Full-wave simulation of focusing light through scattering layers using the T-matrix method

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[4] School of Computer Science, University of Birmingham, Birmingham, UK

Outline

We present a physically realistic and efficient method of modelling wavefront shaping (WFS) through scattering media.

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      1. **The discrete particle model of scattering media**
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Physics of light propagation and *in vivo* implications

Why make a model of WFS?

Physics of light propagation and *in vivo* implications

Why make a model of WFS? What is WFS?

Physics of light propagation and *in vivo* implications

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- Understanding the
  need to model WFS =
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Understanding light-tissue interactions

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- Many modalities rely on the propagation of visible light through biological tissue.

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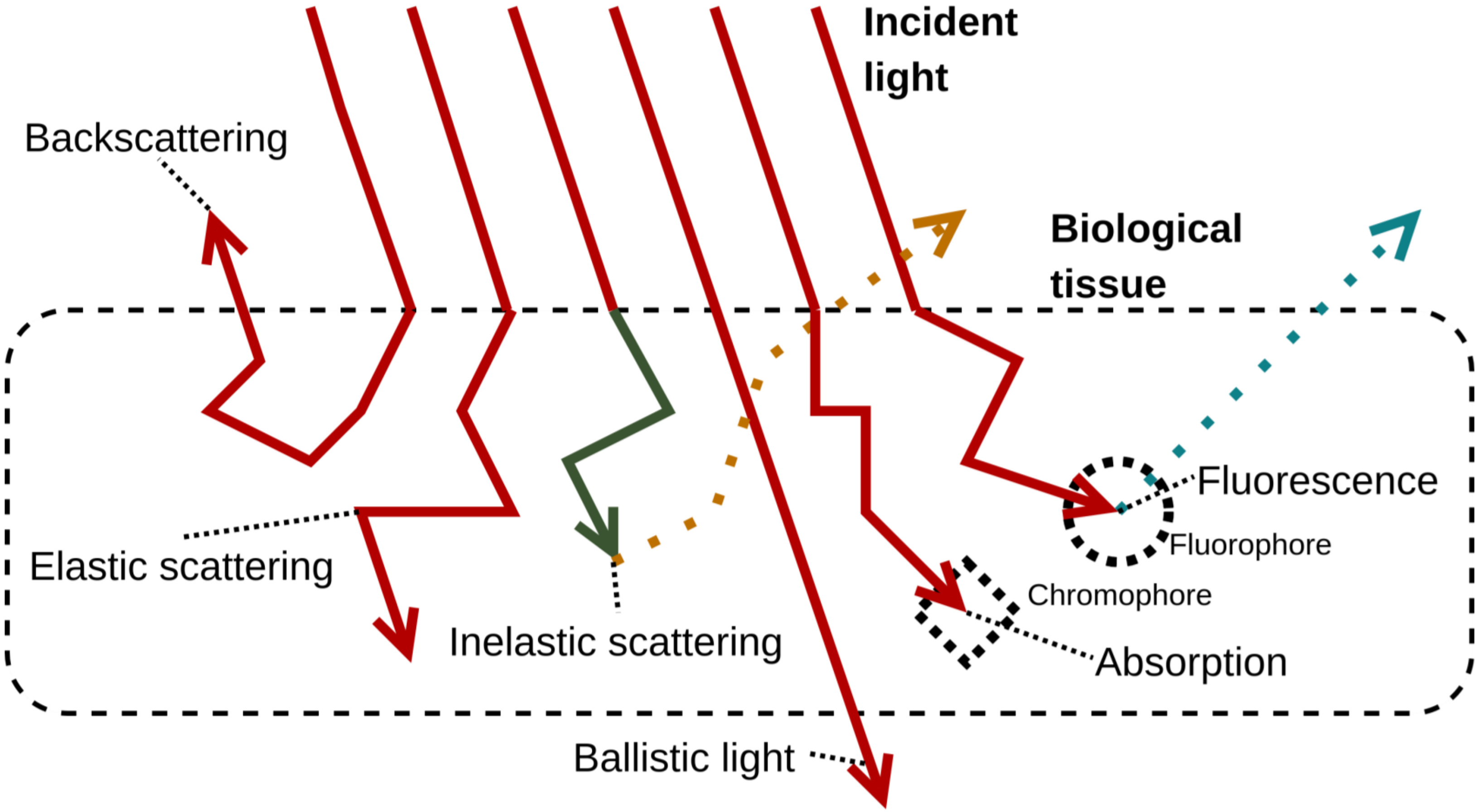
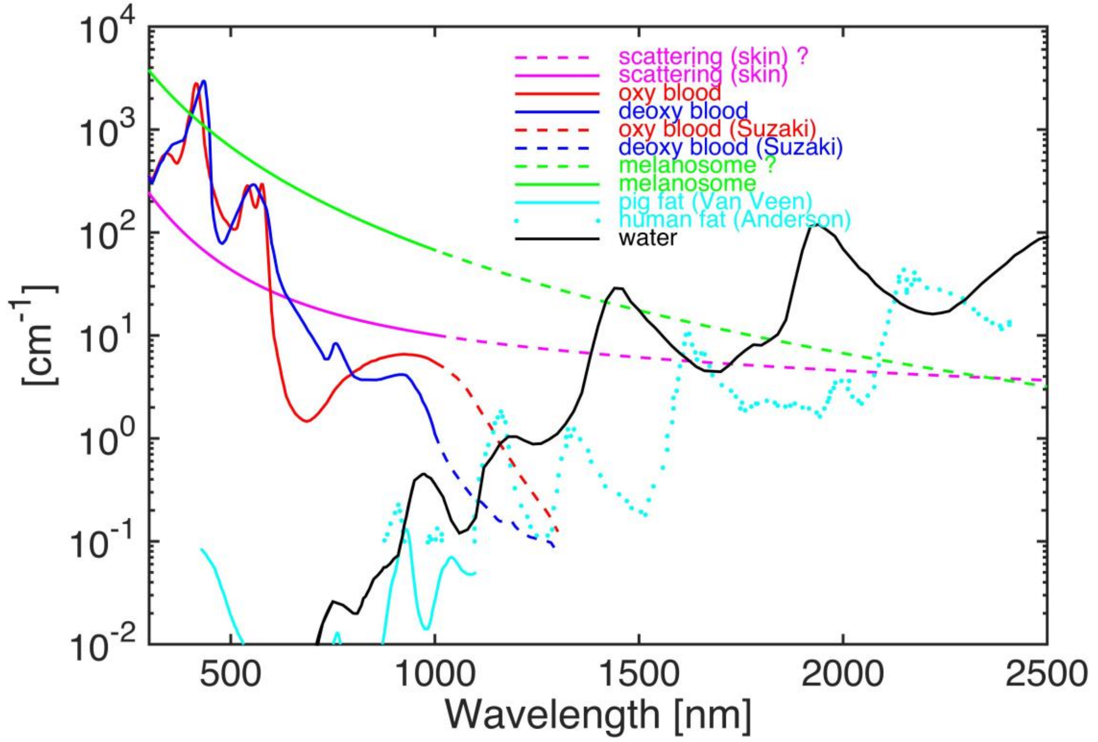


Physics of light propagation and *in vivo* implications

Significance of scattering & absorption



Jacques, Steven L., *Physics in Medicine & Biology,* 2013

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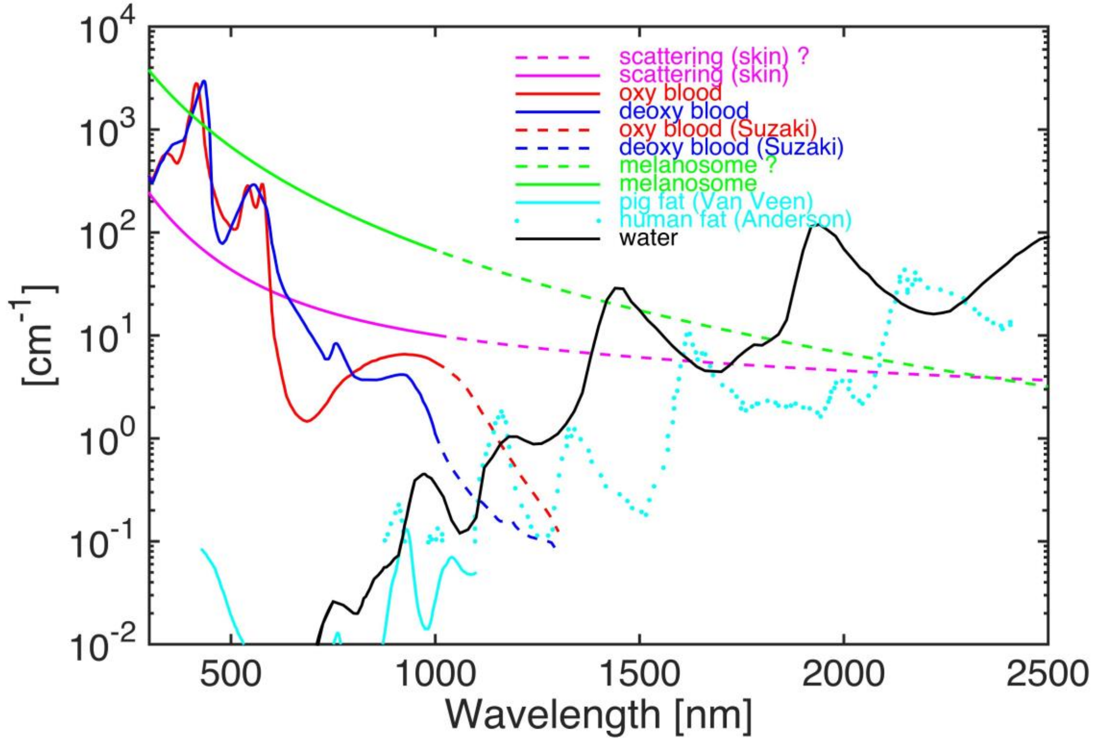

$$\mu_a = BS\mu_{a.oxyHGb} + B(1-S)\mu_{a.deoxyHGb} + W\mu_{a.water} + M\mu_{a.melanosome} + F\mu_{a.fat} + \ldots$$

$$\mu_s' = \mu_{s.500nm}'\left(f\left(\frac{\lambda}{500nm}\right)^{-4} + (1-f)\left(\frac{\lambda}{500nm}\right)^{-b_{mie}}\right)$$

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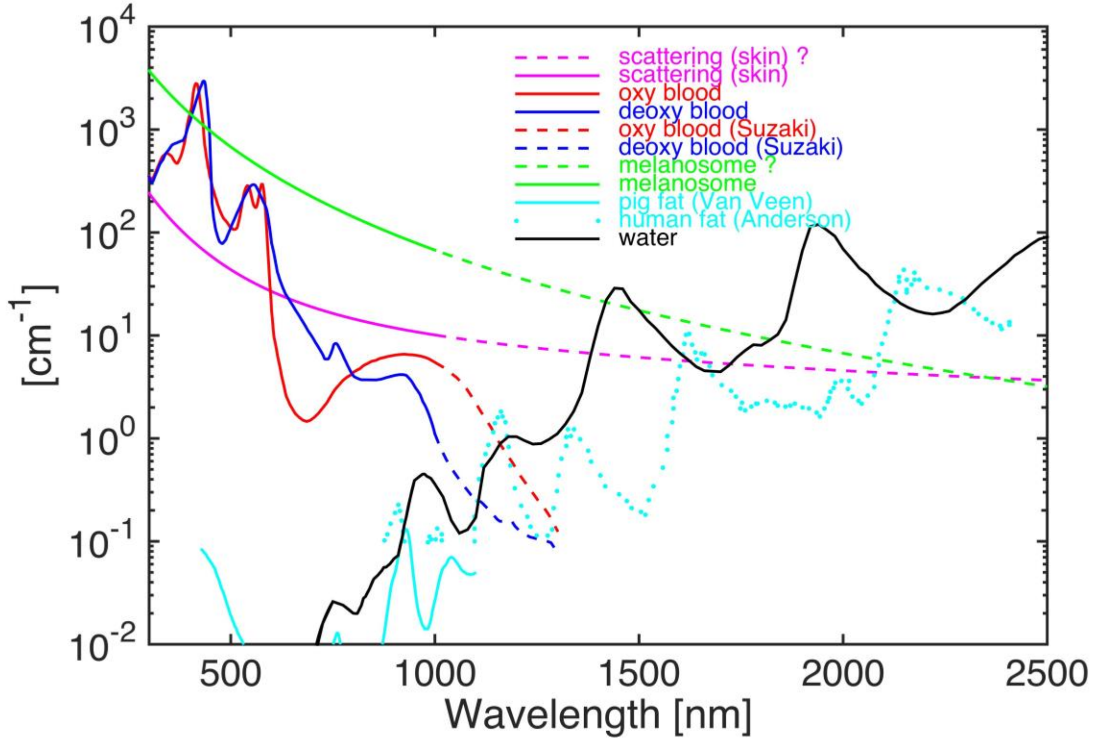

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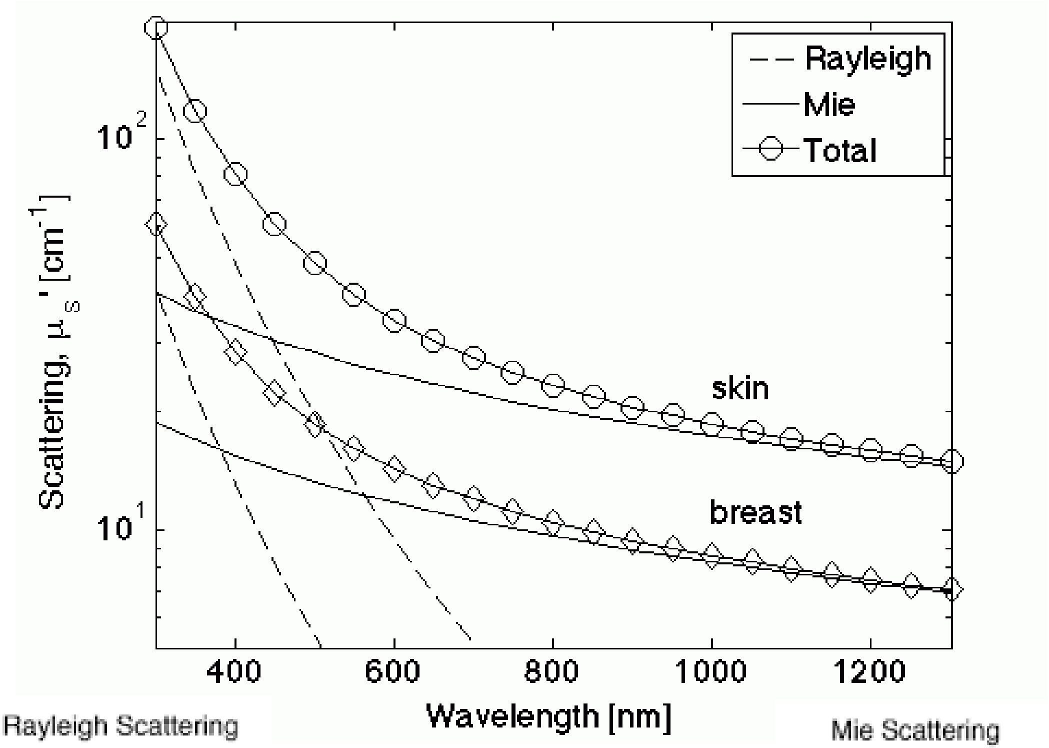
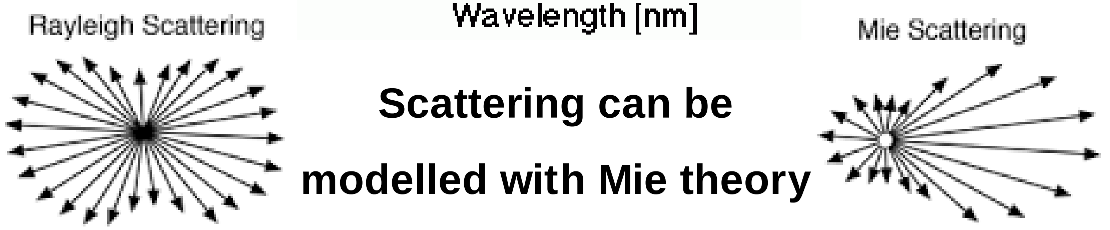
Models of elastic scattering





Scattering can be modelled with Mie theory

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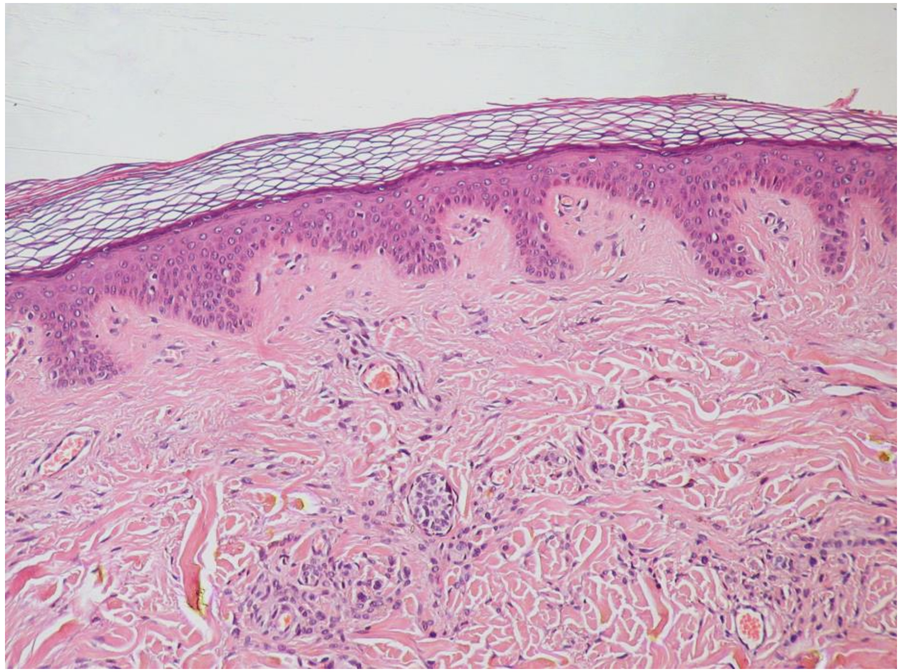
Physics of light propagation and *in vivo* implications

Tissue is a strong scatterer



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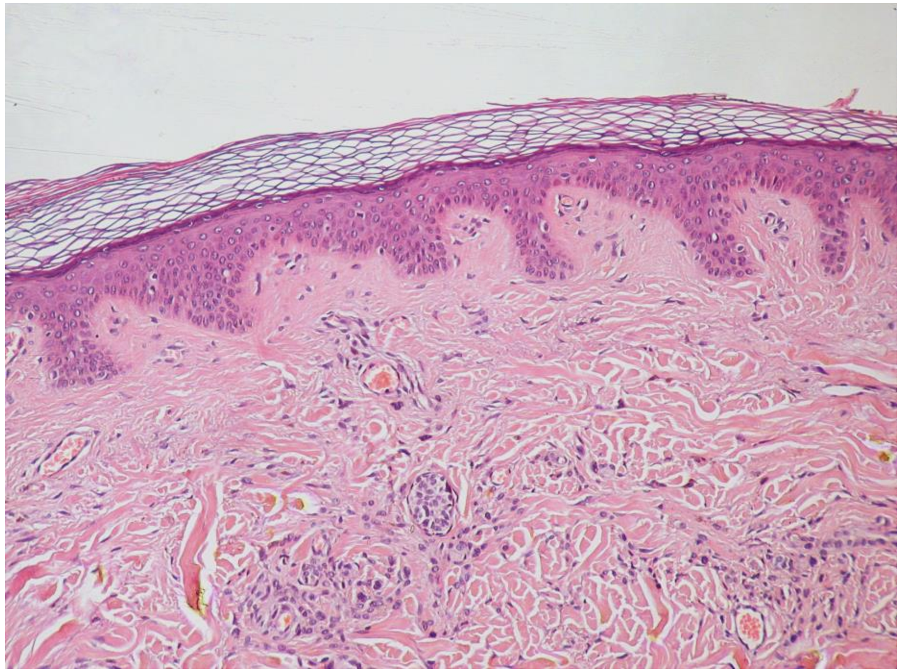

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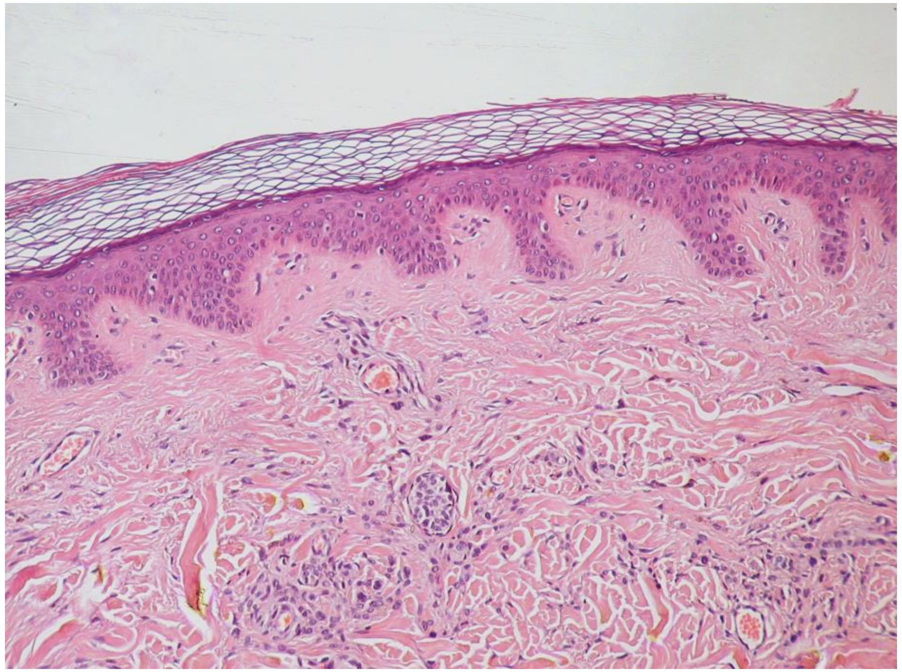
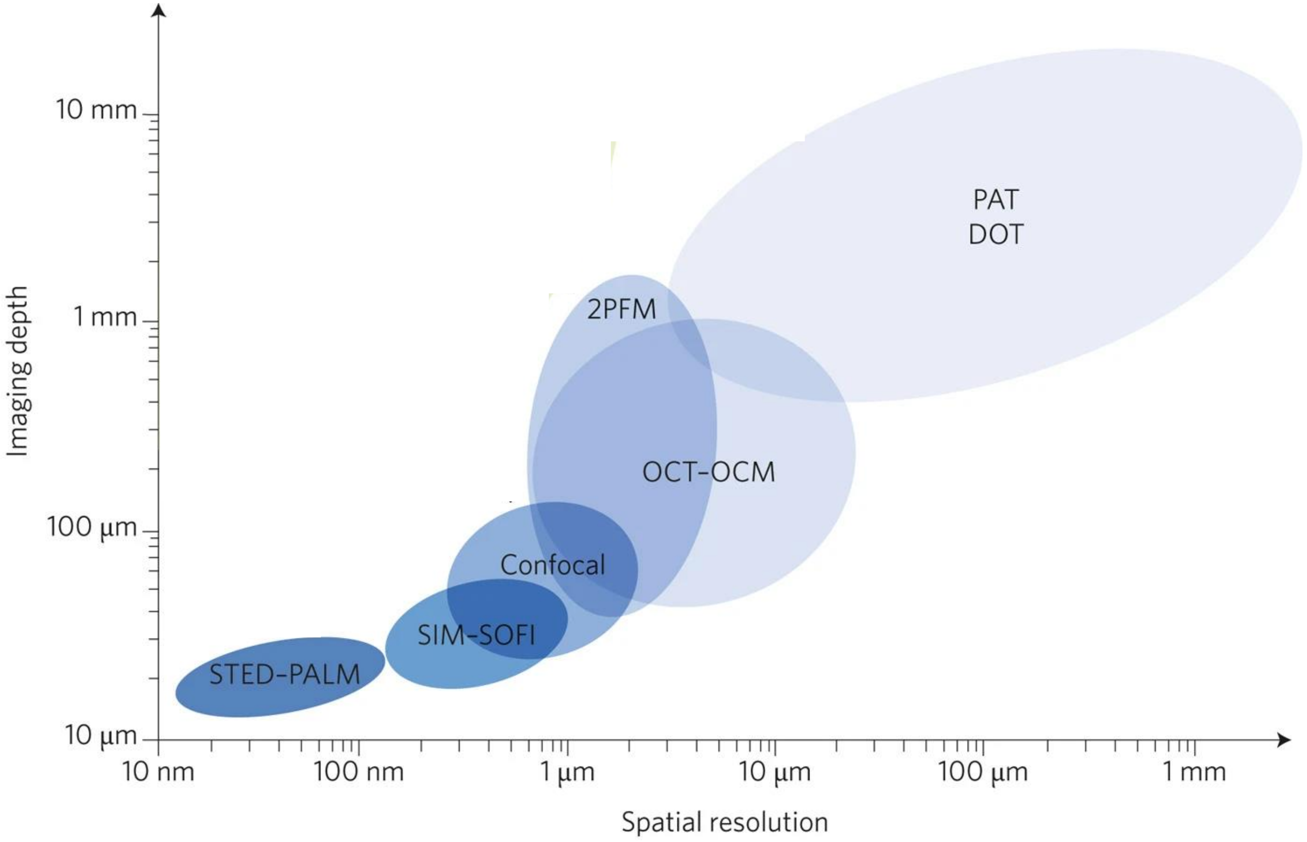


Highly inhomogeneous refractive index = highly scattering medium

Therefore, optical imaging is depth limited



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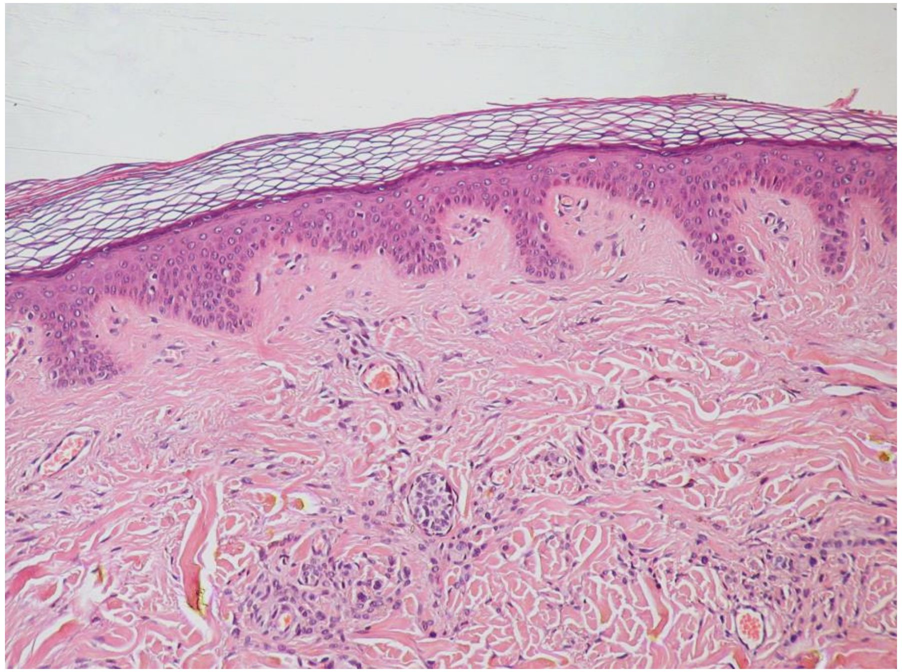

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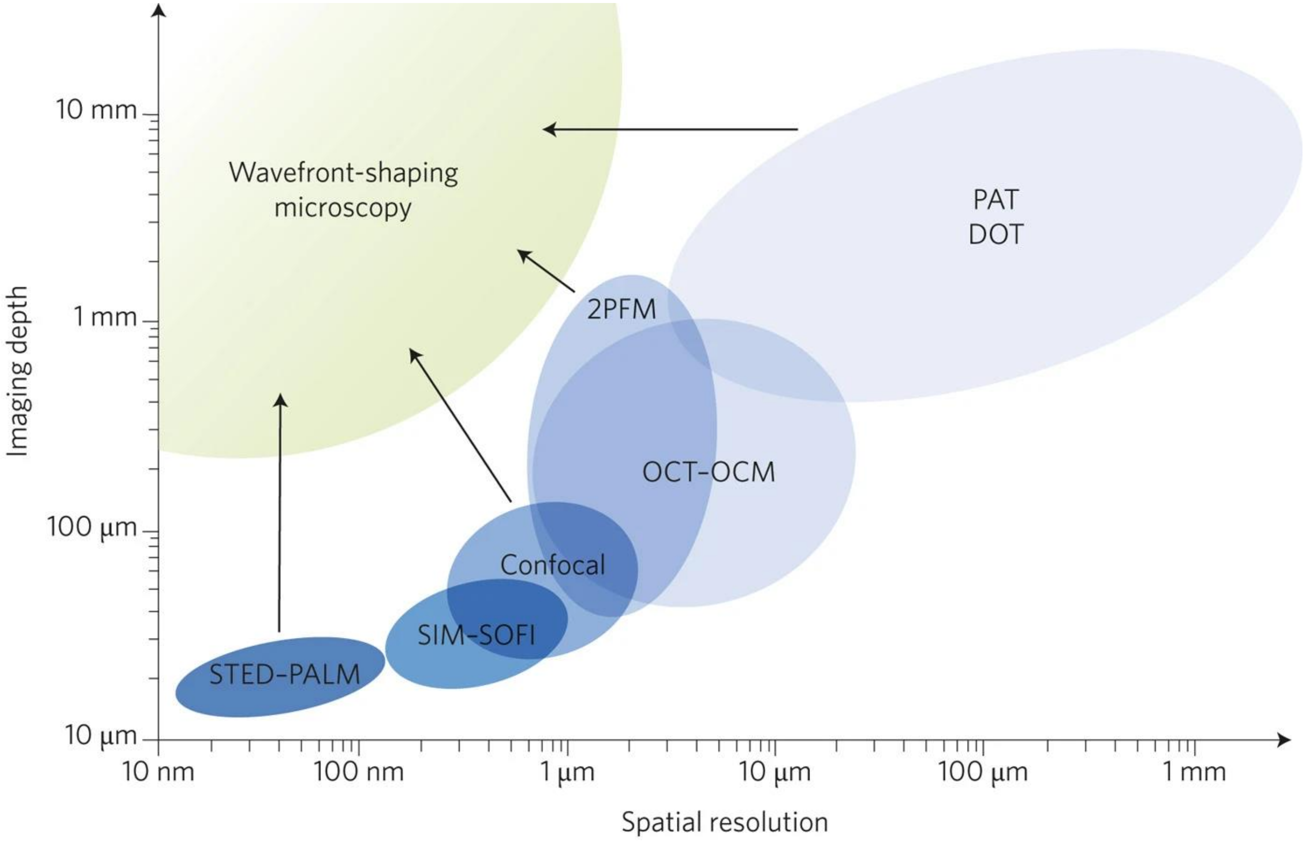
WFS has the potential to increase depth



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Wavefront shaping – principle and applications

What is wavefront shaping?

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Spatially modulating light to construct arbitrary fields

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Spatially modulating light to construct arbitrary fields

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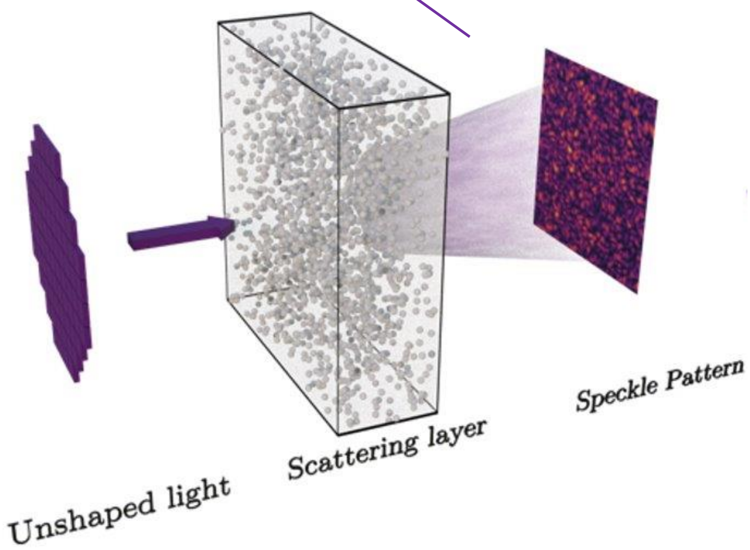

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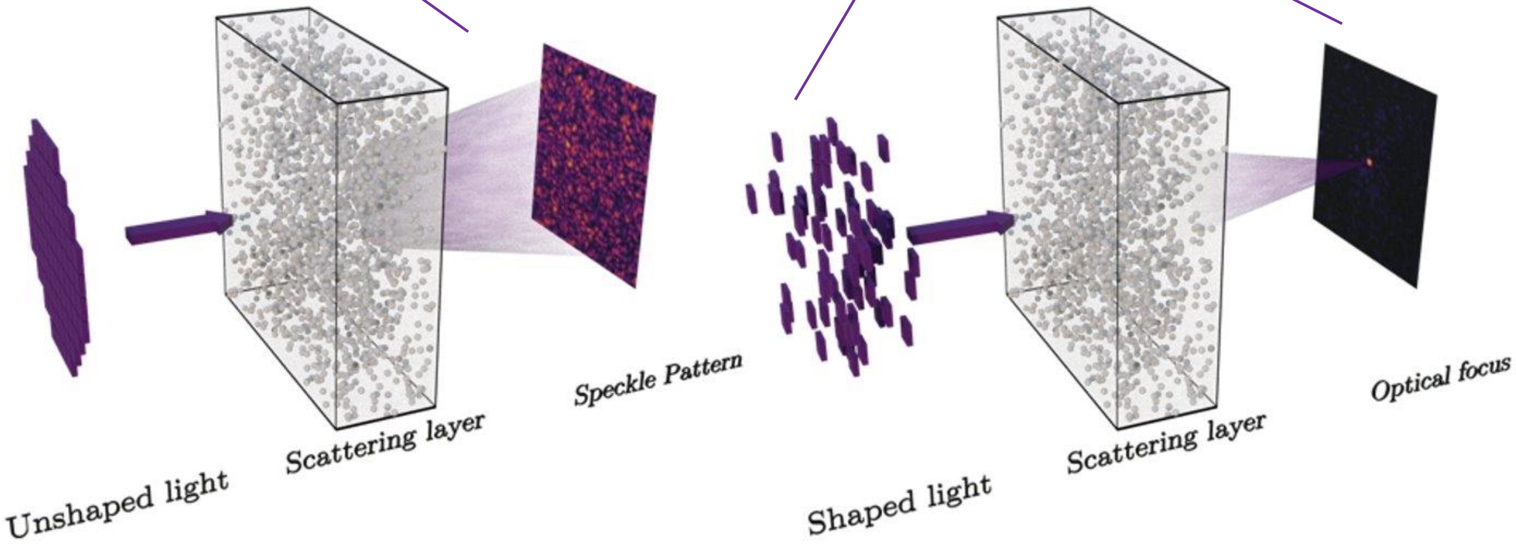
Shaped light constructively interferes and can produce a focus



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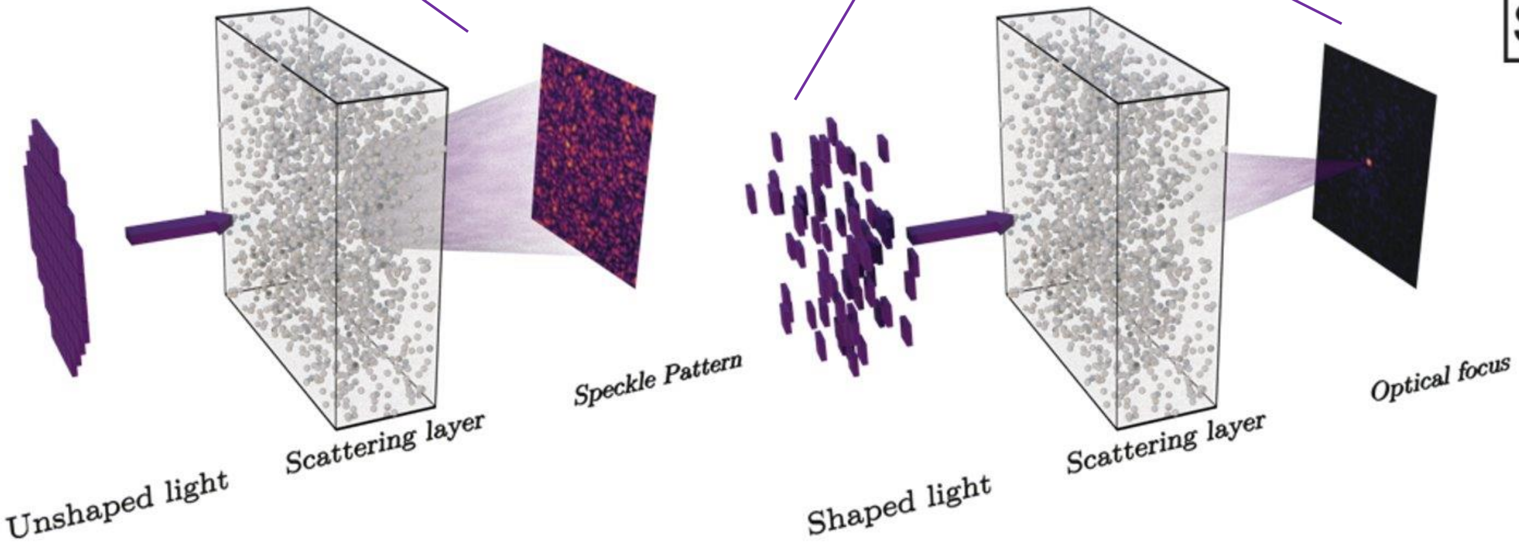
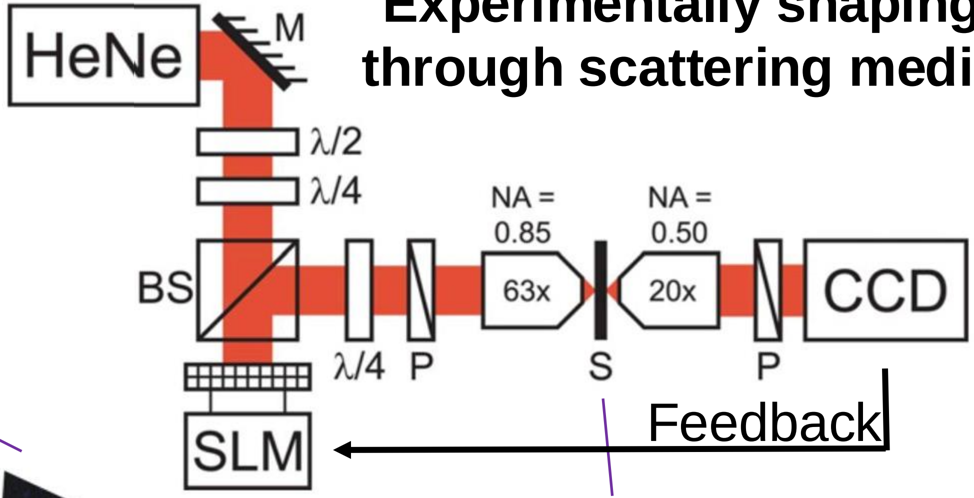
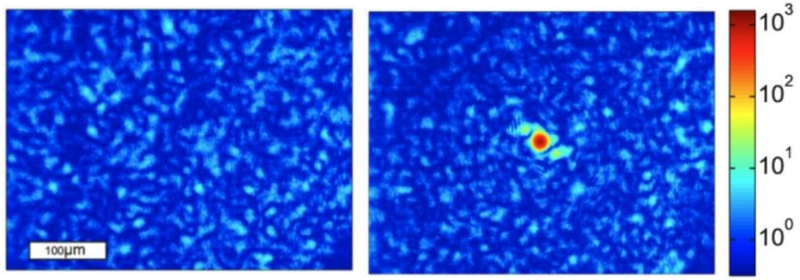


Experimentally shaping through scattering media



Scattering medium

SLM optimizes incident light



Vellekoop and Mosk, *Optics letters*, 2007

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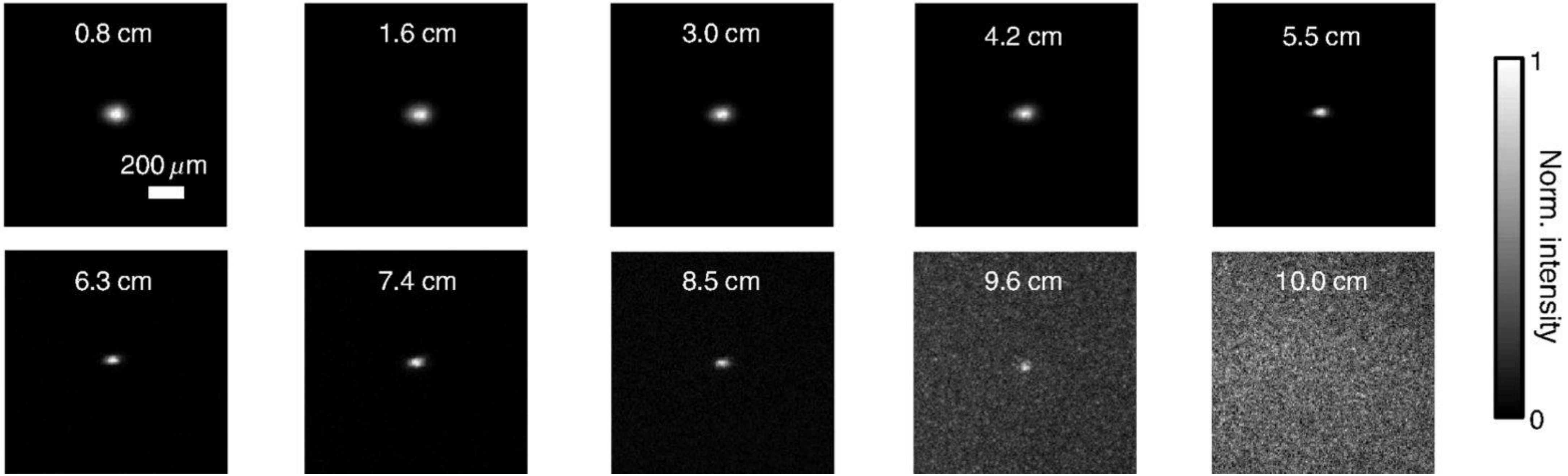
Optical foci have been generated through very deep domains



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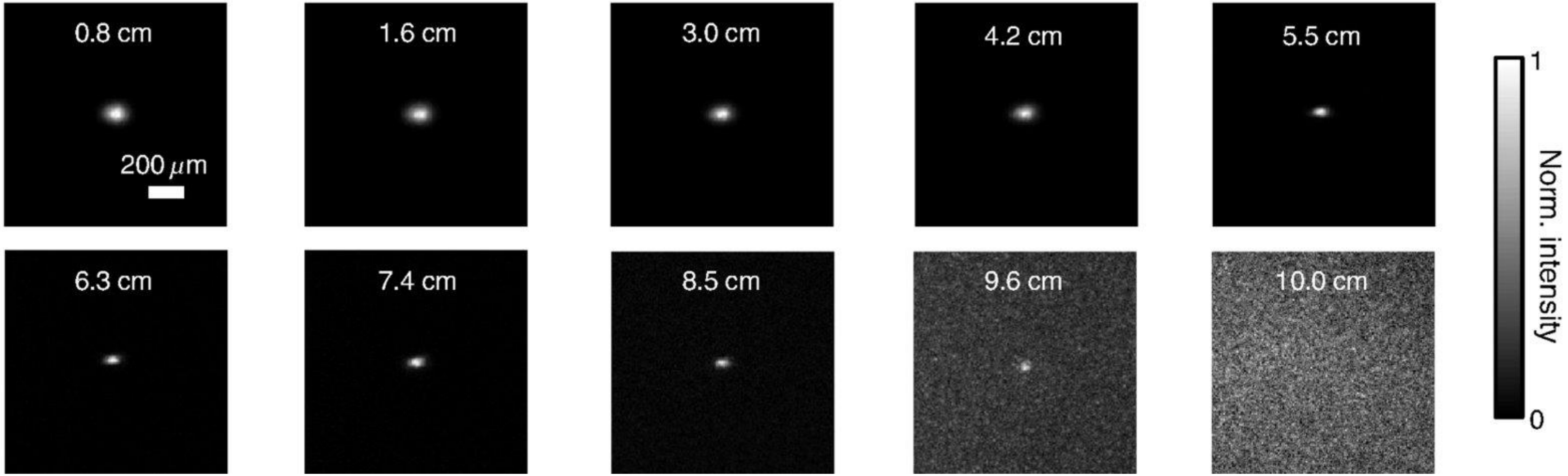

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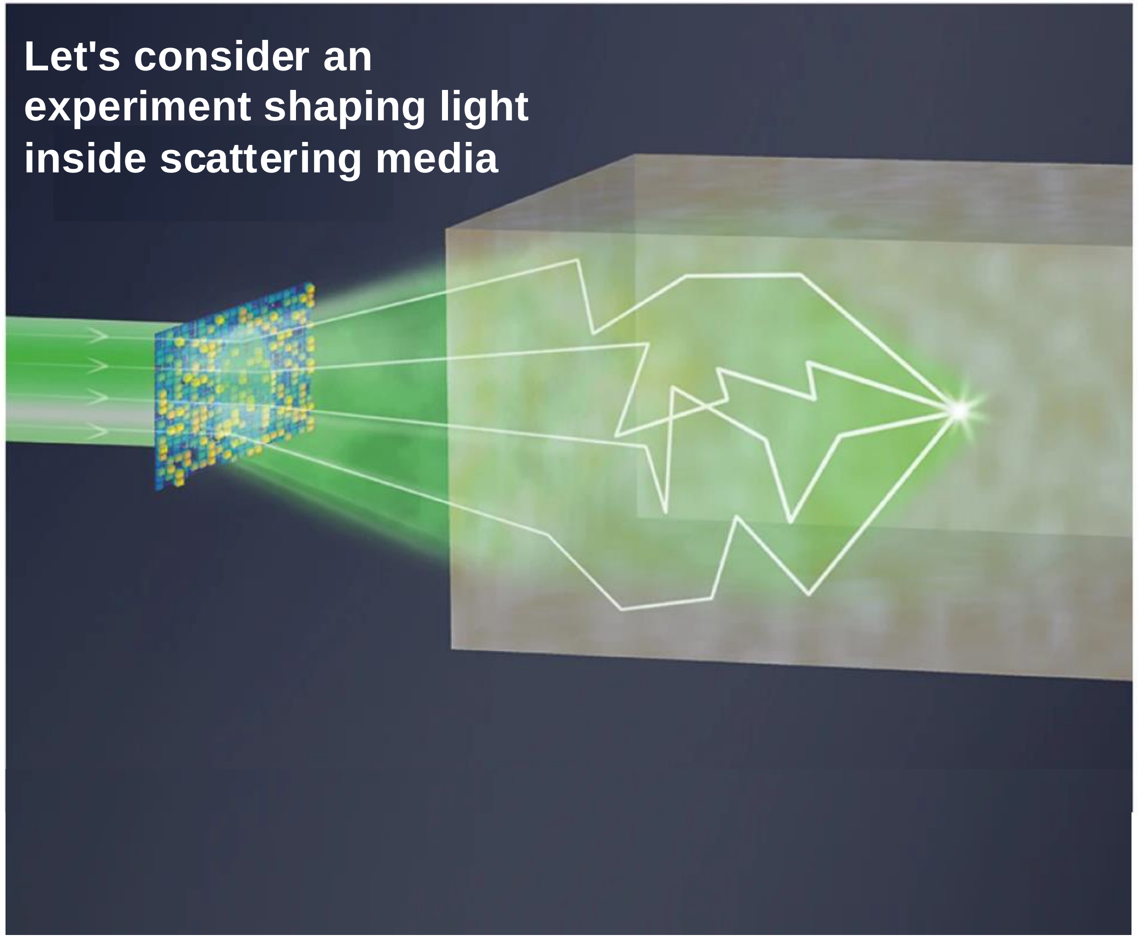
This is how WFS may increase the depth and resolution of optical imaging.

Simulating wavefront shaping – motivation and methods

Experimental concerns and constraints



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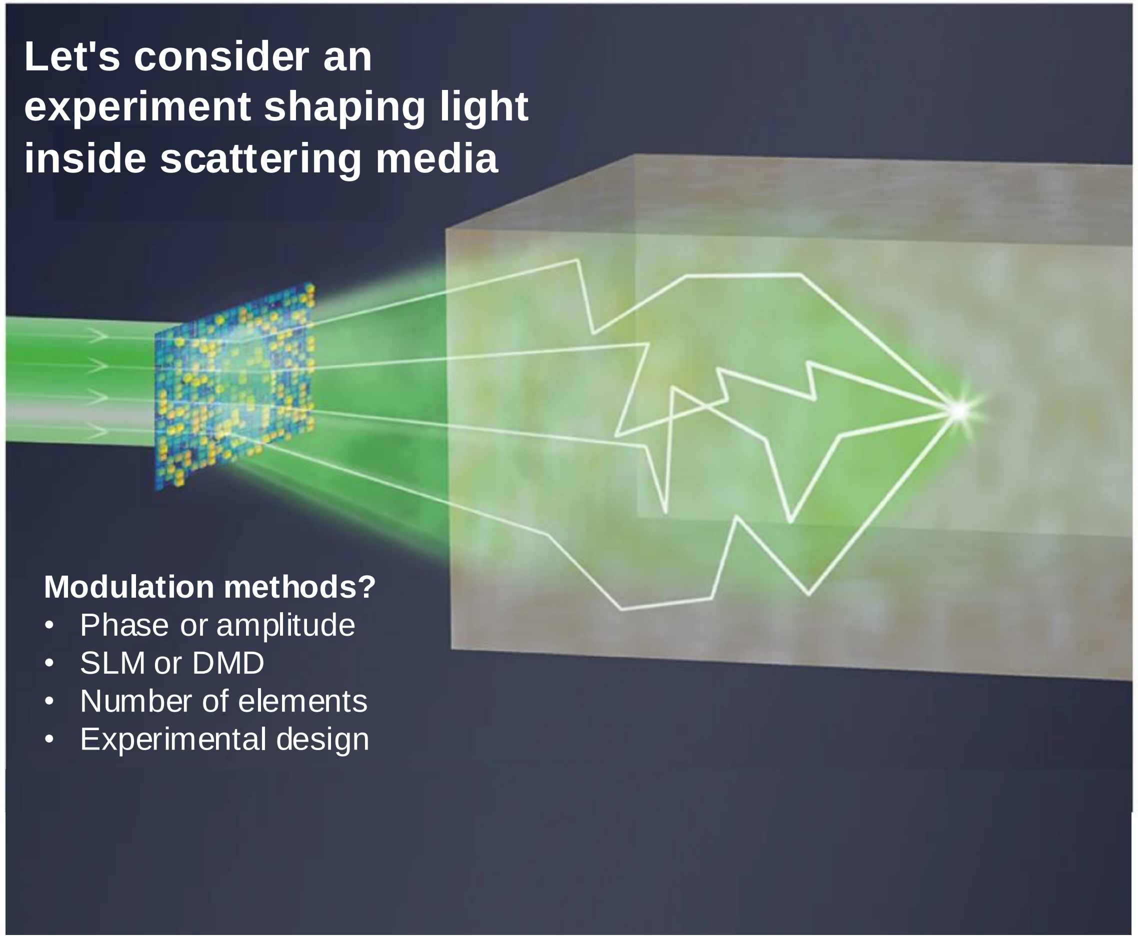

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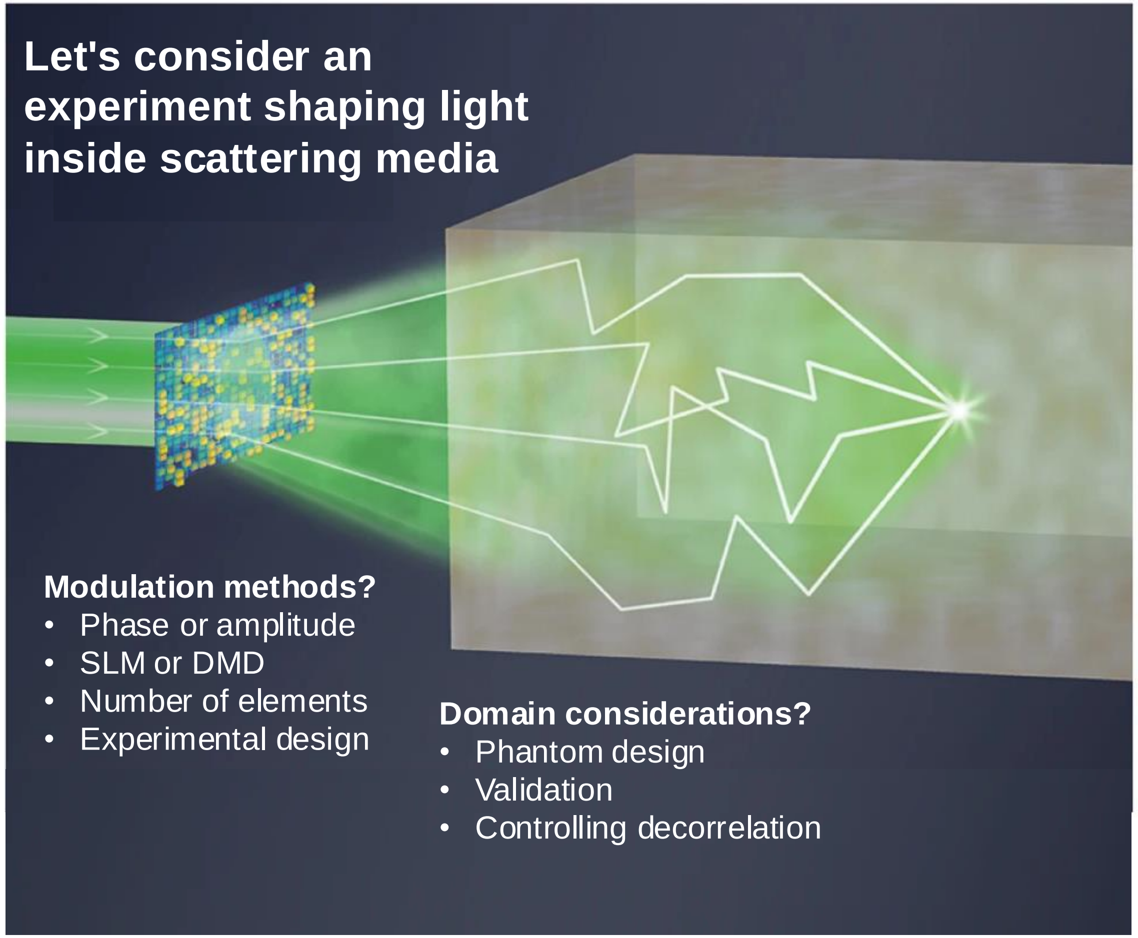

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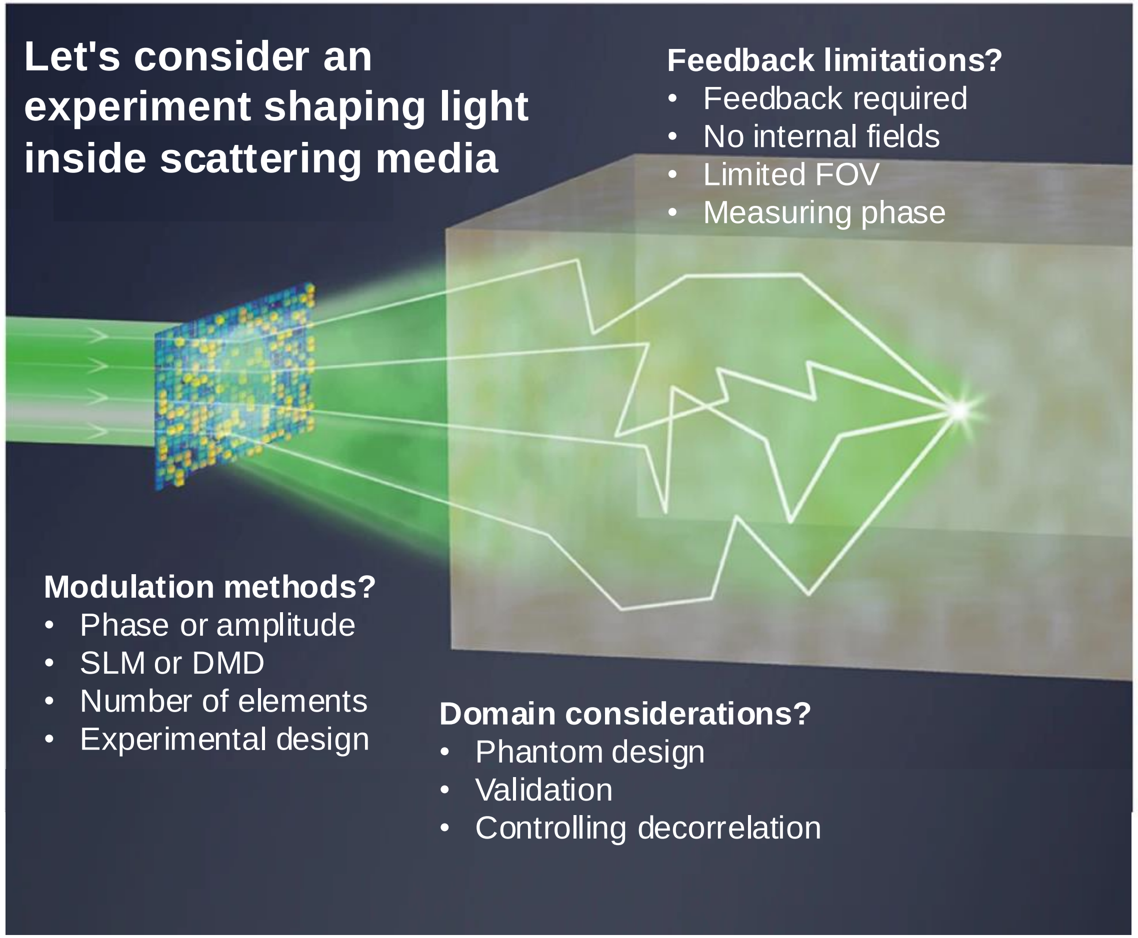

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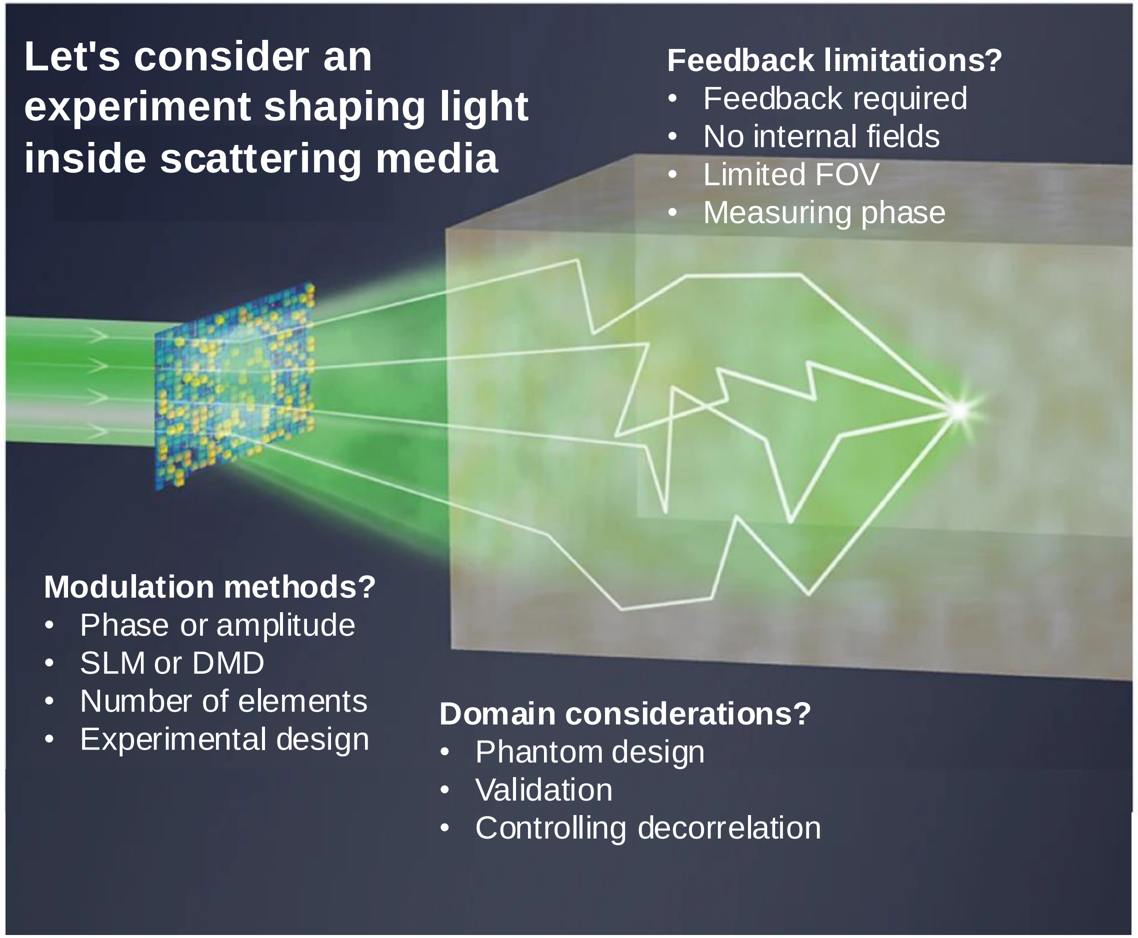

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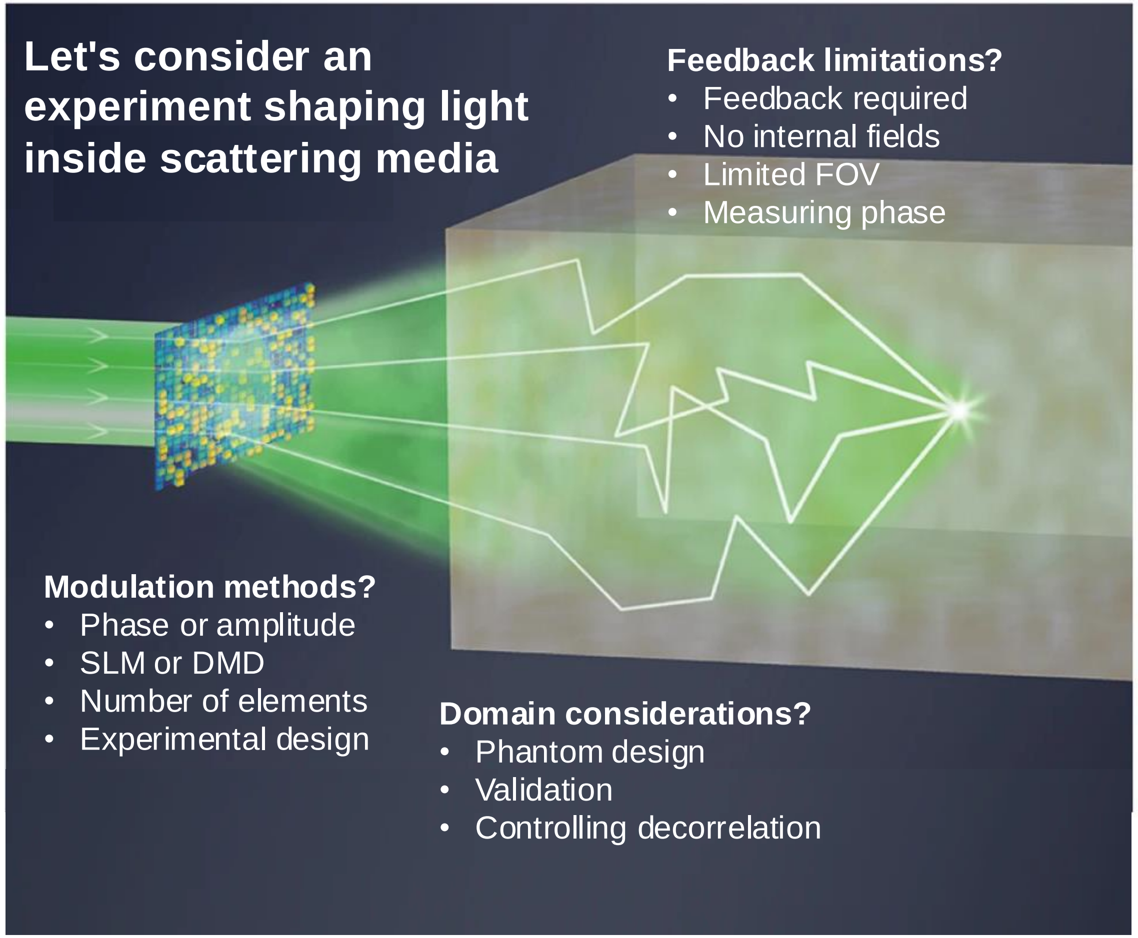

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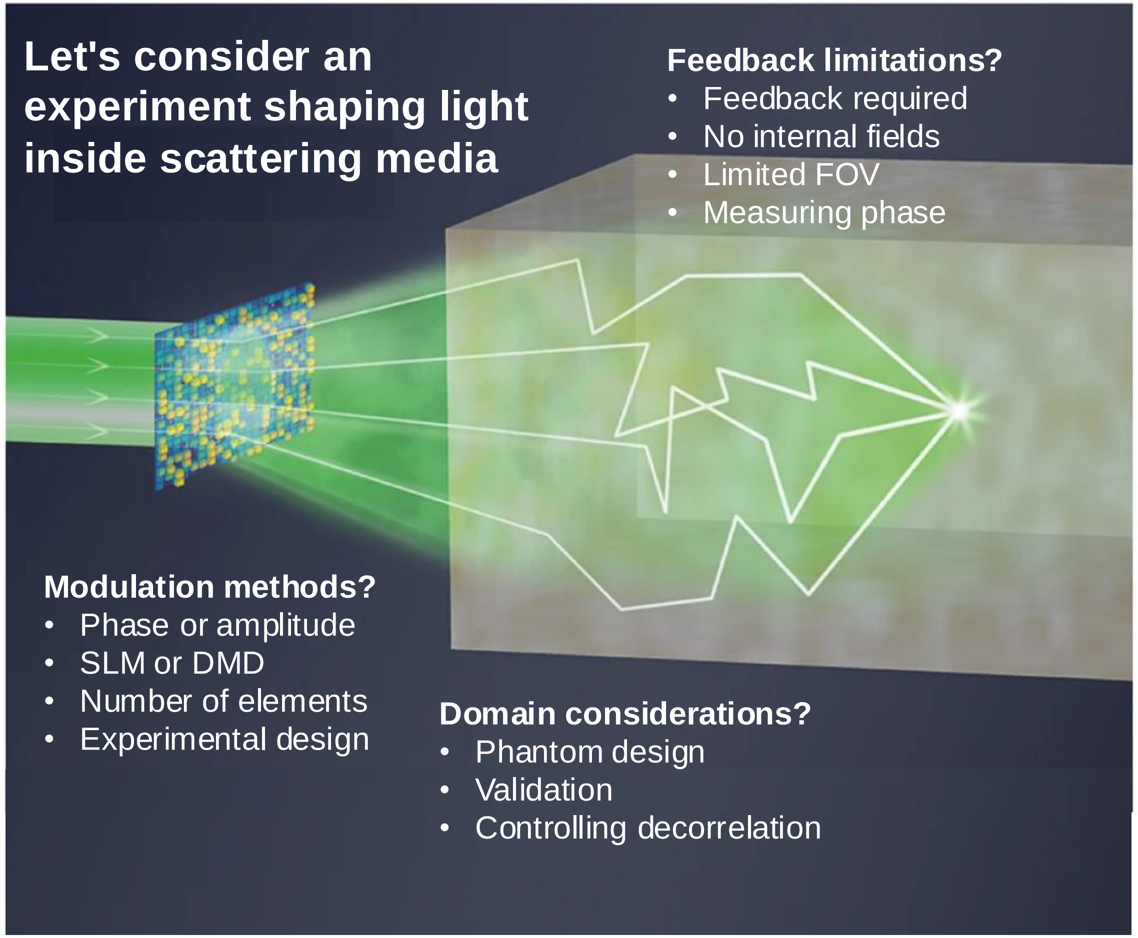

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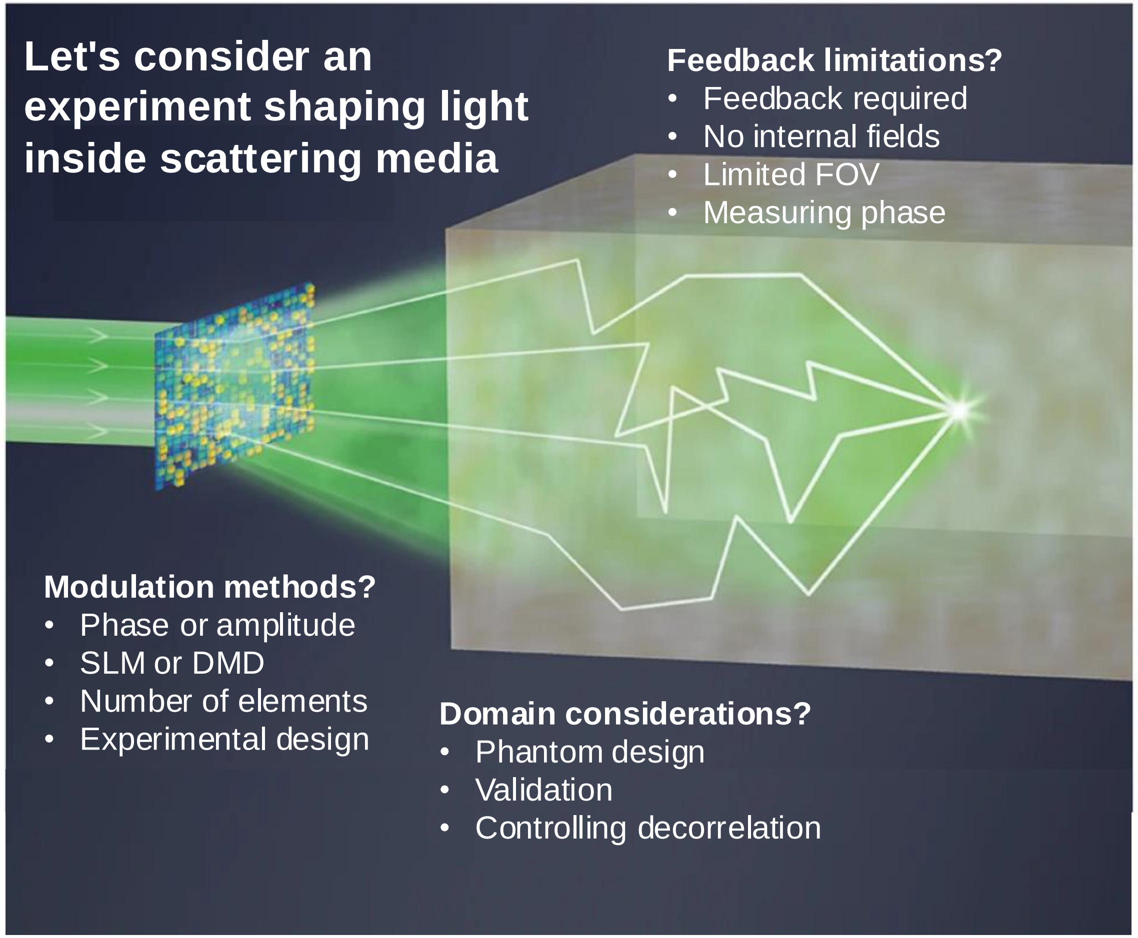

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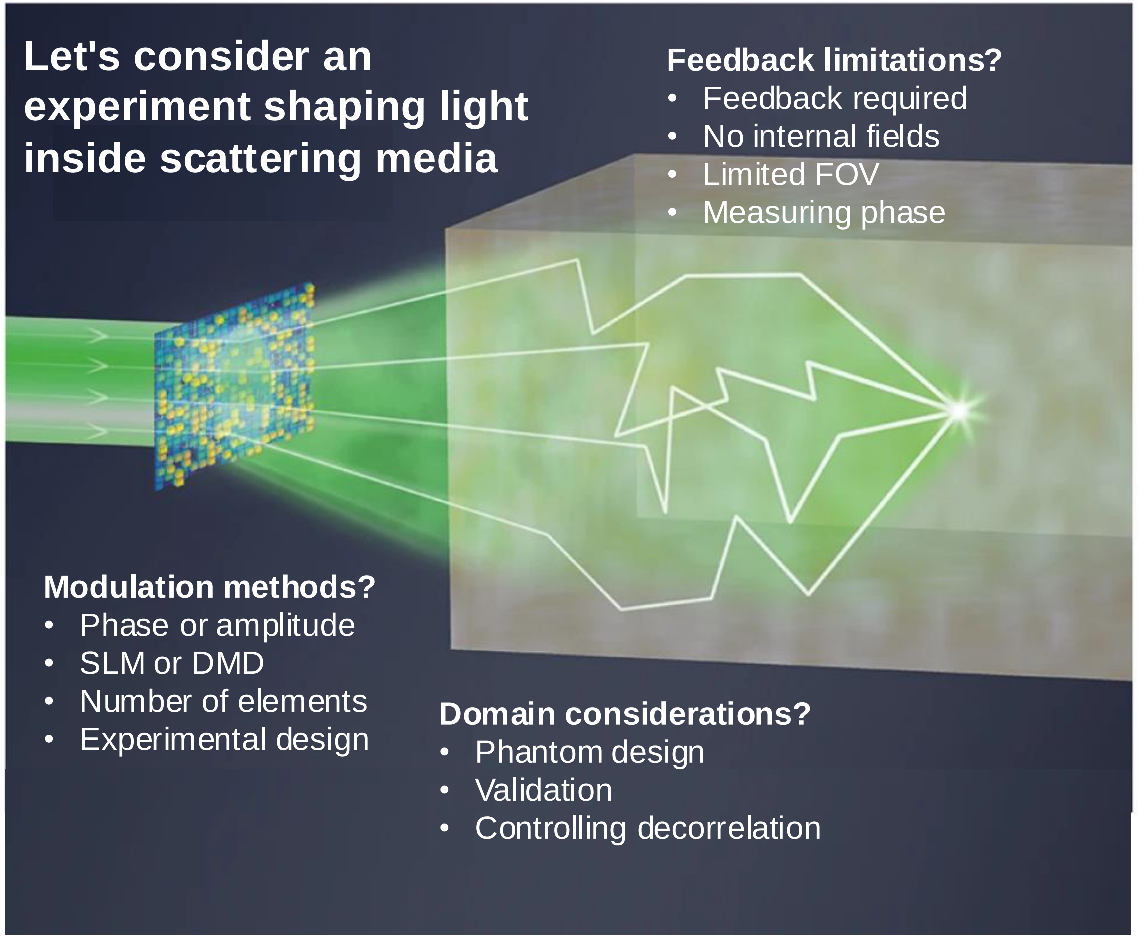

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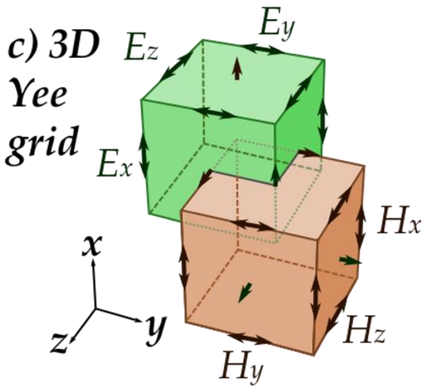
Computational methods are useful to investigate wavefront shaping

Simulating wavefront shaping – motivation and methods

Full-wave modelling of WFS

- Directly solve equations governing light propagation.
- Subwavelength discretization = very computationally expensive.



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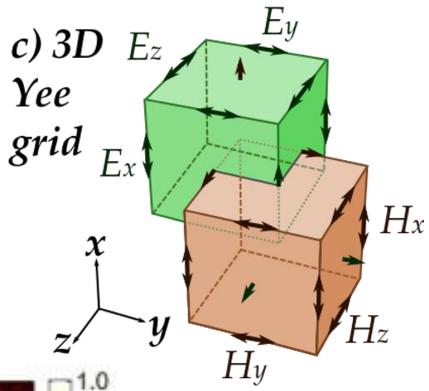

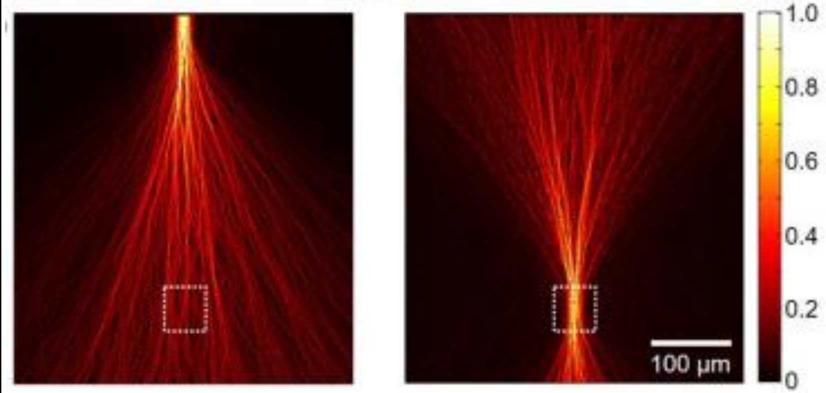

Kim, Jong Uk, et al., *Biomedical Optics Express*, 2018

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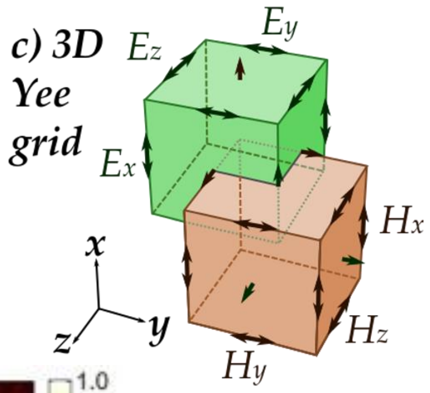

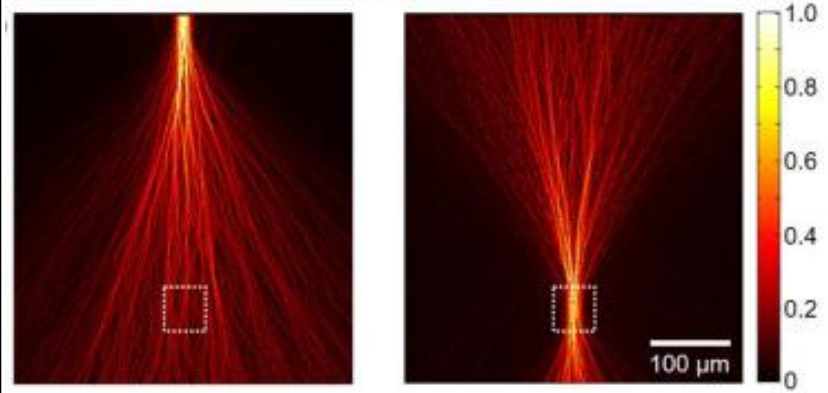

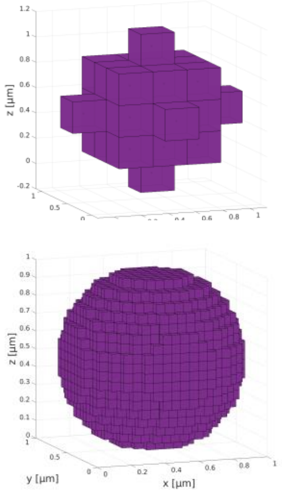

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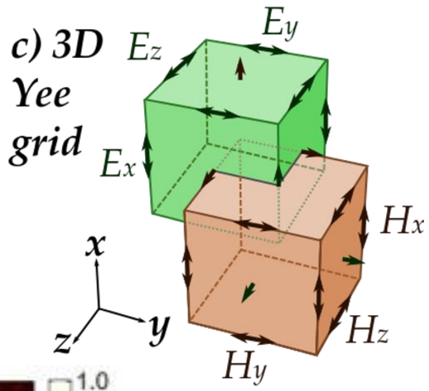

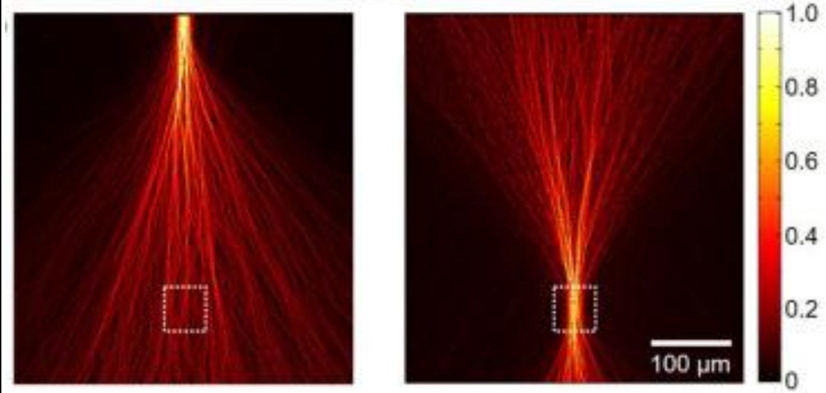

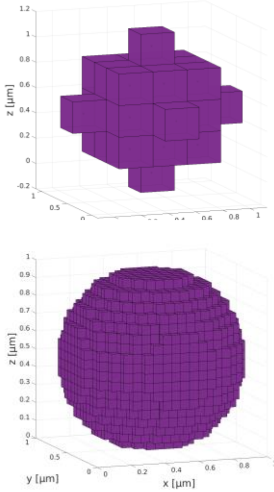

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Ansatz modelling of WFS

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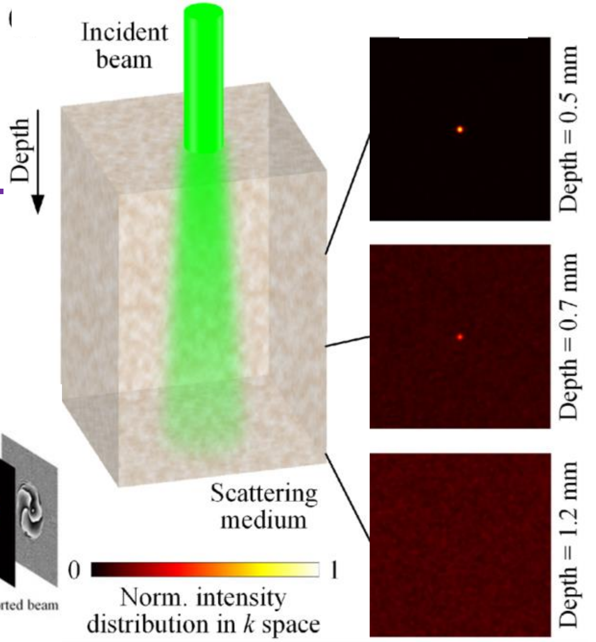

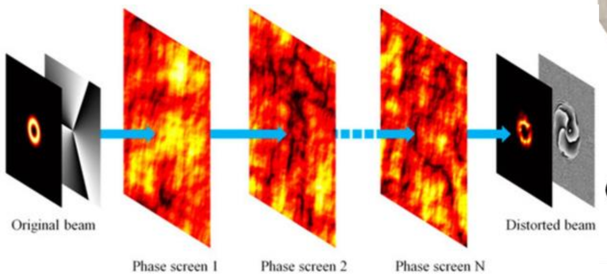

Dedo, Maxime Irene, et al., *Applied Sciences*, 2019 Yang, Jiamiao, et al., *Optica,* 2019

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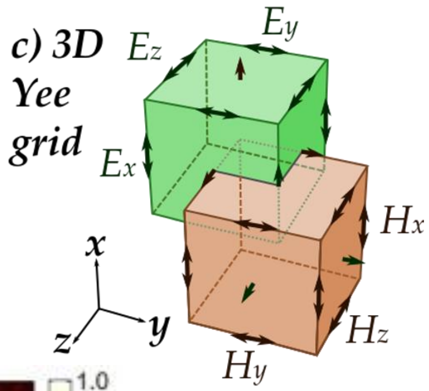

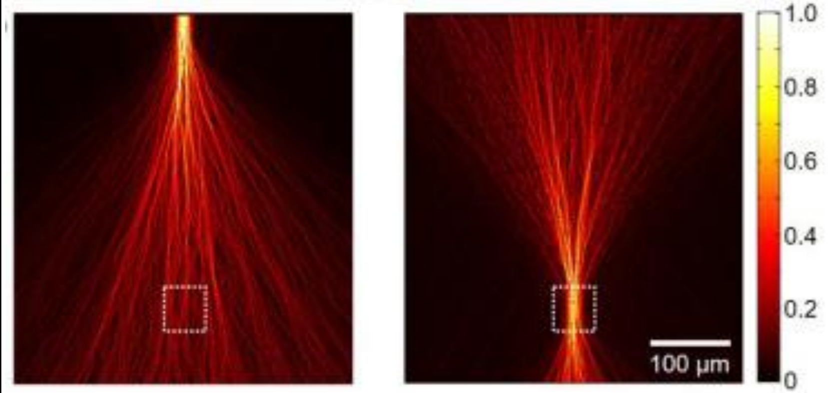

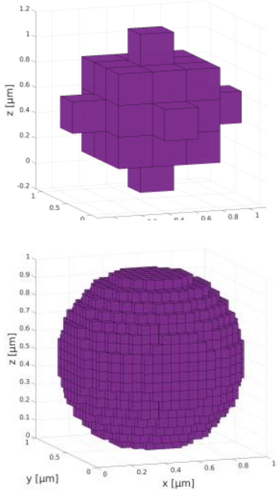

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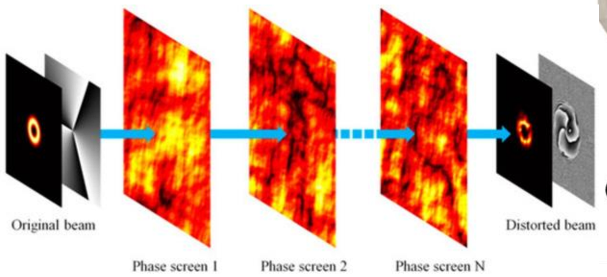
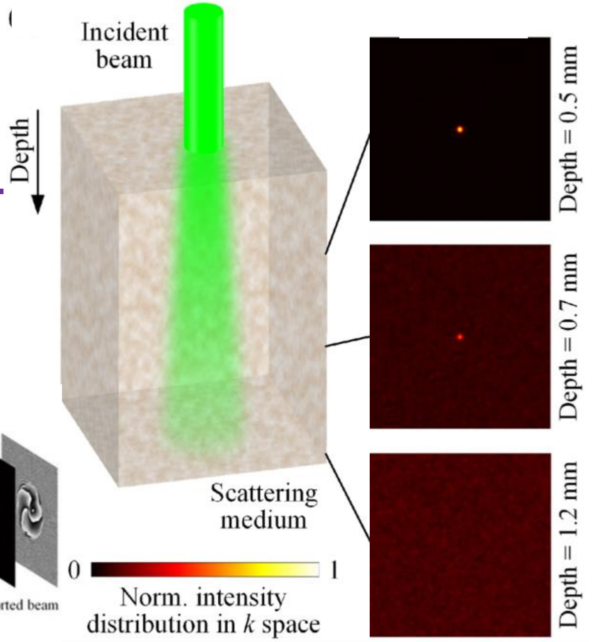
- Non-physical, and might not match experimental data.





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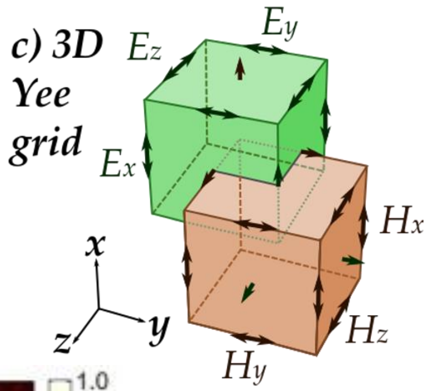
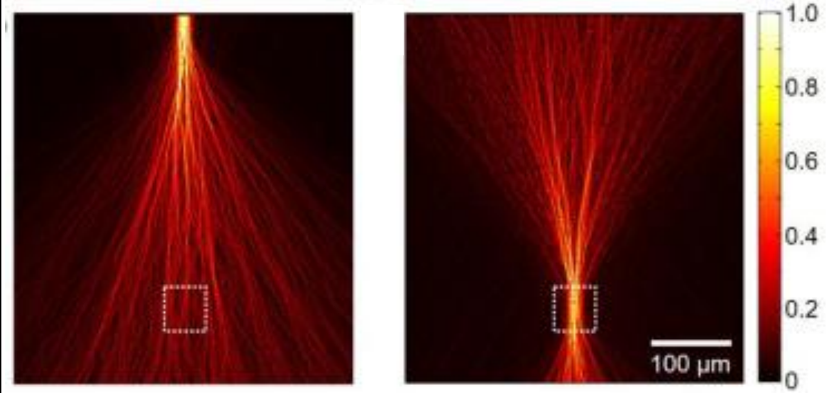
Yang, Jiamiao, et al., *Optica,* 2019

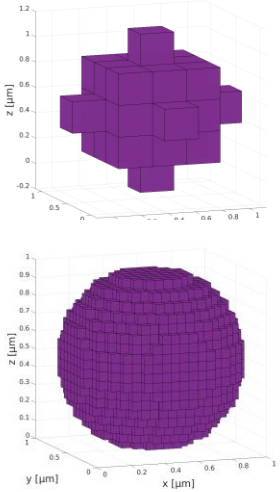
Simulating wavefront shaping – motivation and methods

Full-wave modelling of WFS

- Directly solve equations governing light propagation.
- Subwavelength discretization = very computationally expensive.







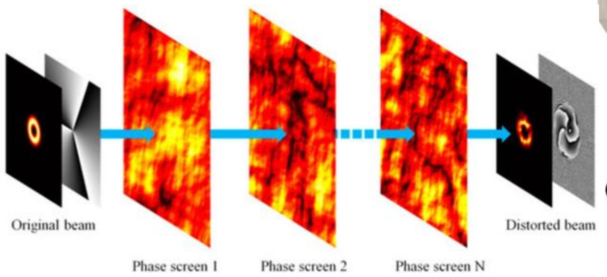
Kim, Jong Uk, et al., *Biomedical Optics Express*, 2018

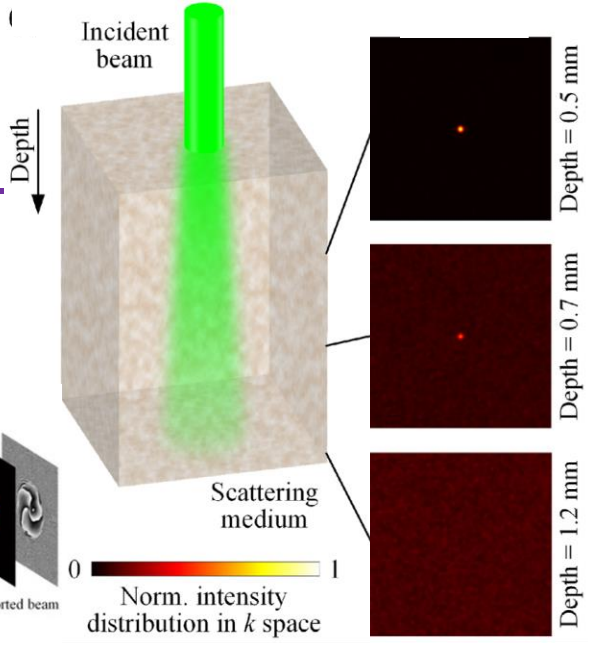
Modelled WFS for OCT

Fine mesh needed for small geometry

Ansatz modelling of WFS

- Simplify the physics of scattering to improve performance.
- Non-physical, and might not match experimental data.





Dedo, Maxime Irene, et al., *Applied Sciences*, 2019

Yang, Jiamiao, et al., *Optica*, 2019

Efficient, full-wave, computational methods are useful to investigate wavefront shaping

Our contributions + solutions

We present a physically realistic and efficient method of modelling wavefront shaping (WFS) through scattering media.

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4. **Exploiting our model** – *what is special about our model?*

Constructing our model:
The discrete particle model of scattering media

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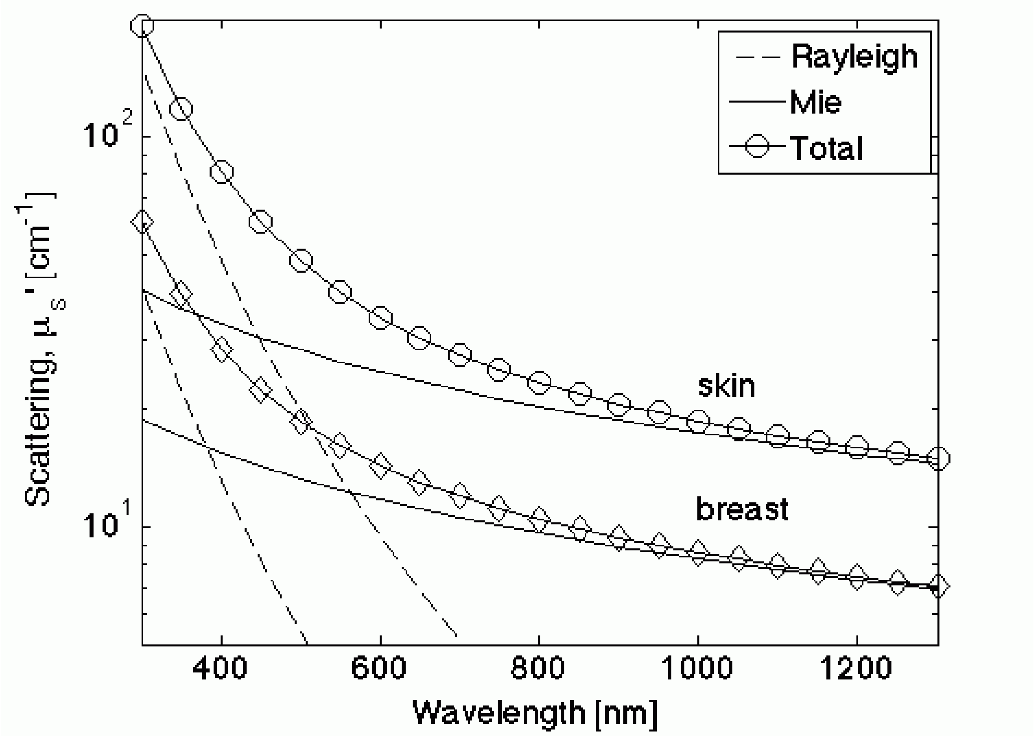
The Mie theory can be used to model light scattering in tissue



Jacques, Steven L., *Physics in Medicine & Biology,* 2013

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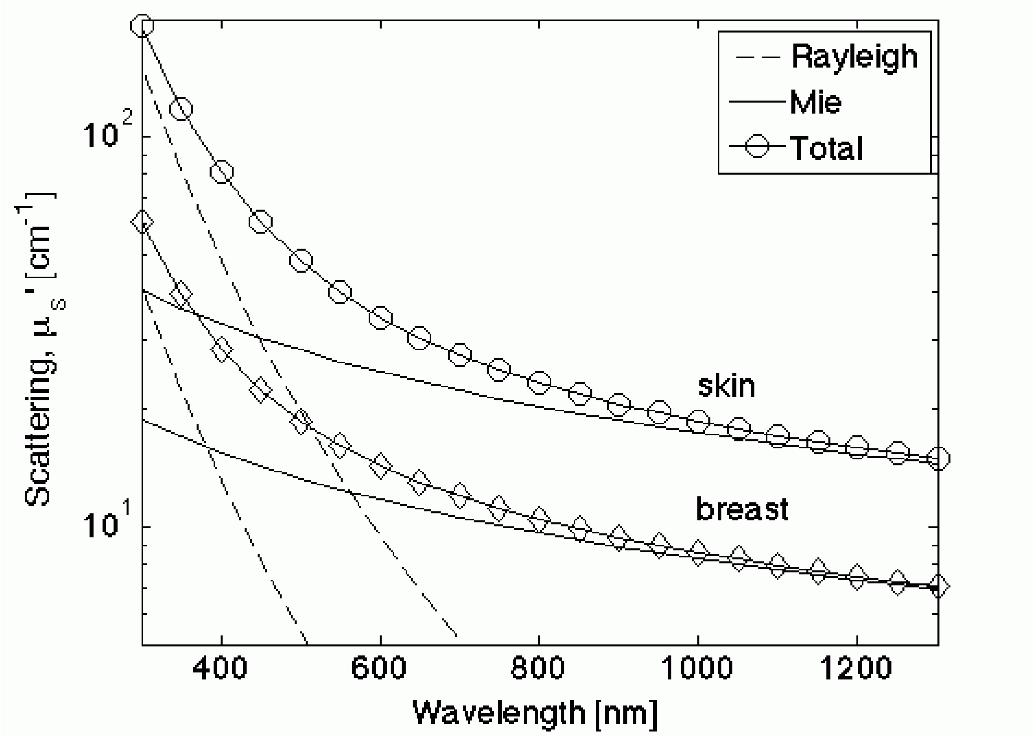
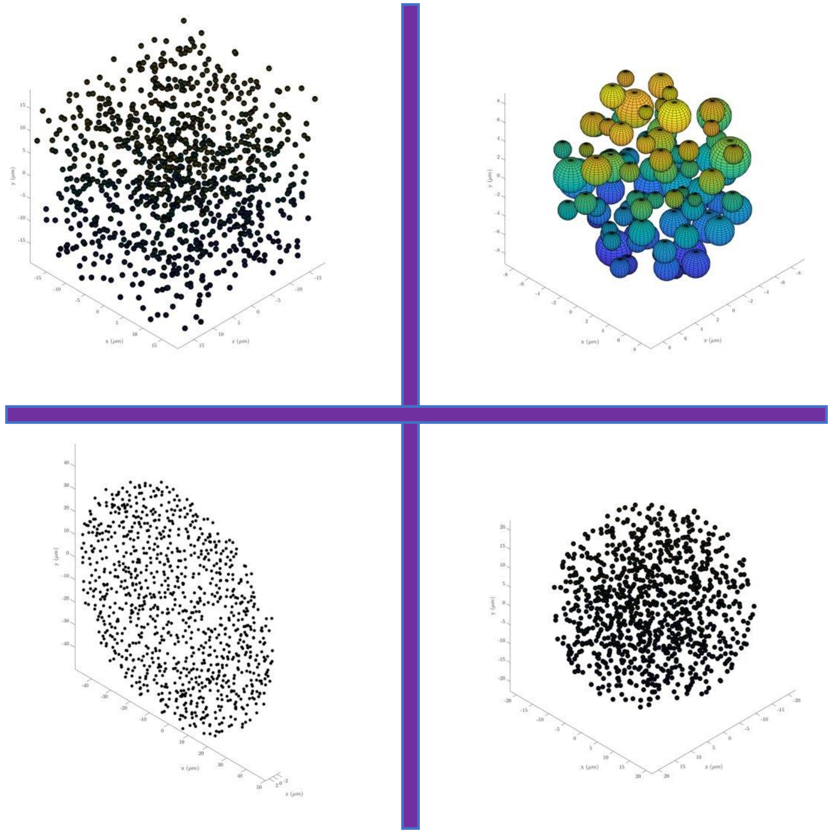


This is the discrete particle model



Scatterer refractive index, size and density define bulk optical properties

Jacques, Steven L., *Physics in Medicine & Biology,* 2013

Constructing our model:
The T-matrix method – theory and peculiarities

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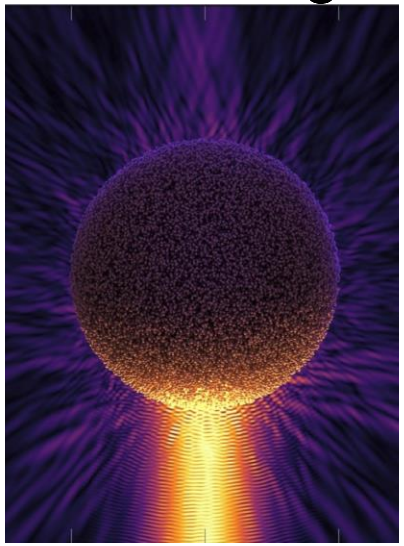
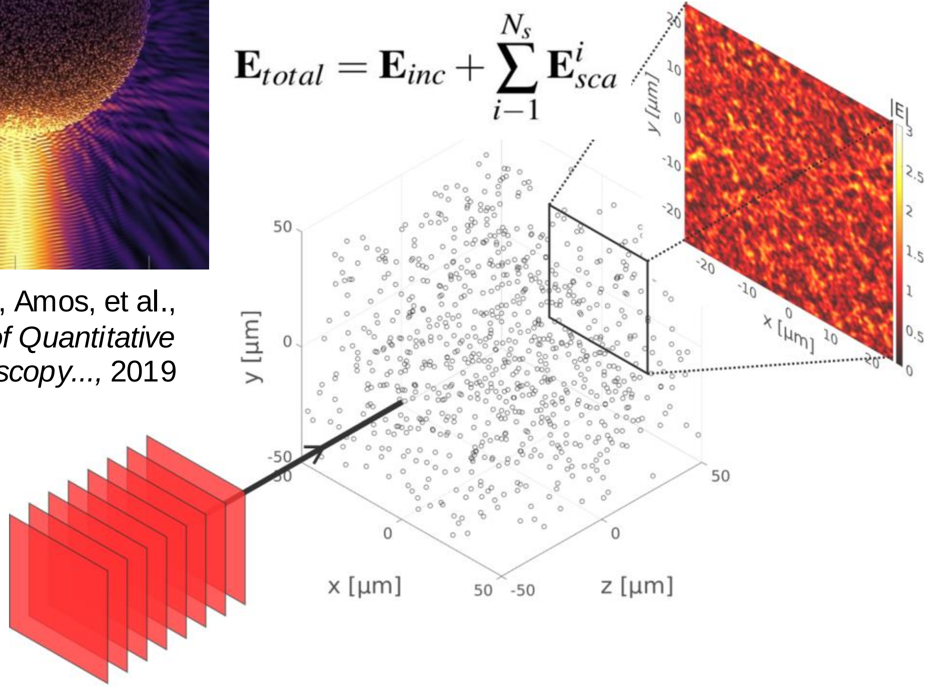
Simulating discrete particle domains



Egel, Amos, et al., *Journal of Quantitative Spectroscopy...*, 2019

- **T-matrix** is an extension of Mie theory to multi-sphere domains
- Total field is the sum of the scattered fields from each individual sphere.

$$\mathbf{E}_{total} = \mathbf{E}_{inc} + \sum_{i-1}^{N_s} \mathbf{E}_{sca}^{i}$$



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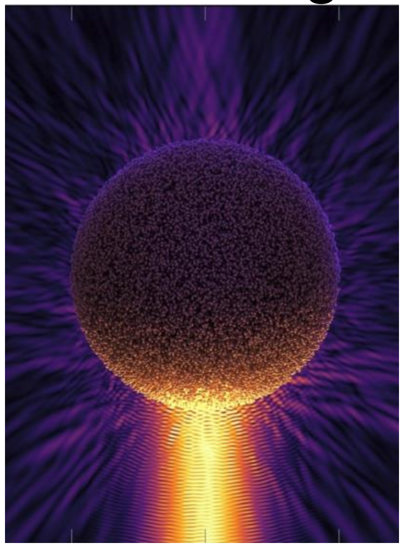

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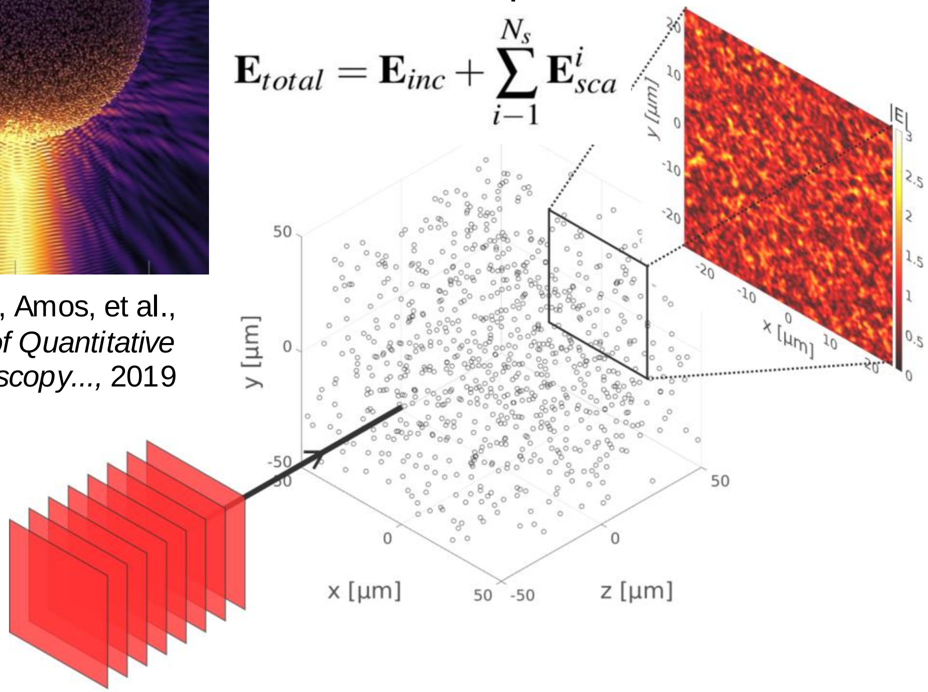
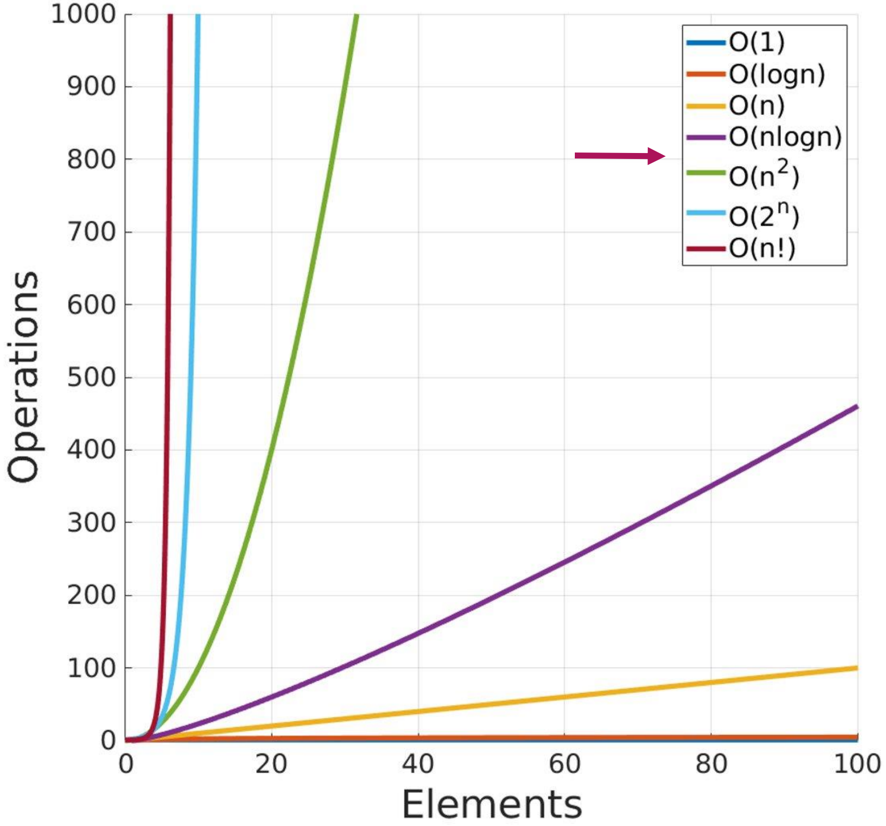


Scaling of the T-matrix method



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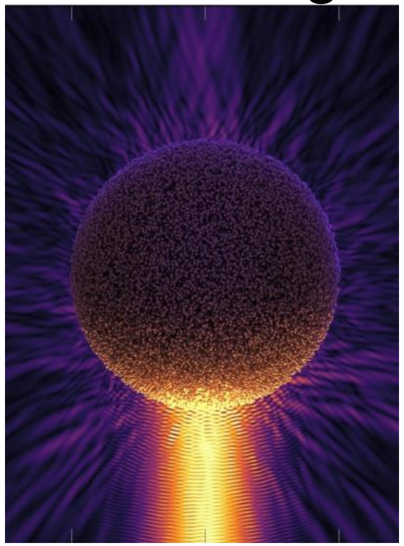

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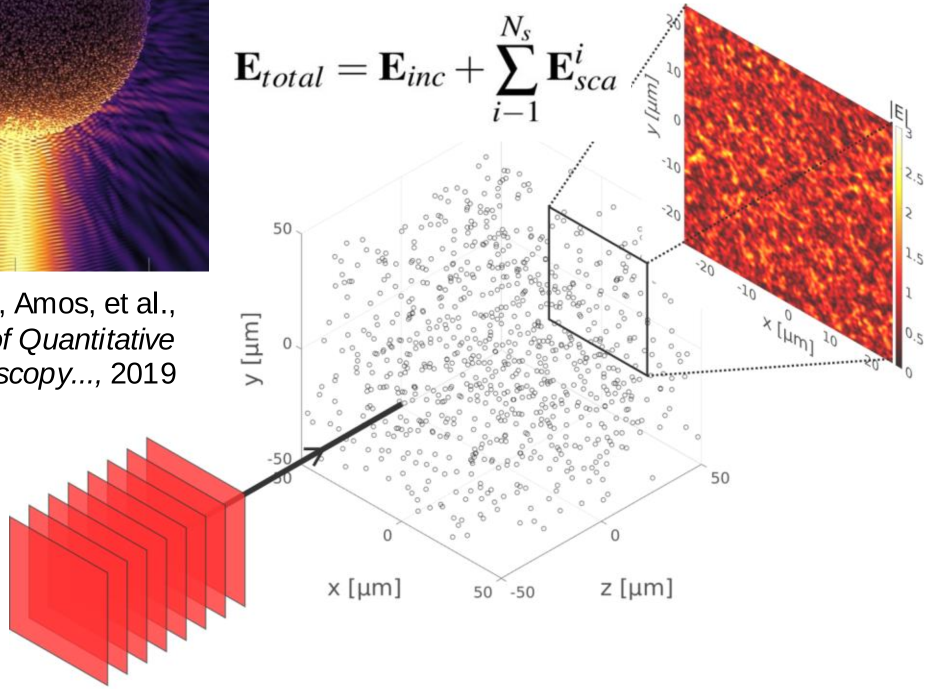

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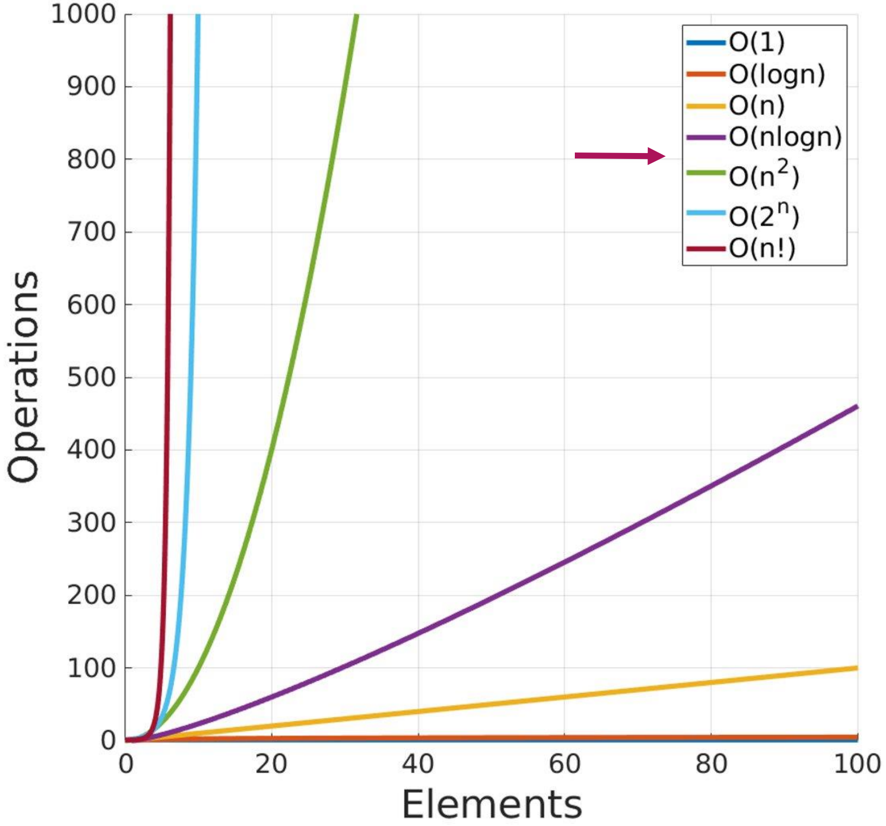

Efficient as no need to mesh space between spheres

Same domain: FDTD (~4 hrs), T-matrix (10 mins)

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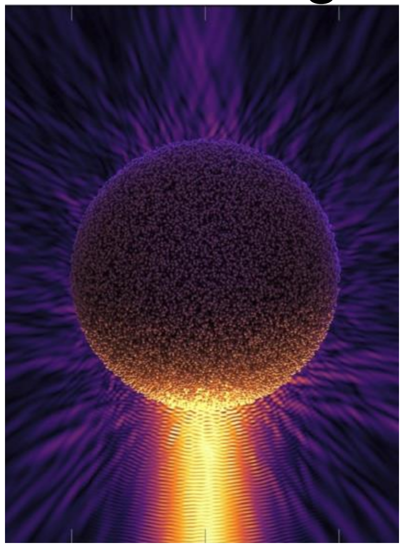

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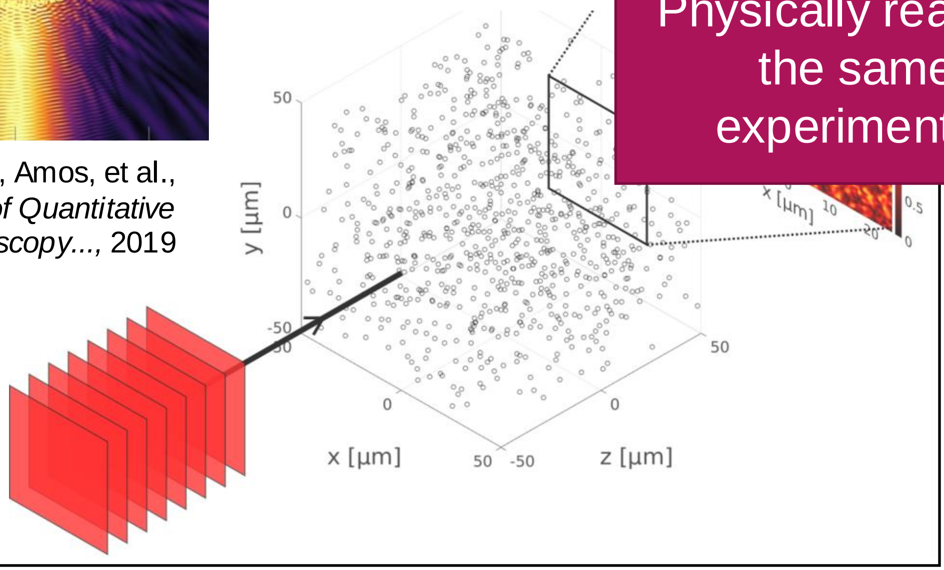
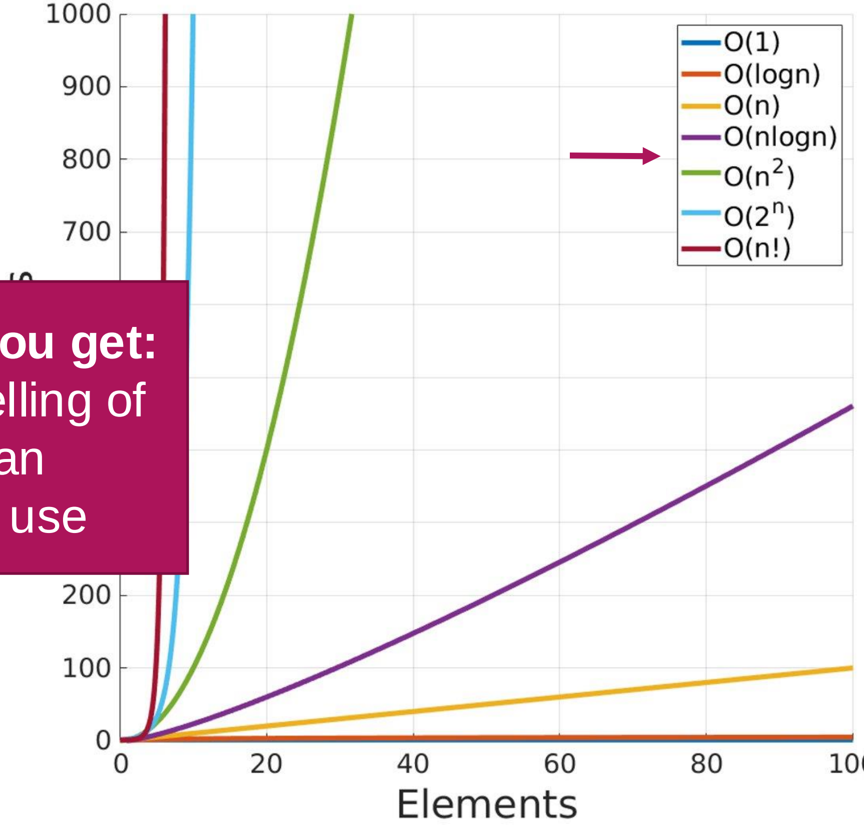


What you see is what you get:
Physically realistic modelling of the same domains an experimentalist might use

Scaling of the T-matrix method



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Constructing our model:
Simulating wavefront shaping

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Our method for simulating WFS

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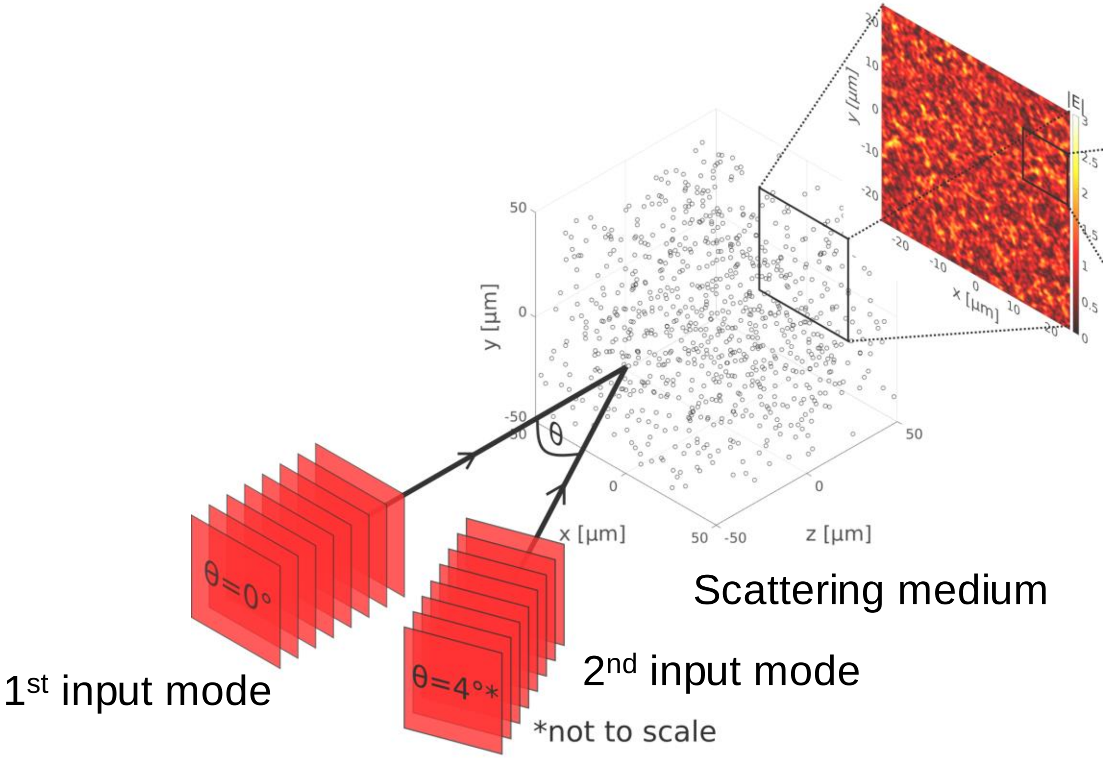

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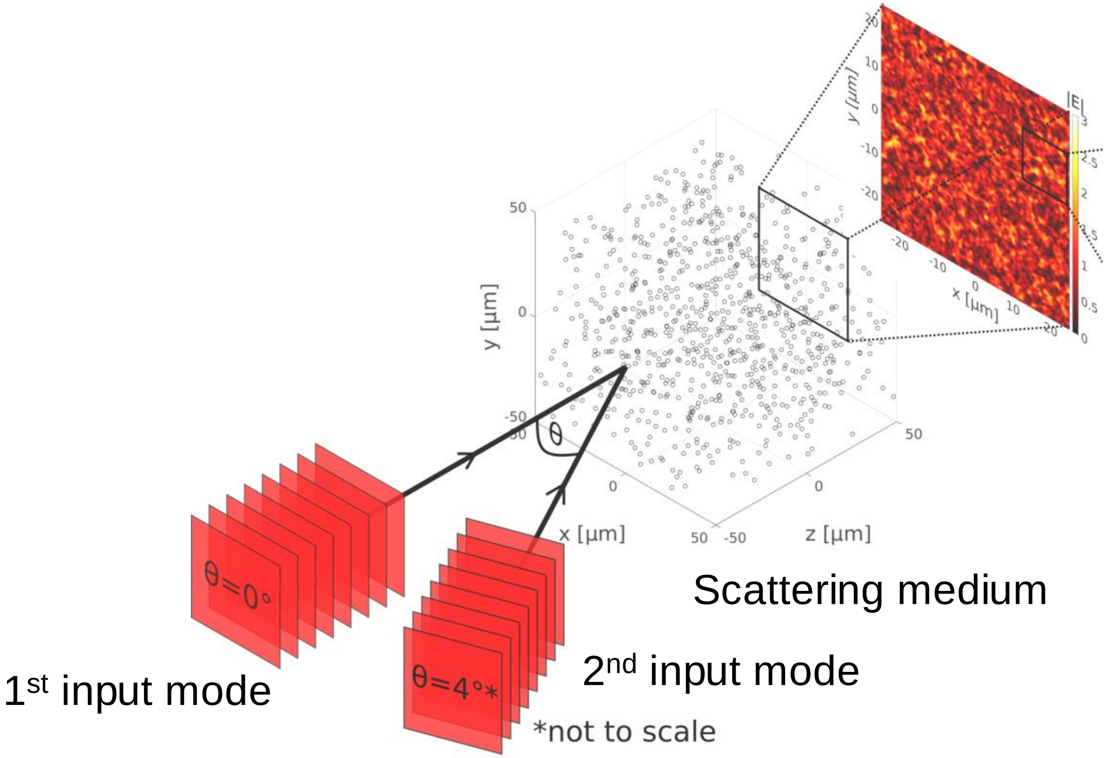

Constructing our model: Simulating wavefront shaping

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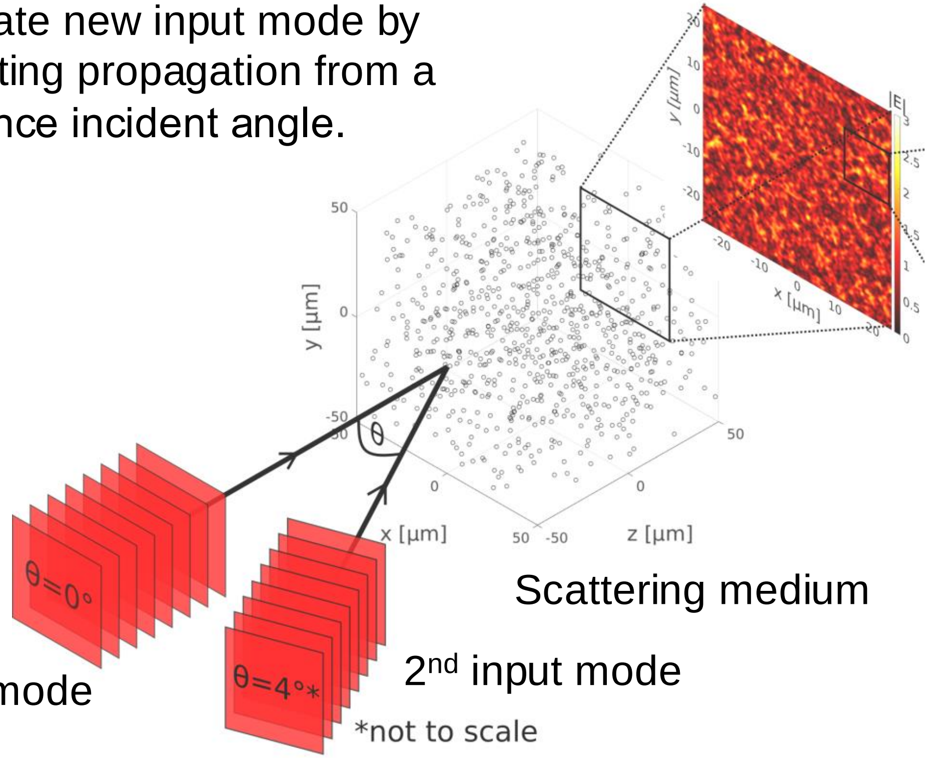

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Constructing our model: Simulating wavefront shaping

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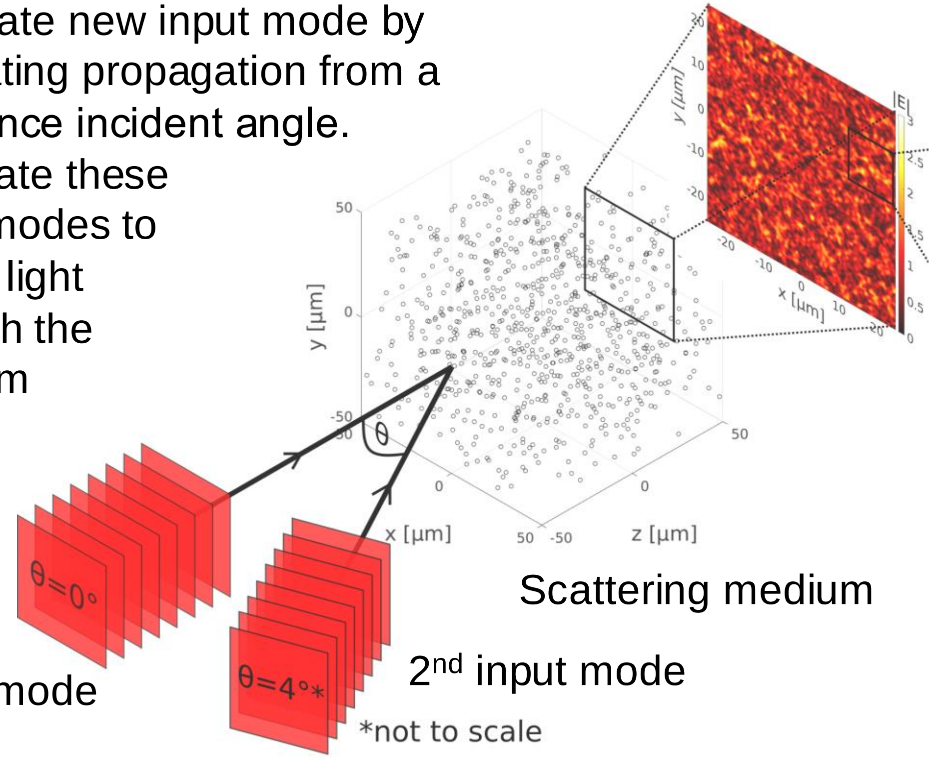

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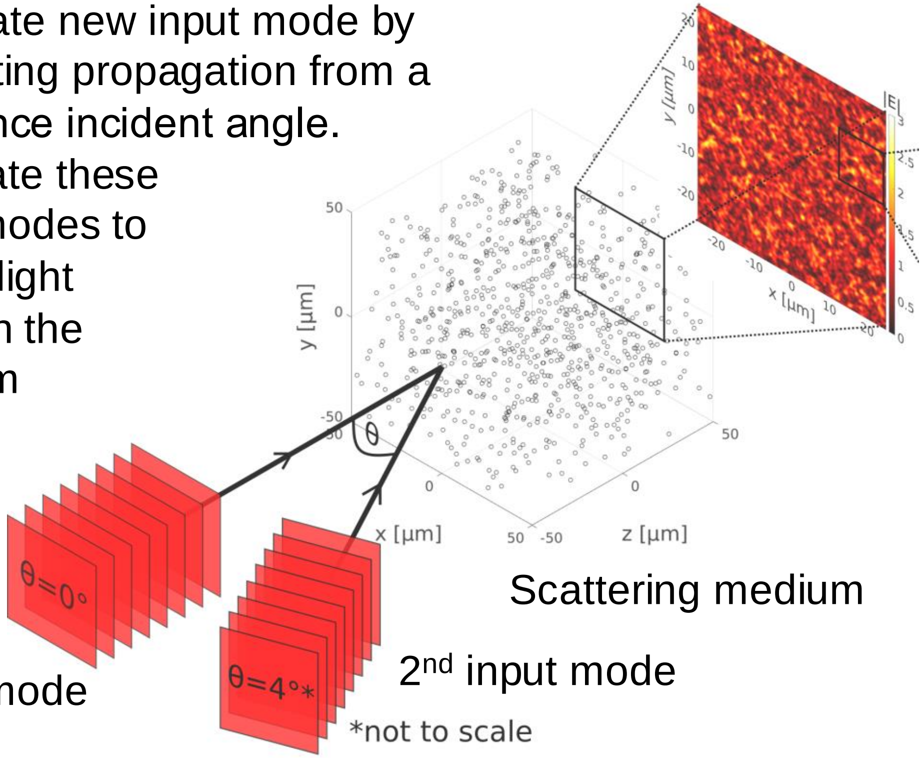
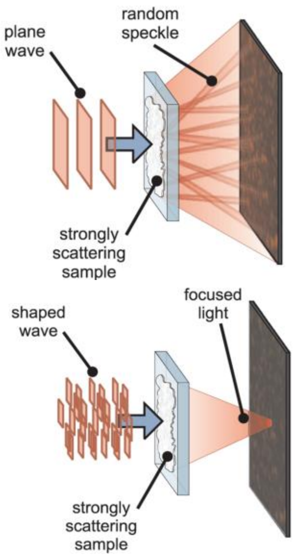


1st input mode

Constructing a titanium dioxide domain



Vellekoop and Mosk, *Optics letters*, 2007

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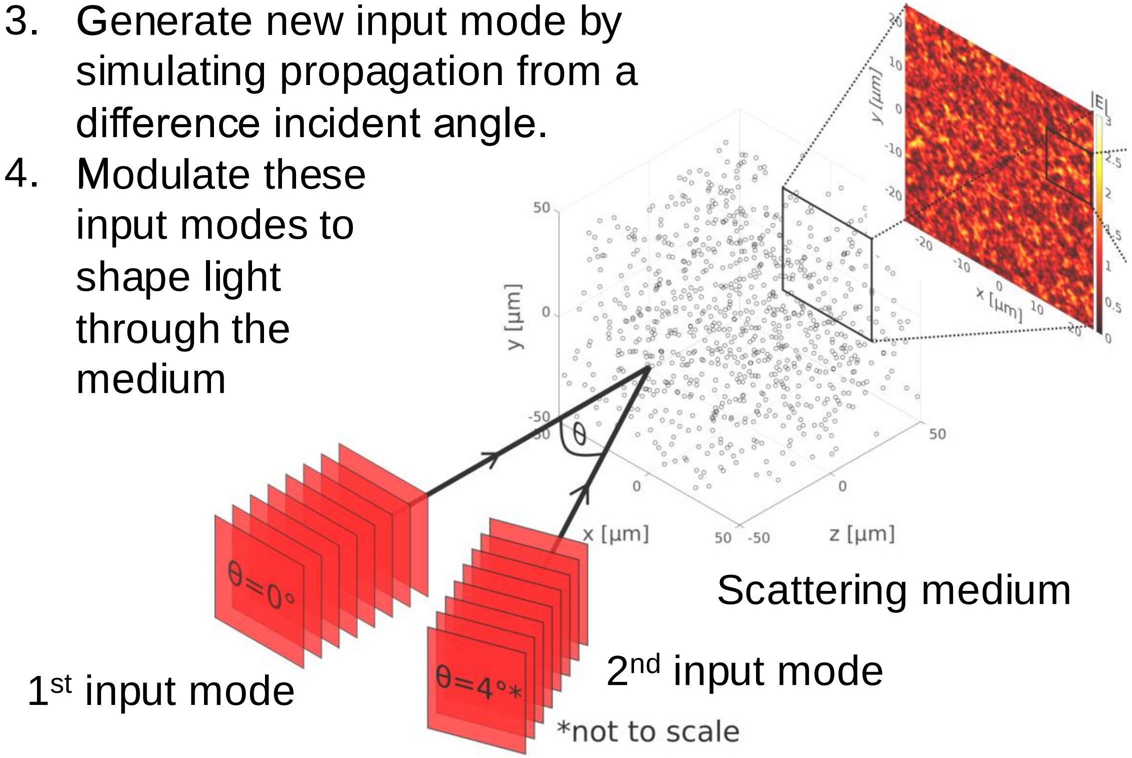

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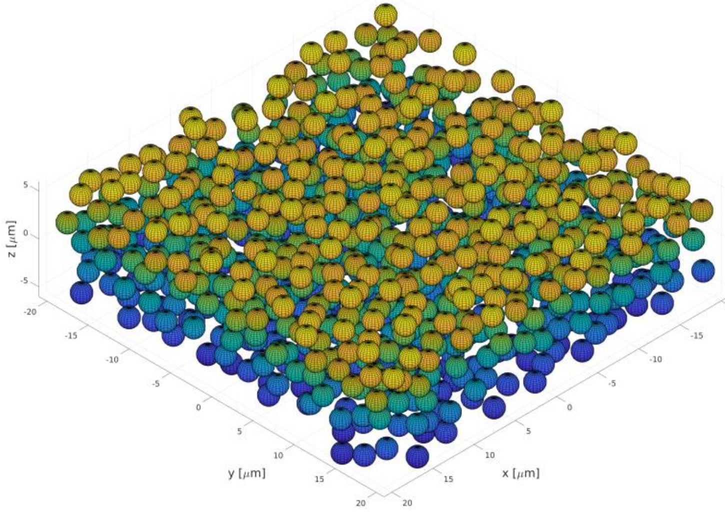

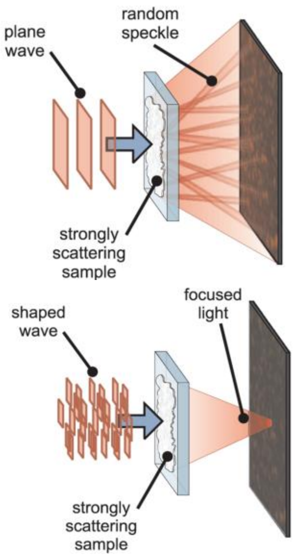

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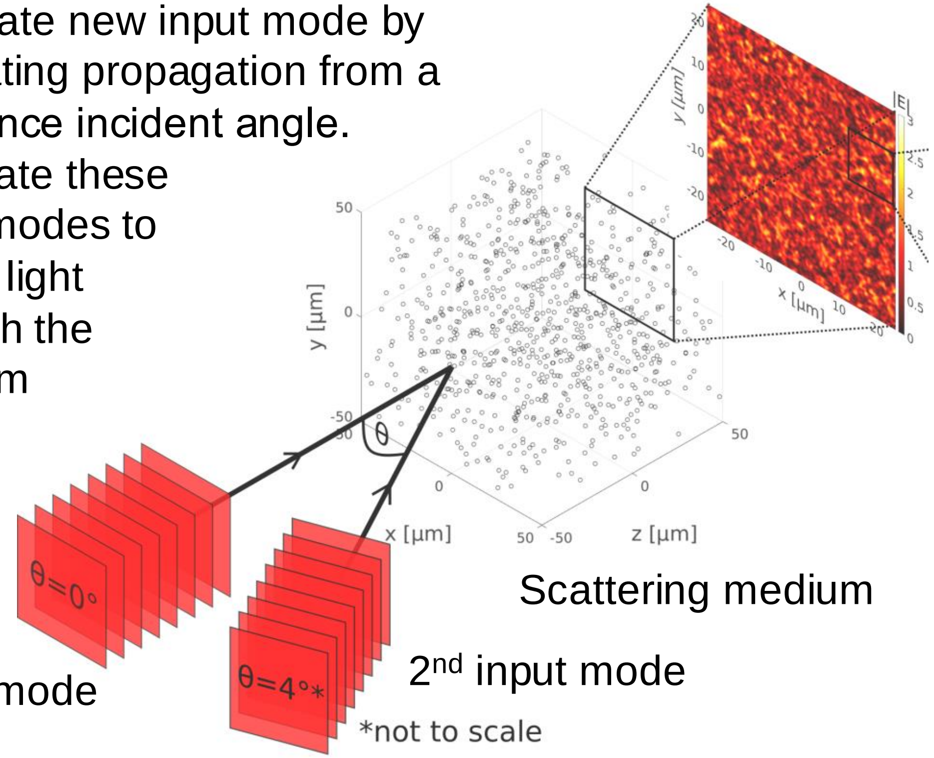

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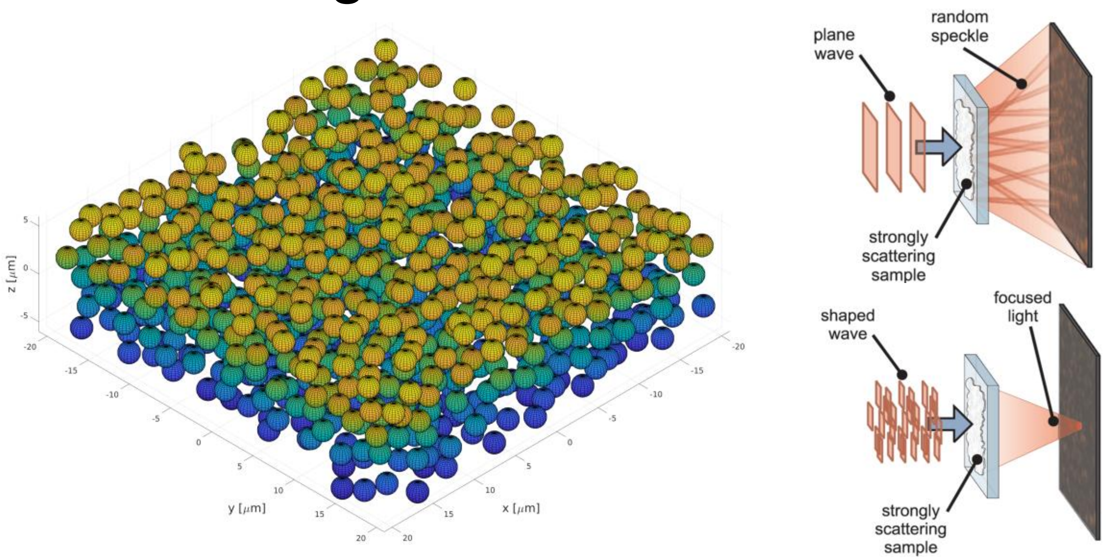

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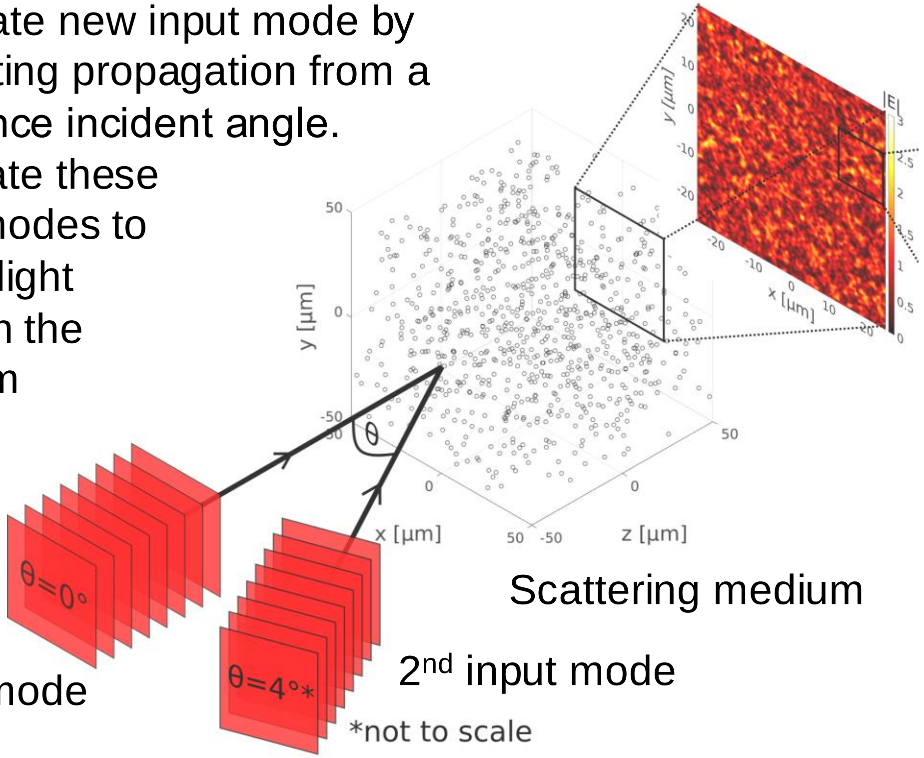


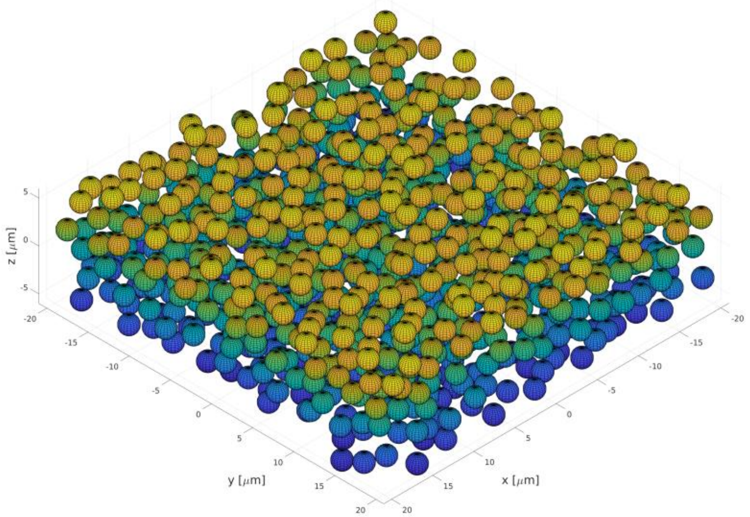
Scattering medium

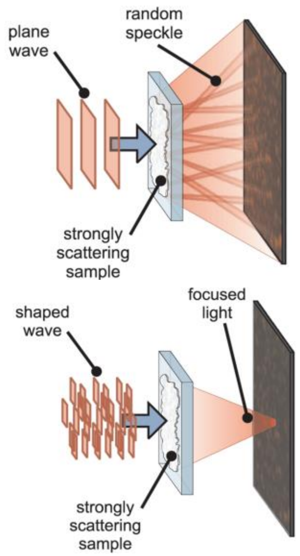
1st input mode

2nd input mode

*not to scale

Constructing a titanium dioxide domain





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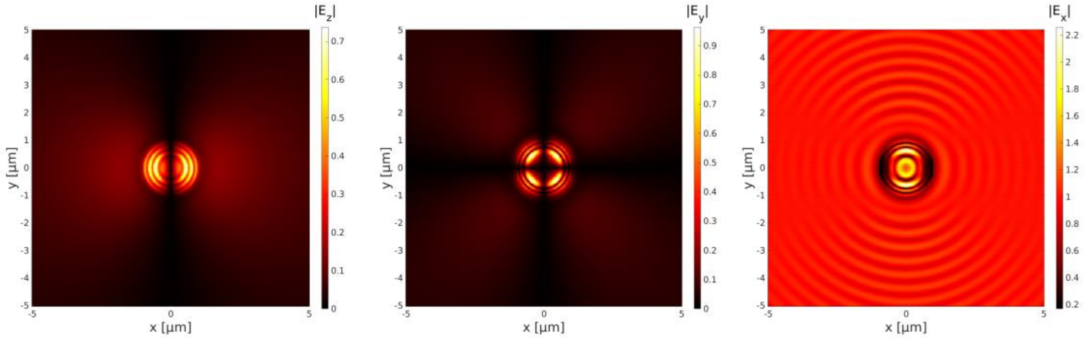
- Stepwise sequential algorithm used to spatially modulate light.

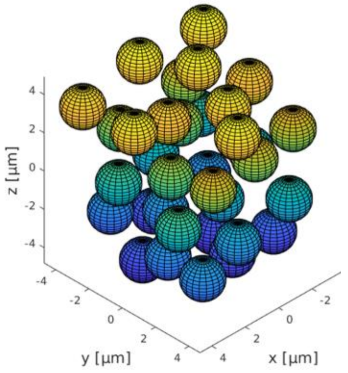
Validating the model

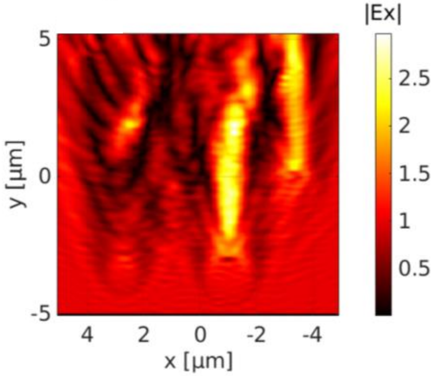
Validating the model

Numerical validation *(Mie theory + FDTD)*



- Compared single sphere fields against Mie theory to validate numerical implementation of T-matrix.
- Constructed 30 sphere scaled down domain and compared simulated field against FDTD.





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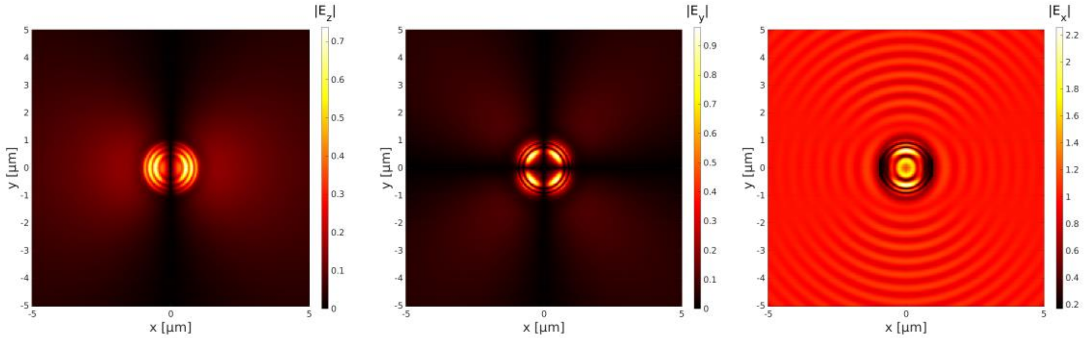

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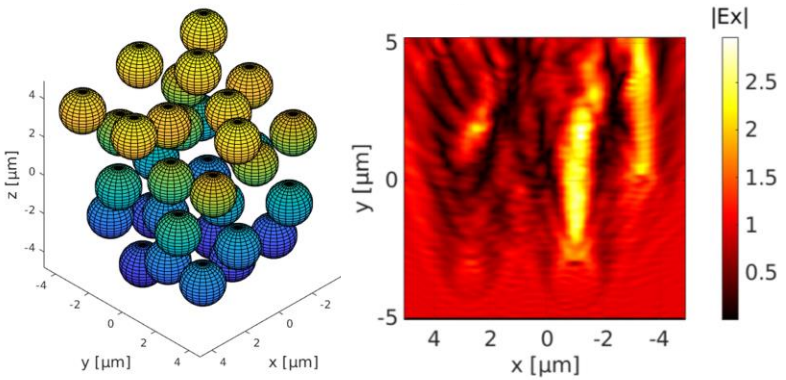
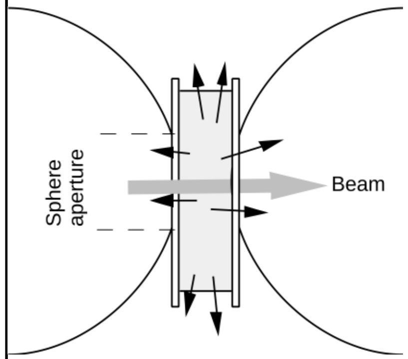
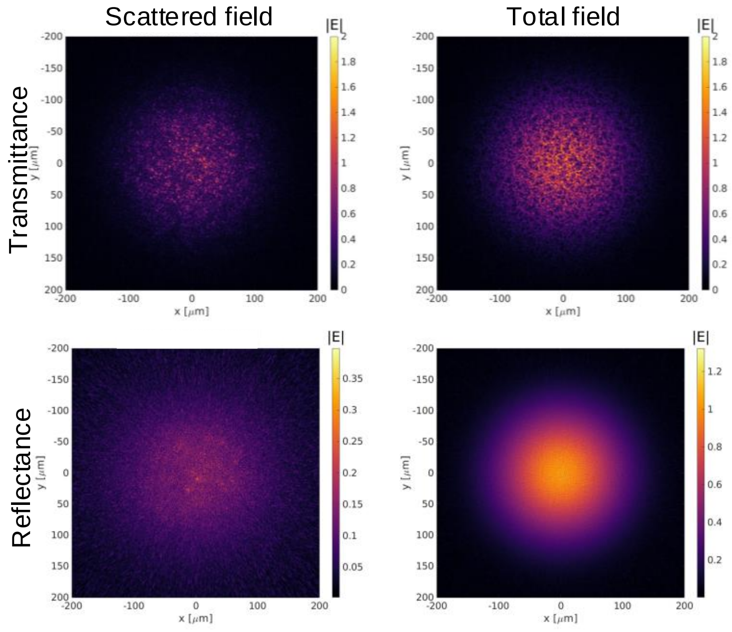


Domain validation *(Inverse Adding-Doubling)*

IAD can be used to independently measure the optical properties of a domain.





Measurements of transmittance and reflectance were taken by simulating the propagation of a Gaussian beam through scattering domains.

For all domains, IAD derived scattering coefficients and anisotropies matched theory (<3% error).

Focusing through titanium dioxide phantoms

Using iterative phase modulation to focus through TiO_2 (can we model WFS?)

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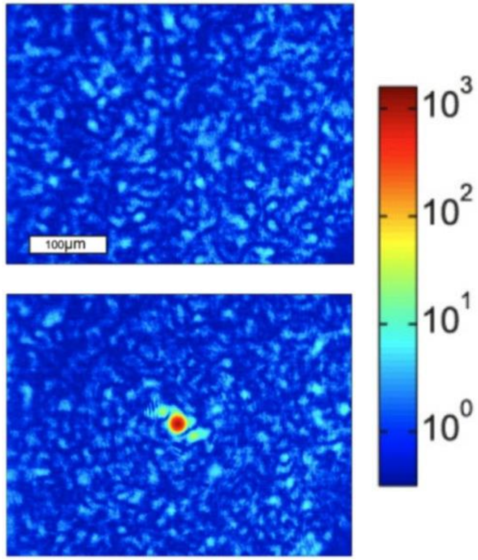

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Replicating original Vellekoop and Mosk demonstration by focusing through TiO_2

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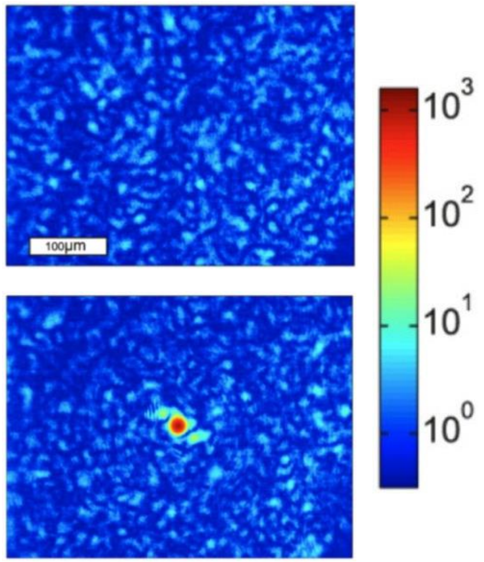

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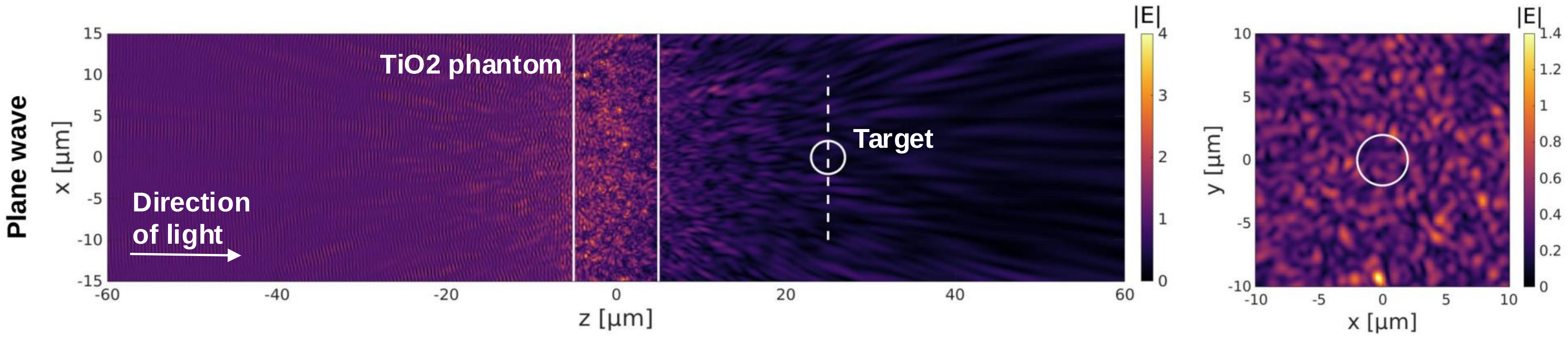

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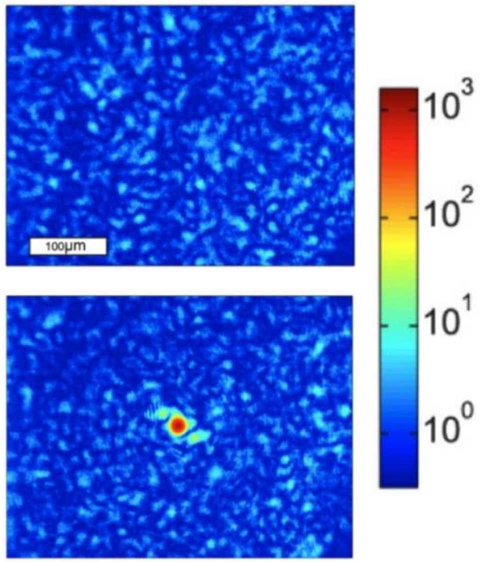

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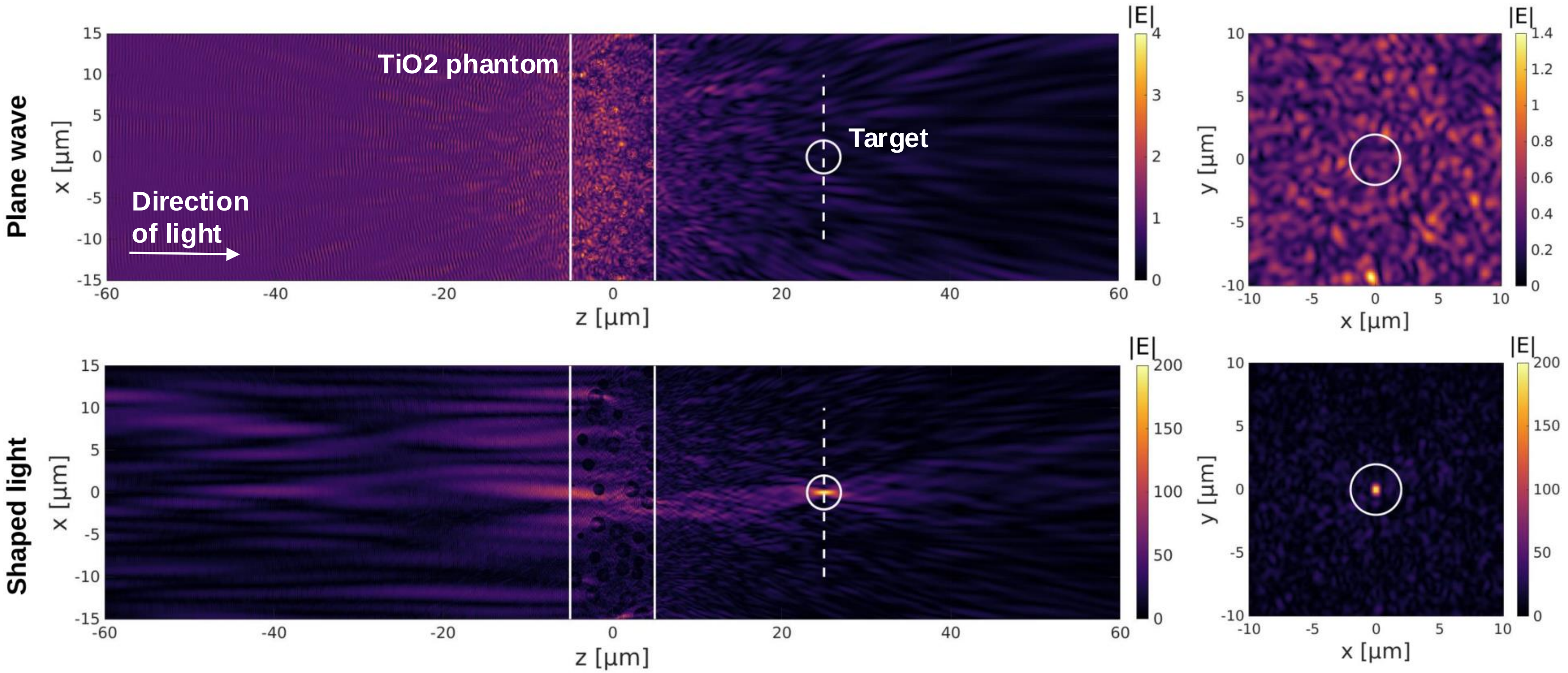

Phase of 441 different input modes optimized to generate an optical focus.

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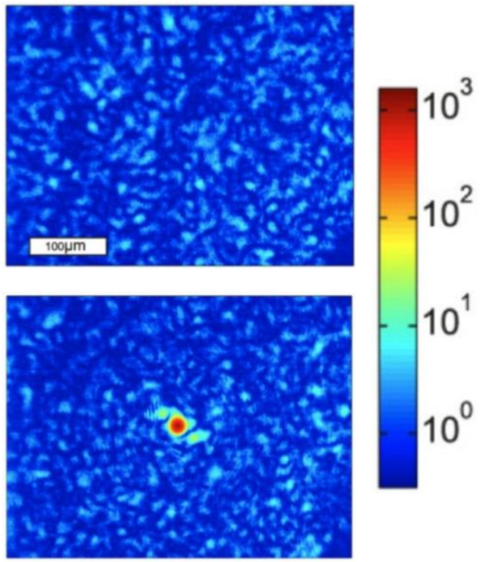

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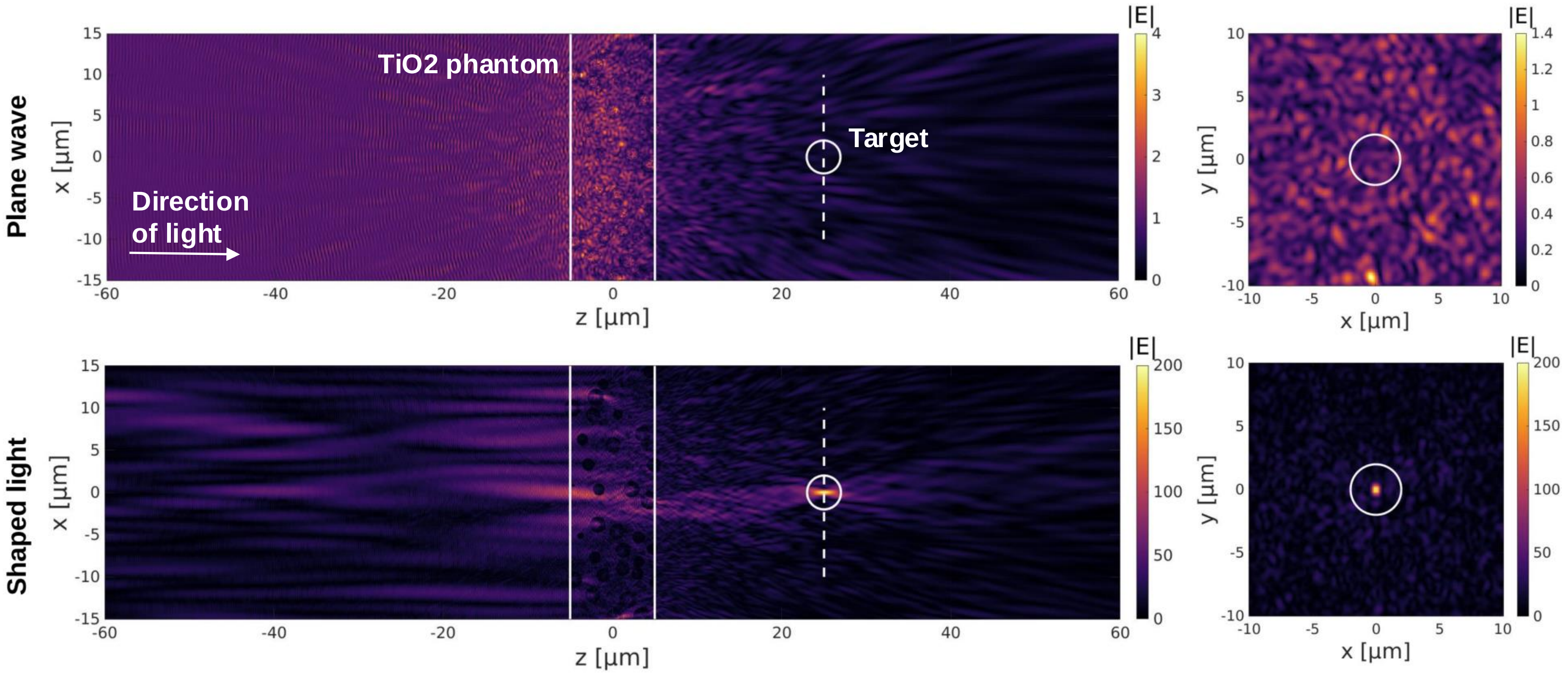


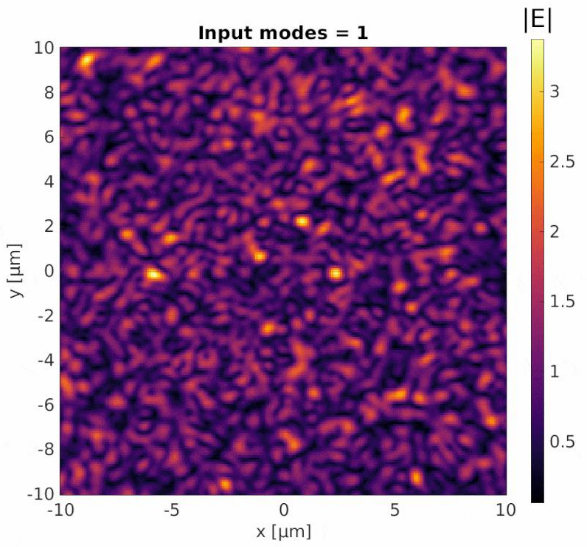
Replicating original Vellekoop and Mosk demonstration by focusing through TiO_2

Phase of 441 different input modes optimized to generate an optical focus.

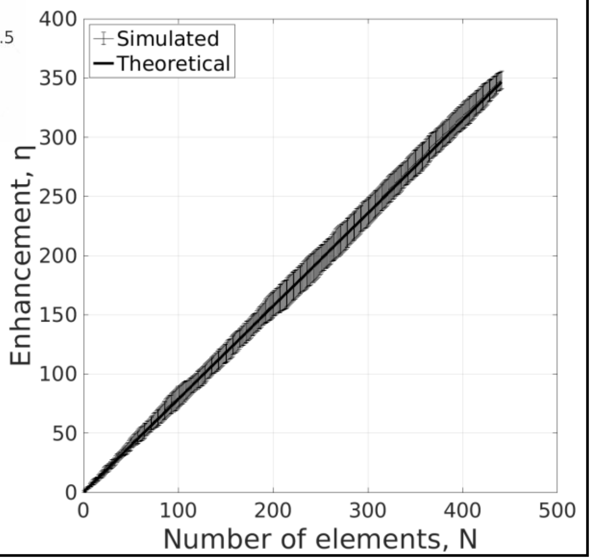
Our model is able to simulate WFS through highly scattering media

Focusing through titanium dioxide phantoms

Enhancement vs elements



Enhancement is defined as the intensity of the optimized focus to the average intensity of the unoptimized speckle

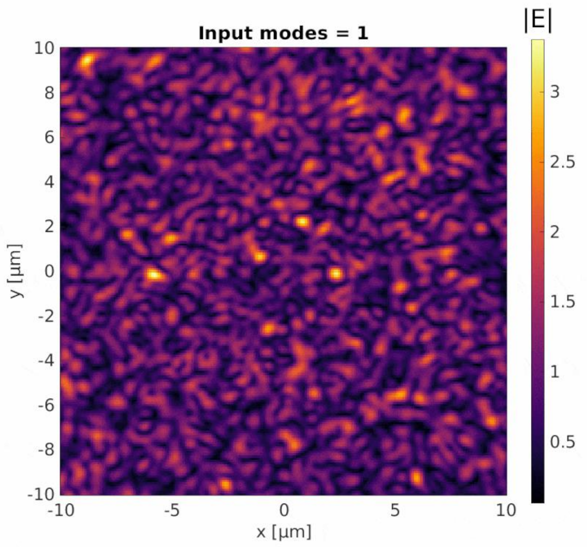


We find that our simulation of enhancement vs number of input modes scales with theory:

$$\eta = \frac{\pi}{4}(N-1)+1.$$

Focusing through titanium dioxide phantoms

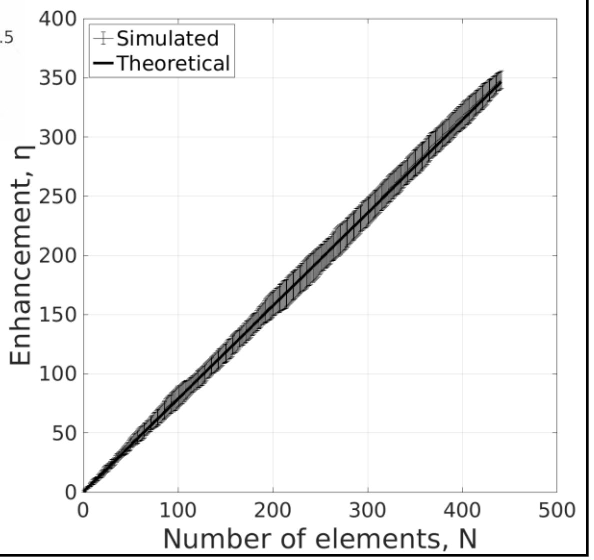
Enhancement vs elements



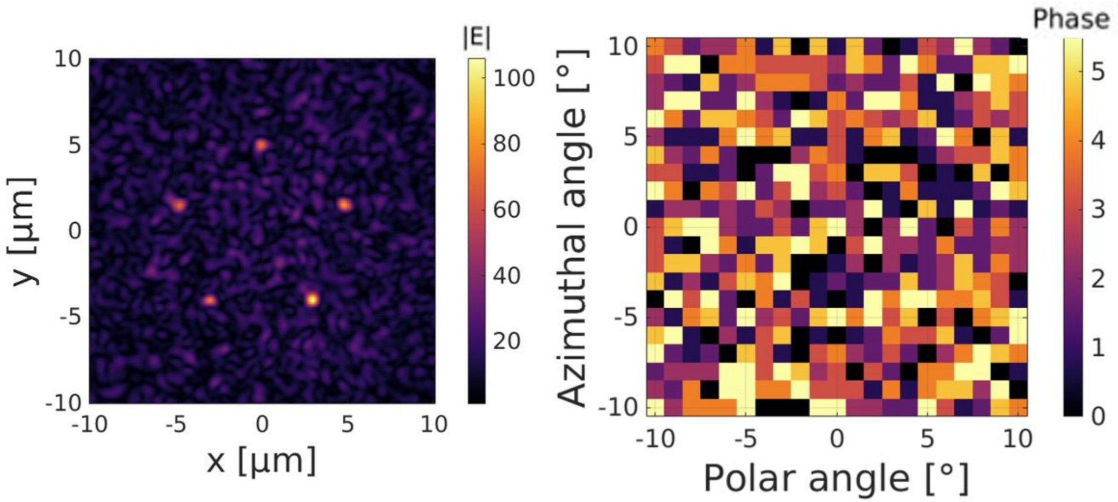
Enhancement is defined as the intensity of the optimized focus to the average intensity of the unoptimized speckle

We find that our simulation of enhancement vs number of input modes scales with theory:

$$\eta = \frac{\pi}{4}(N-1) + 1.$$



Multiple foci



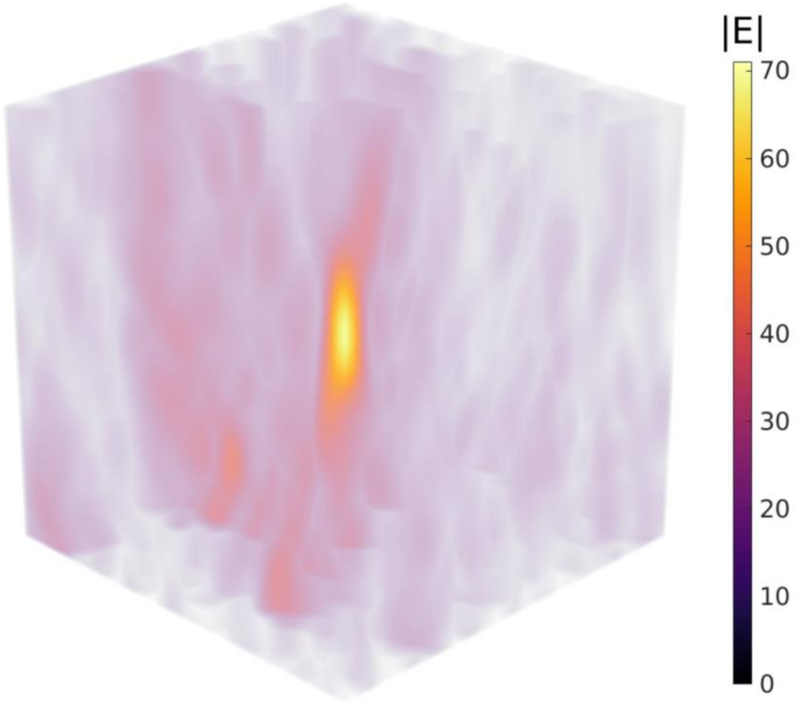
Our method is capable of generating arbitrary fields, as shown above

Exploiting wavefront shaping models

Exploiting wavefront shaping models

3D & internal focusing

- Computational models can be used to evaluate the field at arbitrary locations.
- Below is a 3D focus optimized to generate inside the TiO_2 domain.



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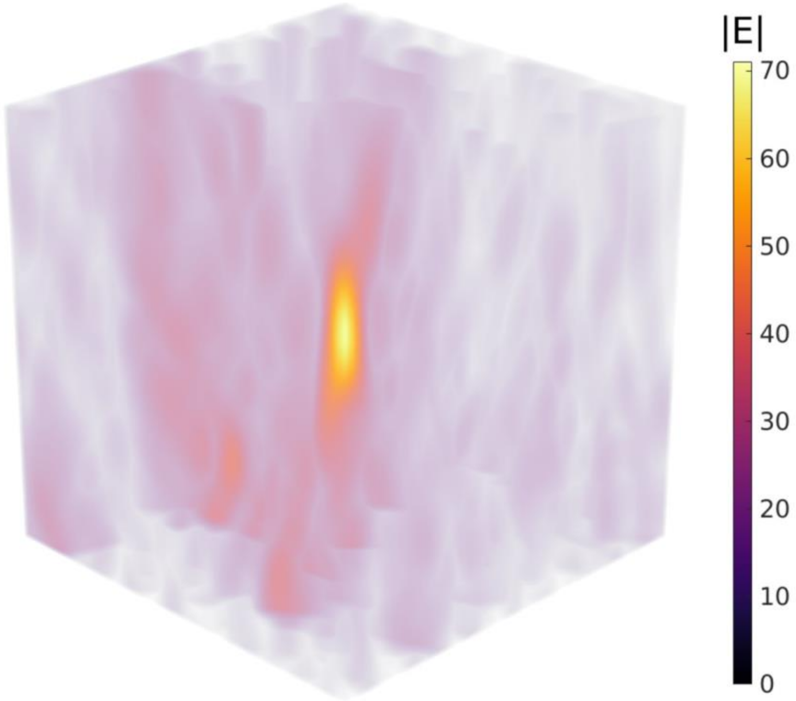
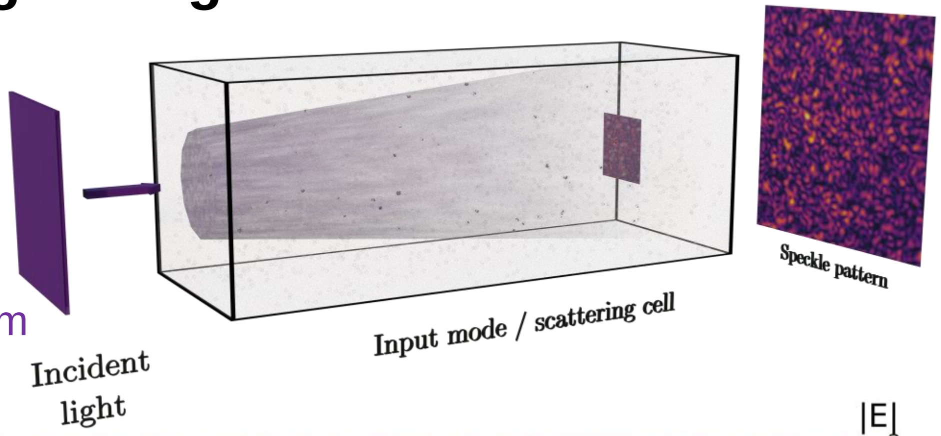
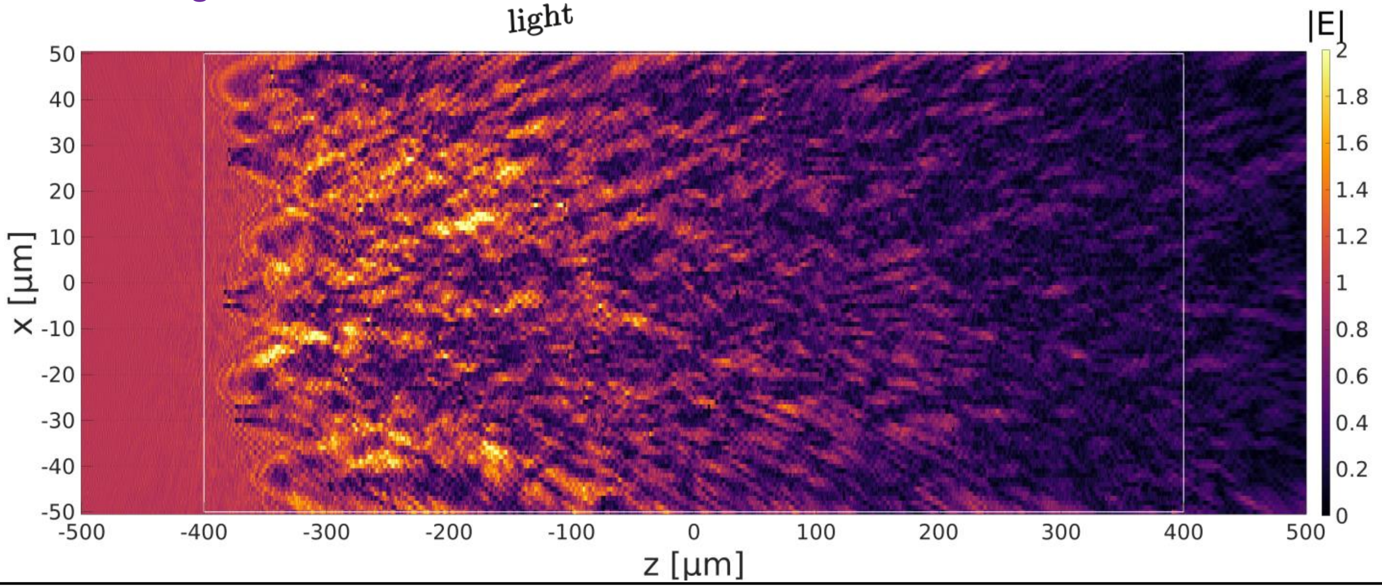


Scattering through tissue-like media

Biological tissue can be modelled using discrete particle domains.

We have simulated light propagation through ~mm scale biological tissue.



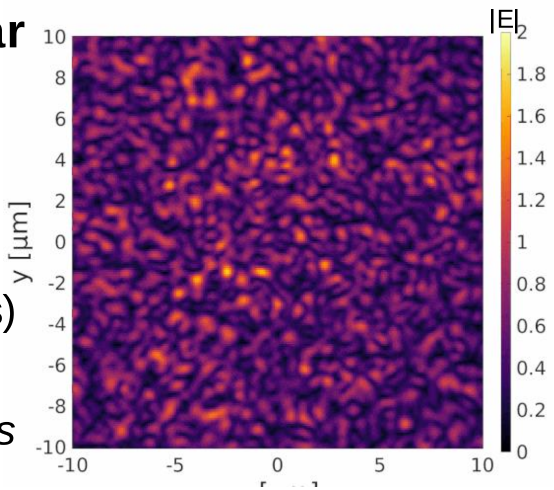


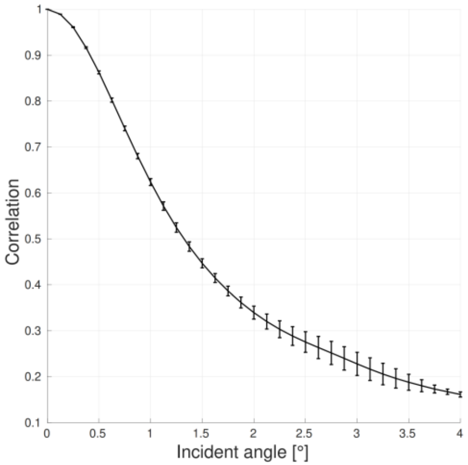
Exploiting wavefront shaping models

Measuring the angular memory effect range

Ansatz methods have struggled to model coherent phenomena (e.g. memory correlations)

Some methods exploit these correlations to focus light into scattering media.





Exploiting wavefront shaping models

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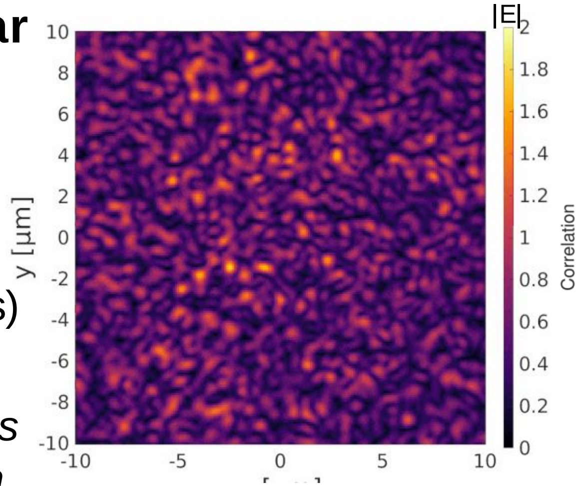
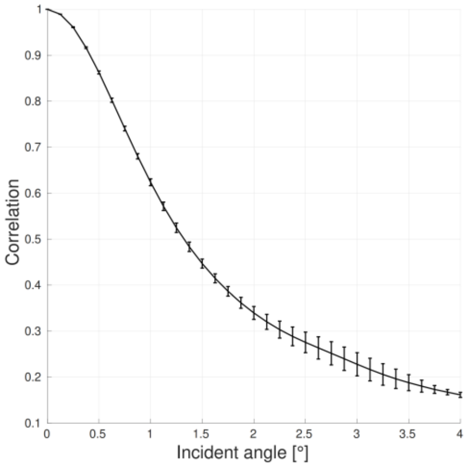
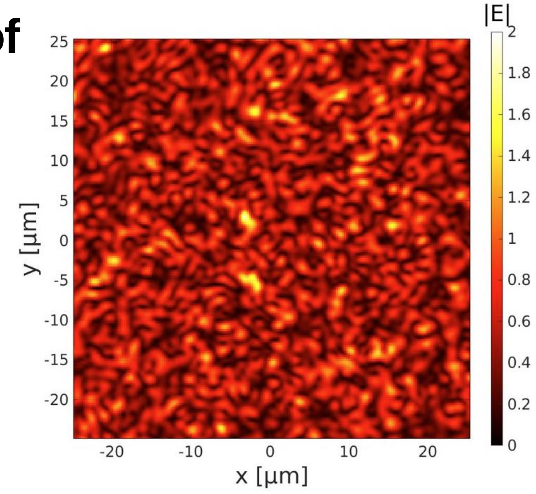


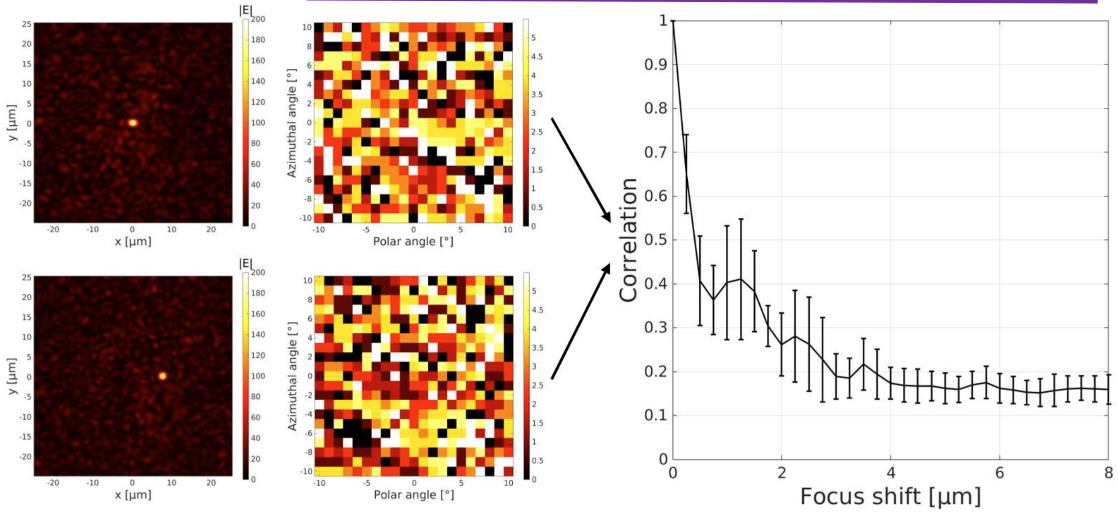


Modelling the angular range of an optimized focus

Imaging FOV could be increased by exploiting memory correlations to translate already optimized foci.

Focusing might also be able to be accelerated by exploiting priors (e.g. sharing phase maps between input modes).





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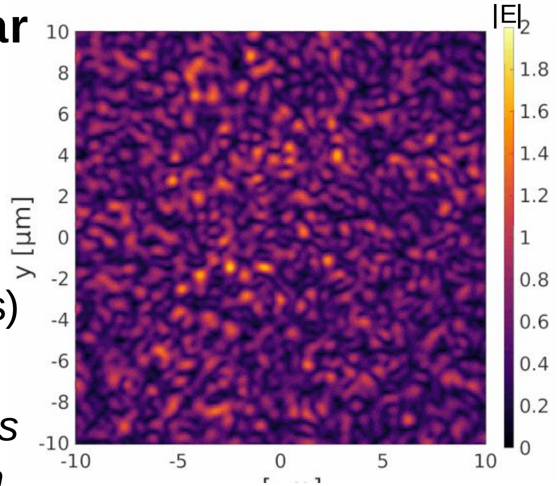
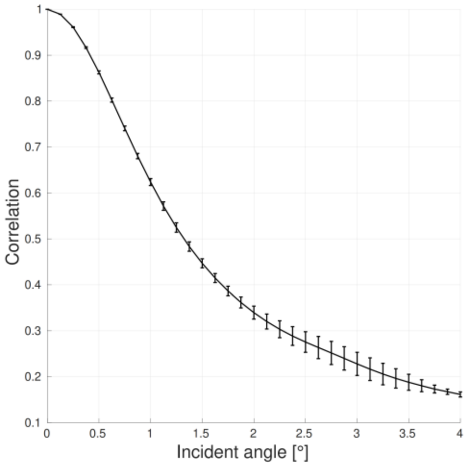
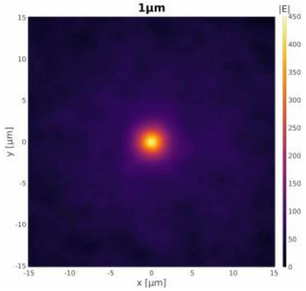
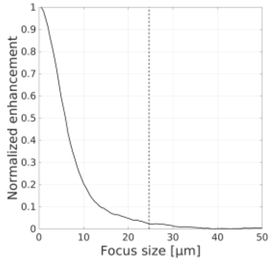




Enhancement vs focus size





Relationship between enhancement and focus size important for photoacoustic wavefront shaping

Modelling the angular range of an optimized focus

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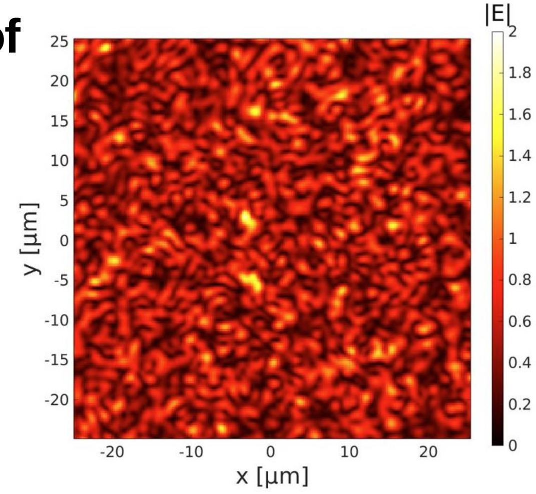
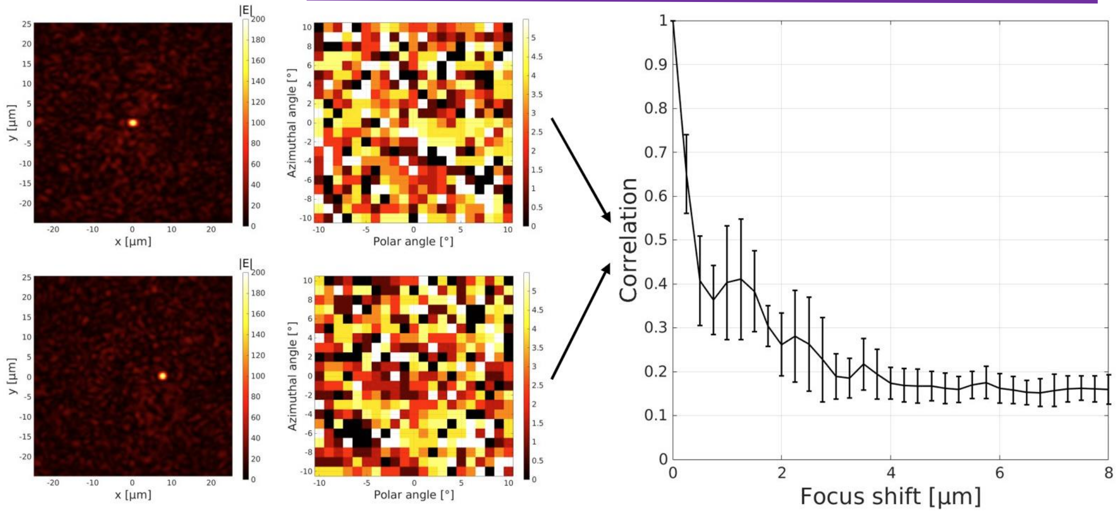
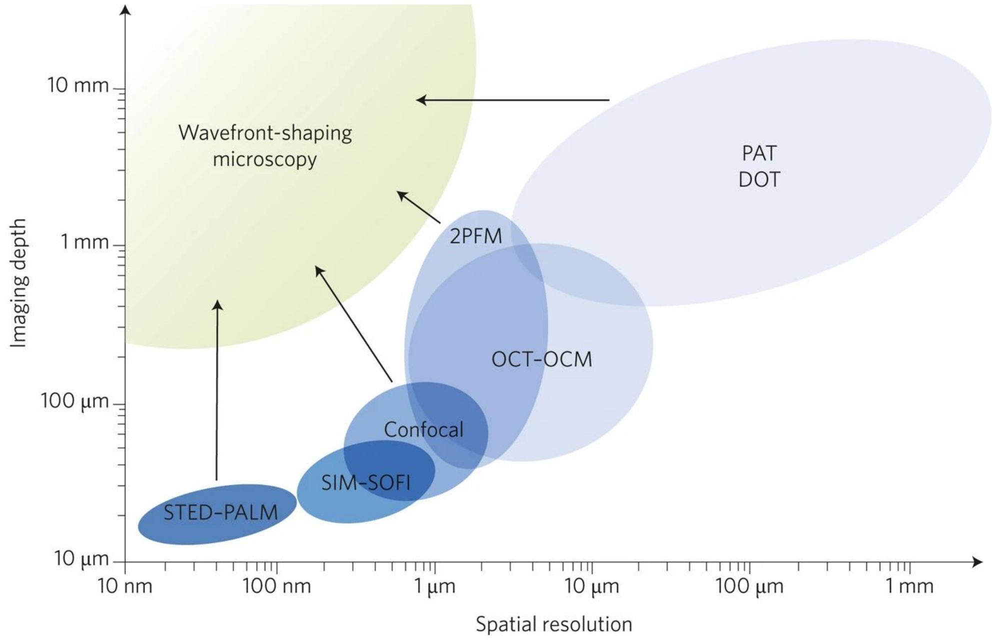


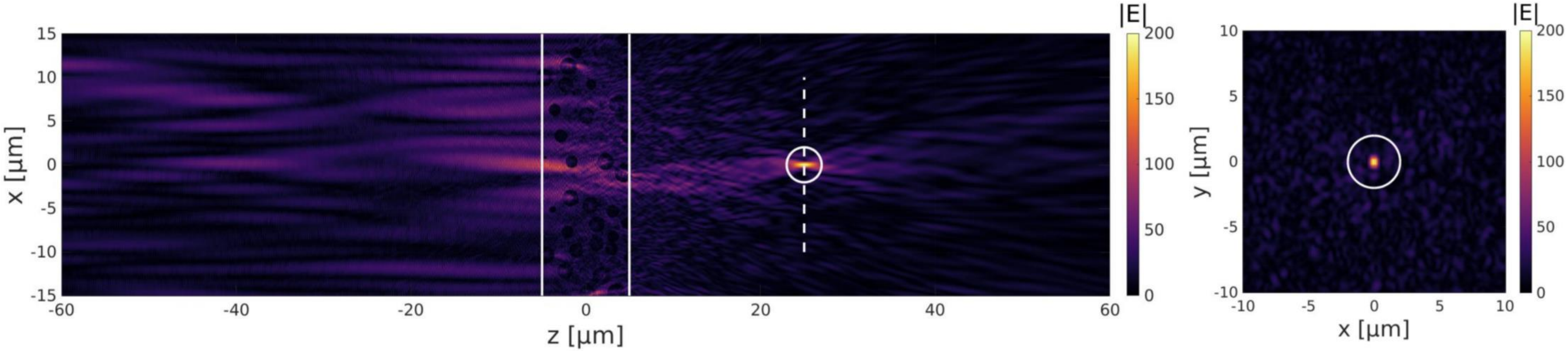


Conclusions

1. **WFS has the potential to enhance the depth and resolution of optical imaging modalities.**



Gigan, Sylvain., *Nature Photonics*, 2017



Conclusions

1. **WFS has the potential to enhance the depth and resolution of optical imaging modalities.**
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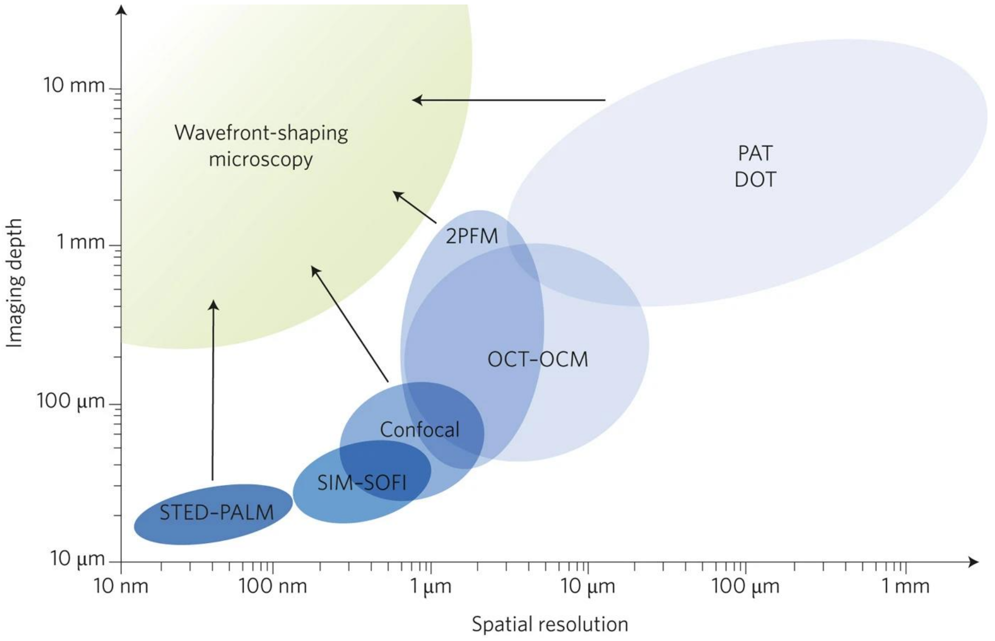
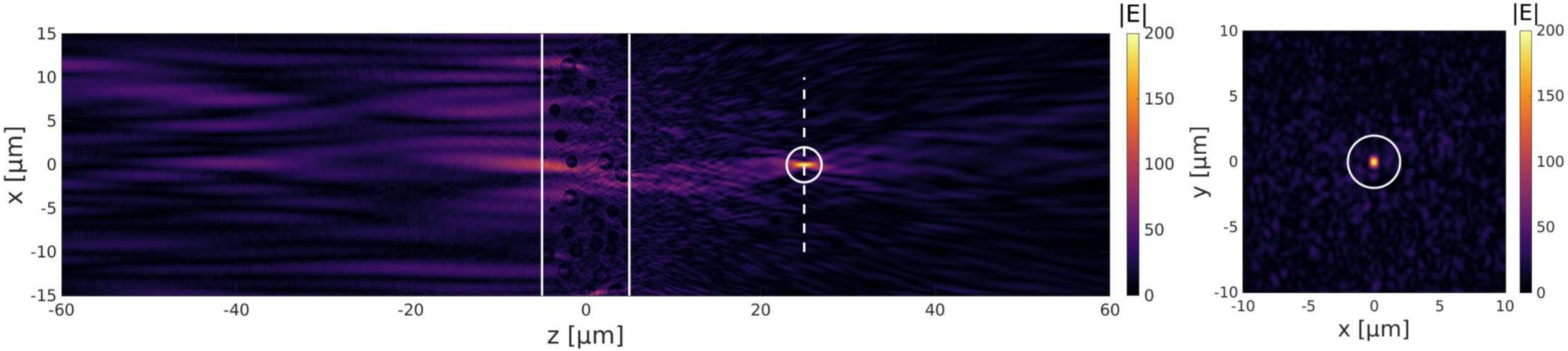


Gigan, Sylvain., *Nature Photonics*, 2017



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1. **WFS has the potential to enhance the depth and resolution of optical imaging modalities.**
2. **Computational models can augment research of WFS by allowing for the measurement of internal fields and phase.**
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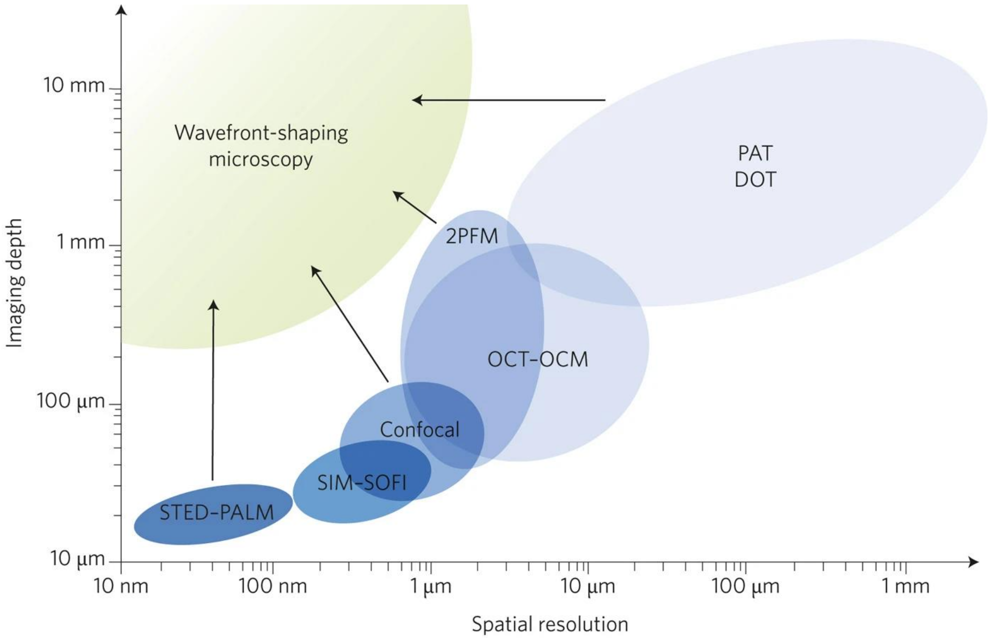
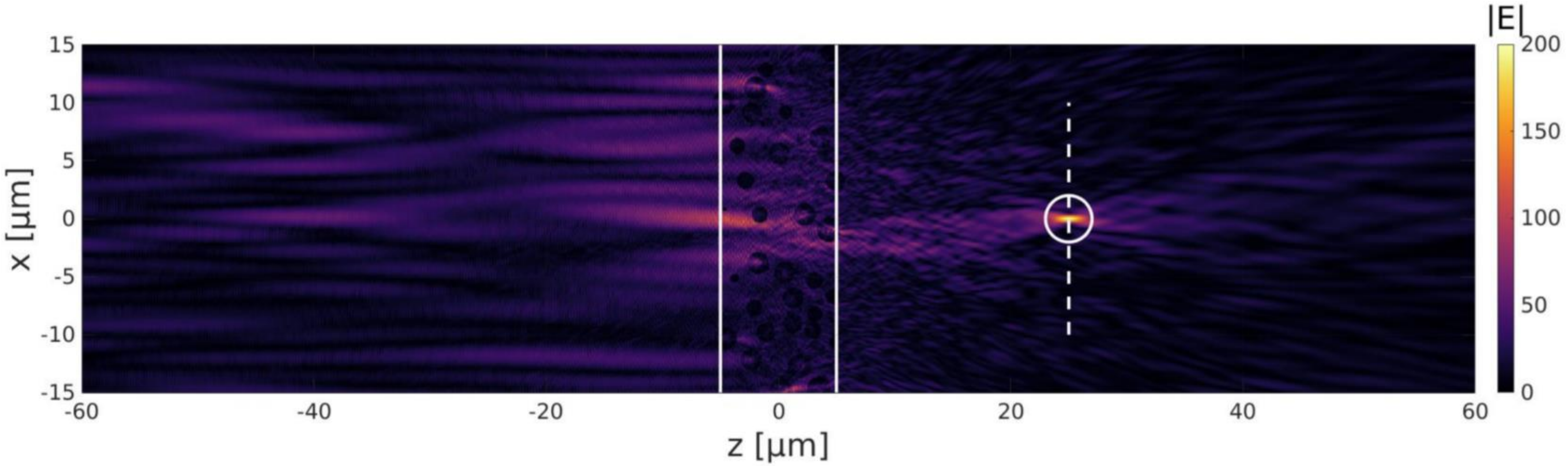
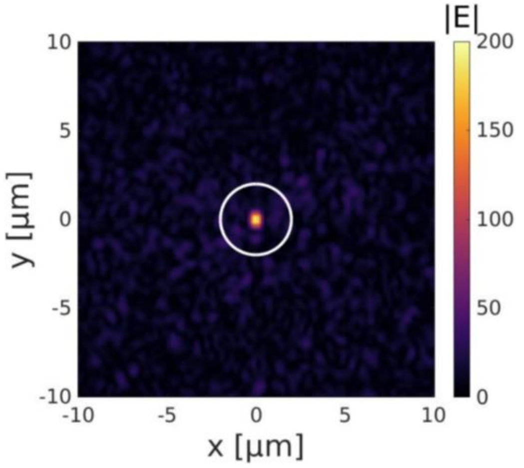


Gigan, Sylvain., *Nature Photonics*, 2017





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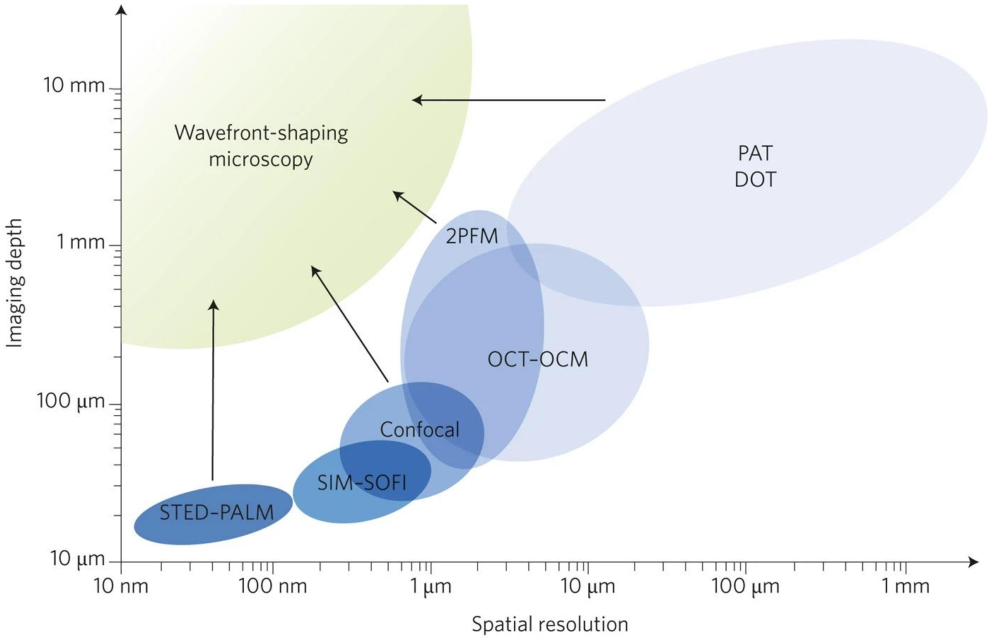
If interested, please attend my P+U talk tomorrow.



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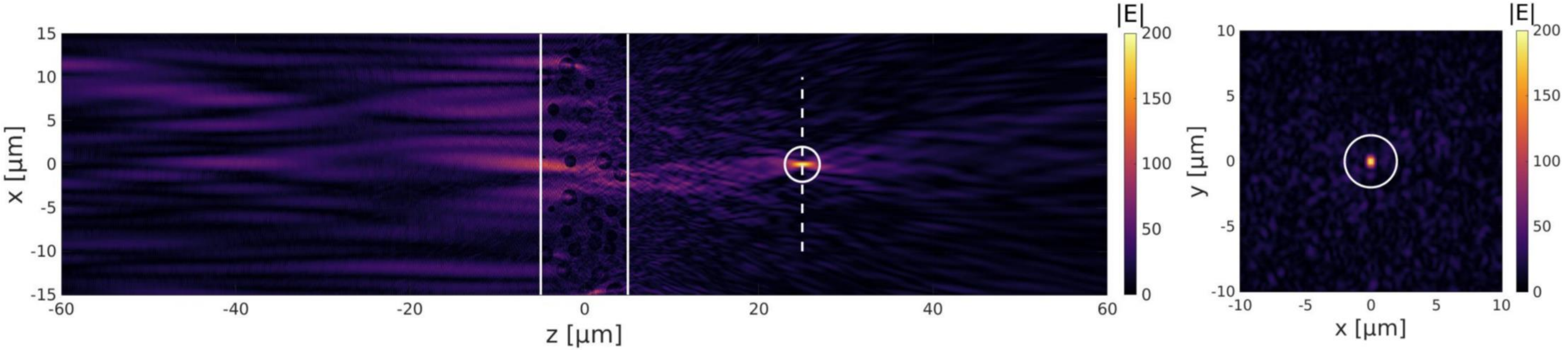

Acknowledgements

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Full-wave simulation of focusing light through scattering layers using the T-matrix method

Jake A. J. Bewick[1] , Peter R. T. Munro[1], Simon R. Arridge[2], James A. Guggenheim[1,3,4]

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[2] Department of Computer Science, UCL, London, UK
[3] Institute of Cardiovascular Sciences, University of Birmingham, Birmingham, UK
[4] School of Computer Science, University of Birmingham, Birmingham, UK

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