南京理工大学
NANJING UNIVERSITY OF SCIENCE & TECHNOLOGY

计算光学成像与光信息处理技术前沿

（第8讲）

左 超

南京理工大学电光学院光电技术系

Jiangsu Key Laboratory of Spectral Imaging & Intelligent Sense (SIIS)
Nanjing University of Science and Technology,
Nanjing, Jiangsu Province 210094, China

电子工程与光电技术学院
School of Electronic and Optical Engineering

江苏省光谱成像与智能感知重点实验室
Jiangsu Key Laboratory of Spectral Imaging & Intelligent Sense

南京理工大学
NANJING UNIVERSITY OF SCIENCE & TECHNOLOGY

光学前沿在线 2020
光学成像与显示
2020年6月19-20日

光强传输方程

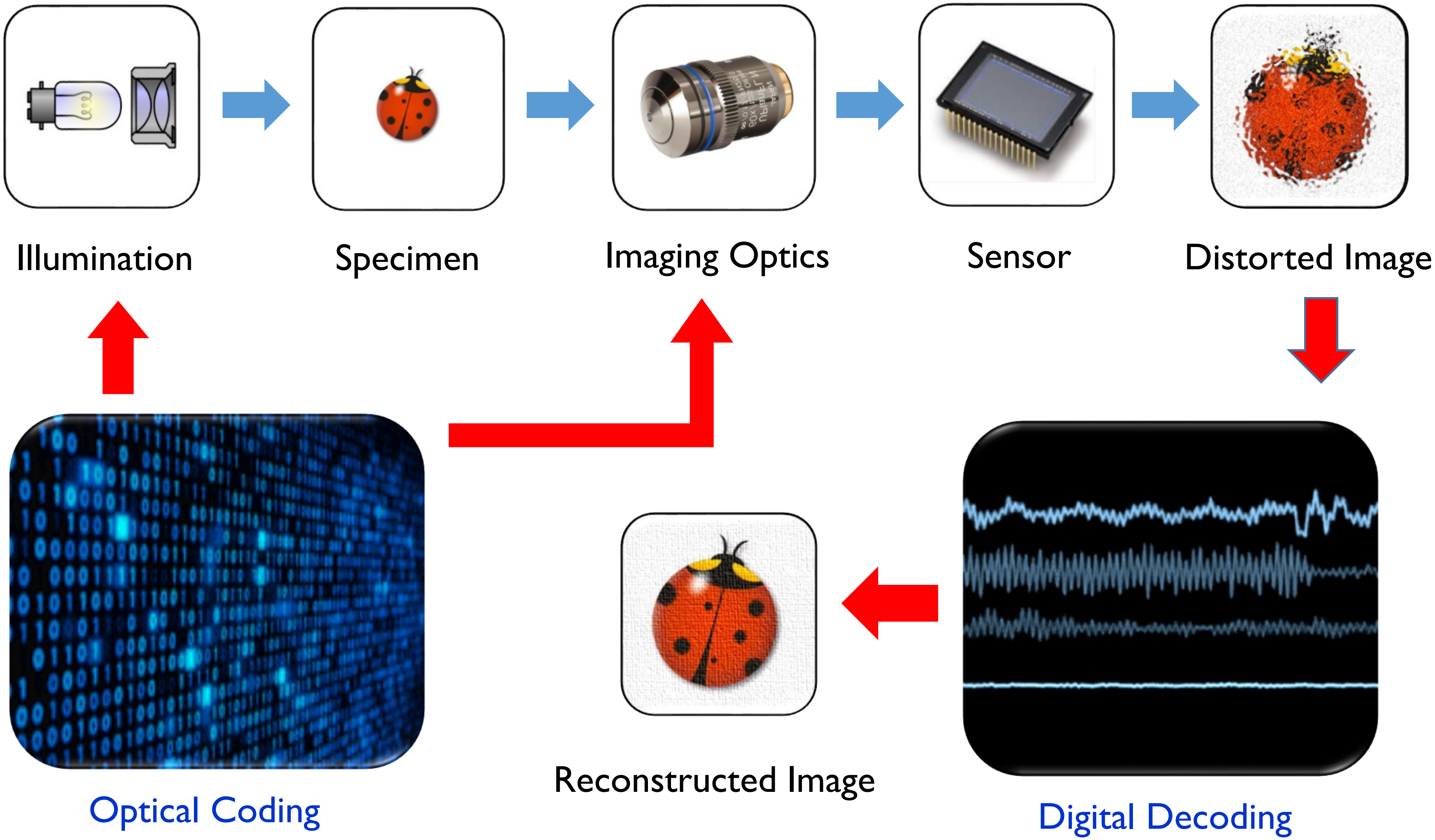
Transport of intensity equation

Chao Zuo（左超）

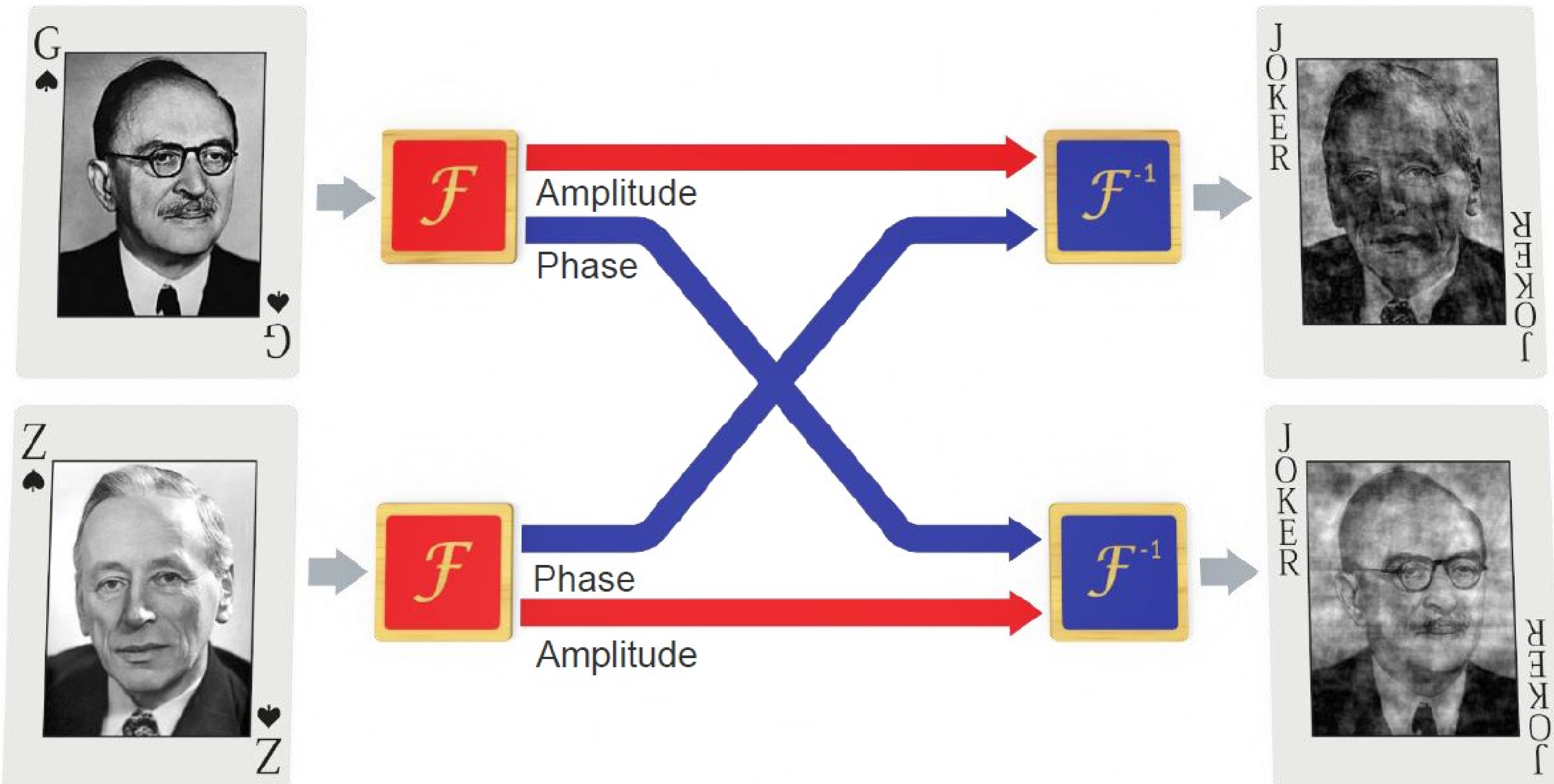
Smart Computational Imaging Laboratory (SCILab)
Jiangsu Key Laboratory of Spectral Imaging & Intelligent Sense (SIIS)
Nanjing University of Science and Technology,
Nanjing, Jiangsu Province 210094, China

Smart Computational Imaging

Computational microscopy



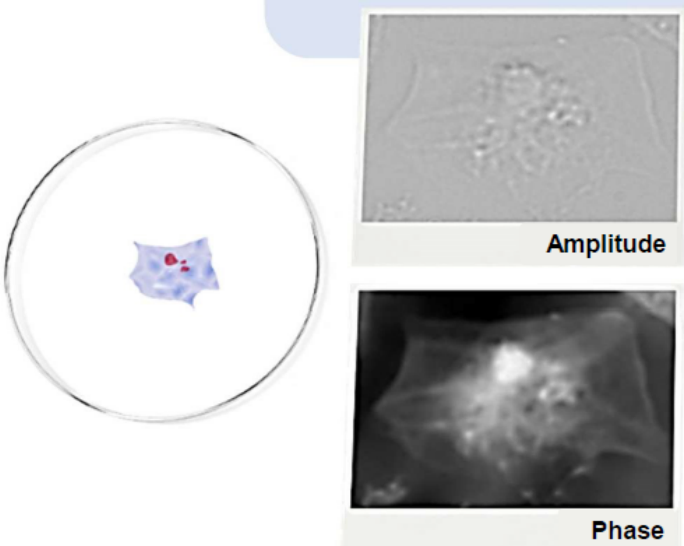
Phase of a image



Phase of a object

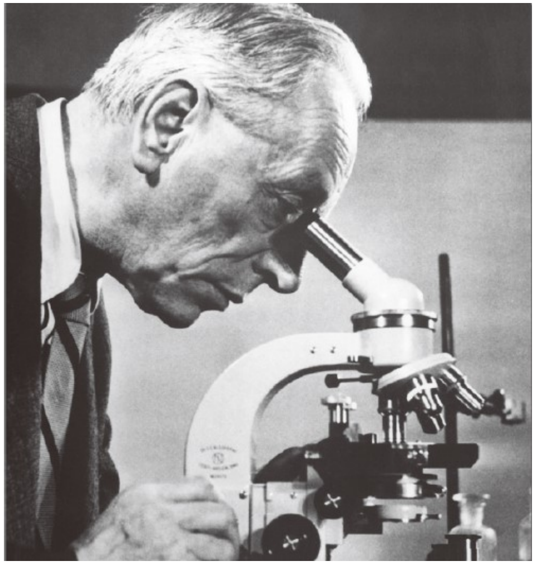
$$\underbrace{U(x,y)}_{\text{Complex Amplitude}} = \underbrace{A(x,y)}_{\text{Amplitude}}\, e^{\underbrace{j\phi(x,y)}_{\text{Phase}}}$$

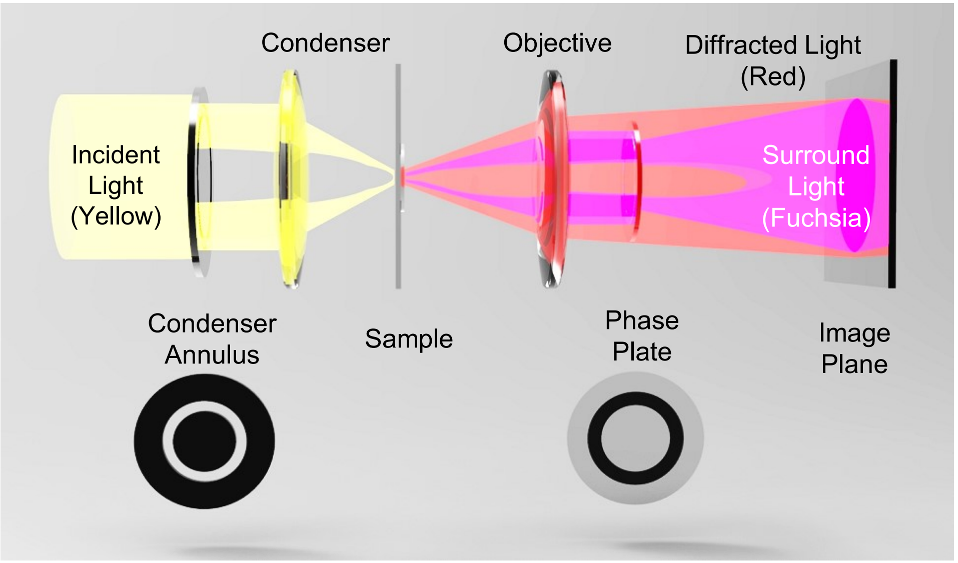
$$A(x,y) = \sqrt{\underbrace{I(x,y)}_{\text{Intensity}}}$$

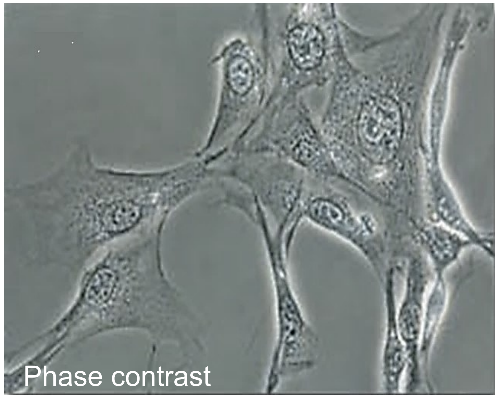


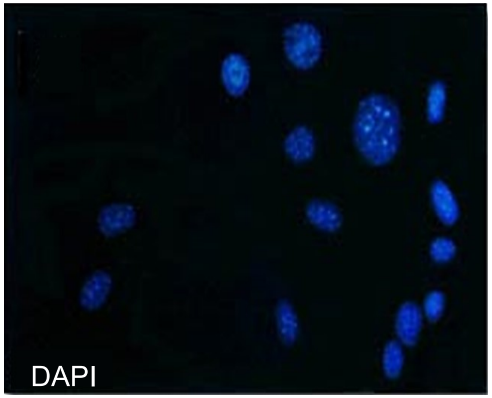
Cameras can see Amplitude only!

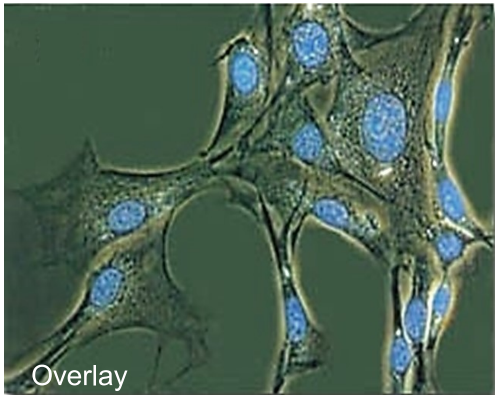
Phase contrast microscopy



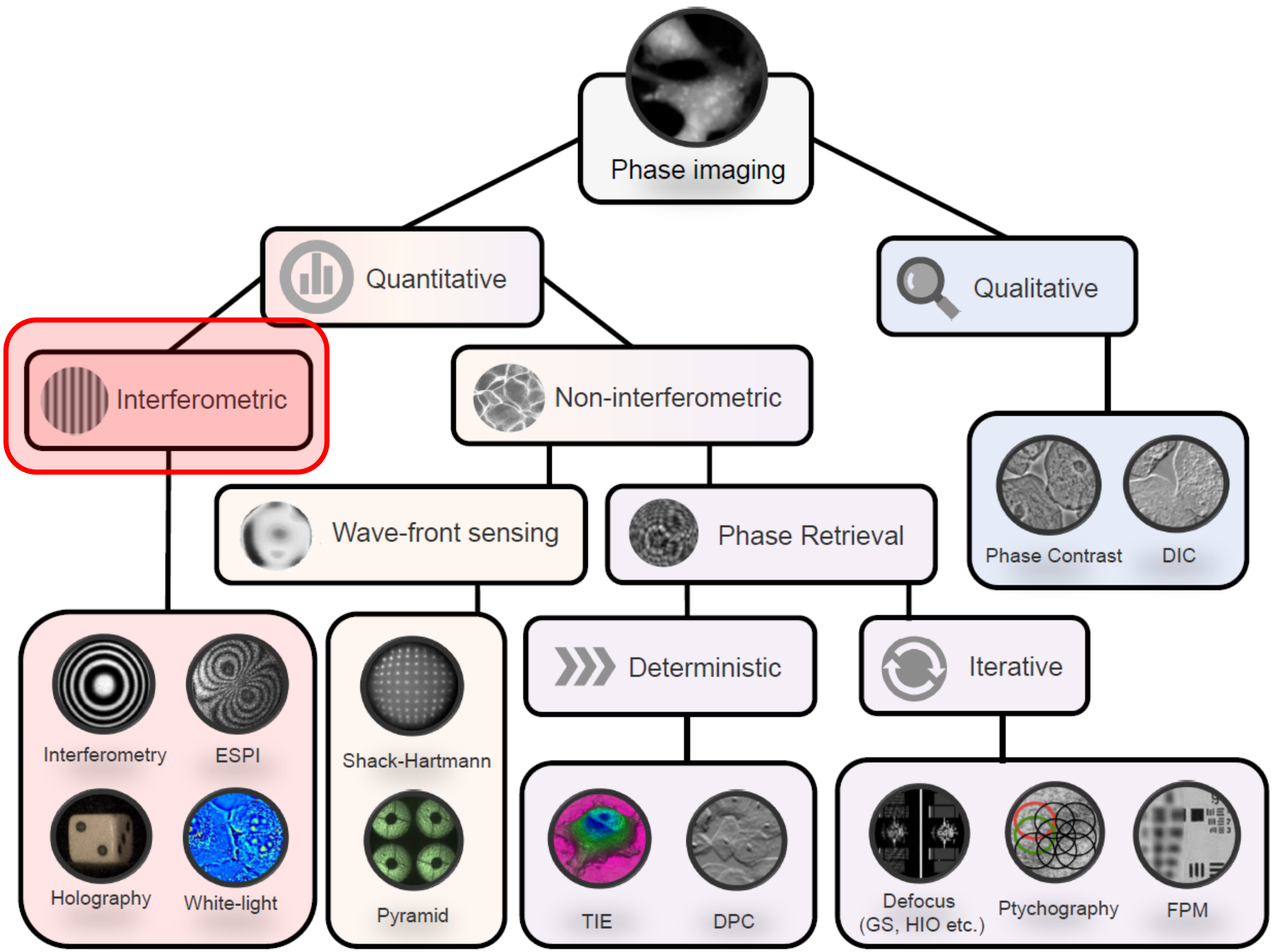




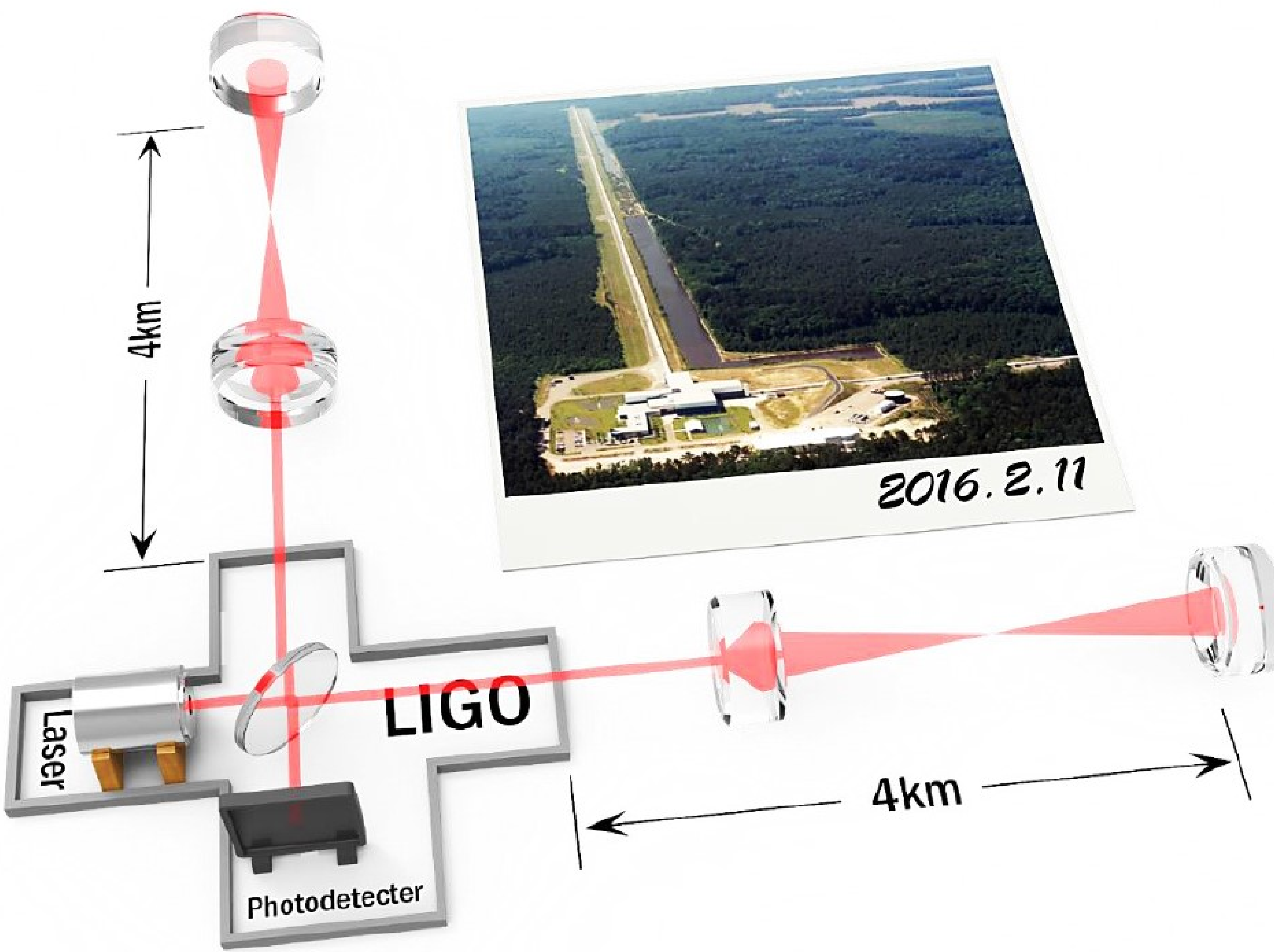




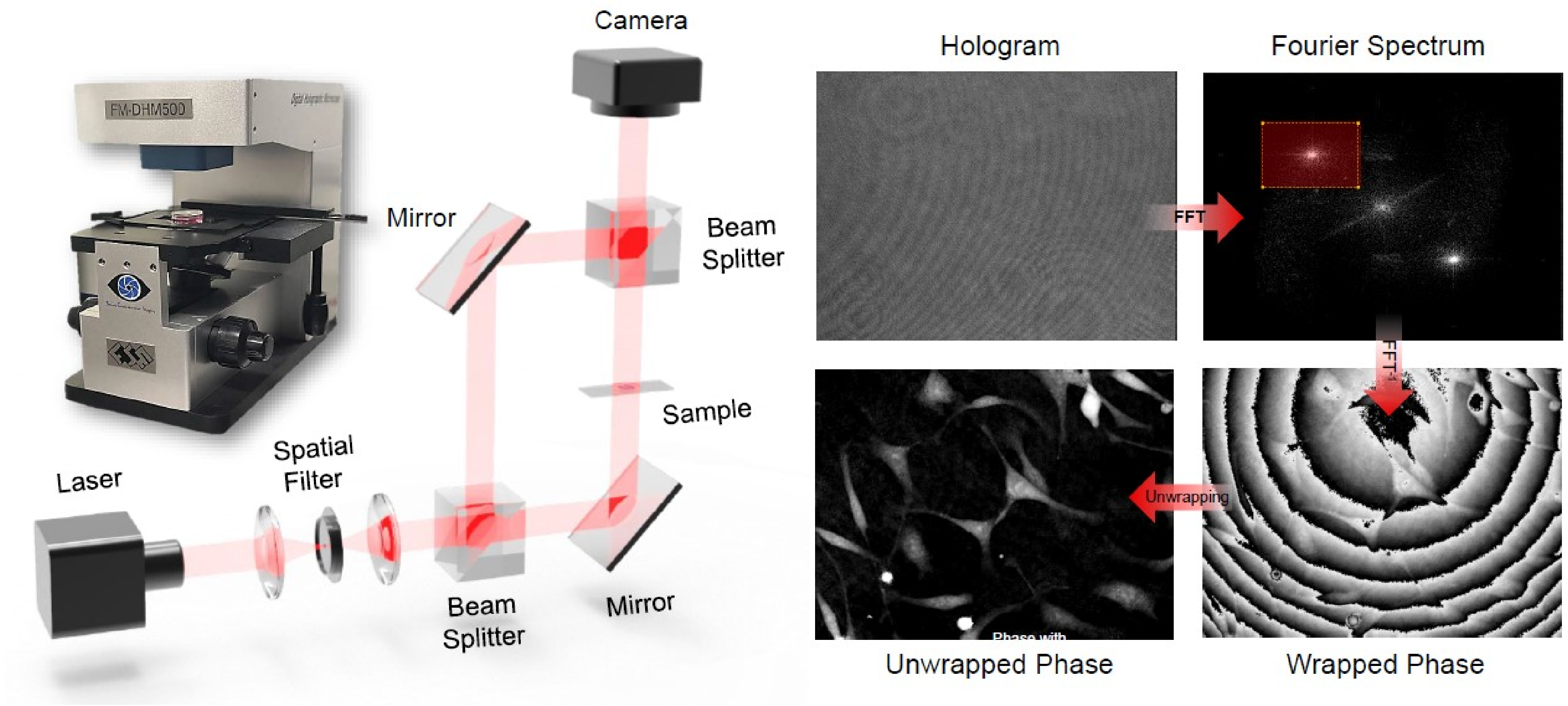
Phase imaging



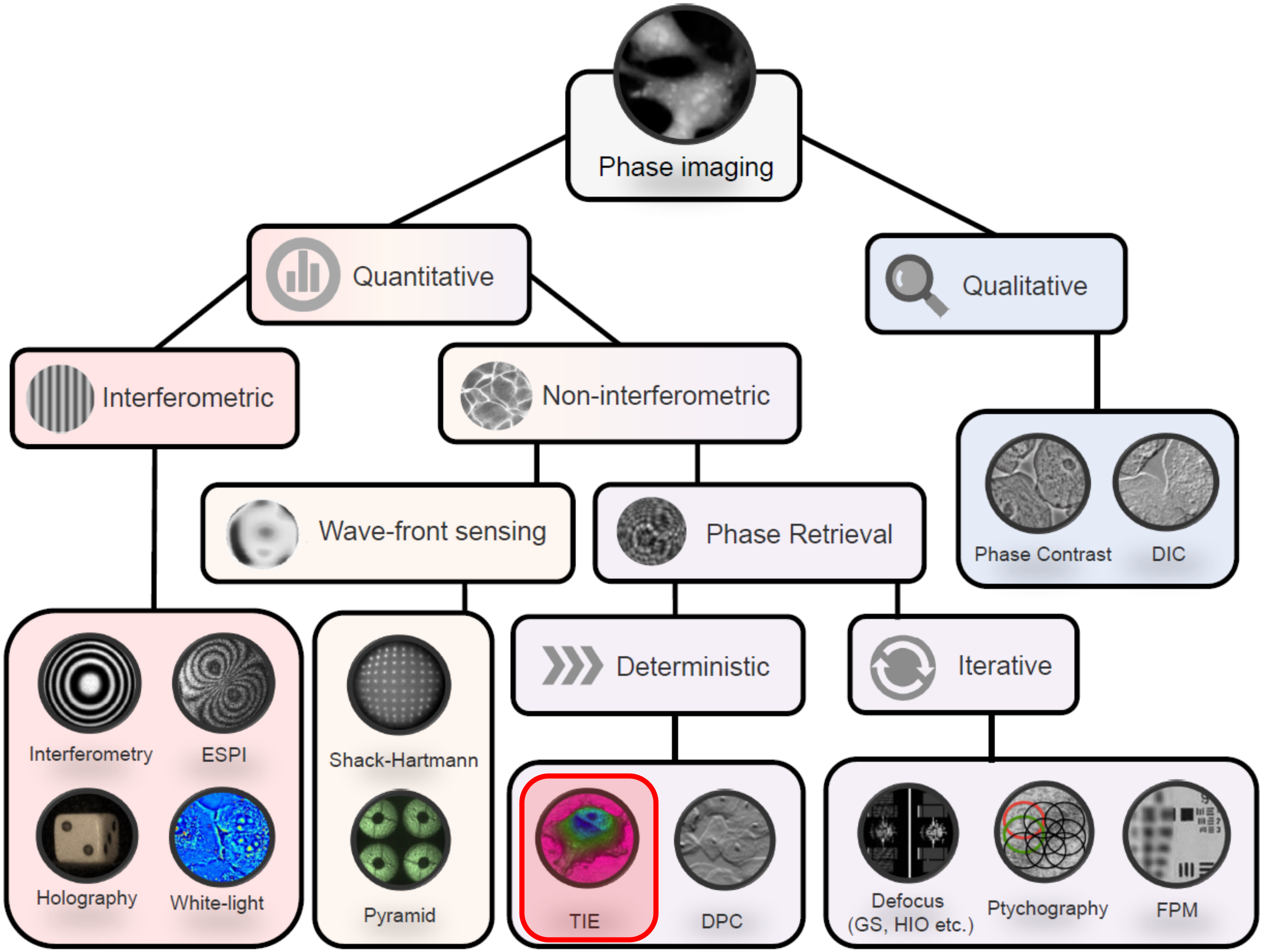
Interferometry



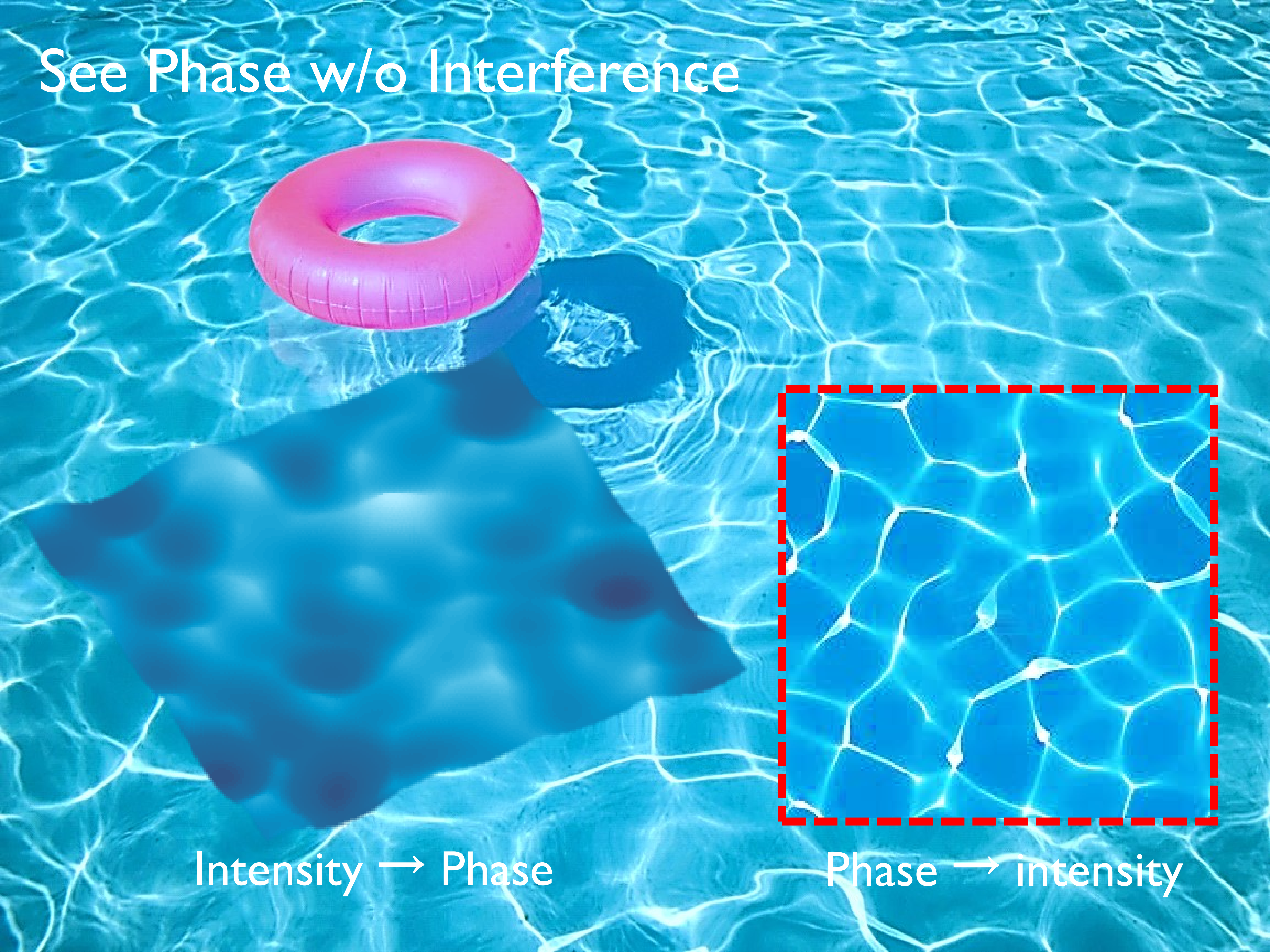
Digital Holography



Phase imaging

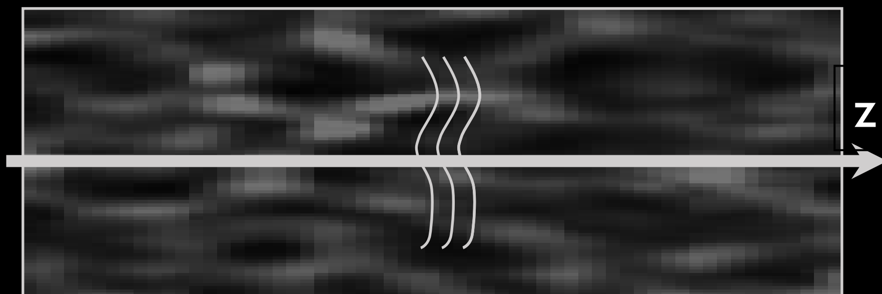


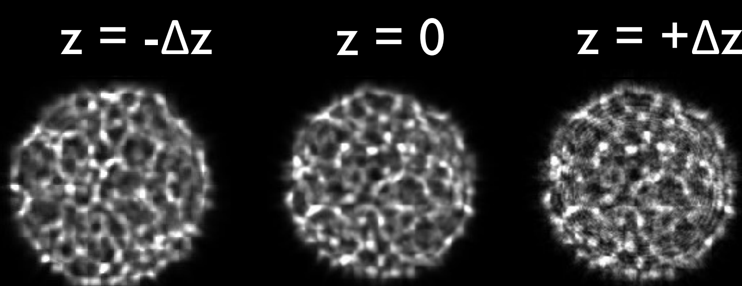
See Phase w/o Interference



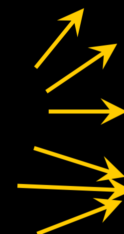
How does wave propagate?

Non-planar phase changes the intensity during wave propagation





$$U(x,y) = \sqrt{I(x,y)}e^{i\phi(x,y)}$$



Light spreads out – dimmer

Light is concentrated – brighter

$$\phi(x,y) = \text{constant}$$

Helmholtz Wave Equation

$$\nabla^2 U(\mathbf{r}) + k^2 U(\mathbf{r}) = 0$$

Paraxial Wave Equation

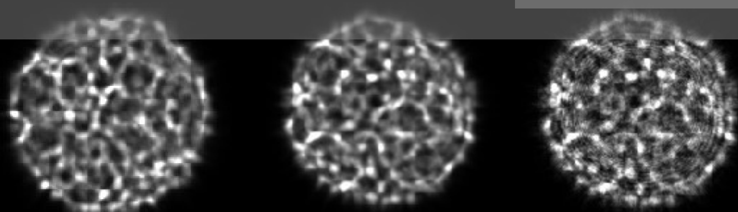
$$\nabla^2 U(x,y) + 2ik\frac{\partial U(x,y)}{\partial z} = 0$$

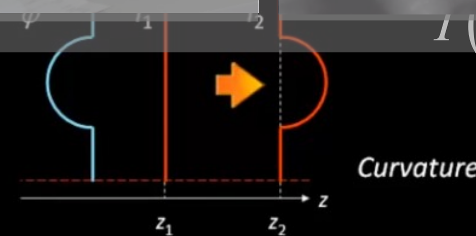
$$-k\frac{\partial I(x,y)}{\partial z} = \nabla \cdot \left[I(x,y) \nabla \phi(x,y) \right]$$

Transport-of-intensity equation (TIE)[1]

[1] M. Reed Teague, J. Opt. Soc. Am. 73, 1434-1441 (1983) .

Transport-of-intensity equation (TIE)





$$\approx \frac{I_{+\Delta z}(x,y) - I_{-\Delta z}(x,y)}{2\Delta z}$$

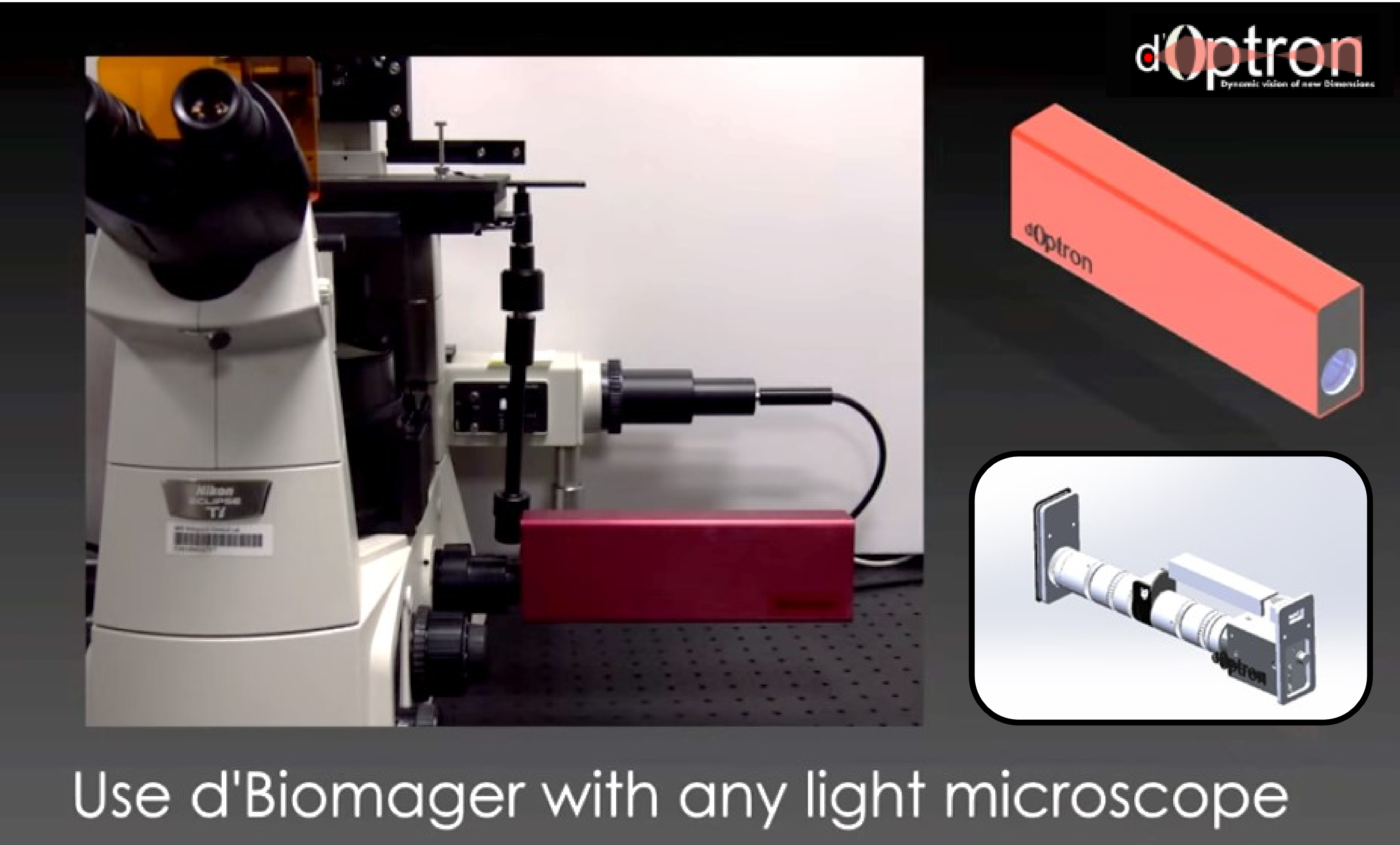
Transport-of-intensity equation (TIE)

$$-k\frac{\partial I(x,y)}{\partial z} = \nabla \cdot \left[I(x,y) \nabla \right.$$  $$\left. \right]$$

Code & dataset available @
www.scilaboratory.com

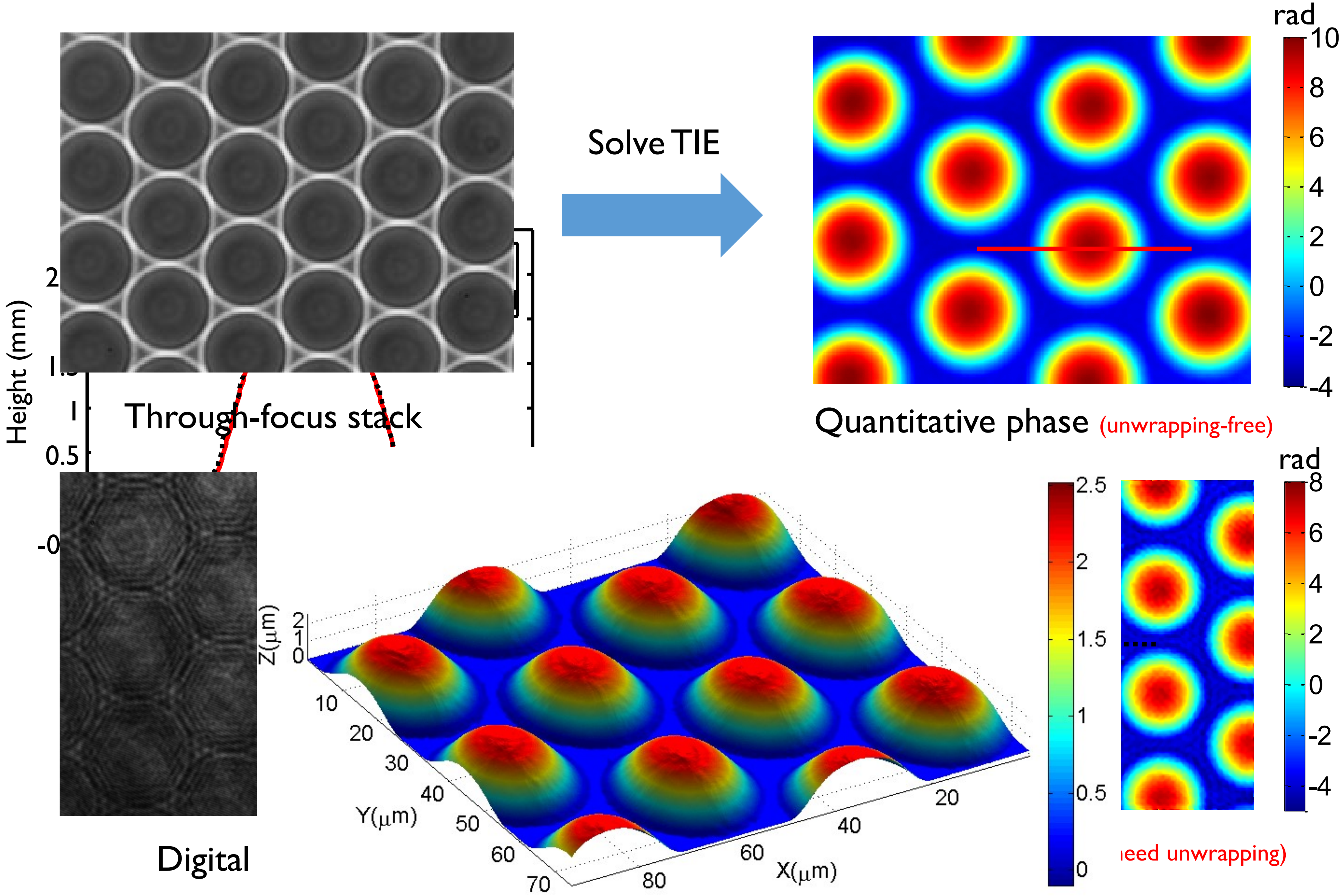
[1] M. Reed Teague, J. Opt. Soc. Am. 73, 1434-1441 (1983) .
[2] C. Zuo, Q. Chen, Y. Yu, and A. Asundi, Optics Express 21, 5346-5362 (2013).
[3] C. Zuo, Q. Chen, and A. Asundi, Optics Express 22, 9220-9244 (2014).
[4] C. Zuo, Q. Chen, H. Li, W. Qu, and A. Asundi Optics Express 22, 18310-18324 (2014).

Dynamic TIE microscopy



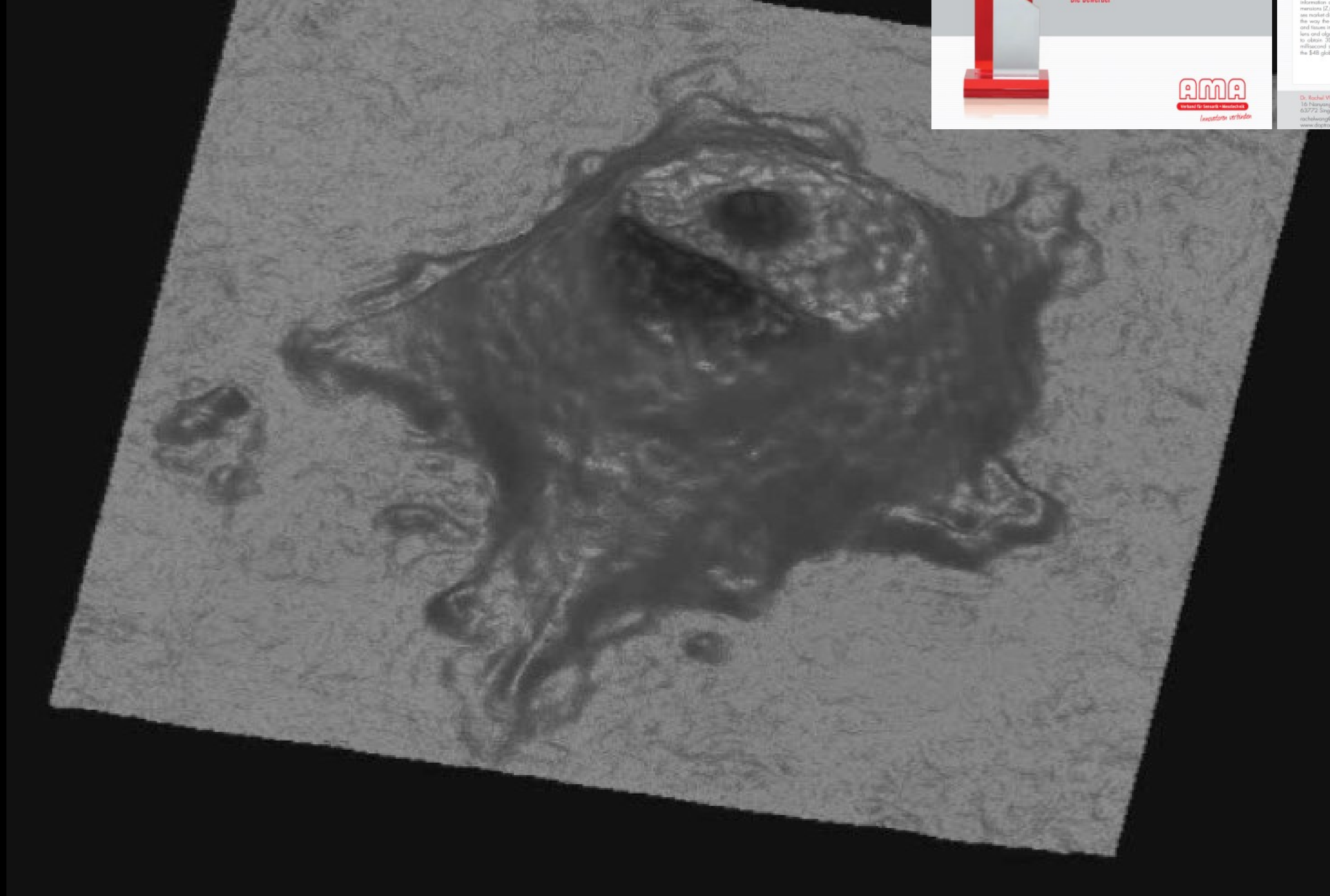
C. Zuo, Q. Chen, W. Qu, A. Asundi, Optics Express, 21 (2013) 24060-24075.

Dynamic TIE microscopy



C. Zuo, Q. Chen, W. Qu, A. Asundi, *Optics Express*, 21 (2013) 24060-24075.

Dynamic TIE microscopy

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(10) International Publication Number
WO 2015/002614 A1

C. Zuo, Q. Chen, W. Qu, A. Asundi, *Optics Express*, 21 (2013) 24060-24075.

Letter
Vol. 43, No. 22 / 15 November 2018 / Optics Letters 5689

Optics Letters

Dual-mode phase and fluorescence imaging with a confocal laser scanning microscope

JUANJUAN ZHENG,[3] CHAO ZUO,[4] PENG GAO,[1,2] AND G. ULRICH NIENHAUS[1,2,5,6,*]

[1]Institute of Applied Physics, Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany
[2]Institute of Nanotechnology, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany
[3]School of Physics and Optoelectronic Engineering, Xidian University, 710071 Xi'an, China
[4]School of Electronic and Optical Engineering, Nanjing University of Science and Technology, 210094 Nanjing, China
[5]Institute of Toxicology and Genetics, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany
[6]Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA
*Corresponding author: uli@uiuc.edu

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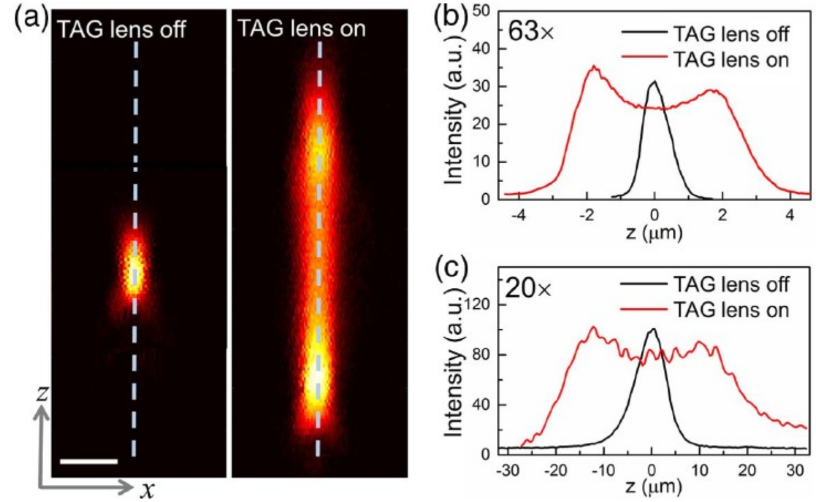
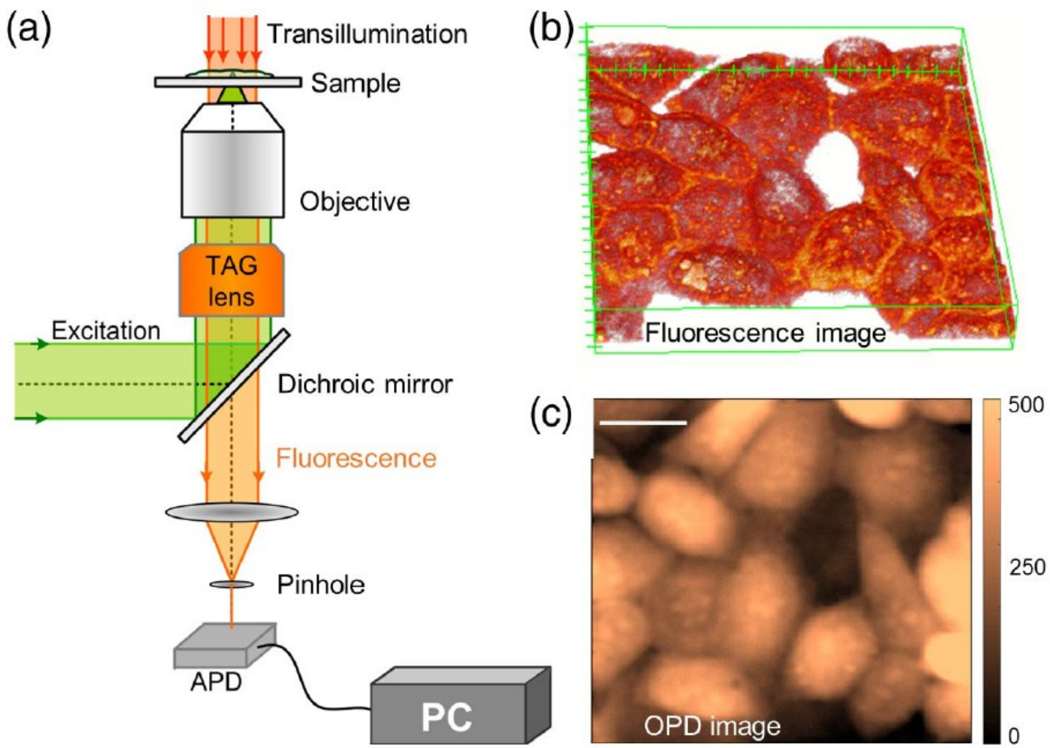
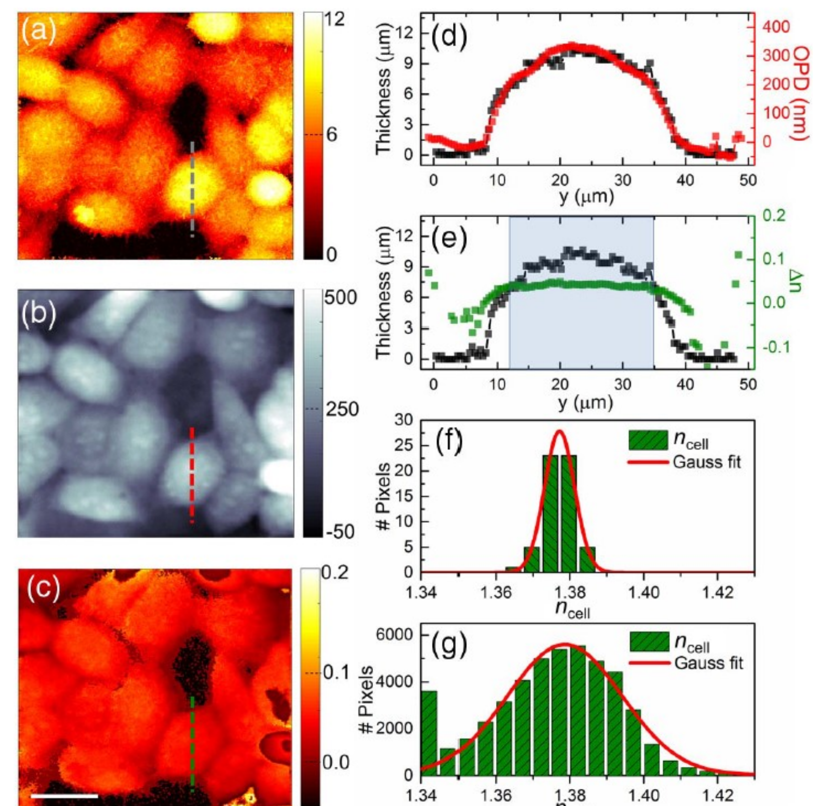
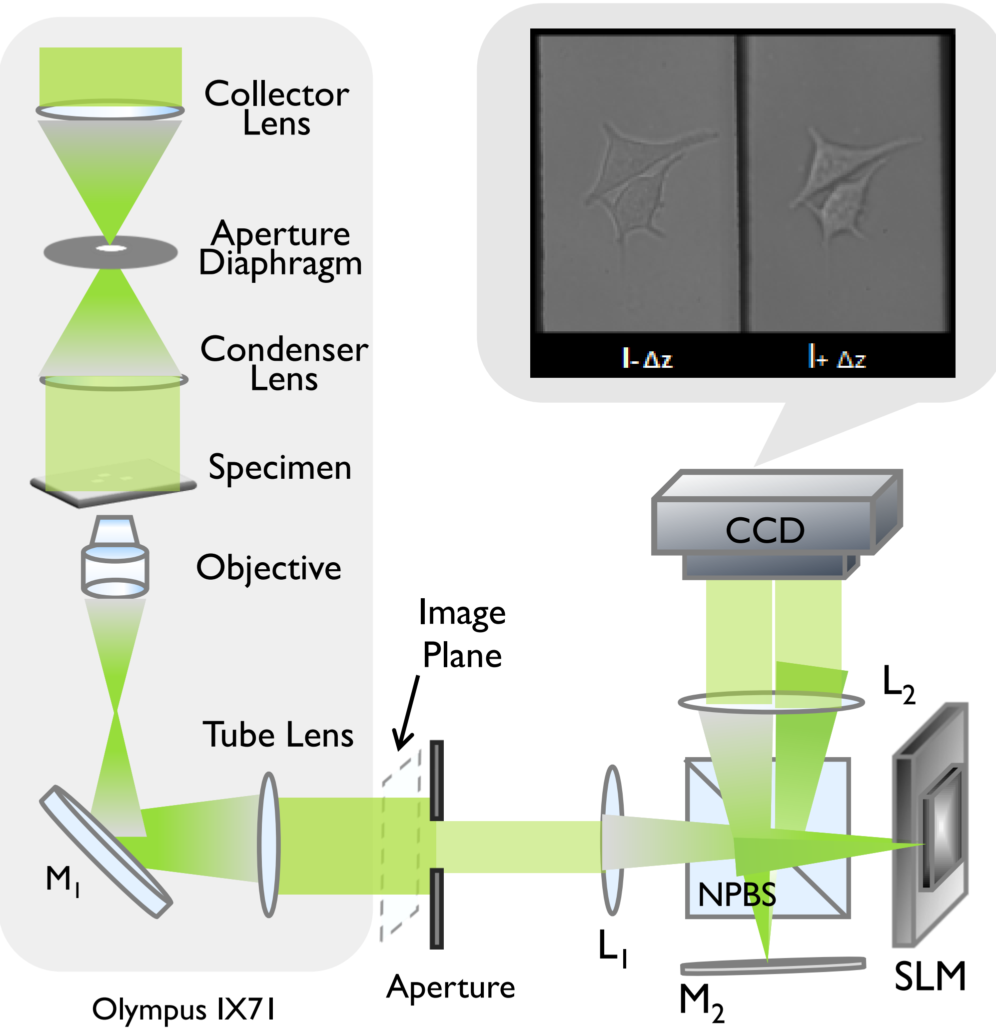






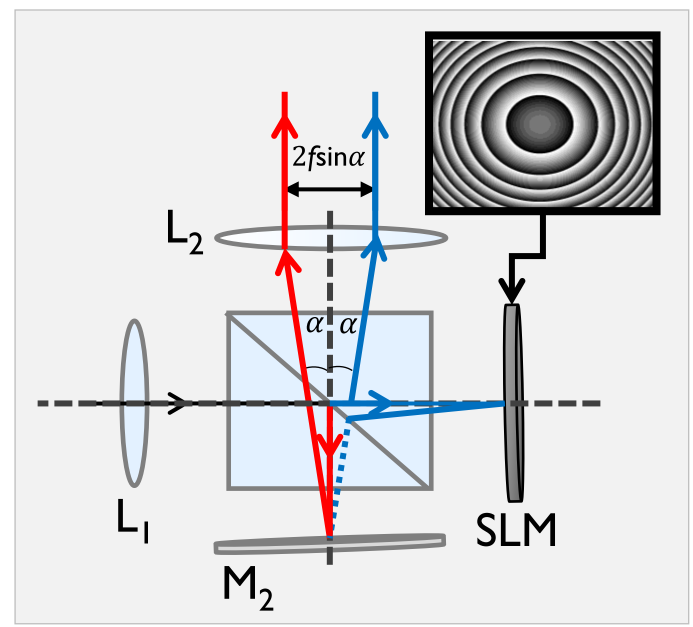
Dynamic TIE microscopy

Single-shot quantitative phase microscopy (SQPM)



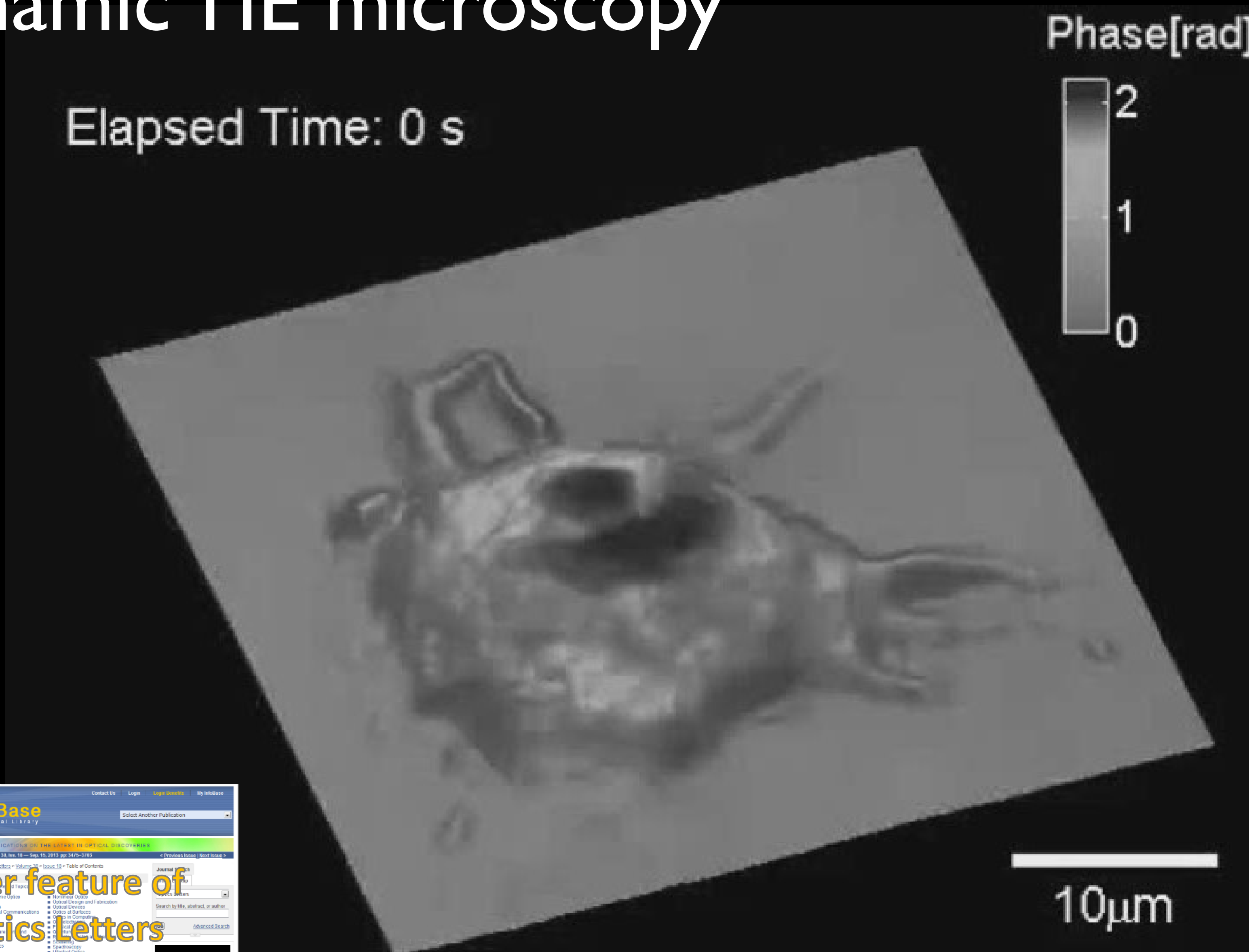
Free space
Propagation kernel

$$\exp\left(-i2\pi\Delta z\sqrt{1-(\lambda\xi)^2-(\lambda\eta)^2}/\lambda\right)$$



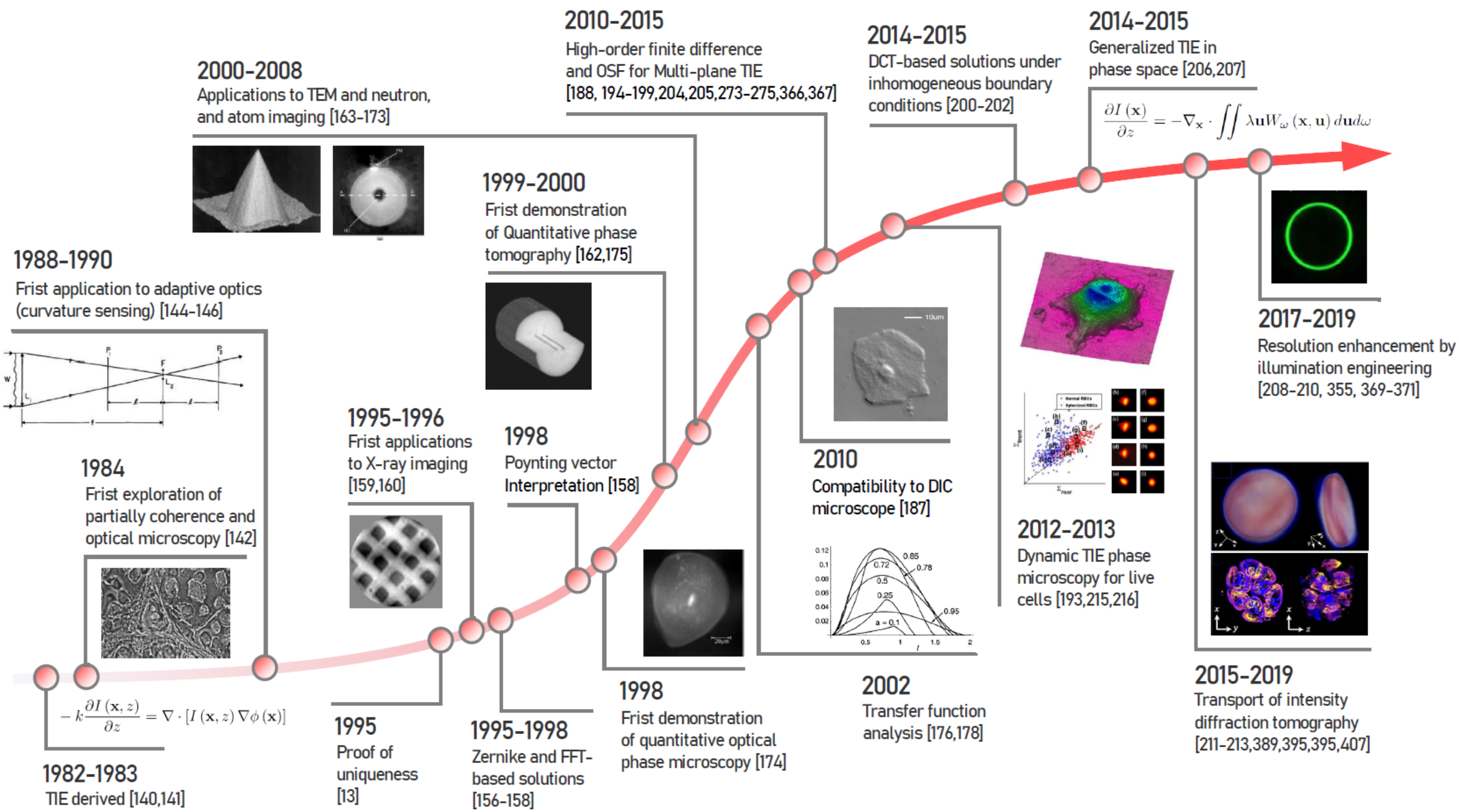
C. Zuo, Q. Chen, W. Qu, A. Asundi, *Optics Letters*, 38 (2013) 3538-3541.

Dynamic TIE microscopy



C. Zuo, Q. Chen, W. Qu, A. Asundi, *Optics Letters*, 38 (2013) 3538-3541.

Transport of intensity equation



Transport of intensity equation

$$-k\frac{\partial I(\mathbf{x},z)}{\partial z} = \nabla\cdot\left[I(\mathbf{x},z)\nabla\phi(\mathbf{x})\right]$$

Solution

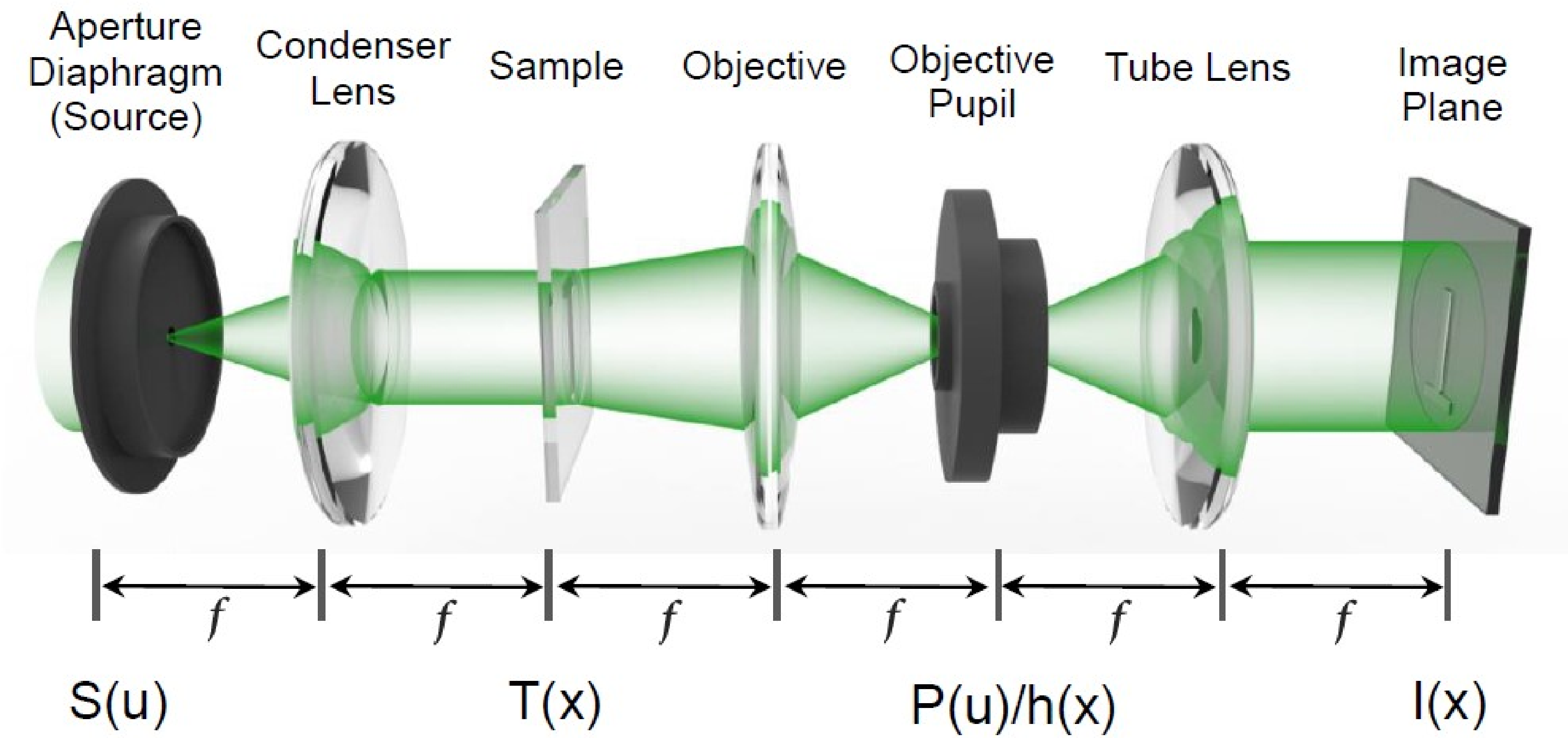
$$\phi(\mathbf{x}) = -k\nabla^{-2}\nabla \cdot \left[I^{-1}(\mathbf{x})\, \nabla\nabla^{-2} \frac{\partial I(\mathbf{x})}{\partial z} \right]$$

Coherent TIE

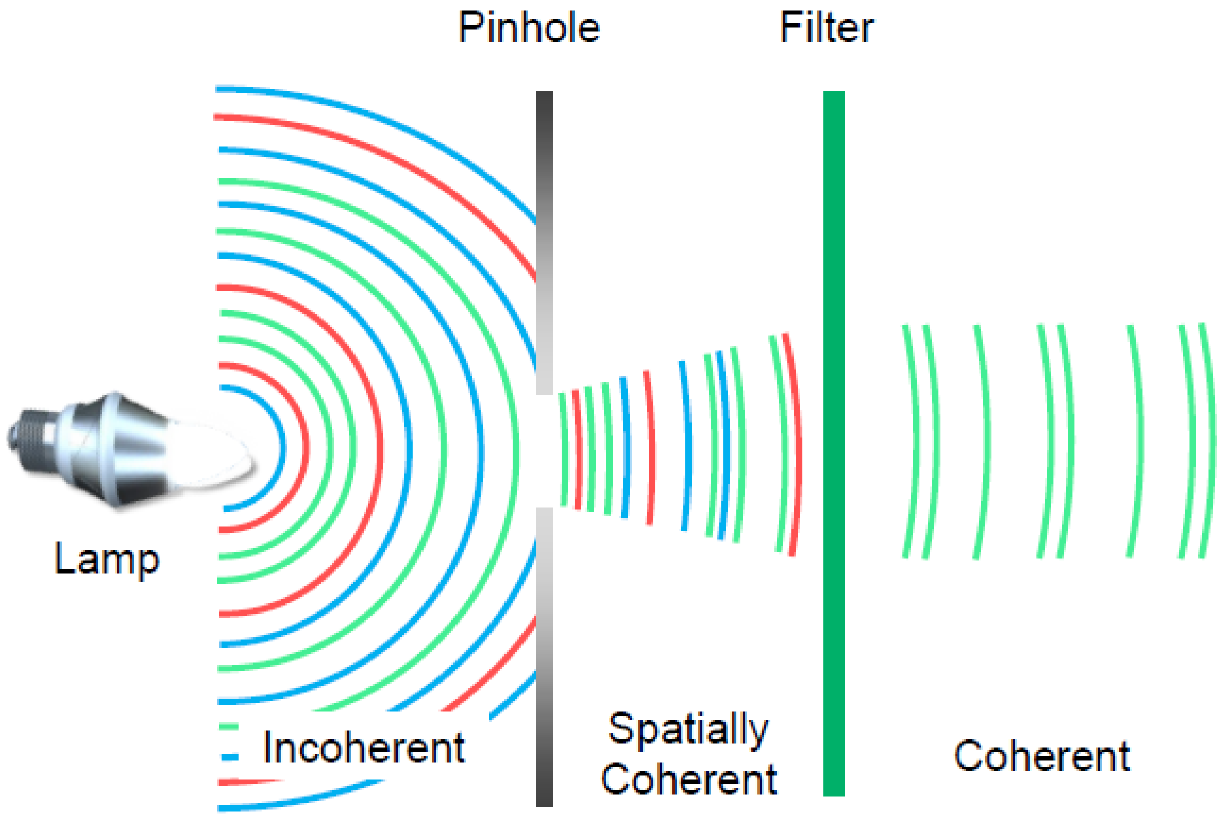
Methods	Approximation conditions	Phase reconstruction algorithms
TIE	Paraxial approximation $\lambda^2\lvert\mathbf{u}\rvert^2 \ll 1$ Weak defocusing approximation $\Delta z \to 0$	$-k\frac{\partial I(\mathbf{x})}{\partial z} = \nabla \cdot [I(\mathbf{x})\nabla\phi(\mathbf{x})]$ Fourier solution: $\phi(\mathbf{x}) = -k\mathscr{F}^{-1}\{\frac{j2\pi\mathbf{u}}{4\pi^2\lvert\mathbf{u}\rvert^2+\varepsilon}\mathscr{F}[\frac{1}{I(\mathbf{x})}\mathscr{F}^{-1}\{\frac{j2\pi\mathbf{u}}{4\pi^2\lvert\mathbf{u}\rvert^2+\varepsilon}\mathscr{F}[\frac{\partial I(\mathbf{x})}{\partial z}]\}]\}$ $\varepsilon > 0$ is a small constant.

Coherent illumination, ideal imaging?

Imaging System



Illumination



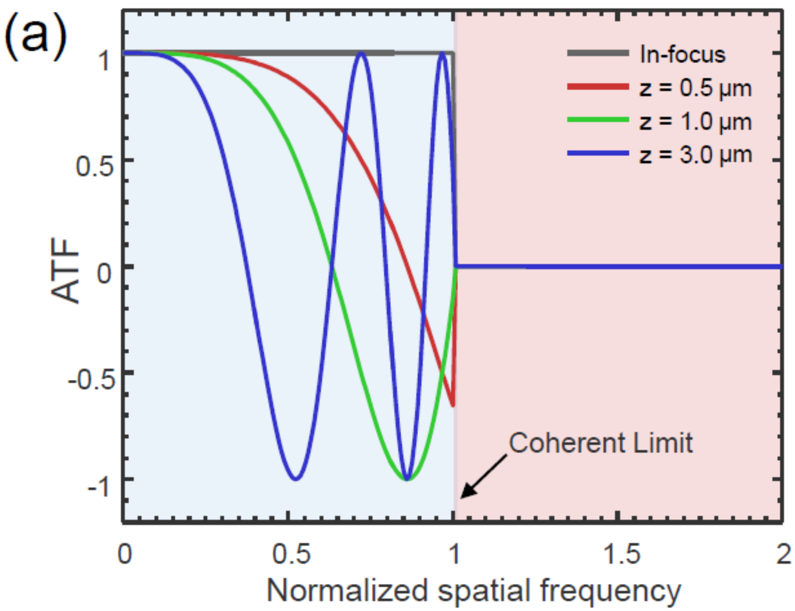
Coherent Imaging System

$$H\left(\mathbf{u}\right) = P\left(\mathbf{u}\right) H_{\Delta z}(\mathbf{u}) = P\left(\mathbf{u}\right) e^{jk\Delta z\sqrt{1-\lambda^2|\mathbf{u}|^2}},$$

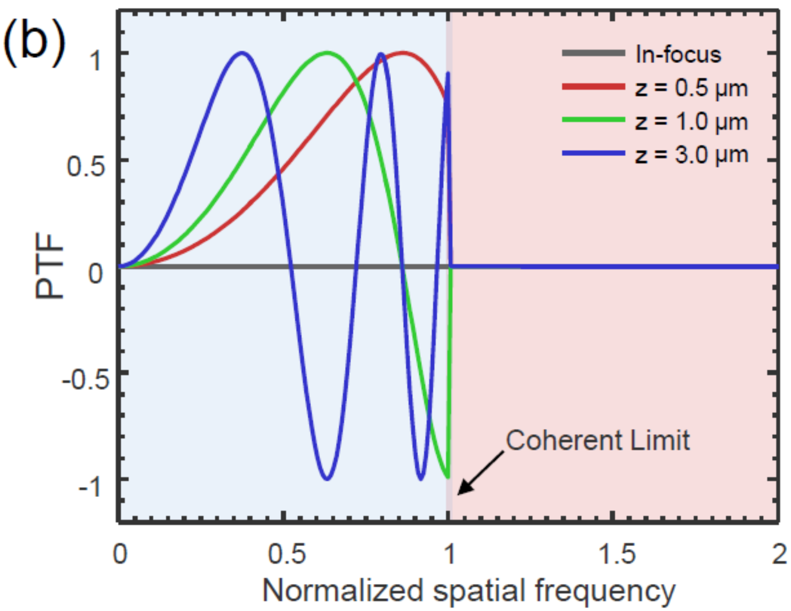
$$P(\mathbf{u}) = circ\left(\frac{\mathbf{u}}{NA/\lambda}\right) = \begin{cases} 1 & |\mathbf{u}| \leq \frac{NA}{\lambda} \\ 0 & \text{else} \end{cases}$$

$$\begin{aligned} h\left(r\right) &= \int_{\rho} circ\left(\frac{\rho}{NA/\lambda}\right) J_0\left(2\pi r\rho\right) 2\pi\rho d\rho \\ &= \frac{NA}{\mu\lambda} J_1\left(2\pi r\frac{NA}{\lambda}\right) \\ &= \pi\left(\frac{NA}{\lambda}\right)^2 \left[\frac{2J_1\left(\bar{r}\right)}{\bar{r}}\right] \end{aligned}$$

Coherent Limit

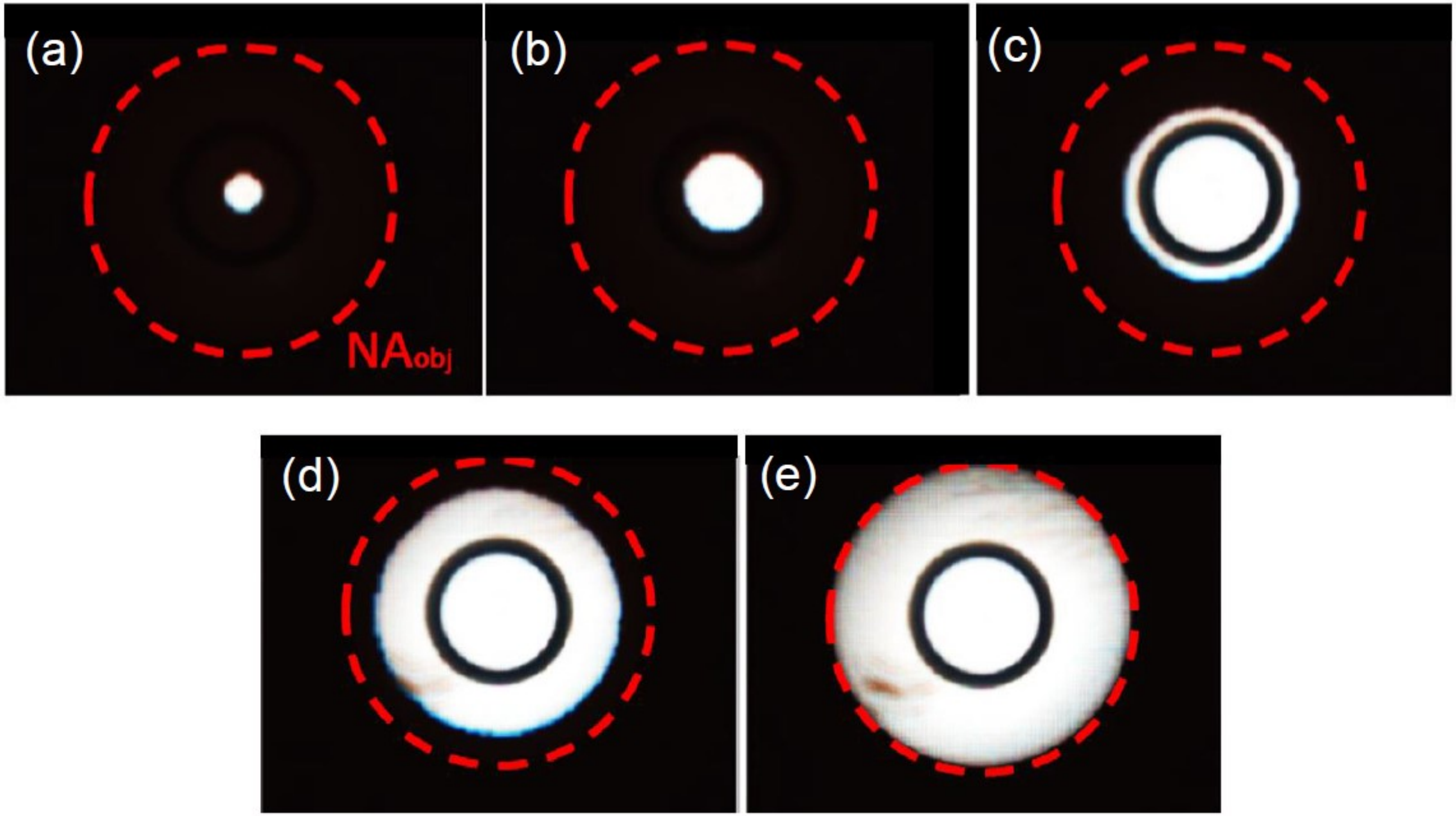


Amplitude

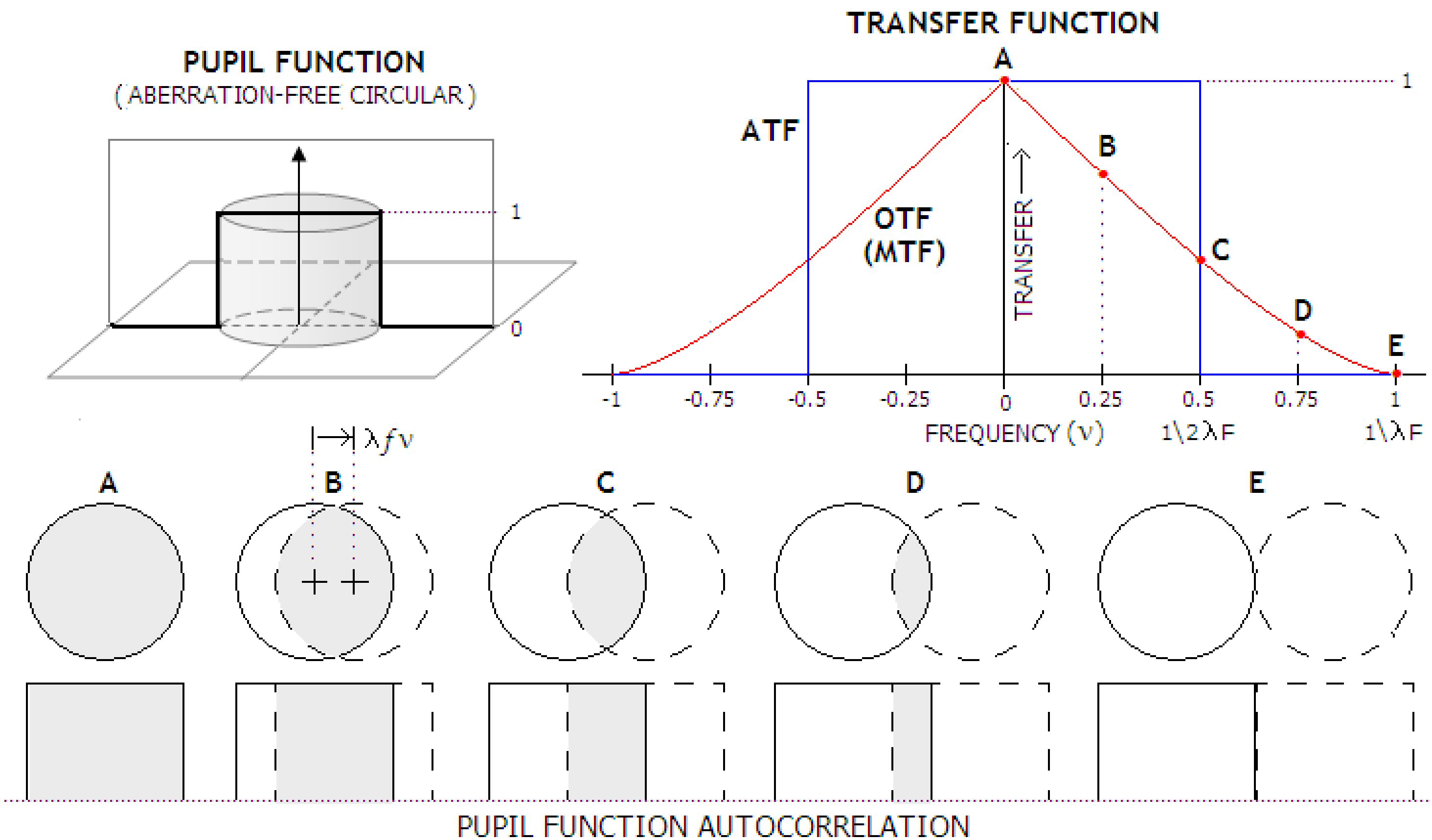


Phase

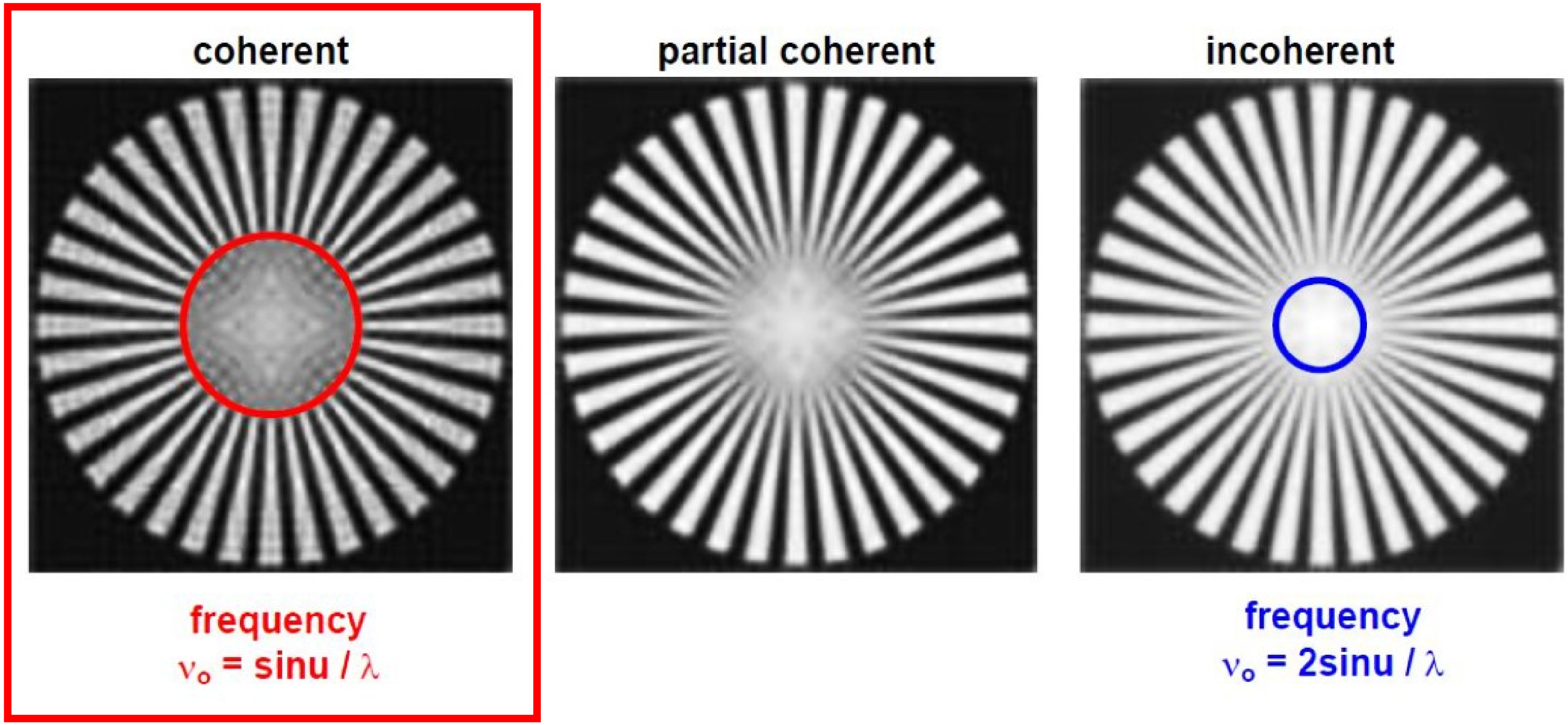
Coherence in a microscope



Coherent Limit



Coherent Limit



Resolution improvement in DHM

Superresolution digital holographic microscopy for three-dimensional samples

Vicente Micó[1*], Zeev Zalevsky[2], Carlos Ferreira[1], and Javier García[1]
[1]Departamento de Óptica, Universitat de Valencia, C/Dr. Moliner, 50, 46100 Burjassot, Spain
[2]School of Engineering, Bar-Ilan University, Ramat-Gan, 52900 Israel
*Corresponding author: vicente.mico@uv.es

Resolution improvement in digital holography by angular and polarization multiplexing

Caojin Yuan,[1,2*] Guohai Situ,[2] Giancarlo Pedrini,[2] Jun Ma,[2] and Wolfgang Osten[2]

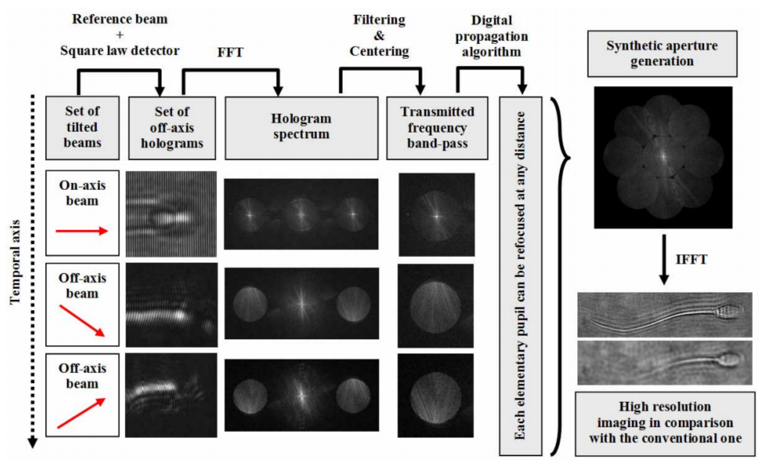
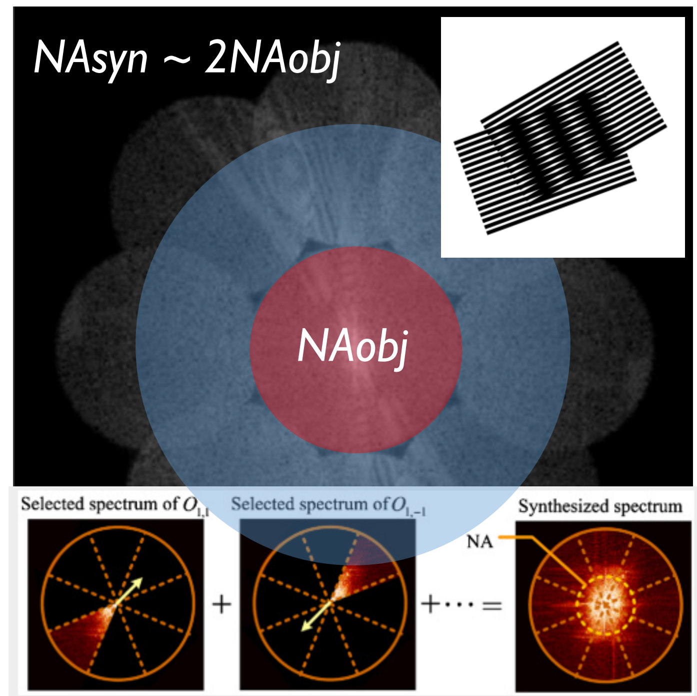


Fig. 3. Schematic chart of the used methodology used where the images depicted in the chart correspond with experimental results obtained with the proposed approach.

1328 OPTICS LETTERS / Vol. 38, No. 8 / April 15, 2013

Structured illumination for resolution enhancement and autofocusing in digital holographic microscopy

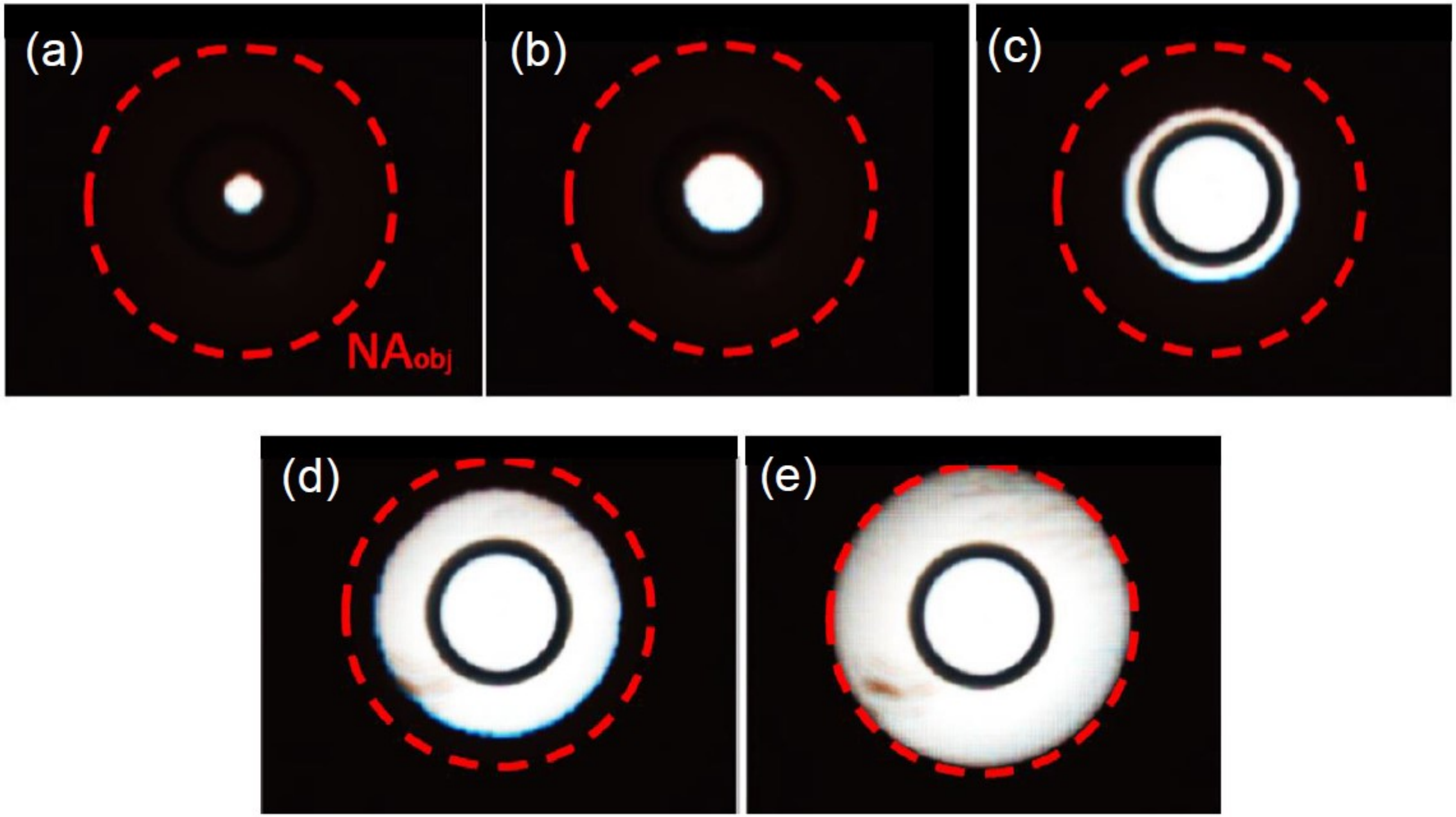
Peng Gao,[1,2,*] Giancarlo Pedrini,[1] and Wolfgang Osten[1]
[1]Institut für Technische Optik, Universität Stuttgart, Pfaffenwaldring 9, Stuttgart 70569, Germany
[2]State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710119, China
*Corresponding author: peng.gao@ito.uni-stuttgart.de



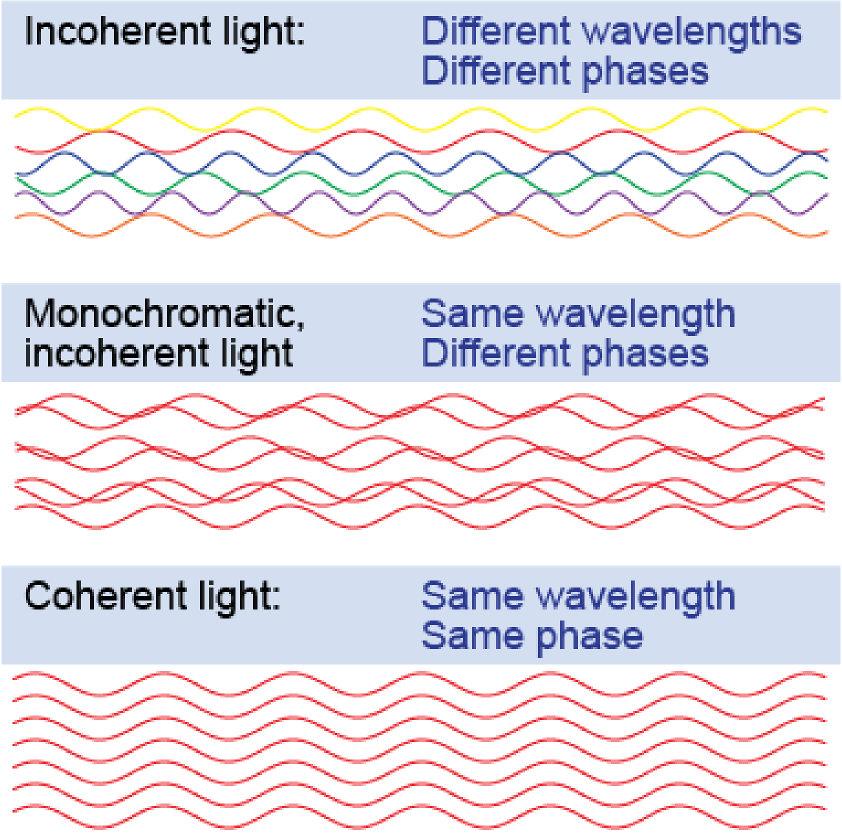
Synthetic Aperture (Beam scanning or Structured illumination)

Multi-angle measurement to achieve ~ 2NAobj

Coherence in a microscope



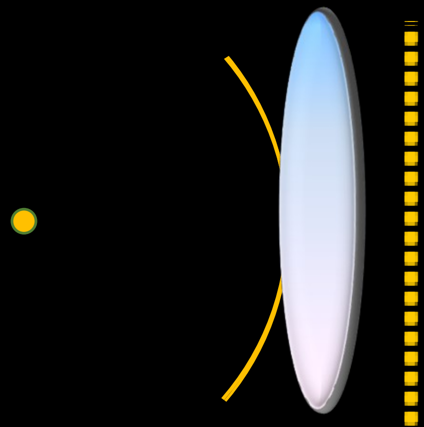
No interference



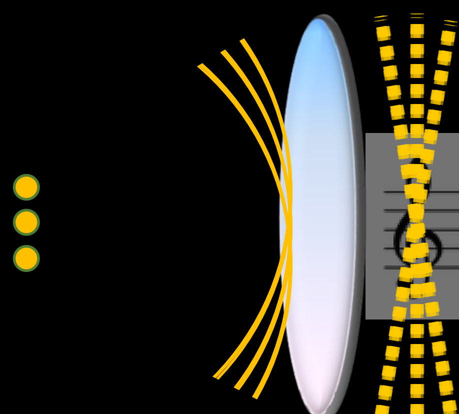
Transport of intensity equation ?

$$-k\frac{\partial I(\mathbf{x},z)}{\partial z} = \nabla\cdot\left[I(\mathbf{x},z)\nabla\phi(\mathbf{x})\right]$$

Effect of partially coherent illumination



Purely coherent field



Partially coherent field

Transport of intensity equation ?

$$- k\frac{\partial I(\mathbf{x}, z)}{\partial z} = \nabla \cdot [I(\mathbf{x}, z)\nabla\phi(\mathbf{x})]$$

Generalized transport of intensity equation

$$\frac{\partial I\left(\mathbf{x}\right)}{\partial z} = -\nabla_{\mathbf{x}} \cdot \iint \lambda \mathbf{u} W_{\omega}\left(\mathbf{x}, \mathbf{u}\right) d\mathbf{u} d\omega$$

OPTICS LETTERS / Vol. 39, No. 3 / February 1, 2014

Light field moment imaging: comment

Chao Zuo,[1,2,3] Qian Chen,[1,*] and Anand Asundi[2]

[1]*Jiangsu Key Laboratory of Spectral Imaging & Intelligence Sense, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China*

[2]*Centre for Optical and Laser Engineering, Nanyang Technological University, Singapore 639798*

Optics and Lasers in Engineering 71 (2015) 20–32

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Transport of intensity phase retrieval and computational imaging for partially coherent fields: The phase space perspective

Chao Zuo [a,b,*], Qian Chen [a], Lei Tian [c], Laura Waller [c], Anand Asundi [b]

[a] Jiangsu Key Laboratory of Spectral Imaging & Intelligence Sense, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China

[b] Centre for Optical and Laser Engineering, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 639798 Singapore

[c] Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720, USA

Generalized transport of intensity equation

$$\frac{\partial I\left(\mathbf{x}\right)}{\partial z}=-\lambda\nabla_{\mathbf{x}}\cdot\int\mathbf{u}W\left(\mathbf{x},\mathbf{u}\right)d\mathbf{u}.$$

OPTICS LETTERS / Vol. 39, No. 3 / February 1, 2014

Light field moment imaging: comment

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[1]*Jiangsu Key Laboratory of Spectral Imaging & Intelligence Sense, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China*

[2]*Centre for Optical and Laser Engineering, Nanyang Technological University, Singapore 639798*

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Transport of intensity phase retrieval and computational imaging for partially coherent fields: The phase space perspective

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[a] Jiangsu Key Laboratory of Spectral Imaging & Intelligence Sense, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China

[b] Centre for Optical and Laser Engineering, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 639798 Singapore

[c] Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720, USA

Transport of intensity equation

$$-k\frac{\partial I(\mathbf{x},z)}{\partial z}=\nabla\cdot\left[I(\mathbf{x},z)\nabla\phi(\mathbf{x})\right]$$

OPTICS LETTERS / Vol. 39, No. 3 / February 1, 2014

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Transport of intensity phase retrieval and computational imaging for partially coherent fields: The phase space perspective

CrossMark

Chao Zuo [a,b,*], Qian Chen [a], Lei Tian [c], Laura Waller [c], Anand Asundi [b]

[a] Jiangsu Key Laboratory of Spectral Imaging & Intelligence Sense, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China

[b] Centre for Optical and Laser Engineering, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 639798 Singapore

[c] Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720, USA

Generalized Phase

$$\frac{\int \mathbf{u} W(\mathbf{x},\mathbf{u})\, d\mathbf{u}}{\int W(\mathbf{x},\mathbf{u})\, d\mathbf{u}} = \frac{1}{2\pi} \nabla_{\mathbf{x}} \hat{\phi}(\mathbf{x})$$

OPTICS LETTERS / Vol. 39, No. 3 / February 1, 2014

Light field moment imaging: comment

Chao Zuo,[1,2,3] Qian Chen,[1,*] and Anand Asundi[2]
[1]*Jiangsu Key Laboratory of Spectral Imaging & Intelligence Sense, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China*
[2]*Centre for Optical and Laser Engineering, Nanyang Technological University, Singapore 639798*

Optics and Lasers in Engineering 71 (2015) 20–32
Contents lists available at ScienceDirect
Optics and Lasers in Engineering
journal homepage: www.elsevier.com/locate/optlaseng

Transport of intensity phase retrieval and computational imaging for partially coherent fields: The phase space perspective

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[a] *Jiangsu Key Laboratory of Spectral Imaging & Intelligence Sense, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China*
[b] *Centre for Optical and Laser Engineering, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 639798 Singapore*
[c] *Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720, USA*

Light field ~ Wigner distribution

$$L\left(\mathbf{x},\theta\right)\approx W\left(\mathbf{x},\lambda\mathbf{u}\right)$$

Z. Zhang and M. Levoy, "Wigner distributions and how they relate to the light field," in "2009 IEEE International Conference on Computational Photography (ICCP)," (2009), pp. 1–10.

A. Walther, "Radiometry and coherence," J. Opt. Soc. Am. **58**, 1256–1259 (1968).

A. Walther, "Radiometry and coherence," J. Opt. Soc. Am. **58**, 1256–1259 (1973).

Computational light field imaging

Two images with slight

$I(x,y)$

tive

$$\frac{\partial I(x,y)}{\partial z}$$

OPTICS LETTERS / Vol. 38, No. 15 / August 1, 2013

Light field mome

Antony Orth[1,2] and Kenneth
[1]Harvard University School of Engineering and Applied Sciences, Cambridge, Massachusetts 02138, USA
[2]e-mail: tonyorth@seas.harvard.edu
[3]e-mail: kcrozier@seas.harvard.edu

maging: comment

and Anand Asundi[2]
[1]Jiangsu Key Laboratory of Spectral Imaging & Intelligence Sense, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China
[2]Centre for Optical and Laser Engineering, Nanyang Technological University, Singapore 639798

Computational light field imaging

OPTICS LETTERS / Vol. 38, No. 15 / August 1, 2013

Light field m

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[3]e-mail: kcrozier@seas.harvard.edu

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Generalized Phase

$$\frac{\int \mathbf{u} W(\mathbf{x},\mathbf{u})\, d\mathbf{u}}{\int W(\mathbf{x},\mathbf{u})\, d\mathbf{u}} = \frac{1}{2\pi} \nabla_{\mathbf{x}} \hat{\phi}(\mathbf{x})$$

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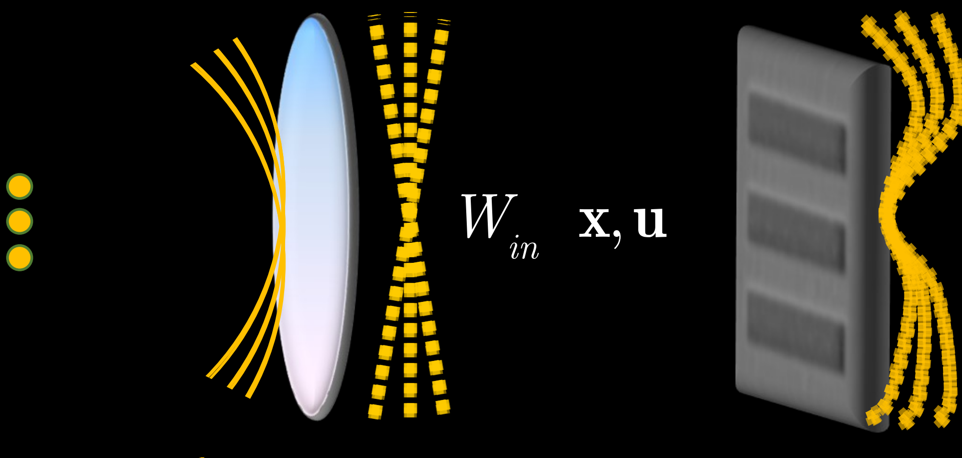
[b] Centre for Optical and Laser Engineering, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 639798 Singapore
[c] Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720, USA

Phase of the object



$W_{in}(\mathbf{x},\mathbf{u})$

$W_T(\mathbf{x},\mathbf{u})$

$$W_{out}(\mathbf{x},\mathbf{u}) = W_{in}(\mathbf{x},\mathbf{u}) \underset{\mathbf{u}}{\otimes} W_T(\mathbf{x},\mathbf{u})$$

Generalized Phase

$$\frac{\int \mathbf{u} W_{out}(\mathbf{x},\mathbf{u})\,d\mathbf{u}}{\int W_{out}(\mathbf{x},\mathbf{u})\,d\mathbf{u}} = \frac{\int \mathbf{u} W_{T}(\mathbf{x},\mathbf{u})\,d\mathbf{u}}{\int W_{T}(\mathbf{x},\mathbf{u})\,d\mathbf{u}} + \frac{\int \mathbf{u} W_{in}(\mathbf{x},\mathbf{u})\,d\mathbf{u}}{\int W_{in}(\mathbf{x},\mathbf{u})\,d\mathbf{u}}$$

OPTICS LETTERS / Vol. 39, No. 3 / February 1, 2014

Light field moment imaging: comment

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[c] Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720, USA

Generalized Phase

$$\nabla_{\mathbf{x}} \hat{\phi}_{out}\left(\mathbf{x}\right) = \nabla_{\mathbf{x}}\left[\hat{\phi}_{in}\left(\mathbf{x}\right) + \phi\left(\mathbf{x}\right)\right]$$

OPTICS LETTERS / Vol. 39, No. 3 / February 1, 2014

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"Zero-moment" condition

$$\int \mathbf{u} W_{in}\left(\mathbf{x},\mathbf{u}\right) d\mathbf{u} = 0$$

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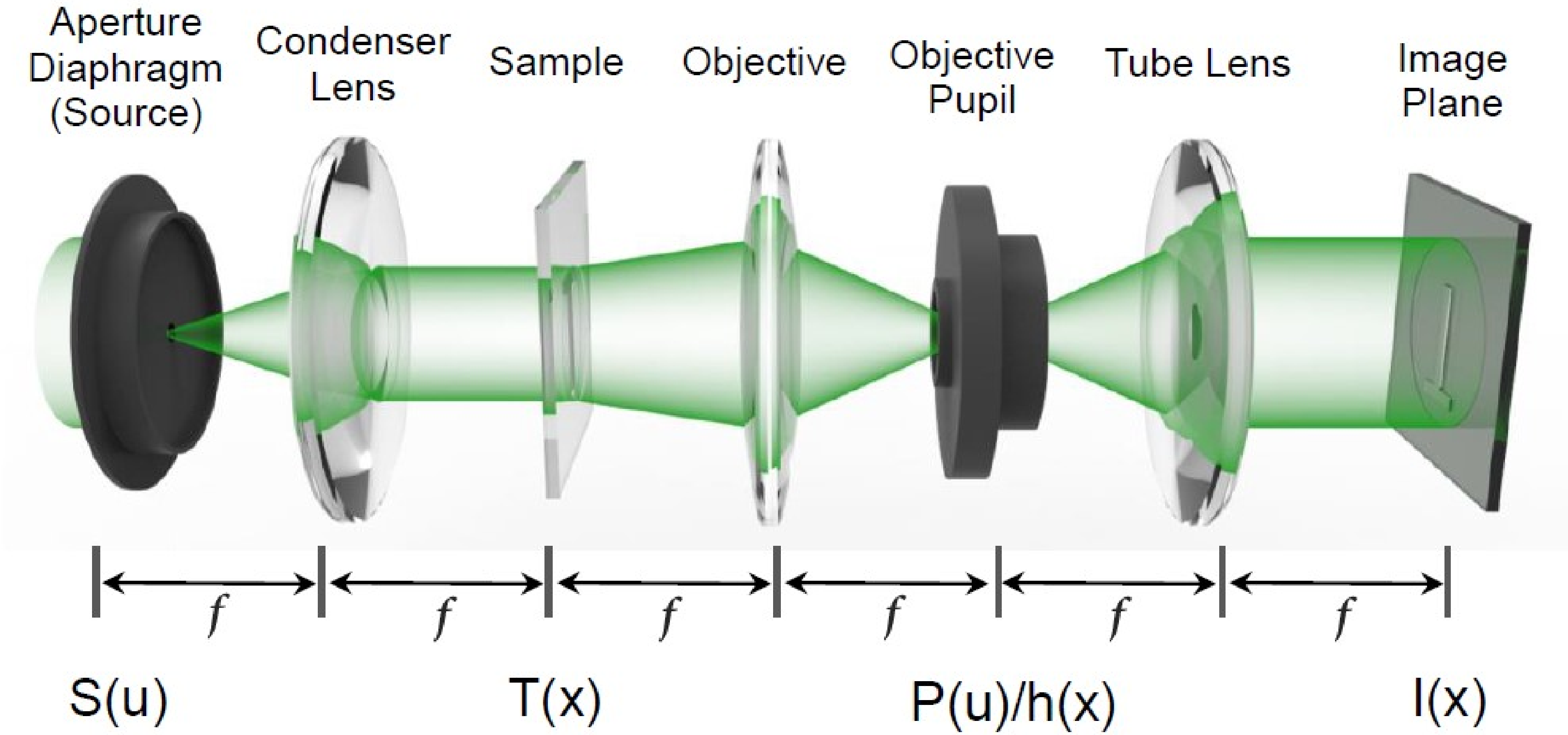
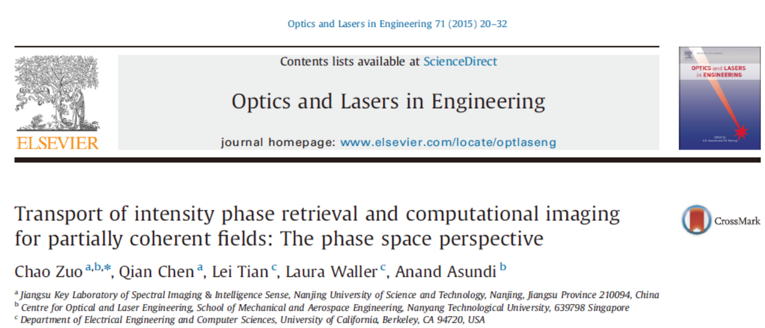
[c] Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720, USA

Imaging System



Imaging System

$$
\begin{aligned}
W_{image}\left(\mathbf{x},\mathbf{u}\right) &= \int \Gamma_{image}\left(\mathbf{x}+\frac{\mathbf{x}'}{2},\mathbf{x}-\frac{\mathbf{x}'}{2}\right)\exp\left(-j2\pi\mathbf{u}\mathbf{x}'\right)d\mathbf{x}' \\
&= W_{out}\left(\mathbf{x},\mathbf{u}\right)\underset{\mathbf{x}}{\otimes}W_{psf}\left(\mathbf{x},\mathbf{u}\right) \\
&= W_{T}\left(\mathbf{x},\mathbf{u}\right)\underset{\mathbf{u}}{\otimes}W_{in}\left(\mathbf{x},\mathbf{u}\right)\boxed{\underset{\mathbf{x}}{\otimes}W_{psf}\left(\mathbf{x},\mathbf{u}\right)}
\end{aligned}
$$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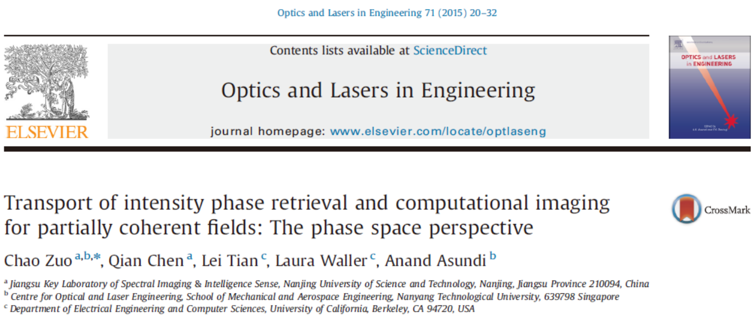
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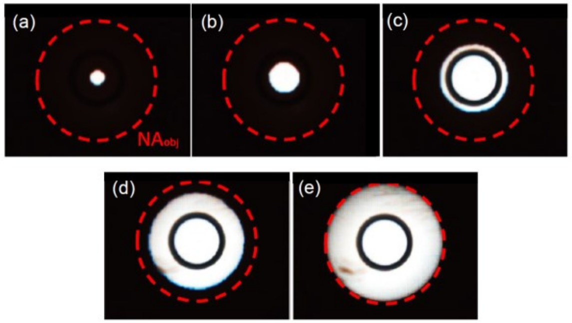
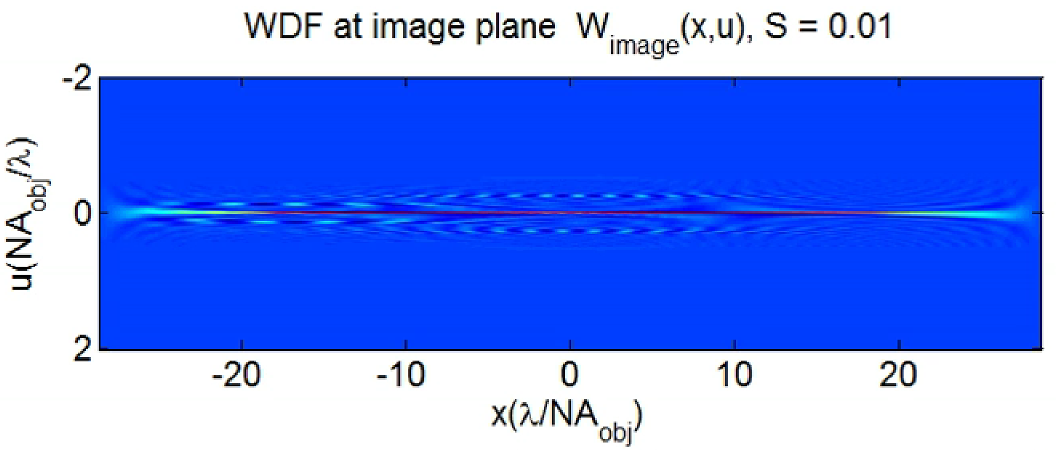
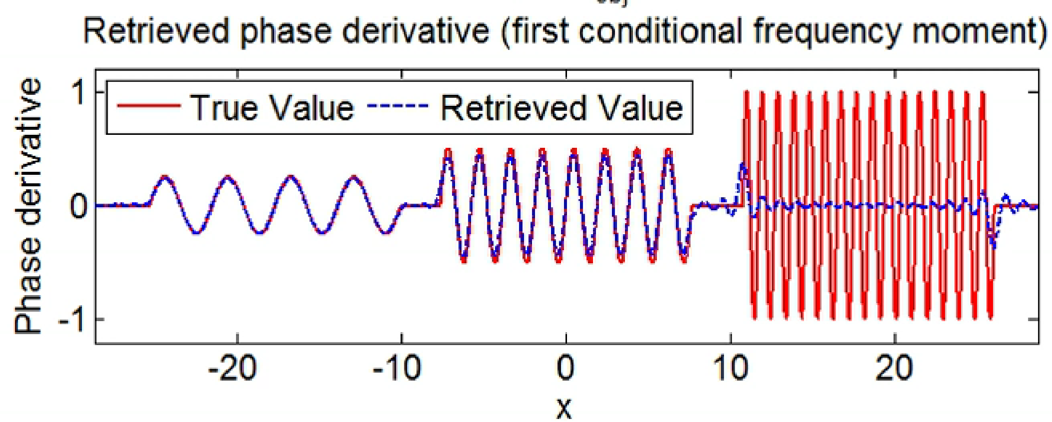
[c] Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720, USA



Imaging System





Invited Paper

Proc. of SPIE Vol. 9718 97180A-1

Phase microscope imaging in phase space

Colin J. R. Sheppard*[a], Shalin B. Mehta[b]
[a]Nanoscopy, Nanophysics, Istituto Italiano di Tecnologia, Via Morego 30, Genoa, 16163, Italy;
[b]Eugene Bell Center for Regenerative Biology & Tissue Engineering, Marine Biological Laboratory, Woods Hole, MA 02543, USA.

6. THE IMAGE IN PHASE SPACE

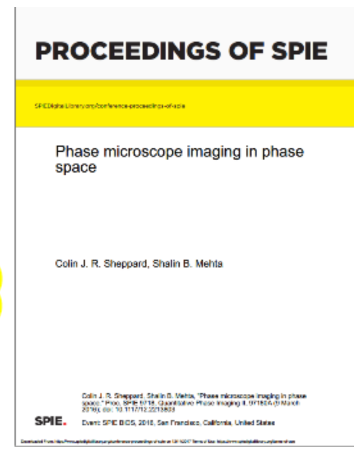
This approach can be extended to consider the partial coherence of the image itself. In particular, we can consider the mutual intensity, WDF or ambiguity function of the image. It is important to note that Ψ is not a WDF, and *not* the WDF of the image. The phase space representations of the image have relevance to phase reconstruction methods such as phase space tomography, or the transport of intensity equation approach, and to the 3D image properties.

In phase space tomography, knowledge of the mutual intensity of a wave field in 3D can be used to reconstruct the wave field, including its phase and the correlation coefficient [33-38].

It is interesting to note that Hopkins calculated the image intensity in a partially coherent microscope by propagating the mutual intensity through the system, but did not give an expression for the mutual intensity of the image [23]. The mutual intensity of the image is [39]

$$J(\mathbf{x}_1,\mathbf{x}_2)=\iiint P(\mathbf{m}_1+\xi)P^*(\mathbf{m}_2+\xi)S(\xi)T(\mathbf{m}_1)T^*(\mathbf{m}_2)\exp\{i2\pi[(\mathbf{m}_1+\xi)\cdot\mathbf{x}_1-(\mathbf{m}_2+\xi)\cdot\mathbf{x}_2]\}\,\mathrm{d}\mathbf{m}_1\,\mathrm{d}\mathbf{m}_2\,\mathrm{d}\xi.$$

[39] Zuo, C., Chen, Q., Tian, L., Waller, L. and Asundi, A. "Transport of intensity phase retrieval and computational imaging for partially coherent fields: The phase space perspective," Optics and Lasers in Engineering 71, 20-32 (2015).


PROCEEDINGS OF SPIE

Phase microscope imaging in phase space

Colin J. R. Sheppard, Shalin B. Mehta

SPIE.

Proc. of SPIE Vol. 9718 97180A-1

1272 Vol. 35, No. 8 / August 2018 / Journal of the Optical Society of America A Research

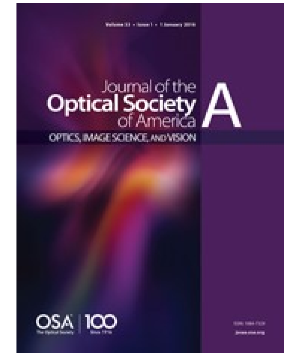
Journal of the Optical Society of America A
OPTICS, IMAGE SCIENCE, AN

Partially coherent microscope in phase space

Shalin B. Mehta[1] and Colin J. R. Sheppard[2,3,*]

[1]Advanced Optical Microscopy, Chan Zuckerberg Biohub, 499 Illinois Street, San Francisco, California 94158, USA
[2]Nanophysics, Istituto Italiano di Tecnologia, via Morego 30, 16163 Genova, Italy
[3]School of Chemistry, University of Wollongong, Northfields Avenue, Wollongong, NSW 2522, Australia
*Corresponding author: colinjrsheppard@gmail.com

Received 20 March 2018; revised 1 June 2018; accepted 5 June 2018; posted 6 June 2018 (Doc. ID 326408); published 9 July .

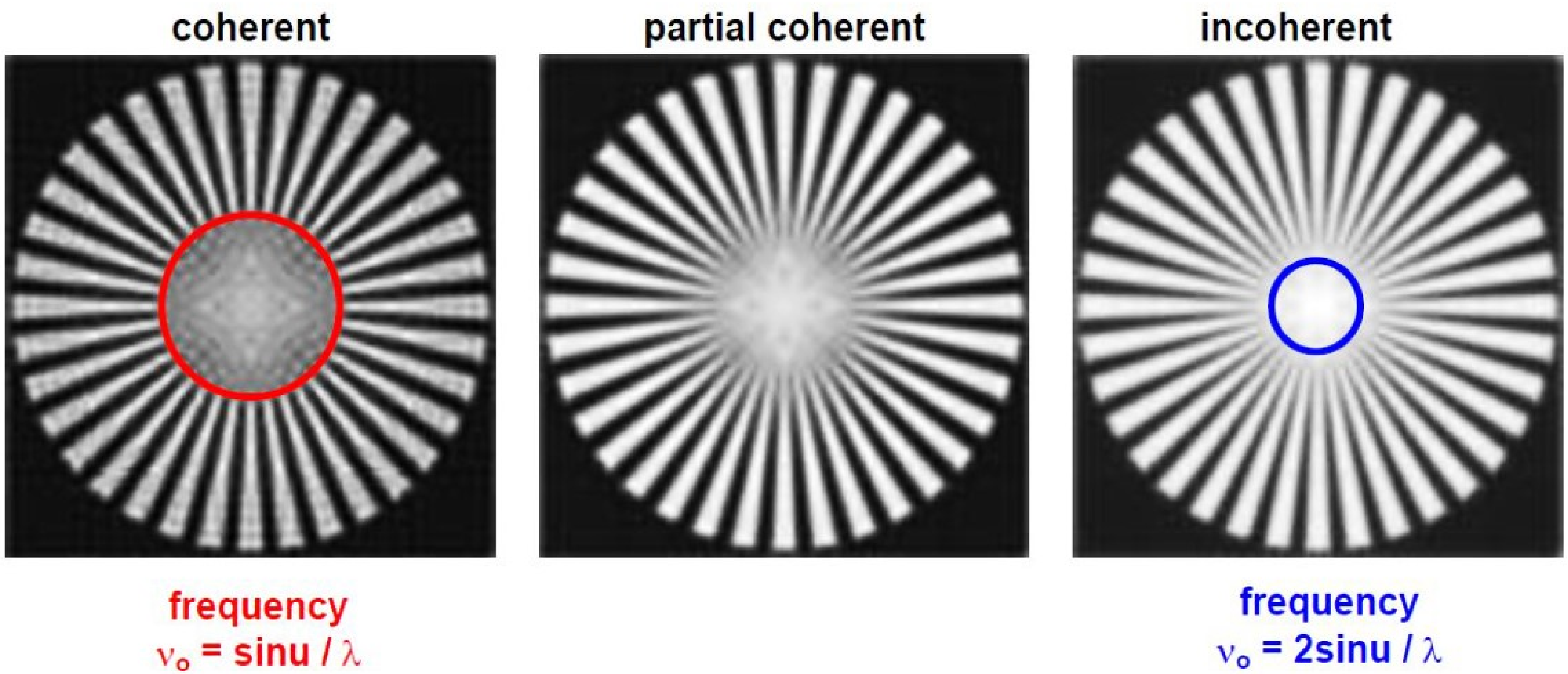


JOSA A **35, 8 (2018)**

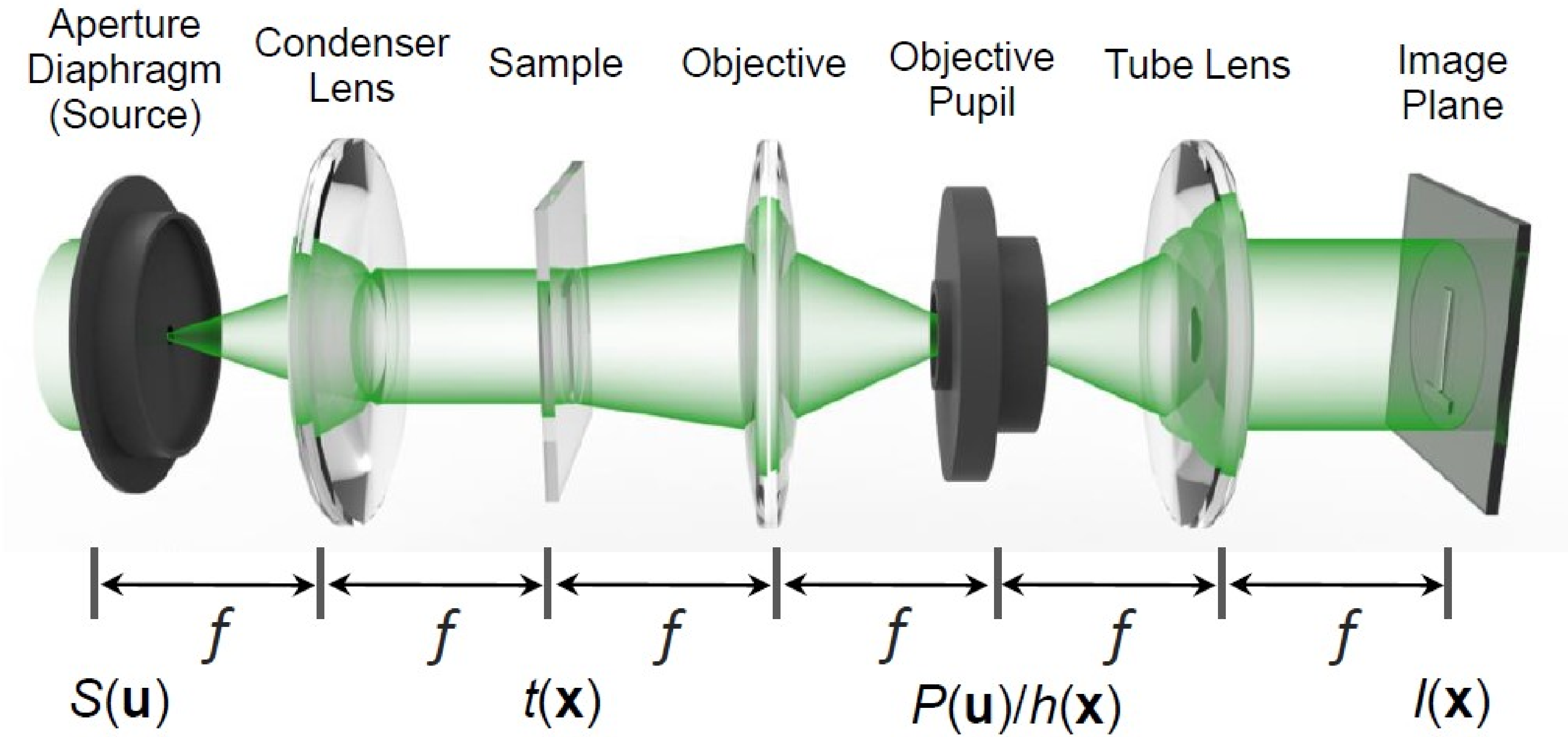
taken into account [12–14]. Significant advances have been made in describing partially coherent fields with phase space distributions [15]. However, only a few papers have addressed the question of what forward model to use for elegantly capturing the properties of partially coherent imaging [16–18]. Even

16. S. B. Mehta and C. J. R. Sheppard, "Phase-space representation of partially-coherent imaging systems using the Cohen class distribution," Opt. Lett. **35**, 348–350 (2010).
17. S. B. Mehta and C. J. R. Sheppard, "Using the phase-space imager to analyze partially coherent imaging systems: bright-field, phase contrast, differential interference contrast, differential phase contrast, and spiral phase contrast," J. Mod. Opt. **57**, 718–739 (2010).
18. C. Zuo, Q. Chen, L. Tian, L. Waller, and A. Asundi, "Transport of intensity phase retrieval and computational imaging for partially coherent fields: the phase space perspective," Opt. Lasers Eng. **71**, 20–32 (2015).

Coherent Limit



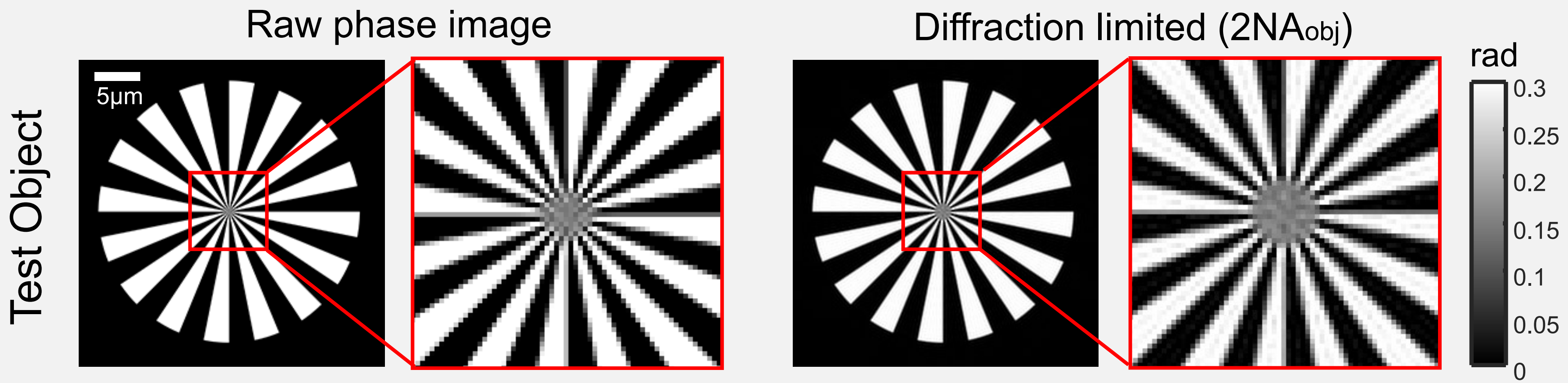
Tradeoff between resolution and contrast

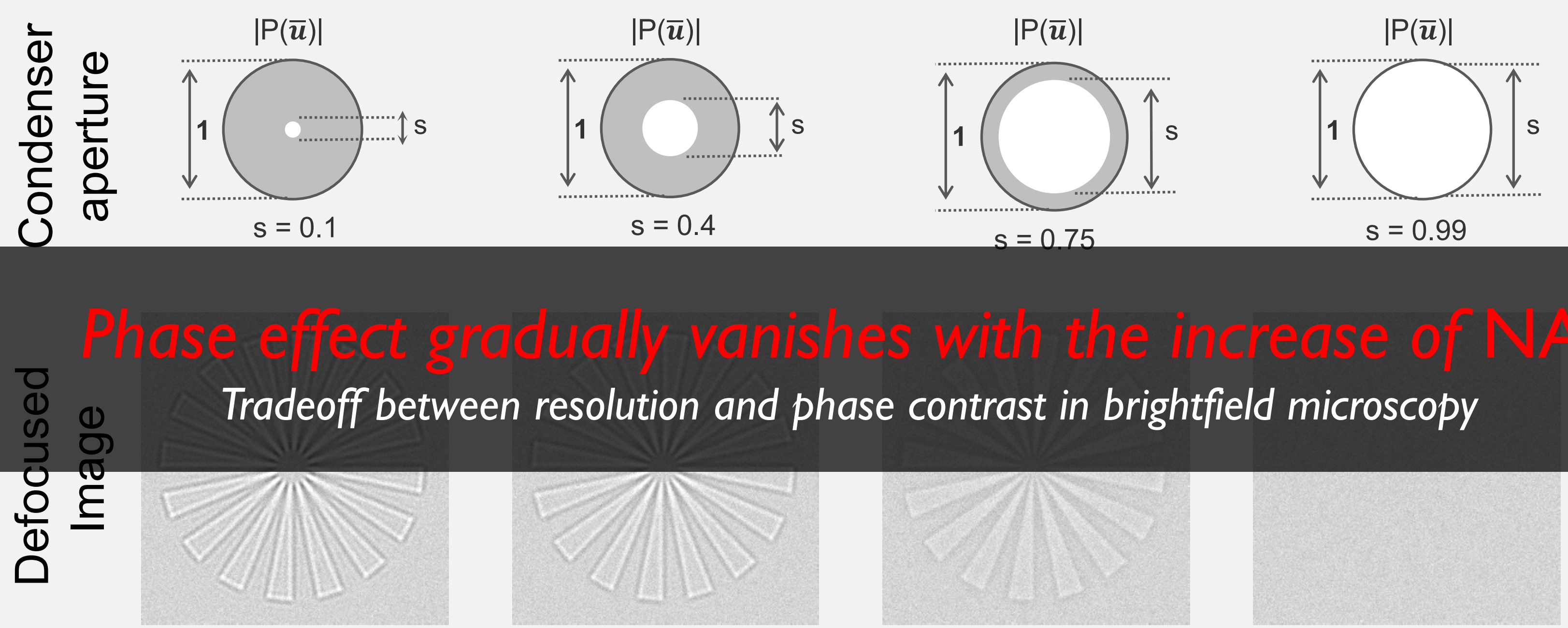


Microscope based on Köhler Illumination: 6f system

Partially coherent diffraction limit $NA_{eff} = NA_{obj} + NA_{ill} \leq 2NA_{obj}$ Incoherent limit

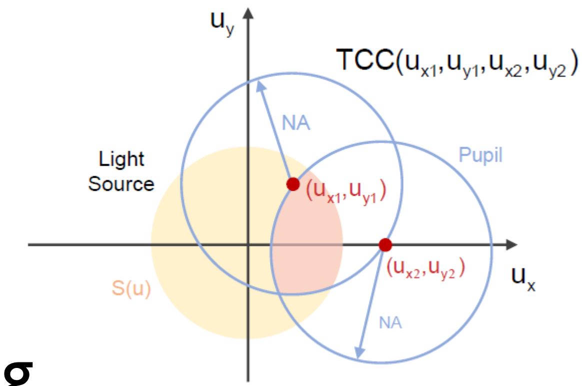
Tradeoff between resolution and contrast





Phase effect gradually vanishes with the increase of NA_{ill}

Tradeoff between resolution and phase contrast in brightfield microscopy



Partially coherent imaging

$$WOTF(\mathbf{u}) \equiv TCC(\mathbf{u}, 0) =$$

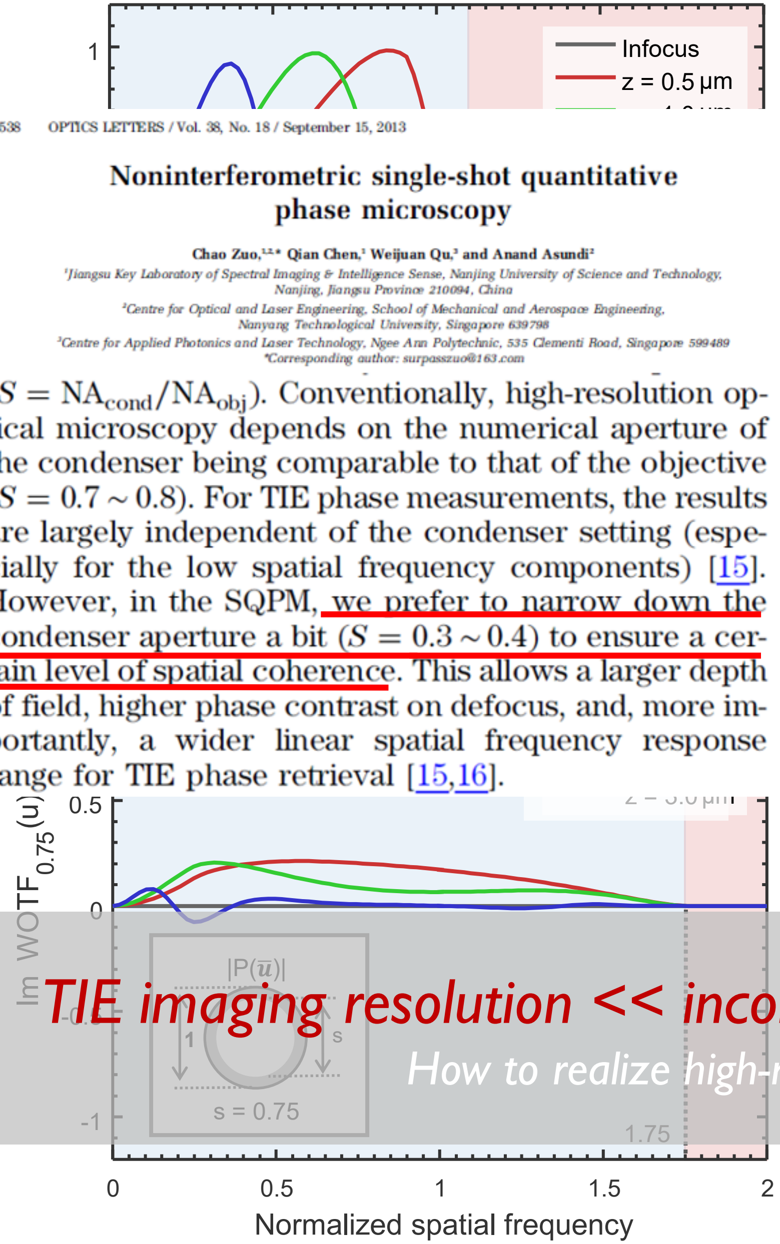
$$\iint S(\mathbf{u}') P(\mathbf{u}') P(\mathbf{u}' + \mathbf{u})$$

$$e^{jk\Delta z\left(-\sqrt{1-\lambda^2|\mathbf{u}'|^2}+\sqrt{1-\lambda^2|\mathbf{u}+\mathbf{u}'|^2}\right)} d\mathbf{u}'$$

C. J. R. SHEPPARD and A. CHOUDHURY
Image formation in the scanning microscope
OPTICA ACTA, 1977, VOL. 24, NO. 10, 1051–1073

On the diffraction theory of optical images
By H. H. Hopkins
Proc. R. Soc. Lond. A **217**, 408 (1953)

Tradeoff between resolution and contrast



3538 OPTICS LETTERS / Vol. 38, No. 18 / September 15, 2013

Noninterferometric single-shot quantitative phase microscopy

Chao Zuo,[1,2,*] Qian Chen,[1] Weijuan Qu,[3] and Anand Asundi[2]

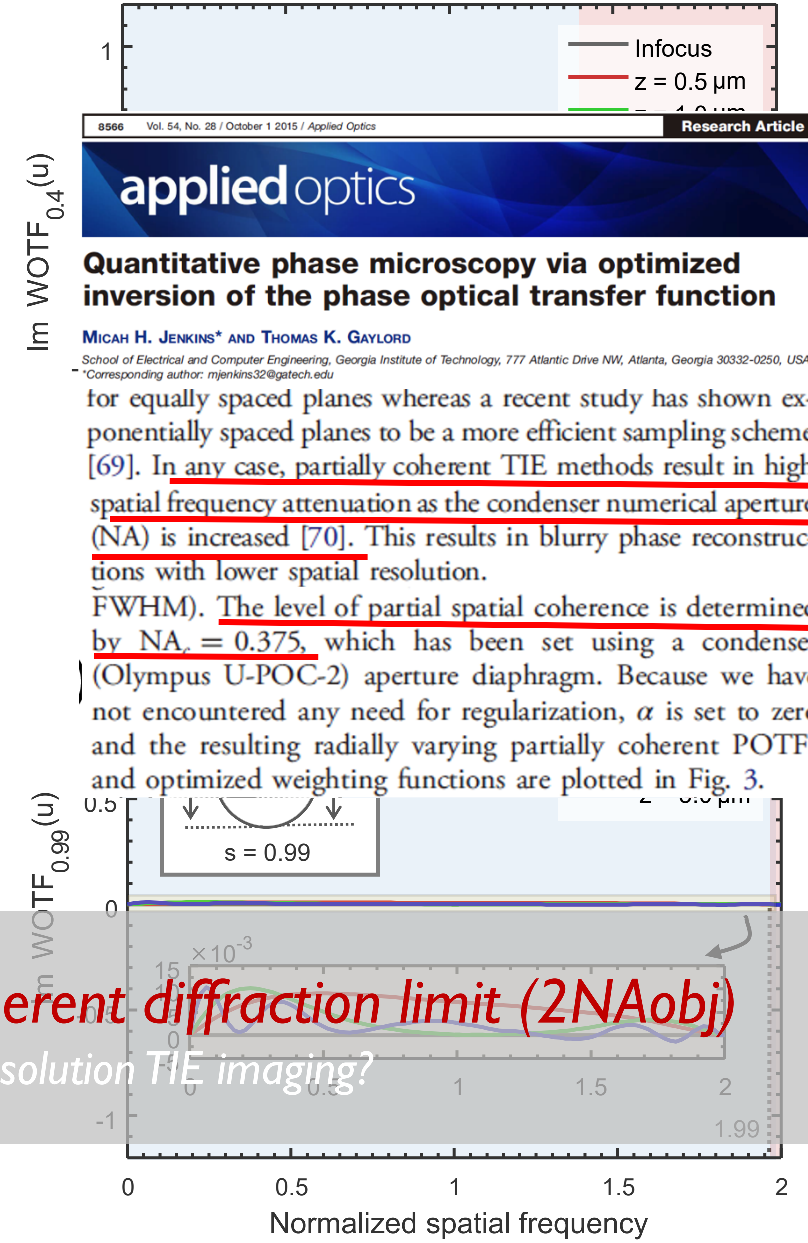
[1]Jiangsu Key Laboratory of Spectral Imaging & Intelligence Sense, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China

[2]Centre for Optical and Laser Engineering, School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798

[3]Centre for Applied Photonics and Laser Technology, Ngee Ann Polytechnic, 535 Clementi Road, Singapore 599489

*Corresponding author: surpasszuo@163.com

($S = \mathrm{NA_{cond}}/\mathrm{NA_{obj}}$). Conventionally, high-resolution optical microscopy depends on the numerical aperture of the condenser being comparable to that of the objective ($S = 0.7 \sim 0.8$). For TIE phase measurements, the results are largely independent of the condenser setting (especially for the low spatial frequency components) [15]. However, in the SQPM, we prefer to narrow down the condenser aperture a bit ($S = 0.3 \sim 0.4$) to ensure a certain level of spatial coherence. This allows a larger depth of field, higher phase contrast on defocus, and, more importantly, a wider linear spatial frequency response range for TIE phase retrieval [15,16].



8566 Vol. 54, No. 28 / October 1 2015 / Applied Optics Research Article

applied optics

Quantitative phase microscopy via optimized inversion of the phase optical transfer function

Micah H. Jenkins* and Thomas K. Gaylord

School of Electrical and Computer Engineering, Georgia Institute of Technology, 777 Atlantic Drive NW, Atlanta, Georgia 30332-0250, USA

*Corresponding author: mjenkins32@gatech.edu

for equally spaced planes whereas a recent study has shown exponentially spaced planes to be a more efficient sampling scheme [69]. In any case, partially coherent TIE methods result in high spatial frequency attenuation as the condenser numerical aperture (NA) is increased [70]. This results in blurry phase reconstructions with lower spatial resolution.

FWHM). The level of partial spatial coherence is determined by $\mathrm{NA}_c = 0.375$, which has been set using a condenser (Olympus U-POC-2) aperture diaphragm. Because we have not encountered any need for regularization, α is set to zero and the resulting radially varying partially coherent POTFs and optimized weighting functions are plotted in Fig. 3.

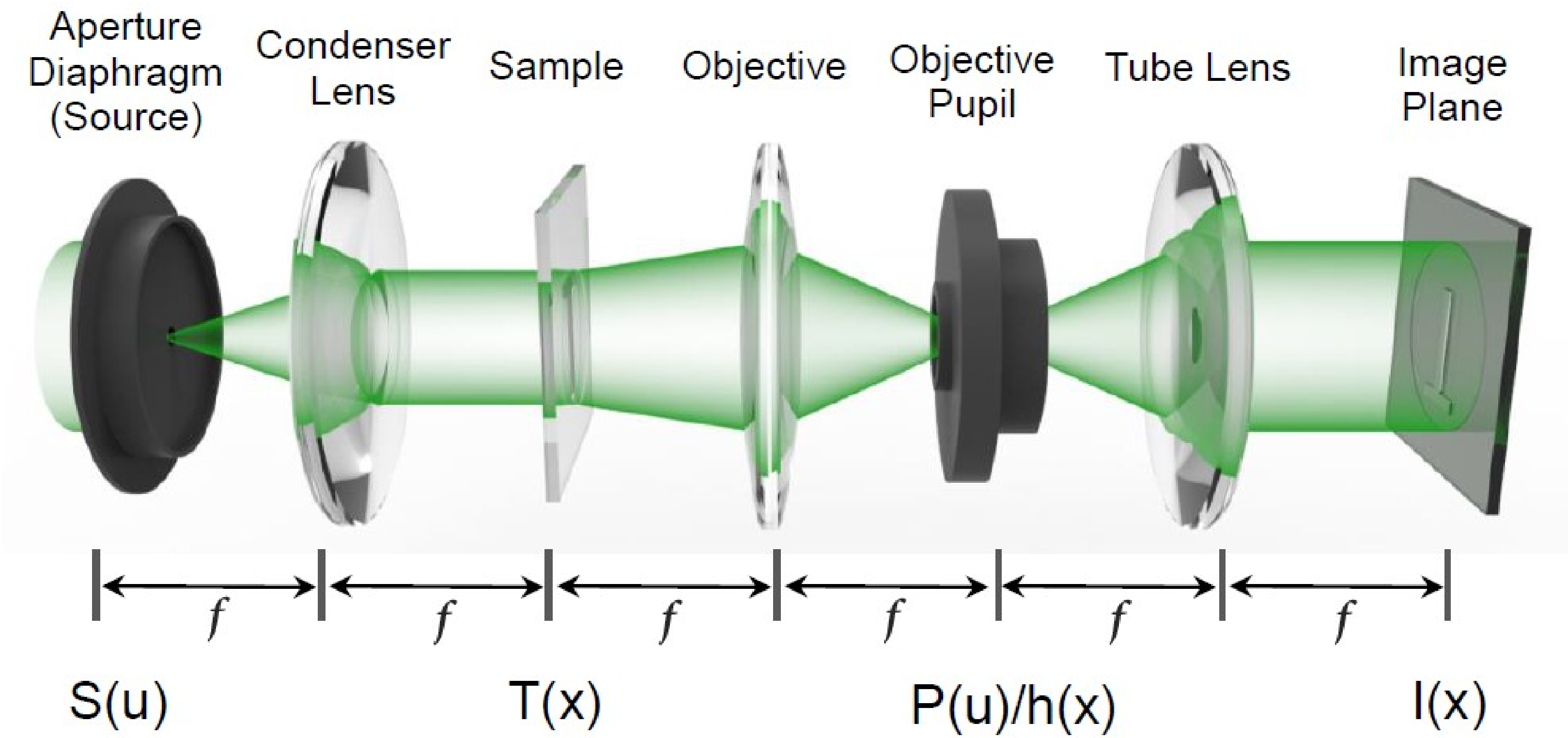
TIE imaging resolution << incoherent diffraction limit (2NAobj)

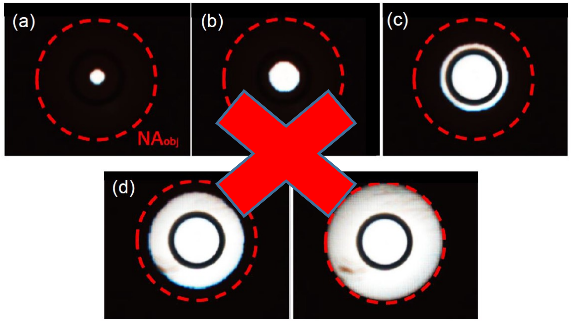
How to realize high-resolution TIE imaging?

Transport of intensity equation ?

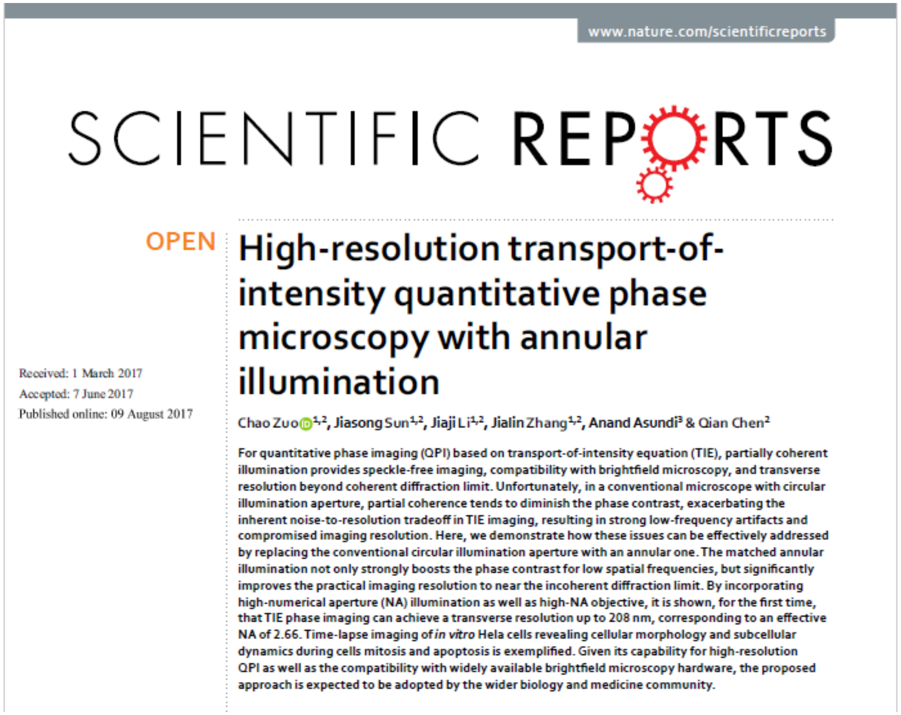
$$-k\frac{\partial I(\mathbf{x},z)}{\partial z}=\nabla\cdot\left[I(\mathbf{x},z)\nabla\phi(\mathbf{x})\right]$$

Imaging System !





Illumination Engineering


www.nature.com/scientificreports

SCIENTIFIC REPORTS

OPEN

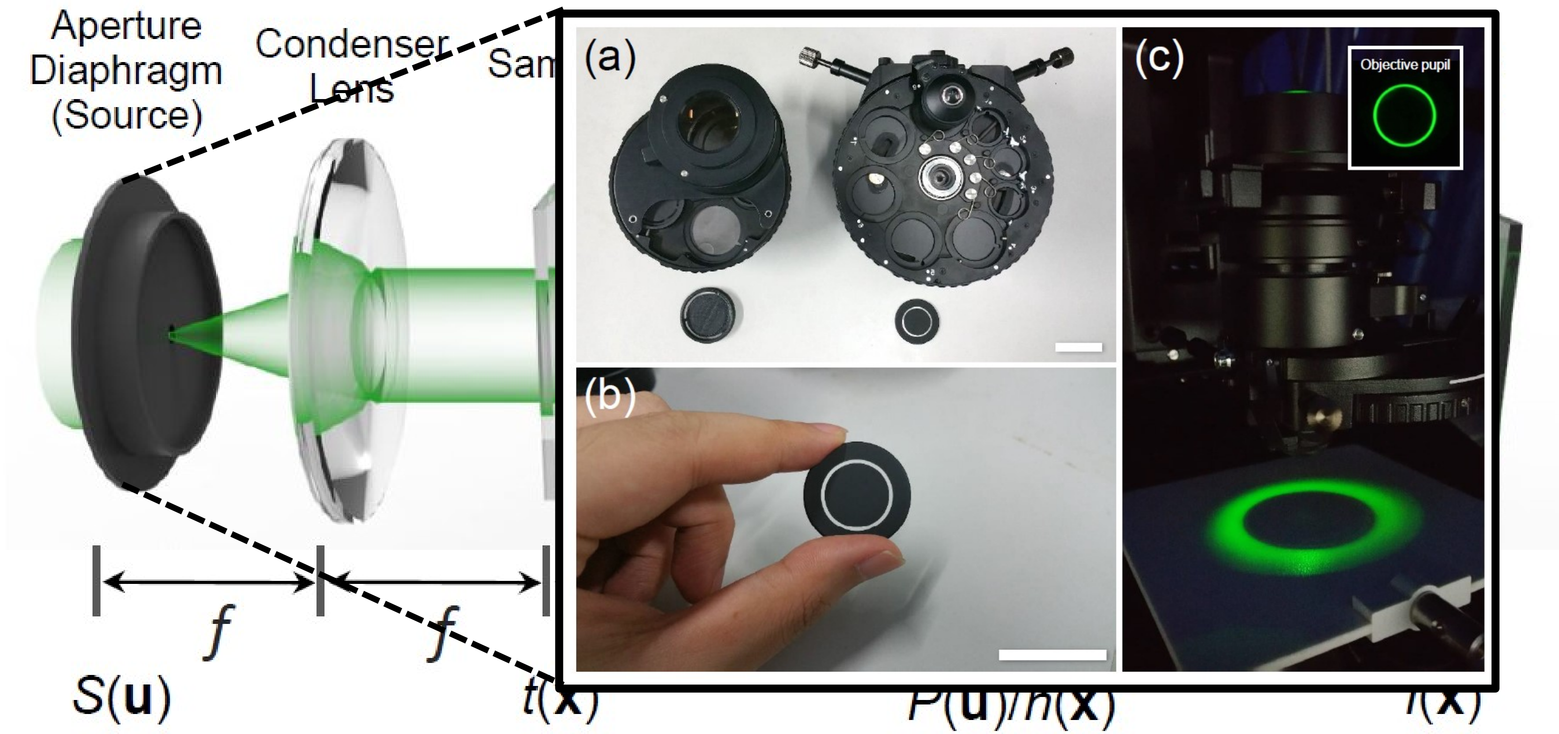
High-resolution transport-of-intensity quantitative phase microscopy with annular illumination

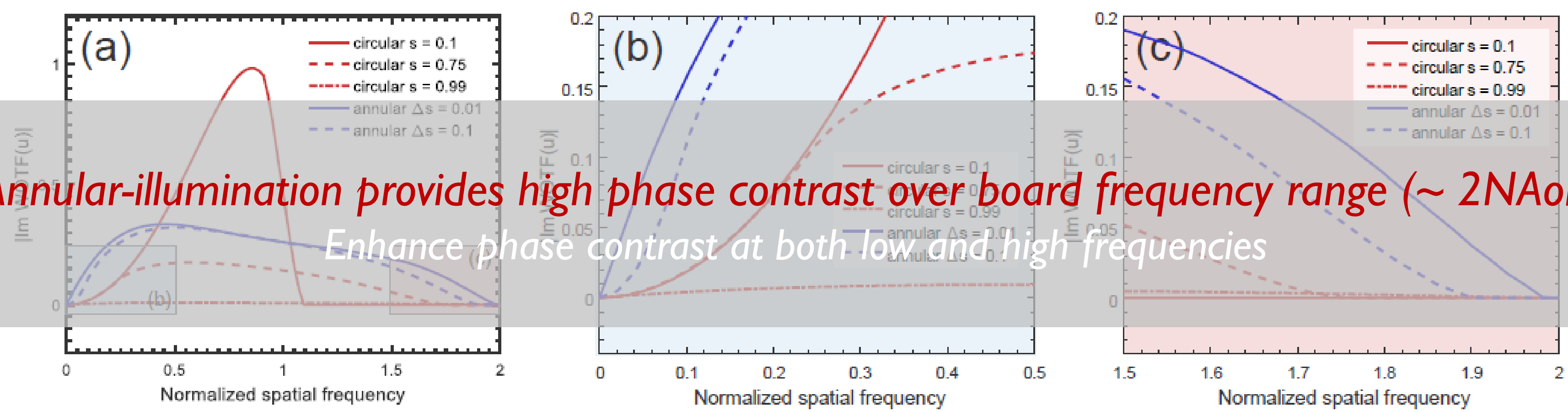
Received: 1 March 2017
Accepted: 7 June 2017
Published online: 09 August 2017

Chao Zuo[1,2], Jiasong Sun[1,2], Jiaji Li[1,2], Jialin Zhang[1,2], Anand Asundi[3] & Qian Chen[2]

For quantitative phase imaging (QPI) based on transport-of-intensity equation (TIE), partially coherent illumination provides speckle-free imaging, compatibility with brightfield microscopy, and transverse resolution beyond coherent diffraction limit. Unfortunately, in a conventional microscope with circular illumination aperture, partial coherence tends to diminish the phase contrast, exacerbating the inherent noise-to-resolution tradeoff in TIE imaging, resulting in strong low-frequency artifacts and compromised imaging resolution. Here, we demonstrate how these issues can be effectively addressed by replacing the conventional circular illumination aperture with an annular one. The matched annular illumination not only strongly boosts the phase contrast for low spatial frequencies, but significantly improves the practical imaging resolution to near the incoherent diffraction limit. By incorporating high-numerical aperture (NA) illumination as well as high-NA objective, it is shown, for the first time, that TIE phase imaging can achieve a transverse resolution up to 208 nm, corresponding to an effective NA of 2.66. Time-lapse imaging of *in vitro* Hela cells revealing cellular morphology and subcellular dynamics during cells mitosis and apoptosis is exemplified. Given its capability for high-resolution QPI as well as the compatibility with widely available brightfield microscopy hardware, the proposed approach is expected to be adopted by the wider biology and medicine community.

Annular-illumination TIE





Annular-illumination provides high phase contrast over board frequency range (~ 2NAobj)

Enhance phase contrast at both low and high frequencies

C. Zuo, J. Sun, J. Li *et.al.*, *Scientific Reports* **7**, 7654, (2017).

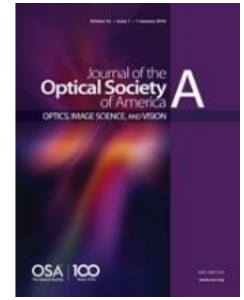
1846 Vol. 35, No. 11 / November 2018 / Journal of the Optical Society of America A Research Article

Journal of the Optical Society of America A

OPTICS, IMAGE SCIENCE, AND VISION

Partially coherent microscope imaging system in phase space: effect of defocus and phase reconstruction

COLIN J. R. SHEPPARD[1,2]



JOSA A
35, 11 (2018)

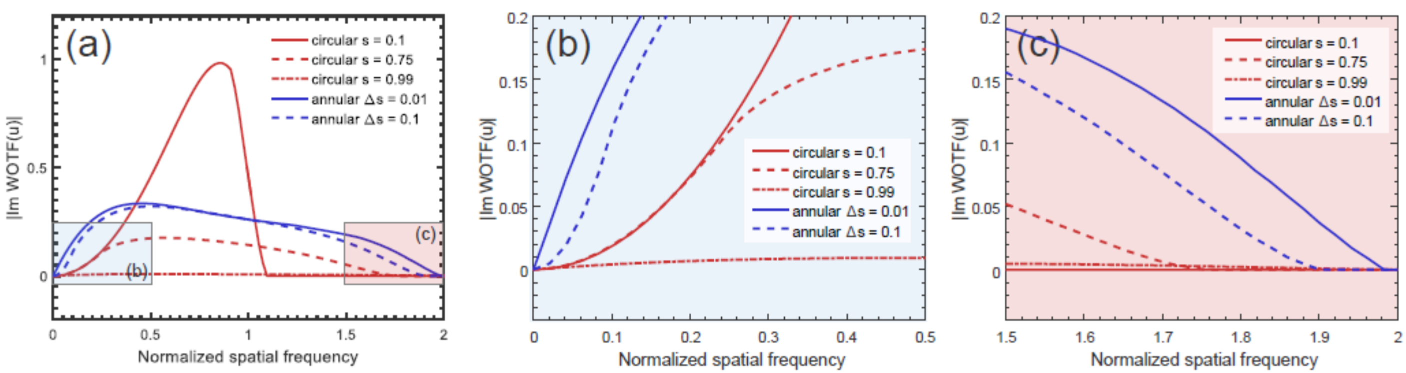
circular source for $S = 0.613$. In each case the maximum values have been normalized to unity. It is seen that the annular source has a broader spatial frequency response. An interesting and important feature is that the parabolic region for low spatial frequencies for the circular case vanishes for the annular case, so that low spatial frequencies are imaged more efficiently. The imaginary part of the WOTF for different values of defocus has been presented by Zuo *et al.* [40].

Interestingly, for $S = 1$, $C_{CG}(l)$ is very close to linear over its whole non-zero domain, so this is a good arrangement for performing TIE, but the scaling of the phase would need to be calibrated. We find that

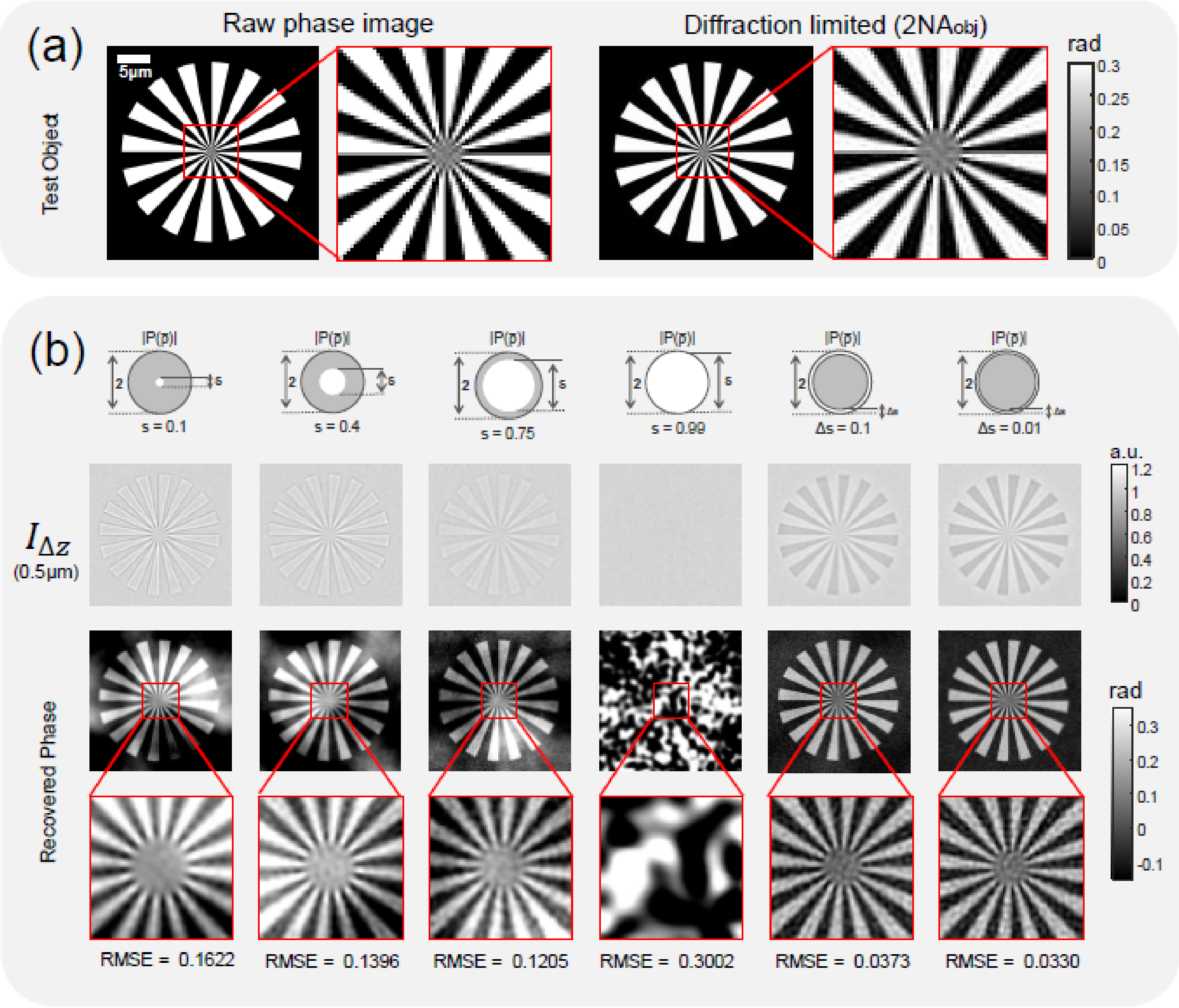
$$C_{CG}(l) = -\frac{2}{\pi} + \left(\frac{\pi^2-2}{\pi^2}\right)l + \left(\frac{\pi^2-8}{4\pi^3}\right)l^2 + \left(\frac{\pi^2-12}{6\pi^4}\right)l^3 + \ldots$$
$$= -0.637 + 0.797l + 0.015l^2 - 0.0036l^3 + \ldots \quad \textbf{(53)}$$

In fact, using an annular source for the TIE has been proposed by Zuo *et al.* [40].

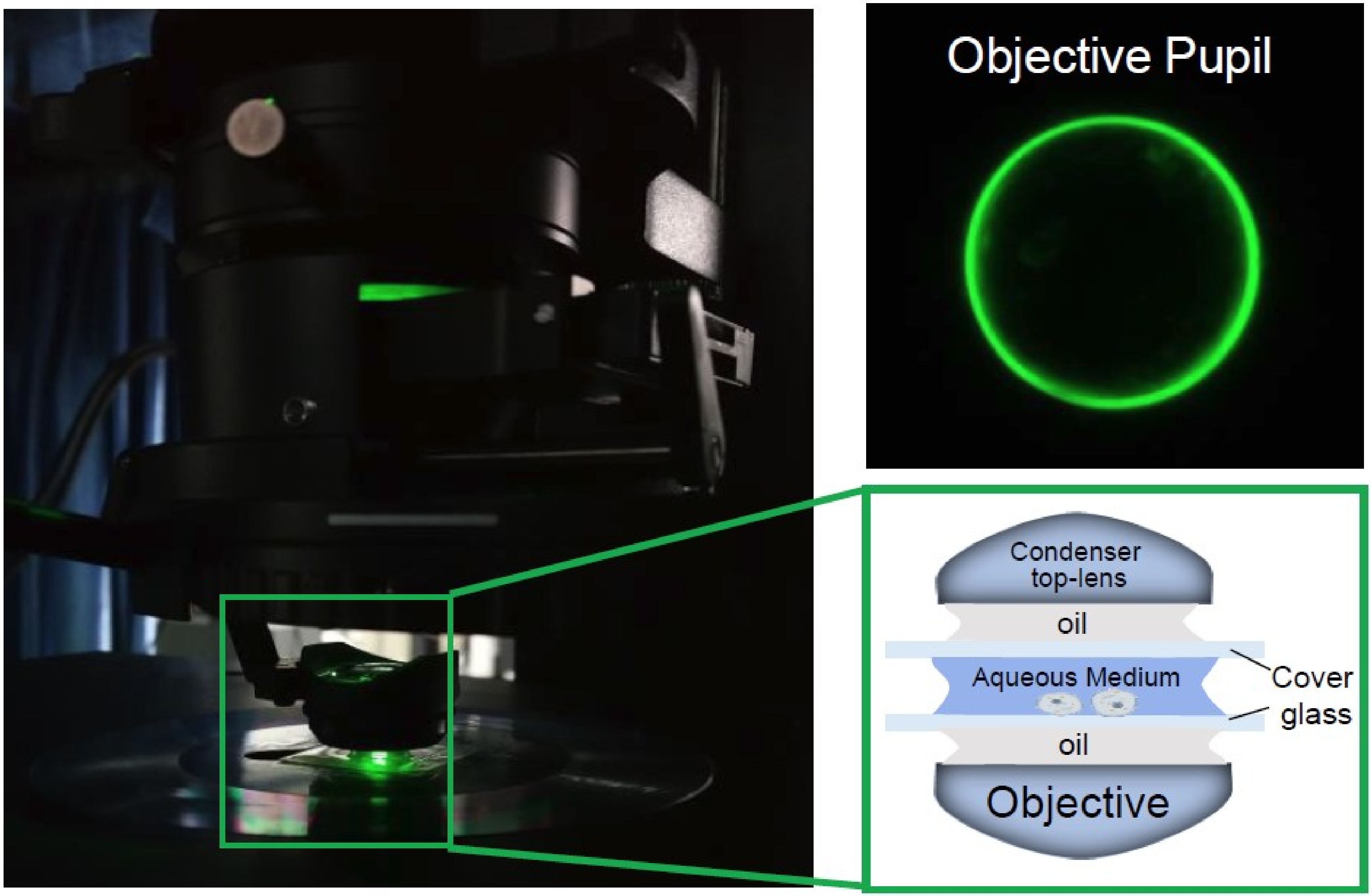
40. C. Zuo, J. Sun, J. Li, J. Zhang, A. Asundi, and Q. Chen, "High-resolution transport-of-intensity quantitative phase microscopy with annular illumination," Sci. Rep. **7**, 7654 (2017).



Annular-illumination TIE



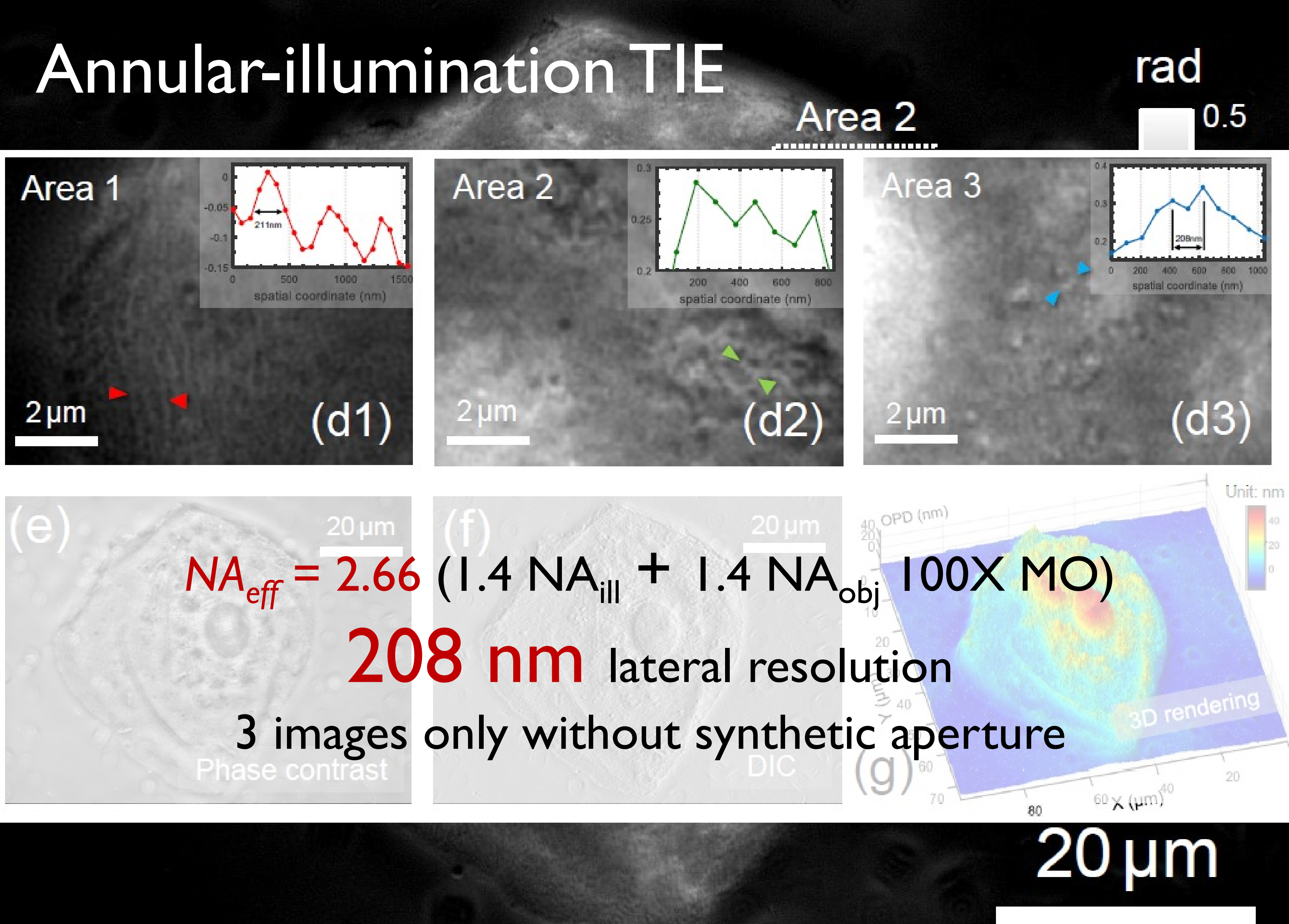
Annular-illumination TIE



Experimental setup: 1.4 NA_{ill} + 1.4 NA_{obj} 100X MO

C. Zuo, J. Sun, J. Li *et.al.*, *Scientific Reports* **7**, 7654, (2017).

Annular-illumination TIE



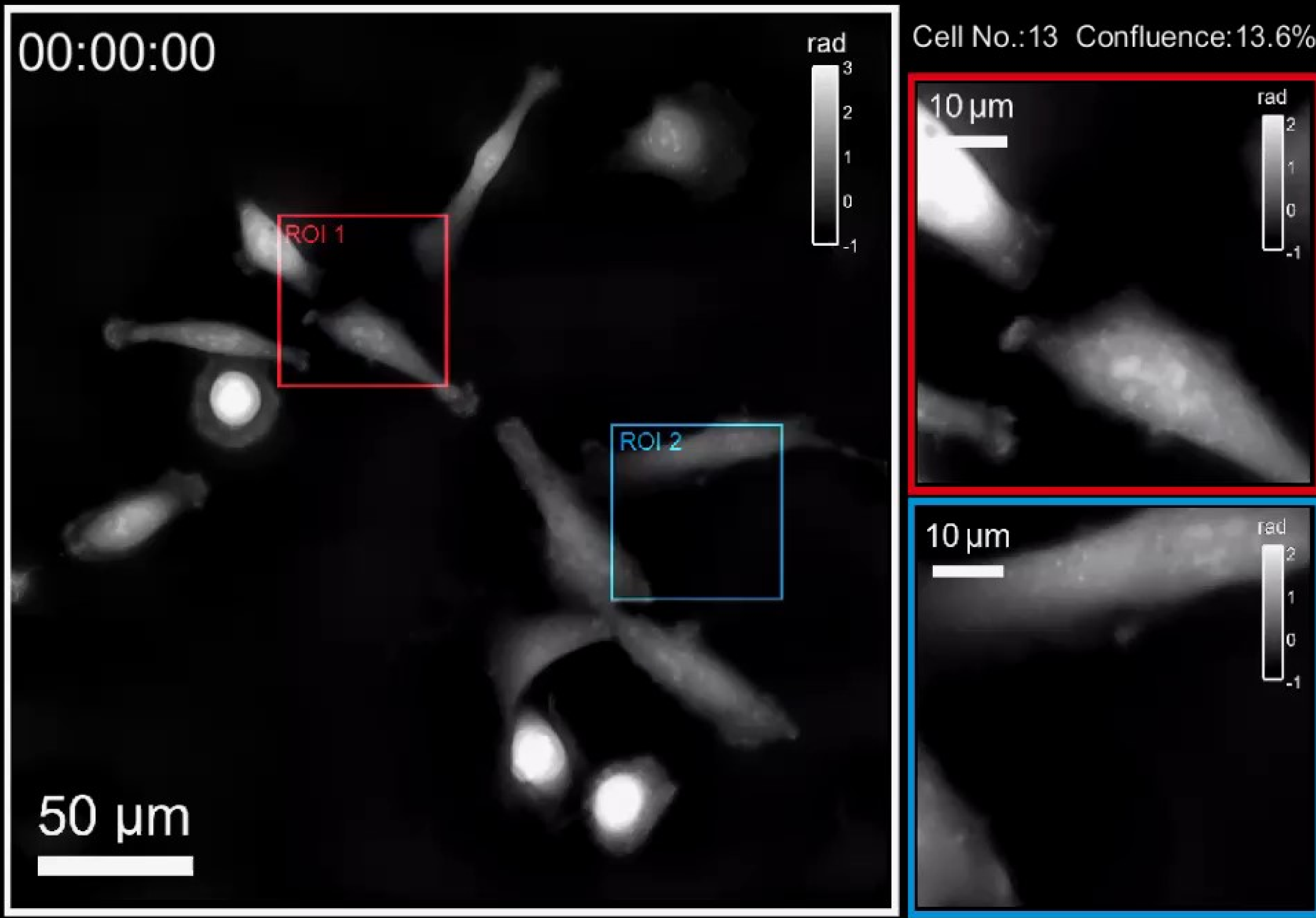
NA_{eff} = 2.66 (1.4 NA_{ill} + 1.4 NA_{obj} 100X MO)

208 nm lateral resolution

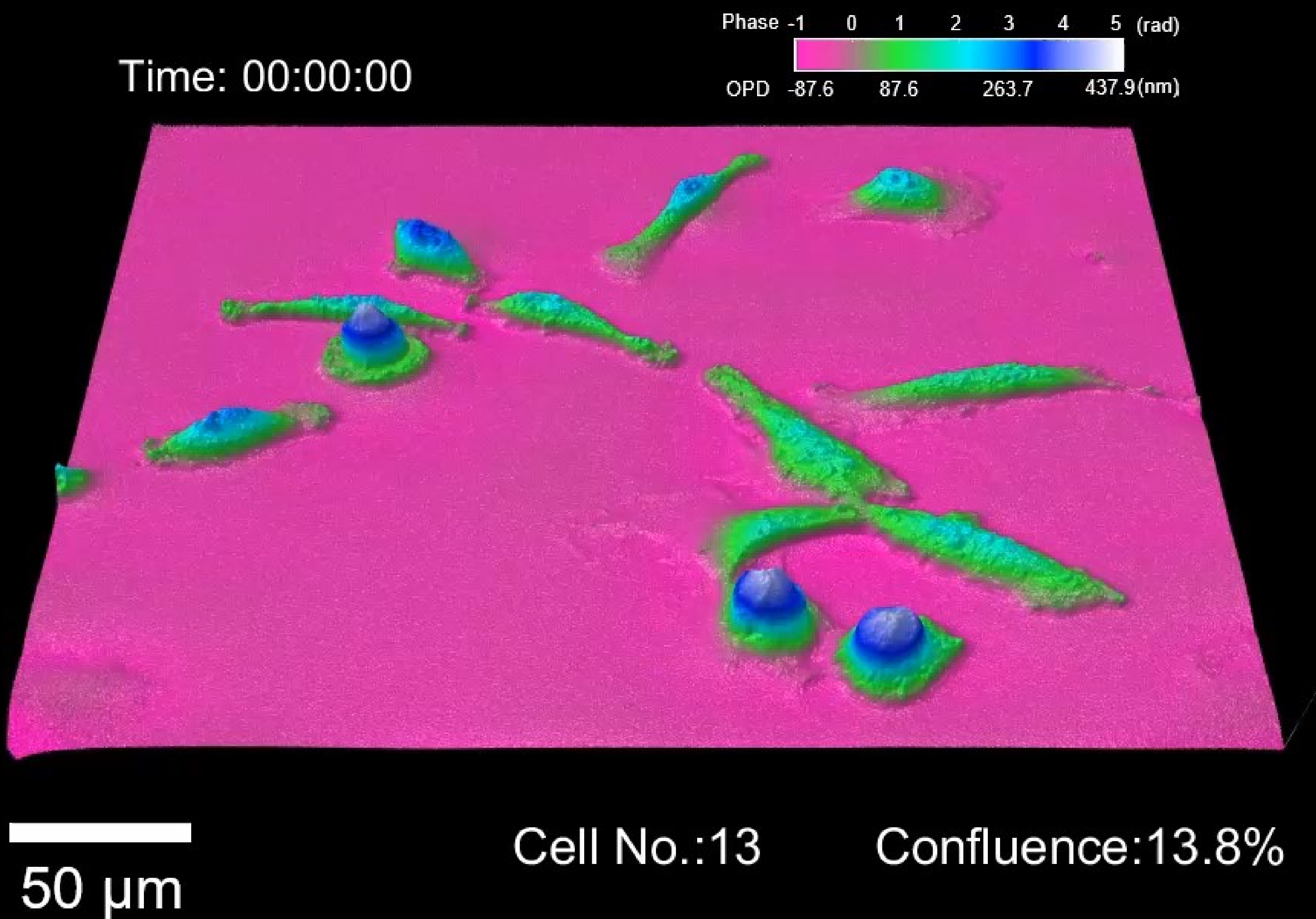
3 images only without synthetic aperture

C. Zuo, J. Sun, J. Li *et.al.*, *Scientific Reports* **7**, 7654, (2017).

Long-term time-lapse imaging of HeLa cell dividing in culture (60 h)

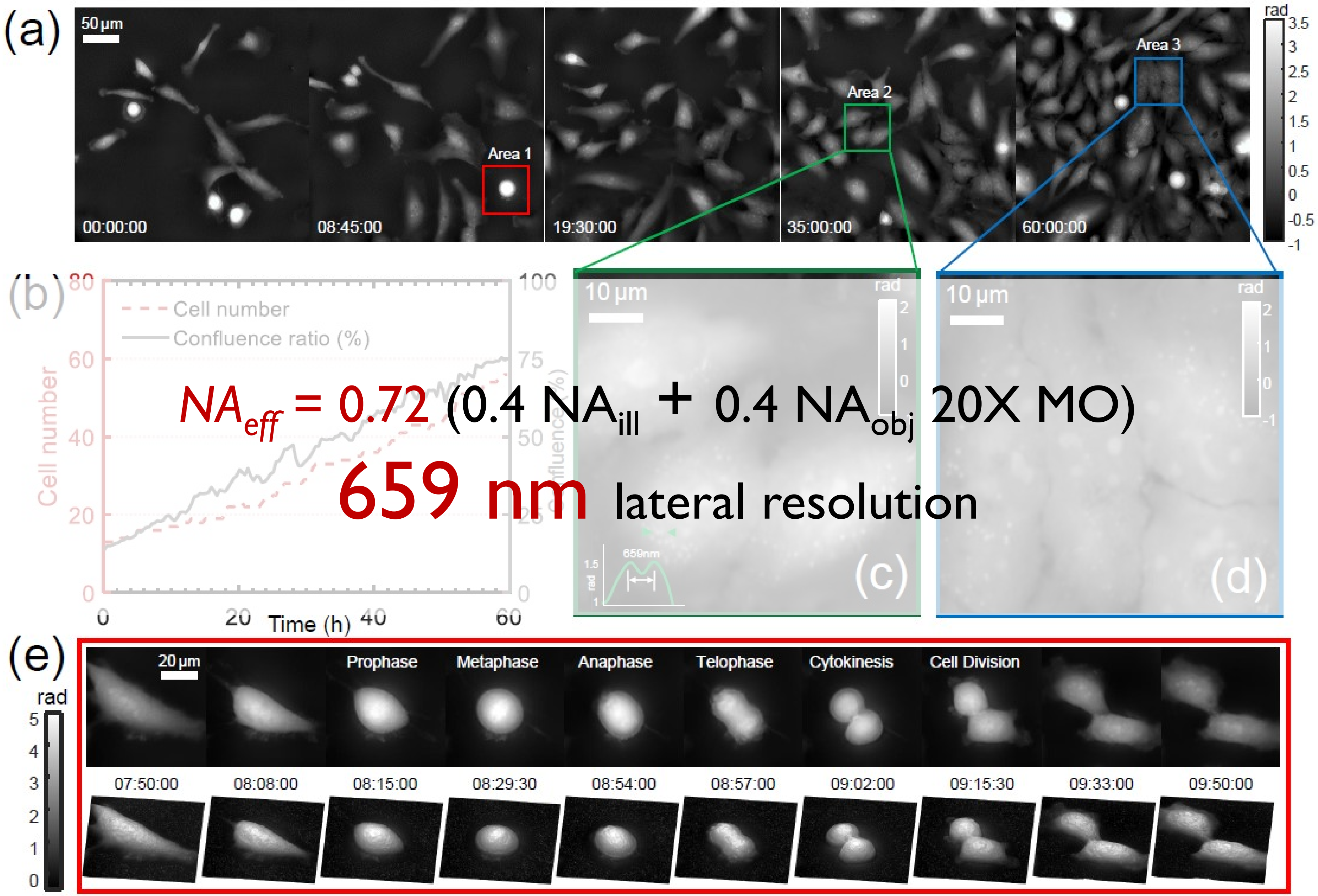


Long-term time-lapse imaging of HeLa cell dividing in culture (60 h)



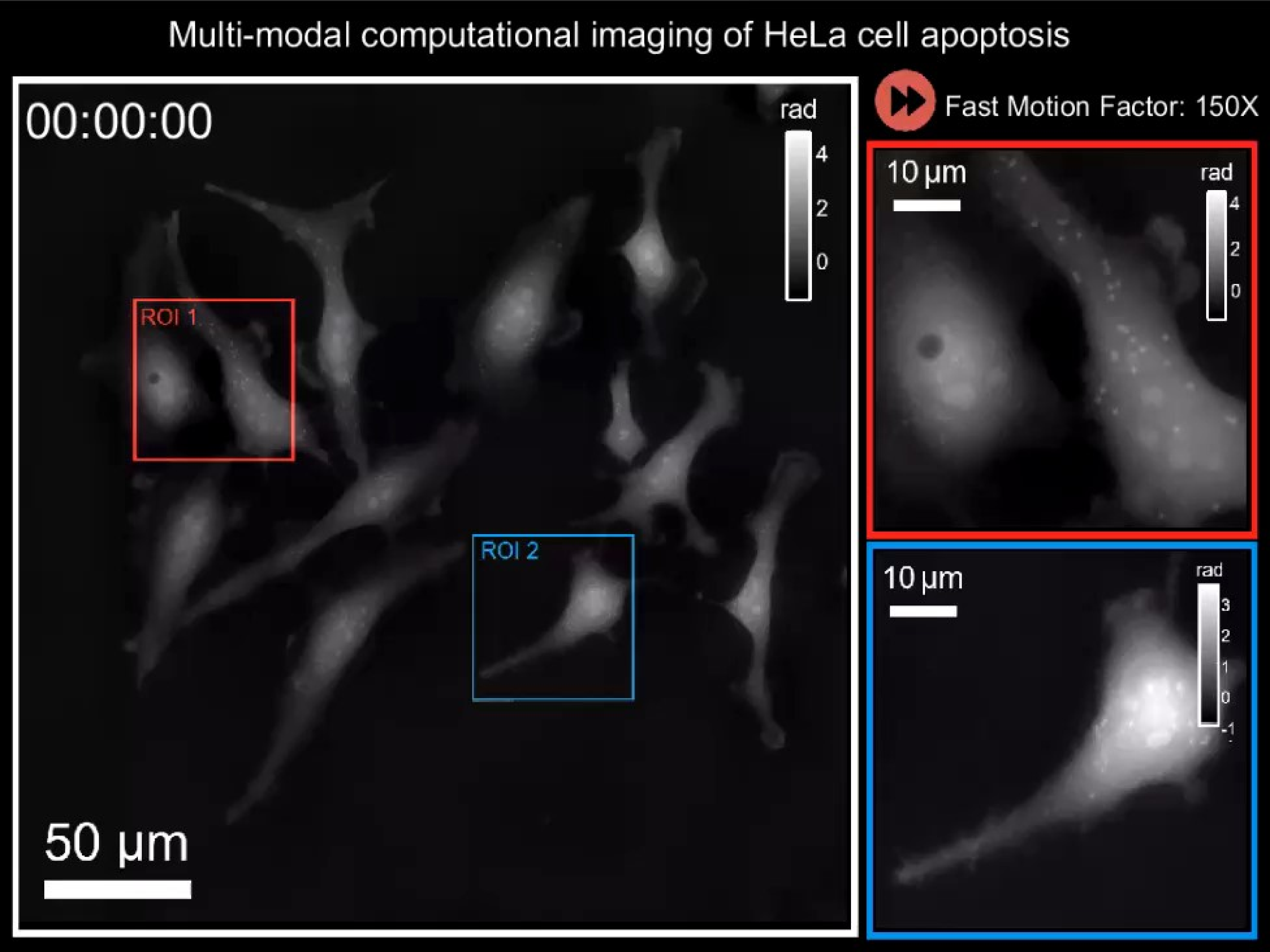
C. Zuo, J. Sun, J. Li *et.al.*, *Scientific Reports* **7**, 7654, (2017).

Annular-illumination TIE



NA_{eff} = 0.72 (0.4 NA_{ill} + 0.4 NA_{obj} 20X MO)

659 nm lateral resolution


Multi-modal computational imaging of HeLa cell apoptosis
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rad
4
2
0
ROI 1
ROI 2
50 µm
Fast Motion Factor: 150X
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2
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10 µm
rad
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2
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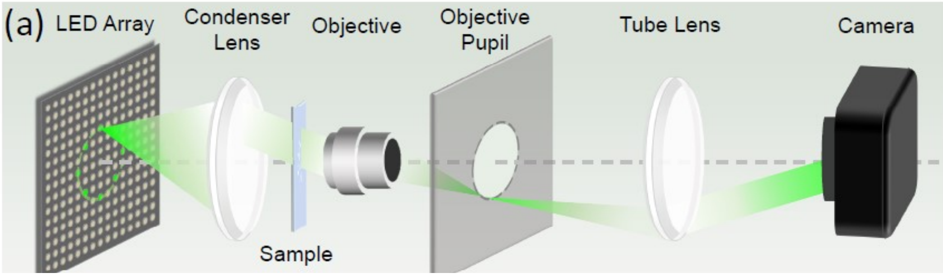
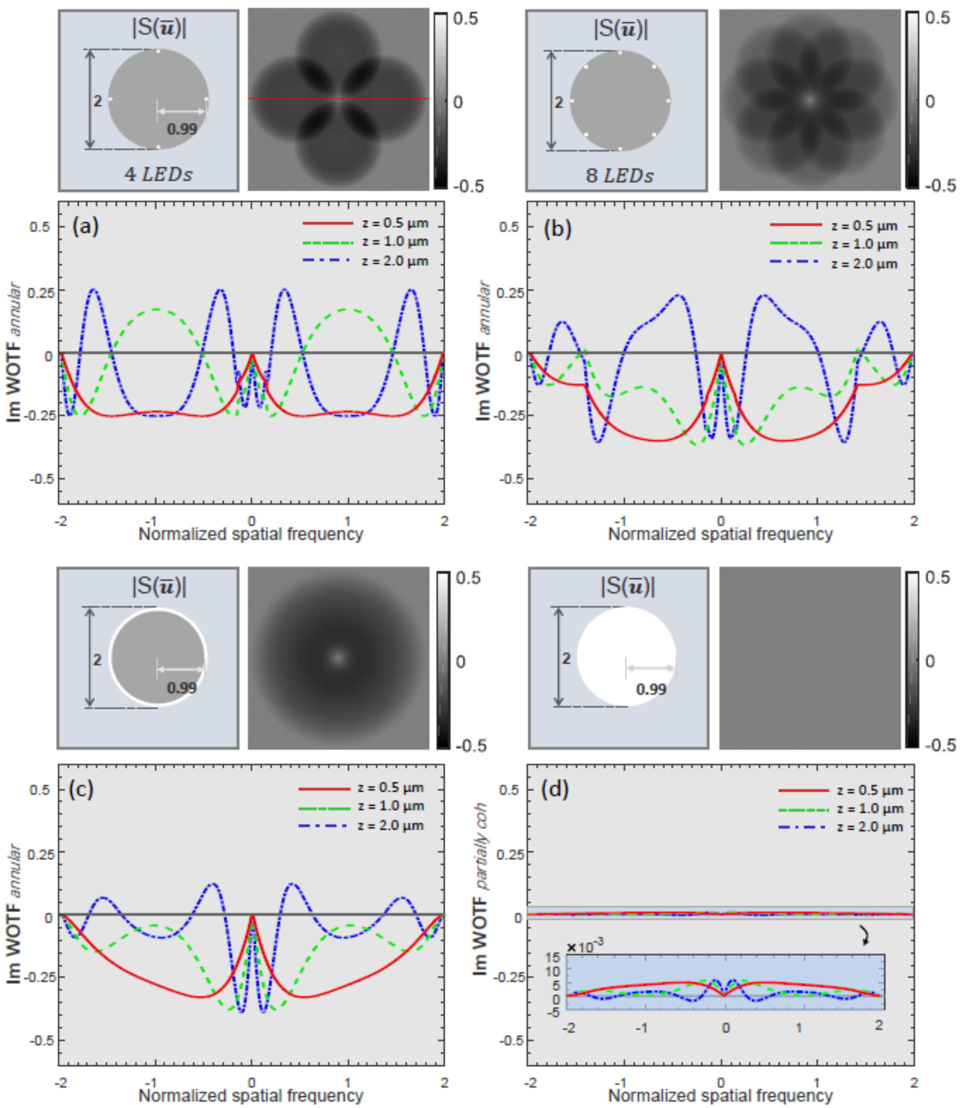
-1

Multi-modal Imaging



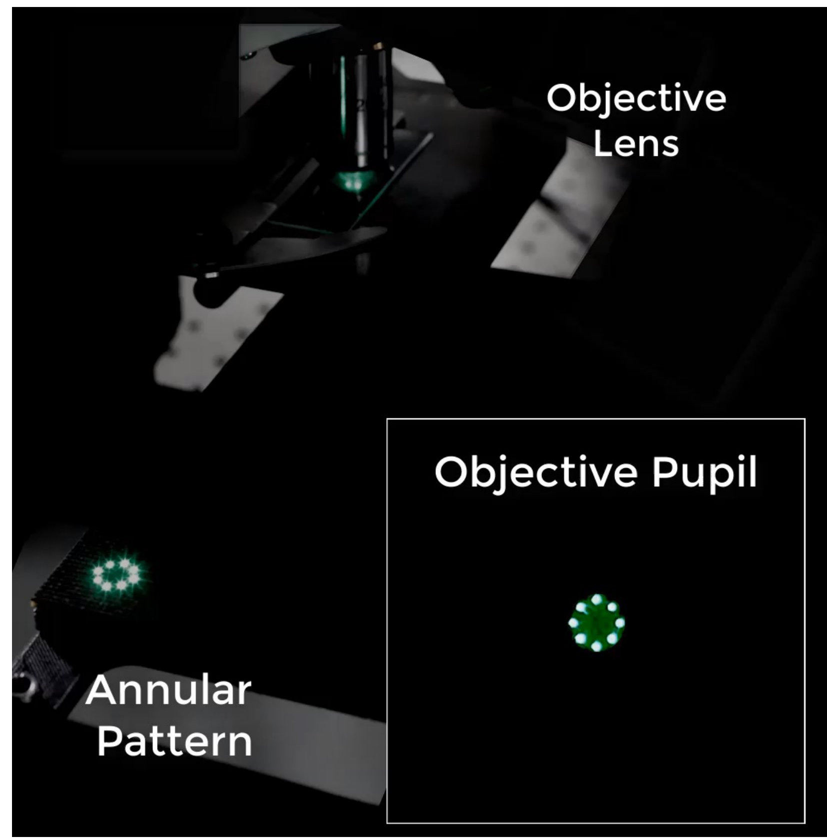


Research Article
Vol. 8, No. 10 | 1 Oct 2017 | BIOMEDICAL OPTICS EXPRESS 4687
Biomedical Optics EXPRESS

Efficient quantitative phase microscopy using programmable annular LED illumination

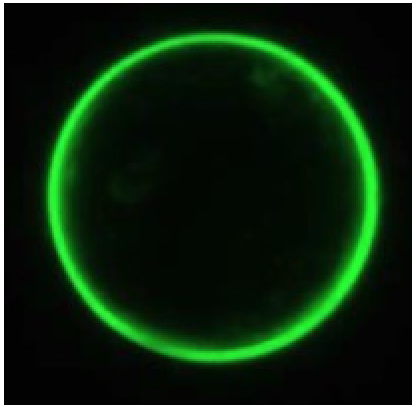
JIAJI LI,[1,2,3,4] QIAN CHEN,[1,2] JIALIN ZHANG,[1,2,3] YAN ZHANG,[1,2,3] LINPENG LU,[1,2,3] AND CHAO ZUO[1,2,3,*]

[1] *School of Electronic and Optical Engineering, Nanjing University of Science and Technology, No. 200 Xiaolingwei Street, Nanjing, Jiangsu Province 210094, China*
[2] *Jiangsu Key Laboratory of Spectral Imaging & Intelligent Sense, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China*
[3] *Smart Computational Imaging (SCI) Laboratory, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China*
[4] *jiajili@njust.edu.cn*
[*] *zuochao@njust.edu.cn*

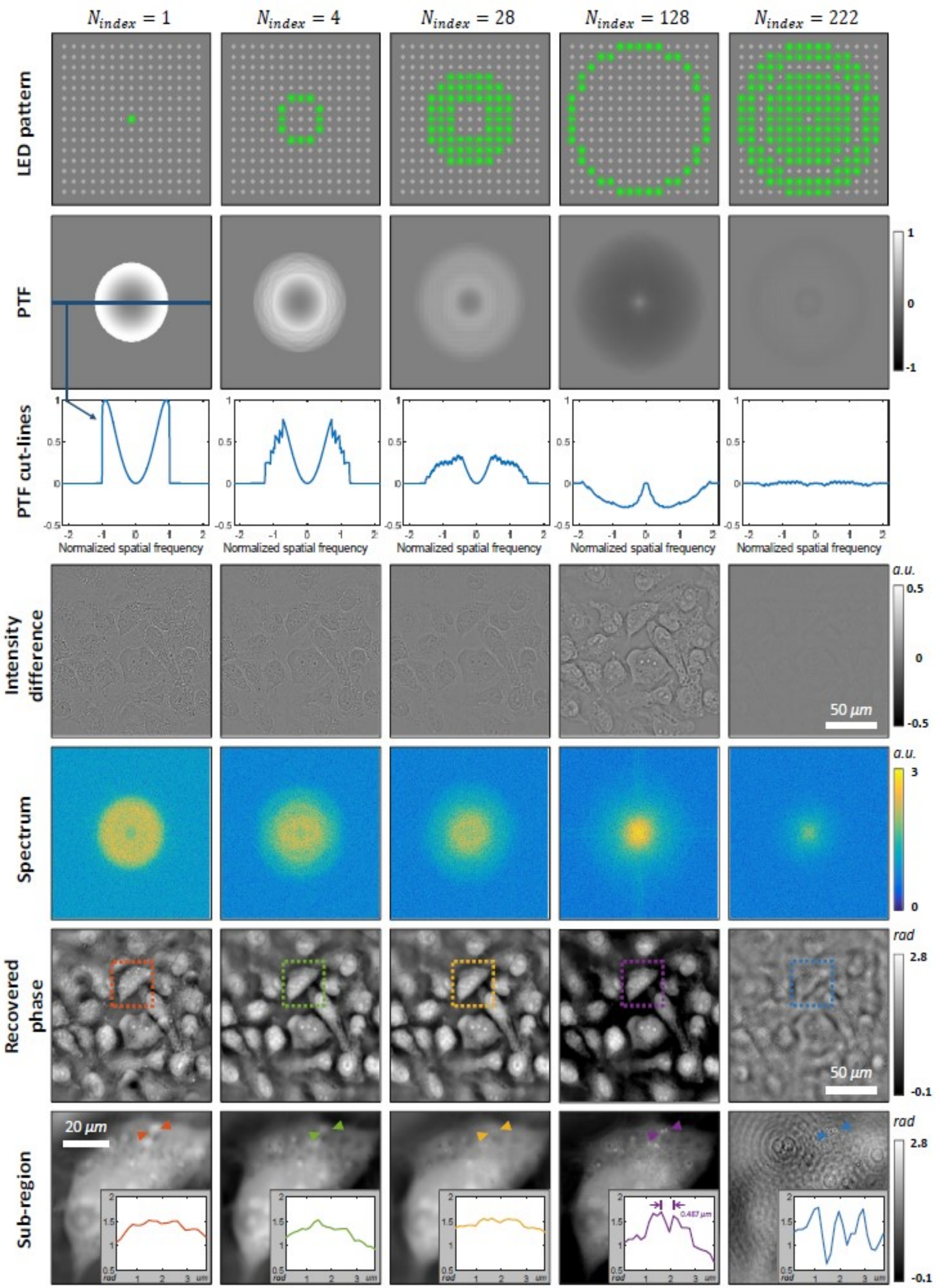


J Li, C. Zuo et. al. Biomedical Optics Express 8 (10), 4687-4705

Best?



Yes!

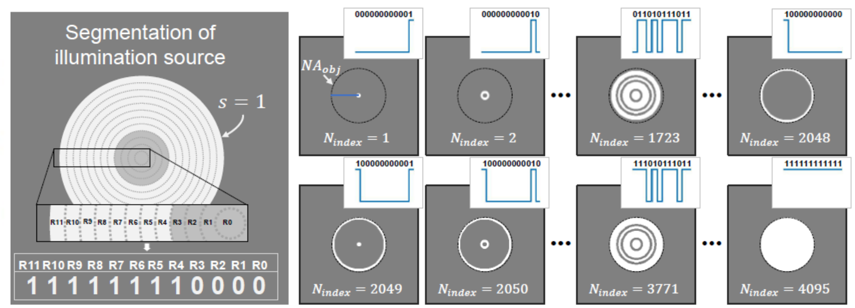


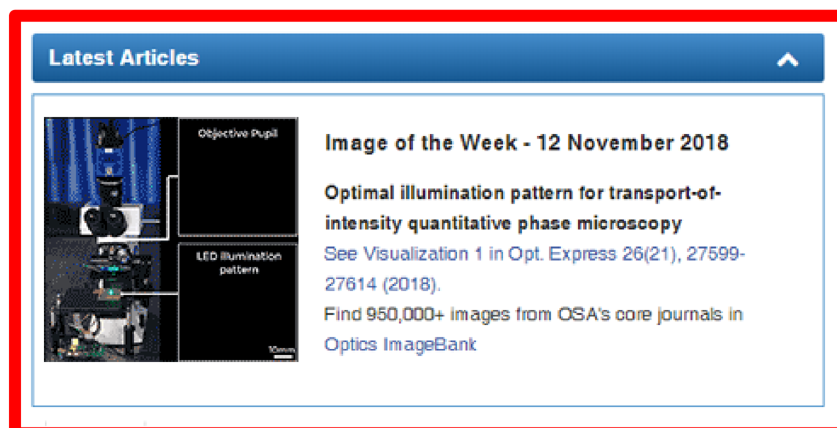
Research Article | Vol. 26, No. 21 | 15 Oct 2018 | OPTICS EXPRESS 27599
Optics EXPRESS

Optimal illumination pattern for transport-of-intensity quantitative phase microscopy

JIAJI LI,[1,2,3] QIAN CHEN,[1,2,4] JIASONG SUN,[1,2,3] JIALIN ZHANG,[1,2,3] XIANGPENG PAN,[1,2,3] AND CHAO ZUO[1,2,3,*]

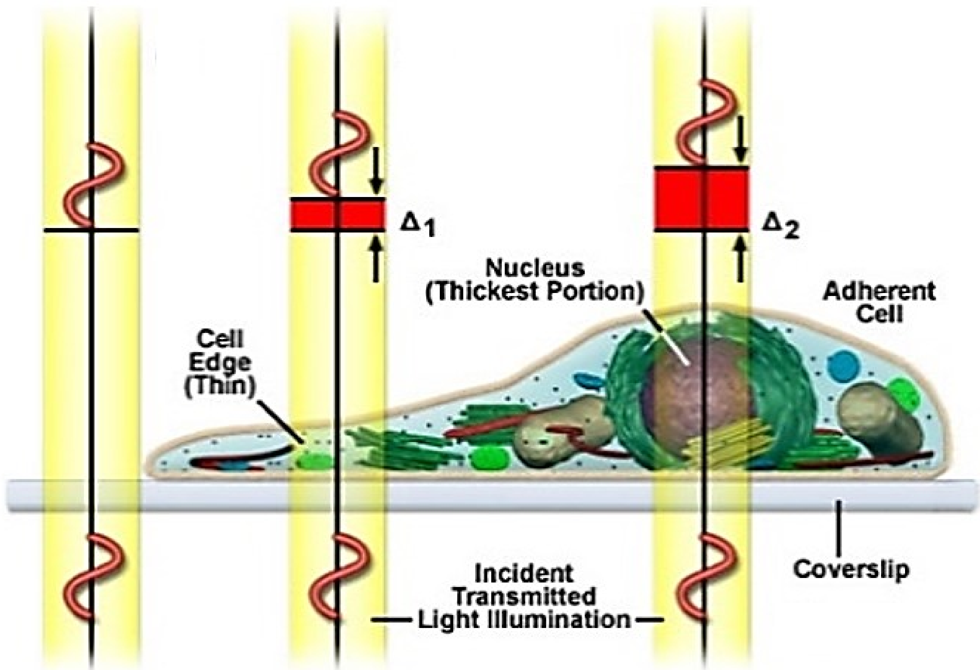
[1] School of Electronic and Optical Engineering, Nanjing University of Science and Technology, No. 200 Xiaolingwei Street, Nanjing, Jiangsu Province 210094, China
[2] Jiangsu Key Laboratory of Spectral Imaging & Intelligent Sense, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China
[3] Smart Computational Imaging Laboratory (SCILab), Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China
[4] chenqian@njust.edu.cn
[*] surpasszuo@163.com; zuochao@njust.edu.cn



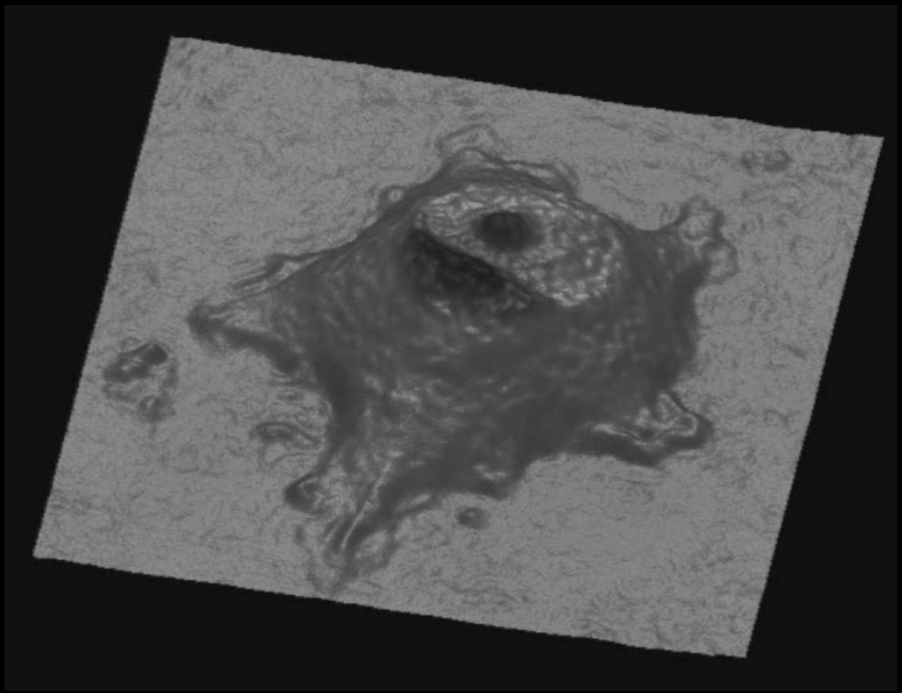


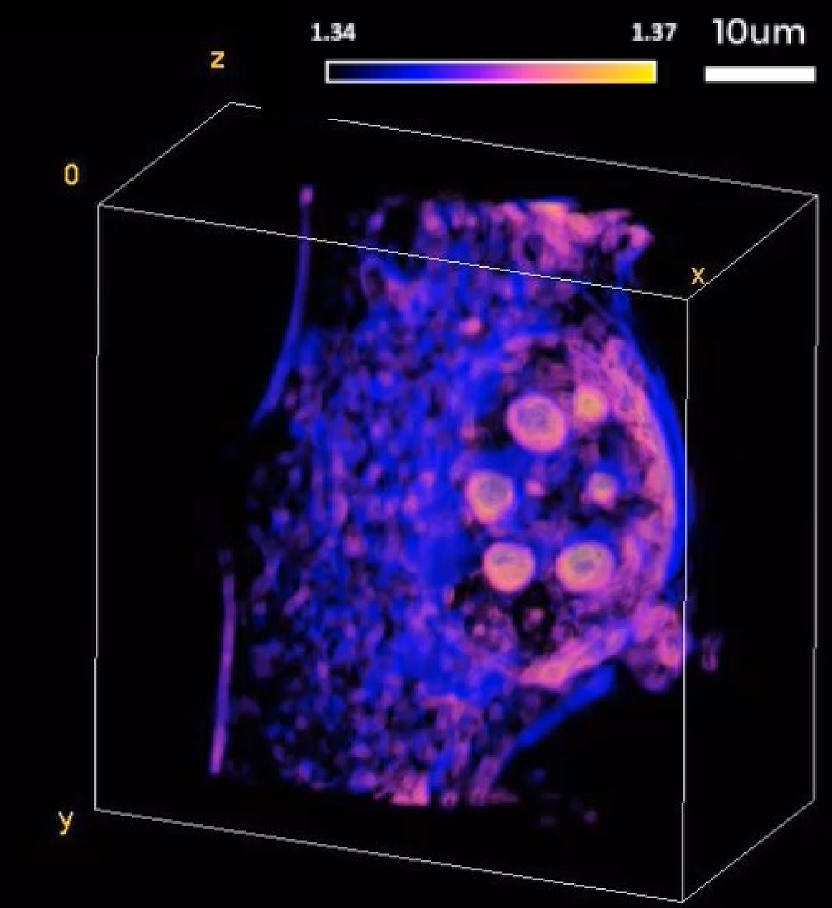
J Li, C. Zuo et. al. Biomedical Optics Express 8 (10), 4687-4705, (2017)

3D phase imaging ?



QPI vs ODT （optical diffraction tomography）





QPI: 2.5D optical path length

Profile

C. Zuo, et. al. , Opt Express, 21 24060-24075 (2013) .

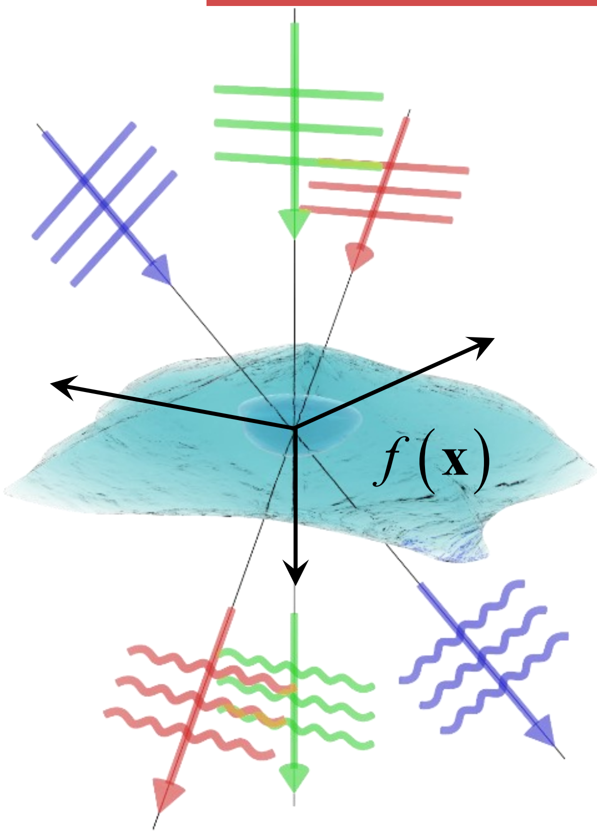
ODT: true 3D refractive index

Volume

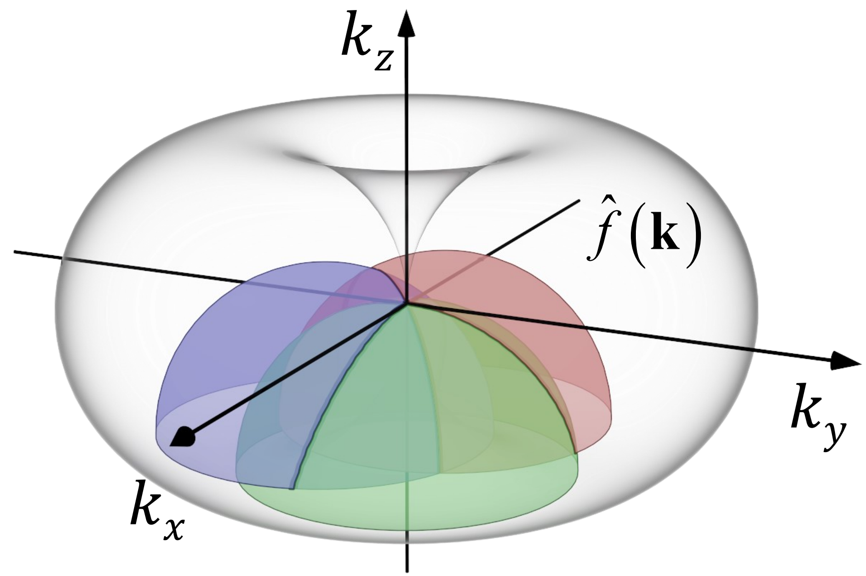
J Li, et. al. Biomed. Opt. Express 9, 2526-2542 (2018)

Transport-of-intensity diffraction tomography (TIDT)

Fourier diffraction theorem



3D real space



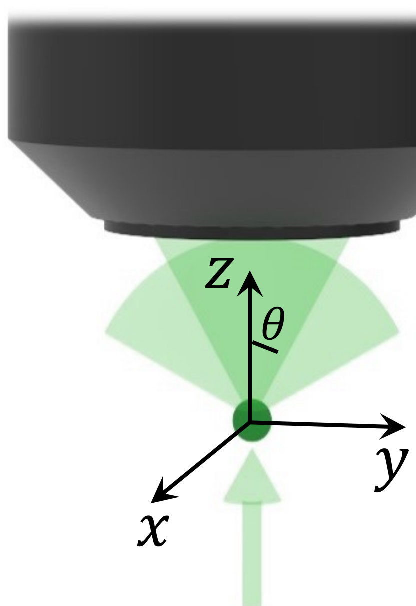
3D Fourier space

Free-space: semi-sphere in 3D Fourier space

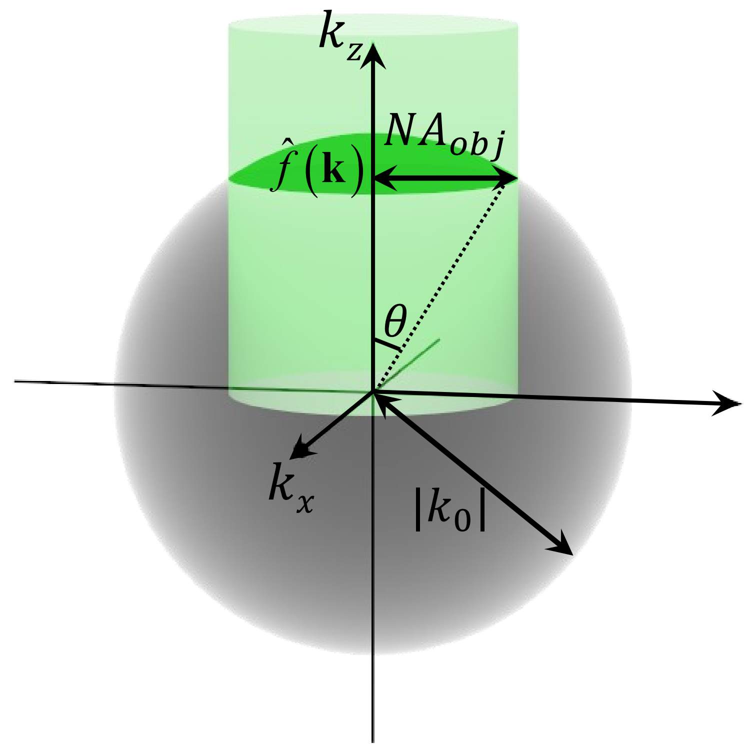
E Wolf. Opt. Commun. 1, 153–156 (1969).

Transport-of-intensity diffraction tomography (TIDT)

Fourier diffraction theorem for a limit-aperture system



3D real space

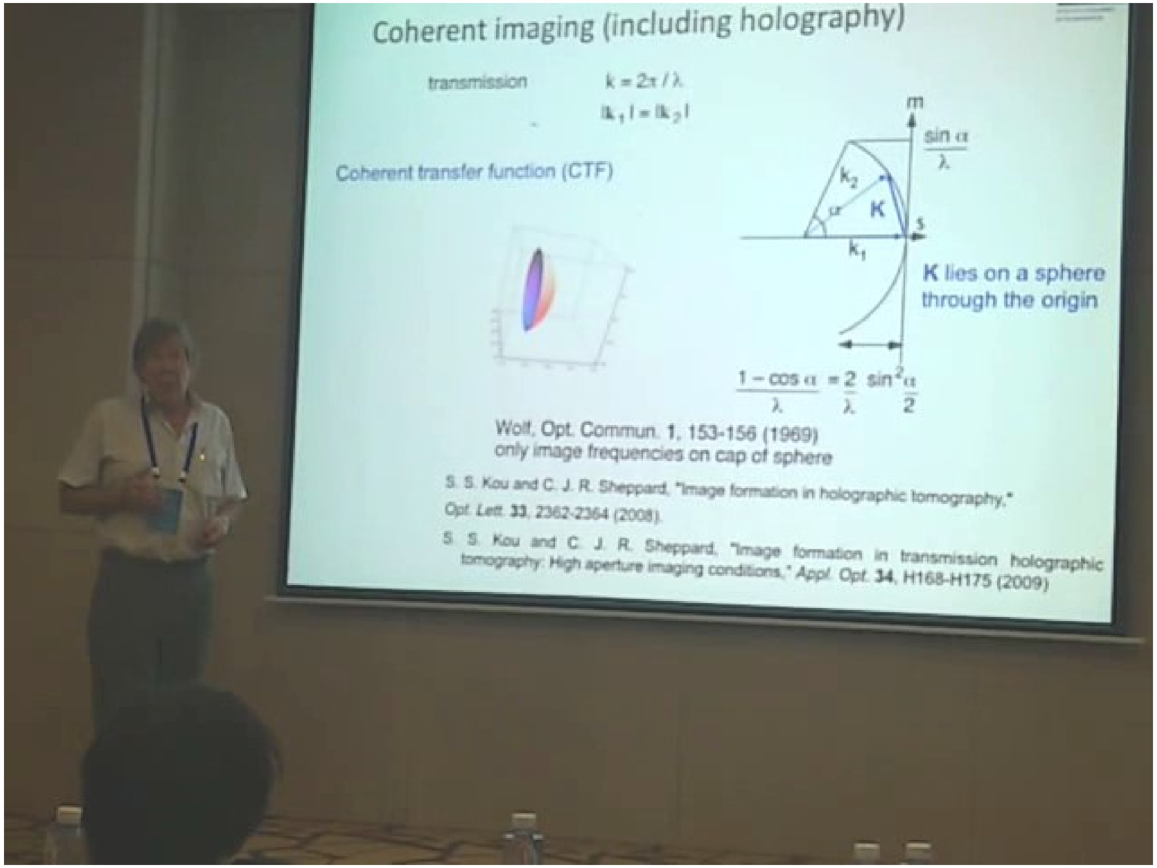


3D Fourier space

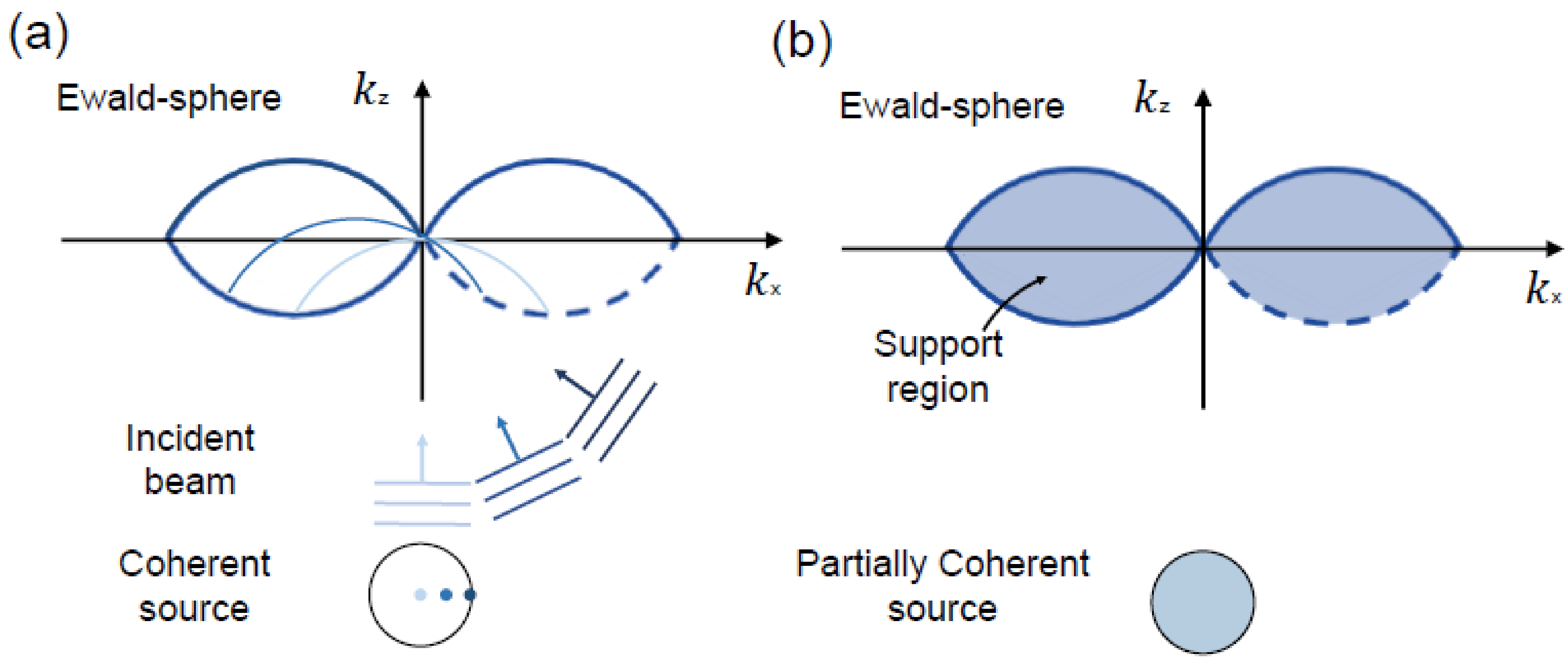
Microscopic imaging: partial spherical cap bounded by the lens aperture

E Wolf. Opt. Commun. 1, 153–156 (1969).

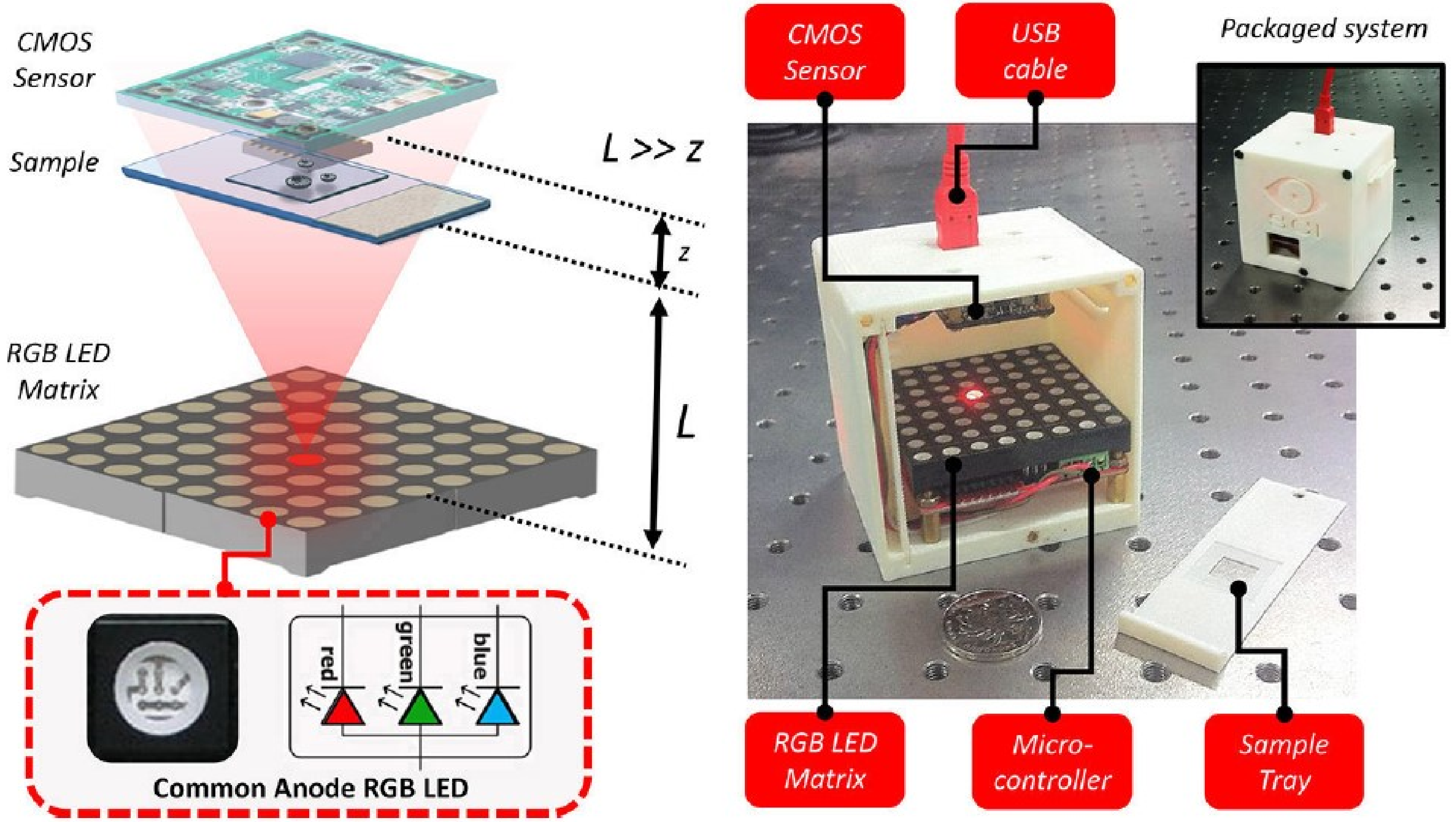
3D phase imaging ?



Coherent / partially coherent ODT

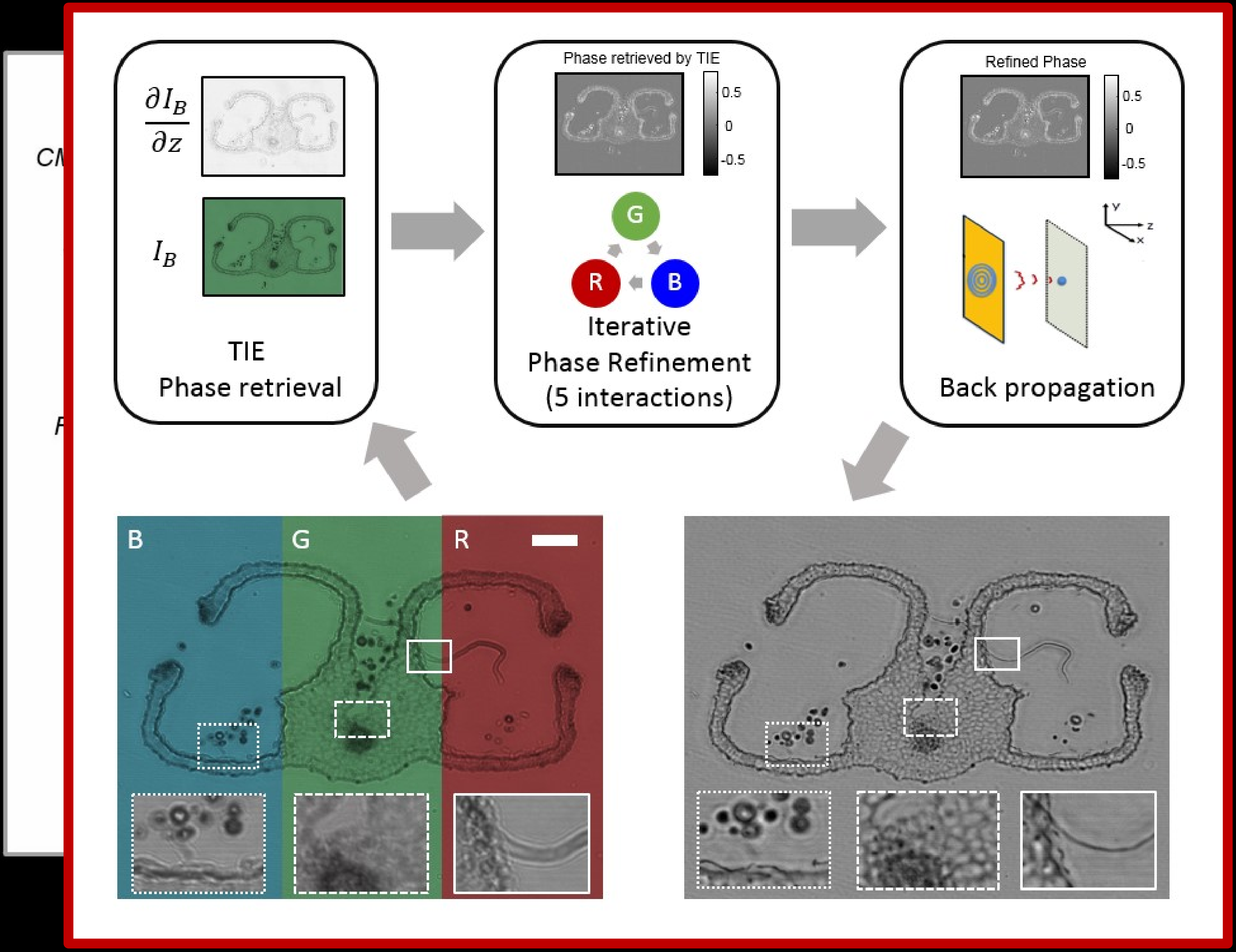


Lensless TIE microscopy



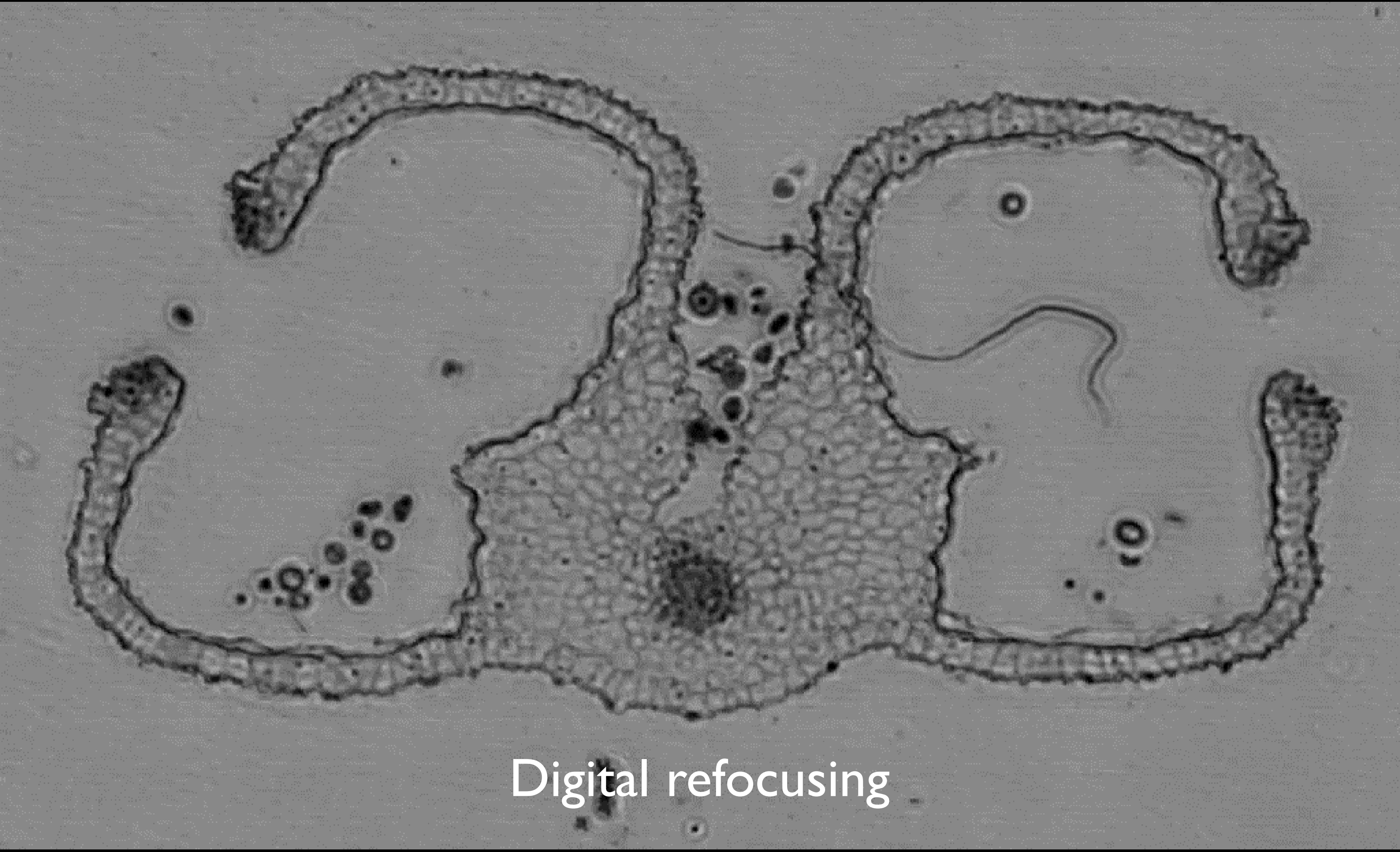
Lensless TIE microscope

Lensless TIE microscopy



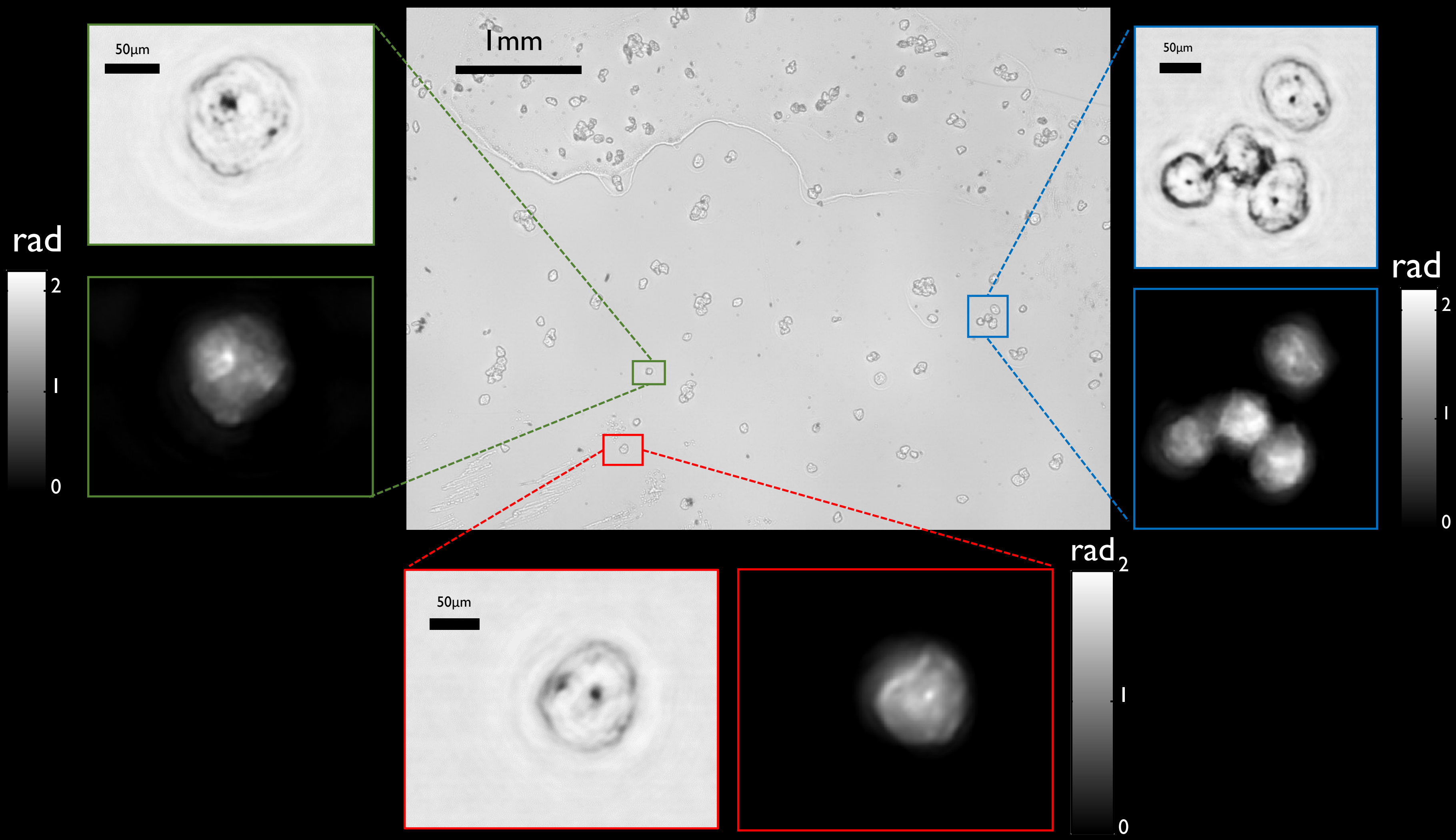
C. Zuo, J. Sun, J. Zhang, Y. Hu, and Q. Chen, Optics Express 23, 14314-14328 (2015).

Lensless TIE microscopy



C. Zuo, J. Sun, J. Zhang, Y. Hu, and Q. Chen, Optics Express 23, 14314-14328 (2015).

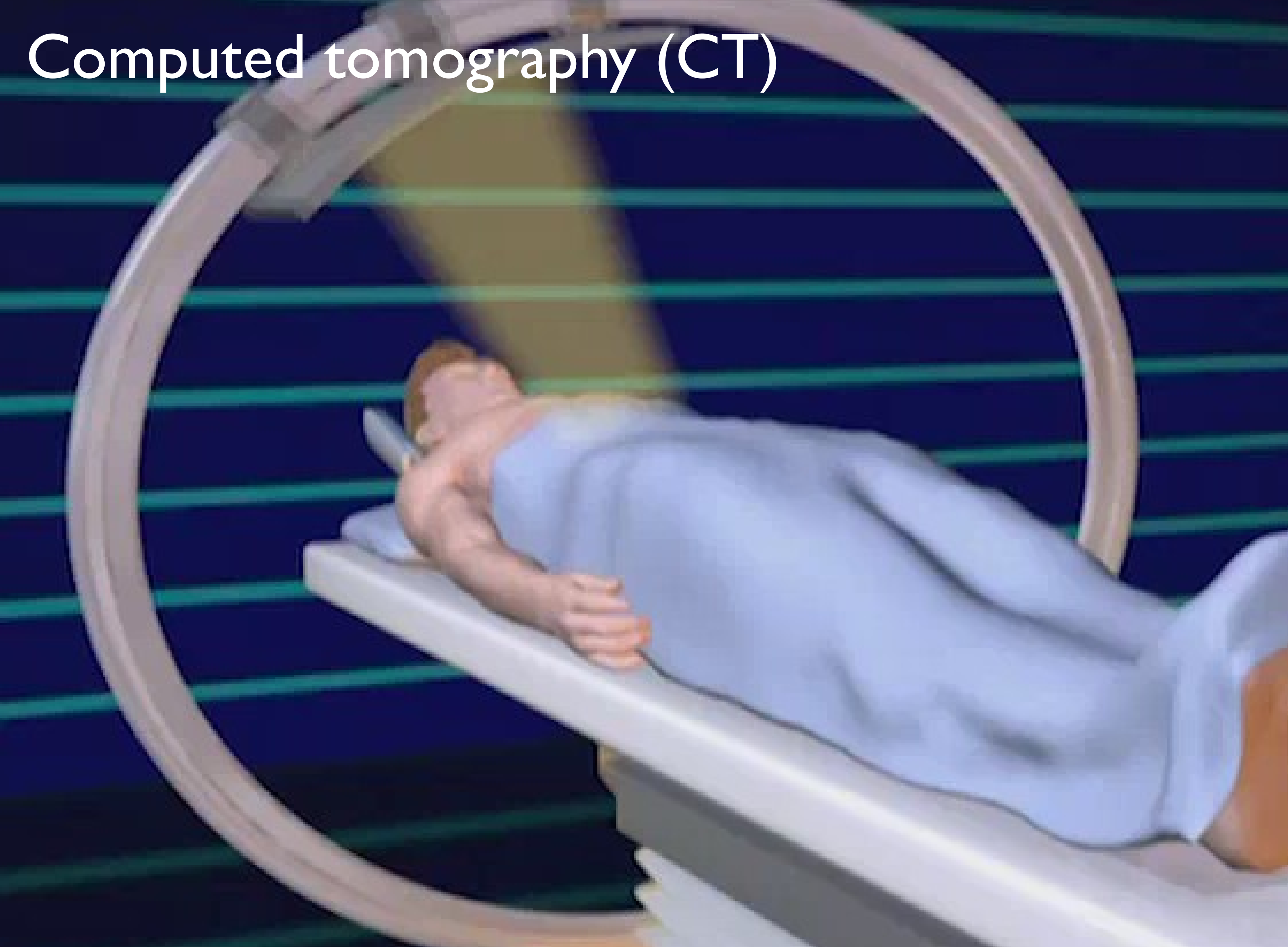
Lensless TIE microscopy



Quantitative phase of cheek cells (entire FOV 24mm^2)

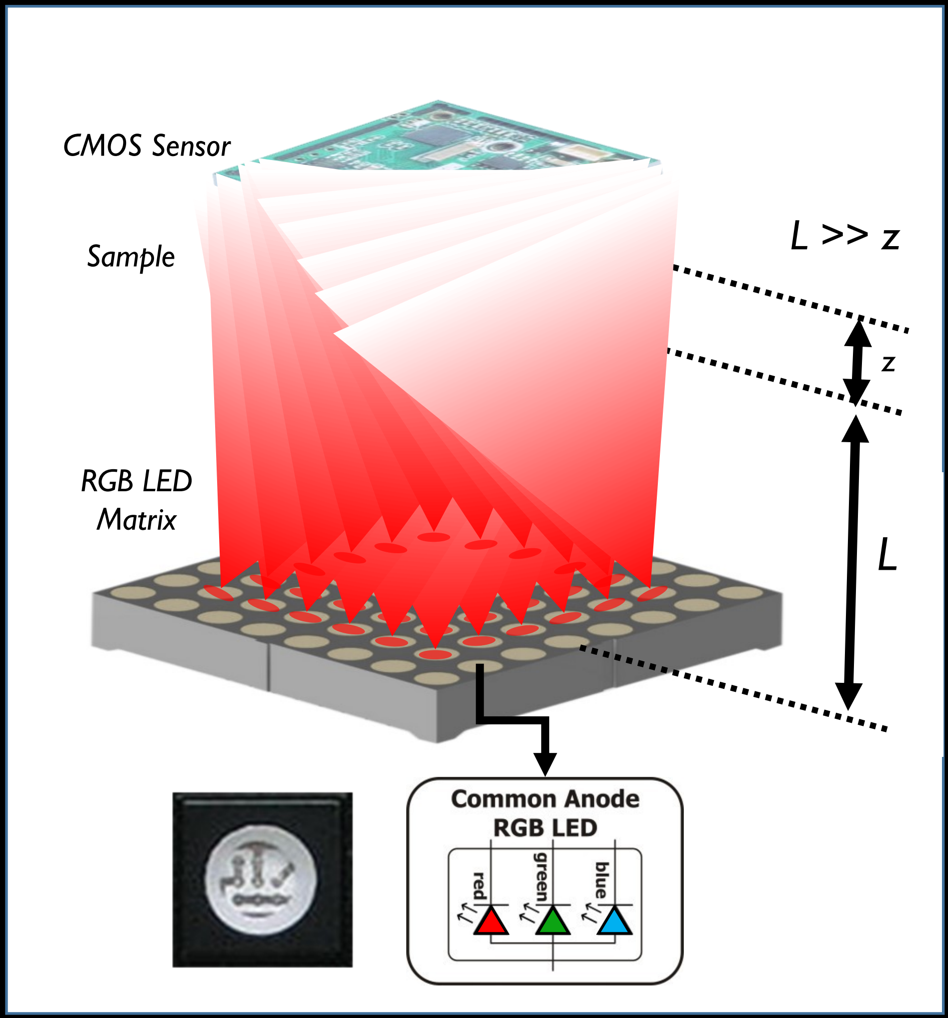
C. Zuo, J. Sun, J. Zhang, Y. Hu, and Q. Chen, Optics Express 23, 14314-14328 (2015).

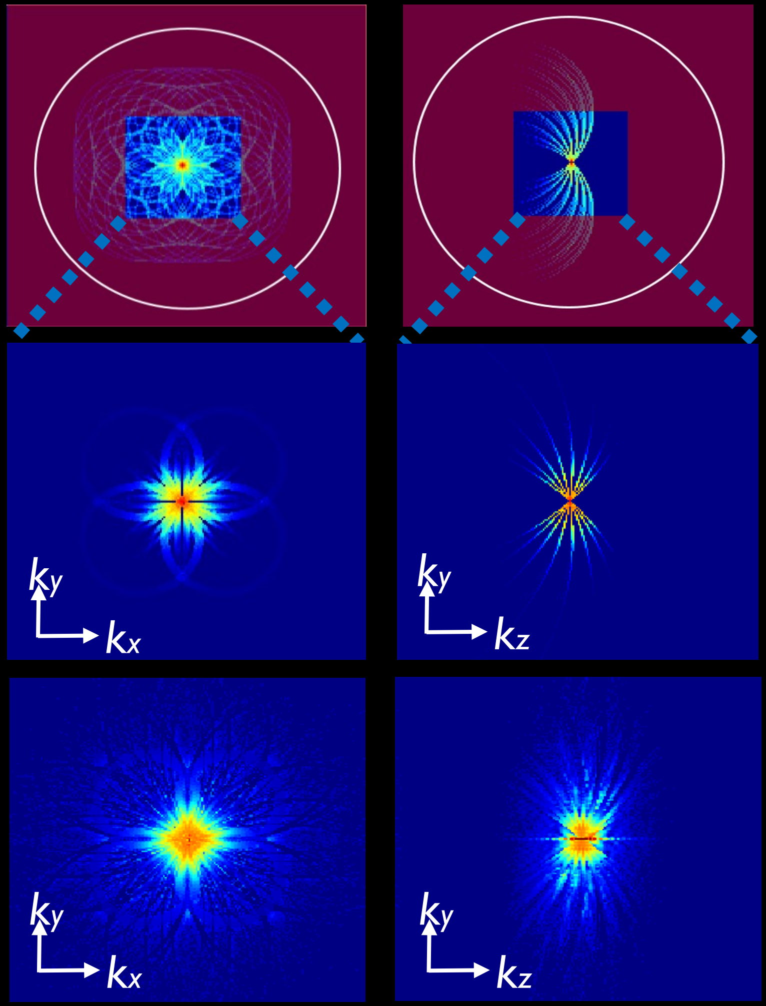
Computed tomography (CT)



http://www.merckmanuals.com/home/special-subjects/common-imaging-tests/computed-tomography-ct

Lensless TIE tomography





Change Illumination angle (≈±45°)

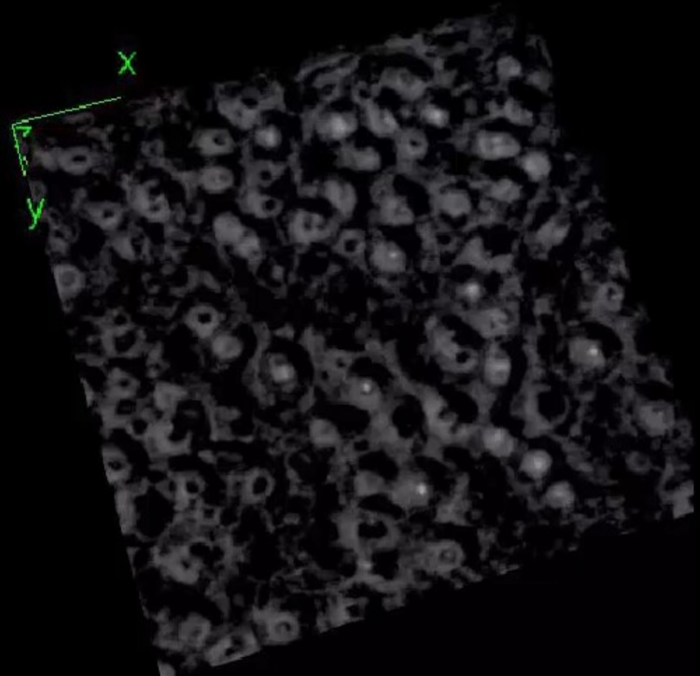
Fill the 3D Fourier Space of the object

C. Zuo, J. Sun, J. Zhang, Y. Hu, and Q. Chen, Optics Express 23, 14314-14328 (2015).

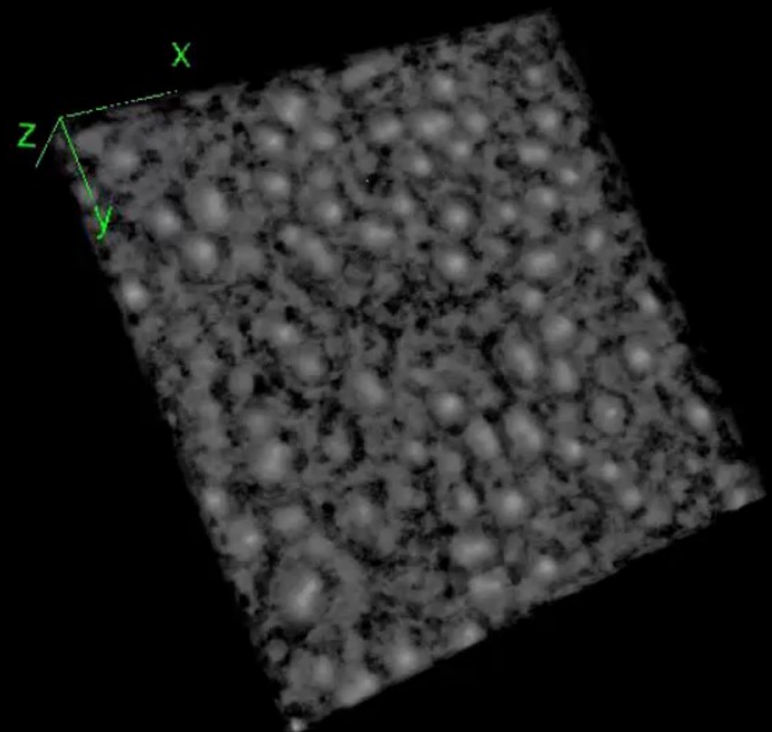
Lensless TIE tomography

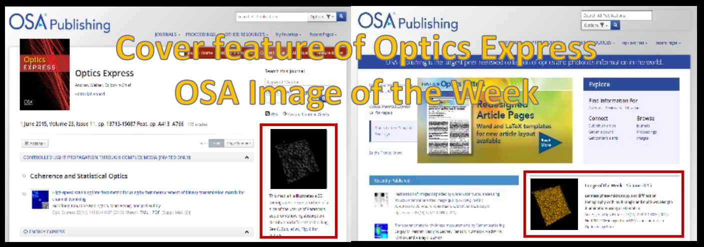
The uterus of Parascaris equorum

Phase tomography

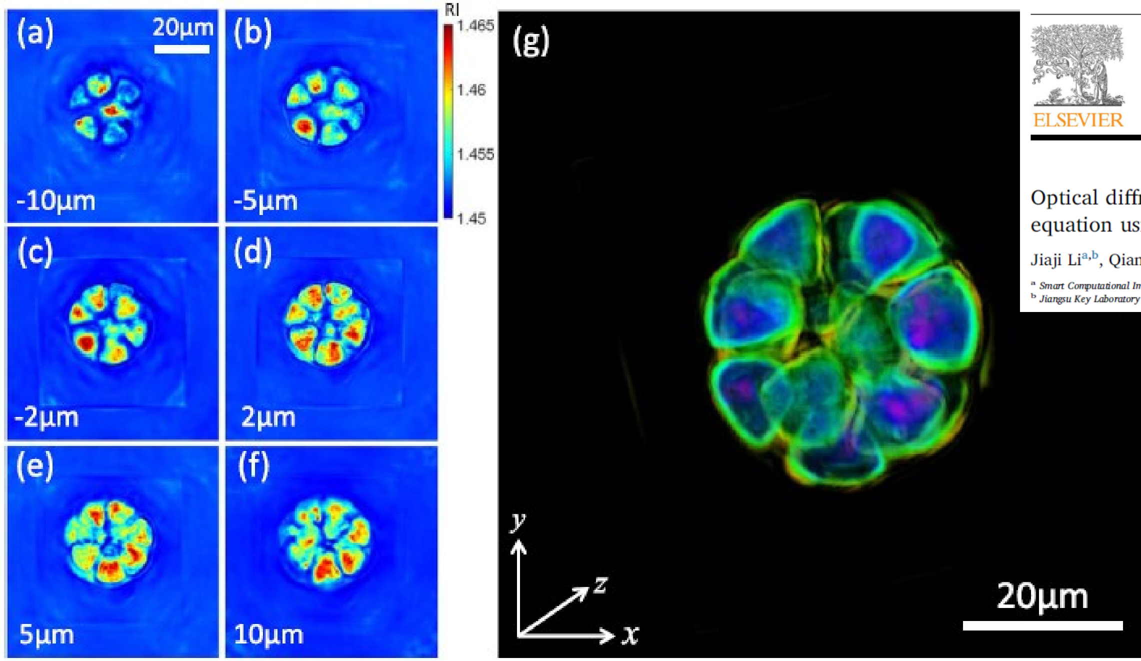


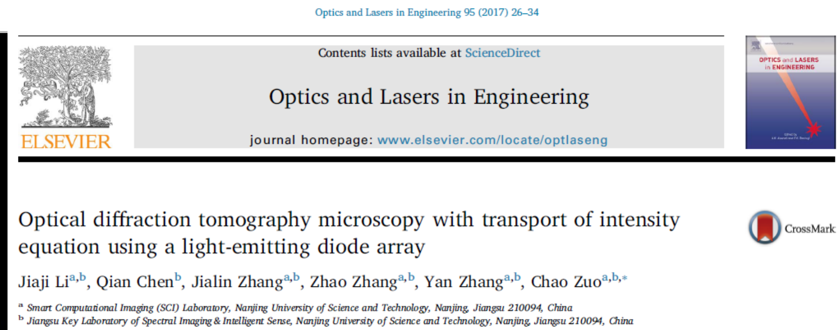
Absorption tomography





C. Zuo, J. Sun, J. Zhang, Y. Hu, and Q. Chen, Optics Express 23, 14314-14328 (2015).





Optics and Lasers in Engineering 95 (2017) 26–34

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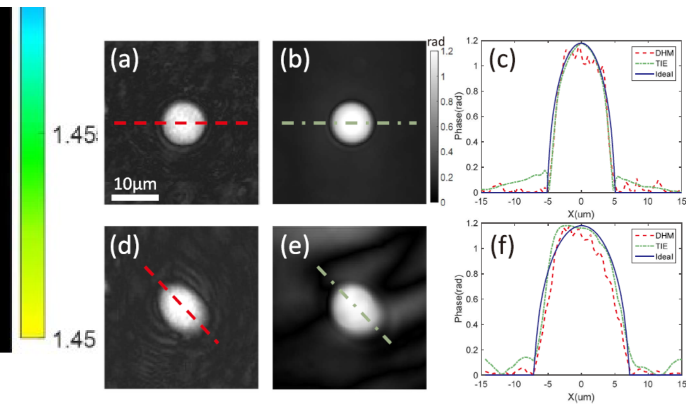
journal homepage: www.elsevier.com/locate/optlaseng

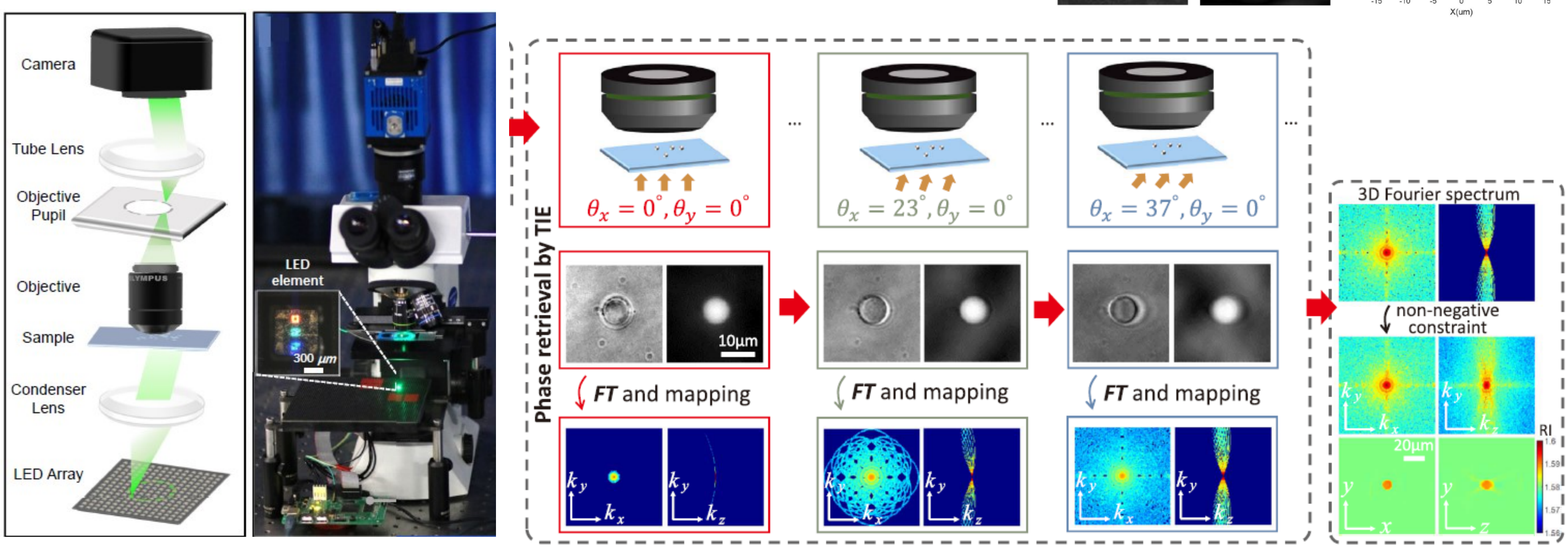
Optical diffraction tomography microscopy with transport of intensity equation using a light-emitting diode array

Jiaji Li[a,b], Qian Chen[b], Jialin Zhang[a,b], Zhao Zhang[a,b], Yan Zhang[a,b], Chao Zuo[a,b,*]

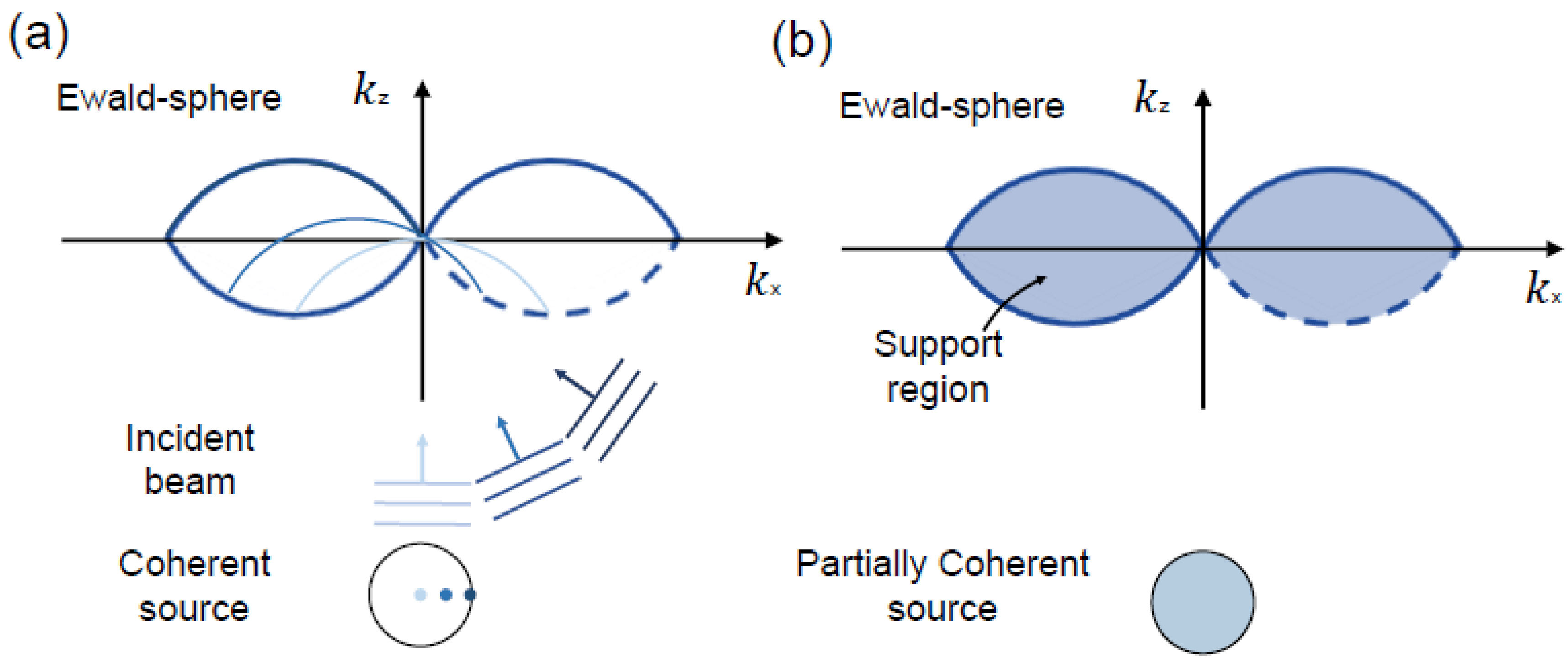
[a] Smart Computational Imaging (SCI) Laboratory, Nanjing University of Science and Technology, Nanjing, Jiangsu 210094, China

[b] Jiangsu Key Laboratory of Spectral Imaging & Intelligent Sense, Nanjing University of Science and Technology, Nanjing, Jiangsu 210094, China

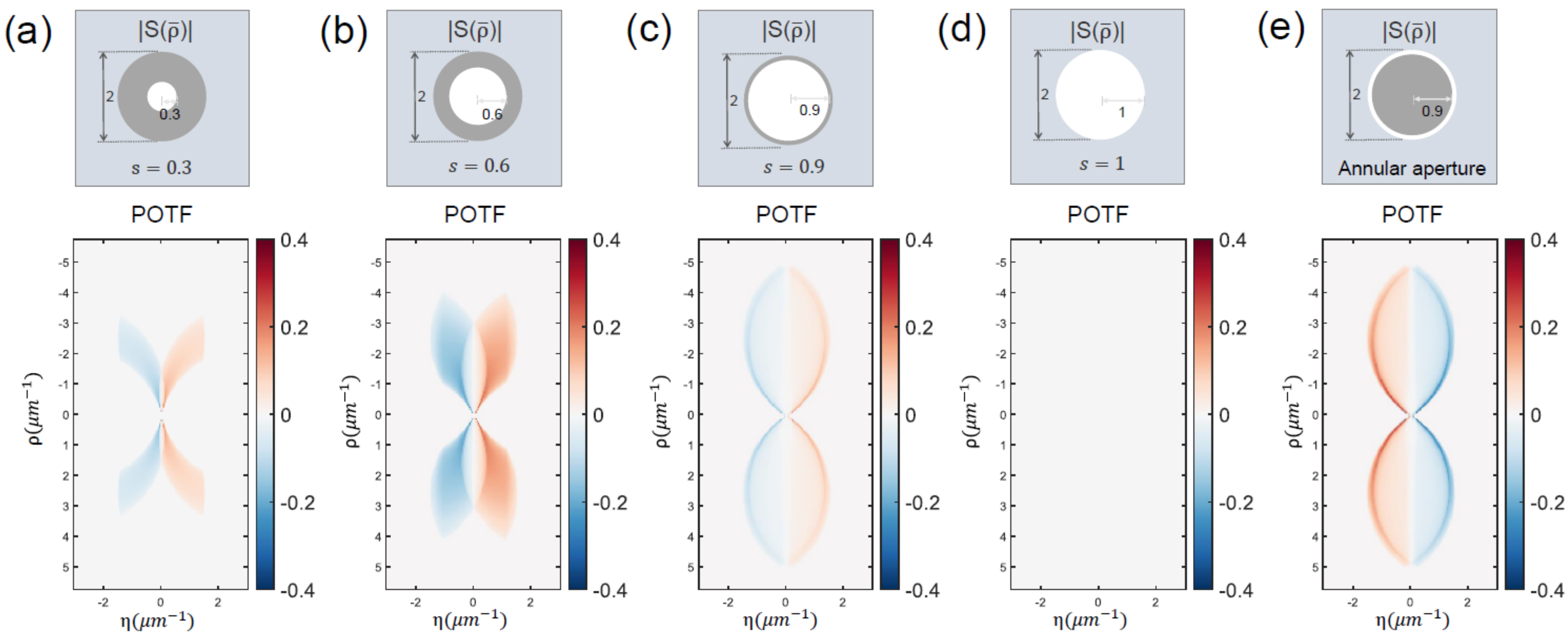




Partially coherent ODT



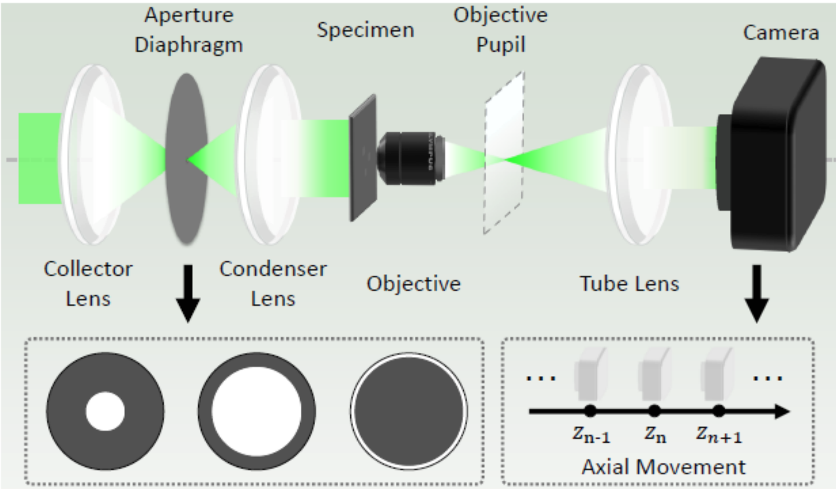
Partially coherent 3D imaging



Partially coherent 3D imaging

$$\begin{aligned} WOTF(\mathbf{u}) &\equiv TCC(\mathbf{u},\mathbf{0}) \\ &= \iint S(\mathbf{u}')\, H(\mathbf{u}'+\mathbf{u})\, H^{*}(\mathbf{u}')\, d\mathbf{u}' \end{aligned}$$

$$\begin{aligned} H(\rho, l) &= \int P(\rho)\, e^{jkz\sqrt{1-\lambda^2\rho^2}}\, e^{-j2\pi z l}\, dz \\ &= P(\rho)\, \delta\left(l - \sqrt{\left(\frac{1}{\lambda}\right)^2 - \rho^2}\right) \end{aligned}$$



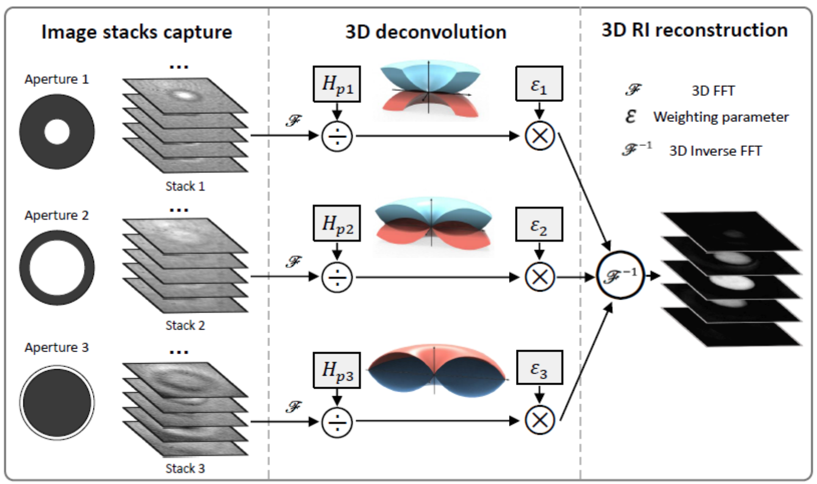
Research Article Vol. 9, No. 6 | 1 Jun 2018 | BIOMEDICAL OPTICS EXPRESS 2526

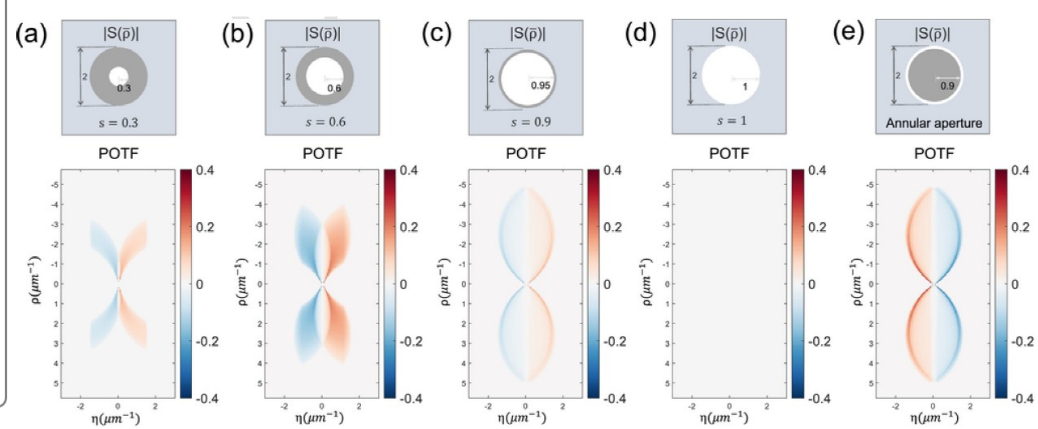
Biomedical Optics EXPRESS

Three-dimensional tomographic microscopy technique with multi-frequency combination with partially coherent illuminations

JIAJI LI,[1,2,3] QIAN CHEN,[1,2,4] JIASONG SUN,[1,2,3] JIALIN ZHANG,[1,2,3] JUNYI DING,[1,2,3] AND CHAO ZUO[1,2,3,*]

[1]School of Electronic and Optical Engineering, Nanjing University of Science and Technology, No. 200 Xiaolingwei Street, Nanjing, Jiangsu Province 210094, China
[2]Jiangsu Key Laboratory of Spectral Imaging & Intelligent Sense, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China
[3]Smart Computational Imaging Laboratory (SCILab), Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China
[4]chenqian@njust.edu.cn
*surpasszuo@163.com





3D intensity spectrum

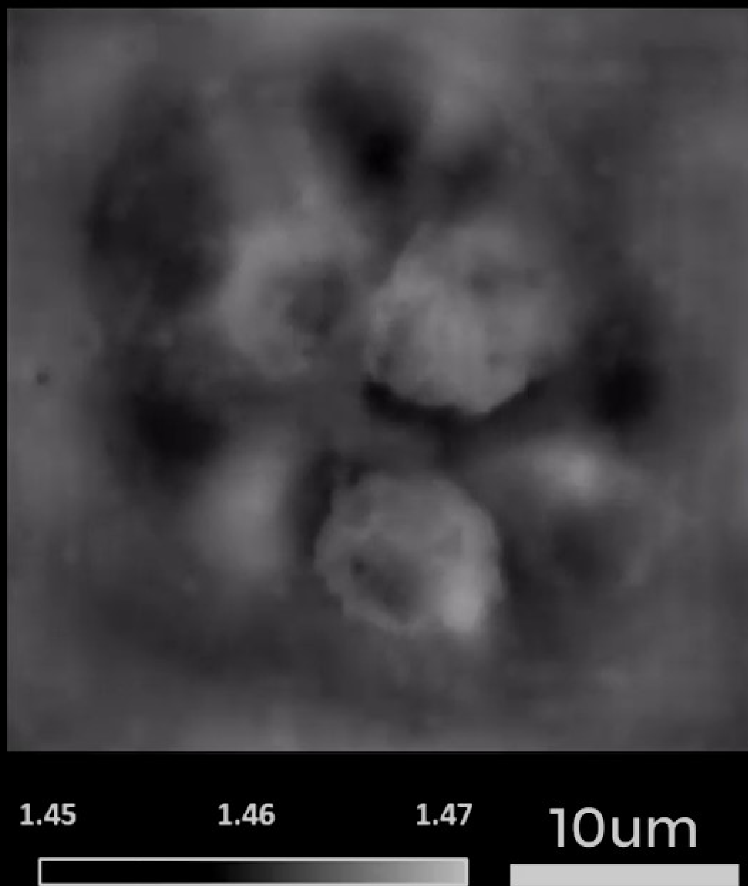
$$\tilde{I}(\zeta) = B\delta(\zeta) + \tilde{\Phi}(\zeta) T_P(\zeta) + \tilde{A}(\zeta) T_A(\zeta)$$

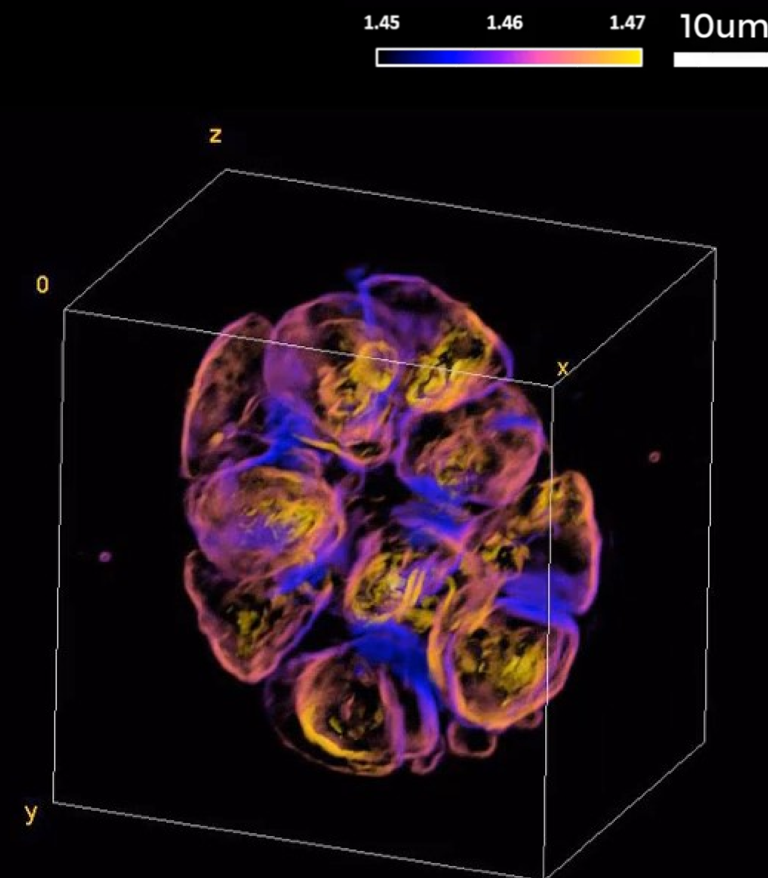
3D phase / amplitude transfer function

Transport-of-intensity diffraction tomography (TIDT)

J Li, et. al. *Biomed. Opt. Express 9, 2526-2542* (2018)

Annular-illumination ODT



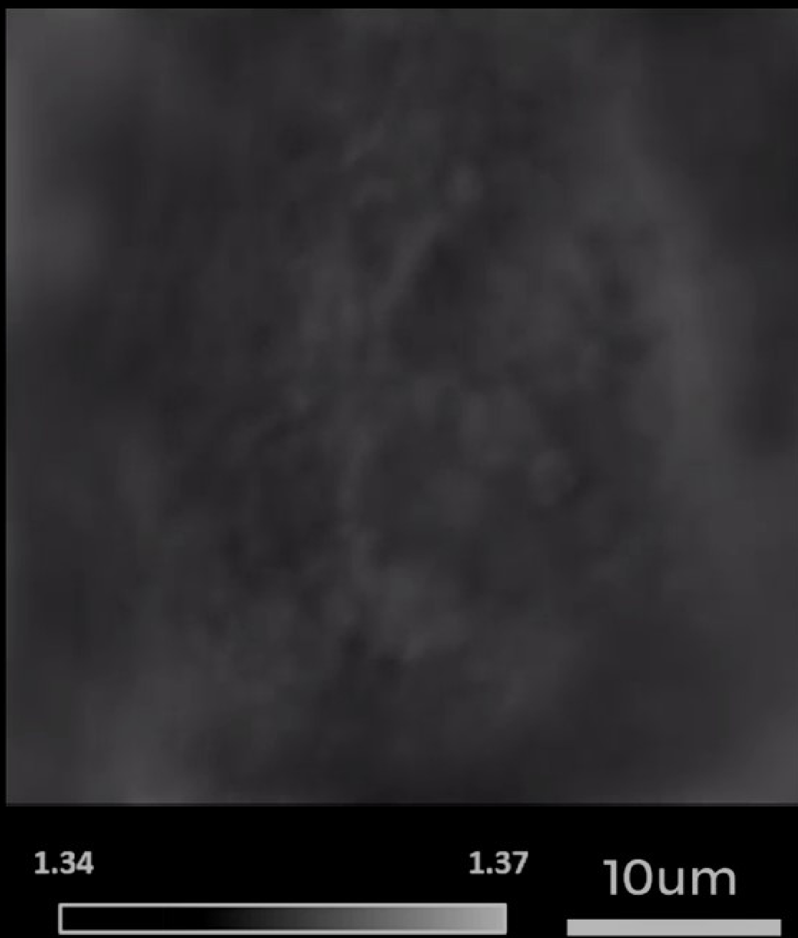


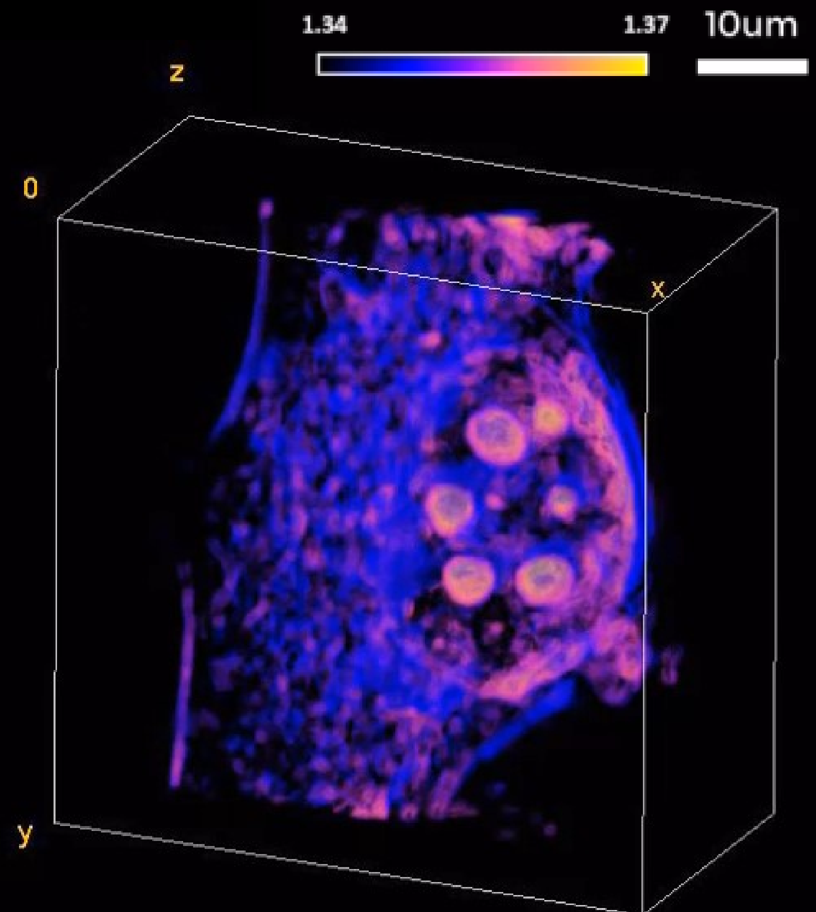
3D rendering of Pandorina

1.4 NAill + 1.4 NAobj 100X MO; Lateral resolution 200nm; axial resolution 650 nm.

J Li, et. al. Biomed. Opt. Express 9, 2526-2542 (2018)

Annular-illumination ODT



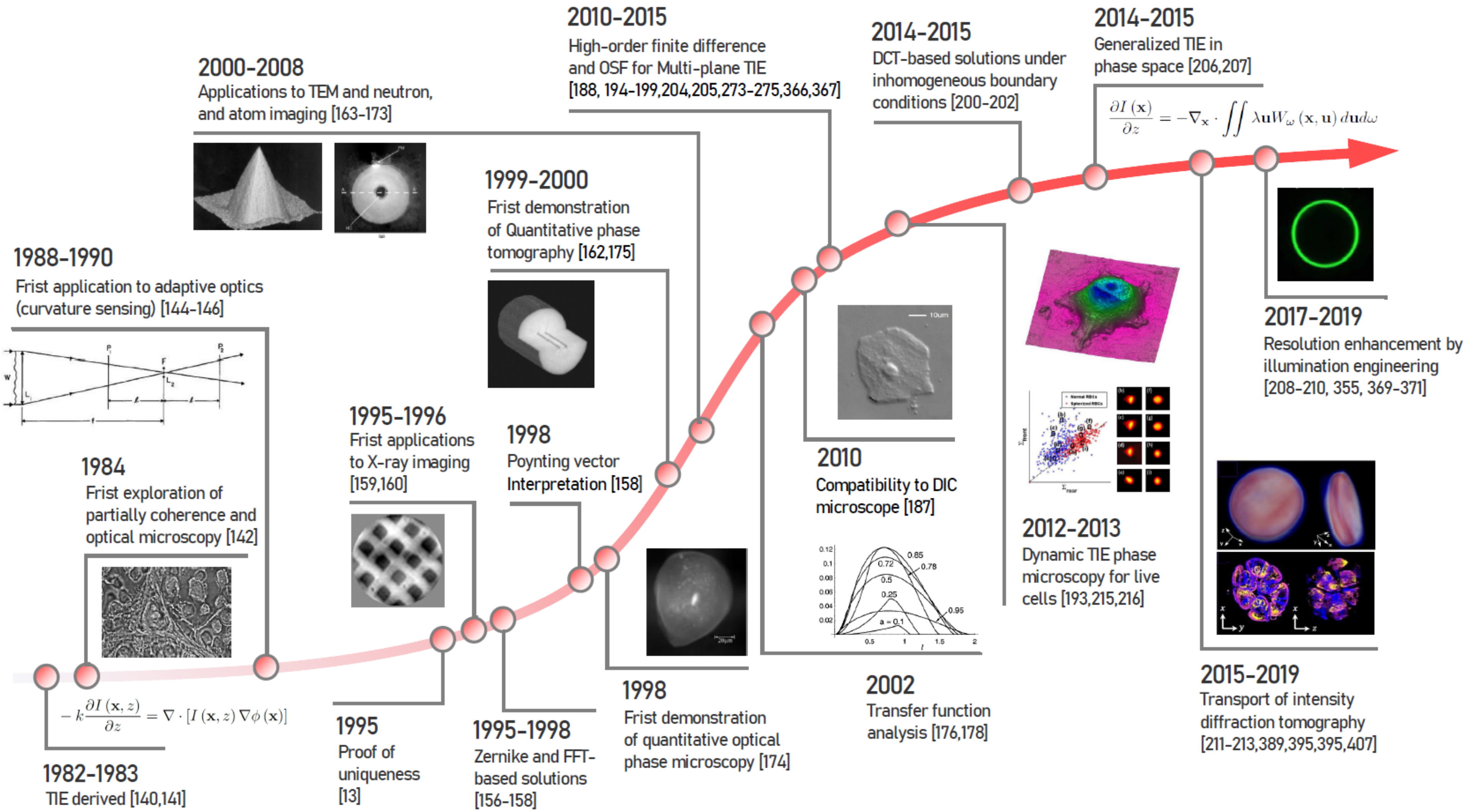


3D rendering of Hela cell

1.4 NAill + 1.4 NAobj 100X MO; Lateral resolution 200nm; axial resolution 650 nm.

J Li, et. al. Biomed. Opt. Express 9, 2526-2542 (2018)

Transport of intensity equation



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Outline

- Highlights
- Abstract
- Keywords
- 1. Introduction
- 2. Basic concept of TIE
- 3. Solutions to TIE
- 4. Image formation of coherent imaging ar
- 5. Axial intensity derivative estimation
- 6. Image formation under partially coheren
- 7. Generalized TIE under partially coherent
- 8. 3D phase imaging under partially cohere
- 9. Applications of TIE in optical imaging an
- 10. Conclusions and future directions
- CRediT authorship contribution statement
- Declaration of Competing Interest
- Acknowledgments
- Appendix A. Supplementary materials

Processing math: 26%

Transport of intensity equation: a tutorial

Chao Zuo [*, a, b], Jiaji Li [a, b], Jiasong Sun [a, b], Yao Fan [a, b], Jialin Zhang [a, b], Linpeng Lu [a, b], Runnan Zhang [a, b], Bowen Wang [a, b], Lei Huang [c], Qian Chen [b]

[a] Smart Computational Imaging (SCI) Laboratory, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China
[b] Jiangsu Key Laboratory of Spectral Imaging & Intelligent Sense, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China
[c] Brookhaven National Laboratory, NSLS II 50 Rutherford Drive, Upton, NY 11973-5000, United States

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ABSTRACT

When it comes to "phase measurement" or "quantitative phase imaging", many people will automatically connect them with "laser" and "interferometry". Indeed, conventional quantitative phase imaging and phase measurement techniques generally rely on the superposition of two beams with a high degree of coherence: complex interferometric configurations, stringent requirements on the environmental stabilities, and associated laser speckle noise severely limit their applications in optical imaging and microscopy. On a different note, as one of the most well-known phase retrieval approaches, the transport of intensity equation (TIE) provides a new non-interferometric way to access quantitative phase information through intensity only measurement. Despite the insufficiency for interferometry, TIE is applicable under partially coherent illuminations (like the Köhler's illumination in a conventional microscope), permitting optimum spatial resolution, higher signal-to-noise ratio, and better image quality. In this tutorial, we give an overview of the basic principle, research fields, and representative applications of TIE, focus particularly on optical imaging, metrology, and microscopy. The purpose of this tutorial is twofold. It should serve as a self-contained introduction to TIE for readers with little or no knowledge of TIE. On the other hand, it attempts to give an overview of recent developments in this field. These results highlight a new era in which strict coherence and interferometry are no longer prerequisites for quantitative phase imaging and diffraction tomography, paving the way toward new generation label-free three-dimensional microscopy, with applications in all branches of biomedicine.

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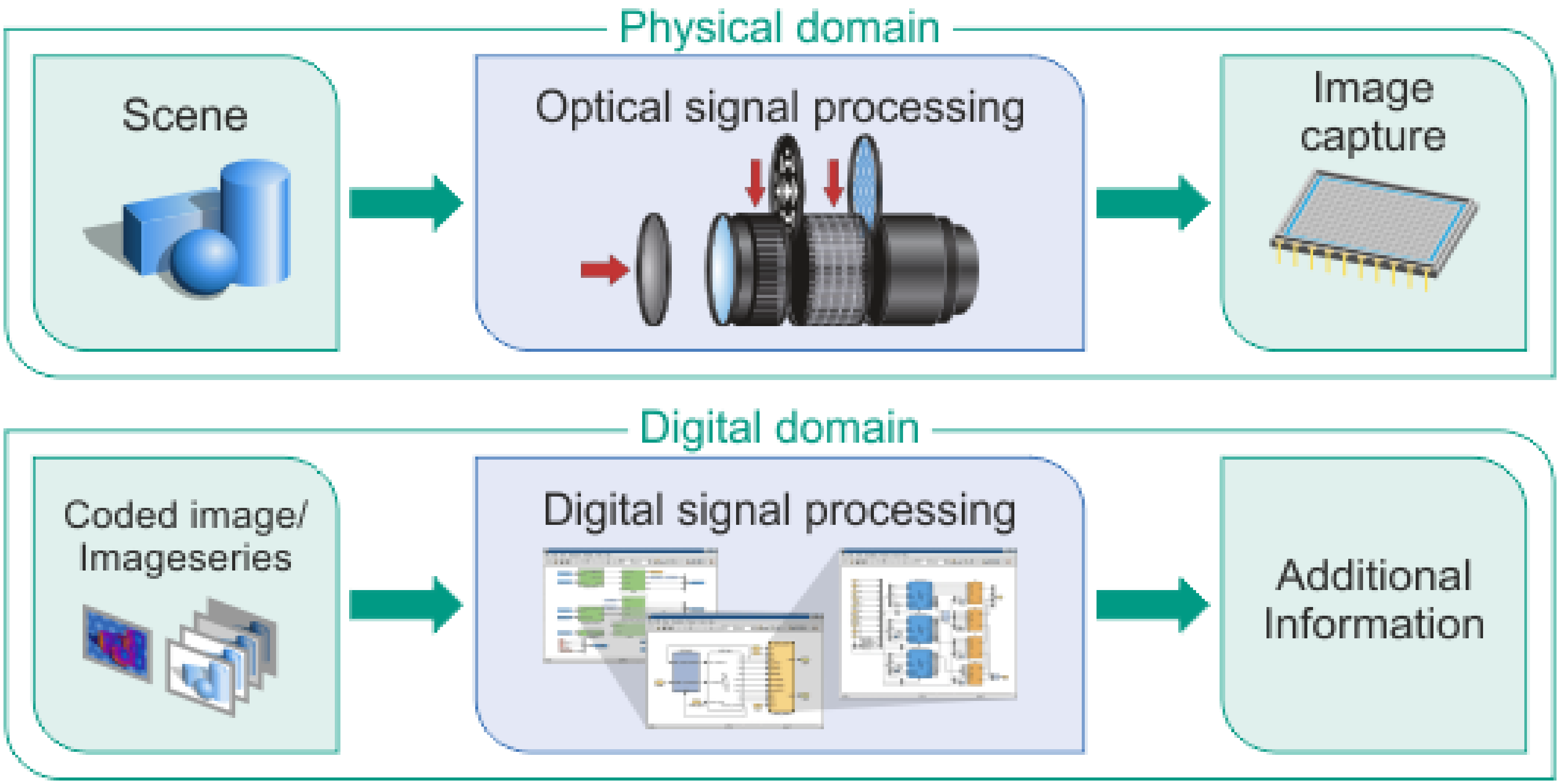
Computational imaging



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·特邀综述·

深度学习下的计算成像:现状、挑战与未来

左超[1,2], 冯世杰[1,2], 张翔宇[1,2], 韩静[2], 陈钱[2*]

[1]南京理工大学电子工程与光电技术学院,智能计算成像实验室(SCILab),江苏 南京 210094;

[2]南京理工大学江苏省光谱成像与智能感知重点实验室,江苏 南京 210094

摘要 近年来,光学成像技术已经由传统的强度、彩色成像发展进入计算光学成像时代。计算光学成像基于几何光学、波动光学等理论对场景目标经光学系统成像再到探测器采样这一完整图像生成过程建立精确的正向数学模型,再求解该正向成像模型所对应的"逆问题",以计算重构的方式来获得场景目标的高质量图像或者传统技术无法直接获得的相位、光谱、偏振、光场、相干度、折射率、三维形貌等高维度物理信息。然而,计算成像系统的实际成像性能也同样极大程度地受限于"正向数学模型的准确性"以及"逆向重构算法的可靠性",实际成像物理过程的不可预见性与高维病态逆问题求解的复杂性已成为这一领域进一步发展的瓶颈问题。近年来,人工智能与深度学习技术的飞跃式发展为计算光学成像技术开启了一扇全新的大门。不同于传统计算成像方法所依赖的物理驱动,深度学习下的计算成像是一类由数据驱动的方法,它不但解决了许多过去计算成像领域难以解决的难题,还在信息获取能力、成像的功能、核心性能指标(如成像空间分辨率、时间分辨率、灵敏度等)上都获得了显著提升。基于此,首先概括性介绍深度学习技术在计算光学成像领域的研究进展与最新成果,然后分析了当前深度学习技术在计算光学成像领域面临的主要问题与挑战,最后展望了该领域未来的发展方向与可能的研究方向。

关键词 成像系统; 计算成像; 深度学习; 光学成像; 光信息处理

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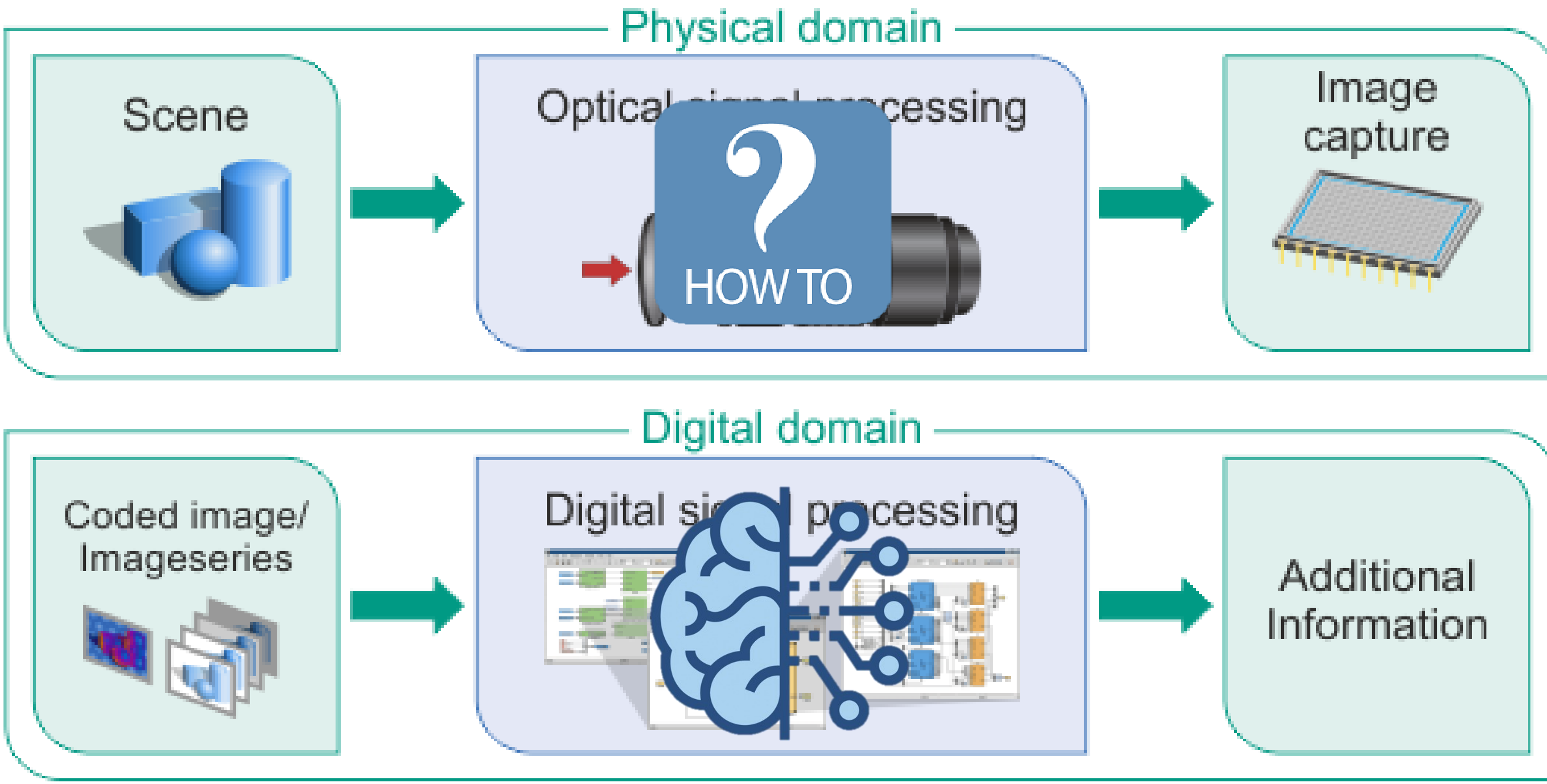
Computational imaging



Thank you

zuochao@njust.edu.cn