Metamaterials, Artificial Intelligence and Deeply Subwavelength Optical Imaging and Metrology

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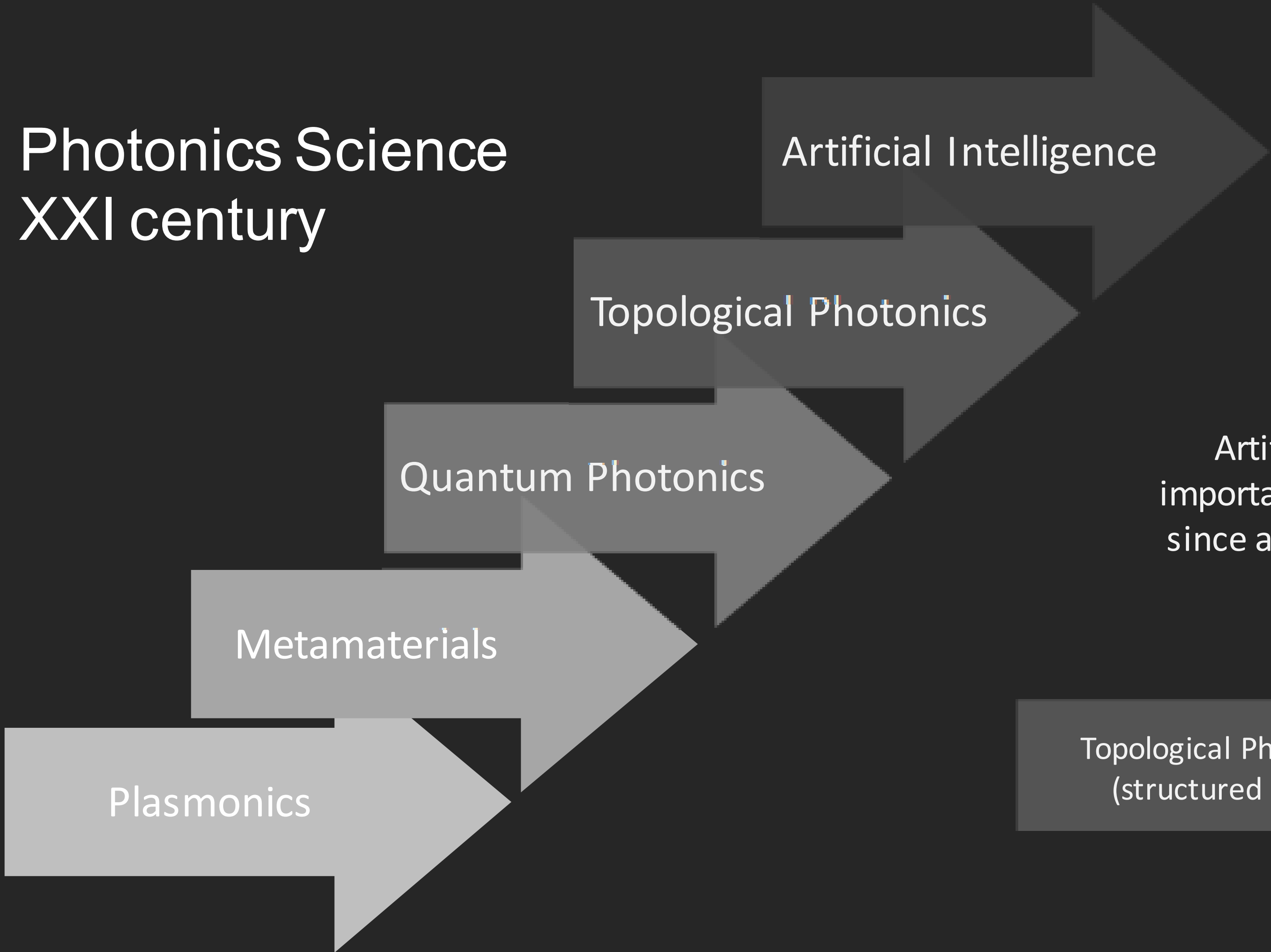
University of Southampton, UK & Nanyang Technological University, Singapore

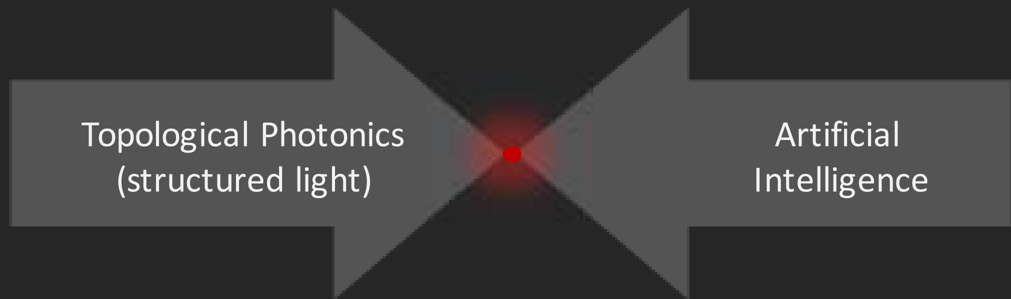
Plenary talk at the Metamaterials Congress 2020
29 September 2020. 9:00 -10:00 NY, 14:00 – 15:00 UK

The drivers of future of photonic technologies

Photonics Science
XXI century



Artificial intelligence is the most important new methodology in science since adoption of quantum mechanics



The Challenge:

Universal practical far-field microscopy
with deep sub-wavelength resolution does not exist

There are powerful STED/PAL/STORM techniques,
but they require labelling of samples (2014 Nobel Prize)

There is SNOM,
but it requires probe at the nanoscale vicinity of the sample

There is exciting negative metamaterial index super-lens idea...

Is far-field, optical microscopy of unlabelled samples possible with the atomic, molecular level of resolution?

Is there another route to deeply subwavelength optical imaging?

Part I

- Superoscillations – Curiosity and Reality
- Subwavelength Energy Hotsports and Superoscillatory Lenses
- Super-resolution Imaging with Superoscillatory Lenses

(localization of energy → resolution beyond λ/2 …)

Part II

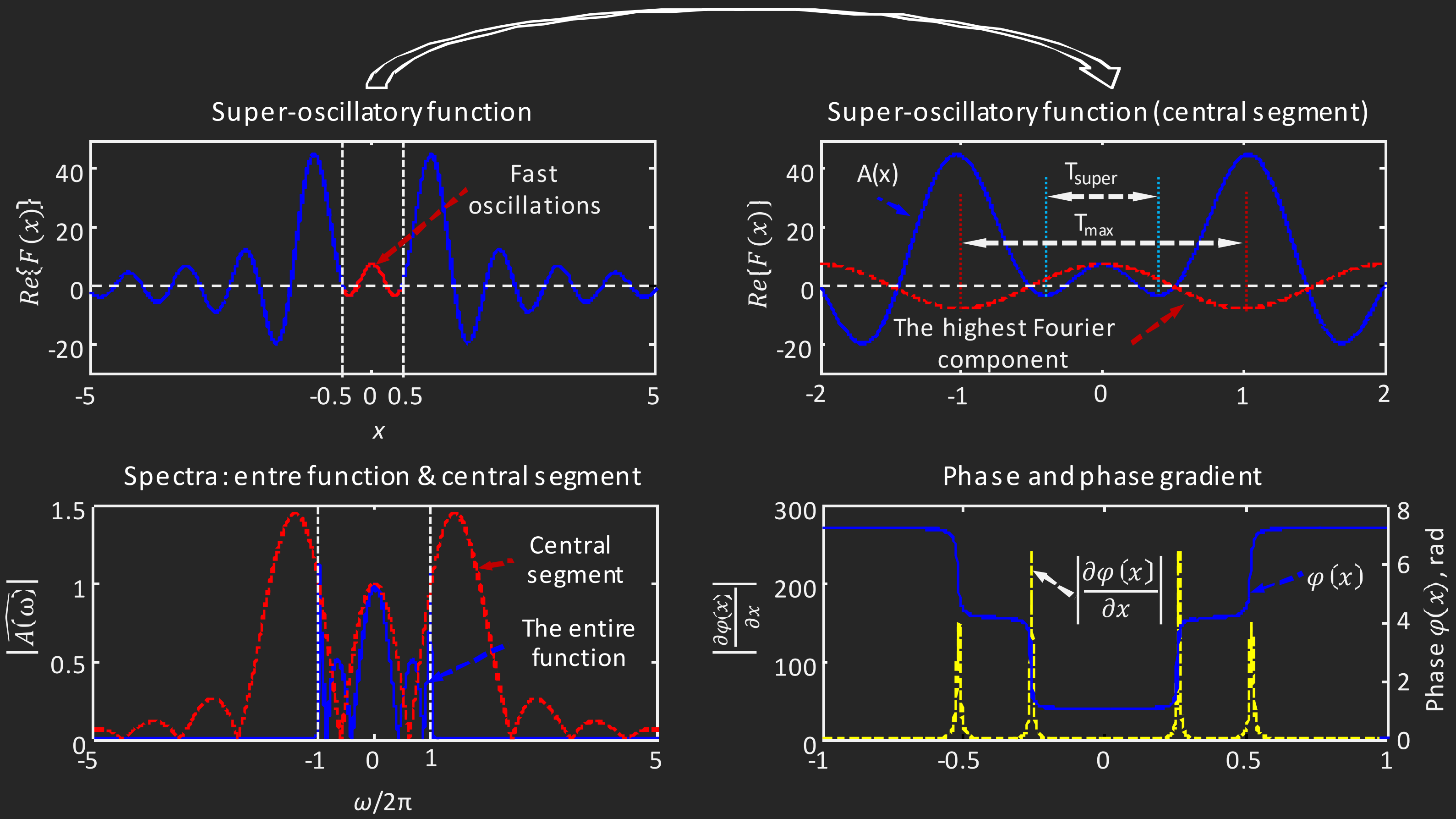
- “Plasmonics” in Free Space and Deeply Subwavelength Structured Light
- Nanometrology with Deeply Subwavelength Structured Light
- Deeply subwavelength optical imaging enabled by Artificial Intelligence

(localization of phase change → resolution beyond λ/1000 …)

Part I
Superoscillations – Curiosity and Reality

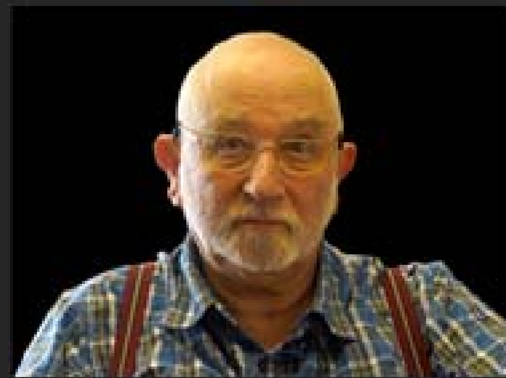
Superoscillatory functions

(that oscillate much, much faster than its highest Fourier harmonic)



$F(x) = A(x)\, e^{i\varphi(x)} = 1.8126 * S_2 + S_3$

(prolate spheroidal functions)

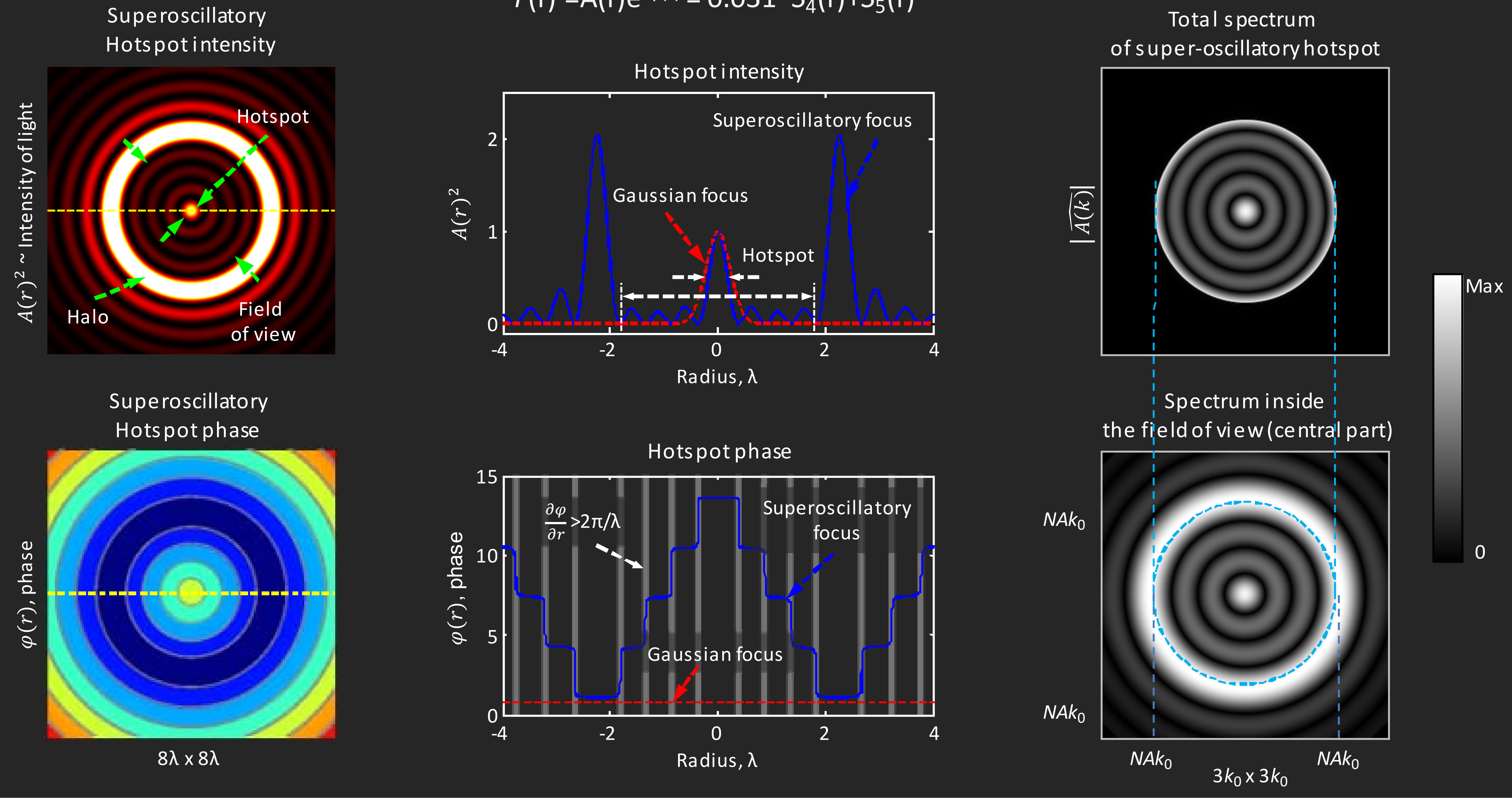


"In the Wigner representations of the local Fourier transform …. can have both positive and negative values, which causes subtle cancellations in the Fourier integration over all of the function"

Berry & Popescu. J. Phys. A: Math. Gen. (2006)

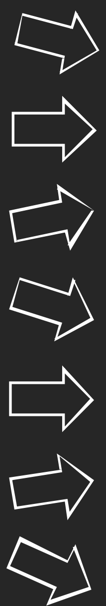
2D Superoscillatory functions & small hotspots (optics)

$F(r) = A(r)e^{i\varphi(r)} = 0.031 * S_4(r) + S_5(r)$

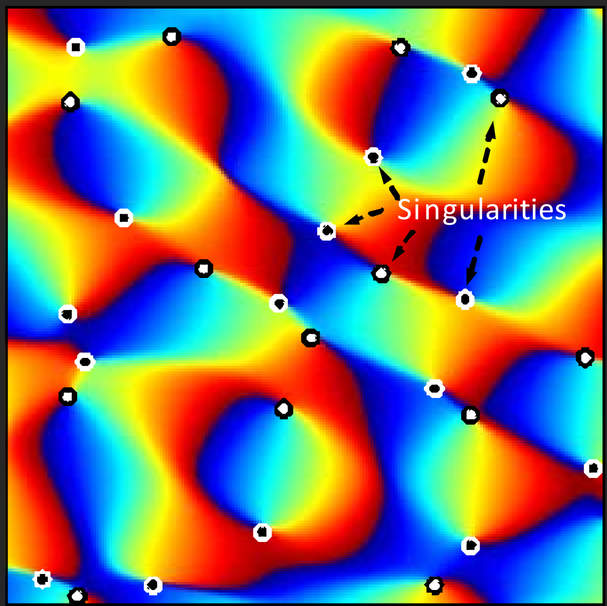


Superoscillations are widespread in optics

50 coherent plane waves



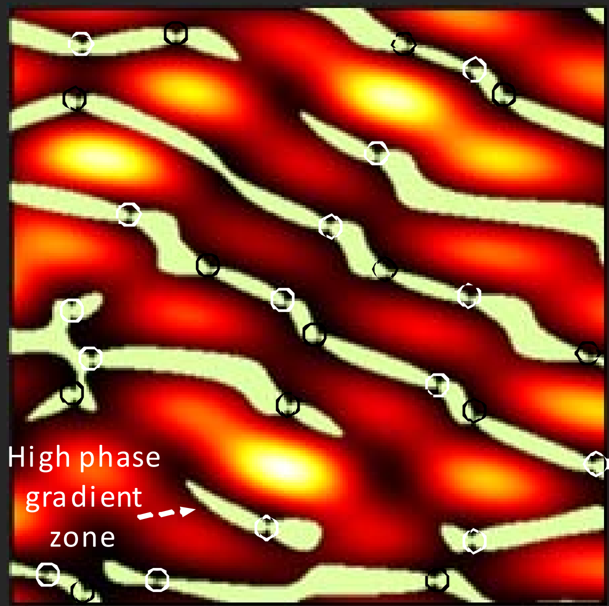
Phase map and singularities



4λ x 4λ

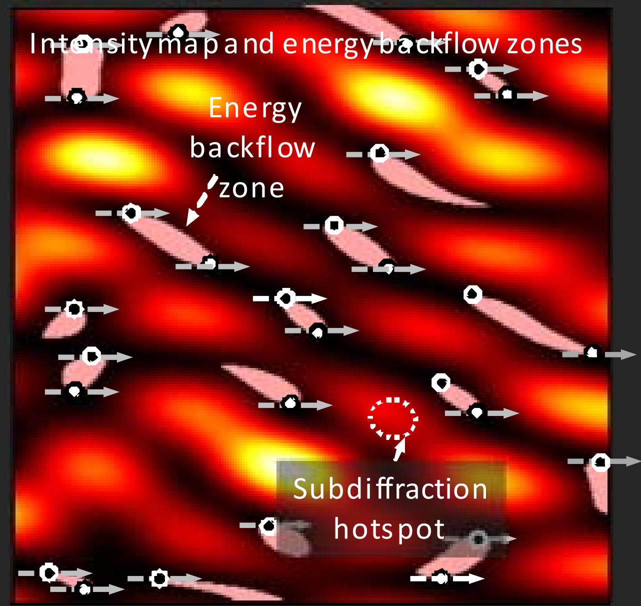
λ

Intensity map and high k_{local} -vector zones



$k_{local} = |grad(\varphi)|$

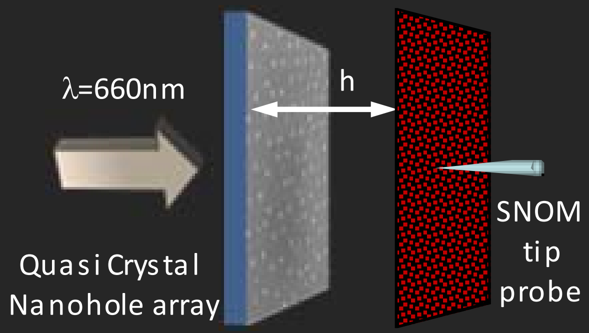
Intensity map and energy backflow zones

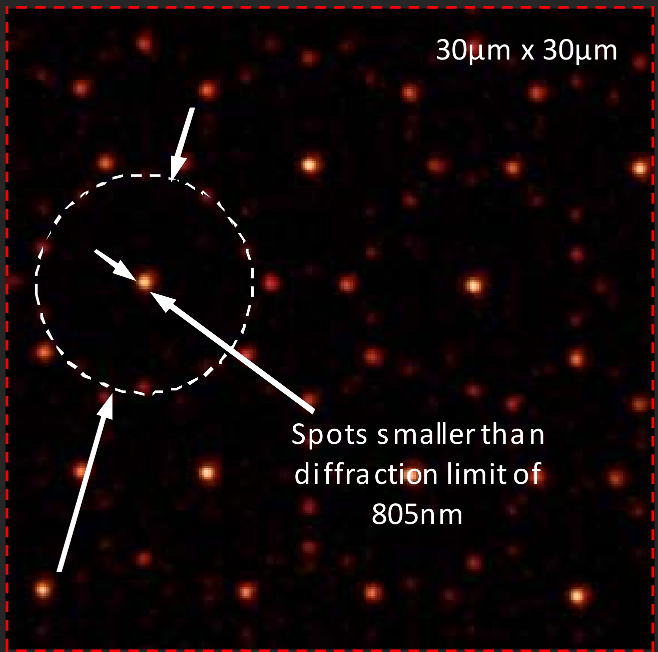


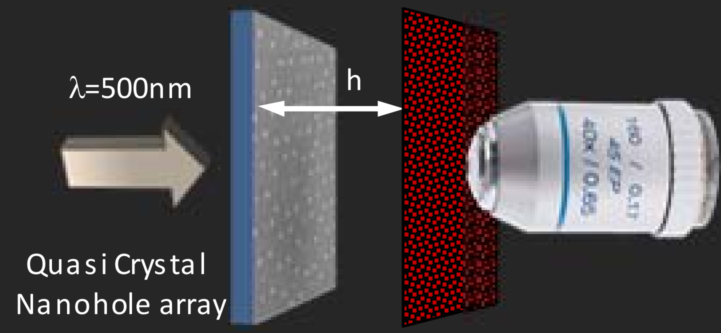
"… the regions of backflow are considerably smaller than the wavelength; this reflects the well-known fact that in the neighbourhood of phase singularities wavefunctions can vary on sub-wavelength scales."

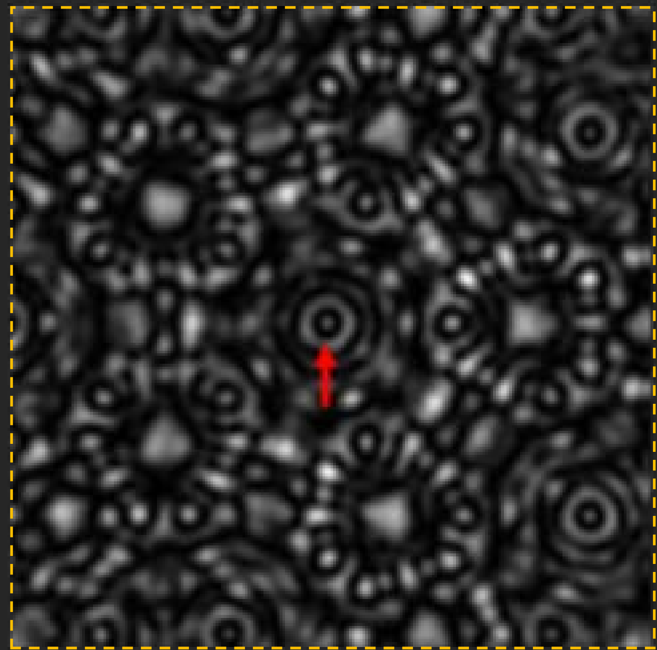
B.V.Berry. Quantum backflow, negative kinetic energy, and optical retro-propagation| J.Phys. A: Math. Theor. 43, 415302 (2010)

Observation of optical super-oscillations (2007)









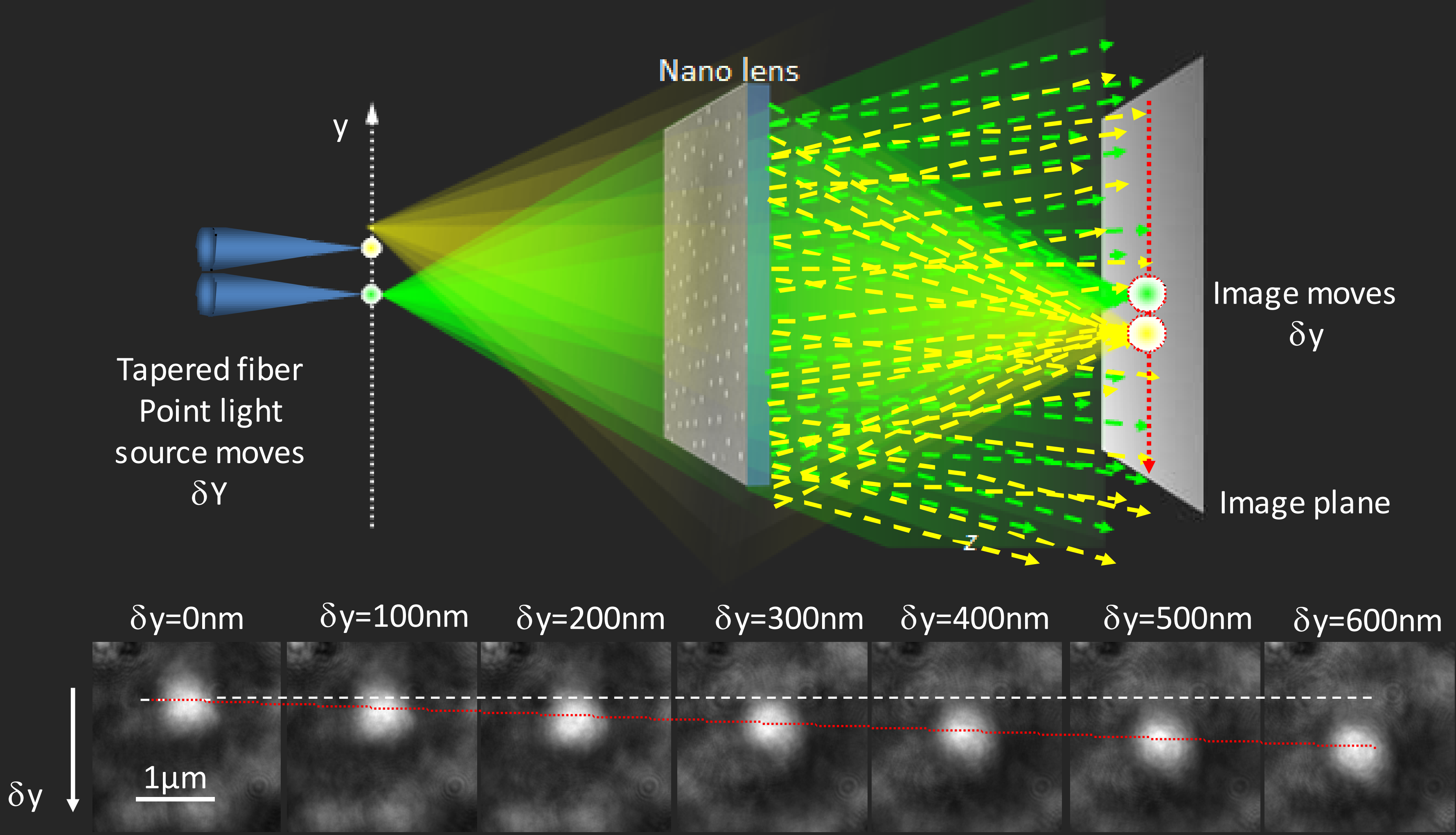
Superoscillatory fields contain NO EVANESCENT FIELDS & can be imaged with conventional microscope!

Focusing of light by a nanohole array
Huang, Zheludev, Chen, García de Abajo. *APL* 90, 091119 (2007)

Optical super-resolution through super-oscillations
Huang, Chen, García de Abajo, Zheludev. *J. Opt. A* 9, S285 (2007)

Subwavelength Energy Hotsports and Superoscillatory Lenses

Imaging with superoscillating array



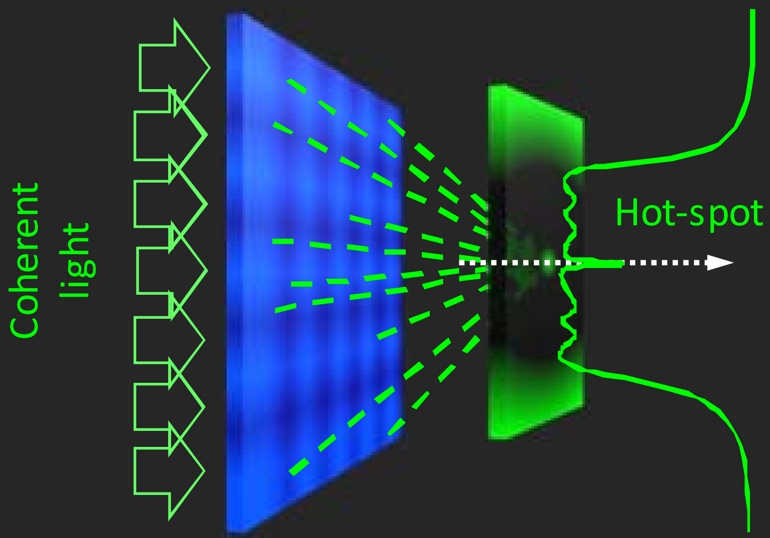
Nanohole array as a lens

Huang, Kao, Fedotov, Chen, Zheludev. *Nano Lett.* **8**, 2469 (2008)

How to engineer a superoscillatory hotspot?

There is NO fundamental limit to how small the hotspot could be

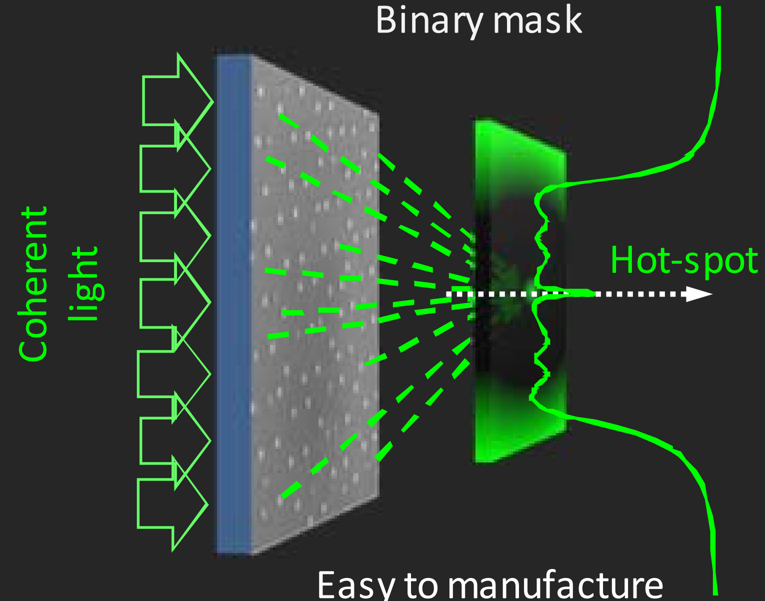
Continuous mask



Hard to manufacture
Full control of super-oscillations

Metamaterial superlens 2.0

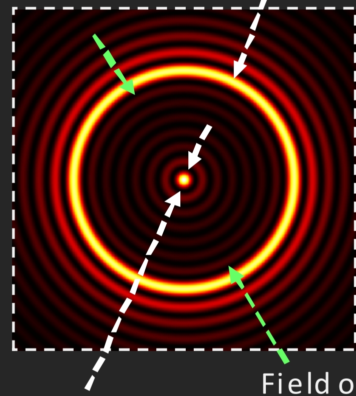
Binary mask



Easy to manufacture
Partial control of super-oscillations

Intensity and phase binary masks

“Halo” (Side lobs)



Field of view

δ, super-oscillatory Focus

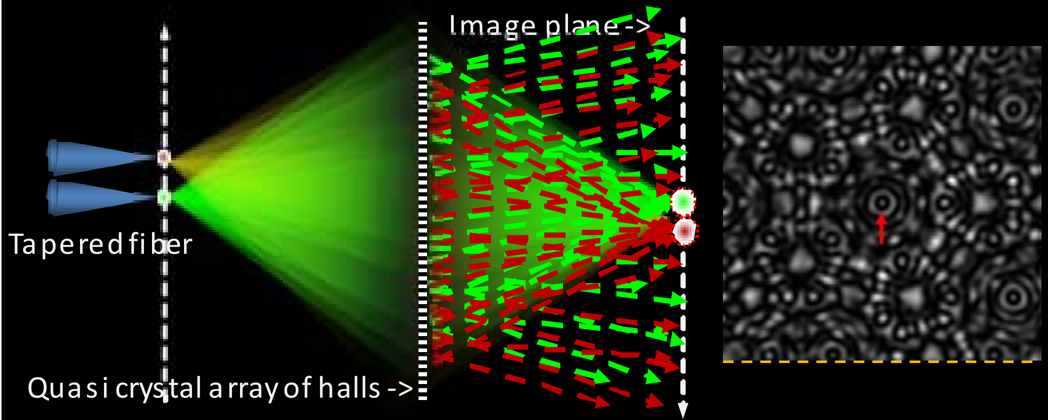
The proportion of energy that can be focused in SO hotspot is a polynomial function of δ, P(δ) (Ferreira & Kempf 2006)

Super-resolution without evanescent waves
Huang & Zheludev, *Nano Lett.*, 9, 1249 (2009)

Optimising superoscillatory spots for far-field super-resolution imaging
Rogers, Bourdakos, Yuan, Mahajan, Rogers. *Opt. Express* **26**(7), 8085 (2018)

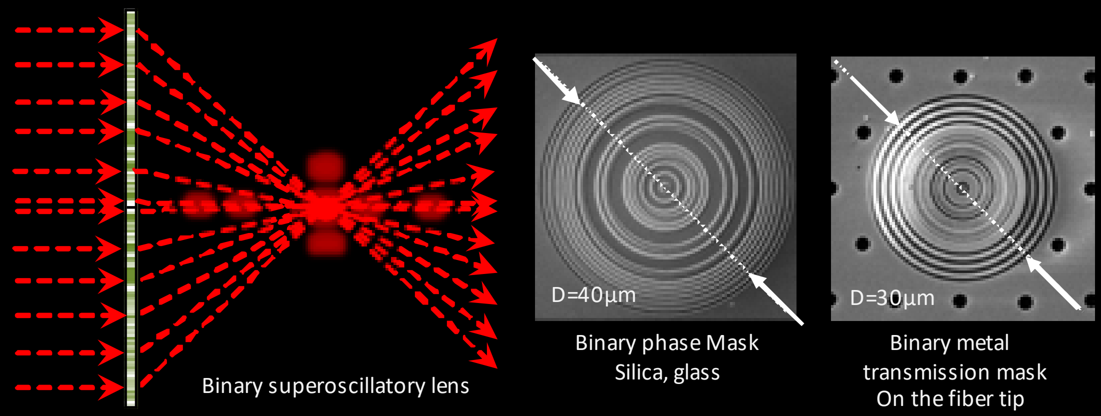
How to engineer a superoscillatory hotspot?

Quasi-crystal array of halls



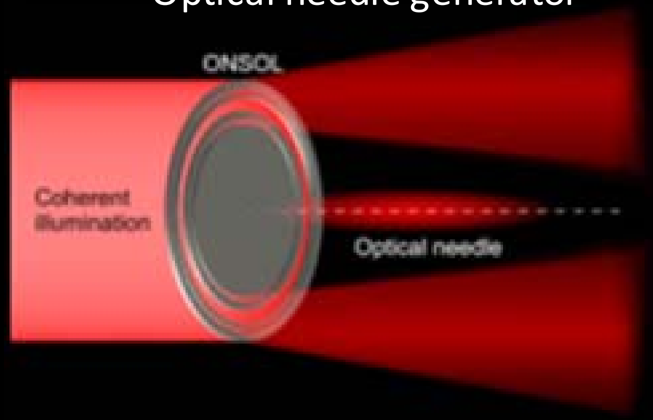
Nanohole array as a lens
Huang, Kao, Fedotov, Chen, Zheludev. *Nano Lett.* **8**, 2469 (2008)

Phase or amplitude binary mask



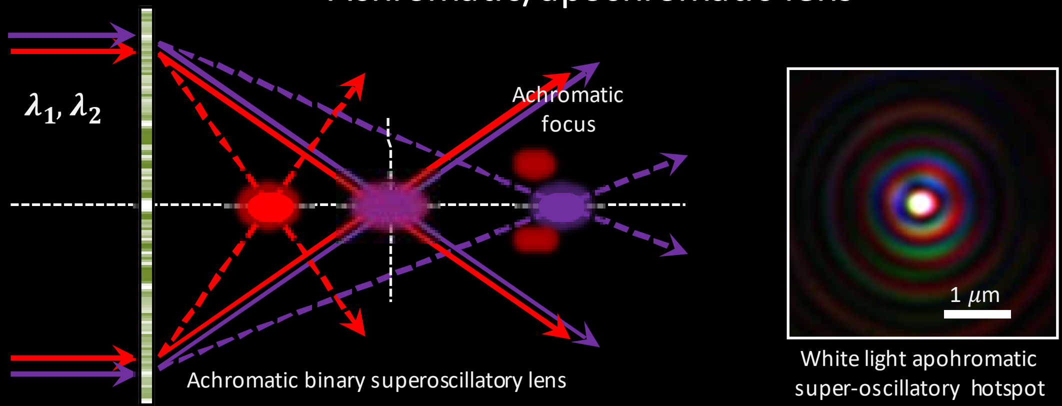
Superoscillatory quartz lens with effective NA greater than one
Yuan, Lin, Tsai and Zheludev. *Appl. Phys. Lett.* **117**, 021106 (2020)

Optical needle generator



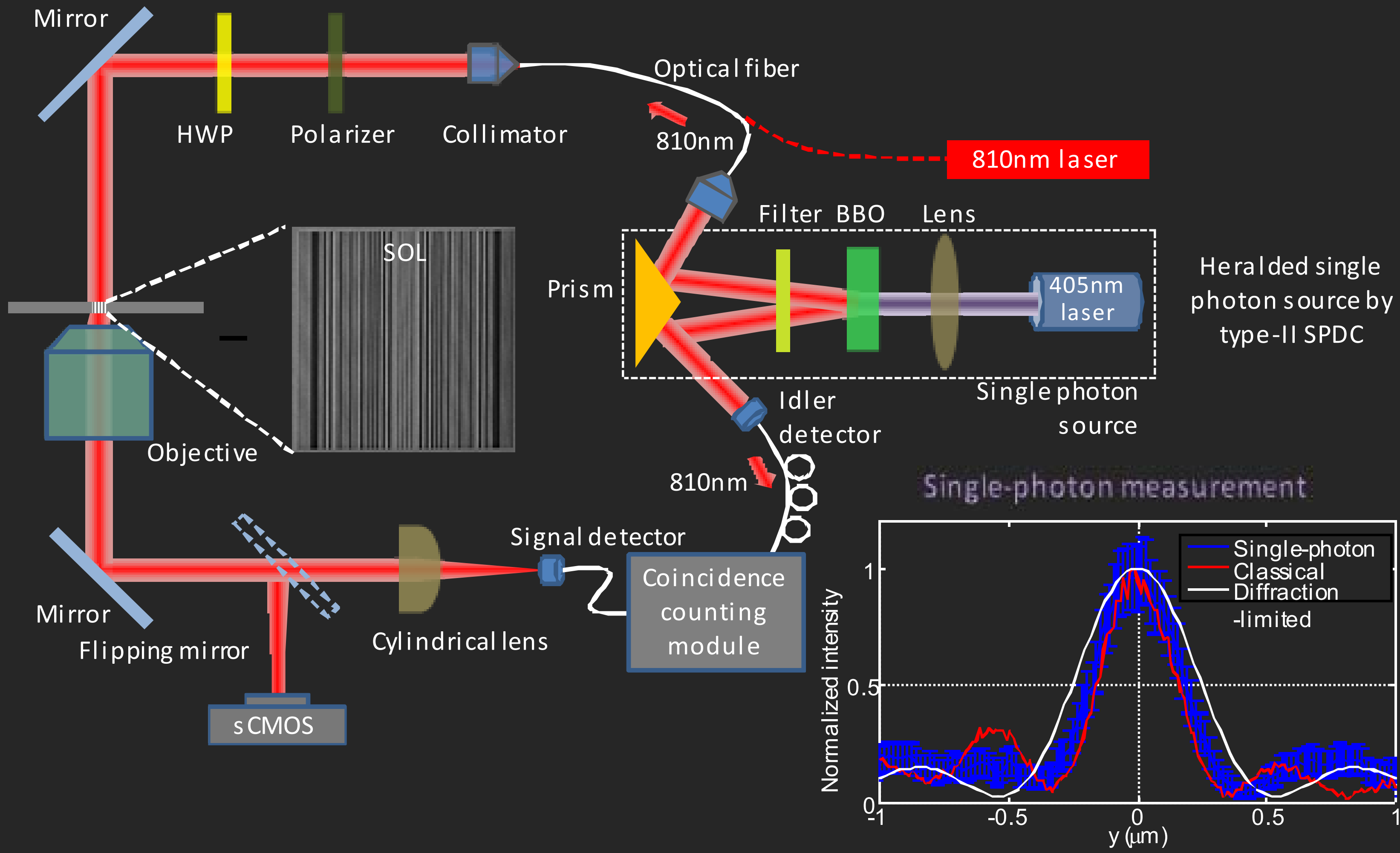
Super-oscillatory optical needle.
Rogers, Savo, Lindberg, Roy, Dennis, Zheludev. APL 102, 031108 (2013)

Achromatic/apochromatic lens



Achromatic super-oscillatory lenses with sub-wavelength focusing
Yuan, Rogers, Zheludev. Nature | Light Sci. Appl. **6**, e17036 (2017)

Super-oscillation of a single photon

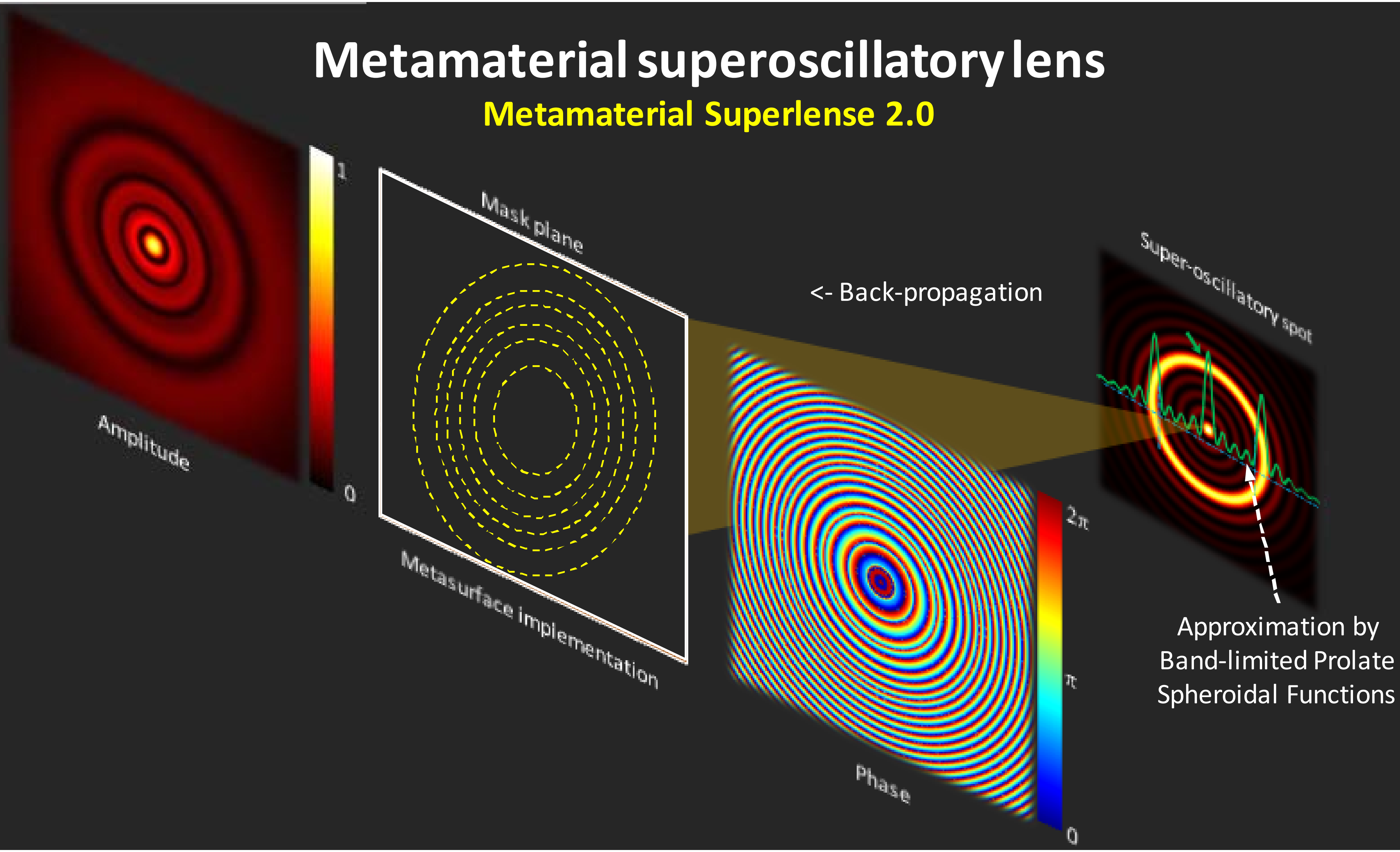


Quantum super-oscillation of a single photon

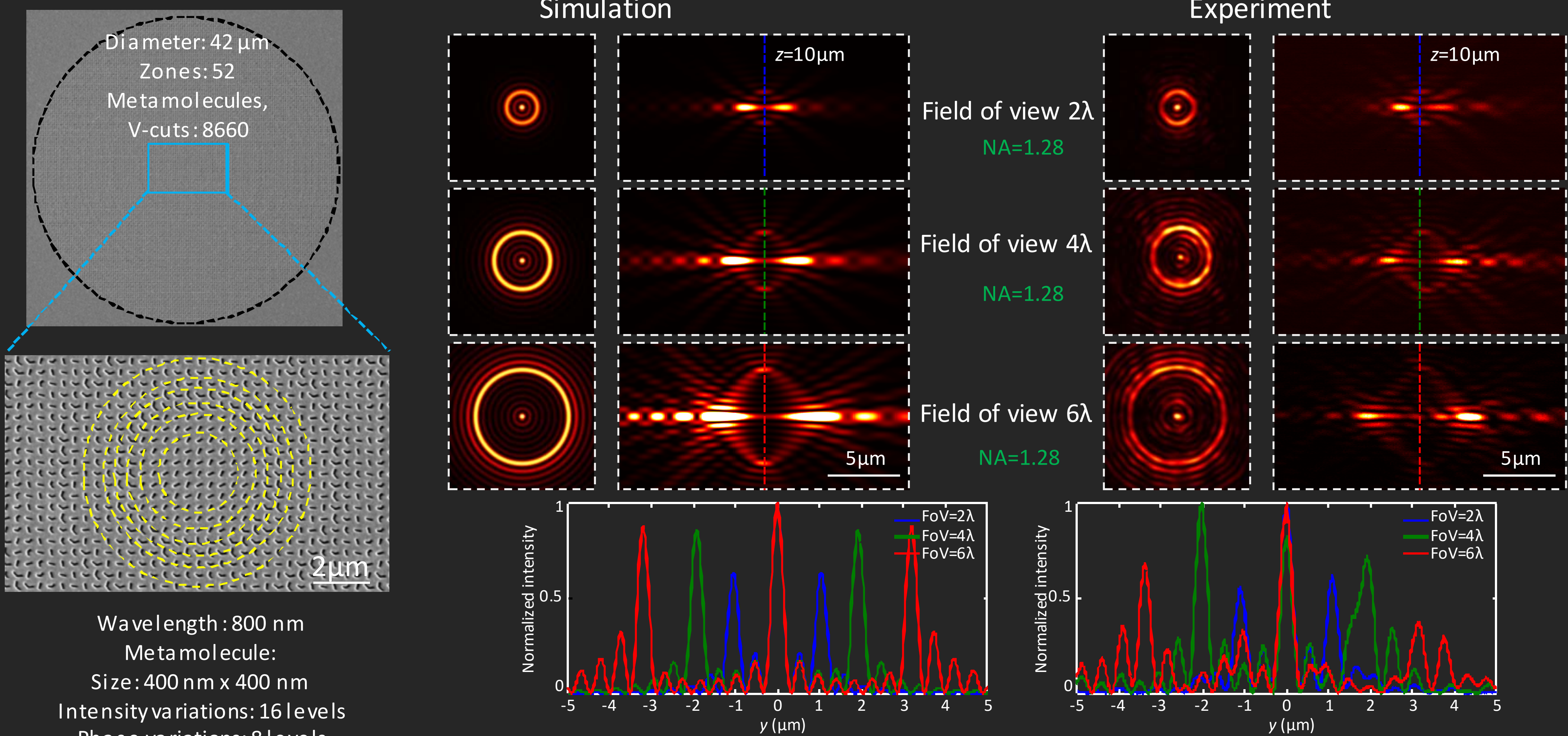
Yuan, Vezzoli, Altuzarra, Rogers, Couteau, Soci, Zheludev. *Nature | Light: Science & Applications* **5**, e16127 (2016)

Metamaterial superoscillatory lens

Metamaterial Superlense 2.0



Far-field metamaterial superoscillatory lens (large FOV)



Wavelength: 800 nm
Metamolecule:
Size: 400 nm x 400 nm
Intensity variations: 16 levels
Phase variations: 8 levels

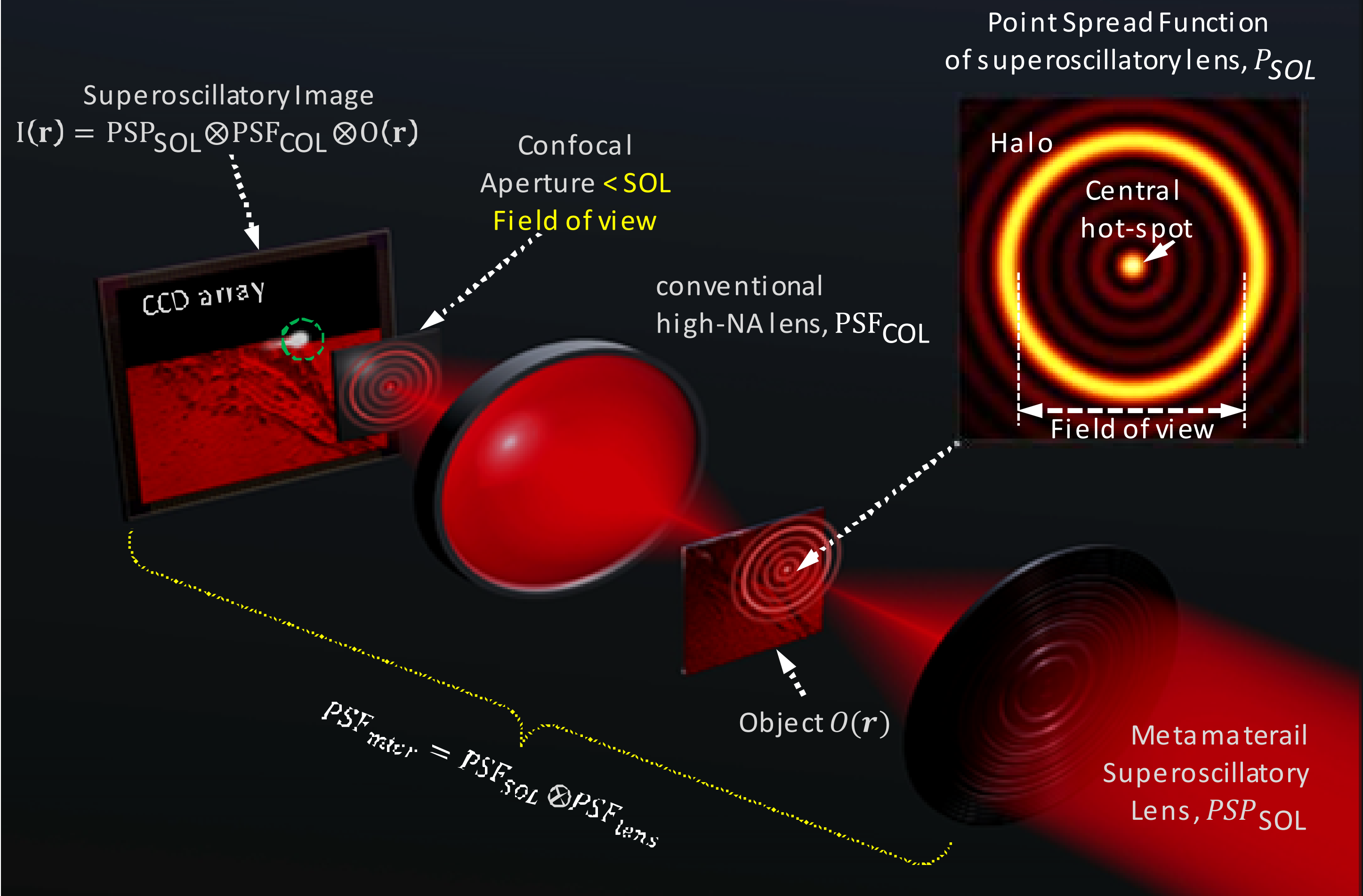
Far-field superoscillatory metamaterial superlens

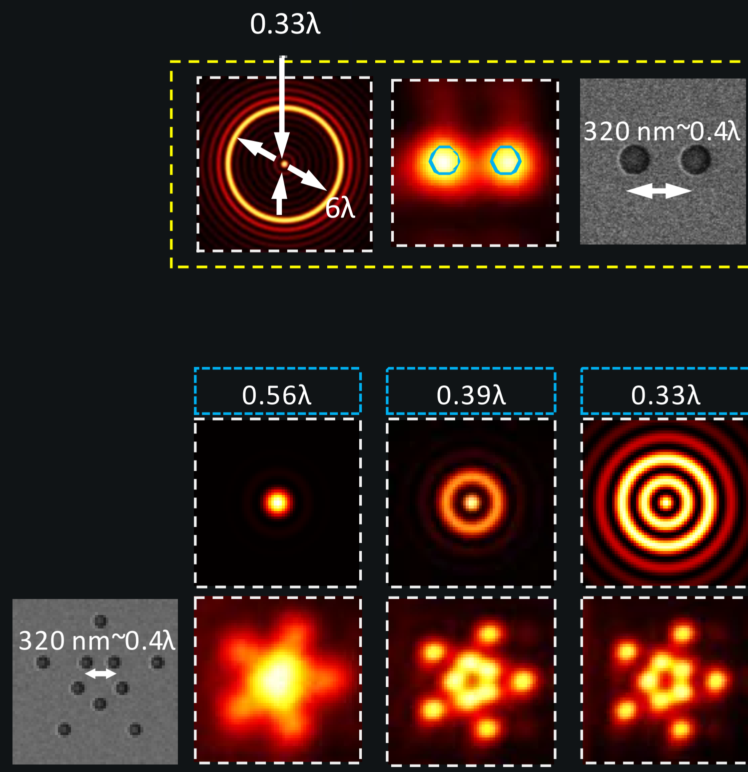
Yuan, Rogers, E. Rogers, Zheludev. Phys. Rev. Applied **11**, 064016 (2019)

Super-resolution Imaging with Superoscillatory Lenses

(a camel going through the eye of a needle)

Superesolution Imaging with metamaterial superlens 2.0



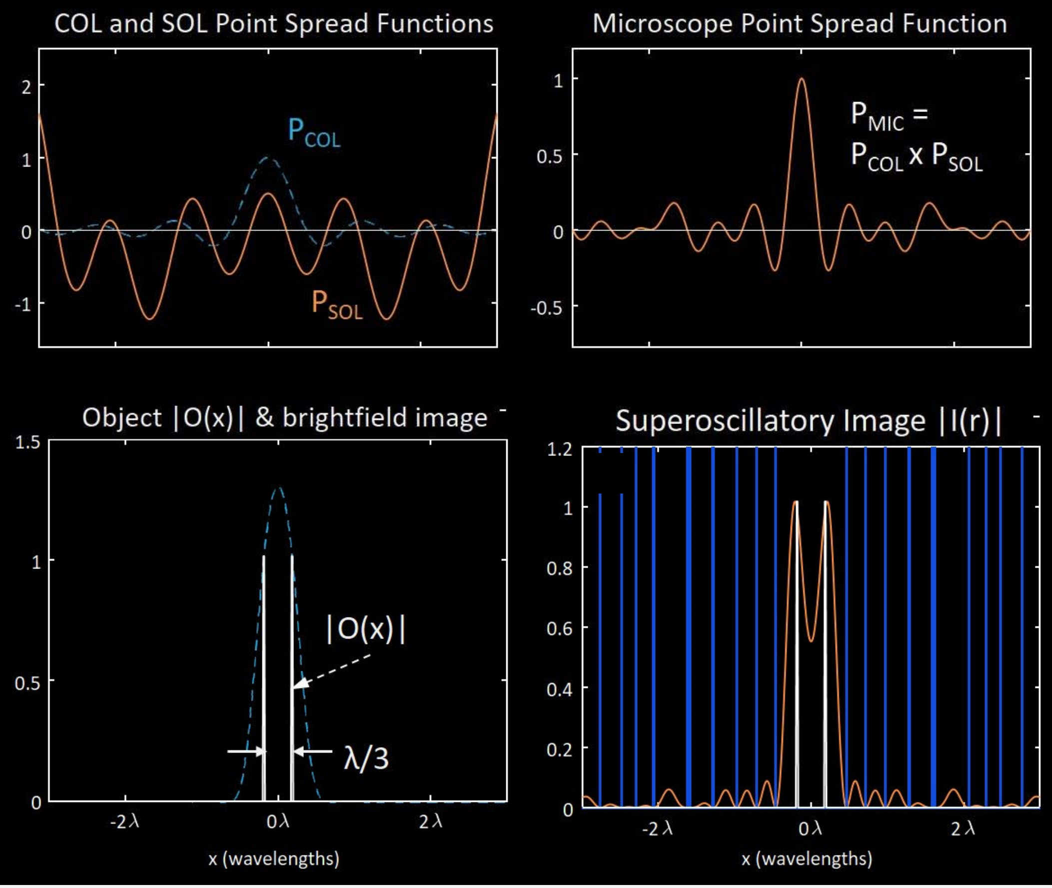


A super-oscillatory lens optical microscope for subwavelength imaging
Rogers, Lindberg, Roy, Savo, Chad, Dennis, Zheludev. *Nature Mat.* **11**, 432 (2012)

Far-field superoscillatory metamaterial superlens
Yuan, Rogers, Zheludev. Phys. Rev. Applied **11**, 064016 (2019)

Super-resolution imaging with superoscillatory illumination

A camel going through the eye of a needle, or
how to create super-resolution image with a band-limited optical system ?



Images obtained with superoscillatory illumination are superoscillatory

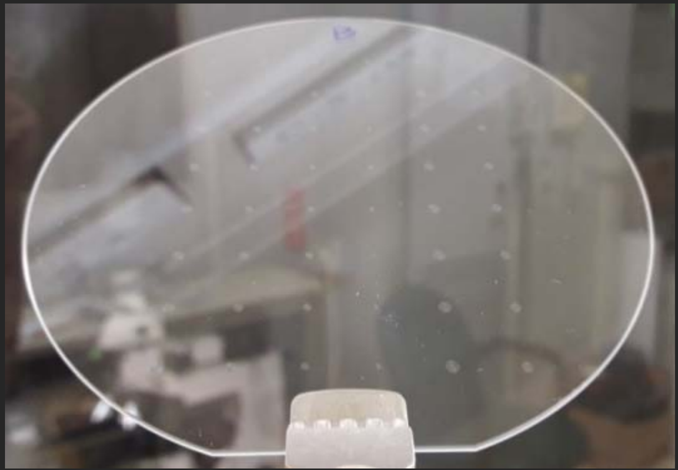
Supersocillatory features are resolved beyond the “diffraction limit”

Resolution of super-oscillatory imaging is the size of superoscillatory hot-spot

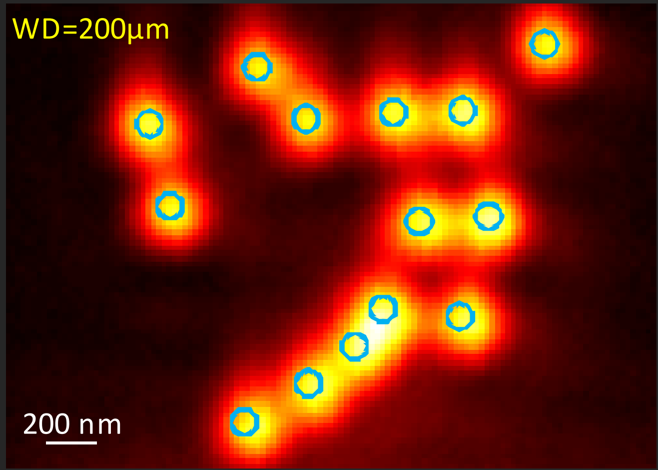
Far-field unlabeled super-resolution imaging with superoscillatory illumination
Rogers, Quraishe, Rogers, Newman, Smith and Zheludev. *APL Photonics* **5**, 066107 (2020)

Superoscillatory imaging with quartz superlens (633 nm)

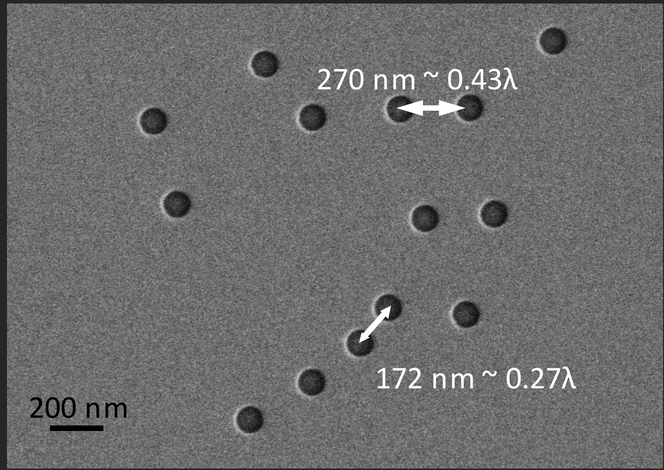
Quartz wafer with superoscillatory lenses



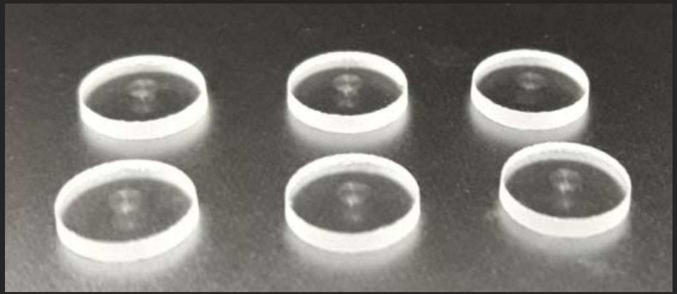
Optical image of the pattern at 633nm



Ursa Pattern: array of halls



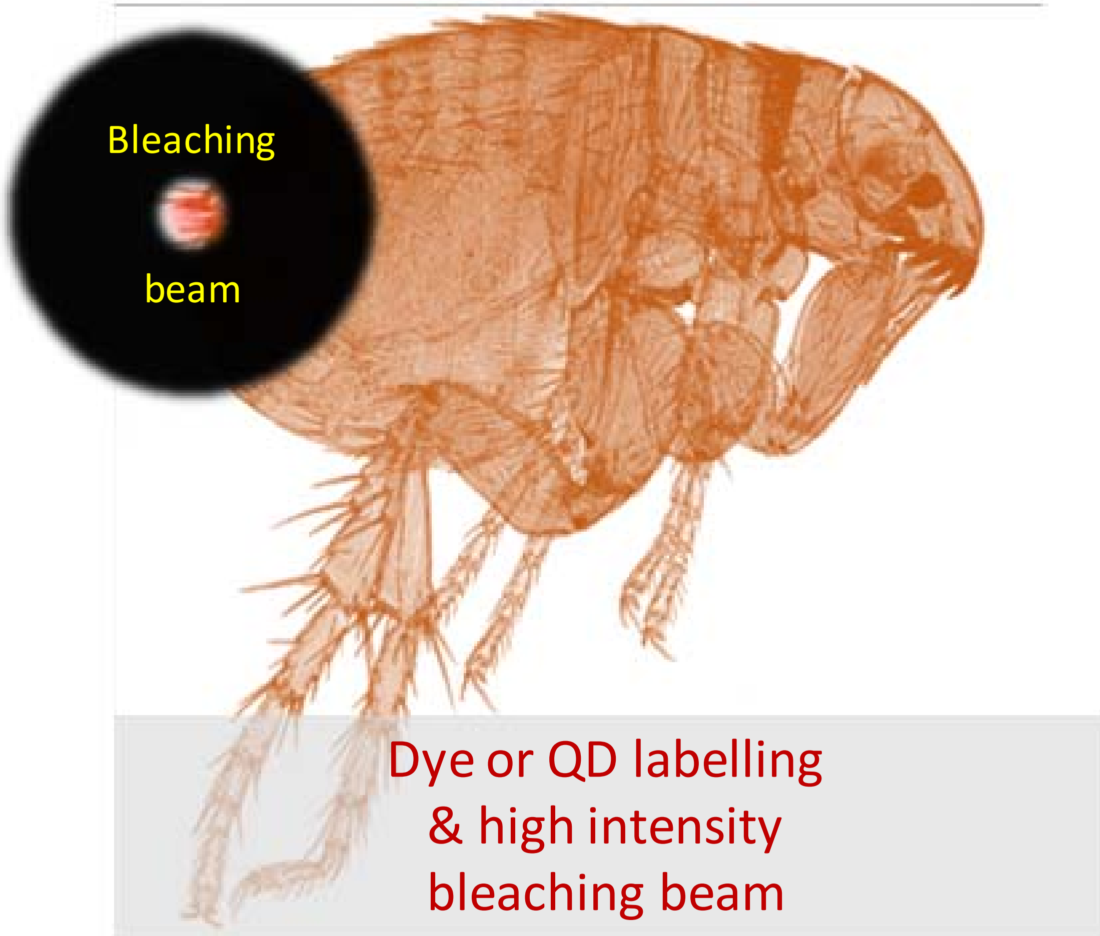
Individual lenses cut from the wafer



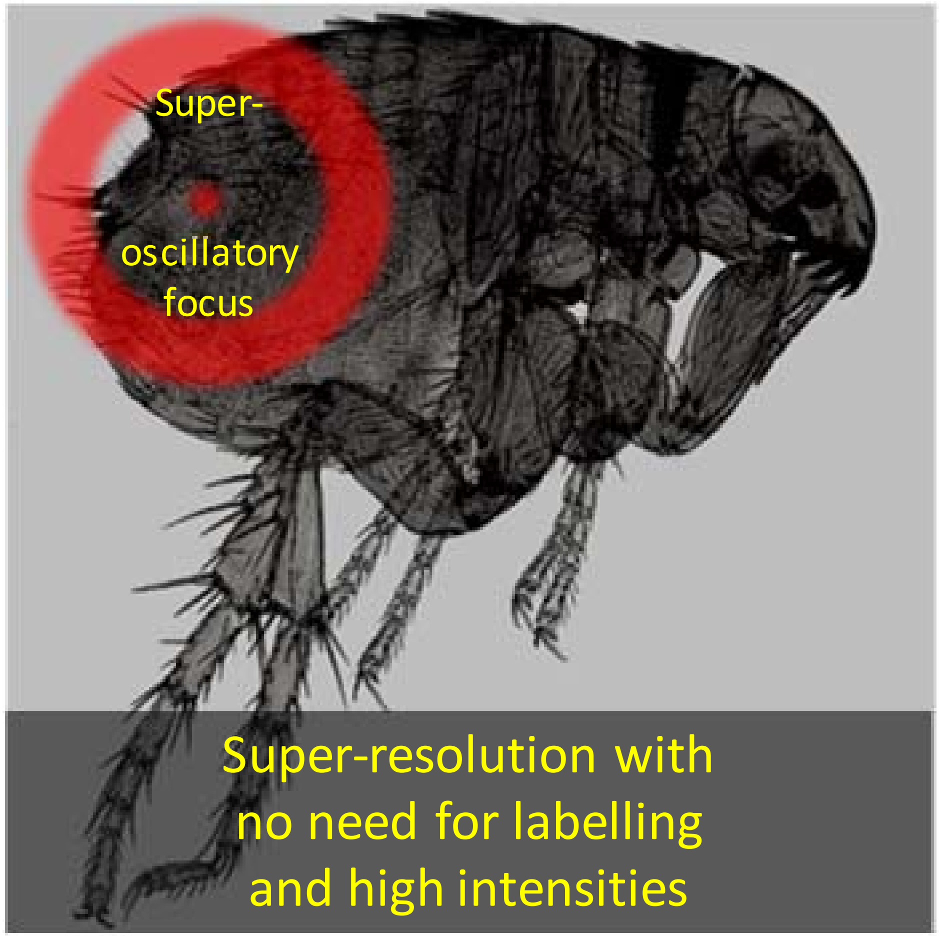
Ursa Major
& Ursa Minor

Superoscillatory quartz lens with effective numerical aperture greater than one
Yuan, Lin, Tsai and Zheludev. APL **117**, 021106 (2020)

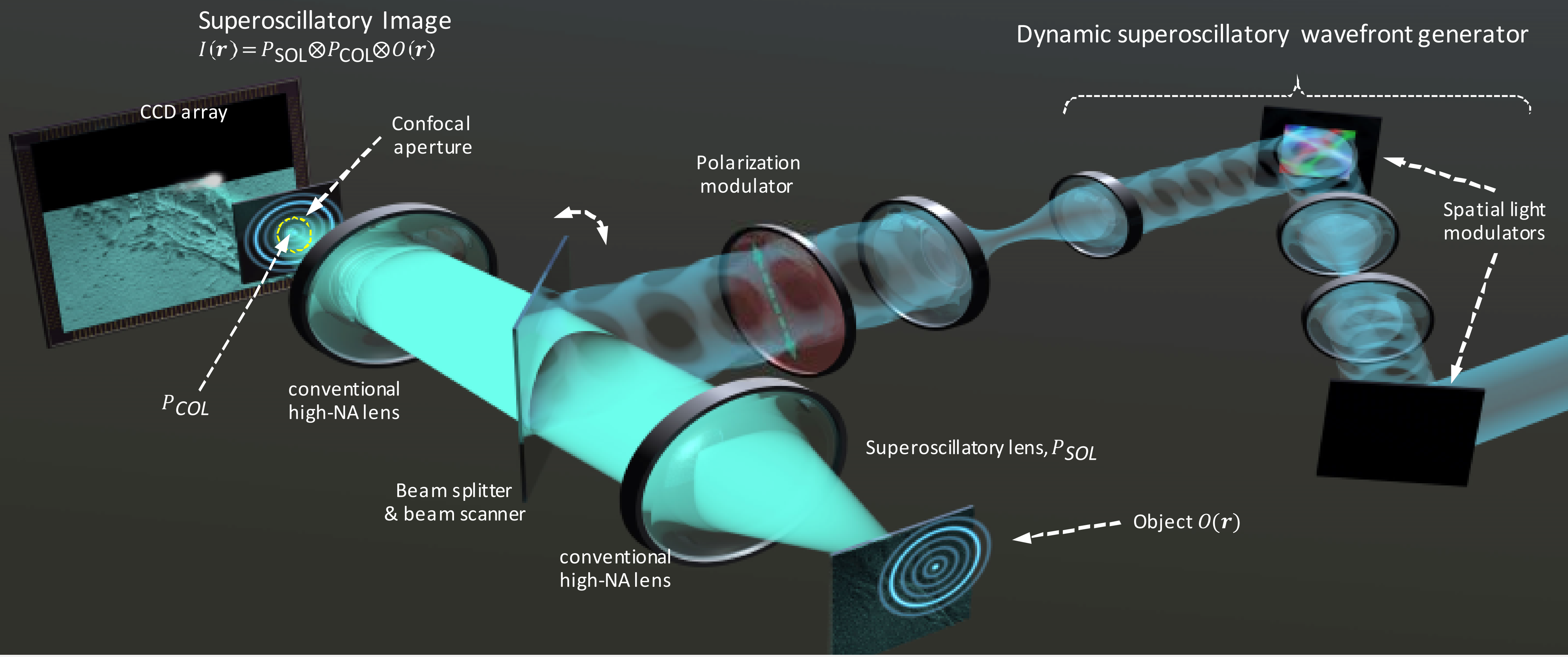
STED imaging



Super-oscillatory imaging



Super-oscillatory biological microscope

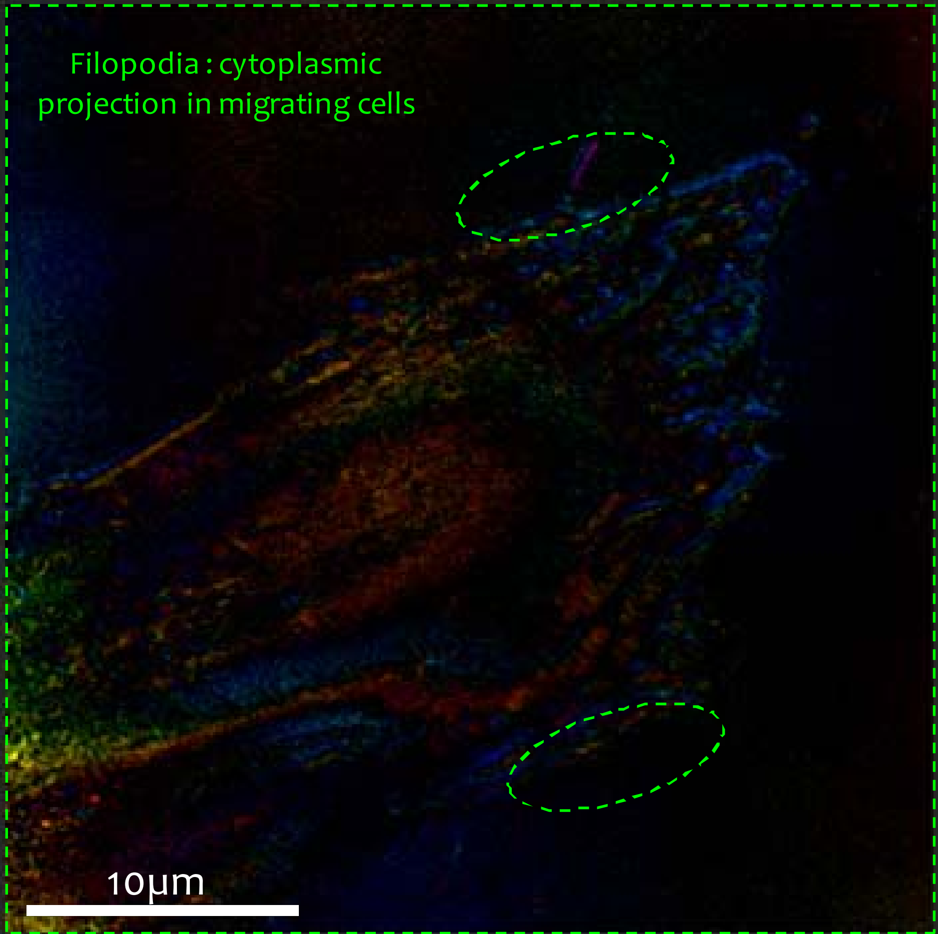


Far-field unlabeled super-resolution imaging with superoscillatory illumination

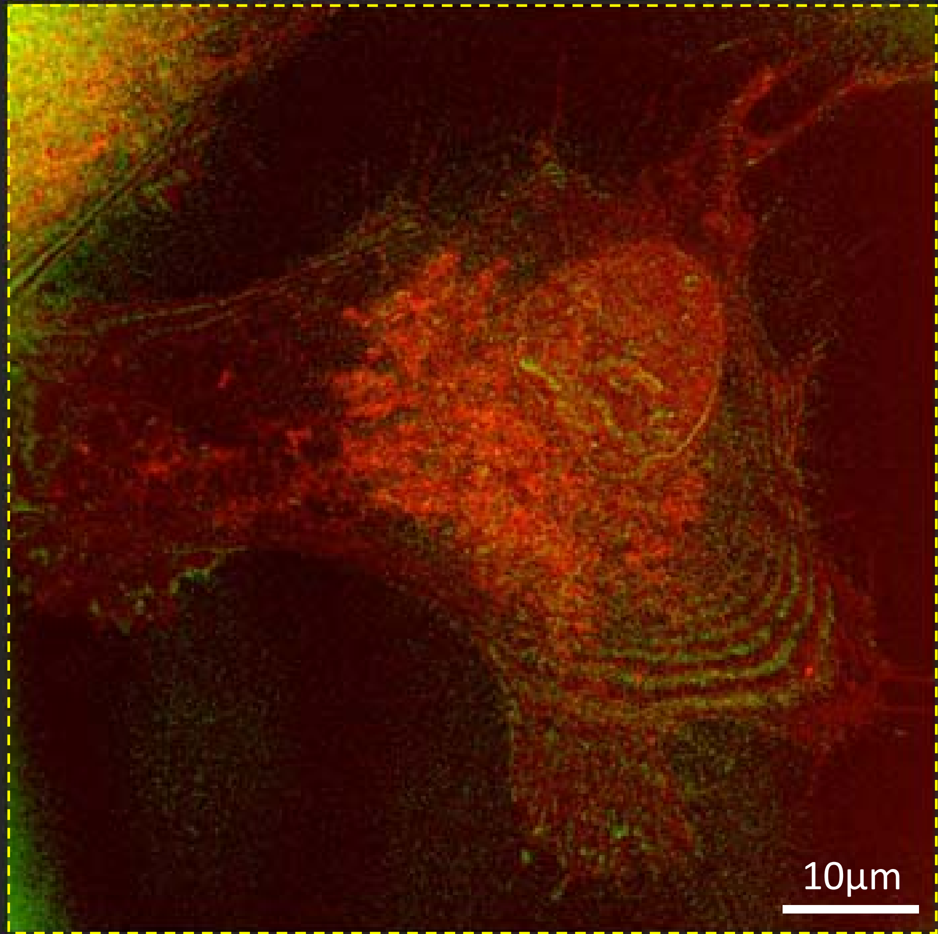
Rogers, Quraishe, Rogers, Newman, Smith and Zheludev. *APL Photonics* **5**, 066107 (2020)

Superoscillatory bio-imaging

Collaboration with S Quraishe, TA Newman, JE Chad, PJS Smith, IfLS University of Southampton



Unlabelled bone stem cell line MG63;
15s/frame, 20min total



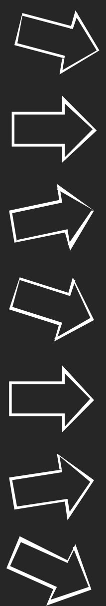
MG63 cells; 5s/frame, 5min total
Green: super-oscillatory
Red: Mitotracker

Bot this is not yet λ/1000 …

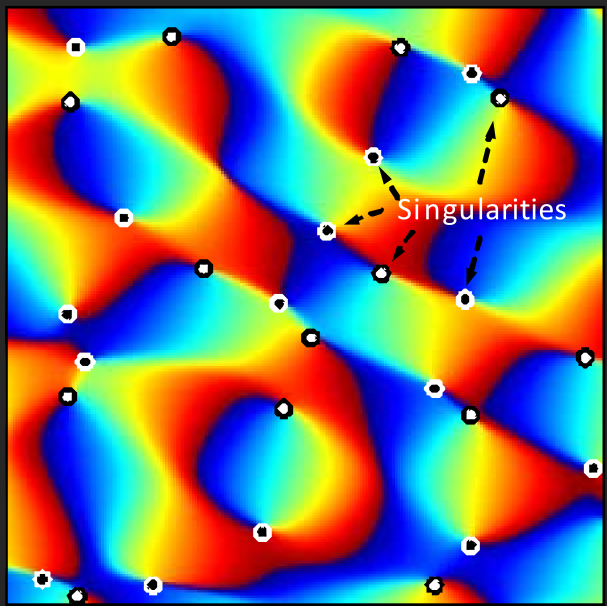
Part II
“Plasmonics” in Free Space

Superoscillations are widespread in optics

50 coherent plane waves



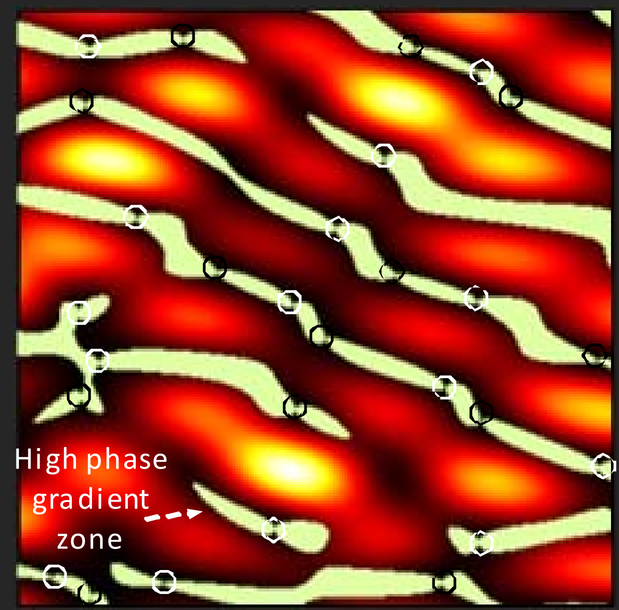
Phase map and singularities



4λ x 4λ

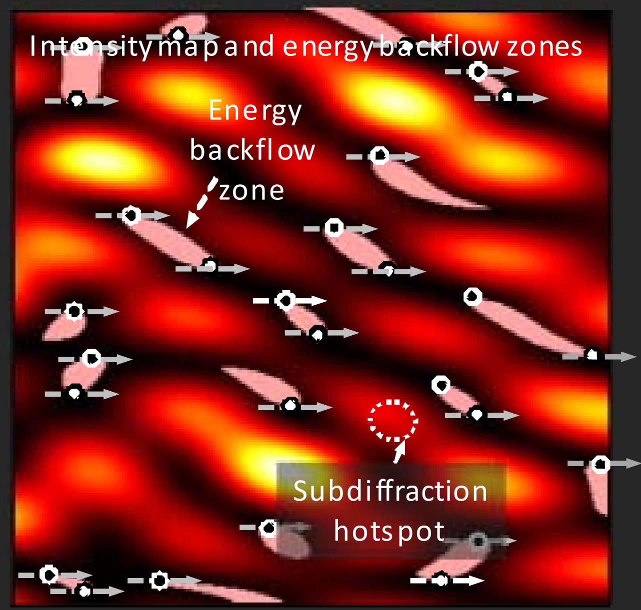
λ

Intensity map and high k_{local} -vector zones



$k_{local} = |grad(\varphi)|$

Intensity map and energy backflow zones

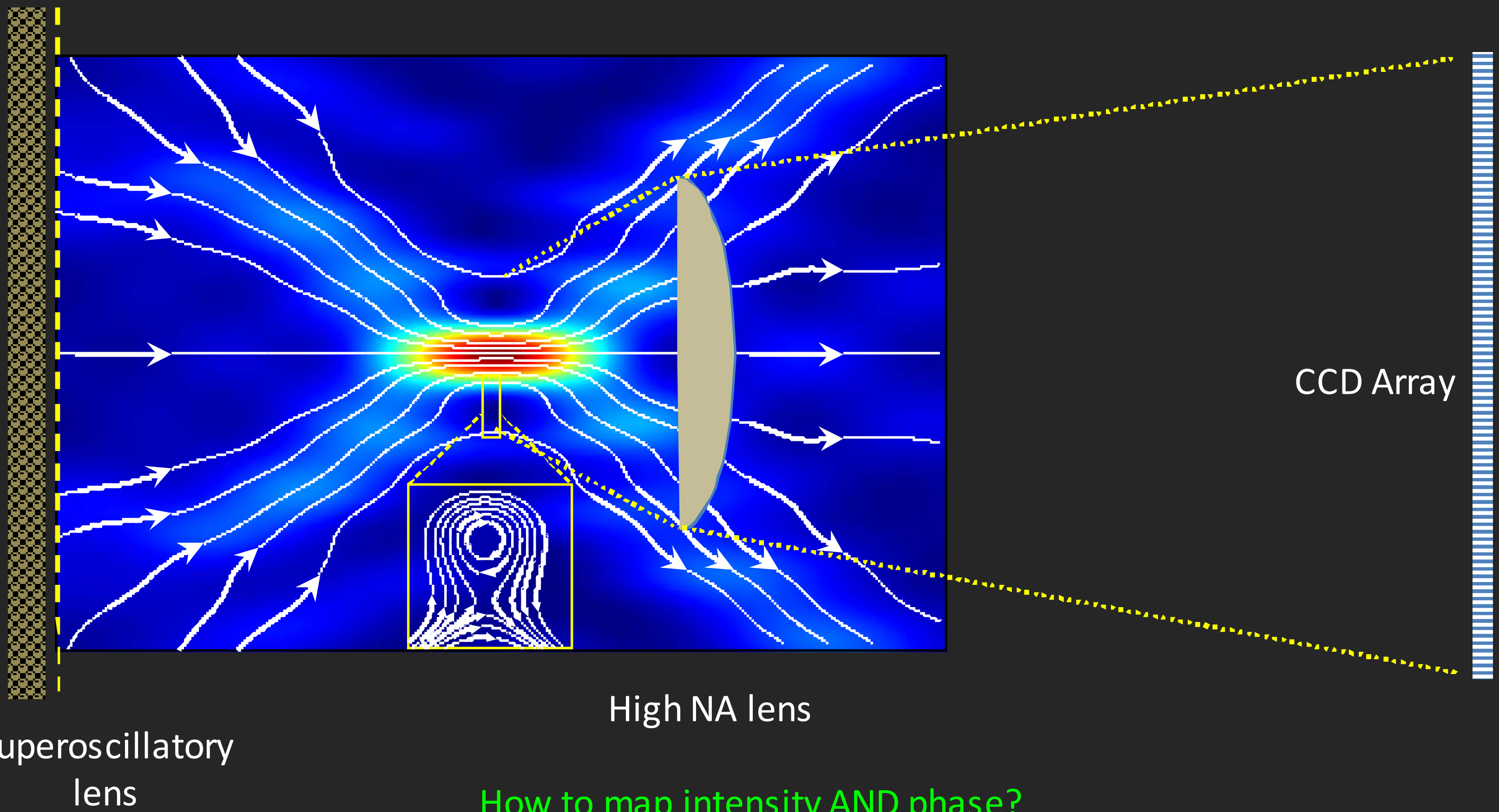


"… the regions of backflow are considerably smaller than the wavelength; this reflects the well-known fact that in the neighbourhood of phase singularities wavefunctions can vary on sub-wavelength scales."

B.V.Berry. Quantum backflow, negative kinetic energy, and optical retro-propagation| J.Phys. A: Math. Theor. 43, 415302 (2010)

How to map complex superoscillatory field?

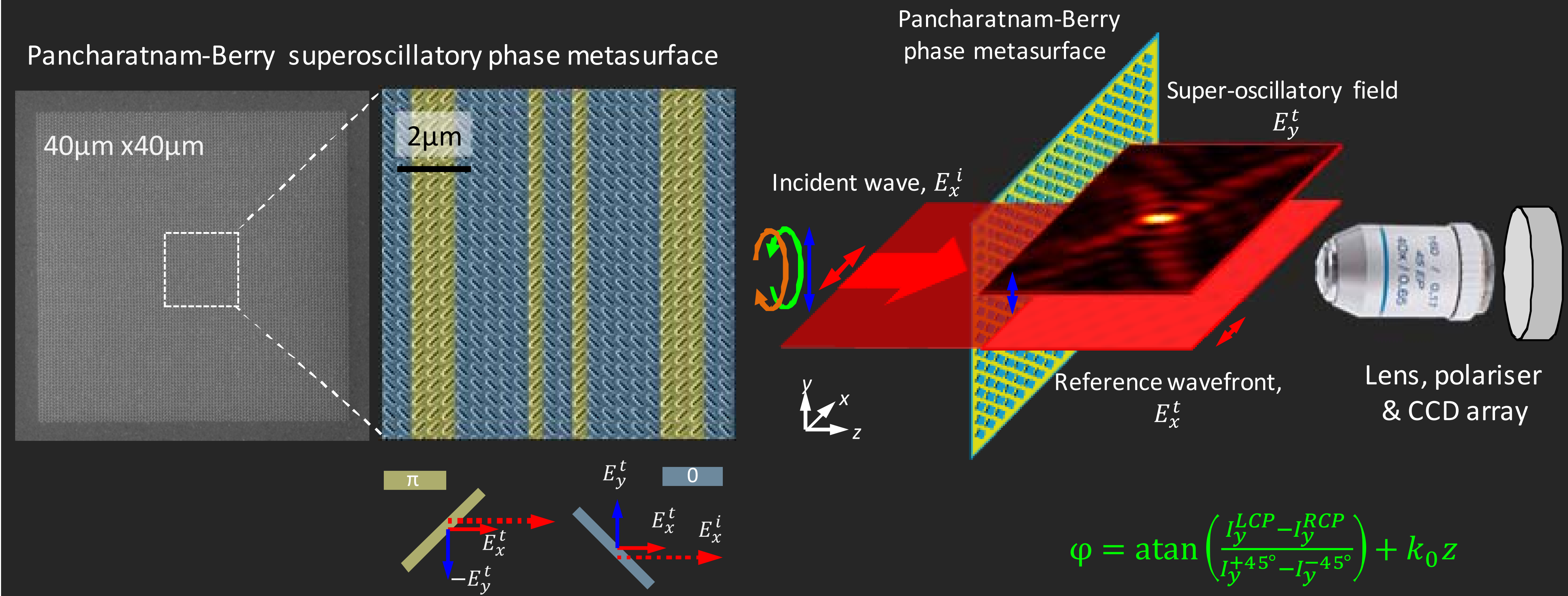
(that has some very small features…)



How to map intensity AND phase?

How to do this with deep sub-wavelenghth resolution?

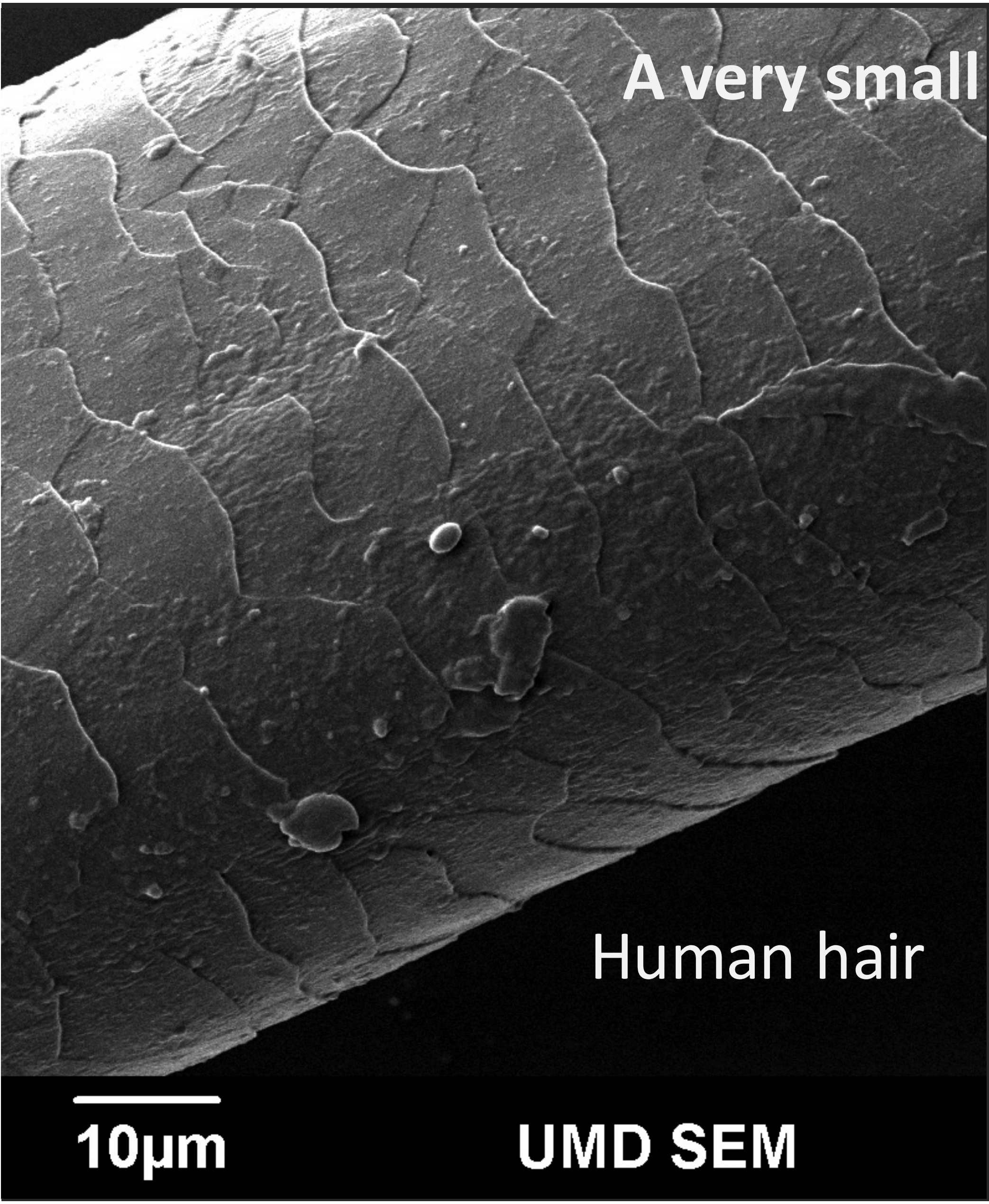
How to map structure of superoscillatory field?

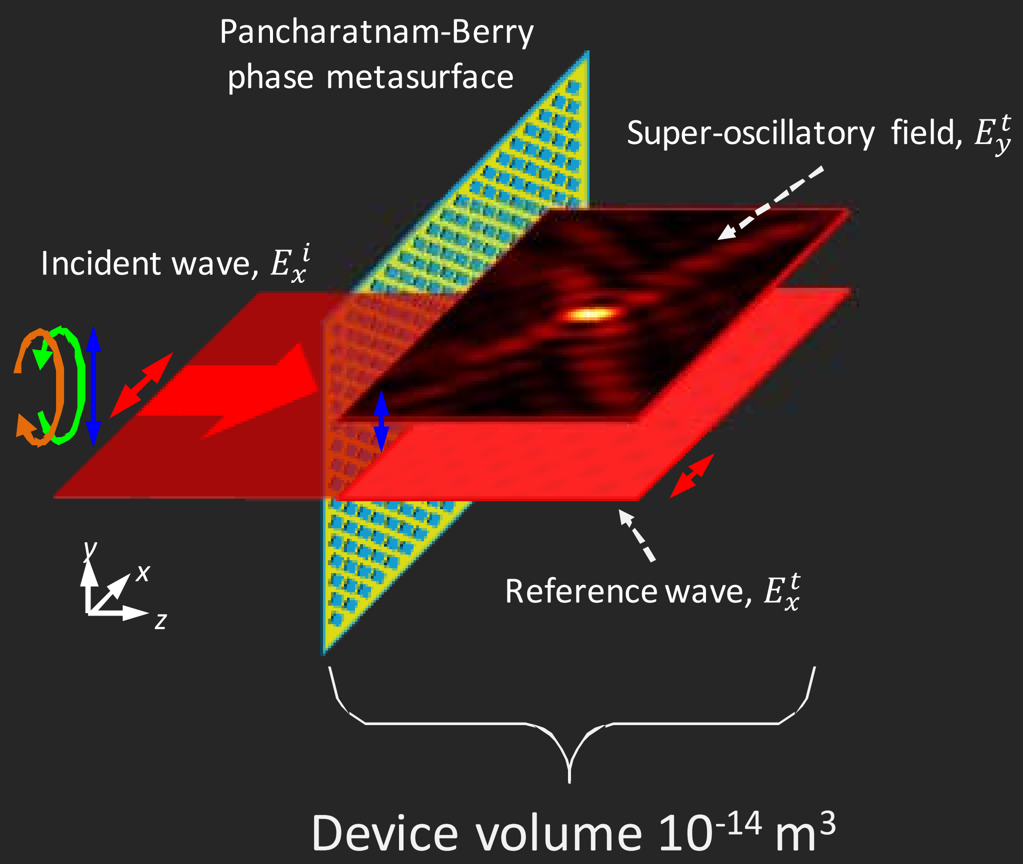


$$\varphi = \text{atan}\left(\frac{I_y^{LCP} - I_y^{RCP}}{I_y^{+45°} - I_y^{-45°}}\right) + k_0 z$$

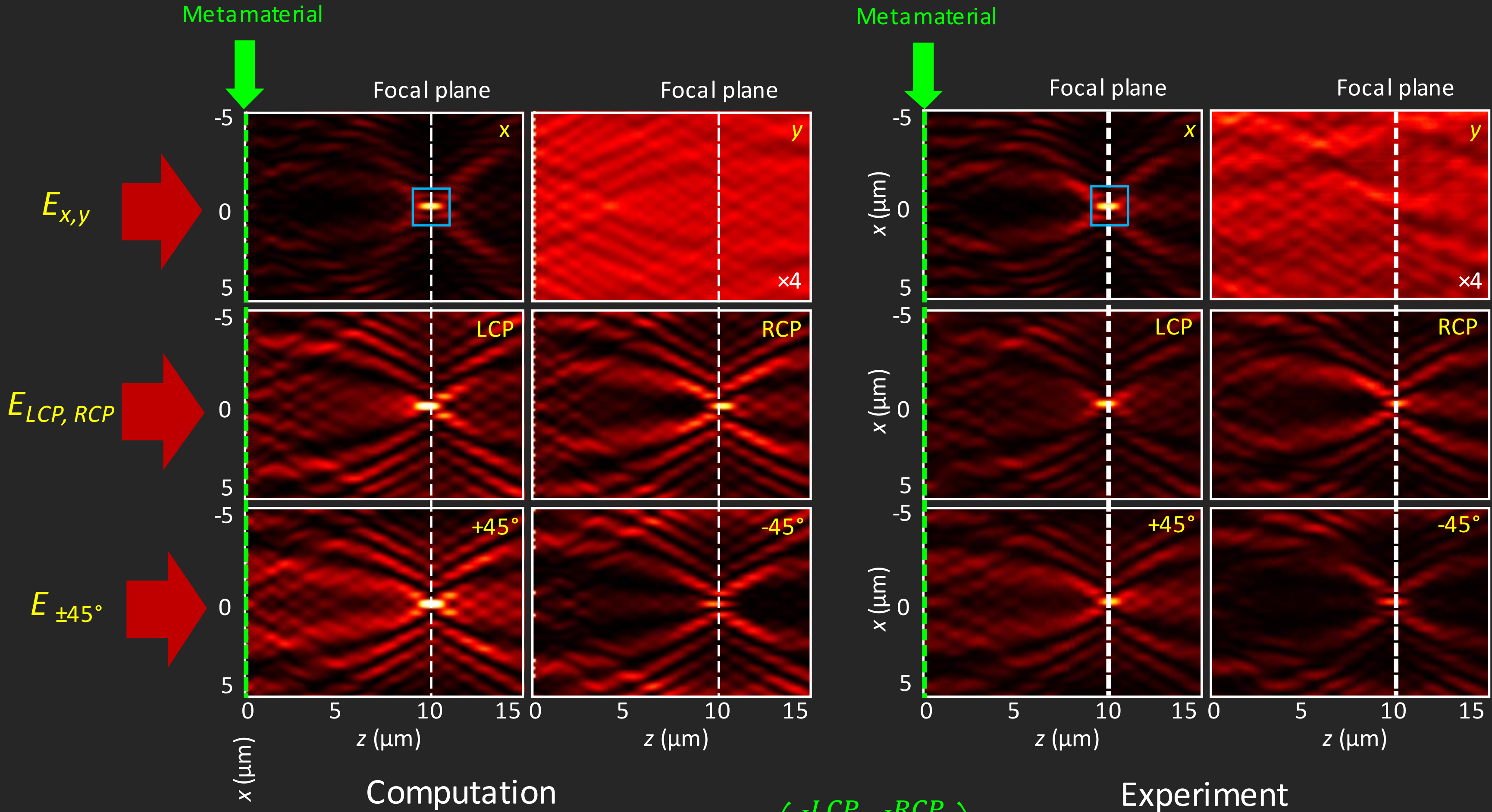
"Plasmonics" in free space: observation of giant wavevectors, vortices and energy backflow in super-oscillatory optical filed
Yuan, Rogers and Zheludev. Nature | Light Science and Applications, **8**, 2 (2019)

A very small interferometer ...



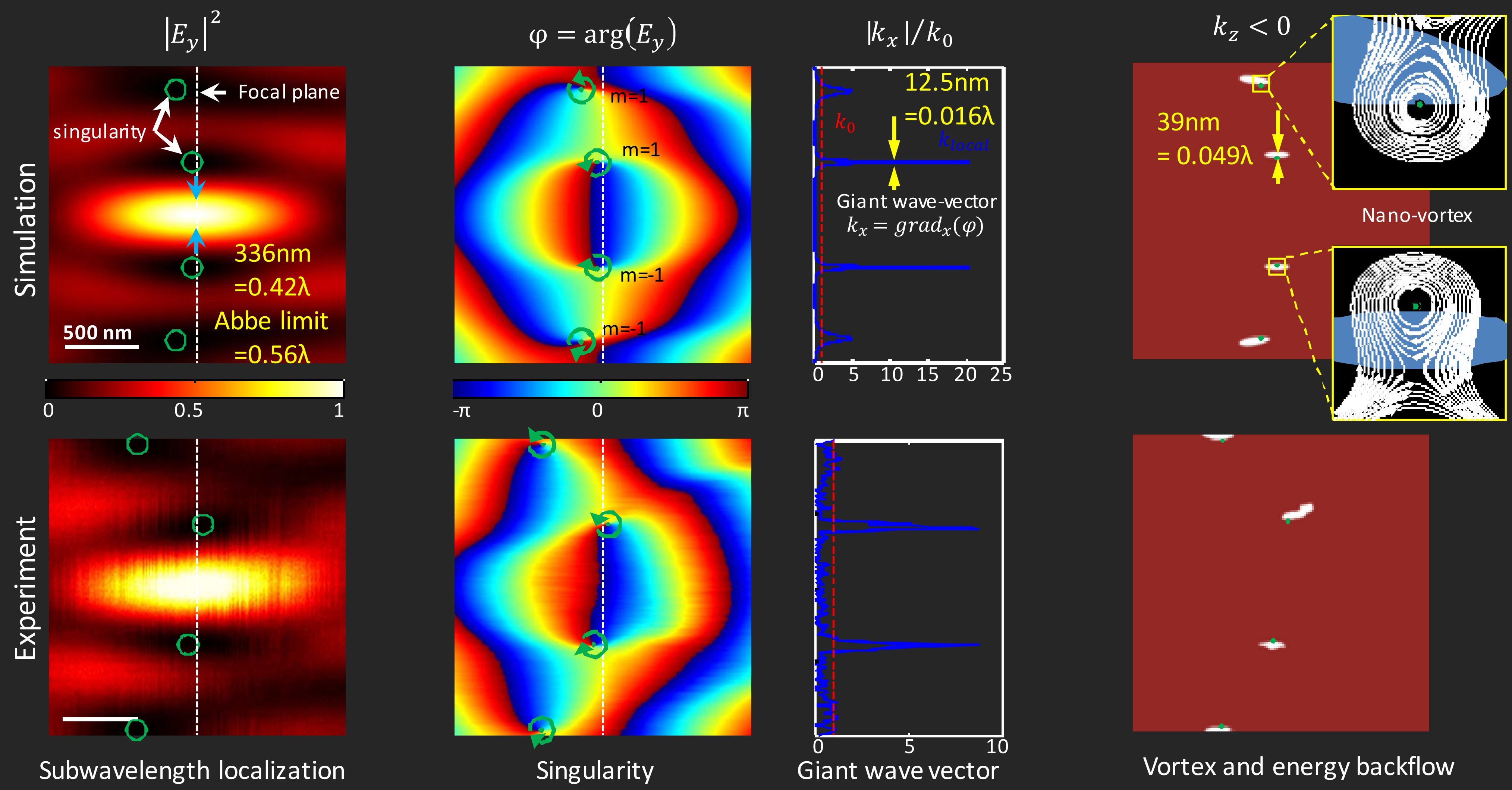


Superoscillatory intensity maps for different incident polarizations



$$\varphi_{TE} = \mathrm{atan}\left(\frac{I_y^{LCP} - I_y^{RCP}}{I_y^{+45°} - I_y^{-45°}}\right) + k_0 z$$

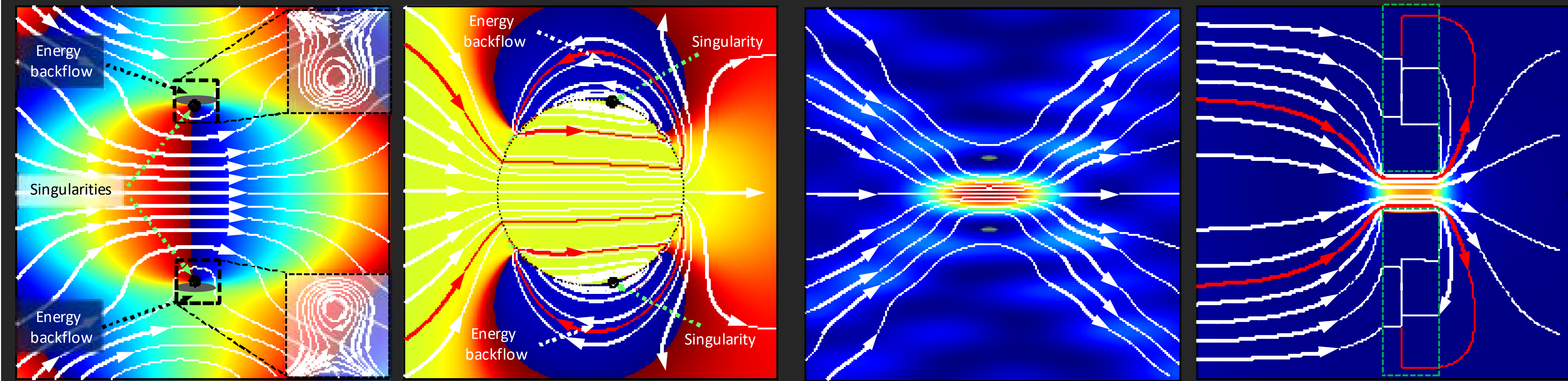
Phase singularities, nano-vortices, giant wave vectors and energy backflows at the super-oscillatory hotspot



"Plasmonics" in free space

(Evanescent plamonic waves vs free-space super-oscillatory fields)

Superoscillatory field in free space | Plasmonic resonance on a nanowire | Superoscillatory focus in free space | Nanohole in plasmonic layer



Phase map, pointing vector, singularities and energy backflow zones | Phase map, Pointing vector, singularities and energy backflow zones | Intensity map and Pointing vector | Intensity map and Pointing vector

Similarities:

1. Large local k-vectors
2. Phase singularities
3. Nano-vortices
4. Energy backflow

Similarities:

1. Light localization
2. Nanohole throughput efficiency ~ $(a/\lambda)^4$
3. Nanoparticle: absorption cross-section ~ $a^2 (a/\lambda)^4$
4. Superoscillations throughput efficiency ~ $P(a/\lambda)$

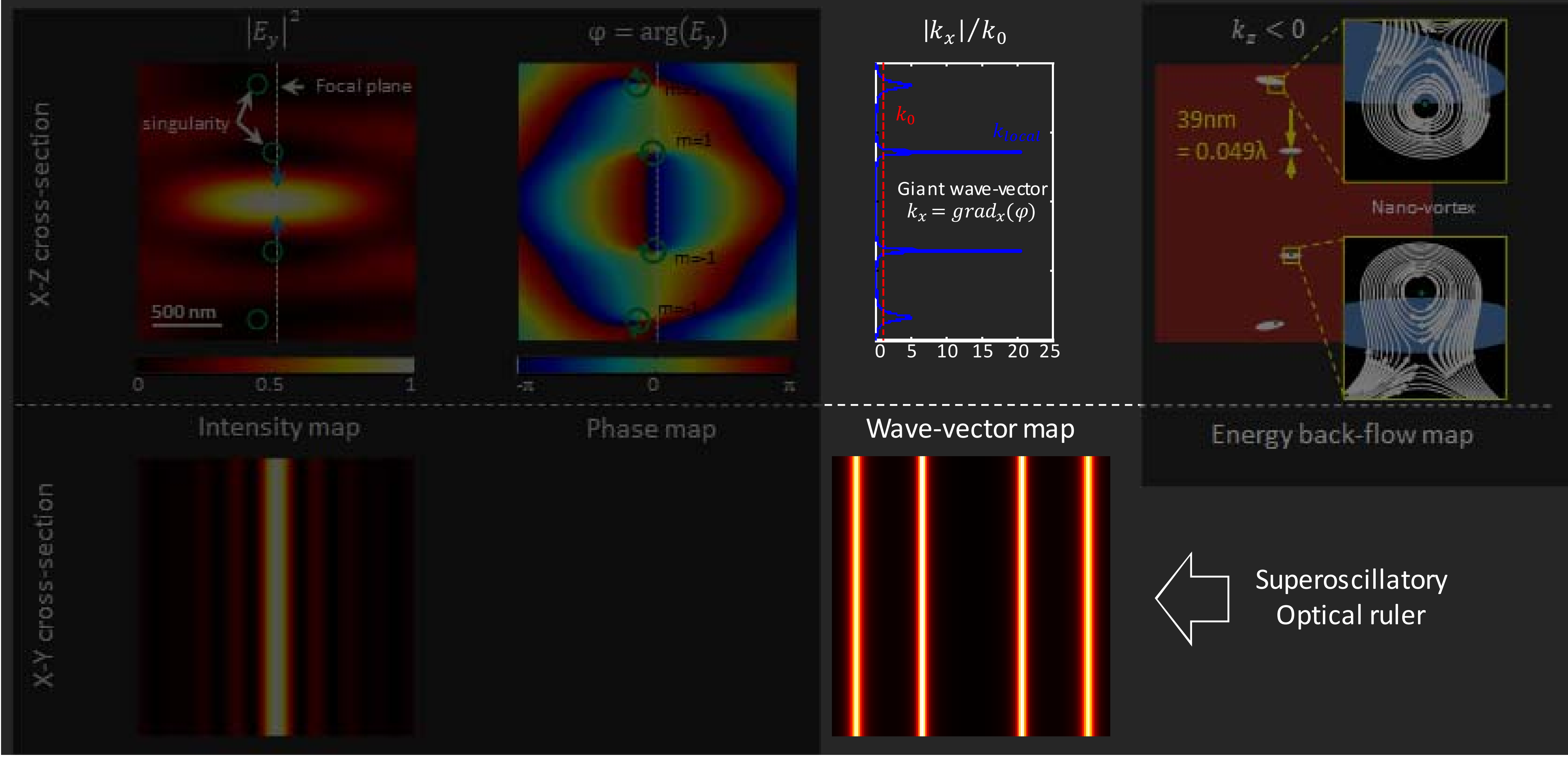
"Plasmonics" in free space: observation of giant wavevectors, vortices and energy backflow in super-oscillatory optical filed

Yuan, Rogers and Zheludev. Nature| Light Science and Applications, **8**, 2 (2019)

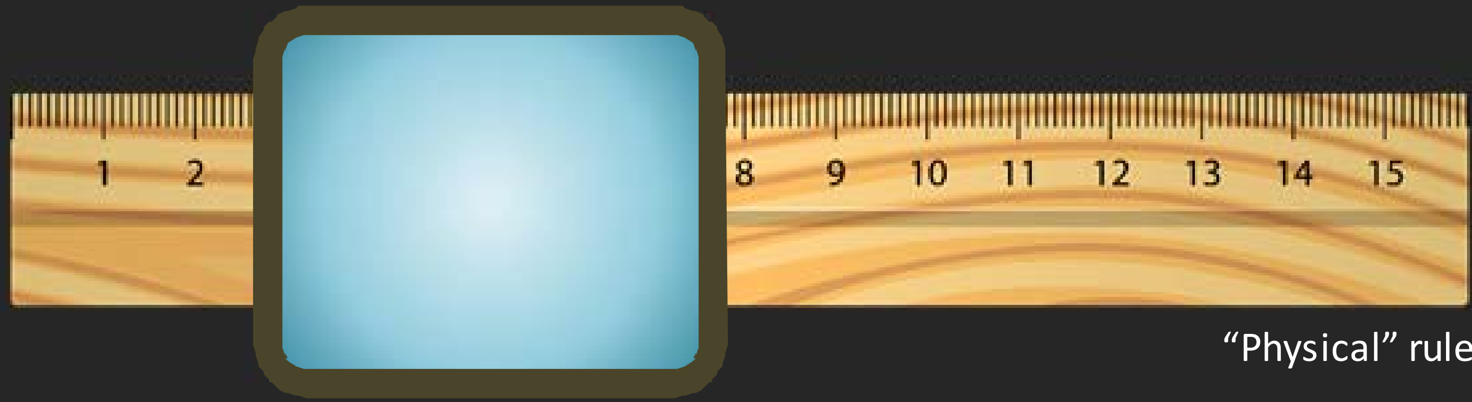
Nanometrology with Deeply Subwavelength Structured Light

“Optical Ruler”

“Optical Ruler”

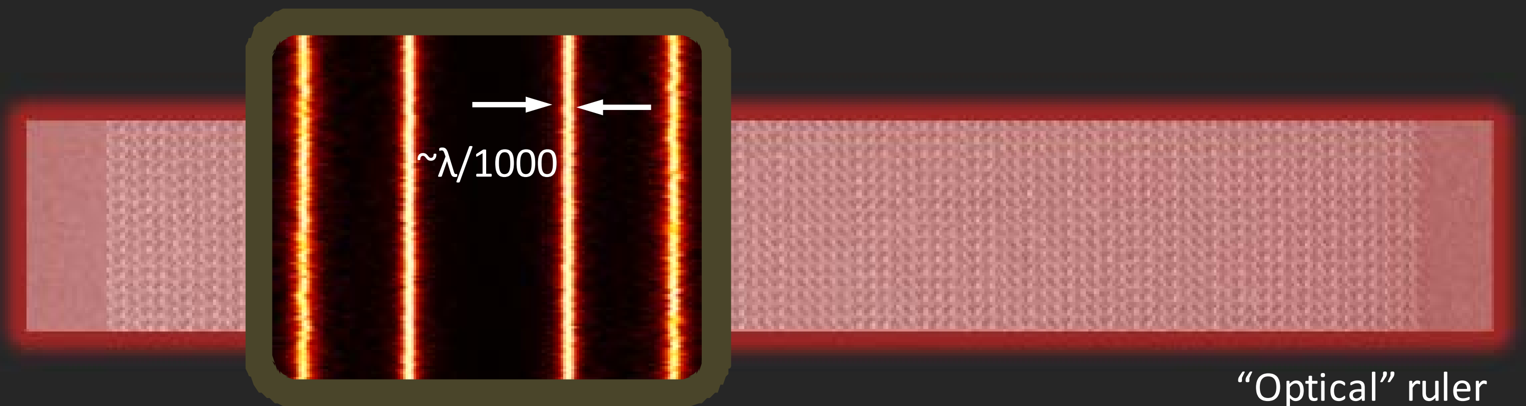


Optical Ruler



“Physical” ruler

Resolution of far-field metrology with conventional ruler is limited to ~ λ/2



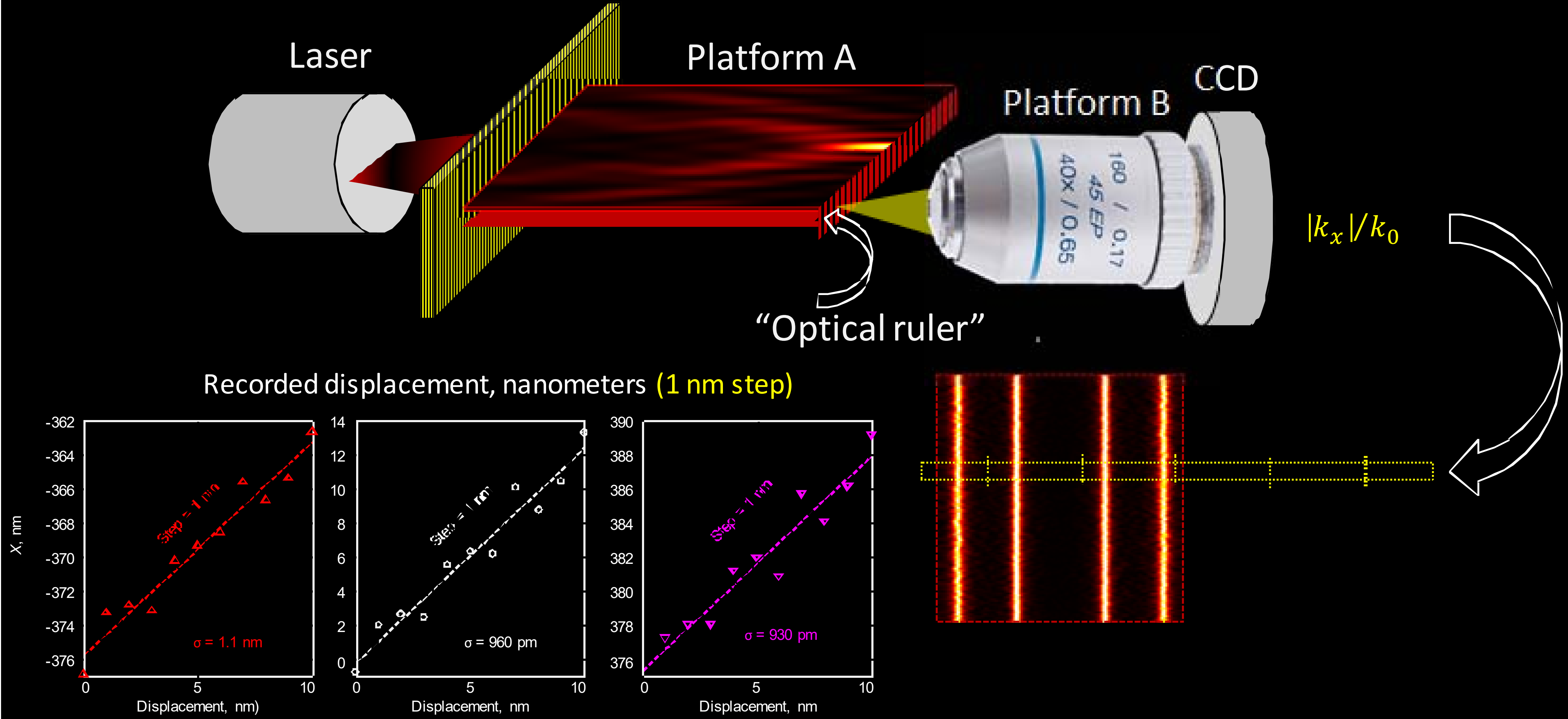
“Optical” ruler

Resolution of far-field metrology with “optical” ruler can be orders of magnitude higher than λ/2

Detecting nanometric displacements with optical ruler metrology

Yuan & Zheludev. *Science*, 364, 771 (2019)

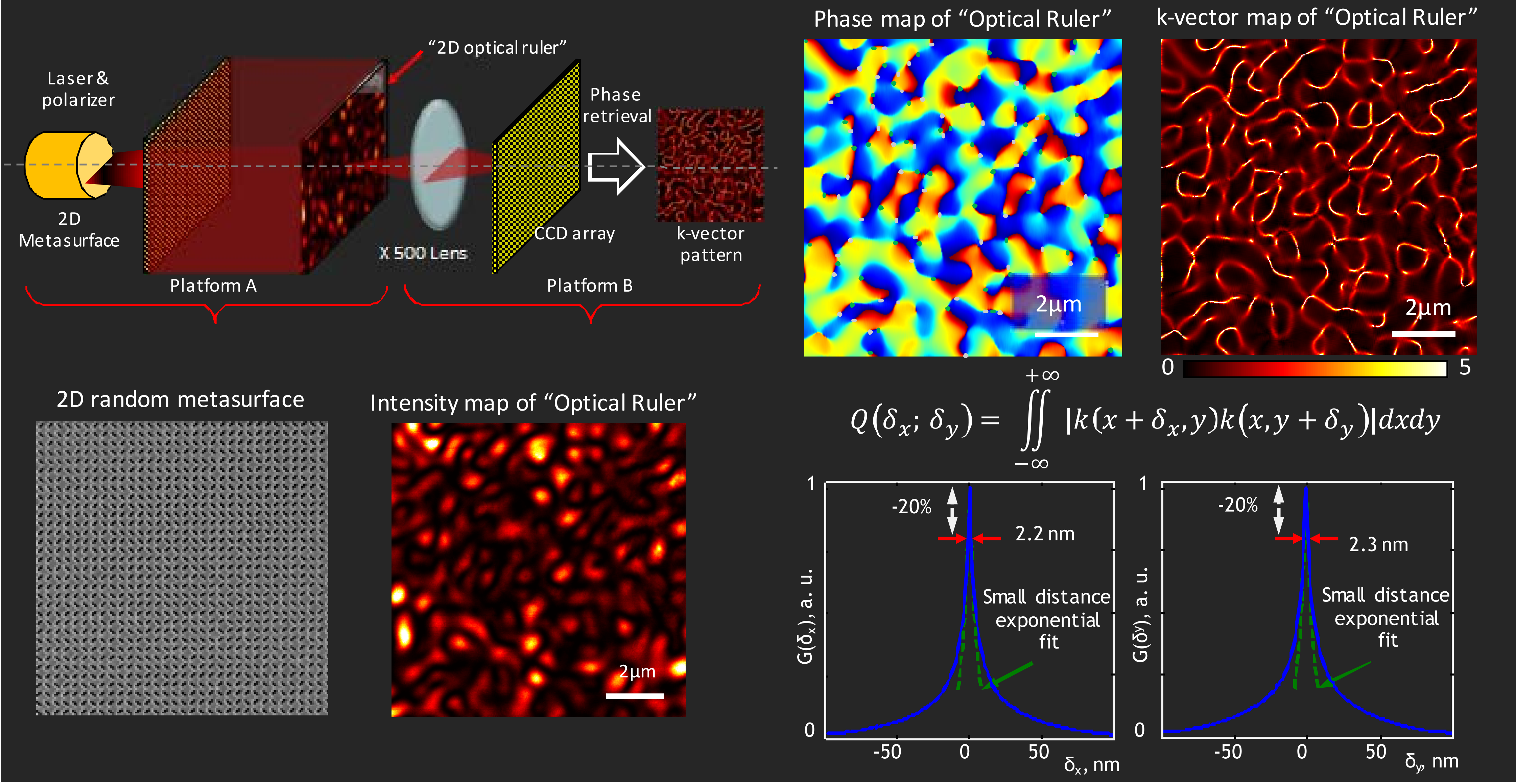
“Optical ruler” displacement metrology



Detecting nanometric displacements with optical ruler metrology

Yuan & Zheludev. *Science*, 364, 771 (2019)

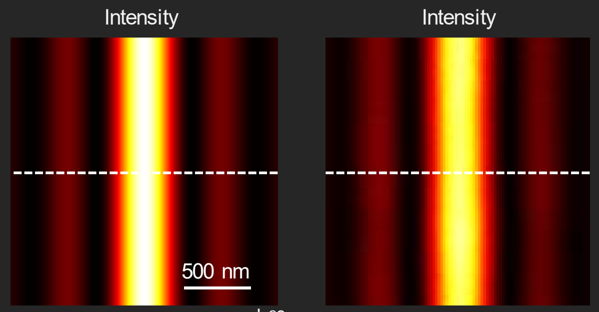
Superoscillatory displacement metrology 2D



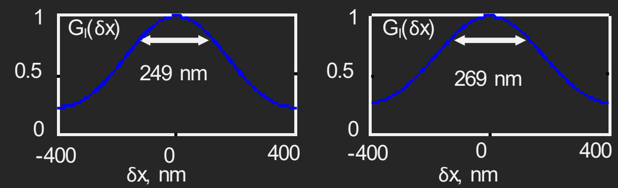
$$Q(\delta_x;\,\delta_y) = \iint_{-\infty}^{+\infty} |k(x+\delta_x, y)k(x, y+\delta_y)|\,dxdy$$

Resolution of 1D optical ruler displacement metrology

“Optical ruler” intensity profile

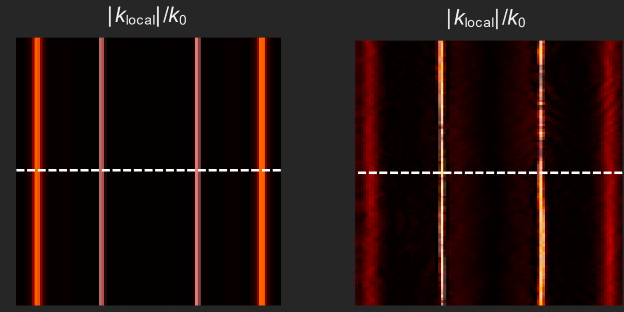


$G(\delta x) = \int_{-\infty}^{+\infty} I(x)I(x+\delta x)dx$

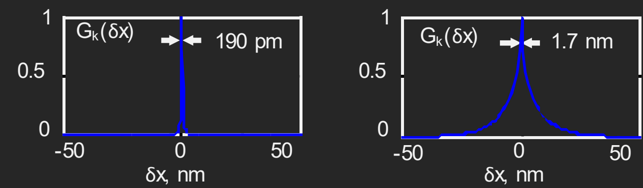


← Autocorrelation functions →

“Optical ruler” –wave-vector profile: $|k_{local}|/k_0$



$G(\delta x) = \int_{-\infty}^{+\infty} |k(x)k(x+\delta x)|dx$



Potential resolution of the optical ruler metrology

λ = 800nm; NA= 0.89	**Imaging a ruler**	**Imaging a ruler (superoscillatory)**	**Imaging an “optical ruler”**
Spot size	449 nm (λ/1.6)	336 nm (λ/2.4)	2.1 nm (λ/380)
Resolution from $G(\delta x)$ (-20%)	**360 nm (λ/2.2)**	249 nm (λ/3.2)	**190 pm (λ/4200)**

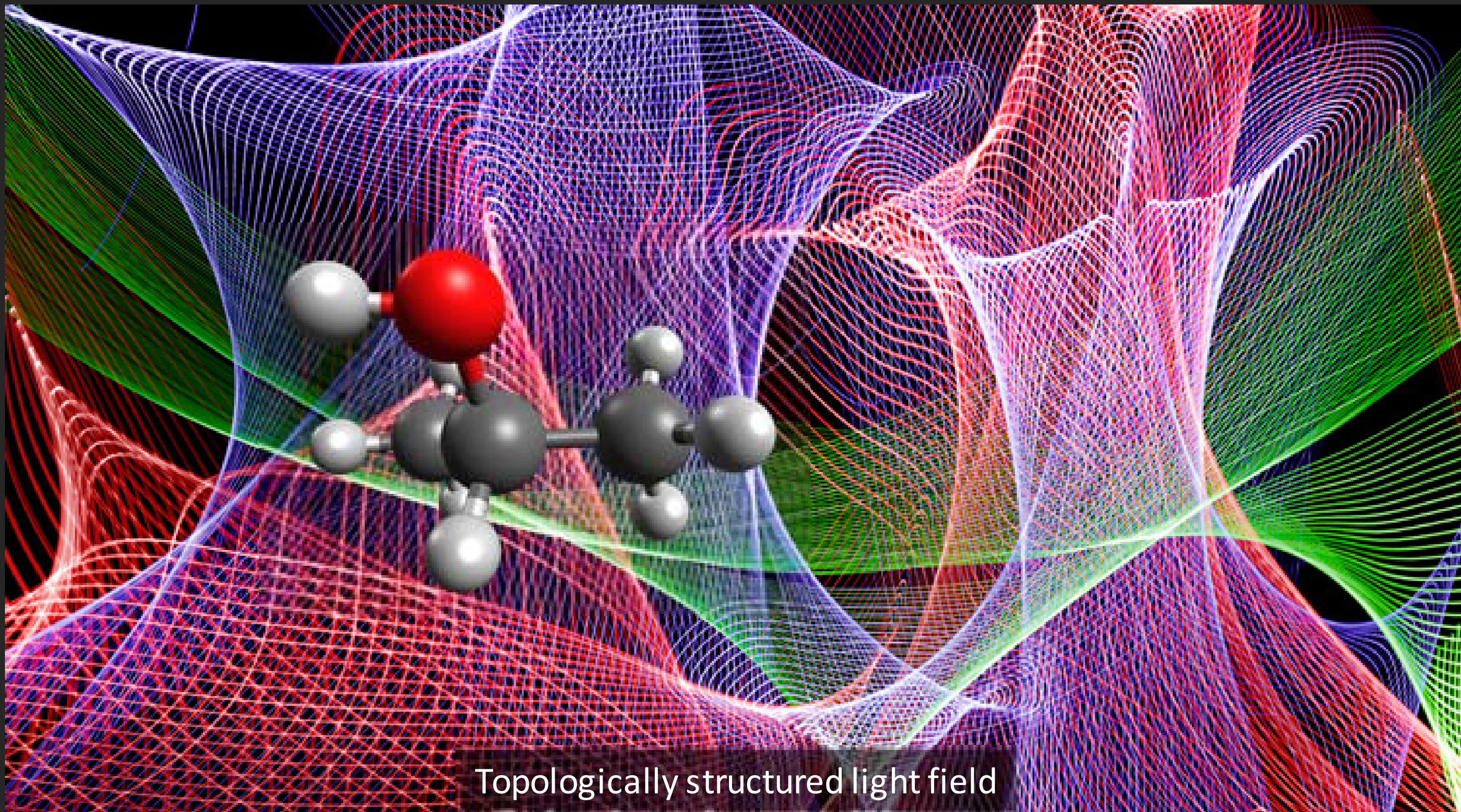
Detecting nanometric displacements with optical ruler metrology
Yuan & Zheludev. *Science*, 364, 771 (2019)

Deeply subwavelength imaging enabled by Artificial Intelligence

(Educating the Microscope)

Deeply Subwavelength Imaging

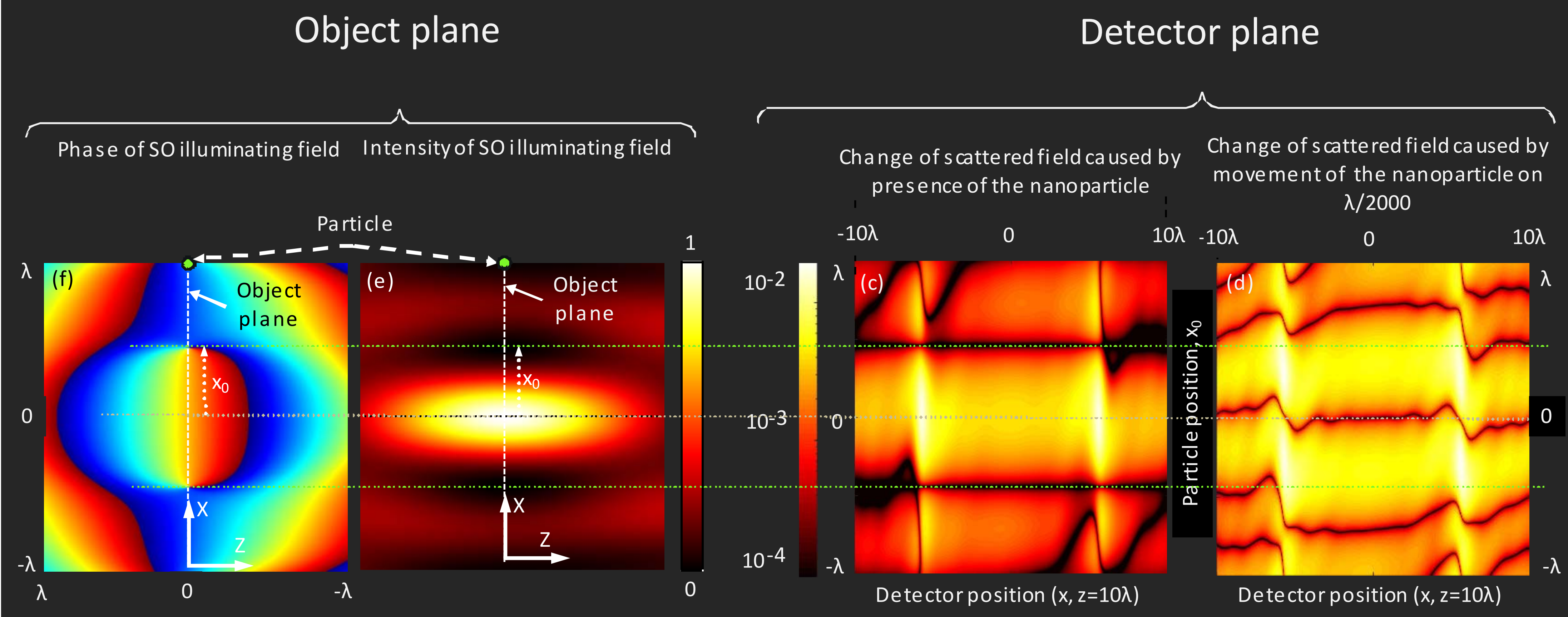
with Topological Illumination



Unlabelled Far-field Deeply Subwavelength Superoscillatory Imaging

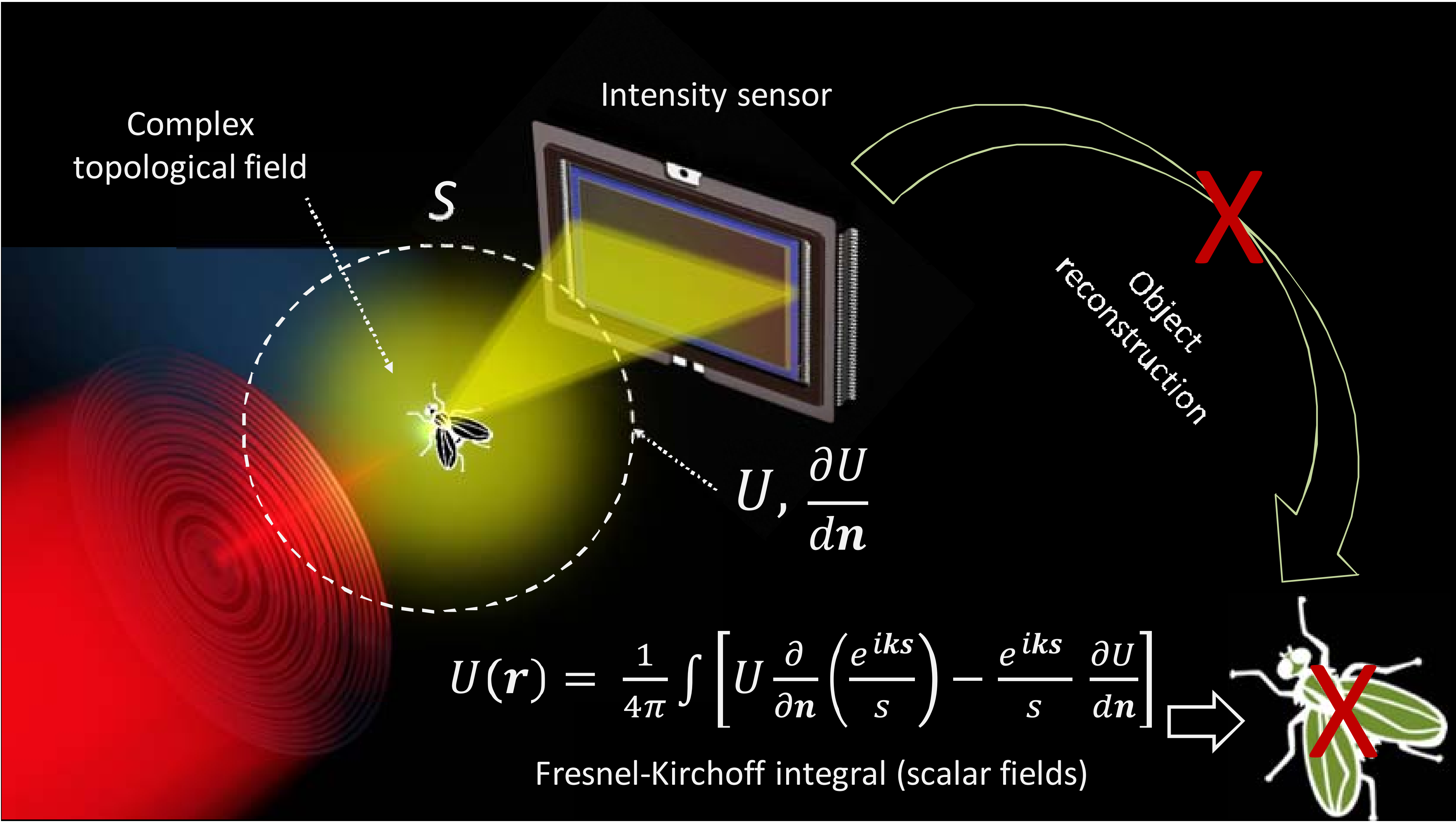
Pu, Savinov, Yuan, Papasimakis, Zheludev. arXiv:1908.00946 (2019)

Scattering of superoscillatory field by a λ/1000 nanoparticle



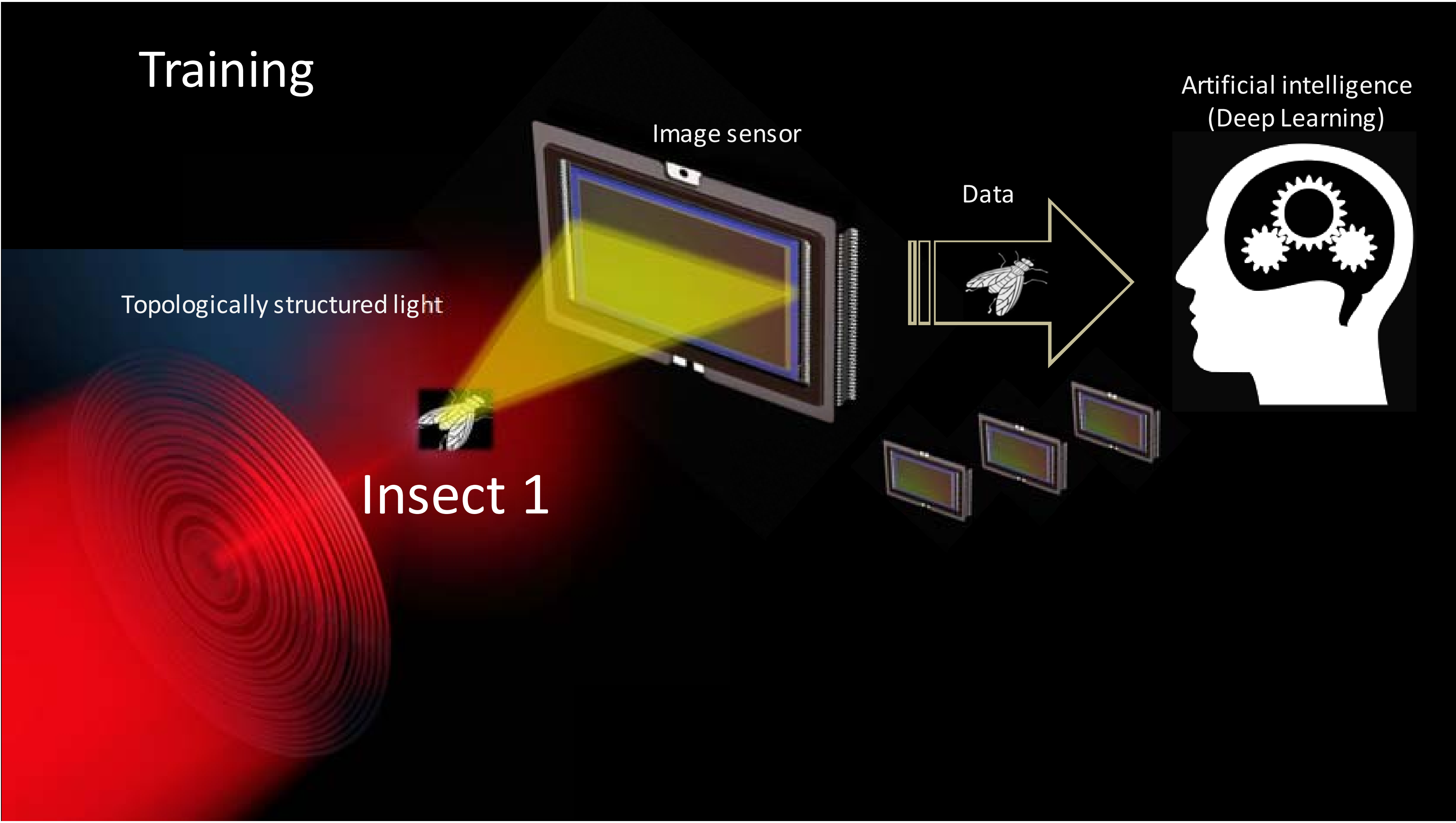
Unlabelled Far-field Deeply Subwavelength Superoscillatory Imaging (DSSI)

Pu, Savinov, Yuan, Papasimakis, Zheludev. **Advanced Science**, in press (2020). arXiv:1908.00946 (2019).

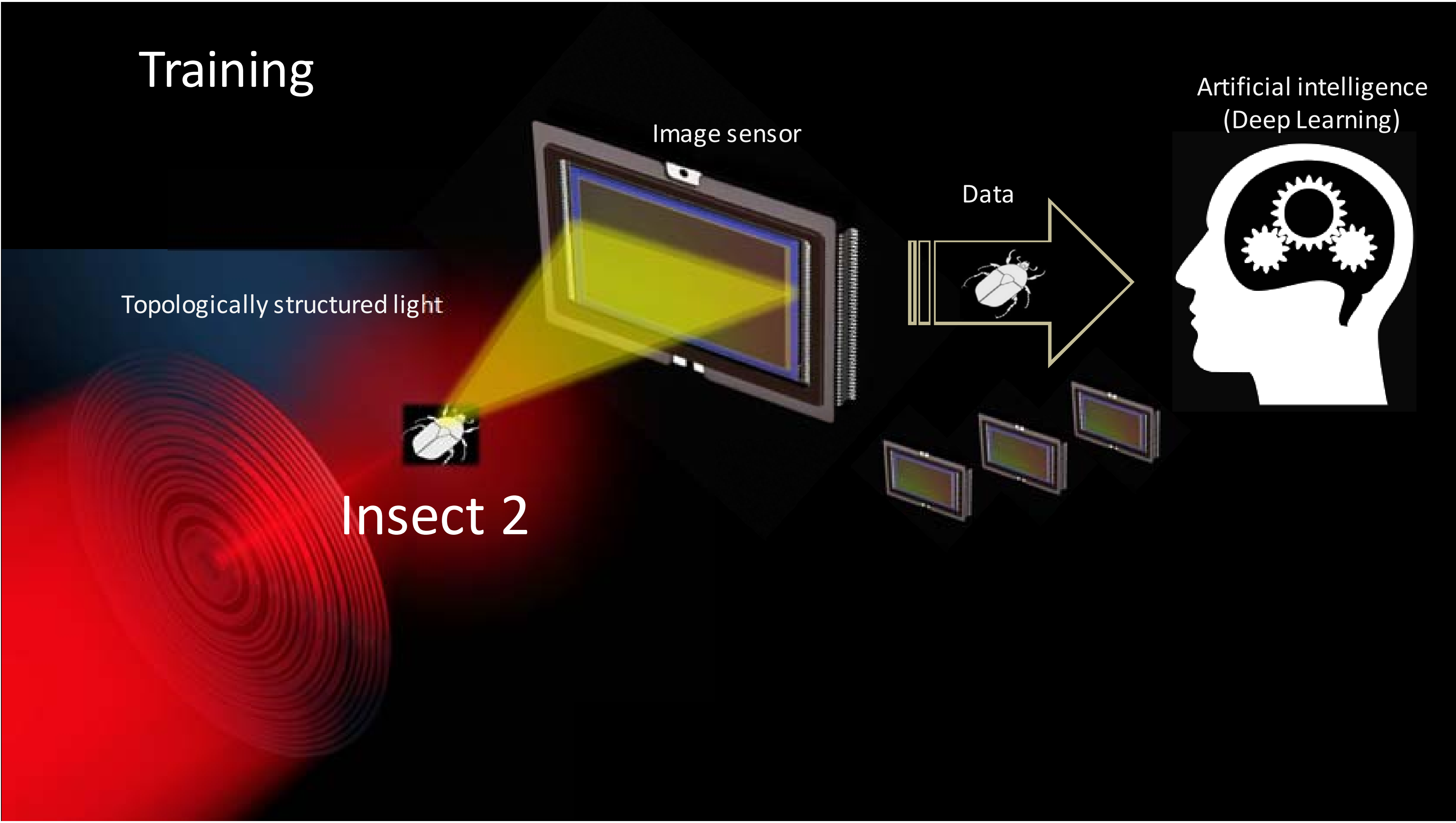

Intensity sensor
Complex
topological field
S
Object
reconstruction
$U, \frac{\partial U}{dn}$
$U(\boldsymbol{r}) = \frac{1}{4\pi}\int\left[U\frac{\partial}{\partial n}\left(\frac{e^{iks}}{s}\right) - \frac{e^{iks}}{s}\frac{\partial U}{dn}\right]$
Fresnel-Kirchoff integral (scalar fields)

Artificial Intelligence (Deep learning) comes to help with ill-posed deconvolution problem

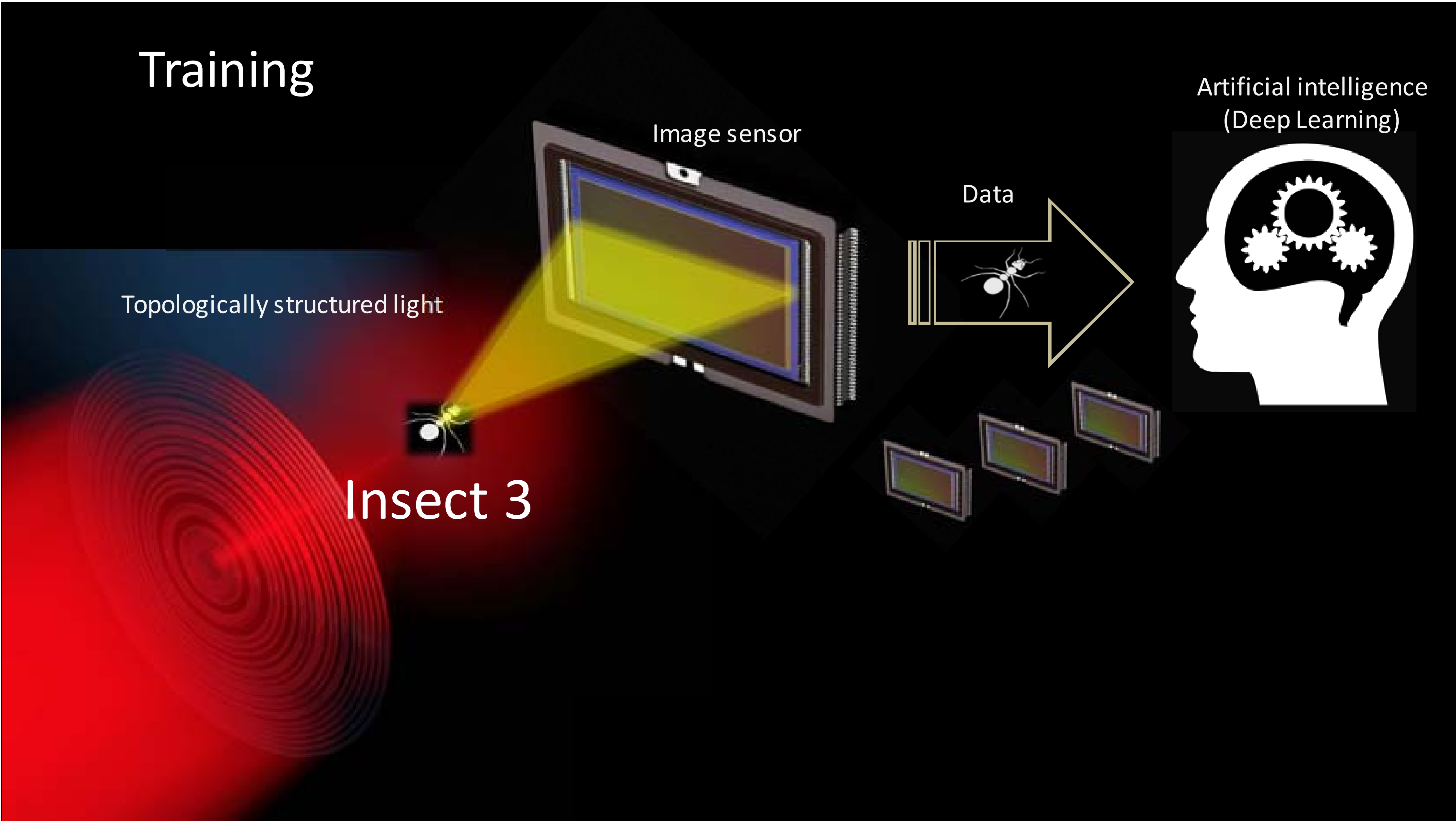
Artificial Intelligence for Photonics and Photonic Materials
Piccinotti, MacDonald, Gregory, Youngs and Zheludev. *Reports on Progress in Physics*, (in press) 2020
https://iopscience.iop.org/article/10.1088/1361-6633/abb4c7



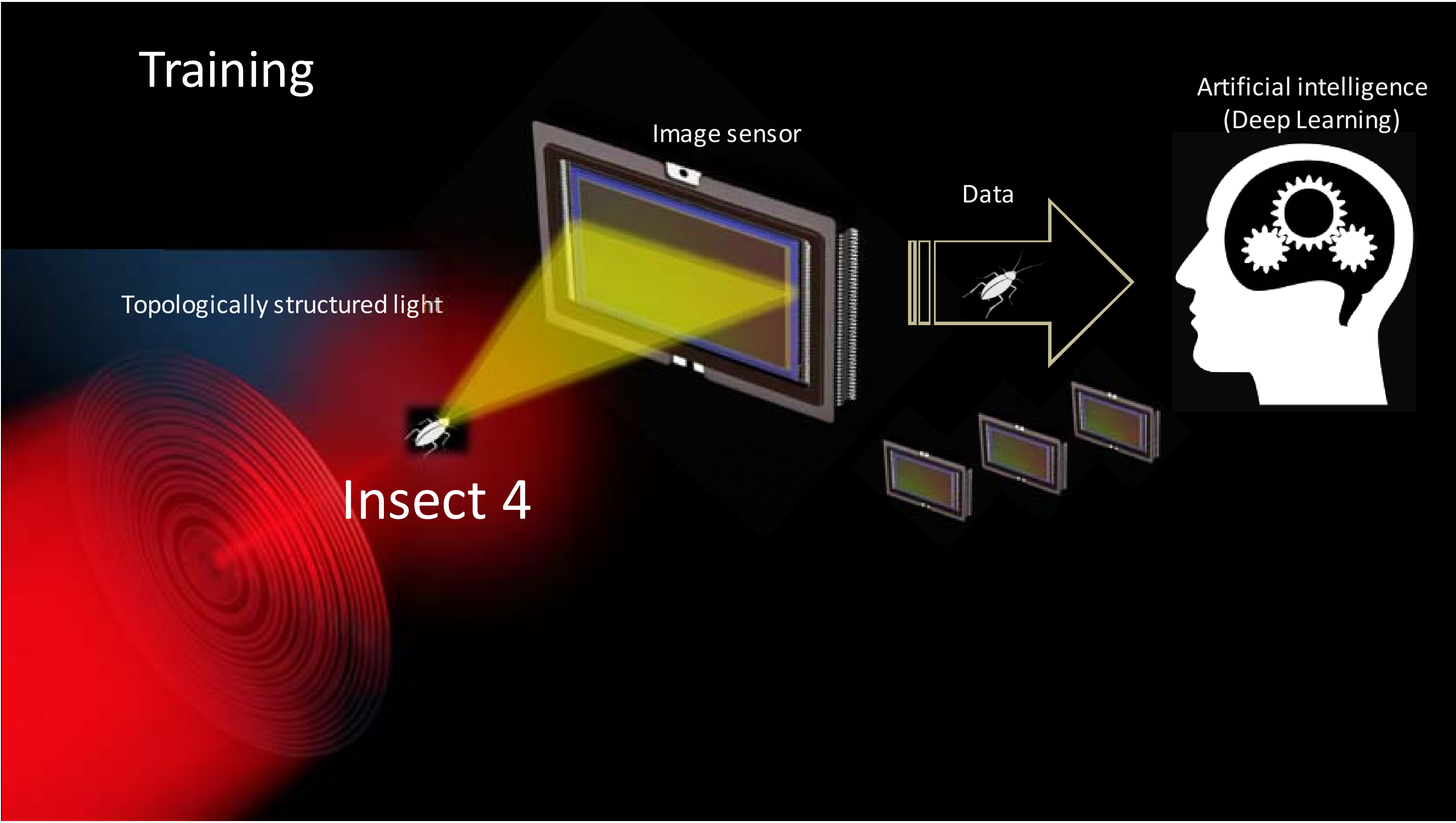
Training
Image sensor
Artificial intelligence
(Deep Learning)
Data
Topologically structured light
Insect 1

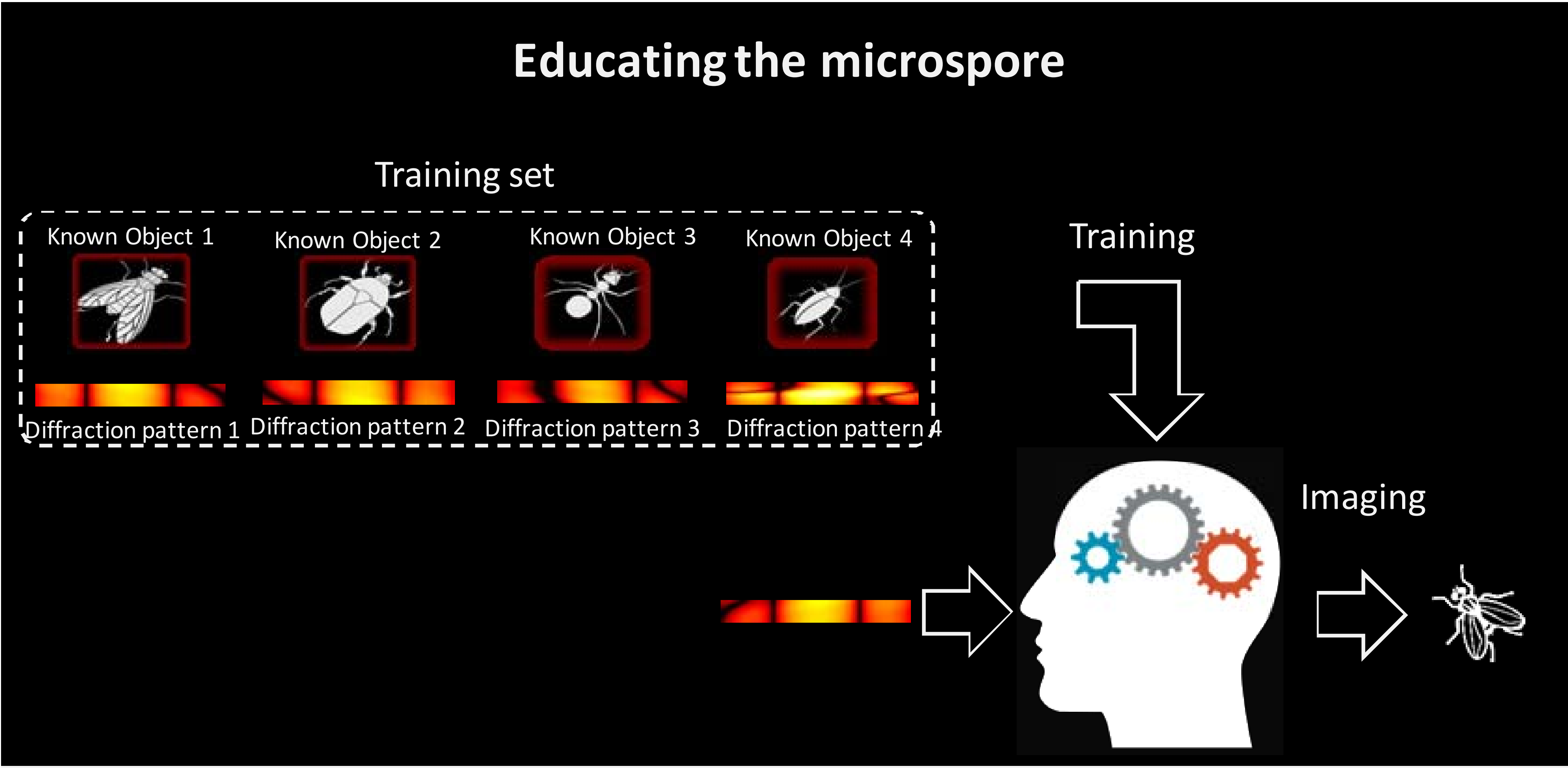


Training
Image sensor
Artificial intelligence
(Deep Learning)
Data
Topologically structured light
Insect 2



Training
Image sensor
Artificial intelligence
(Deep Learning)
Data
Topologically structured light
Insect 3

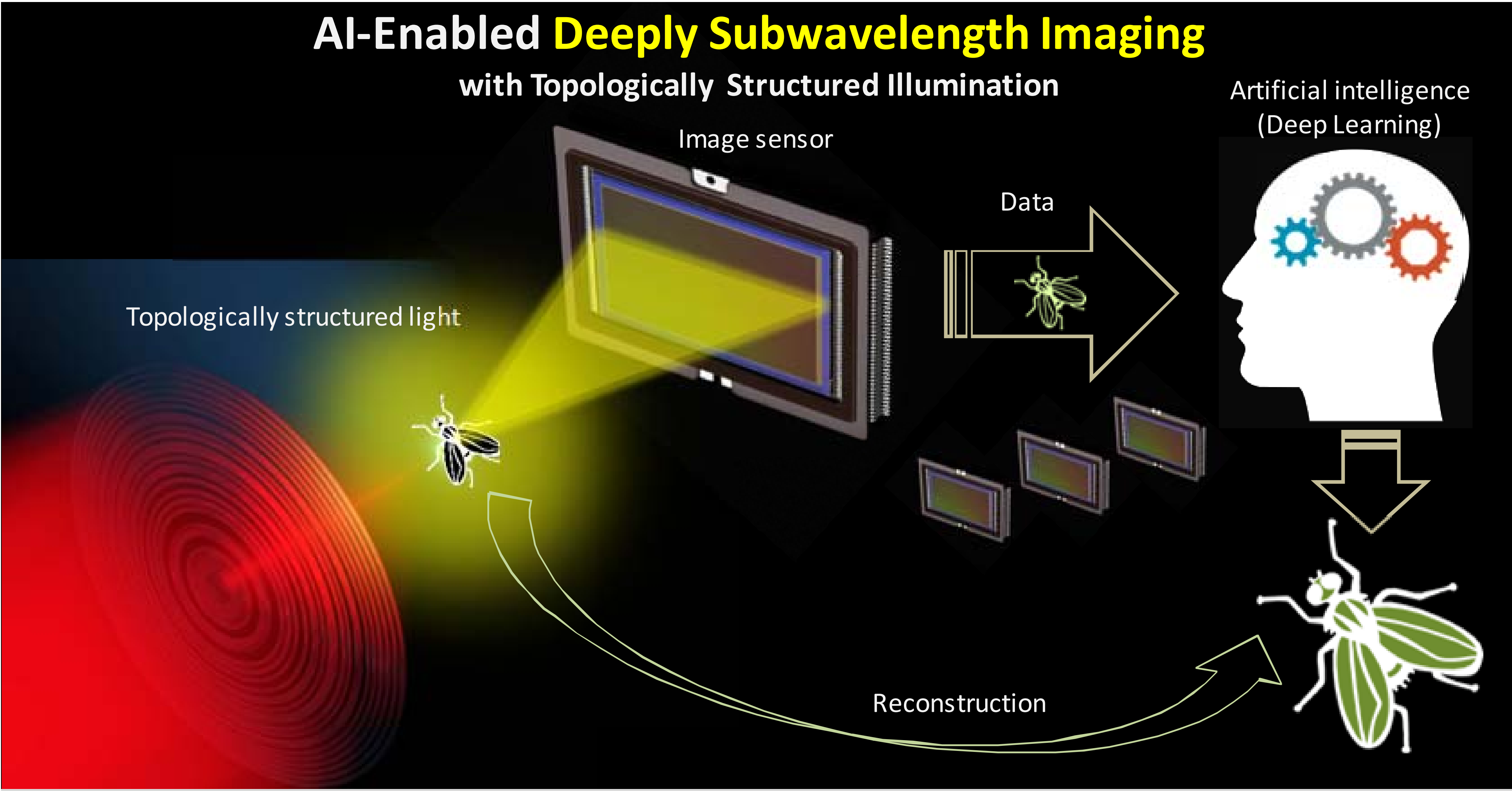

Training
Image sensor
Artificial intelligence
(Deep Learning)
Data
Topologically structured light
Insect 4



Artificial Intelligence for Photonics and Photonic Materials

Piccinotti, MacDonald, Gregory, Youngs and Zheludev. *Reports on Progress in Physics*, (in press) 2020

https://iopscience.iop.org/article/10.1088/1361-6633/abb4c7



Unlabelled Far-field Deeply Subwavelength Superoscillatory Imaging (DSSI)
Pu, Savinov, Yuan, Papasimakis, Zheludev. **Advanced Science**, in press (2020). arXiv:1908.00946 (2019).

How to train an AI microscope?

Computational training set

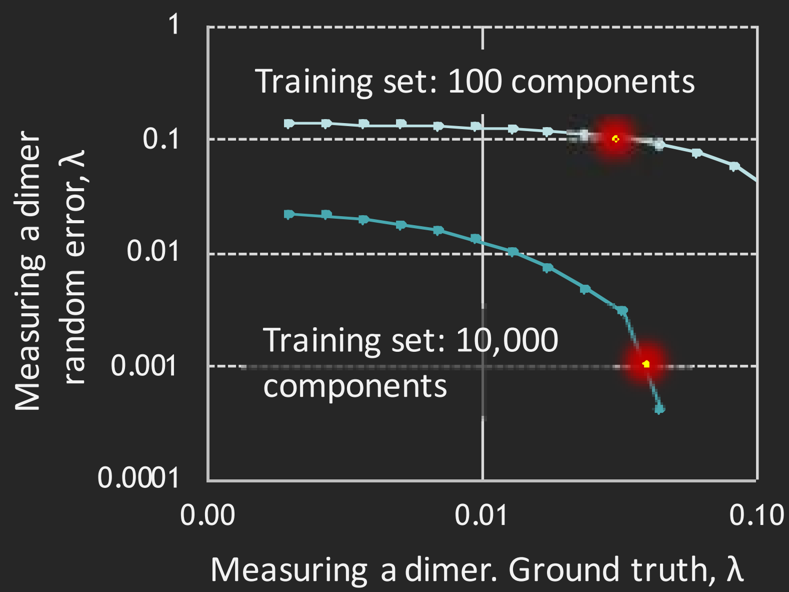
To design a (random) set of test objects → To calculate their diffraction patterns → Microscope's neural network

Easy to generate but difficult to make congruent with the imaging instrument

Physical training set

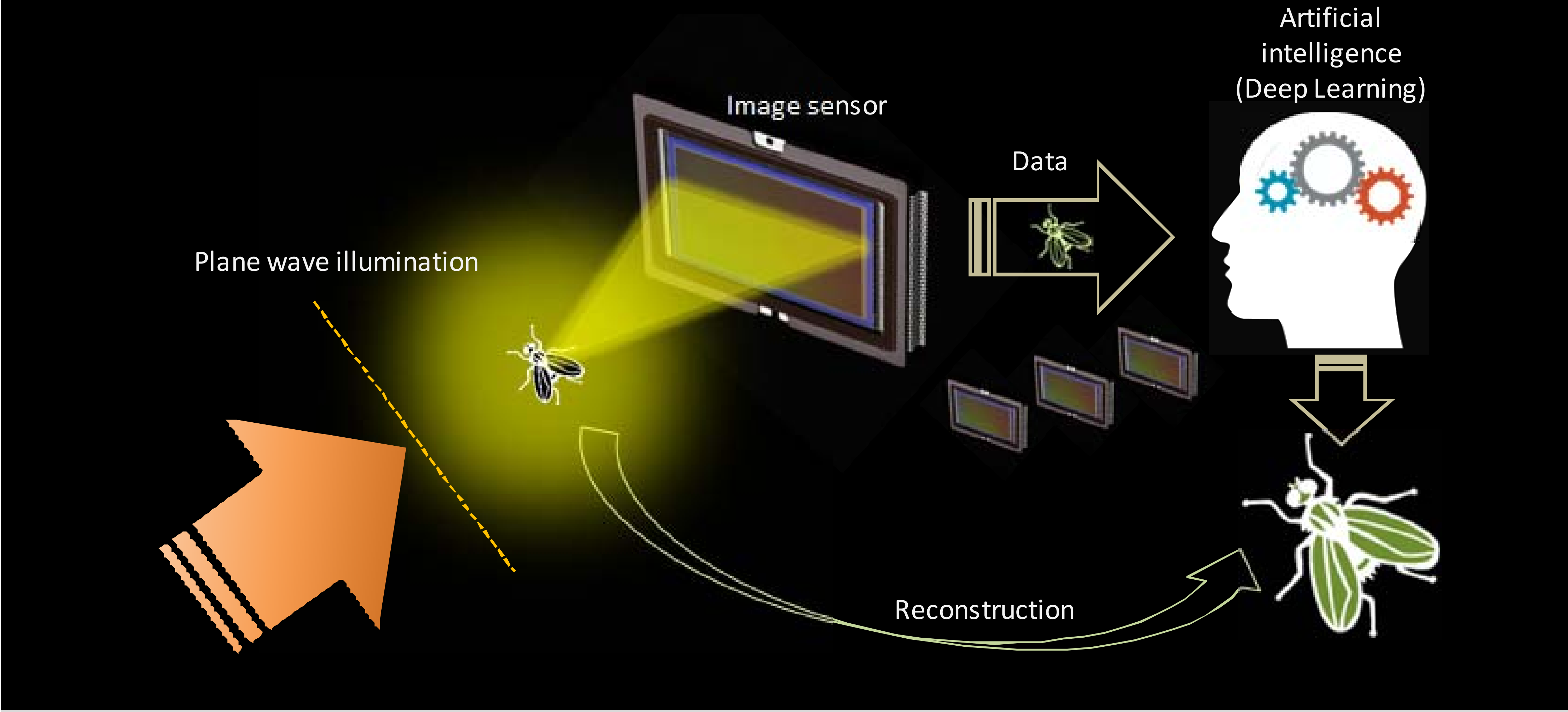
To nano-fabricate a (random) set of test objects → To measure their diffraction patterns → Microscope's neural network

Labor intensive to generate but is naturally congruent with the imaging instrument



AI-Enabled Deeply Subwavelength Imaging

Plane Wave Illumination

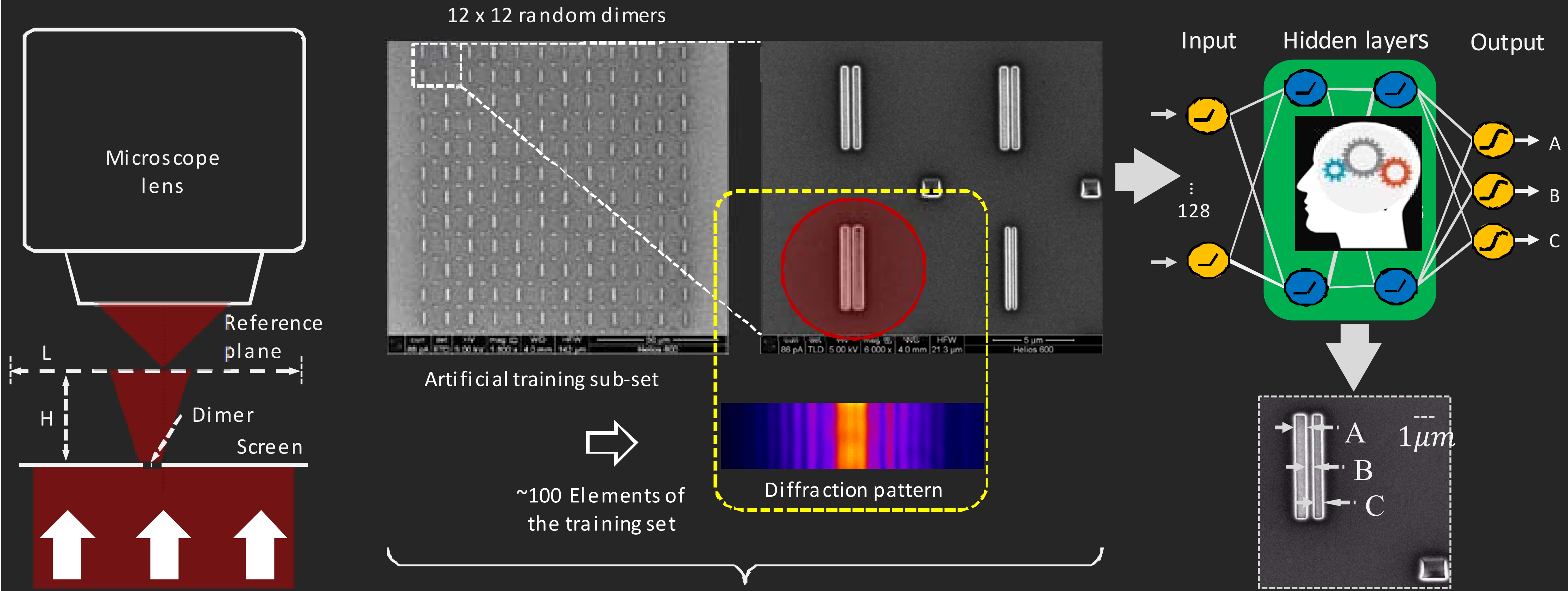


Unlabelled Far-field Deeply Subwavelength Superoscillatory Imaging (DSSI)

Pu, Savinov, Yuan, Papasimakis, Zheludev. **Advanced Science**, in press (2020). arXiv:1908.00946 (2019).

AI-enabled Deeply Subwavelength Imaging of a Dimer:

Plane wave illumination, training set ~ 100



Plane wave illumination

The Training set

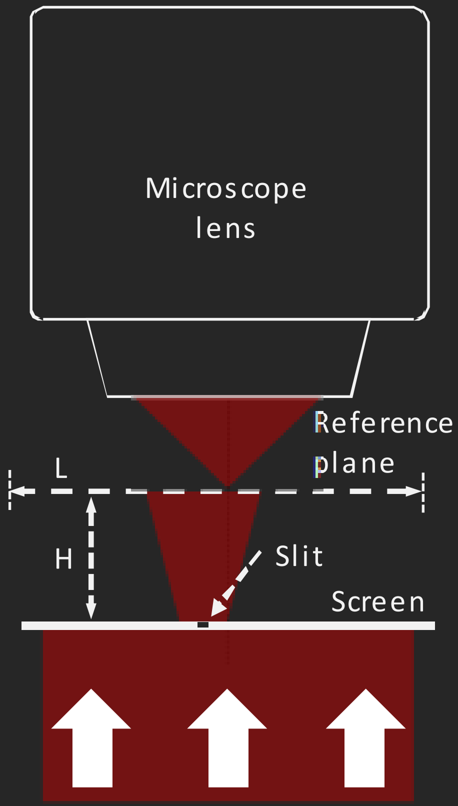
A,B,C, Measured with precision of λ/10 with probability > 95%

Label-free deeply subwavelength optical microscopy

Pu, Ou, Papasimakis and Zheludev. *Appl. Phys. Lett.* **116** 131105 (2020)

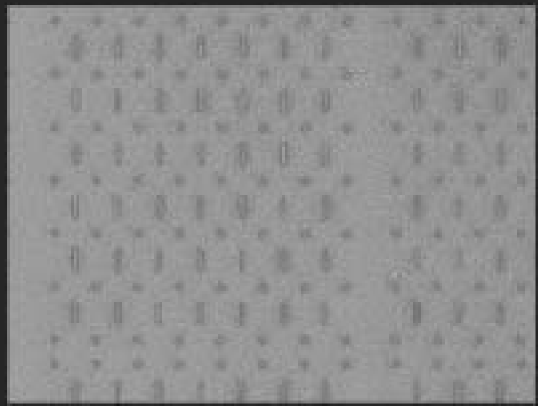
AI-enabled Deeply Subwavelength Imaging of a Monomer:

Plane wave illumination, training set ~ 1000

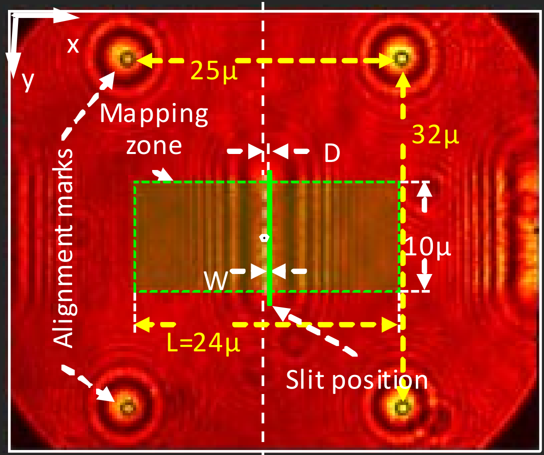


Plane wave illumination, λ=633nm

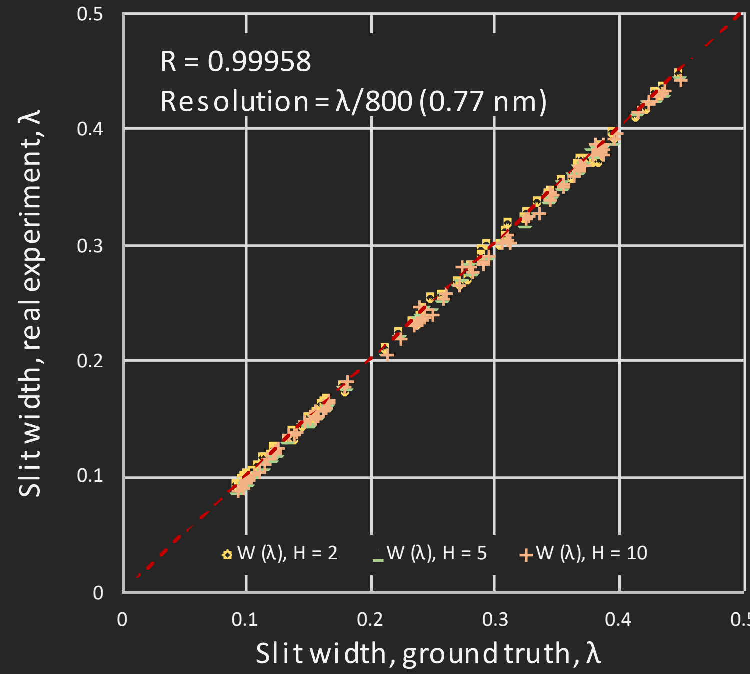
Random **sub-wavelength** slits



Diffraction pattern of a single slit

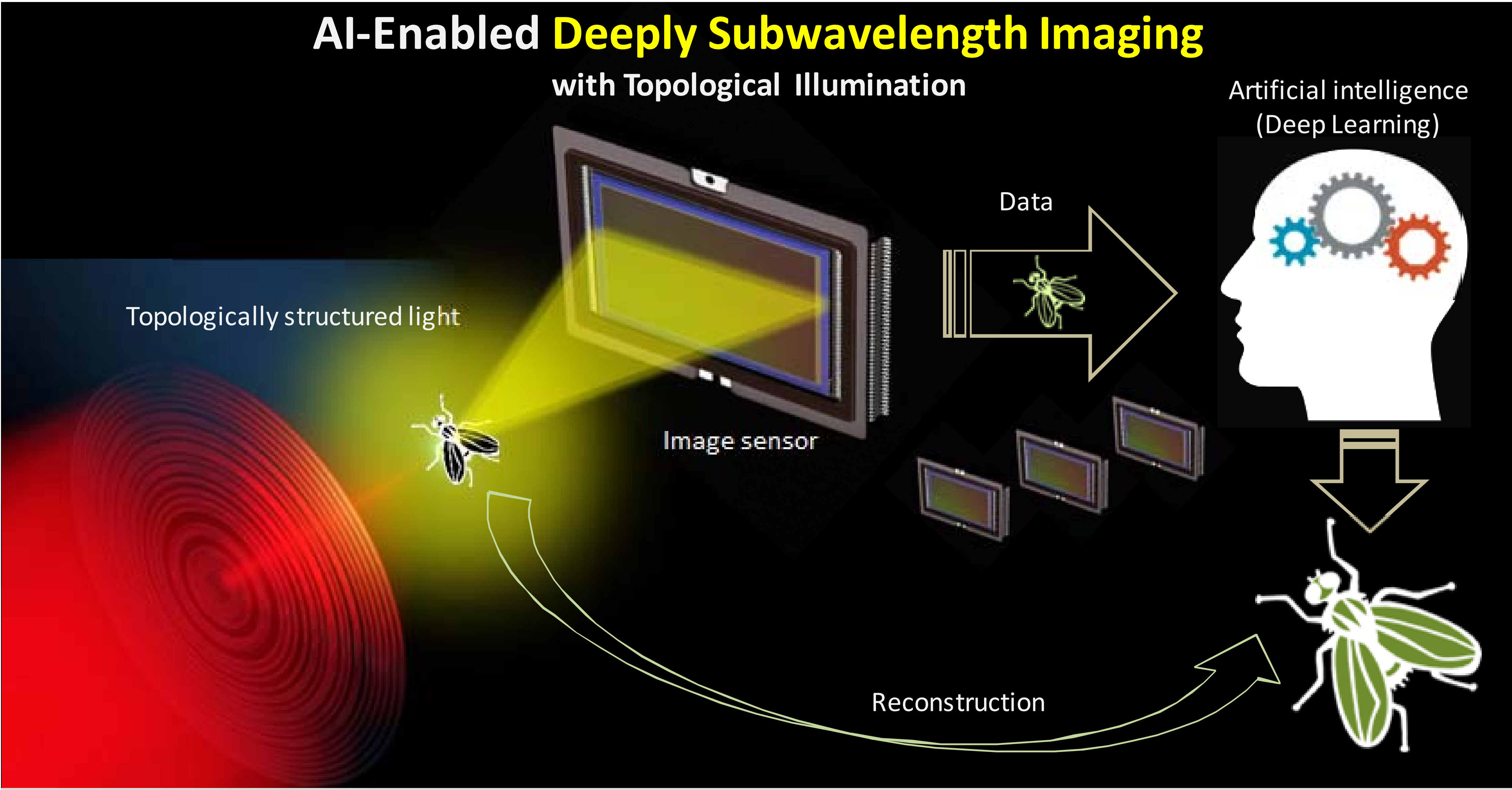


Measured Width vs Ground Truth



- **Optical metrology of sub-wavelength objects!**
- **Resolution challenges electron beam and ion beam lithographies**

Optical Metrology of Sub-Wavelength Objects Enabled by Artificial Intelligence
Barraza, Chan, Yuan, Adamo, Pu, Zheludev. *arXiv*:2005.04905 (2020)

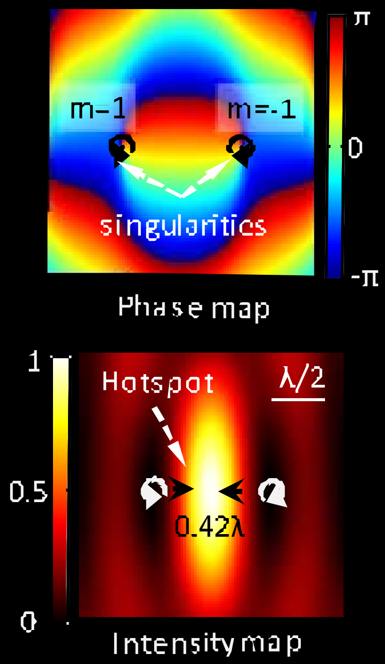


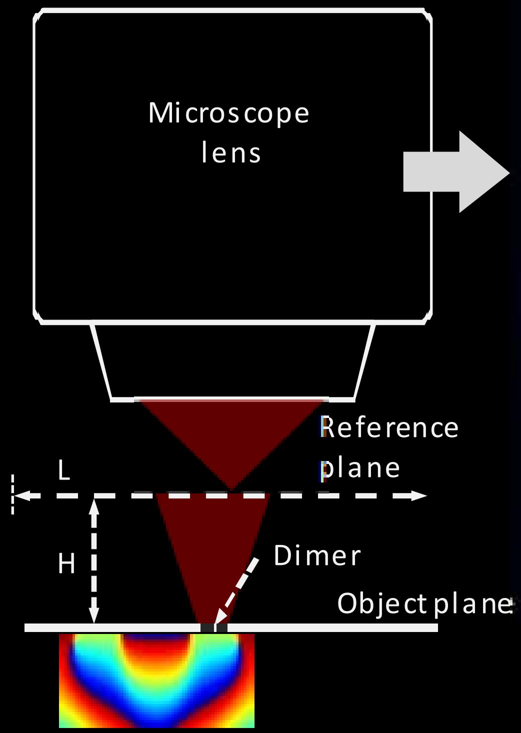
Unlabelled Far-field Deeply Subwavelength Superoscillatory Imaging (DSSI)

Pu, Savinov, Yuan, Papasimakis, Zheludev. **Advanced Science**, in press (2020). arXiv:1908.00946 (2019).

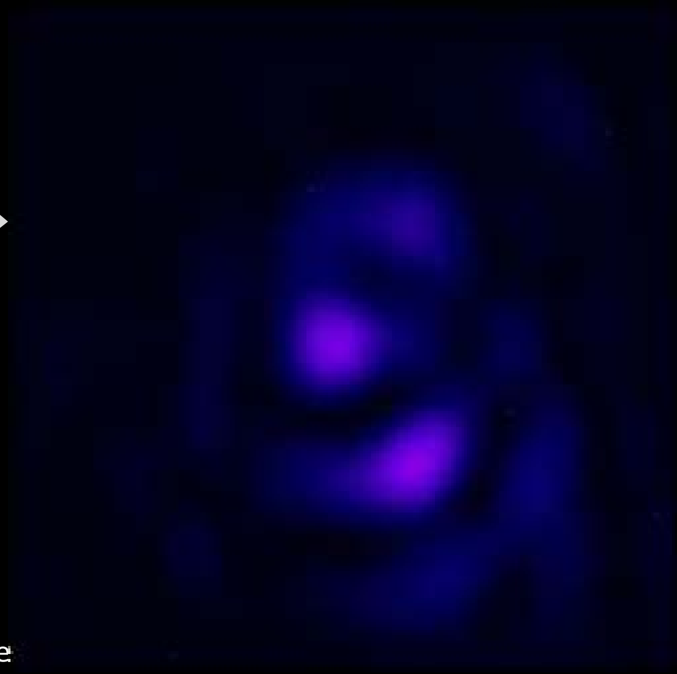
Deeply Subwavelength Imaging

with Topological Illumination (training set ~150)



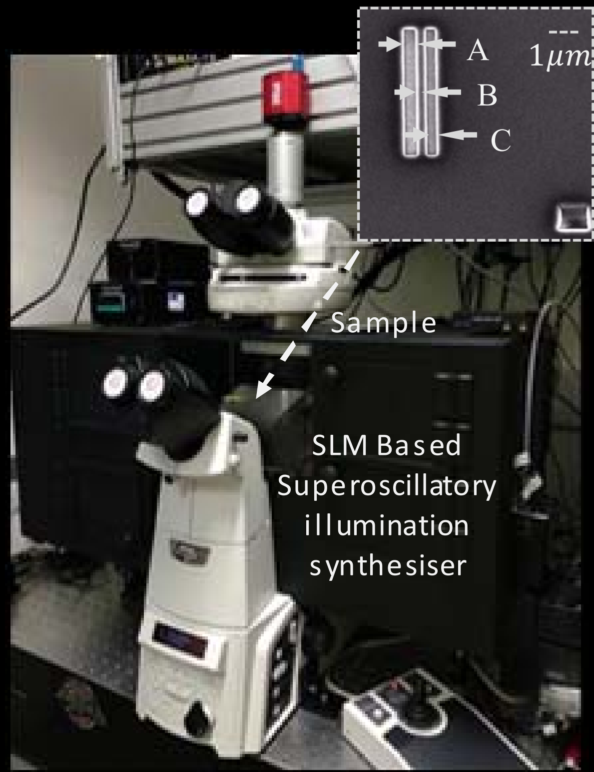


Superoscillatory illumination



Diffraction pattern at H = 2λ
20 x 100 nm steps

Dimer sample
A,B,C range: 0.12λ to 1.02λ

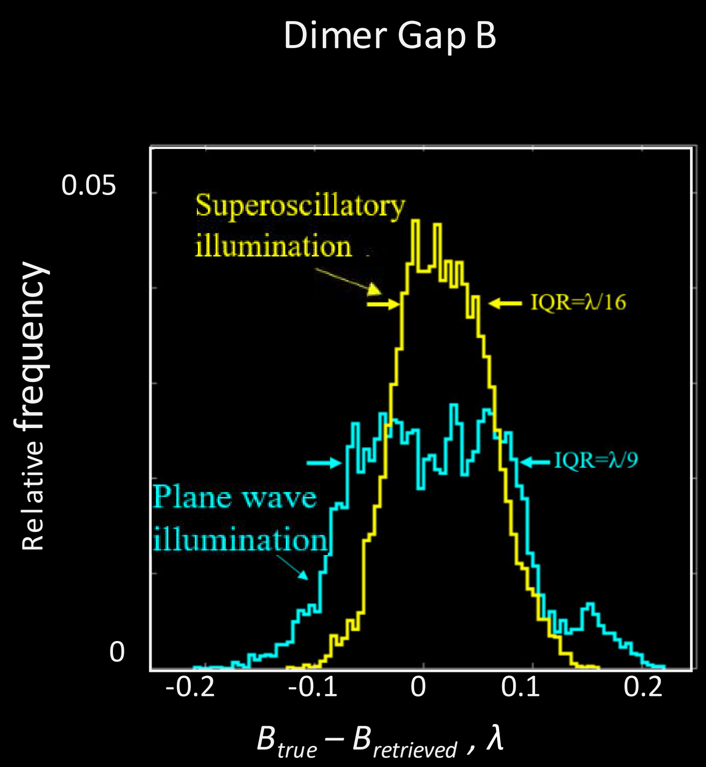


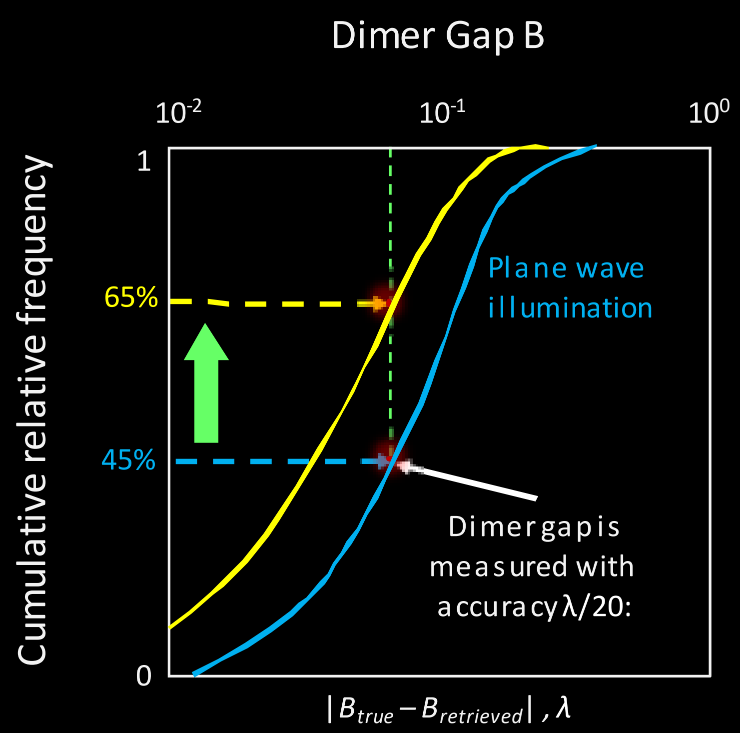
Unlabelled Far-field Deeply Subwavelength Superoscillatory Imaging (DSSI)

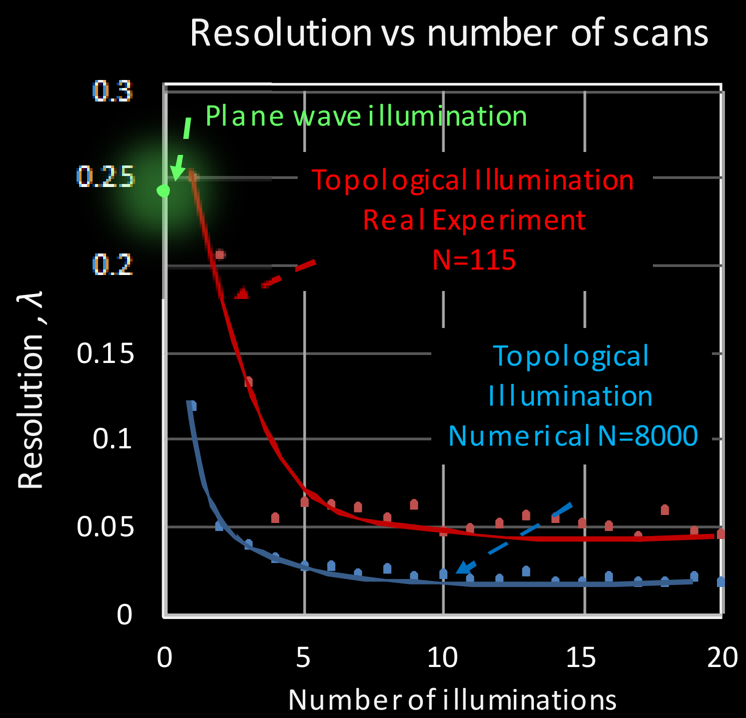
Pu, Savinov, Yuan, Papasimakis, Zheludev. **Advanced Science**, in press (2020). arXiv:1908.00946 (2019).

AI-Enabled Deeply Subwavelength Imaging of a dimer

with Topological Illumination (training set, N=115 elements)



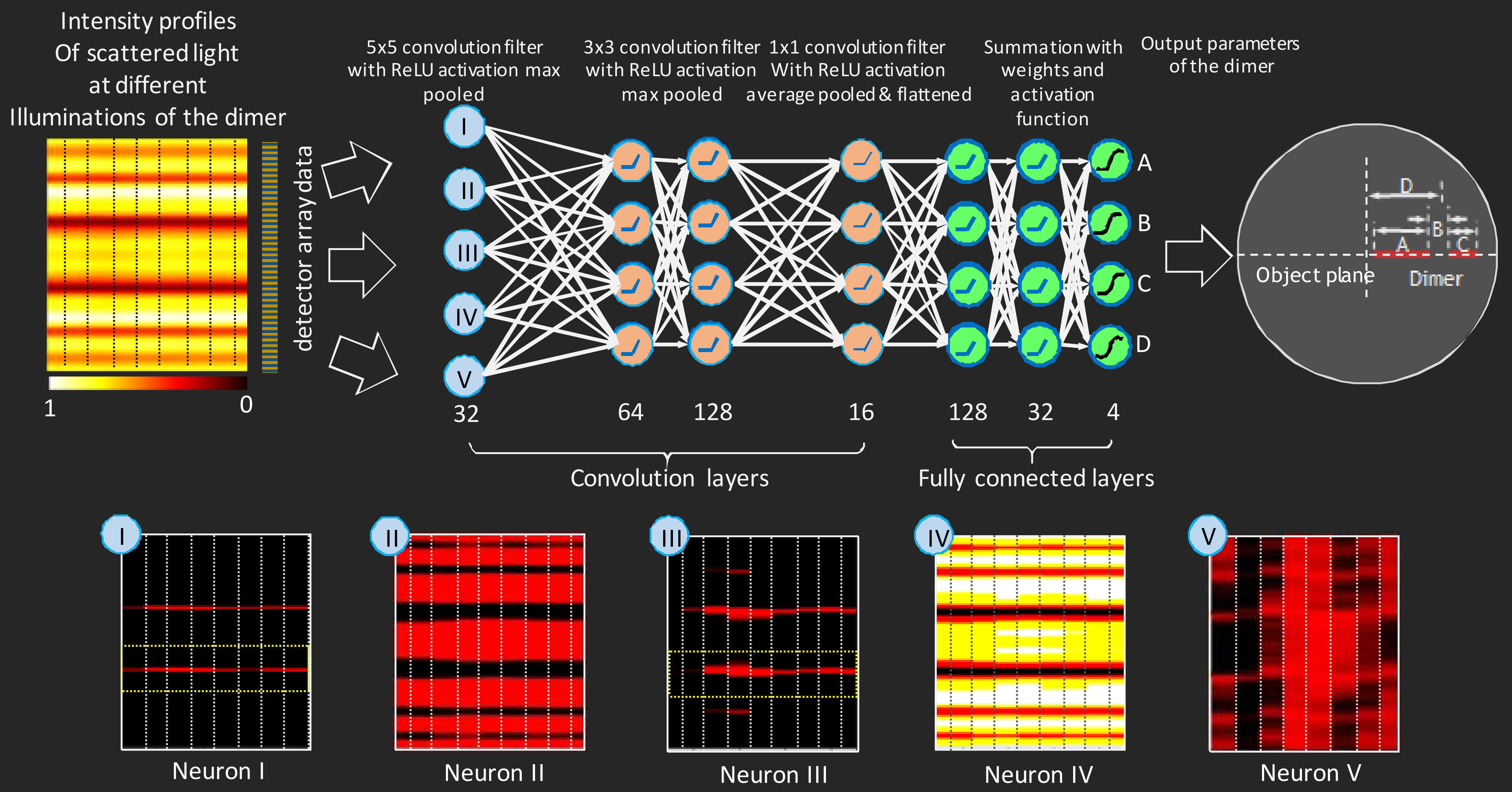




Unlabelled Far-field Deeply Subwavelength Superoscillatory Imaging (DSSI)

Pu, Savinov, Yuan, Papasimakis, Zheludev. **Advanced Science**, in press (2020). arXiv:1908.00946 (2019).

How does the neural network work: Deeply Subwavelength Imaging ?



What is imaging?

Imaging is the representation or reproduction of an object's form; especially a visual representation (i.e., the formation of an image). https://en.wikipedia.org/wiki/Imaging

formation of an image

On a retina

On a photographic film

On a screen

In a computer memory

On a disk …

Other examples of computer-enabled imaging techniques

SNOM

STED

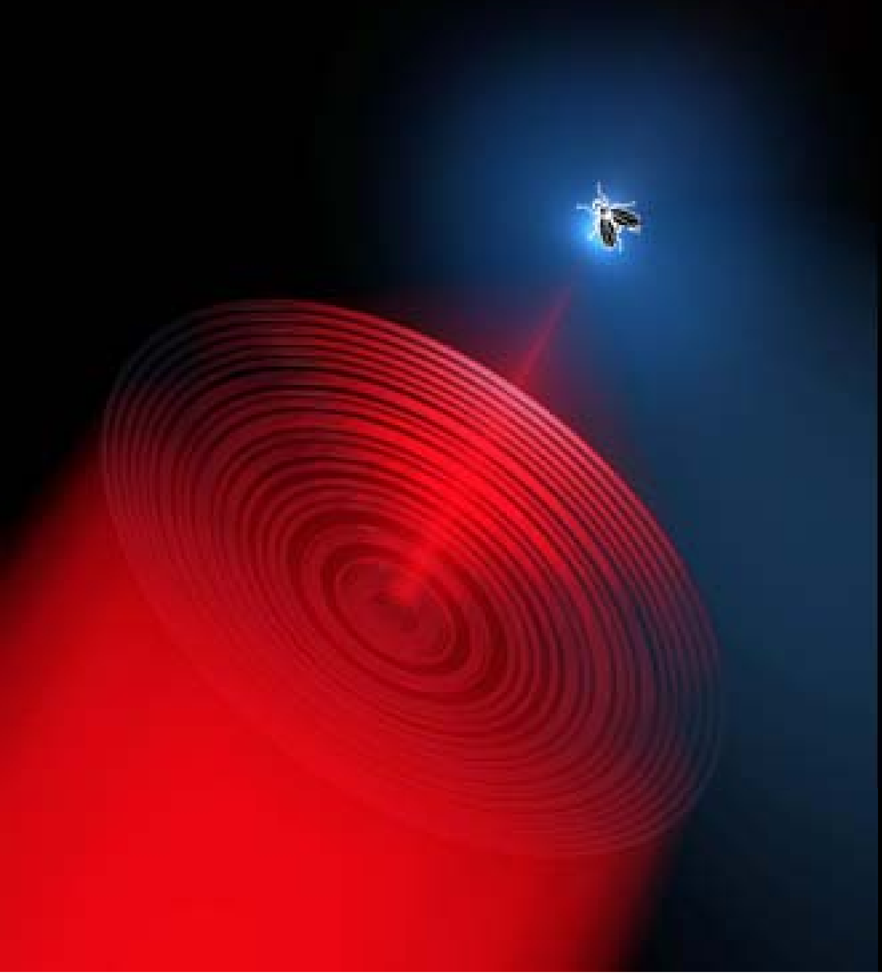
SEM/TEM

….

AI-enable Deeply Subwavelength Imaging

Why AI-enabled **Deeply Subwavelength Imaging** beats the Abbe “diffraction limit” of ~λ/2?

(by orders of magnitude)



- The deep learning process trained on a large data set creates accurate deconvolution mechanism
- Sparsity of and prior knowledge about the object helps the retrieval process
- Multiple scattering patterns provides more information than in the lens-generated single image
- Topological illumination ensures presence of high wave vectors and high sensitivity to small features of the object

Edward T. F. Rogers

Guanghui Yuan

Nikitas Papasimakis

Carolina Rendon Barraza

Jun-Yu Ou

Eng Aik Chan

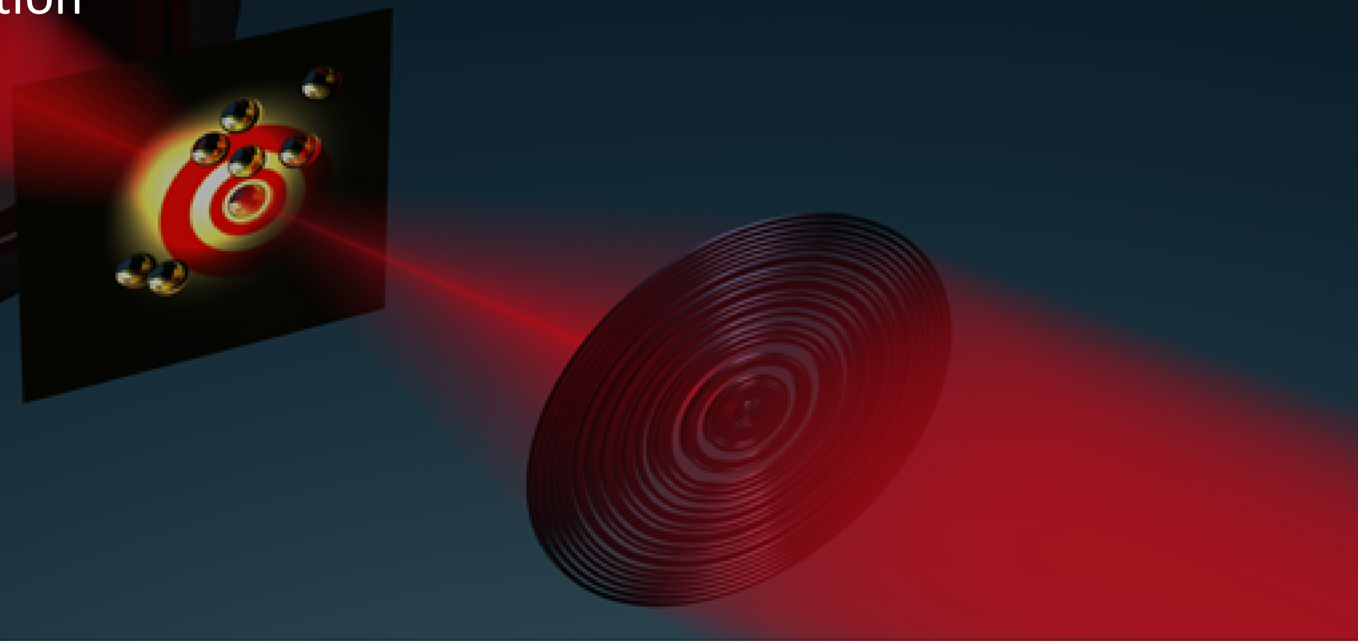
Tanchao Pu

TPI The Photonics Institute

Light

To Take Home

- Topologically structured light contains deeply subwavelength features
- Superoscillatory and plasmonic fields have strong similarities
- Artificial Intelligence offer a route to metrology and imaging with λ/1000+ resolution



www.nanophotonics.org.uk
www.nanophotonics.sg