



# PHOT 451: Microscale optical system design

## LECTURE 04

*Michaël Barbier, Fall semester (2025-2026)*

# OVERVIEW OF THE COURSE

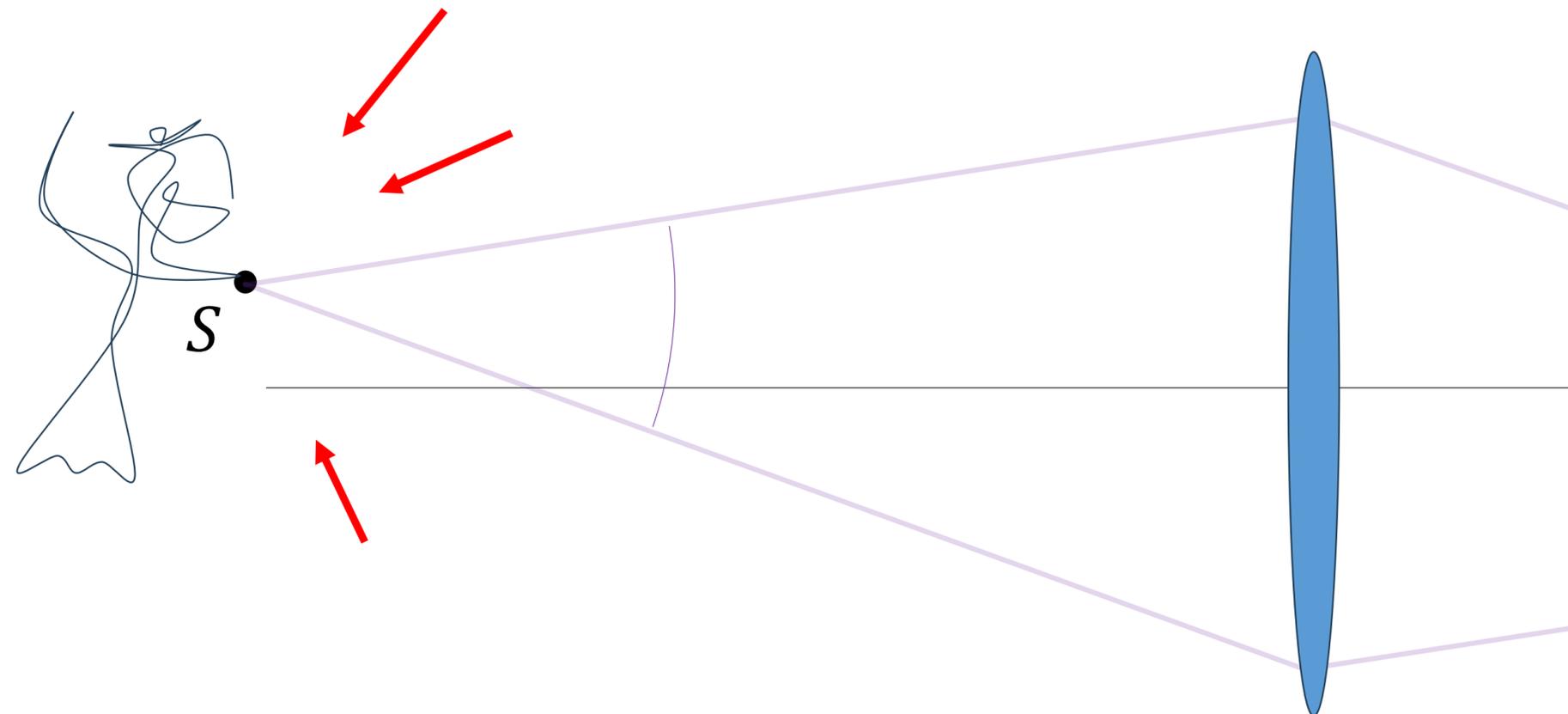
week	Topic
Week 1	Introduction to micro-scale optical components
Week 2	Light propagation in free space
Week 3	Geometric optics and raycasting
Week 4	Diffraction limit & Abberations
Week 5	<b>Quiz</b> + Beam propagation
Week 6	Refractive optical elements Microlenses
Week 7	Blazed Fresnel lenses
Week 8	Digital lenses
Week 9	Diffractive optical elements
Week 10	<b>Quiz</b> + Wave guides and beam propagation
Week 11	Wave mixing
Week 12	Gratings, periodic structures
Week 13	photonic crystals
Week 14	Whole optical system optimization



# Optical Systems for imaging

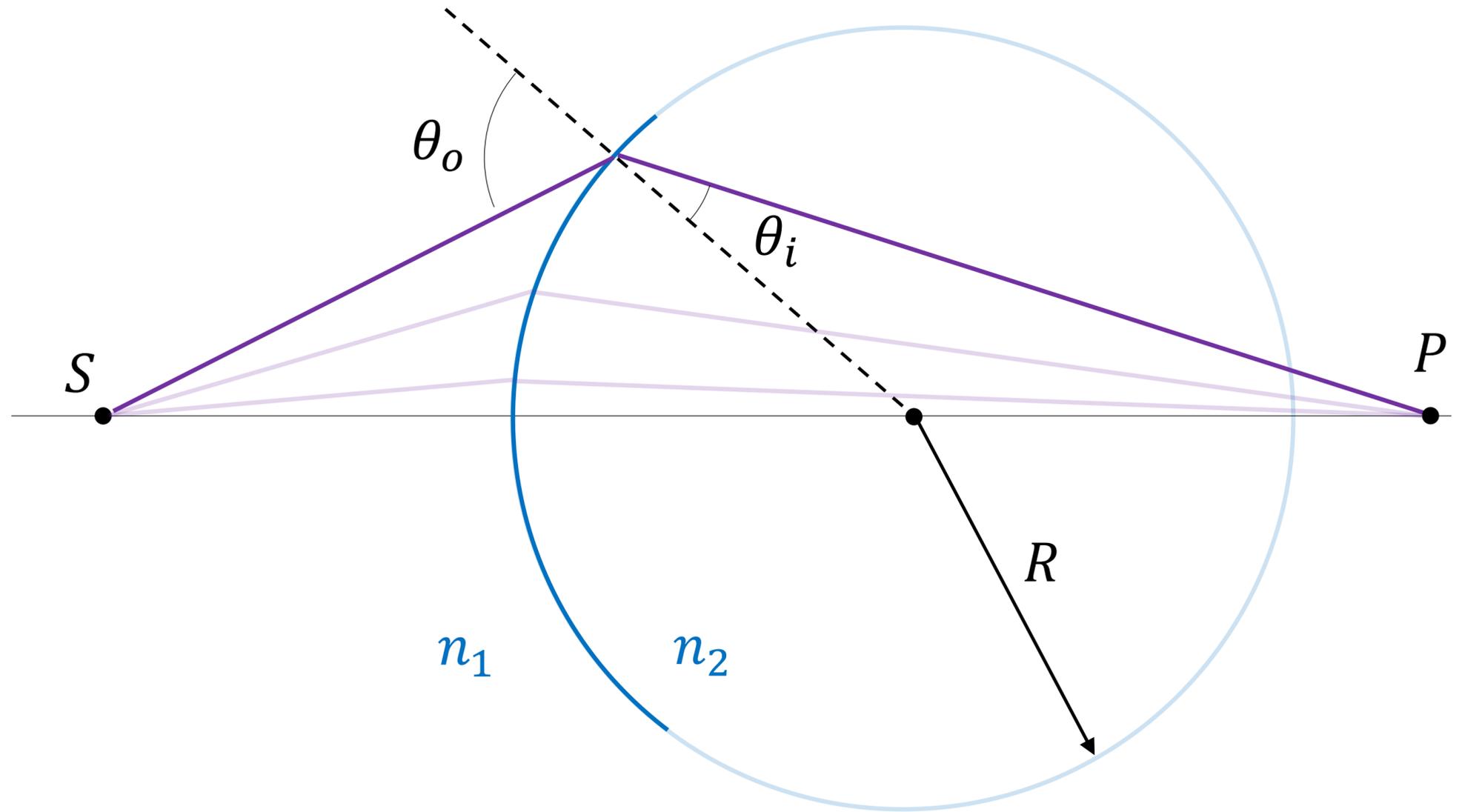
# IMAGING

- Light reflected from object
- Small angle of light captured by optical system



# DIRECTING LIGHT: SPHERICAL SURFACES

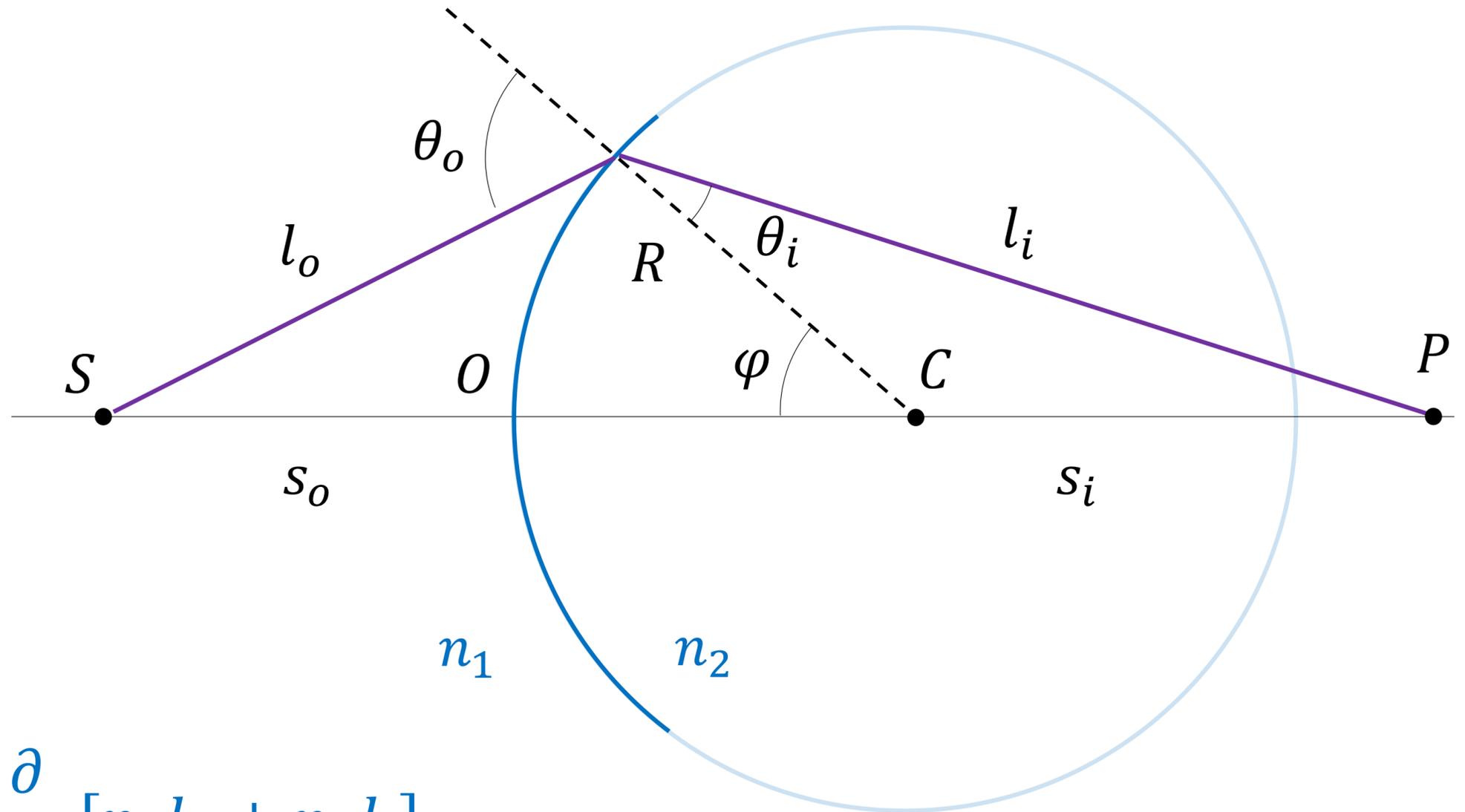
- Single surface
  - Curvature radius  $R$
  - Refraction index  $n_2$
- At surface: Snell's law
- Rays from  $S$  to  $P$  ?
- Apply Fermat's principle



# SPHERICAL SURFACES

- Optical Path Length

$$\begin{aligned} \text{OPL} &= \int_A^B n(x, y, z) dl \\ &= n_1 l_o + n_2 l_i \end{aligned}$$



- Fermat's principle

$$0 = \delta \left[ \int_A^B n(x, y, z) dl \right] = \frac{\partial}{\partial \varphi} [n_1 l_o + n_2 l_i]$$



$$\frac{1}{R} \left[ -\frac{n_1 s_o}{l_o} + \frac{n_2 s_i}{l_i} \right] = \frac{n_1}{l_o} + \frac{n_2}{l_i}$$

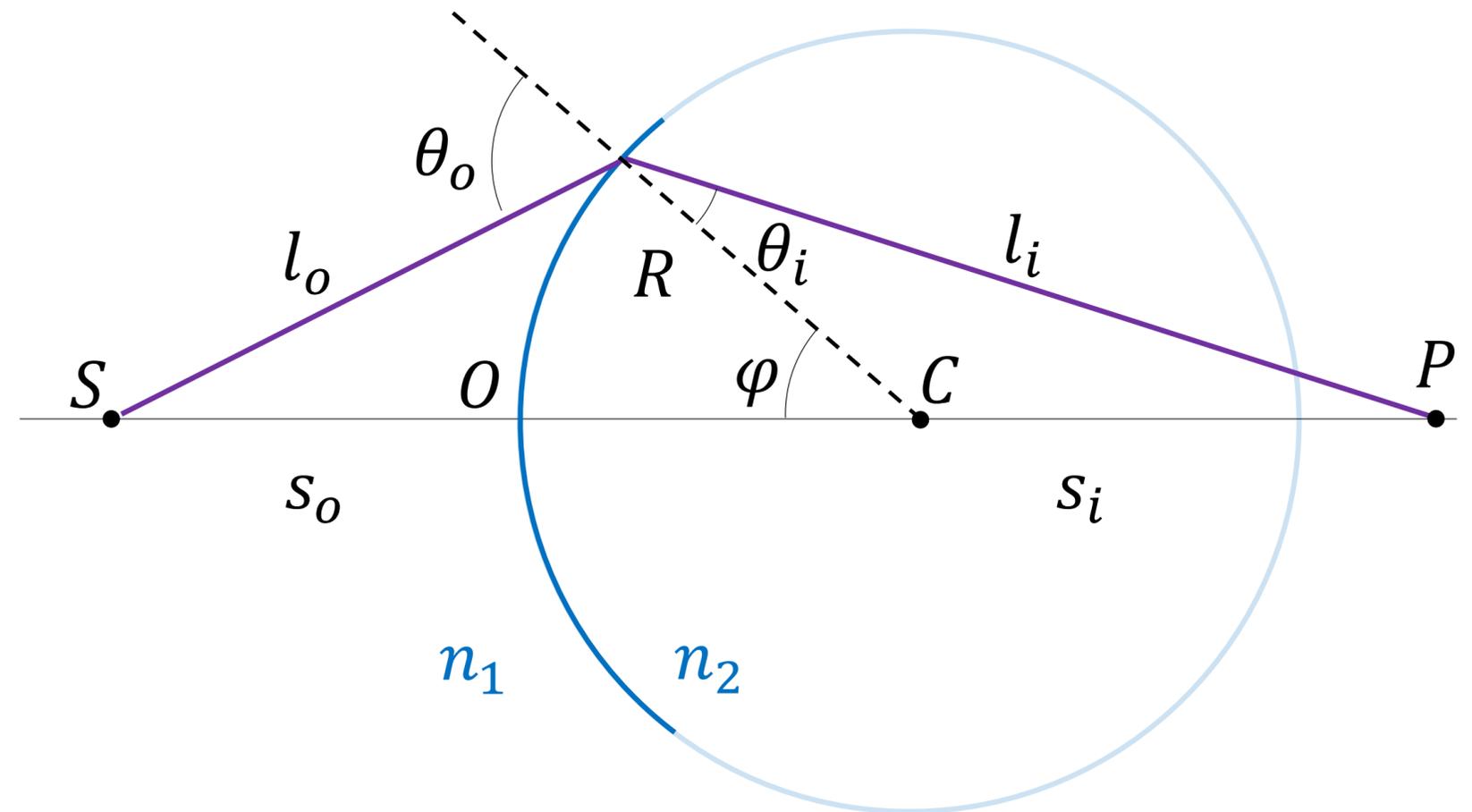
# SPHERICAL SURFACES

$$\frac{1}{R} \left[ -\frac{n_1 s_o}{l_o} + \frac{n_2 s_i}{l_i} \right] = \frac{n_1}{l_o} + \frac{n_2}{l_i}$$

- Problem: depends on  $\varphi$

- Paraxial approximation

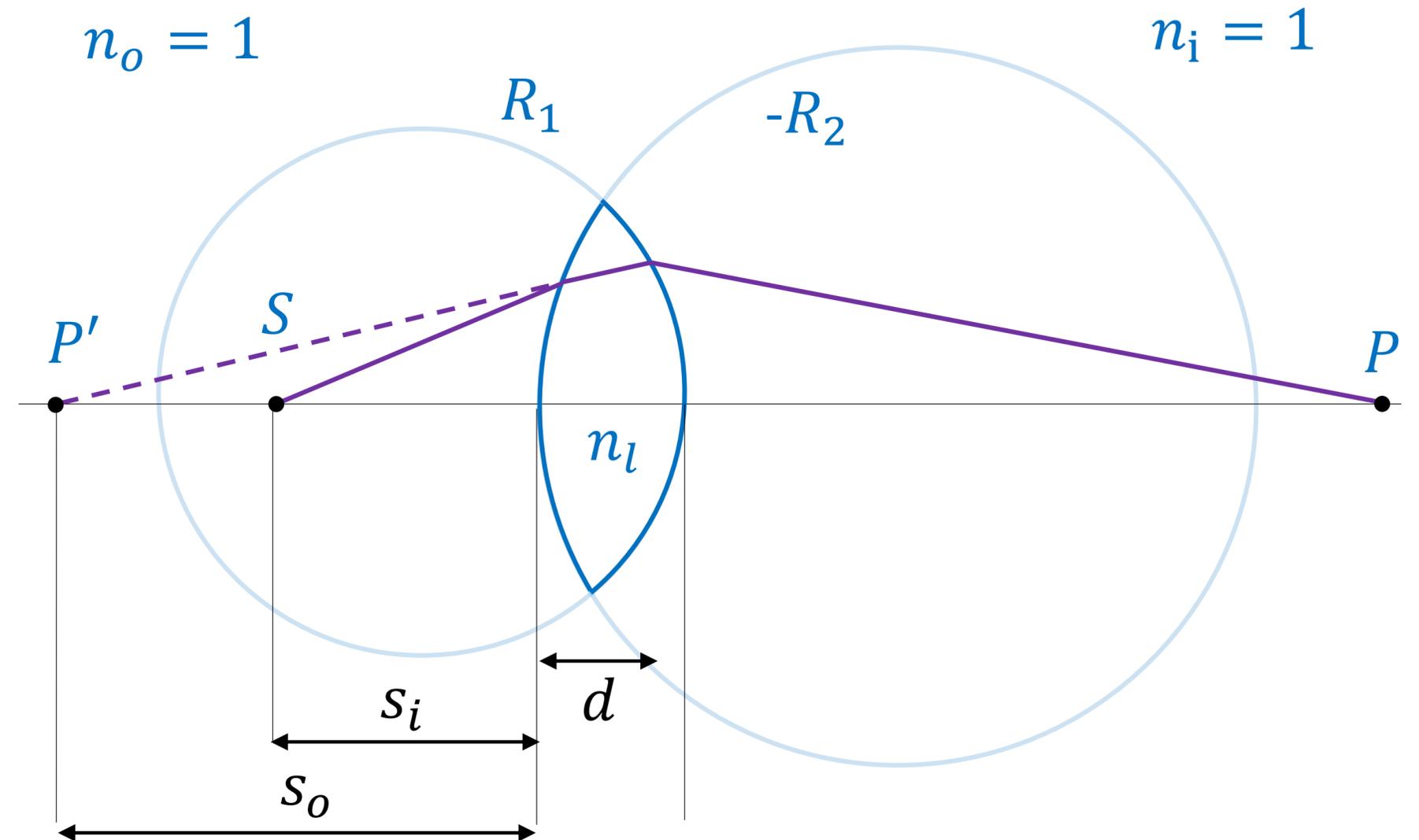
$$\cos \varphi \approx 1 \quad \& \quad s_o \approx l_o \quad \& \quad s_i \approx l_i$$



$$\frac{n_2 - n_1}{R} = \frac{n_1}{s_o} + \frac{n_2}{s_i}$$

# LENSMAKER'S FORMULA

- Paraxial approximation
- Thin lenses, in air  
 $n_o = n_i = 1$
- Perfect focus,  
image in plane



# A THIN LENS

- Paraxial approximation

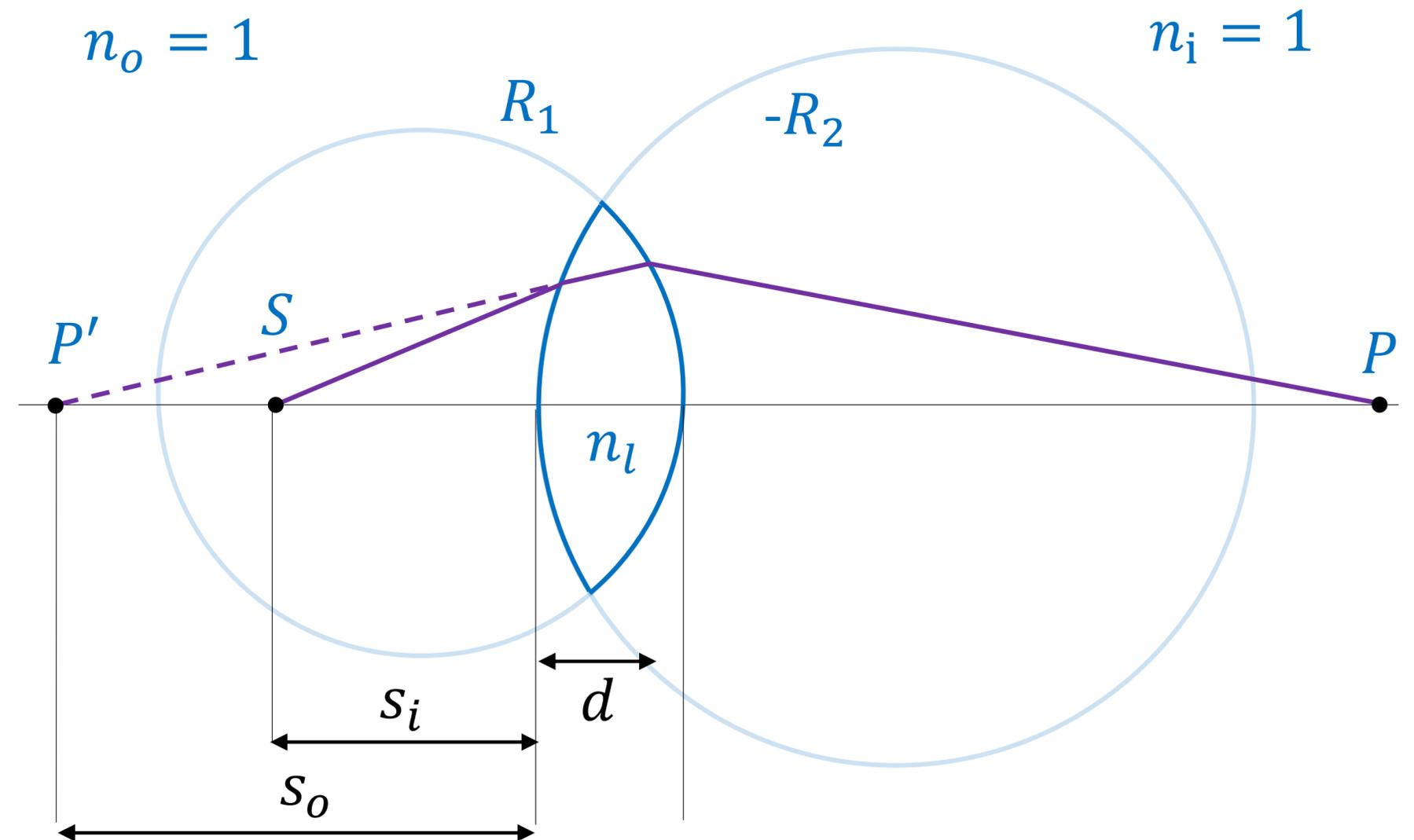
- Thin lenses, in air

$$n_o = n_i = 1$$

- Perfect focus, image in plane

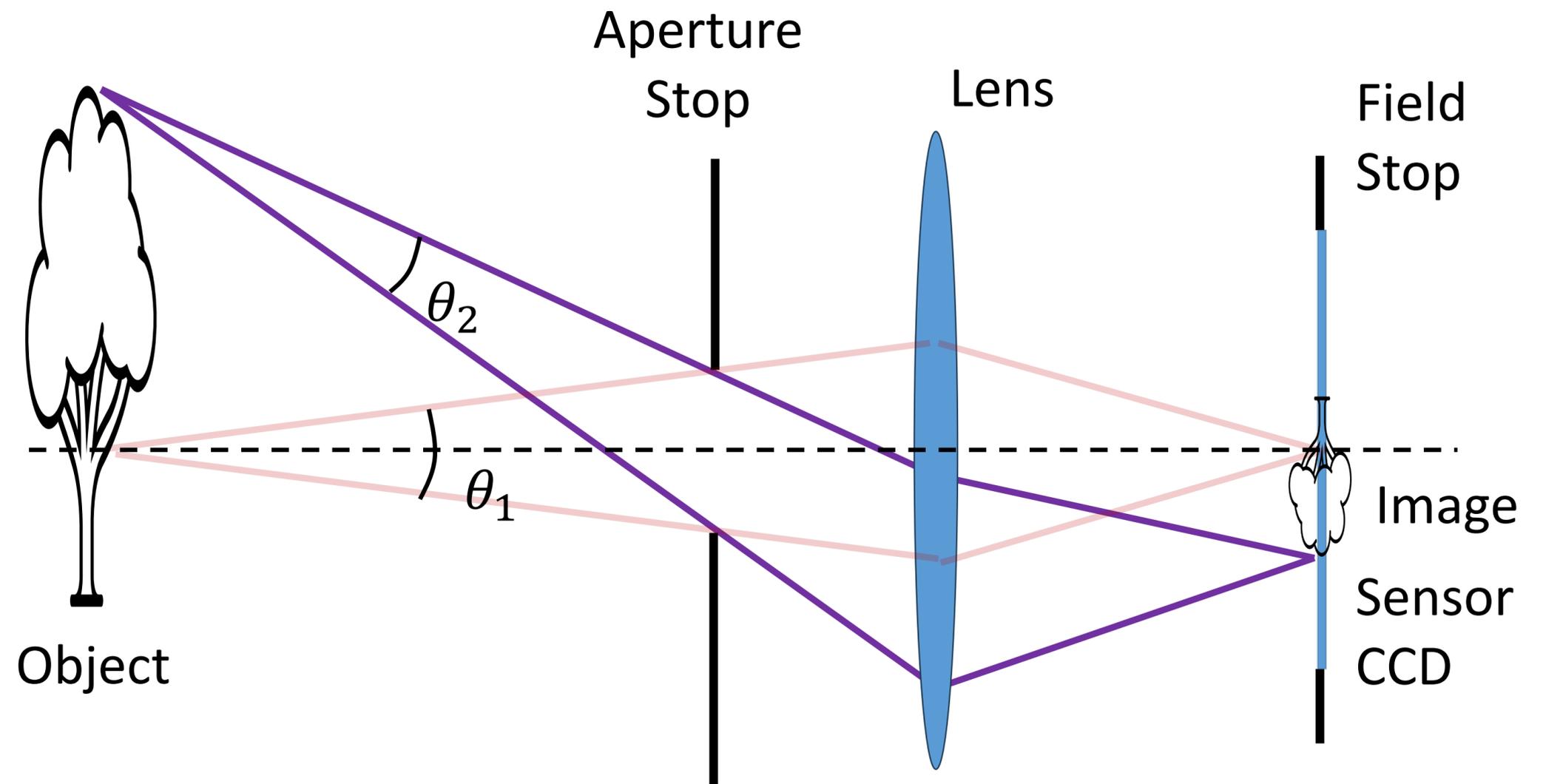
- The Lensmaker's formula

$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f} = (n_l - 1) \left( \frac{1}{R_1} - \frac{1}{R_2} \right)$$



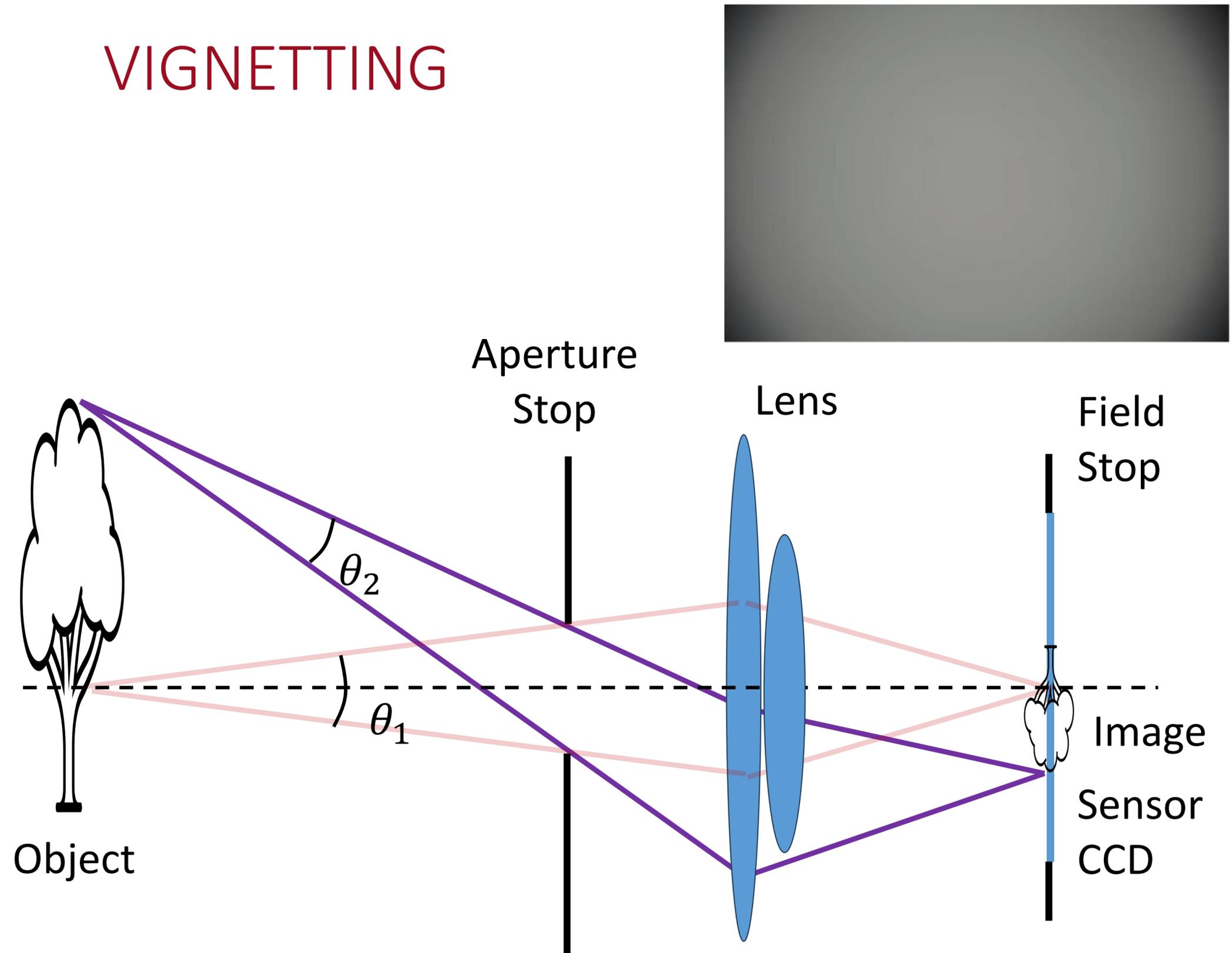
# WHOLE IMAGING SYSTEM

- Lenses
- Aperture stops
- Sensor, sensor size and field stops



# VIGNETTING

- Intensity depends on angle  $\theta$
- Angle  $\theta_2 < \theta_1$
- Edges have less intensity
- Apertures and clear lens diameters are important





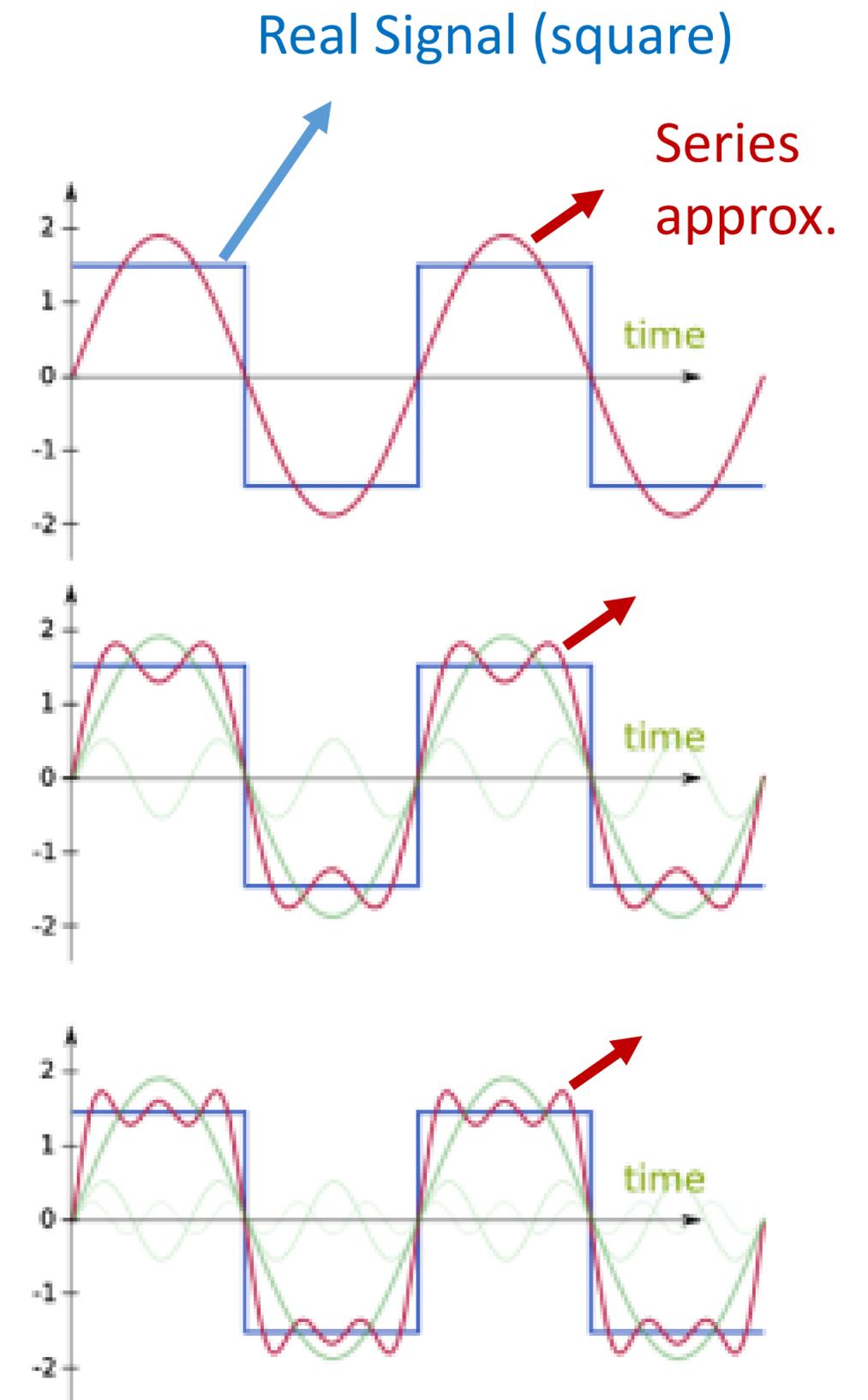
# The Diffraction Limit

# THE FOURIER SERIES

- Express signals in cosine + sines

$$f(x) = a_0 + \sum_{n=1}^{\infty} \left[ a_n \cos\left(\frac{2\pi n}{L}x\right) + b_n \sin\left(\frac{2\pi n}{L}x\right) \right]$$

- Examples
  - Square wave
  - sawtooth



Adapted from: Lê Nguyễn Hoàng, Fourier Analysis: Signals and Frequencies, Science4All

# THE FOURIER SERIES

- Express signals in cosine + sines

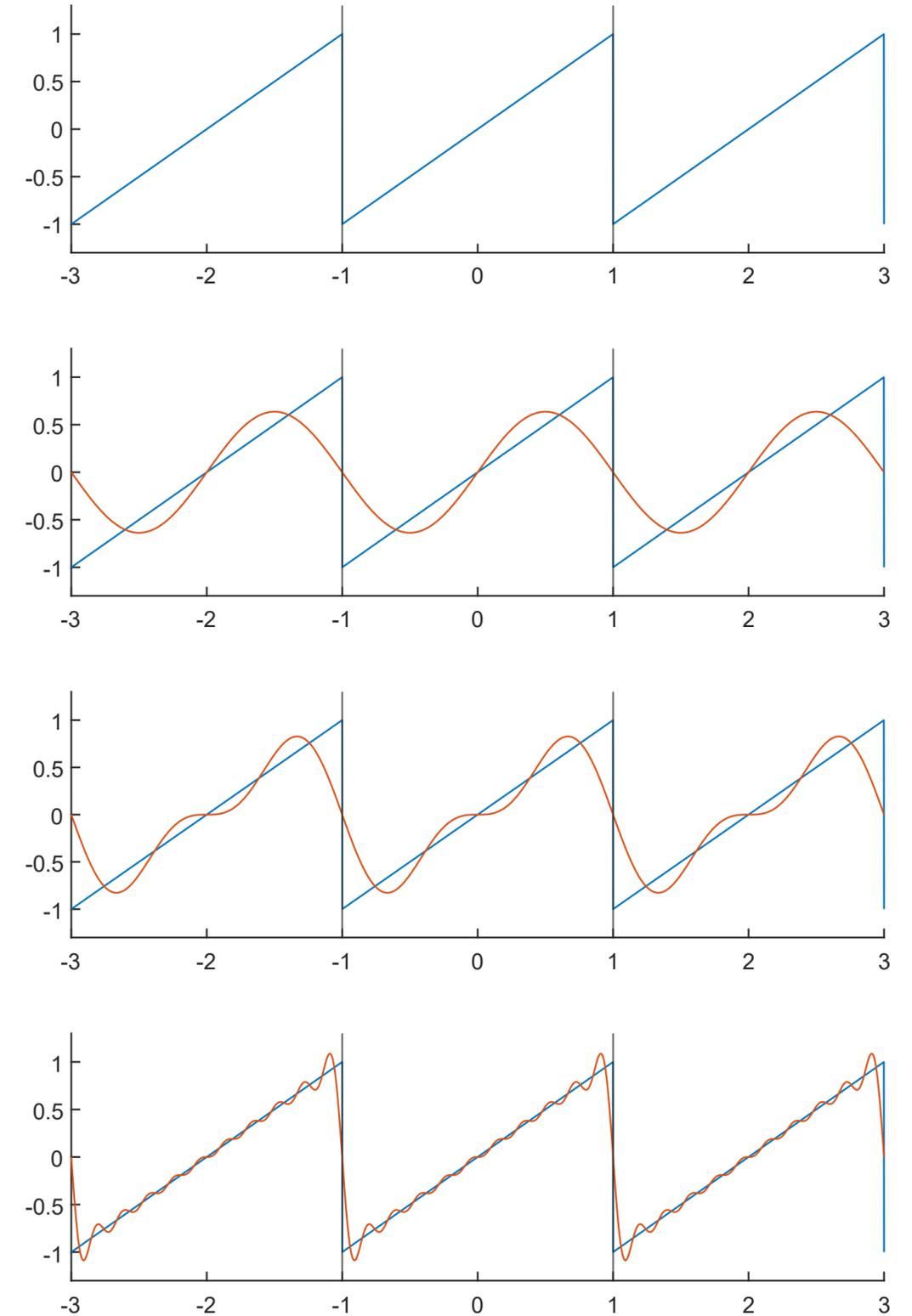
$$f(x) = a_0 + \sum_{n=1}^{\infty} \left[ a_n \cos\left(\frac{2\pi n}{L}x\right) + b_n \sin\left(\frac{2\pi n}{L}x\right) \right]$$

- Examples

- Square wave
- Sawtooth

- Artifacts

- Larger when series finite
- Can persist for infinite series



# THE FOURIER TRANSFORM

- Complex form

$$e^{i\phi} = \cos(\phi) + i \sin(\phi)$$

- Forward Spatial Fourier transform

$$f(x) = F_k^{-1}[\tilde{f}(k)] = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \tilde{f}(k) e^{ikx} dk$$

- Inverse Spatial Fourier transform

$$\tilde{f}(k) = F_x[f(x)] = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(x) e^{-ikx} dx$$

# THE FOURIER TRANSFORM

- Spatial Fourier transform

$$f(x) = F_k^{-1}[\tilde{f}(k)] = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \tilde{f}(k) e^{ikx} dk$$

$$\tilde{f}(k) = F_x[f(x)] = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(x) e^{-ikx} dx$$

- Frequency Fourier transform

$$f(t) = F_{\omega}^{-1}[\tilde{f}(\omega)] = \int_{-\infty}^{\infty} \tilde{f}(\omega) e^{-i\omega t} d\omega$$

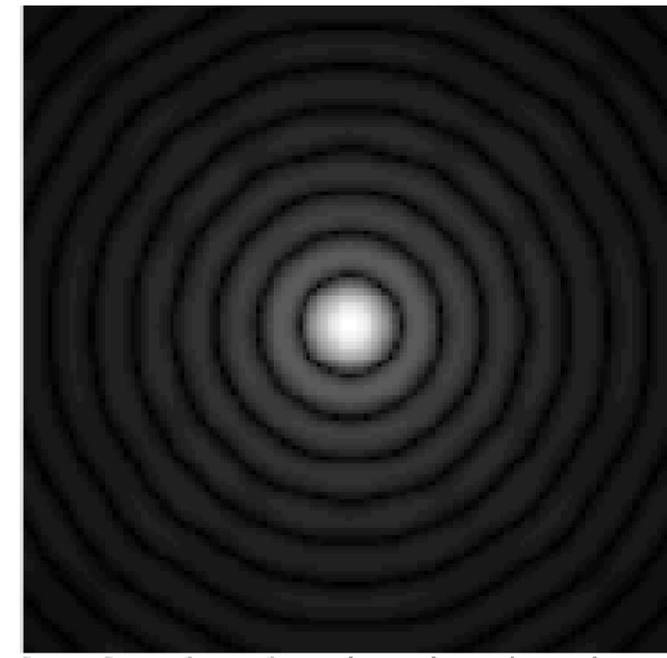
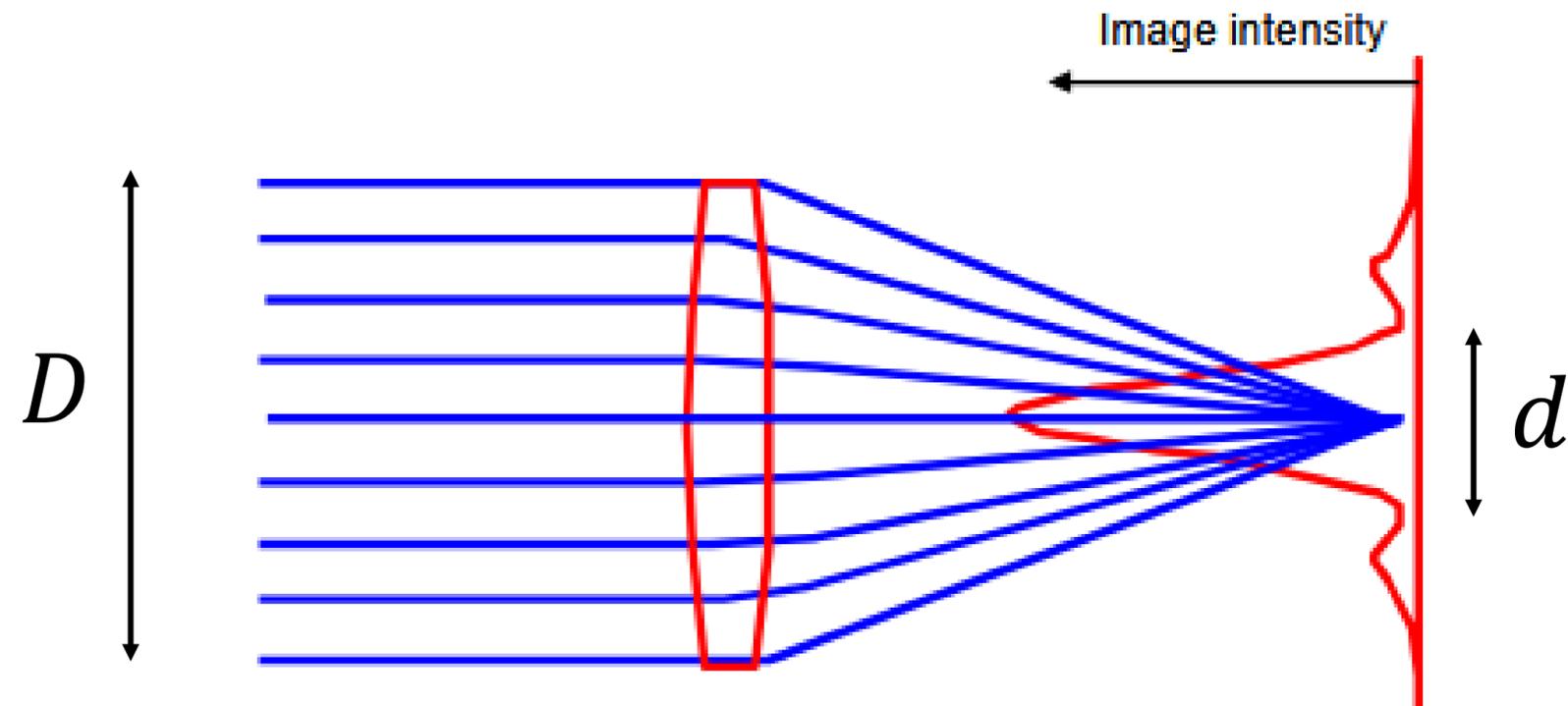
$$\tilde{f}(\omega) = F_t[f(t)] = \frac{1}{2\pi} \int_{-\infty}^{\infty} f(t) e^{i\omega t} dt$$

# THE POINT SPREAD FUNCTION

- Airy disk diameter

$$d = 2.44 \lambda \frac{f}{D}$$

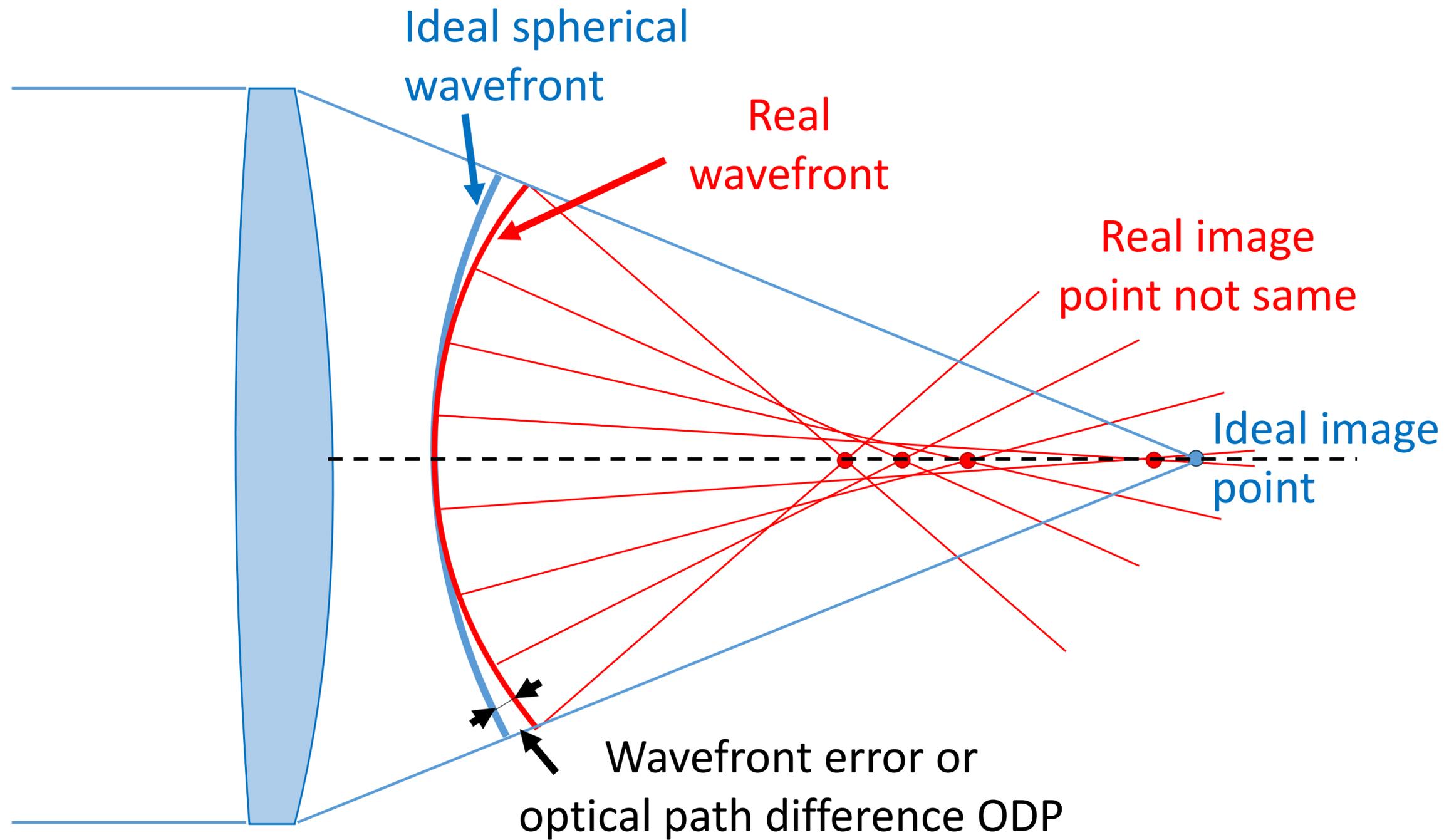
- First ring of the Point Spread Function  
84% of the intensity



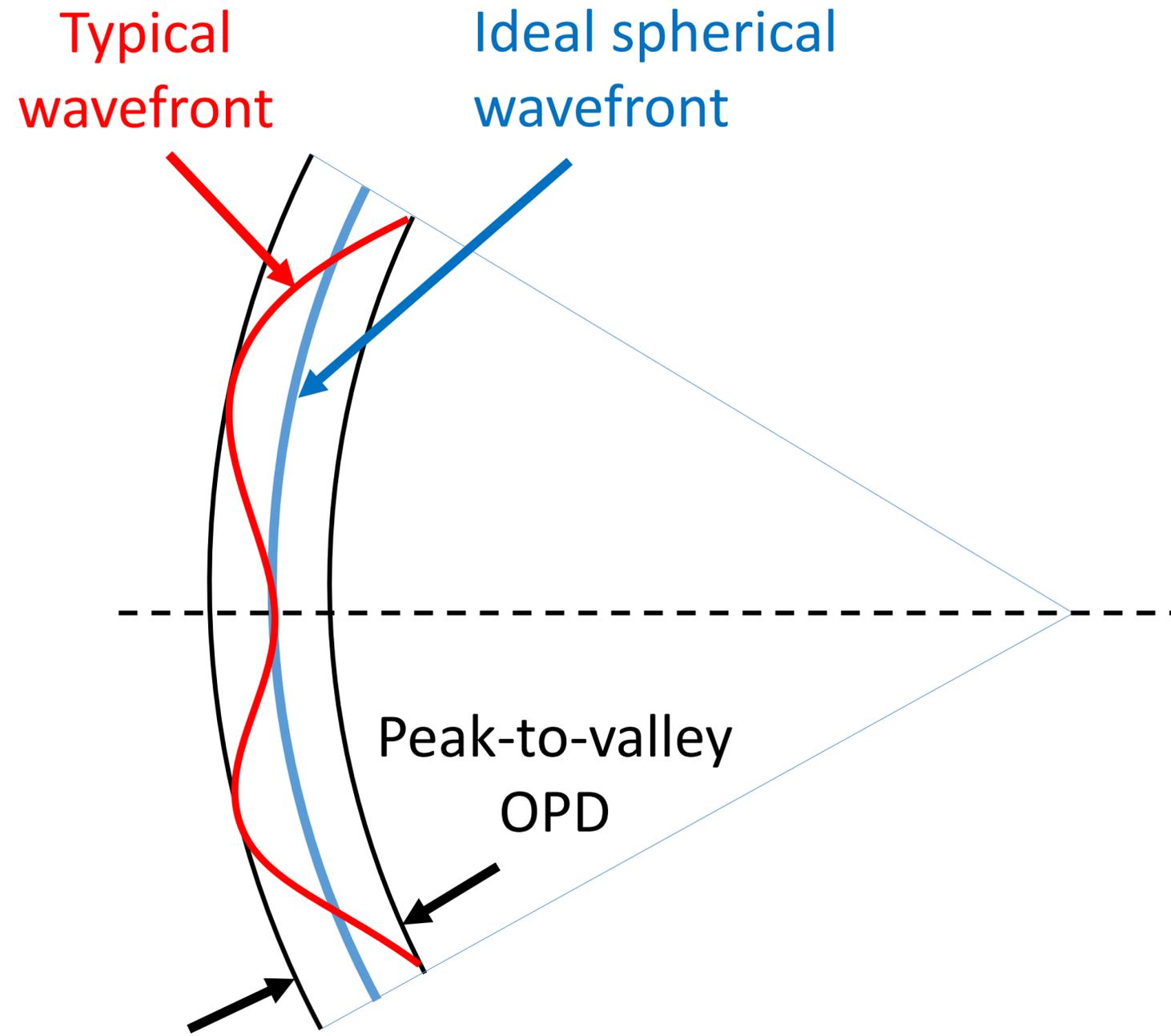


# Aberrations

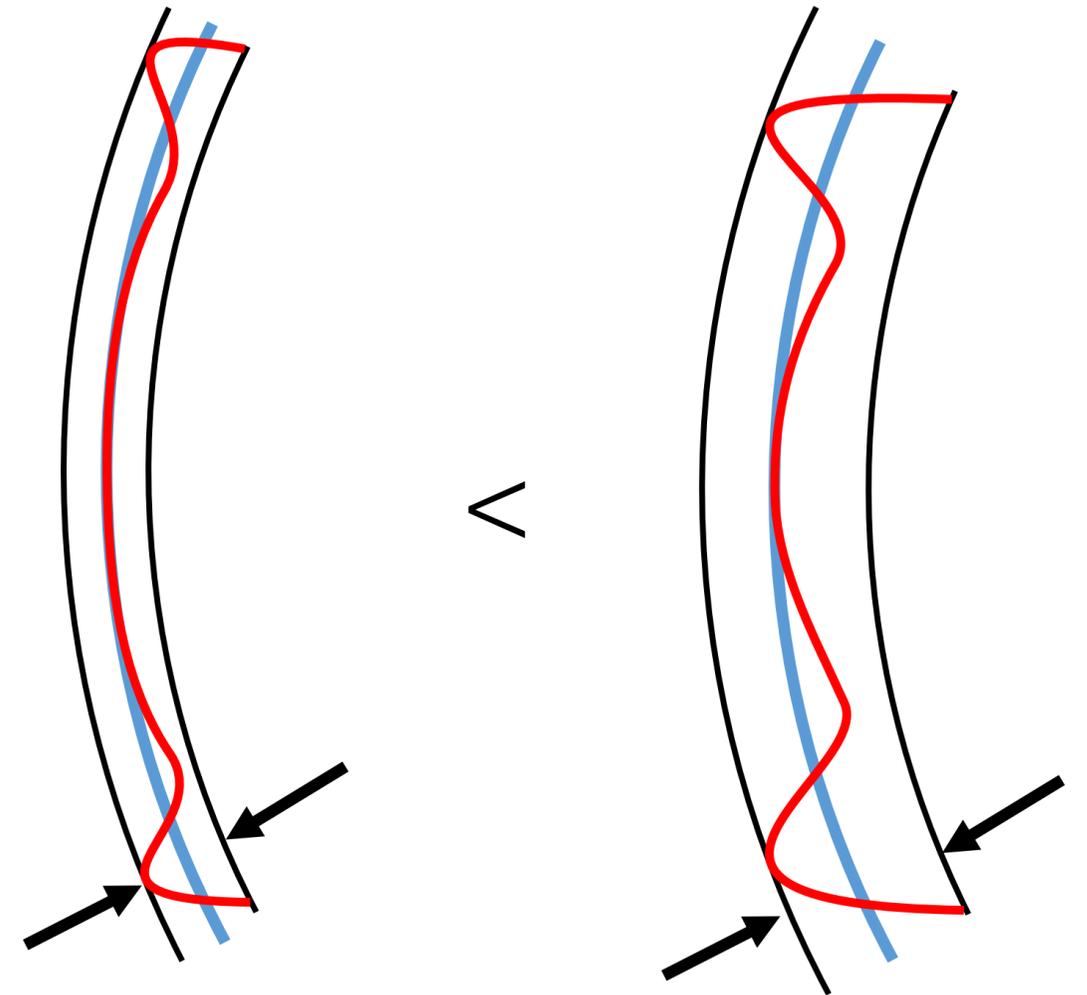
# OPTICAL PATH DIFFERENCE



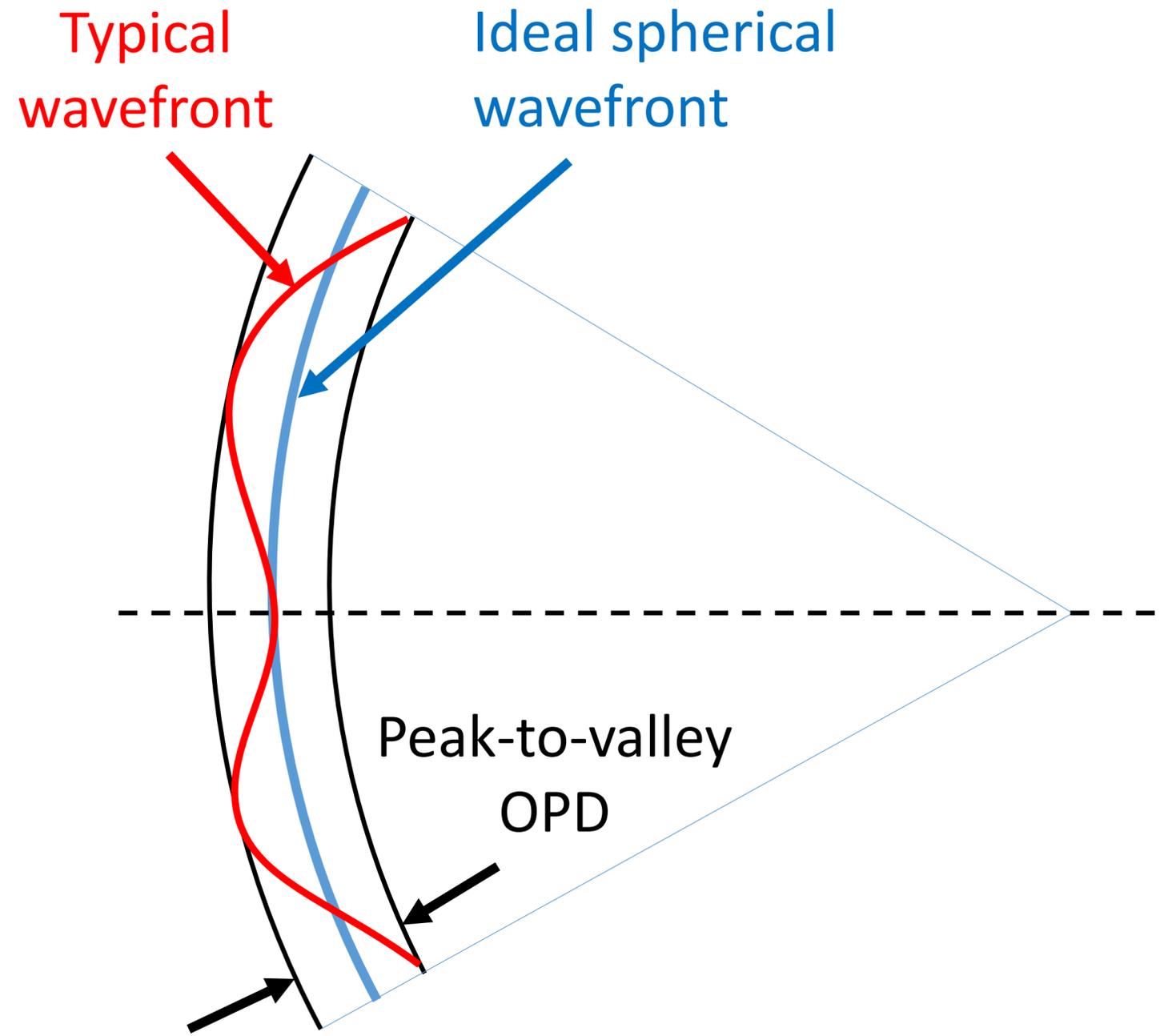
# OPTICAL PATH DIFFERENCE



## Peak-to-valley OPD

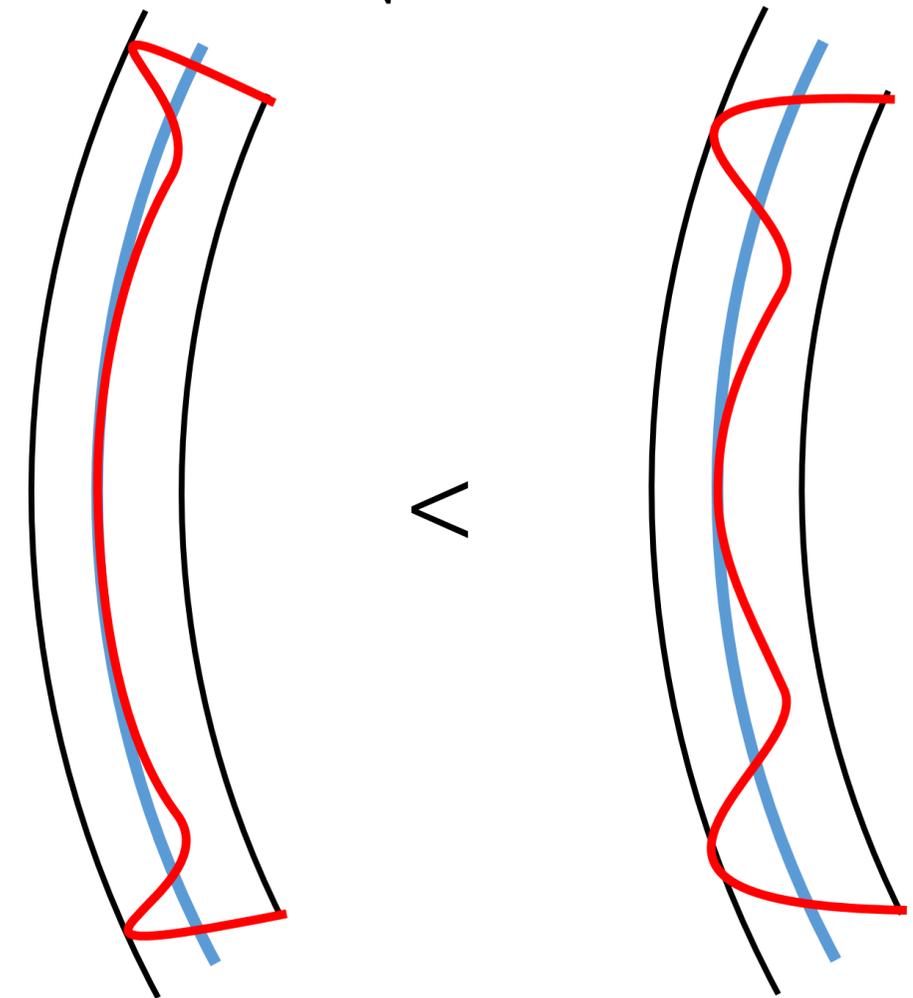


# OPTICAL PATH DIFFERENCE

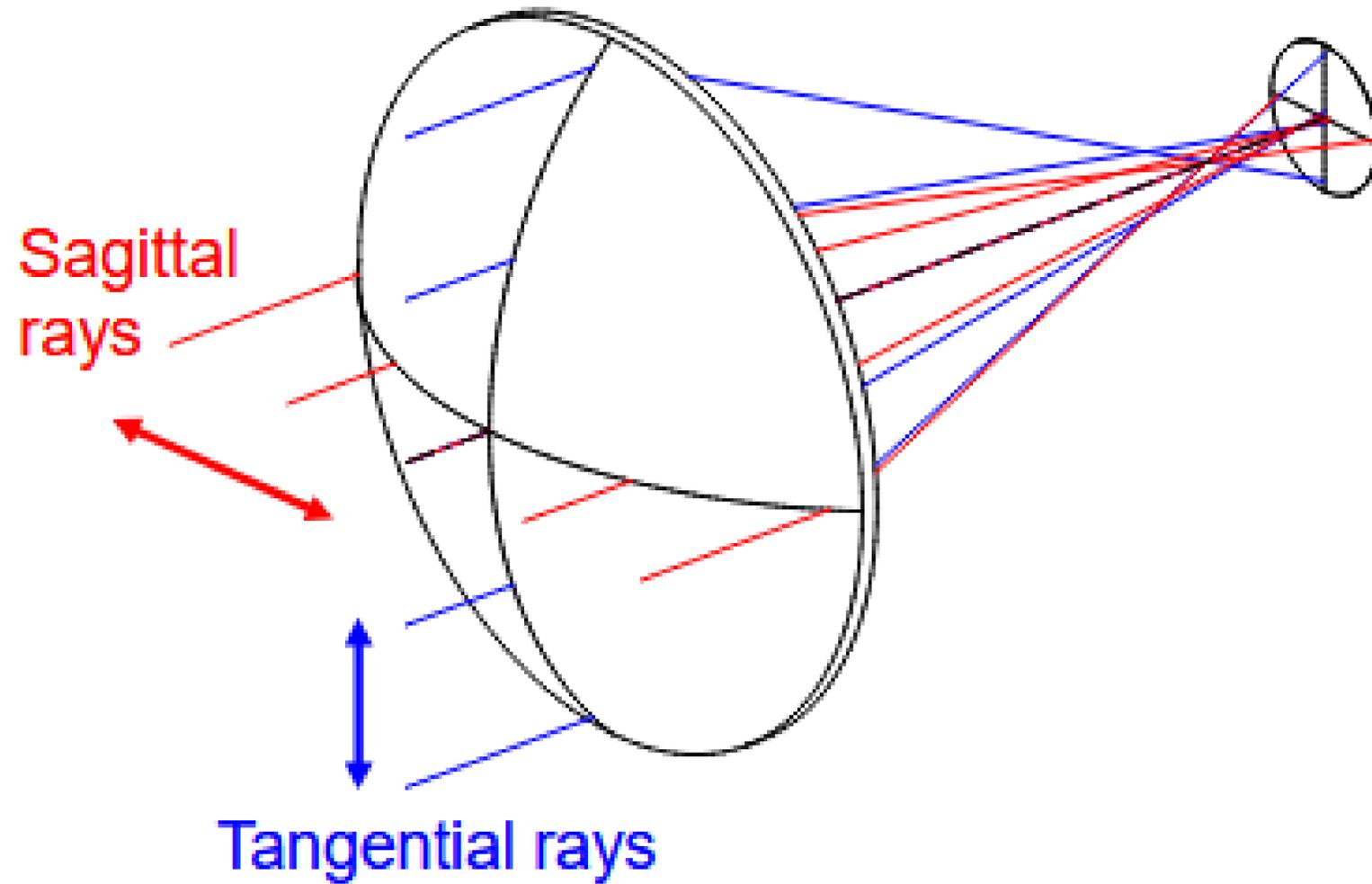


## Root Mean Square RMS OPD

$$\text{RMS} = \sqrt{\sum_j \text{OPD}^2 / N}$$

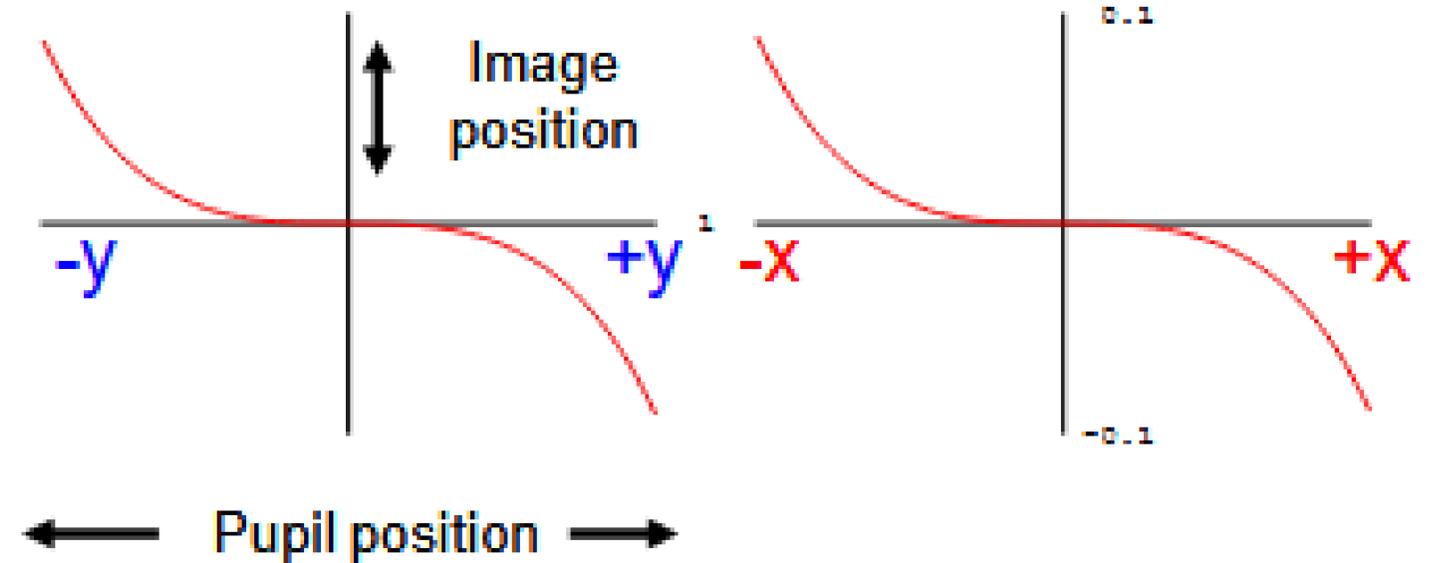


# RAY ABERRATION CURVES



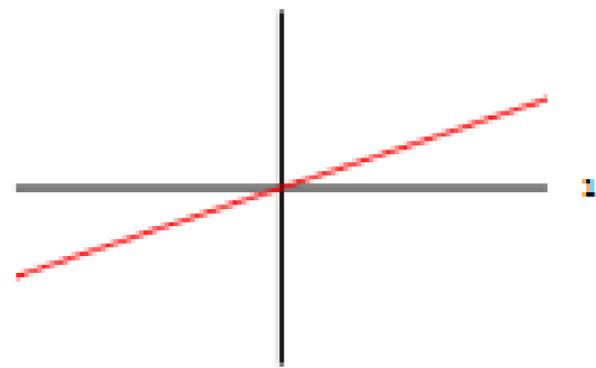
$\Delta y$  values for tangential rays

$\Delta x$  values for sagittal rays

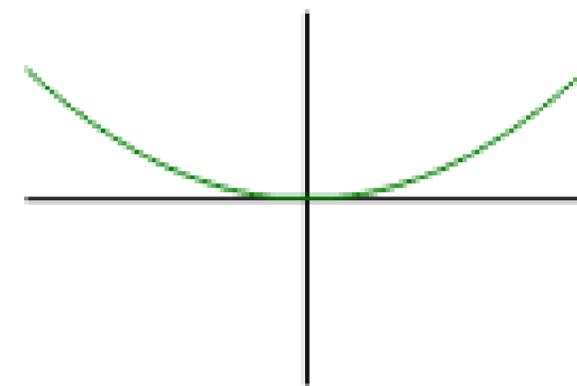
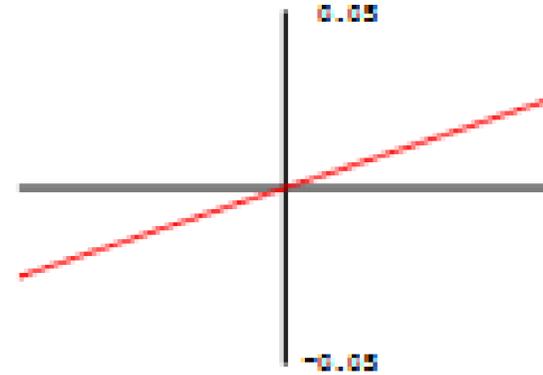


# ABBERATION TYPES AND RAY ABERRATION CURVES

Tangential fan

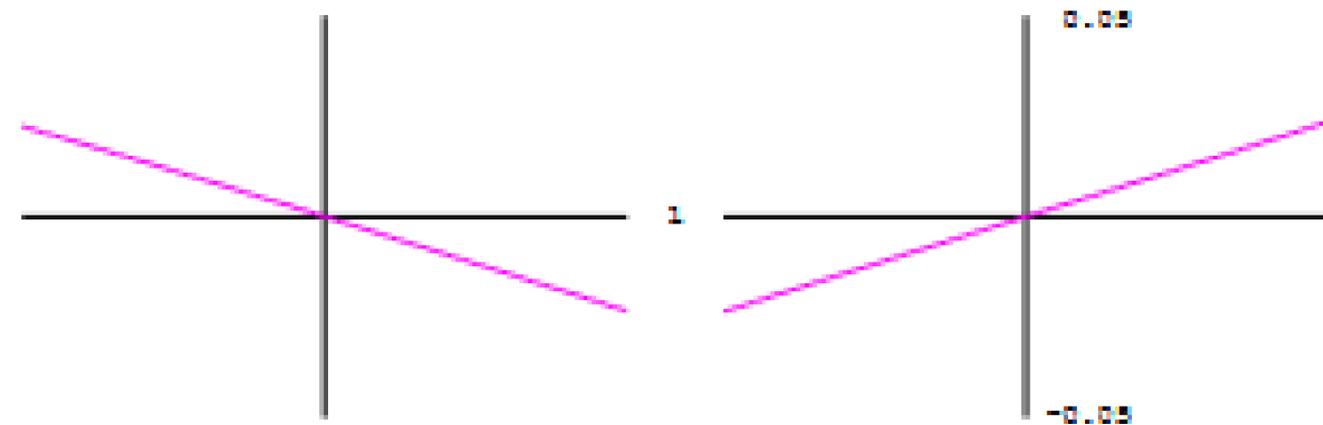
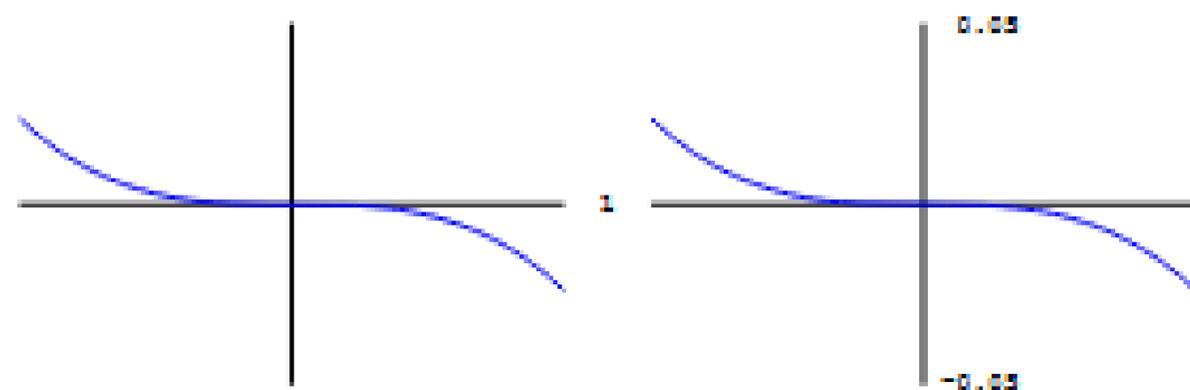


Sagittal fan



Defocus

Coma



Third-order spherical

Astigmatism



# ZEMAX Practical session

# SPOT DIAGRAM

Start ZEMAX

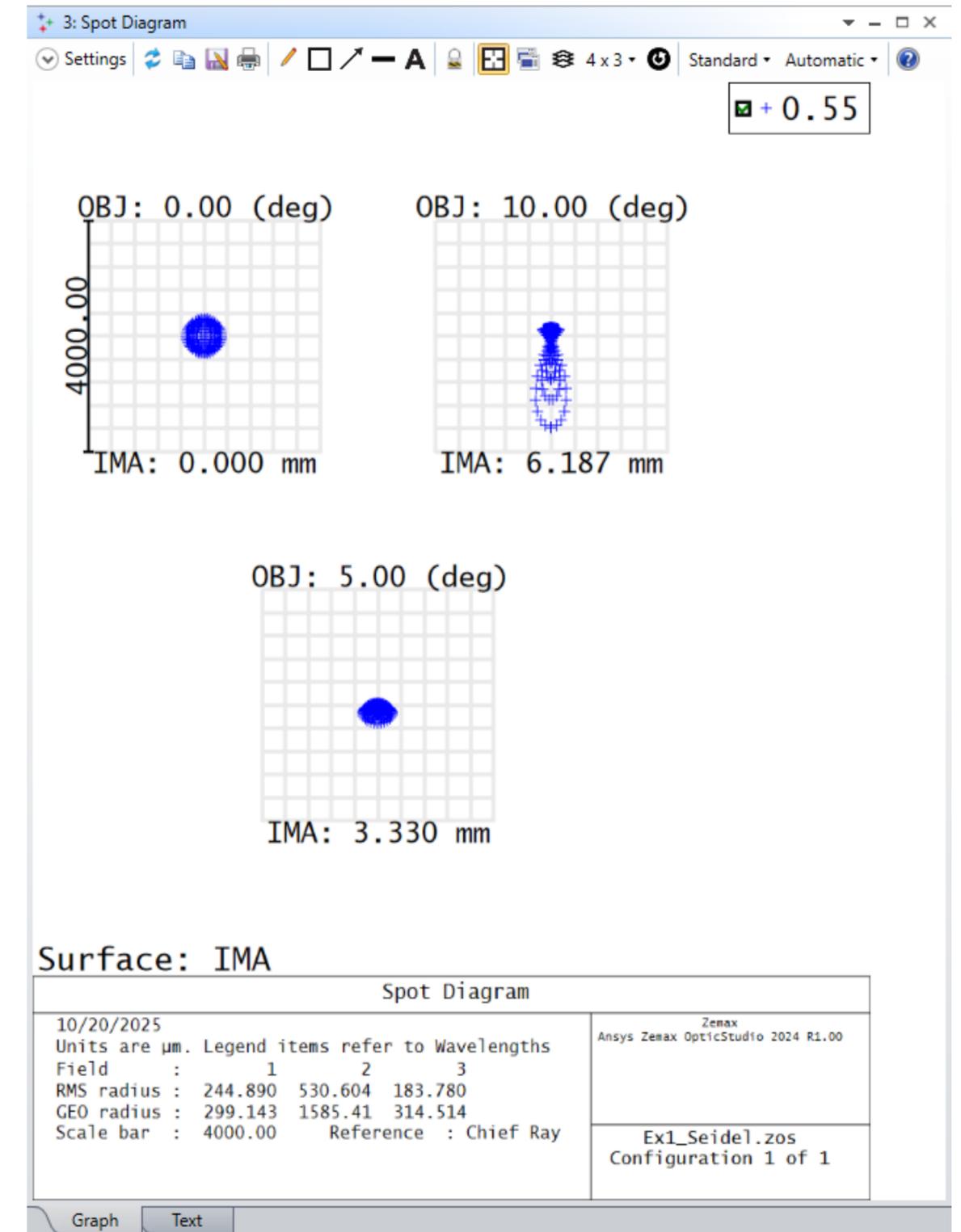
Save your file

Open convenient tabs:

1. System Explorer
2. Lens Data
3. Field Data Editor
4. Wavelength Data
5. Layout

# SPOT DIAGRAM

## Analysis – Rays & Spots – Standard Spot Diagram



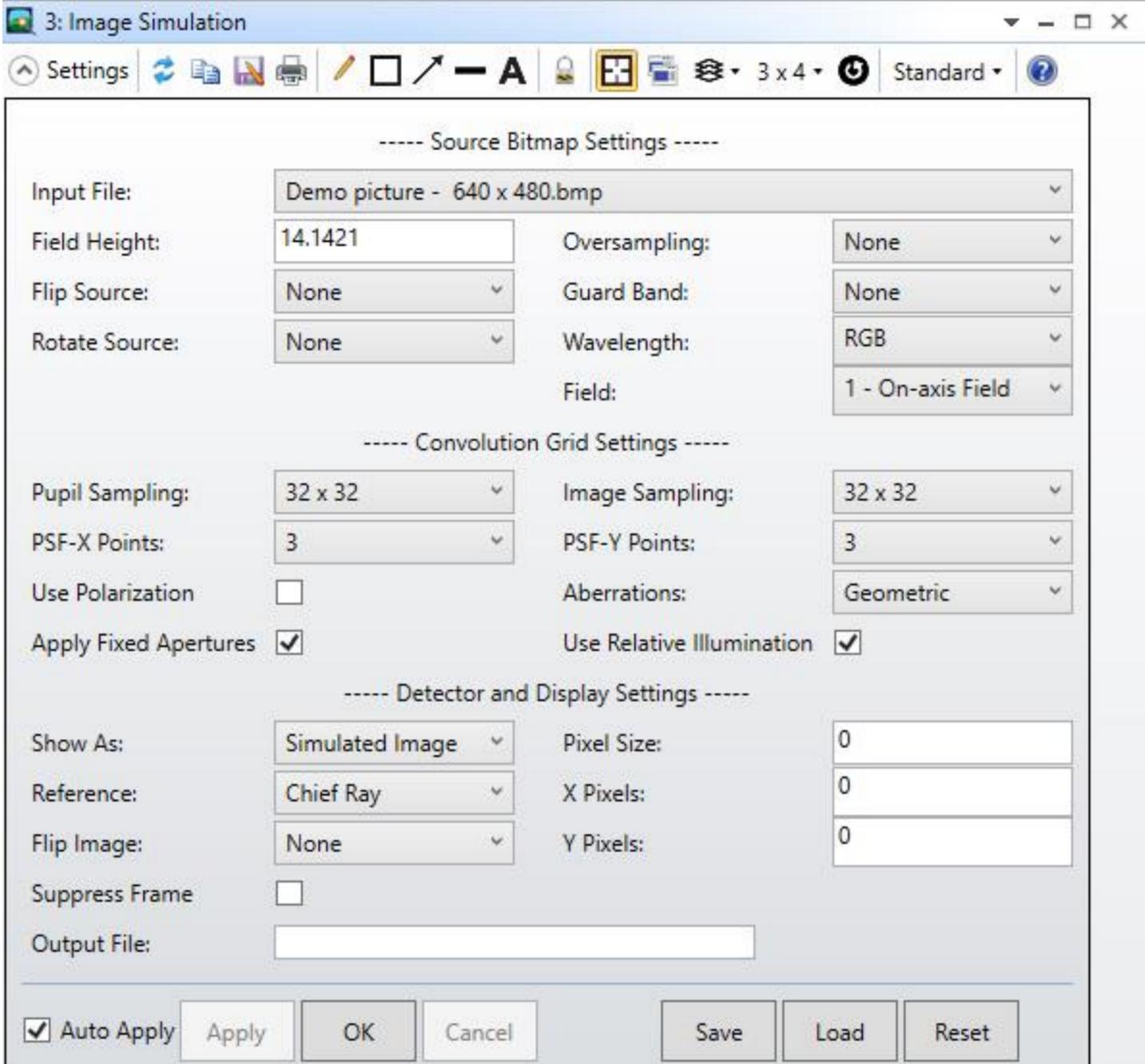
# IMAGE SIMULATION

## Analysis - Extended Scene Analysis – Image Simulation



Consider changing the Field type to object height for improved accuracy. See Help Files for more details.

Image Simulation: Geometric Aberrations	
10/20/2025 Object height is 14.1421 degrees. Field position: 0.00 (deg) Center: chief ray Image size is 12.7894 W x 9.5921 H (Millimeters)	Zemax Ansys Zemax OpticStudio 2024 R1.00 Ex1_Seidel.zos Configuration 1 of 1



3: Image Simulation

Settings | 3 x 4 | Standard

----- Source Bitmap Settings -----

Input File: Demo picture - 640 x 480.bmp

Field Height: 14.1421

Flip Source: None

Rotate Source: None

Oversampling: None

Guard Band: None

Wavelength: RGB

Field: 1 - On-axis Field

----- Convolution Grid Settings -----

Pupil Sampling: 32 x 32

PSF-X Points: 3

Use Polarization:

Apply Fixed Apertures:

Image Sampling: 32 x 32

PSF-Y Points: 3

Aberrations: Geometric

Use Relative Illumination:

----- Detector and Display Settings -----

Show As: Simulated Image

Reference: Chief Ray

Flip Image: None

Suppress Frame:

Output File:

Pixel Size: 0

X Pixels: 0

Y Pixels: 0

Auto Apply | Apply | OK | Cancel | Save | Load | Reset