



**Institute of
Applied Physics**

Friedrich-Schiller-Universität Jena

Imaging and Aberration Theory

Lecture 6: Spherical aberration

2018-11-23

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Schedule - Imaging and aberration theory 2018

1	19.10.	Paraxial imaging	paraxial optics, fundamental laws of geometrical imaging, compound systems
2	26.10.	Pupils, Fourier optics, Hamiltonian coordinates	pupil definition, basic Fourier relationship, phase space, analogy optics and mechanics, Hamiltonian coordinates
3	02.11.	Eikonal	Fermat principle, stationary phase, Eikonals, relation rays-waves, geometrical approximation, inhomogeneous media
4	09.11.	Aberration expansions	single surface, general Taylor expansion, representations, various orders, stop shift formulas
5	16.11.	Representation of aberrations	different types of representations, fields of application, limitations and pitfalls, measurement of aberrations
6	23.11.	Spherical aberration	phenomenology, sph-free surfaces, skew spherical, correction of sph, aspherical surfaces, higher orders
7	30.11.	Distortion and coma	phenomenology, relation to sine condition, aplanatic systems, effect of stop position, various topics, correction options
8	07.12.	Astigmatism and curvature	phenomenology, Coddington equations, Petzval law, correction options
9	14.12.	Chromatical aberrations	Dispersion, axial chromatical aberration, transverse chromatical aberration, spherochromatism, secondary spectrum
10	21.12.	Sine condition, aplanatism and isoplanatism	Sine condition, isoplanatism, relation to coma and shift invariance, pupil aberrations, Herschel condition, relation to Fourier optics
11	11.01.	Wave aberrations	definition, various expansion forms, propagation of wave aberrations
12	18.01.	Zernike polynomials	special expansion for circular symmetry, problems, calculation, optimal balancing, influence of normalization, measurement
13	25.01.	Point spread function	ideal psf, psf with aberrations, Strehl ratio
14	01.02.	Transfer function	transfer function, resolution and contrast
15	08.02.	Additional topics	Vectorial aberrations, generalized surface contributions, Aldis theorem, intrinsic and induced aberrations, reverbability

1. Spherical aberration representations
2. Single lens spherical aberration
3. Aplanatic surfaces
4. Higher order spherical aberration
5. Correction of spherical aberration
6. Aspherical surfaces

Spherical Aberration: Angle of Incidence

- Spherical aberration: non-linearity of the law of refraction for finite angles of incidence i
- Example single plano-convex lens:

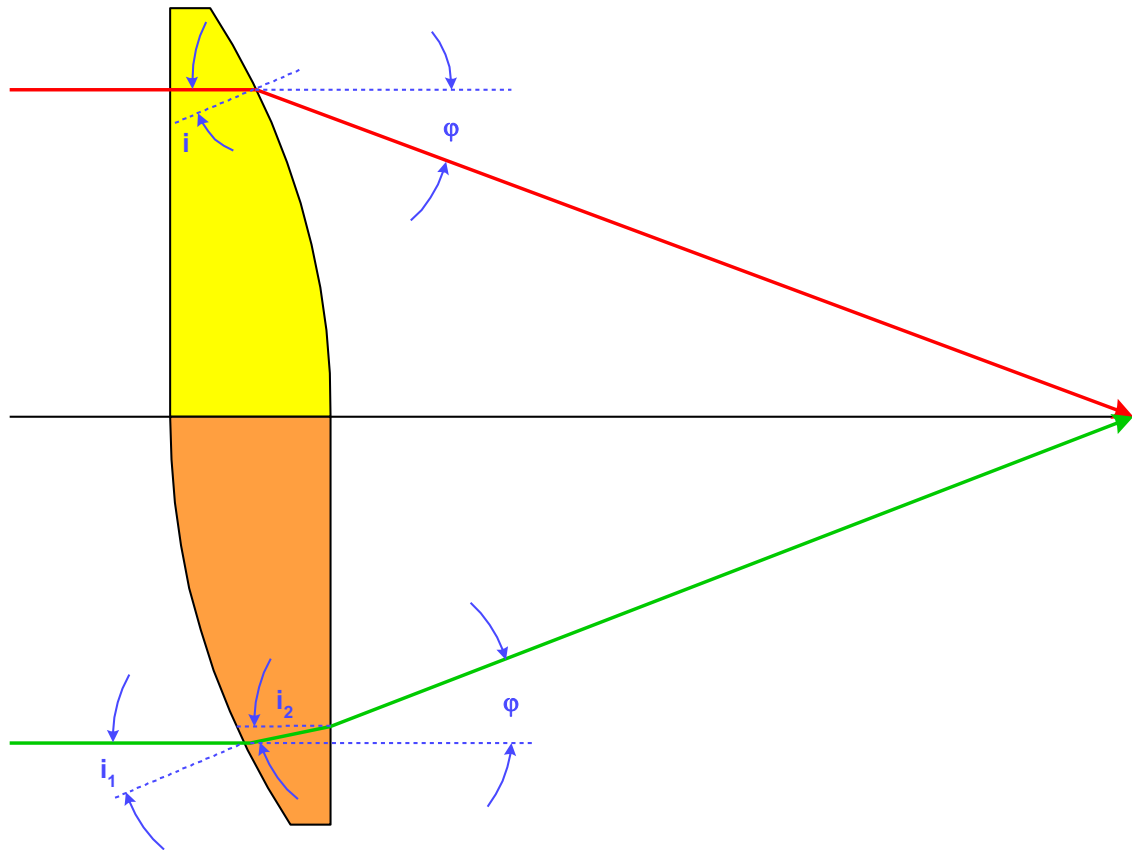
1. bad orientation (red ray):

$$\sin i = i - \frac{i^3}{6}$$

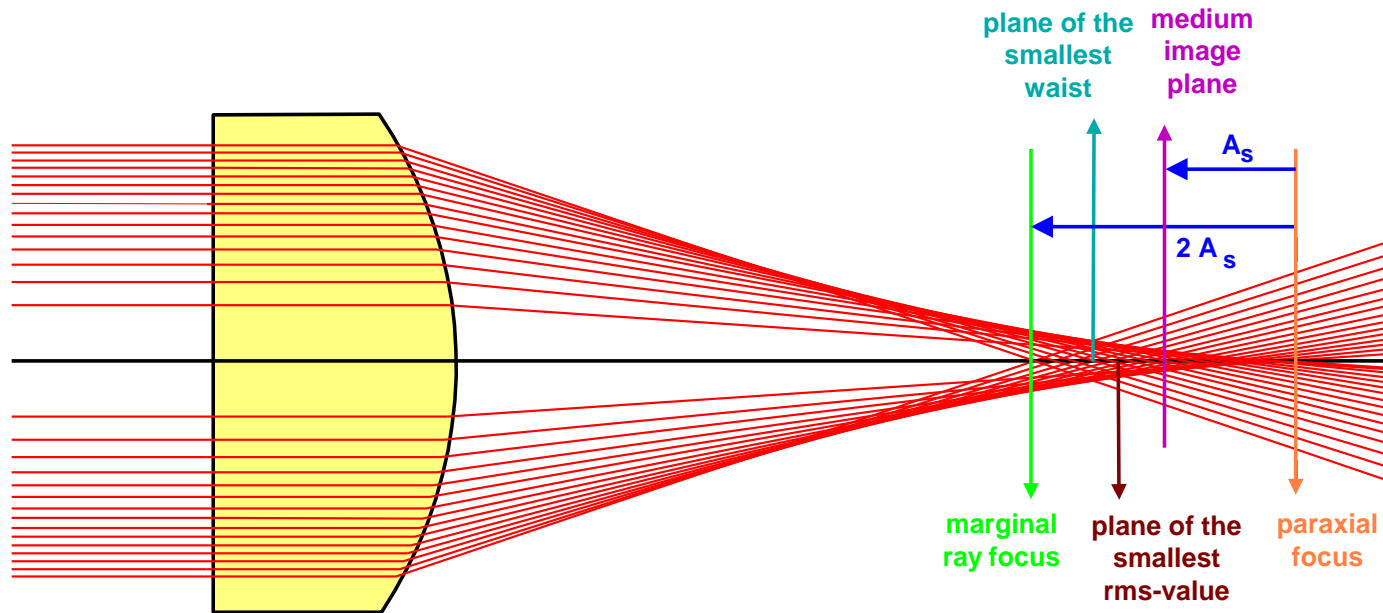
2. optimal orientation
(green ray):
approximation for
refractive index $n=1.5$

$$2 \cdot \sin \frac{i}{2} = i - \frac{2}{6} \cdot \left(\frac{i}{2} \right)^3 = i - \frac{i^3}{24}$$

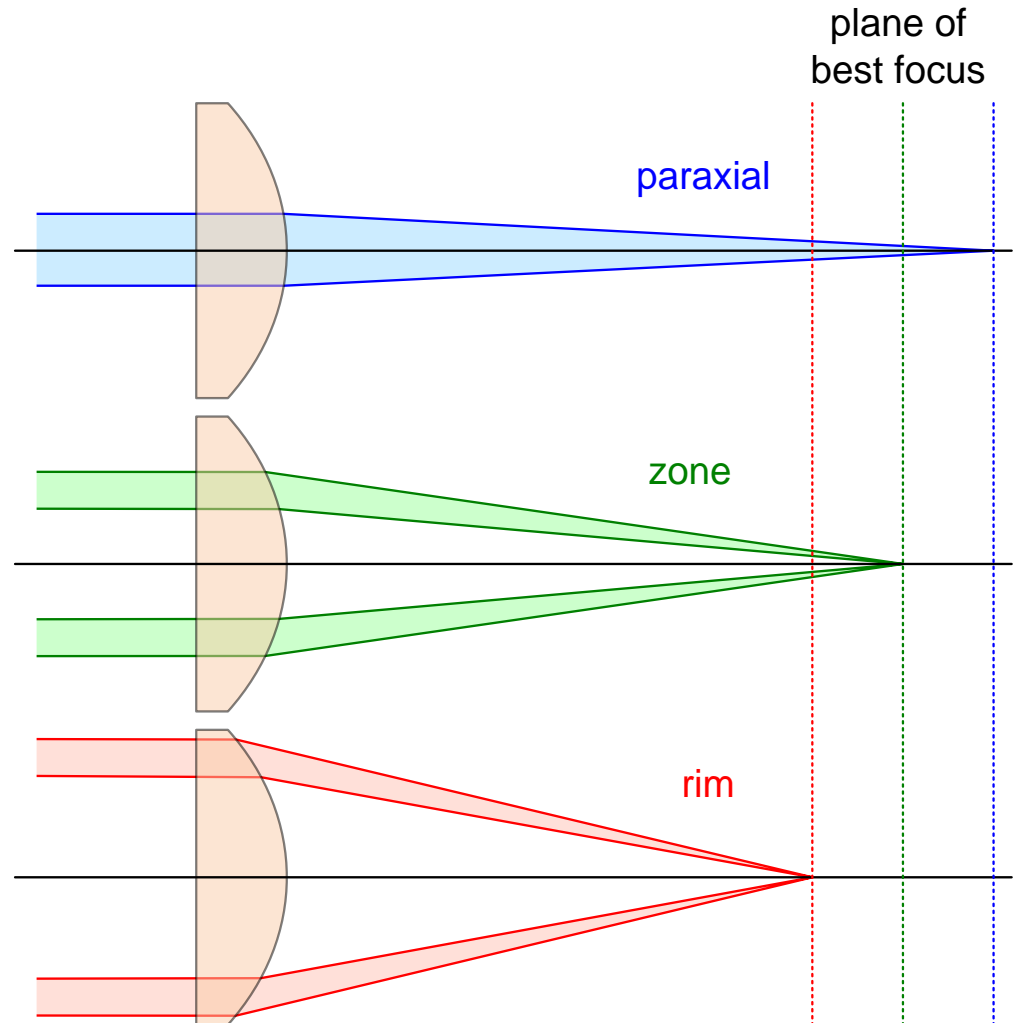
- Spherical aberration differs by a factor of 4



- Spherical aberration:
 - On axis, circular symmetry
- Perfect focussing near axis: paraxial focus
- Real marginal rays: shorter intersection length (for single positive lens)
- Optimal image plane: circle of least rms value



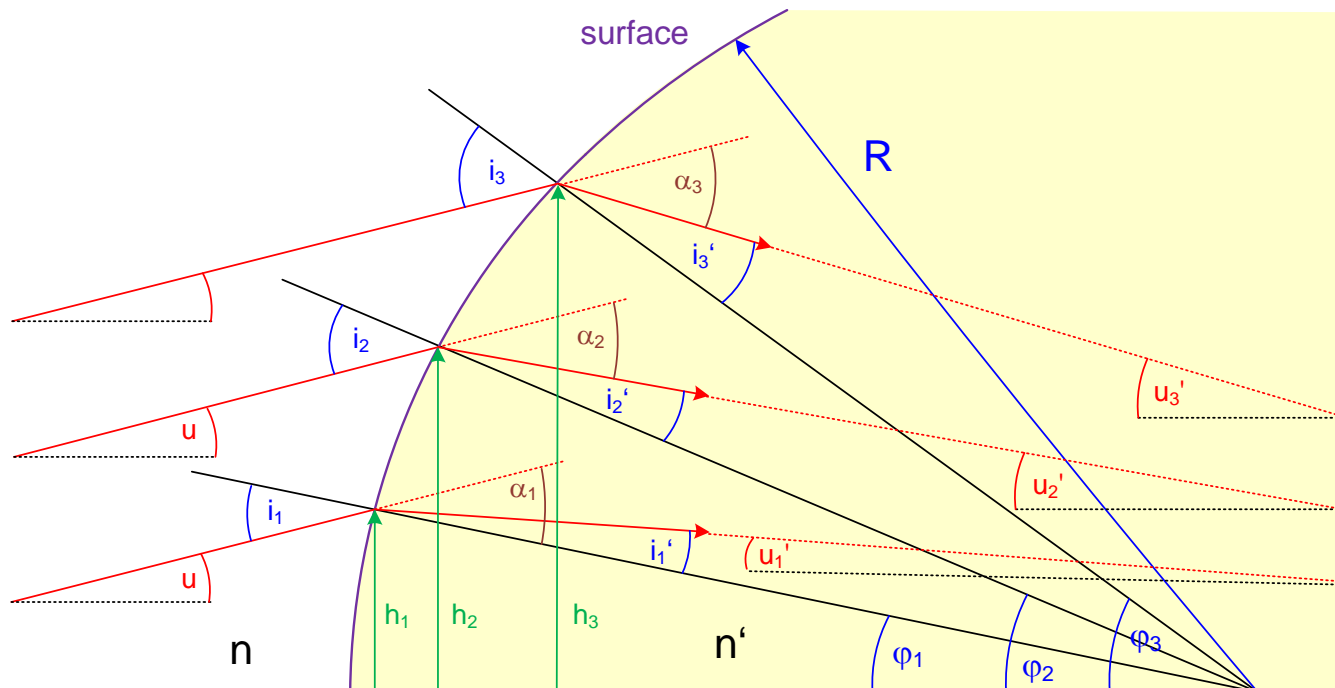
- Single positive lens
- Paraxial focal plane near axis,
Largest intersection length
- Shorter intersection length for
rim ray and outer aperture zones



- Dependence of the aberration surface contribution on the geometry

$$S_I = -\sum A_j^2 \cdot h_j \cdot \Delta \left(\frac{u_j}{n_j} \right) = -\sum n_j^2 i_j^2 \cdot h_j \cdot \left(\frac{u'_j}{n'_j} - \frac{u_j}{n_j} \right)$$

- Driving forces for aberrations are:
 - spherical aberrations grows linear with the field height h
 - spherical aberration grows quadratical with the incidence angle i^2
 - no impact, if the aplanatic condition is fulfilled





Aberration Dependence on Incidence Point

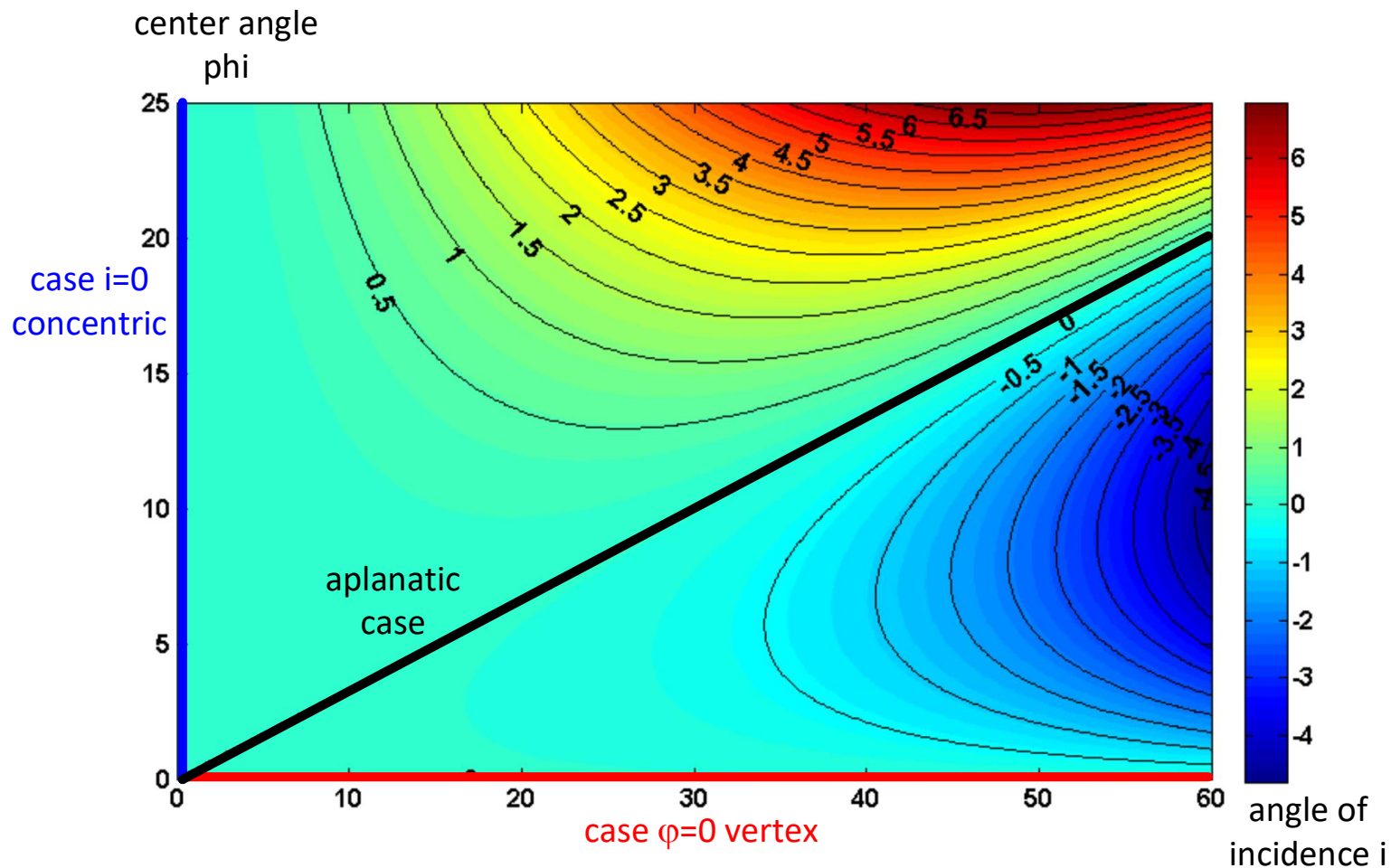
- Usual argumentation: spherical aberration grows with
 1. ray height h
 2. incidence angle i
 3. ray bending angle δ
 4. stronger curvature c of the surface
- But: no impact in case of
 1. vertex intersection
 2. concentric transition
 3. aplanatic constellation
- Parameter selection:
 1. the ray bending dependence corresponds to incidence i :

$$\delta = u' - u = i' - i = i \cdot \left(\frac{n'}{n} - 1 \right) \propto i$$
 2. to get rid of the curvature it make sense to use the center angle φ instead of h as a normalization: $h = \varphi/c$
 3. therefore it make sense to calculate the spherical aberration as a function of
 - incidence i
 - center angle φ
 4. the dependence on δ and h is then automatically covered

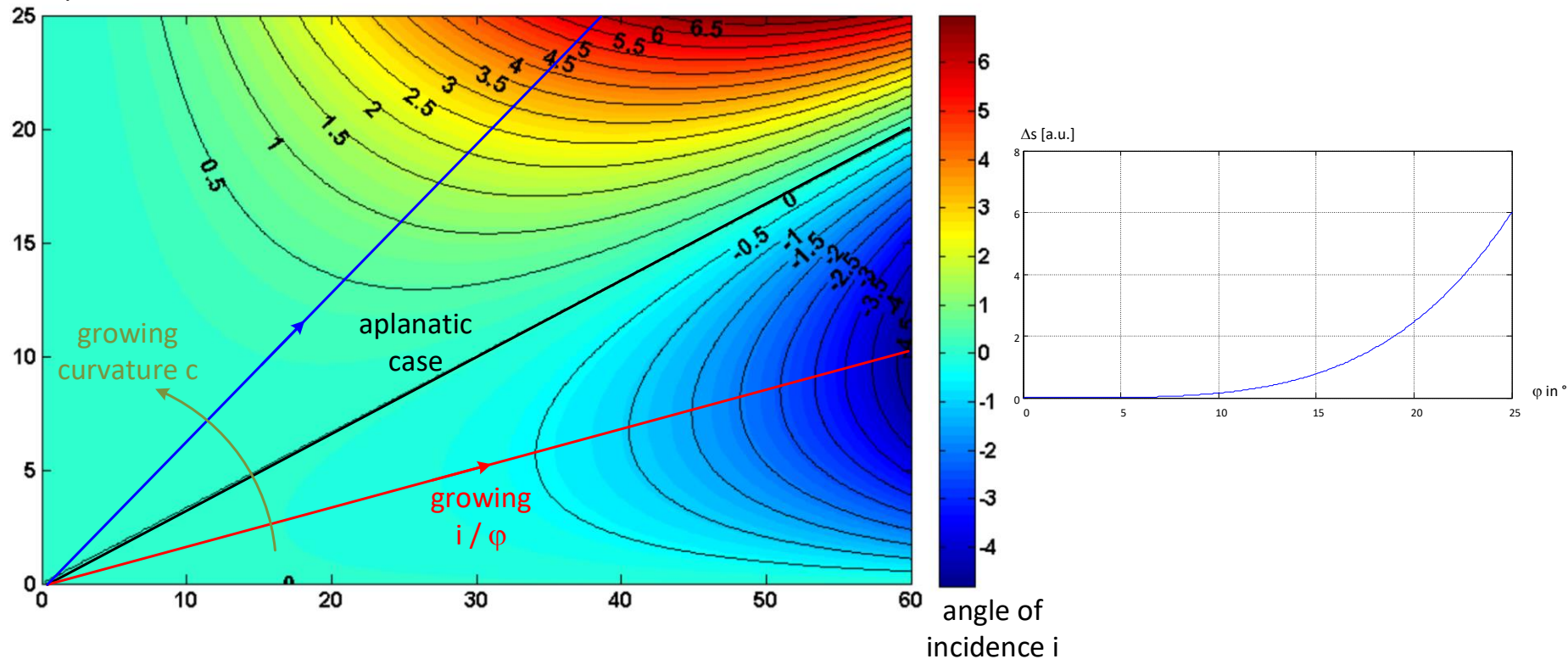


Aberration Dependence on Incidence Point

- Plot of spherical aberration as a function of i and δ :
three lines with vanishing aberration



- center angle
phi

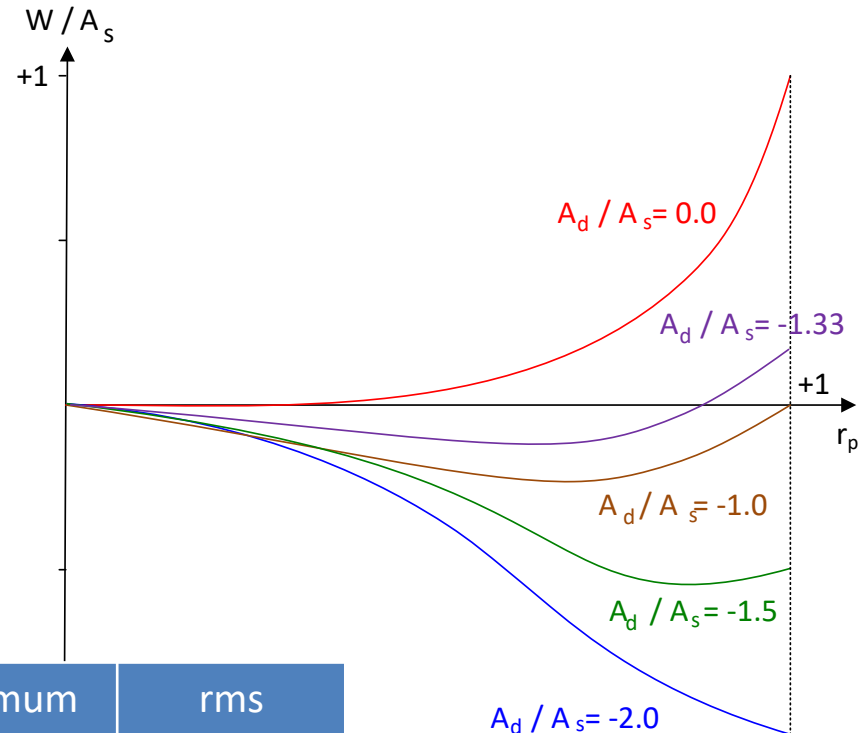


Spherical Aberration: Best Image Location

- Spherical wave aberration

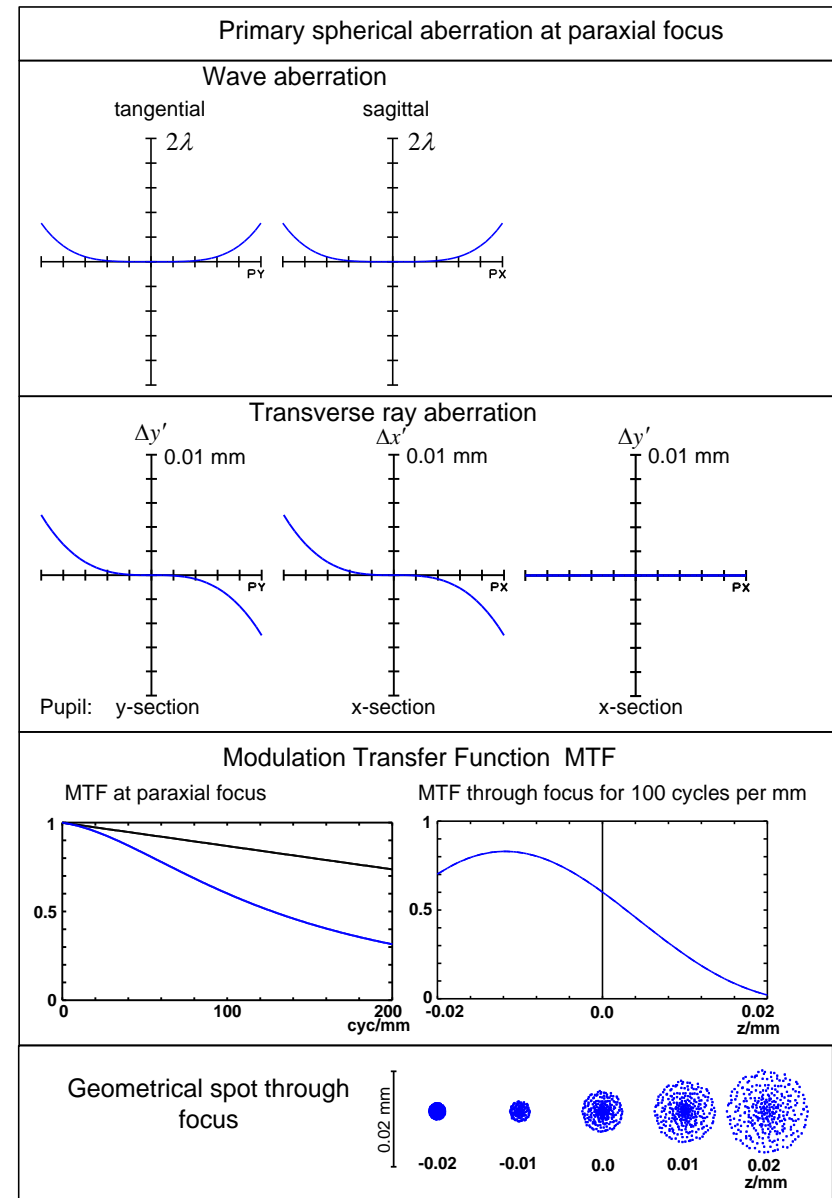
$$W = A_d r_p^2 + A_s r_p^4$$

- Best image location by choice of defocus parameter A_d
- Several solutions dependent on criterion



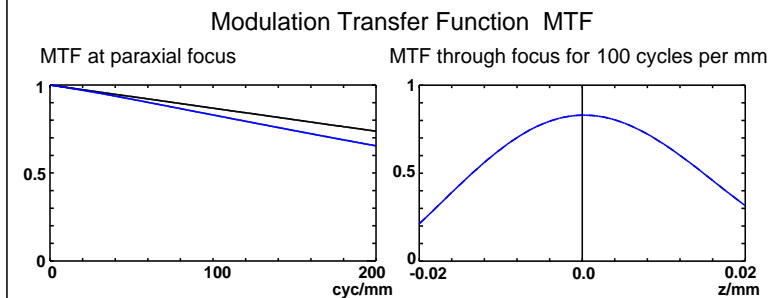
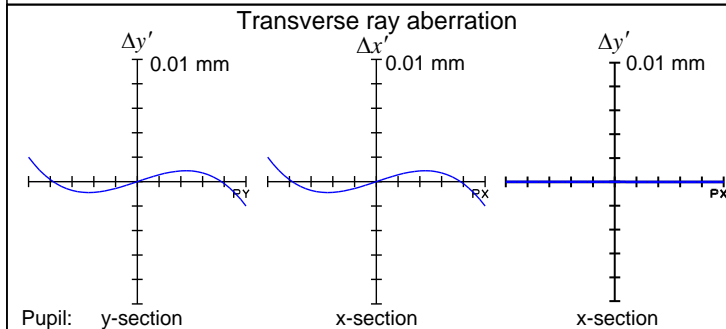
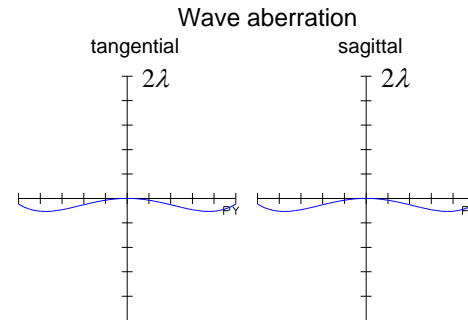
	defocus A_d [A_s]	maximum spotradius [8 R A_s]	rms spotradius [8 R A_s]
Paraxial image position	0	1	0.5
Medium image position	-1	0.5	0.204
Smallest rms of spot	-1.333	0.333	0.167
Smallest diameter	-1.5	0.25	0.177
Marginal image position	-2	0.385	0.289

- Different representations
- At paraxial Gaussian image location as reference

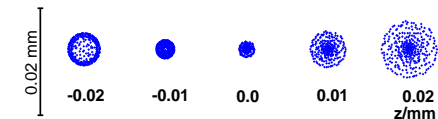


- Different representations
- At best plane, with optimal defocus

Primary spherical aberration with compensating defocus

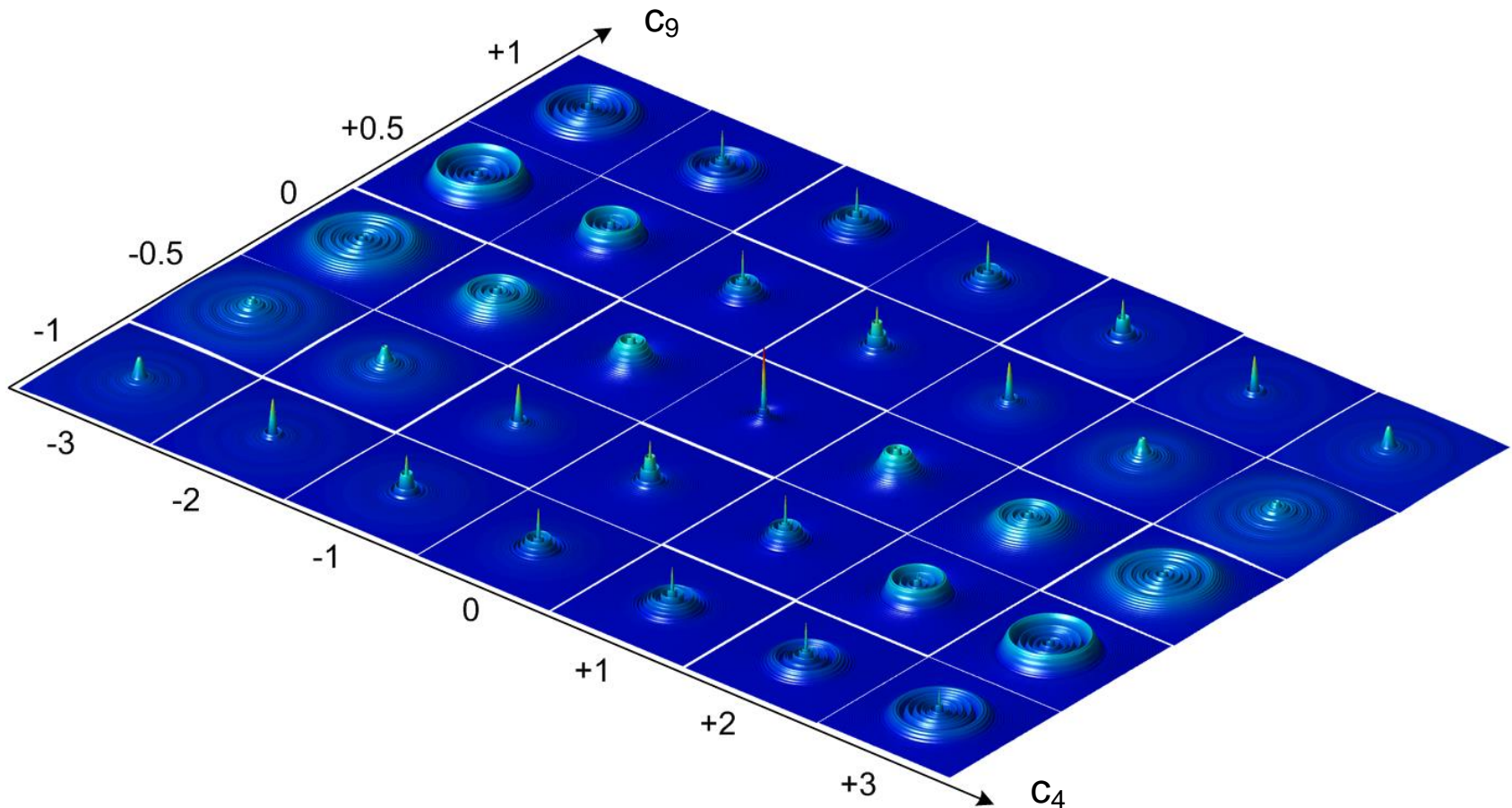


Geometrical spot through focus



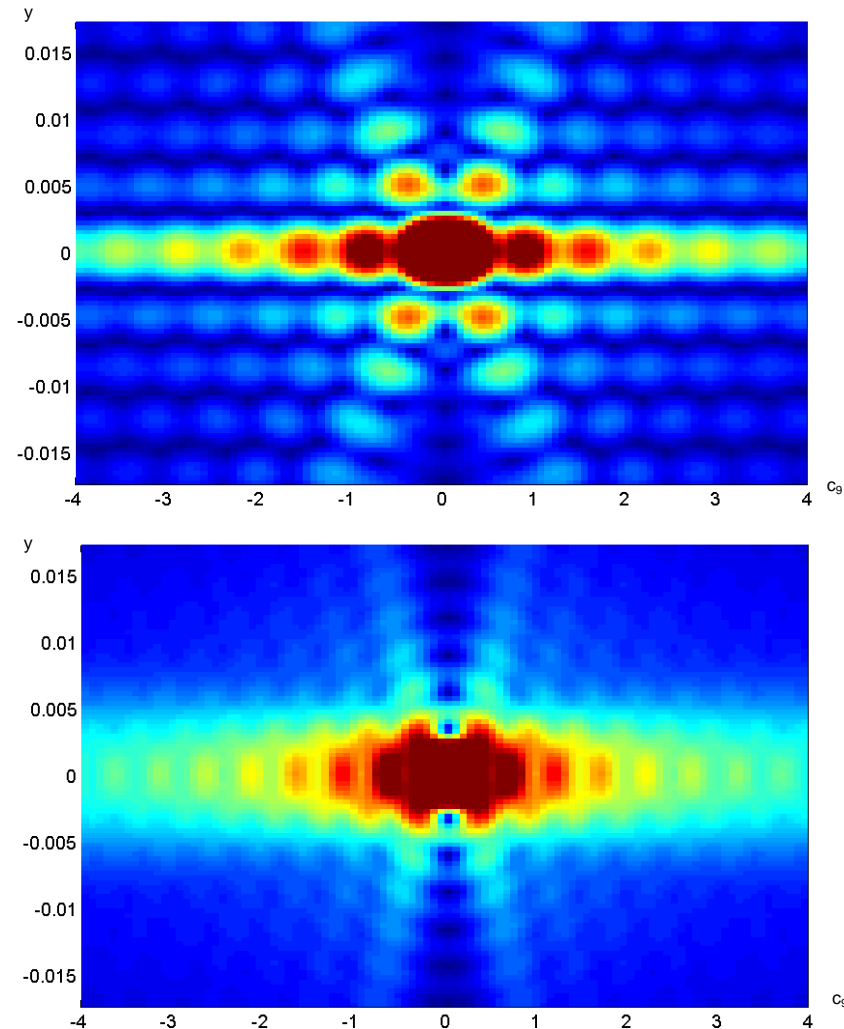
Psf for Spherical Aberration

- Point spread function for different amounts of spherical aberration and defocus
- Unsymmetrical behavior around the image plane (ring vs. compact profile)
- Symmetrical behavior for change of sign in c_4 and c_9



Caustic with Spherical aberration

- Definition of spherical aberration according to
 1. Zernike, with appropriate defocussing
 2. Seidel, only higher order power
- Examples of the changing intensity distribution in the image plane for different aberration coefficients with amplitude above 0.3
- The behavior is completely symmetric relative to the sign of the coefficient c
- Larger aberrations gives a smaller central peak and growing rings with large extent



Caustic with Spherical aberration

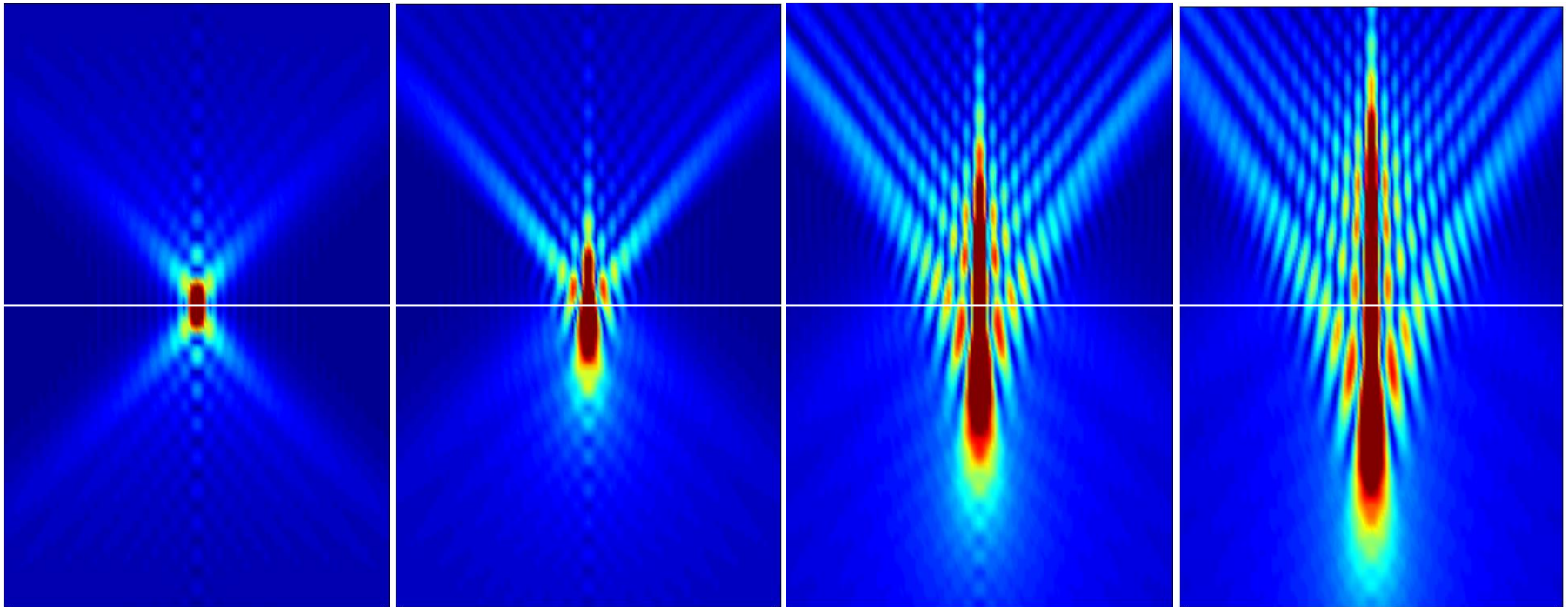
- Growing spherical aberration shows an asymmetric behavior around the nominal image plane for defocussing

$c_9 = 0$

$c_9 = 0.3$

$c_9 = 0.7$

$c_9 = 1$





Spherical Corrected Surface

- Seidel contribution of spherical aberration with

$$\omega_j = \frac{h_j}{h_1} \quad Q_j = n_j \cdot \left(\frac{1}{R_j} - \frac{1}{s_j} \right)$$

$$S_j = \omega_j^4 Q_j^2 \left(\frac{1}{n'_j s'_j} - \frac{1}{n_j s_j} \right)$$

- Result

$$S_j = \left(\frac{h_j}{h_1} \right)^4 \cdot n_j^2 \cdot \left(\frac{1}{R_j} - \frac{1}{s_j} \right)^2 \cdot \left(\frac{1}{n'_j s'_j} - \frac{1}{n_j s_j} \right)$$

- Vanishing contribution:

1. first bracket: vertex ray

$$h_j = 0$$

2. second bracket: concentric

$$R_j = s_j$$

3. bracket: aplanatic surface

$$n'_j s'_j = n_j s_j$$

- Discussion with the Delano formula

$$\Delta s'_{SPH} = \Delta s_{SPH} \cdot \frac{n_1 U_1 \sin u_1}{n'_k U'_k \sin u'_k} + \sum_j \frac{n_j}{n'_j} \cdot h \cdot \sin \frac{i'-i}{2} \cdot \frac{2i \cdot \sin \frac{i'-u}{2}}{U'_j \sin u'_j}$$

2. concentric corresponds to $i' = i$

3. aplanatic condition corresponds to $i' = u$

Delano's Representation of Spherical Aberration

- Paraxial optics: Delano relation

$$n' \cdot q' \cdot U' = n \cdot q \cdot U + n \cdot i \cdot (Q' - Q)$$

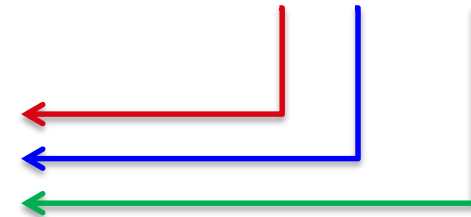
- Real ray comparison:
Delano surface contribution

$$\Delta s'_{SPH} = \Delta s_{SPH} \cdot \frac{n_1 U_1 \sin u_1}{n'_k U'_k \sin u'_k} + \sum_j \frac{(Q - Q') \cdot i \cdot n_j}{n'_j U'_j \sin u'_j}$$

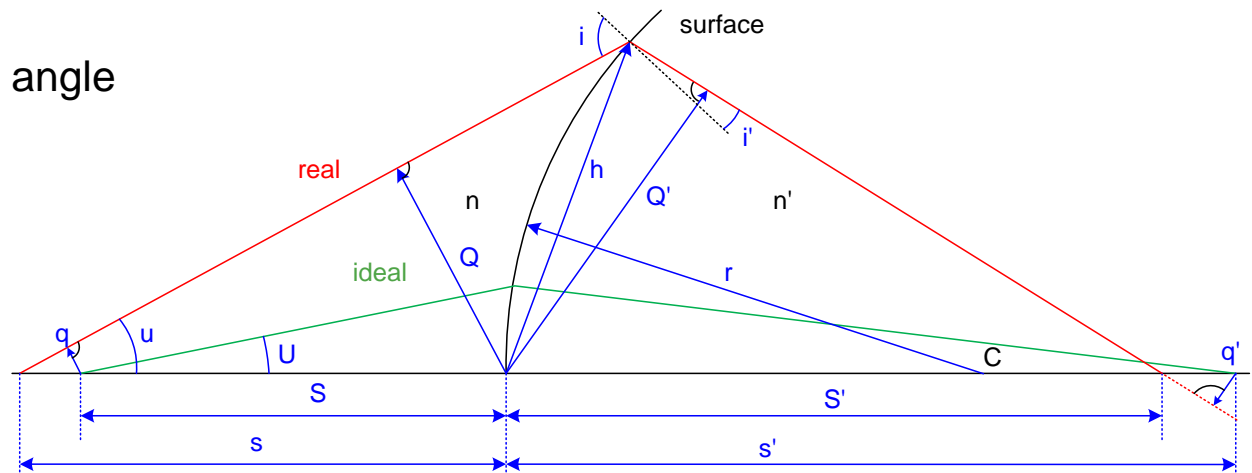
$$\Delta s'_{SPH} = \Delta s_{SPH} \cdot \frac{n_1 U_1 \sin u_1}{n'_k U'_k \sin u'_k} + \sum_j \frac{n_j}{n'_j} \cdot h \cdot \sin \frac{i' - i}{2} \cdot \frac{2i \cdot \sin \frac{i' - u}{2}}{U'_j \sin u'_j}$$

Surface contribution grows with

1. ratio of refractive indices
2. height of the marginal ray
3. Influence of ray bending angle



- Influence of ray bending angle



Aplanatic Surfaces with Vanishing Spherical Aberration

- Aplanatic surfaces: zero spherical aberration:

1. Ray through vertex

$$s' = s = 0$$

2. concentric

$$s' = s \quad \text{und} \quad u = u'$$

3. Aplanatic

$$ns = n' s'$$

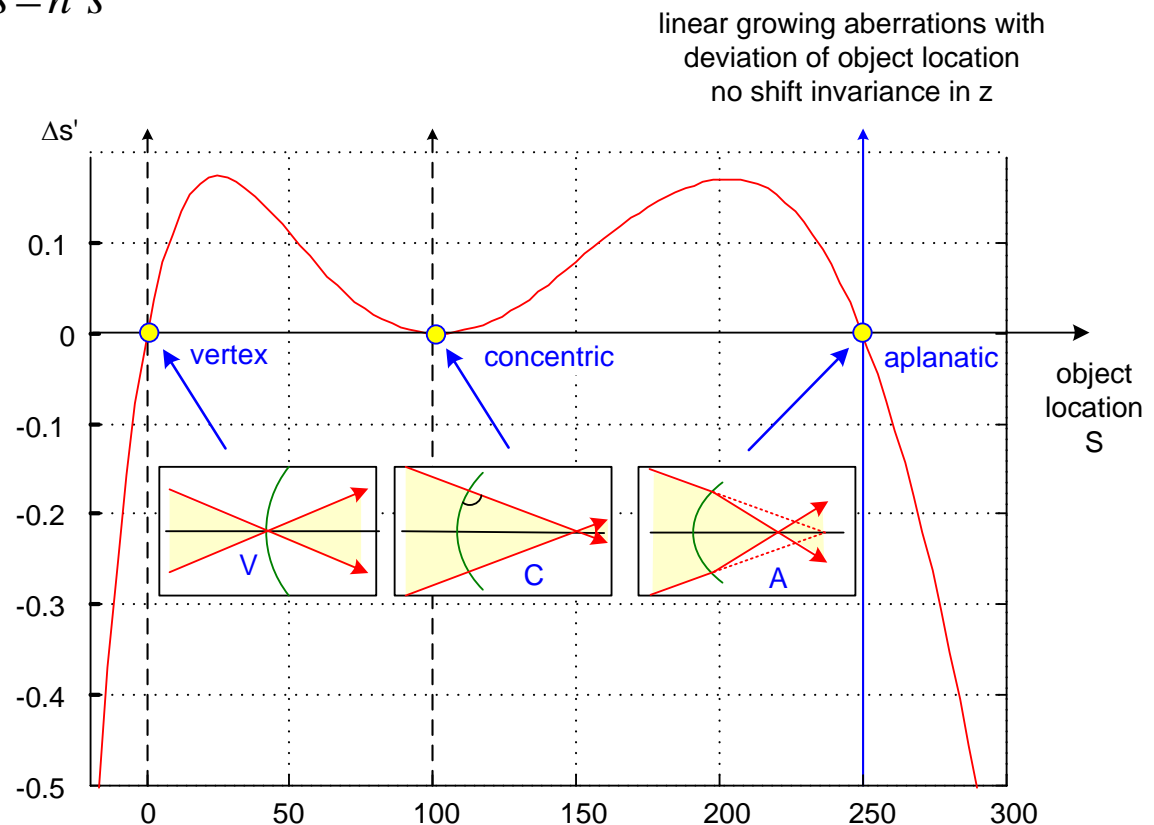
- Condition for aplanatic surface:

$$r = \frac{ns}{n + n'} = \frac{n' s'}{n + n'} = \frac{ss'}{s + s'}$$

- Virtual image location

- Applications:

- Microscopic objective lens
- Interferometer objective lens



Spherical Corrected Singlets

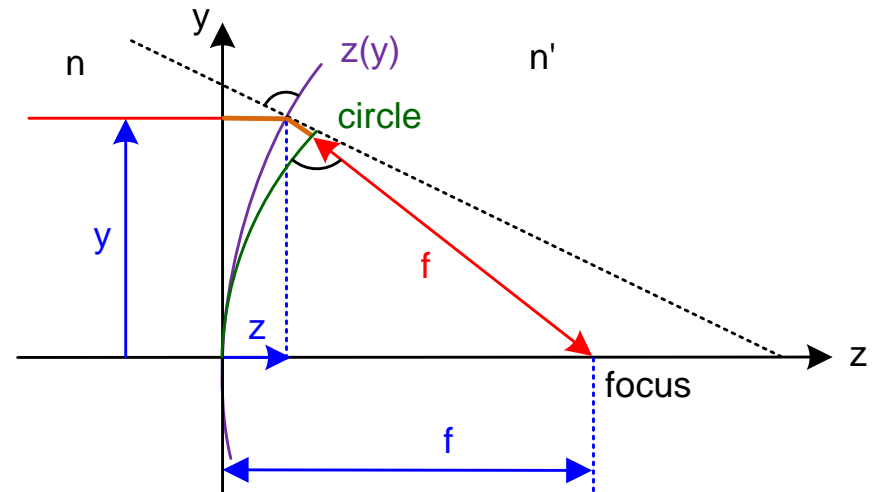
- Exact surface without spherical aberration
- Approach with Fermat principle

$$n \cdot z + n' \cdot \sqrt{(f - z)^2 + y^2} = f \cdot n'$$

- Result: depending on ratio of refractive indices

$$\left[\frac{z - \frac{n' f}{n + n'}}{\frac{n' f}{n + n'}} \right]^2 - \frac{n + n'}{n - n'} \cdot y^2 = 1$$

- Ray bending at one surface only: very sensitive component

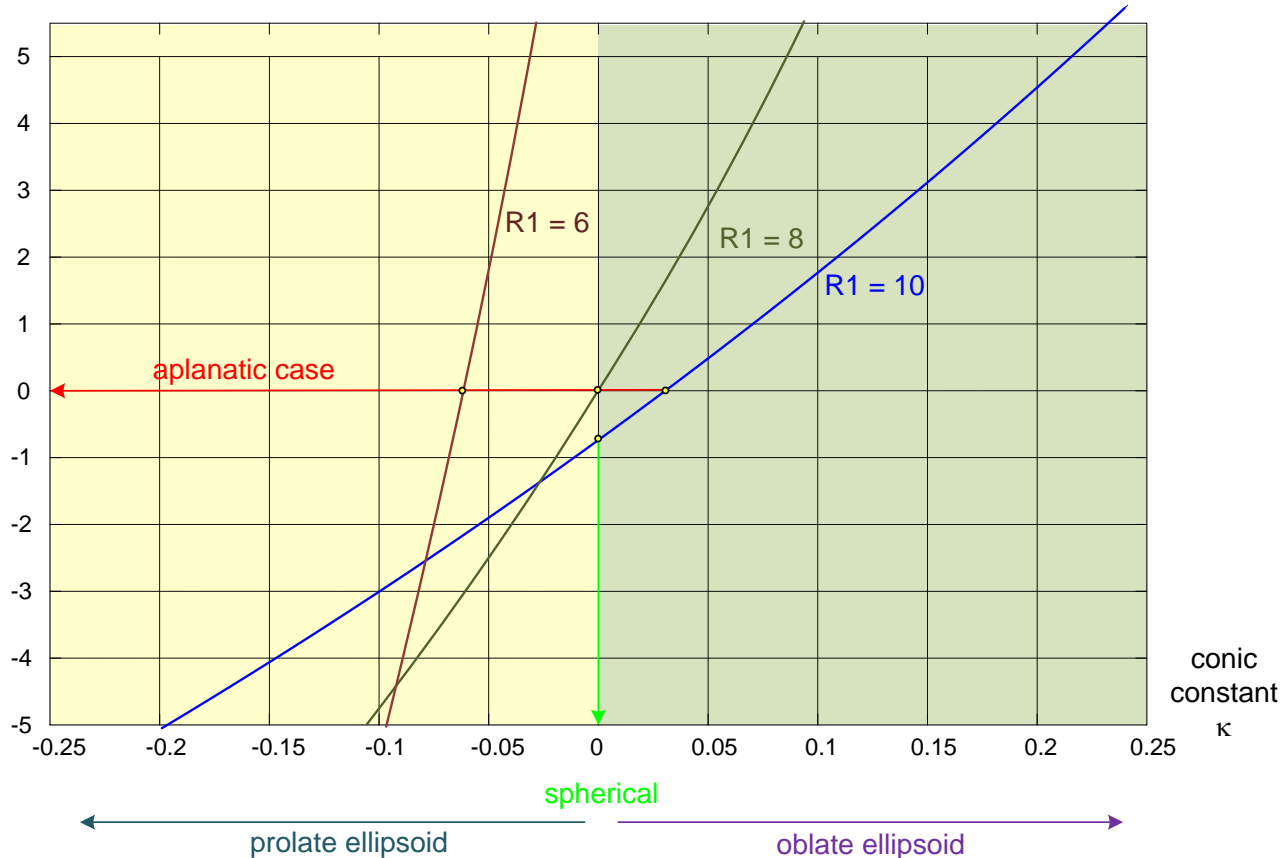




Elliptical Surface and Aplanatic Case

- Meniscus lens with concentric rear surface
- Change of front radius $R1 = 6 / 8 / 10$ mm
- Spherical aberration c_9 for variation of conic constant κ
- Generally corrected for elliptical shape
- Special case of aplanatic spherical surface

spherical aberration c_9

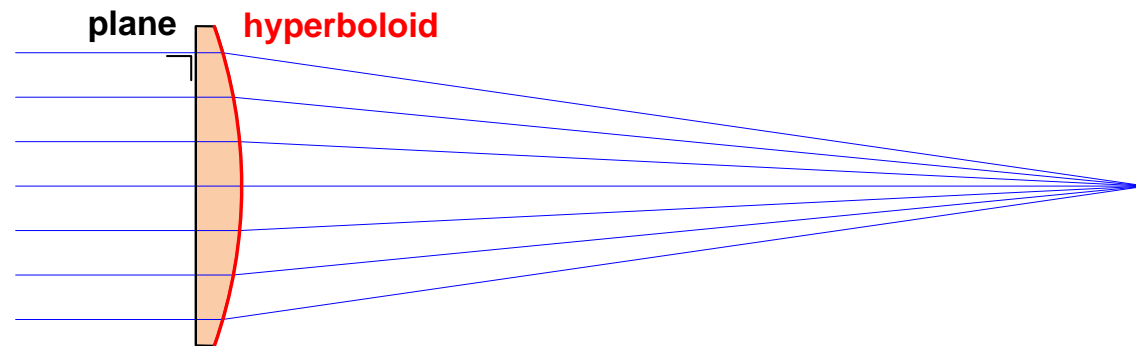




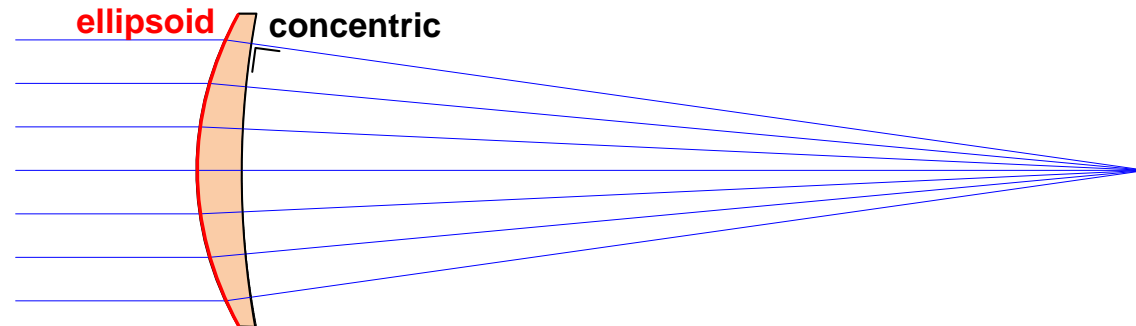
Single Lens free of Spherical aberration

- Object location at infinity
- Refraction with only one surface: exact analytical solution

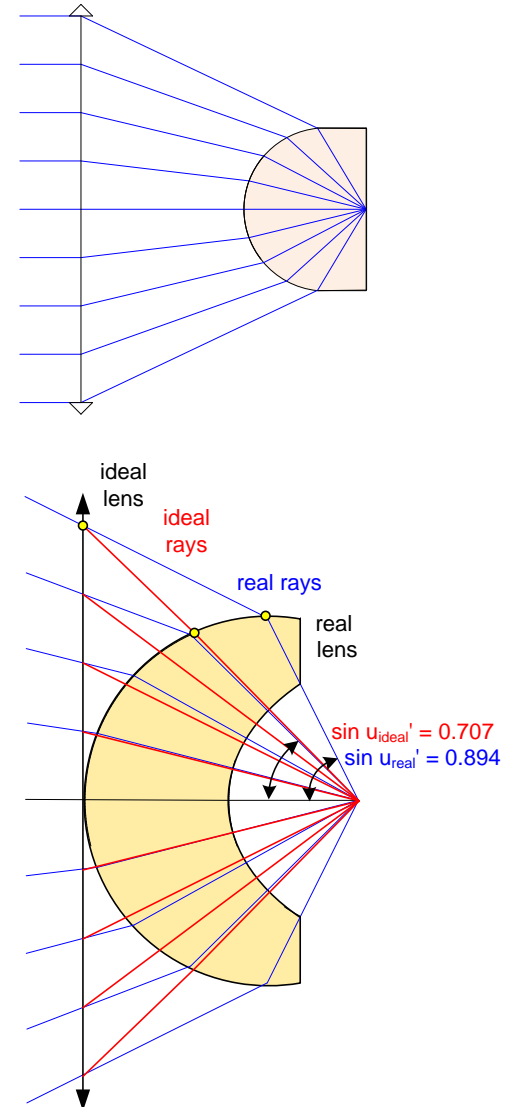
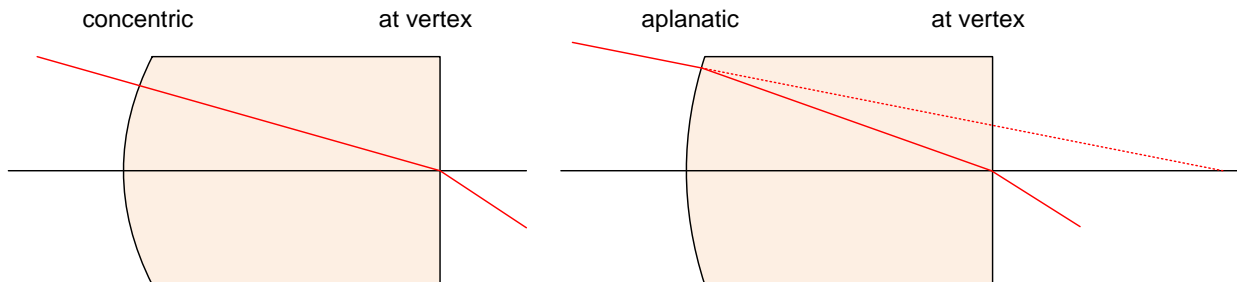
a) Rear surface
exact hyperbola
front surface plane
 $\kappa_2 = -2.35$



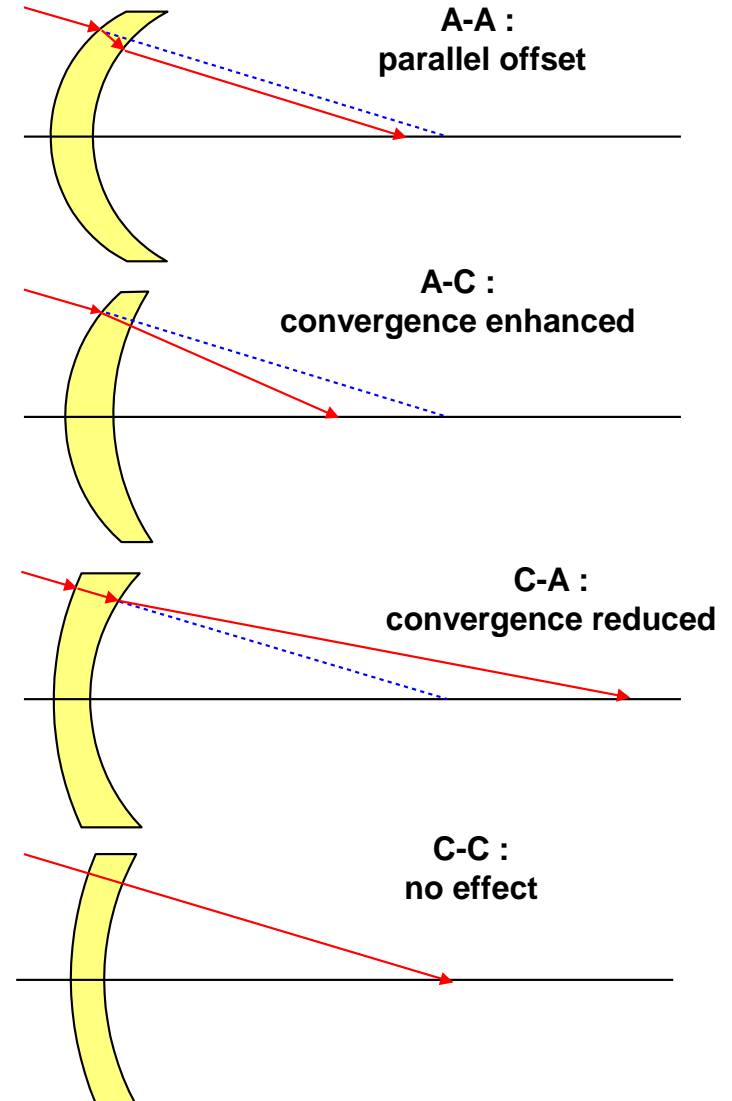
b) Front surface
exact ellipsoid
rear surface
concentric
 $\kappa_1 = -0.434$



- Spherical aberration vanishes for all orders
- Aplanatic lens at high NA:
effective real NA is higher than paraxial
- Further possible aplanatic lenses
 1. less practical importance
 2. used in microscopic objective front lens

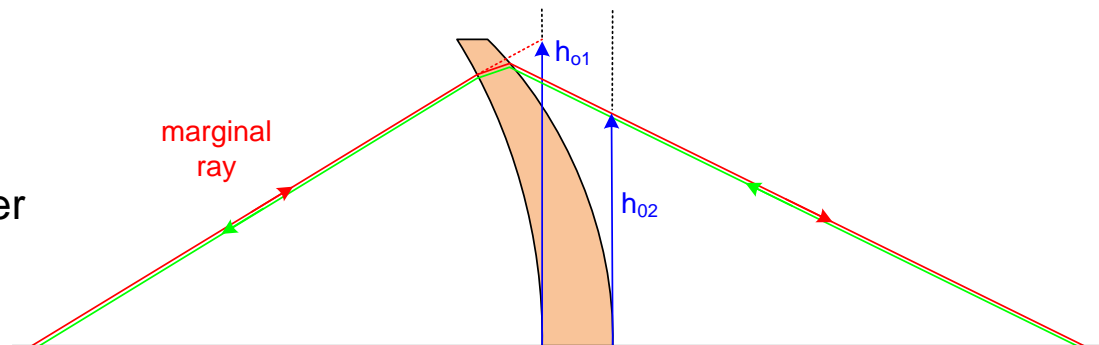
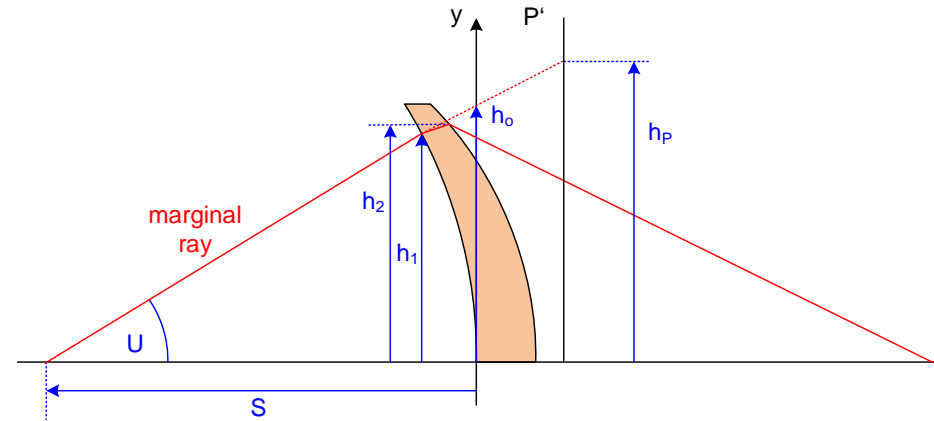
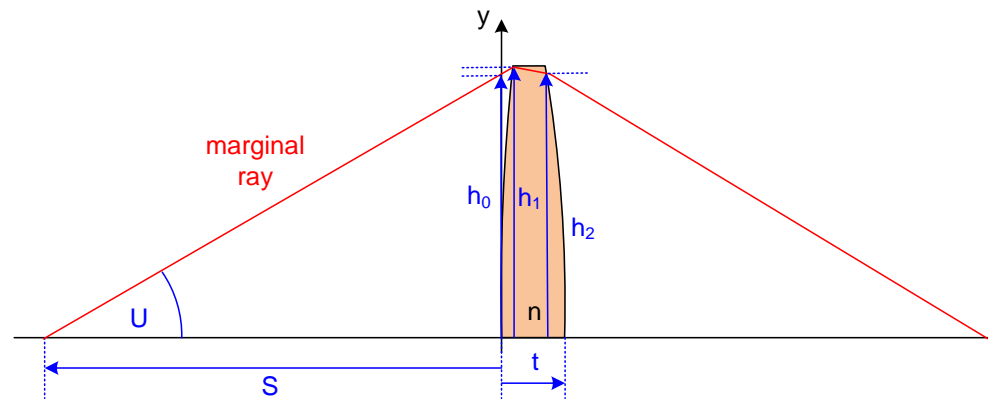


- Aplanatic lenses
- Combination of one concentric and one aplanatic surface:
zero contribution of the whole lens to spherical aberration
- Not useful:
 1. aplanatic-aplanatic
 2. concentric-concentricbended plane parallel plate,
nearly vanishing effect on rays



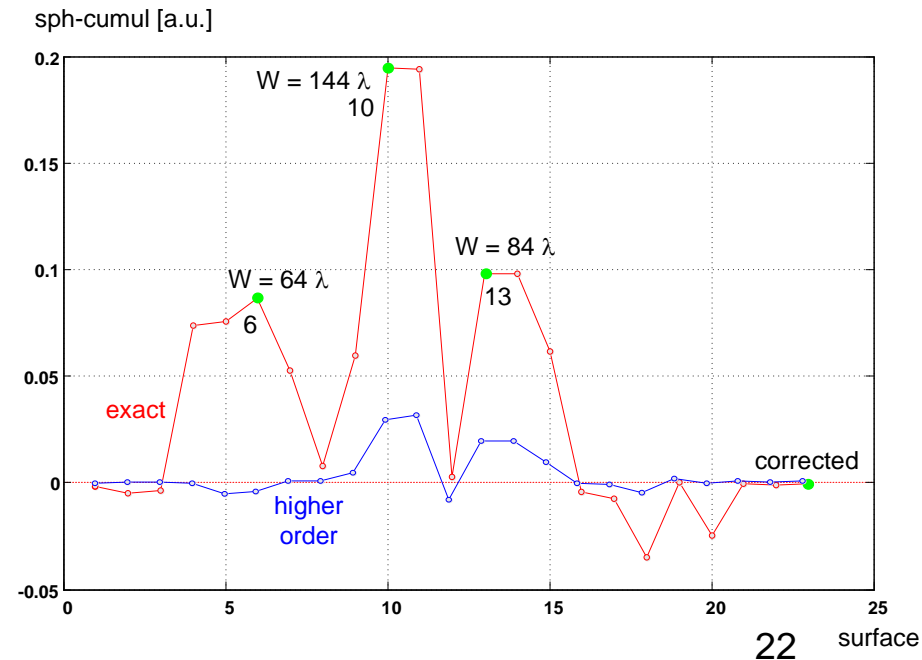
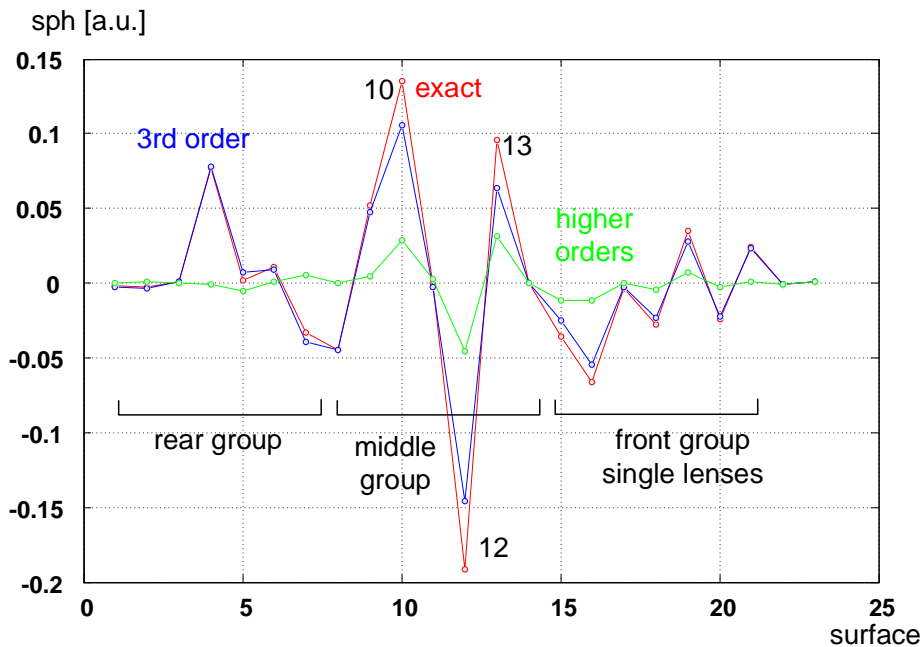
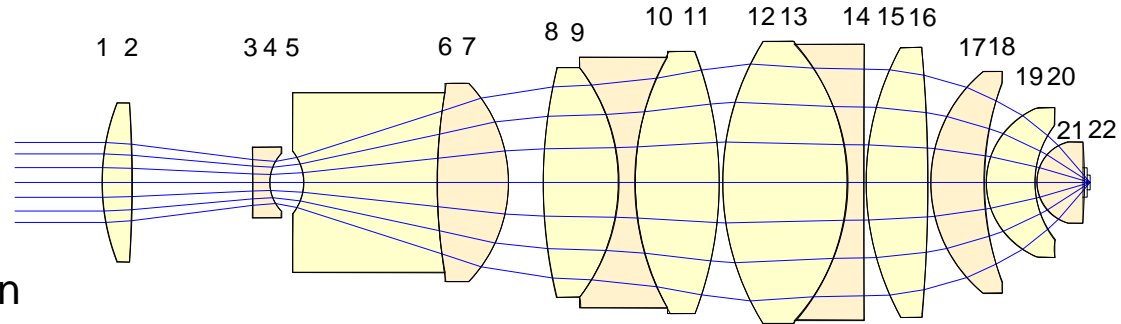
Selection of Expansion Height for a Lens

- Usual selection of expansion height for Seidel formulas:
Vertex plane height h_0
- Thin Lens with small X:
 - height h_1 , h_2 , h_0 nearly the same
 - no severe problems
- Thin lens with large bending:
 - large height differences
 - changes by reverted lens
 - additional option: height h_p in the principal plane
- Reversed lens:
 - now h_{02} gives a difference in higher orders than h_{01}

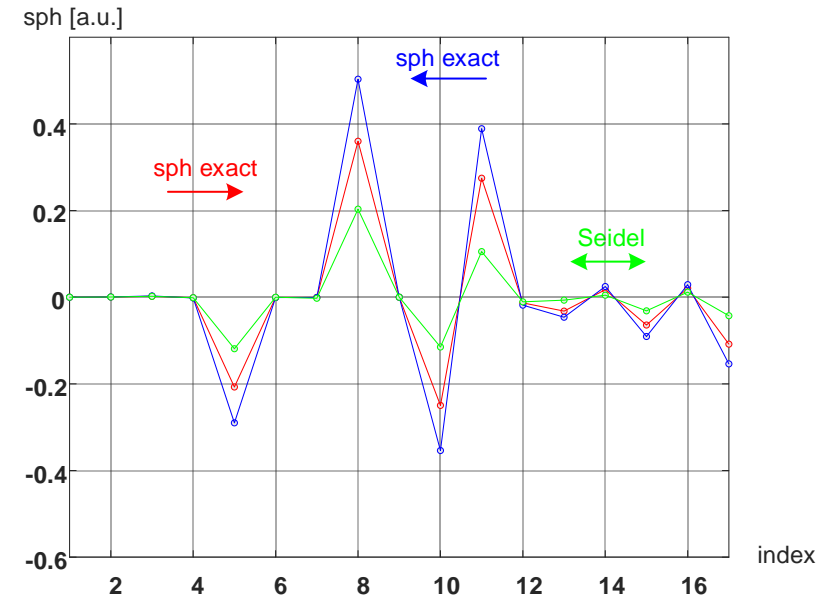


Microscopic Lens

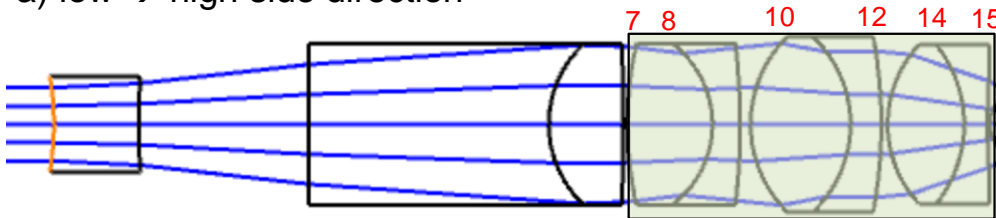
- Microscopic lens
100x1.3 oil / Kuda
Patent US 5978147
- Huge intermediate aberrations
- Large higher orders mainly at cemented surfaces with small Δn
- Front group: alternating sign due to r below/above aplanatic radius



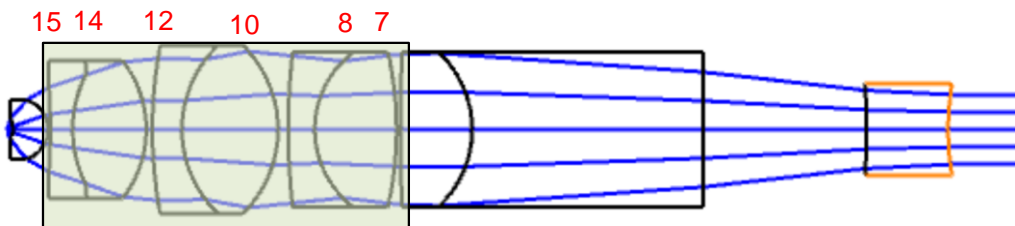
- High-NA microscopic lens: 100x0.95 air
- Differences of ideal vs real MR ray heights up to 25%
- Consequence:
 - Seidel surface contributions identical for both ray directions
 - difference of exact spherical surface contributions depending on direction of rays
 - sensitivity evaluation depends on orientation of the system



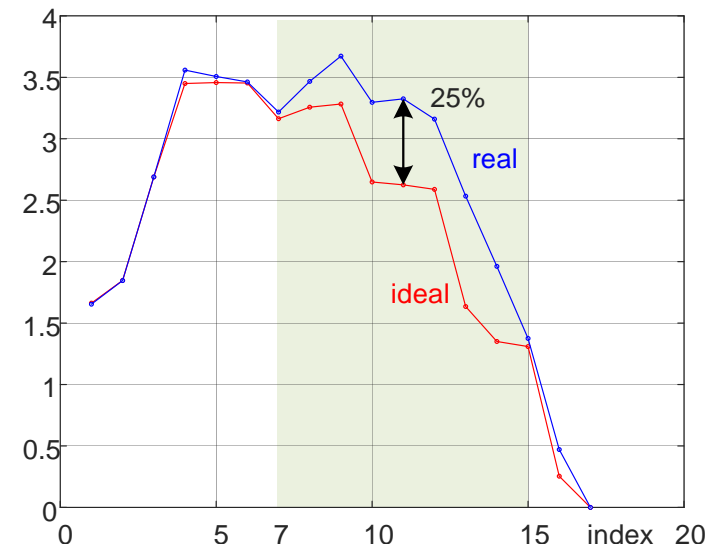
a) low → high side direction



b) high → low side direction



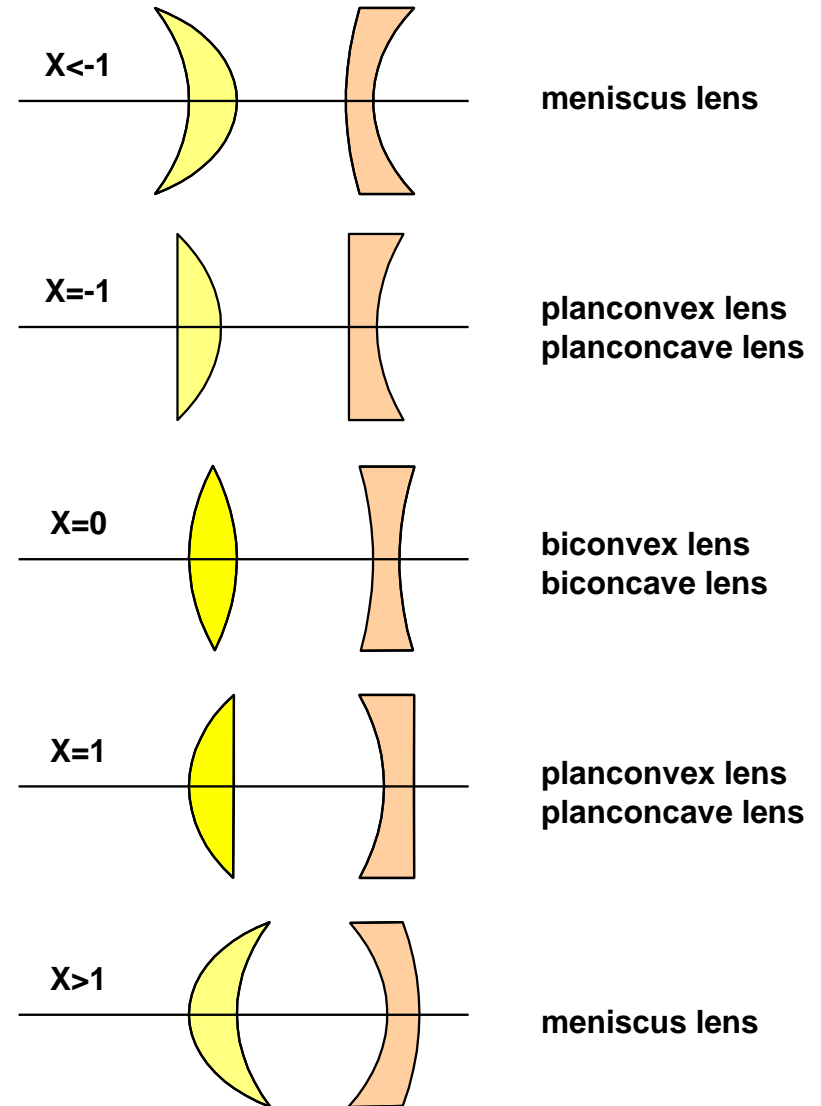
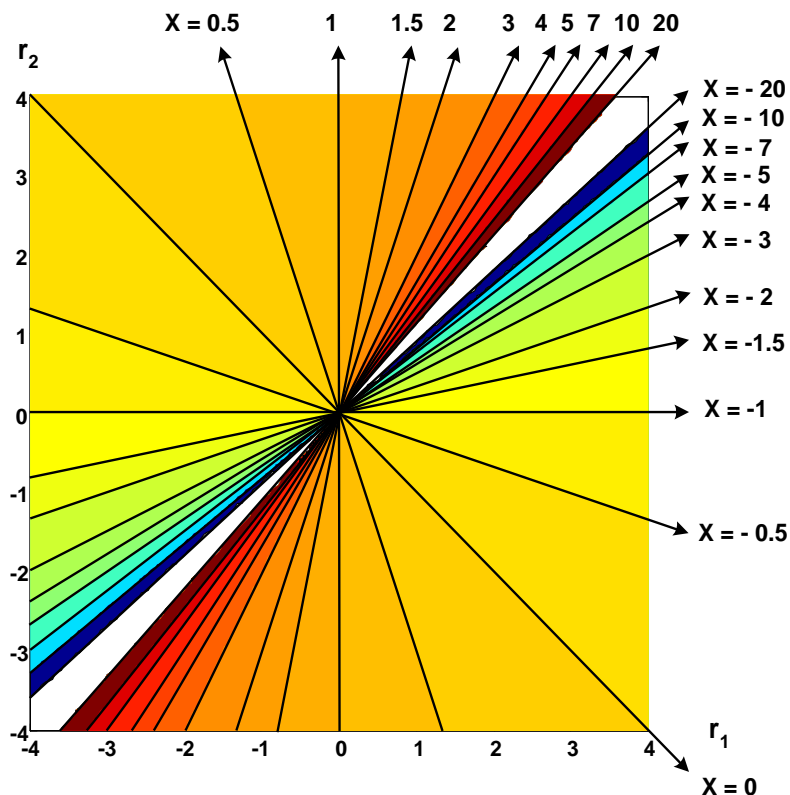
MR ray height



Bending of a Lens

- Bending: change of shape for invariant focal length
- Parameter of bending

$$X = \frac{r_1 + r_2}{r_2 - r_1}$$

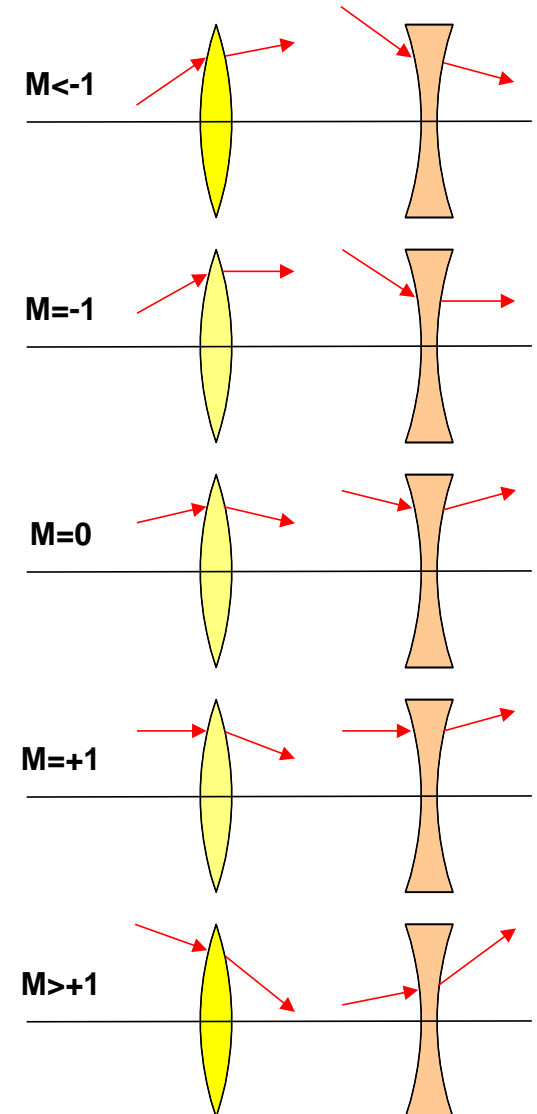


Magnification / Conjugation Parameter

- Magnification/conjugation parameter M :
defines ray path through the lens

$$M = \frac{U'+U}{U'-U} = \frac{1+m}{1-m} = \frac{2f}{s} + 1 = \frac{2f}{s'} - 1$$

- Special cases:
 1. $M = 0$: symmetrical 4f-imaging setup
 2. $M = -1$: object in front focal plane
 3. $M = +1$: object in infinity
- The parameter M strongly influences the aberrations





Lens Contributions of Seidel

- Spherical aberration

$$S_{lens} = \frac{1}{32n(n-1)f^3} \left[\frac{n^3}{n-1} + \frac{n+2}{n-1} \cdot \left(X - \frac{2(n^2-1)}{n+2} \cdot M \right)^2 - \frac{n^2(n-1)}{n+2} \cdot M^2 \right]$$

- Special impact on correction:

1. Special quadratic dependence on bending X

Minimum at

$$X_{sph \min} = -\frac{2(n^2-1)}{n+2} M$$

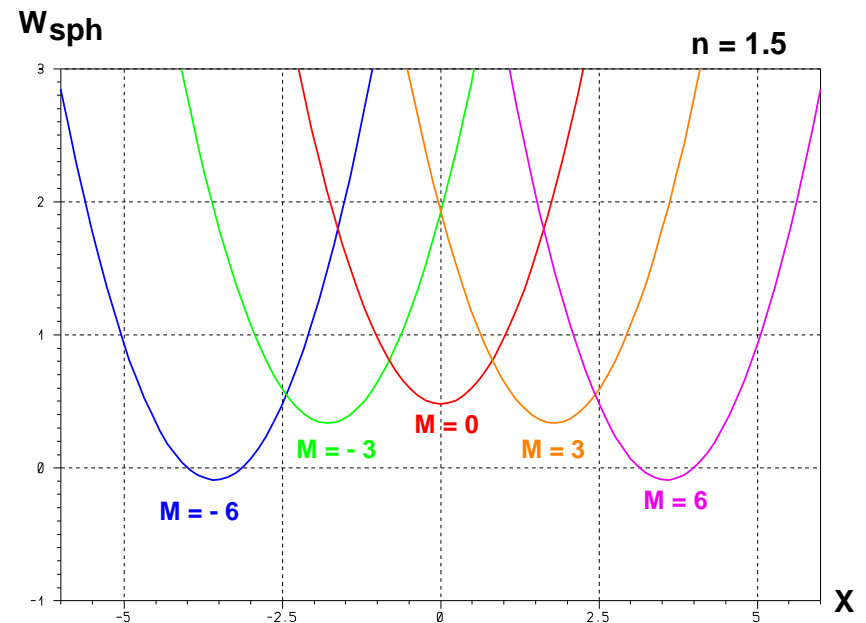
2. No correction for small n and M

3. Correction for large n: infrared materials

M: virtual imaging

Limiting value

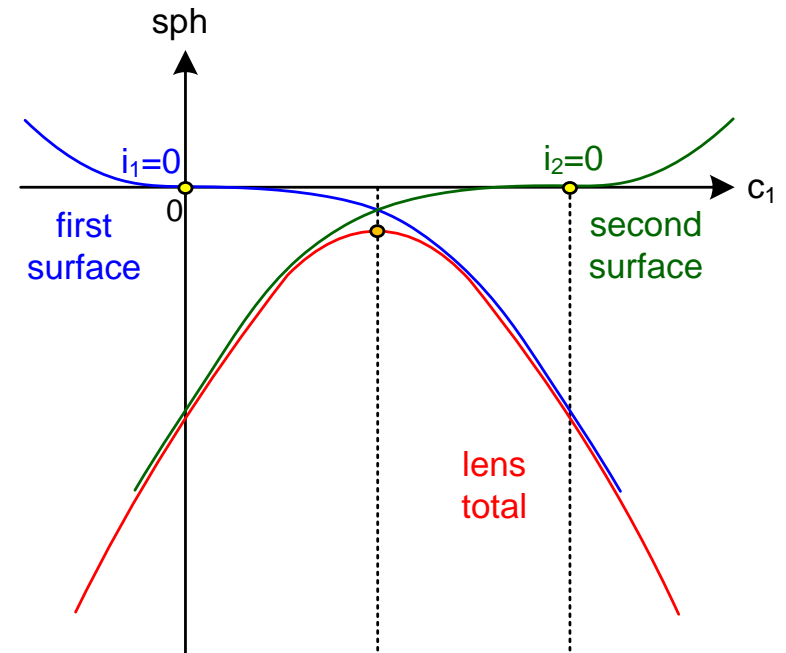
$$M_{s=0}^2 = \frac{n(n+2)}{(n-1)^2}$$





Spherical Aberration of a bended Lens

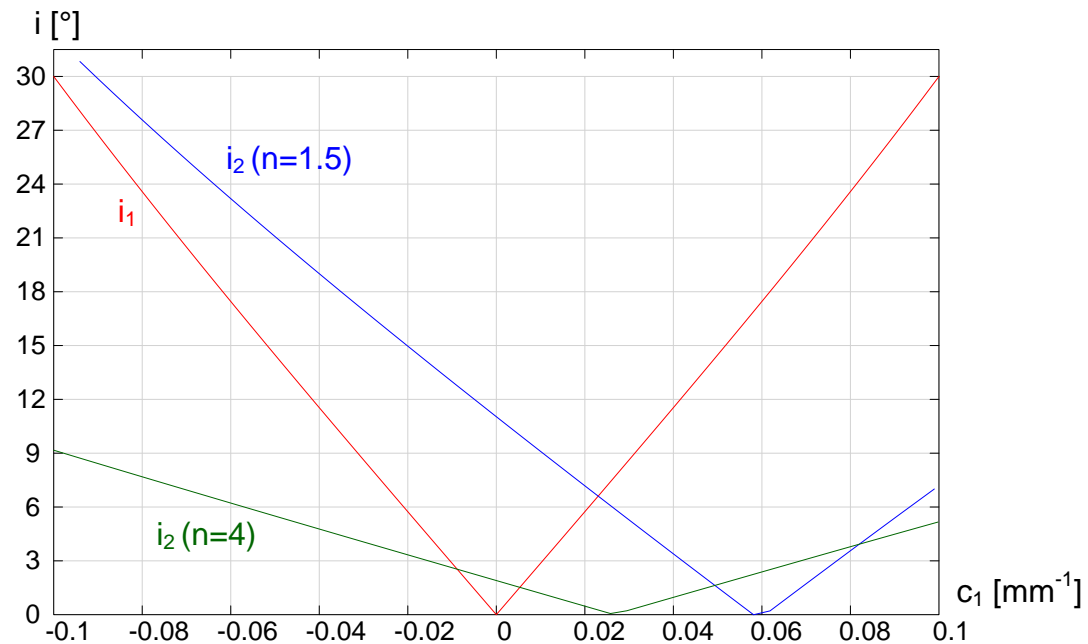
- Separation of the spherical aberration of a thin lens into the contributions of the two surfaces
- Effect of bending, represented by the curvature c_1 of the front surface





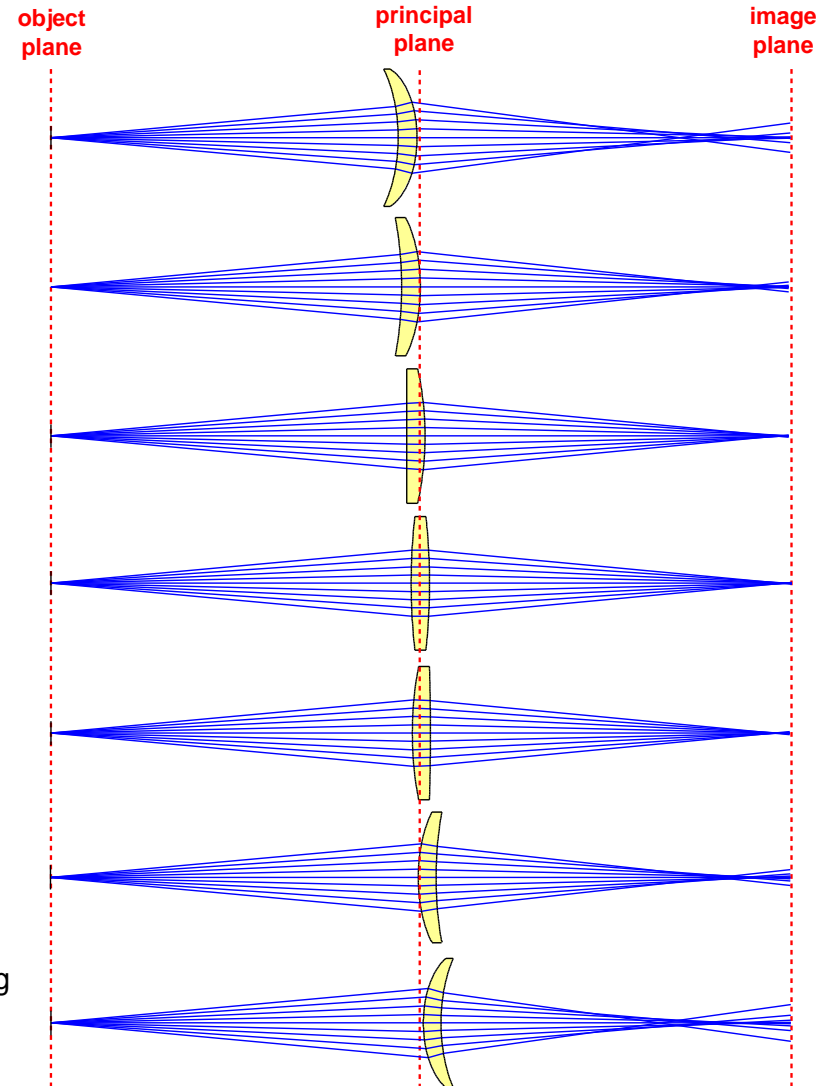
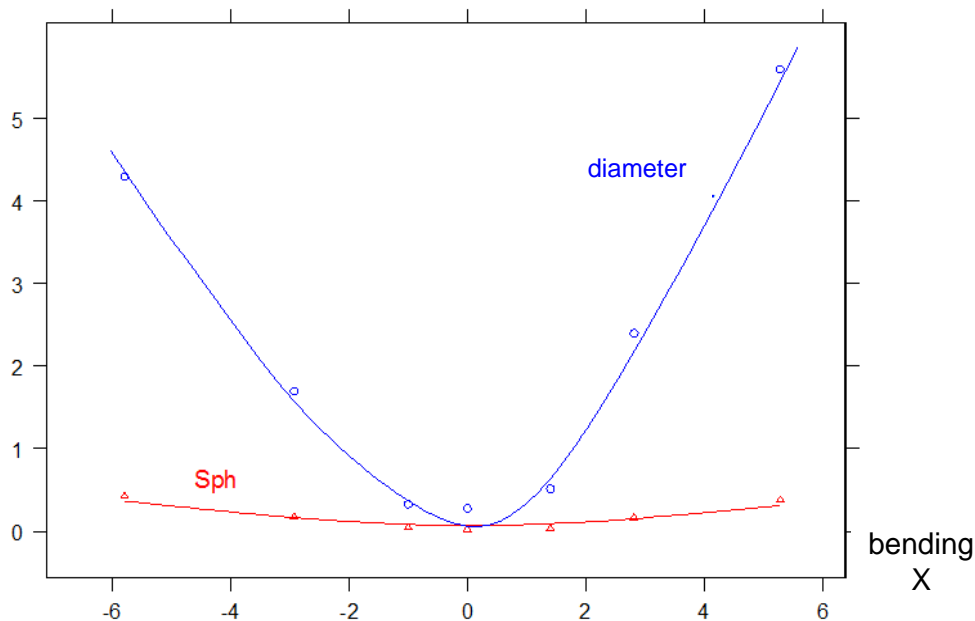
Incidence of Bended Lens

- Changes of the incidence angles at the front and the rear surface of a bended lens
- Figure without sign of incidence angle
- Angle at the second surface depends on the refractive index



Spherical Aberration: Lens Bending

- Spherical aberration and focal spot diameter as a function of the lens bending (for $n=1.5$)
- Optimal bending for incidence averaged incidence angles
- Minimum larger than zero: usually no complete correction possible





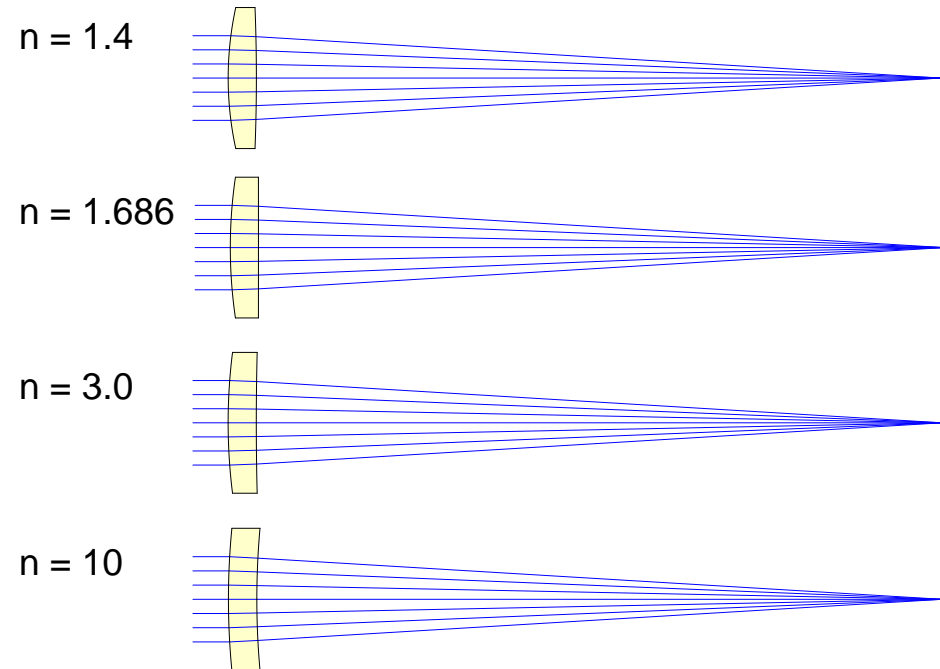
Lens of Best Shape

- Optimal bending of a focussing lens for collimated input : $M = +1$

$$X_{sph\ min} = -\frac{2(n^2 - 1)}{n + 2} M$$

- Plan convex lens for $n = 1.686$
- Higher indices: meniscus shape

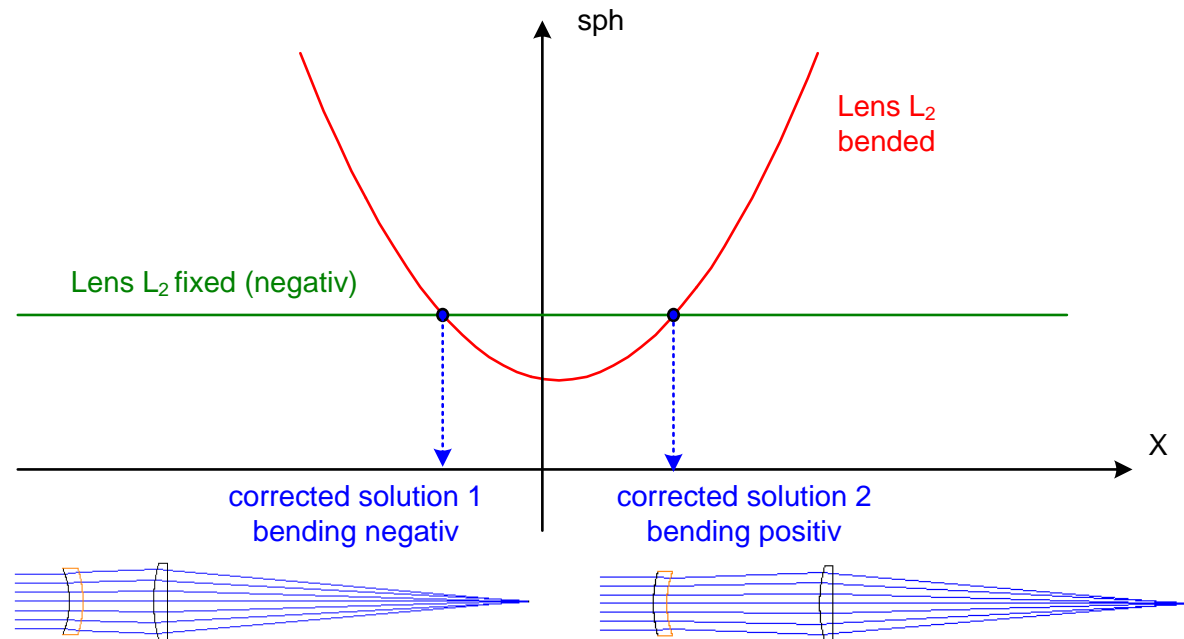
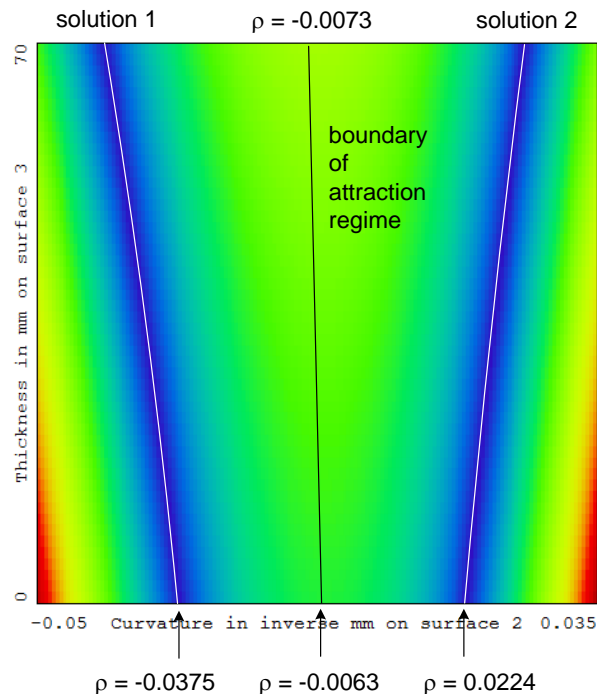
index n	bending X	shape
1.4	-0.565	bi convex
1.686	-1	plan convex
2	-1.5	meniscus
3	-3.2	meniscus
4	-5	meniscus
10	-16.5	meniscus





Spherical Aberration Correction by Bending

- Fixed plano-convex lens L_2
- Correction of spherical aberration by bended negative lens L_1
- Compensation of negative SPH_1 by positive SPH_2
- Two solutions with different sign of bending
- Solutions asymmetric due to shift of principal plane
- Small nonlinearity due to growing height at lens 2
- Adapted distance to keep total focal length constant
- Diagram:
merit function spot size as function distance and bending





G-Sum Formula

- Alternative formula for the 3rd order spherical aberration of a thin lens:

G-sum formula of Conrady

$$\Delta s'_{sph} = -\frac{h^4}{n'u'} \cdot \sum G_1 c^3 - G_2 c^2 c_1 + G_3 c^2 v + G_4 c c_1^2 - G_5 c c_1 v + G_6 c v^2$$

- Vergence / object distance

$$v = \frac{1}{s}$$

- Curvatures

$$c = \frac{n-1}{f'} \quad , \quad c_1 = \frac{1}{r_1}$$

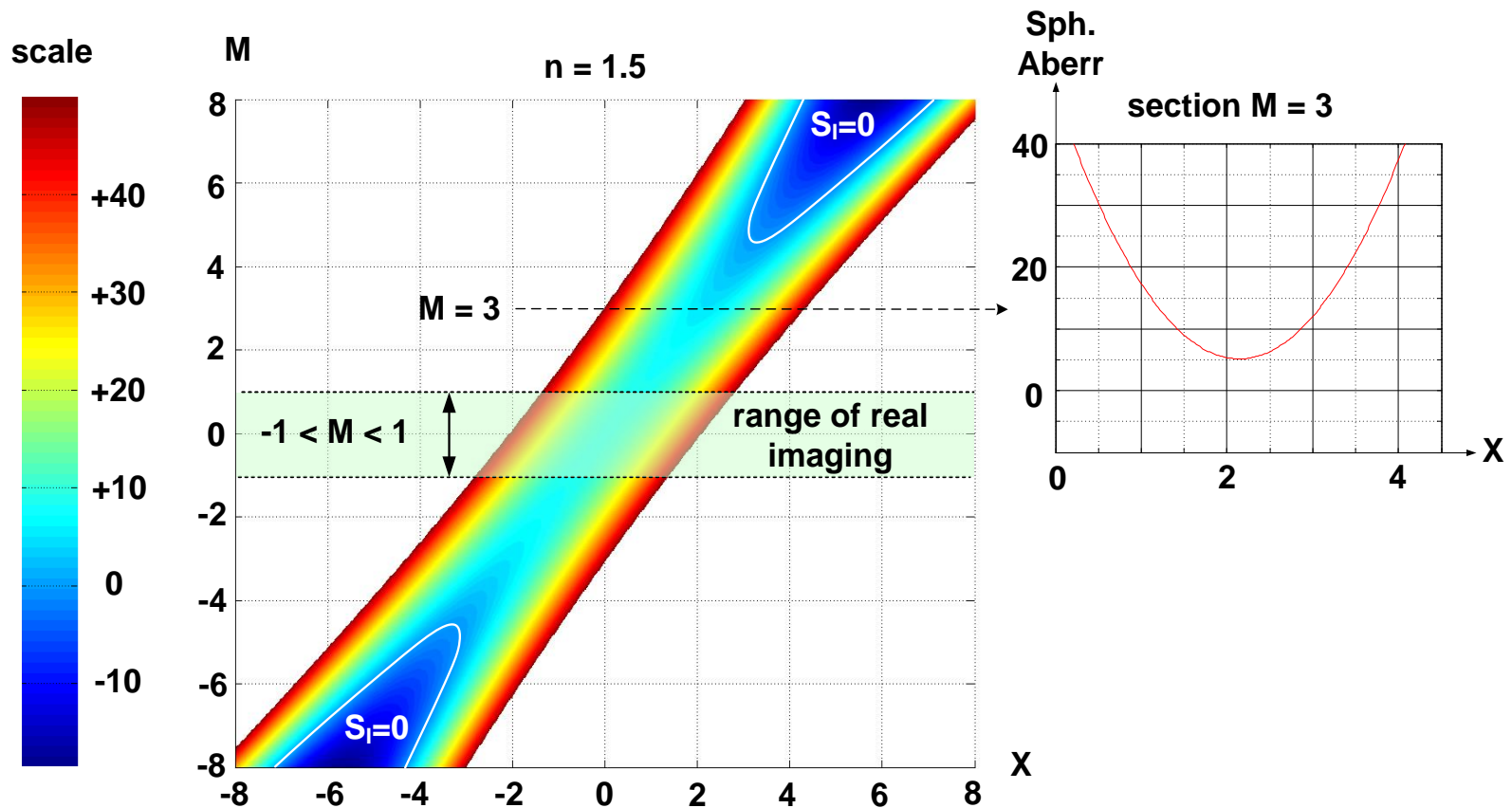
- G-factors for refractive index

$$G_1 = \frac{1}{2} \cdot n^2 \cdot (n-1) \quad , \quad G_2 = \frac{1}{2} \cdot (2n+1) \cdot (n-1)$$

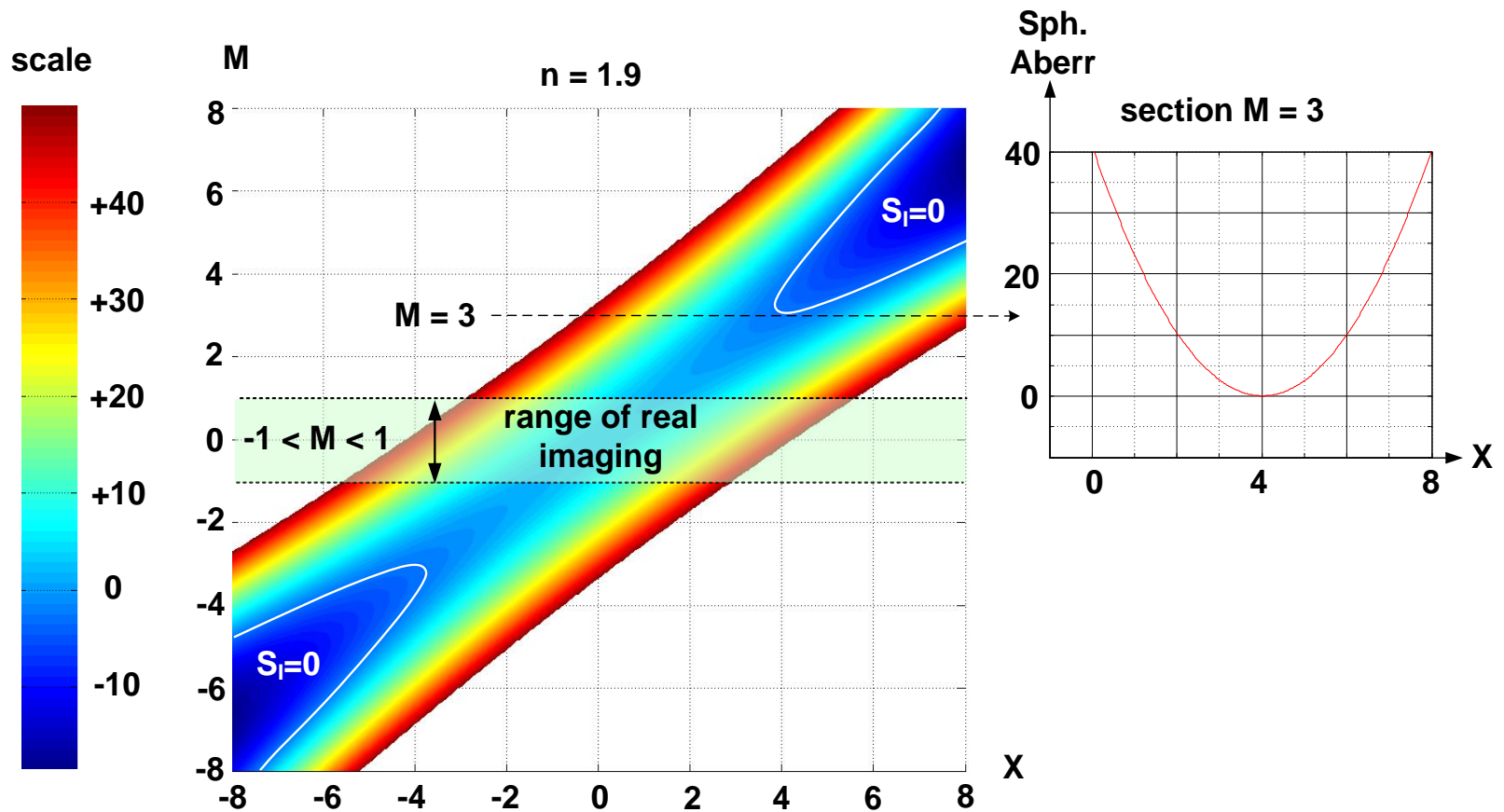
$$G_3 = \frac{1}{2} \cdot (3n+1) \cdot (n-1) \quad , \quad G_4 = \frac{1}{n} \cdot (n+2) \cdot (n-1)$$

$$G_5 = \frac{2}{n} \cdot (n^2 - 1) \quad , \quad G_6 = \frac{1}{2n} \cdot (3n+2) \cdot (n-1)$$

- Lens bending for $n = 1.5$



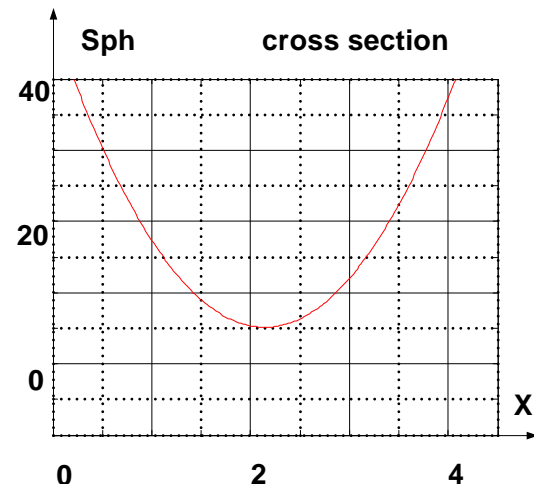
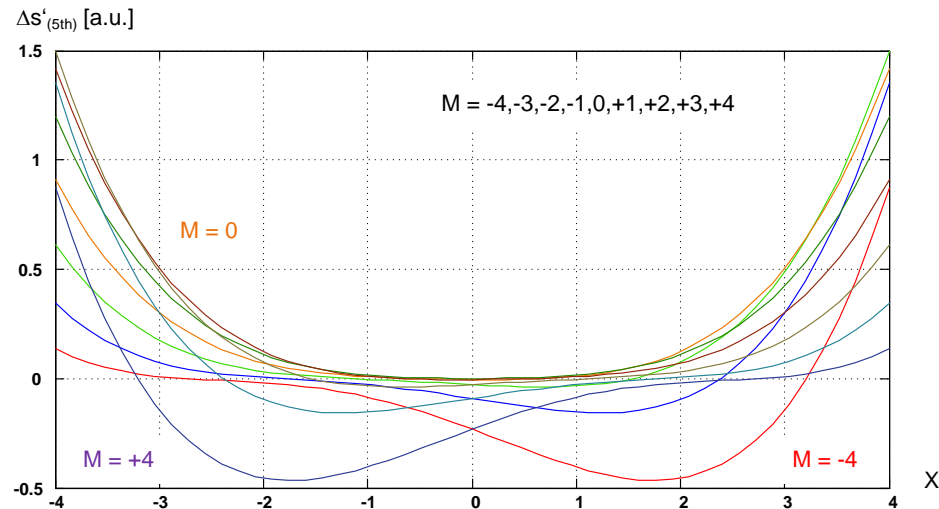
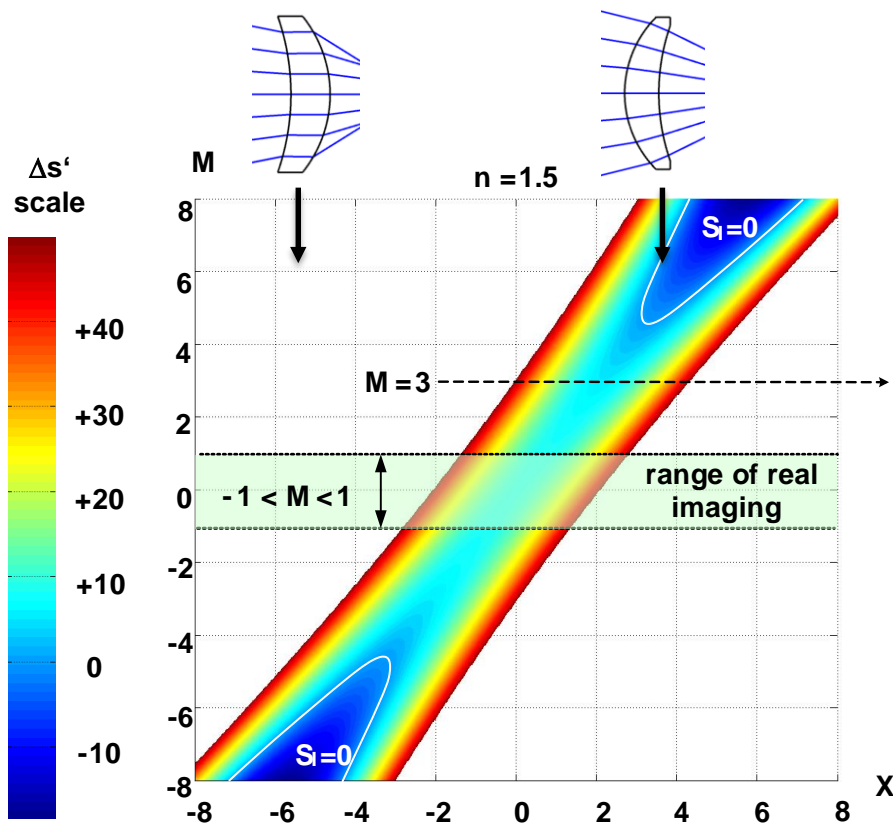
- Lens Bending for $n = 1.9$



Higher Order Spherical Aberration at a Thin Lens



- In particular for large $|X|$, $|M|$ the higher order spherical aberration of a thin lens is not well described by 3rd order due to large incidence angles i_1 , i_2
- The parabolic behavior of a spherical correction in 3rd order is too simple





Spherical Correction of a Single Lens

- Spherical aberration of a single lens
- Optimal bending for given n and M

$$X_{sph\ min} = -\frac{2(n^2 - 1)}{n + 2} M$$

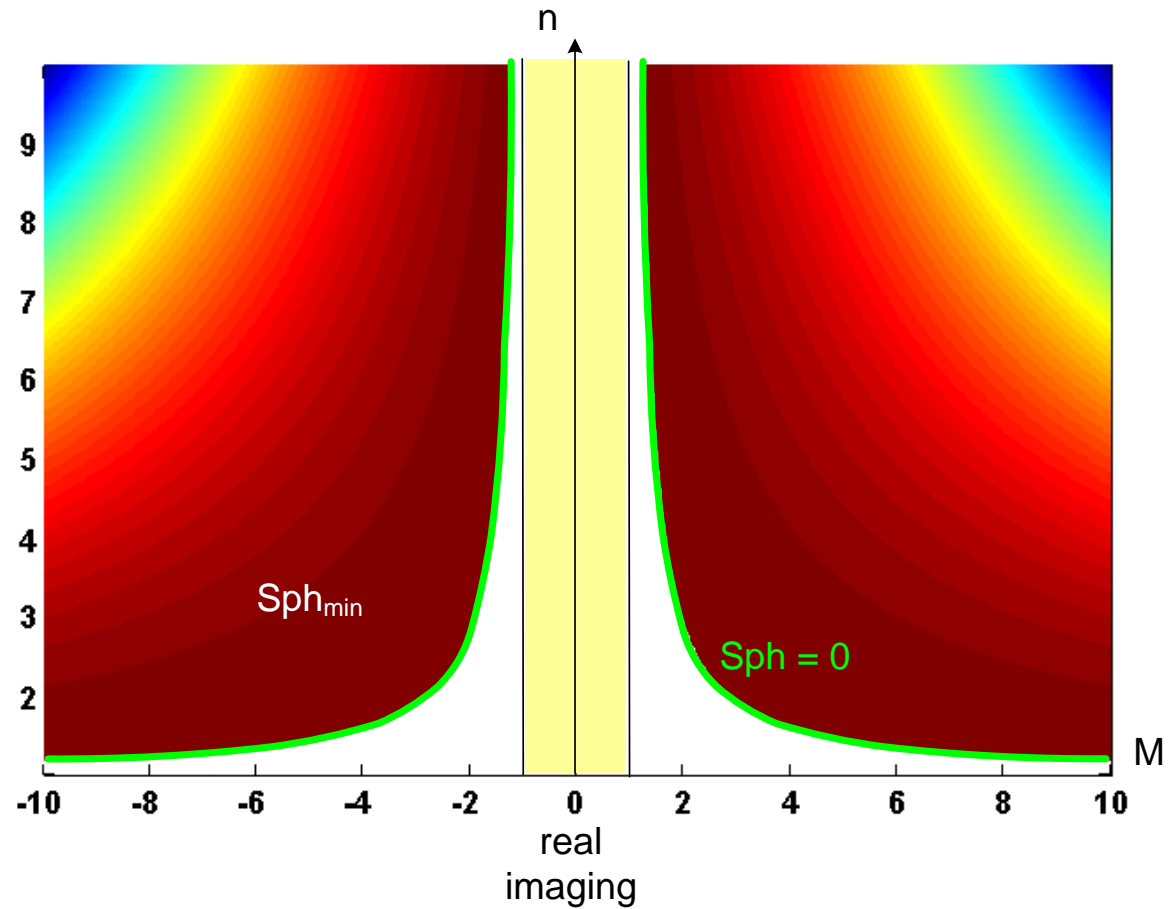
- Correction possible only for virtual imaging with

$$M_{s=0} = \frac{\sqrt{n(n+2)}}{n-1}$$

$$n > \frac{M^2 + 1 + \sqrt{3M^2 + 1}}{M^2 - 1}$$

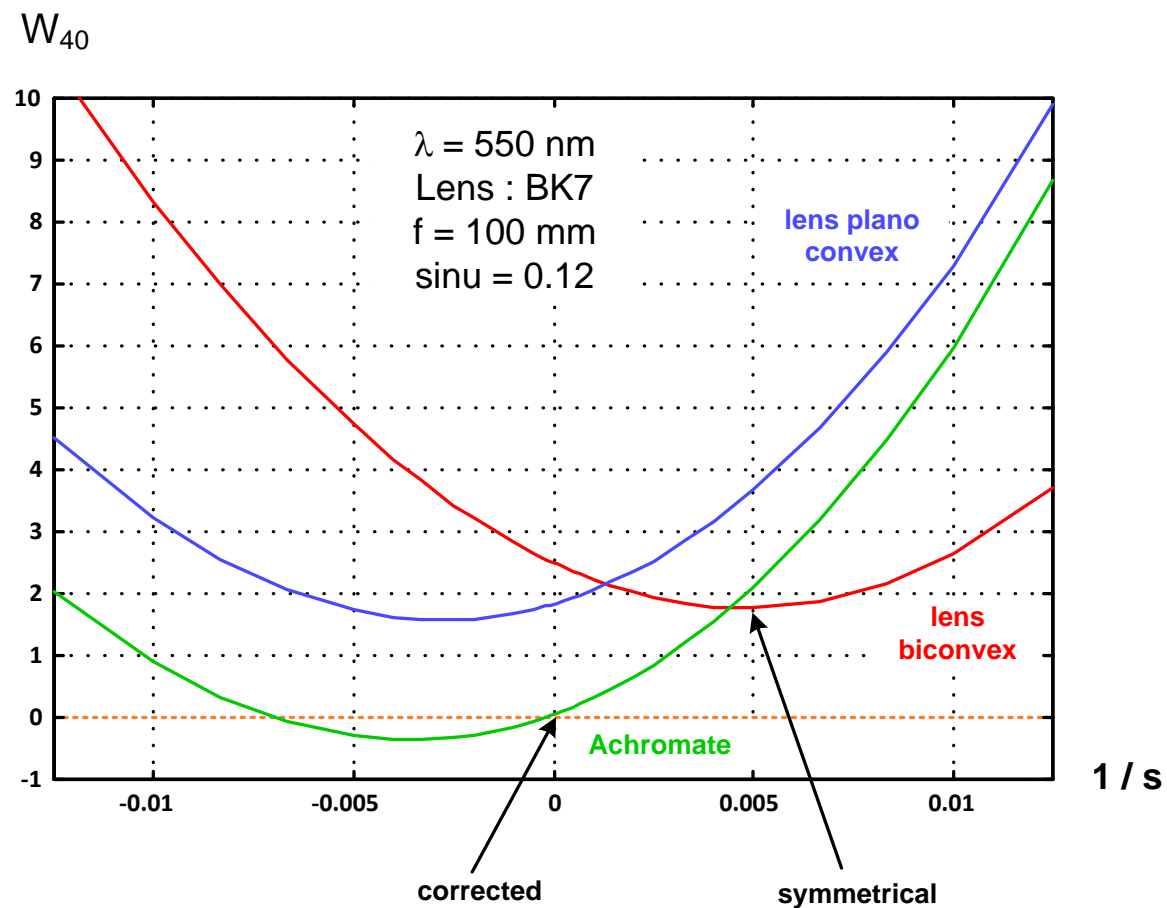
$$S_{lens} = \frac{1}{32n(n-1)f^3} \left[\frac{n^3}{n-1} + \frac{n+2}{n-1} \cdot \left(X - \frac{2(n^2-1)}{n+2} \cdot M \right)^2 - \frac{n^2(n-1)}{n+2} \cdot M^2 \right]$$

M	n_{min}
2	2.869
3	1.914
4	1.600
5	1.447



- Change of the object distance for
 1. plano convex lens
 2. biconvex lens
 3. achromate

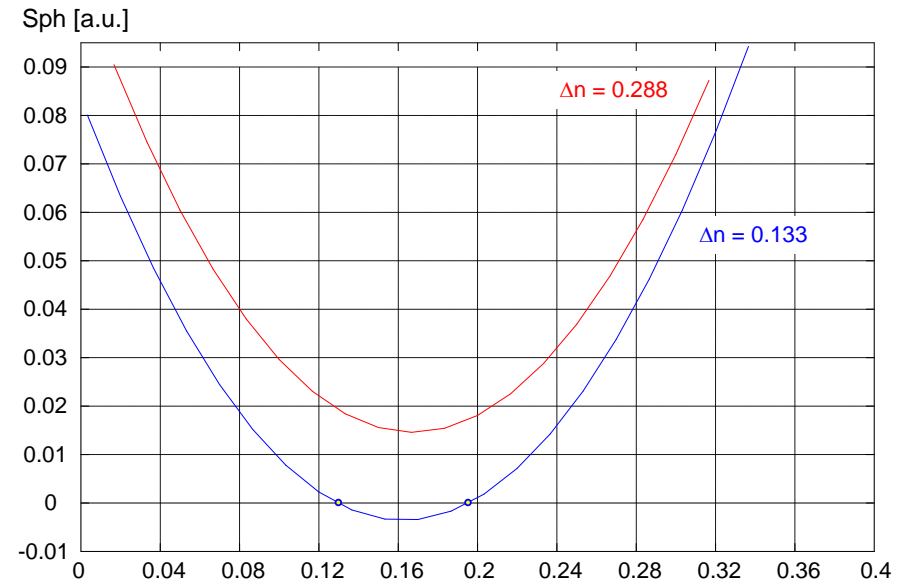
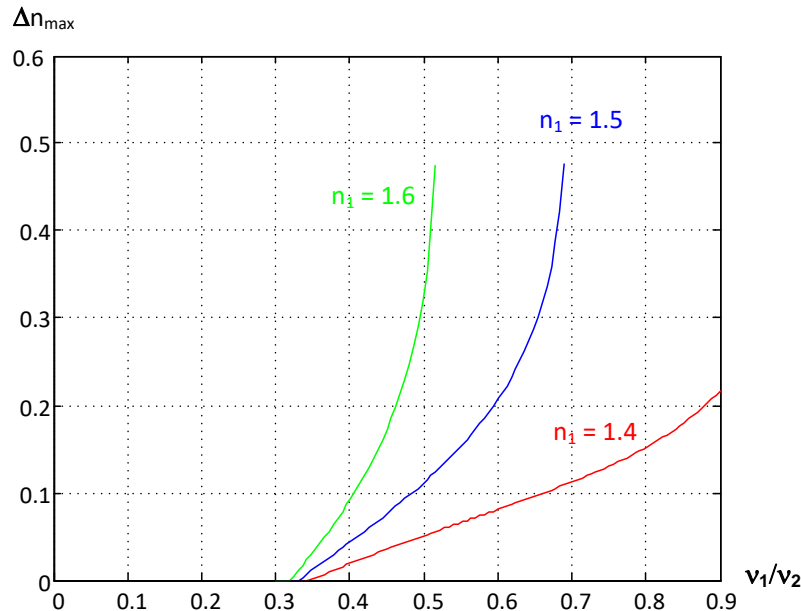
- Variation of spherical aberration with the distance
Mainly quadratic





Spherical Aberration of an Achromate

- Achromatic condition does not contain the curvature:
- Bending can be used to correct for spherical aberration at the edge for the center wavelength
- Index difference must be small enough to allow for spherical correction
- Complex dependence on indices and Abbe number ratio





Spherical Aberration: Zone Error

- Wave aberration of 6th order
- Zonal coefficient A_z
- Spherical aberration with correction at the edge
 $A_z = -A_s$
- Smallest wave aberration at zone
- Smallest spot diameter for $A_d = -3/2A_s$ at

$$W = A_d r_p^2 + A_s r_p^4 + A_z r_p^6$$

$$\Delta s'_R = 0$$

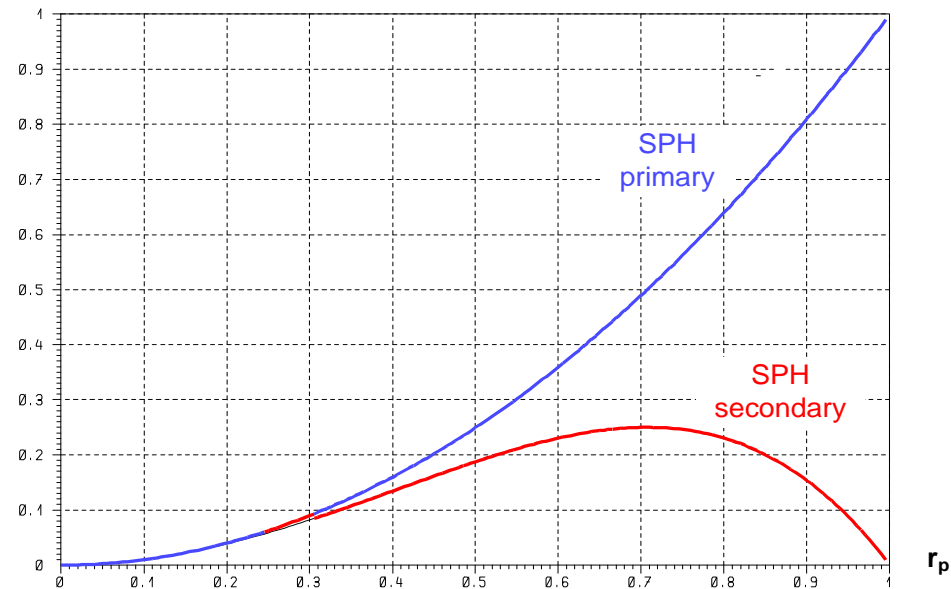
$$r_p = 1/\sqrt{2} = 0.707$$

$$\Delta s'_{\min} = -\frac{3A_s}{\sin^2 u'} = \frac{3}{4} \Delta s'_R$$

with diameter

$$\begin{aligned} D_{\min} &= \frac{2A_s}{\sin u'} = -\frac{1}{2} \Delta s'_R \sin u' \\ &= \frac{1}{4} D_{\text{parax}} \end{aligned}$$

SPH

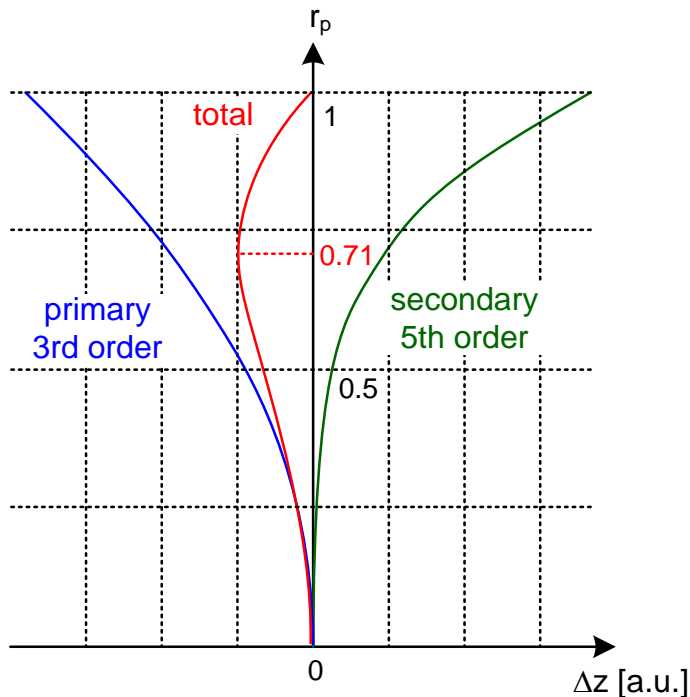




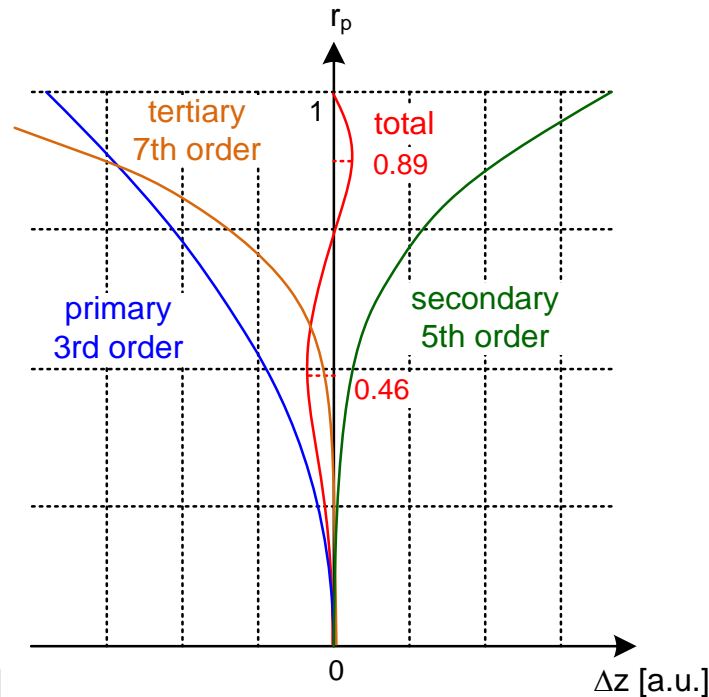
Spherical Correction / Higher Orders

- Partial correction of residual spherical aberration by 5th order or 5th and 7th order
- Different (alternating) sign of coefficients
- Residual total error significantly smaller
- Large gradients at the edge
- 3rd and 5th order compensation: residual zonal error at $\frac{1}{\sqrt{2}} = 0.707$ of the pupil radius

a) 2 orders



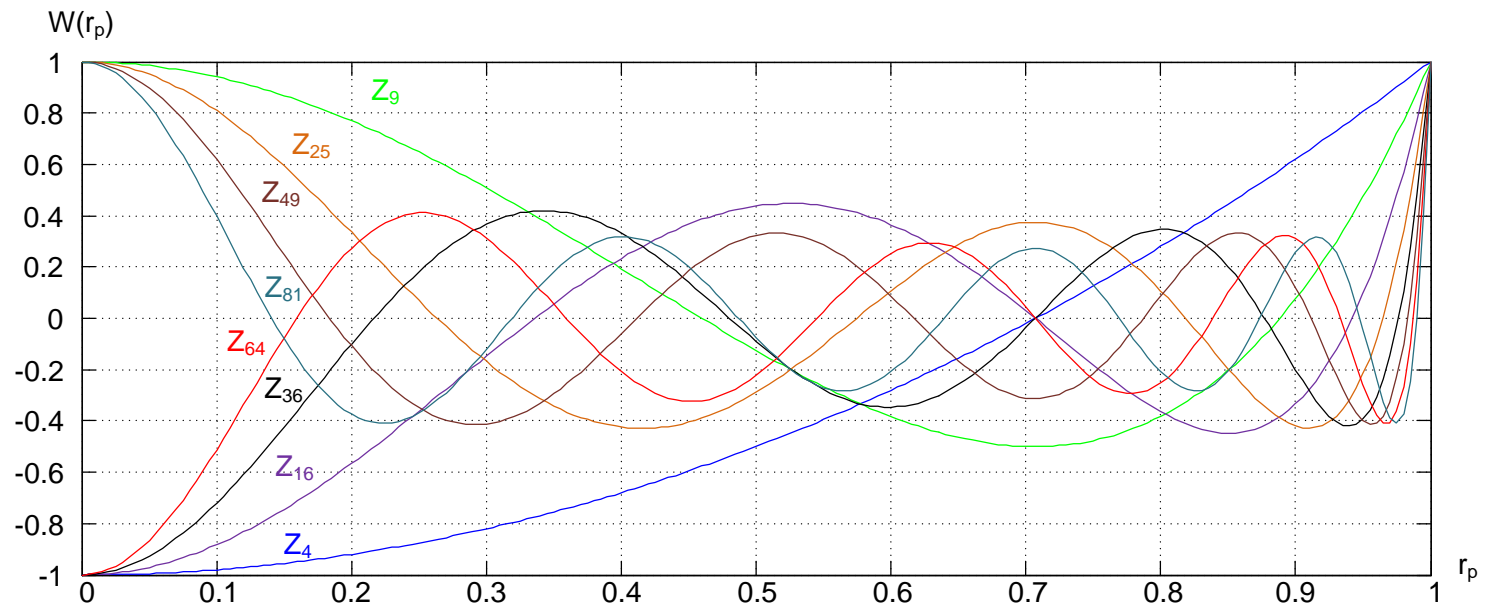
b) 3 orders





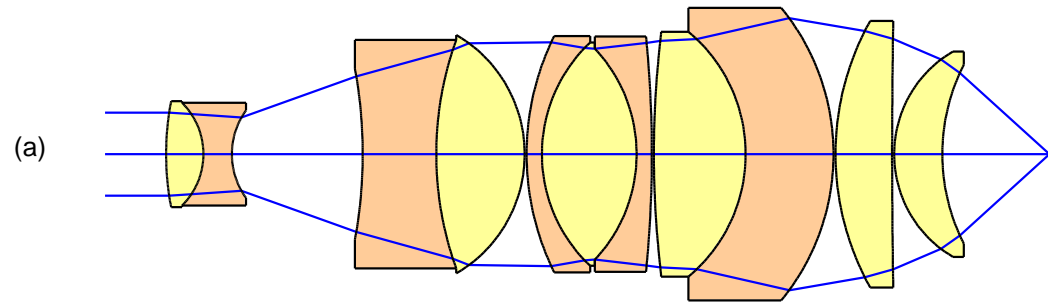
Higher Order Circular Symmetric Zernikes

- Zernike function with circular symmetry with growing order
- Normalized to ± 1 in centre and at the edge
- Growing spatial frequencies
- Highest slope at the edge of the pupil



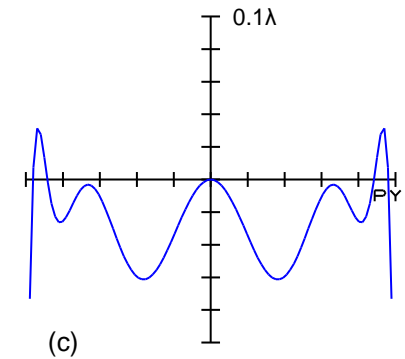
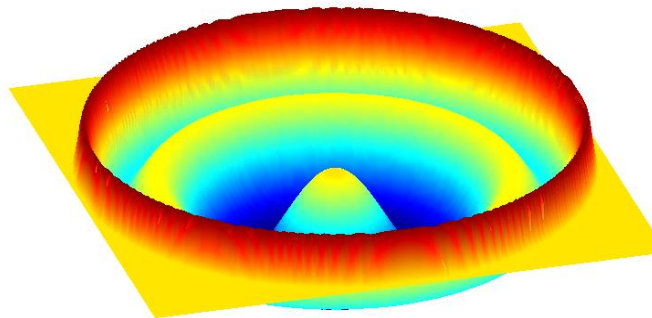
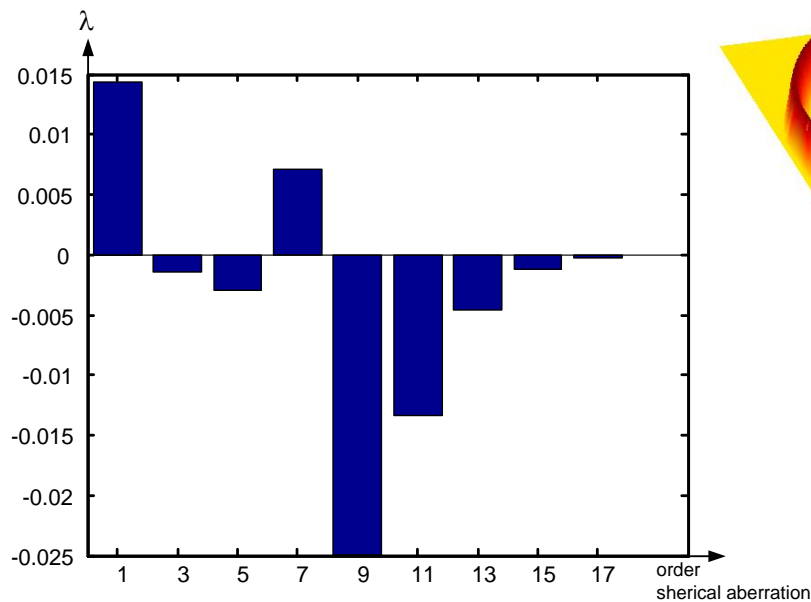
Spherical Aberration of Higher Order

- Microscope Lens
- Zernike spectrum shows large higher contributions



wavefront surface

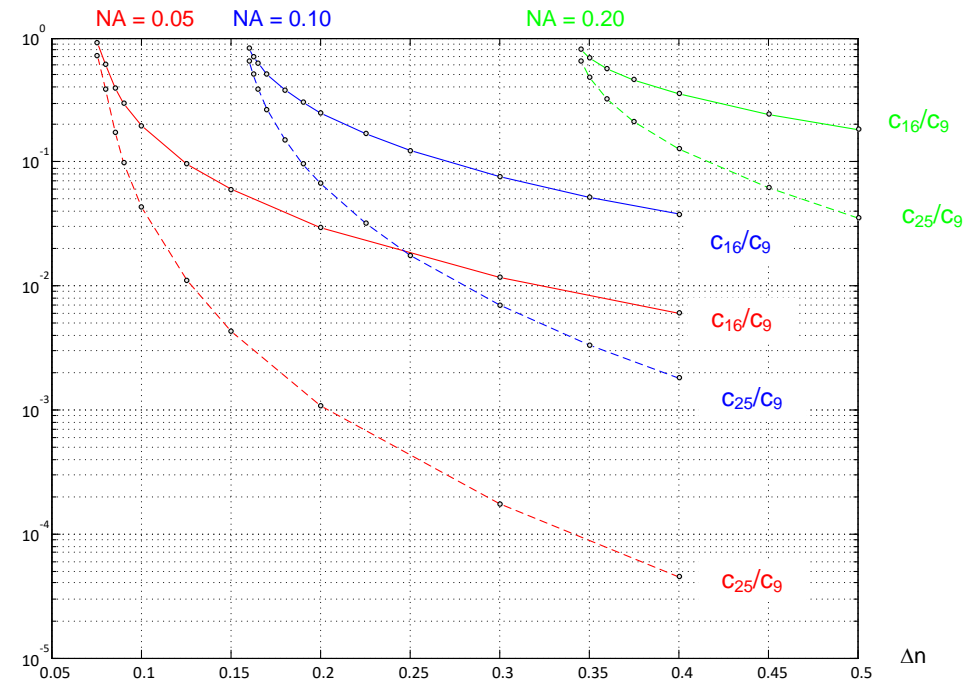
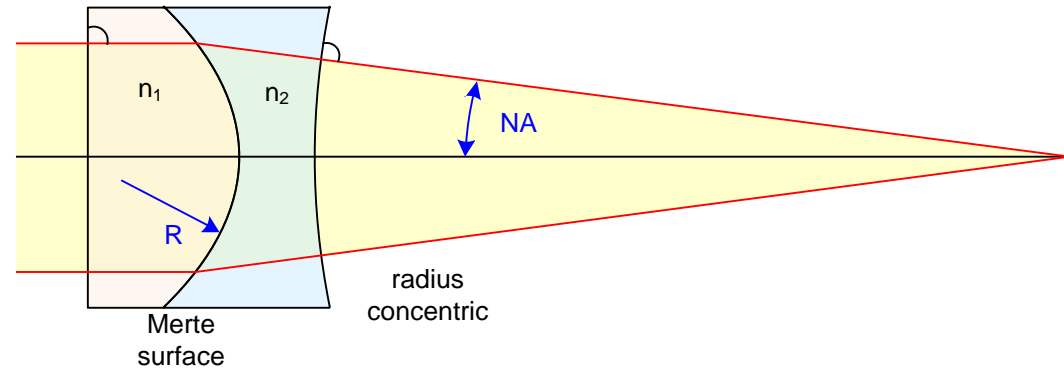
wavefront section





Merte Surface

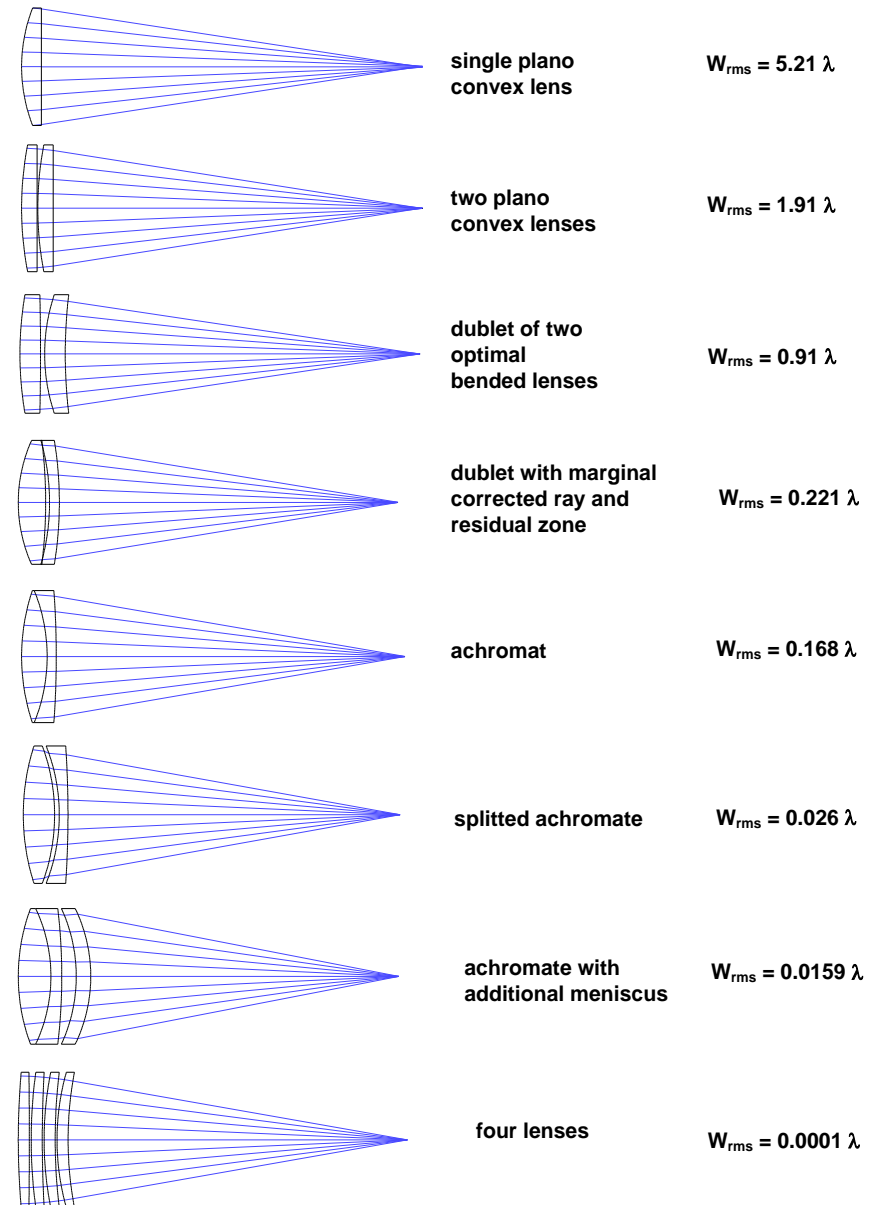
- Small difference in refractive index
- Growing higher order contributions





Spherical Aberration Correction

- Correction of spherical aberration by splitting the ray bending
- Optimal bending of lenses
- Splitting of lenses
- Smooth reducing of spherical aberration or marginal correction



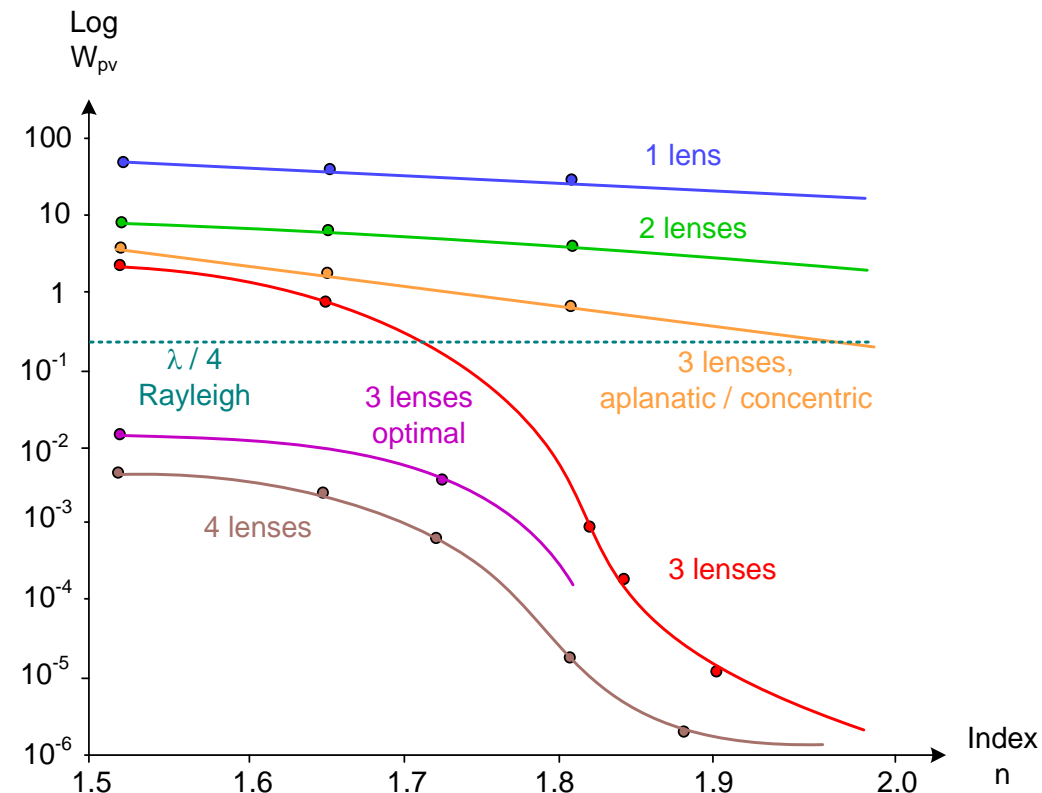


Correction of Spherical Aberration

Nr	System	Spot-Ø geo. [μm]	Spot-Ø rms [μm]	Wave ab. rms [λ]	Strehl ratio [%]
1	Plano convex lens	366	206	5.21	1.7
2	Dublett of plano convex lenses	136	76.8	1.91	5.2
3	Dublett with meniscus lenses	63.9	36.2	0.903	12.8
4	Dublett, edge corrected	26.1	13.5	0.221	23.1
5	Achromate , cemented	21.4	11.1	0.168	35.8
6	Achromate ,spitted	5.1	2.54	0.024	97.3
7	Achromate with mesniscus	2.94	1.48	0.0167	98.8
8	Four lens system optimized	0.008	0.005	0.0001	100.0

■ Comparison of lenses for the same aperture:

1. single lens with optimal bending
2. Dublett with optimal bending
3. Triplet with optimal bending
4. Triplet with aplanatic-concentric meniscus lenses
5. Triplet with compensating negative lens
6. Four lenses





General Aspherical Surface

- Conic surface as basic shape

- Additional correction of the sag by a Taylor expansion
Only even powers: no kink at $r=0$

$$z(x, y) = \frac{c(x^2 + y^2)}{1 + \sqrt{1 - (1 + \kappa) \cdot c^2(x^2 + y^2)}} + \sum_{k=2}^{k_{\max}} a_k \cdot (x^2 + y^2)^k$$

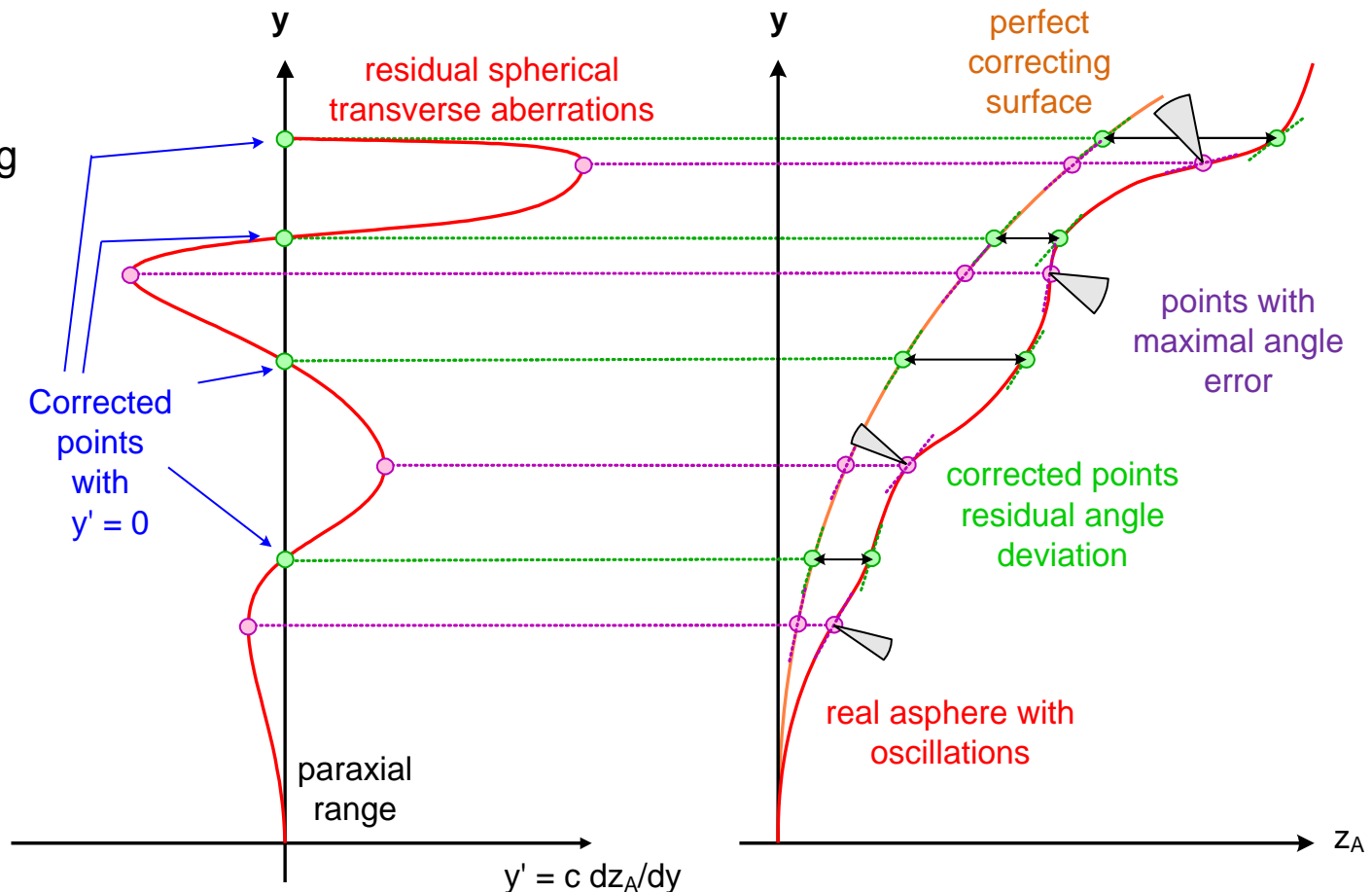
- Mostly rotational symmetric shape considered

$$z(r) = \frac{c \cdot r^2}{1 + \sqrt{1 - (1 + \kappa) \cdot c^2 r^2}} + \sum_{k=2}^{k_{\max}} a_k \cdot r^{2k}$$

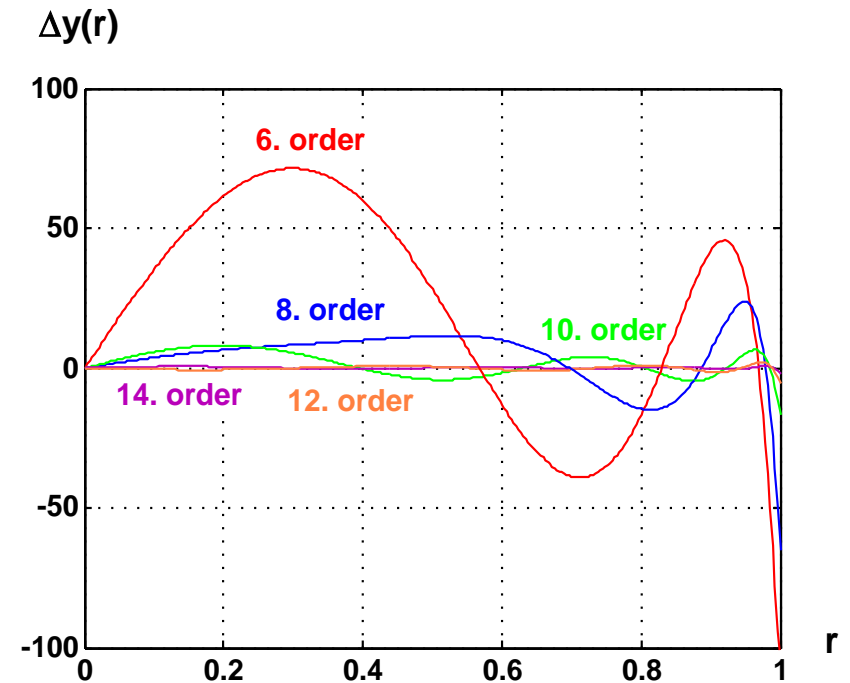
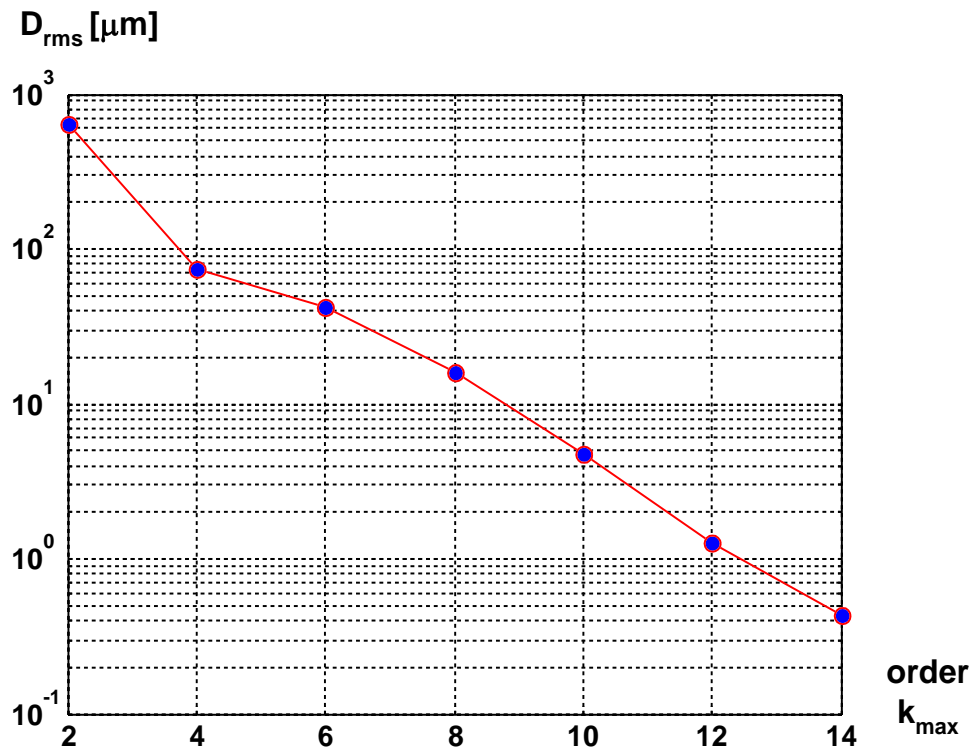
- Problems with this representation:
 - added contributions not orthogonal, bad performance during optimization
 - non-normalized representation, coefficients depend on absolute size of the diameter (very small high order coefficients for large diameters)
 - Oscillatory behavior, large residual slope error can occur
 - in optics slope and not sag is relevant
 - the coefficients can not be measured/are hard to control, tolerancing is critical and complicated
 - the added sag is along z , more important is a correction perpendicular to the surface for strong aspheres

Aspheres: Correction of Higher Order

- Correction at discrete sampling
- Large deviations between sampling points
- Larger oscillations for higher orders
- Better description: slope, defines ray bending



- Improvement by higher orders
- Generation of high gradients



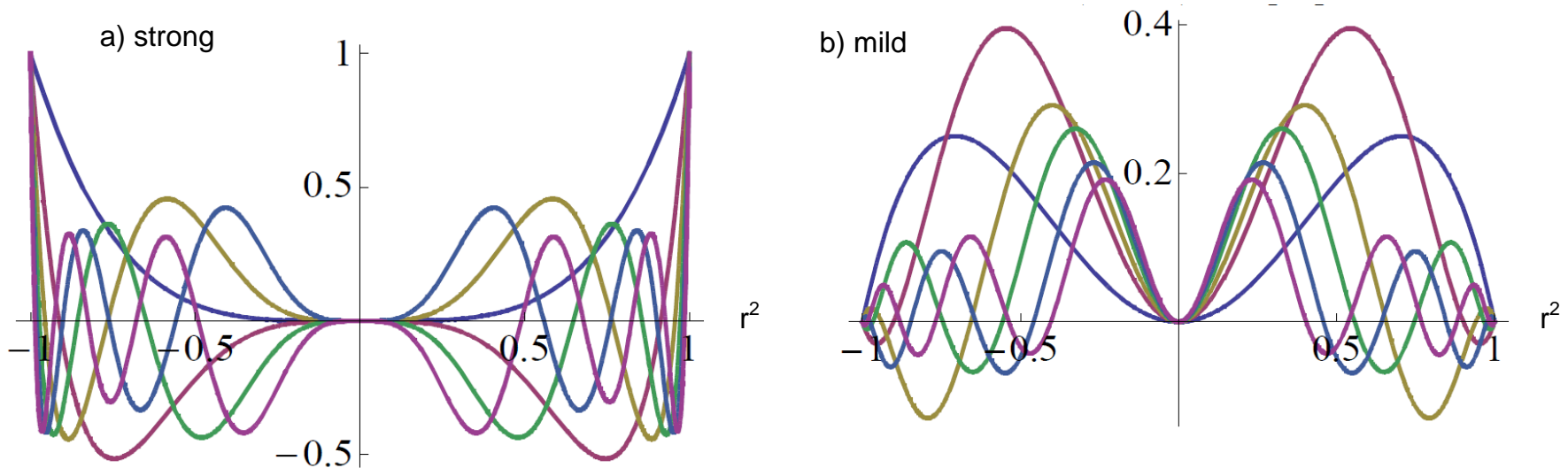
- New representation of aspherical expansions according to Forbes (2007)

$$z(r) = \frac{c \cdot r^2}{1 + \sqrt{1 - (1 + \kappa) \cdot c^2 r^2}} + \sum_{k=2}^{k_{\max}} a_k \cdot Q_k(r^2)$$

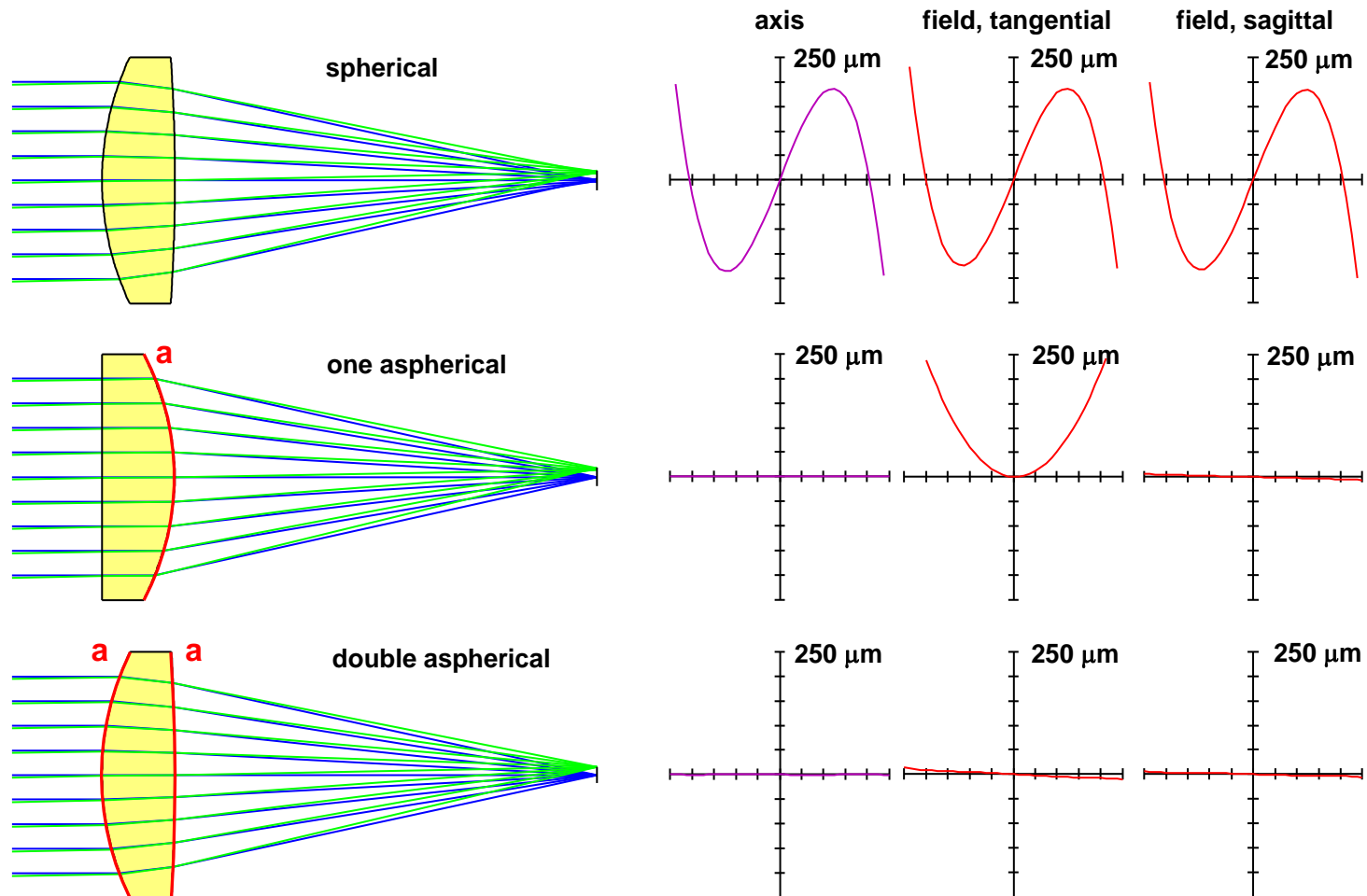
- Special polynomials $Q_k(r^2)$:
 1. Contributions are orthogonal slope
 2. tolerancing is easily measurable
 3. optimization has better performance
 4. usually fewer coefficients are necessary
 5. use of normalized radial coordinate makes coefficients independent on diameter
- Two different versions possible:
 - a) strong aspheres: deviation defined along z
 - b) mild aspheres: deviation defined perpendicular to the surface

- New representations of Forbes

Typical shape of contributions of the 6 lowest correction terms

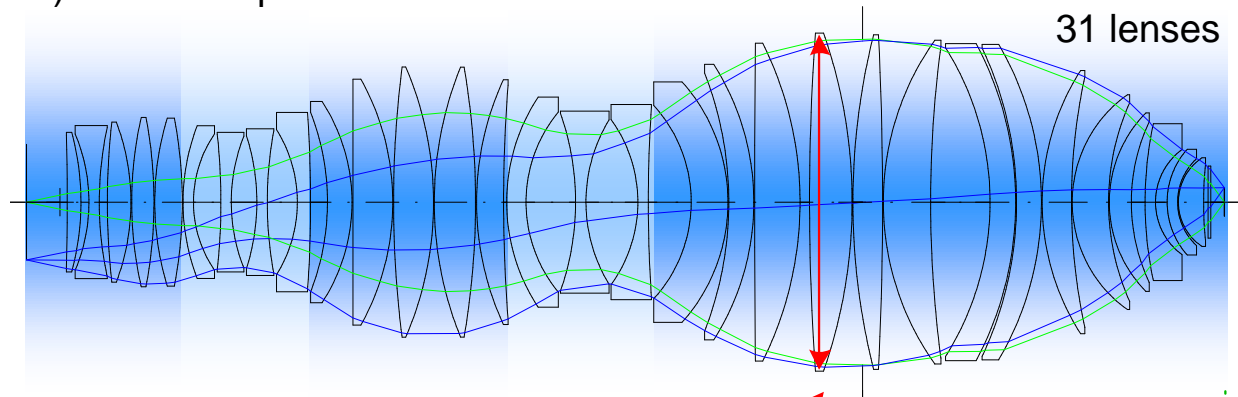


- Correction on axis and field point
- Field correction: two aspheres

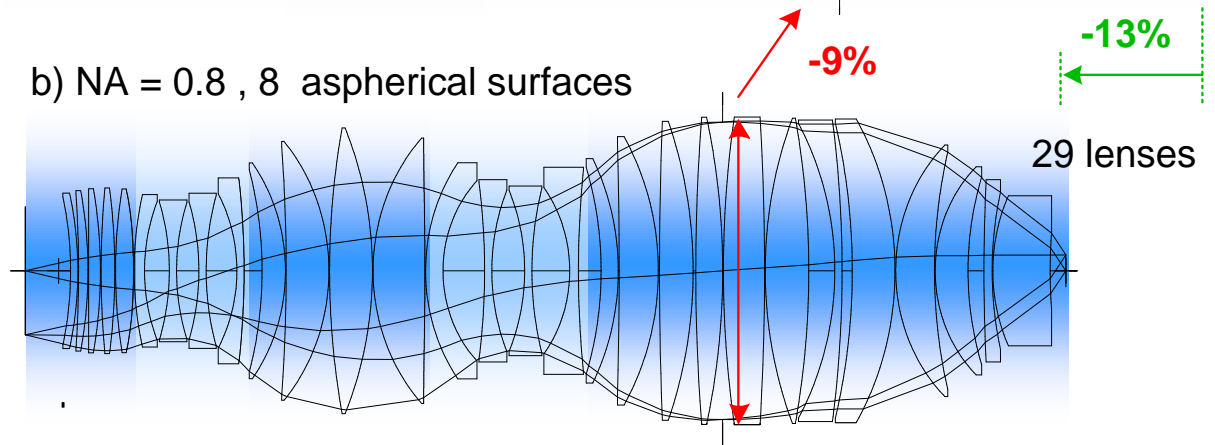


- Considerable reduction of length and diameter by aspherical surfaces
- Performance equivalent
- 2 lenses removable

a) NA = 0.8 spherical



b) NA = 0.8 , 8 aspherical surfaces





Best Position of Aspheres

- Location depending on correction target:
spherical : pupil plane
coma and astigmatism: field plane
- No effect on Petzval curvature

