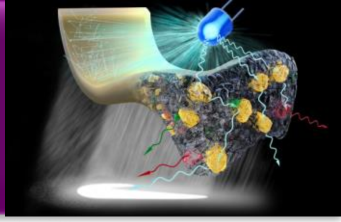
# Work package C: Homogenization and diffusion

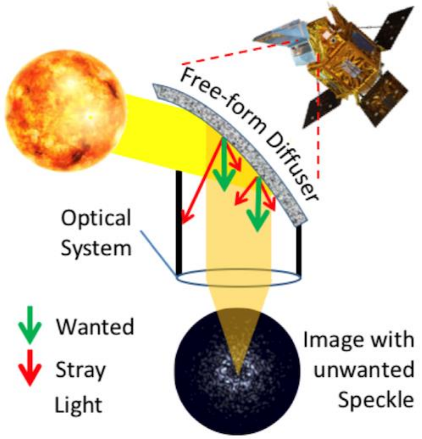
Martijn Anthonissen, Vì Kronberg, Sudhir Saini, Alfredo Rates, Robert van Gestel

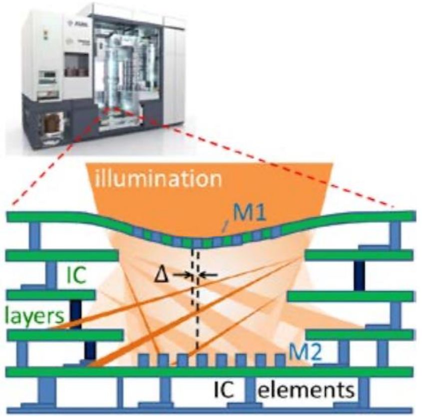
Eindhoven University of Technology, University of Twente

# Homogenization and diffusion

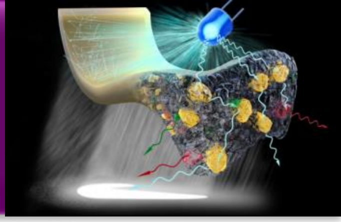


- Many sensors detect differences in light intensity
- Homogeneous light intensity needed
  Can be obtained by:
  - Using a freeform optical system
  - Diffusing light in nanophotonic medium
- Combination gives more freedom to designers
- Goal of WP-C
  *Understand how the combination works*

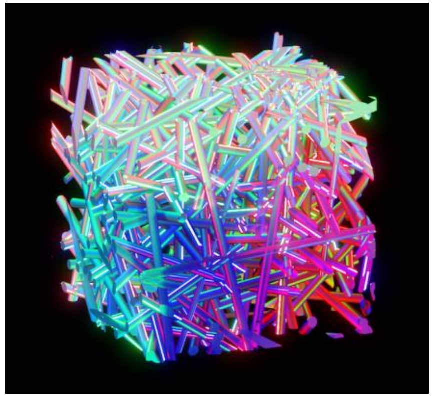


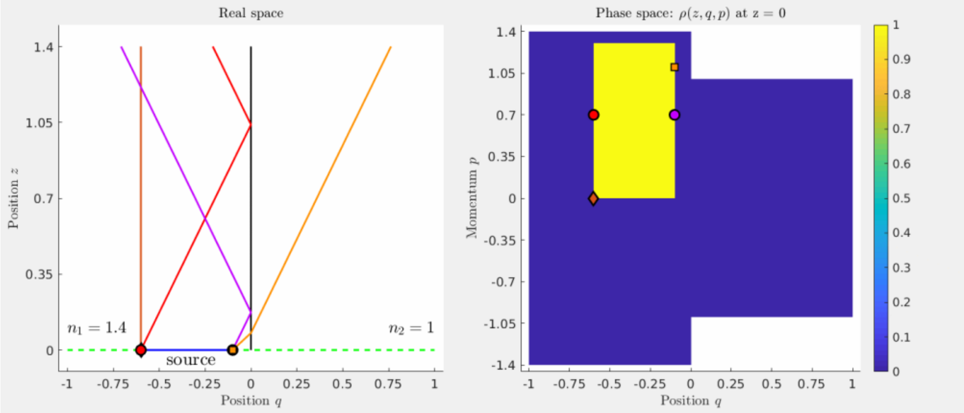



# Freeform Scattering Optics

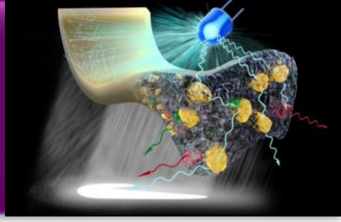


- Combine light scattering with freeform optics
- Different technologies:
  - *Scattering:* microscale
  - *Freeform optics:* macroscale
- Multidisciplinary team:
  - *Physics:* control light and optical processes in nanophotonic structures
  - *Mathematics:* mathematical description of optical systems, numerical simulation





# WP-C: Homogenization and diffusion

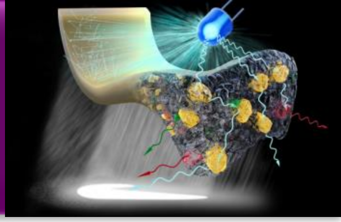


- C1
  *Freeform optics with scattering*
  Vì Kronberg, TU/e

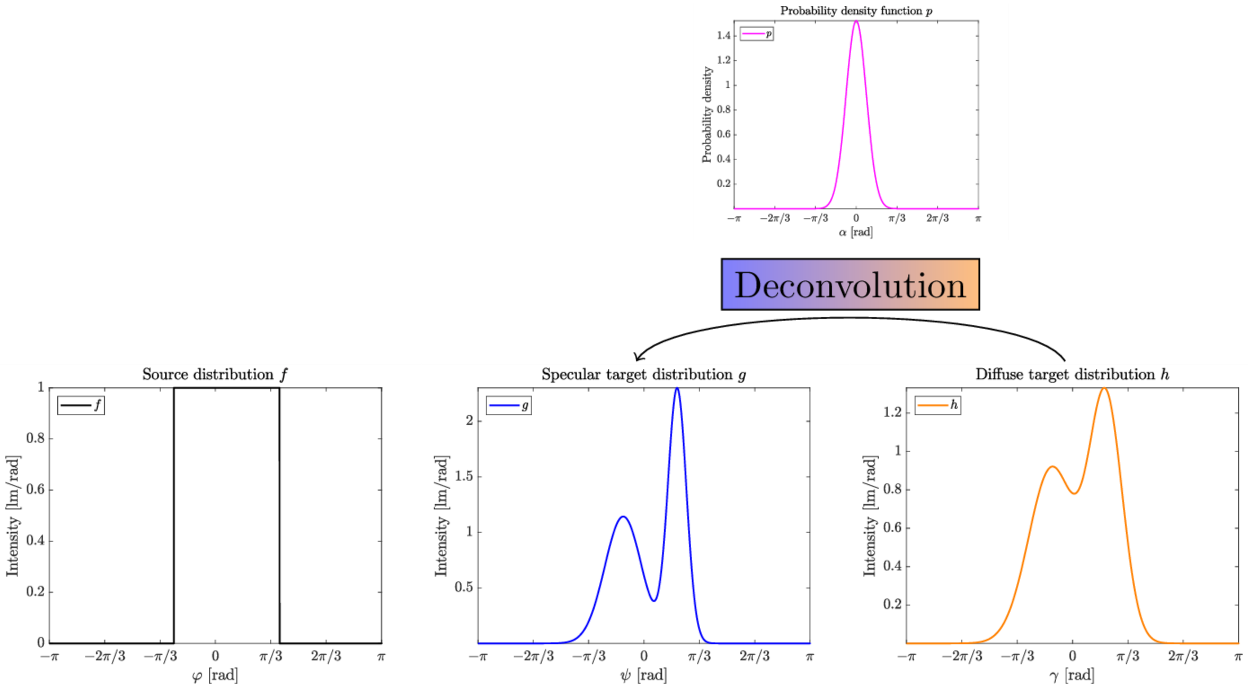
- C2
  *Scattering with freeforms*
  Sudhir Saini, UT
  Alfredo Rates, UT

- C3
  *Homogeneous illumination*
  Robert van Gestel, TU/e

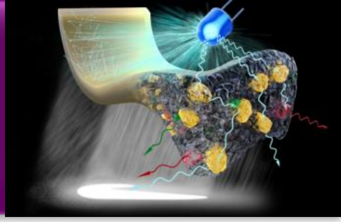
# C1 Freeform optics with scattering



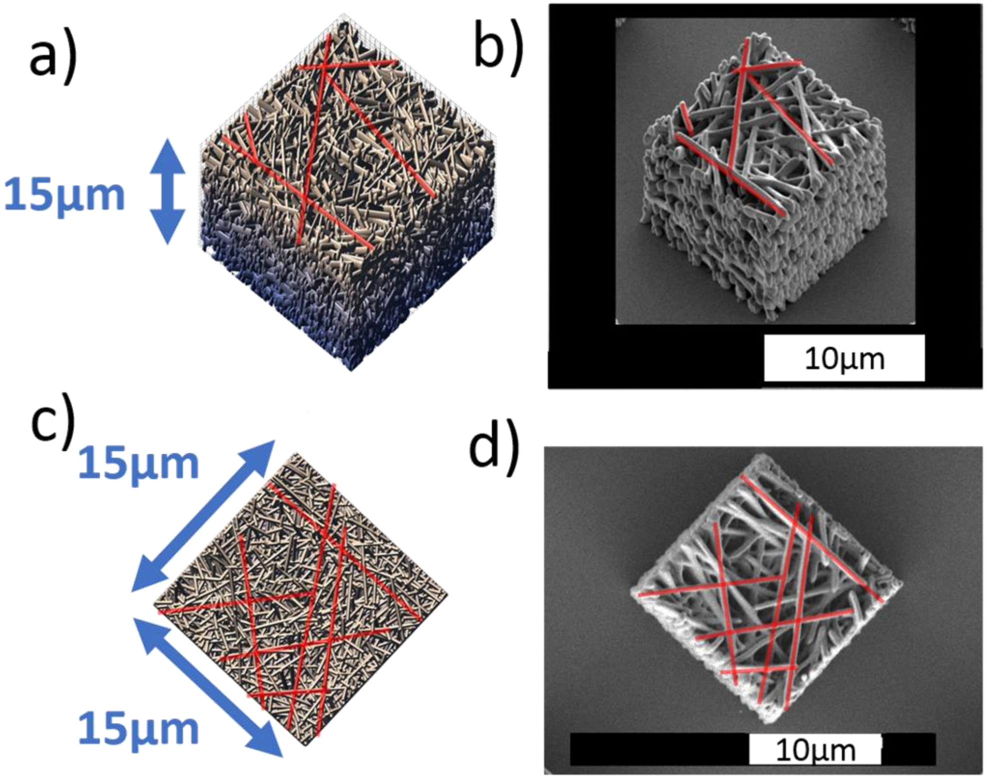
- Goal: include diffuse reflection in inverse problem of optical design
- Idea:
  - Diffuse target distribution given
  - Subtract effect of scattering (maths: deconvolution)
  - Solve freeform problem without scattering (WP-B)
- Large curvatures, little scattering



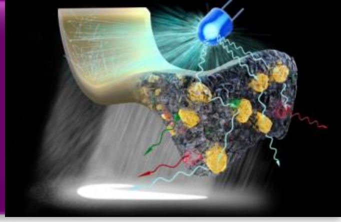
# C2 Scattering with freeforms



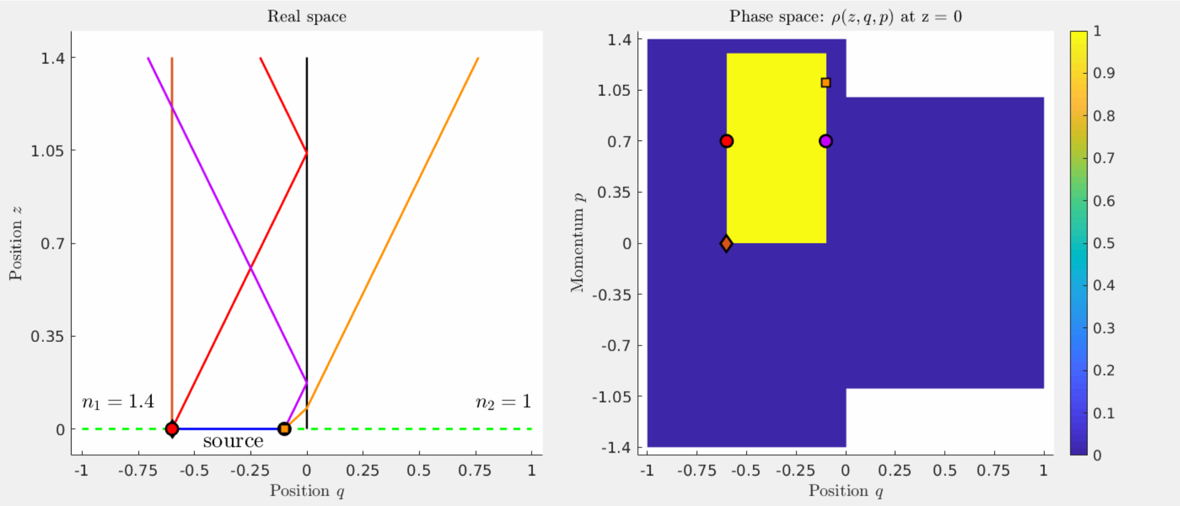
- Start from scattering and add freeform effects
- First simple slab (1D)
- Extend to more complicated geometry
- Small curvatures, much scattering



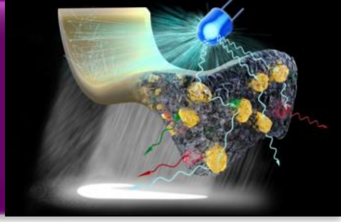
# C3 Homogeneous illumination

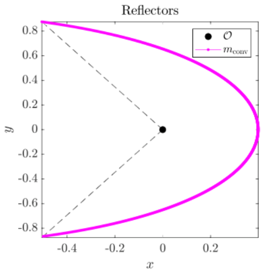


- Scattering elements can be used for homogeneous illumination but cause light loss
- Alternative: *light guides*
- Describe using Liouville's equation from Hamiltonian optics in phase space
- Accurate solver needed due to chaotic paths of light in light guide



# Deliverables



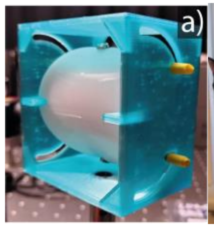


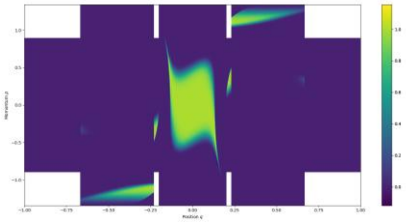

## C1 Freeform optics with scattering

- Rotationally symmetric design strategy
- Non-rotationally symmetric

## C2 Scattering with freeforms

- Analytic model of scattering in presence of freeform effects
- Scattering and design rules



## C3 Homogeneous illumination

- Extension of active flux scheme to 4D phase space
- Design rules for non-extruded light guides

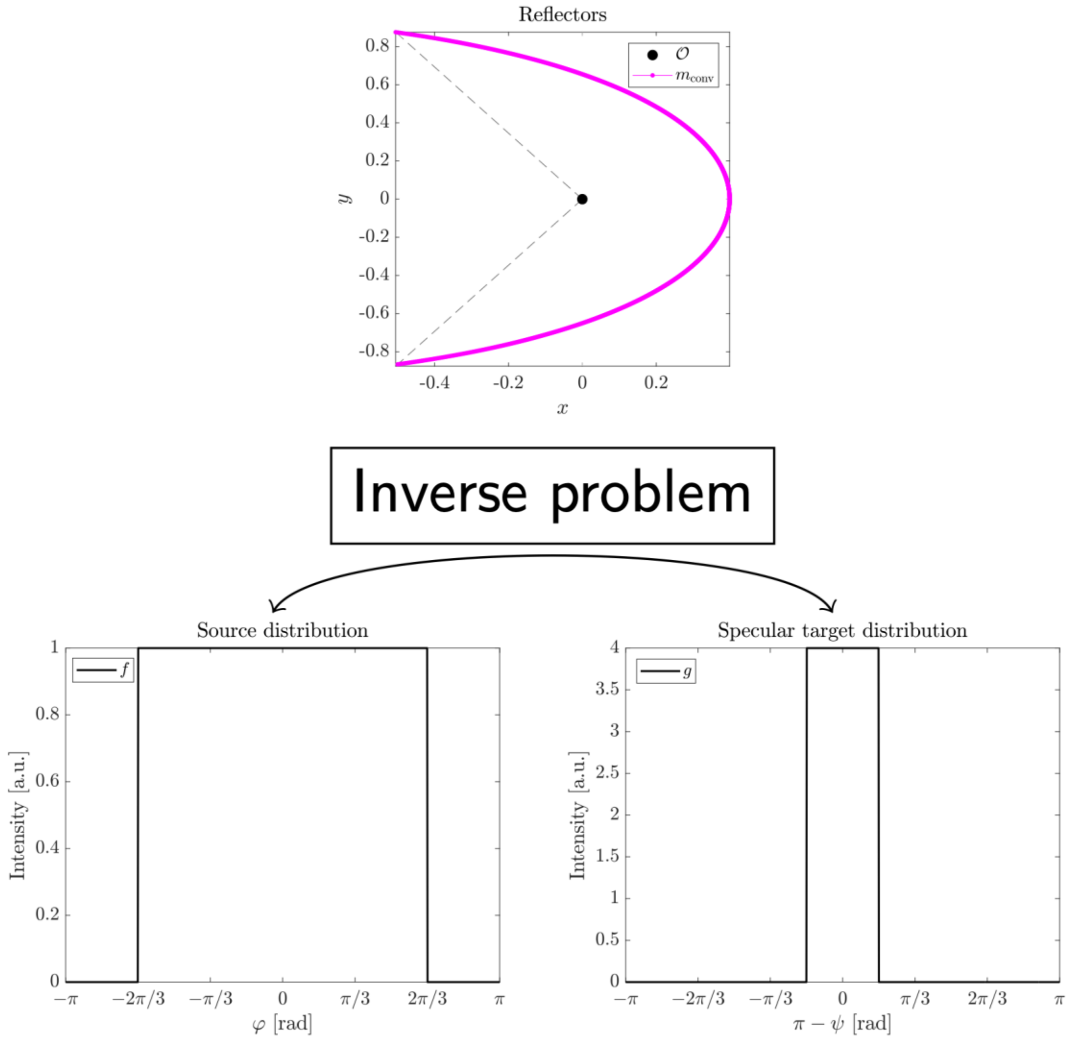
# An Inverse Model for Two-Dimensional Reflectors With Scattering

*Vì* Kronberg[†,*], *Martijn* Anthonissen[†],
*Jan* ten Thije Boonkkamp[†], and *Wilbert* IJzerman[†,‡]

[†]Eindhoven University of Technology, Eindhoven, The Netherlands
[‡]Signify Research, Eindhoven, The Netherlands
[*]Corresponding author: v.c.e.kronberg@tue.nl

# Definitions

# Freeform Scattering Optics




- **Inverse problem:** determine an optical system (reflector) from given source and target light distributions.

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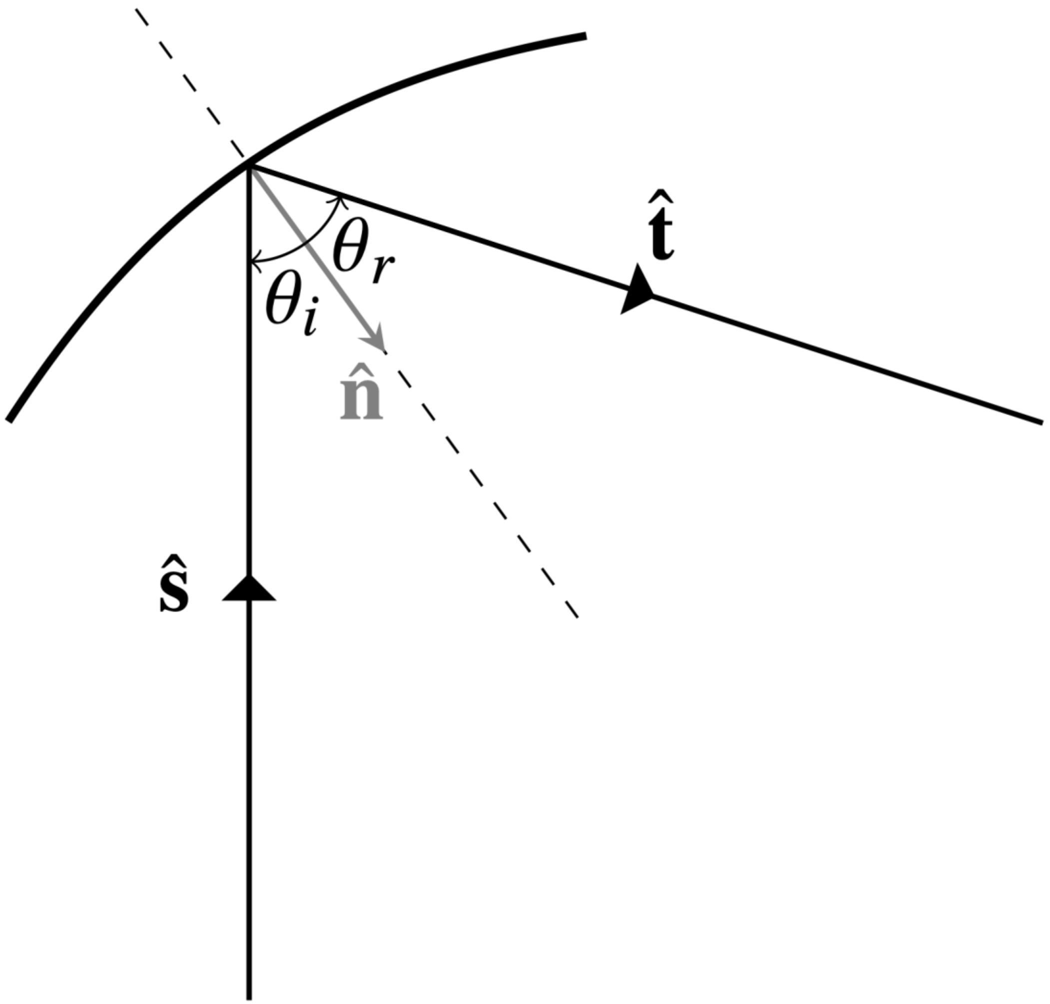


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- **Geometrical optics (GO):** ray formulation of light propagation.

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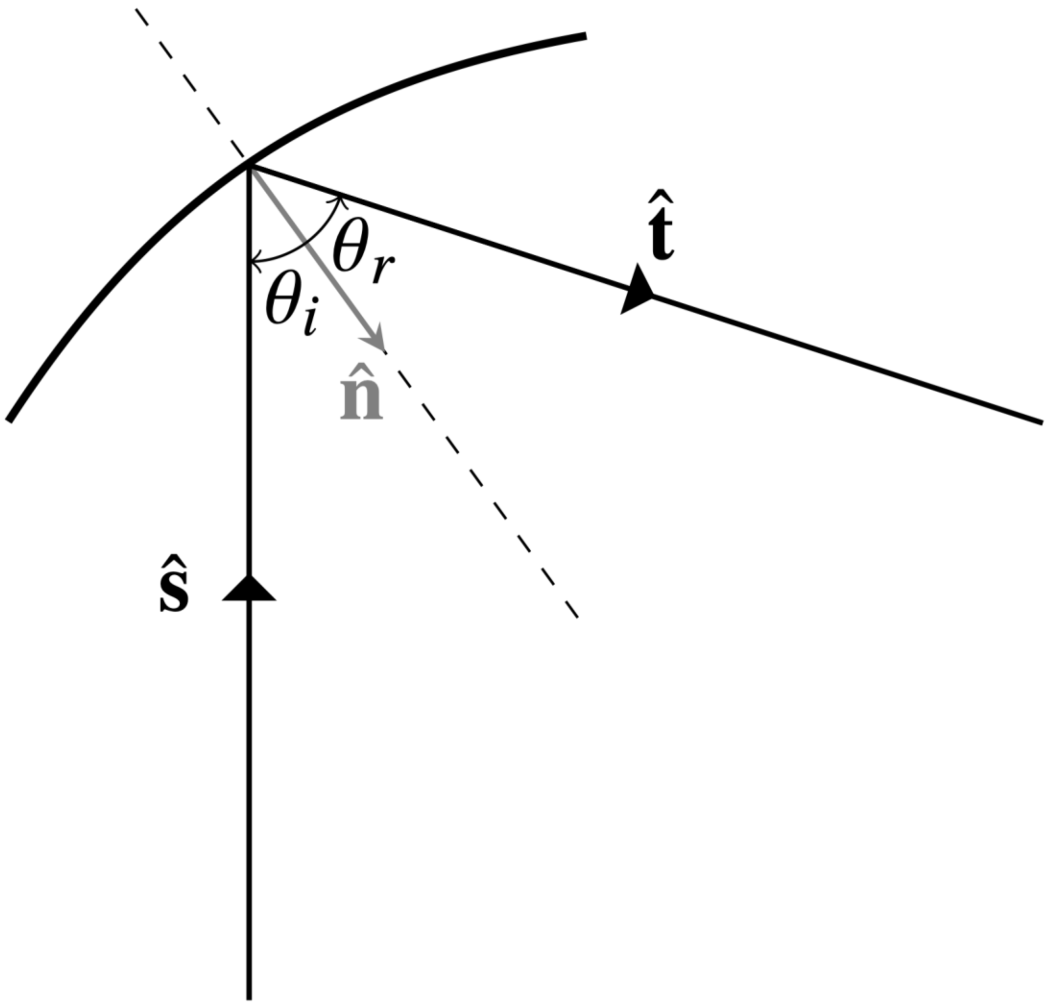


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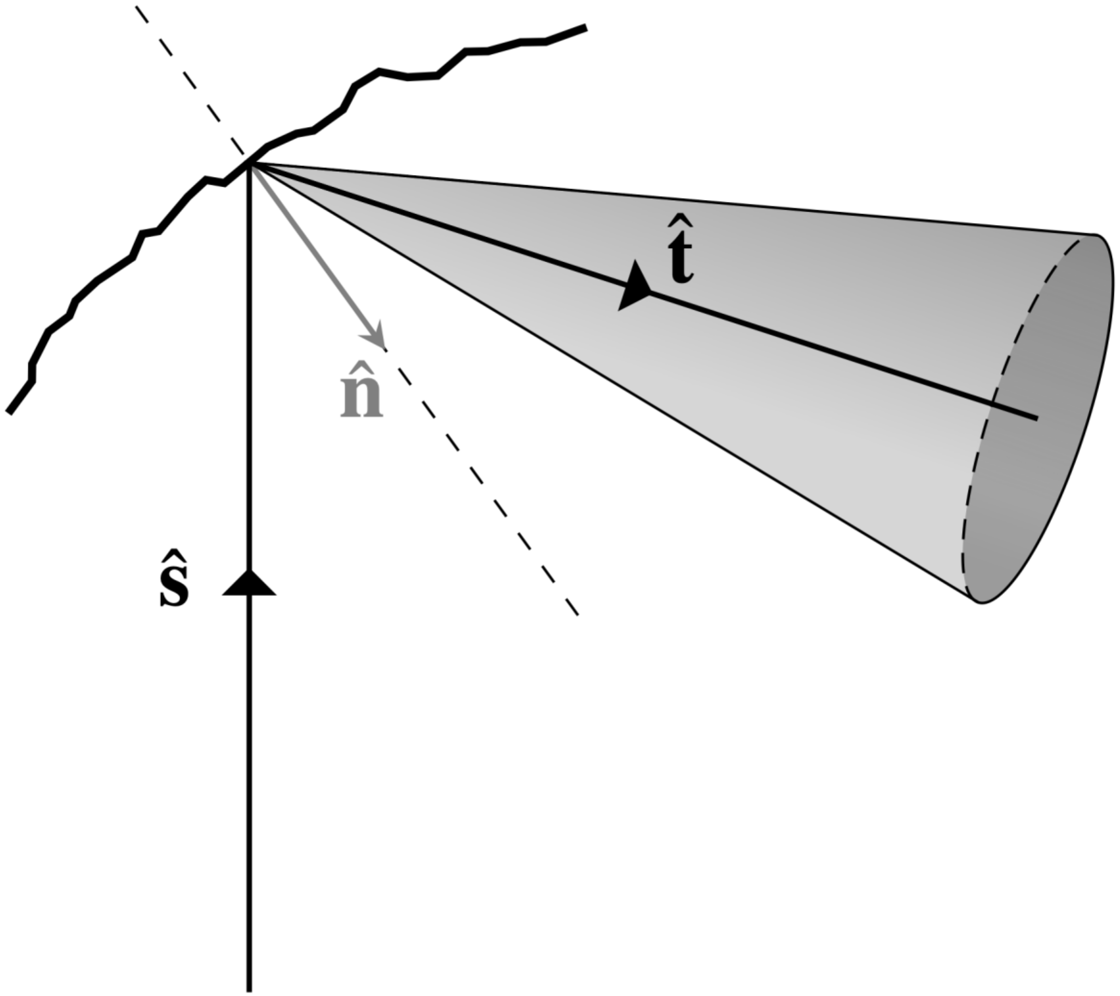


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- **Geometrical optics (GO):** ray formulation of light propagation.
- **Specular reflection:** mirror-like reflection where $\theta_i = \theta_r$.
- **Diffuse reflection / light scattering:** incident ray is scattered in multiple directions.

## Background

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- Contemporary design procedures generally use the **GO approximation**.
- **Result:** scattering effects are difficult to account for when solving the **inverse problem**.

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- **Result:** scattering effects are difficult to account for when solving the **inverse problem**.
- **Specular reflector design (inverse problem):**
  - Rotationally and cylindrically symmetric problems $\rightarrow$ two-dimensions $\rightarrow$ system of ODEs (Maes, Philips 1997).
  - General problems $\rightarrow$ Monge-Ampère equation (see presentation by Romijn from TU/e).

# Goal & Approach

# Freeform Scattering Optics

**Goal:** include diffuse reflection in the inverse problem of optical design.

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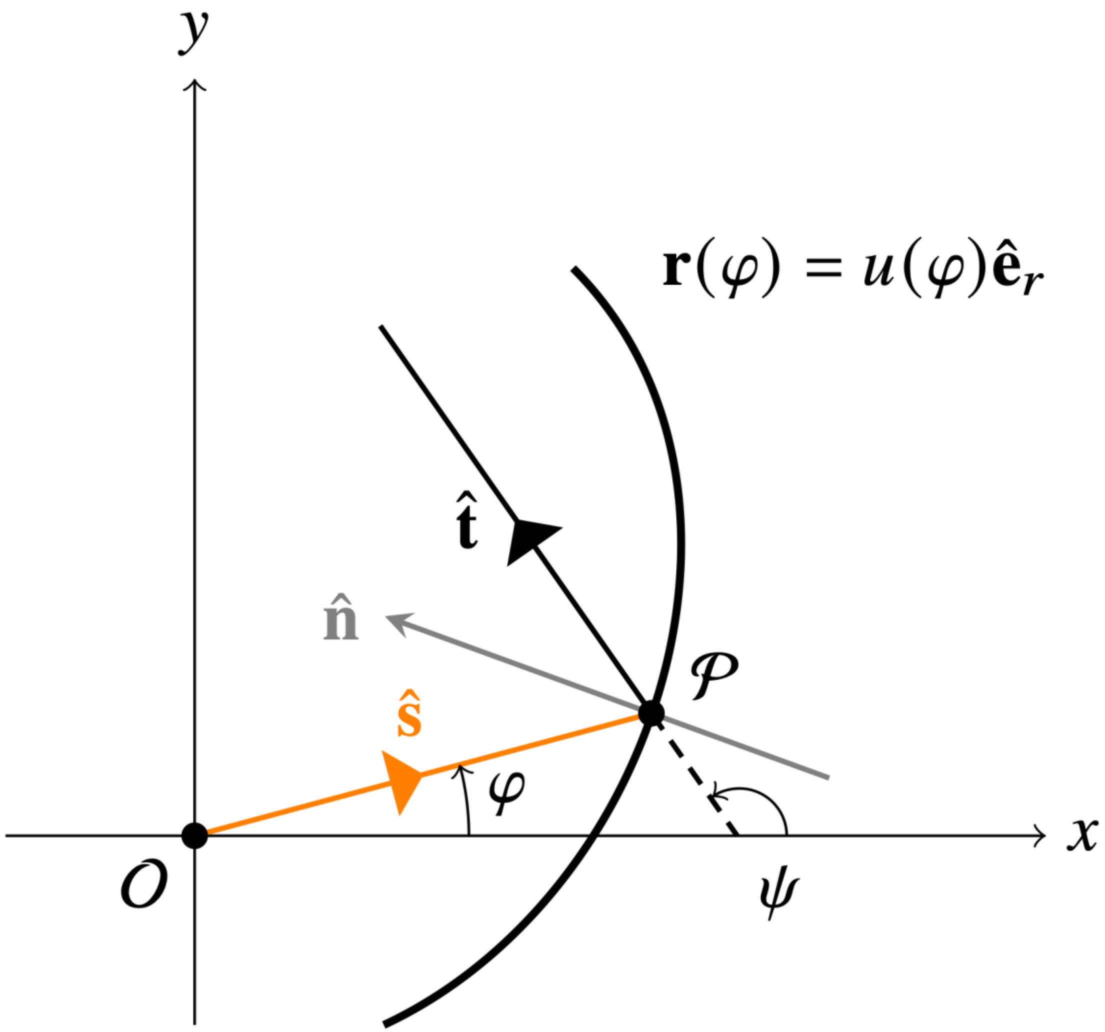
- **Chosen approach: Transform** the *diffuse target distribution* into an *"equivalent" specular distribution*, then solve the inverse problem.
- **Pillars of our approach:**
  - Energy conservation.
  - Specular map.
  - Scattering map.
  - Numerical deconvolution/unfolding.

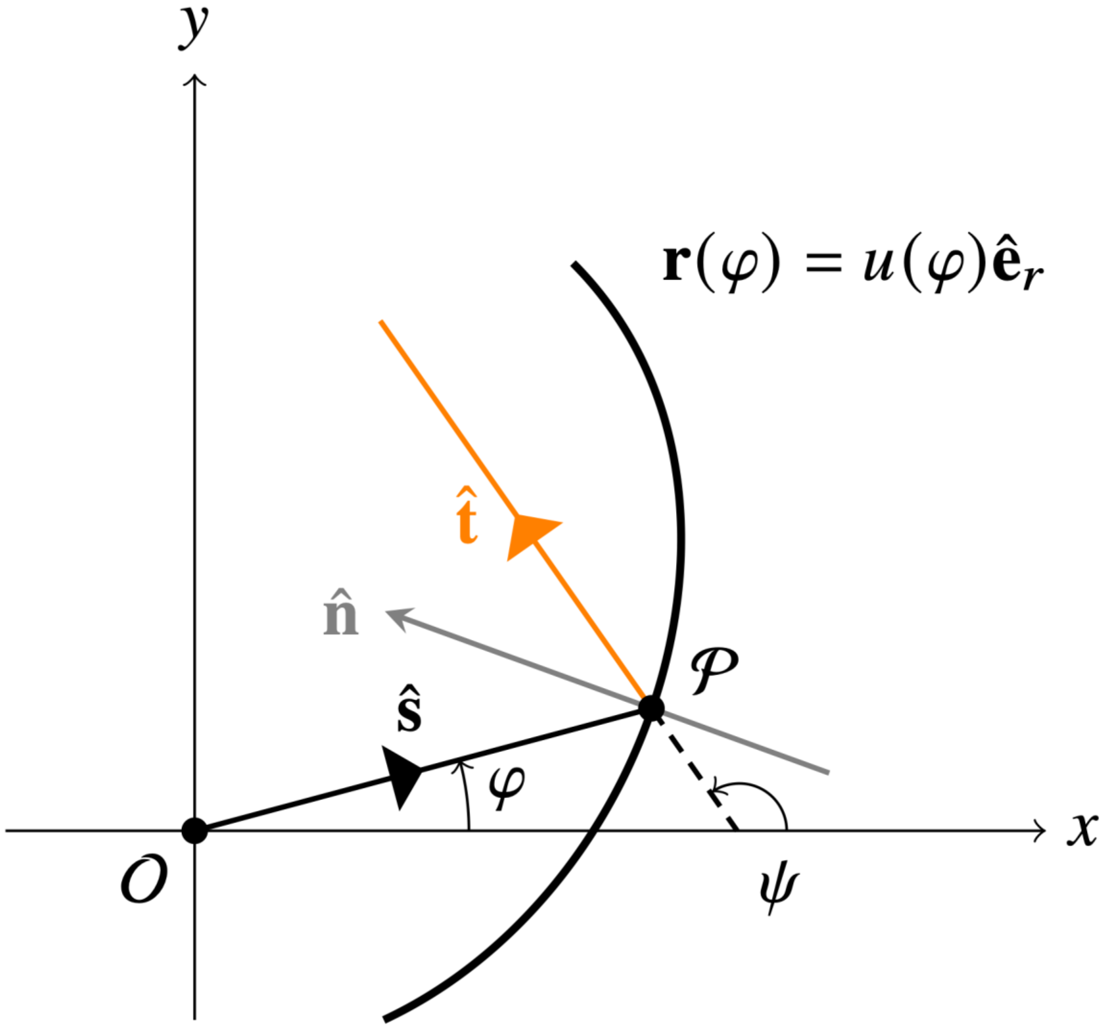
# Model Proposal

# Freeform Scattering Optics




- **Source ray:** $\hat{\mathbf{s}}(\varphi)$.

# Freeform Scattering Optics




- **Source ray:** $\hat{\mathbf{s}}(\varphi)$.
- **Specular ray:** $\hat{\mathbf{t}}(\psi)$.
  $\hat{\mathbf{t}} = \hat{\mathbf{s}} - 2(\hat{\mathbf{s}} \cdot \hat{\mathbf{n}})\hat{\mathbf{n}}$
- **Specular map:** $m(\varphi) = \psi$.

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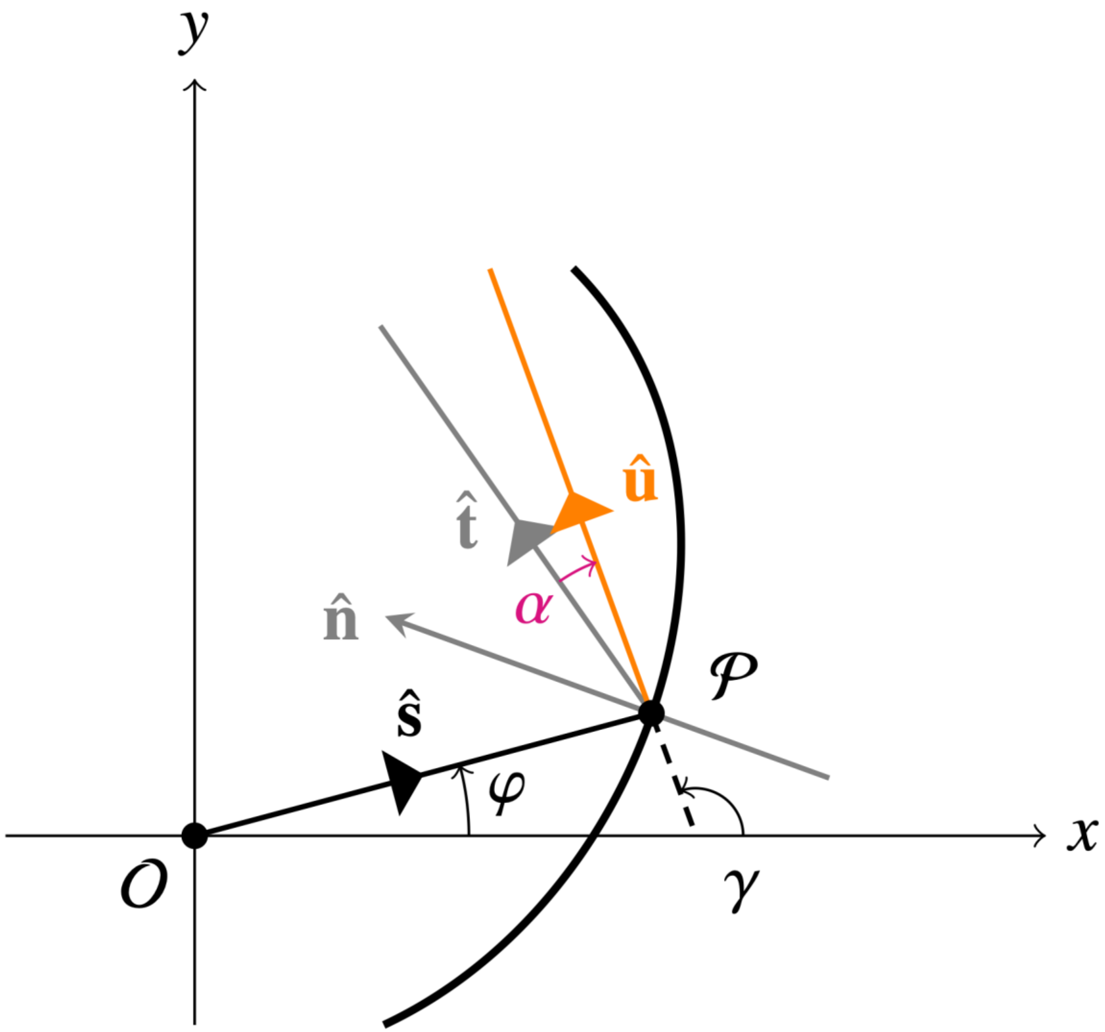


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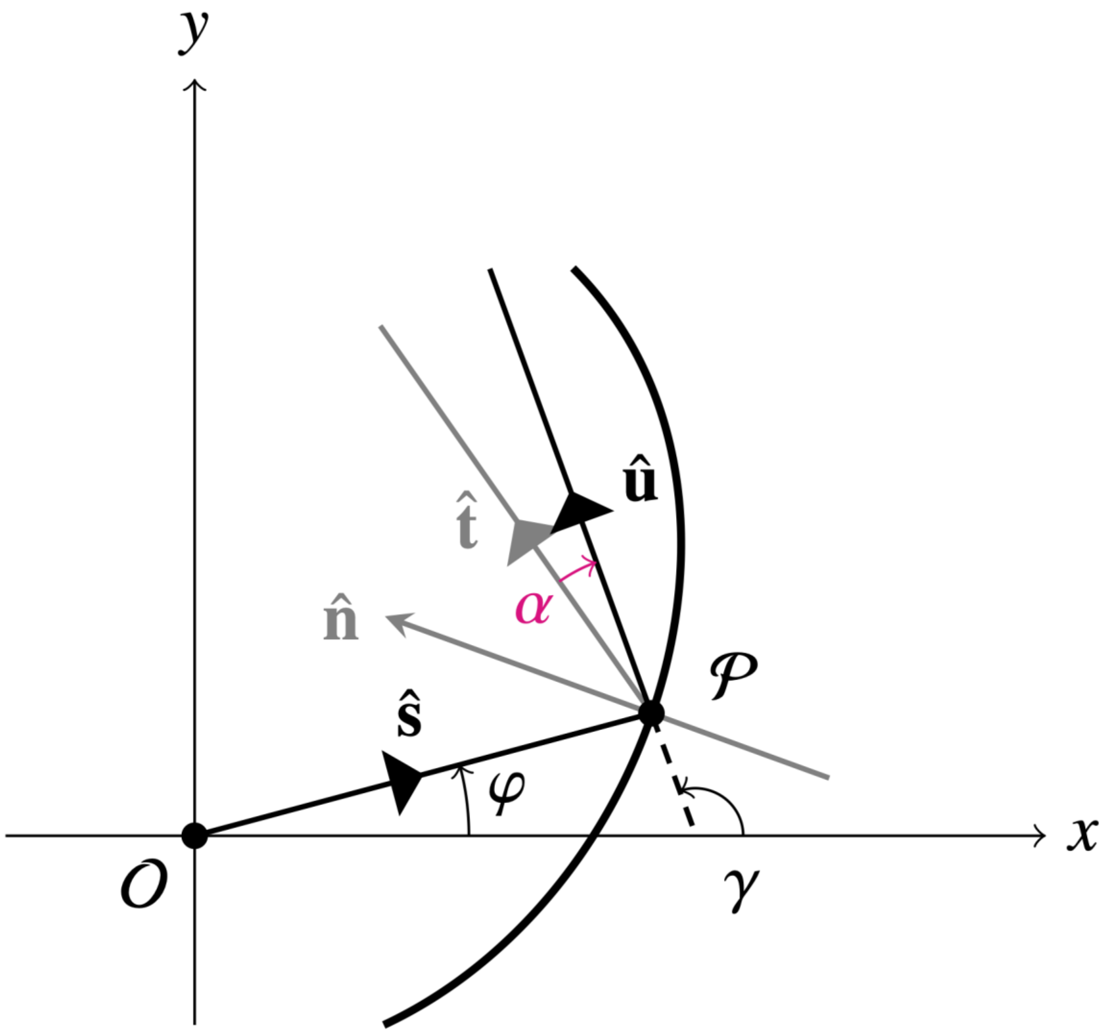
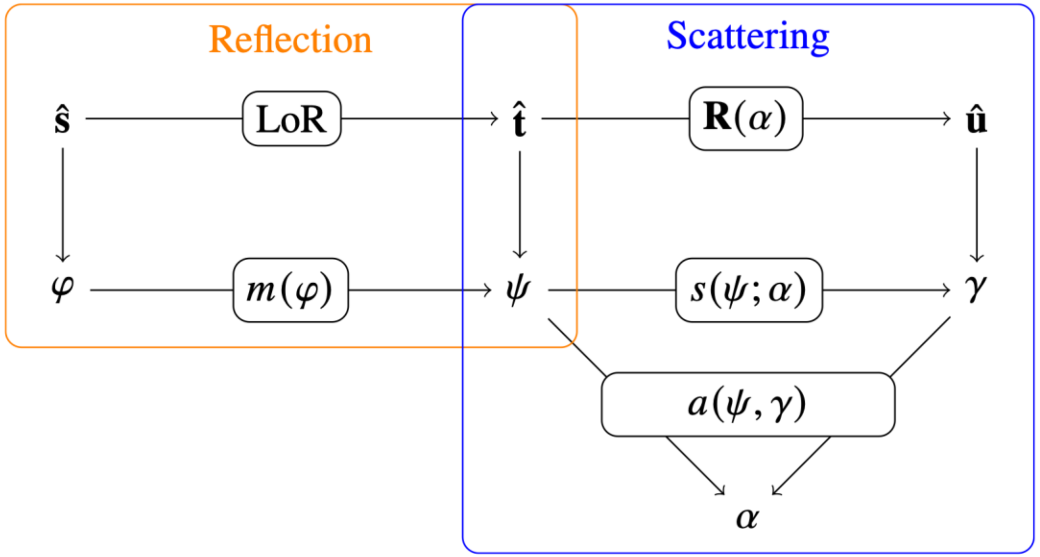
- **Specular map:** $m(\varphi) = \psi$.
- **Scattered ray:** $\hat{\mathbf{u}}(\gamma)$.
- **Scattering map:** $s(\psi; \alpha) = \gamma$.
  $\alpha$ is a **stochastic parameter**.

# Freeform Scattering Optics

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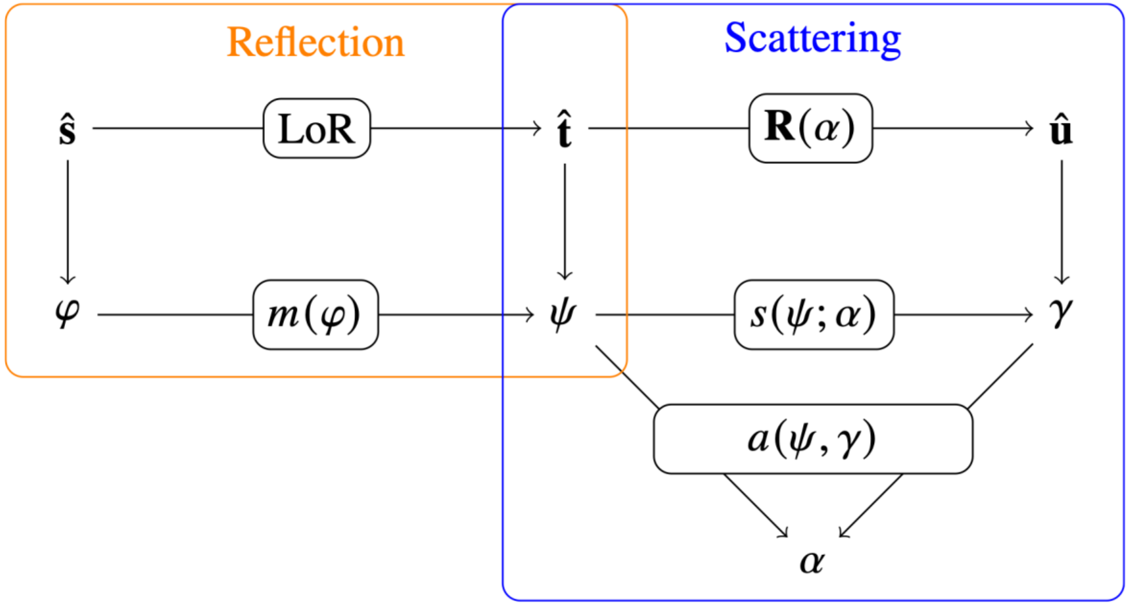
# Mappings

We shall consider the following mappings:

$$\begin{aligned} s(\psi;\alpha) &= \psi + \alpha \equiv \gamma, \\ s^{-1}(\gamma;\alpha) &= \gamma - \alpha \equiv \psi, \\ a(\psi,\gamma) &= \gamma - \psi \equiv \alpha. \end{aligned}$$



## Energy Balances

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- **Intensity distributions [lm/rad]:**
  - $f(\varphi) > 0$, $\varphi \in [\varphi_1, \varphi_2]$ source
  - $g(\psi) > 0$, $\psi \in [\psi_1, \psi_2]$ specular target
  - $h(\gamma) > 0$, $\gamma \in [\gamma_1, \gamma_2]$ diffuse target

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- **Energy balances:**

$$\int_{\varphi_1}^{\varphi_2} f(\varphi)\,\mathrm{d}\varphi = \int_{\psi_1}^{\psi_2} g(\psi)\,\mathrm{d}\psi = \int_{\gamma_1}^{\gamma_2} h(\gamma)\,\mathrm{d}\gamma.$$

# Density

# Freeform Scattering Optics

- This concept is inspired by optimal mass transportation.
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# Freeform Scattering Optics

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  "What is the best way to move a pile of sand from A to B?"
- **Introduce density:**

$$\rho(\psi,\gamma) \geq 0,\ \psi \in [\psi_1,\psi_2],\ \gamma \in [\gamma_1,\gamma_2],$$

such that

$$\int_{\psi_1}^{\psi_2} \rho(\psi,\gamma)\,\mathrm{d}\psi = h(\gamma) \quad \text{and} \quad \int_{\gamma_1}^{\gamma_2} \rho(\psi,\gamma)\,\mathrm{d}\gamma = g(\psi).$$

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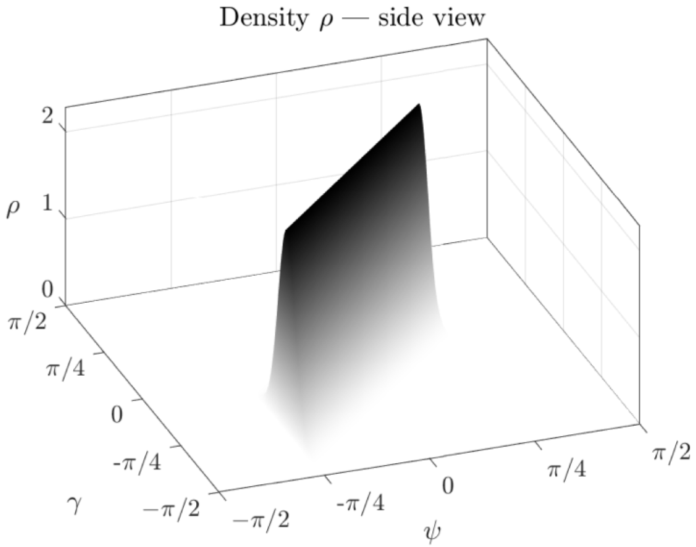
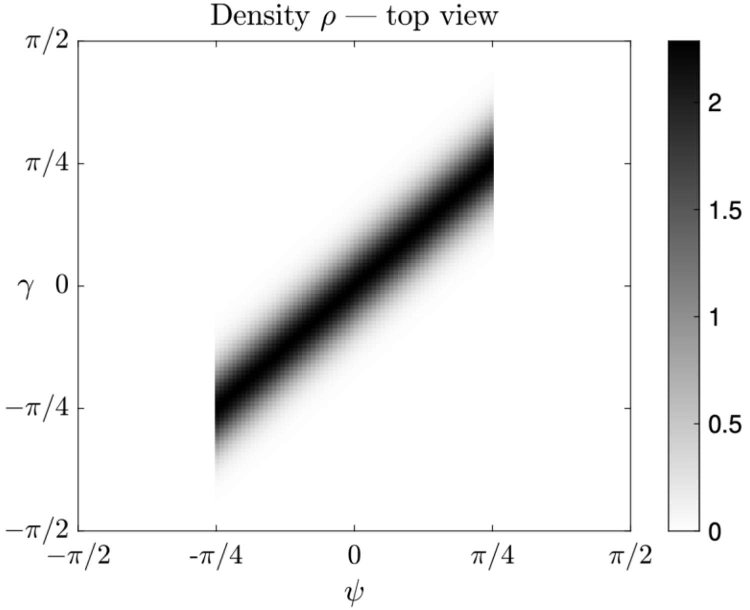
- We choose (isotropic scattering): $\rho(\psi,\gamma) = p\big(a(\psi,\gamma)\big)g(\psi) = p(\gamma-\psi)g(\psi)$.



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- Insertion into relation for $h$ yields (**convolution**):

$$h(\gamma) = \int_{\psi_1}^{\psi_2} p(\gamma-\psi)g(\psi)\,\mathrm{d}\psi.$$

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$$h(\gamma) = \int_{\psi_1}^{\psi_2} p(\gamma-\psi)g(\psi)\,\mathrm{d}\psi.$$

- Transforming $\psi$ to $\alpha$ yields:

$$h(\gamma) = \int_{\alpha_1}^{\alpha_2} p(\alpha)g(\gamma-\alpha)\,\mathrm{d}\alpha.$$

# Algorithm

# Freeform Scattering Optics

**Given:**

- **Source intensity distribution** $f(\varphi)$.
- **Diffuse target distribution** $h(\gamma)$.
- **Scattering probability density function** $p(\alpha)$.

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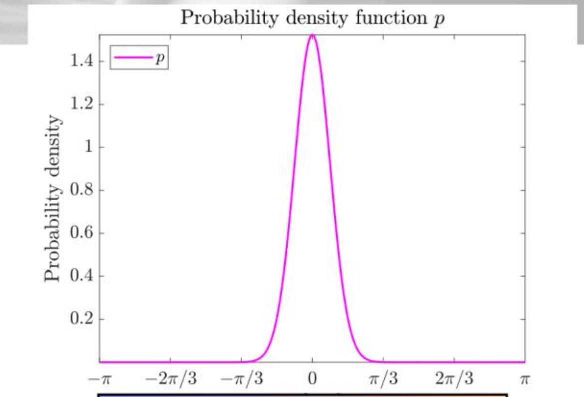
**Algorithm:**

1. **Solve** for the *intermediate specular target distribution* $g(\psi)$ by **deconvolving**

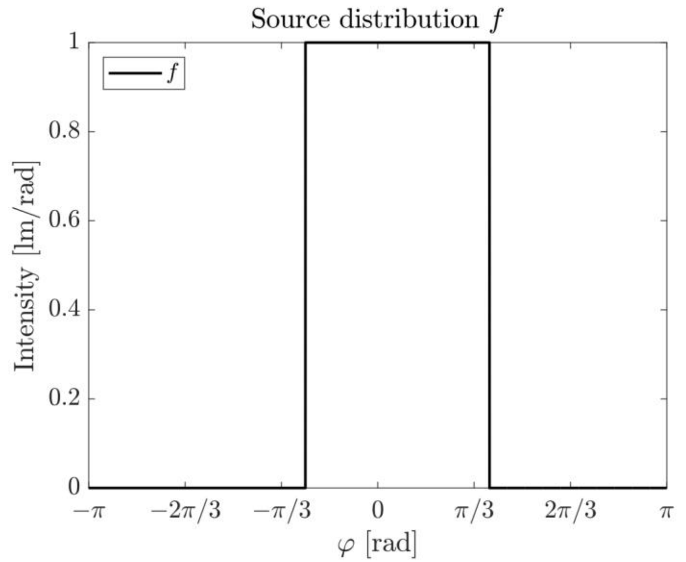
$$h(\gamma) = \int_{\alpha_1}^{\alpha_2} p(\alpha) g(\gamma - \alpha)\, \mathrm{d}\alpha.$$

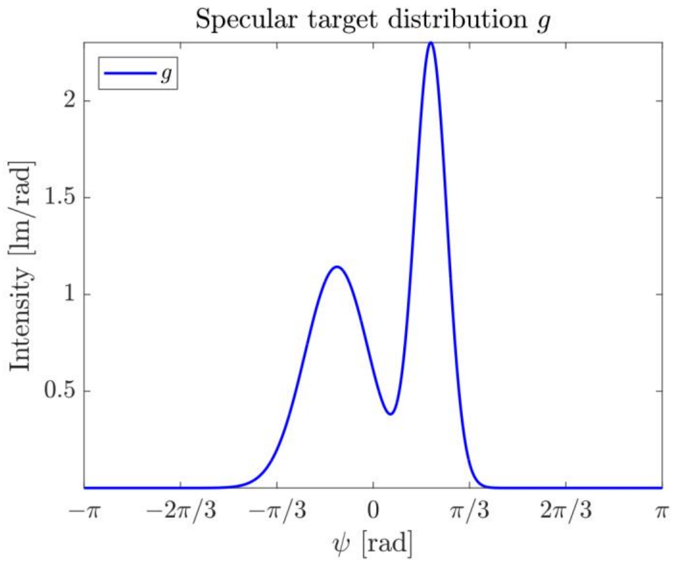
2. **Compute** the **reflector surface** in the form of a *specular design problem* with $f(\varphi)$ and $g(\psi)$.

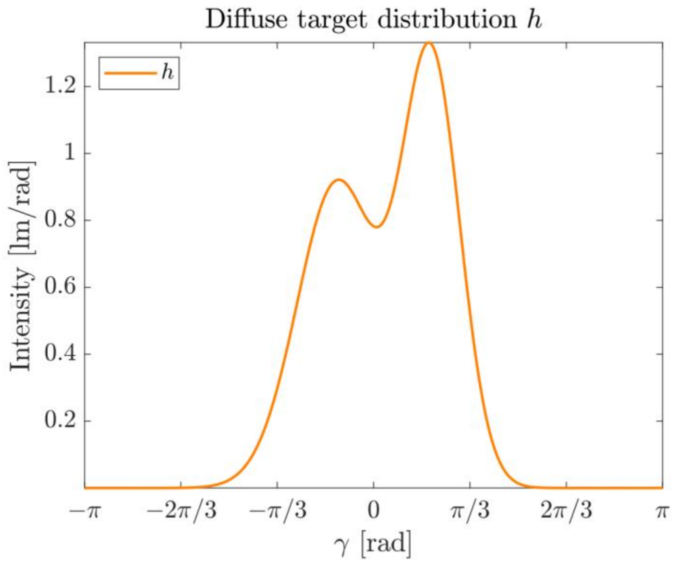
## Proof-of-Concept




Deconvolution



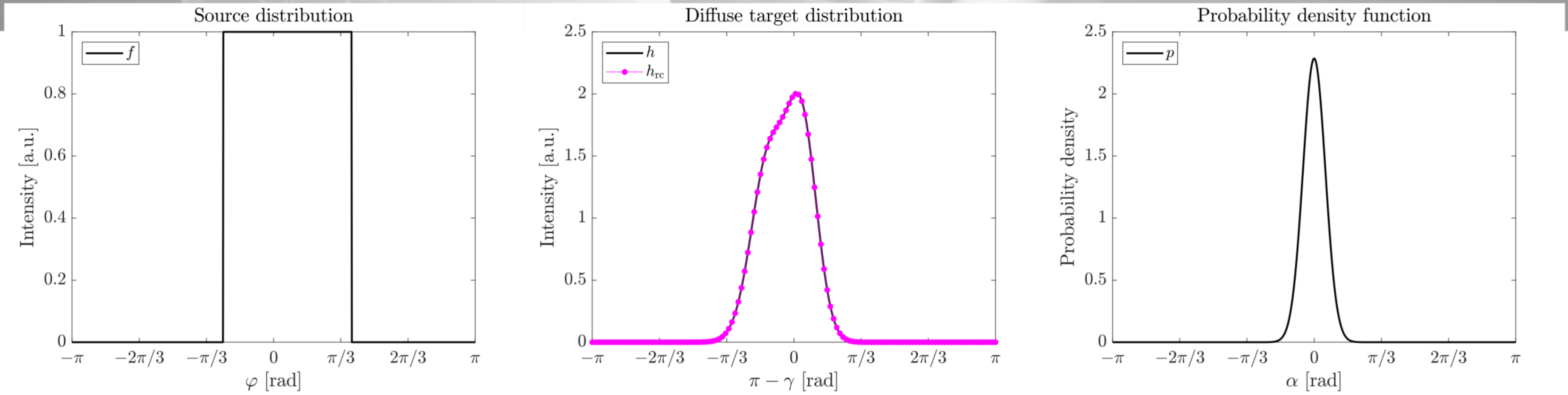



**Example**

WP-C1

# Freeform Scattering Optics



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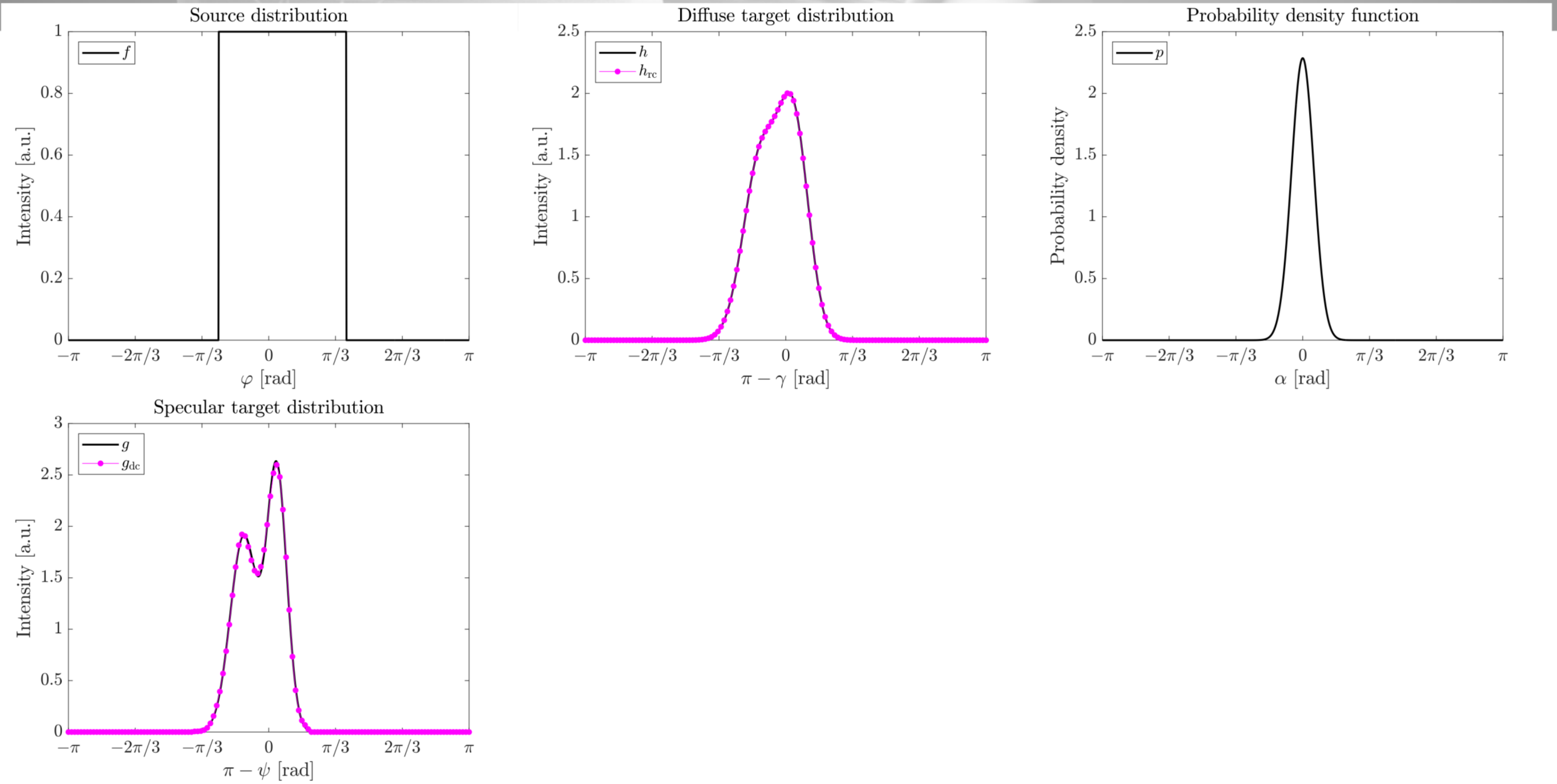

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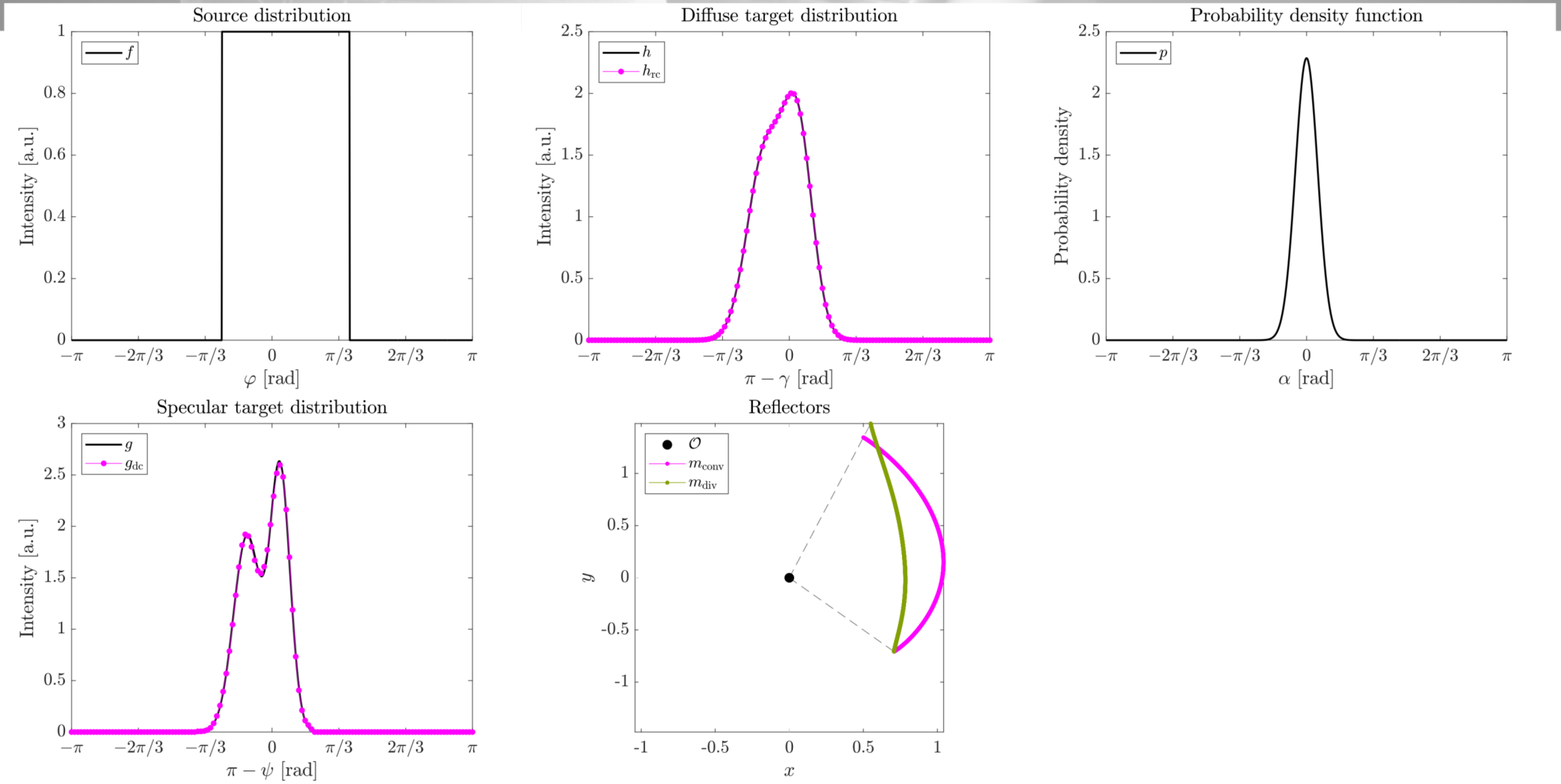

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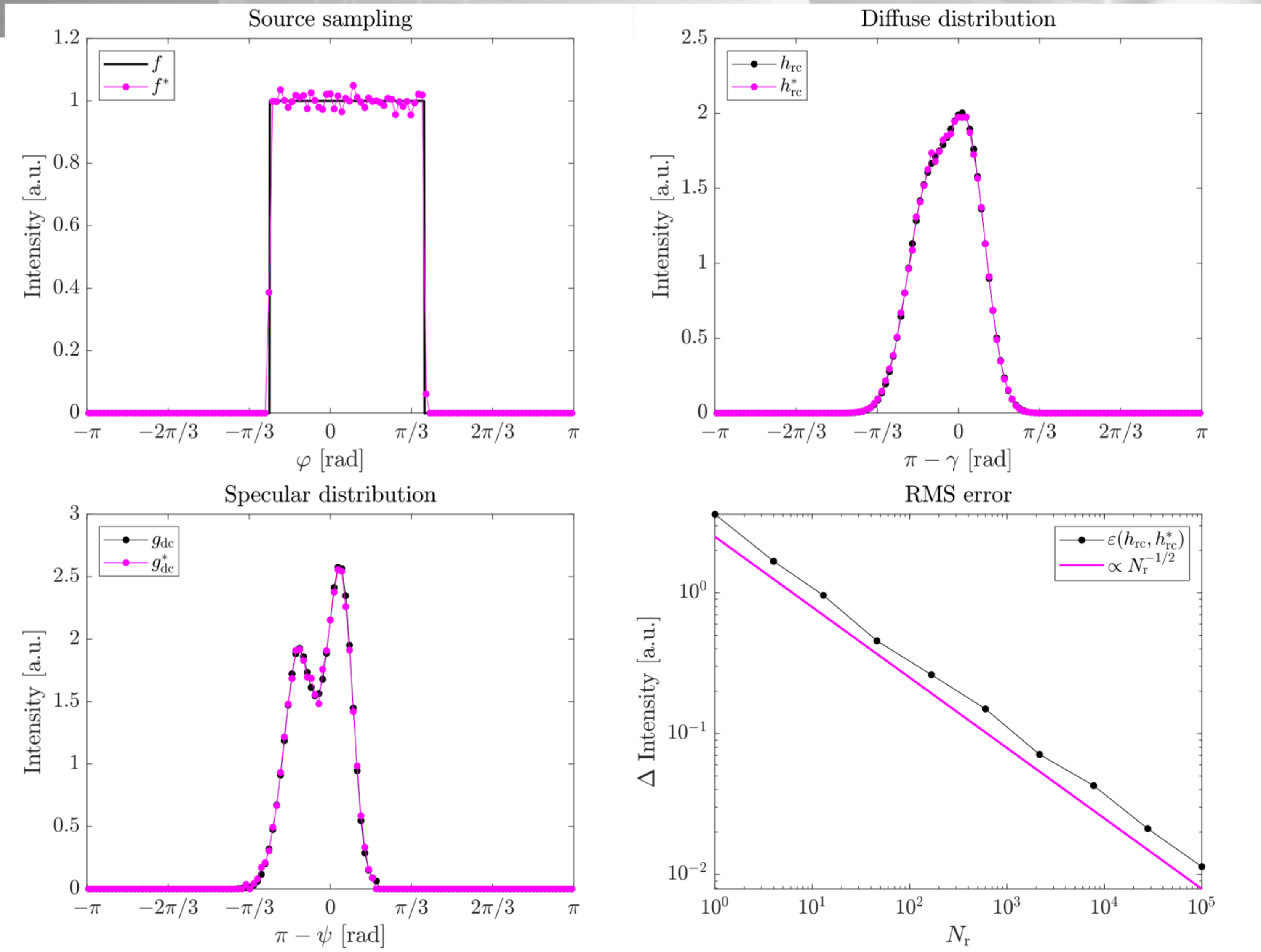

# Conclusion

WP-C1

# Freeform Scattering Optics

- **Novel modelling approach for scattering**
  - Convolution integral between a scattering function and a specular distribution.

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- **Advantage of our approach:** Possibility of harnessing the powerful specular design methods when solving diffuse problems.

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**Outlook:**

- Relation to bidirectional reflectance distribution function (BRDF).
- Extension to three-dimensional freeform surfaces.

# Symmetric disordered scattering media

**Team**

**Sudhir Saini**

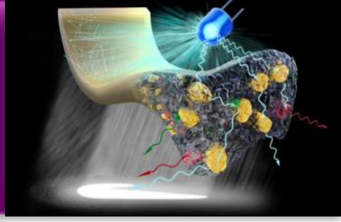
**Kayleigh Start**

**Pepijn Pinkse**

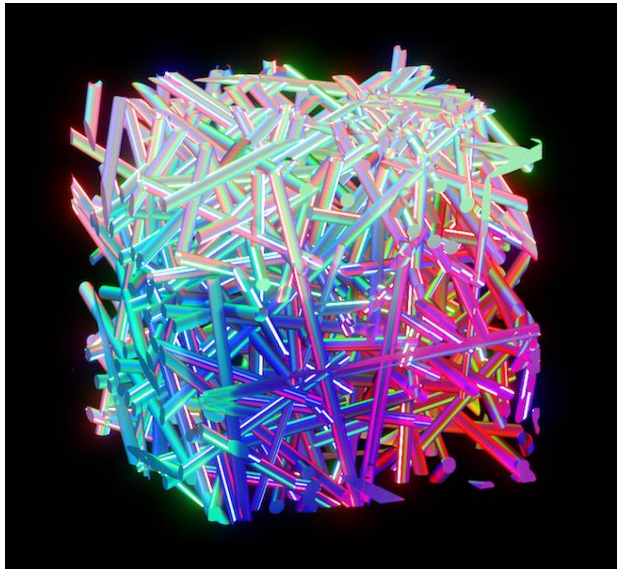
ADAPTIVE QUANTUM OPTICS

MESA+ INSTITUTE FOR NANOTECHNOLOGY

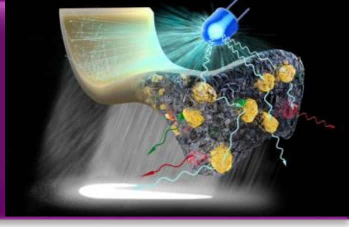
# Outline

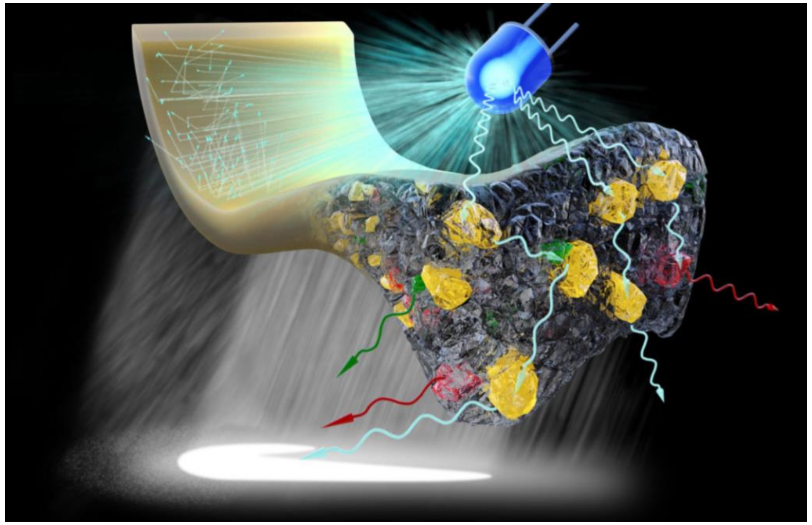


1. **Multiple scattering**
2. **Motivation**
3. **Deterministic Scattering Media**
4. **Symmetry and randomness**
5. **Applications and Outlook**

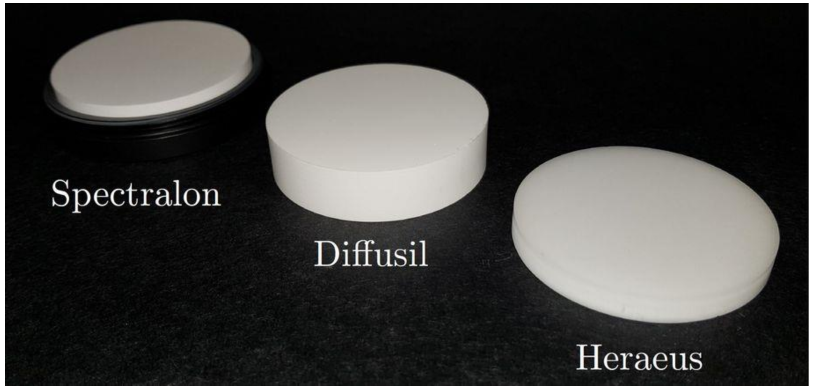


# Multiple scattering

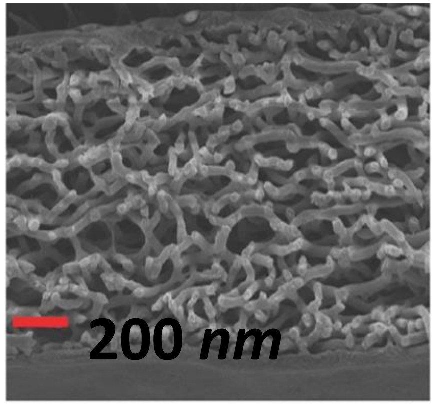


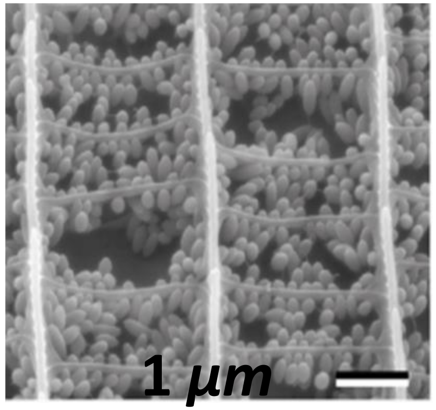


LED



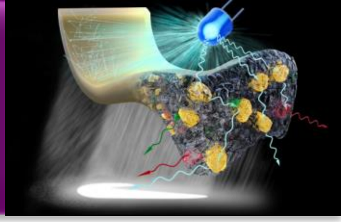

Diffusers slabs



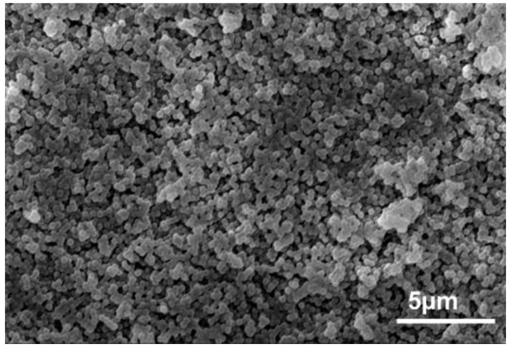




B. D. Wilts, et al. Adv.Opt. Mat. 5, 1600879 (2017)
M. Burresi, et al. Sci. Rep. **4**, 6075 (2014).

# Motivation

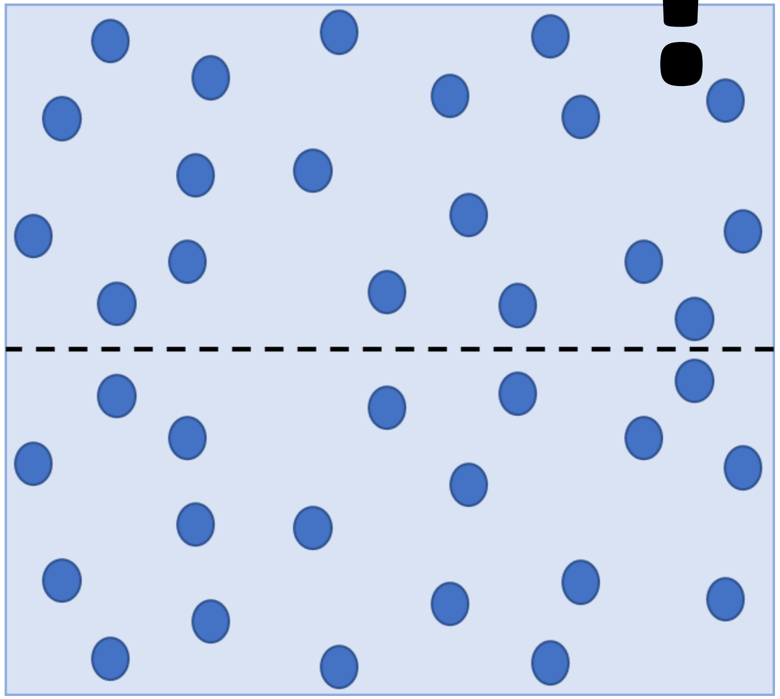


## Random $TiO_2$

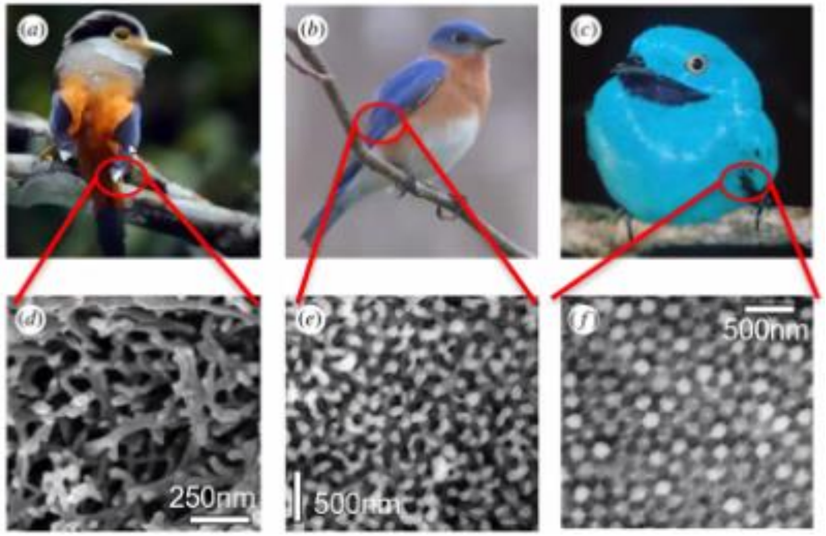


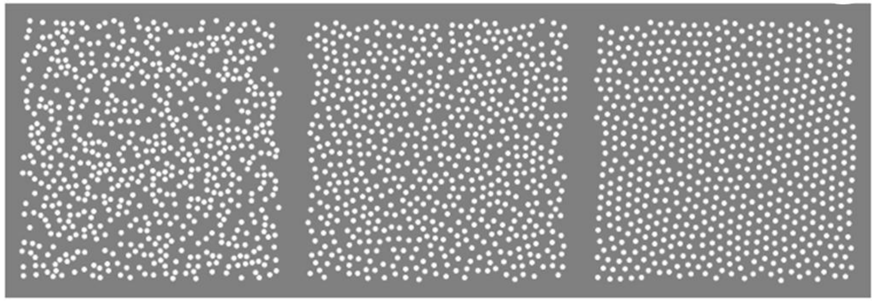

- Optimize scattering length scale ($l_s$ and $l_t$) ?
  - ✓ Fill fraction.
  - ✓ Refractive index contrast.
- Directional scattering control ?

**Symmetry ?**



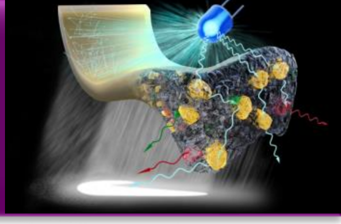
## Correlated disorder



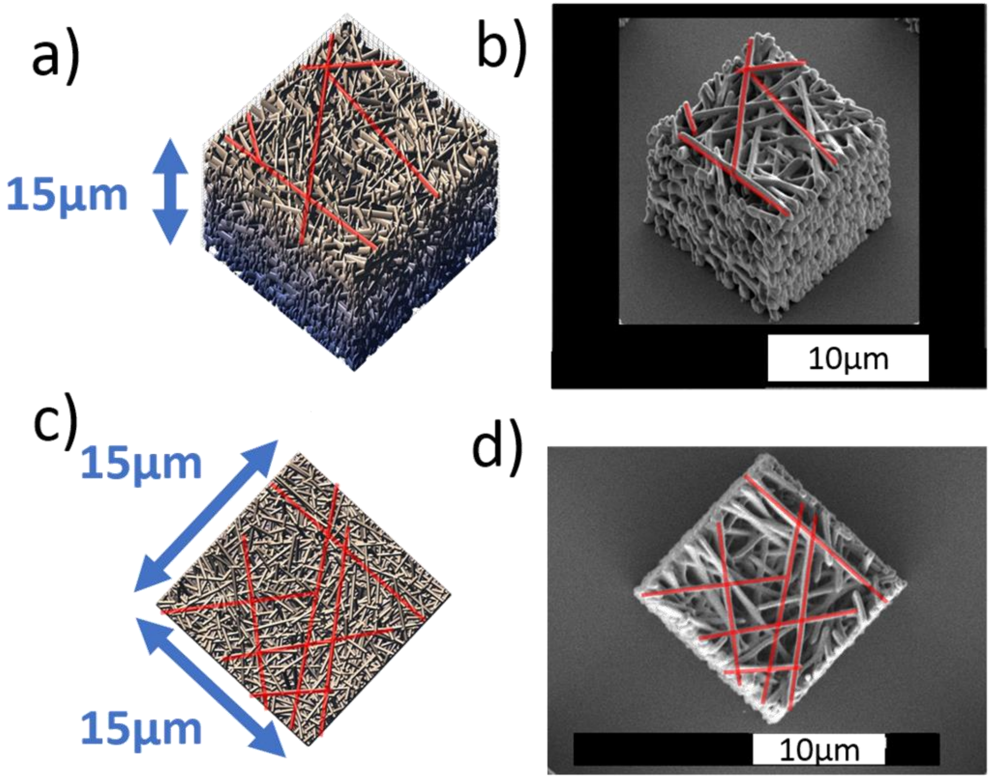



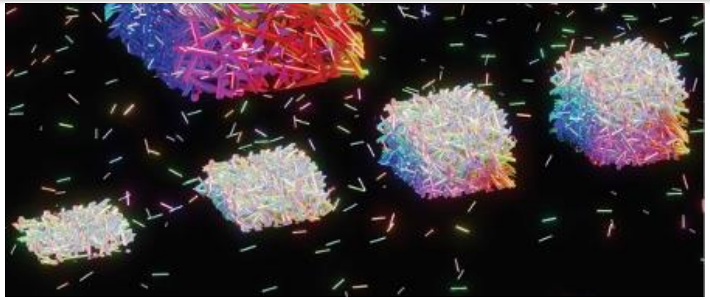
G. M. Conley, et al, *Phys. Rev. Lett.* **112**, 143901 (2014) S. F. Liew et al, Opt. Exp. 19, 8208-8217 (2011).
G. Jacucci et al, Proc. Natl. Acad. Sci. 117, 23345 (2020).

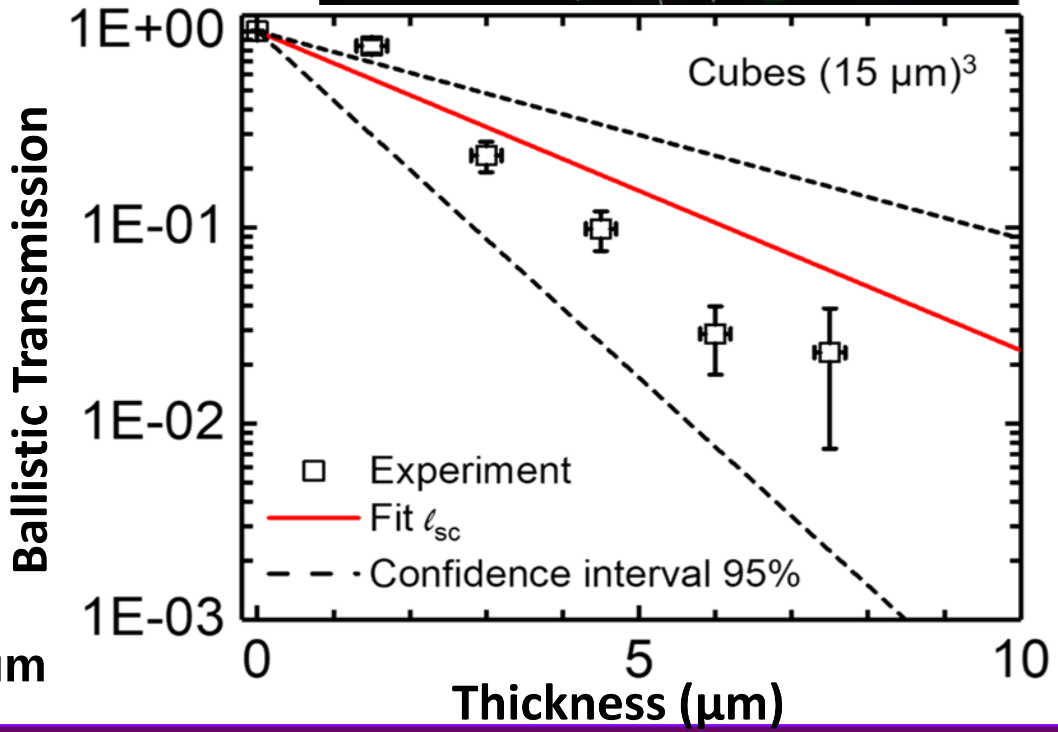
# Deterministic disordered media



## Direct laser writing



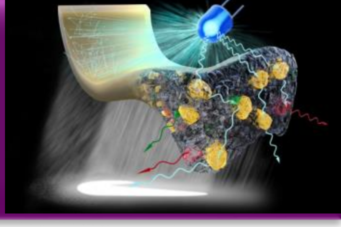





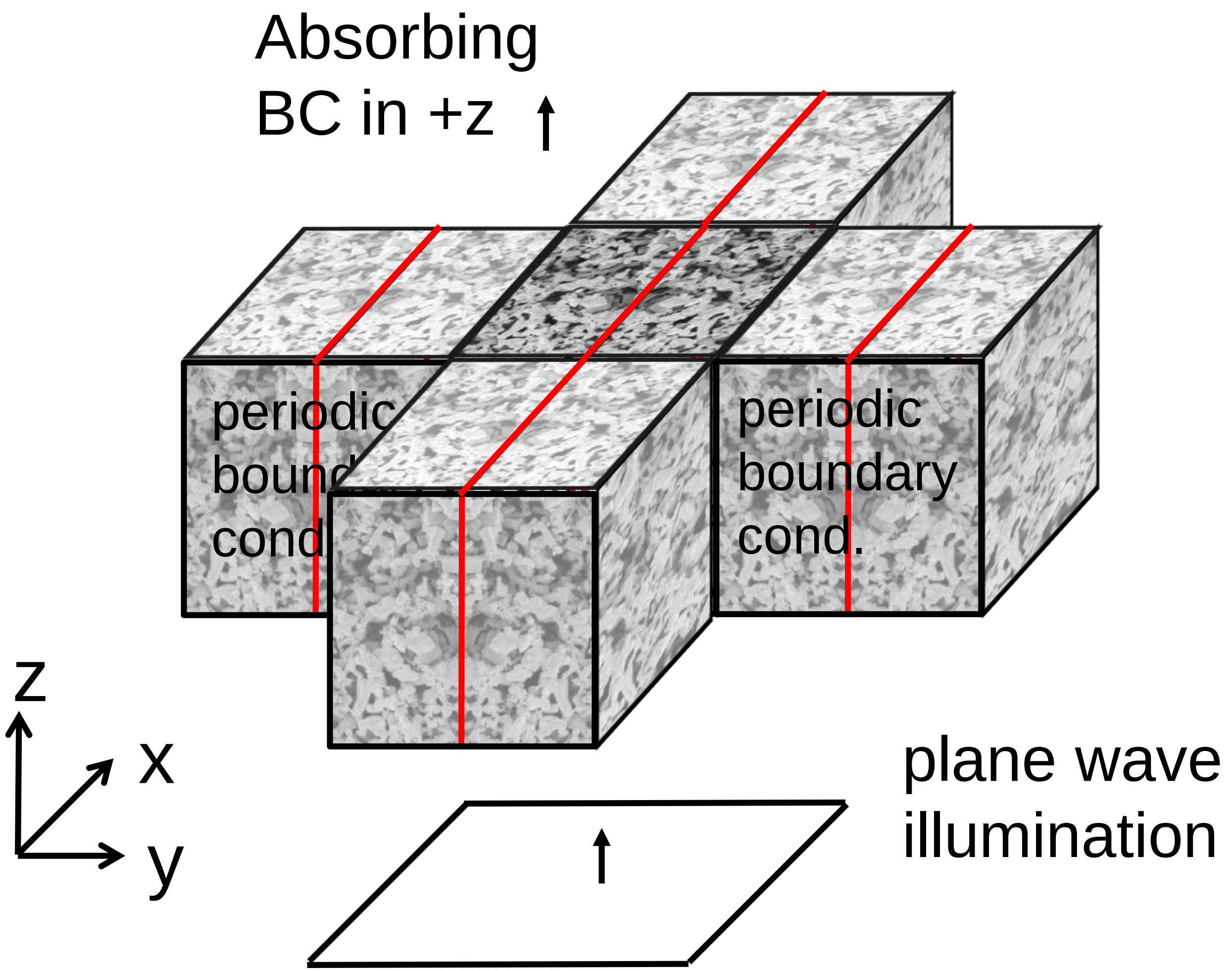

- $l_{sc}$=2.6±1.5µm

*Deterministic and controllable photonic scattering media via direct laser writing*,
Marakis, Uppu, Meretska, Gorter, Vos & Pinkse, Adv. Opt. Mat. 2020, 2001438 (2020).

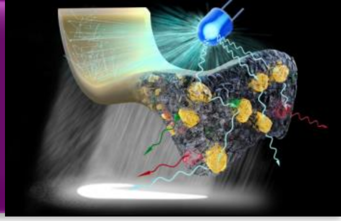
# Symmetry & Randomness

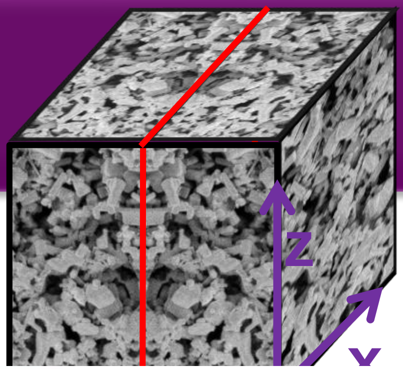


- Point scatterers.
- Symmetry along y direction.
- Illuminated in positive z-direction.
- Should work with white light!

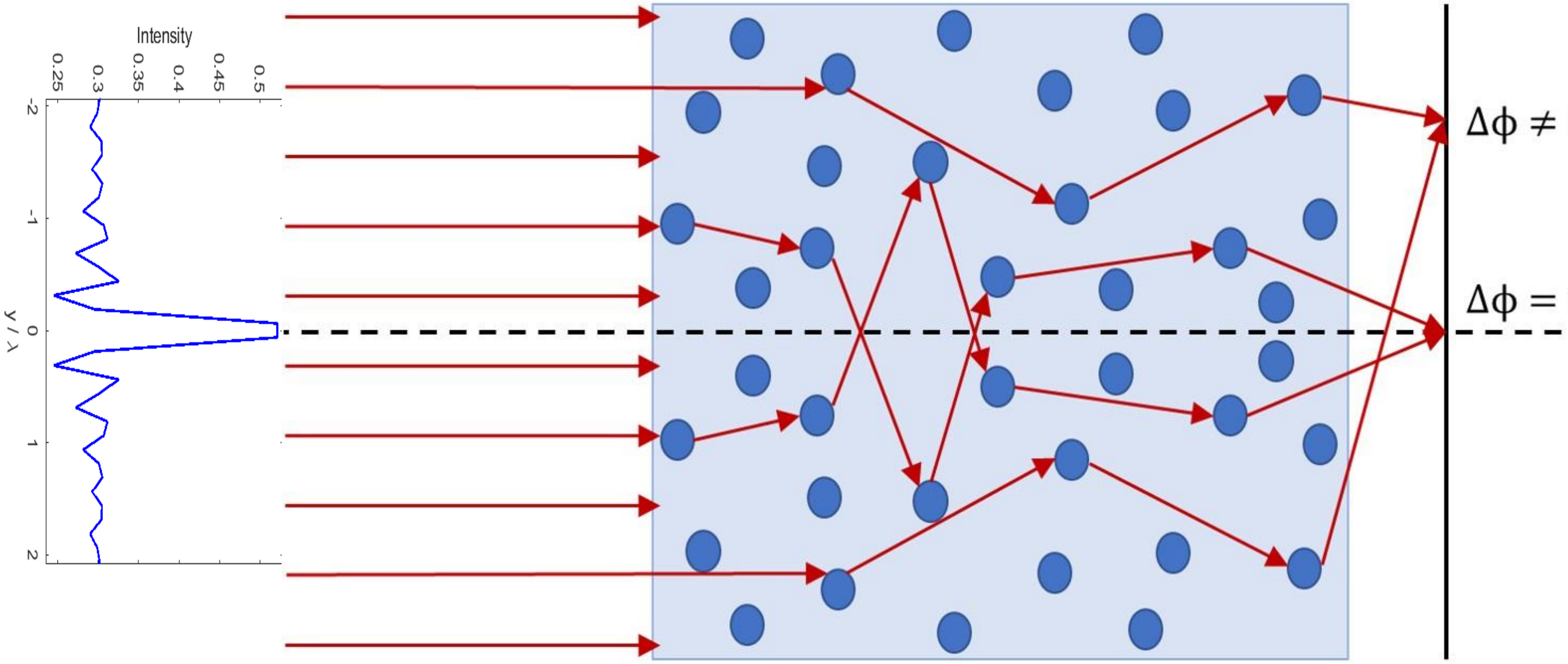


# Intensity profile

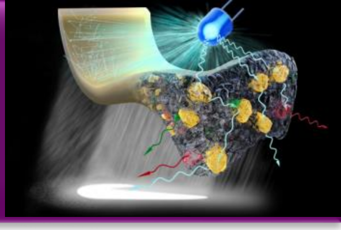


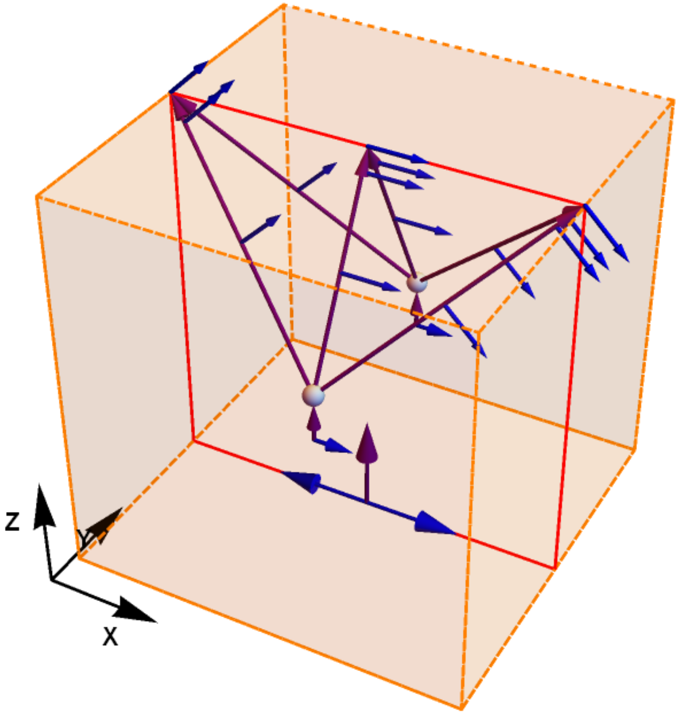


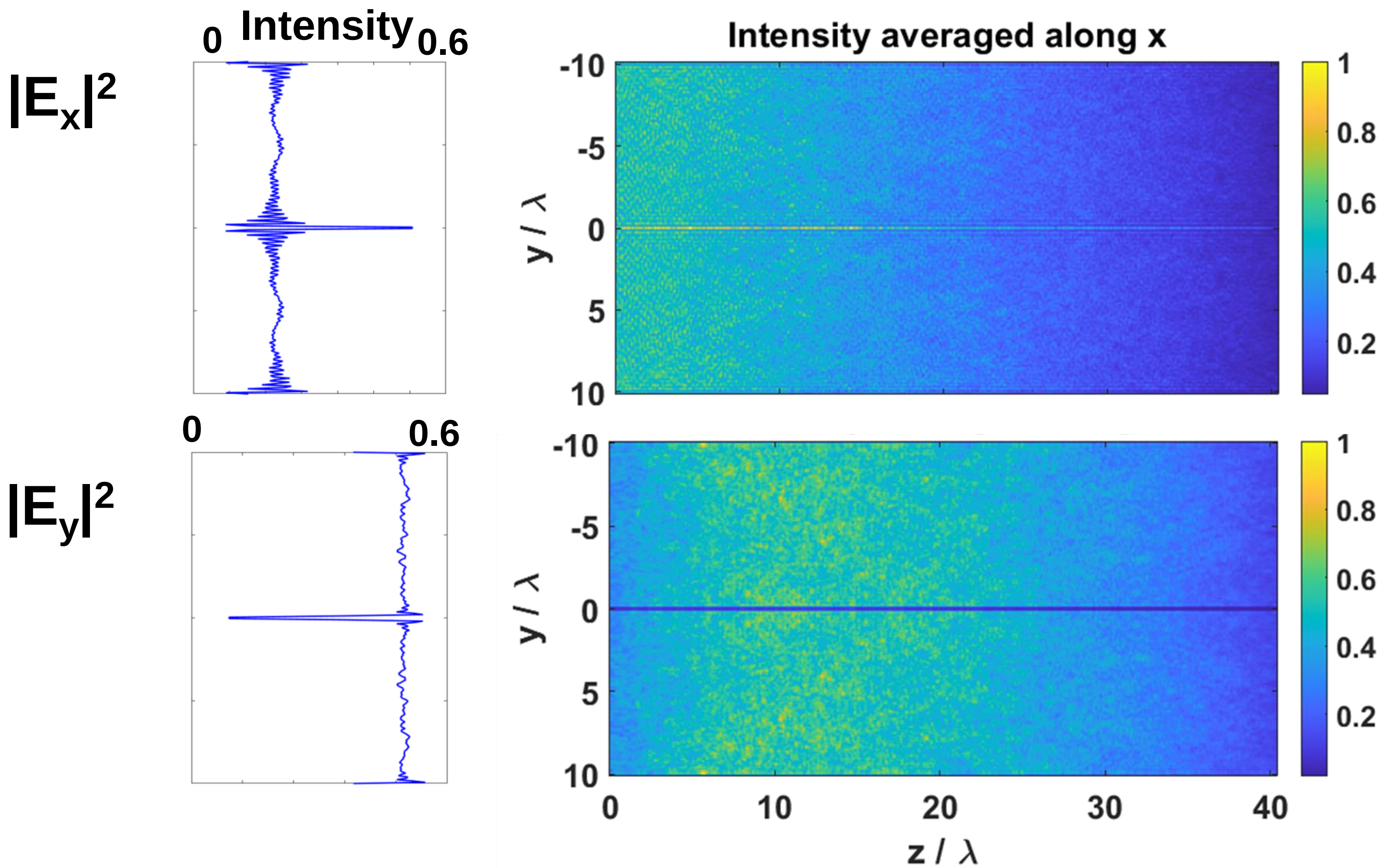

Polarization?



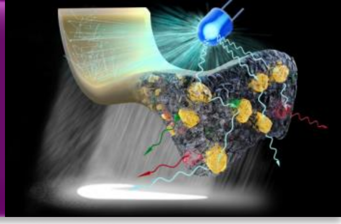
# Input polarization in x-direction

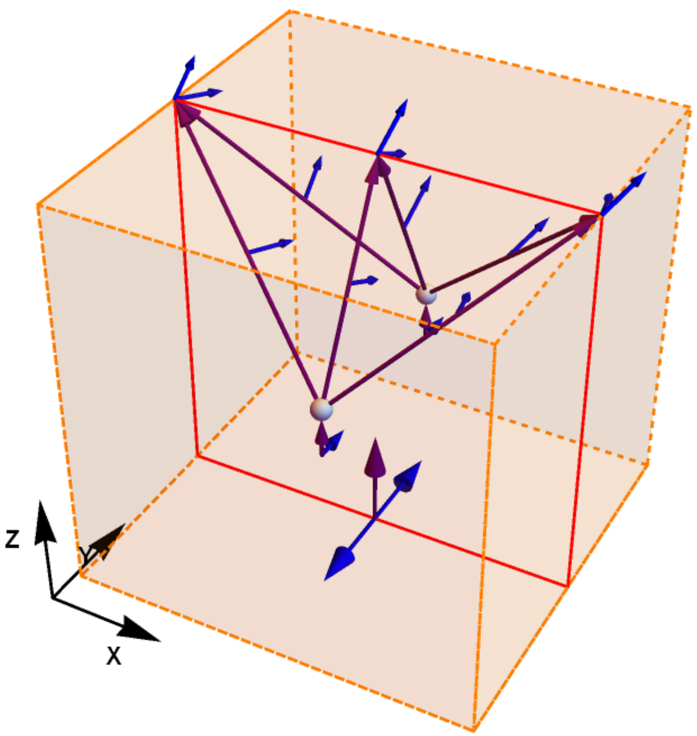




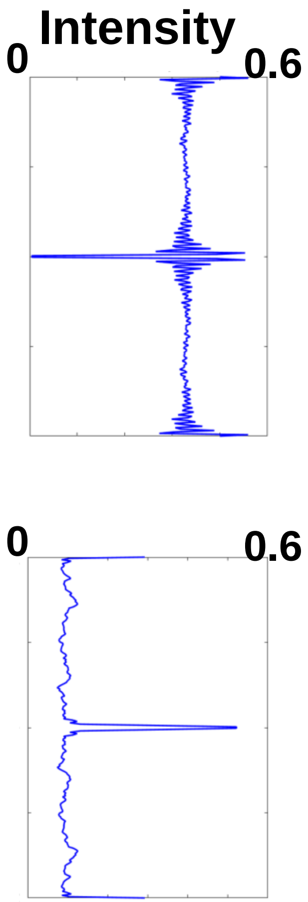
# Input polarization in y-direction

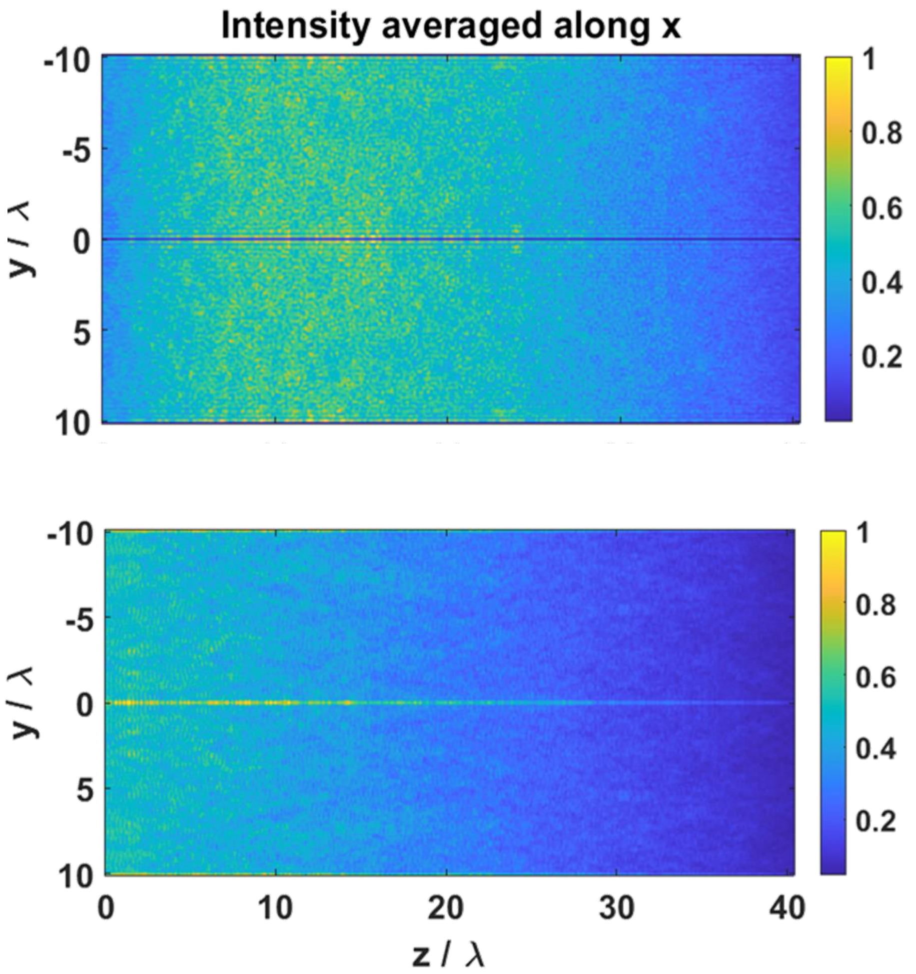




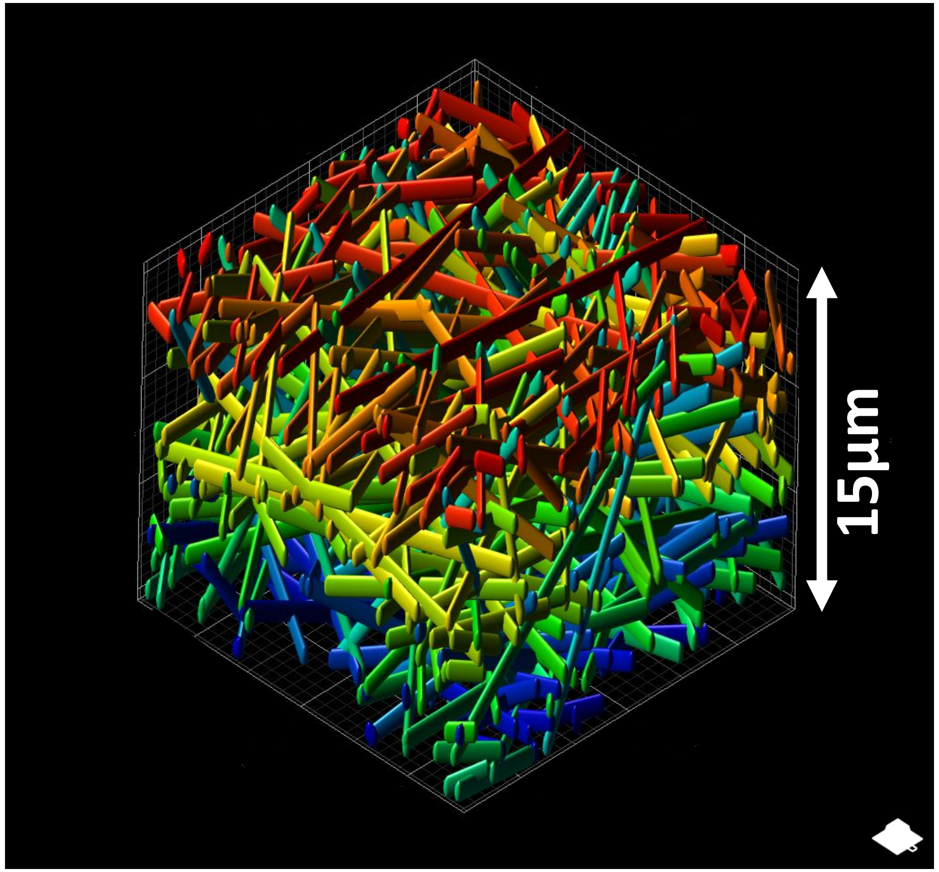

$|E_x|^2$

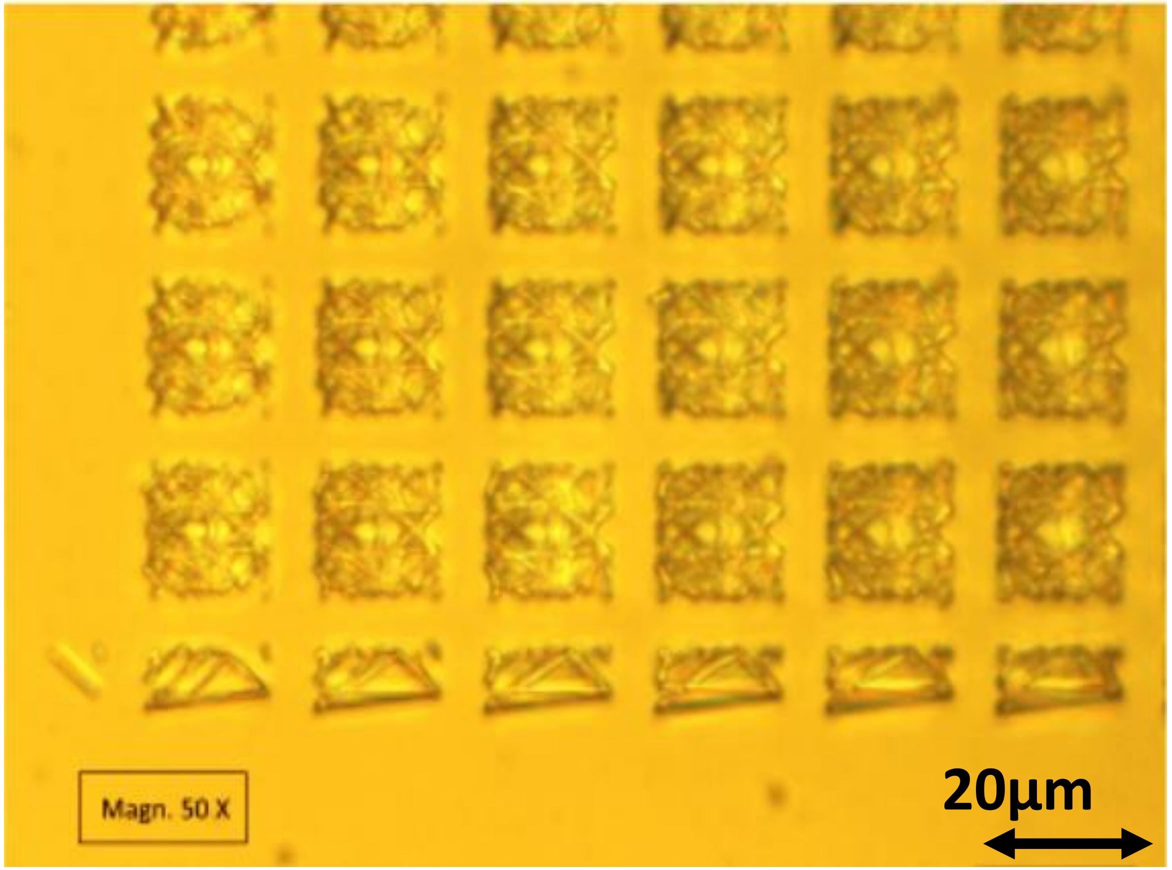
$|E_y|^2$



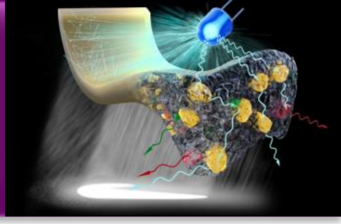



# Nanoscribe samples

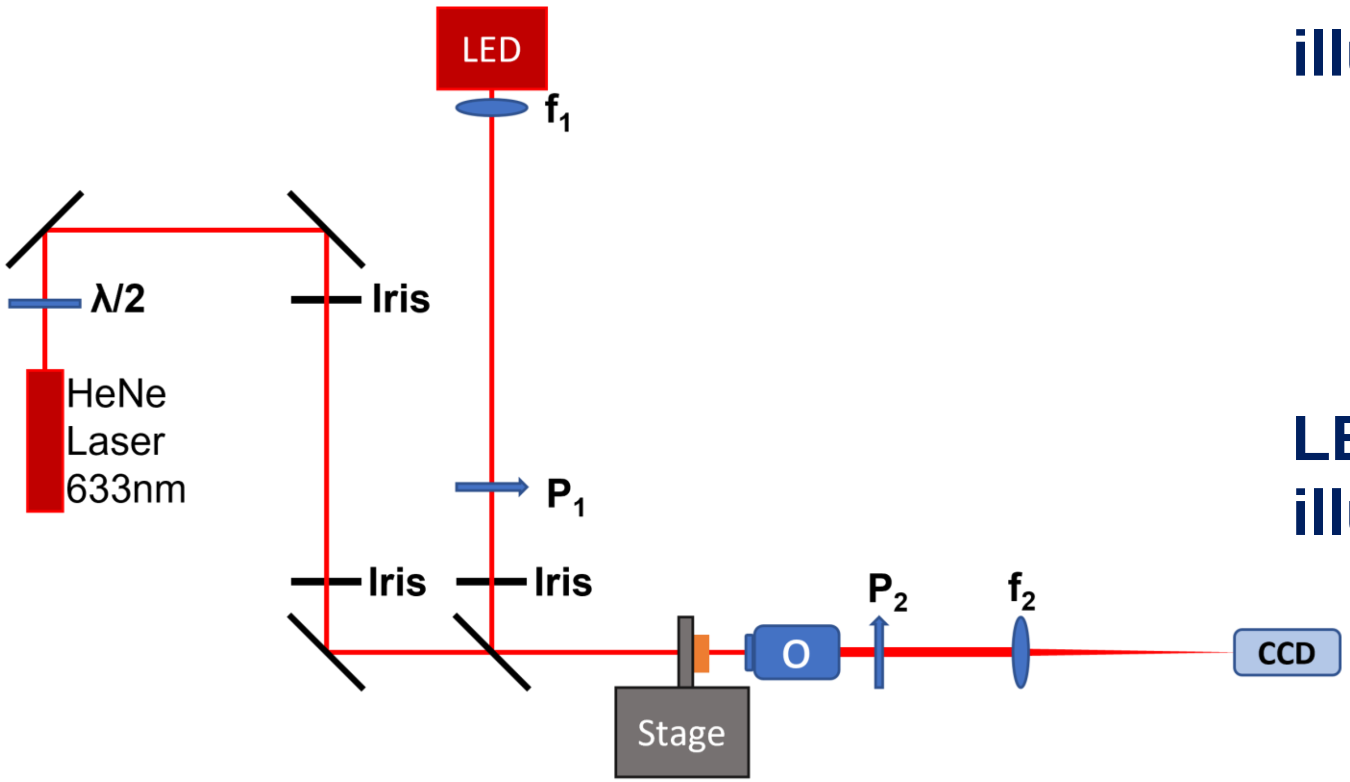


# Experiments

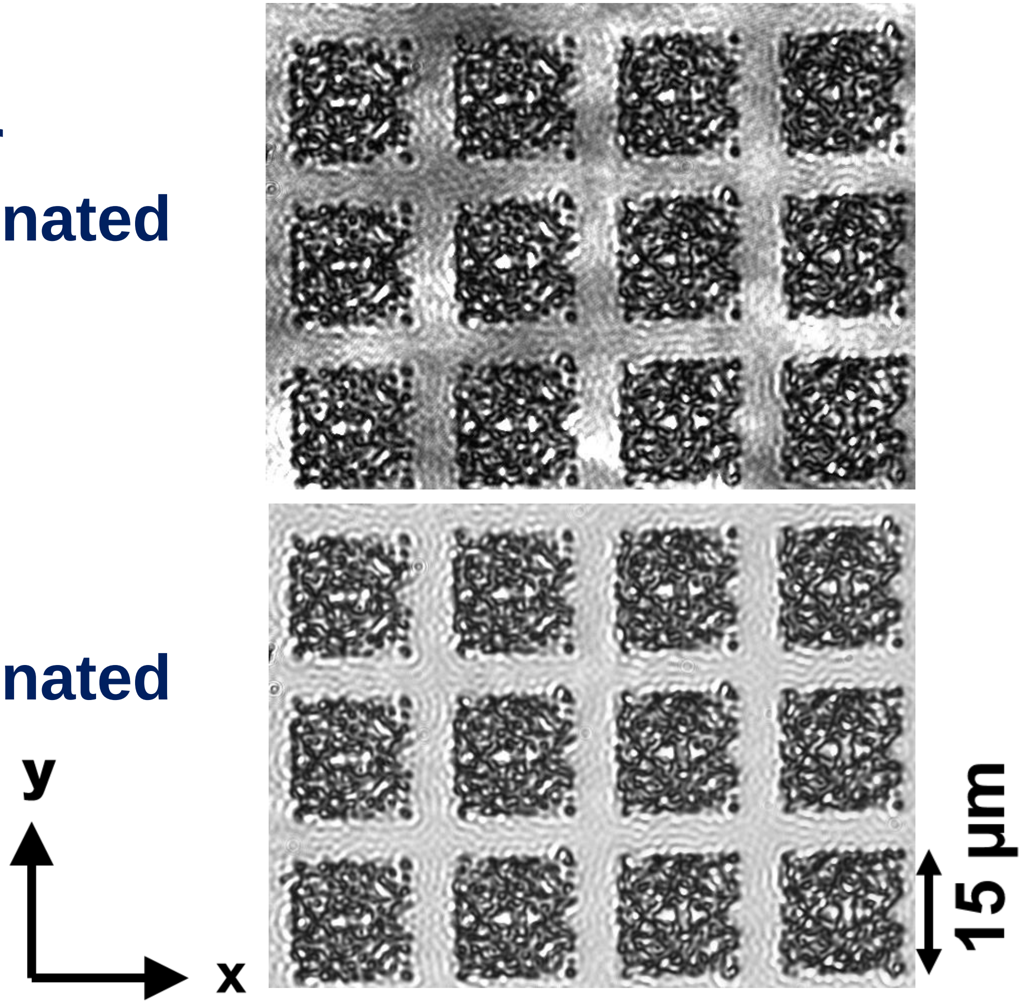


## Optical Setup

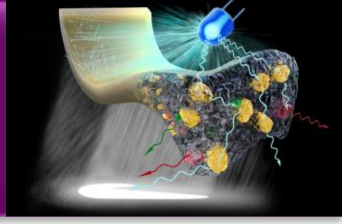


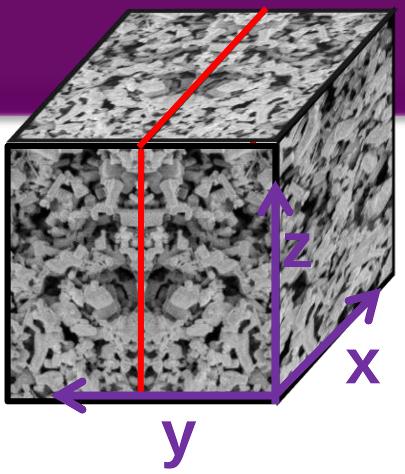

**Laser illuminated**

**LED illuminated**



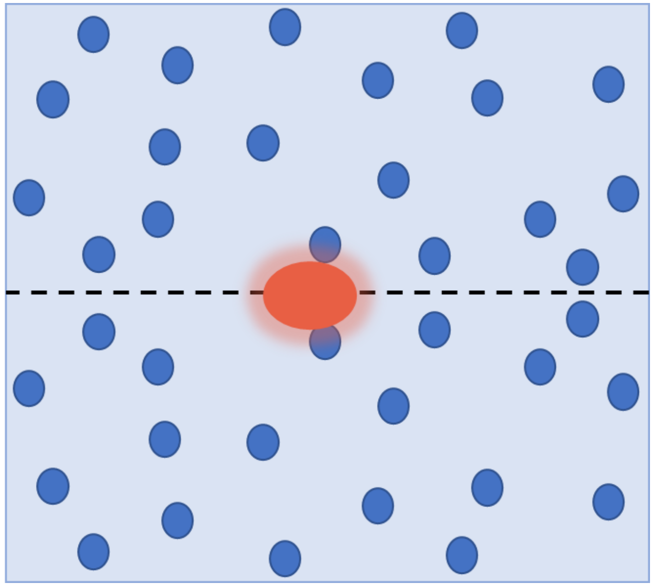
# Applications?





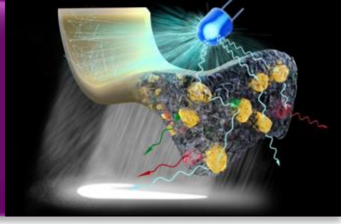

- ✓ Contrast depends on manufacturing quality.
  - Test of manufacturing quality

- ✓ Anticounterfeiting.

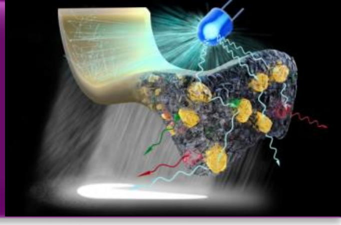


- ✓ Emission control of embedded emitters in the mirror symmetric medium.

# Outlook



- More measurements: LED & Laser, Polarization.
- Better analysis, compare different structures.
- Mirror in two directions.
- Making a sample by engraving in glass.
- Emission of embedded emitters in the mirror symmetric medium.
- Design and fabrication of correlated disorder systems.



# Thanks to:

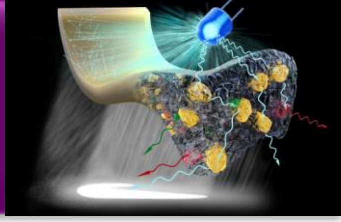
- Huib van Vossen
- Evangelos Marakis
- Ravi Uppu
- Gerwin Osnabrugge
- Ivo Vellekoop
- Daan Stellinga
- Ad Lagendijk

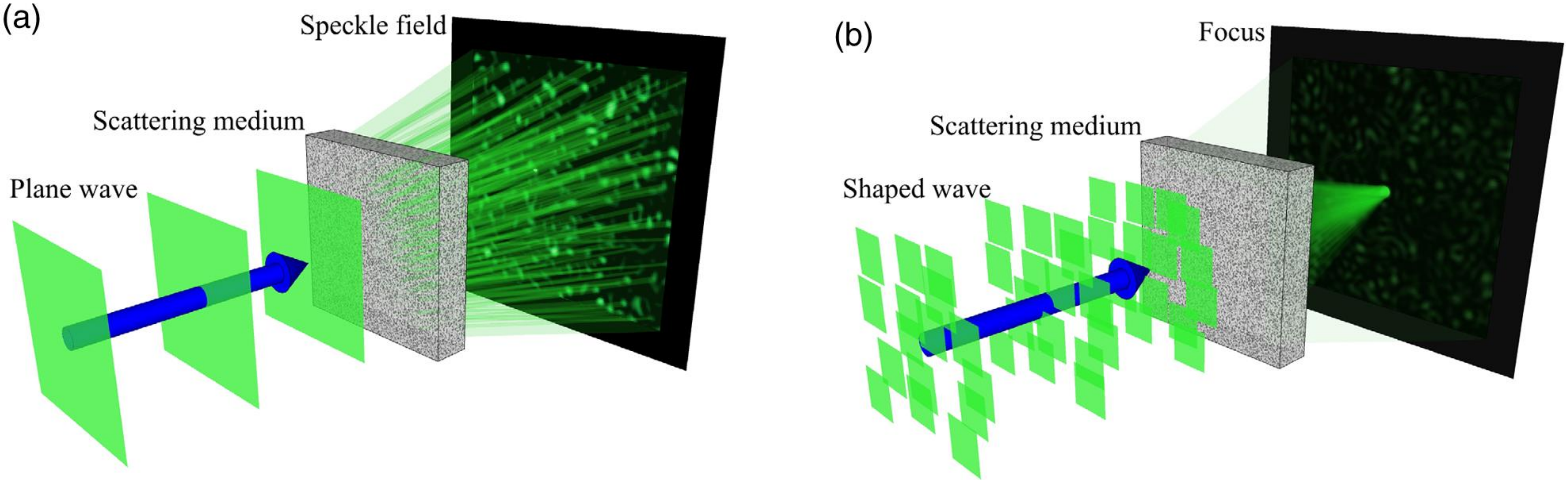
# Focusing light through a free-form object

**Alfredo Rates**

**University of Twente**

# Wavefront shaping (WFS)

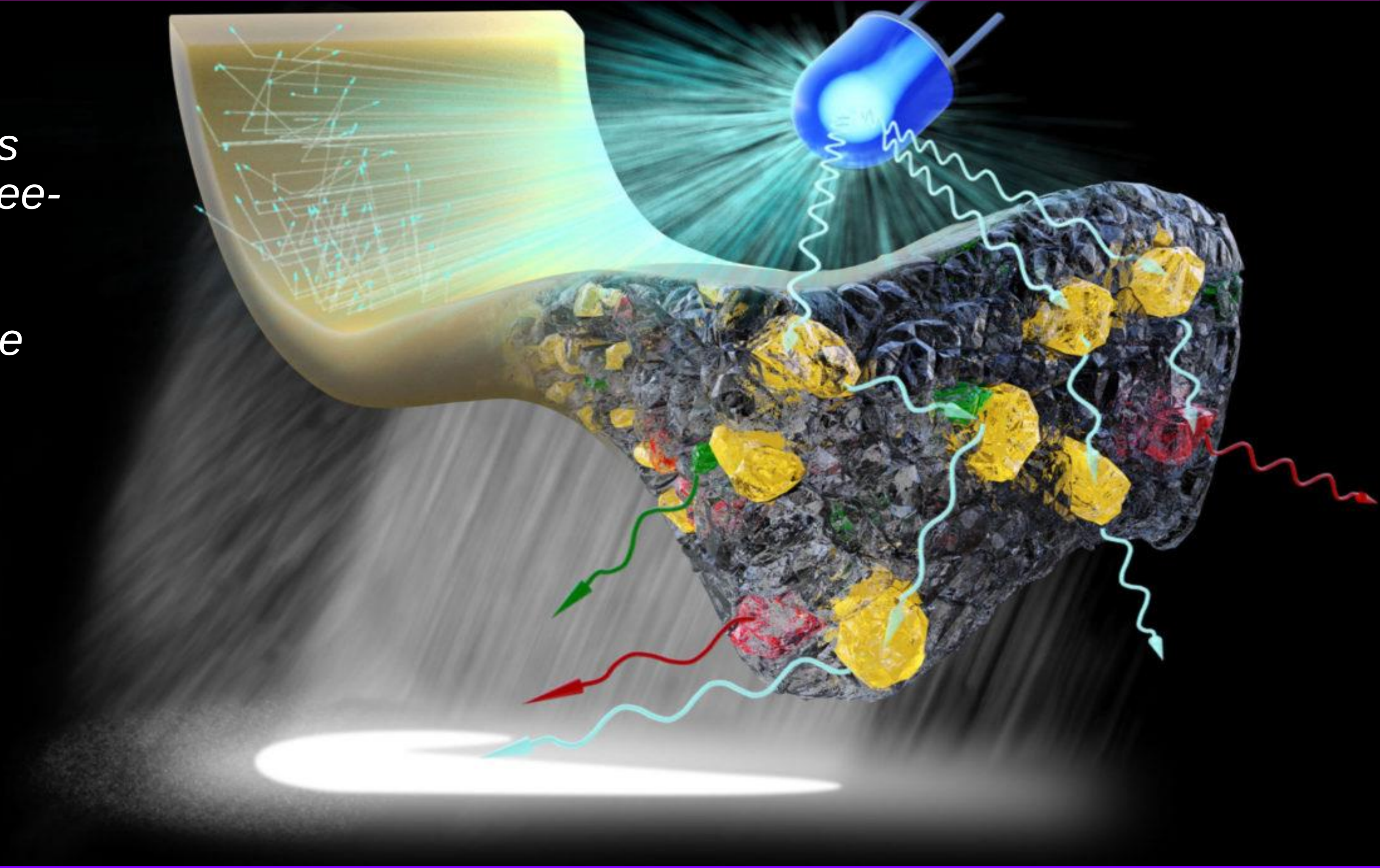





I. M. Vellekoop and A. P. Mosk, *Opt. Lett.* **32**, 2309–2311 (2007)
A. S. Hemphill, J. W. Tay, L. V. Wang, *J. of Bio. Opt*., **21**, 121502 (2016)

# Why free-form?

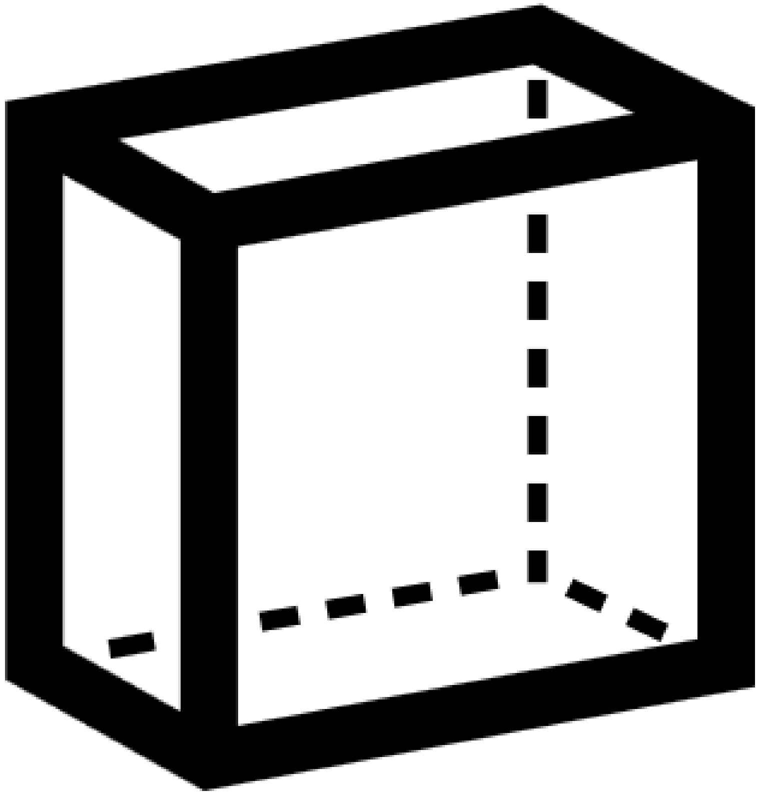
*Currently, high-tech industry is developing a surge of novel devices that combine light scattering with free-formed optics (…) Due to a lack of fundamental know-how on the combination of the technologies, the devices are being designed by educated guesses, which limits progress and applications.*



**Bottleneck: Moving particles inside the material**

- Only slab geometries are discussed
- Changing in the geometry also plays a role

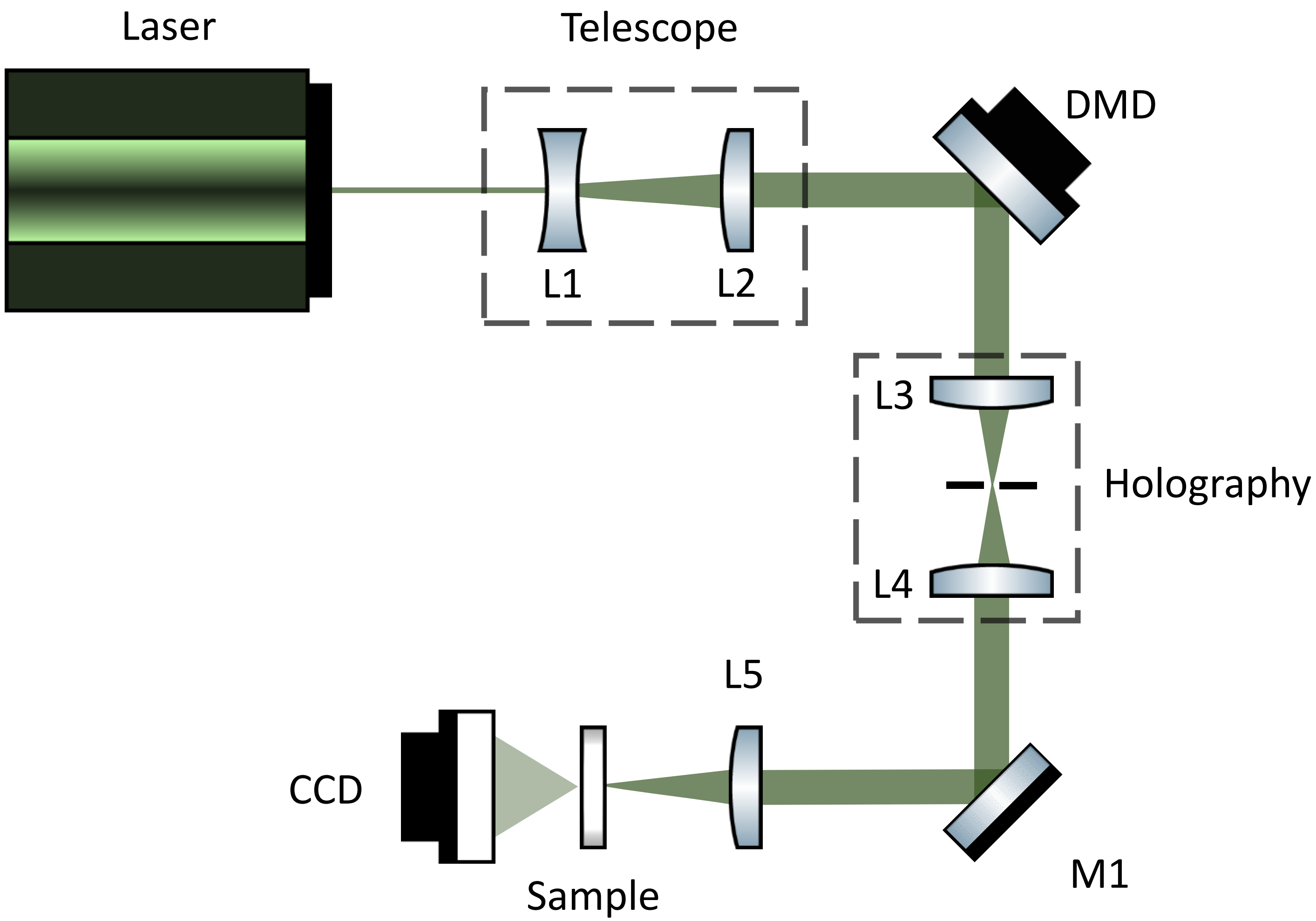
**Does WFS works in a free-form material?**



M. M. Qureshi, *et. al.*, *Biomed. Opt. Exp.* **8**, 4855–4864 (2017).

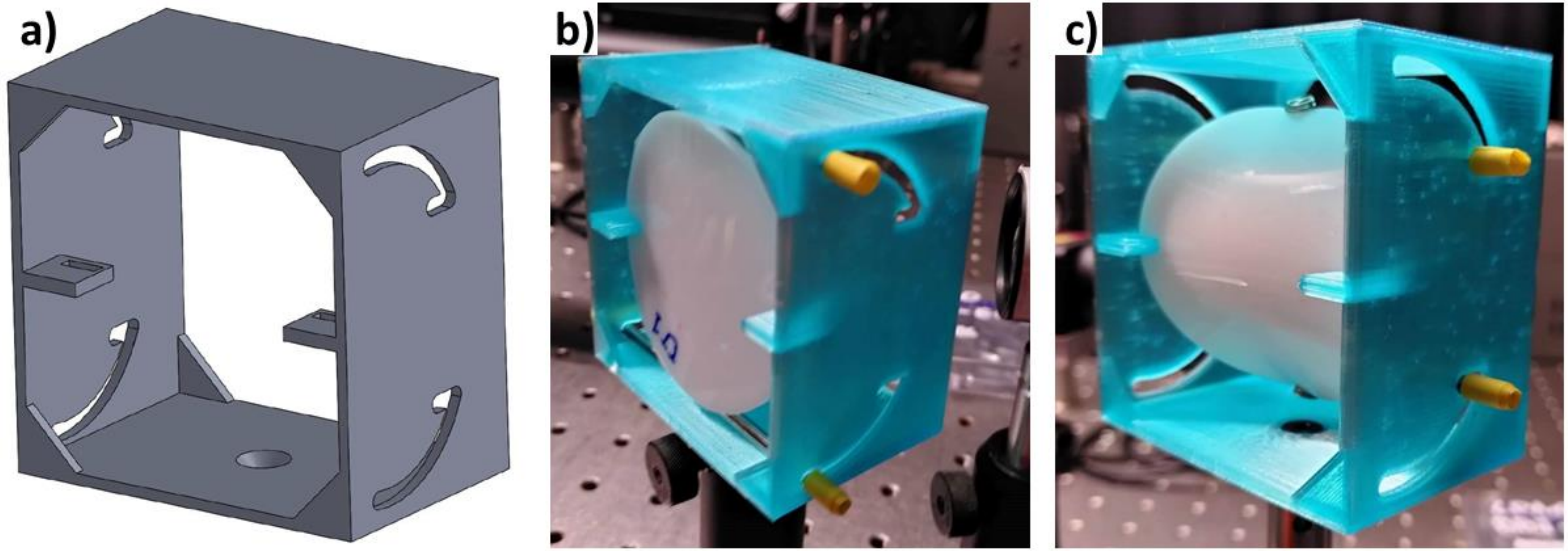
# Experiment

- Digital Micro-mirror Device (DMD)
- 530 nm laser
- Lee Holography method

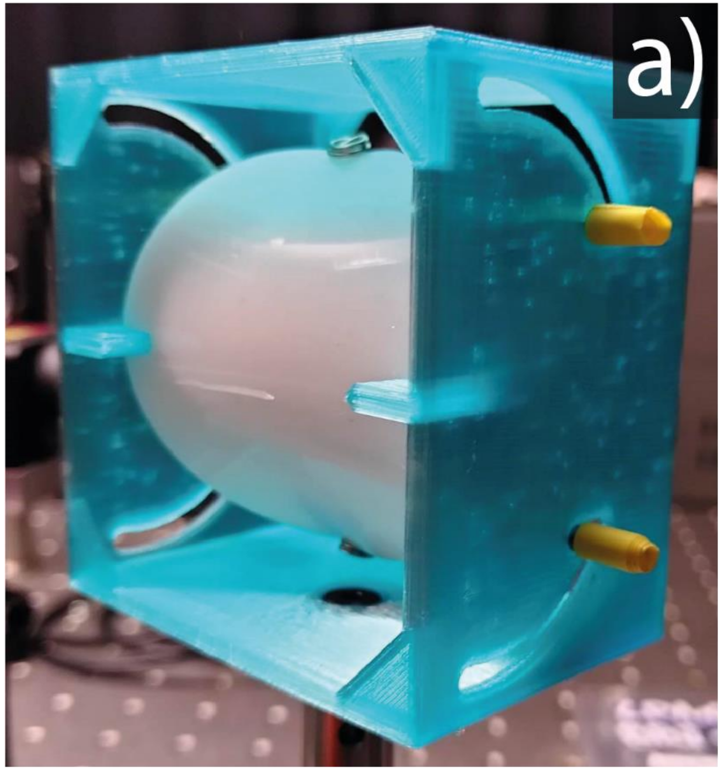


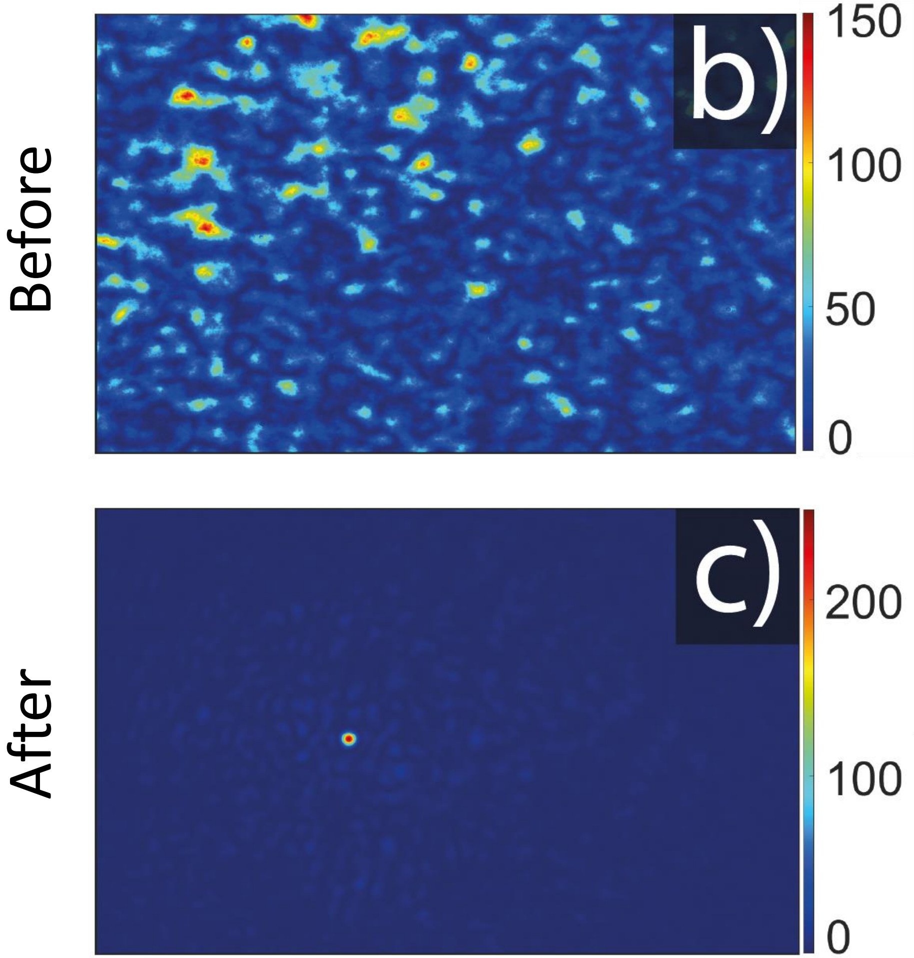
# Experiment

$TiO_2$ particles suspended in silicone



# Results – Fixed number of segments

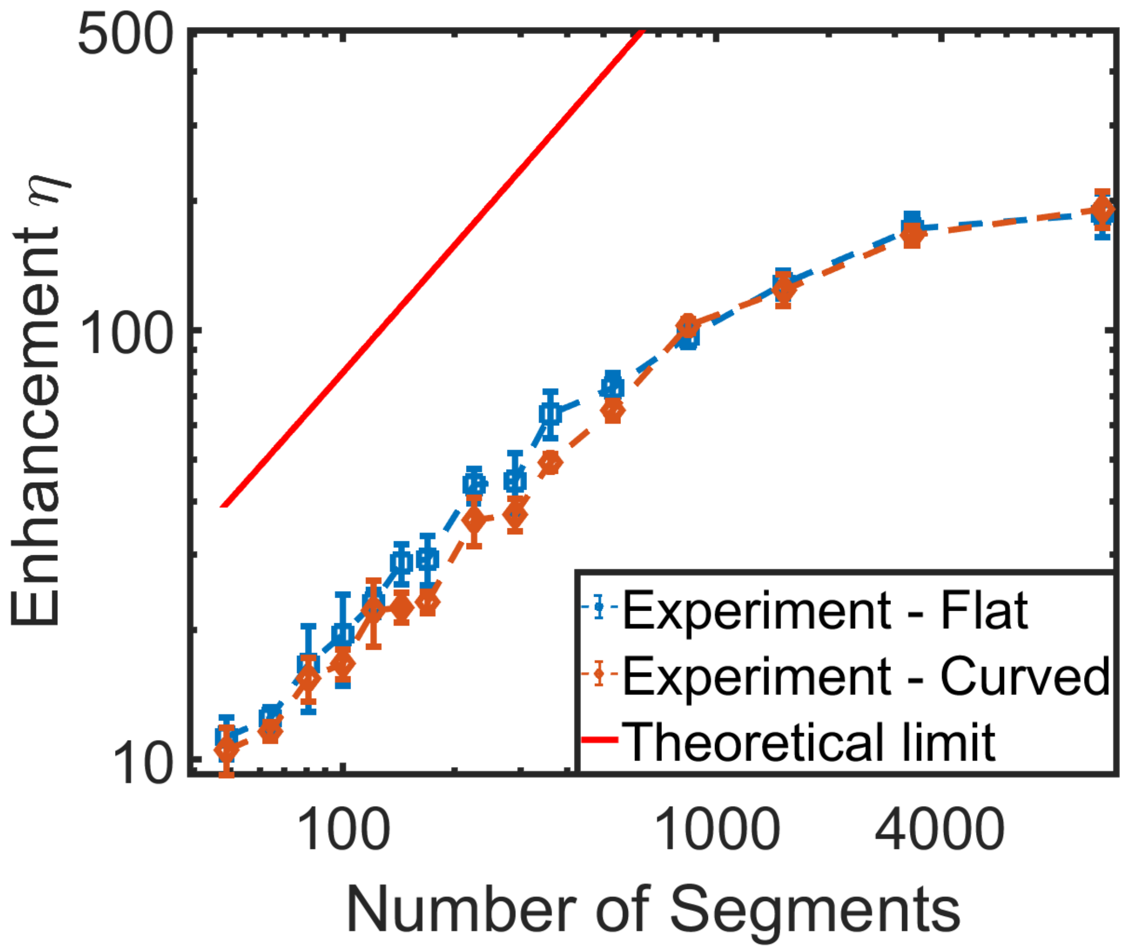


# Final results

- Changing number of segments without changing area
- Enhancement:

$$\eta = \frac{I_{opt}}{\langle I_{rand} \rangle}$$



# Conclusions & Outlook

- WFS is as efficient in a free-form sample as in a flat, slab geometry
- How to quantify the effect of the curvature?

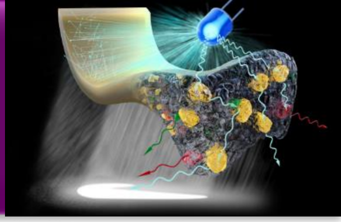
- Next steps: Realtime curving of the sample

# Computational illumination optics using Liouville's equation

**Robert van Gestel**

**Eindhoven University of Technology**

# Introduction



Light input → Optical system → Light output (illuminance or luminous intensity)

**Goal:** compute light output efficiently

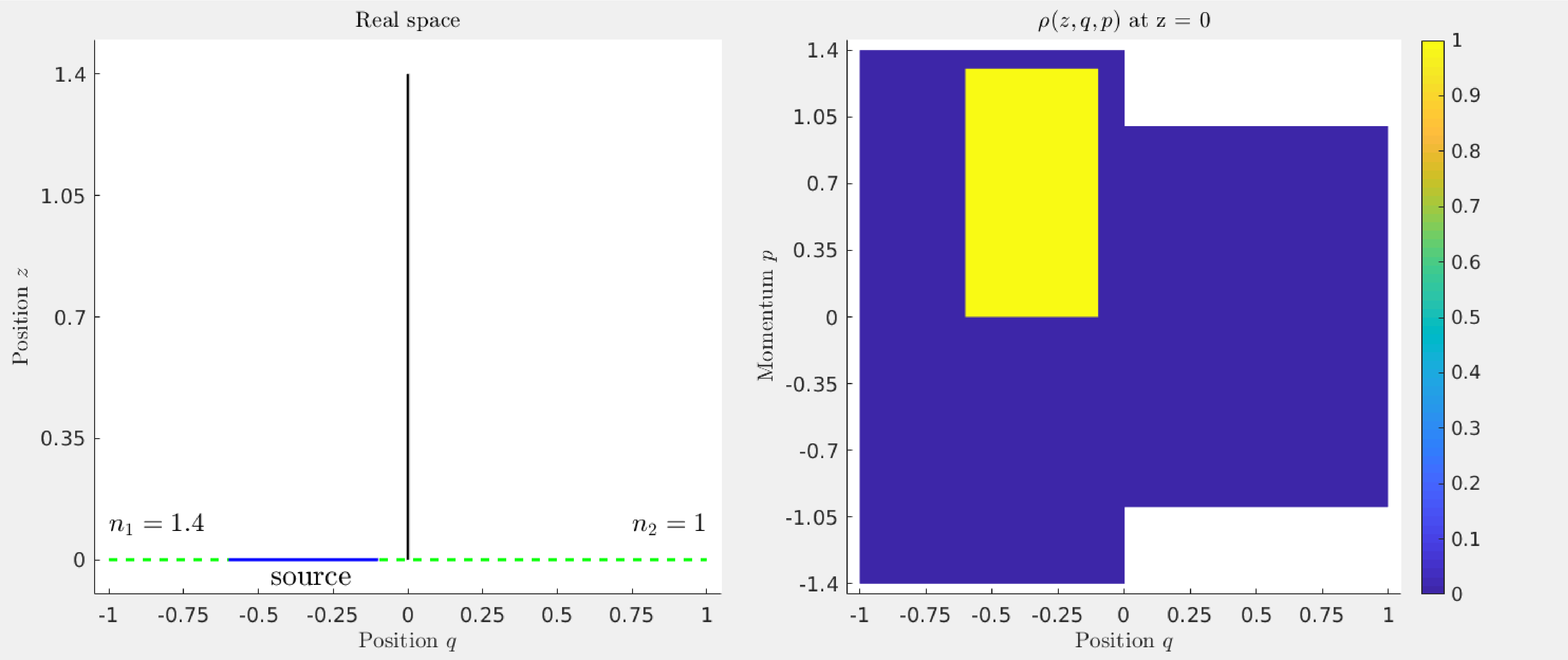
**Quasi-Monte Carlo ray tracing:**

- Robust
- Slow convergence

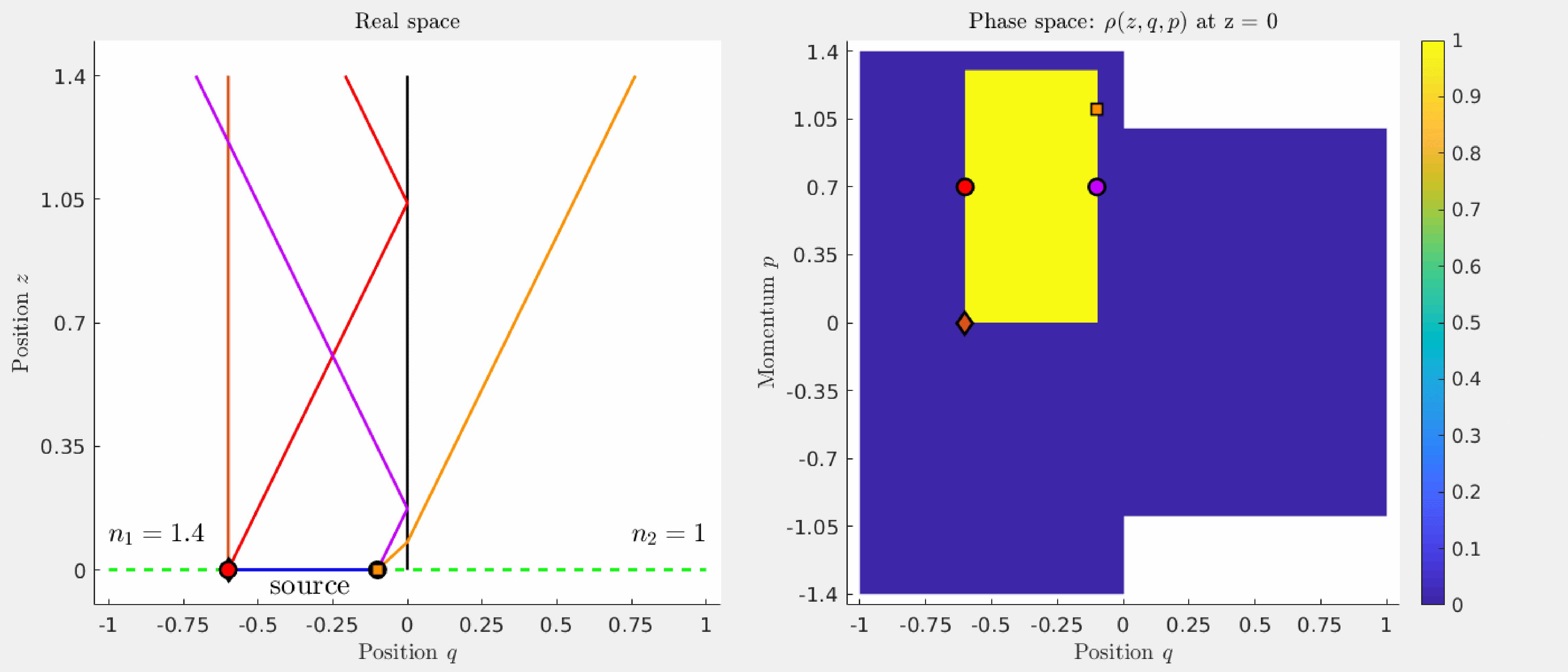
**Liouville's equation based on:**

- Conservation of energy and phase space volume (étendue)

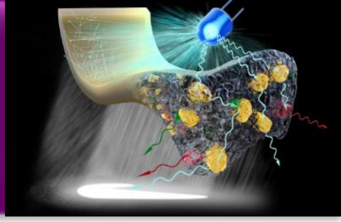
# Optics in phase space



# Optics in phase space



# Light rays and Liouville's equation



Transport of basic luminance $\rho$:

$$\frac{\partial \rho}{\partial z} + \nabla \cdot (\rho \boldsymbol{u}) = 0$$

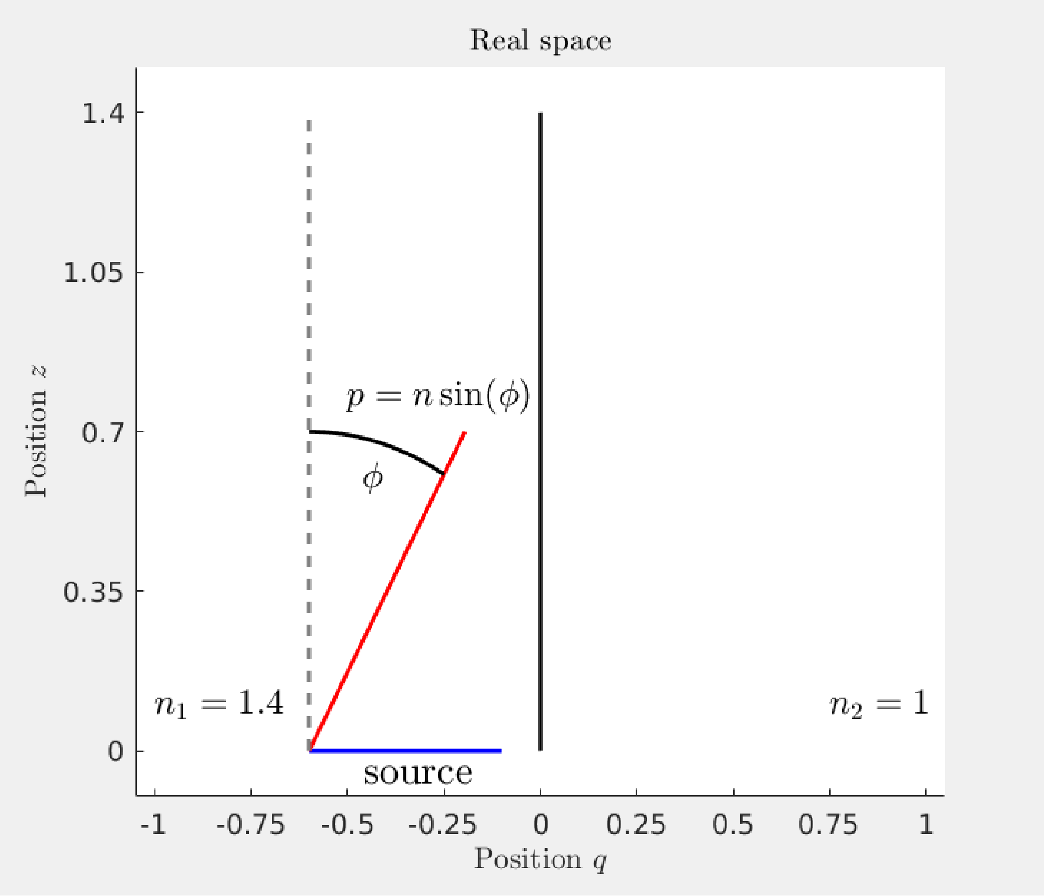
with velocity field $\boldsymbol{u}$:

$$\boldsymbol{u} = \frac{1}{\sqrt{n^2 - p^2}} \begin{pmatrix} p \\ n \frac{\partial n}{\partial q} \end{pmatrix}$$

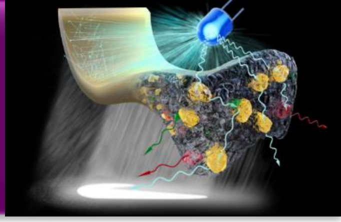
basic luminance $\rho$ defined by:

$$\rho = \frac{\rho^*}{n},$$

with $\rho^*$ the luminance [lm / m / rad]

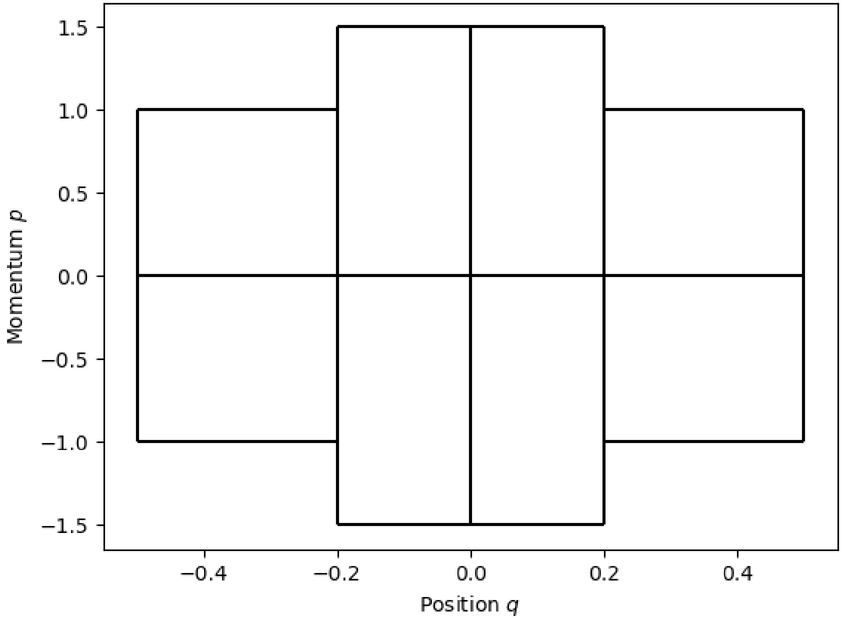


# Numerical method

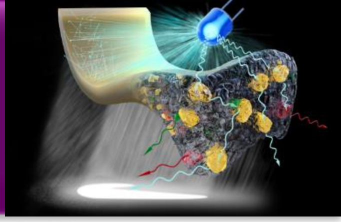


1. Divide phase space in $K$ finite elements (rectangles)
   - moving elements: aligns elements with optical interfaces
   - adaptive mesh refinement (AMR): high mesh quality

$$\frac{\partial \rho}{\partial z} + \nabla \cdot (\rho \boldsymbol{u}) = 0$$



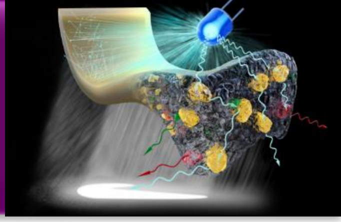
# Numerical method



1. Divide phase space in $K$ finite elements (rectangles)
   - moving elements: aligns elements with optical interfaces
   - adaptive mesh refinement (AMR): high mesh quality
2. Approximate the solution by a high degree ($N$) polynomial: discontinuous Galerkin (DG)
3. Explicit one-step high order integration using Arbitrary Derivative (ADER)

$$\frac{\partial \rho}{\partial z} + \nabla \cdot (\rho \boldsymbol{u}) = 0$$

# Numerical method



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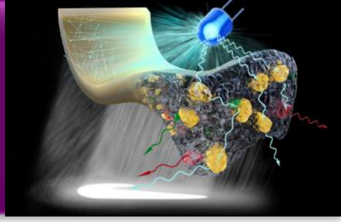
3. Explicit one-step high order integration using Arbitrary Derivative (ADER)
4. Optical interface: corrections to non-local boundary conditions to ensure energy conservation [1]

$$\frac{\partial \rho}{\partial z} + \nabla \cdot (\rho \boldsymbol{u}) = 0$$

1: R.A.M. van Gestel, M.J.H. Anthonissen, J.H.M. ten Thije Boonkkamp, W.L. IJzerman, "An Energy Conservative hp-method for Liouville's Equation of Geometrical Optics" *Journal of Scientific Computing 89.1 (2021)*

# Numerical method



1. Divide phase space in $\boxed{K}$ finite elements (rectangles)
    - moving elements: aligns elements with optical interfaces
    - adaptive mesh refinement (AMR): high mesh quality
2. Approximate the solution by a high degree ($\boxed{N}$) polynomial: discontinuous Galerkin (DG)
3. Explicit one-step high order integration using Arbitrary Derivative (ADER)
4. Optical interface: corrections to non-local boundary conditions to ensure energy conservation [1]

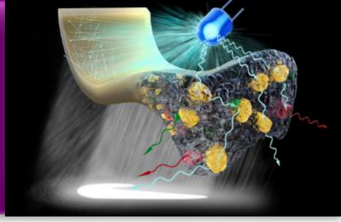
$$\frac{\partial \rho}{\partial z} + \nabla \cdot (\rho \boldsymbol{u}) = 0$$

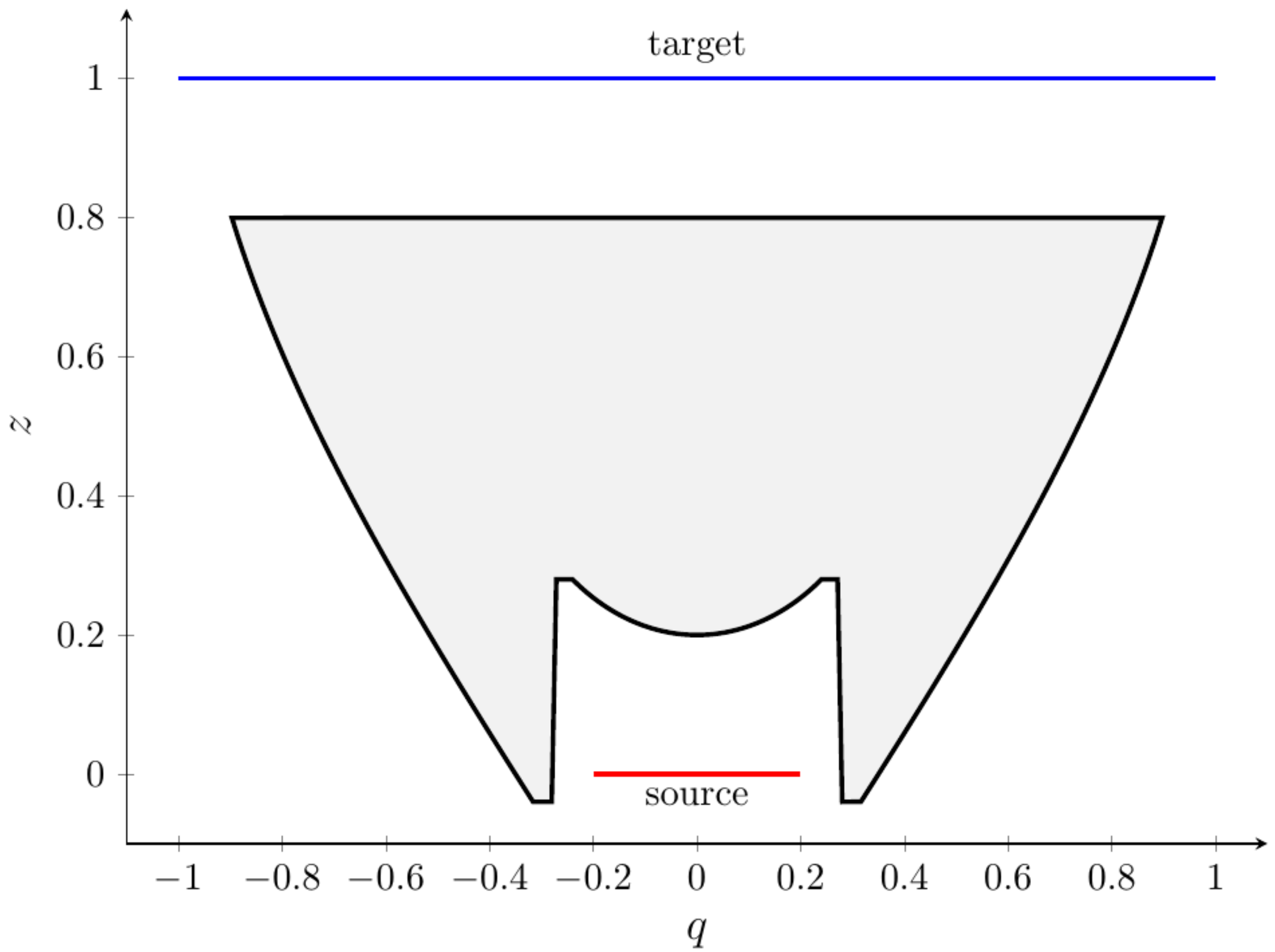
**Decrease error by increasing:**

- $K$ number of elements
- $N$ degree of polynomial

1: R.A.M. van Gestel, M.J.H. Anthonissen, J.H.M. ten Thije Boonkkamp, W.L. IJzerman, “An Energy Conservative hp-method for Liouville’s Equation of Geometrical Optics” *Journal of Scientific Computing 89.1 (2021)*

# TIR-collimator

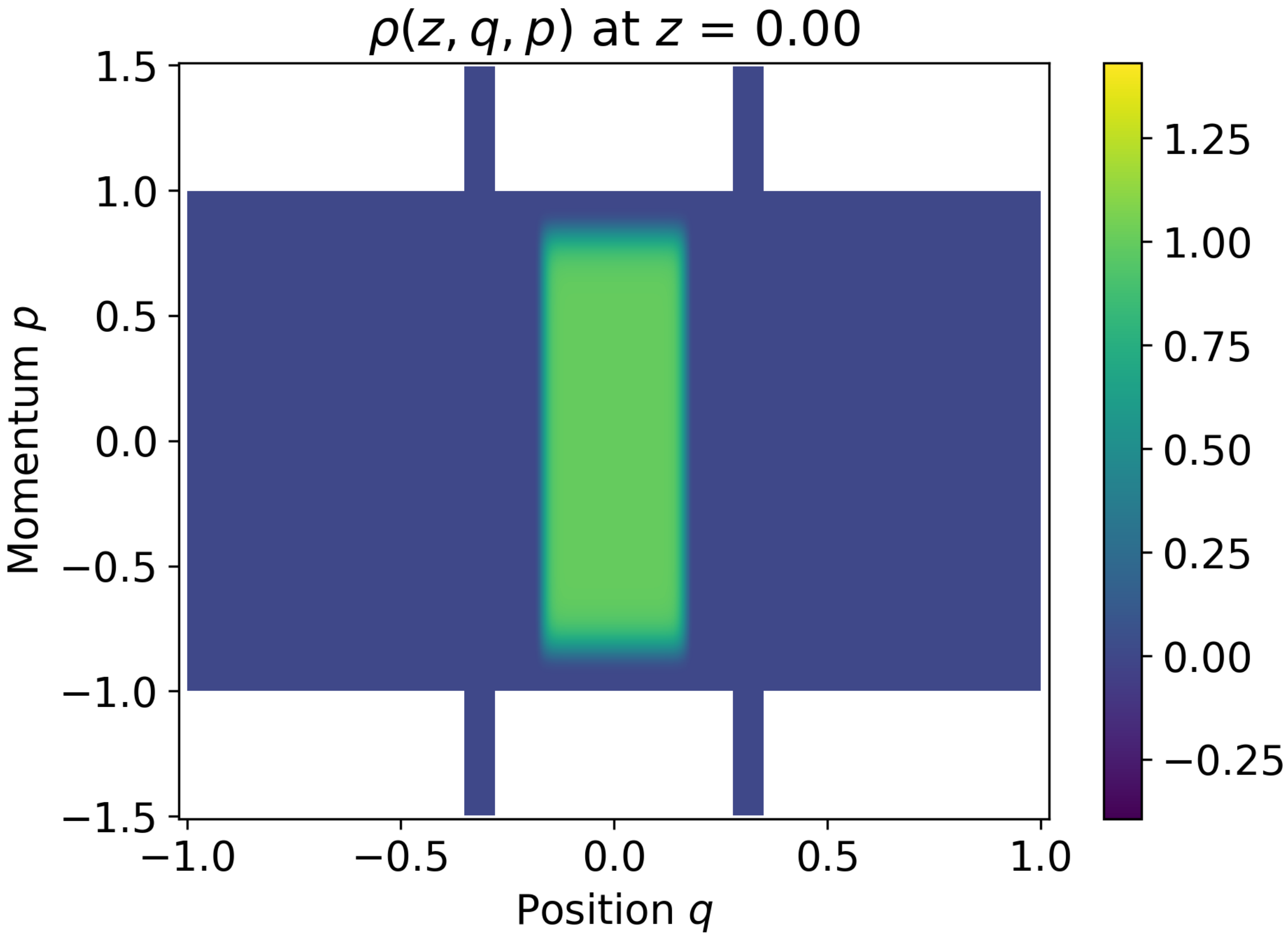


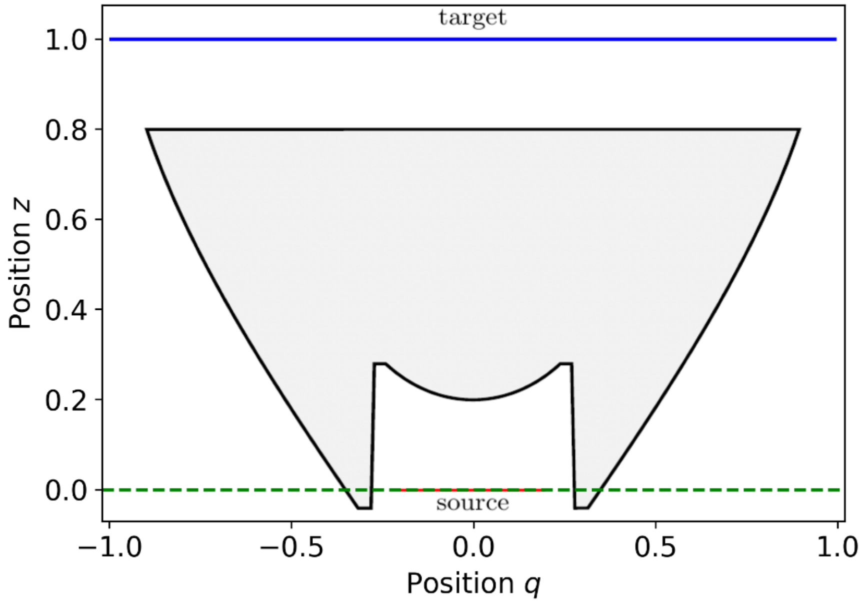



White region $n = 1$

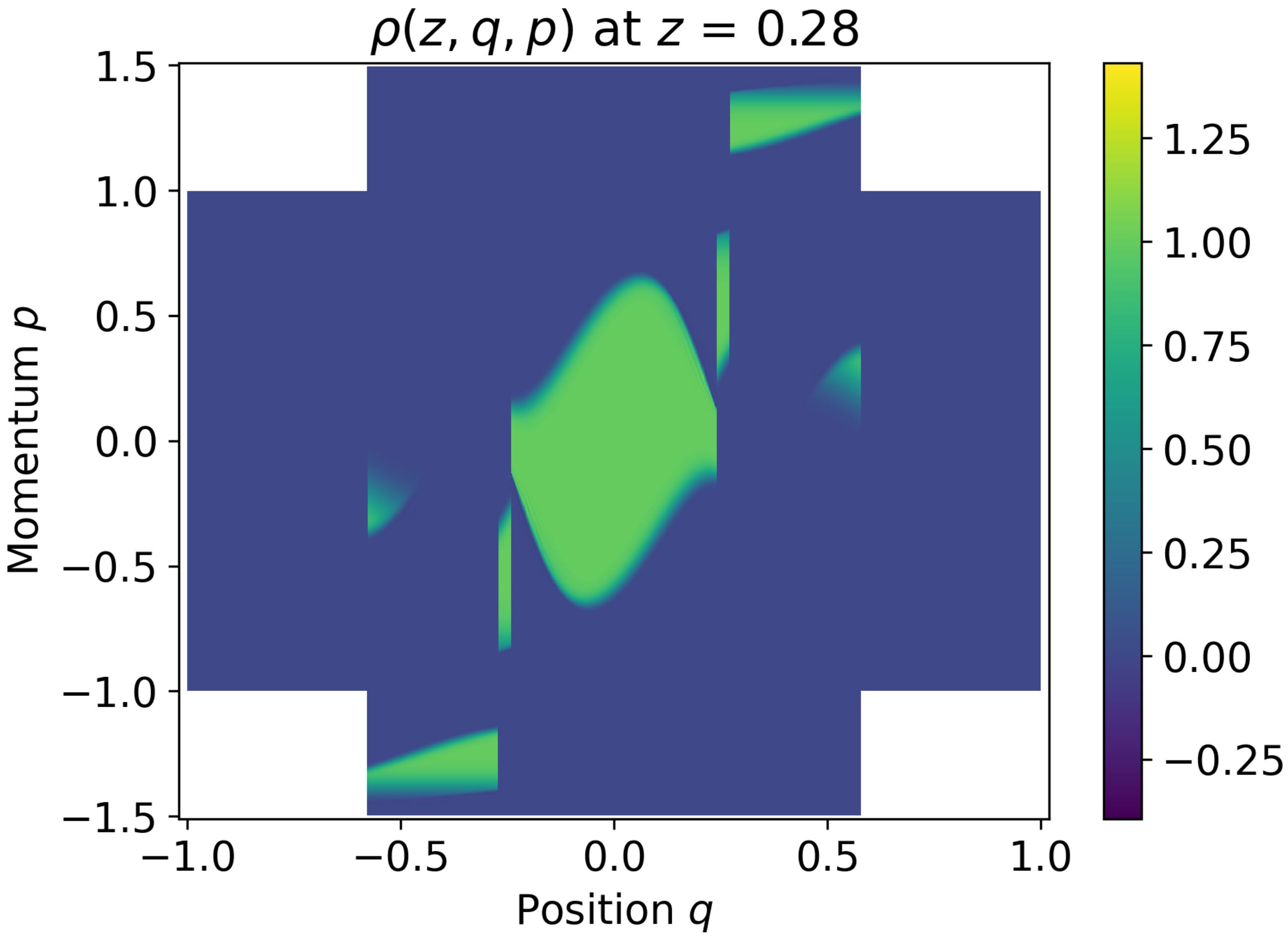
Gray region $n = 1.5$

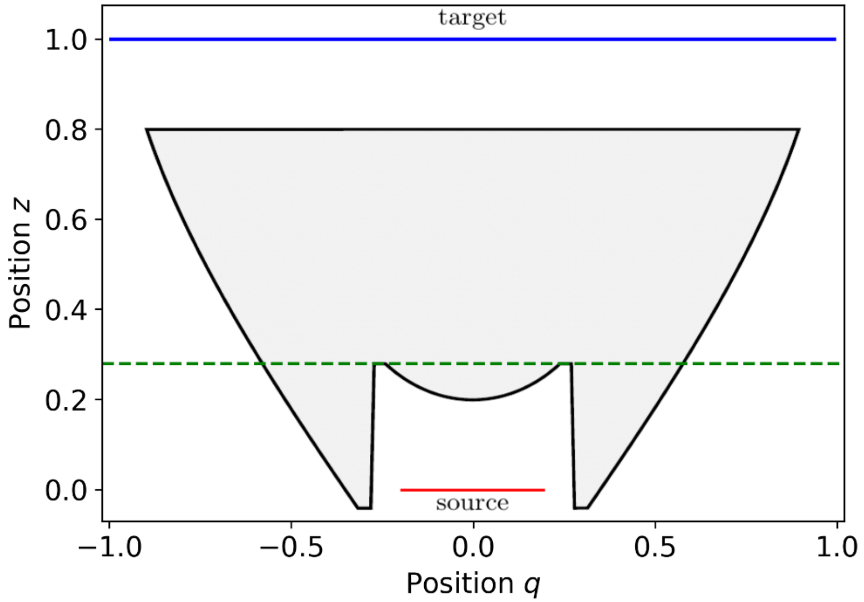
# TIR-collimator: source



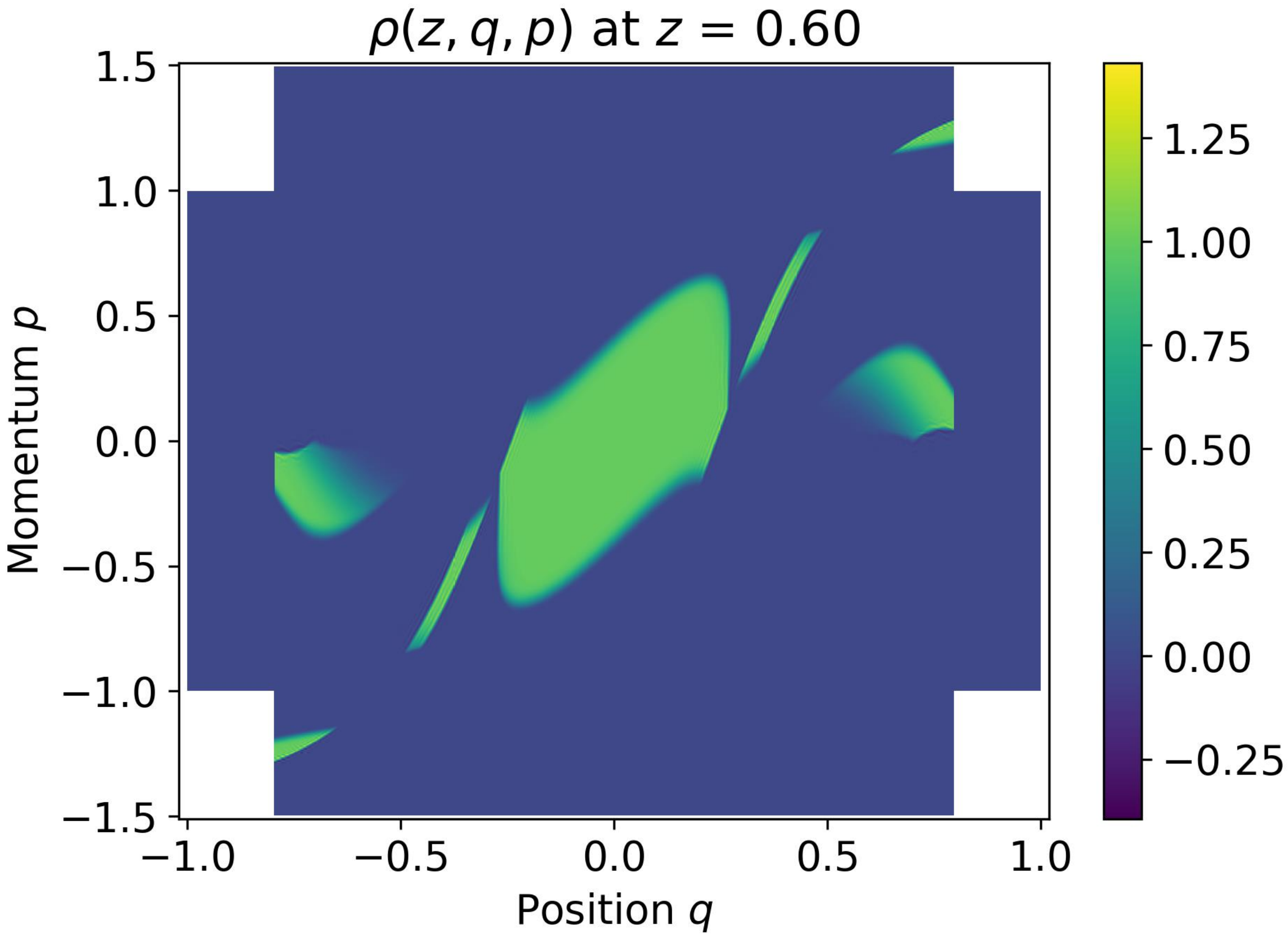



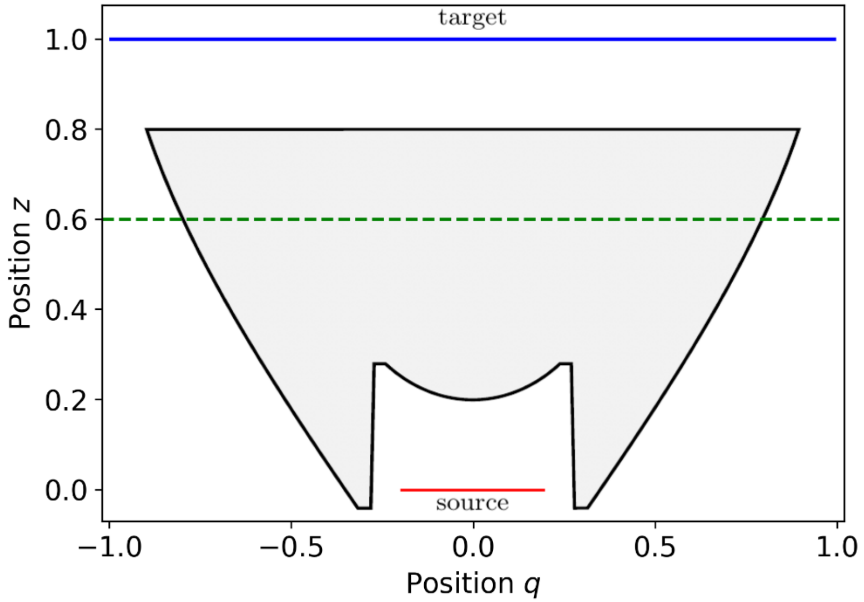
# TIR-collimator: result



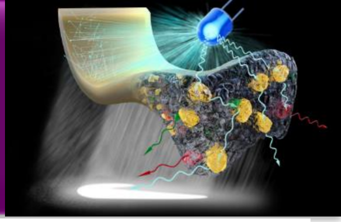



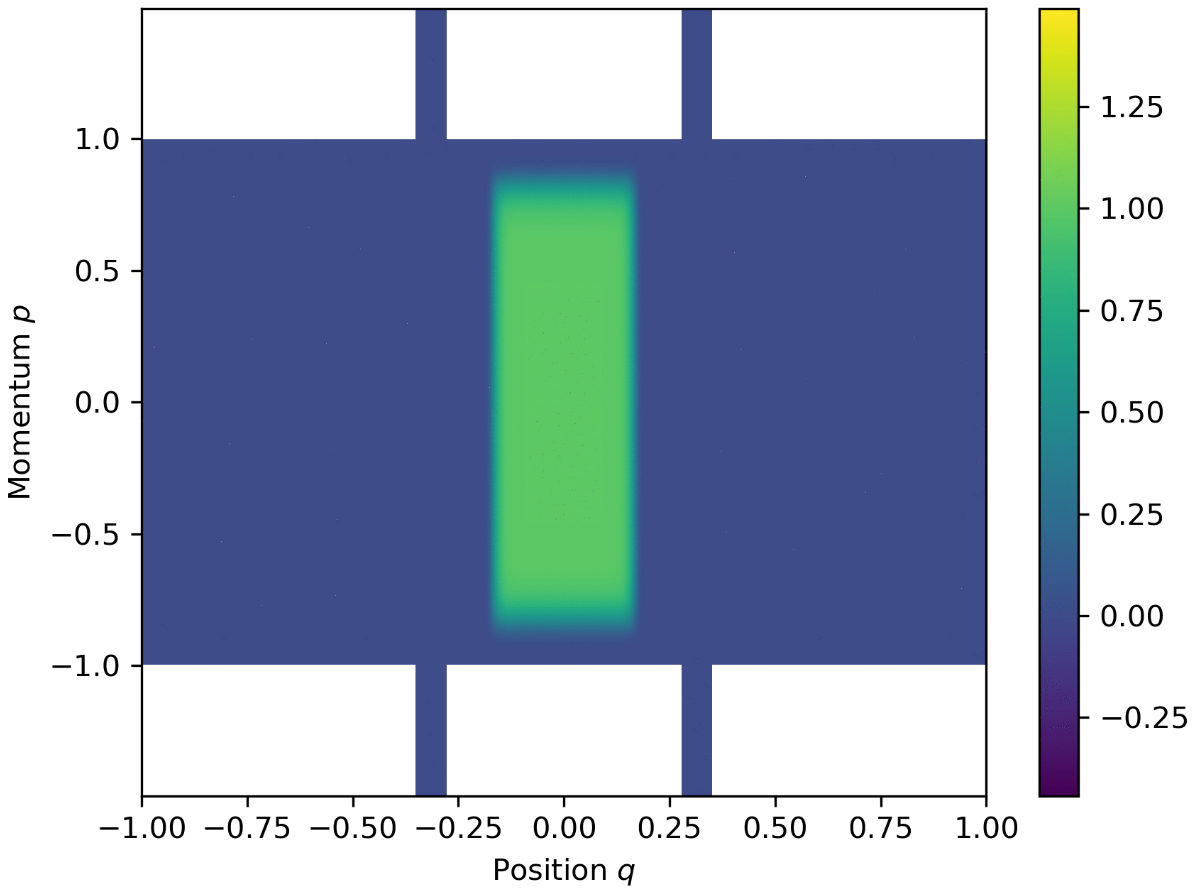
# TIR-collimator: result

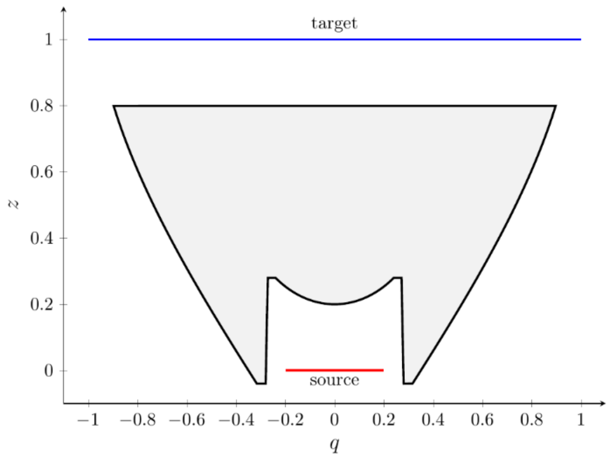


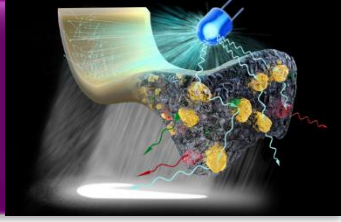
# TIR-collimator: result

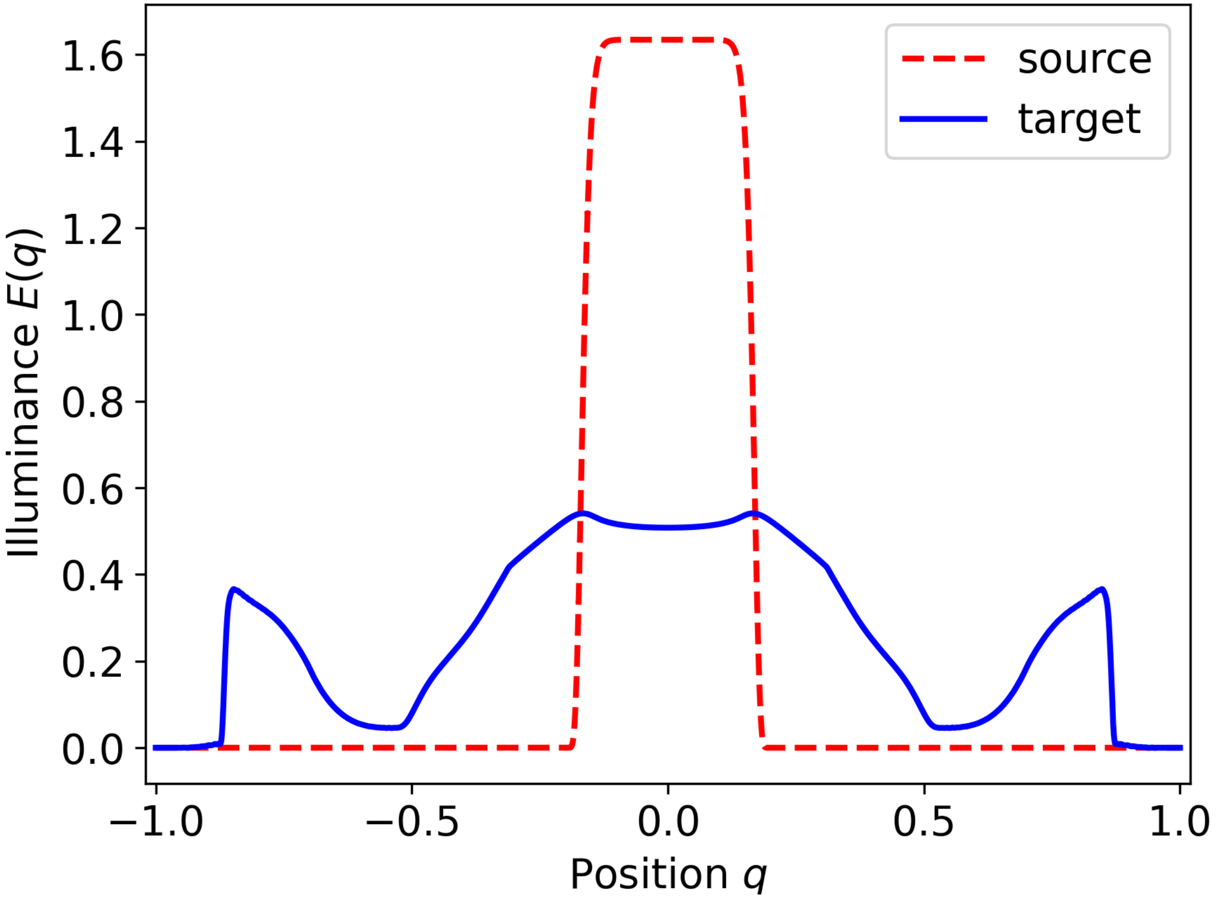




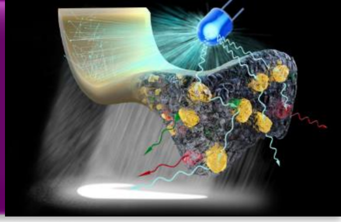



# TIR-collimator: illuminance





# Conclusions & Outlook

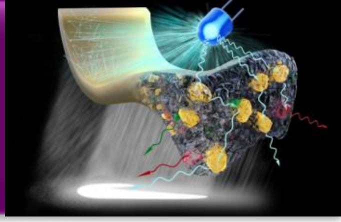


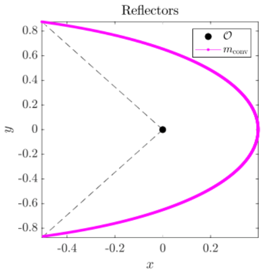
- Liouville’s equation of geometrical optics
- Able to solve complex optical systems:
  - high order efficient solution method
  - obeys energy conservation
- Result for a TIR-collimator

Outlook:

- Add Fresnel reflections
- Extend method to 3D optics (4D phase space)

# Deliverables



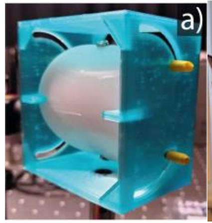


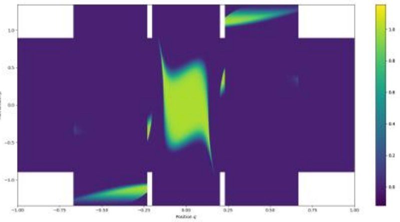

## C1 Freeform optics with scattering

- Rotationally symmetric design strategy
- Non-rotationally symmetric

## C2 Scattering with freeforms

- Analytic model of scattering in presence of freeform effects
- Scattering and design rules



## C3 Homogeneous illumination

- Extension of active flux scheme to 4D phase space
- Design rules for non-extruded light guides