LightTrans

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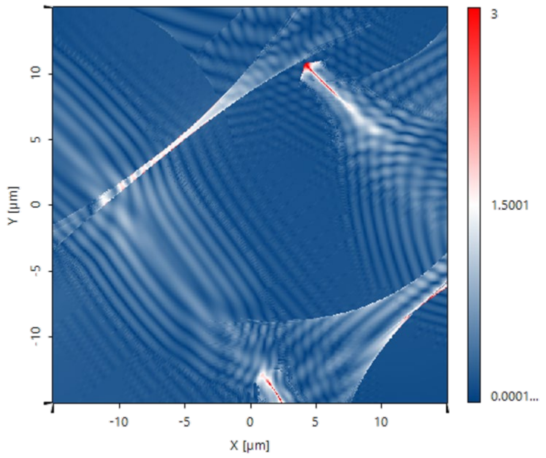
Webinar Photonics Media, 18.01.2022

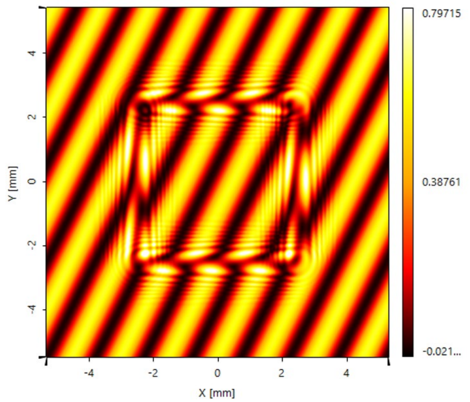
Next Generation Optics Software – Trends in Technology

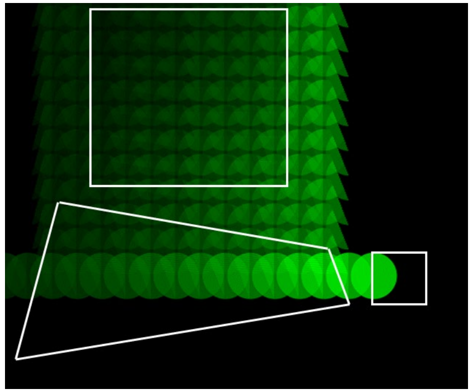
Frank Wyrowski

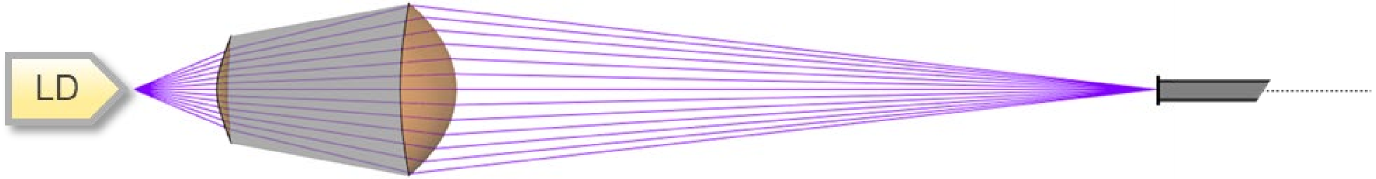
Content Overview

- Introduction to a unified approach in optical modeling
- Theoretical considerations on physical optics modeling
- Modeling examples
  - Talk
  - Follow-up material









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Almost
equation free!

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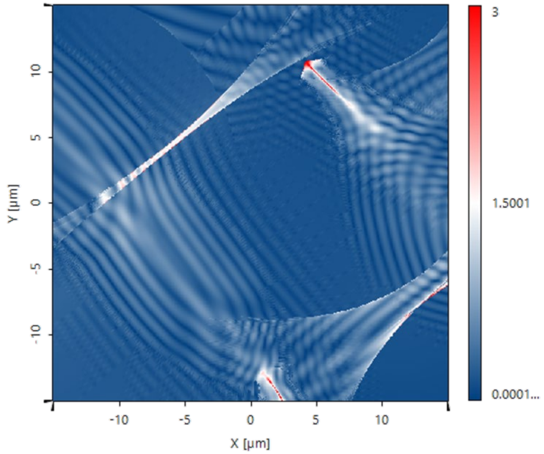

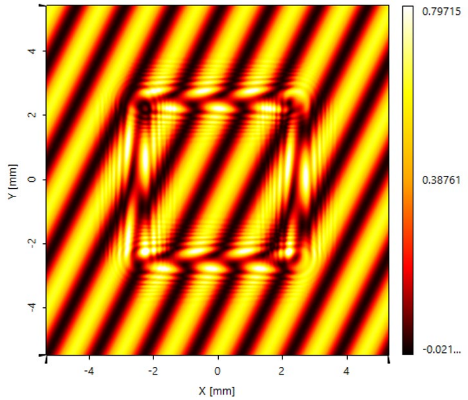

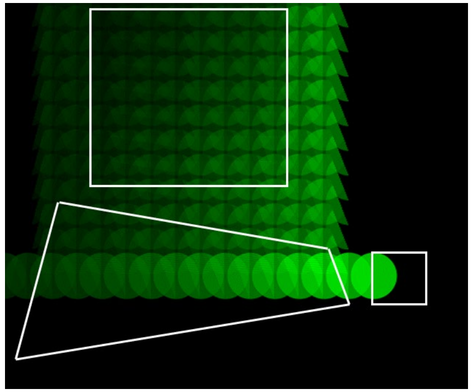

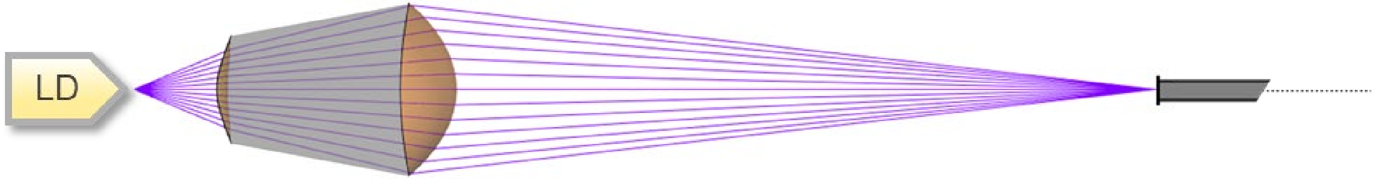

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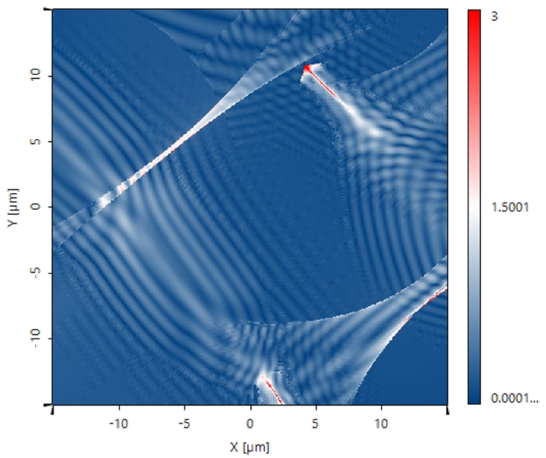
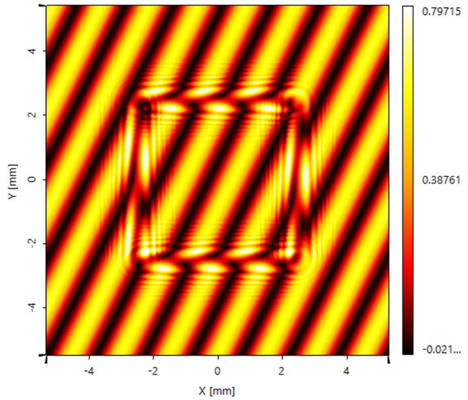
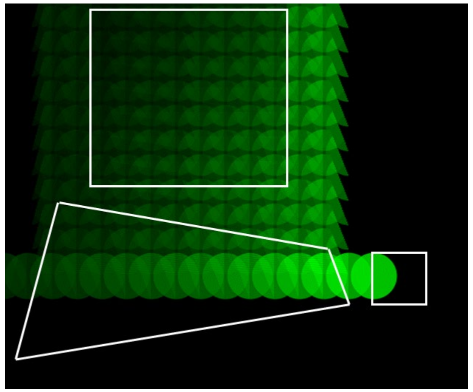
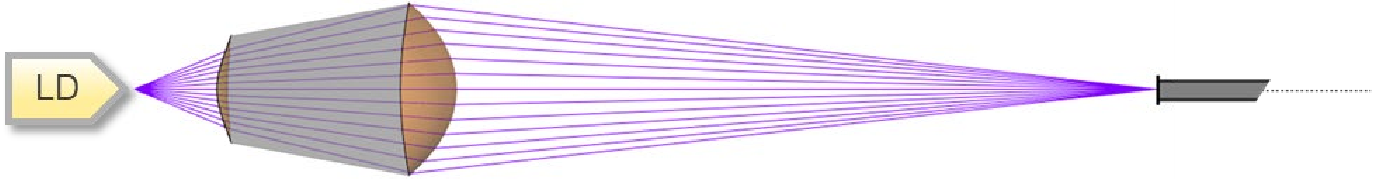


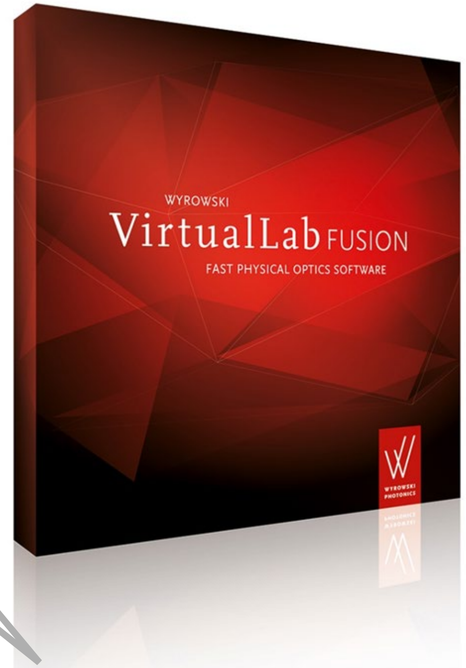


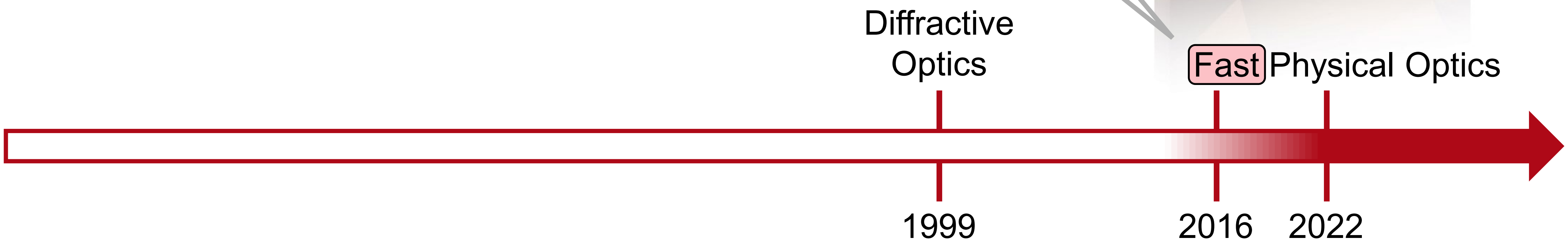




VirtualLab Fusion Software

We aim to develop and apply algorithms, whose numerical complexity is linear in number of sampling points wherever possible.

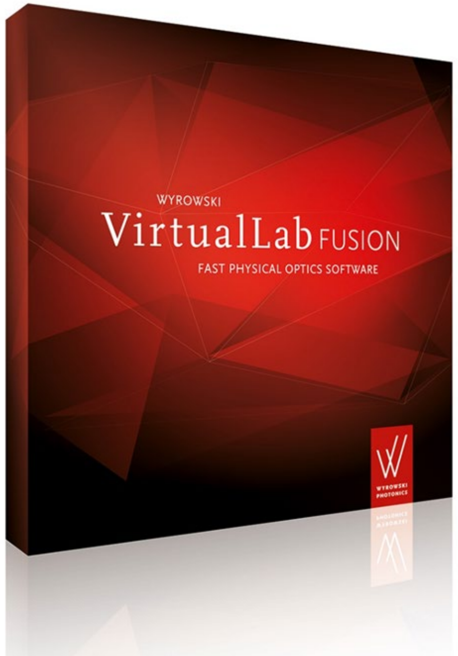


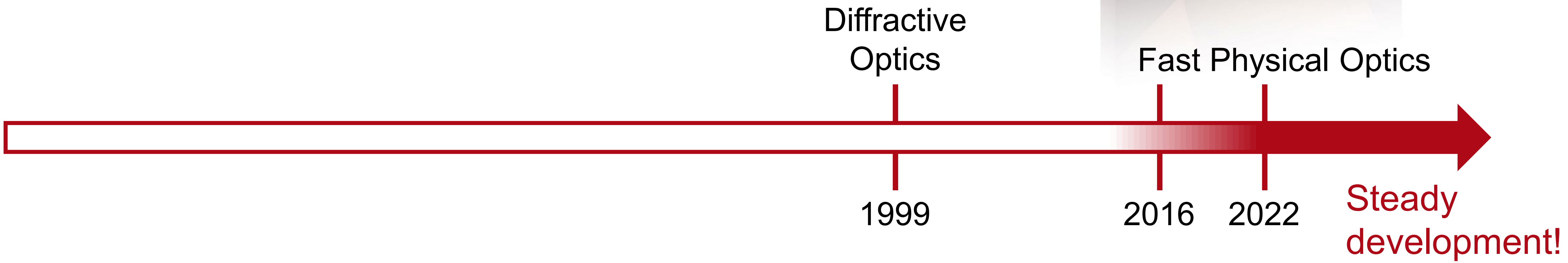


VirtualLab Fusion Software

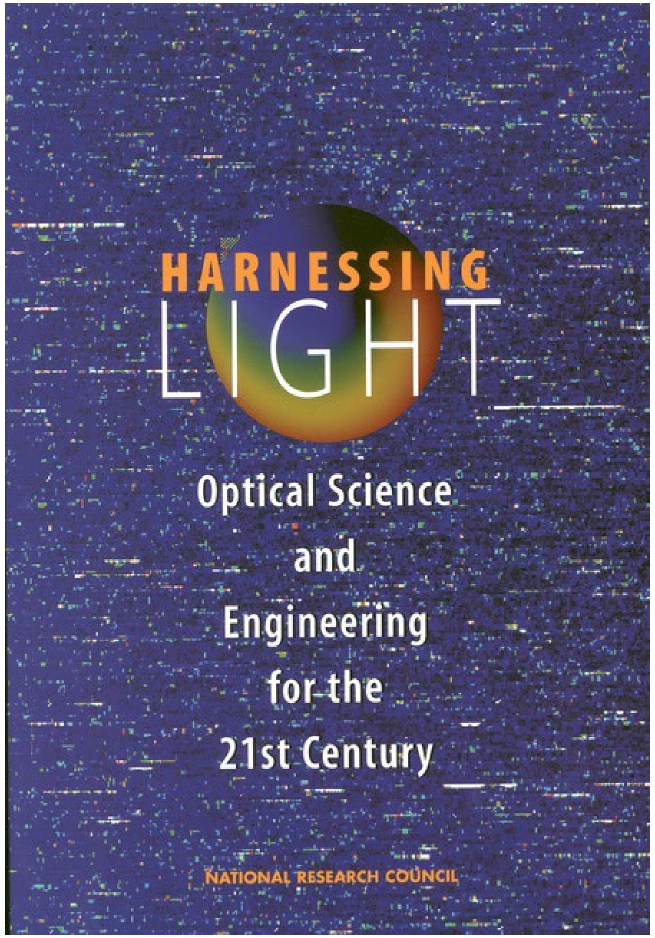
All examples in the talk are done with this software.

The software is based on ideas and concepts presented in talk.





Optics: A Pervasive Enabler



Harnessing Light

Optical Science and Engineering for the 21st Century

Committee on Optical Science and Engineering

Board on Physics and Astronomy

National Materials Advisory Board

Commission on Physical Sciences, Mathematics, and Applications

Commission on Engineering and Technical Systems

National Research Council

National Academy Press
Washington, D.C.
1998

1998

fiber-optic communications, compact disks, laser surgery of the retina, and laser welding. Other developments in optics have perhaps been less obvious, but their impact can be equally well seen in the commodities and conveniences of our world. Examples include optical lithography systems for making computer chips, high-resolution microscopes, adaptive optics for ground-based astronomy, infrared sensors for a multitude of applications, and highly efficient lighting sources. The sidebar on page 7 suggests some of the ways in which these and other optical technologies affect our everyday lives.

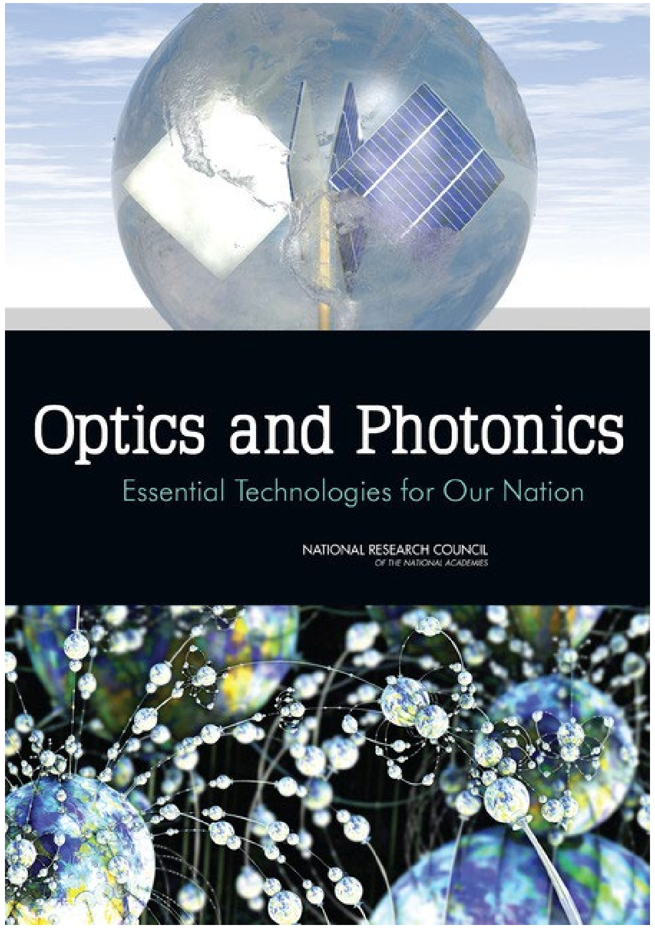
OPTICS: A PERVASIVE ENABLER

Not surprisingly, then, optics is rapidly becoming an important focus for new businesses in the global economy. In the United States, both large and small businesses are significant players in emerging optics business activity. Optics-related companies number more than 5,000, and their net financial impact amounts to more than $50 billion annually. More significant than this, however, is the role of optics as an *enabler.* Just as a lens in a pair of glasses enables clear vision, so an investment of a few hundred million dollars in optical-fiber technology has enabled a trillion-dollar worldwide communications revolution. A mere six laser transmitters are used in a transatlantic undersea telephone transmission system that can carry 40 million simultaneous conversations. The cost of the lasers is a tiny fraction of the cost of the system or the revenue it generates, but without them the system would be useless. Indeed, in his report to Congress on July 22, 1997, Federal Reserve chairman Alan Greenspan alluded to this enabling role: "We may be observing ... a number of key technologies, some even mature, finally interacting to create significant new opportunities for value creation. For example, the applications for the laser were modest until the later development of fiber optics engendered a revolution in telecommunications."

As another instance, a compact disk player incorporates hundreds of intricate electronic and mechanical parts, all working together and all absolutely dependent on a single laser costing less than a dollar to illuminate the spinning disk. The following pages contain dozens of additional examples. Often, perhaps even usually, those who developed the enabling optical technologies never imagined their ultimate applications. In this report, the committee has thus sought to address the pivotal question, *How does one support and strengthen a field such as optics whose value is primarily enabling?*

The remarkable breadth of optics' enabling role is both an indicator of the field's importance and a source of challenges. Virtually every

Optics and Photonics: Enabling Technology



Optics and Photonics

Essential Technologies for Our Nation

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
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
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2013

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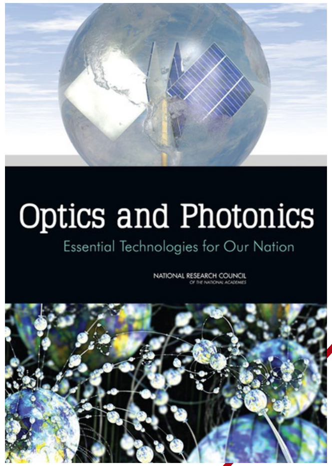


5 ENERGY

10 DISPLAYS

6 HEALTH AND MEDICINE

7 ADVANCED MANUFACTURING

9 STRATEGIC MATERIALS FOR OPTICS

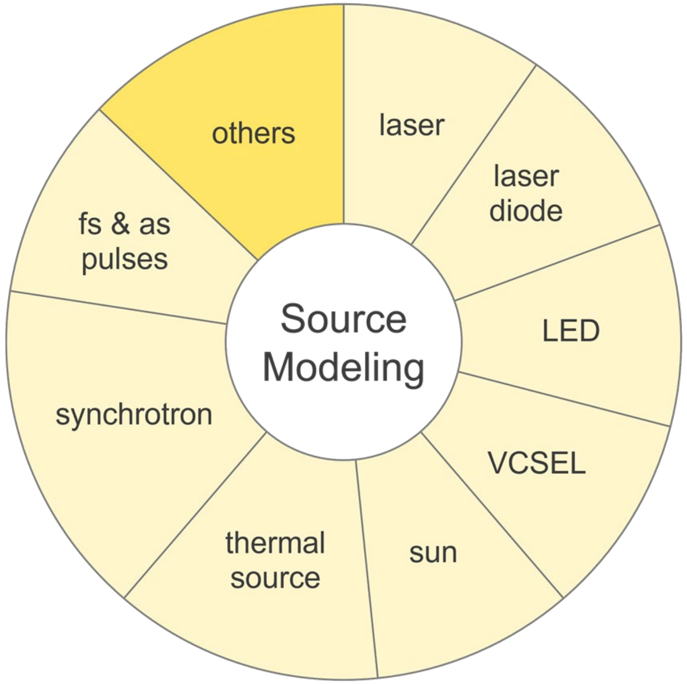
3 COMMUNICATIONS, INFORMATION PROCESSING, AND DATA STORAGE

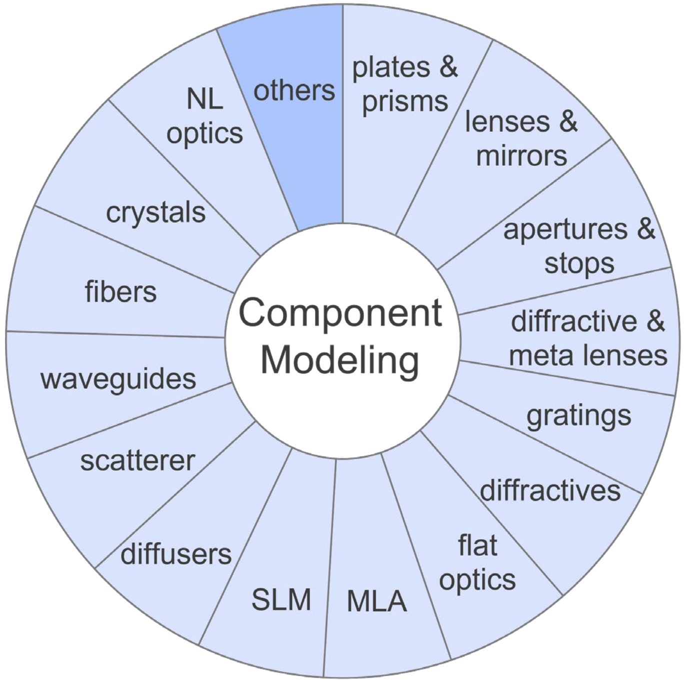
8 ADVANCED PHOTONIC MEASUREMENTS AND APPLICATIONS

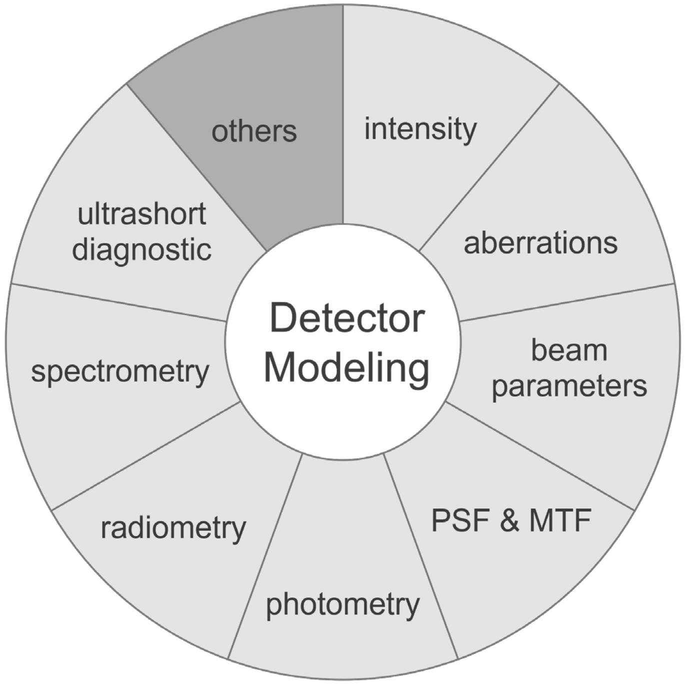
4 DEFENSE AND NATIONAL SECURITY

What is needed in optical modeling and design?

Sources, Components, and Detectors

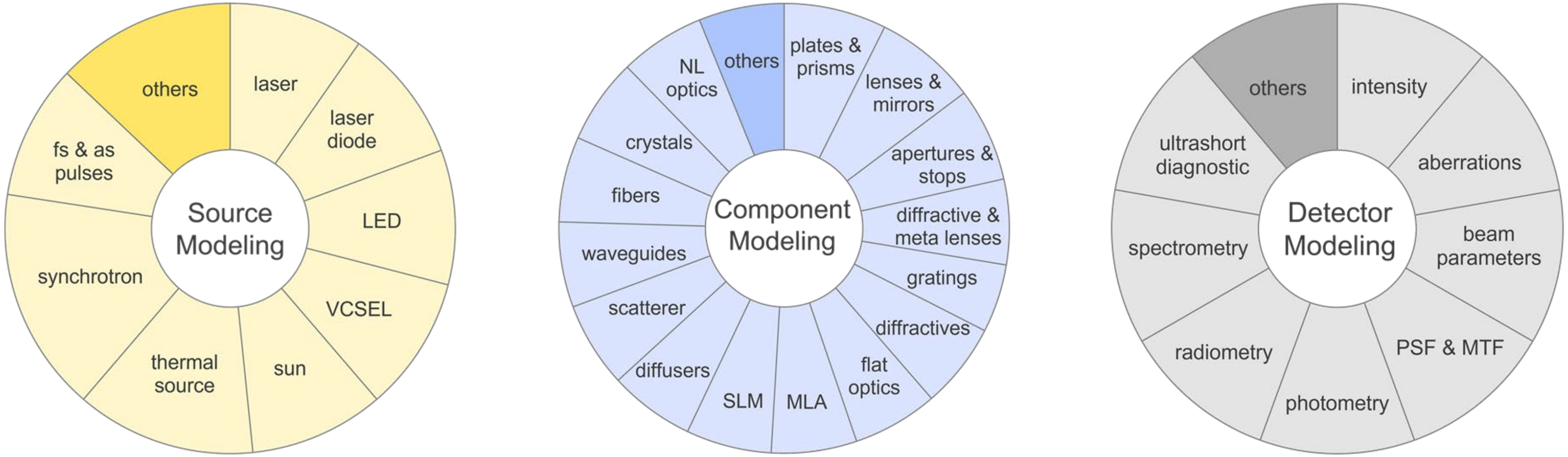


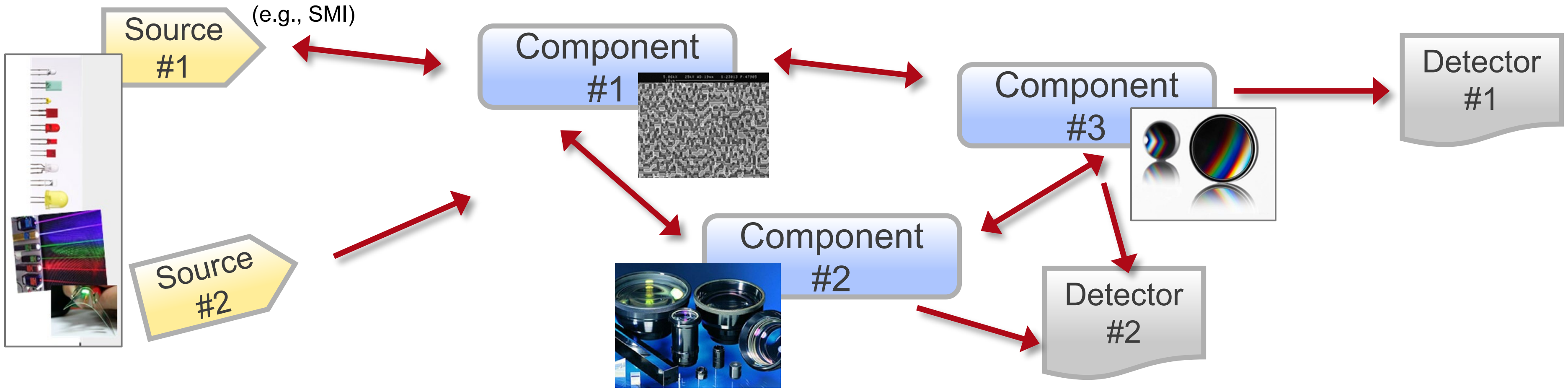




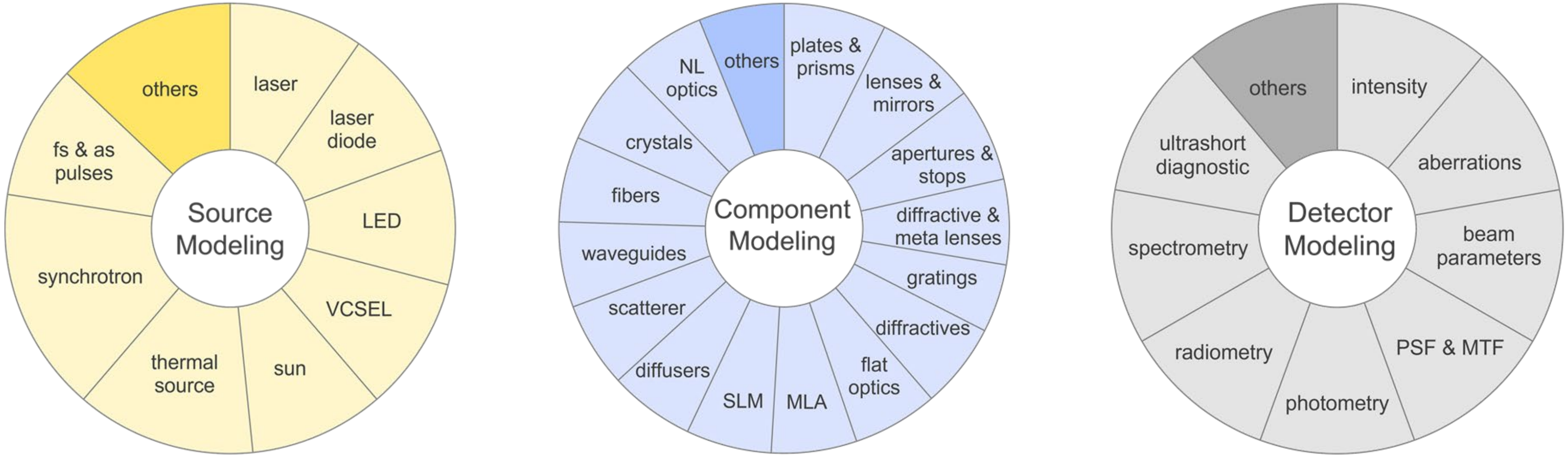
Optics as enabling technology requires maximum flexibility in source, component and detector modeling.

System Modeling and Design





System Modeling and Design: Digital Twin (Optics & Photonics)

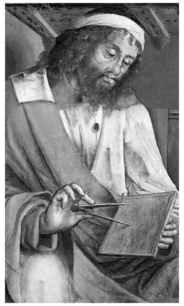


What theories and technologies can be used for modeling and design?

Geometrical and Physical Optics

- Geometrical (ray) optics is very powerful in optical modeling and design in a wide range of applications.
  - Comment: Special connection to physical optics is essential for PSF/MTF calculation in lens design.
- Geometrical optics dominates optical modeling and design in theory, practice, and software products.

- Physical optics provides solutions beyond geometrical optics, because …

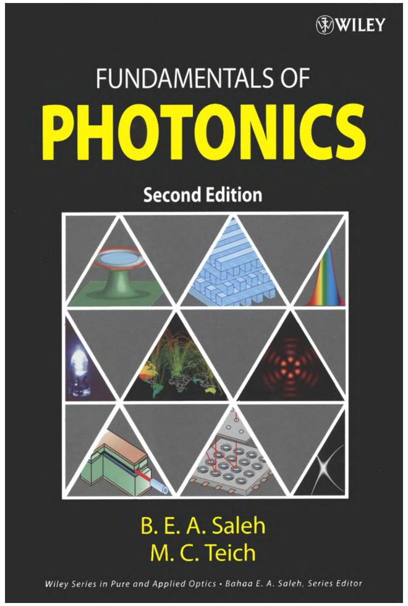


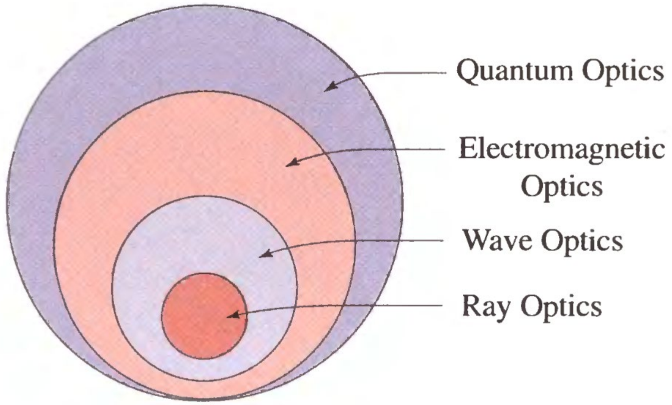
Euclid of Alexandria
(c. 325 BC – 265 BC)

Pierre de Fermat
(1601 - 1665)

James Clerk Maxwell
(1831 – 1879)

… Physical Optics Includes Geometrical Optics





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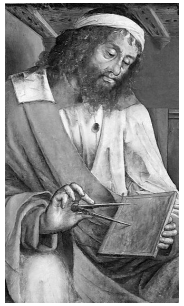
James Clerk Maxwell
(1831 – 1879)



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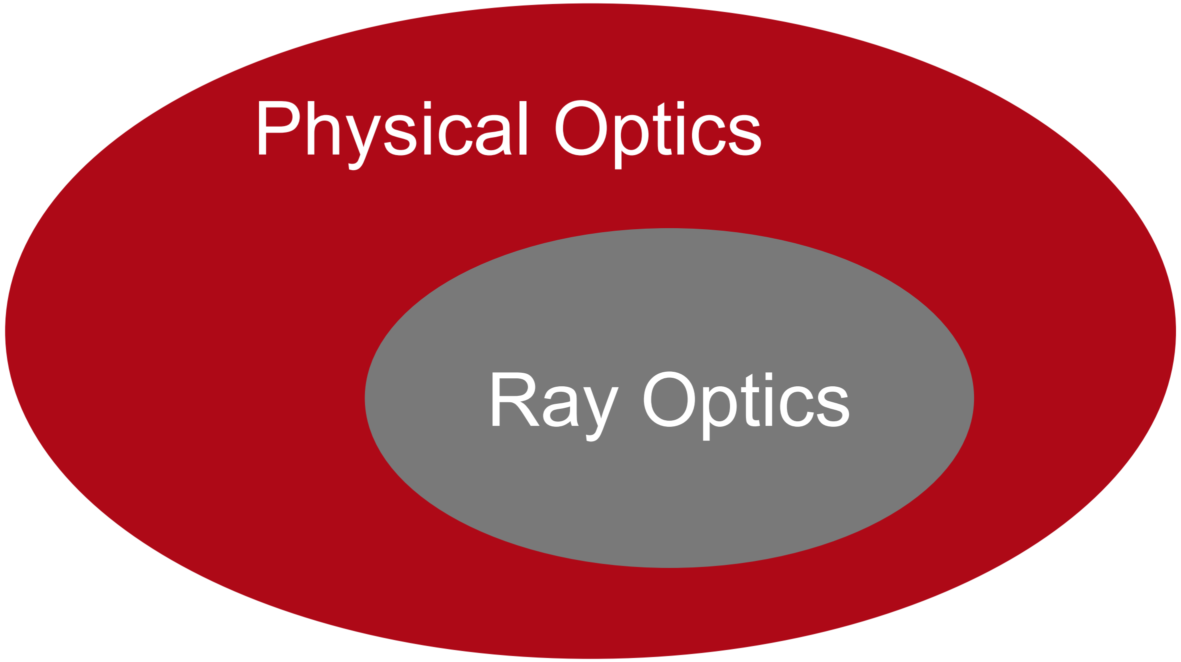
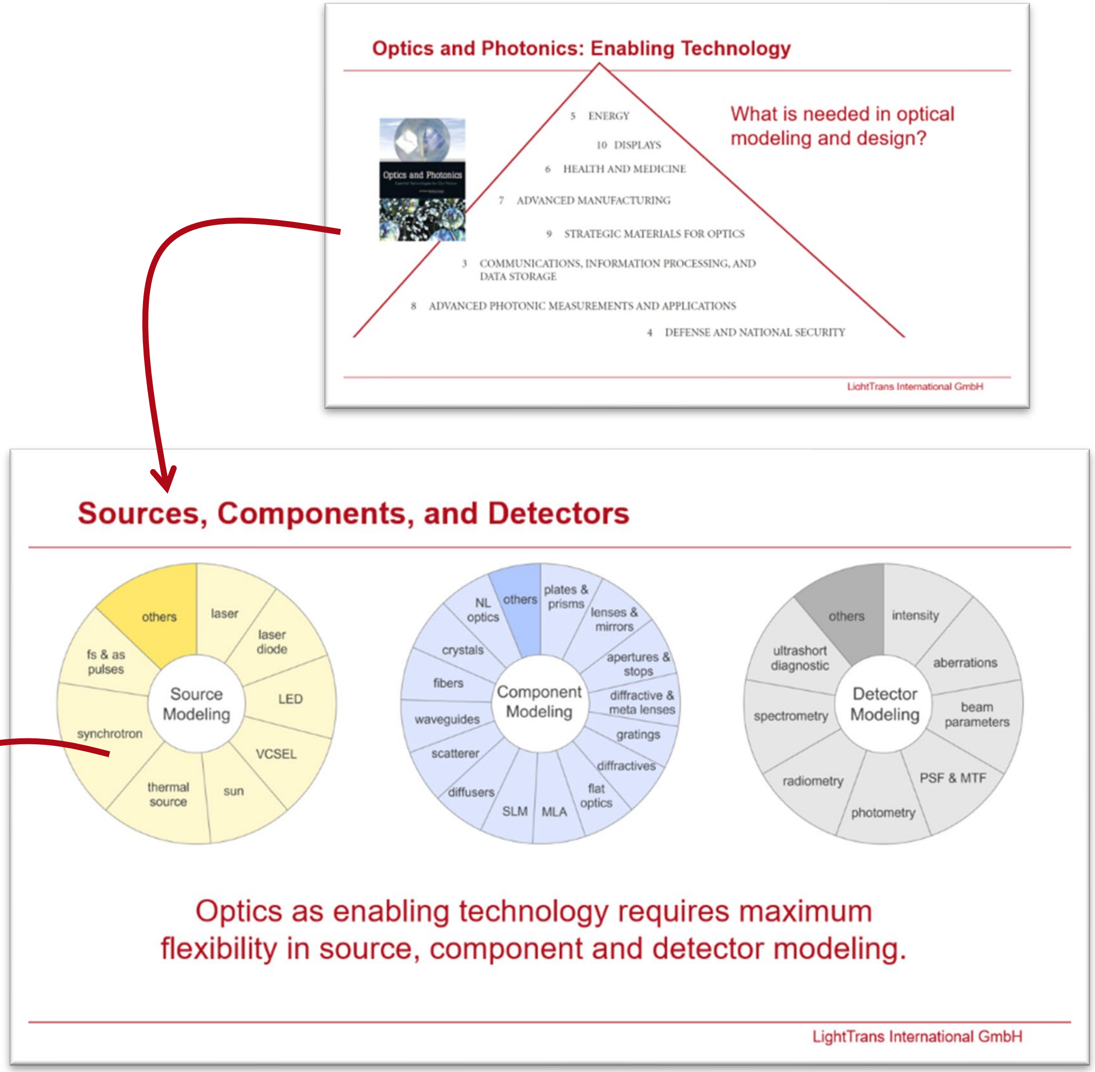
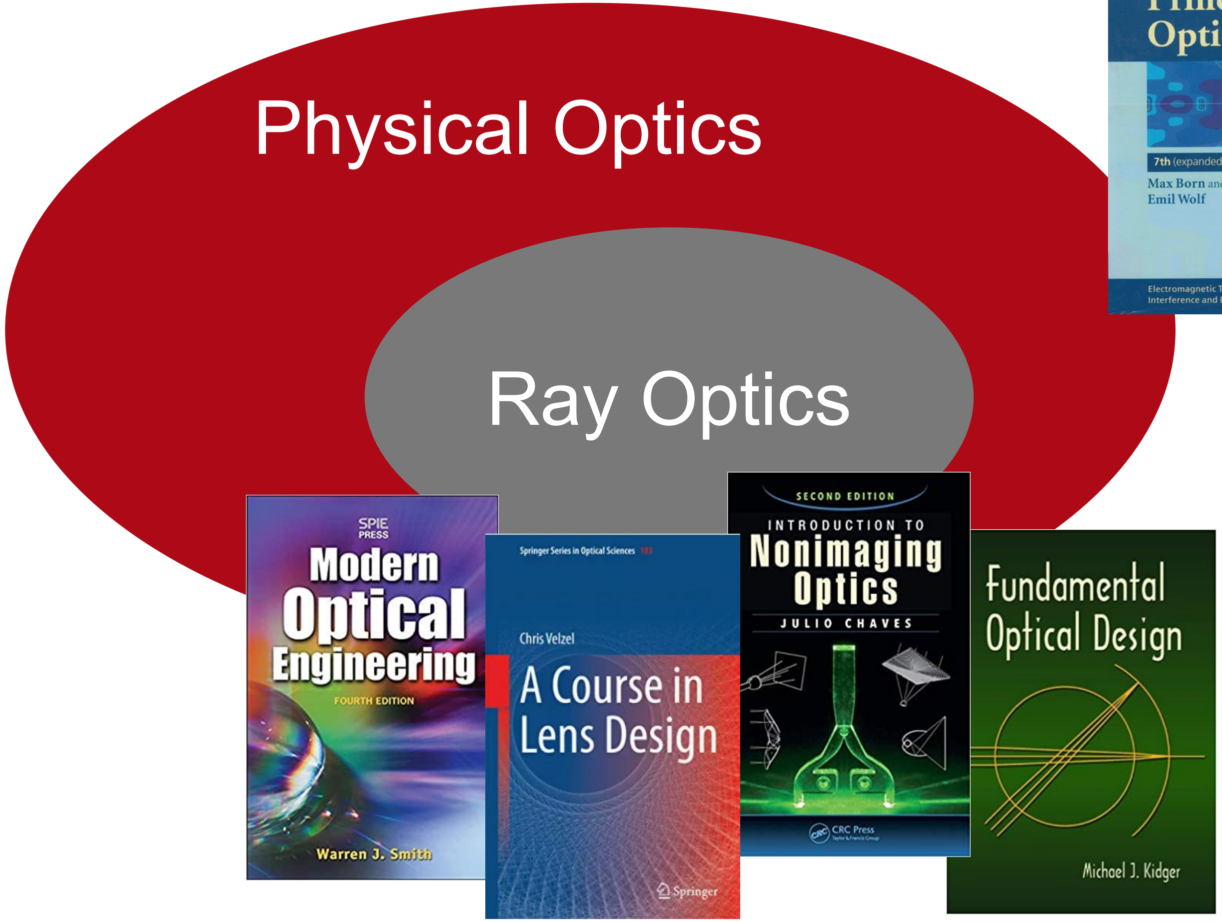
Physical Optics Includes Geometrical Optics

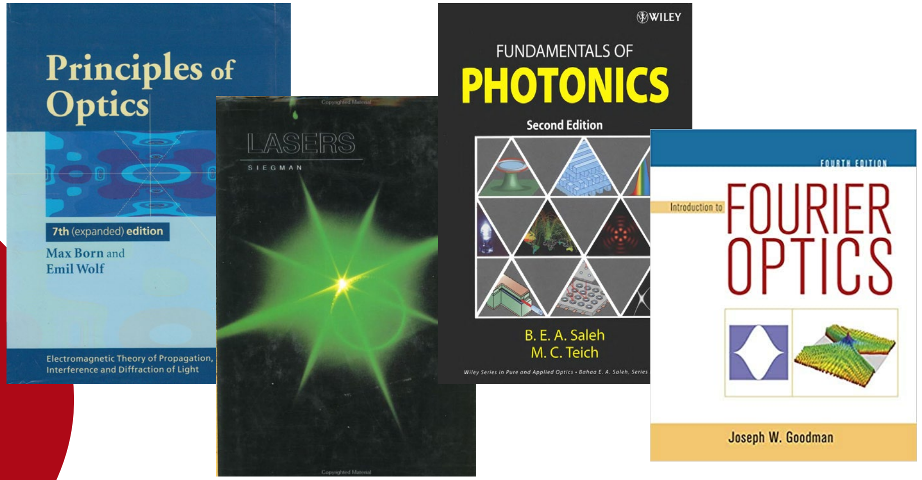




- Physical optics provides the needed flexibility in optical modeling and design.
- But this fact has no strong practical consequences yet.

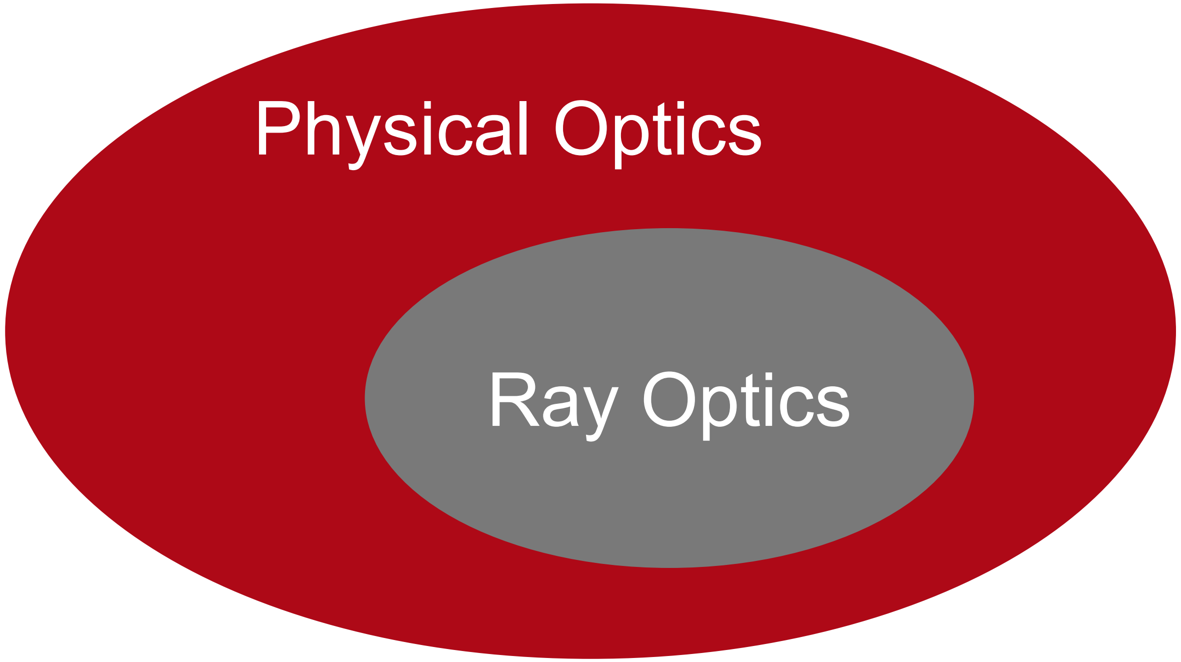
Physical and Geometrical Optics: Theory





The connection between geometrical and physical optics is almost not visible.

Physical and Geometrical Optics: Practice



Physical optics software, e.g.,
- FDTD
- FEM
- S matrix coating
- S matrix grating (FMM/RCWA)
- Special mode solver
- BPM

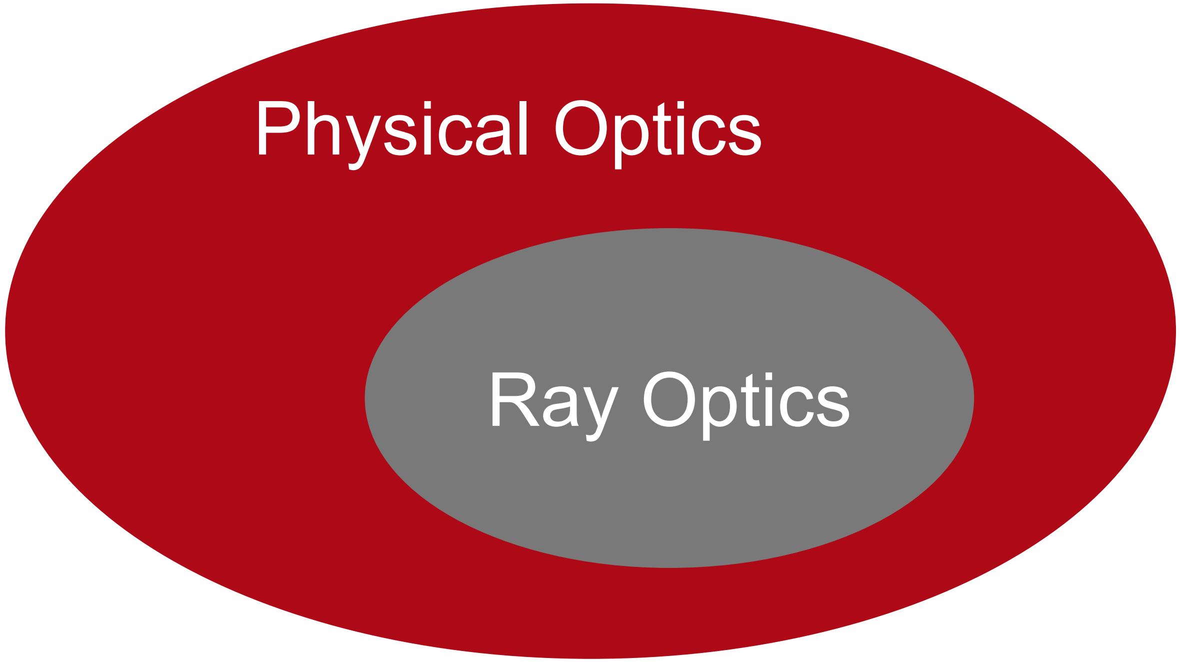
Not suitable for system modeling

Some connections

Ray optics (tracing) software for, e.g.,
- Lens design
- Lighting

Optical **system** modeling relies on ray tracing software.

Physical and Geometrical Optics: Practice



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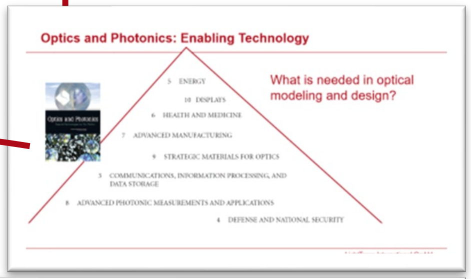
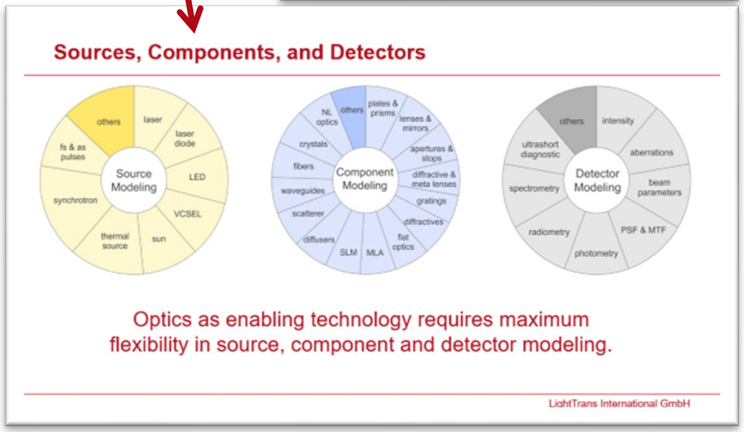
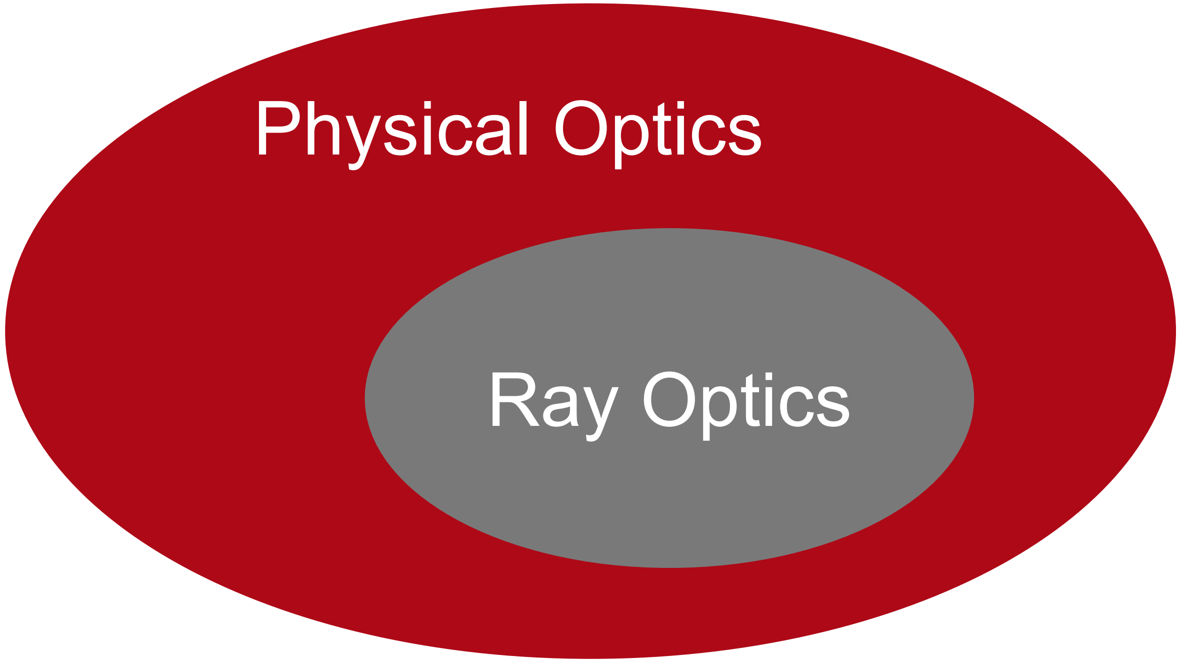




Physical and Geometrical Optics: Demand



Current situation:

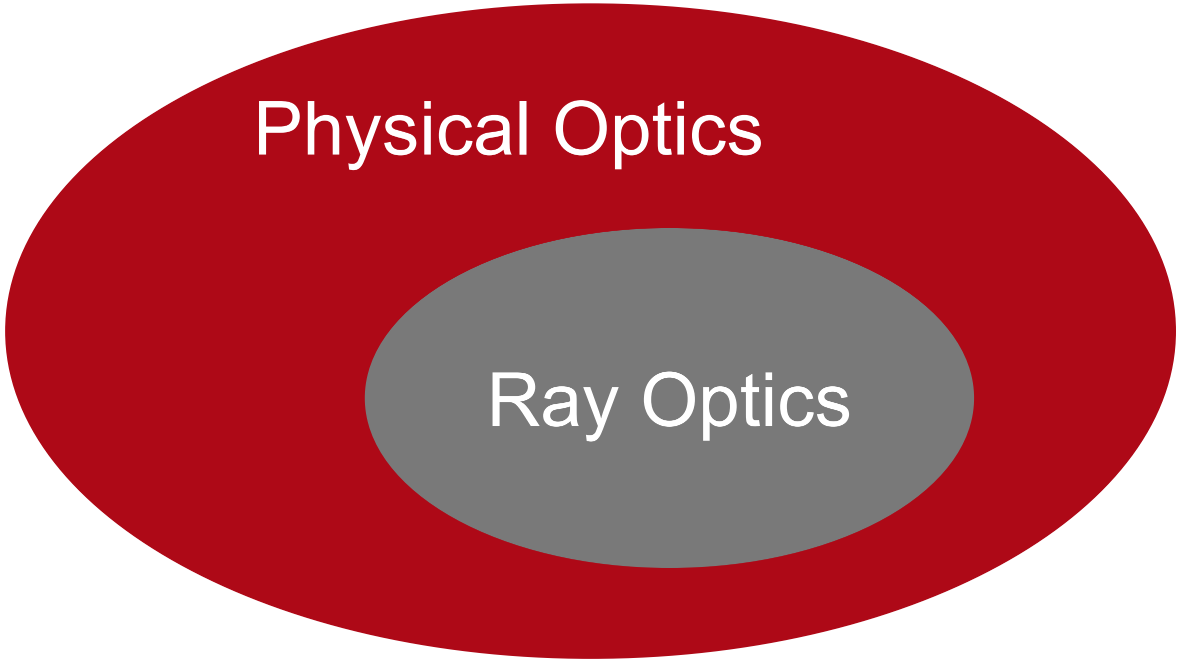
- Geometrical and physical optics coexist without a powerful connection in theory and practice.
- Some design tasks apply specialized connections, e.g., PSF/MTF calculation in lens design.

Demand:

- Seamless transition between geometrical and physical optics in theory and practice.

Is that a reasonable demand?

Physical and Geometrical Optics: Light Representation



- Light representation in physical optics: $\boldsymbol{E}(\boldsymbol{r}) = (E_x(\boldsymbol{r}), E_y(\boldsymbol{r}), E_z(\boldsymbol{r}))$ and $\boldsymbol{H}(\boldsymbol{r}) = (H_x(\boldsymbol{r}), H_y(\boldsymbol{r}), H_z(\boldsymbol{r}))$
- Light representation in geometrical optics: Ray position $\boldsymbol{r}$, direction $\boldsymbol{s}$, OPL, and flux Φ

Demand:

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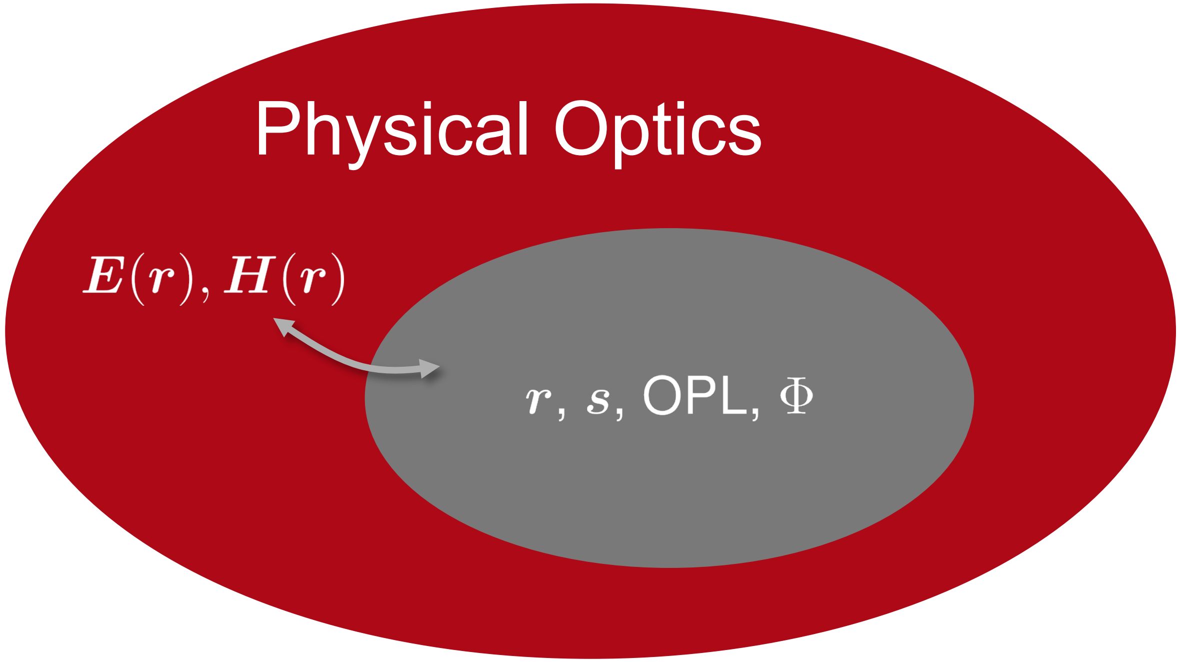
Is that a reasonable demand?

Physical and Geometrical Optics: Light Representation

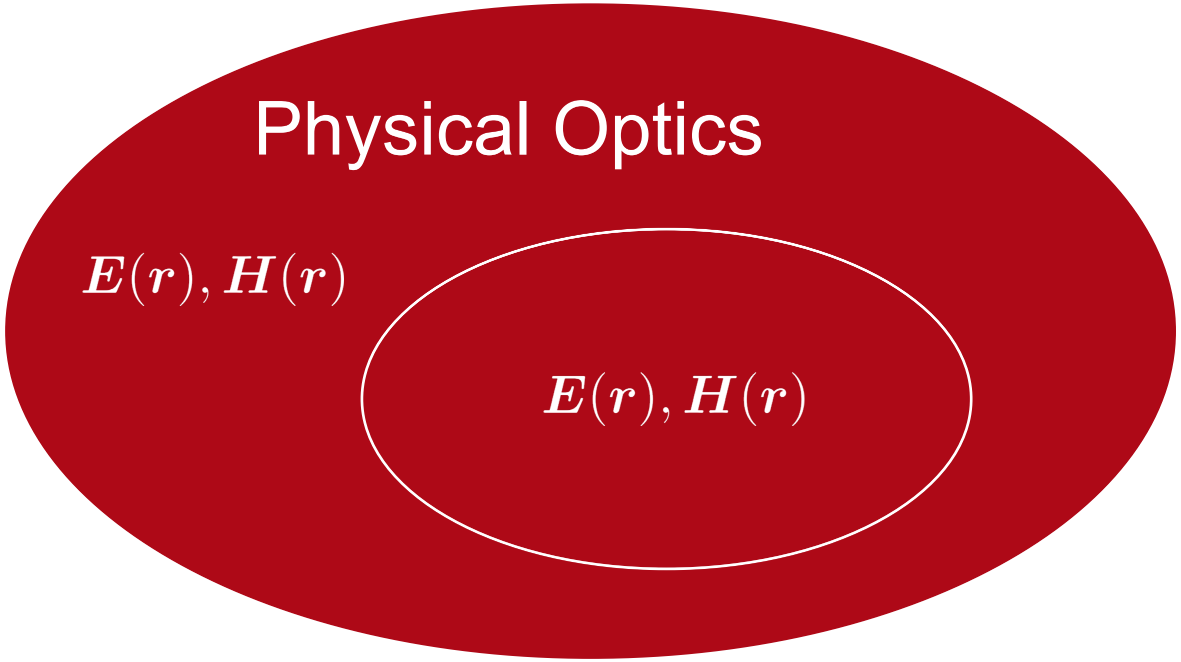


- Light representation in physical optics: $\boldsymbol{E}(\boldsymbol{r}) = (E_x(\boldsymbol{r}), E_y(\boldsymbol{r}), E_z(\boldsymbol{r}))$ and $\boldsymbol{H}(\boldsymbol{r}) = (H_x(\boldsymbol{r}), H_y(\boldsymbol{r}), H_z(\boldsymbol{r}))$
- Light representation in geometrical optics: Ray position $\boldsymbol{r}$, direction $\boldsymbol{s}$, OPL, and flux Φ

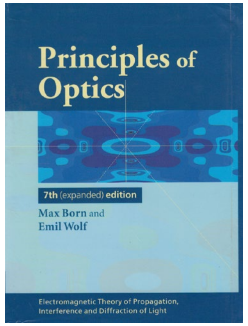
Different light representations prevent a seamless transition between physical and geometrical optics!

We must formulate our objective in a different way!

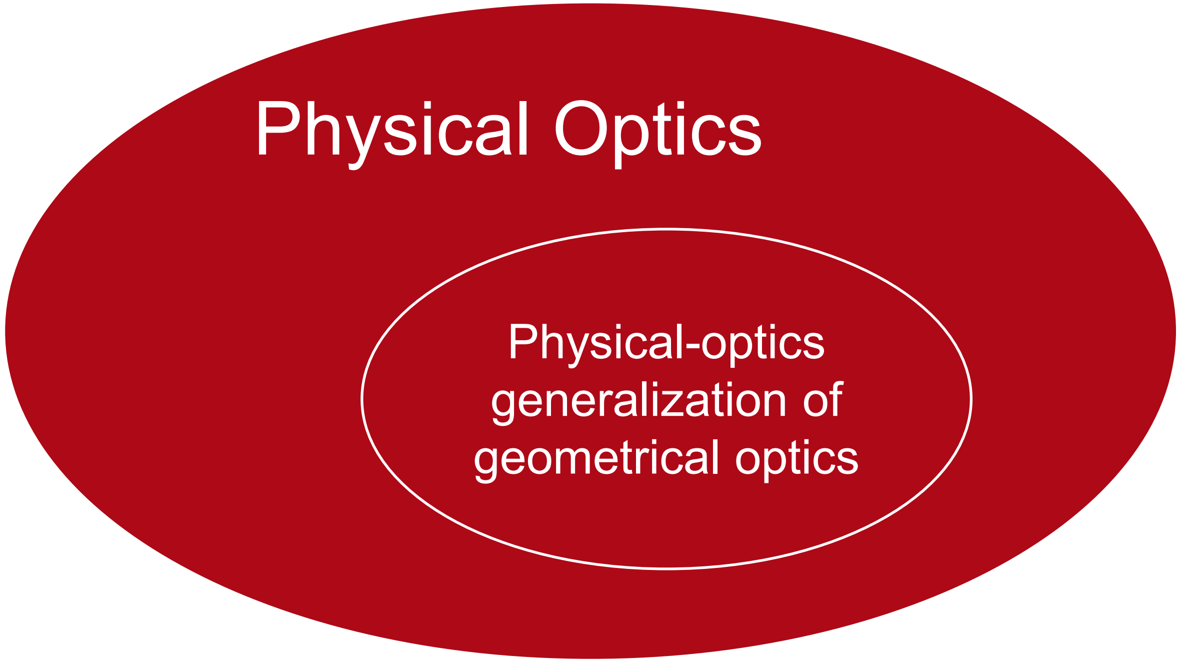
Physical and Geometrical Optics: Light Representation



We need to identify that part of physical optics, which deals with the “***geometrical laws relating to the propagation of the 'amplitude vectors' E and H.***”

Citation from  page 125

Geometric Branch of Physical Optics



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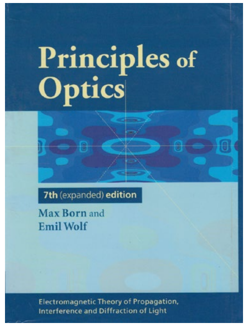
Citation from 

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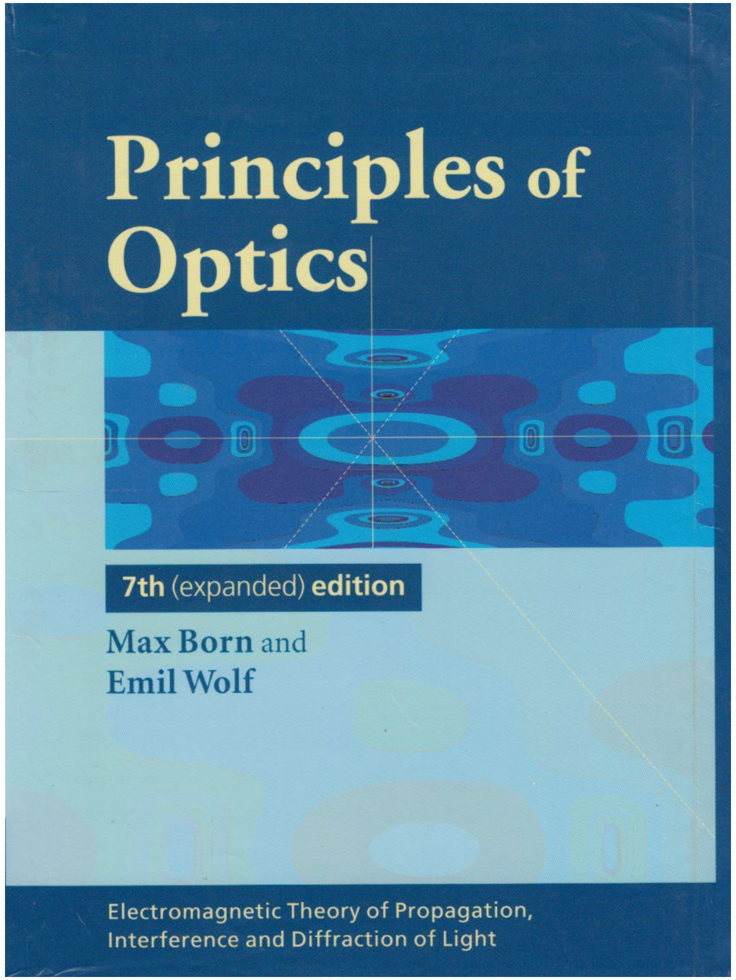
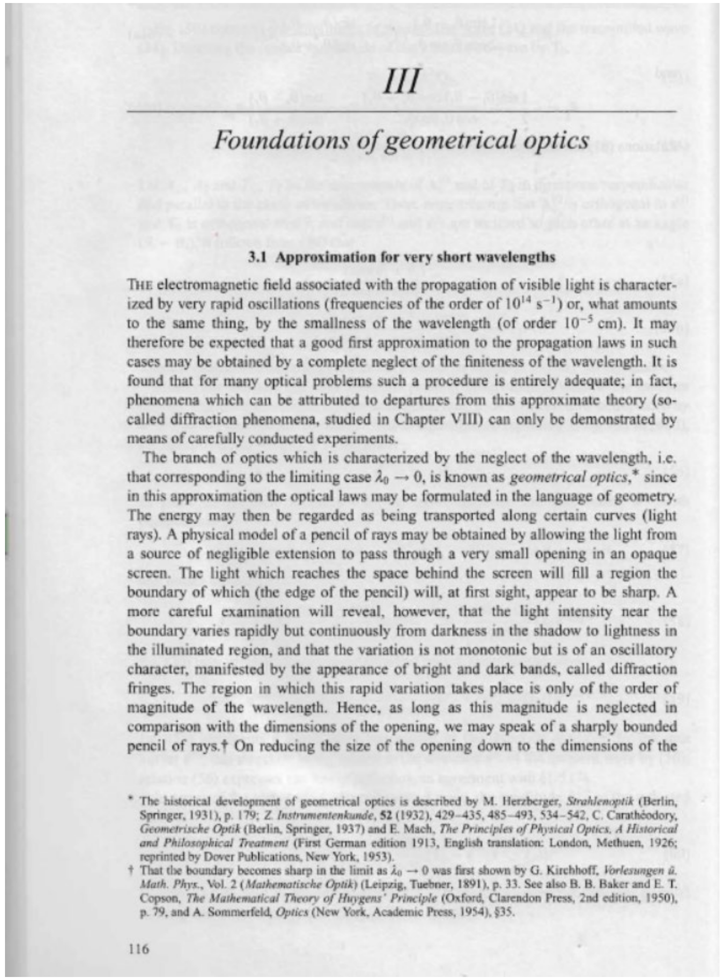
Geometric Branch of Physical Optics





III

Foundations of geometrical optics

3.1 Approximation for very short wavelengths

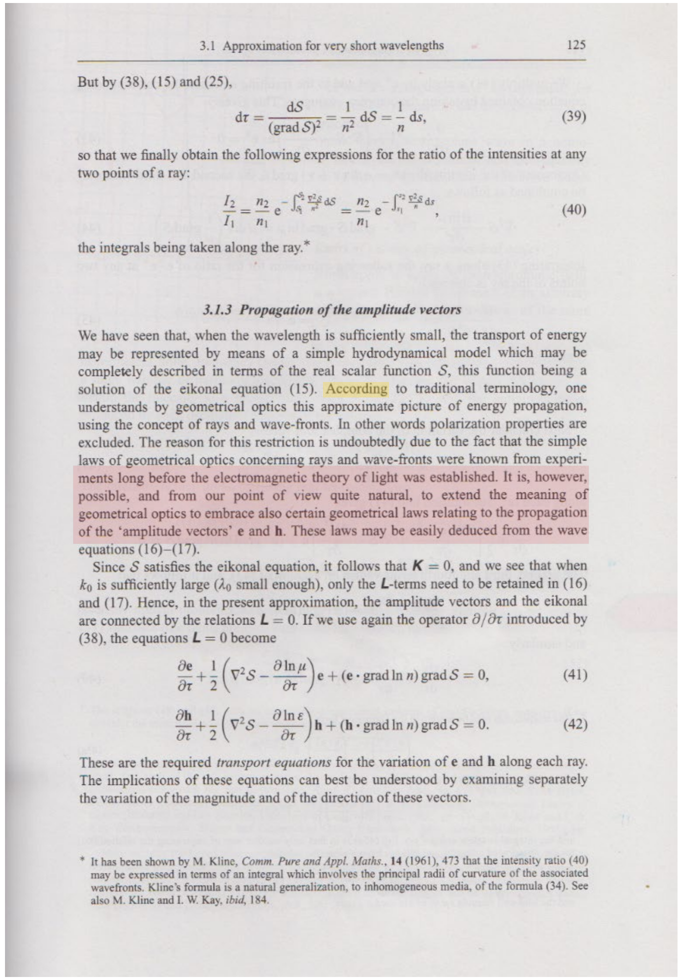
THE electromagnetic field associated with the propagation of visible light is characterized by very rapid oscillations (frequencies of the order of 10^{14} s^{-1}) or, what amounts to the same thing, by the smallness of the wavelength (of order 10^{-5} cm). It may therefore be expected that a good first approximation to the propagation laws in such cases may be obtained by a complete neglect of the finiteness of the wavelength. It is found that for many optical problems such a procedure is entirely adequate; in fact, phenomena which can be attributed to departures from this approximate theory (so-called diffraction phenomena, studied in Chapter VIII) can only be demonstrated by means of carefully conducted experiments.

The branch of optics which is characterized by the neglect of the wavelength, i.e. that corresponding to the limiting case $\lambda_0 \to 0$, is known as *geometrical optics*,* since in this approximation the optical laws may be formulated in the language of geometry. The energy may then be regarded as being transported along certain curves (light rays). A physical model of a pencil of rays may be obtained by allowing the light from a source of negligible extension to pass through a very small opening in an opaque screen. The light which reaches the space behind the screen will fill a region the boundary of which (the edge of the pencil) will, at first sight, appear to be sharp. A more careful examination will reveal, however, that the light intensity near the boundary varies rapidly but continuously from darkness in the shadow to lightness in the illuminated region, and that the variation is not monotonic but is of an oscillatory character, manifested by the appearance of bright and dark bands, called diffraction fringes. The region in which this rapid variation takes place is only of the order of magnitude of the wavelength. Hence, as long as this magnitude is neglected in comparison with the dimensions of the opening, we may speak of a sharply bounded pencil of rays.† On reducing the size of the opening down to the dimensions of the

* The historical development of geometrical optics is described by M. Herzberger, *Strahlenoptik* (Berlin, Springer, 1931), p. 179; Z. *Instrumentenkunde*, **52** (1932), 429–435, 485–493, 534–542, C. Carathéodory, *Geometrische Optik* (Berlin, Springer, 1937) and E. Mach, *The Principles of Physical Optics, A Historical and Philosophical Treatment* (First German edition 1913, English translation: London, Methuen, 1926; reprinted by Dover Publications, New York, 1953).

† That the boundary becomes sharp in the limit as $\lambda_0 \to 0$ was first shown by G. Kirchhoff, *Vorlesungen ü. Math. Phys.*, Vol. 2 (*Mathematische Optik*) (Leipzig, Tuebner, 1891), p. 33. See also B. B. Baker and E. T. Copson, *The Mathematical Theory of Huygens' Principle* (Oxford, Clarendon Press, 2nd edition, 1950), p. 79, and A. Sommerfeld, *Optics* (New York, Academic Press, 1954), §35.

Geometric Branch of Physical Optics



3.1 Approximation for very short wavelengths 125

But by (38), (15) and (25),

$$d\tau = \frac{d\mathcal{S}}{(\mathrm{grad}\,\mathcal{S})^2} = \frac{1}{n^2}\,d\mathcal{S} = \frac{1}{n}\,ds, \qquad (39)$$

so that we finally obtain the following expressions for the ratio of the intensities at any two points of a ray:

$$\frac{I_2}{I_1} = \frac{n_2}{n_1}\,e^{-\int_{\mathcal{S}_1}^{\mathcal{S}_2}\frac{\nabla^2\mathcal{S}}{n^2}\,d\mathcal{S}} = \frac{n_2}{n_1}\,e^{-\int_{s_1}^{s_2}\frac{\nabla^2\mathcal{S}}{n}\,ds}, \qquad (40)$$

the integrals being taken along the ray.*

3.1.3 *Propagation of the amplitude vectors*

We have seen that, when the wavelength is sufficiently small, the transport of energy may be represented by means of a simple hydrodynamical model which may be completely described in terms of the real scalar function $\mathcal{S}$, this function being a solution of the eikonal equation (15). According to traditional terminology, one understands by geometrical optics this approximate picture of energy propagation, using the concept of rays and wave-fronts. In other words polarization properties are excluded. The reason for this restriction is undoubtedly due to the fact that the simple laws of geometrical optics concerning rays and wave-fronts were known from experiments long before the electromagnetic theory of light was established. It is, however, possible, and from our point of view quite natural, to extend the meaning of geometrical optics to embrace also certain geometrical laws relating to the propagation of the 'amplitude vectors' **e** and **h**. These laws may be easily deduced from the wave equations (16)–(17).

Since $\mathcal{S}$ satisfies the eikonal equation, it follows that $\boldsymbol{K} = 0$, and we see that when k_0 is sufficiently large (λ_0 small enough), only the $\boldsymbol{L}$-terms need to be retained in (16) and (17). Hence, in the present approximation, the amplitude vectors and the eikonal are connected by the relations $\boldsymbol{L} = 0$. If we use again the operator $\partial/\partial\tau$ introduced by (38), the equations $\boldsymbol{L} = 0$ become

$$\frac{\partial \mathbf{e}}{\partial\tau} + \frac{1}{2}\left(\nabla^2\mathcal{S} - \frac{\partial \ln\mu}{\partial\tau}\right)\mathbf{e} + (\mathbf{e}\cdot\mathrm{grad}\ln n)\,\mathrm{grad}\,\mathcal{S} = 0, \qquad (41)$$

$$\frac{\partial \mathbf{h}}{\partial\tau} + \frac{1}{2}\left(\nabla^2\mathcal{S} - \frac{\partial \ln\varepsilon}{\partial\tau}\right)\mathbf{h} + (\mathbf{h}\cdot\mathrm{grad}\ln n)\,\mathrm{grad}\,\mathcal{S} = 0. \qquad (42)$$

These are the required *transport equations* for the variation of **e** and **h** along each ray. The implications of these equations can best be understood by examining separately the variation of the magnitude and of the direction of these vectors.

* It has been shown by M. Kline, *Comm. Pure and Appl. Maths.*, **14** (1961), 473 that the intensity ratio (40) may be expressed in terms of an integral which involves the principal radii of curvature of the associated wavefronts. Kline's formula is a natural generalization, to inhomogeneous media, of the formula (34). See also M. Kline and I. W. Kay, *ibid*, 184.

page 125

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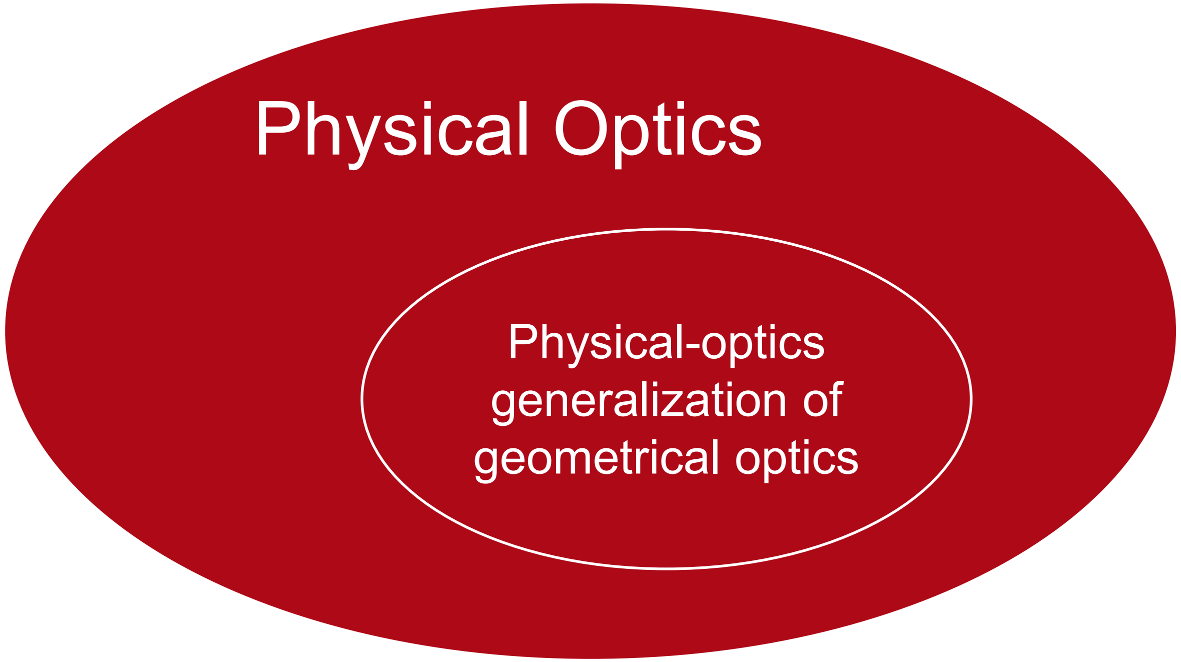
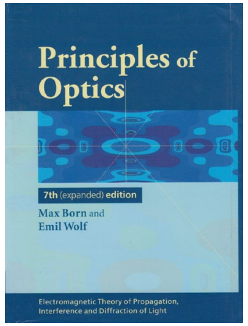
Geometric Branch of Physical Optics



We need to identify that part of physical optics, which deals with the “***geometrical laws relating to the propagation of the 'amplitude vectors' E and H***.”

Citation from



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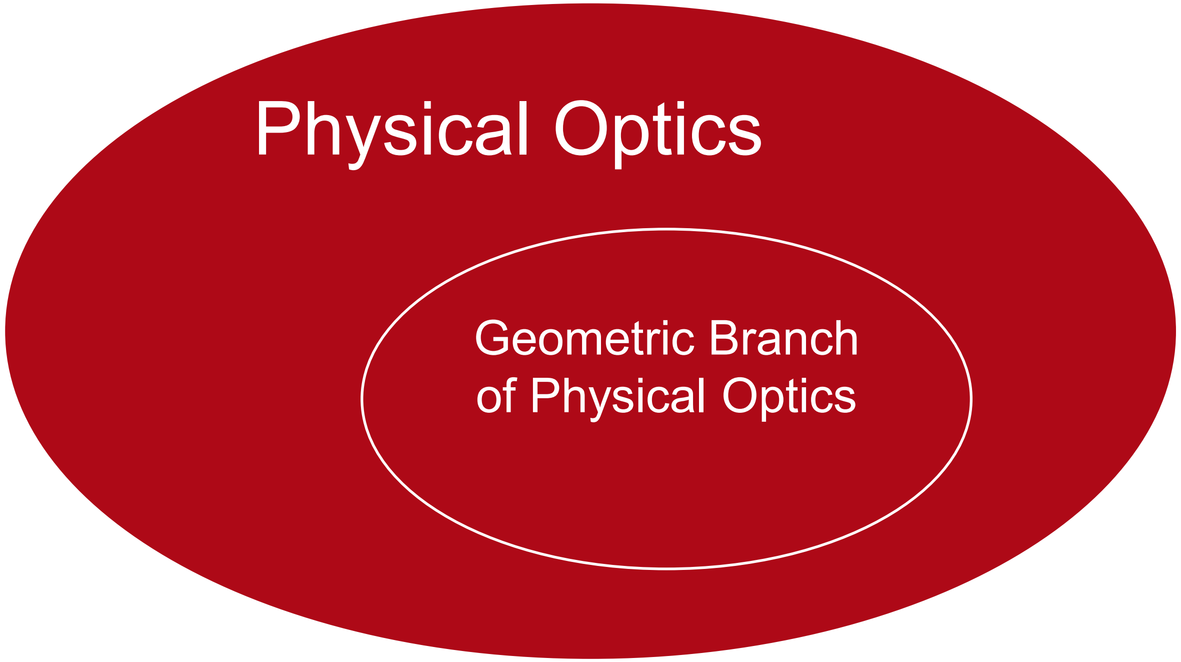
We follow Max Born’s and Emil Wolf’s advice!

Geometric Branch of Physical Optics



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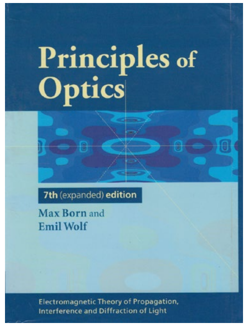
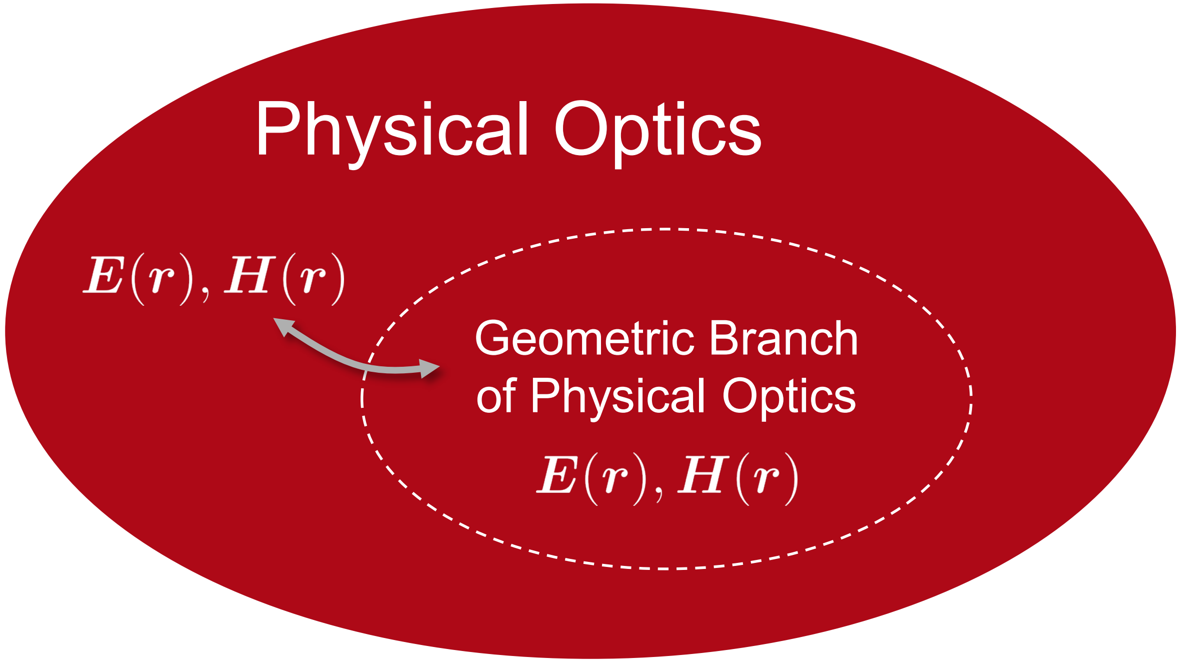


page 125

We follow Max Born's and Emil Wolf's advice!

Physical and Geometrical Optics: The Objective



Search for a seamless transition reasonable!

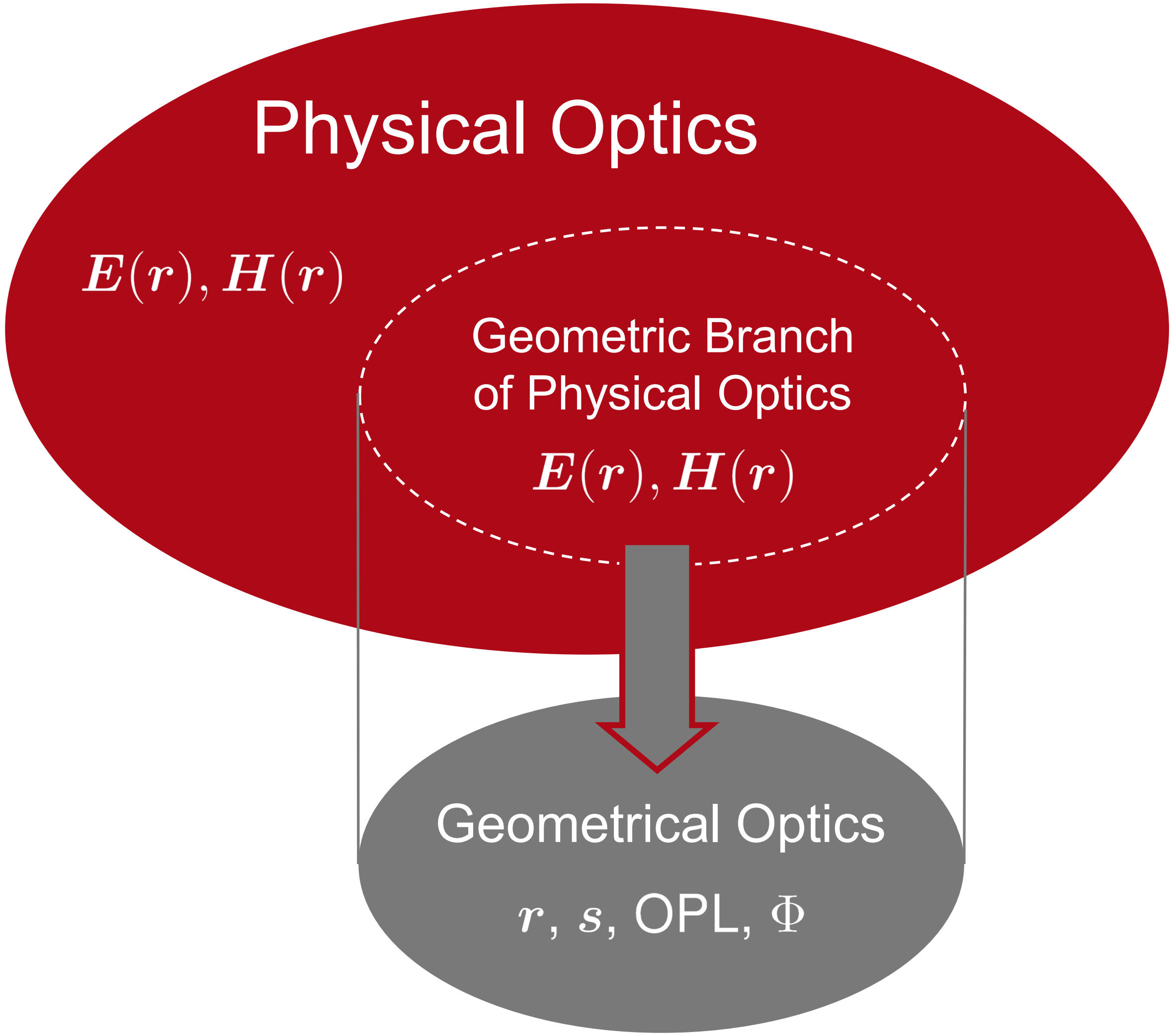
Current situation:

- Geometrical and physical optics coexist without a powerful connection in theory and practice.
- Some design tasks apply specialized connections, e.g., PSF/MTF calculation in lens design.

Our objective:

- Seamless transition between physical optics and its *geometric branch* in theory and practice.

Physical and Geometrical Optics: The Objective



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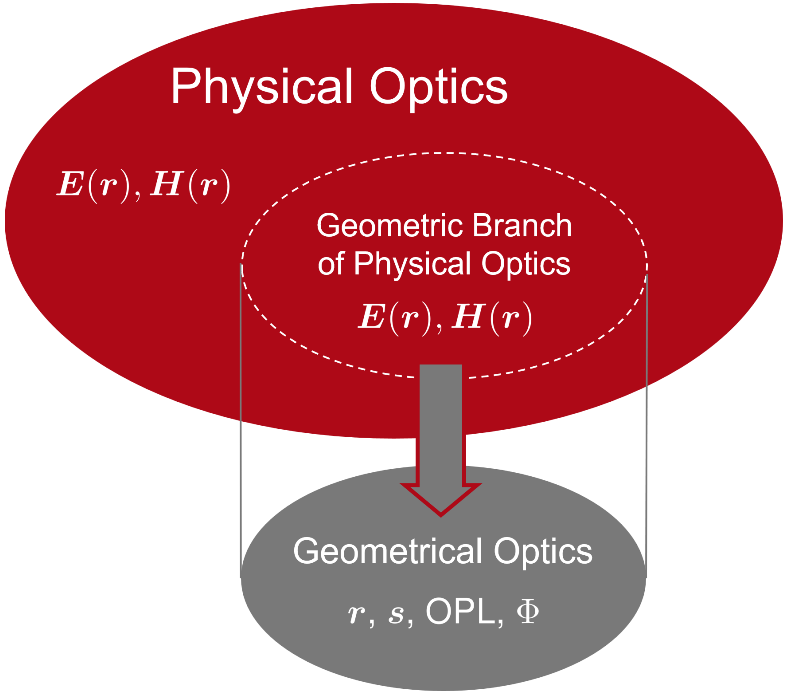
- Geometrical optics follows from the geometric branch by restricting to a ray-optical light representation.

Unified Modeling: The Major Trend



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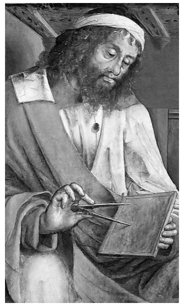

Euclid of Alexandria
(c. 325 BC – 265 BC)

Pierre de Fermat
(1601 - 1665)

James Clerk Maxwell
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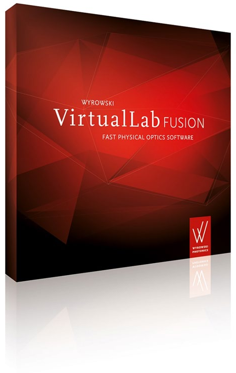
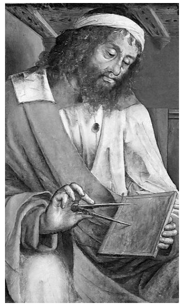
Unified Modeling: The Major Trend



Unified modeling provides the foundation and the direction of the software development!



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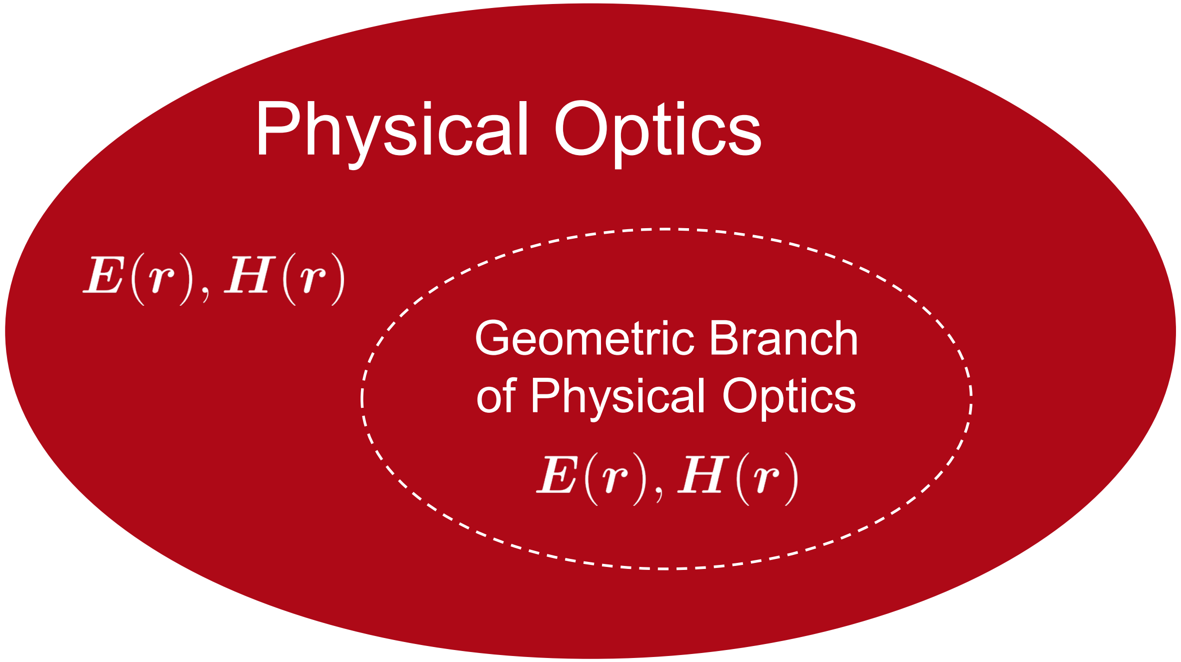
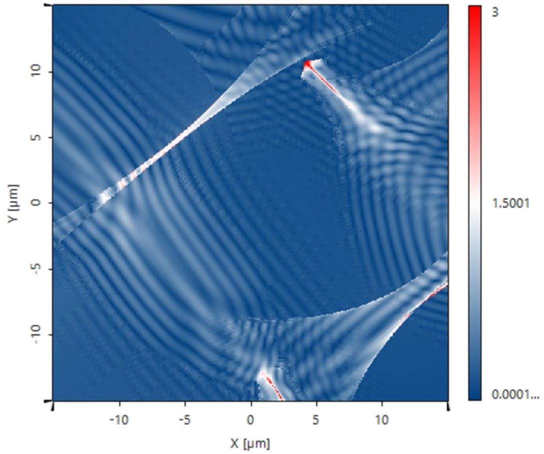
Geometric Branch of Physical Optics

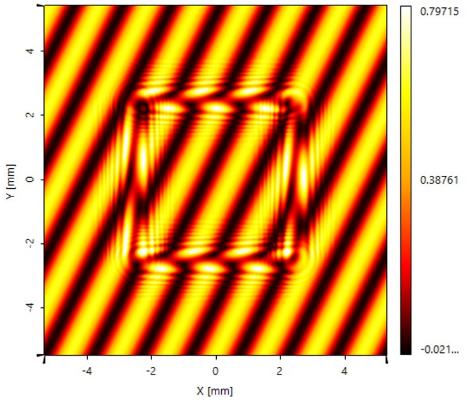


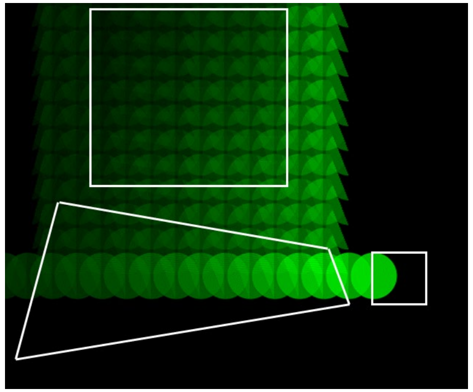
How to define the geometric branch of physical optics?

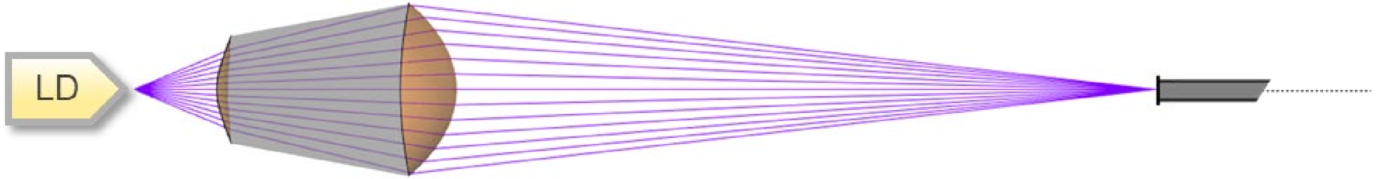
Content Overview

- **Introduction to a unified approach in optical modeling**
- Theoretical considerations on physical optics modeling
- Modeling examples
  - Talk
  - Follow-up material









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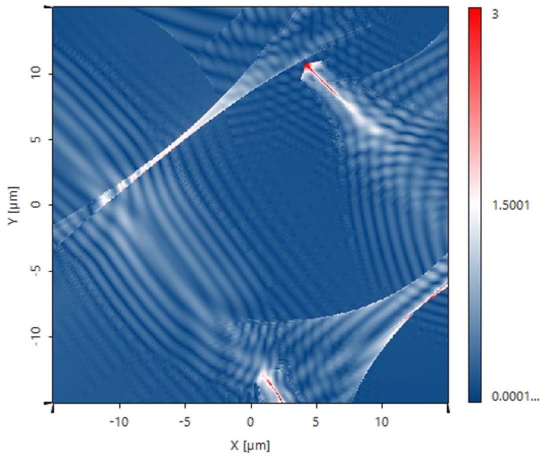
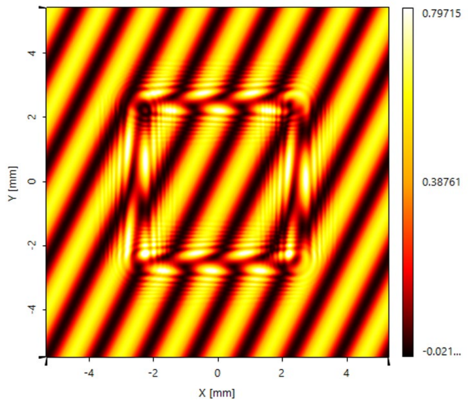
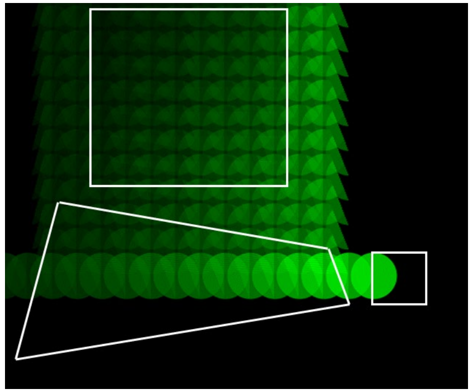
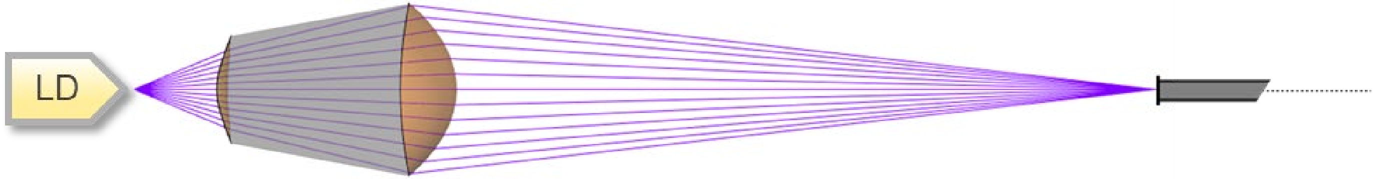
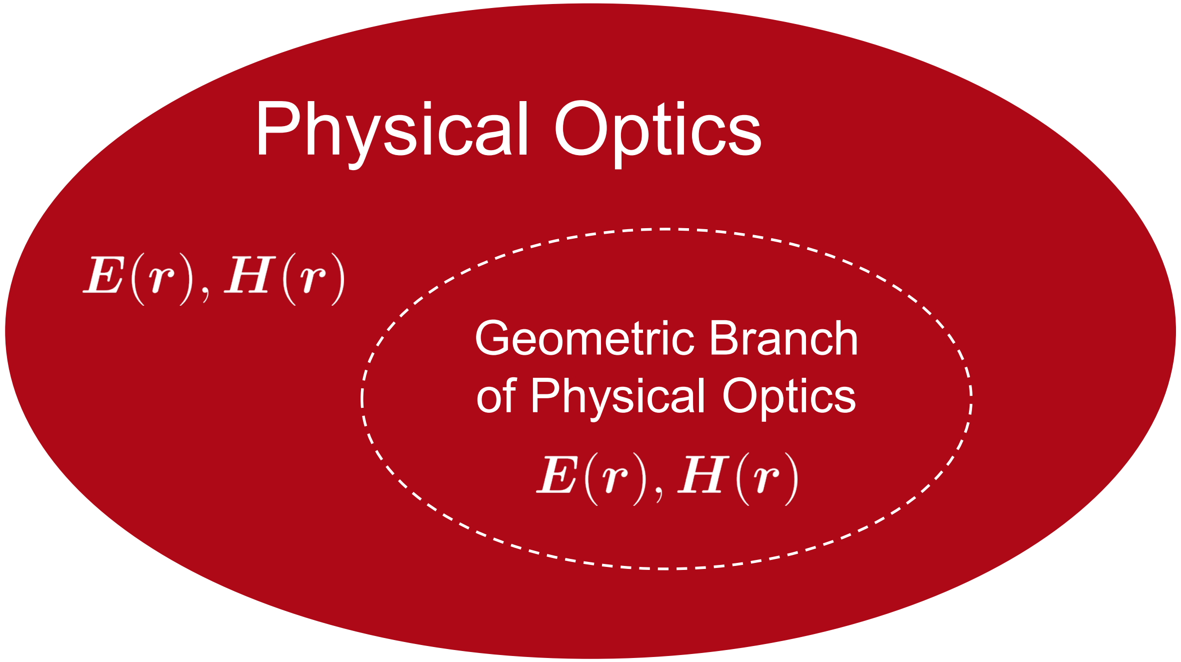






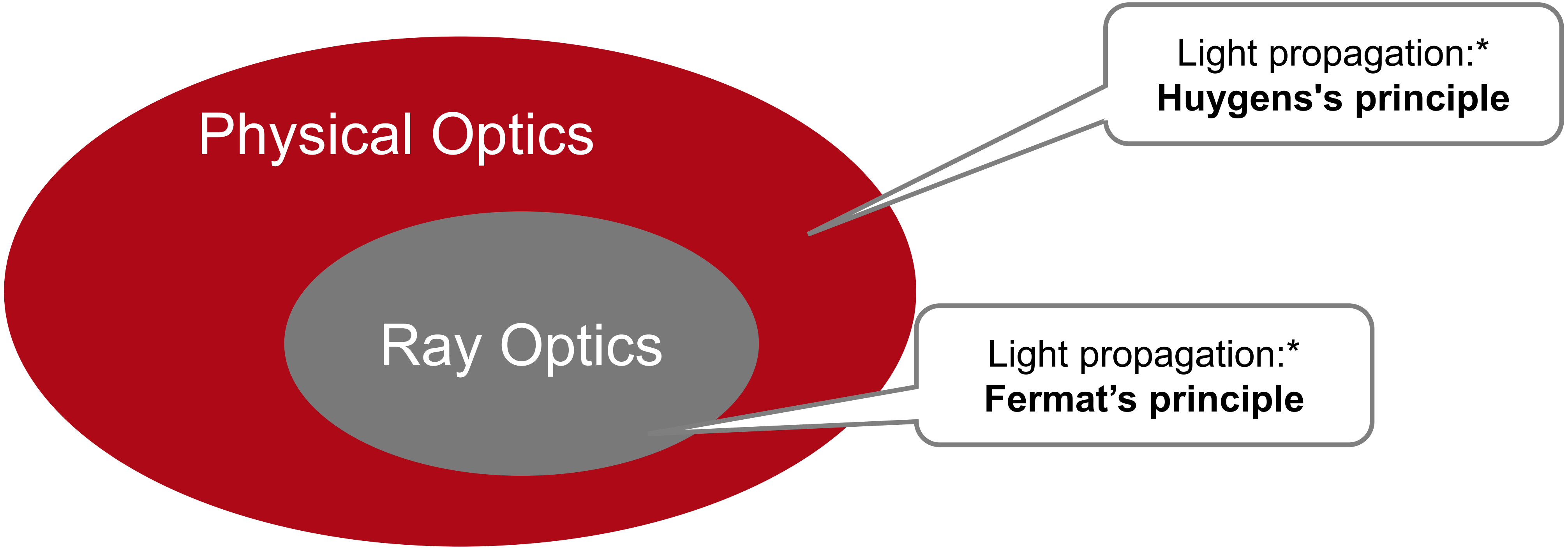


Geometric Branch of Physical Optics



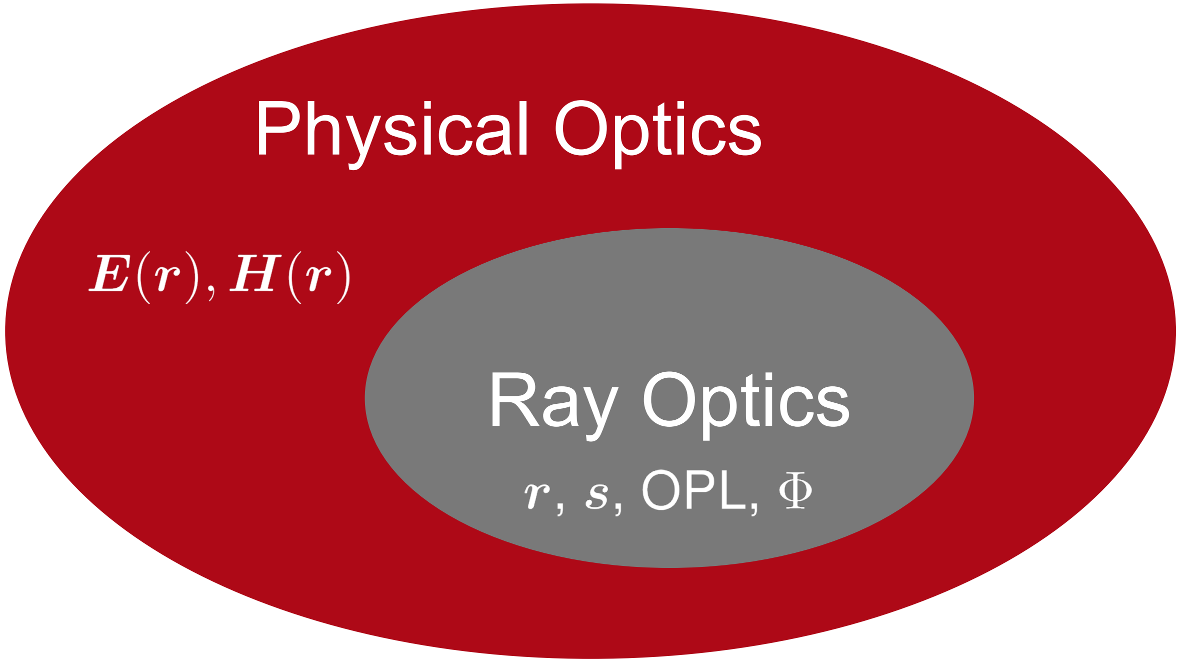
How to define the geometric branch of physical optics?

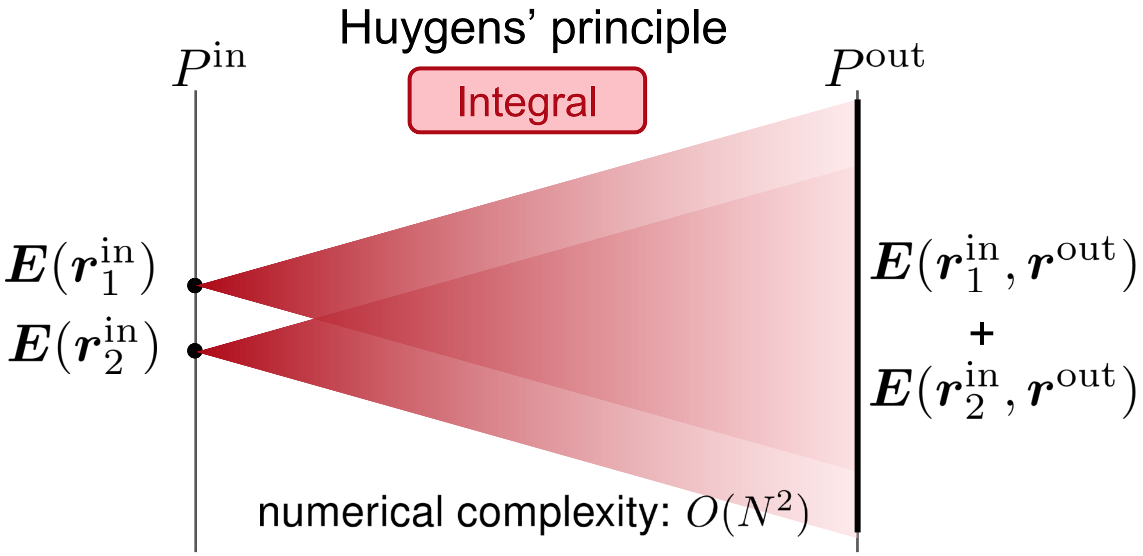
Physical and Geometrical Optics: Light Propagation

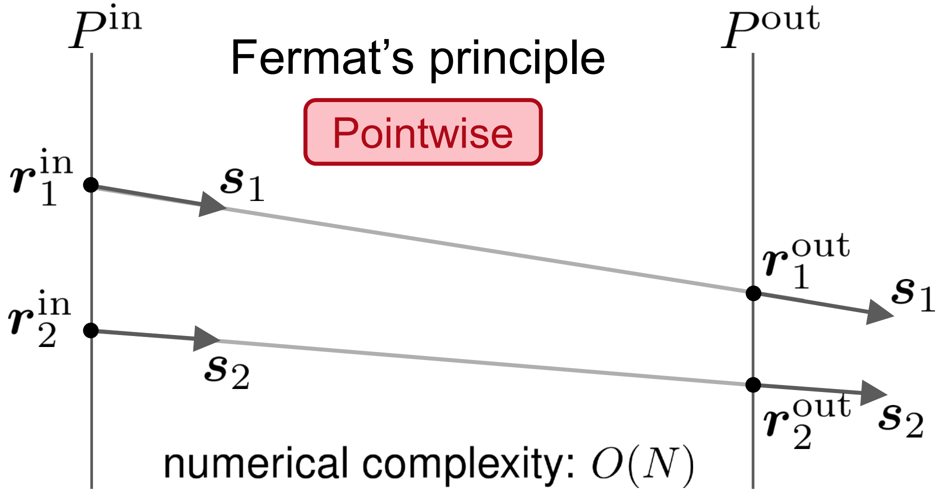


*Here: Propagation in homogeneous media

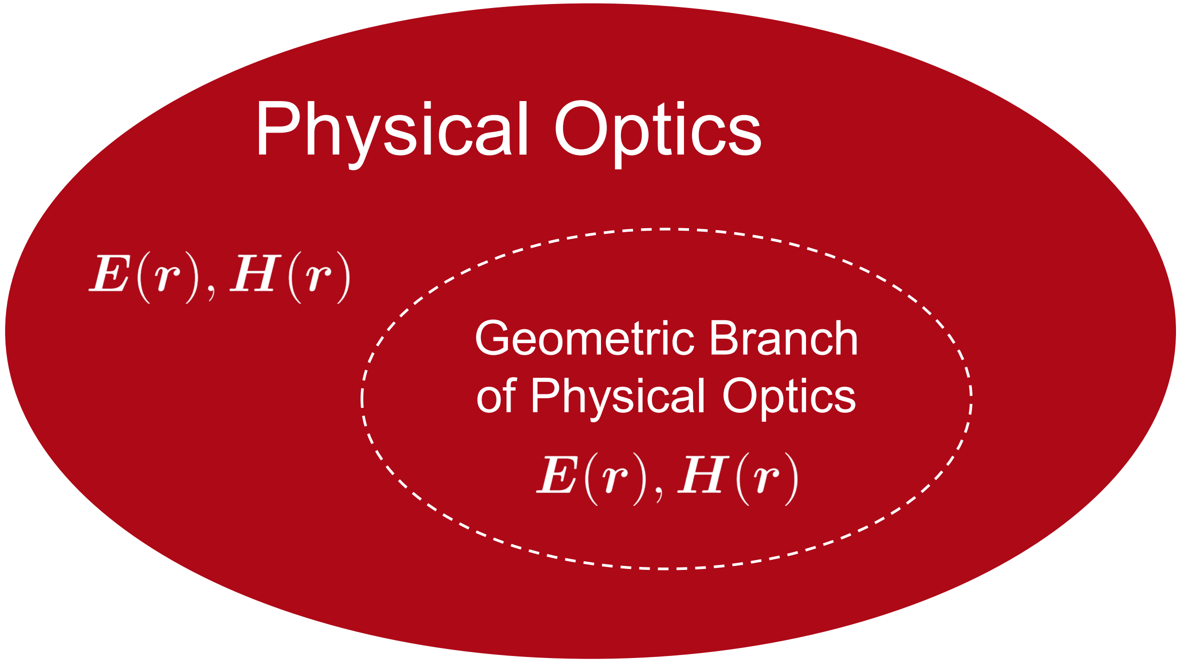
Physical and Geometrical Optics: Light Propagation

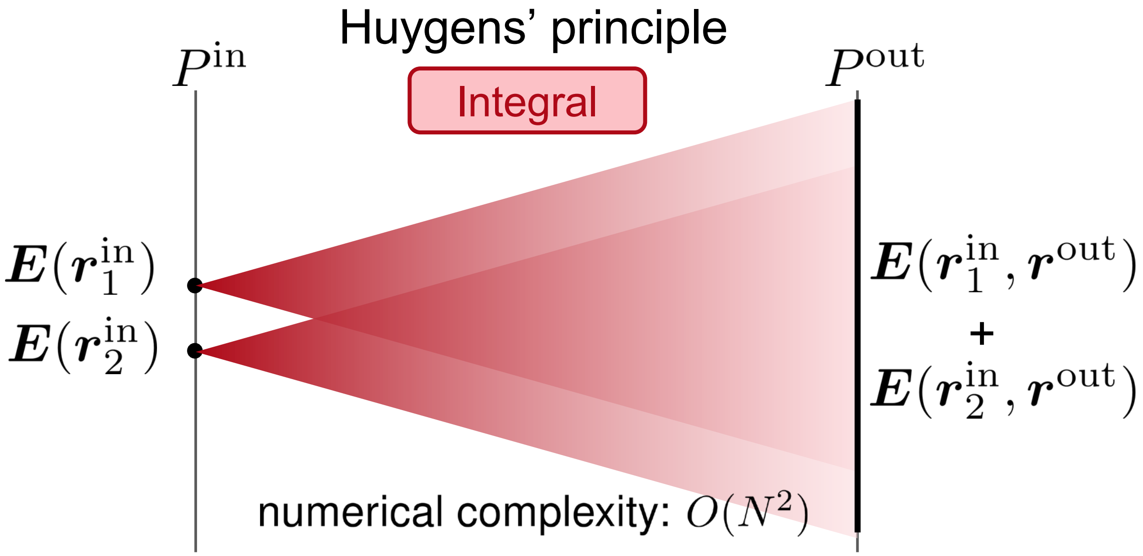


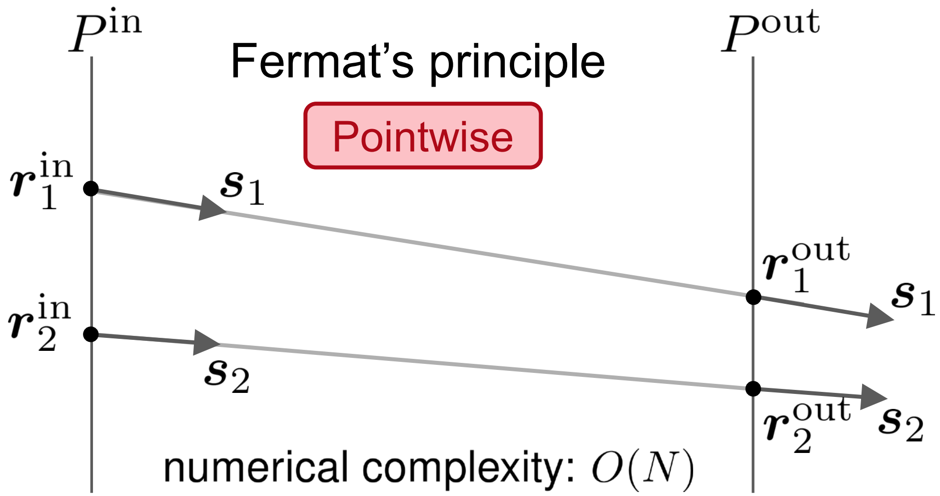




Geometric Branch of Physical Optics: Pointwise Operations







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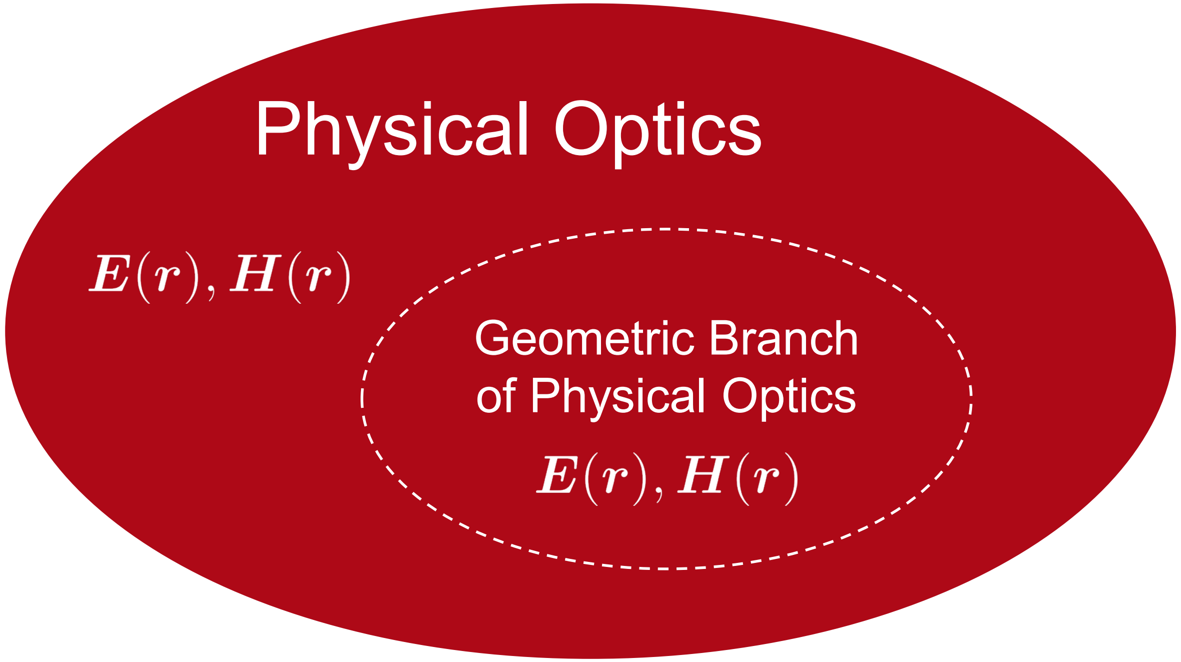

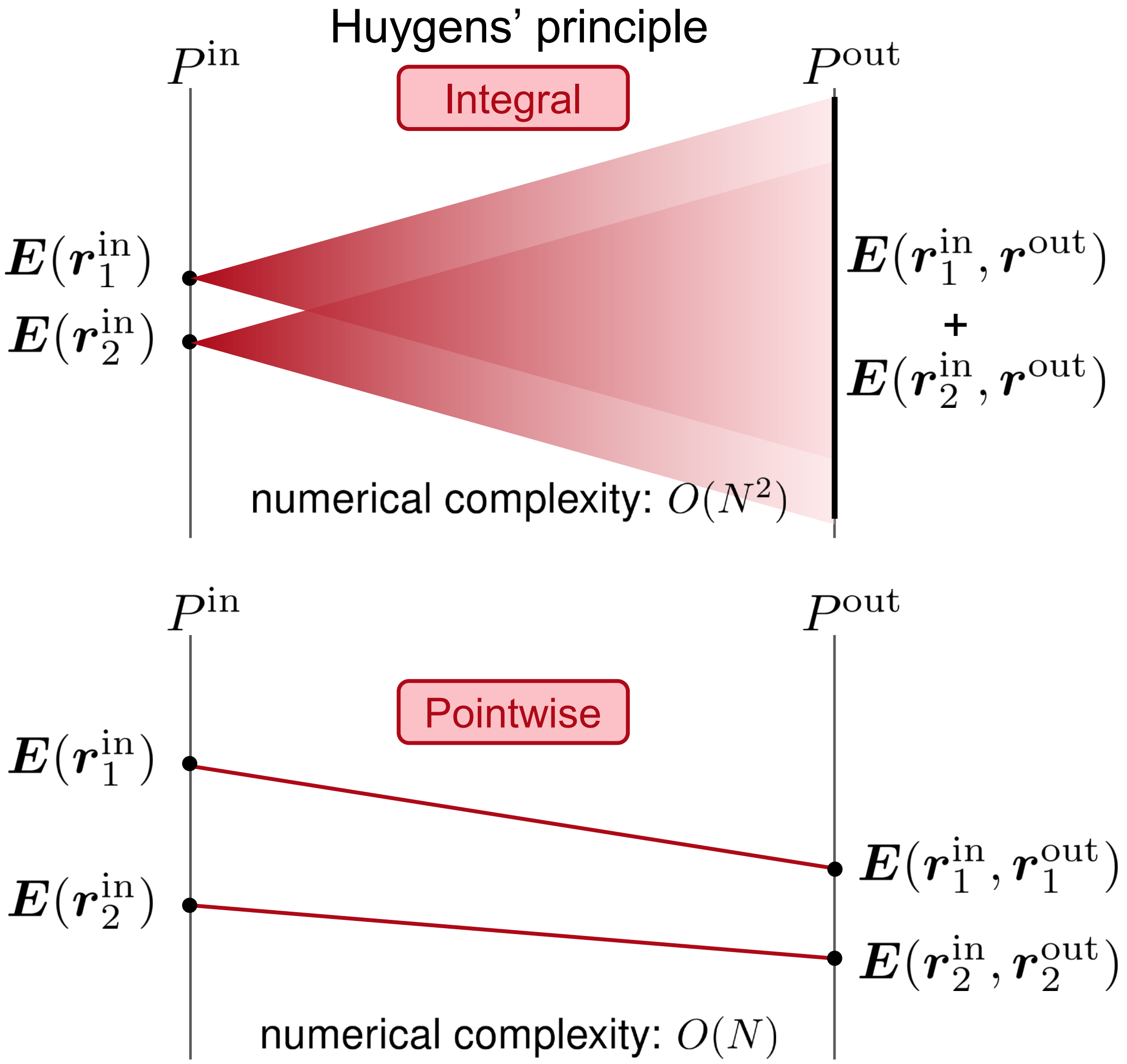

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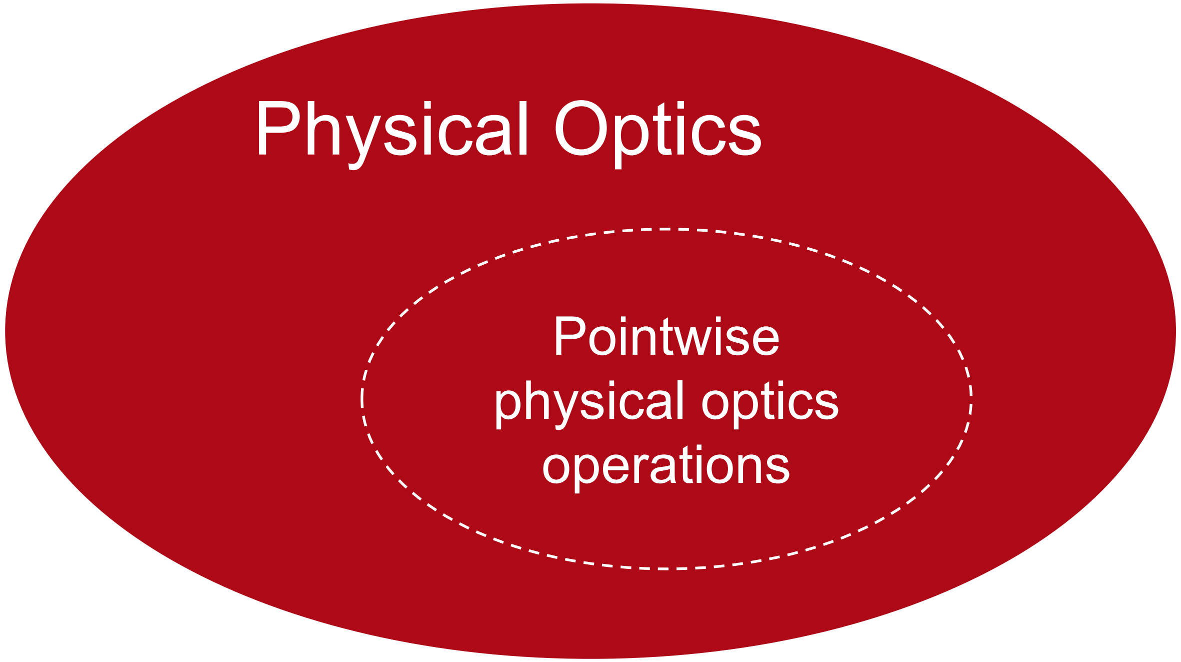

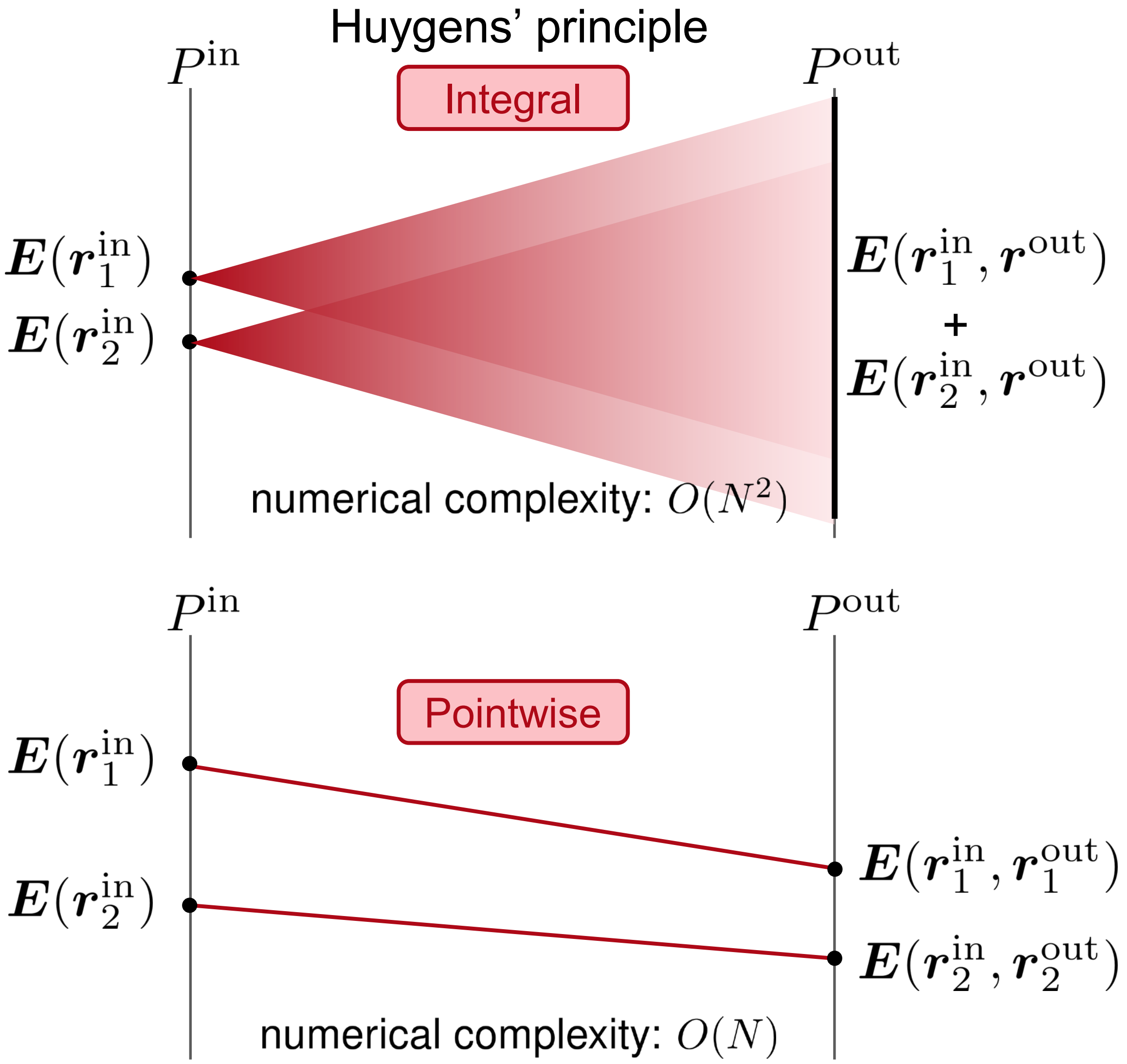

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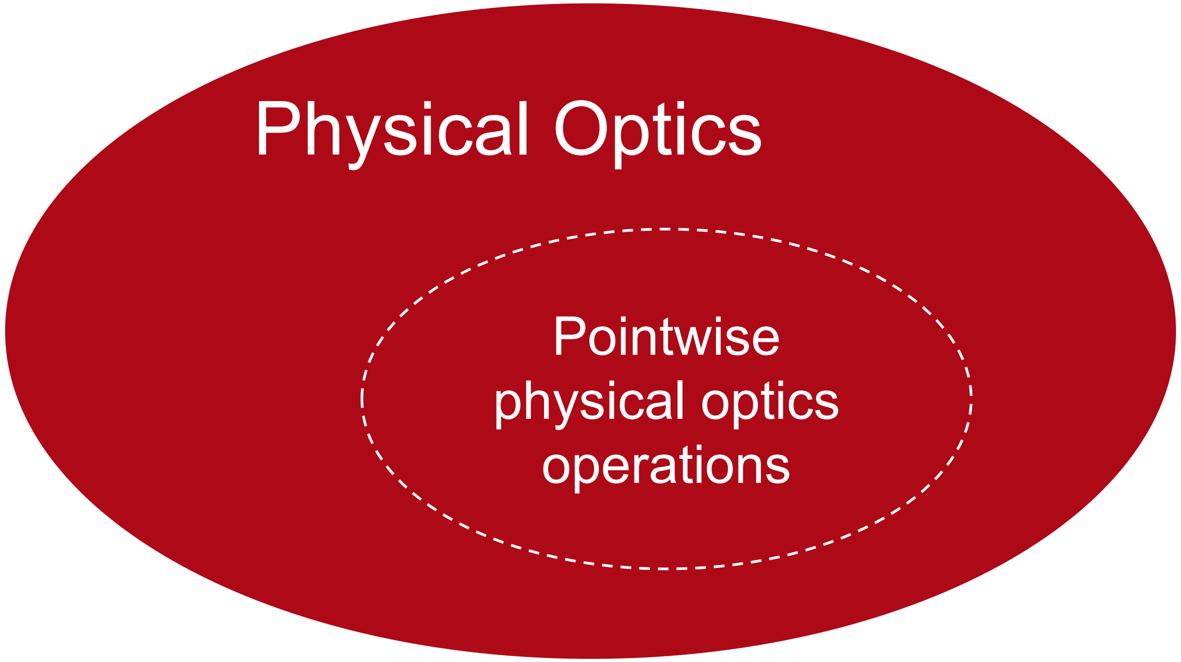


P^{in} $\boldsymbol{\rho}' = (x', y')$ — **Integral** — P^{out} $\boldsymbol{\rho} = (x, y)$

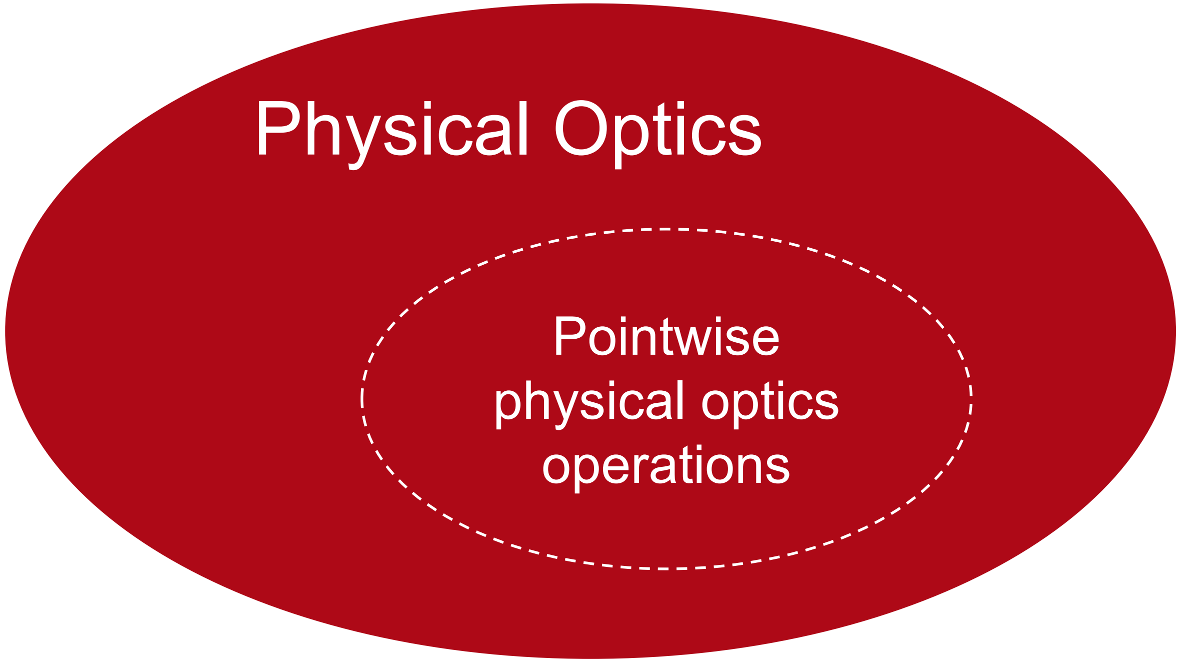
$$\boldsymbol{E}^{\mathrm{out}}(\boldsymbol{\rho}) = \int\int_{P^{\mathrm{in}}} \mathbf{B}(\boldsymbol{\rho}, \boldsymbol{\rho}')\boldsymbol{E}^{\mathrm{in}}(\boldsymbol{\rho}')\,\mathrm{d}x'\,\mathrm{d}y'$$

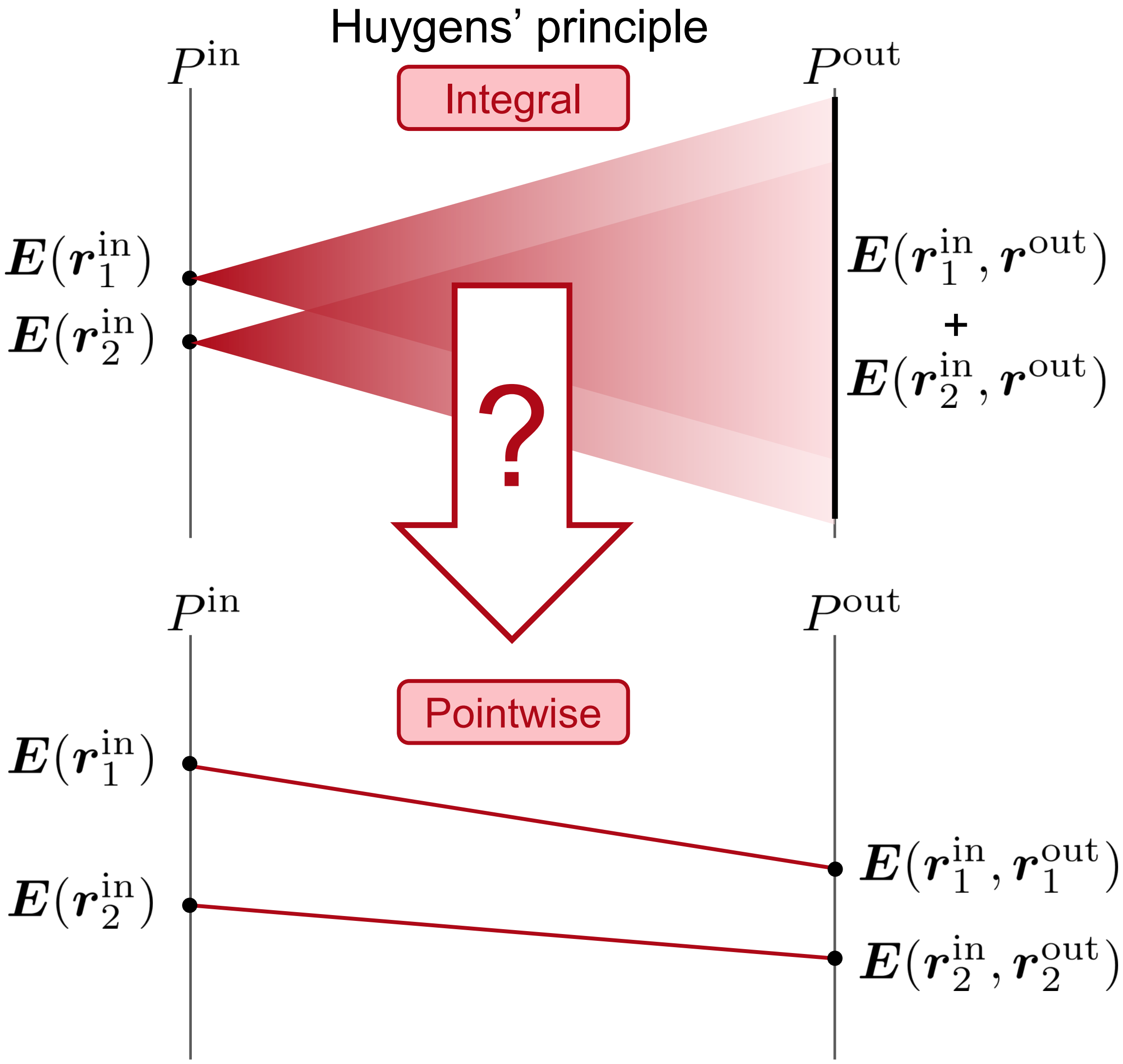
P^{in} $\boldsymbol{\rho}'$ — **Pointwise** — P^{out} $\boldsymbol{\rho}$

$$\underline{\mathbf{B}}(\boldsymbol{\rho}')\boldsymbol{E}^{\mathrm{in}}(\boldsymbol{\rho}') \mapsto \boldsymbol{E}^{\mathrm{out}}(\boldsymbol{\rho})$$

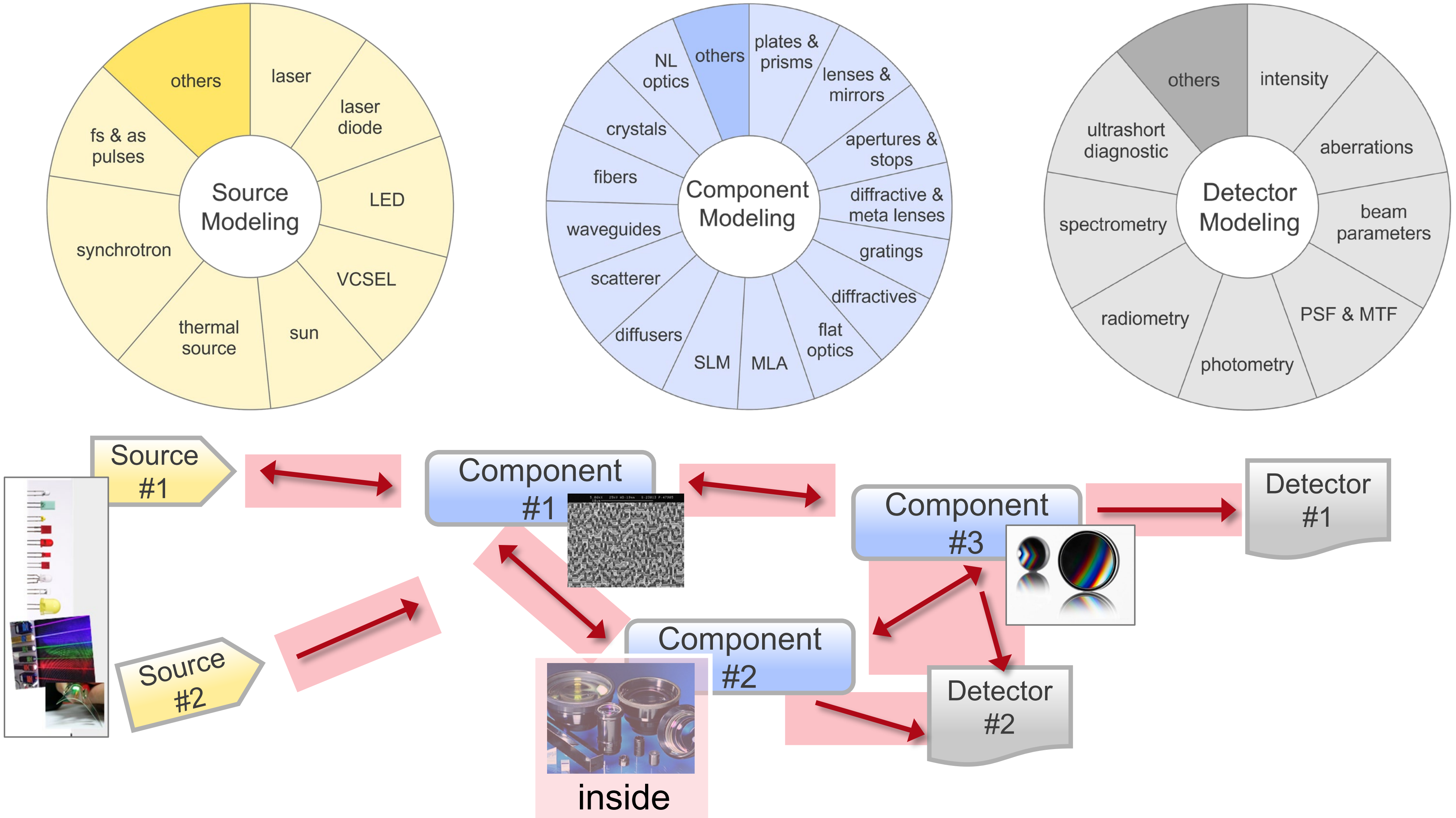
with coordinate mapping $\boldsymbol{\rho}' \mapsto \boldsymbol{\rho}(\boldsymbol{\rho}')$

Geometric Branch of Physical Optics: Pointwise Operations





Propagation in Homogeneous Isotropic Media*



*Homogeneous media examples: vacuum, glasses, plastic, water, oil

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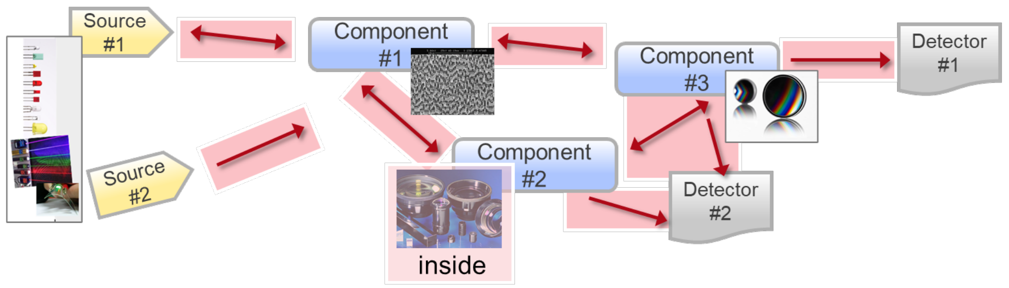
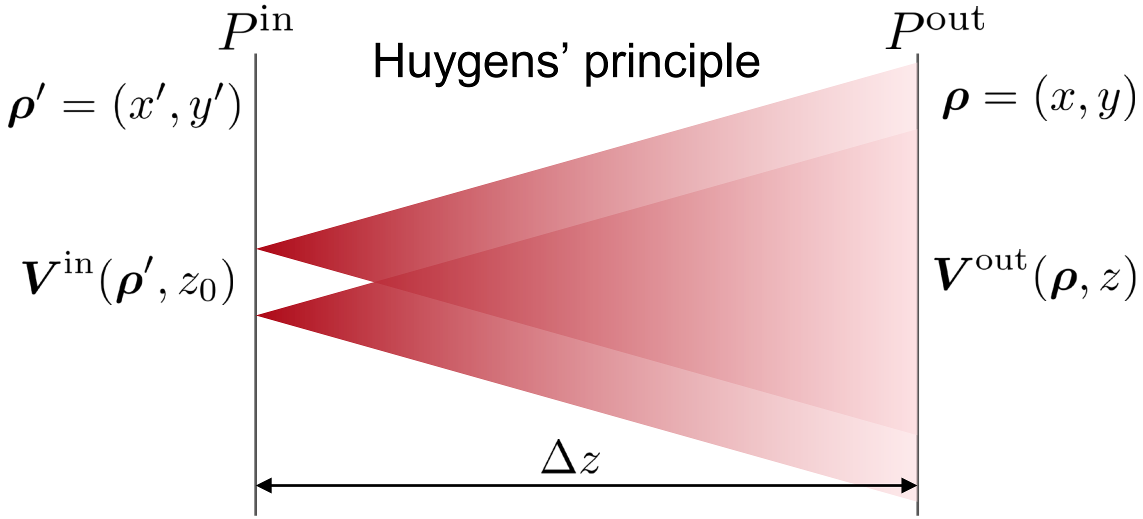




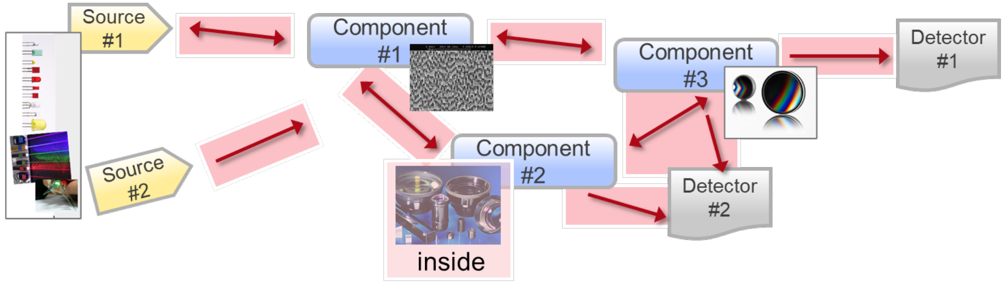
- Propagating an electromagnetic field

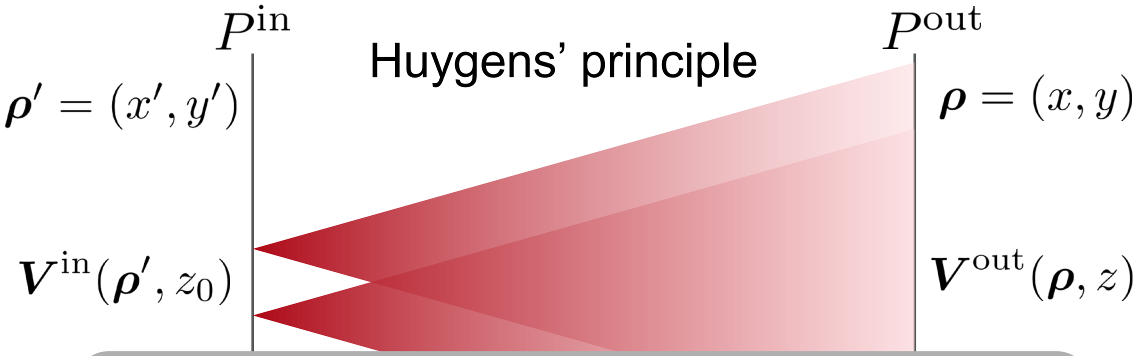
$$\boldsymbol{V} := \left(E_x, E_y, E_z, H_x, H_y, H_z\right)^T$$

between planes of arbitrary orientation or surfaces constitutes a **key technology in physical optics modeling**.

*Homogeneous media examples: vacuum, glasses, plastic, water, oil

Propagation in Homogeneous Isotropic Media*





$$V(\boldsymbol{\rho}, z) = -\frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} V(\boldsymbol{\rho}', z_0) \frac{\partial}{\partial z} \frac{\mathrm{e}^{\mathrm{i}k_0 \check{n} R}}{R} \, \mathrm{d}x' \, \mathrm{d}y'$$

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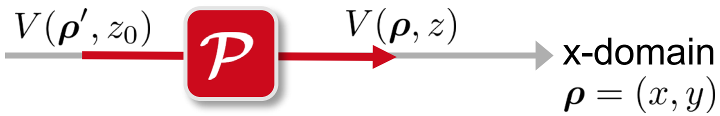

- In x-domain propagation is expressed by the Rayleigh-Sommerfeld **integral**

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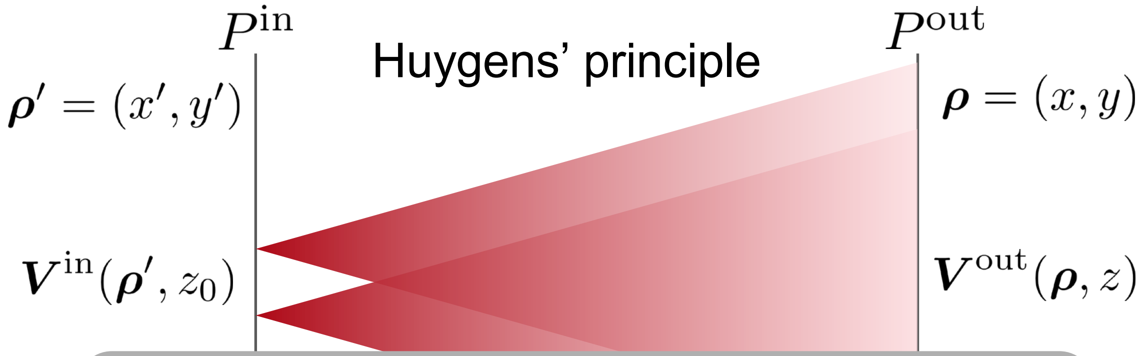

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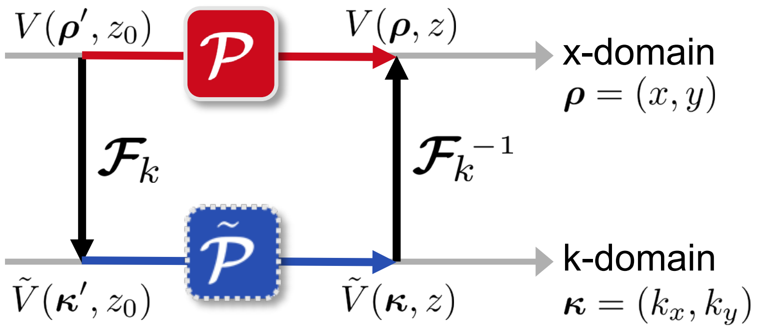
Propagation in Homogeneous Isotropic Media*



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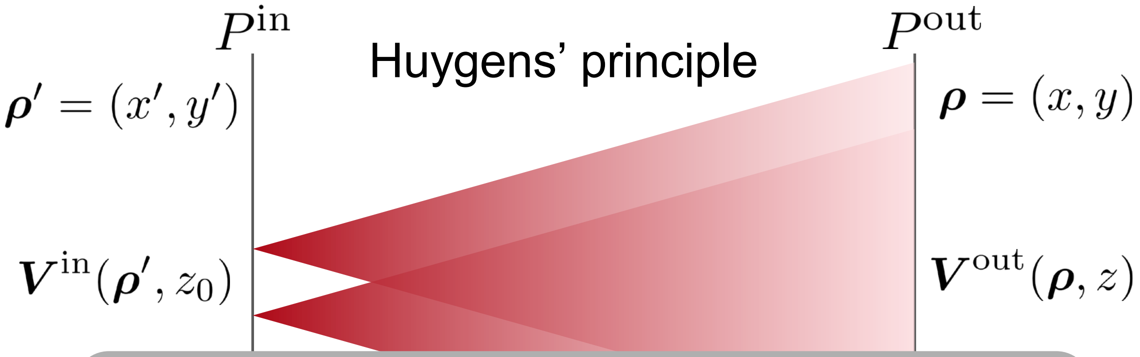
- In k-domain we apply the **pointwise operation**

$$\tilde{\mathcal{P}} : \tilde{V} \mapsto \tilde{V} \times e^{i\check{k}_z(\boldsymbol{\kappa})\Delta z} .$$

- The Fourier transform $\mathcal{F}_k$ is an integral operator:

$$\tilde{V}(\boldsymbol{\kappa}, z) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} V(\boldsymbol{\rho}, z)\exp(-i\boldsymbol{\kappa}\cdot\boldsymbol{\rho})\,dx\,dy$$



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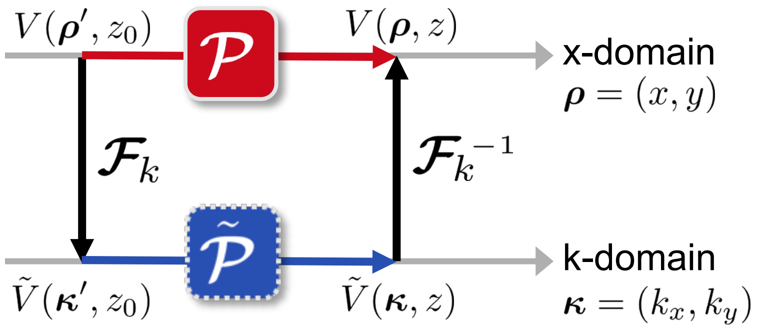
Propagation in Homogeneous Isotropic Media



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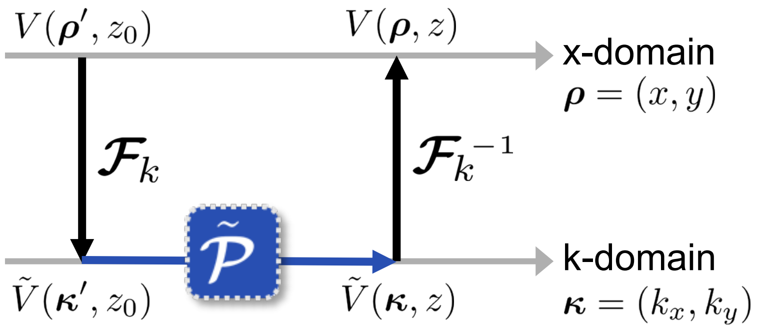
Numerical complexity: $O(N^2)$

Numerical complexity because of FFT: $O(N)$

Propagation in Homogeneous Isotropic Media



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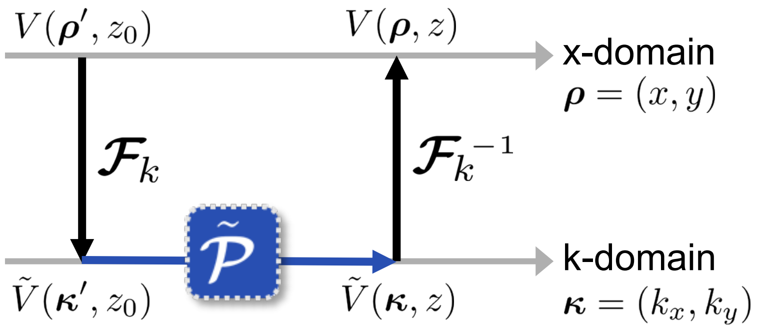
A pointwise physical-optics propagation in homogeneous media can only be obtained, if both **Fourier transforms become (approximately) pointwise.**

Propagation in Homogeneous Isotropic Media



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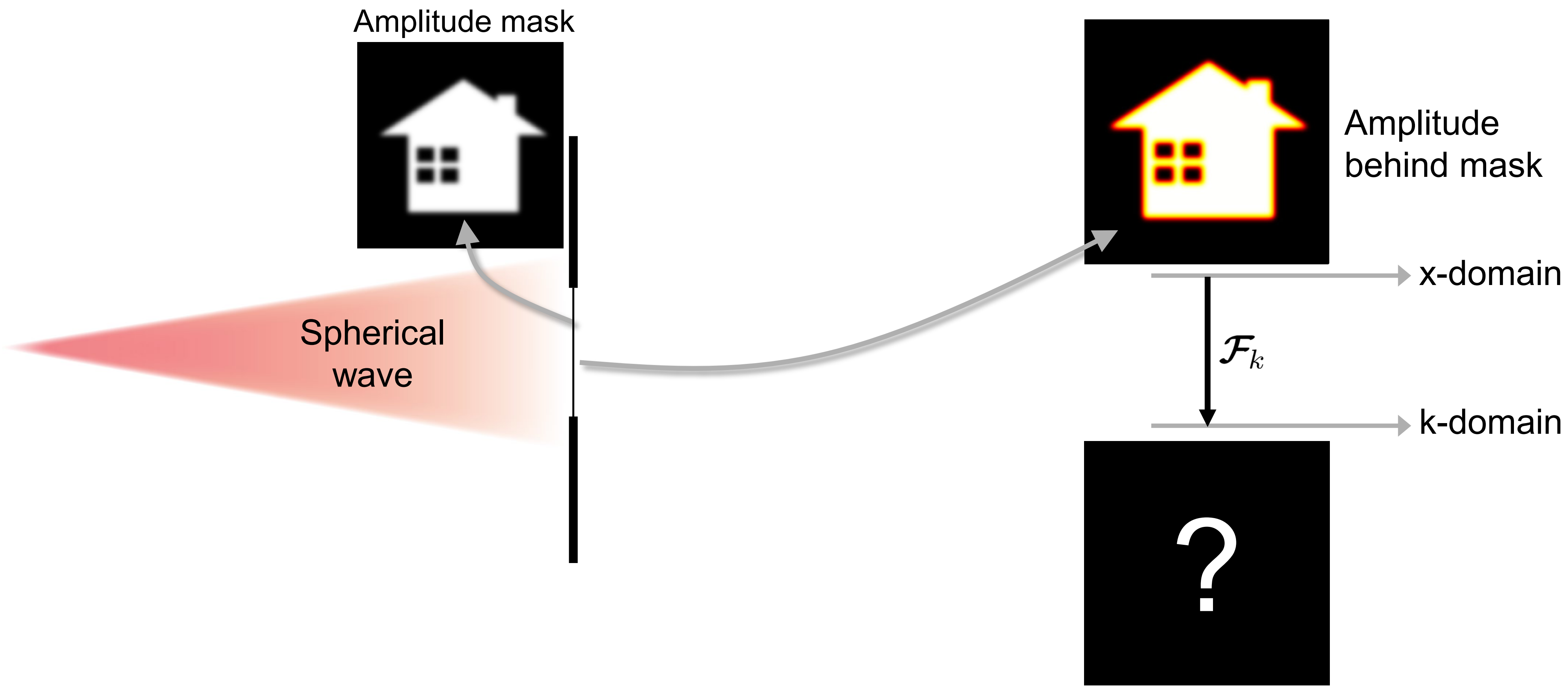
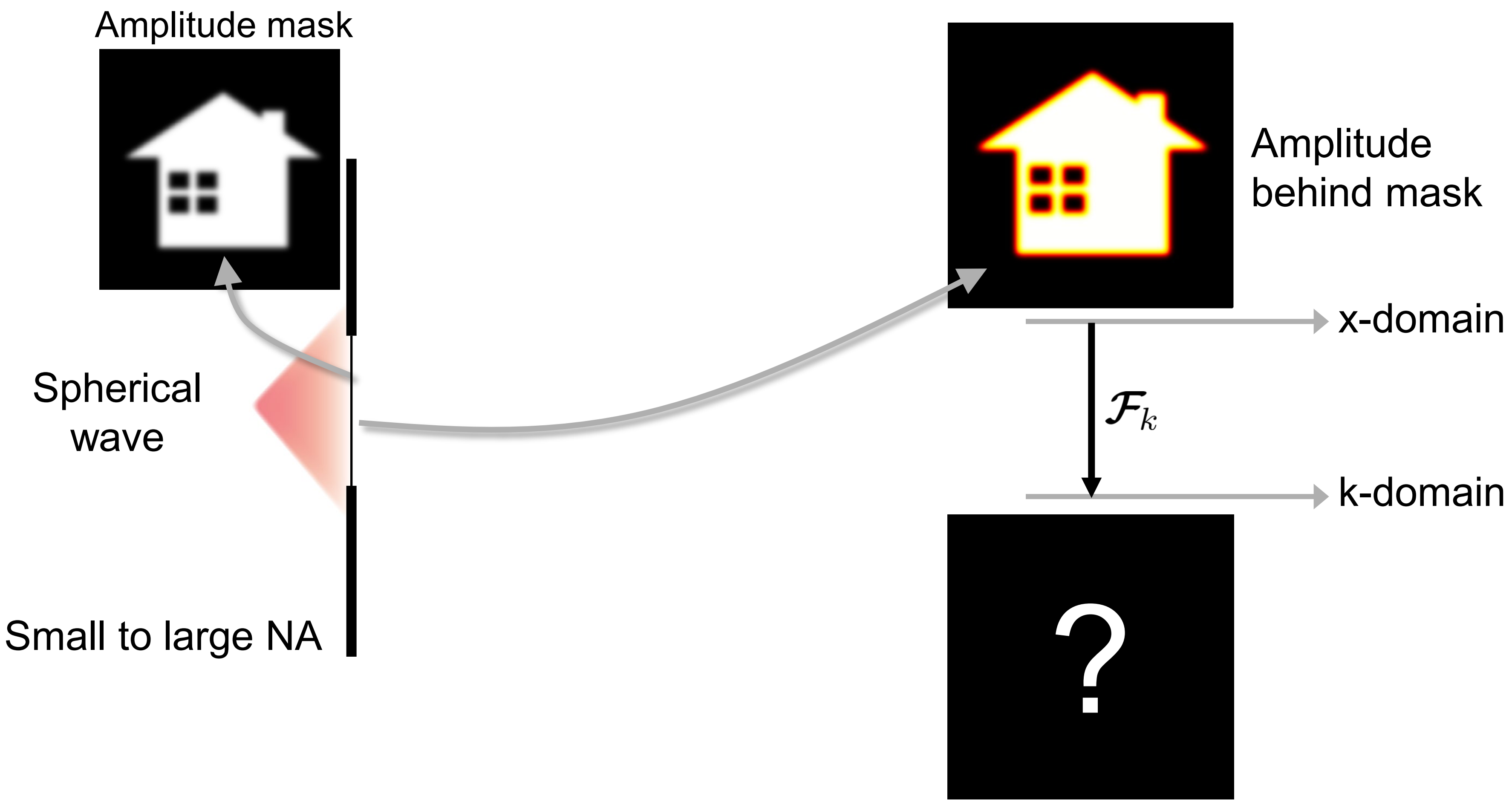
Pointwise Fourier transform constitutes key technology of physical optics modeling.

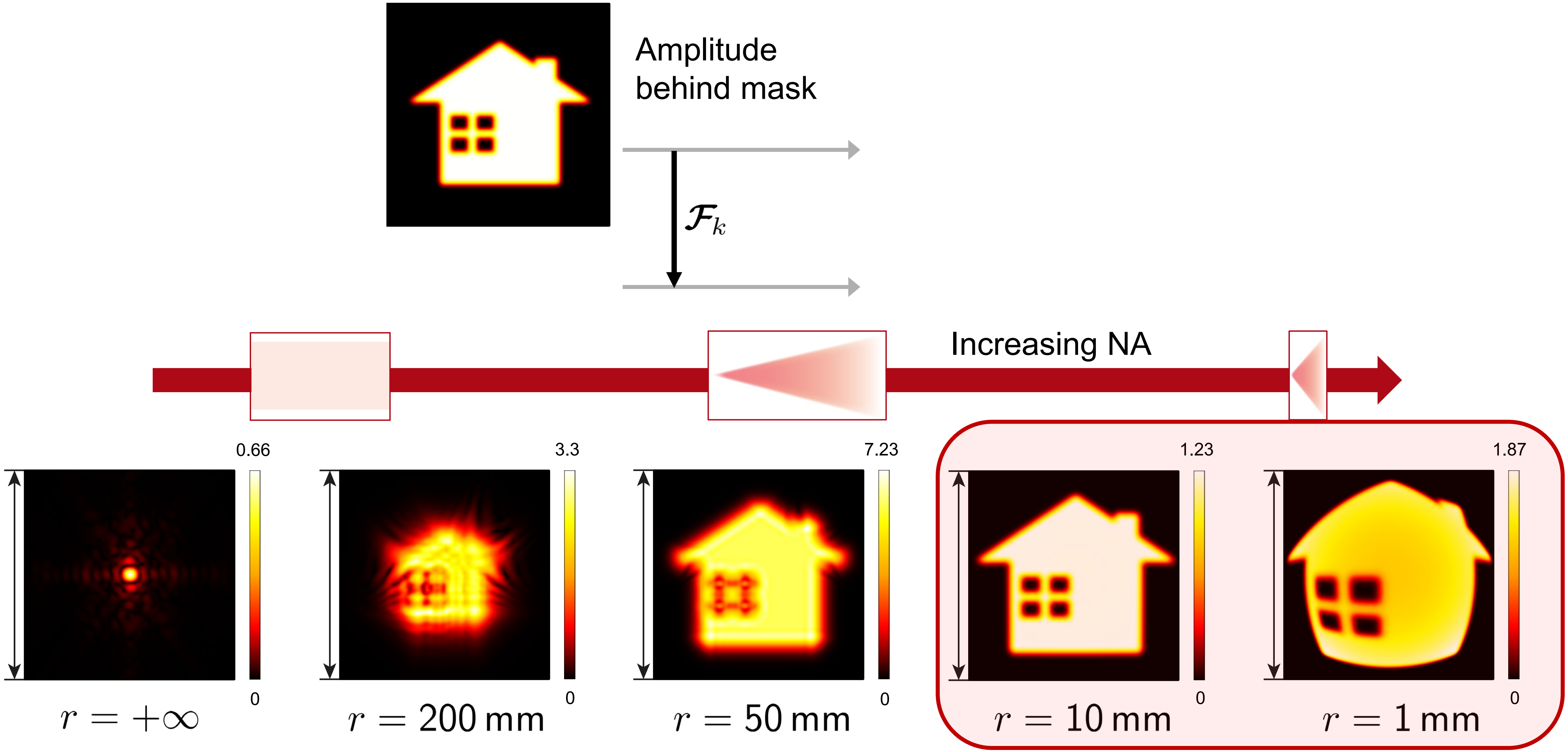
Pointwise Fourier Transform: Demonstration



Pointwise Fourier Transform: Demonstration



Results of Fourier Transform

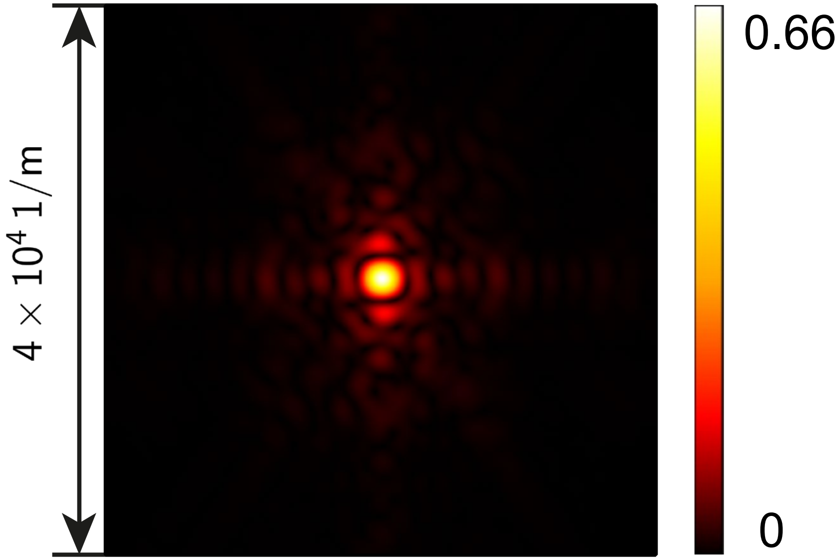


Pointwise vs. Integral Fourier Transform @ NA = 0

Sampling Points for Different Fourier Transform Techniques		
	PFT	**FFT**
NA = 0	73 x 59	(73 x 59)

$$\tilde{V}(\boldsymbol{\kappa}) = \left(\mathcal{F}_k^{1:1} V\right)(\boldsymbol{\kappa}) = \left(f(\boldsymbol{\rho}) V(\boldsymbol{\rho})\right)[\boldsymbol{\rho} \leftarrow \boldsymbol{\rho}(\boldsymbol{\kappa})]$$

$$\tilde{V}(\boldsymbol{\kappa}, z) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} V(\boldsymbol{\rho}, z) \exp(-\mathrm{i}\boldsymbol{\kappa} \cdot \boldsymbol{\rho}) \, \mathrm{d}x \, \mathrm{d}y$$



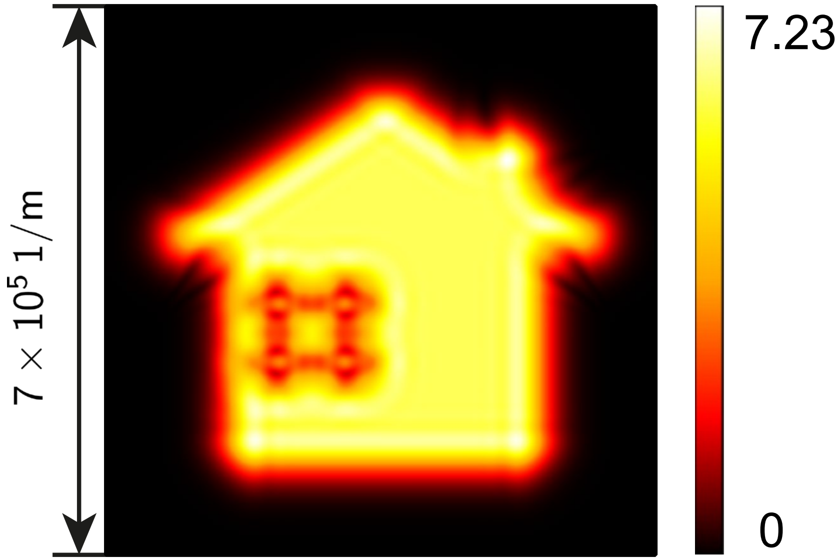
Pointwise vs. Integral Fourier Transform @ NA = 0.027

Sampling Points for Different Fourier Transform Techniques

	PFT	FFT
NA = 0.027	(73 x 59)	(315 x 262)

$$\tilde{V}(\boldsymbol{\kappa}) = \left(\mathcal{F}_k^{1:1} V\right)(\boldsymbol{\kappa}) = \left(f(\boldsymbol{\rho})V(\boldsymbol{\rho})\right)[\boldsymbol{\rho} \leftarrow \boldsymbol{\rho}(\boldsymbol{\kappa})]$$

$$\tilde{V}(\boldsymbol{\kappa}, z) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} V(\boldsymbol{\rho}, z)\exp(-\mathrm{i}\boldsymbol{\kappa}\cdot\boldsymbol{\rho})\,\mathrm{d}x\,\mathrm{d}y$$



Pointwise vs. Integral Fourier Transform @ NA = 0.134

Sampling Points for Different Fourier Transform Techniques

	PFT	FFT
NA = 0.134	(73 x 59)	(1333 x 925)

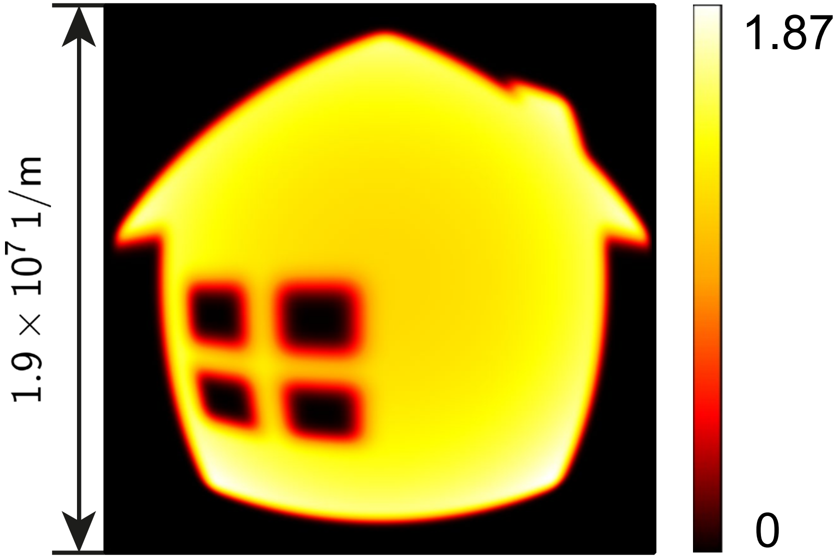
$$\tilde{V}(\boldsymbol{\kappa}) = \left(\mathcal{F}_k^{1:1} V\right)(\boldsymbol{\kappa}) = \left(f(\boldsymbol{\rho})V(\boldsymbol{\rho})\right)[\boldsymbol{\rho} \leftarrow \boldsymbol{\rho}(\boldsymbol{\kappa})]$$

$$\tilde{V}(\boldsymbol{\kappa}, z) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} V(\boldsymbol{\rho}, z)\exp(-\mathrm{i}\boldsymbol{\kappa}\cdot\boldsymbol{\rho})\,\mathrm{d}x\,\mathrm{d}y$$

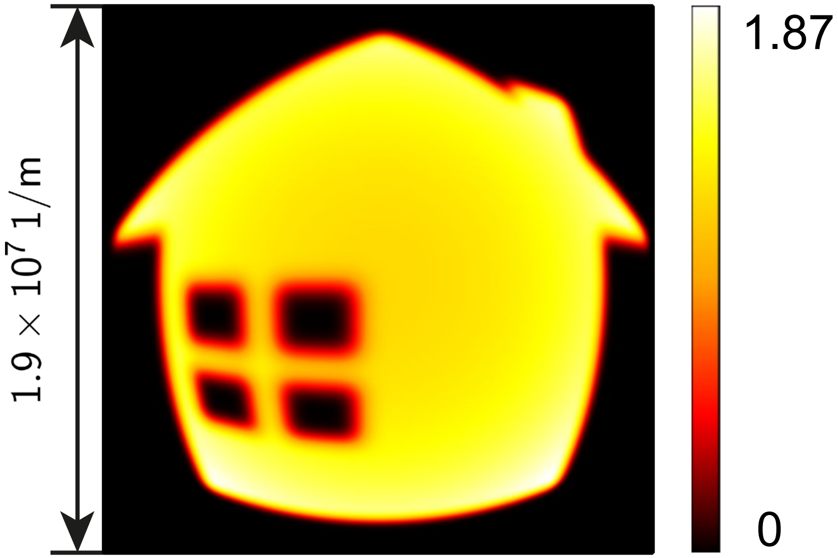
Pointwise vs. Integral Fourier Transform @ NA = 0.804

Sampling Points for Different Fourier Transform Techniques		
	PFT	**FFT**
NA = 0.804	(73 x 59)	(7947 x 6225)

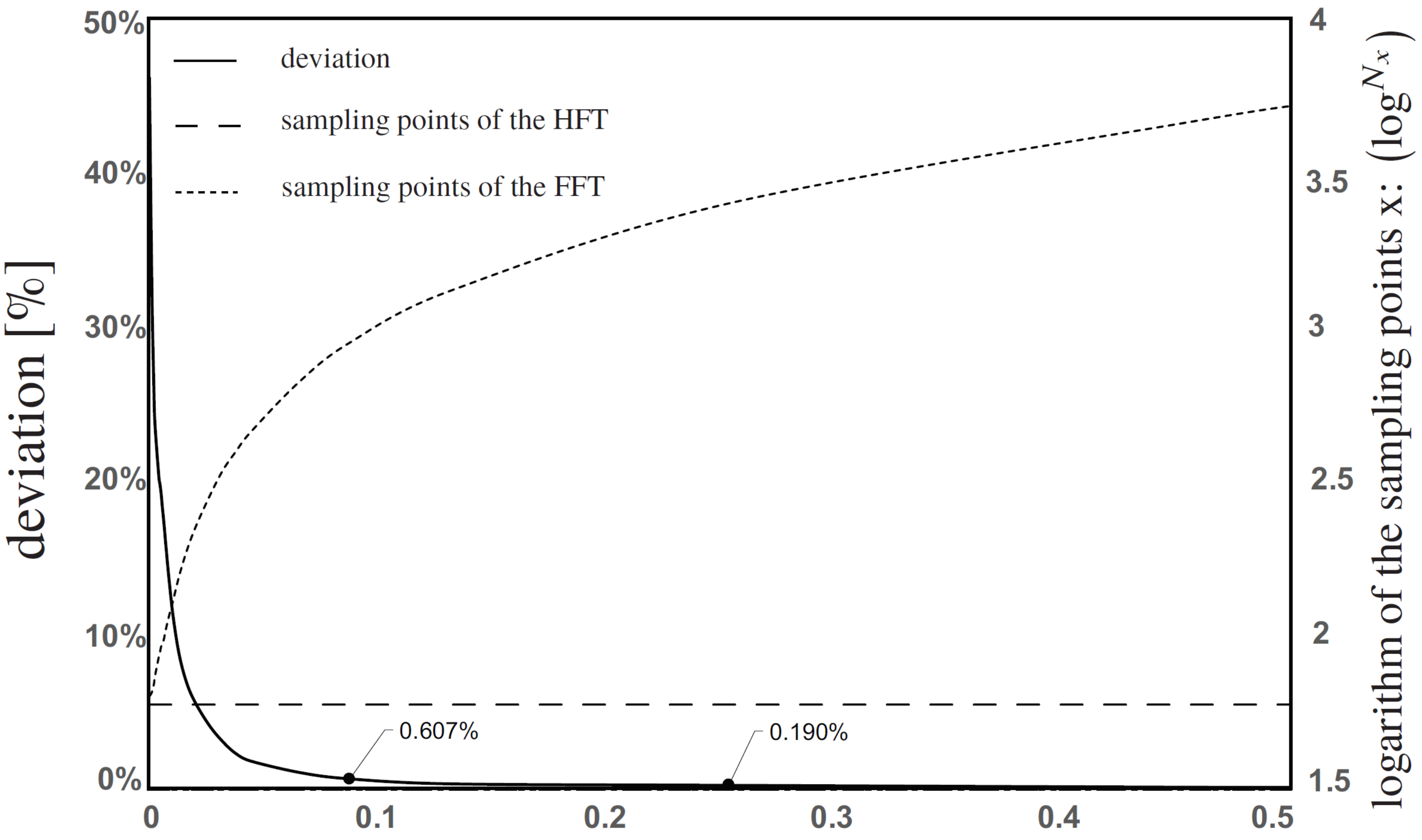
$$\tilde{V}(\boldsymbol{\kappa}) = \left(\mathcal{F}_k^{1:1} V\right)(\boldsymbol{\kappa}) = \left(f(\boldsymbol{\rho}) V(\boldsymbol{\rho})\right)[\boldsymbol{\rho} \leftarrow \boldsymbol{\rho}(\boldsymbol{\kappa})]$$



$$\tilde{V}(\boldsymbol{\kappa}, z) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} V(\boldsymbol{\rho}, z) \exp(-\mathrm{i}\boldsymbol{\kappa} \cdot \boldsymbol{\rho}) \, \mathrm{d}x \, \mathrm{d}y$$

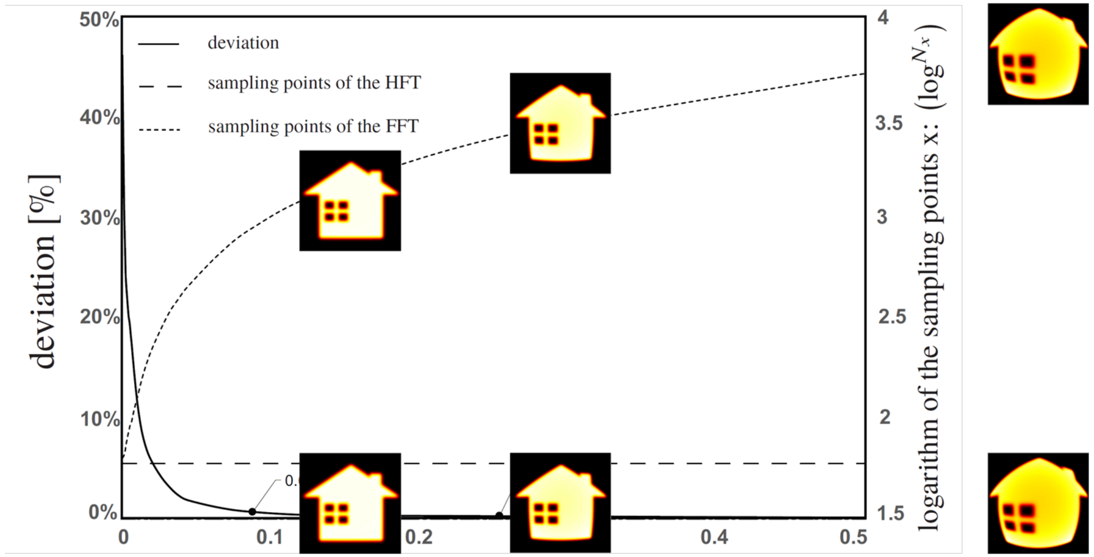


Comparison of the Numerical Effort and Accuracy



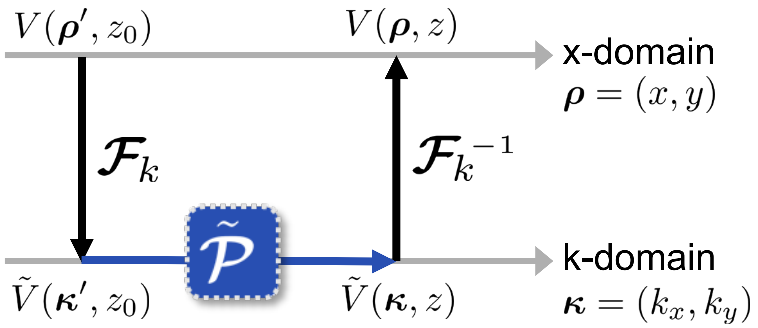
Facts About Pointwise Fourier Transform

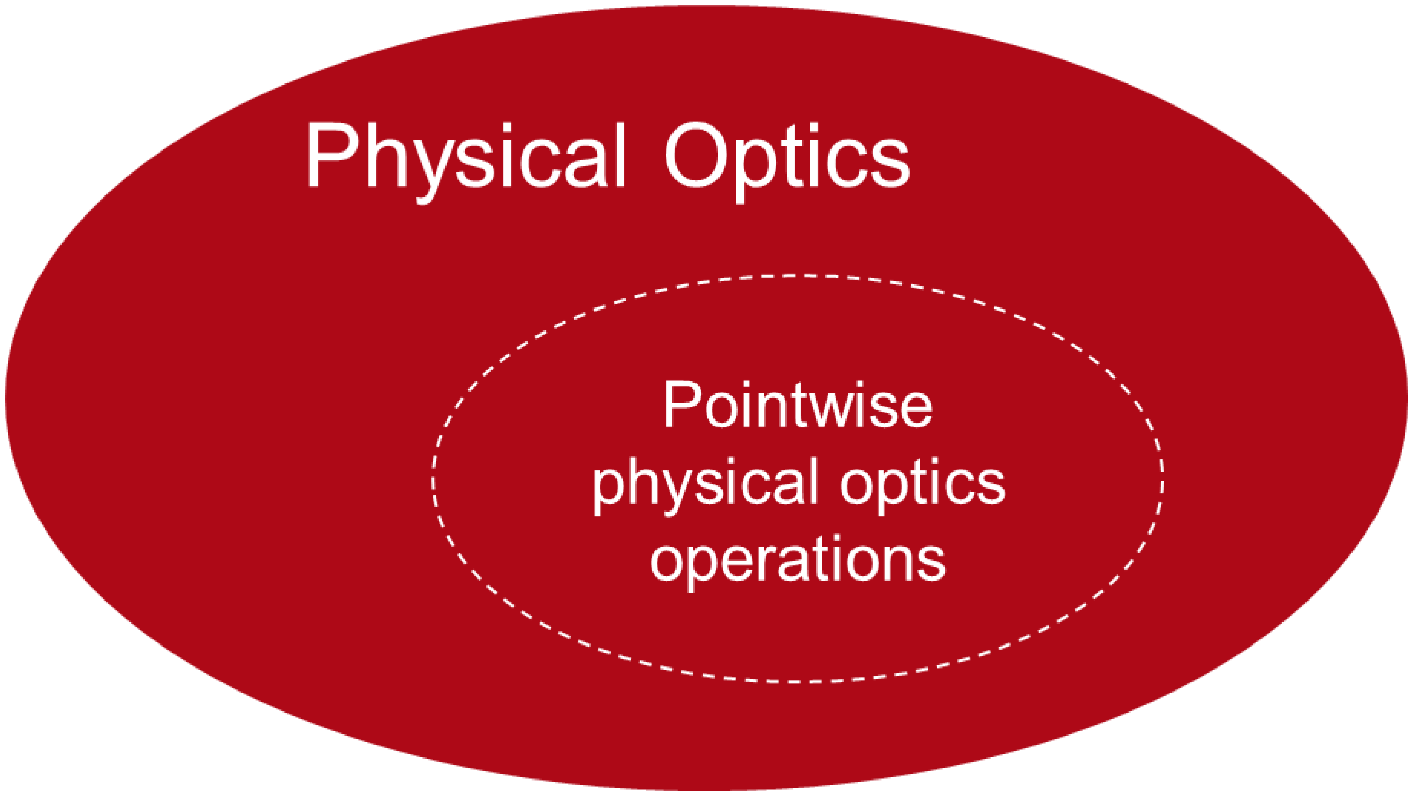
- The pointwise Fourier transform (PFT) is valid for field components with sufficiently **strong spherical and aberrated wavefront phases**.
- The validity can be estimated for any field component by a pointwise transformation index.
- That enables a **seamless transition between integral and pointwise Fourier transform** in physical optics modeling algorithms by pure mathematical arguments.
- PFT and FFT have a numerical complexity of $O(N)$. However, the number of sampling points N for PFT is significantly smaller: $N^{\mathrm{PFT}} \ll N^{\mathrm{FFT}}$
- Typical numbers:
  $N^{\mathrm{FFT}} = 10^6 - 10^8$ and $N^{\mathrm{PFT}} = 10^2 - 10^3$



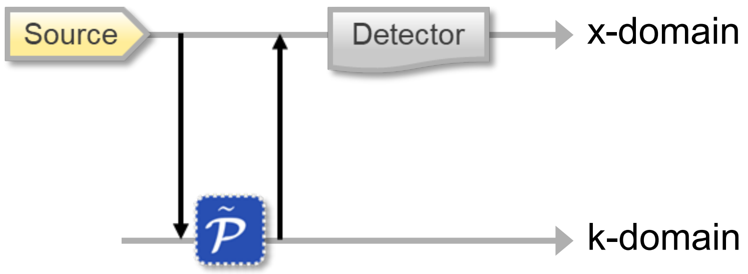
Z. Wang, O. Baladron-Zorita, C. Hellmann, and F. Wyrowski, "Theory and algorithm of the homeomorphic Fourier transform for optical simulations," Opt Express **28**, 10552–10571 (2020).

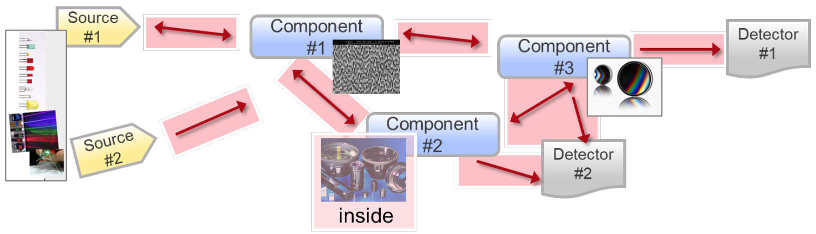
Consequences for Physical Optics Modeling

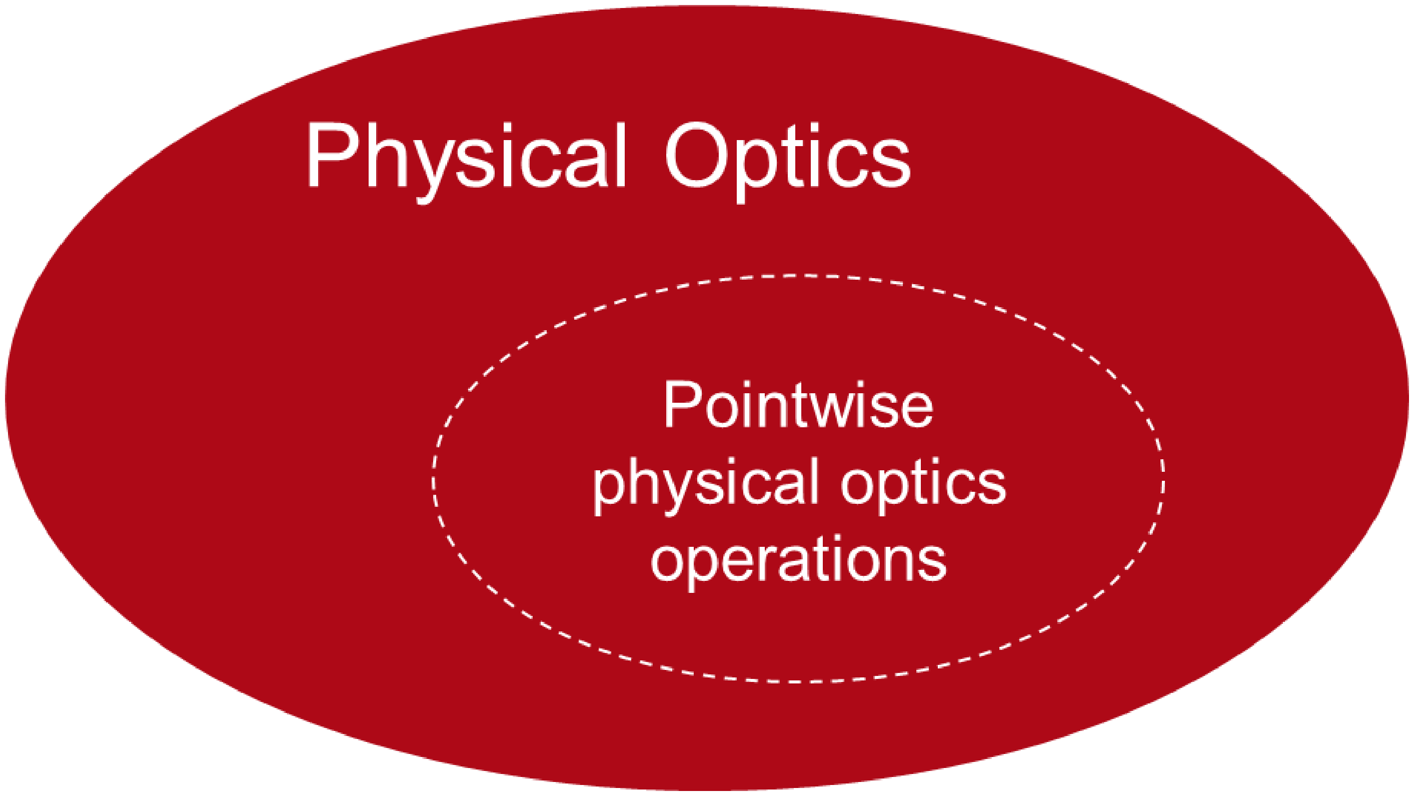




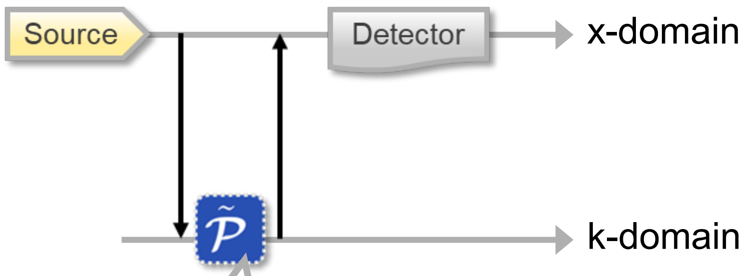
Consequences for Physical Optics Modeling





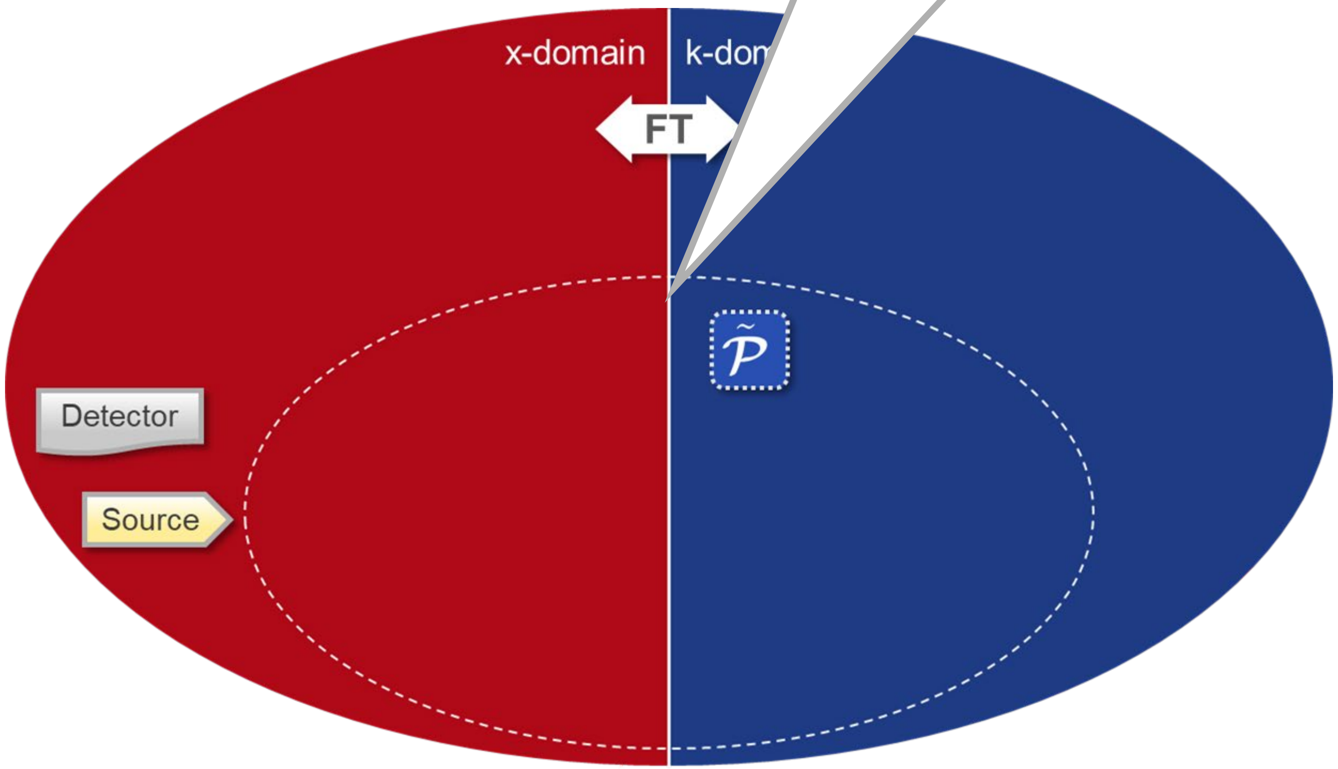


Consequences for Physical Optics Modeling

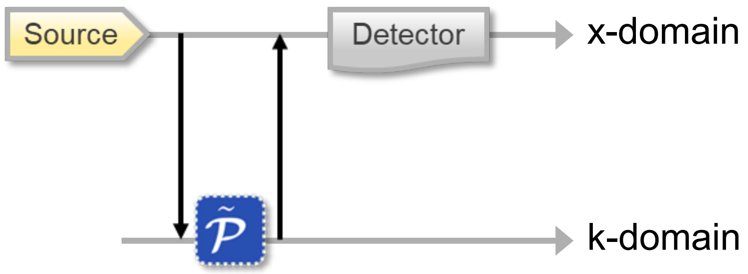


Blue with dashed line indicates pointwise operation in k-domain.

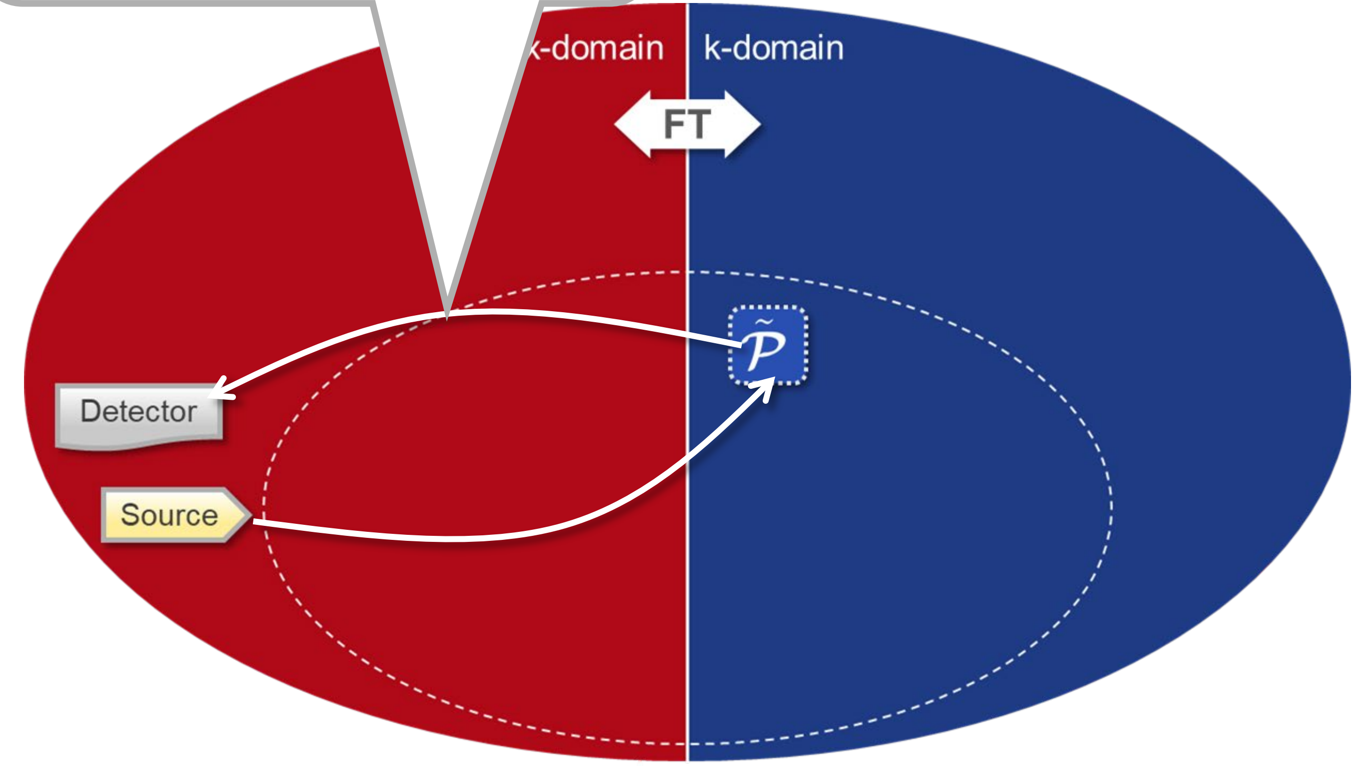
Subset of pointwise operations in x-domain (red) and k-domain (blue).



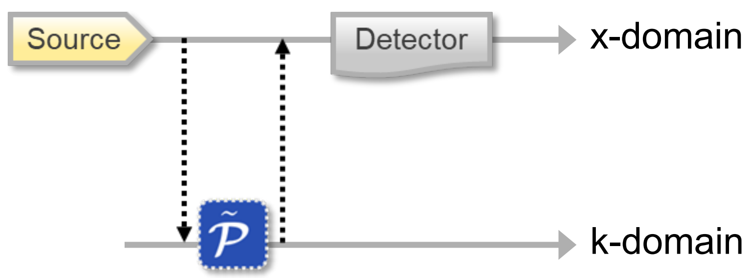
Consequences for Physical Optics Modeling



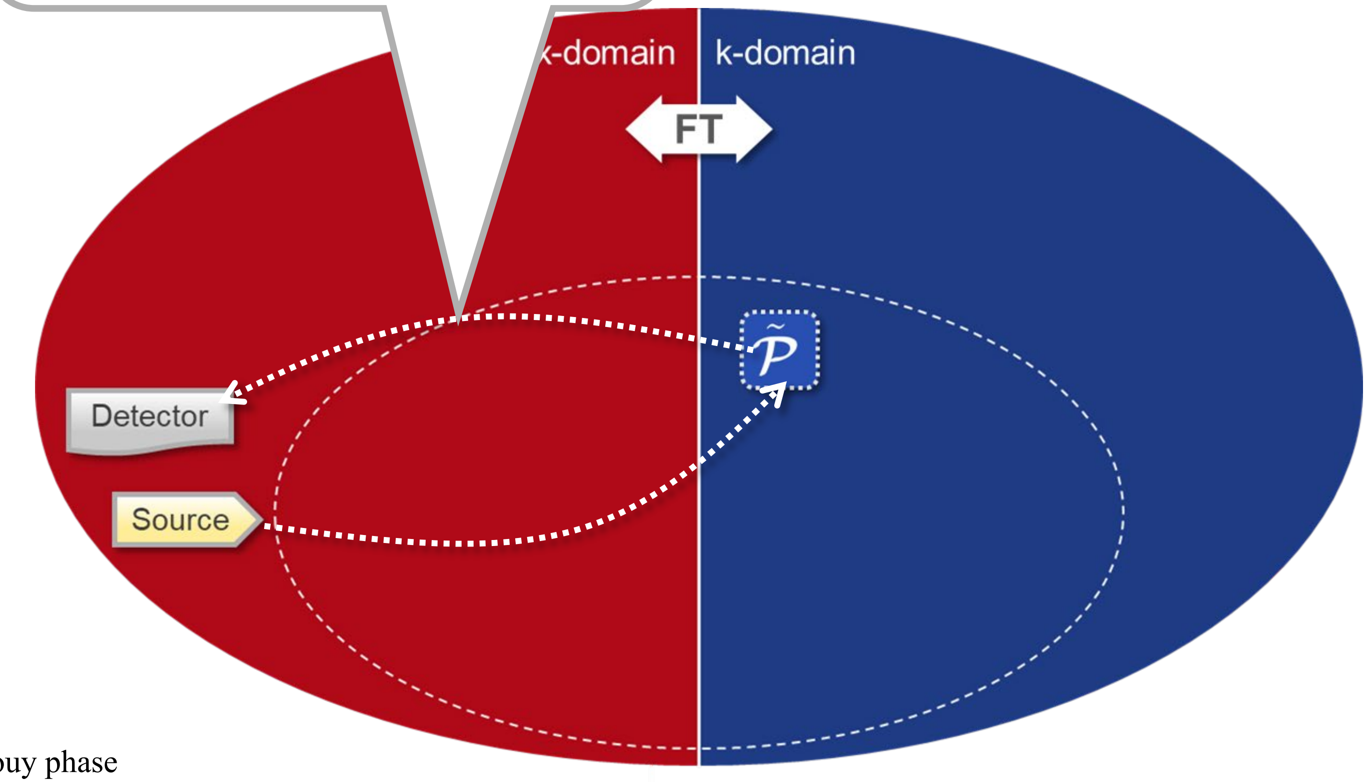
Connections between blue and red indicate Fourier transforms.



Consequences for Physical Optics Modeling



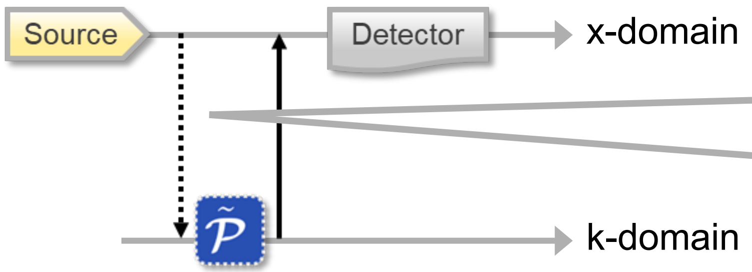
Dashed connections between blue and red indicate pointwise Fourier transforms.



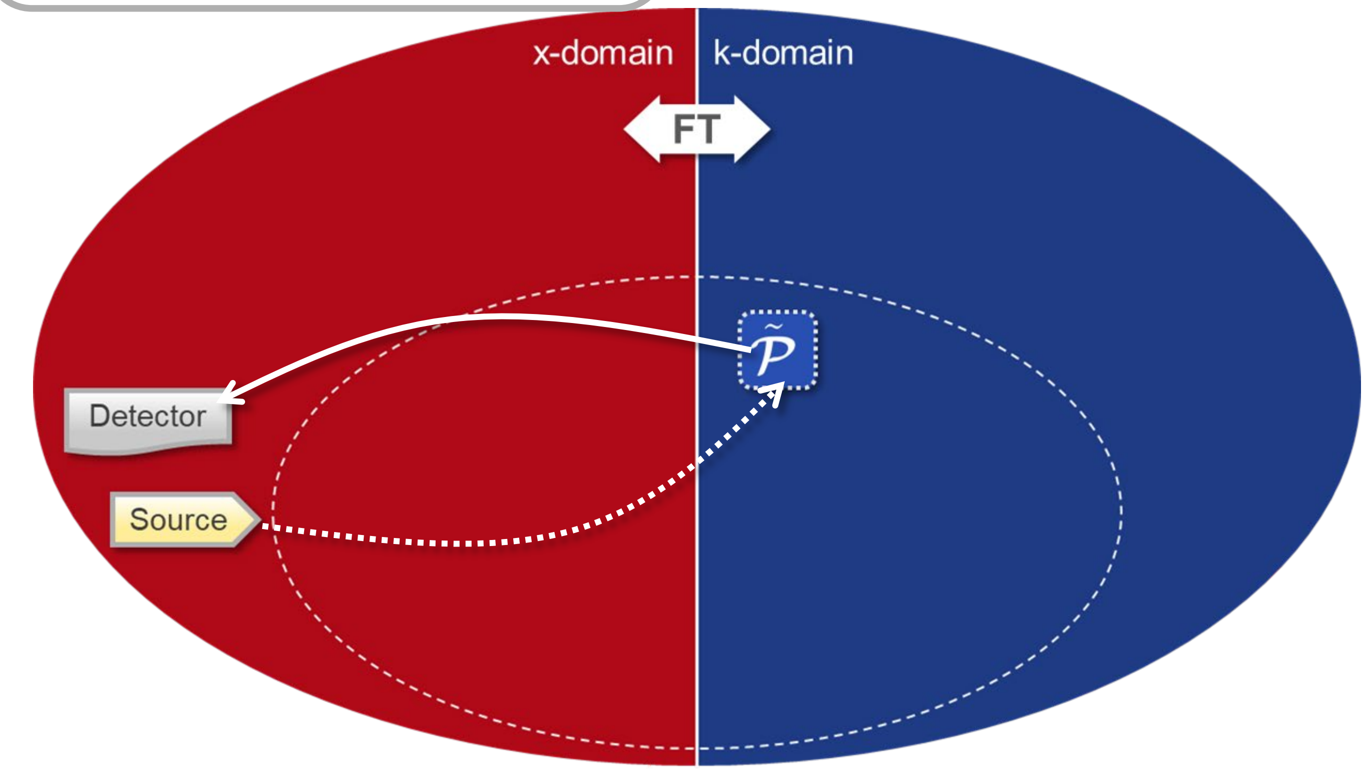
Pointwise Propagation

O. Baladron-Zorita, Z. Wang, C. Hellmann, and F. Wyrowski, "Isolating the Gouy phase shift in a full physical-optics solution to the propagation problem," J. Opt. Soc. Am. A **36**, 1551–1558 (2019).

Consequences for Physical Optics Modeling



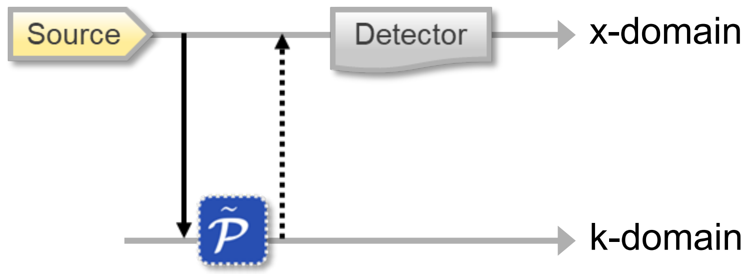
Dashed line indicates pointwise Fourier transform.



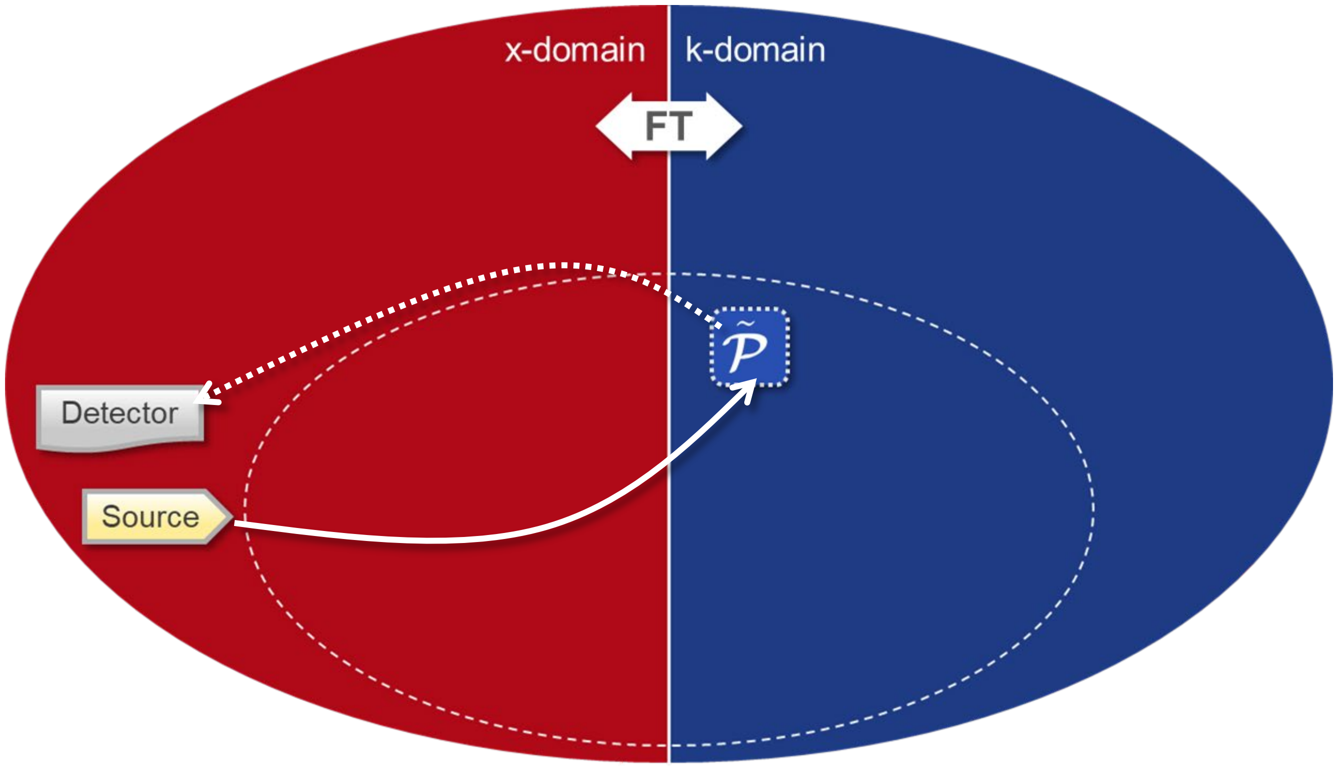
Generalized Debye Integral

Z. Wang, O. Baladron-Zorita, C. Hellmann, and F. Wyrowski, "Generalized Debye integral," Opt. Express **28**, 24459–24470 (2020).

Consequences for Physical Optics Modeling

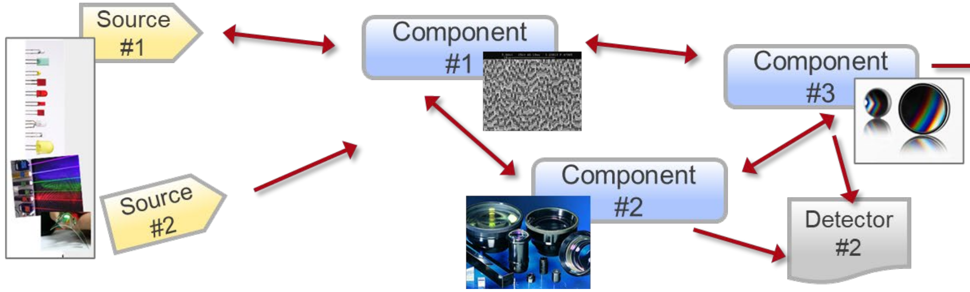


Generalized Far Field Integral

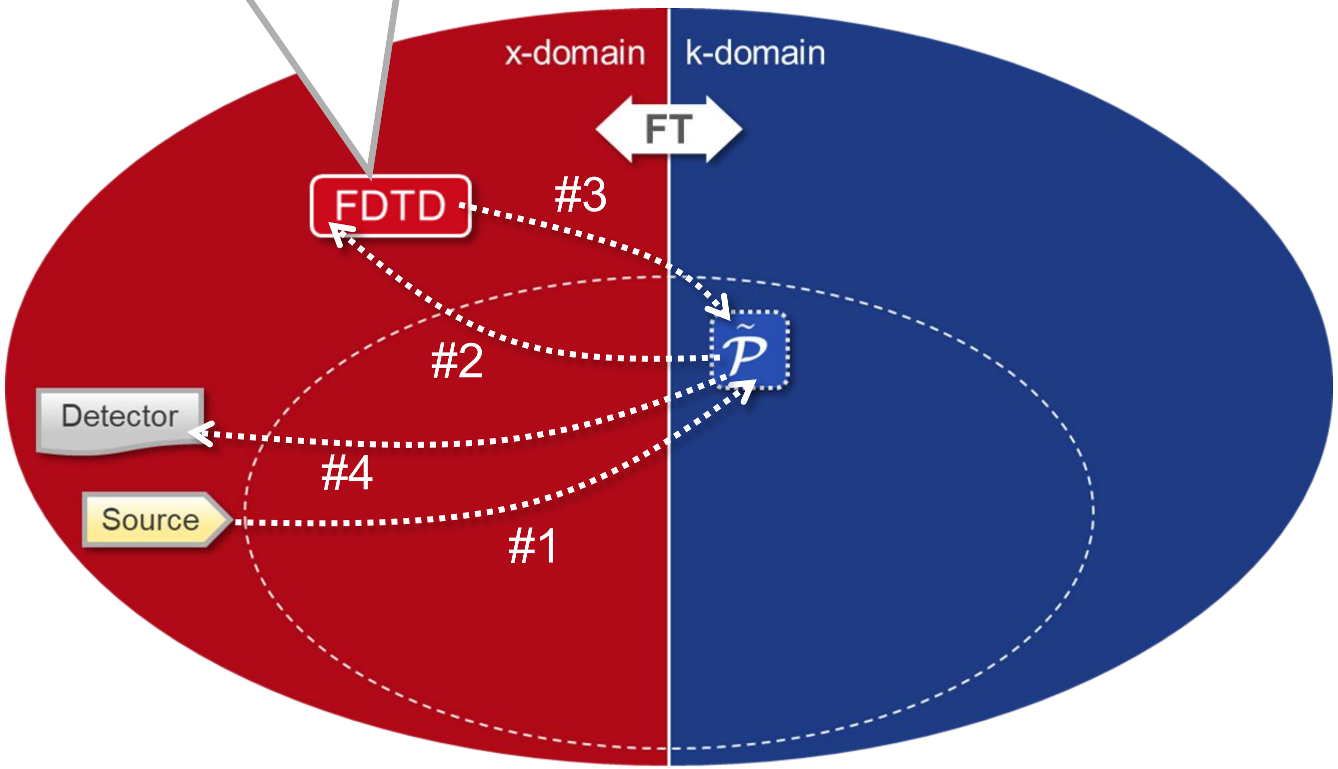


Z. Wang, O. Baladron-Zorita, C. Hellmann, and F. Wyrowski, "Generalized far-field integral," Opt. Express **29**, 1774–1787 (2021).

Consequences for Physical Optics System Modeling

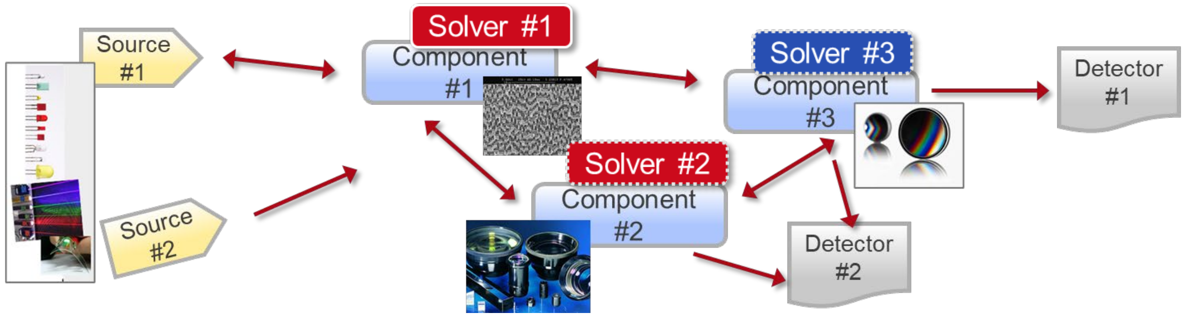


Solid boundary indicates integral operator.



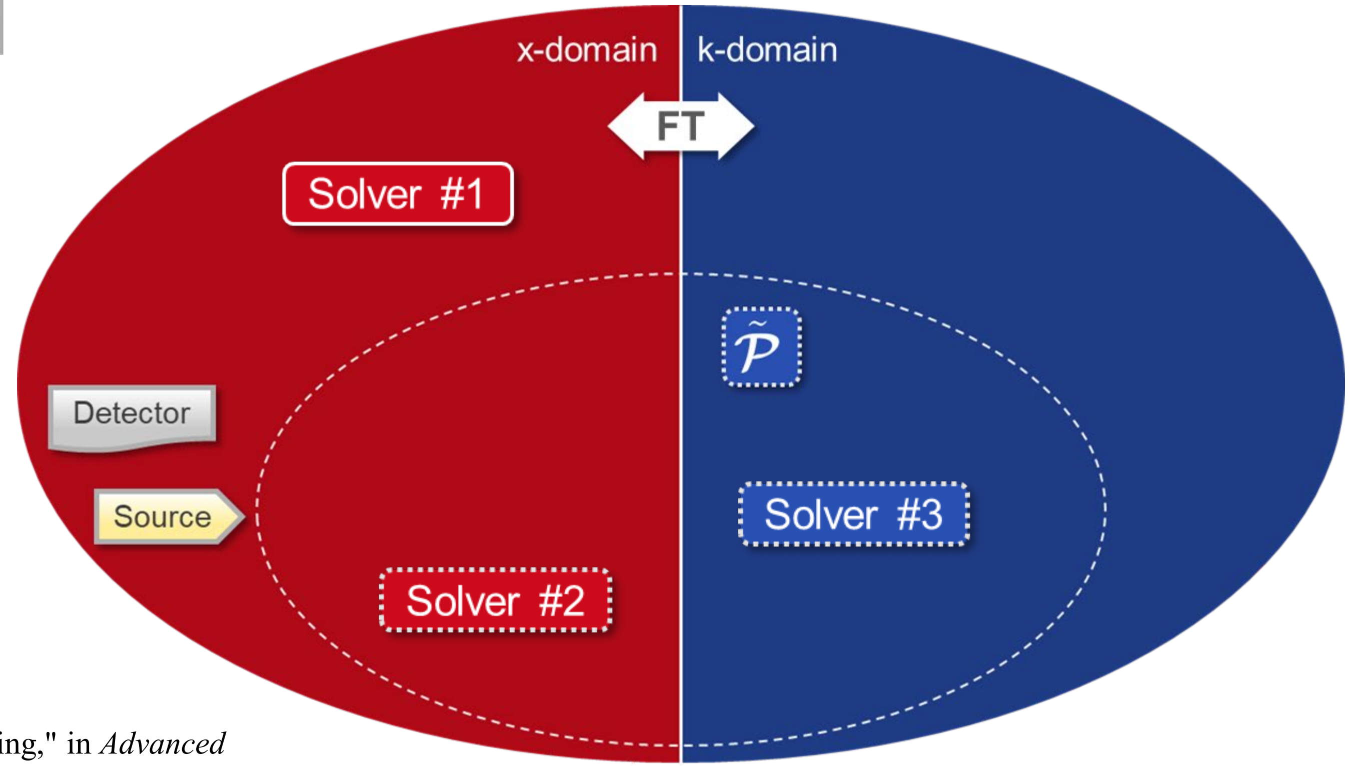
Seamless transition to pointwise modeling impossible, since FDTD not pointwise.

Consequences for Physical Optics System Modeling



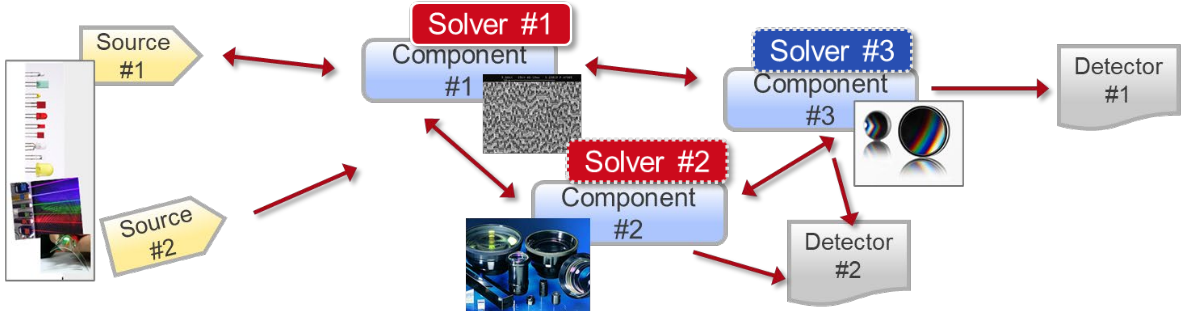
Instead of using one solver only …

Connecting solvers is a key technology for physical-optics system modeling!

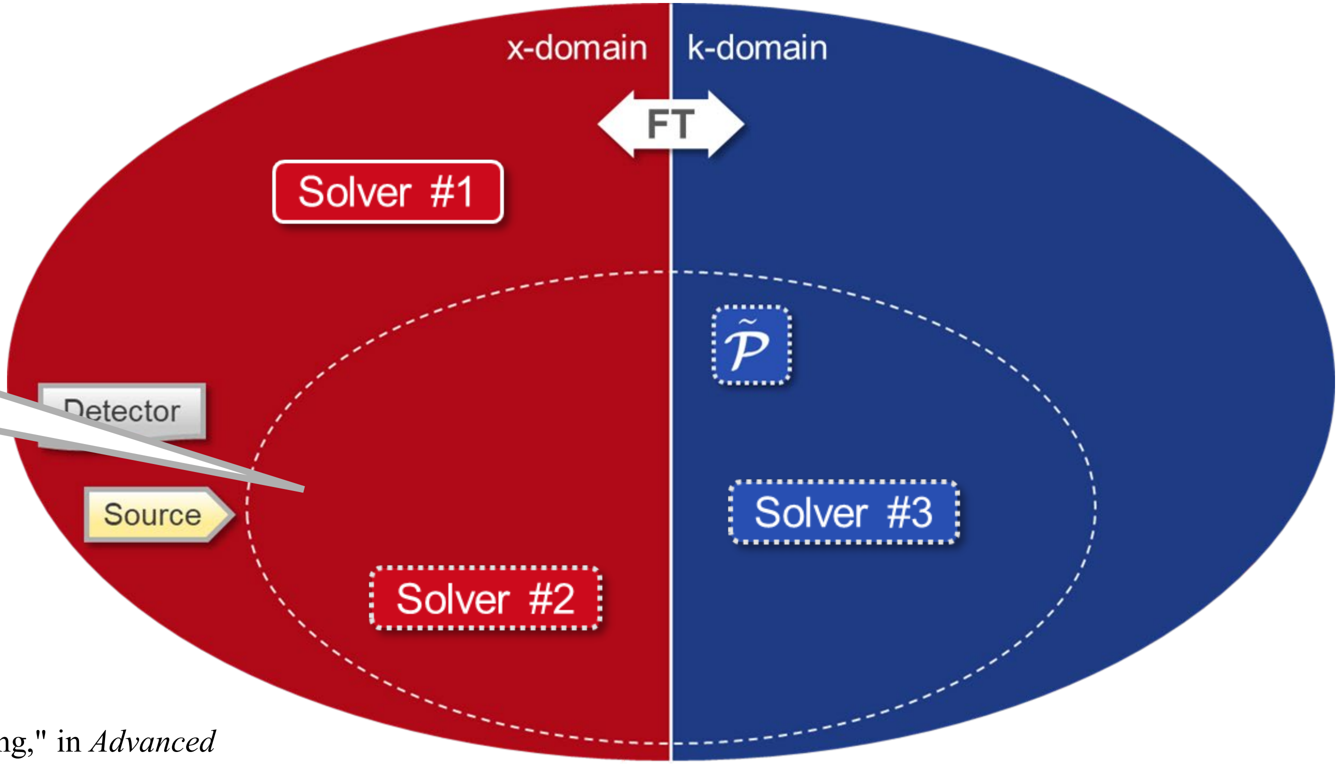


M. Kuhn, F. Wyrowski, and C. Hellmann, "Non-sequential Optical Field Tracing," in *Advanced Finite Element Methods and Applications*, T. Apel and O. Steinbach, eds., Lecture Notes in Applied and Computational Mechanics (Springer Berlin Heidelberg, 2013), Vol. 66, pp. 257–273.

Consequences for Physical Optics System Modeling

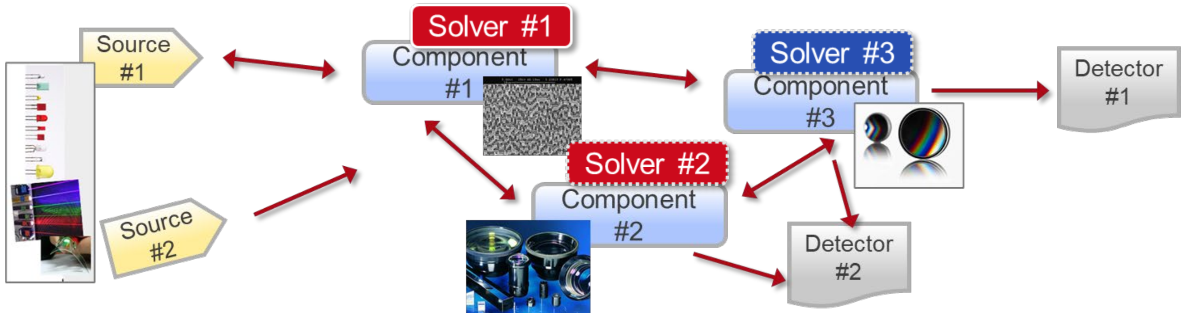


Include rigorous and approximated pointwise solver.

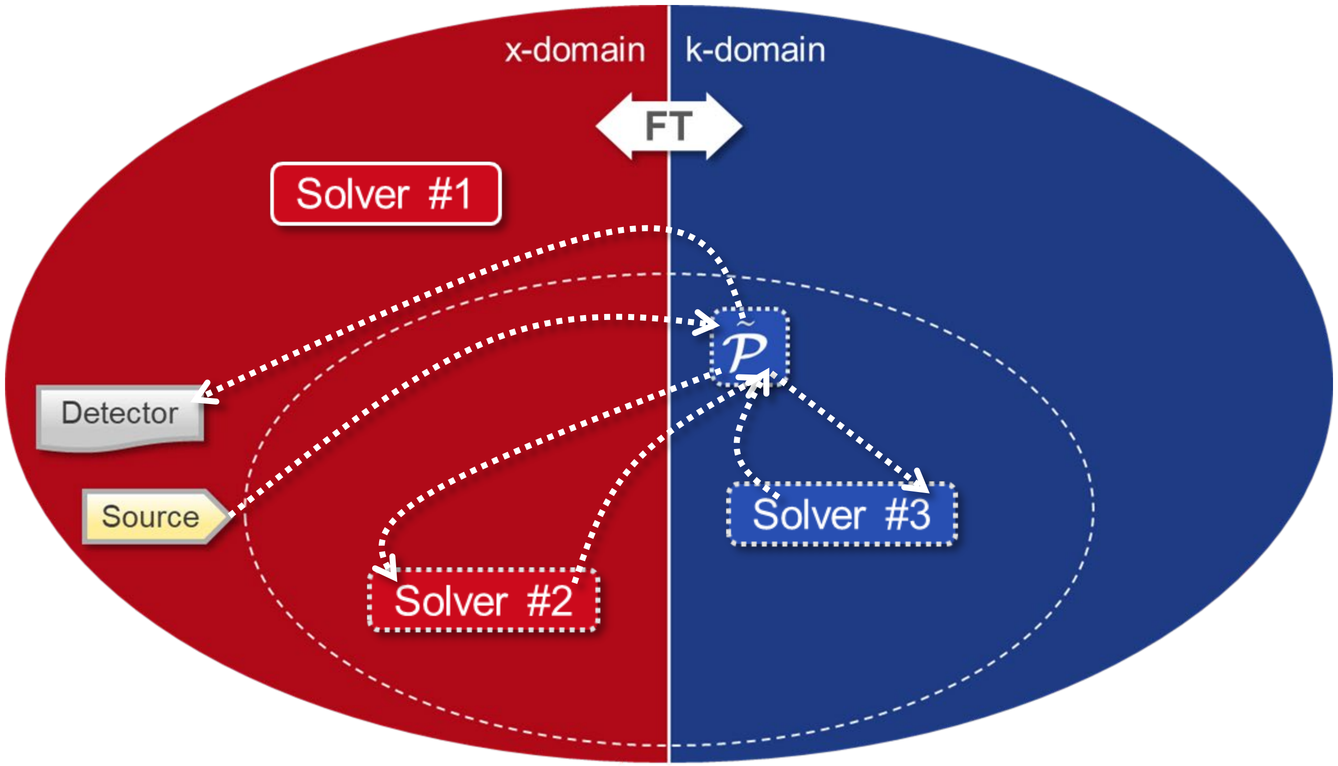


M. Kuhn, F. Wyrowski, and C. Hellmann, "Non-sequential Optical Field Tracing," in *Advanced Finite Element Methods and Applications*, T. Apel and O. Steinbach, eds., Lecture Notes in Applied and Computational Mechanics (Springer Berlin Heidelberg, 2013), Vol. 66, pp. 257–273.

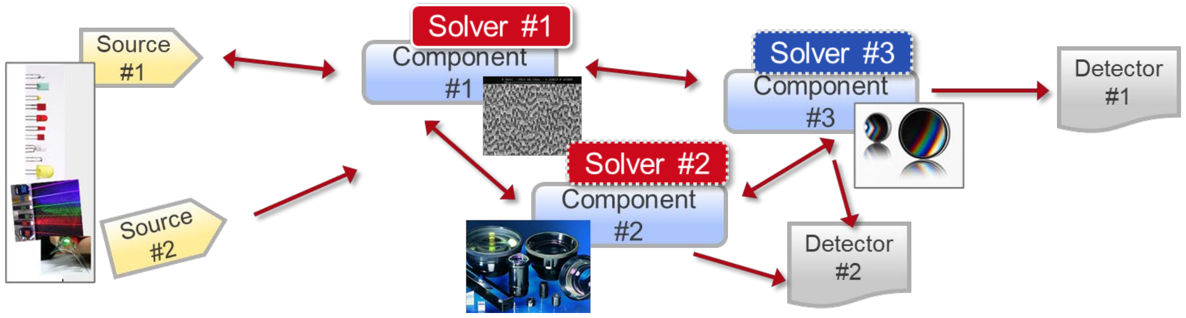
Consequences for Physical Optics System Modeling

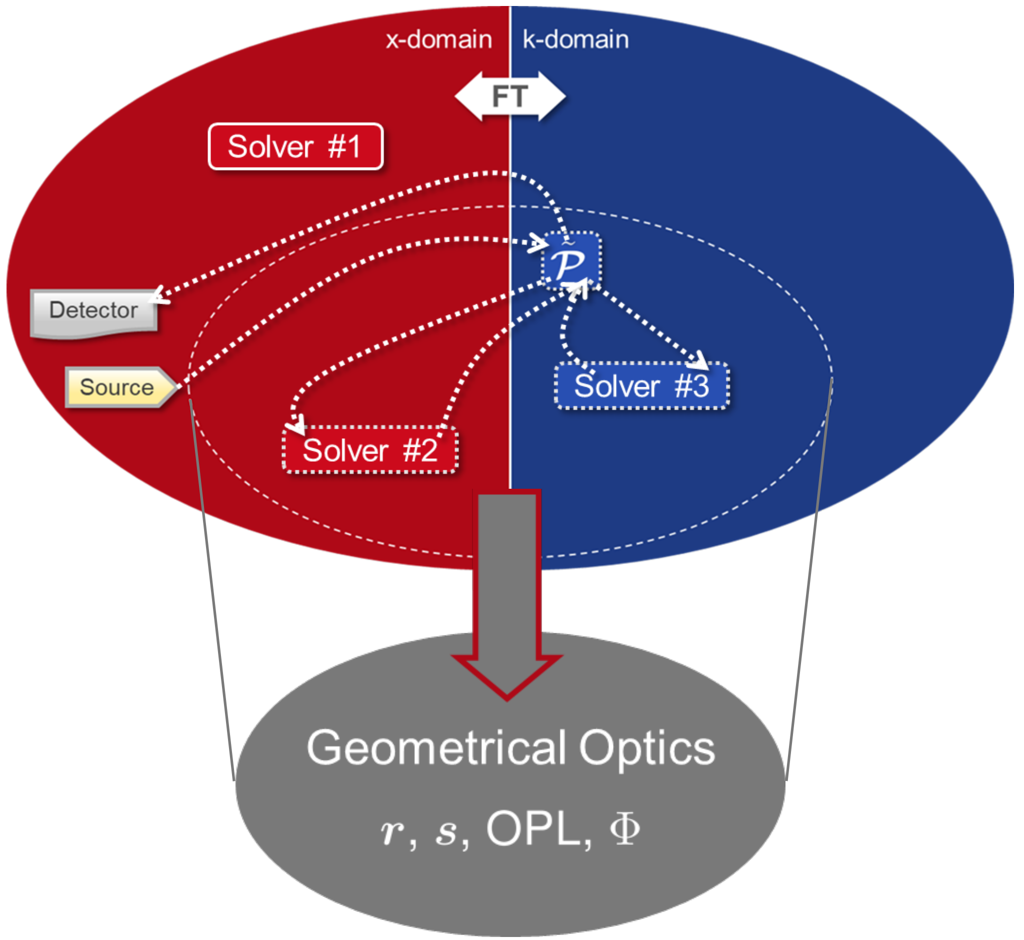


Pointwise physical-optics system modeling feasible.



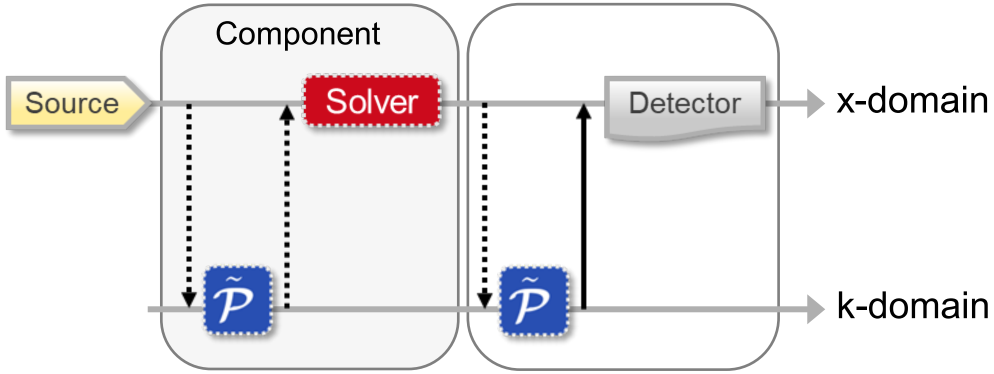
Consequences for Physical Optics System Modeling



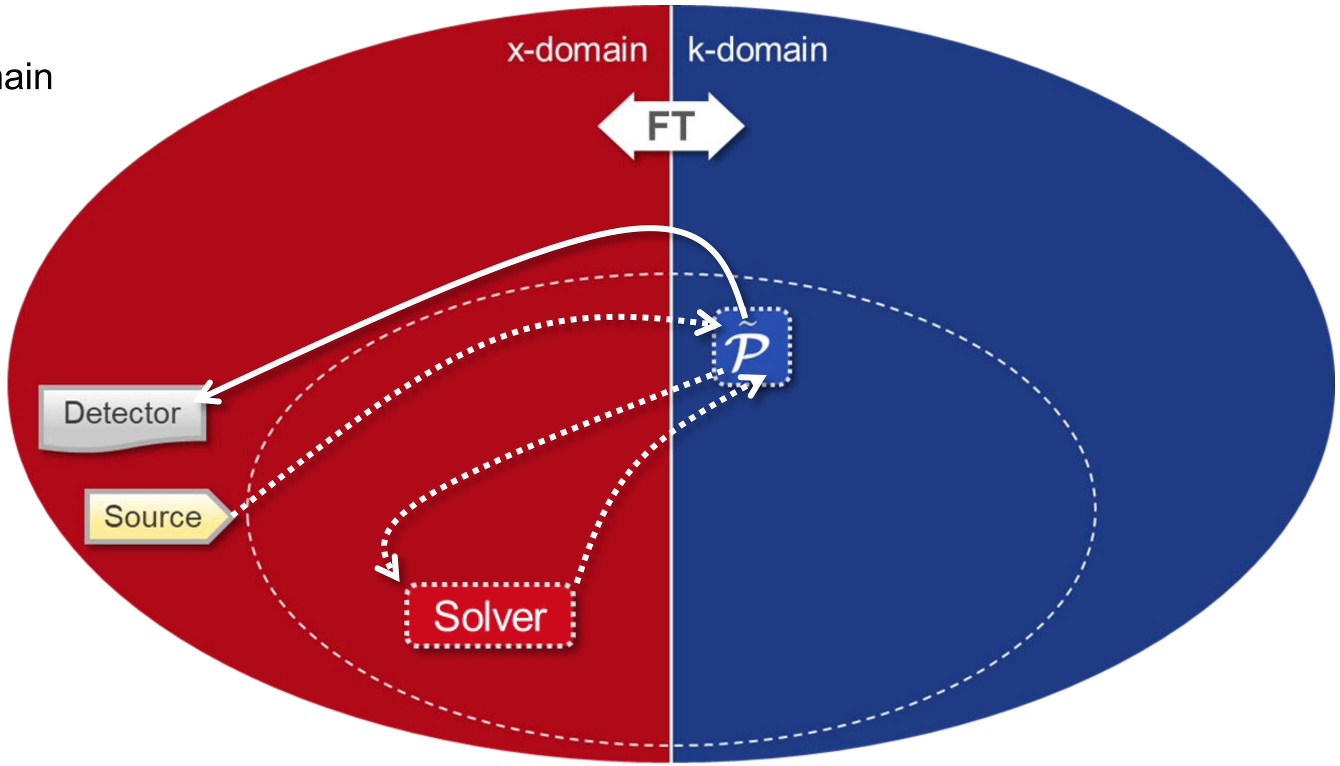


Pointwise physical-optics system modeling feasible.

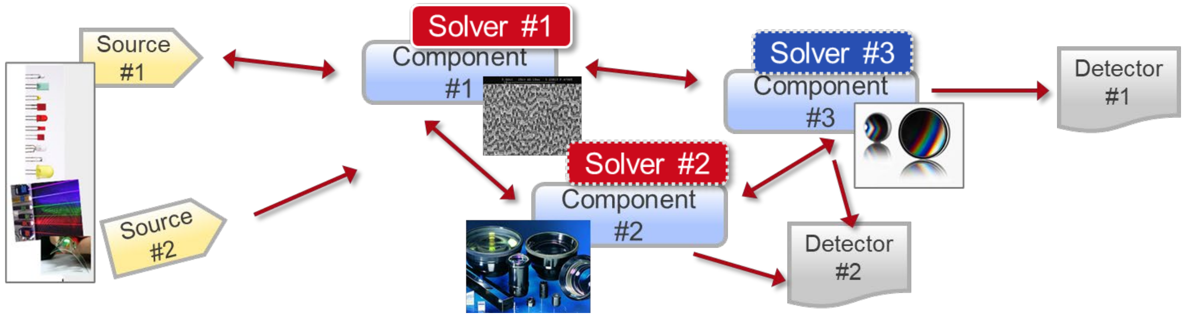
Modeling Diagrams



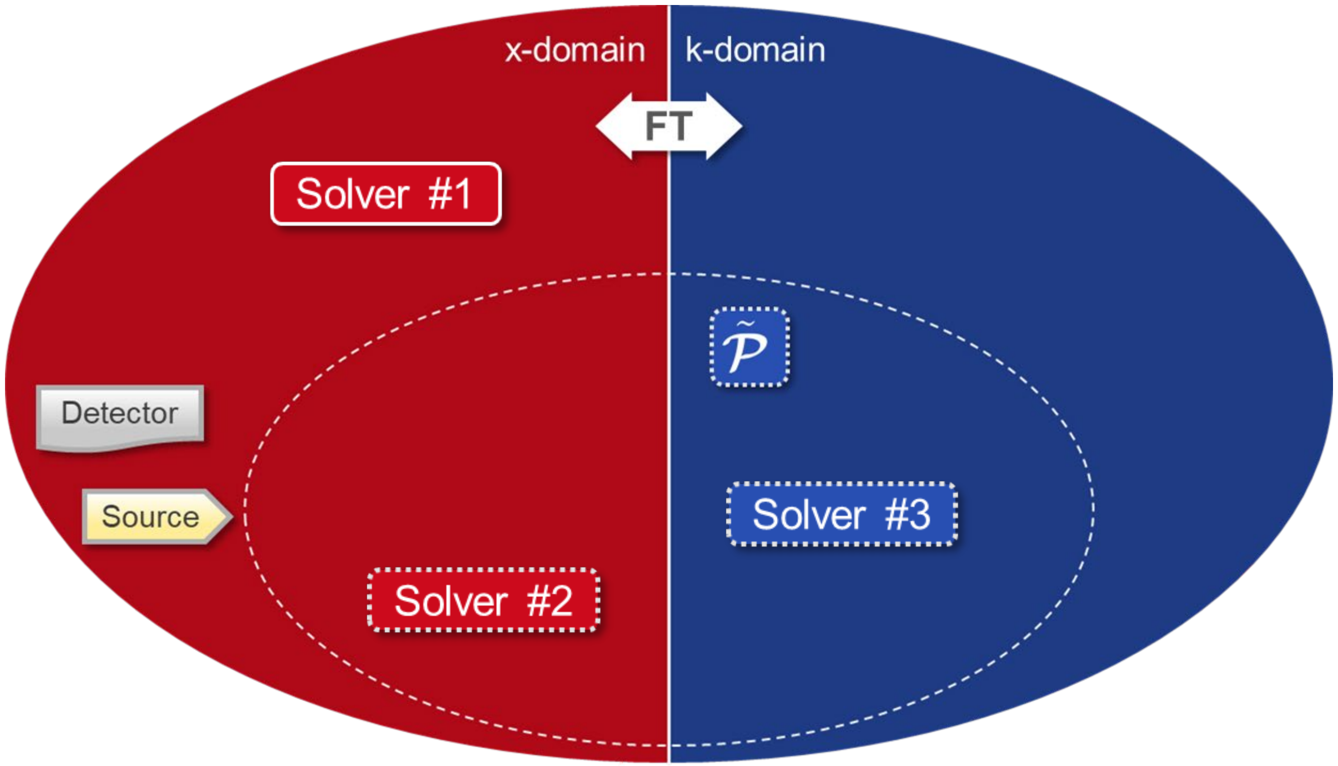
Types of illustrations of the connecting solvers technology.



Consequences for Physical Optics System Modeling

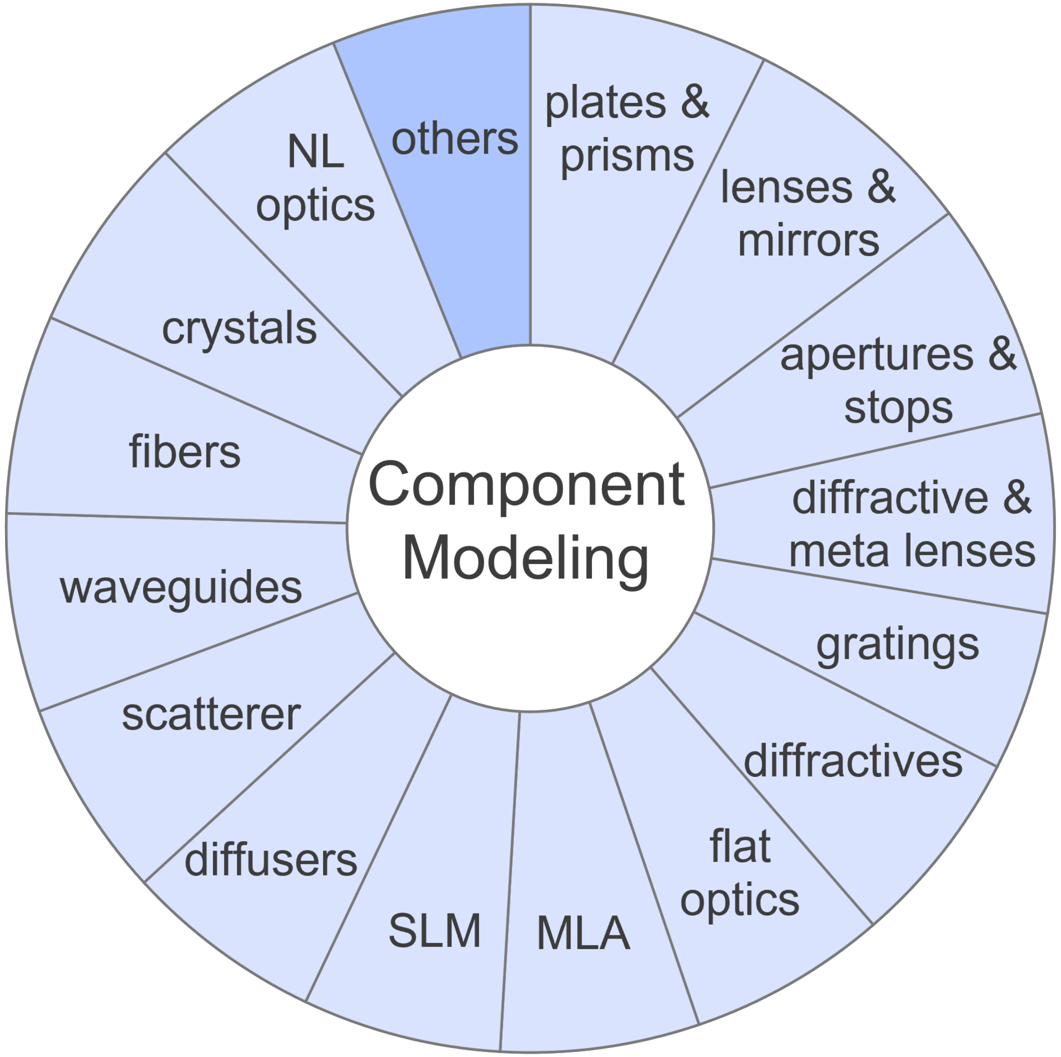


Connecting solvers is a key technology for physical-optics system modeling!

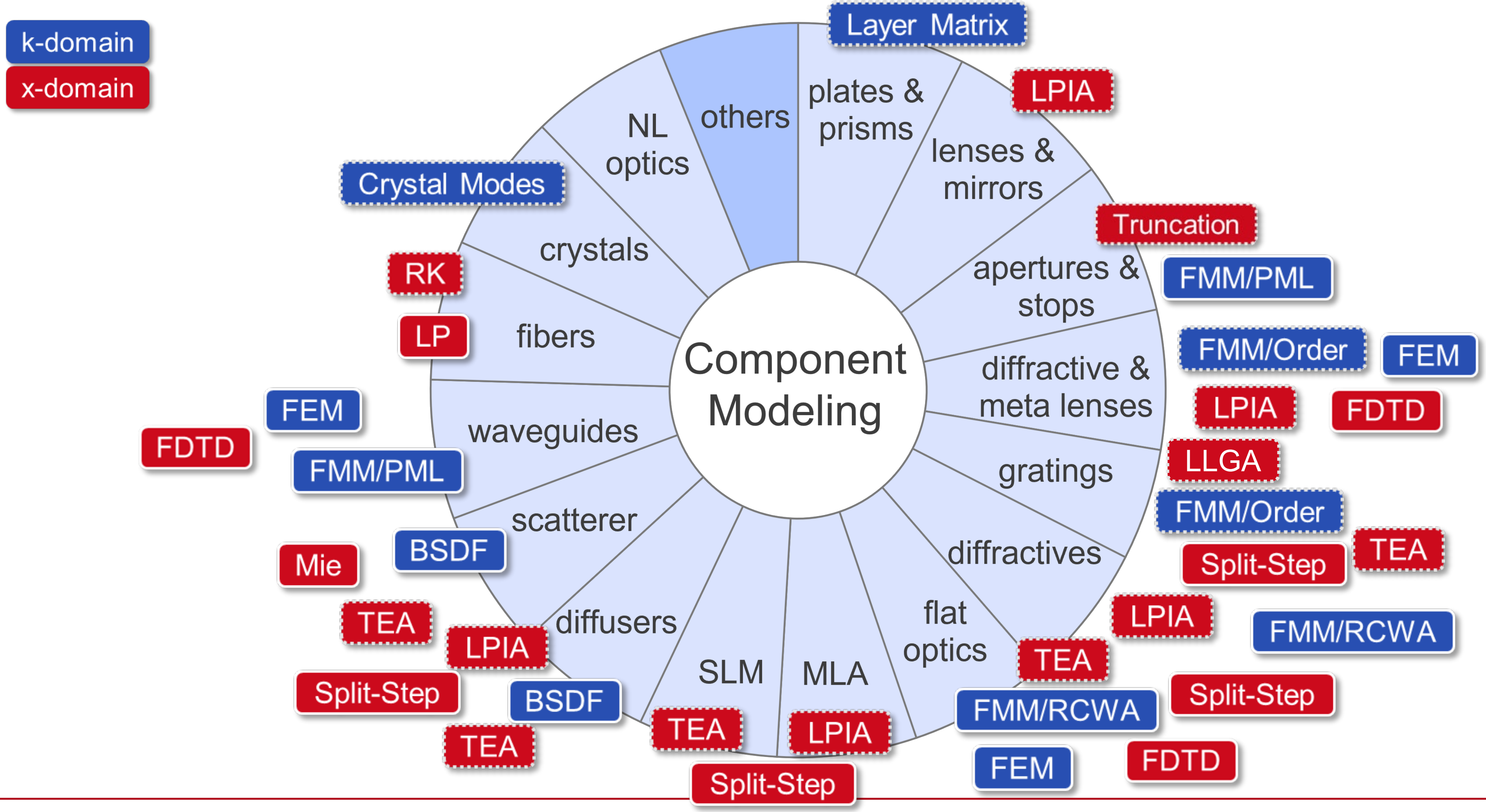


Suitable Solvers per Component

k-domain
x-domain



Solvers per Component



Solvers per Component

BSDF Bidirectional Scattering Distribution Function

FDTD Finite Different Time Domain

FEM Finite Element Method

FMM Fourier Modal Method

FMM/Order FMM with mode decomposition

FMM/PML FMM with Perfect Matched Layer

LLGA Local Linear Grating Approximation

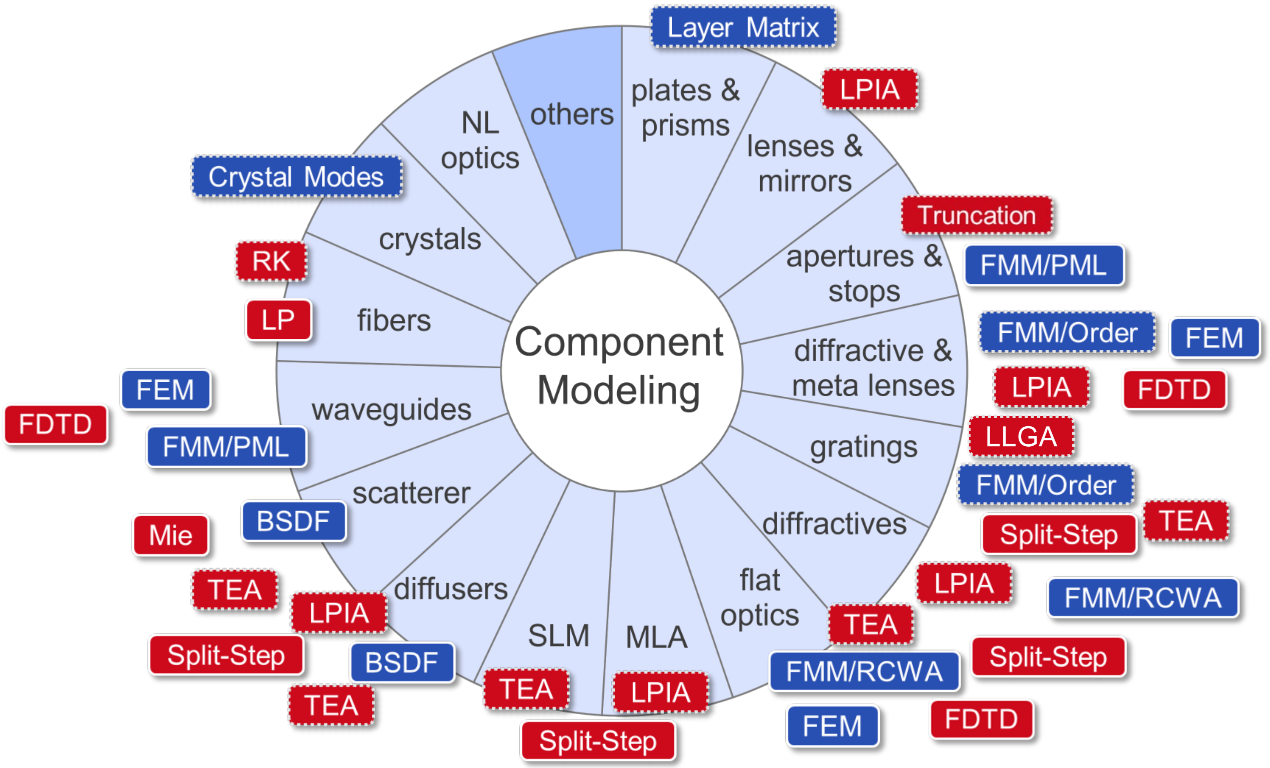
LP Linearly Polarized mode solver

LPIA Local Plane Interface Approximation

RCWA Rigorous Coupled Wave Approach

RK Runge-Kutta solver for GRIN media

TEA Thin Element Approximation



LPIA

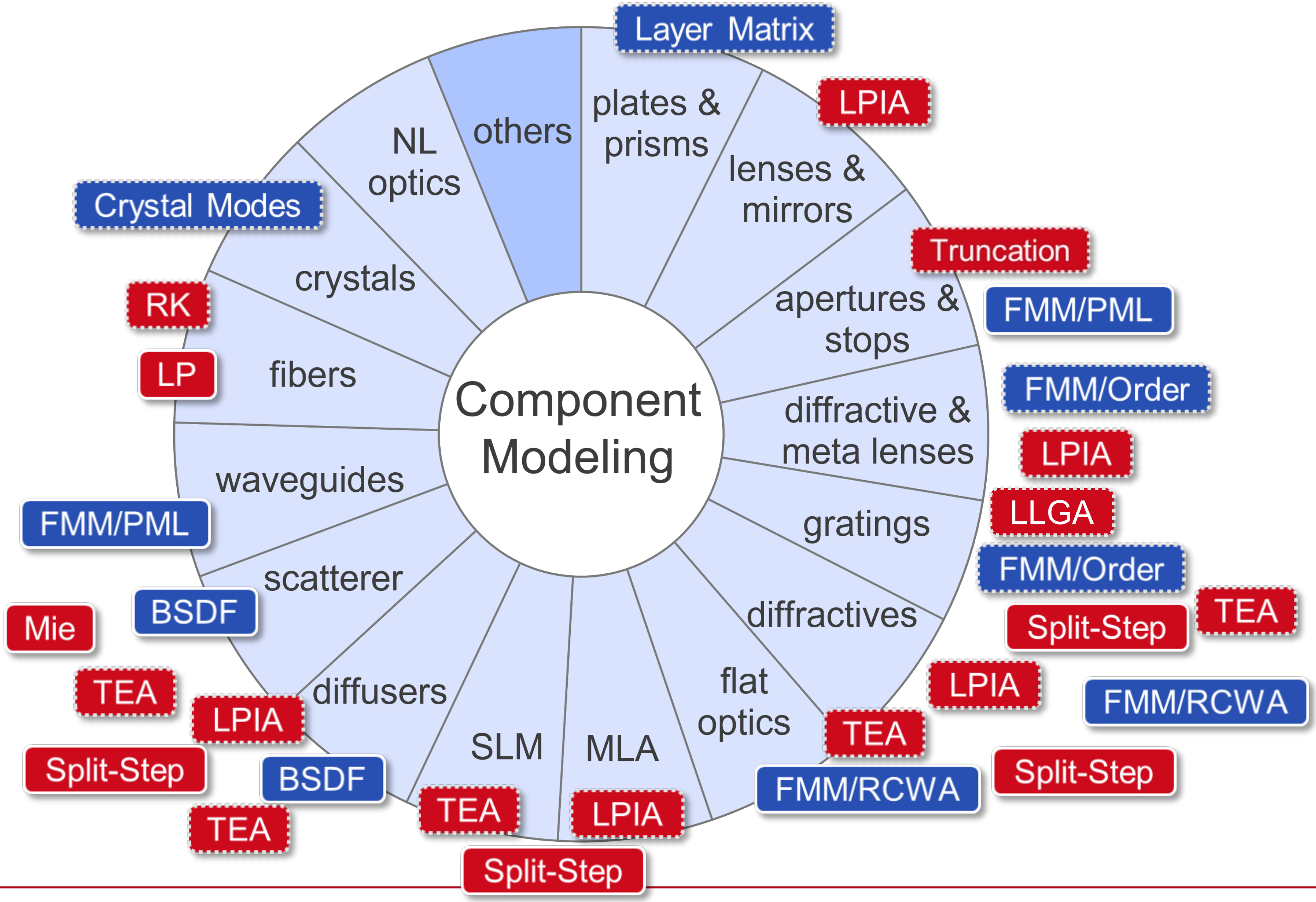
A. V. Pfeil and F. Wyrowski, "Wave-optical structure design with the local plane-interface approximation," J. Mod. Optics **47**, 2335–2350 (2000).

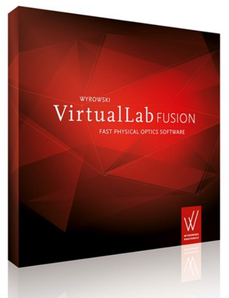
A. v Pfeil, F. Wyrowski, A. Drauschke, and H. Aagedal, "Analysis of optical elements with the local plane-interface approximation," Appl. Opt. **39**, 3304–3313 (2000).

R. Shi, C. Hellmann, and F. Wyrowski, "Physical-optics propagation through curved surfaces," J. Opt. Soc. Am. A **36**, 1252 (2019).

Solvers per Component

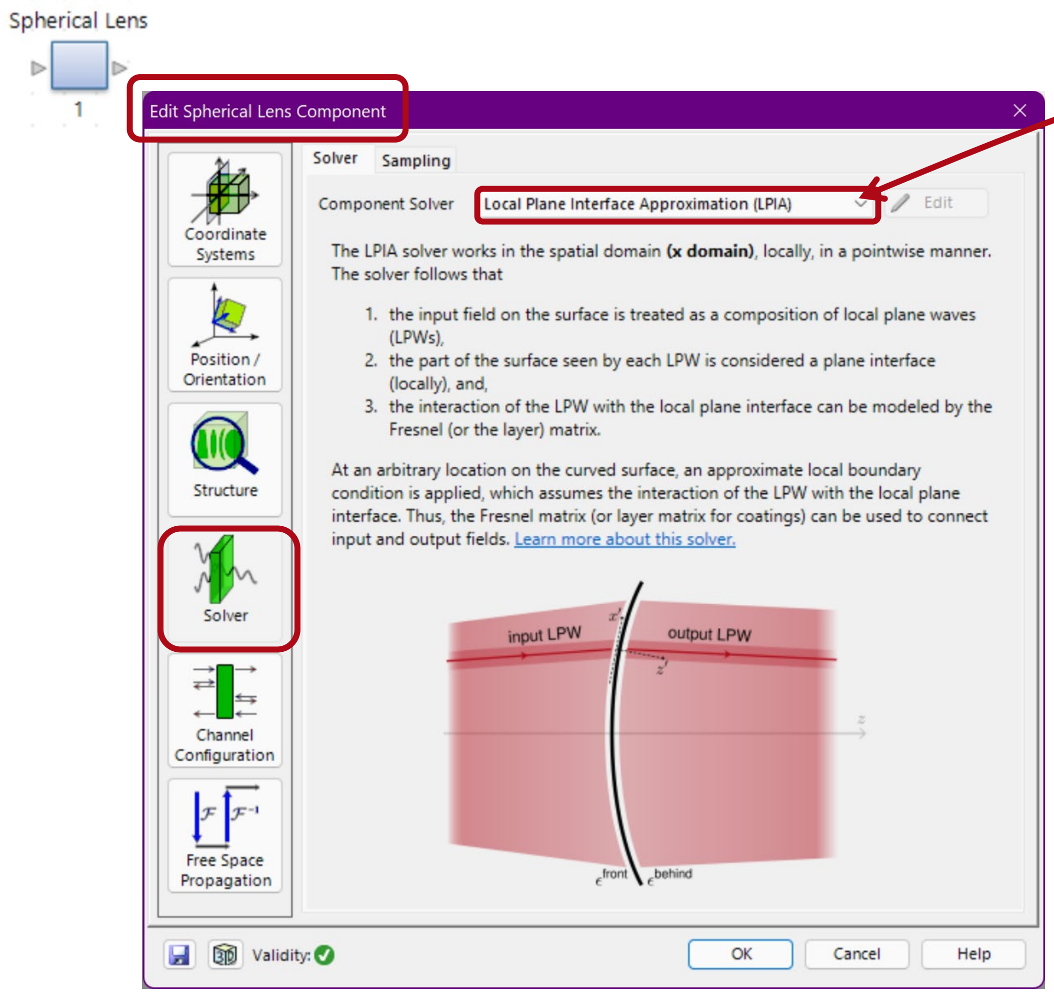
k-domain
x-domain

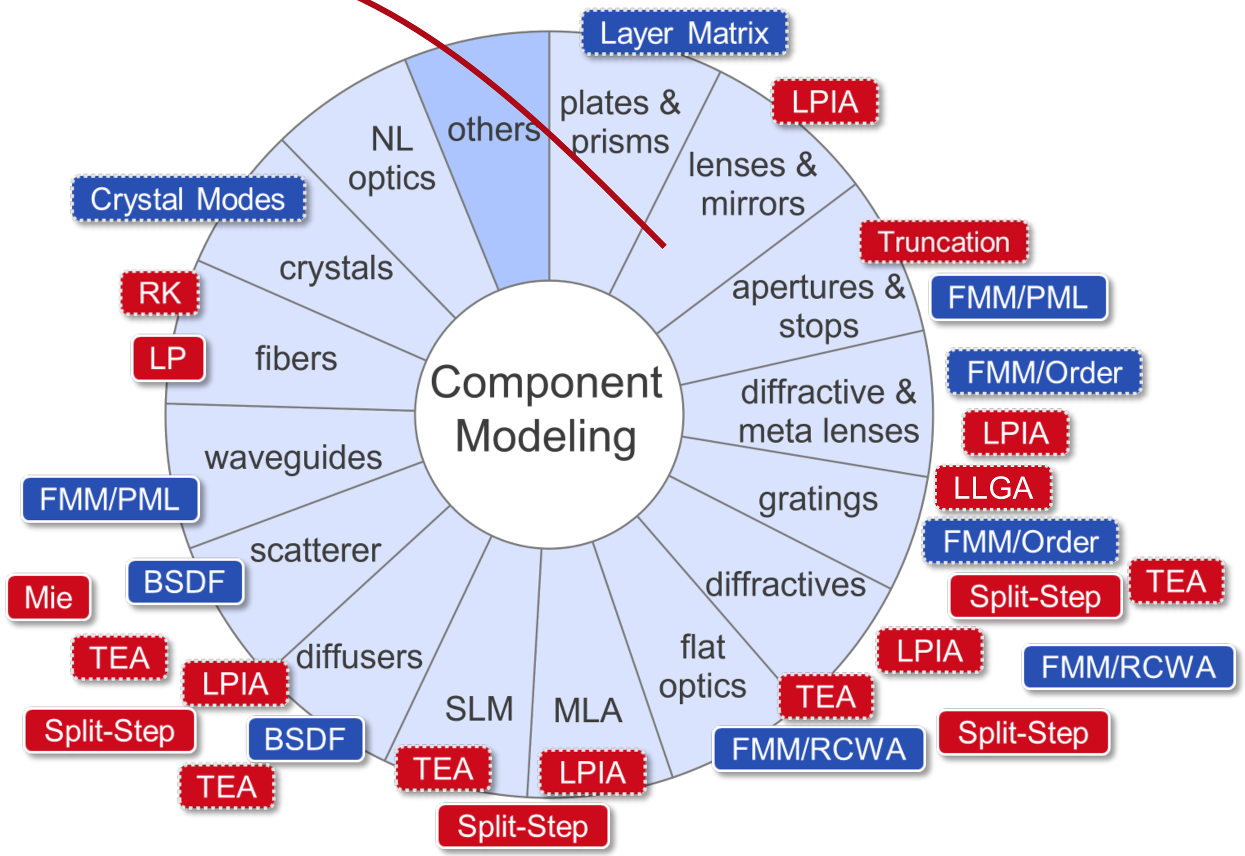




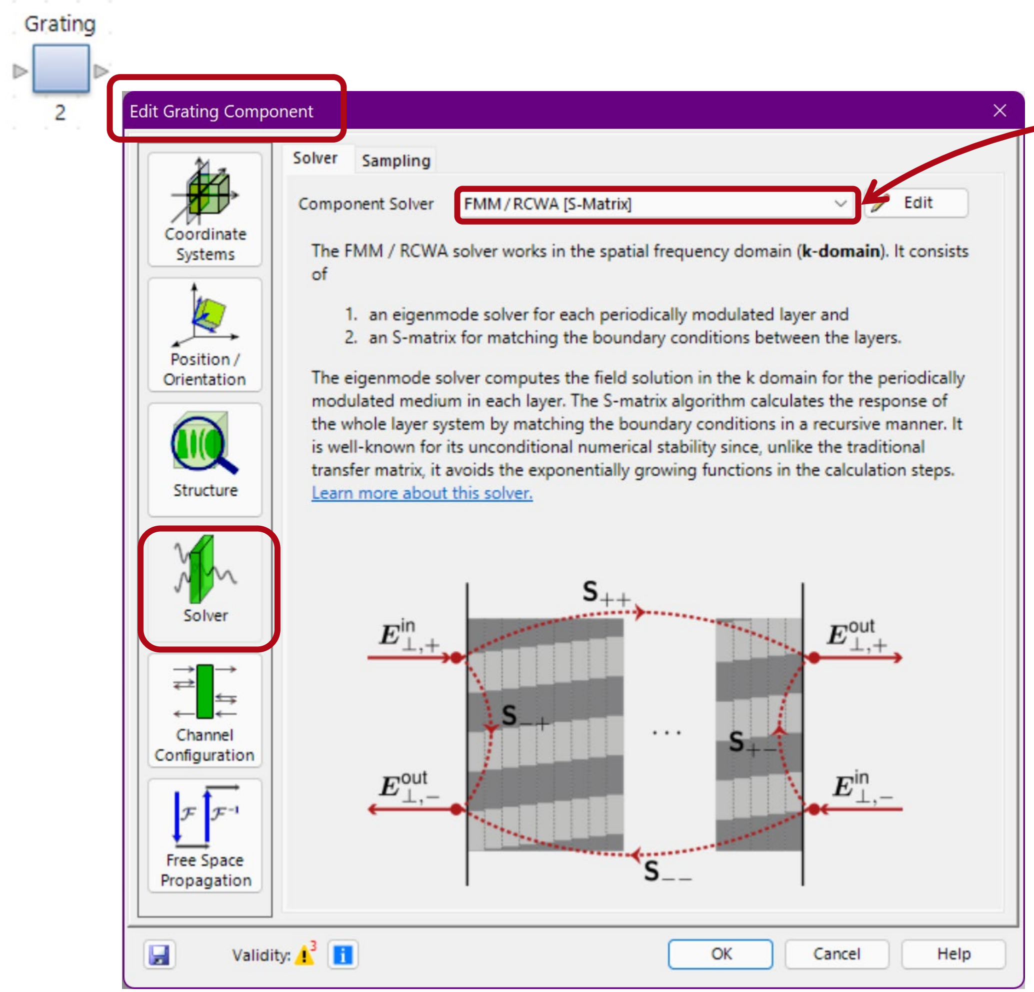
2022

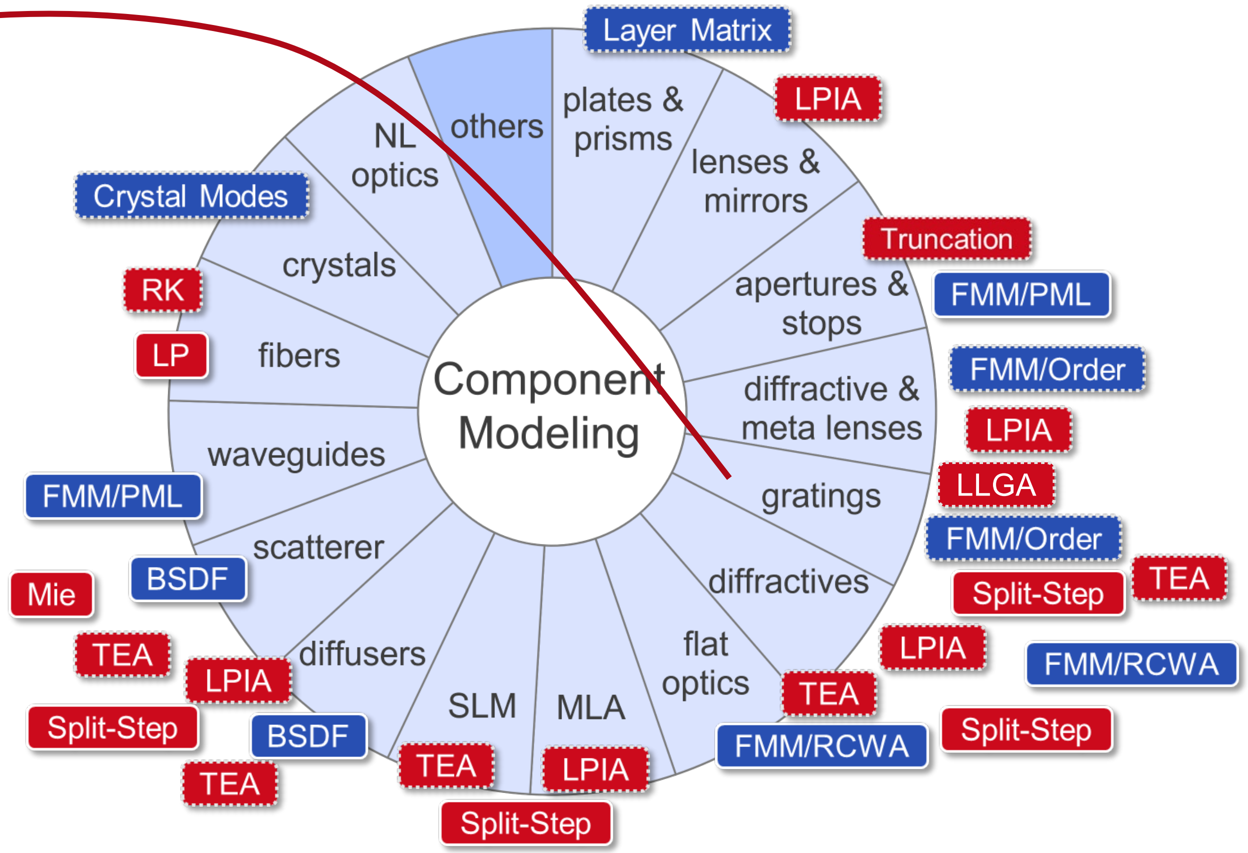
Solvers per Component



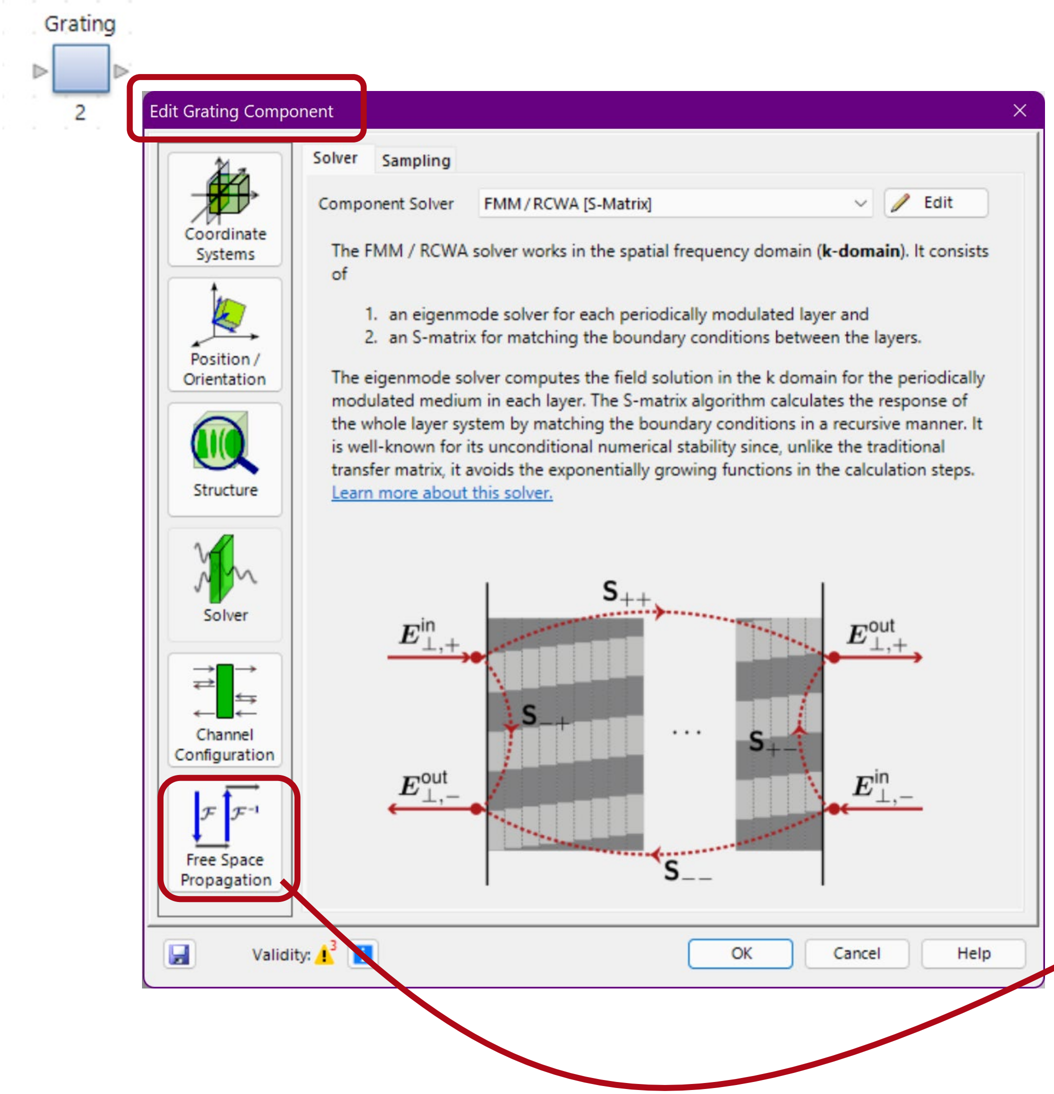


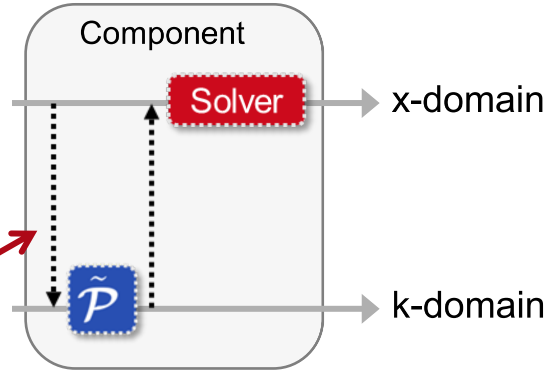
Solvers per Component





Propagation to Component Settings: Fourier Transforms





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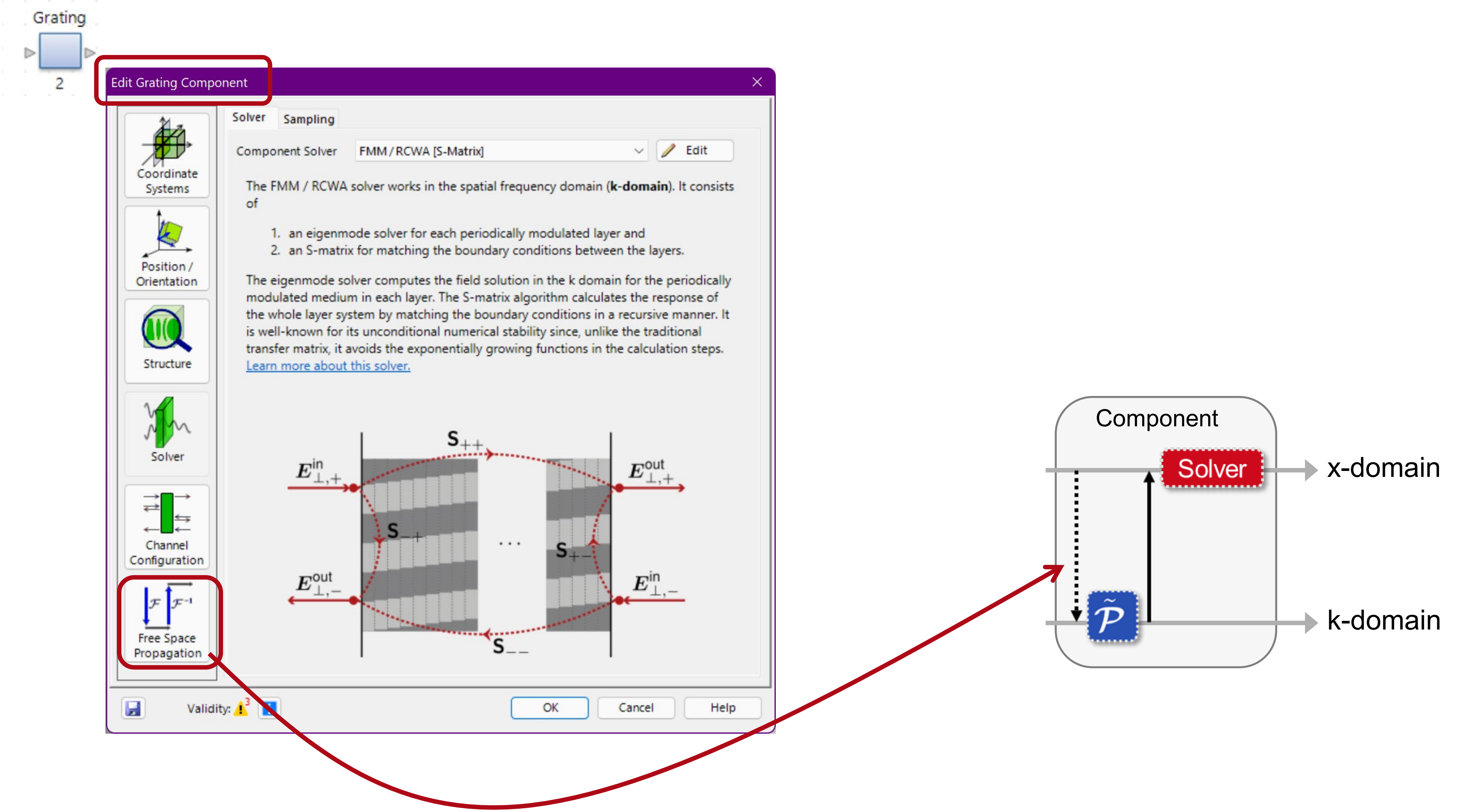
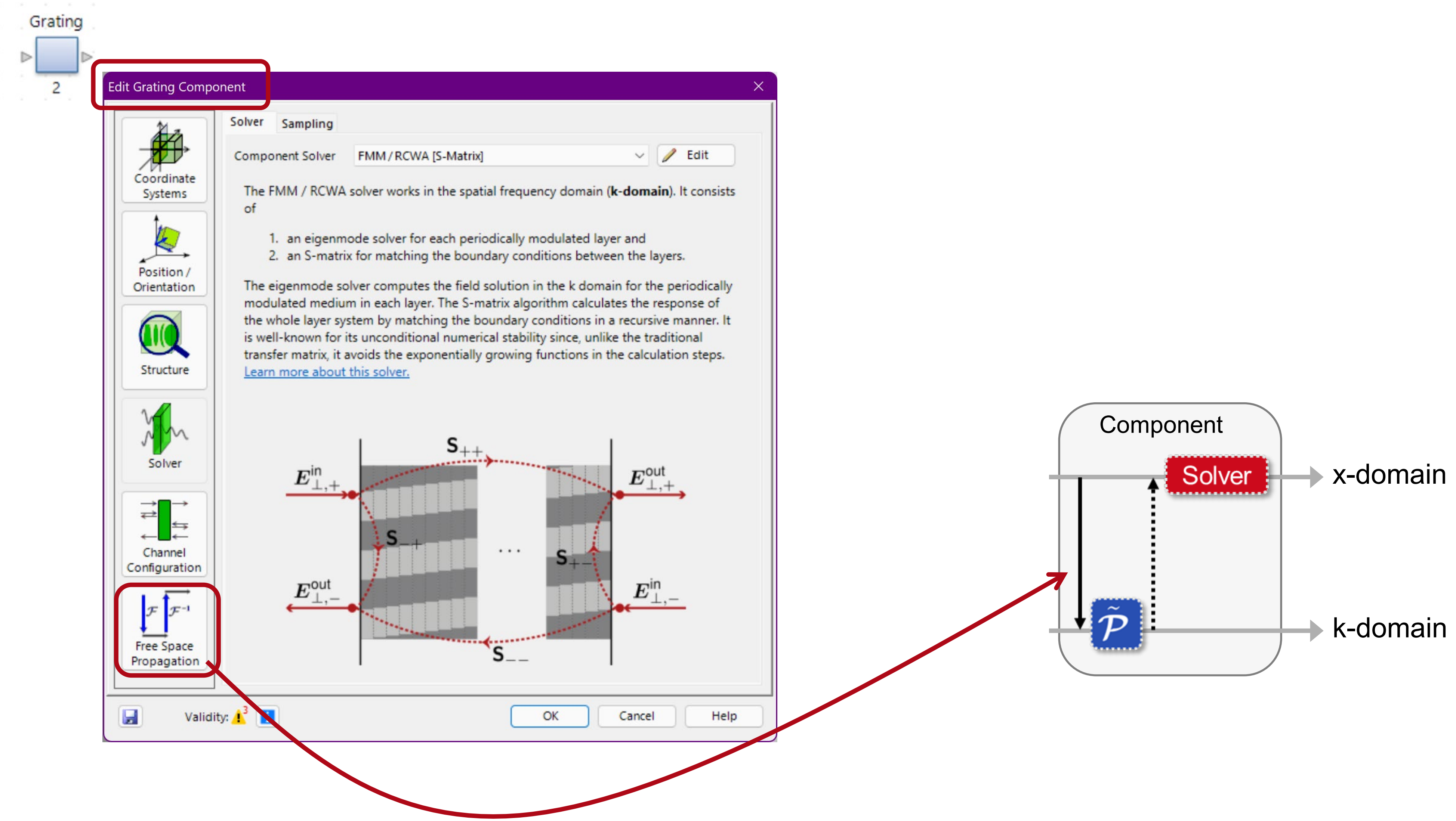
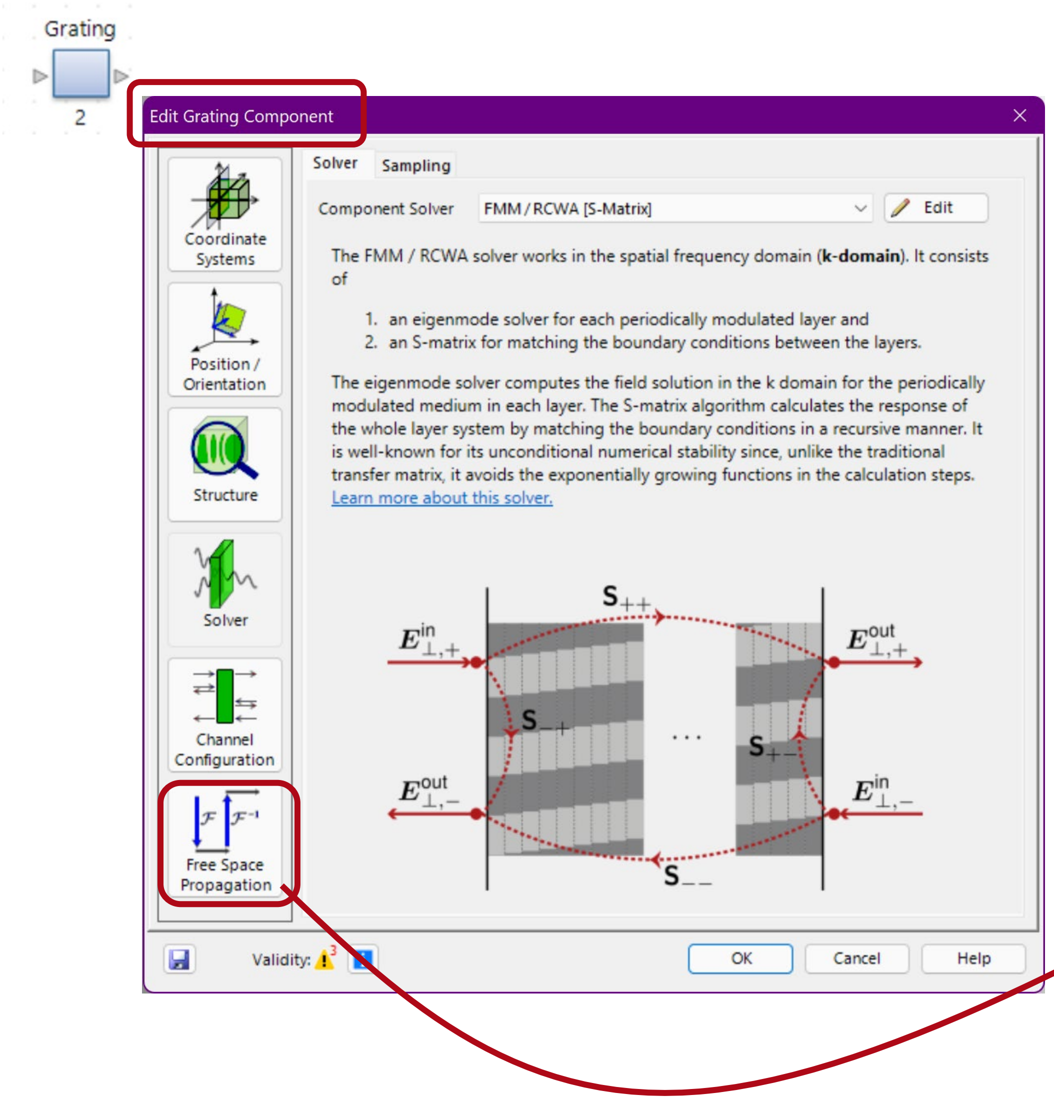
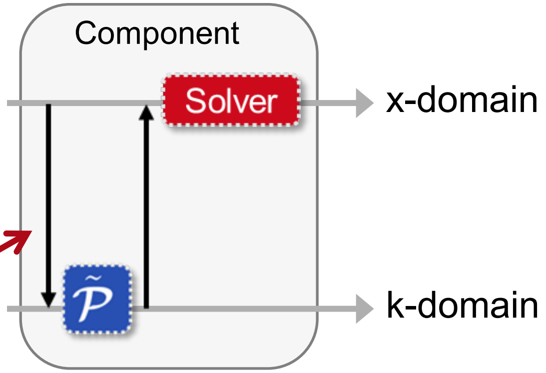


Propagation to Component Settings: Fourier Transforms

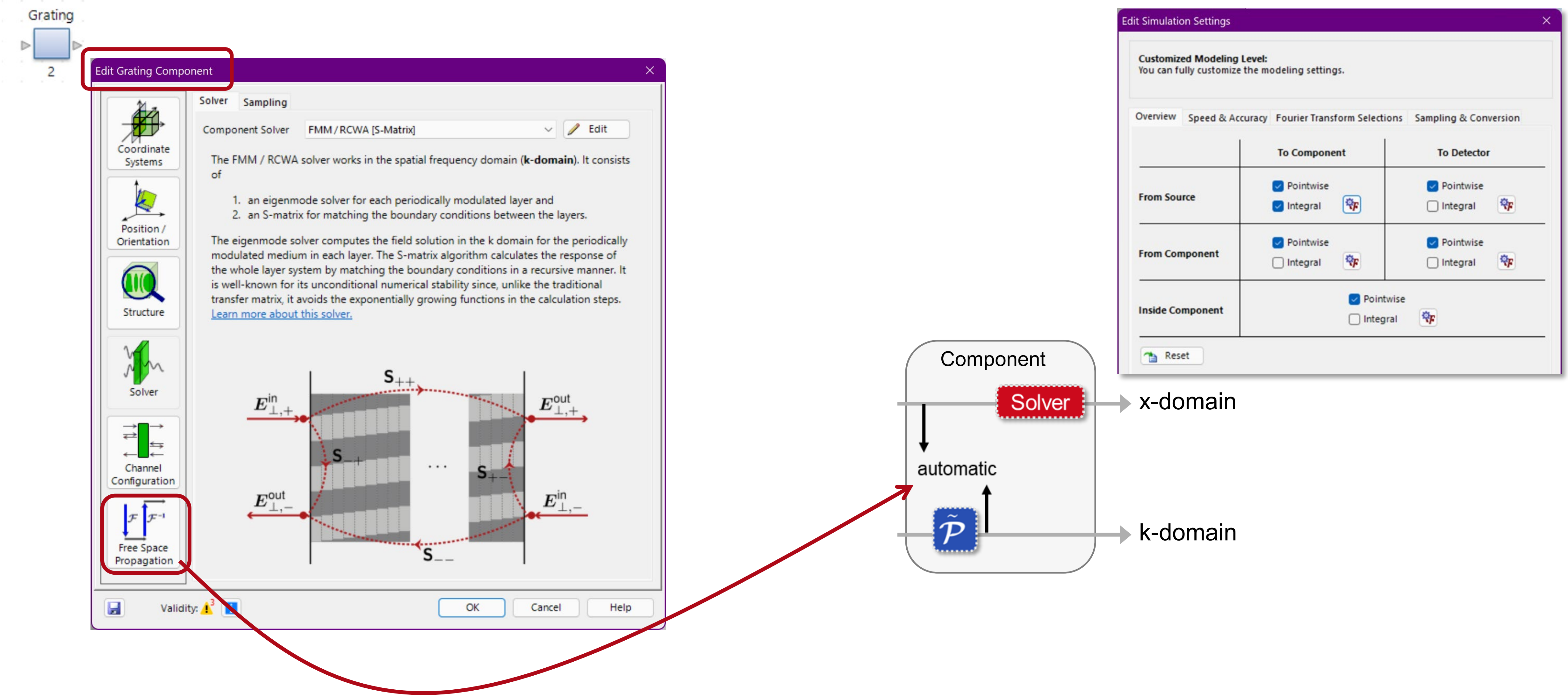


Propagation to Component Settings: Fourier Transforms

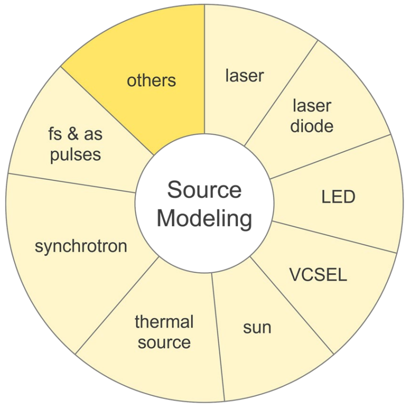


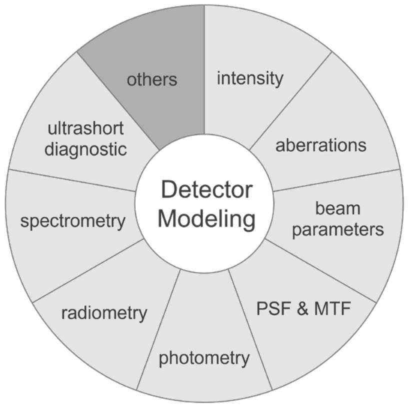


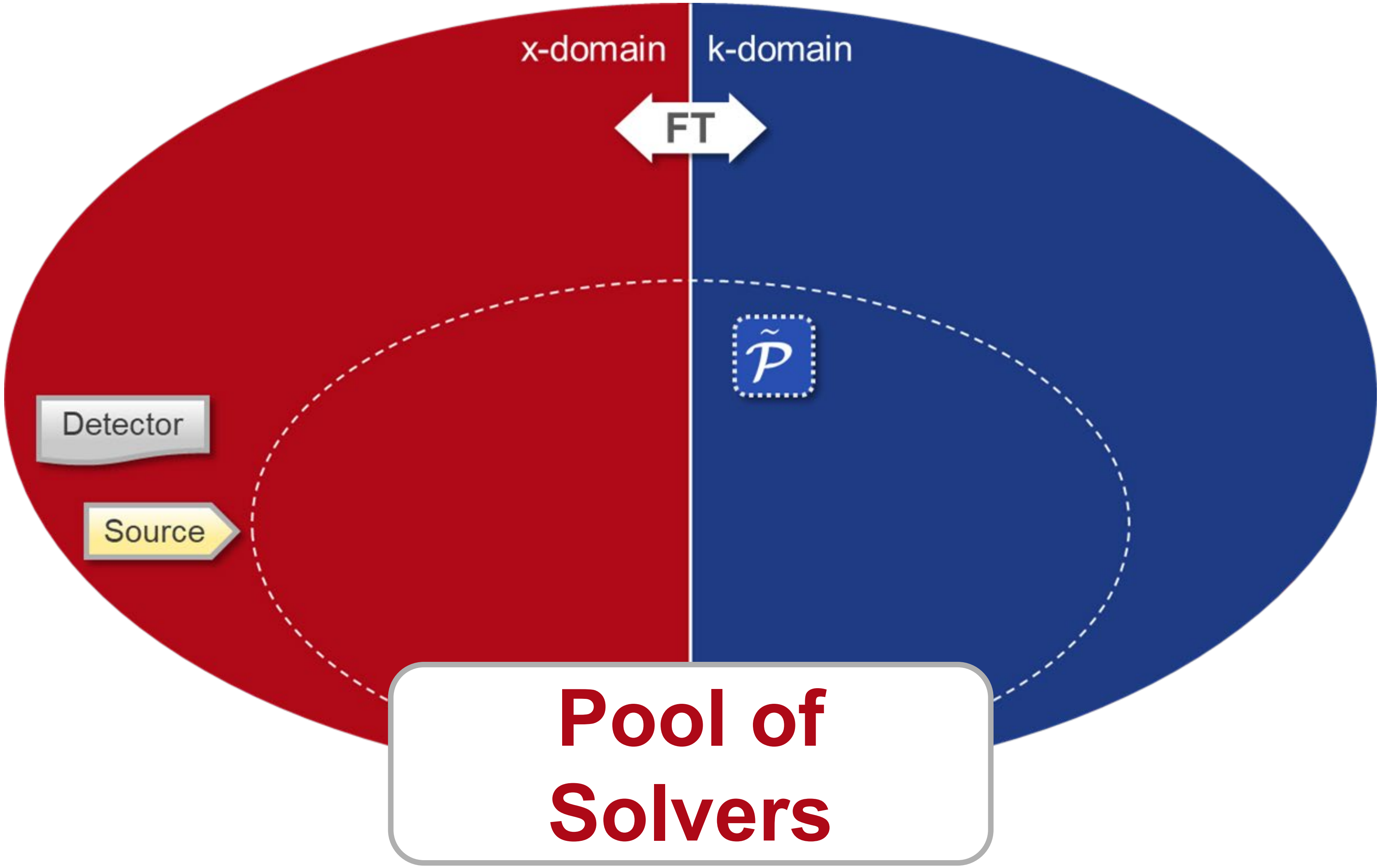
Propagation to Component Settings: Fourier Transforms



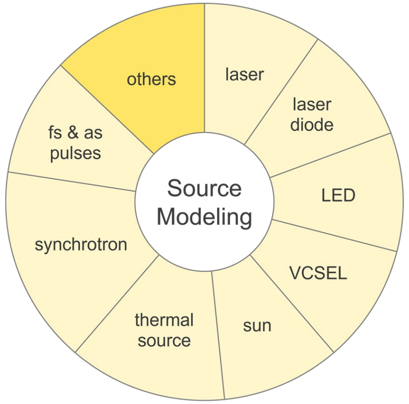
Connecting Solvers

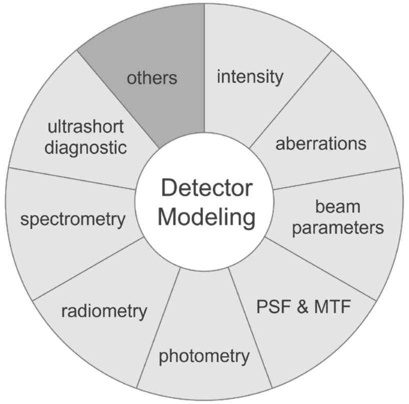


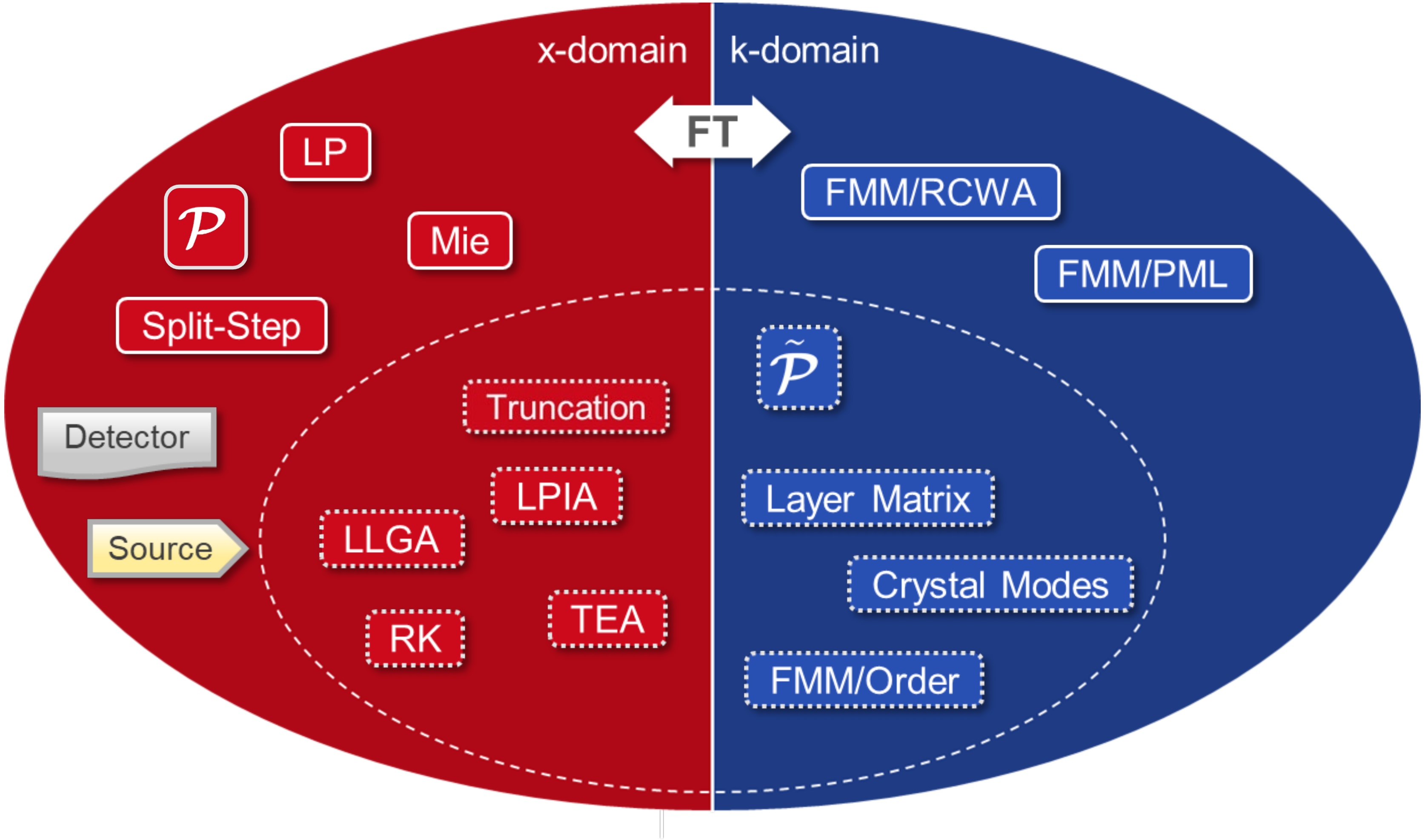




Connecting Solvers



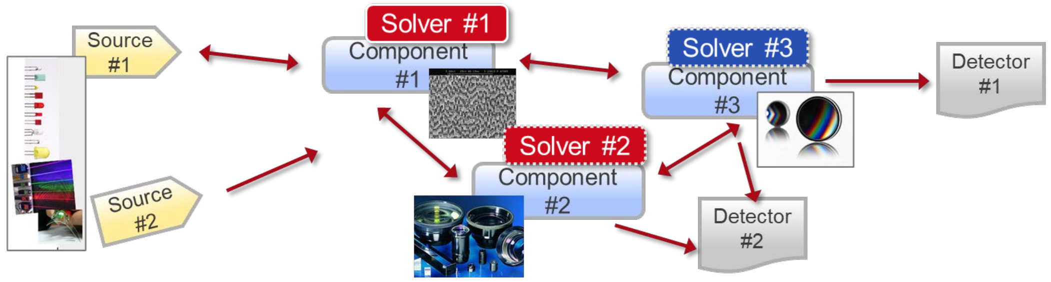


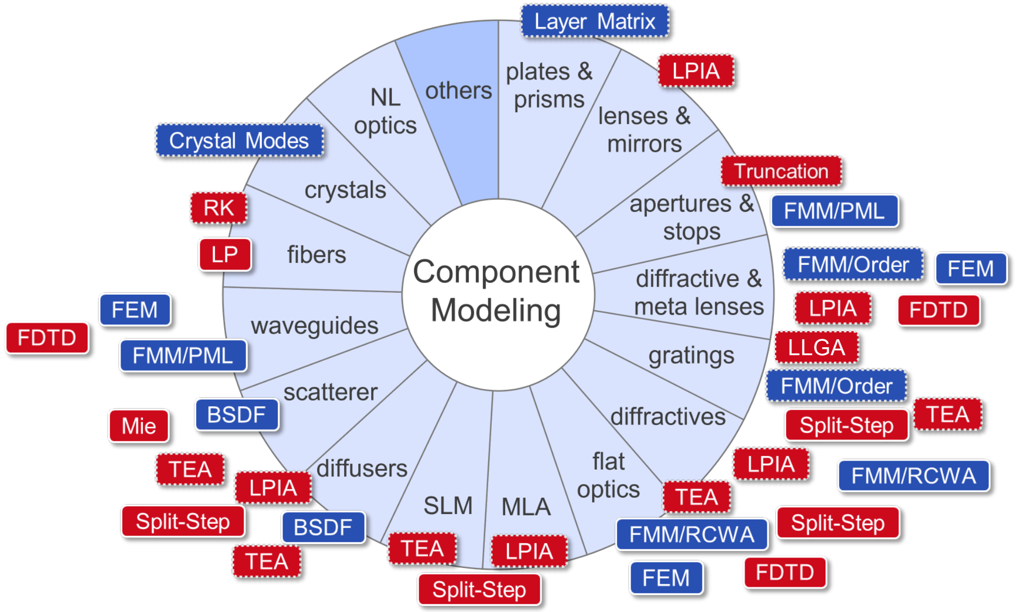


Connecting Solvers

- Build the system by selecting and positioning components.
- Select the Fourier transforms.
- Customize settings on demand.

- Software evaluates all relevant lightpaths through the system based on the 3D system configuration.
- Software knows and evaluates all lightpaths by connecting solvers in a non-sequential way.





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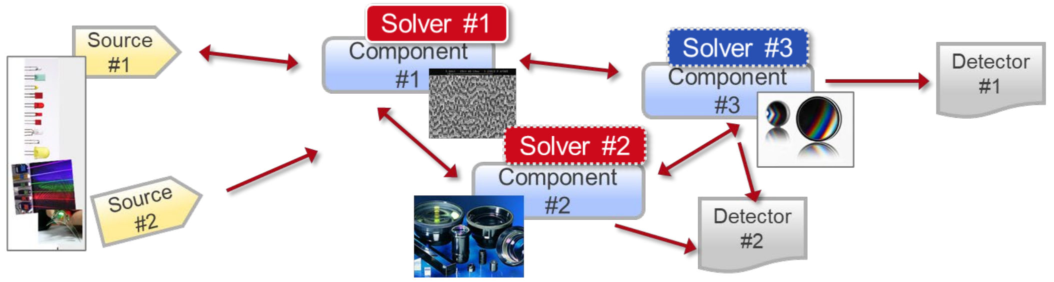
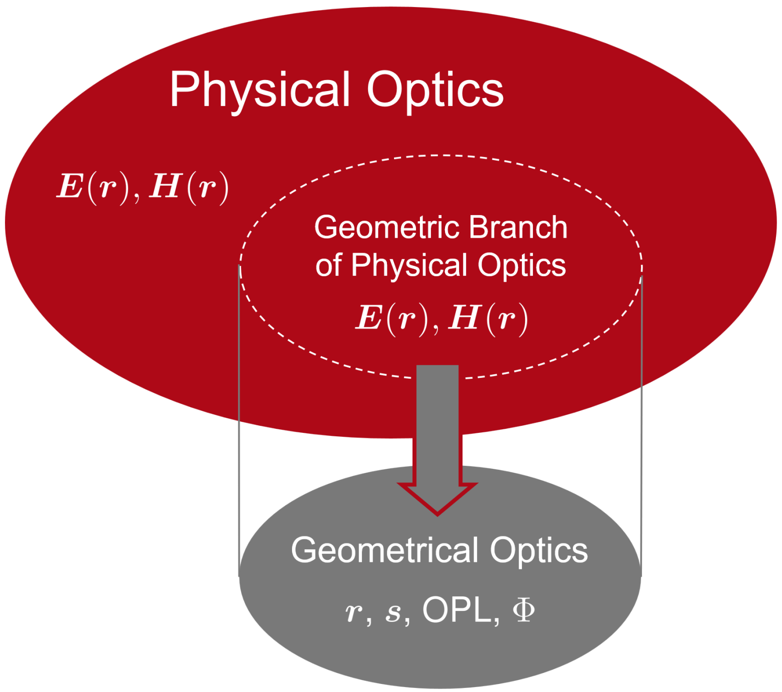
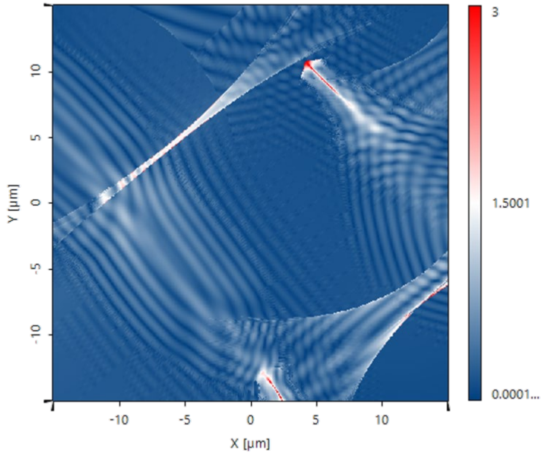
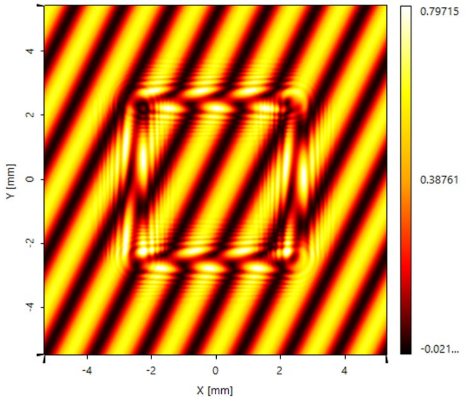


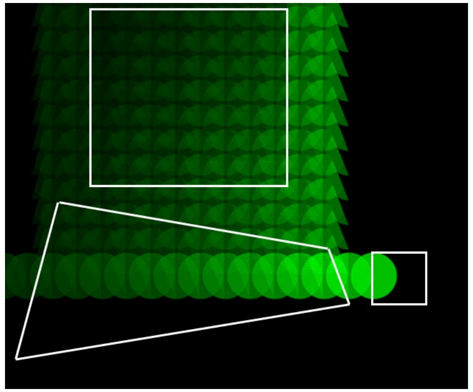


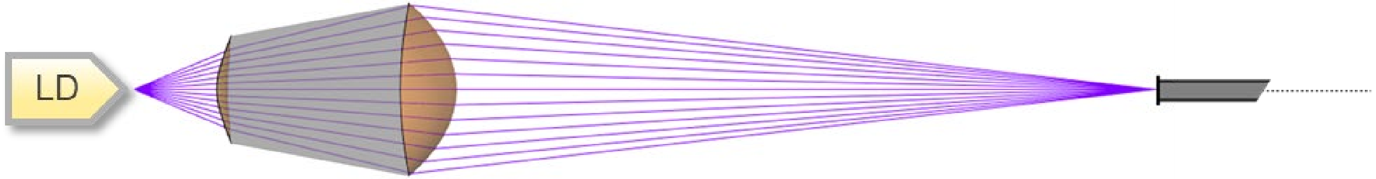
Content Overview

- Introduction to a unified approach in optical modeling
- **Theoretical considerations on physical optics modeling**
- Modeling examples
  - Talk
  - Follow-up material









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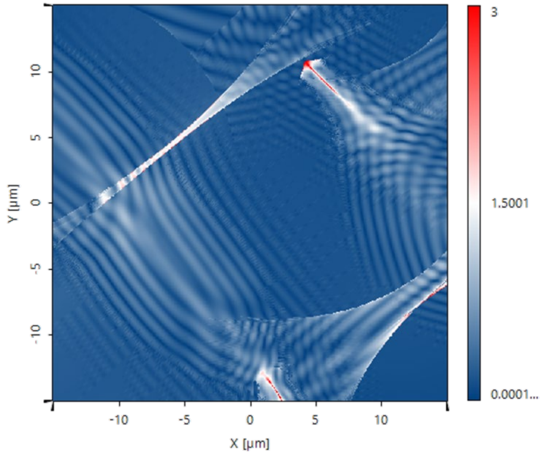
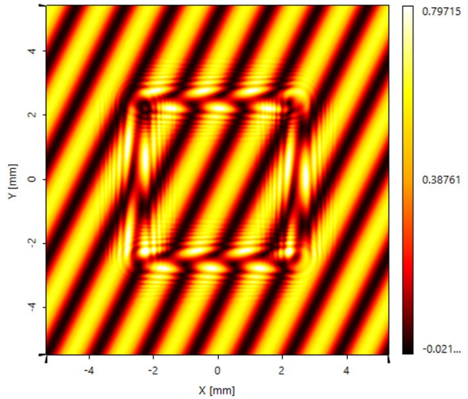
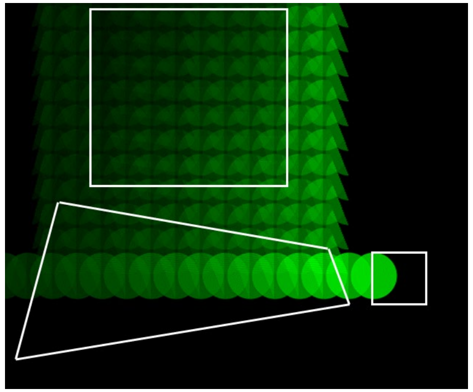
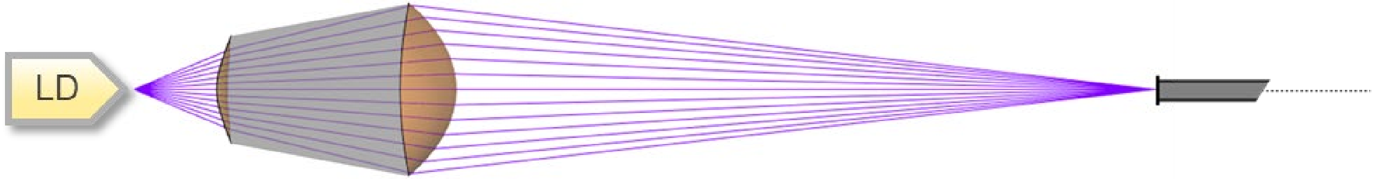
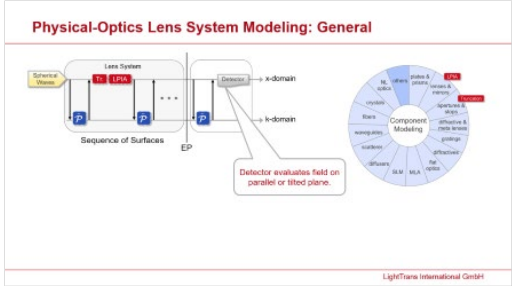


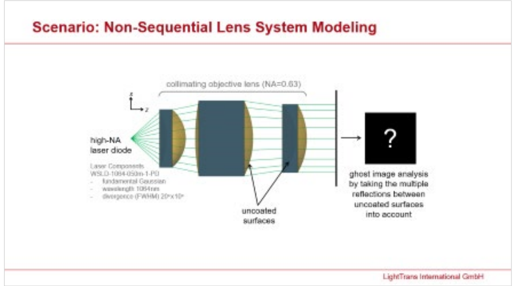


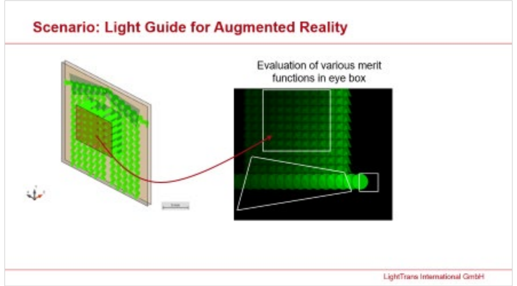


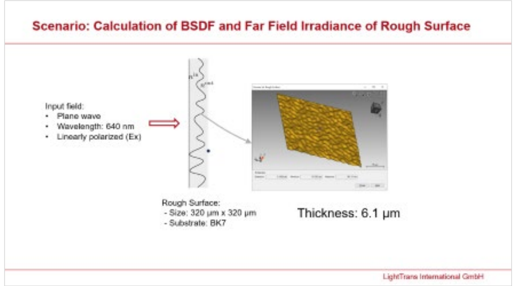


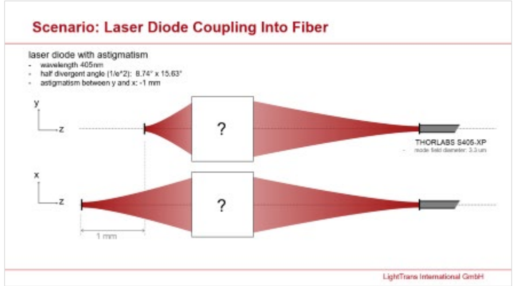
Modeling and Design Examples

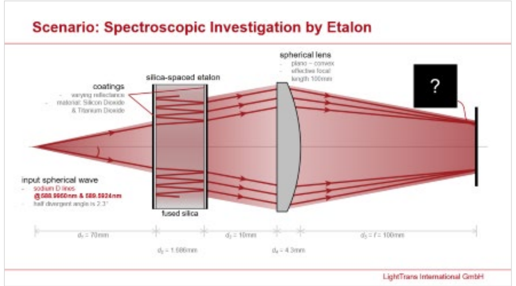


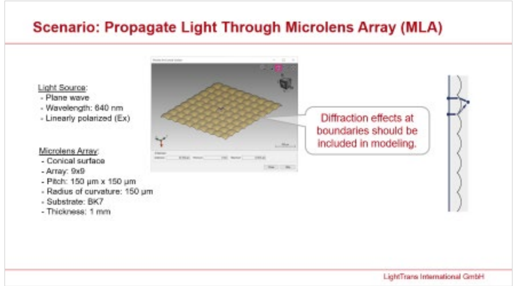


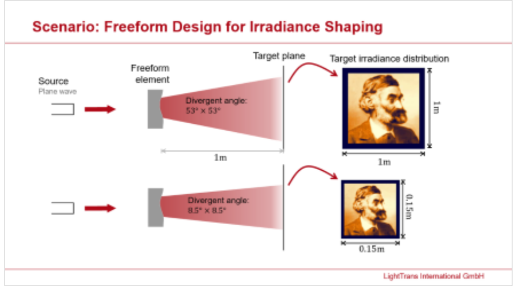


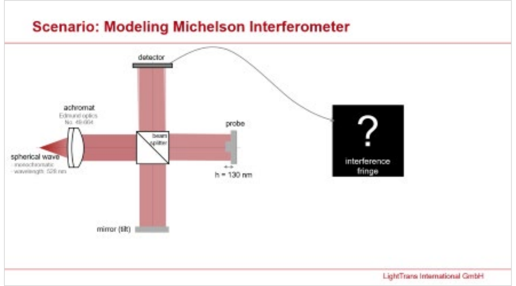


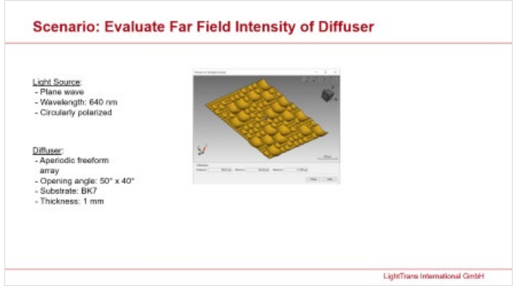


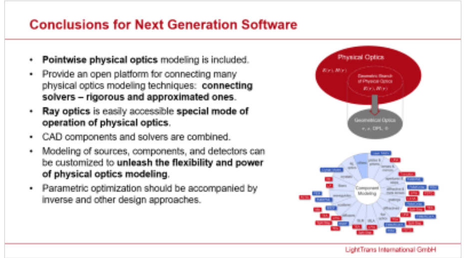




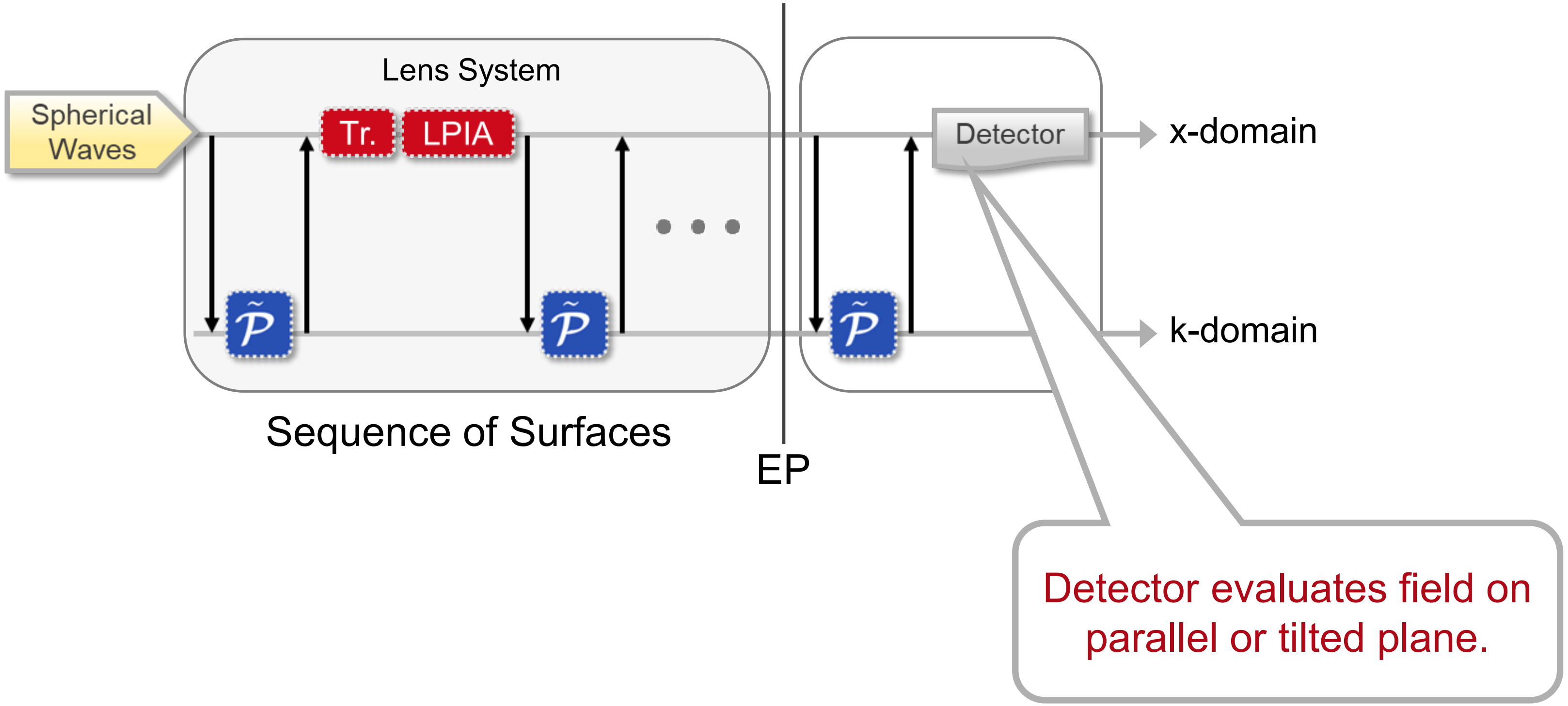


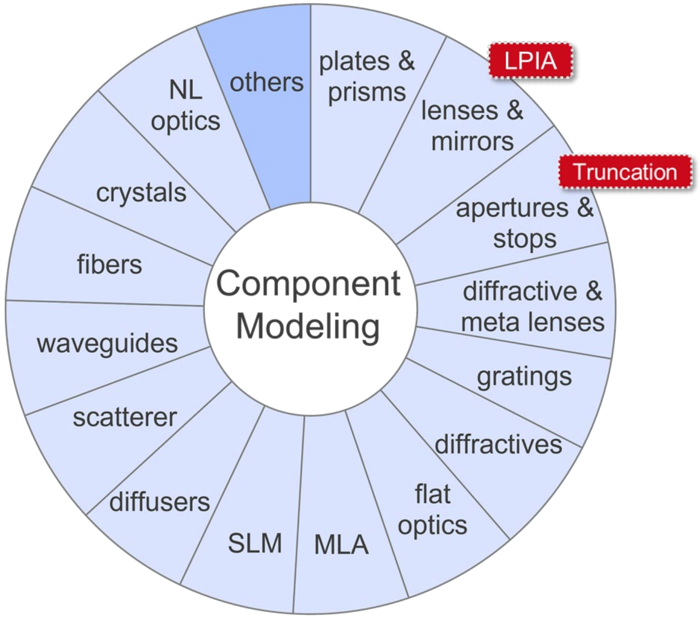




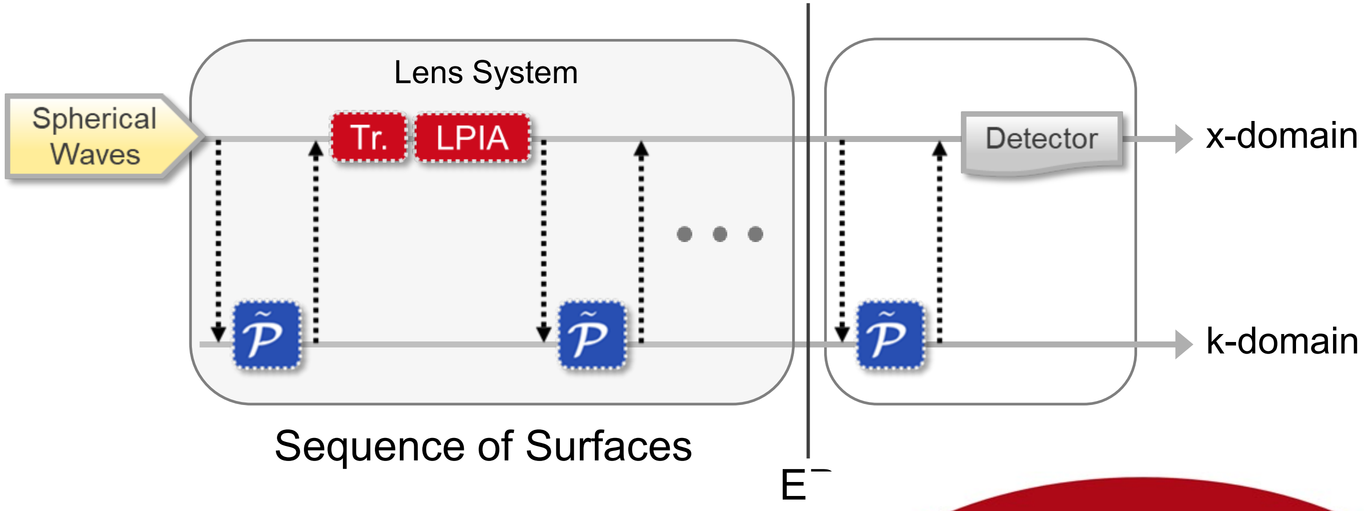


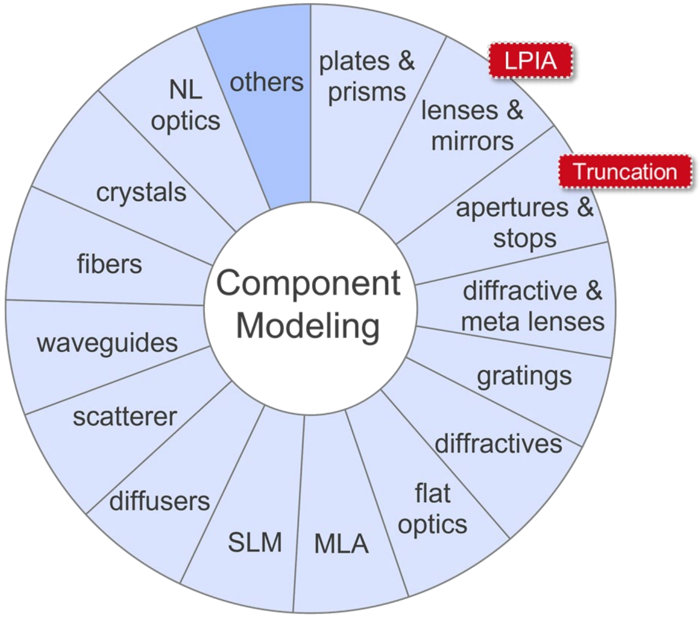
Physical-Optics Lens System Modeling: General

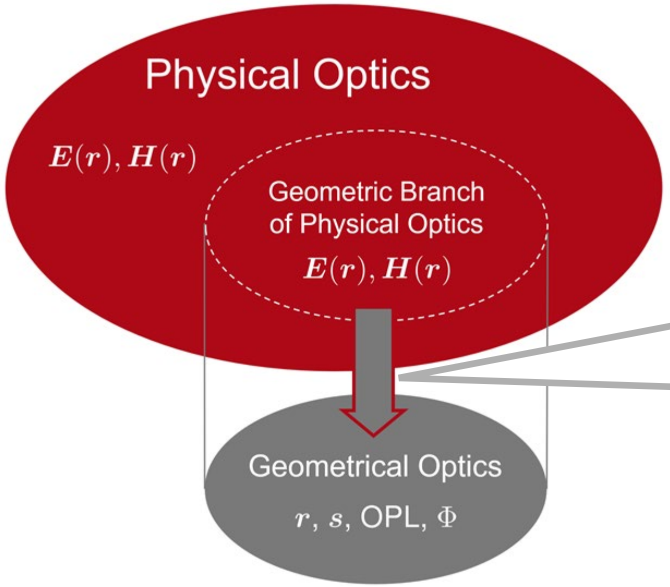




Lens System Modeling: Pointwise

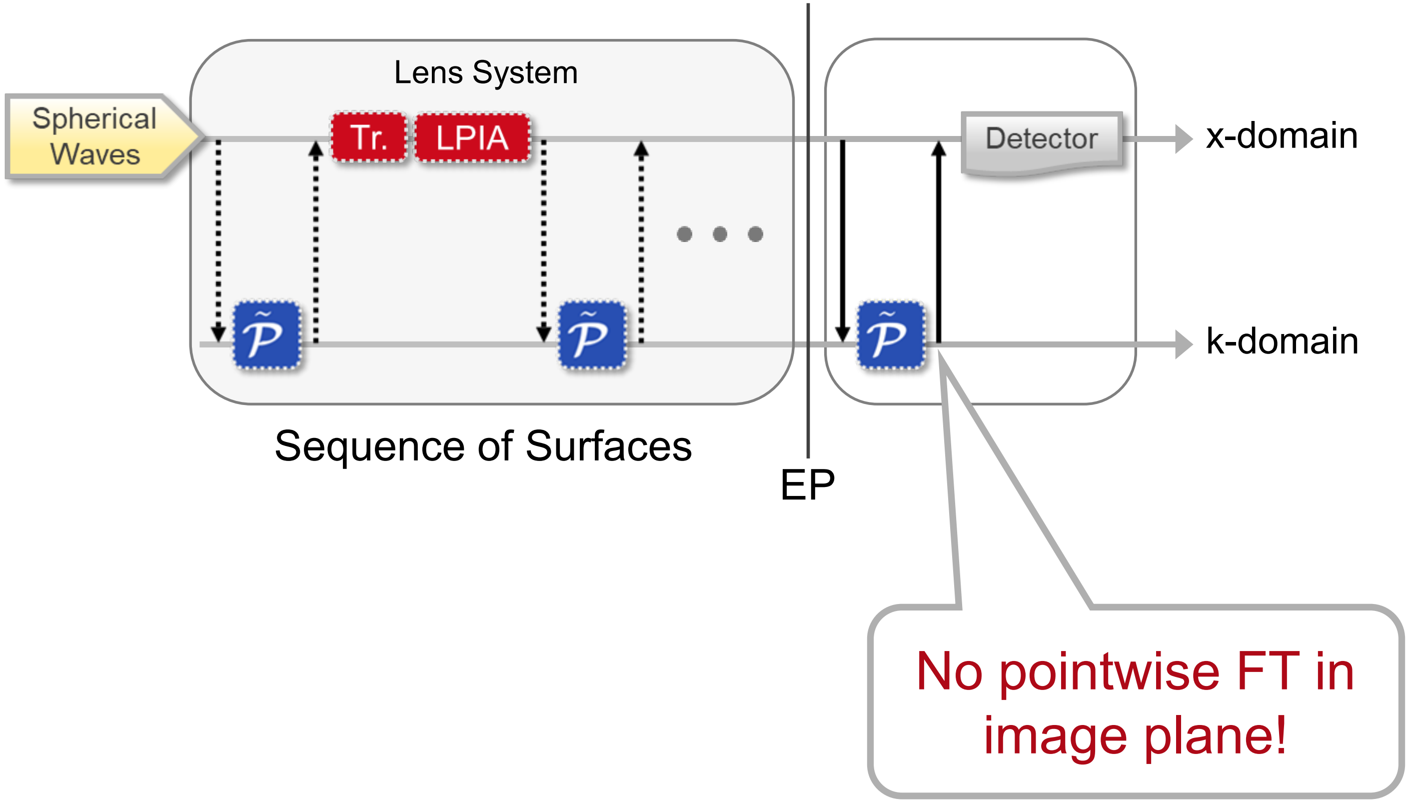


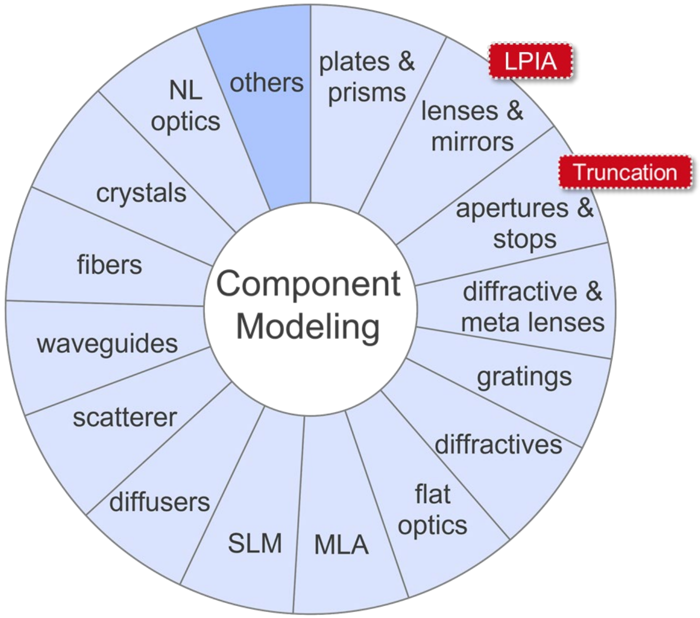




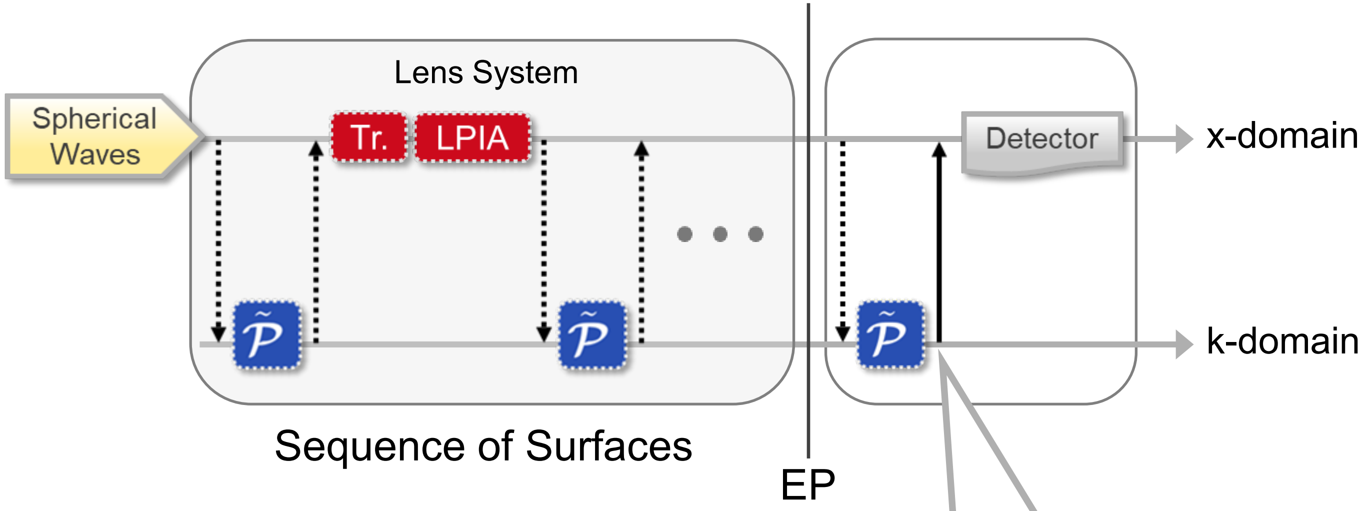
Pointwise physical-optics modeling provides results known from ray tracing with identical numerical complexity!

Lens System Modeling: PSF Calculation



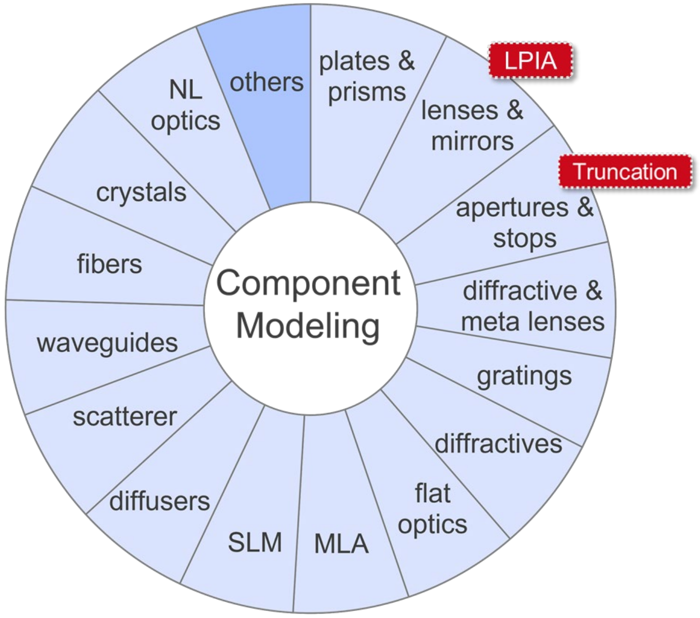


Lens System Modeling: PSF Calculation (Debye Integral)

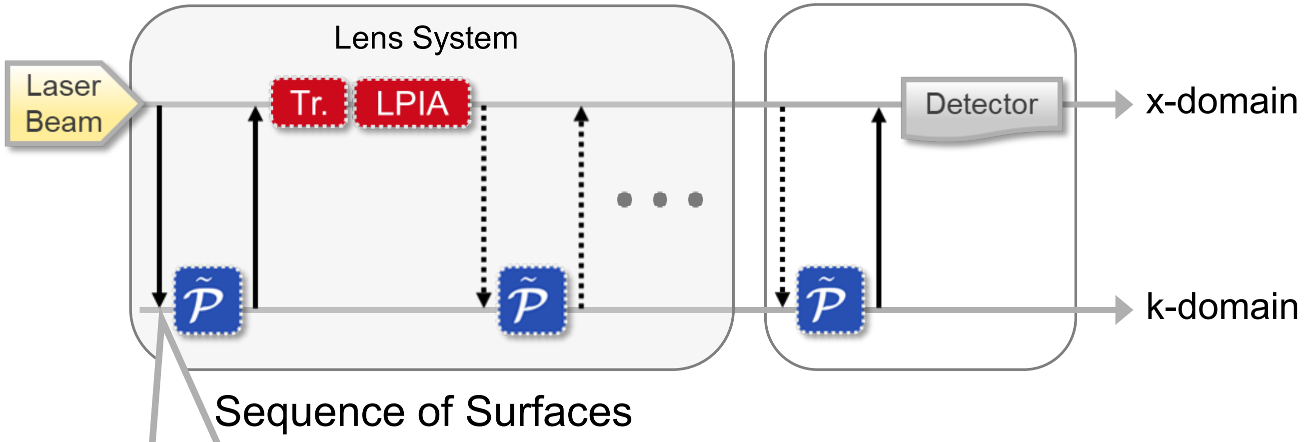


No pointwise FT in image plane!

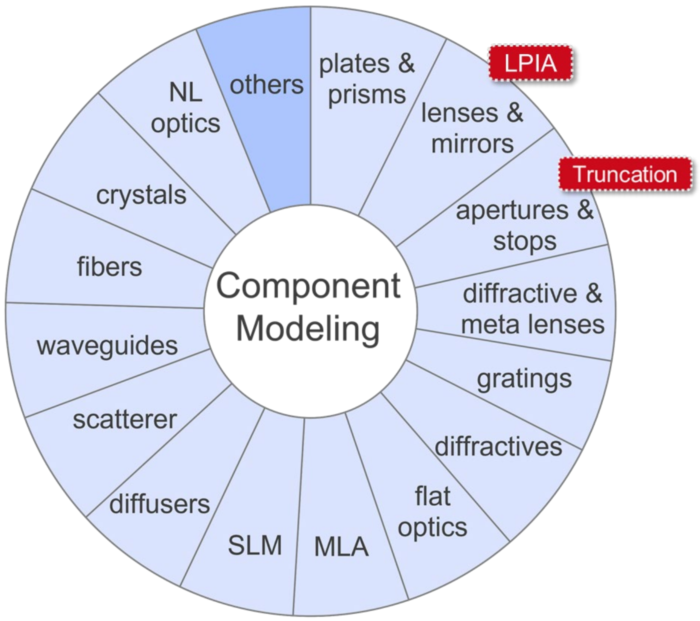
This modeling configuration is typically assumed in ray tracing software for PSF calculation.



Lens System Modeling: Laser Beam



Gaussian beam in its waist does not allow PFT.



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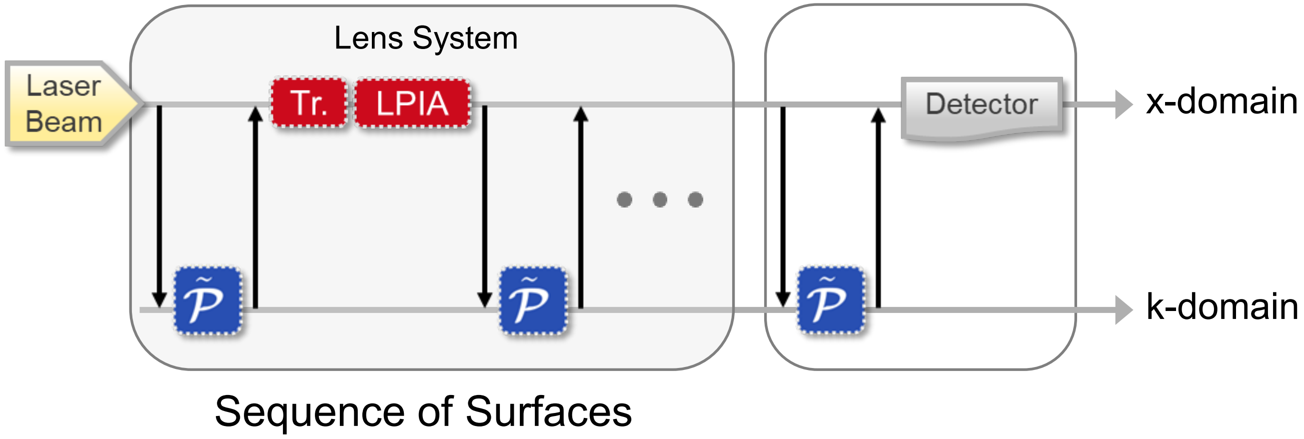
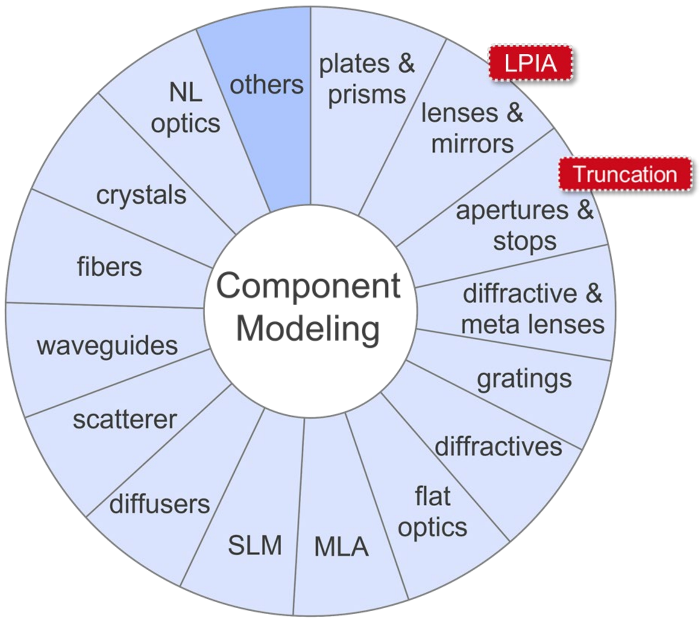
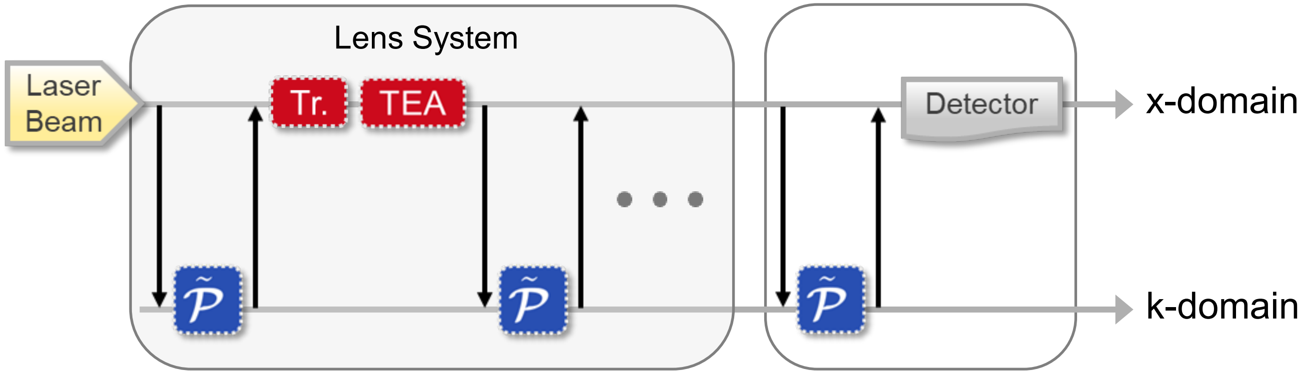




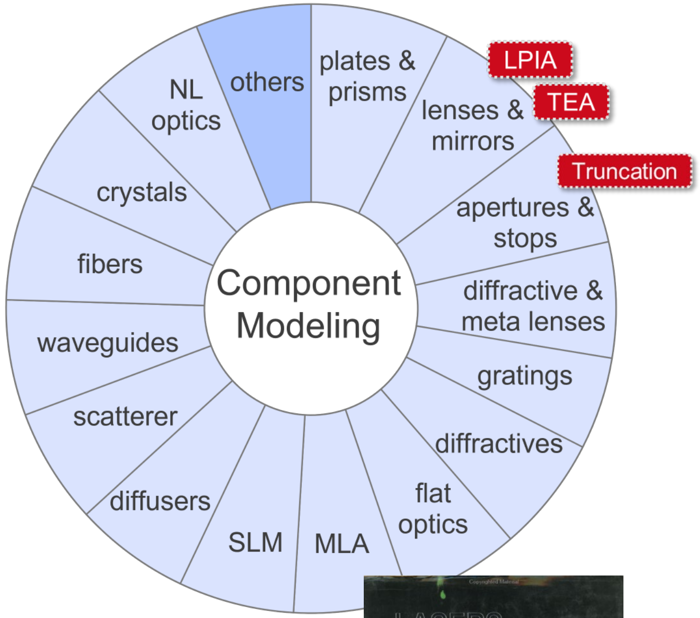
Paraxial fields typically require integral FT.

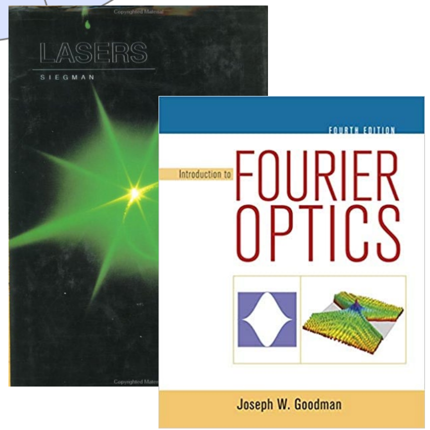
By switching the type of Fourier transforms any kind of lens modeling is enabled, including lens system modeling for paraxial light.

Paraxial Lens System Modeling



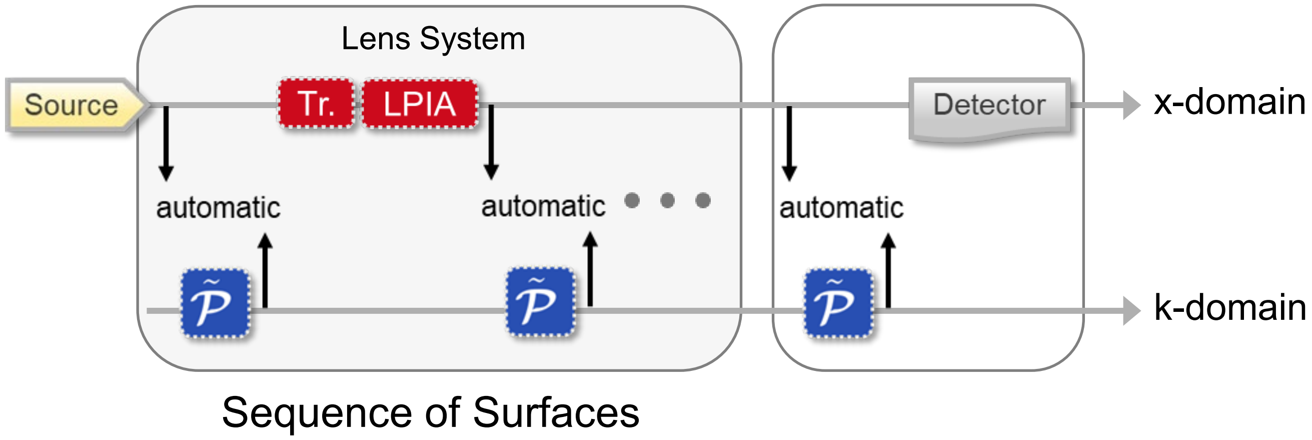
Paraxial lens modeling allows use of TEA.

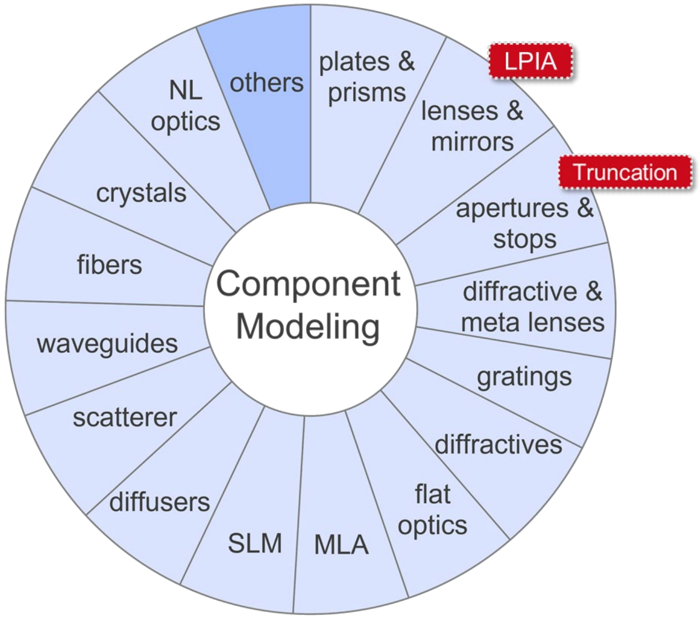




This modeling configuration is typically used in Fourier optics and laser optics books.

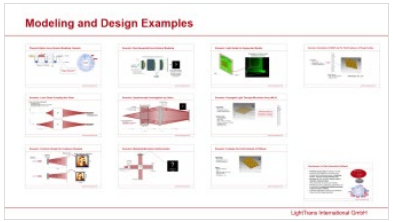
Lens System Modeling: General





Software algorithms decide about FT selection according to accuracy criterion.

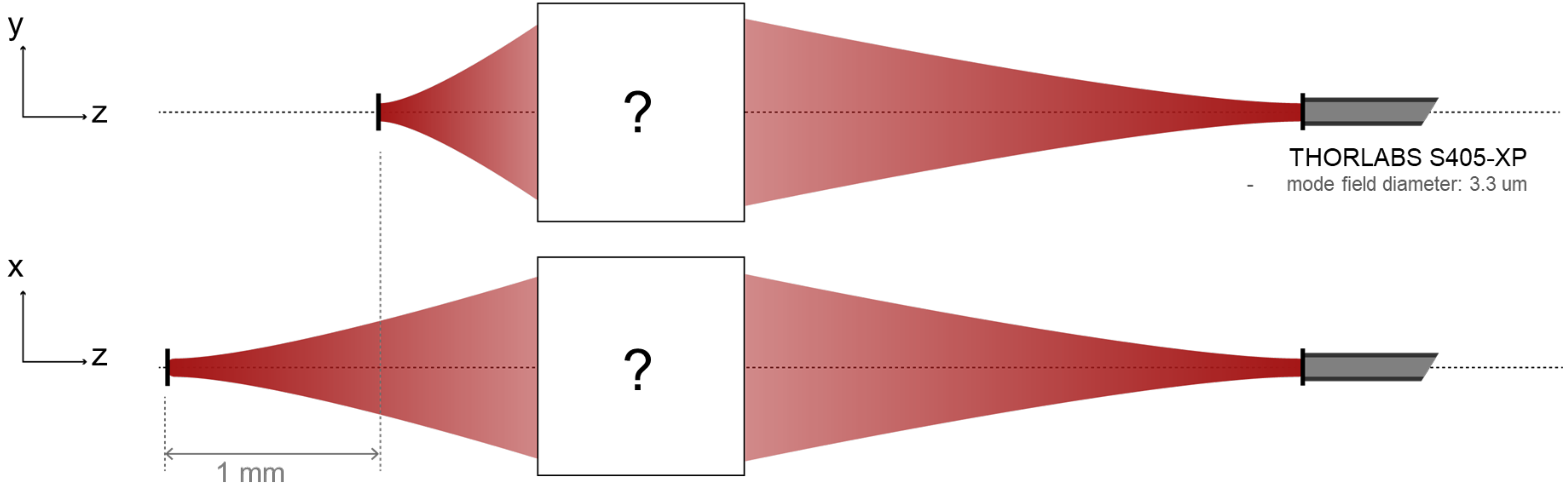
All lens modeling situations are included in a seamless modeling approach!



Scenario: Laser Diode Coupling Into Fiber

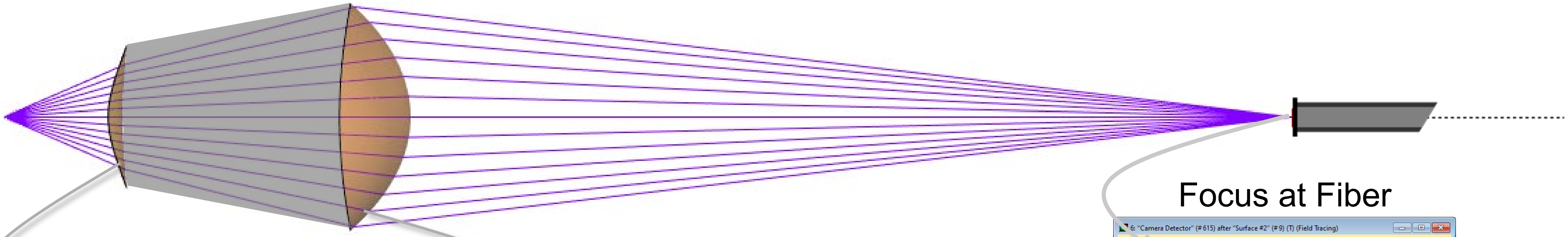
laser diode with astigmatism

- wavelength 405 nm
- half divergent angle (1/e^2): 8.74° x 15.63°
- astigmatism between y and x: -1 mm

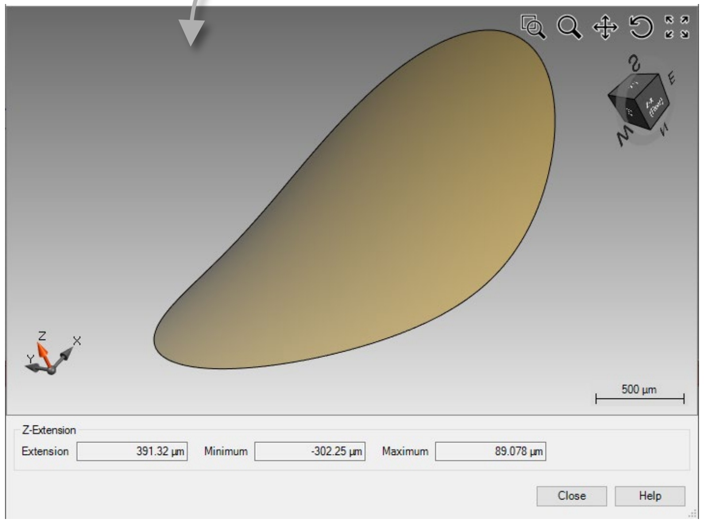


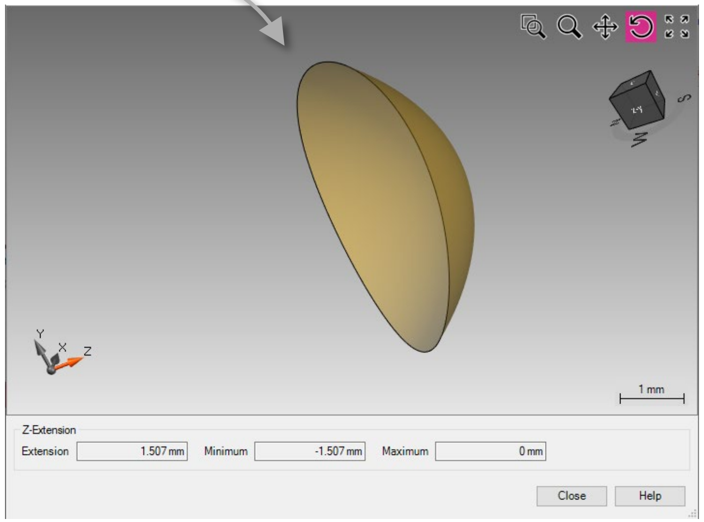
Laser Diode Coupling Into Fiber: Freeform Design

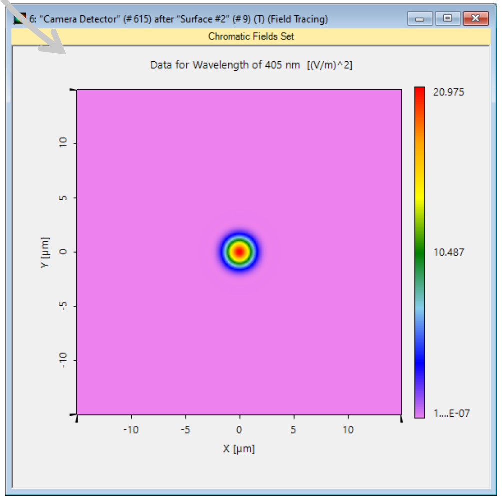
By Inverse Design



Focus at Fiber

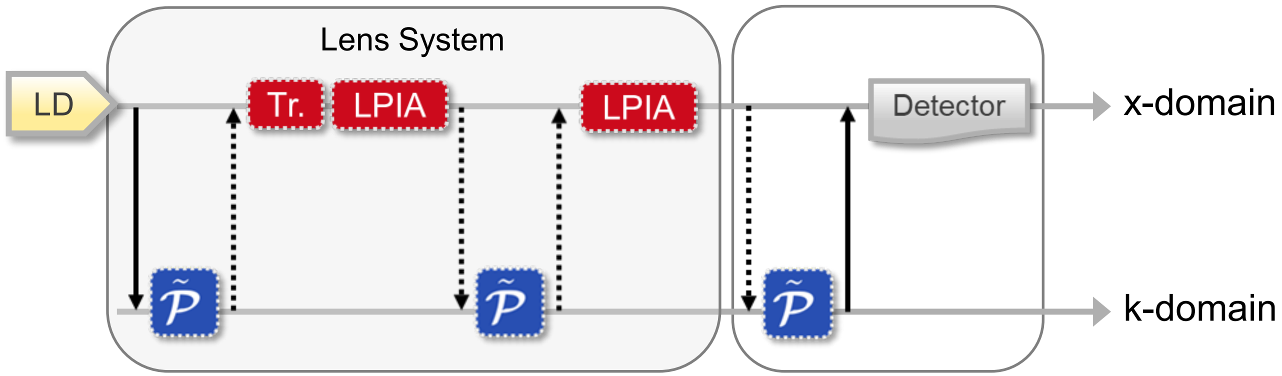


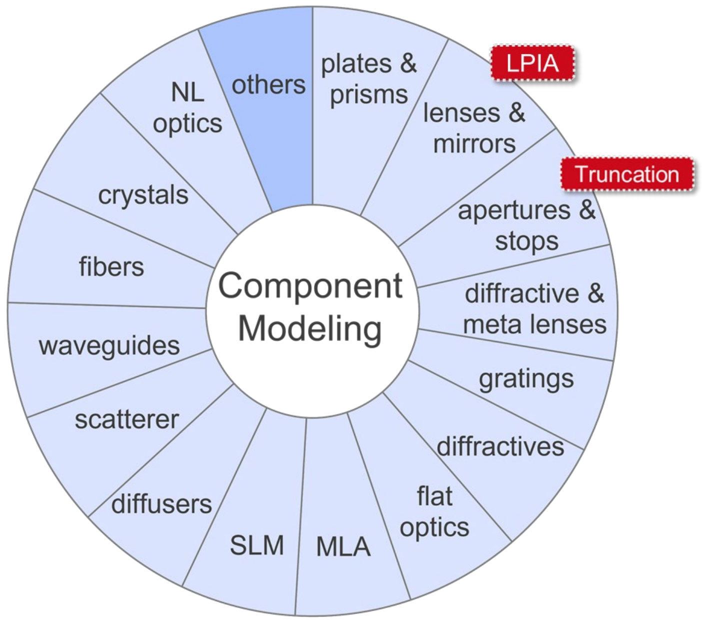


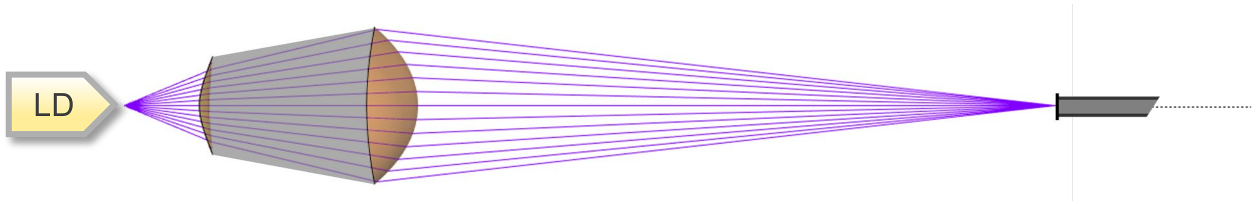


Incoupling Efficiency: 98%

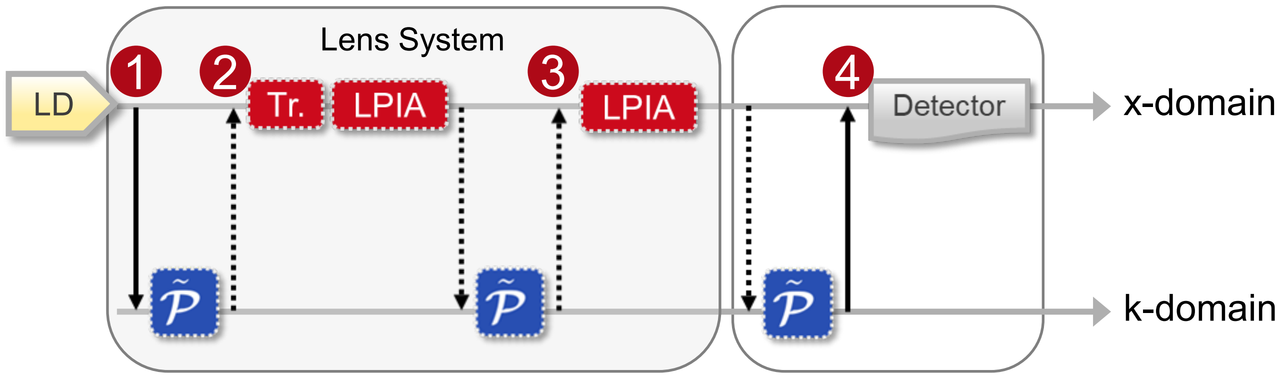
Lens System Modeling: Laser Diode Fiber Coupling



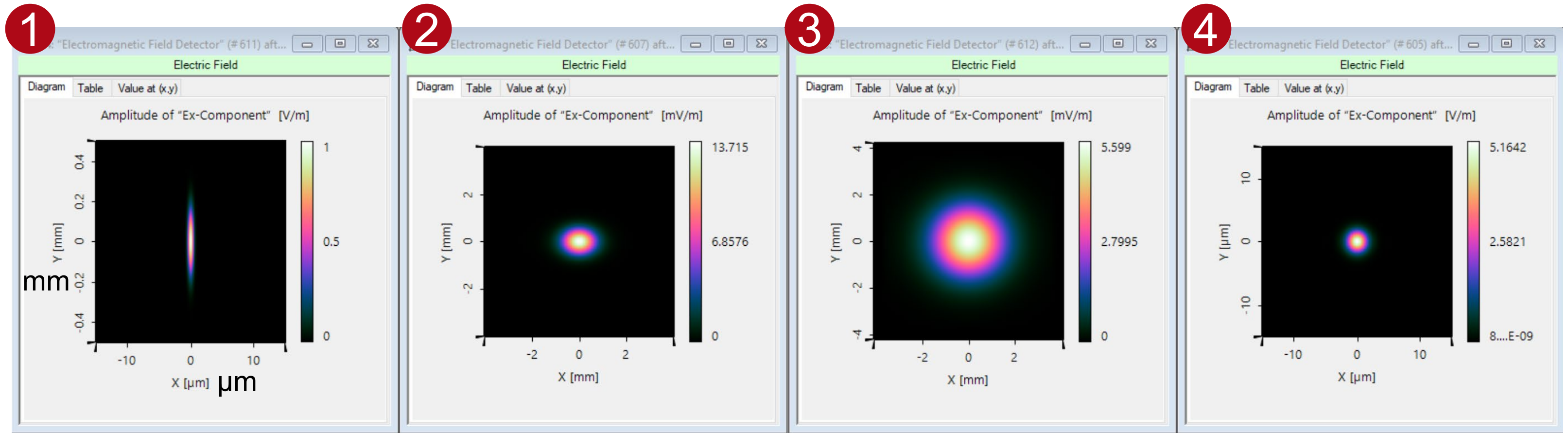


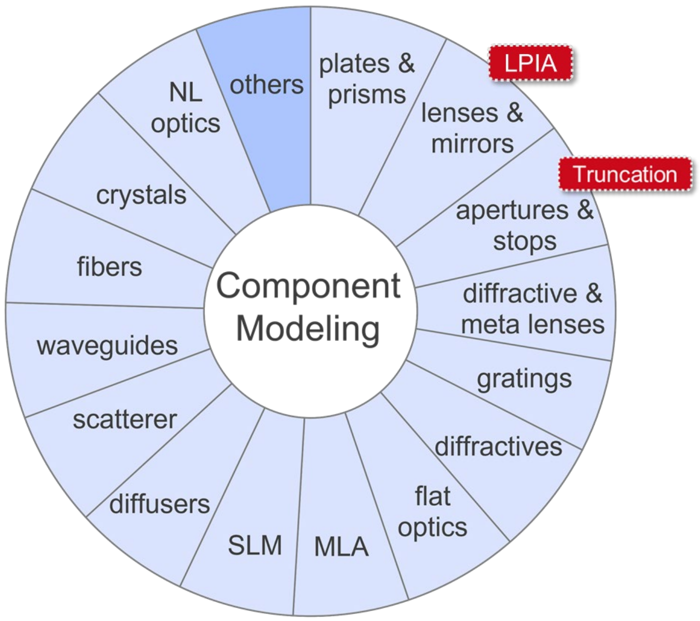


Lens System Modeling: Laser Diode Fiber Coupling

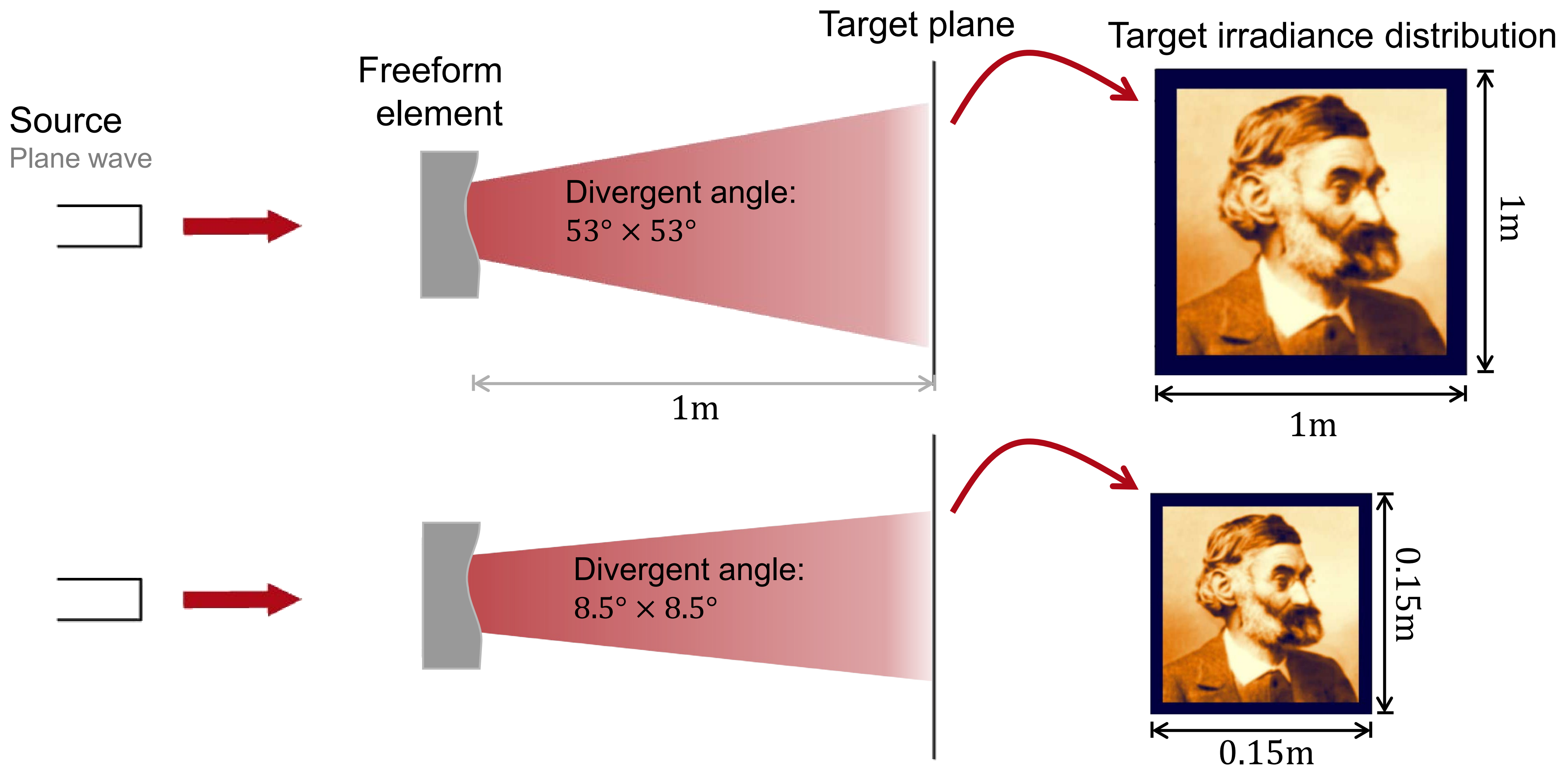


Field Amplitudes

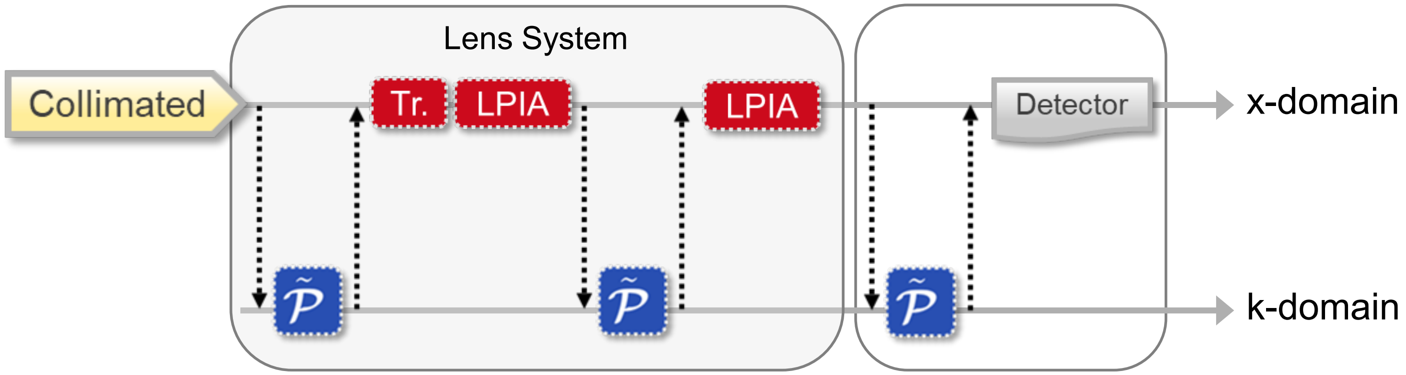


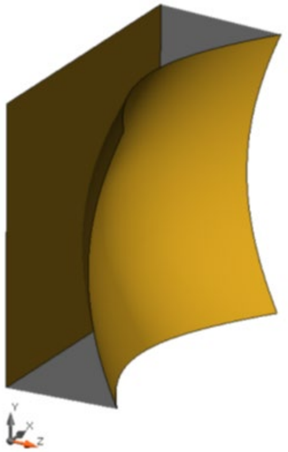


Scenario: Freeform Design for Irradiance Shaping

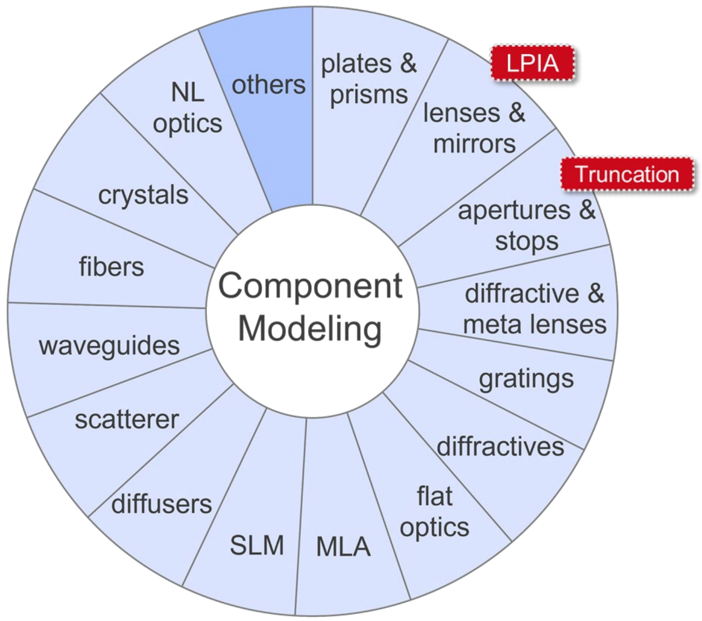


Freeform Design for Irradiance Shaping: Pointwise Design

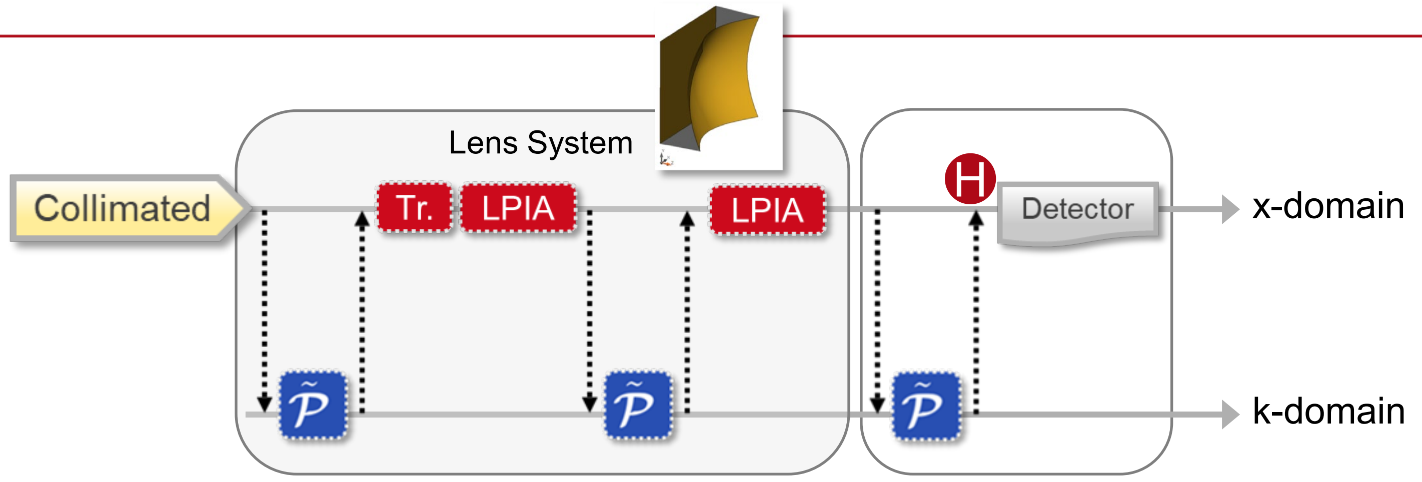


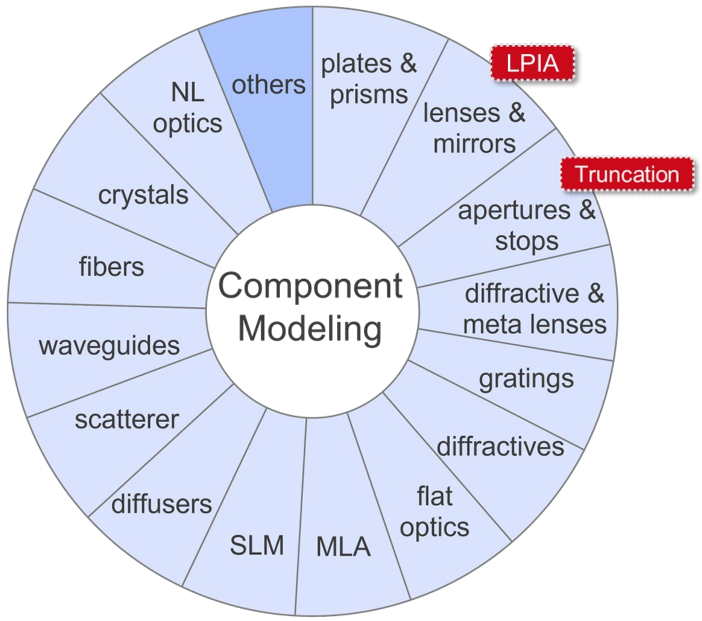


Design method is based on pointwise Fourier transform.

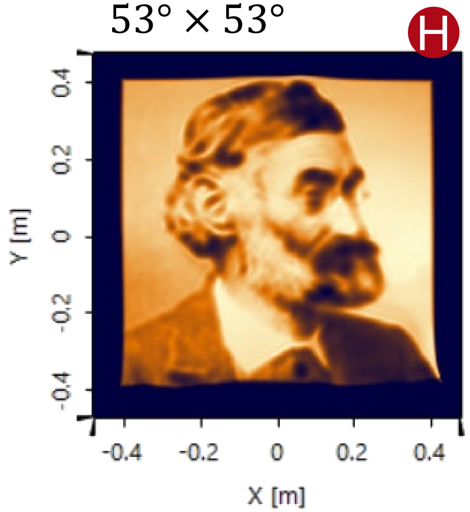


Freeform Design for Irradiance Shaping: Pointwise Modeling

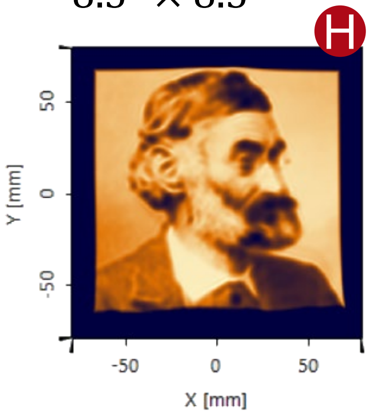




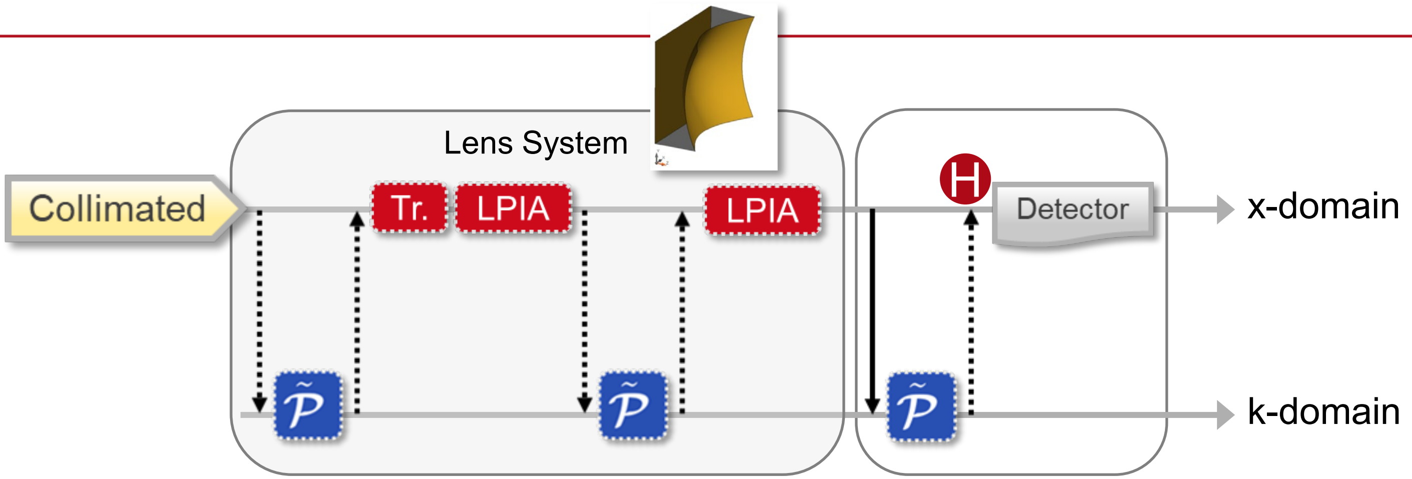
Divergent angle:
53° × 53°

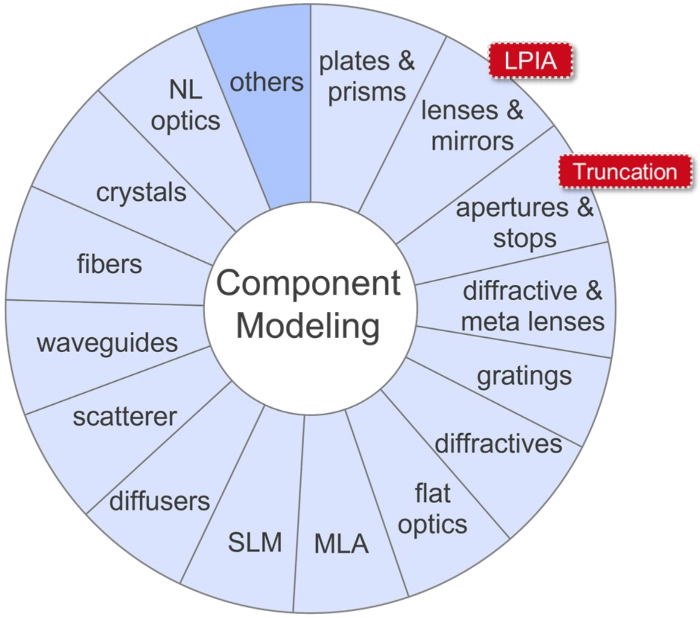


Divergent angle:
8.5° × 8.5°

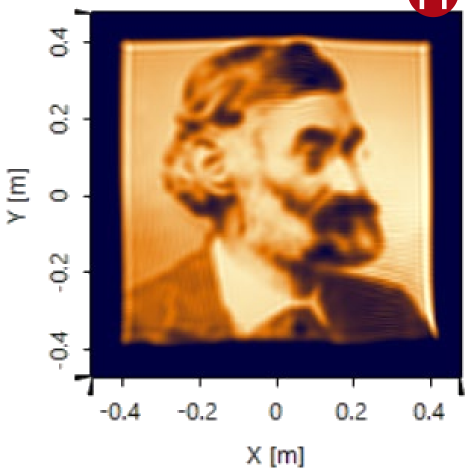


Freeform Design for Irradiance Shaping: Integral Modeling

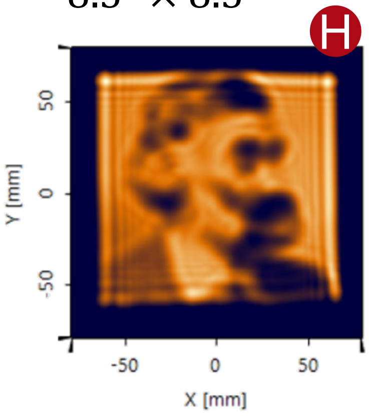




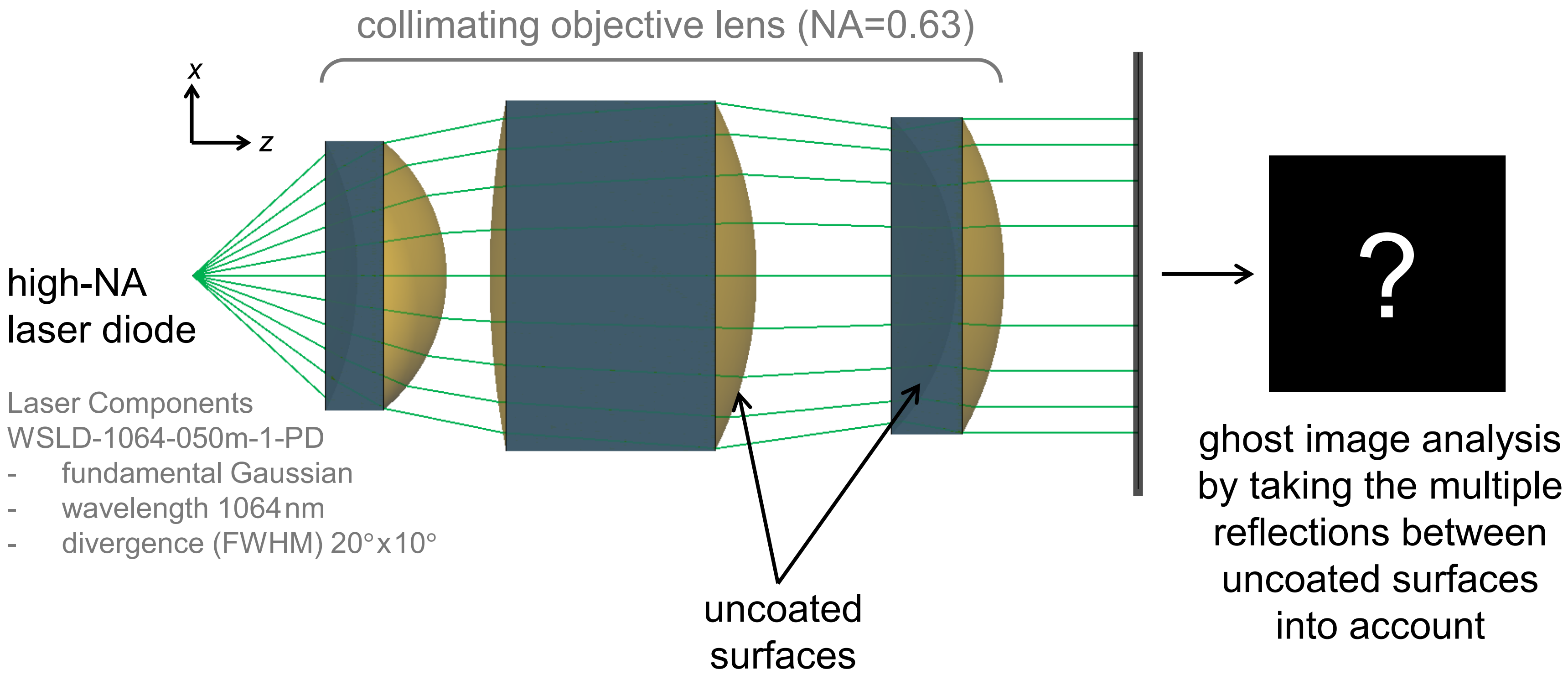
Divergent angle:
53° × 53°



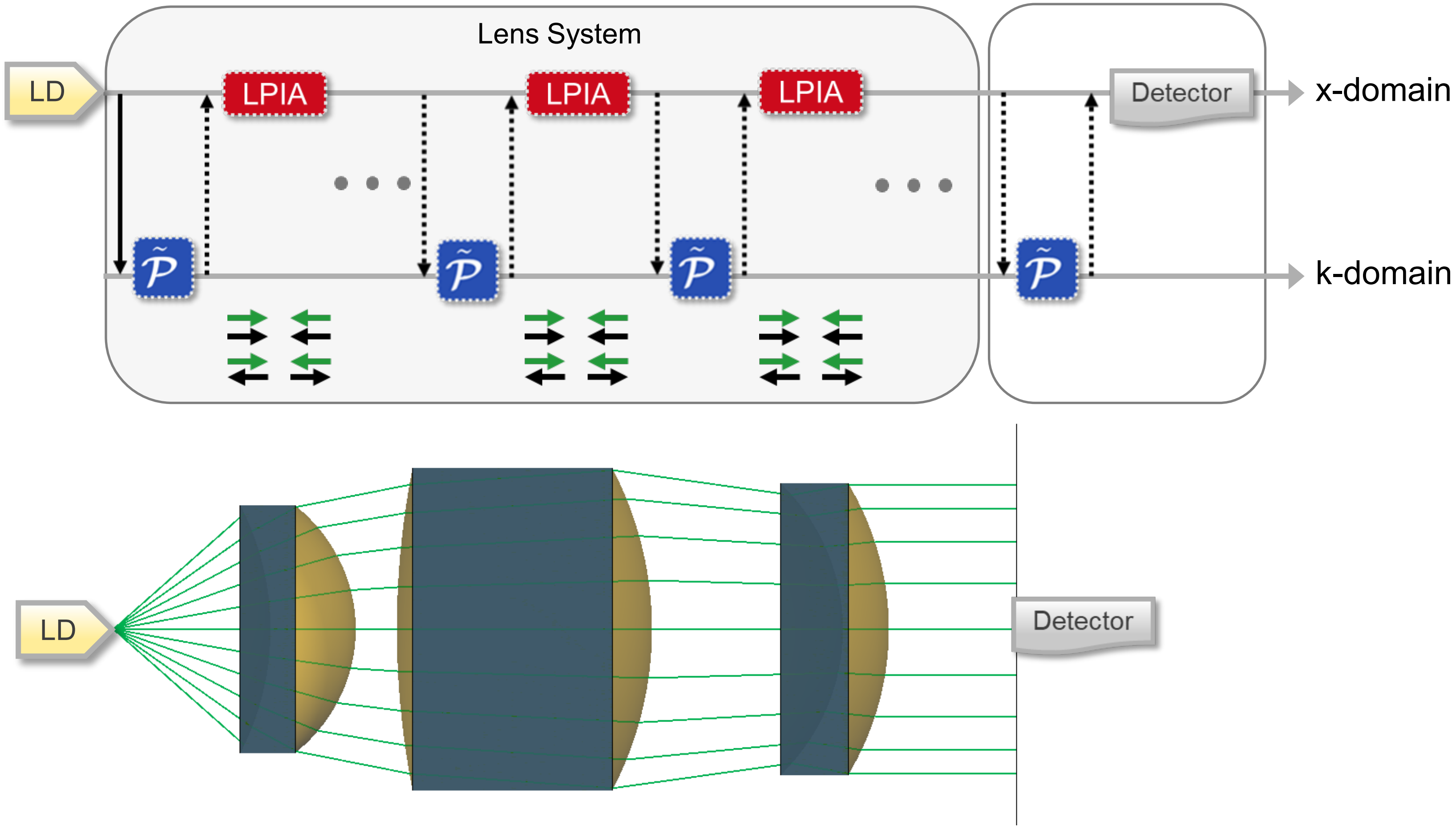
Divergent angle:
8.5° × 8.5°

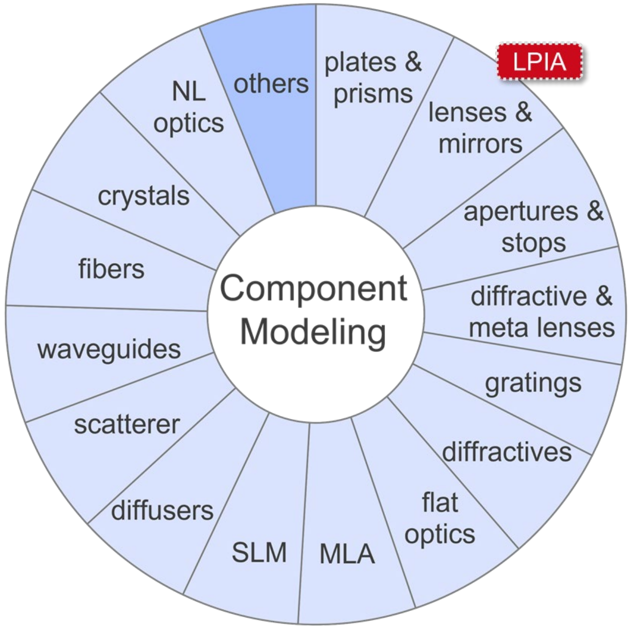


Scenario: Non-Sequential Lens System Modeling

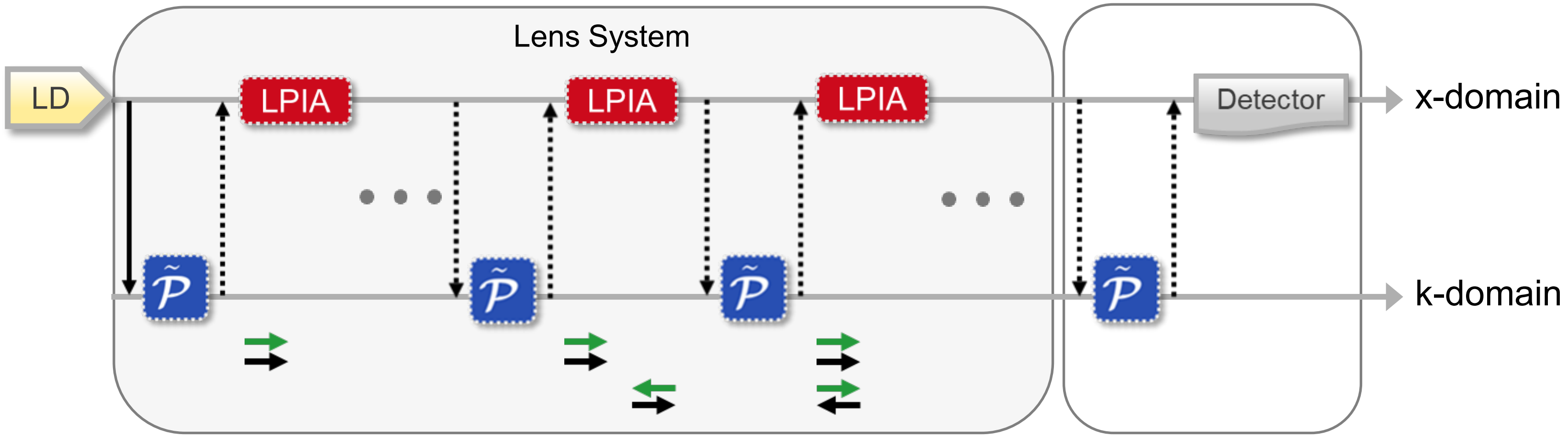


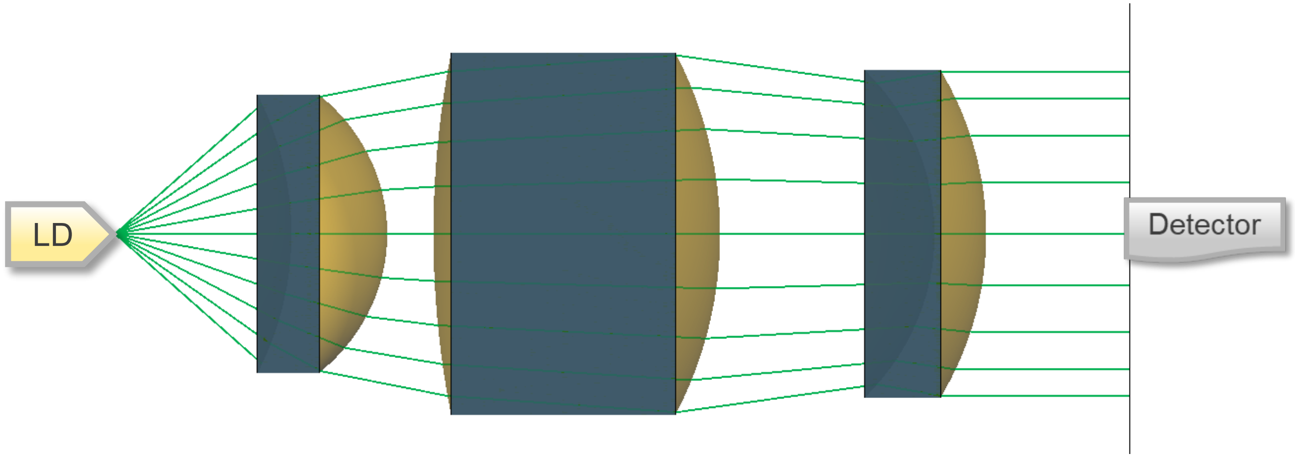
Scenario: Non-Sequential Lens System Modeling



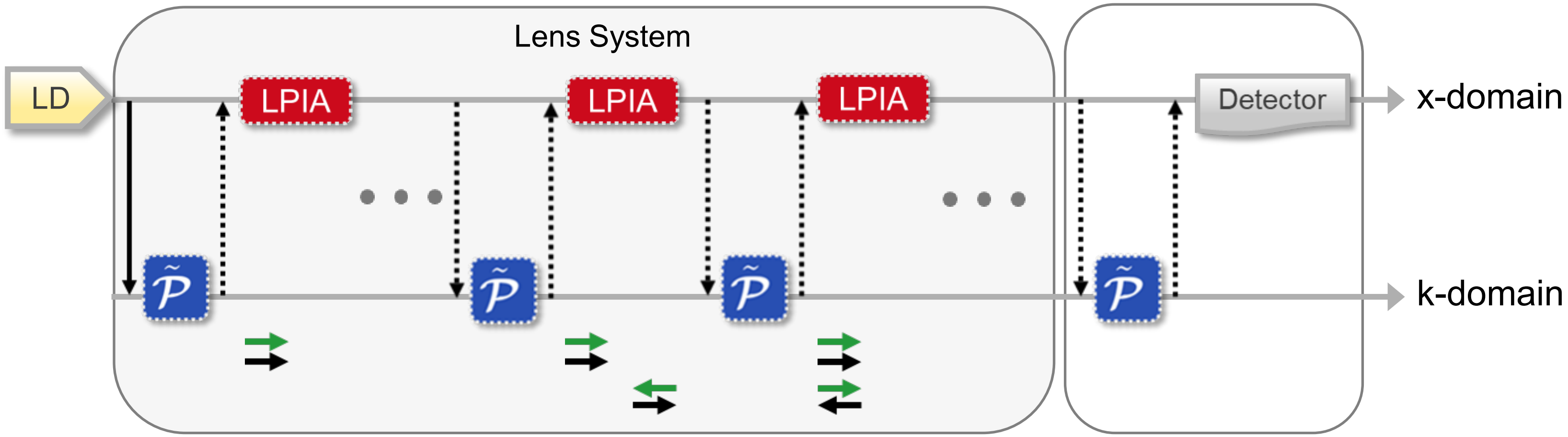


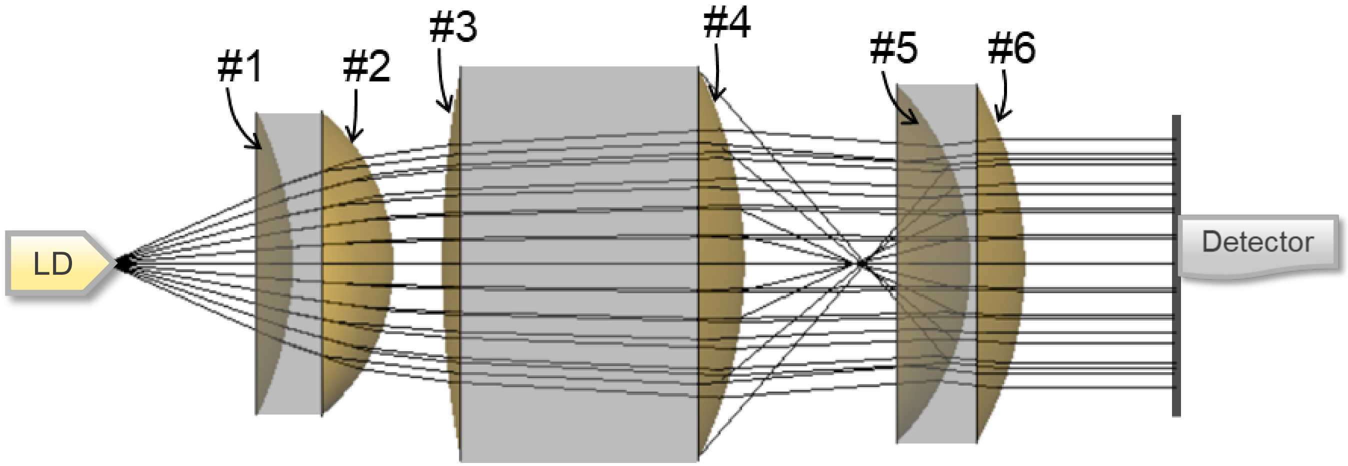
Scenario: Non-Sequential Lens System Modeling





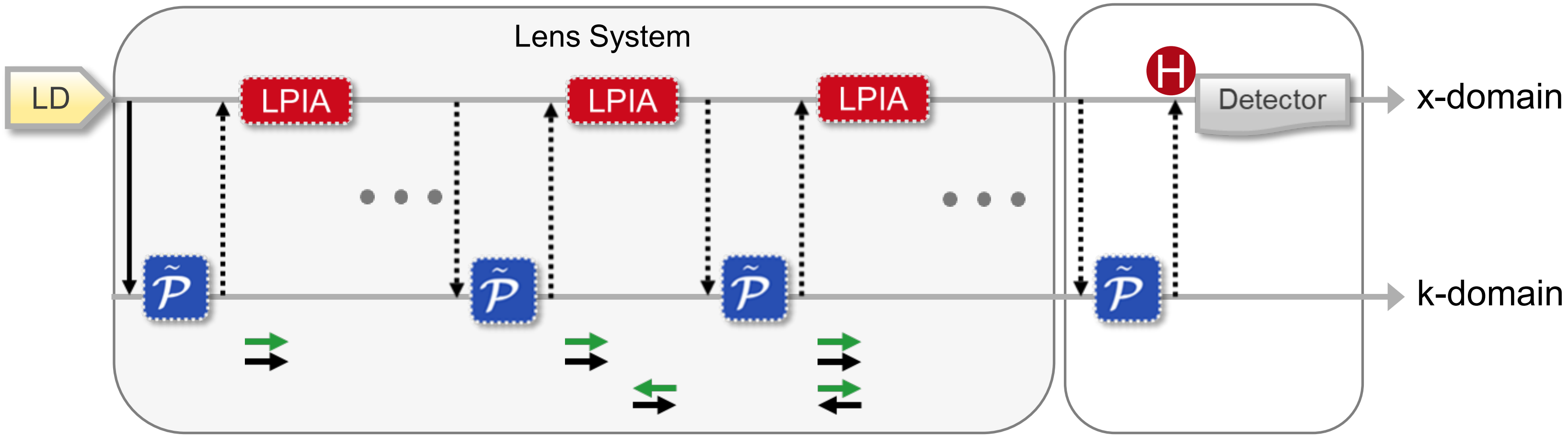
Scenario: Non-Sequential Lens System Modeling

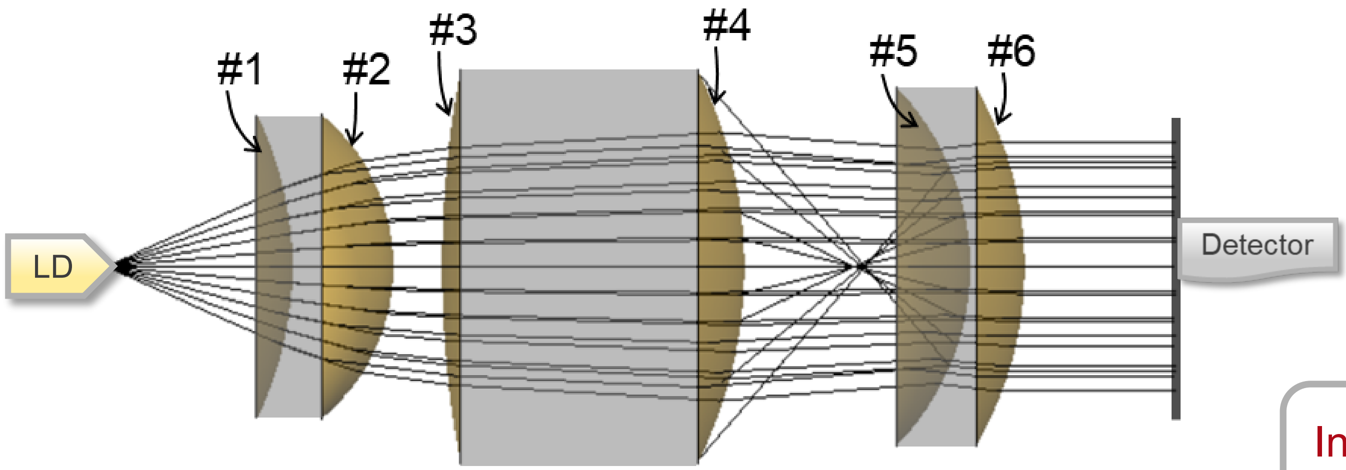




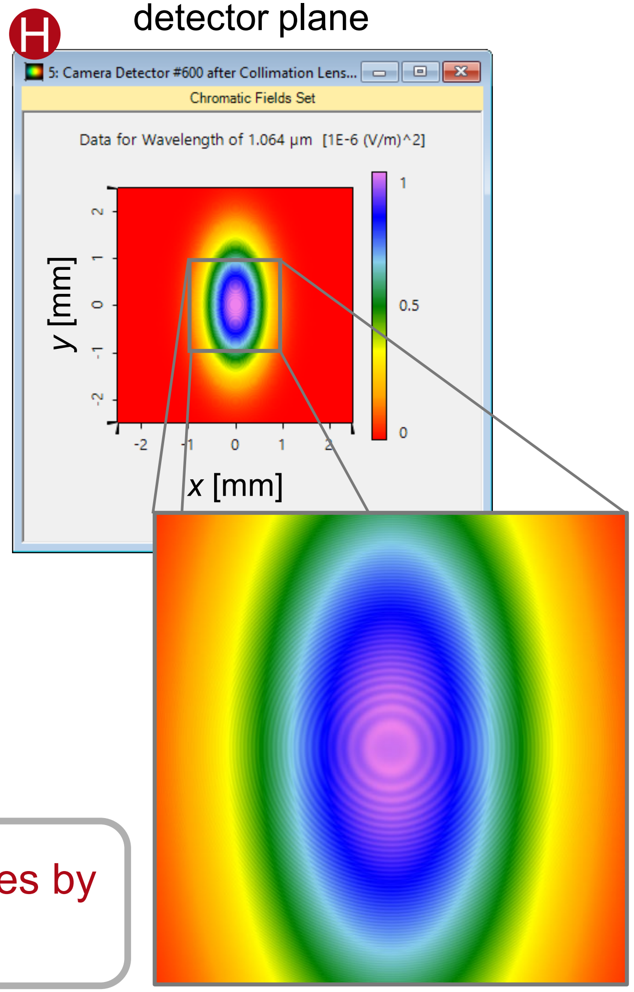
	#1	#2	#3	#4	#5	#6
+/+	√	√	√	√	√	√
+/-					√	
-/-						
-/+				√		

Scenario: Non-Sequential Lens System Modeling



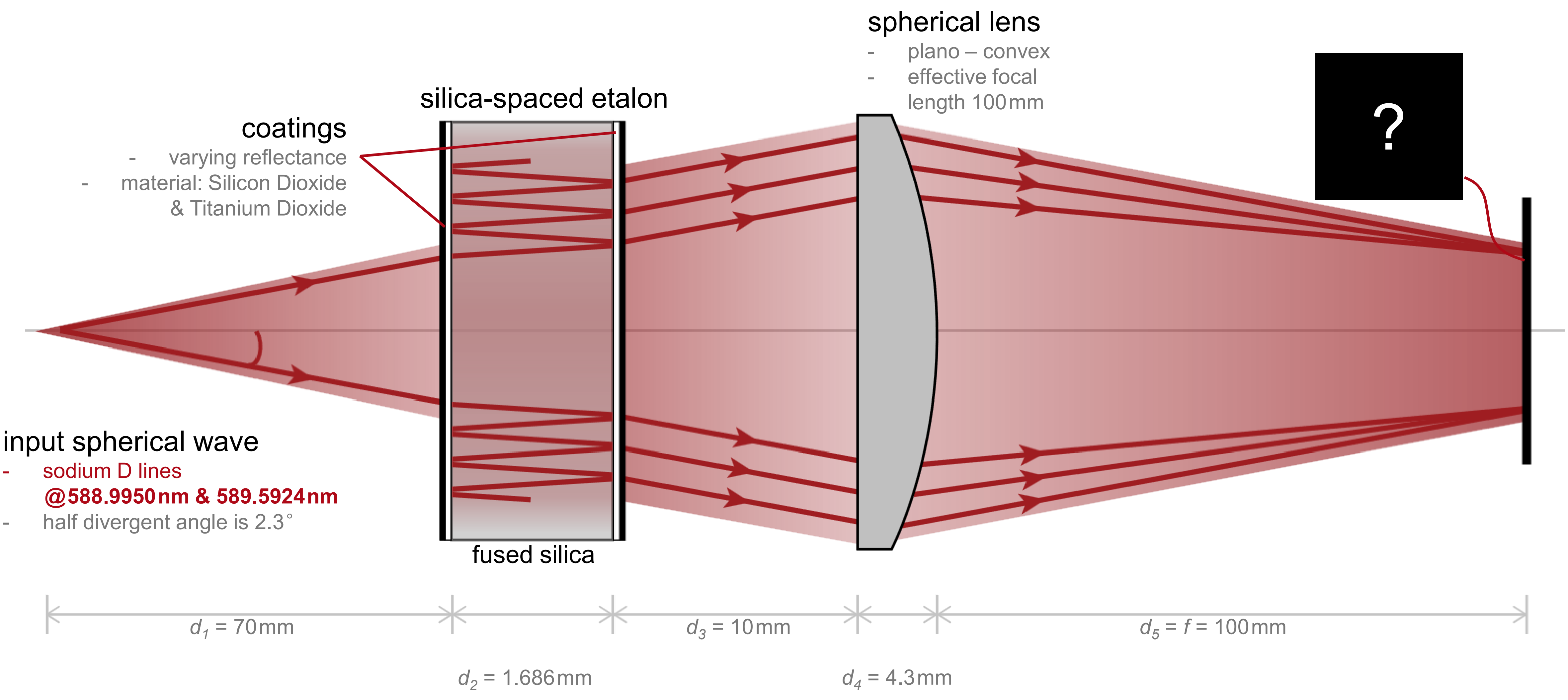


Amplitude on detector plane

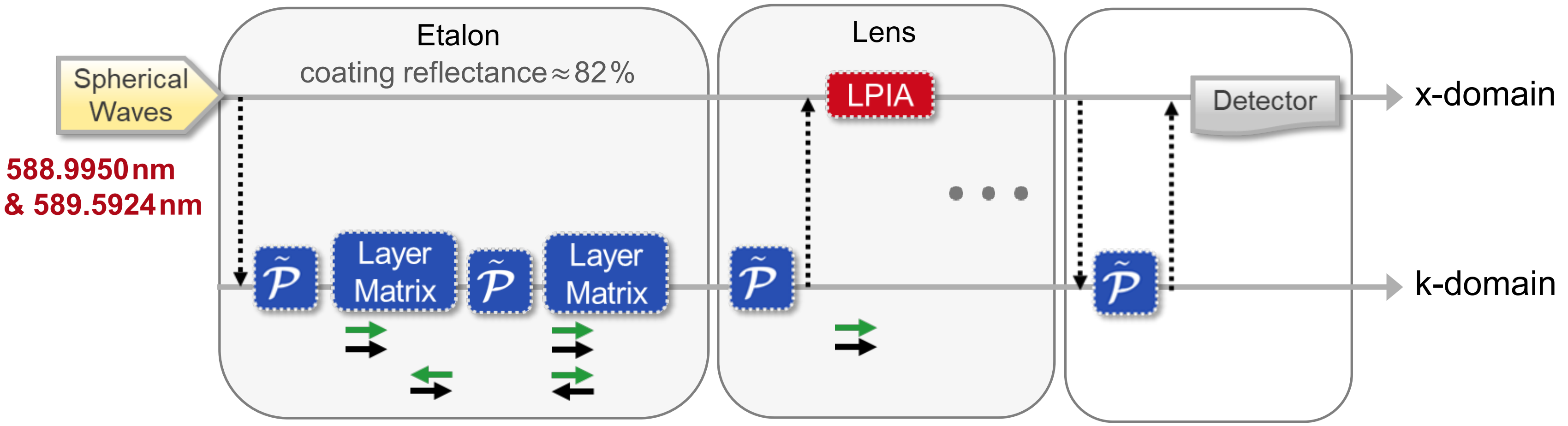


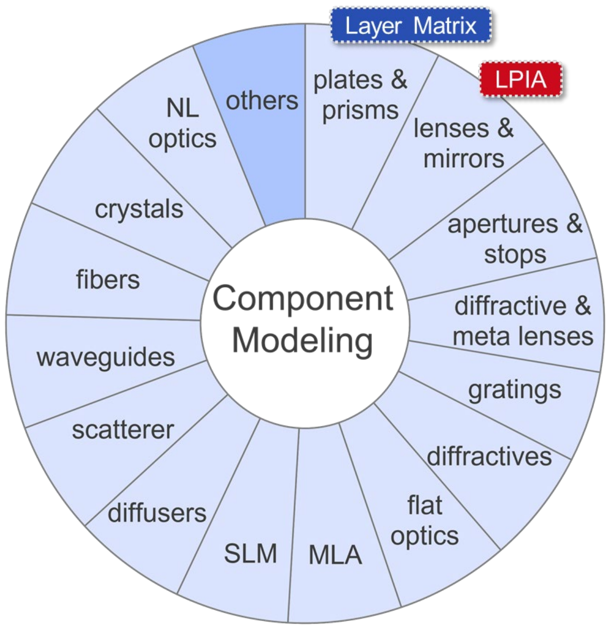
Interference of two modes by internal reflection.

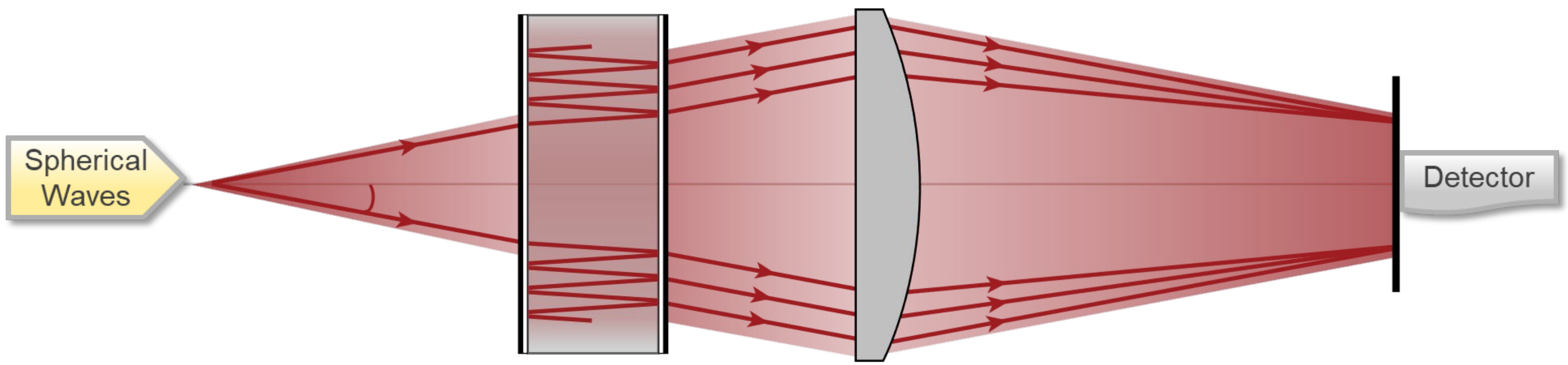
Scenario: Spectroscopic Investigation by Etalon



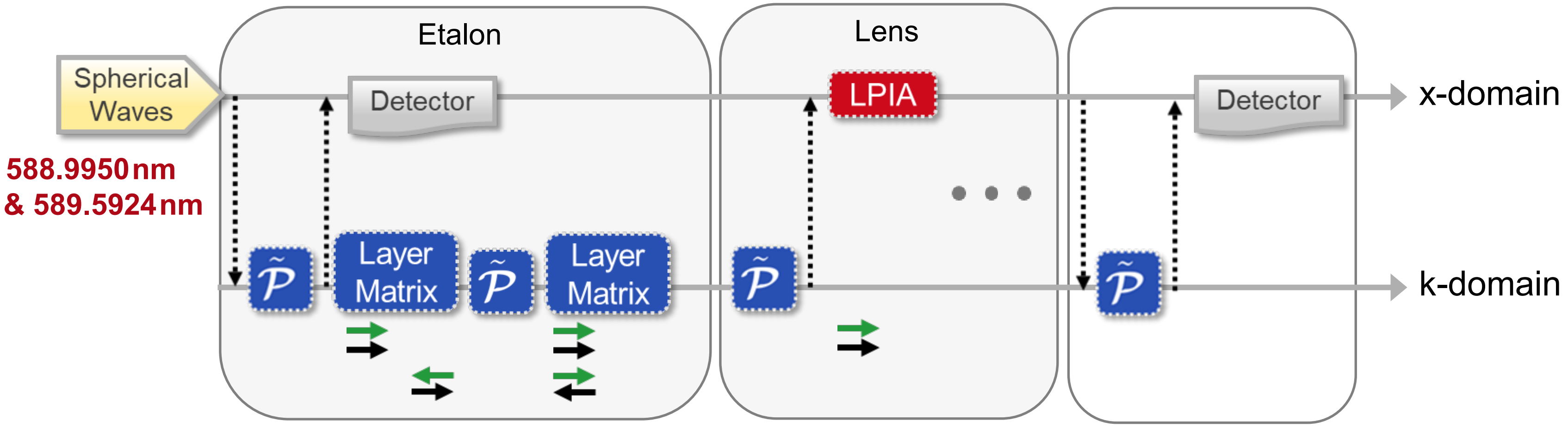
Non-Sequential Pointwise Modeling Etalon + Lens

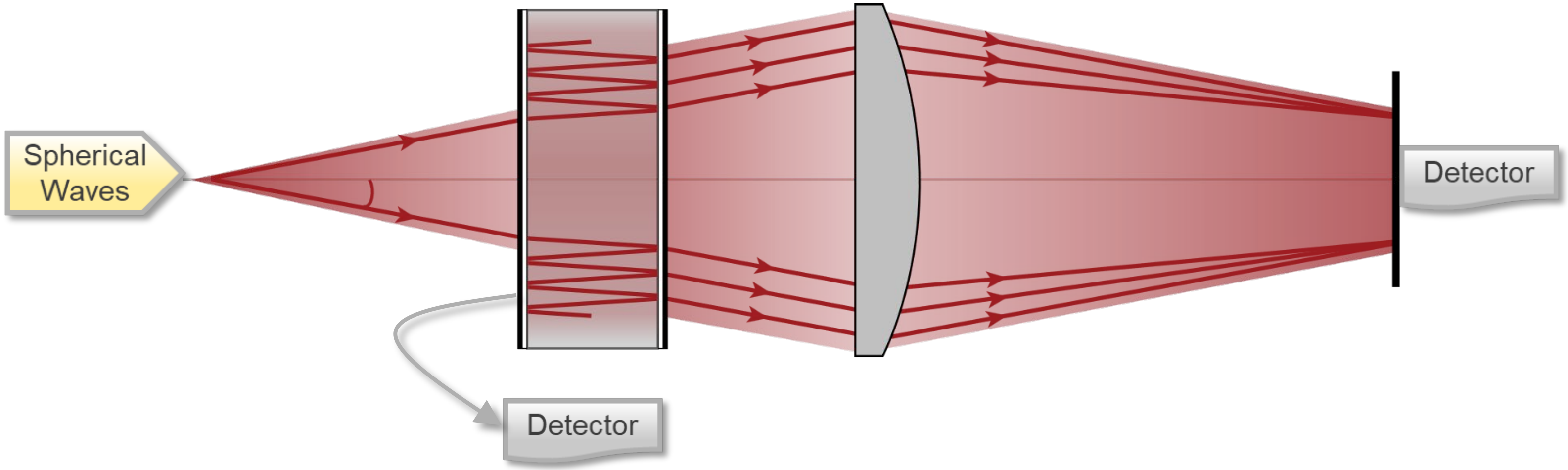




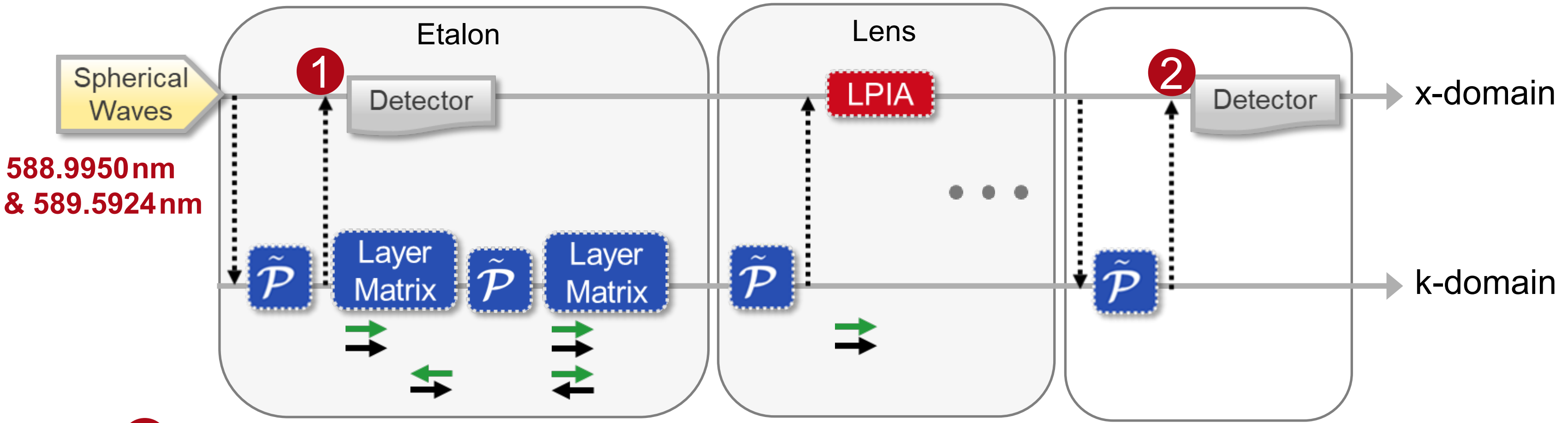


Non-Sequential Pointwise Modeling Etalon + Lens

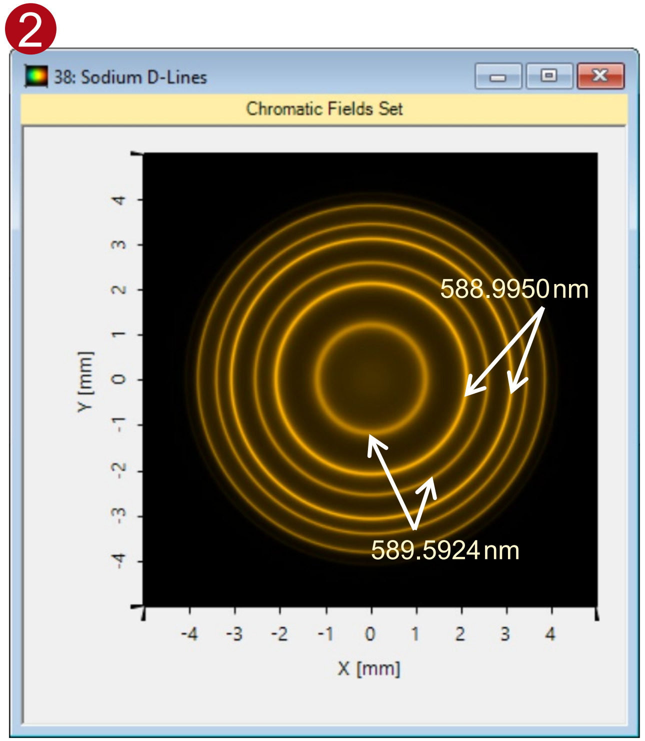


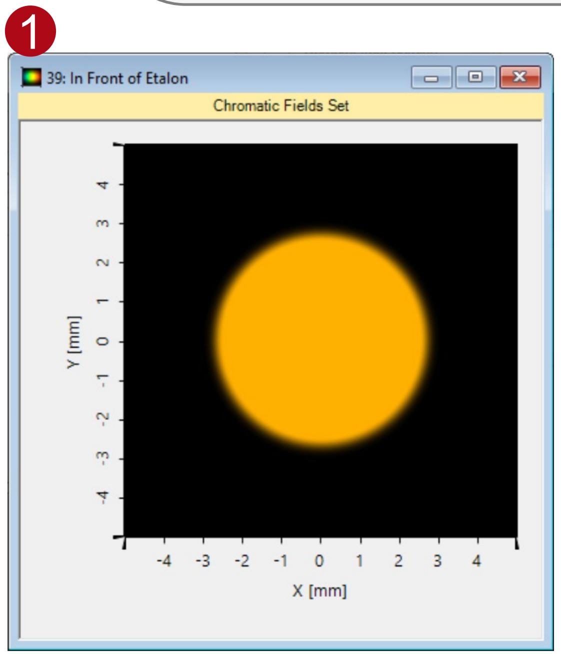


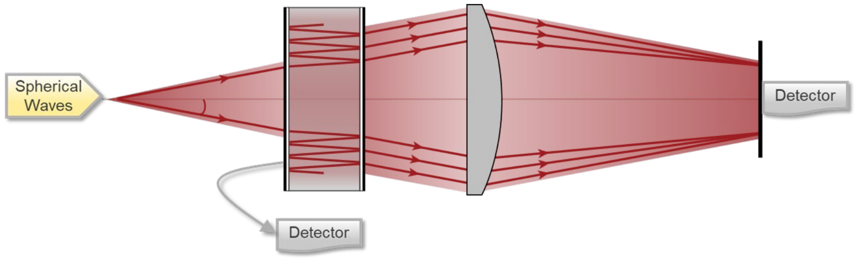
Non-Sequential Pointwise Modeling Etalon + Lens



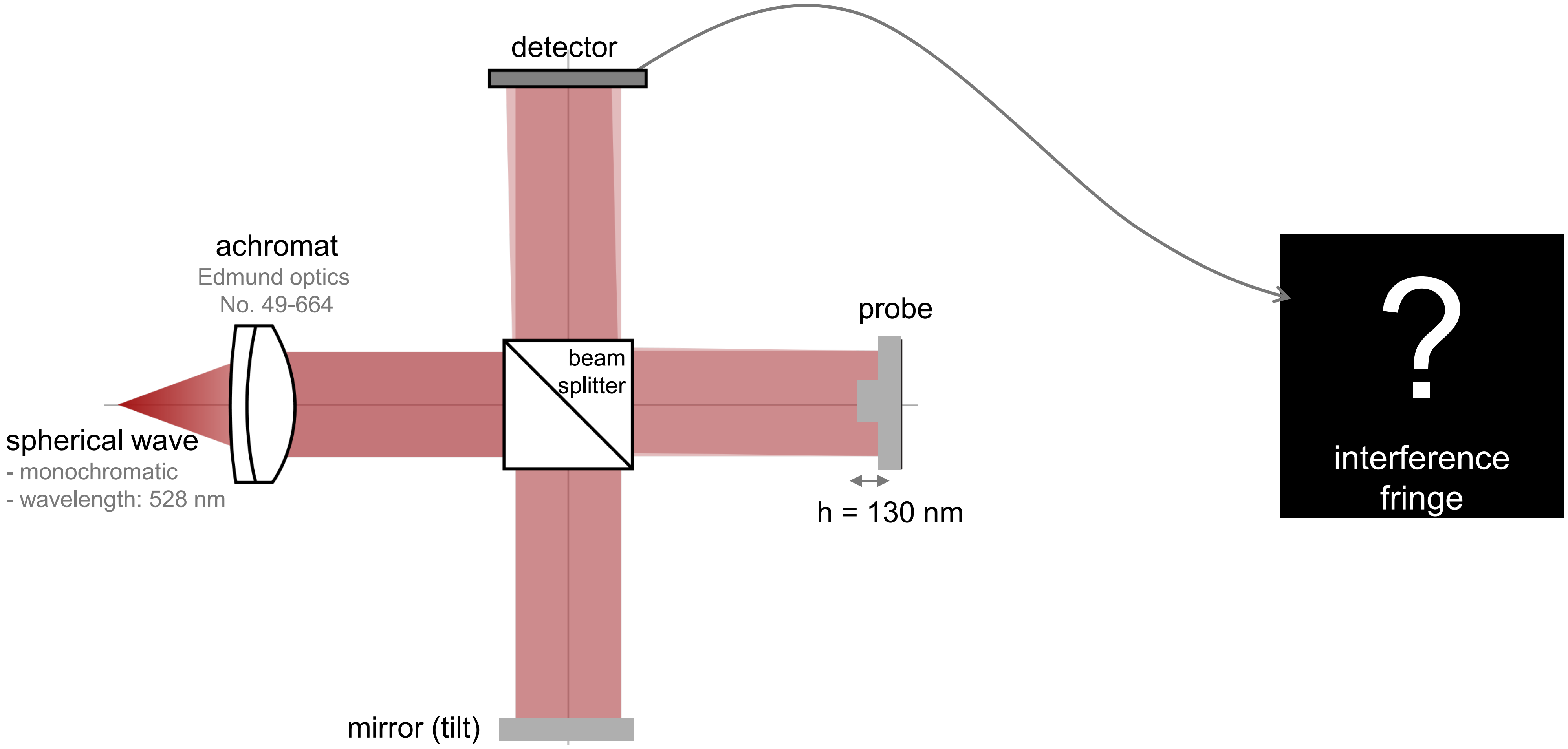
Interference of more than 10 modes by internal reflection.



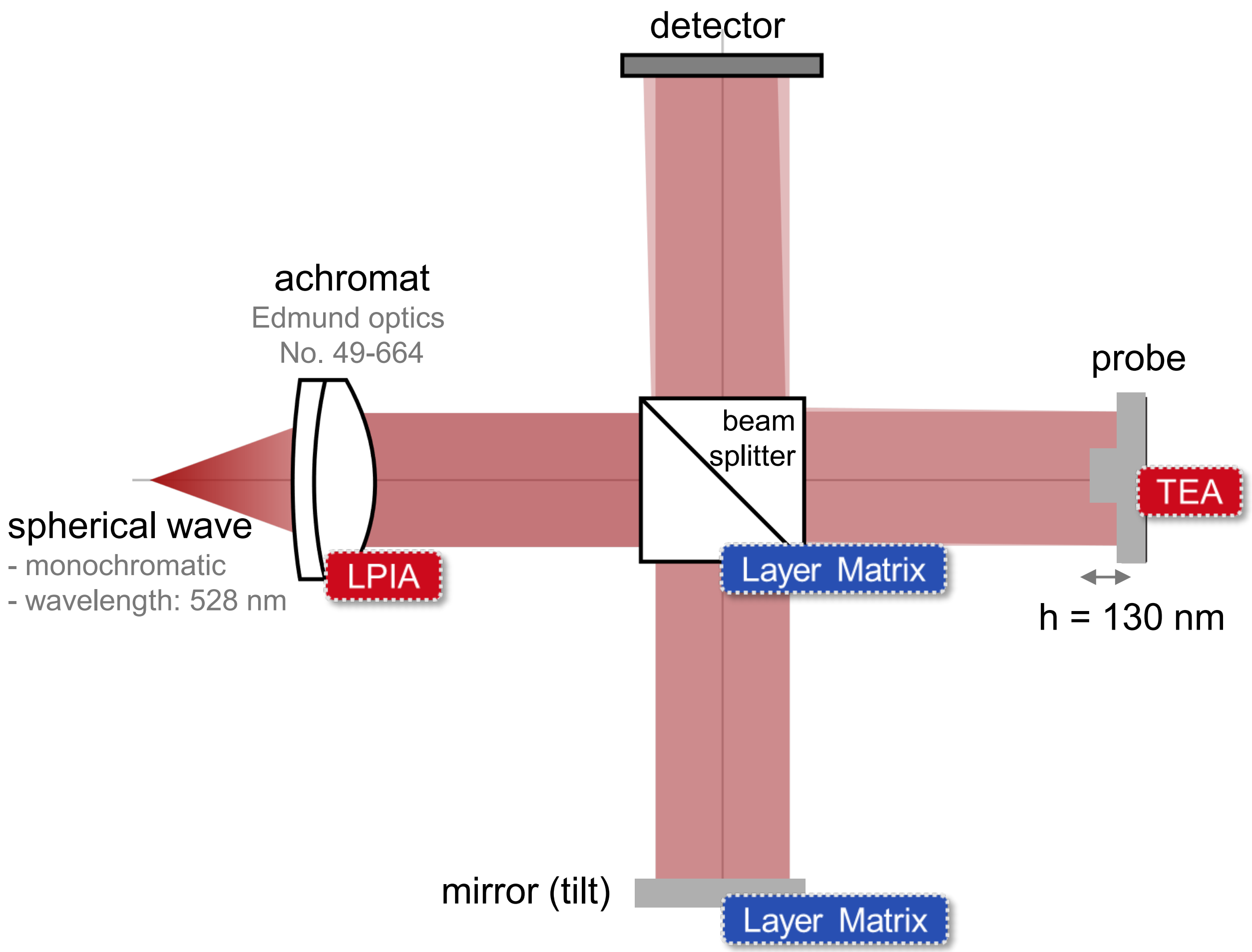


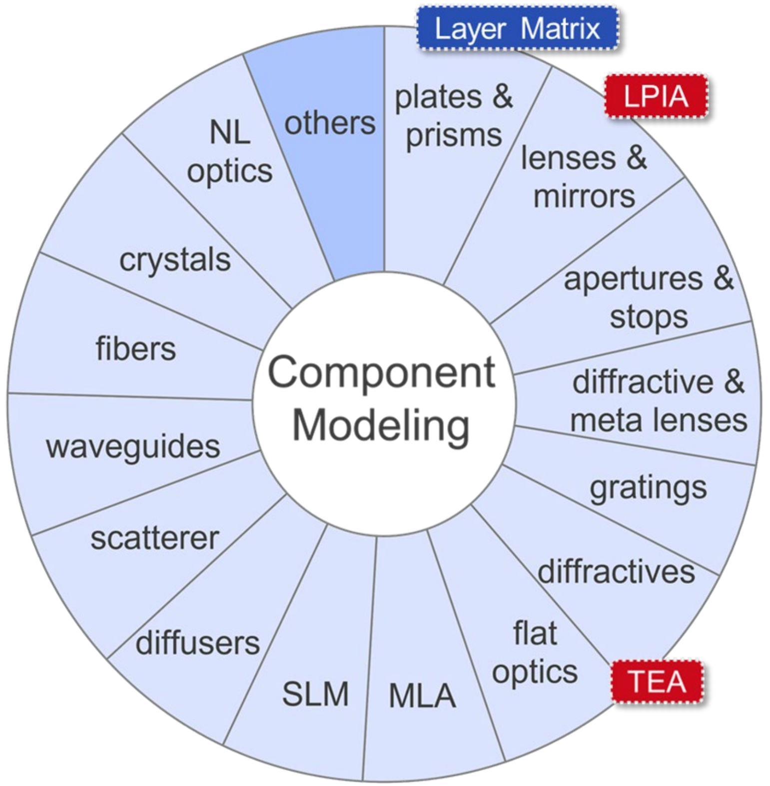


Scenario: Modeling Michelson Interferometer

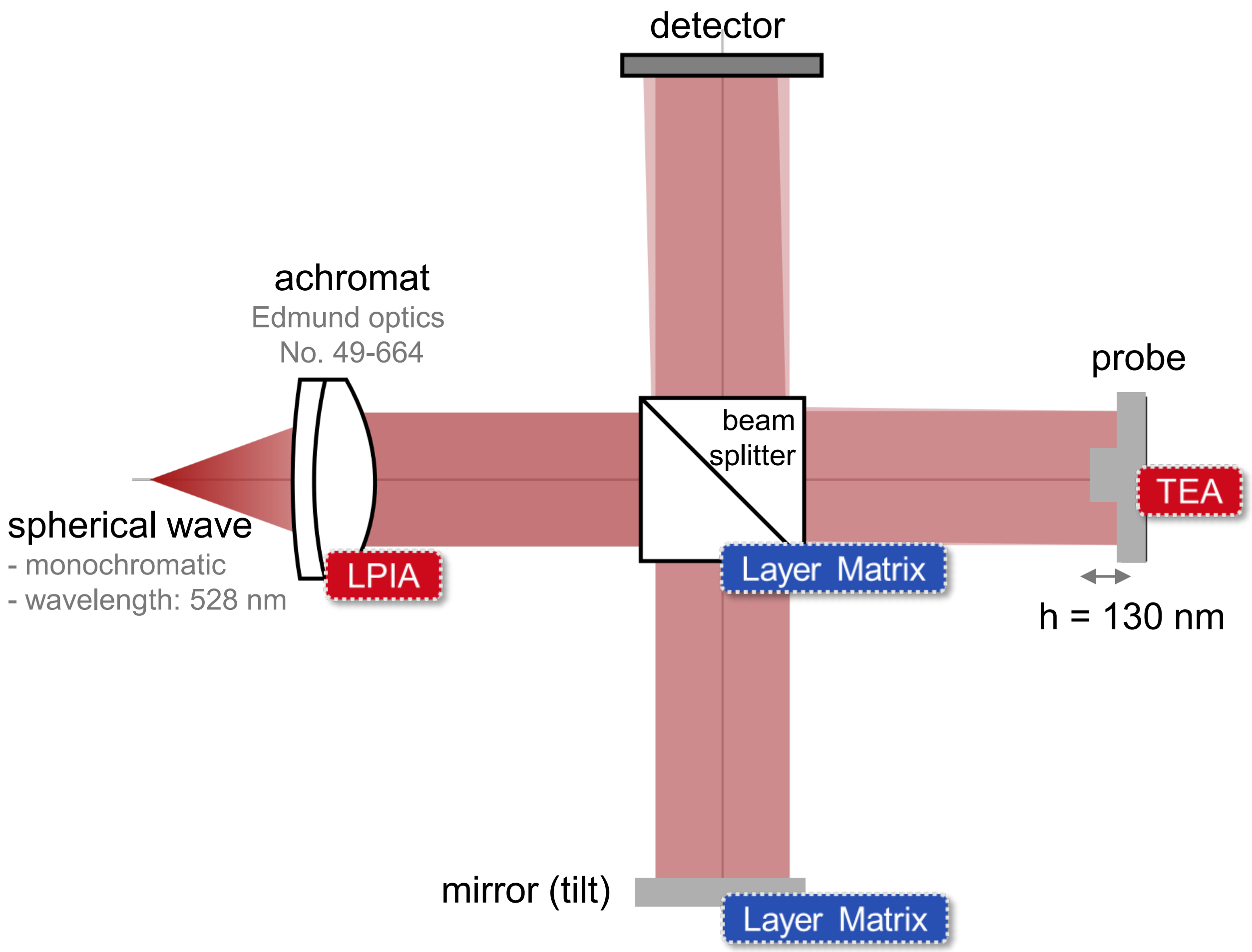


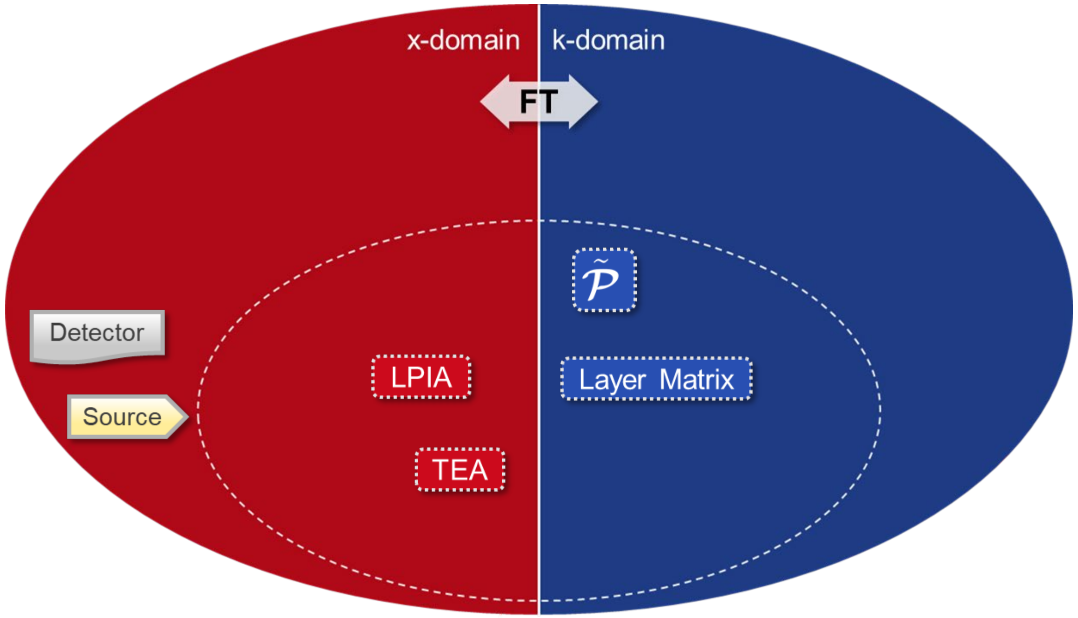
Modeling Michelson Interferometer



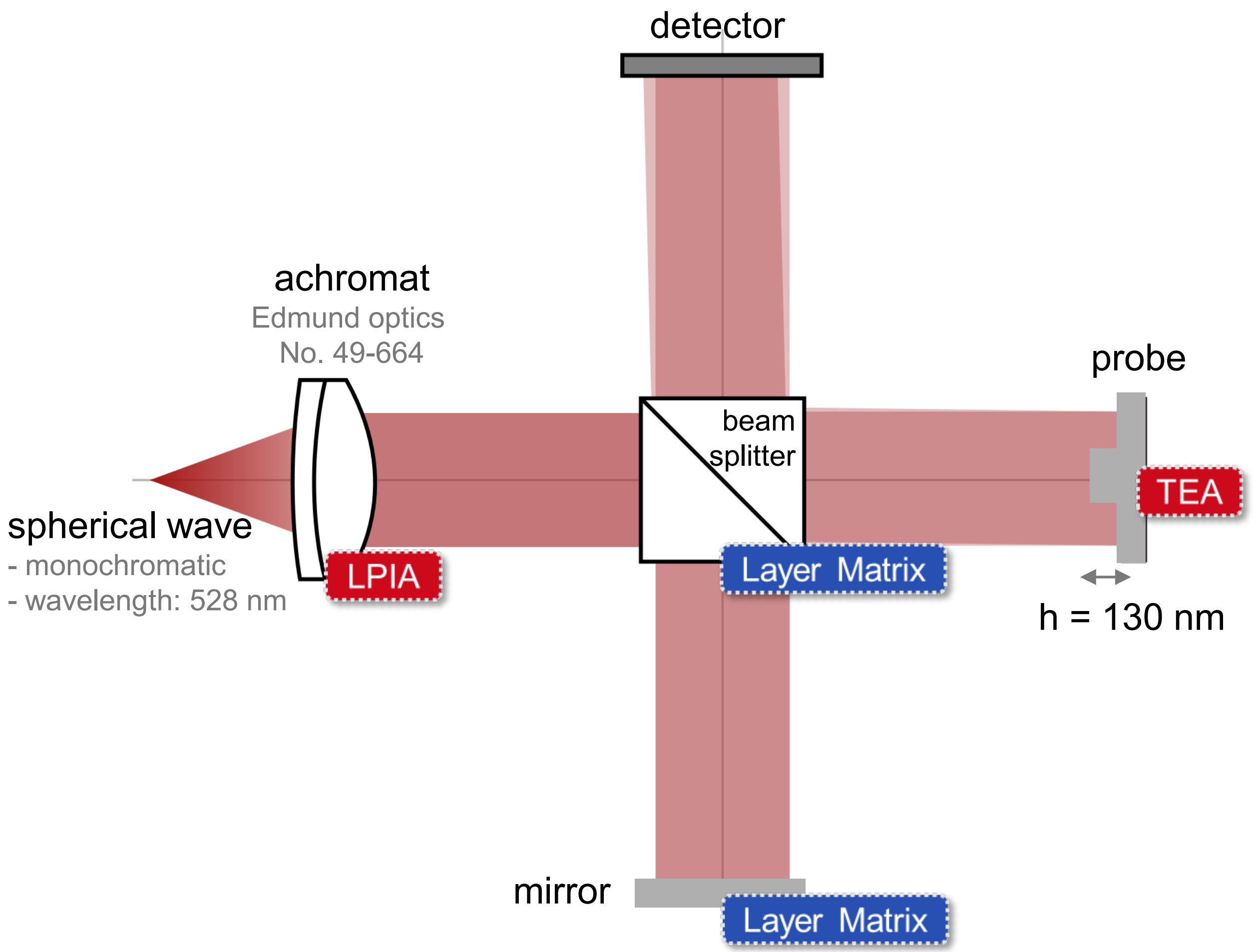


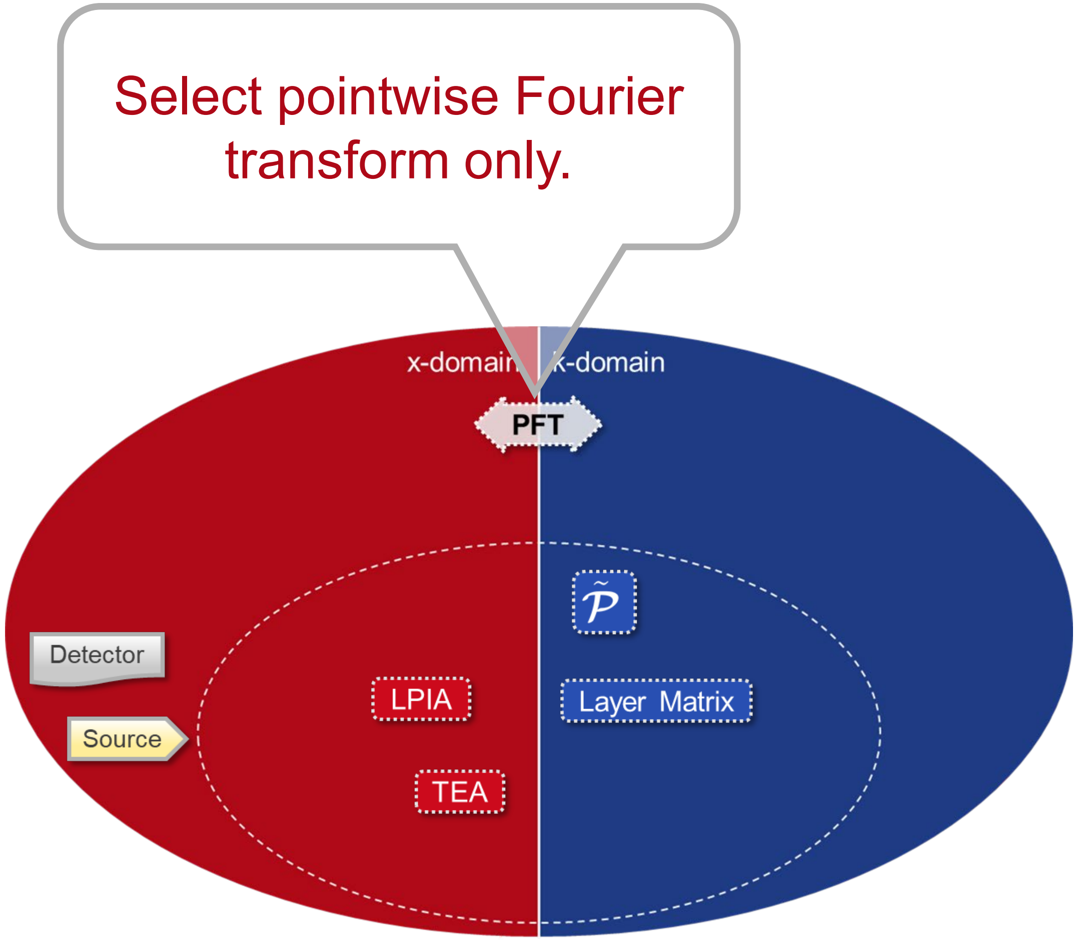
Modeling Michelson Interferometer



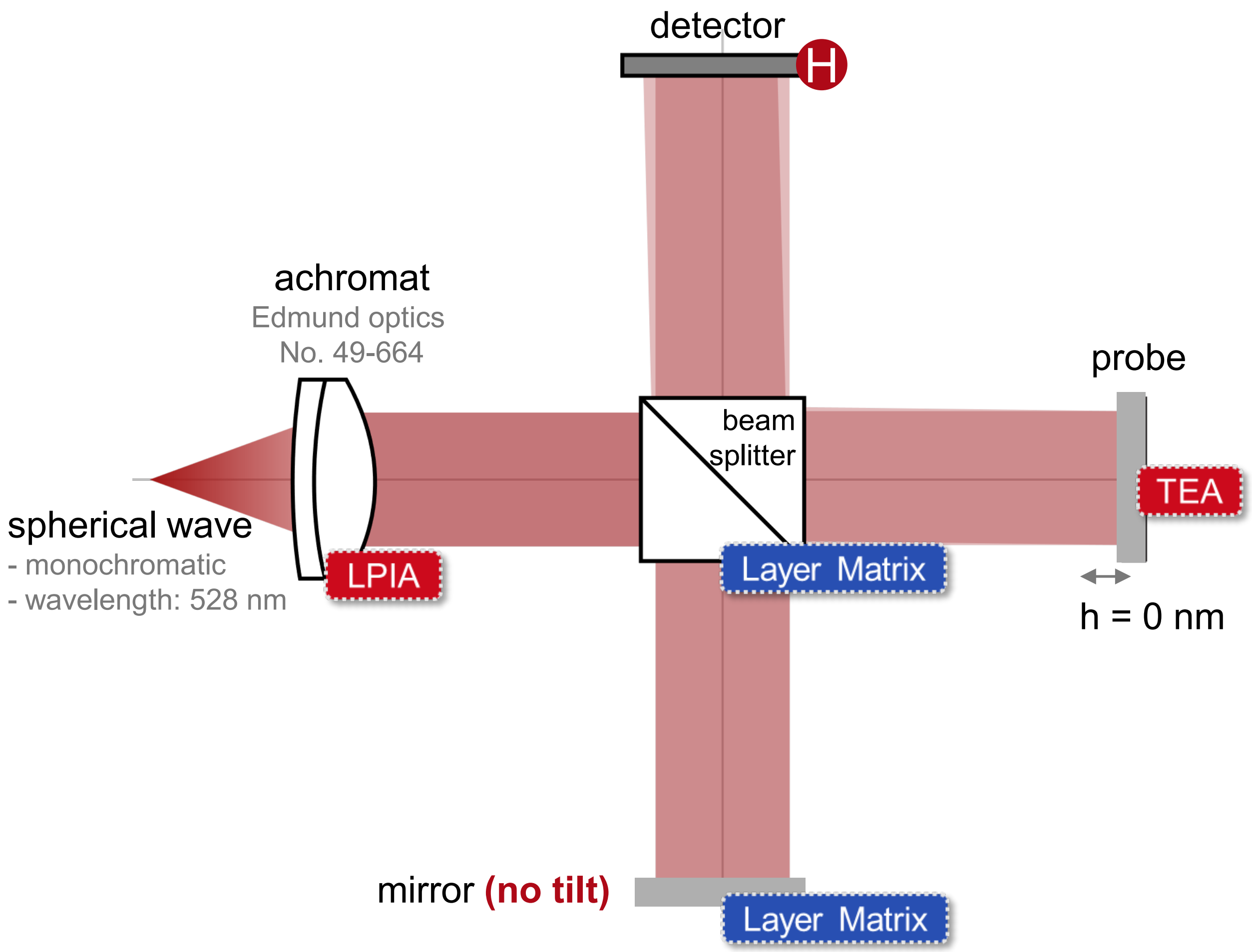


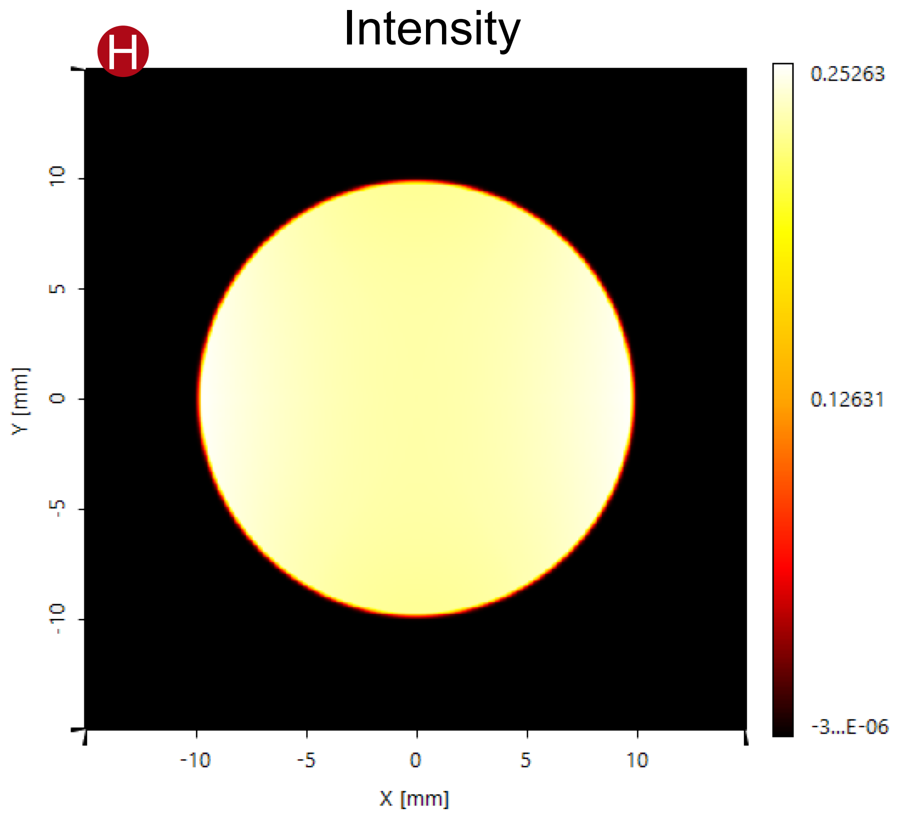
Modeling Michelson Interferometer: Pointwise



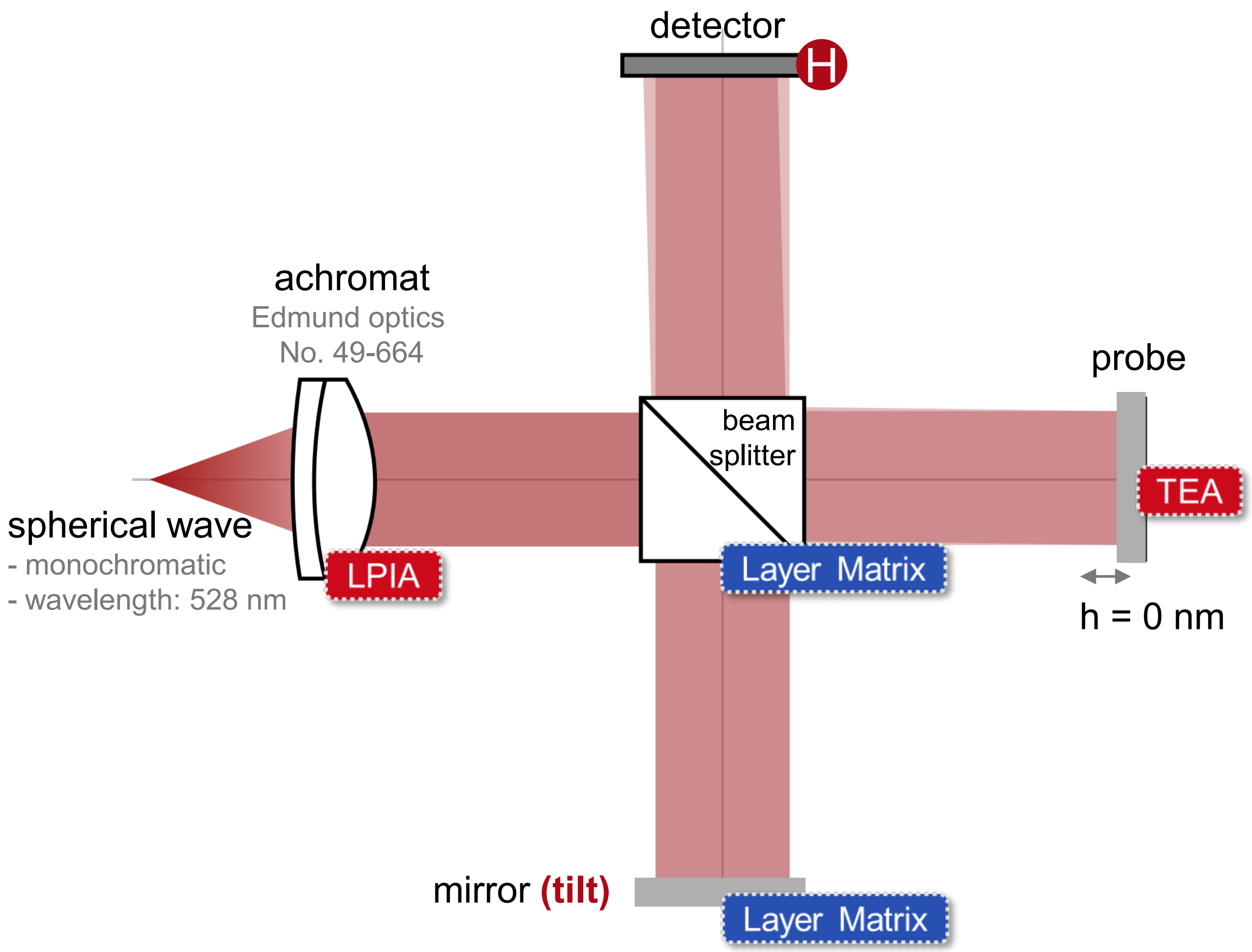


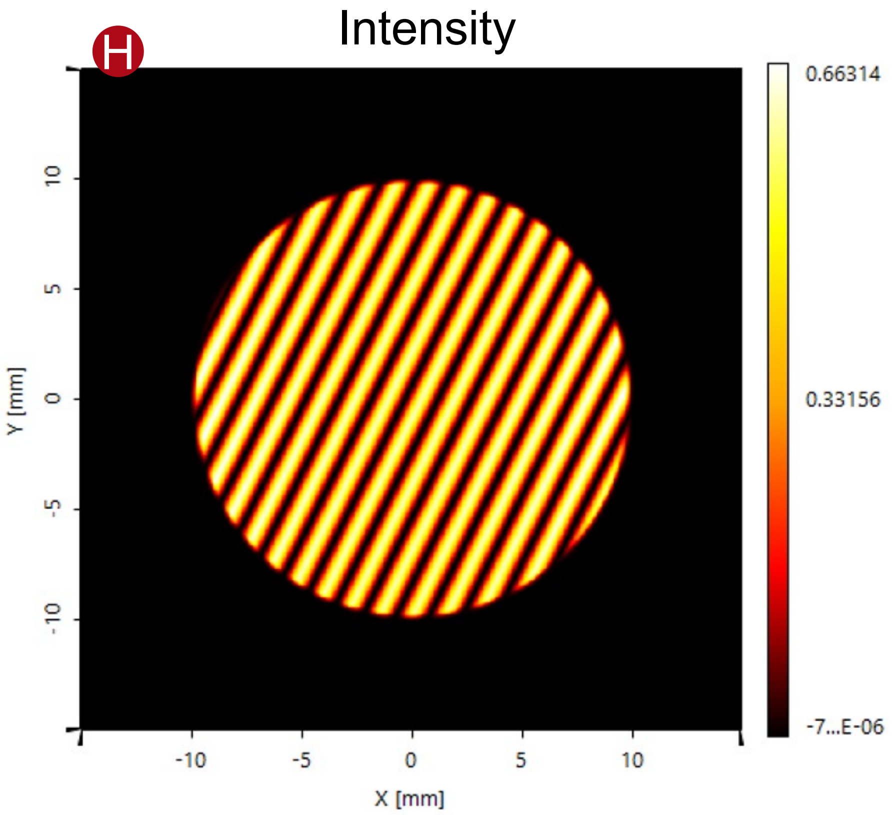
Modeling Michelson Interferometer: Pointwise



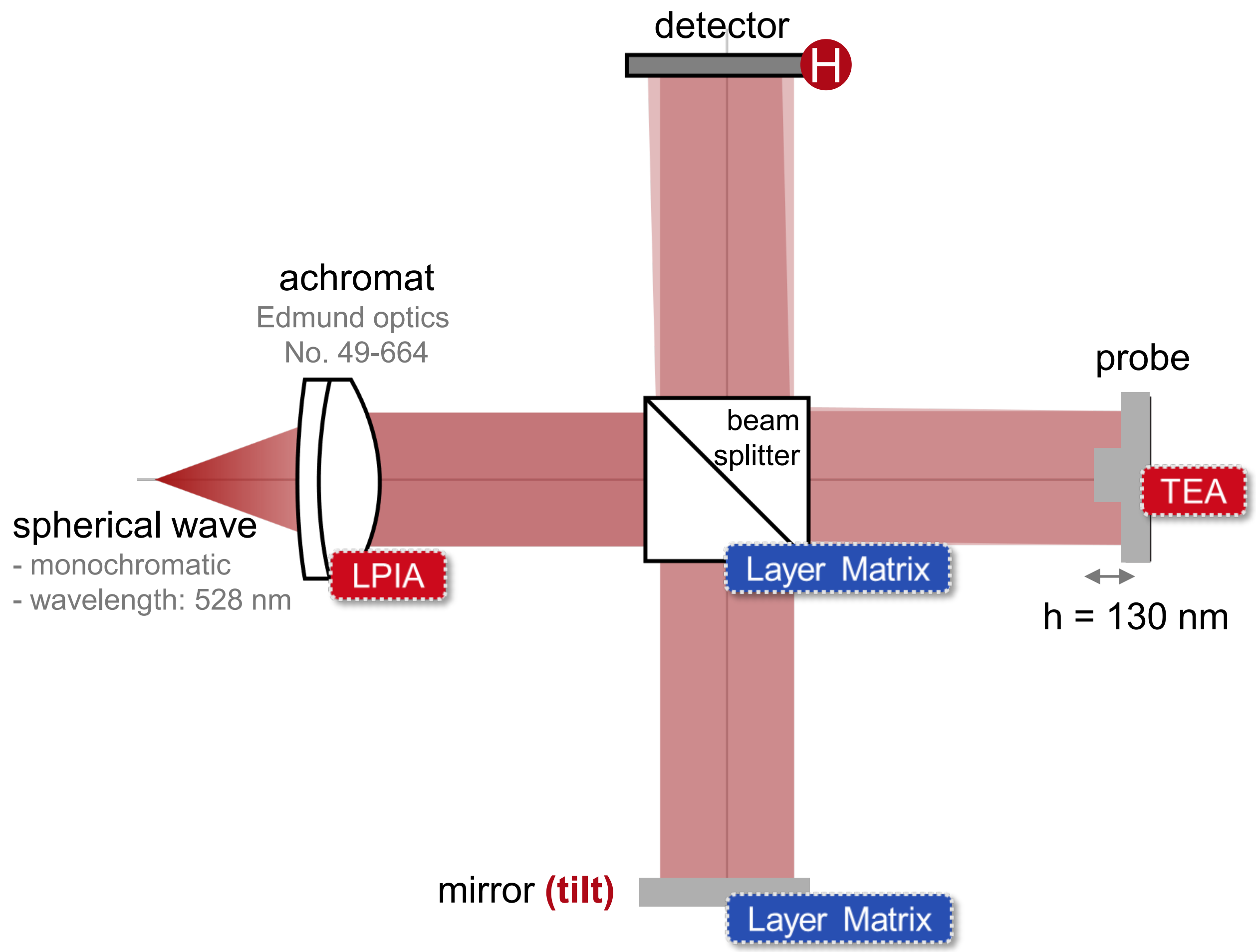


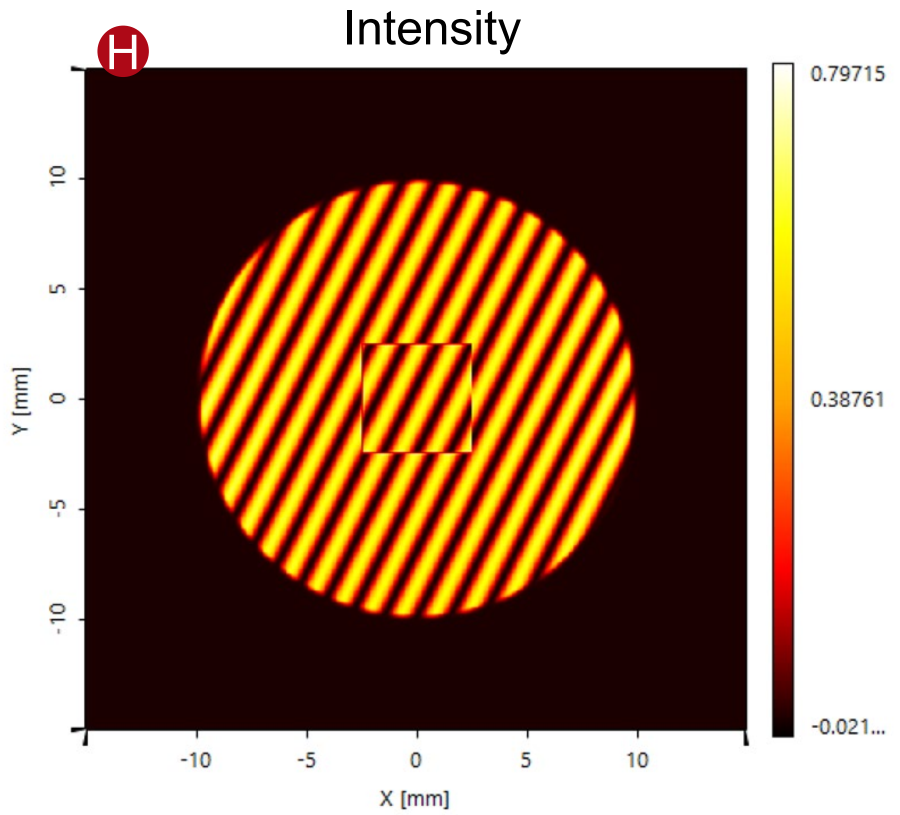
Modeling Michelson Interferometer: Pointwise



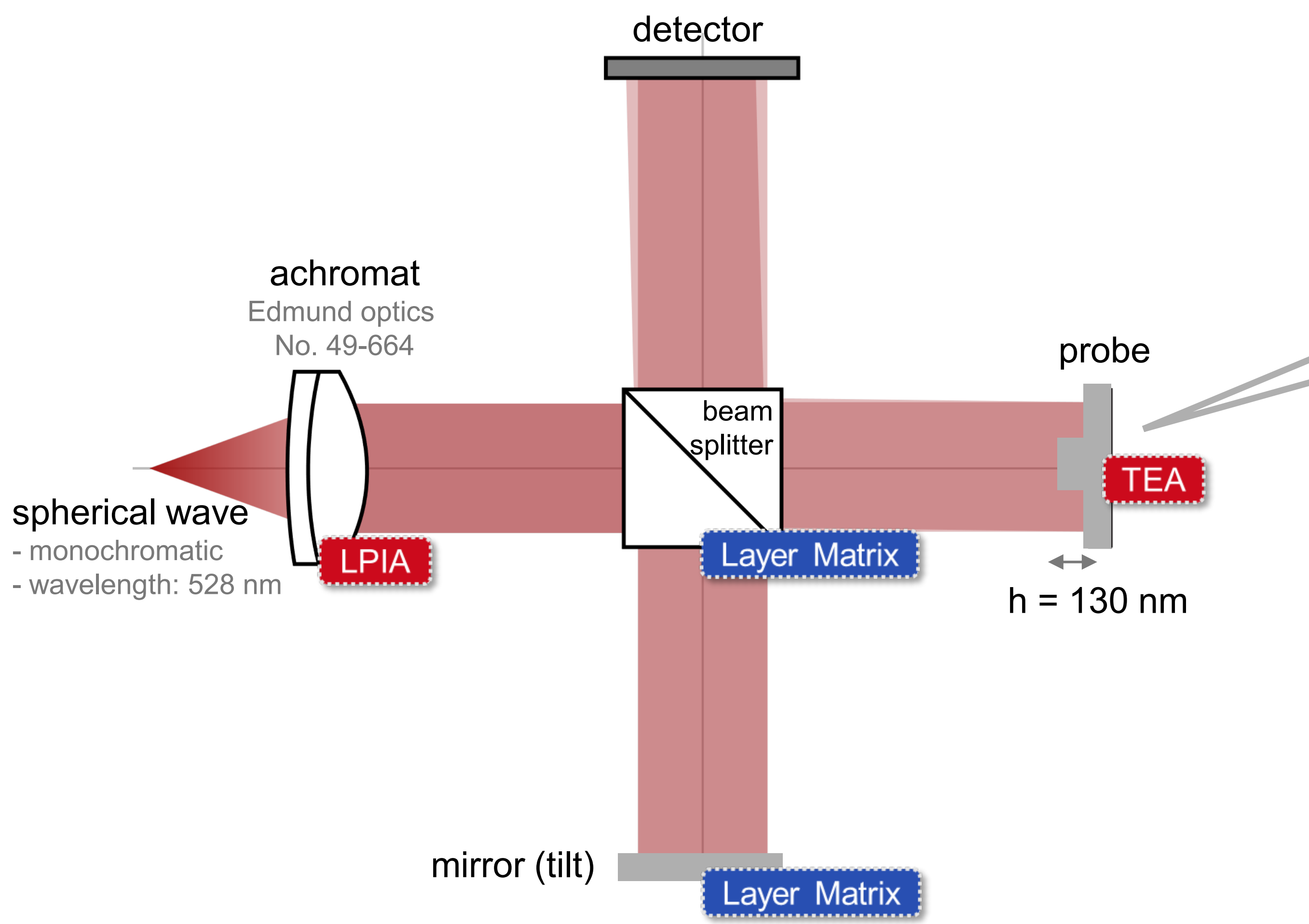


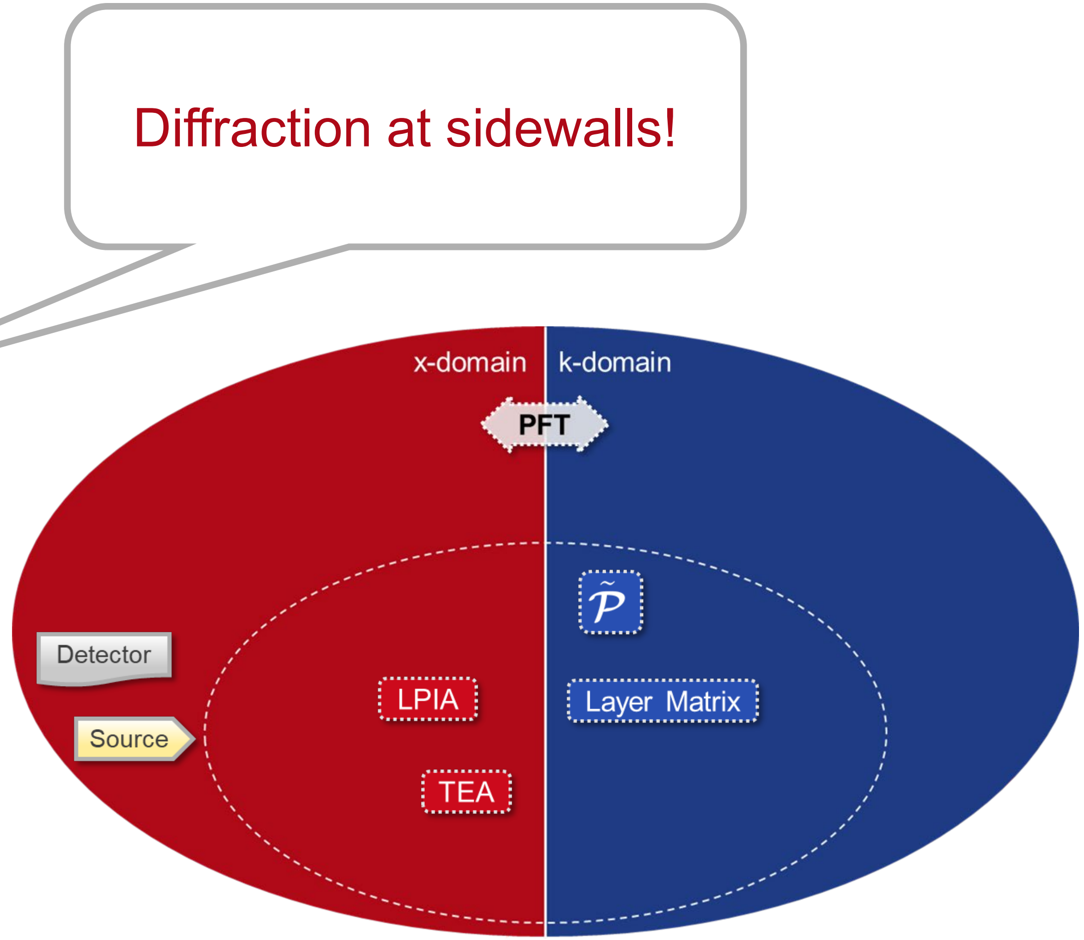
Modeling Michelson Interferometer: Pointwise



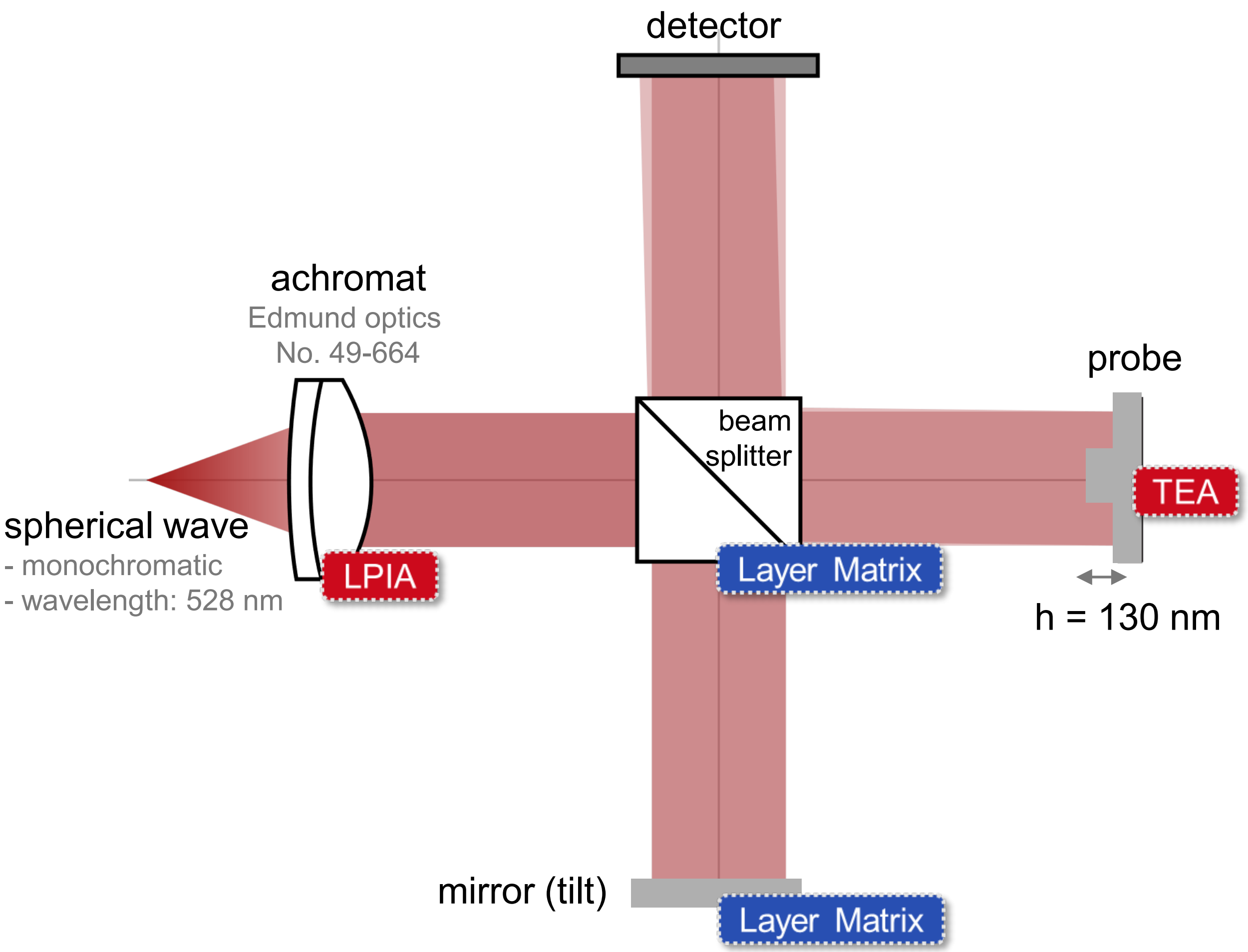


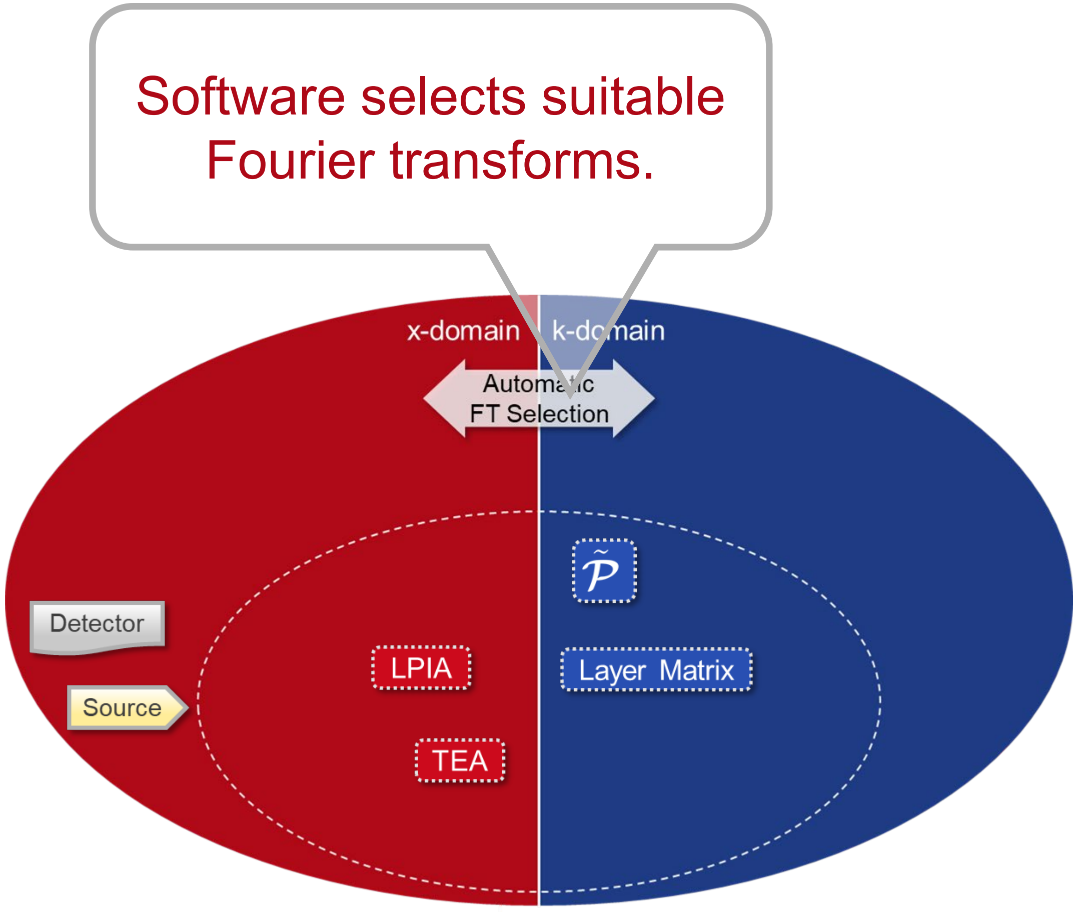
Modeling Michelson Interferometer: Pointwise



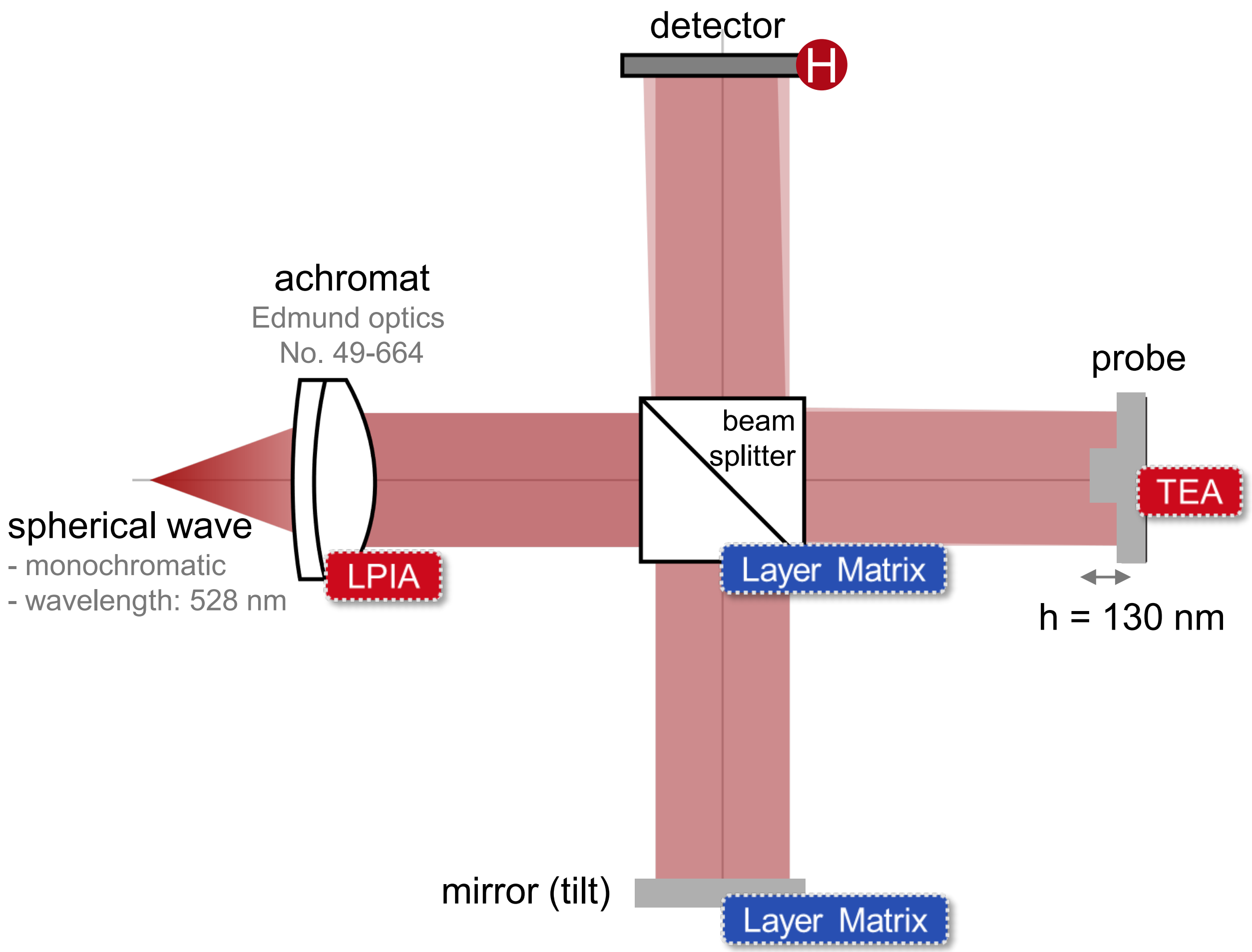


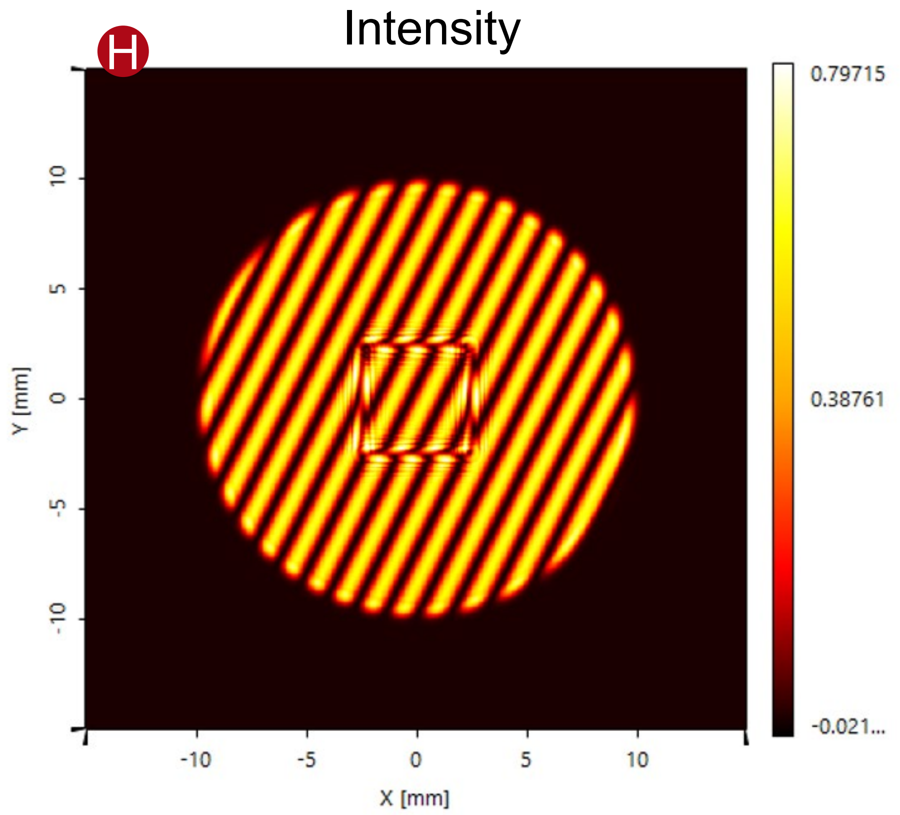
Modeling Michelson Interferometer: Automatic FT Selection



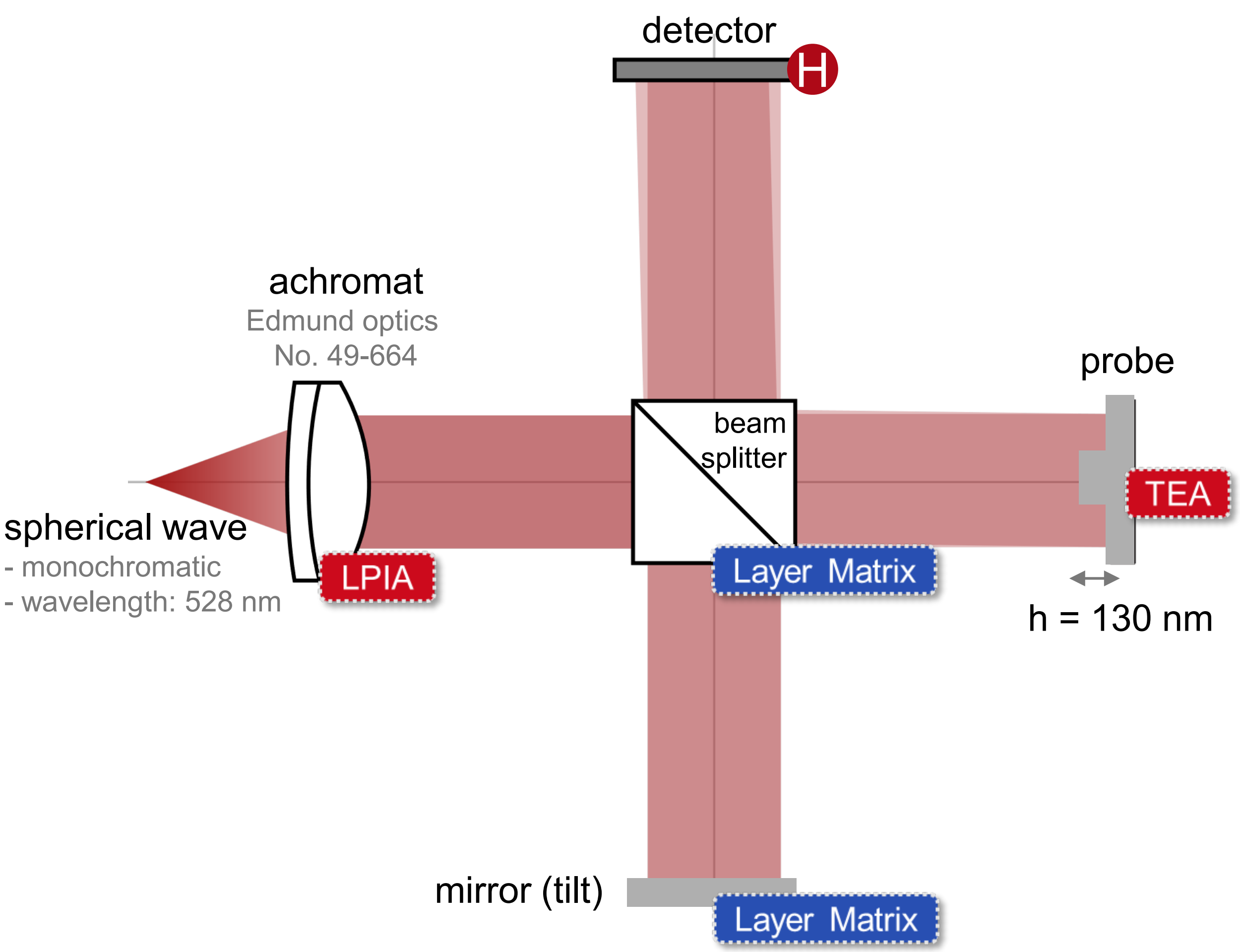


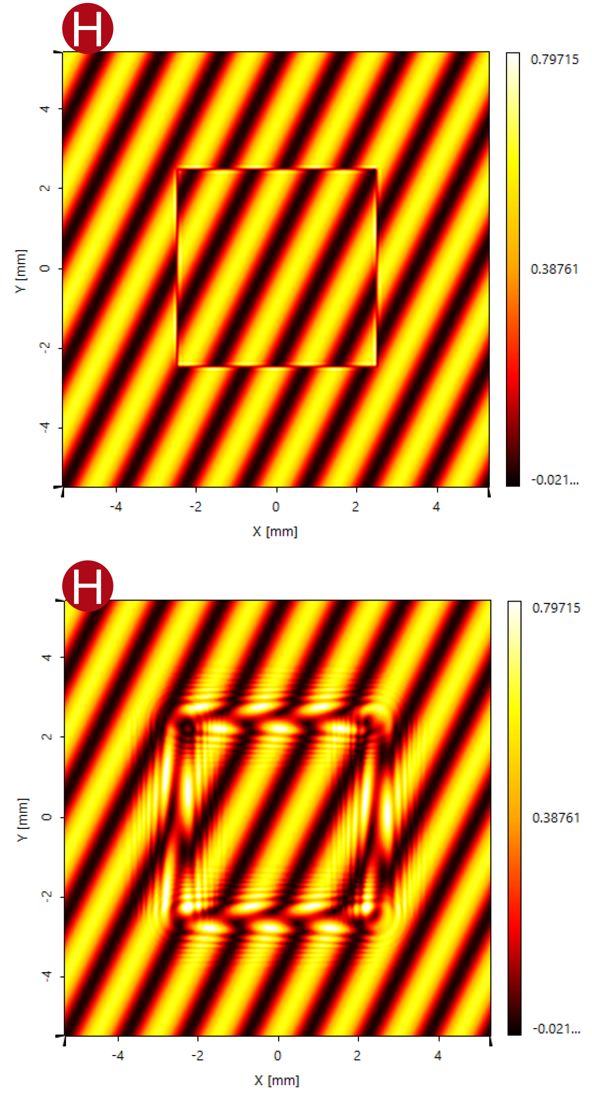
Modeling Michelson Interferometer: Automatic FT Selection





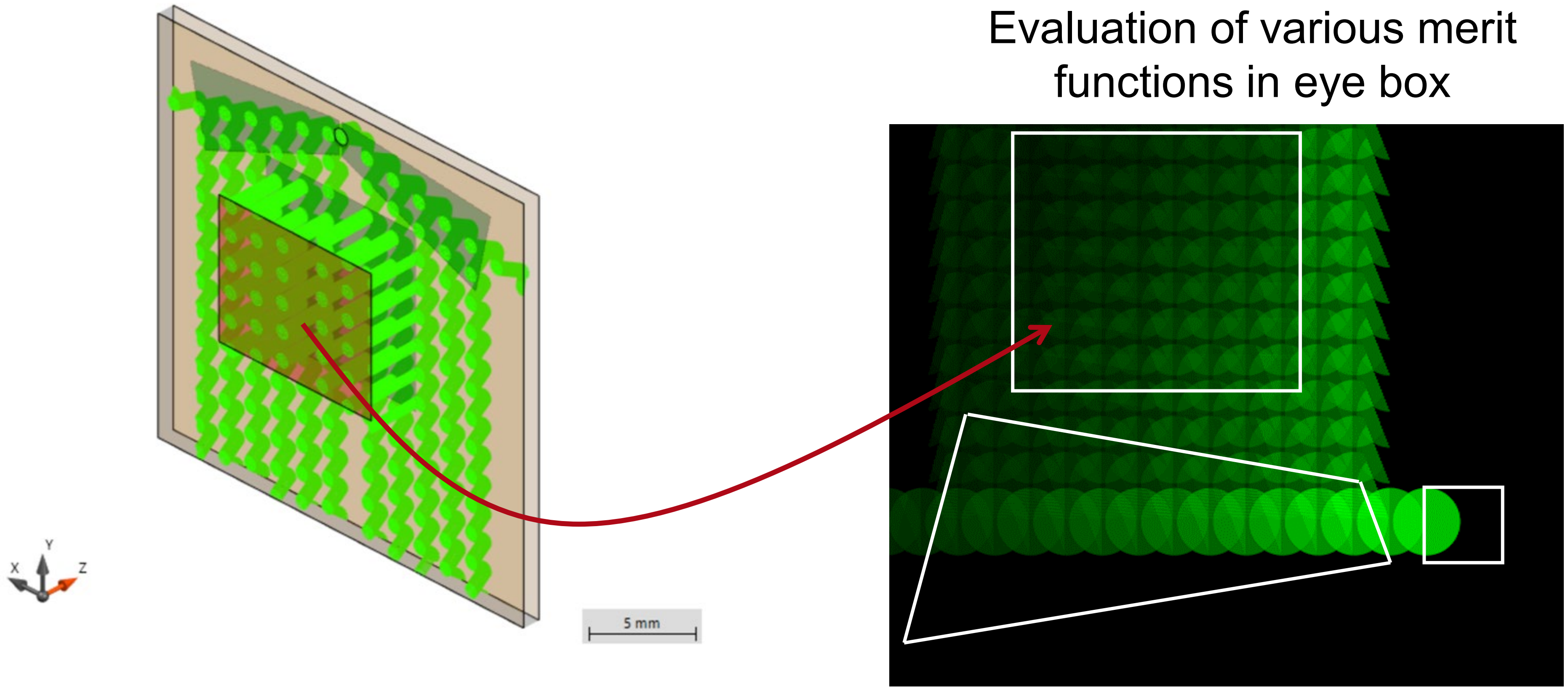
Modeling: PFT vs. Automatic FT Selection



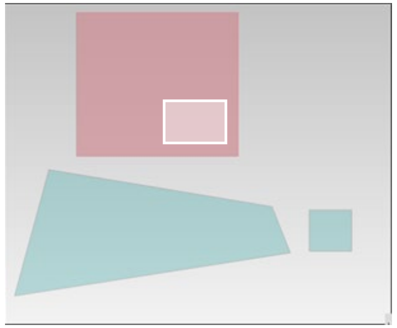


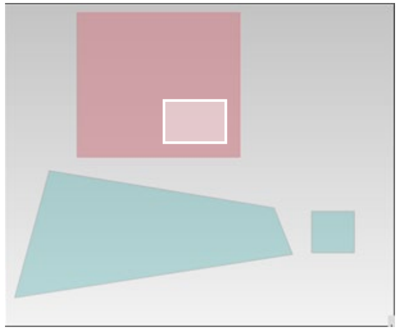
Scenario: Light Guide for Augmented Reality

Evaluation of various merit functions in eye box



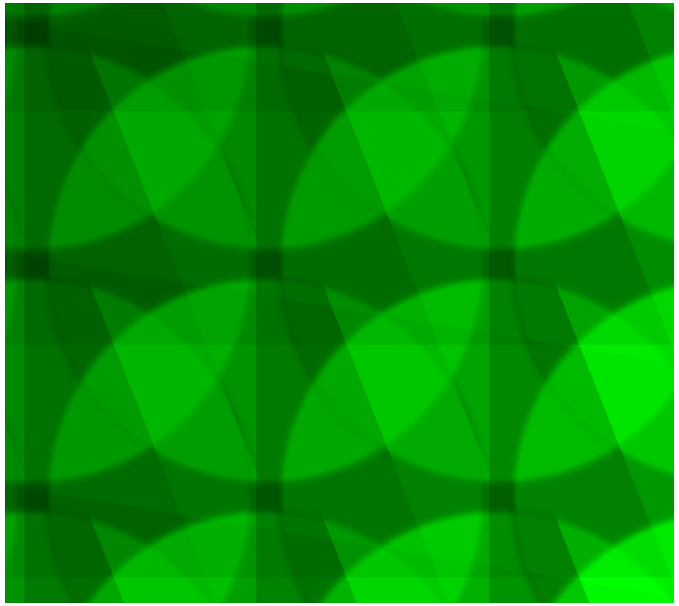
Intensity Detector: Output View in Eyebox

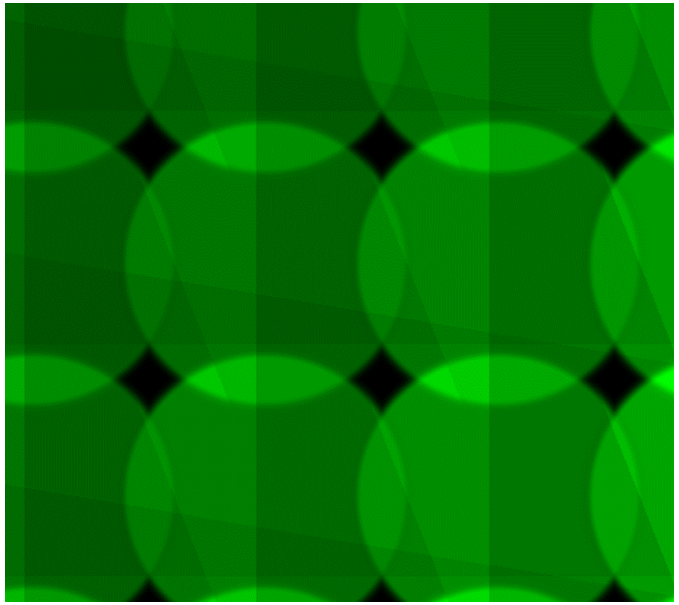




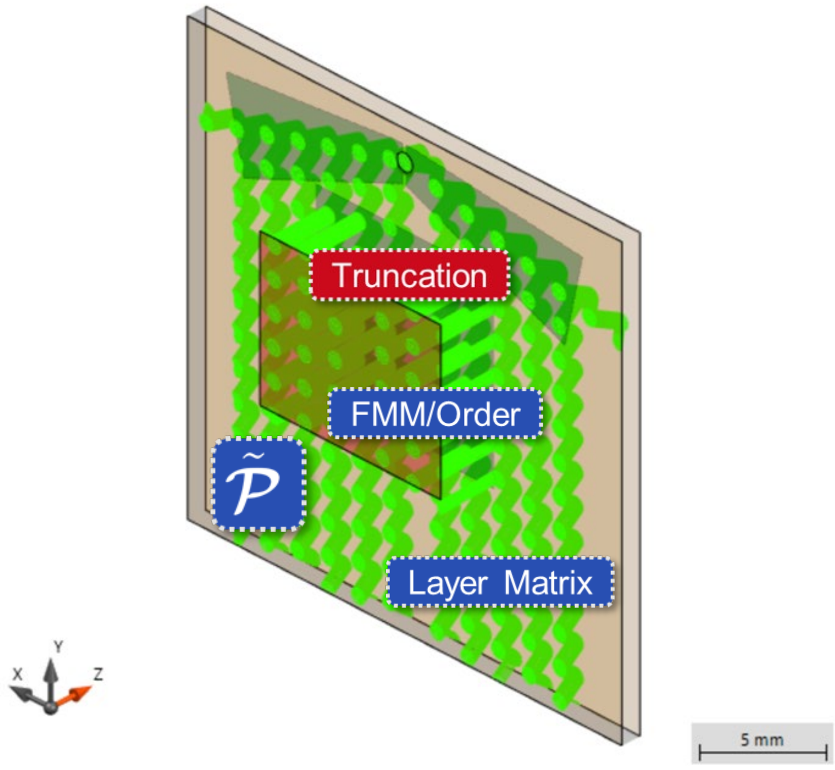
$E_x^{\text{in}} = 1, E_y^{\text{in}} = 0$
$\lambda = 530\,\text{nm}$
$r = 1.5\,\text{mm}$ (left) and $1\,\text{mm}$ (right)

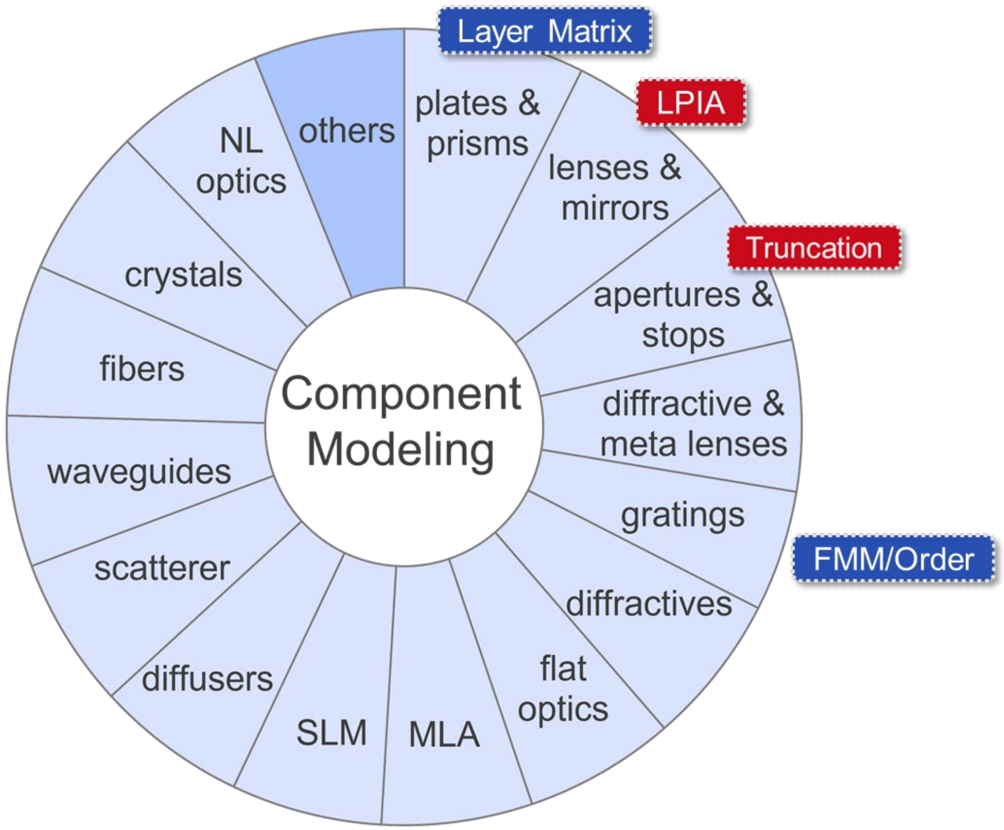
Source beam radius



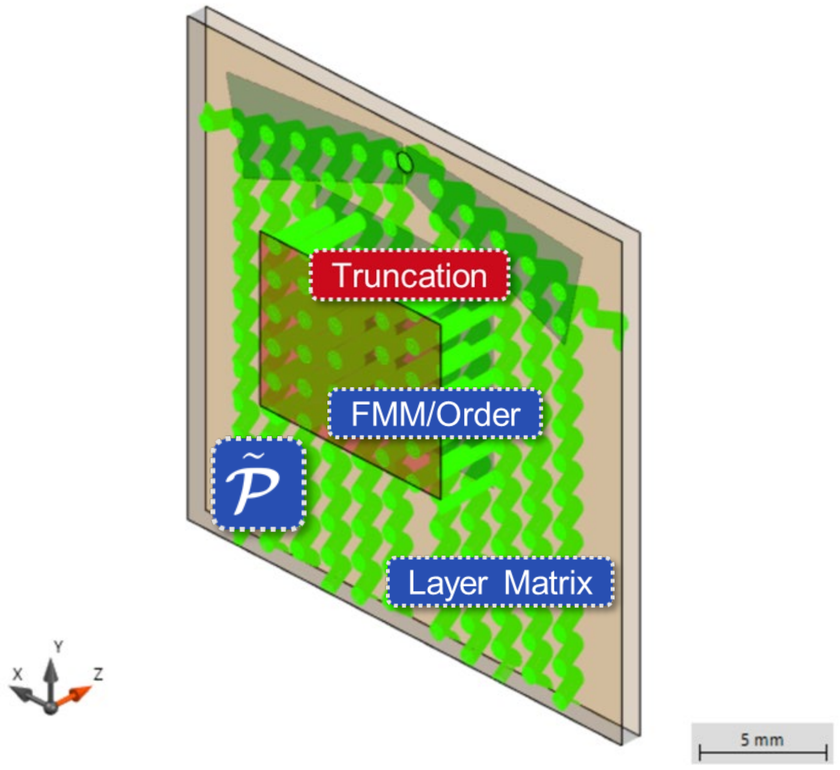


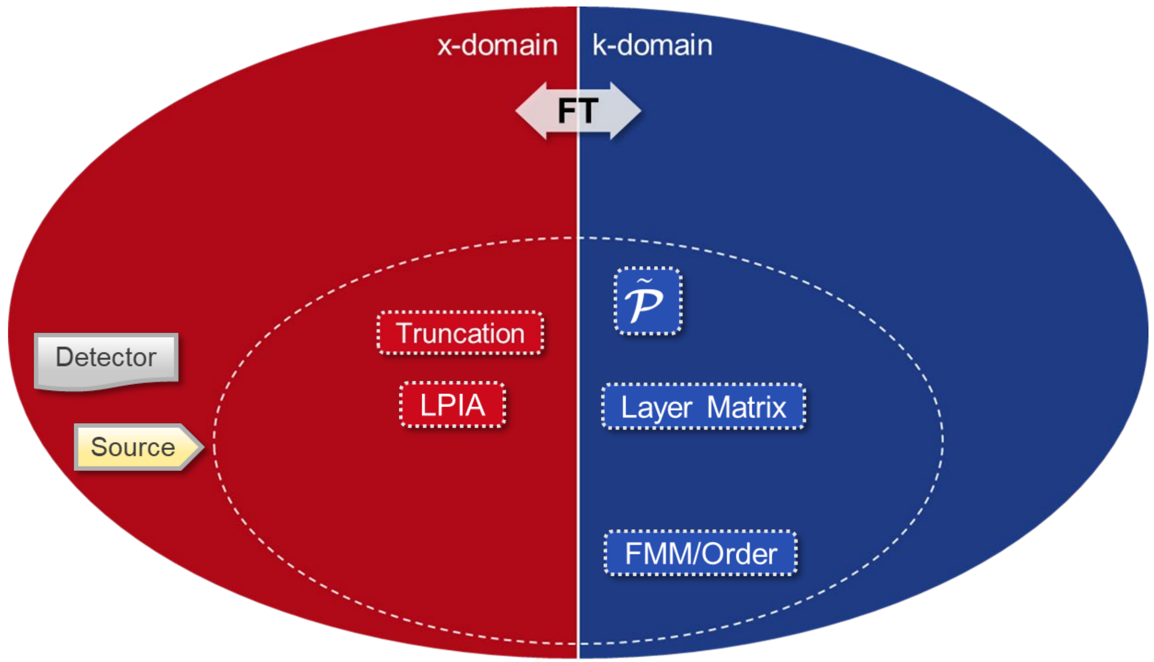
Light Guide for Augmented Reality: Modeling



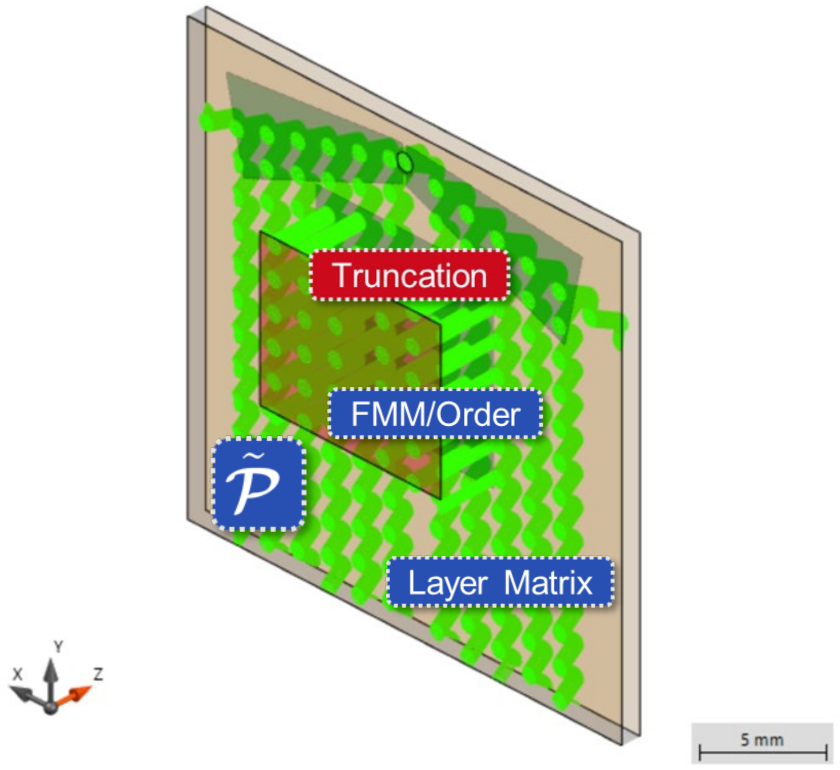


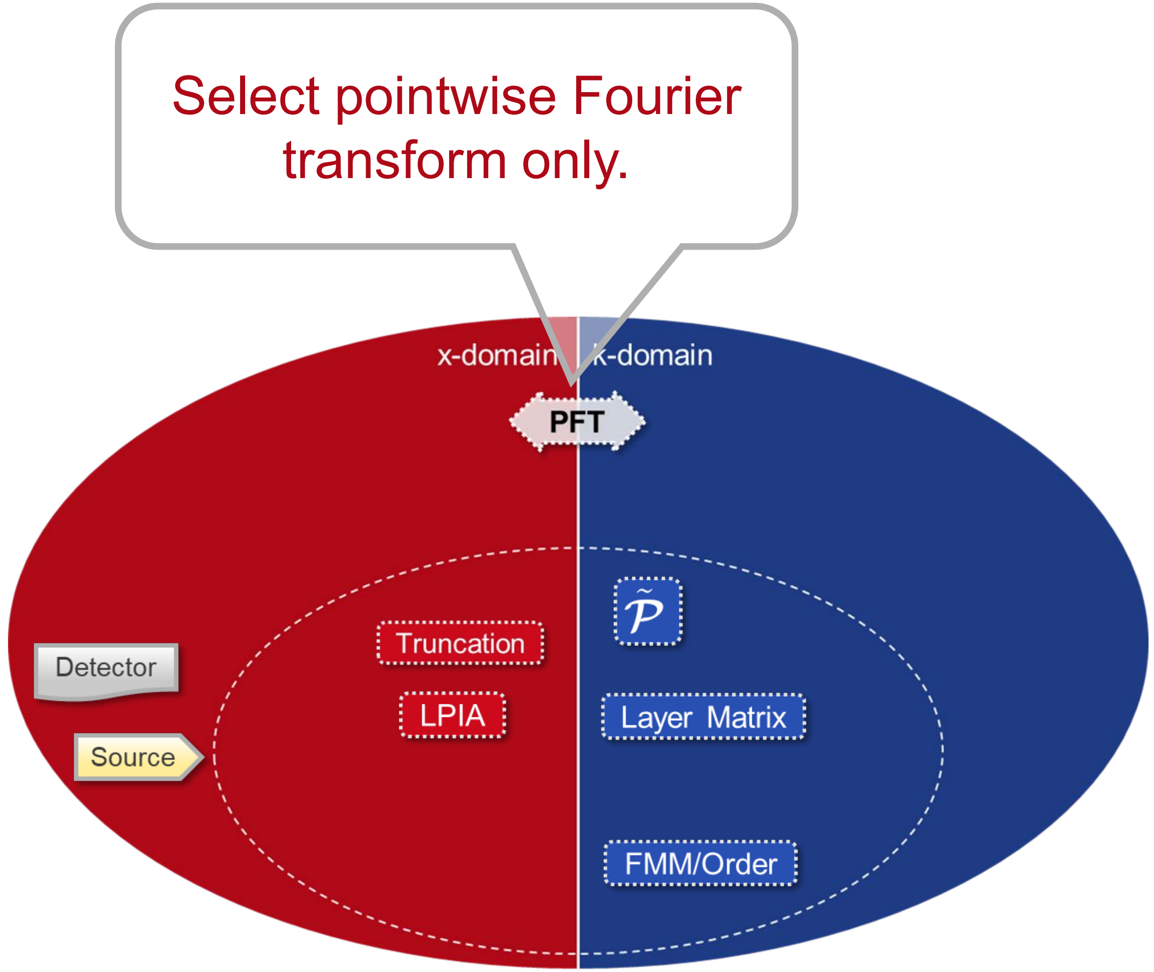
Light Guide for Augmented Reality: Modeling





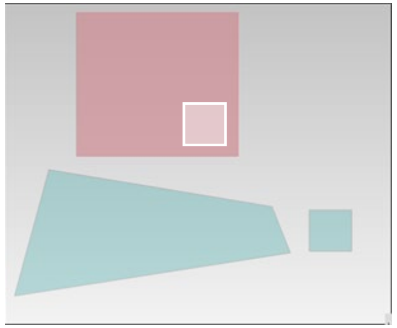
Light Guide for Augmented Reality: Pointwise Modeling

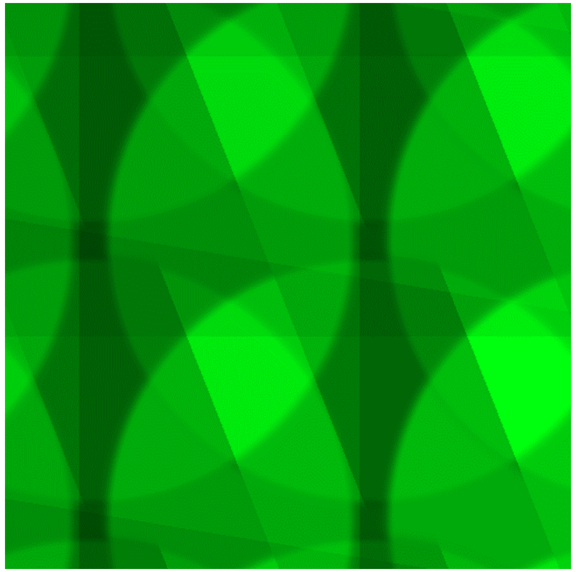




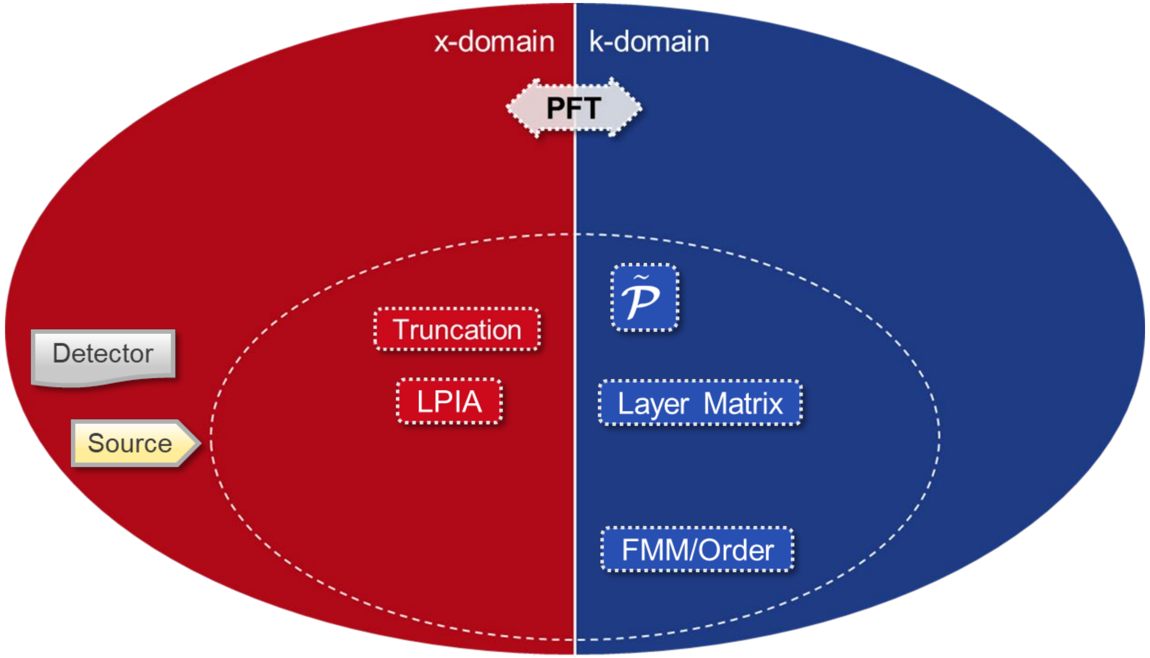
Intensity Detector: Eyebox

$E_x^{\text{in}} = 1, E_y^{\text{in}} = 0$
$\lambda = 530\,\text{nm}$
$\Delta\lambda = 0\,\text{nm}$
$r = 1.5\,\text{mm}$



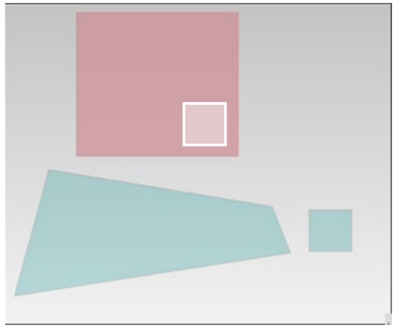


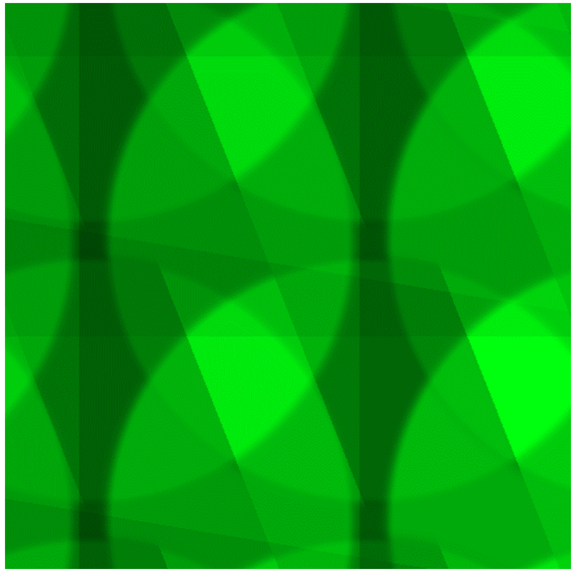
PFT



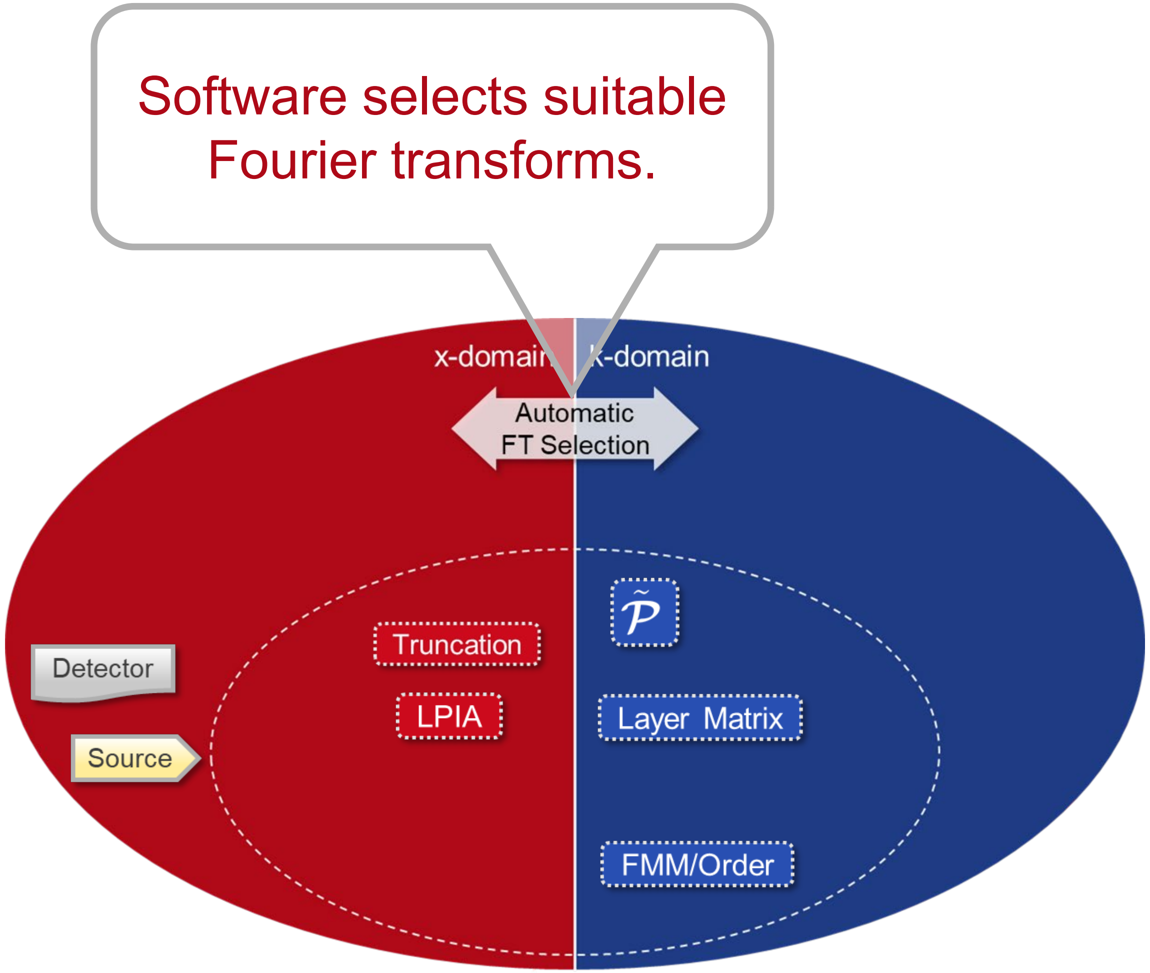
Intensity Detector: Eyebox

$E_x^{\text{in}} = 1, E_y^{\text{in}} = 0$
$\lambda = 530\,\text{nm}$
$\Delta\lambda = 0\,\text{nm}$
$r = 1.5\,\text{mm}$

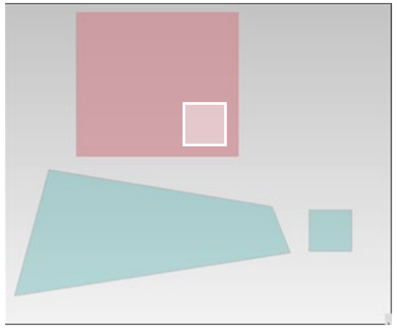


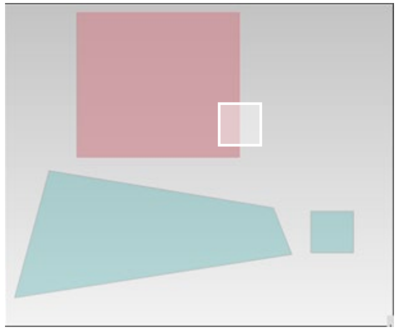


PFT

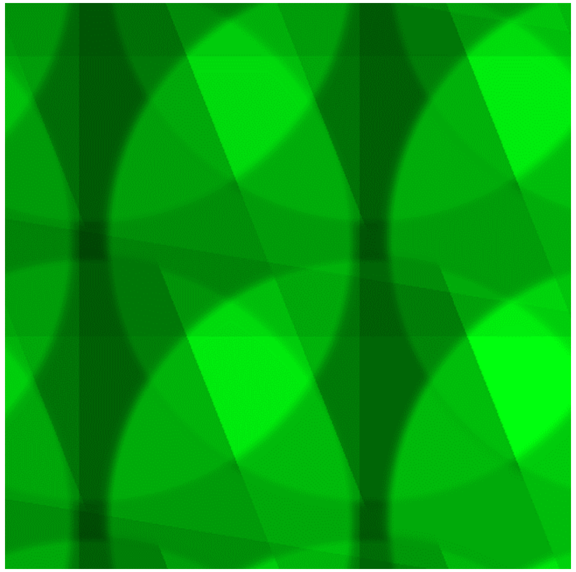


Intensity Detector: Eyebox

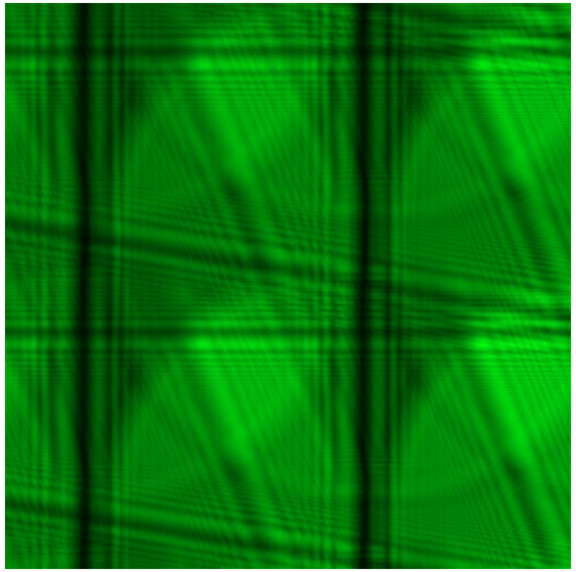




$E_x^{\text{in}} = 1, E_y^{\text{in}} = 0$
$\lambda = 530\,\text{nm}$
$\Delta\lambda = 0\,\text{nm}$
$r = 1.5\,\text{mm}$



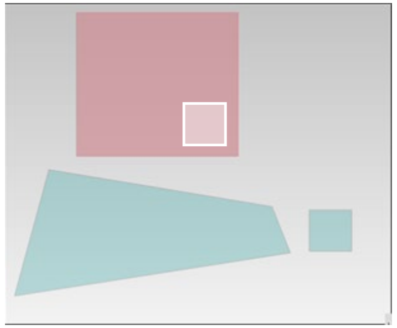
PFT

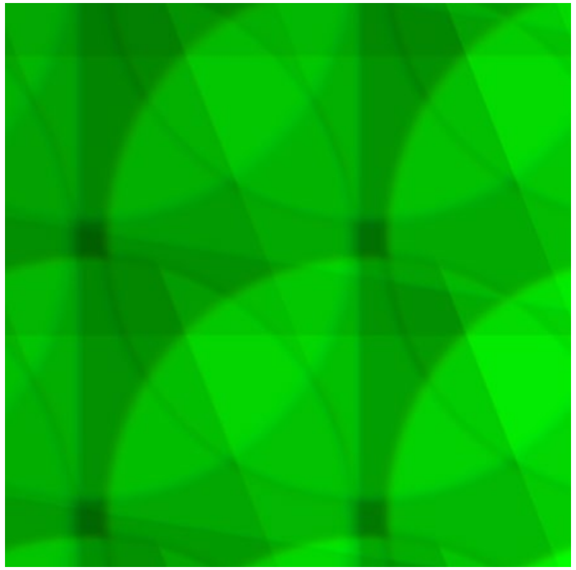


Automatic FT selection

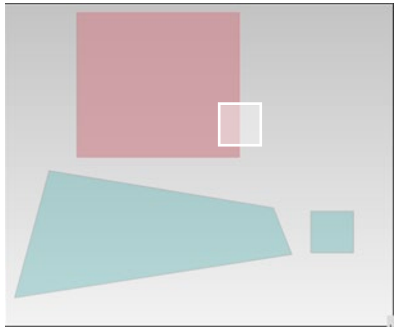
Intensity Detector: Eyebox (Partial Coherent)

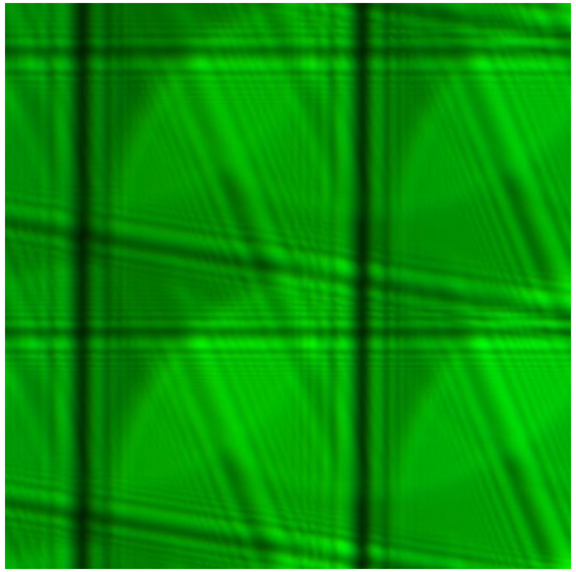
$E_x^{\mathrm{in}} = 1, E_y^{\mathrm{in}} = 0$
$\lambda = 530\,\mathrm{nm}$
$\Delta\lambda = 1\,\mathrm{nm}$
$r = 1.5\,\mathrm{mm}$





PFT

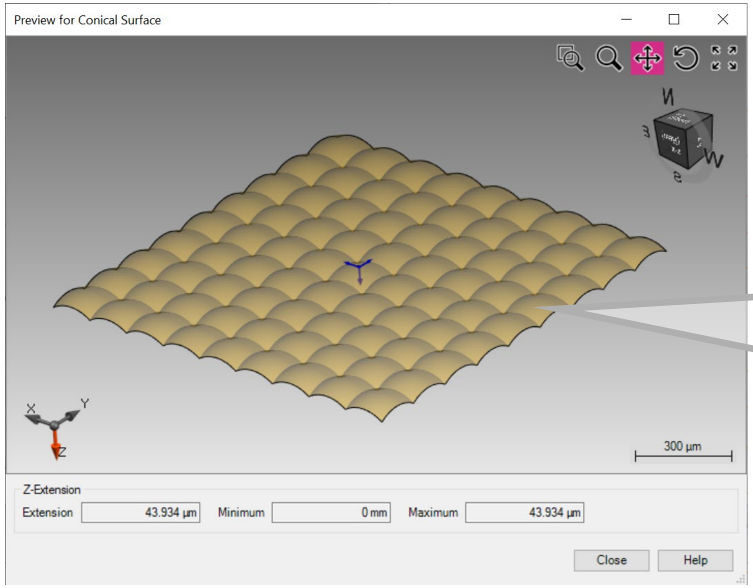




Automatic FT selection

Scenario: Propagate Light Through Microlens Array (MLA)

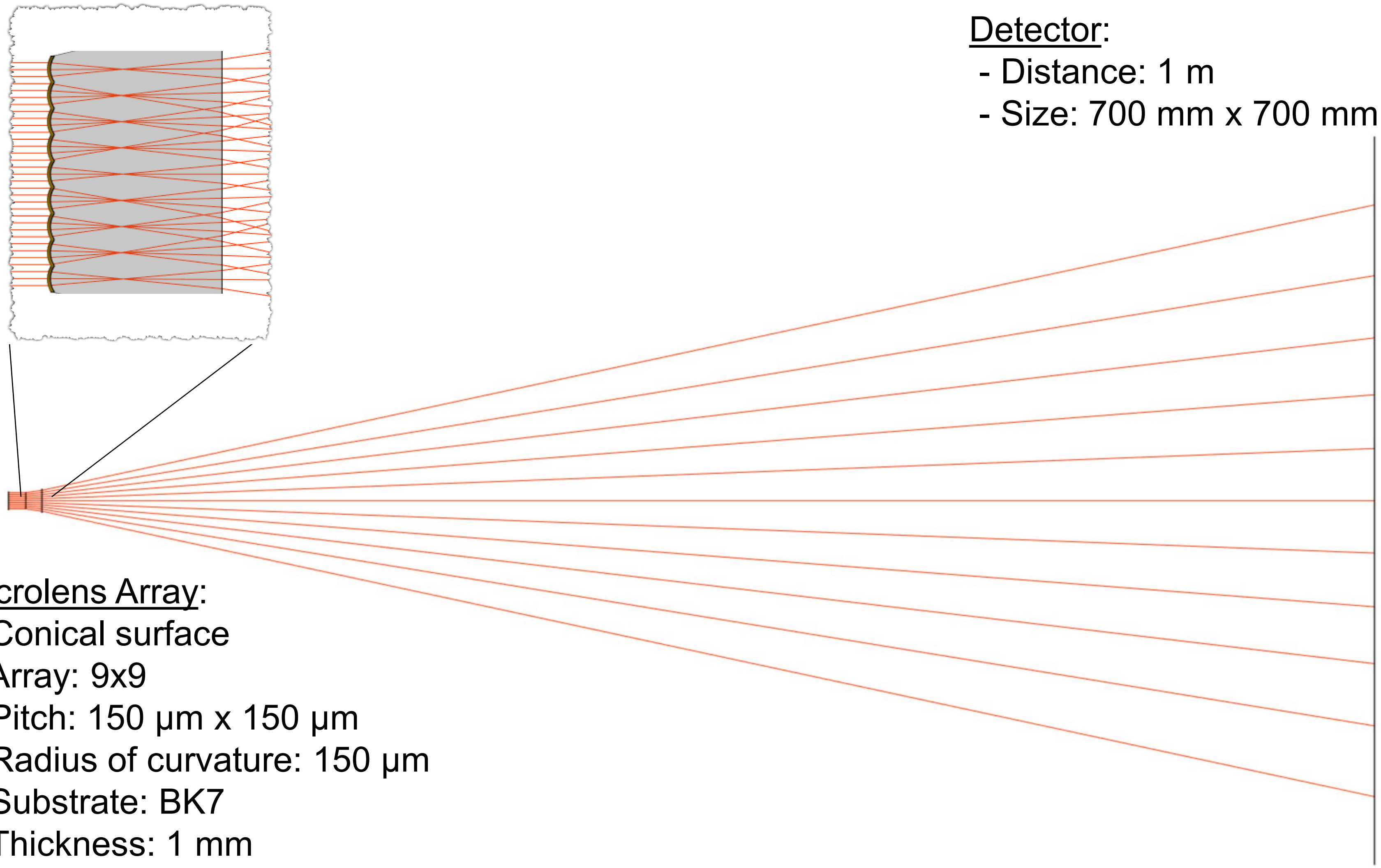
<u>Light Source</u>:
- Plane wave
- Wavelength: 640 nm
- Linearly polarized (Ex)



Diffraction effects at boundaries should be included in modeling.

<u>Microlens Array</u>:
- Conical surface
- Array: 9x9
- Pitch: 150 µm x 150 µm
- Radius of curvature: 150 µm
- Substrate: BK7
- Thickness: 1 mm

Scenario: Propagate Light Through Microlens Array (MLA)

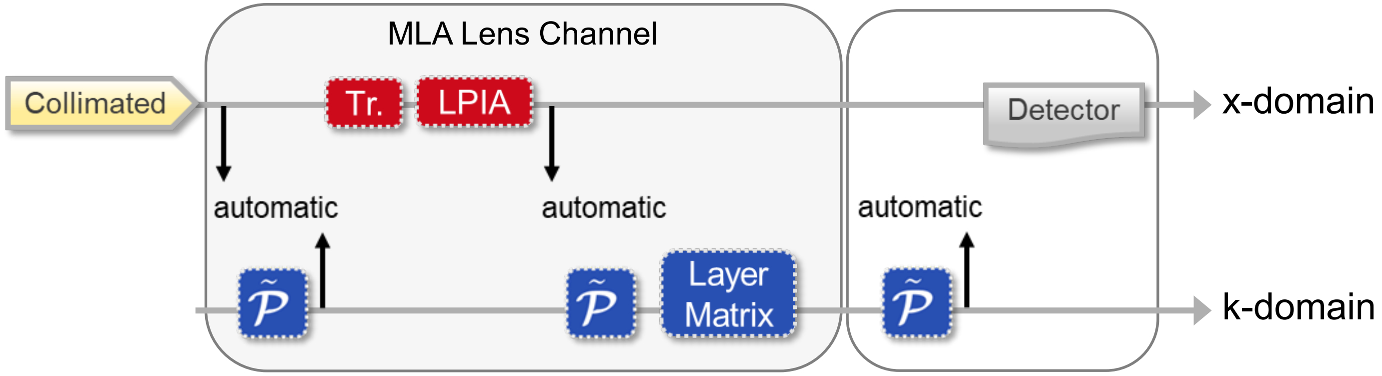


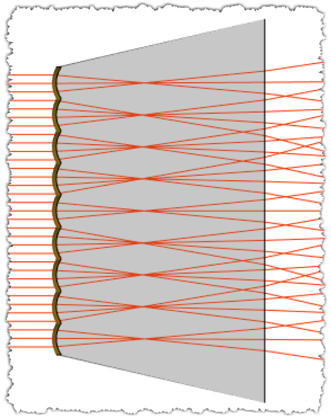
__Light Source__:
- Plane wave
- Wavelength: 640 nm
- Linearly polarized (Ex)

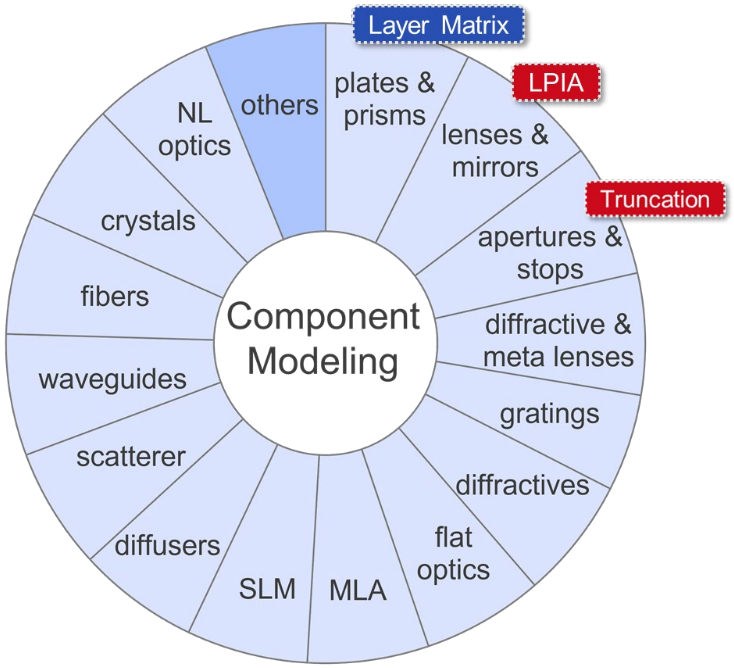
__Microlens Array__:
- Conical surface
- Array: 9x9
- Pitch: 150 µm x 150 µm
- Radius of curvature: 150 µm
- Substrate: BK7
- Thickness: 1 mm

__Detector__:
- Distance: 1 m
- Size: 700 mm x 700 mm

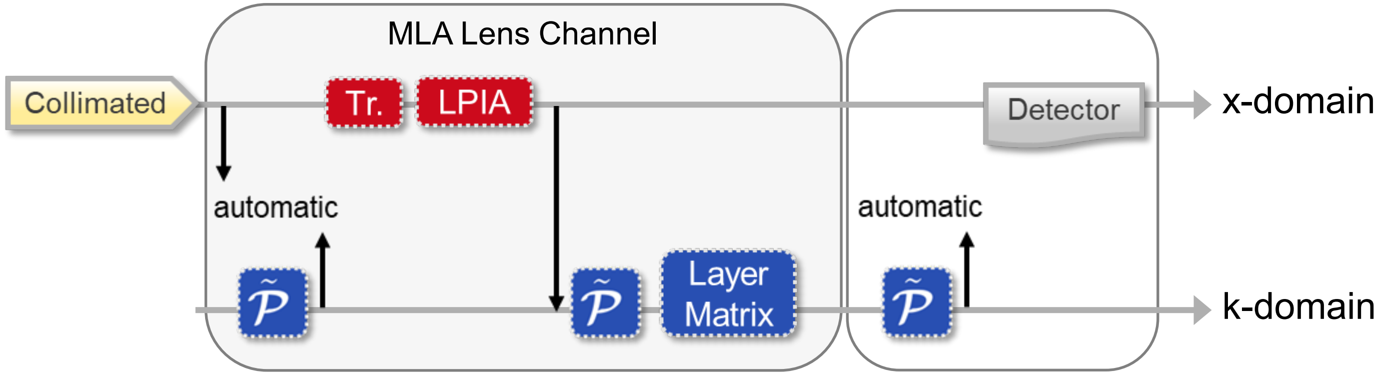
MLA Modeling by Lens Channels

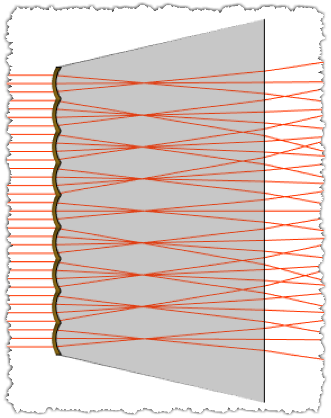


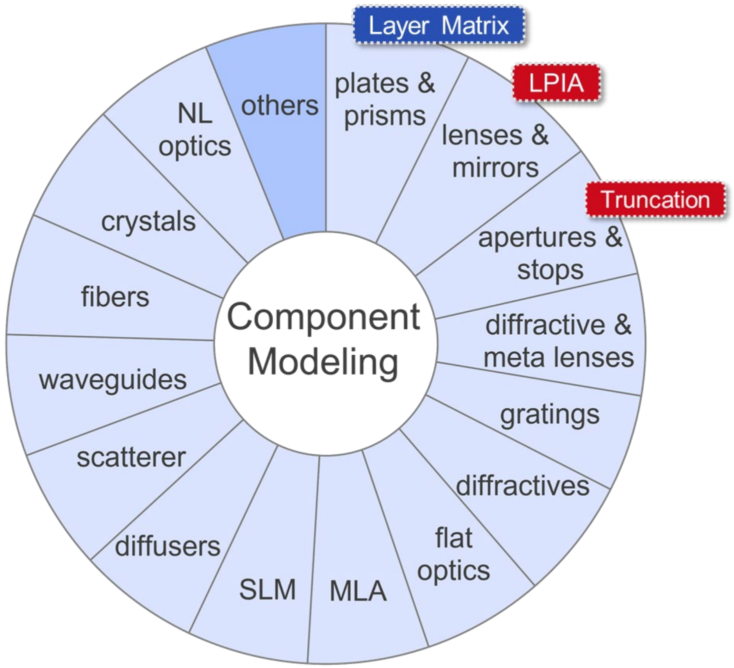




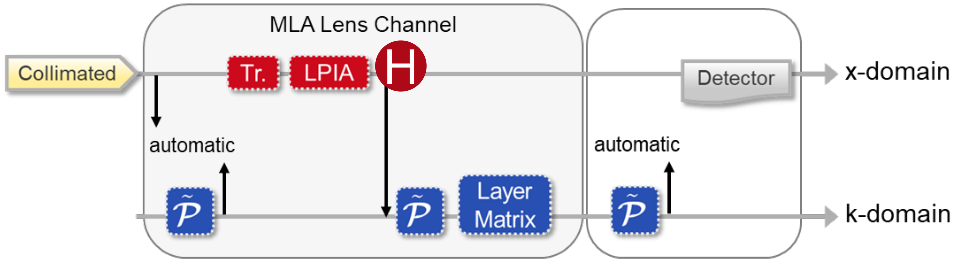
MLA Modeling by Lens Channels

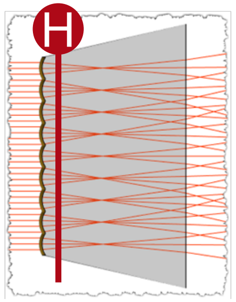


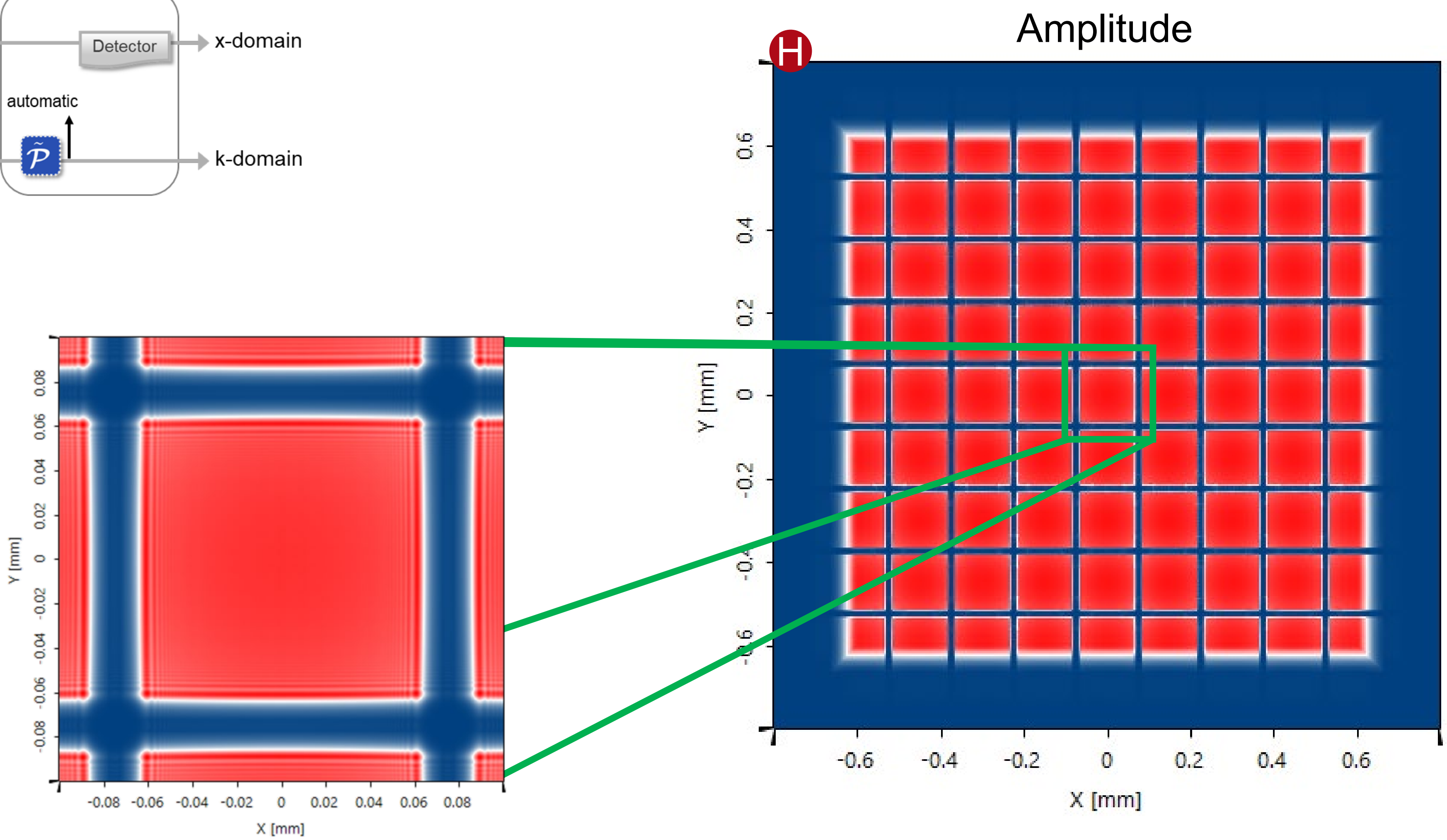




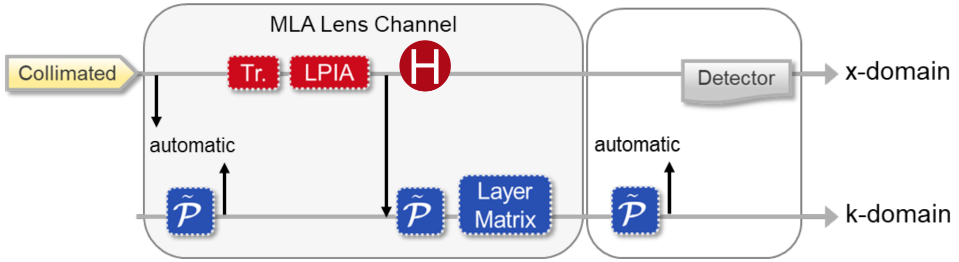
MLA Modeling: Near Field

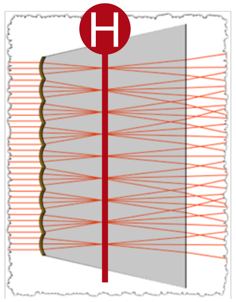


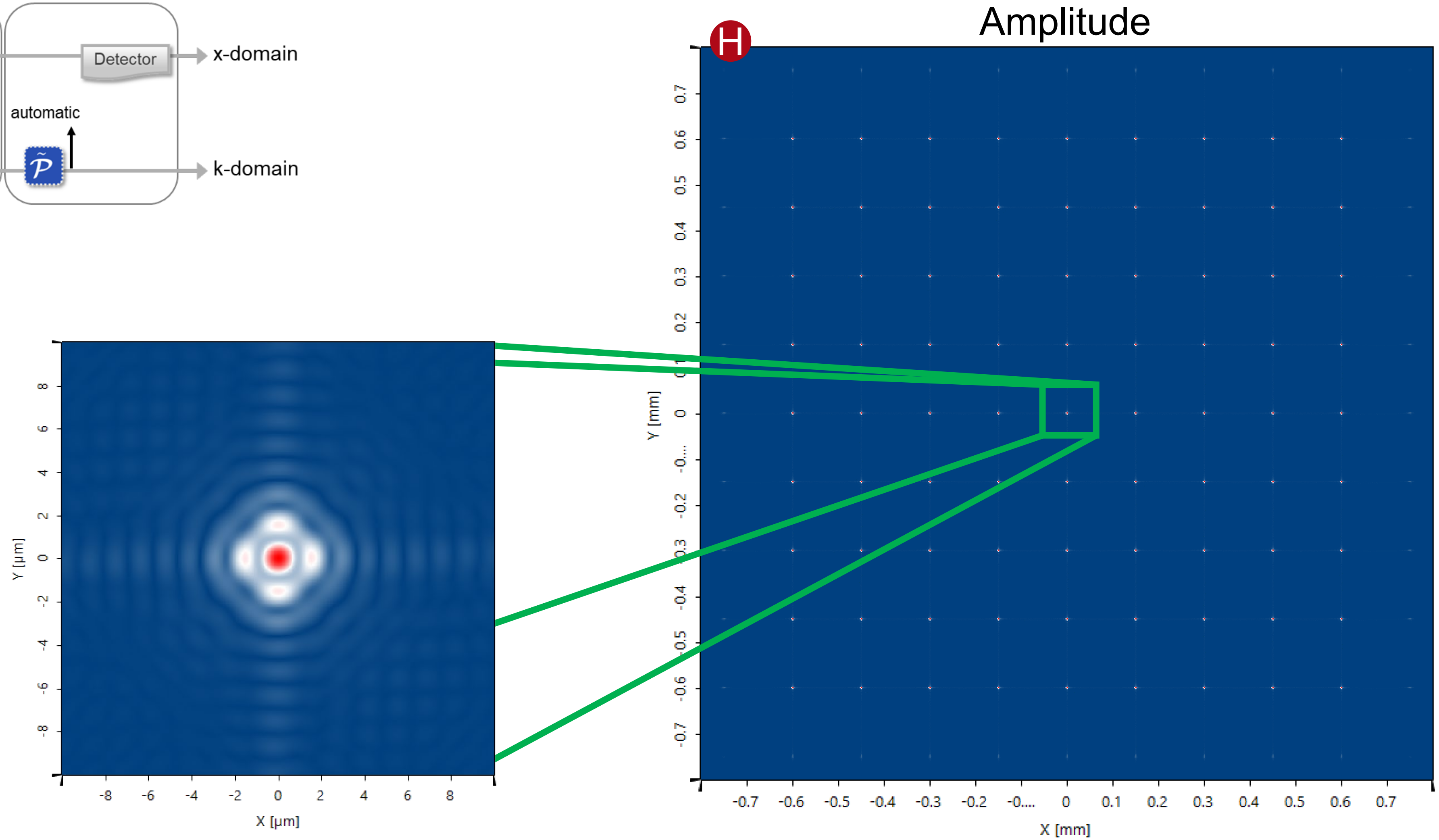




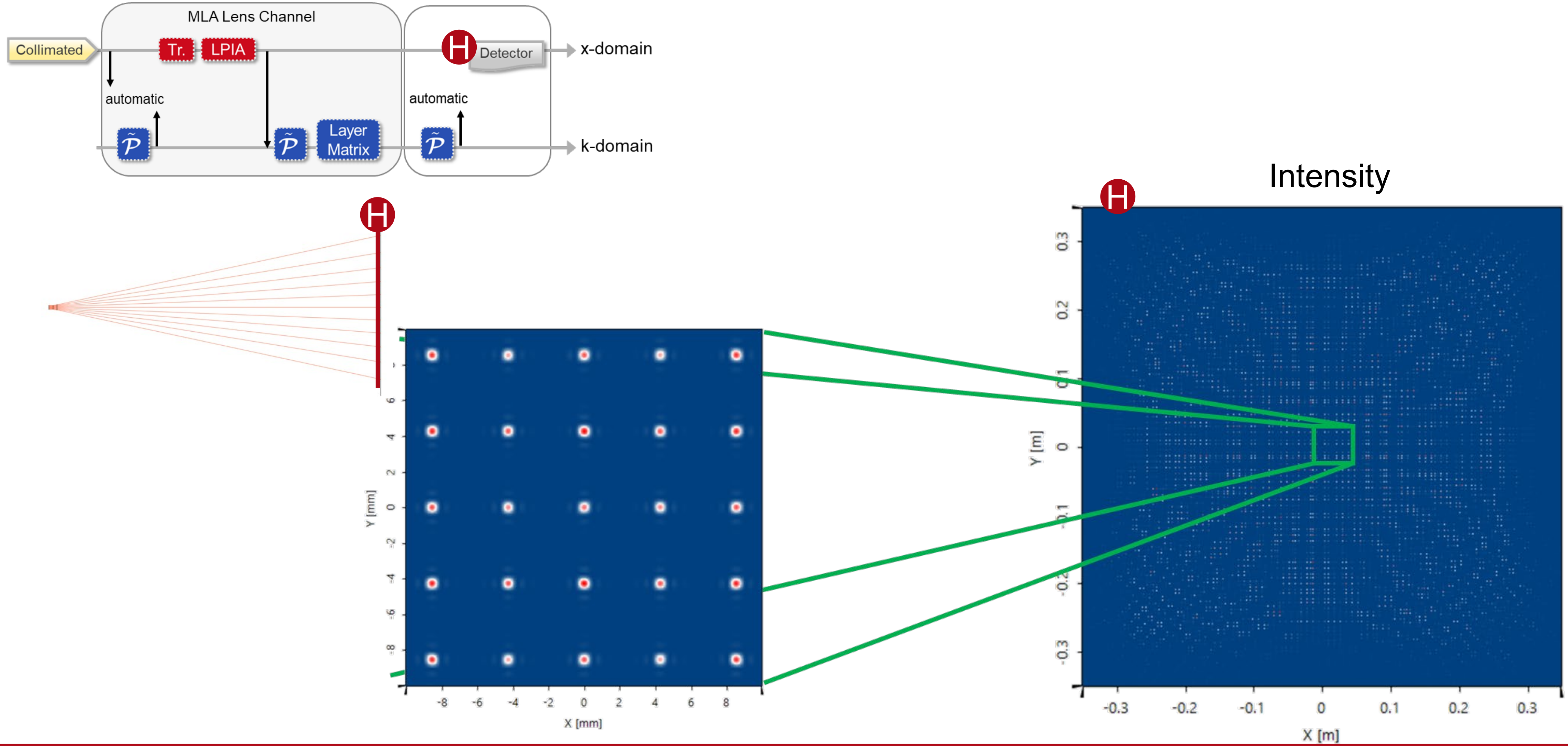
MLA Modeling: Foci Plane





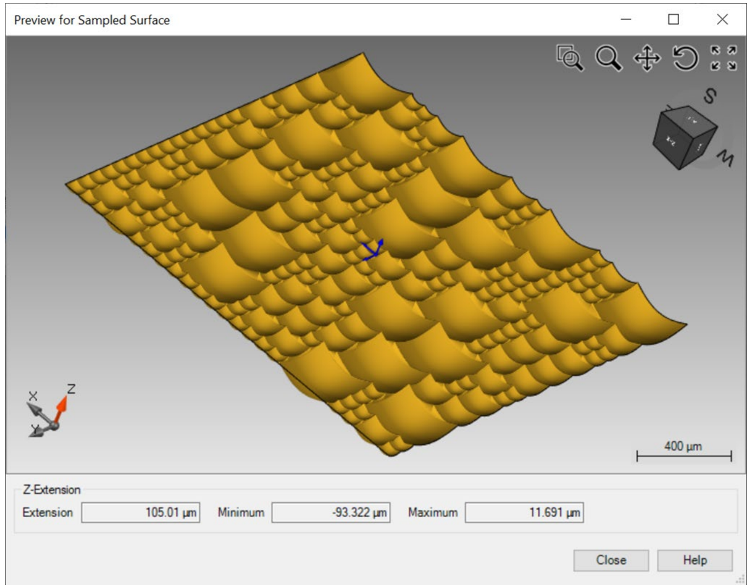


MLA Modeling: Far Field Intensity



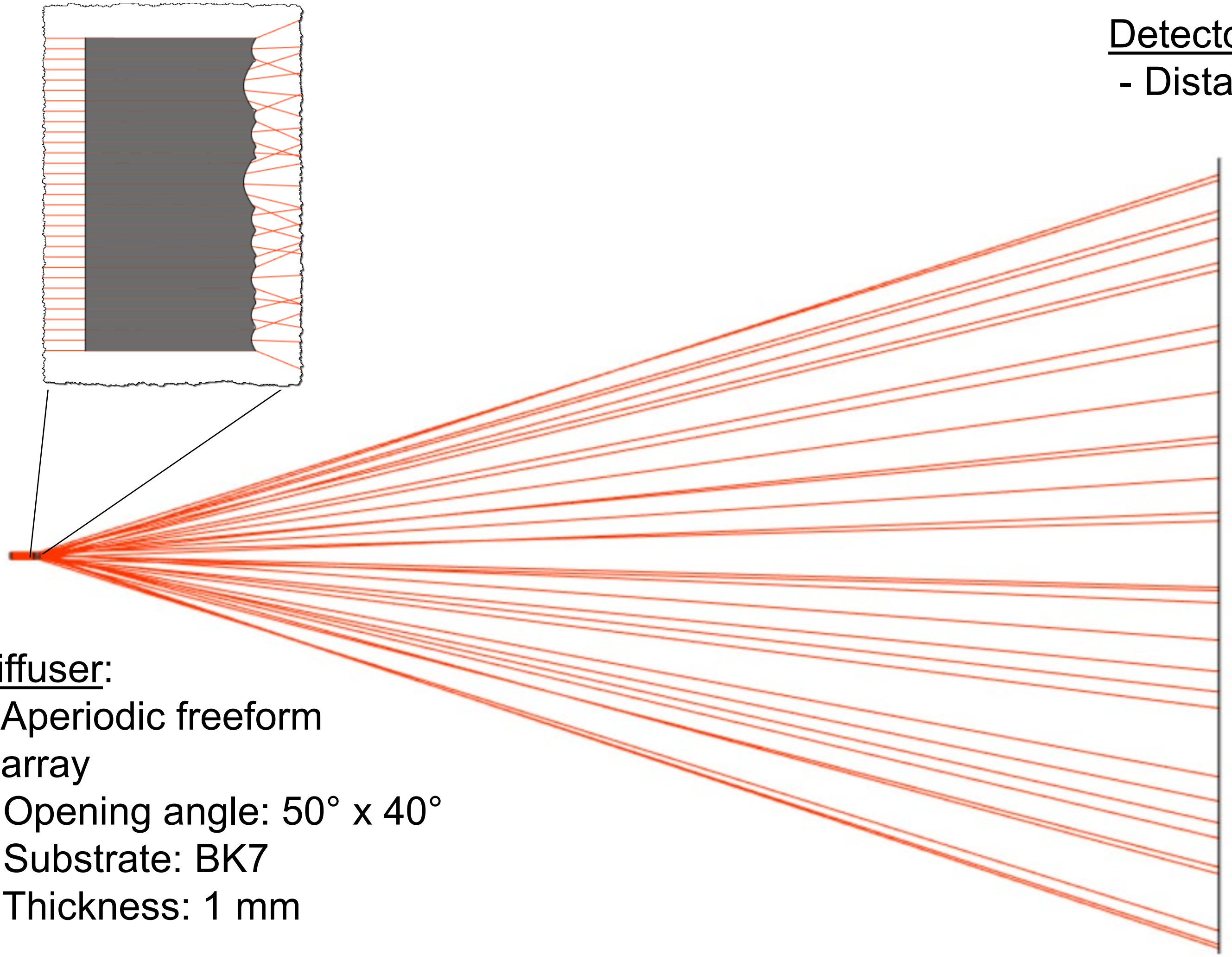
Scenario: Evaluate Far Field Intensity of Diffuser

Light Source:
- Plane wave
- Wavelength: 640 nm
- Circularly polarized



Diffuser:
- Aperiodic freeform array
- Opening angle: 50° x 40°
- Substrate: BK7
- Thickness: 1 mm

Scenario: Evaluate Far Field Irradiance of Diffuser

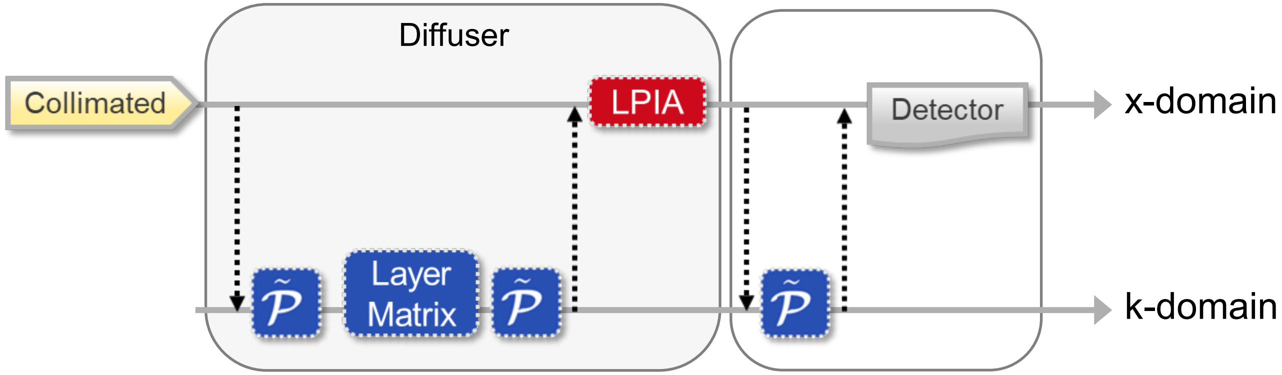


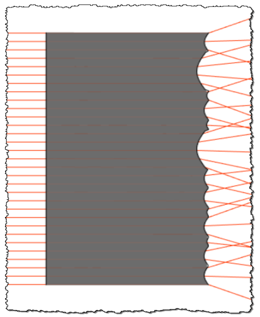
Detector:
- Distance: 1 m

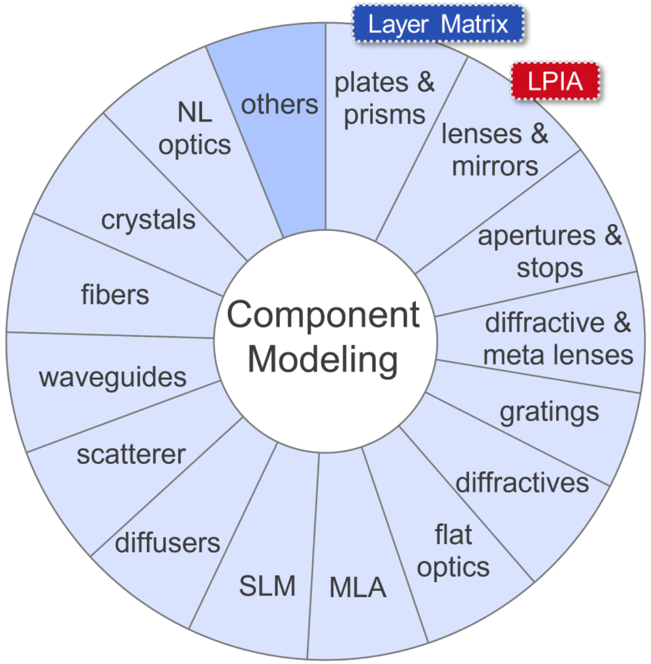
Light Source:
- Plane wave
- Wavelength: 640 nm
- Circularly polarized

Diffuser:
- Aperiodic freeform array
- Opening angle: 50° x 40°
- Substrate: BK7
- Thickness: 1 mm

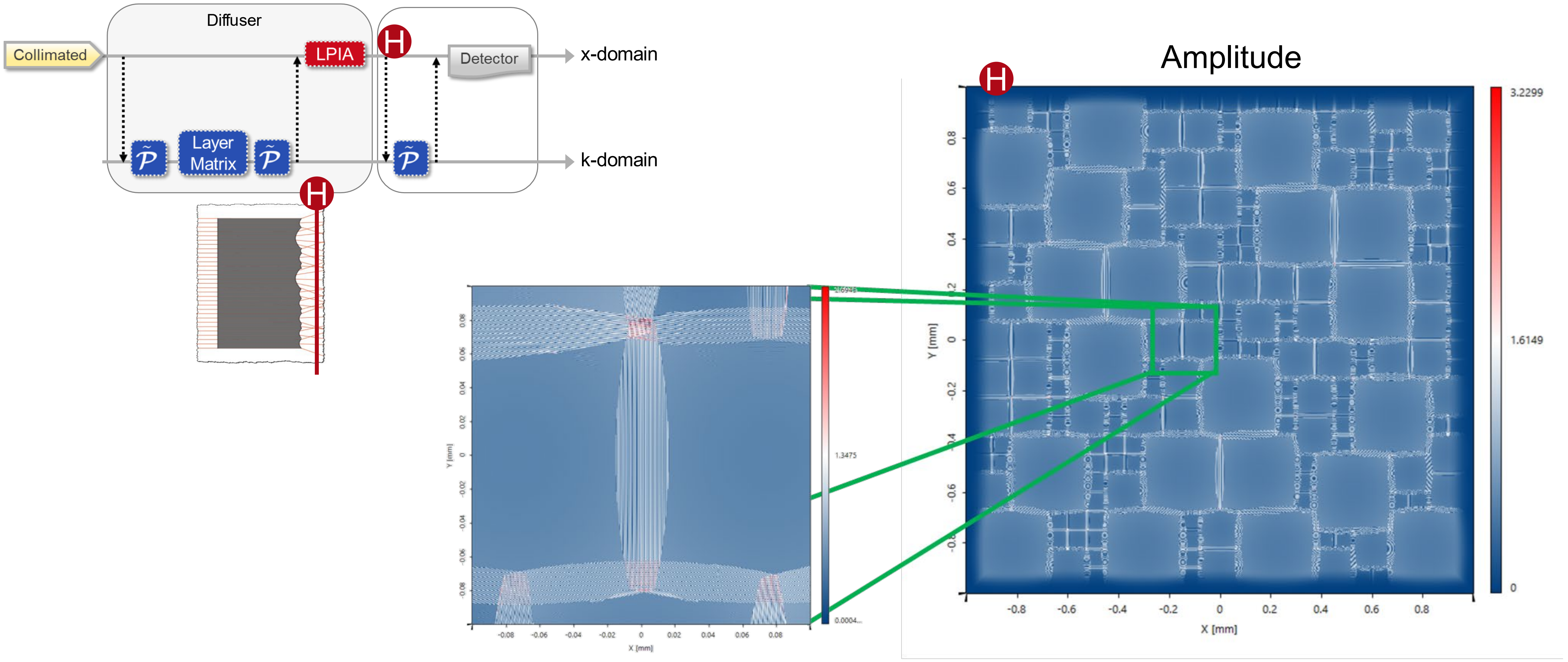
Pointwise Diffuser Modeling



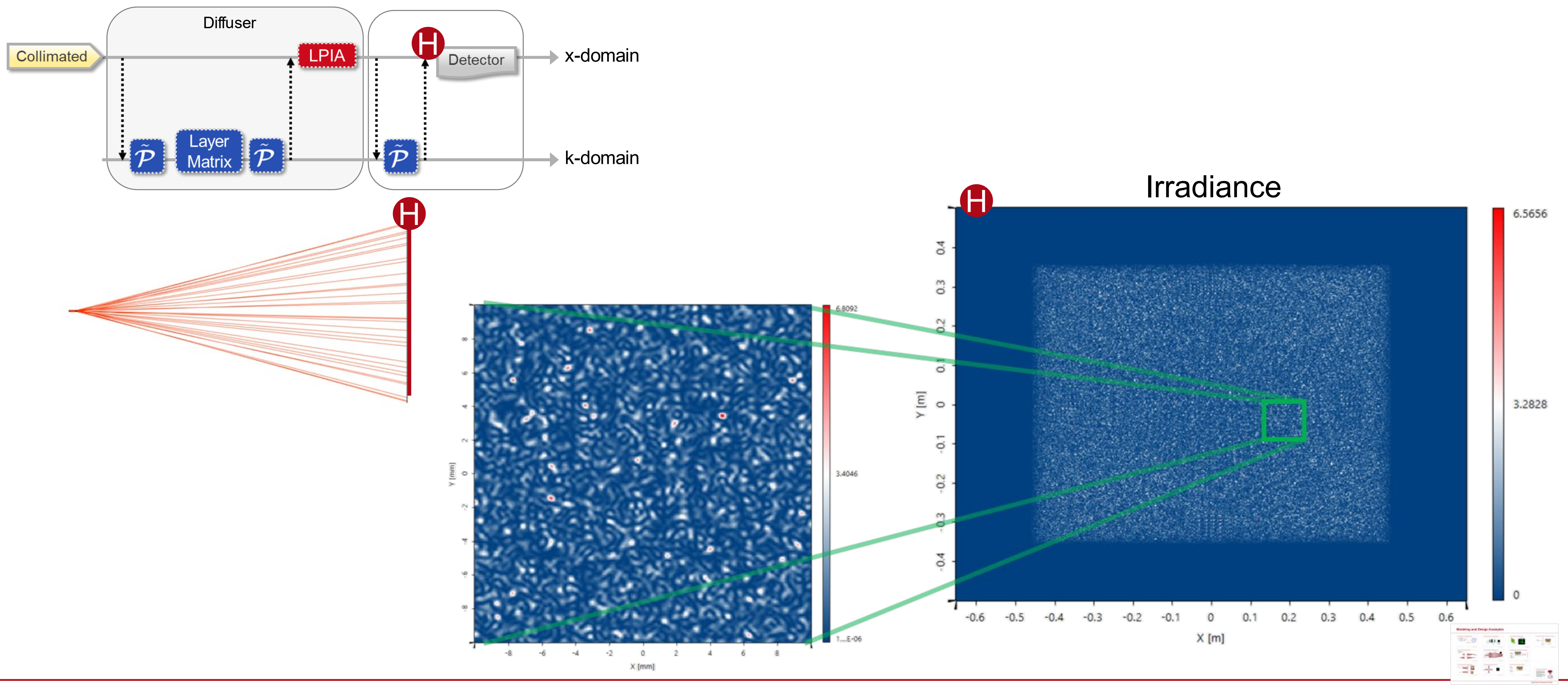




Pointwise Diffuser Modeling: Near Field

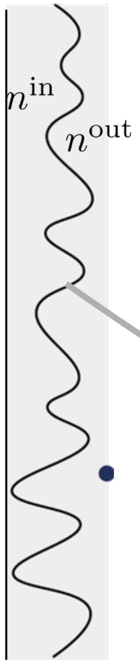


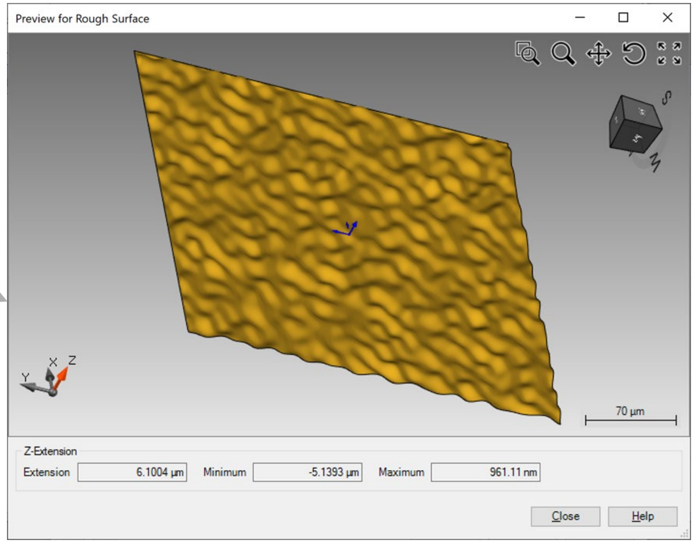
Pointwise Diffuser Modeling: Far Field Irradiance



Scenario: Calculation of BSDF and Far Field Irradiance of Rough Surface

Input field:
- Plane wave
- Wavelength: 640 nm
- Linearly polarized (Ex)

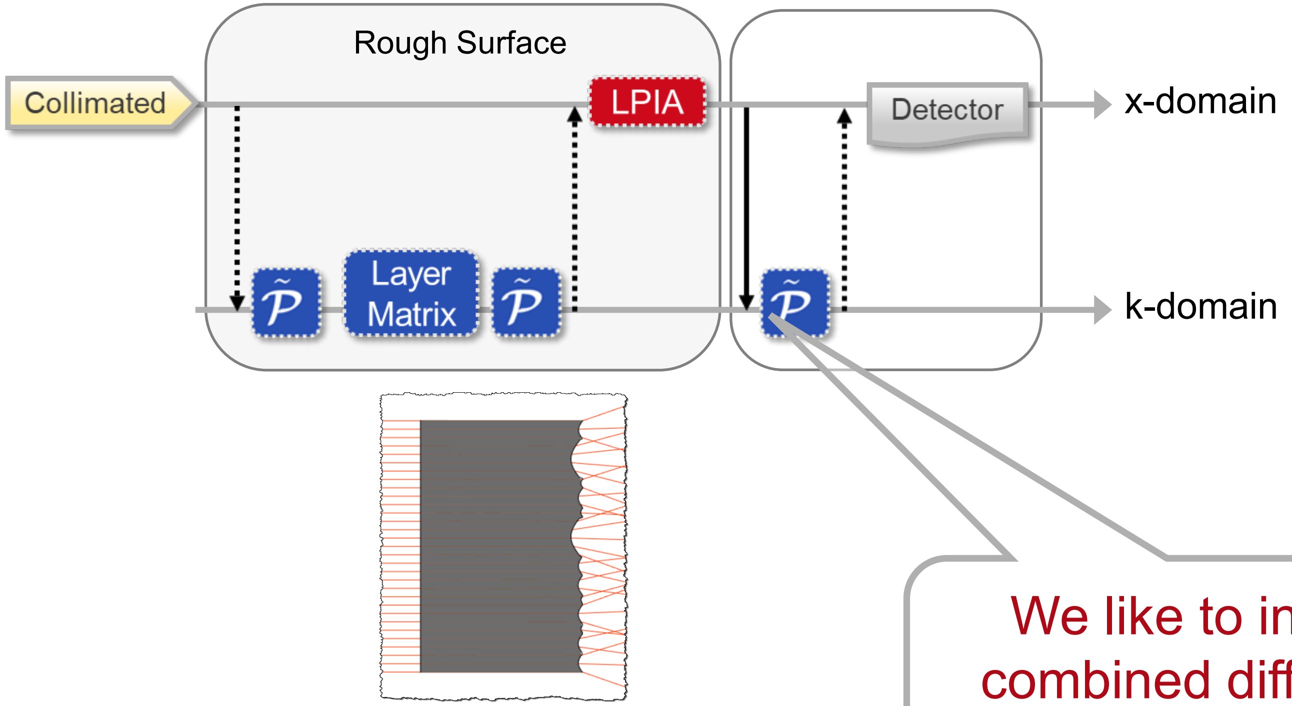




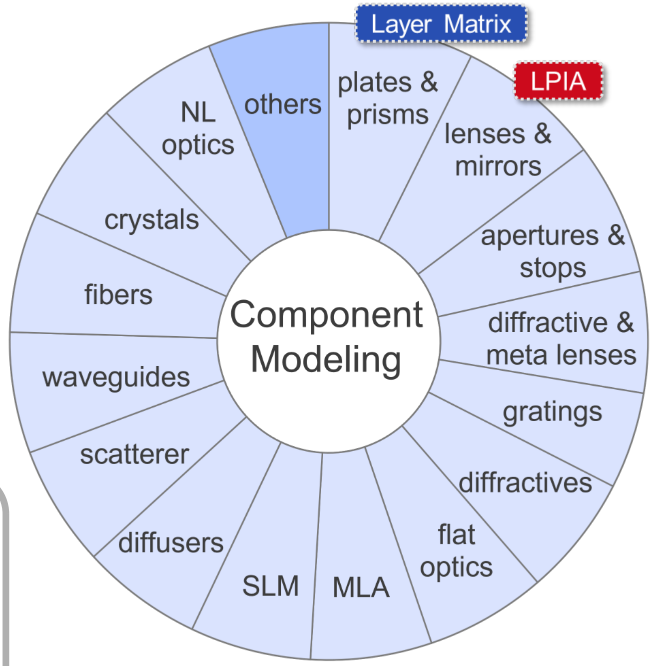
Rough Surface:
- Size: 320 µm x 320 µm
- Substrate: BK7

Thickness: 6.1 µm

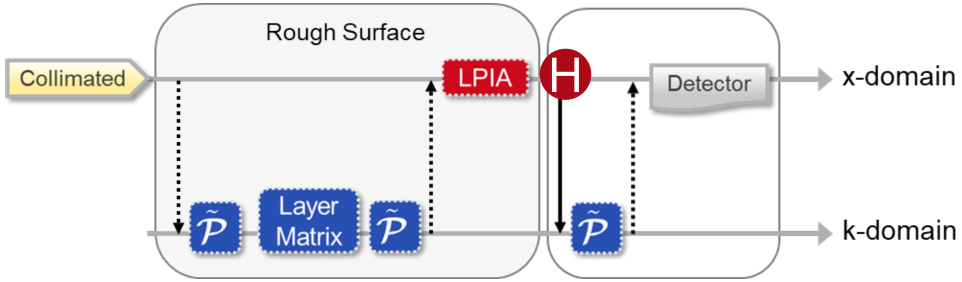
Non-Pointwise Rough Surface Modeling

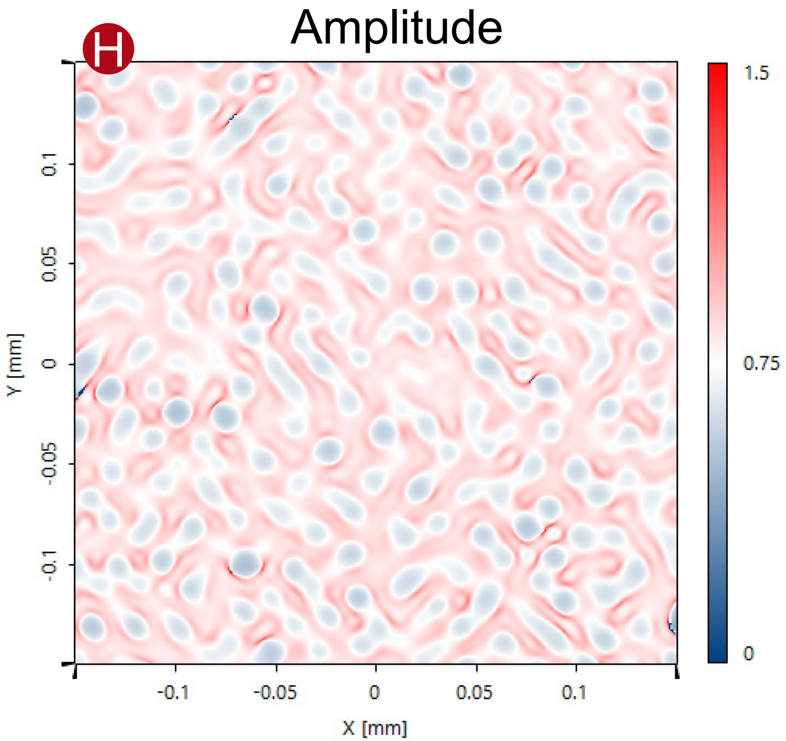


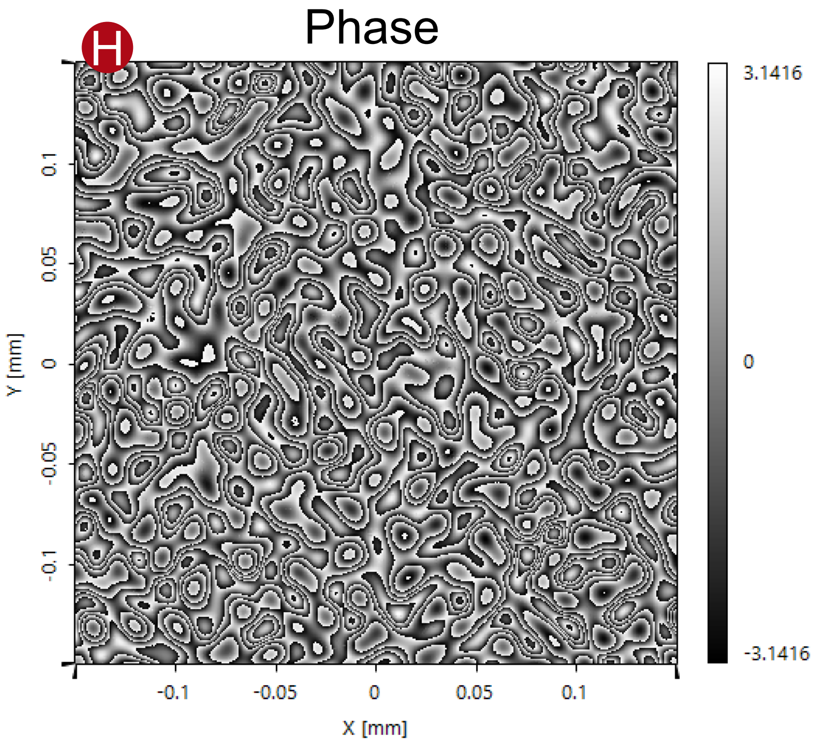
We like to include combined diffraction and scattering.



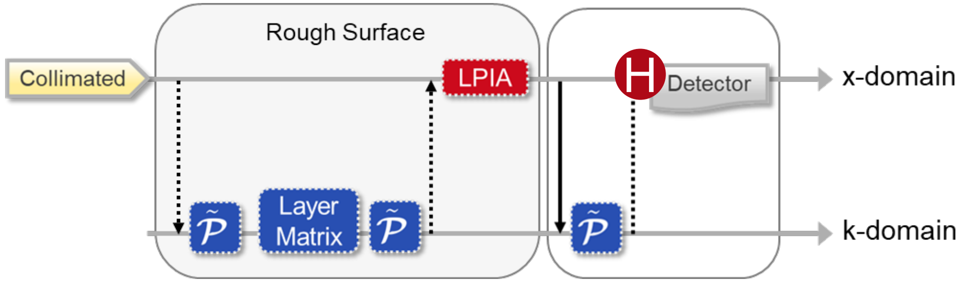
Rough Surface Modeling: Near Field



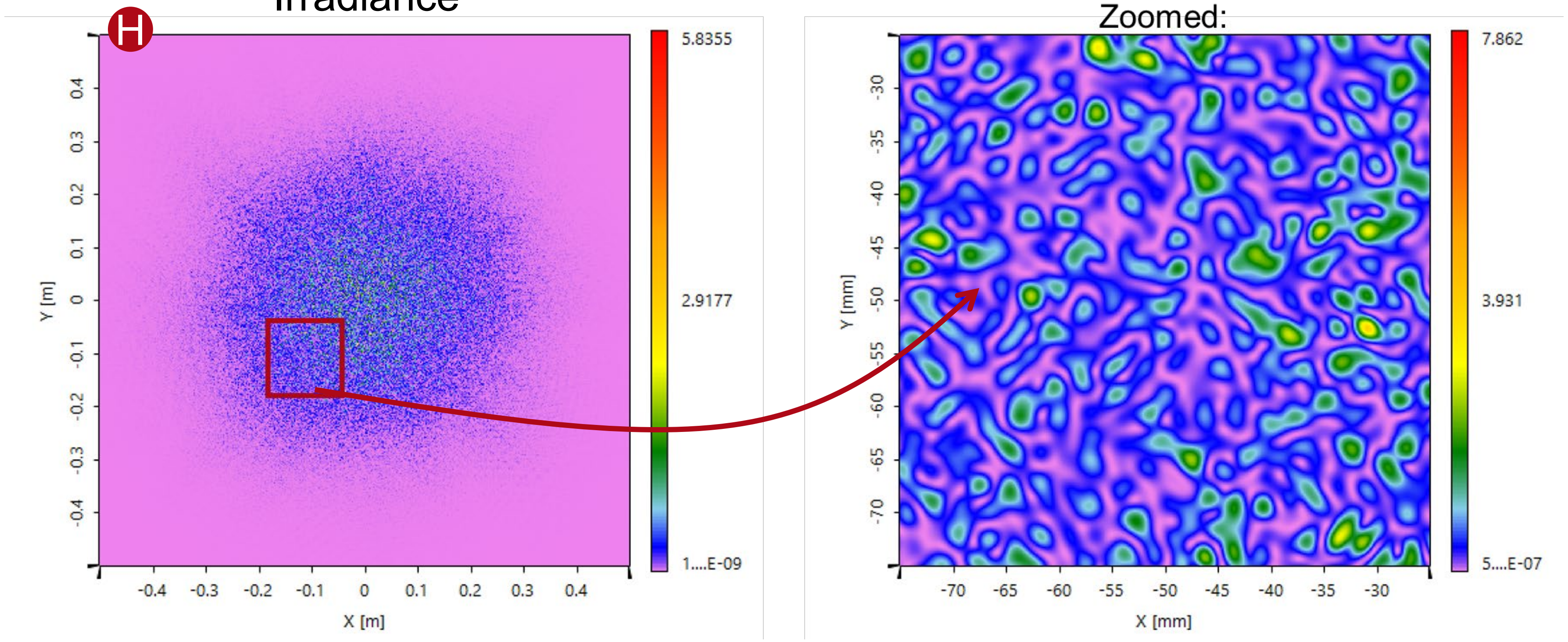




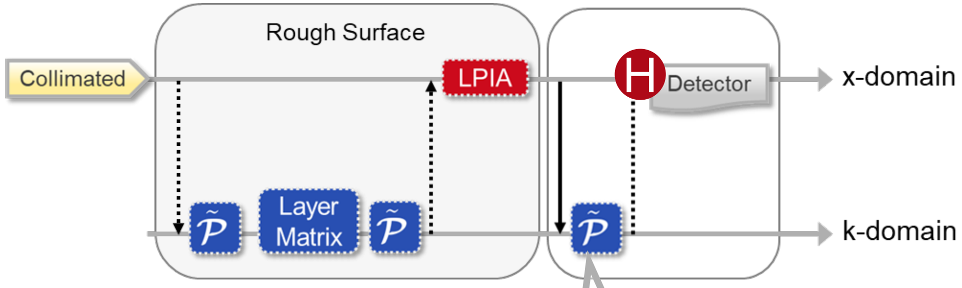
Rough Surface Modeling: Far Field



Irradiance



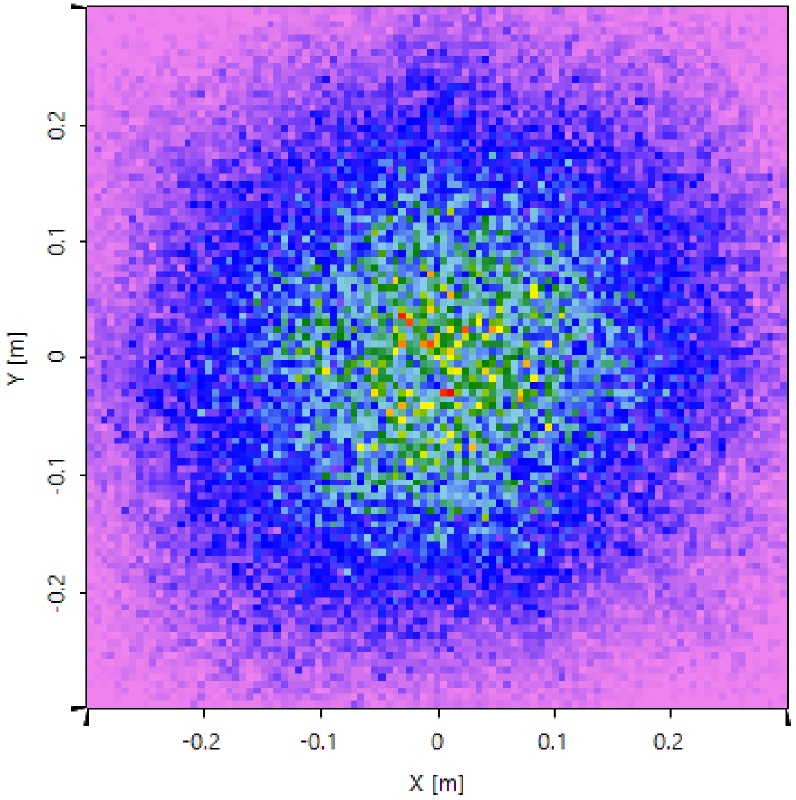
Rough Surface Modeling: Far Field

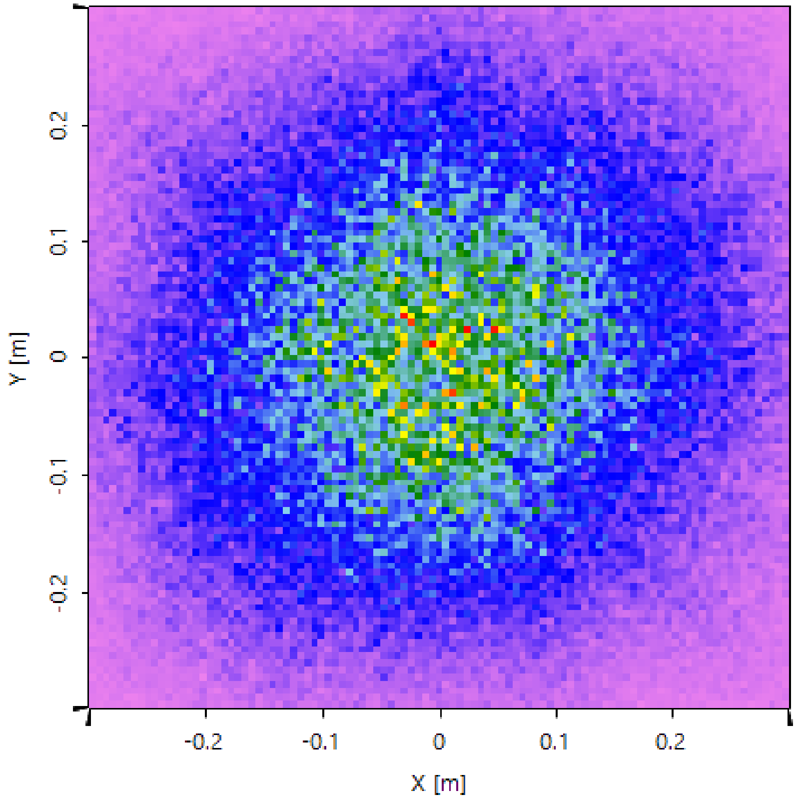


Modeling enables determination of BSDF of the rough surface!

Far Field Modeling: Monte Carlo vs. Physical Optics Modeling

Detector resolution: **101 x 101**





Monte Carlo

Number samples: 437.000

Simulation time: 10 seconds

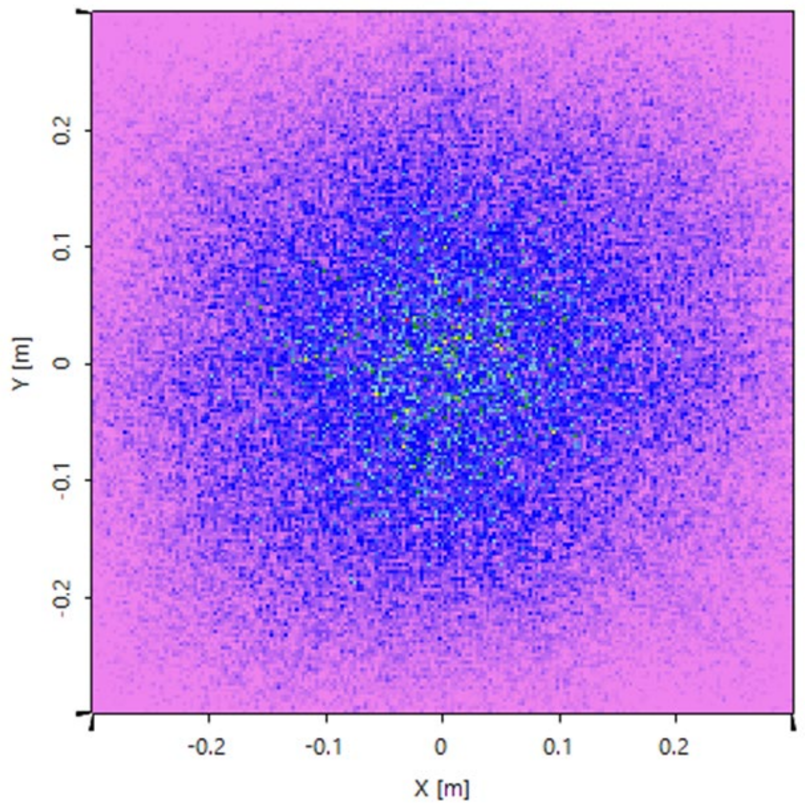
Physical Optics

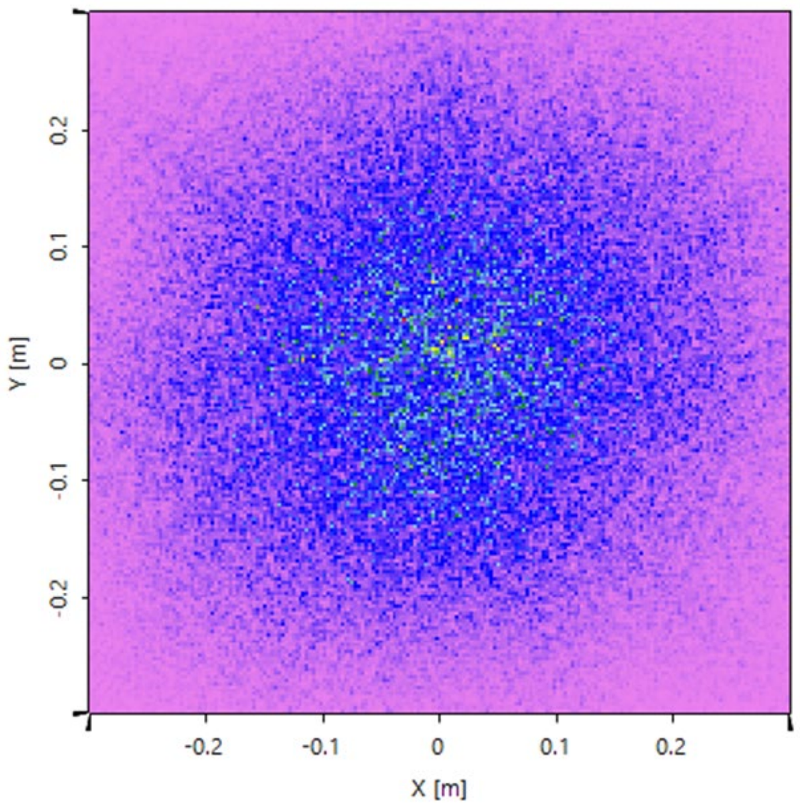
Number samples: 27.000

Simulation time: 5 seconds

Far Field Modeling: Monte Carlo vs. Physical Optics Modeling

Detector resolution: **201 x 201**





Monte Carlo

Number samples: 1.334.000

Simulation time: 27 seconds

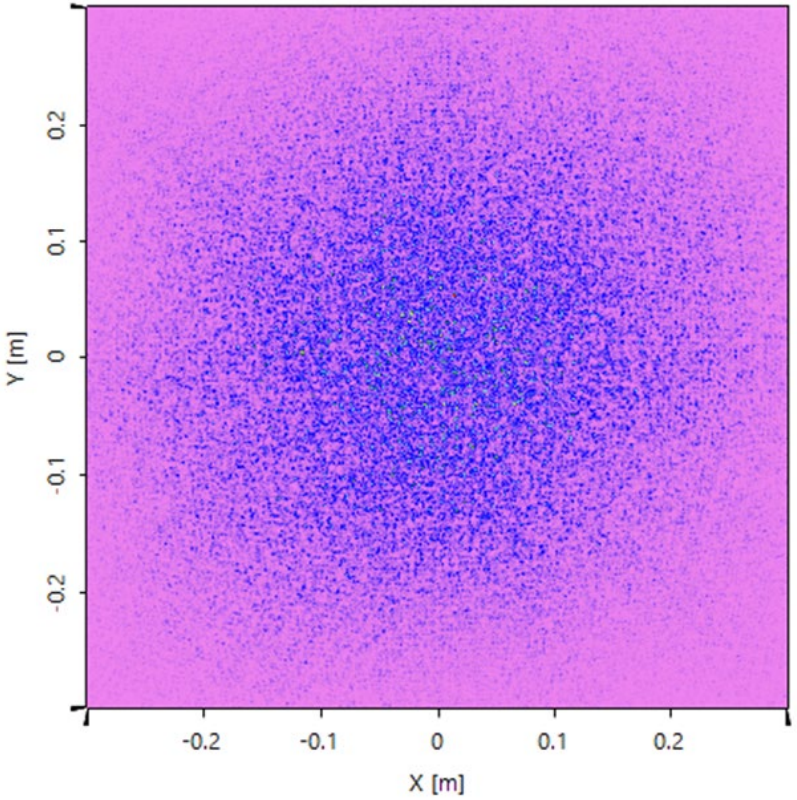
Physical Optics

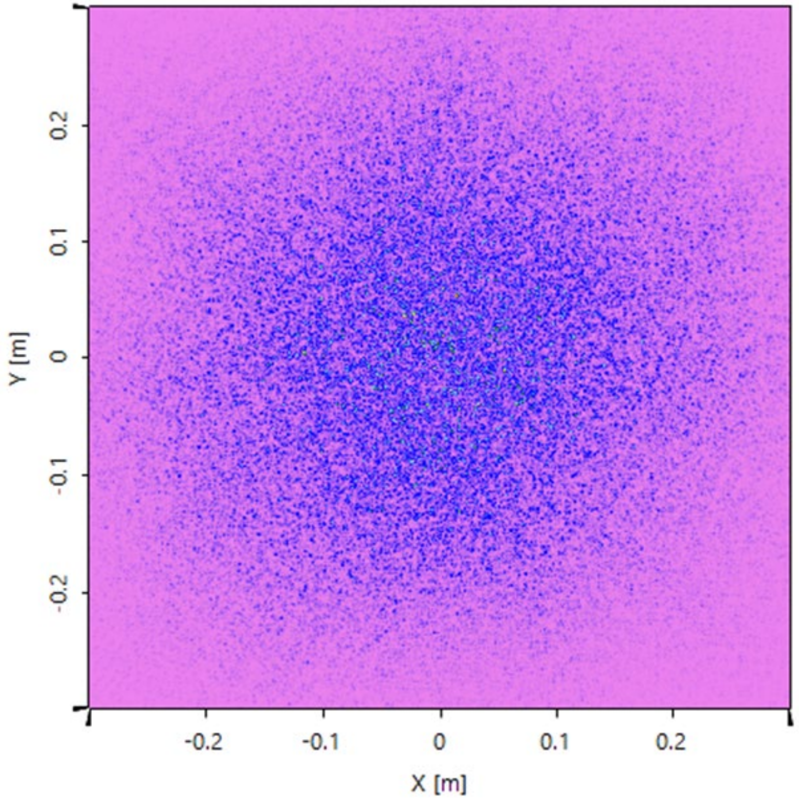
Number samples: 27.000

Simulation time: 5 seconds

Far Field Modeling: Monte Carlo vs. Physical Optics Modeling

Detector resolution: **401 x 401**





Monte Carlo

Number samples: 3.924.000

Simulation time: 77 seconds

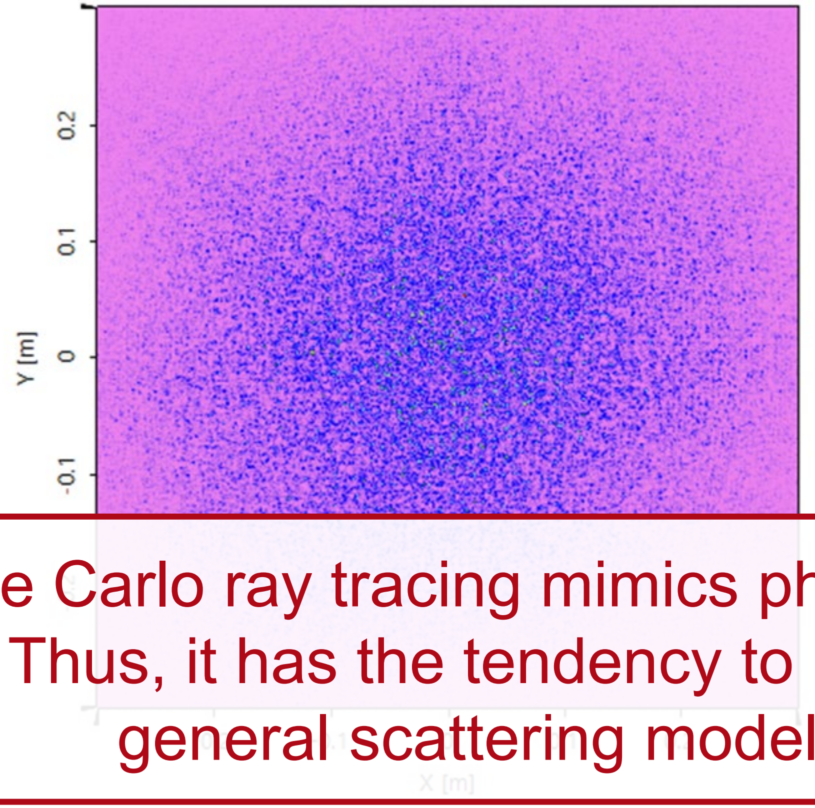
Physical Optics

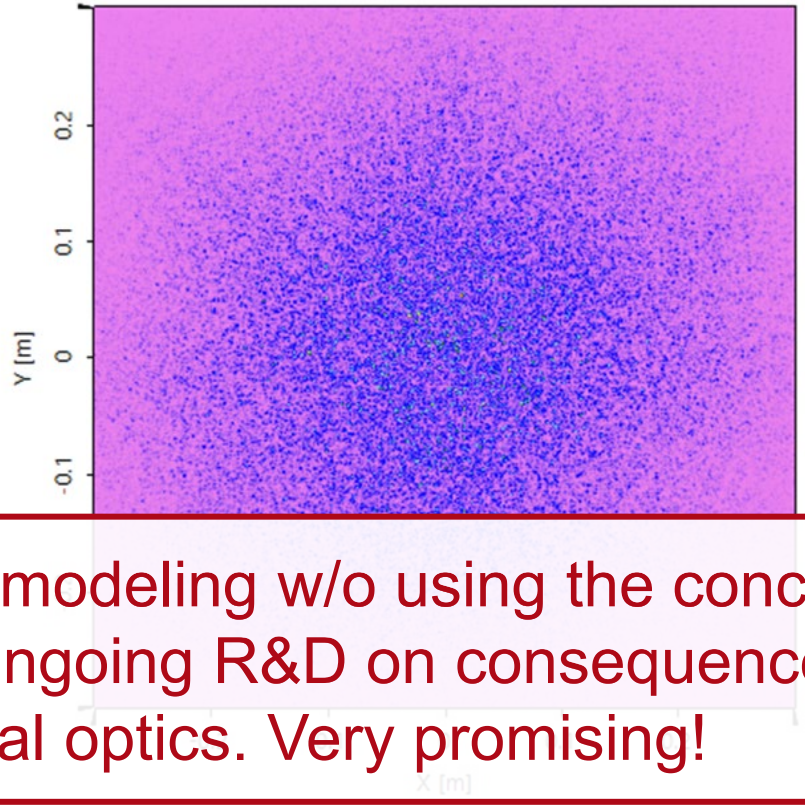
Number samples: 27.000

Simulation time: 5 seconds

Far Field Modeling: Monte Carlo vs. Physical Optics Modeling

Detector resolution: **401 x 401**





Monte Carlo ray tracing mimics physical optics modeling w/o using the concept of FFT. Thus, it has the tendency to be not fast. Ongoing R&D on consequences for general scattering modeling by physical optics. Very promising!

Monte Carlo

Number samples: 3.924.000

Simulation time: 77 seconds

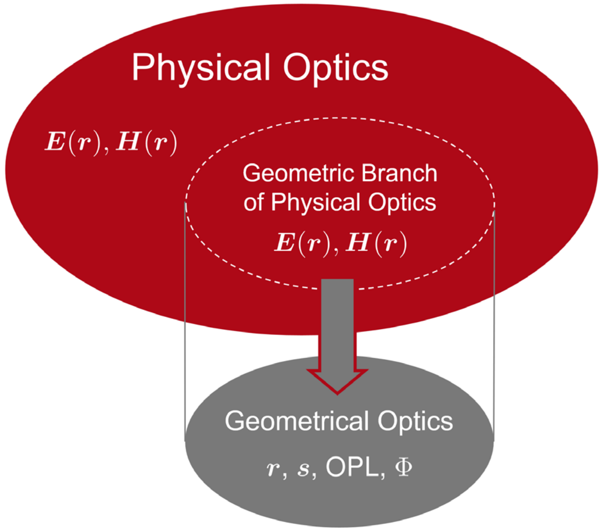
Physical Optics

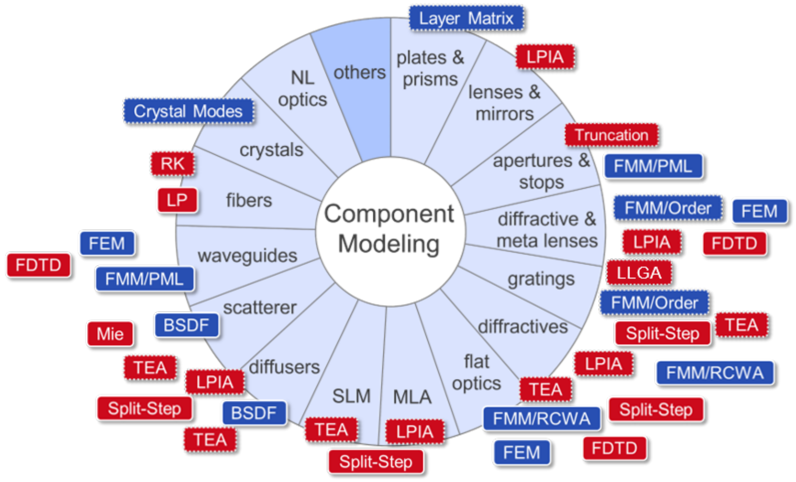
Number samples: 27.000

Simulation time: 5 seconds

Conclusions for Next Generation Software

- **Pointwise physical optics** modeling is included.
- Provide an open platform for connecting many physical optics modeling techniques: **connecting solvers – rigorous and approximated ones**.
- **Ray optics** is easily accessible **special mode of operation of physical optics**.
- CAD components and solvers are combined.
- Modeling of sources, components, and detectors can be customized to **unleash the flexibility and power of physical optics modeling**.
- Parametric optimization should be accompanied by inverse and other design approaches.





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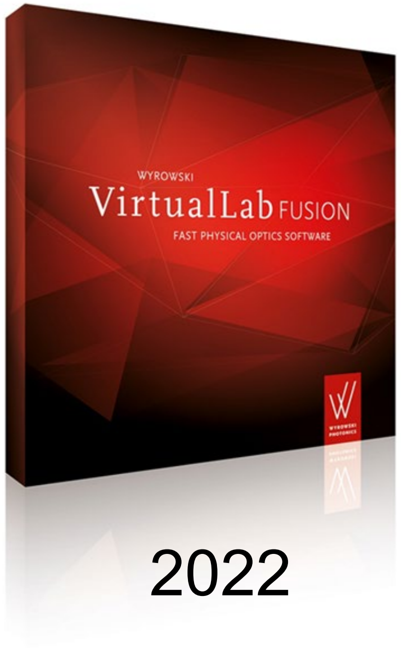

2022