



**Institute of  
Applied Physics**

Friedrich-Schiller-Universität Jena

# Imaging and Aberration Theory

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Lecture 8: Astigmatism and curvature

2018-12-07

Herbert Gross

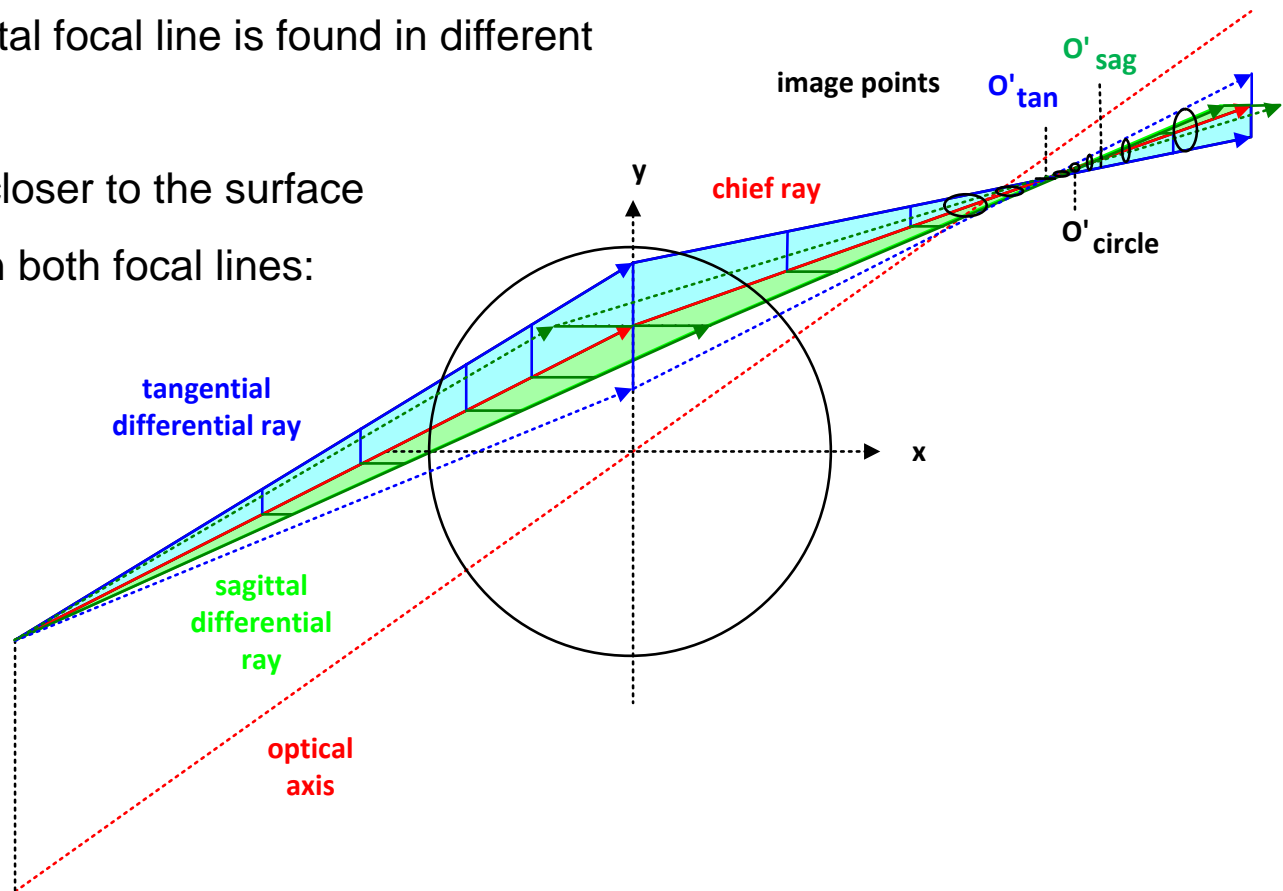


# Schedule - Imaging and aberration theory 2018

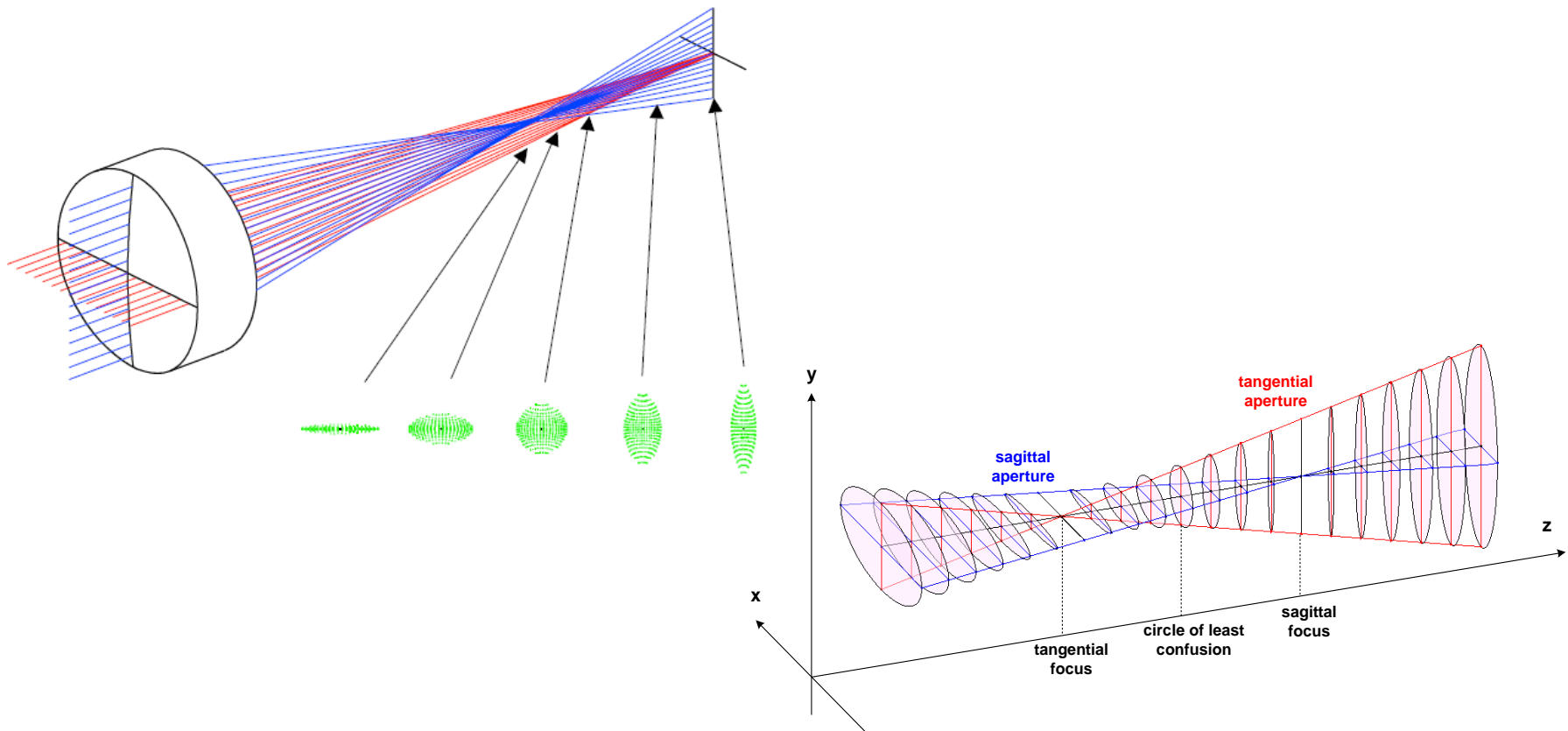
1	19.10.	Paraxial imaging	paraxial optics, fundamental laws of geometrical imaging, compound systems
2	26.10.	Pupils, Fourier optics, Hamiltonian coordinates	pupil definition, basic Fourier relationship, phase space, analogy optics and mechanics, Hamiltonian coordinates
3	02.11.	Eikonal	Fermat principle, 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, reverbility

1. Geometrical astigmatism
2. Point spread function for astigmatism
3. Field curvature
4. Petzval theorem
5. Correcting field curvature
6. Examples

- Reason for astigmatism:  
chief ray passes a surface under an oblique angle,  
the refractive power in tangential and sagittal section are different
- The astigmatism is influenced by the stop position
- A tangential and a sagittal focal line is found in different distances
- Tangential rays meet closer to the surface
- In the midpoint between both focal lines:  
circle of least confusion



- Beam cross section in the case of astigmatism:
  - Elliptical shape transforms its aspect ratio
  - degenerate into focal lines in the focal plane distances
  - special case of a circle in the midpoint: smallest spot





# Primary Aberration Spot Shape for Astigmatism

- Seidel formulas for field point only in  $y'$  considered

$$\Delta y' = S' \cdot r_p'^3 \cos \varphi_p + C' \cdot y' \cdot r_p'^2 (2 + \cos 2\varphi_p) + (2A' + P') \cdot y'^2 \cdot r_p' \cos \varphi_p + D' \cdot y'^3$$

$$\Delta x' = S' \cdot r_p'^3 \sin \varphi_p + C' \cdot y' \cdot r_p'^2 \cdot \sin 2\varphi_p + P' \cdot y'^2 \cdot r_p' \sin \varphi_p$$

- Field curvature:  
circle

$$\Delta y' = P' \cdot y'^2 \cdot r_p' \cos \varphi_p, \quad \Delta x' = P' \cdot y'^2 \cdot r_p' \sin \varphi_p$$

$$\Delta x'^2 + \Delta y'^2 = P'^2 y'^4 r_p'^2$$

- Astigmatism:  
focal line

$$\Delta y' = 2A' \cdot y'^2 \cdot r_p' \cos \varphi_p, \quad \Delta x' = 0$$

- General spot with defocus:  
wave aberration

$$W(x, y) = c_{20} \cdot (x^2 + y^2) + c_{22} \cdot y^2$$

Transverse aberrations

$$\Delta x = -R \cdot \frac{\partial W}{\partial x} = -2Rc_{20}x, \quad \Delta y = -R \cdot \frac{\partial W}{\partial y} = -2Ry \cdot (c_{20} + c_{22})$$

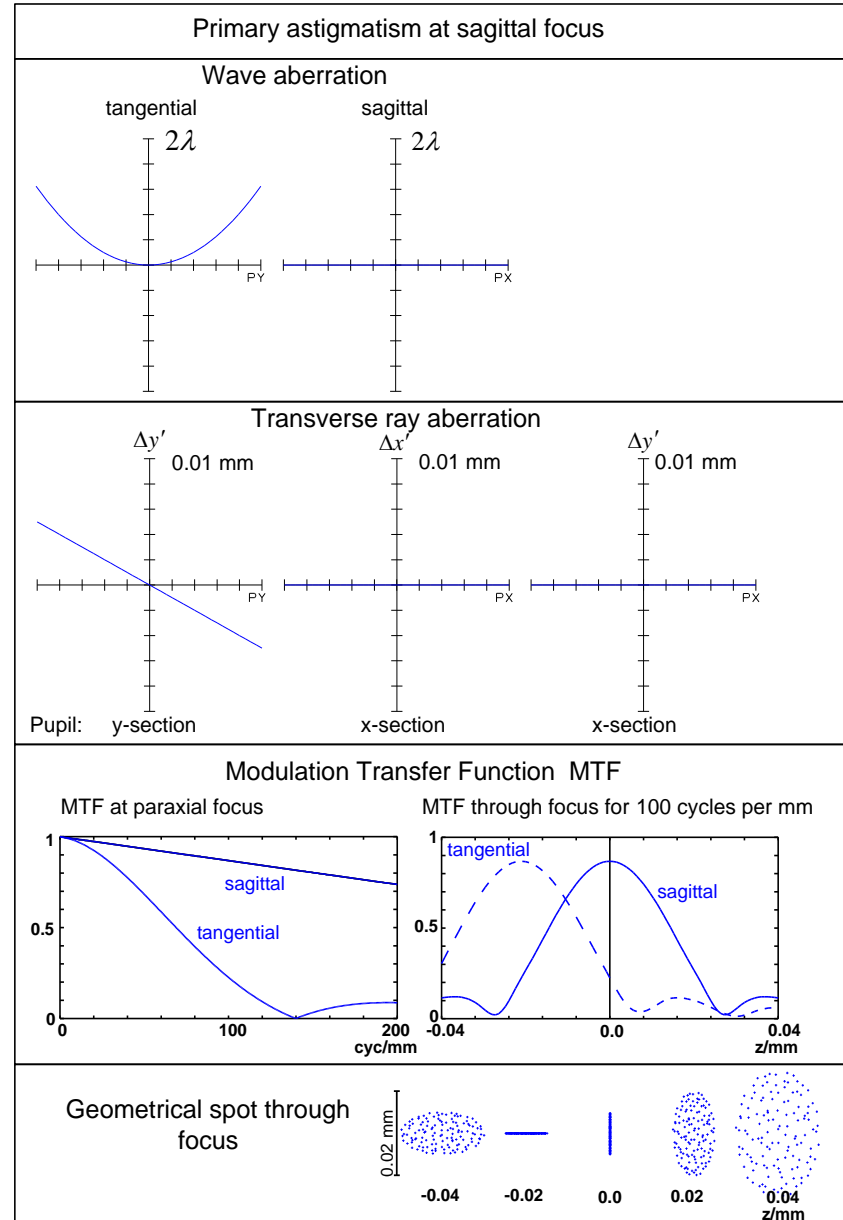
Circle/ring in the pupil  $r^2 = x^2 + y^2$   
delivers an elliptical spot in the image

$$\frac{\Delta x^2}{(2Rrc_{20})^2} + \frac{\Delta y^2}{[2Rr \cdot (c_{20} + c_{22})]^2} = 1$$

Special case for  $c_{20} = -c_{22}/2$ :  
circle of least confusion

$$\frac{\Delta x^2}{(Rrc_{22})^2} + \frac{\Delta y^2}{(Rrc_{22})^2} = 1$$

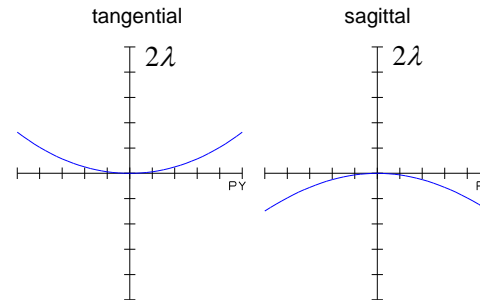
- At sagittal focus
- Defocus only in tangential cross section



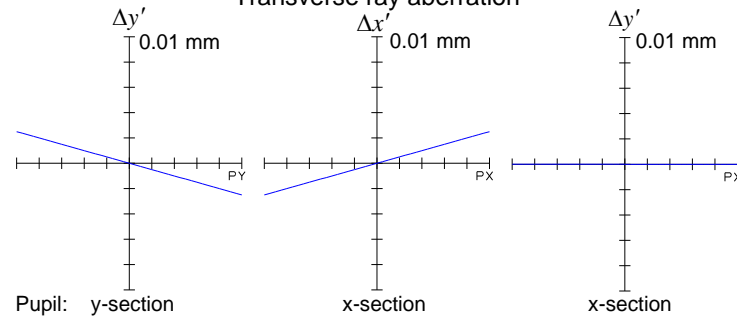
- At median focus
- Anti-symmetrical defocus in T-S-cross section

## Primary astigmatism at medial focus

### Wave aberration

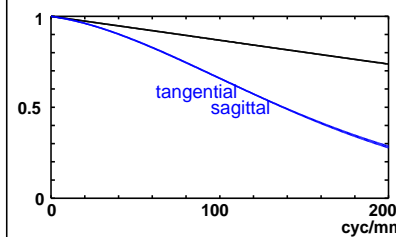


### Transverse ray aberration

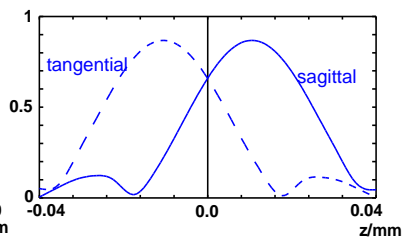


### Modulation Transfer Function MTF

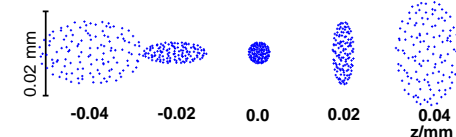
#### MTF at paraxial focus



#### MTF through focus for 100 cycles per mm

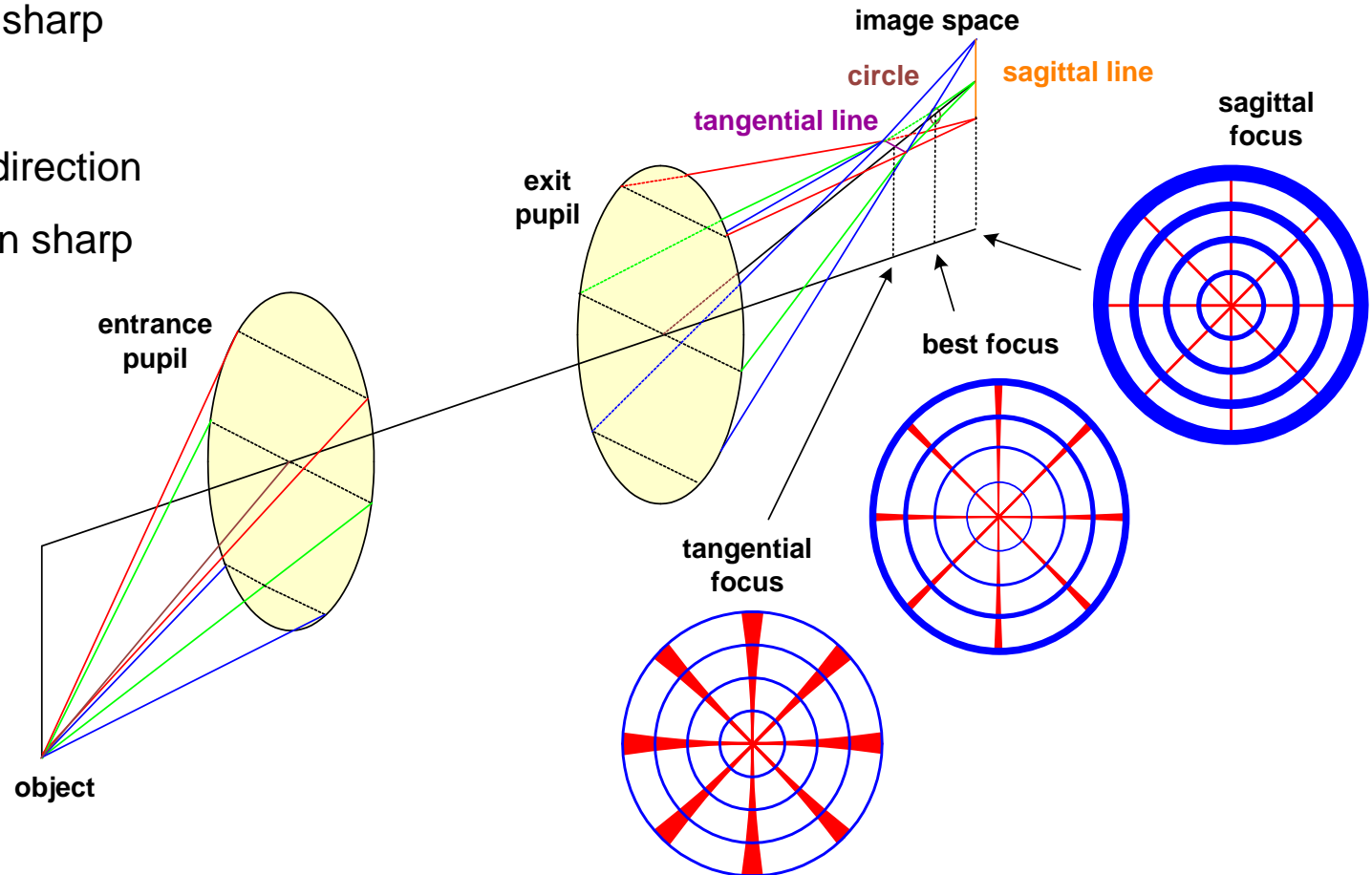


### Geometrical spot through focus

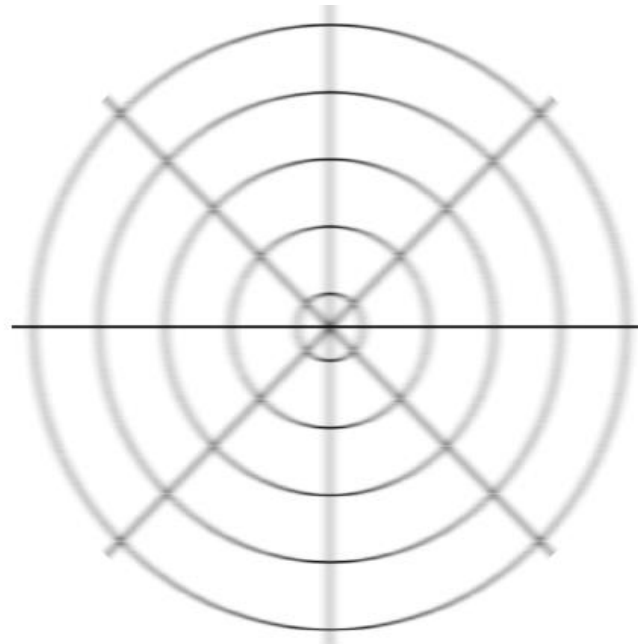
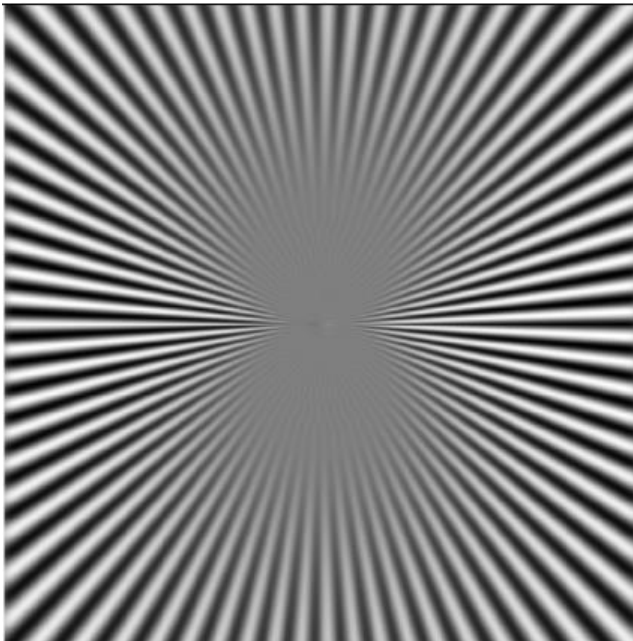
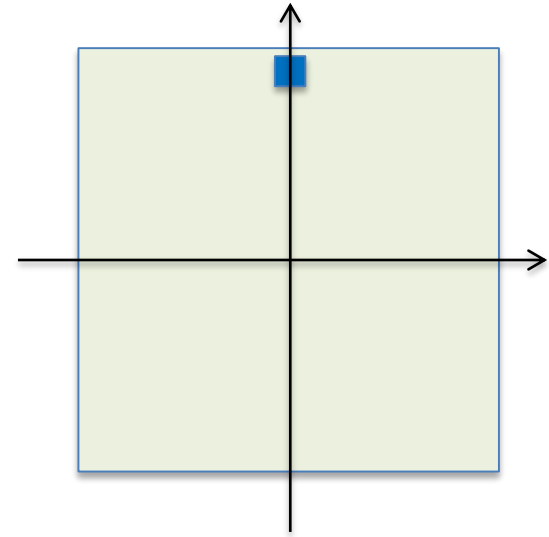




- Imaging of a polar grid in different planes
- Tangential focus:
  - blur in azimuthal direction
  - rings remain sharp
- Sagittal focus:
  - blur in radial direction
  - spokes remain sharp



- Behavior of a local position of the field:
  1. good resolution of horizontal structures
  2. bad resolution of vertical structures
- Imaging of polar diagram shows not the classical behaviour of the complete field



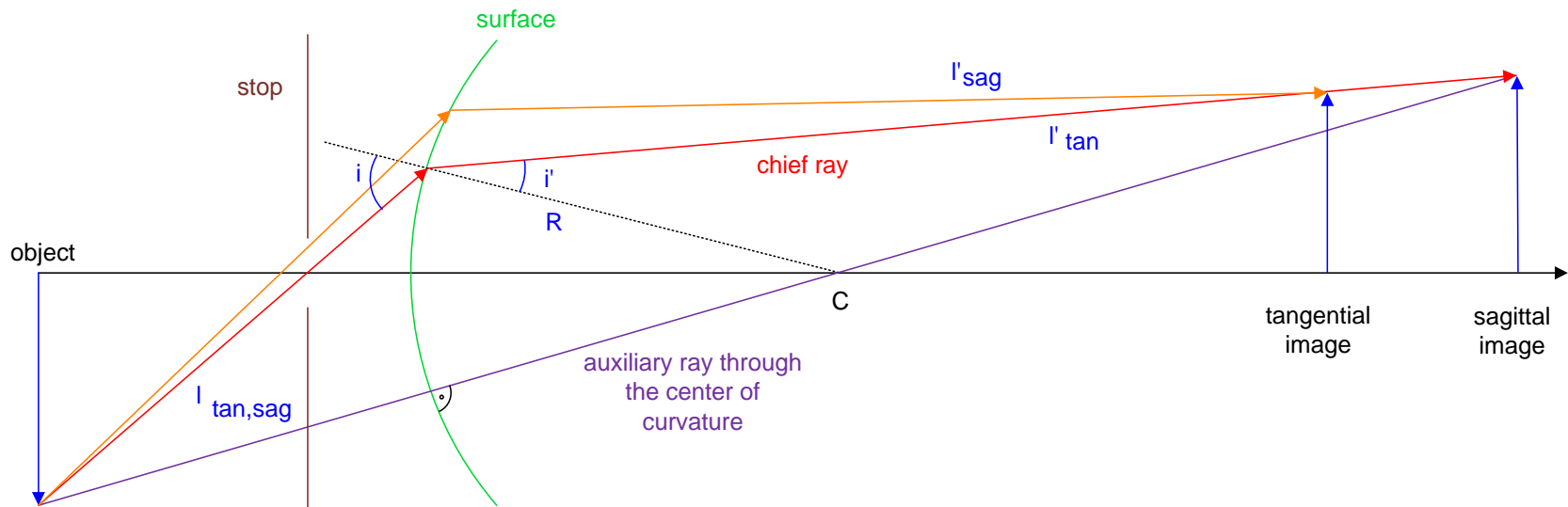
# Coddington Equations

- For an oblique ray, the effective curvatures of the spherical surface depend on azimuth
- There are two focal points for sagittal / tangential aperture rays
- This splitting occurs already for infinitesimal aperture angles around the chief ray
- Intersection lengths along the chief ray: Coddington equations

$$\frac{n' \cos^2 i'}{l'_{\tan}} - \frac{n \cos^2 i}{l_{\tan}} = \frac{n' \cos i' - n \cos i}{R}$$

$$\frac{n'}{l'_{\text{sag}}} - \frac{n}{l_{\text{sag}}} = \frac{n' \cos i' - n \cos i}{R}$$

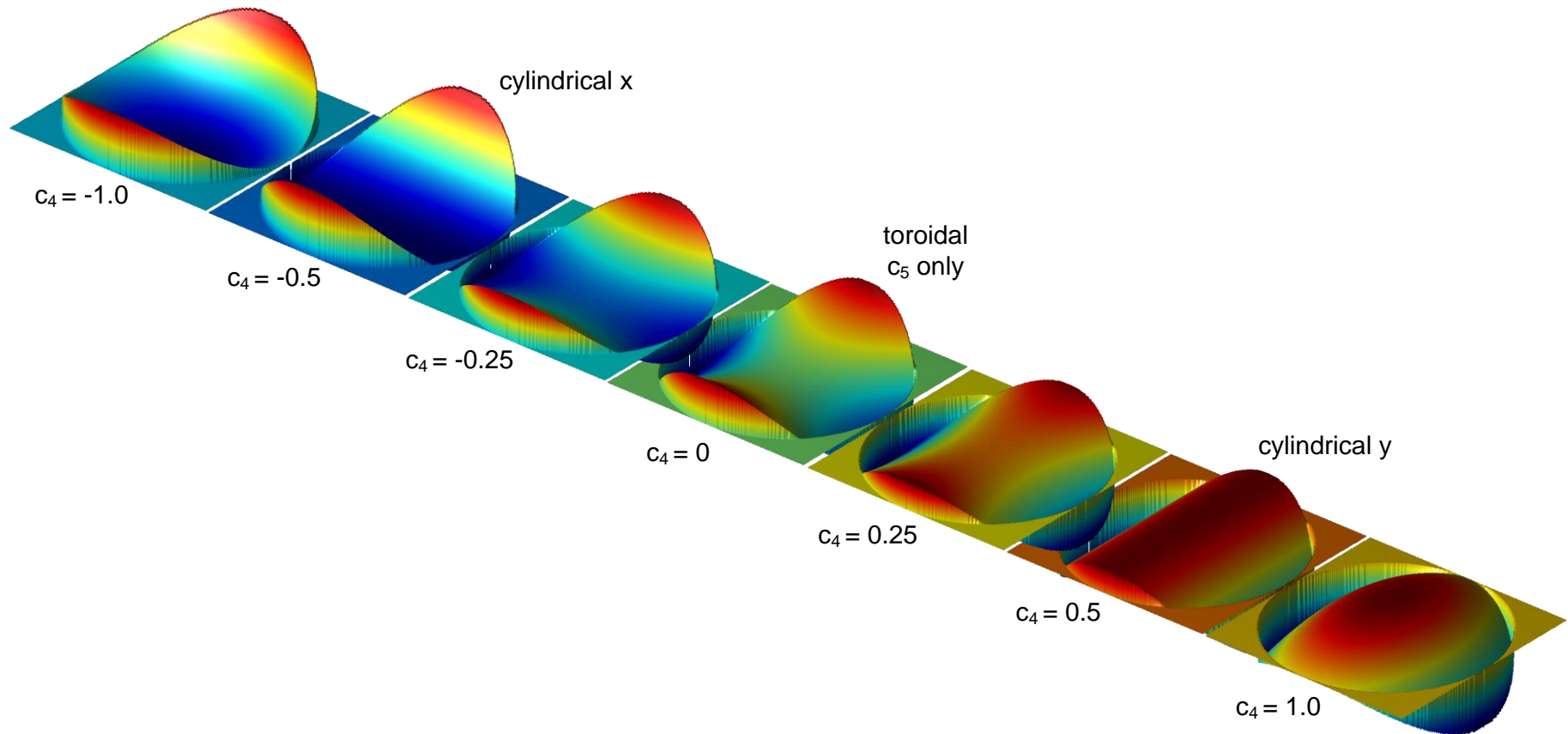
- Right side: oblique power of the spherical interface
- The sagittal image must be located on the auxiliary axis by symmetry



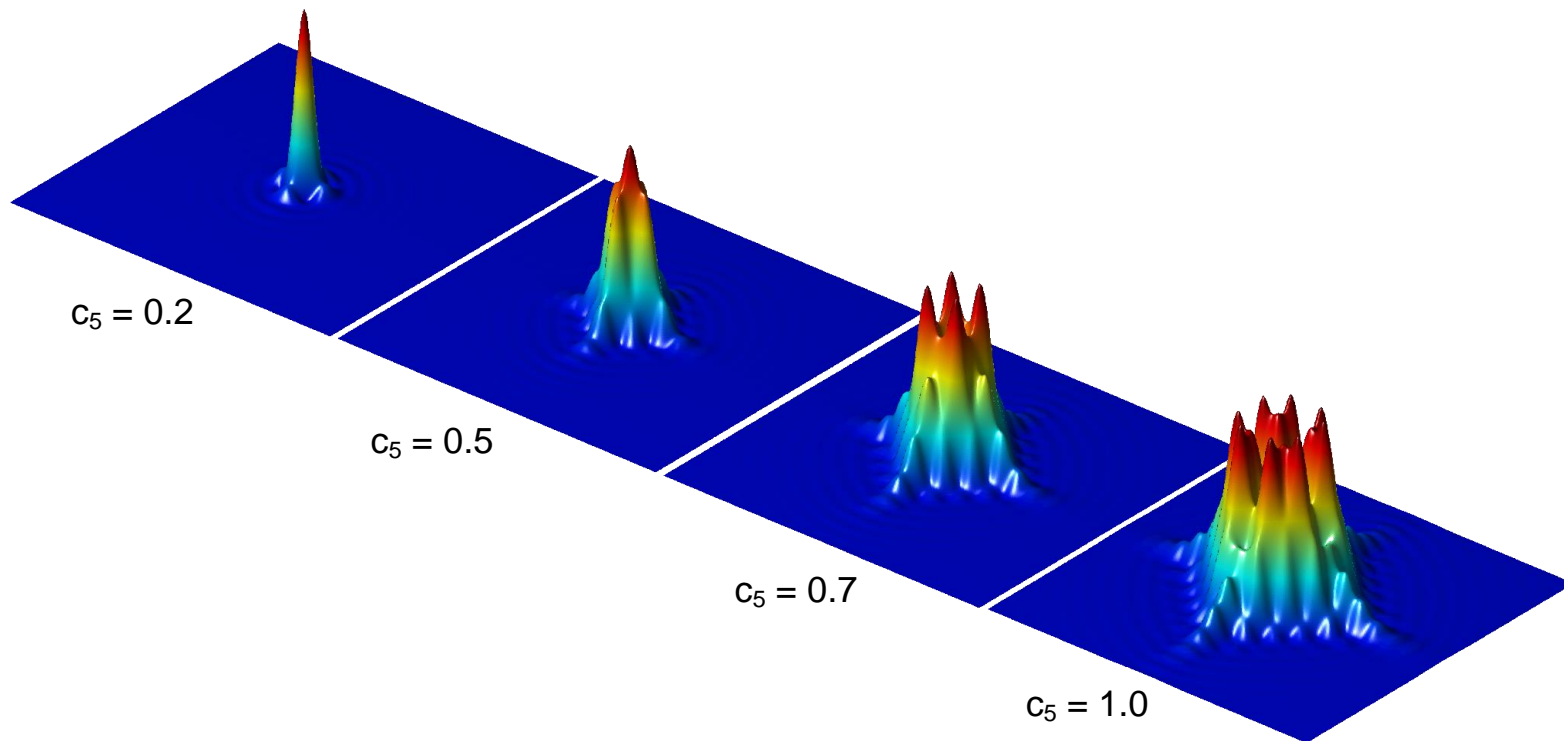


# Wavefront for Astigmatism with Defocus

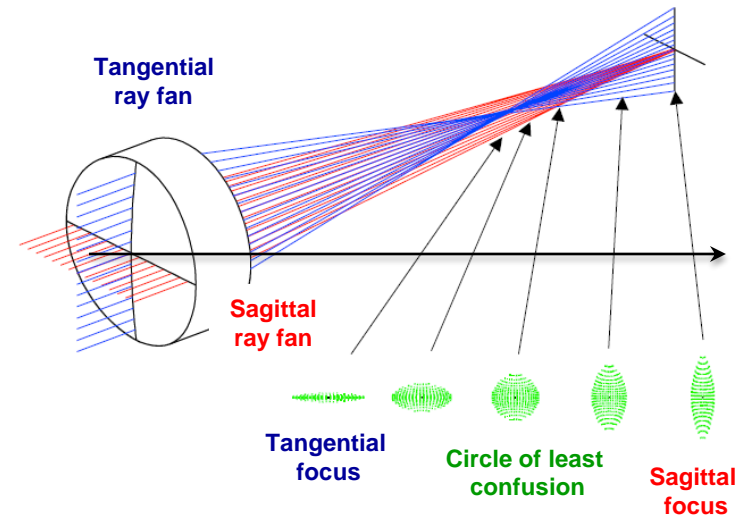
- Astigmatic wavefront ( $c_5$ ) with defocus ( $c_4$ )
- Purely cylindrical for focal lines in x/y
- Purely toroidal without defocus: circle of least confusion



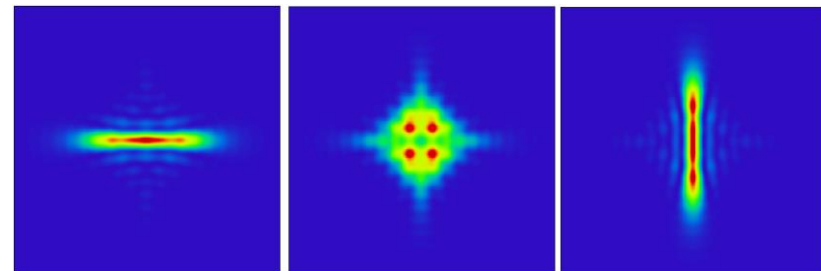
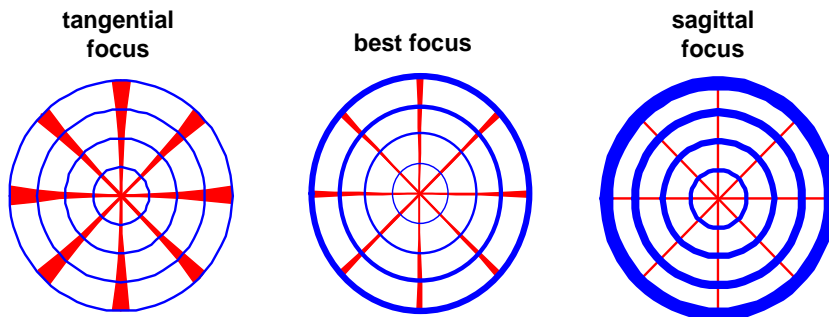
- Zernike coefficients  $c$  in  $\lambda$
- Pure astigmatism
- Shape is not circular symmetric due to finite width of focal lines



- In Seidel contribution term  $(3B3 + B4) \rho y^2 \cos \phi$  corresponds to astigmatism and Petzval
- For a single positive lens:
  - chief ray passes surface under oblique angle
- projection of surface curvatures
- different powers in tangential and sagittal section
- tangential and sagittal focal lines
- tangential rays meet at first
- circle of least confusion with smallest spot size
- sagittal focus before paraxial focus



Imaging of a circular grid in different planes

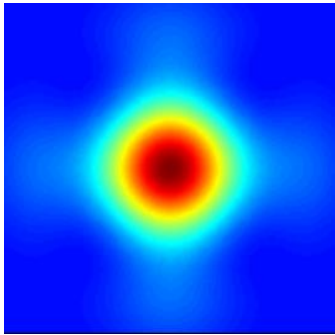




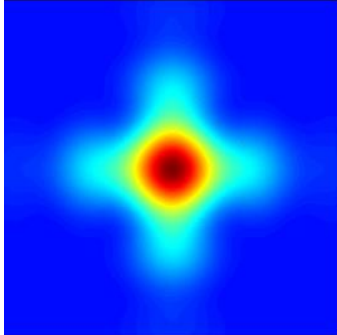
# Symmetry of the Astigmatic Spot

- Geometrical spot shape: perfect spherical
- Medium aberration with diffraction:  
squared, cartesian symmetry due to finite focal line width
- Large aberrations: nearly spherical, large astigmatic difference, finite line width negligible

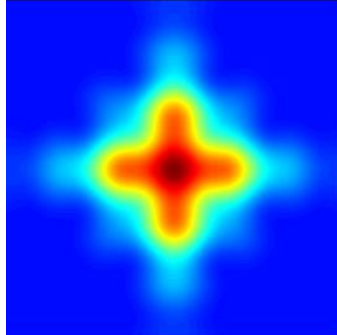
$c_5=0.25$



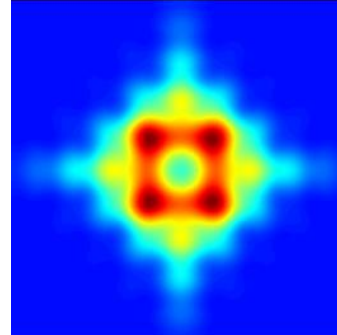
$c_5=0.35$



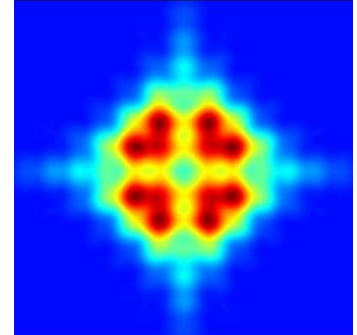
$c_5=0.5$



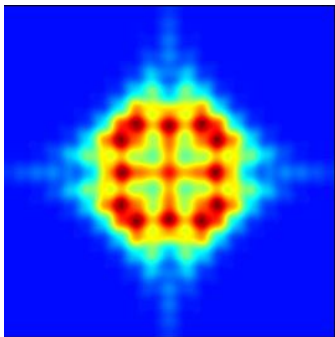
$c_5=0.75$



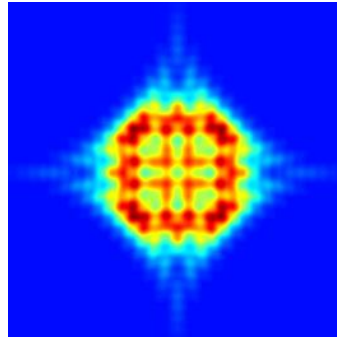
$c_5=1$



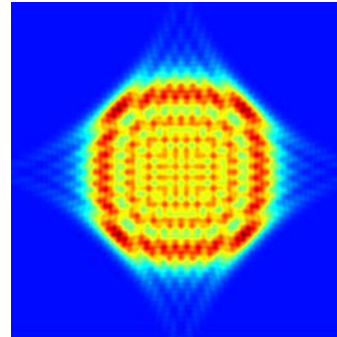
$c_5=1.5$



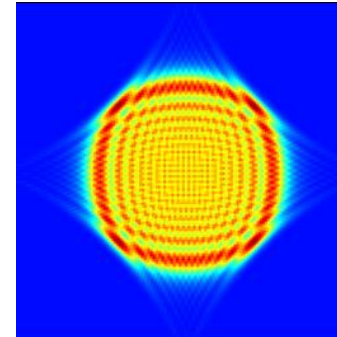
$c_5=2$



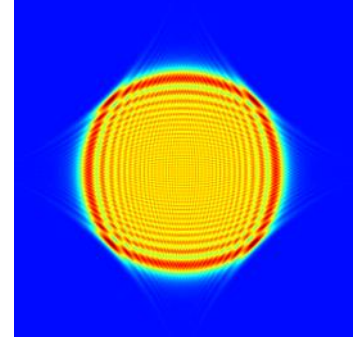
$c_5=5$



$c_5=10$

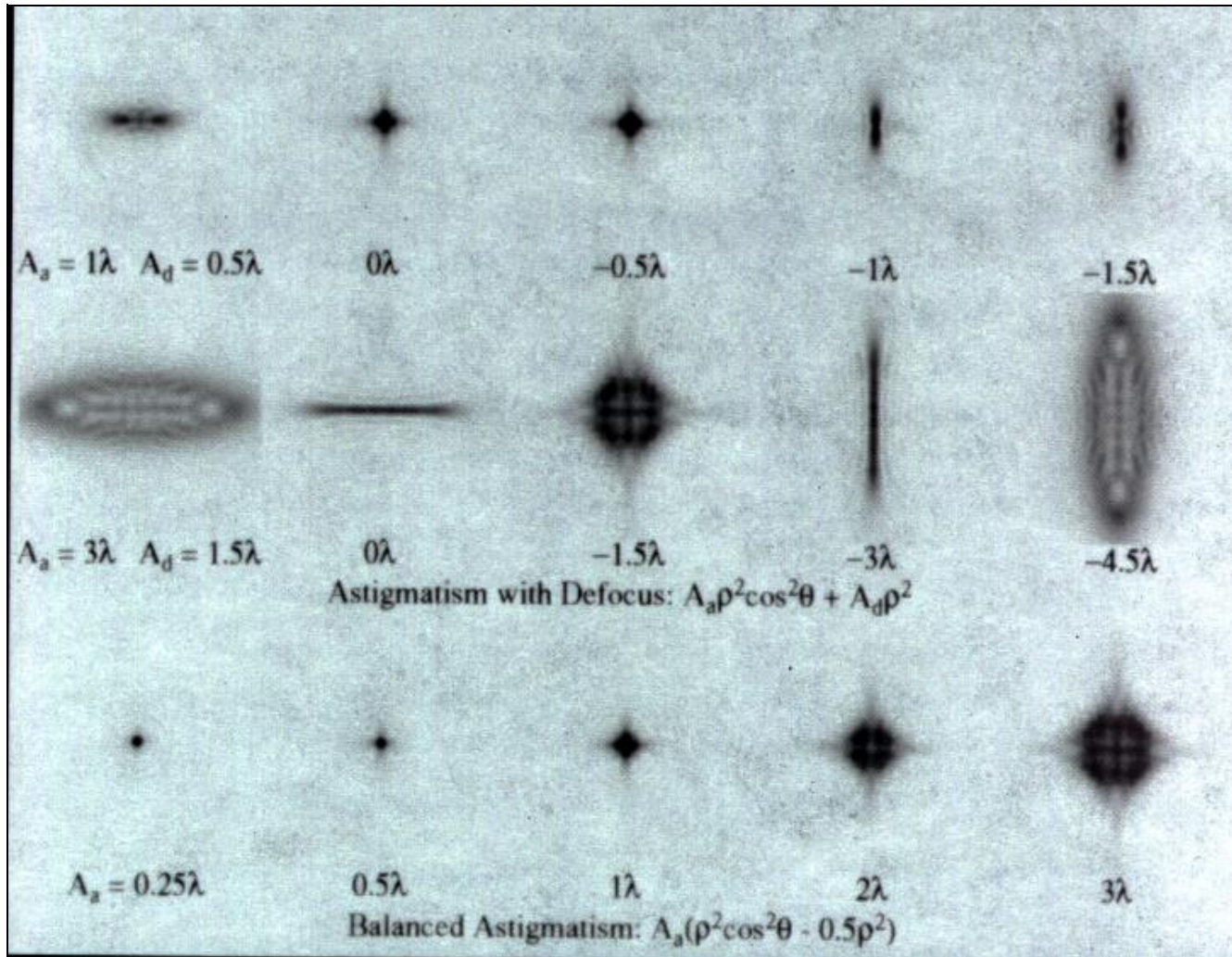


$c_5=20$





# Psf bei Astigmatismus

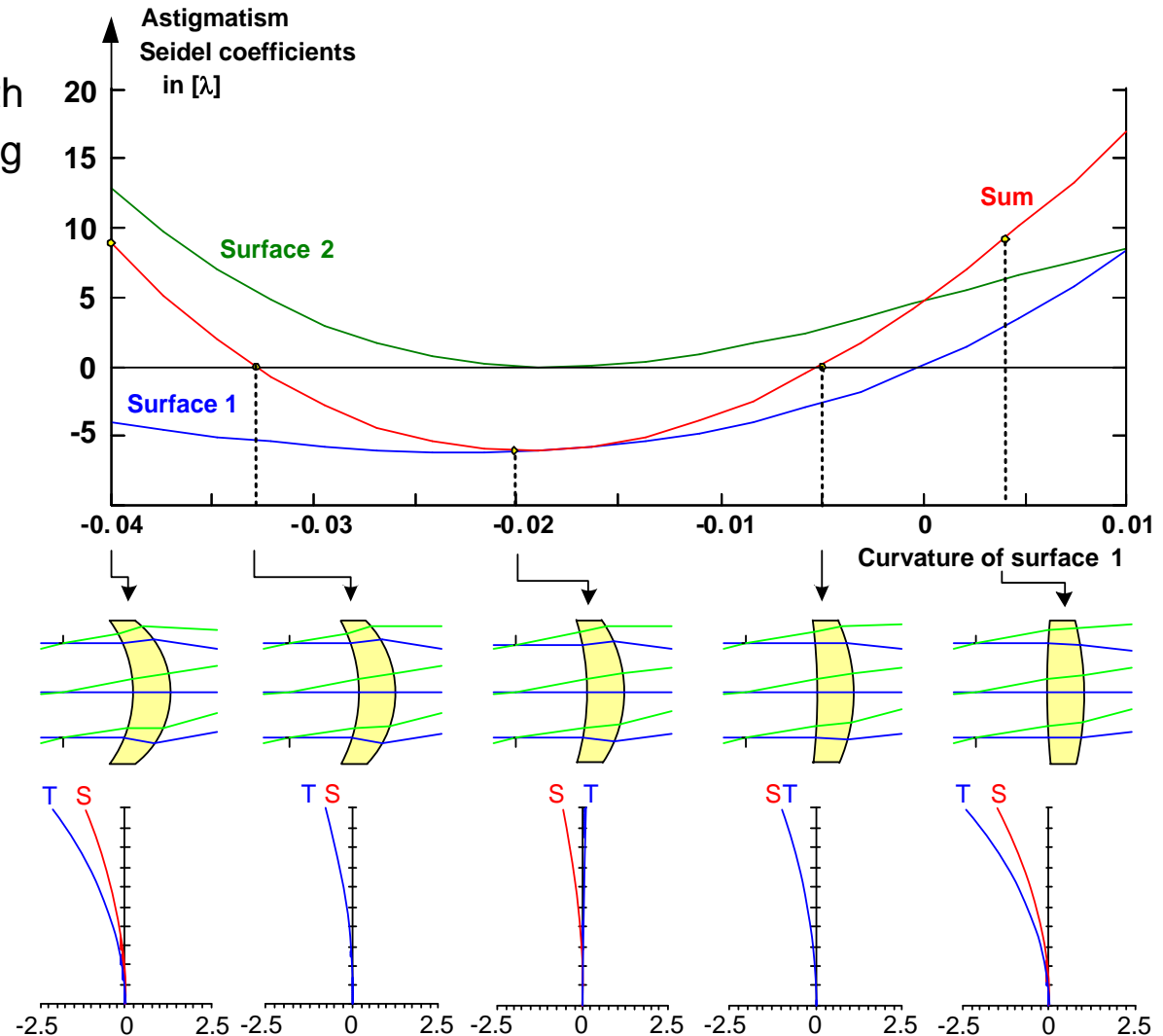






# Astigmatism: Lens Bending

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





# Conic Sections

- Explicite surface equation, resolved to z

Parameters: curvature  $c = 1 / R$

conic parameter  $\kappa$

- Influence of  $\kappa$  on the surface shape

$$z = \frac{c(x^2 + y^2)}{1 + \sqrt{1 - (1 + \kappa)c^2(x^2 + y^2)}}$$

Parameter	Surface shape
$\kappa = -1$	paraboloid
$\kappa < -1$	hyperboloid
$\kappa = 0$	sphere
$\kappa > 0$	oblate ellipsoid (disc)
$0 > \kappa > -1$	prolate ellipsoid (cigar)

- Relations with axis lengths a,b of conic sections

$$\kappa = \left(\frac{a}{b}\right)^2 - 1$$

$$c = \frac{b}{a^2}$$

$$b = \frac{1}{|c(1 + \kappa)|}$$

$$a = \frac{1}{|c\sqrt{1 + \kappa}|}$$

- Radii of curvature

$$R_T = \frac{1}{c} \cdot (1 - \kappa c^2 x^2)^{3/2}, \quad R_S = \frac{1}{c} \cdot (1 - \kappa c^2 x^2)^{1/2}$$

# Astigmatism of Oblique Mirrors

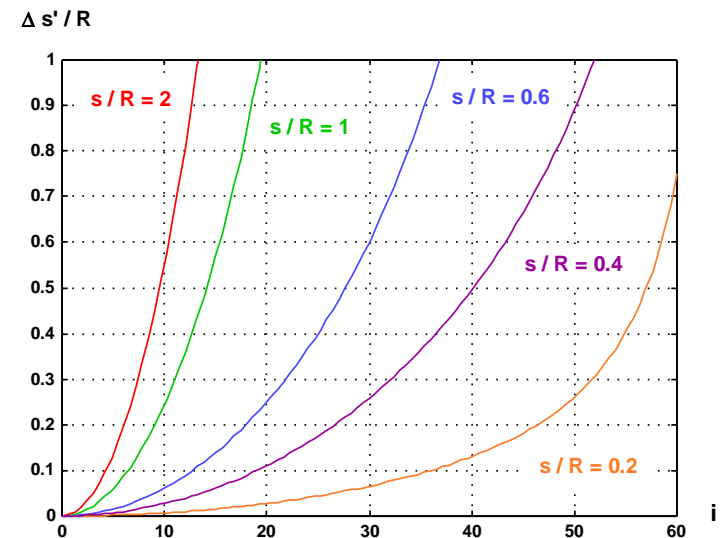
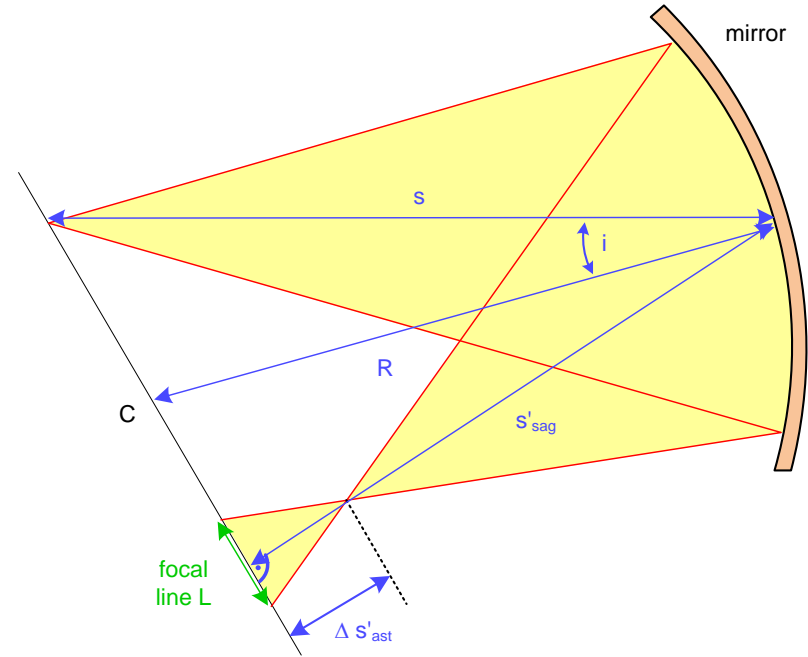
- Mirror with finite incidence angle:  
effective focal lengths

$$f_{\tan} = \frac{R \cdot \cos i}{2} \quad f_{\text{sag}} = \frac{R}{2 \cos i}$$

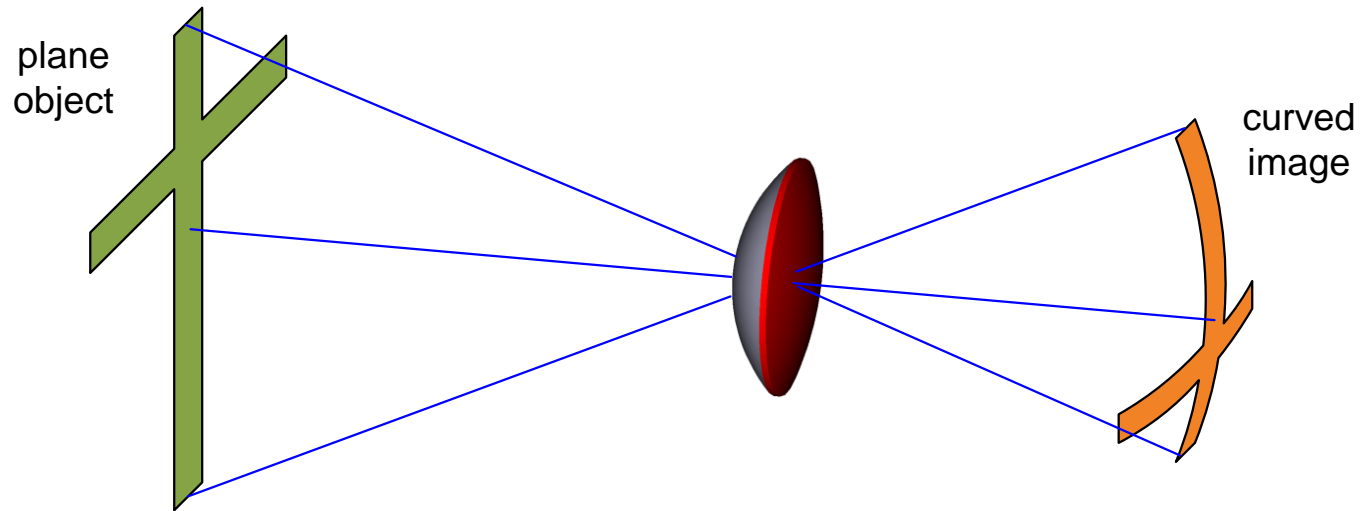
- Mirror introduces astigmatism

$$\Delta s'_{\text{ast}} = \frac{s^2 \cdot R \cdot \sin^2 i}{2 \cos i \cdot \left( s - \frac{R \cos i}{2} \right) \cdot \left( s - \frac{R}{2 \cos i} \right)}$$

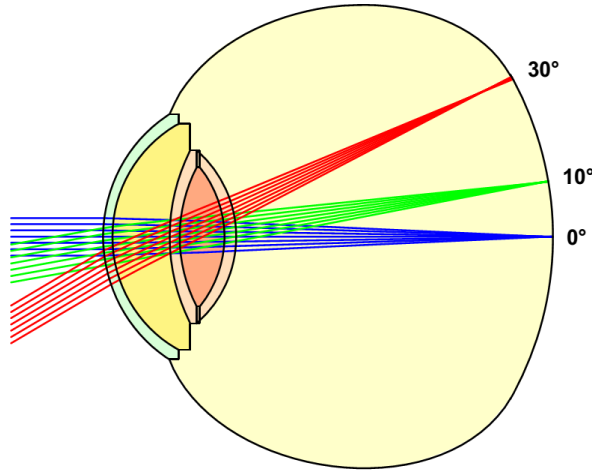
- Parametric behavior of scales astigmatism



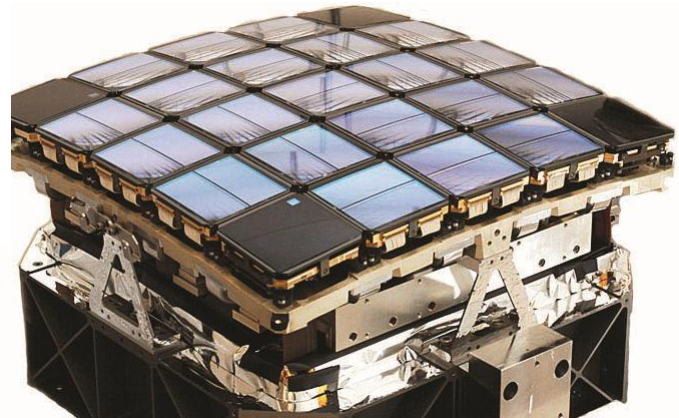
- Basic observation:  
A plane object gives a curved image



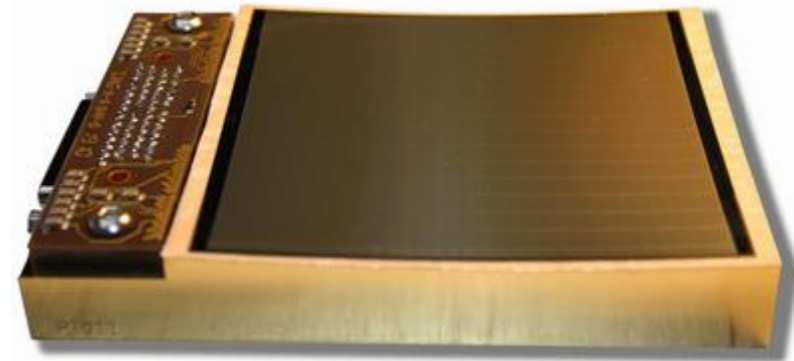
- Human eye



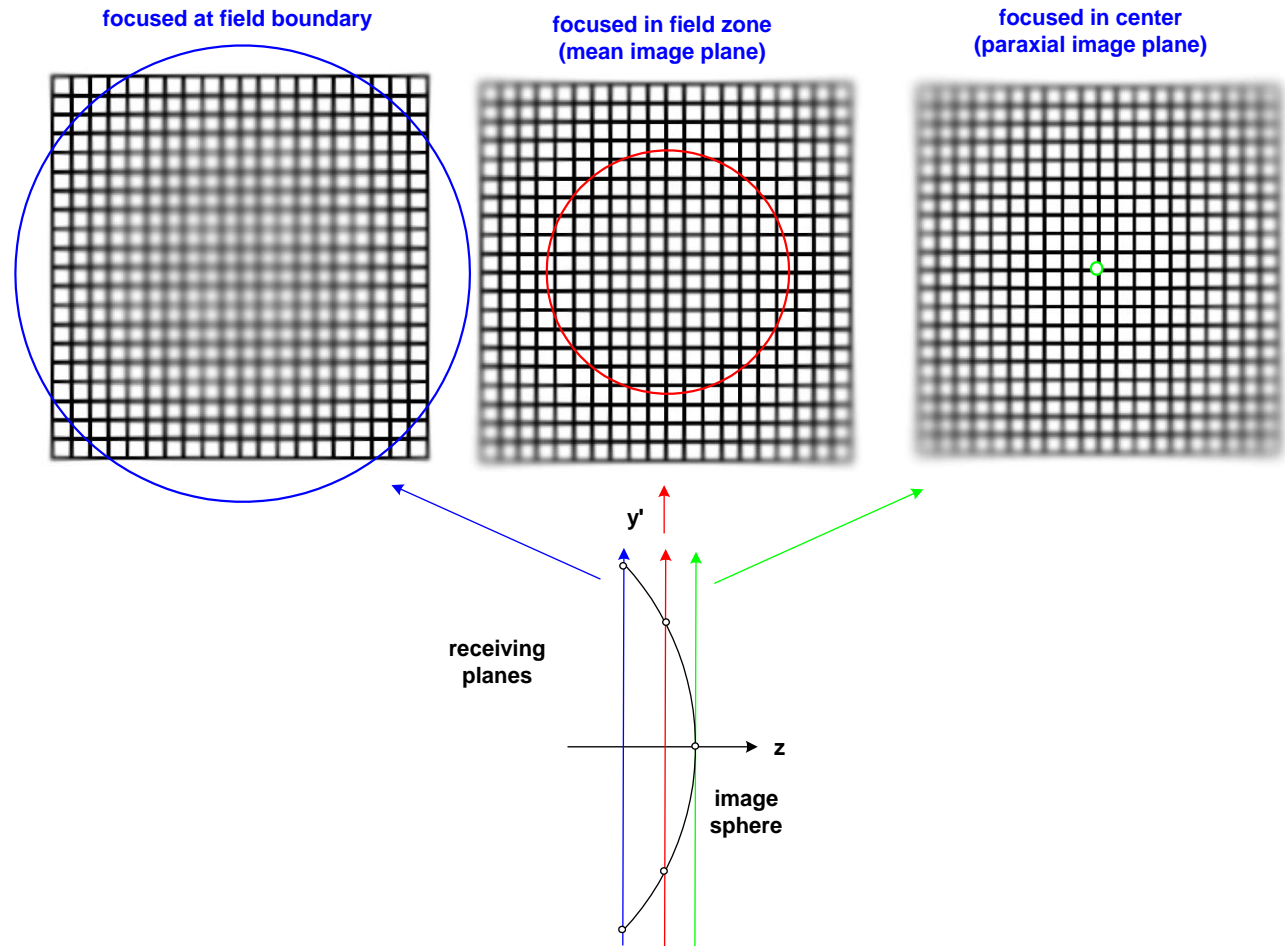
- Detector of NASA's Kepler space telescope



- Also small, curved CMOS image detectors have recently become available for consumer optics.

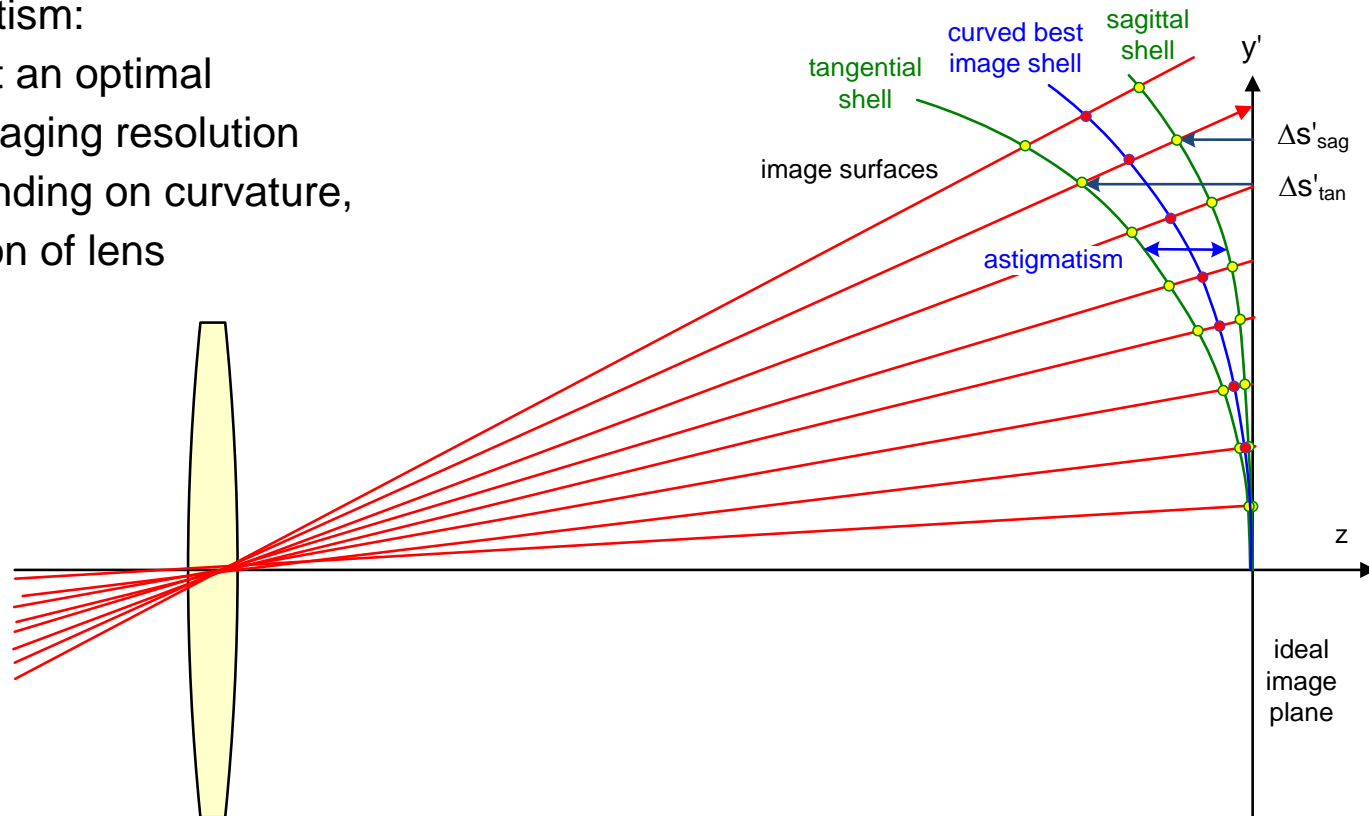


- Focussing into different planes of a system with field curvature
- Sharp imaged zone changes from centre to margin of the image field



# Field Curvature and Image Shells

- Imaging with astigmatism:  
Tangential and sagittal image shell sharp depending on the azimuth
- Difference between the image shells: astigmatism
- Astigmatism corrected:  
It remains one curved image shell,  
Bended field: also called Petzval curvature
- System with astigmatism:  
Petzval sphere is not an optimal  
surface with good imaging resolution
- No effect of lens bending on curvature,  
important: distribution of lens  
powers and indices







# Astigmatisms and Curvature of Field

- Image surfaces:
  1. Gaussian image plane
  2. tangential and sagittal image shells (curved)
  3. mean image shell of best sharpness
  4. Petzval shell, arteficial, not a good image

- Seidel theory:

$$\Delta s'_{\tan} - \Delta s'_{pet} = 3 \cdot (\Delta s'_{sag} - \Delta s'_{pet})$$

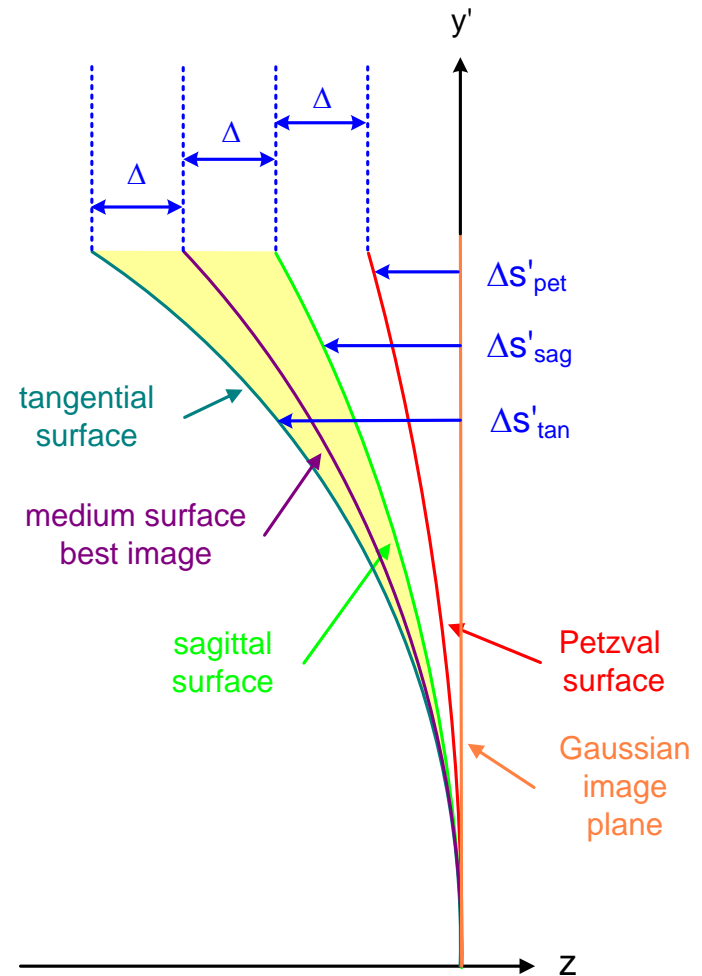
$$\Delta s'_{pet} = \frac{3\Delta s'_{sag} - \Delta s'_{\tan}}{2}$$

- Astigmatism is difference

$$\Delta s'_{ast} = \Delta s'_{\tan} - \Delta s'_{sag}$$

- Best image shell

$$\Delta s'_{best} = \frac{\Delta s'_{sag} + \Delta s'_{\tan}}{2}$$



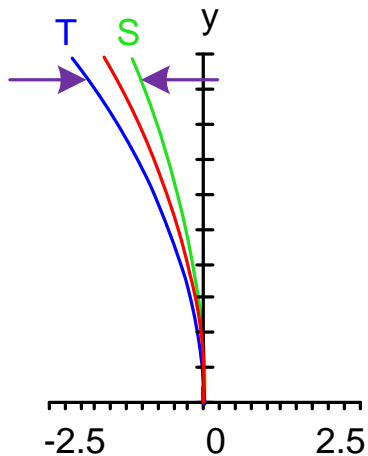




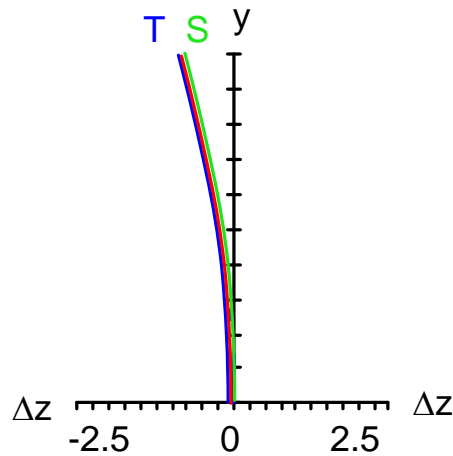
# Correction of Astigmatism and Field Curvature

- Different possibilities for the correction of astigmatism and field curvature
- Two independent aberrations allow 4 scenarios

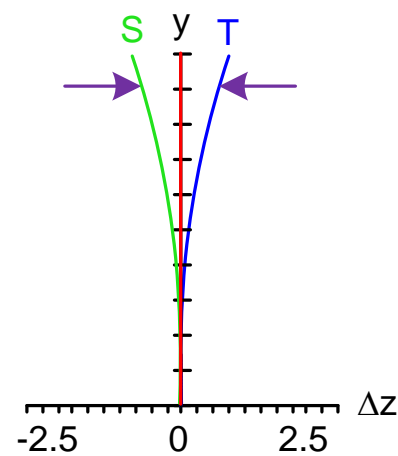
a) **bended**  
image plane  
residual  
astigmatism



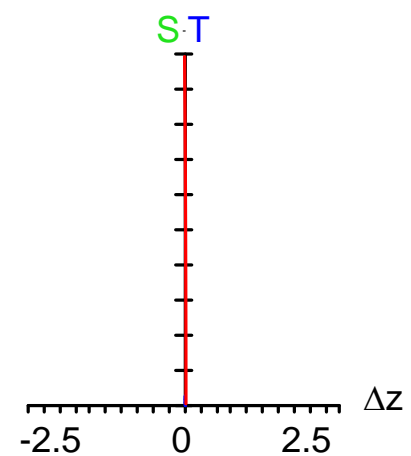
b) **bended**  
image plane  
corrected  
astigmatism



c) **flattened**  
image plane  
residual  
astigmatism



d) **flattened**  
image plane  
corrected  
astigmatism



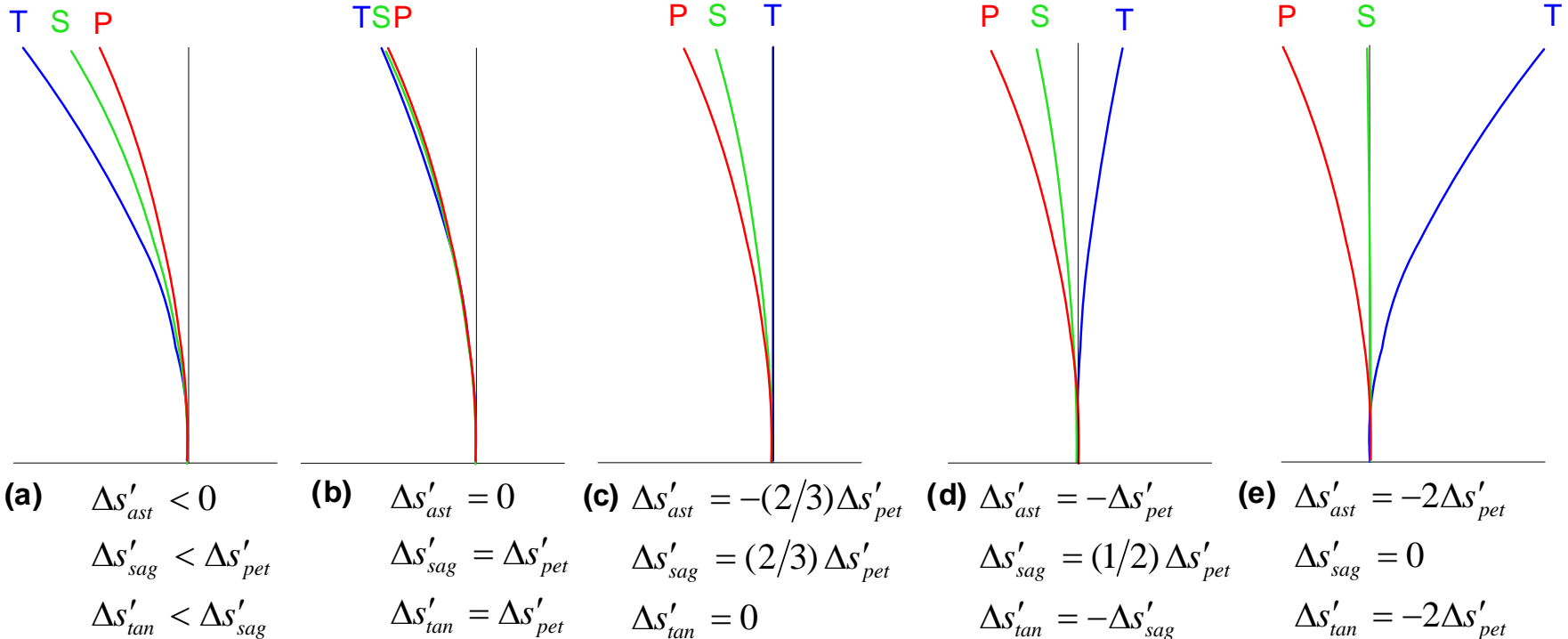


# Petzval Shell

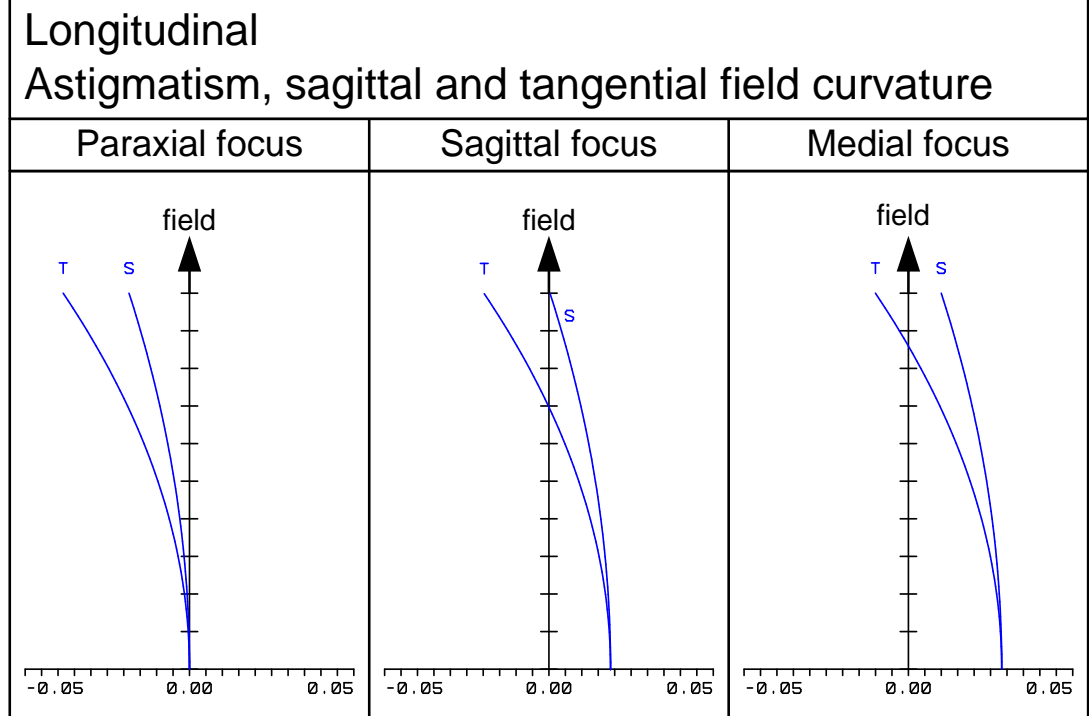
- The Petzval shell is not a desirable image surface
- It lies outside the S- and T-shell:

$$\Delta s'_{pet} = \frac{3\Delta s'_{sag} - \Delta s'_{tan}}{2}$$

- The Petzval curvature is a result of the Seidel aberration theory



- The image splits into two curved shells in the field
- The two shells belong to tangential / sagittal aperture rays
- There are two different possibilities for description:
  1. sag and tan image shell
  2. difference (astigmatism) and mean (medial image shell) of sag and tan





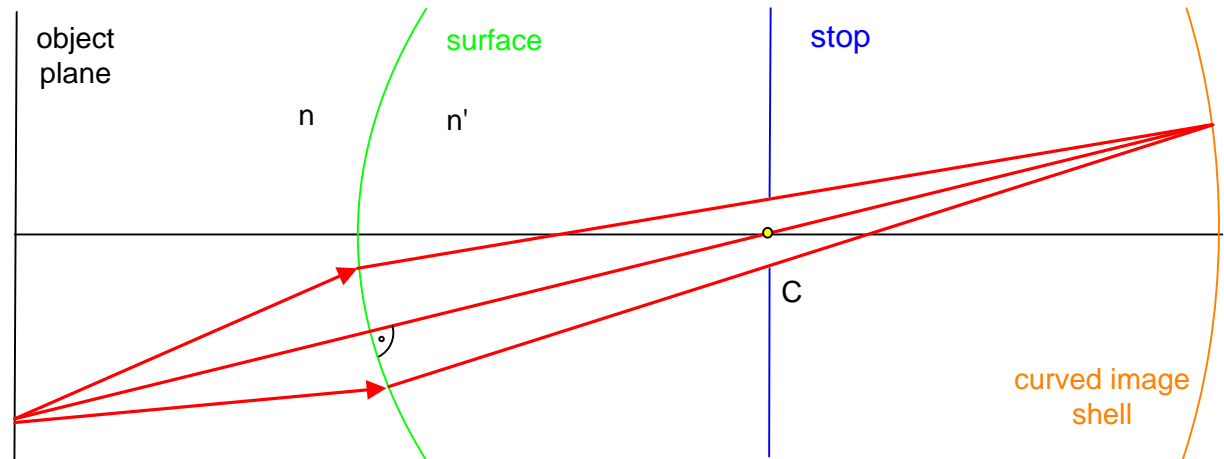
# Field for Single Surface

- The image is generated on a curved shell
- In 3rd order, this is a sphere
- For a single refracting surface, the Petzval radius is given by

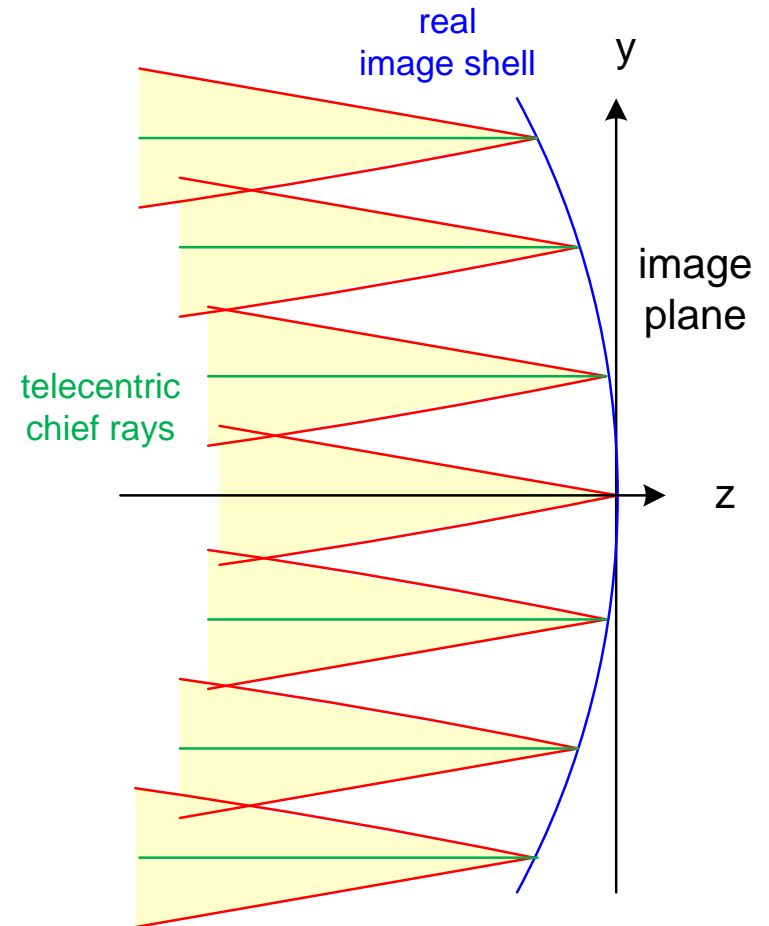
$$r_p = -\frac{nr}{n'-n}$$

- For a system of several lenses, the Petzval curvature is given by

$$\frac{1}{r_p} = -n' \cdot \sum_k \frac{1}{n_k \cdot f_k}$$



- Special visualization of field curvature in case of a telecentric ray path



# Petzval Theorem for Field Curvature

- Petzval theorem for field curvature:

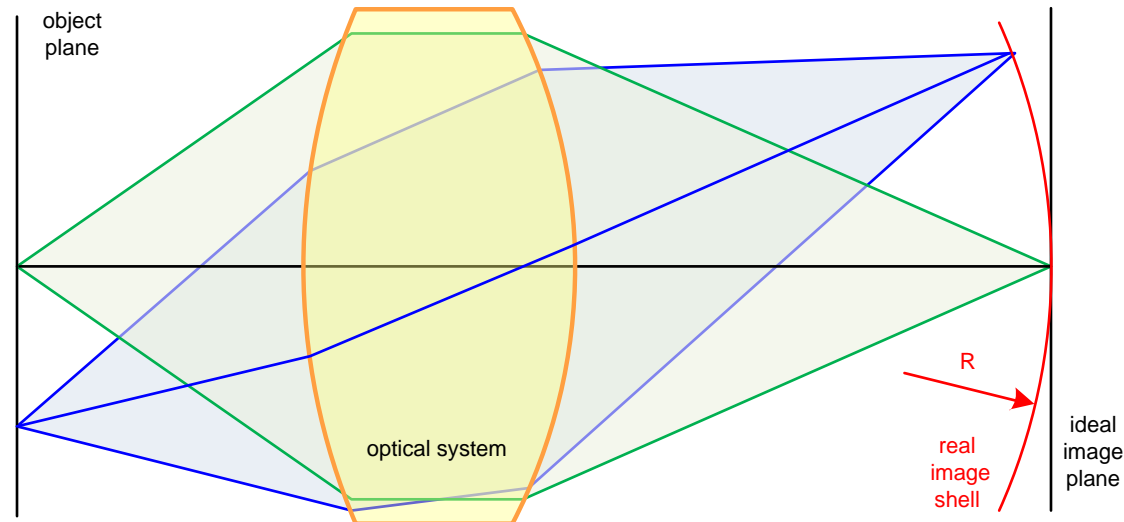
1. formulation for surfaces

$$\frac{1}{R_{ptz}} = -n'_m \sum_k \frac{n'_k - n_k}{n_k \cdot n'_k \cdot r_k}$$

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

- Elementary derivation by a momocentric system of three surfaces:  
interface surface with  $r$ , object and image surface

- Consideration of a skew auxiliary axis

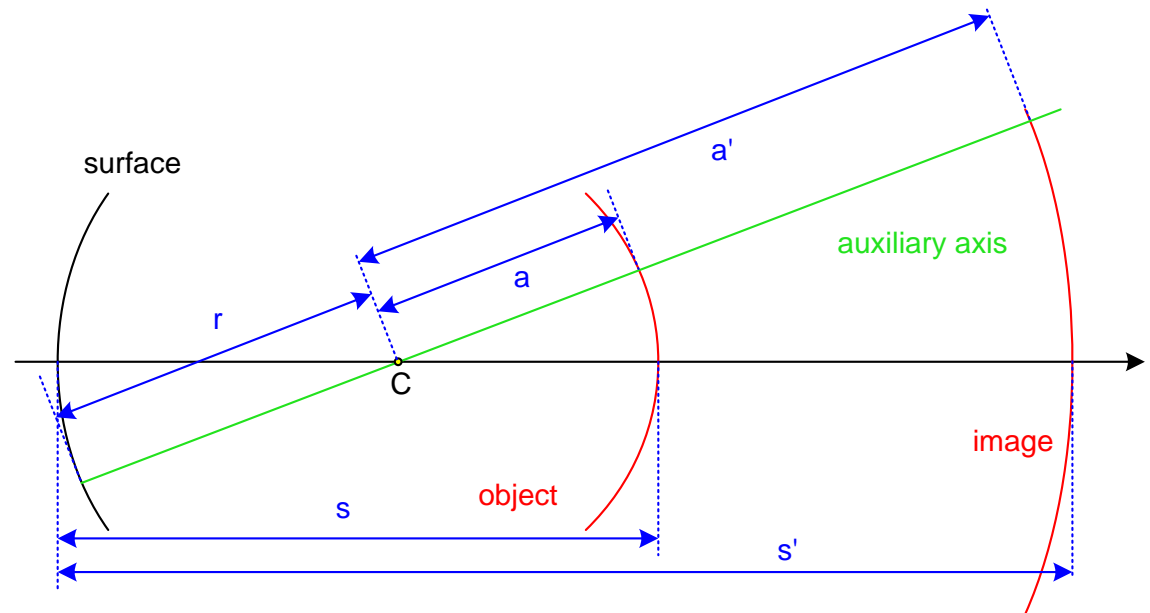
$$a = s - r, \quad a' = s' - r$$

- Imaging condition

$$\frac{n'}{s'} - \frac{n}{s} = \frac{n' - n}{r}$$

- For the special case of a flat object gives with  $a' = R_p, \quad a \rightarrow \infty$

$$\frac{1}{R_p} - = \frac{n' - n}{nr}$$





# 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

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

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
- small marginal ray heights
- gives small negative contribution to power and high weighting in Petzval sum



- Petzval curvature  
thin lenses:

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

thick lenses

$$\frac{1}{R_{ptz}} = - \sum_{k=1}^2 \frac{n_k' - n_k}{n_k \cdot n_k' \cdot r_k} = - \frac{1}{n \cdot f} + \left( \frac{n-1}{n} \right)^2 \cdot \frac{d}{r_1 r_2}$$

and positive total refractive power

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

- Solutions:

1. Mirrors: formal  $n < 0$ , positive contribution to field curvature

$$\frac{1}{R_{ptz}} = + \frac{1}{f_{mirror}} > 0$$

2. Negative field lens near image plane with minor effect of image formation:  $h = 0$

3. Thick meniscus lenses with positive contribution to field curvature

$$\Delta \left( \frac{1}{R_{ptz}} \right) = + \left( \frac{n-1}{n} \right)^2 \cdot \frac{d}{r_1 r_2} > 0$$

4. Combination of lenses with P-N-P

power positive (n large) - negative (n small) - positive (n large)

- Possible lenses / lens groups for correcting field curvature
- Interesting candidates: thick meniscus shaped lenses

$$\frac{1}{R_{ptz}} = - \sum_k \frac{n_k' - n_k}{n_k \cdot n_k' \cdot r_k} = - \frac{1}{n \cdot f} + \left( \frac{n-1}{n} \right)^2 \cdot \frac{d}{r_1 r_2}$$

1. Hoeghs meniscus: identical radii
  - Petzval sum zero
  - remaining positive refractive power

$$F' = \frac{(n-1)^2 d}{n \cdot r^2}$$

2. Concentric meniscus,
  - Petzval sum negative
  - weak negative focal length
  - refractive power for thickness d:

$$r_2 = r_1 - d$$

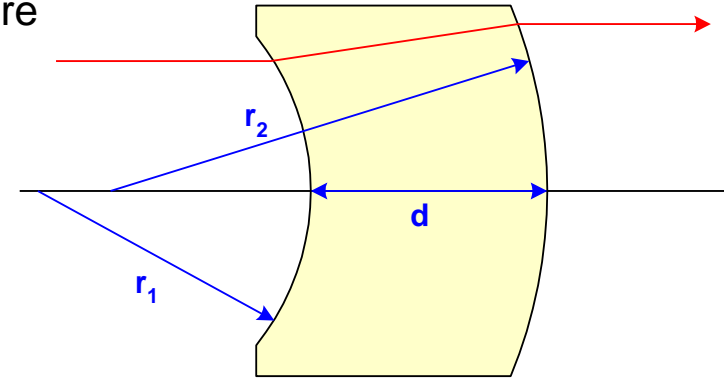
$$\frac{1}{R_{ptz}} = \frac{(n-1) \cdot d}{n r_1 \cdot (r_1 - d)}$$

$$F' = - \frac{(n-1)d}{n r_1 (r_1 - d)}$$

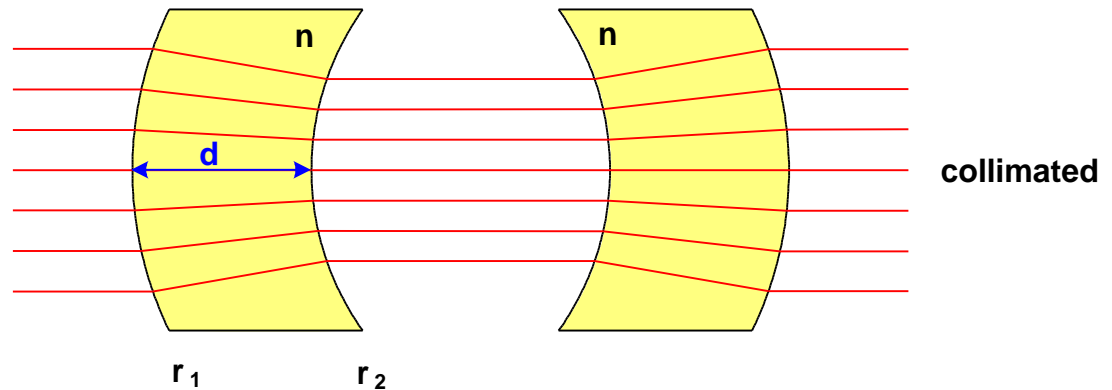
3. Thick meniscus without refractive power  
Relation between radii

$$r_2 = r_1 - d \cdot \frac{n-1}{n}$$

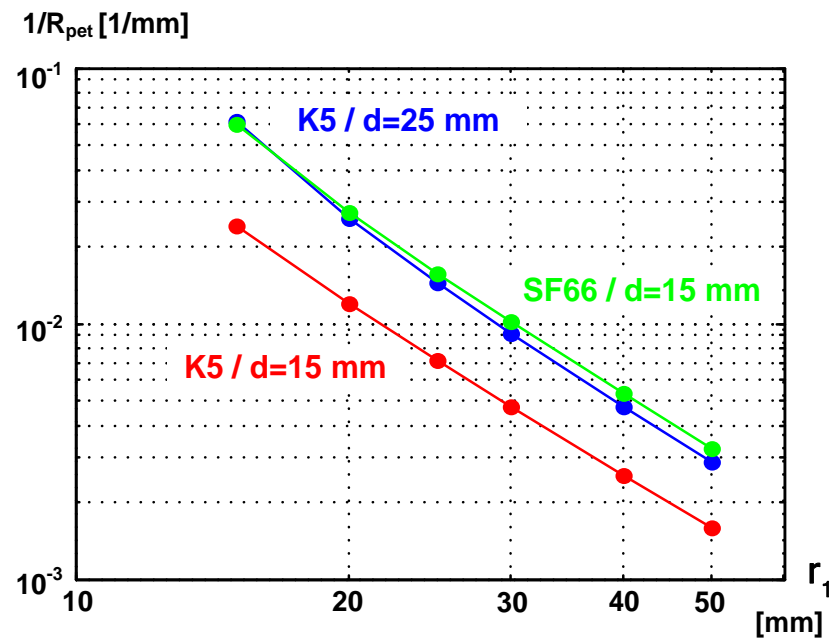
$$\frac{1}{R_{ptz}} = \frac{(n-1)^2 \cdot d}{n r_1 \cdot [n r_1 - d \cdot (n-1)]} > 0$$



- Group of meniscus lenses



- Effect of distance and refractive indices

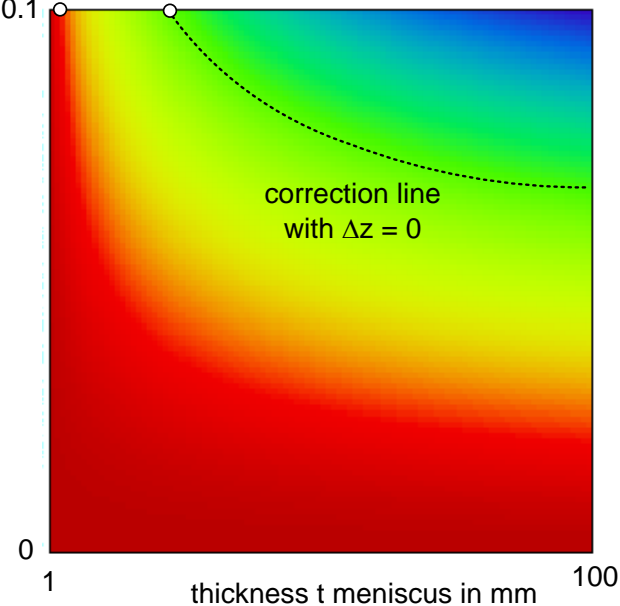
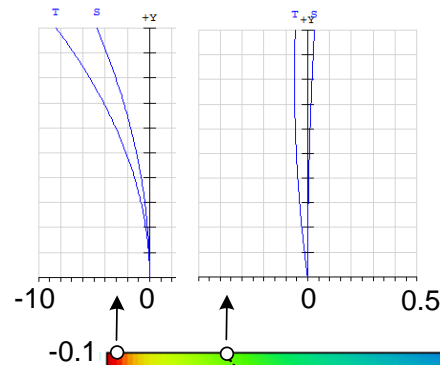
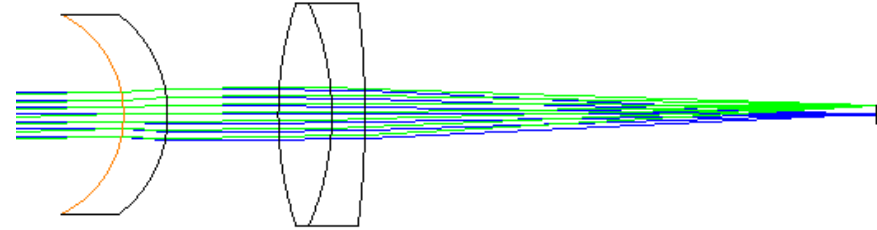


# Field Flattening by Meniscus Lens

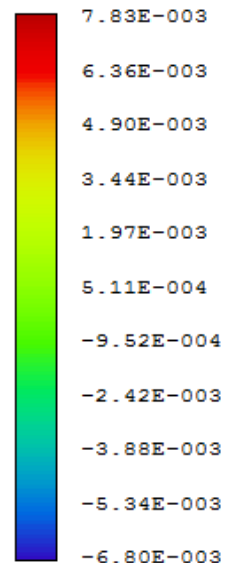
- Compensating the field curvature of an achromate by a meniscus lens
- Meniscus with power  $F = 0$  and

$$\frac{1}{R_{ptz}} = \frac{(n-1)^2 \cdot t}{n r_1 \cdot [n r_1 - t \cdot (n-1)]}$$

- Variation of curvature and thickness
- Optimal thickness decreases for stronger meniscus bending
- Orientation of meniscus not identical for larger  $t$ -values:  
negative  $R_1$  more beneficial

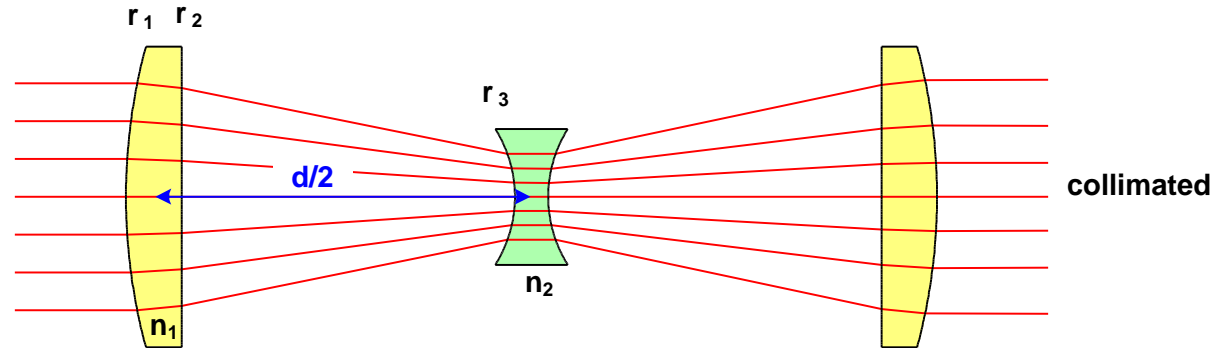


sag of field curvature  
in mm

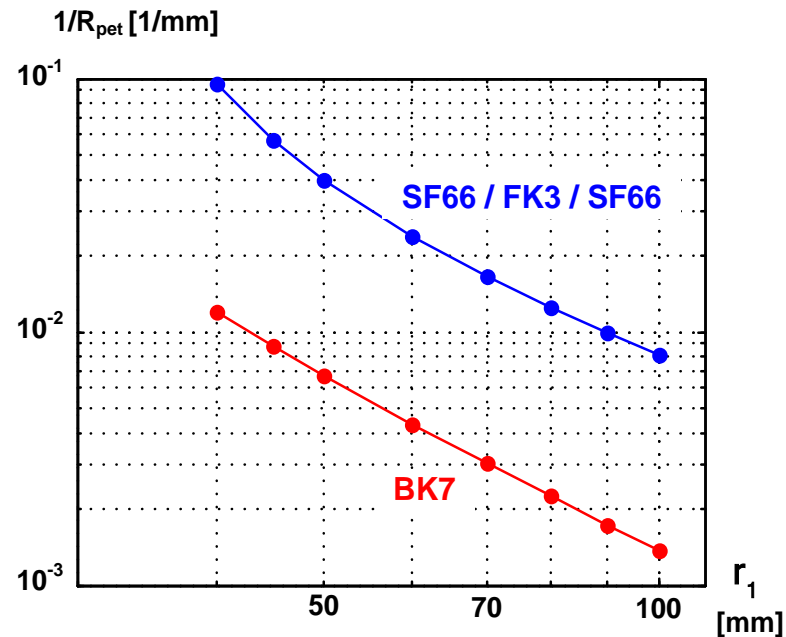


# Correcting Petzval Curvature

- Triplet group with + - +



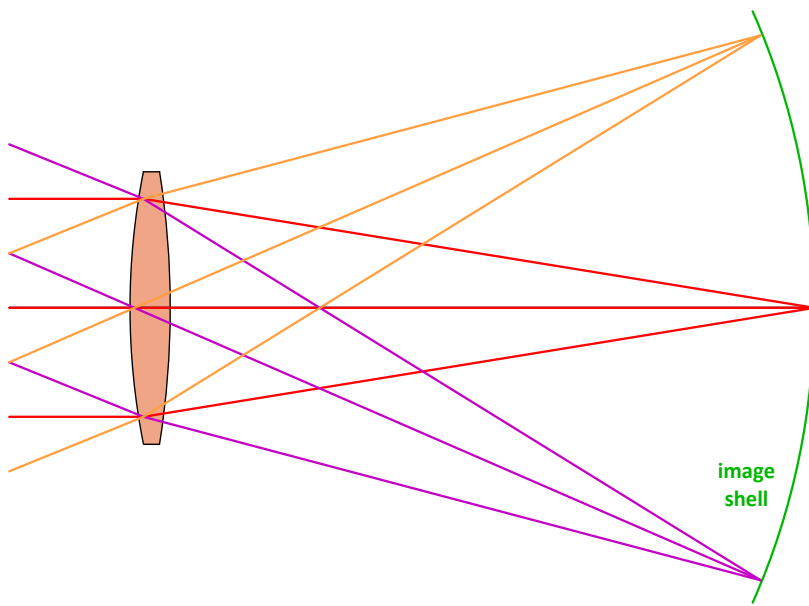
- Effect of distance and refractive indices



## Effect of a field lens for flattening the image surface

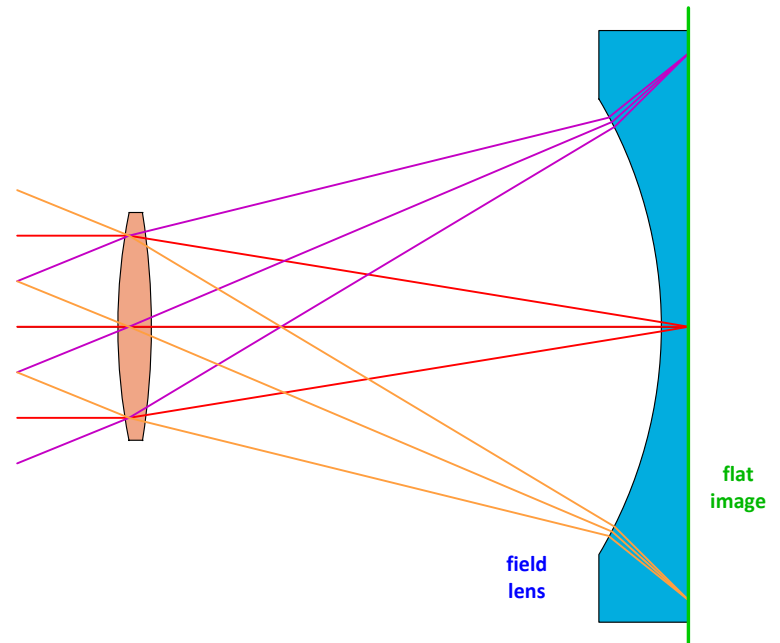
### 1. Without field lens

curved image surface



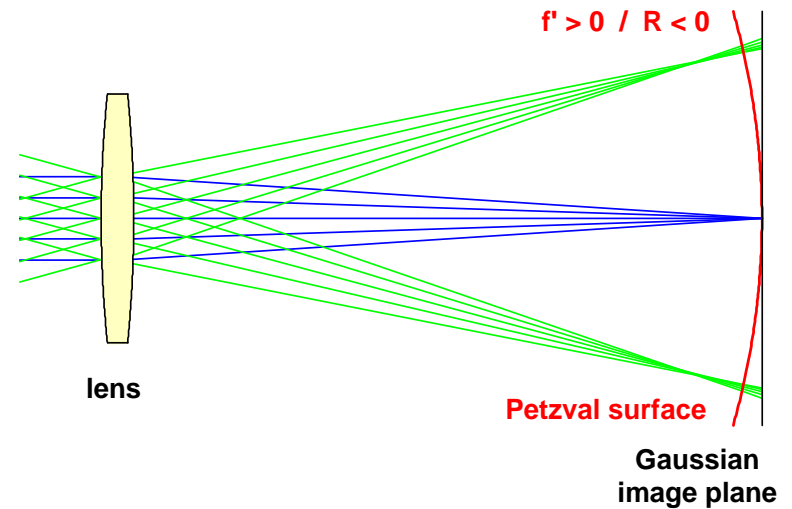
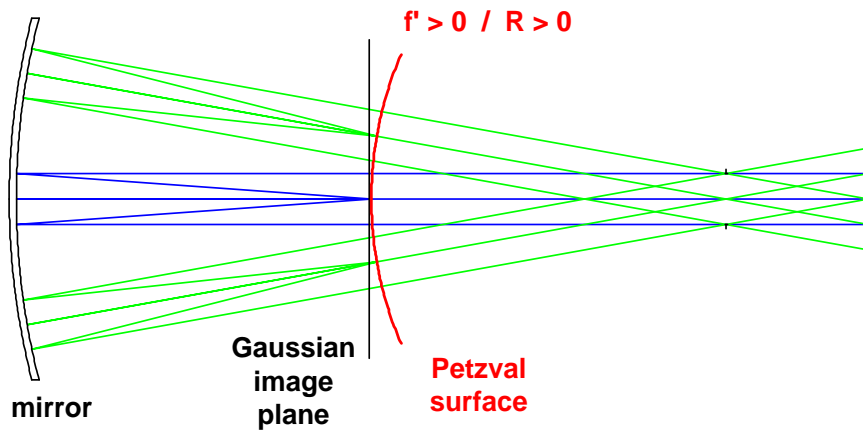
### 2. With field lens

image plane



# Field Curvature of a Mirror

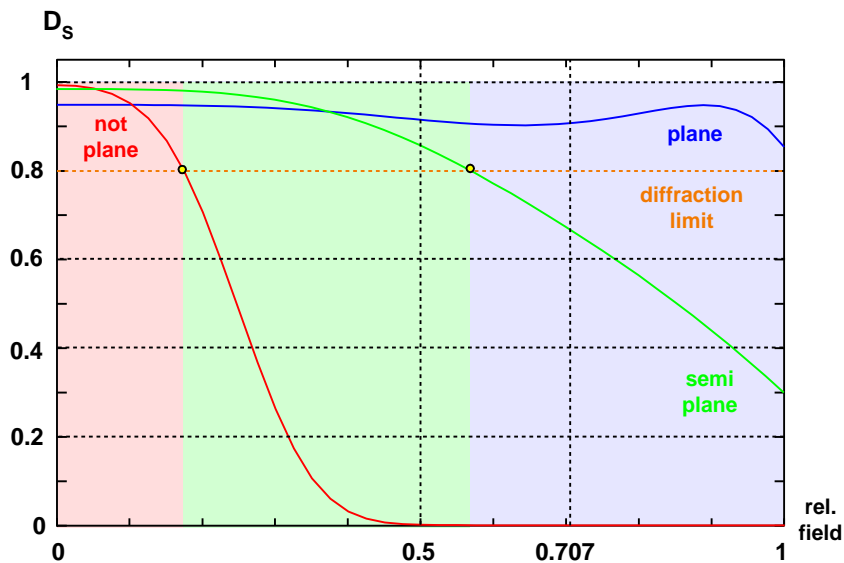
- Mirror: opposite sign of curvature than lens
- Correction principle: field flattening by mirror



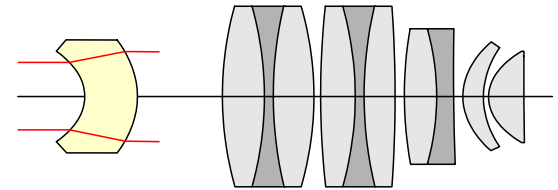


# Microscope Objective Lens

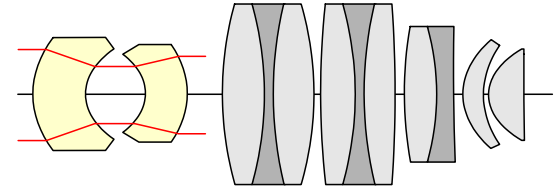
- Possible setups for flattening the field
- Goal:
  - reduction of Petzval sum
  - keeping astigmatism corrected
- Three different classes:
  1. No effort
  2. Semi-flat
  3. Completely flat



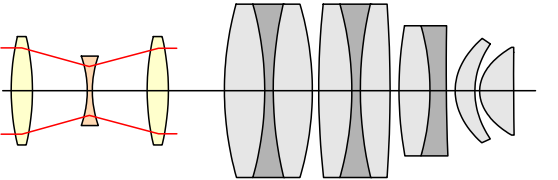
a)  
single  
meniscus  
lense



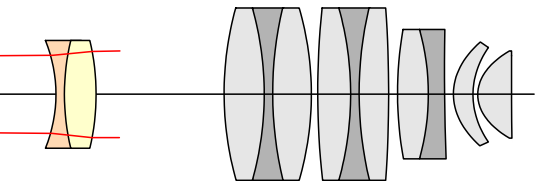
b)  
two  
meniscus  
lenses



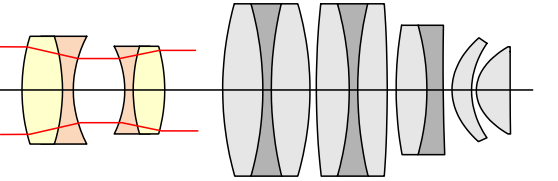
c)  
symmetrica  
I  
triplet



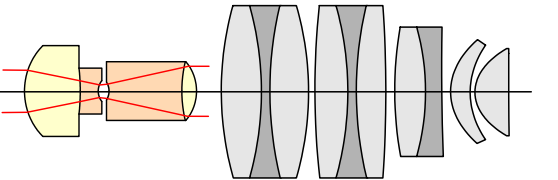
d)  
achromatized  
meniscus lens



e)  
two meniscus  
lenses  
achromatized



f)  
modified  
achromatized  
triplet solution





- An achromate is typically corrected for axial chromatical aberration
- The achromatization condition for two thin lenses close together reads

$$\frac{F_1}{v_1} + \frac{F_2}{v_2} = 0$$

- The Petzval sum usually is negative and the field is curved

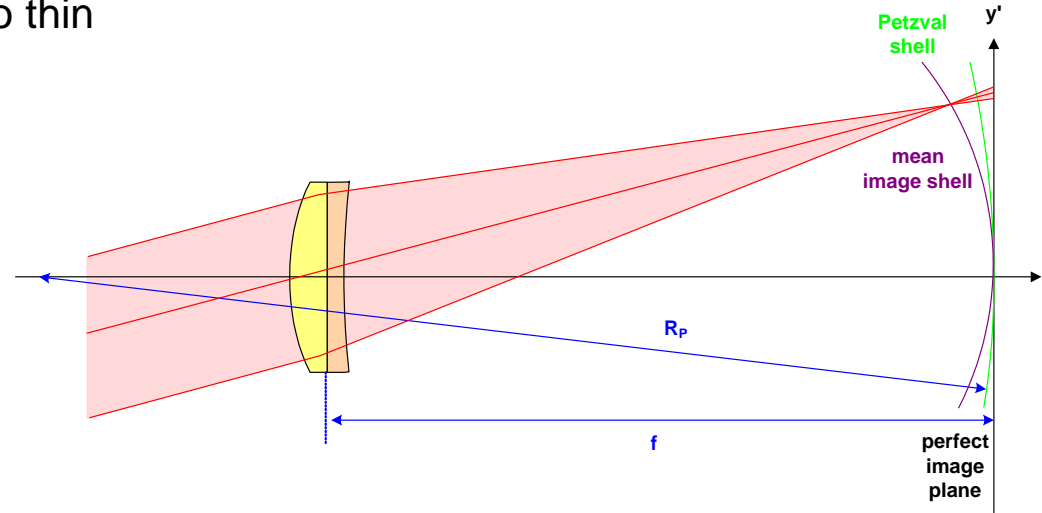
$$\frac{1}{R_p} = -\sum_j \frac{1}{n_j f_j}$$

- A flat field is obtained, if the following condition is fulfilled

$$\frac{F_1}{n_1} + \frac{F_2}{n_2} = 0$$

- This gives the special condition of simultaneous correction of achromatization and flatness of field

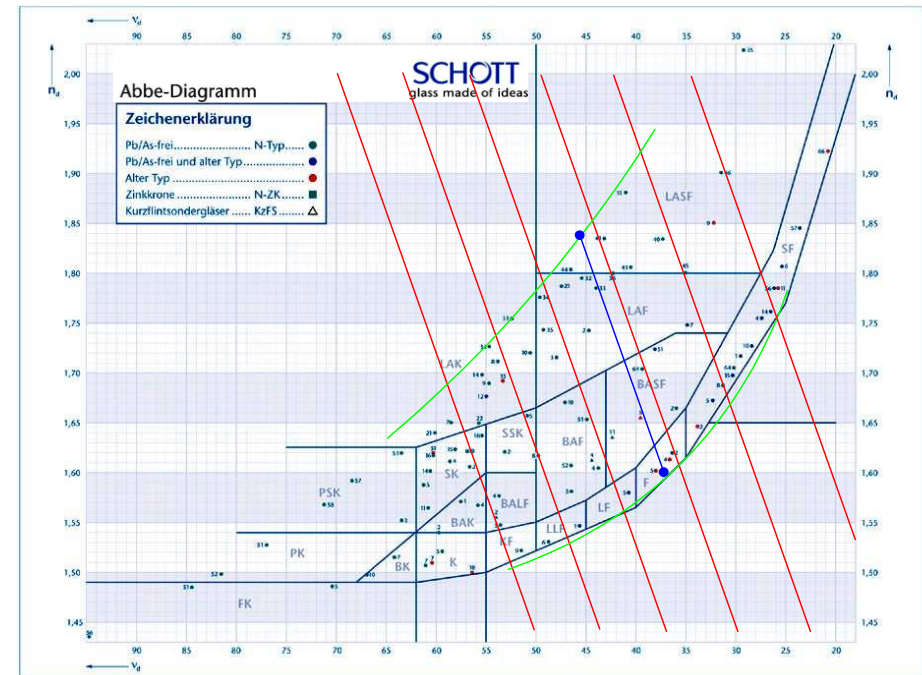
$$\frac{v_1}{v_2} = \frac{n_1}{n_2}$$



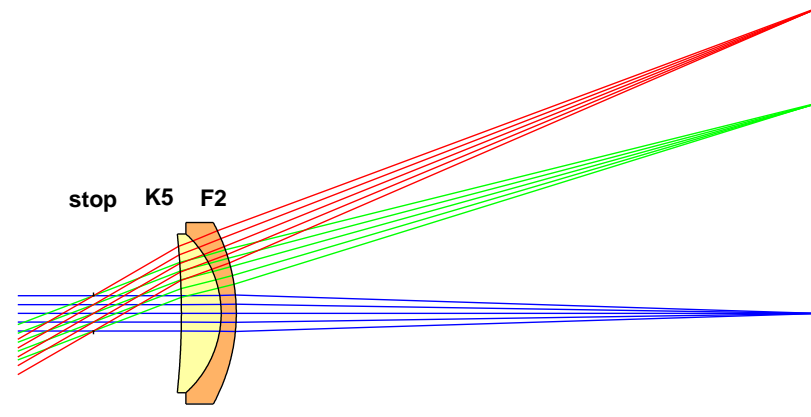


# New Achromate

- This condition corresponds to the requirement to find two glasses on one straight line in the glass map

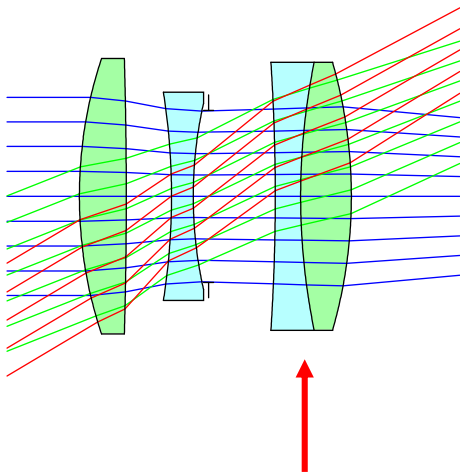


- The solution is well known as simple photographic lens (landscape lens)



- Correction of Petzval curvature in photographic lens Tessar
- Positive lenses: green  $n_j$  small
- Negative lenses: blue  $n_j$  large
- Correction principle: special choice of refractive indices

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

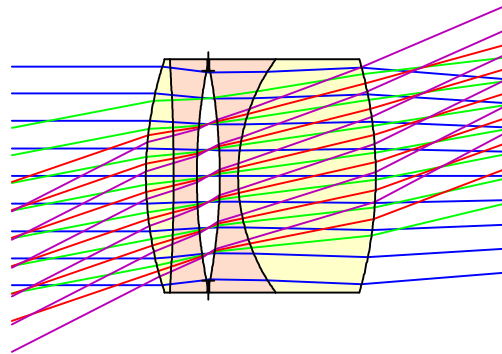


- Cemented component: New Achromate
- Spherical aberration not correctable in the New Achromate

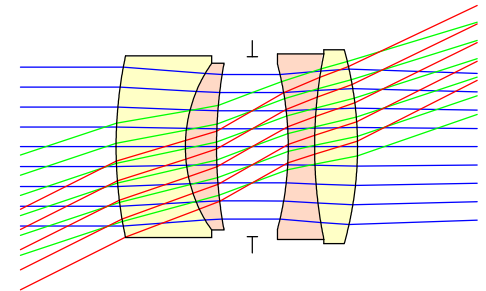
# Asymmetrical Anastigmatic Doublets



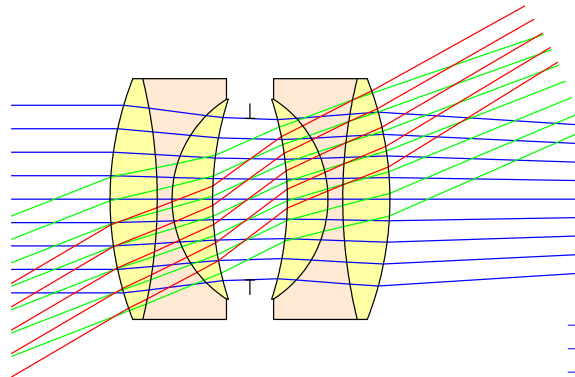
- Antiplanet



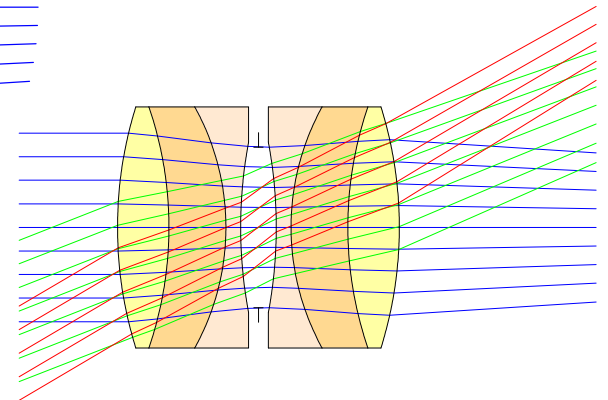
- Protar



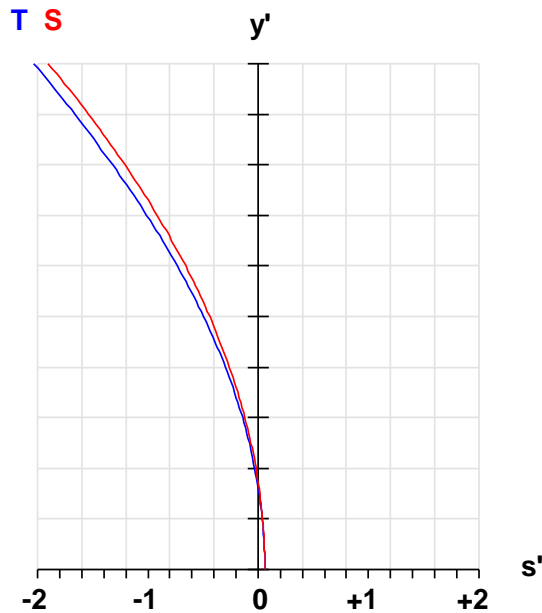
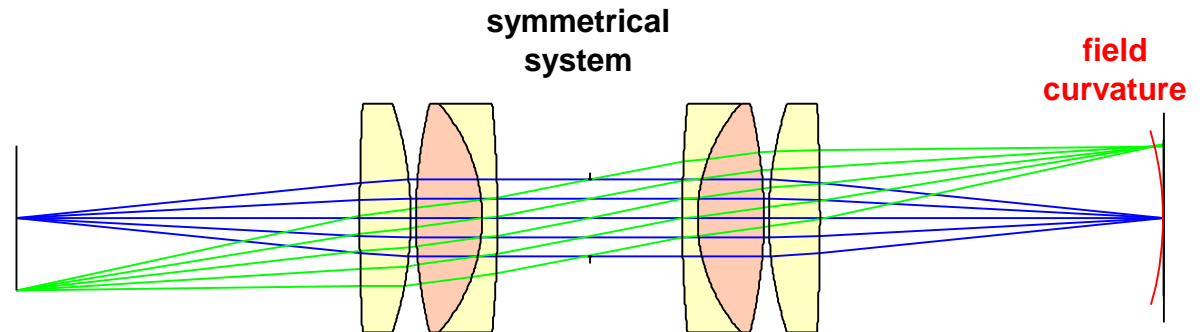
- Dagor



- Orthostigmat



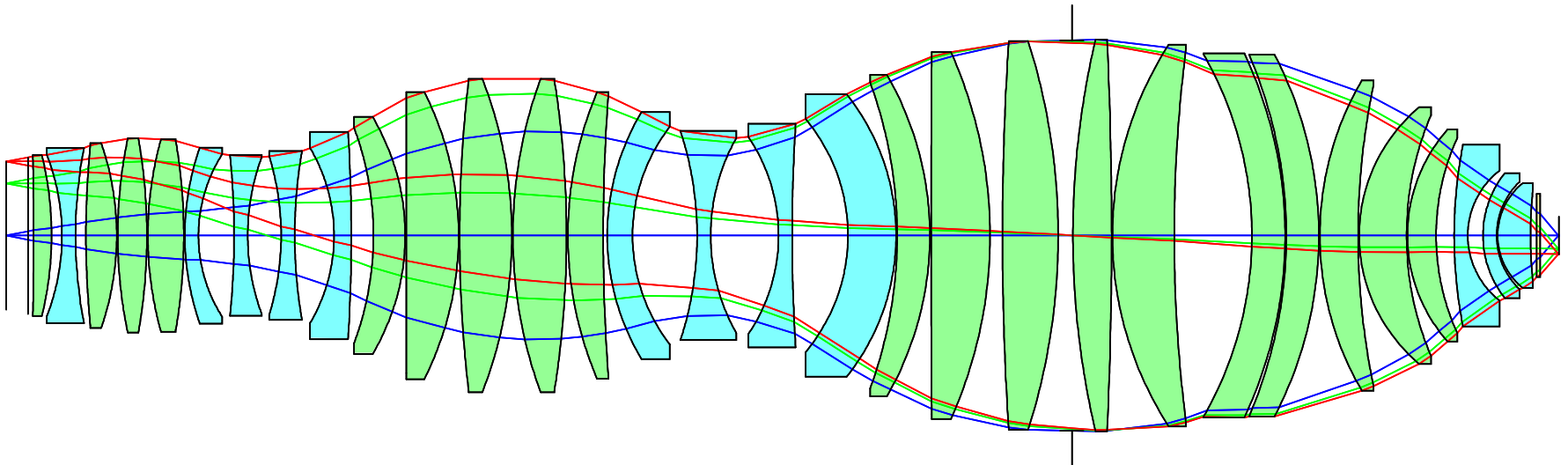
- Symmetrical system
- Astigmatism corrected
- Field curvature remains



- Correction of Petzval field curvature in lithographic lens for flat wafer
- Positive lenses: green  $h_j$  large,  $n_j$  large
- Negative lenses : blue  $h_j$  small,  $n_j$  small
- Correction principle: certain number of bulges

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

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

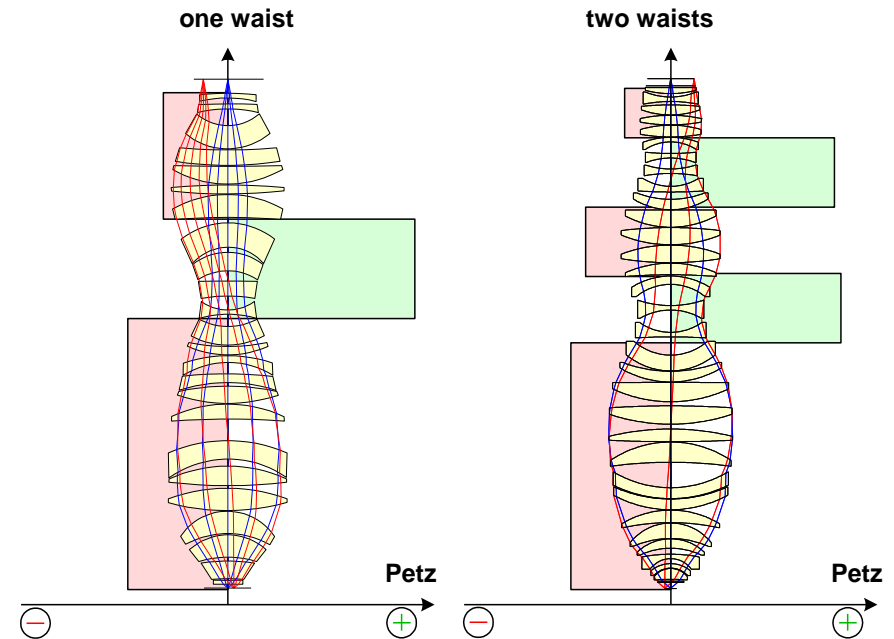
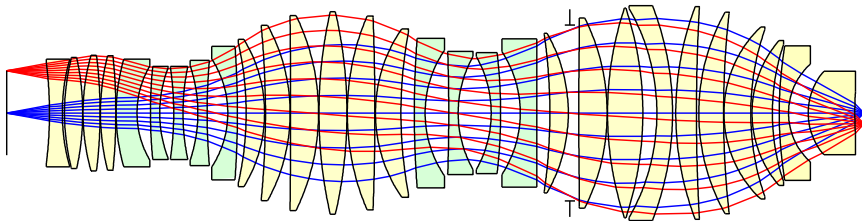
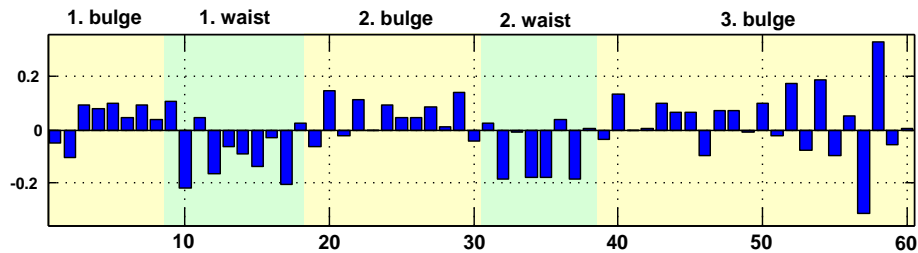


# Field Flatness

- Principle of multi-bulges to reduce Petzval sum

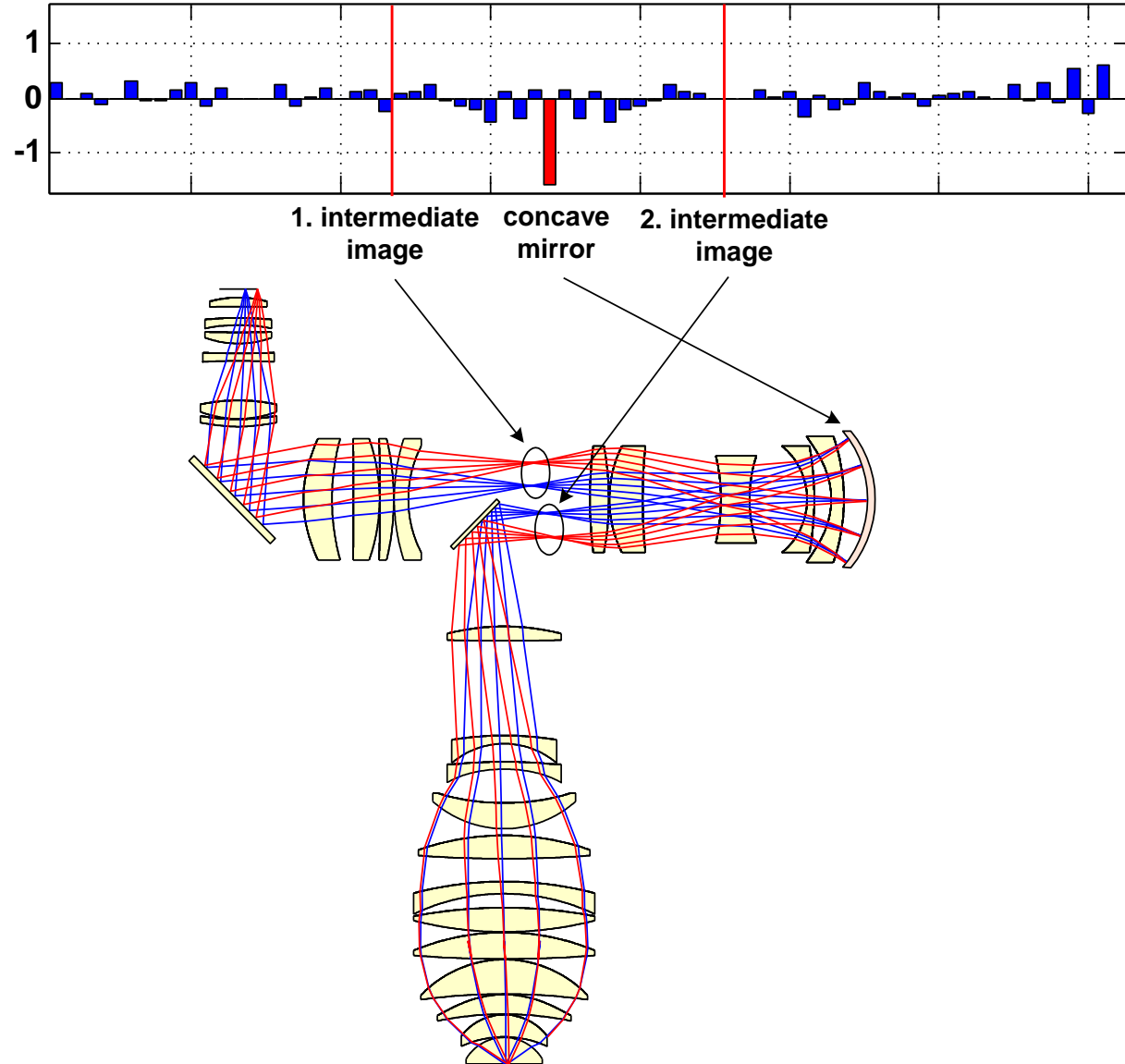
$$\frac{1}{r_p} = -n' \cdot \sum_k \frac{1}{n_k \cdot f_k}$$

- Seidel contributions show principle





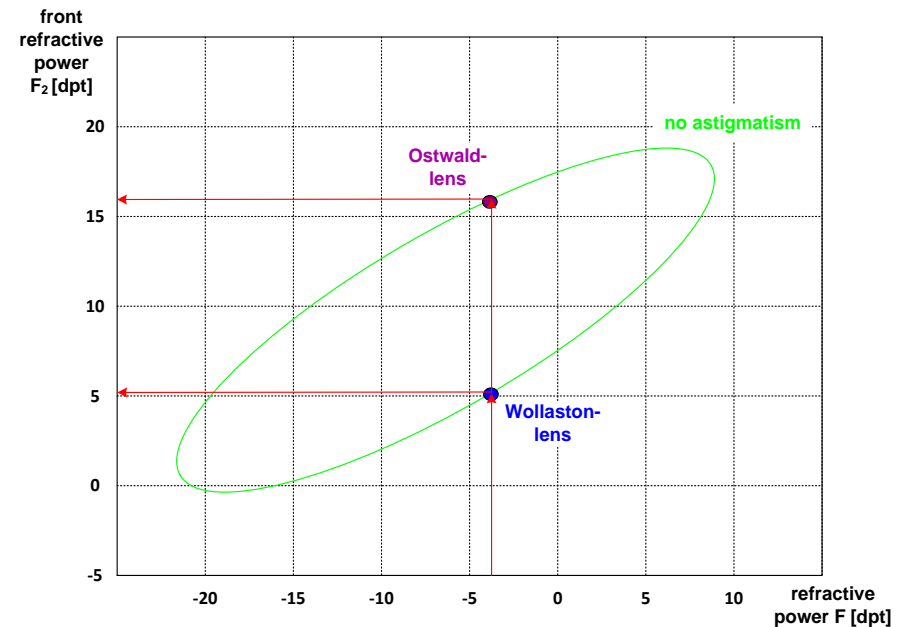
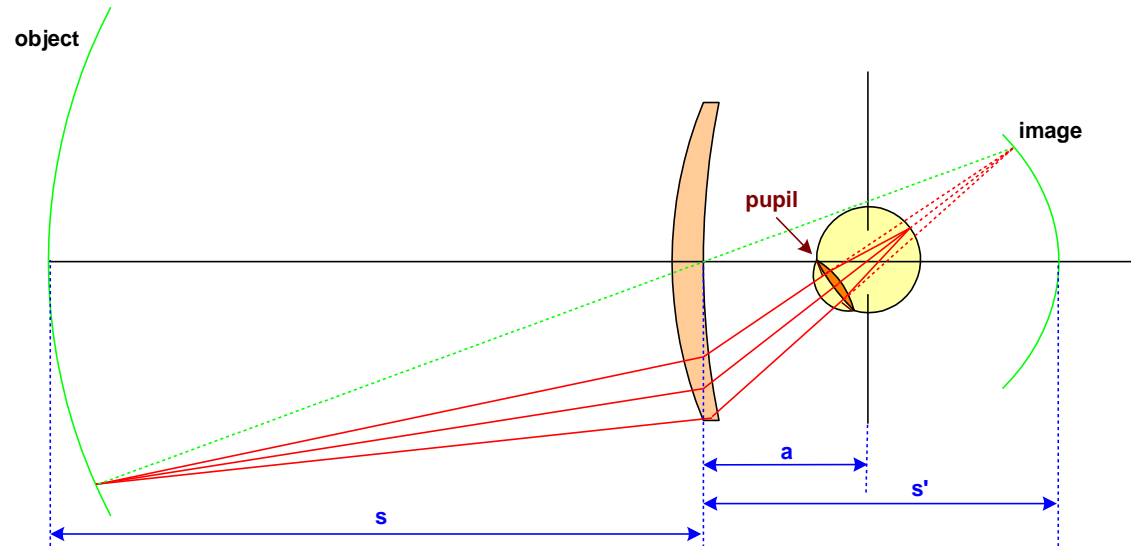
- Effect of mirror on Petzval sum
- Flatness of field for catadioptric lenses



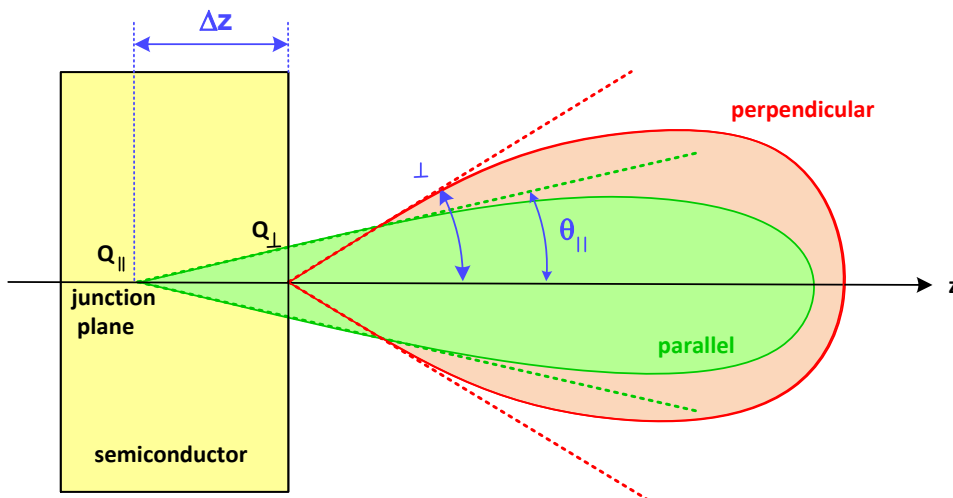
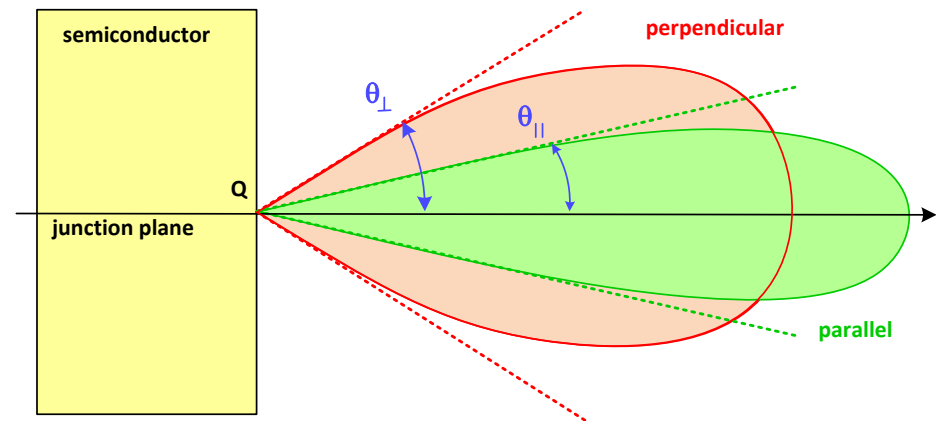


# Astigmatism of Eyeglasses with Rotating Eye

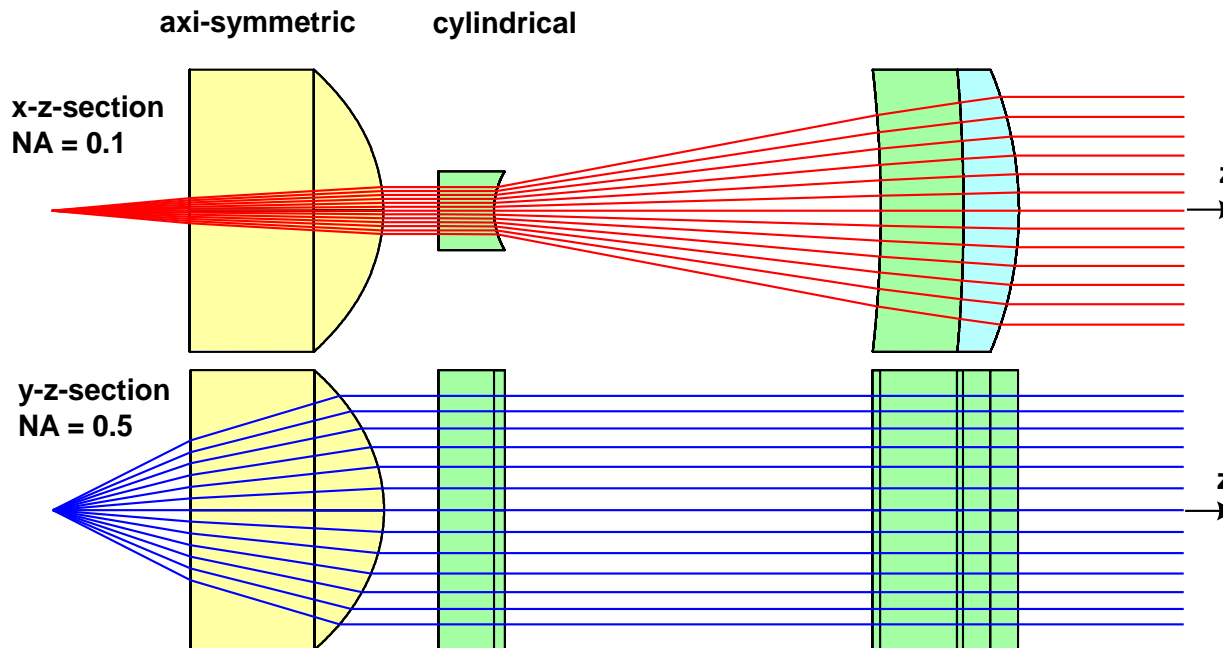
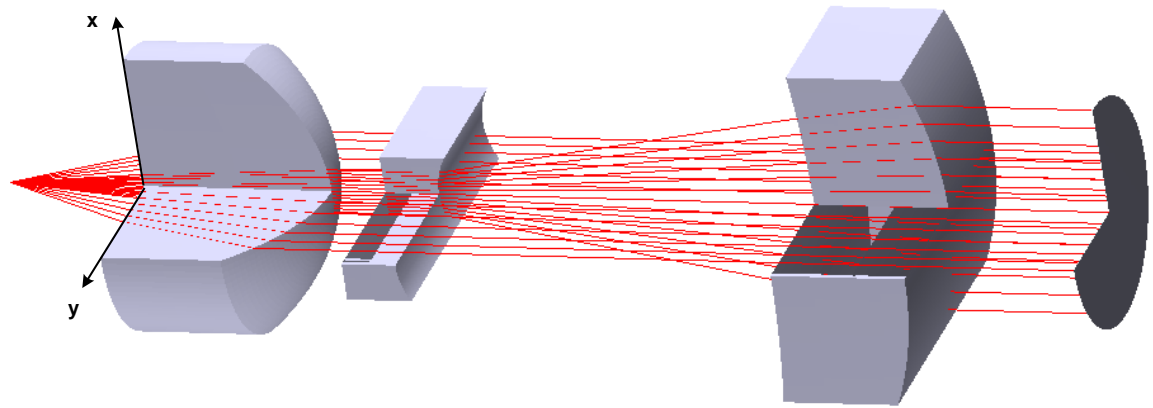
- Rotating eye: Astigmatism
- Coddington equations:  
Elliptical line with vanishing  
astigmatism:  
Tscherning ellipses



- Semiconductor laser sources show two types of astigmatism:
  1. elliptical anamorphic aperture (not a real astigmatism)
  2. z-variation of the internal source points in case of index guiding)
- In laser physics, the quadratic astigmatic beam shape is not considered to be a degradation, the  $M^2$  is constant, it can be corrected by a simple cylindrical optic



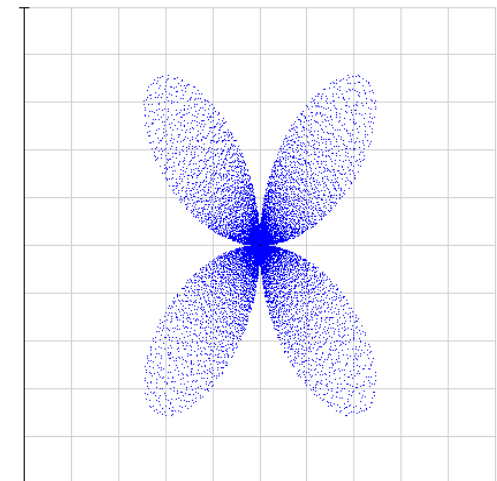
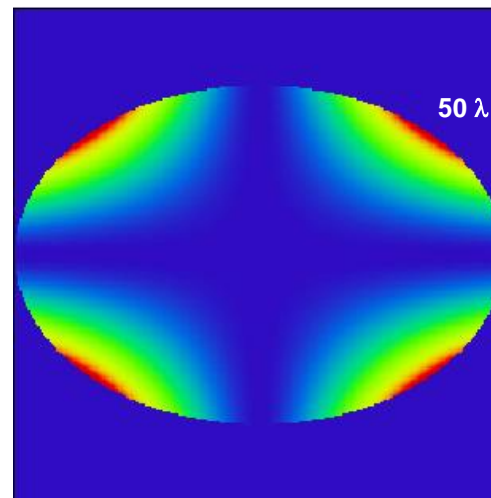
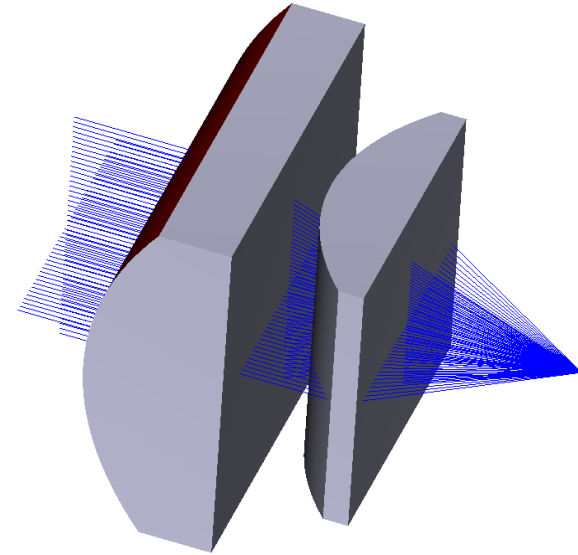
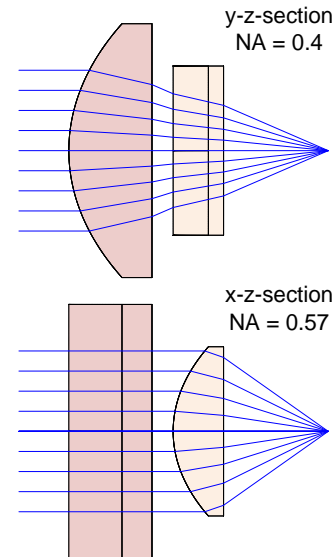
- Anamorphic or cylindrical/toroidal system are used to get a circular profile from a semiconductor laser
- Example:  
laser beam collimator





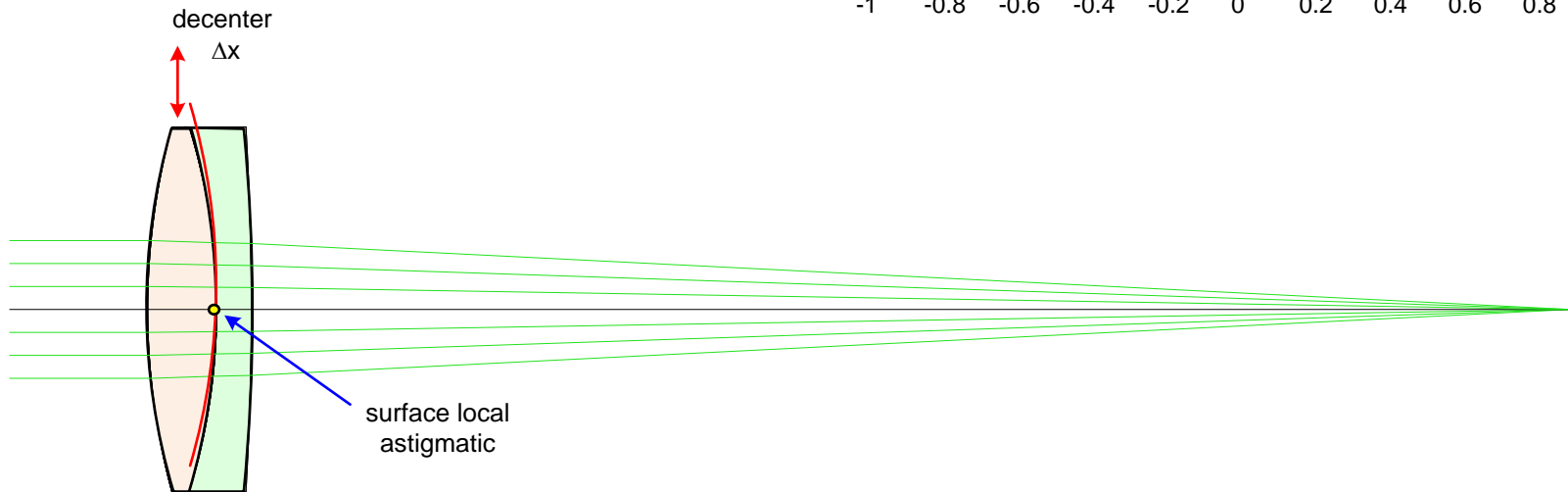
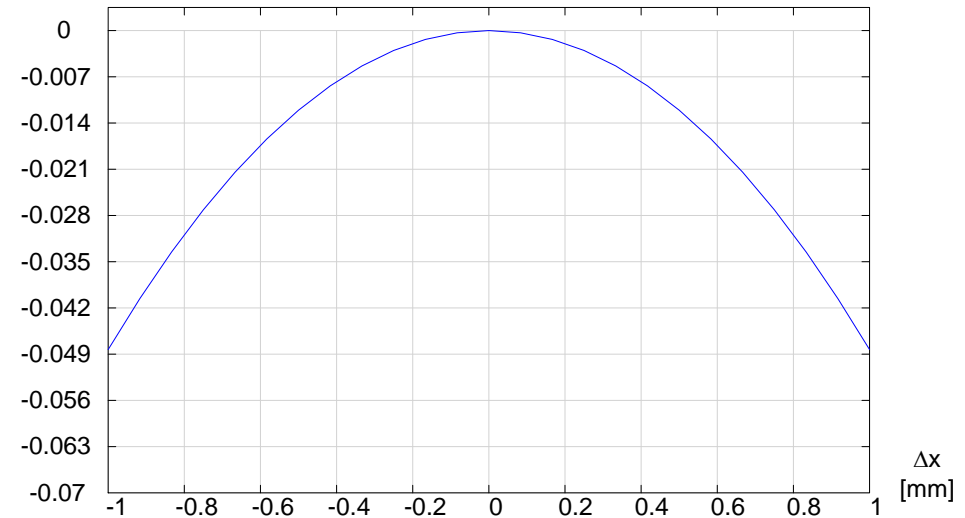
# 45° Effects of Anamorphic Systems

- Example of two aspherical cylindrical lenses with different focal lengths
- For high numerical apertures:  
no longer additivity and decoupling  
of x-and y-cross section
- The wavefront shows the deviations  
in the 45° directions



# Decentered System

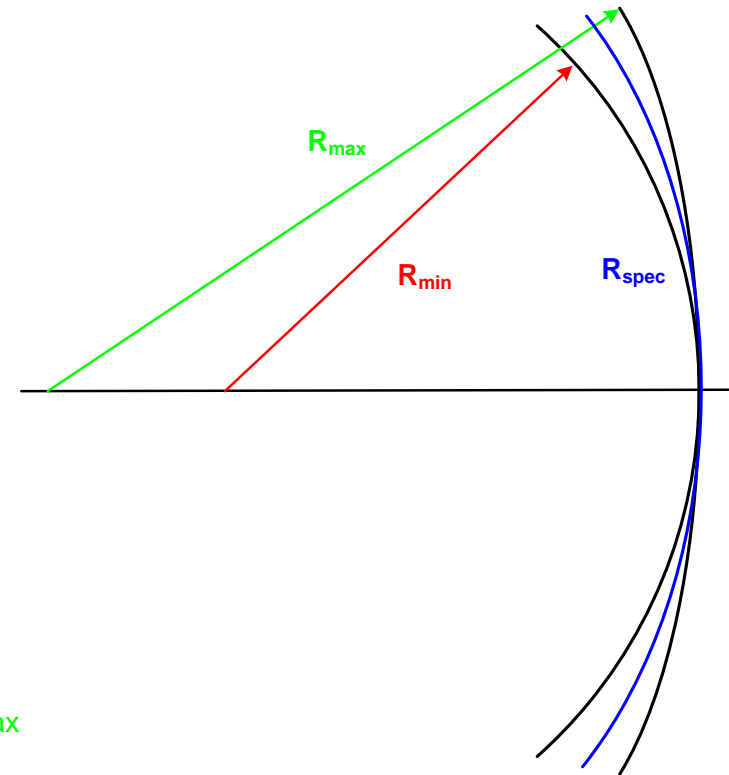
- Real systems with centering errors:
  - non-circular symmetric surface on axis
  - astigmatism on axis
  - point spread function no longer circular symmetric





# Astigmatism due to Fabrication Errors

- Real surfaces with varying radius of curvature
- Toroidal surface shape with  $R_{\max}$ ,  $R_{\min}$
- Astigmatic effects on axis
- Irregularity errors in tolerancing measured by interferometry as ring difference



circular symmetric  
surface



surface with  
irregularity error



$R_{\max}$

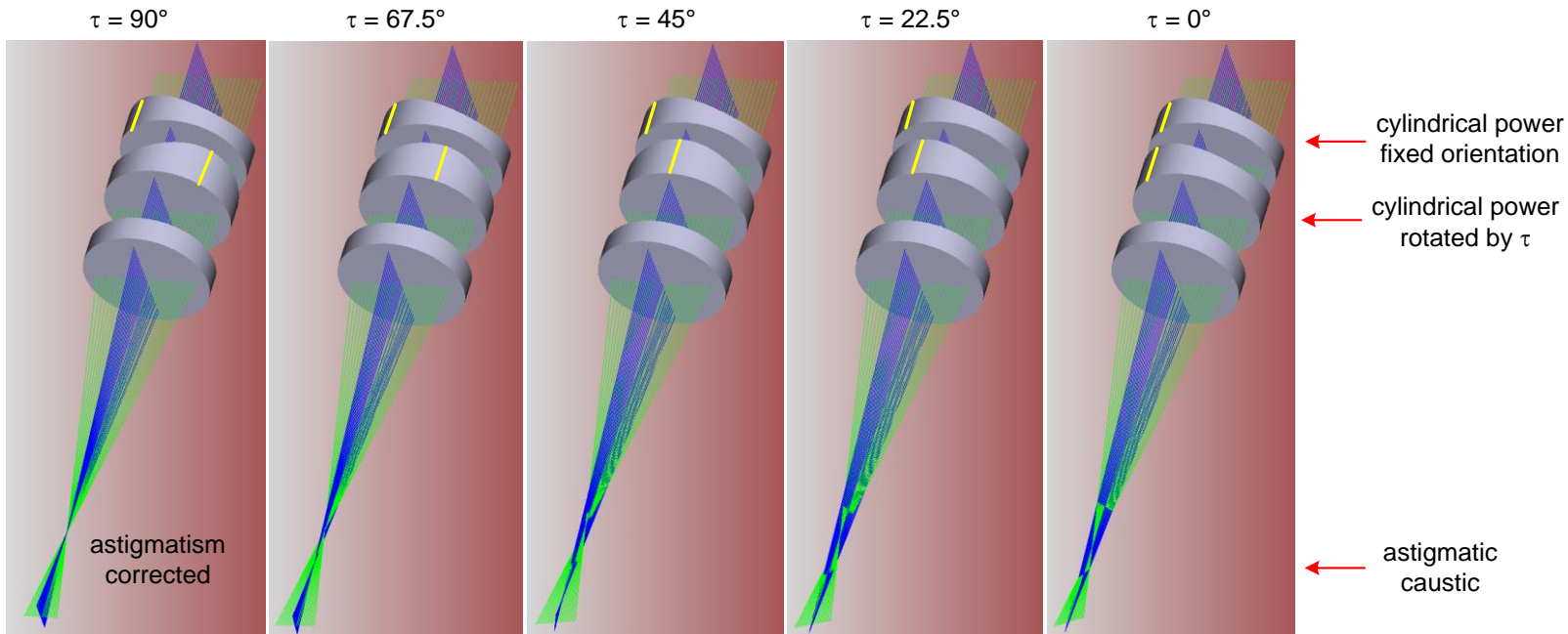
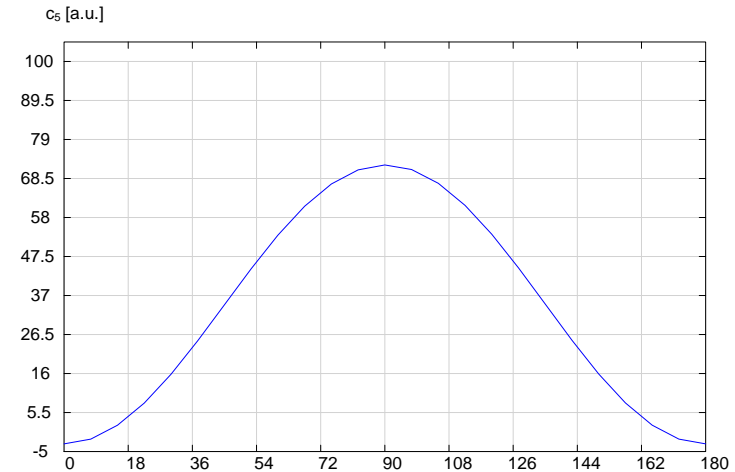
$R_{\min}$





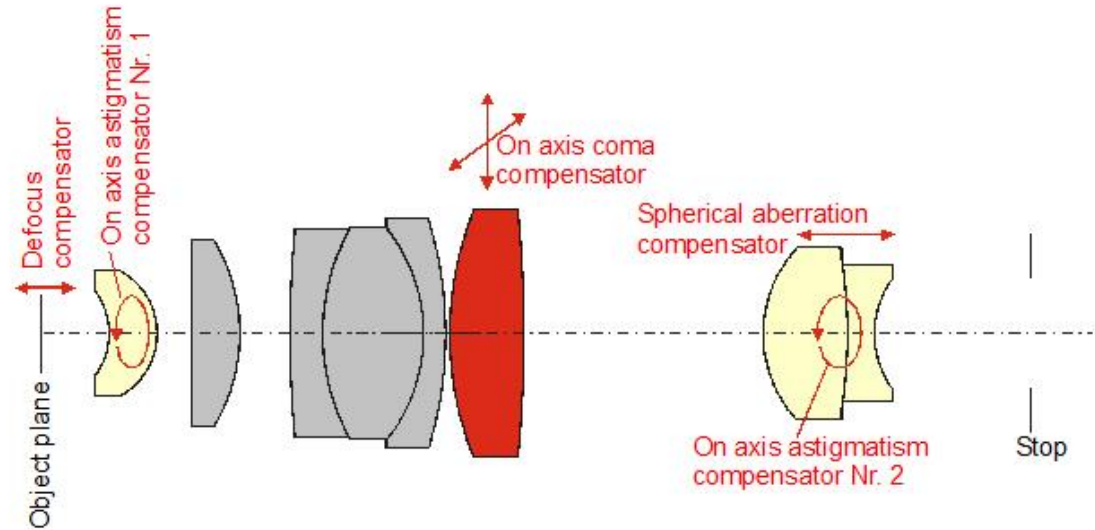
# Astigmatic Correction by Clocking

- Two lens surfaces nearby with equal astigmatism due to manufacturing errors
- Azimuthal rotation of one lens against the other compensates astigmatism in first approximation
- This clocking procedure is used in practice for adjusting sensitive systems

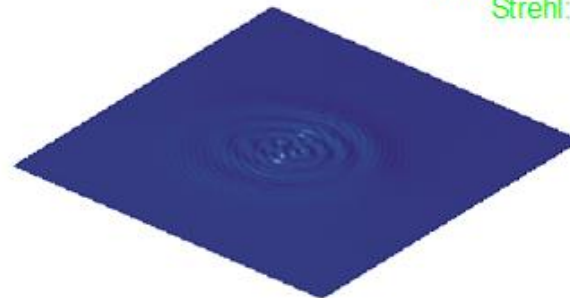


# Adjustment and Compensation

- Example Microscopic lens
- Adjusting:
  1. Axial shifting lens : focus
  2. Clocking: astigmatism
  3. Lateral shifting lens: coma
- Ideal : Strehl  $D_S = 99.62 \%$   
 With tolerances :  $D_S = 0.1 \%$   
 After adjusting :  $D_S = 99.3 \%$

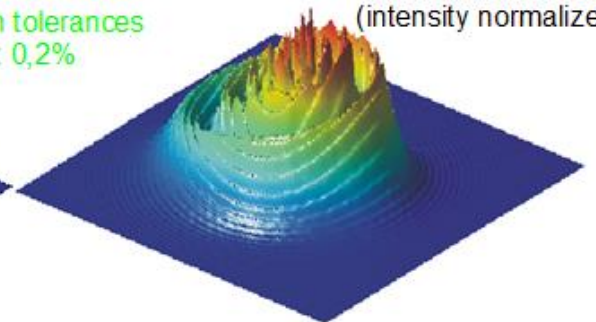


PSF  
(energy normalized)



System with tolerances  
Strehl: 0,2%

PSF  
(intensity normalized)



# Adjustment and Compensation

## ▪ Successive steps of improvements

