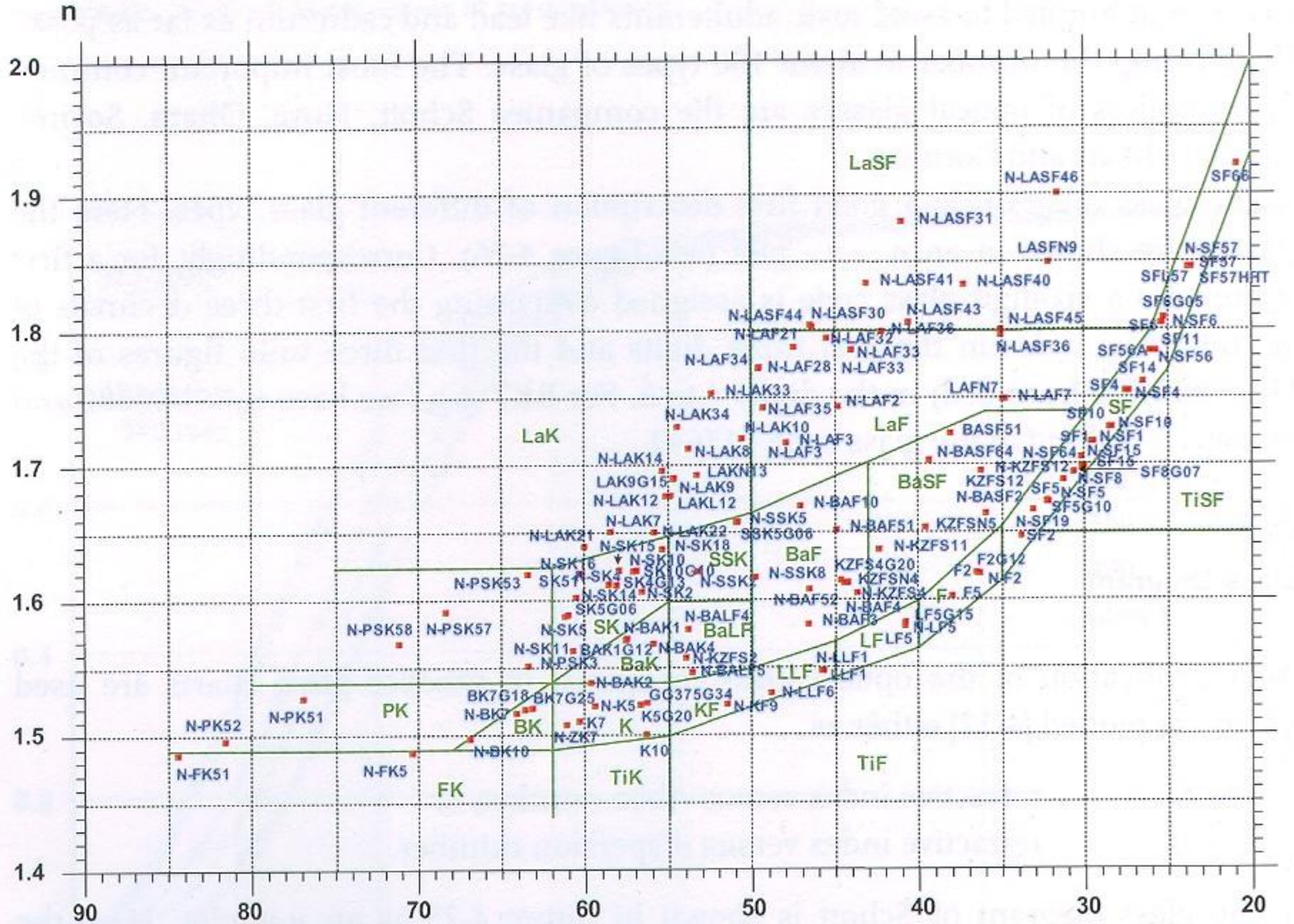
Paraxial imaging equations

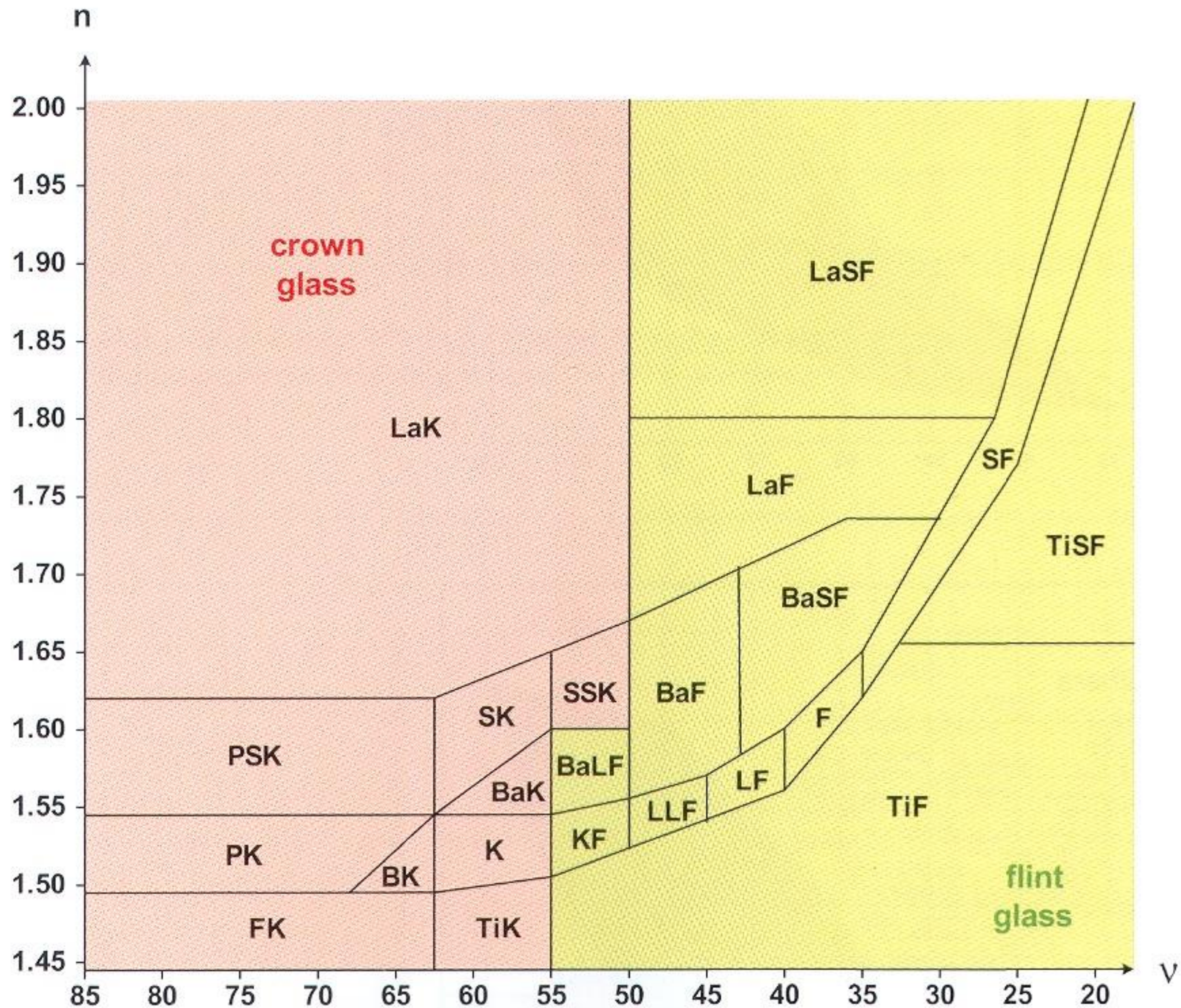
Quantity to be calculated	Calculation equations		
s	$s=\frac{s'f'}{f'-s'}$	$s=s'-L$	$s=\frac{s'}{m}$
	$s=-\frac{L}{s}\pm\sqrt{\frac{L^2}{4}-f'\cdot L}$	$s=\frac{(1-m)\cdot f'}{m}$	$s=\frac{L}{m-1}$
s'	$s'=\frac{s\cdot f'}{f'+s}$	$s'=s+L$	$s'=\frac{L}{m-1}$
	$s'=\frac{L}{2}\pm\sqrt{\frac{L^2}{4}-f'\cdot L}$	$s'=f'\cdot(1-m)$	$s'=\frac{L\cdot m}{m-1}$
f'	$f'=\frac{s\cdot s'}{s-s'}$	$f'=-\frac{s\cdot(L+s)}{L}$	$f'=\frac{s\cdot m}{1-m}$
	$f'=\frac{s'\cdot(L-s')}{L}$	$f'=\frac{s'}{1-m}$	$f'=-\frac{L\cdot m}{(1-m)^2}$
L	$L=s\cdot(m-1)$	$L=s'-s$	$L=-\frac{s^2}{s+f'}$
	$L=\frac{s'^2}{s'-f'}$	$L=\frac{s'\cdot(m-1)}{m}$	$L=f'\cdot\left(2-m-\frac{1}{m}\right)$
m	$m=\frac{s'}{s}$	$m=\frac{f'}{s+f'}$	$m=\frac{f'-s'}{f'}$
	$m=\frac{L+s}{s}$	$m=\frac{s'}{s'-L}$	$m=1-\frac{L}{2f'}\pm\sqrt{\frac{L}{f'}\cdot\left(\frac{L}{4f'}-1\right)}$

Wavelengths of the most important spectral lines.

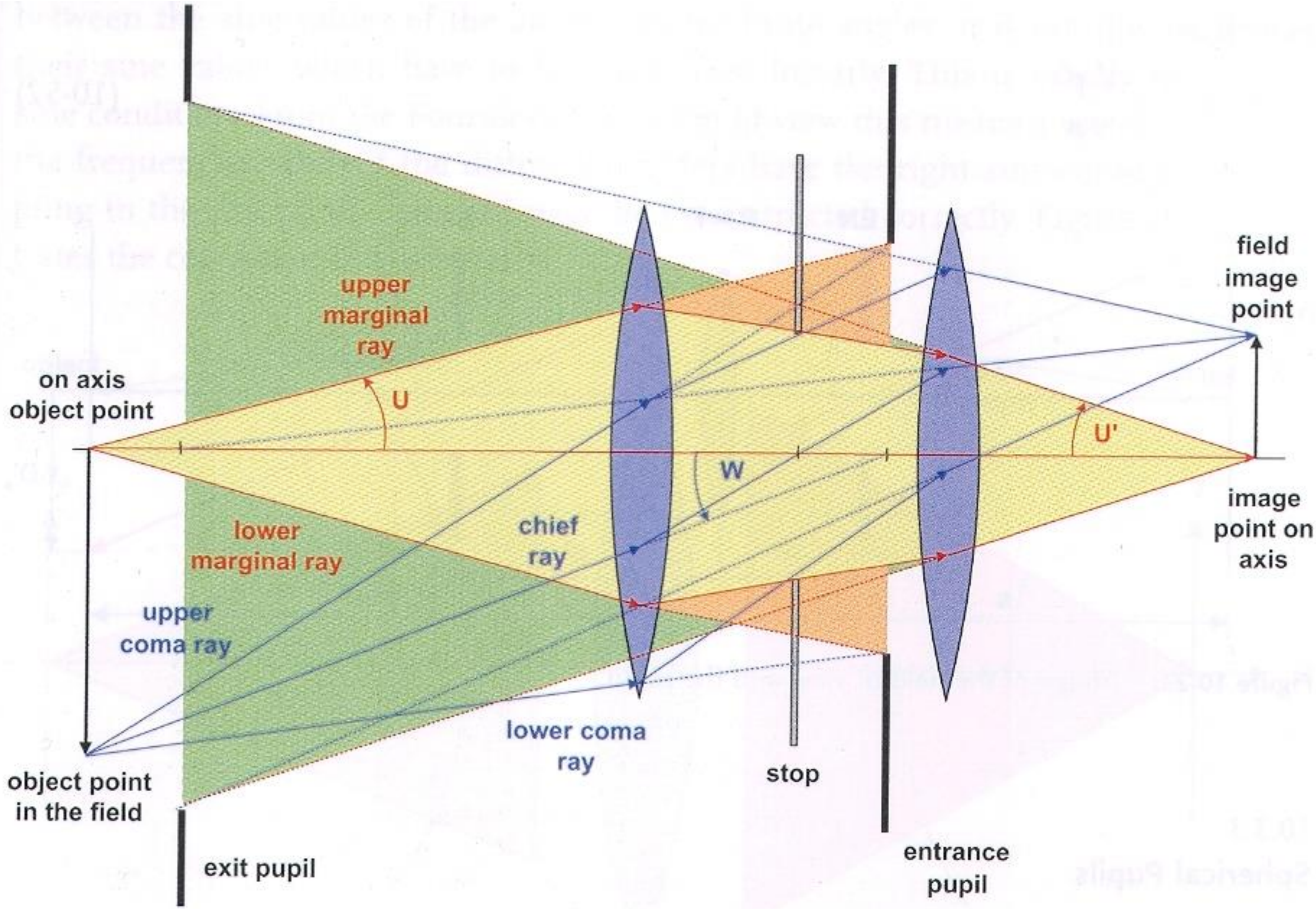
λ in [nm]	Name	Color	Element
248.3		UV	Hg
280.4		UV	Hg
296.7278		UV	Hg
312.5663		UV	Hg
334.1478		UV	Hg
365.0146	i	UV	Hg
404.6561	h	violet	Hg
435.8343	g	blue	Hg
479.9914	F′	blue	Cd
486.1327	F	blue	H
546.0740	e	green	Hg
587.5618	d	yellow	He
589.2938	D	yellow	Na
632.8		red	HeNe laser
643.8469	C′	red	Cd
656.2725	C	red	H
706.5188	r	red	He
852.11	s	NIR	Cs
1013.98	t	NIR	Hg
1060.0		IR	Nd-glass laser
1529.582		IR	Hg line in the IR
1970.09		IR	Hg line in the IR
2325.42		IR	Hg line in the IR



Glass diagram of Schott, n-ν-plot.

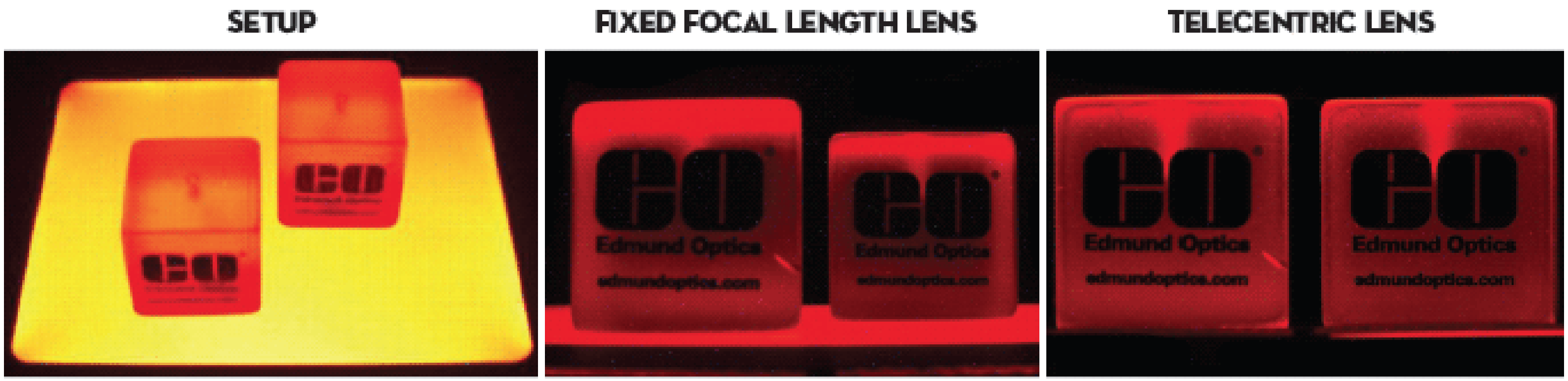


Glass diagram of Schott. Division into ranges of glass families.

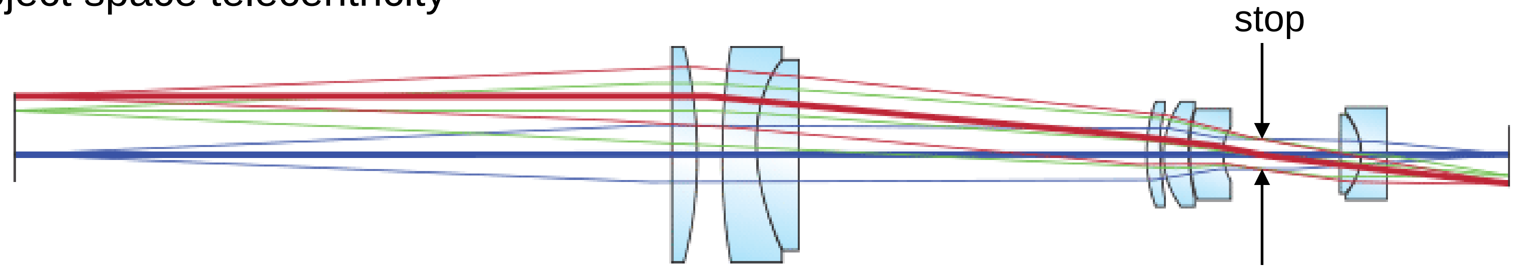


Definition of stops, entrance and exit pupil.

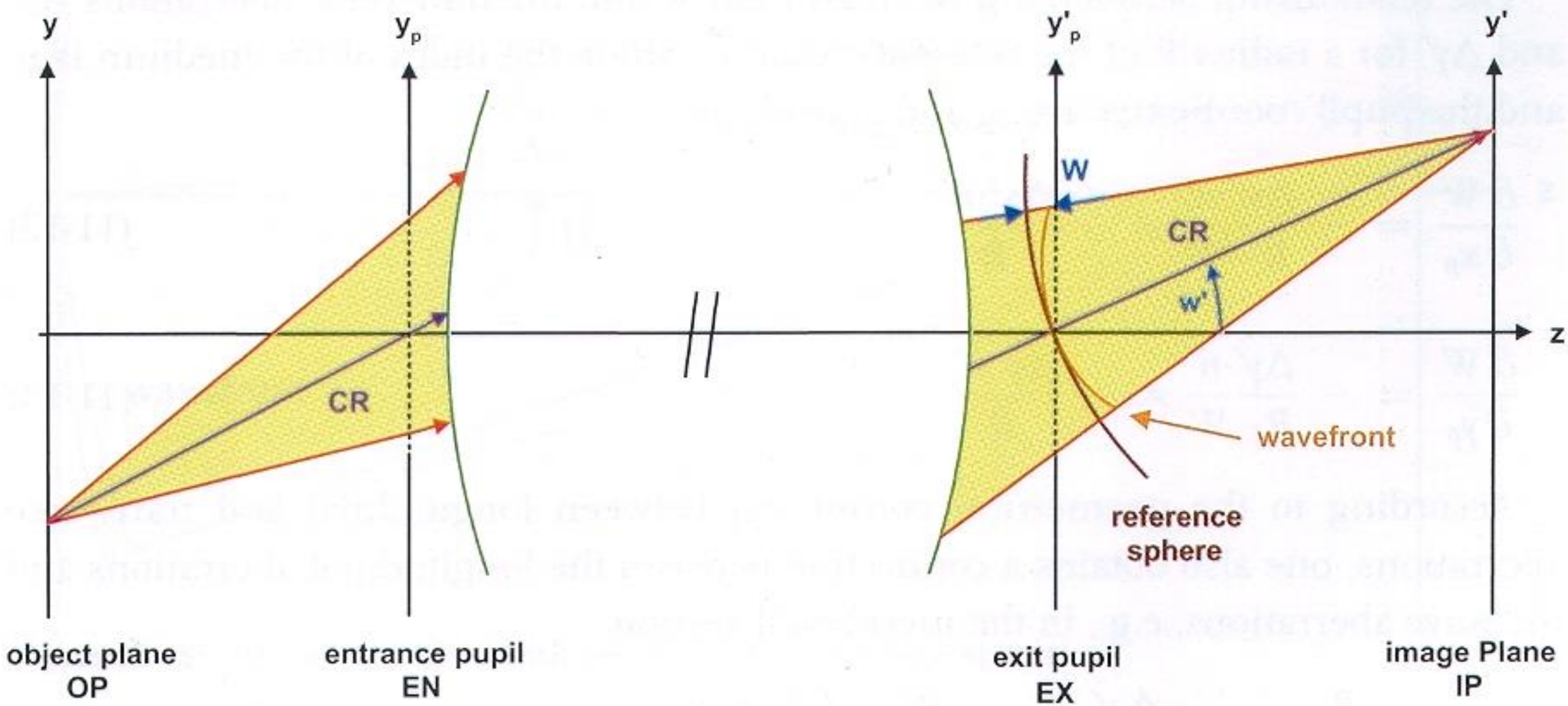
Telecentric Imaging



Object space telecentricity



source: edmund optics



Wave aberrations for an optical system.

The 5 classical Seidel Aberrations

$$W(\beta, r, \psi) = \underbrace{W_{000}}_{\text{Piston Error}}$$

$$+ \underbrace{W_{200} \cdot \beta^2}_{\text{Piston error}} + \underbrace{W_{020} \cdot r^2}_{\text{Defocus}} + \underbrace{W_{111} \cdot \beta \cdot r \cdot \cos\psi}_{\text{Lateral Magnification Error}}$$

$$+ \underbrace{W_{400} \cdot \beta^4}_{\text{Piston Error}} + \underbrace{W_{040} \cdot r^4}_{\text{SA}} + \underbrace{W_{131} \cdot \beta \cdot r^3 \cdot \cos\psi}_{\text{Coma}} + \underbrace{W_{222} \cdot \beta^2 \cdot r^2 \cdot \cos^2\psi}_{\text{Astigmatism}}$$

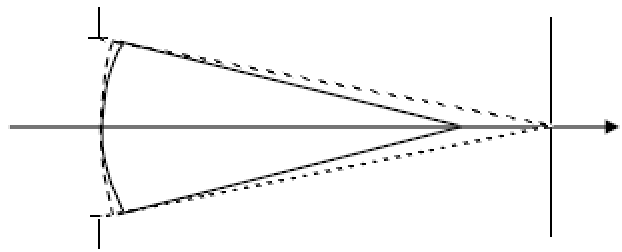
$$+ \underbrace{W_{220} \cdot \beta^2 \cdot r^2}_{\text{Field Curvature}} + \underbrace{W_{311} \cdot \beta^3 \cdot r \cdot \cos\psi}_{\text{Distortion}}$$

+ … aberrations of higher order

First order aberrations

Defocus

$W_{020}\, r^2$



Longitudinal Focal Shift

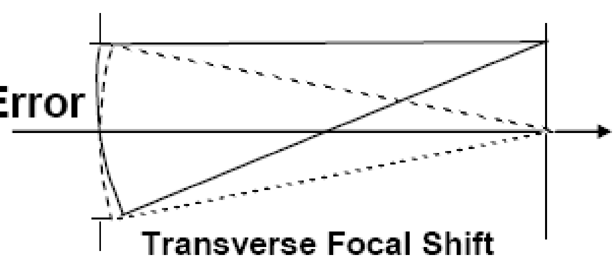
Simply changes the curvature.

Still a spherical wavefront!

Still a good image!

Lateral Magnification Error

$W_{111}\, \beta\, r \cos \psi$

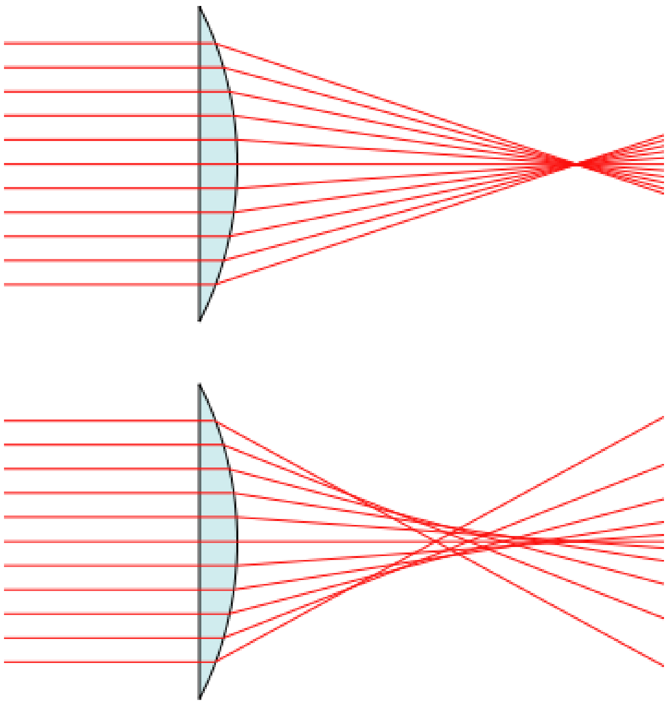


Transverse Focal Shift

Changes the position of the center of curvature. Still a spherical wavefront! Points are still imaged into points and lines are still imaged into lines.

Spherical Aberration (~r^4)

Origin: different focal lengths for different ray heights

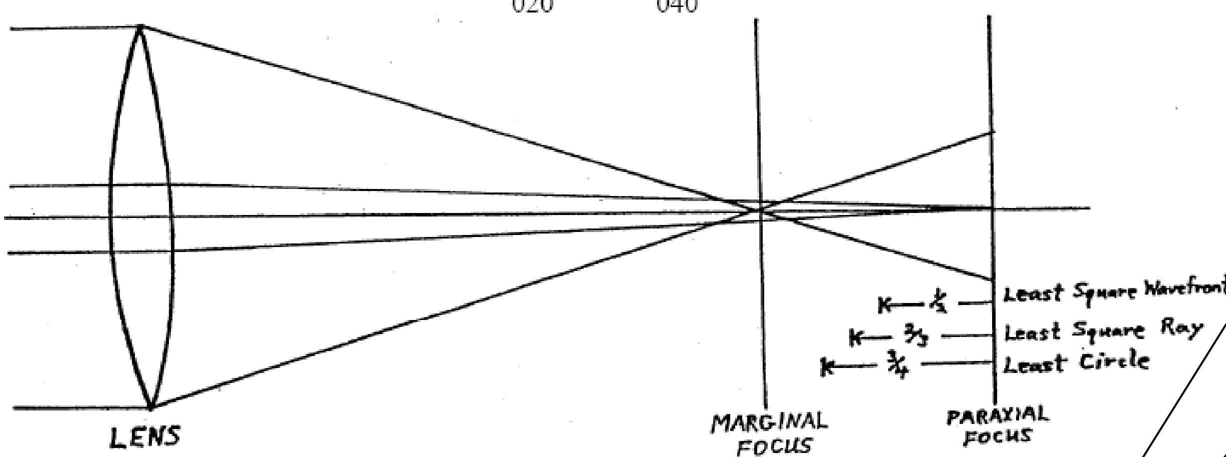


Spherical aberration. A perfect lens (top) focuses all incoming rays to a point on the optic axis. A real lens with spherical surfaces (bottom) suffers from spherical aberration: it focuses rays more tightly if they enter it far from the optic axis than if they enter closer to the axis. It therefore does not produce a perfect focal point.

Getting rid of **Spherical Aberration (~r^4)**

by balancing with defocus

$$W = W_{020} r^2 + W_{040} r^4$$



There are several criteria for the "best" focus:

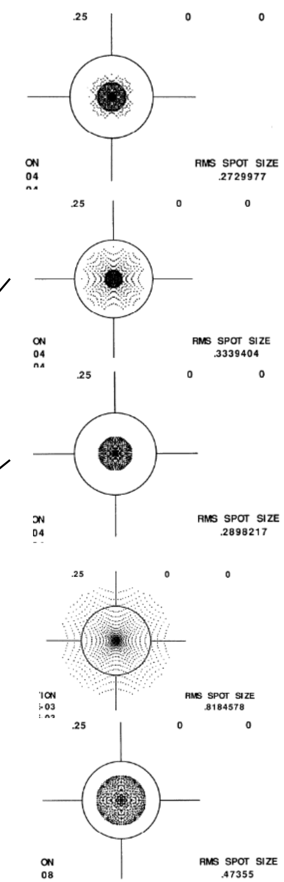
Least square ray criteria - $W_{020} = -\frac{4}{3} W_{040}$

Least square wavefront error - - - - - - - - - - - - - - - - - - - $W_{020} = -W_{040}$

Least circle (smallest circle containing all rays) - - - - - - $W_{020} = -\frac{3}{2} W_{040}$

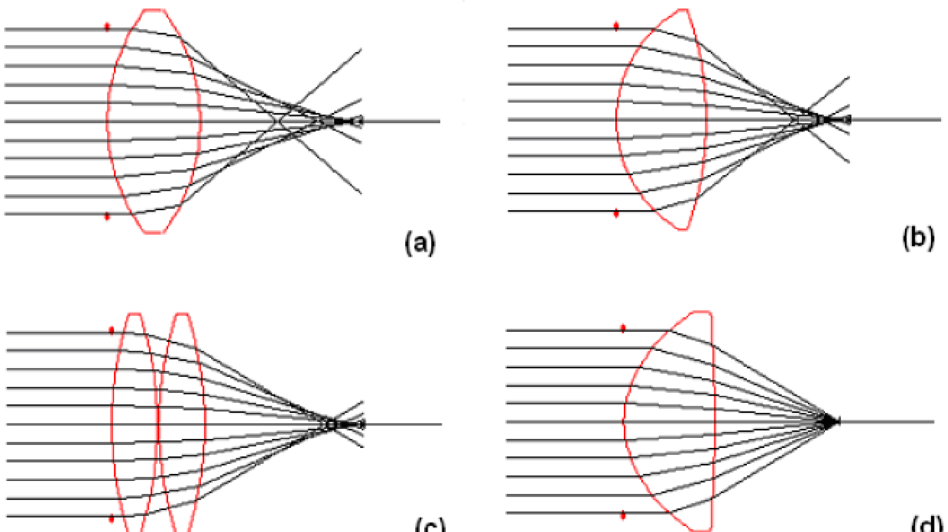
Paraxial focus - $W_{020} = 0$

Marginal focus - $W_{020} = -2 W_{040}$



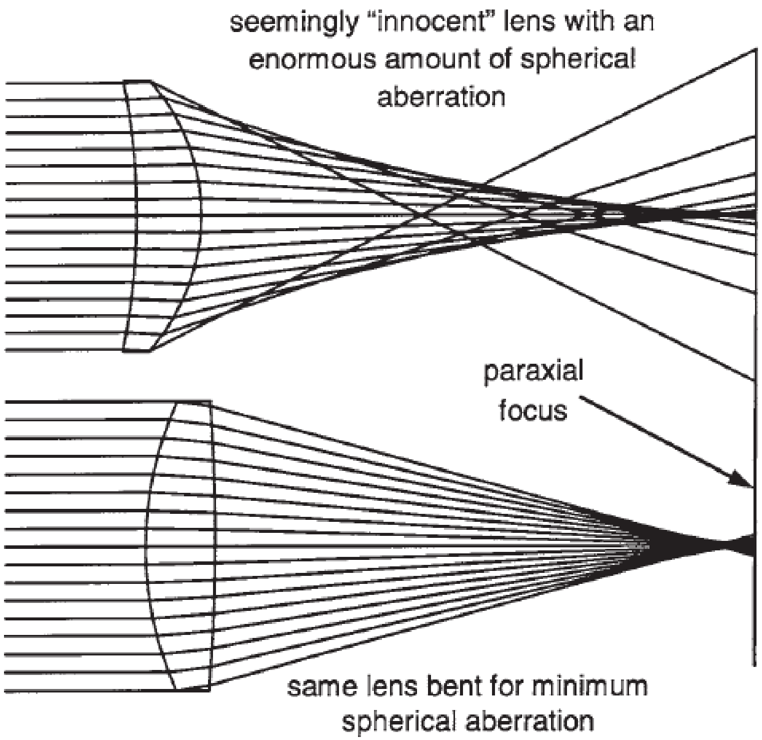
Getting rid of **Spherical Aberration ($\sim r^4$)**

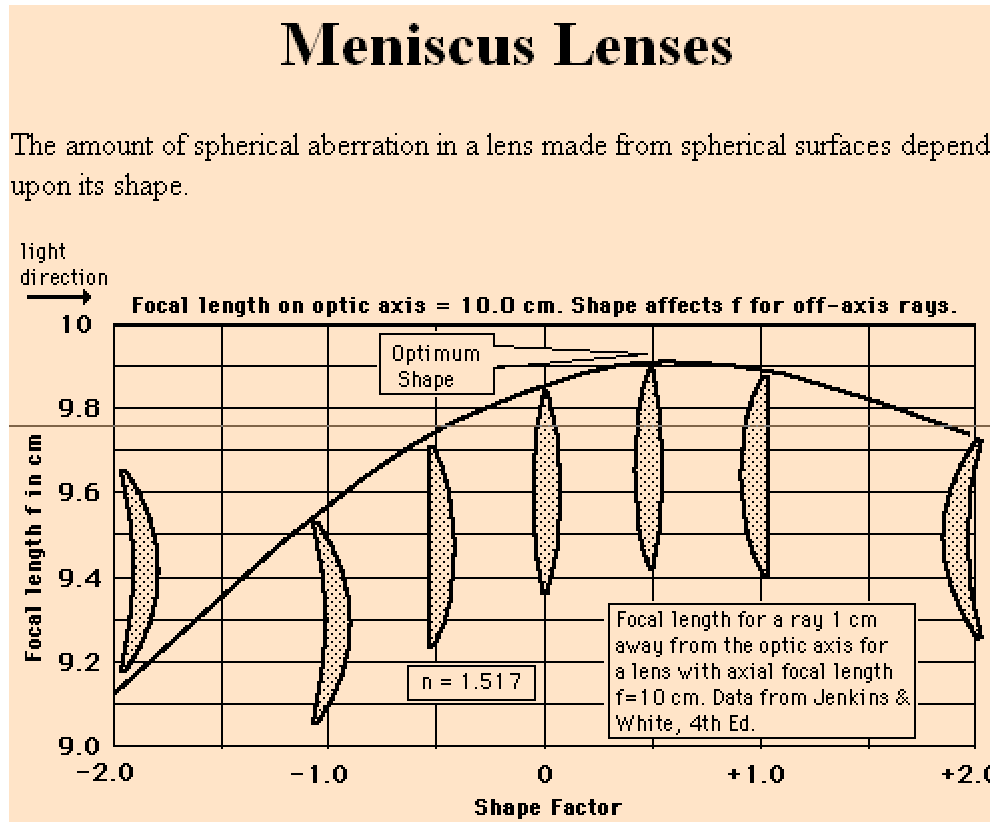
- Lens bending (b)
- Lens splitting (c)
- High refractive index
- Aspheric lenses (d)



Getting rid of **Spherical Aberration (~r^4)**

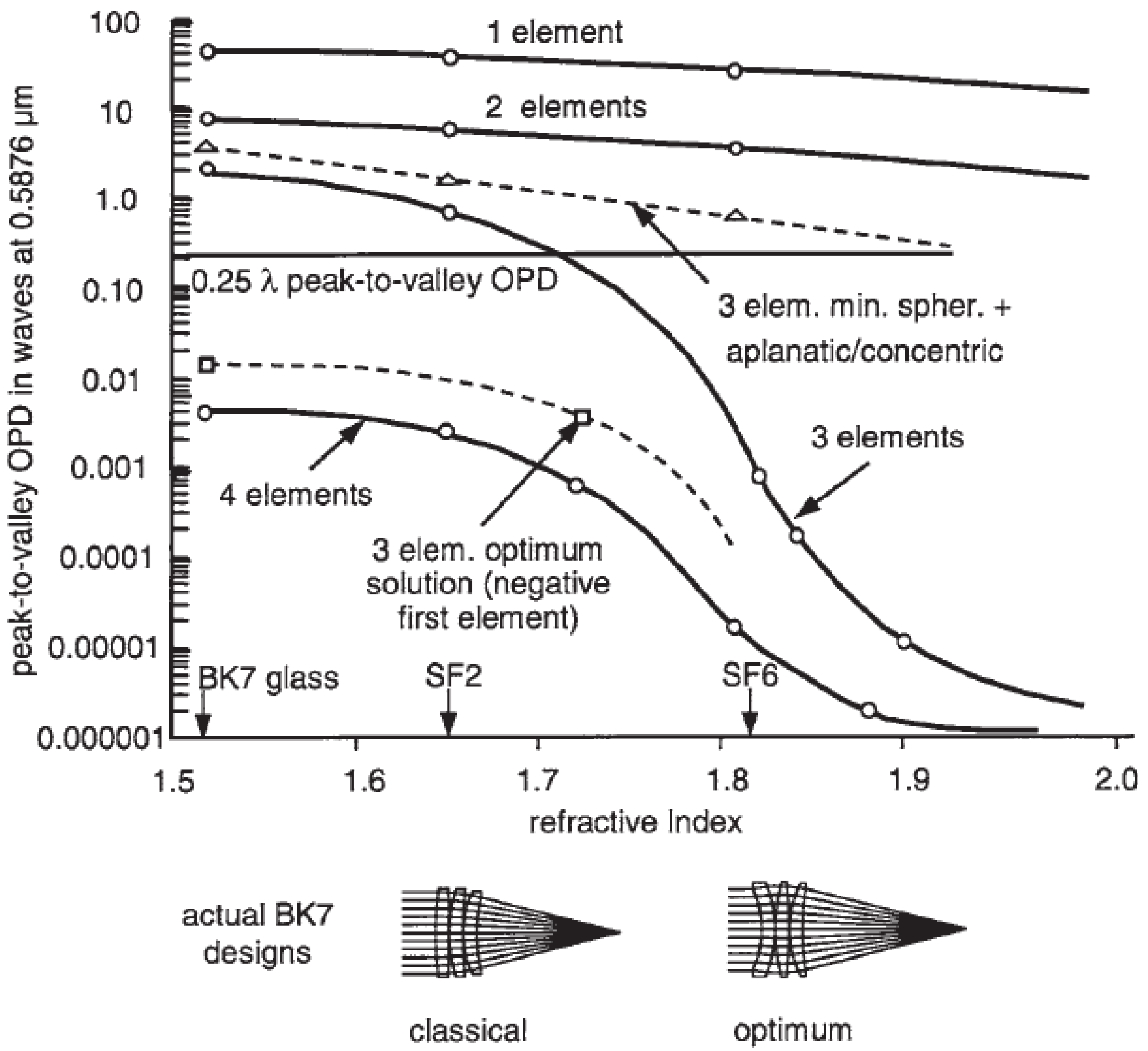
Effect of lens bending





Getting rid of **Spherical Aberration (~r^4)**

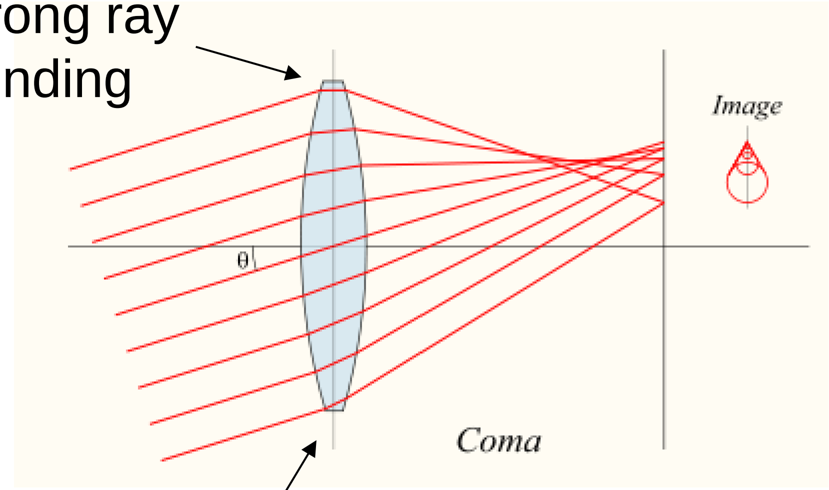
Effect of material choice and # of elements



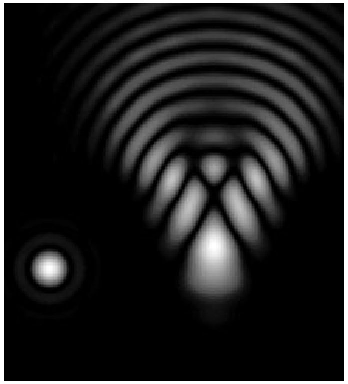
Coma ($\sim \beta\, r^3 \cos\psi$)

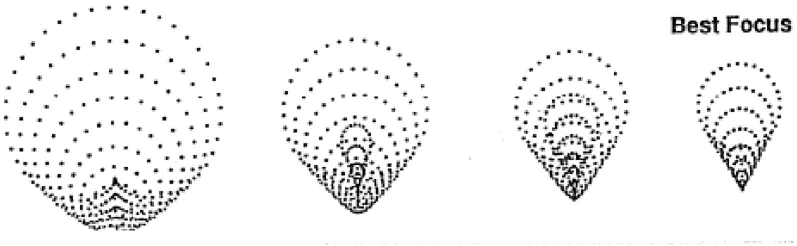
Origin: Non-symmetry of bundle around chief ray
→ “non-symmetry error“

strong ray bending



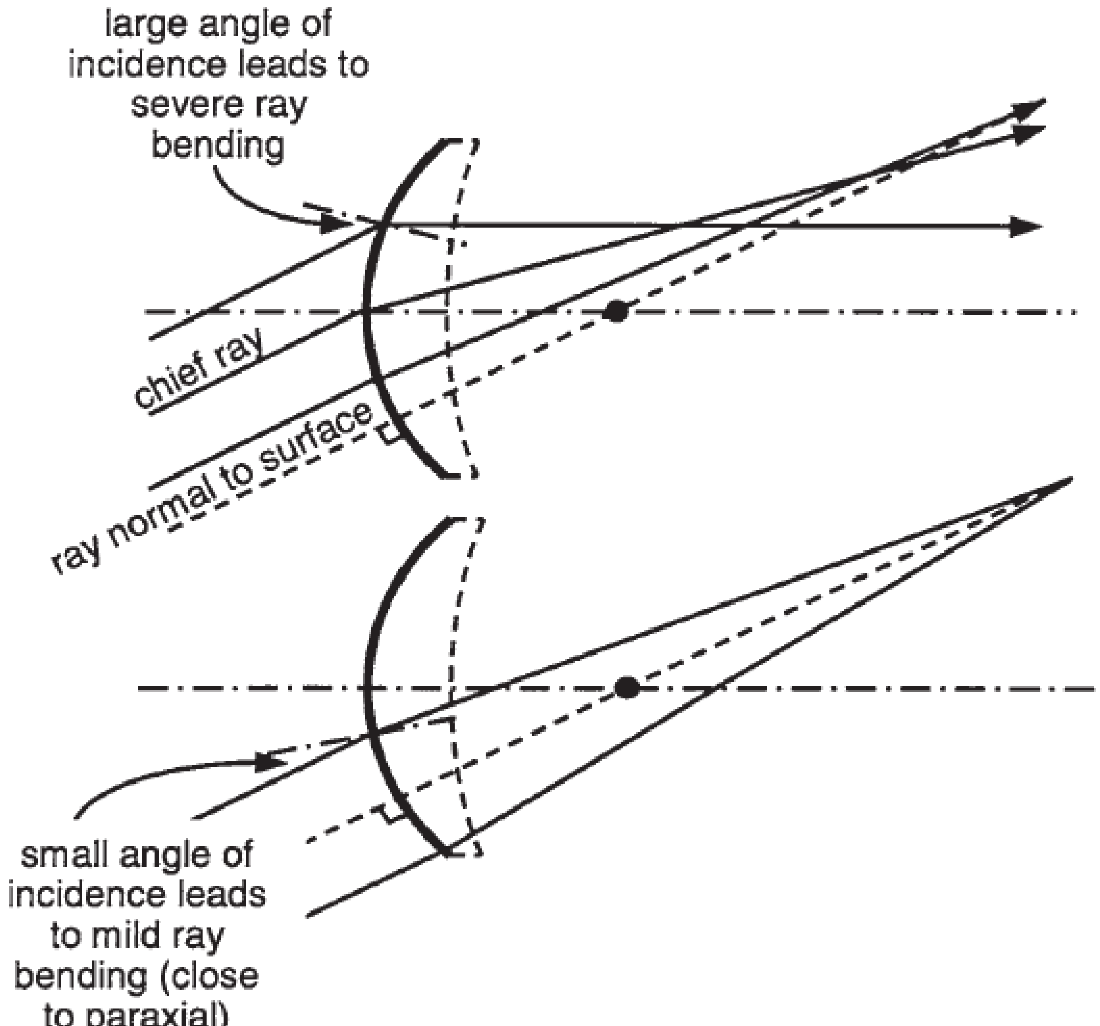
weak ray bending





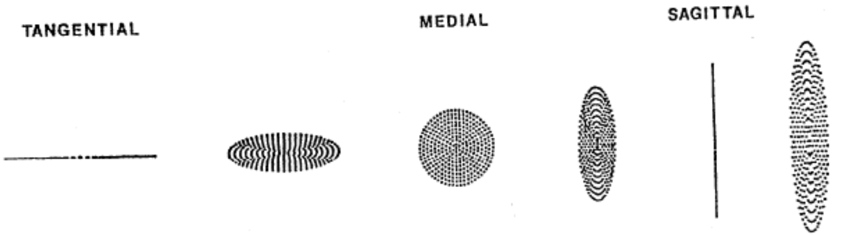
Getting rid of **Coma ($\sim \beta\, r^3 \cos \psi$)**

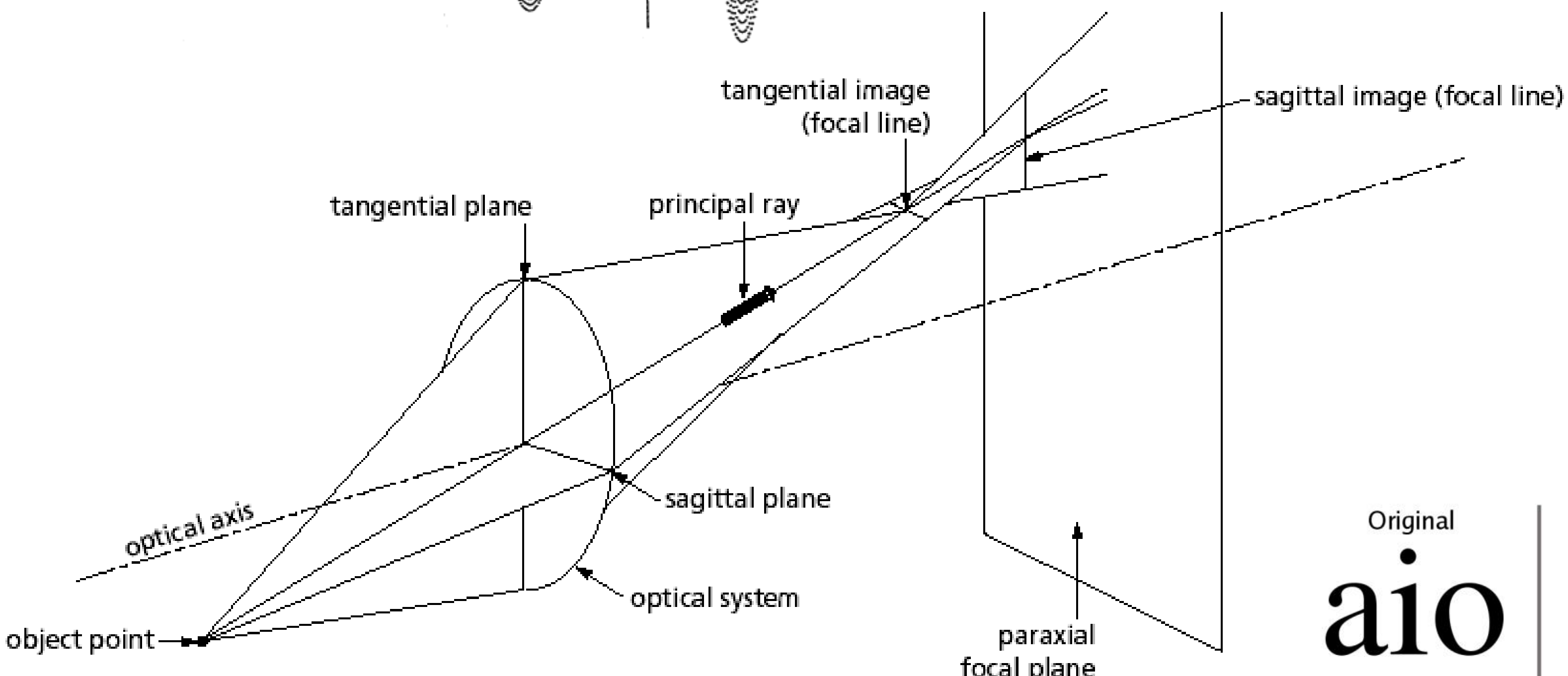
Move stop!

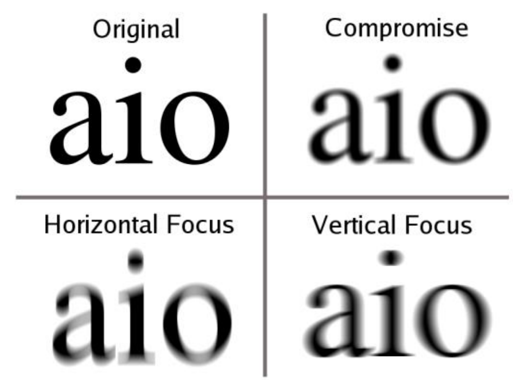


Astigmatism ($\sim \beta^2 r^2 \cos^2 \psi$)

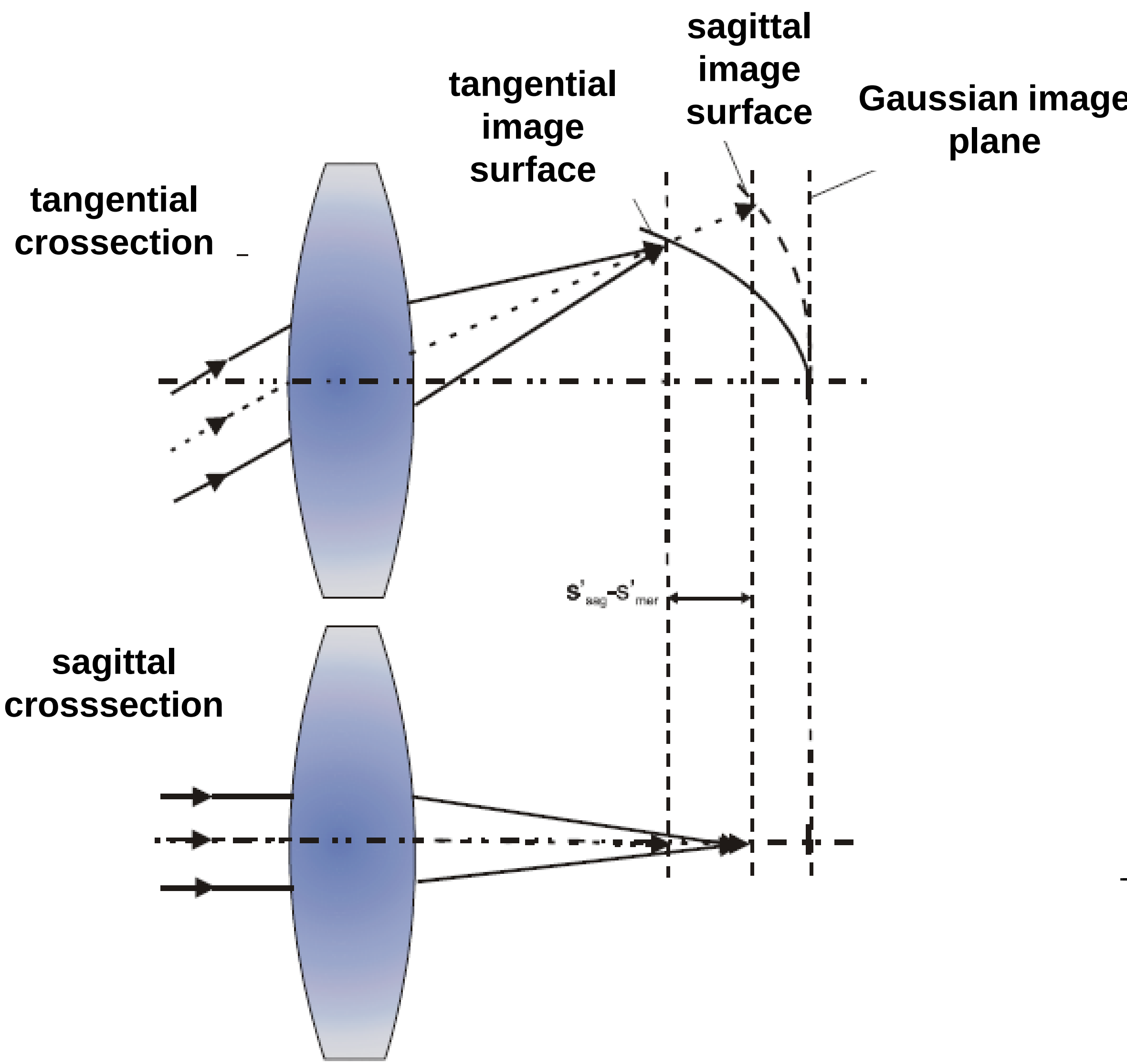
Origin: different optical powers in x and y due to oblique incidence / projection



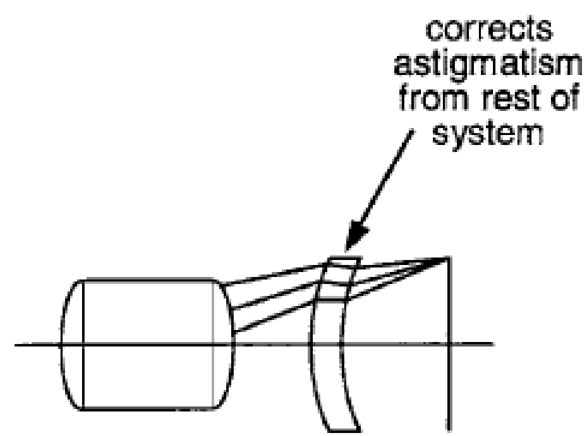




Astigmatism ($\sim \beta^2 r^2 \cos^2 \psi$)

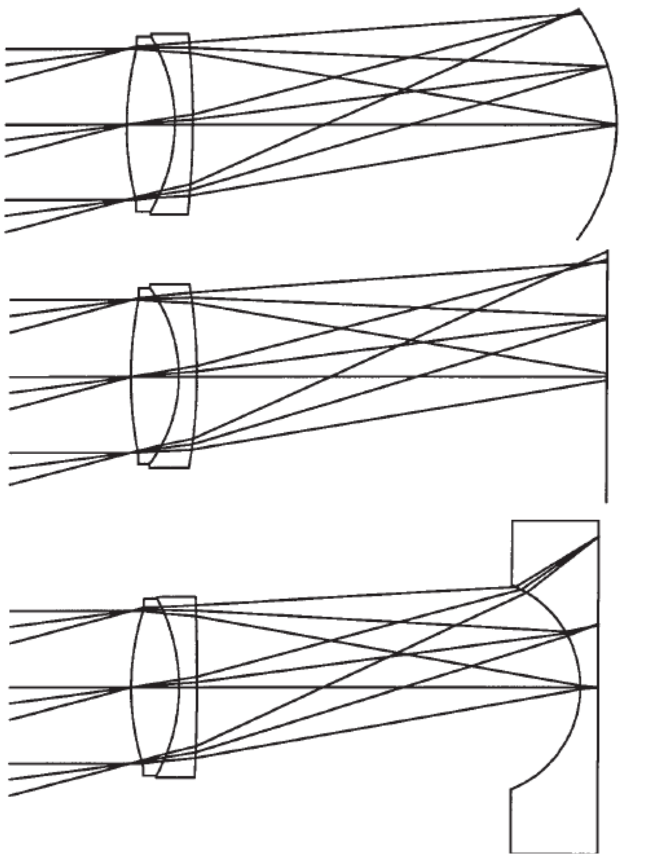


Correction by applying menisc lenses



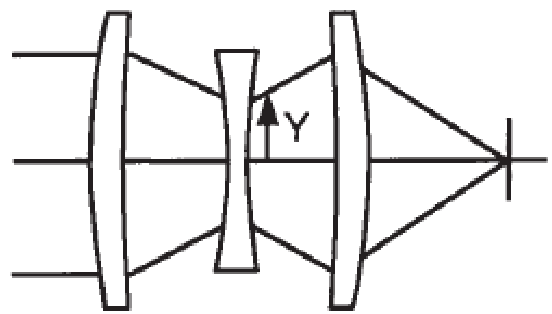
Field curvature ($\sim \beta^2 r^2$)

Origin: natural image surface is spherical, not planar
→ “Petzval curvature“



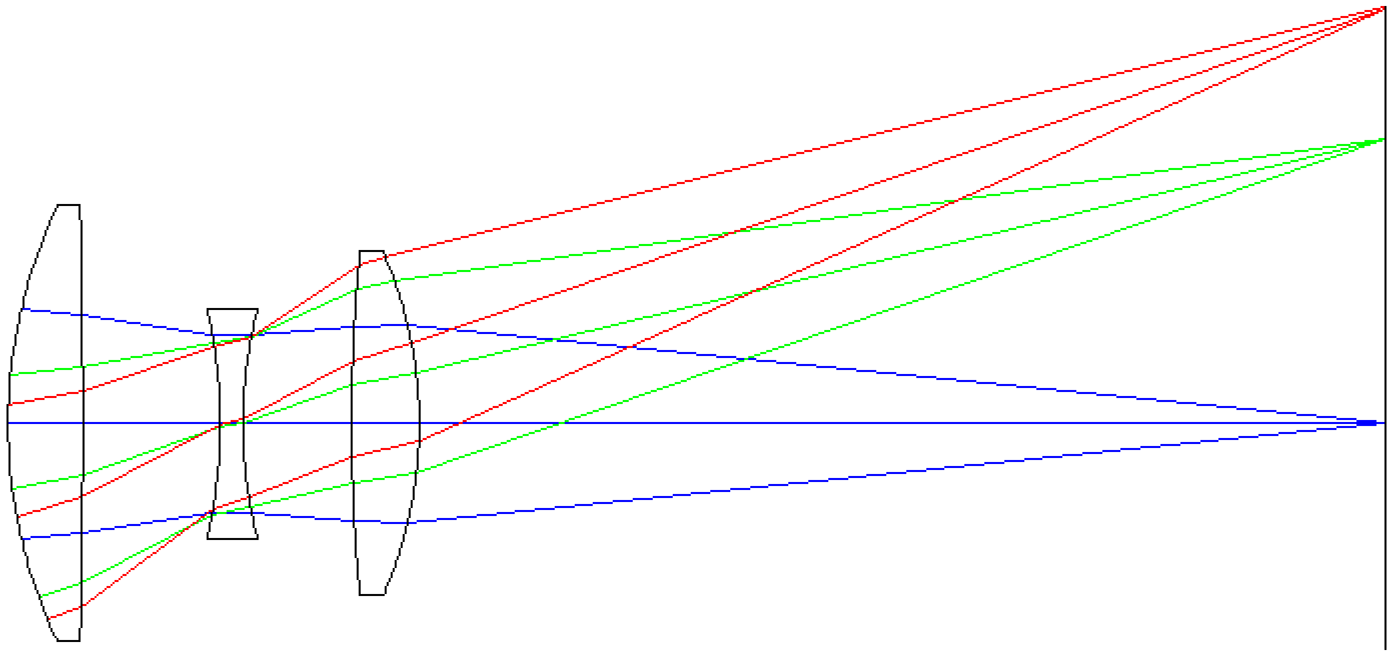
lens with field flattener
(Petzval lens)

- Make Petzval sum equal zero!
- Balance with astigmatism!



Cooke Triplet

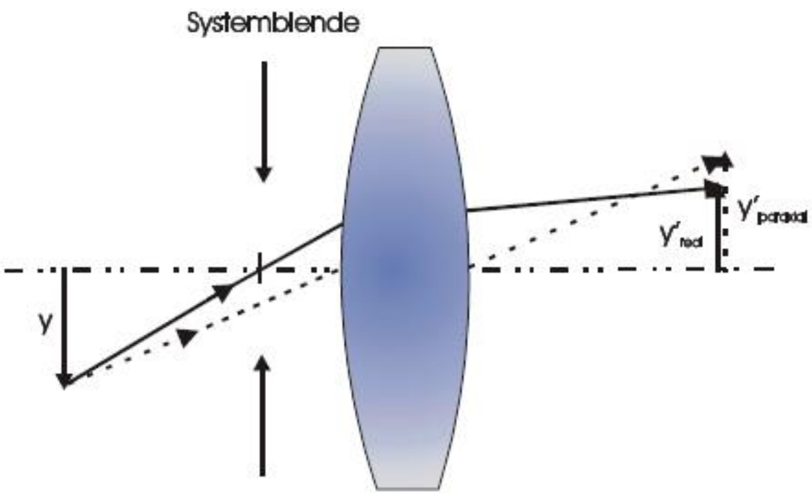
The Cooke Triplet

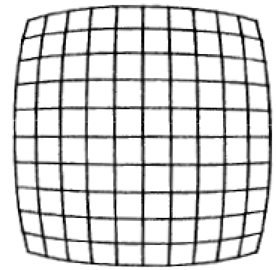


Cooke triplet lenses

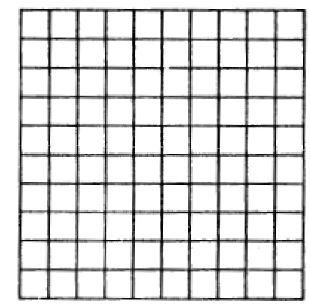
Cooke triplet is a well-know lens form that provides good imaging performance over a field of view of +/- 20-25 degrees. Many consumer grade film cameras use lenses of this type.

Distortion ($\sim \beta^3 r \cos \psi$)

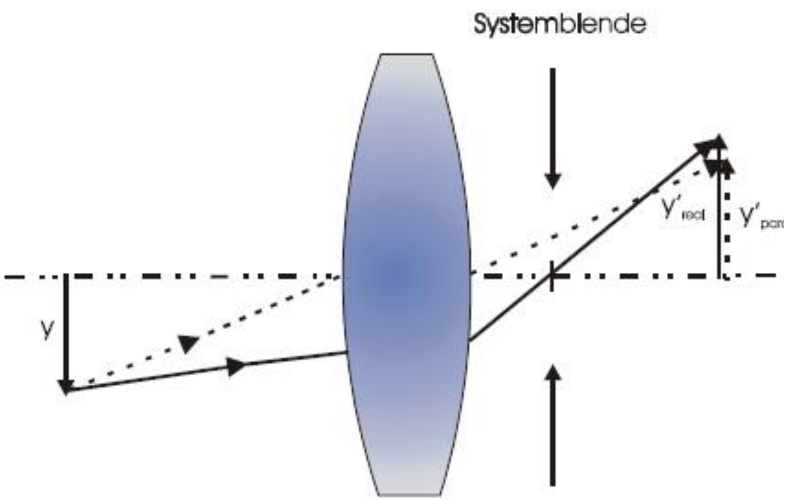


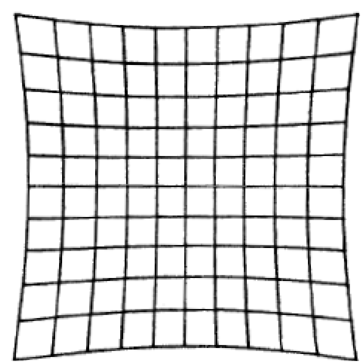


Positive (Barrel) Distortion



No Distortion





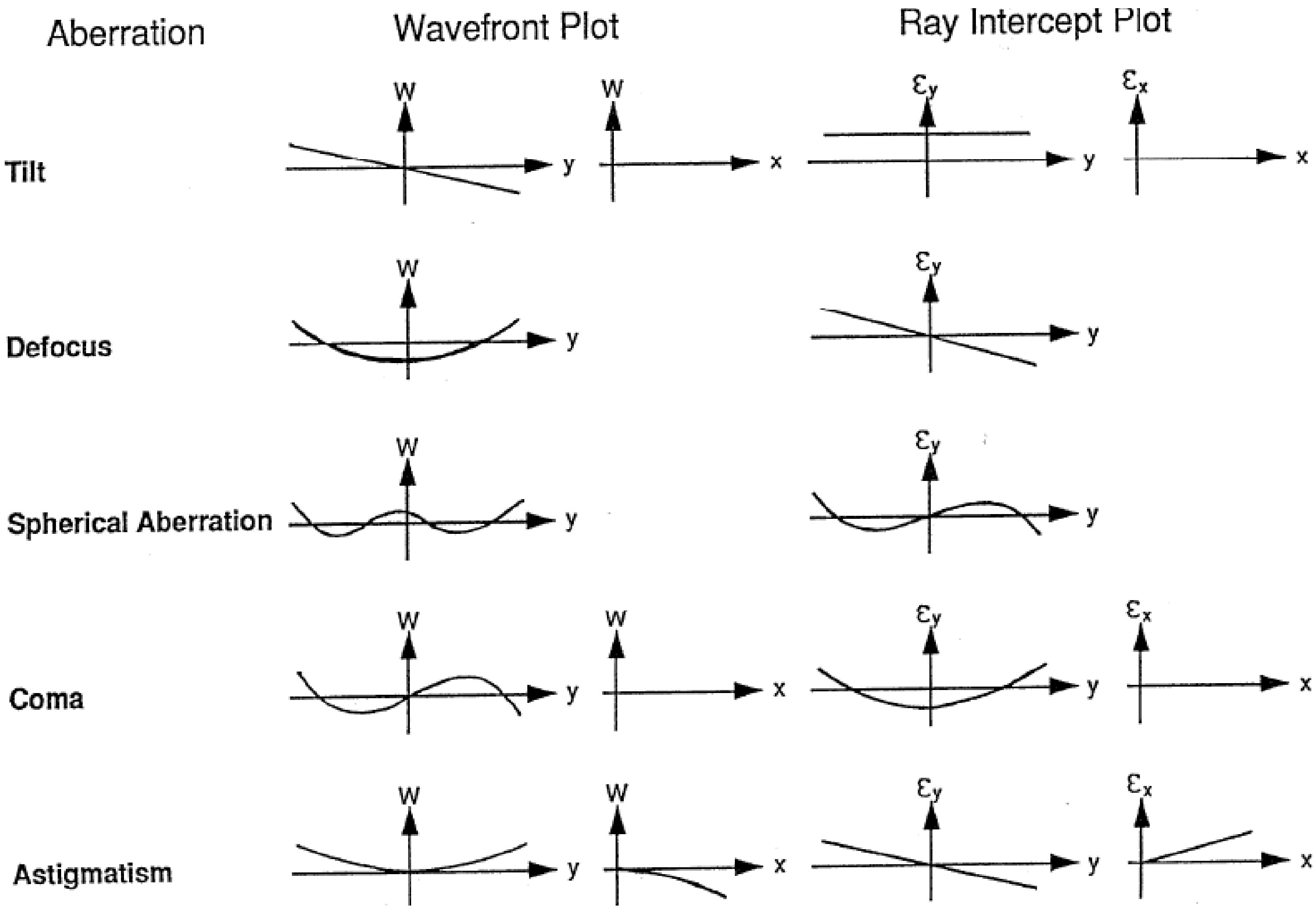
Negative (Pincushion) Distortion

Summary (of wavefront aberrations)

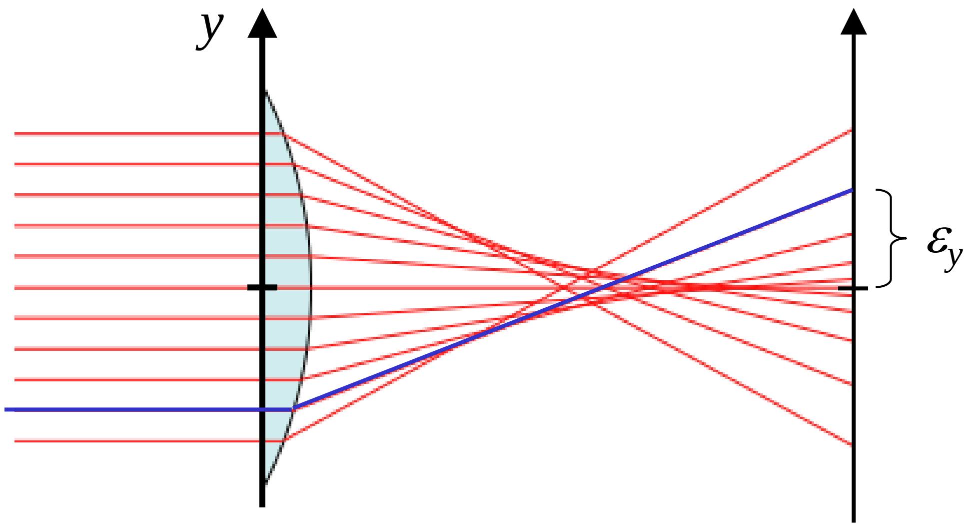
Longitudinal color	$f(\lambda)$	Varying focus with wavelength
Lateral color	$\beta(\lambda)$	Varying magnification with wavelength
Defocus	$\sim r^2$	Longitudinal focal shift
Tilt	$\sim \beta\ r \cos\ \psi$	Transverse focal shift
Spherical	$\sim r^4$	Varying focus with radius in pupil plane
Coma	$\sim \beta\ r^3 \cos \psi$	Varying magnification and focus with radius in pupil
Astigmatism	$\sim \beta^2\ r^2 \cos^2\psi$	Varying focus with azimuthal angle in pupil
Field curvature	$\sim \beta^2\ r^2$	Varying focus with field
Distortion	$\sim \beta^3\ r \cos \psi$	Varying magnification with field

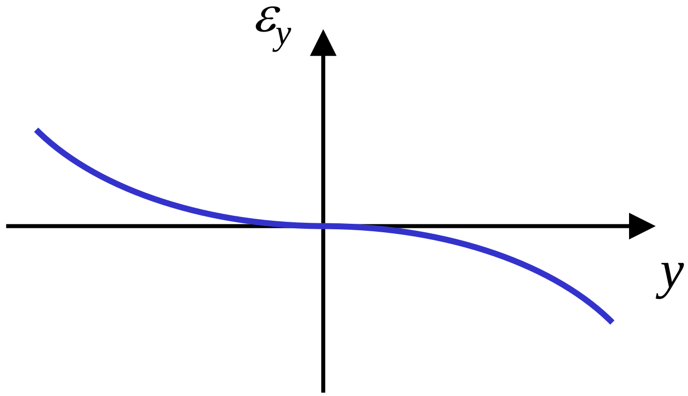
Wavefront and Ray Intercept Plots

Balanced



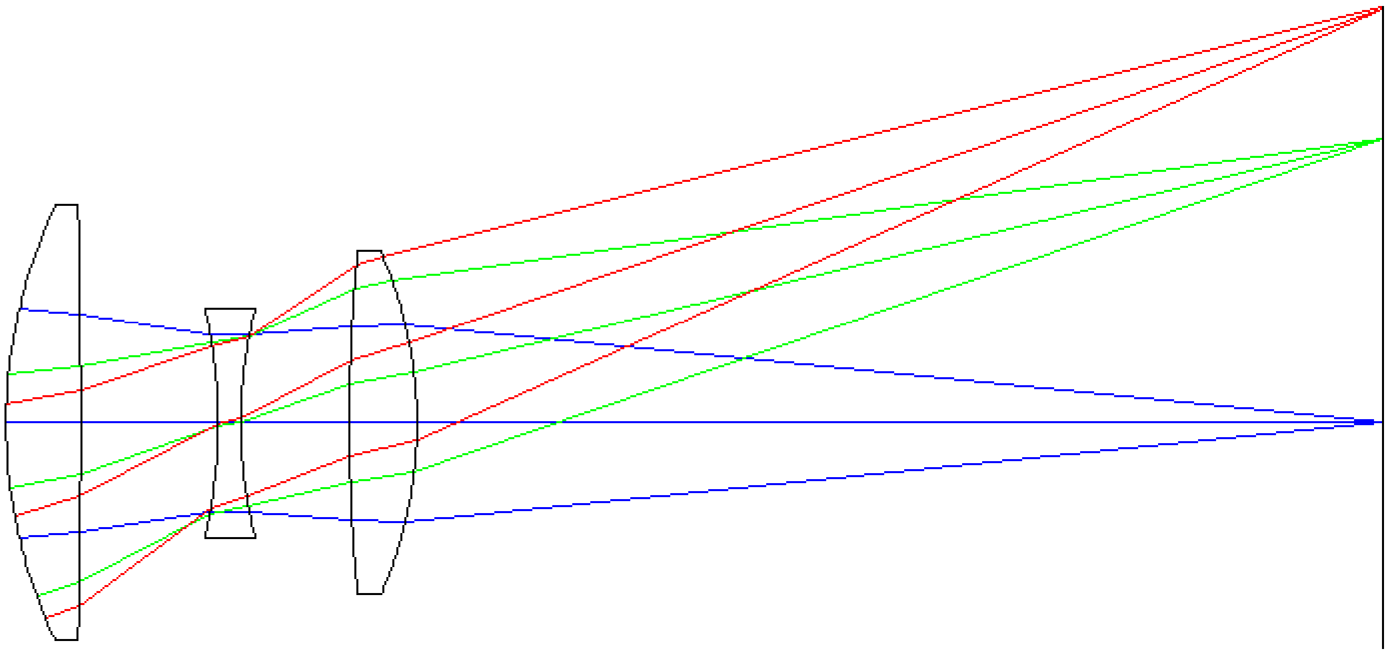
Ray Intercept Plot





here: spherical aberrations

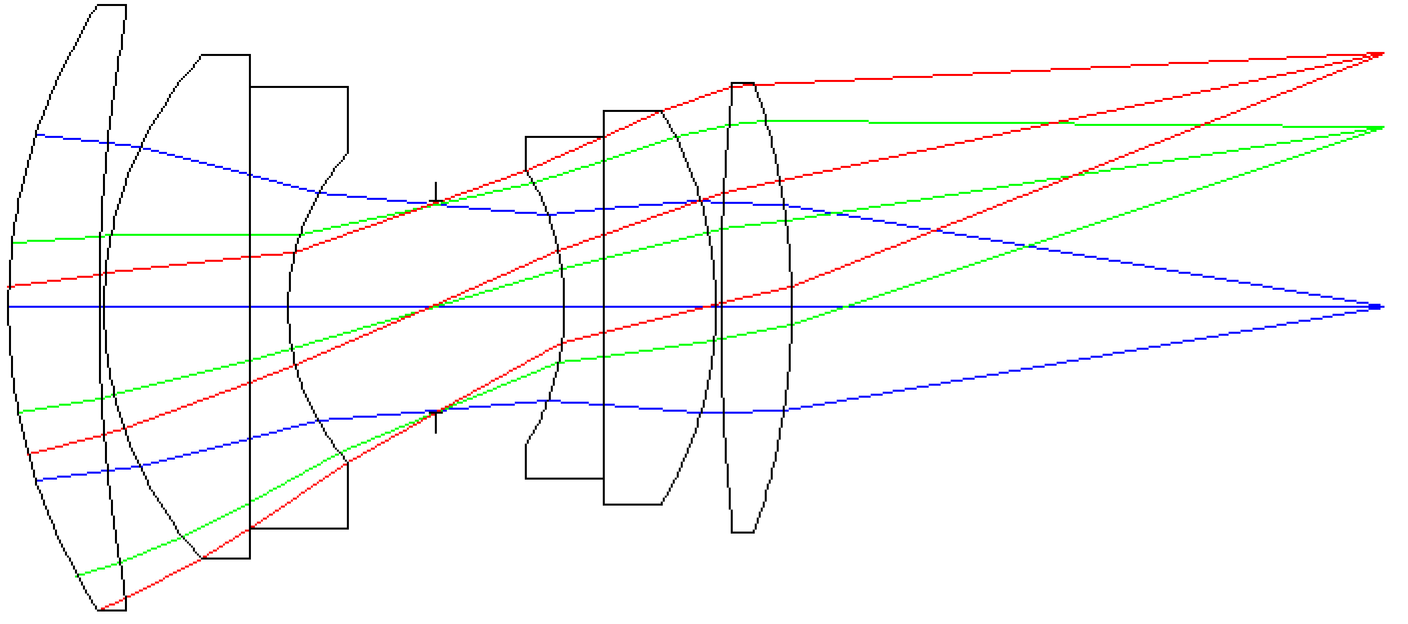
Some common design forms



Cooke triplet lenses

Achromats and Apochromats provide improved performance on-axis only. To achieve good performance both on- and off-axis, more complex lens forms are required. Cooke triplet is a well-know lens form that provides good imaging performance over a field of view of +/- 20-25 degrees. Many consumer grade film cameras use lenses of this type.

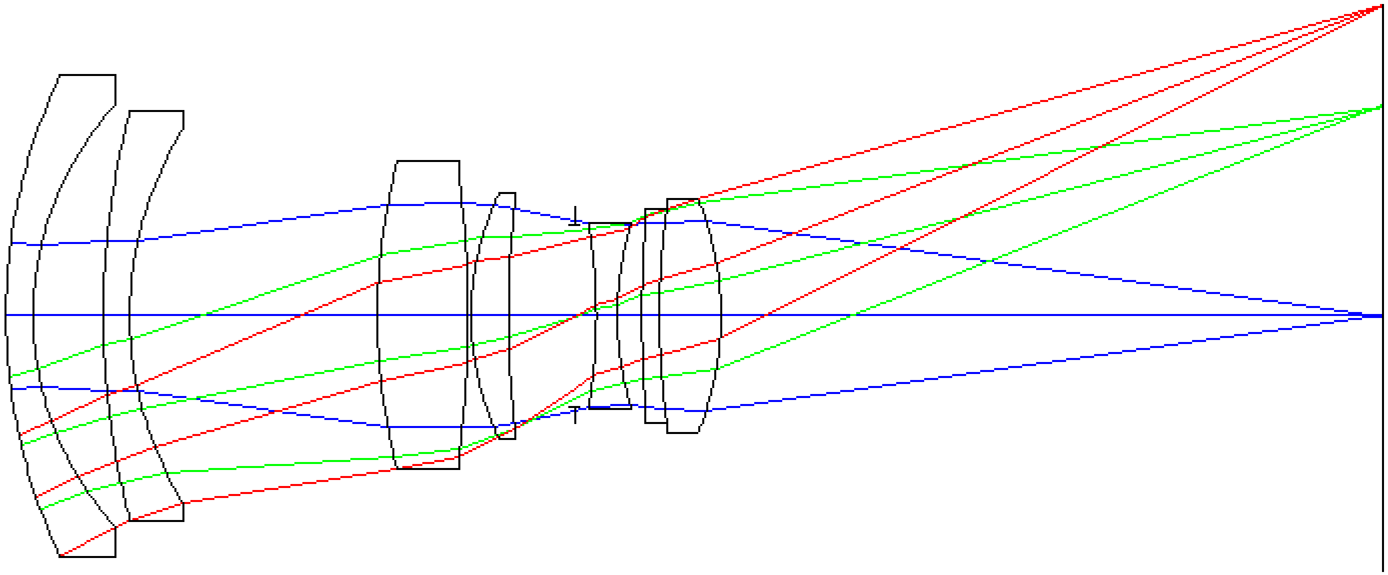
Some common design forms



Double Gaussian lens

To achieve higher image quality and to increase the relative aperture (i.e, lowering the f/#) over a Cooke triplet, a lens form known as "Double Gaussian" is used. The double Gaussian design uses two cemented doublets and two companion singlets. This lens form offers excellent performance over a significant field of view, and the relative aperture can be as low as F/1.2. Double Gaussian lenses are used in many SLR lenses, and C-mount lenses for electronic cameras.

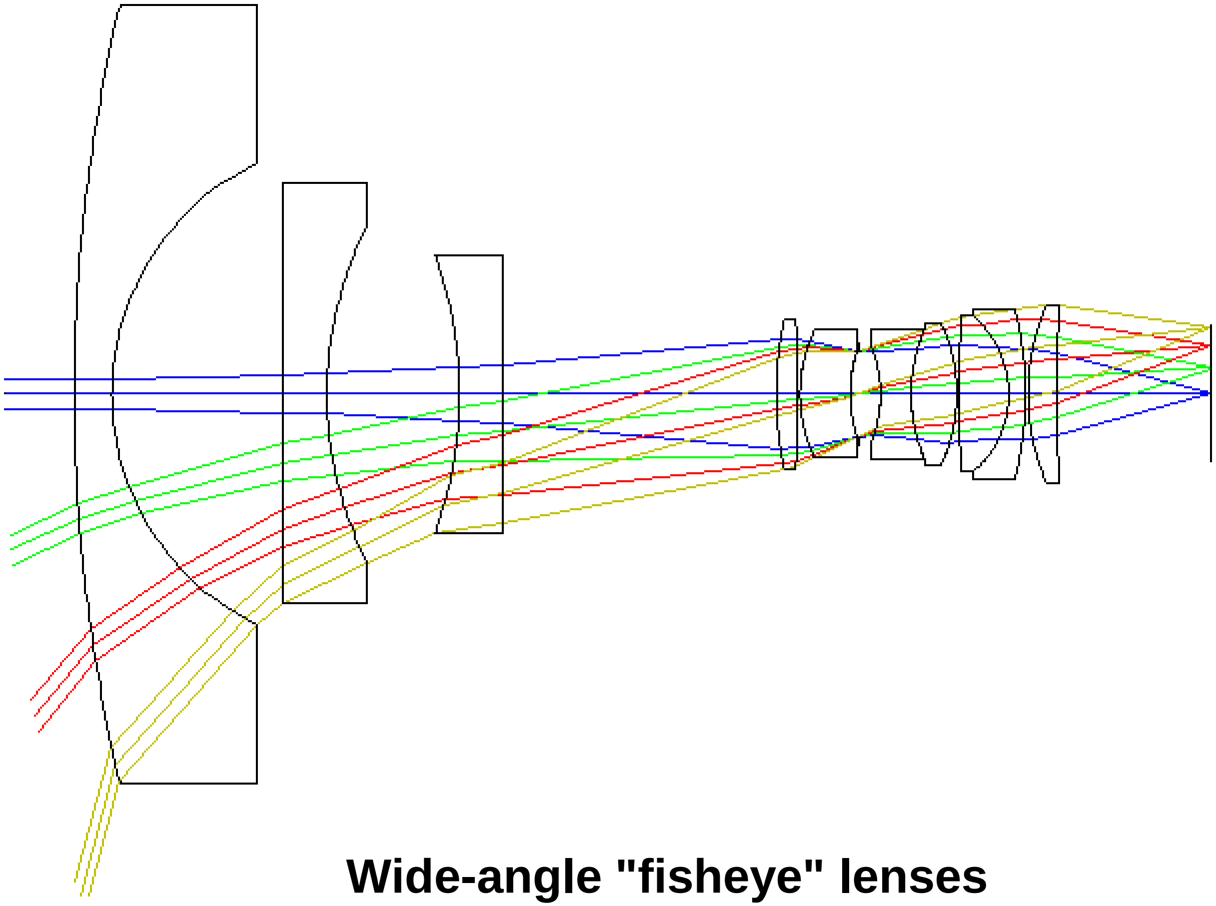
Some common design forms



Reverse telephoto lens

To provide more field of view coverage, a reverse telephoto lens type is often used. The front lens group has negative power which reduces the input field of view. The second group is positive and it does the focus. With this configuration, the field of view can be increased to +/-35 degrees. The other advantage of this configuration is that the system back focal length can be longer than the effective focal length. This property makes this design form very attractive to short focal length lenses commonly seen on digital cameras.

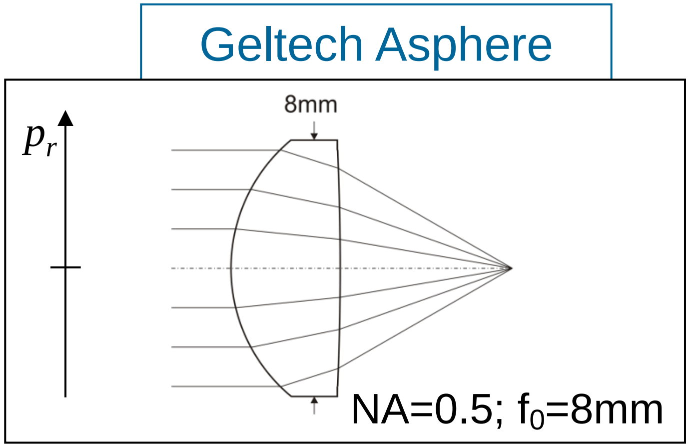
Some common design forms



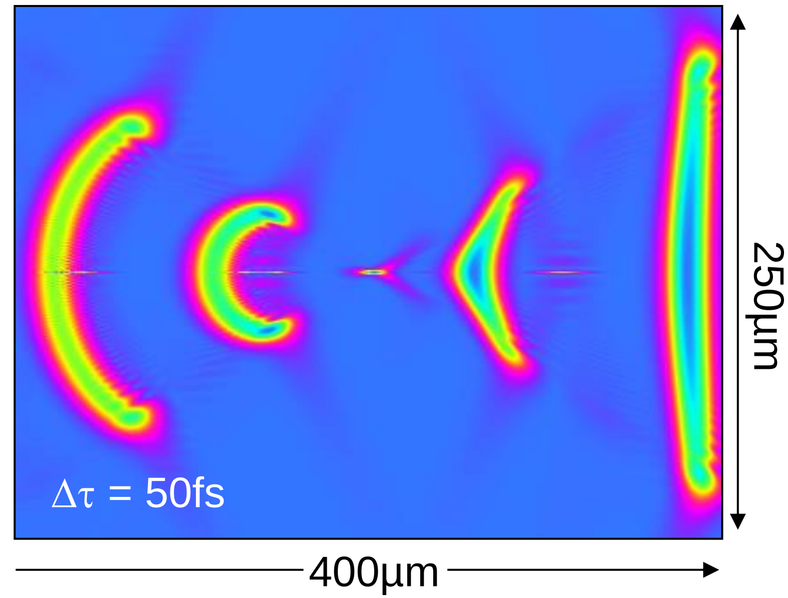
Wide-angle "fisheye" lenses

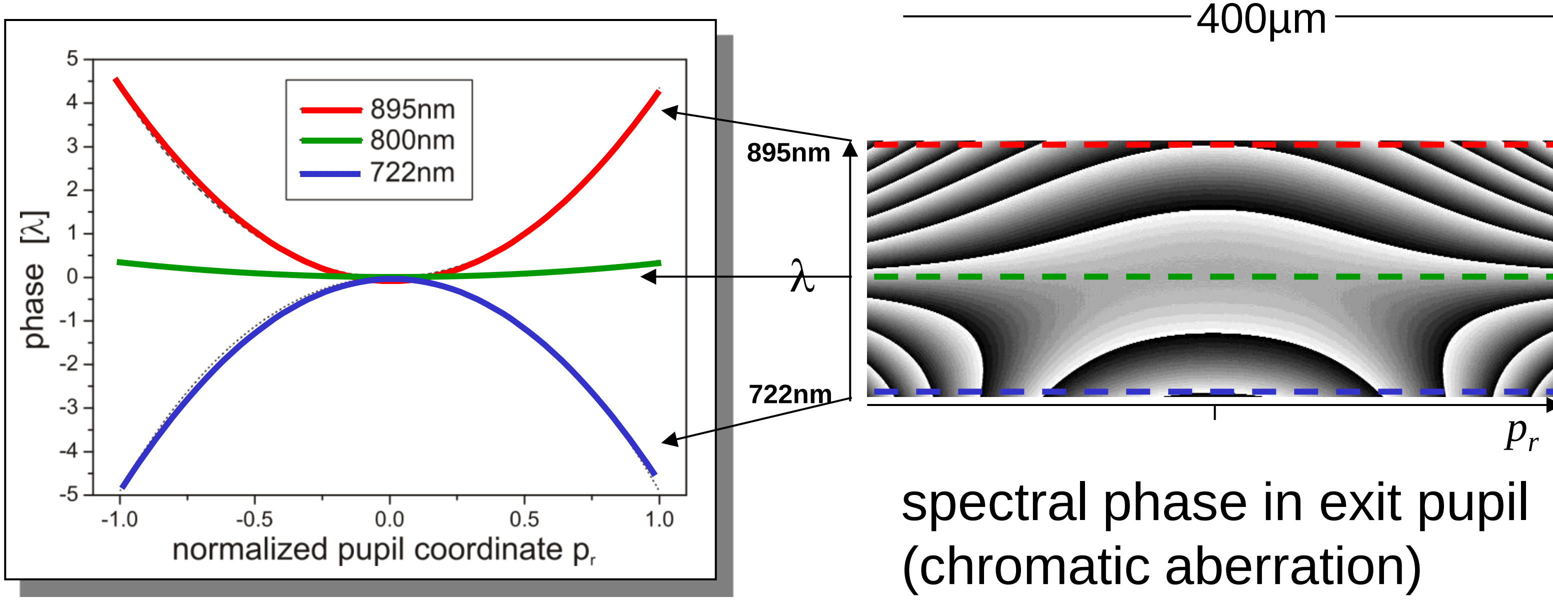
Wide-angle "fisheye" lenses are sometimes required for security and surveillance applications. These lenses require significant number of components. It is also worth noting that the distortion of such lenses can be very significant.

Focusing of a 50fs pulse with an aspheric lens



pulse in the vicinity of the focus





spectral phase in exit pupil
(chromatic aberration)