Photoacoustic wavefront shaping to focus light in deep tissue: a computational feasibility study

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[3] Institute of Cardiovascular Sciences, University of Birmingham, Birmingham, UK
[4] School of Computer Science, University of Birmingham, Birmingham, UK

Outline

We use computational methods to investigate the requirements for a photoacoustic system to focus light into biological tissue

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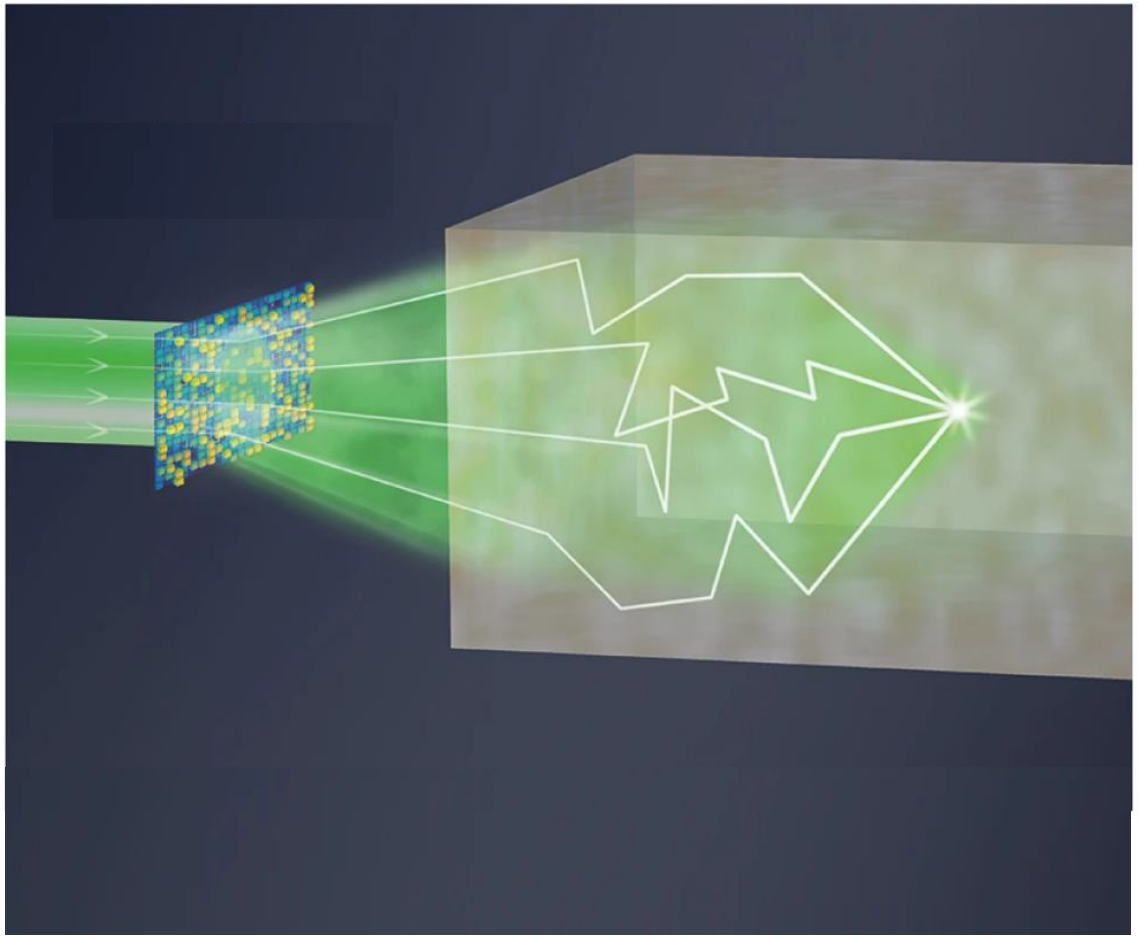
3. Conclusions
4. Acknowledgements

What are the challenges of internal wavefront shaping?

Consider trying to focus light inside biological tissue:



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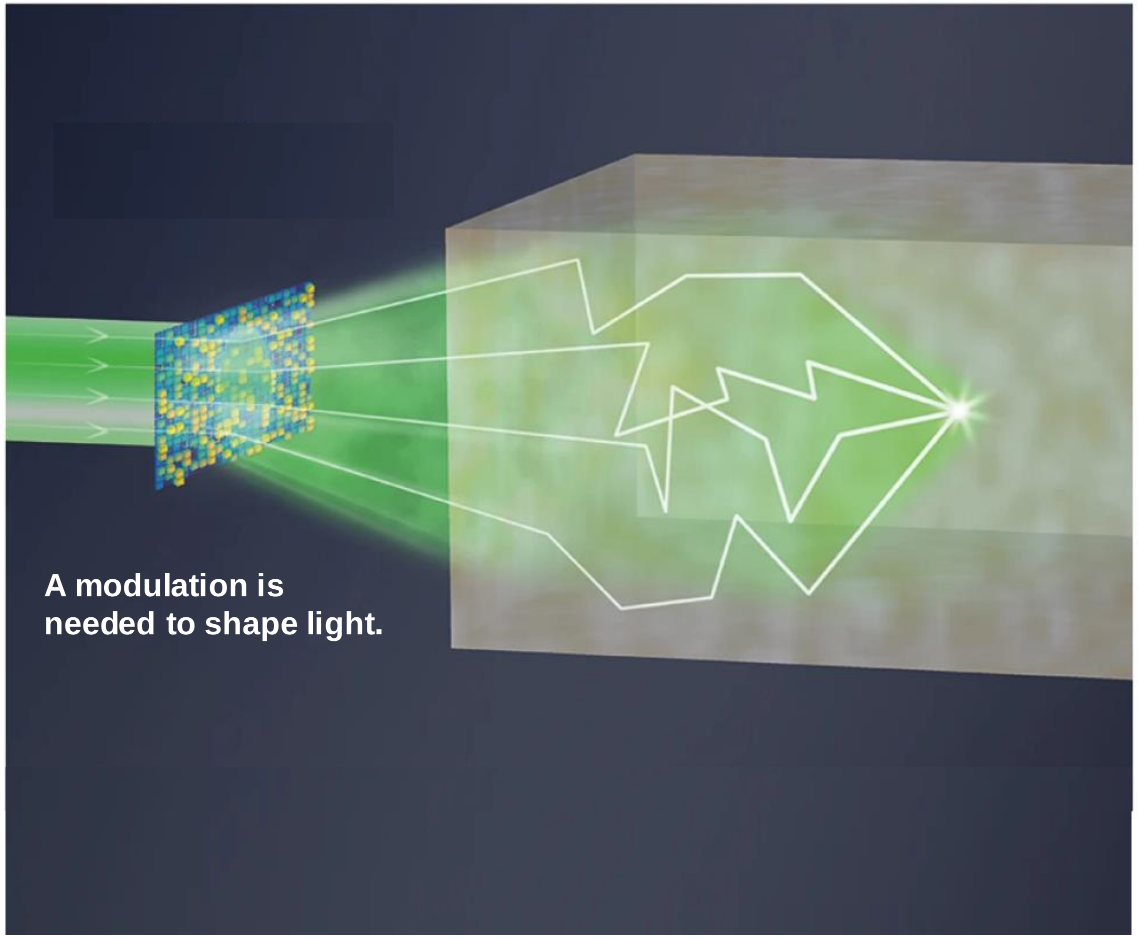

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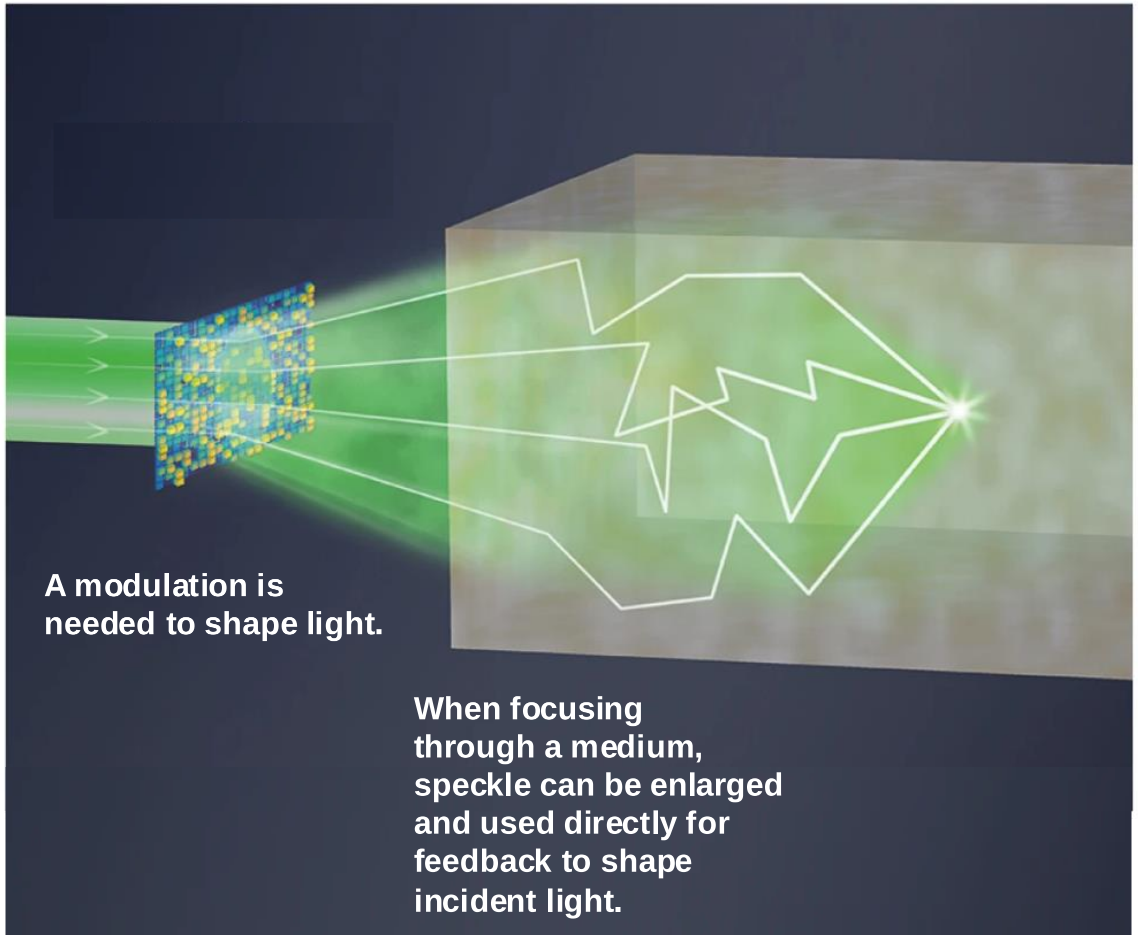

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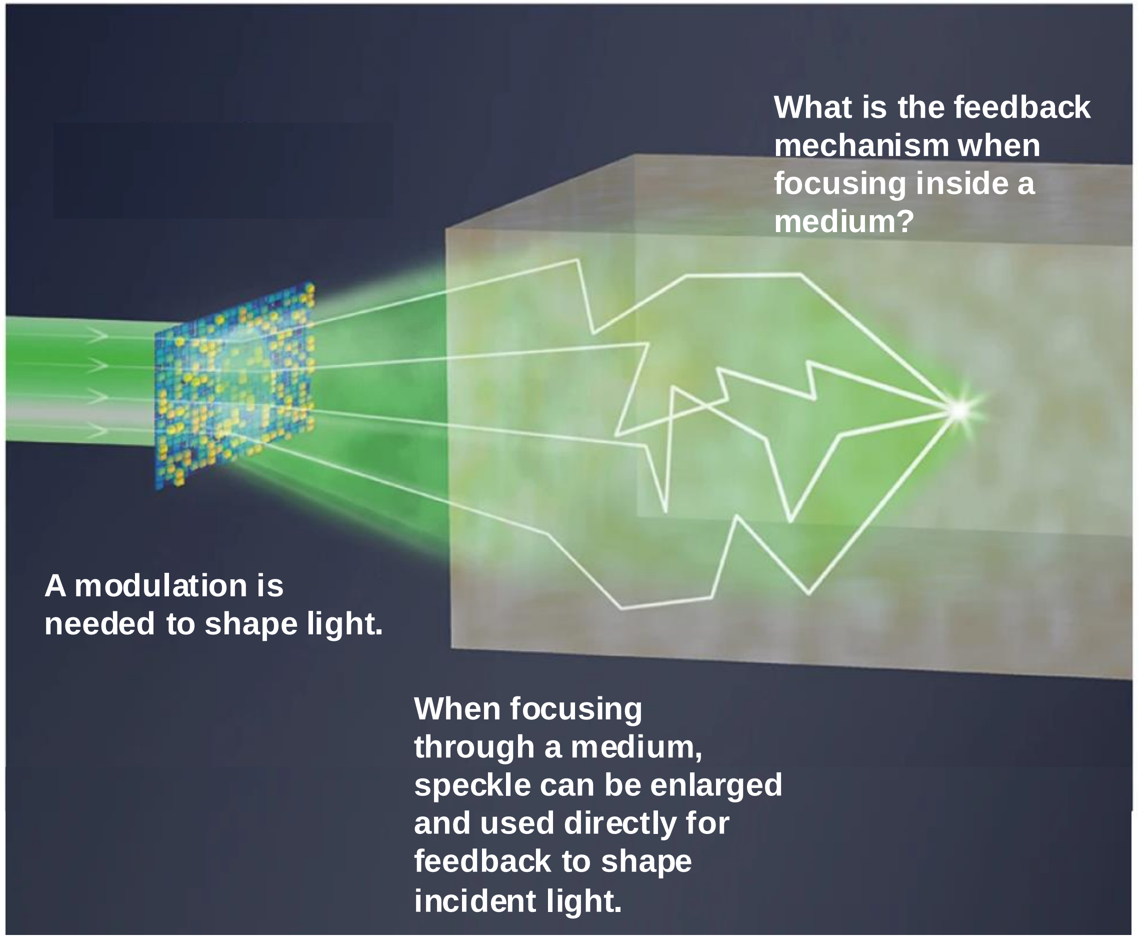

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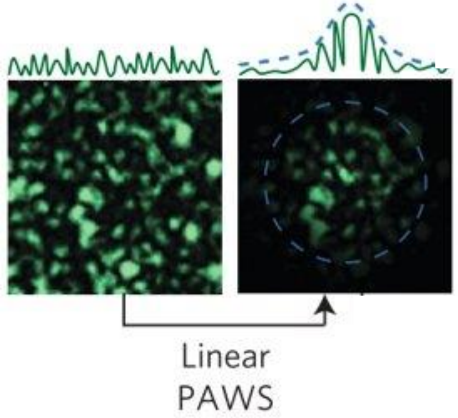
Photoacoustic wavefront shaping (PAWS)

Exploiting photoacoustic feedback



- **Non-invasive** feedback
- Potentially able to generate focus inside tissue
- Has been demonstrated **through** scatterers

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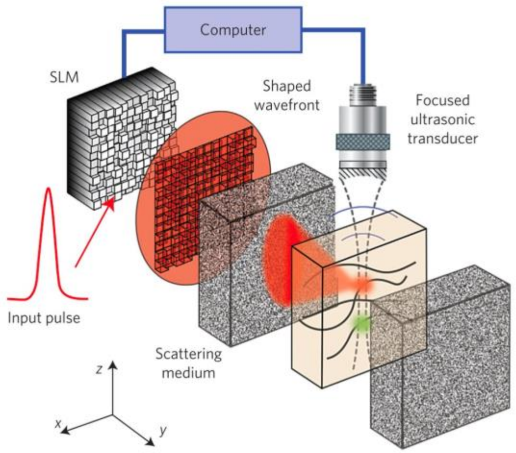

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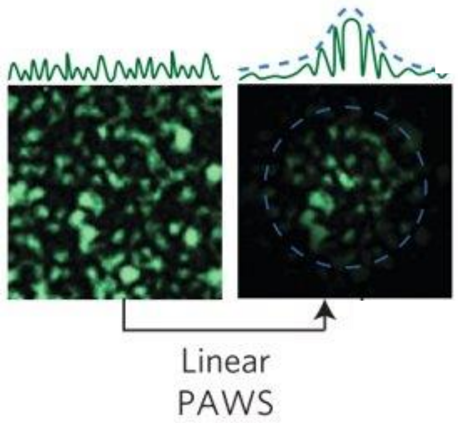

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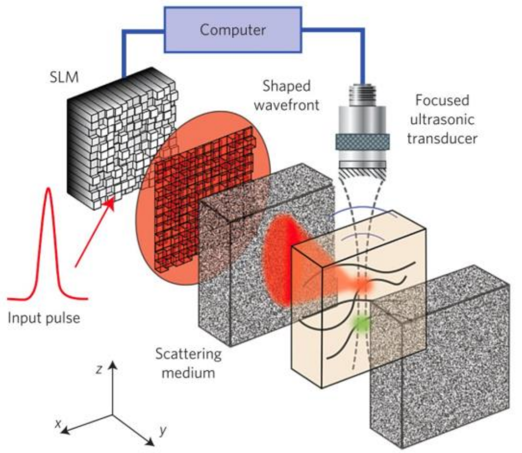

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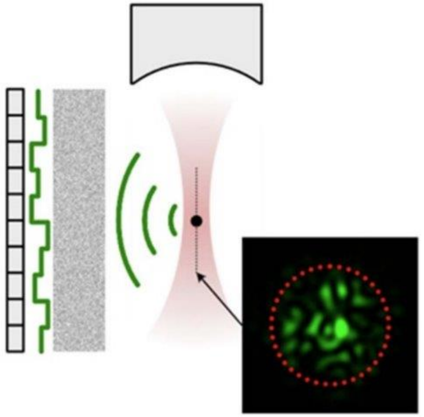
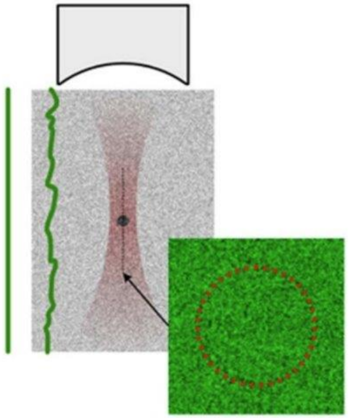
Challenges with PAWS



<u>Number of input modes</u>

- Size of target defined by **acoustic diffraction limit**.
- Volume **encompasses many optical speckle.**
- **Large number of input modes needed**



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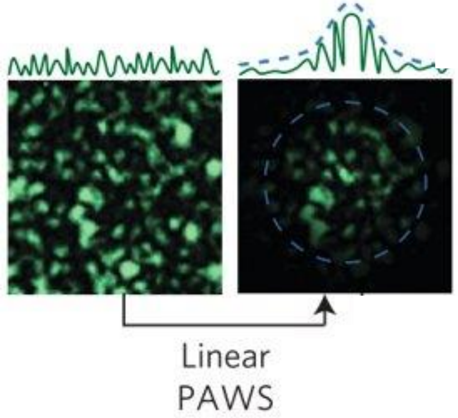

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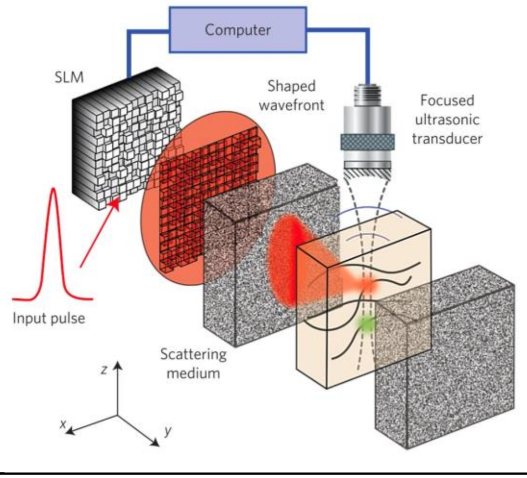

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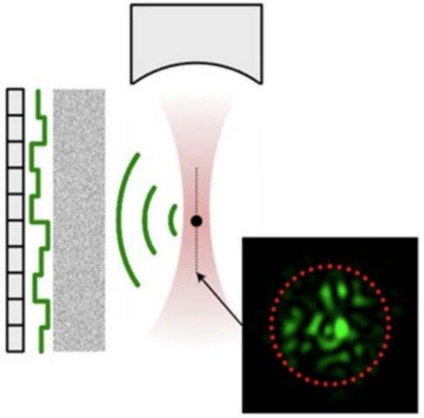

Number of input modes

Degree of control over incident light, e.g. SLM elements

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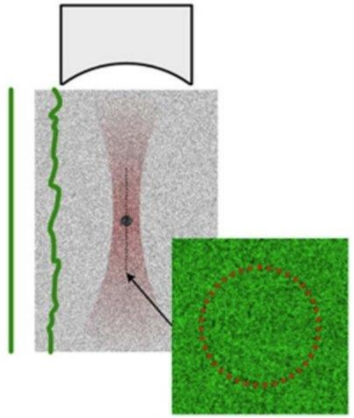

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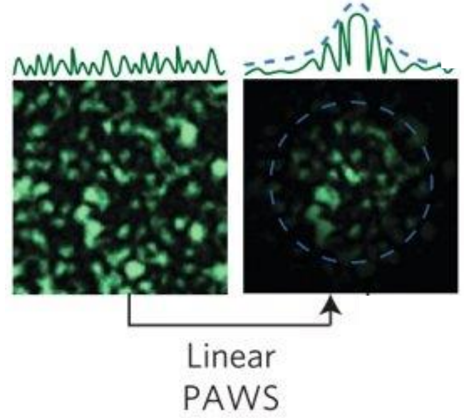

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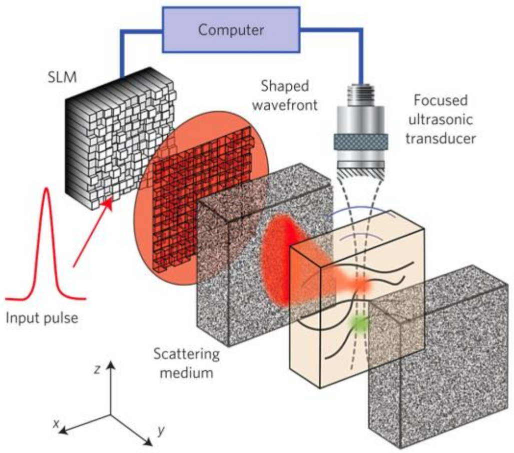

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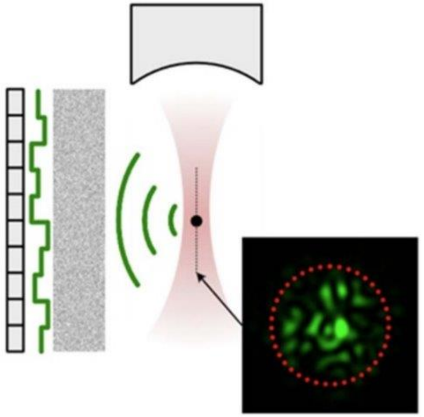

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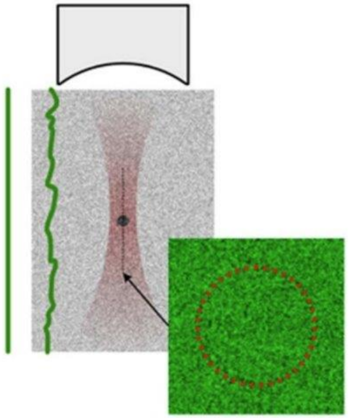

<u>Sensitivity of PAWS system</u>

- **Modulation per input mode is weaker** when focusing into **multiple speckle.**
- **High sensitivity required** to detect this modulation

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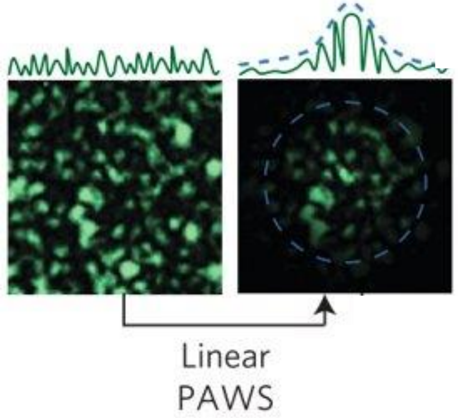

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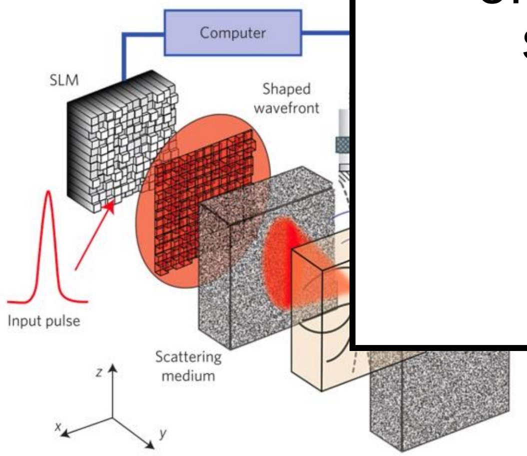

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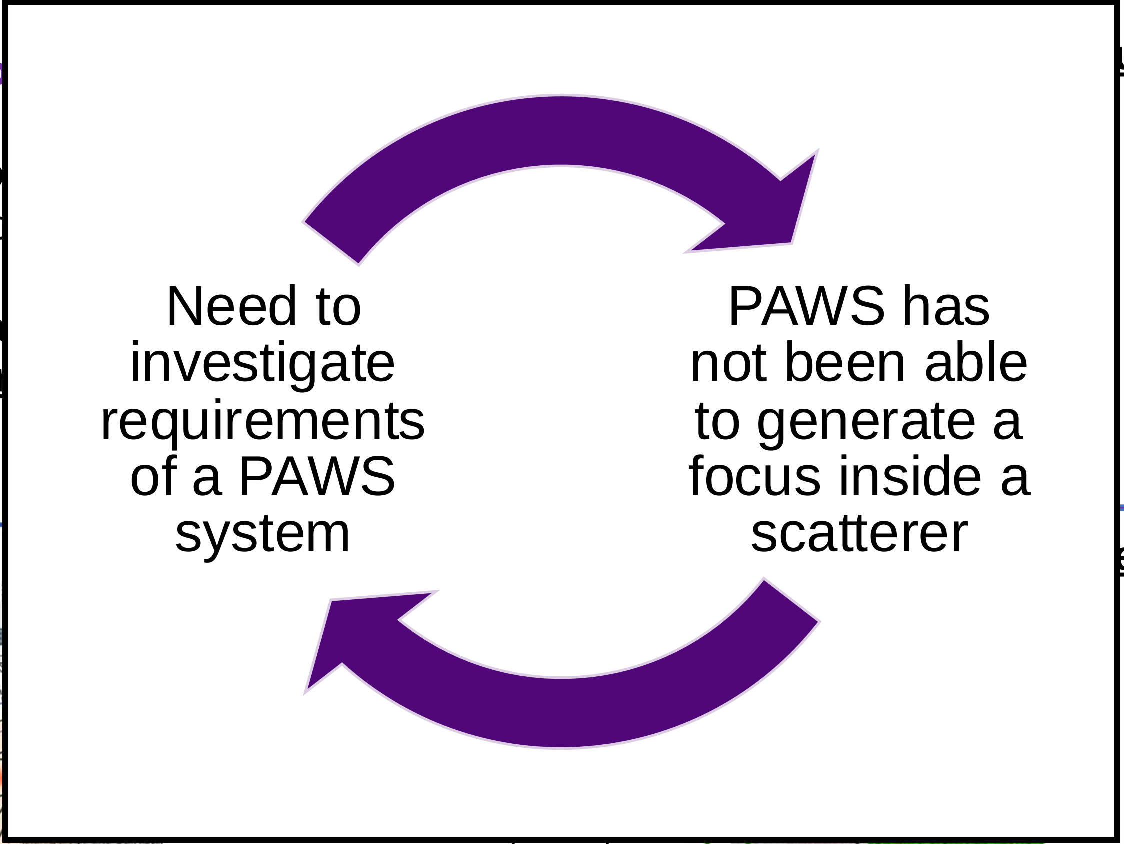

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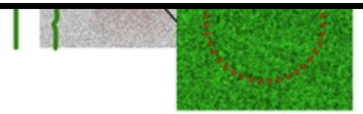

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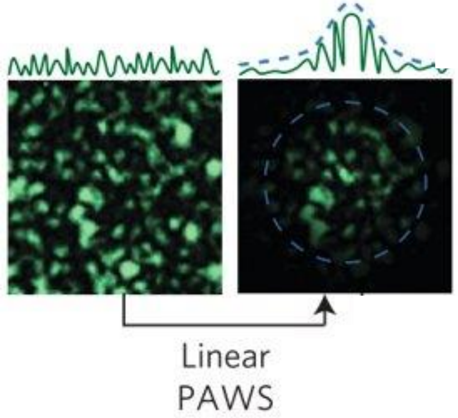

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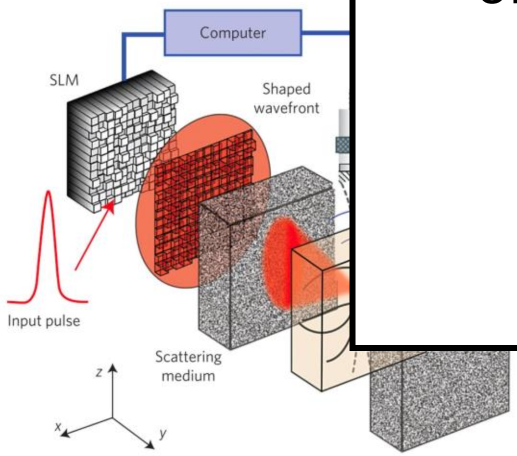

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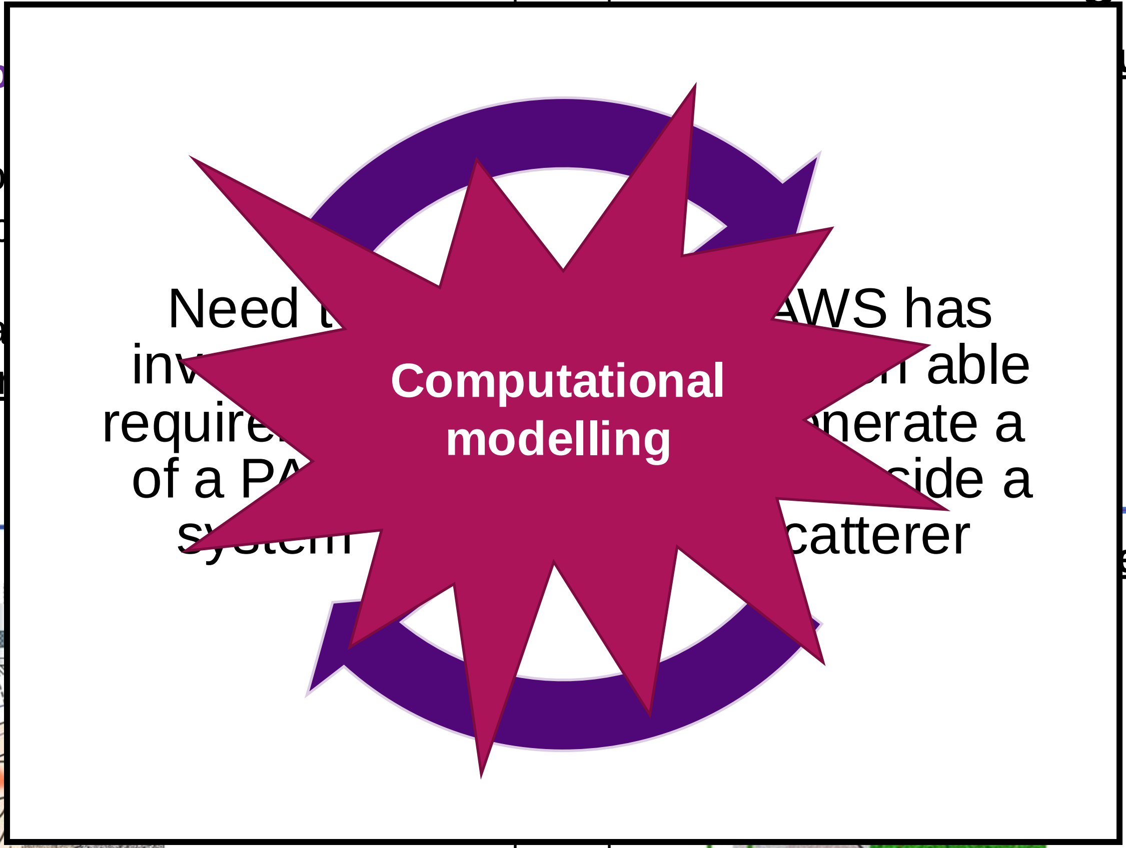

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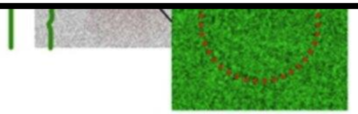

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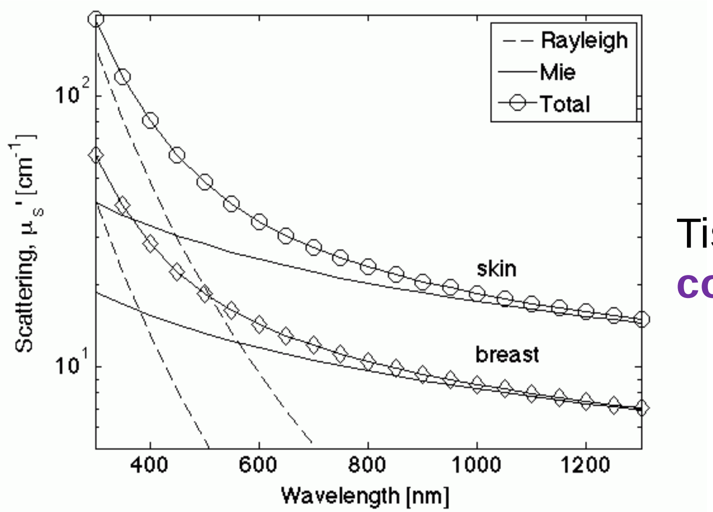
Modelling scattering using particles



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Tissue modelled as **collection of spheres**

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

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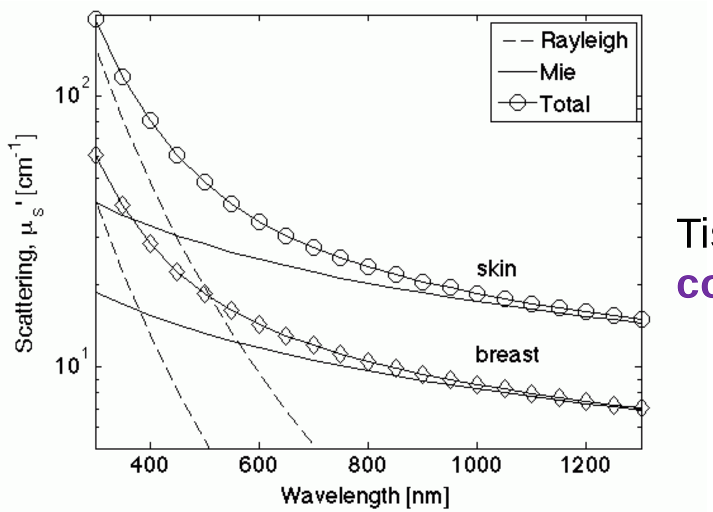

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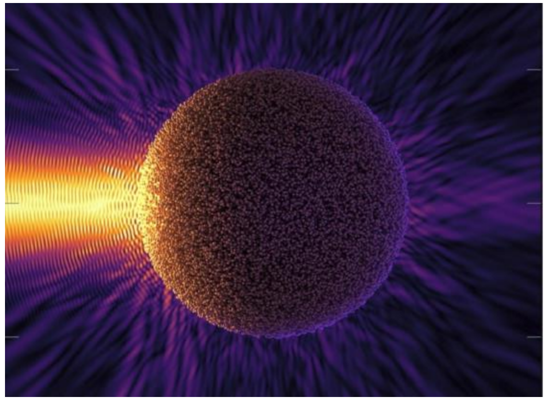

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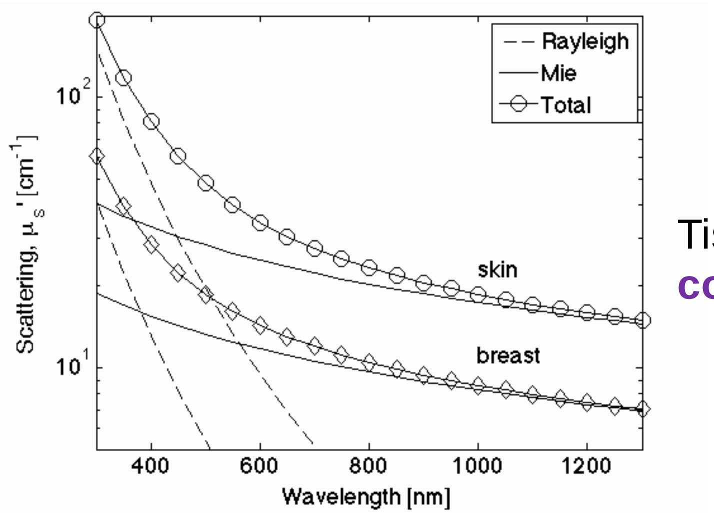

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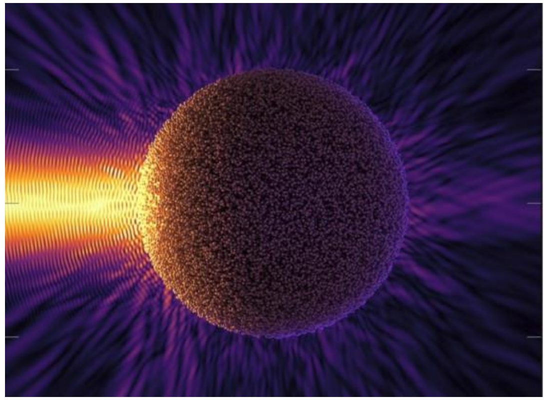

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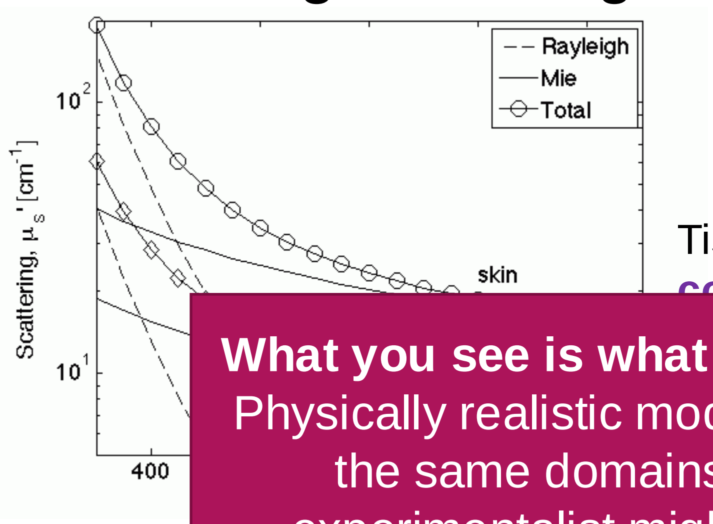

Jacques, Steve

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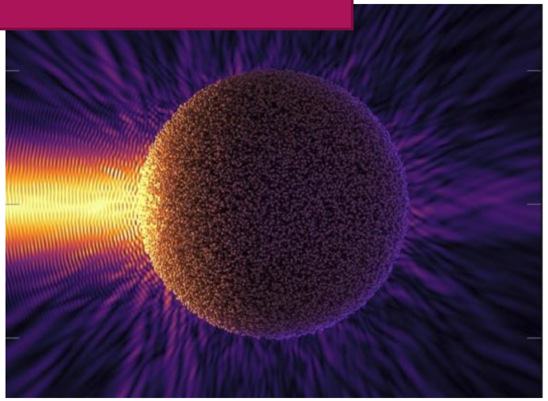
What you see is what you get:
Physically realistic modelling of the same domains an experimentalist might use



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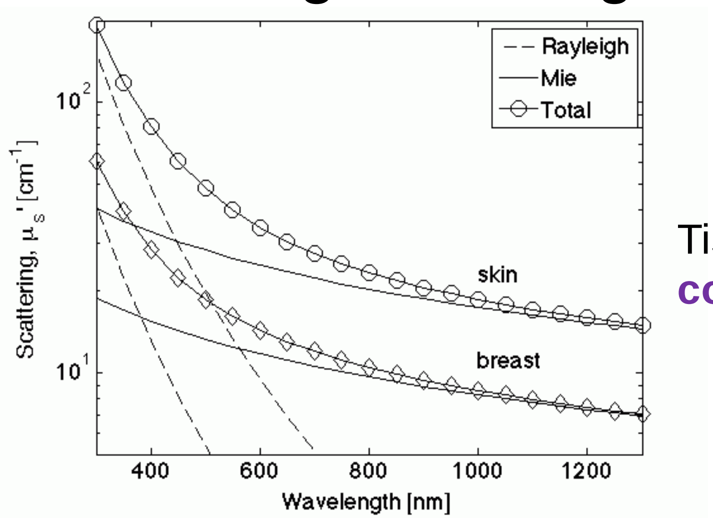

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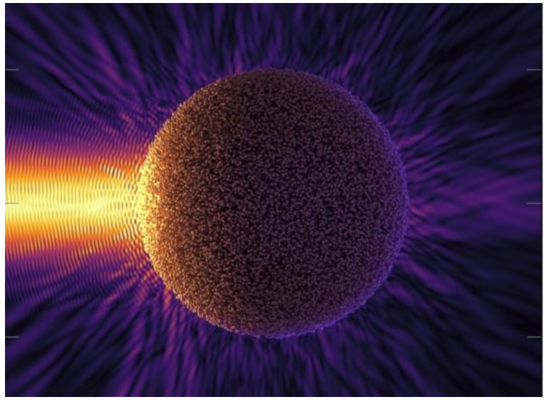

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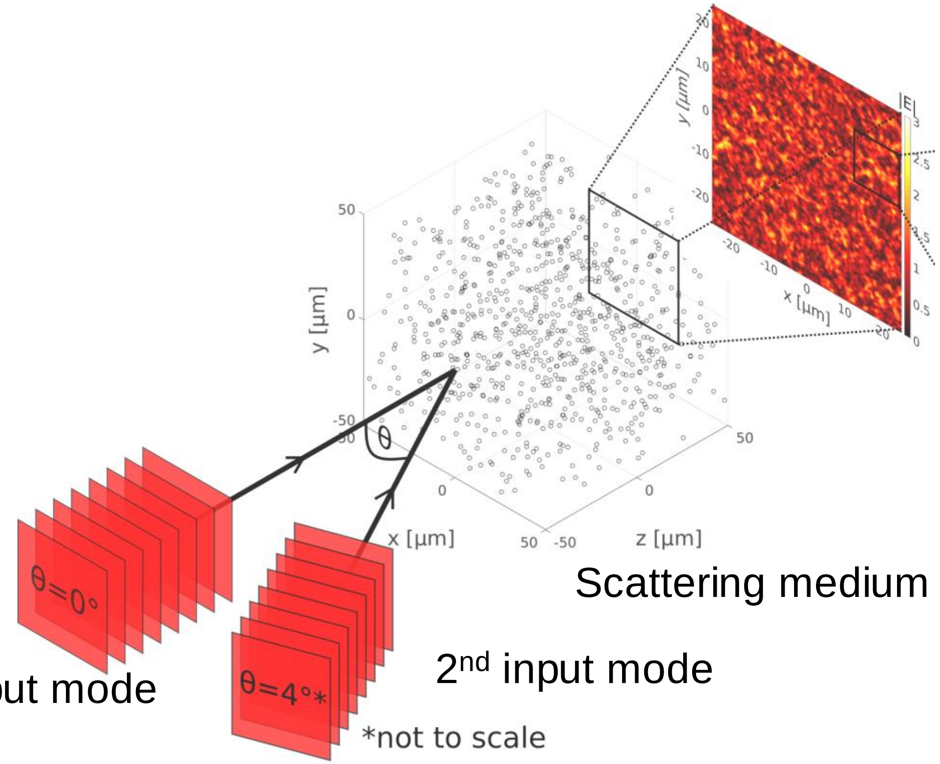
Our method for simulating WFS



Scattering medium

1^{st} input mode

2^{nd} input mode

*not to scale

Designing simulations of light propagation

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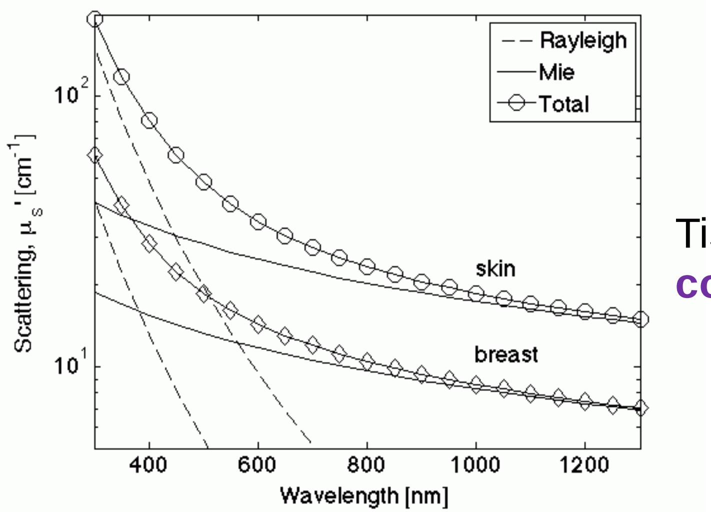

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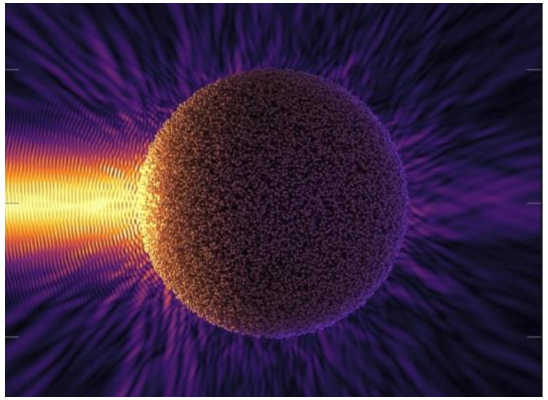

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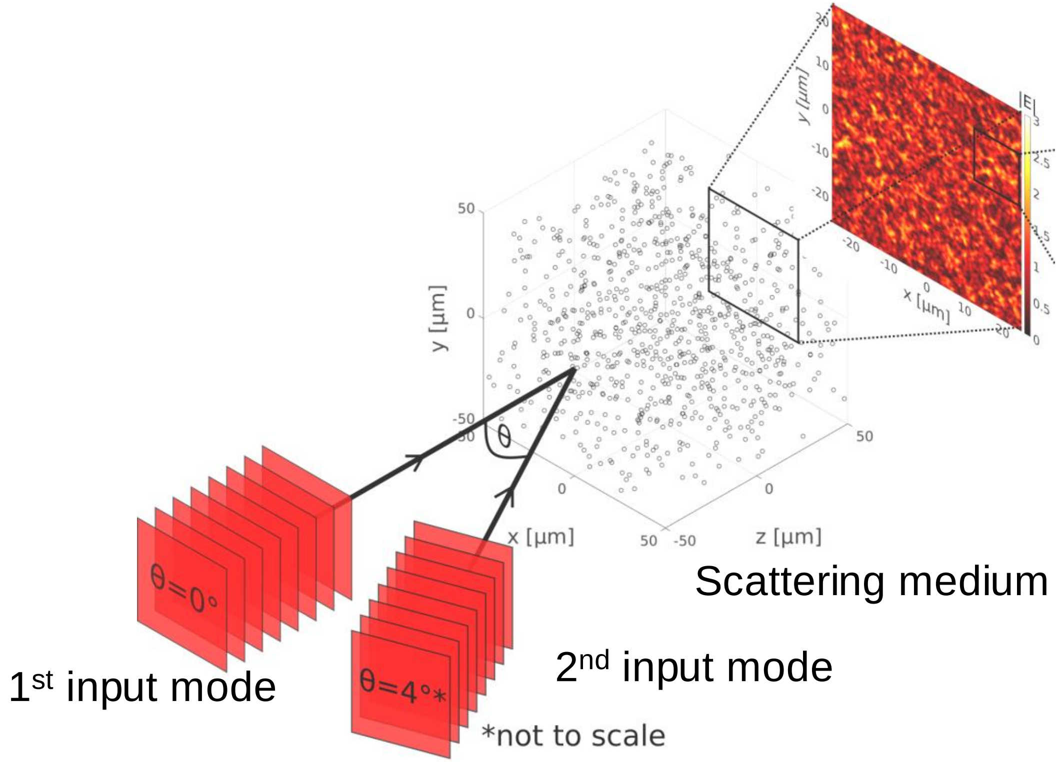

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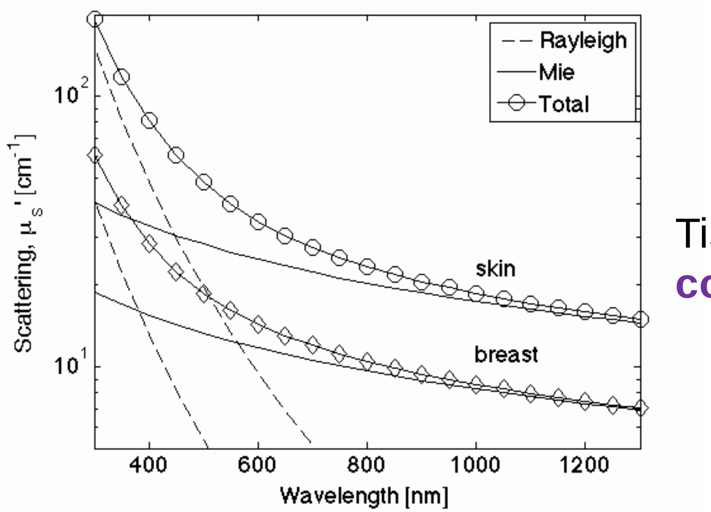

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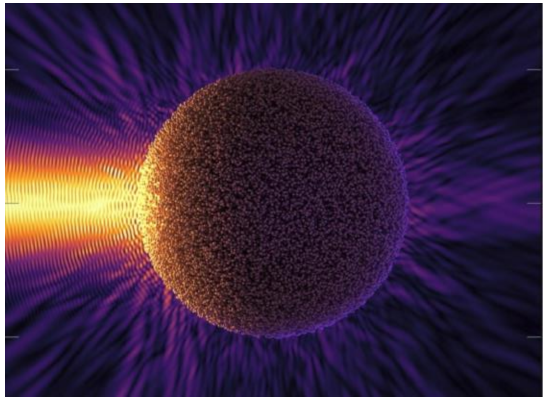

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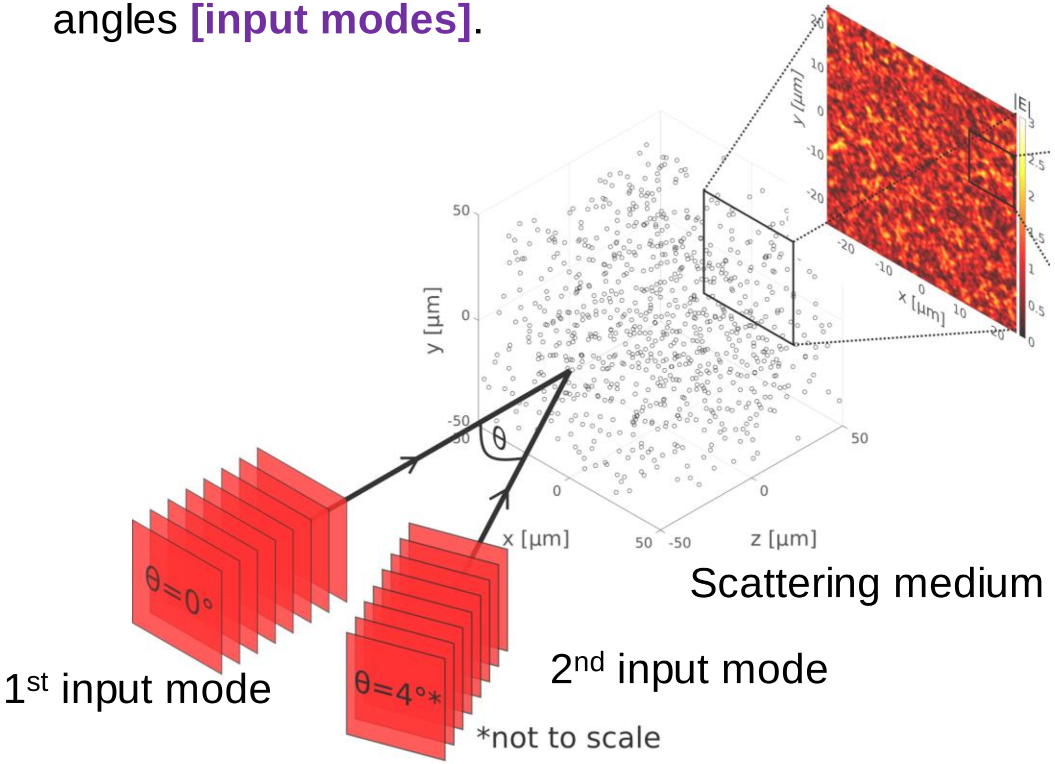

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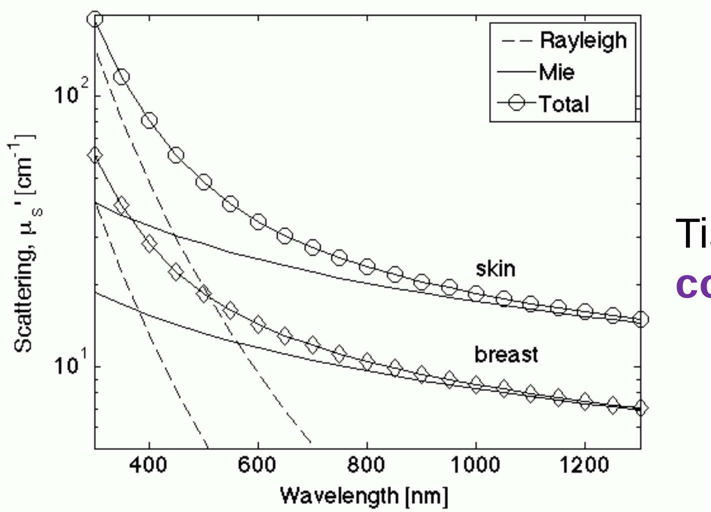

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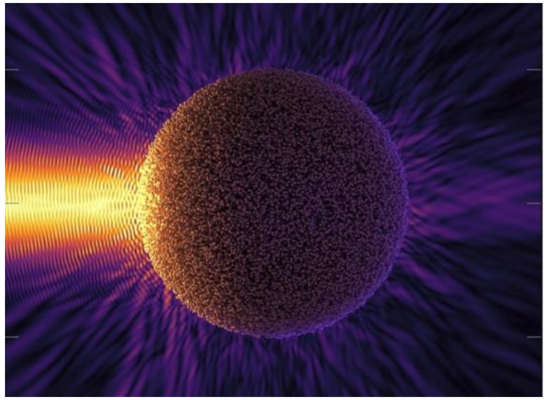

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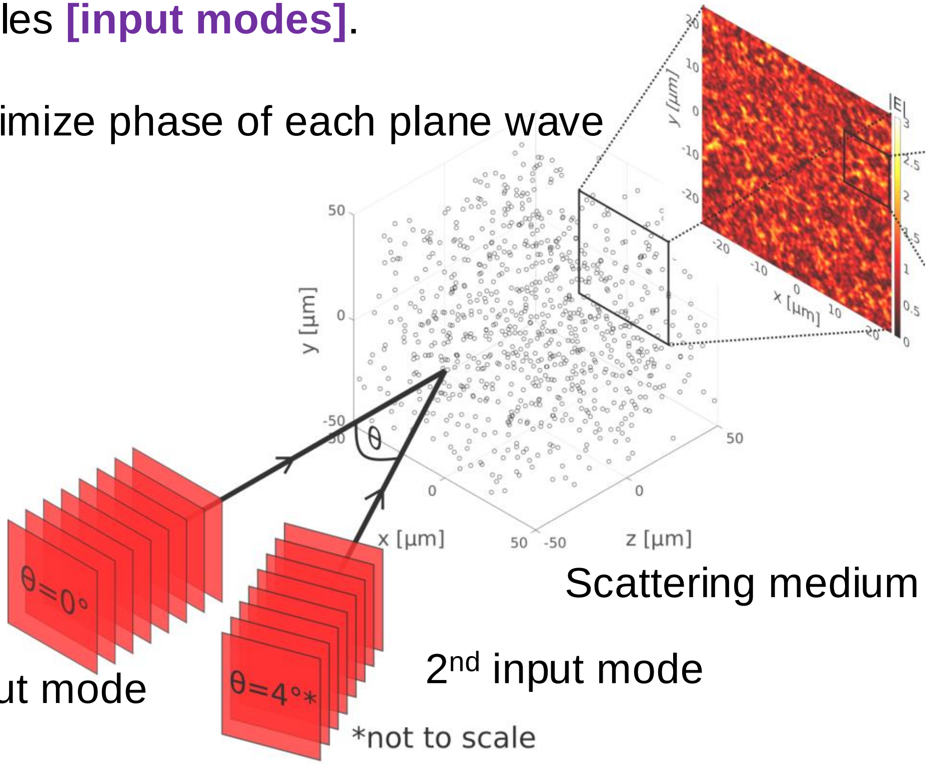

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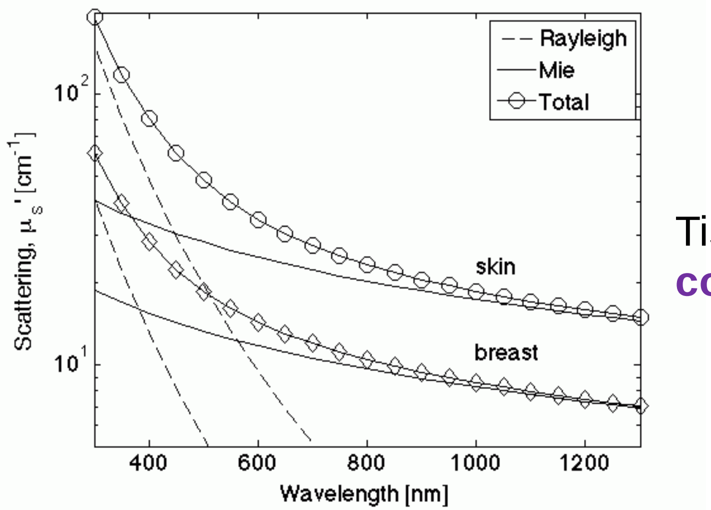

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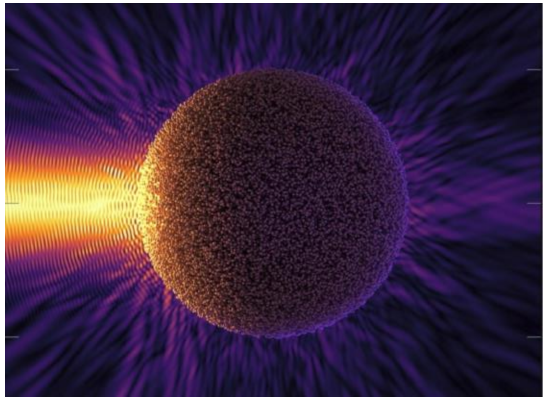

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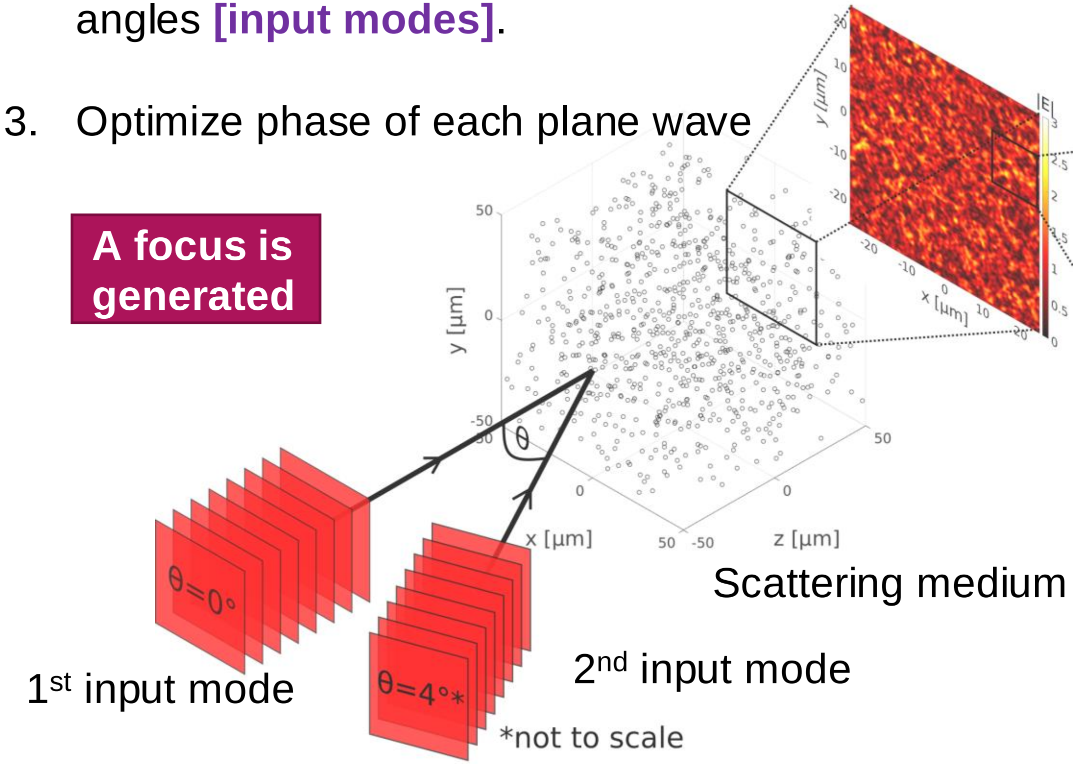
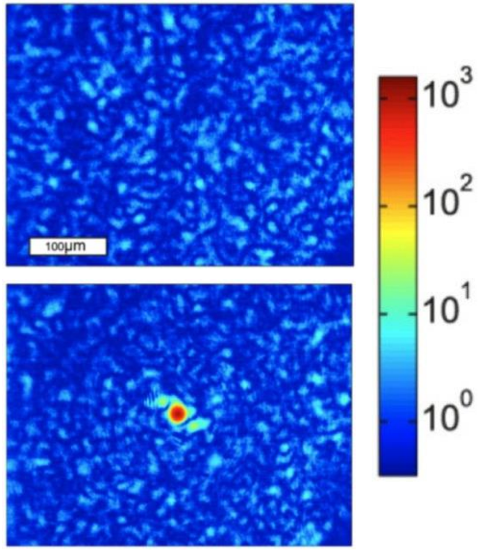


Focusing through titanium dioxide phantoms

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



Vellekoop and Mosk, *Optics letters*, 2007

Replicate Vellekoop & Mosk

10µm TiO_2 phantom with transport mean free path of ~5µm^{-1}).

441 input modes

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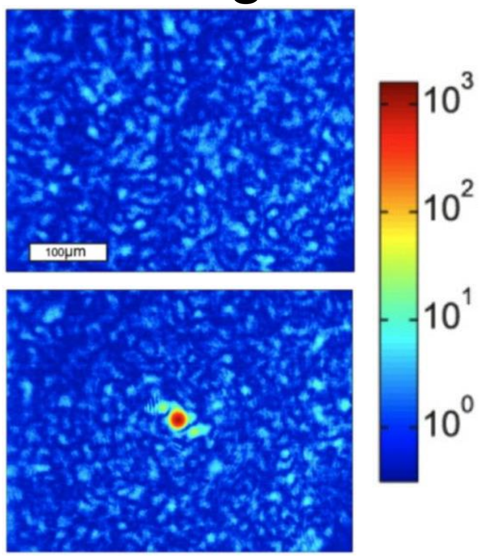

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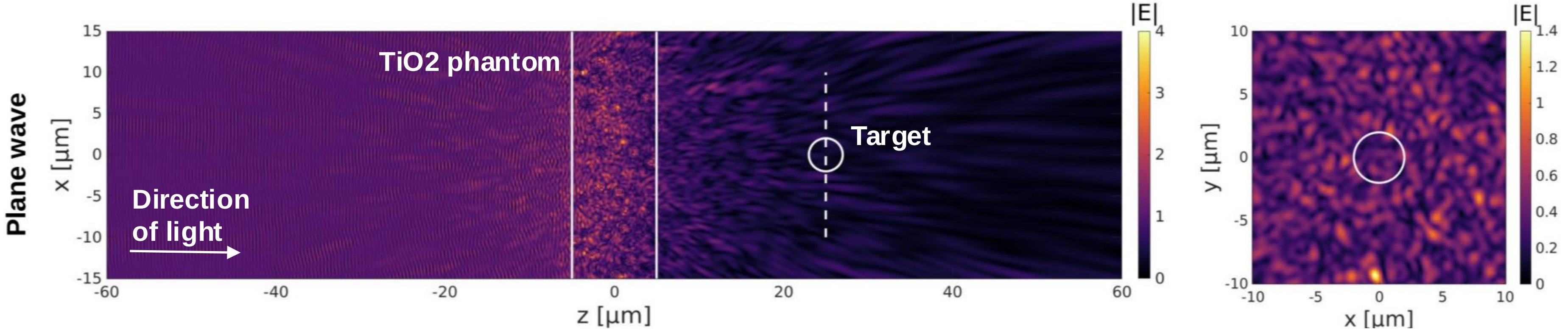

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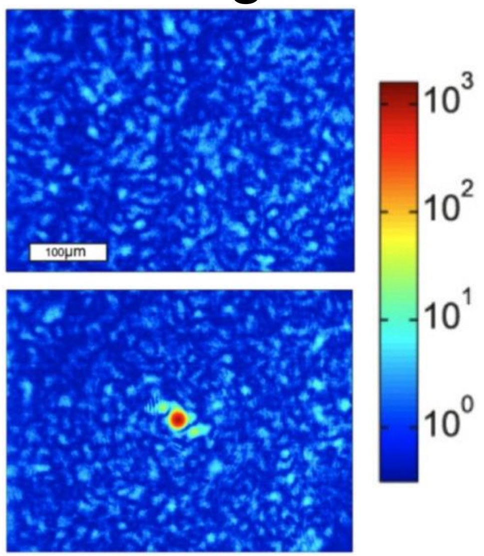

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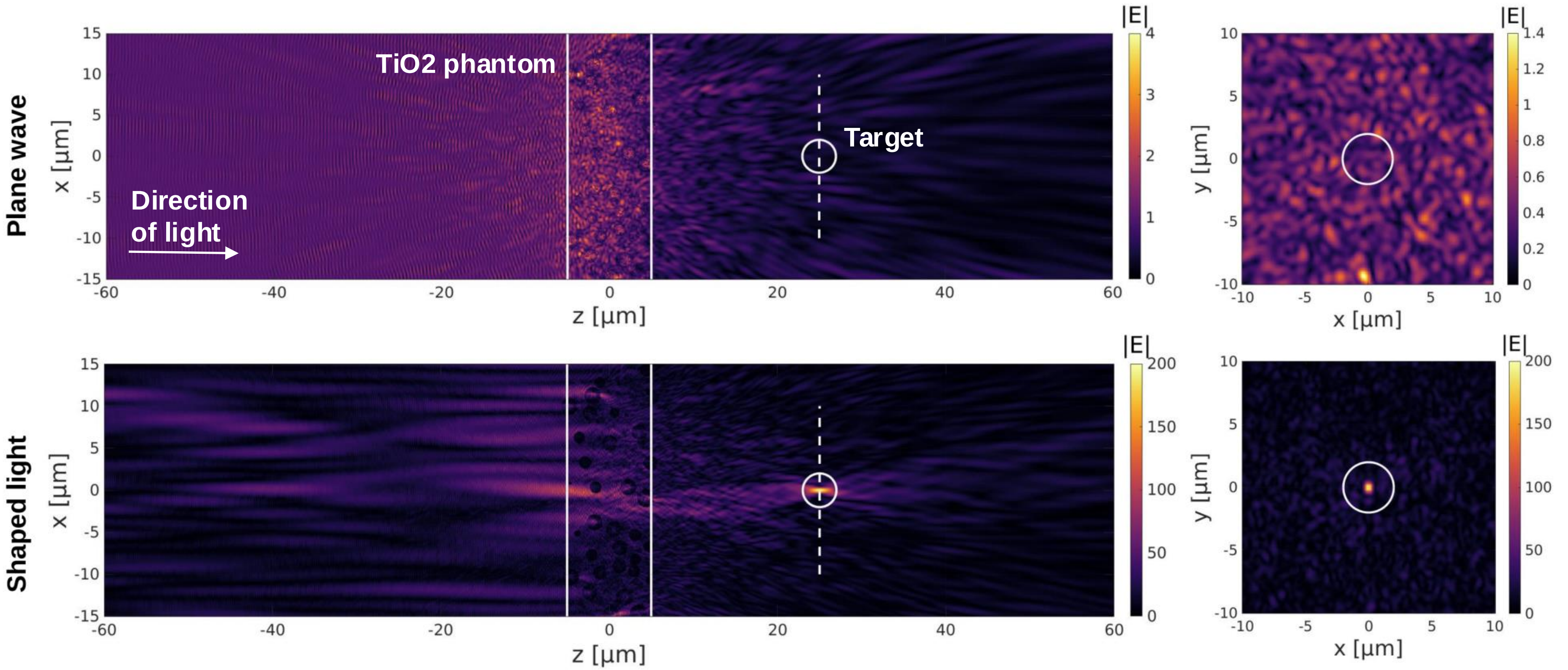

Optimize phase through phantom to generate an optical focus

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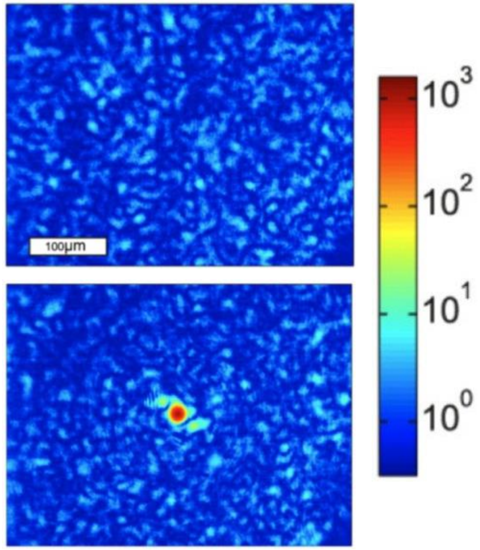

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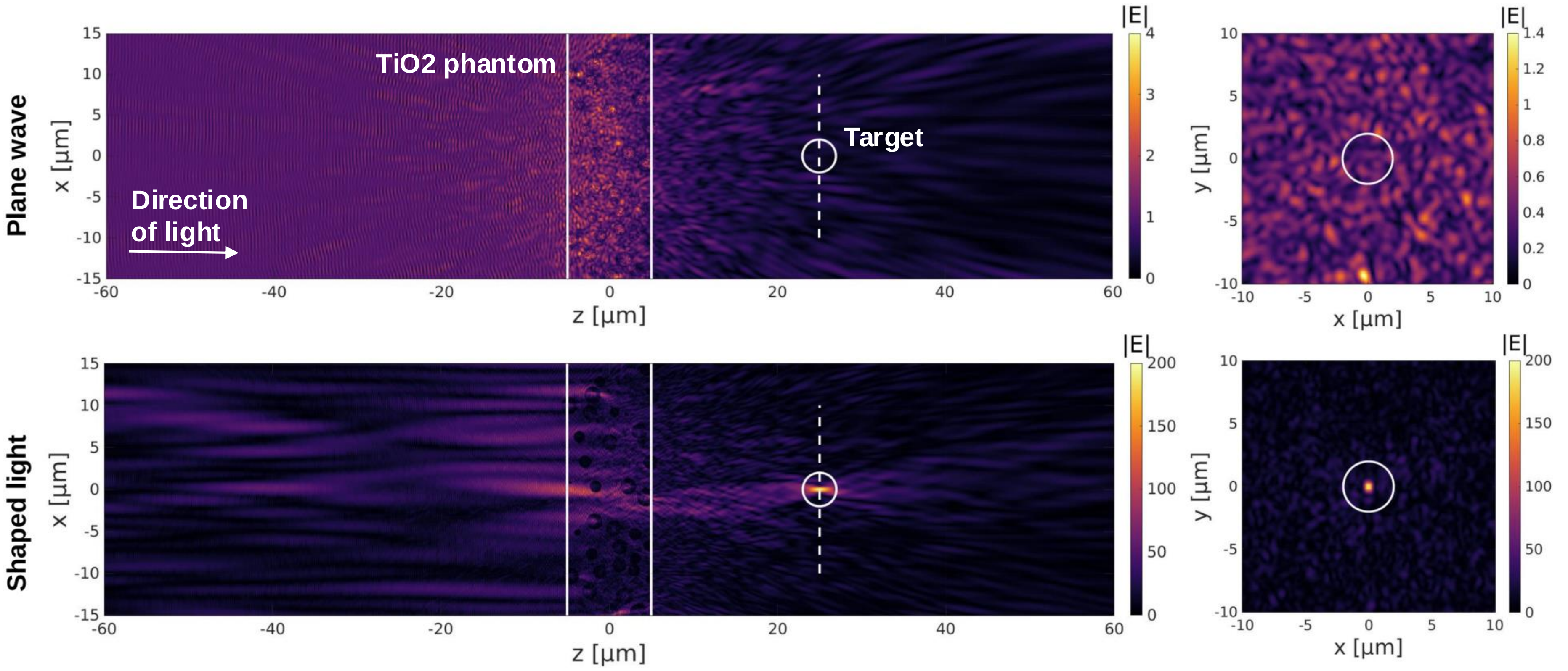


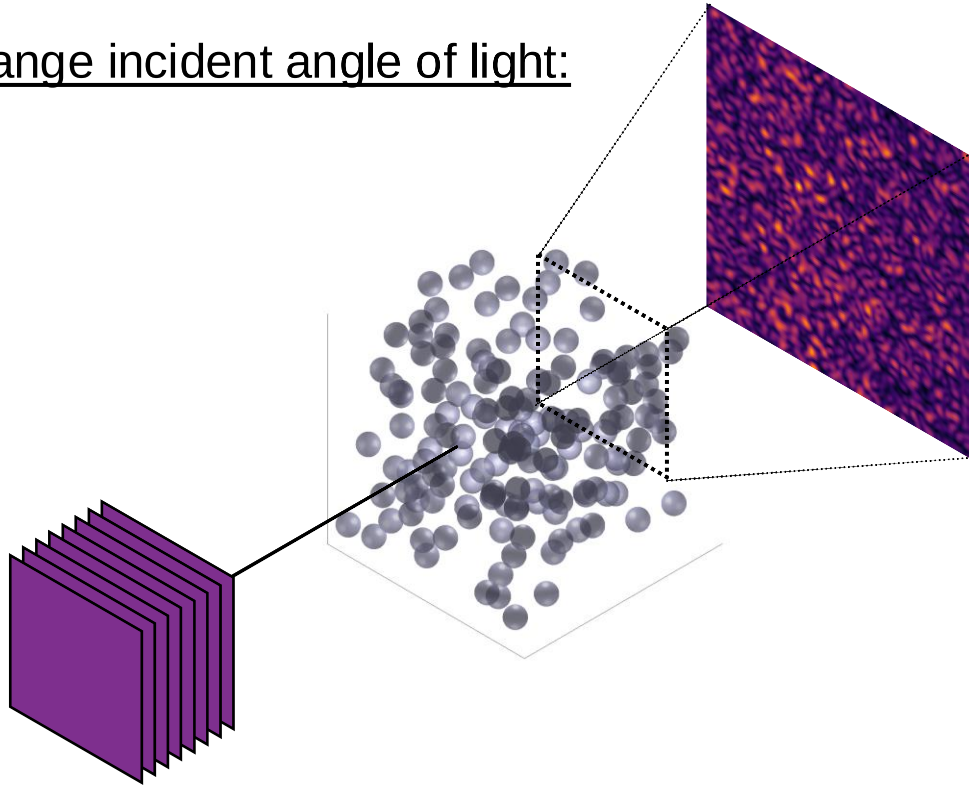
Optimize phase through phantom to generate an optical focus

Our model is able to simulate WFS through highly scattering media

Isolating correlations within tissue

Angular spectrum method

Change incident angle of light:



Random medium method

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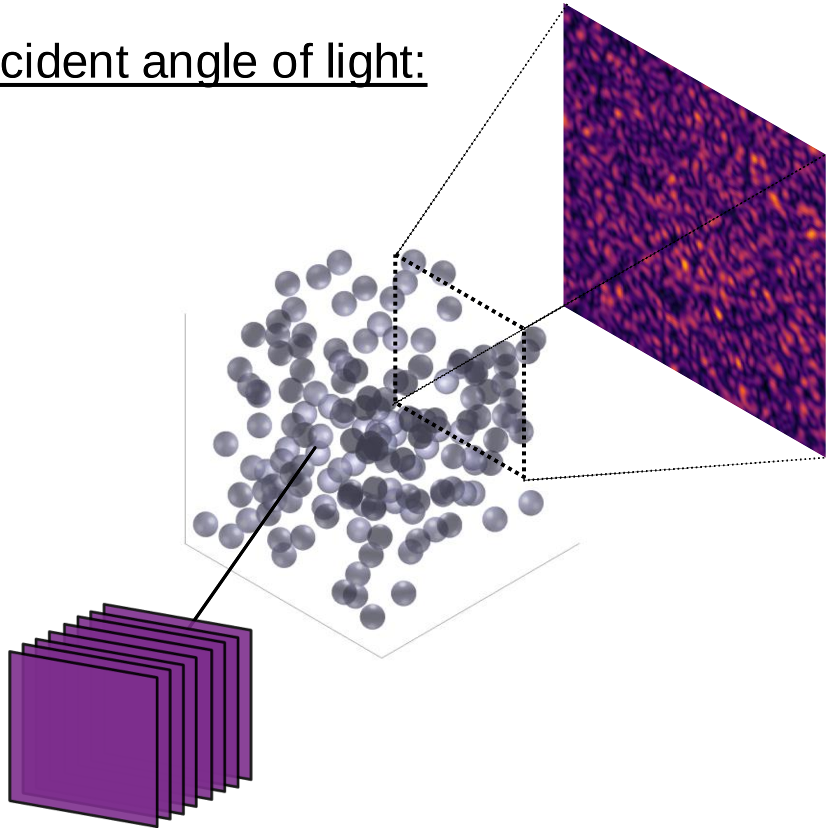

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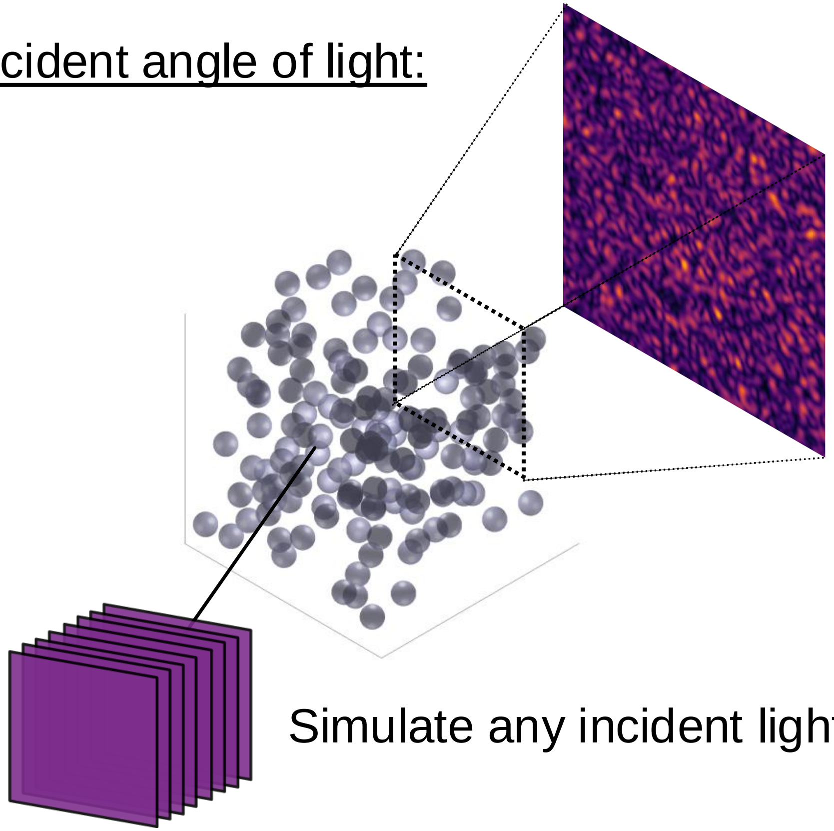

Simulate any incident light ✓

Random medium method

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Angular spectrum method

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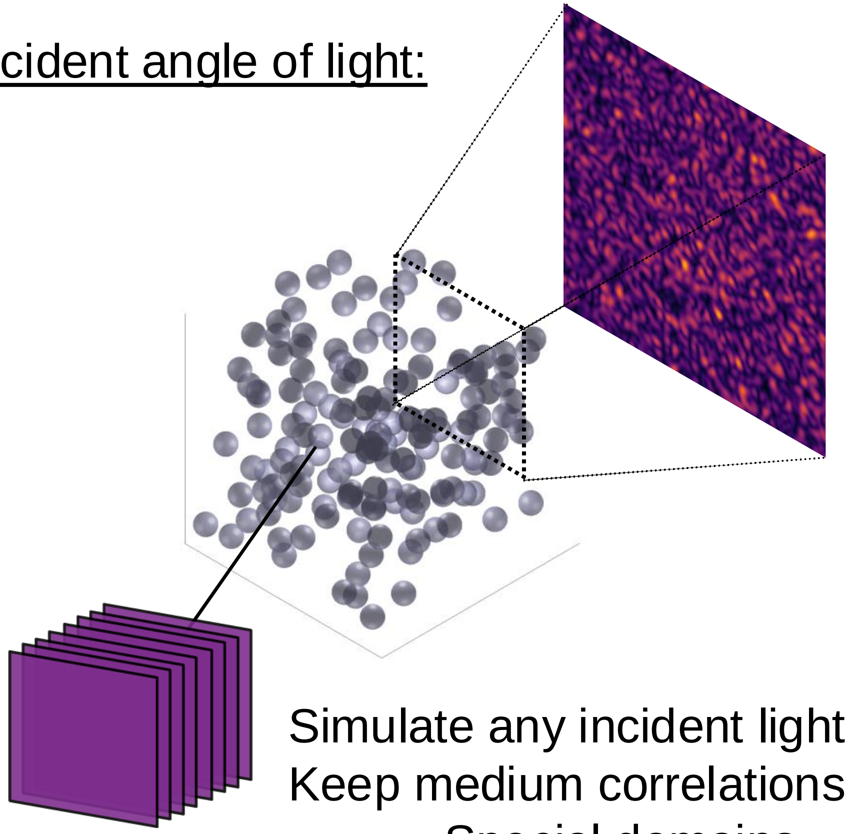

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Keep medium correlations ✓
- Special domains
- Memory effects

Random medium method

Isolating correlations within tissue

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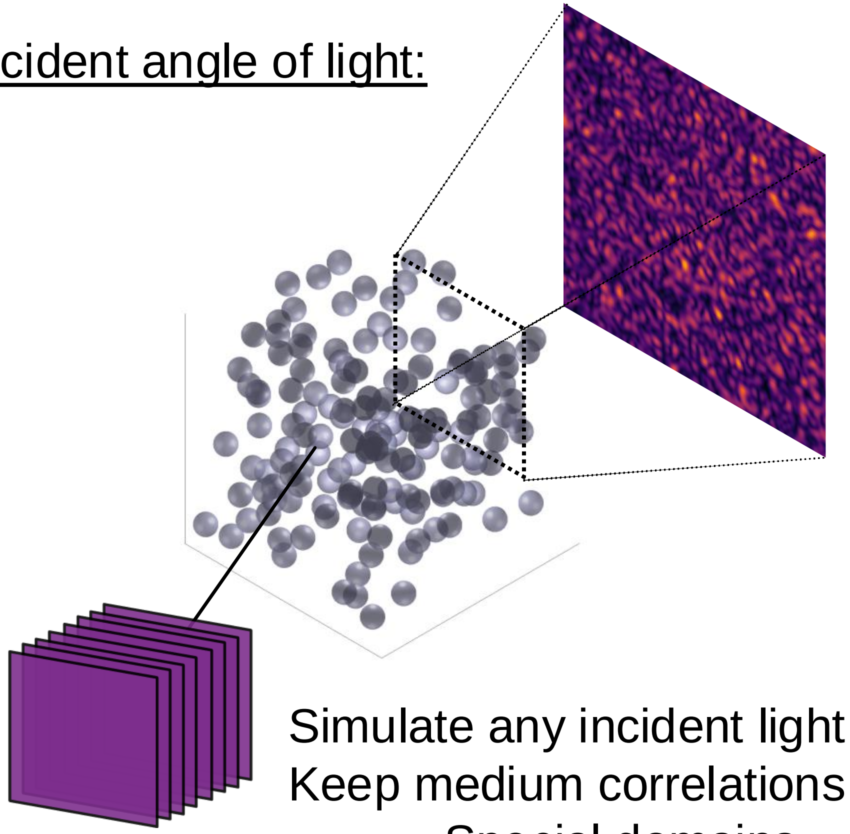

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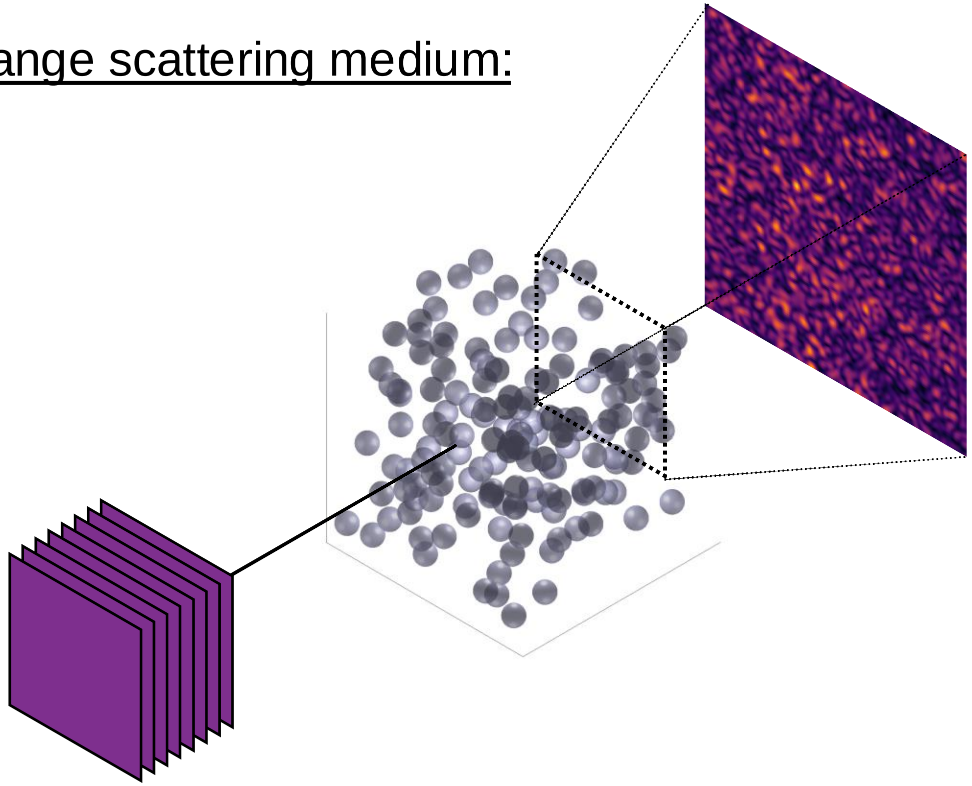

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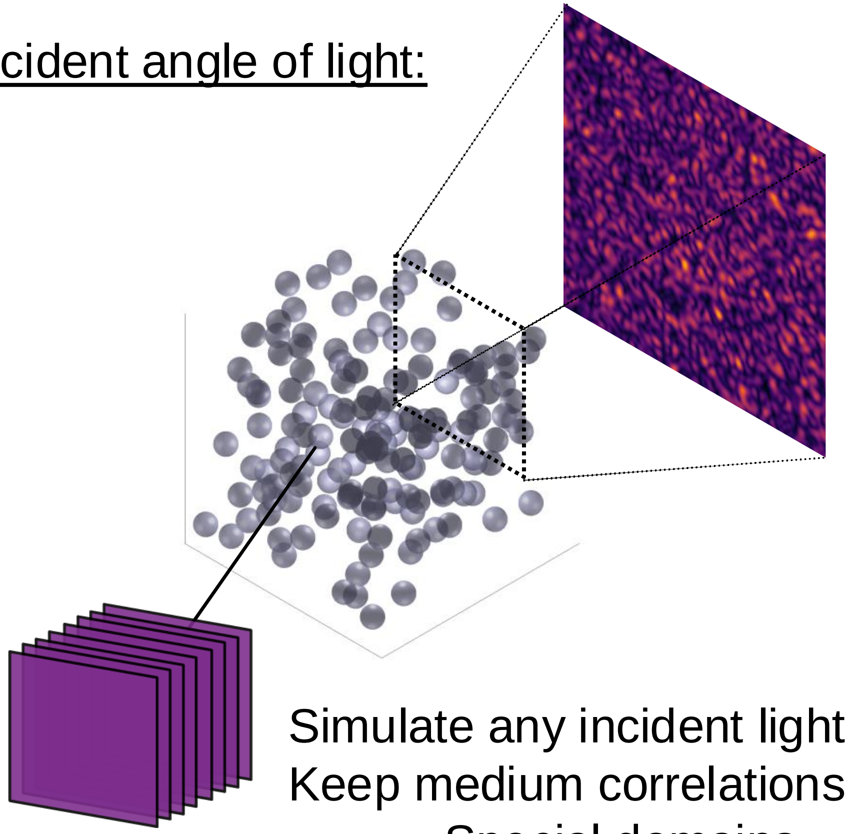

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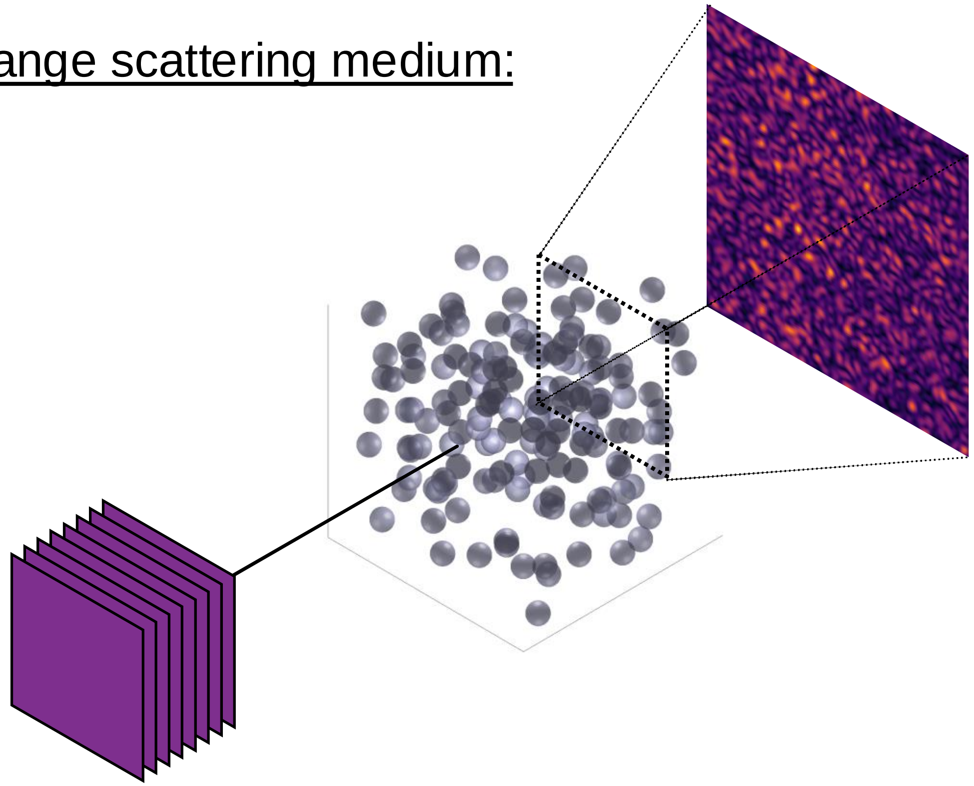

Isolating correlations within tissue

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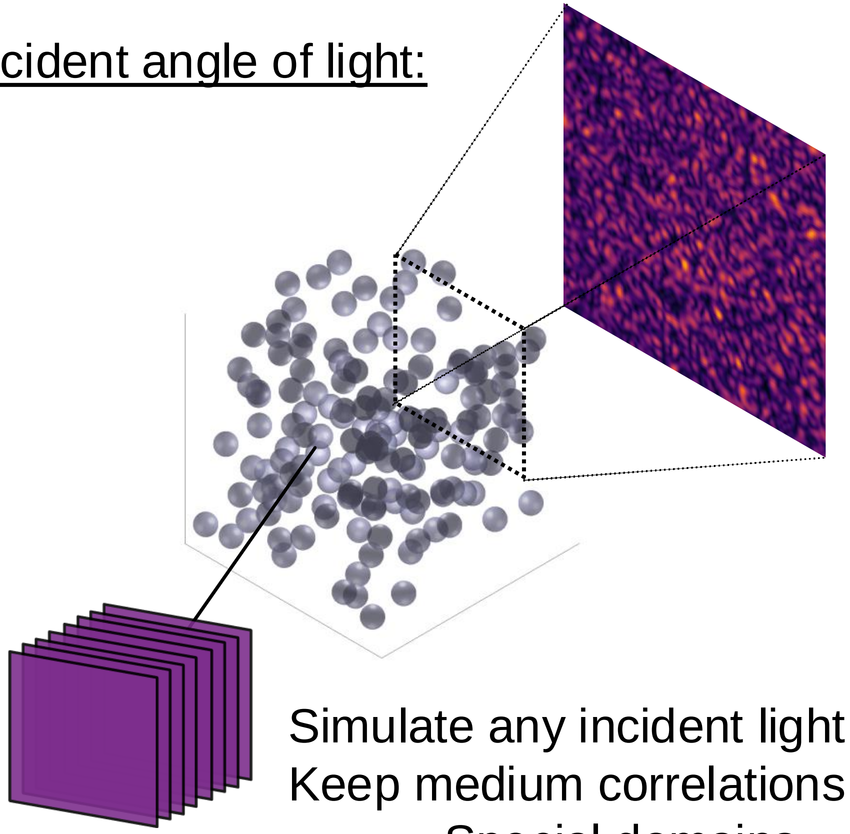

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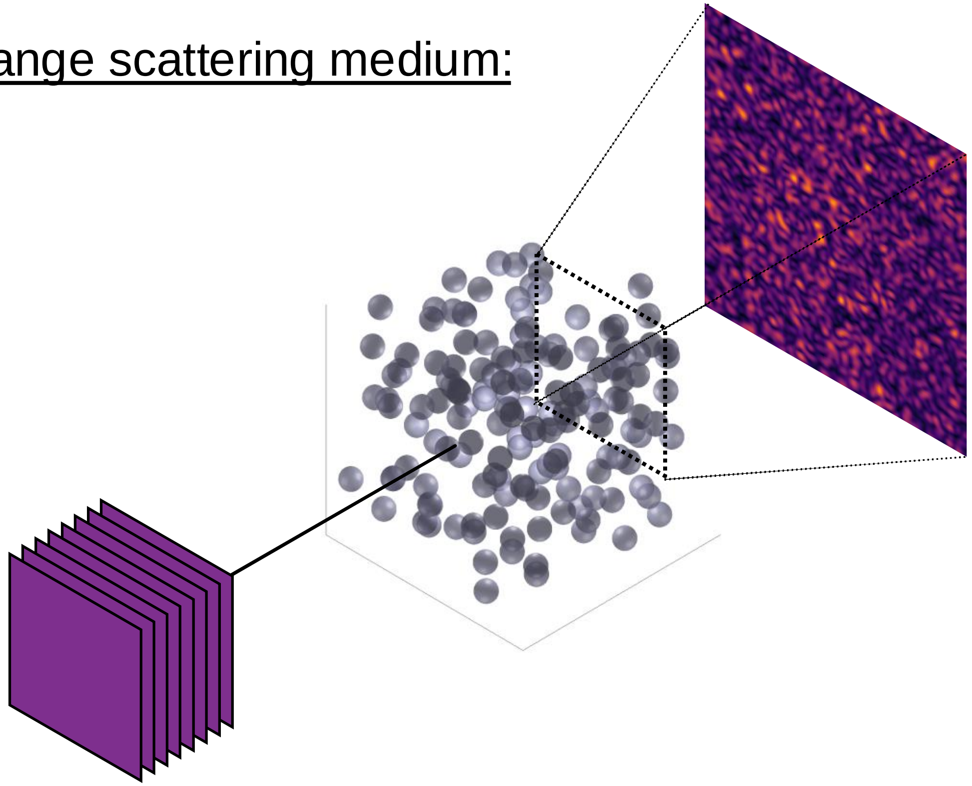

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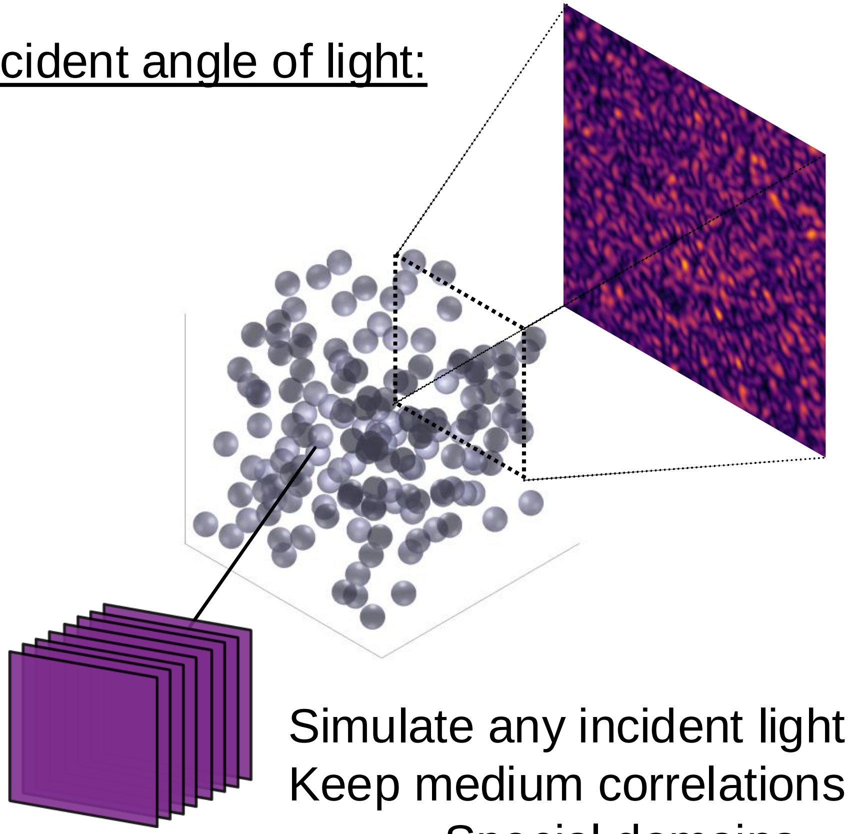

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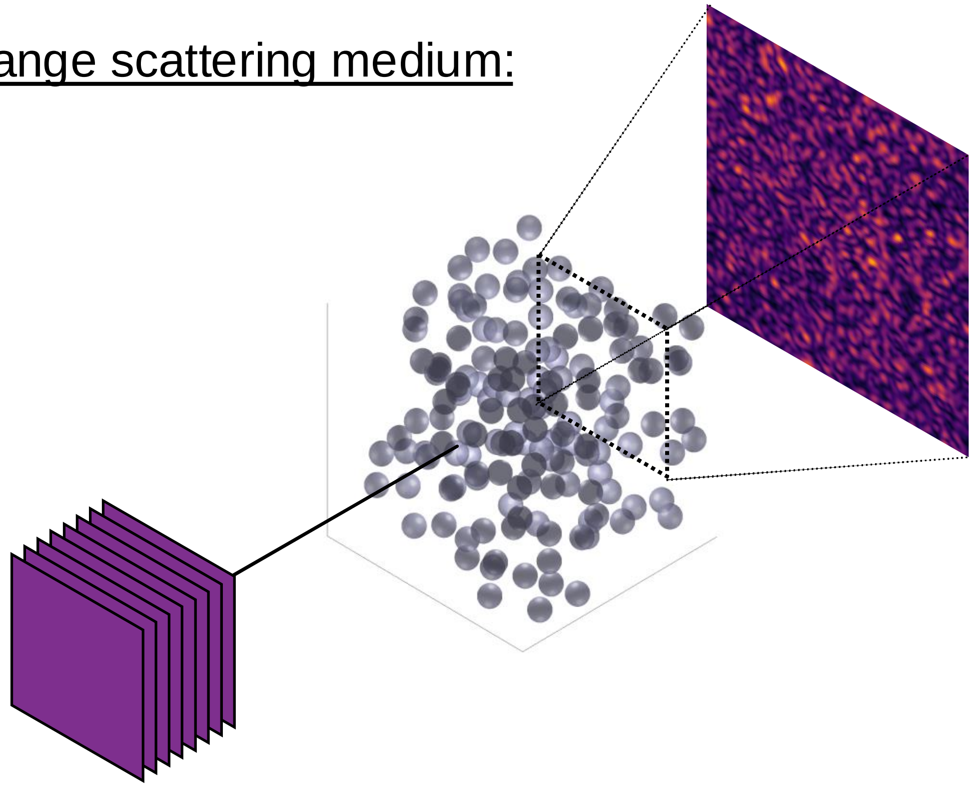

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Angular spectrum method

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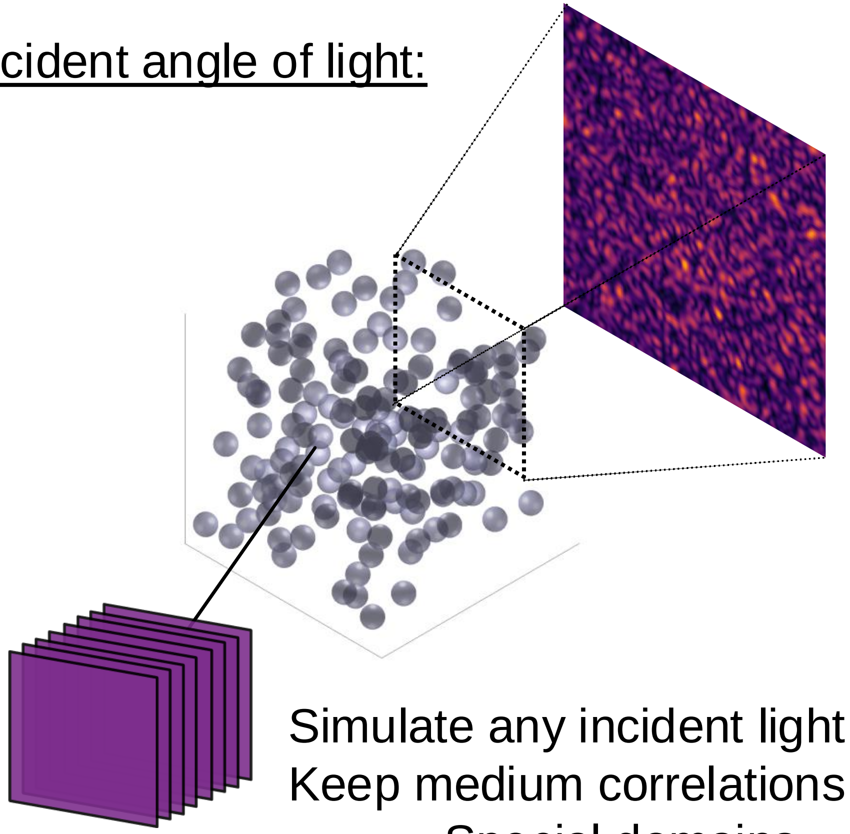

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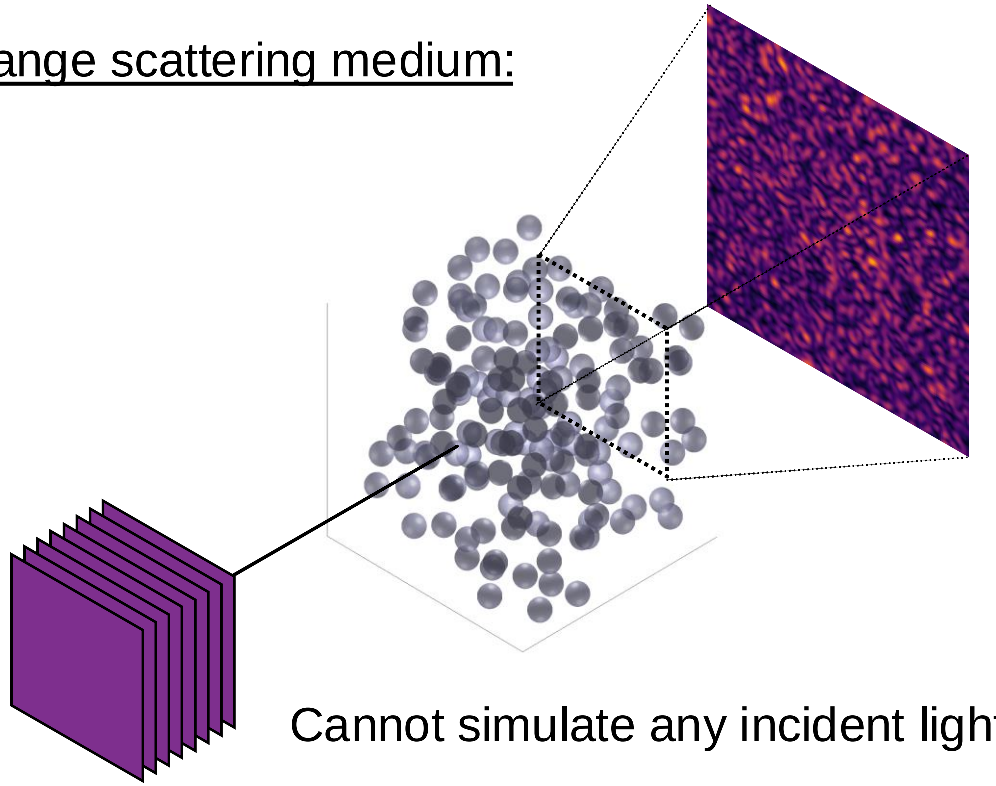
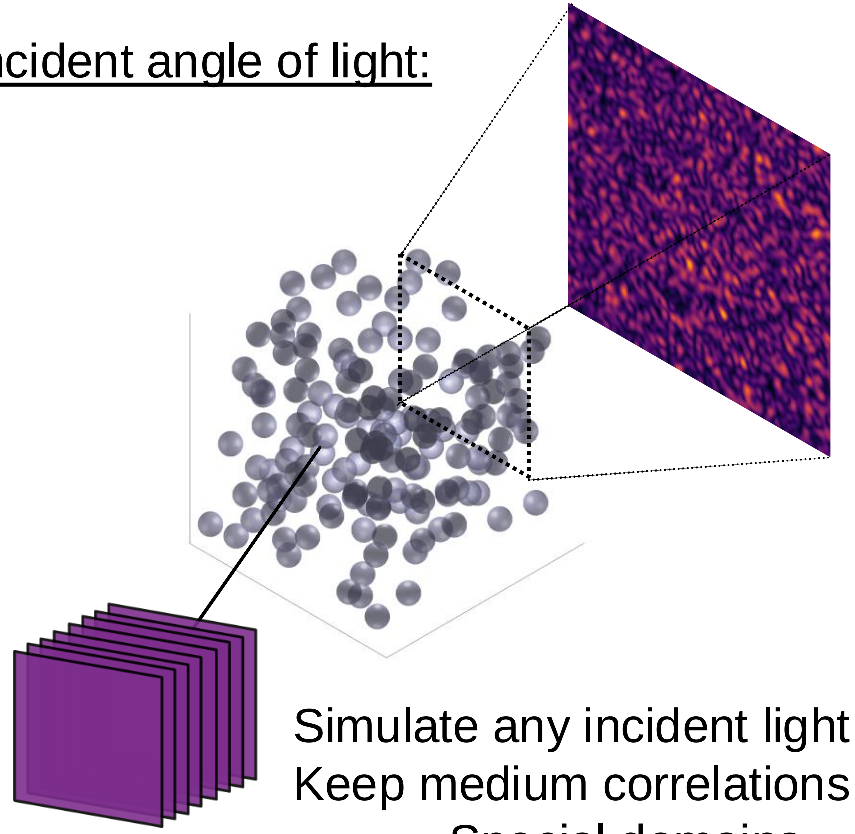


Cannot simulate any incident light ✗

Isolating correlations within tissue

Angular spectrum method

Change incident angle of light:



Simulate any incident light ✓
Keep medium correlations ✓

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Random medium method

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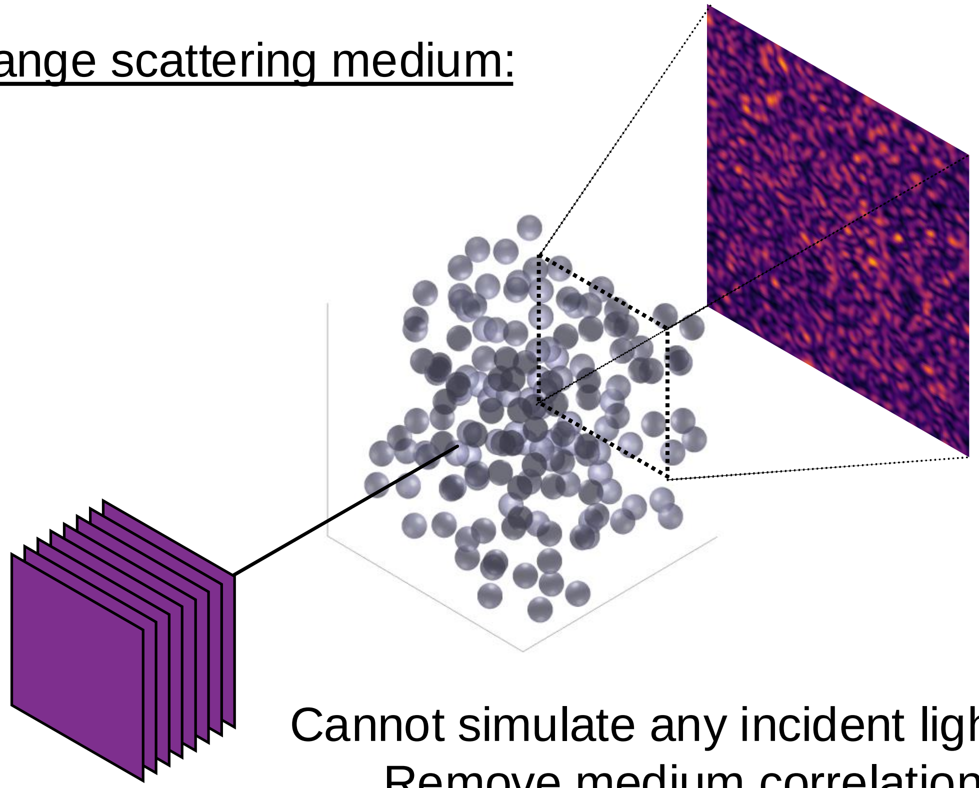

Cannot simulate any incident light ✗
Remove medium correlations ?

Isolating correlations within tissue

Angular spectrum method

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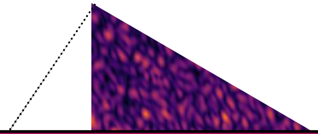

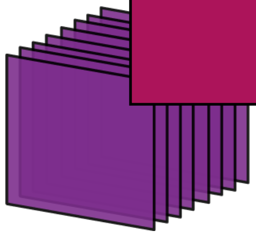

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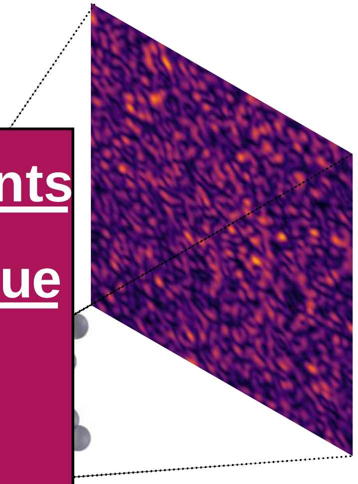
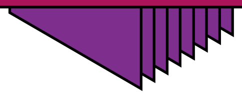




Cannot simulate any incident light ✗
Remove medium correlations ?

We use computational methods to investigate the requirements for a photoacoustic system to focus light into biological tissue

- Number of input modes
- Sensitivity

Would be useful to isolate medium specific effects

Simulating the propagation light through tissue-like media

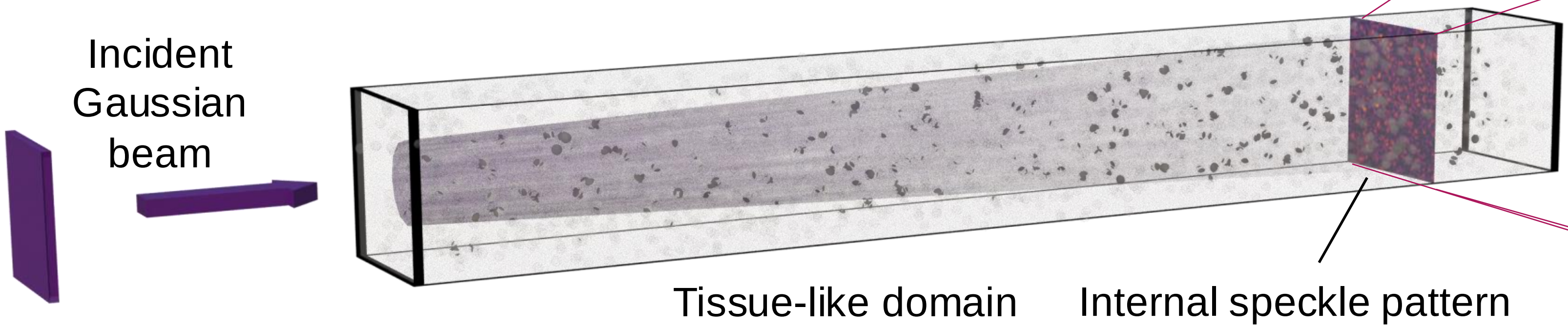
Constructing tissue-like discrete particle domains

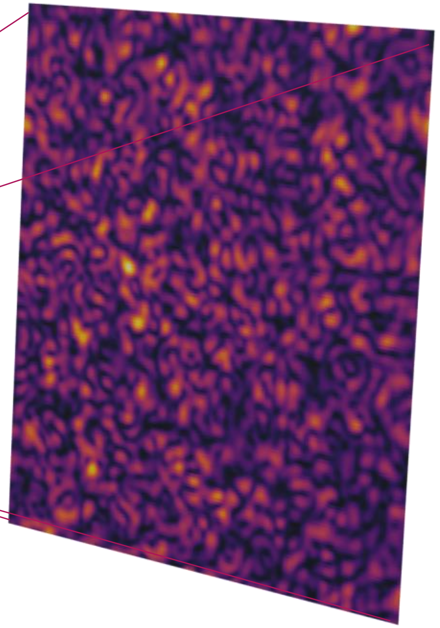
6000+ 100x100x800μm^3 **random, tissue-like** scattering domains *(μ_s=15.67mm^{-1}, g=0.95)*

[input modes]

Propagated **Gaussian beams** through domains, forming internal speckle patterns

[output modes]





Simulating the propagation light through tissue-like media

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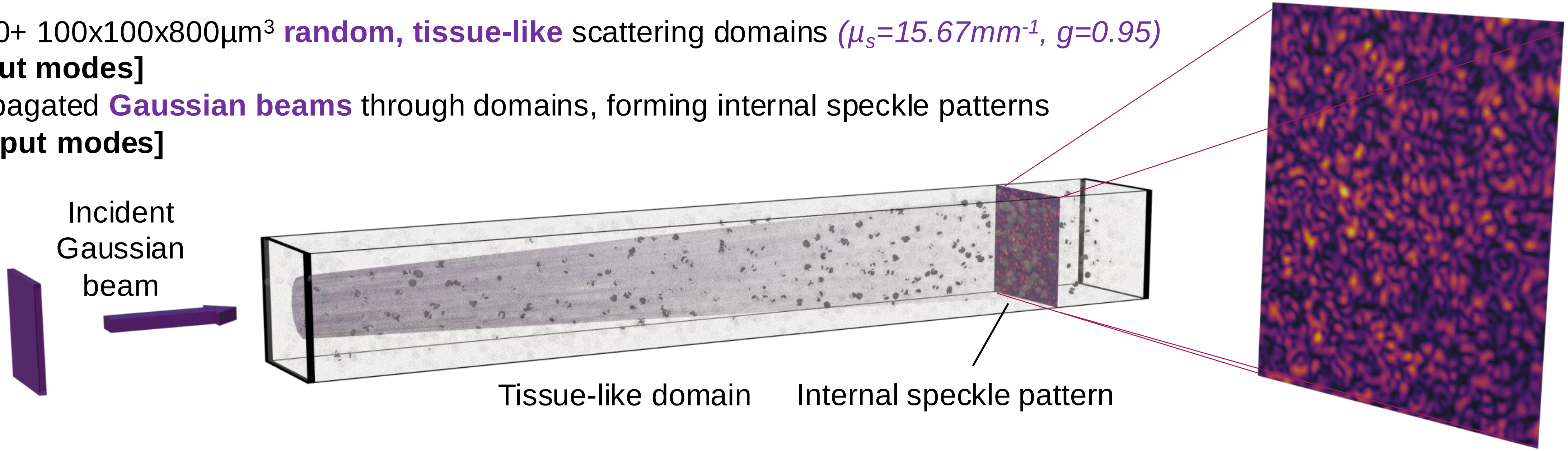
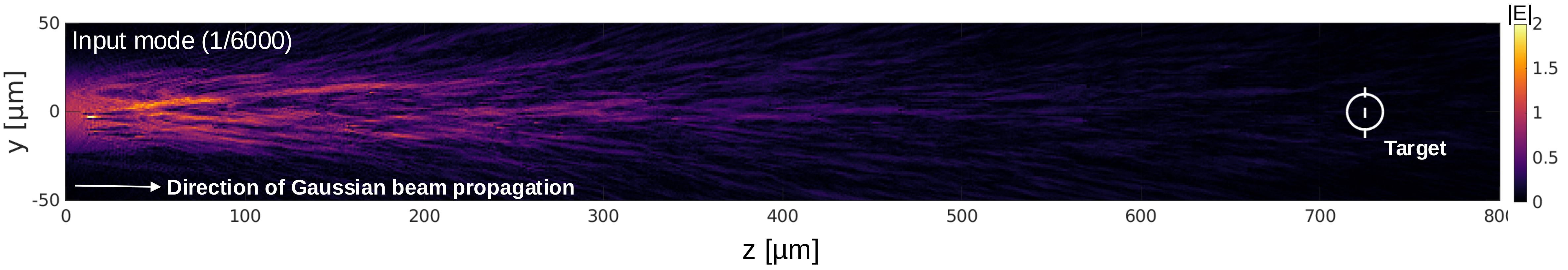


Validating tissue-like domains and the T-matrix method

- **Numerical validation** through comparison with Mie theory & Finite-Difference Time-Domain
  [are the simulated fields correct?]
- **Domain validation** with Monte Carlo and Inverse Adding doubling.
  [is the domain large enough?]

see 12388-15

Forming a focus inside tissue-like media



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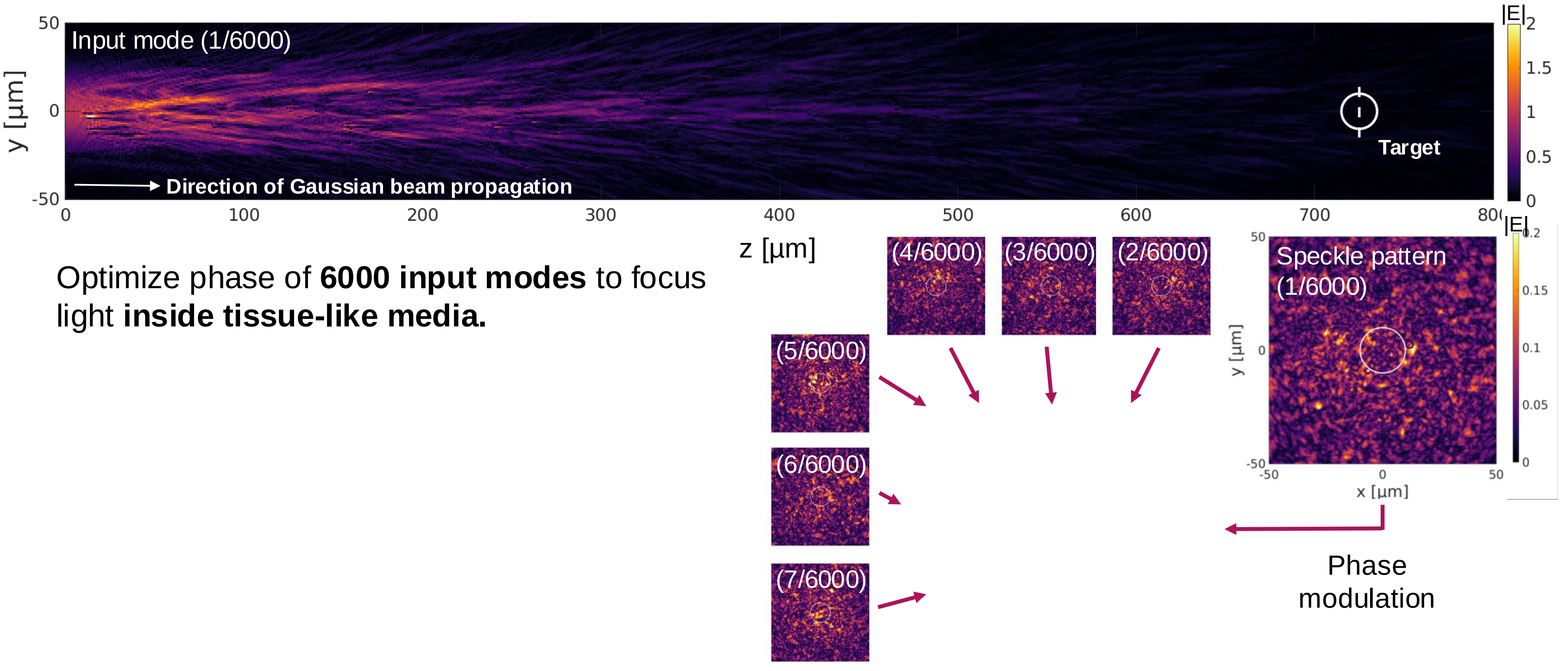

Optimize phase of **6000 input modes** to focus light **inside tissue-like media.**

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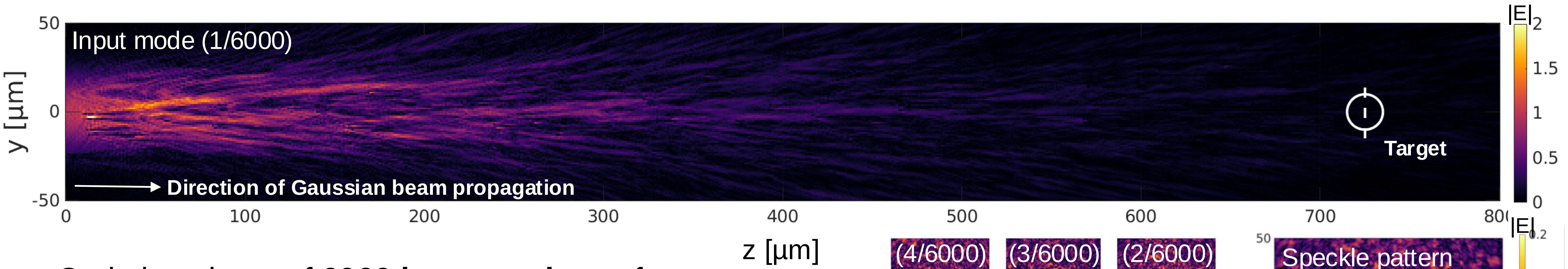

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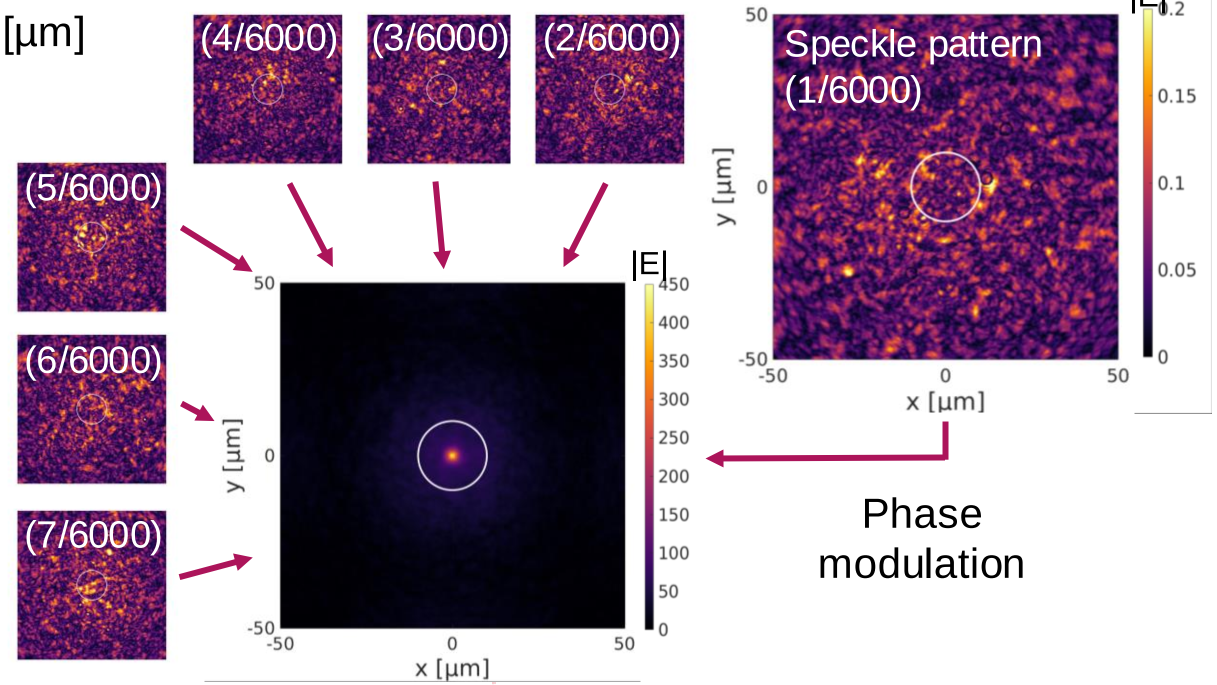

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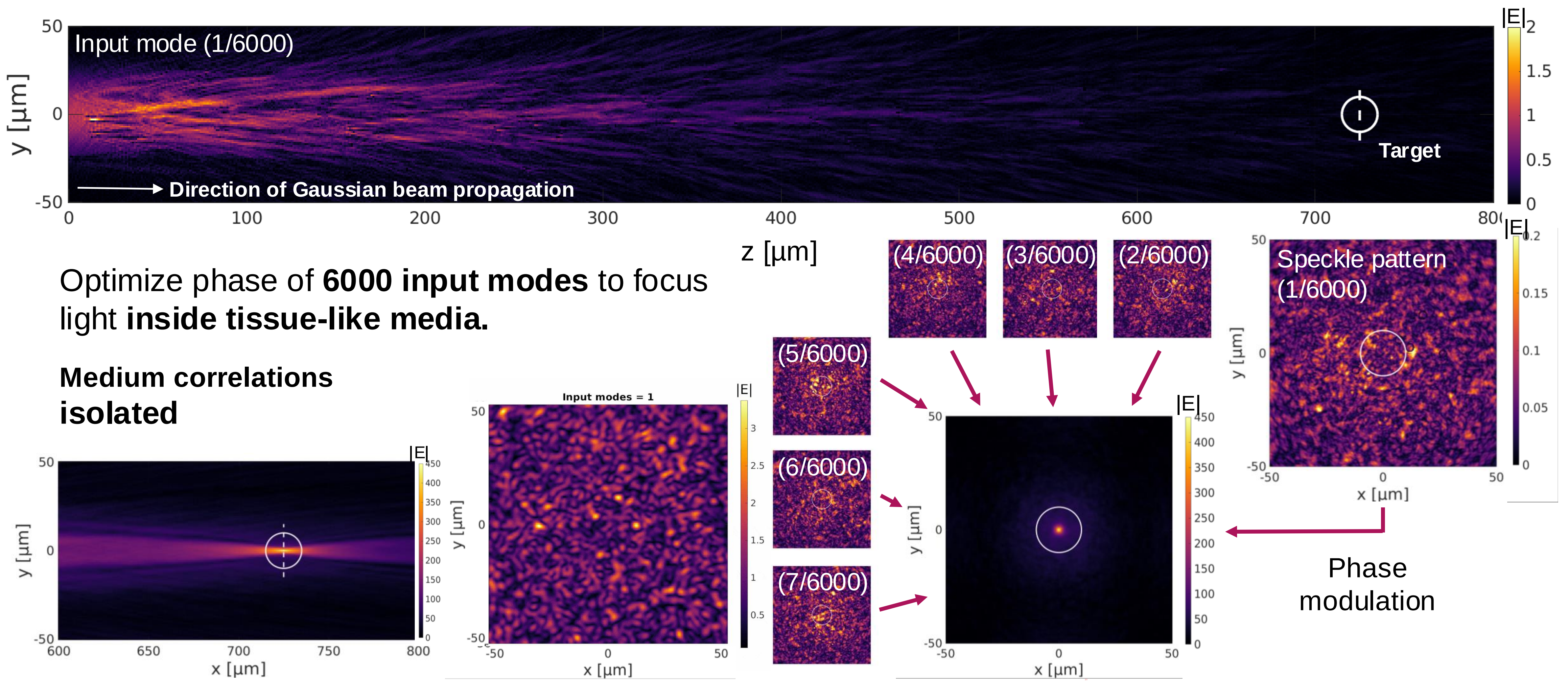

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Medium correlations isolated

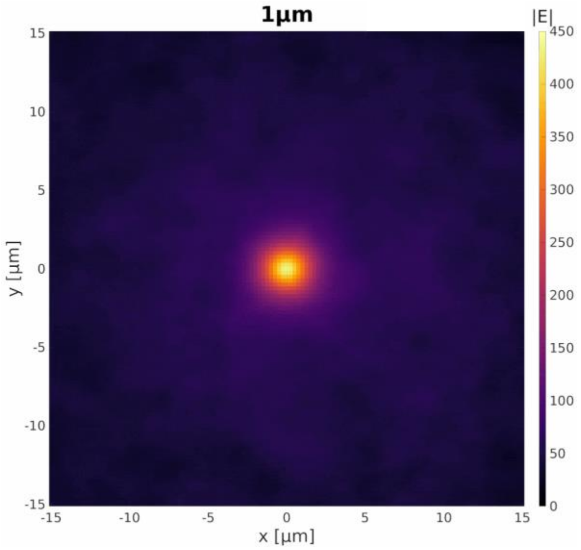
Why is internal photoacoustic wavefront shaping challenging? Investigating the enhancement of acoustic diffraction limited foci

Why is internal photoacoustic wavefront shaping challenging? Investigating the enhancement of acoustic diffraction limited foci

Focusing into a single speckle

↓

Focusing into a volume



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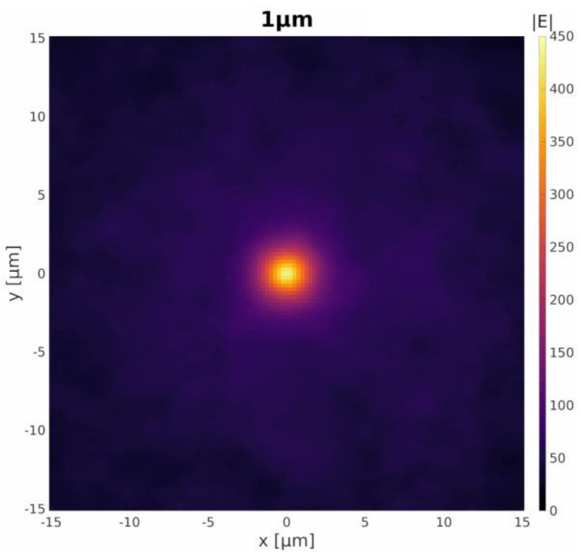

- **PAWS cannot** focus light into a **single speckle**
- Constrained by **acoustic diffraction limit.**
- Many **more input modes** required.

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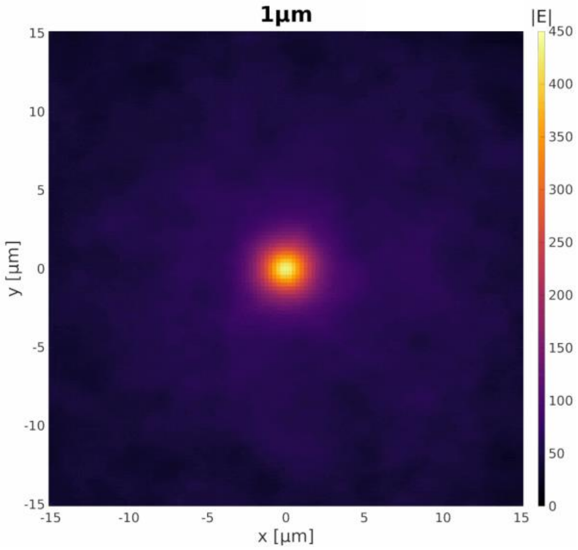
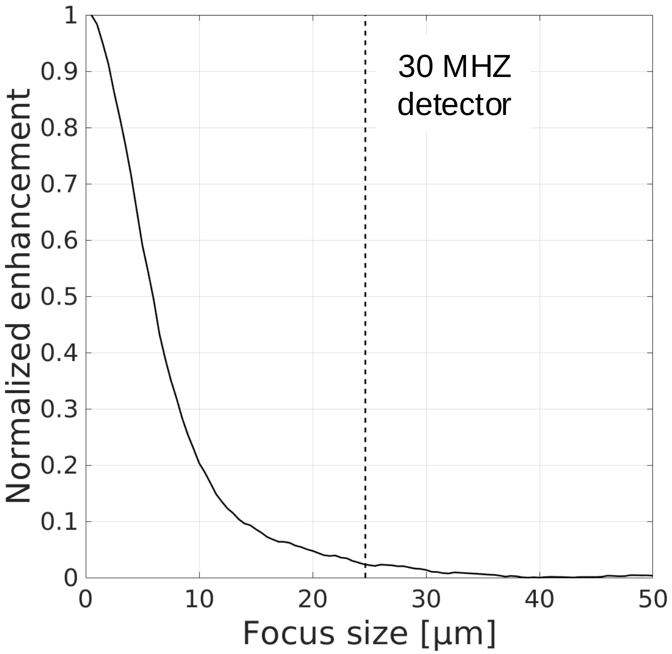


Plot enhancement vs acoustic voxel size.



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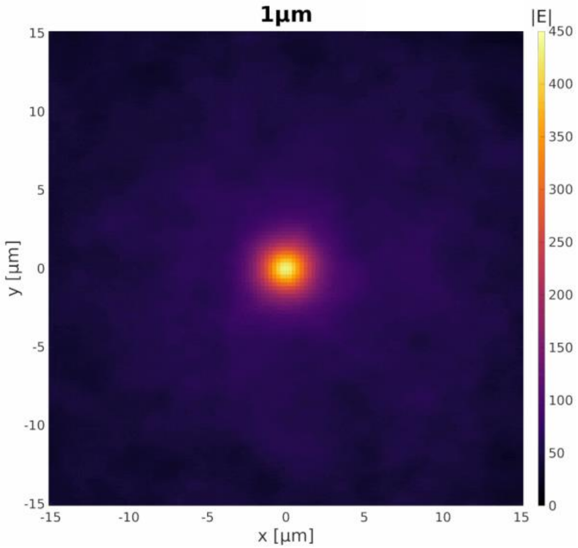
Focusing into a single speckle
↓
Focusing into a volume



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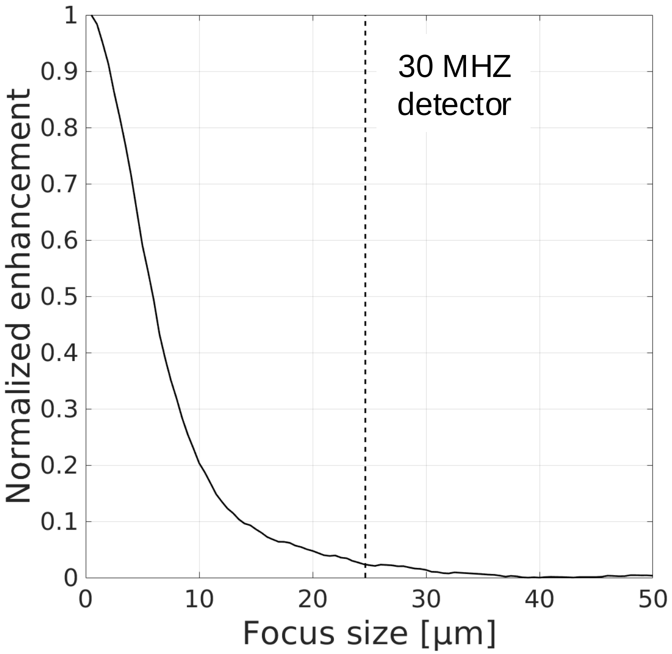

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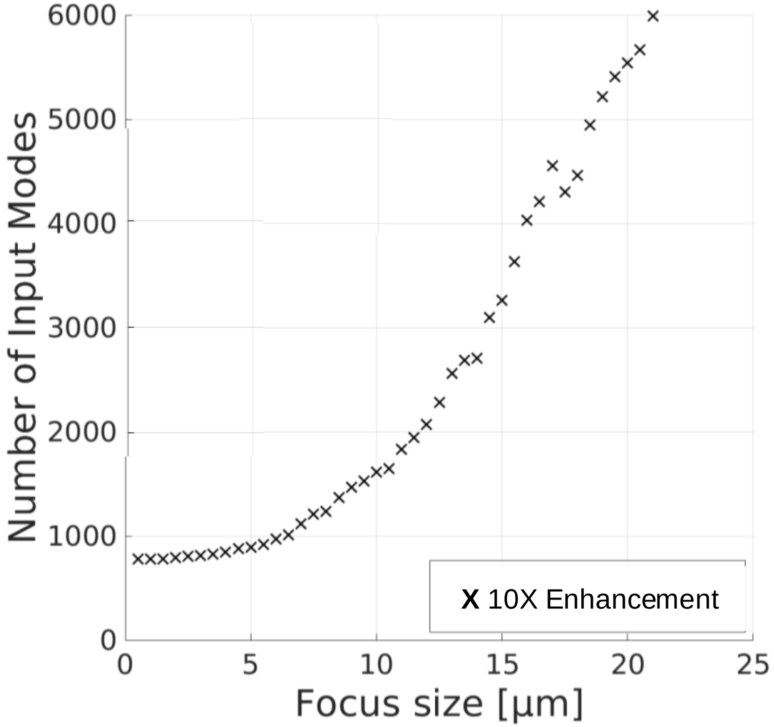
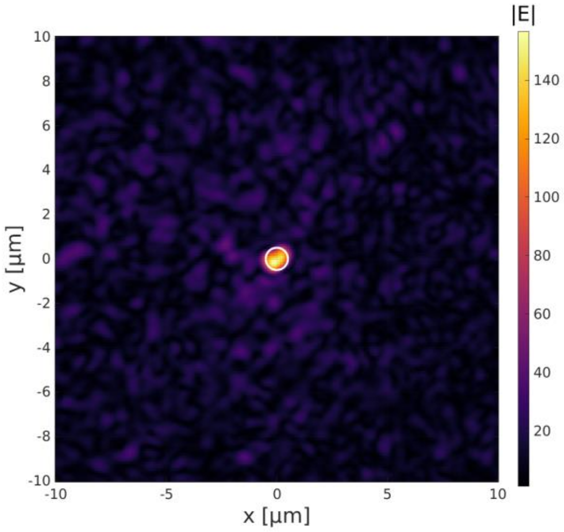


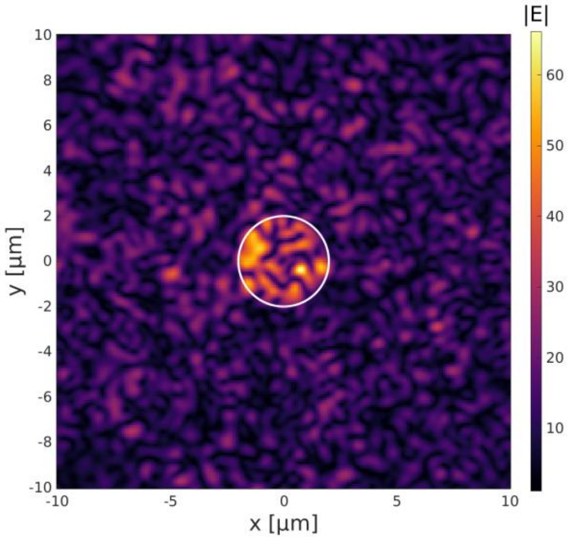
Number of modes required to generate foci with a given enhancement grows rapidly.

Why is internal photoacoustic wavefront shaping challenging? Investigating the sensitivity requirements of a PAWS system

Why is internal photoacoustic wavefront shaping challenging? Investigating the sensitivity requirements of a PAWS system

Consider focusing into a single speckle vs multiple speckles:





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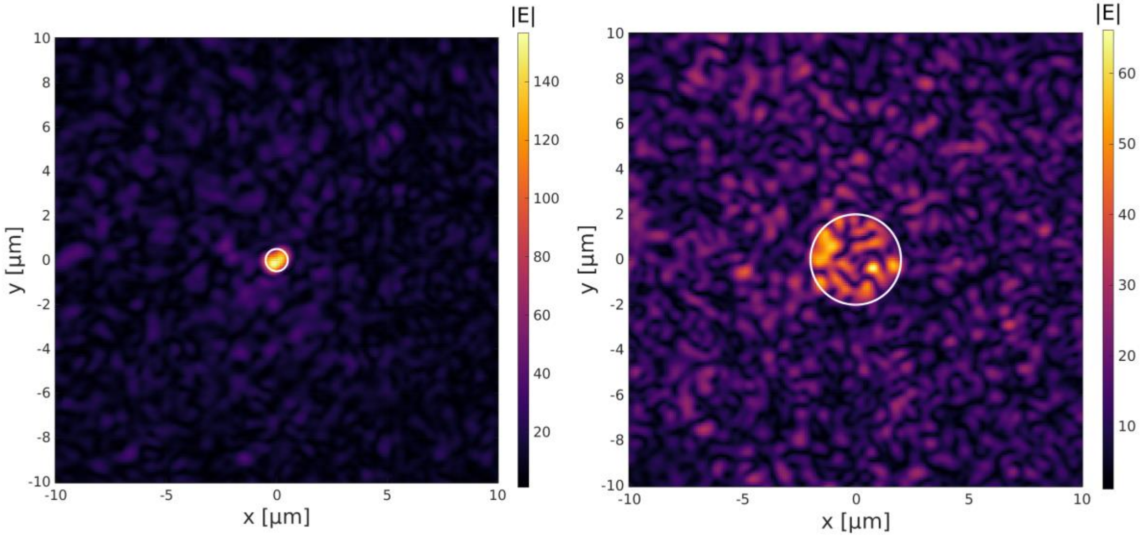

1. *More input modes are required to achieve a focus with a given intensity.*
2. **Not every speckle can be made to constructively interfere simultaneously:**
    - For fully developed speckle **some grains will always be out of phase** and destructively interfere.
    - The enhancement per modulation approaches zero as the number of speckle increases.

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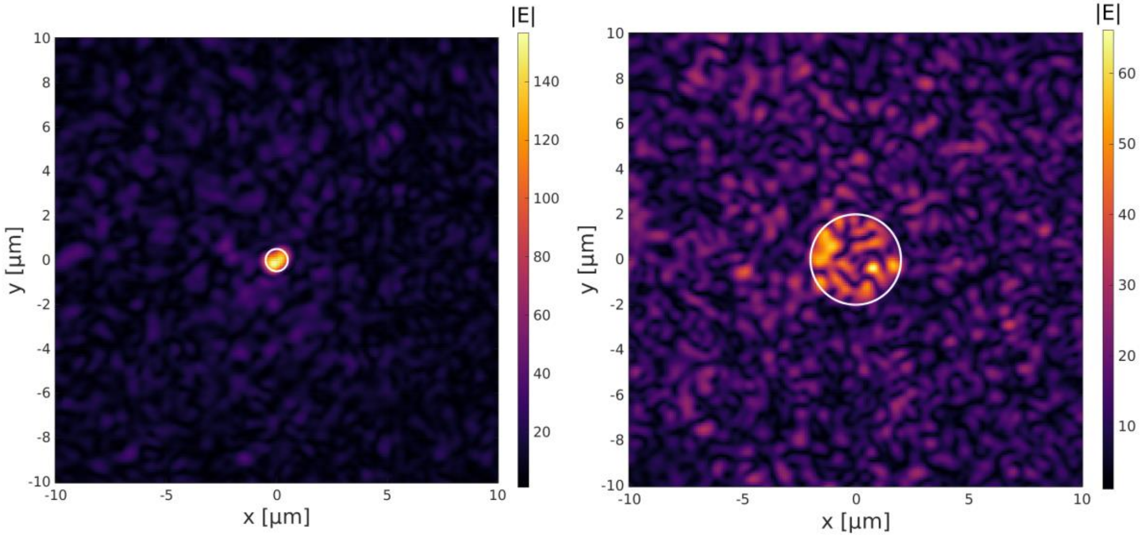

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→ ***Increased sensitivity requirements of a PAWS system to detect the effect of a given modulation***

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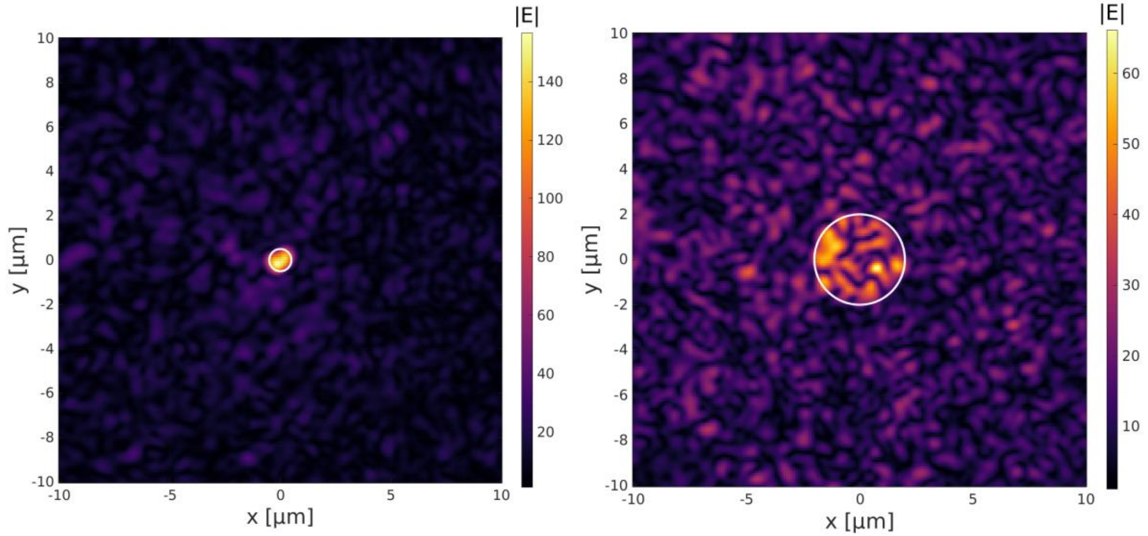

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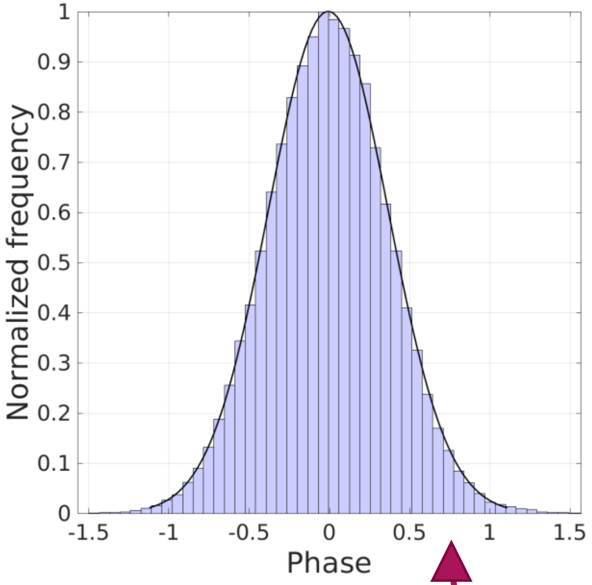
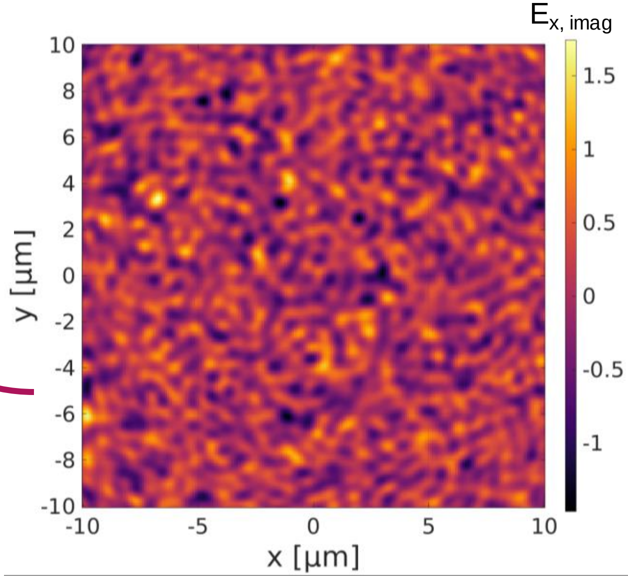


Phase is normally distributed.

Shaping into acoustic diffraction limit foci requires **sensitive detectors**, particularly if there is noise.



Our method allows phase to be measured ***inside the medium***

Increased sensitivity requirements of a PAWS system to detect the effect of a given modulation

What is exciting about this model?
Modelling correlations inside scattering media

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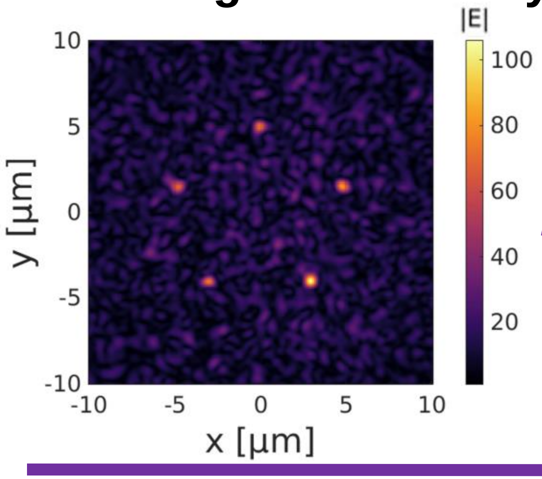
Modelling correlations inside scattering media

Focusing into arbitrary fields



Can be used to measure amplitude and phase of light shaped into any desired field.

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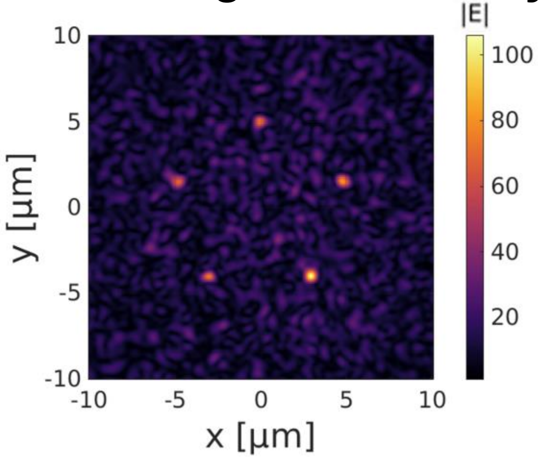
Focusing into arbitrary fields

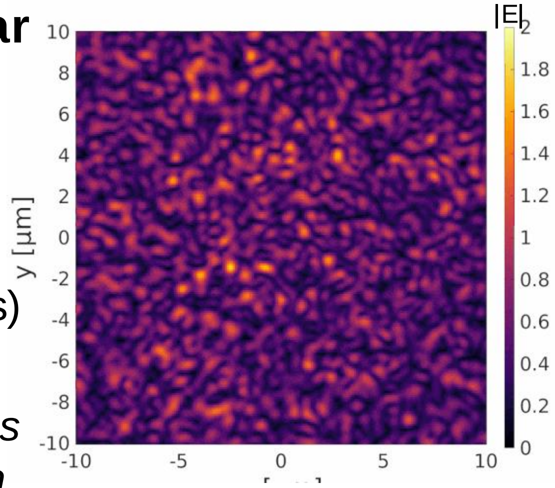


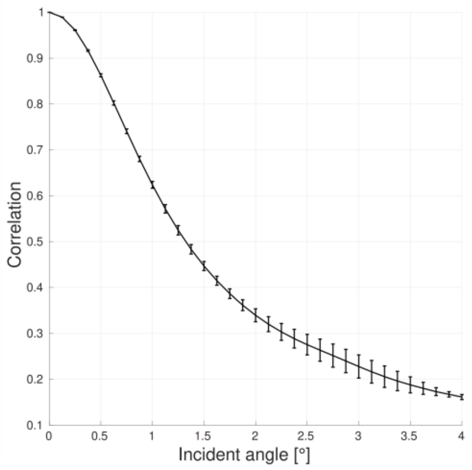
Can be used to measure amplitude and phase of light shaped into any desired field.

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.





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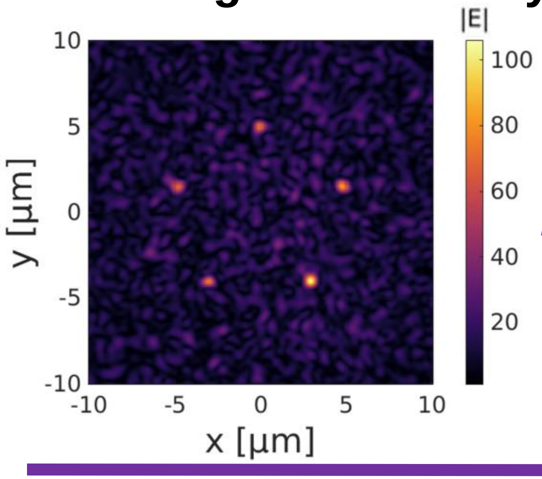
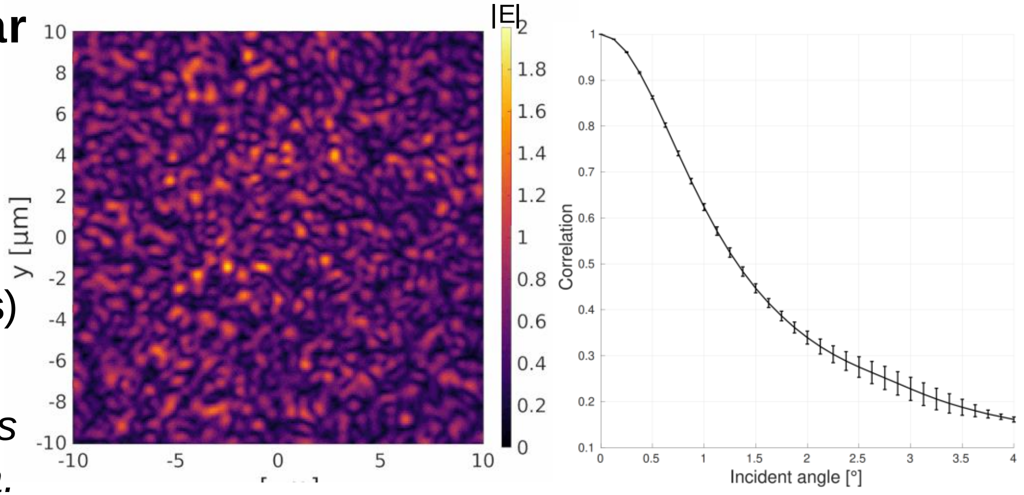


Can be used to measure amplitude and phase of light shaped into any desired field.

Measuring the angular memory effect range

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

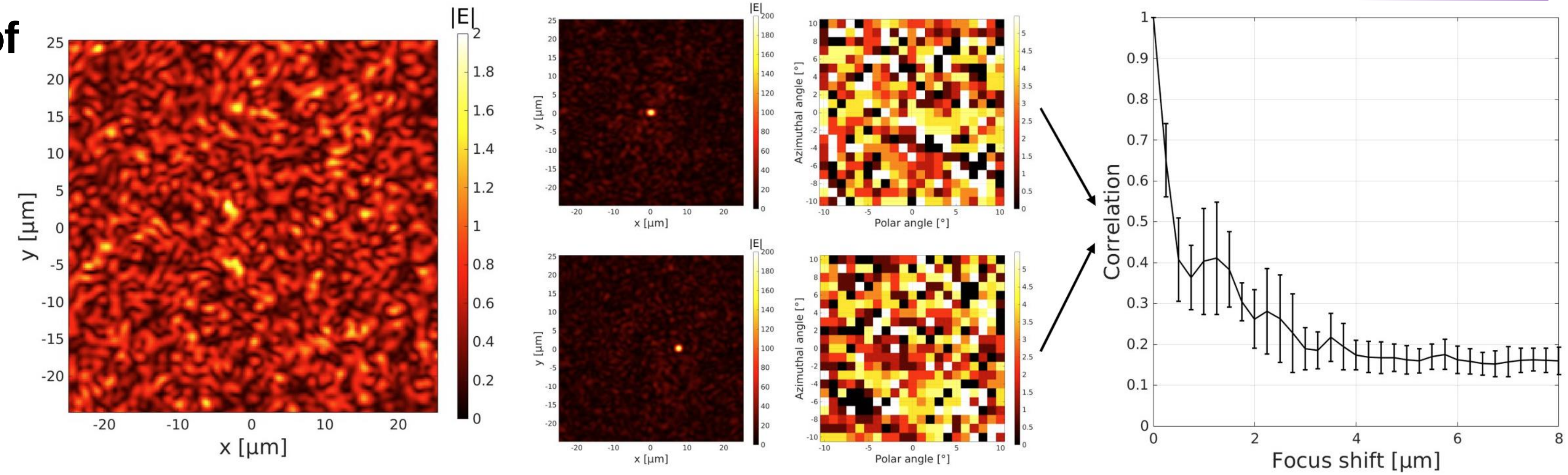
Some methods exploit these correlations to focus light into scattering media.



Modelling the angular range of an optimized focus

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

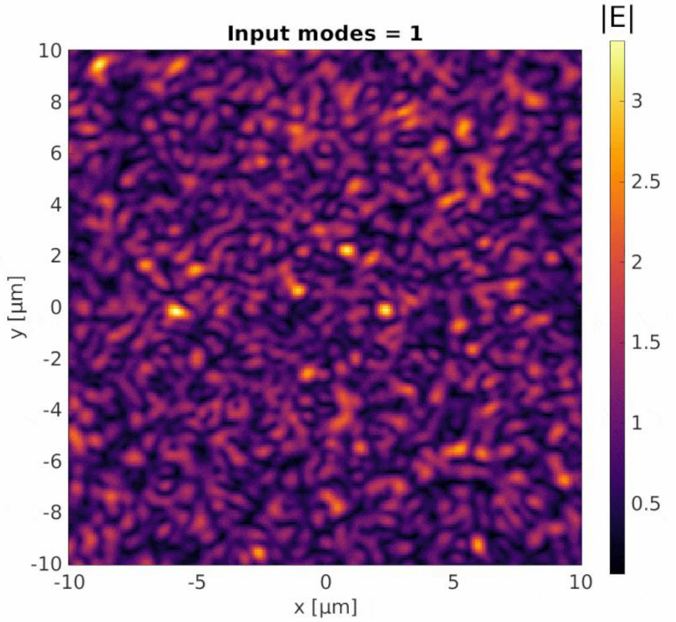
Focusing might also be able to be accelerated by exploiting priors (e.g. sharing phase maps between input modes).

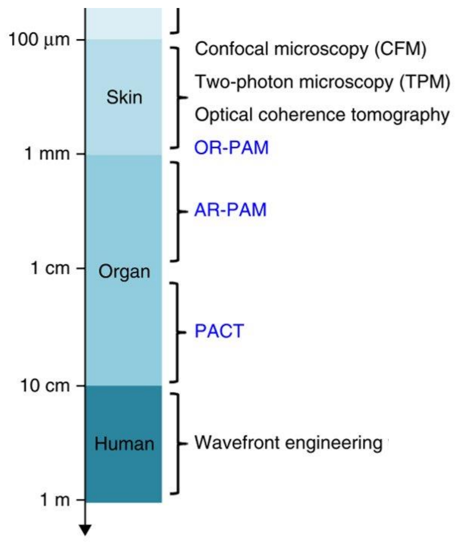


Conclusions

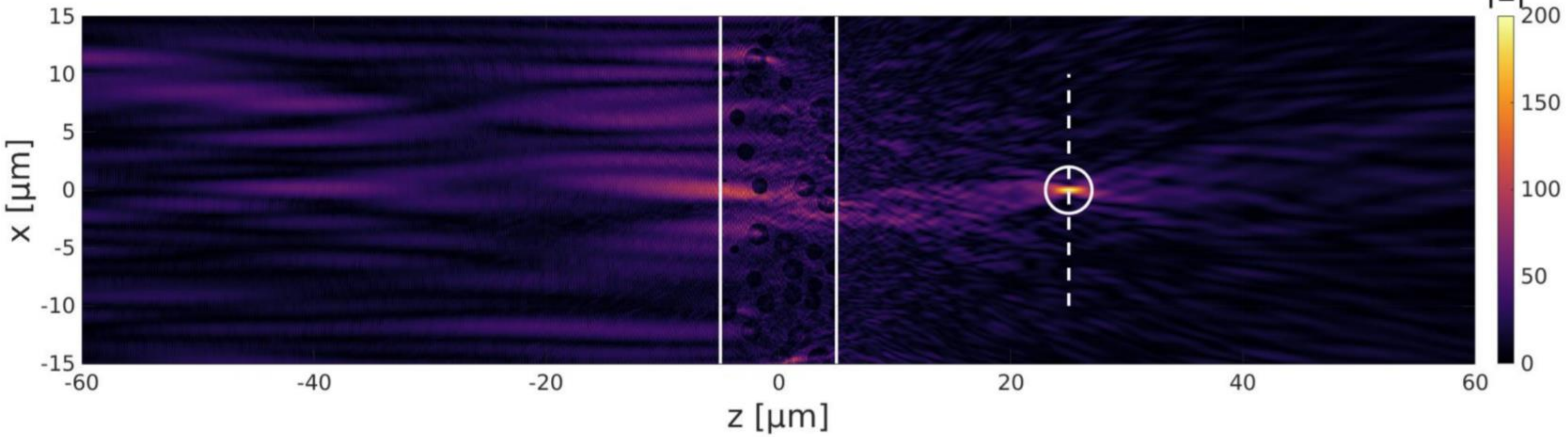
1. **PAWS has the potential to enhance the depth of optical imaging modalities.**
2. **Rigorous computational model can be used to investigate the challenges of achieving an internal focusing using PAWS.**
3. **Our proposed model can be used to investigate the requirements of a PAWS system, and how correlations inside biological tissue can be exploited.**

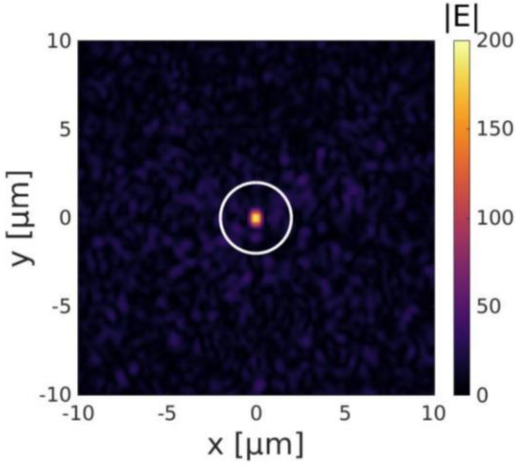
I'm happy to chat about any of my research, and if you're particularly interested in the model please review my talk yesterday (12388-15).





Wang & Yao, *Nature Methods*, 2016





Acknowledgements

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Computational wavefront shaping to focus light in deep tissue: a computational feasibility study

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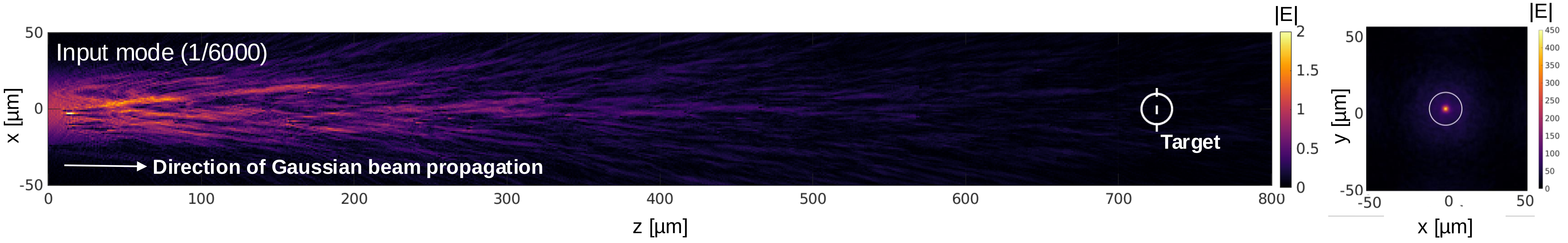
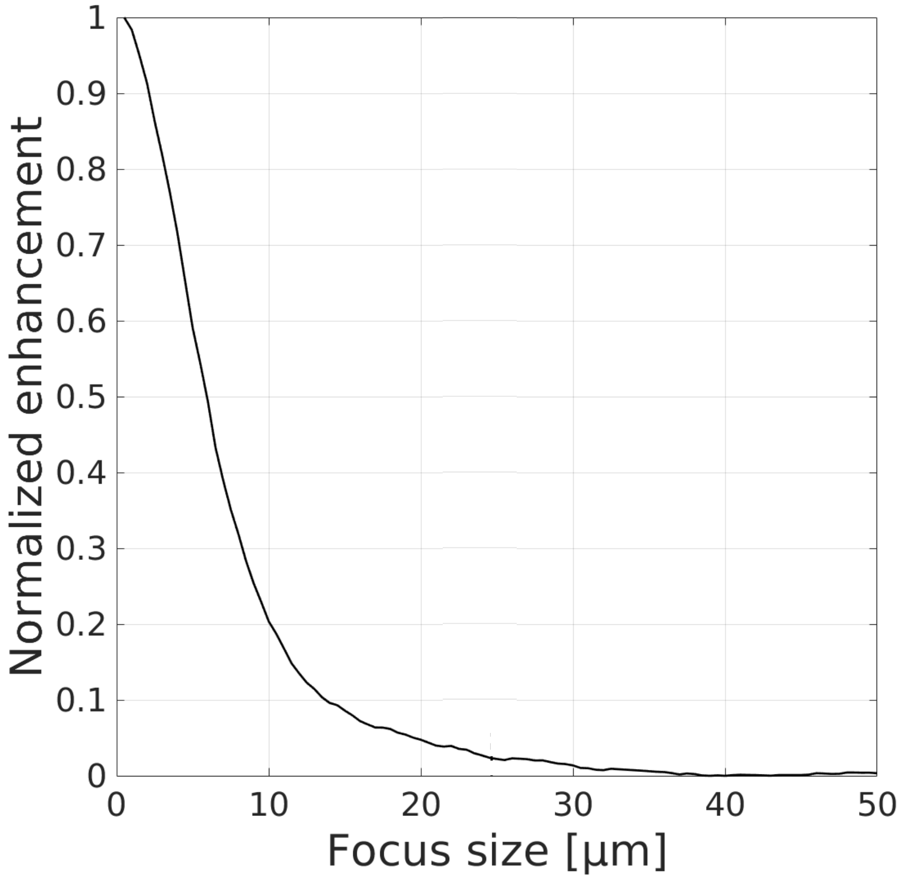
Forming a focus inside tissue-like media




Normalized enhancement
Focus size [µm]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50

Simulating the propagation light through tissue-like media