PHOT 451: Microscale optical system design
LECTURE 06

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	**Quiz** + Beam propagation
Week 6	Refractive optical elements Microlenses
Week 7	Blazed Fresnel lenses
Week 8	Digital lenses
Week 9	Diffractive optical elements
Week 10	**Quiz** + Wave guides and beam propagation
Week 11	Wave mixing
Week 12	Gratings, periodic structures
Week 13	photonic crystals
Week 14	Whole optical system optimization

Imaging Qualitity Metrics

How to compare different imaging optical systems

SUMMARY IMAGE QUALITY METRICS

Rays or Wavefronts

- Ray aberration curves
- Spot diagrams
- Seidel aberrations
- Encircled (or ensquared) energy
- RMS Optical Path Difference (or wavefront error)
- Modulation transfer function (MTF)

Diffraction-based

- Point spread function (PSF)
- Encircled (or ensquared) energy
- MTF
- Strehl Ratio

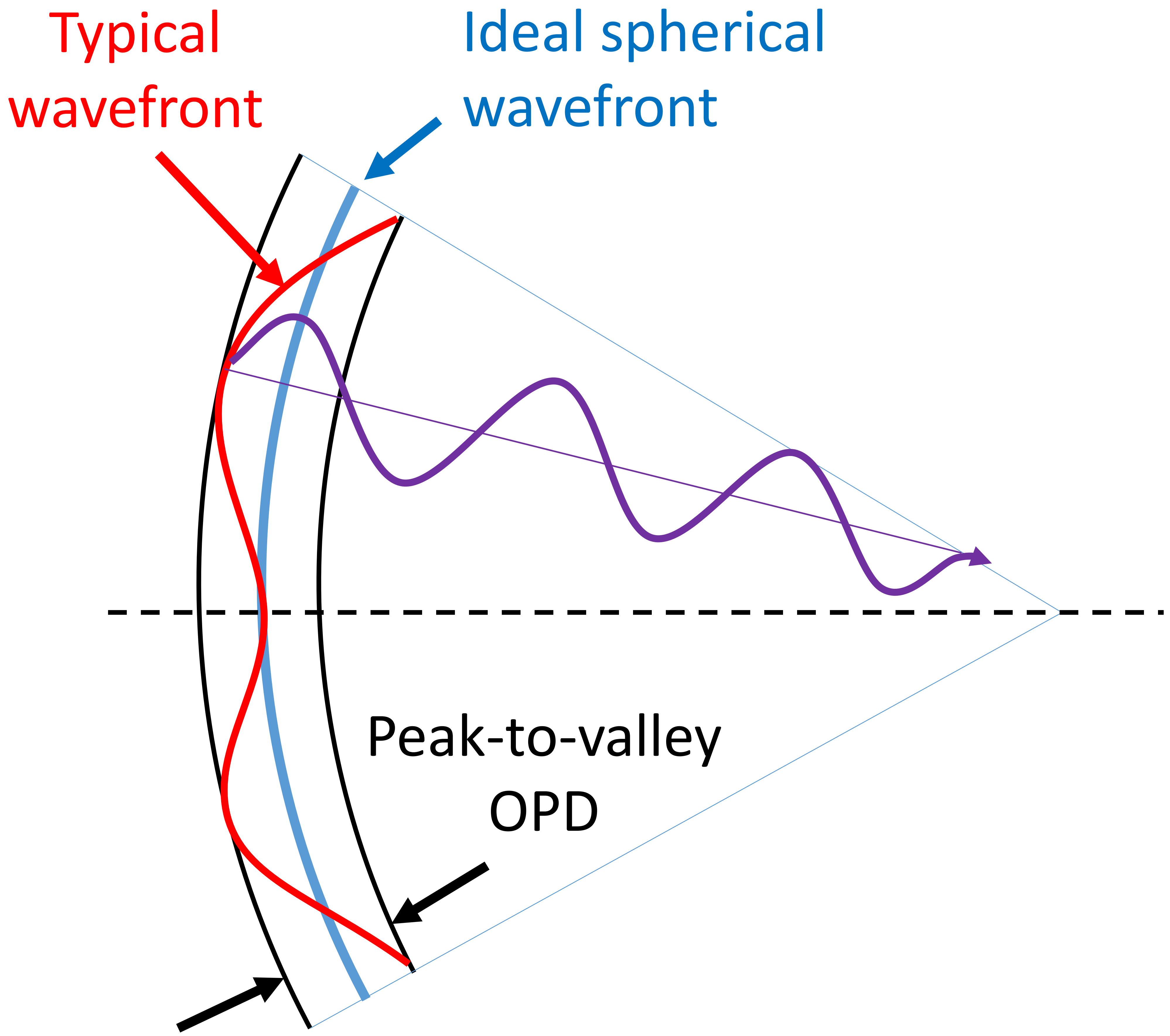
PEAK-TO-VALLEY AND RMS OPTICAL PATH DIFFERENCE

- Optical Path Difference (OPD) relates to phase difference ϕ via:

$$\text{OPD} = \frac{w}{\lambda} = \frac{2\pi\phi}{\lambda}$$

- Often wavelength units (λ)
- Typical OPD $w < \lambda$
- Peak-to-valley OPD: $\max(w)$
- RMS OPD in wavelength:

$$\sigma_w = \frac{2\pi}{\lambda}\sqrt{\langle\phi^2\rangle - \langle\phi\rangle^2}$$



PEAK-TO-VALLEY AND RMS OPTICAL PATH DIFFERENCE

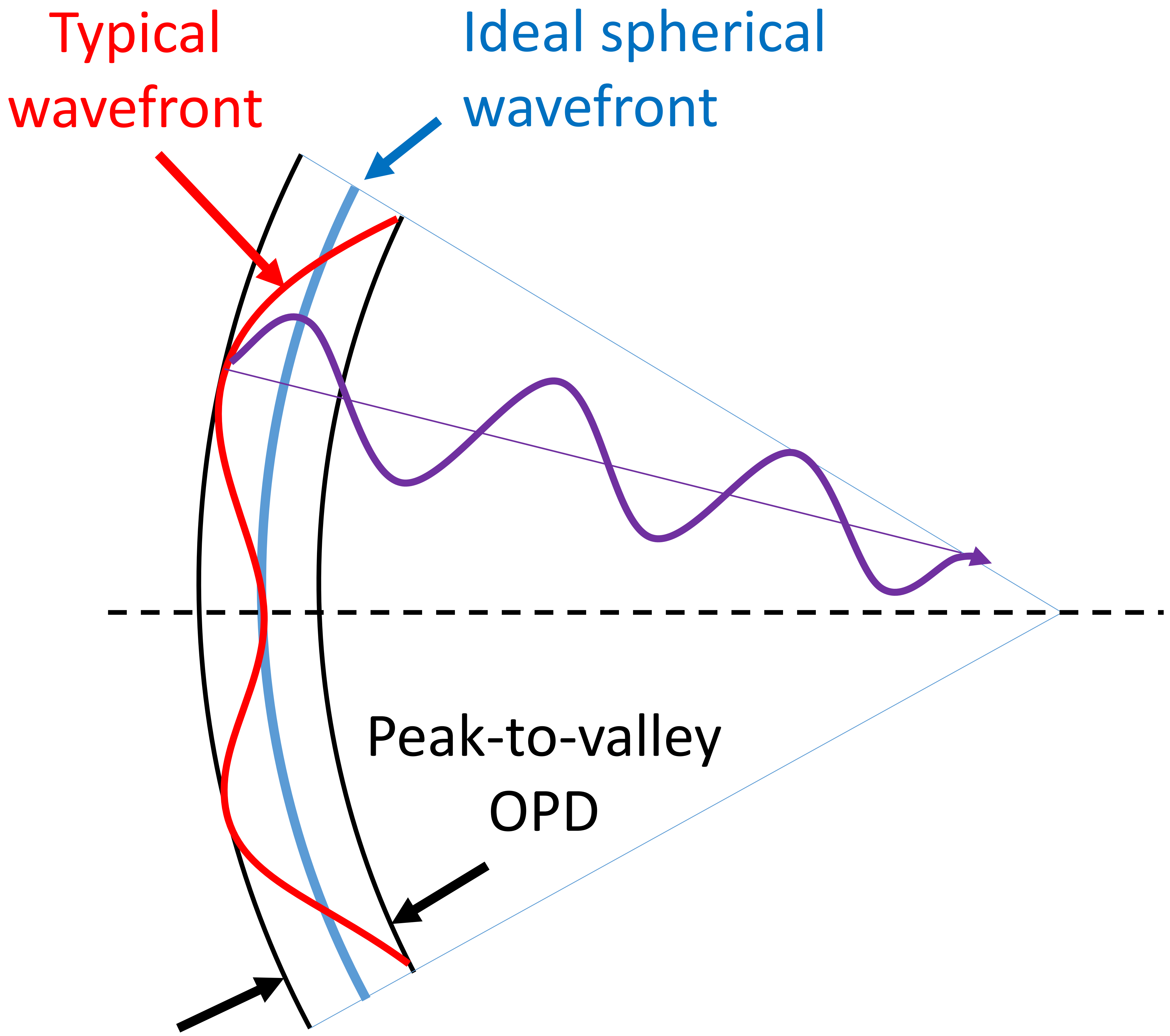
- RMS OPD < peak-to-valley

$$\sigma_w < \max(w)$$

- Combined metric:

$$\frac{\text{Peak-to-valley}}{\text{RMS}} = \frac{\max(w)}{\sigma_w}$$

Gives a sense of how well RMS OPD σ_w represents the error.

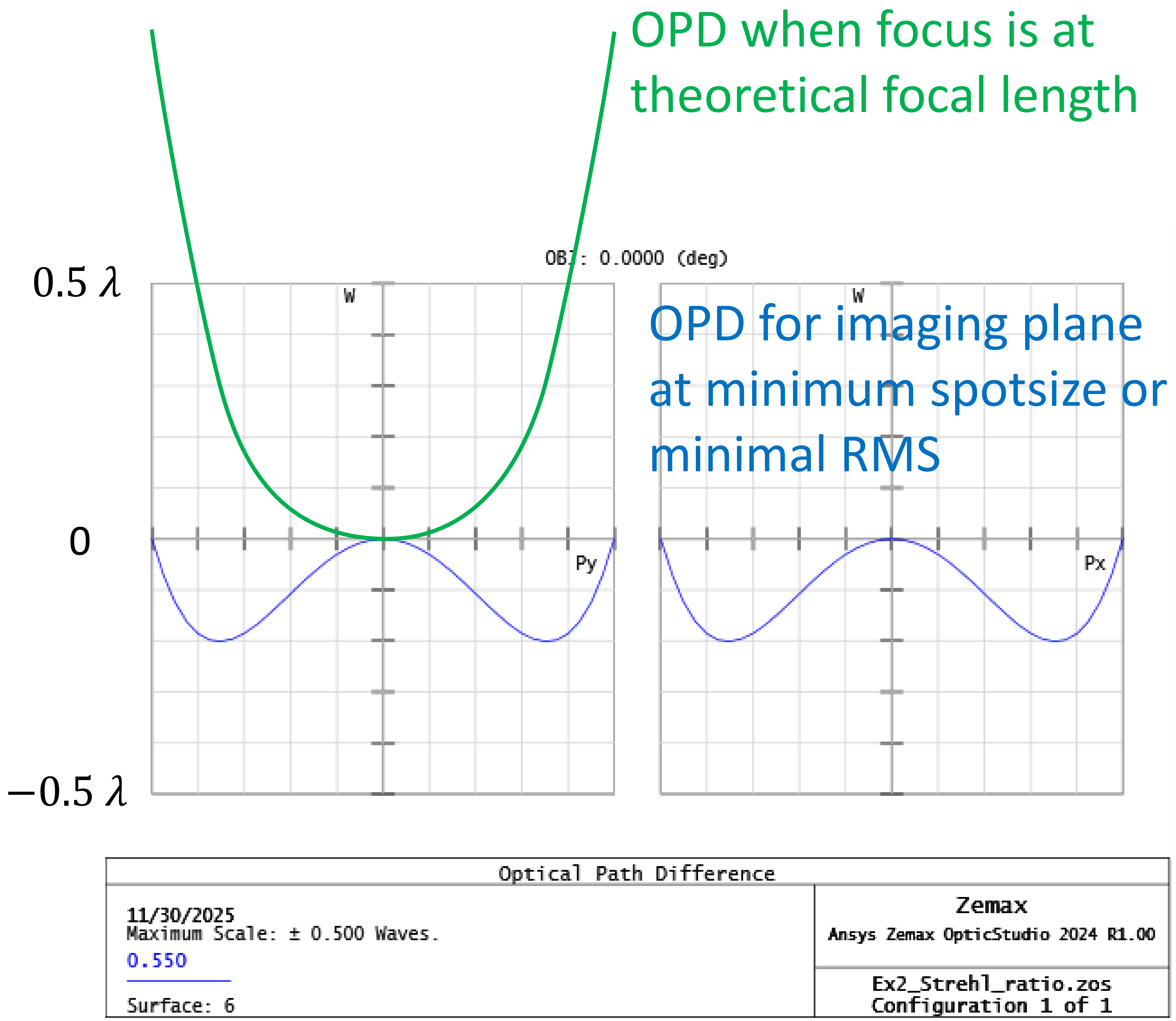


OPTICAL PATH DIFFERENCE AND IMAGE PLANE

- The optical path difference is sensitive to the position of the imaging plane
- Optimize the image plane distance first

Spherical aberration

of single biconvex lens



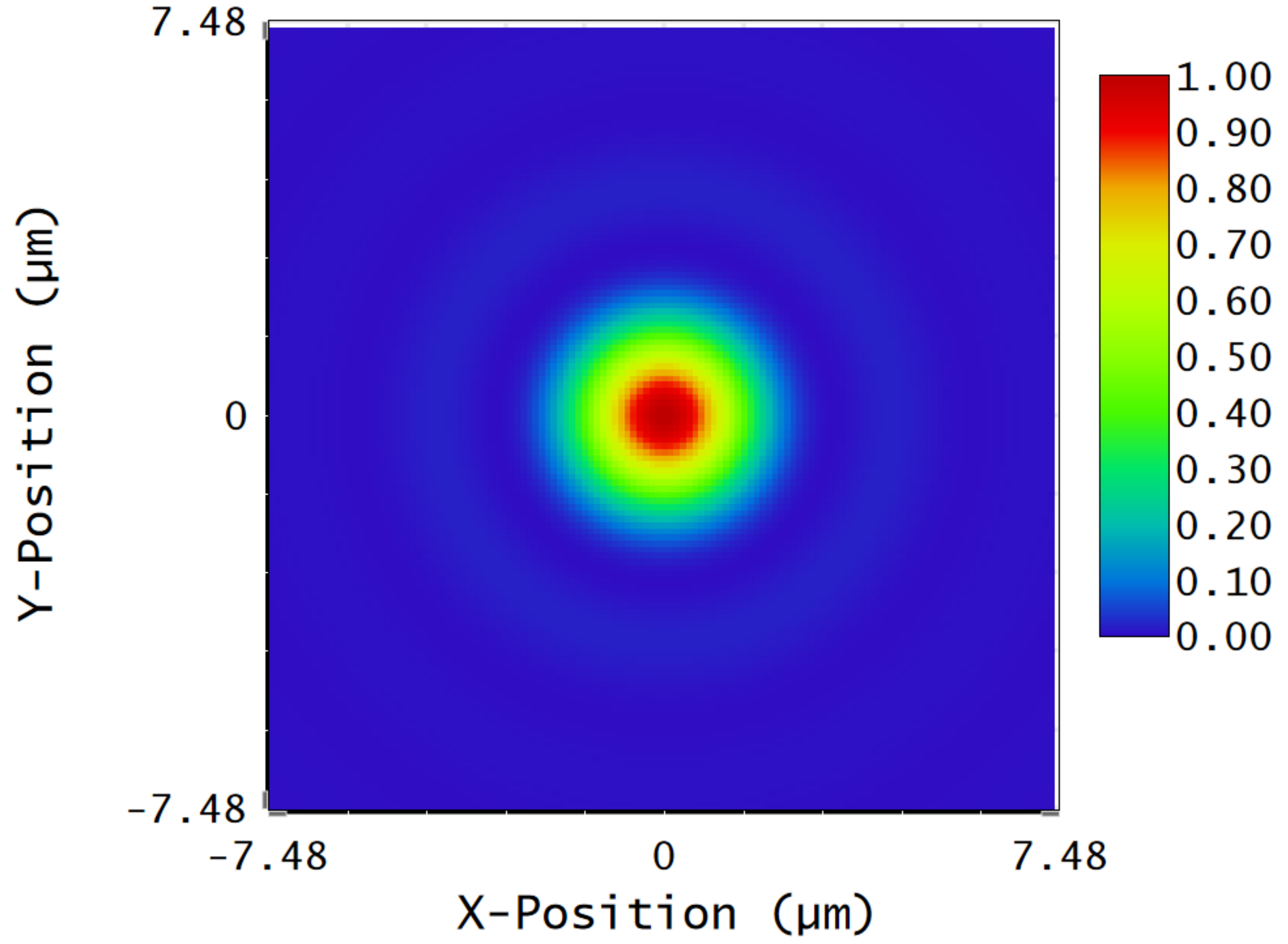
STREHL RATIO

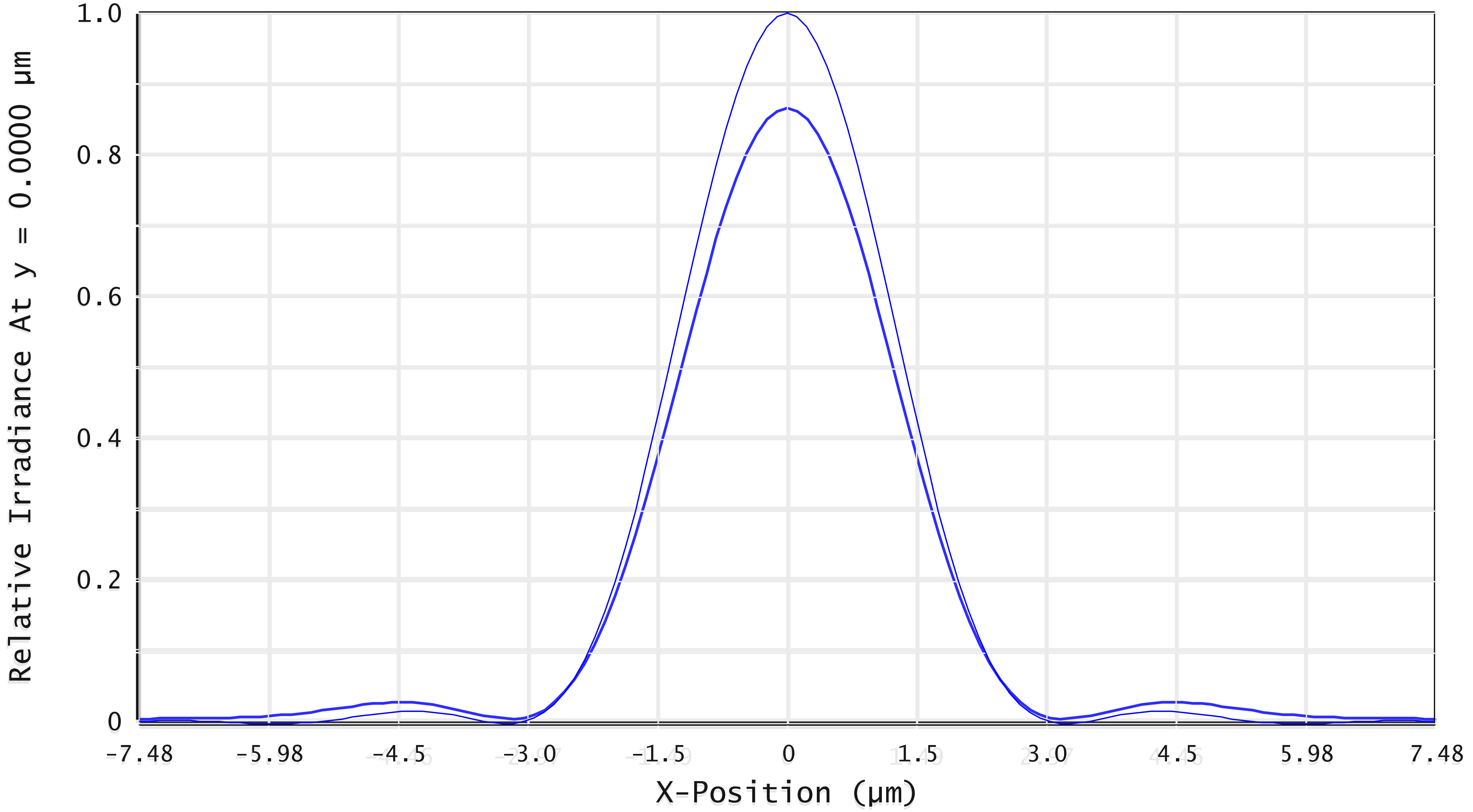
- 1895: Dr. Karl Strehl
- Strehl ratio = peak diffraction intensity ratio:

$$S = \frac{I_{\text{peak}}}{I_{0,\text{peak}}} = \frac{I \text{ aberrated}}{I_0 \text{ perfect}}$$

- Relates PSF with aberrations

- Disadvantage:
  - Difficult to calculate





STREHL RATIO

- Strehl ratio:

$$S = \frac{I_{\text{peak}}}{I_{0,\text{peak}}} \approx e^{-\sigma_\phi^2}$$

Accurate for RMS wavefront errors

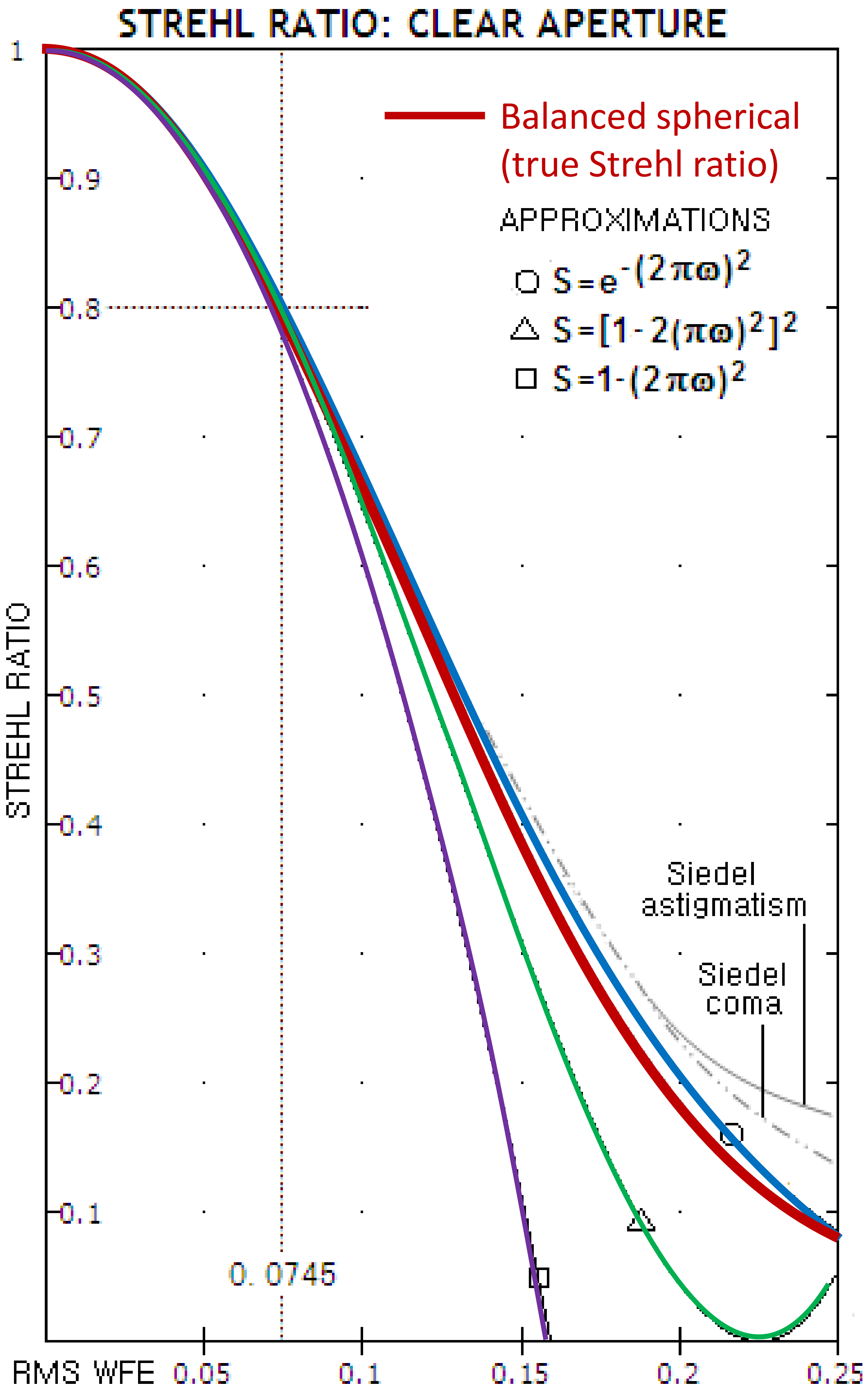
$$\Delta w \le \lambda/4$$

Where $\sigma_\phi^2 = \left(\frac{2\pi}{\lambda}\right)^2 \Delta w^2$

Δw = RMS OPD in radians/wave

$$\approx \left[1 - \frac{1}{2}(2\pi w)^2\right]^2 \qquad \Delta w \le \lambda/10$$

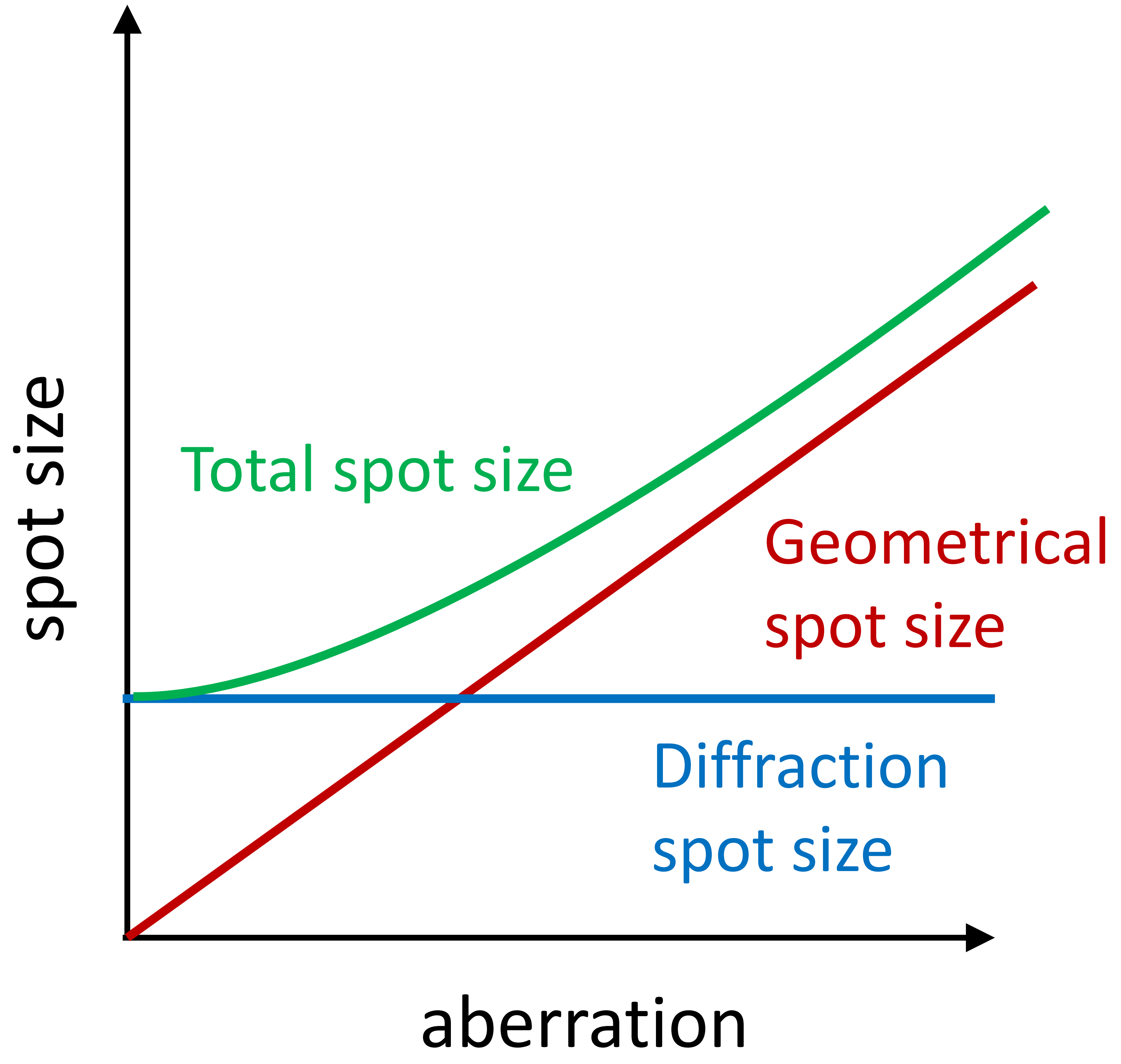
$$\approx 1 - (2\pi w)^2 \qquad \Delta w \le \lambda/15$$



Adapted from: https://www.telescope-optics.net/Strehl.htm

STREHL RATIO & DIFFRACTION LIMITED SYSTEMS

- Strehl ratio: How well does the system approximate the “perfect” diffraction limited system for a given aperture
- S becomes better when reducing aperture of the system
- Reducing the aperture does reduce the resolution (increase the PSF)
- A “diffraction limited system” has limited geometrical aberration contribution to total spot size



Total spot size = Diffraction spot size + geometrical spot size

Chromatic Aberration

CHROMATIC ABERRATION

- The refractive index can depend on the wavelength

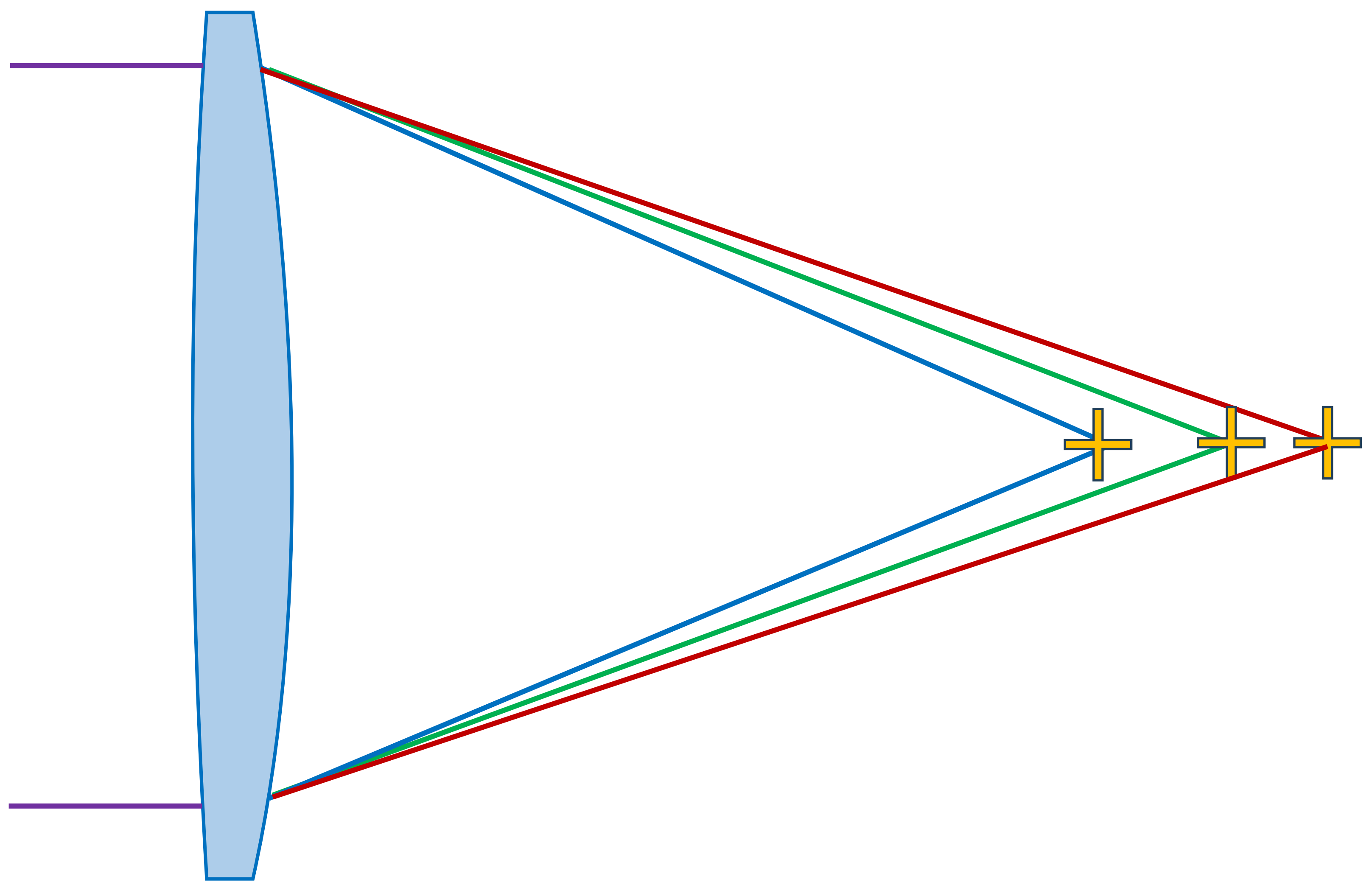
➡ **Dispersion** of the material

- **Abbe ν-number**:

$$\nu = \frac{(n_{\text{middle}} - 1)}{n_{\text{short}} - n_{\text{long}}}$$

- 3 wavelengths depend on material
- For glasses - visible light:

  F (486 nm), d (588 nm), C (656 nm)



Short wavelengths have most often higher refraction indices resulting in shorter focal lengths

CHROMATIC ABERRATION: APPROXIMATIONS DISPERSION

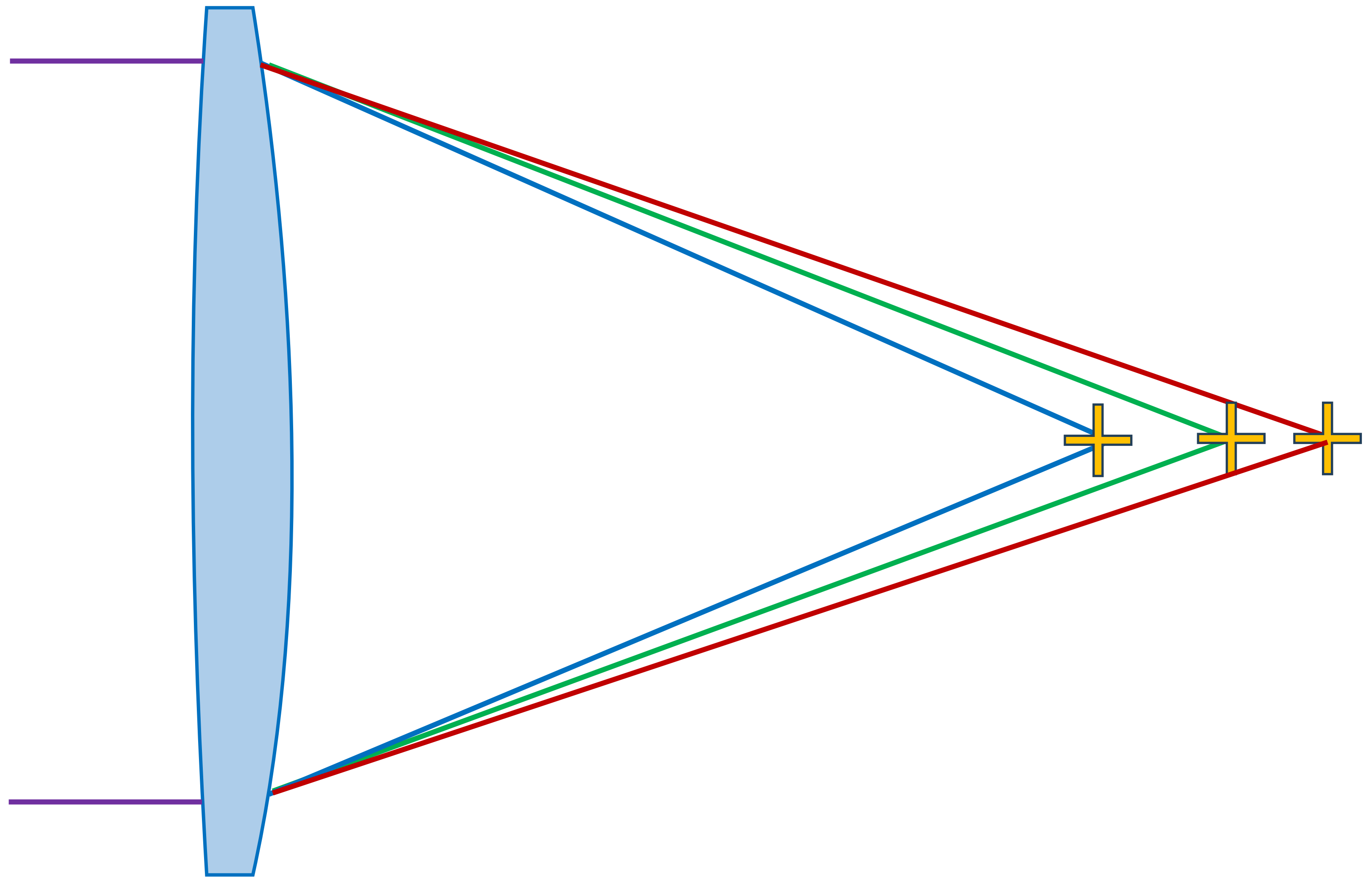
- Dispersion curve: all information

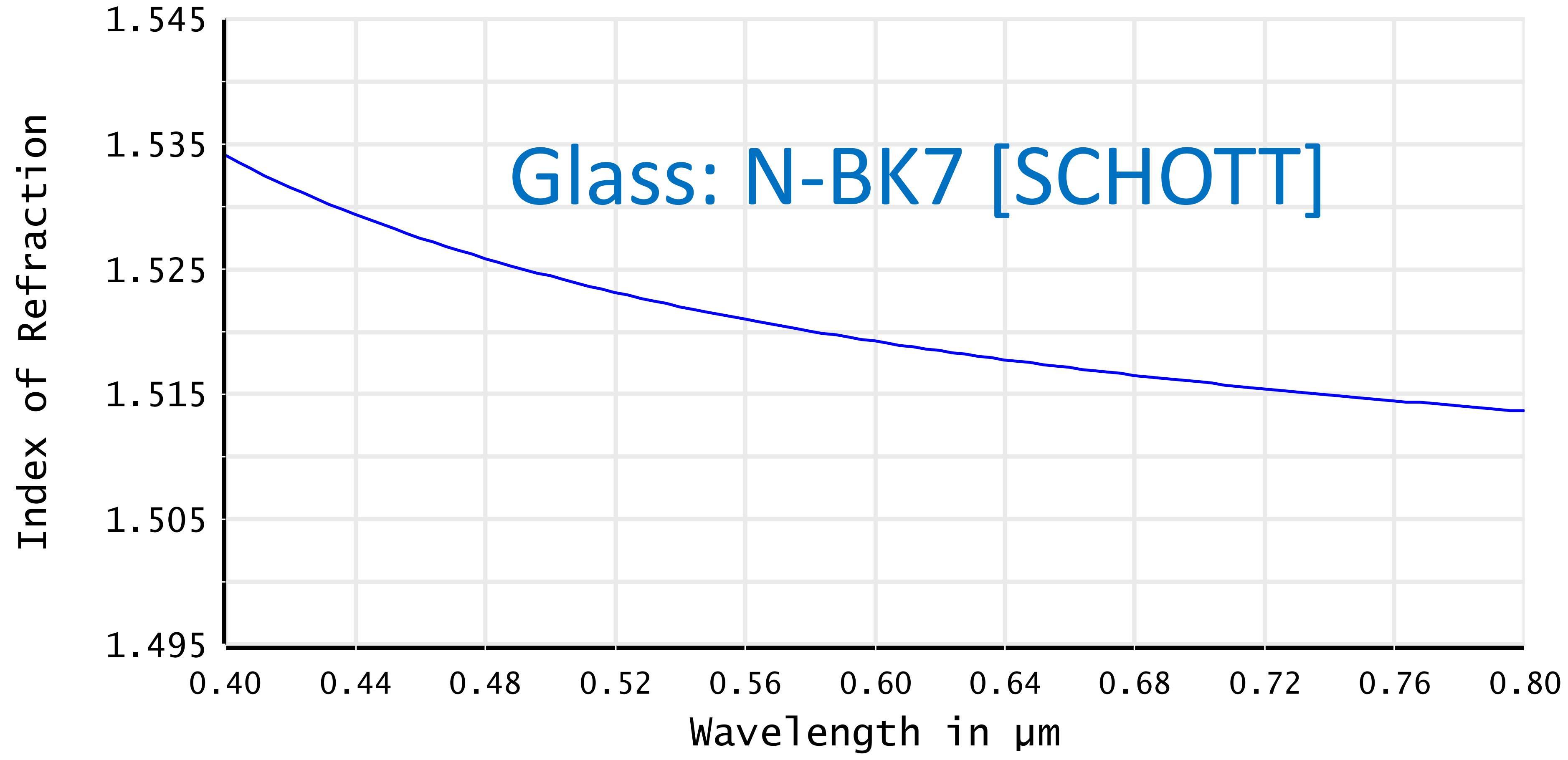
- Abbe ν-number gives average

$$\nu = \frac{(n_{\text{middle}} - 1)}{n_{\text{short}} - n_{\text{long}}}$$

- Refraction index by linear interpolation for small deviations $\Delta\lambda$

$$n \approx n_0 + \Delta\lambda \, \frac{\mathrm{d}n(\lambda)}{\mathrm{d}\lambda}$$





Theory Seidel Aberrations

SEIDEL ABERRATIONS: 3RD ORDER ABERRATIONS

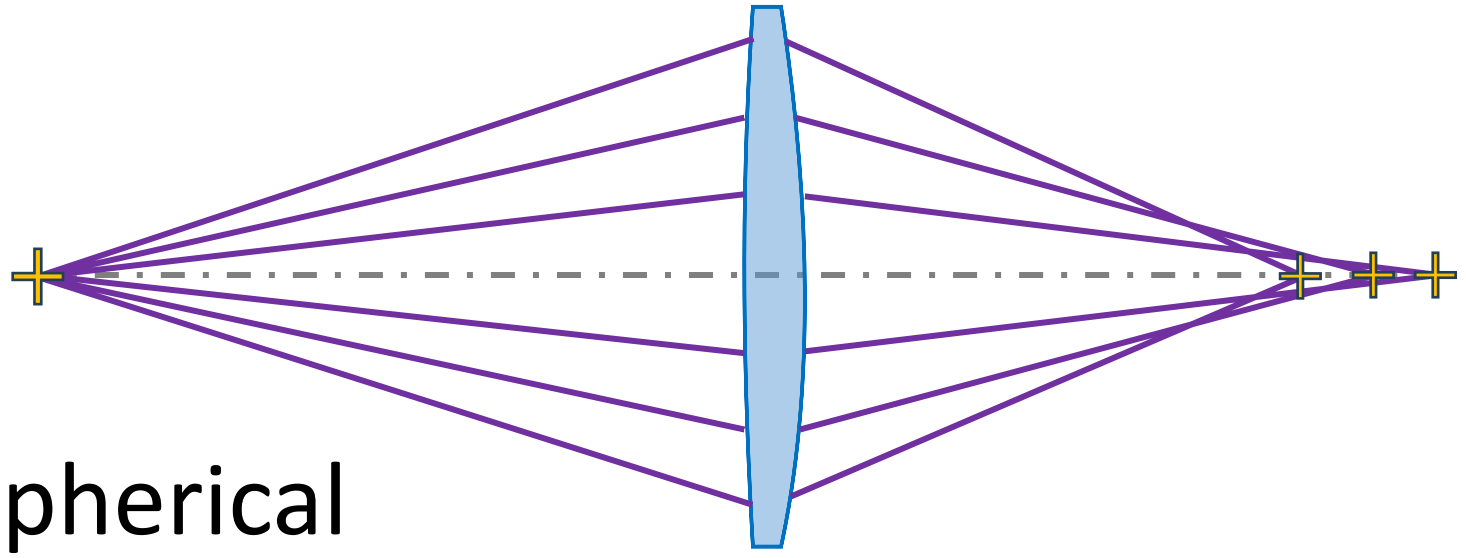
- Seidel aberrations are the 5 standard aberrations
  1. (1) Spherical,
  2. (2) Coma,
  3. (3) Astigmatism,
  4. (4) Field curvature
  5. (5) Distortion

- Additional: Defocus + Chromatic aberration

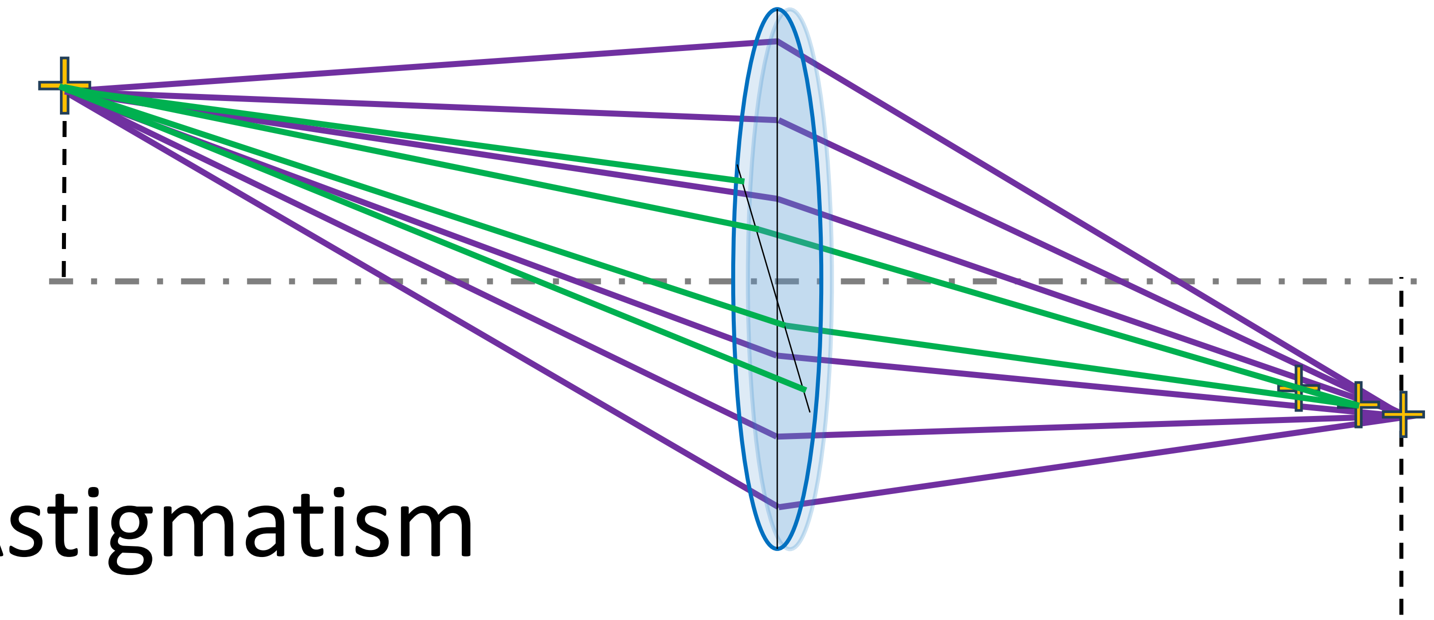
- Obtained via lowest order Taylor expansion (3rd order in pupil & object coordinates) of wavefront aberrations

- **Advantages**: Per surface analysis, additive property, intuitive
- **Disadvantage**: Higher order aberrations can matter!

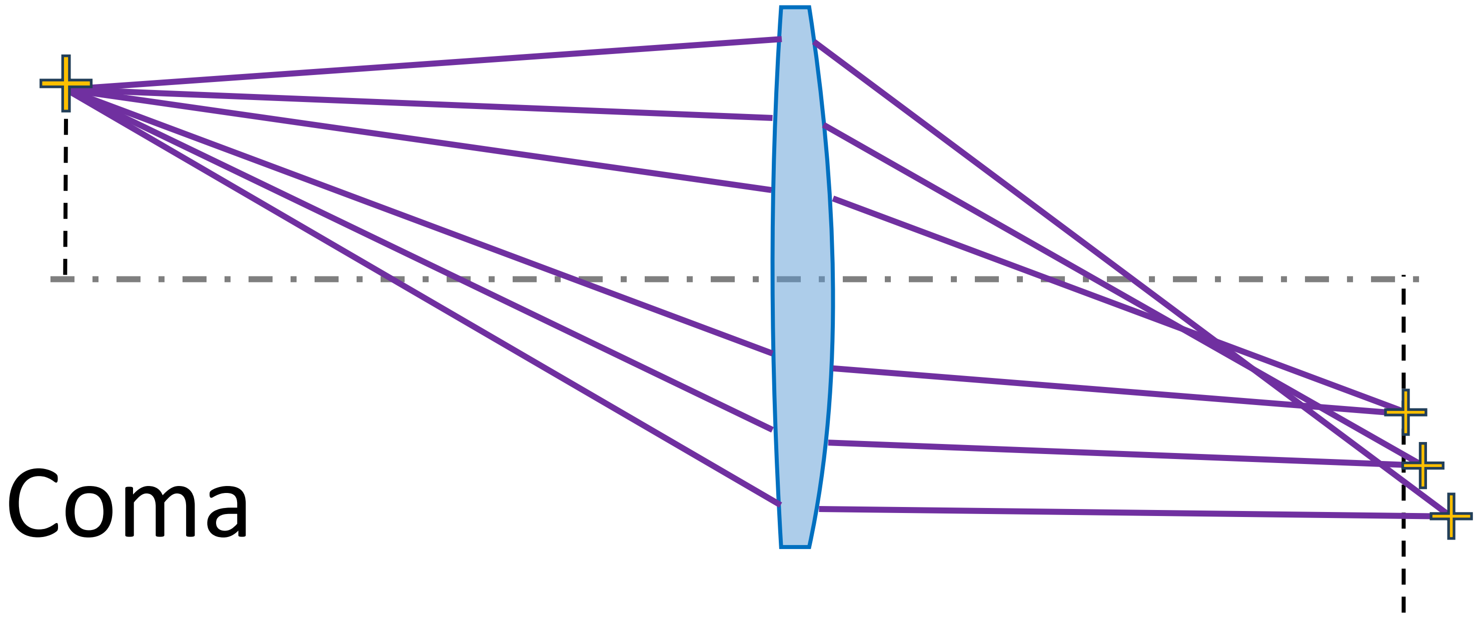
SEIDEL ABERRATIONS



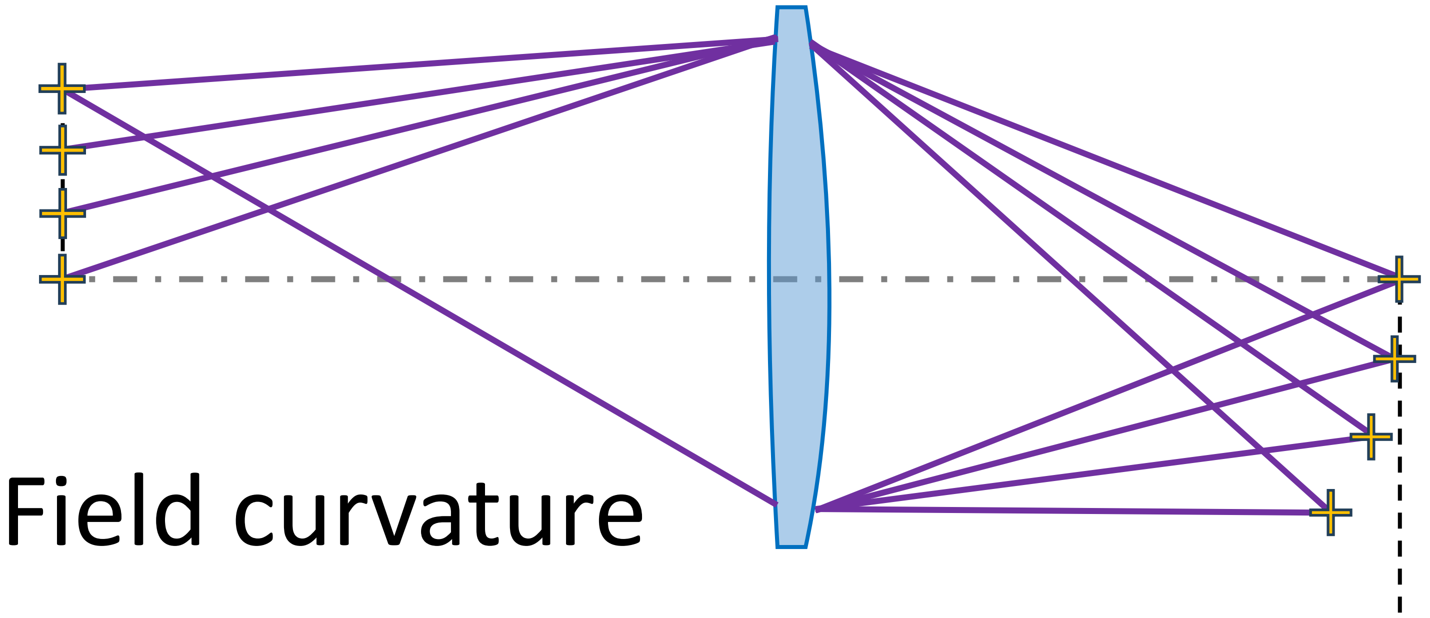
Spherical



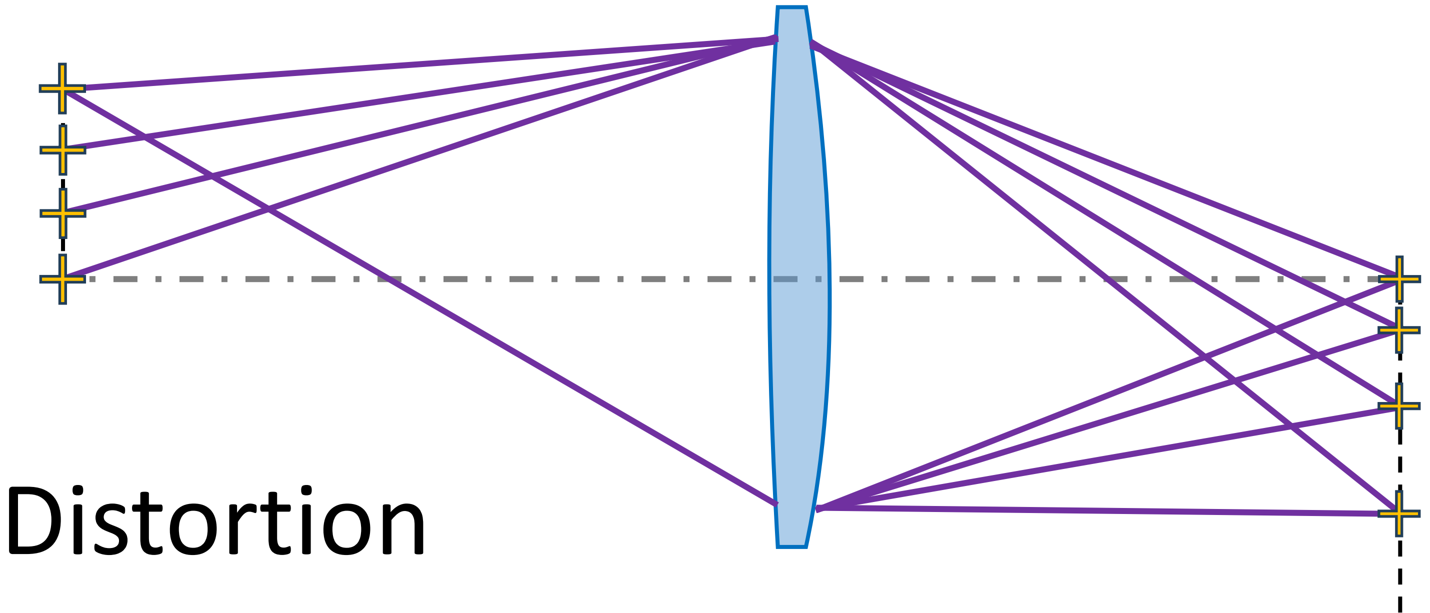
Astigmatism



Coma



Field curvature



Distortion

Rules of Thumb & Criteria

Deciding on what is “good” image quality

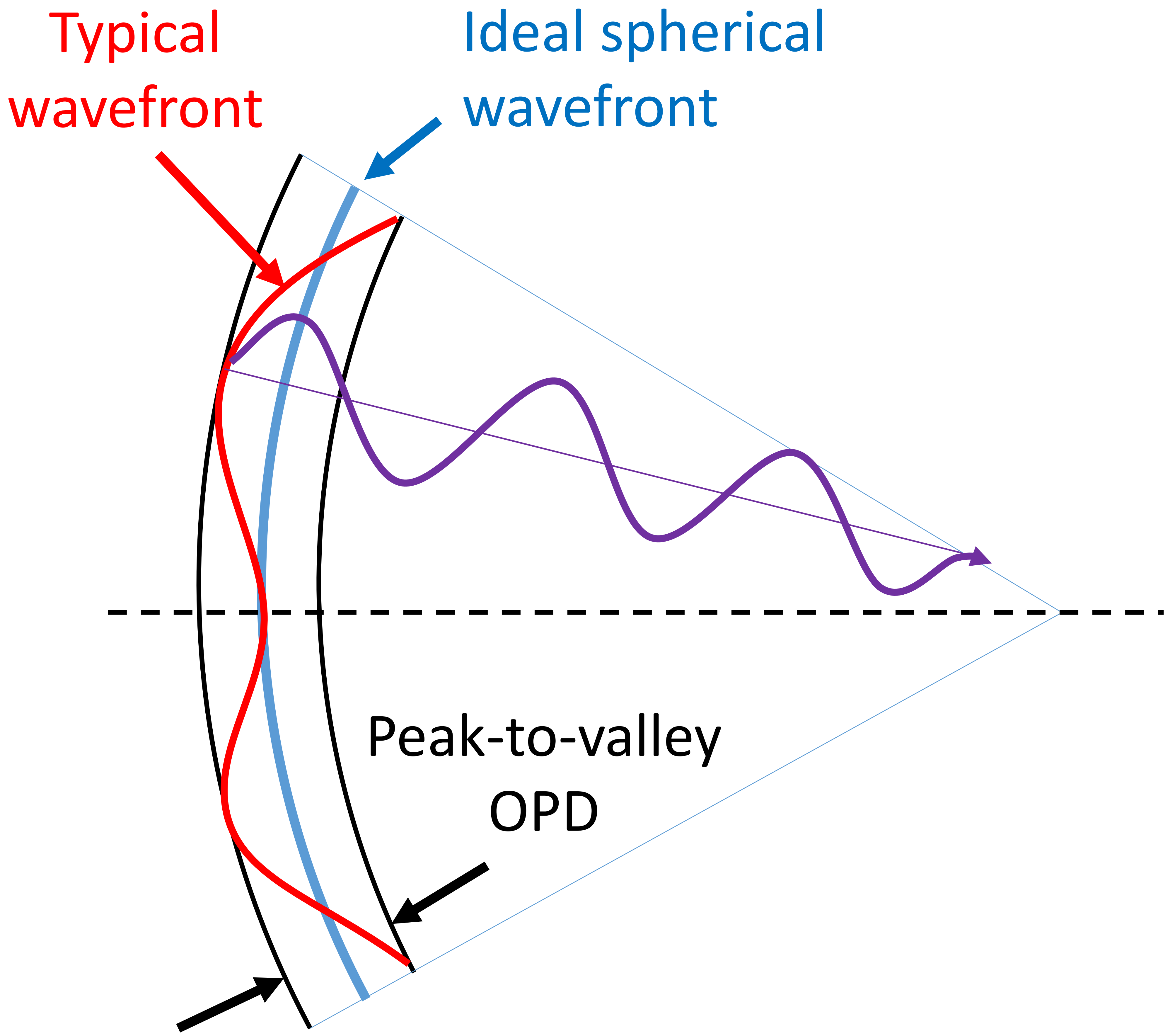
RAYLEIGH CRITERION

- Lens has "good" image quality when:

$$\text{Peak-to-valley OPD} < \frac{\lambda}{4}$$

- Same as: $\lambda/4$ optical path difference at focus

- Disadvantages:
  - ignores (non)smoothness
  - Ignores average error



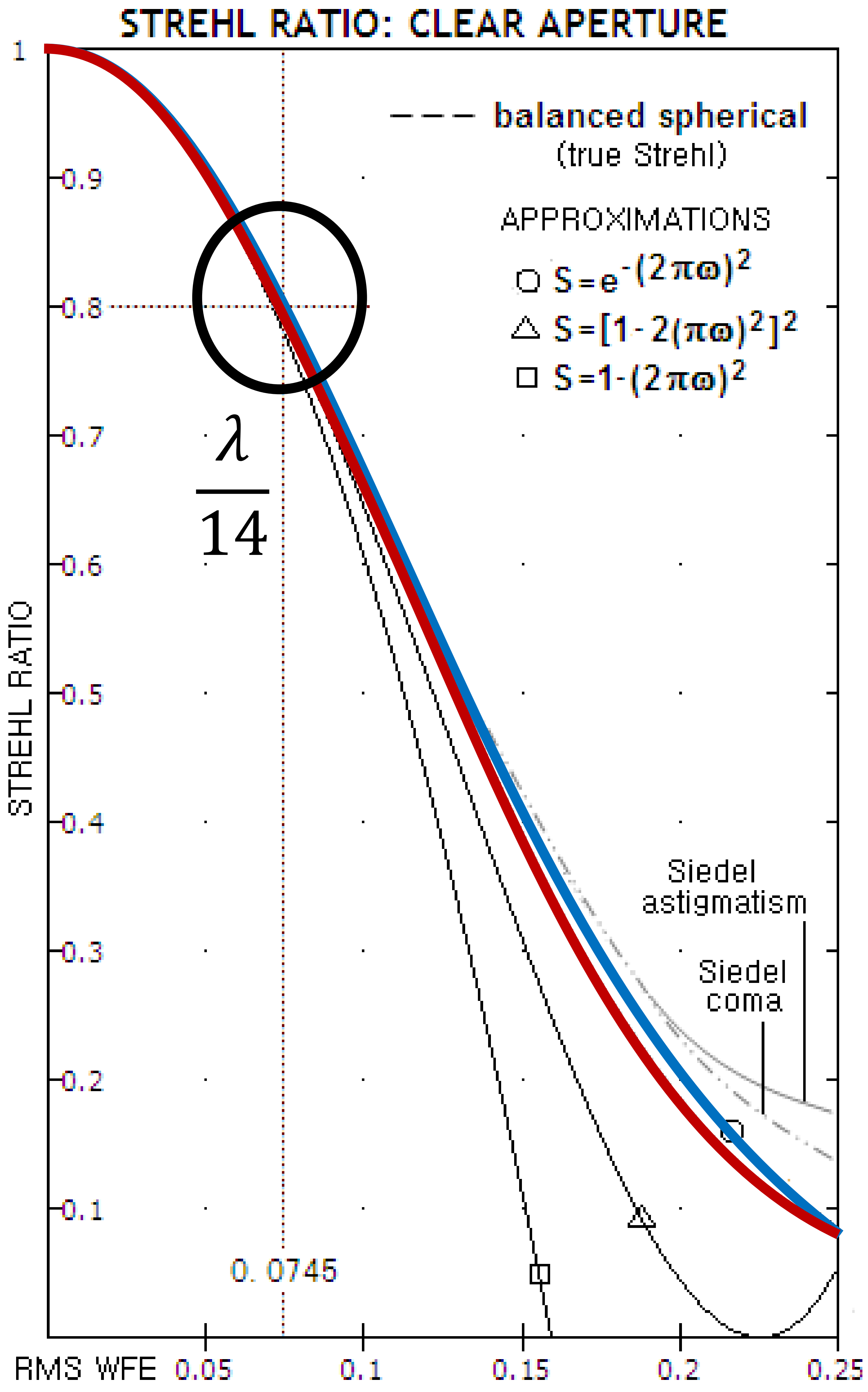
MARECHAL CRITERION

- Minimum Strehl ratio = 0.82

$$S \geq 0.82 \approx e^{-\sigma_\phi^2} = e^{-\left(\frac{2\pi}{\lambda}\right)^2 \Delta w^2}$$

- Approx. maximum RMS OPD is $\frac{\lambda}{14}$

- More accurate than Rayleigh criterion
- Disadvantage: ignores smoothness of the OPD



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ZEMAX Practical session