



UNIVERSITÉ
DE GENÈVE

FACULTY OF SCIENCE
Department of Informatics

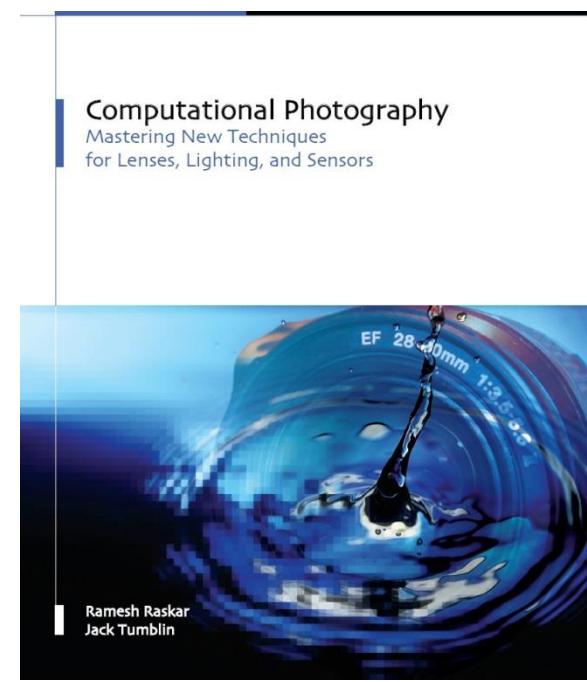
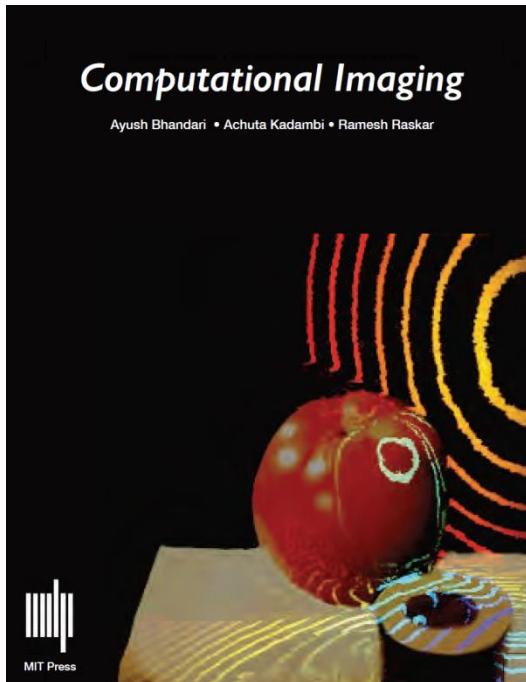
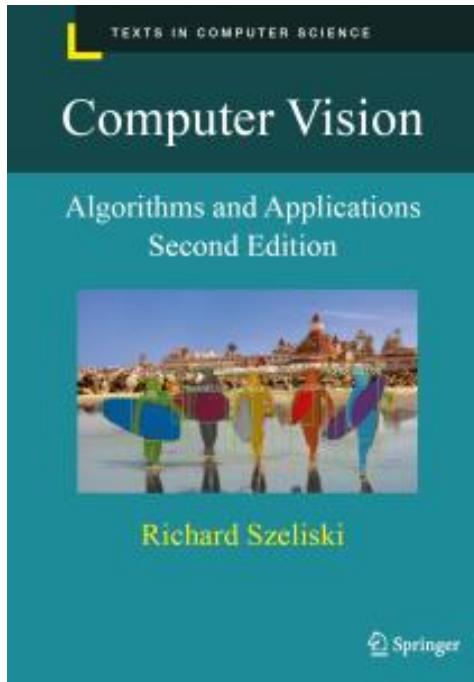


stochastic
information
processing

Computational imaging

Taras Holotyak

Recommended books



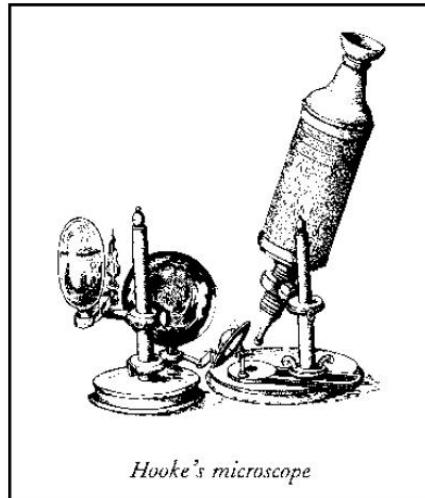
Main topics of computational imaging

- Human visual system
- Digital photography
- Computational photography
- Deep learning for computational imaging
- Optimization and deep learning
- Compressive imaging
- Introduction to wave optics and deep optics
- Computational displays

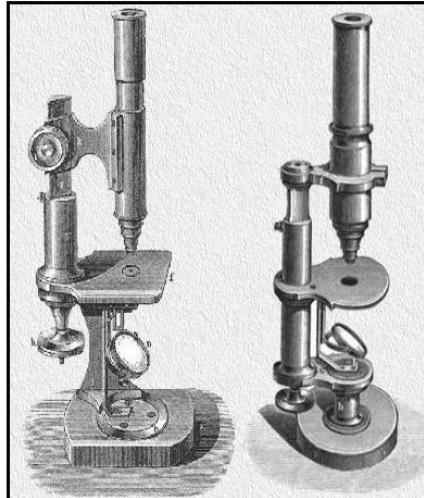
Content

- Two-photon and light-field microscopy
- Fourier ptychographic imaging

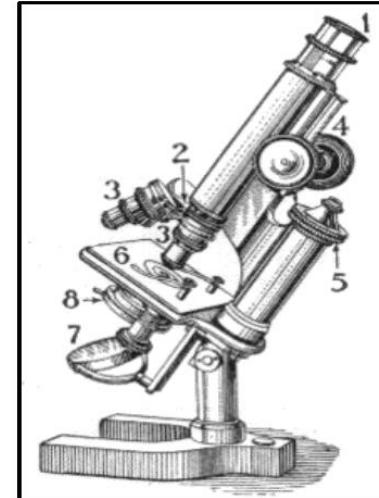
Development of conventional optical microscopes



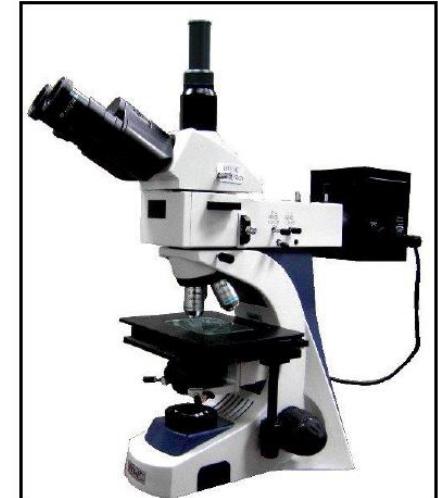
16th
century



18th
century

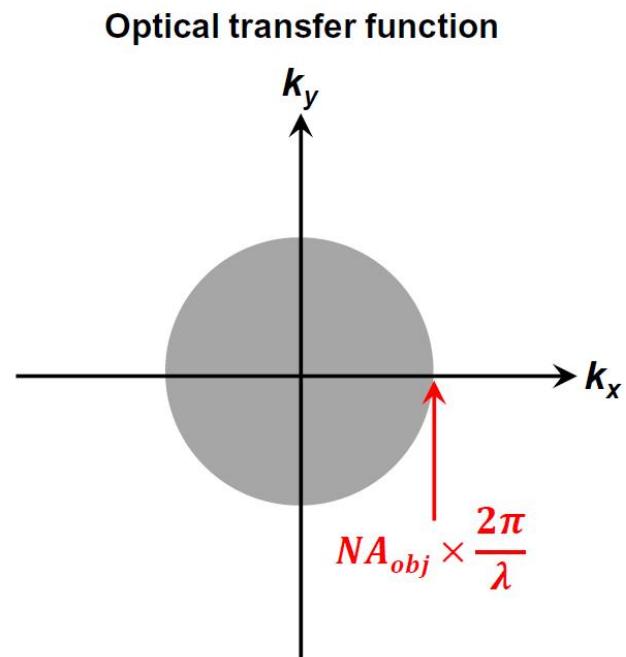
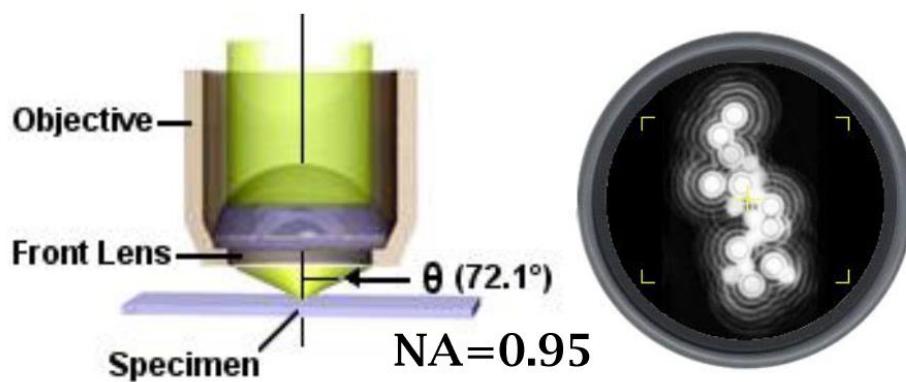
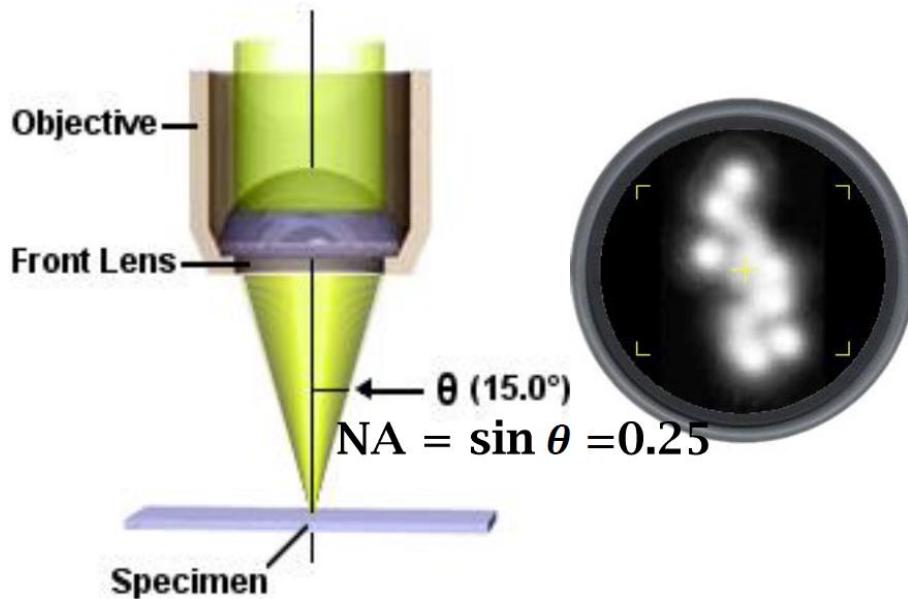


Early 20th
century

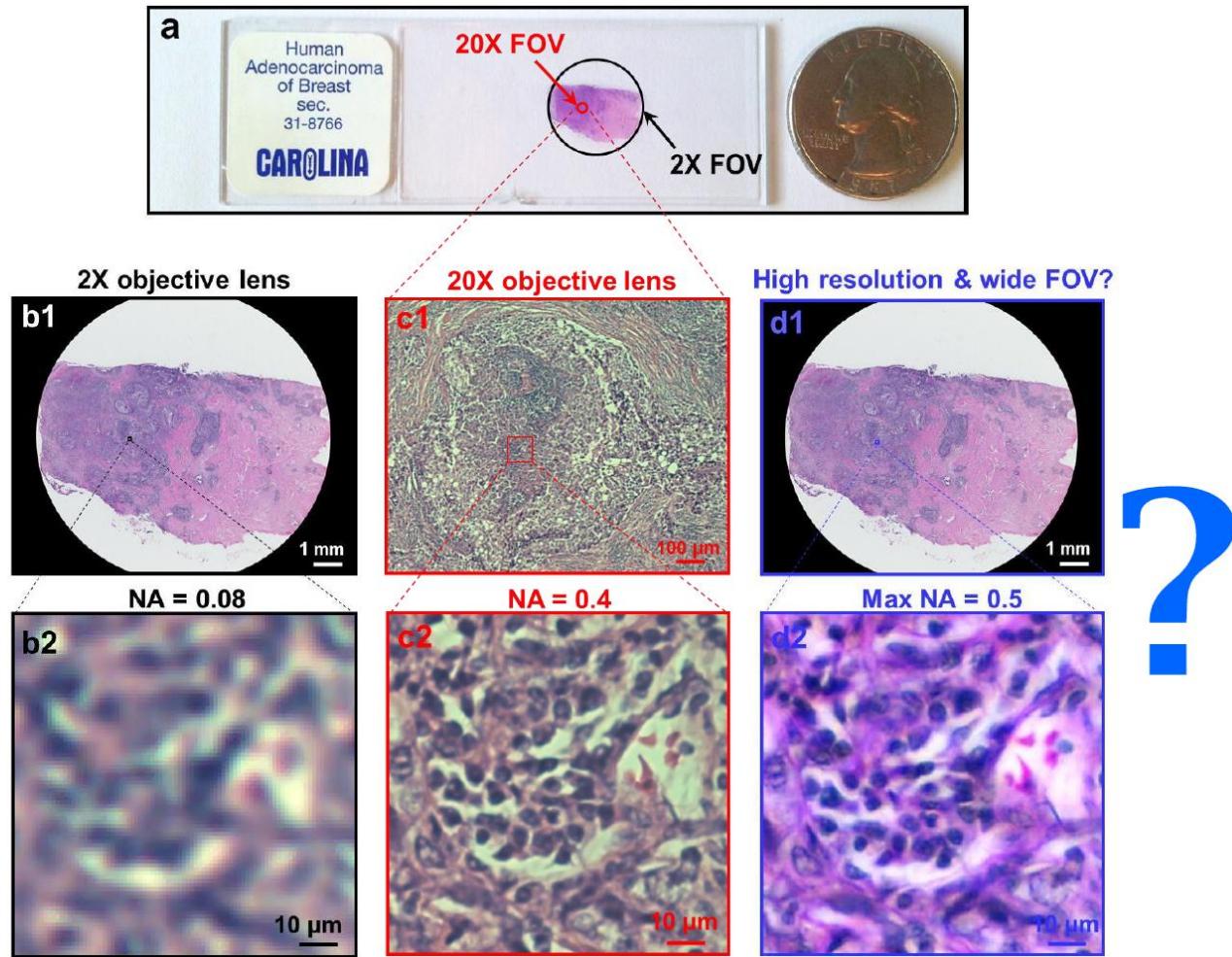


21st
century

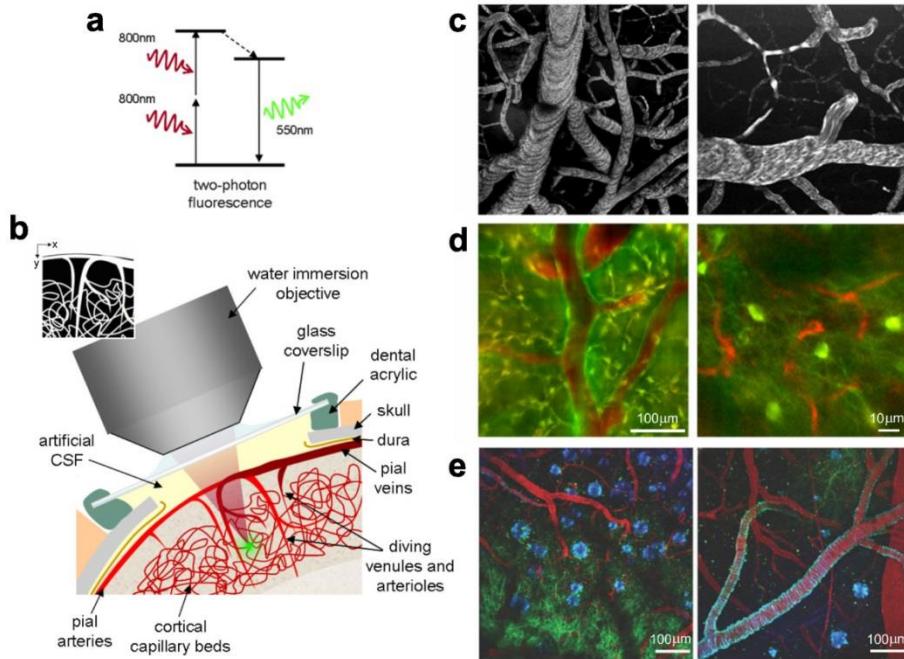
Optical transfer function



Resolution vs. field-of-view (FOV)



Two-photon microscopy



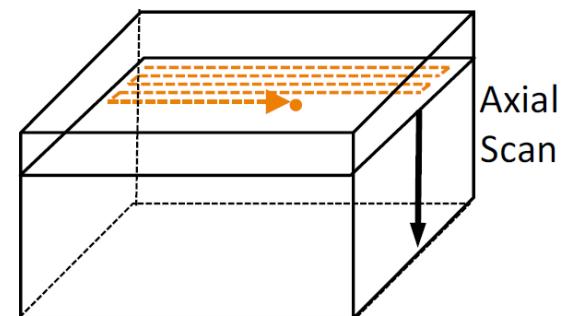
Two-photon excitation microscopy is a fluorescence imaging technique that allows imaging of living tissue up to about one millimeter in thickness, with $0.64 \mu\text{m}$ lateral and $3.35 \mu\text{m}$ axial spatial resolution. Unlike traditional fluorescence microscopy, in which the excitation wavelength is shorter than the emission wavelength, two-photon excitation requires simultaneous excitation by two photons with longer wavelength than the emitted light.

Two-photon excitation microscopy typically uses near-infrared (NIR) excitation light which can also excite fluorescent dyes. However, for each excitation, two photons of NIR light are absorbed. Using infrared light minimizes scattering in the tissue. Due to the multiphoton absorption, the background signal is strongly suppressed. Both effects lead to an increased penetration depth for this technique. Two-photon excitation can be a superior alternative to confocal microscopy due to its deeper tissue penetration, efficient light detection, and reduced photobleaching

Two-photon microscopy

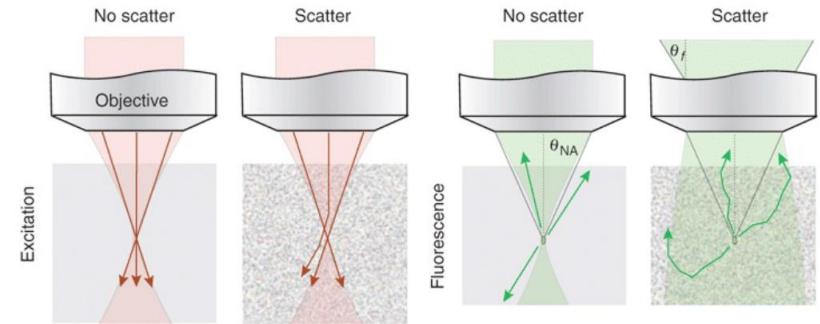
- Fluorescent sensors within tissues
- Highly localized laser excites fluorescence from sensors
- Photons emitted from tissue are collected
- Focal spot sequentially scanned across samples to form image

Point scanning (2PLSM)



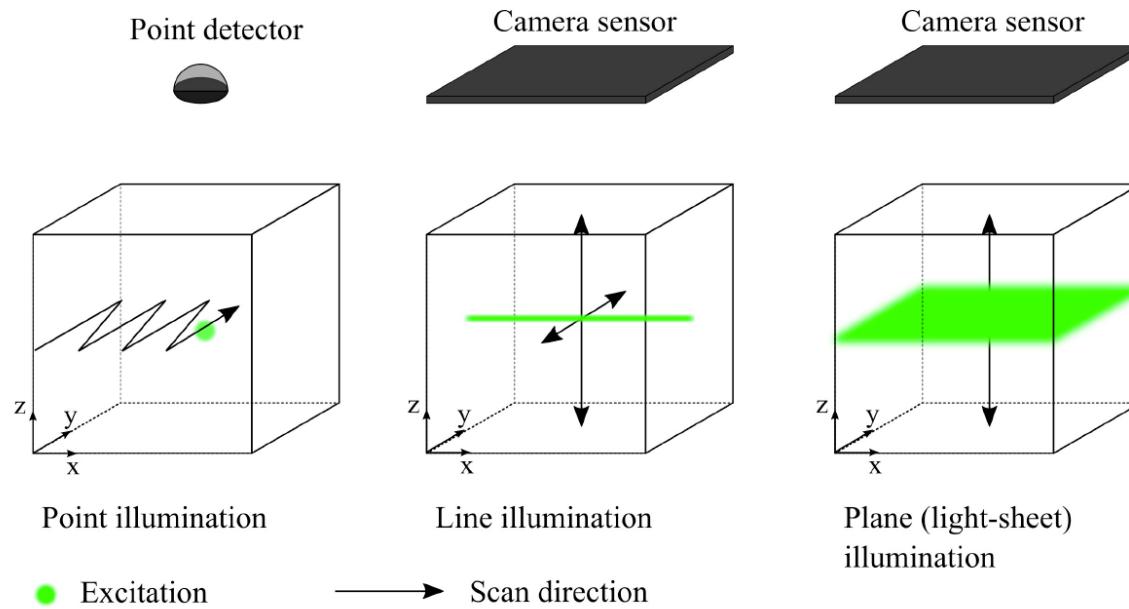
Two-photon microscopy

- Fluorescent sensors within tissues
- Highly localized laser excites fluorescence from sensors
- Photons emitted from tissue are collected
- Focal spot sequentially scanned across samples to form image
- Two-photon microscopes in raster scan modality can go deep in the tissue but are **slow**



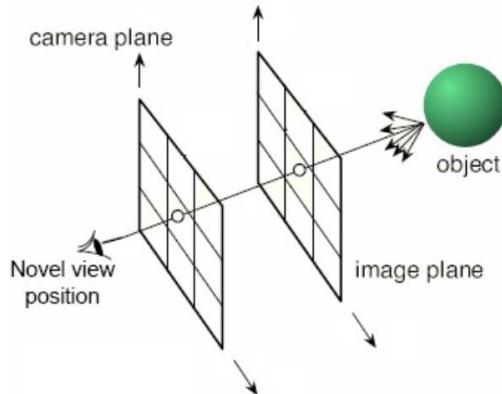
Two-photon microscopy

- In order to speed up acquisition one can change the illumination strategy
- This mitigates the issue but does not fix it



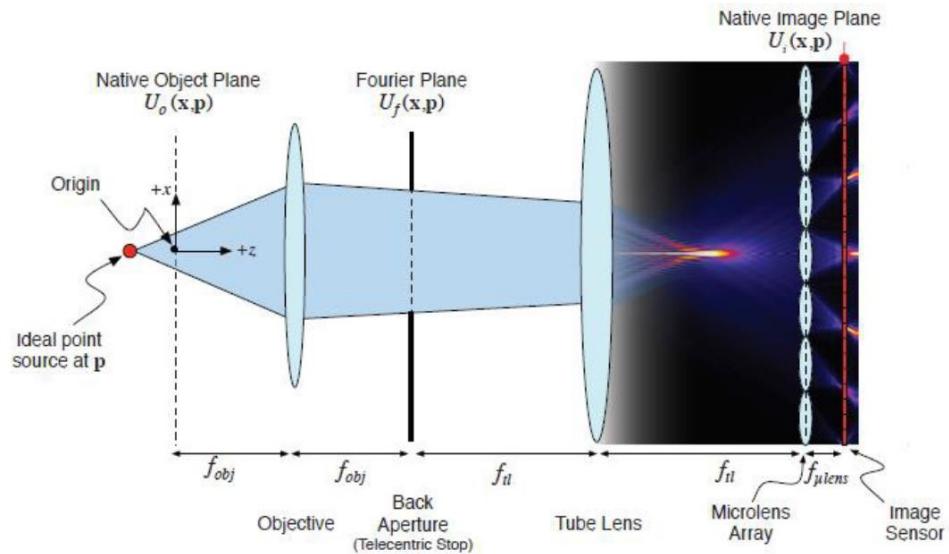
Light field

- Light rays are characterized by their intersection with the camera plane and the image plane
- 4D parameterization of the lightfield

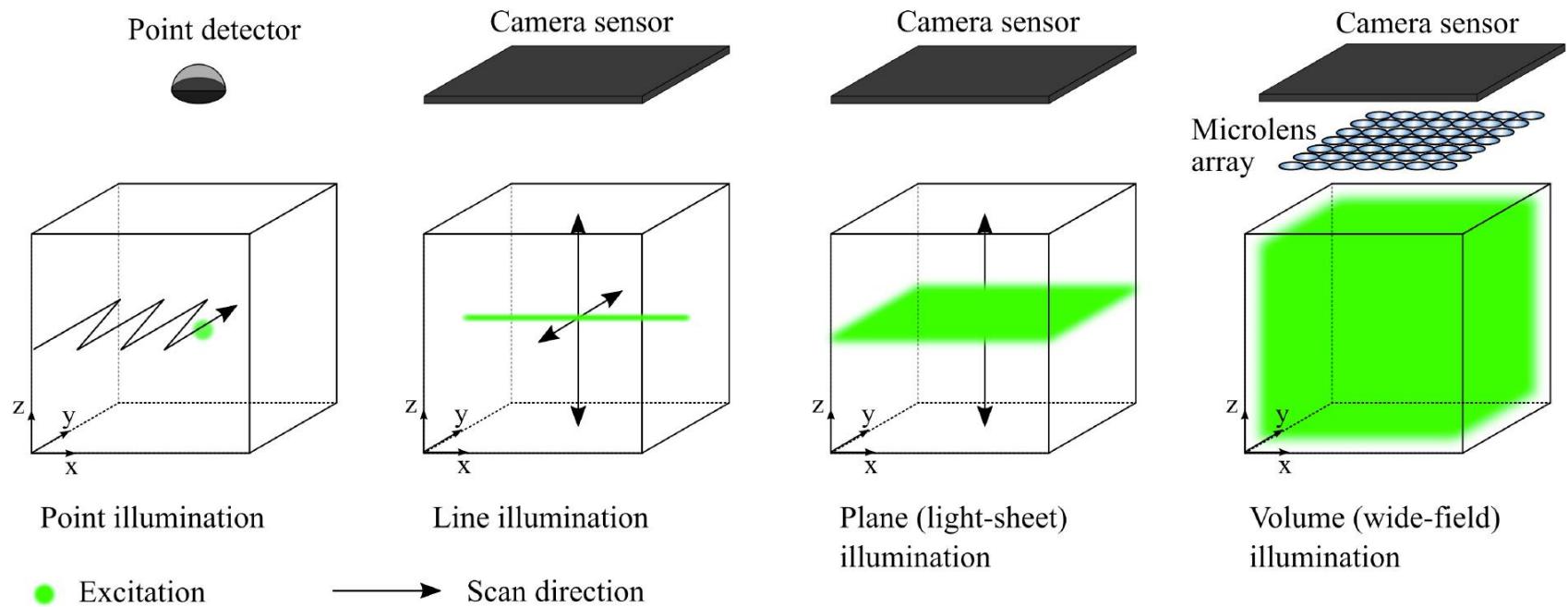


Light-field microscopy

Light-Field Microscopy (LFM) is a high-speed imaging technique that uses a simple modification of a standard microscope to capture a 3D image of an entire volume in a single camera snapshot



Light-field microscopy



Coherent microscope imaging model

$$I(x, y) = |(O(x, y) \cdot P(x, y)) * PSF|^2$$

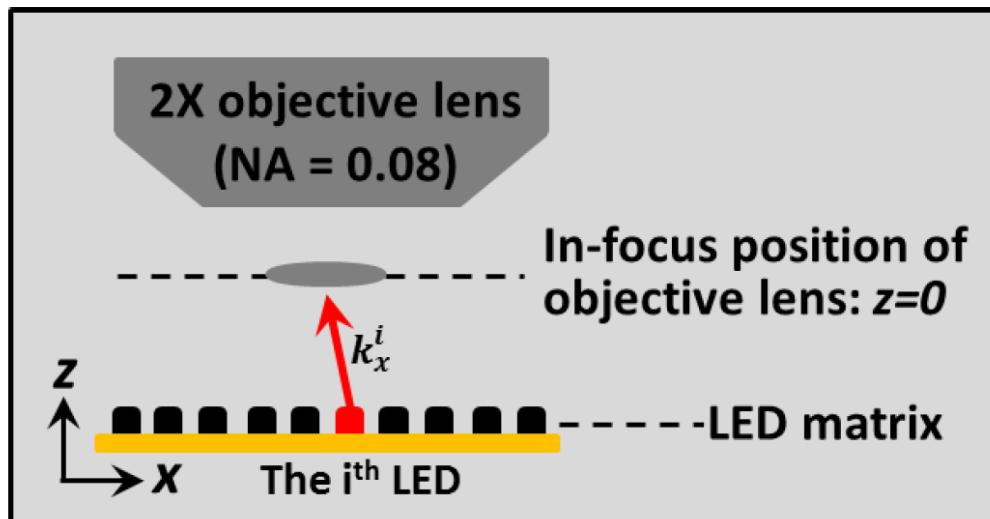
$O(x, y)$ is the object, complex and unknown

$P(x, y) = e^{ik_{xn}x} \cdot e^{ik_{yn}y}$, plane wave illumination; (k_{xn}, k_{yn}) represent incident angle

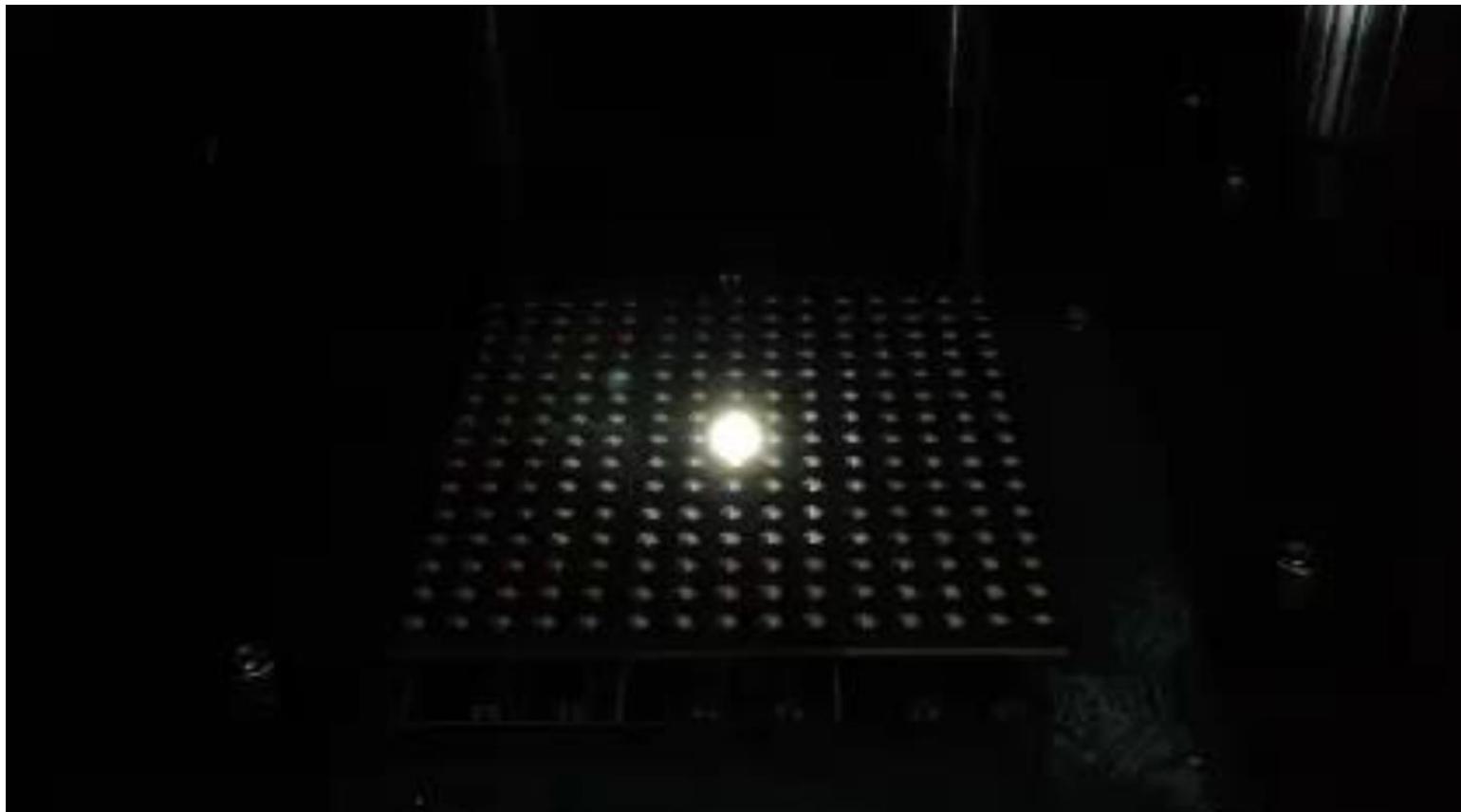
$OTF = FT\{PSF\} = circ(k_{max}) \cdot e^{i\varphi(k_x, k_y)}$; $\varphi(k_x, k_y)$ is the aberration; $\varphi(k_x, k_y) = 0$ for diffraction limited system

Fourier ptychographic microscopy (FPM)

- Low-NA objective lens → **Wide field-of-view, low resolution**
- Acquire multiple low res images under different incident angles → **High-resolution**



LED matrix



Simplified imaging model

$$I_n(x, y) = |(O(x, y) \cdot P_n(x, y)) * PSF|^2$$

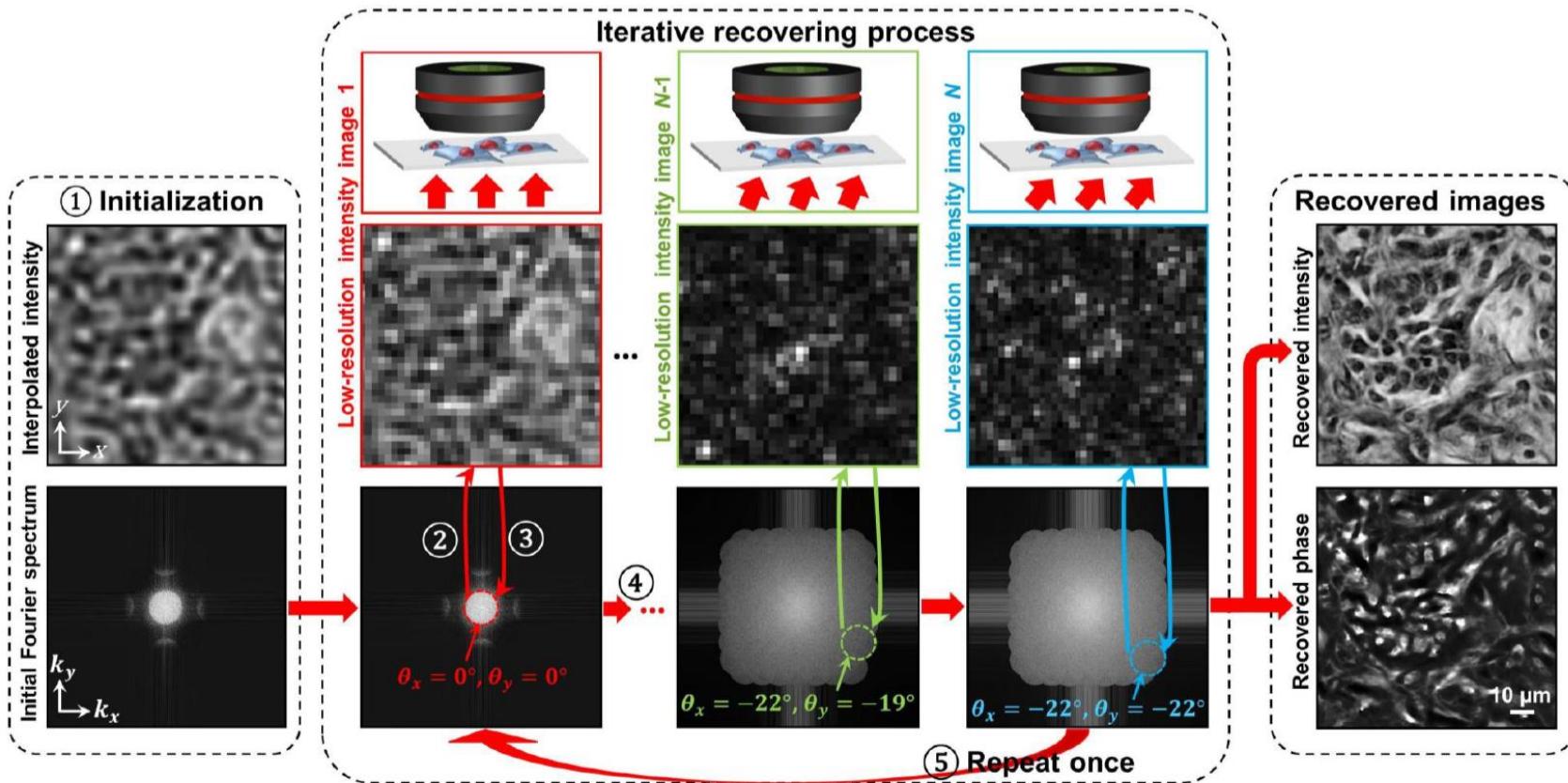
$O(x, y)$ is the object, complex and unknown

$P_n(x, y) = e^{ik_{xn}x} \cdot e^{ik_{yn}y}$, plane wave illumination;
 (k_{xn}, k_{yn}) represent incident angle; $n = 1, 2, 3, \dots$

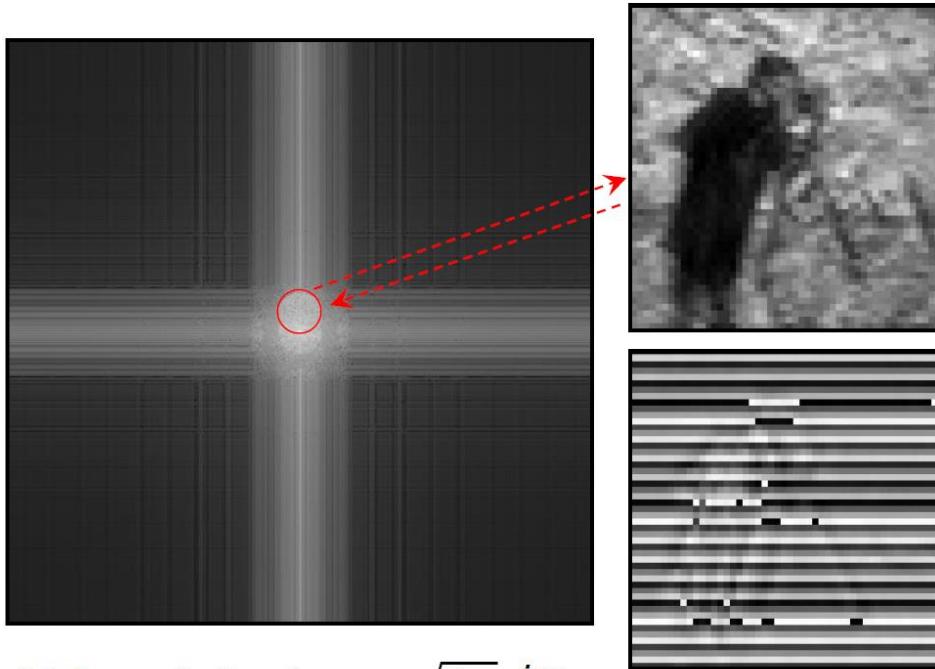
$FT\{PSF\} = circ(kmax) \cdot e^{i\varphi(kx, ky)}$; $\varphi(kx, ky)$ is the aberration;
 $\varphi(kx, ky) = 0$ for diffraction limited system

- Goal: to recover $O(x, y)$ from $I_n(x, y)$ ($n = 1, 2, 3, \dots$)

Iterative reconstruction process

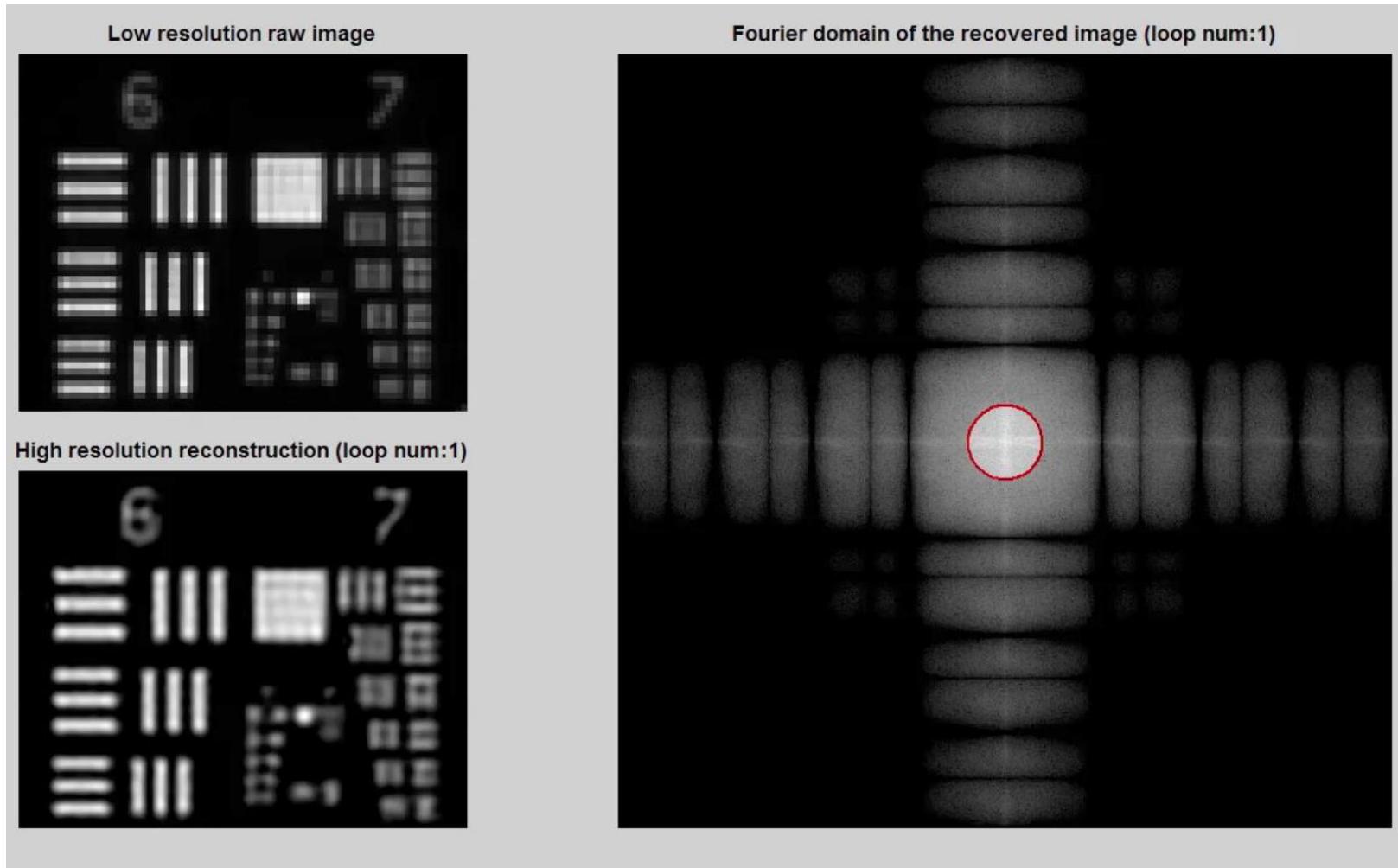


Iterative reconstruction process



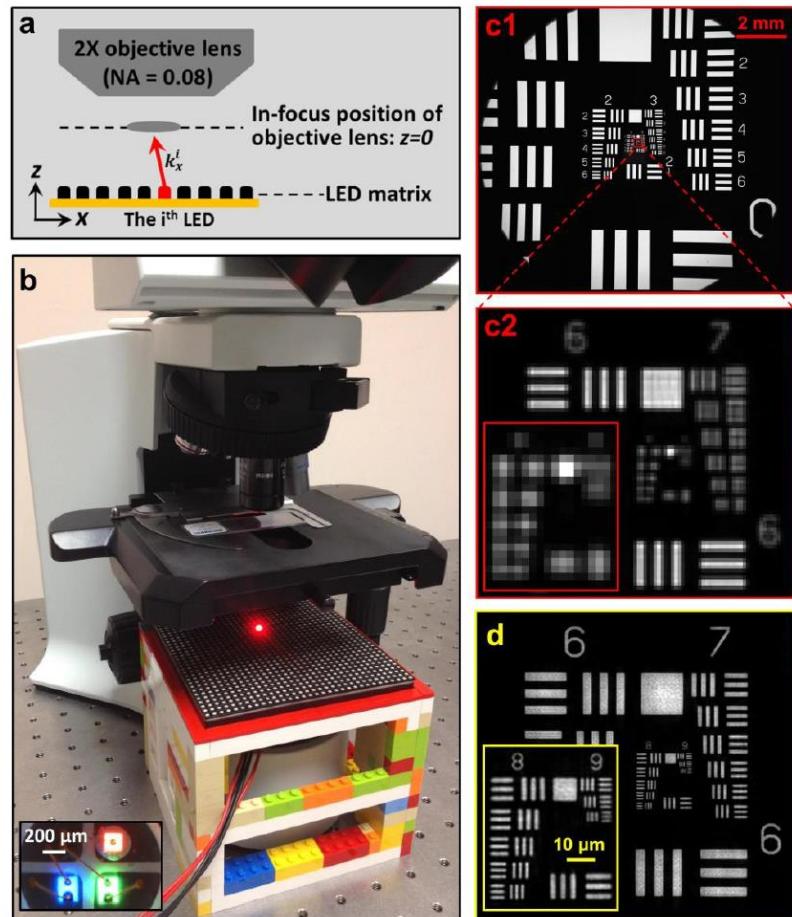
- ① Initialize the high resolution image: $\sqrt{I_{hr}}e^{i\varphi_{hr}}$
- ② Generate a low-resolution image $\sqrt{I_l}e^{i\varphi_l}$ corresponding to a plane wave incidence
- ③ Replace I_l by the intensity measurement I_{lm} : $\sqrt{I_l}e^{i\varphi_l} \rightarrow \sqrt{I_{lm}}e^{i\varphi_l}$. Update the corresponding region of $\sqrt{I_{hr}}e^{i\varphi_{hr}}$ in Fourier space (i.e., the area within the red circle)
- ④ Repeat steps 2-3 for other plane wave incidences (total N intensity images)
- ⑤ Repeat steps 2-4 for one more time

Iterative reconstruction process



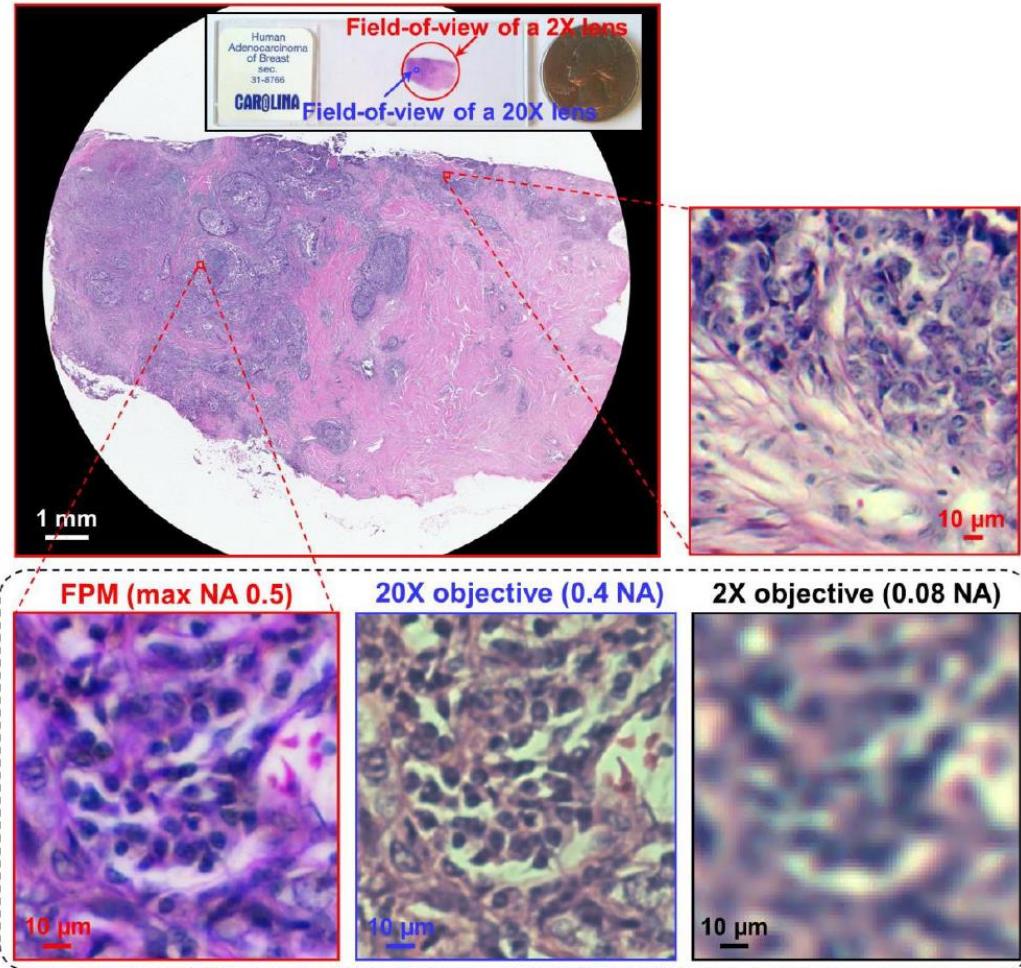
Experimental setup

- Compatible to most microscopes
- Based on 2X lens (0.08 NA)
- Effective FOV: ~1.2 cm in diameter
- No mechanical scanning involved
- 137 low resolution frames acquired
- Maximum NA= ~ 0.5



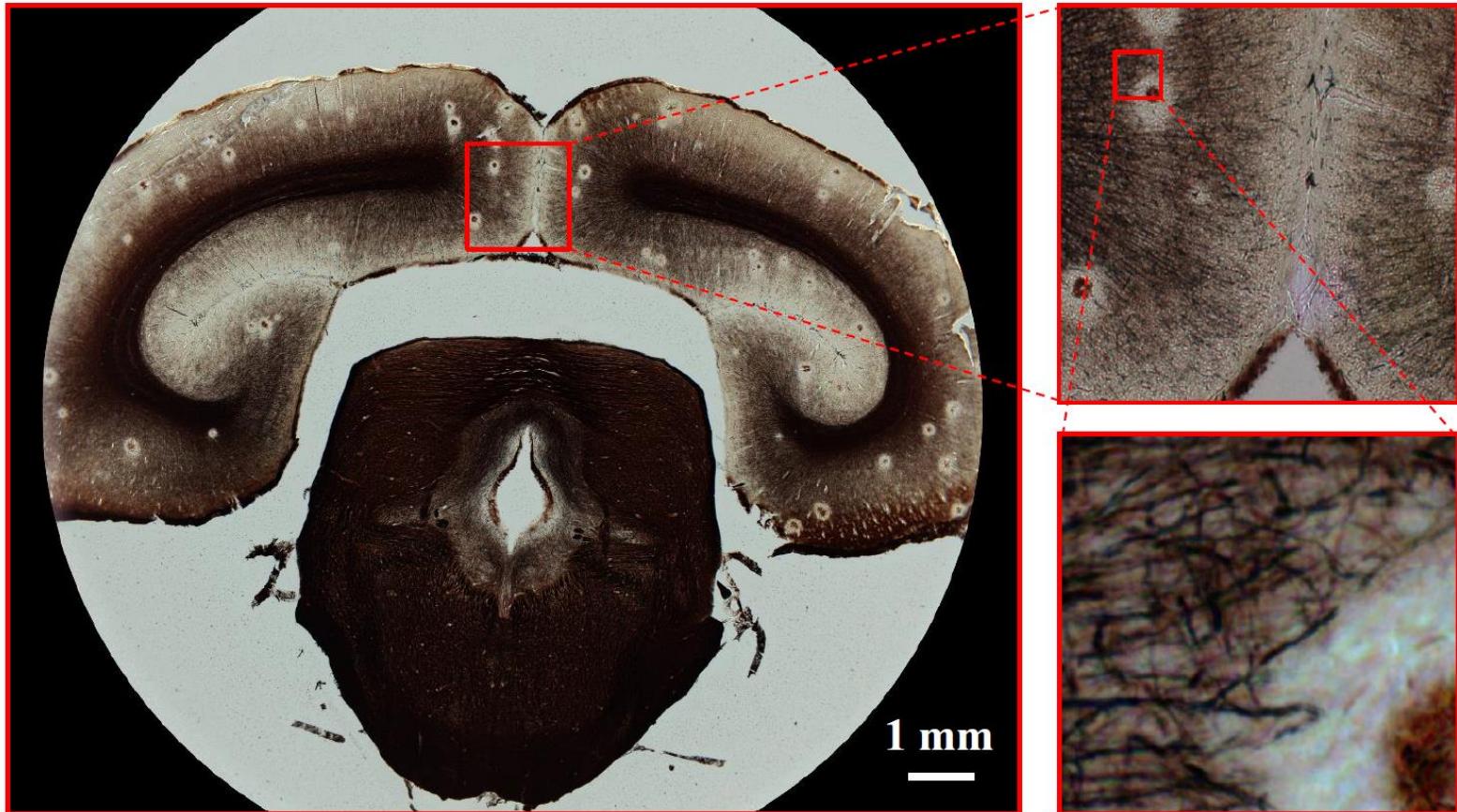
Guoan Zheng, Roarke Horstmeyer and Changhuei Yang, "Wide-field, high-resolution Fourier ptychographic microscopy," Nature Photonics, 7, 739-745 (2013).

FPM based gigapixel imaging



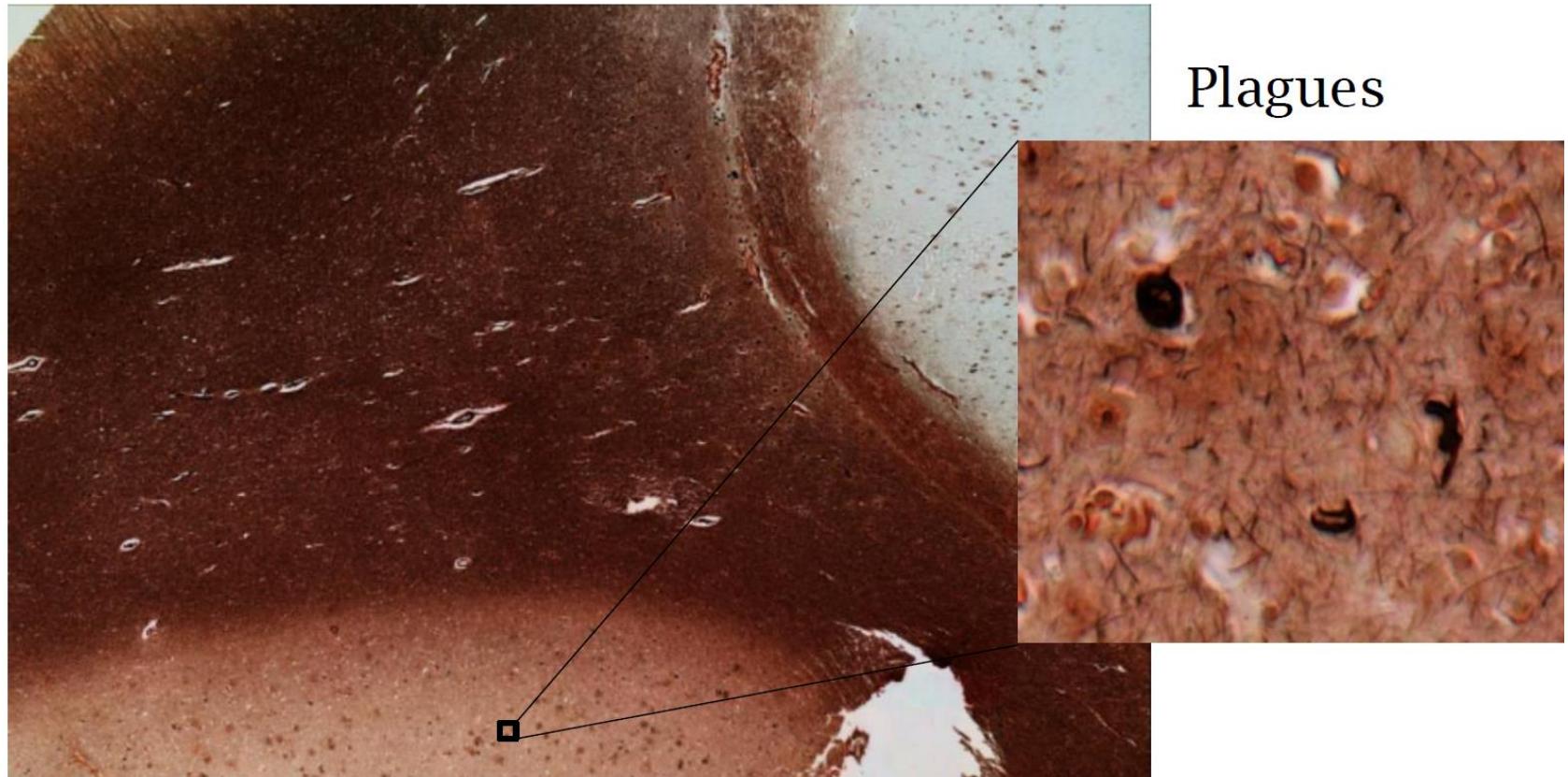
FPM based gigapixel imaging

Mice brain, with silver stain

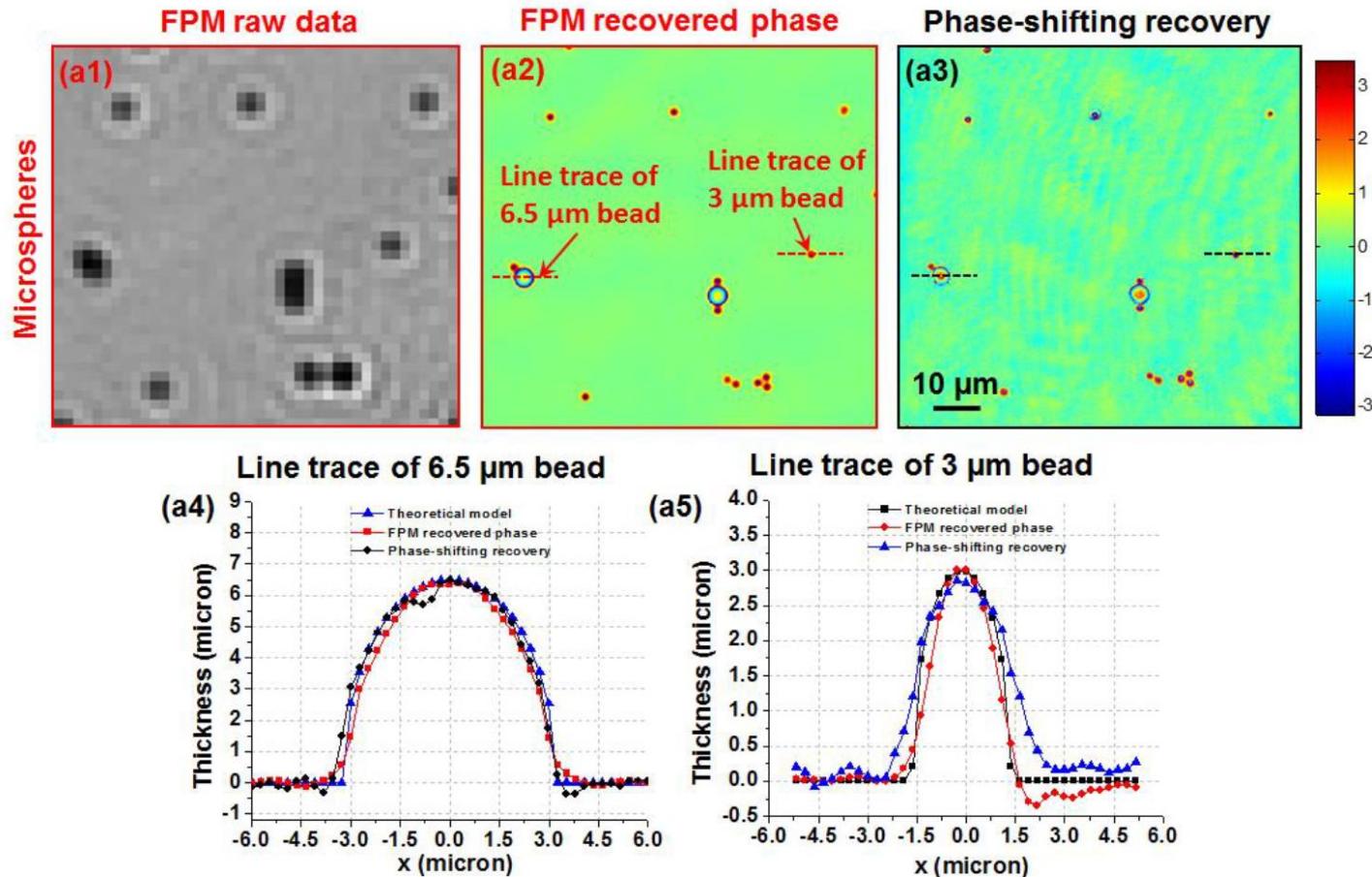


FPM based gigapixel imaging

- Human brain section with Alzheimer disease



Phase imaging in FPM

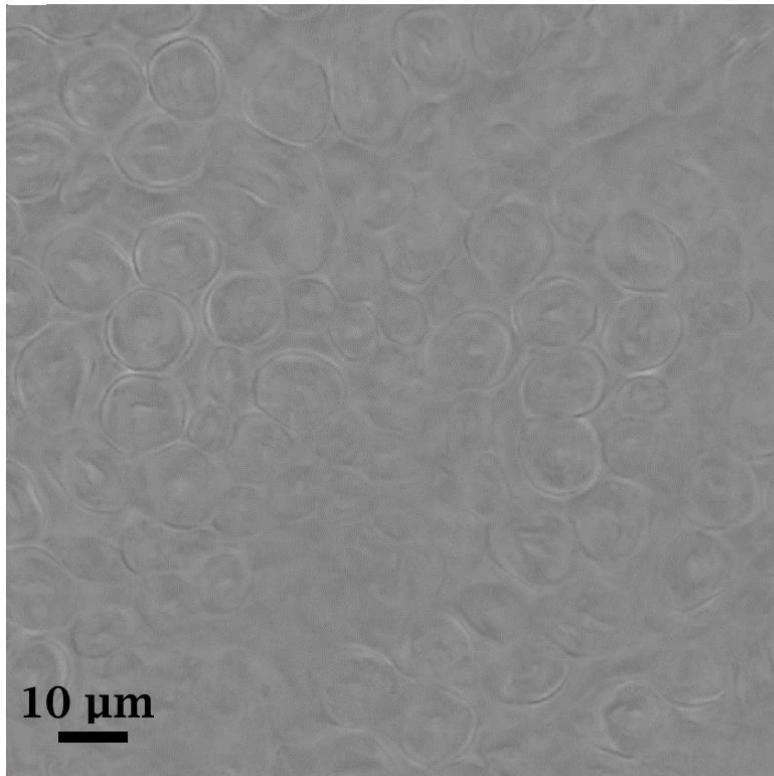


Xiaoze Ou, Roarke Horstmeyer, Changhuei Yang and Guoan Zheng*, "Quantitative phase imaging via Fourier ptychographic microscopy," Optics Letters, 38(22), 4845-4848 (2013).

Phase imaging in FPM

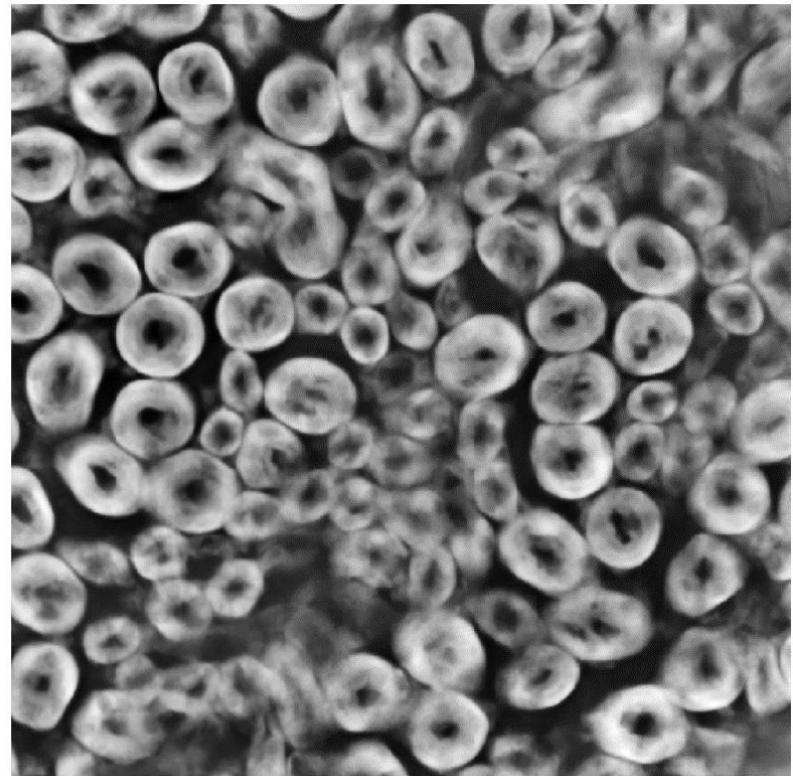
□ Unstained mouse kidney

FPM recovered intensity

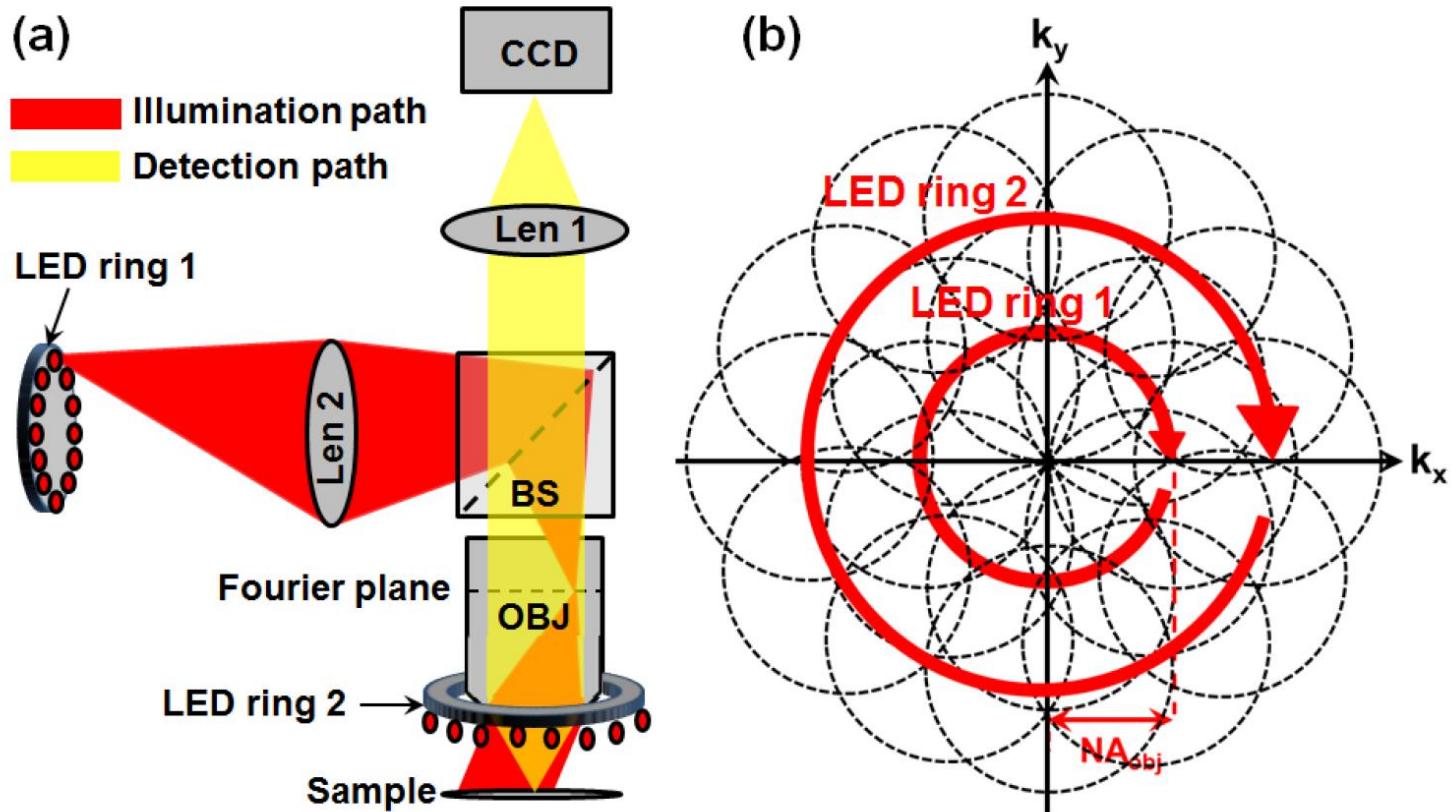


10 μm

FPM recovered phase

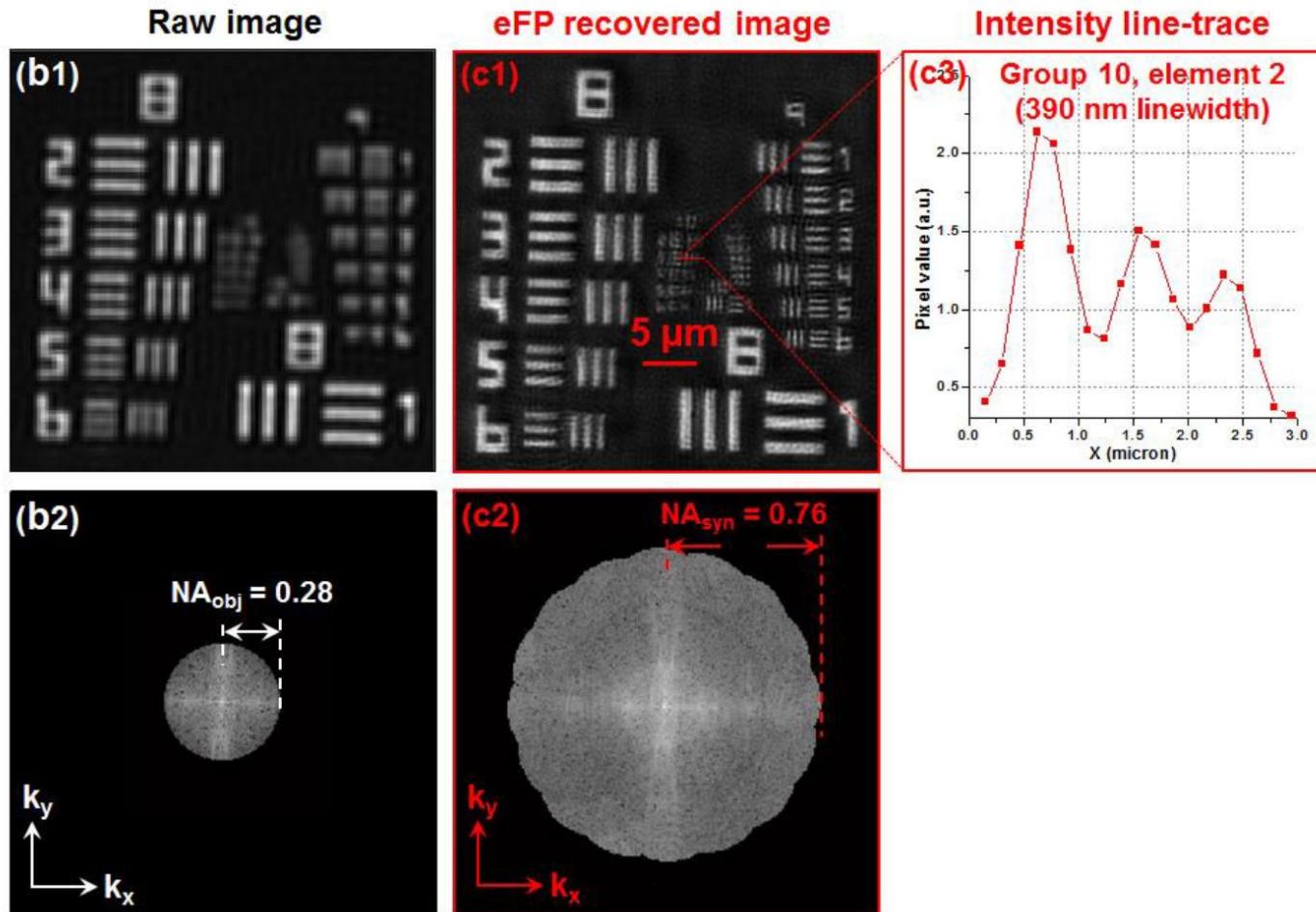


Epi-illuminated Fourier ptychography

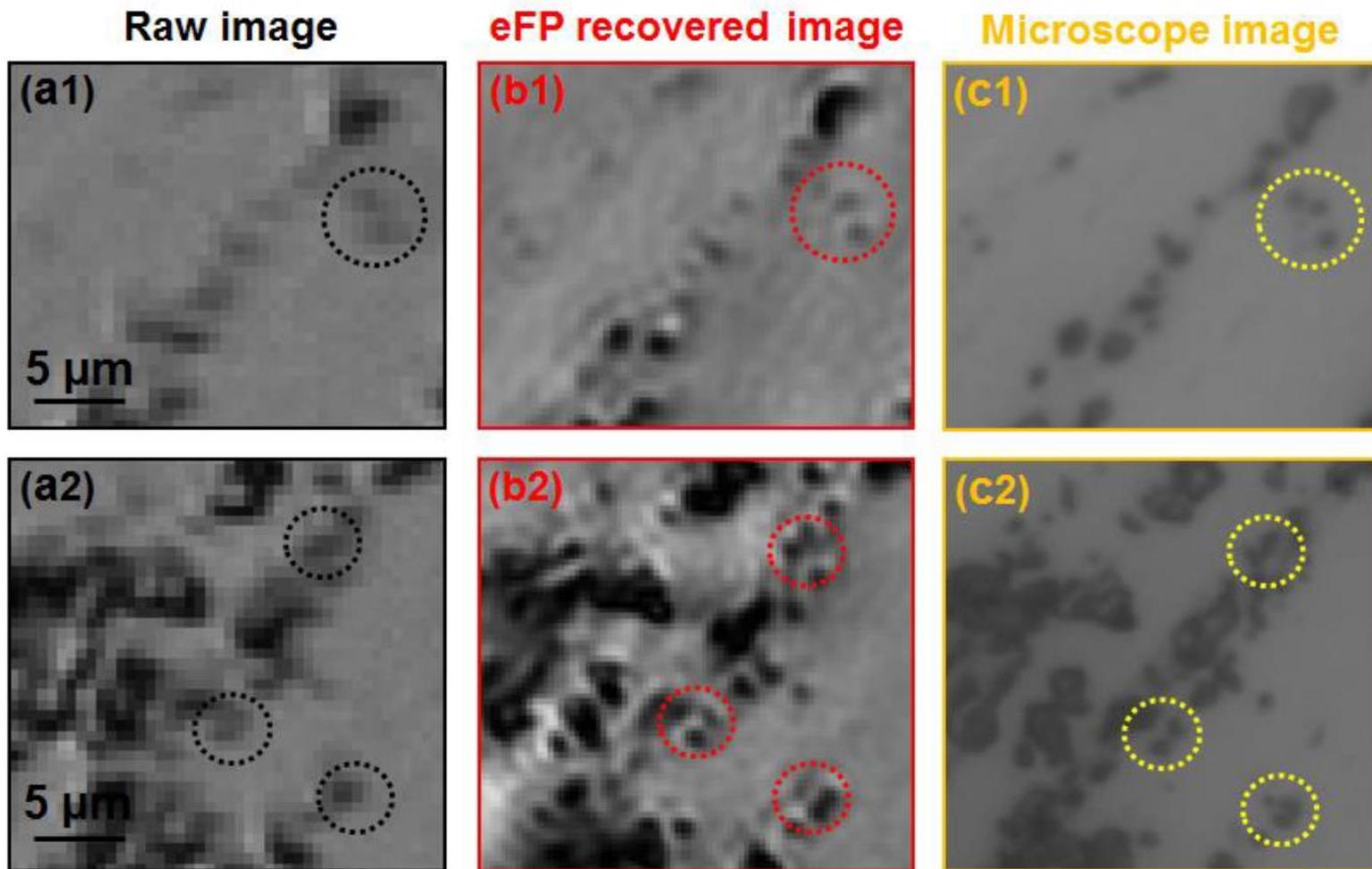


Kaikai Guo, Siyuan Dong, and Guoan Zheng, "Fourier Ptychography for Brightfield, Phase, Darkfield, Reflective, Multi-slice, and Fluorescence Imaging," IEEE Journal of Selected Topics in Quantum Electronics (2015).

Epi-illuminated Fourier ptychography

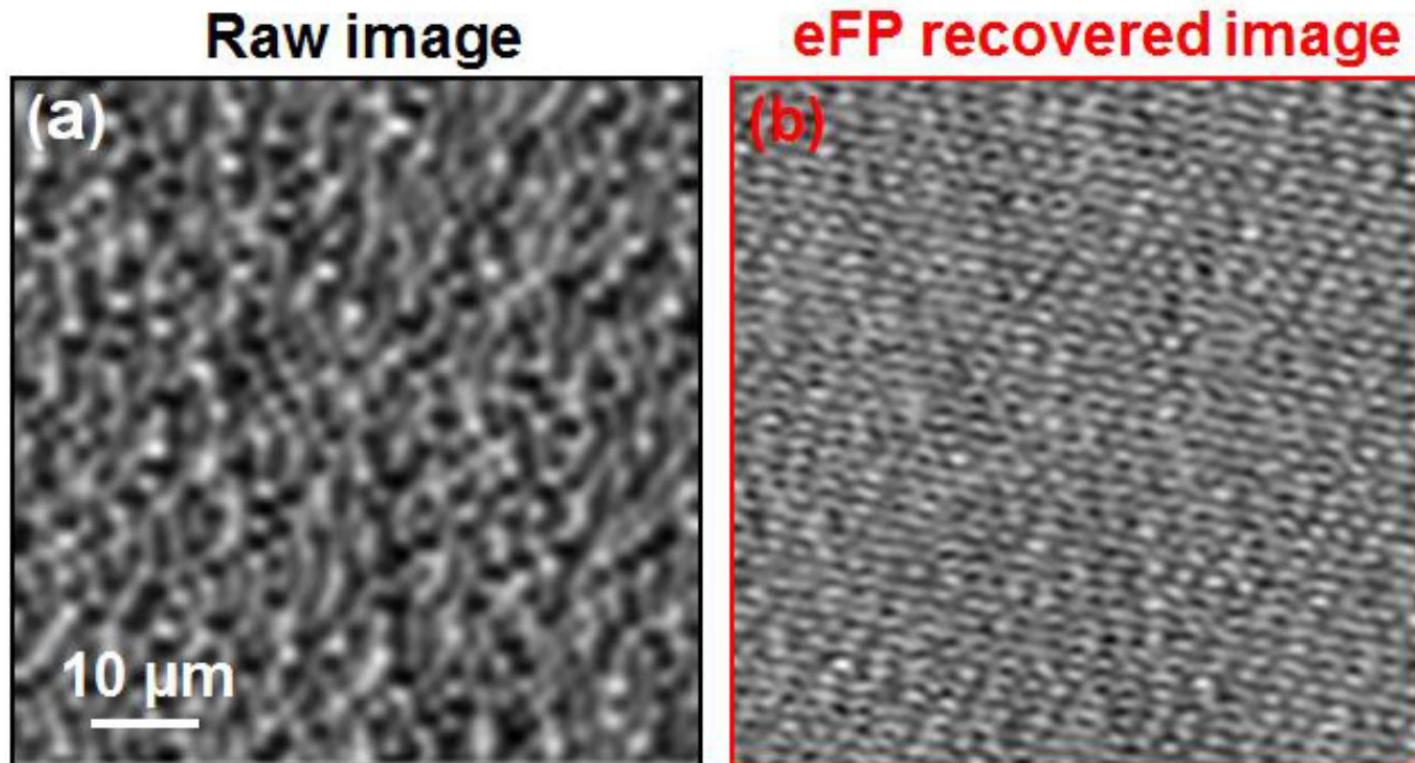


Epi-illuminated Fourier ptychography

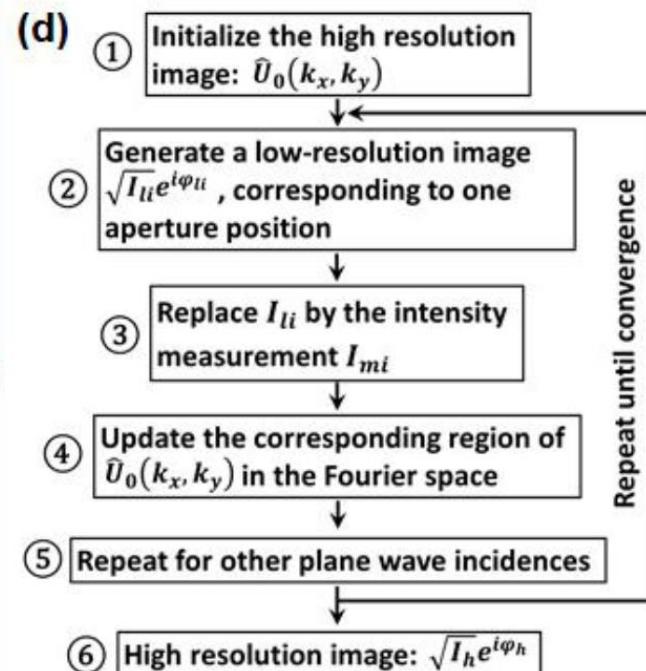
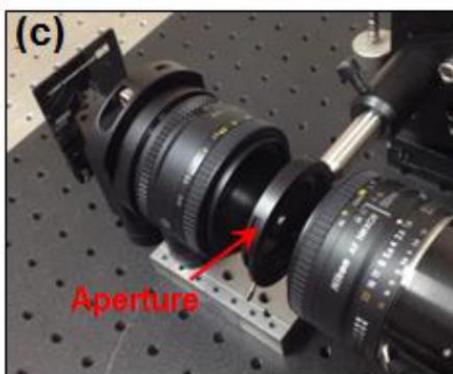
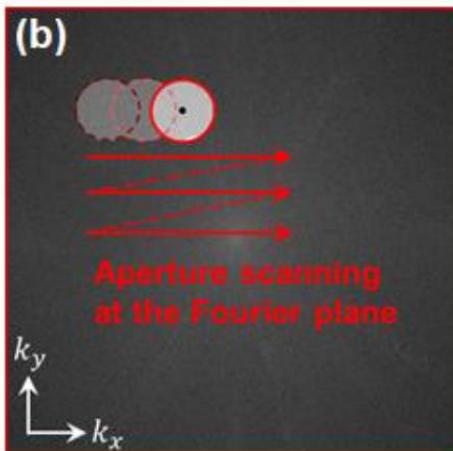
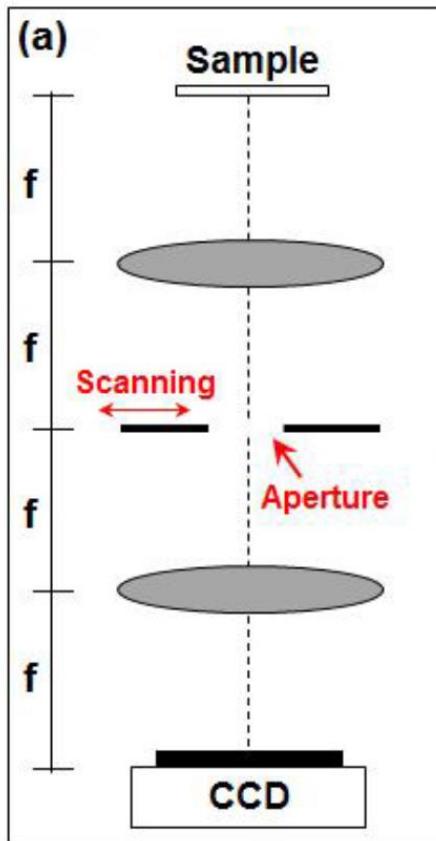


Epi-illuminated Fourier ptychography

Compact Disc

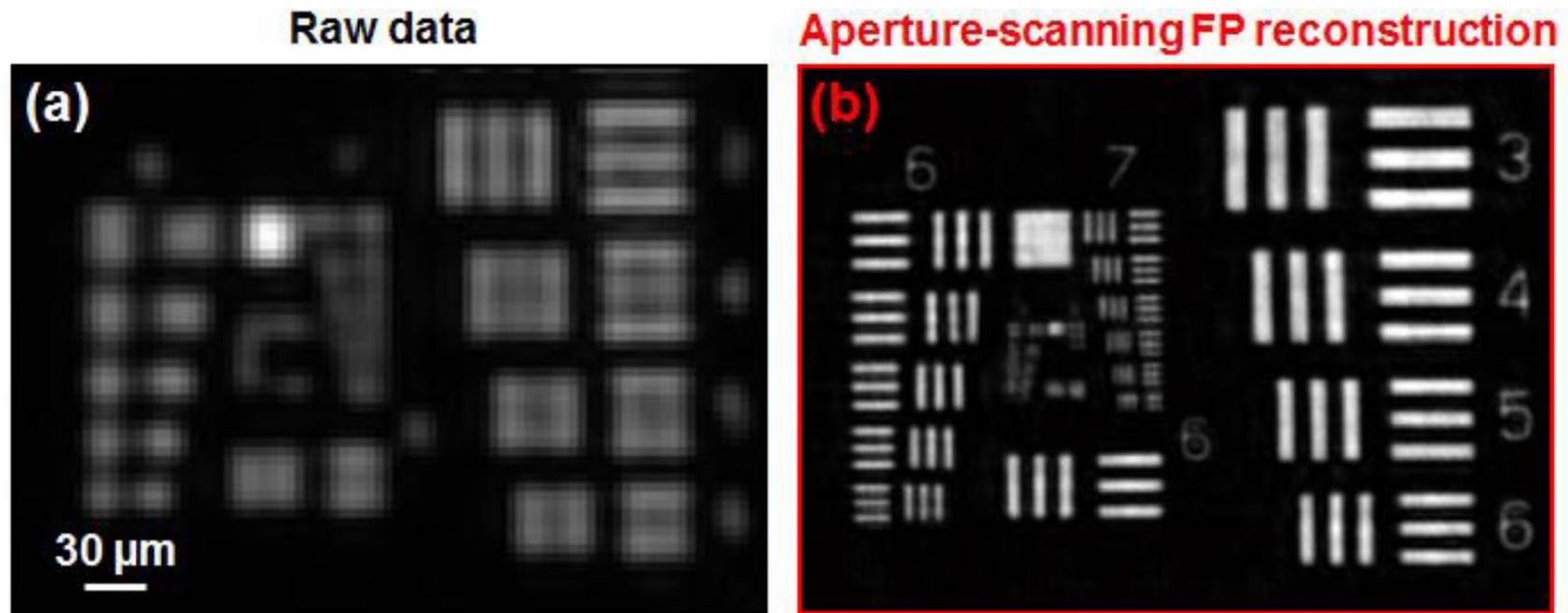


FP imaging at detection path



- Aperture scanning at the Fourier plane

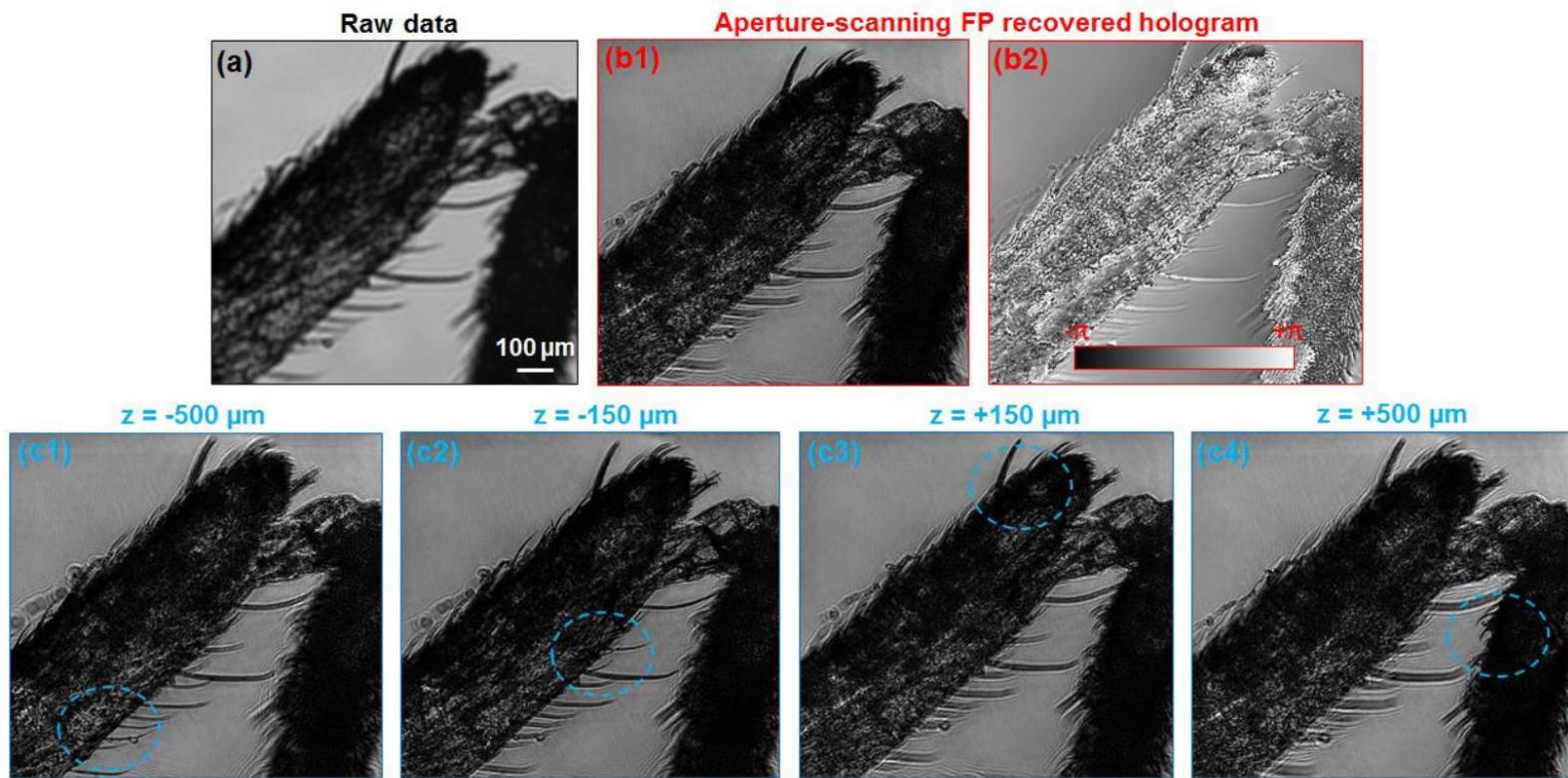
FP imaging at detection path



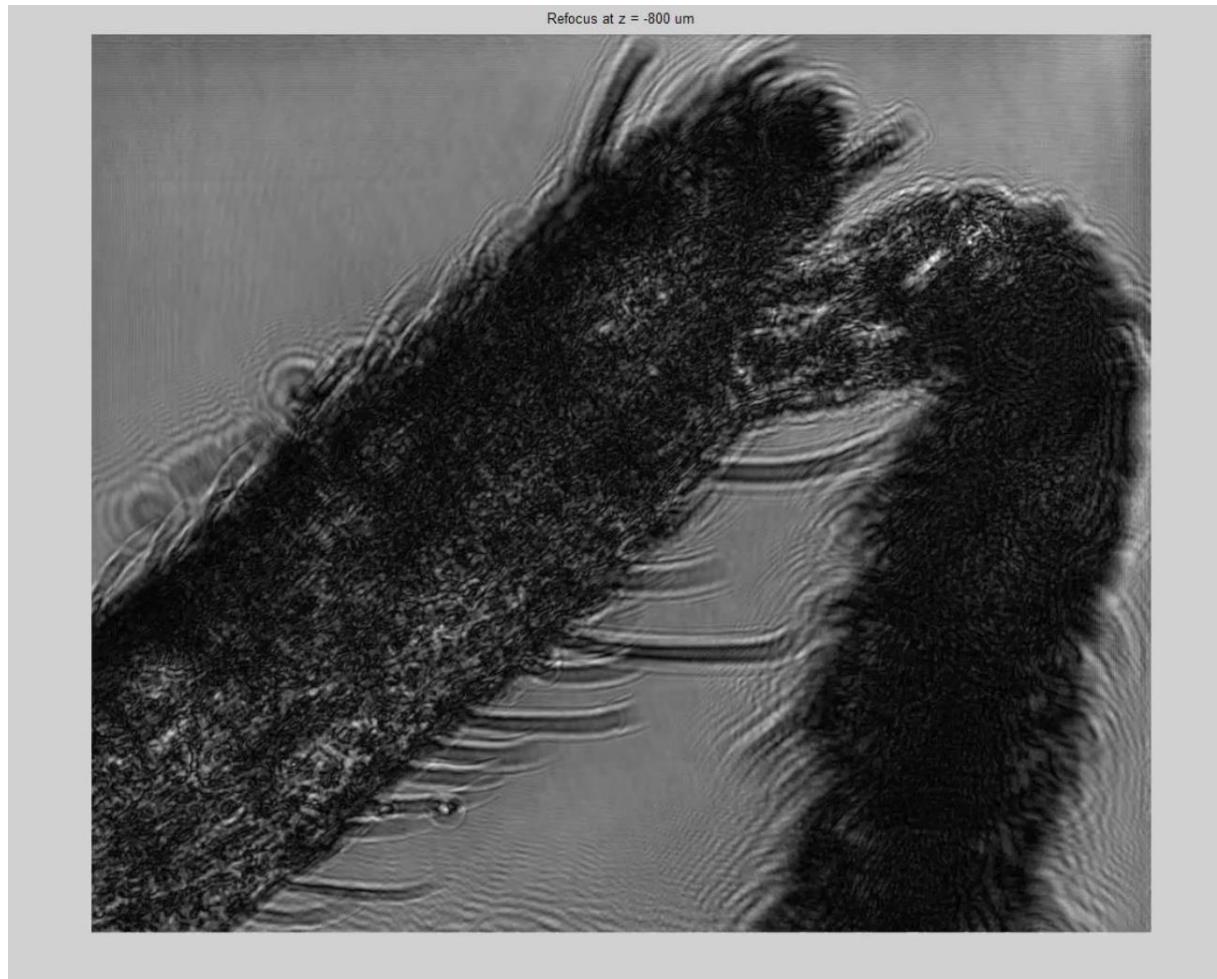
Siyuan Dong, Roarke Horstmeyer, Radhika Shiradkar, Kaikai Guo, Xiaoze Ou, Zichao Bian, Huolin Xin, and Guoan Zheng, "Aperture-scanning Fourier ptychography for 3D refocusing and super-resolution macroscopic imaging," Optics Express, 22 (11), 13586-13599, (2014)

FP imaging at detection path

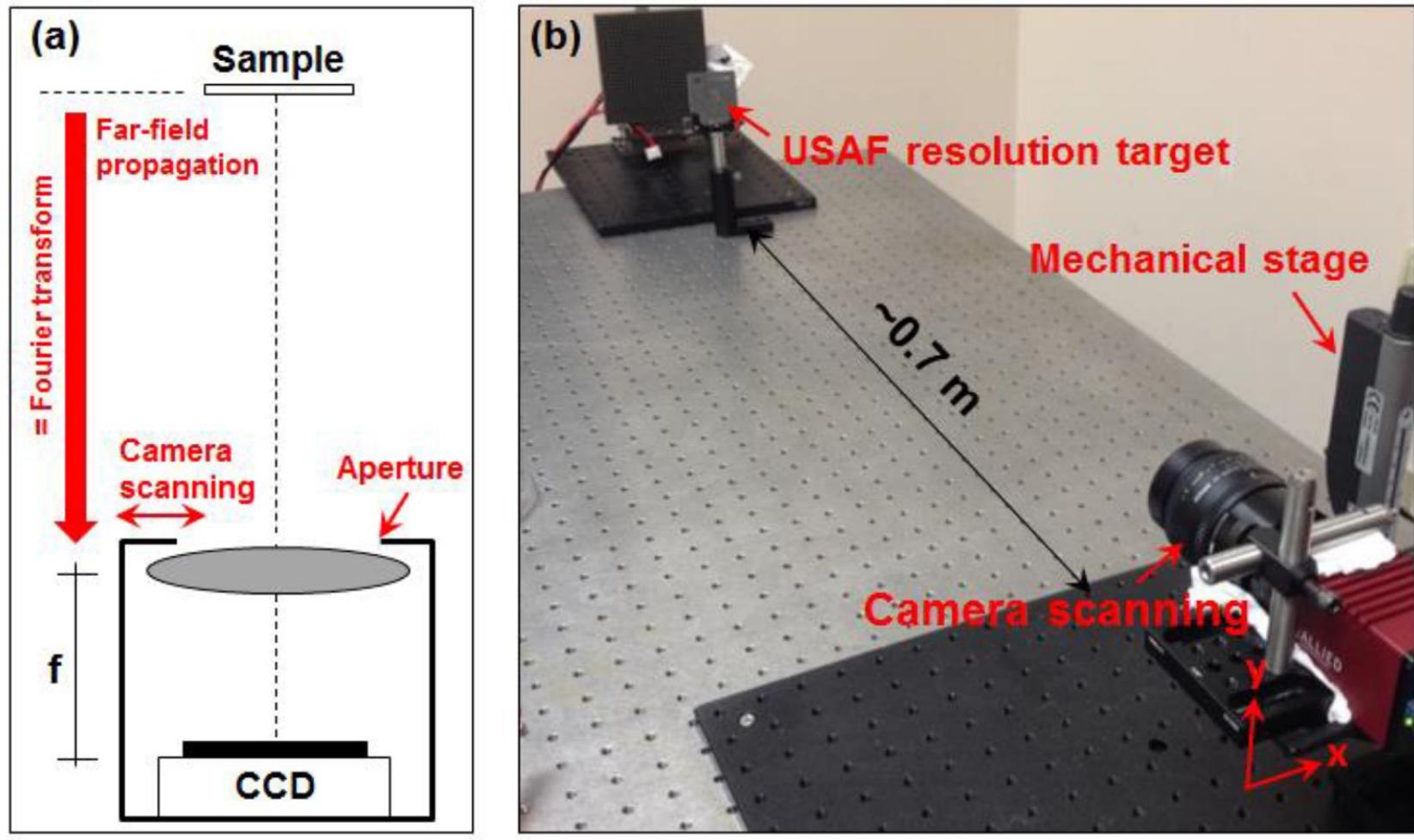
- 3D holographic imaging based on the recovered intensity and phase



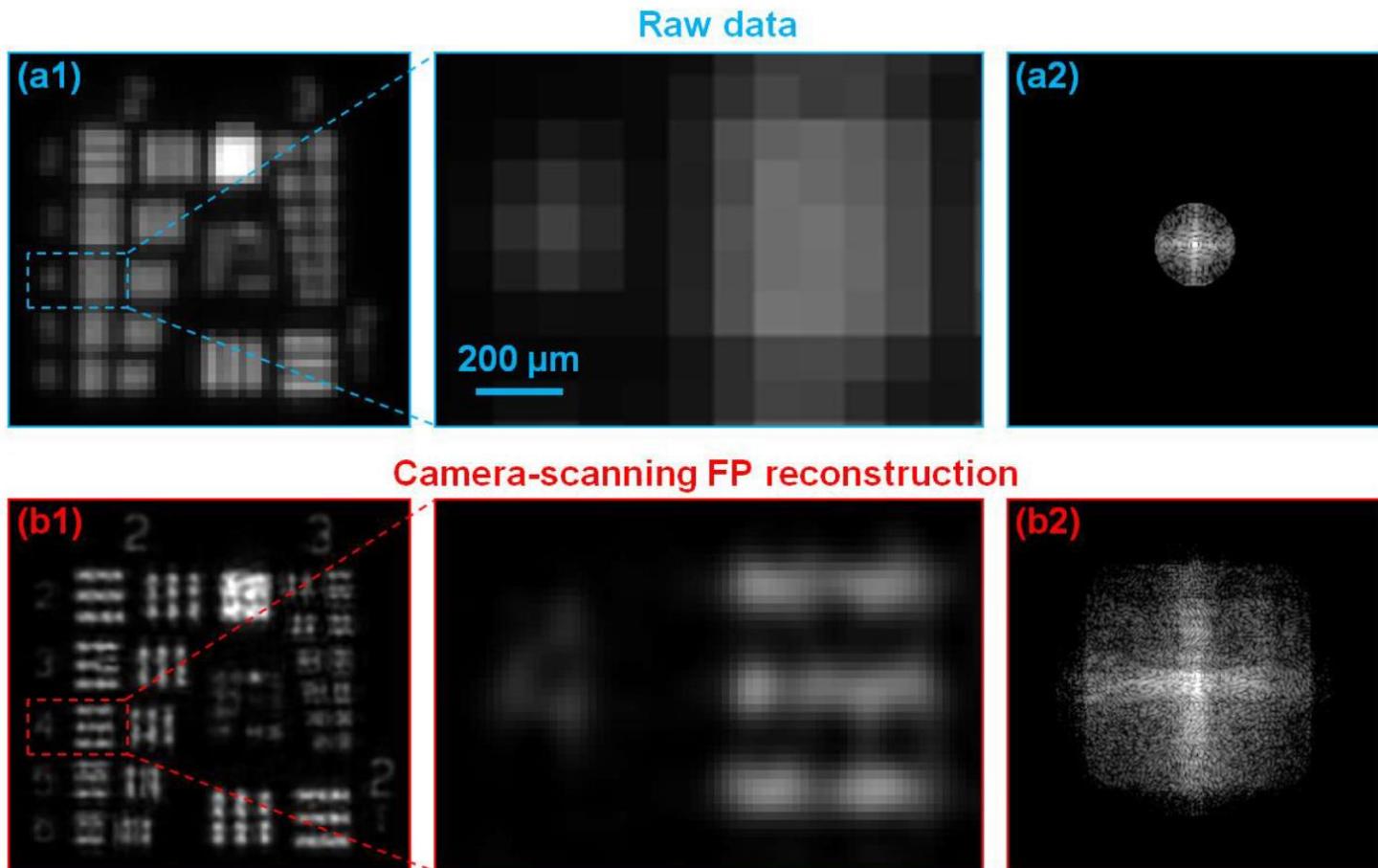
FP imaging at detection path



Macroscopic FP imaging



Macroscopic FP imaging



Siyuan Dong, Roarke Horstmeyer, Radhika Shiradkar, Kaikai Guo, Xiaoze Ou, Zichao Bian, Huolin Xin, and Guoan Zheng, "Aperture-scanning Fourier ptychography for 3D refocusing and super-resolution macroscopic imaging," Optics Express, 22 (11), 13586-13599, (2014)

Aberration recovery

$$I_n(x, y) = |(O(x, y) \cdot P_n(x, y)) * PSF|^2$$

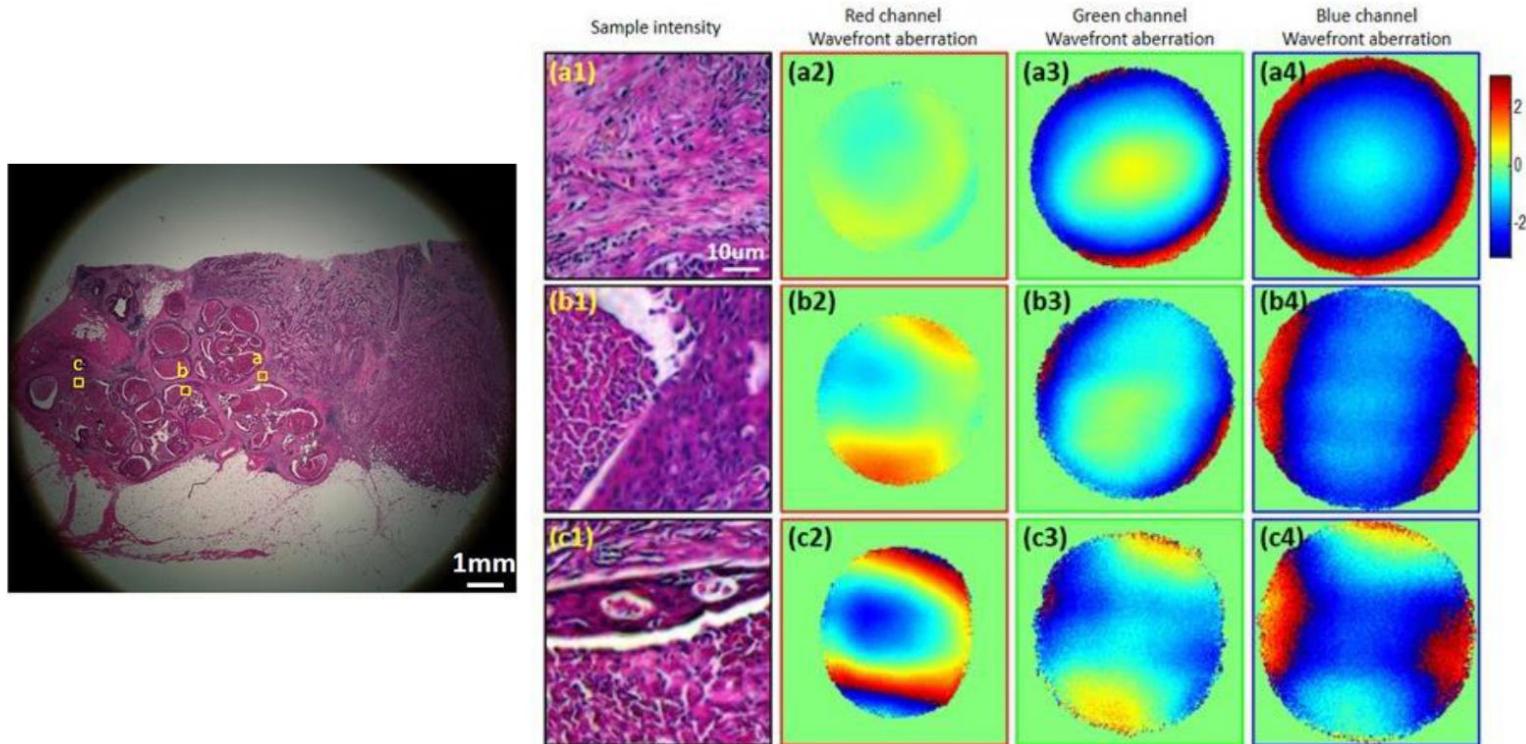
$O(x, y)$ is the object, complex and unknown

$P_n(x, y) = e^{ik_{xn}x} \cdot e^{ik_{yn}y}$, plane wave illumination;
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$FT\{PSF\} = circ(k_{max}) \cdot e^{i\varphi(k_x, k_y)}$; $\varphi(k_x, k_y)$ is the aberration;
 $\varphi(k_x, k_y) = 0$ for diffraction limited system

- Goal: to recover $O(x, y)$ and PSF from $I_n(x, y)$ ($n = 1, 2, 3, \dots$)

Aberration recovery

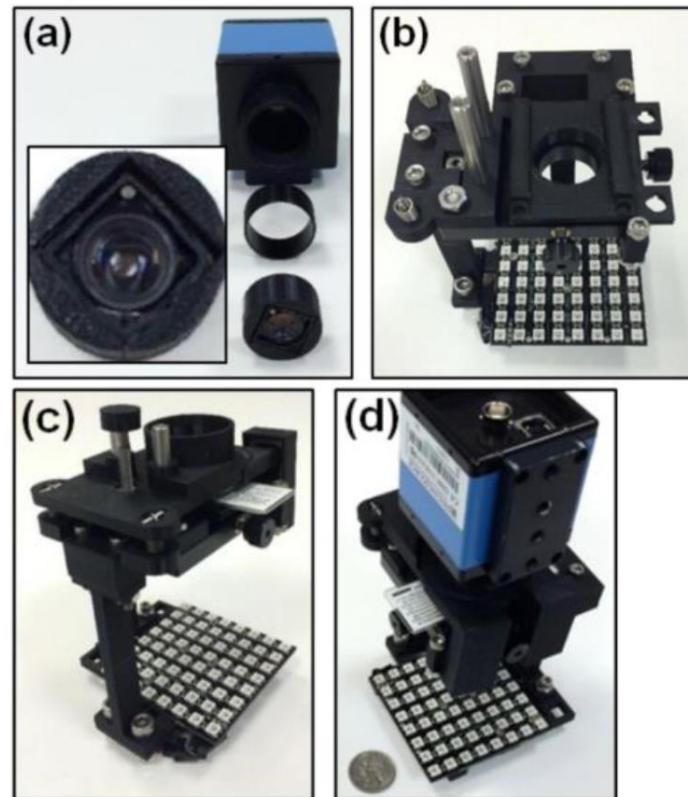
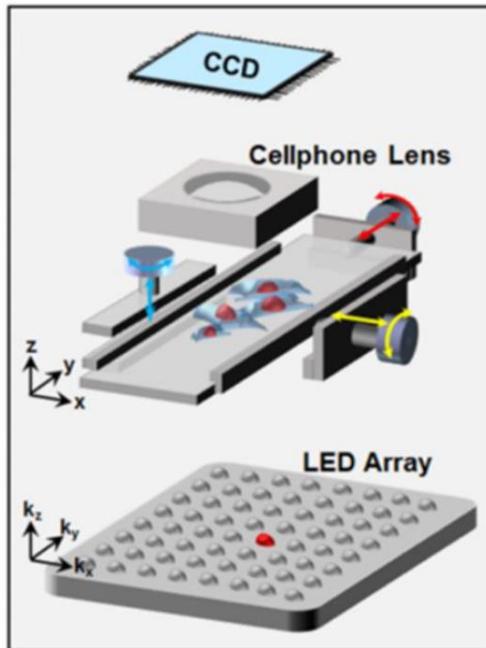


- Use it for aberration characterization (contact lens)

Xiaoze Ou, Guoan Zheng, and Changhuei Yang, "Embedded pupil function recovery for Fourier ptychographic microscopy", Optics Express, 22(5), 4960-4972 (2014).

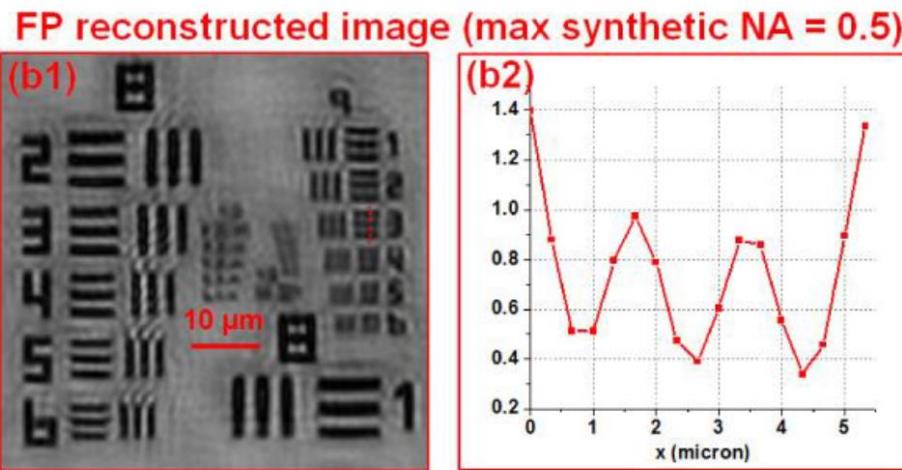
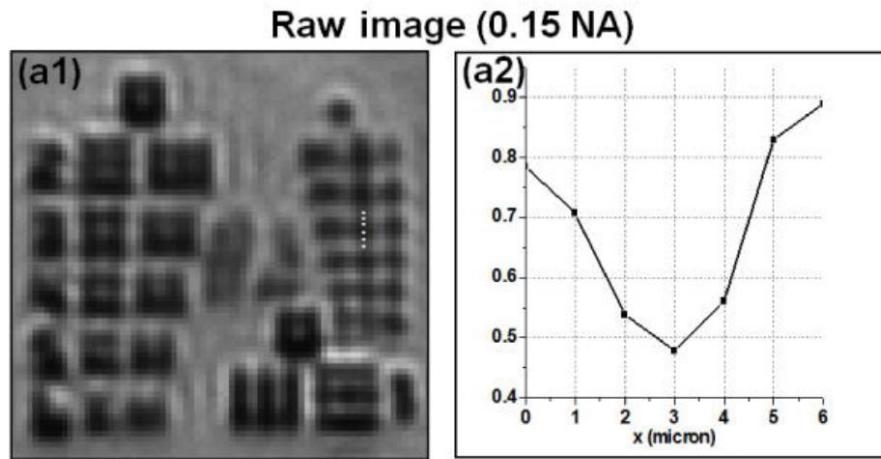
Mobile phone based field-portable microscope

- Resolution and aberration in FPM
- High-resolution microscopy using a cellphone lens

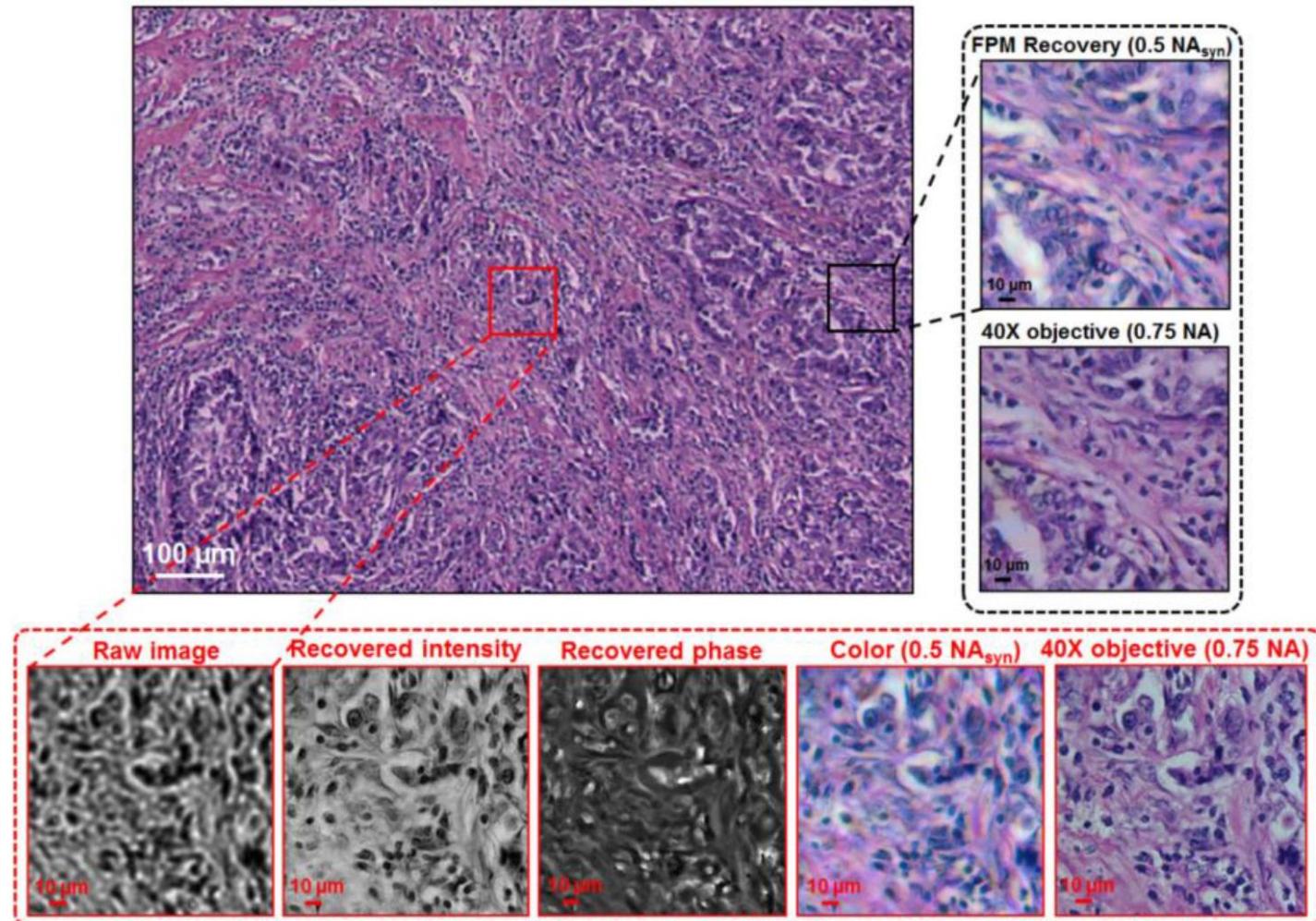


Siyuan Dong, Kaikai Guo, Pariksheet Nanda, Radhika Shiradkar, and Guoan Zheng*, "FPscope: a field-portable high-resolution microscope using a cellphone lens," Biomedical Optics Express, 5 (10), 3305-3310 (2014).

Mobile phone based field-portable microscope

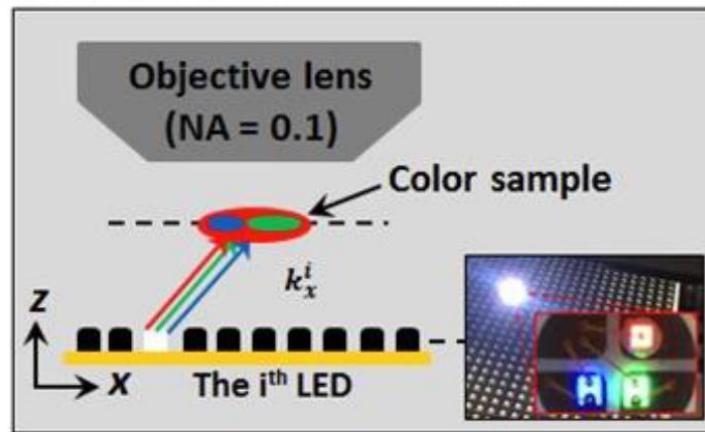


Mobile phone based field-portable microscope



Spectrum multiplexing

R/G/B LEDs are turned on simultaneously

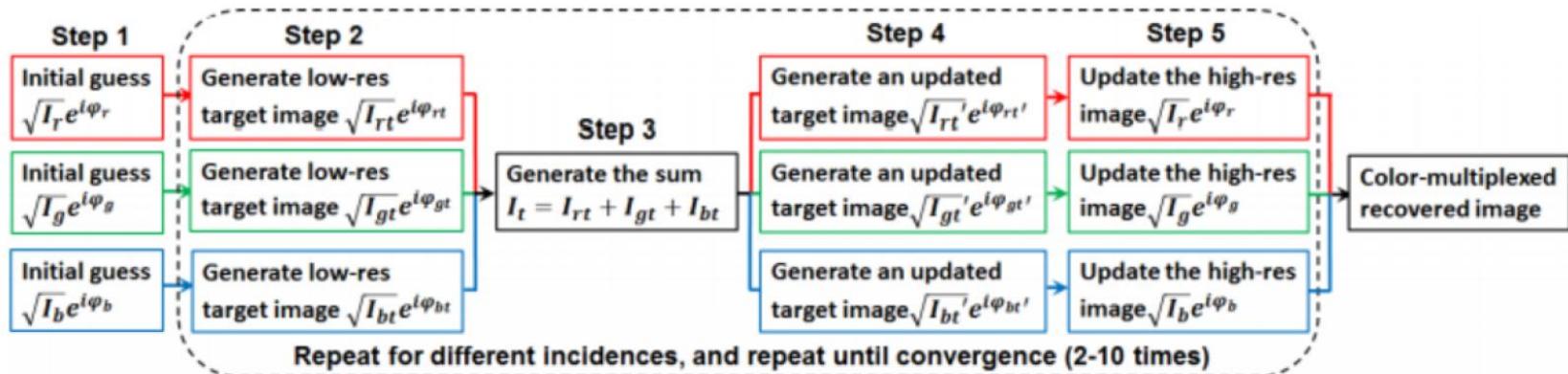


$$I_n(x, y) = \sum_i |(O_i(x, y) \cdot P_n(x, y)) * PSF_i|^2$$

$P_n(x, y) = e^{ik_{xn}x} \cdot e^{ik_{yn}y}$, plane wave illumination;
 (k_{xn}, k_{yn}) represent incident angle; $n = 1, 2, 3, \dots$

- Goal: to recover $O_i(x, y)$ ($i = 1, 2, 3, \dots$) from $I_n(x, y)$
($n = 1, 2, 3, \dots$)

Spectrum multiplexing

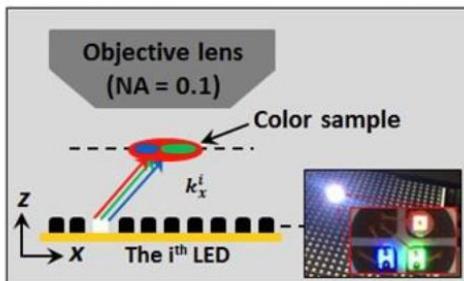


Step 1: Initialization (image can be a random guess).

Step 2: Generate low-res target image by imposing the pupil function to the high-res initial guess.

Step 3: Sum up the intensity components of the target images: $I_t = I_{rt} + I_{gt} + I_{bt}$.

R/G/B LEDs are turned on simultaneously

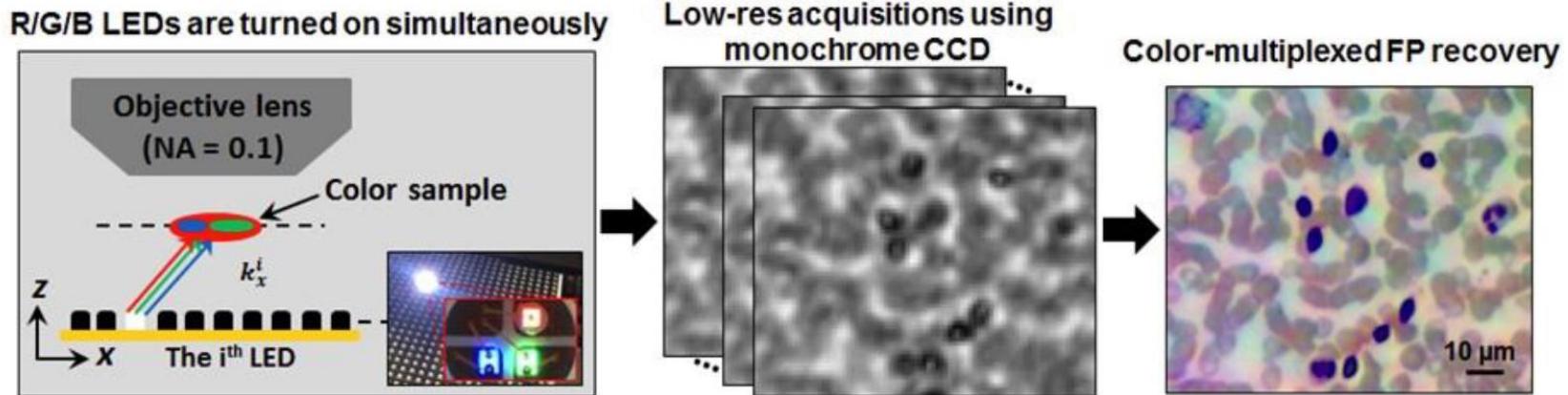


Step 4: $I'_{rt} = \frac{I_m}{I_t} * I_{rt}$, where I_m is the low-res measurement (same treatment for I'_{gt} and I'_{bt}). Phase is kept unchanged.

Step 5: Update the corresponding spectral region of the high-res image.

Siyuan Dong, Radhika Shiradkar, Pariksheet Nanda, Guoan Zheng "Spectrum multiplexing and coherent-state decomposition in Fourier ptychographic imaging," Biomedical Optics Express, 5(6), 1757-1767 (2014).

Spectrum multiplexing



- No spectral filter is needed
- Computational multispectral imaging

Siyuan Dong, Radhika Shiradkar, Pariksheet Nanda, Guoan Zheng "Spectrum multiplexing and coherent-state decomposition in Fourier ptychographic imaging," Biomedical Optics Express, 5(6), 1757-1767 (2014).

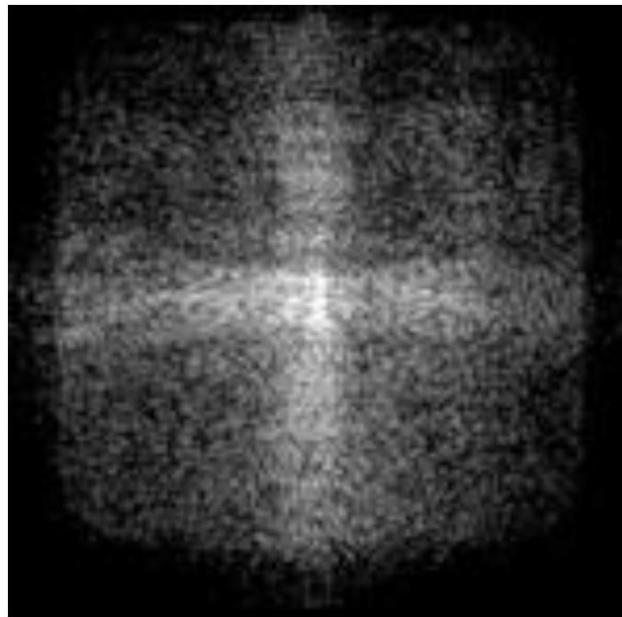
Modeling of partially coherent effect

$$I_n(x, y) = \sum \sum_{\Delta_x, \Delta_y=-t}^t |(O(x, y) \cdot e^{i(k_{xn} + \Delta_x)x} \cdot e^{i(k_{yn} + \Delta_y)y}) * PSF_i|^2$$

$P_n(x, y) = e^{ik_{xn}x} \cdot e^{ik_{yn}y}$, plane wave illumination;
 (k_{xn}, k_{yn}) represent incident angle; $n = 1, 2, 3, \dots$

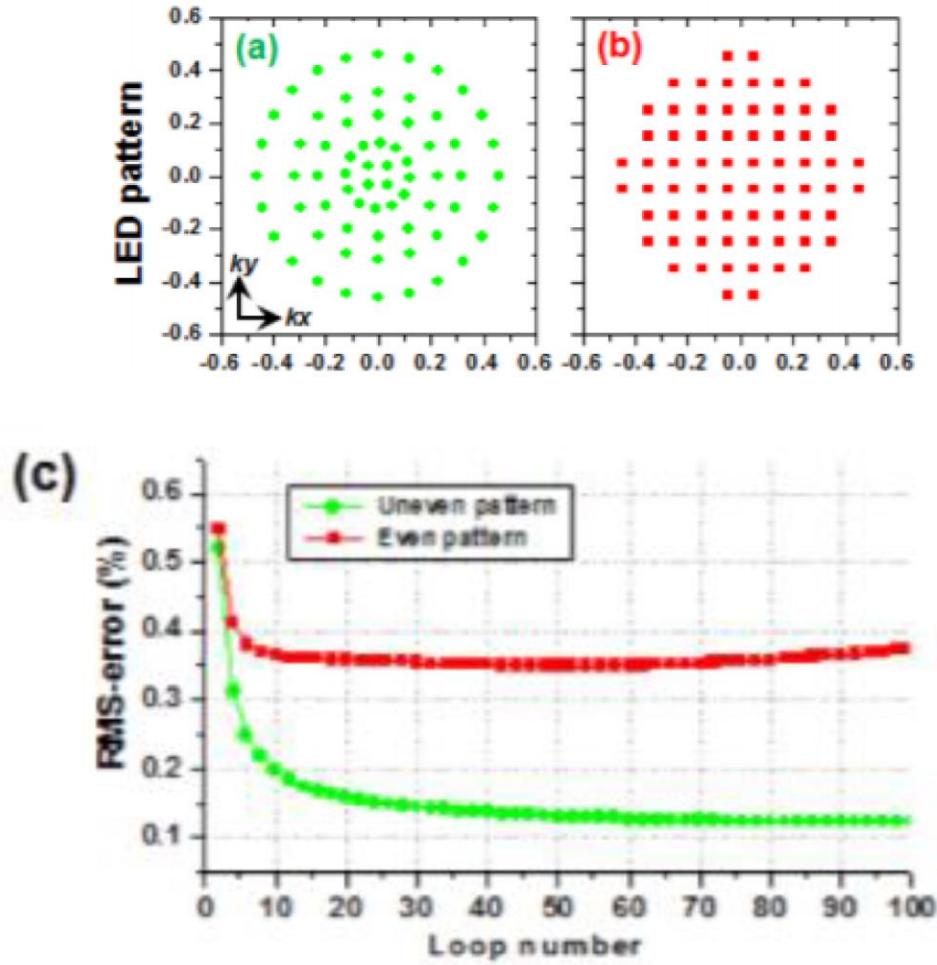
- Goal: to recover $O(x, y)$ ($i = 1, 2, 3, \dots$) from $I_n(x, y)$
 $(n = 1, 2, 3, \dots)$

Sampling strategy

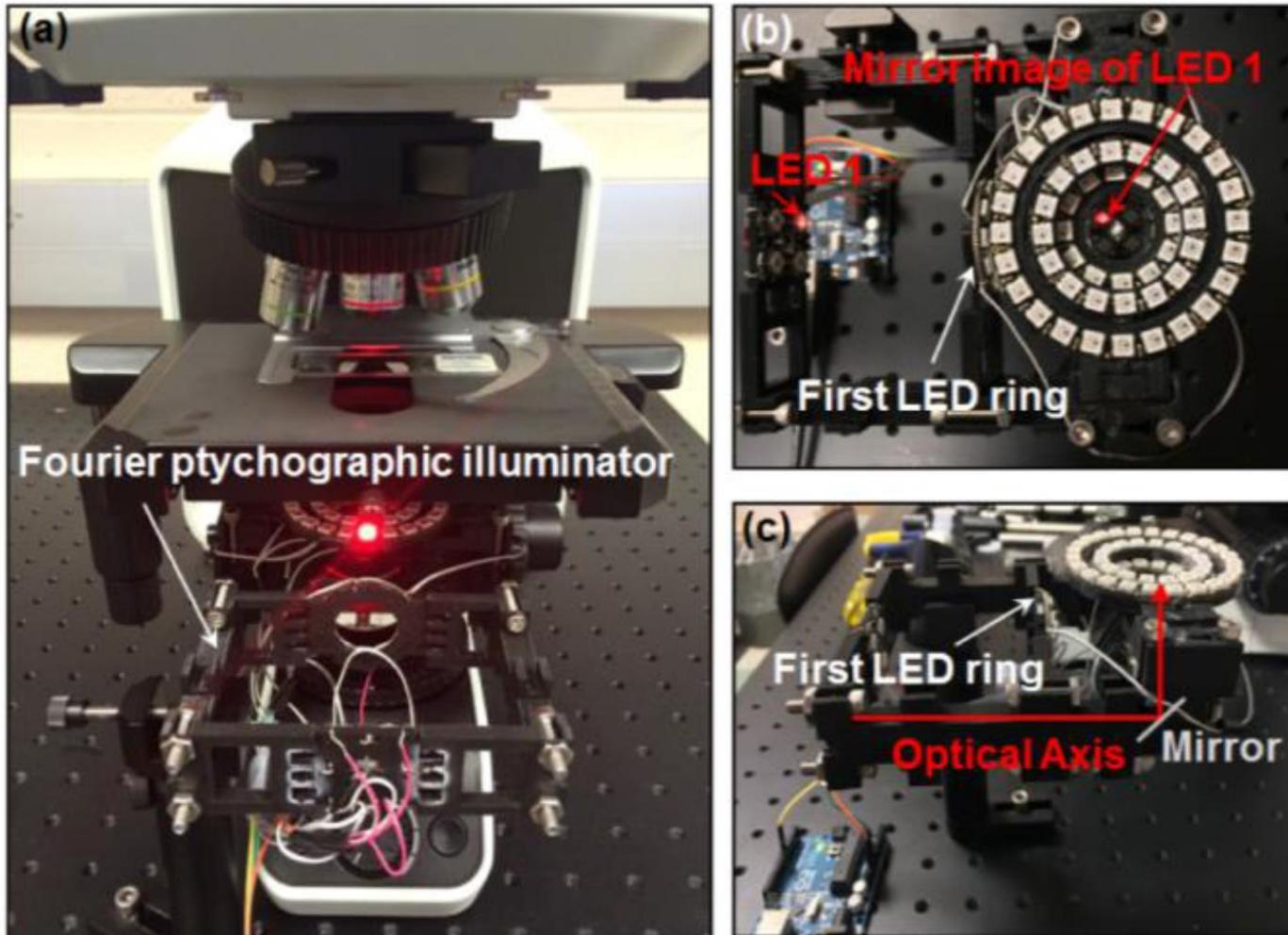


- Energy concentrated at the center
- More LED sampling at the central regions

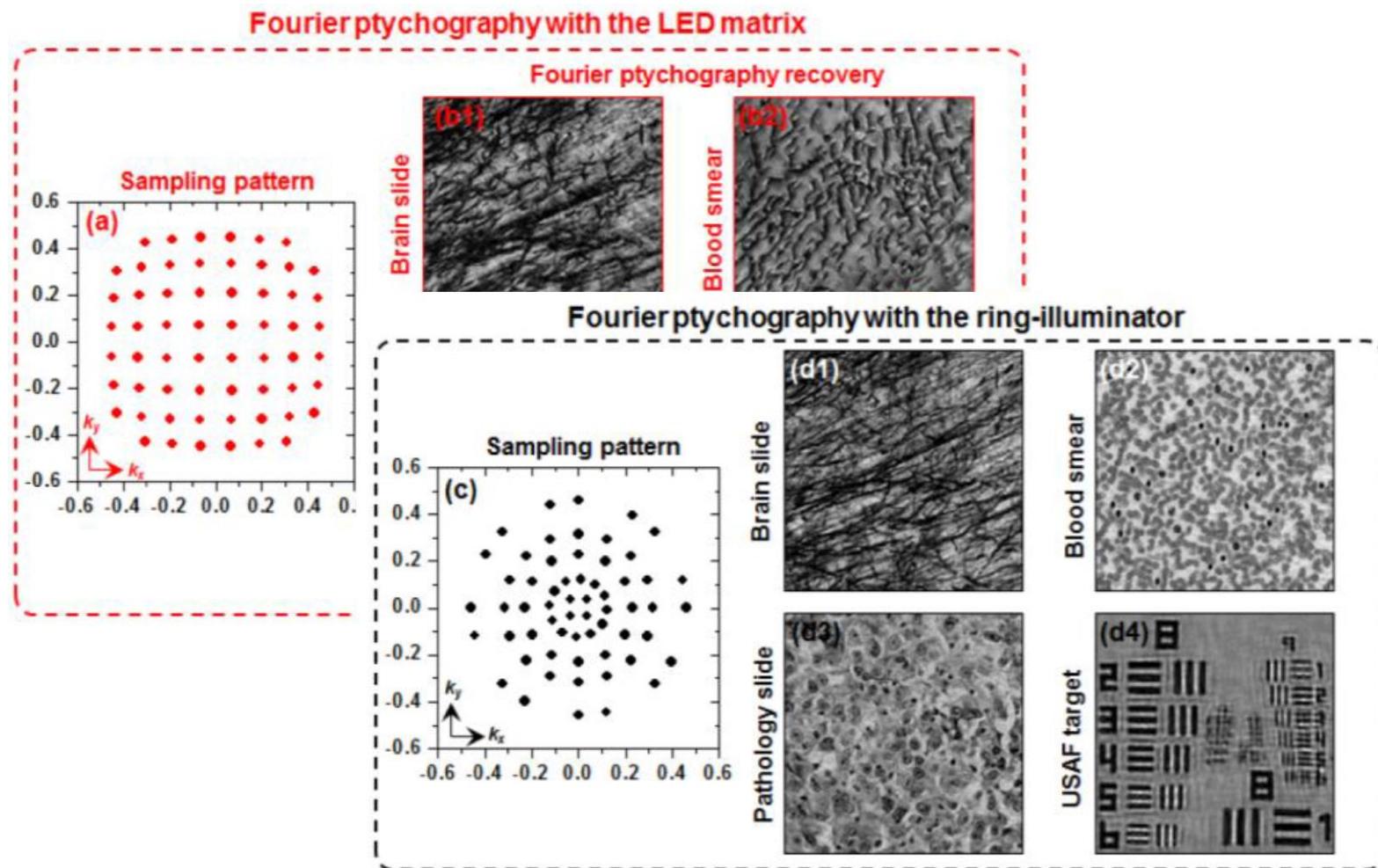
Sampling strategy



Sampling strategy



Sampling strategy



Sampling strategy

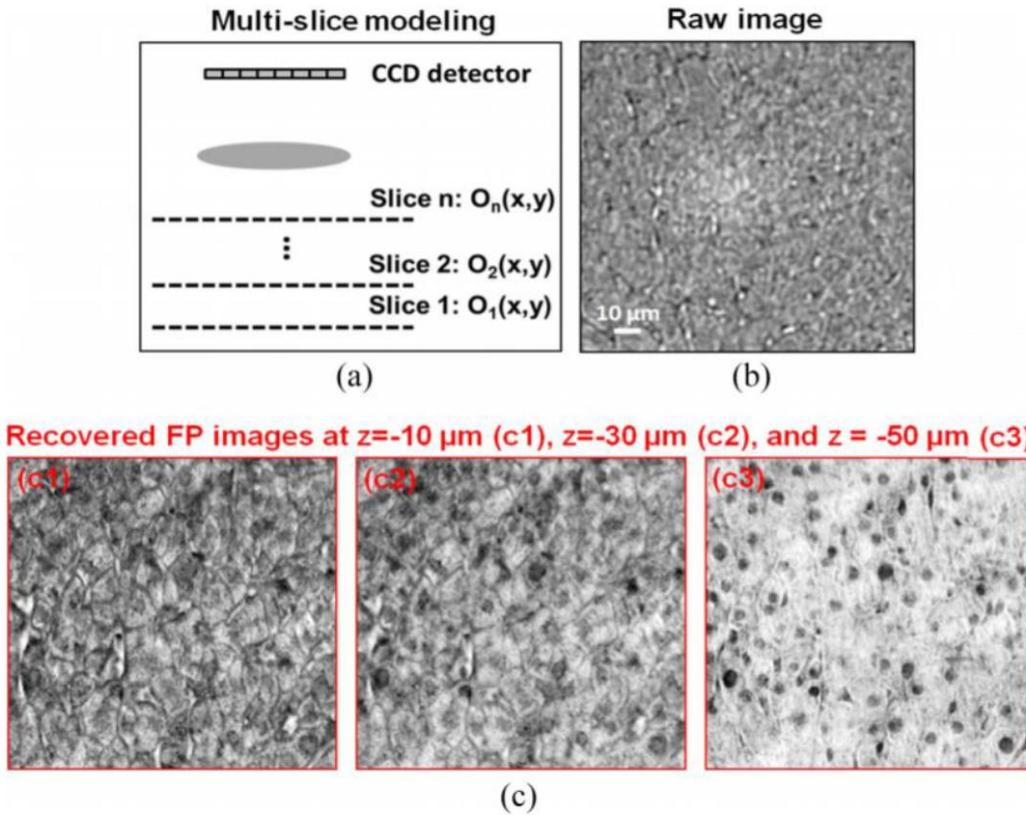
$$I_n(x, y) = |(O(x, y) \cdot P_n(x, y)) * PSF|^2$$

$O(x, y)$ is the object, complex and unknown

$P_n(x, y) = e^{ik_{xn}x} \cdot e^{ik_{yn}y}$, plane wave illumination;
 (k_{xn}, k_{yn}) represent incident angle; $n = 1, 2, 3, \dots$

- If we know the energy distribution of $\text{FT}\{O(x, y)\}$,
how to choose incident angles (k_{xn}, k_{yn})

Multilayer modeling



Kaikai Guo, Siyuan Dong, and Guoan Zheng, "Fourier Ptychography for Brightfield, Phase, Darkfield, Reflective, Multi-slice, and Fluorescence Imaging," IEEE Journal of Selected Topics in Quantum Electronics (2015).

Multilayer modeling

$$I_n(x, y) = |(O(x, y) \cdot P_n(x, y)) * PSF|^2$$

$O(x, y) \cdot P_n(x, y)$ should be better expressed as

$$(O_1(x, y) \cdot P_n(x, y)) * psf_t \cdot O_2(x, y) * psf_t \cdot O_3(x, y) * psf_t$$

$$\text{FT}\{psf_t\} = e^{\sqrt{k_0^2 - k_x^2 - k_y^2} \Delta z}, k_0, \Delta z \text{ constant}$$

Extension for incoherent imaging

- Fourier ptychography

$$I_n(x, y) = |(O(x, y) \cdot P_n(x, y)) * PSF|^2$$

- Incoherent imaging setting

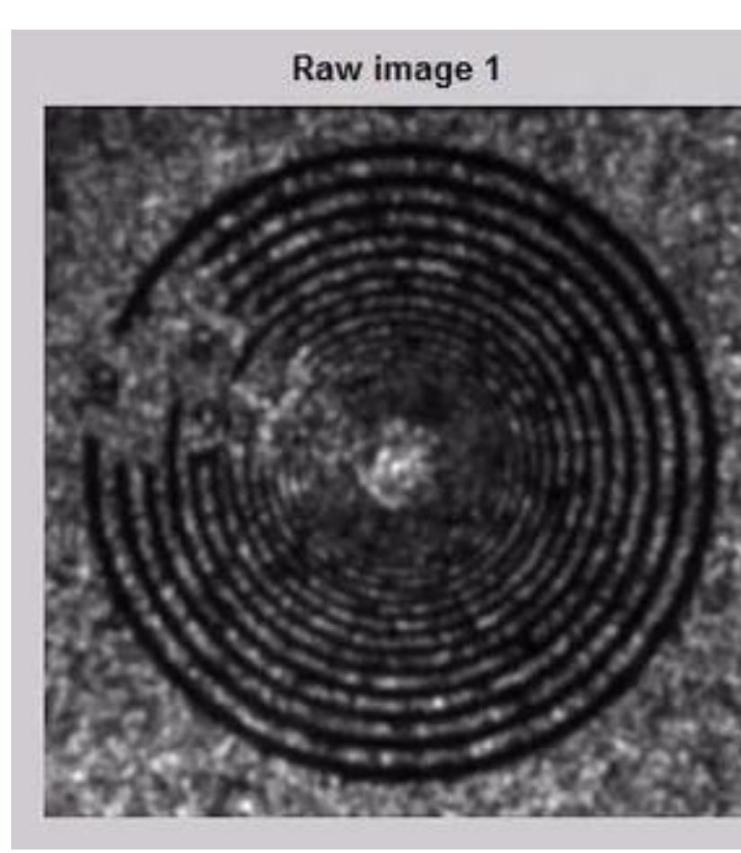
$$I_n(x, y) = (O(x, y) \cdot P_n(x, y)) * |PSF|^2$$

$$O(x, y), P_n(x, y) > 0$$

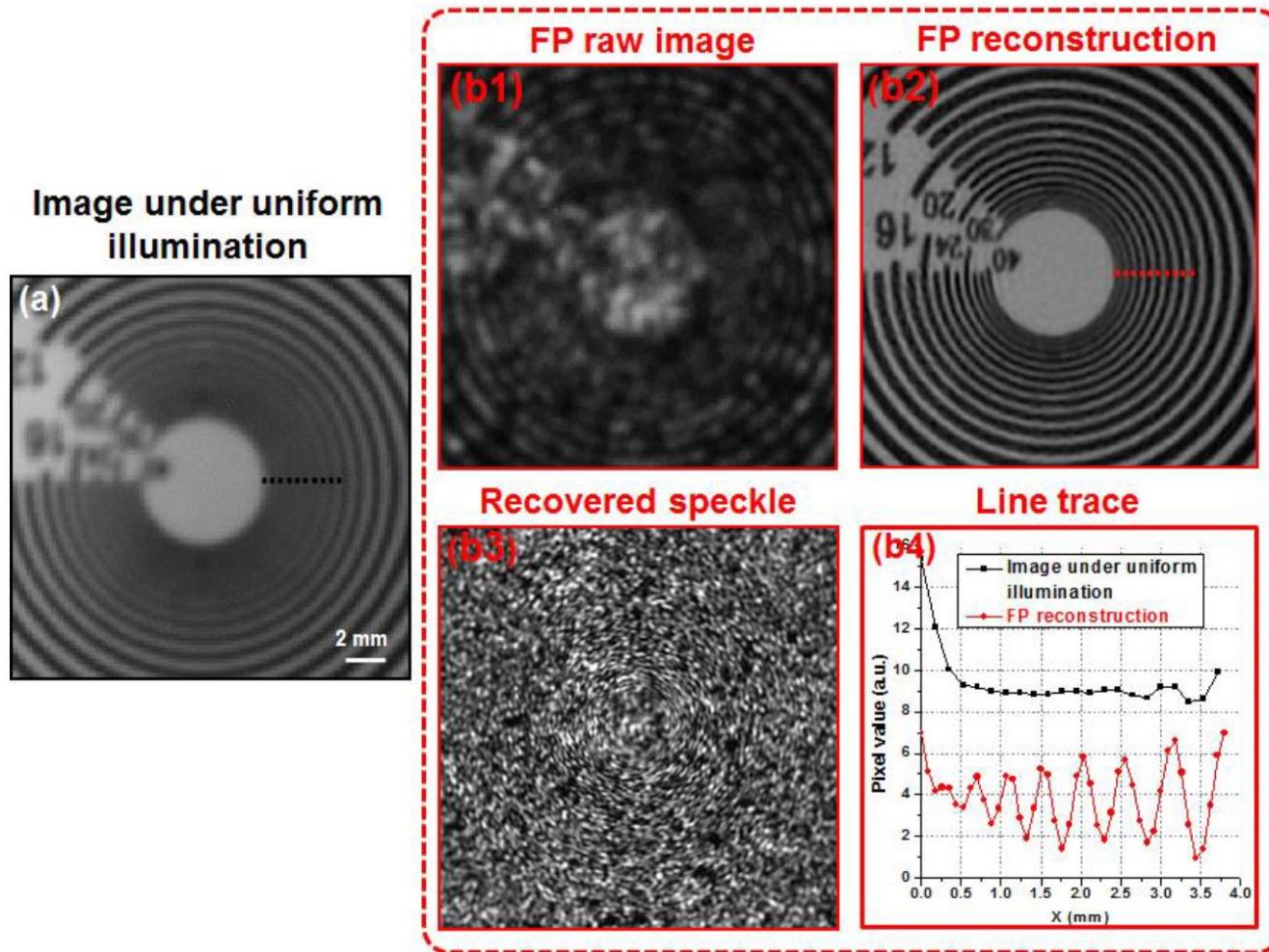
$$I_n(x, y) = (O(x, y) \cdot P(x - x_n, y - y_n)) * |PSF|^2$$

Incoherent imaging

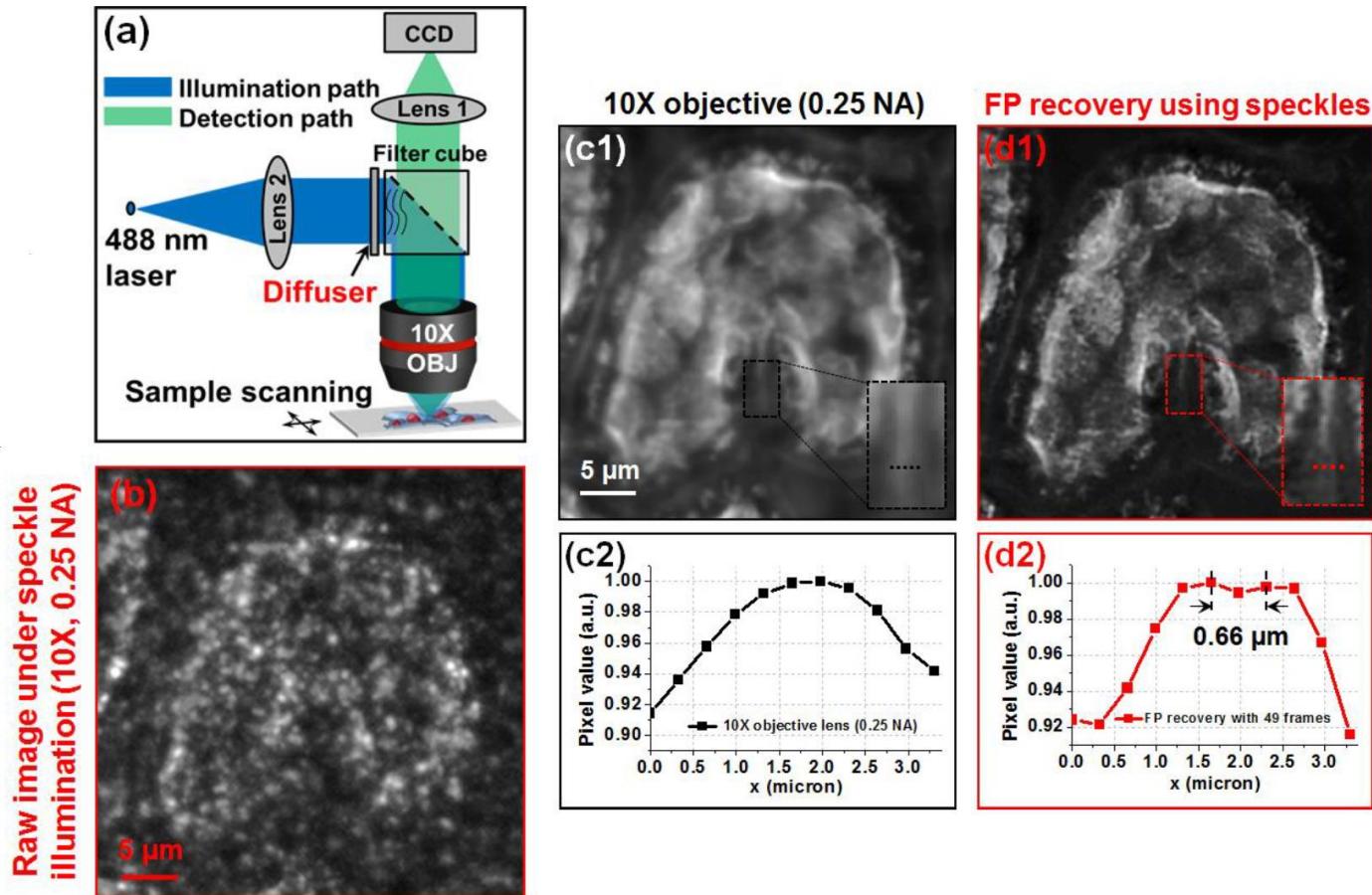
- Scan a unknown speckle pattern on the sample
- Recover the sample and the unknown speckle at the same time



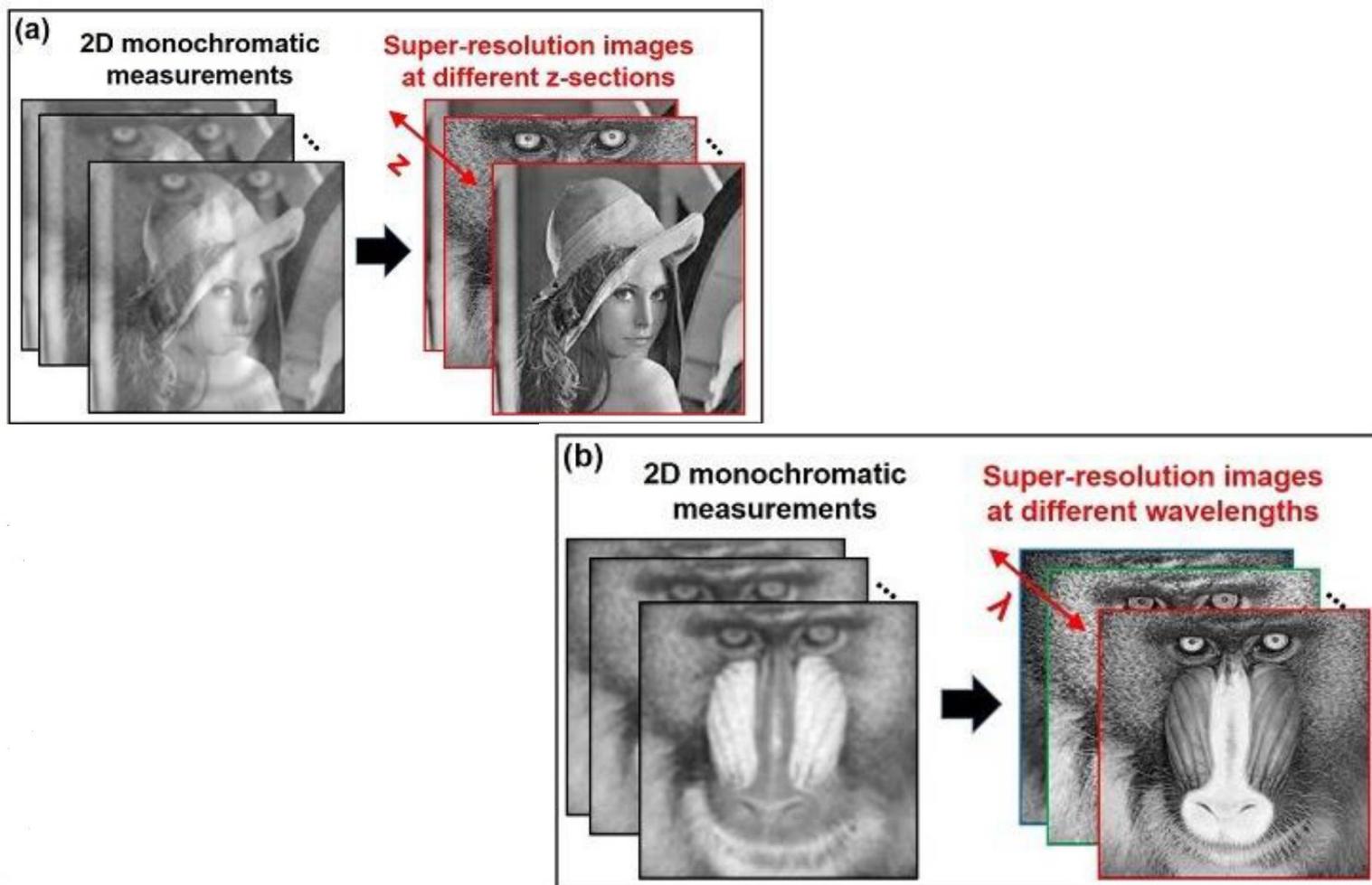
Incoherent imaging



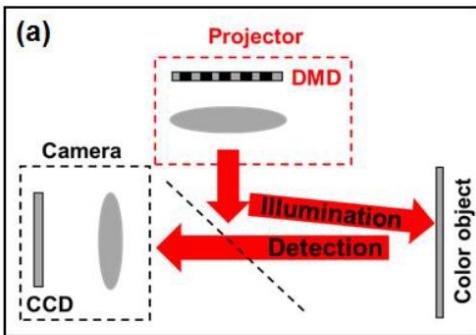
Fluorescence imaging



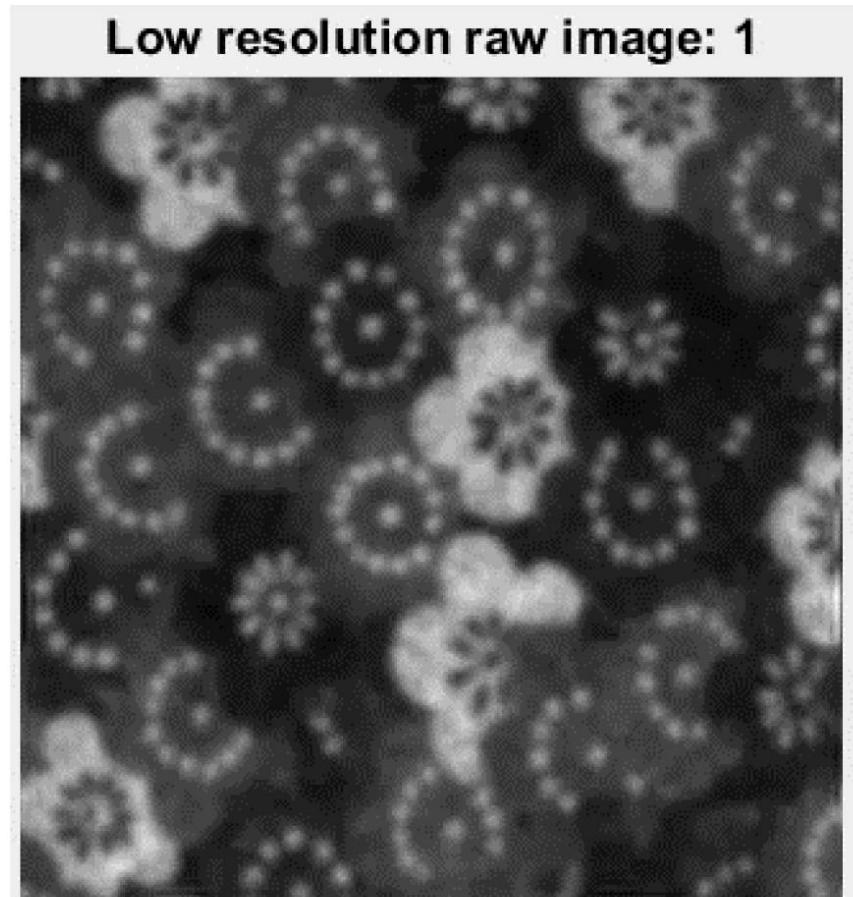
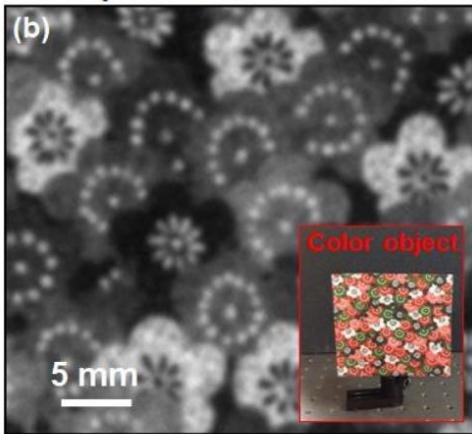
Multiplexed incoherent imaging



Spectrum recovering from monochromic measurements

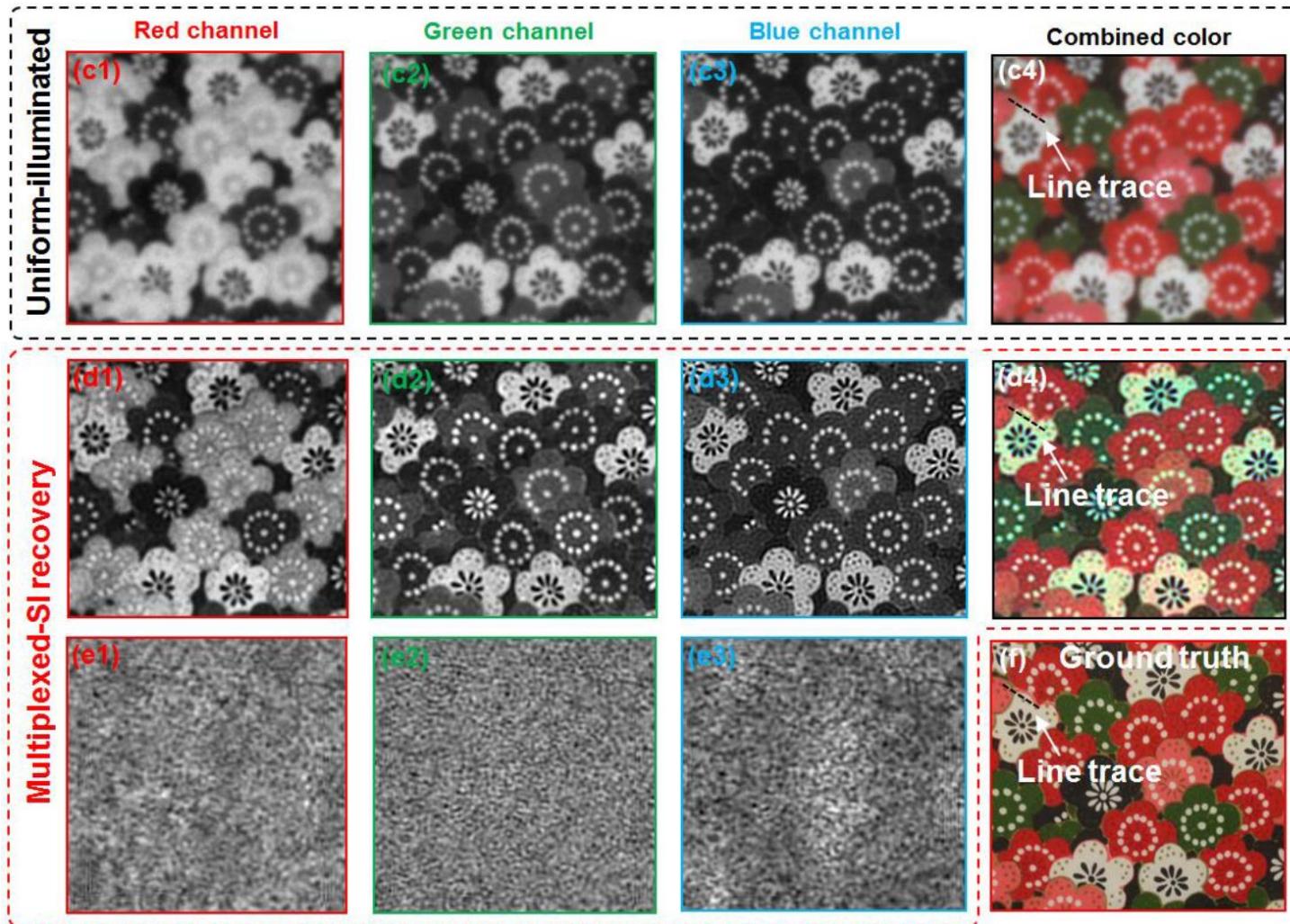


Monochromatic image under speckle illumination



Siyuan Dong, Kaikai Guo, Shaowei Jiang, and Guoan Zheng, "Recovering higher dimensional image data using multiplexed structured illumination," Optics Express, 23, 23, 30393 (2015).

Spectrum recovering from monochromic measurements



References

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- Computational Photography SIGGRAPH Course (Raskar & Tumblin)
- Digital and Computational Photography (Durand & Freeman, MIT)
- Computational Photography (Efros, CMU)
- Computational Photography (Gkioulekas, CMU)
- Computational Imaging (Wetzstein, Stanford)
- Computational Photography (Fergus, NYU)
- Computational Imaging (Dragotti, Imperial College)
- Computer Vision (Seitz & Szeliski, UWashington)
- Introduction to Visual Computing and Visual Modeling (Kutulakos, UToronto)