EPIC Meeting on Advanced Microoptics, 11-12 May 2022, Karlsruhe @ Nanoscribe

# Examples of Flat Optics Designs

Frank Wyrowski

- University of Jena, Germany
- LightTrans International GmbH
- Wyrowski Photonics GmbH
- Beijing Luoxun Technology Co., Ltd.

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# Physical Optics vs. Ray Optics and Conclusions for Flat Optics

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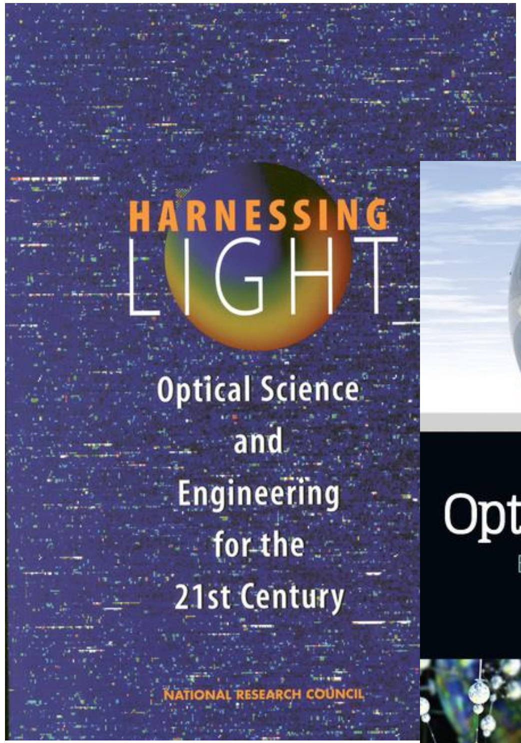
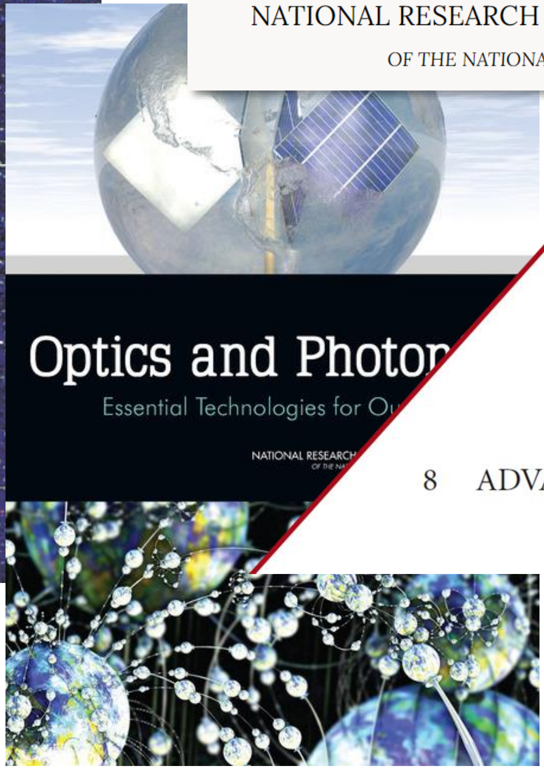
# Optics and Photonics: Enabling Technology




1998




2013

Committee on Harnessing Light: Capitalizing on Optical Science Trends and Challenges for Future Research

National Materials and Manufacturing Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
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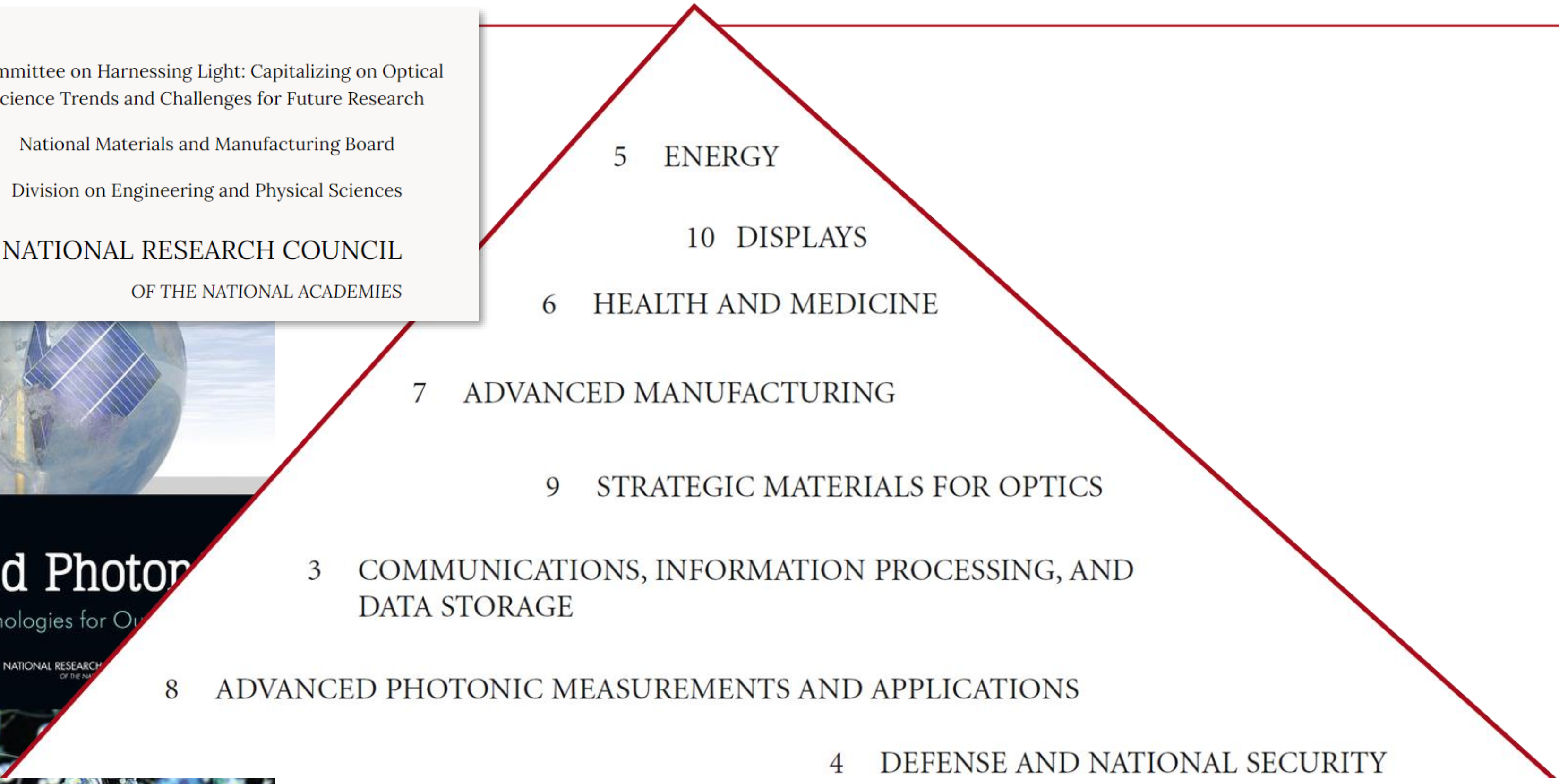
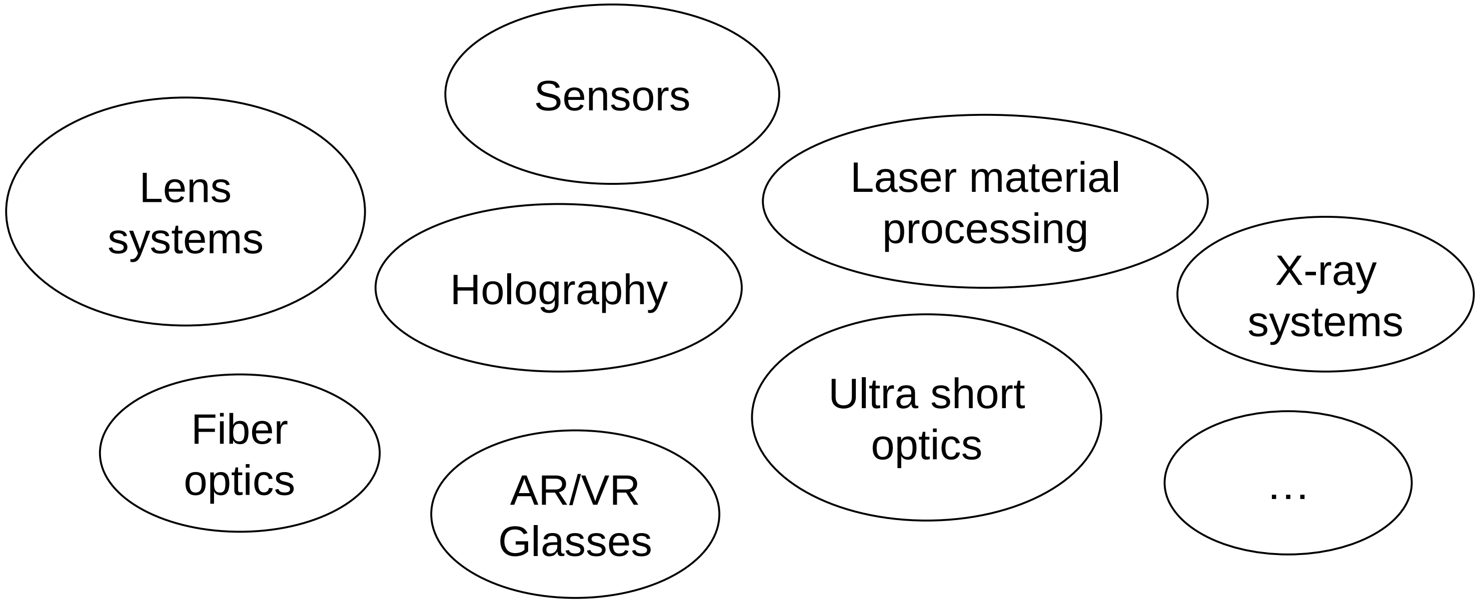


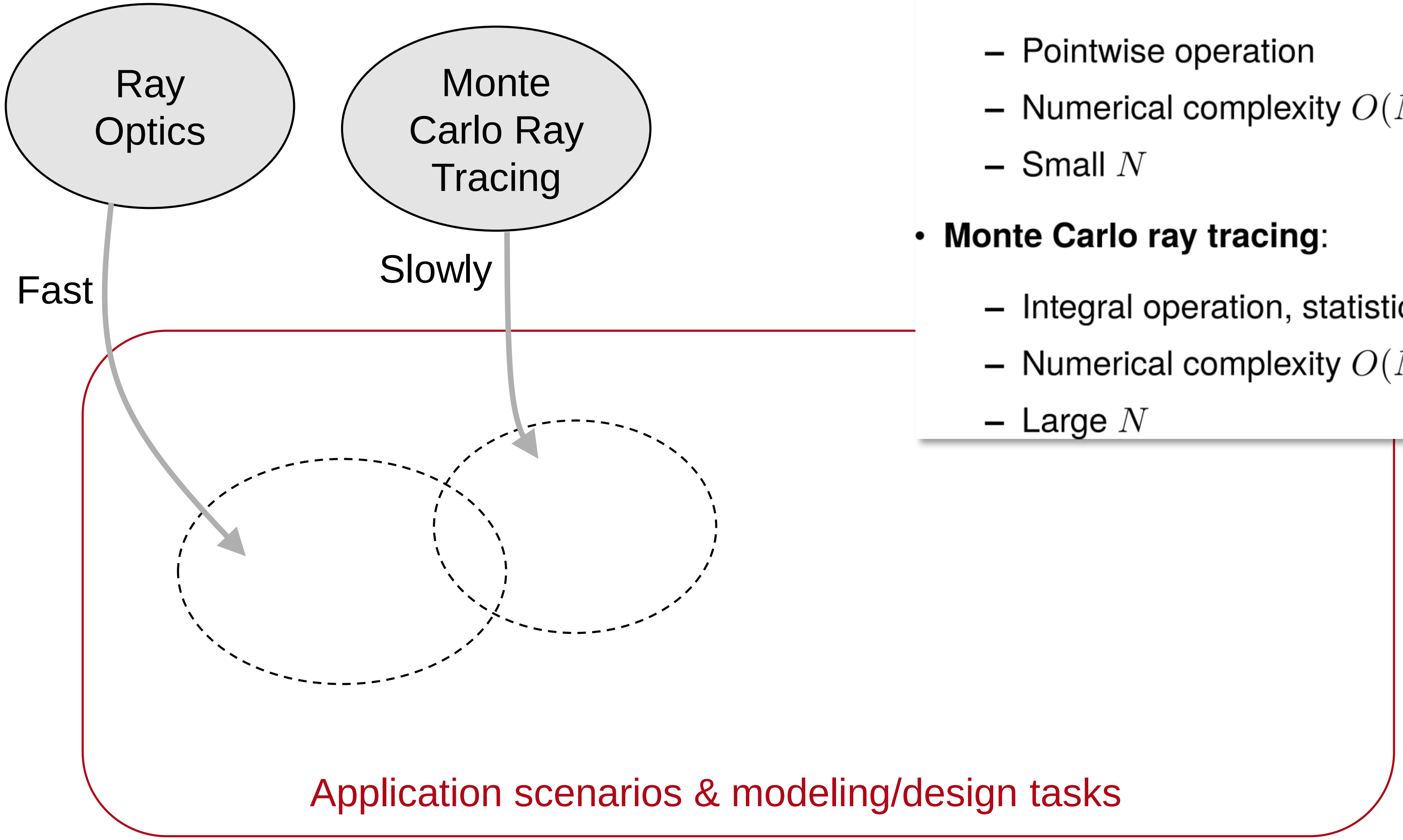
# Enabling Technology: Huge Variety of Application Scenarios



# Enabling Technology: Huge Variety of Application Scenarios

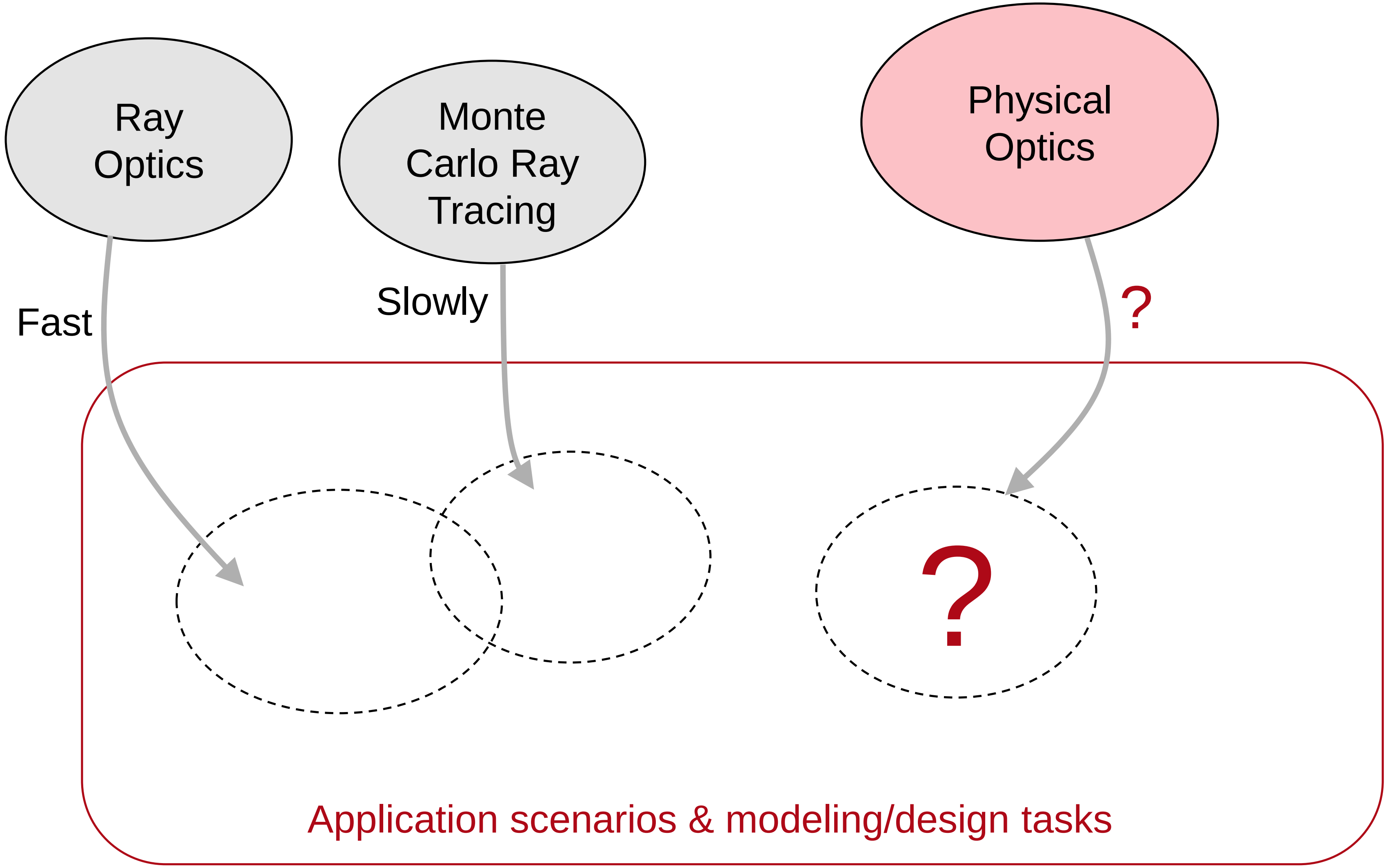
Application scenarios & modeling/design tasks

# Modeling Techniques

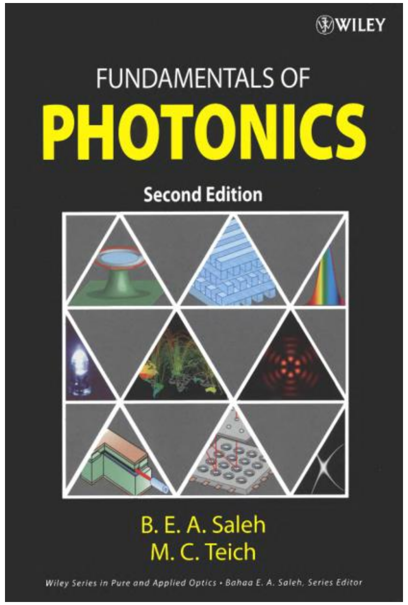


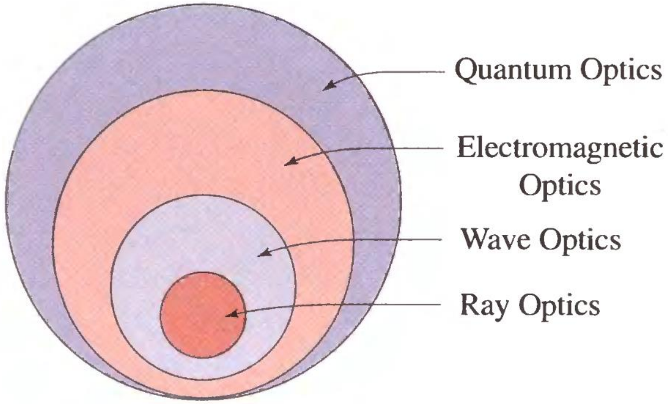

- **Ray tracing**:
  - Pointwise operation
  - Numerical complexity $O(N)$ ($N$ number of rays)
  - Small $N$
- **Monte Carlo ray tracing**:
  - Integral operation, statistical evaluation
  - Numerical complexity $O(N^2)$ ($N$ number of ray bundles)
  - Large $N$

# Modeling Techniques



# Physical Optics Includes Ray Optics



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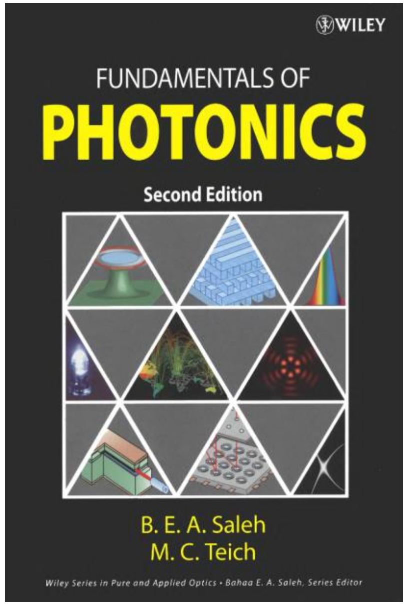
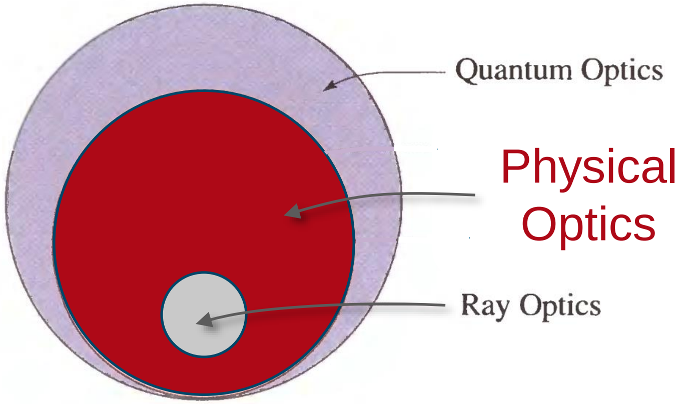
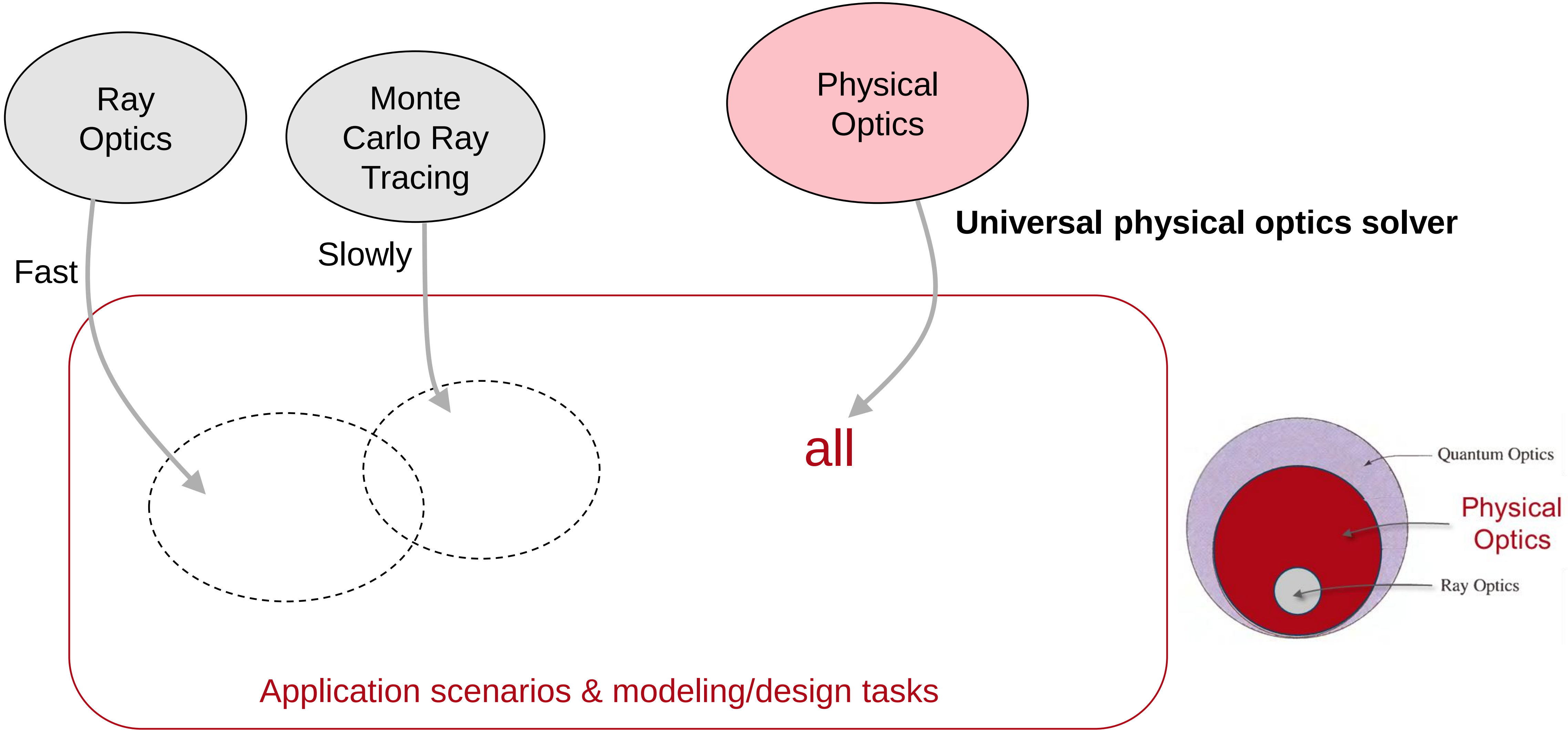



- **Universal physical optics solver**:
  - Integral operation
  - Numerical complexity $O(N^2)$ and higher ($N$ number of field sampling values)
  - Large to huge $N$ (proportional to modeling volume $(\Delta s/\lambda)^3$)

# Modeling Techniques



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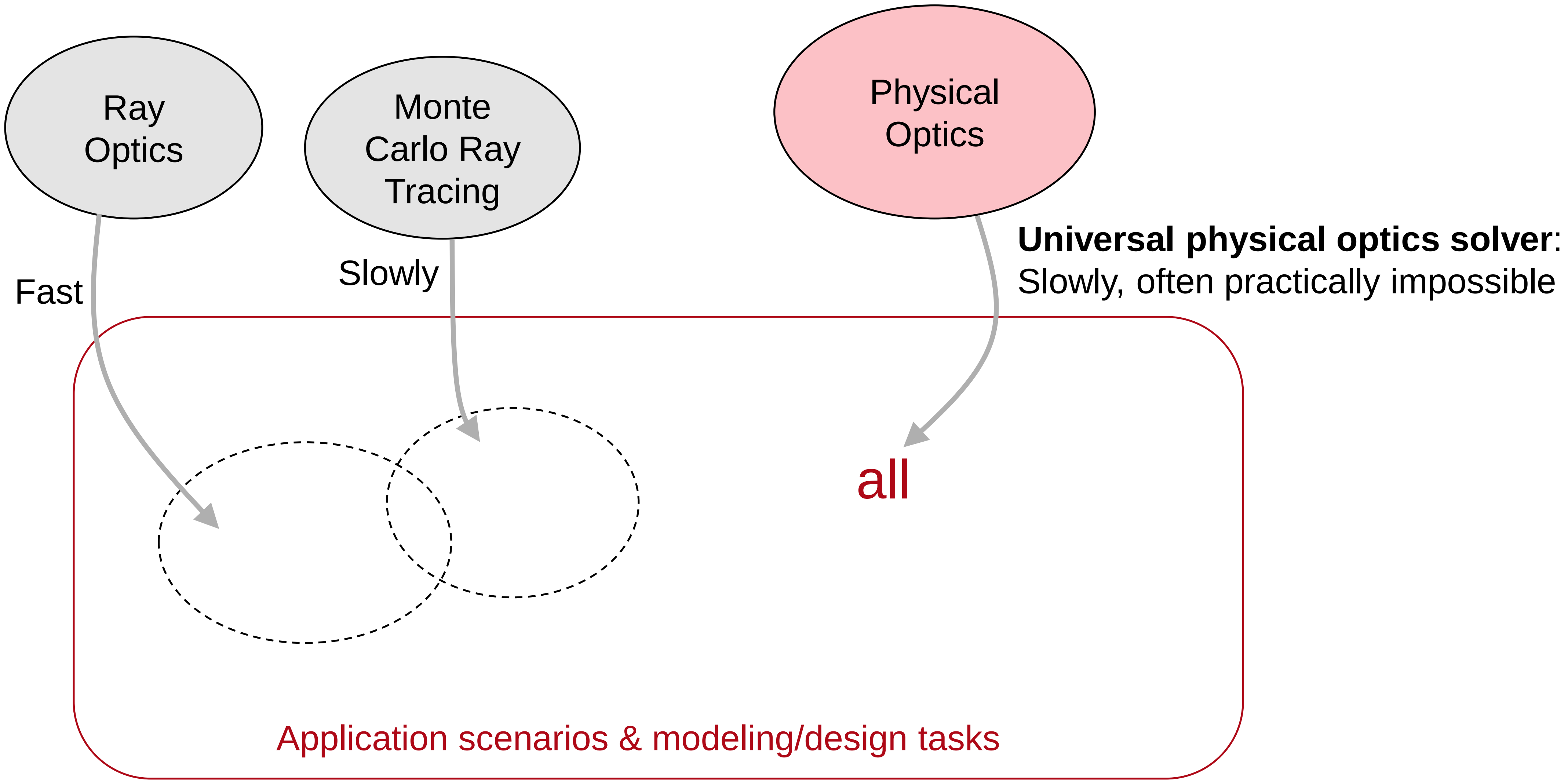

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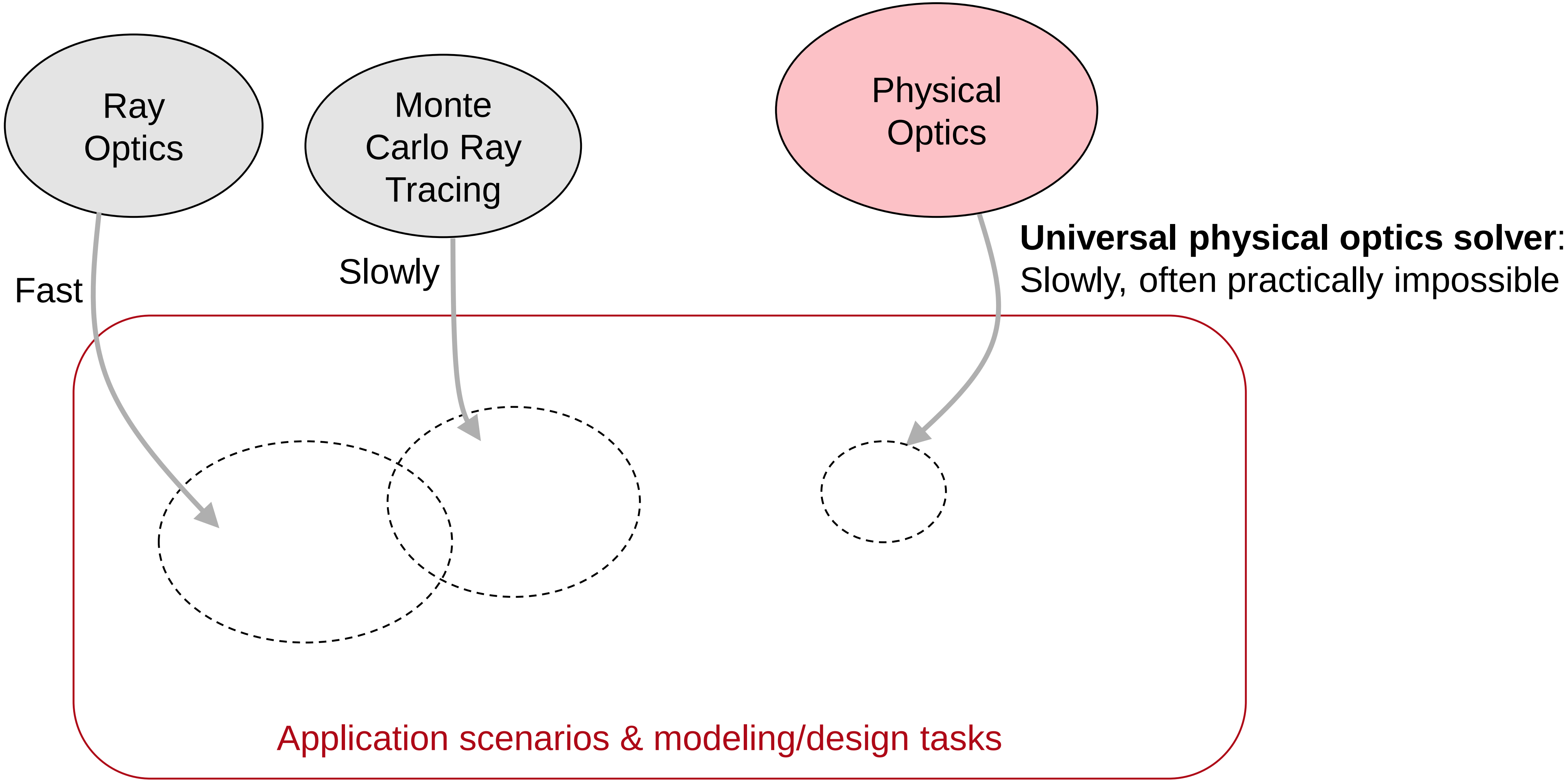
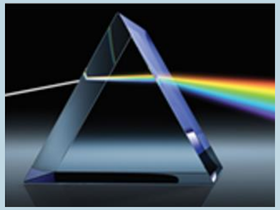


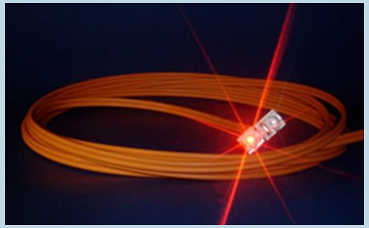
# Physical Optics Modeling by Universal Solver

Universal Solver

$$O(N^2), O(N^3)$$





Components in optical system

- **Universal physical optics solver**:
  - Integral operation
  - Numerical complexity $O(N^2)$ and higher ($N$ number of field sampling values)
  - Large to huge $N$ (proportional to modeling volume $(\Delta s/\lambda)^3$)

# Physical Optics Modeling by Universal Solver

One-size-fits-all physical-optics solver

↓

Various specialized physical-optics solvers

Universal Solver

$O(N^2)$, $O(N^3)$

Components in optical system

**Universal physical optics solver:**

- Integral operation
- Numerical complexity $O(N^2)$ and higher ($N$ number of field sampling values)
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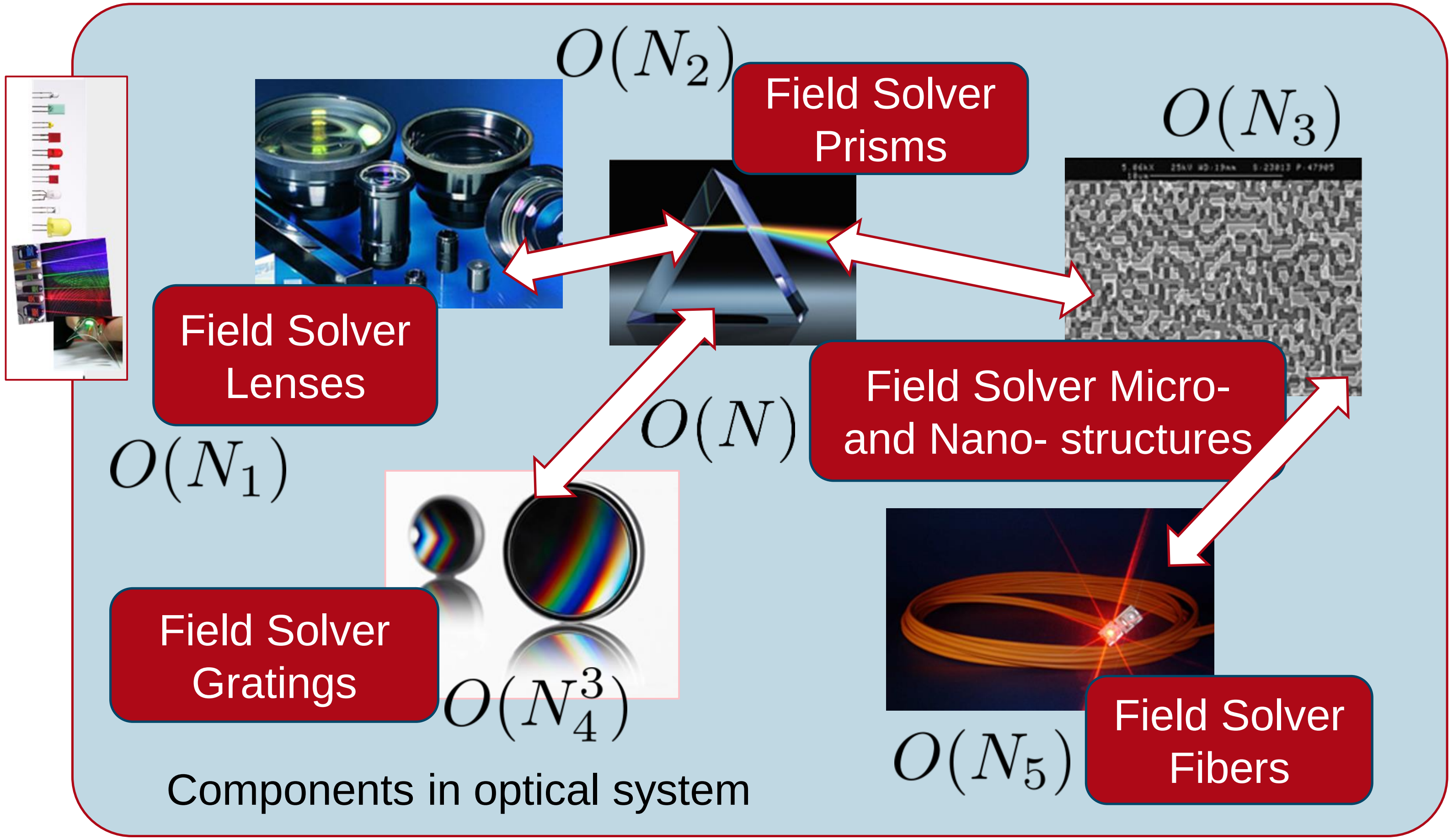
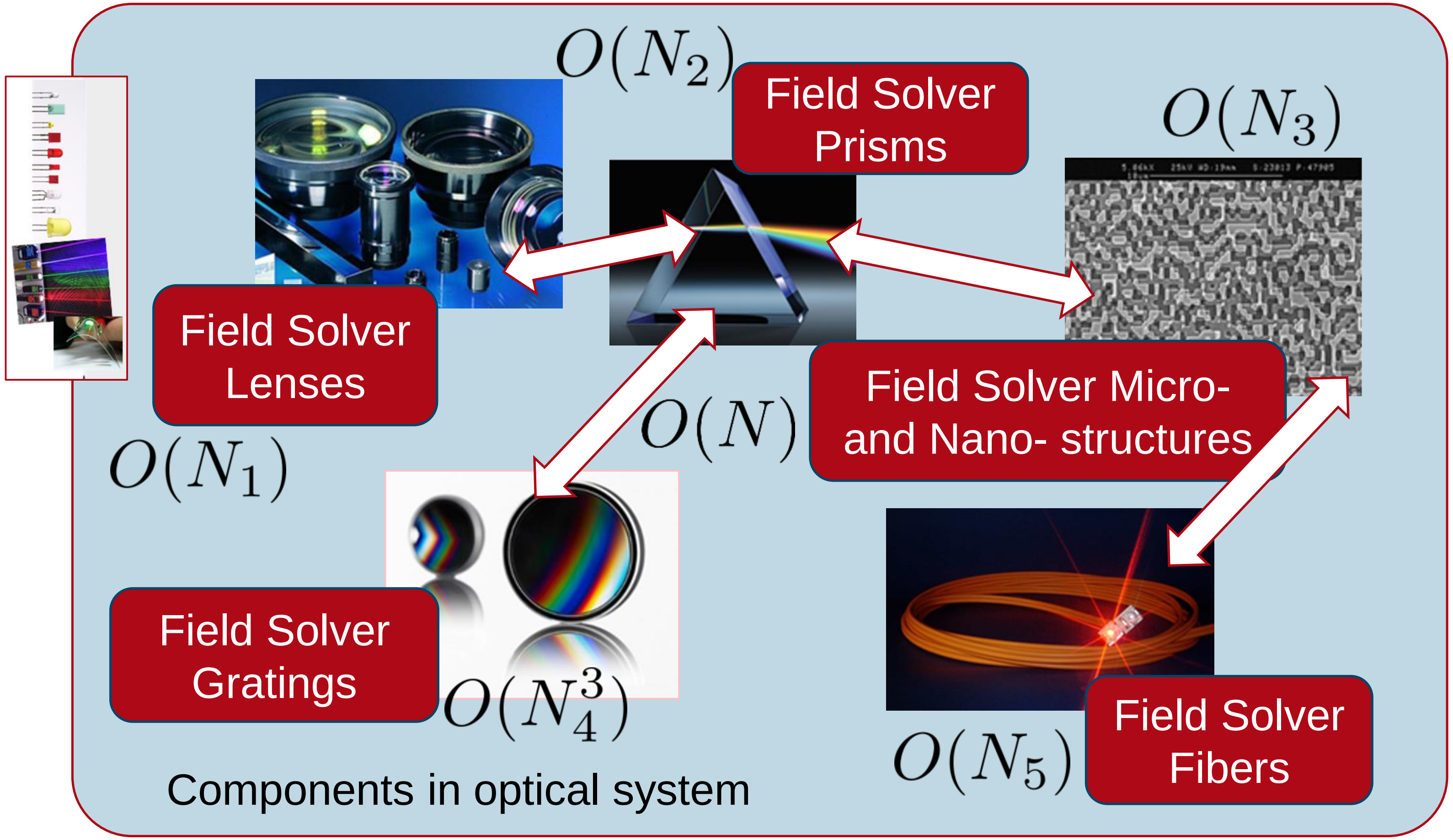
# Physical Optics Modeling by Connecting Solvers



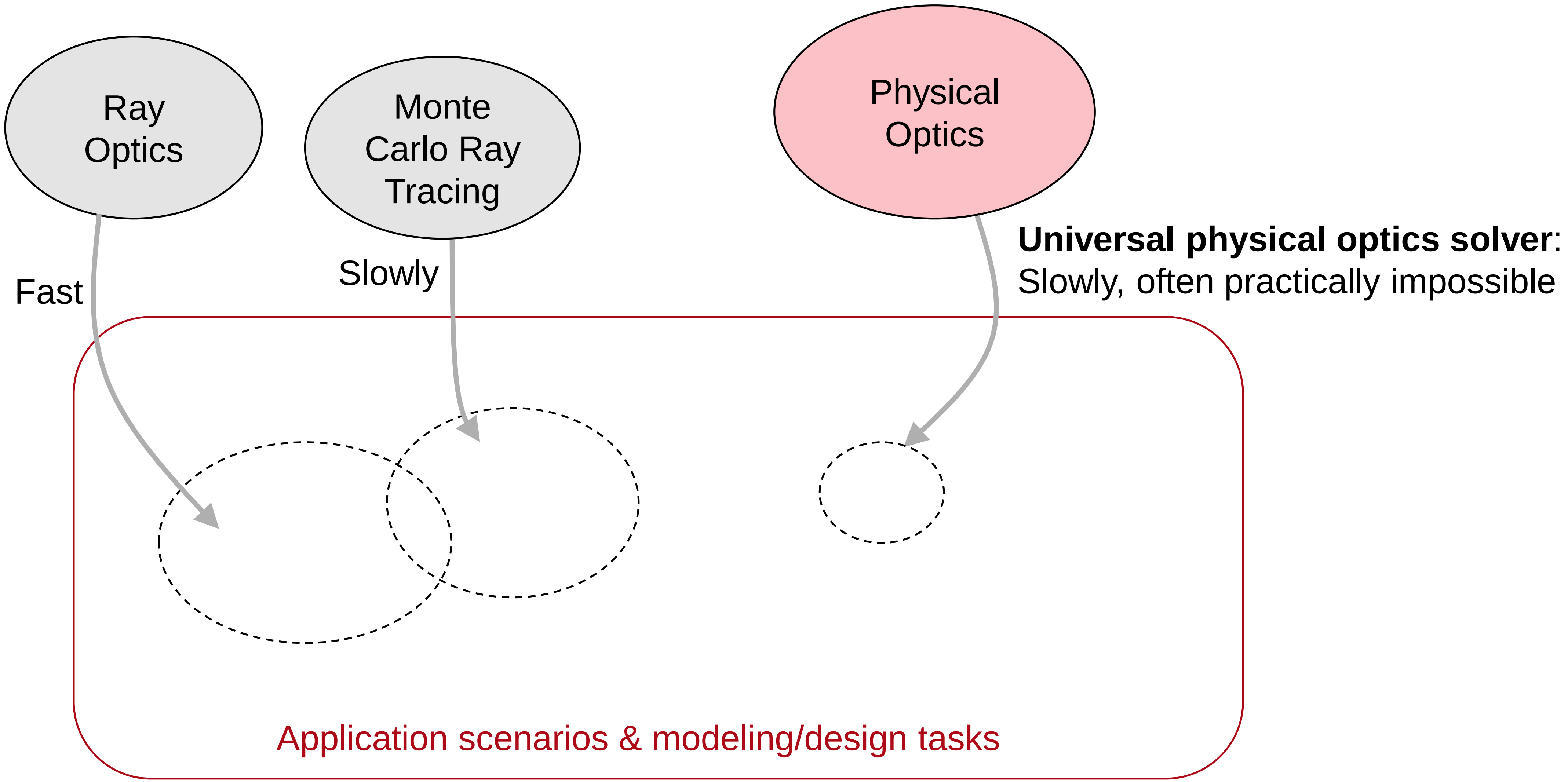

- **Connecting specialized physical optics solvers**:
  - Pointwise and integral operations for different components (index $j$)
  - Numerical complexity of different solvers varies from $O(N_j)$ to $O(N_j^2)$ and higher
  - Minimized $N_j$: small to large
- Dominant integral operation is Fourier transform; FFT complexity $O(N \log N)$

# Fast Physical Optics

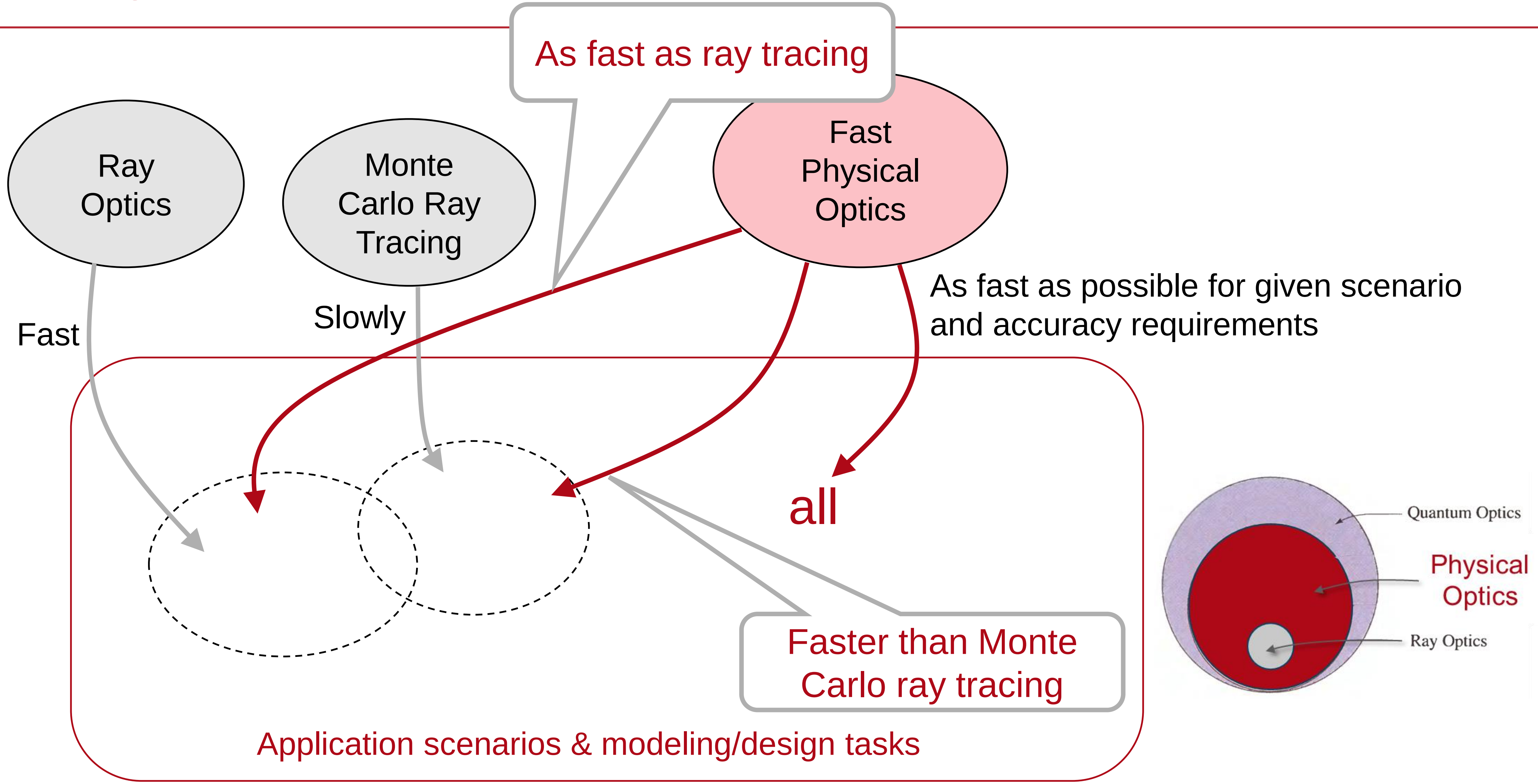



- Apply tailored solvers and sampling $N$ per component.
- Use solvers with numerical complexity $O(N)$ wherever possible.

# Modeling Techniques

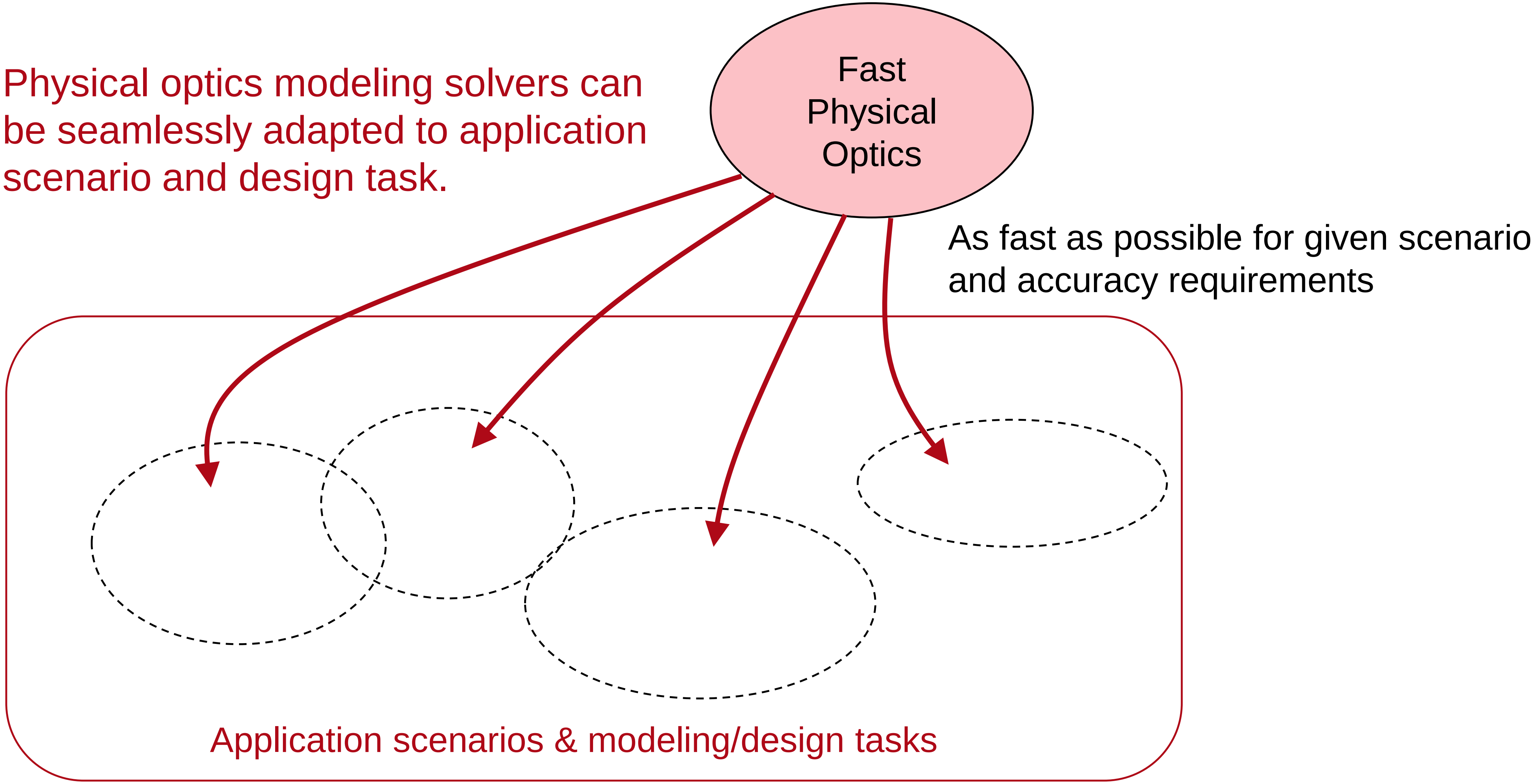


# Modeling Techniques



# Fast Physical Optics Modeling and Design

Physical optics modeling solvers can be seamlessly adapted to application scenario and design task.



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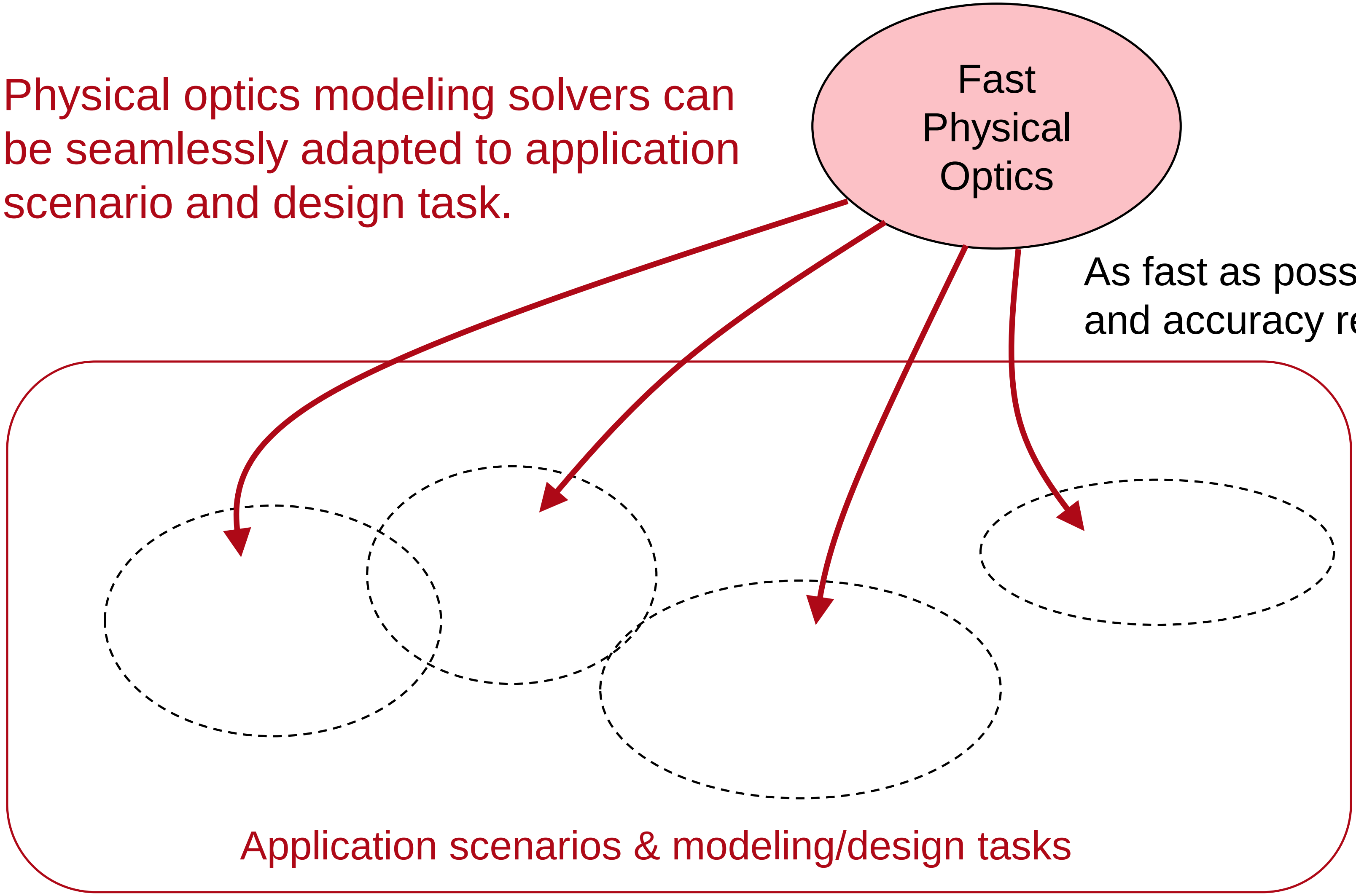
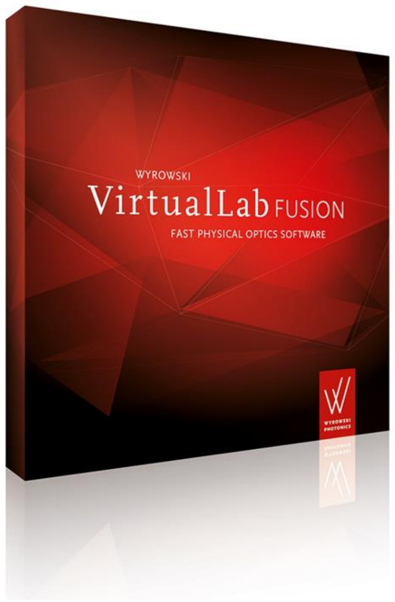



As fast as possible for given scenario and accuracy requirements



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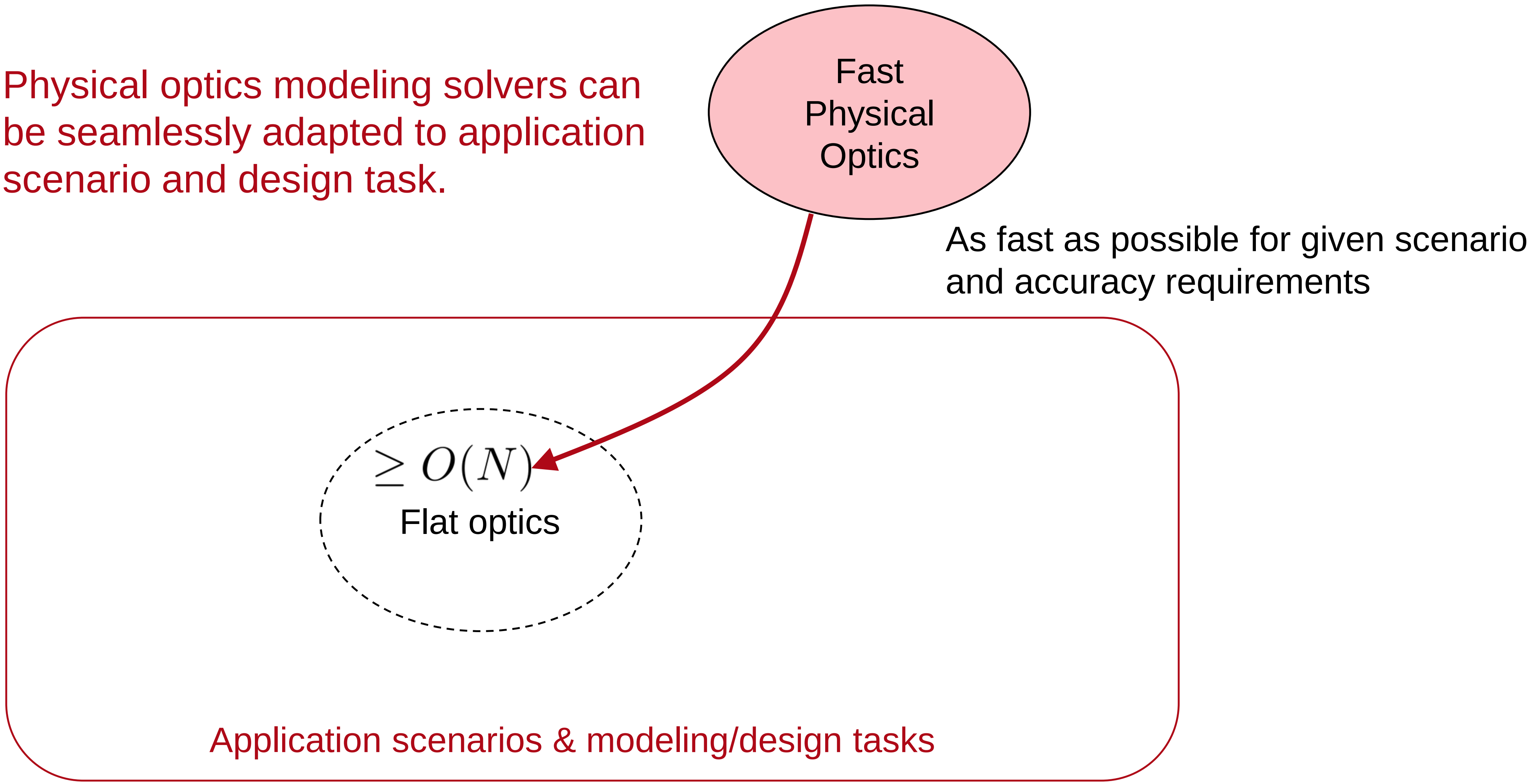
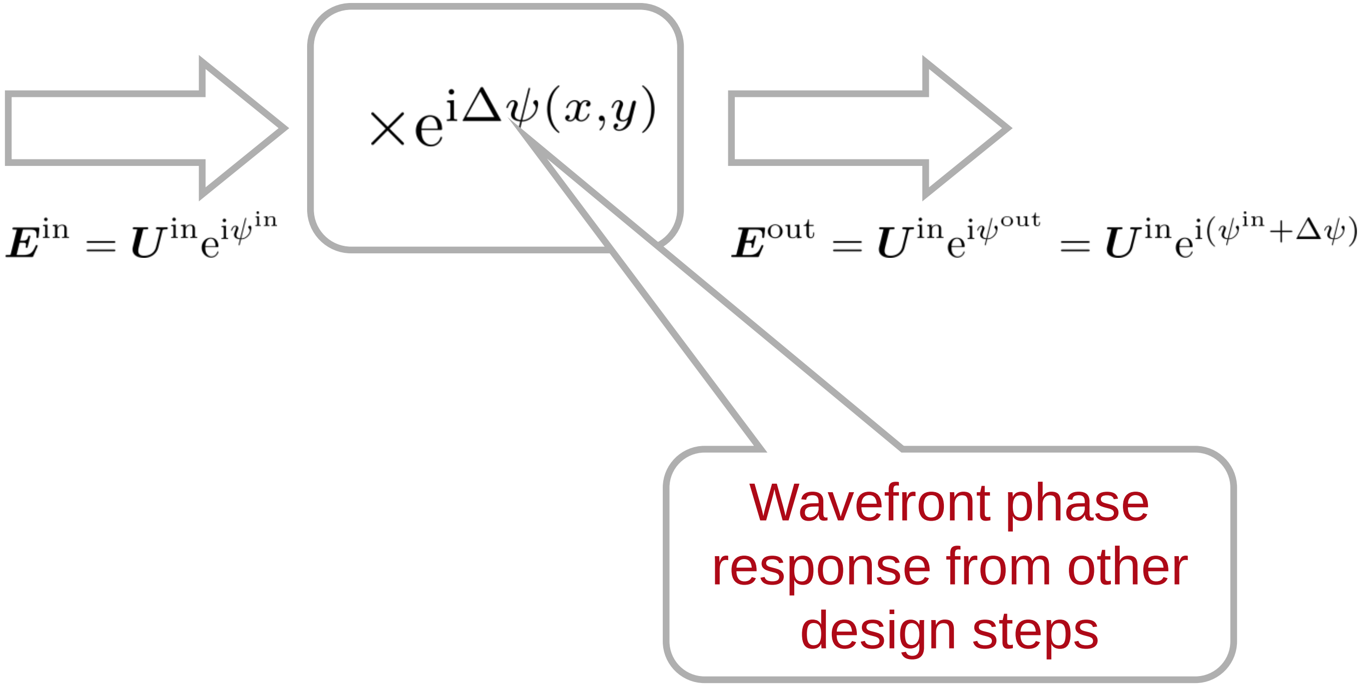


# Wavefront Phase Manipulation



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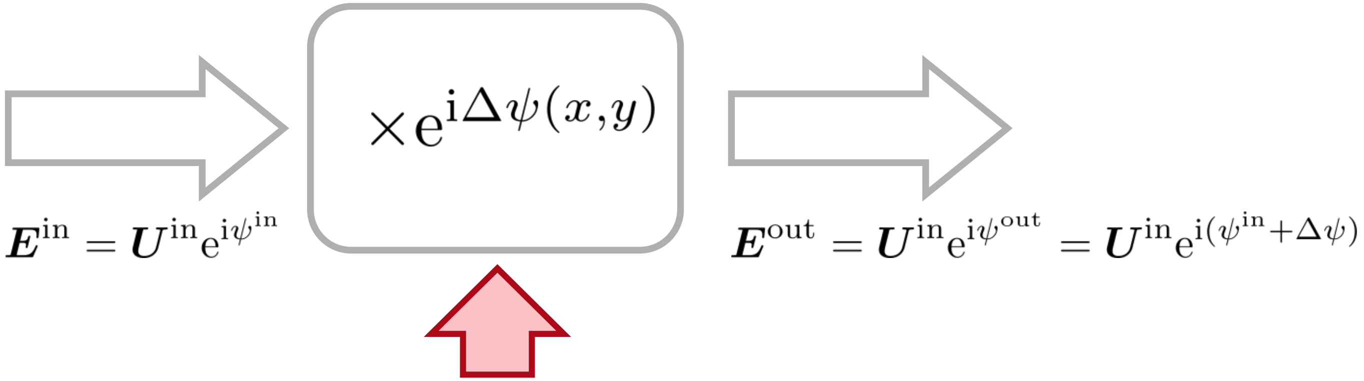
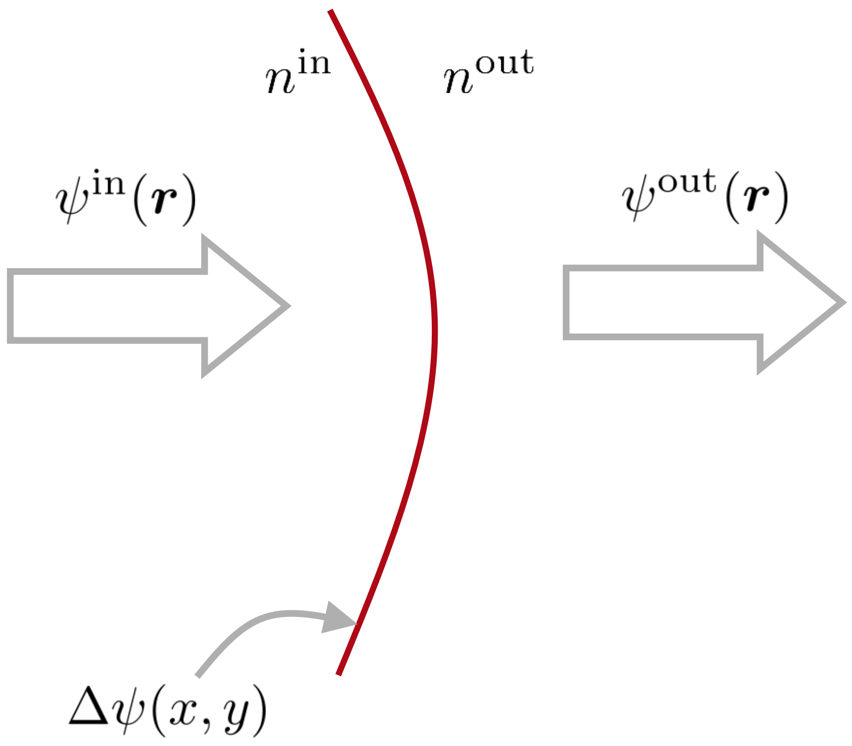
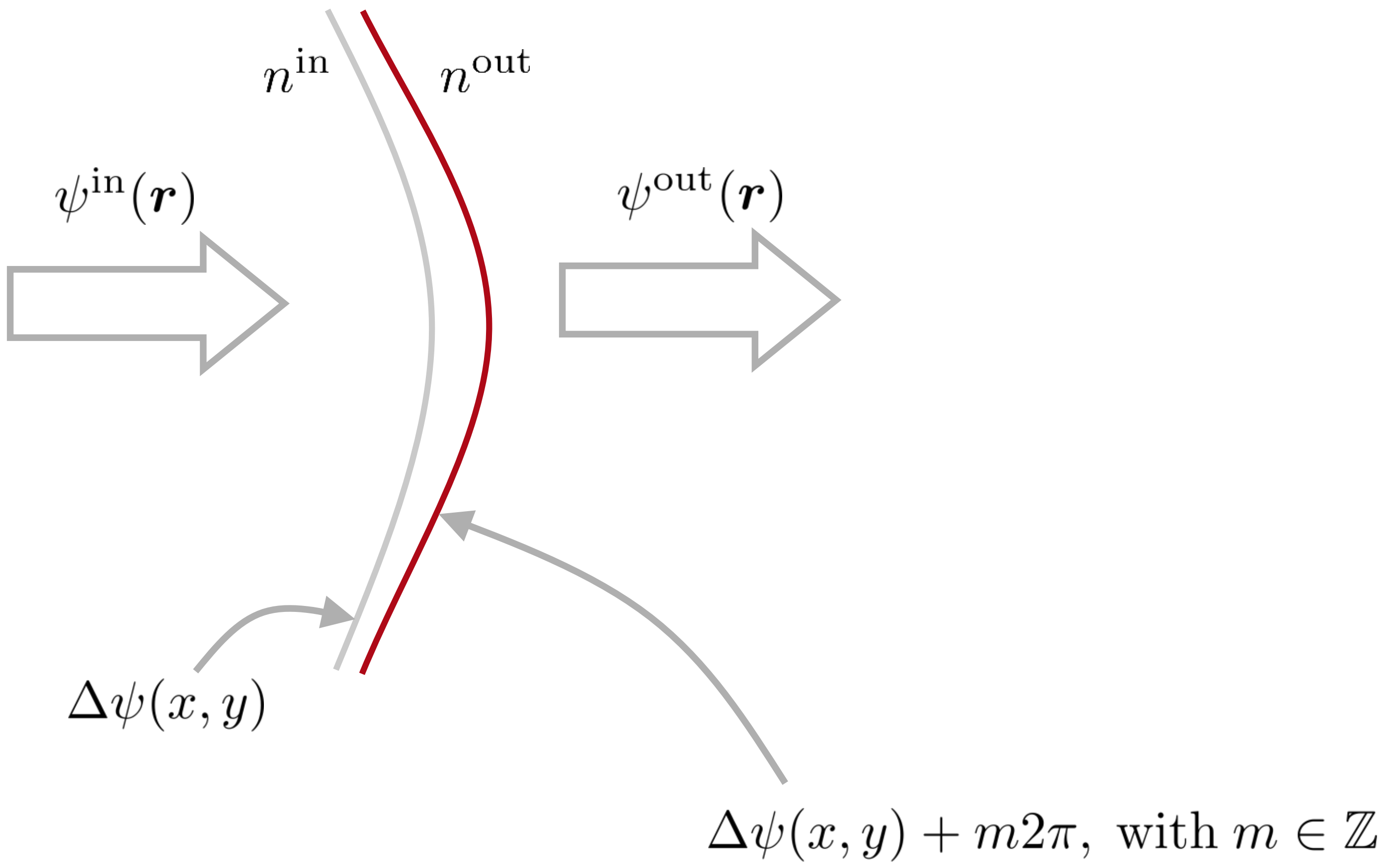



Which structures can be used to realize wavefront phase response in practice?

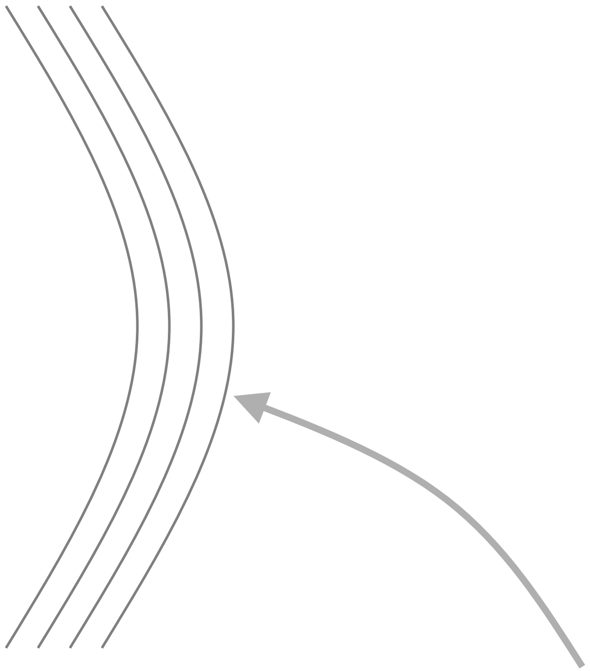
# Smooth Surface Design



# Multiple Surface Designs



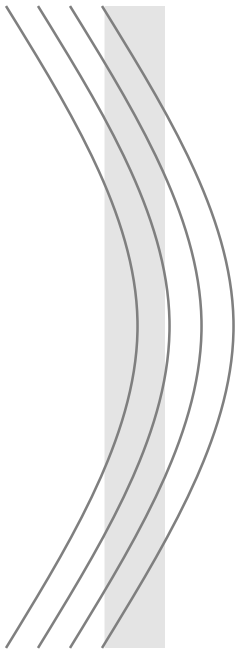
# Multiple Surface Designs



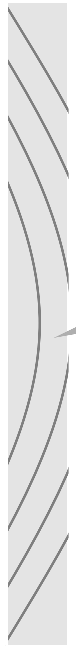
Set of surface designs with:

$$\Delta\psi(x, y) + m2\pi, \text{ with } m \in \mathbb{Z}$$

# Regional Usage of Multiple Surfaces: Flatten of Surface

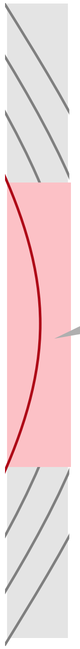


# Regional Usage of Multiple Surfaces: Flatten of Surface



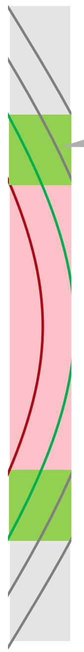
All surfaces can be used for the wavefront manipulation. So, we may use them in different regions as well.

# Regional Usage of Multiple Surfaces: Flatten of Surface



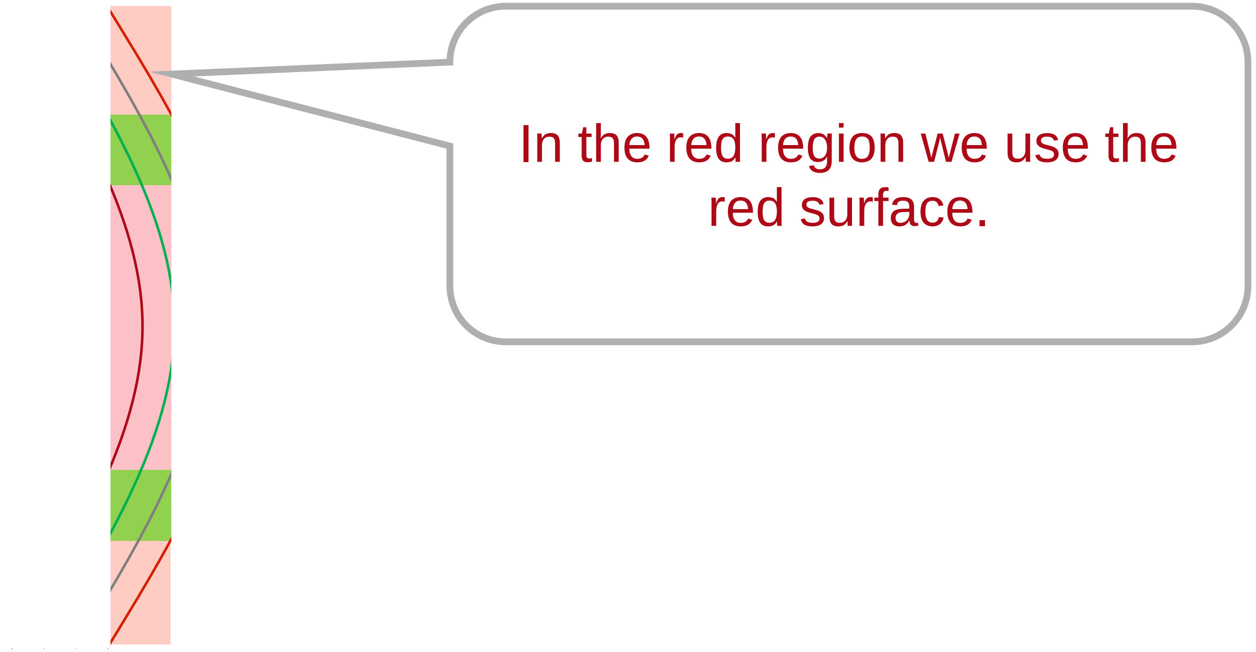
In the red region we use the red surface.

# Regional Usage of Multiple Surfaces: Flatten of Surface

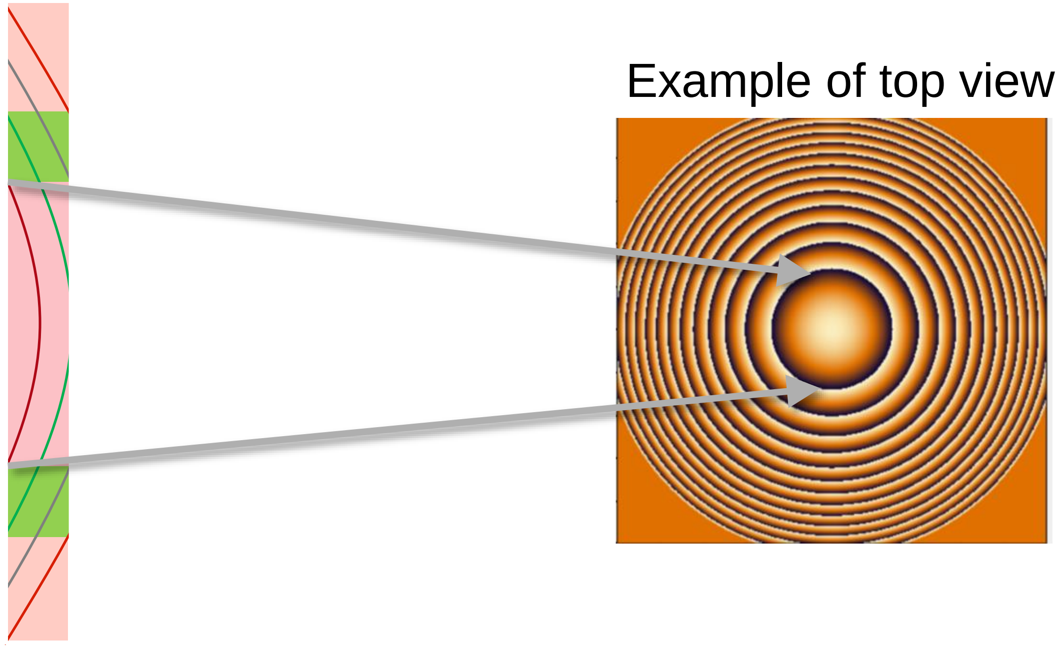


In the green region we use the green surface.

# Regional Usage of Multiple Surfaces: Flatten of Surface



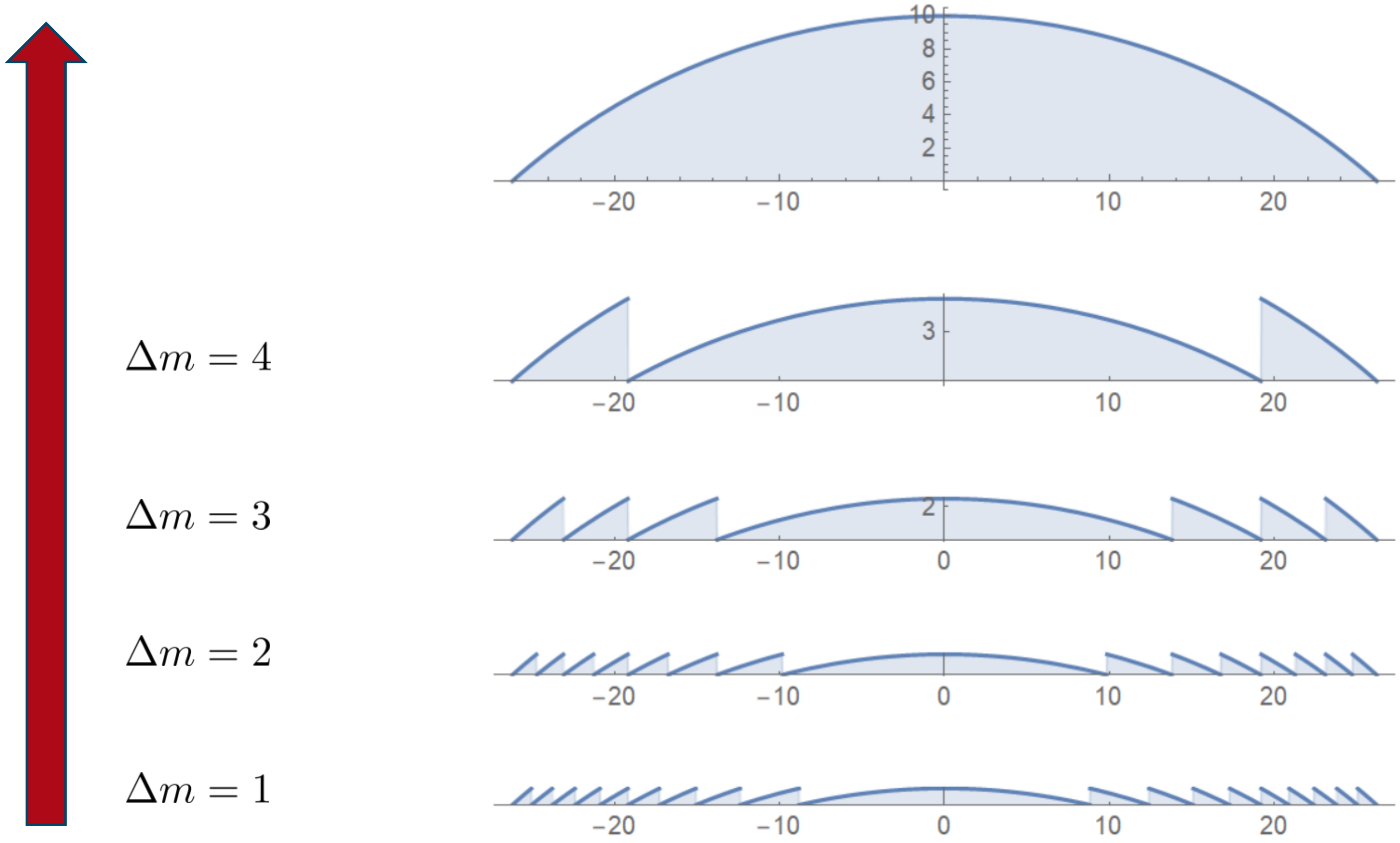
# Regional Usage of Multiple Surfaces: Flatten of Surface



# Example: Oculus Rift S VR Glasses (Meta)

# Segmented Surfaces

Schematic figure only!



# Segmented Surfaces

Schematic figure only!

Refractive lens
Freeform lens/surface
Aspherical lens

.
.
.

Segmented lens/surface
Fresnel lens

.
.
.

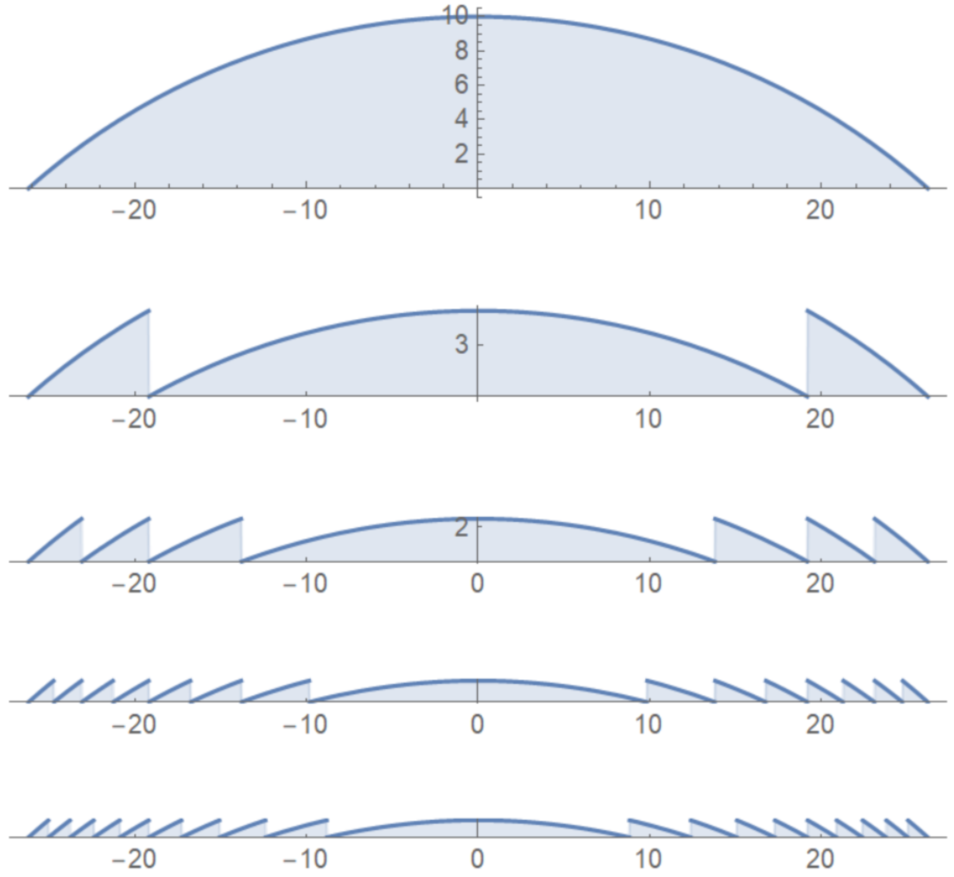
Diffractive lens, DOE
Holographic optical element (HOE)

$\Delta m = 4$

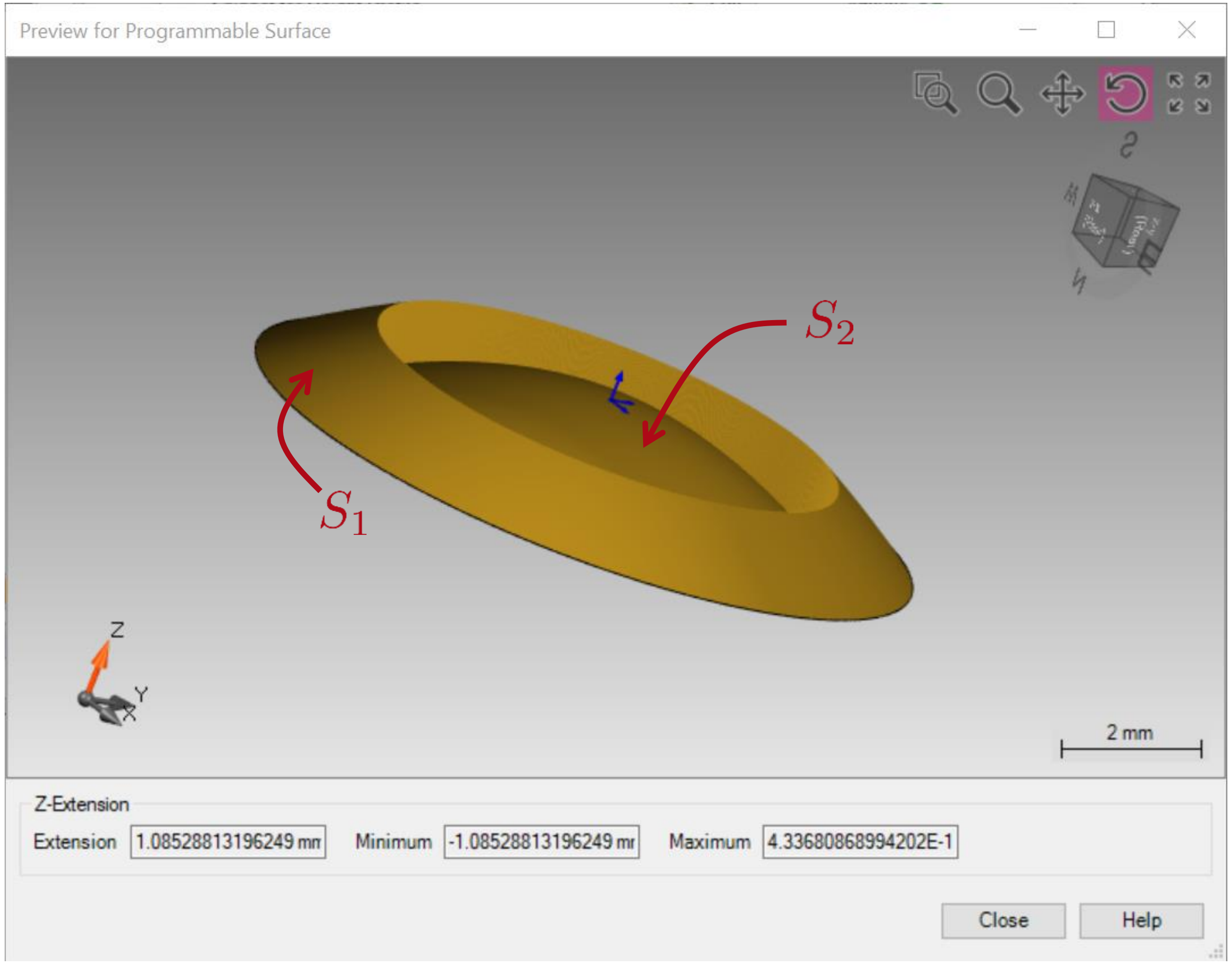
$\Delta m = 3$

$\Delta m = 2$

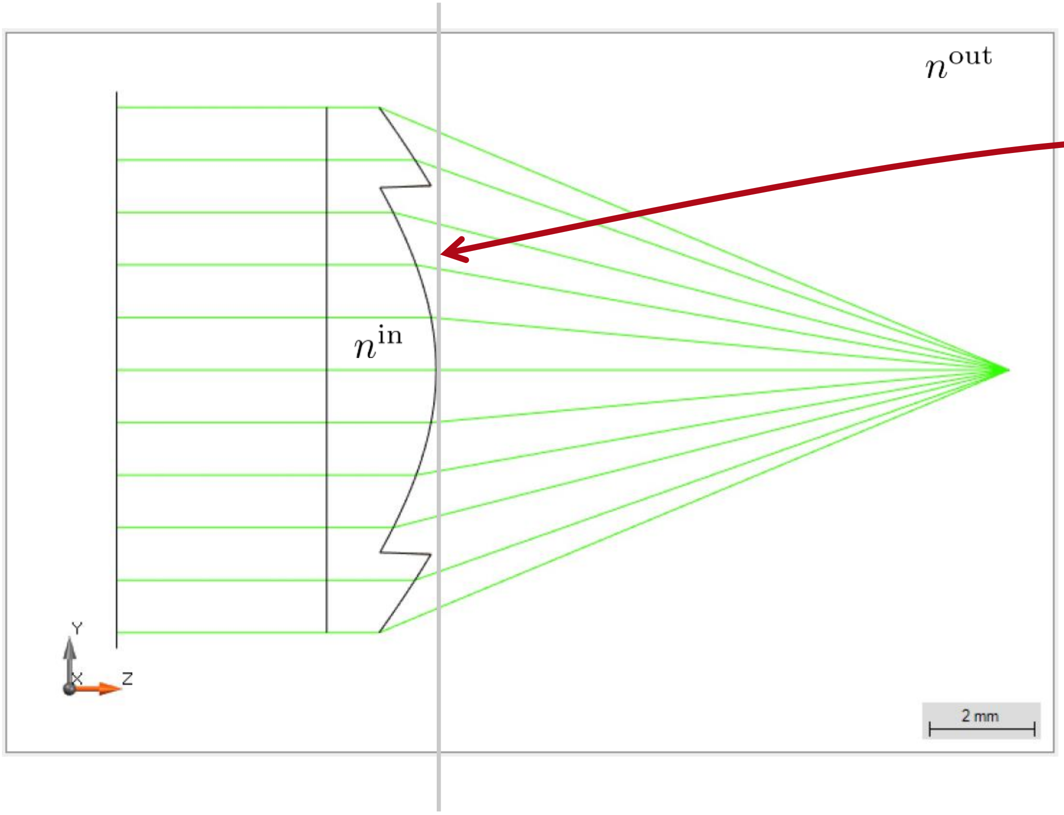
$\Delta m = 1$

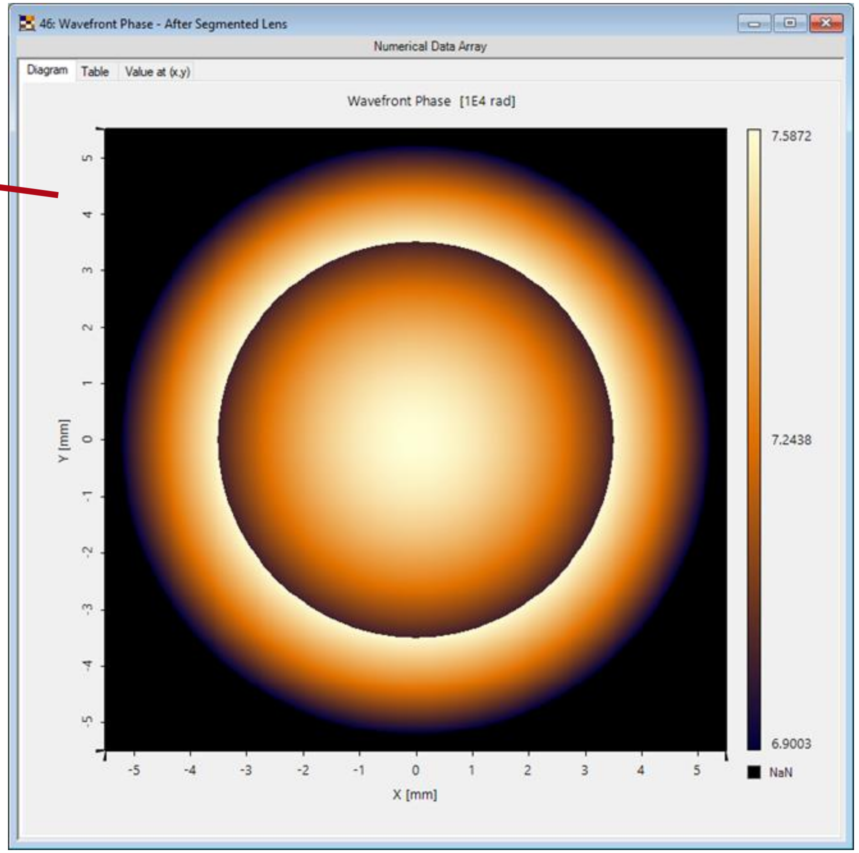


# Structural Design Segmented Lens: Focusing NA 0.4



# Focusing (NA = 0.4) Lens: Physical-Optics Modeling

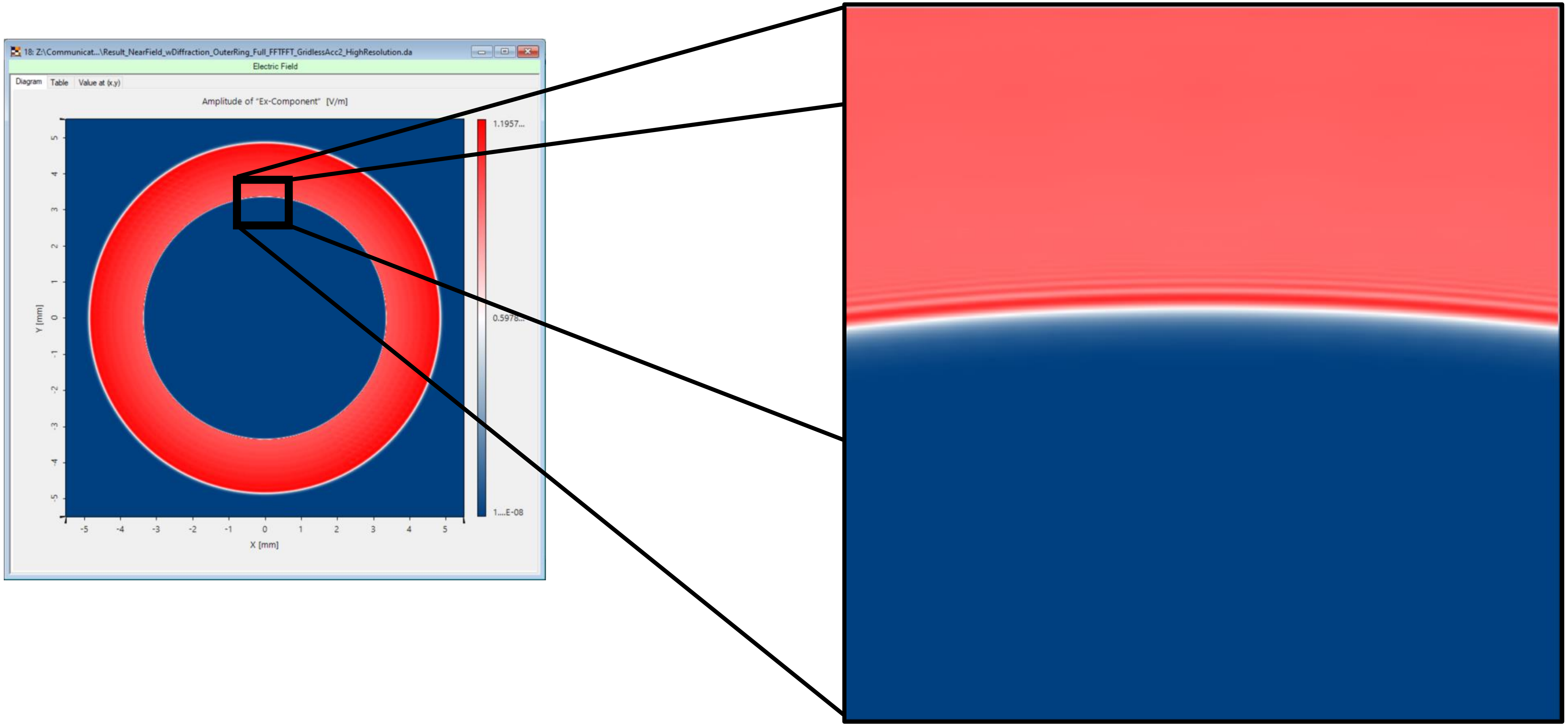



Phase behind lens

# Focusing (NA = 0.4) Lens: Physical-Optics Modeling

**Near Field Analysis – 500µm after Segmented Lens:**



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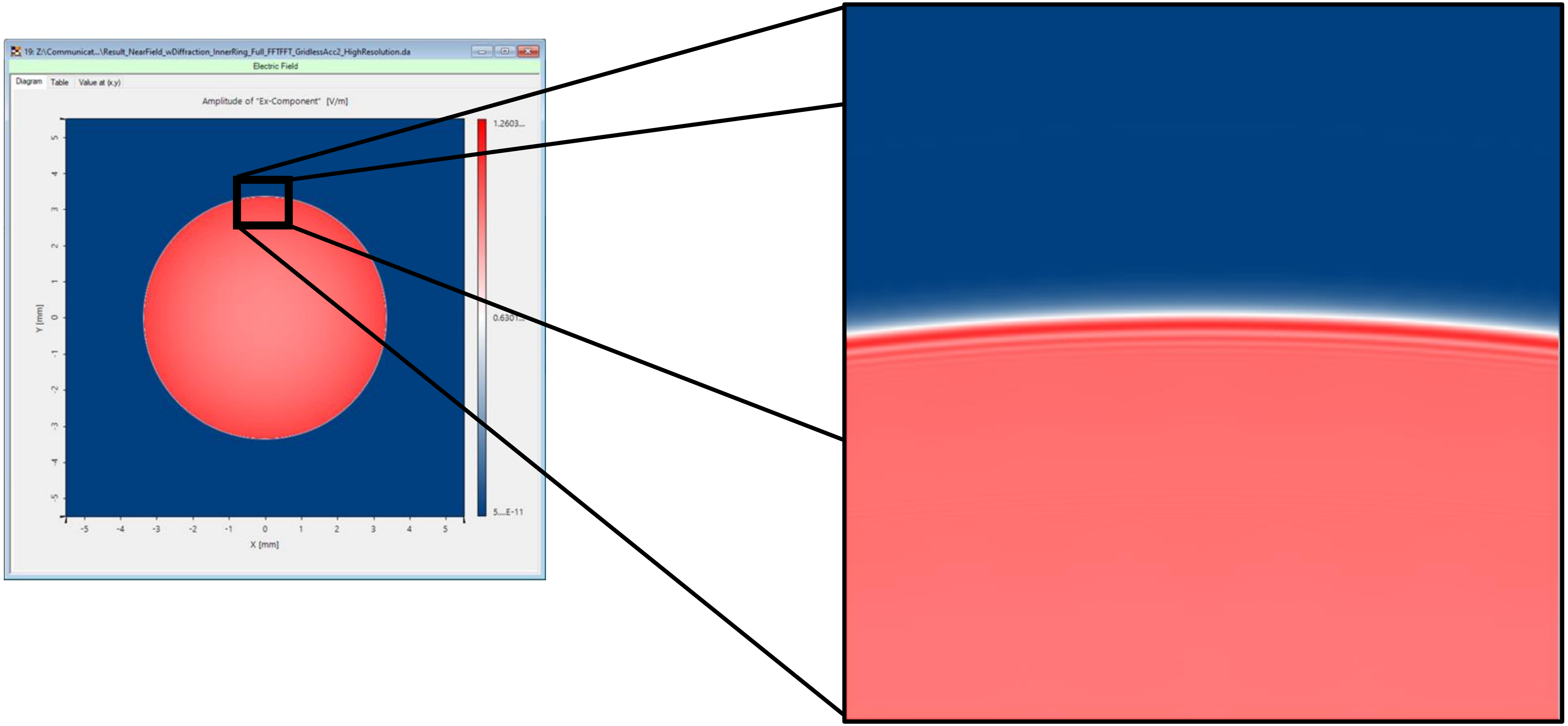

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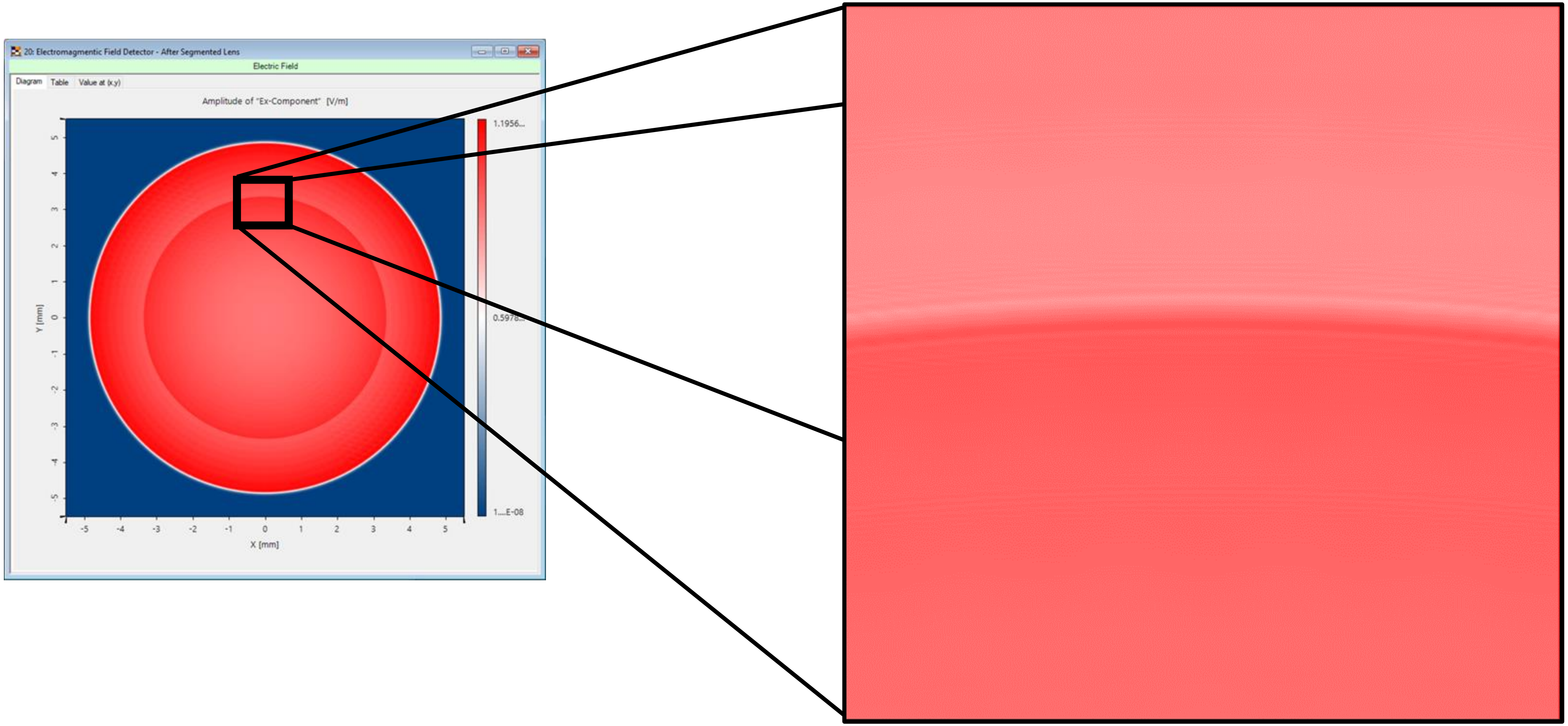

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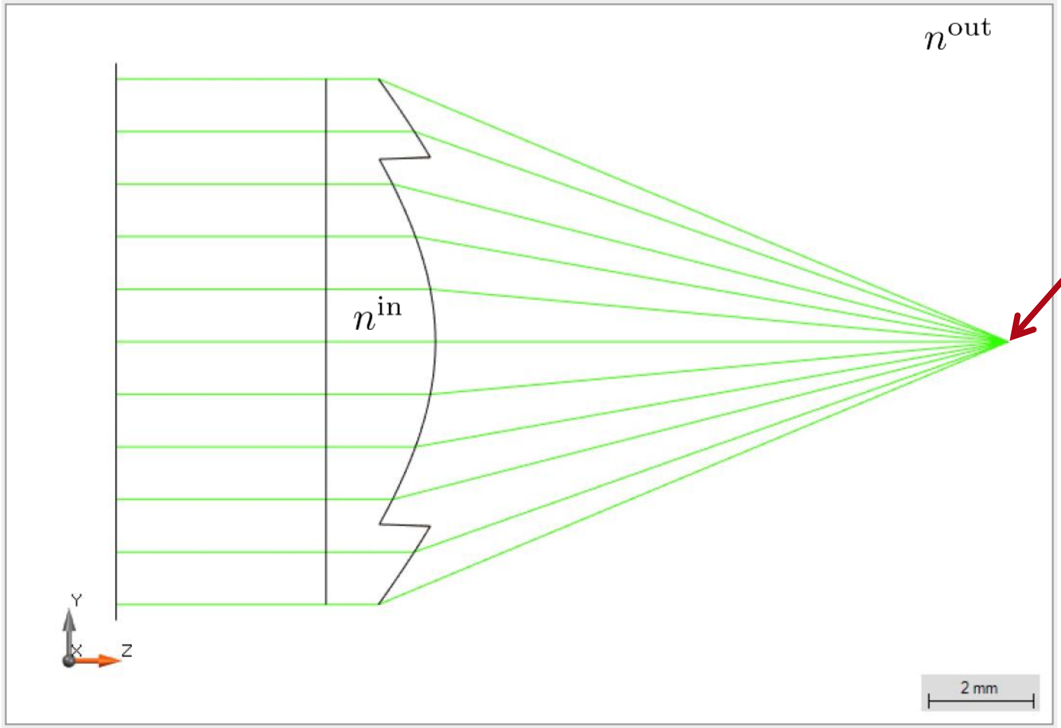
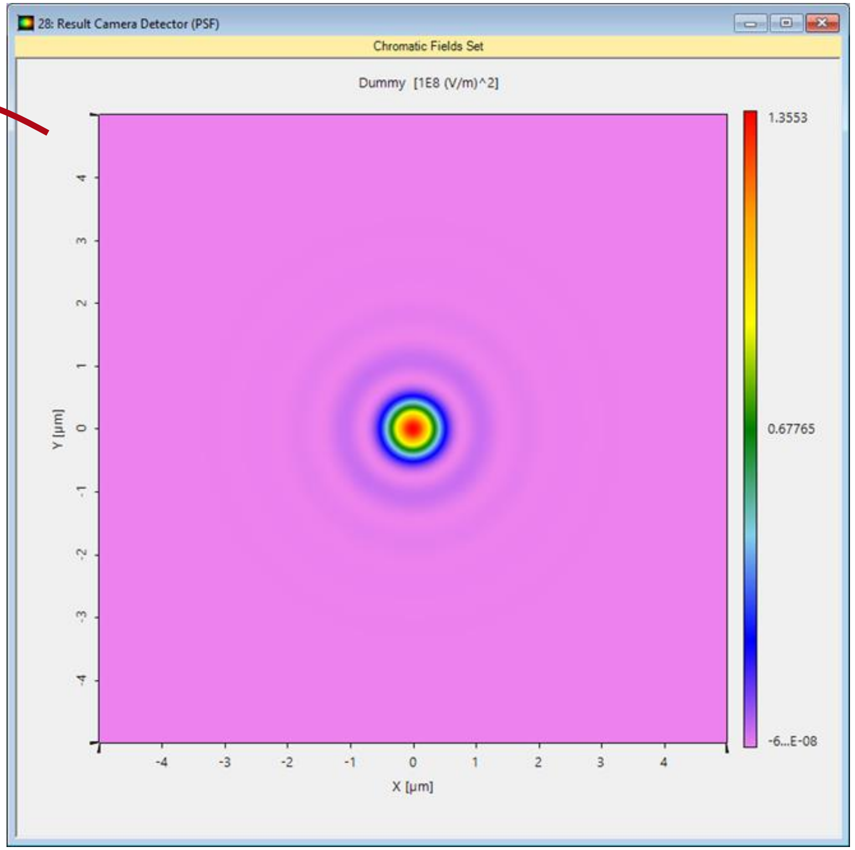
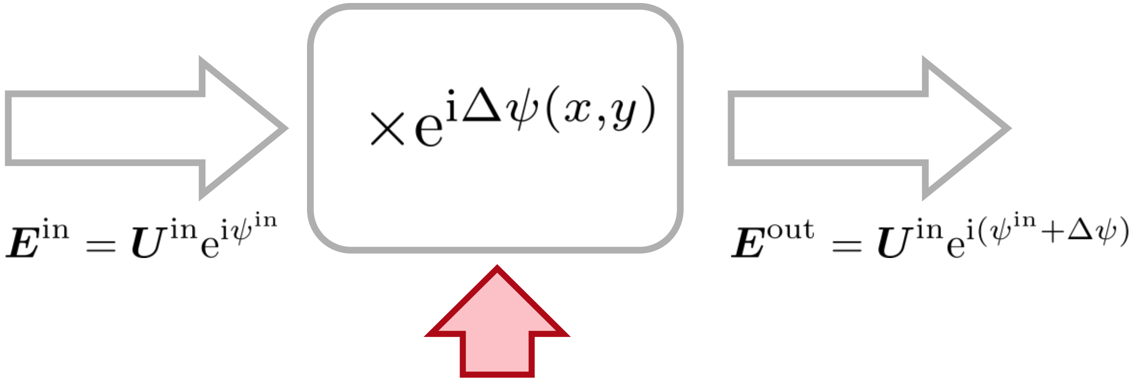



Intensity in focus

# Wavefront Phase Manipulation




Which structures can be used to realize wavefront phase response in practice?

# Wavefront Phase Manipulation

$$\boldsymbol{E}^{\mathrm{in}} = \boldsymbol{U}^{\mathrm{in}} \mathrm{e}^{\mathrm{i}\psi^{\mathrm{in}}}$$

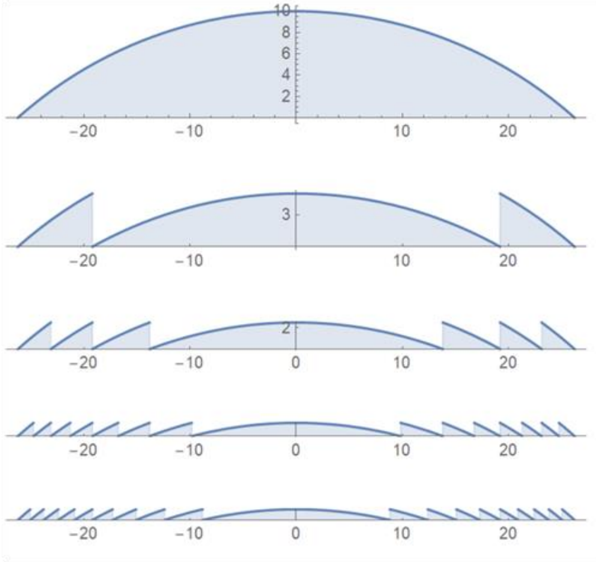
$$\times \mathrm{e}^{\mathrm{i}\Delta\psi(x,y)}$$

$$\boldsymbol{E}^{\mathrm{out}} = \boldsymbol{U}^{\mathrm{in}} \mathrm{e}^{\mathrm{i}(\psi^{\mathrm{in}}+\Delta\psi)}$$

Freeform

Fresnel Zone Surface

Diffractive/Holographic Optical Element




All surfaces control phase via optical path and height profile.

# Wavefront Phase Manipulation

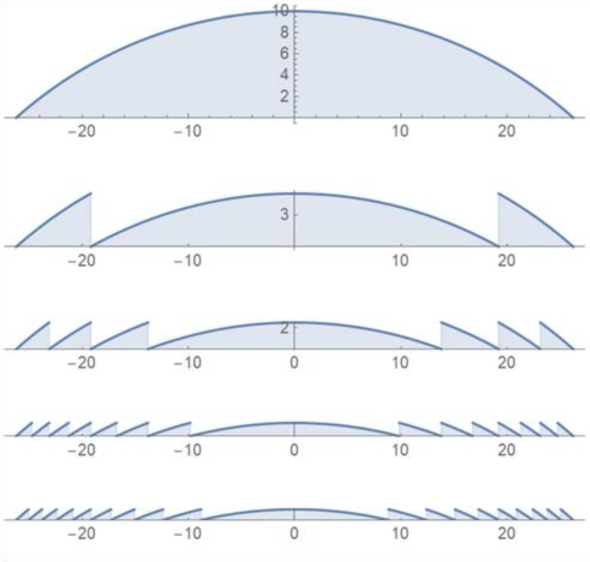
$$\boldsymbol{E}^{\mathrm{in}} = \boldsymbol{U}^{\mathrm{in}} \mathrm{e}^{\mathrm{i}\psi^{\mathrm{in}}} \quad \times \mathrm{e}^{\mathrm{i}\Delta\psi(x,y)} \quad \boldsymbol{E}^{\mathrm{out}} = \boldsymbol{U}^{\mathrm{in}} \mathrm{e}^{\mathrm{i}(\psi^{\mathrm{in}}+\Delta\psi)}$$

Use of effects at subwavelength structures for phase control.

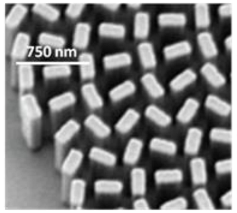
Freeform

Fresnel Zone Surface

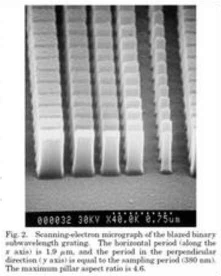
Diffractive/Holographic Optical Element




Metasurfaces

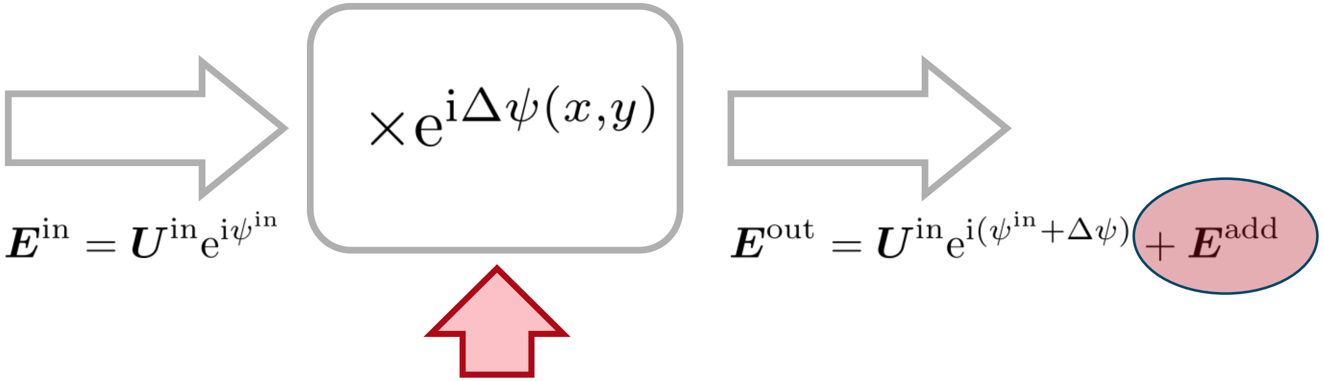



M. Khorasaninejad *et al.* Science **352**, 1190-1194 (2016)



P. Lalanne, *et al.*, "Blazed binary subwavelength gratings with efficiencies larger than those of conventional échelette gratings," Opt. Lett. 23, 1081-1083 (1998)

# Wavefront Phase Manipulation



$$\boldsymbol{E}^{\mathrm{in}} = \boldsymbol{U}^{\mathrm{in}} \mathrm{e}^{\mathrm{i}\psi^{\mathrm{in}}}$$

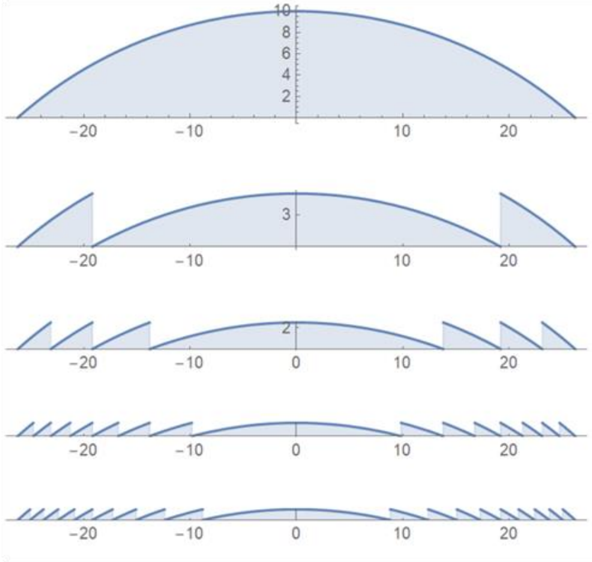
$$\times \mathrm{e}^{\mathrm{i}\Delta\psi(x,y)}$$

$$\boldsymbol{E}^{\mathrm{out}} = \boldsymbol{U}^{\mathrm{in}} \mathrm{e}^{\mathrm{i}(\psi^{\mathrm{in}}+\Delta\psi)} + \boldsymbol{E}^{\mathrm{add}}$$

Freeform

Fresnel Zone Surface

Diffractive/Holographic Optical Element

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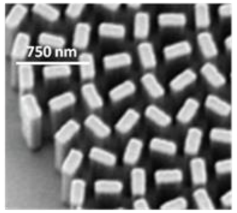
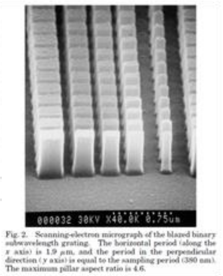



M. Khorasaninejad *et al.* Science **352**, 1190-1194 (2016)



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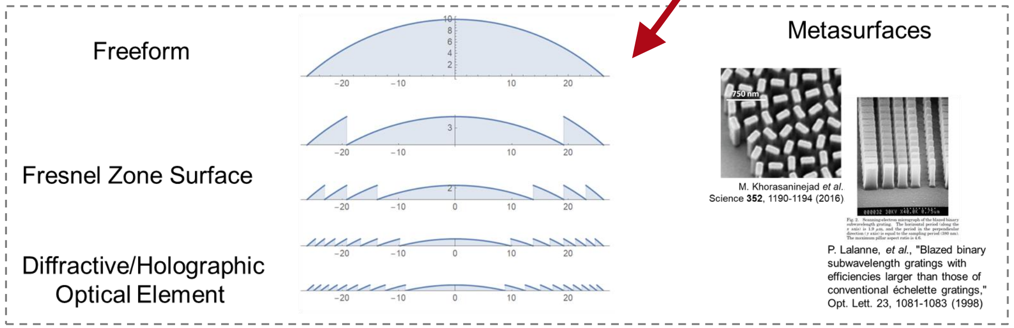
# Fast Physical Optics Modeling and Design: Flat Optics

Physical optics modeling solvers can be seamlessly adapted to application scenario and design task.

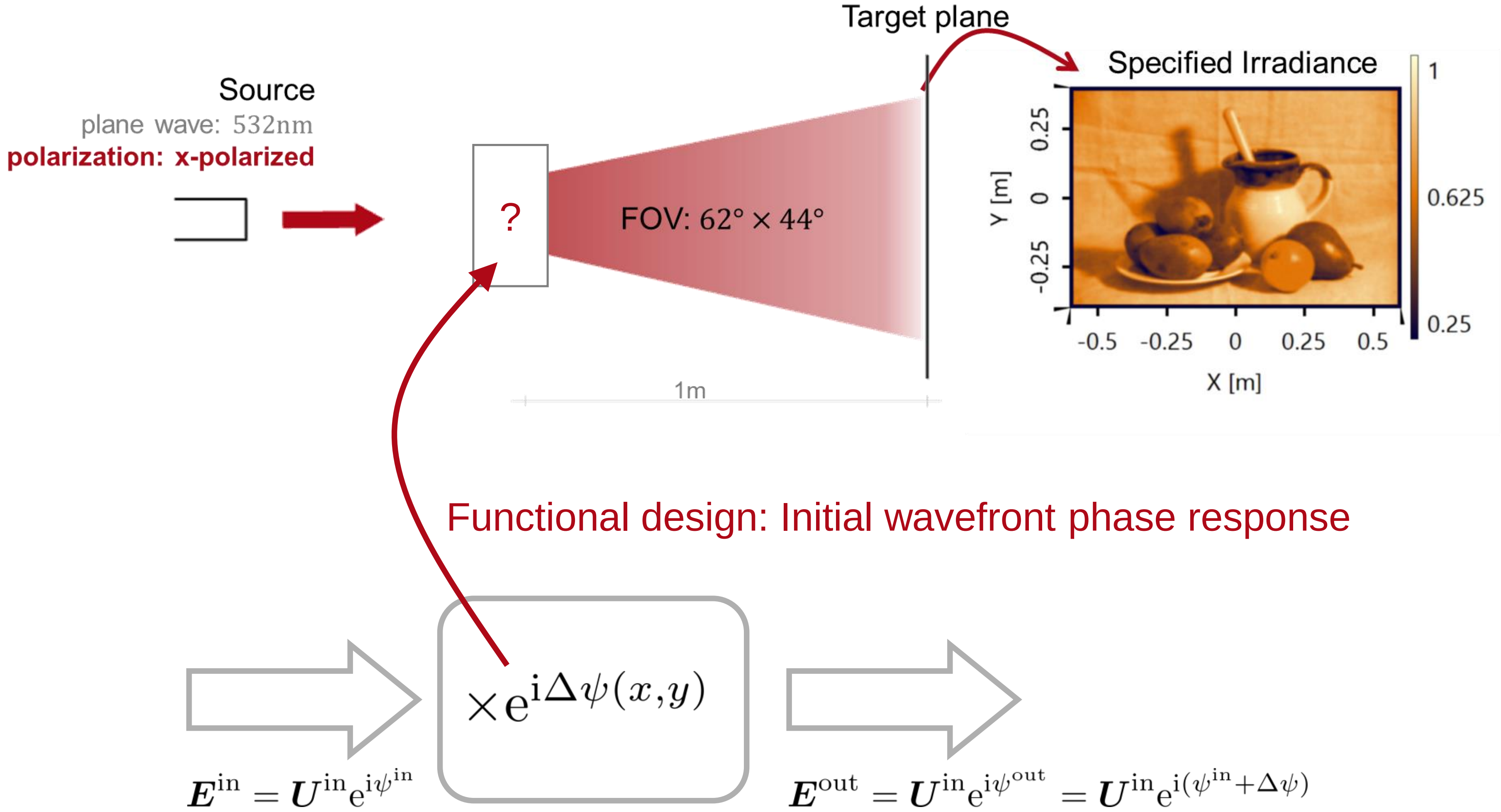
Fast Physical Optics

As fast as possible for given scenario and accuracy requirements




Application scenarios & modeling/design tasks

# Scenario: Plane Wave to General Irradiance in Far Field



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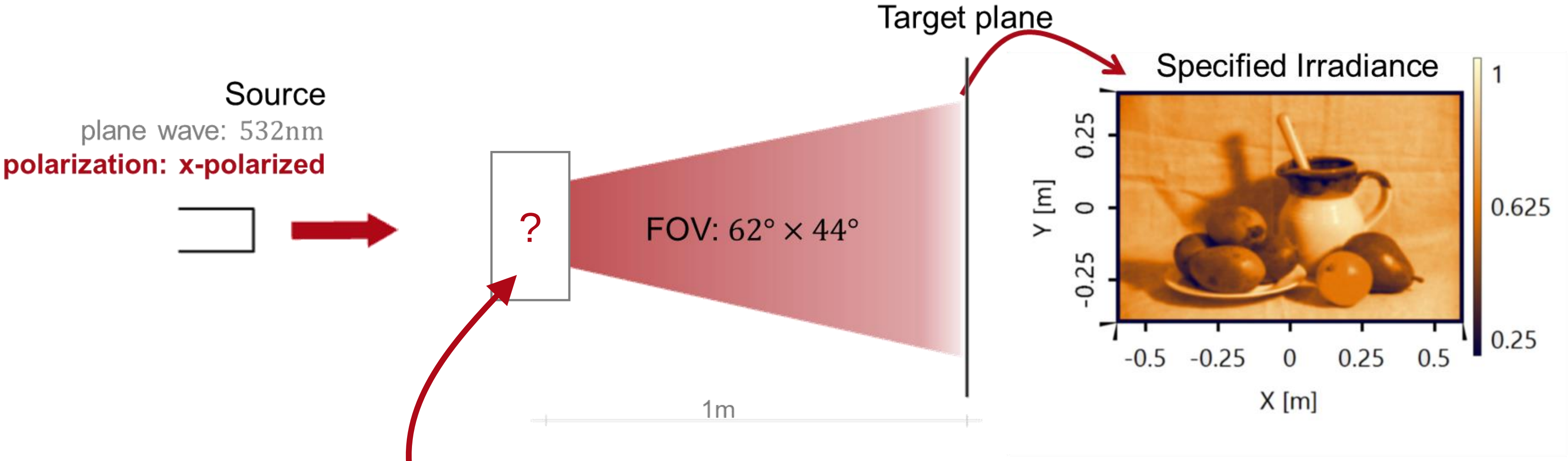
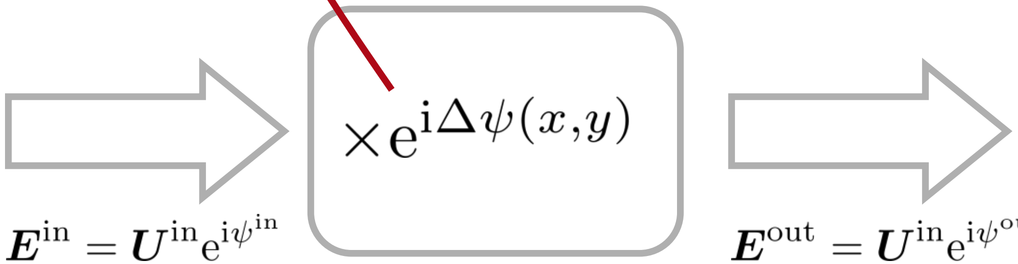


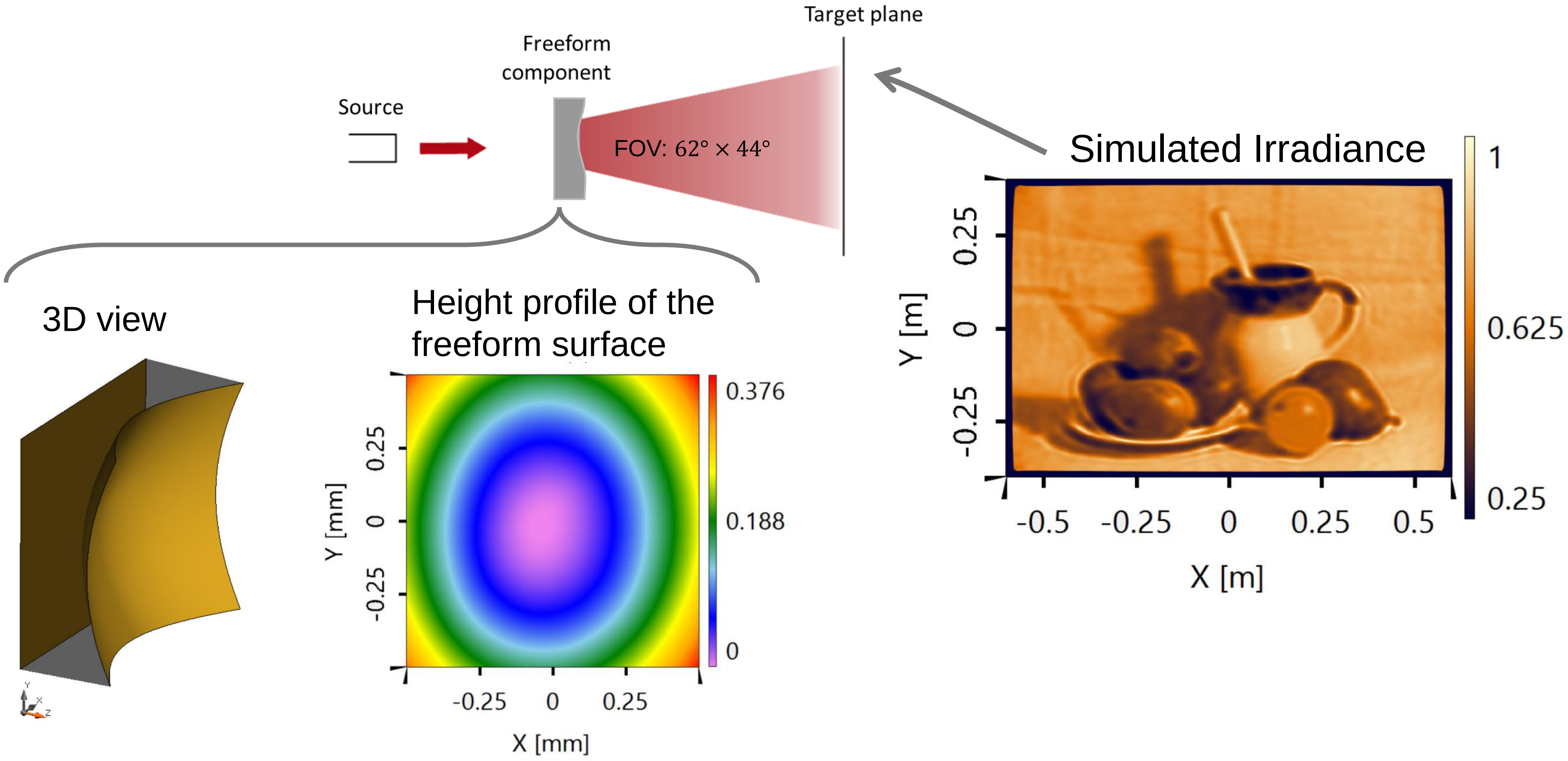

Structural design, e.g., smooth freeform surface



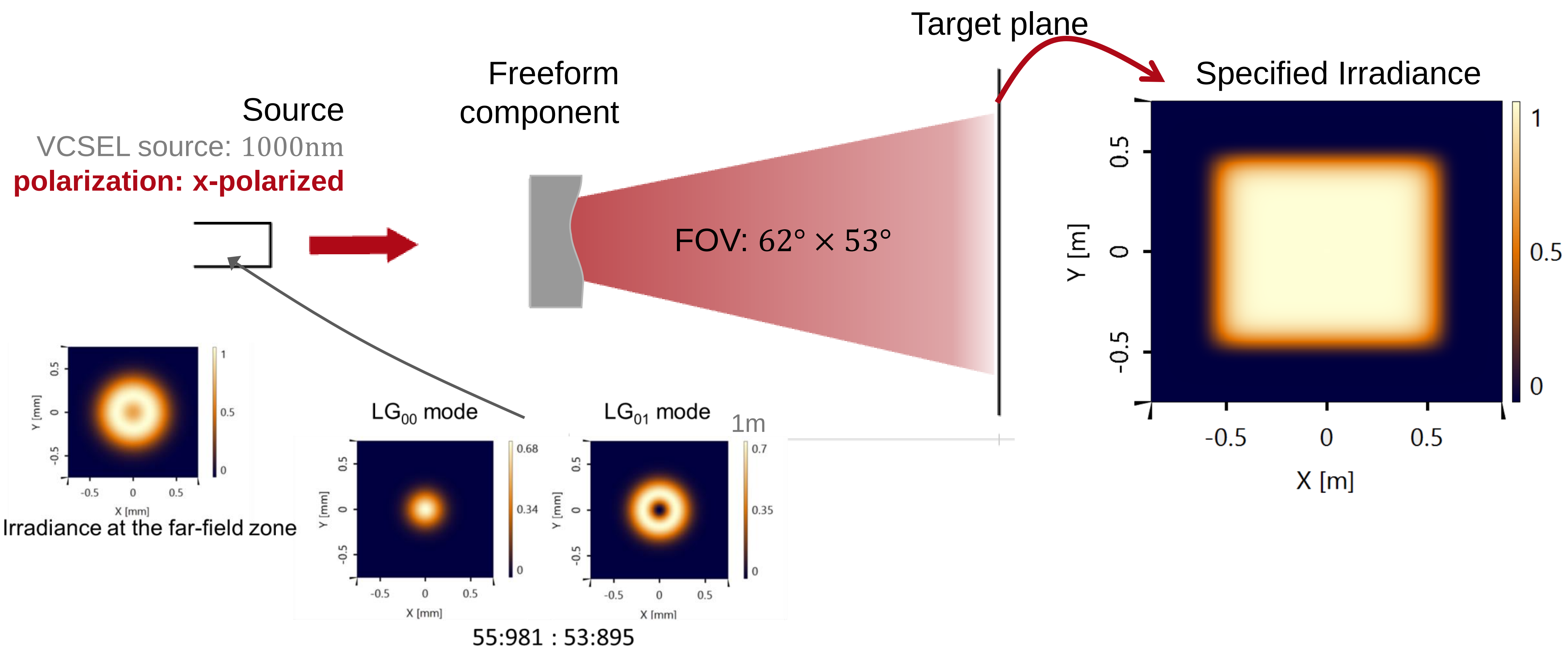

$\boldsymbol{E}^{\mathrm{in}} = \boldsymbol{U}^{\mathrm{in}} e^{i\psi^{\mathrm{in}}}$

$\boldsymbol{E}^{\mathrm{out}} = \boldsymbol{U}^{\mathrm{in}} e^{i\psi^{\mathrm{out}}} = \boldsymbol{U}^{\mathrm{in}} e^{i(\psi^{\mathrm{in}} + \Delta\psi)}$

# Scenario: Plane Wave to General Irradiance in Far Field

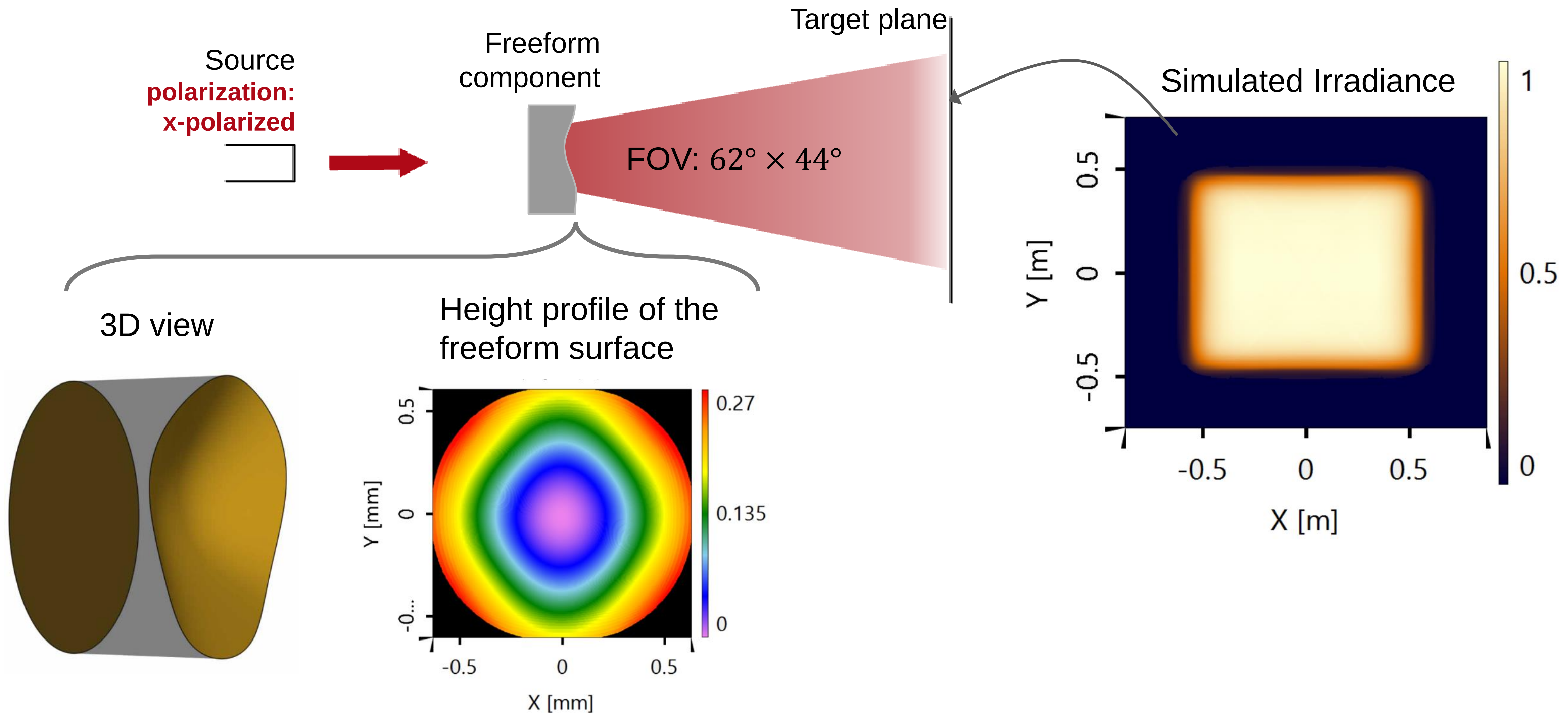


# Scenario: Multimode Source to Top Hat in Far Field

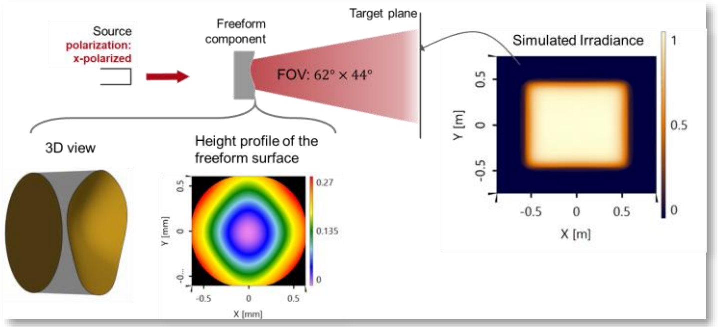



Source with two modes

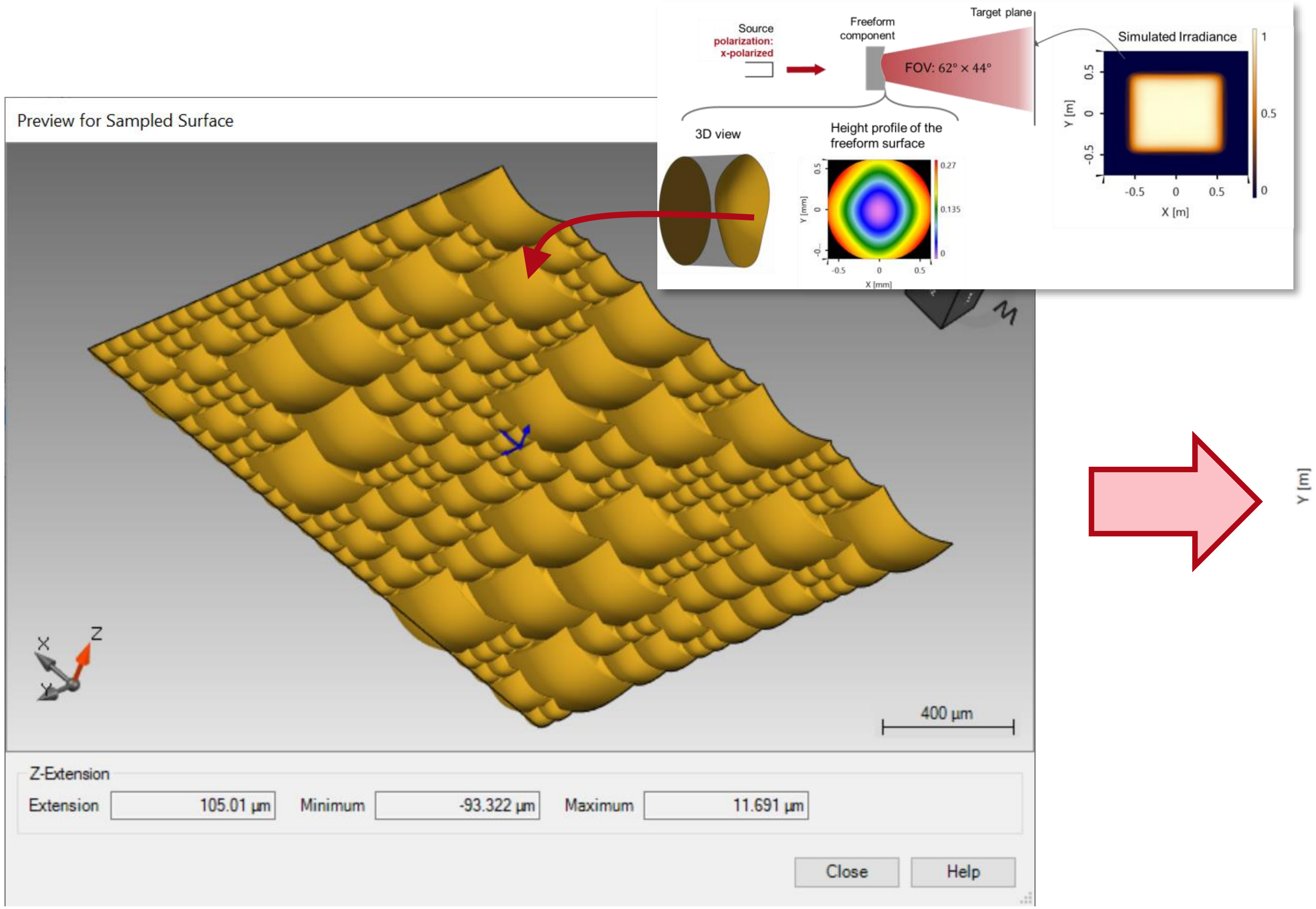
# Scenario: Multimode Source to Top Hat in Far Field



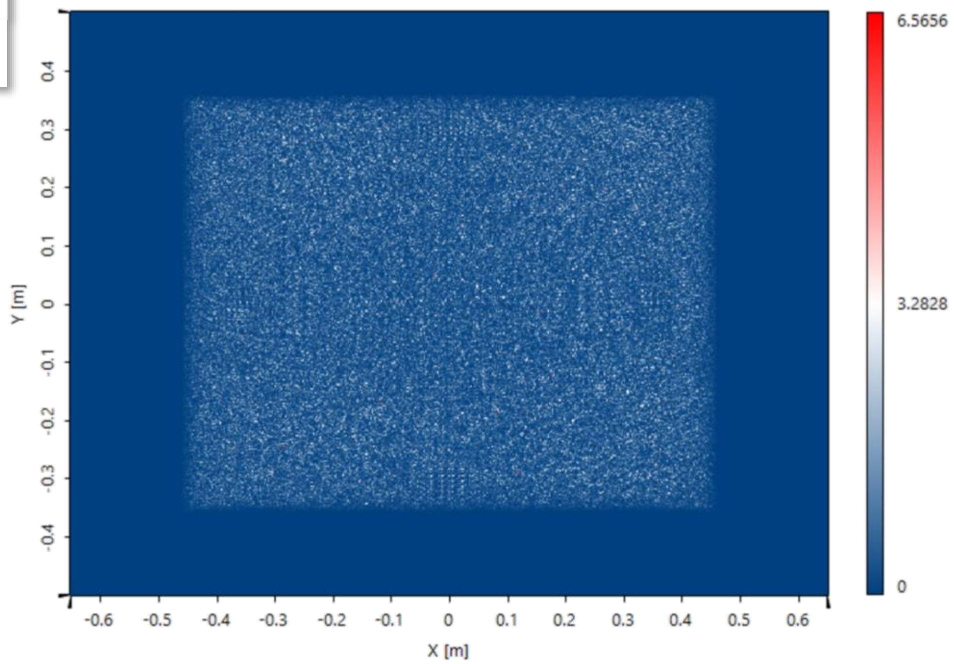
# Diffuser Design and Modeling



# Diffuser Design and Modeling




Far Field Irradiance

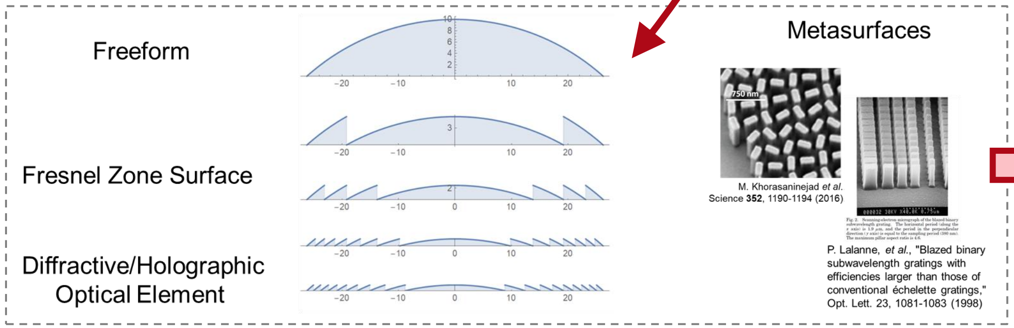


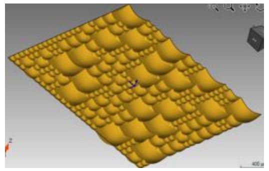
# Fast Physical Optics Modeling and Design: Flat Optics

Physical optics modeling solvers can be seamlessly adapted to application scenario and design task.

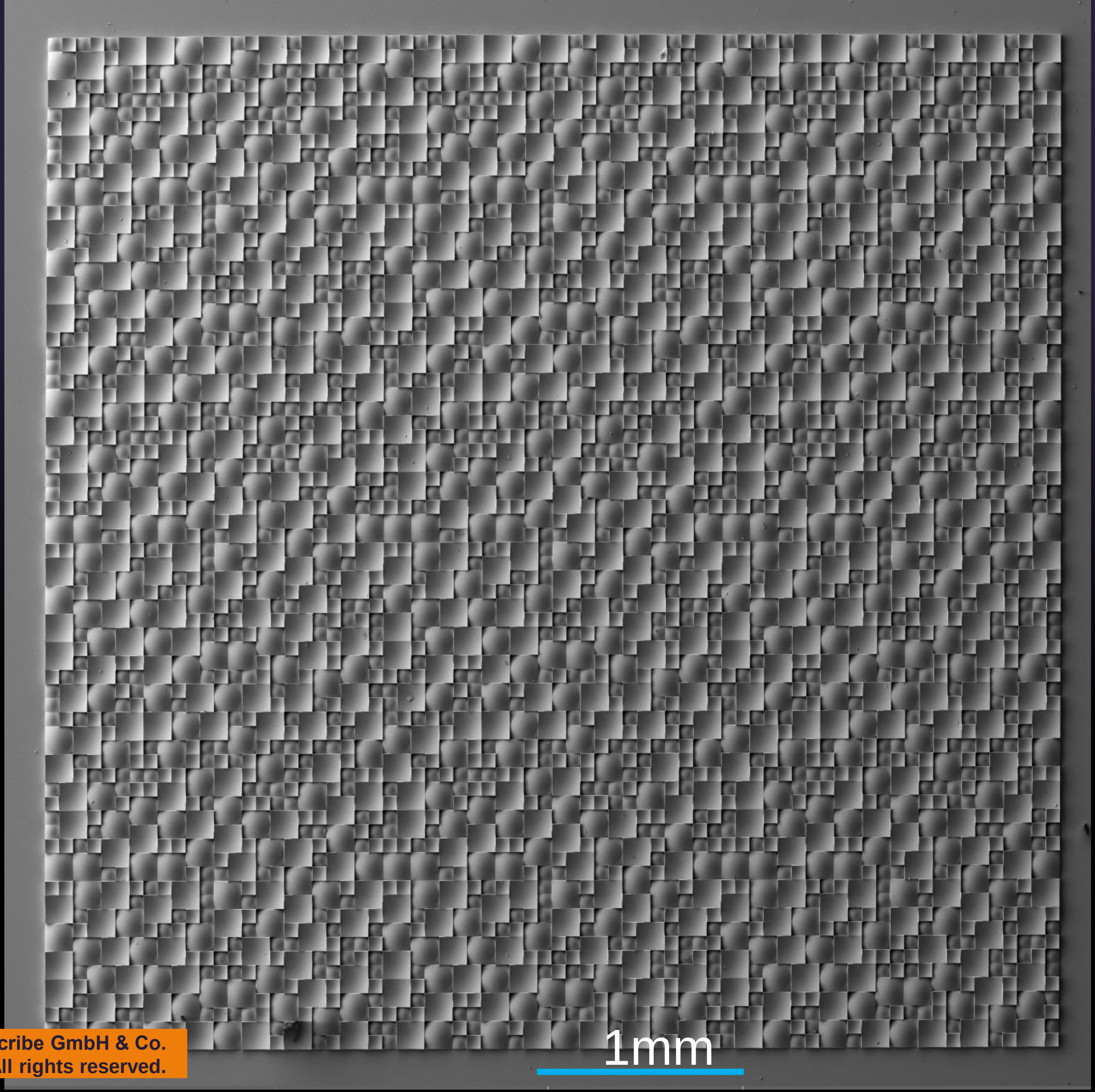
Fast Physical Optics

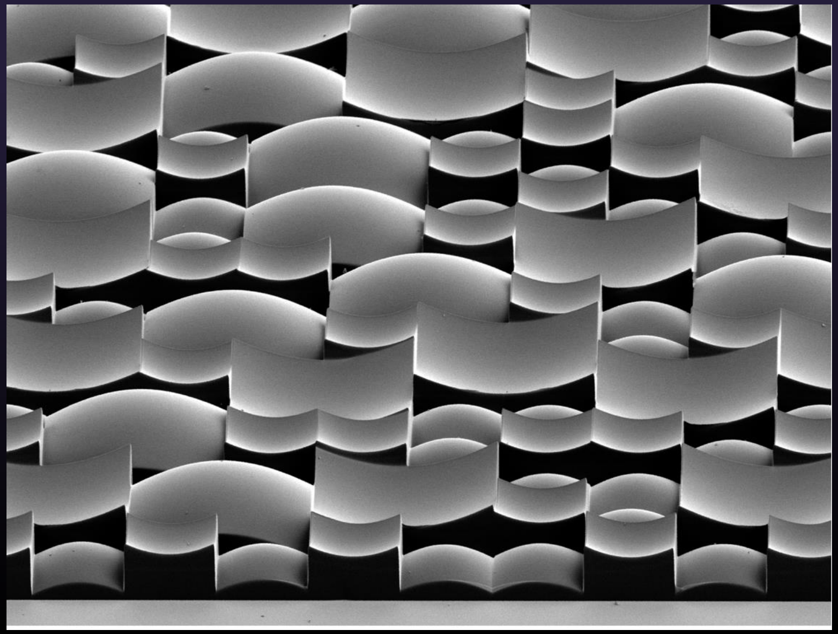
As fast as possible for given scenario and accuracy requirements



Application scenarios & modeling/design tasks

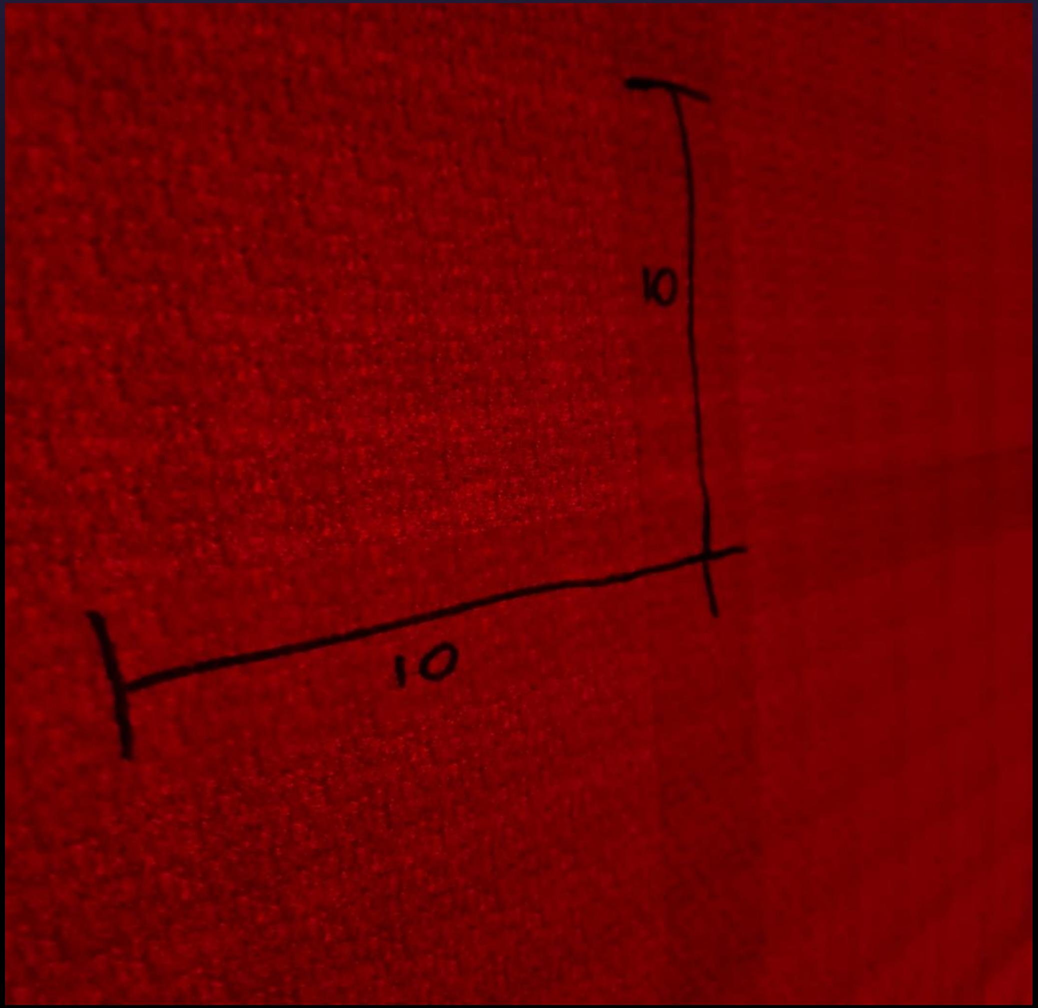


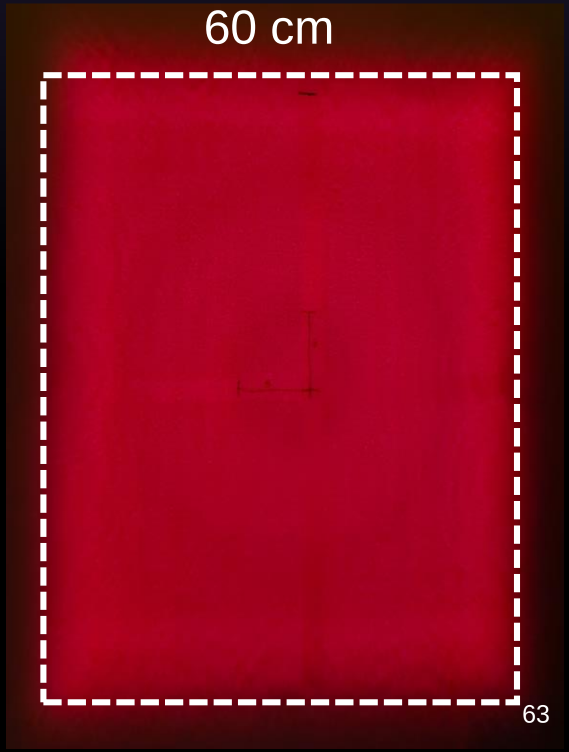
Very uniform patterning accuracy over extensive areas
5.4 mm by 5.4 mm

# Diffuser based on randomized array of freeform light shaper

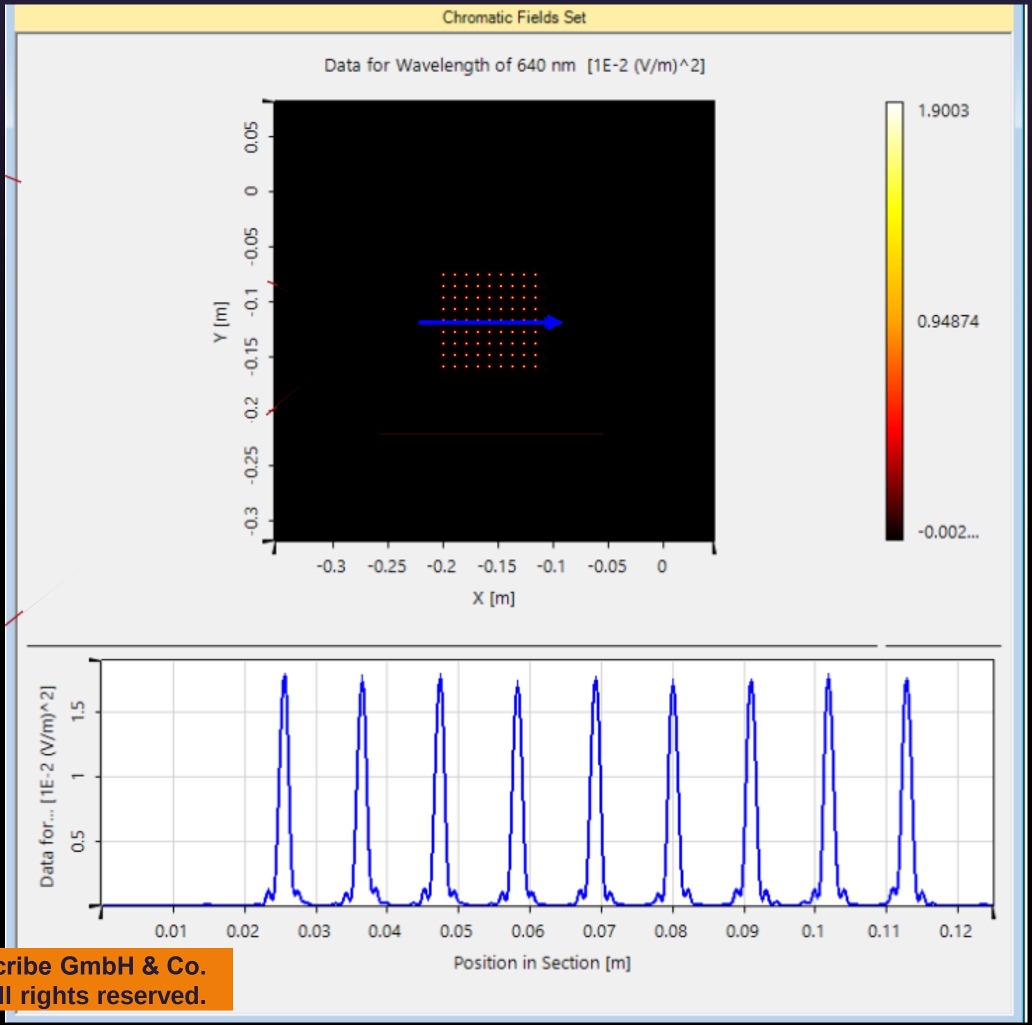
- Experimental results




Mixed

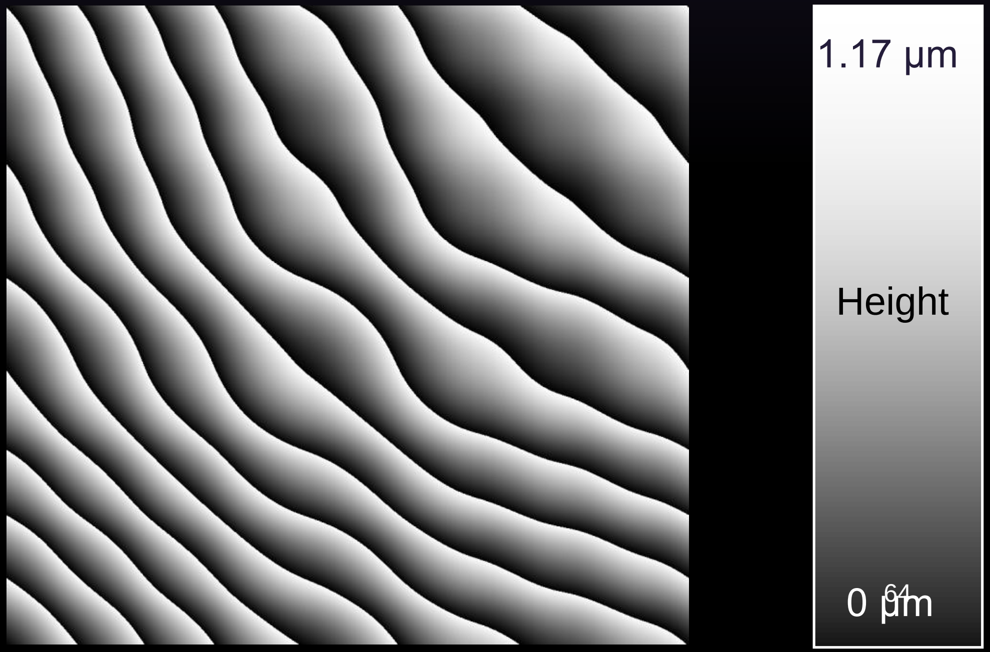


# Grating for 9x9 dot grid projection (off-axis)

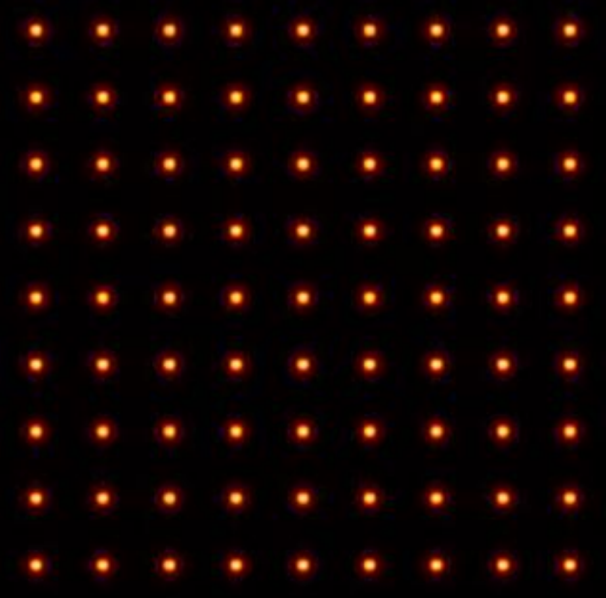




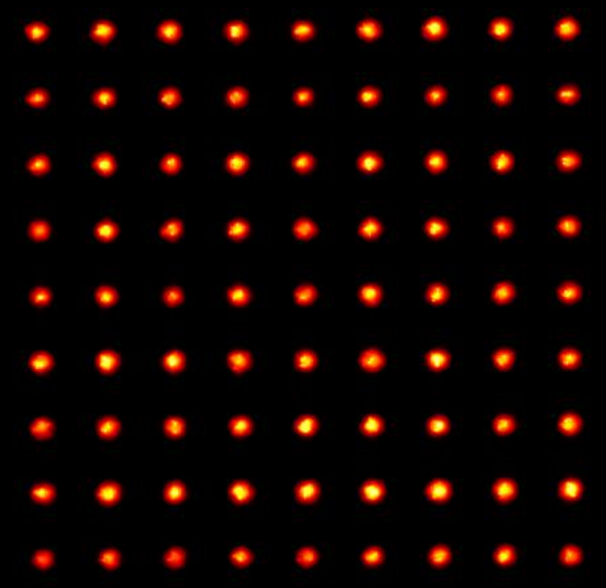

- Continuous height profile with 65535 levels
- Printing time independent from level number with 2GL



# DOE for 9x9 dot grid projection



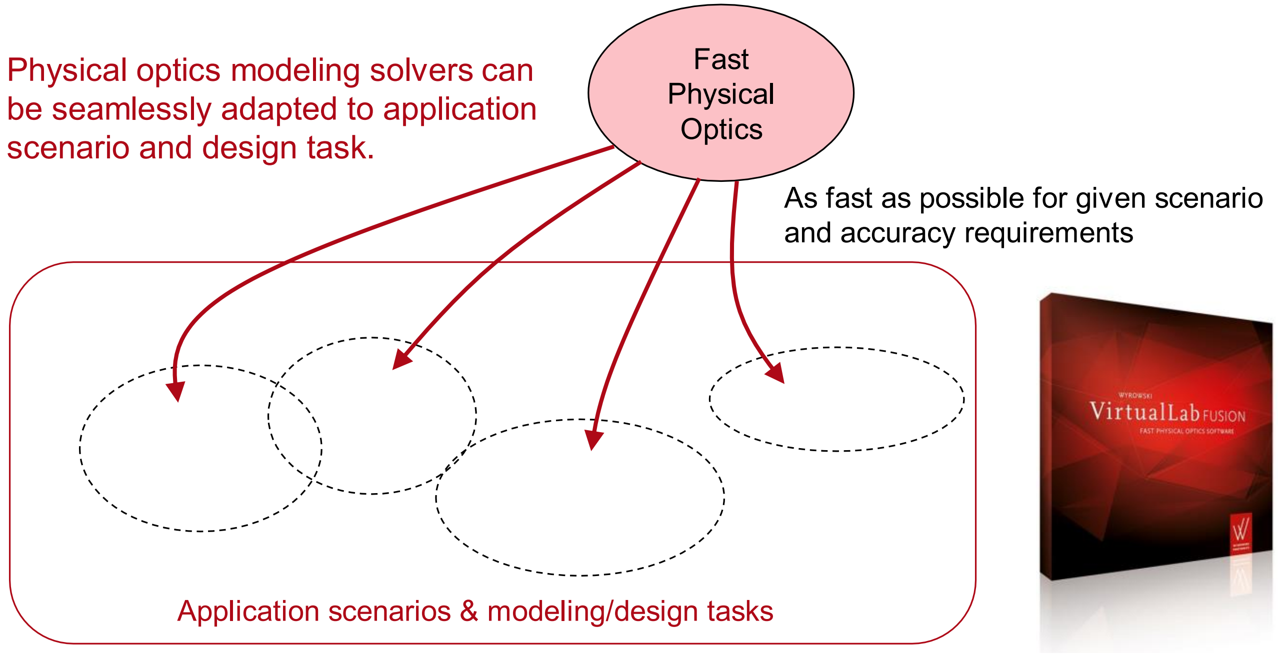
- Simulation (off-axis)



- optical experiment (off-axis)

# Summary

- Fast physical optics theory and software most flexible in modeling and design.
- Flat optics examples:
  - Segmented smooth surfaces
  - Subwavelength structures (meta surfaces)
  - Regular and randomized arrays
- Nanoscribe greyscale technology very promising for fabrication of flat optics.



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