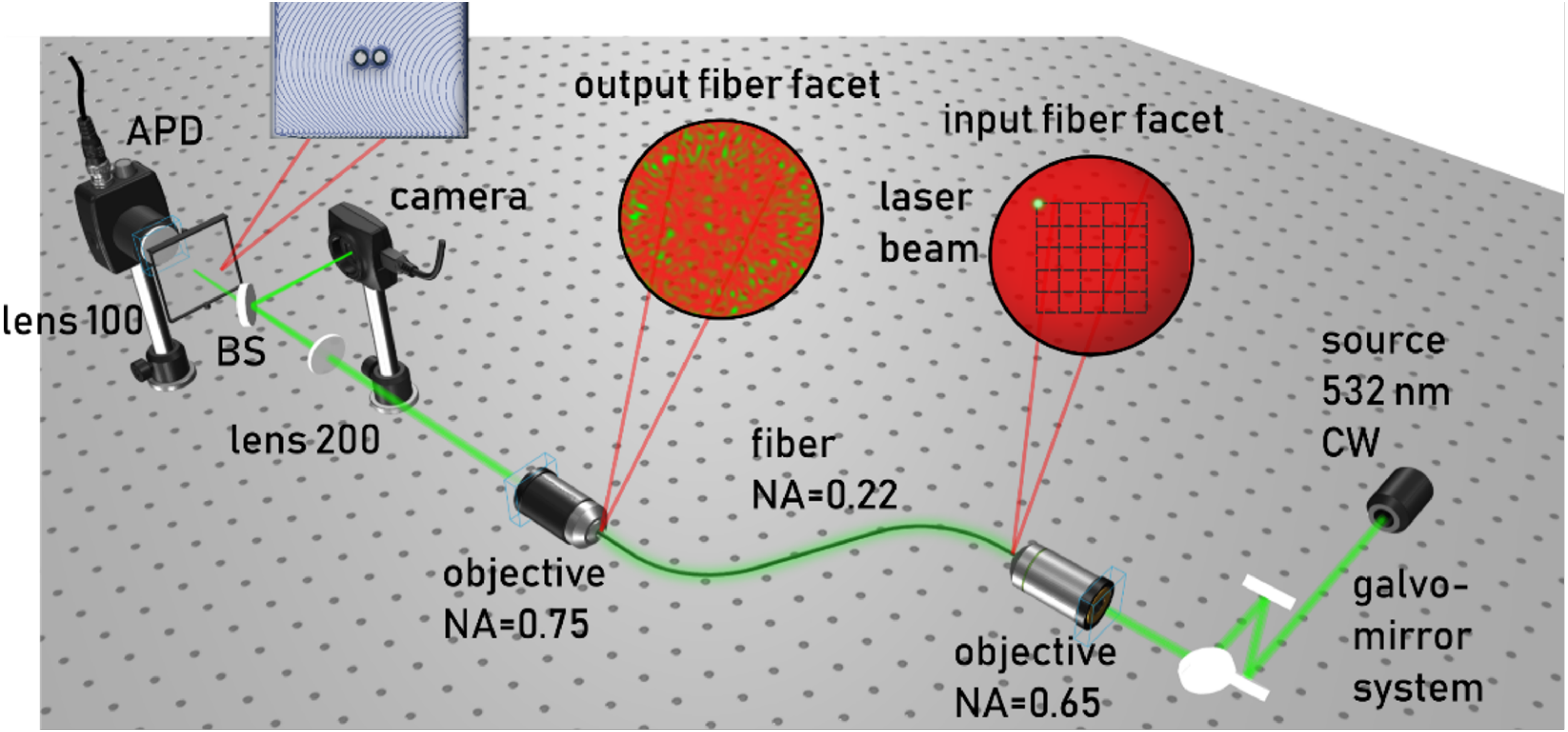


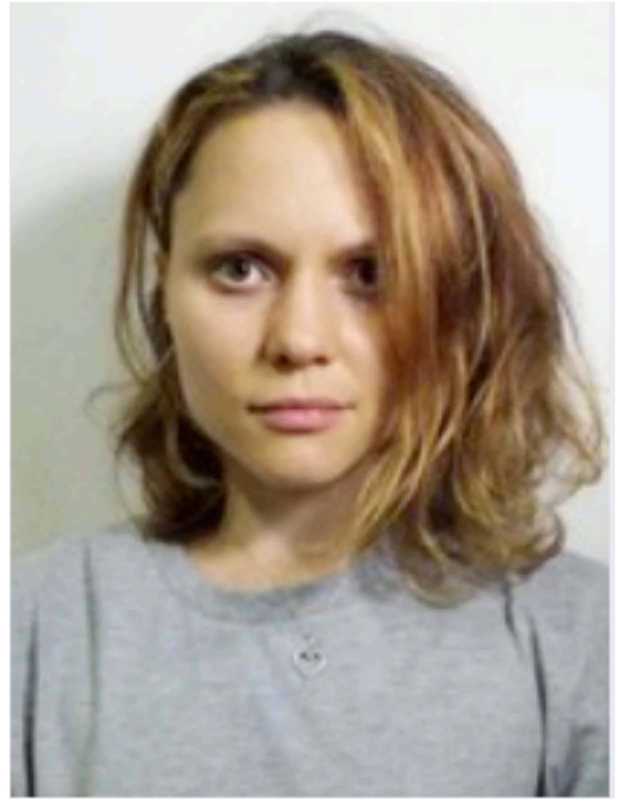
The Nobel Prize in Chemistry 2014 was awarded jointly to Eric Betzig, Stefan W. Hell and William E. Moerner "for the development of super-resolved fluorescence microscopy."

"…Helped by fluorescent molecules the Nobel Laureates in Chemistry 2014 ingeniously circumvented this limitation. Their ground-breaking work has brought optical microscopy into the nanodimension…"

[1] L. Schermelleh, A. Ferrand, T. Huser, C. Eggeling, M. Sauer, O. Biehlmaier, and G. P. C. Drummen, Nature Cell Biology **21**, 72–84 (2019).

Far-field label-free super-resolution





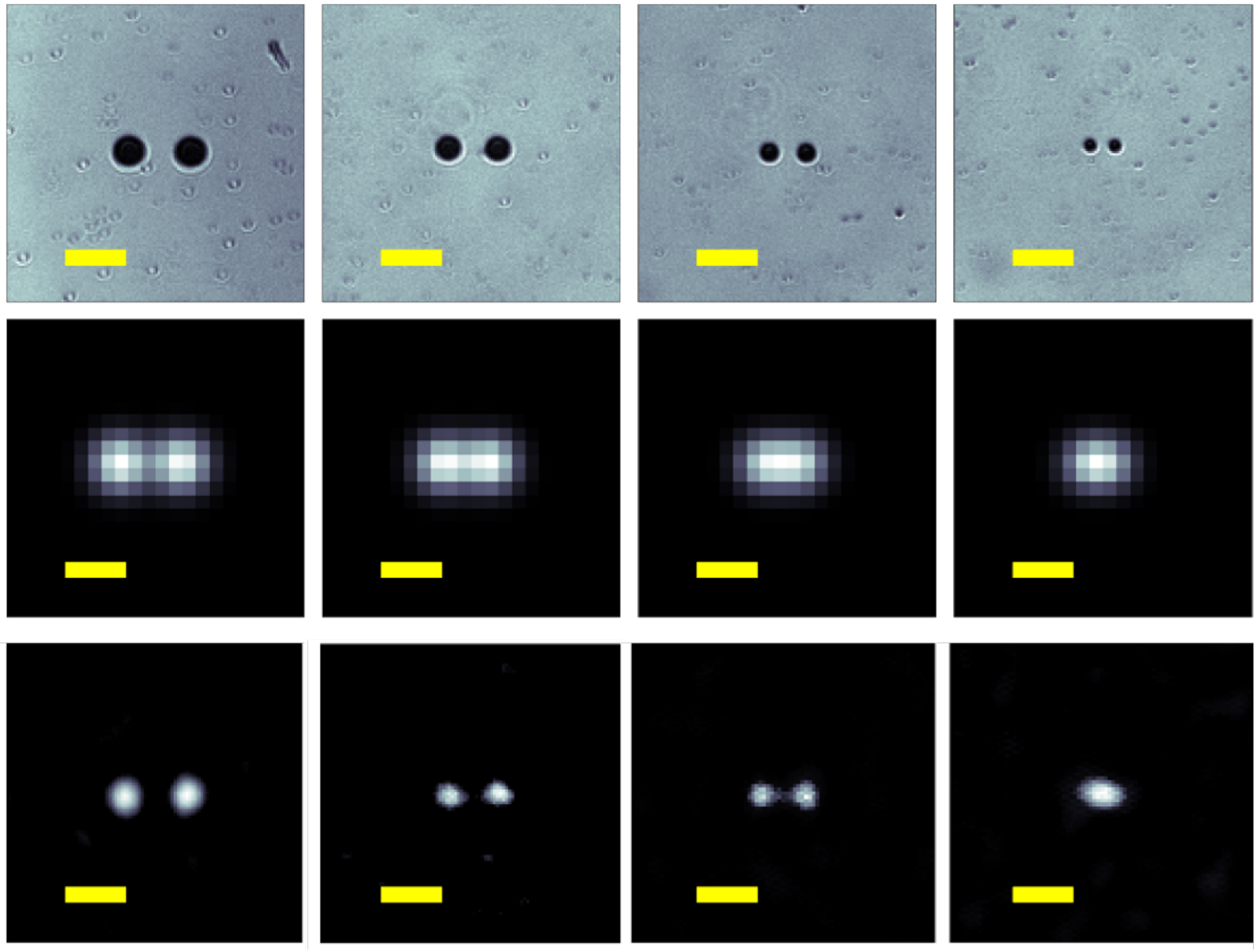
Dr. Ksenia Abrashitova

Far-field label-free super-resolution

Sample

Diffraction-limited far field imaging

Computational compressive imaging



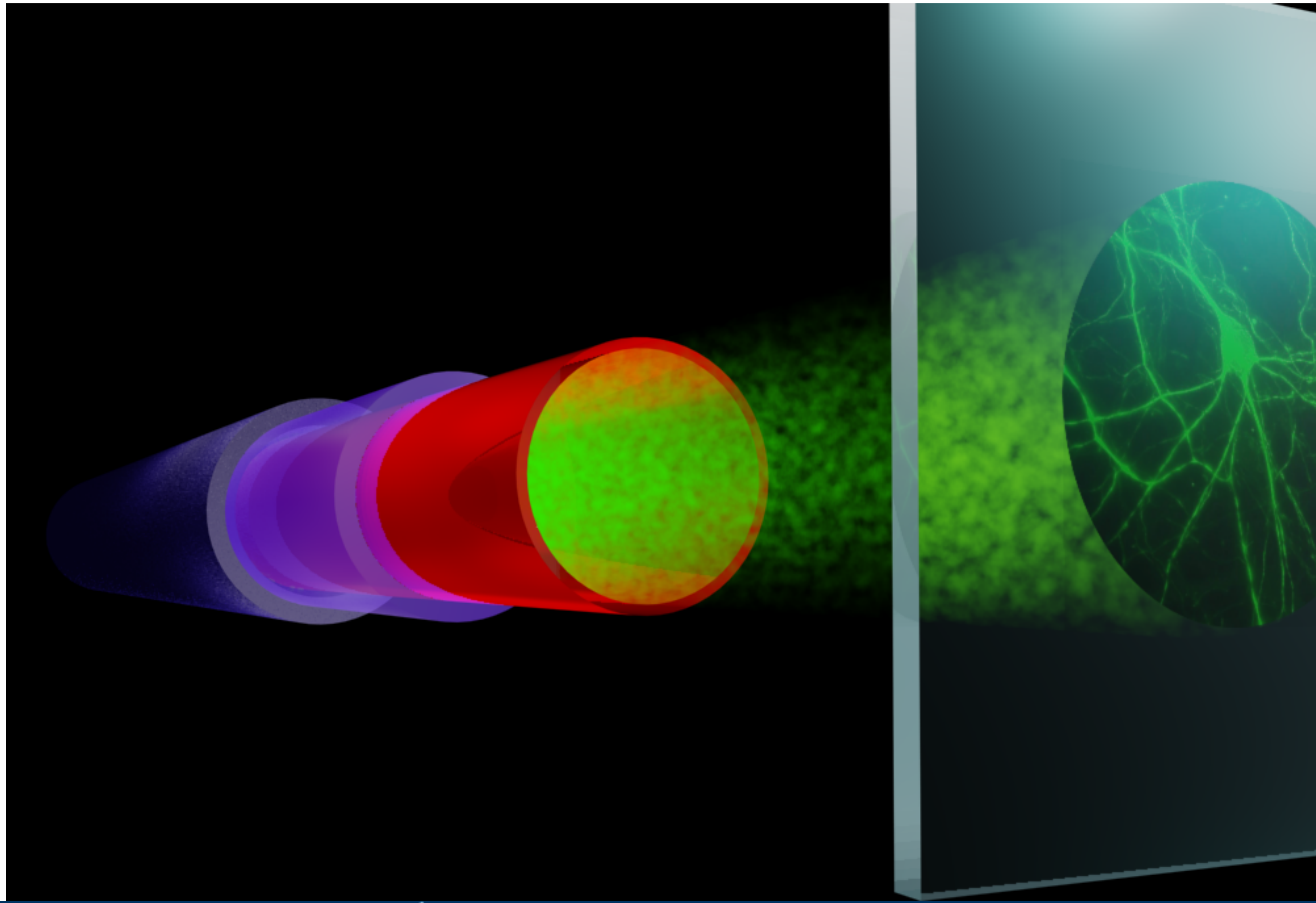
Resolution
> 2.5 times below the Abbe limit

Imaging speed
> 15 times better than Nyquist limit

Summary

A new concept that allows 'imaging beyond the limits' was proposed and experimentally demonstrated

- Ultra-compact imaging sensor. FOV and resolution are uncoupled
- Beyond the Nyquist limit: ultra-hight speed > 20 times faster than is required for a raster scanning approach
- Beyond the Abbe limit: resolution > 2 times better than the diffraction limit
- No special marks are needed



Thanks to

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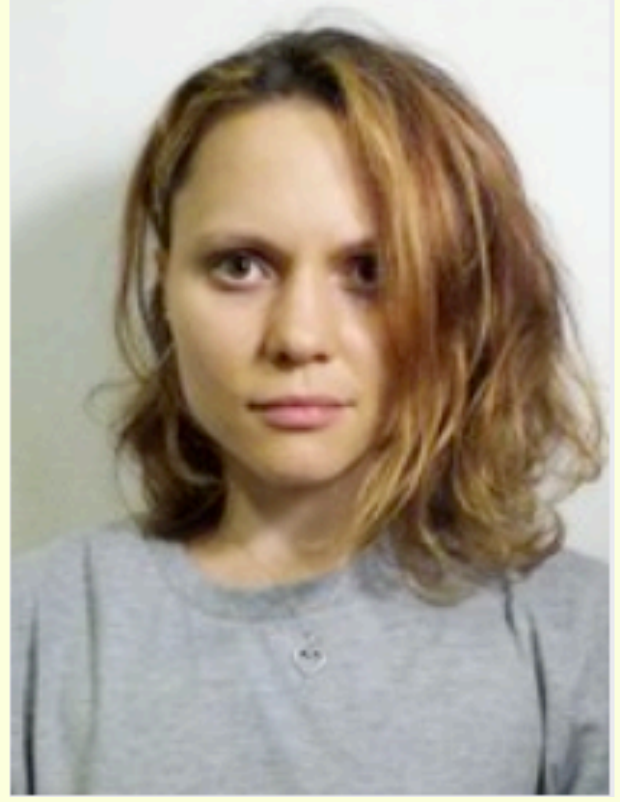


Dr. Ksenia Abrashitova

Zhouping Lyu

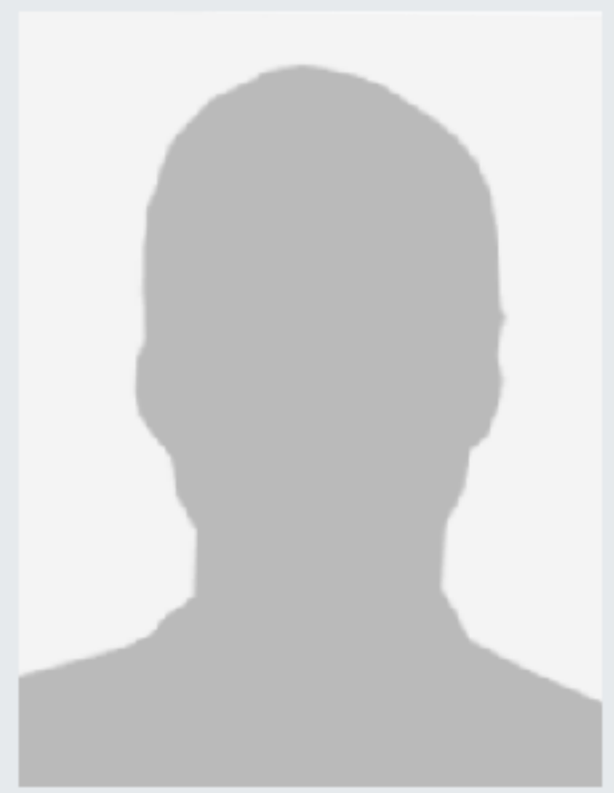
Mark Mol

Dr. Benjamin Lochocki

Max Verweg

Dr. Gerwin Osnabrugge

Dr. Wei Li



PhD vacancy

Isabel Droste

Active collaborations:

Prof. J.F. de Boer

Prof. P.W.H. Pinkse

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UNIVERSITY OF TWENTE.