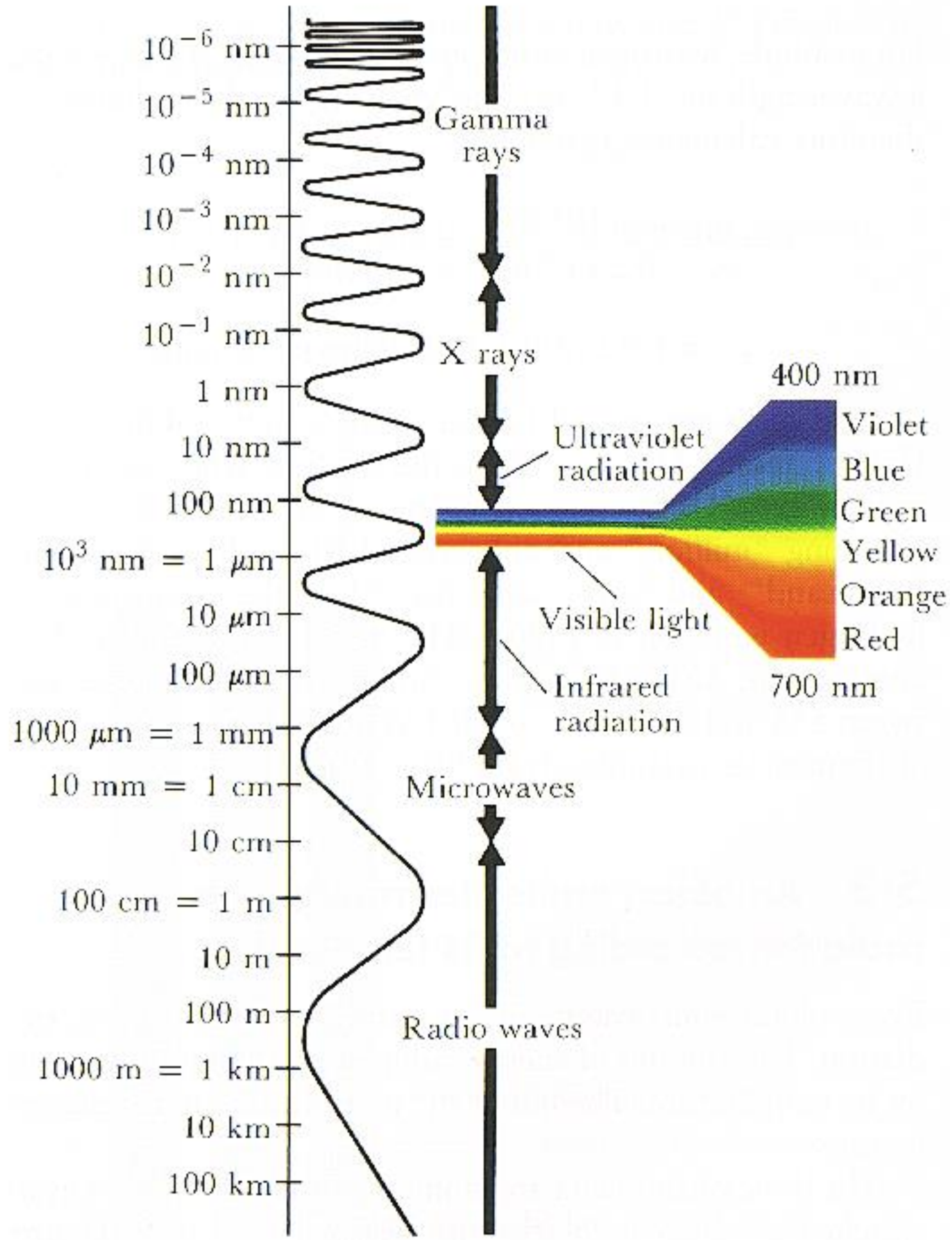
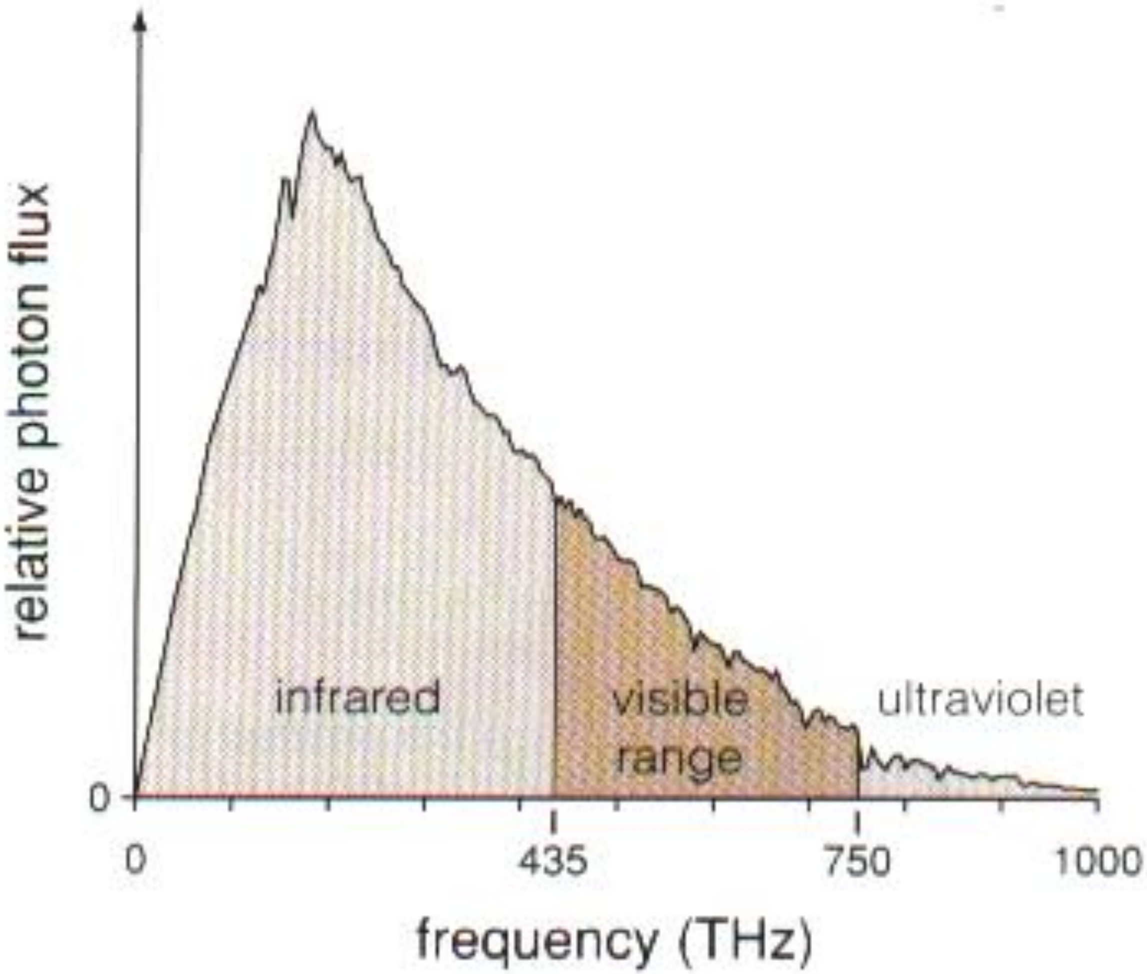
VS 212A Proseminar
Optics and Dioptrics of the Eye

Austin Roorda, PhD

Part 1: Light and Spectra

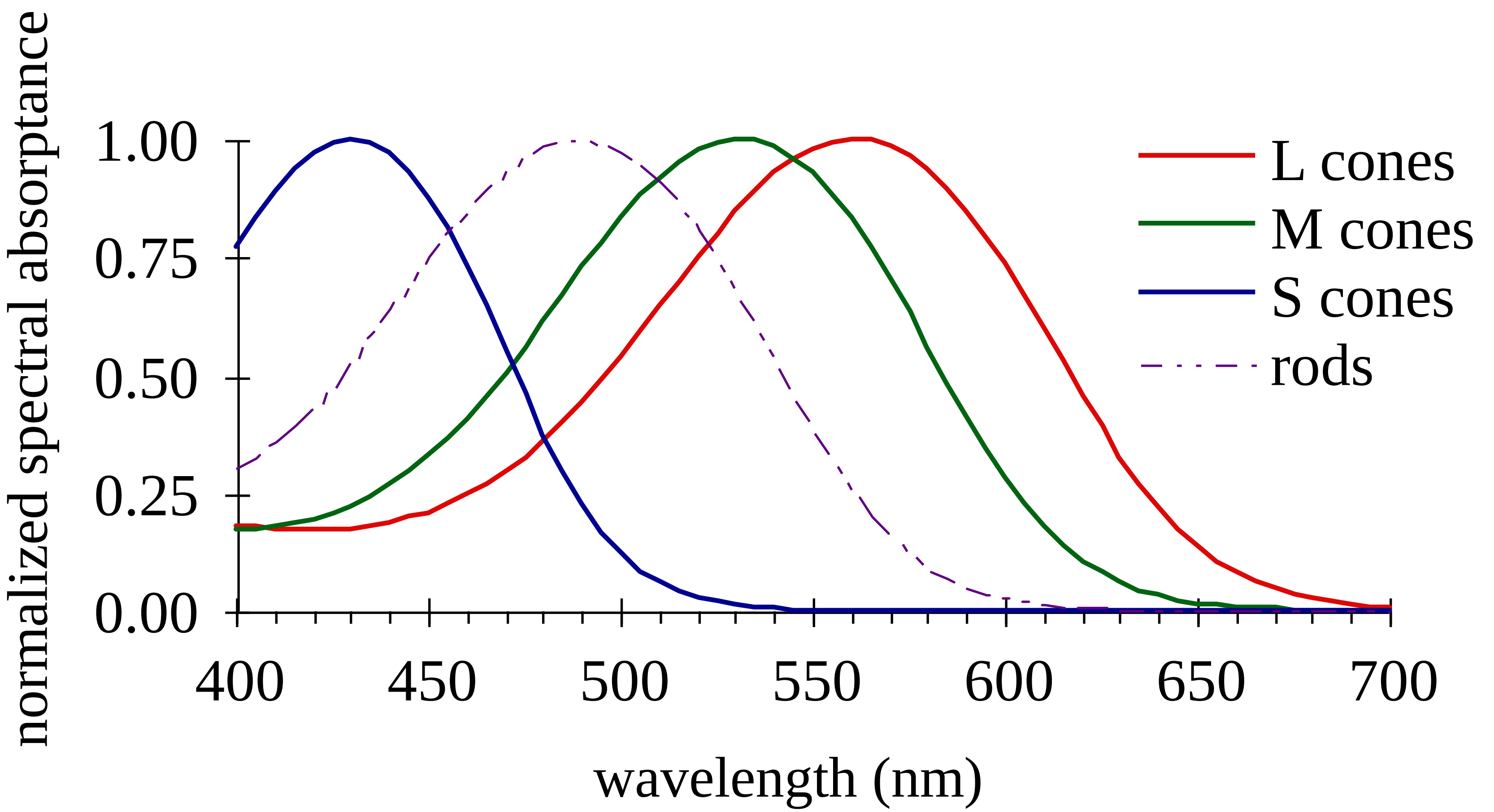


10^{-6} nm
10^{-5} nm
10^{-4} nm
10^{-3} nm
10^{-2} nm
10^{-1} nm
1 nm
10 nm
100 nm
10^3 nm = 1 μm
10 μm
100 μm
1000 μm = 1 mm
10 mm = 1 cm
10 cm
100 cm = 1 m
10 m
100 m
1000 m = 1 km
10 km
100 km
Gamma rays
X rays
Ultraviolet radiation
Visible light
Infrared radiation
Microwaves
Radio waves
400 nm
Violet
Blue
Green
Yellow
Orange
Red
700 nm



Rodieck, B. *The First Steps in Seeing*

Relative Spectral Absorptance



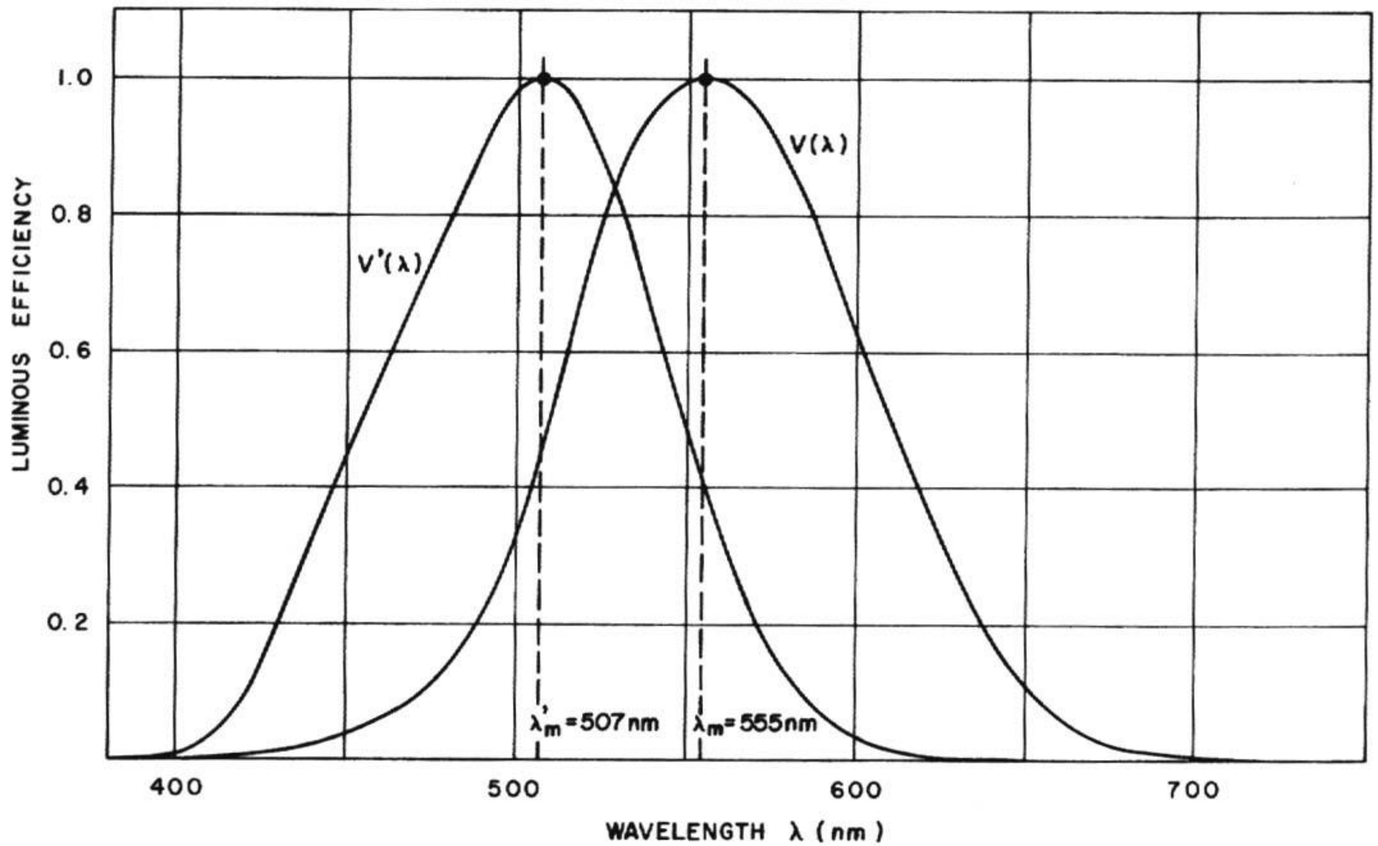
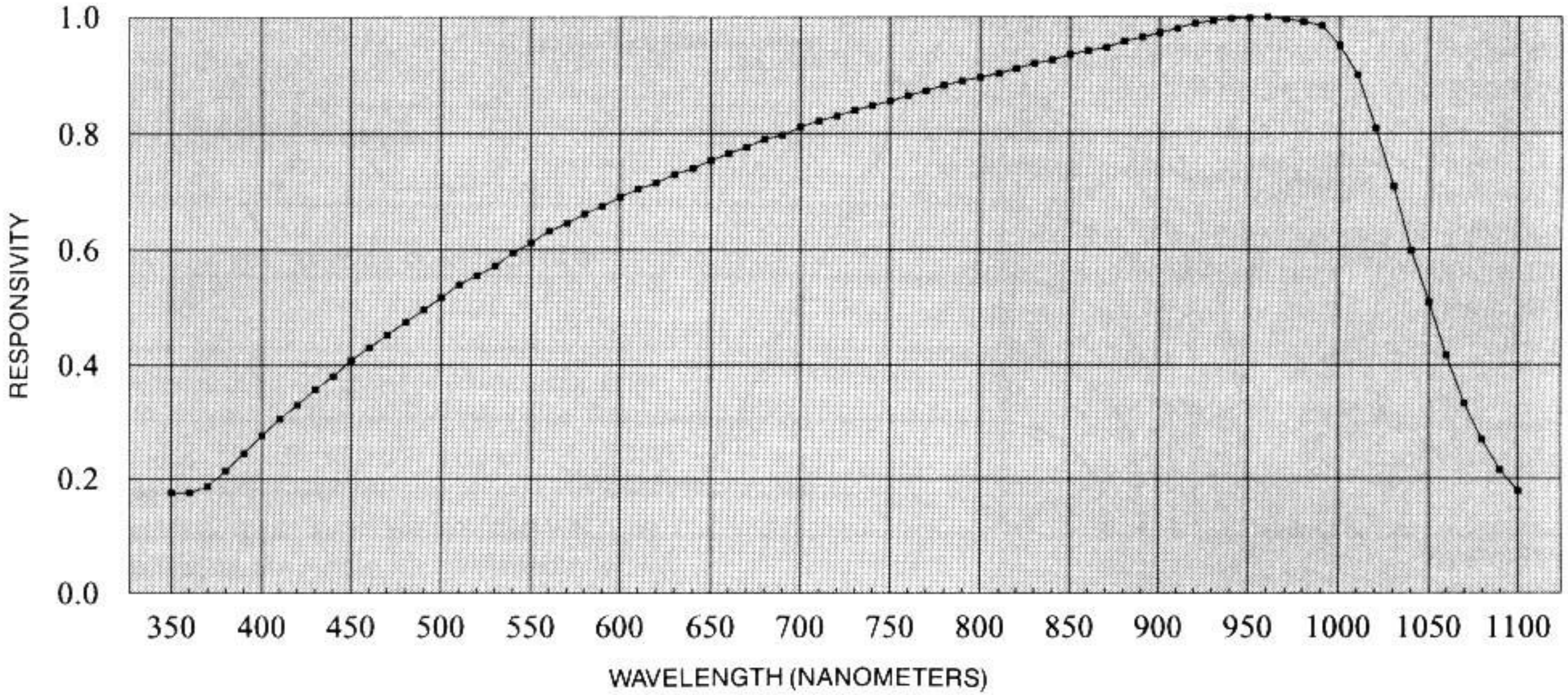


Fig. 1(4.3.2). Spectral luminous efficiency functions $V(\lambda)$ and $V'(\lambda)$ defining the standard photopic and standard scotopic observer, respectively. Each function is normalized to have a maximum value of unity which occurs at $\lambda_m = 555$ nm for $V(\lambda)$ and at $\lambda'_m = 507$ nm for $V'(\lambda)$.

figure from Wyszecki and Stiles, 1982

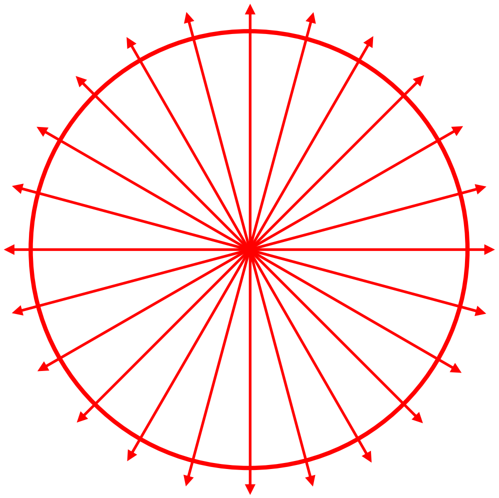
FIGURE 4
SPECTRAL RESPONSIVITY
NORMALIZED TYPICAL SILICON PHOTODIODE



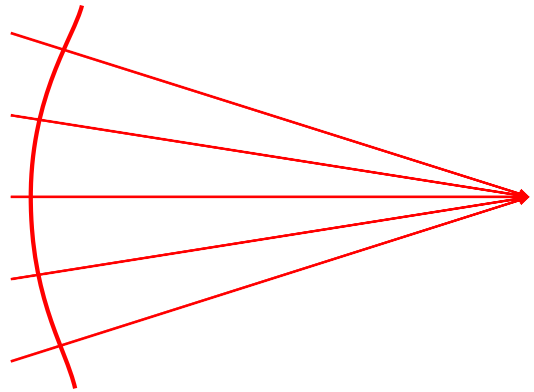
UDT sensors catalog

Part 2: Basic Optics

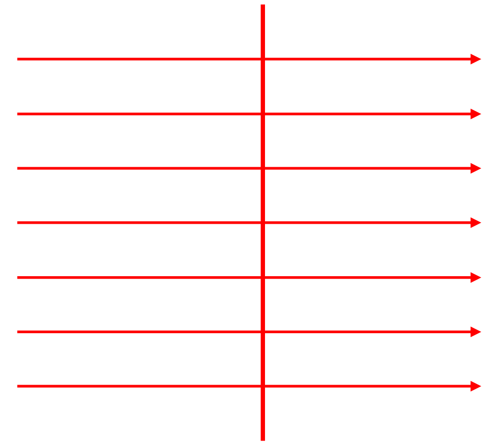
Rays and Wavefronts



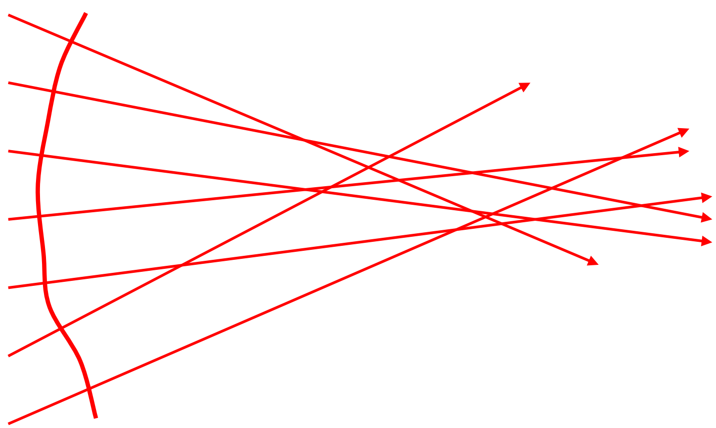
a) Spherical diverging wavefront formed by a point source



b) Spherical converging wavefront formed by a lens



c) Planar wavefront

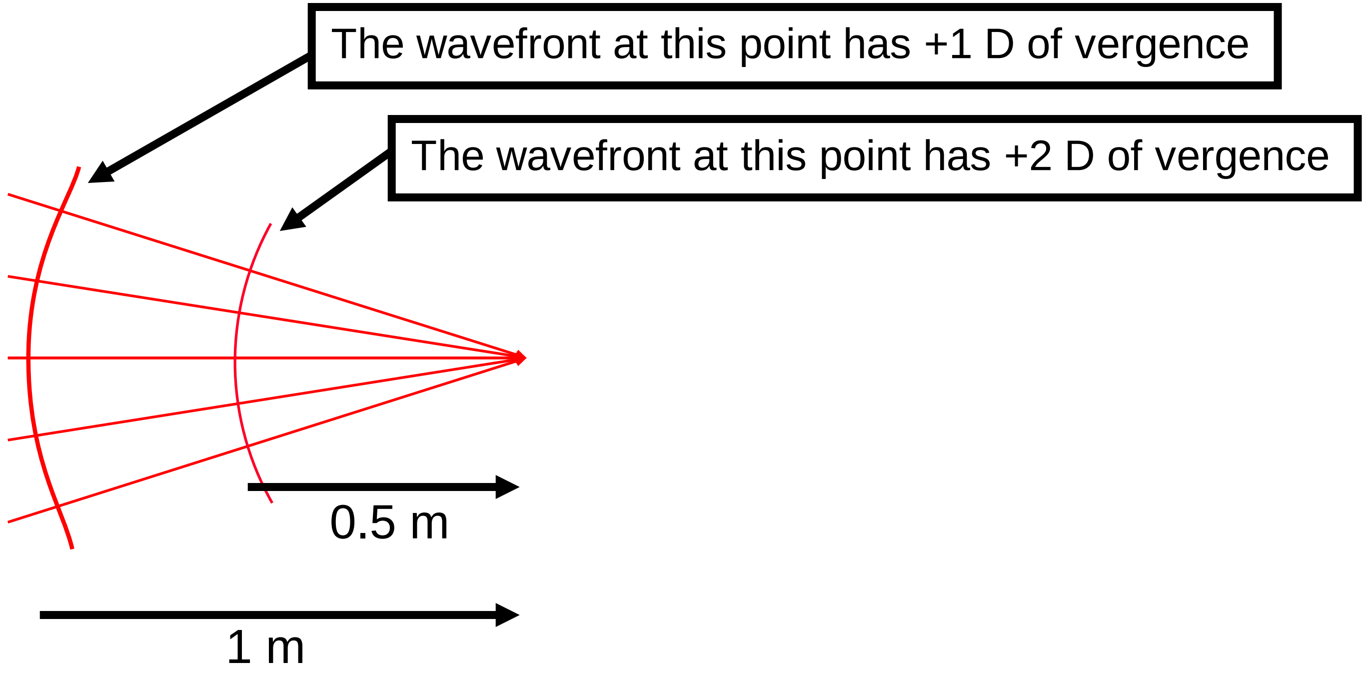


d) Aberrated wavefront

Vergence

- The vergence of a wavefront is equal to the inverse of the distance from the wavefront to its origin, apparent origin, or destination
- Inverse distance in meters has units of diopters [D]

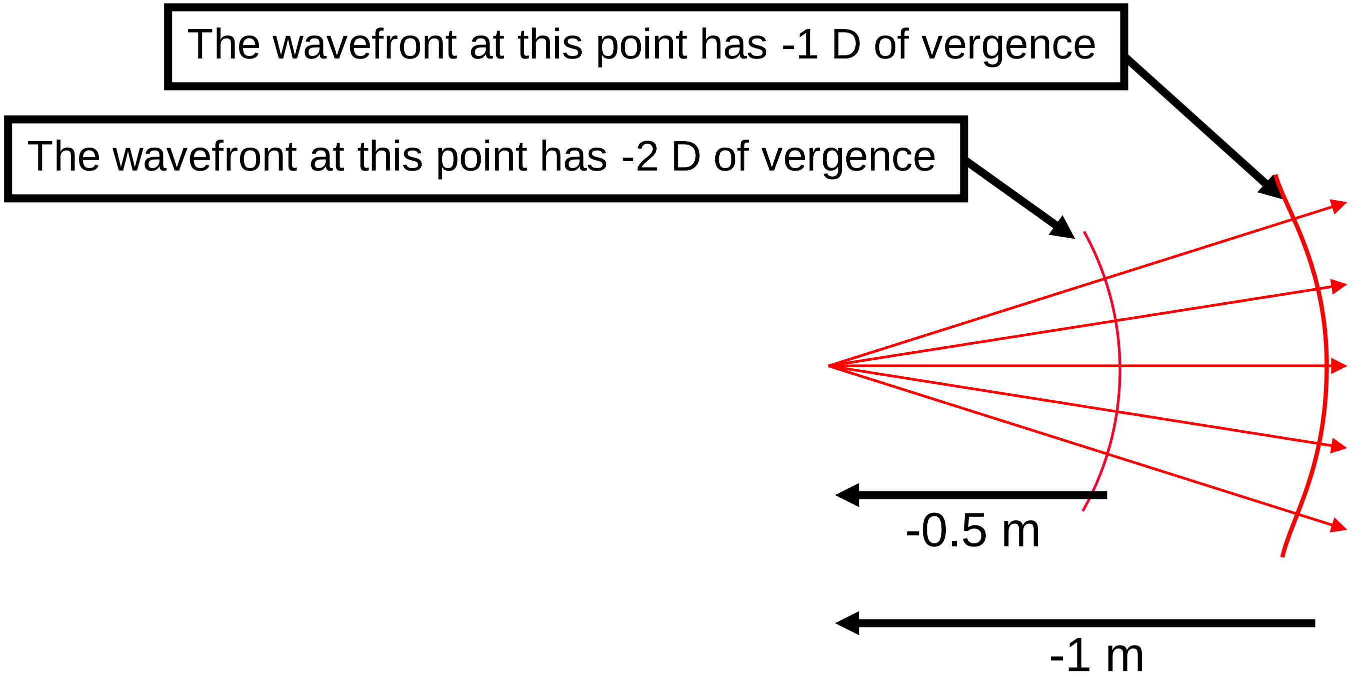
<u>Converging wavefront</u>



Distances measured in the direction of the propagating light are given positive values

Vergence

Diverging wavefront



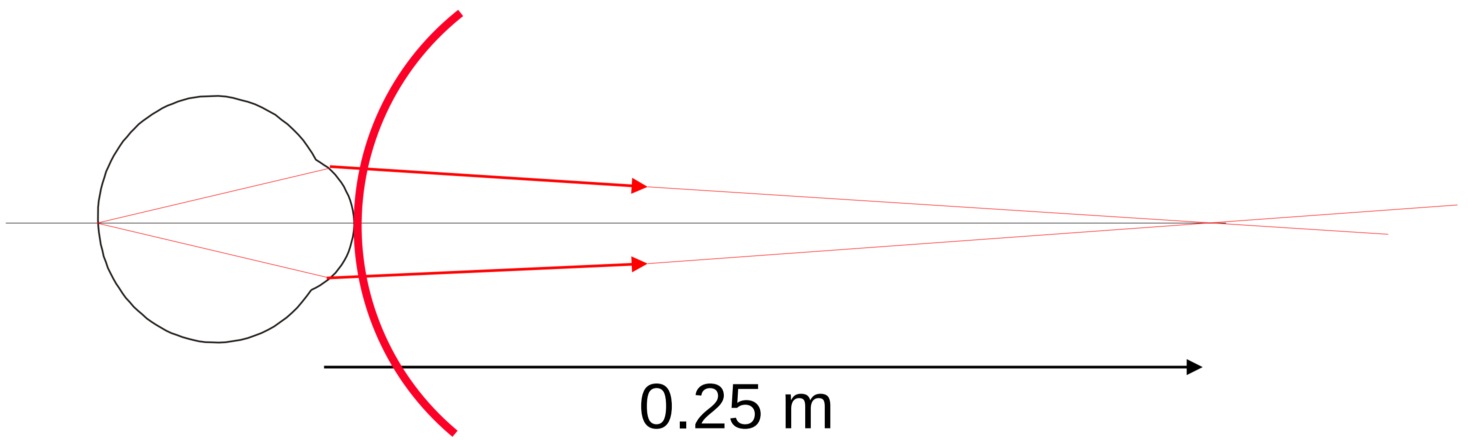
Distances measured against the direction of the propagating light are given negative values

Vergence of an Object

- When an object is placed in front of an observer, it has a vergence that is equal to 1/(distance from eye to object)
- For example, an object held at 25 cm from the eye has -4 D vergence (ie divergent light)

Refractive Error and Vergence

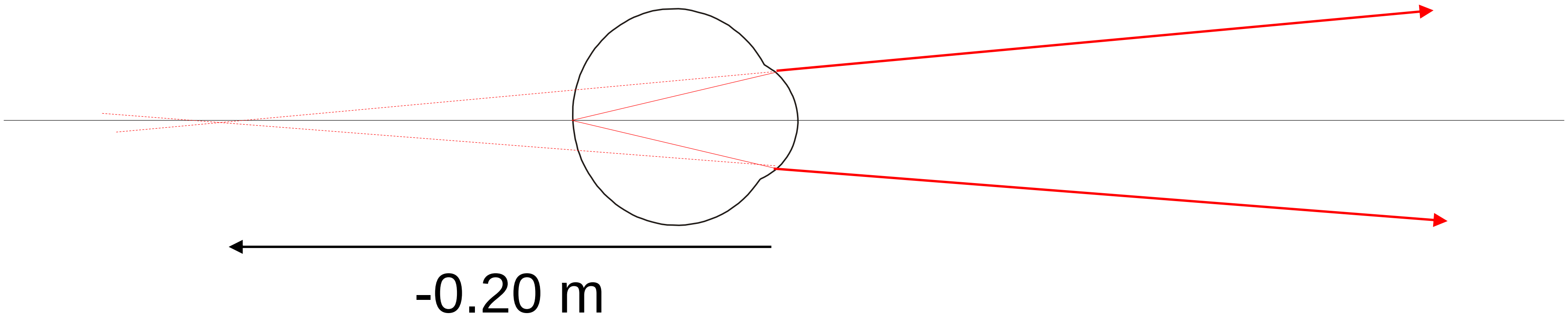
- Your refractive error is -1X the vergence of the wavefront that emerges from a point source on your retina



Vergence is 4 D, refractive error is -4 D (since a -4 D lens is required to correct the error)

Refractive Error and Vergence

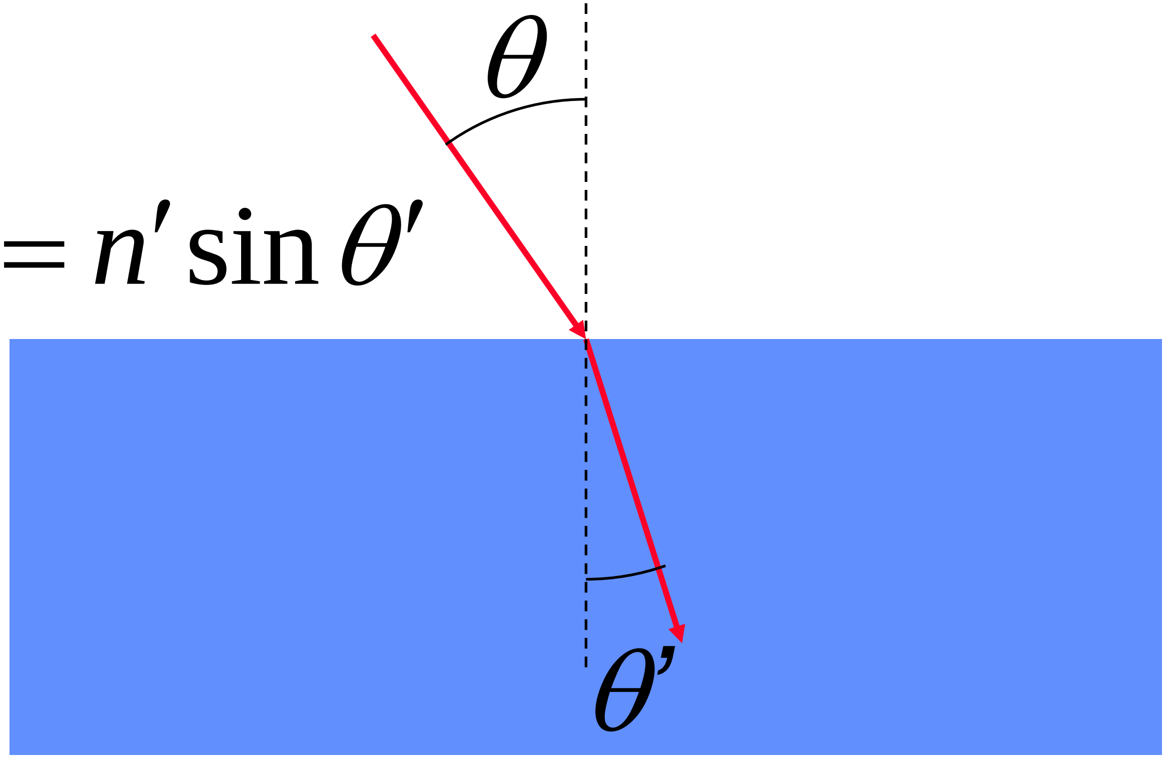
- Your refractive error is -1X the vergence of the wavefront that emerges from a point source on your retina



Vergence is -5 D, refractive error is +5 D (since a +5 D lens is required to correct the error)

Refraction: Snell's Law

$$n \sin\theta = n' \sin\theta'$$

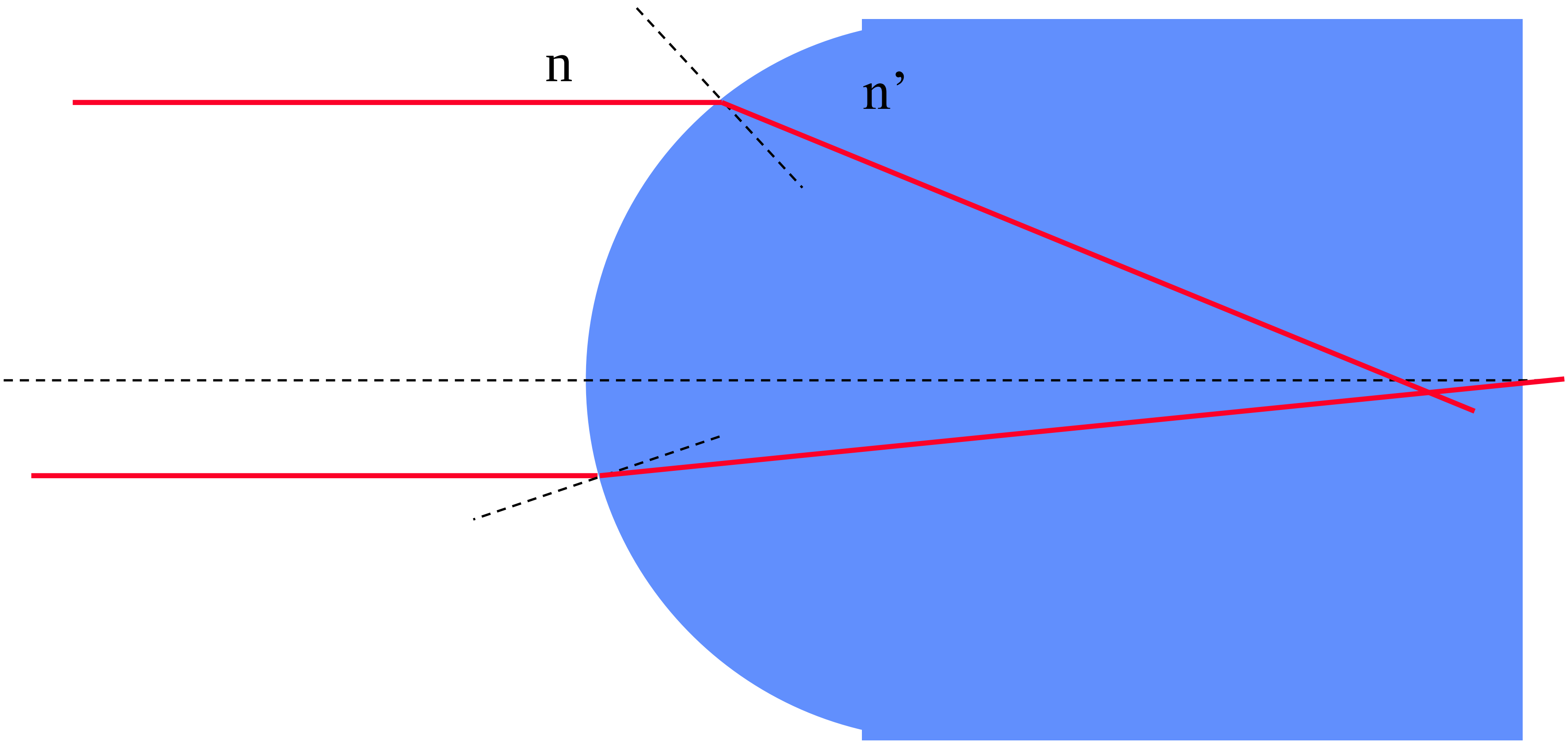


n – index of refraction, *n=1* (vacuum), n~1.5 (glass)

The speed of light in any media is… $\frac{1}{n} \times c$

where c = speed of light in a vacuum = 3×10^8 *m/s*

Application of Snell's Law for Ray Tracing



Light paths through most optical systems can be traced exactly using Snell's Law.

Approximation to Snell's Law

Power series expansion for sin(θ)

$$\sin(\theta) = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \frac{\theta^7}{7!} + ...$$

First order, or paraxial approximation

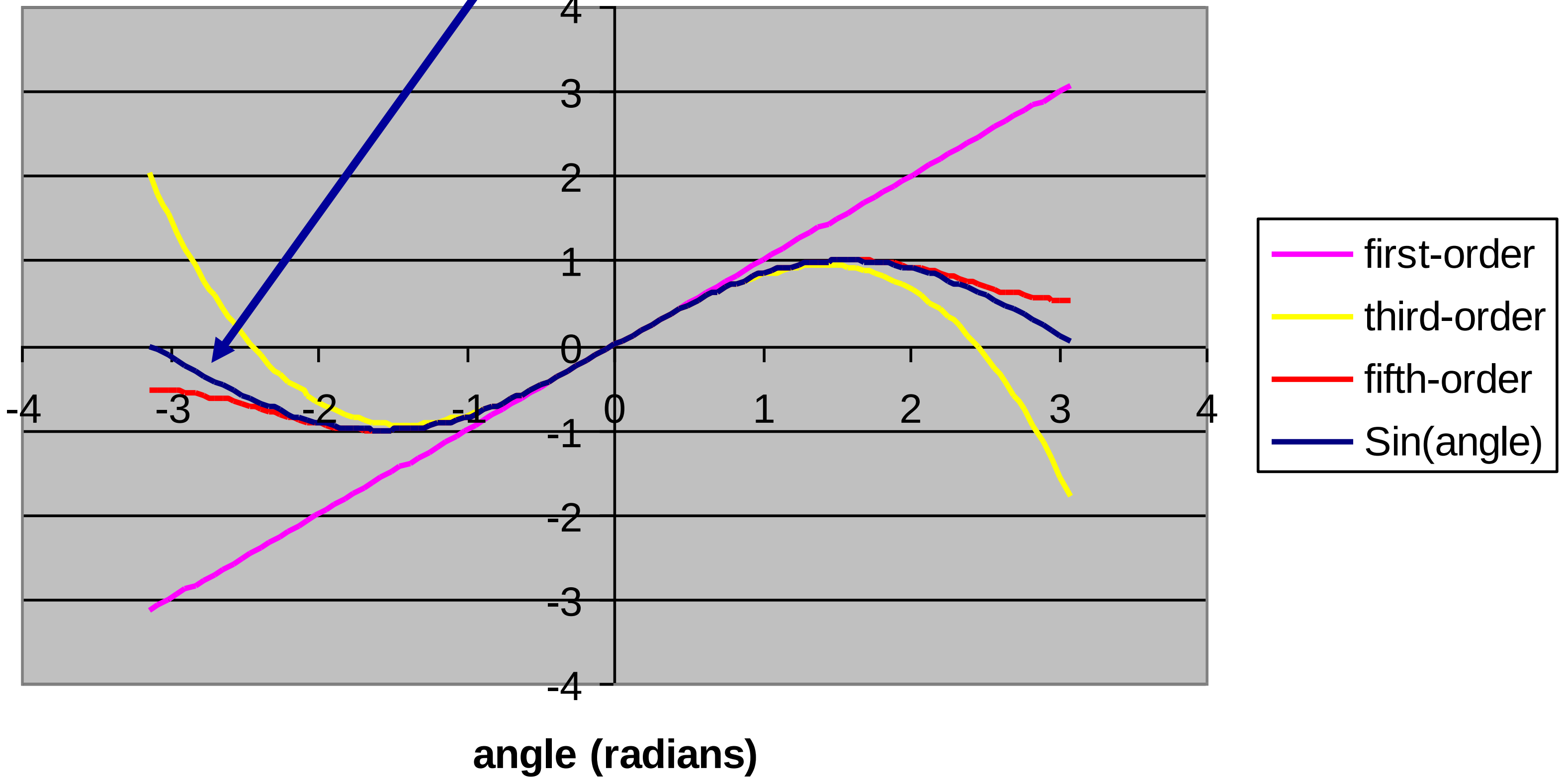
$$\sin\theta = \theta \qquad \Rightarrow \qquad n\theta = n'\theta'$$

Third order approximation (Seidel)

$$\sin\theta = \theta - \frac{\theta^3}{3!} \qquad \Rightarrow \qquad n\left(\theta - \frac{\theta^3}{3!}\right) = n'\left(\theta' - \frac{\theta'^3}{3!}\right)$$

Approximations

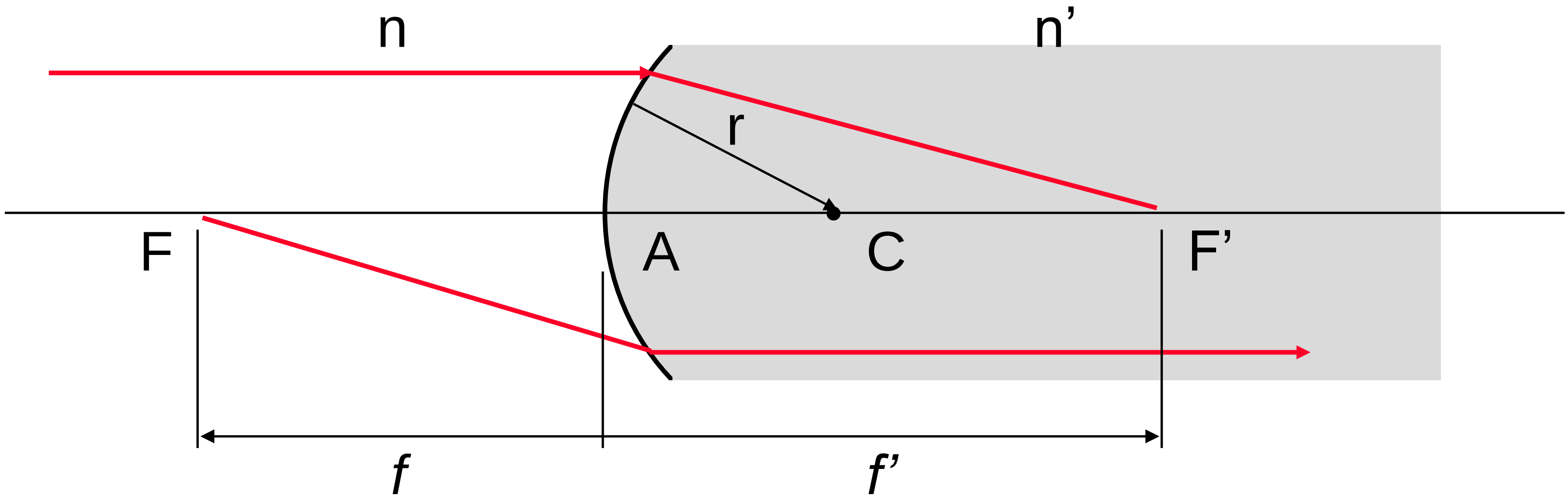
The goal of the approximation is to make a simpler equation that looks like this function



Role of Approximations

- The role of the approximation is to generate predictive relationships for ray paths in simple optical systems without using Snell's Law – based ray tracing
- Gauss (1843) used the first order approximation to compute basic object image relationships for spherical refracting surfaces

Refraction and Image Formation

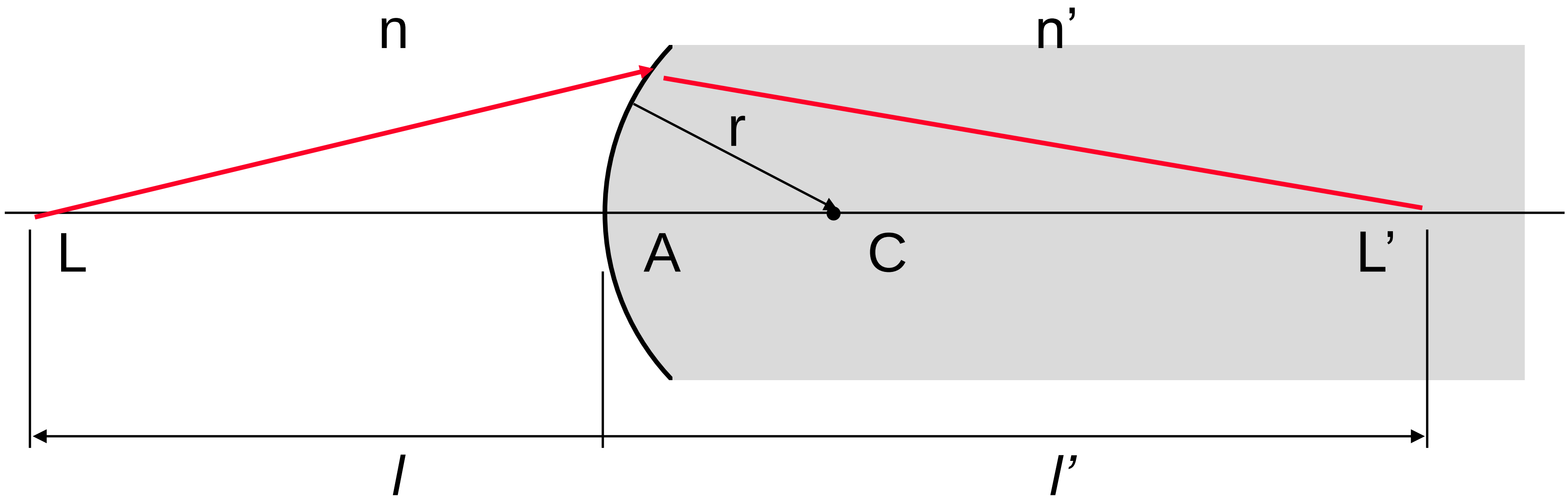


$$F = \frac{-n}{f}$$

$$F' = \frac{n'}{f'}$$

$$R = \frac{1}{r}$$

Refraction and Image Formation



define:

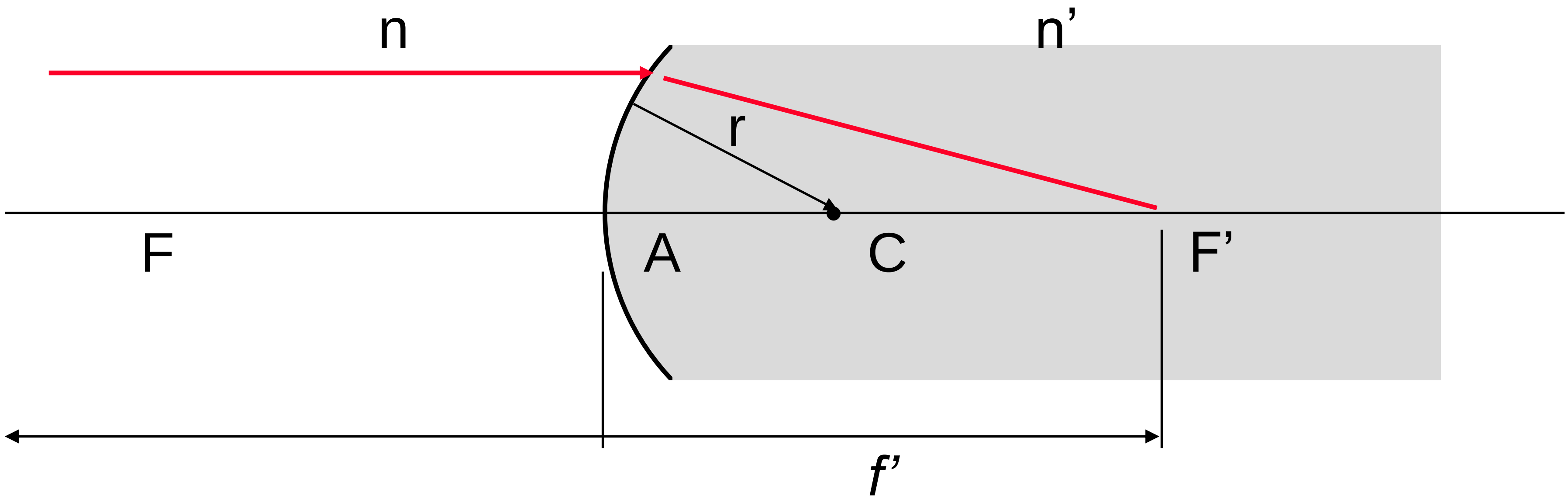
$$\frac{n'}{l'} = \frac{n}{l} + \frac{n'-n}{r}$$

$$L = \frac{n}{l}$$ object vergence at surface

$$L' = \frac{n'}{l'}$$ image vergence at surface

$$L' = L + \frac{n'-n}{r}$$

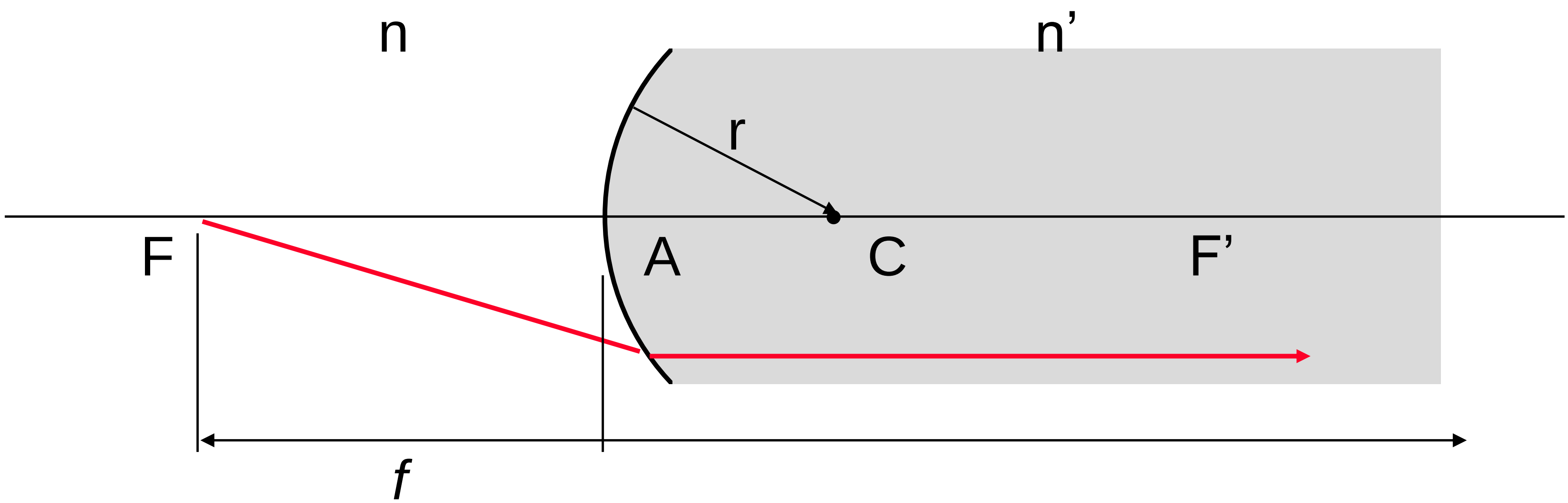
Refraction and Image Formation



special case 1: object at infinity => L = 0 & L'=F'

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

Refraction and Image Formation



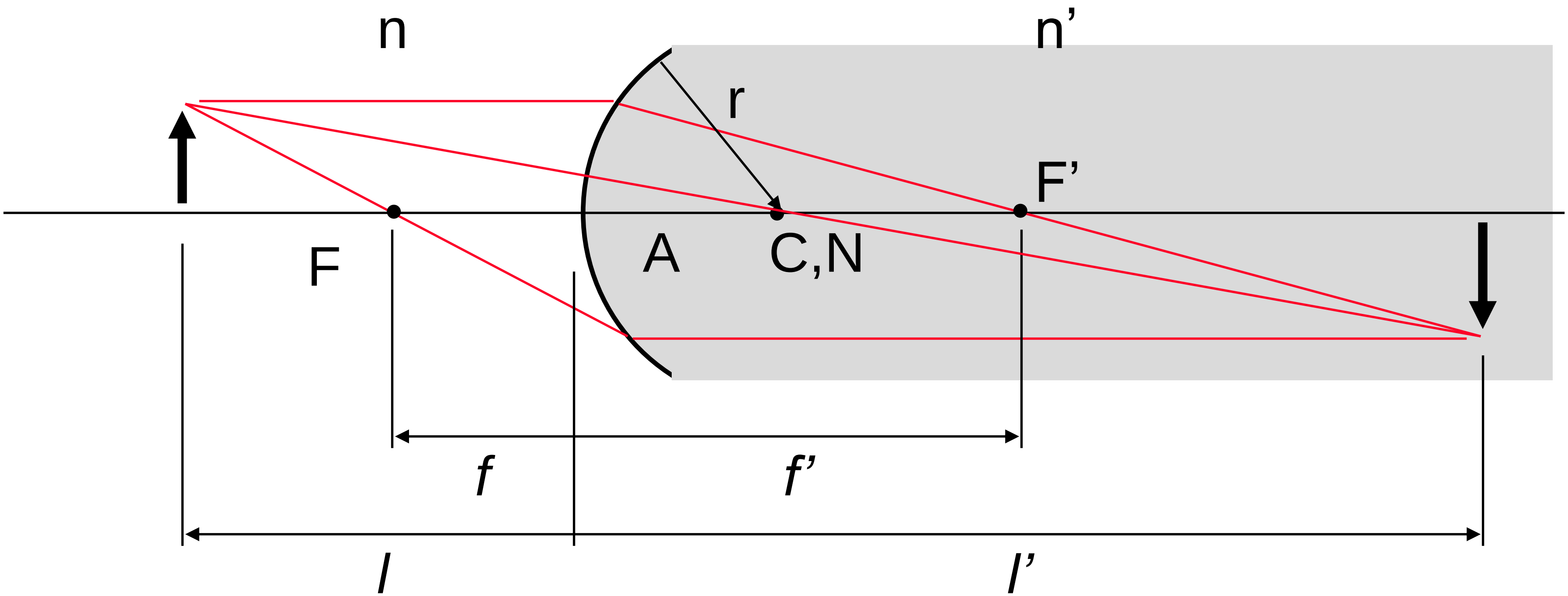
special case 2: image at infinity => L’ = 0 & L=-F

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

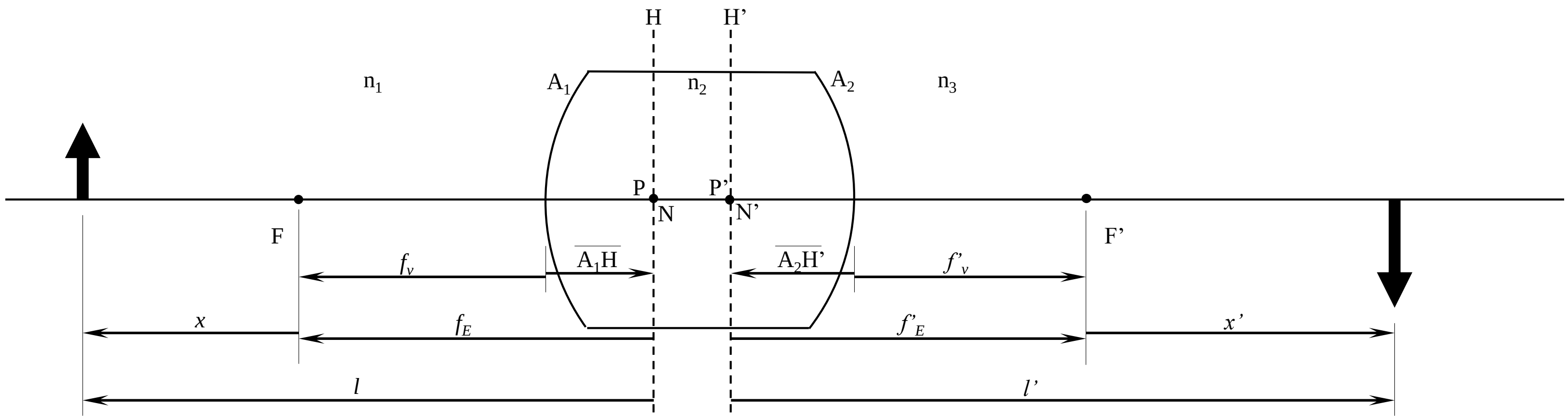
$$L' = L + F'$$

Refraction and Image Formation

Ray tracing



Thick Lenses: Cardinal Points



A_1, A_2….. ≡ first, second…... surface etc.
n_1,n_2,n_3… ≡ index of refraction of 1st 2nd 3rd …... media
H ≡ primary (or first) principal plane
H’ ≡ secondary principal plane
P ≡ primary (or first) principal point
P’ ≡ secondary principal point
N ≡ primary (or first) nodal point *
N’ ≡ secondary nodal point *
F ≡ primary focal point
F’ ≡ secondary focal point
F_1, F_2 …. ≡ power of 1st 2nd…. surfaces
F_E ≡ equivalent power
F_v ≡ front vertex power
F'_v ≡ back vertex power
f_E ≡ primary equivalent focal length
f'_E ≡ secondary equivalent focal length
f_v ≡ first vertex focal length
f'_v ≡ back vertex focal length
l ≡ object distance from first principal plane
l’ ≡ image distance from secondary principal plane
x ≡ distance from primary focal point to object
x’ ≡ distance from secondary focal point to image

$$F_E = F_1 + F_2 - \frac{t}{n_2} F_1 F_2$$

$$F_V = \frac{F_2}{1 - \frac{t}{n_2} F_2} + F_1 = \frac{F_E}{1 - \frac{t}{n_2} F_2}$$

$$F'_V = \frac{F_1}{1 - \frac{t}{n_2} F_1} + F_2 = \frac{F_E}{1 - \frac{t}{n_2} F_1}$$

$$F_E = -\frac{n_1}{f_E} = \frac{n_3}{f'_E}$$

$$F_V = \frac{-n_1}{f_V}$$

$$F'_V = \frac{n_3}{f'_V}$$

$$\overline{A_1H} = f_V - f_E = n_1\left(\frac{t}{n_2}\right)\left(\frac{F_2}{F_E}\right)$$

$$\overline{A_2H'} = f'_V - f'_E = -n_3\left(\frac{t}{n_2}\right)\left(\frac{F_1}{F_E}\right)$$

Keating conventions:

Keating	Class (Freeman)
u,v	l,l’
u_{H1}	l
u_1	l_v
U,V	L,L’
f_f,f_b	f_v,f_v’
F_1,F_2	F,F’
H_1,H_2	H,H’
L_1,L_2	A_1,A_2
neutralizing power	front vertex power

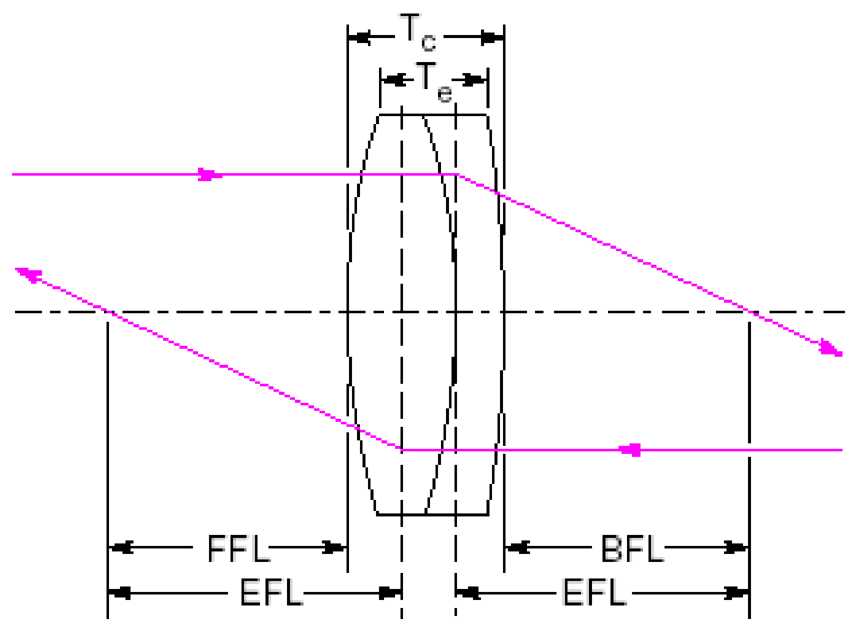
In this example, the thick lens is in air and the nodal points coincide with the principal points. When the image media is different than the object media ($n_3 \neq n_1$) then they do not coincide. We will discuss this in more detail in the lectures.

Thick Lenses and Cardinal Points

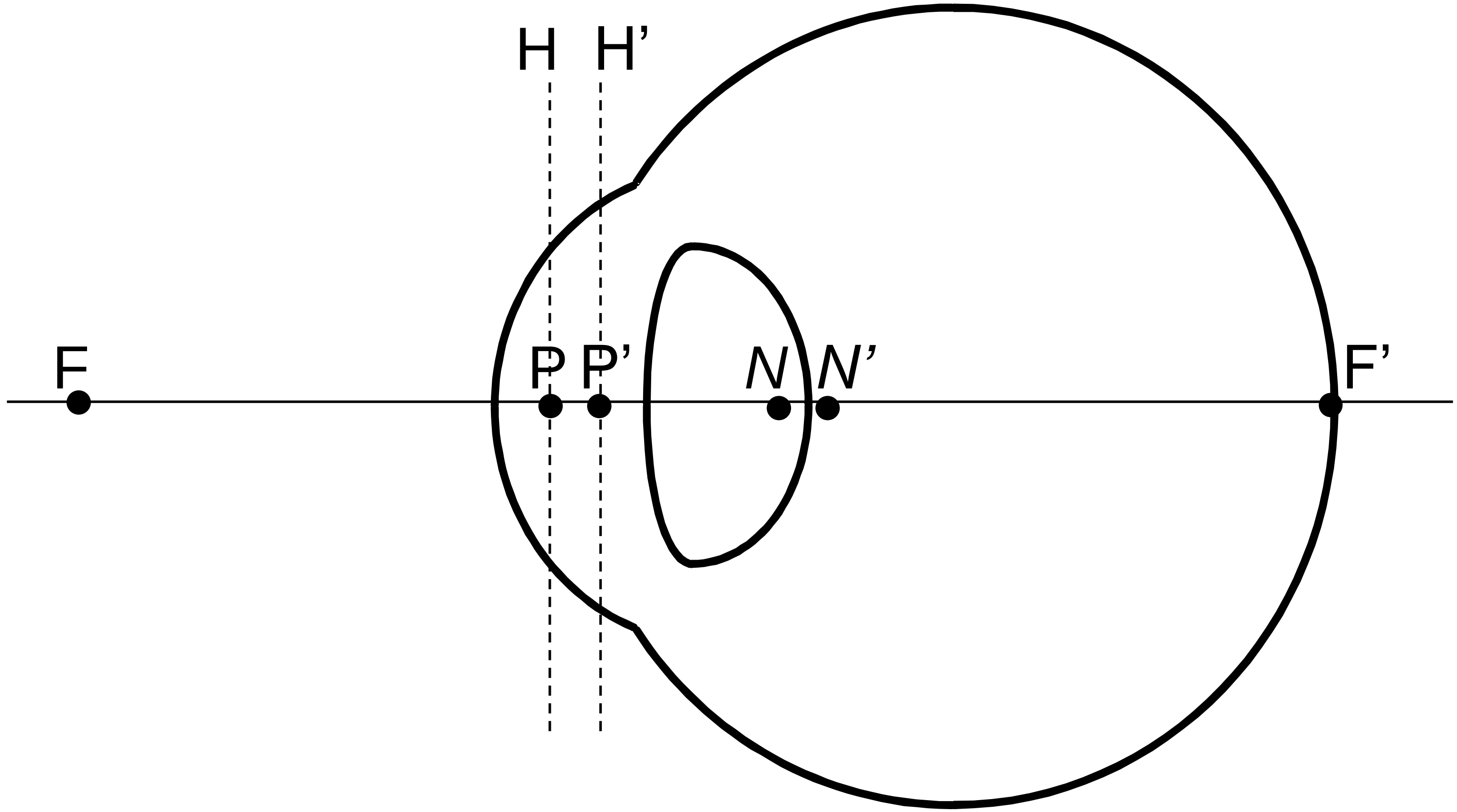
- Paraxial lens formulas can be used as long as object distance are measured from H and image distances are measured from H’ and effective powers are used
- A ray headed toward the first nodal point, emerges from the direction of the second nodal point with the same angle
- Effective power is the inverse of the distance from the principal planes to the focal points. Back and front vertex powers are measured from the lens surfaces

Thick Lenses in Practice (Newport Corp)

Model	Diameter (mm)	EFL (mm)	f/#	BFL (mm)	FFL (mm)	T_c (mm)	T_{c1} (mm)	T_{c2} (mm)	T_e (mm)	R (mm)	R_2 (mm)	R_3 (mm)
PAC010	6.35	12.7	2.0	10.7	12.6	3.4	2.7	0.7	2.7	8.609	-5.134	-57.155
PAC013	6.35	19	3.0	17.4	18.6	3.2	2.2	1.0	2.6	12.020	-9.145	-30.911
PAC016	6.35	25.4	4.0	23.9	24.8	3.0	2.0	1.0	2.5	15.305	-11.266	-33.538
PAC017	6.35	31.8	5.0	29.8	31.6	3.7	2.7	1.0	3.4	22.359	-13.136	-119.838
PAC018	6.35	38.1	6.0	35.7	37.7	4.5	3.0	1.5	4.2	22.841	-19.467	-74.716



Bennett and Rabbetts' Schematic Eye



parameters given in Bennett and Rabbetts 3rd ed p 210

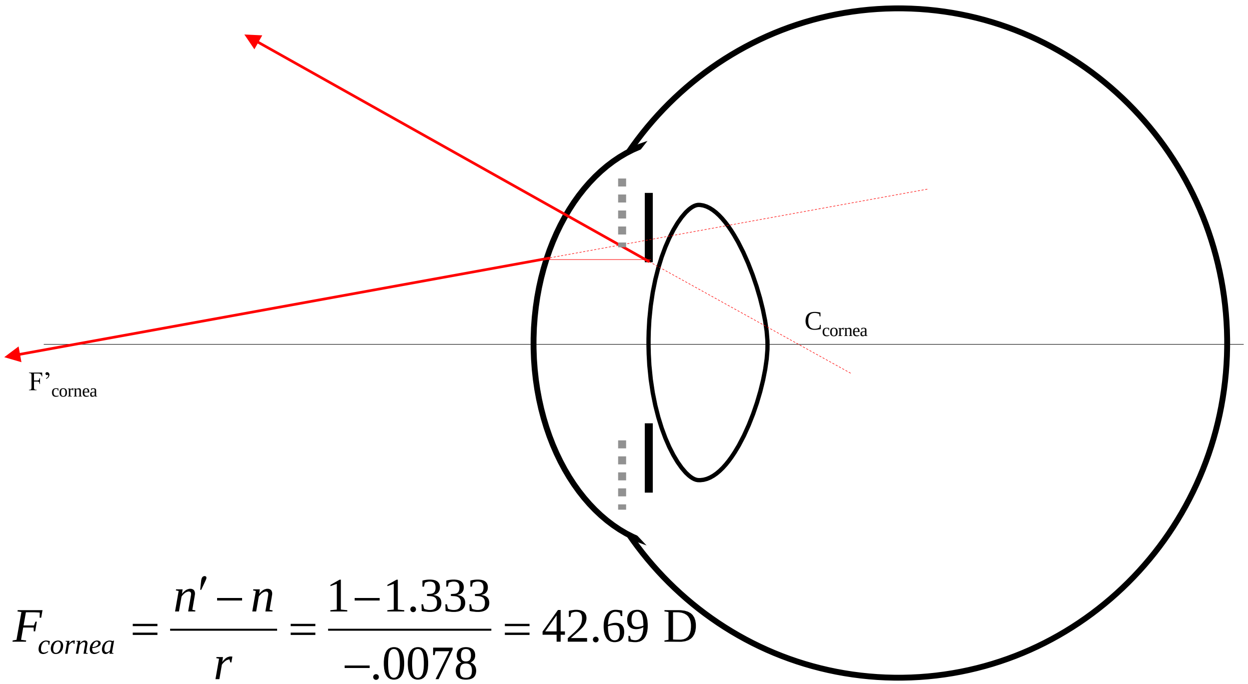
Bennett and Rabbetts' Schematic Eye

Radii of curvature		
Cornea	r_1	+7.80
Crystalline lens: first surface	r_2	+11.00
Crystalline lens: second surface	r_3	-6.47515
Axial separations		
Depth of anterior chamber	d_1	3.60
Thickness of crystalline lens	d_2	3.70
Depth of vitreous body	d_3	16.79
Overall axial length		24.09
Mean refractive indices		
Air	n_1	1
Aqueous humor	n_2	1.336
Crystalline lens	n_3	1.422
Vitreous humor	n_4	1.336
Surface powers		
Cornea	F_1	+43.08
Crystalline lens: first surface	F_2	+7.82
Crystalline lens: second surface	F_3	+13.28
Equivalent powers		
Crystalline lens	F_L	+20.83
Eye	F_o	+60.00
Equivalent focal lengths		
Primary (first) PF	Fo	-16.67
Secondary (second) P'F'	f'o	+22.27
Distances from corneal vertex		
First principal point	A_1P	+1.51
Second principal point	A_1P'	+1.82
First nodal point	A_1N	+7.11
Second nodal point	A_1N'	+7.42
Entrance pupil	A_1E	+3.05
Exit pupil	A_1E'	+3.70
First principal focus	A_1F	-15.16
Second principal focus	A_1F'	+24.09
Refractive state		0

Apertures and Stops

- The ***aperture stop*** in system is the main light limiting aperture for on-axis objects
- The ***entrance pupil*** is the aperture stop as seen from object space (imaged through the optics prior to it)
- The ***exit pupil*** is the aperture stop as seen from image space (imaged through the optics that follow it)
- In the eye the aperture stop is the pupil. The entrance pupil is what you see when you looks at someone’s eye (the real pupil is actually a bit smaller and bit further away than it appears)
- The ***Chief Ray*** is the ray that goes through the center of the entrance pupil (it will also go through the center of the actual pupil). It defines the center of the blur in the presence of defocus.

Entrance Pupil for the Human Eye



Cornea: radius of curvature: 7.8 mm

Pupil: 3.6 mm from corneal vertex

Pupil diameter: 6 mm

Cornea diameter: 15 mm

index inside eye: 1.333

$$F_{cornea} = \frac{n' - n}{r} = \frac{1 - 1.333}{-.0078} = 42.69 \text{ D}$$

for the pupil

$$l = -.0036 \text{ m} \quad \Rightarrow \; L = \frac{1.333}{-0.0036} = -370.28 \text{ D}$$

$$L' = L + F$$

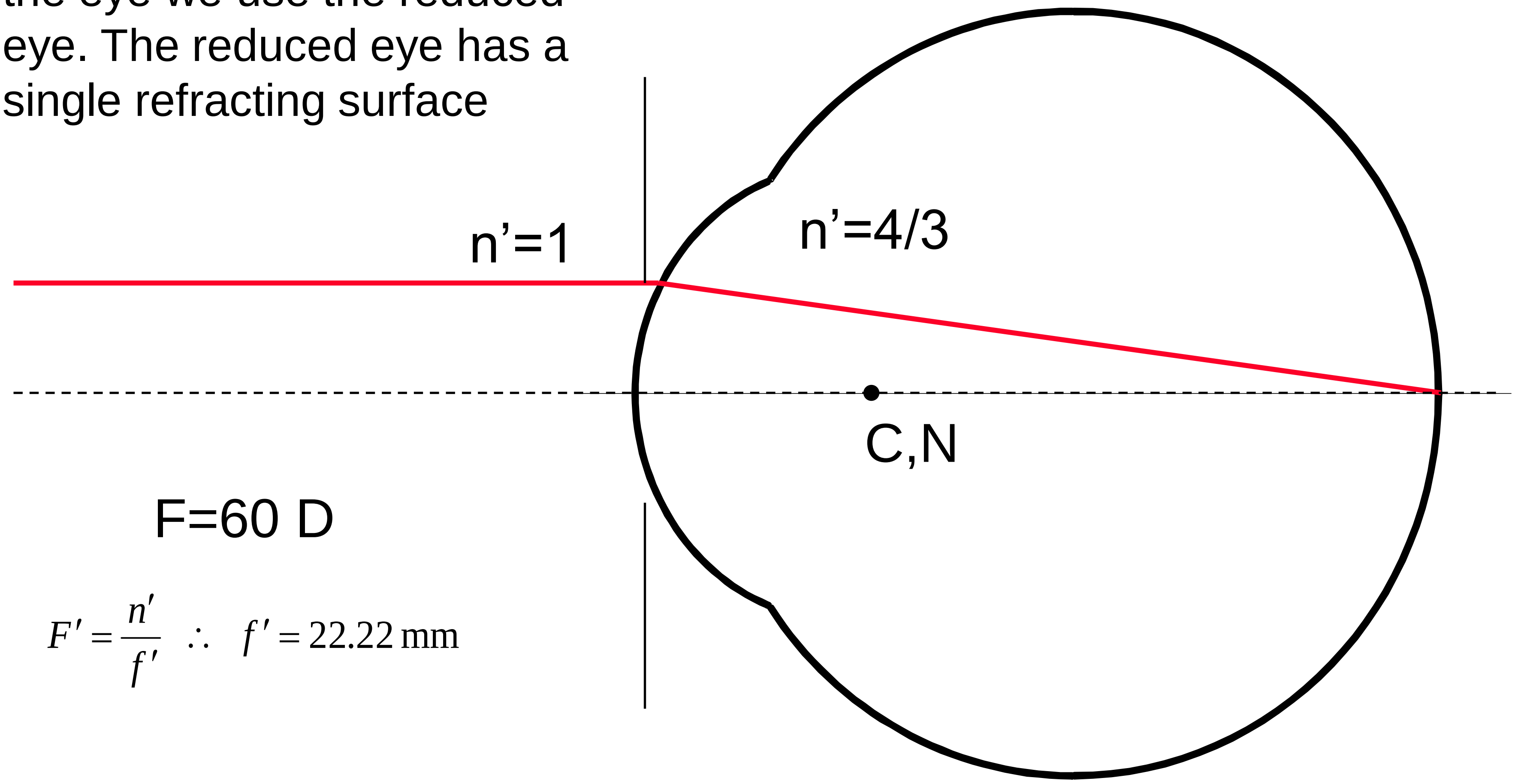
$$L' = -370.28 + 42.69 = -327.59 \text{ D}$$

$$l' = -3 \text{ mm}$$

lateral magnification is $\dfrac{L}{L'} = \dfrac{-370.28}{-327.59} = 1.13$

Reduced Eye Model

To simplify image formation in the eye we use the reduced eye. The reduced eye has a single refracting surface



F=60 D

$$F' = \frac{n'}{f'} \quad \therefore \quad f' = 22.22\,\text{mm}$$

Reduced Eye Model

$$L' = L + F$$

By convention, in the human eye

$$K' = K + F_e \quad \Rightarrow \quad K = K' - F_e$$

In the reduced eye,
k (far point) and k' are measured from the refracting surface.

Whenever k' is equal to the distance from the refracting surface to the retina, then k is equal to the far point of the eye, and K is equal to the refractive error of the eye.

If, under these conditions, k is at infinity, then the eye is considered to be emmetropic

Part 3: Optics of the Eye

Components of the human optical system

Cornea (first surface)

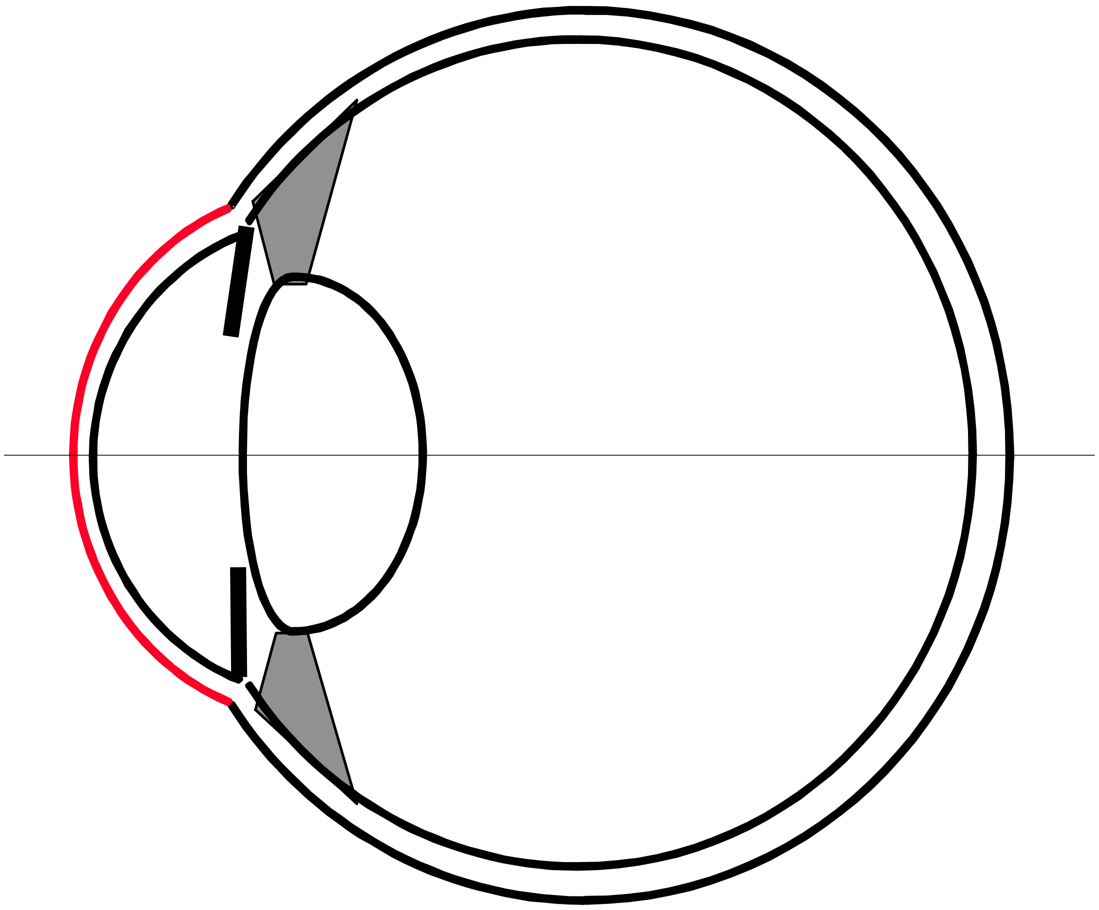
transition from air (n =1)
to front surface of
cornea (n = 1.376)

radius of curvature = 7.7 mm

power: $$F' = \frac{n' - n}{r}$$

$$= \frac{1.376 - 1}{.0077}$$

$$= +48.83 \text{ D}$$



Components of the human optical system

Cornea (second surface)

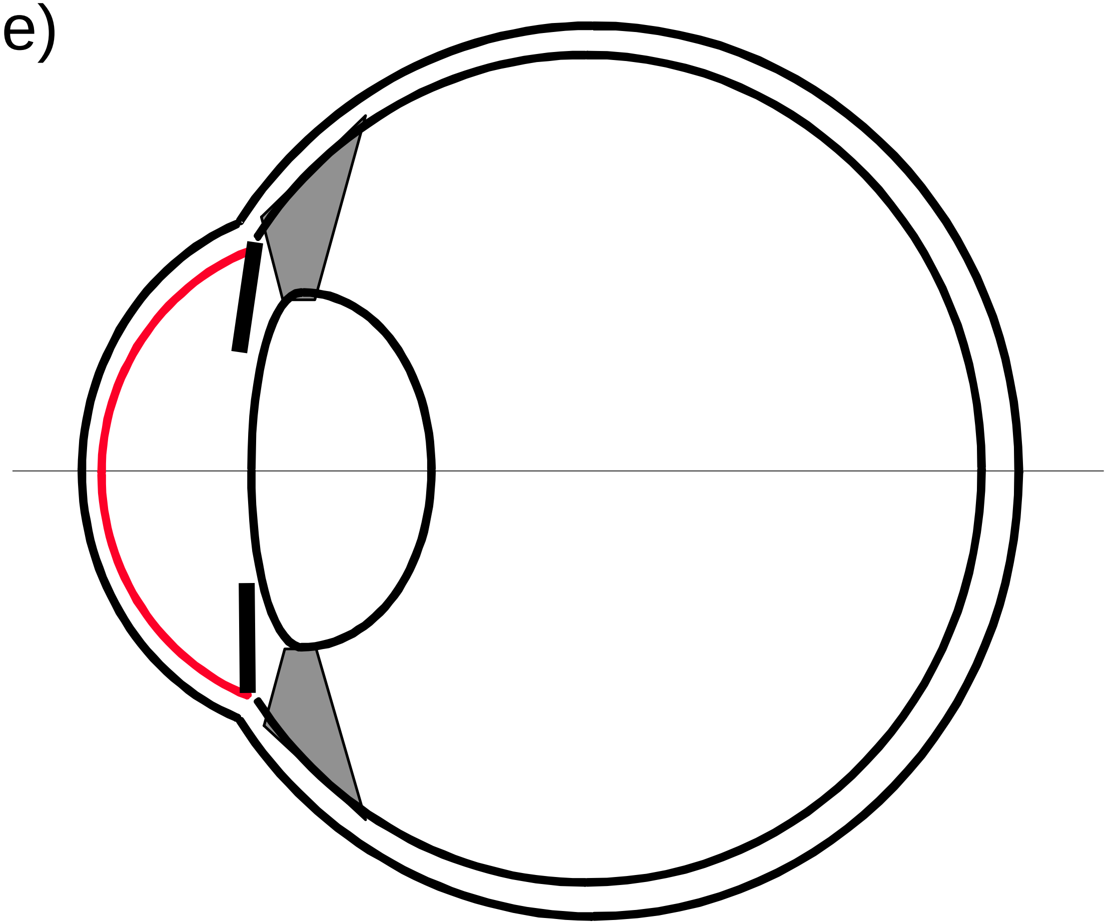
Transition from back surface of cornea (n = 1.376) to the aqueous humor (n = 1.336) radius of curvature = 6.8 mm

power:

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

$$= \frac{1.336 - 1.376}{.0068}$$

$$= -5.88\,\mathrm{D}$$



total power of cornea ~ +43 D

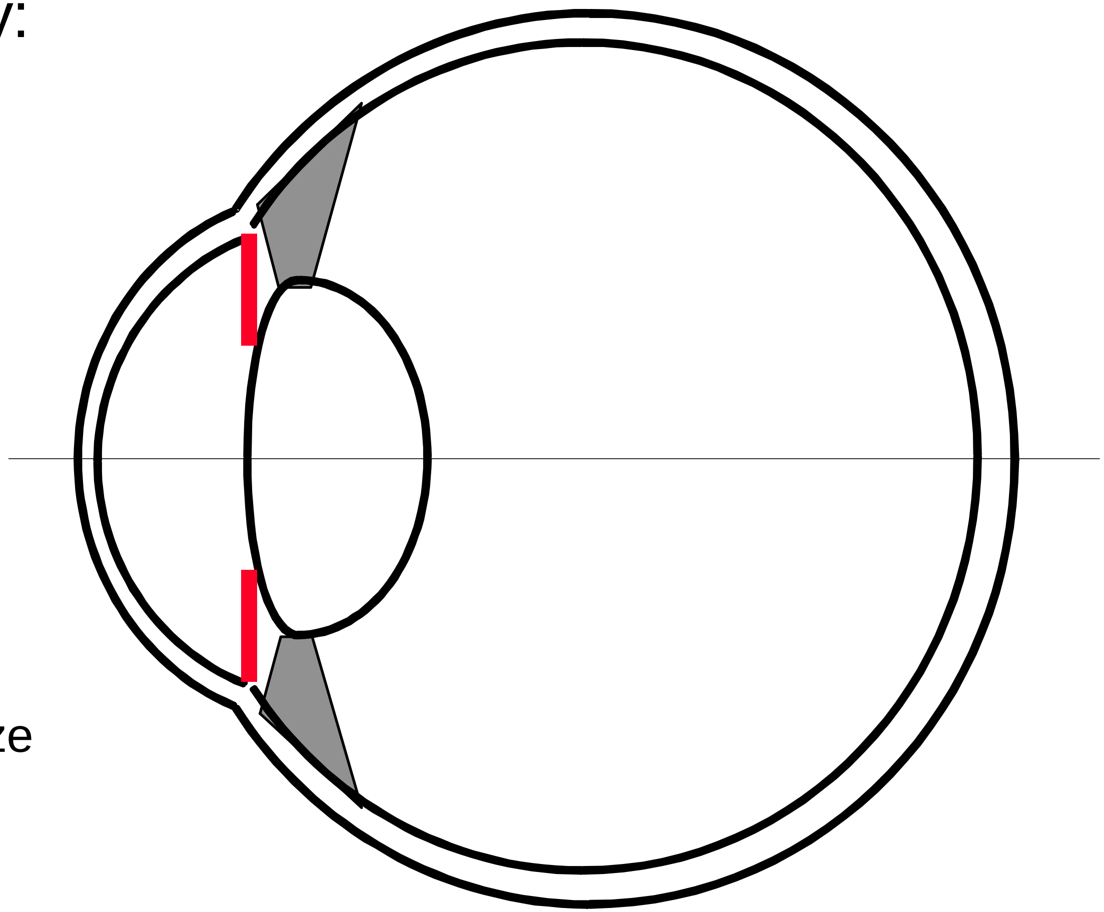
Components of the human optical system

The Pupil is affected by:

Light conditions
Attention
Emotion
Age

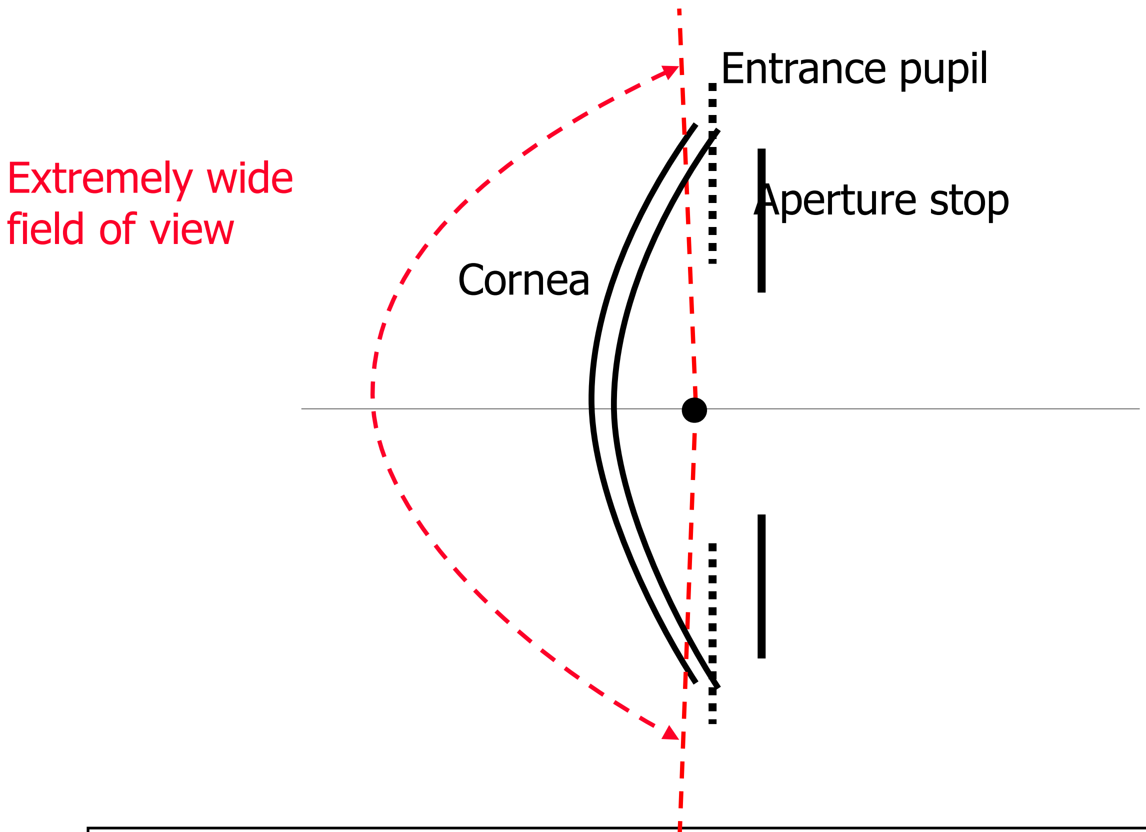
Function:

Govern image quality
Depth of focus
Control light level?
The pupil is located to maximize the field of view of the eye



1.3 Components of the human optical system

The pupil is perfectly located to maximize the field of view of the eye



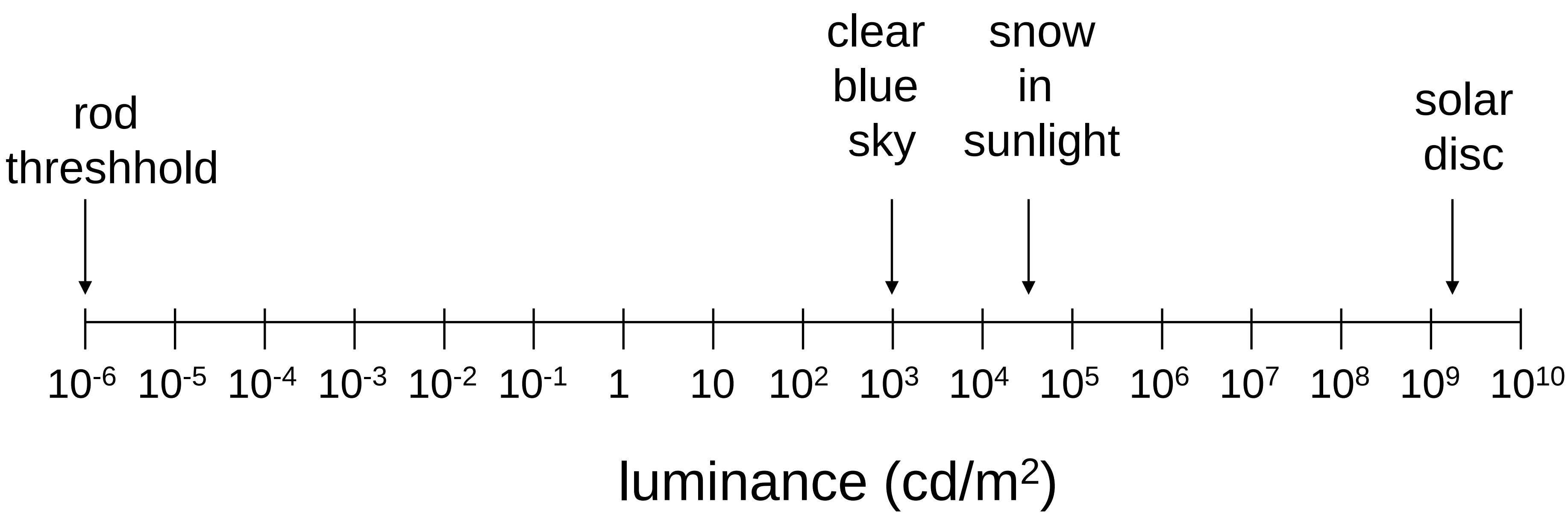
Recall that the ½-illumination field of view is defined as the angle subtended from the center of the entrance pupil to the edges of the field stop.

Factors affecting pupil size

- Stimulus Variables
  - light level
  - spectral composition
  - spatial configurations
    - field size
    - spatial structure of field
  - monocular/binocular view
  - accommodative state
  - non-visual stimuli
    - pain
    - noise
- Observer Variables
  - individual differences
  - age
  - day-to-day within observer variance
  - biomechanical factors
    - respiration
    - heart beat
  - cognitive factors
    - arousal, attention, fright
    - workload
    - hedonistic content

Pokorny and Smith, 1997

The range of light intensities in the environment is enormous!



Rodieck, B. *The First Steps in Seeing*

Components of the human optical system

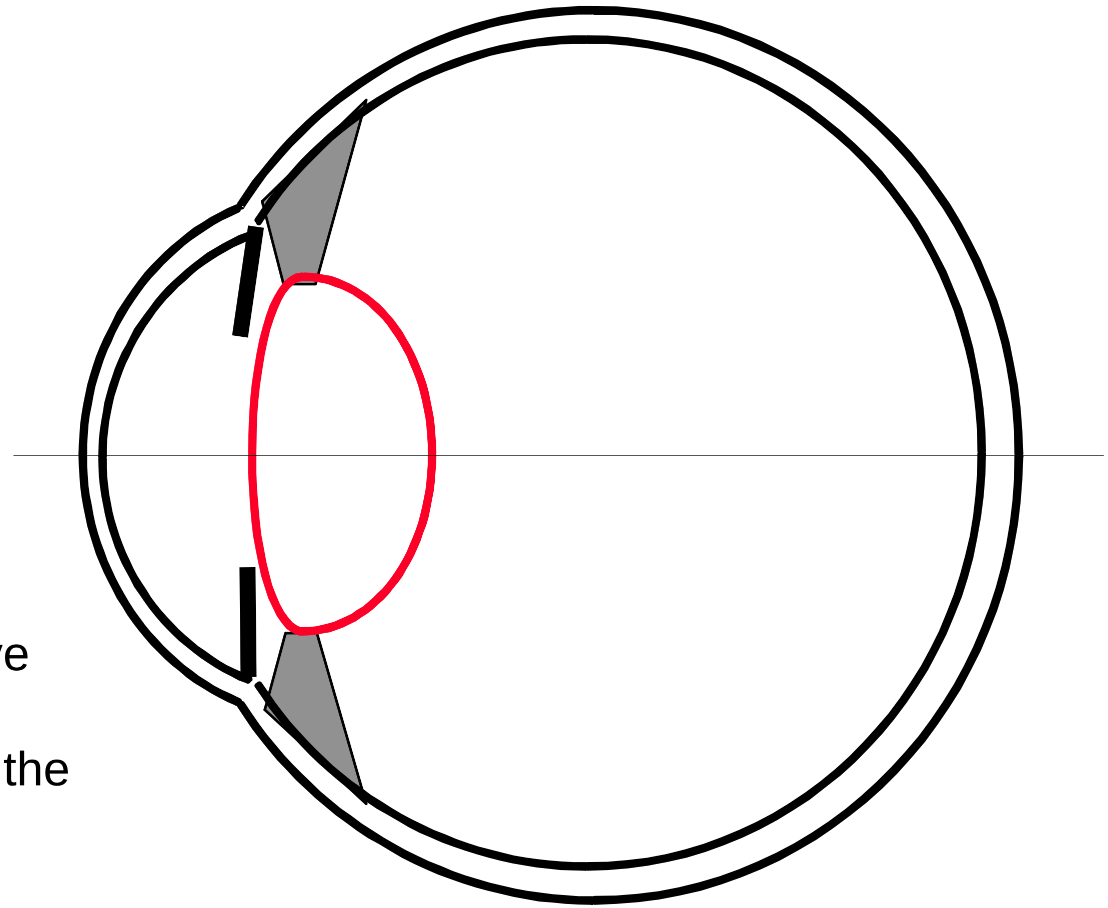
Crystalline Lens

Gradient index of refraction
n = 1.385 at surfaces
n = 1.375 at the equator
n ~= 1.41 at the center

Little refraction takes place at the surface but instead the light curves as it passes through.

For a homogenous lens to have same power, the overall index would have to be greater than the peak index in the gradient.

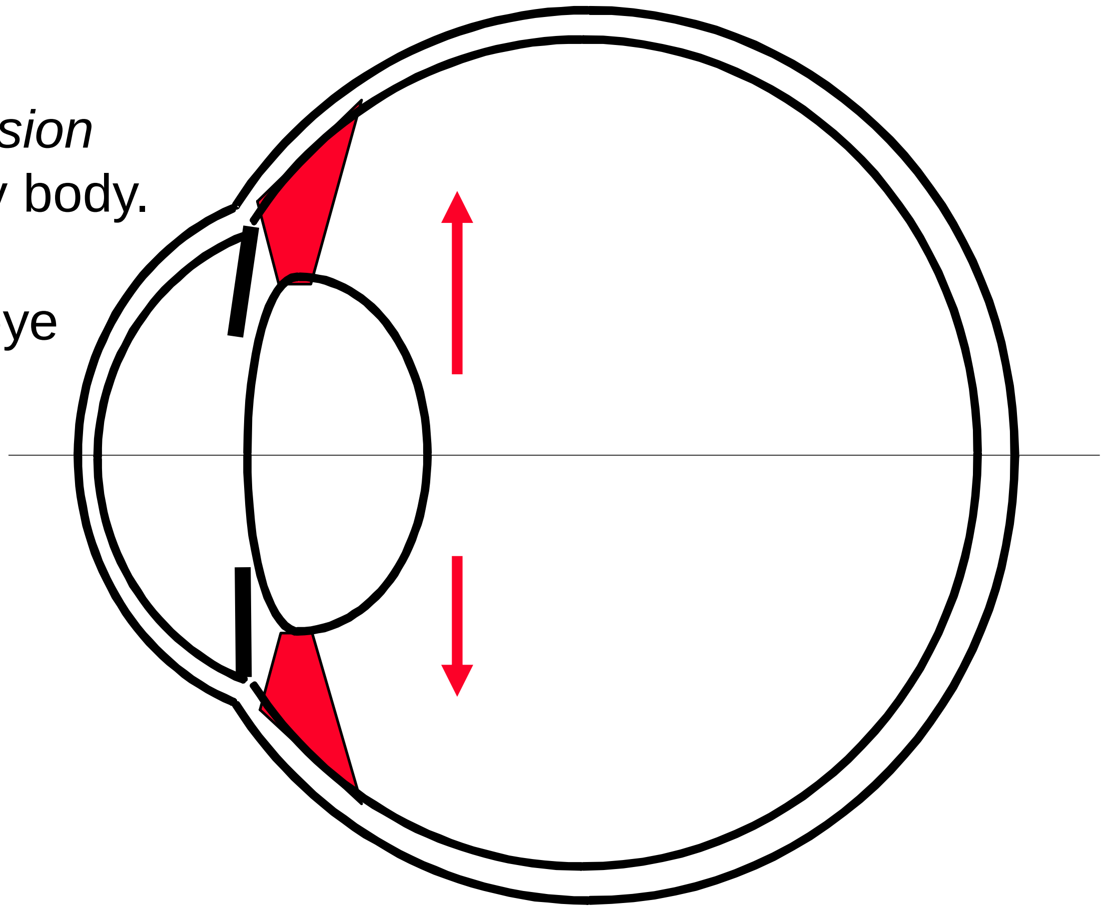
total power of lens ~= 21 D



Components of the human optical system

Accommodation

The relaxed eye is under *tension*
at the equator from the ciliary body.
This keeps the surfaces flat
enough so that for a typical eye
distant objects focus on
the retina.



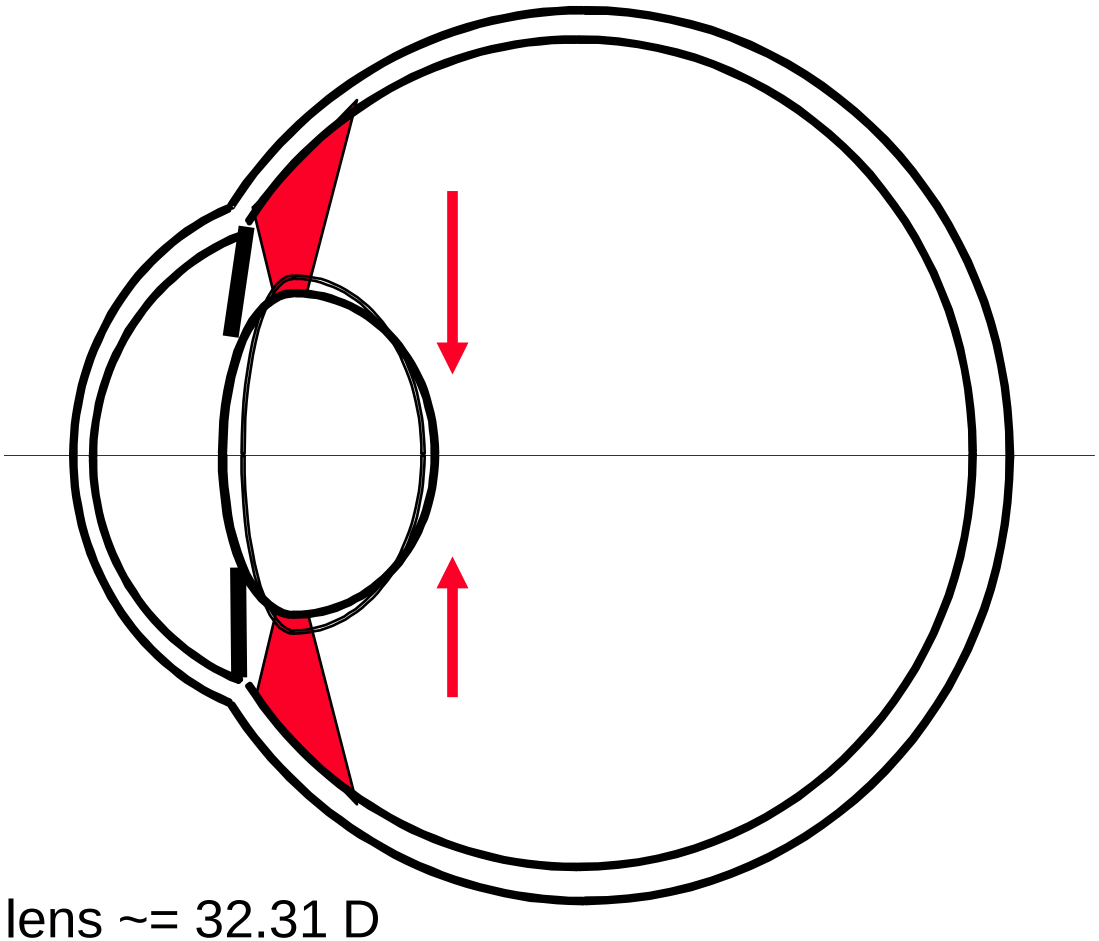
Components of the human optical system

Accommodation

In the accommodated eye, the ciliary muscle constricts and relaxes the tension on the equator of the lens.

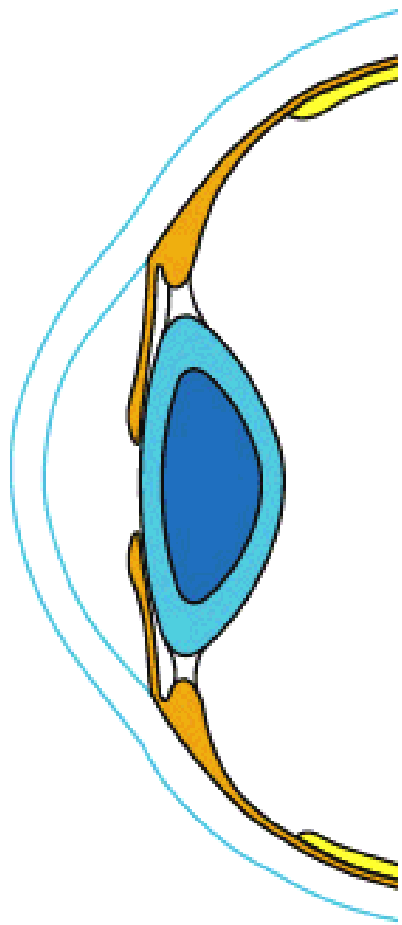
Surface curvature increases.

Power of the lens increases.



Power of the accommodated lens ~= 32.31 D

Optics of the Eye: The Crystalline Lens



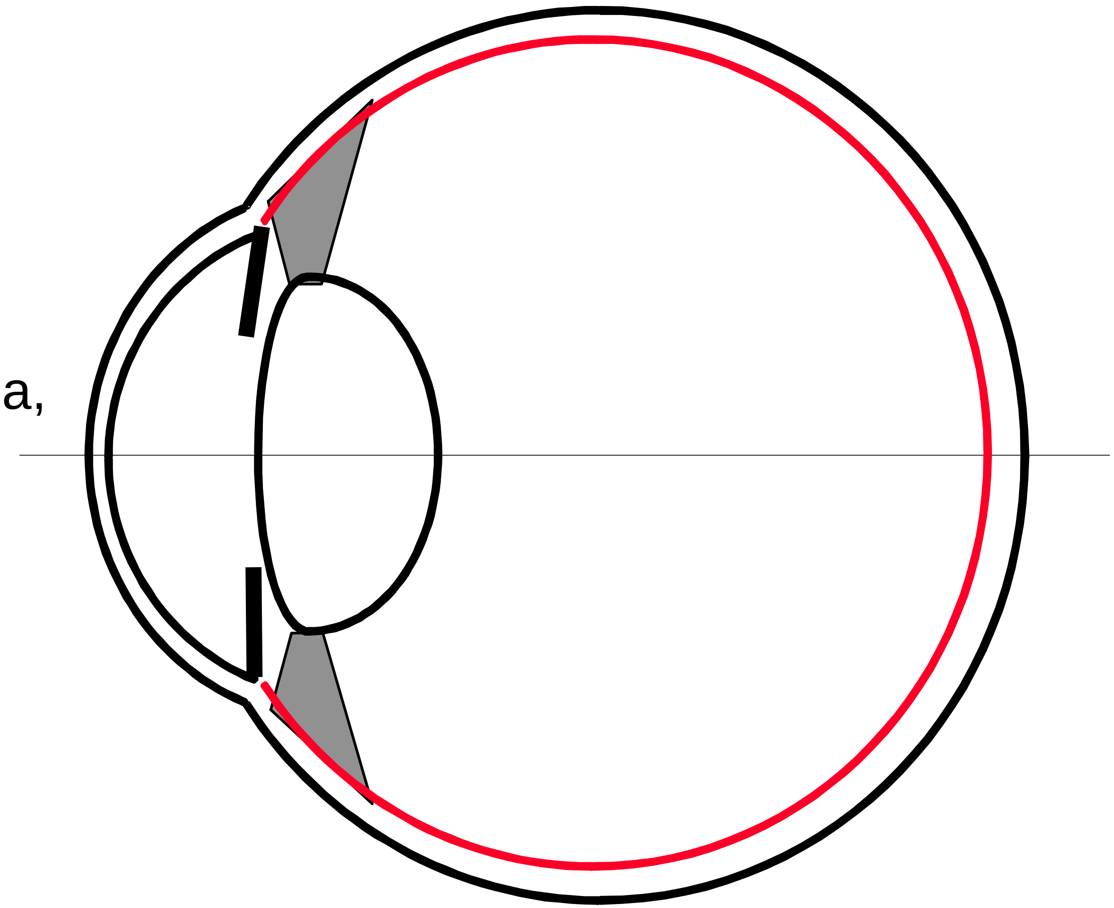
courtesy of Adrian Glasser, PhD

Components of the human optical system

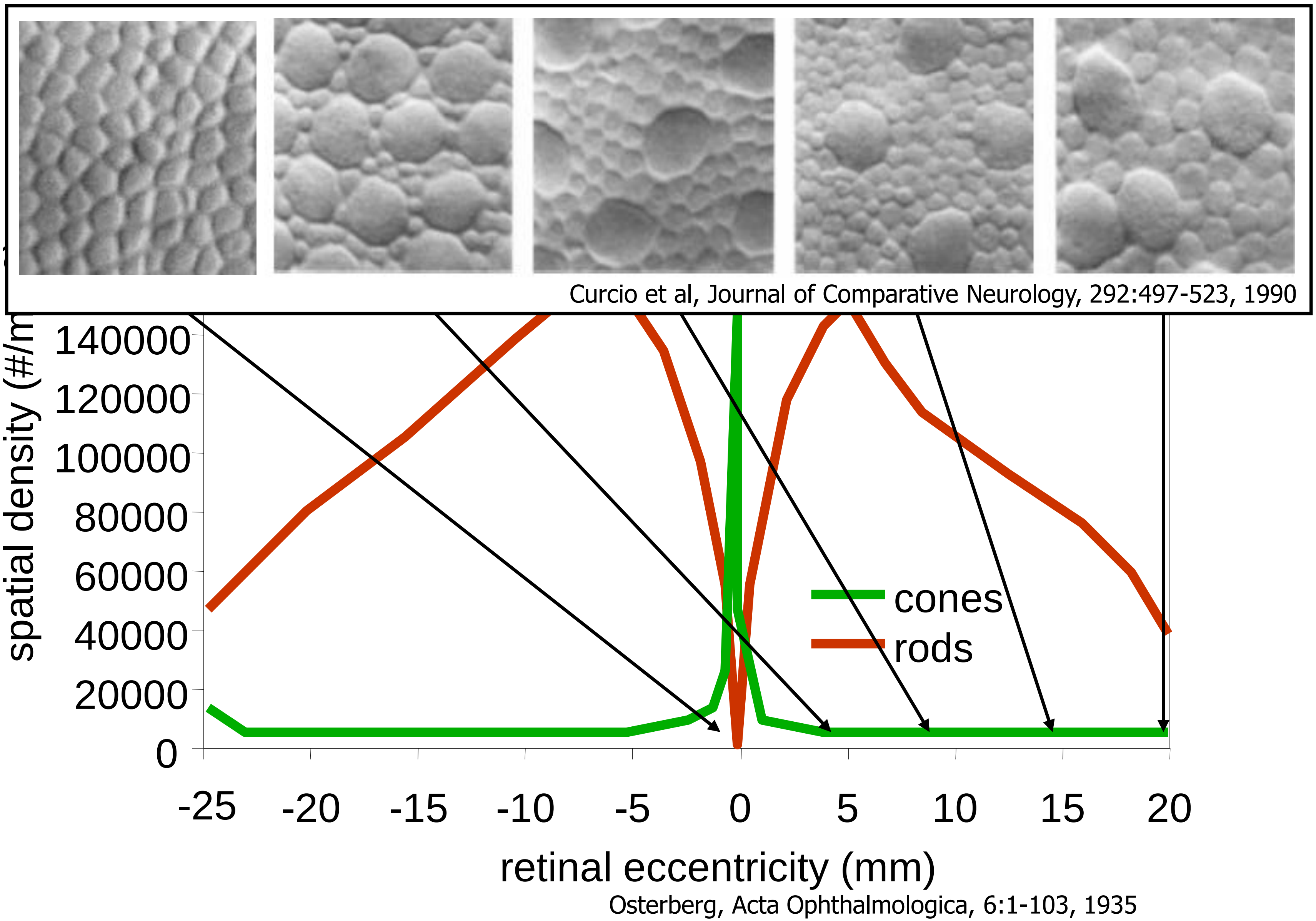
Retina:

Images are sampled by millions of rods and cones.

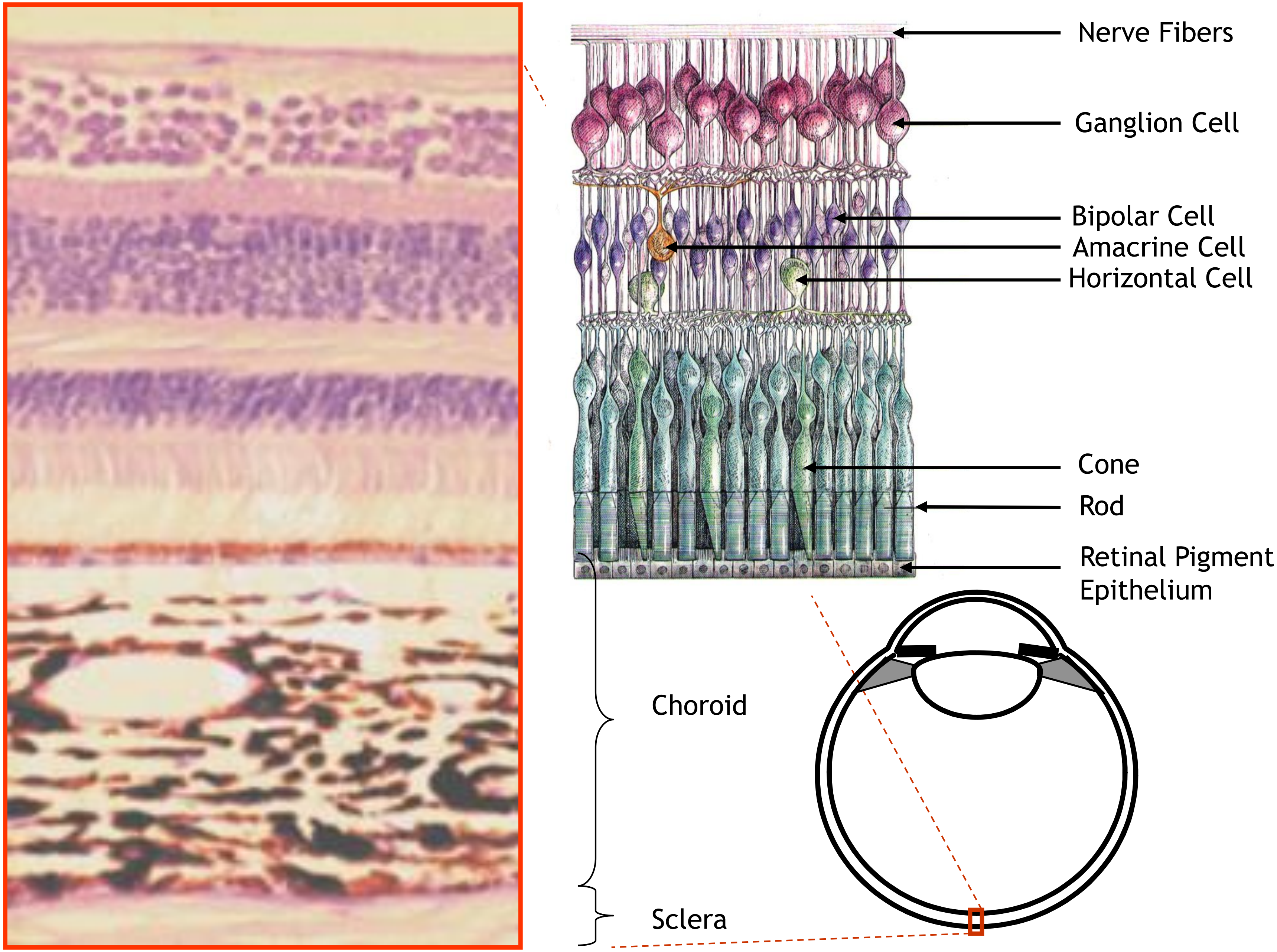
fovea: 5 degrees from optical axis
optic disc: 15 deg from fovea, 10 deg from optical axis.



Cones and Rods are not Evenly Distributed



The retina is a thick-multilayered structure



Diversion: Visual Angle

What is Visual Angle?

It is the angle subtended at the second nodal point by the image
It is also equal to the angle subtended at the first nodal point by the object

The nodal points are points in the optical system where the light passing through emerges at the same angle

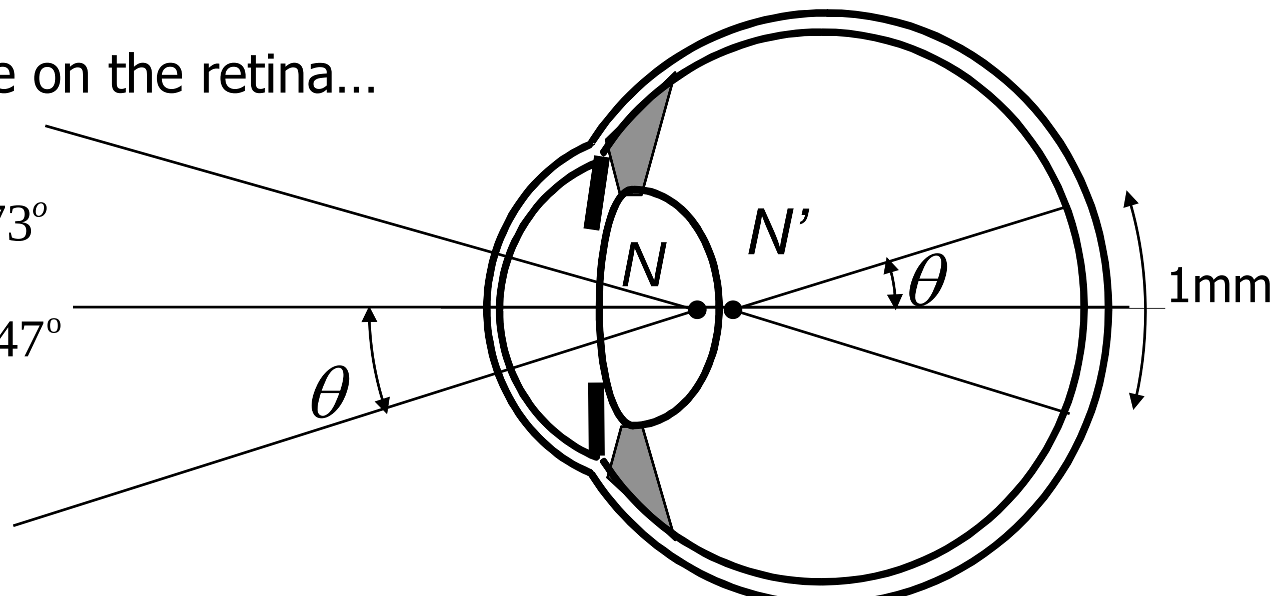
The second nodal point in the eye is about 16.5 mm from the retina

Consider a 1 mm image on the retina…

$$\tan\theta = \frac{0.5}{16.5} \Rightarrow \theta = 1.73^o$$

$$\text{visual angle} = 2\theta = 3.47^o$$

$$1^o = 288\mu m$$

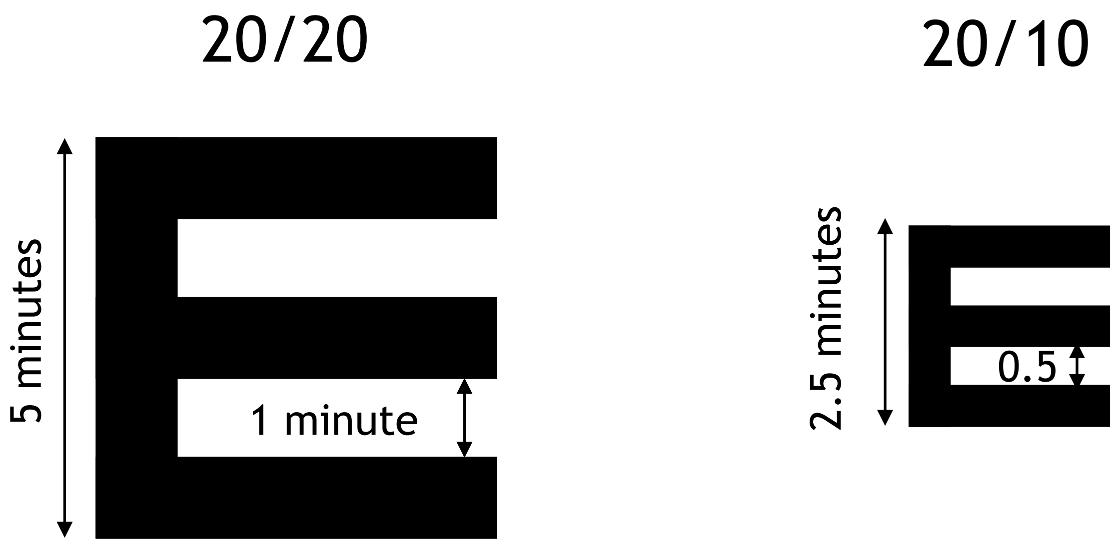


Diversion: Visual Angle

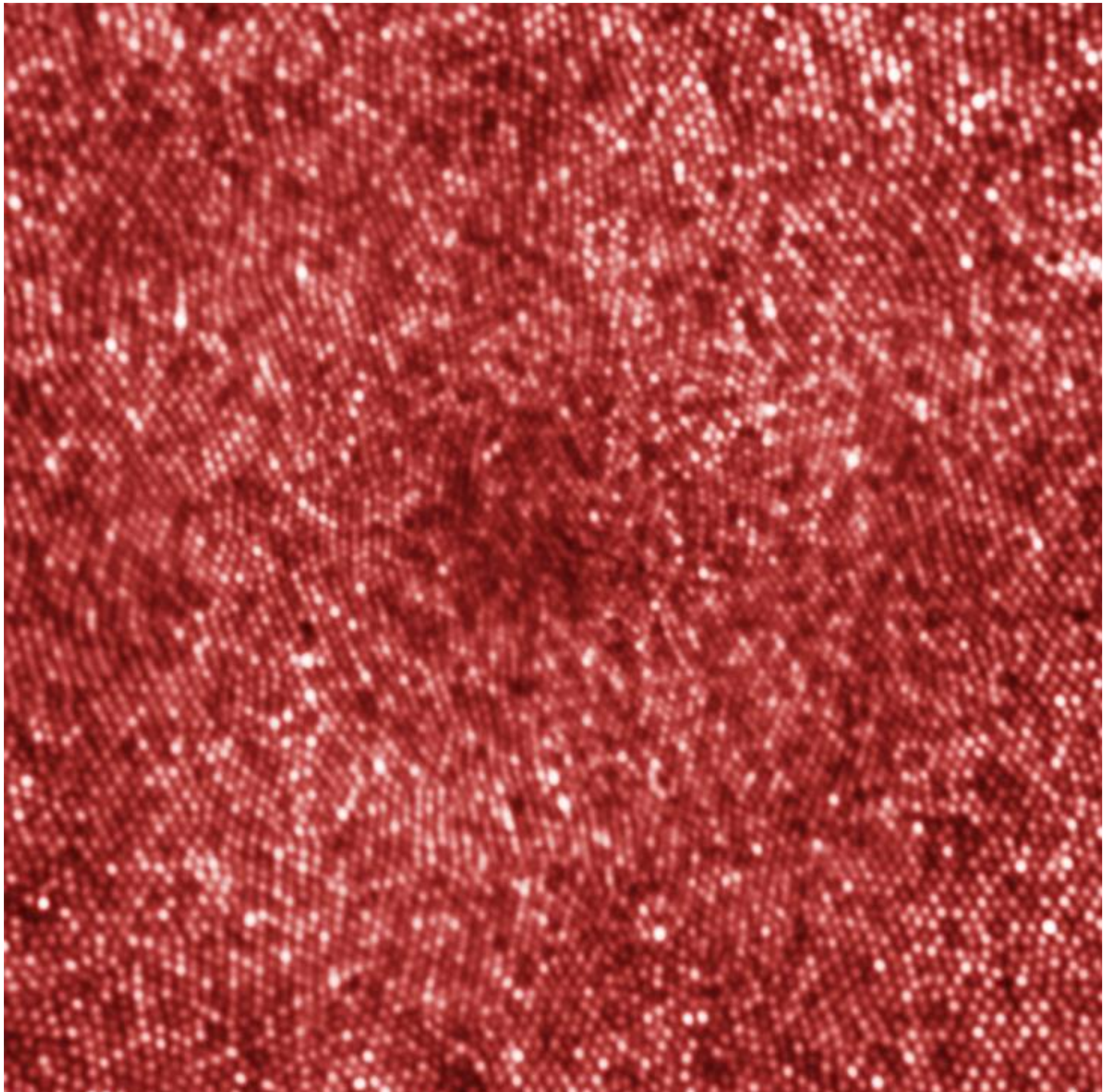
- 1 radian = 57.29 degrees
- 1 degree = .0174 radians = 17.4 mrad
- 1 minute = .29 mrad
- 1 mrad = 3.44 minutes
- 1 minute = 4.8 microns *(depends on axial length)*
- 1 foveal cone = 2.5 microns *(with intersubject variability)*

Diversion: Visual Angle

- letters on an acuity chart are defined by the angles they subtend



Diversion: Visual Angle



1 deg = ~288 microns

1 foveal cone
= ~2.5 microns
= ~0.5 arcmin

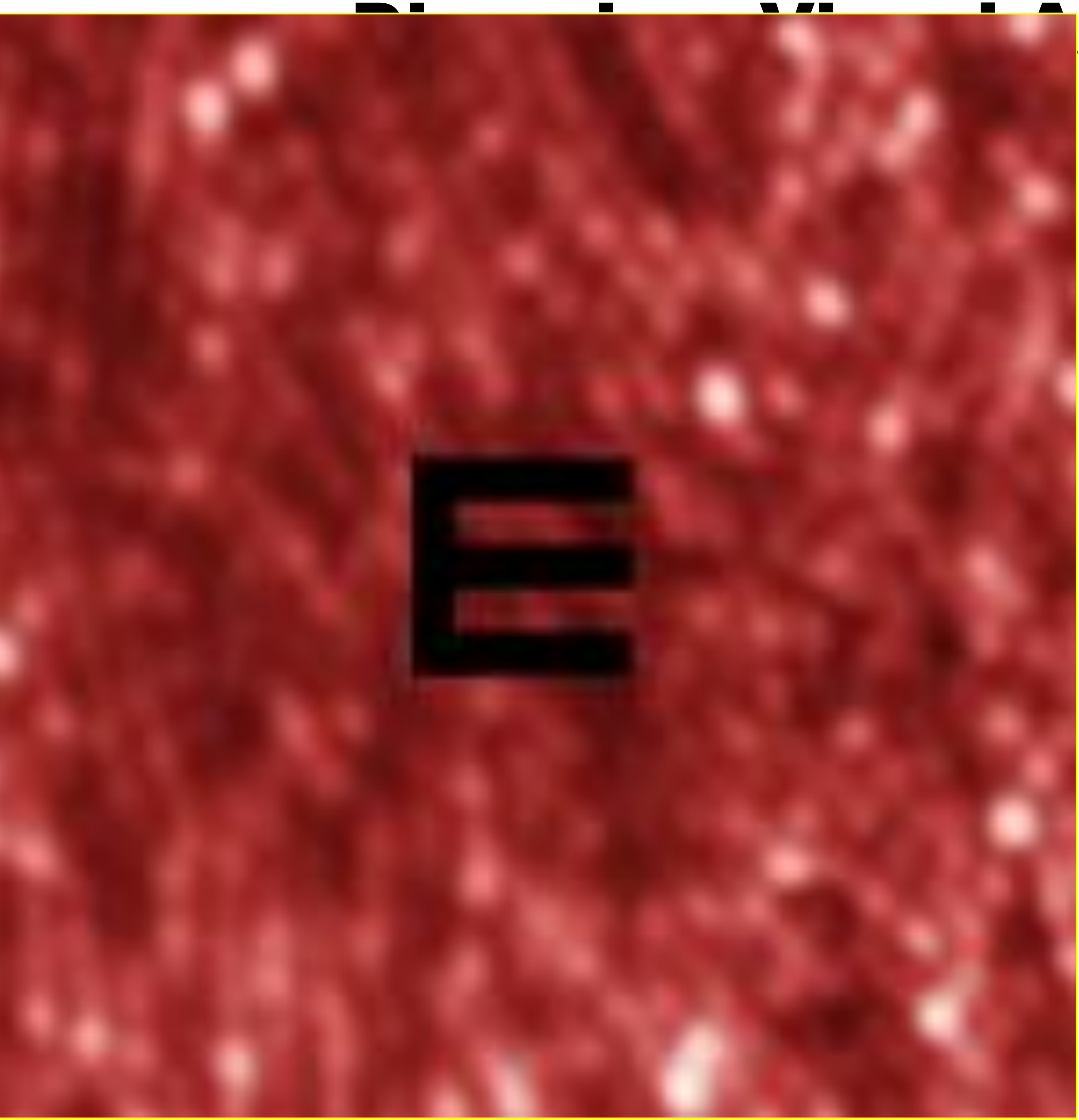
Diversion: Visual Angle

1 foveal cone
= ~2.5 microns
= ~0.5 arcmin

20/20 letter
= 5 arcmin

1 deg = ~288 microns

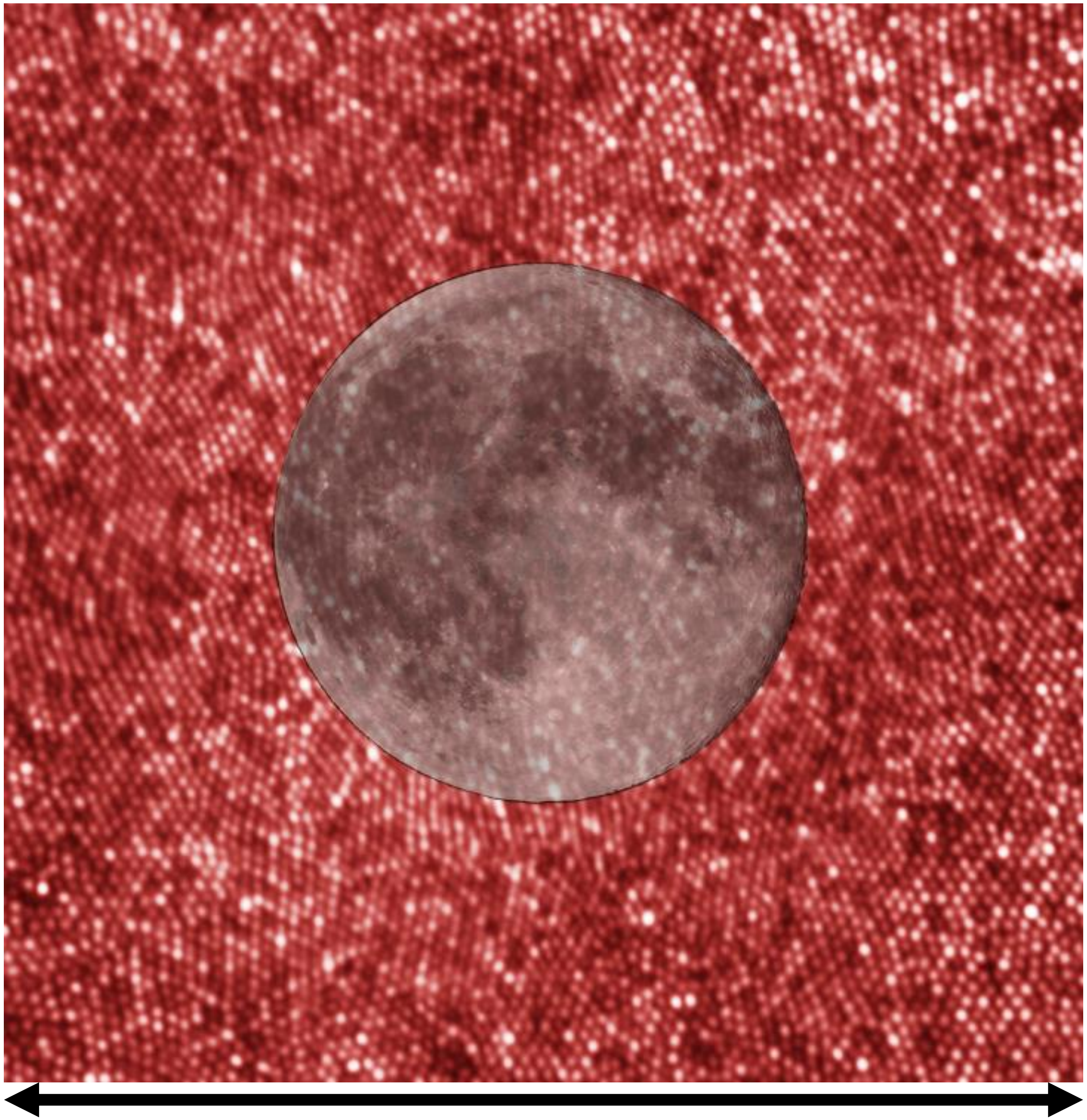
ngle



1 foveal cone
= ~2.5 microns
= ~0.5 arcmin

20/10 letter
= 2.5 arcmin

Diversion: Visual Angle



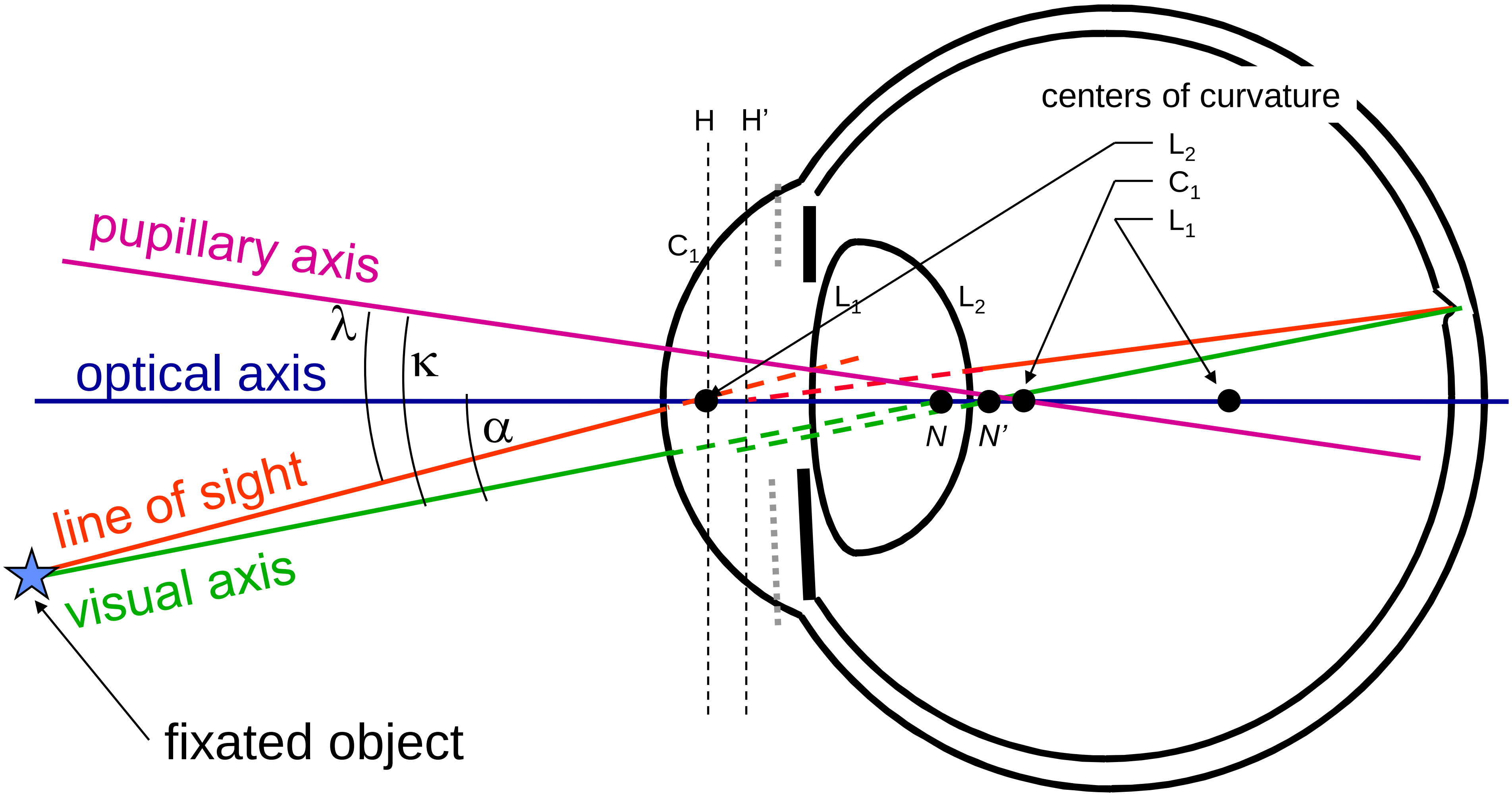
1 deg = ~288 microns

1 foveal cone
  = ~2.5 microns
  = ~0.5 arcmin

Moon
  = 30 arcmin

Diversion: Visual Angle

Axes in the Eye

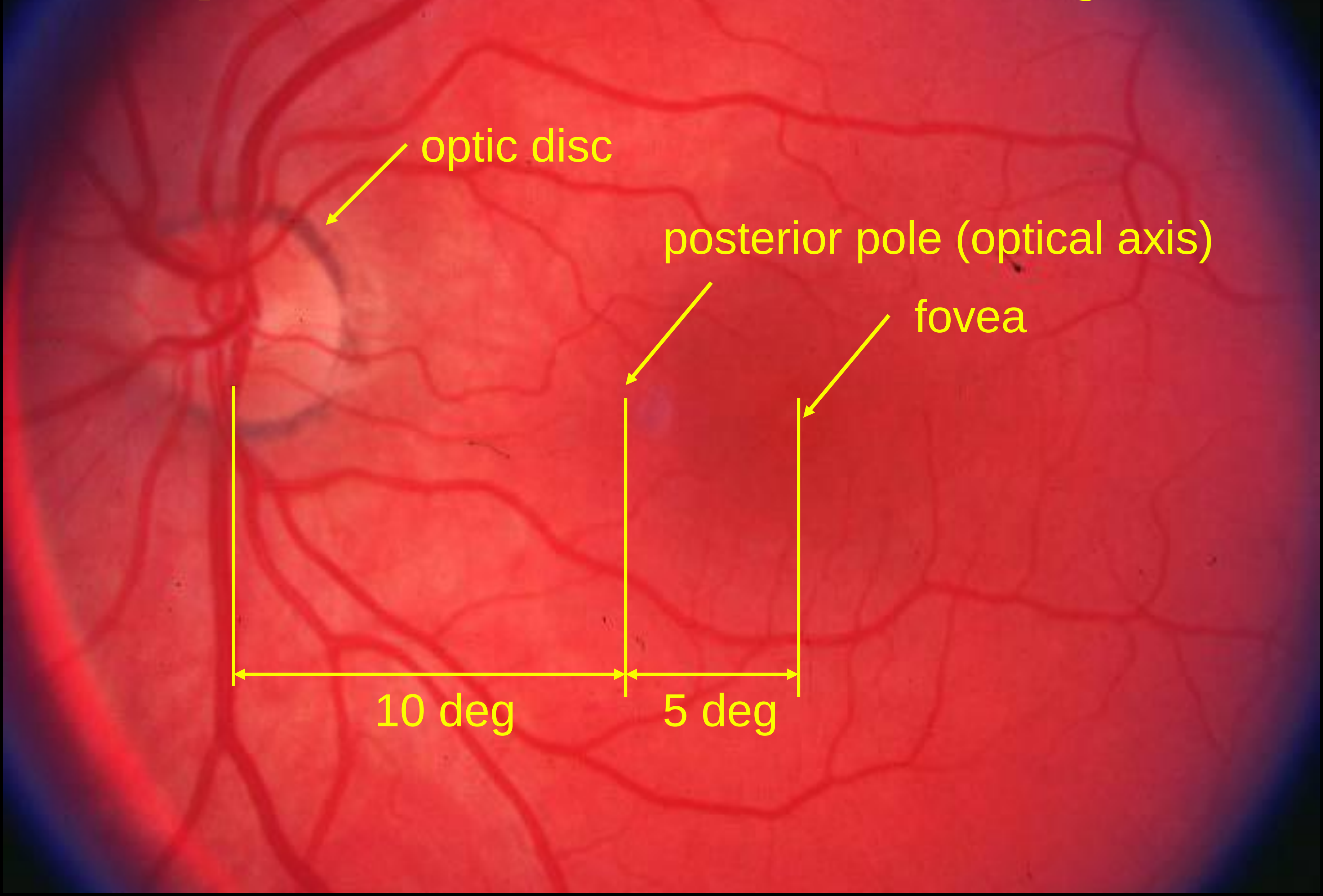


Axes and key angles in the Eye

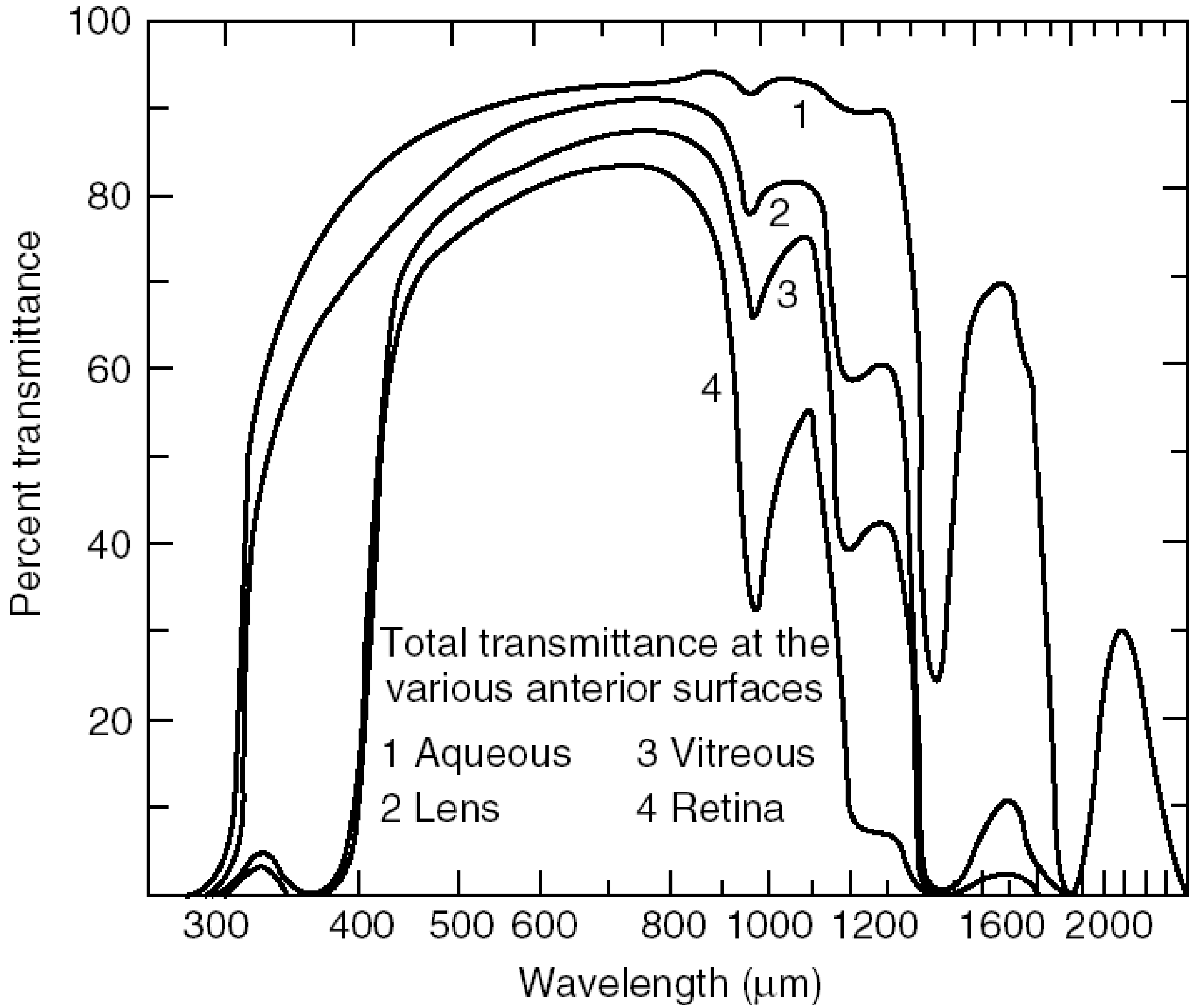
- **Optical axis**: best line joining the centers of curvatures of the optical surfaces
- **Visual axis**: line from fovea through the nodal points
- **Line of sight**: line from object through center of entrance pupil that reaches the fovea (chief ray)
- **Pupillary axis**: line from center of curvature of corneal first surface with pupil center
- **Angle alpha**: angle between optical axis and visual axis
- **Angle kappa**: angle between pupillary axis and visual axis *(angle kappa is easily observed as a displacement of the coaxially viewed corneal reflex from the pupil center of a fixating eye)*
- **Angle lambda**: angle between pupillary axis and line of sight

Visual axis and line of sight are often assumed to be parallel, which is only true for distant objects

Components of the human visual system

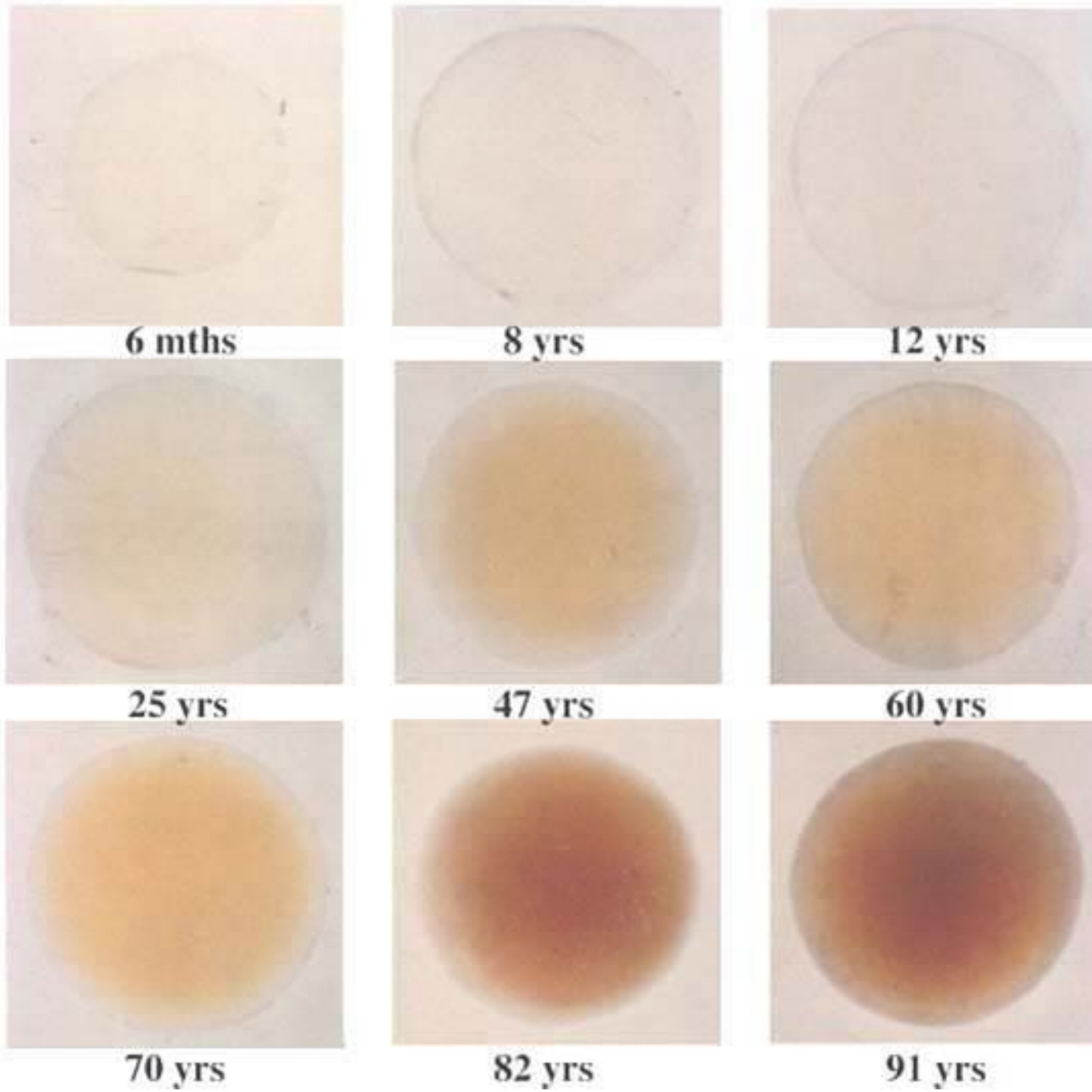


Spectral Transmission of the Whole Eye



Boettner and Wolter, 1962

The aging lens



Spectral Transmission of the Lens

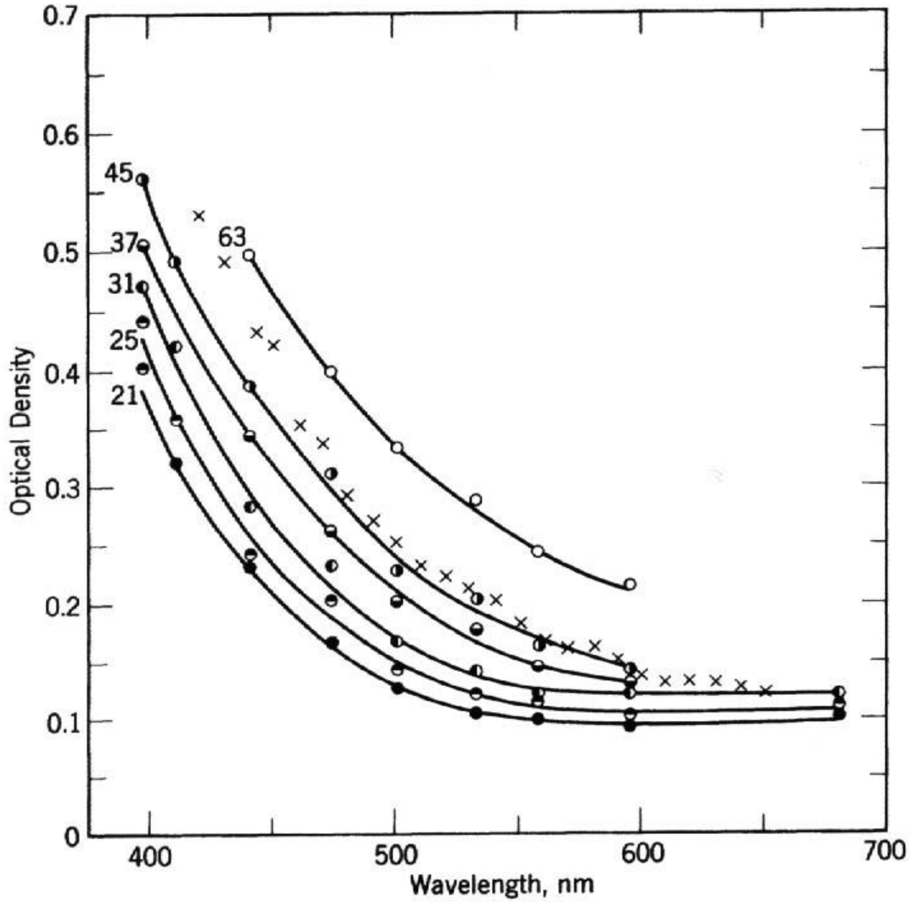
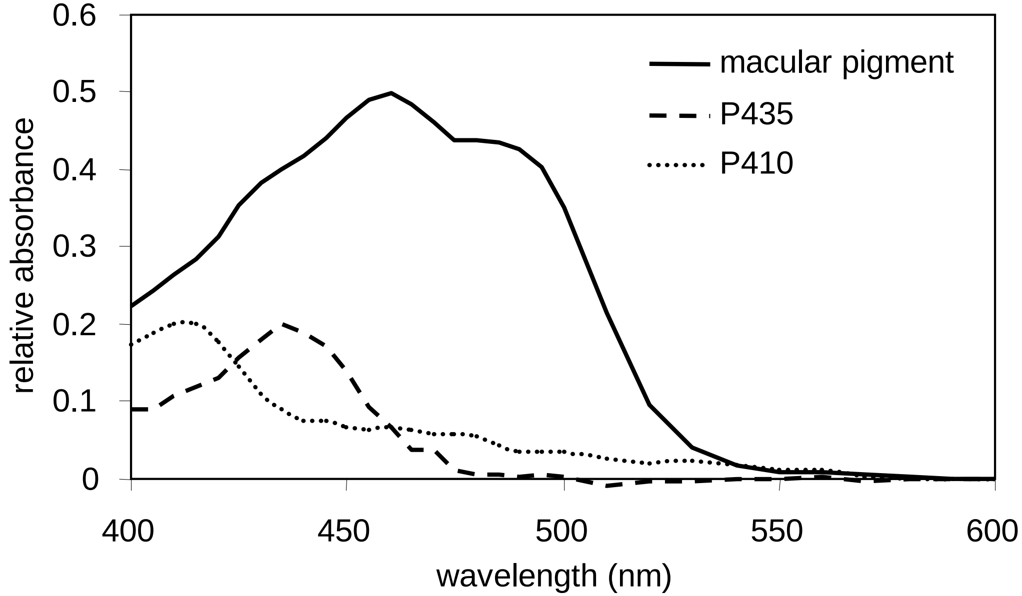
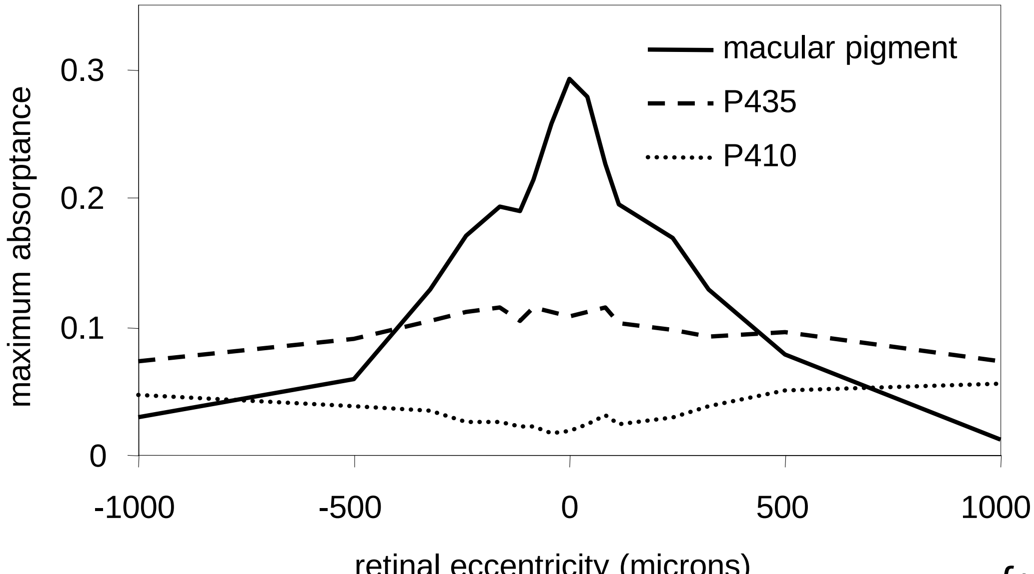


Fig. 2(2.4.6). Spectral density curves of the human eye lens determined for the living eye by an objective method. Data for English observers of different ages (ages are shown against the curves; from Said and Weale, 1959). The crosses refer to mean data for two eyes (ages 48 and 53) obtained, after their removal in operations, by a different method (Weale, 1954).

figure from Wyszecki and Stiles, 1982

Absorbing Pigments in the Retina

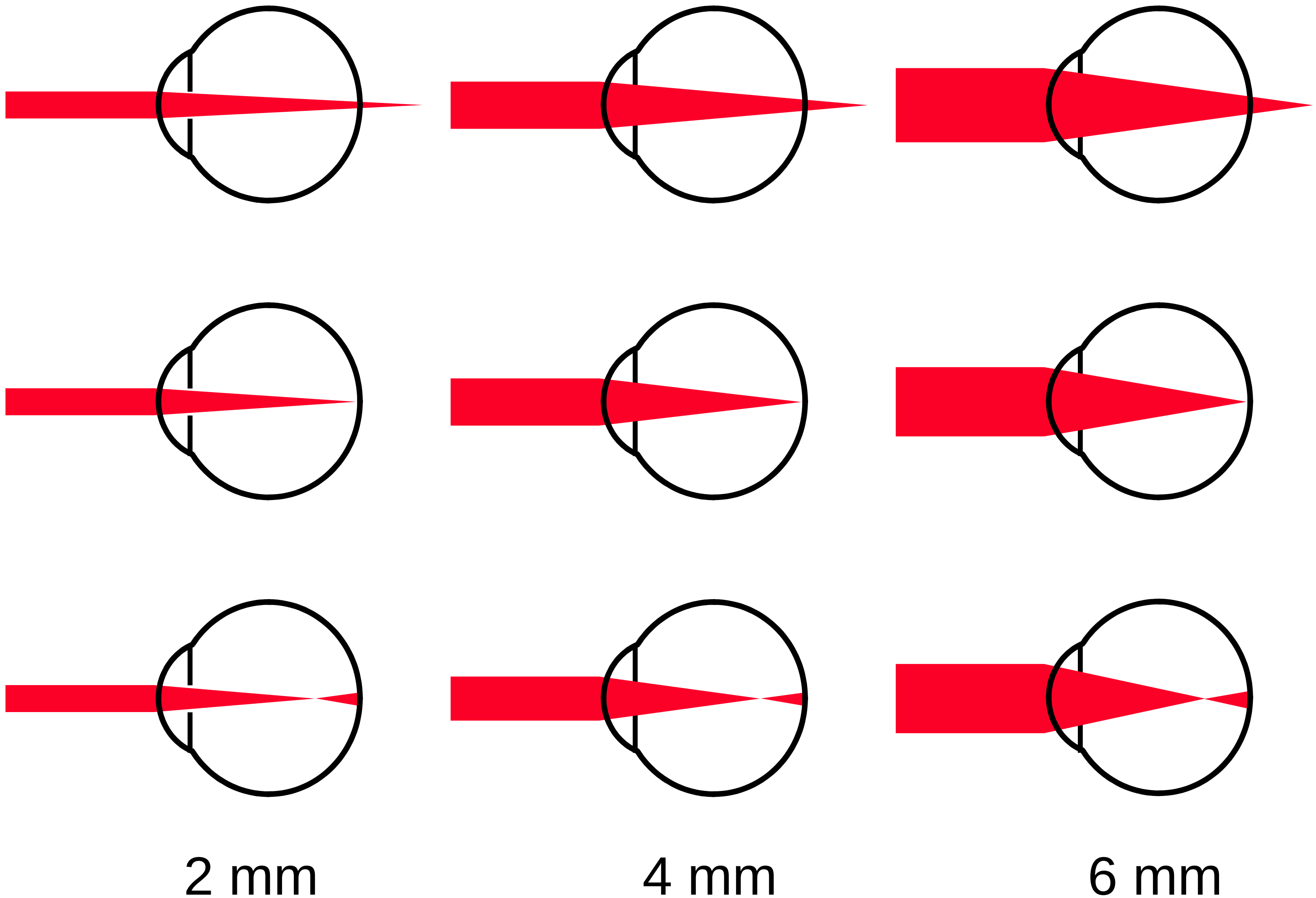




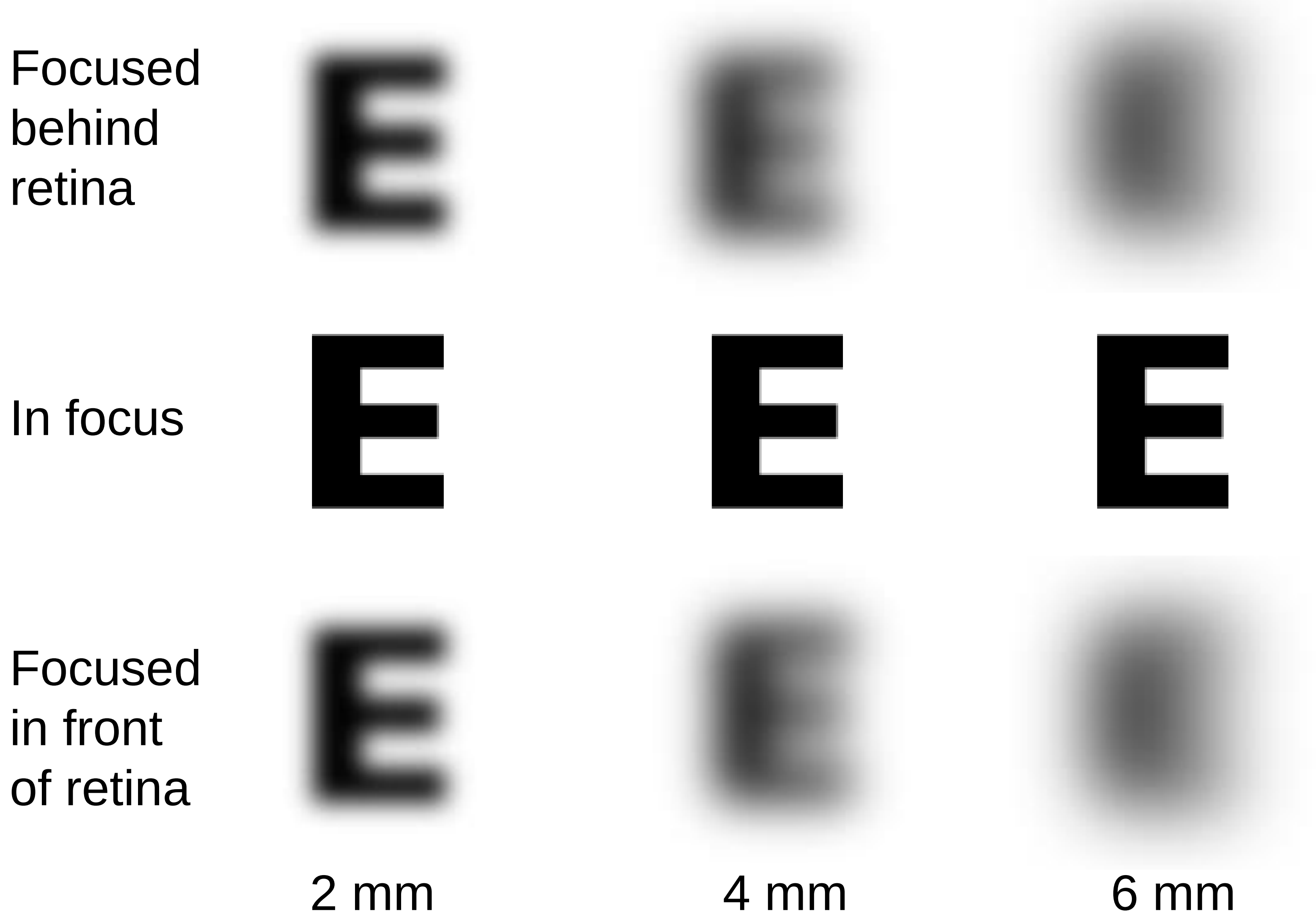
from Snodderly, IOVS, 1984

Part 4: Image Quality in the Eye

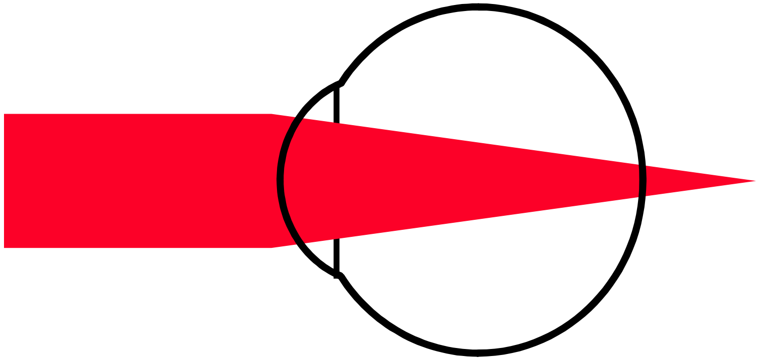
Blur as a function of defocus and pupil size



Blur as a function of defocus and pupil size



Computation of Geometrical Blur Size

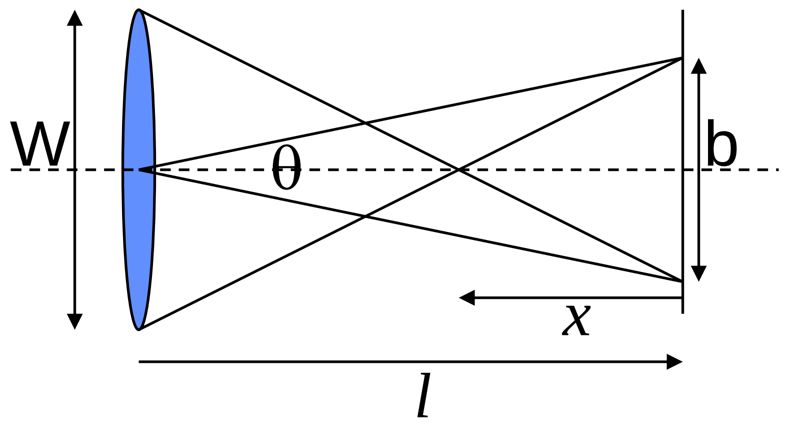


$$\text{blur[mrad]} = D \times pupilsize[mm]$$

$$\text{blur[minutes]} = 3.44 \times D \times pupilsize[mm]$$

where D is the defocus in diopters

Derivation of blur equation



By similar triangles... $\dfrac{W}{l-x} = \dfrac{b}{x}$

use small angle approximation to get... $\dfrac{W}{l-x} = \dfrac{l\theta}{x}$

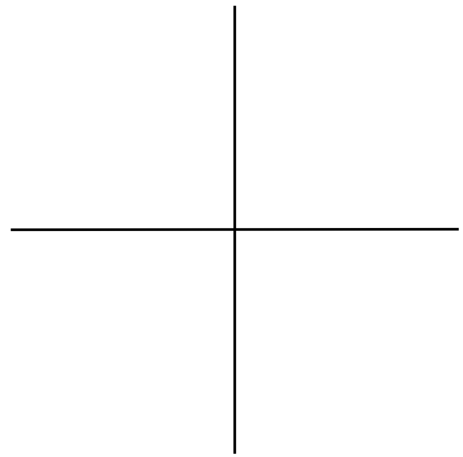
$$\theta = \frac{Wx}{l^2 - lx} = W\left(\frac{x-l+l}{l(l-x)}\right) = W\left(\frac{l}{l(l-x)} - \frac{l-x}{l(l-x)}\right) = W\left(\frac{1}{l-x} - \frac{1}{l}\right) = WD$$

where D is defocus in diopters

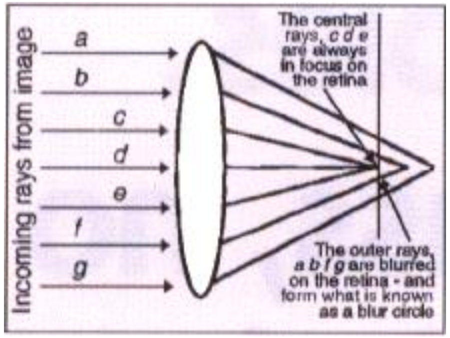
Application of Blur Equation

- 1 D defocus, 8 mm pupil produces 27.52 minute blur size ~ 0.5 degrees

Visualize the retinal blur

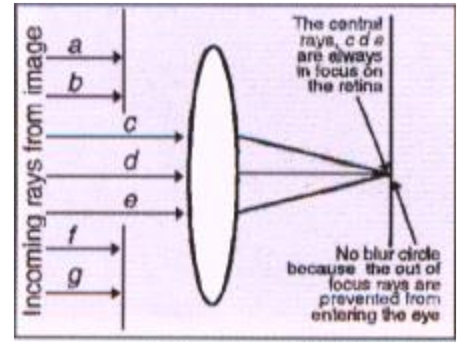


Hold this cross close enough to your eye until it appears blurry. (about 4 cm). Close your eyelid to form a slit aperture and observe the appearance of the cross. What line appears clear? Why does the other line remain blurry?



Pinholes

The natural alternative.



Diffraction

"Any deviation of light rays from a rectilinear path which cannot be interpreted as reflection or refraction"

Sommerfeld, ~ 1894

Fraunhofer Diffraction

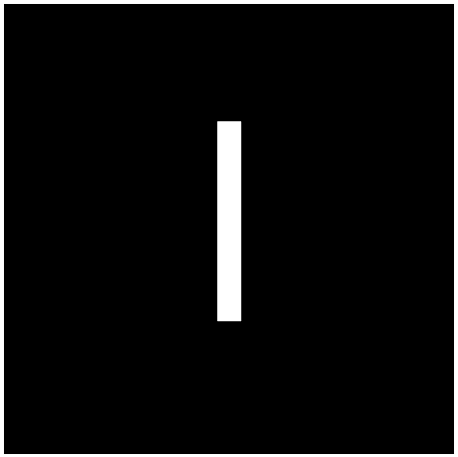
- Also called ***far-field*** diffraction
- Occurs when the screen is held far from the aperture.
- Occurs at the focal point of a lens

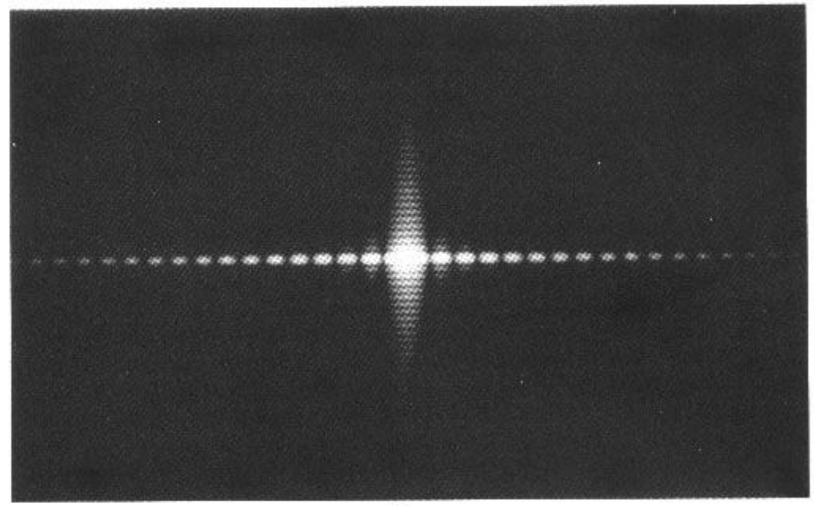
  (replace *s* with *f'*).

Fraunhofer Diffraction

Sec. 19-3 Rectangular and Circular Apertures 393

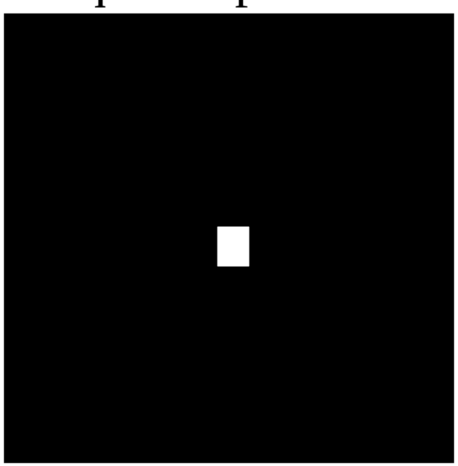
rectangular aperture

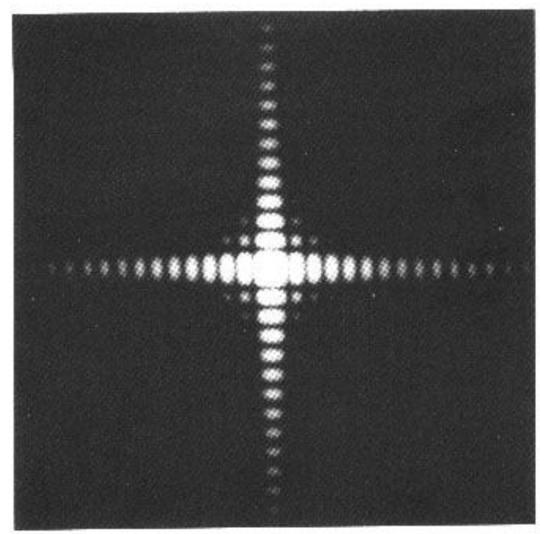




(c)

square aperture



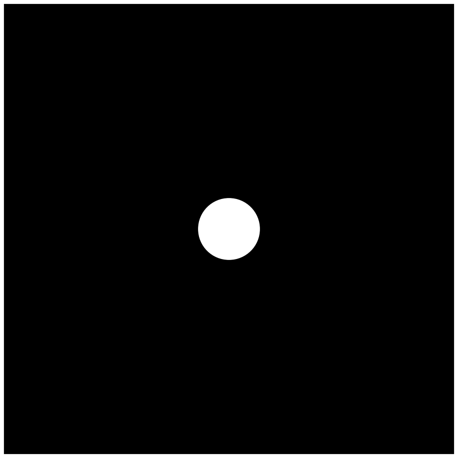


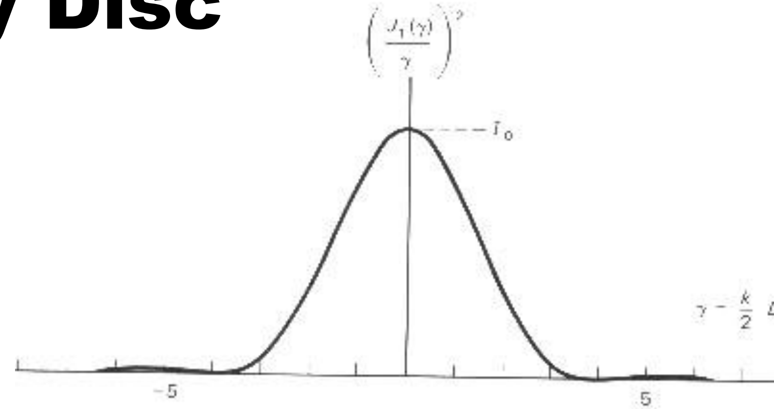
(d)

Figure 19-5 (Continued)

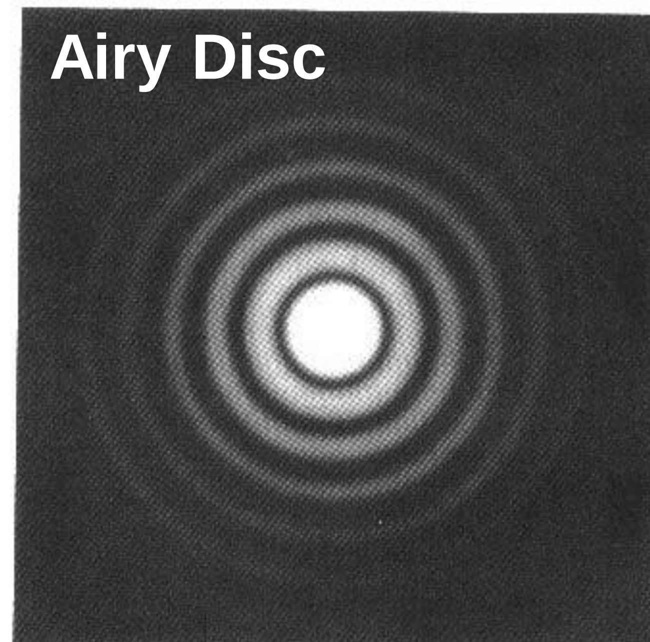
The Airy Disc

circular aperture





(a)



(b)

Sir George Biddel Airy: Inventor of spectacles for astigmatism

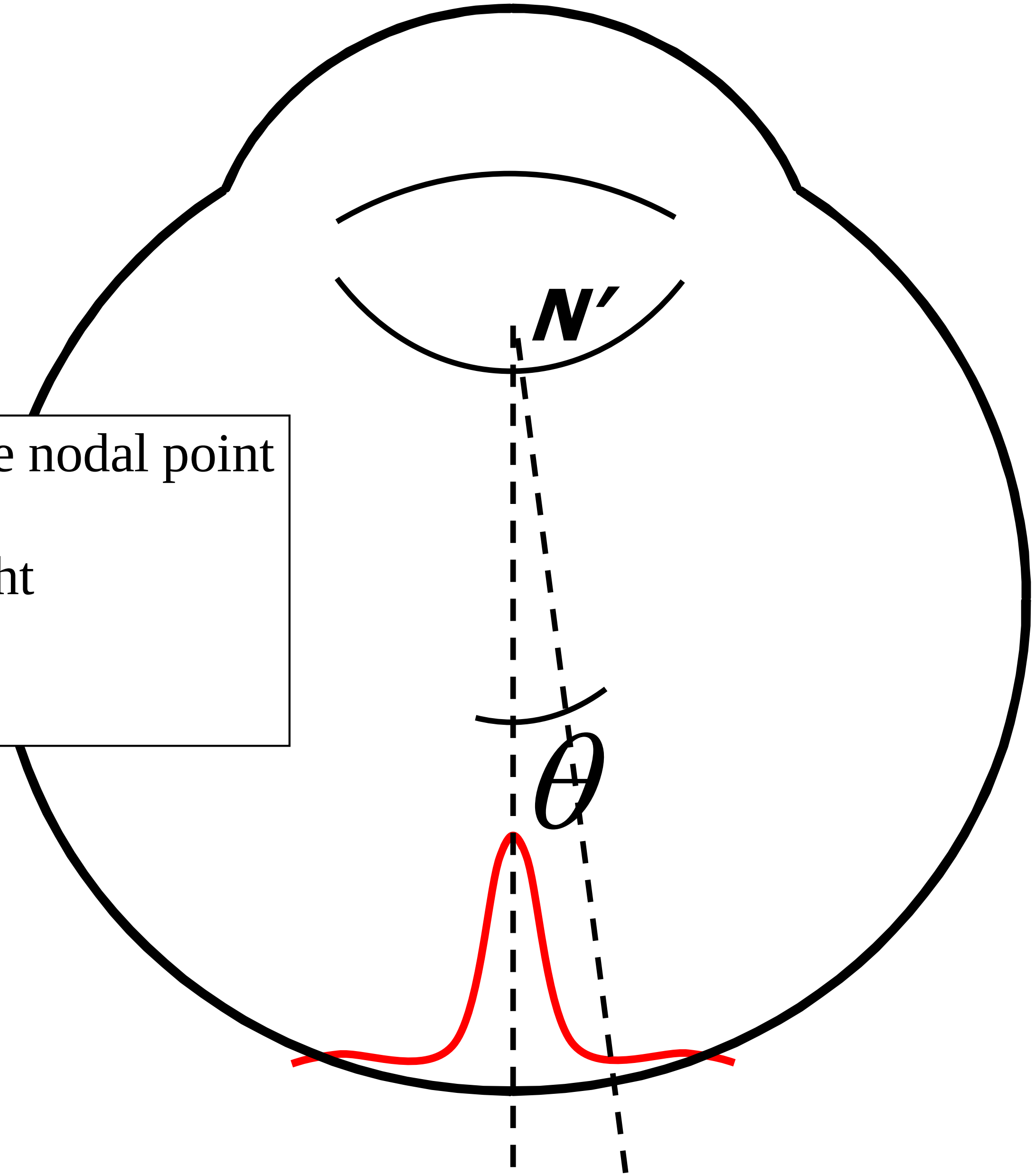
Airy Disk

$$\theta = \frac{1.22 \cdot \lambda}{a}$$

$\theta \equiv$ angle subtended at the nodal point

$\lambda \equiv$ wavelength of the light

$a \equiv$ pupil diameter



The Airy Disk

$$\theta = \frac{1.22 \cdot \lambda}{a}$$

$\theta \equiv$ angle between peak and first minimum (in radians!)

$\lambda \equiv$ wavelength of the light

$a \equiv$ pupil diameter

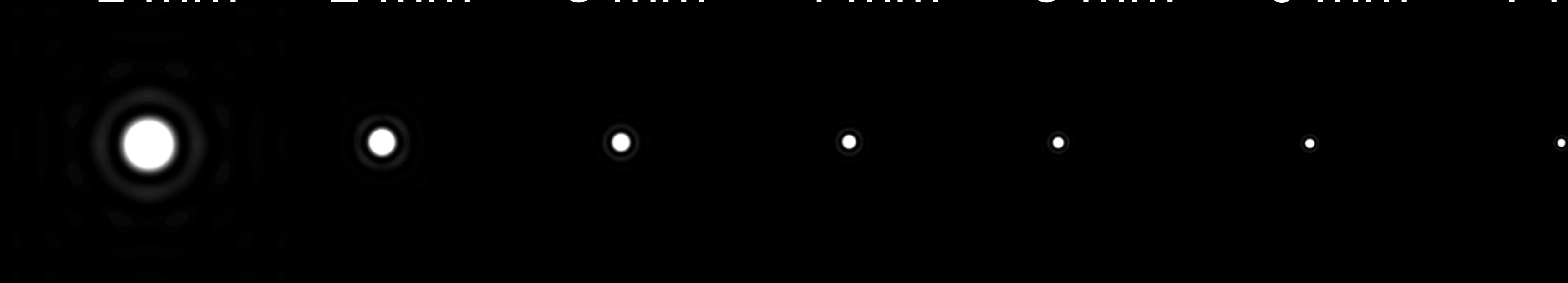
$$1 \text{ radian} = \frac{180}{\pi} \text{degrees}$$

1 degree = 60 minutes of arc

1 minute of arc = 60 seconds of arc

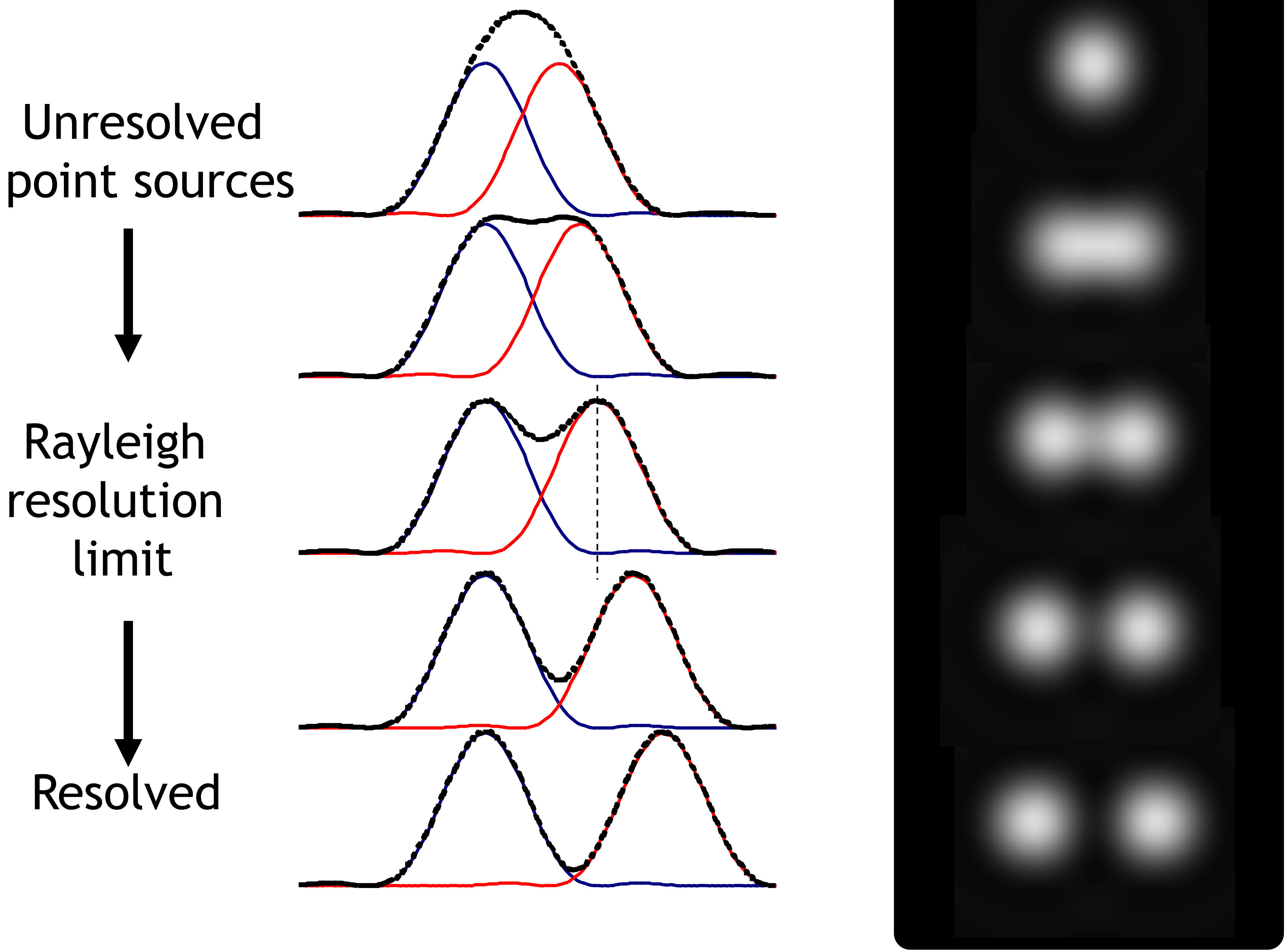
Point Spread Function vs. Pupil Size

1 mm 2 mm 3 mm 4 mm 5 mm 6 mm 7 mm



Diffraction-limited Eye

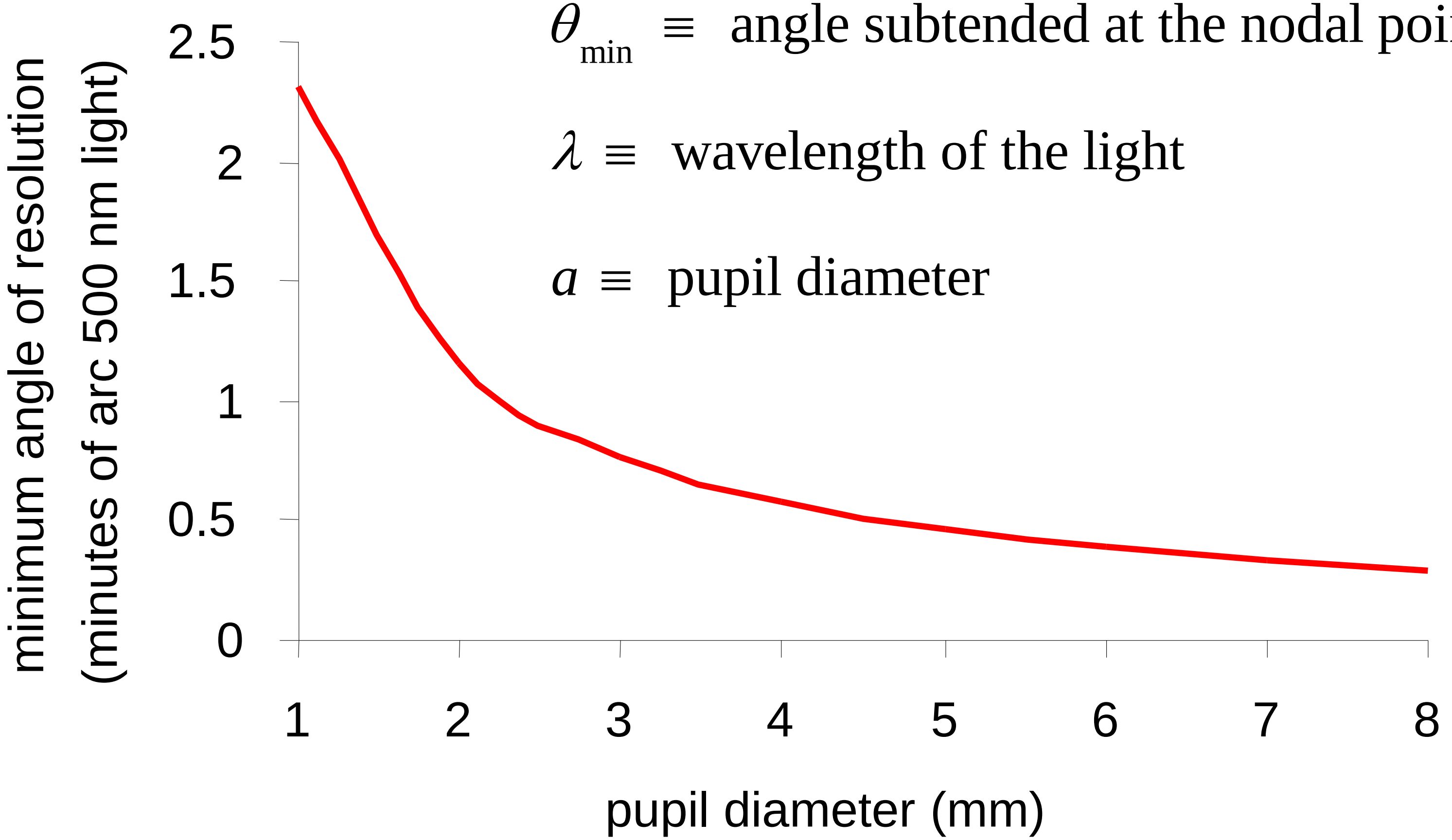
Resolution



Unresolved point sources
Rayleigh resolution limit
Resolved

Resolution

$$\theta_{\min} = \frac{1.22 \cdot \lambda}{a}$$



$\theta_{\min} \equiv$ angle subtended at the nodal point

$\lambda \equiv$ wavelength of the light

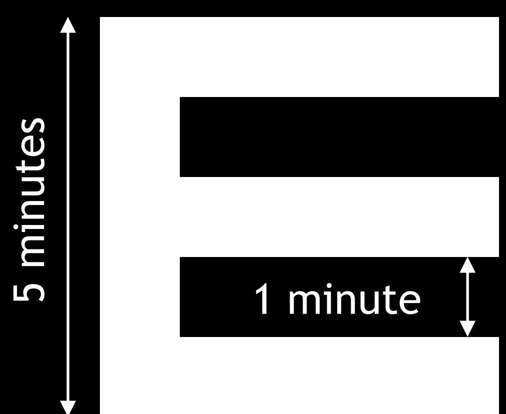
$a \equiv$ pupil diameter

Diffraction Blur and Snellen Letter Size

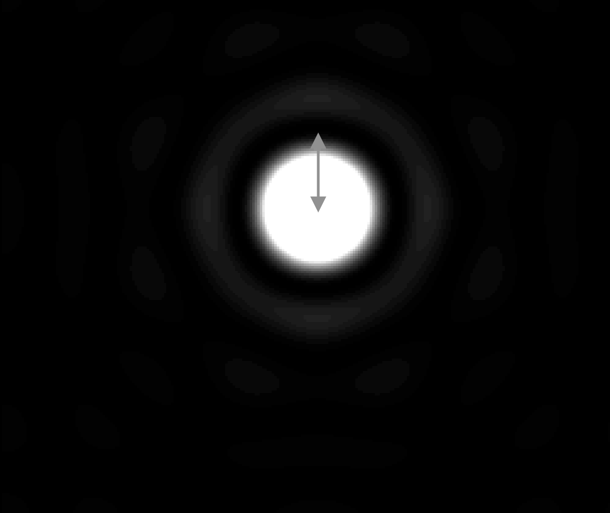
$$\theta_{\min} = 60 \times \frac{180}{\pi} \times \frac{1.22 \cdot \lambda}{a}$$

$\theta_{\min} \equiv$ angle subtended at the nodal point

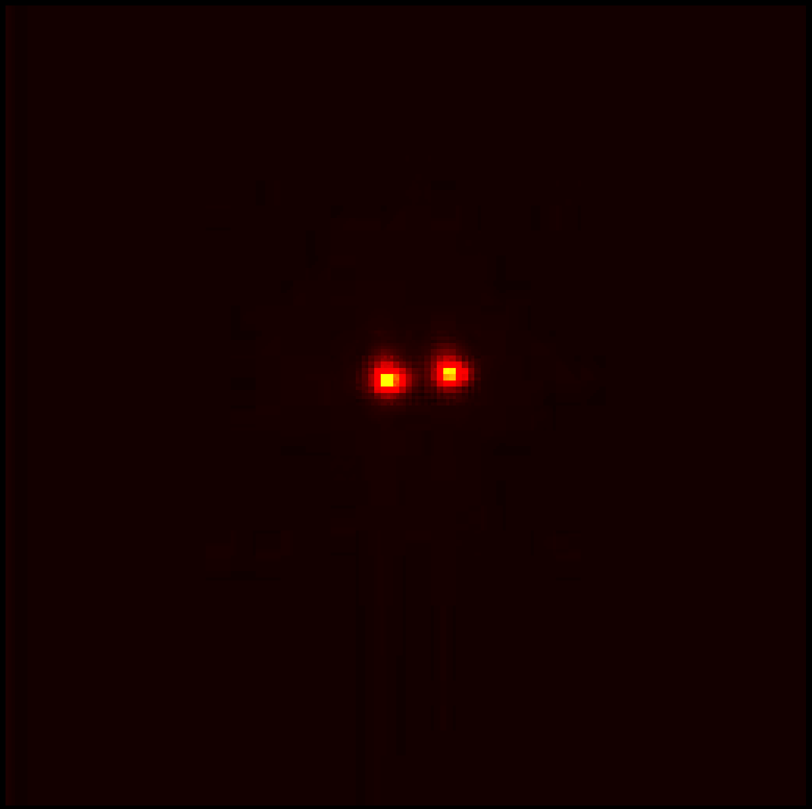
20/20



diffraction limited PSF
2 mm pupil @ 550 nm



20/10

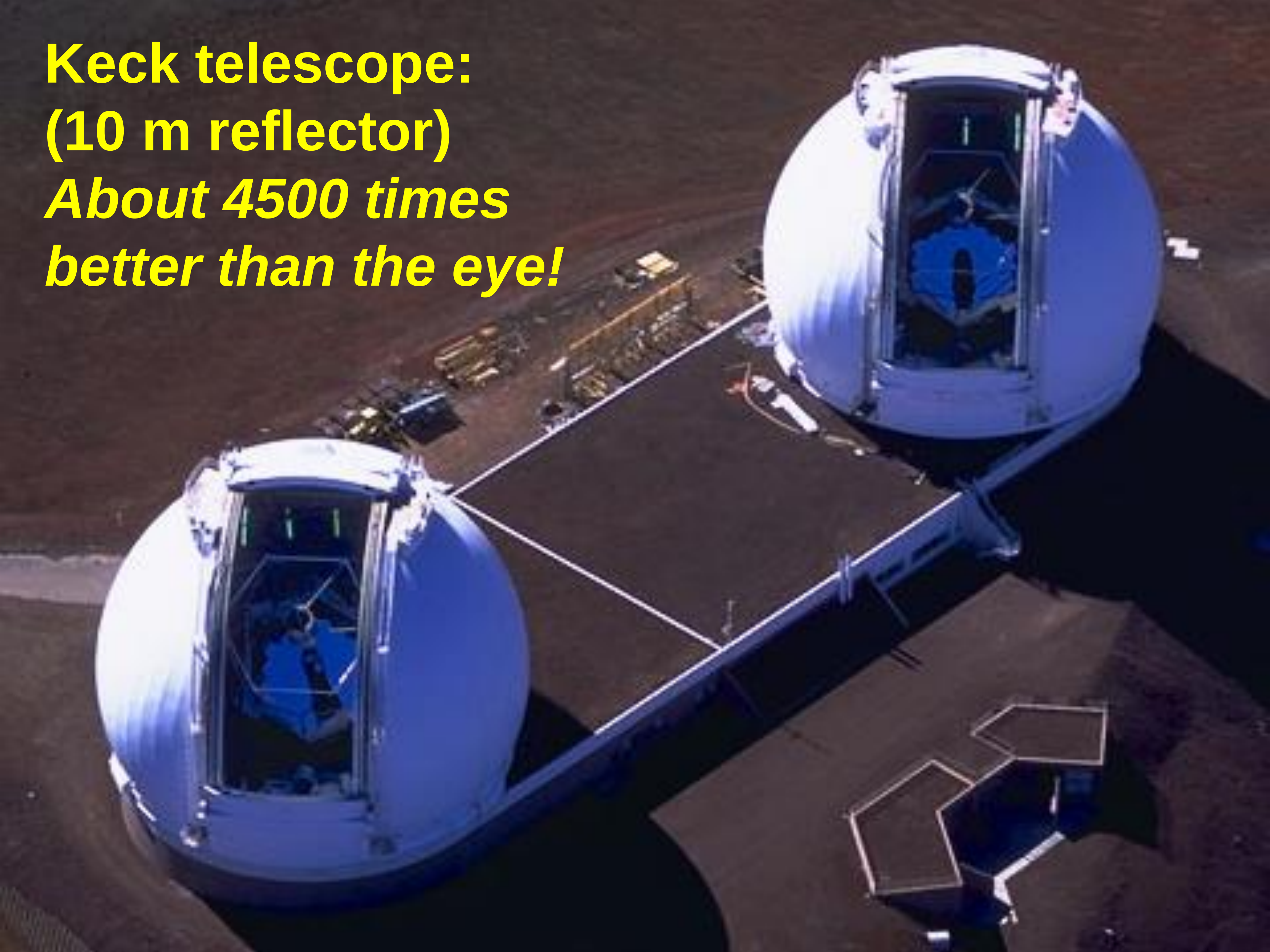


AO image of binary star k-Peg on the 3.5-m telescope at the Starfire Optical Range, Albuquerque, NM, September, 1997.

$$\theta_{\min} = \frac{1.22 \cdot \lambda}{a} = \frac{1.22 \cdot 900 \times 10^{-9}}{3.5} = 0.064 \text{ seconds of arc}$$

About 1000 times better than the eye!

Keck telescope:
(10 m reflector)
About 4500 times better than the eye!



Retinal straylight in the human eye

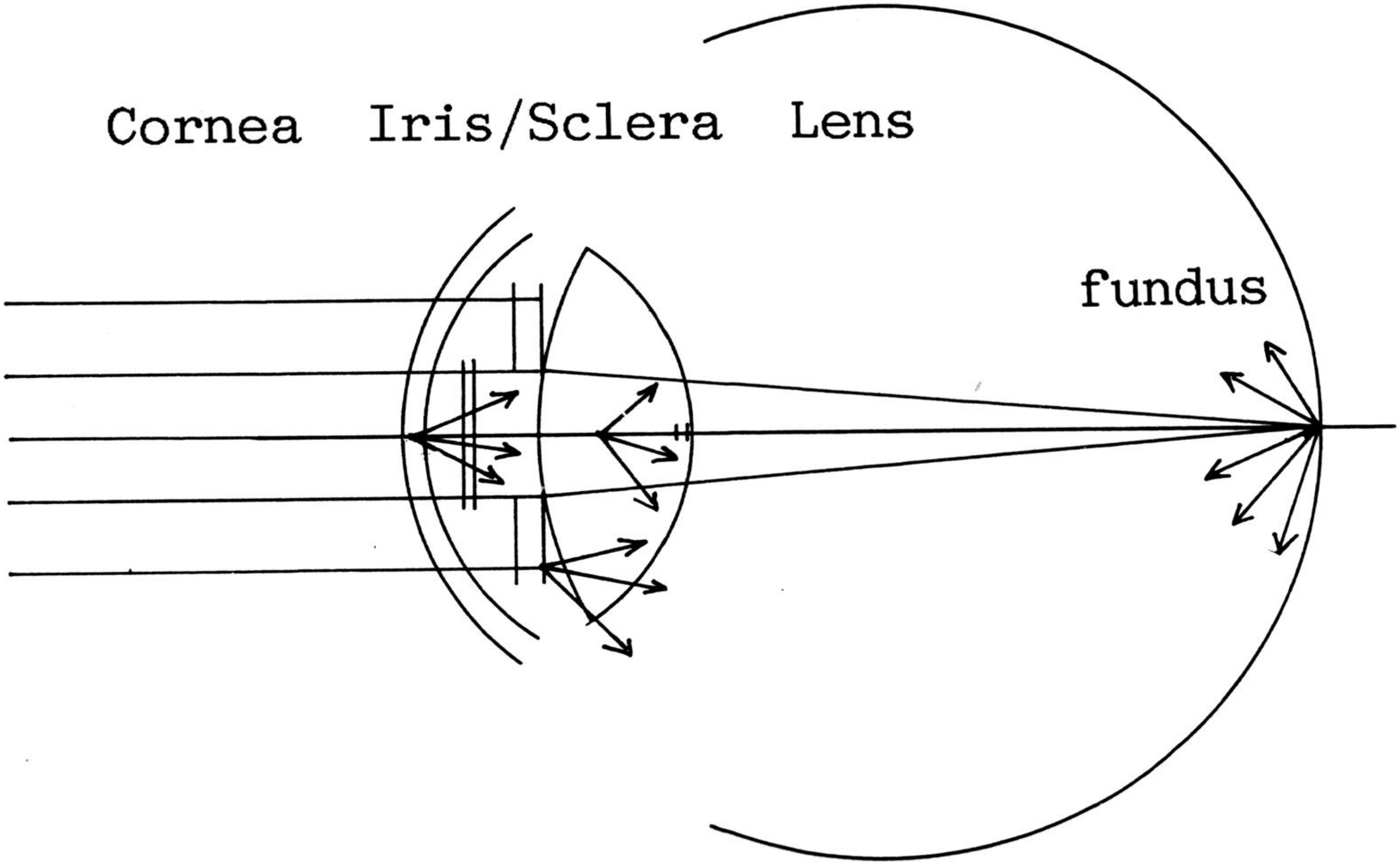
slides courtesy of

Tom van den Berg

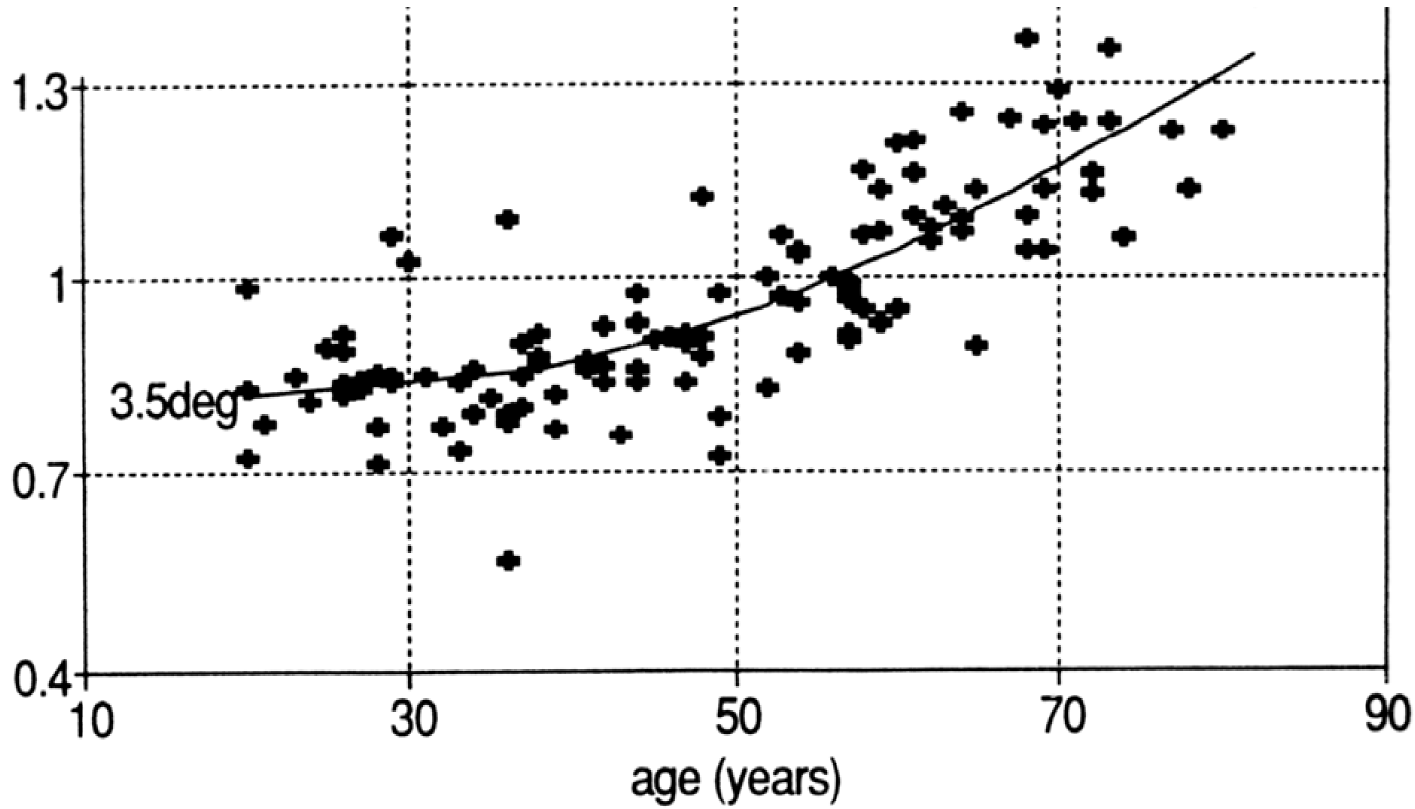
Thomas J. T. P. van den Berg, Michiel P. J. Hagenouw, and Joris E. Coppens
The Ciliary Corona: Physical Model and Simulation of the Fine Needles Radiating from Point Light Sources
IOVS, 46: 2627-2632 (2005).

Tom van den Berg

Primary sources of scattered light



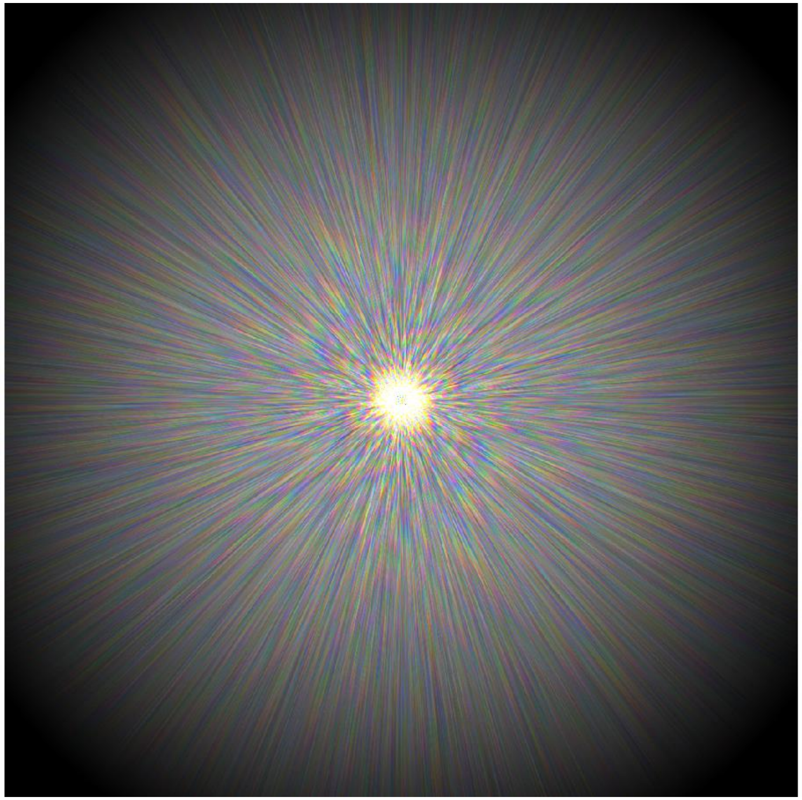
Tom van den Berg



Tom van den Berg

Ciliary corona

Actual subjective appearance of straylight: a pattern of very fine streaks, not at all like the circularly uniform (Airy disc-like) scattering pattern of particles of approximate wavelength size



Tom van den Berg

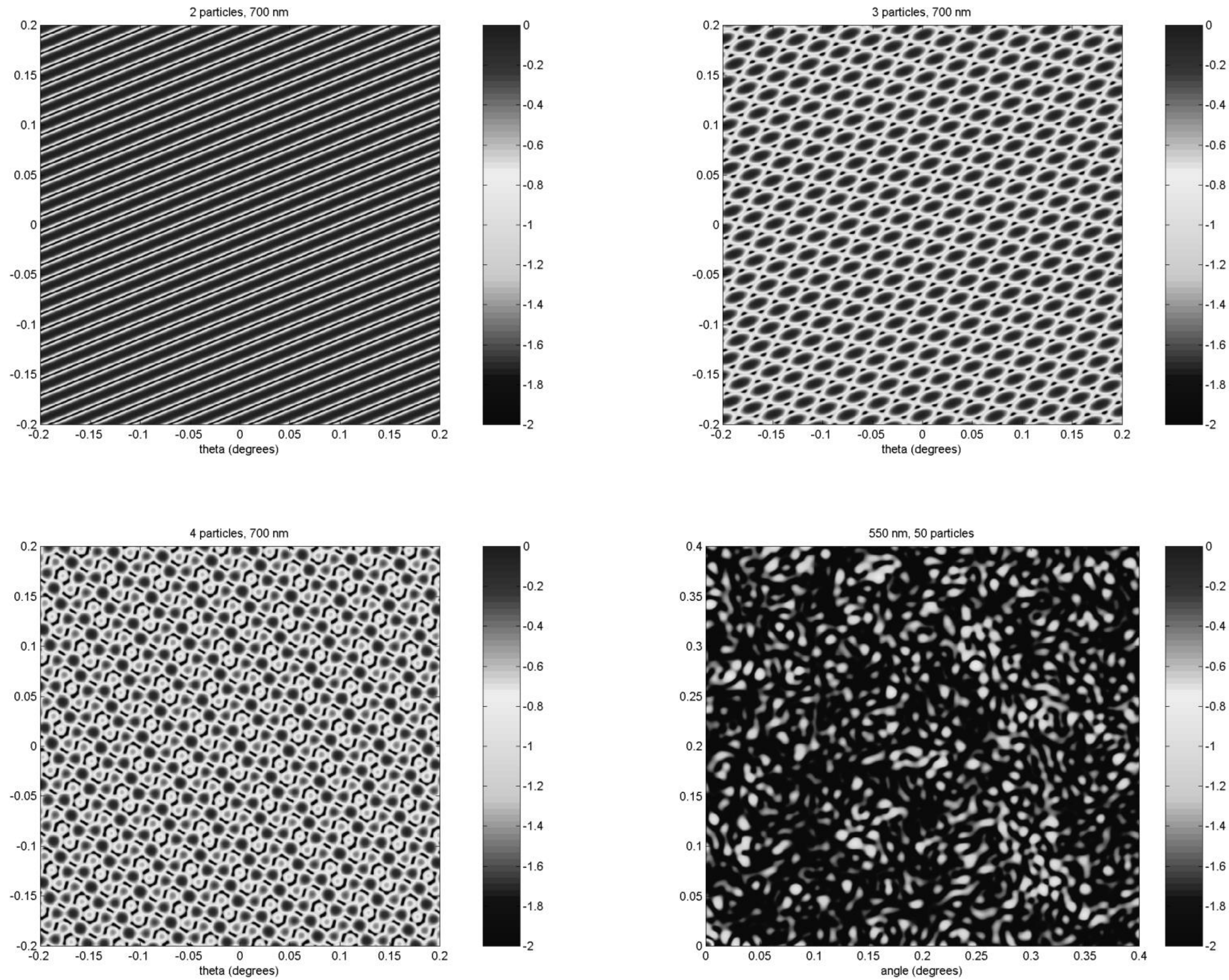
Central diffraction pattern from 2, 3, 4, 50 randomly placed particles

2

3

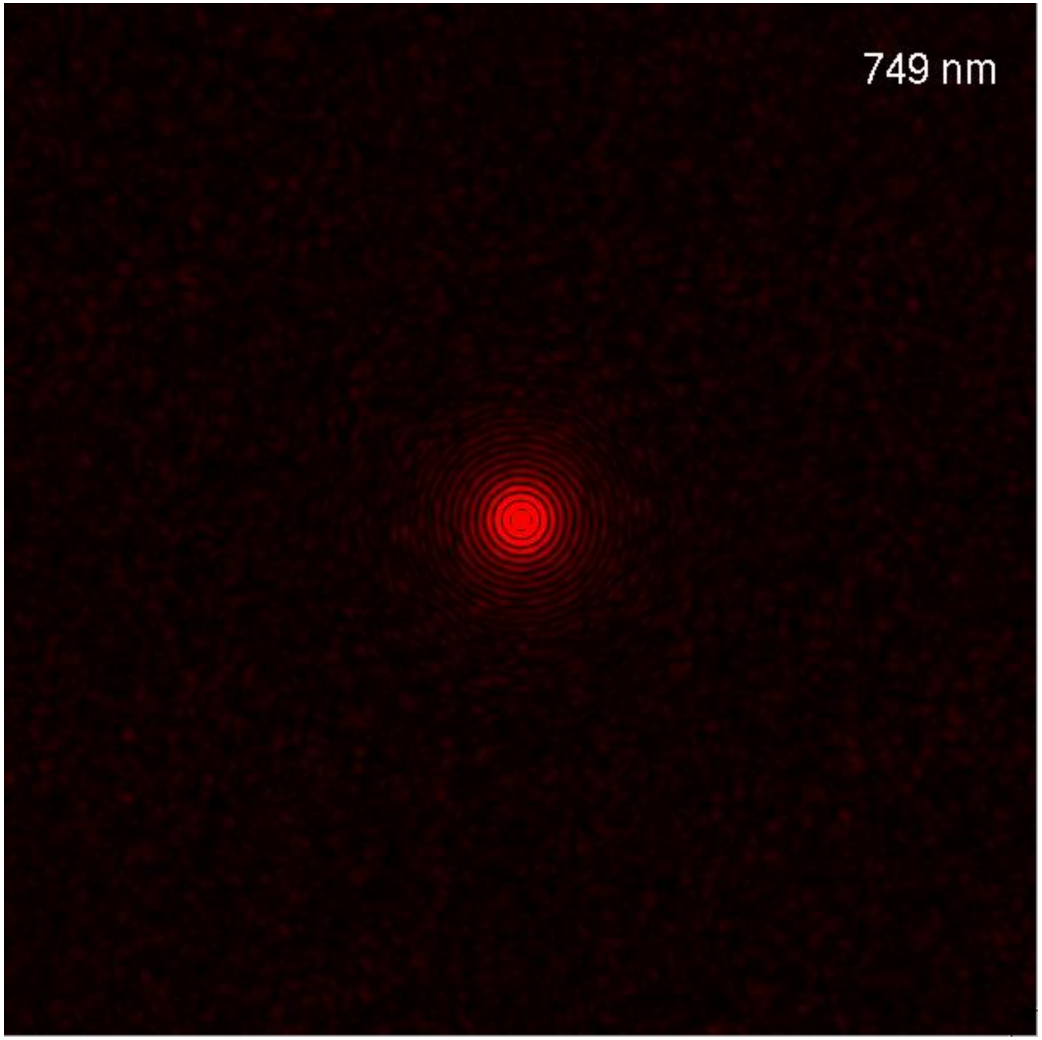
4

50

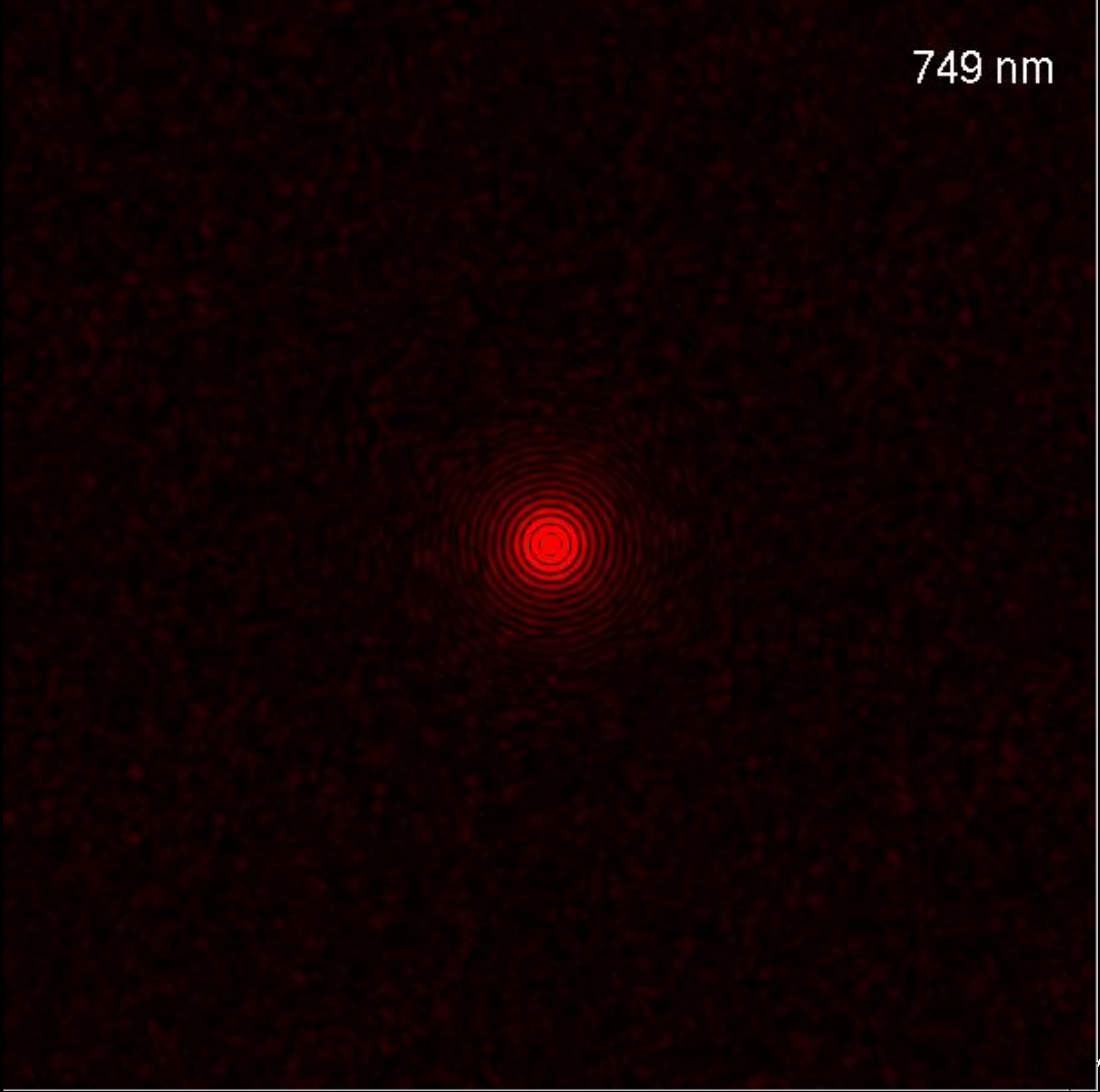


Tom van den Berg

Diffraction pattern for 1000 particles, as a function of wavelength, including spectral luminosity effect.



Tom van den Berg



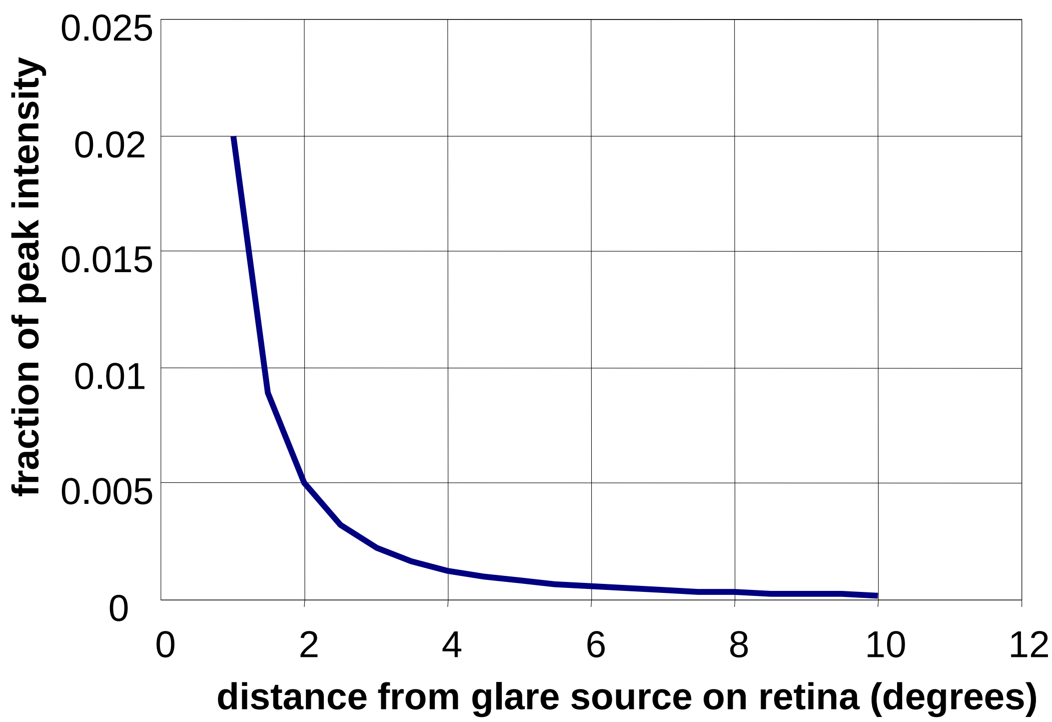
van den Berg

Tom van den Berg

Straylight (Glare) Equation

$$I = \frac{AE}{\theta^n}$$	where *I* is the retinal illuminance at the distance θ from the glare source of illuminance *E*. *A* is a scaling constant. *n* is usually calculated to be 2.

Equation applies outside of about 1 degree from the glare source.
Although 1% at 1 degree seems small, the total flux in the annulus outside of 1 degree can amount to 10% or more.



Aberrations

"*Now, it is not too much to say that if an optician wanted to sell me an instrument which had all these defects, I should think myself quite justified in blaming his carelessness in the strongest terms and giving him back his instrument*"

Helmholtz (1881) on the eye's optics.

Chromatic Aberration

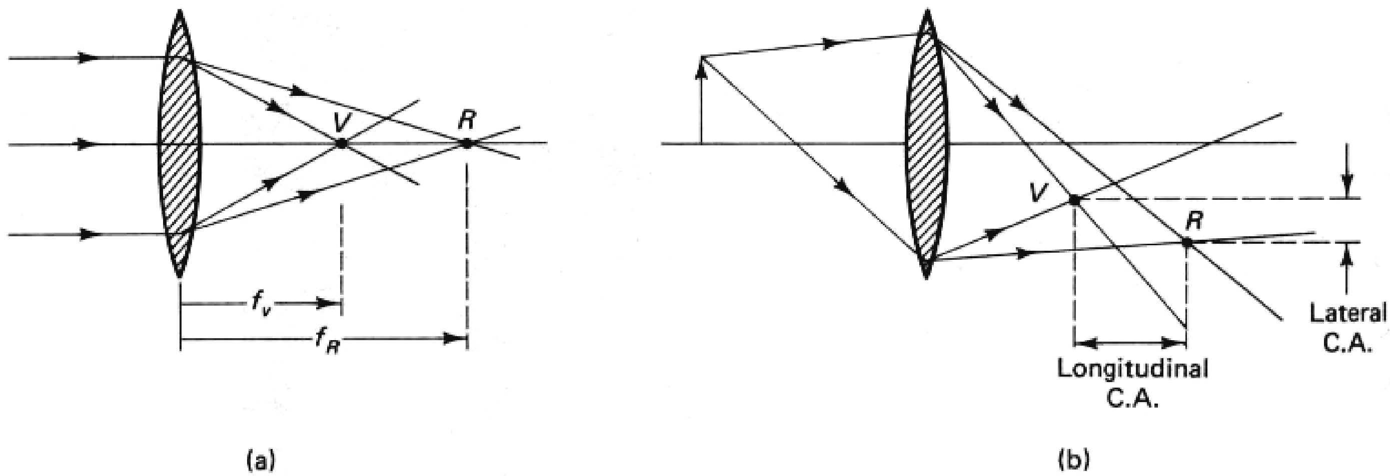


Figure 5-12 Chromatic aberration (exaggerated) for a thin lens, illustrating the effect on the focal length (a) and the lateral and longitudinal misses (b) for red (R) and violet (V) wavelengths.

Pedrotti and Pedrotti, 1987

Chromatic Aberration

Chromatic difference of refraction

$$L' = L + F$$

by definition, in the human eye

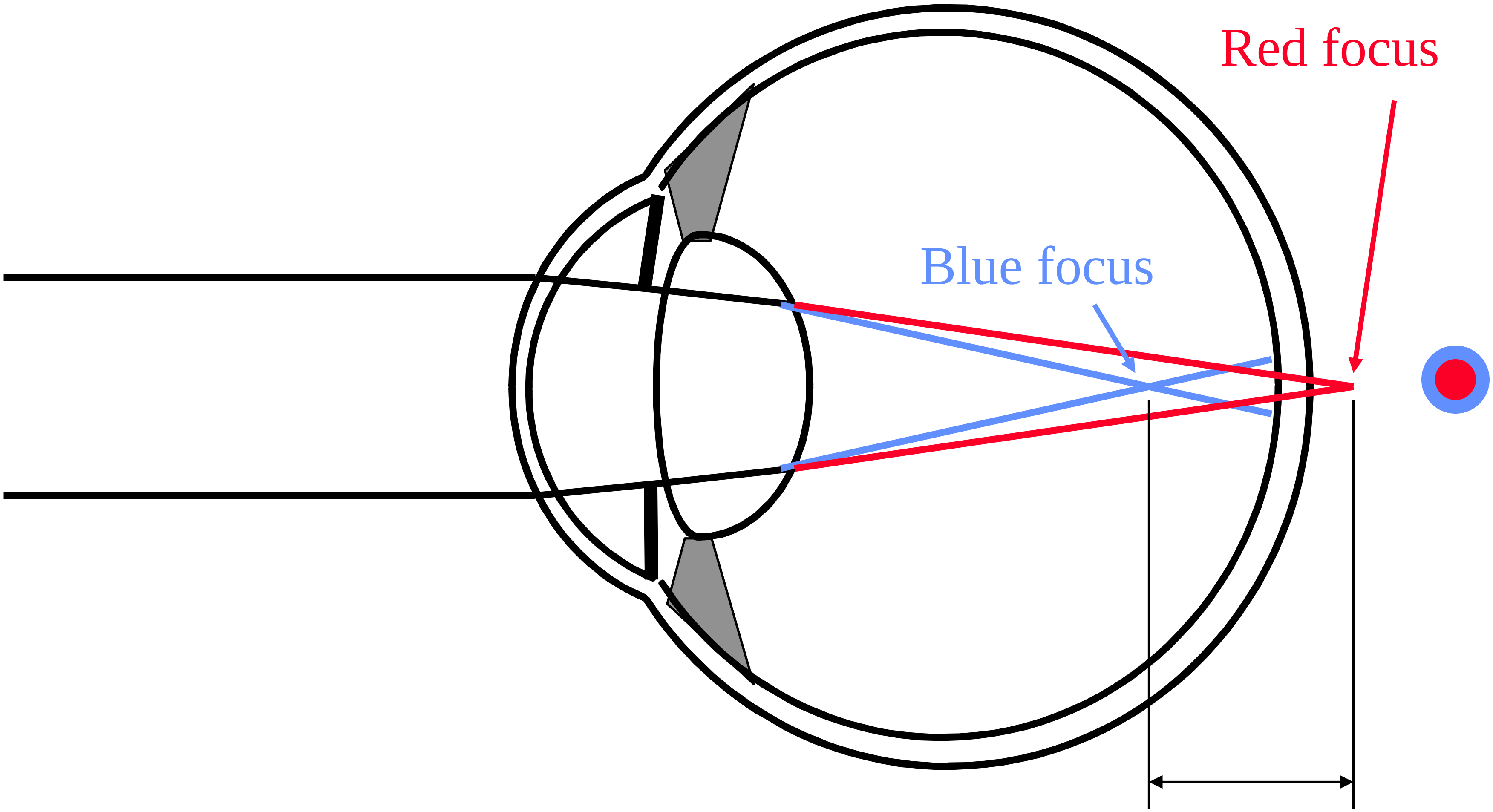
$$K' = K + F_e \quad \Rightarrow \quad K = K' - F_e$$

$$K = \frac{1}{k}$$ *refraction of the eye*

where $$K' = \frac{n'}{k'}$$

$$F_e = \frac{n'}{f'}$$ *power of the eye*

Chromatic Aberration



Longitudinal Chromatic Aberration

Chromatic Difference of Refraction

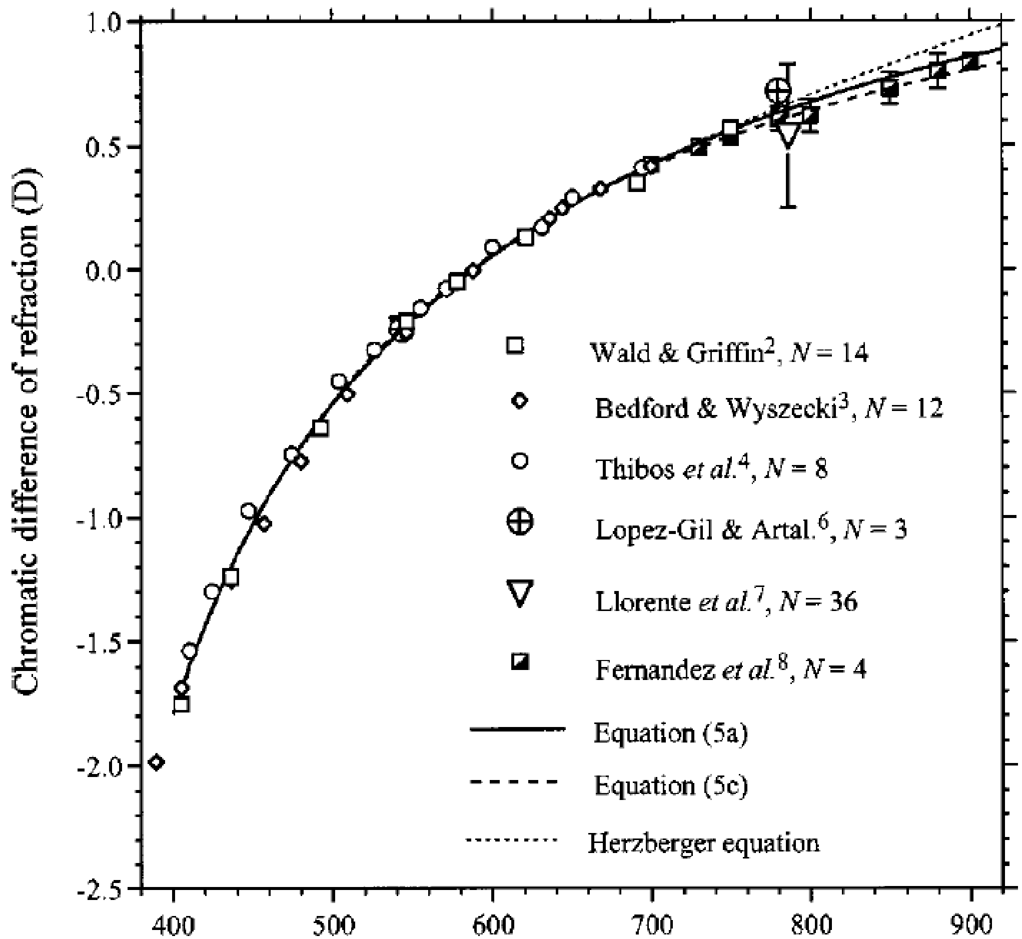


Fig. 1. Chromatic difference of refraction from three experimental studies2–4 in the visible spectrum and best-fit Cauchy equation (5a), Cornu's equation (5c), and Herzberger's equation to the combined studies. All data were set to be zero at 590 nm. Results of three studies6–8 with measurements in the infrared are also shown; we moved the data from these studies studies to coincide with Eq. (5a) at the lower wavelength (543 nm, Refs. 6 and 7) or at the lowest wavelength (700 nm, Ref. 8). Where shown, error bars indicate standard deviations.

Chromatic Aberration

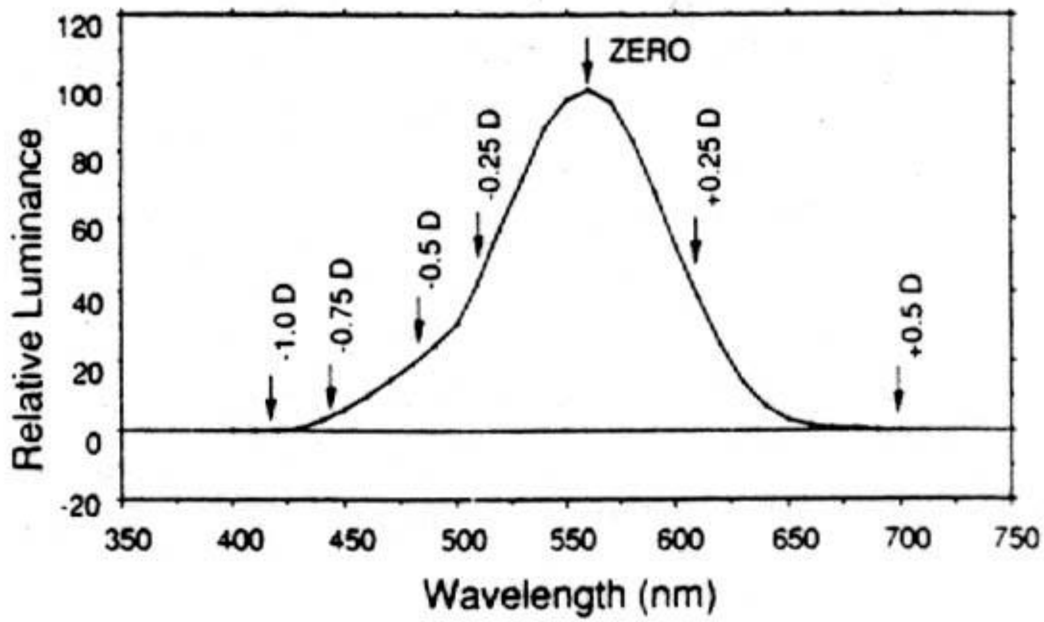
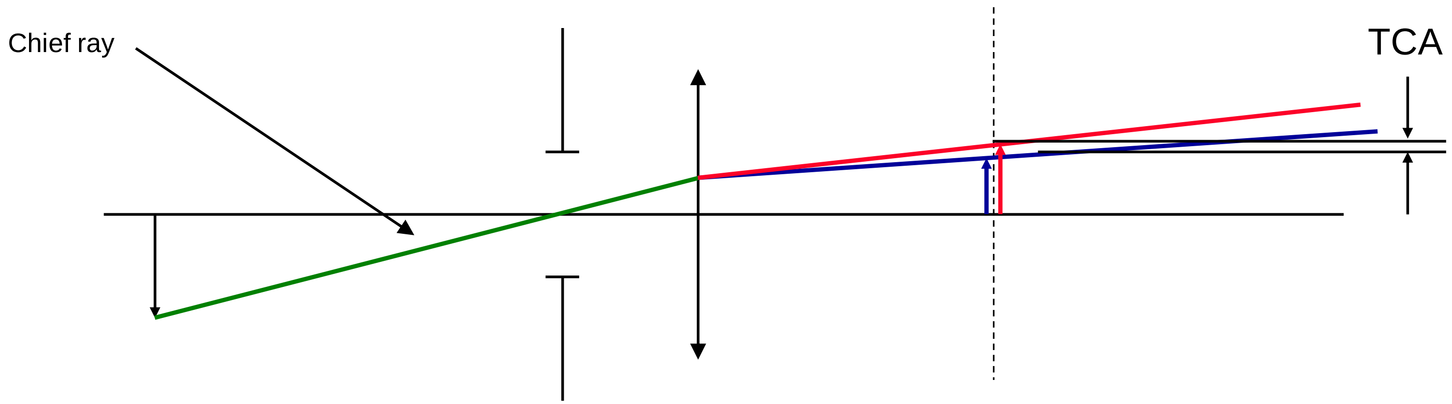


Figure 3. The significance of chromatic defocus depends on luminance. The solid curve shows the luminance spectrum of white-light emitted by the P4 phosphor of cathode ray tubes and arrows mark the amount of defocus if the eye accommodates for 550 nm. When the peak of the luminance spectrum is in focus, most of the light is less than 0.25 D out of focus.

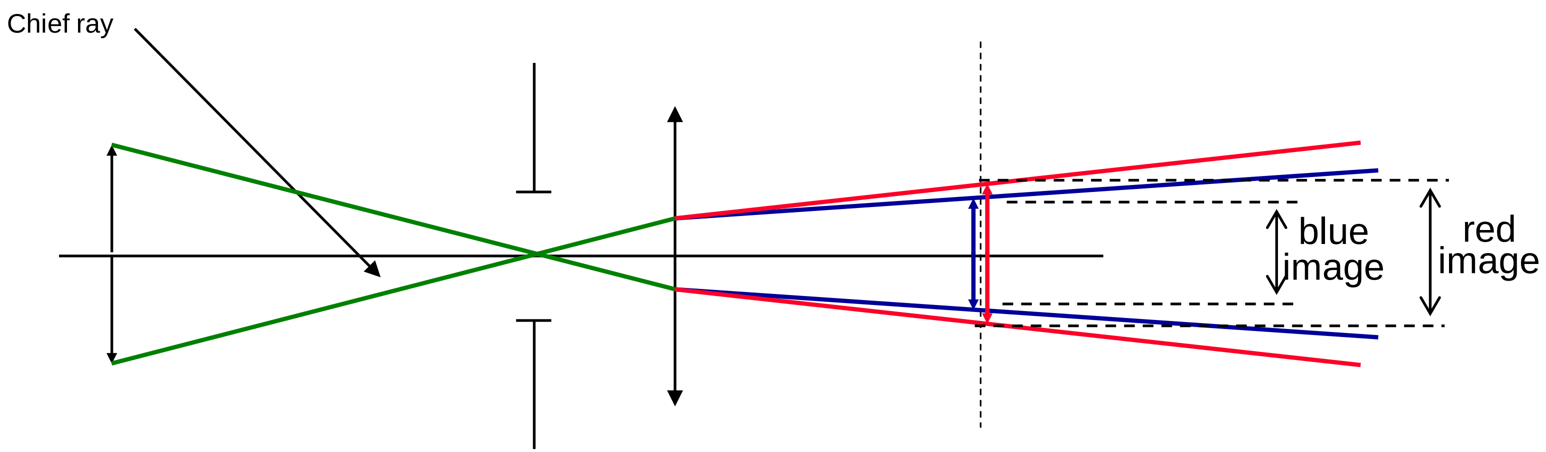
Thibos, Bradley & Zhang, 1989

Transverse Chromatic Aberrartion

Transverse chromatic aberration is a difference in magnification as a function of wavelength. It can be illustrated simply in an aperture lens system.

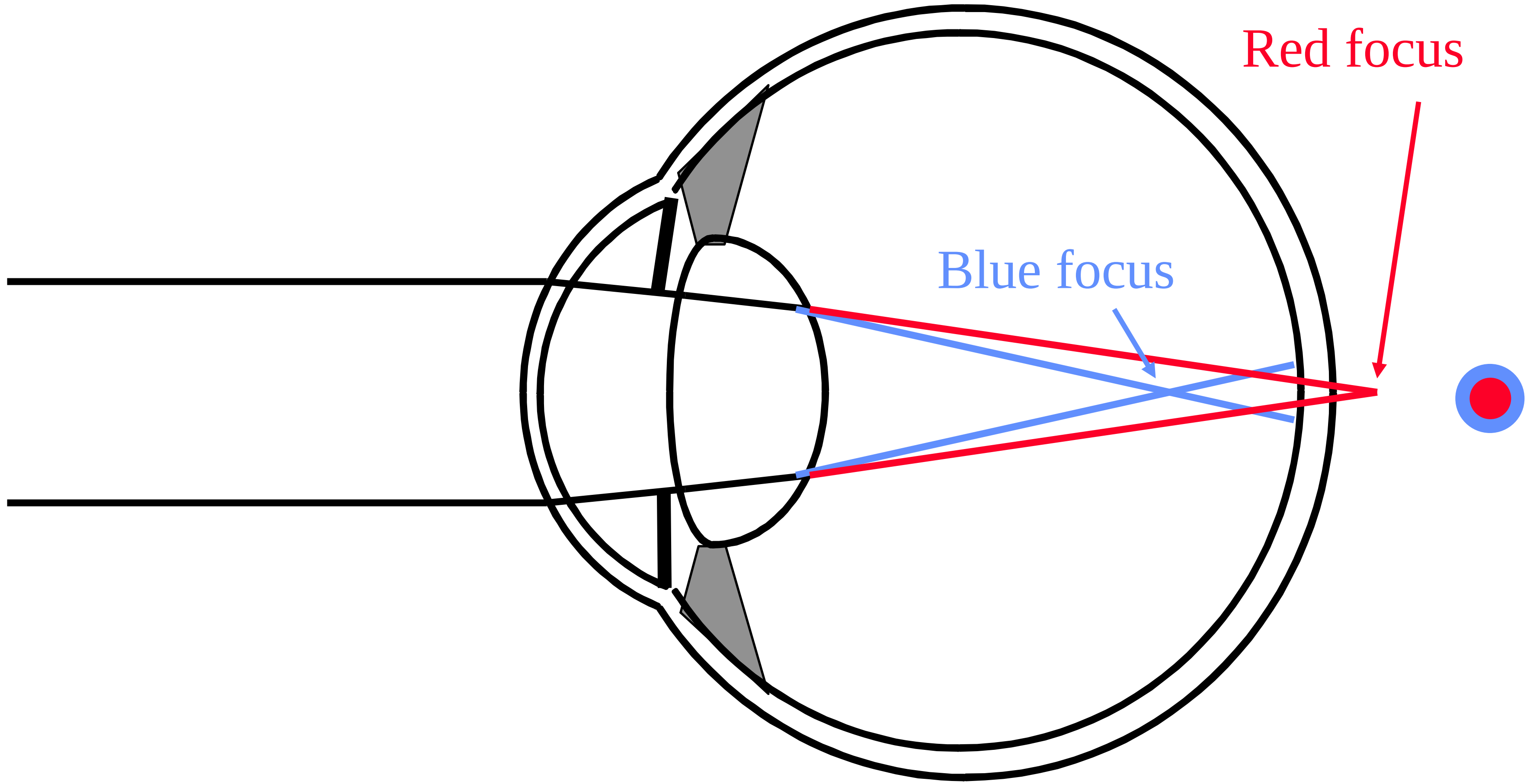


This also gives rise to ***Chromatic Difference of Magnification***.

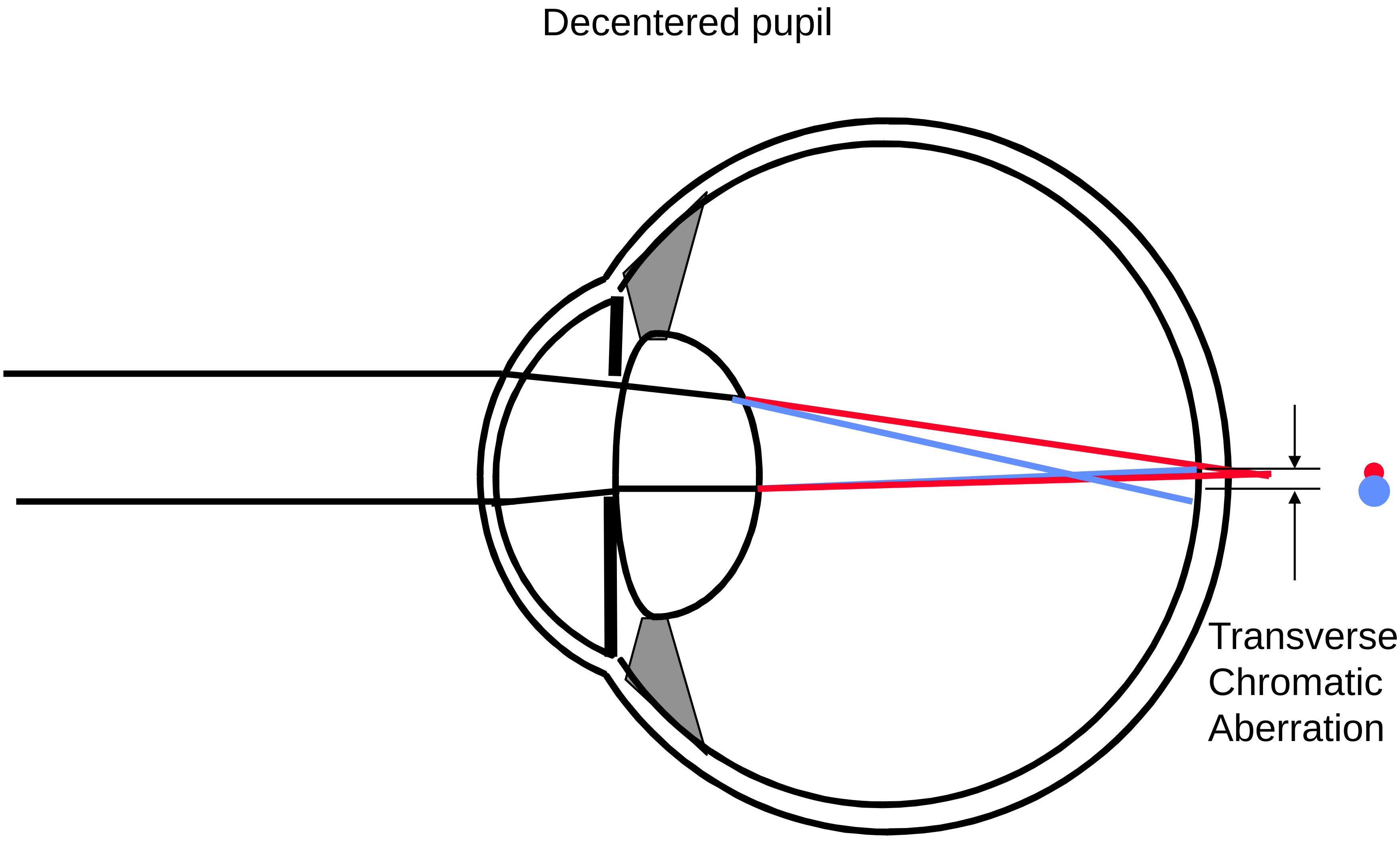


Transverse Chromatic Aberration

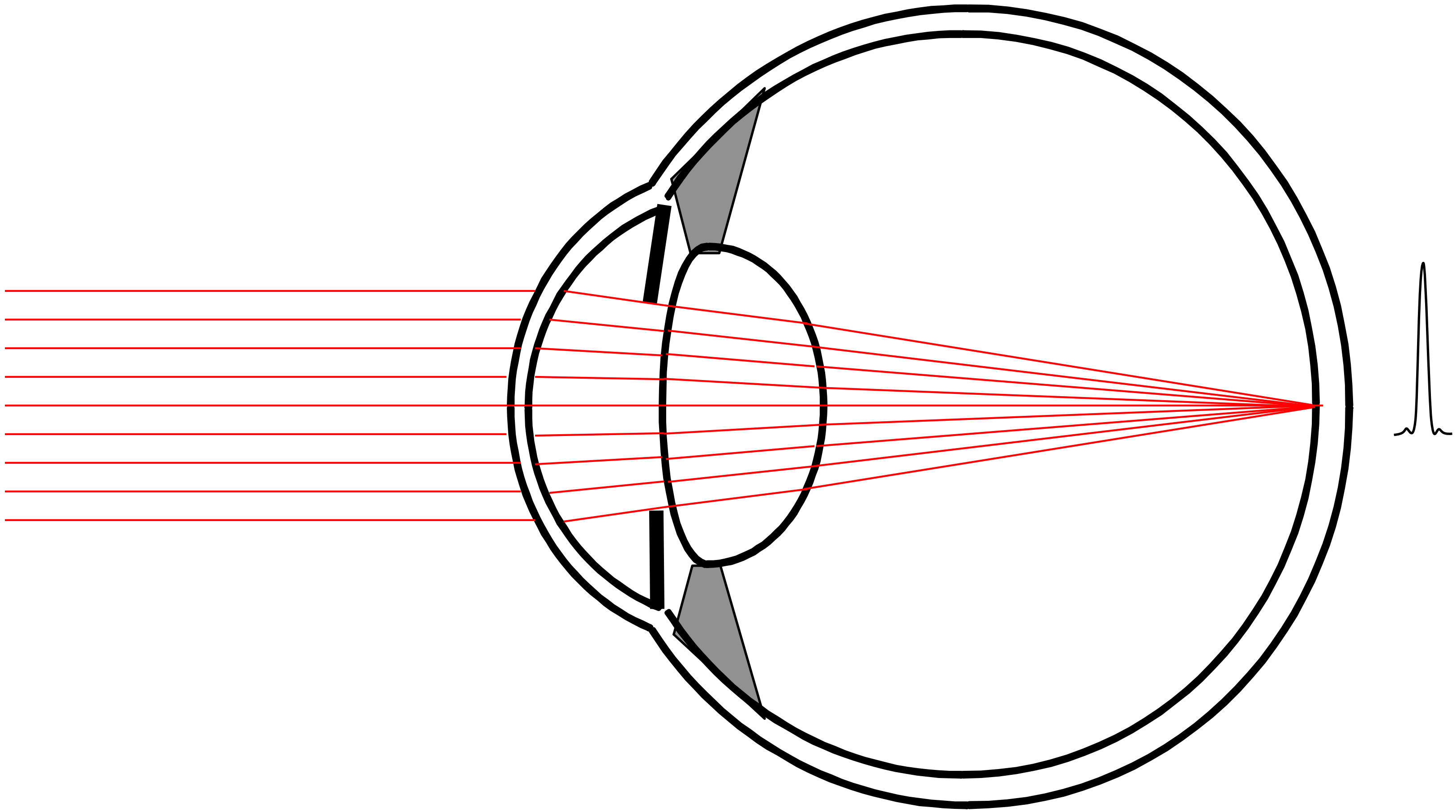
Centered pupil: TCA=0



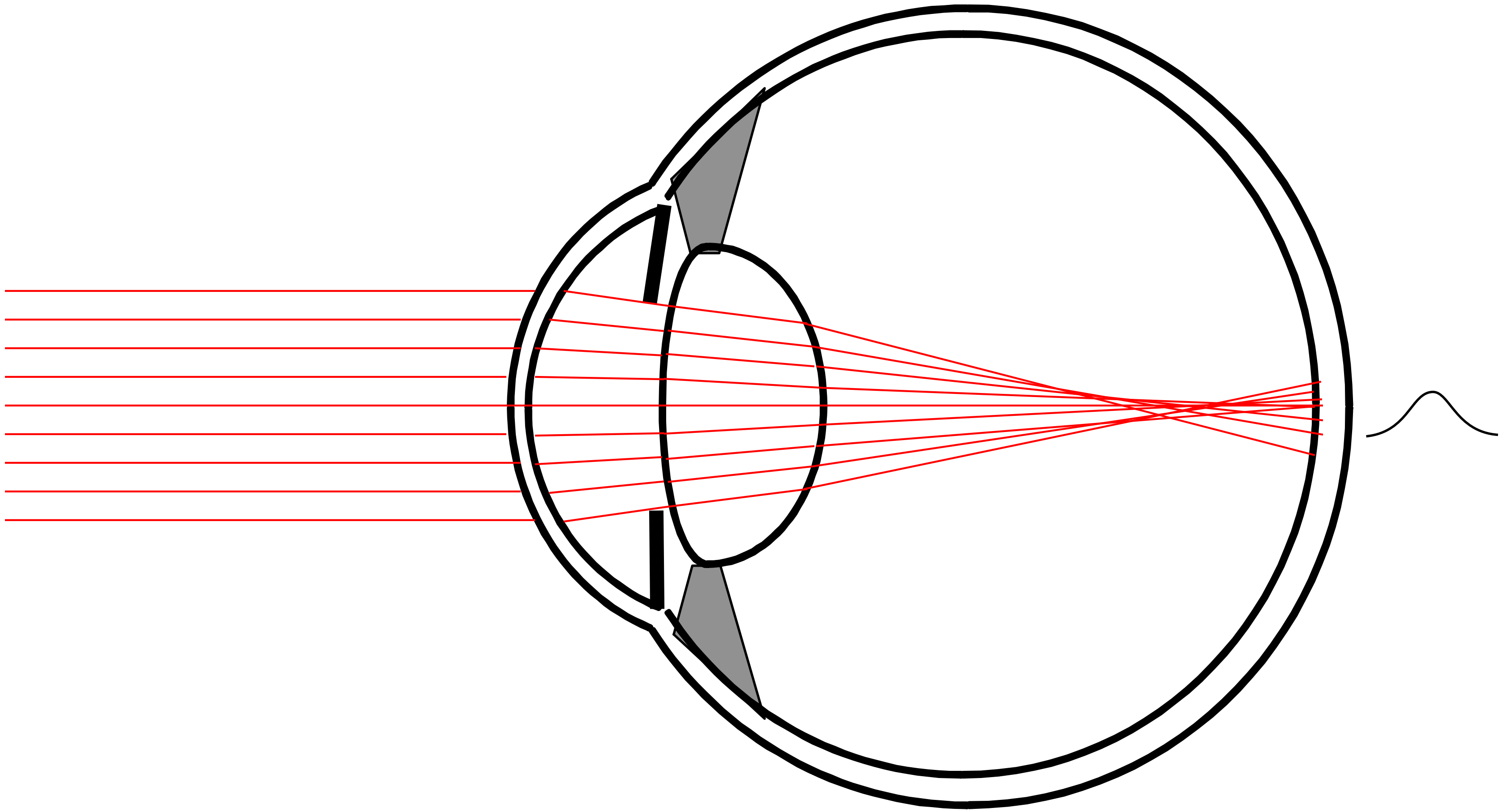
Transverse Chromatic Aberration



Monochromatic Aberrations: Perfect Eye



Monochromatic Aberrations: Aberrated Eye



Approximation to Snell's Law

Power series expansion for sin(θ)

$$\sin(\theta) = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \frac{\theta^7}{7!} + ...$$

First order, or paraxial approximation

$$\sin\theta = \theta \qquad \Rightarrow \qquad n\theta = n'\theta'$$

Third order approximation (Seidel)

$$\sin\theta = \theta - \frac{\theta^3}{3!} \qquad \Rightarrow \qquad n\left(\theta - \frac{\theta^3}{3!}\right) = n'\left(\theta' - \frac{\theta'^3}{3!}\right)$$

Seidel Aberrations : Astigmatism

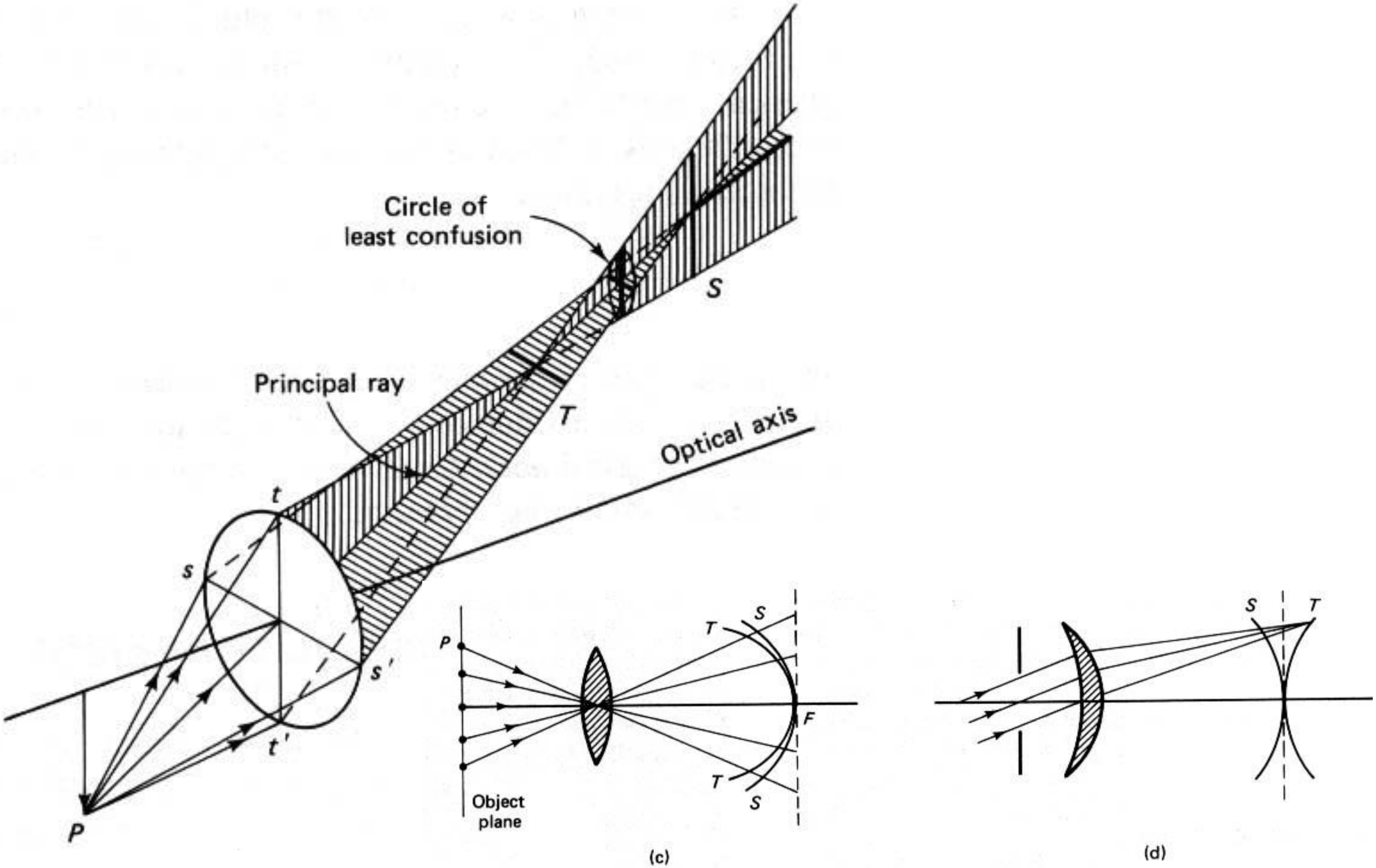


Figure 5-9 (Continued) (c) Astigmatic surfaces in the field of a lens. (d) Use of a stop to artificially "flatten" the field of a lens. The compromise surface between the *S* and *T* surfaces is indicated by the dashed line.

Pedrotti and Pedrotti, 1987

Seidel Aberrations : Spherical Aberration

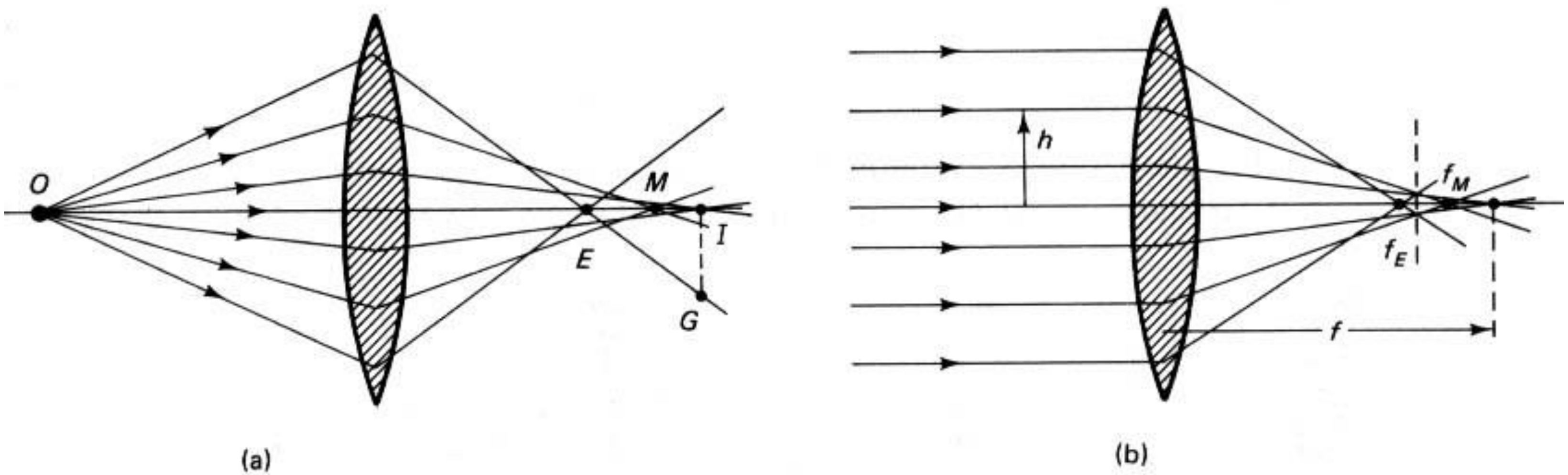
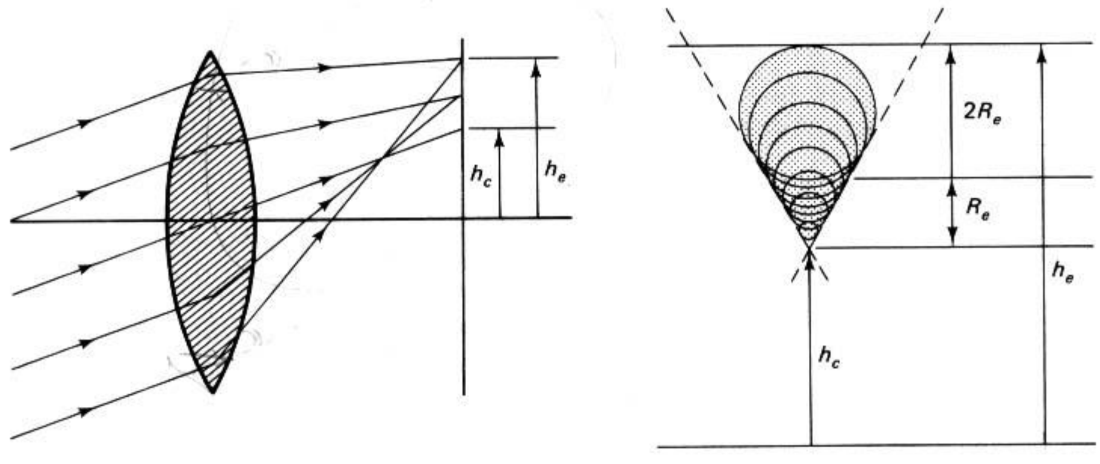


Figure 5-6 Spherical aberration of a lens, producing in (a) different image distances and in (b) different focal lengths, depending on the lens aperture.

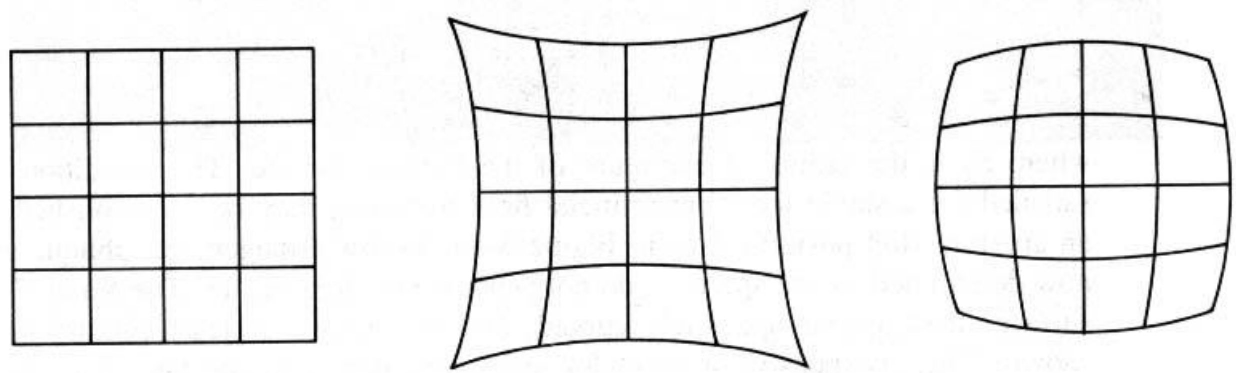
Pedrotti and Pedrotti, 1987

Seidel Aberrations : Coma



(a) (b)

Distortion



(a) (b) (c)

Figure 5-10 Images of a square grid (a) showing pincushion distortion (b) and barrel distortion (c) due to nonuniform magnifications.

Pedrotti and Pedrotti, 1987

Total Aberrations of the Eye

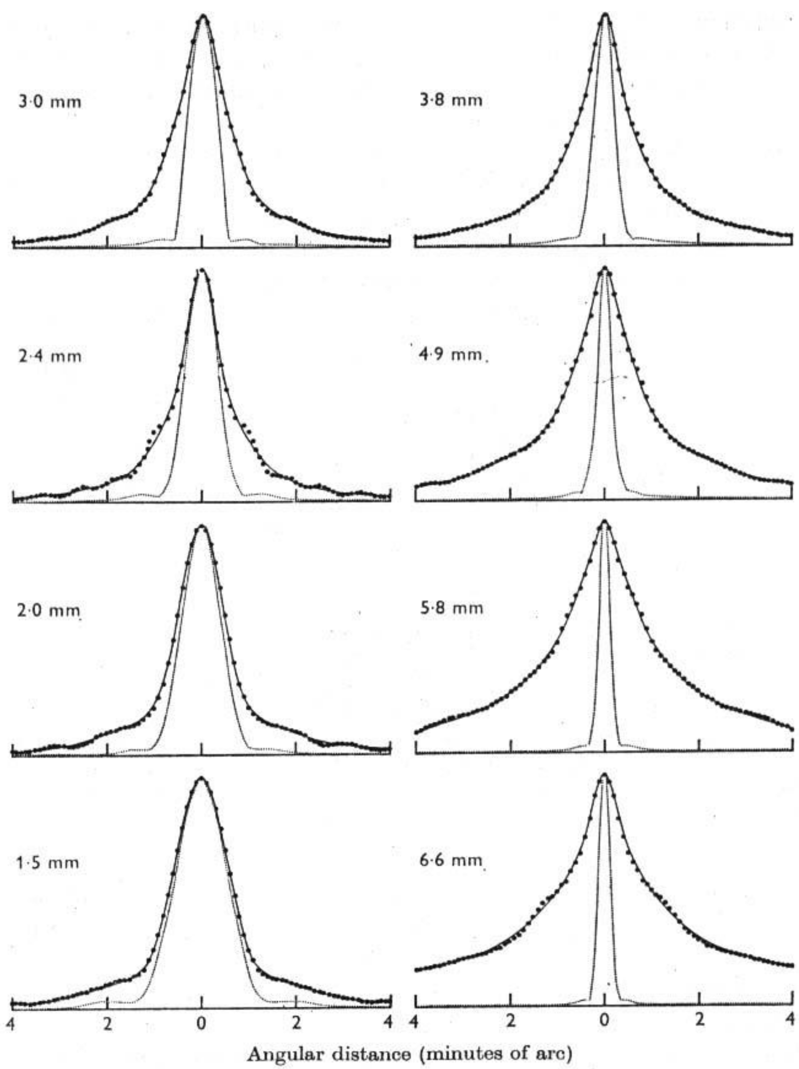
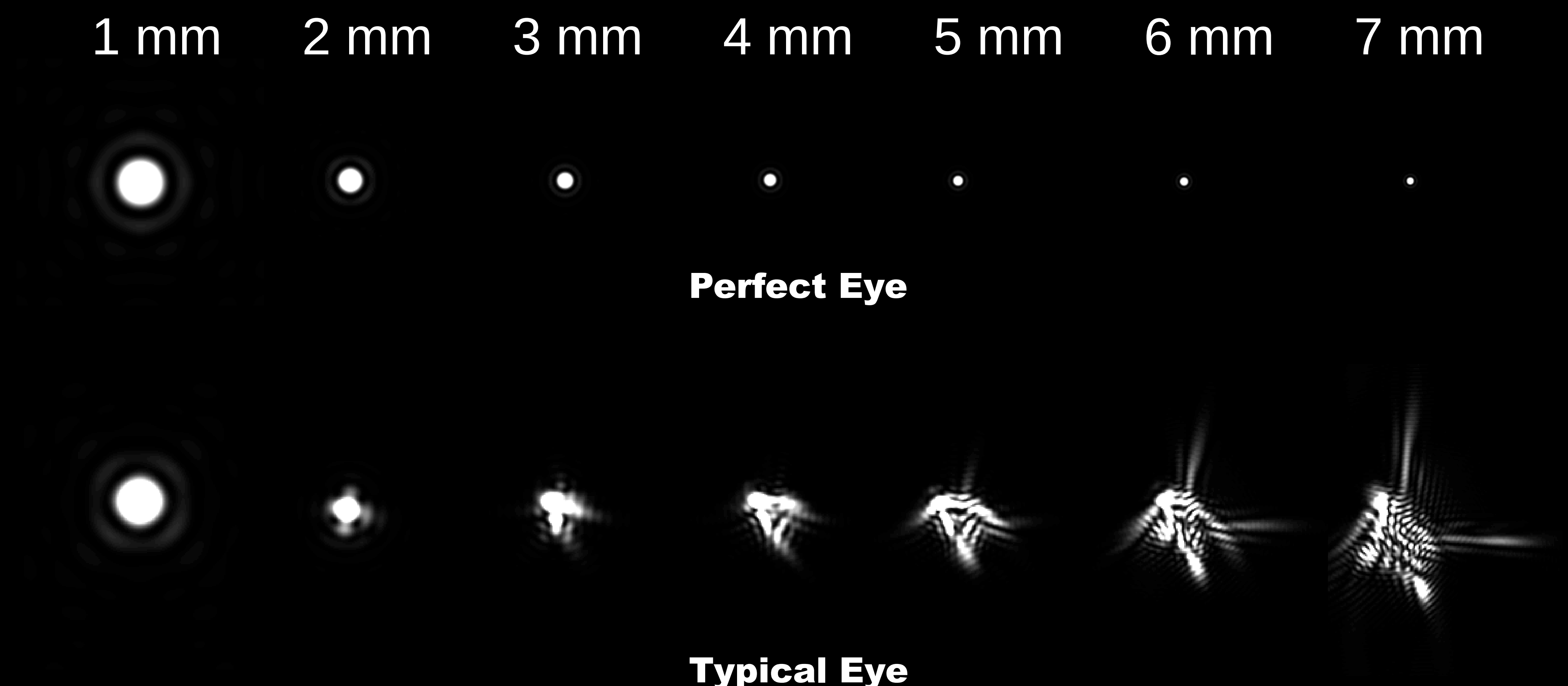


Fig. 10. Optical linespread functions of the human eye. Each curve represents the normalized distribution of illuminance occurring on the fundus for a thin line source of light. Dots occur at 0·1 min increments. Narrower curve indicates the diffraction image of a line at the given pupil diameter.

Campbell & Gubisch, 1966

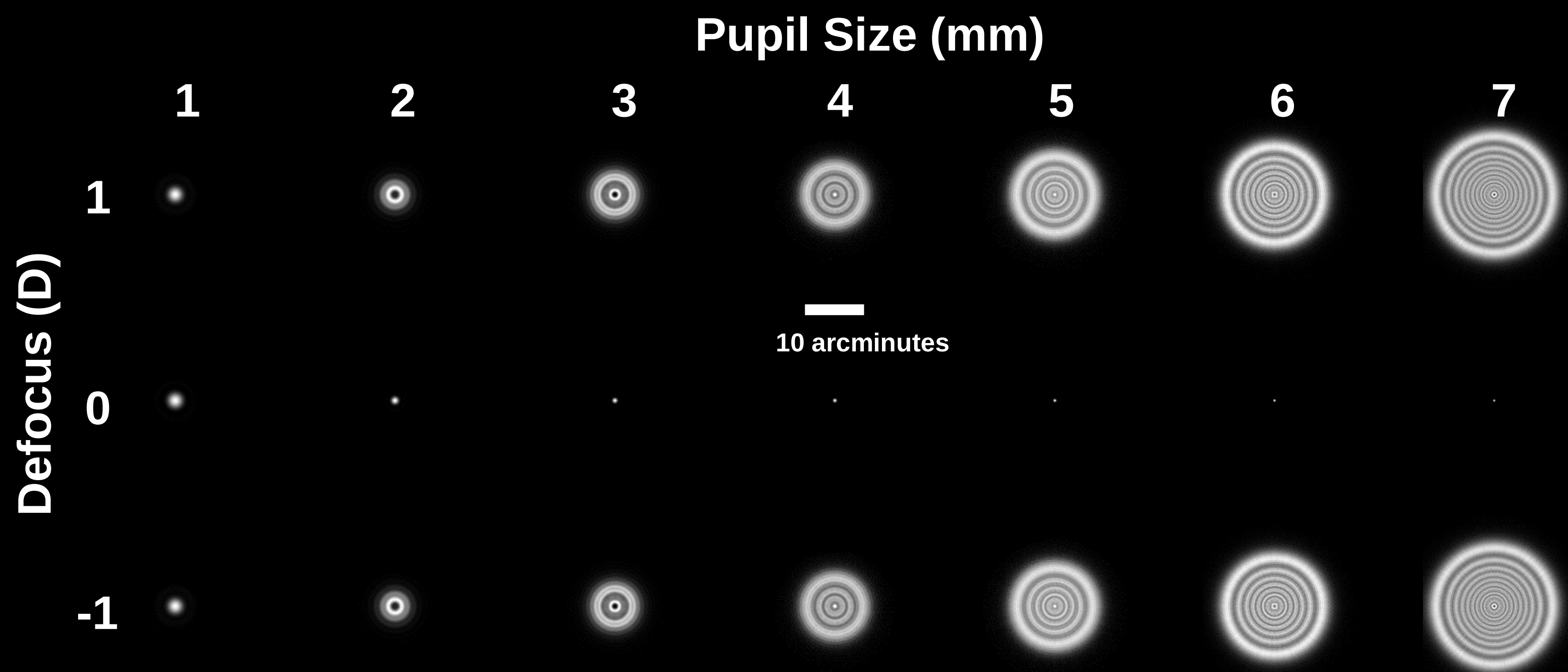
Point Spread Function vs. Pupil Size



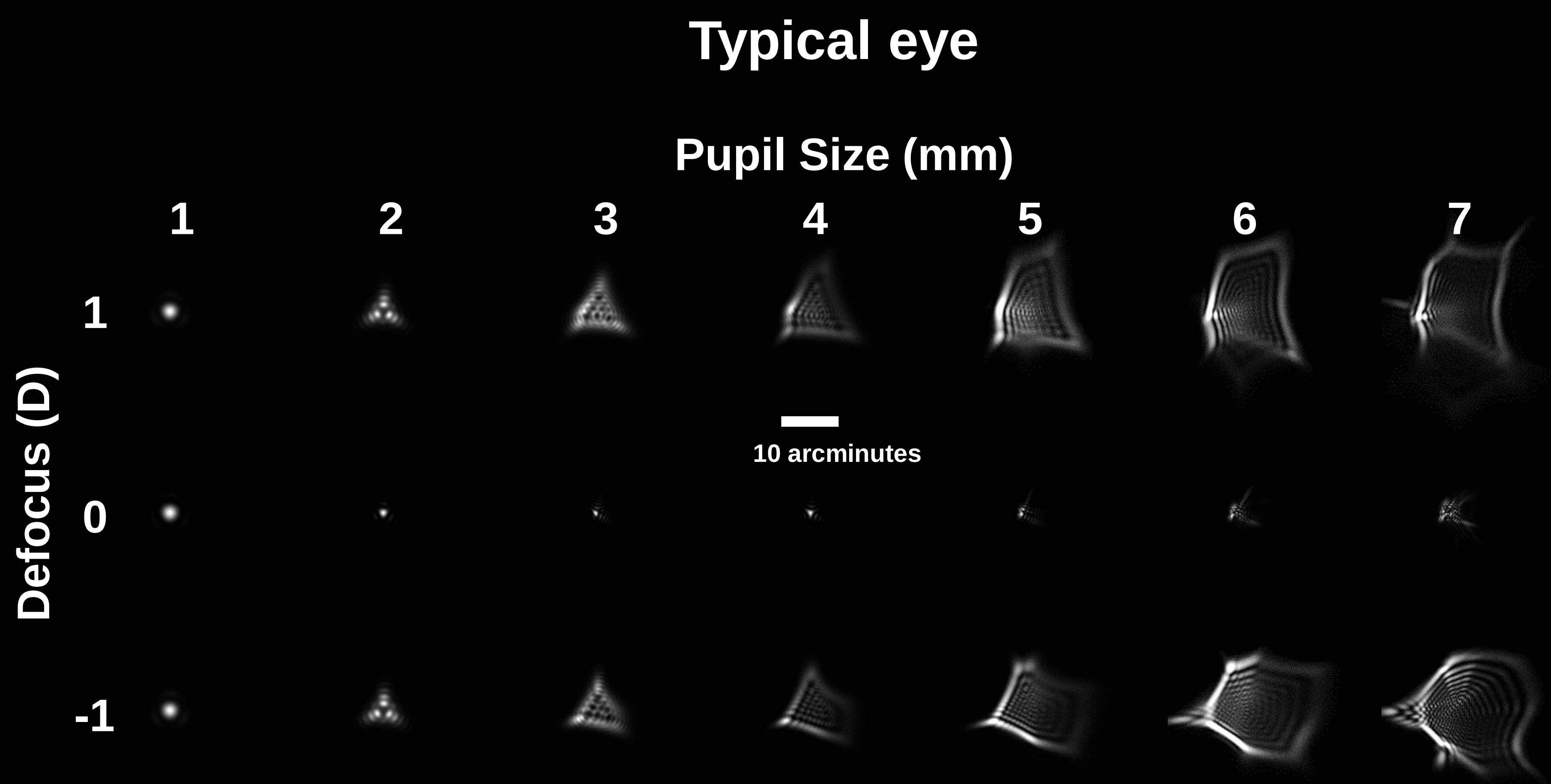
Observe your own point spread function

How do Diffraction and Aberrations Compare with Defocus?

Diffraction-limited eye



How do Diffraction and Aberrations Compare with Defocus?



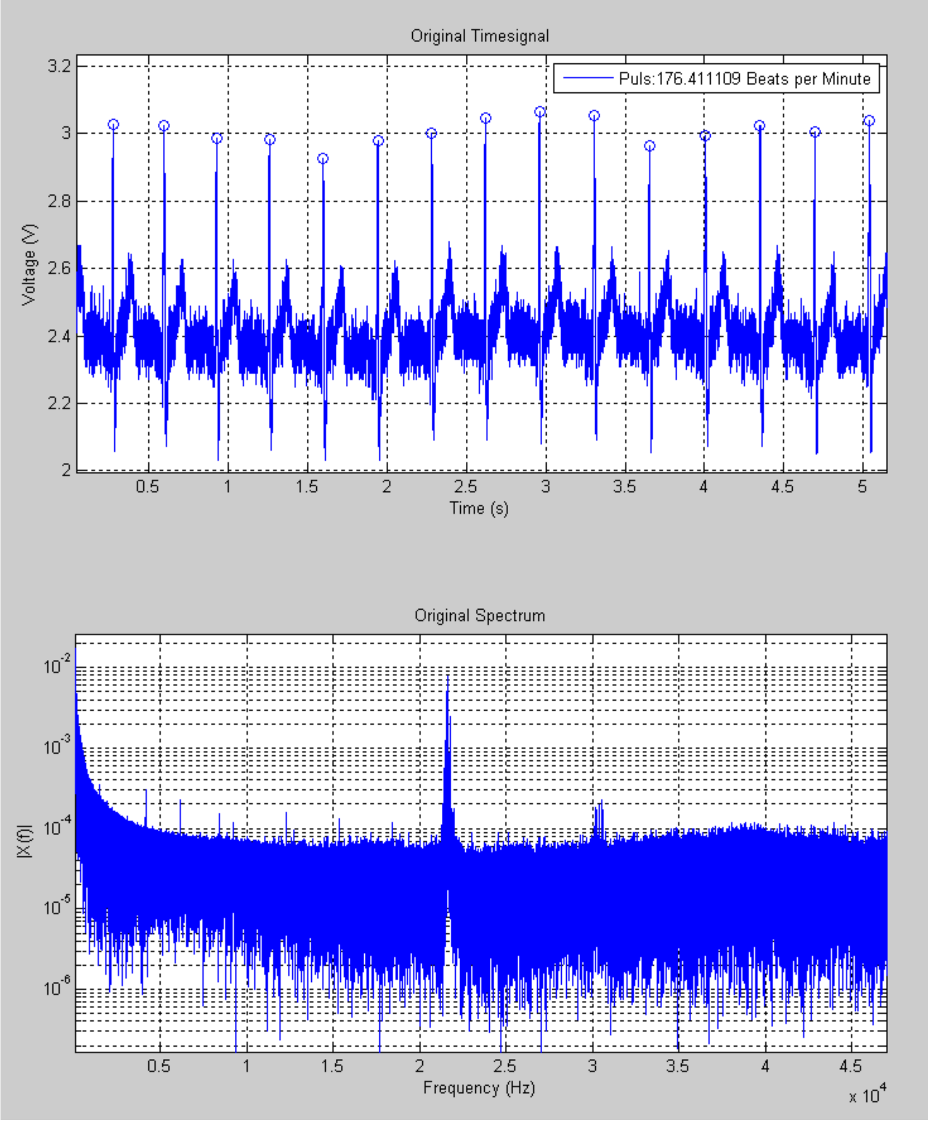
The Fourier Transform

def: means of transforming a signal defined in the spatial (time) domain to the spatial frequency (frequency) domain

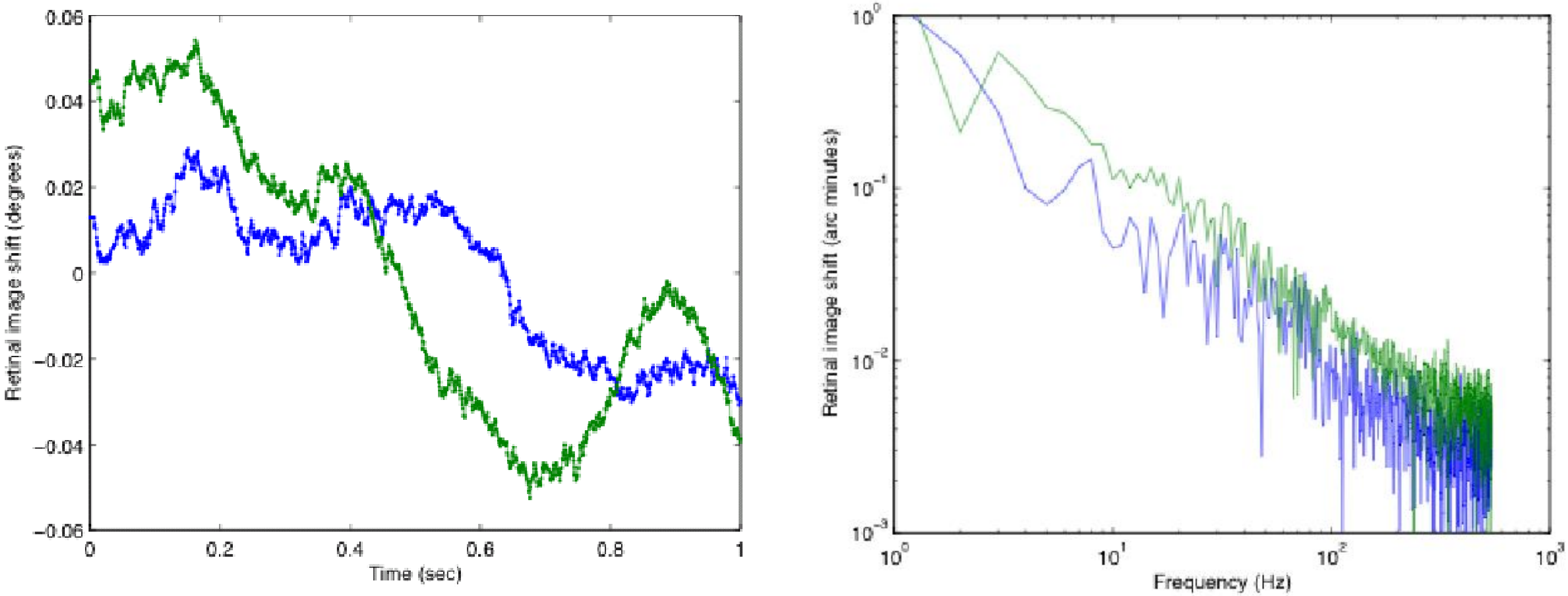
Fourier Transform

- Every time-coded signal can be composed by a superposition of oscillations of different frequencies and phases
- Every 2D pattern can be comprised of a series of sinusoids of different amplitides and phases
- Every object can be considered as being composed of an infinite array of spatial frequencies of all orientations, each with a specific amplitude and phase.

FFT of a heartbeat



Eye Movement Statistics



Power spectrum of eye movements

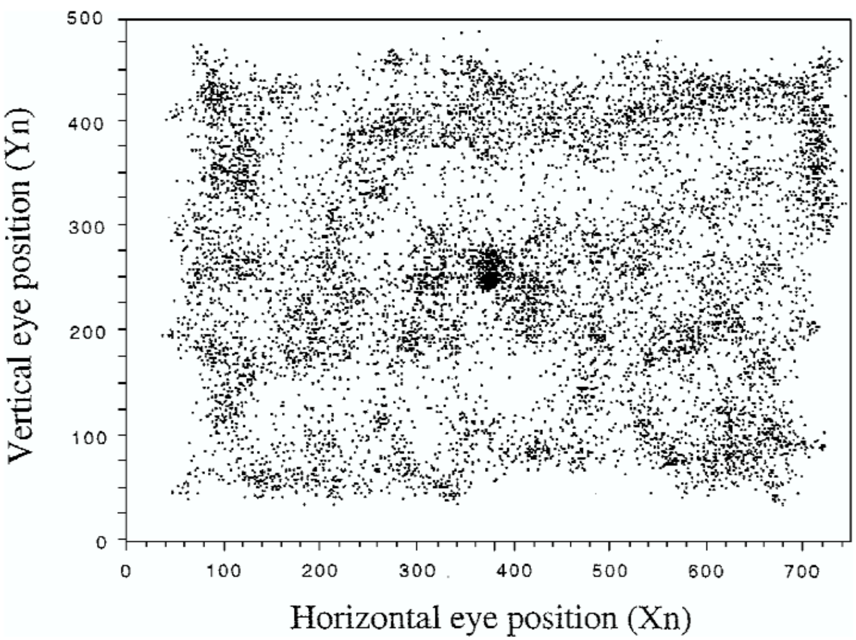


Fig. 1. Scatter plot of 10,215 eye fixations for the entire visual search experiment. Eye fixations are represented across horizontal (x) and vertical (y) screen coordinates in pixel units. There are clear clusters of fixations in the center and near the boundaries, and intermittent gaps throughout the display.

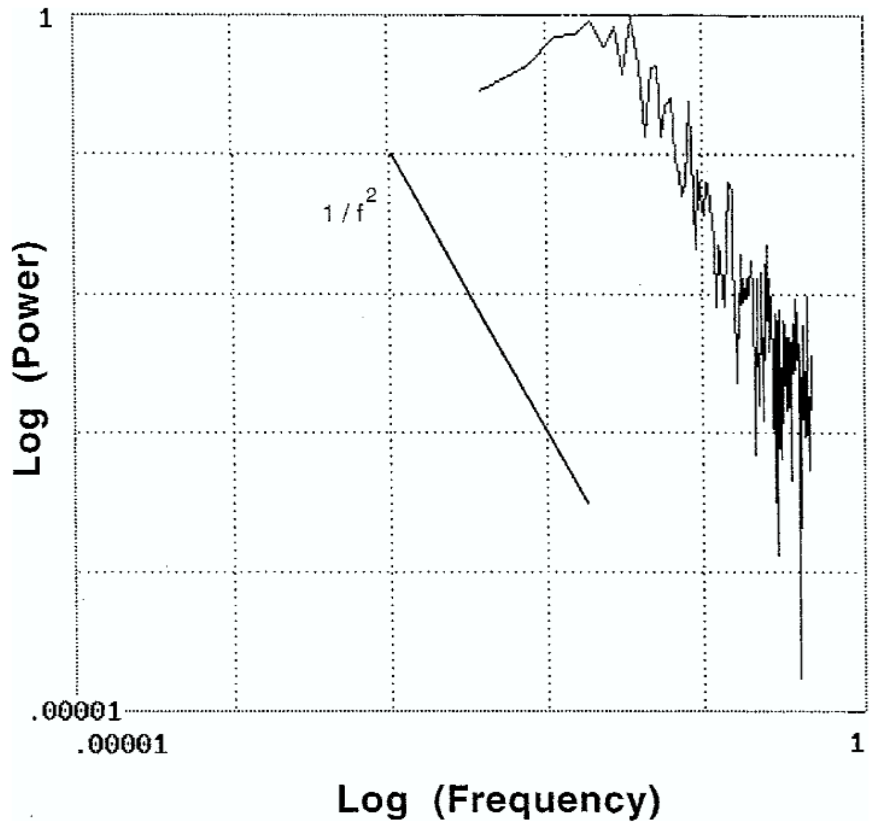
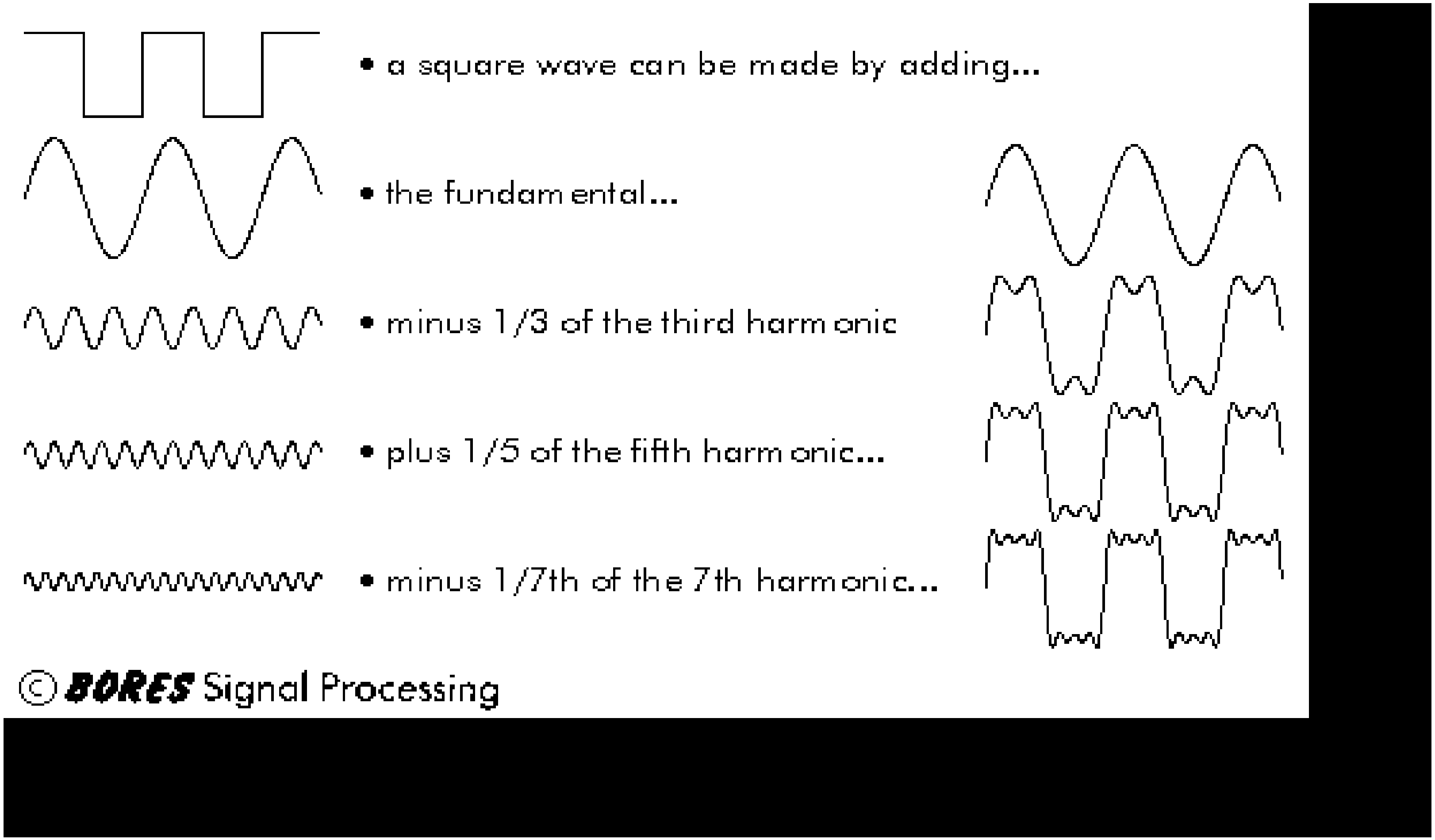


Fig. 4. Power spectra of vertical eye fixation series from the entire visual search experiment. Total power equals mean squared amplitude. Brown ($1/f^2$) noise trends emerge. Also shown is a line depicting an exact $1/f^2$ power spectrum.

Fourier Transform

- Every time-coded signal can be composed by a superposition of oscillations of different frequencies and phases
- Every 2D pattern can be comprised of a series of sinusoids of different amplitides and phases
- Every object can be considered as being composed of an infinite array of spatial frequencies of all orientations, each with a specific amplitude and phase.

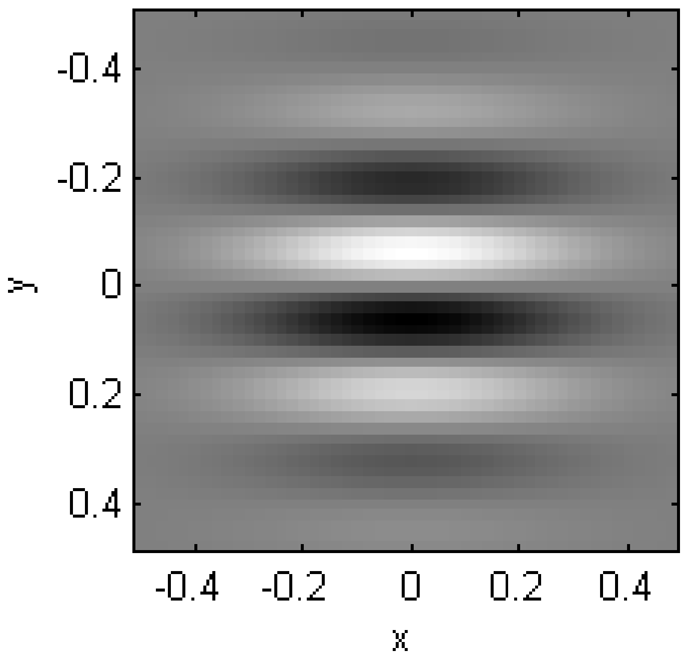
Frequency Space

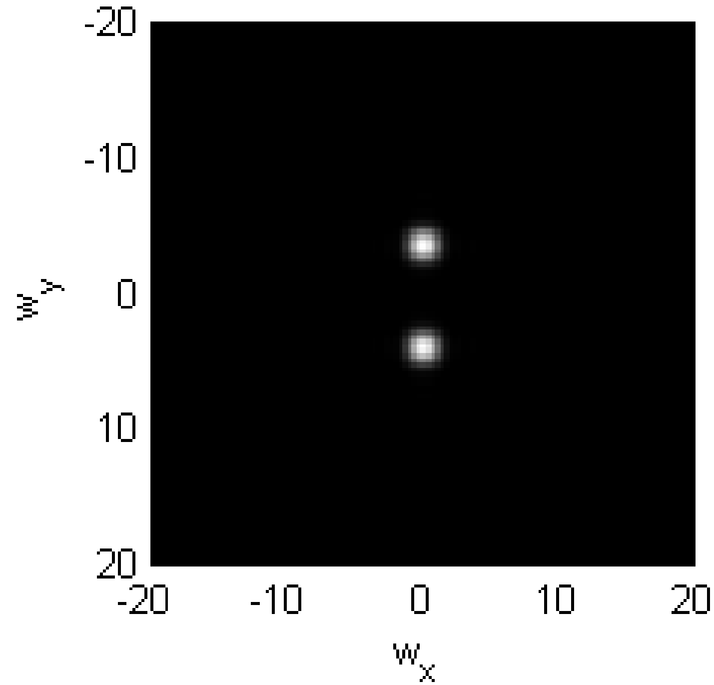


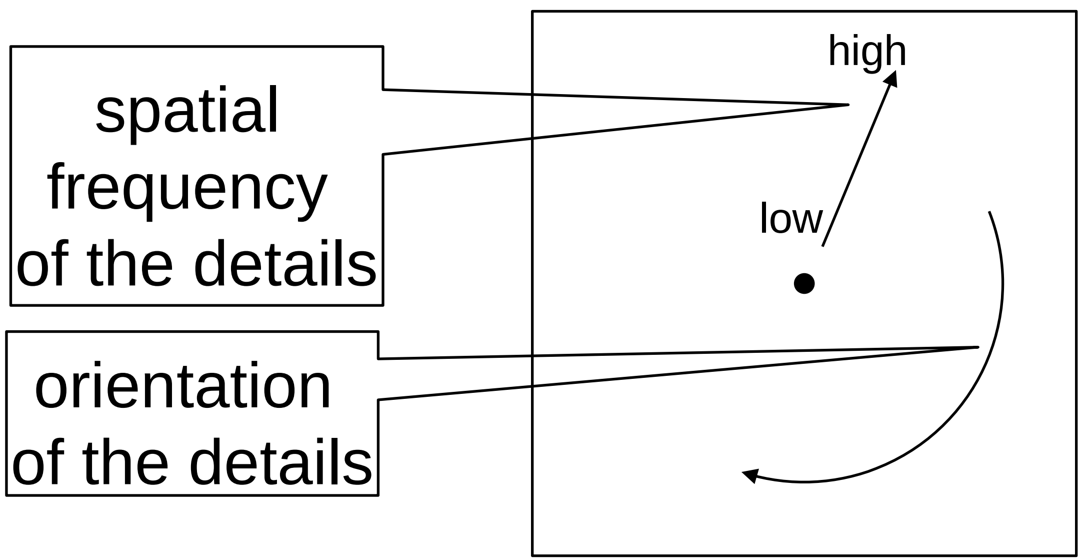
Fourier Transform

- Every time-coded signal can be composed by a superposition of oscillations of different frequencies and phases
- Every 2D pattern can be comprised of a series of sinusoids of different amplitides and phases
- Every object can be considered as being composed of an infinite array of spatial frequencies of all orientations, each with a specific amplitude and phase.

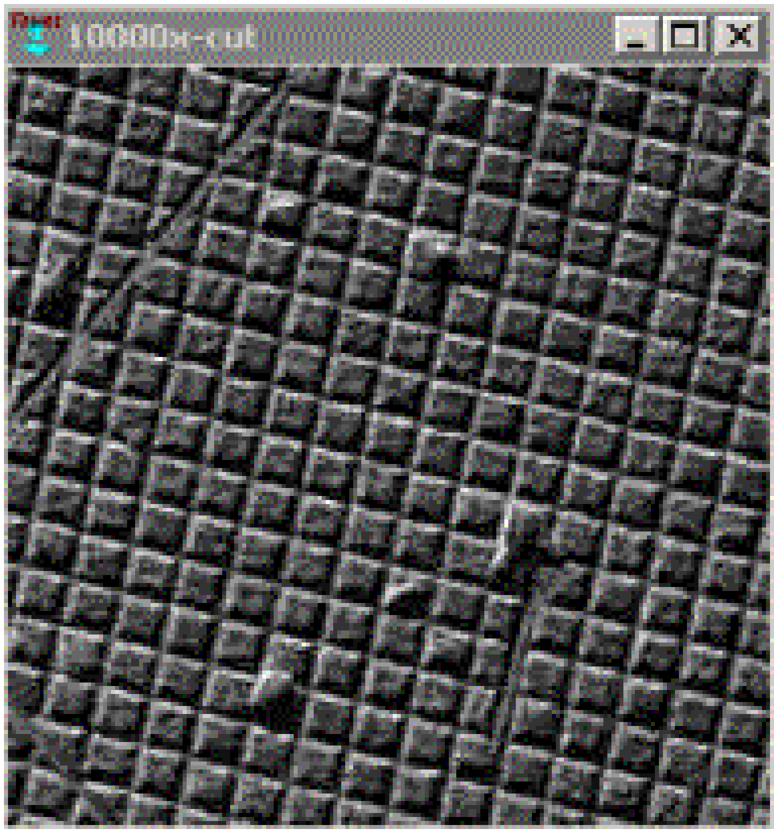
FFT of a 2D image



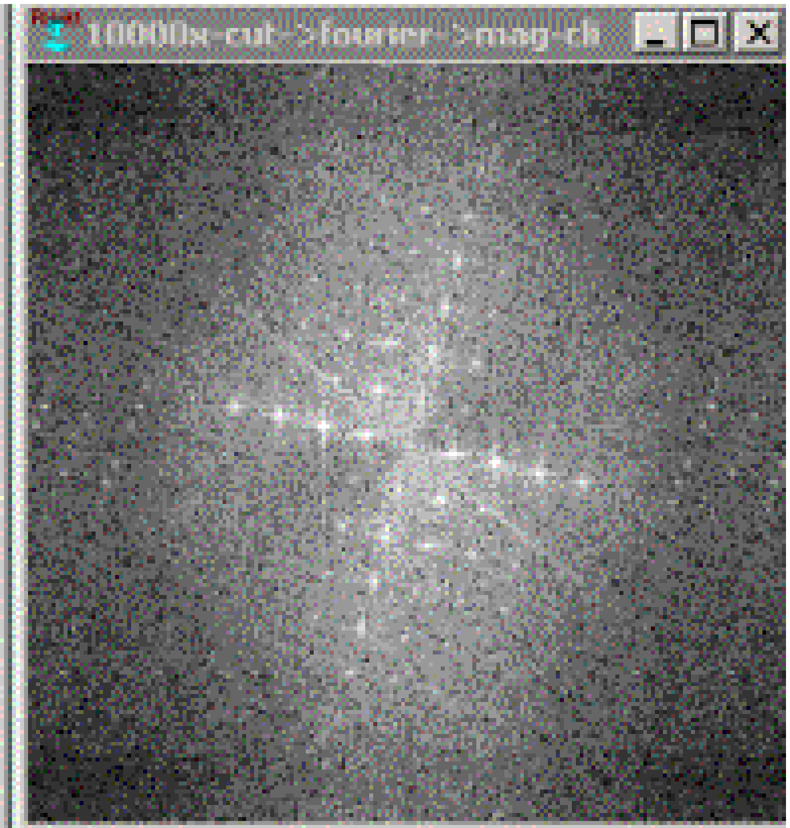




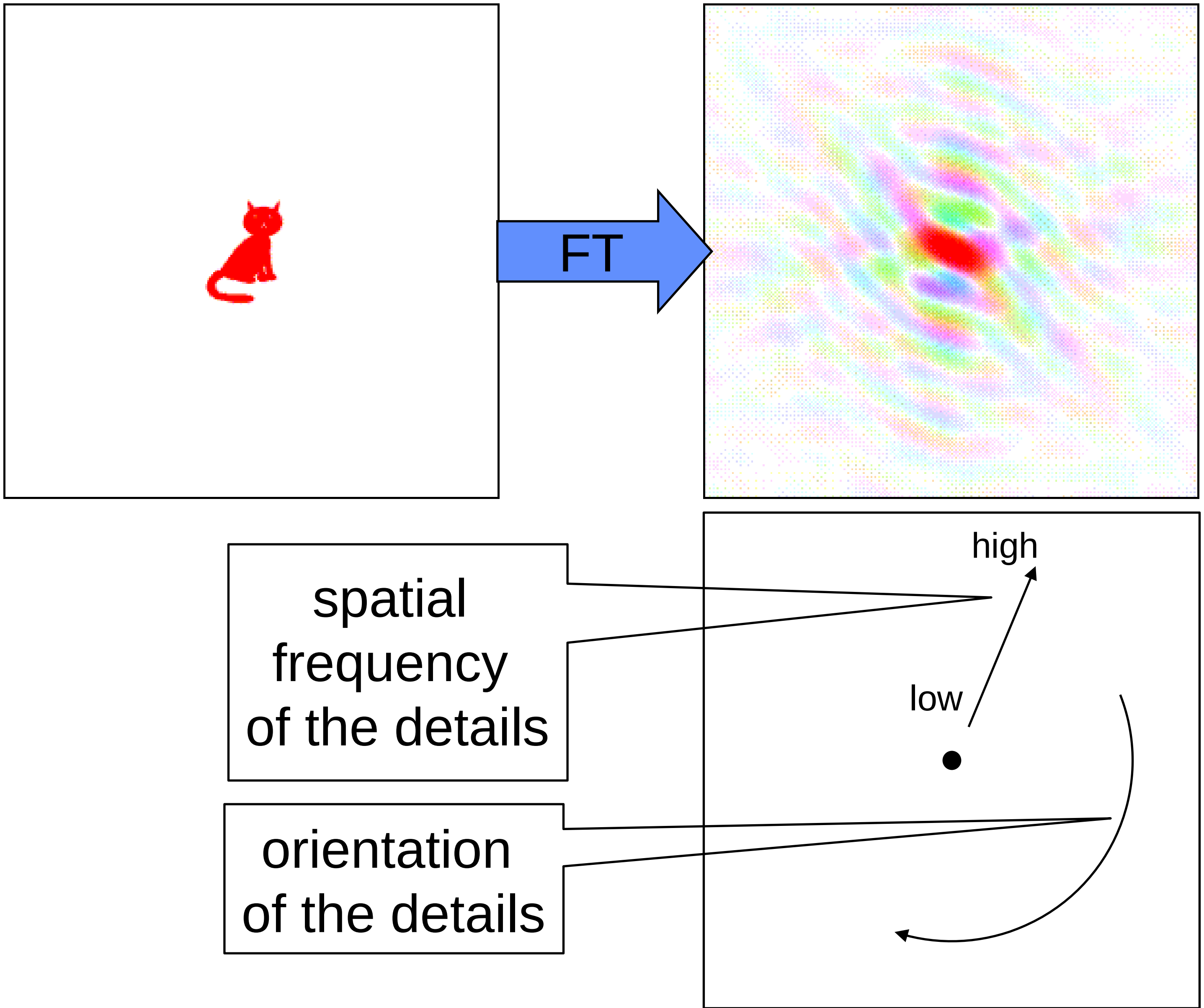
Image



Log (magnitude (FFT))

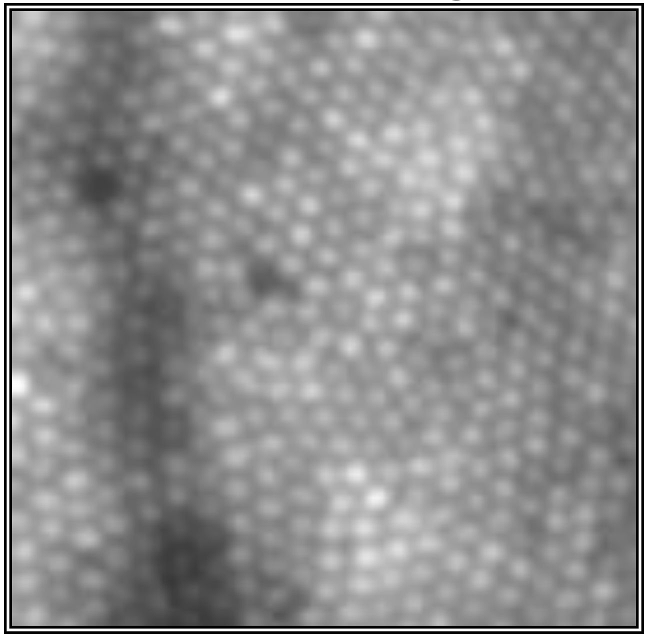


Power Spectrum of an Image

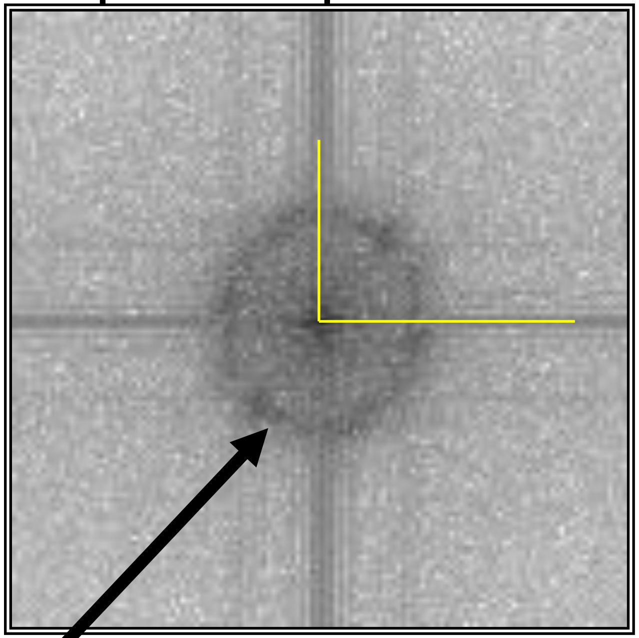


Power Spectrum of an Image

retinal image



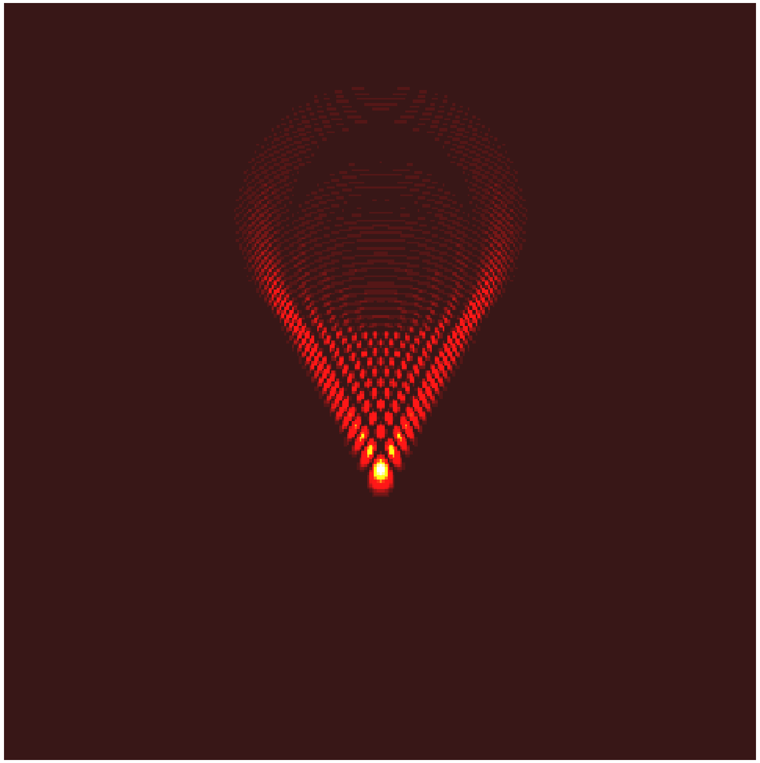
power spectrum



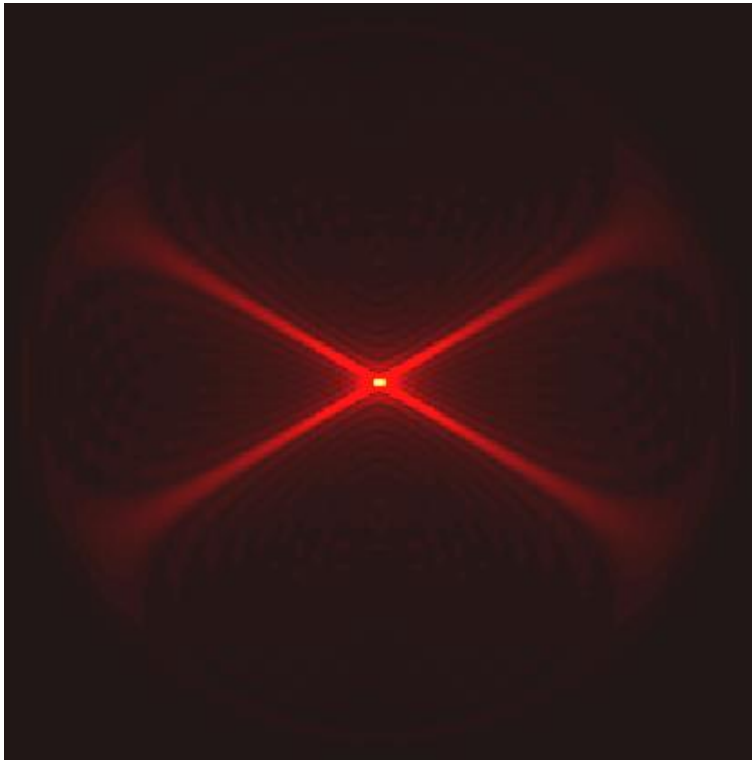
Yellott’s ring (corresponds to the dominant spatial frequency of the photoreceptor array

Power Spectrum of an Image

image



power spectrum



FT of a wavefront

- computes the PSF by adding all the possible interferograms from every pair of points across the wavefront surface.

Application of the FT

- compute the MTF of a wavefront (which spatial frequencies comprise the PSF?)
- compute the PSF from the wavefront (the sum of all the possible interferograms combine to make the PSF)
- compute a convolution

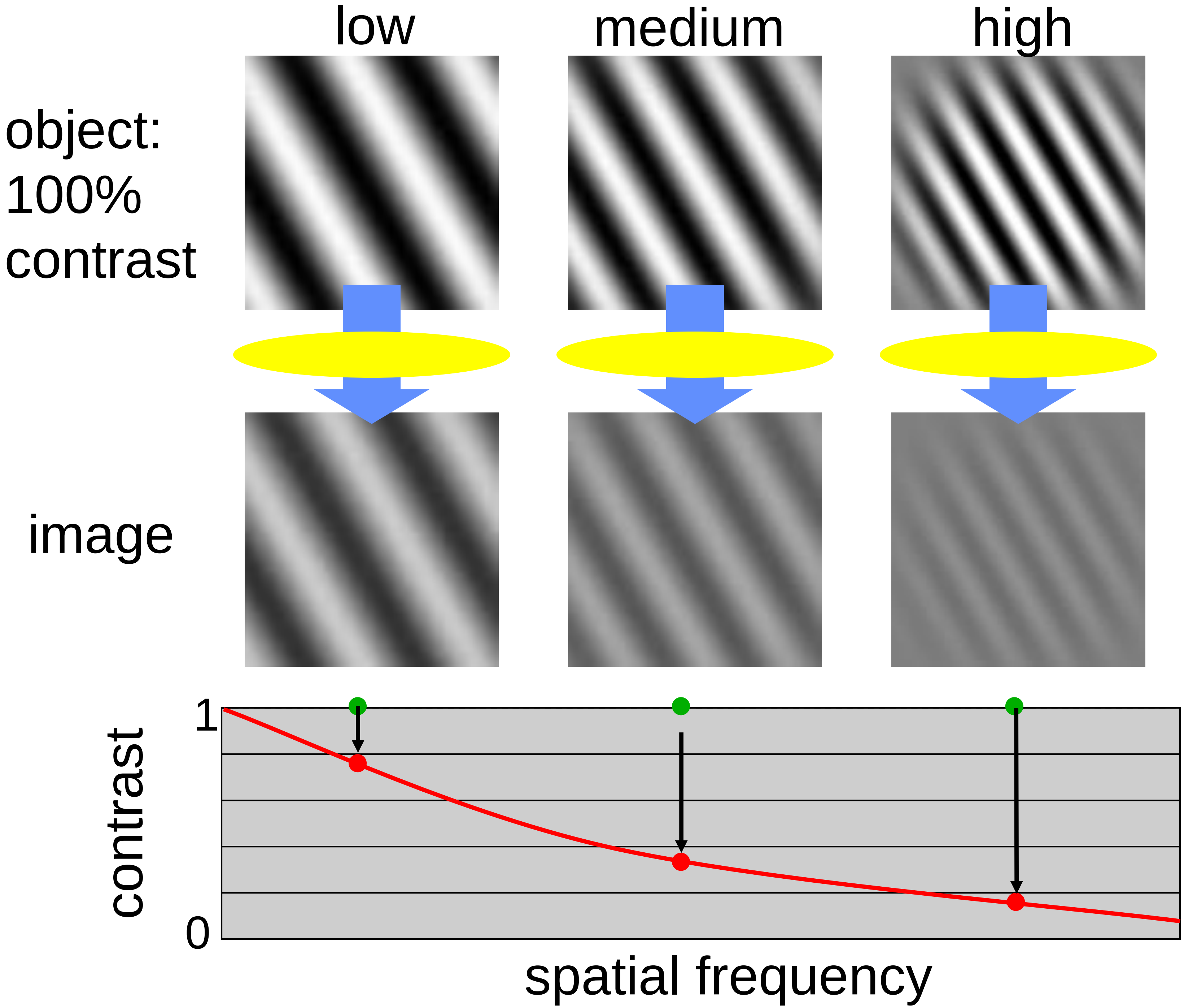
$$f \otimes g = FT\left\{f\right\} \times FT\left\{g\right\}$$

The PSF is the Fourier Transform (FT) of the pupil function

$$PSF\left(x_i, y_i\right) = FT\left\{P(x,y)e^{-i\frac{2\pi}{\lambda}W(x,y)}\right\}$$

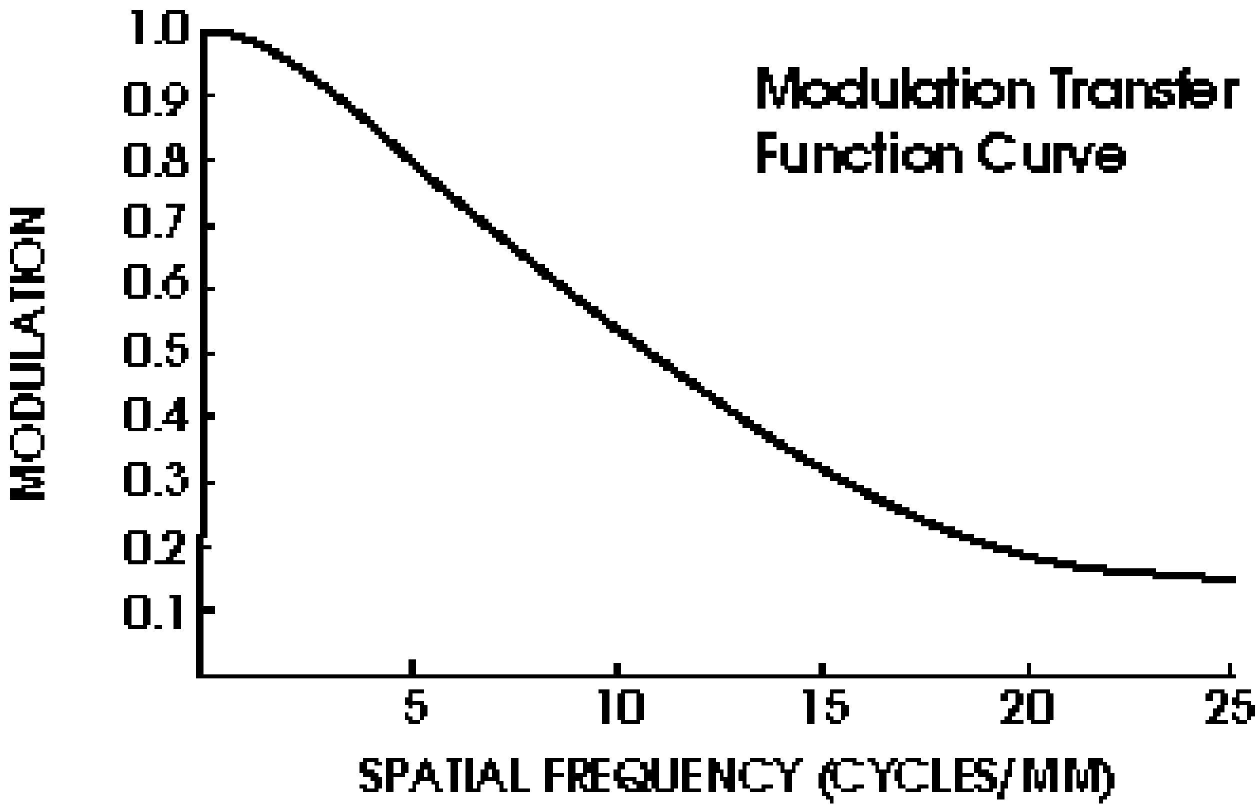
MTF

Modulation Transfer Function


low
medium
high
object:
100%
contrast
image
1
0
contrast
spatial frequency

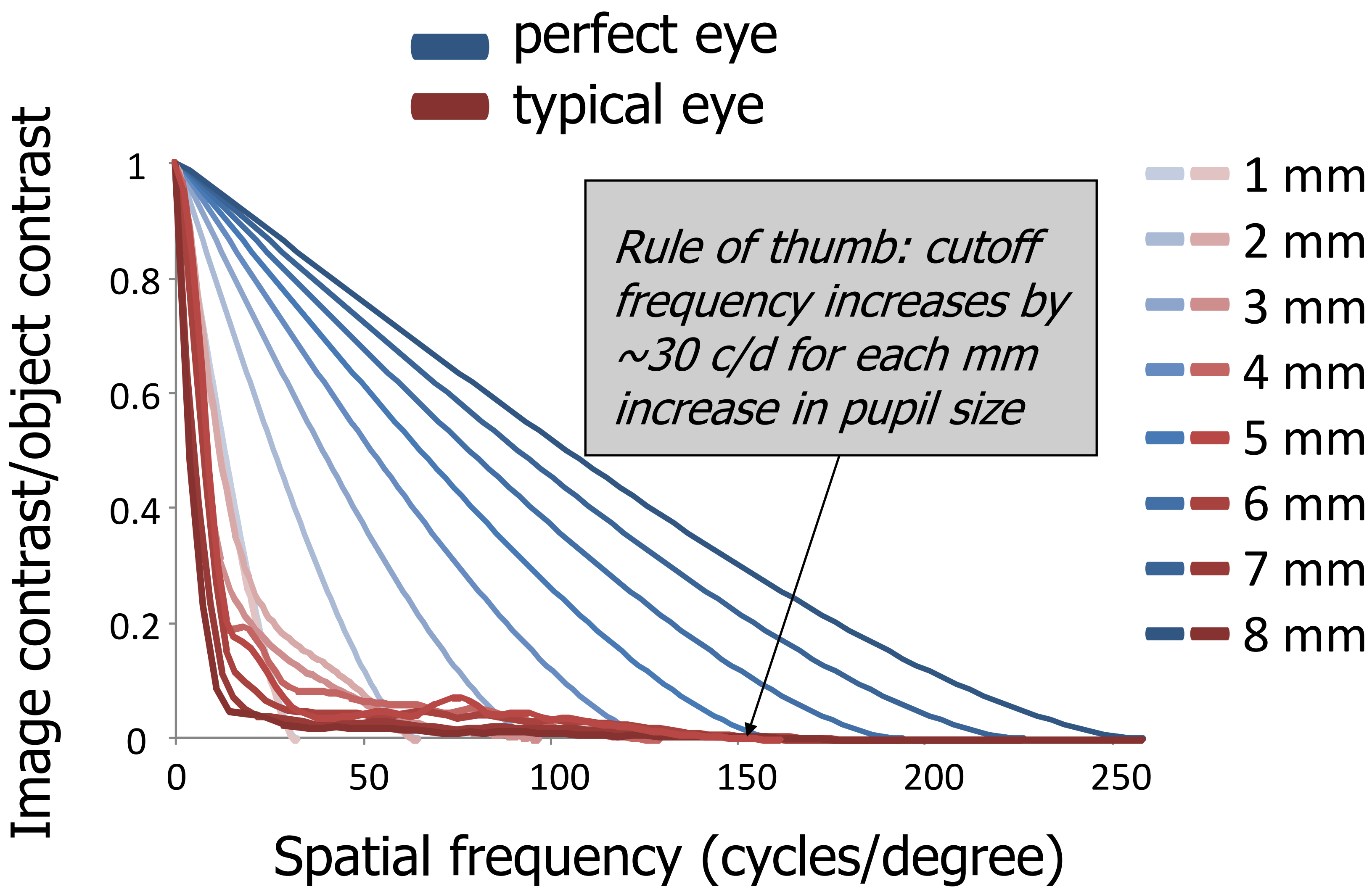
$$\text{Michelson Contrast} = \frac{\max - \min}{\max + \min}$$

- *The modulation transfer function (MTF) indicates the ability of an optical system to reproduce (transfer) various levels of detail (spatial frequencies) from the object to the image.*
- *Its units are the ratio of image contrast over the object contrast as a function of spatial frequency.*
- *It is the optical contribution to the contrast sensitivity function (CSF).*



2.9 The Modulation Transfer Function

Change in MTF with pupil size



2.9 The Modulation Transfer Function

PSFs for the same eye

Change in MTF with pupil size

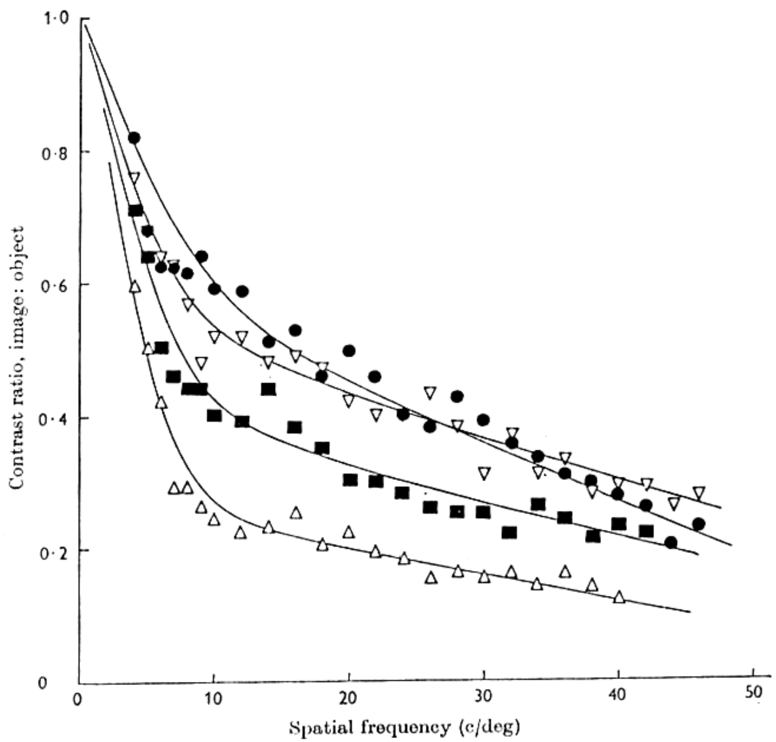


Fig. 10. Calculated contrast transfer functions for the in-focus eye of D.G.G. at four pupil diameters, ●, 2 mm; ▽, 2·8 mm; ■, 3·8 mm; △, 5·8 mm.

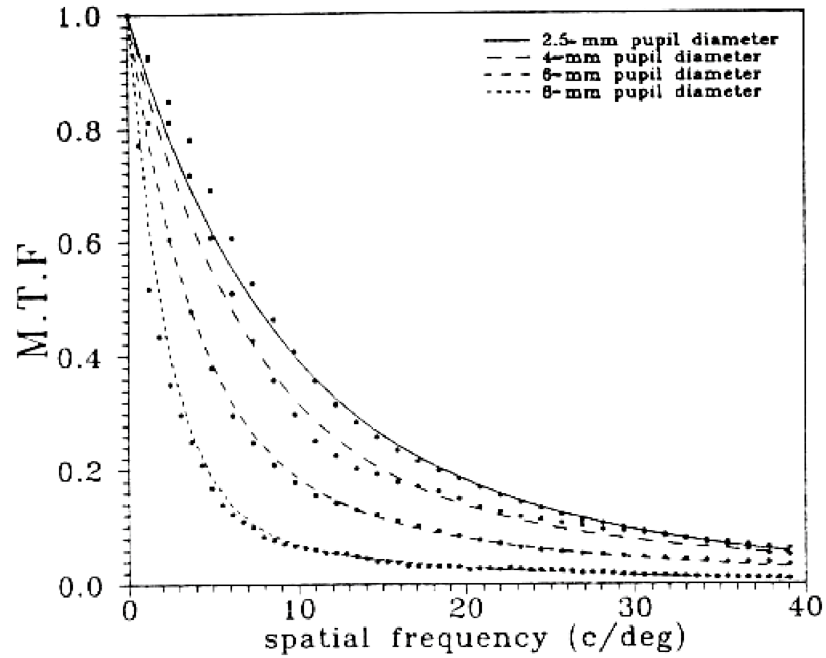
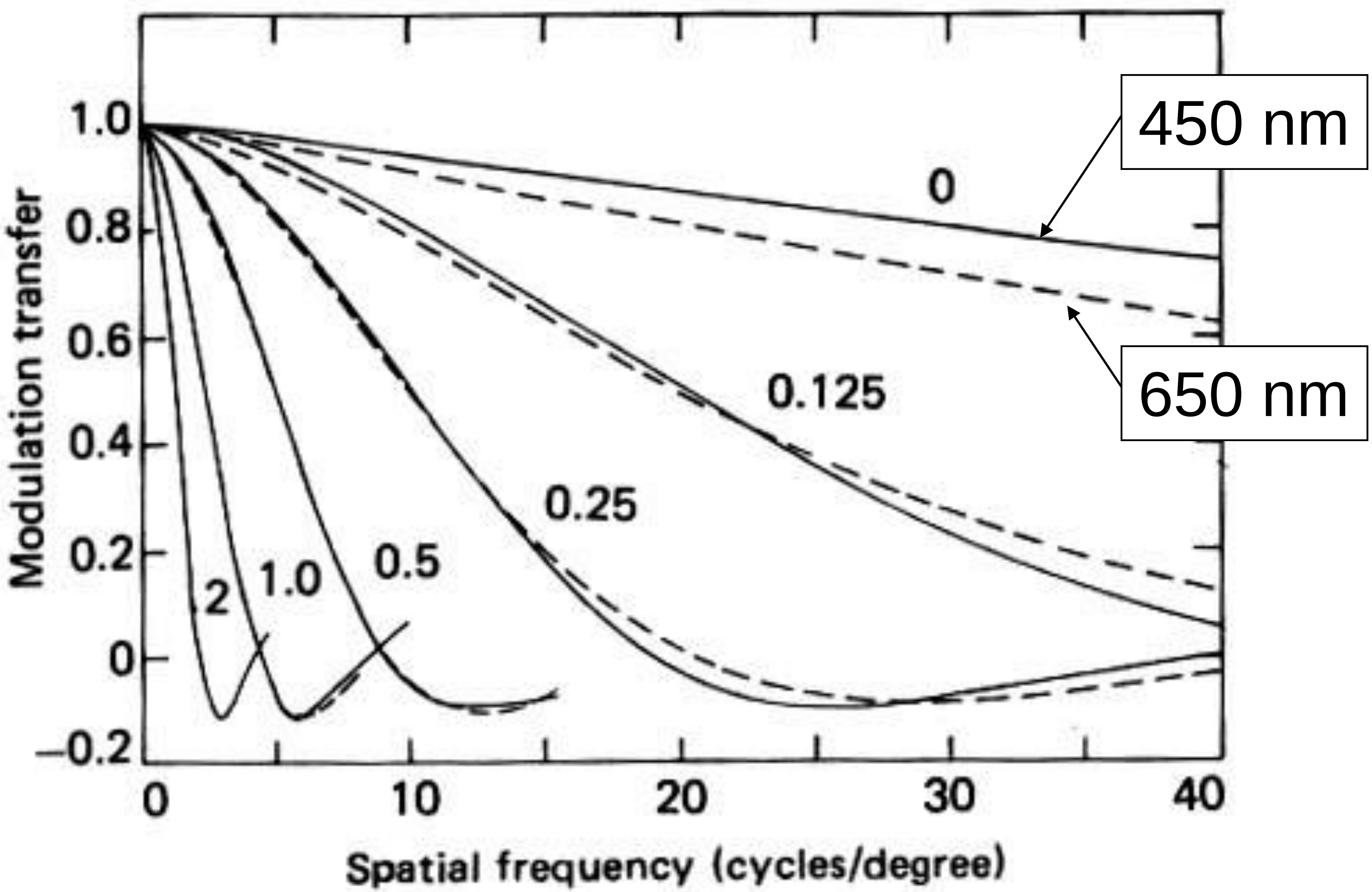


Fig. 3. Average MTF's for four pupil diameters (symbols) and the analytical approximations (curves).

Campbell & Green 1965

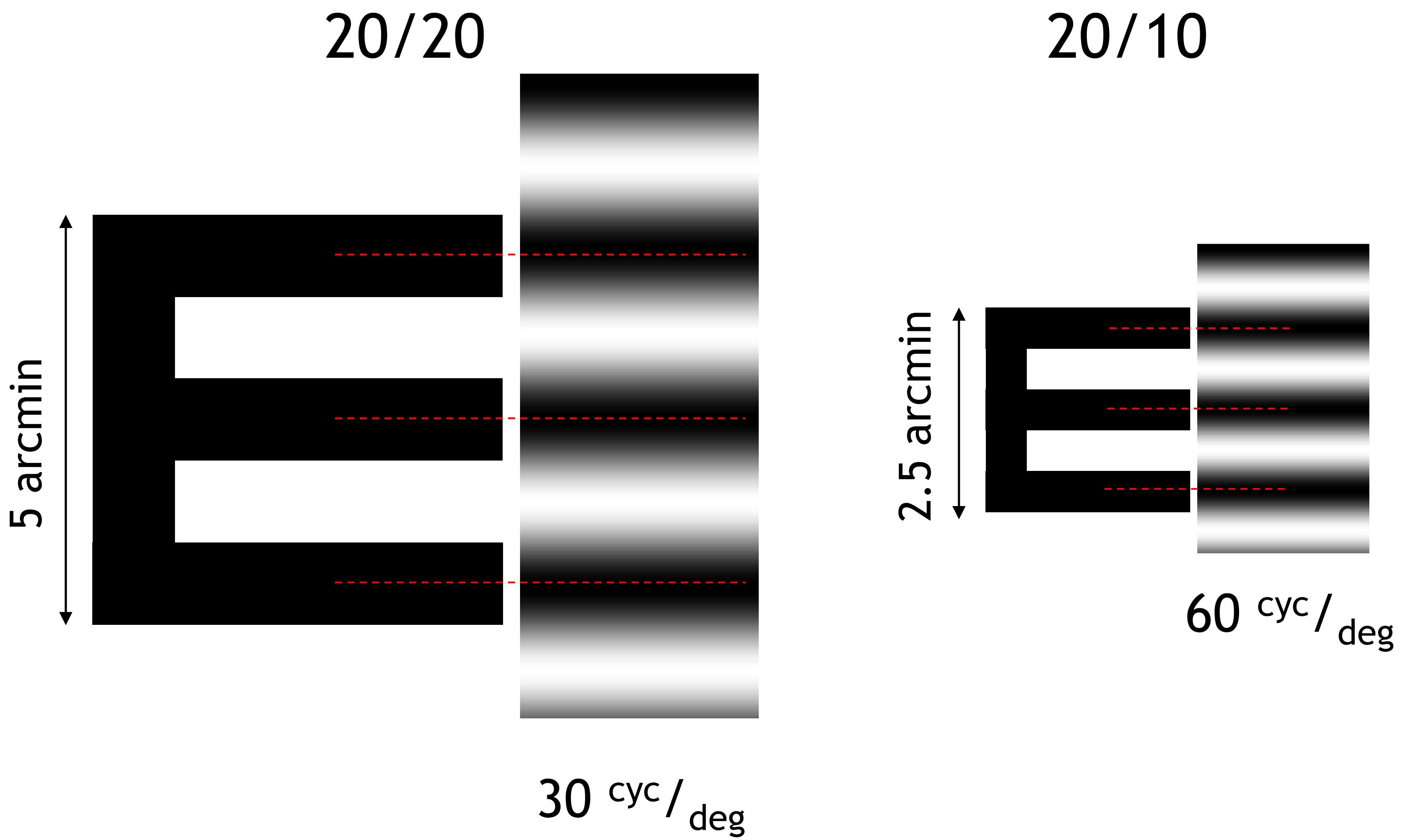
Artal and Navarro 1994

Effect of Defocus on the MTF



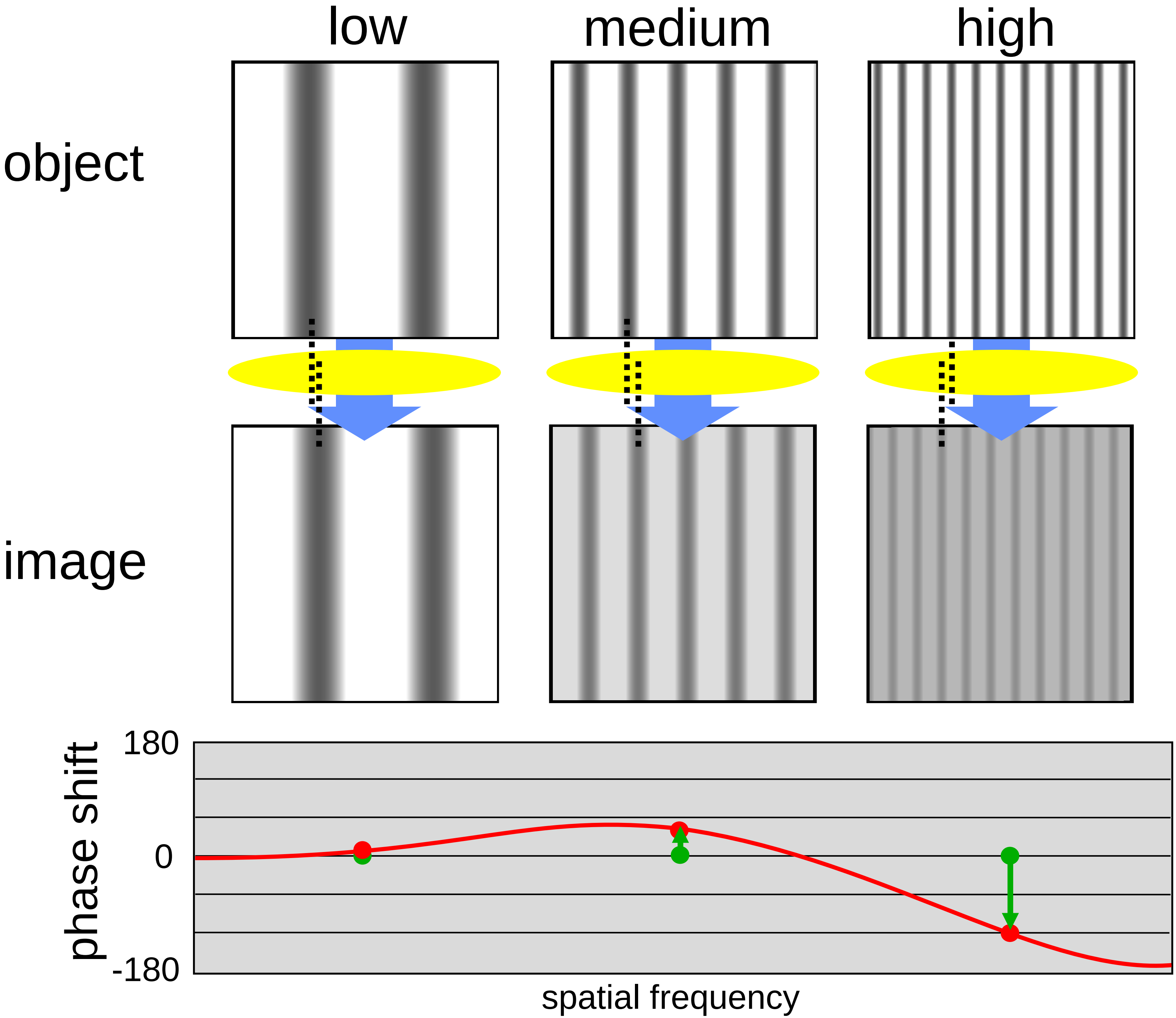
Charman and Jennings, 1976

Spatial frequency



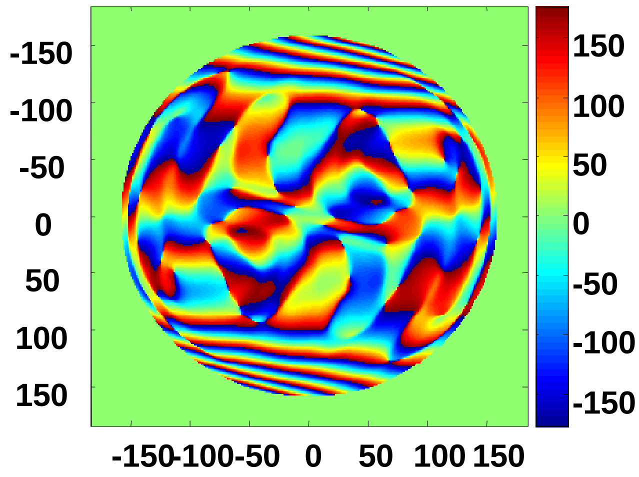
PTF

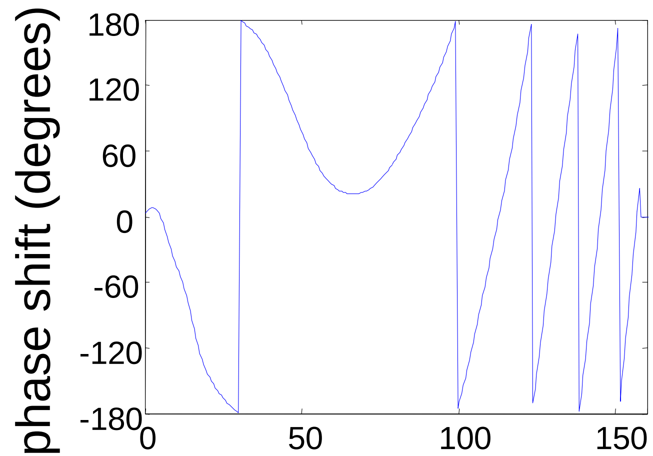
Phase Transfer Function


low
medium
high
object
image
phase shift
180
0
-180
spatial frequency

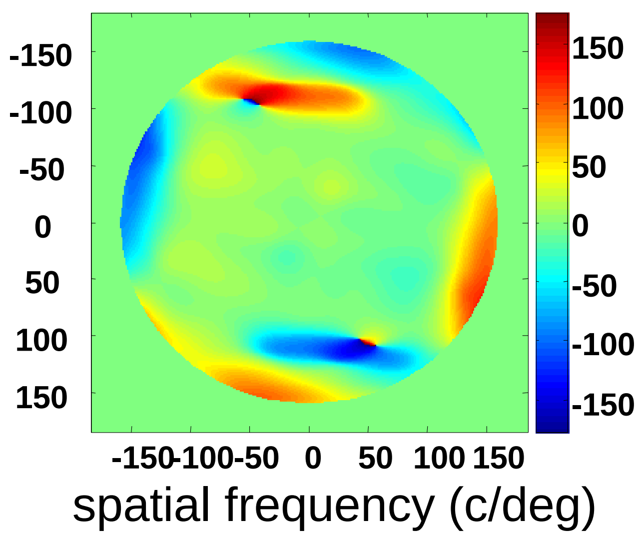
Phase Transfer Function

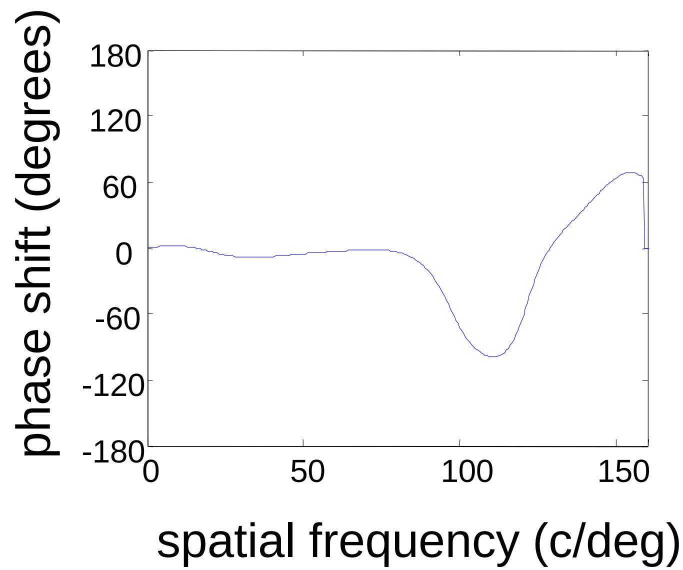
No AO
rms: 0.29 μm





AO corrected
rms: 0.09 μm





Phase Transfer Function

- Contains information about asymmetry in the PSF
- Contains information about contrast reversals (spurious resolution)

The Importance of Phase

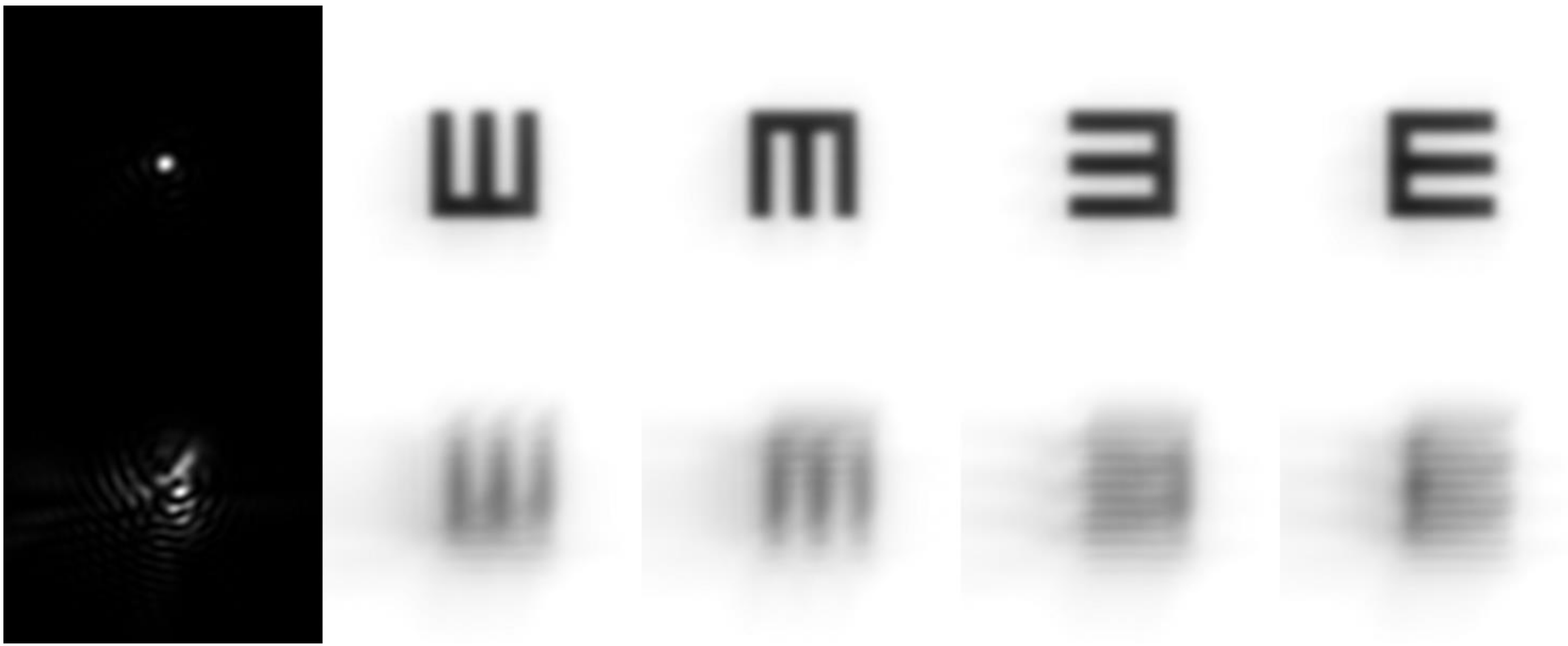
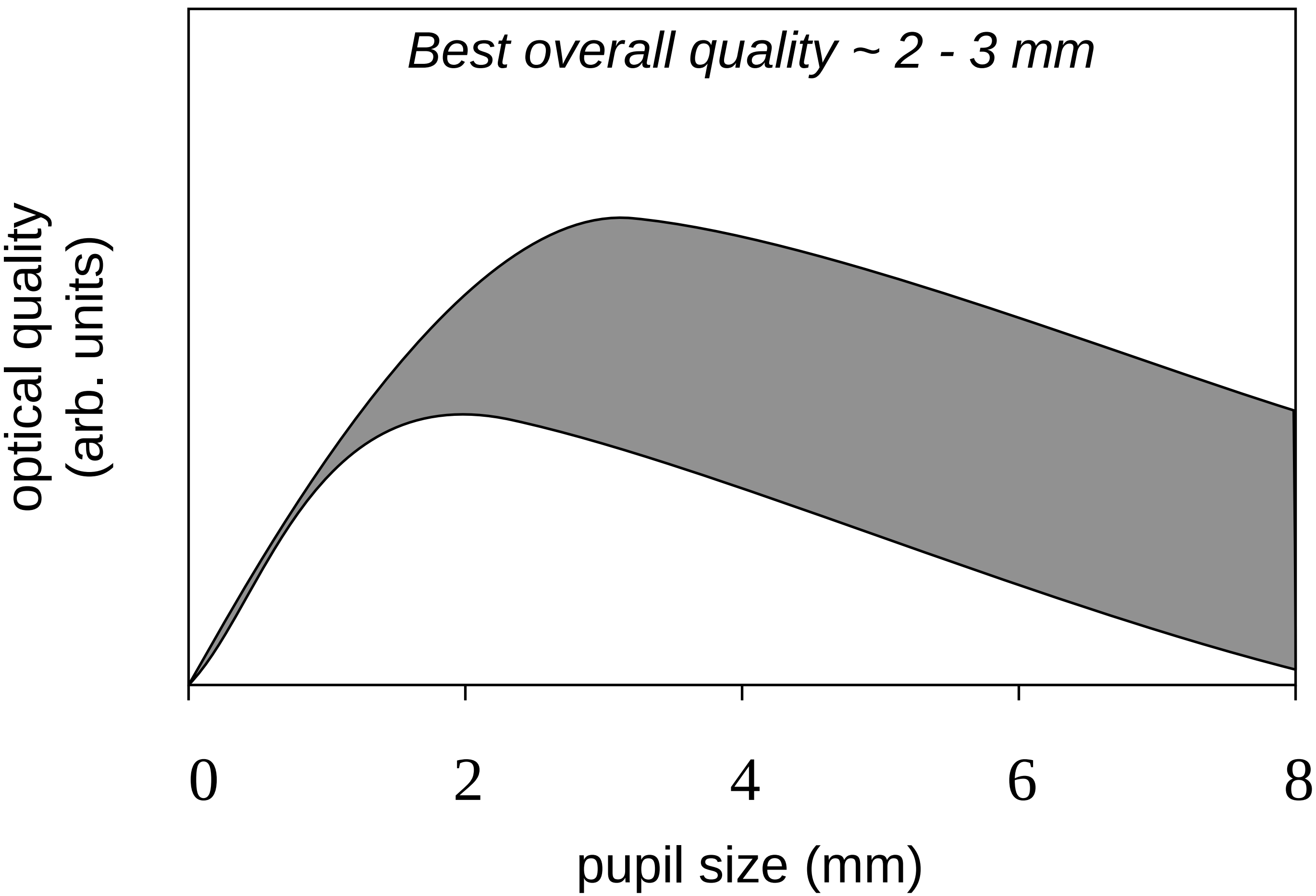
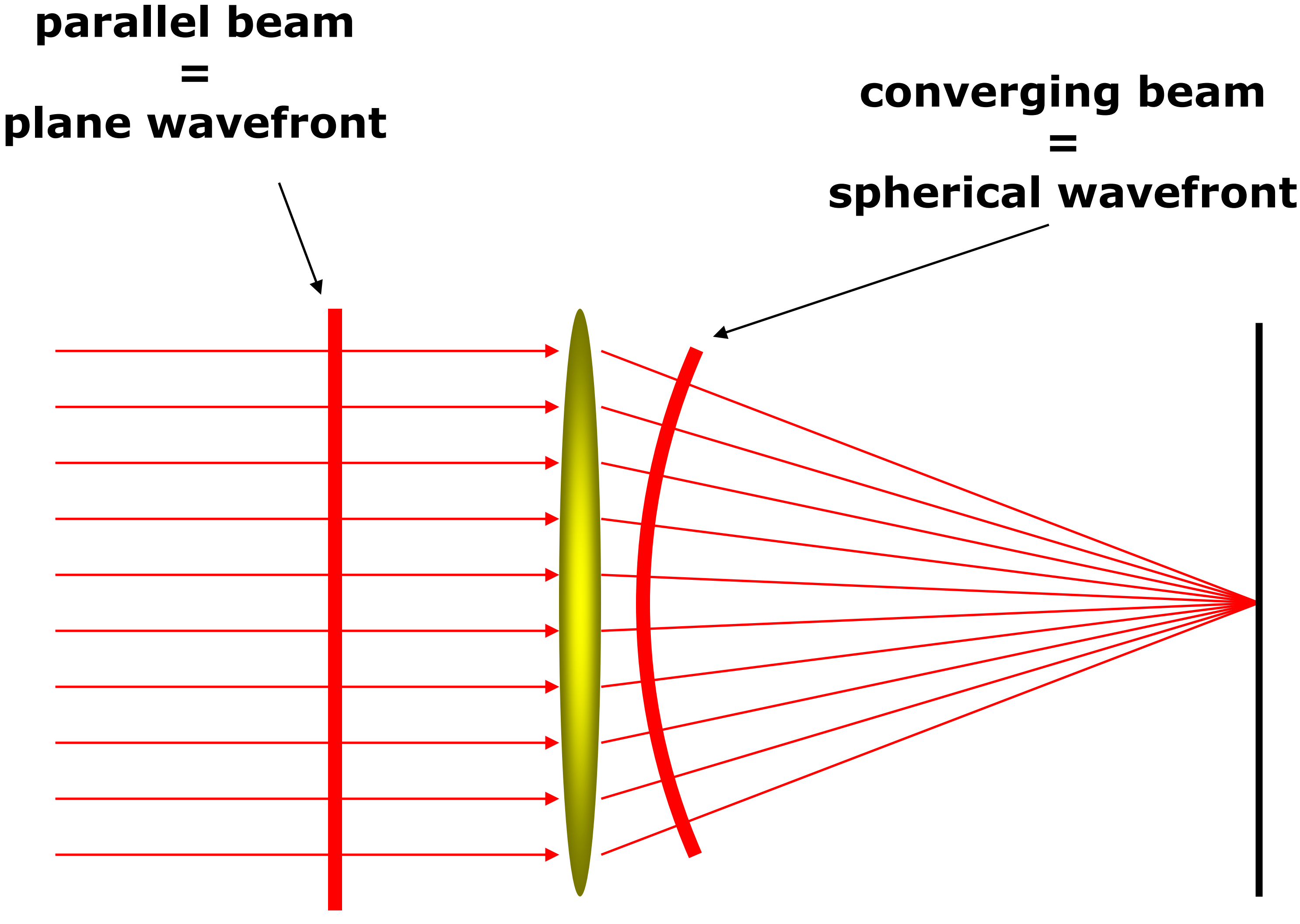


Image quality as a function of pupil size

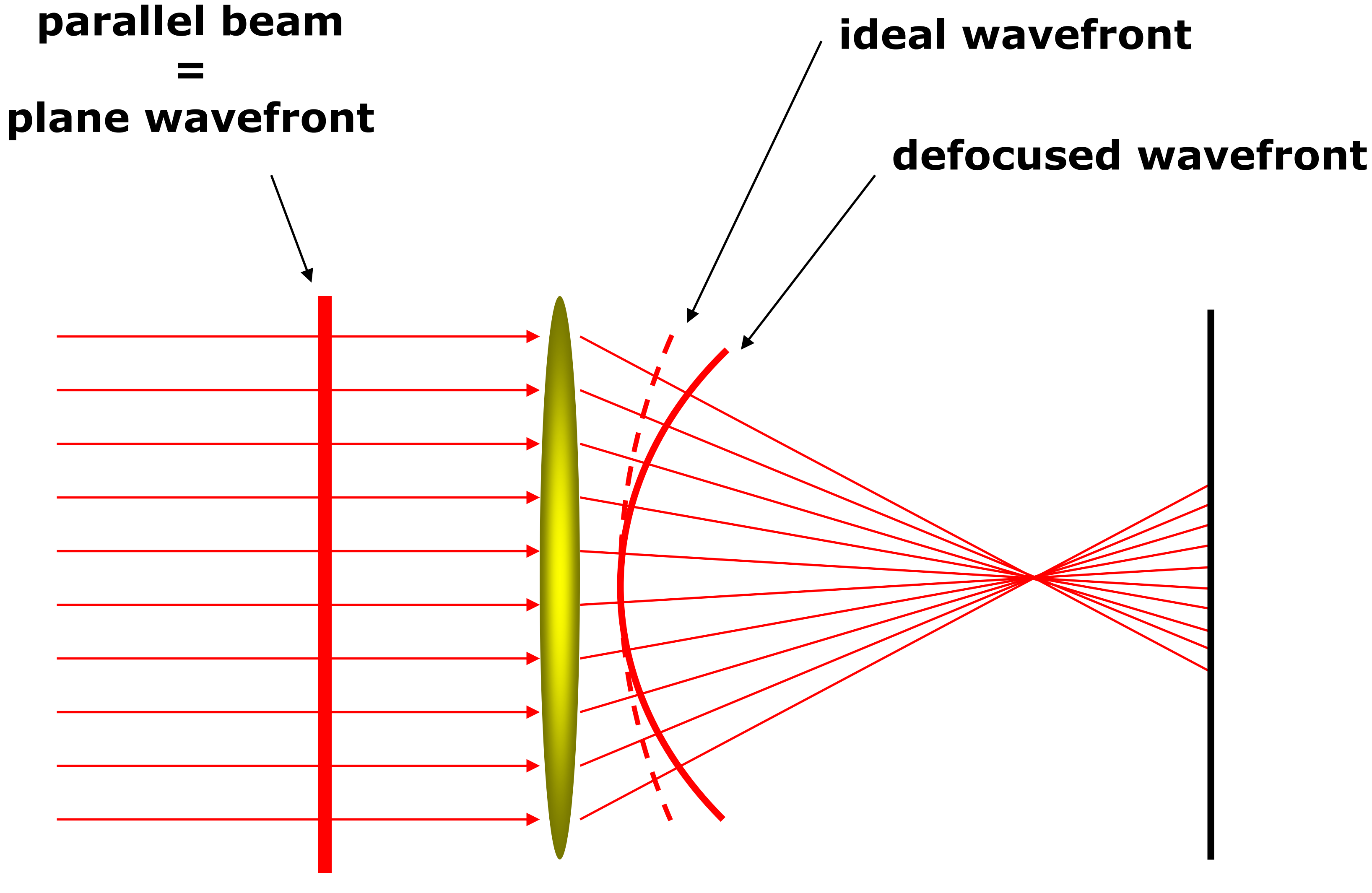


Part 5: Measurement of the Wave Aberration of the Eye

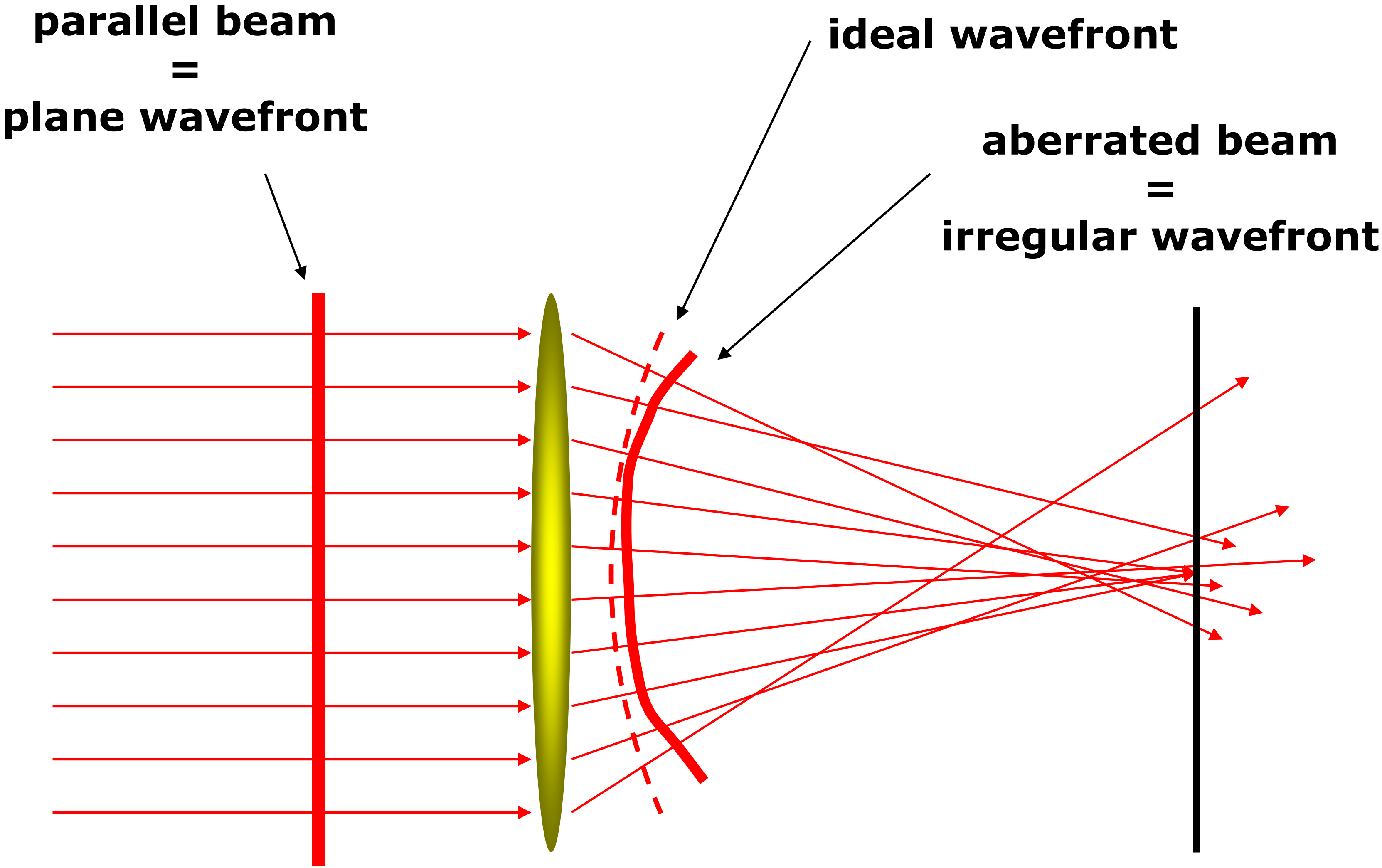
What is the Wavefront?



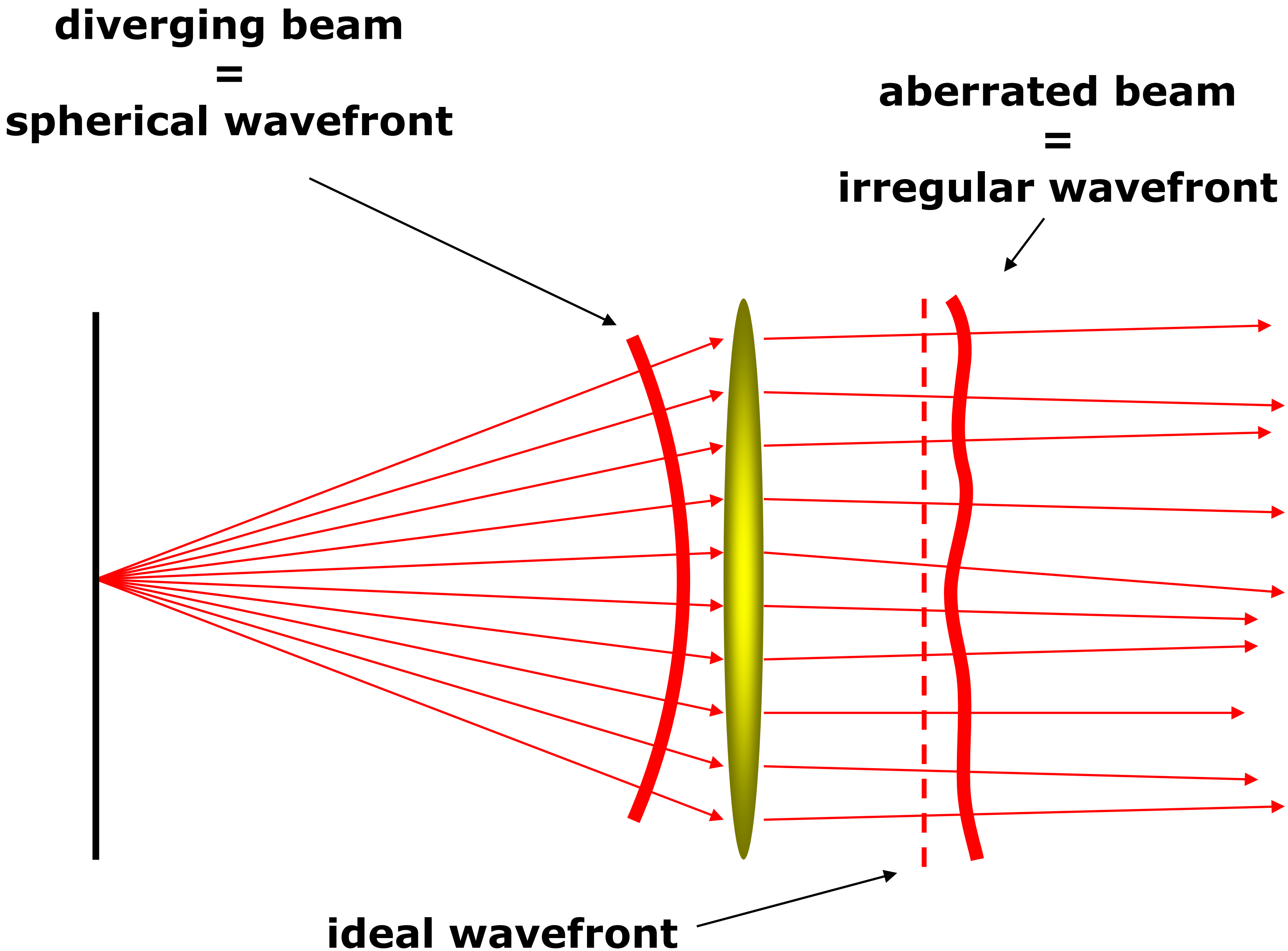
What is the Wavefront?



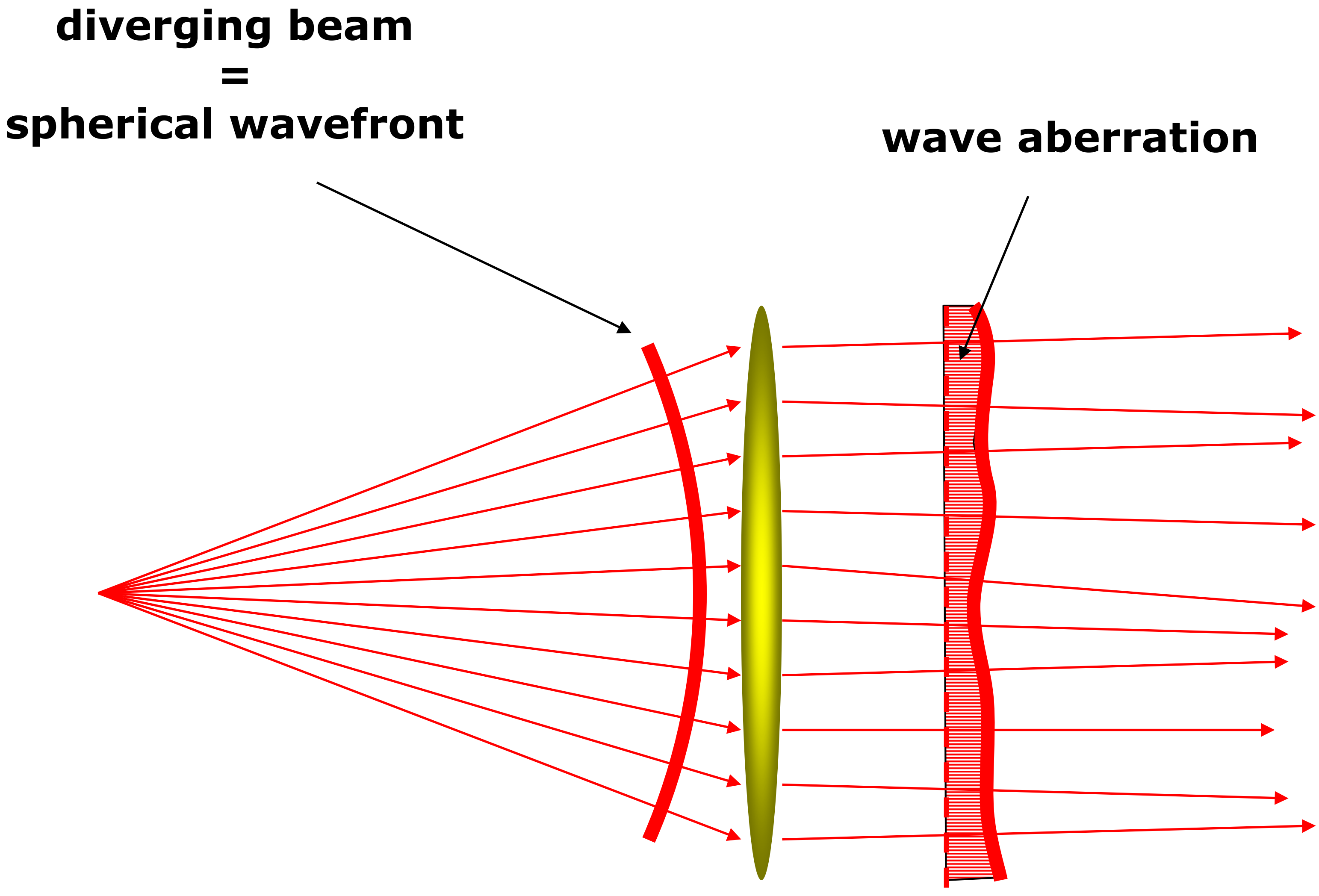
What is the Wavefront?



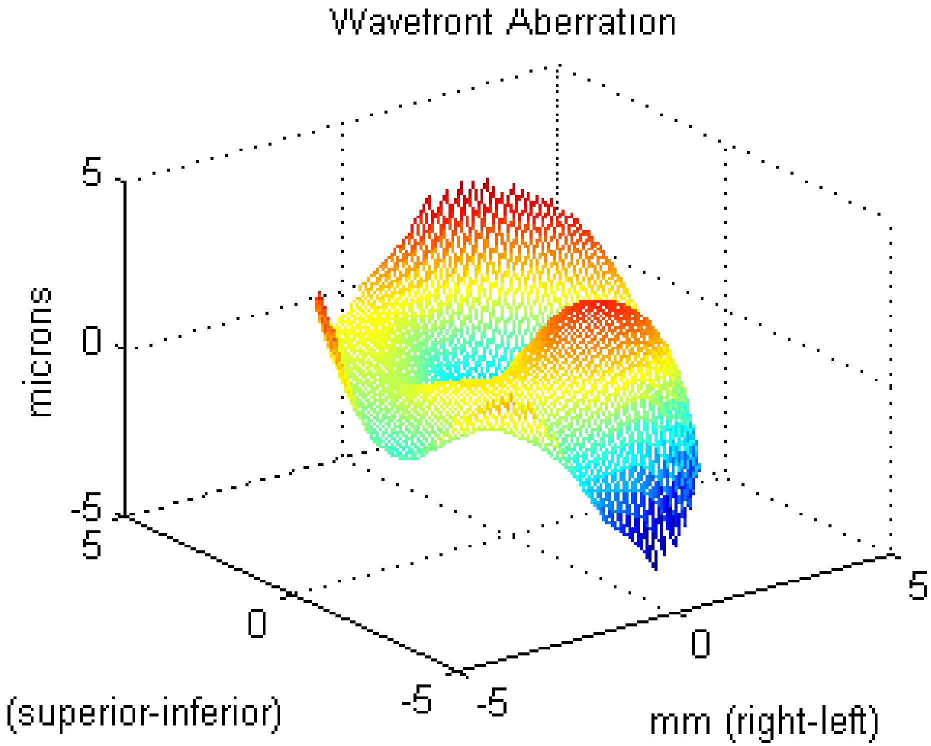
What is the Wavefront?

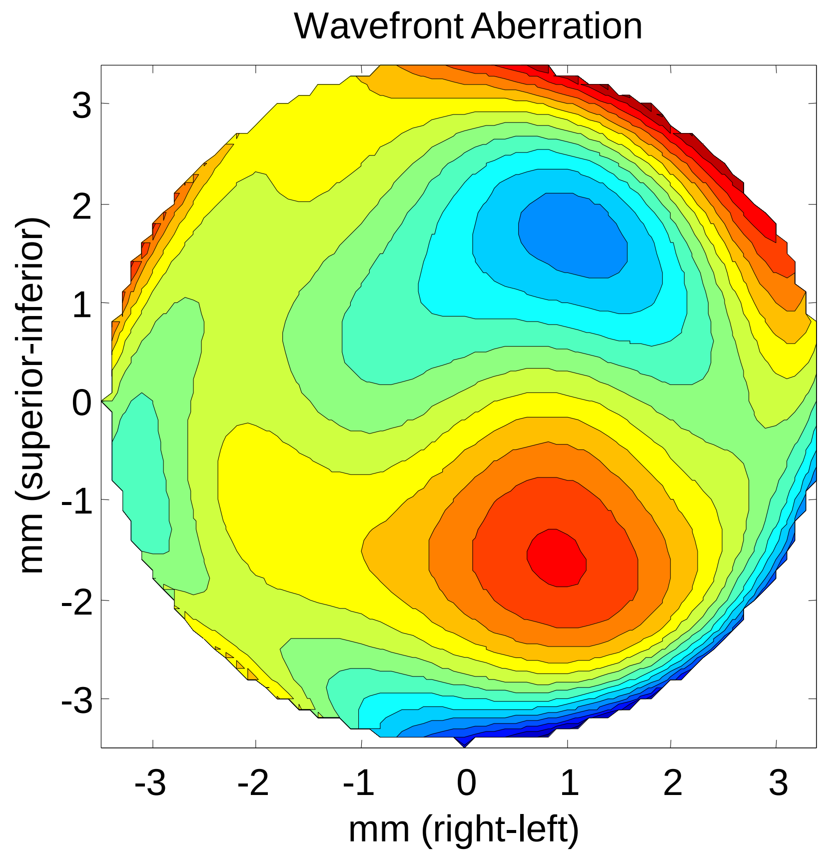


What is the *Wave Aberration*?



Wave Aberration of a Surface

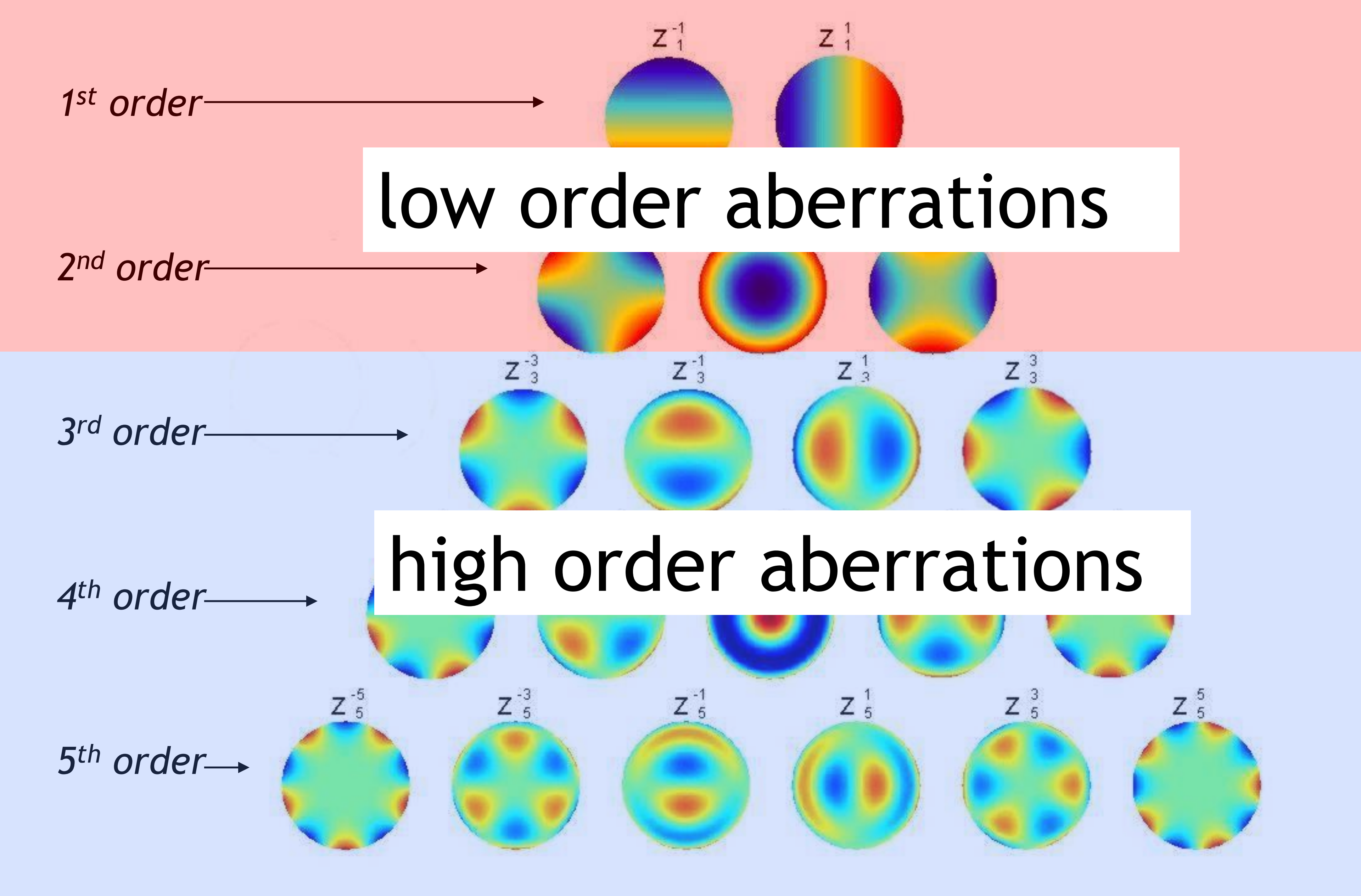




The Zernike Polynomial

```
phase = ...
        c(1)*sqrt(4)*((1)*r^1)*sin(1*angle) + ...
        c(2)*sqrt(4)*((1)*r^1)*cos(1*angle) + ...
        c(3)*sqrt(6)*((1)*r^2)*sin(2*angle) + ...
        c(4)*sqrt(3)*((2)*r^2+(-1)*r^0) + ...
        c(5)*sqrt(6)*((1)*r^2)*cos(2*angle) + ...
        c(6)*sqrt(8)*((1)*r^3)*sin(3*angle) + ...
        c(7)*sqrt(8)*((3)*r^3+(-2)*r^1)*sin(1*angle) + ...
        c(8)*sqrt(8)*((3)*r^3+(-2)*r^1)*cos(1*angle) + ...
        c(9)*sqrt(8)*((1)*r^3)*cos(3*angle) + ...
        c(10)*sqrt(10)*((1)*r^4)*sin(4*angle) + ...
        c(11)*sqrt(10)*((4)*r^4+(-3)*r^2)*sin(2*angle) + ...
        c(12)*sqrt(5)*((6)*r^4+(-6)*r^2+(1)*r^0) + ...
        c(13)*sqrt(10)*((4)*r^4+(-3)*r^2)*cos(2*angle) + ...
        c(14)*sqrt(10)*((1)*r^4)*cos(4*angle) + ...
        c(15)*sqrt(12)*((1)*r^5)*sin(5*angle) + ...
        c(16)*sqrt(12)*((5)*r^5+(-4)*r^3)*sin(3*angle) + ...
        c(17)*sqrt(12)*((10)*r^5+(-12)*r^3+(3)*r^1)*sin(1*angle) + ...
        c(18)*sqrt(12)*((10)*r^5+(-12)*r^3+(3)*r^1)*cos(1*angle) + ...
        c(19)*sqrt(12)*((5)*r^5+(-4)*r^3)*cos(3*angle) + ...
        c(20)*sqrt(12)*((1)*r^5)*cos(5*angle) + ...
        c(21)*sqrt(14)*((1)*r^6)*sin(6*angle) + ...
        c(22)*sqrt(14)*((6)*r^6+(-5)*r^4)*sin(4*angle) + ...
        c(23)*sqrt(14)*((15)*r^6+(-20)*r^4+(6)*r^2)*sin(2*angle) + ...
        c(24)*sqrt(7)*((20)*r^6+(-30)*r^4+(12)*r^2+(-1)*r^0) + ...
        c(25)*sqrt(14)*((15)*r^6+(-20)*r^4+(6)*r^2)*cos(2*angle) + ...
        c(26)*sqrt(14)*((6)*r^6+(-5)*r^4)*cos(4*angle) + ...
        c(27)*sqrt(14)*((1)*r^6)*cos(6*angle) + ...
        c(28)*sqrt(16)*((1)*r^7)*sin(7*angle) + ...
        c(29)*sqrt(16)*((7)*r^7+(-6)*r^5)*sin(5*angle) + ...
        c(30)*sqrt(16)*((21)*r^7+(-30)*r^5+(10)*r^3)*sin(3*angle) + ...
        c(31)*sqrt(16)*((35)*r^7+(-60)*r^5+(30)*r^3+(-4)*r^1)*sin(1*angle) + ...
        c(32)*sqrt(16)*((35)*r^7+(-60)*r^5+(30)*r^3+(-4)*r^1)*cos(1*angle) + ...
        c(33)*sqrt(16)*((21)*r^7+(-30)*r^5+(10)*r^3)*cos(3*angle) + ...
        c(34)*sqrt(16)*((7)*r^7+(-6)*r^5)*cos(5*angle) + ...
        c(35)*sqrt(16)*((1)*r^7)*cos(7*angle) + ...
        c(36)*sqrt(18)*((1)*r^8)*sin(8*angle) + ...
        c(37)*sqrt(18)*((8)*r^8+(-7)*r^6)*sin(6*angle) + ...
        c(38)*sqrt(18)*((28)*r^8+(-42)*r^6+(15)*r^4)*sin(4*angle) + ...
        c(39)*sqrt(18)*((56)*r^8+(-105)*r^6+(60)*r^4+(-10)*r^2)*sin(2*angle) + ...
        c(40)*sqrt(9)*((70)*r^8+(-140)*r^6+(90)*r^4+(-20)*r^2+(1)*r^0) + ...
        c(41)*sqrt(18)*((56)*r^8+(-105)*r^6+(60)*r^4+(-10)*r^2)*cos(2*angle) + ...
        c(42)*sqrt(18)*((28)*r^8+(-42)*r^6+(15)*r^4)*cos(4*angle) + ...
        c(43)*sqrt(18)*((8)*r^8+(-7)*r^6)*cos(6*angle) + ...
        c(44)*sqrt(18)*((1)*r^8)*cos(8*angle) + ...
        c(45)*sqrt(20)*((1)*r^9)*sin(9*angle) + ...
        c(46)*sqrt(20)*((9)*r^9+(-8)*r^7)*sin(7*angle) + ...
        c(47)*sqrt(20)*((36)*r^9+(-56)*r^7+(21)*r^5)*sin(5*angle) + ...
        c(48)*sqrt(20)*((84)*r^9+(-168)*r^7+(105)*r^5+(-20)*r^3)*sin(3*angle) + ...
        c(49)*sqrt(20)*((126)*r^9+(-280)*r^7+(210)*r^5+(-60)*r^3+(5)*r^1)*sin(1*angle) + ...
        c(50)*sqrt(20)*((126)*r^9+(-280)*r^7+(210)*r^5+(-60)*r^3+(5)*r^1)*cos(1*angle) + ...
        c(51)*sqrt(20)*((84)*r^9+(-168)*r^7+(105)*r^5+(-20)*r^3)*cos(3*angle) + ...
        c(52)*sqrt(20)*((36)*r^9+(-56)*r^7+(21)*r^5)*cos(5*angle) + ...
        c(53)*sqrt(20)*((9)*r^9+(-8)*r^7)*cos(7*angle) + ...
        c(54)*sqrt(20)*((1)*r^9)*cos(9*angle) + ...
        c(55)*sqrt(22)*((1)*r^10)*sin(10*angle) + ...
        c(56)*sqrt(22)*((10)*r^10+(-9)*r^8)*sin(8*angle) + ...
        c(57)*sqrt(22)*((45)*r^10+(-72)*r^8+(28)*r^6)*sin(6*angle) + ...
        c(58)*sqrt(22)*((120)*r^10+(-252)*r^8+(168)*r^6+(-35)*r^4)*sin(4*angle) + ...
        c(59)*sqrt(22)*((210)*r^10+(-504)*r^8+(420)*r^6+(-140)*r^4+(15)*r^2)*sin(2*angle) + ...
        c(60)*sqrt(11)*((252)*r^10+(-630)*r^8+(560)*r^6+(-210)*r^4+(30)*r^2+(-1)*r^0) + ...
        c(61)*sqrt(22)*((210)*r^10+(-504)*r^8+(420)*r^6+(-140)*r^4+(15)*r^2)*cos(2*angle) + ...
        c(62)*sqrt(22)*((120)*r^10+(-252)*r^8+(168)*r^6+(-35)*r^4)*cos(4*angle) + ...
        c(63)*sqrt(22)*((45)*r^10+(-72)*r^8+(28)*r^6)*cos(6*angle) + ...
        c(64)*sqrt(22)*((10)*r^10+(-9)*r^8)*cos(8*angle) + ...
        c(65)*sqrt(22)*((1)*r^10)*cos(10*angle);
```

Zernike Polynomials



What are Zernike Polynomials?

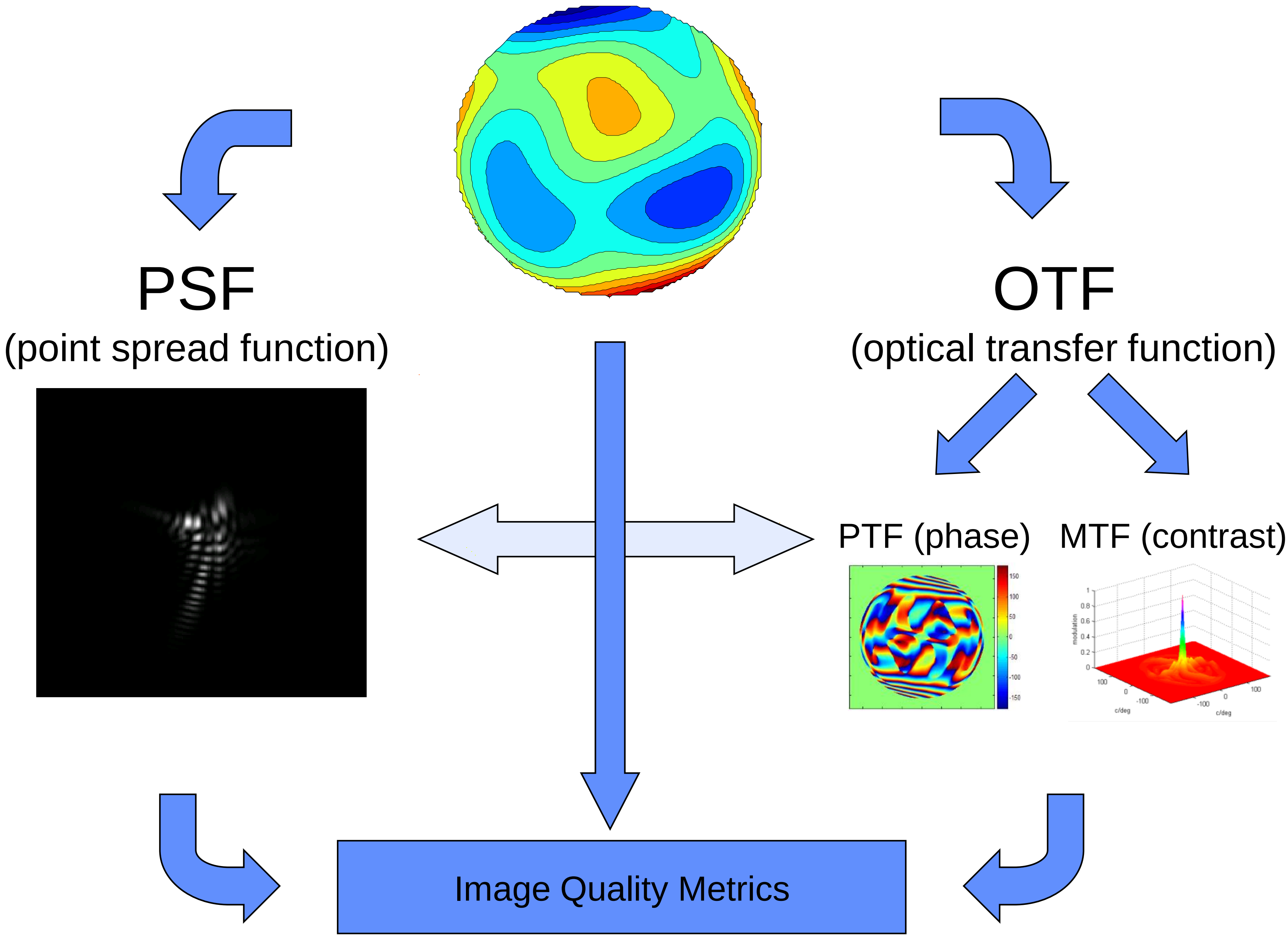
- set of basic shapes that are used to fit the wavefront
- analogous to the parabolic x^2 shape that can be used to fit 2D data

Properties of Zernike Polynomials

- orthogonal
  - terms are not similar in any way, so the weighting of one terms does not depend on whether or not other terms are being fit also
- normalized
  - the RMS wave aberration can be simply calculated as the vector of all or a subset of coefficients
- efficient
  - Zernike shapes are very similar to typical aberrations found in the eye

Relationships Between Wave Aberration, PSF and MTF

The reason we measure the wave aberration



The PSF is the Fourier Transform (FT) of the pupil function

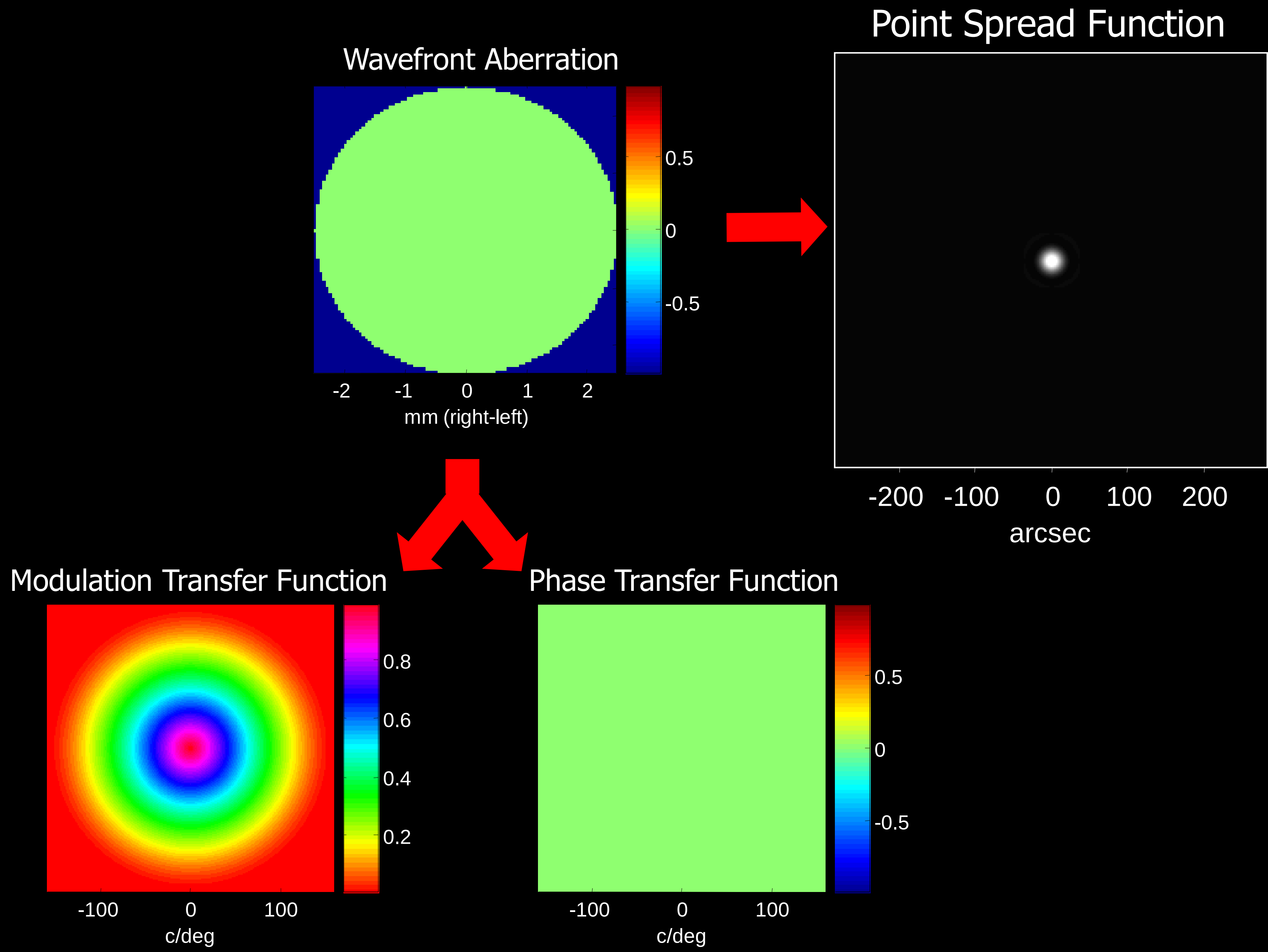
$$PSF\left(x_i, y_i\right) = FT\left\{P(x, y)e^{-i\frac{2\pi}{\lambda}W(x,y)}\right\}$$

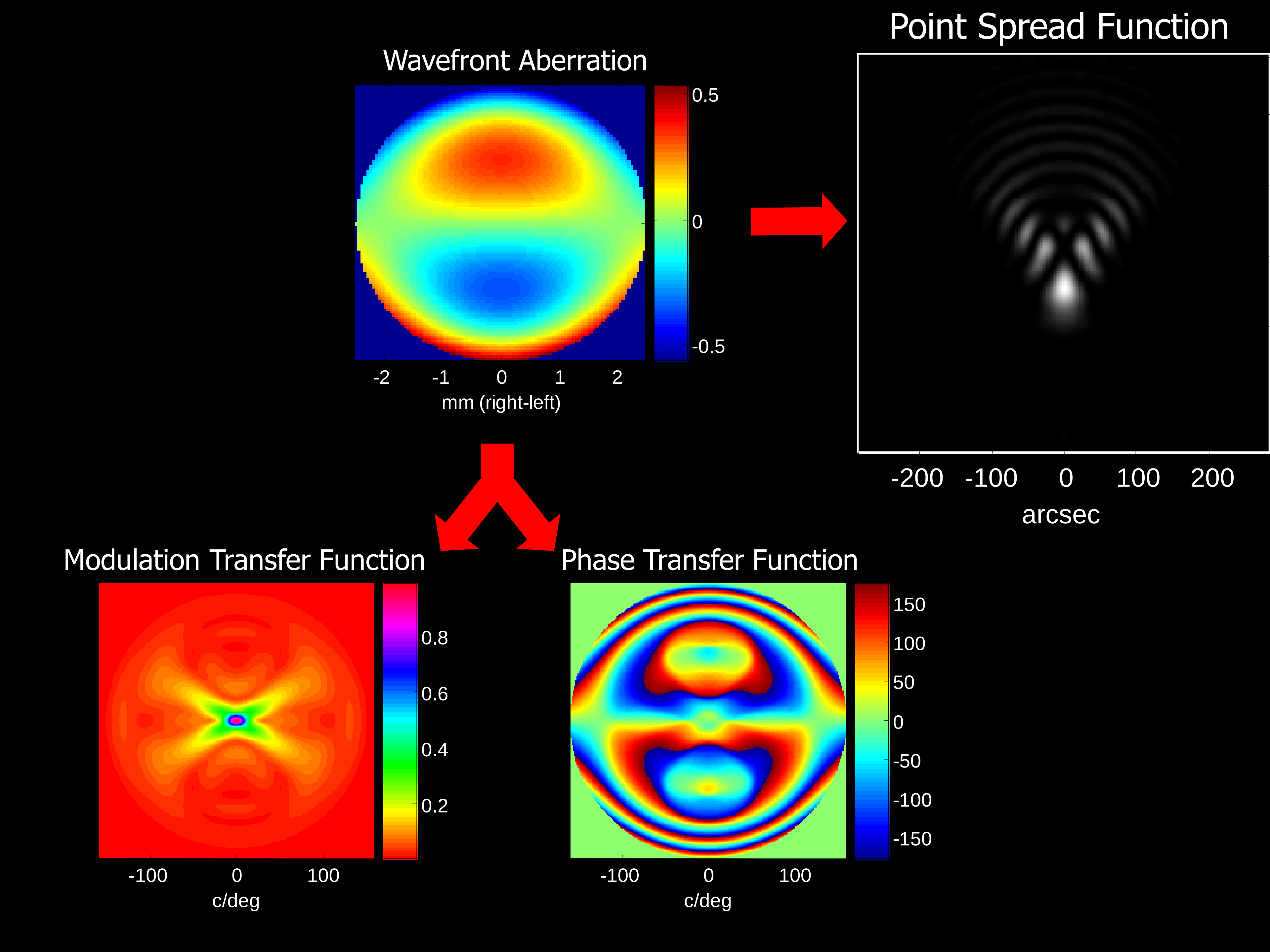
The MTF is the amplitude component of the FT of the PSF

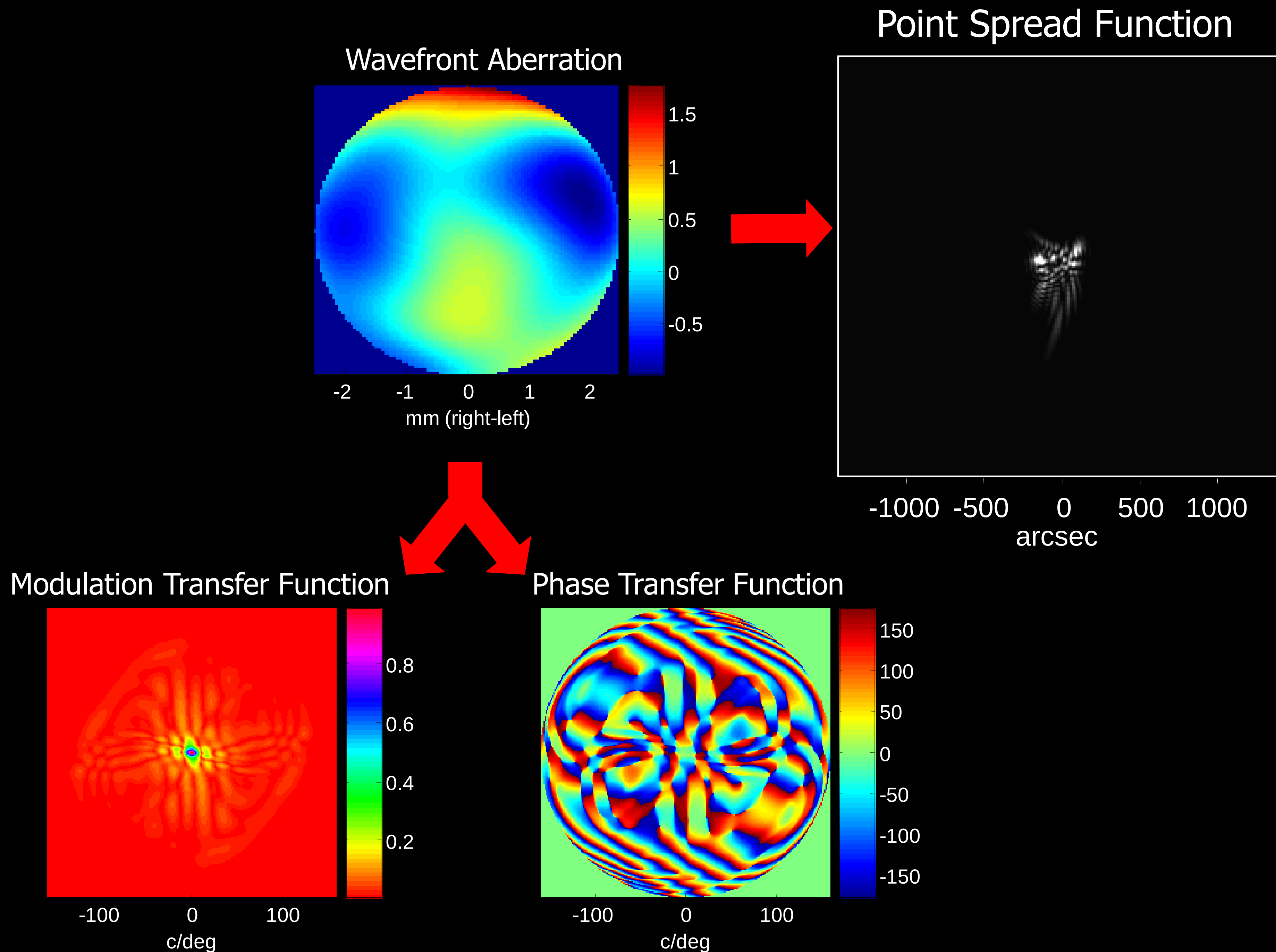
$$MTF\left(f_x, f_y\right) = Amplitude\left[FT\left\{PSF(x_i, y_i)\right\}\right]$$

The PTF is the phase component of the FT of the PSF

$$PTF\left(f_x, f_y\right) = Phase\left[FT\left\{PSF(x_i, y_i)\right\}\right]$$

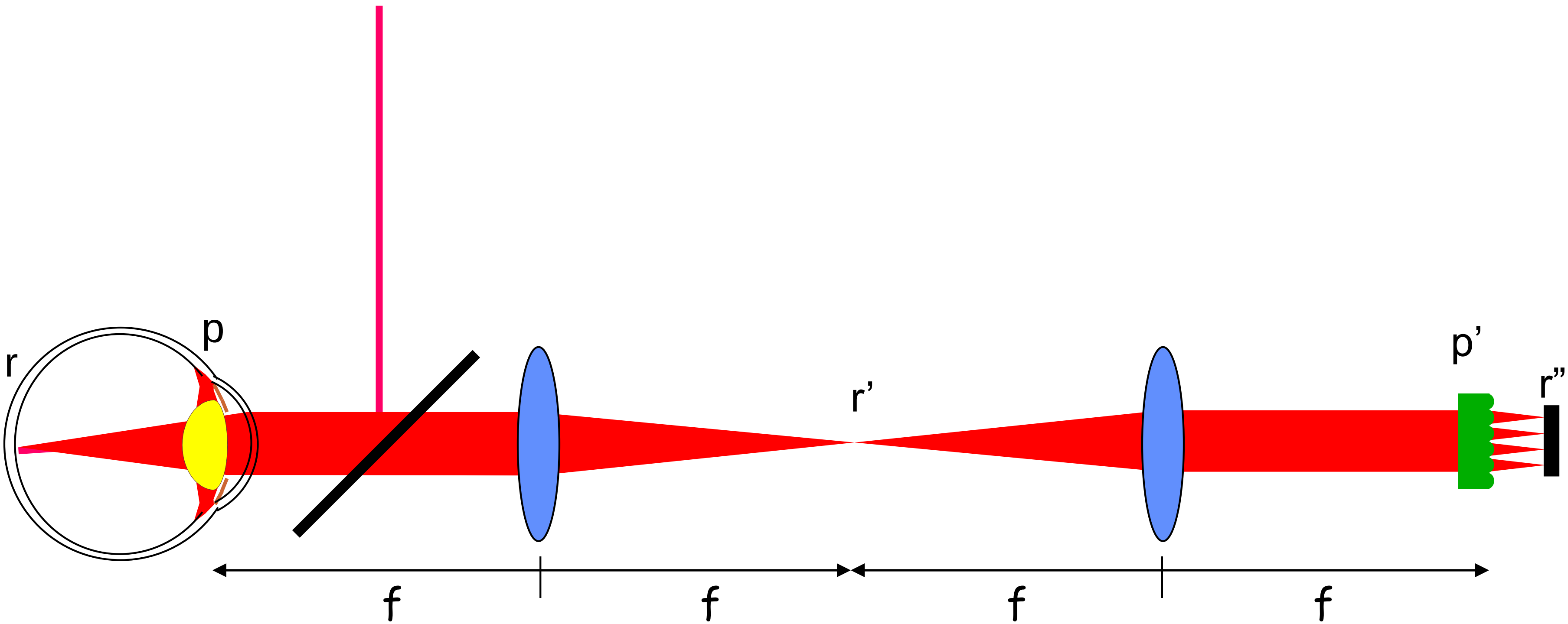

Wavefront Aberration
0.5
0
-0.5
-2
-1
0
1
2
mm (right-left)
Point Spread Function
-200
-100
0
100
200
arcsec
Modulation Transfer Function
0.8
0.6
0.4
0.2
-100
0
100
c/deg
Phase Transfer Function
0.5
0
-0.5
-100
0
100
c/deg


Wavefront Aberration
0.5
0
-0.5
-2 -1 0 1 2
mm (right-left)
Point Spread Function
-200 -100 0 100 200
arcsec
Modulation Transfer Function
0.8
0.6
0.4
0.2
-100 0 100
c/deg
Phase Transfer Function
150
100
50
0
-50
-100
-150
-100 0 100
c/deg

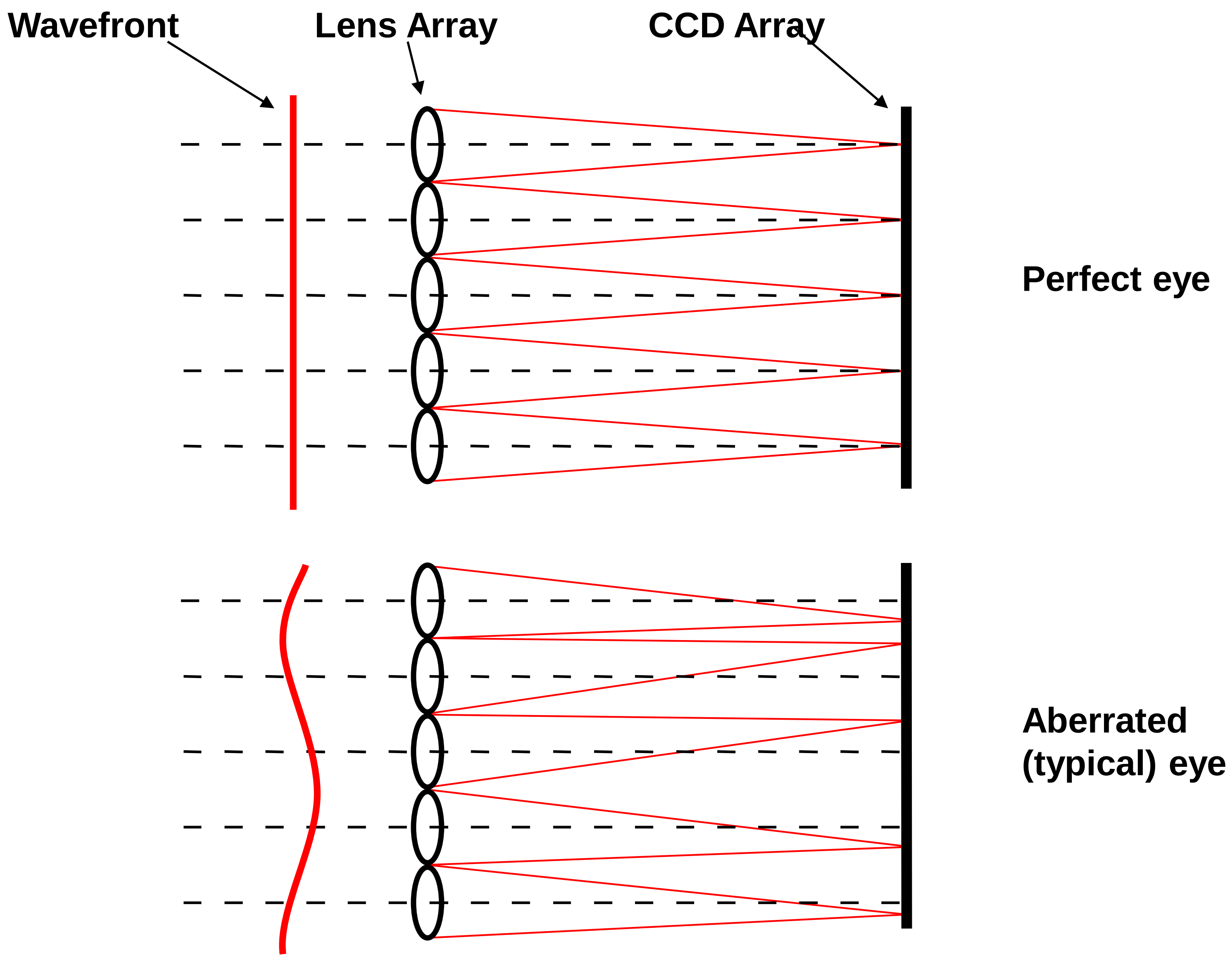


Wavefront Aberration
1.5
1
0.5
0
-0.5
-2 -1 0 1 2
mm (right-left)
Point Spread Function
-1000 -500 0 500 1000
arcsec
Modulation Transfer Function
0.8
0.6
0.4
0.2
-100 0 100
c/deg
Phase Transfer Function
150
100
50
0
-50
-100
-150
-100 0 100
c/deg

Shack-Hartmann Wavefront Sensor



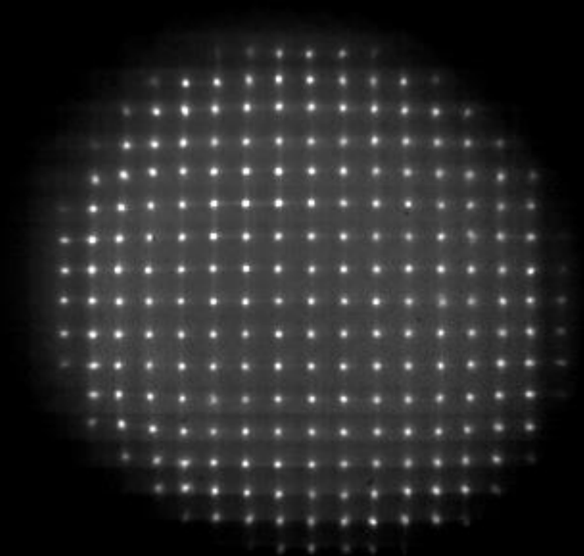
Shack-Hartmann Wavefront Sensor



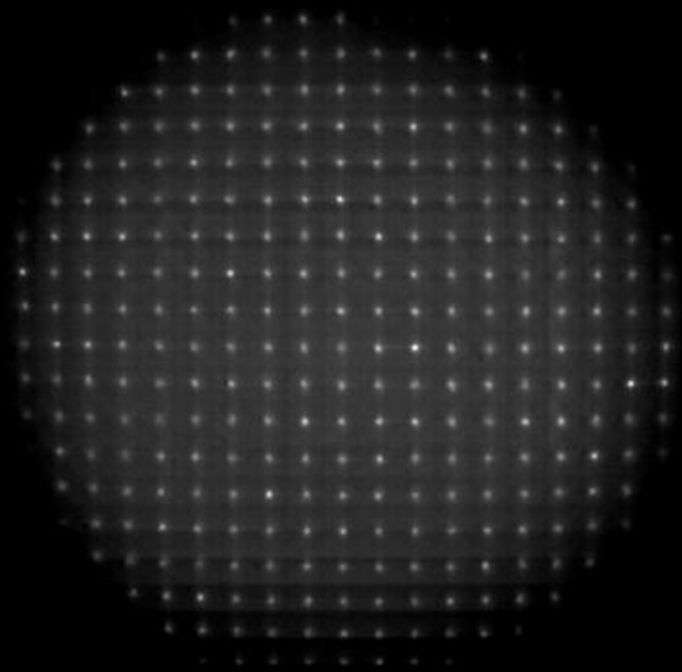
2.11.4 Principles of the Shack-Hartmann Wavefront Sensor: The Lenslet Array

Shack-Hartmann Images

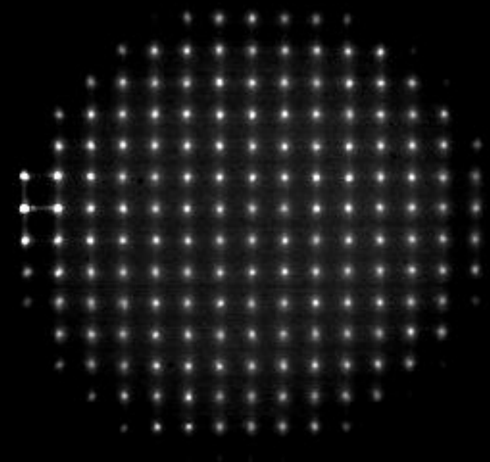
BD



KW

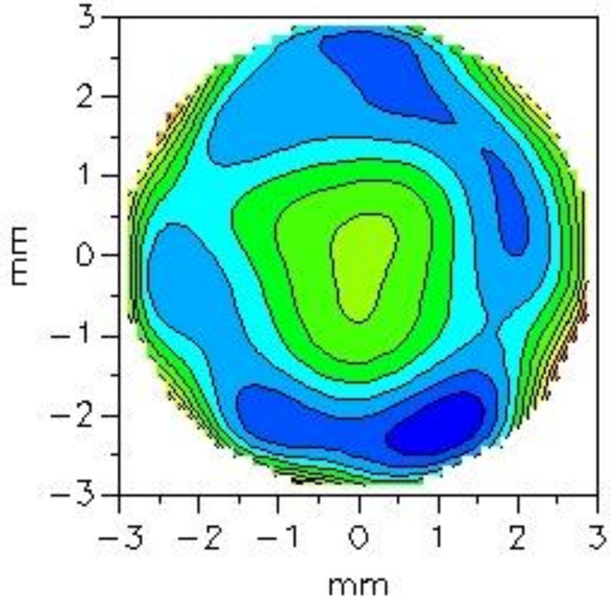


SM



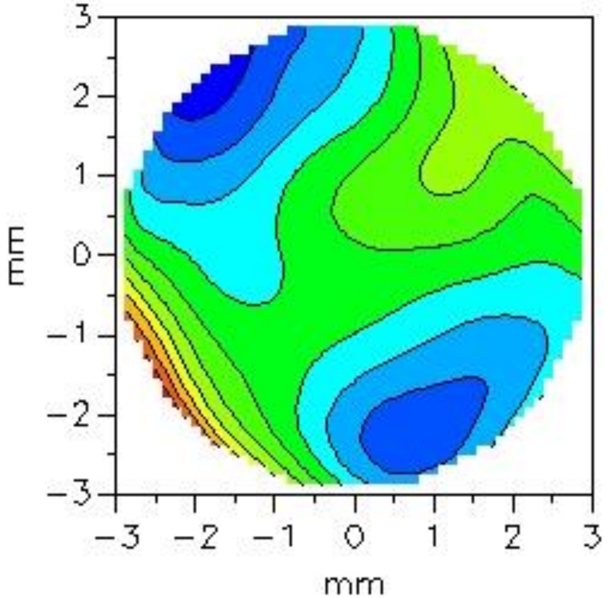
Wavefront Maps
(at best focal plane)

BD



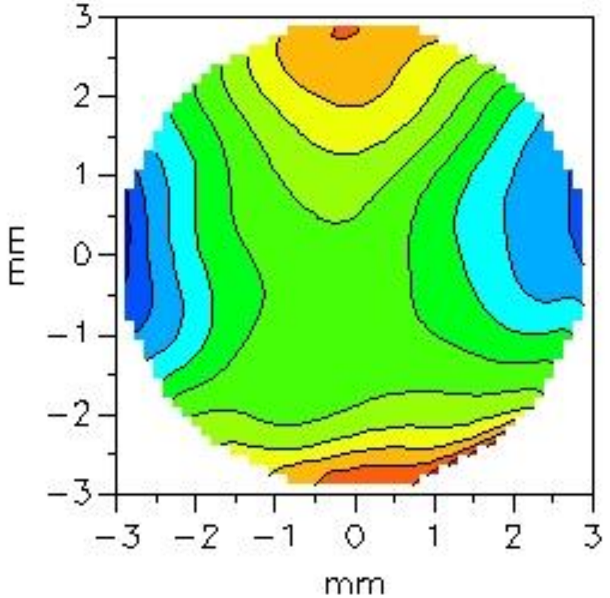
0.33 DS
–0.17 DC X 87

KW



6.42 DS
–0.6 DC X 126

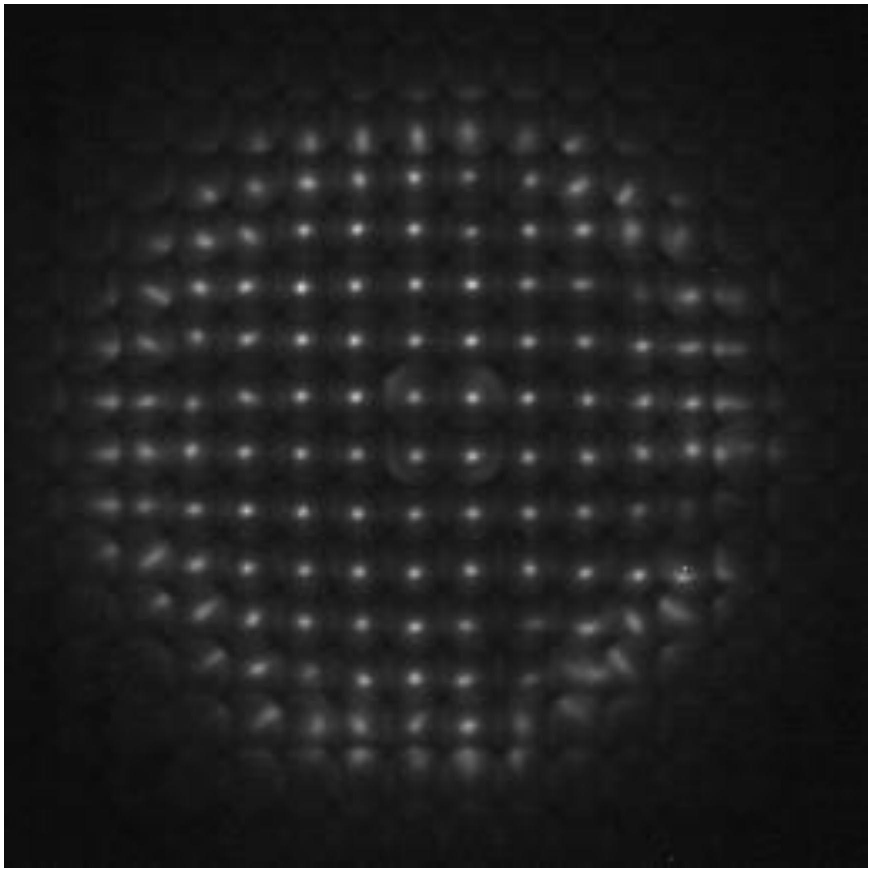
SM



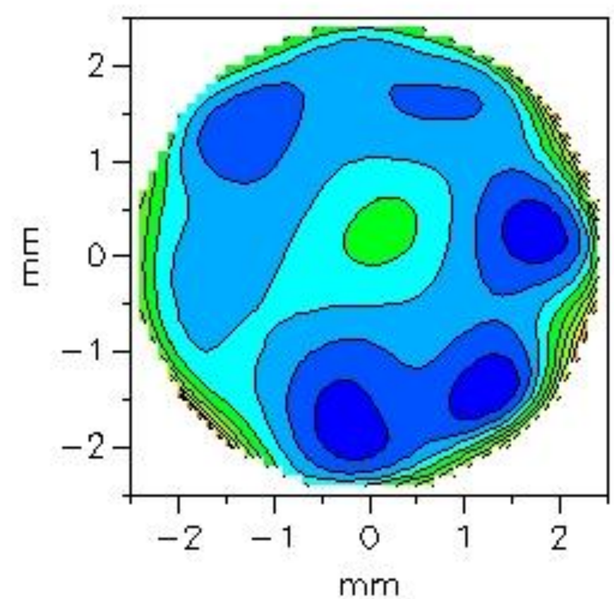
0 DS
–1 DC X 3

Aberrations of an RK patient

Wavefront sensor image

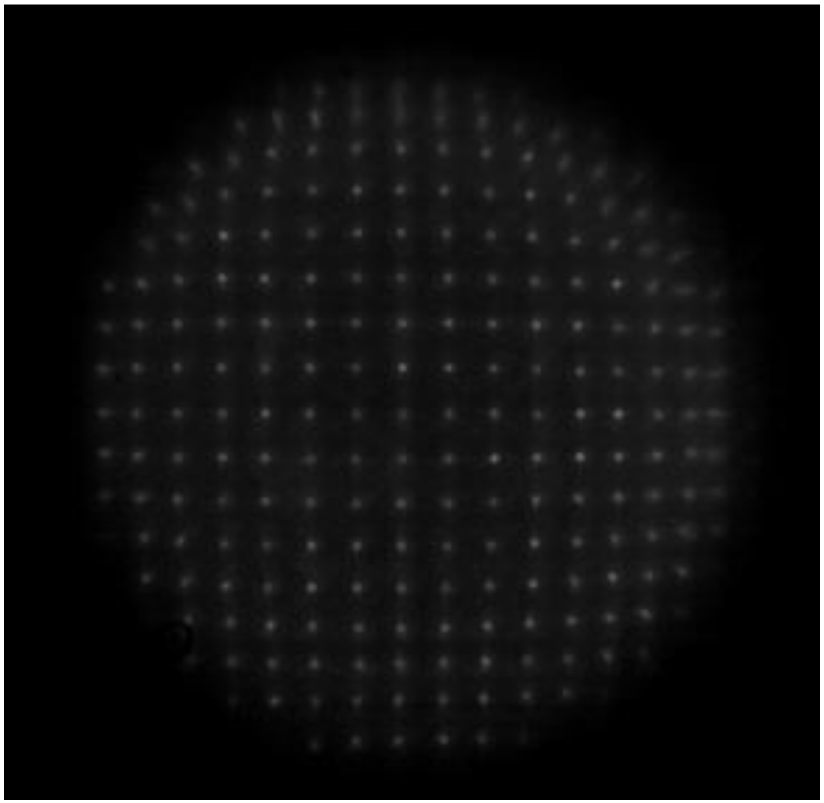


Wavefront aberration

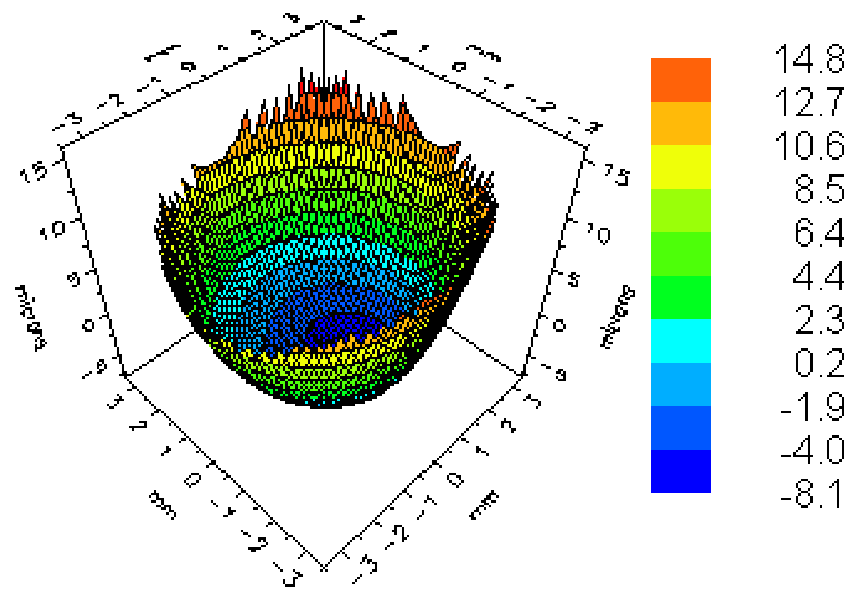


Aberrations of a LASIK patient

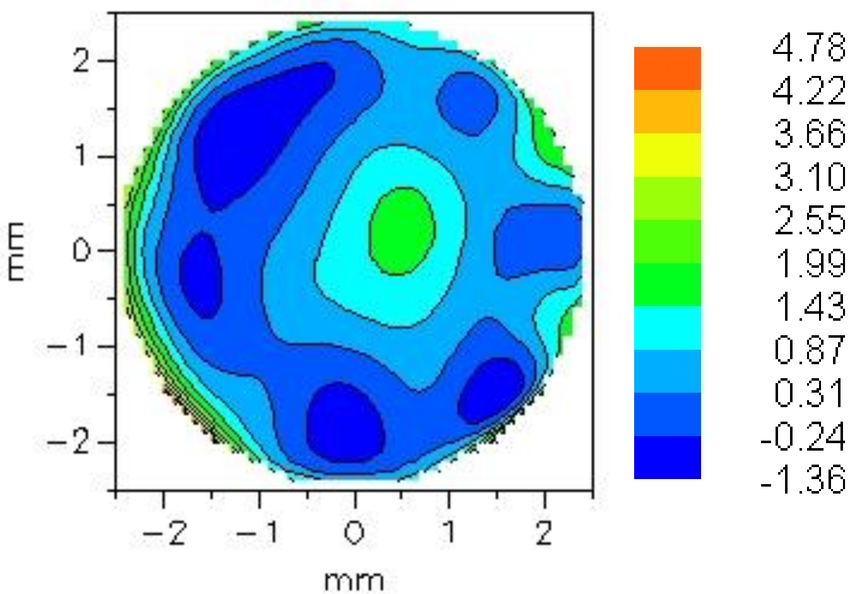
Wavefront sensor image

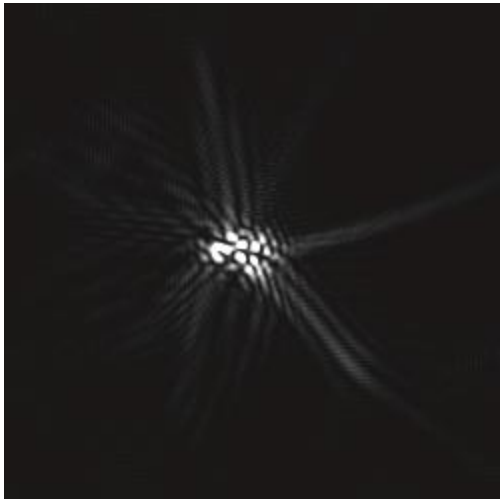


Wavefront aberration

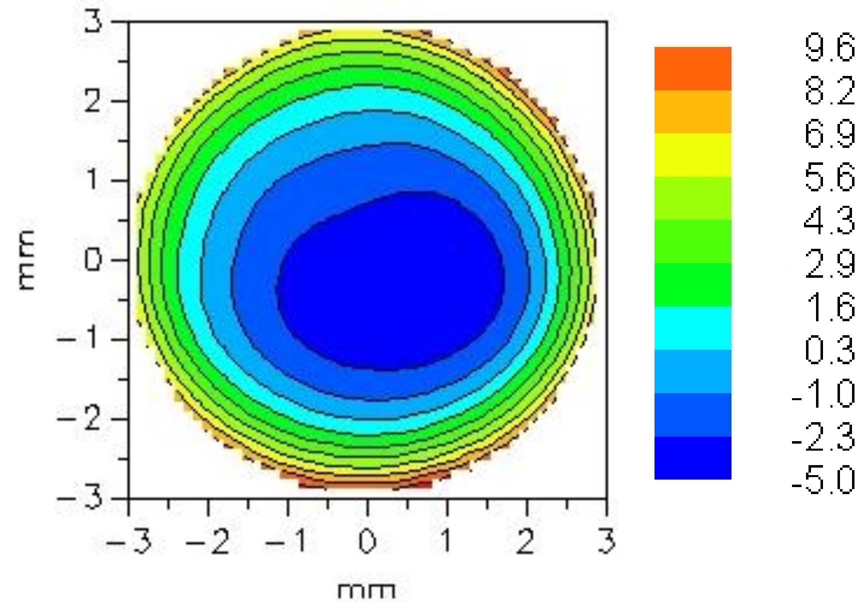


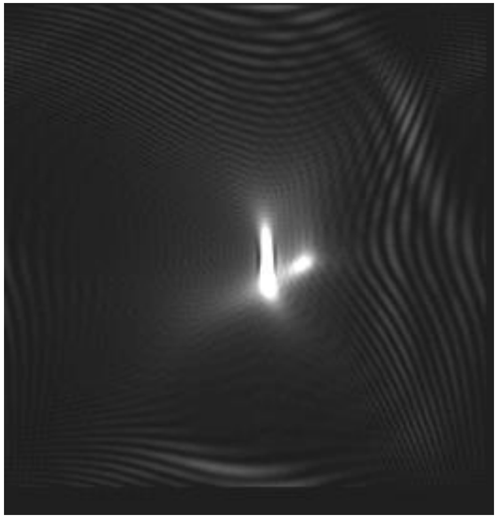
Post - RK



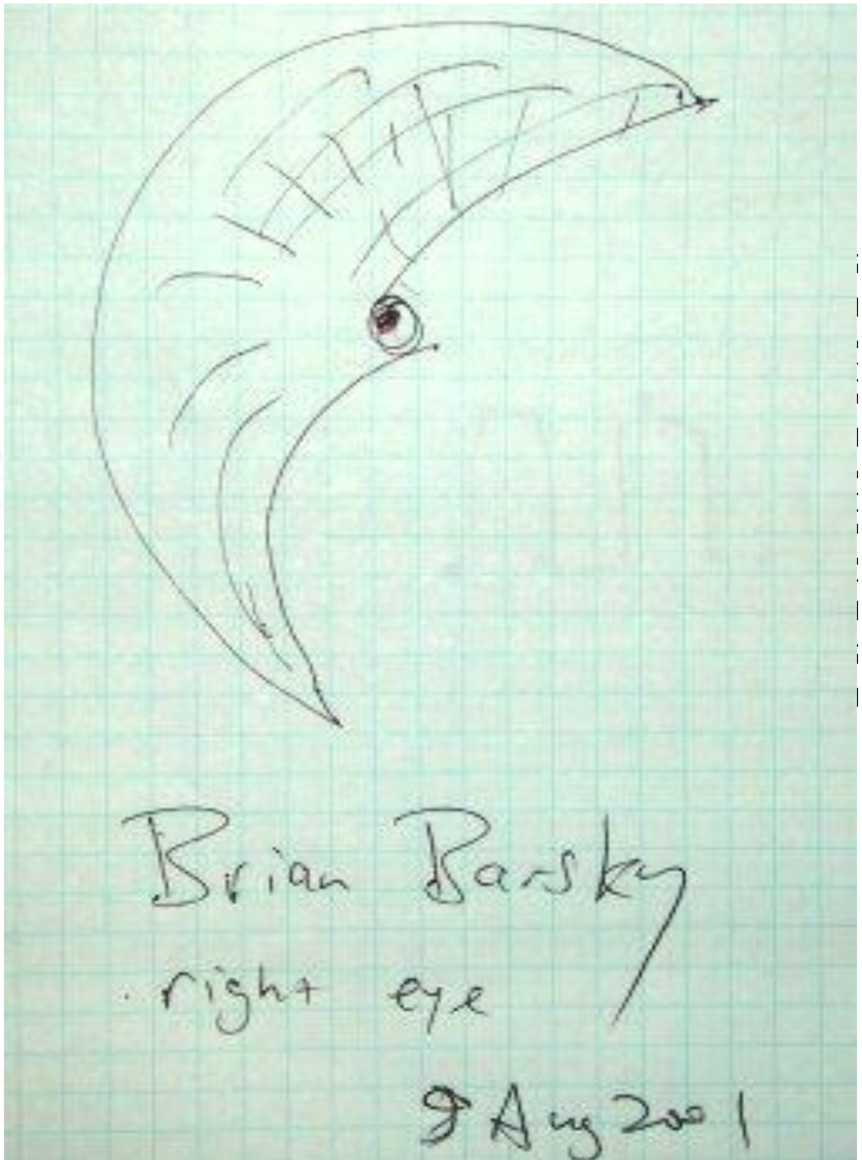


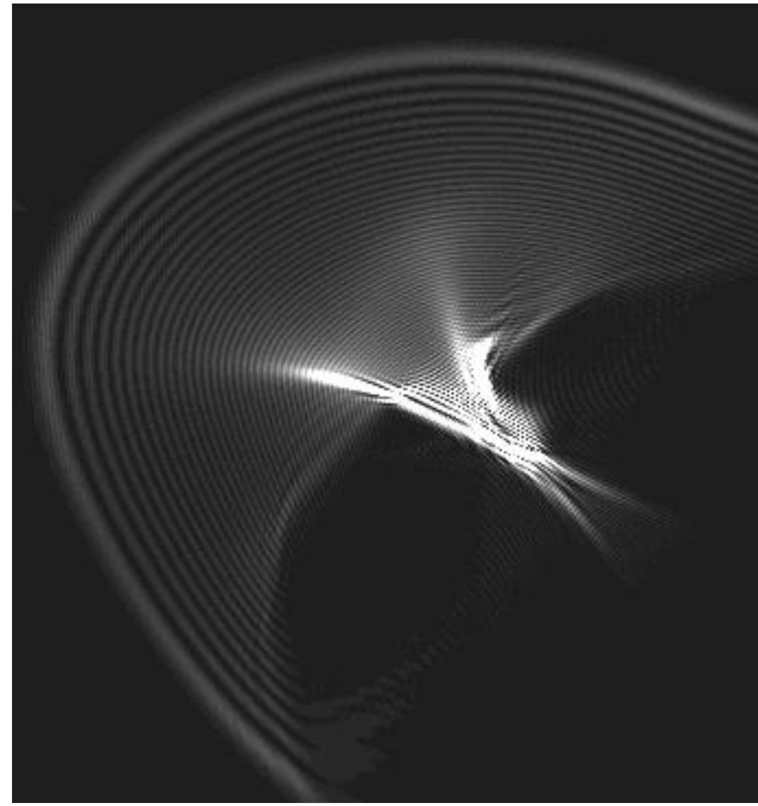
Post - LASIK





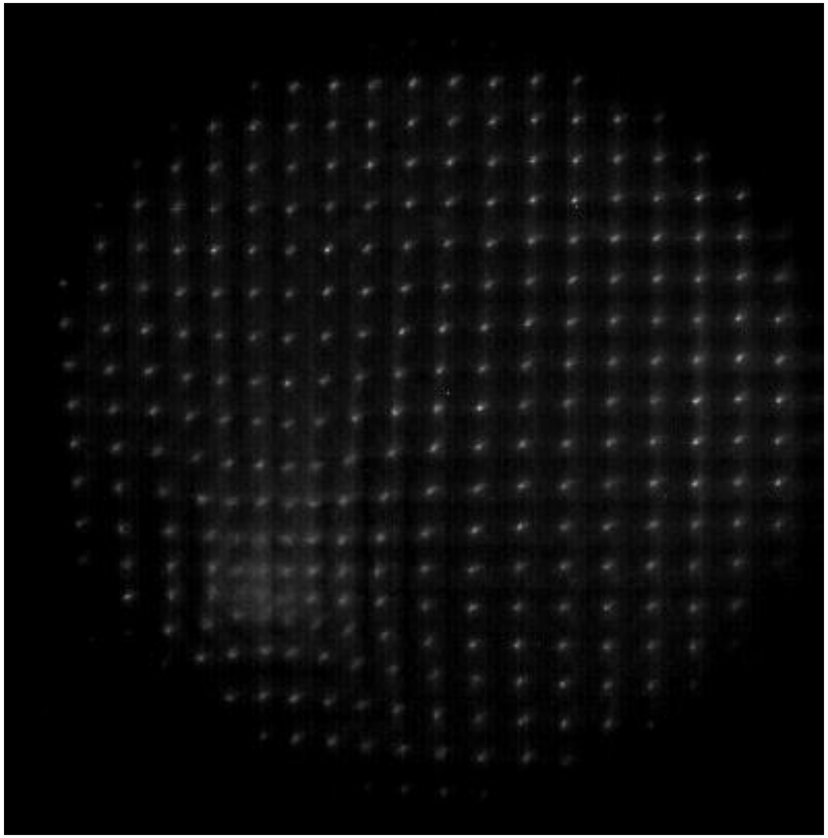
Keratoconus



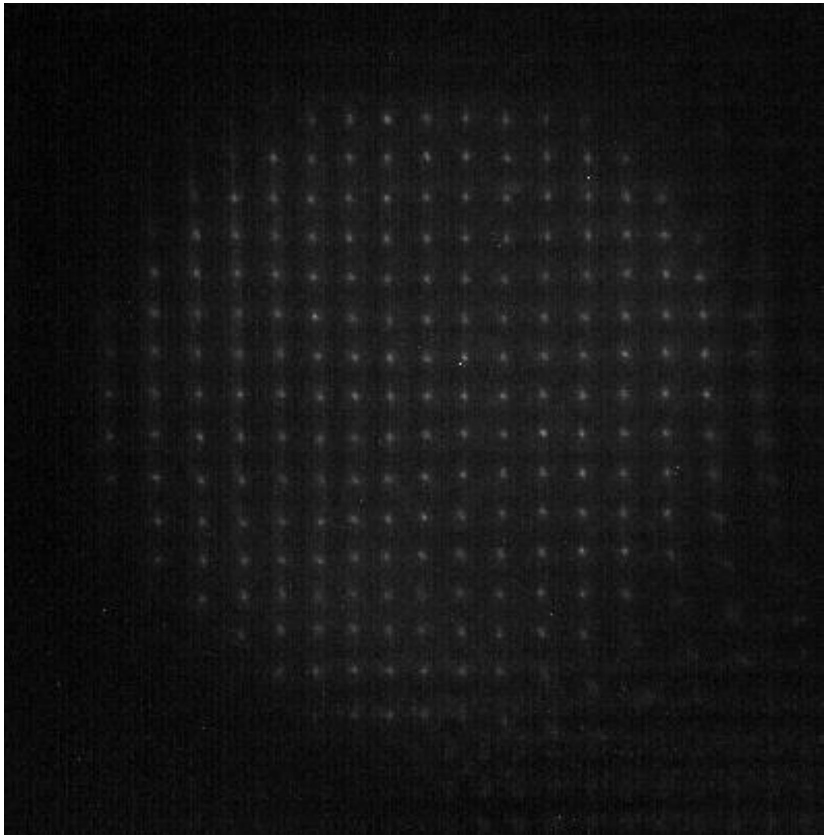


Contact Lenses for Keratoconus

unaided eye

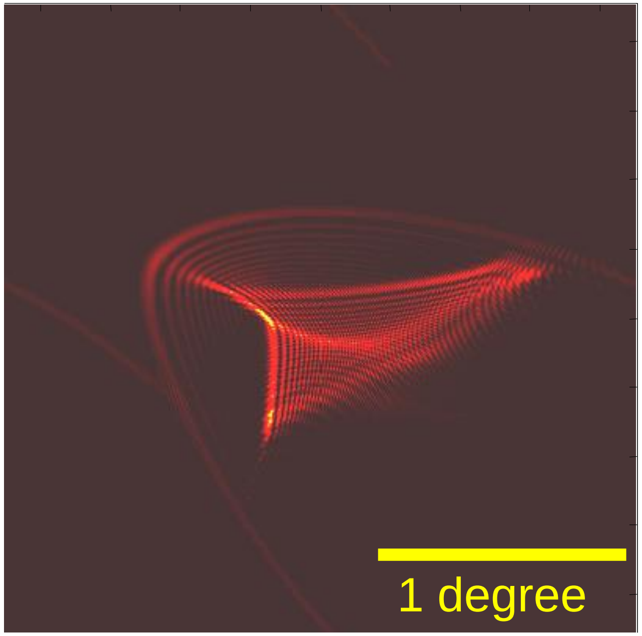


custom contact lens

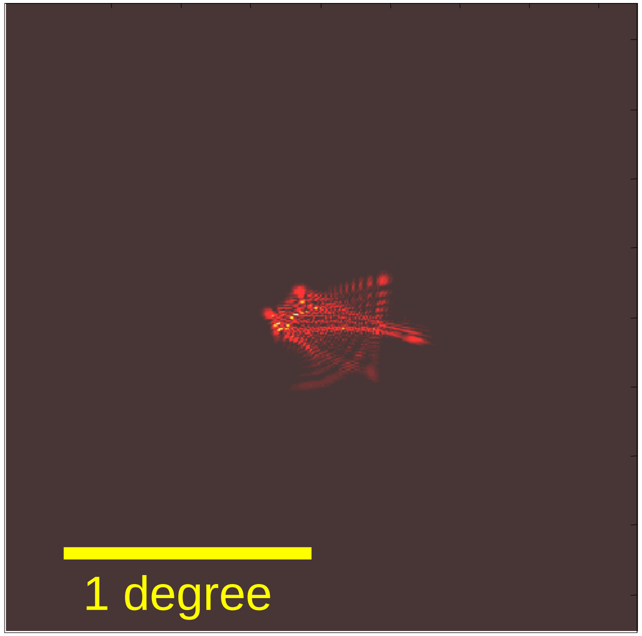


PSFs (for 5 mm pupil)

unaided eye



custom contact lens

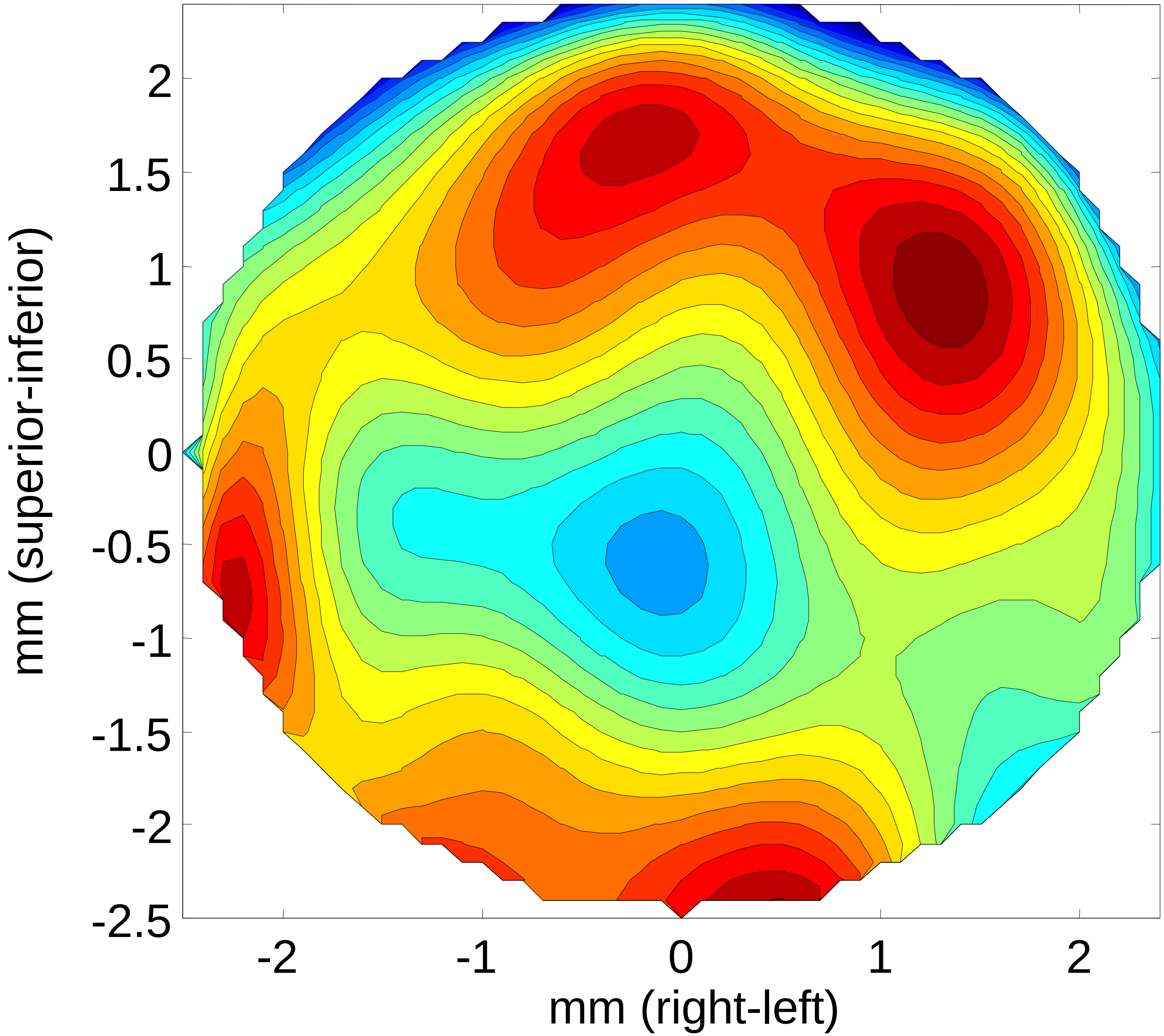


rms = 4.16
strehl ratio = 0.0008

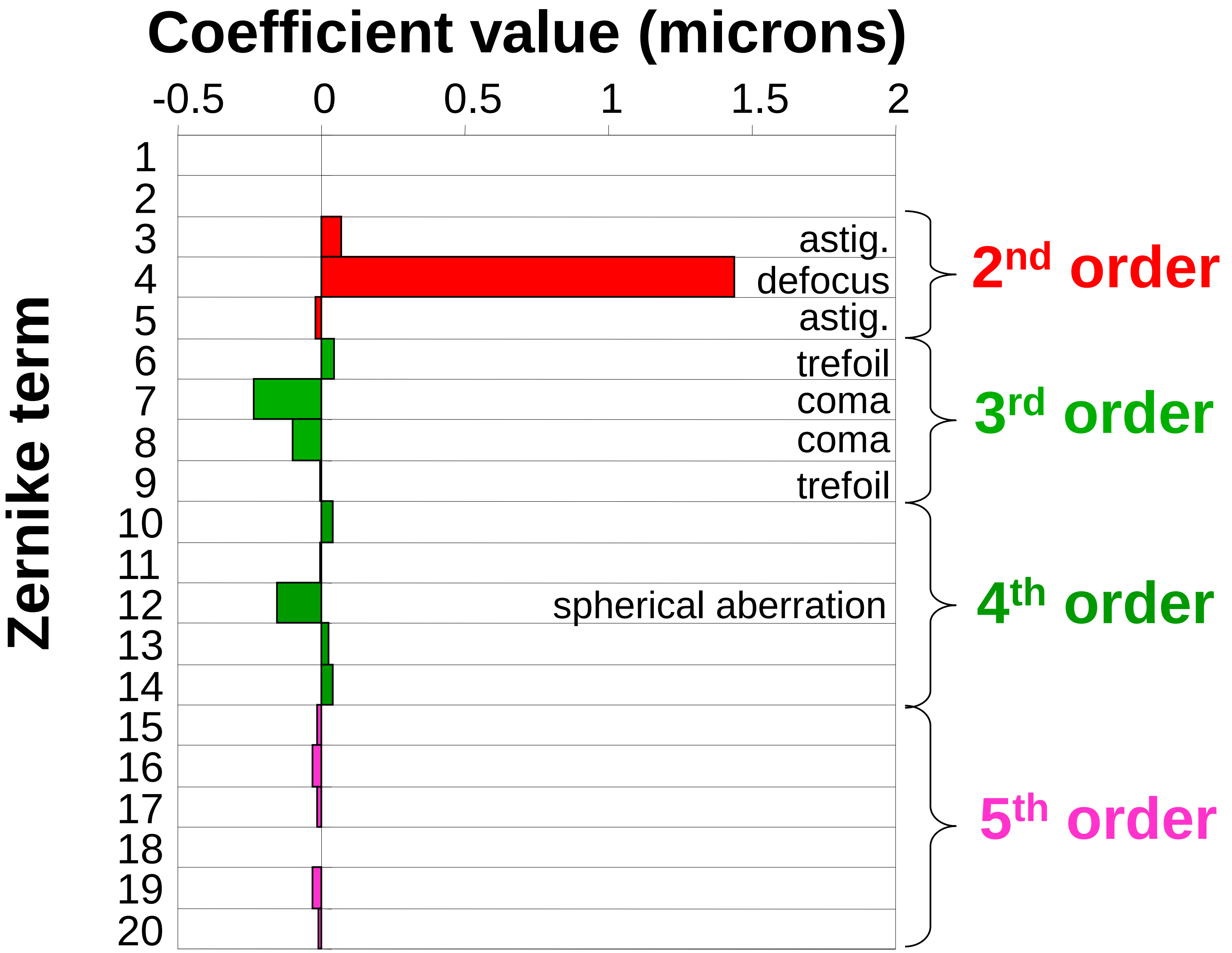
rms = 1.48
strehl ratio = 0.004

Metrics to Define Image Quality

Wave Aberration Contour Map



Breakdown of Zernike Terms



Root Mean Square

$$RMS = \sqrt{\frac{1}{A}\iint \left(W(x,y) - \overline{W(x,y)} \right)^2 dxdy}$$

$A -$ pupil area

$W(x,y) -$ wave aberration

$\overline{W(x,y)} -$ average wave aberration

Root Mean Square

$$RMS = \sqrt{\left(Z_2^{-2}\right)^2 + \left(Z_2^{0}\right)^2 + \left(Z_2^{2}\right)^2 + \left(Z_3^{-1}\right)^2 \ldots\ldots}$$

astigmatism term

defocus term

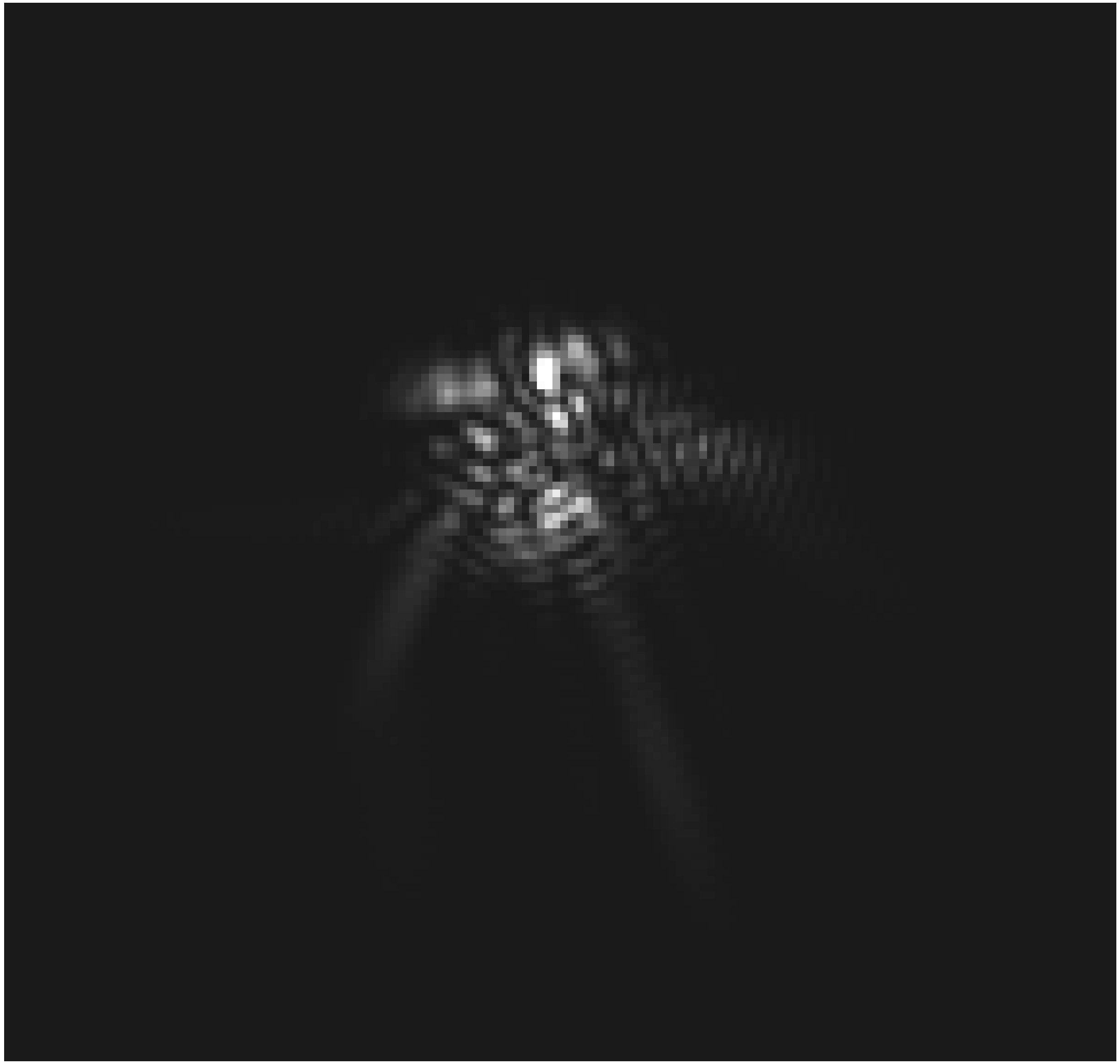
astigmatism term

trefoil term

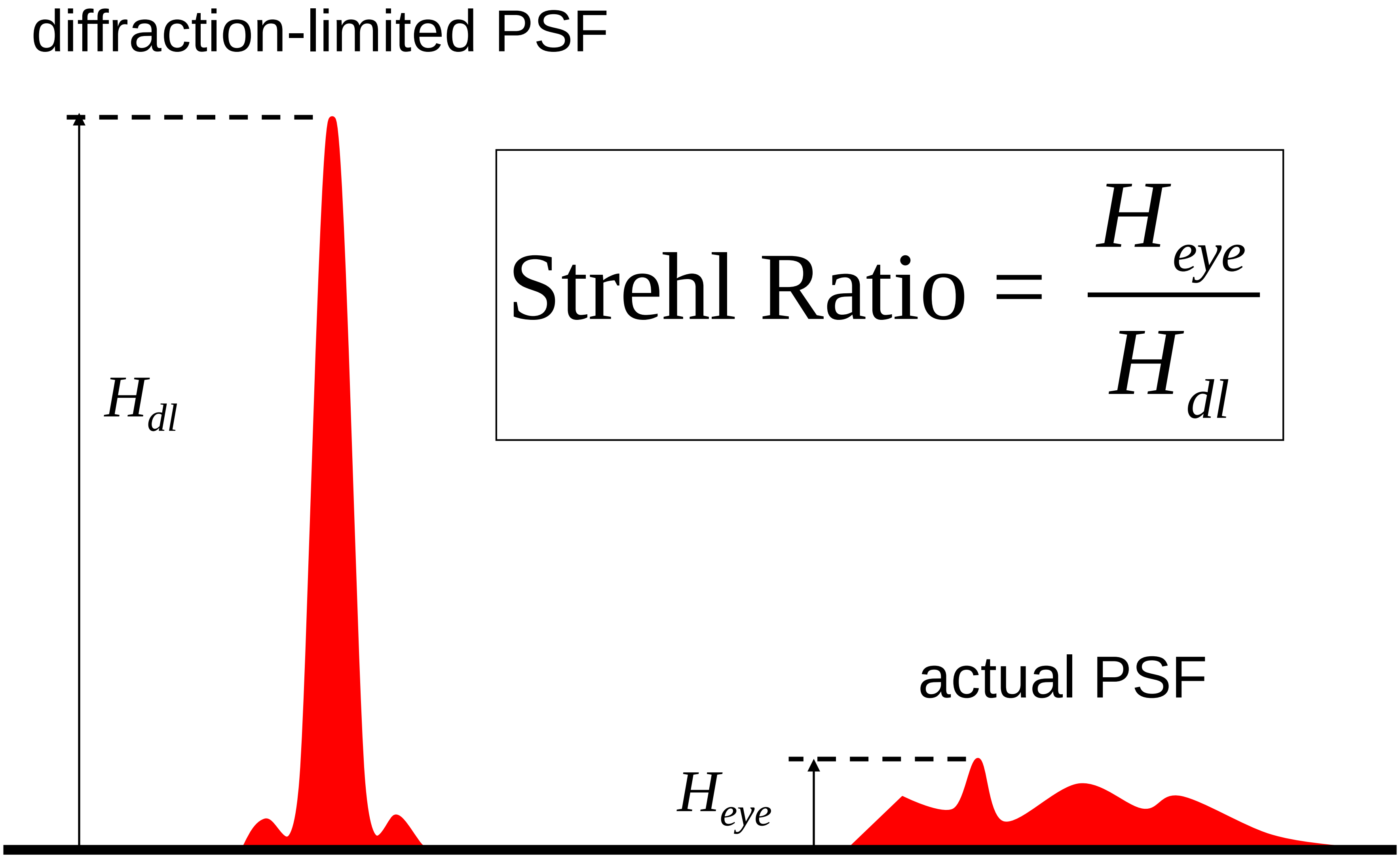
……

Include the terms for which you want to determine their impact (eg defocus and astigmatism only, third order terms or high order terms etc.)

Point Spread Function

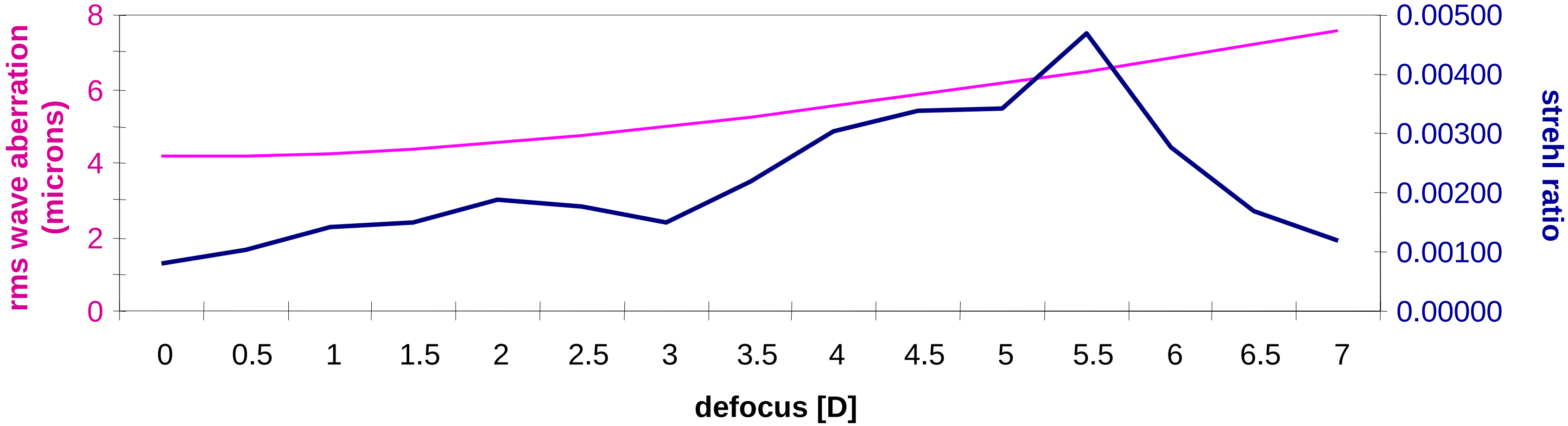


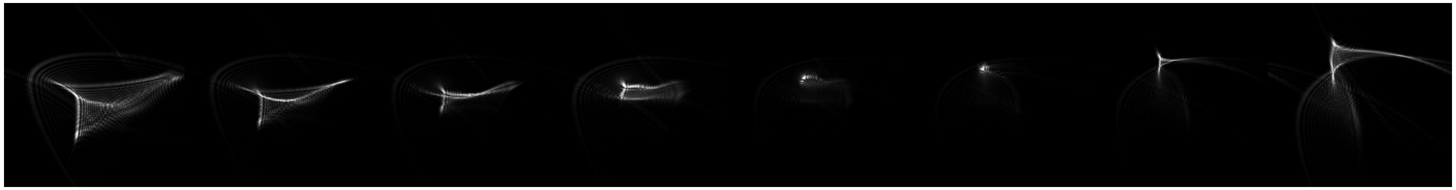
Strehl Ratio



$$\text{Strehl Ratio} = \frac{H_{eye}}{H_{dl}}$$

PSF through-focus (5 mm pupil)





The highest strehl ratio does not correlate with rms when aberrations are high

Typical Values for Wave Aberration

Strehl Ratio

- Strehl ratios are about 5% for a 5 mm pupil that has been corrected for defocus and astigmatism.
- Strehl ratios for small (~ 1 mm) pupils approach 1, but the image quality is poor due to diffraction.

How bad is the eye? Static Aberrations

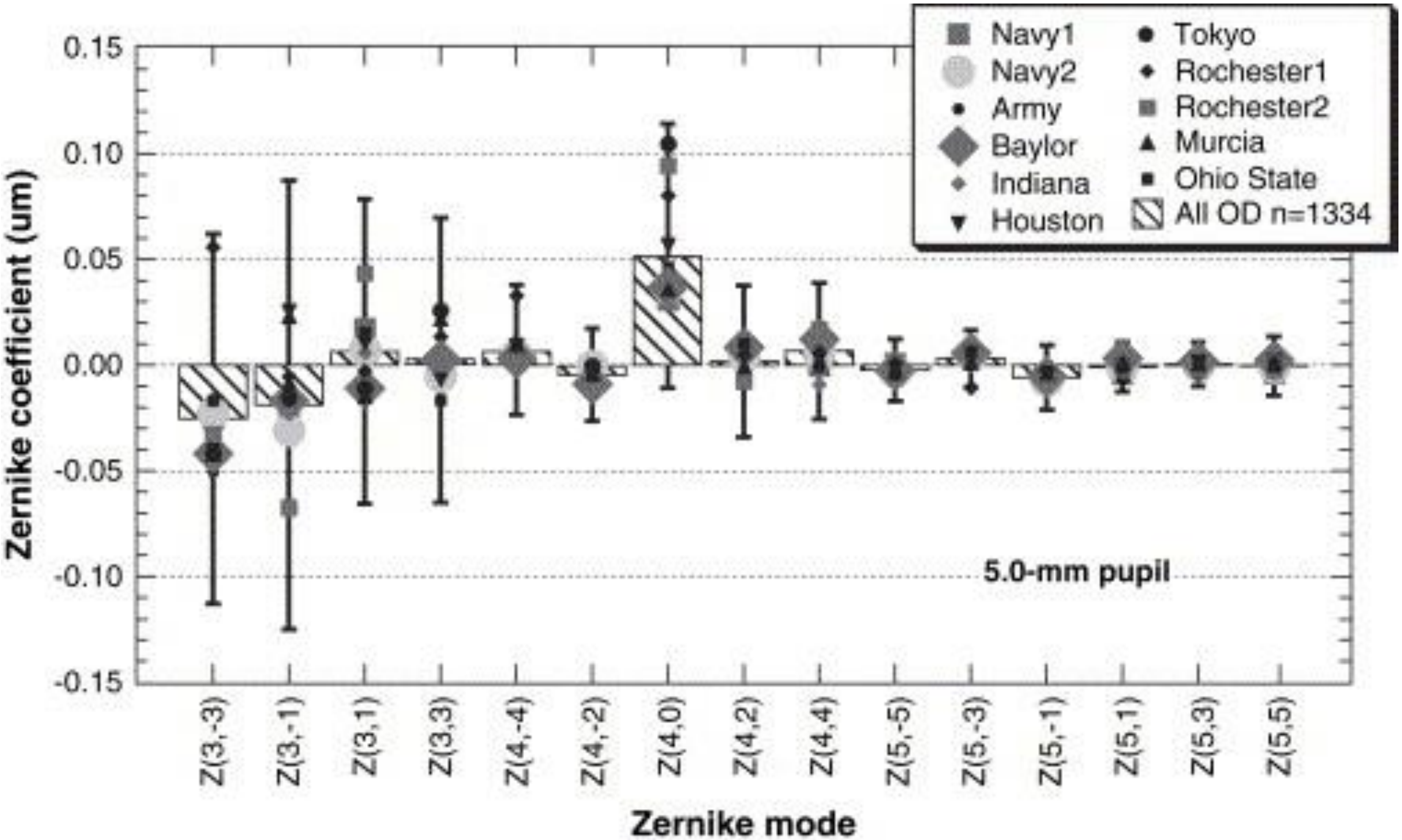
J CATARACT REFRACT SURG - VOL 32, DECEMBER 2006

Normal-eye Zernike coefficients and root-mean-square wavefront errors

Thomas O. Salmon, OD, PhD, Corina van de Pol, OD, PhD

This metastudy compiles population statistics of over 1300 eyes collected from 10 different labs

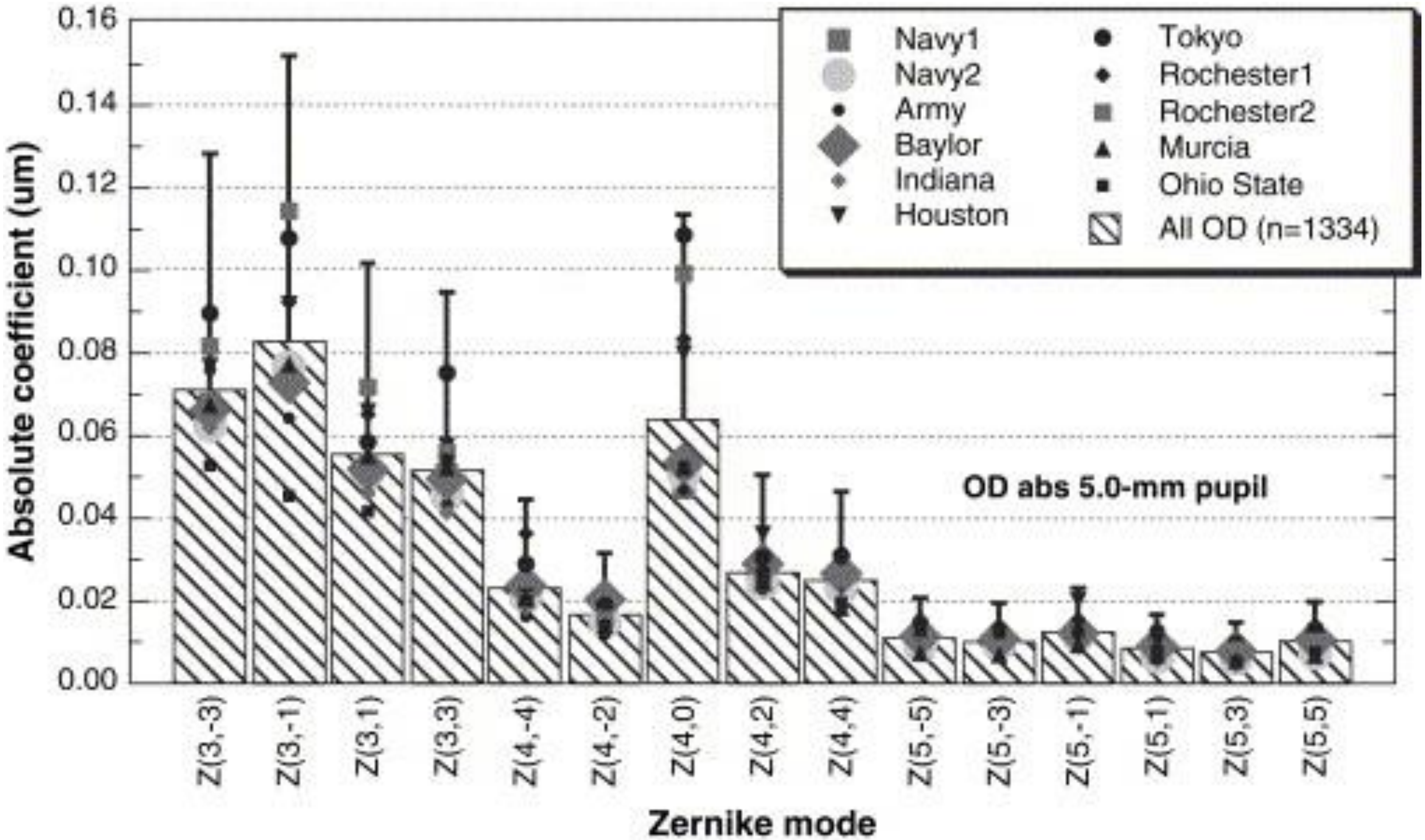
How bad is the eye?: Static Aberrations



For the most part, aberrations in the eye are random. When you average enough eyes together, most terms are no different from zero. The only high order aberrations that is non-zero is spherical aberration, which averages to a small positive value.

Salmon & van de Pol, J Cataract Ref Surg, 2006

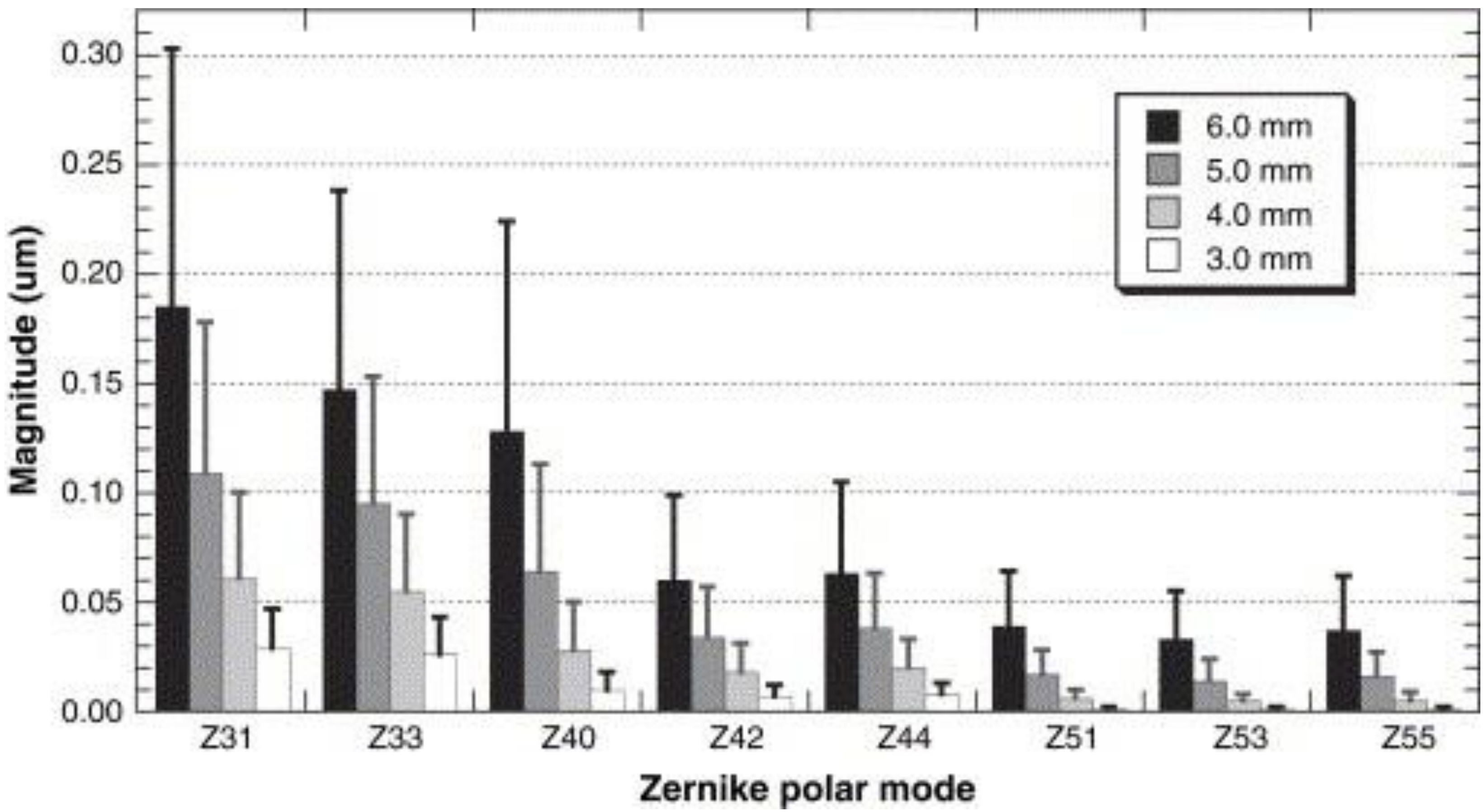
How bad is the eye?: Static Aberrations



A population average of the ***magnitude*** of the Zernike terms shows that high order aberrations are dominated by 3rd order and spherical aberration.

Salmon & van de Pol, J Cataract Ref Surg, 2006

How bad is the eye?: Static Aberrations

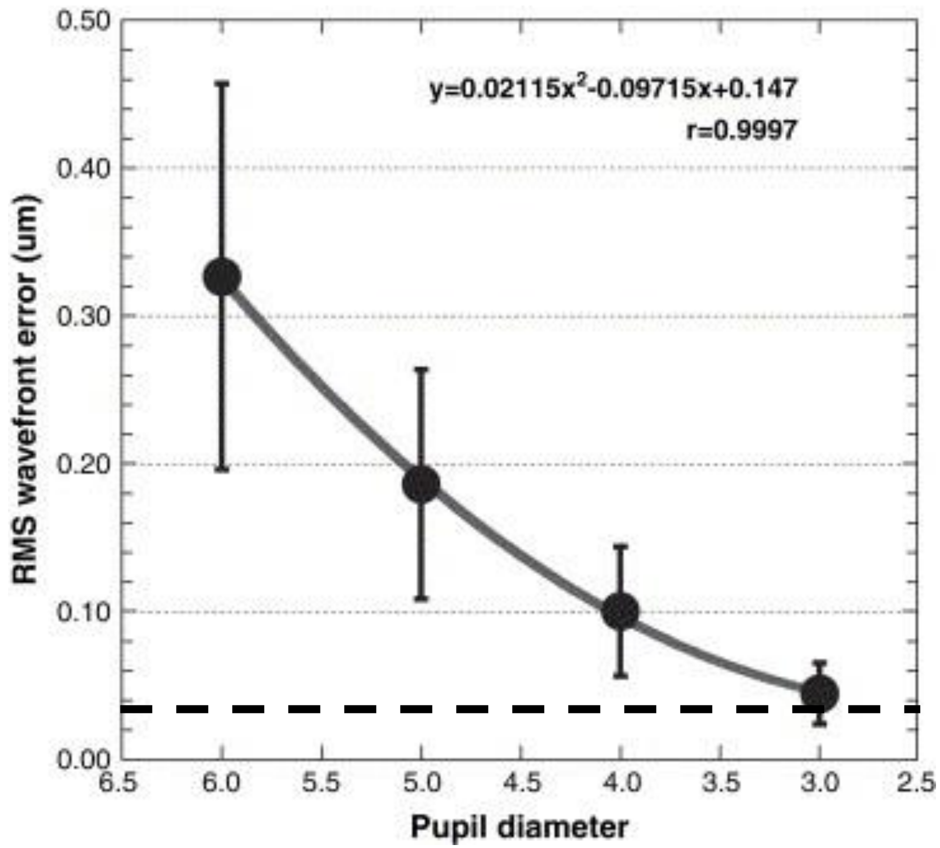


Like most optical systems, the aberrations diminish as the aperture is reduced.

But unlike turbulence from a telescope, the paraxial regions of the eye have lower aberrations than marginal locations (ie Fried's parameter is not constant)

Salmon & van de Pol, J Cataract Ref Surg, 2006

How bad is the eye?: Static Aberrations



Overall, the eye's <u>high order</u> aberrations reduce with pupil size. The dashed line indicates the effective diffraction limit, according to Marachel's criterion (RMS < $\lambda/14$) for 550 nm light.

Salmon & van de Pol, J Cataract Ref Surg, 2006

How bad is the eye?: Dynamic Aberrations

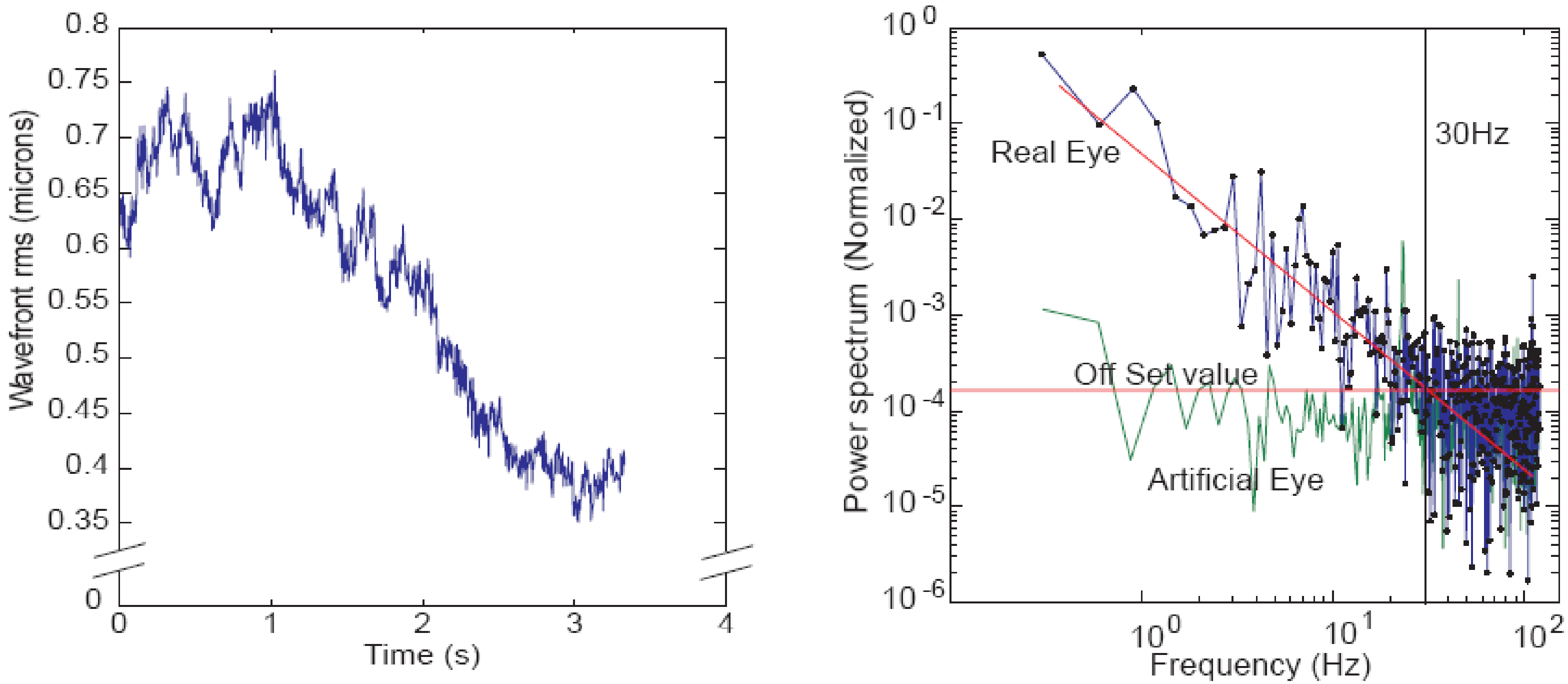


Fig. 2. Dynamics of ocular aberrations. (a) Wavefront rms measured at 240 Hz over approximately 4 s. (b) Power spectrum of the signal in (a) showing dynamic behaviour in excess of 30 Hz.

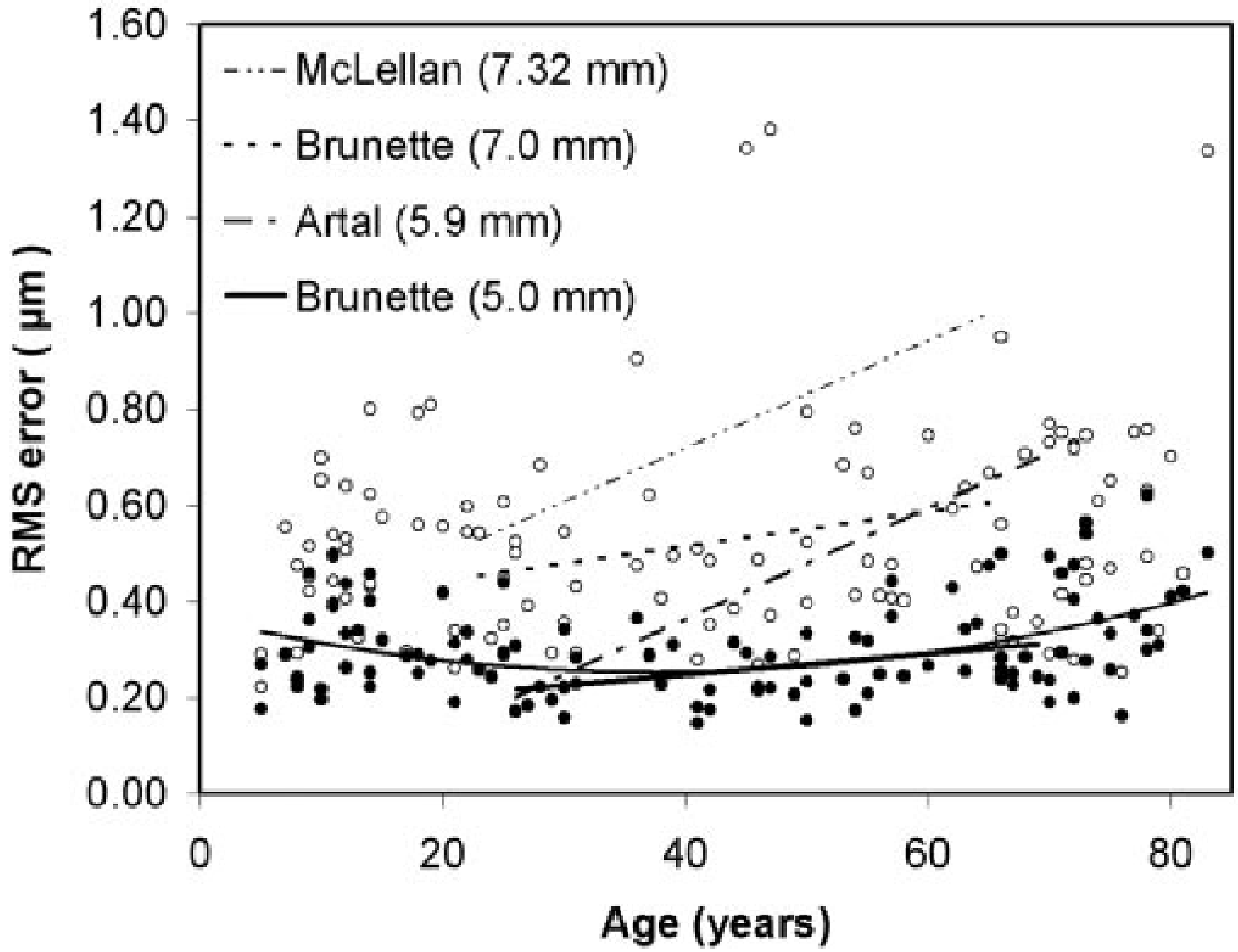
Diaz-Santana et al. Benefit of higher closed-loop bandwidths in ocular adaptive optics, Opt Express, 11: (2003)

How bad is the eye?: Dynamic Aberrations

- Dynamic Changes in the wave aberrations are caused by
  - accommodation
  - eye movement
  - eye translation
  - tear film

Typical Values for Wave Aberration

Change in aberrations with age



Monochromatic Aberrations as a Function of Age, from Childhood to Advanced Age

Isabelle Brunette,[1] Juan M. Bueno,[2] Mireille Parent,[1,3] Habib Hamam,[3] and Pierre Simonet[3]

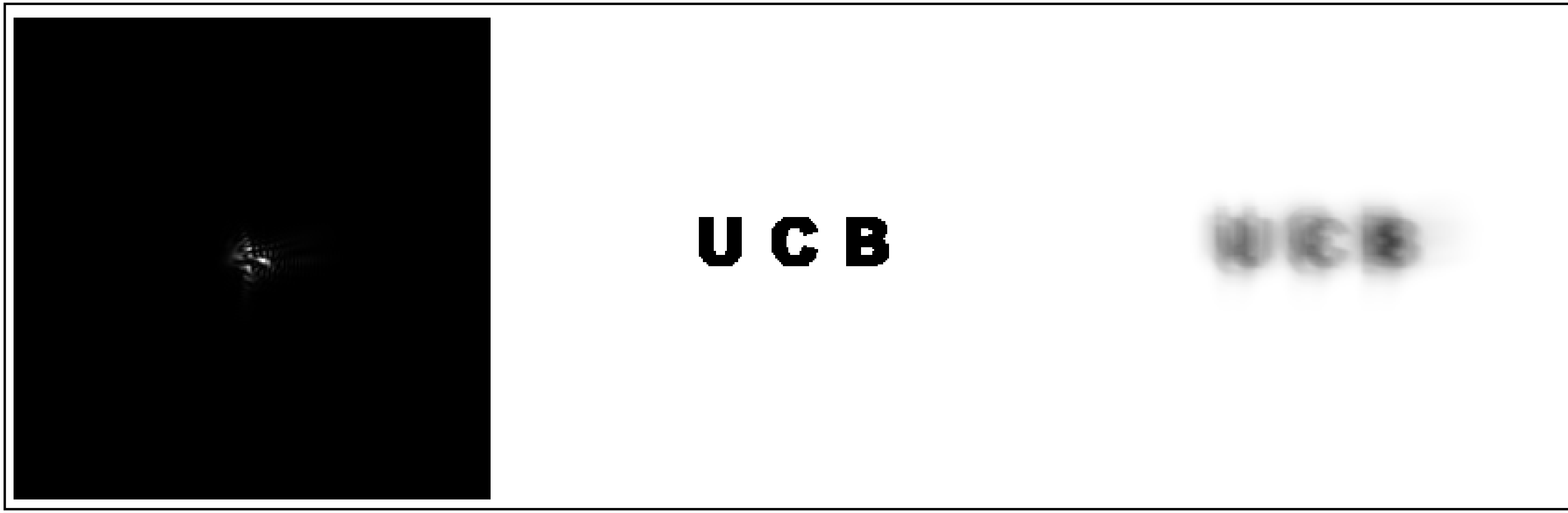
Convolution

Convolution

$$PSF(x,y) \;\otimes\; O(x,y) \;=\; I(x,y)$$

Simulated Images

20/20 letters



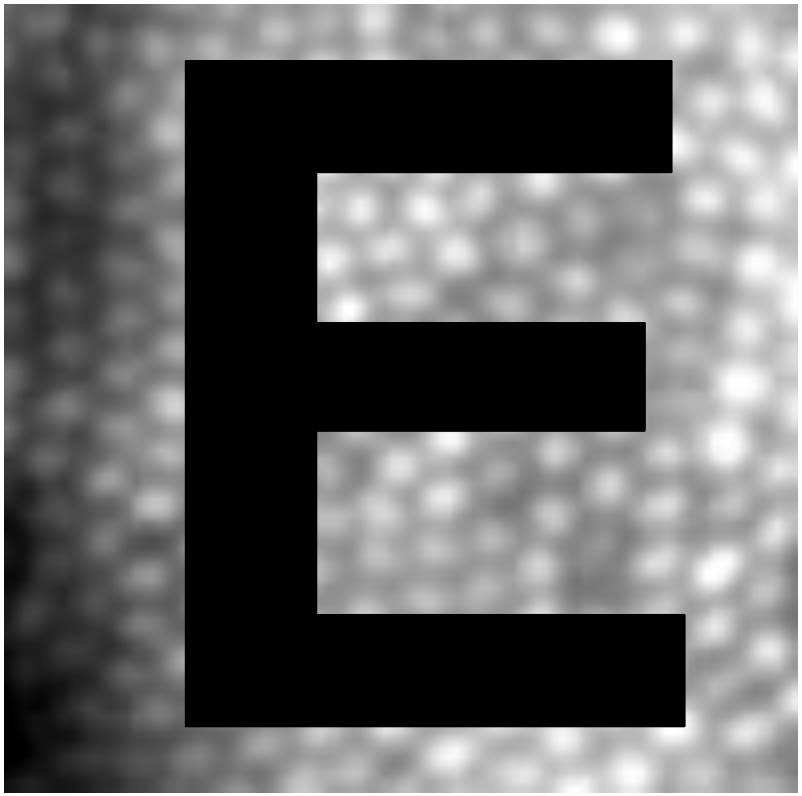
20/40 letters

"*I have never experienced any inconvenience from this imperfection, nor did I ever discover it till I made these experiments; and I believe I can examine minute objects with as much accuracy as most of those whose eyes are differently formed*"

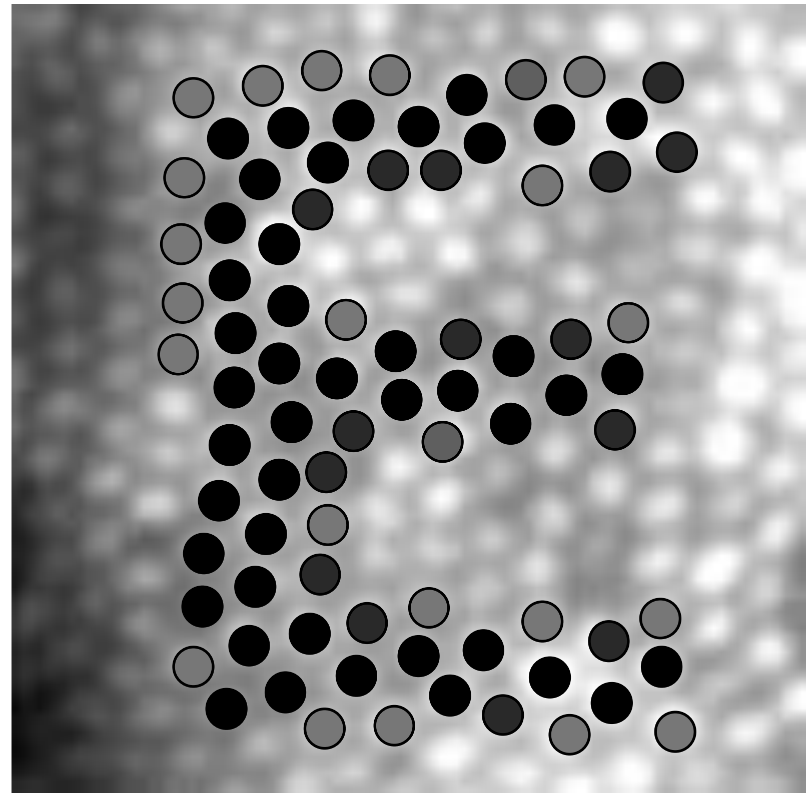
Thomas Young (1801) on his own aberrations.

Retinal Sampling

Sampling by Foveal Cones

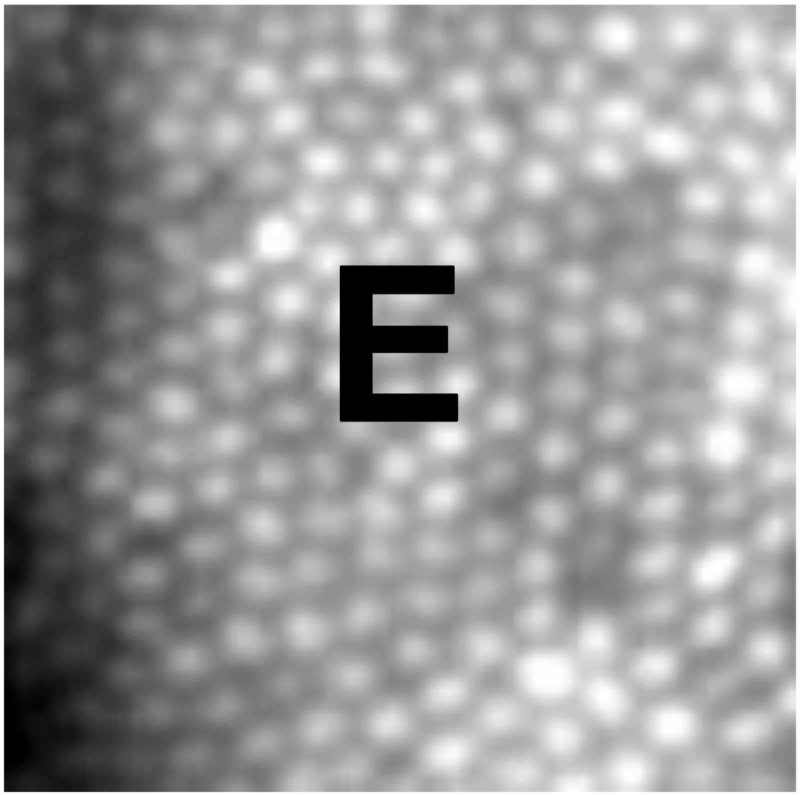


20/20 letter



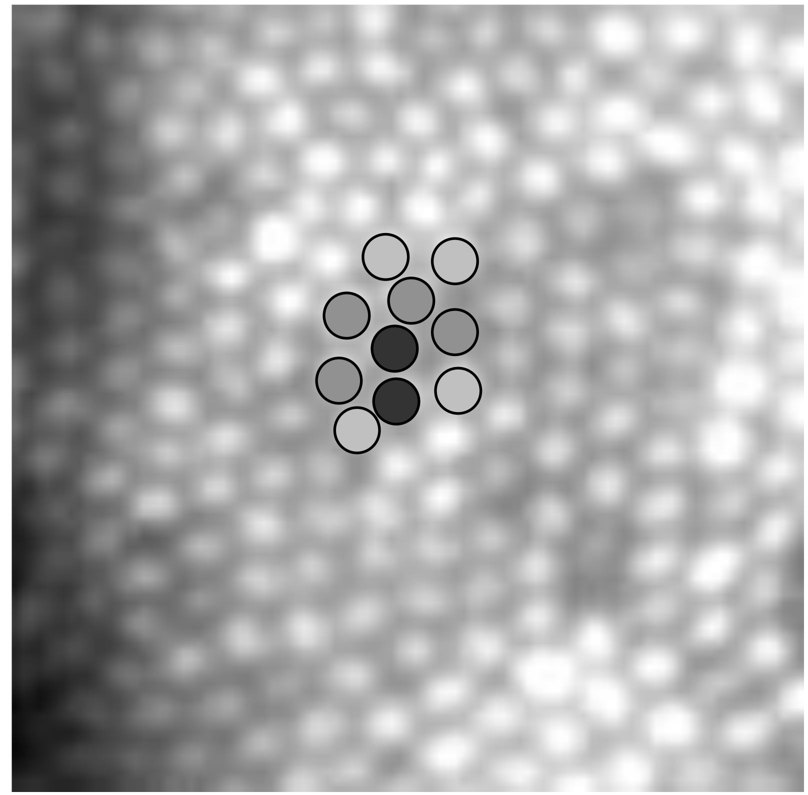
Sampling by Foveal Cones

Projected Image



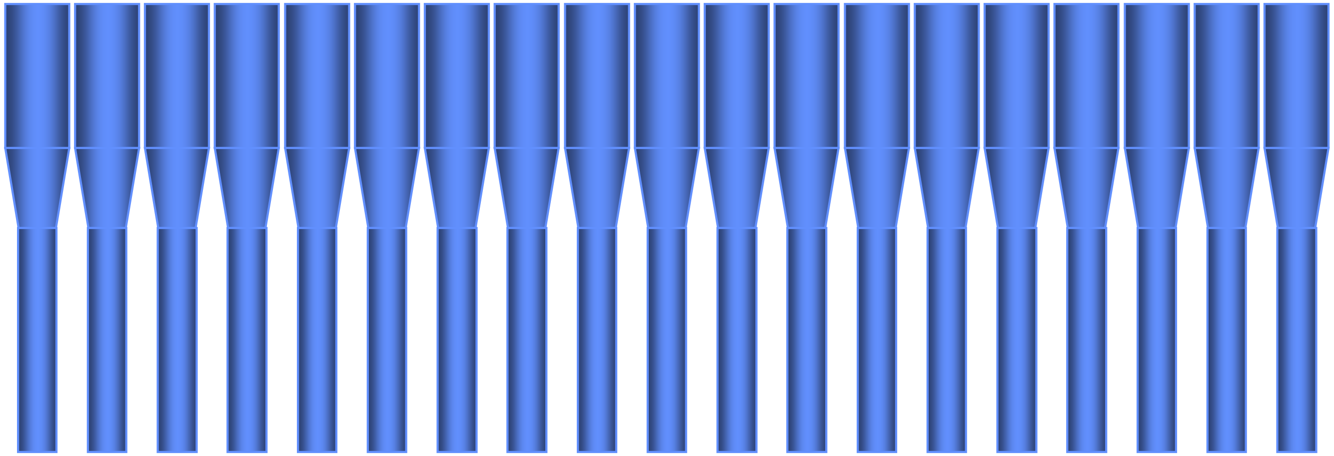
20/5 letter

Sampled Image

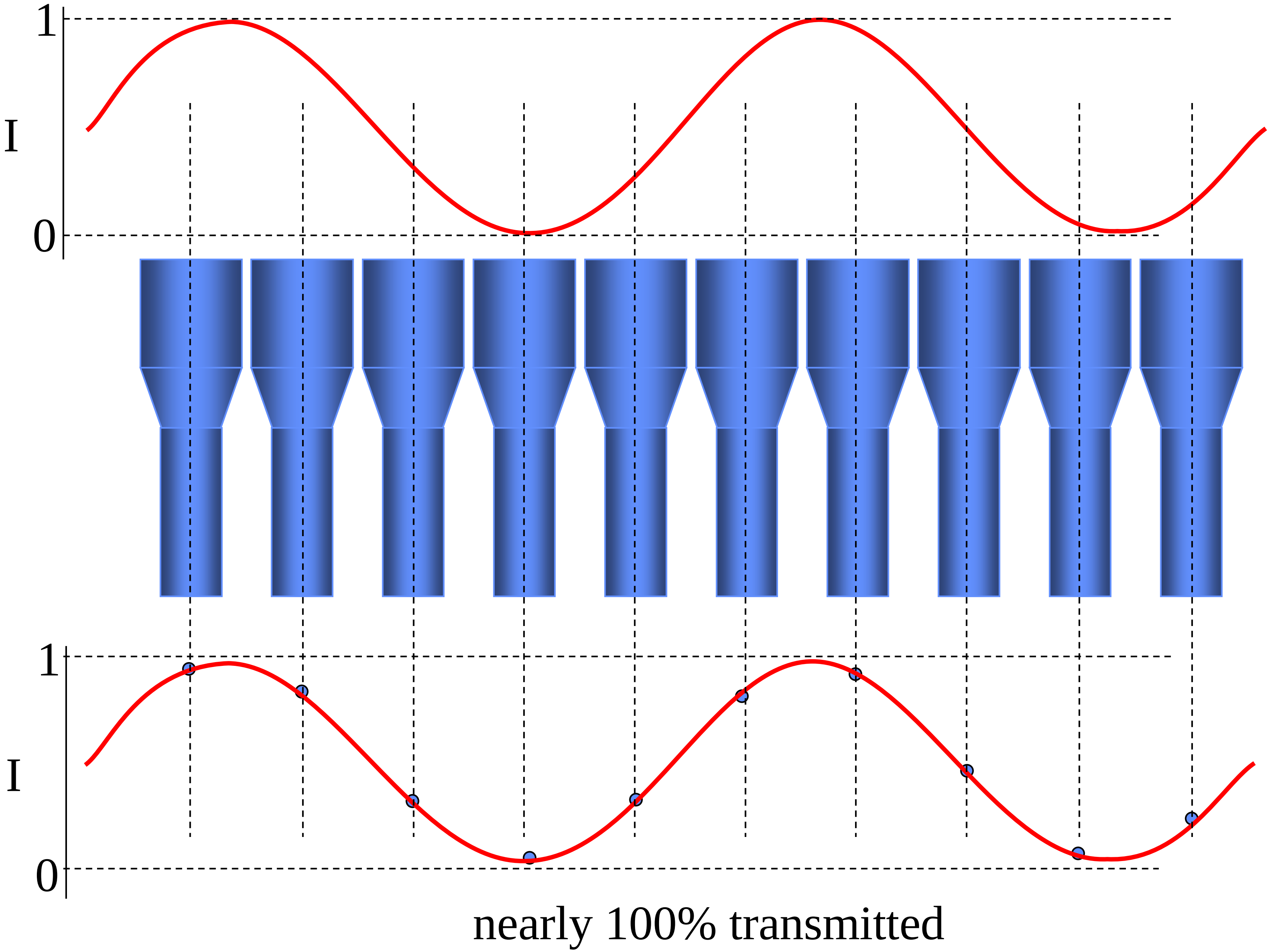


5 arc minutes

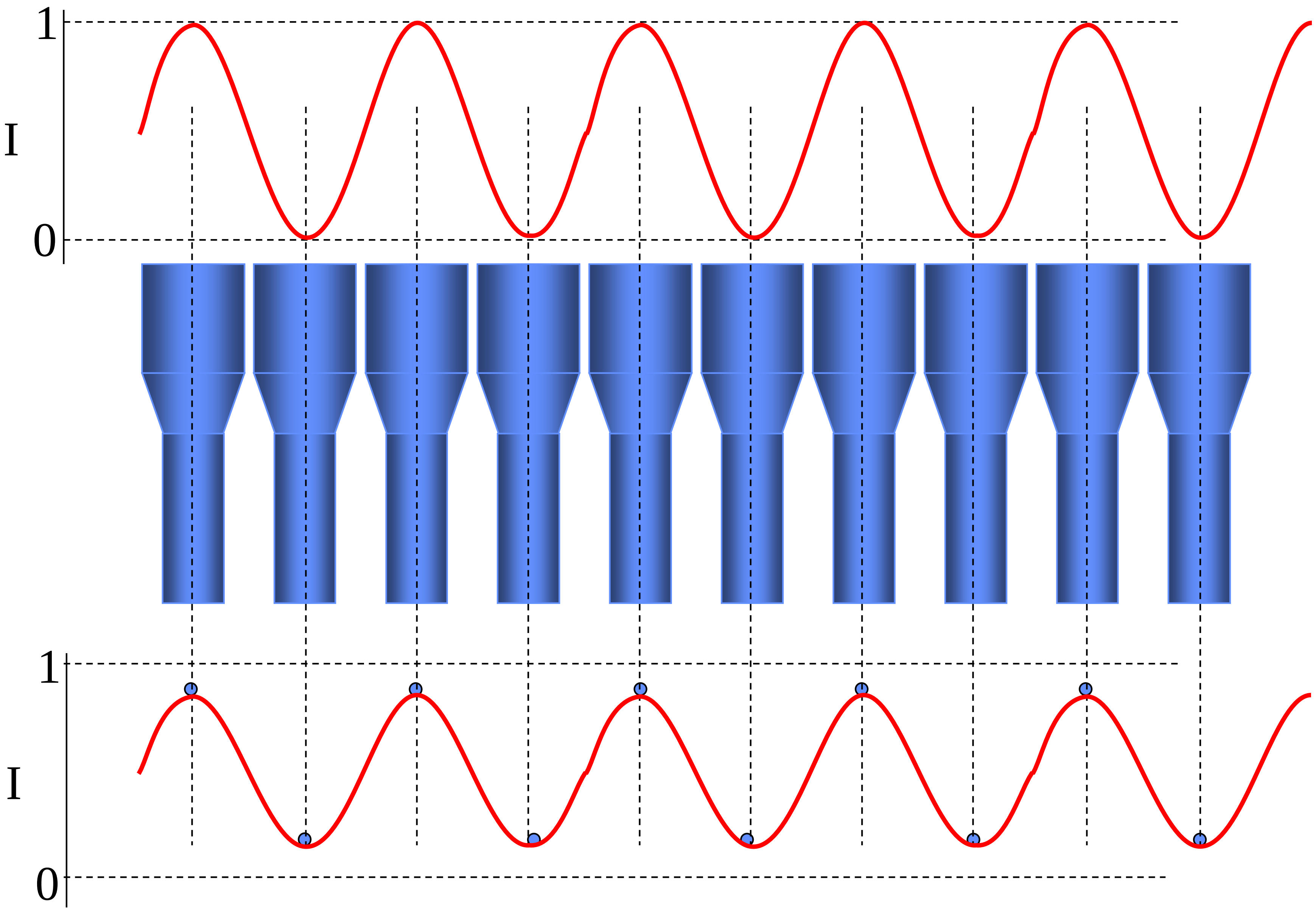
Nyquist Sampling Theorem



Photoreceptor Sampling >> Spatial Frequency

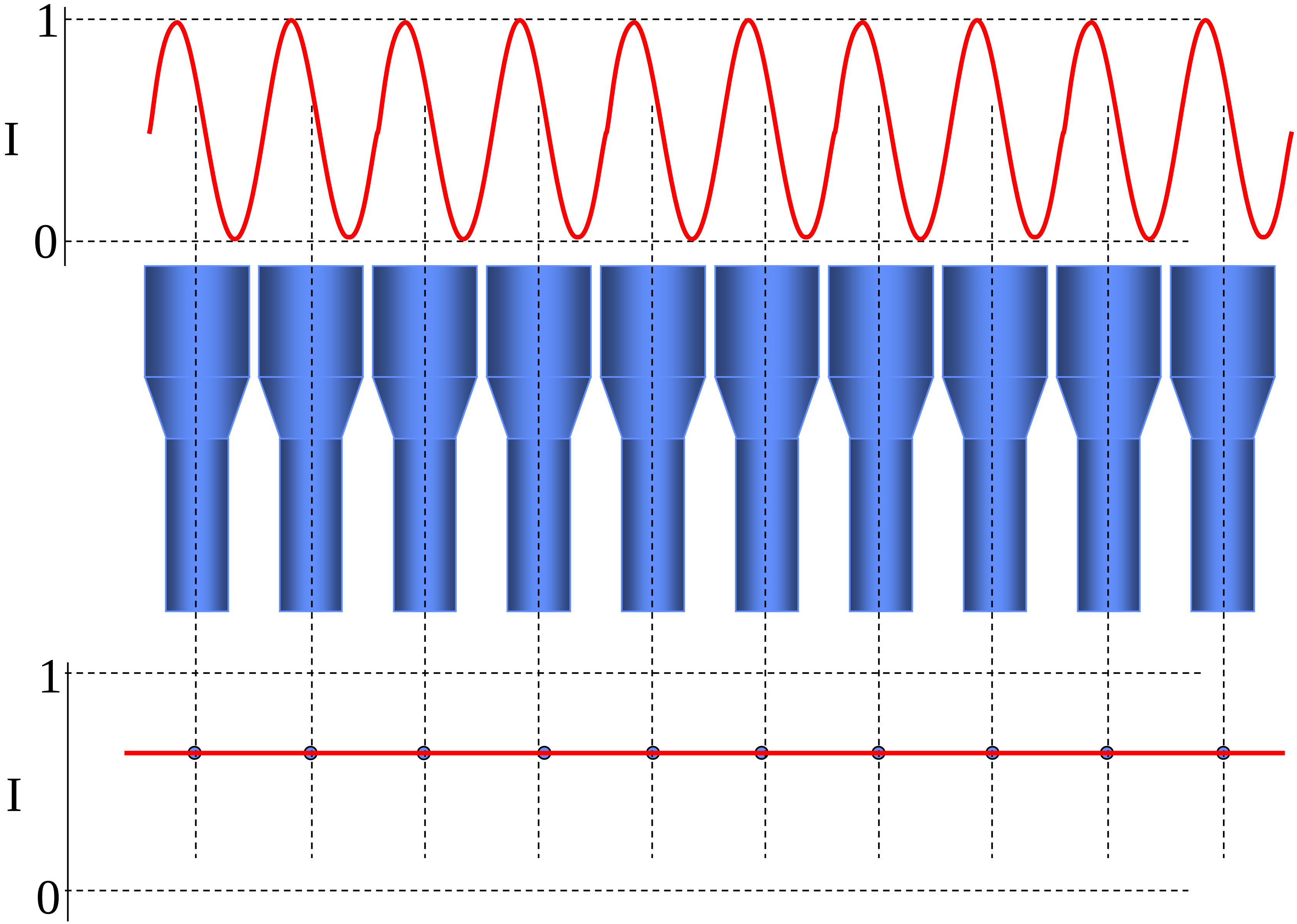


Photoreceptor Sampling = 2 x Spatial Frequency



nearly 100% transmitted

Photoreceptor Sampling = Spatial Frequency

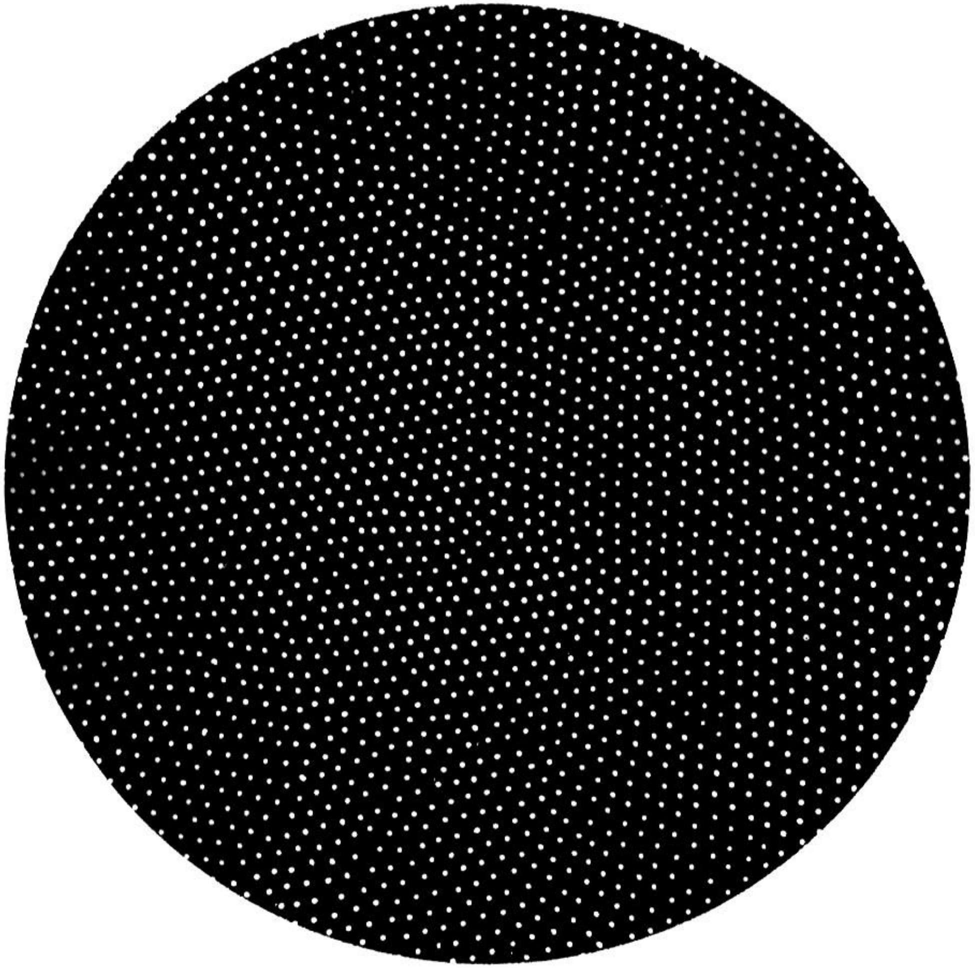


nothing transmitted

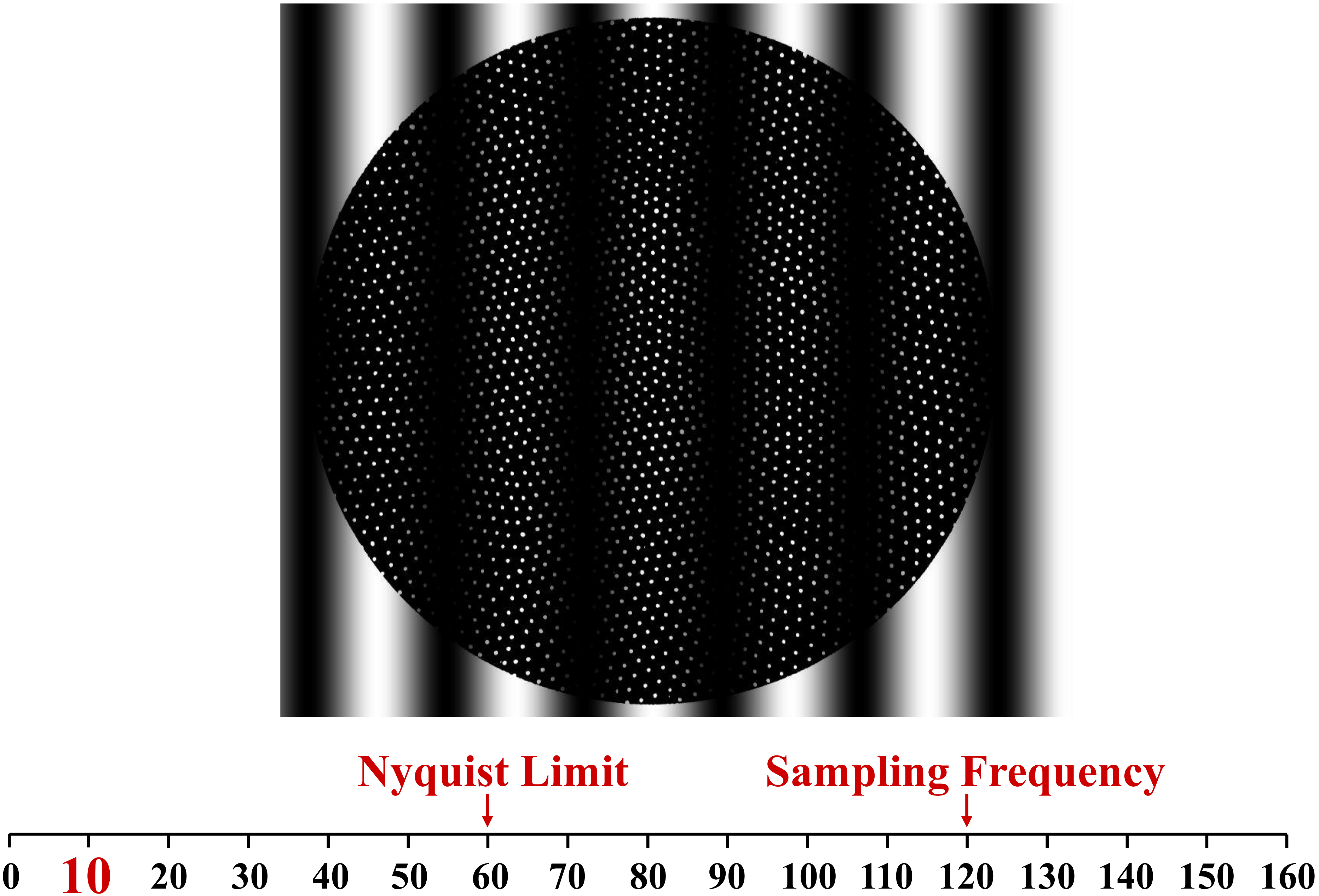
Nyquist theorem:
The maximum spatial frequency that can be detected is equal to ½ of the sampling frequency.

foveal cone spacing ~ 120 samples/deg

maximum spatial frequency:
60 cycles/deg (20/10 or 6/3 acuity)



Primate Central Fovea (0.5 deg)


Nyquist Limit
Sampling Frequency
0
10
20
30
40
50
60
70
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130
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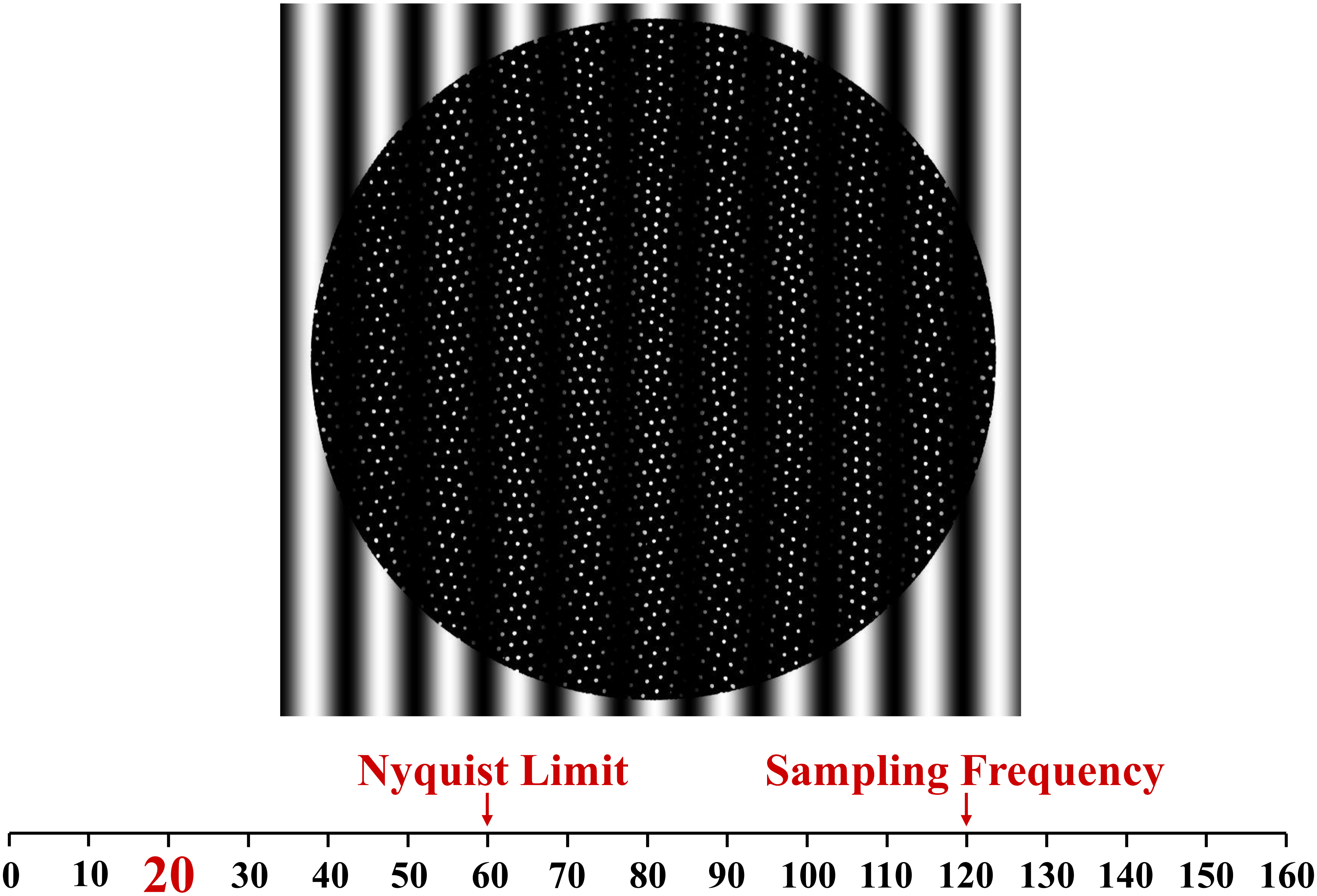
150
160


Nyquist Limit
Sampling Frequency
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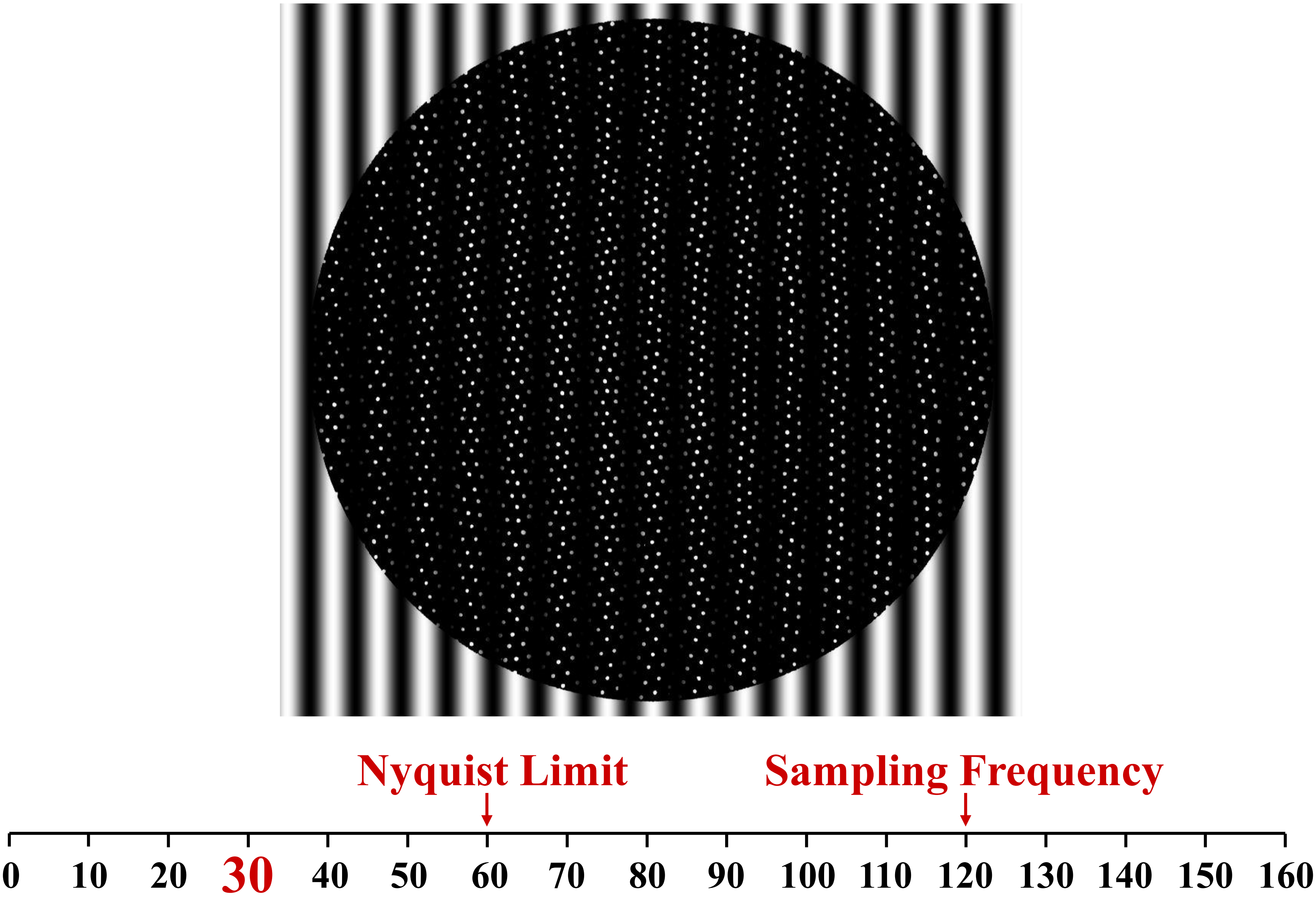

Nyquist Limit
Sampling Frequency
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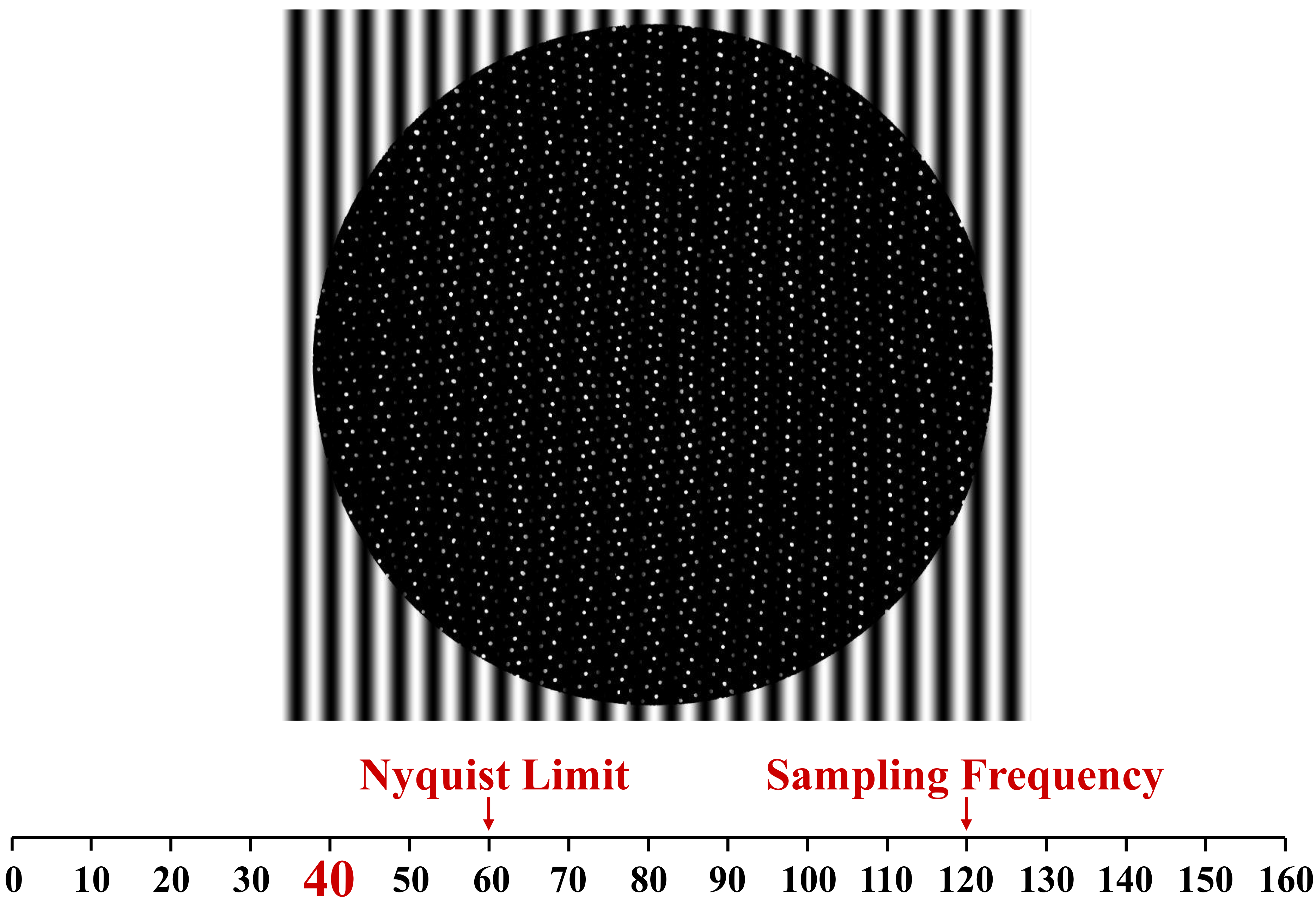
Nyquist Limit
Sampling Frequency
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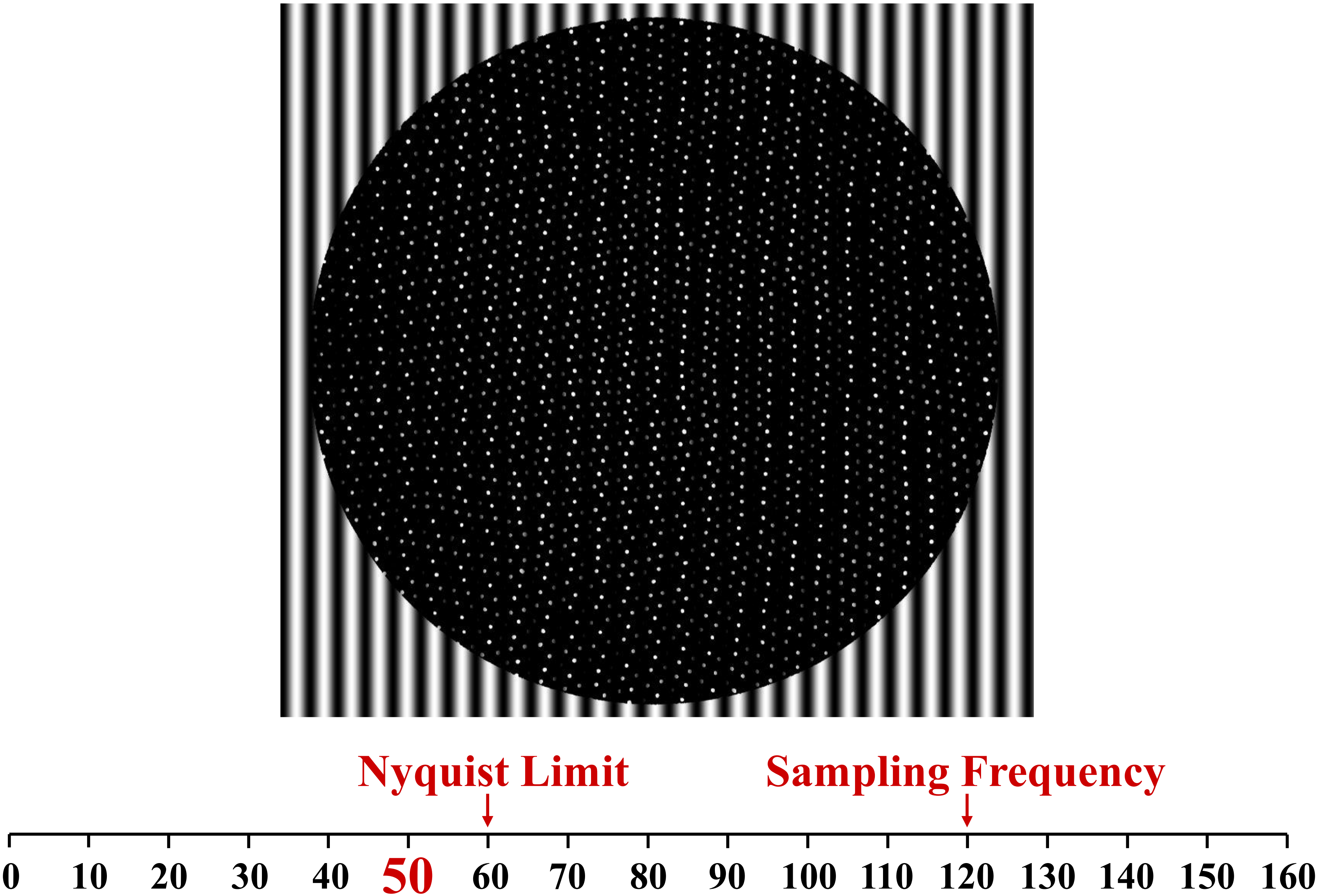
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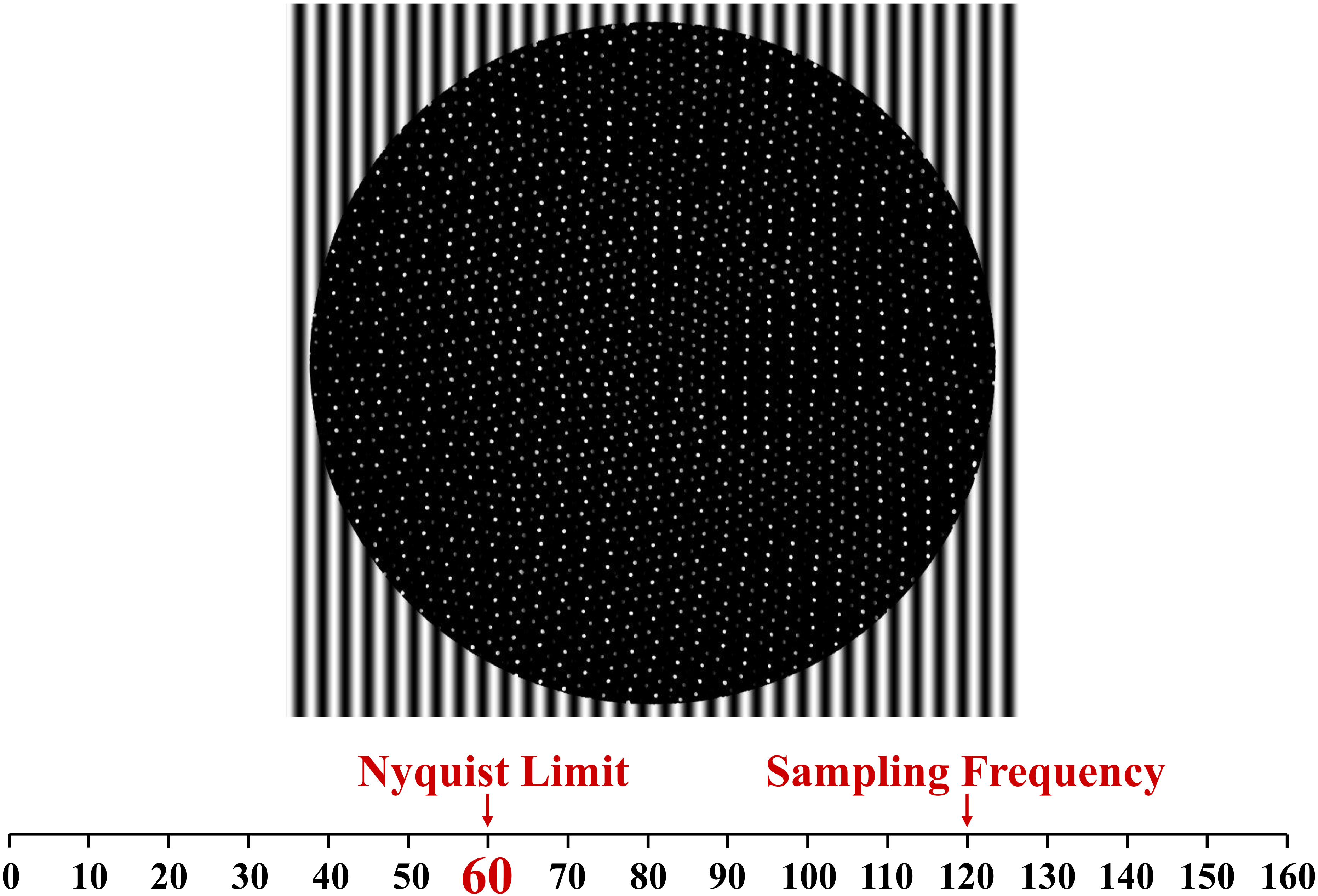
Nyquist Limit
Sampling Frequency
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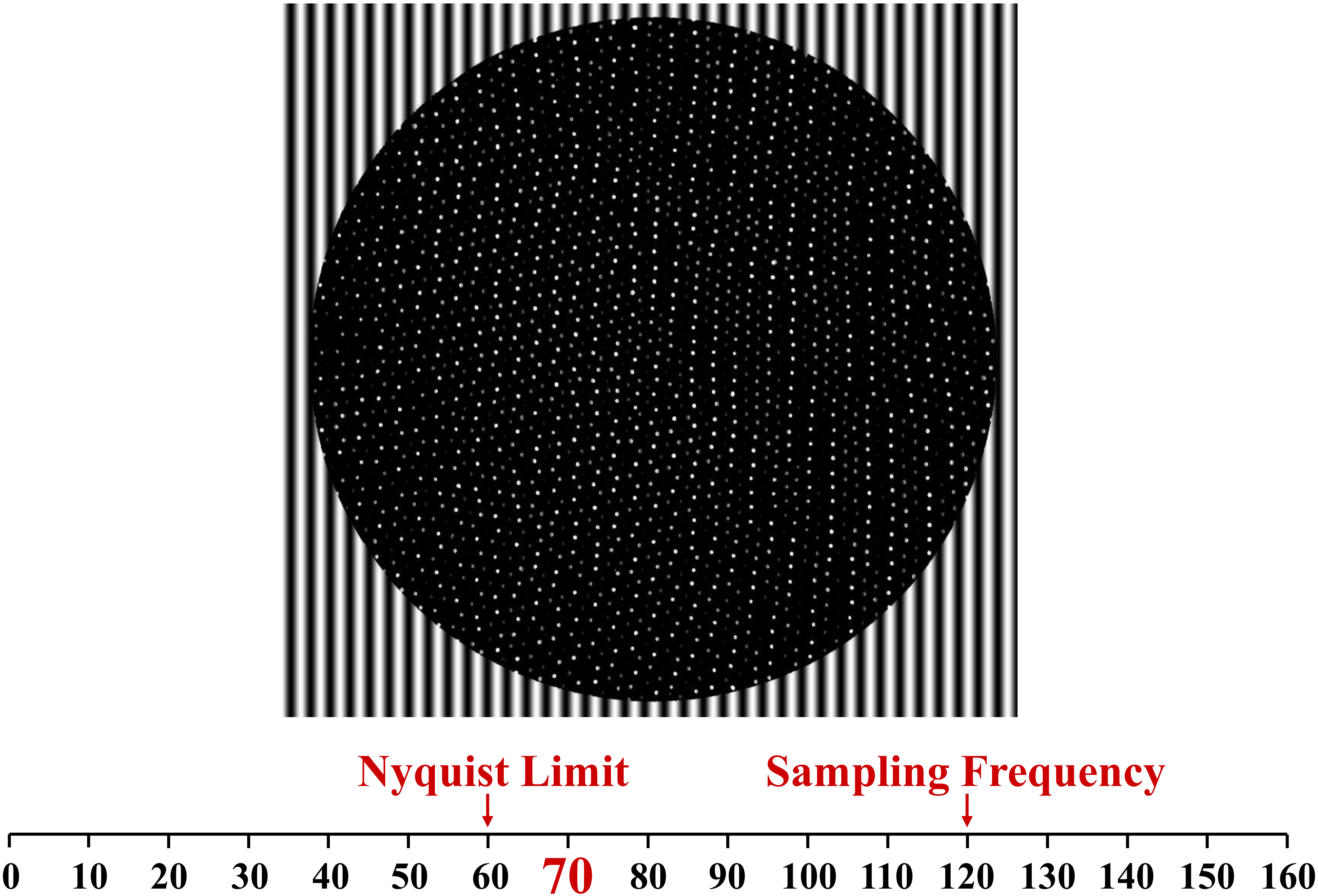
Nyquist Limit
Sampling Frequency
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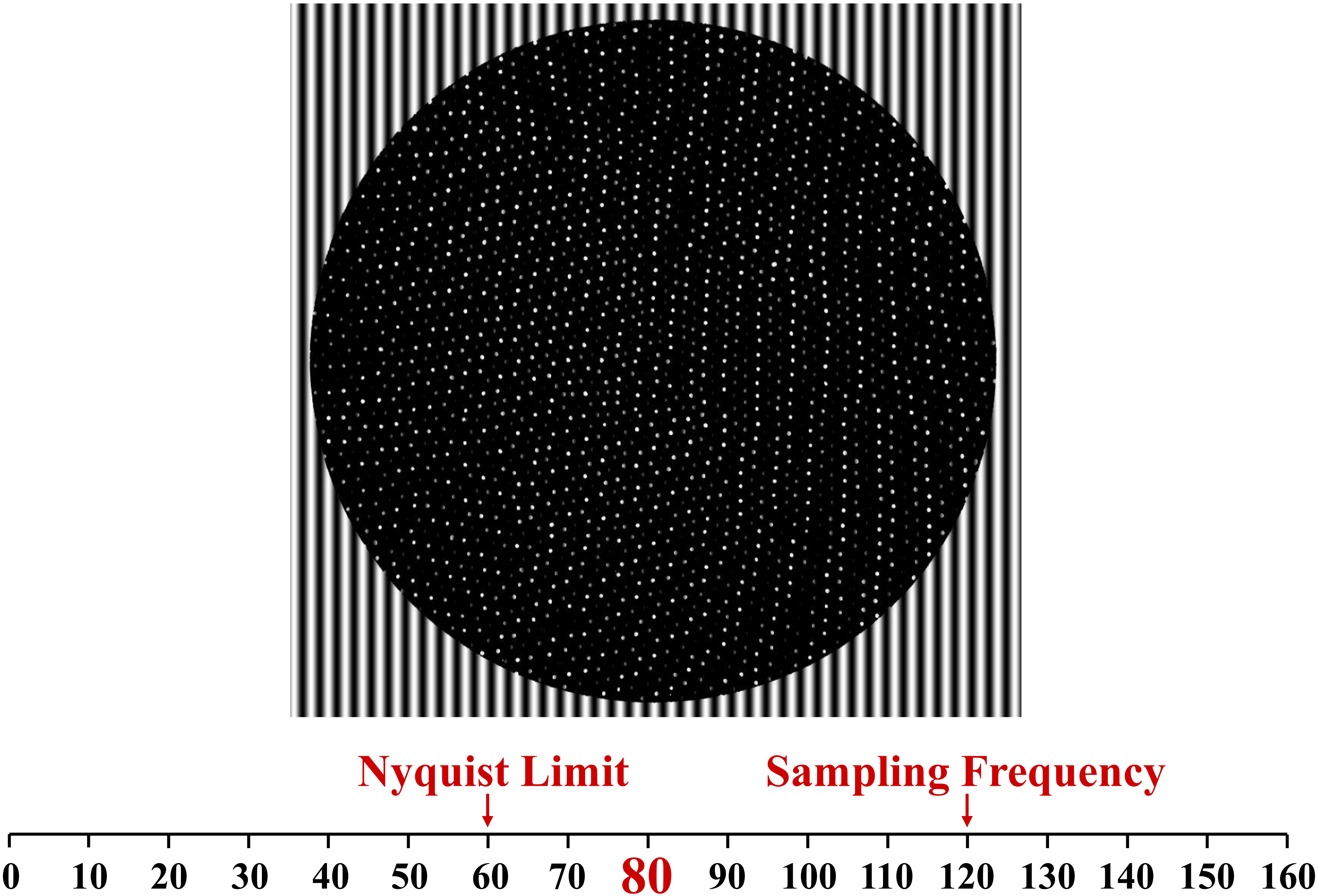
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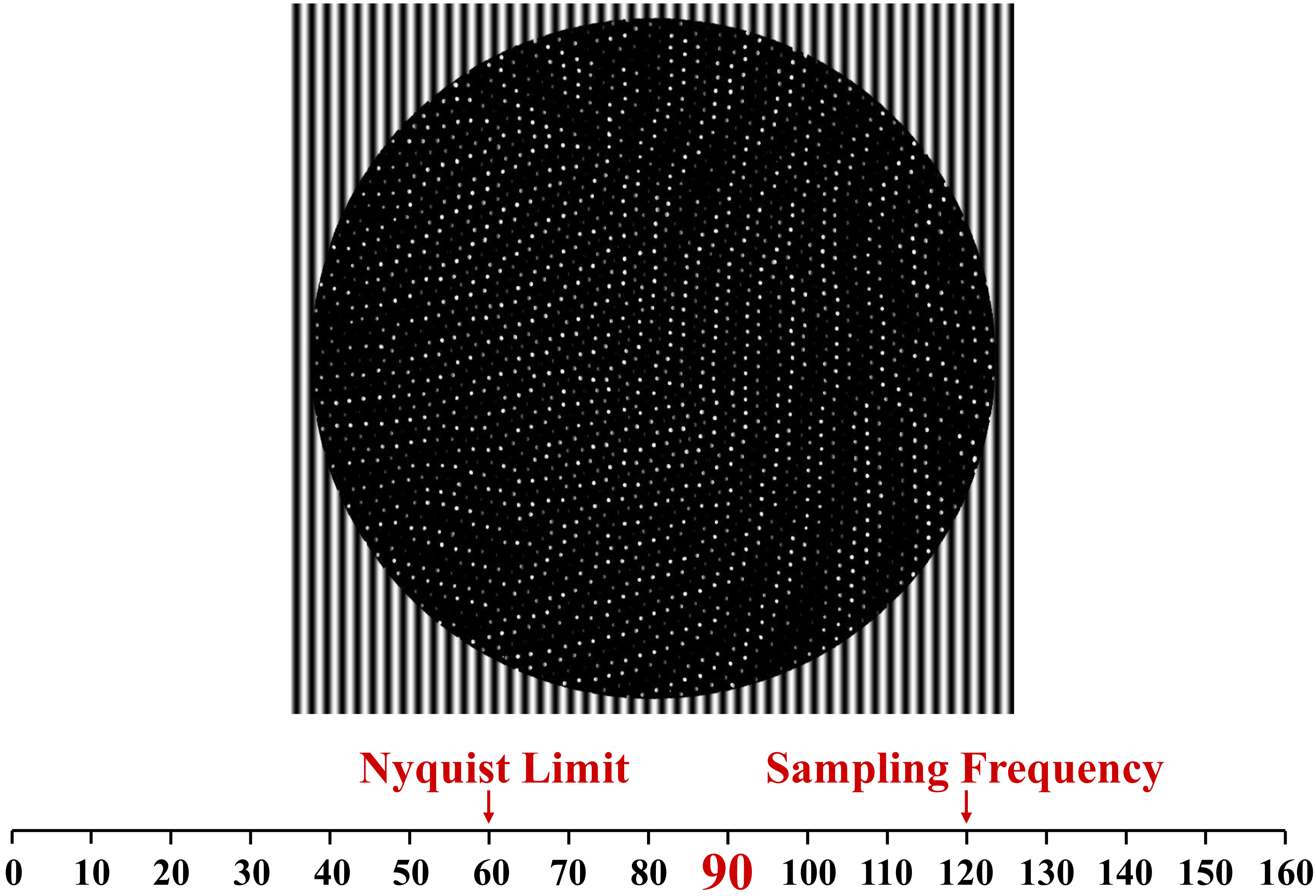
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Sampling Frequency
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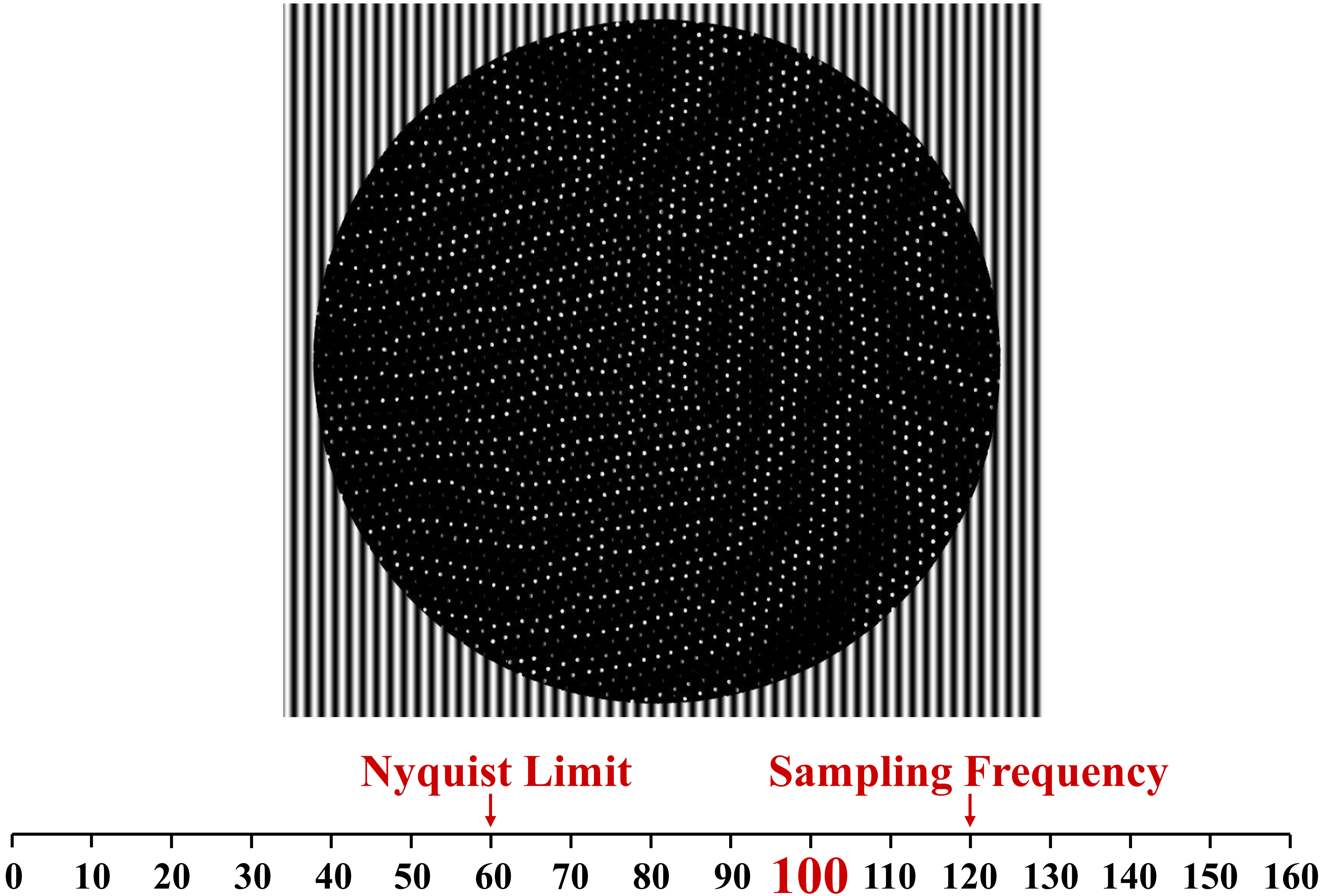
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Sampling Frequency
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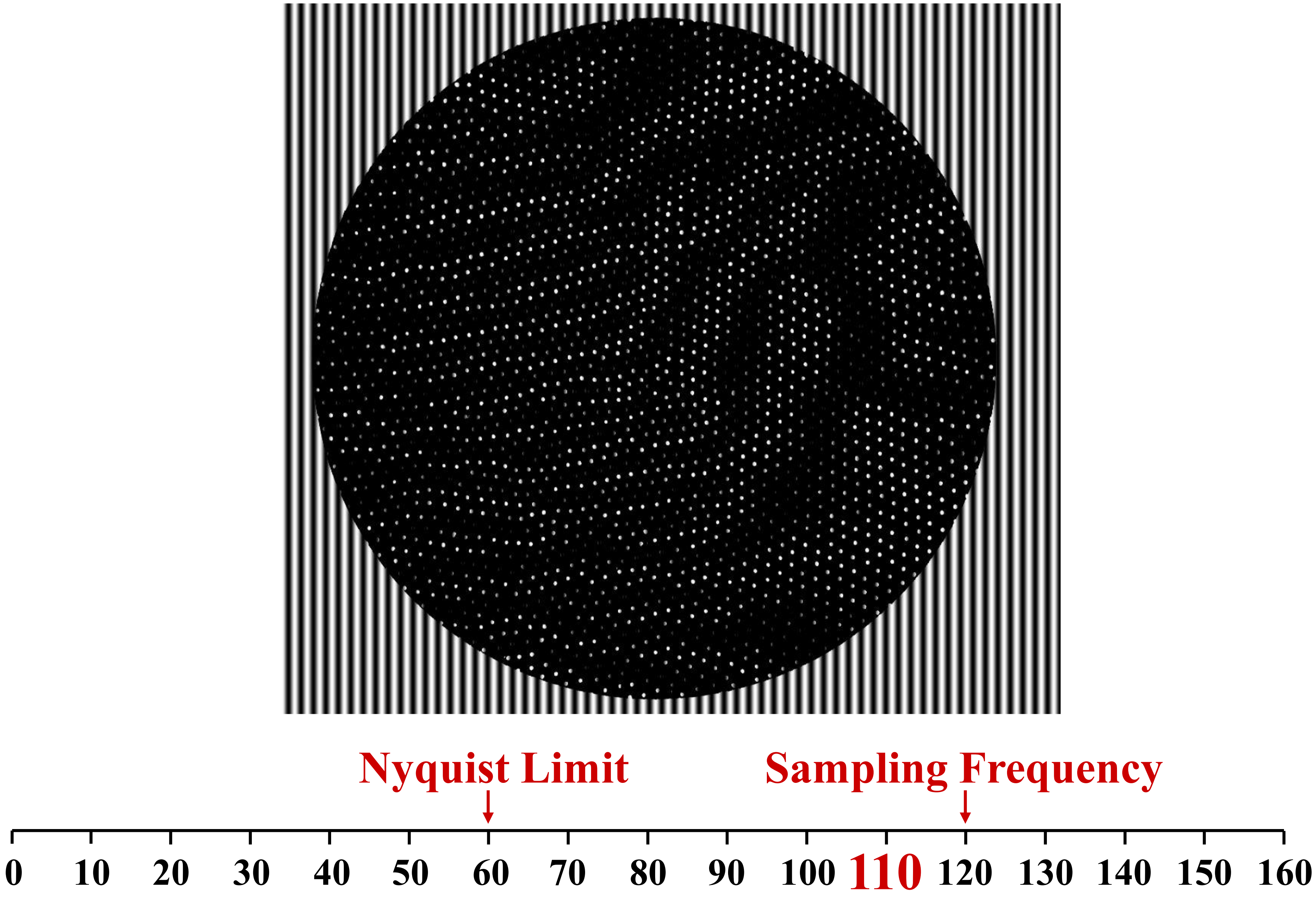
Nyquist Limit
Sampling Frequency
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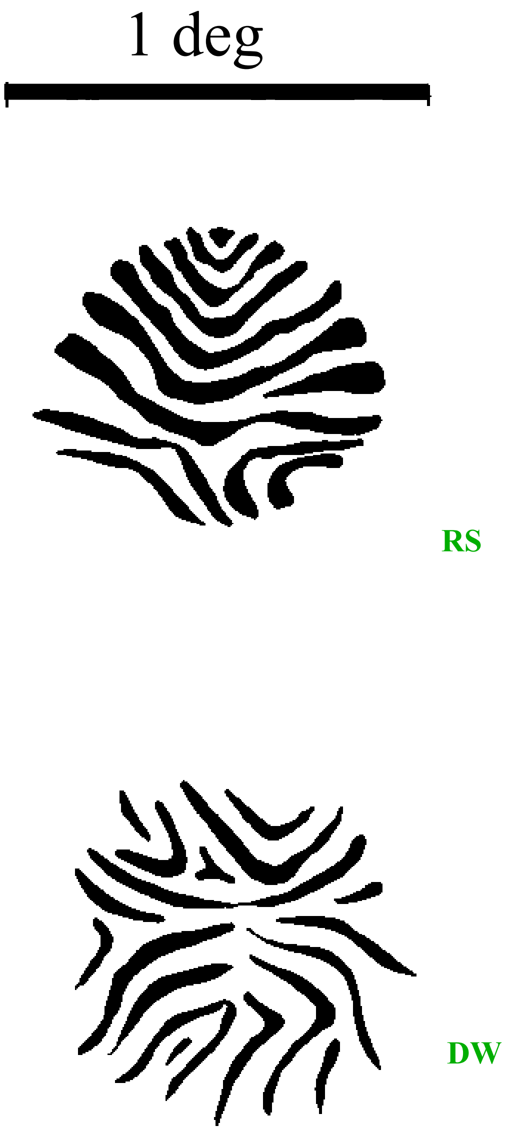
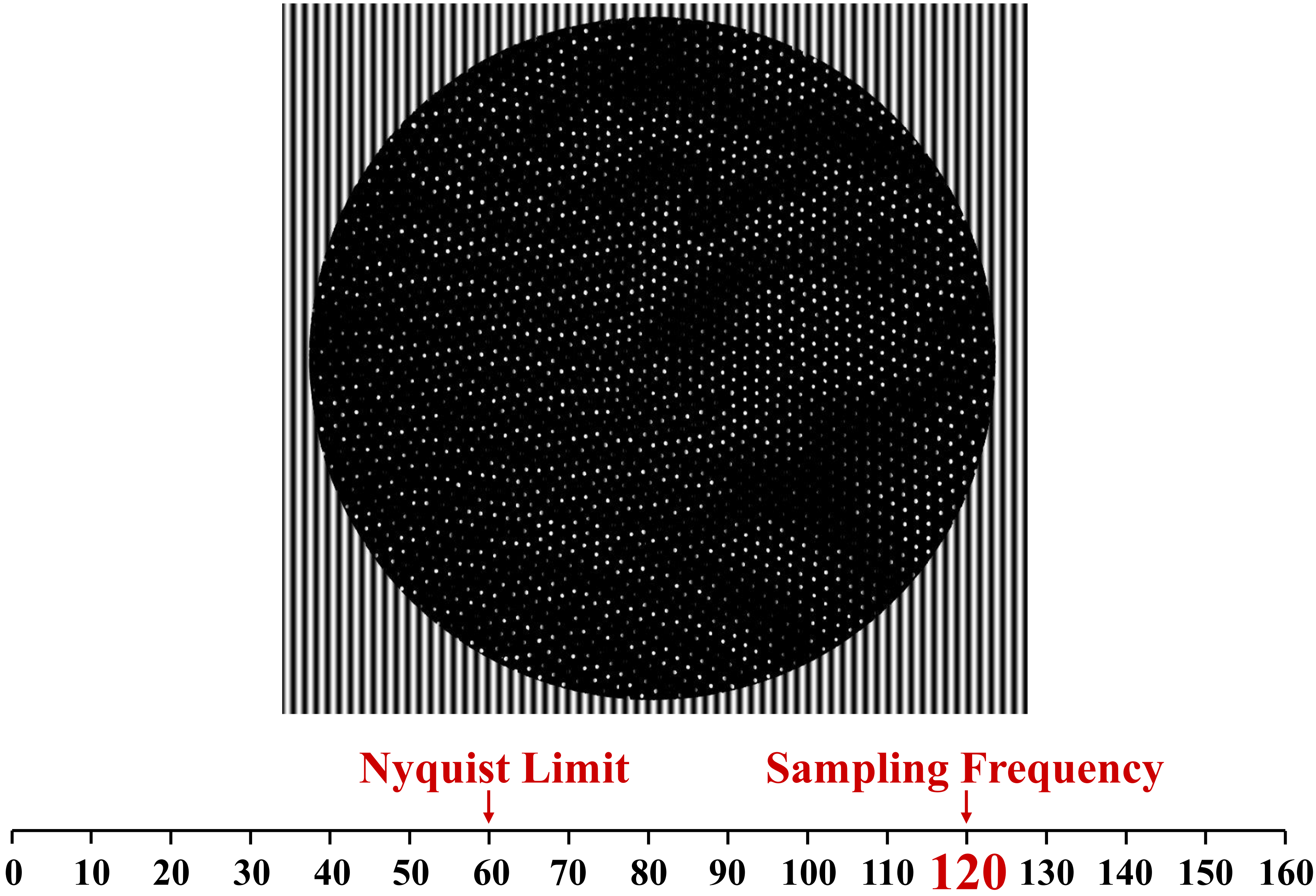
Appearance of 110 c/deg Interference Fringes





Nyquist Limit
Sampling Frequency
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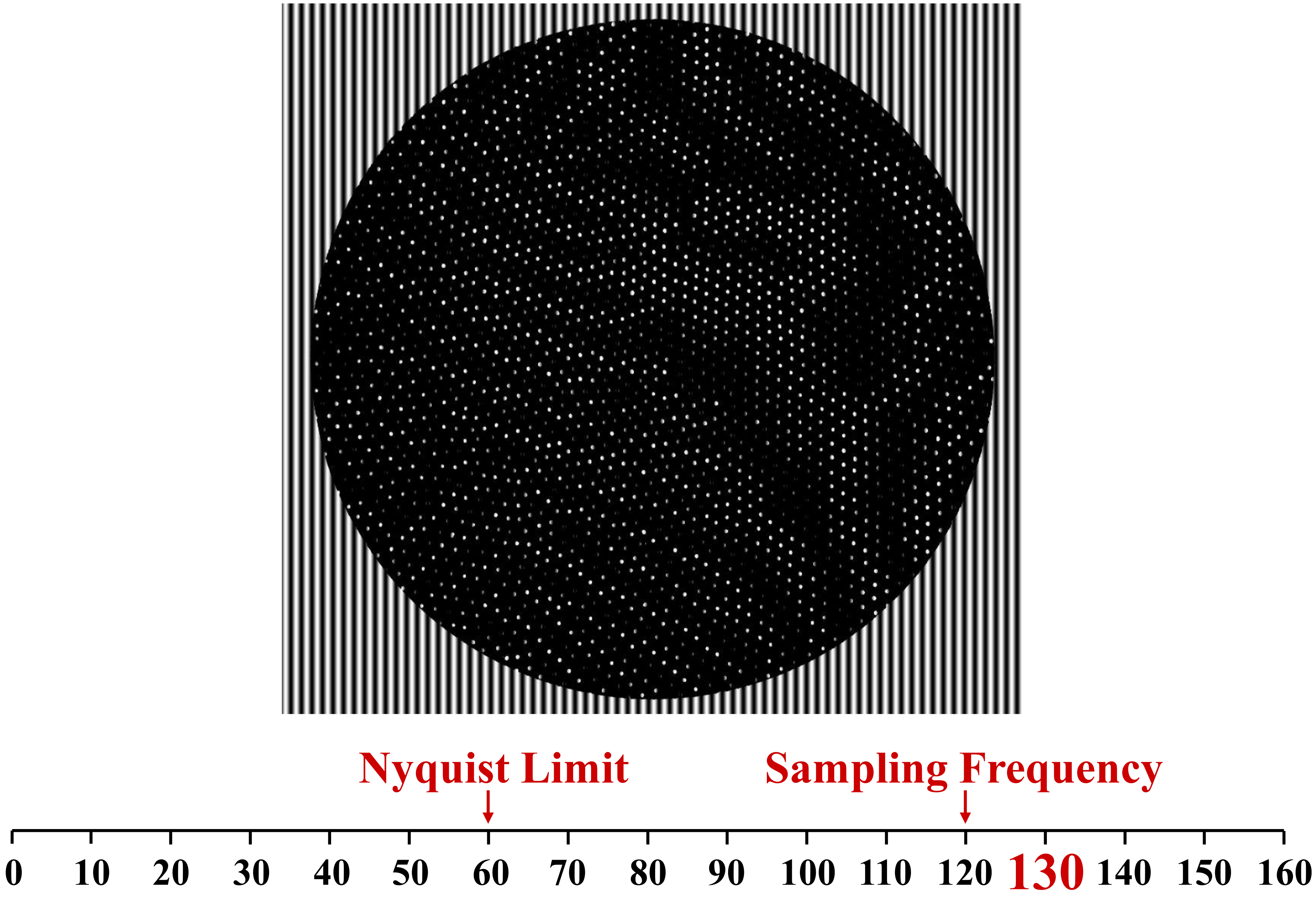
Nyquist Limit
Sampling Frequency
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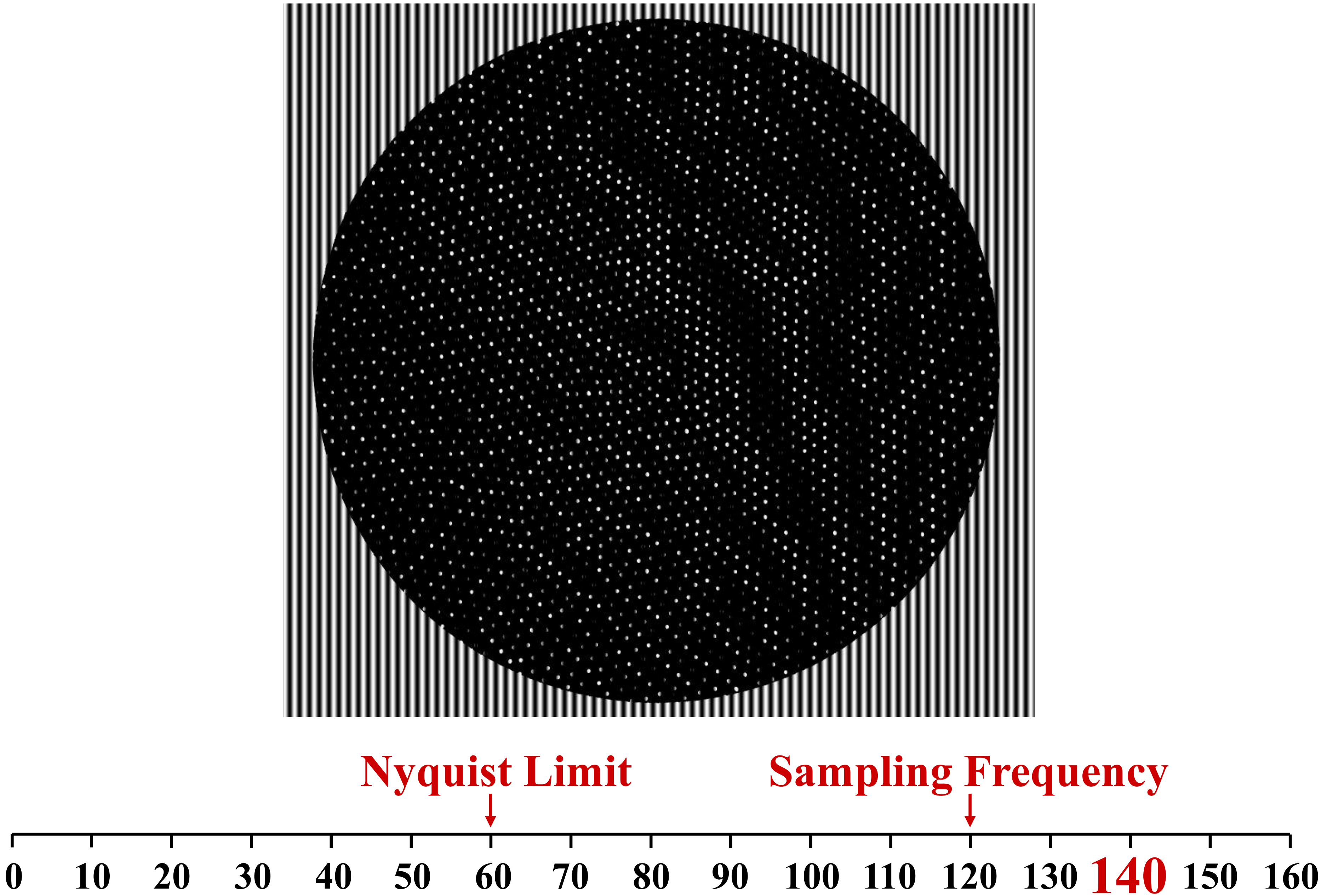
Nyquist Limit
Sampling Frequency
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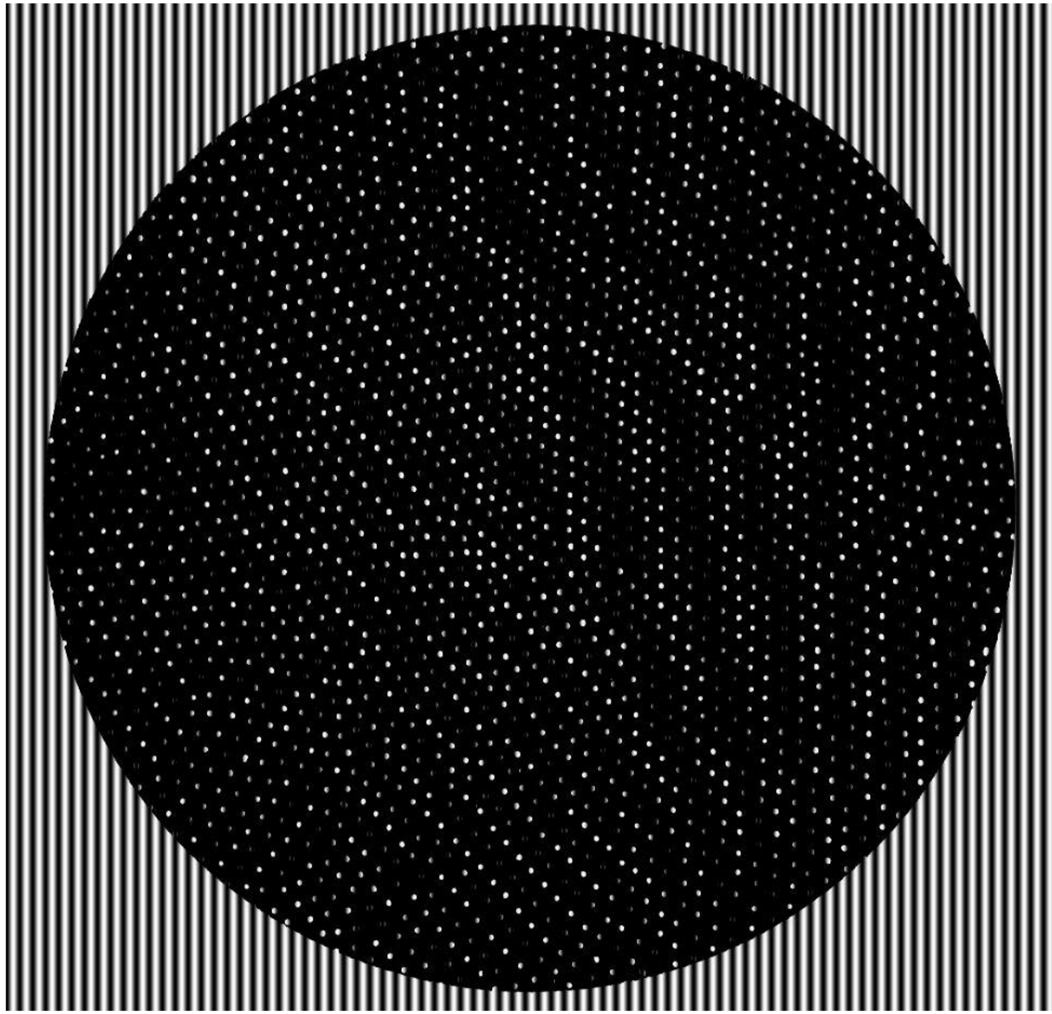
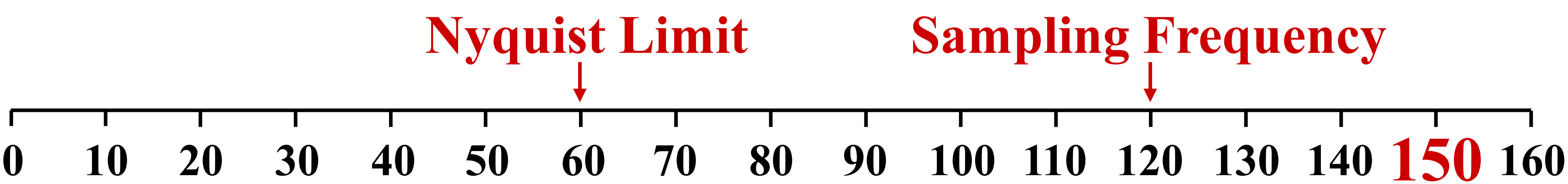
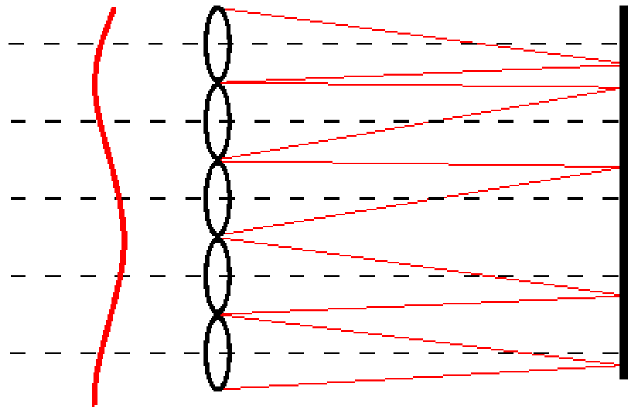


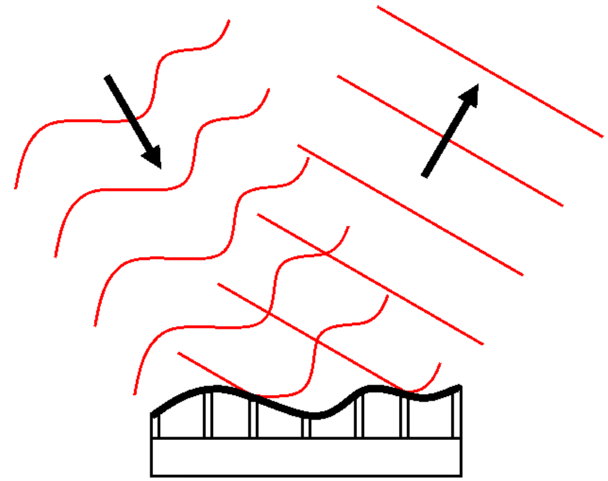
Frequency cut-off
for 8 mm pupil
is 250 c/deg!

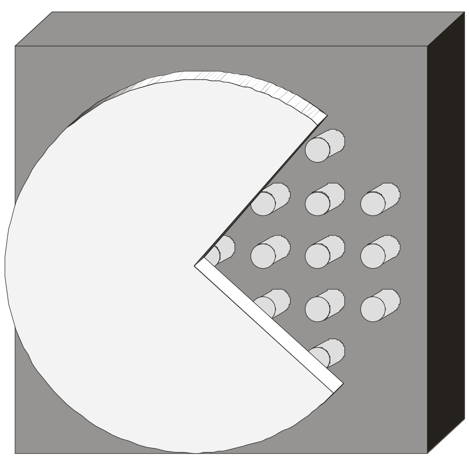
Slide sequence
courtesy of
Yasuki Yamauchi,
Jason Porter
and
David Williams

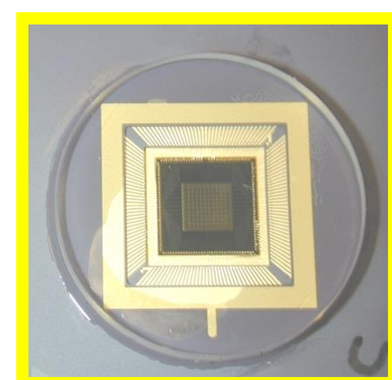


Compensation of Ocular Aberrations

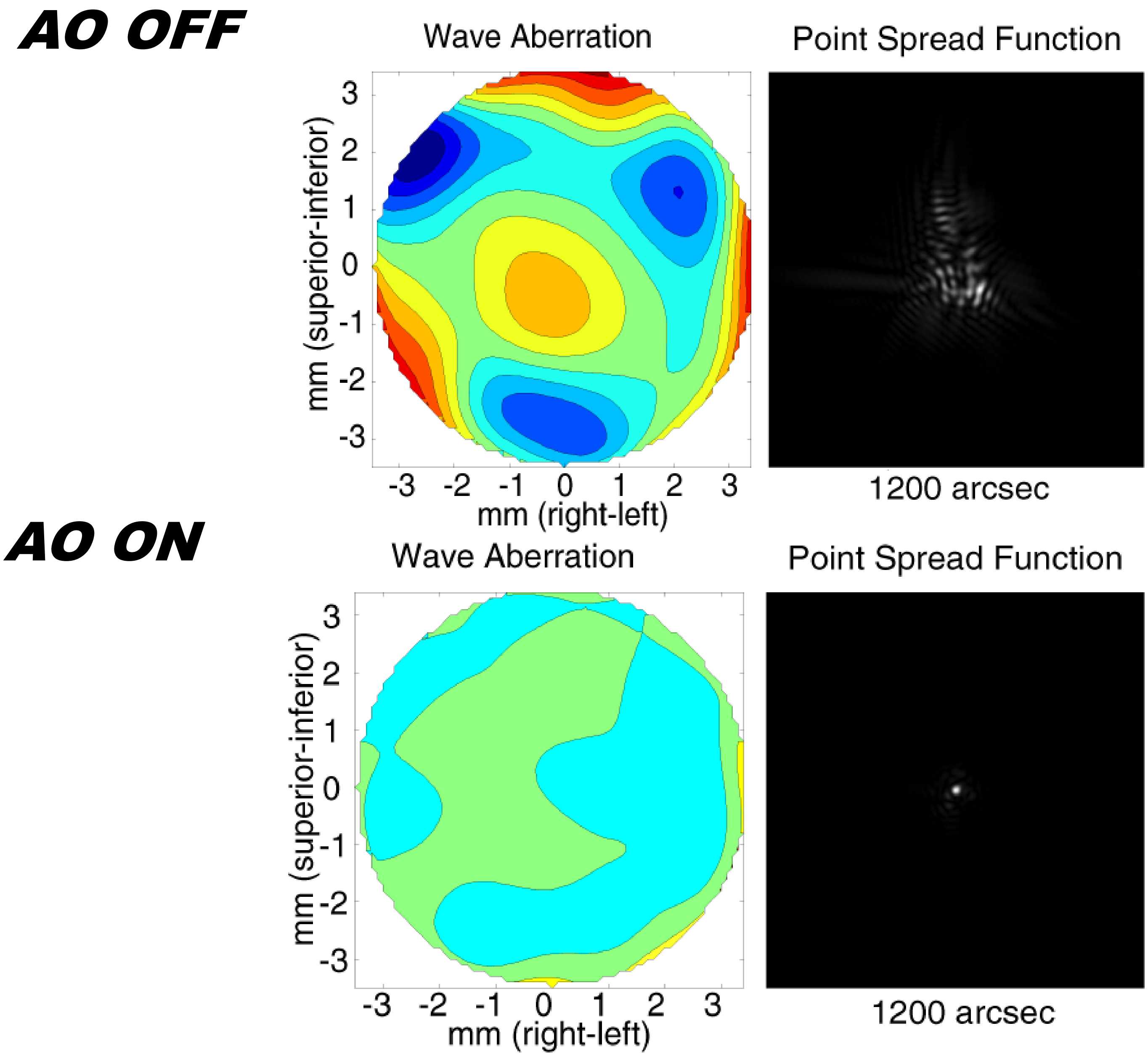




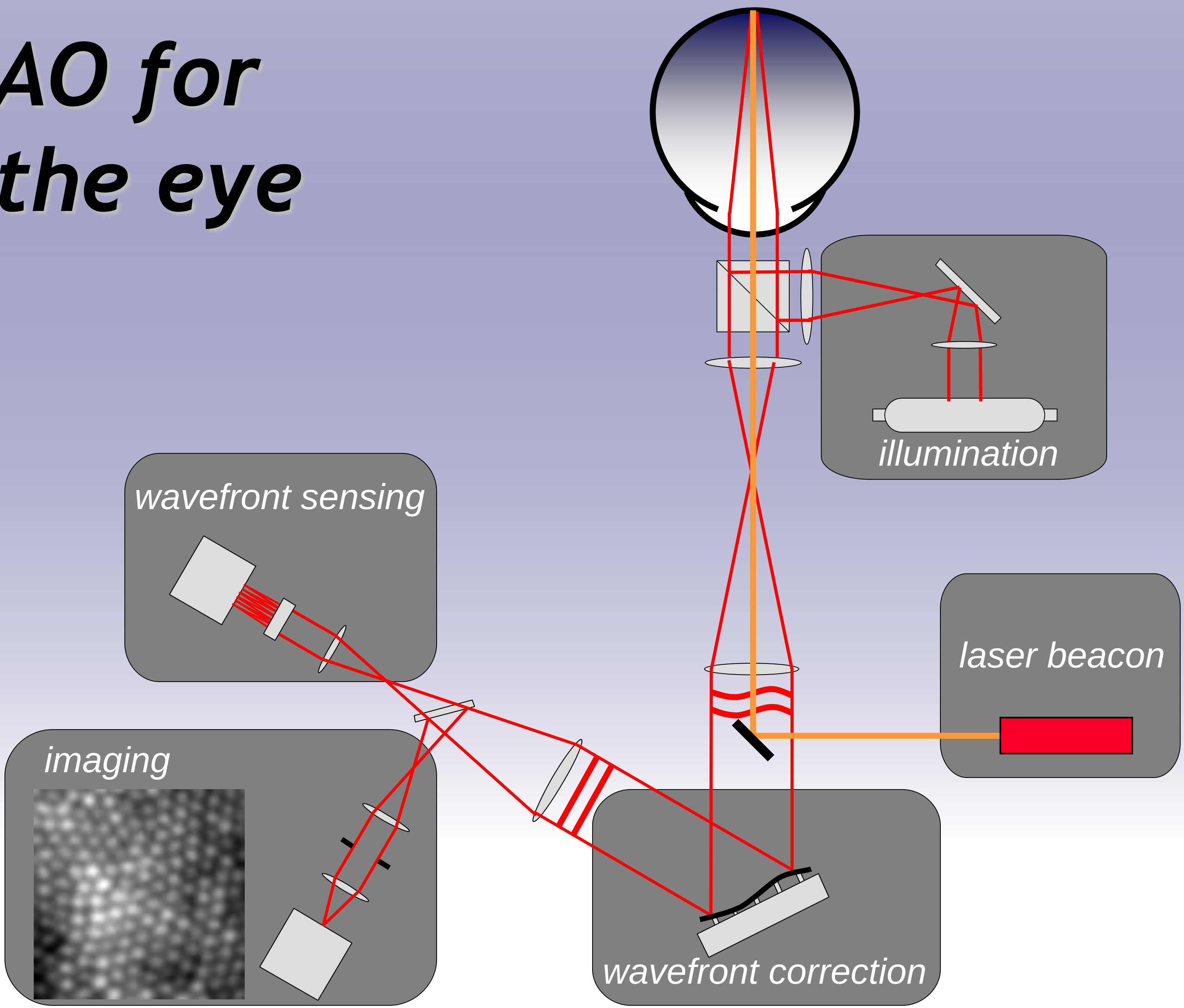




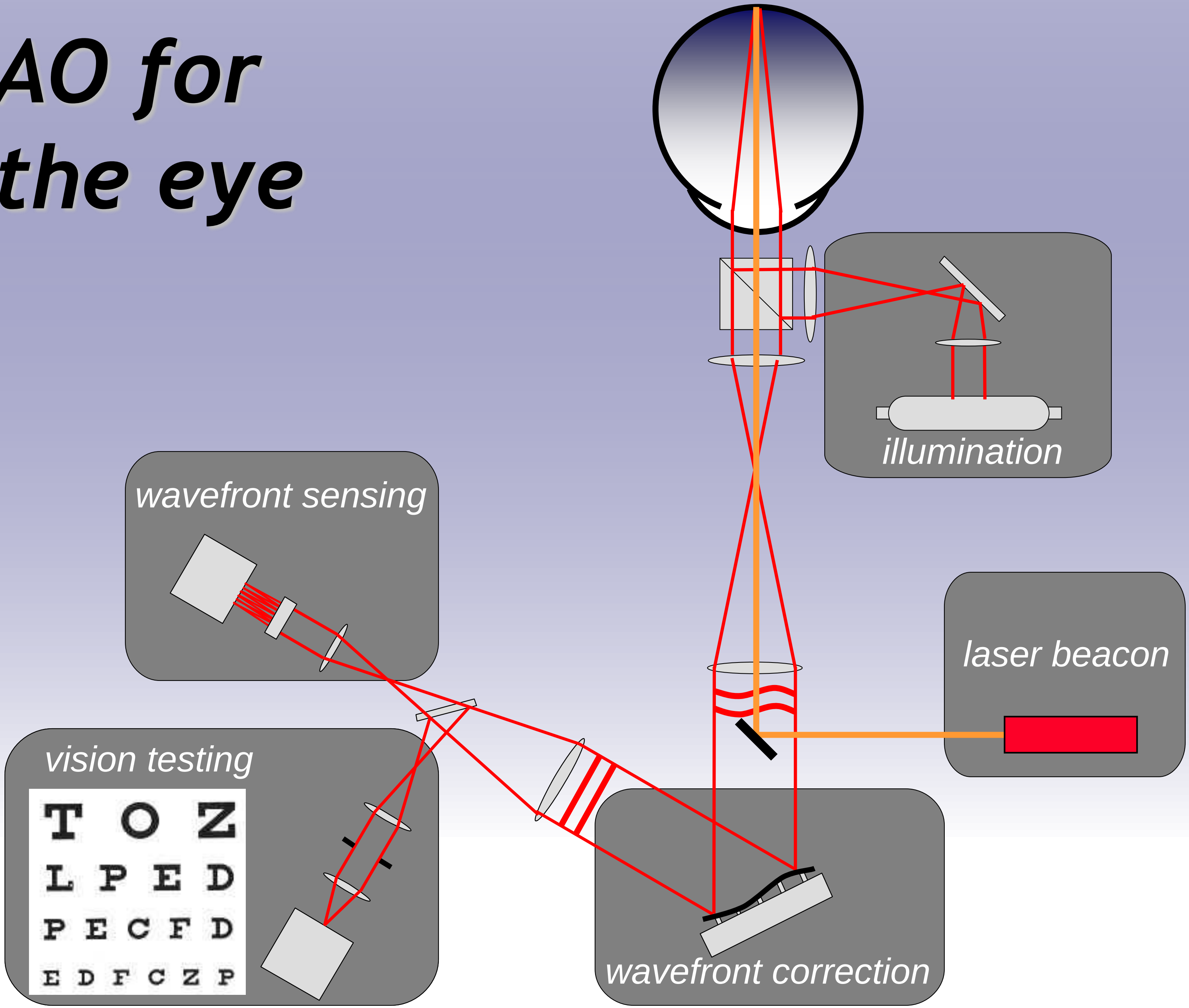
Adaptive Optics Flattens the Wave Aberration



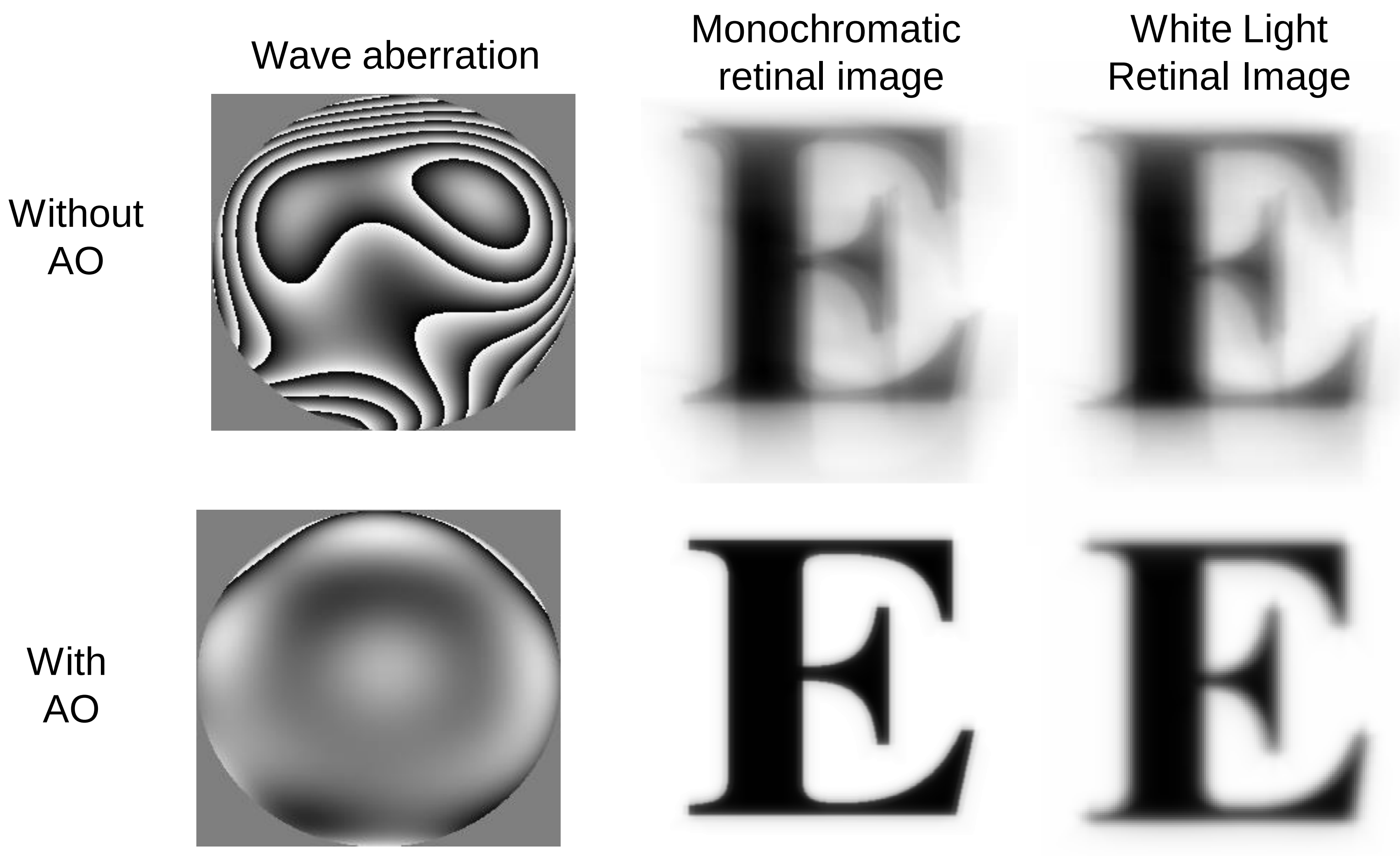
AO for the eye



AO for the eye

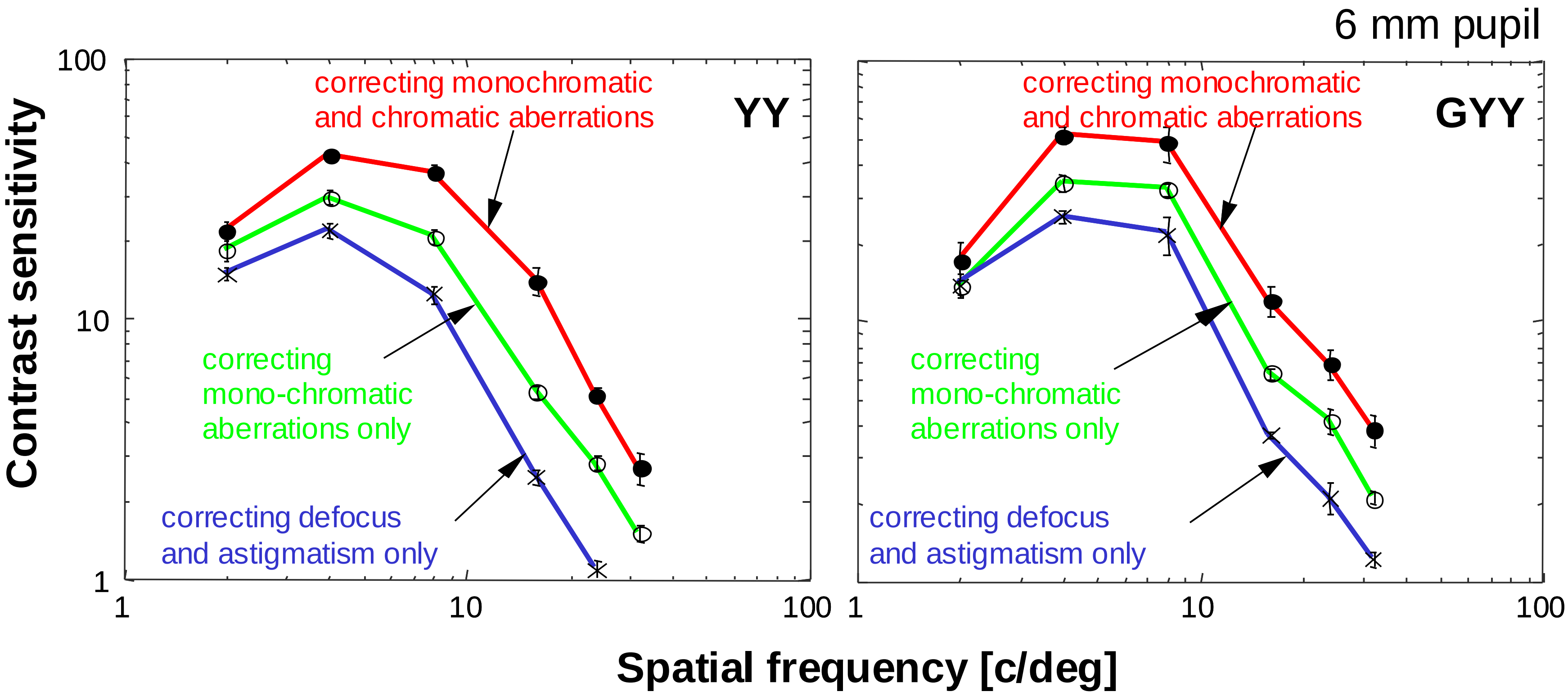


AO Improvement in Vision



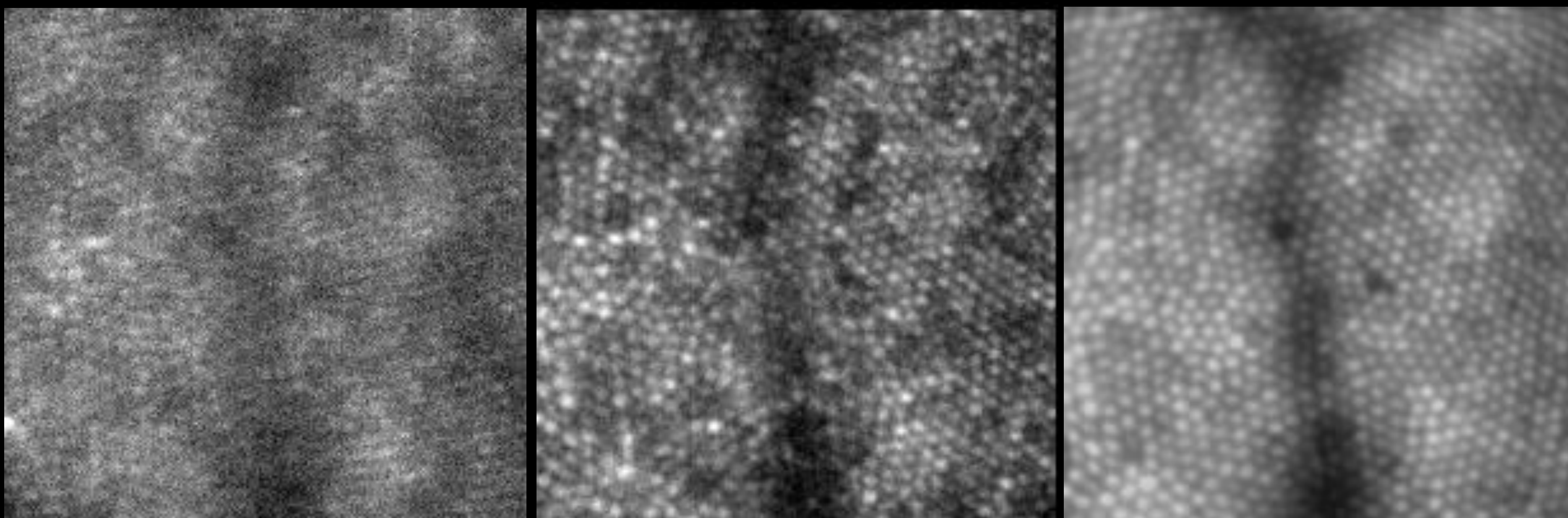
6.8 mm pupil

AO Improvement in Vision



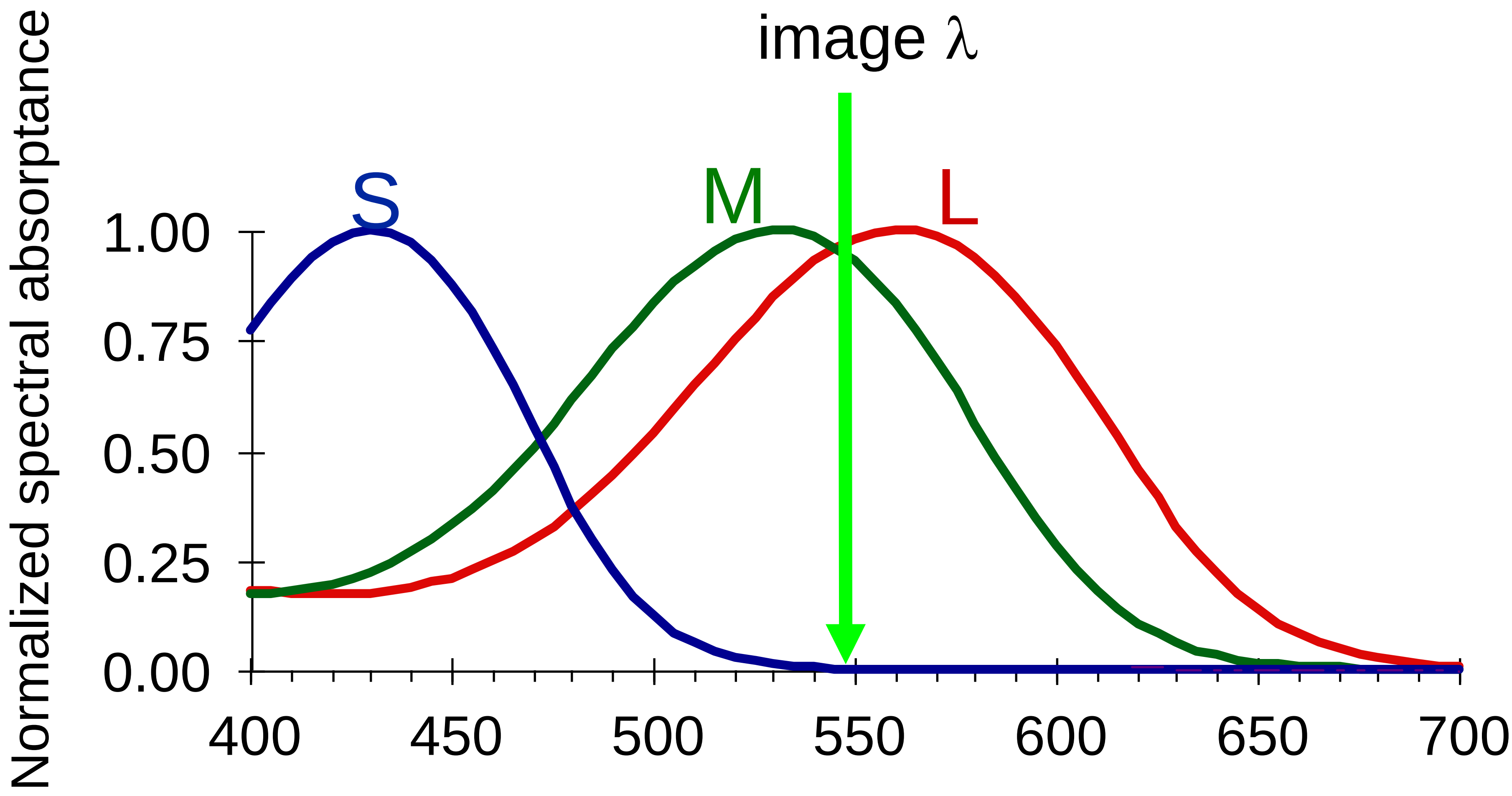
Adaptive Optics Makes it Possible to See Microscopic Features in the Living Eye

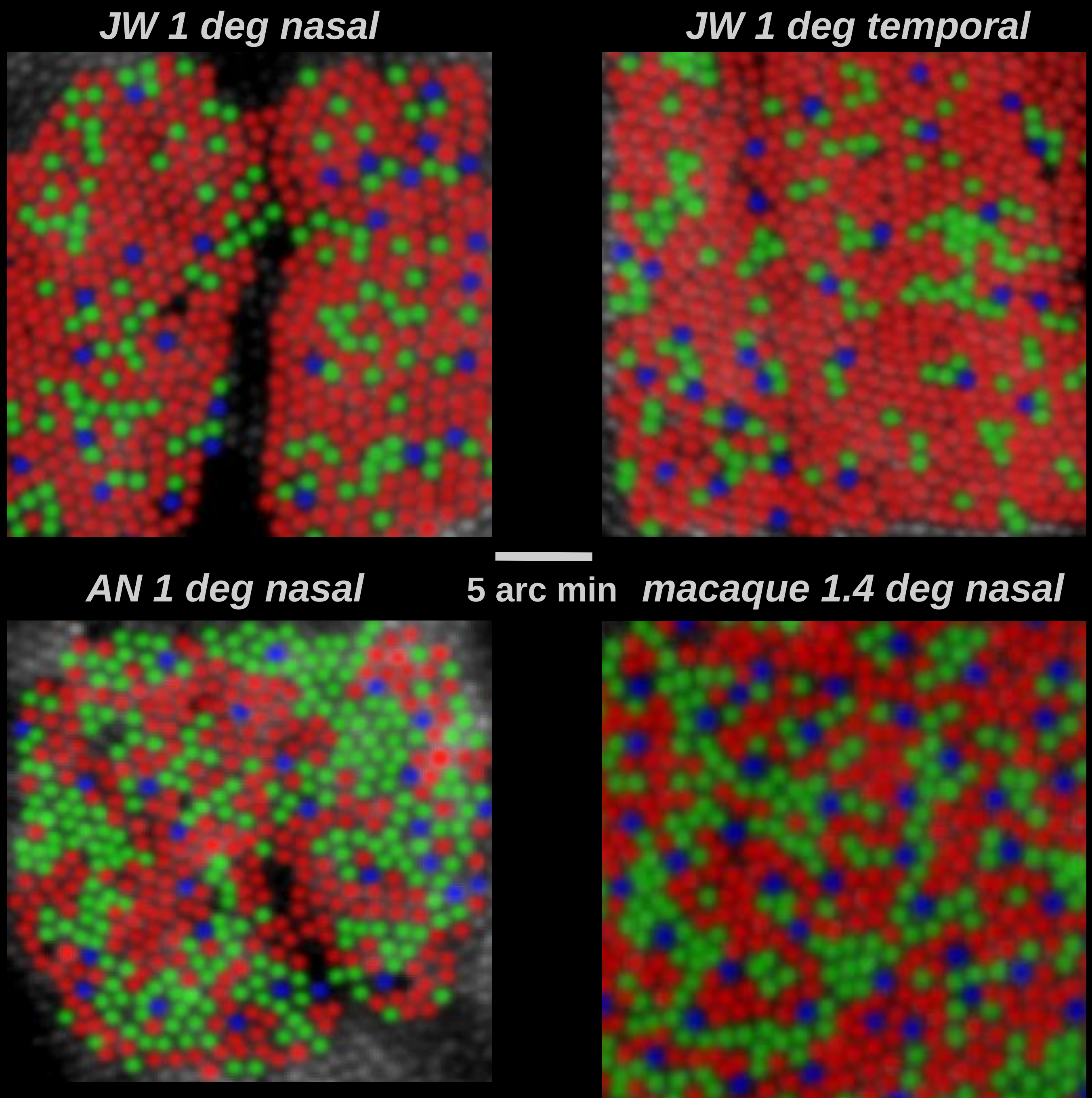
No AO — *With AO* — *multiple AO frames*



JW right eye
1 deg eccentricity
image wavelength = 550 nm

The Trichromatic Cone Mosaic




JW 1 deg nasal
JW 1 deg temporal
AN 1 deg nasal
5 arc min
macaque 1.4 deg nasal