Institute of
Applied Physics
Friedrich-Schiller-Universität Jena

Design and Correction of optical Systems

Part 12: Correction of aberrations 1

Summer term 2012

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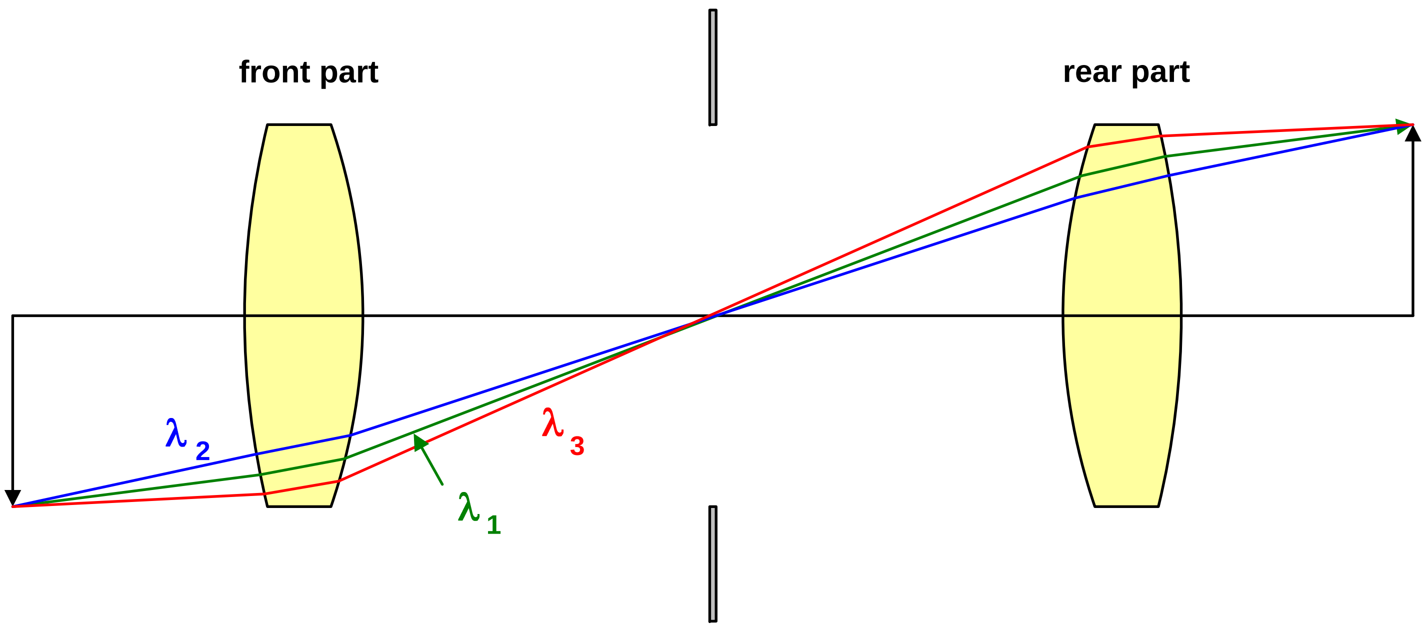
Principle of Symmetry

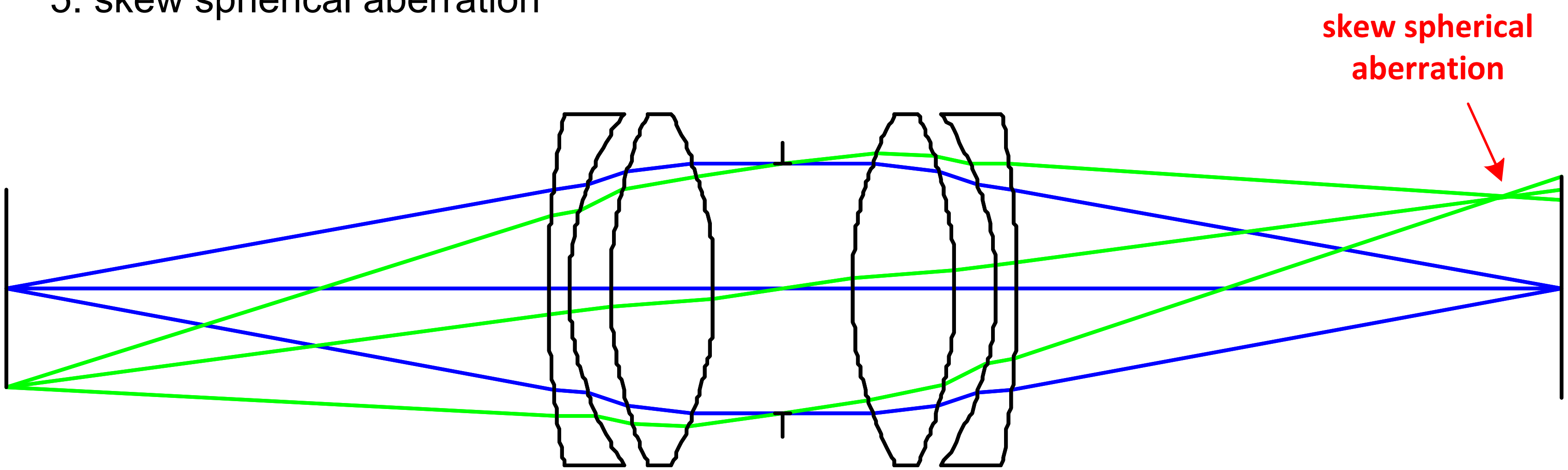
- Perfect symmetrical system: magnification m = -1
- Stop in centre of symmetry
- Symmetrical contributions of wave aberrations are doubled (spherical)
- Asymmetrical contributions of wave aberration vanishes W(-x) = -W(x)
- Easy correction of:
  coma, distortion, chromatical change of magnification



Symmetrical Systems

Ideal symmetrical systems:

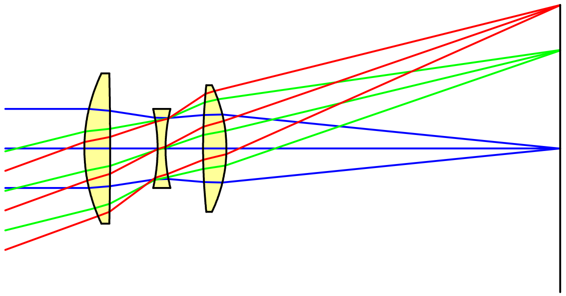
- Vanishing coma, distortion, lateral color aberration
- Remaining residual aberrations:
  1. spherical aberration
  2. astigmatism
  3. field curvature
  4. axial chromatical aberration
  5. skew spherical aberration



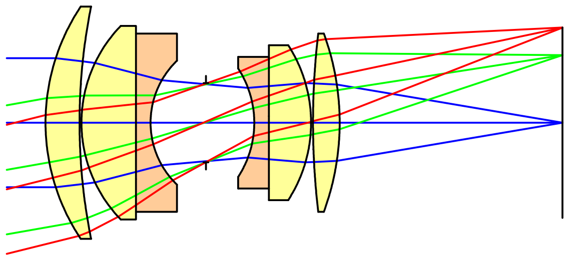
Symmetry Principle

- Application of symmetry principle: photographic lenses
- Especially field dominant aberrations can be corrected
- Also approximate fulfillment of symmetry condition helps significantly:
  quasi symmetry
- Realization of quasi-symmetric setups in nearly all photographic systems

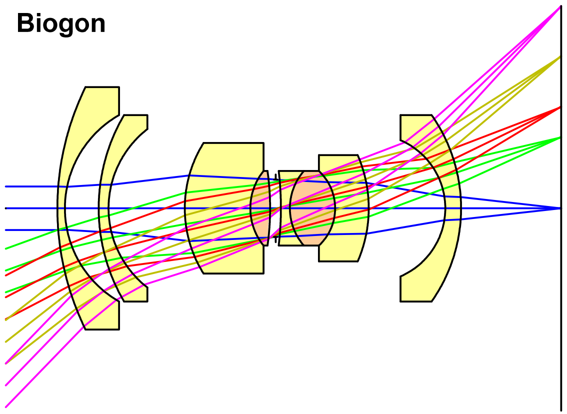
Triplet



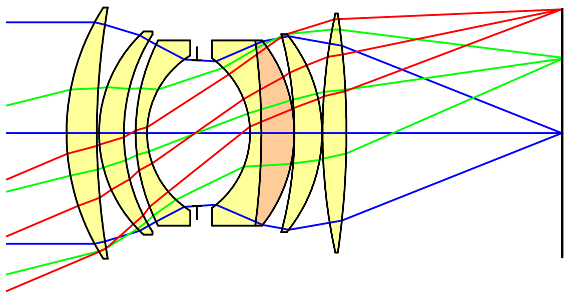
Double Gauss (6 elements)



Biogon



Double Gauss (7 elements)



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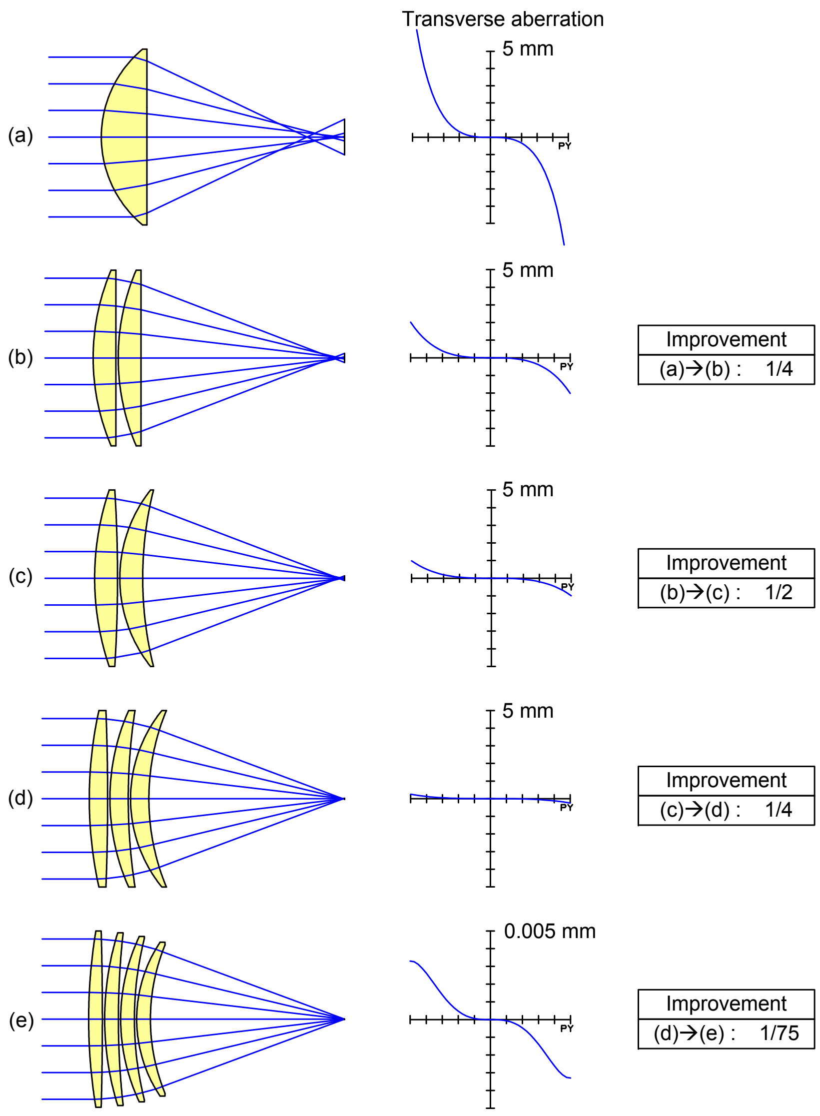
Correcting Spherical Aberration: Lens Splitting

- Correction of spherical aberration:
  Splitting of lenses

- Distribution of ray bending on several surfaces:
  - smaller incidence angles reduces the effect of nonlinearity
  - decreasing of contributions at every surface, but same sign
- Last example (e): one surface with compensating effect



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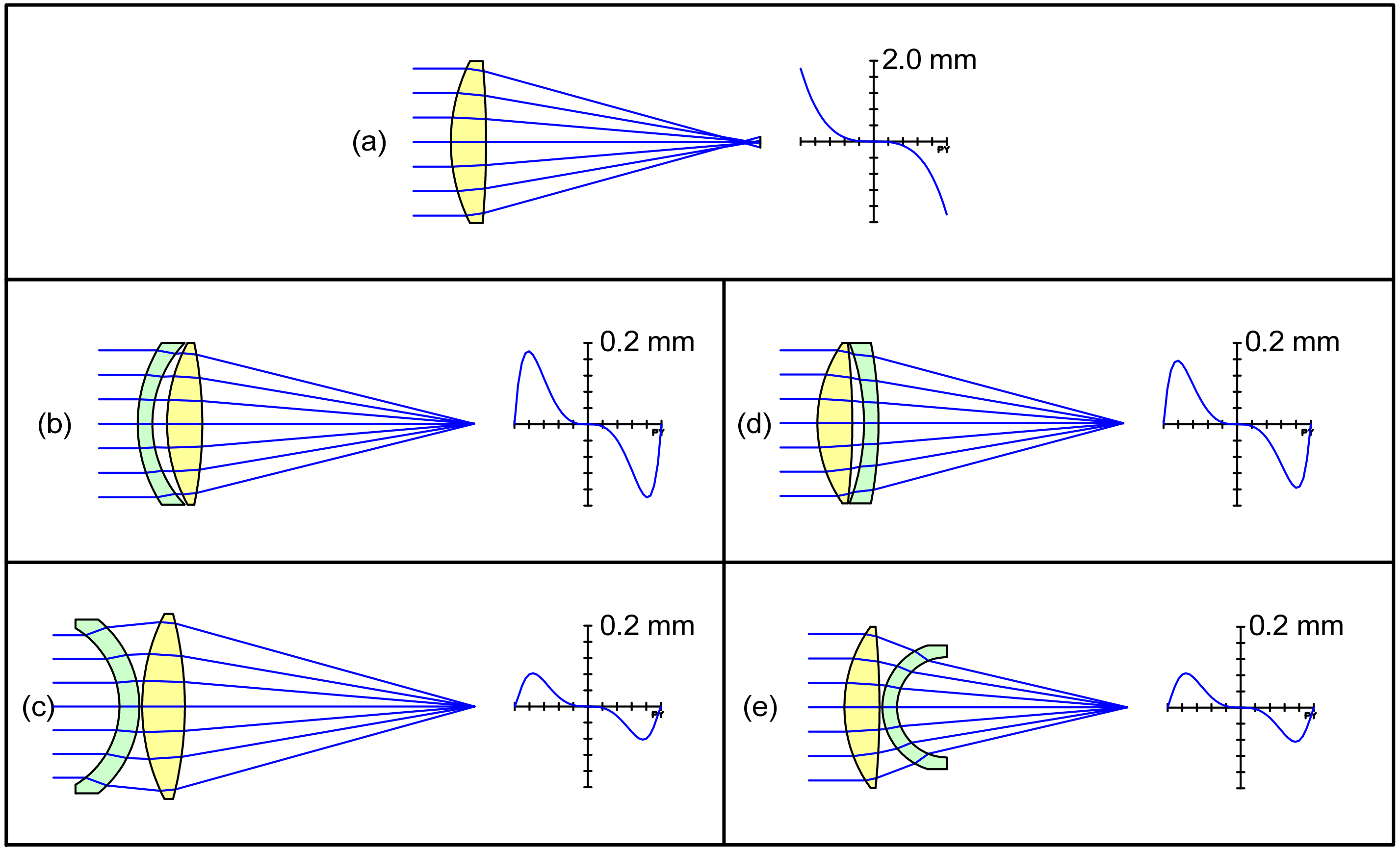
Correcting Spherical Aberration : Power Splitting

Splitting of lenses and appropriate bending:

1. compensating surface contributions
2. Residual zone errors
3. More relaxed setups preferred, although the nominal error is larger



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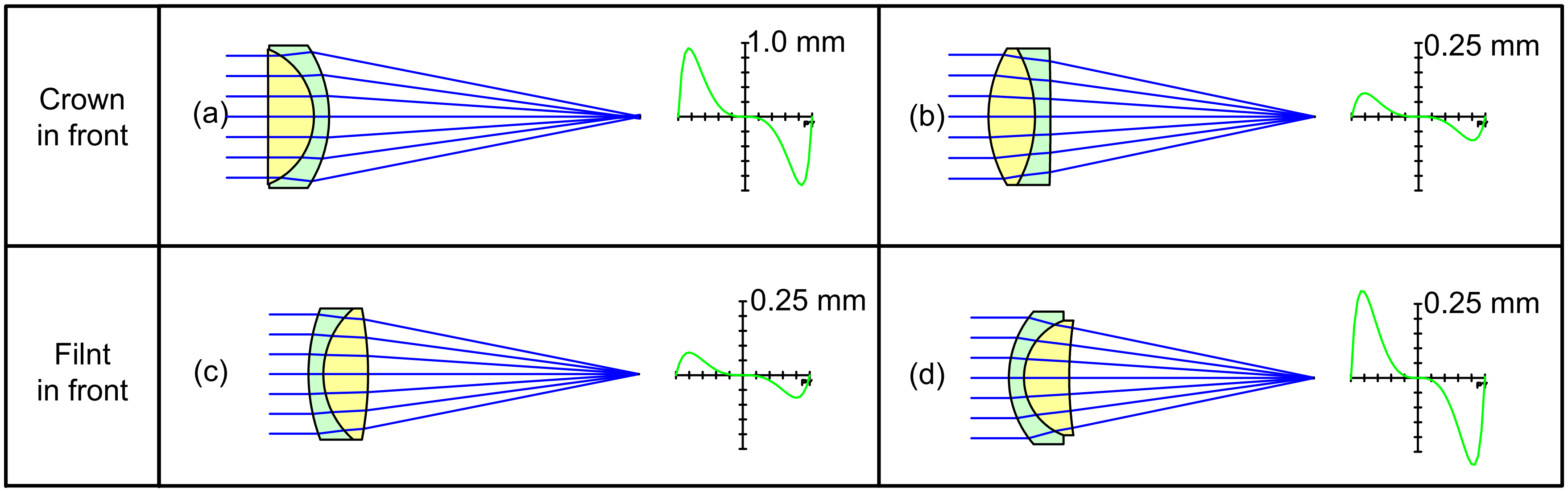
Correcting Spherical Aberration: Cementing

Correcting spherical aberration by cemented doublet:

- Strong bended inner surface compensates
- Solid state setups reduces problems of centering sensitivity
- In total 4 possible configurations:
  1. Flint in front / crown in front
  2. bi-convex outer surfaces / meniscus shape
- Residual zone error, spherical aberration corrected for outer marginal ray



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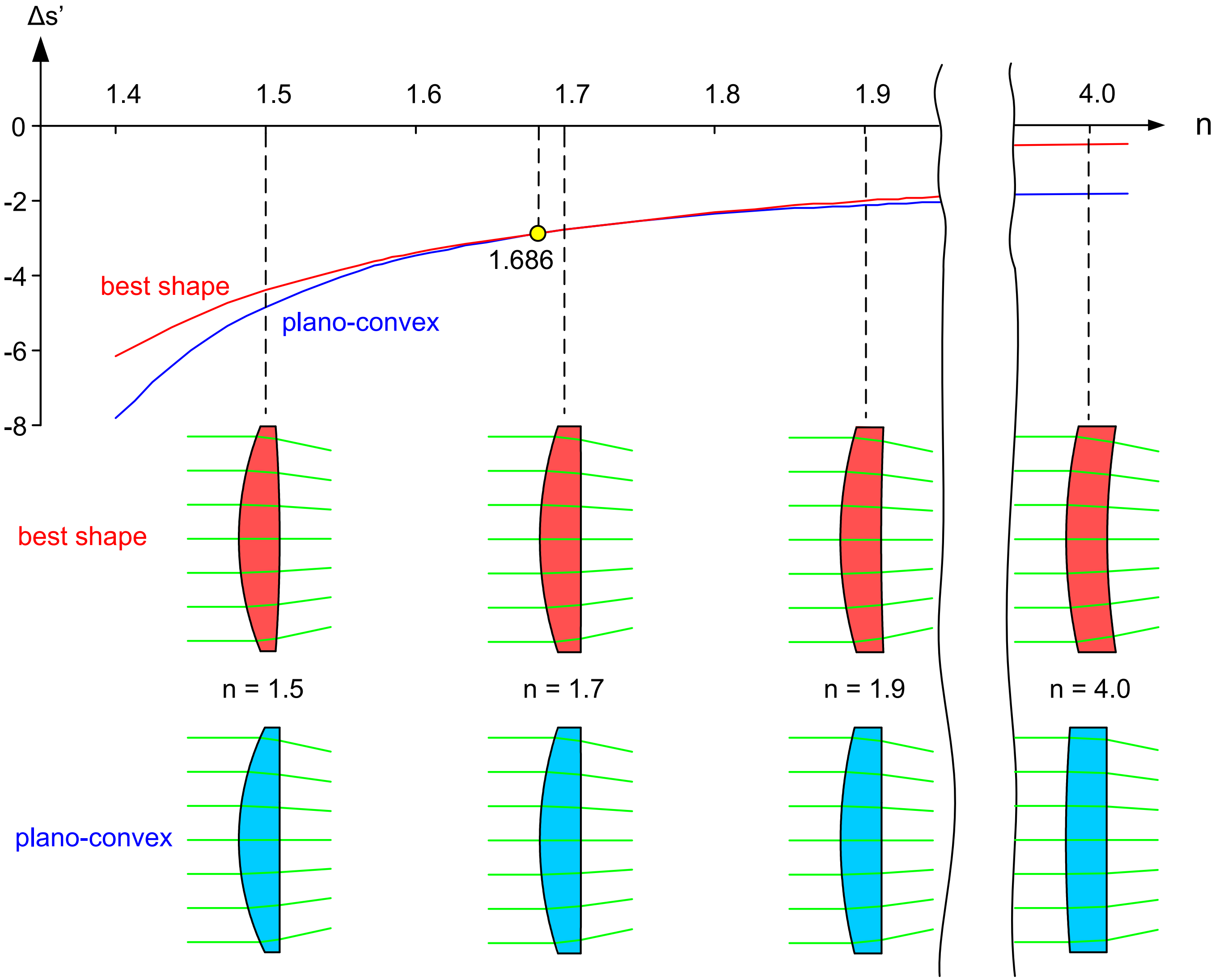
Correcting Spherical Aberration: Refractive Index

- Better correction for higher index
- Shape of lens / best bending changes from
  1. nearly plane convex for n= 1.5
  2. meniscus shape for n > 2



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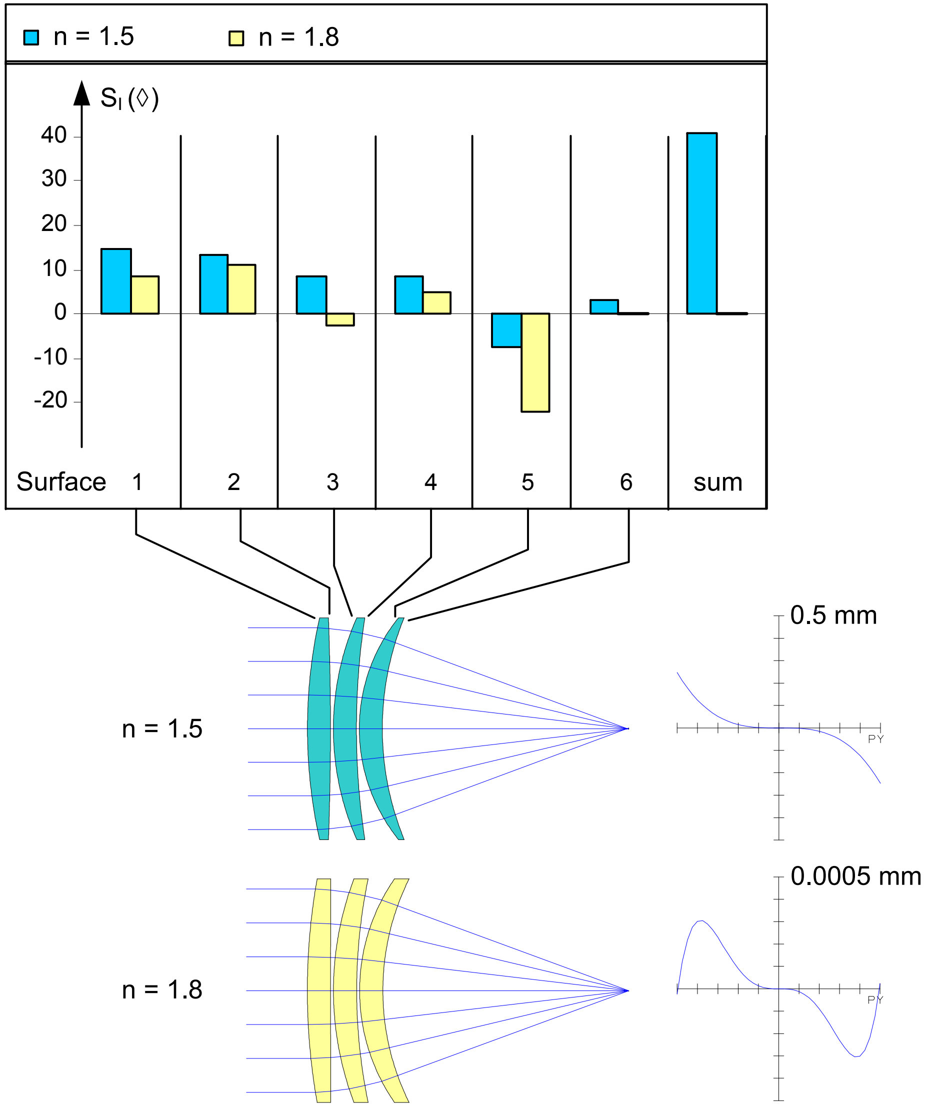
Correcting Spherical Aberration: Refractive Index

- Better correction
  for high index also for meltiple
  lens systems
- Example: 3-lens setup with one
  surface for compensation
  Residual aberrations is quite better
  for higher index



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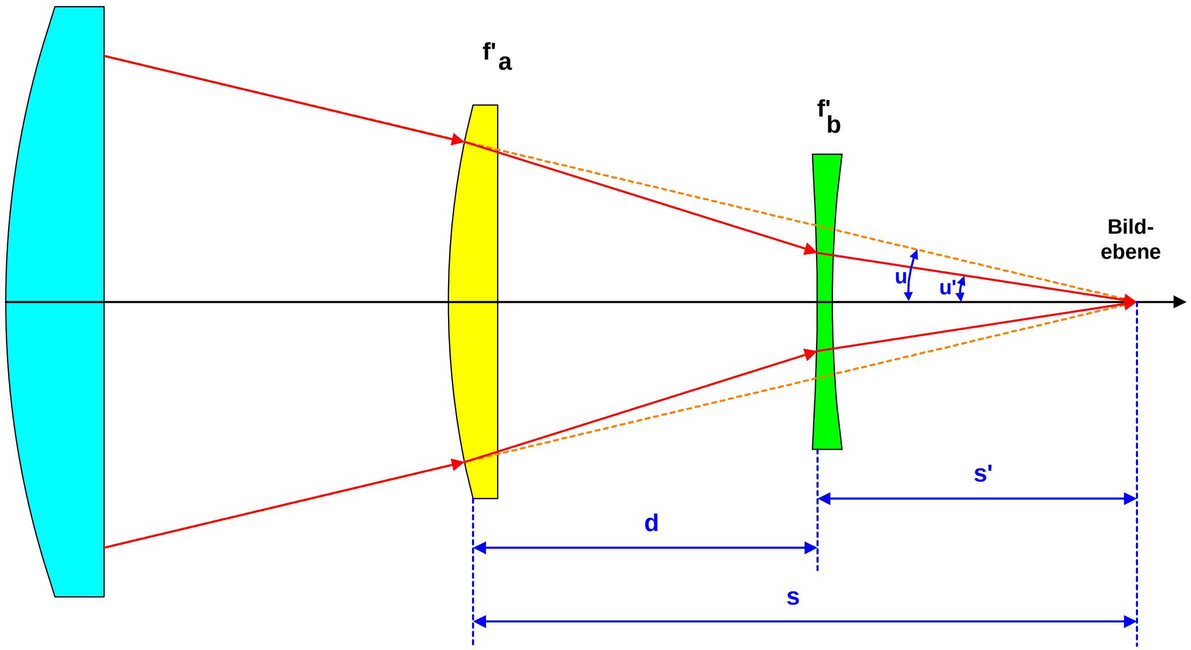
Bravais System

- Combination of positiv and negative lens :
  Change of apertur with factor β without shift of image plane
- Strong impact on spherical aberration
- Principle corresponds the tele photo system
- Calculation of the focal lengths

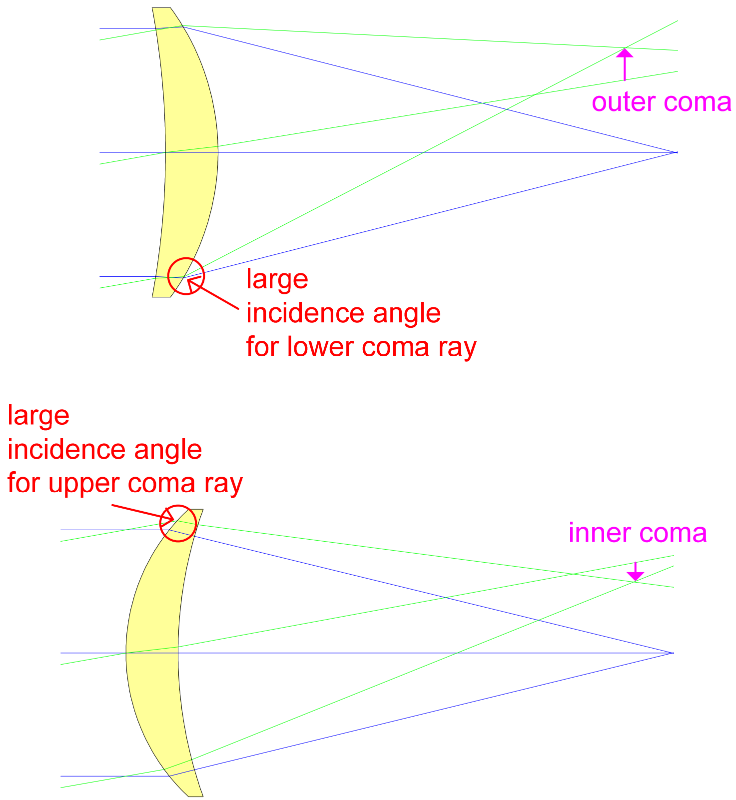
$$\frac{1}{f'_a} = \frac{\beta - 1}{\beta \cdot d} \cdot \left(1 - \frac{d}{s}\right)$$

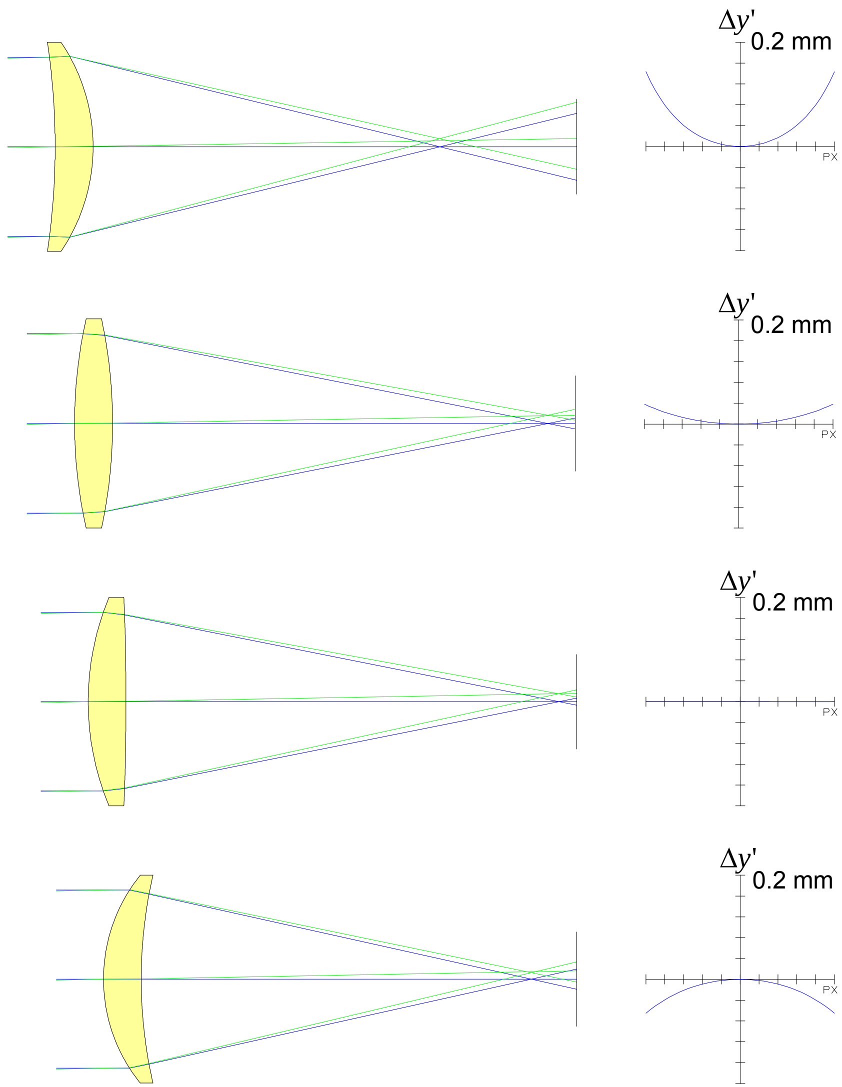
$$\frac{1}{f'_b} = \frac{1 - \beta}{d \cdot \left(1 - \frac{d}{s}\right)}$$



Inner and Outer Coma

- Effect of lens bending on coma
- Sign of coma : inner/outer coma





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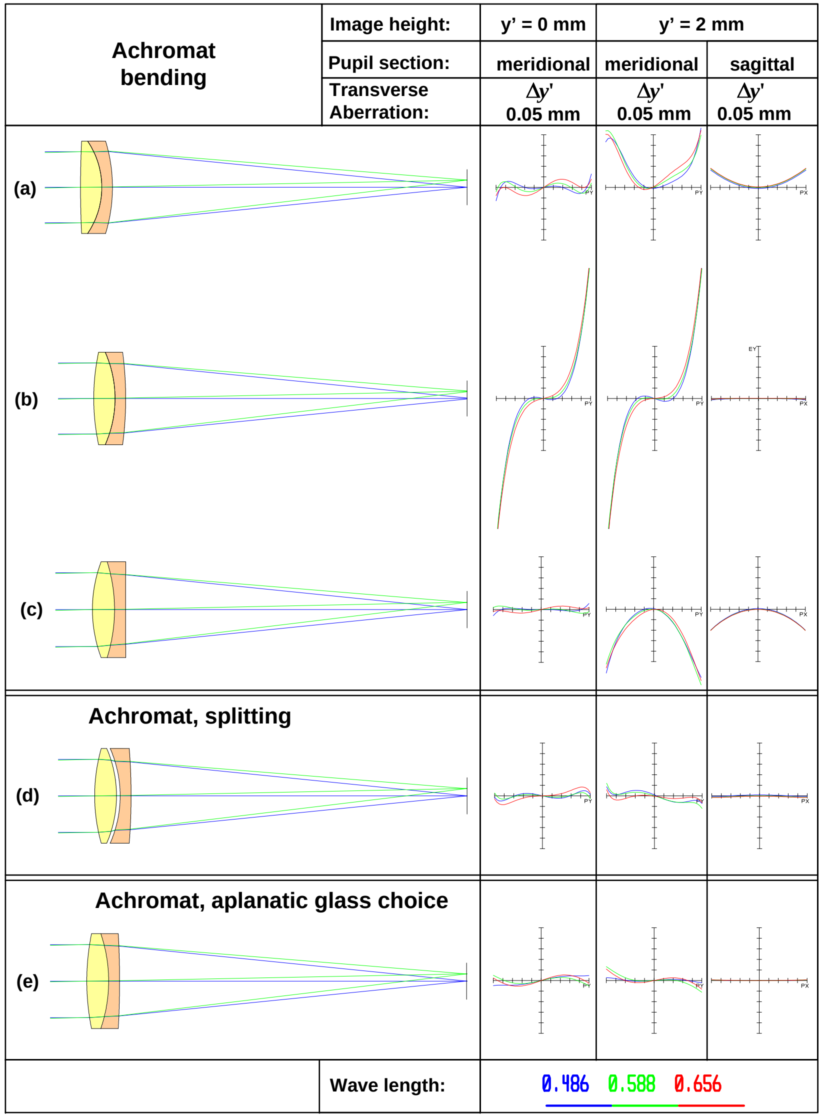
Coma Correction: Achromat

- Bending of an achromate
  - optimal choice: small residual spherical aberration
  - remaining coma for finite field size
- Splitting achromate:
  additional degree of freedom:
  - better total correction possible
  - high sensitivity of thin air space
- Aplanatic glass choice:
  vanishing coma



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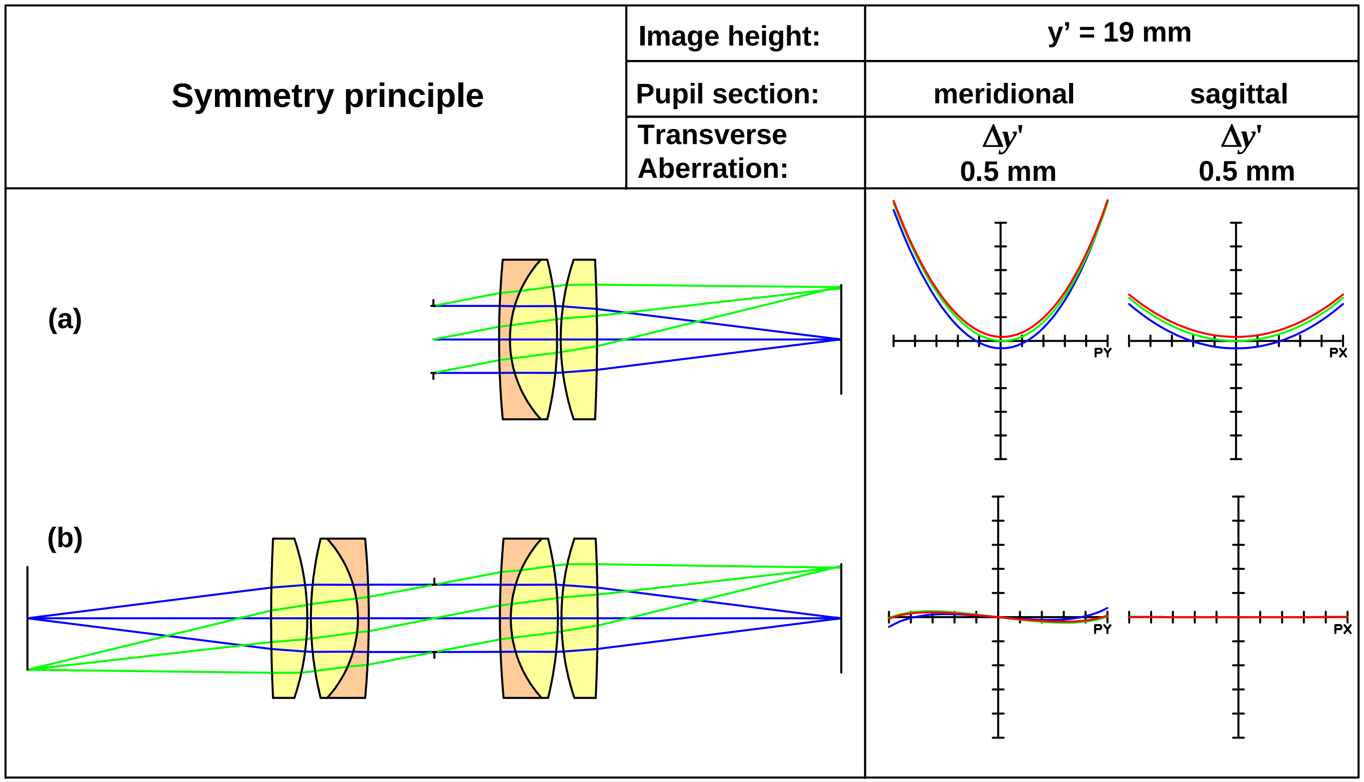
Coma Correction: Symmetry Principle

- Perfect coma correction in the case of symmetry
- But magnification m = -1 not useful in most practical cases



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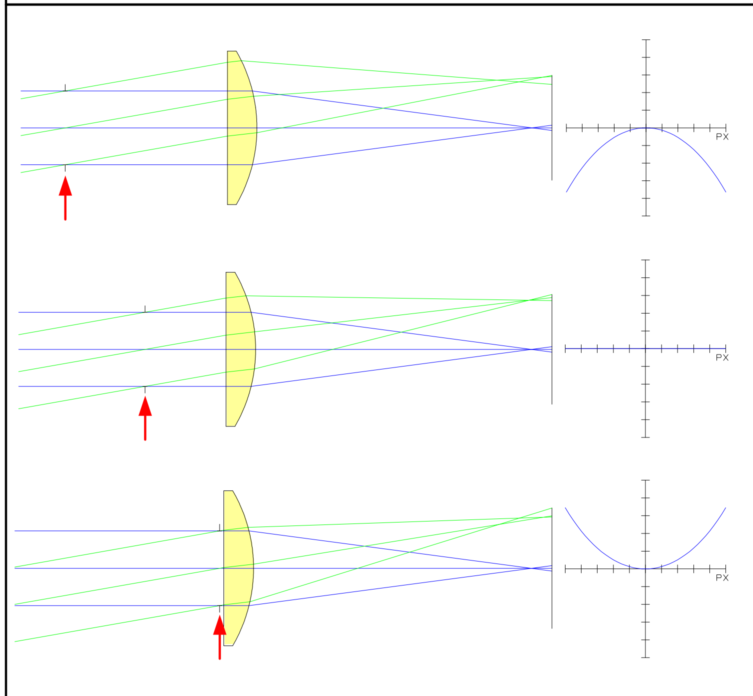
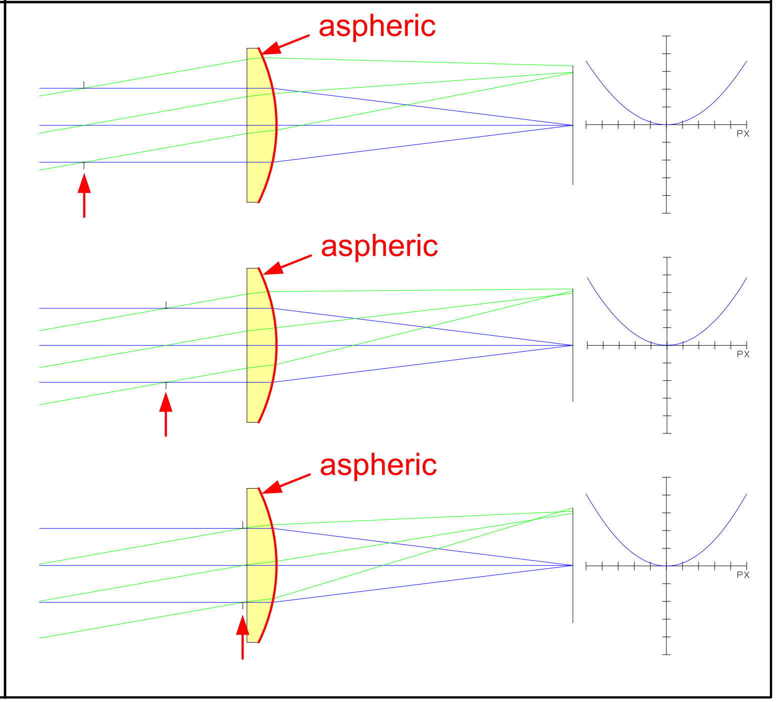
Coma Correction: Stop Position and Aspheres

- Combined effect, aspherical case prevent correction

Plano-convex element exhibits spherical aberration	Sagittal coma $\Delta y'$ 0.5 mm	Spherical aberration corrected with aspheric surface	Sagittal coma $\Delta y'$ 0.5 mm
			

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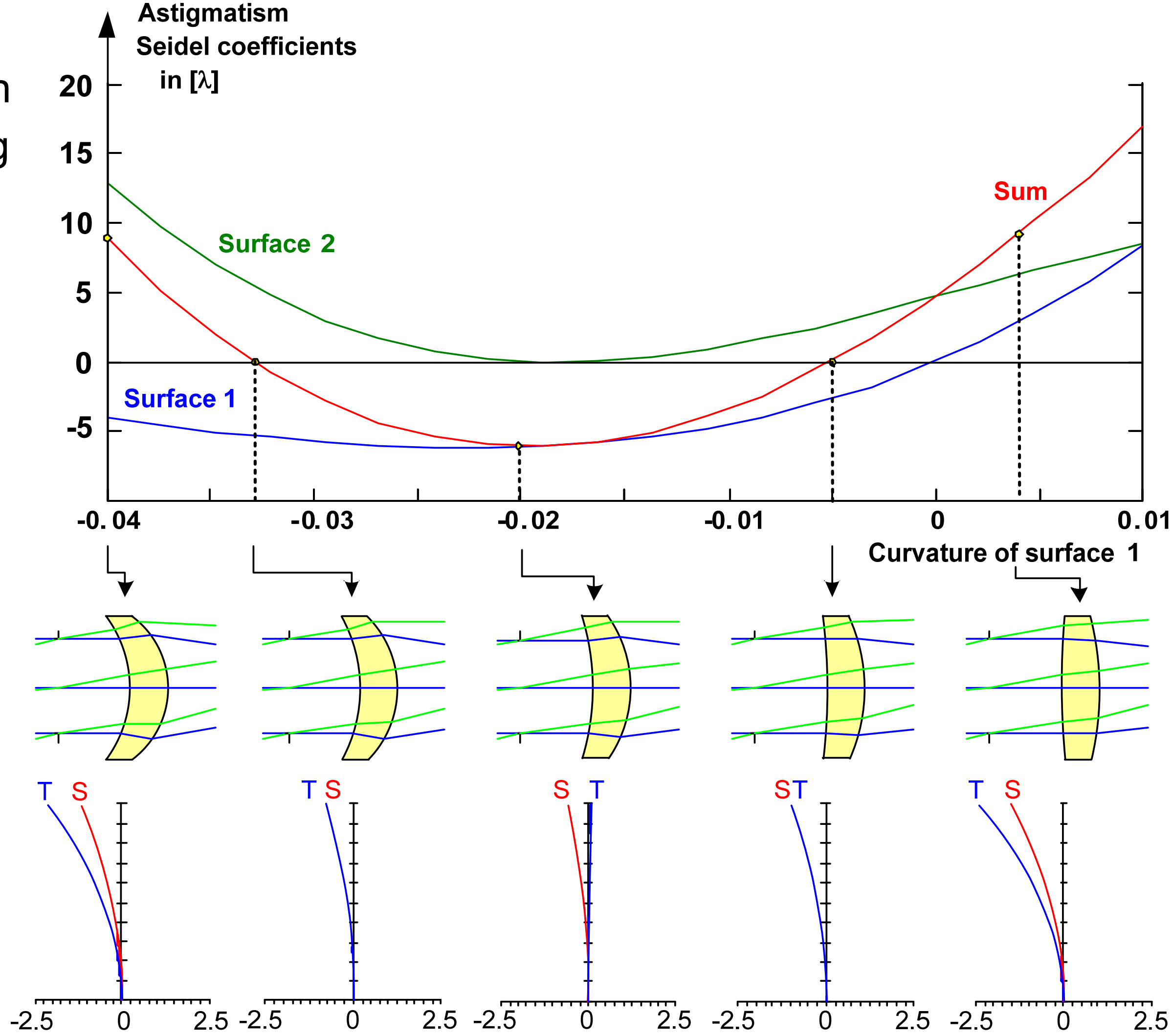
Astigmatism: Lens Bending

- Bending effects astigmatism
- For a single lens 2 bending with zero astigmatism, but remaining field curvature



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Petzval Theorem for Field Curvature

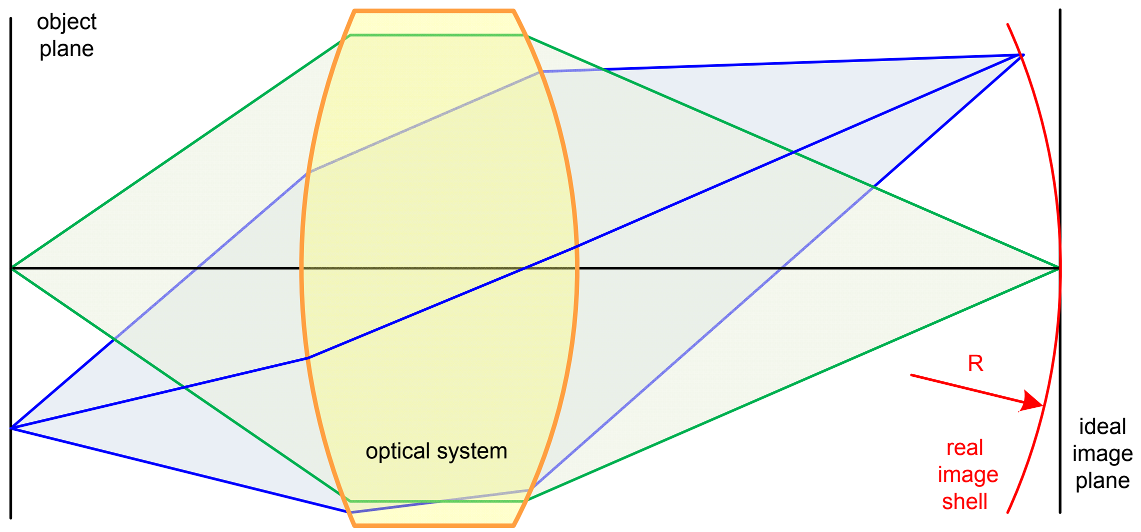
- Petzval theorem for field curvature:
  1. formulation for surfaces

$$\frac{1}{R_{ptz}} = -n_m' \sum_k \frac{n_k' - n_k}{n_k \cdot n_k' \cdot r_k}$$

  2. formulation for thin lenses (in air)

$$\frac{1}{R_{ptz}} = -\sum_j \frac{1}{n_j \cdot f_j}$$

- Important: no dependence on bending
- Natural behavior: image curved towards system
- Problem: collecting systems with f > 0:
  If only positive lenses:
  R_{ptz} always negative



Petzval Theorem for Field Curvature

- Goal: vanishing Petzval curvature

$$\frac{1}{R_{ptz}} = -\sum_j \frac{1}{n_j \cdot f_j}$$

  and positive total refractive power

$$\frac{1}{f} = \sum_j \frac{h_j}{h_1} \cdot \frac{1}{f}$$

  for multi-component systems

- Solution:
  General principle for correction of curvature of image field:
  1. Positive lenses with:
     - high refractive index
     - large marginal ray heights
     - gives large contribution to power and low weighting in Petzval sum
  2. Negative lenses with:
     - low refractive index
     - samll marginal ray heights
     - gives small negative contribution to power and high weighting in Petzval sum

Field Curvature

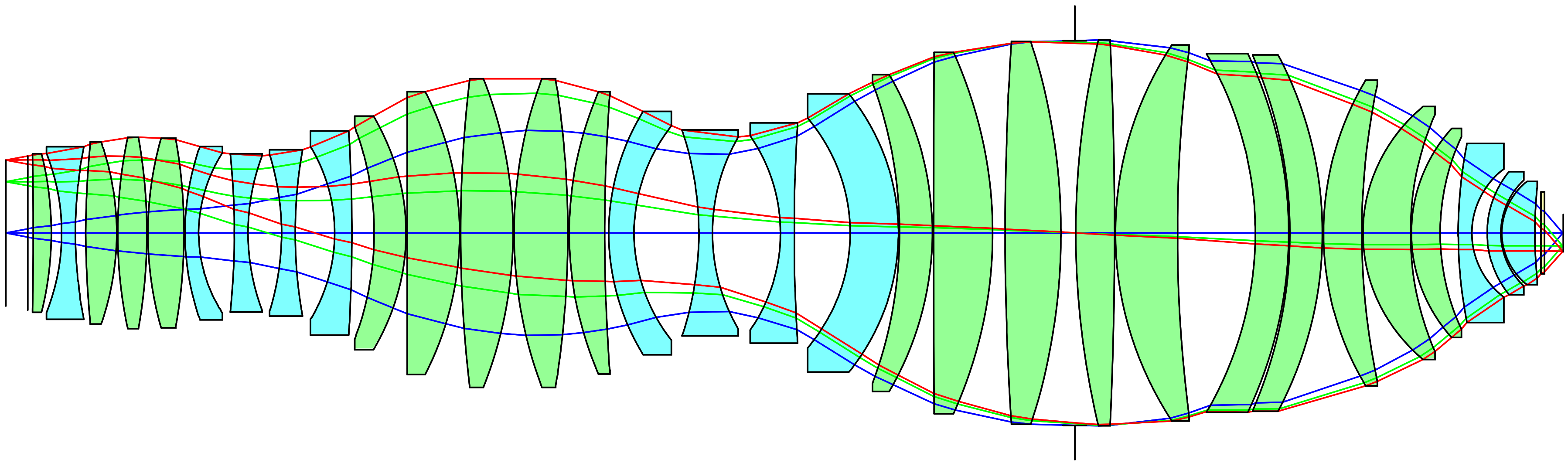
- Correction of Petzval field curvature in lithographic lens for flat wafer

$$\frac{1}{R} = -\sum_j \frac{F_j}{n_j}$$

- Positive lenses: Green h_j large
- Negative lenses : Blue h_j small

$$F = \sum_j \frac{h_j}{h_1} \cdot F_j$$

- Correction principle: certain number of bulges



Flattening Field Lens

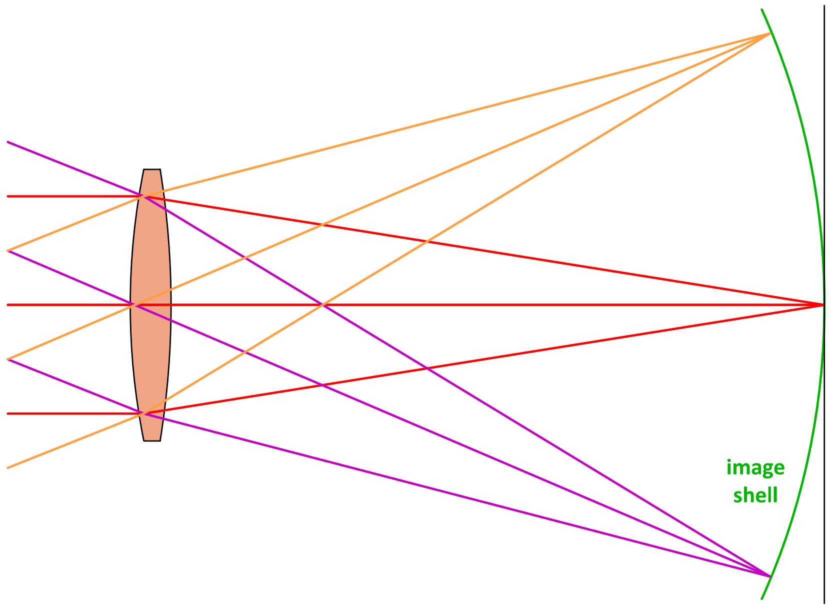
Effect of a field lens for flattening the image surface

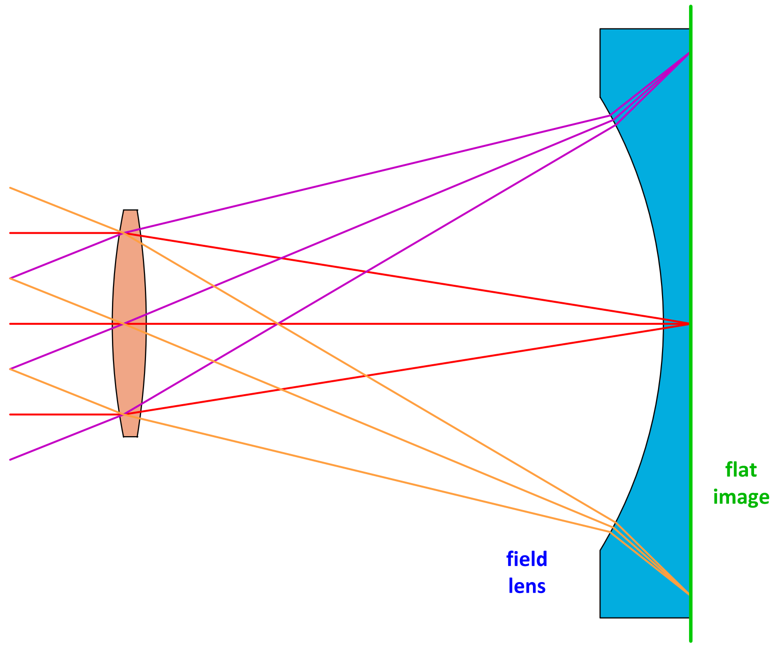
1. Without field lens

   curved image surface

2. With field lens

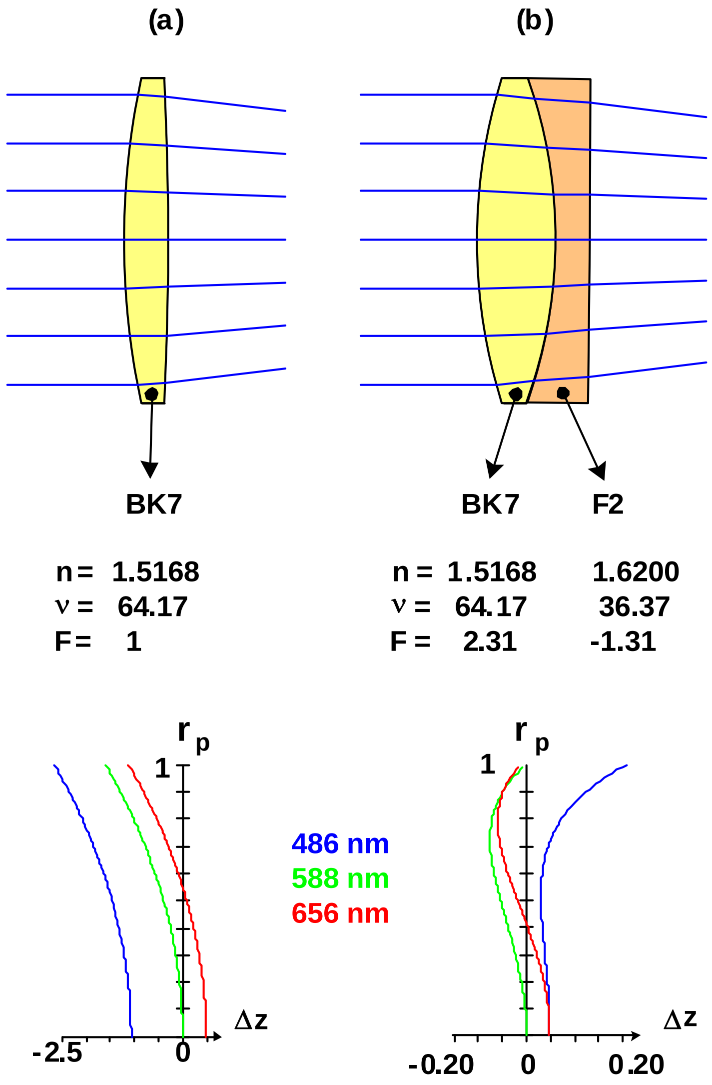
   image plane





Axial Colour: Achromate

- Compensation of axial colour by appropriate glass choice
- Chromatical variation of the spherical aberrations: spherochromatism (Gaussian aberration)
- Therefore perfect axial color correction (on axis) are often not feasable



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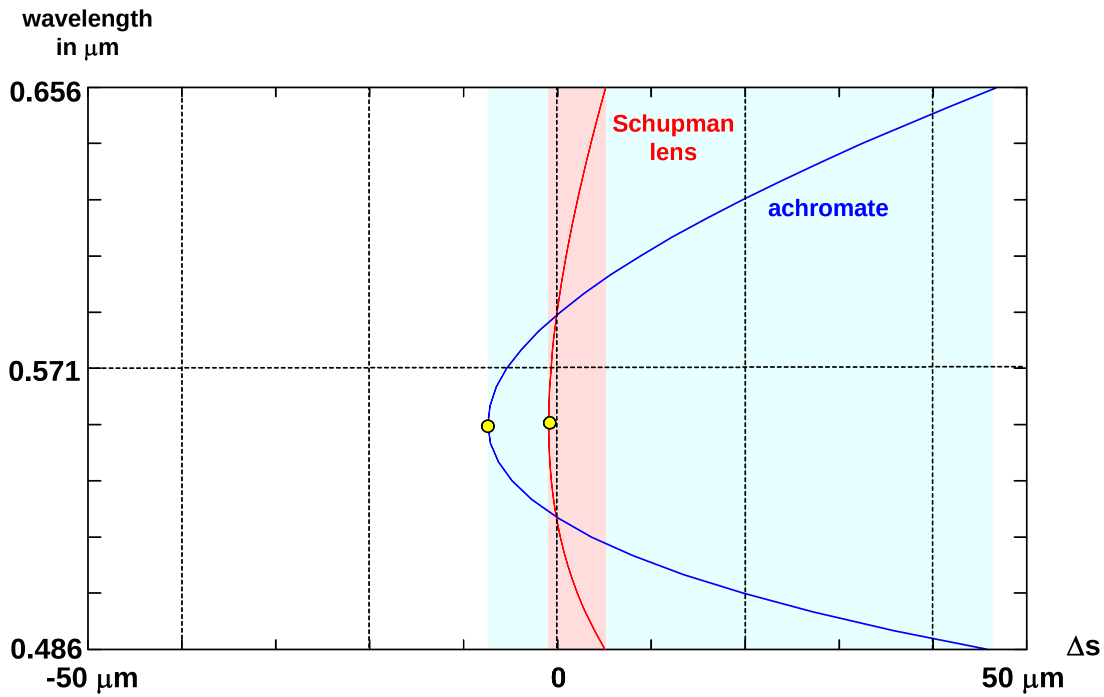
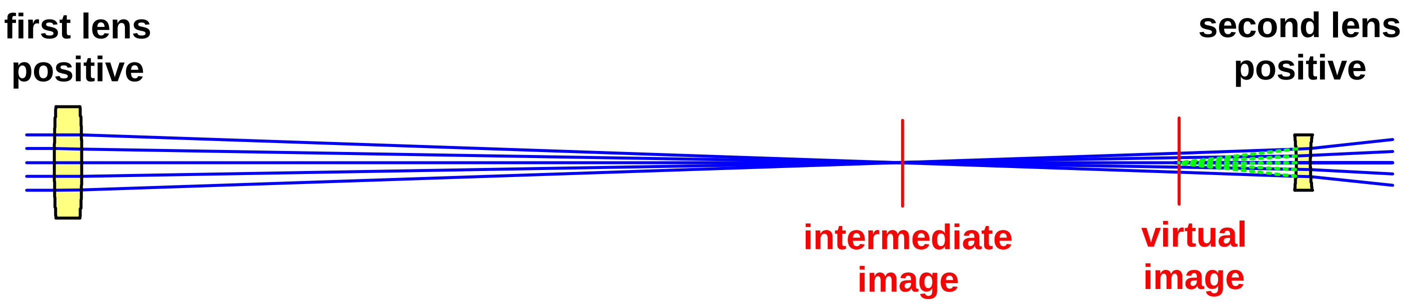
Axial Color Correction with Schupman Lens

- Non-compact system
- Generalized achromatic condition with marginal ray hieghts y_j

$$\frac{y_1^2}{v_1} \cdot F_1 + \frac{y_2^2}{v_2} \cdot F_2 = 0$$

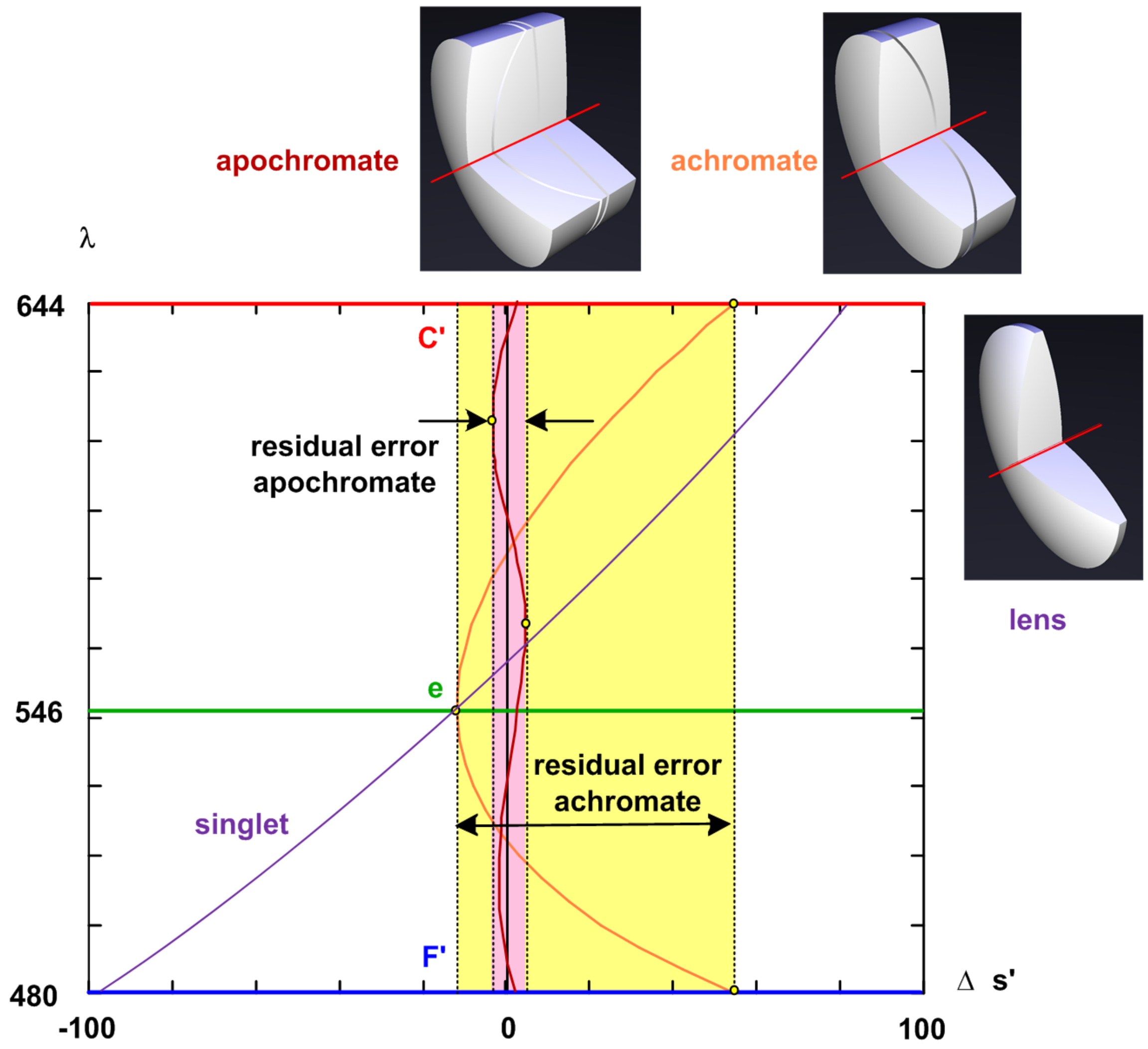
- Use of a long distance and negative F_2 for correction
- Only possible for virtual imaging





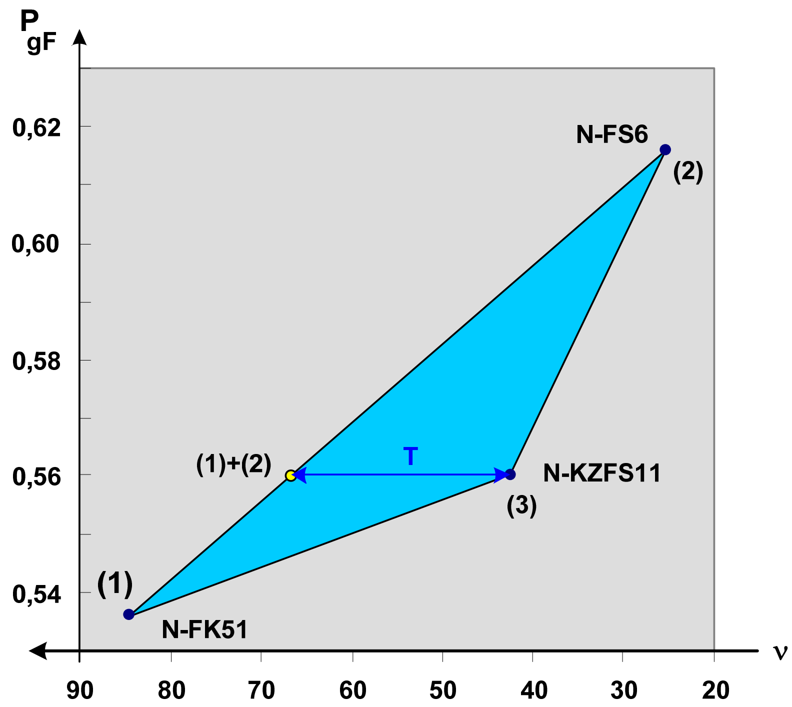
Axial Colour: Achromate and Apochromate

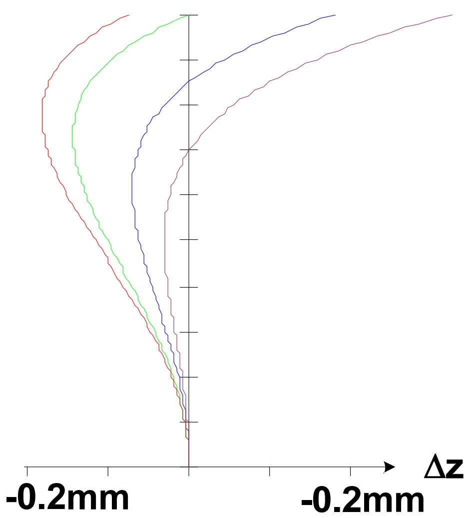
- Effect of different materials
- Axial chromatical aberration changes with wavelength
- Different levels of correction:
  1. No correction: lens, one zero crossing point
  2. Achromatic correction:
     - coincidence of outer colors
     - remaining error for center wavelength
     - two zero crossing points
  3. Apochromatic correction:
     - coincidence of at least three colors
     - small residual aberrations
     - at least 3 zero crossing points
     - special choice of glass types with anomalous partial dispertion necessery

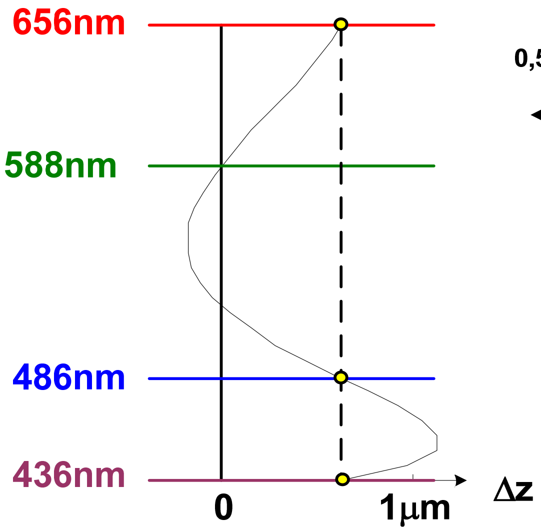


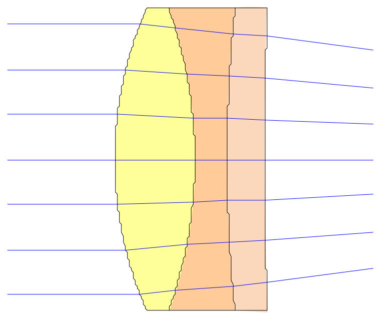
Axial Colour : Apochromate

- Choice of at least one special glass
- Correction of secondary spectrum: anomalous partial dispersion
- At least one glass should deviate significantly form the normal glass line



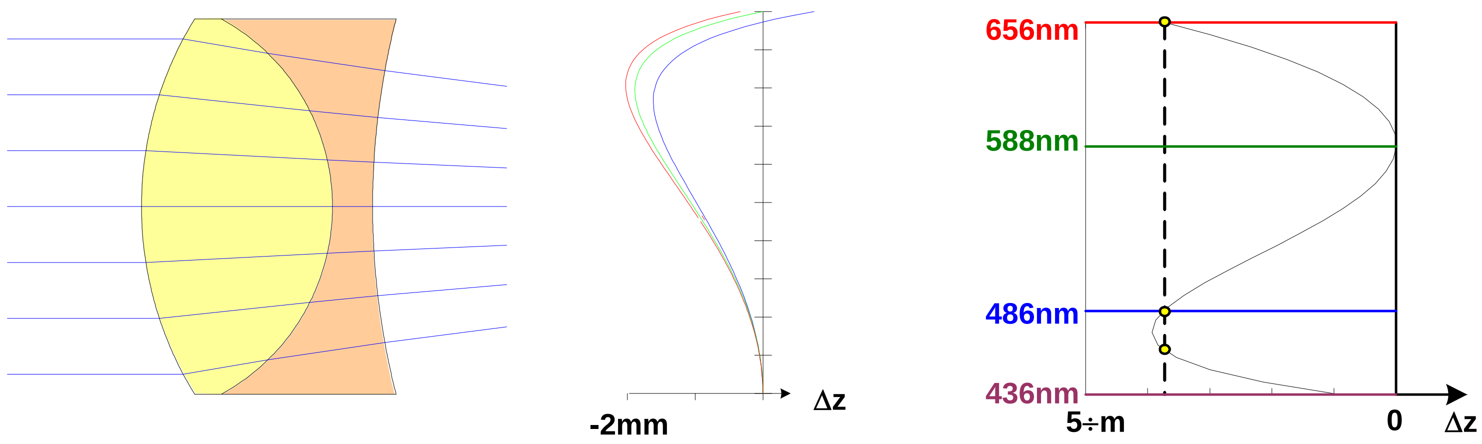






Two-Lens Apochromate

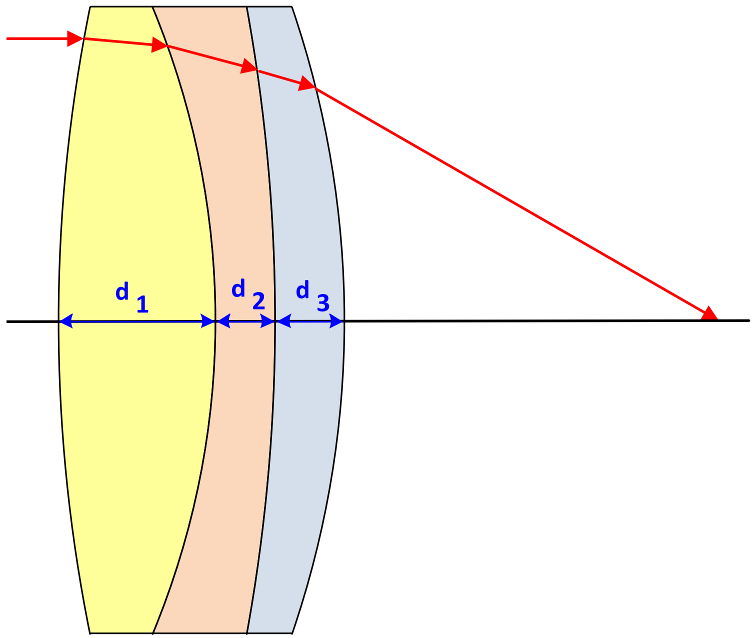
- Special glasses and very strong bending allows for apochromatic correction
- Large remaining spherical zonal aberration
- Zero-crossing points not well distributed over wavelength spectrum



Buried Surface

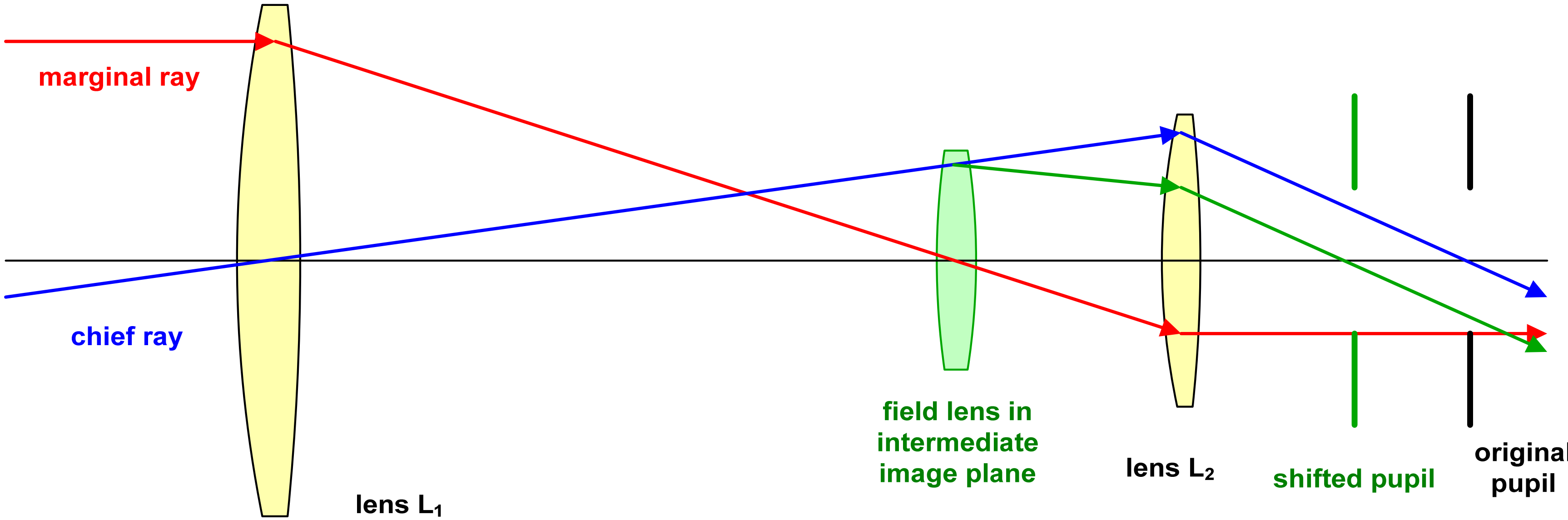
- Cemented surface with perfect refrcative index match
- No impact on monochromatic aberrations
- Only influence on chromatical aberrations
- Especially 3-fold cemented components are advantages
- Can serve as a starting setup for chromatical correction with fulfilled monochromatic correction
- Special glass combinations with nearly perfect parameters

Nr	Glas	n_d	$\Delta\ n_d$	ν_d	$\Delta\nu_d$
1	SK16	1.62031	0.00001	60.28	22.32
	F9	1.62030		37.96	
2	SK5	1.58905	0.00003	61.23	20.26
	LF2	1.58908		40.97	
3	SSK2	1.62218	0.00004	53.13	17.06
	F13	1.62222		36.07	
4	SK7	1.60720	0.00002	59.47	10.23
	BaF5	1.60718		49.24	

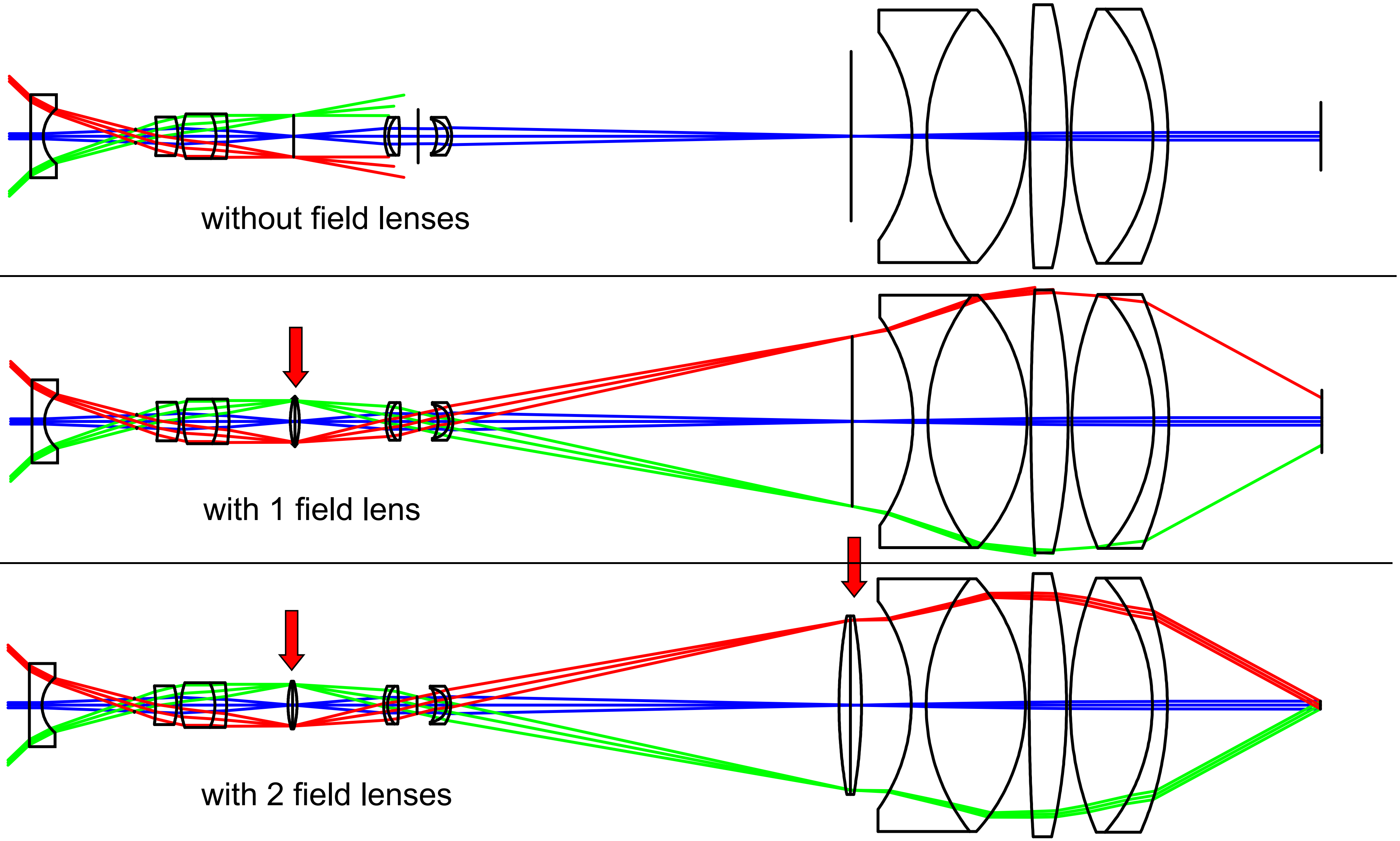


Field Lenses

- Field lens: in or near image planes
- Influences only the chief ray: pupil shifted
- Critical: conjugation to image plane, surface errors sharply seen



Field Lens im Endoscope



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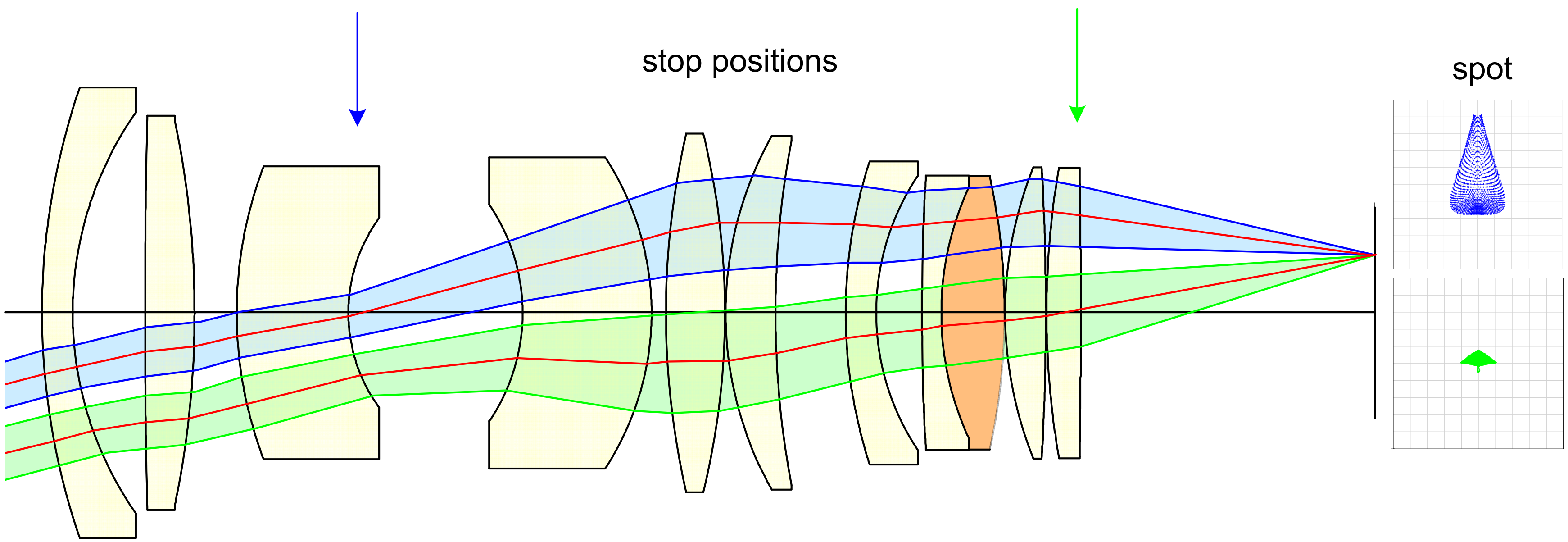
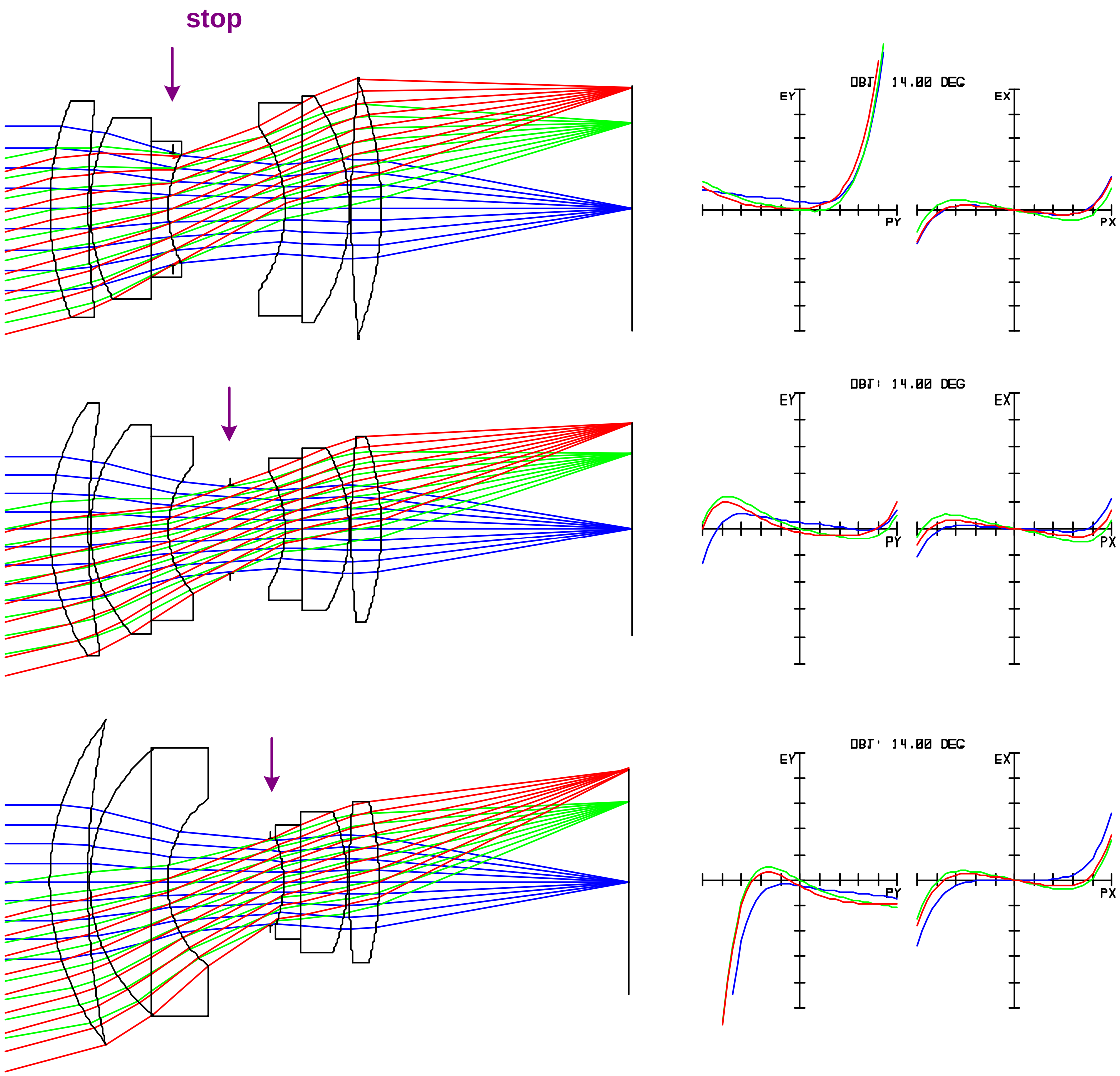
Influence of Stop Position on Performance

- Ray path of chief ray depends on stop position



Effect of Stop Position

- Example photographic lens
- Small axial shift of stop changes tranverse aberrations
- In particular coma is strongly influenced



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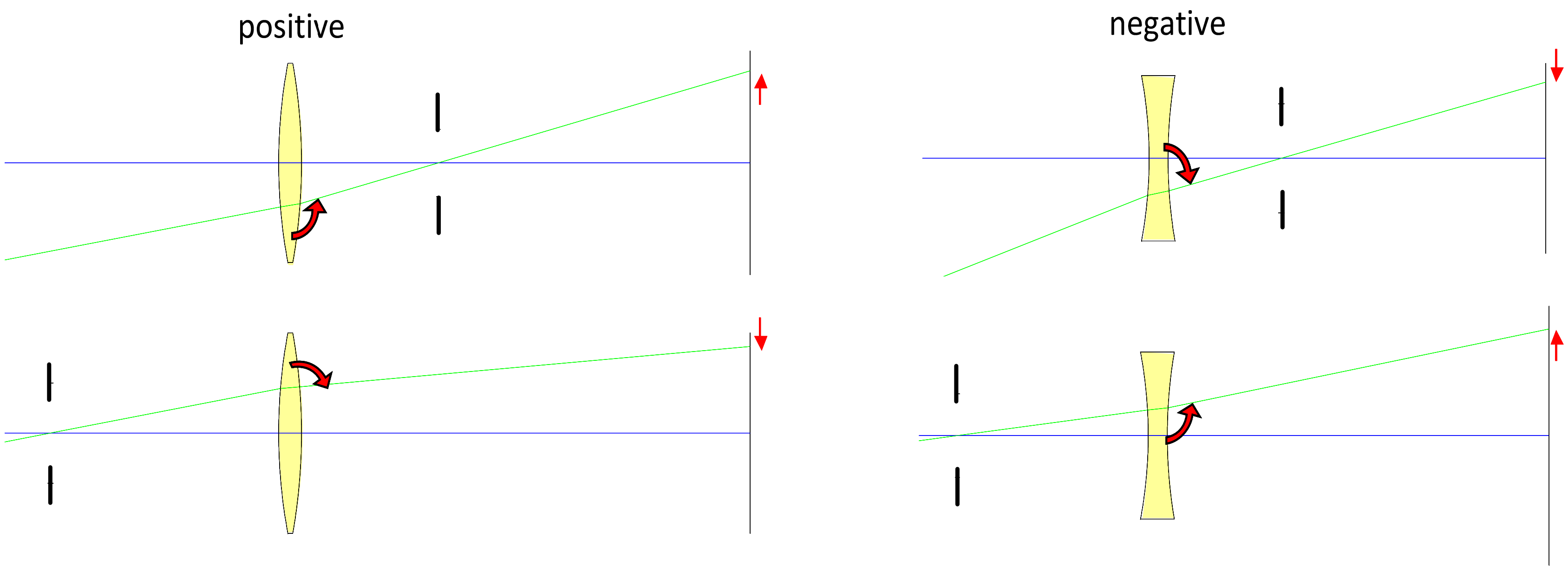
Distortion and Stop Position

- Sign of distortion for single lens: depends on stop position and sign of focal power
- Ray bending of chief ray defines distortion
- Stop position changes chief ray heigth at the lens

Lens	Stop location	Distortion	Examples
positive	rear	V > 0	tele photo lens
negative	in front	V > 0	loupe
positive	in front	V < 0	retrofocus lens
negative	rear	V < 0	reversed binocular



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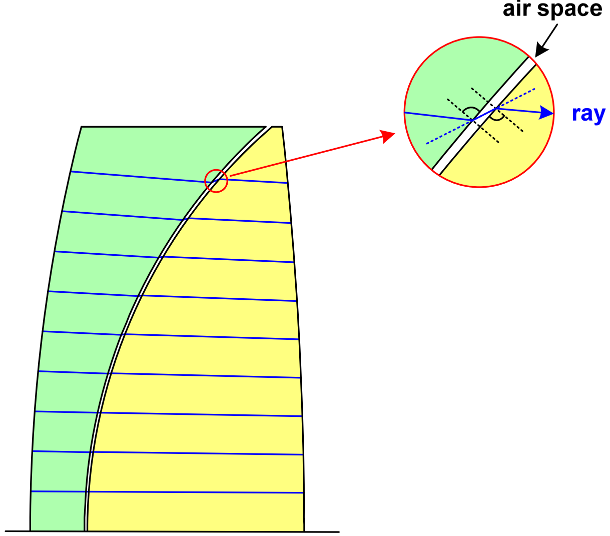
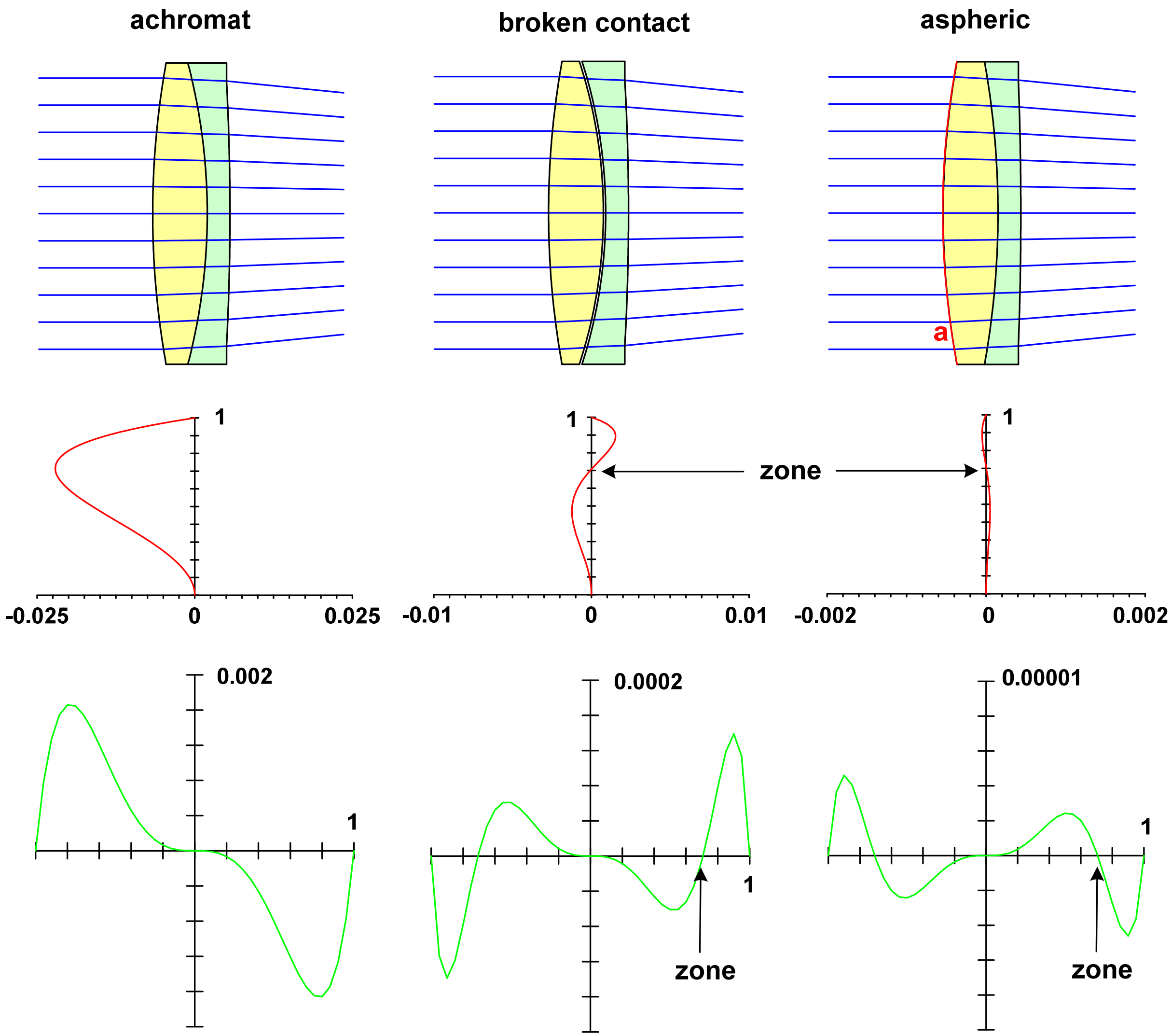
Higher Order Aberrations: Achromate, Aspheres

- Splitted achromate



- Aspherical surface



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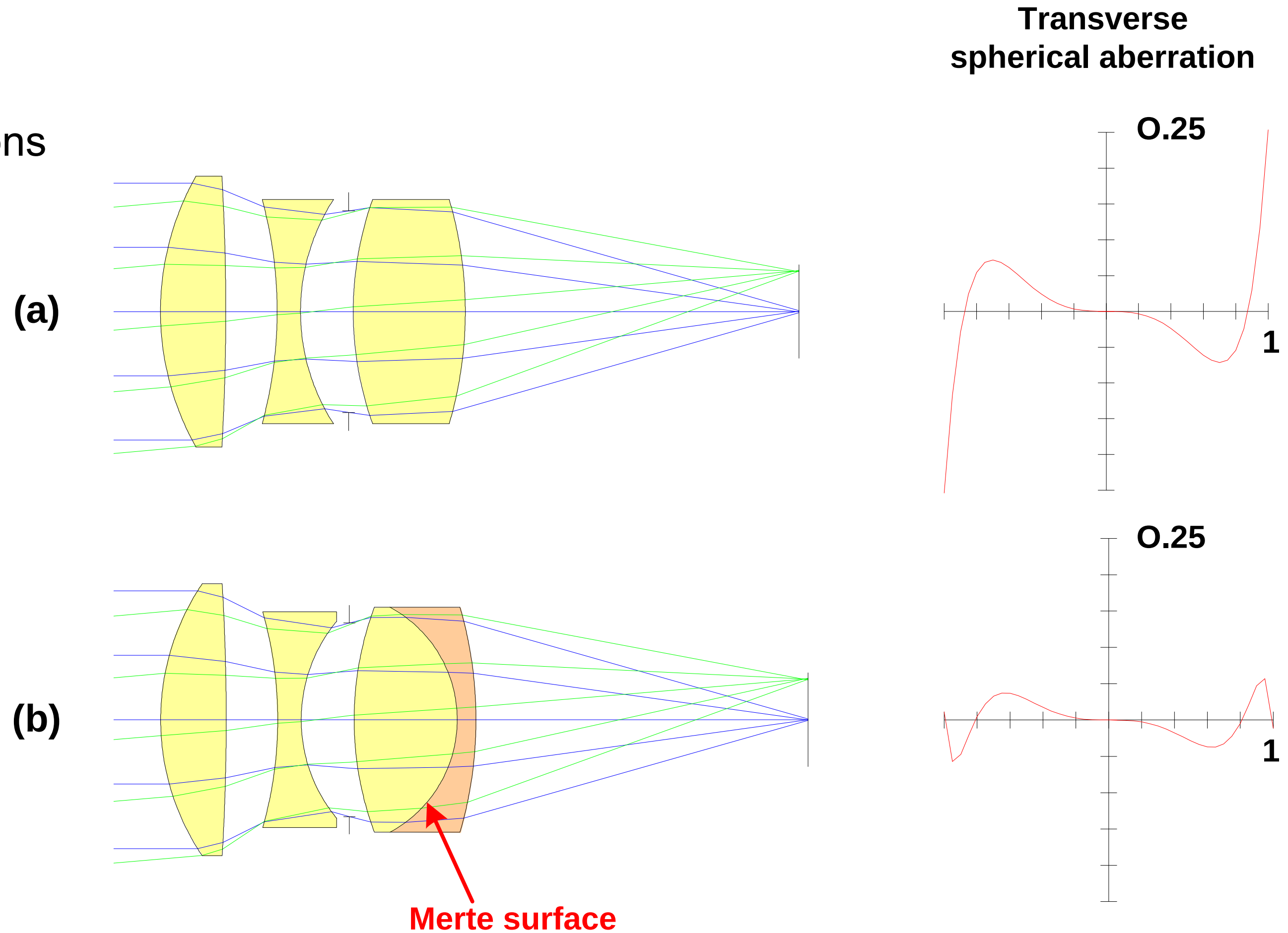
Higher Order Aberrations: Merte Surface

- Merte surface:
  - low index step
  - strong bending
  - mainly higher aberrations generated



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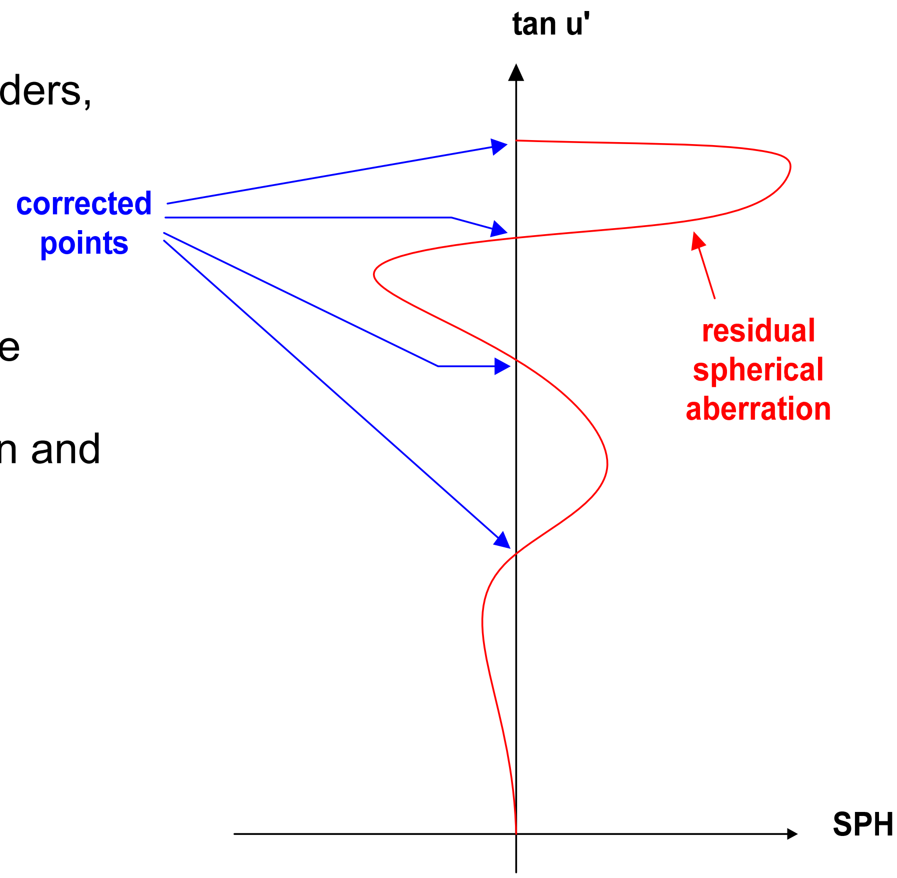
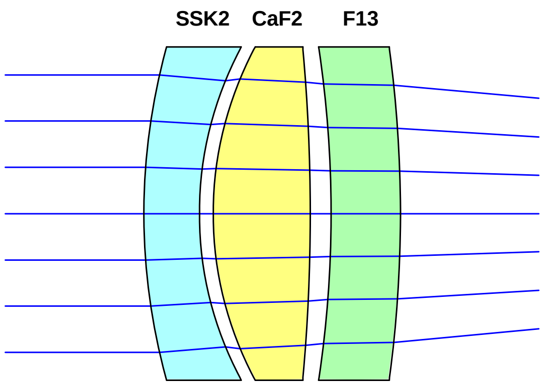
Aspherical Surfaces

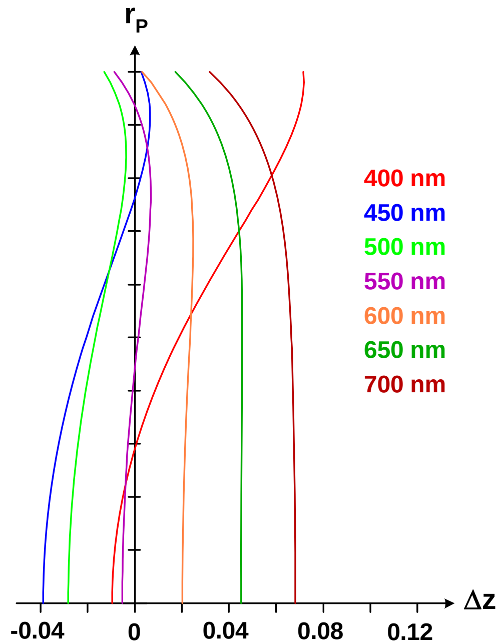
- Additional degrees of freedom for correction
- Exact correction of spherical aberration for a finite number of aperture rays
- Strong asphere: many coefficients with high orders, large oscillative residual deviations in zones
- Location of aspherical surfaces:
  1. spherical aberration: near pupil
  2. distortion and astigmatism: near image plane
- Use of more than 1 asphere: critical, interaction and correlation of higher oders

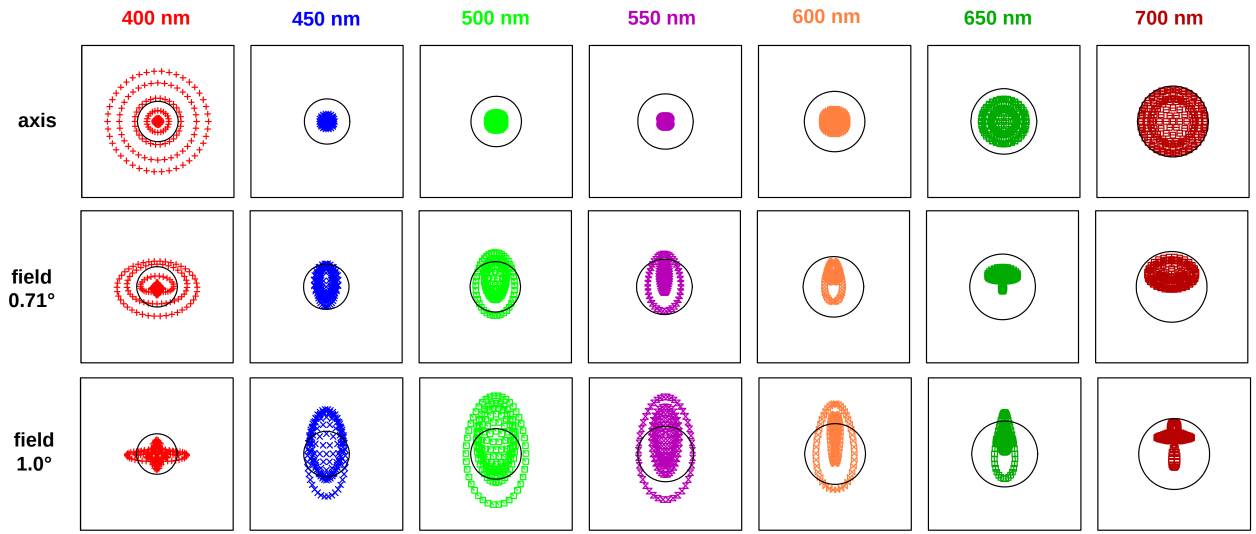


Coexistence of Aberrations : Balance

- Example: Apochromate
- Balance :
  1. zonal spherical
  2. Spot
  3. Secondary spectrum







Summary of Important Topics

- Nearly symmetrical system are goord corrected for coma, distortion and lateral color
- Important influence on correction: bending of a lens
- Correction of spherical aberration: bending, cementing, higher index
- Correction of coma: bending, stop position, symmetry
- Correction of field curvature: thick mensicus, field lens, low index negative lenses with low ray height
- Achromate: coincidence of two colors, spherical correction, higher order zone remains
- Apochromatic correction: three glasses, one with anomalous partial dispersion
- Remaining chromatic error: spherochromatism
- Field lenses: adaption of pupil imaging
- Higher orders of aberrations: occur for large angles
- Whole system: balancing of aberrations and best trade-off is desired