Optics and Image Quality in the Human Eye

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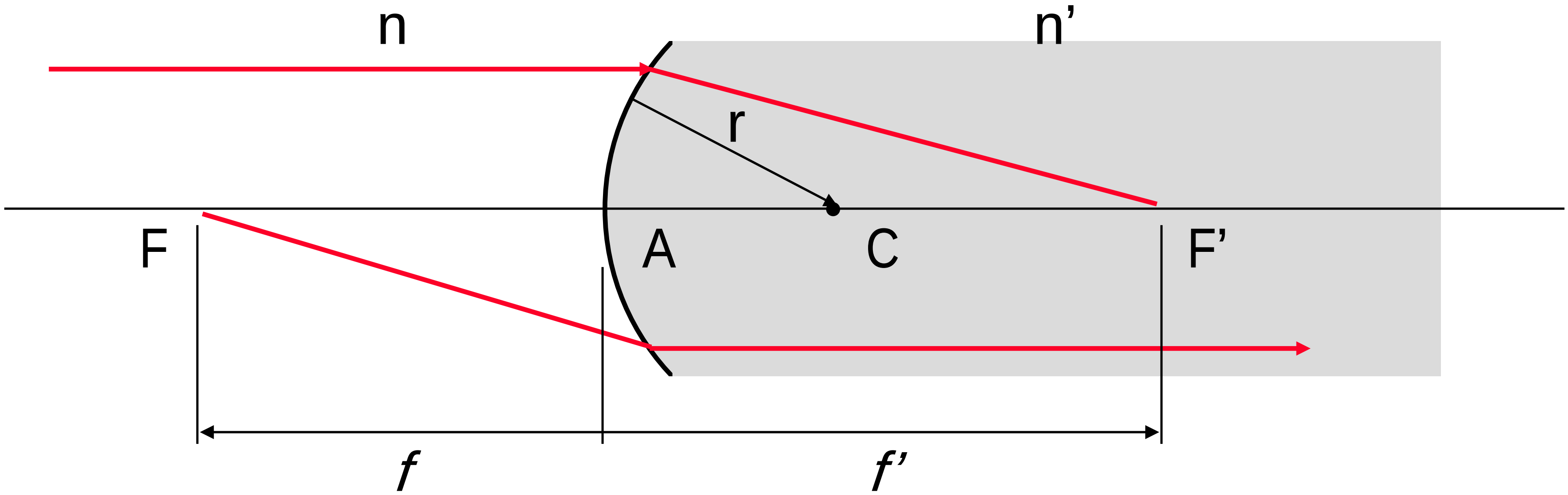
all slides (in color) are available on the web at

- **vision.berkeley.edu/roordalab/**
- *link to courses/resources on left menubar*

Part 1 The Optics of the Eye

(NOTE: sections 1.1 and 1.2 will not be covered in the lecture. They are included for your reference)

Refraction and Image Formation

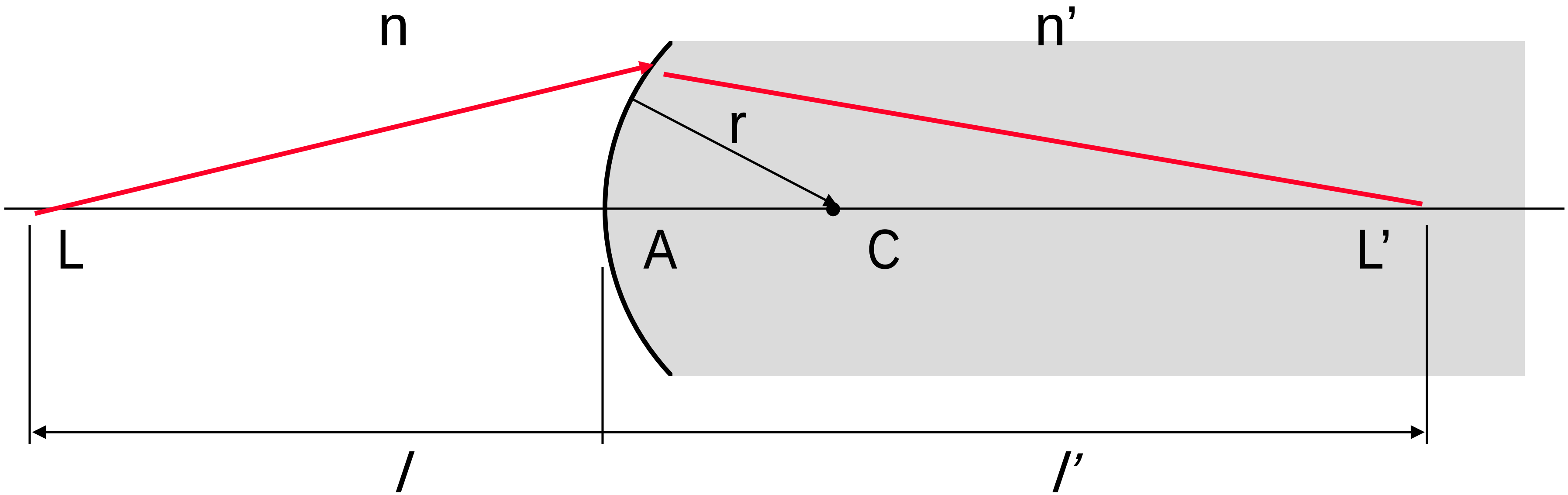


$$F = \frac{-n}{f}$$

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

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

Refraction and Image Formation



define:

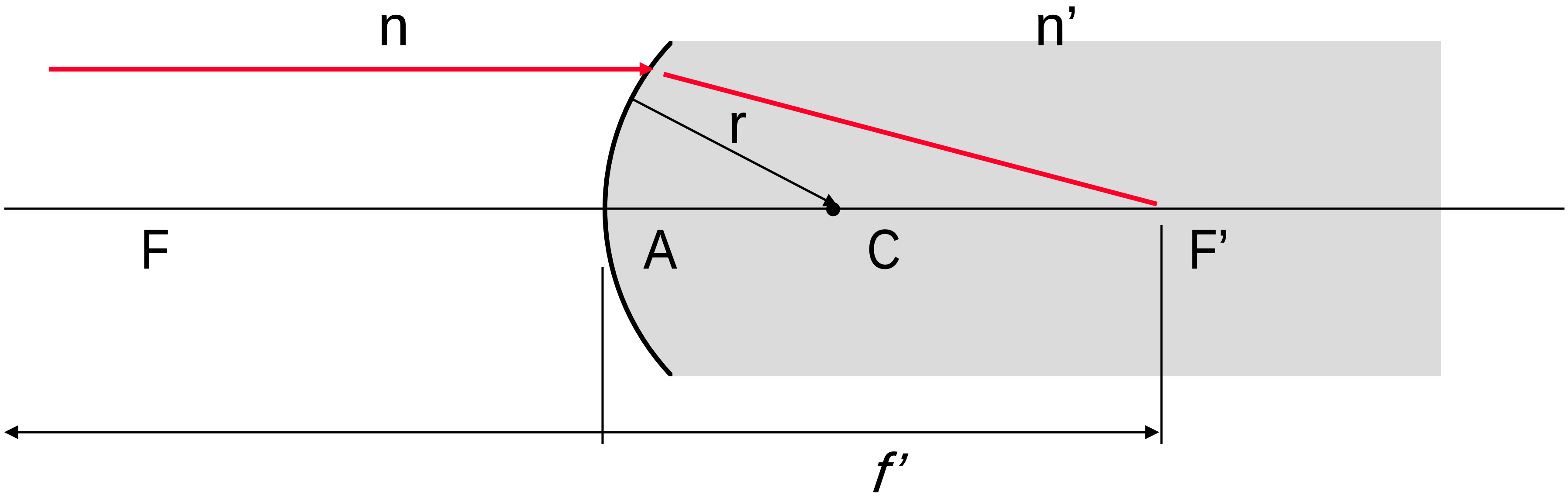
$$\frac{n'}{l'} = \frac{n}{l} + \frac{n'-n}{r}$$

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

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

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

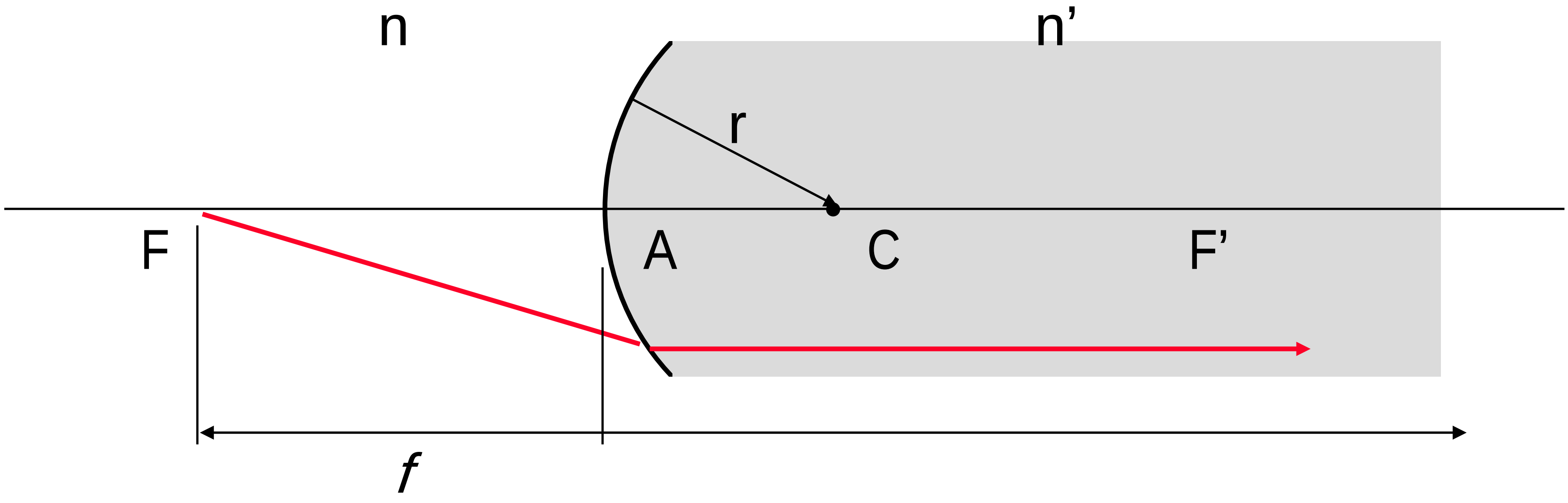
Refraction and Image Formation



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

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

Refraction and Image Formation



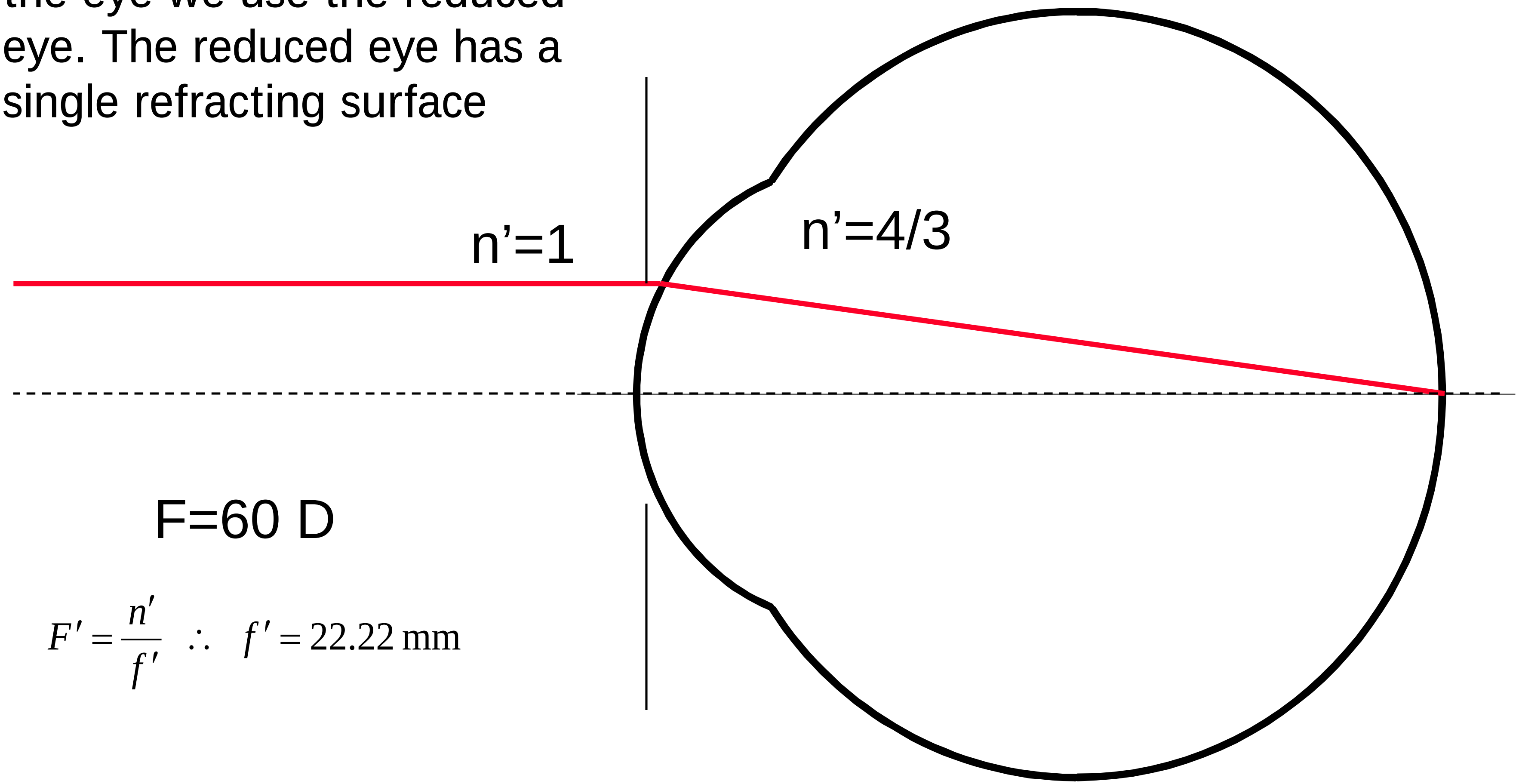
special case 2: image at infinity => L' = 0 & L=-F

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

$$L' = L + F'$$

1.2 The reduced eye

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



F=60 D

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

1.2 The reduced eye

$$L' = L + F$$

By definition, 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.

1.3 Components of the human optical system

Cornea (first surface)

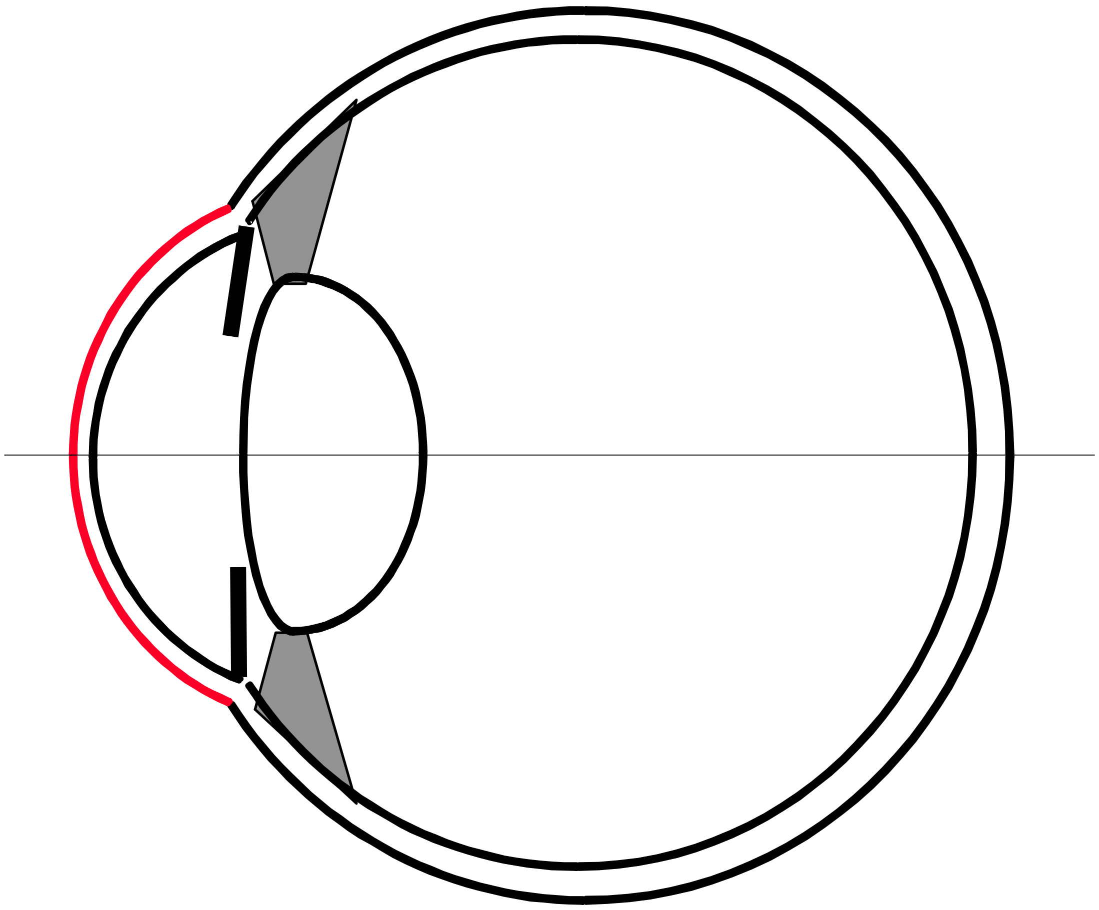
transition from air (n =1)
to front surface of
cornea (n = 1.376)

radius of curvature = 7.7 mm

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

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

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



1.3 Components of the human optical system

Cornea (second surface)

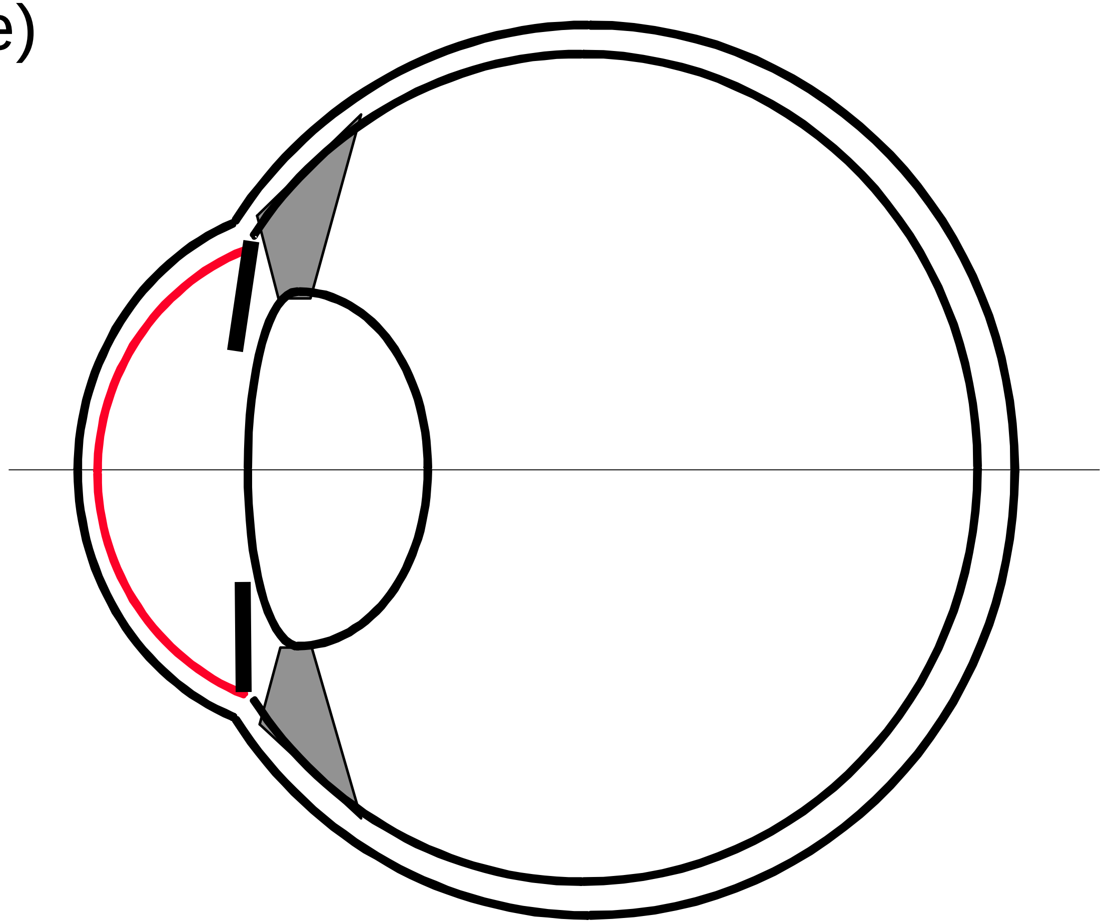
Transition from back surface of cornea (n = 1.376) to the aqueous humor (n = 1.336) radius of curvature = 6.8 mm

power:

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

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

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



total power of cornea ~ +43 D

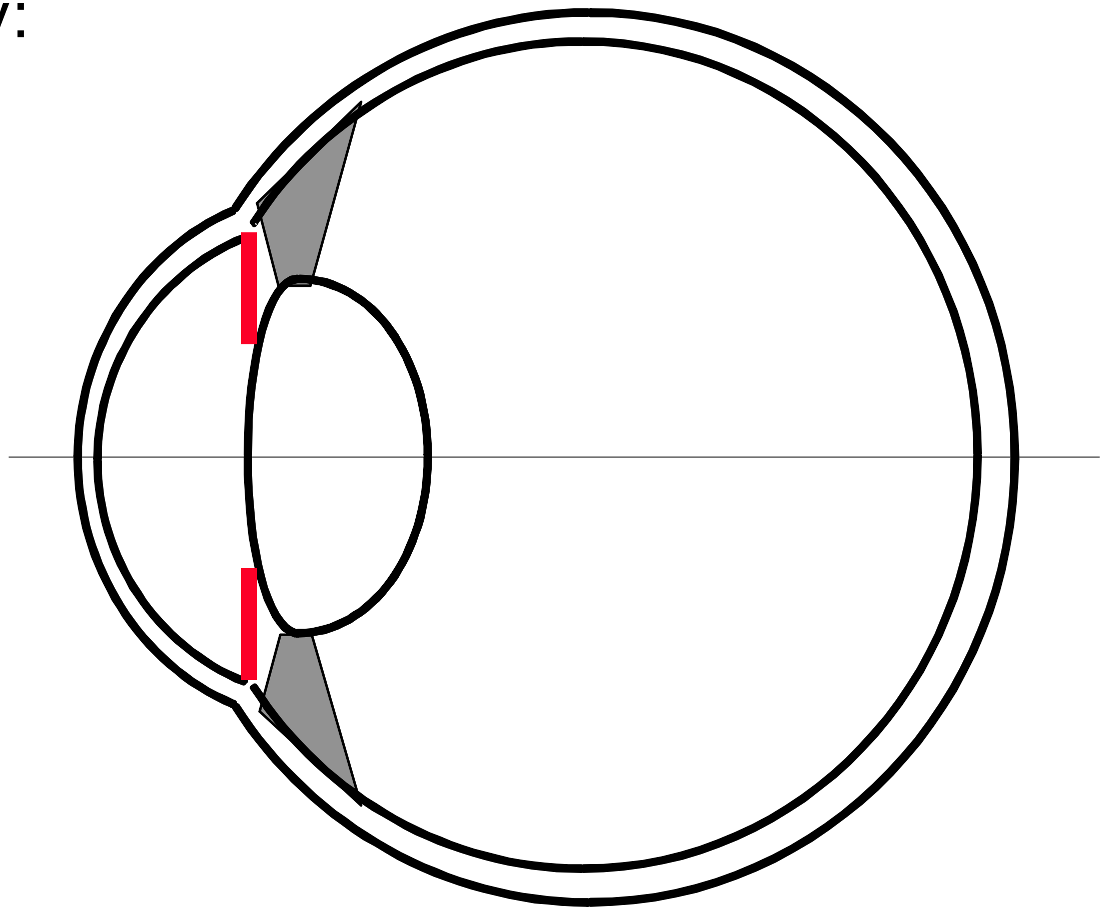
1.3 Components of the human optical system

The Pupil is affected by:

light conditions
attention
emotion
age

Function:

govern image quality
depth of focus
control light level?



1.3 Components of the human optical system

Factors affecting pupil size

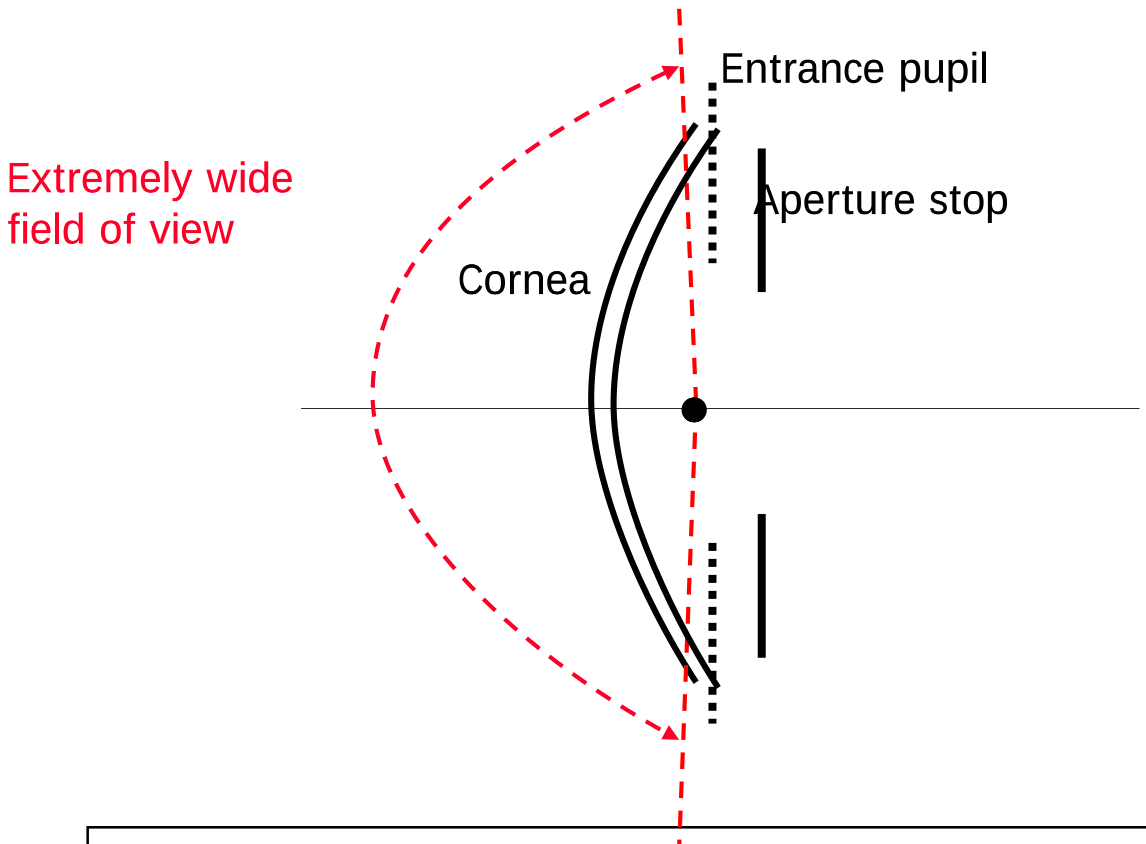
- Stimulus Variables
  - light level
  - spectral composition
  - spatial configurations
    - field size
    - spatial structure of field
  - monocular/binocular view
  - accommodative state
  - non-visual stimuli
    - pain
    - noise

- 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

1.3 Components of the human optical system

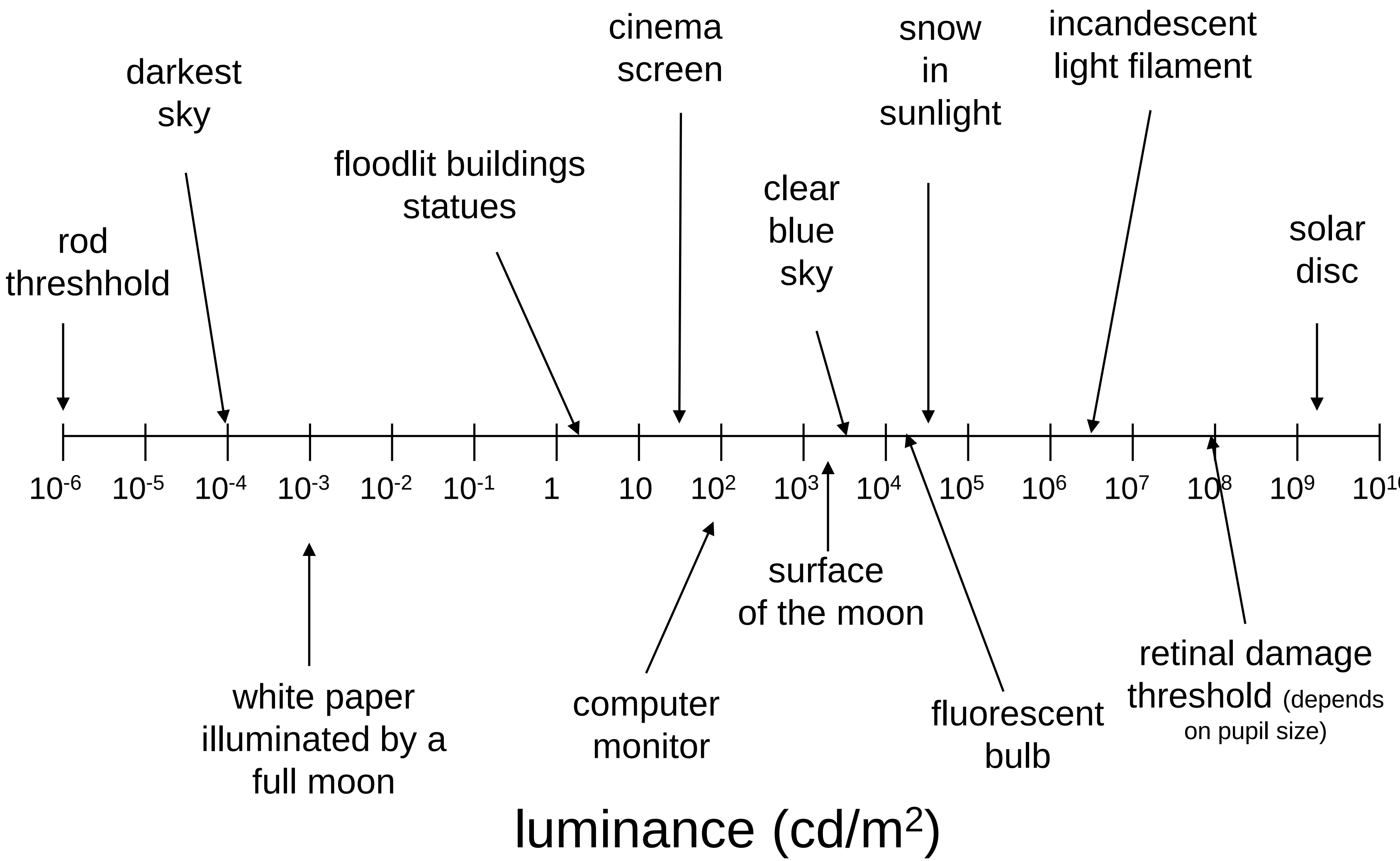
The pupil is perfectly located to maximize the field of view of the eye



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.

1.3 Components of the human optical system

The range of luminances in the environment is enormous!



Rodieck, B. *The First Steps in Seeing*

1.3 Components of the human optical system

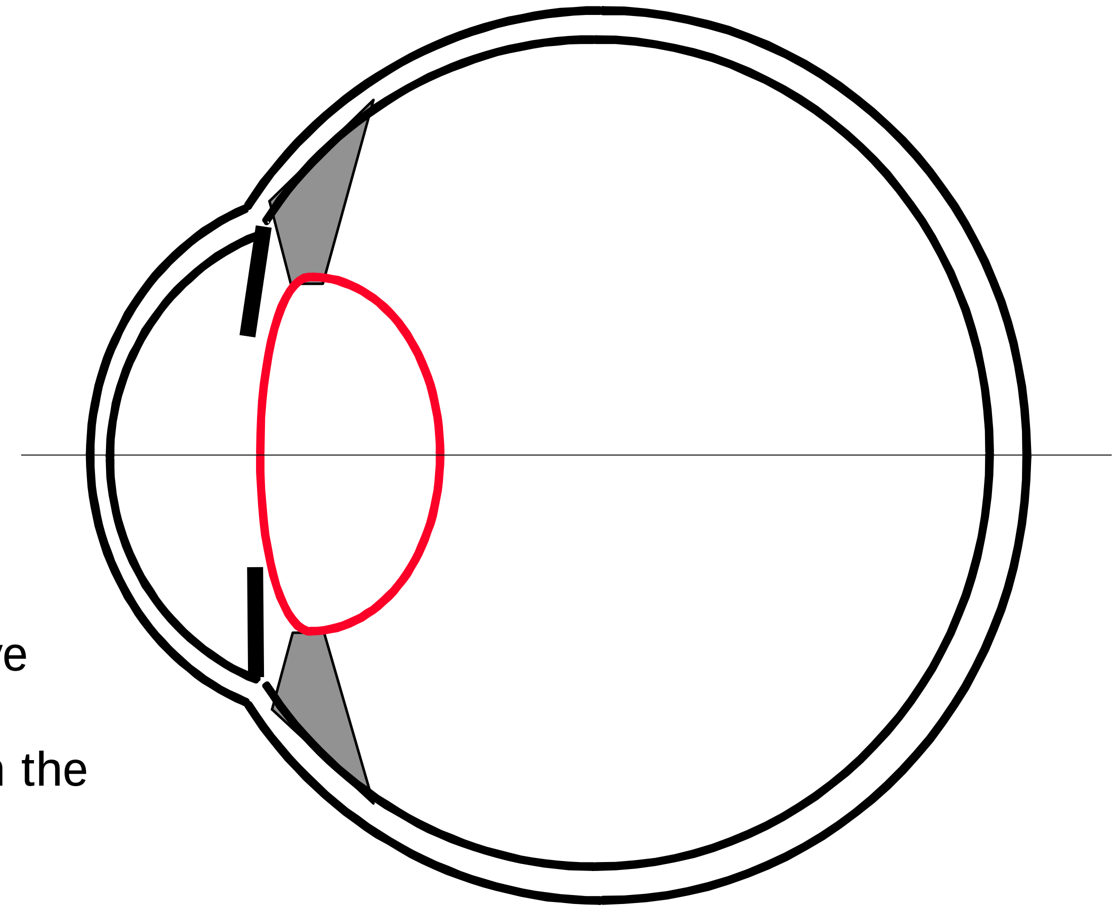
Crystalline Lens

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

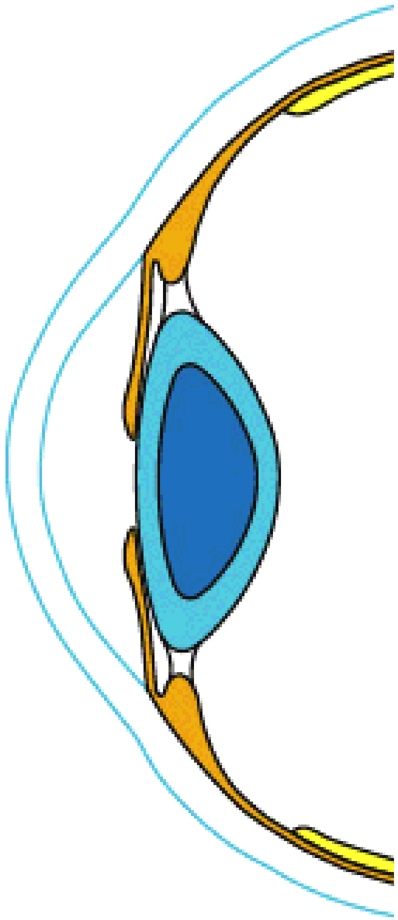
Little refraction takes place at the surface but instead the light curves as it passes through.

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



1.3 Components of the human optical system

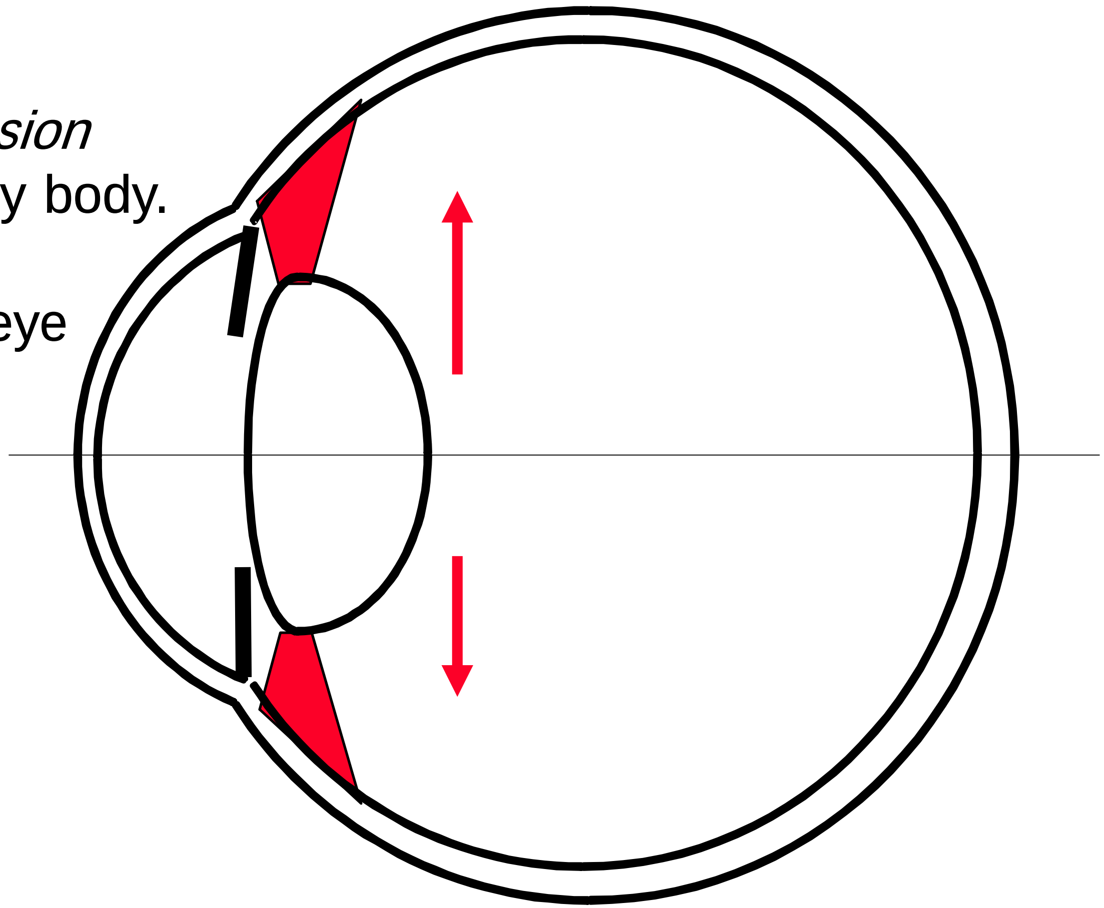


courtesy of Adrian Glasser, PhD

1.3 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.



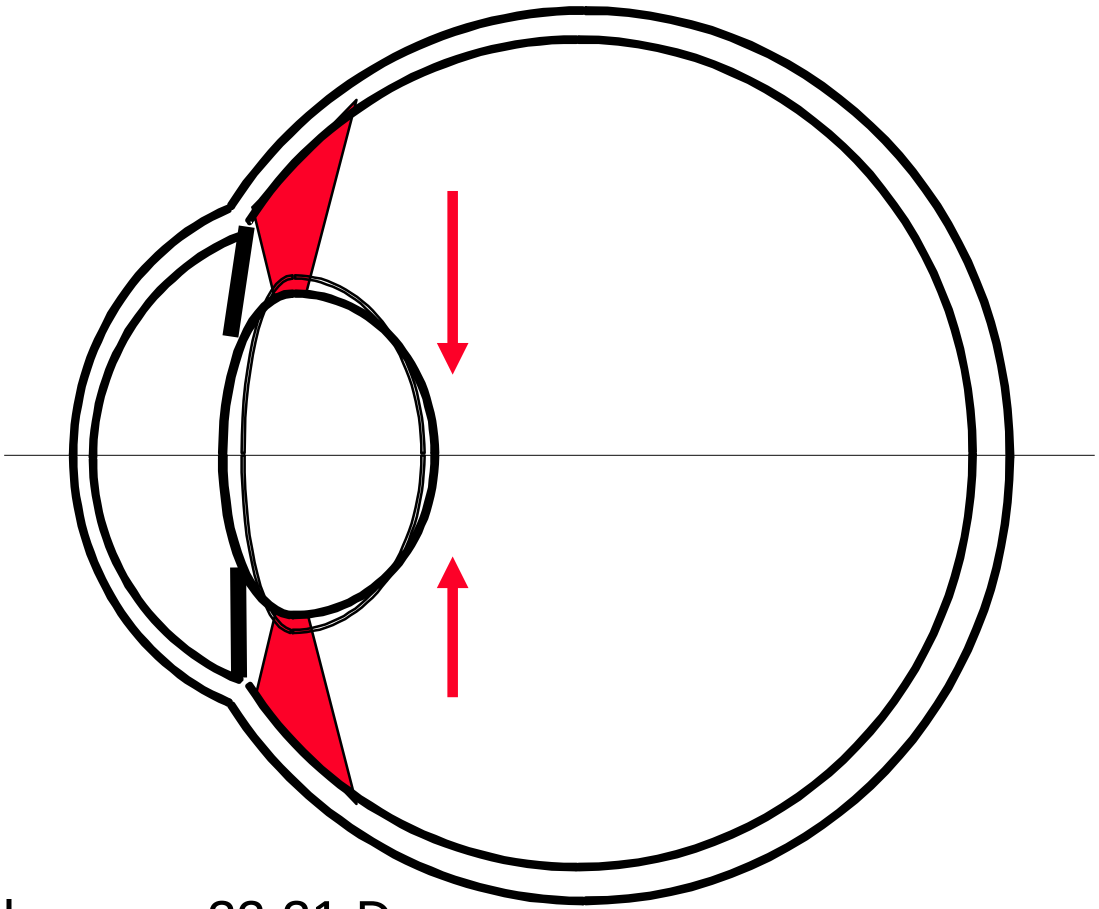
1.3 Components of the human optical system

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

1.3 Components of the human optical system

Accommmodation

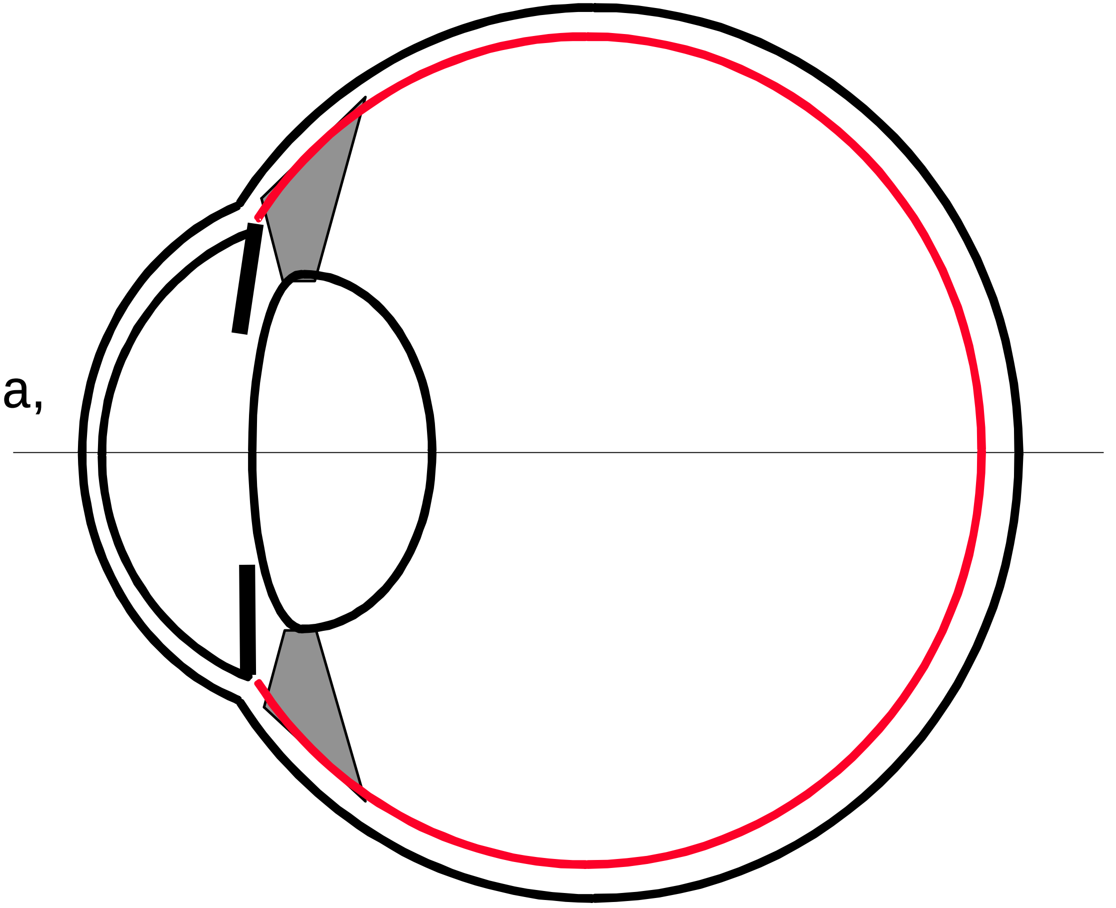
- The eye needs ~ 60D of power to focus light from infinity onto its retina
  - 1.33/60 = .02217 m = 22.17 mm
- Any extra power offered by the lens allows the eye to focus on near objects.
  - 8 D of extra power allows the eye to focus on objects as close as 1/8 = 0.125m = 12.5 cm

1.3 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.



1.3 Components of the human optical system

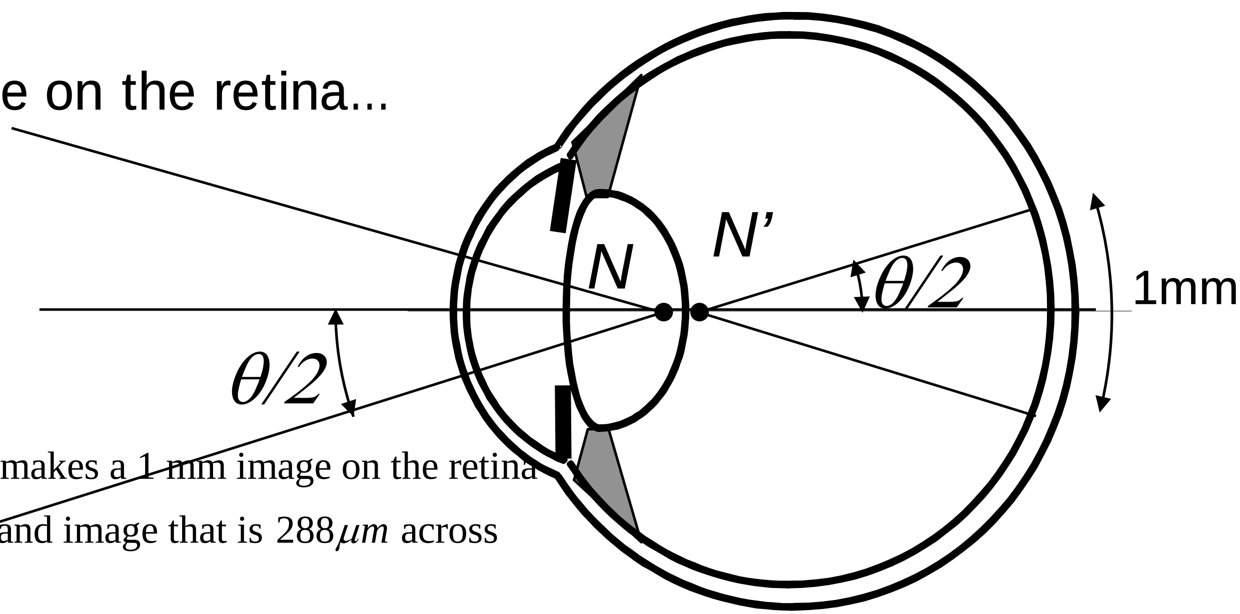
What is Visual Angle?

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...



$$\tan\frac{\theta}{2} = \frac{0.5}{16.5} \Rightarrow \frac{\theta}{2} = 1.73^{o}$$

visual angle = θ =3.47°

an object subtending 3.47 deg makes a 1 mm image on the retina

an object subtending 1^{o} makes and image that is $288\mu m$ across

1.3 Components of the human optical system

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)*

1.3 Components of the human optical system

Why Radians?

Because small angle approximations require the units to be in radians.

$$\sin\theta \cong \theta \quad \text{for small angles}$$

eg. first try using degrees..

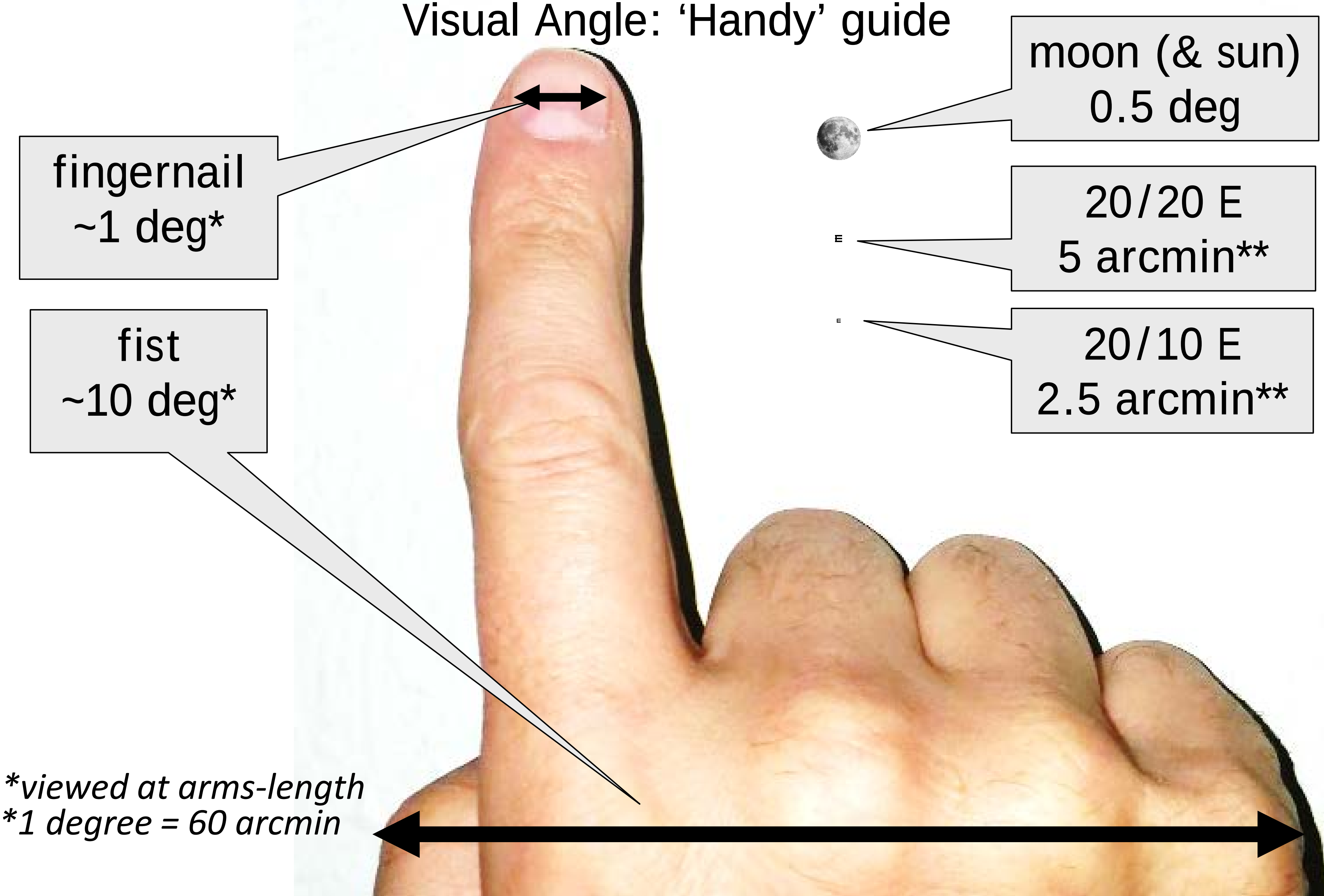
$$\sin(1) = 0.017$$

now try using radians...

$$\sin(0.017453) = 0.017452$$

1.3 Components of the human optical system

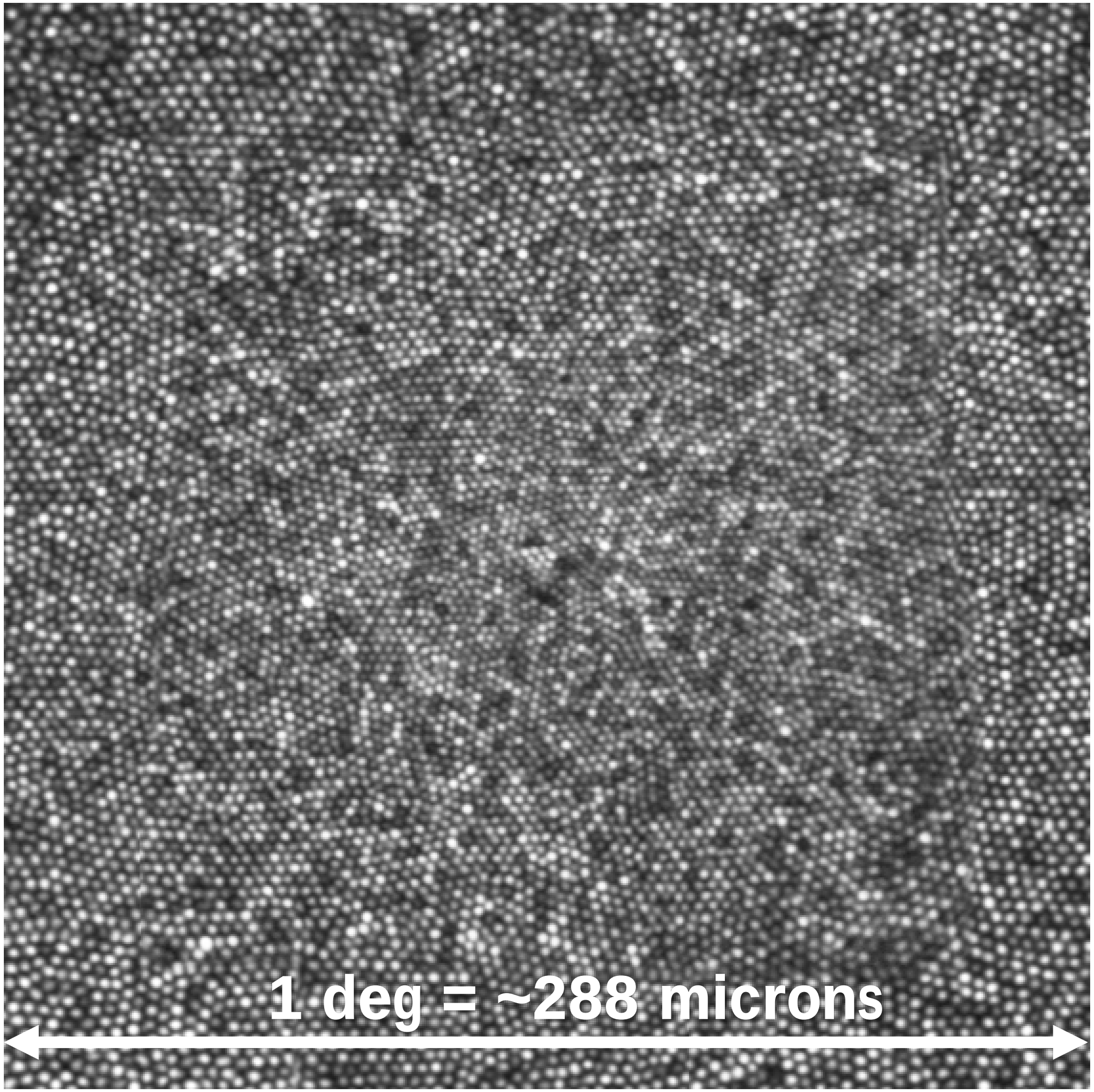
Visual Angle: ‘Handy’ guide



**viewed at arms-length*
***1 degree = 60 arcmin*

1.3 Components of the human optical system

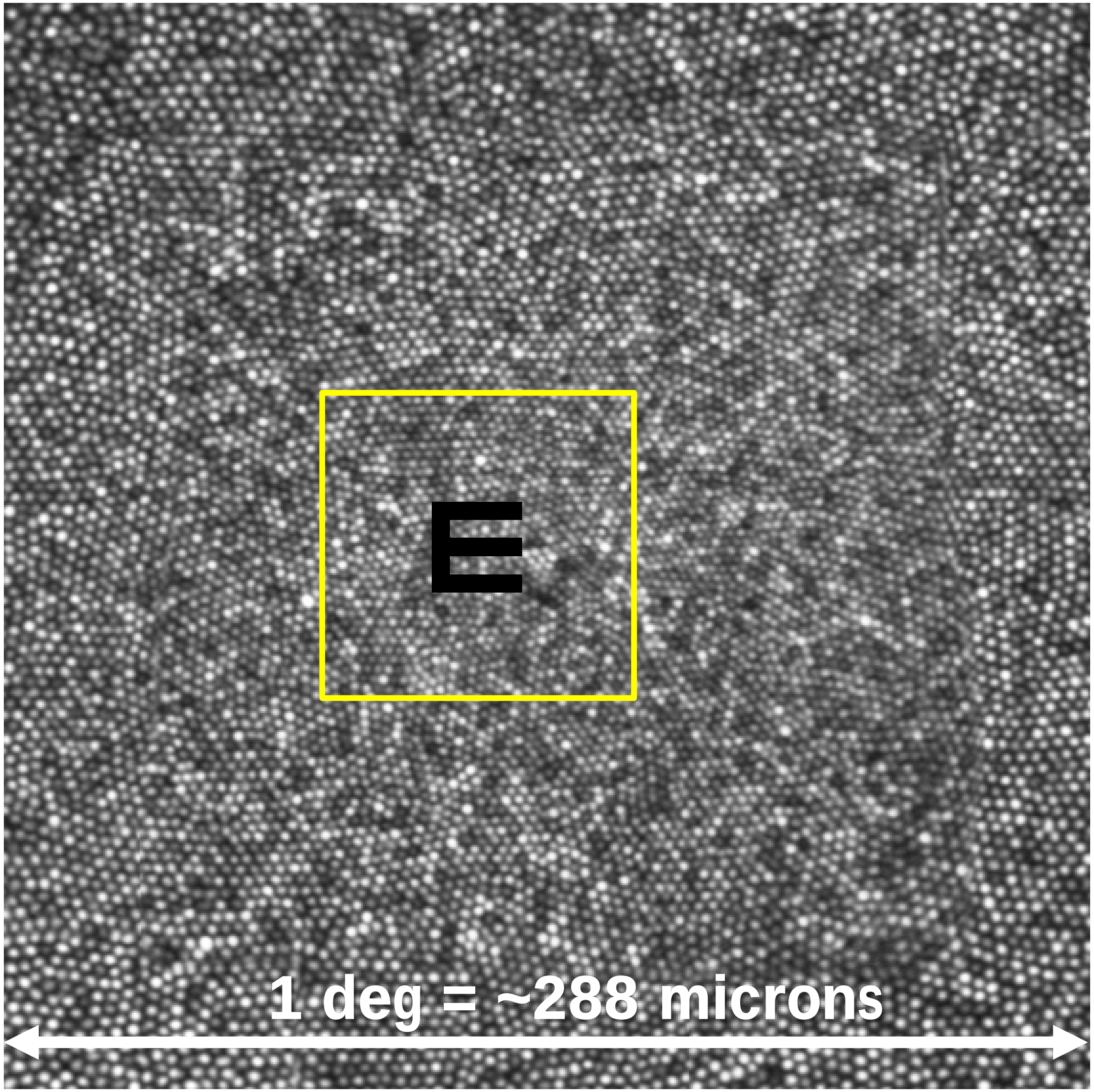
Visual Angle



1 foveal cone
= ~2.5 microns
= ~0.5 arcmin

1.3 Components of the human optical system

Visual Angle

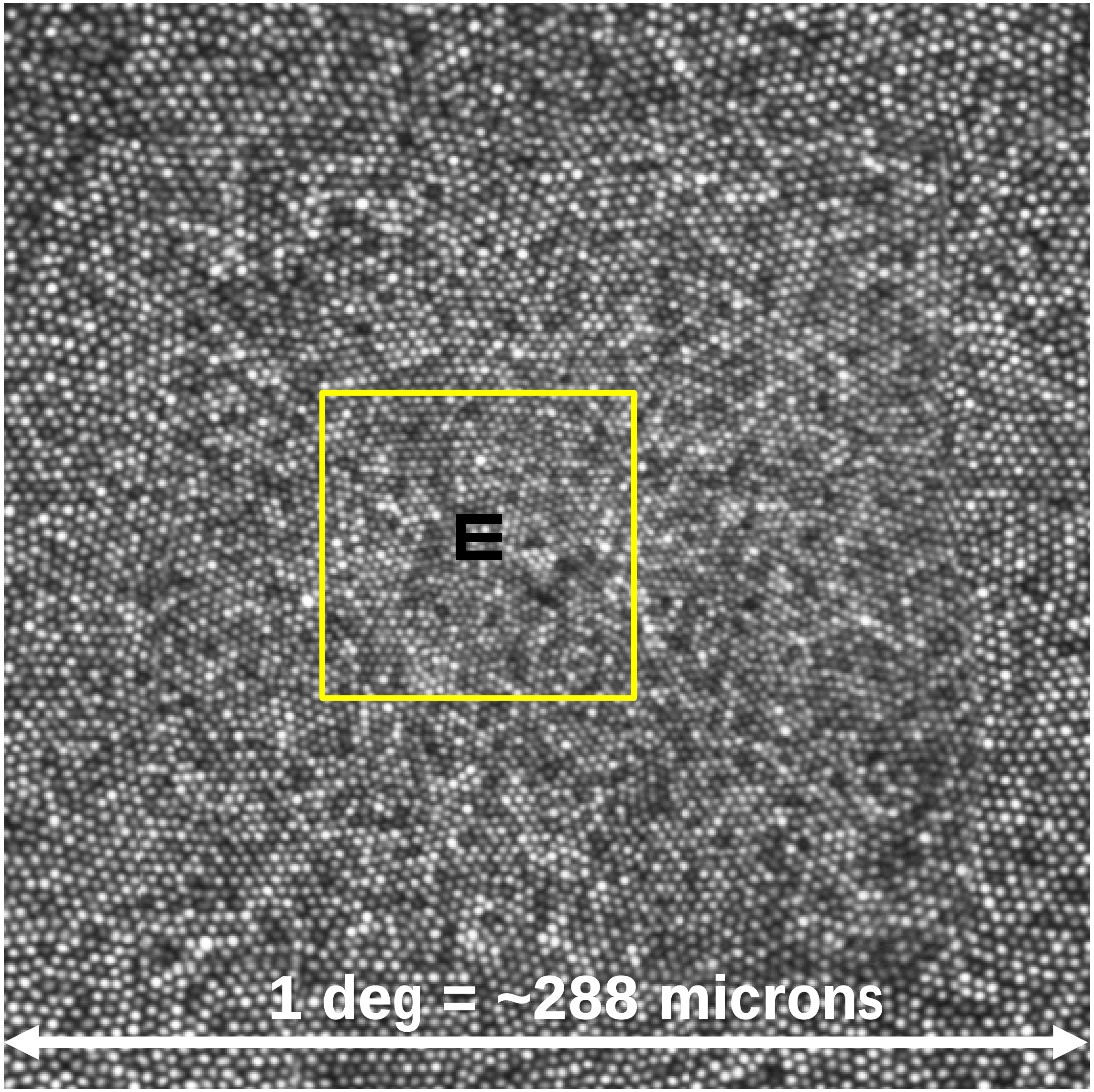


1 foveal cone
= ~2.5 microns
= ~0.5 arcmin

20/20 letter
= 5 arcmin

1.3 Components of the human optical system

Visual Angle

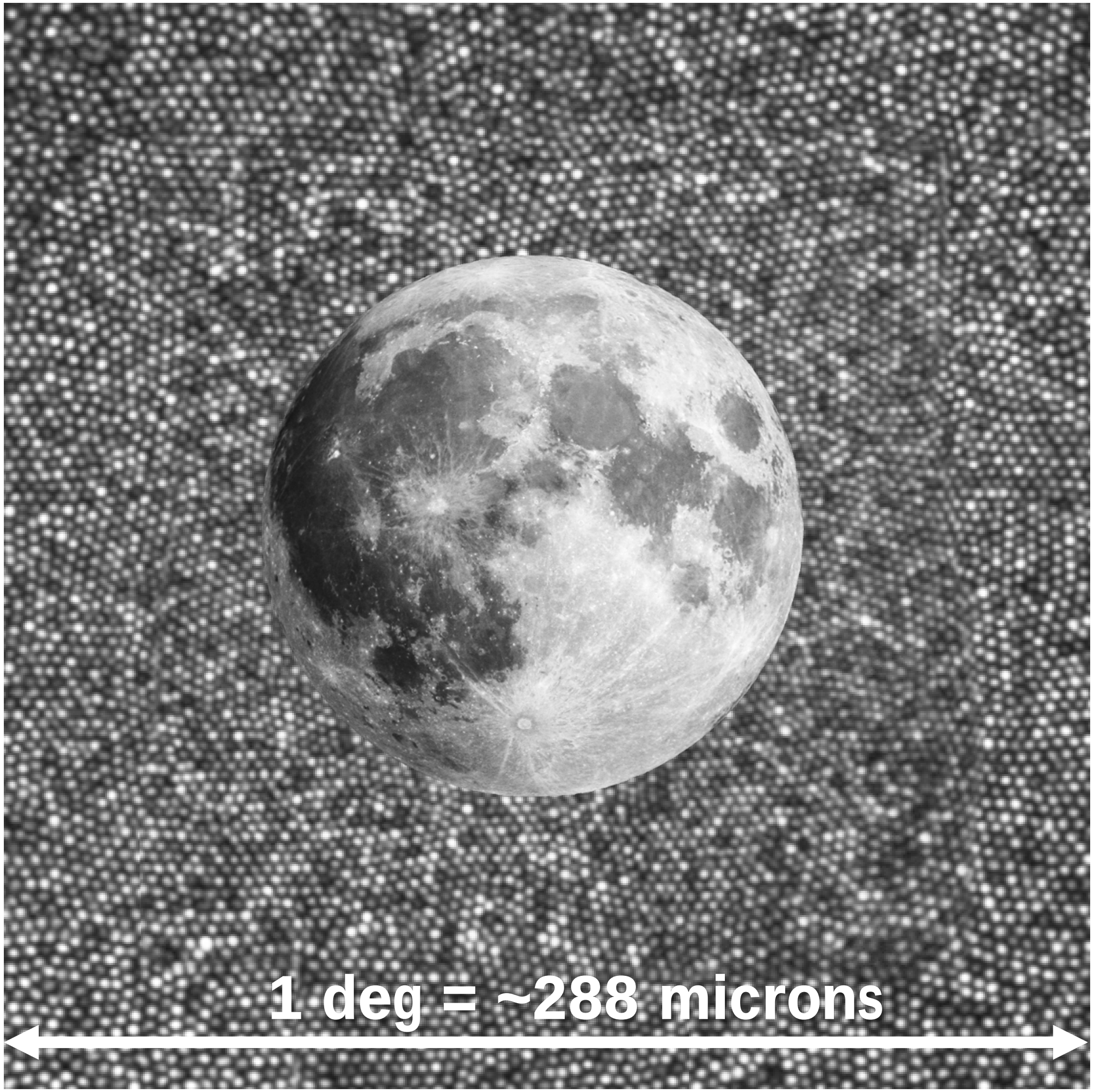


1 foveal cone
= ~2.5 microns
= ~0.5 arcmin

20/10 letter
= 2.5 arcmin

1.3 Components of the human optical system

Visual Angle

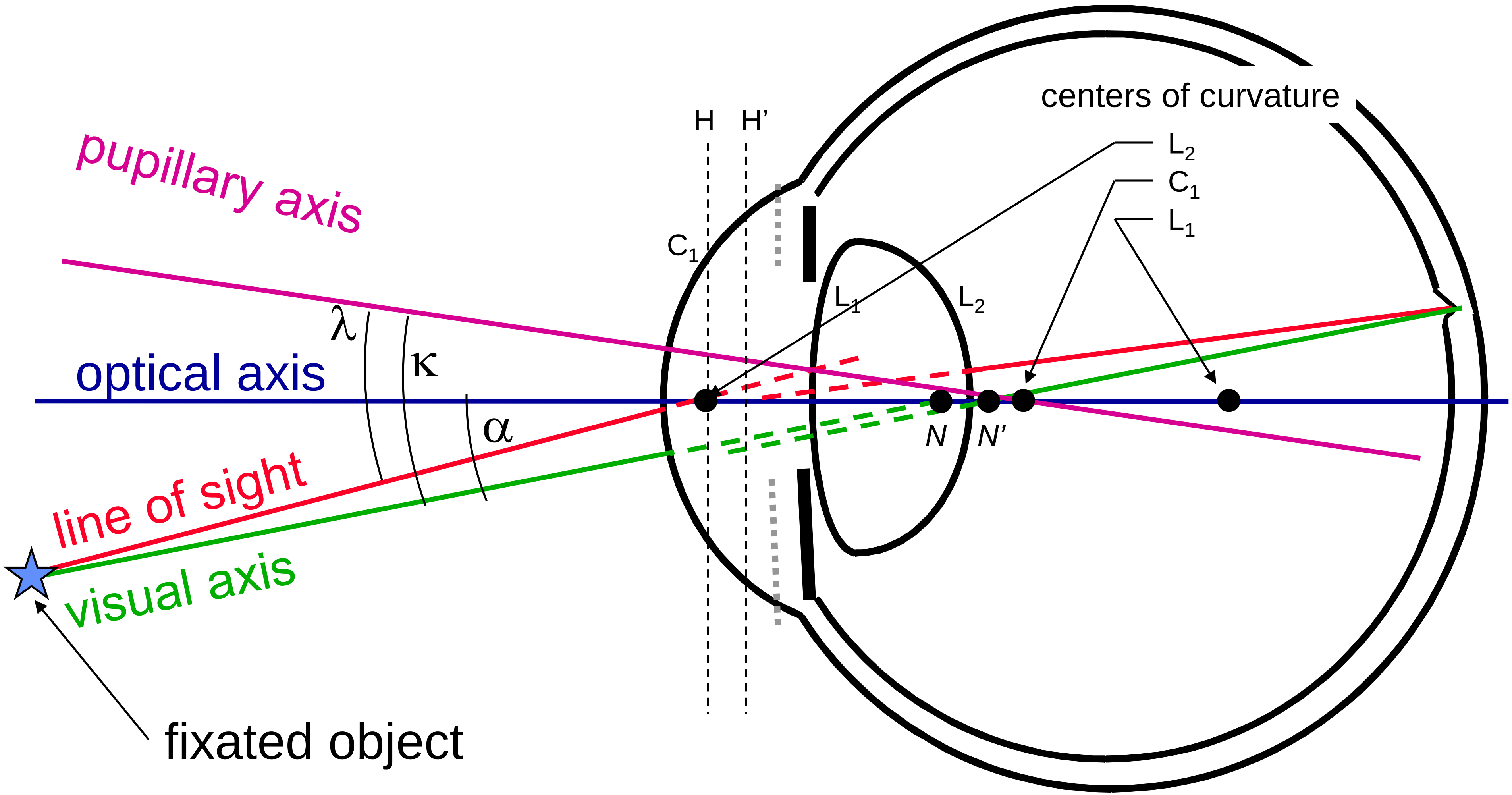


1 foveal cone
= ~2.5 microns
= ~0.5 arcmin

Moon
= 30 arcmin

1.3 Components of the human optical system

Axes in the Eye

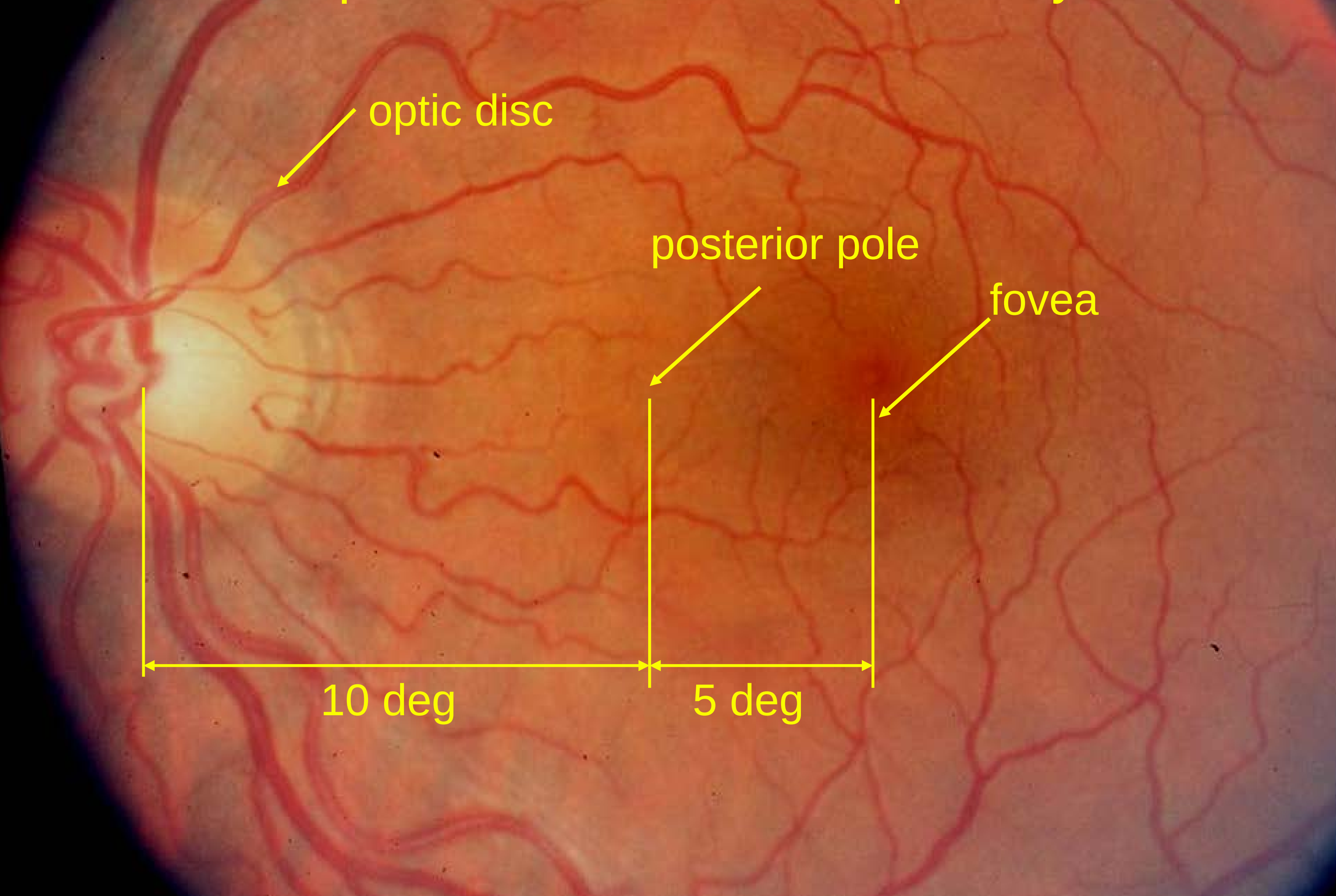


1.3 Components of the human optical system
Axes and Angles in the Eye

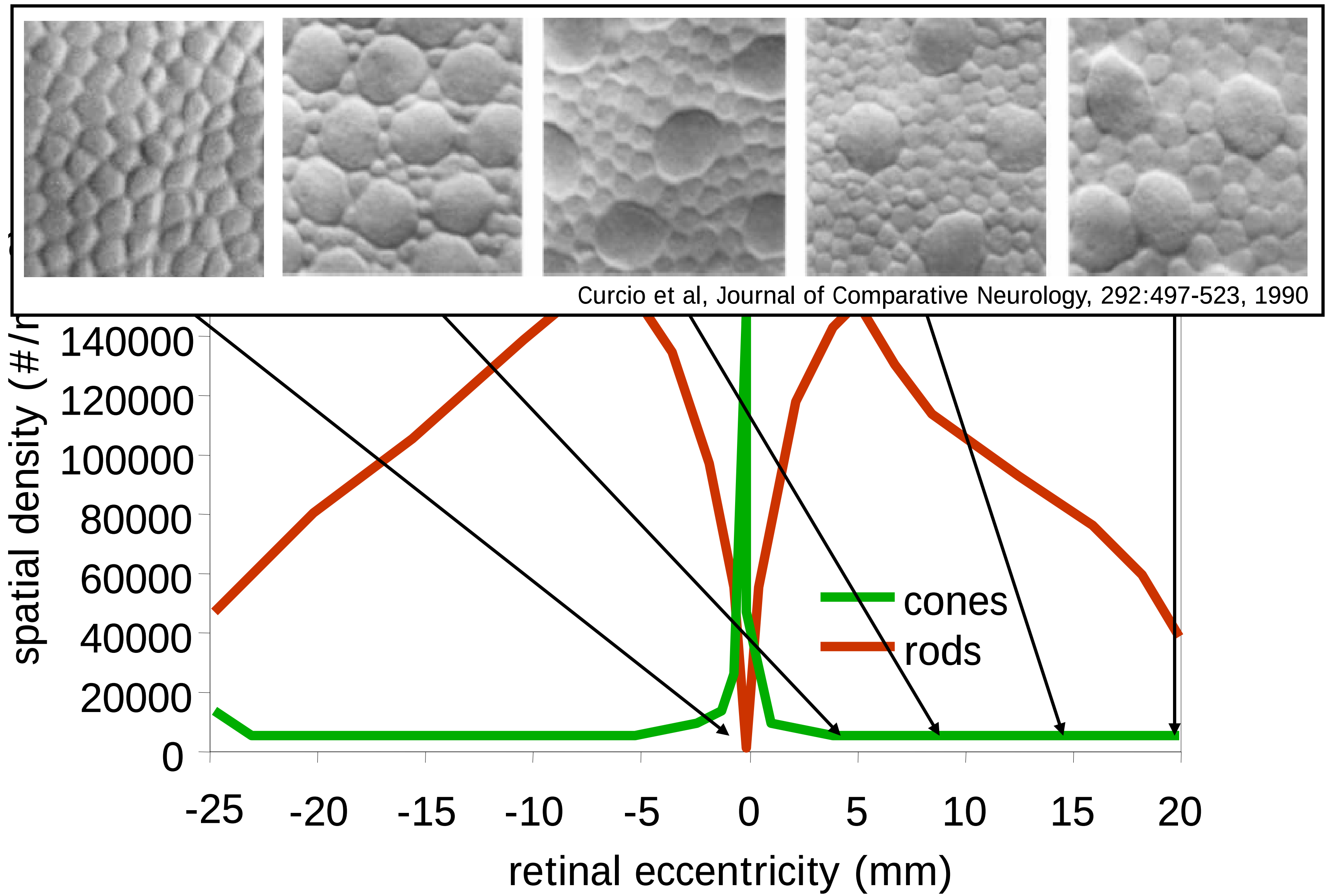
- **Optical axis**: best line joining the centers of curvatures of the optical surfaces
  - Some definitions choose to weight the centers of curvature by the respective powers of the components
- **Visual axis**: line from fovea through the nodal points
- **Line of sight**: line from object through center 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

1.3 Components of the human optical system

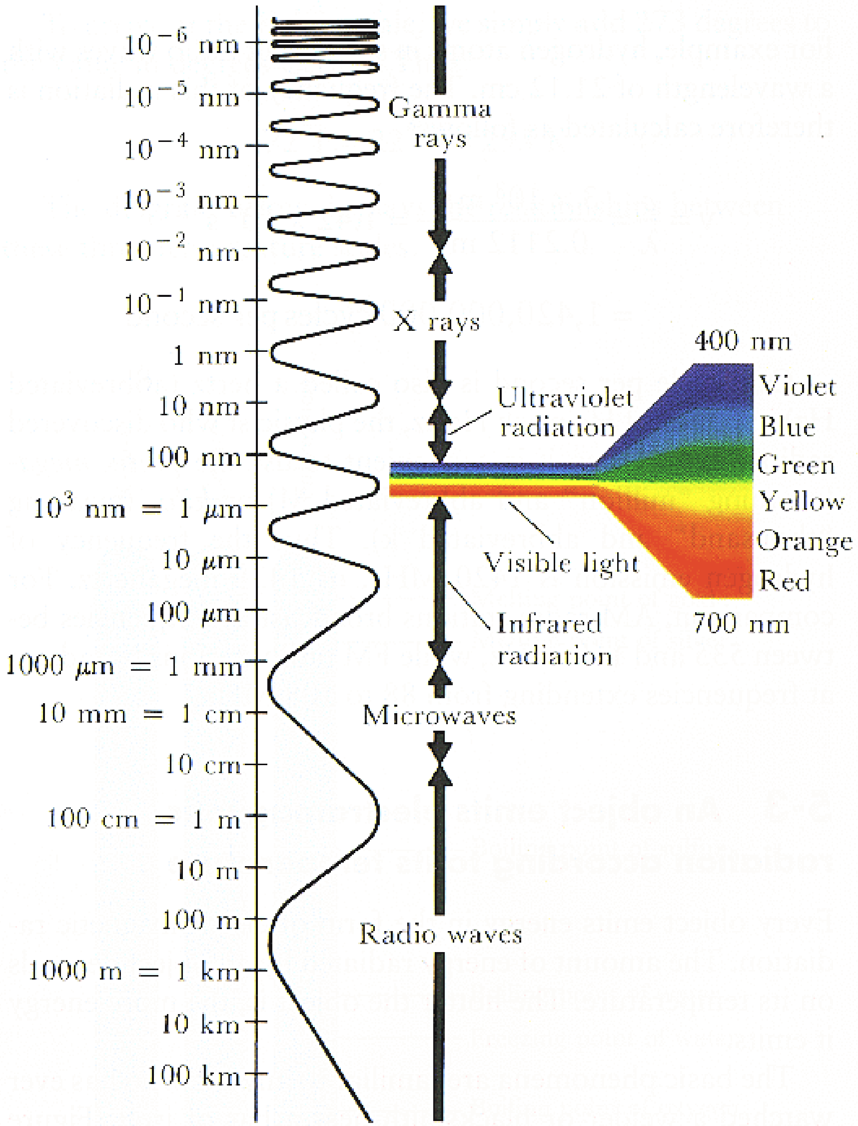


1.3 Components of the human optical system

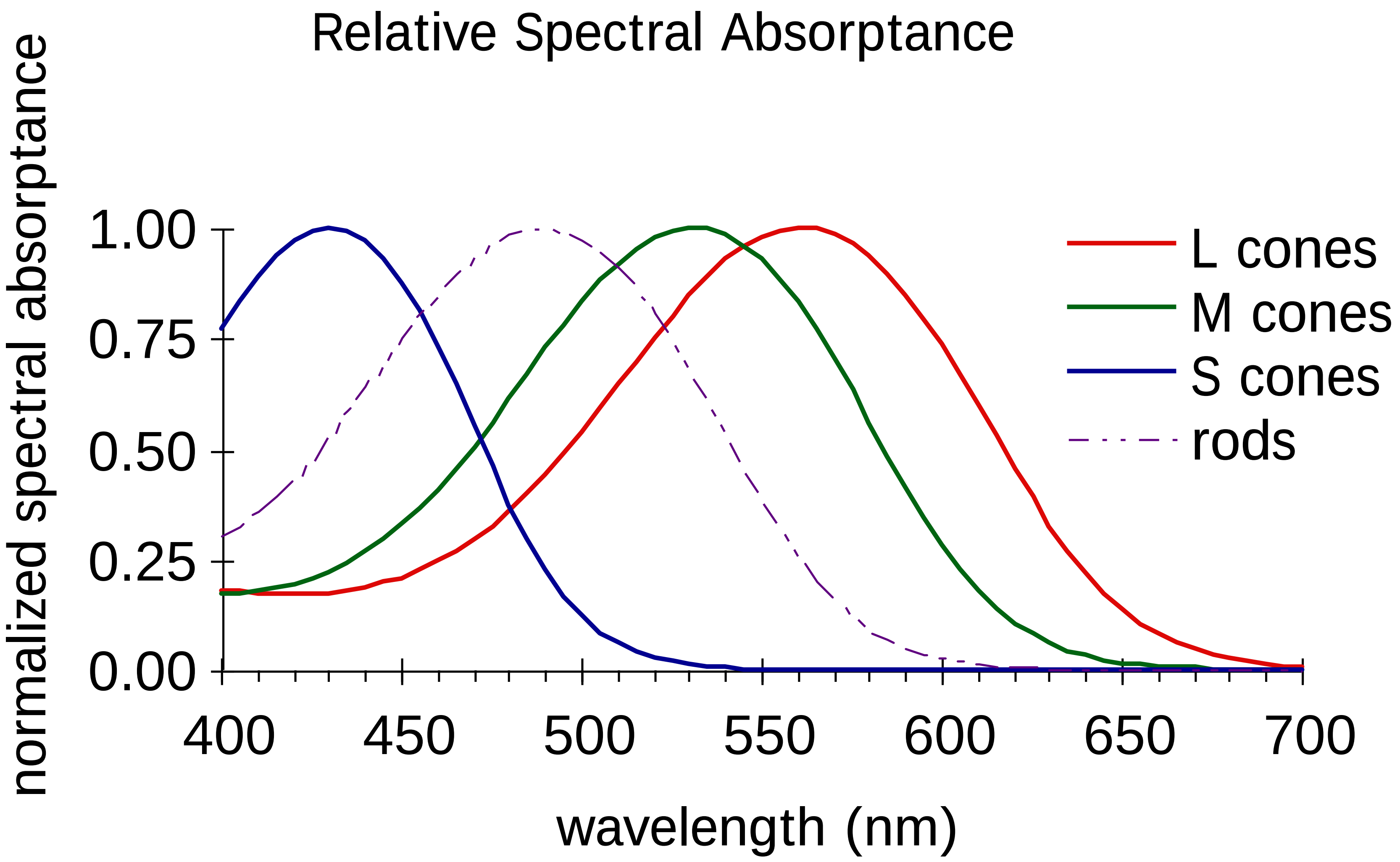


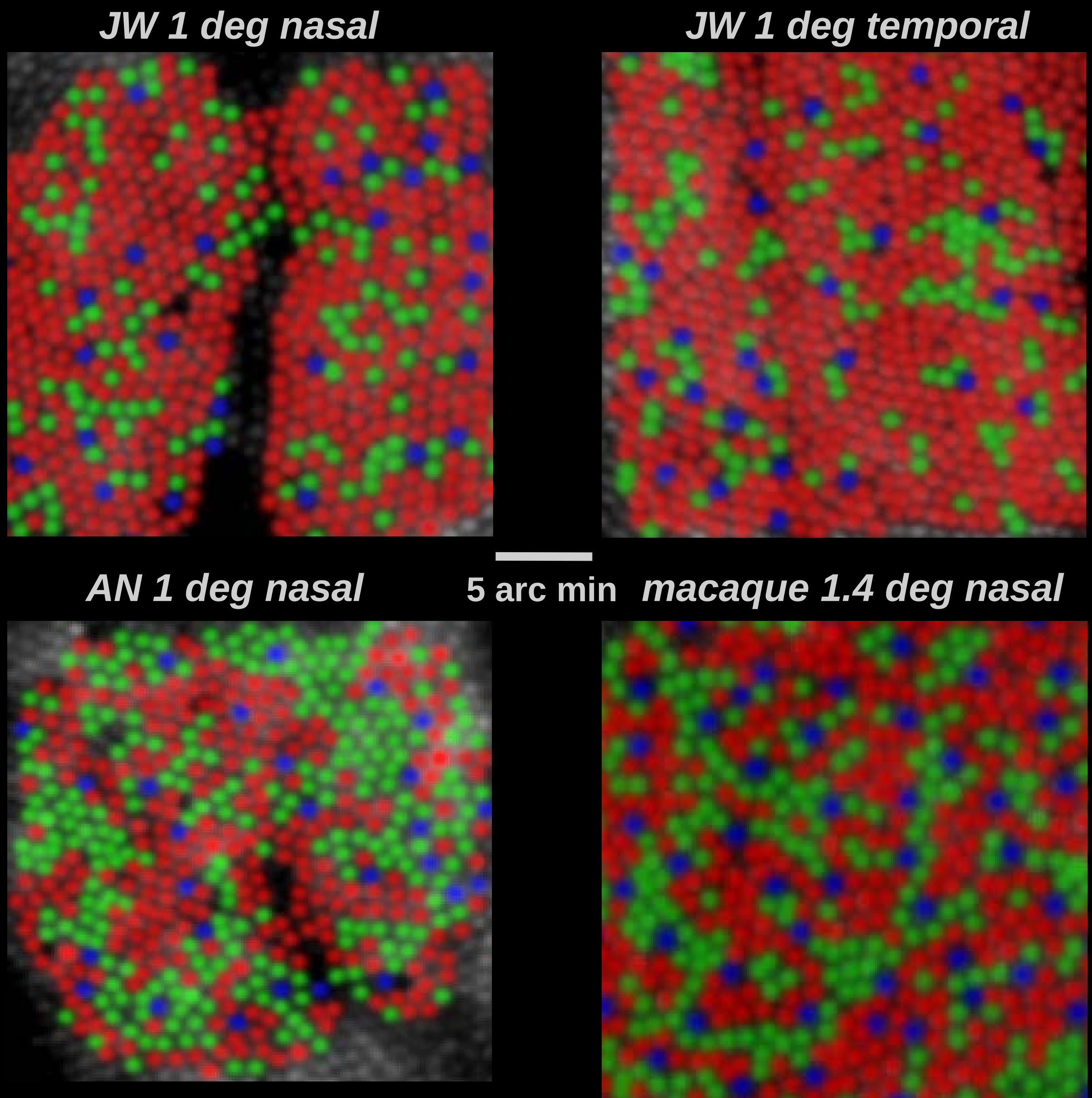
Osterberg, Acta Ophthalmologica, 6:1-103, 1935

1.3 Components of the human optical system

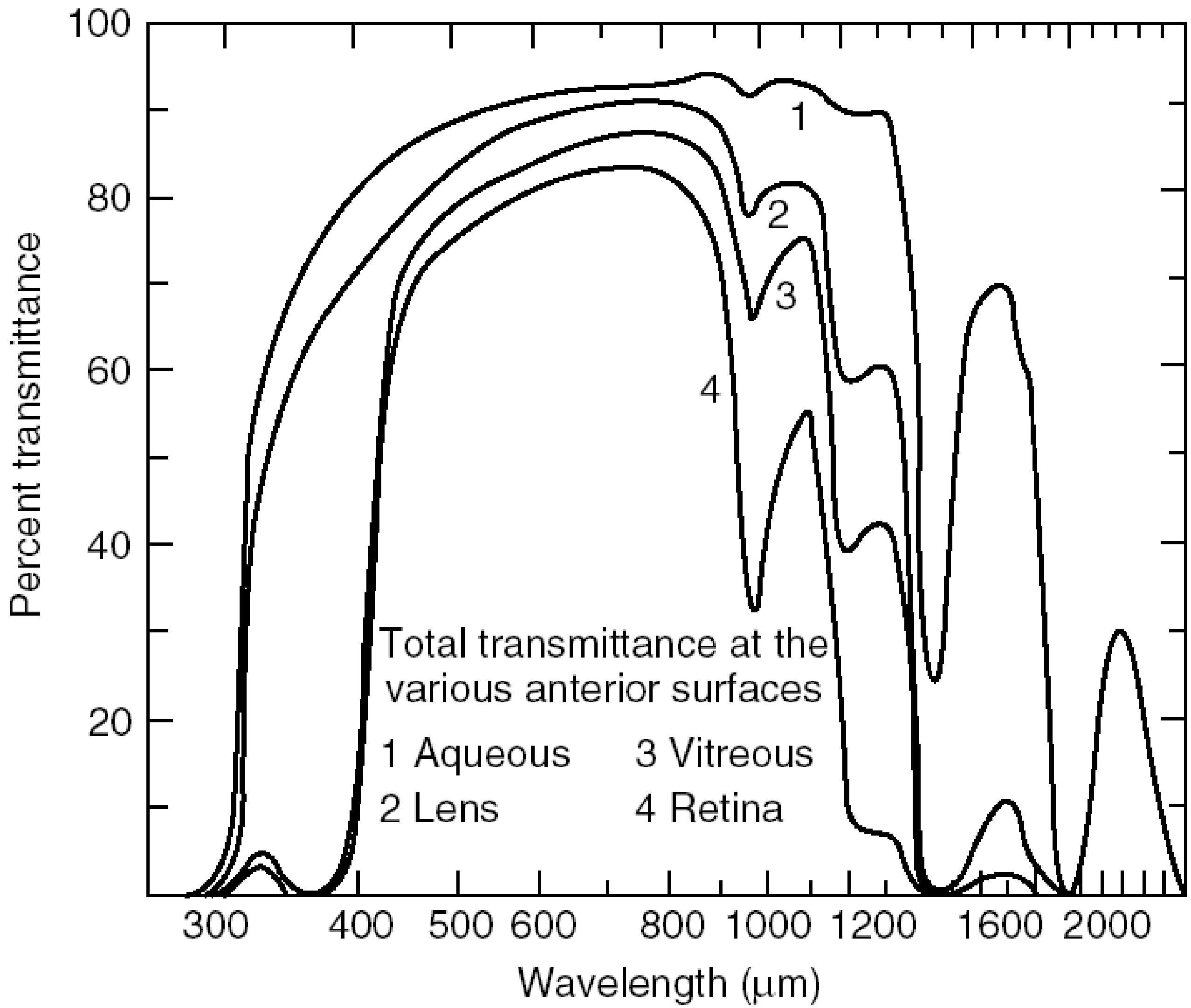


1.3 Components of the human optical system




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

1.4 Transmission of the Ocular Media



Boettner and Wolter, 1962

1.4 Transmission of the Ocular Media

Lens Optical Density Increases with Age

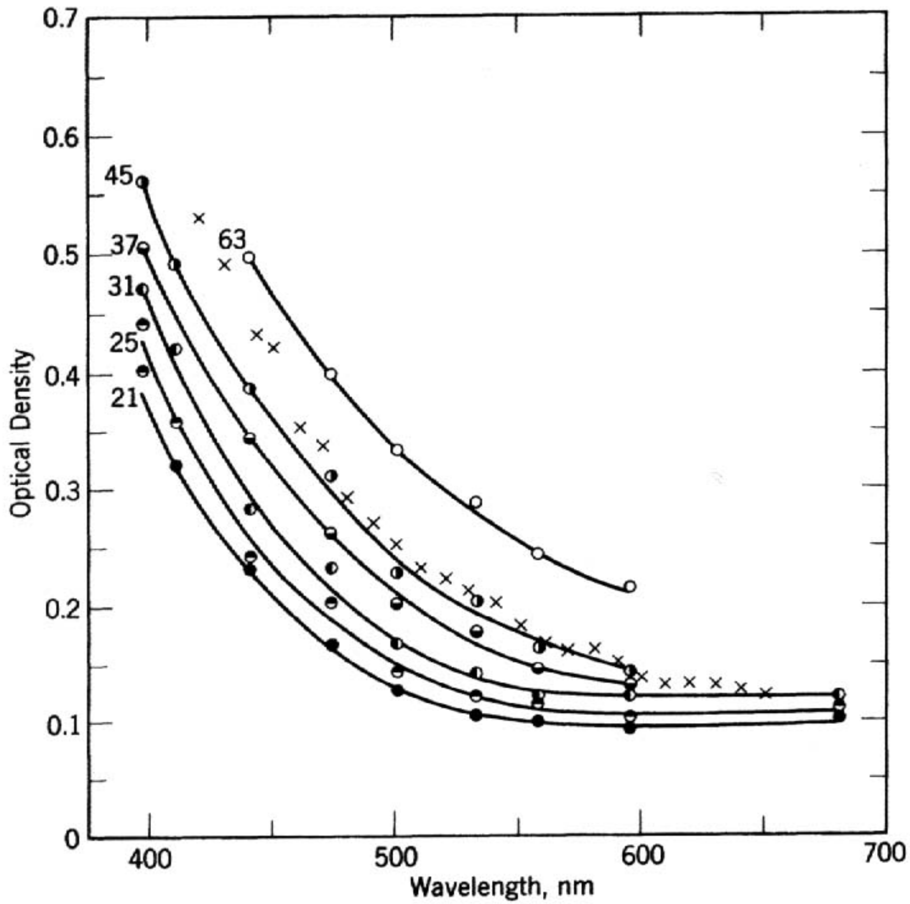
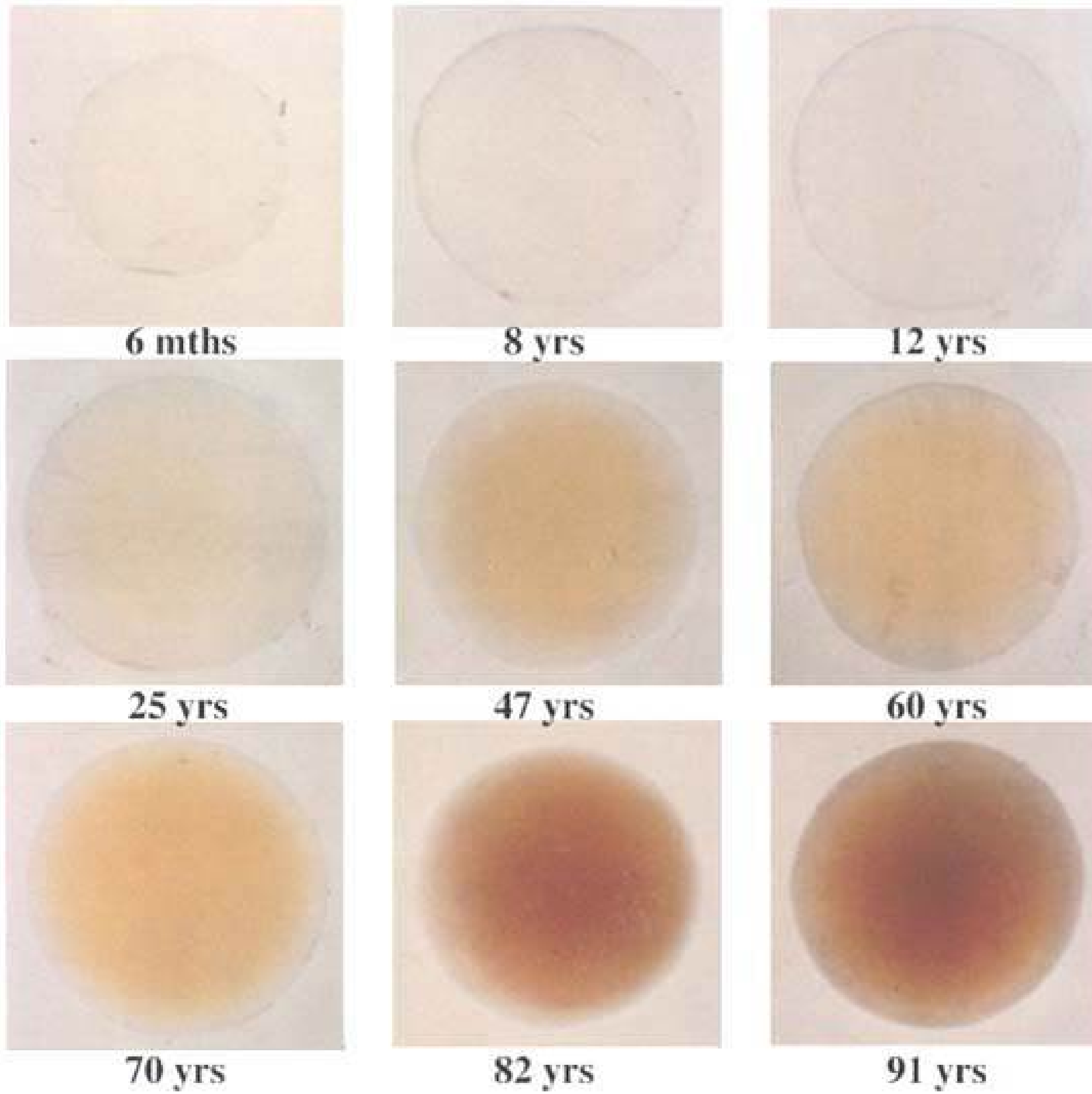


Fig. 2(2.4.6). Spectral density curves of the human eye lens determined for the living eye by an objective method. Data for English observers of different ages (ages are shown against the curves; from Said and Weale, 1959). The crosses refer to mean data for two eyes (ages 48 and 53) obtained, after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

figure from Wyszecki and Stiles, 1982

1.4 Transmission of the Ocular Media

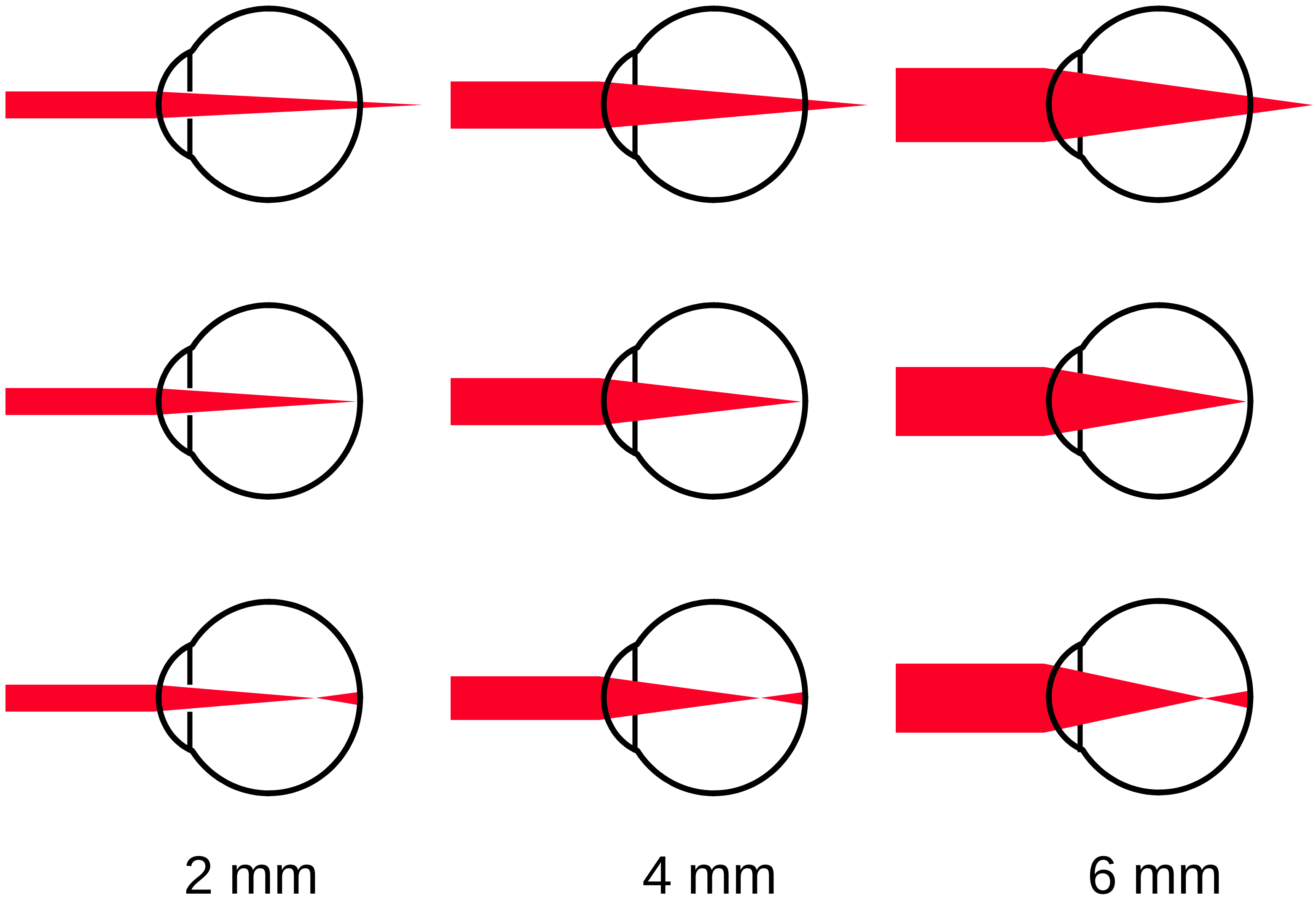


Part 2 Image Quality in the Eye

"*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.

2.1 Blur, Defocus and Pupil Size



2.1 Blur, Defocus and Pupil Size

Focused behind retina

In focus

Focused in front of retina

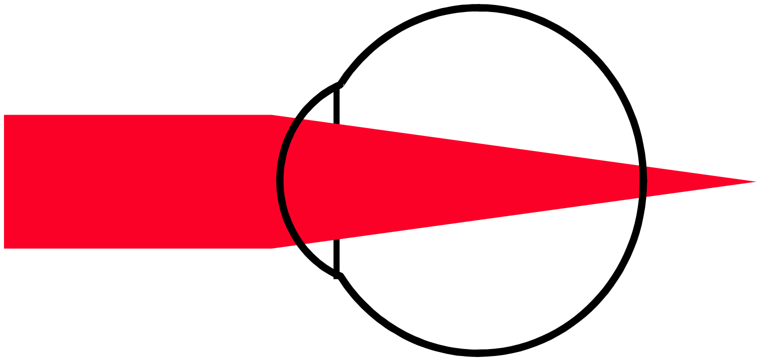
2 mm pupil

4 mm pupil

6 mm pupil

2.1 Depth of focus is a function of pupil size

Computation of Geometric Blur Size



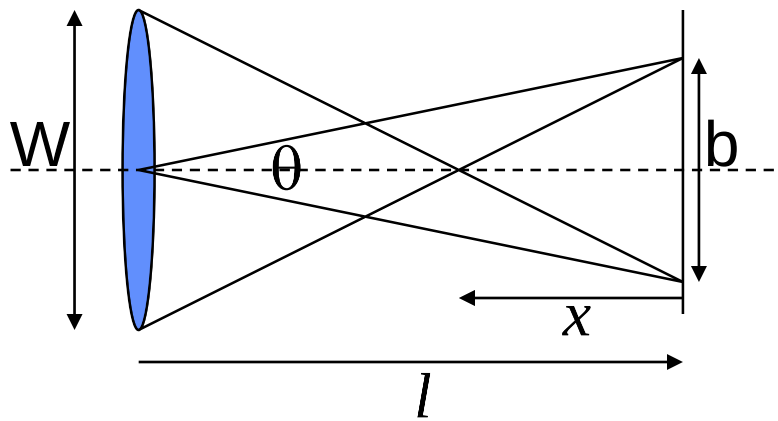
$$\text{blur[mrad]} = D \times pupilsize[mm]$$

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

where D is the defocus in diopters

2.1 Depth of focus is a function of pupil size

Derivation of Geometric Blur Size Eqn.



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

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

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

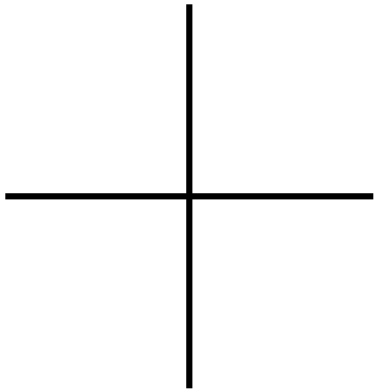
where D is defocus in diopters

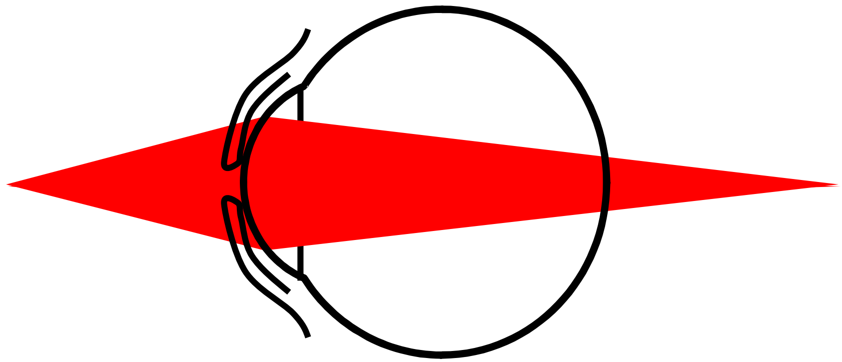
2.1 Depth of focus is a function of pupil size

Application of Blur Equation

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

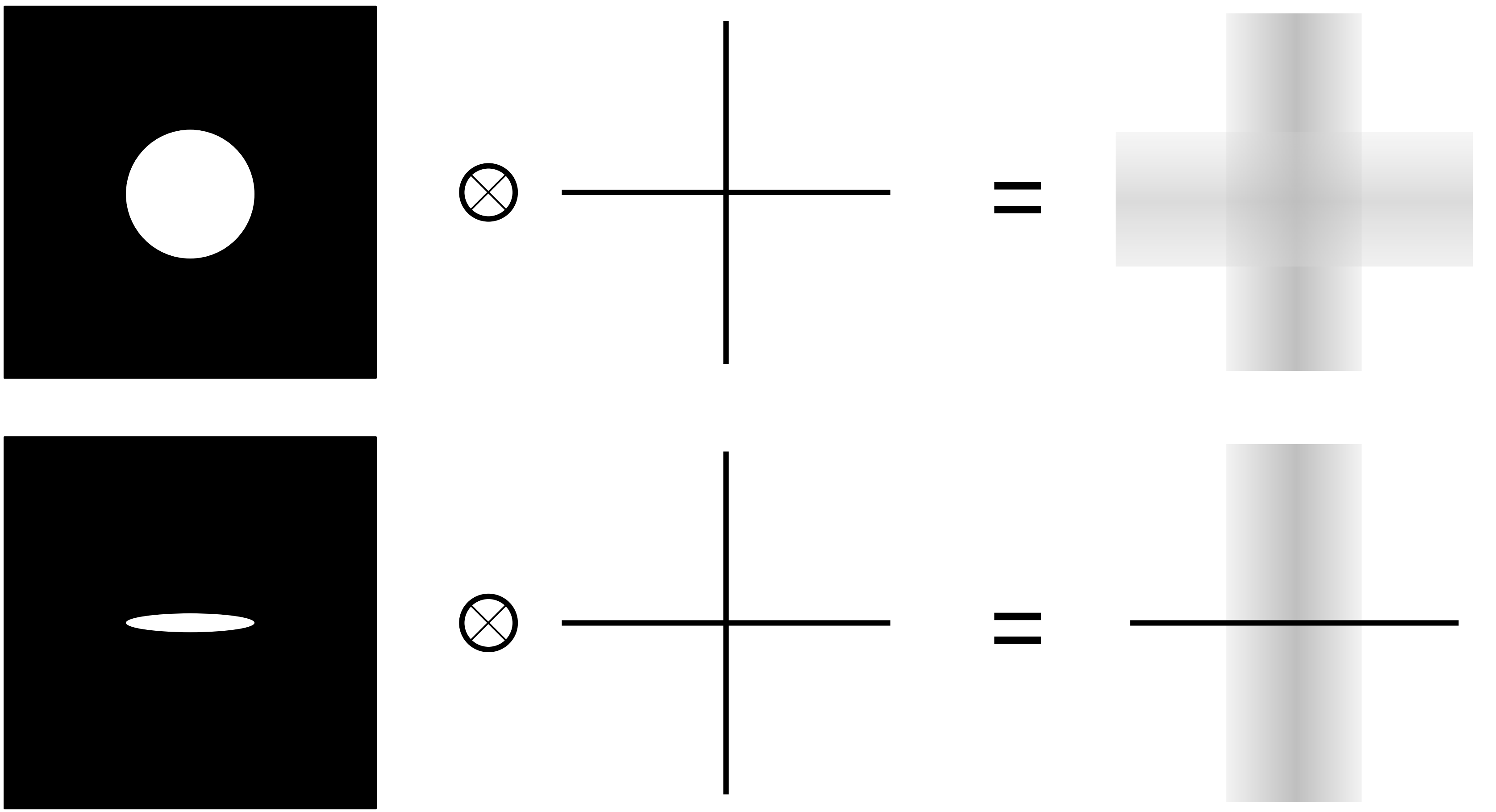
2.1 Depth of focus is a function of pupil size



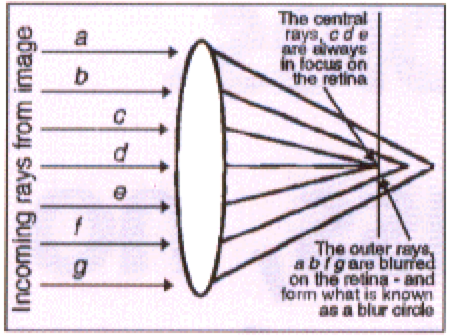


Draw a cross like this one on a page. Hold it so close that is it completely out of focus, then squint. You should see the horizontal line become clear. The line becomes clear because you have used your eyelids to make your effective pupil size smaller, thereby reducing the blur due to defocus on the retina image. Only the horizontal line appears clear because you have only reduced the blur in the horizontal direction.

2.1 Blur, Defocus and Pupil Size

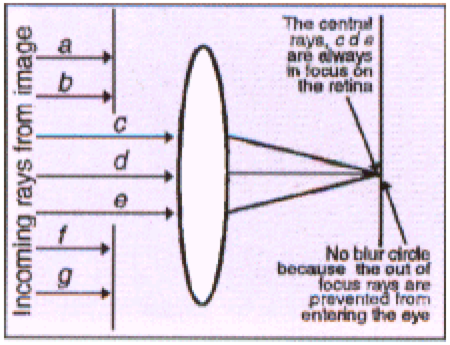


2.1 Depth of focus is a function of pupil size



Pinholes

The natural alternative.



2.2 Diffraction and Interference

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

Sommerfeld, ~ 1894

2.2 Diffraction and Interference

- diffraction causes light to bend perpendicular to the direction of the diffracting edge
- interference causes the diffracted light to have peaks and valleys

2.2 Diffraction and Interference

Fraunhofer Diffraction

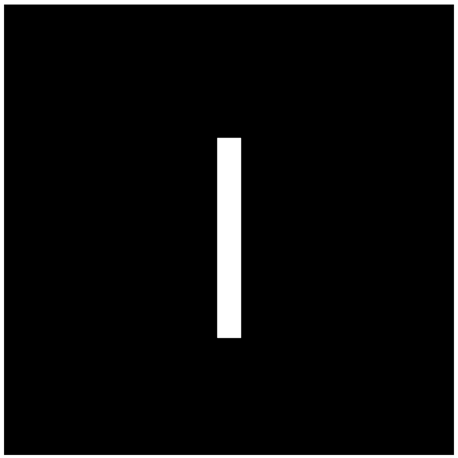
- Also called ***far-field*** diffraction
- Occurs when the screen is held far from the aperture.

- **Occurs at the focal point of a lens!**

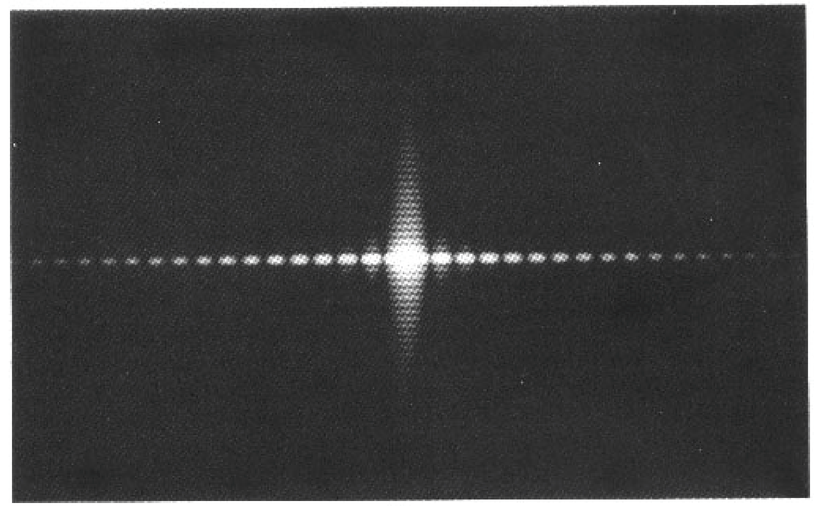
2.2 Diffraction and Interference

Fraunhofer Diffraction

rectangular aperture

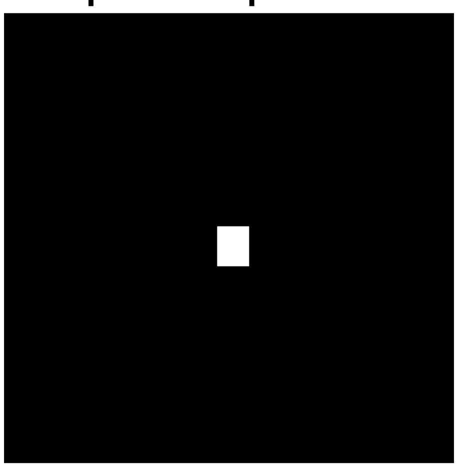


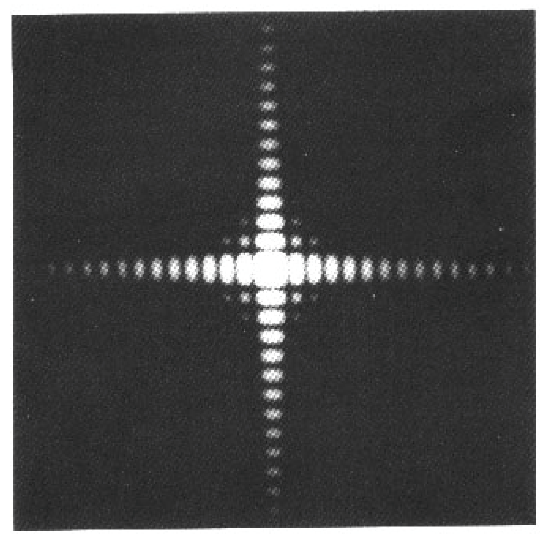
Sec. 19-3 Rectangular and Circular Apertures 393



(c)

square aperture

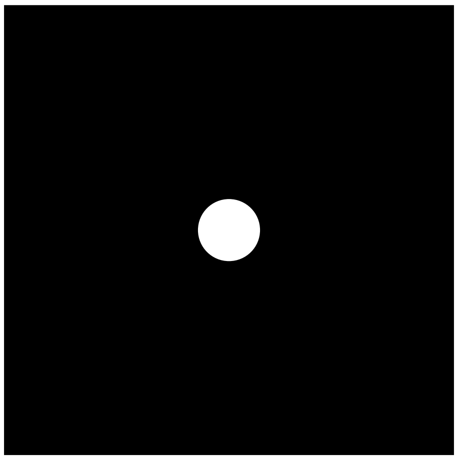


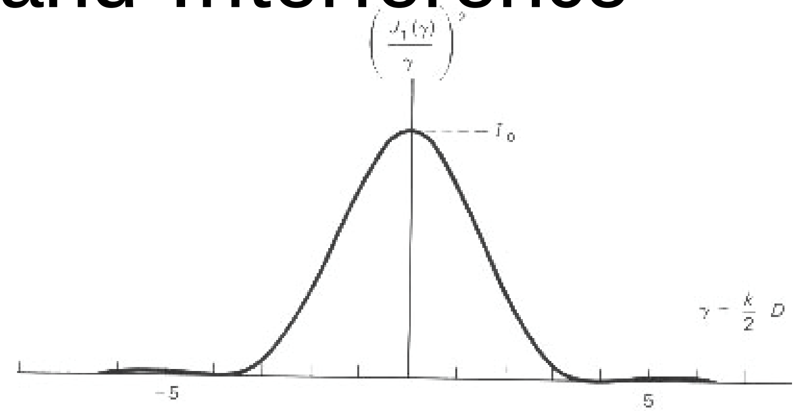


(d)

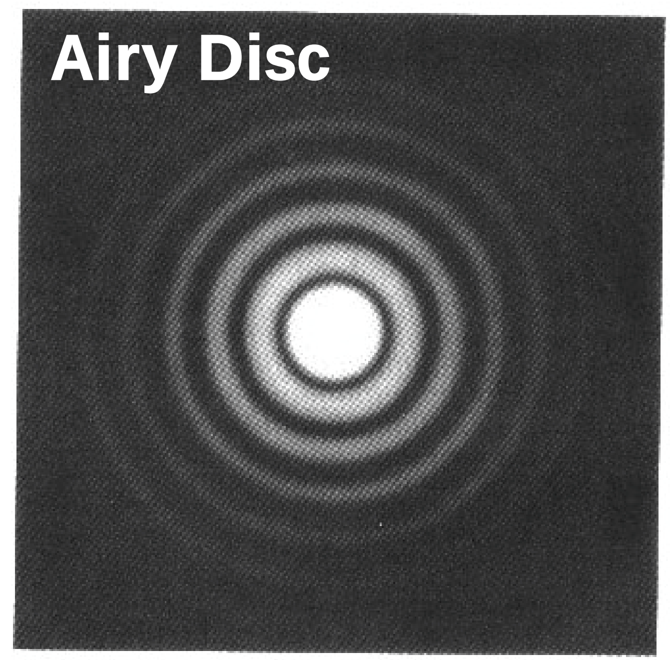
2.2 Diffraction and Interference

circular aperture





(a)



(b)

Sir George Biddel Airy: Inventor of spectacles for astigmatism

2.3 The Point Spread Function

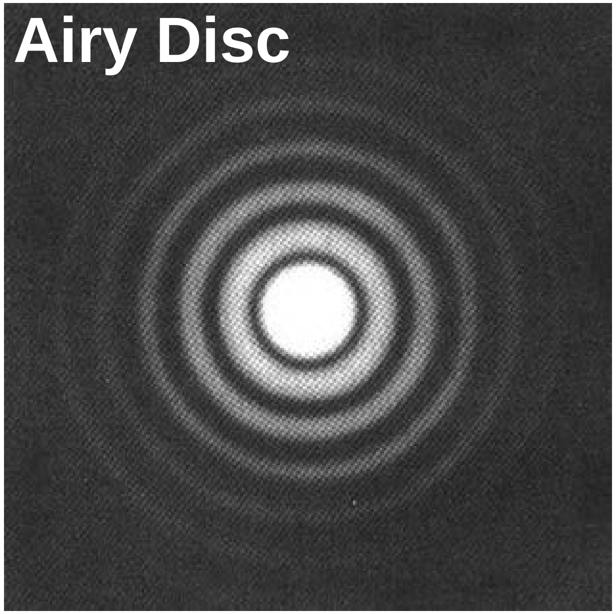
The Point Spread Function, or PSF, is the image that an optical system forms of a point source.

The point source is the most fundamental object, and forms the basis for any complex object.

The PSF is analogous to the Impulse Response Function in electronics.

2.3 The Point Spread Function

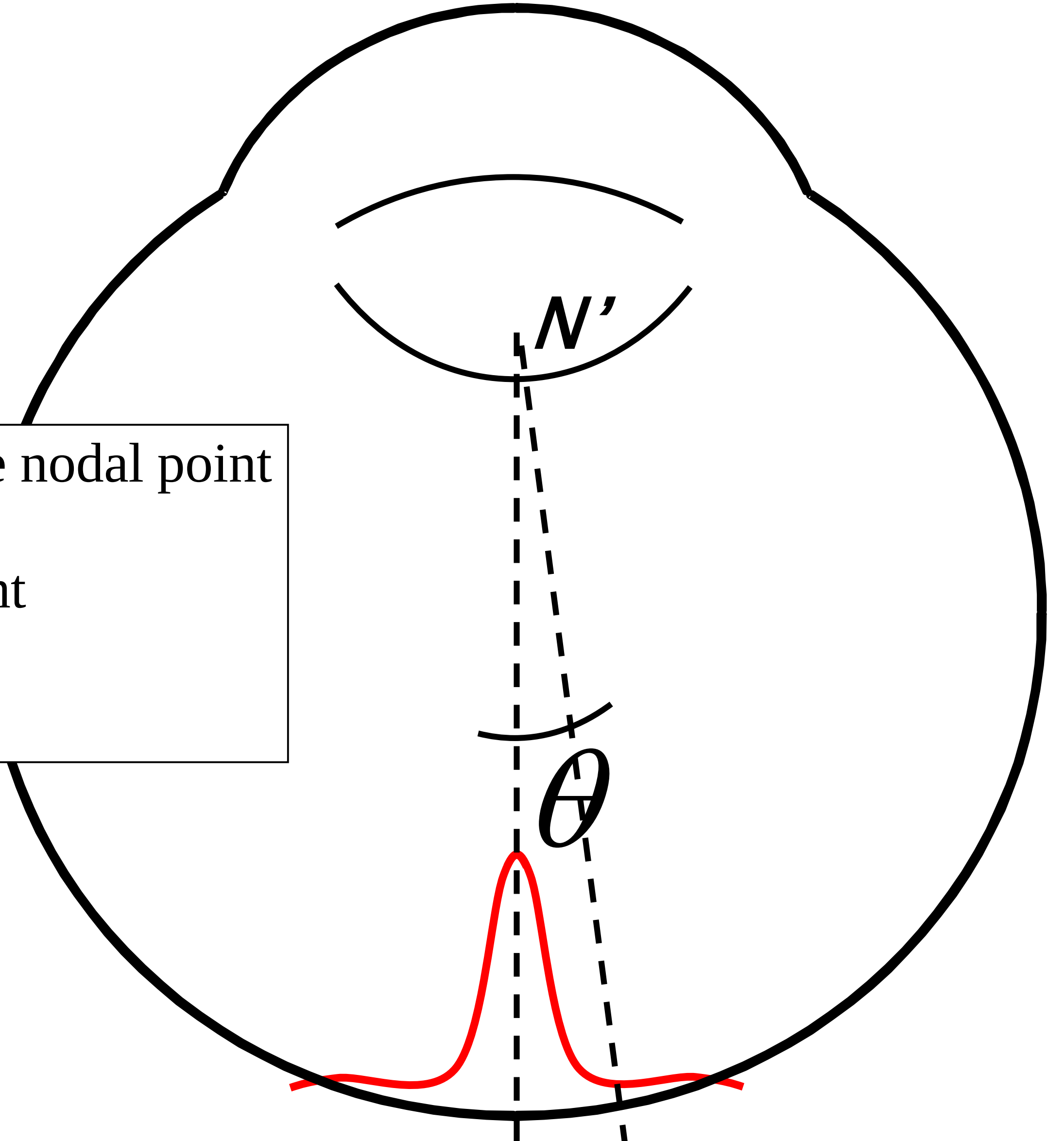
The PSF for a perfect optical system is the Airy disc, which is the Fraunhofer diffraction pattern for a circular pupil.



2.3 The Point Spread Function

The Airy Disc

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



θ	$\equiv$	angle subtended at the nodal point
λ	$\equiv$	wavelength of the light
a	$\equiv$	pupil diameter

2.3 The Point Spread Function

The Airy Disc

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

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

$\lambda \equiv$ wavelength of the light

$a \equiv$ pupil diameter

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

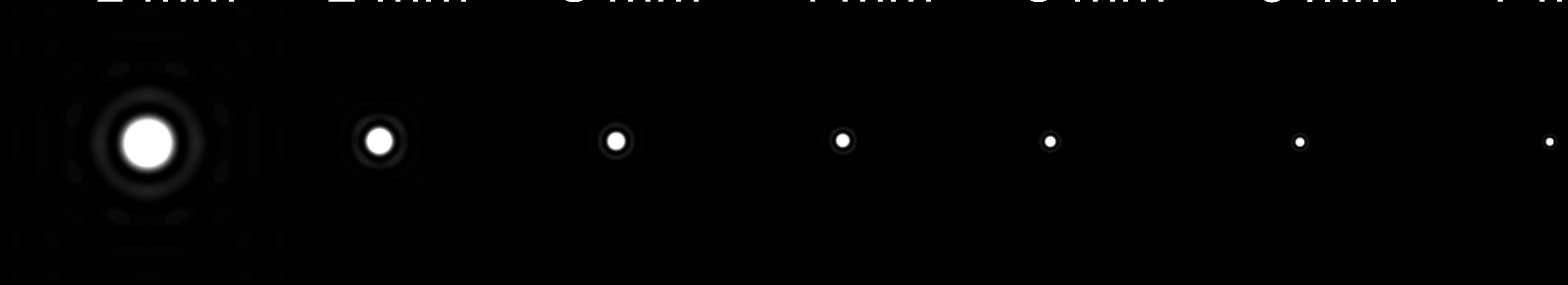
1 degree = 60 minutes of arc

1 minute of arc = 60 seconds of arc

2.3 The Point Spread Function

PSF vs. Pupil Size: Perfect Eye

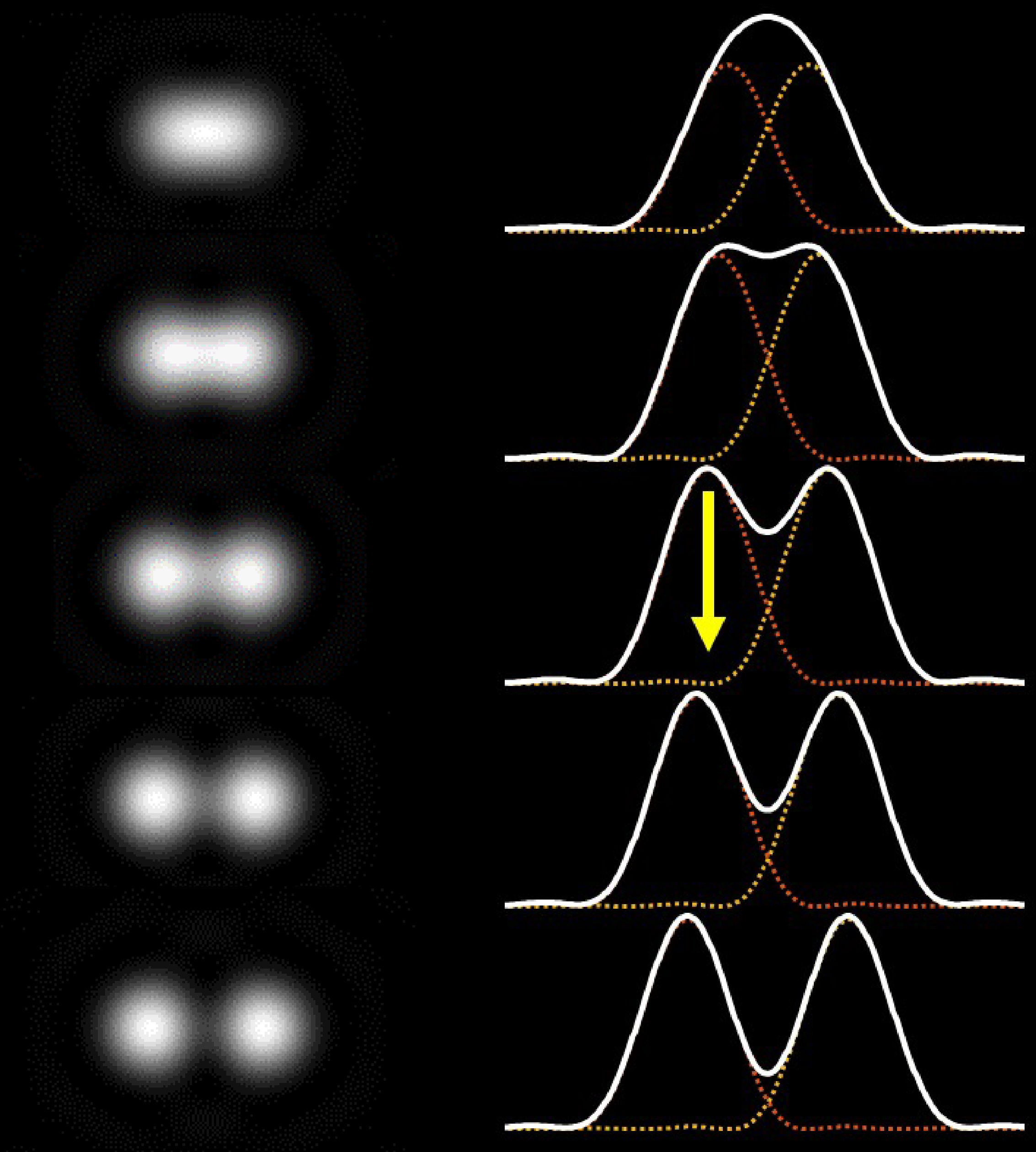
1 mm 2 mm 3 mm 4 mm 5 mm 6 mm 7 mm



Diffraction-limited Eye

2.4 Resolution

Unresolved
point sources



Rayleigh
resolution
limit

Resolved

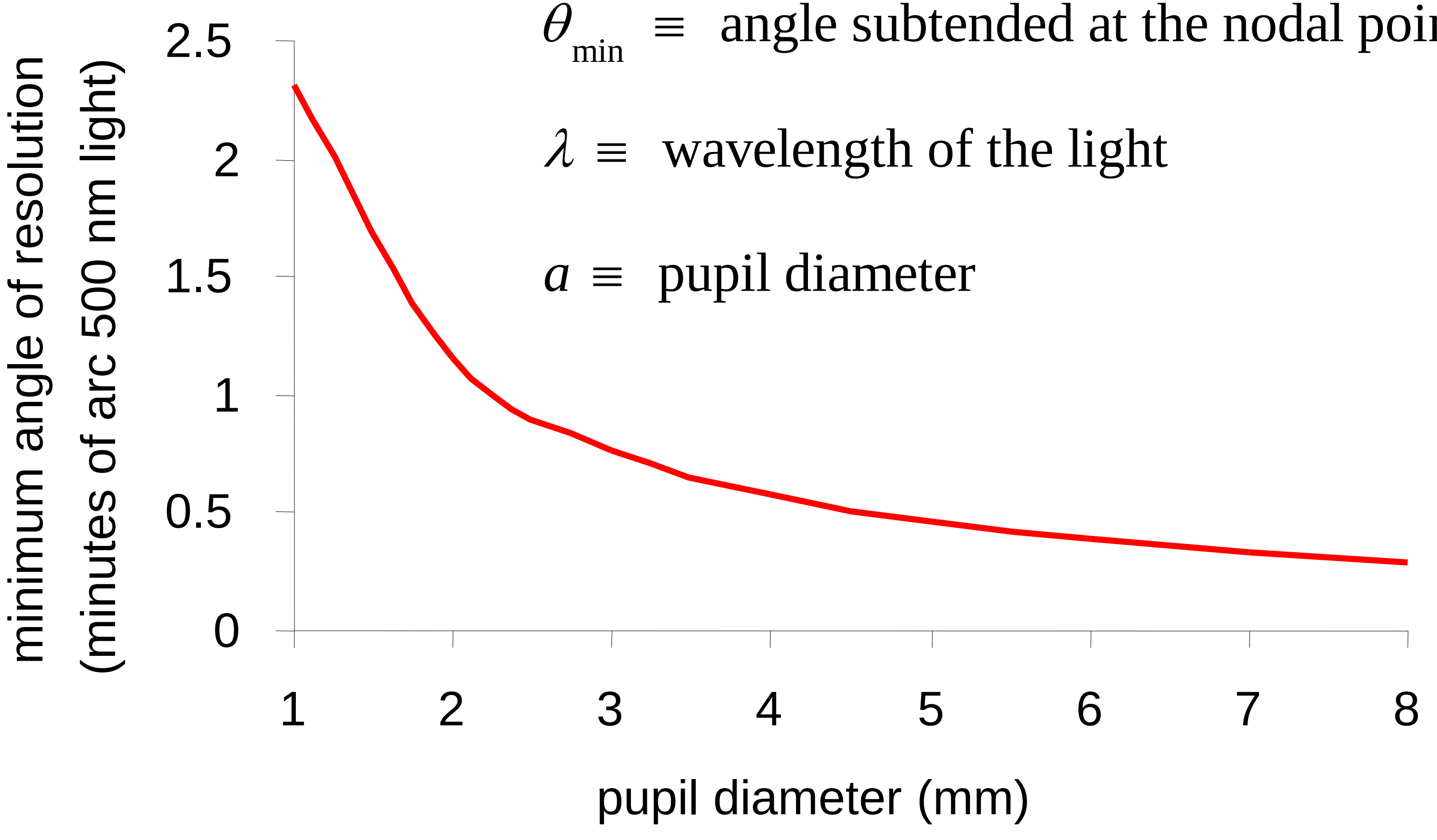
2.4 Resolution

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

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

$\lambda \equiv$ wavelength of the light

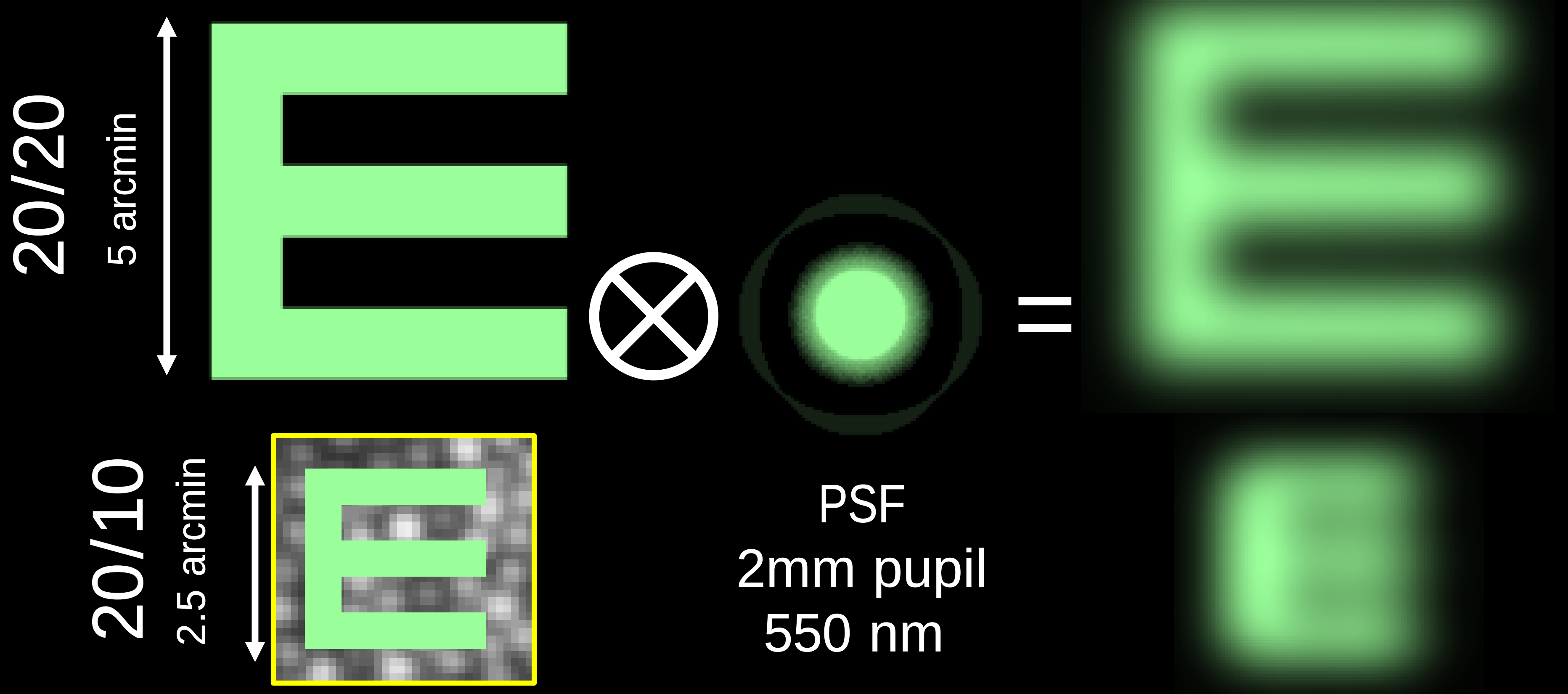
$a \equiv$ pupil diameter



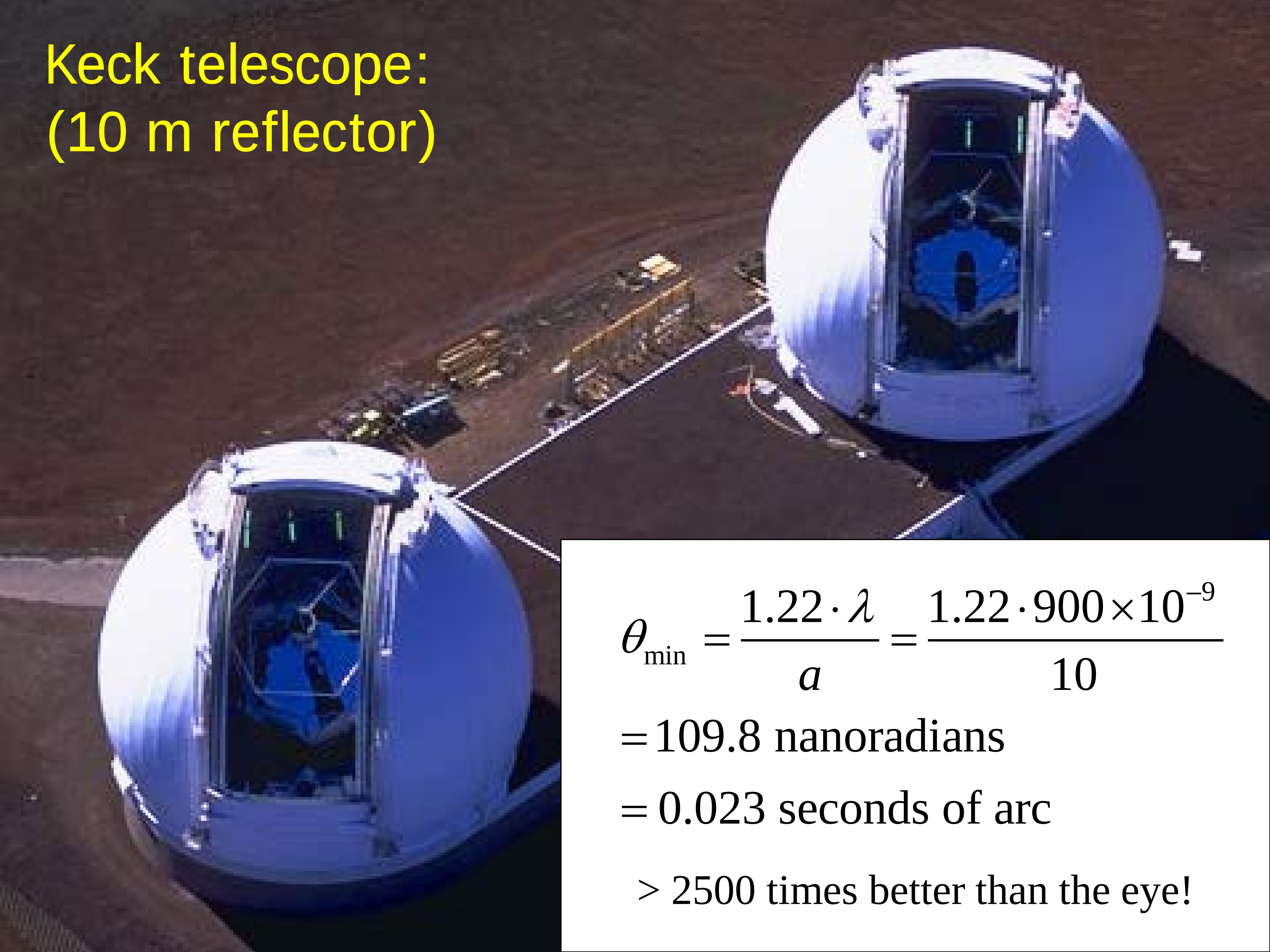
2.4 Resolution

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

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



Keck telescope:
(10 m reflector)



$$\theta_{\min} = \frac{1.22 \cdot \lambda}{a} = \frac{1.22 \cdot 900 \times 10^{-9}}{10}$$

$$= 109.8 \text{ nanoradians}$$

$$= 0.023 \text{ seconds of arc}$$

> 2500 times better than the eye!

2.5 Light scatter in the human eye

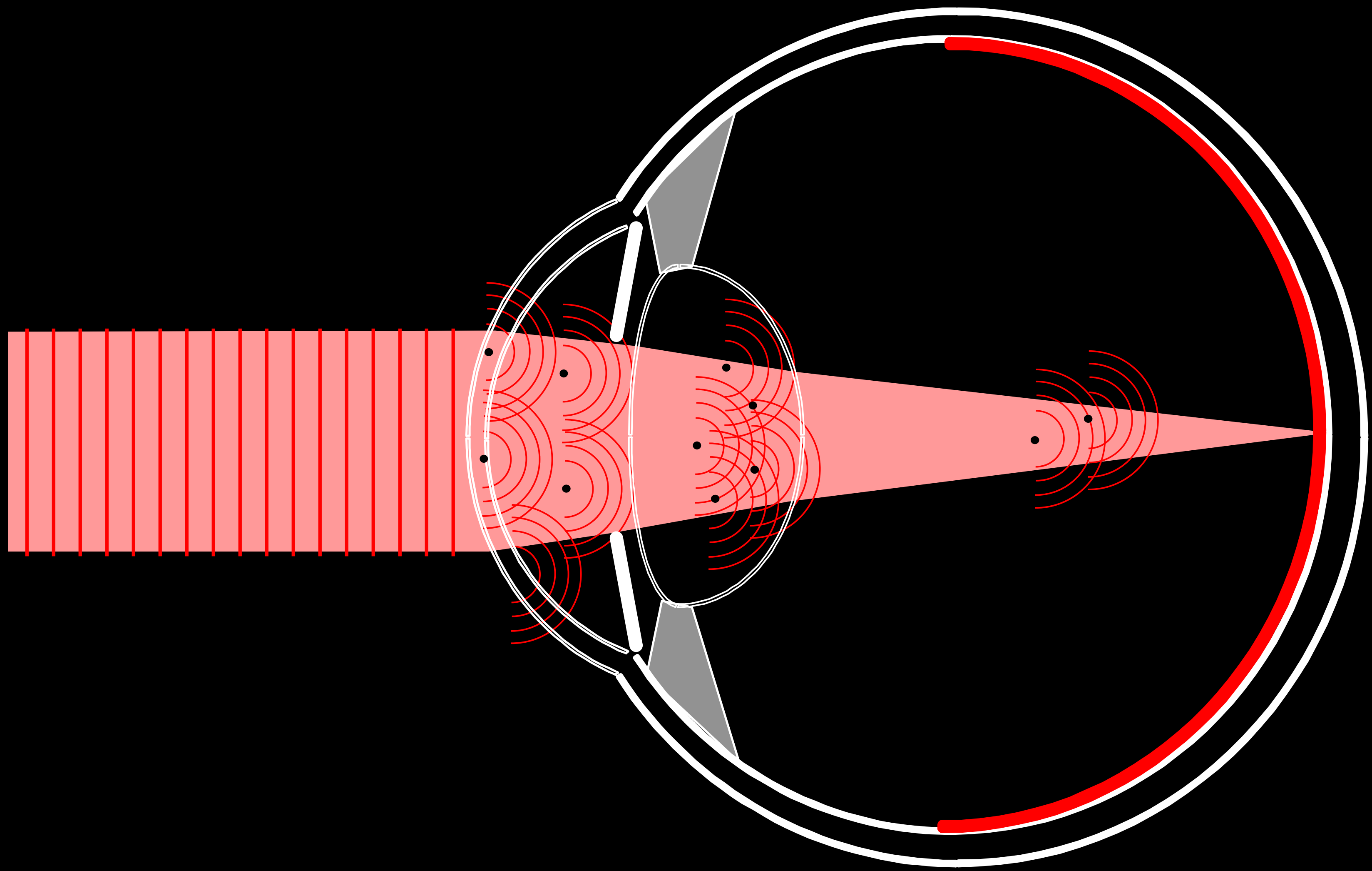
slides courtesy of
Thomas J. T. P. van den Berg
The Netherlands Ophthalmic Research Institute of the Royal Netherlands Academy of Arts and Sciences,
Amsterdam, The Netherlands;

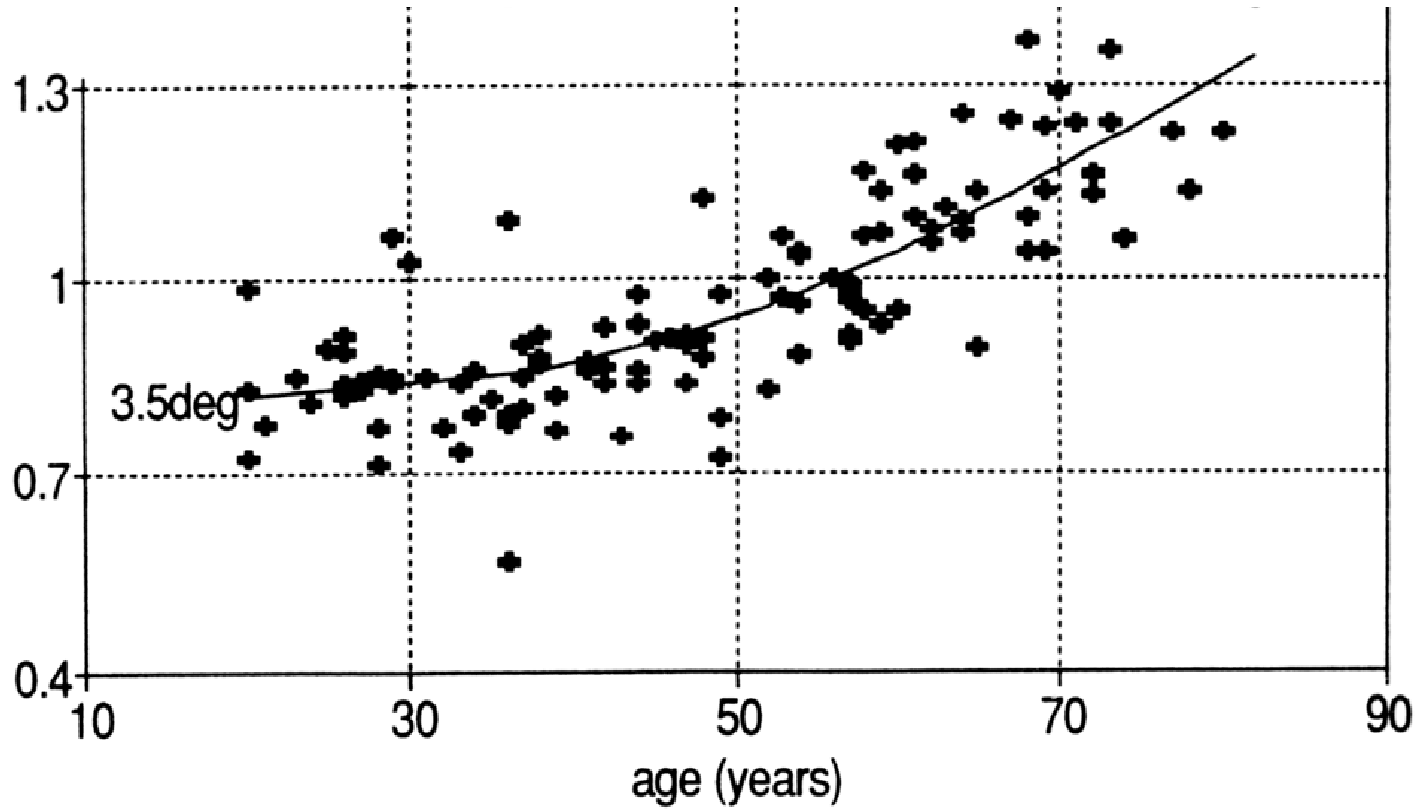
Published in:

van den Berg TJ, Hagenouw MP, Coppens JE. The ciliary corona: physical model and simulation of the fine needles radiating from point light sources. Invest Ophthalmol Vis Sci 2005; 46(7):2627-2632.

Tom van den Berg

Sources of Scatter

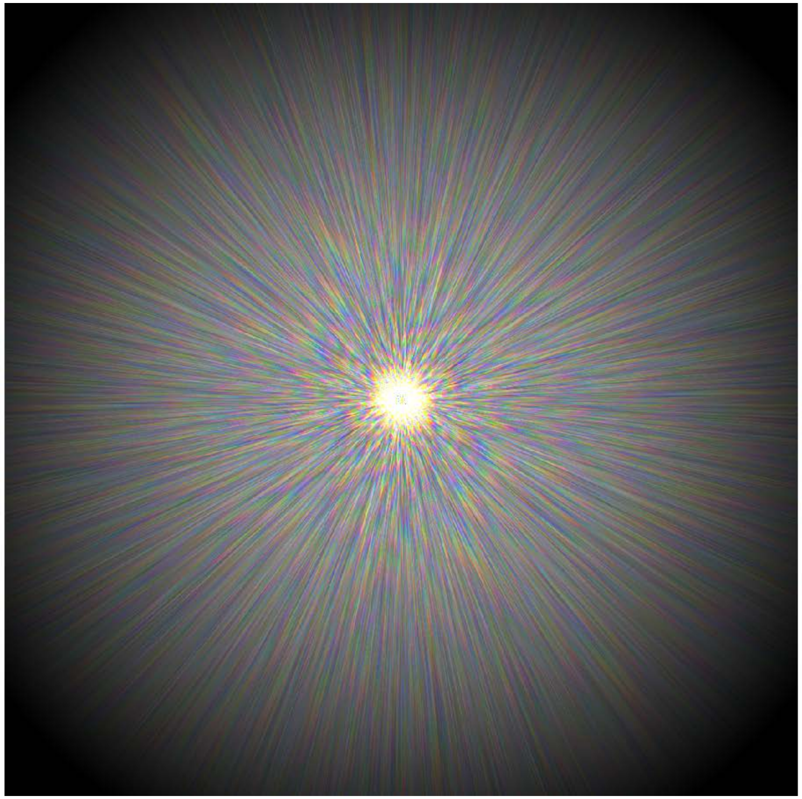




Tom van den Berg

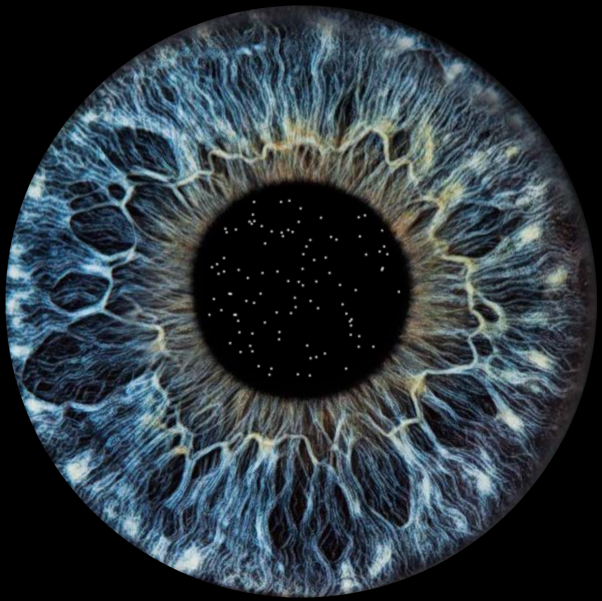
Ciliary corona

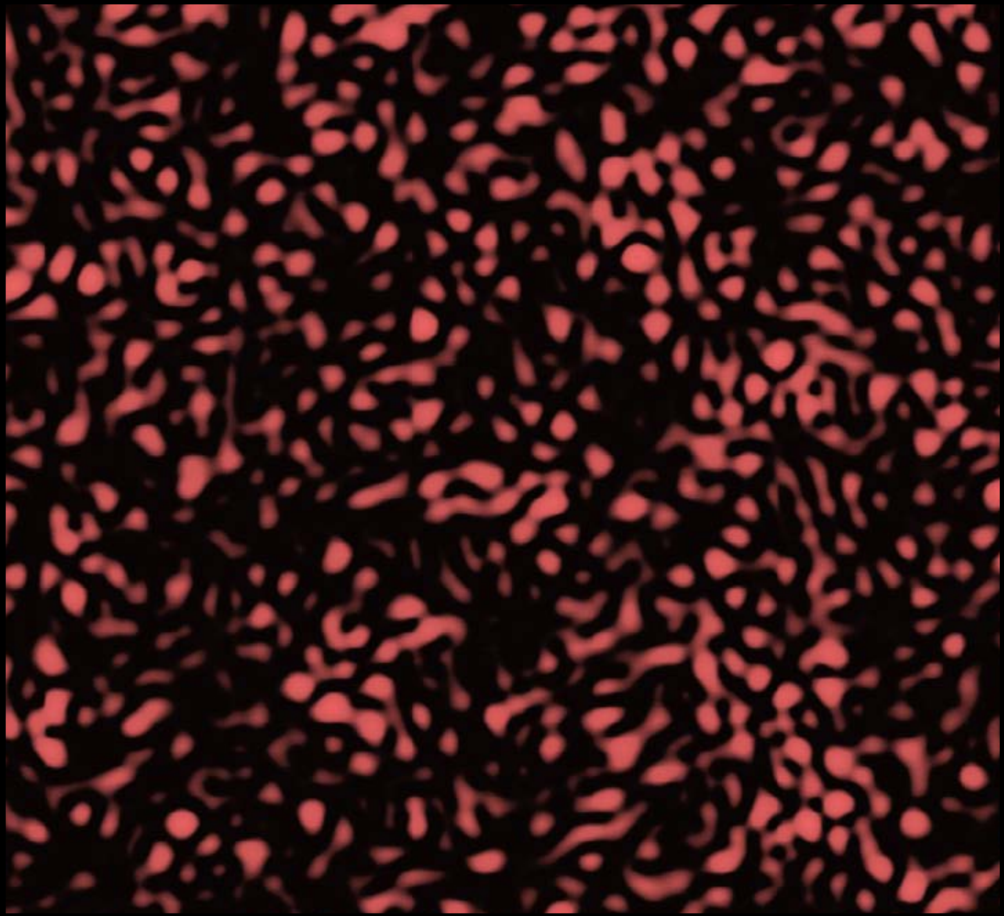
Actual subjective appearance of straylight: a pattern of very fine streaks, not at all like the circularly uniform (Airy disc-like) scattering pattern of particles of approximate wavelength size

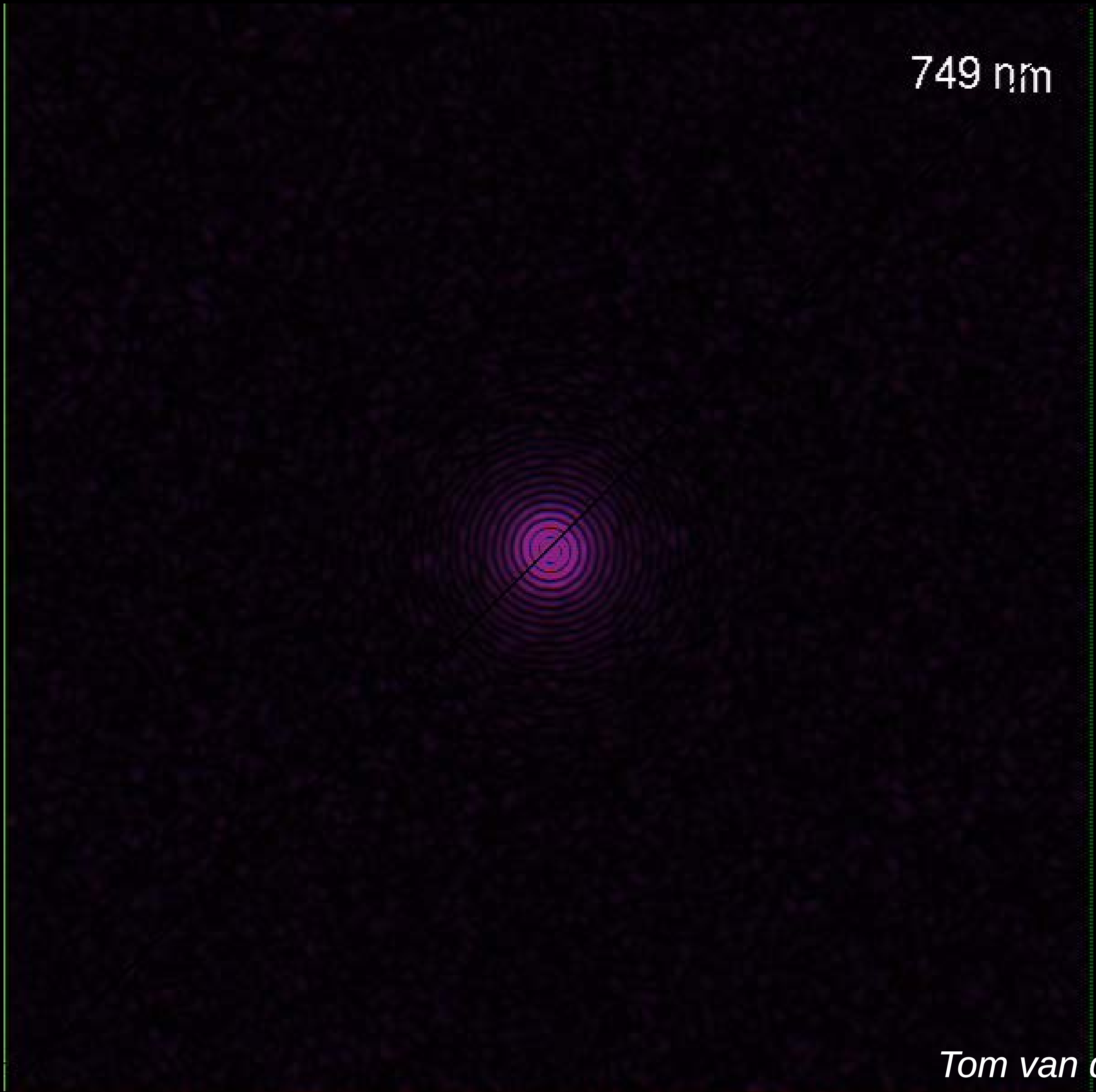


Tom van den Berg

Effect of Scatter on Retinal Surface







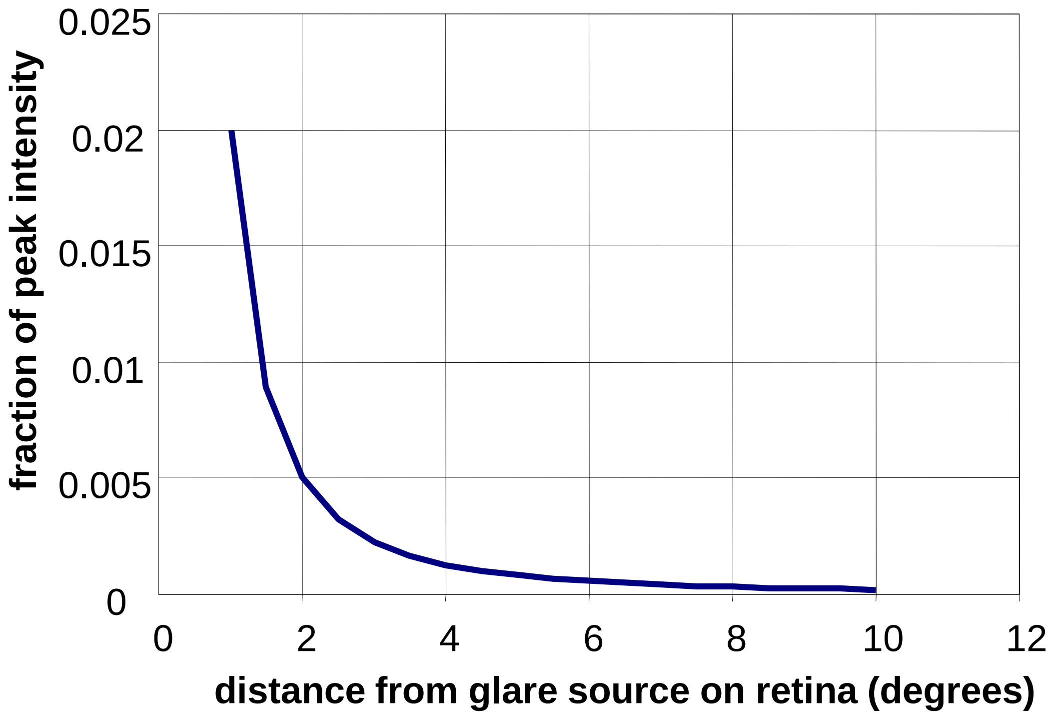
Tom van den Berg

Tom van den Berg

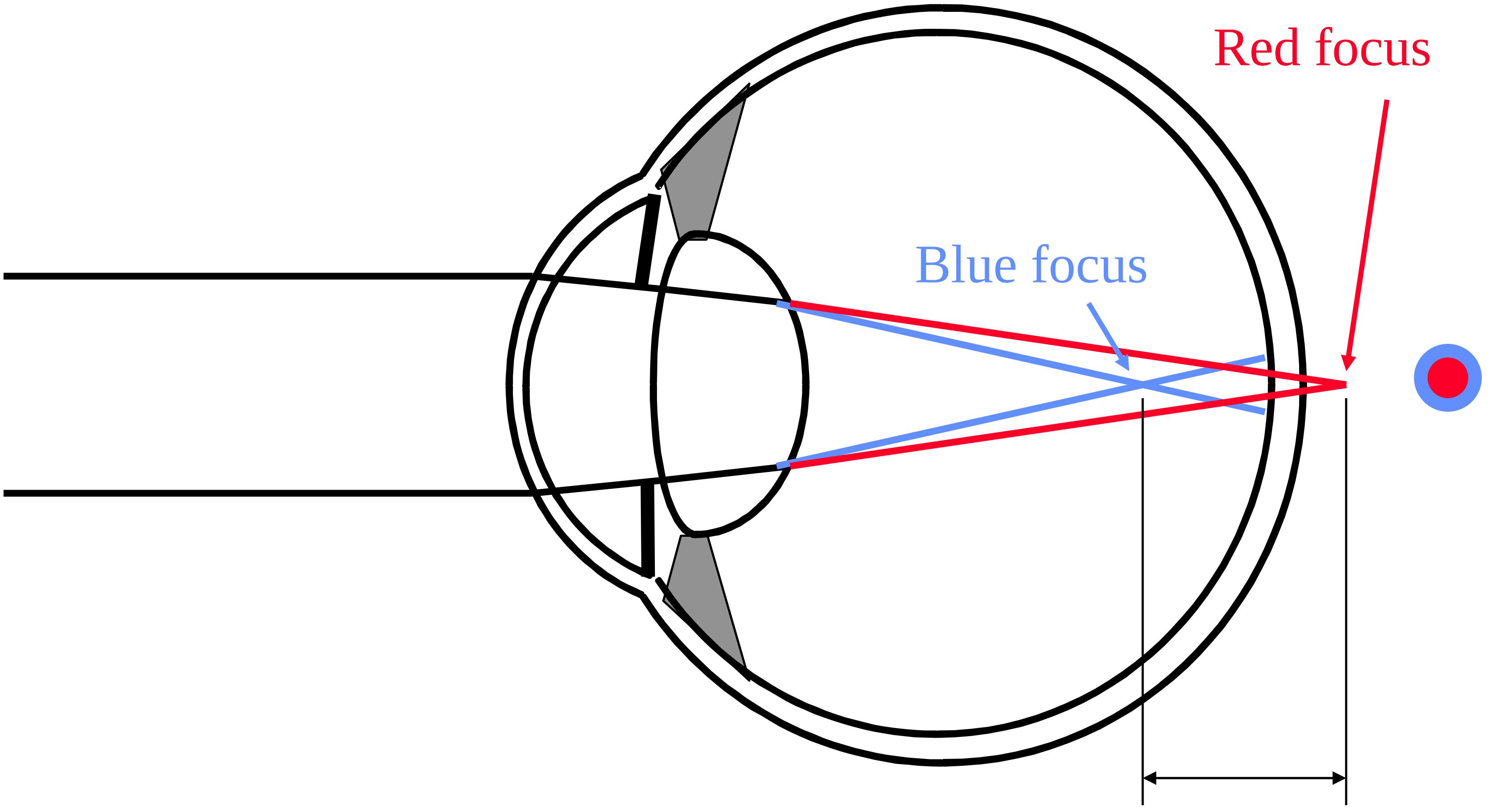
2.5 Straylight (Glare) Equation

$$I = \frac{AE}{\theta^n}$$	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.

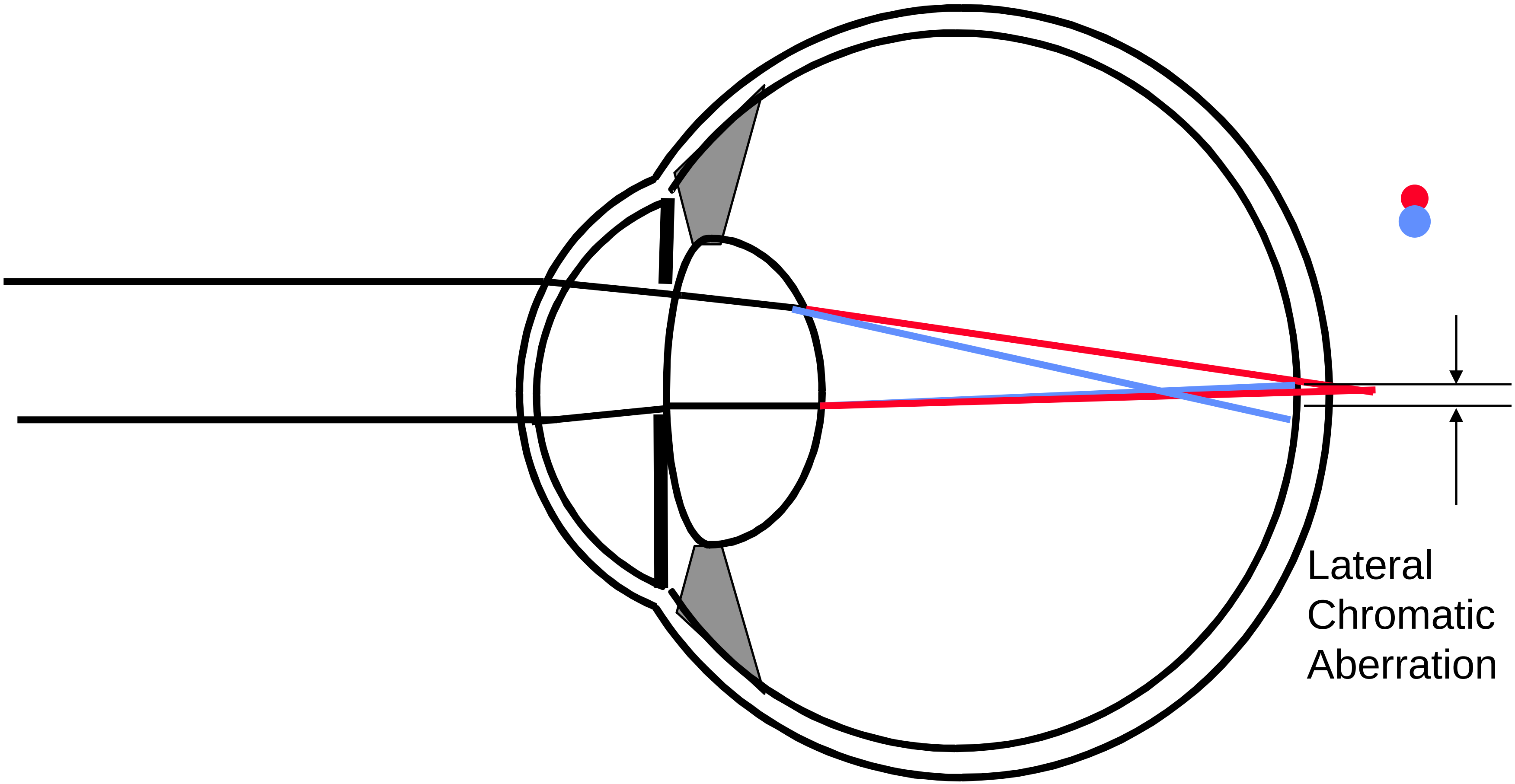


2.6 Chromatic Aberration



Longitudinal Chromatic Aberration

2.6 Chromatic Aberration



2.6 Chromatic Aberration

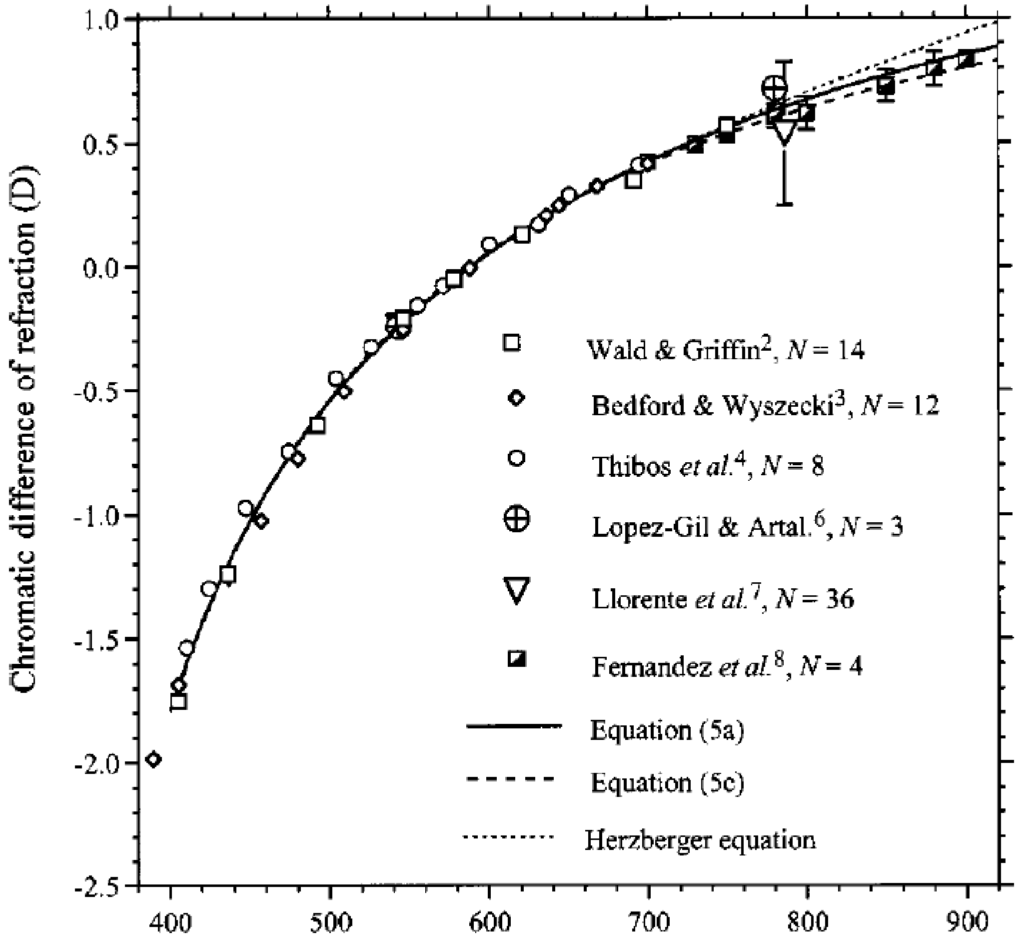


Fig. 1. Chromatic difference of refraction from three experimental studies2–4 in the visible spectrum and best-fit Cauchy equation (5a), Cornu's equation (5c), and Herzberger's equation to the combined studies. All data were set to be zero at 590 nm. Results of three studies6–8 with measurements in the 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.

2.6 Chromatic Aberration

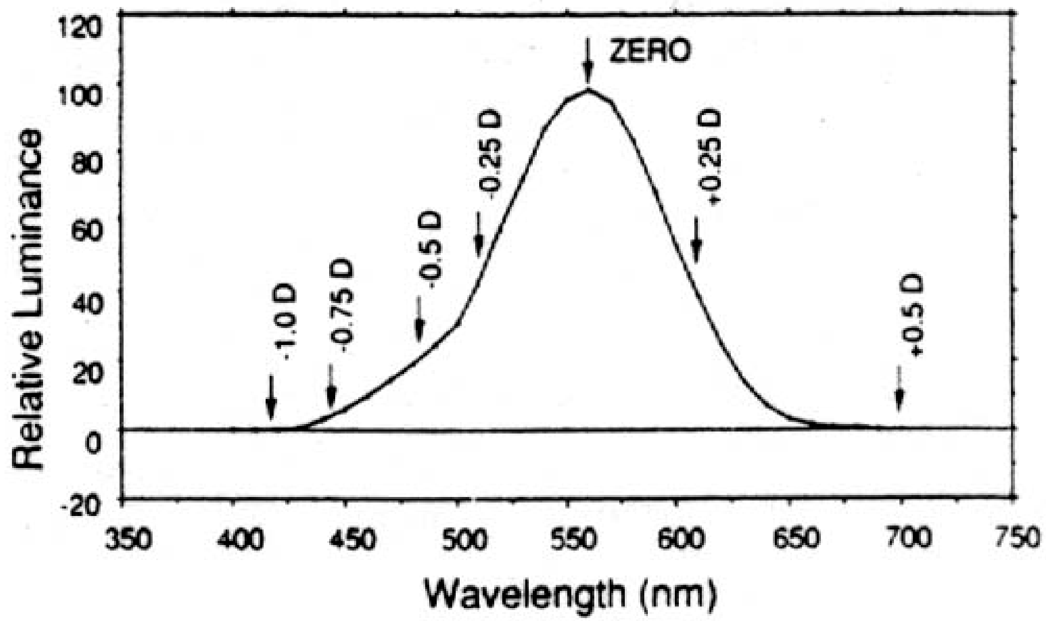
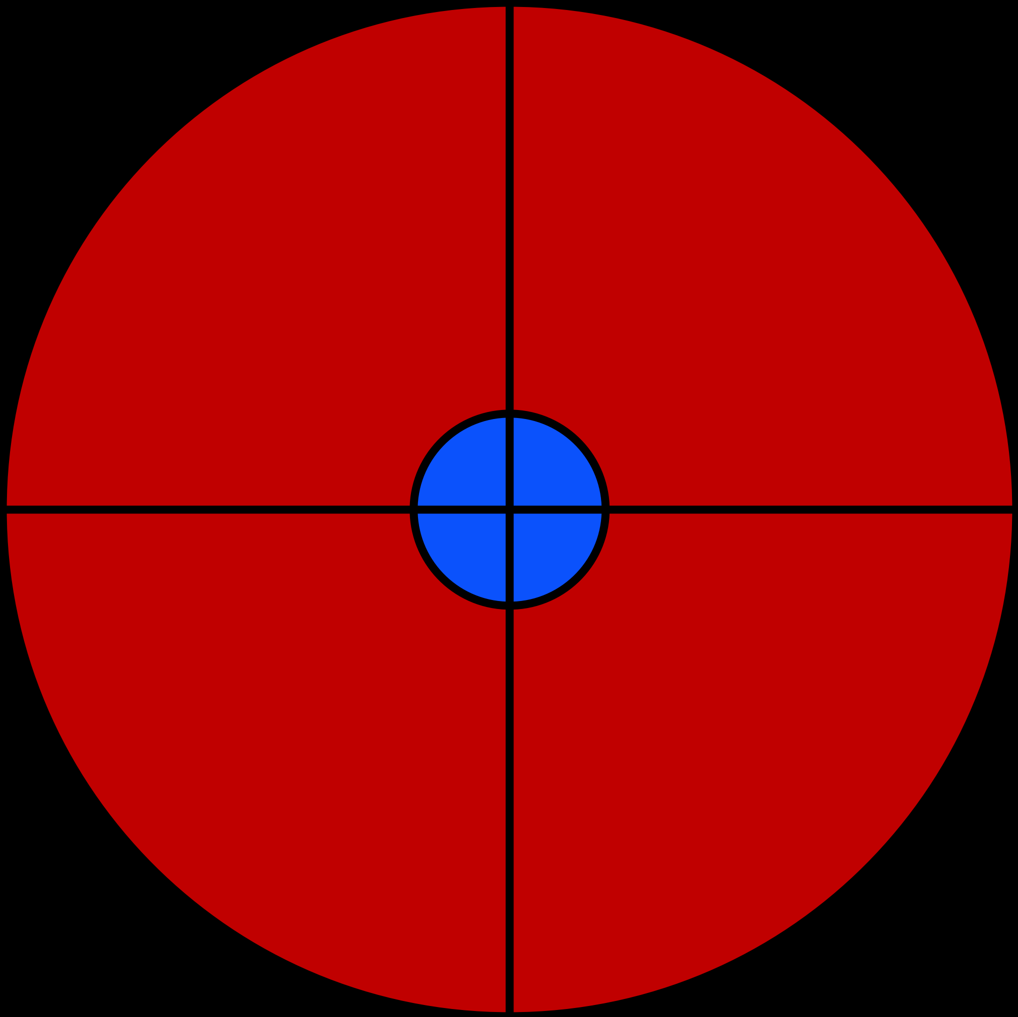


Figure 3. The significance of chromatic defocus depends on luminance. The solid curve shows the luminance spectrum of white-light emitted by the P4 phosphor of cathode ray tubes and arrows mark the amount of defocus if the eye accommodates for 550 nm. When the peak of the luminance spectrum is in focus,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

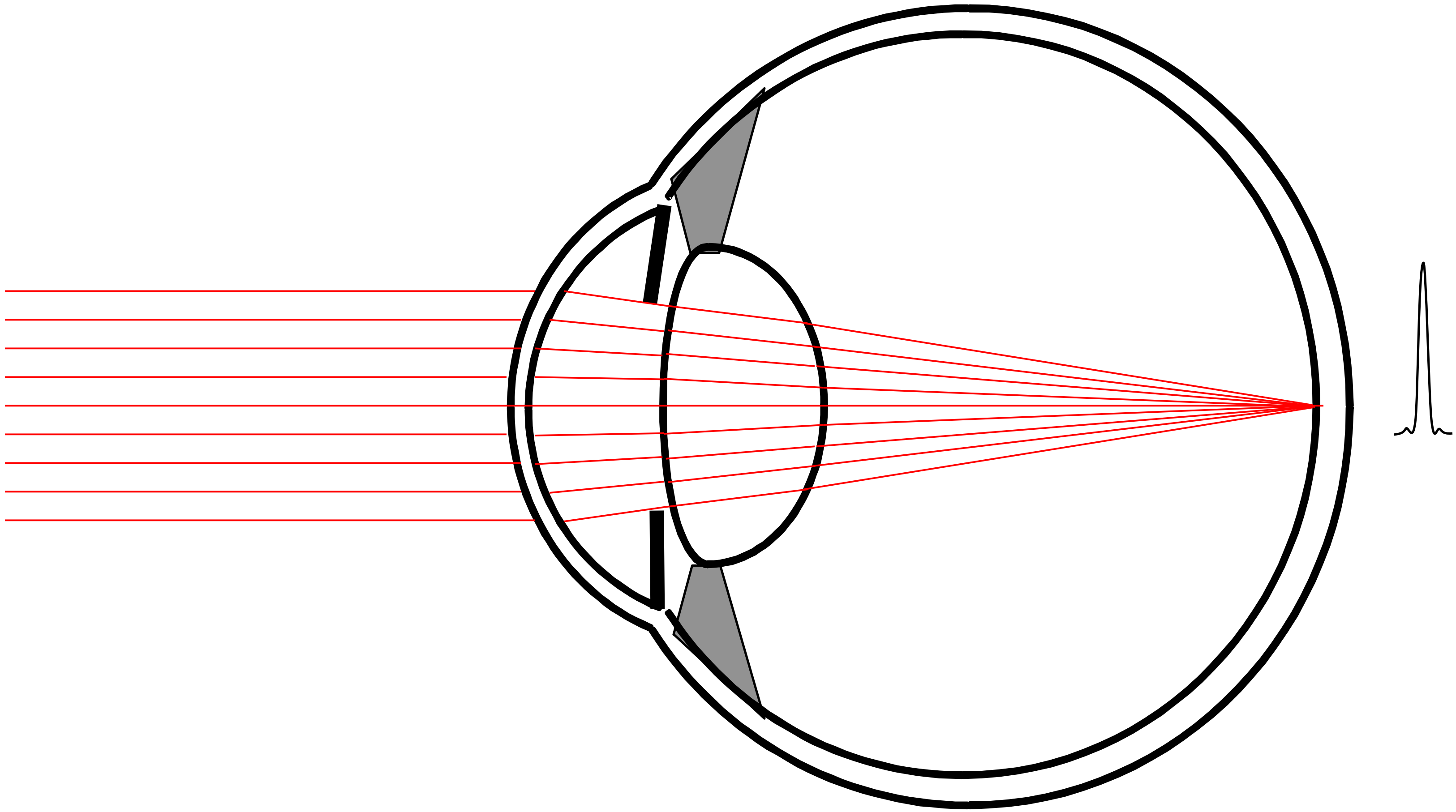
Thibos, Bradley & Zhang, 1989

2.6 Chromatic Aberration



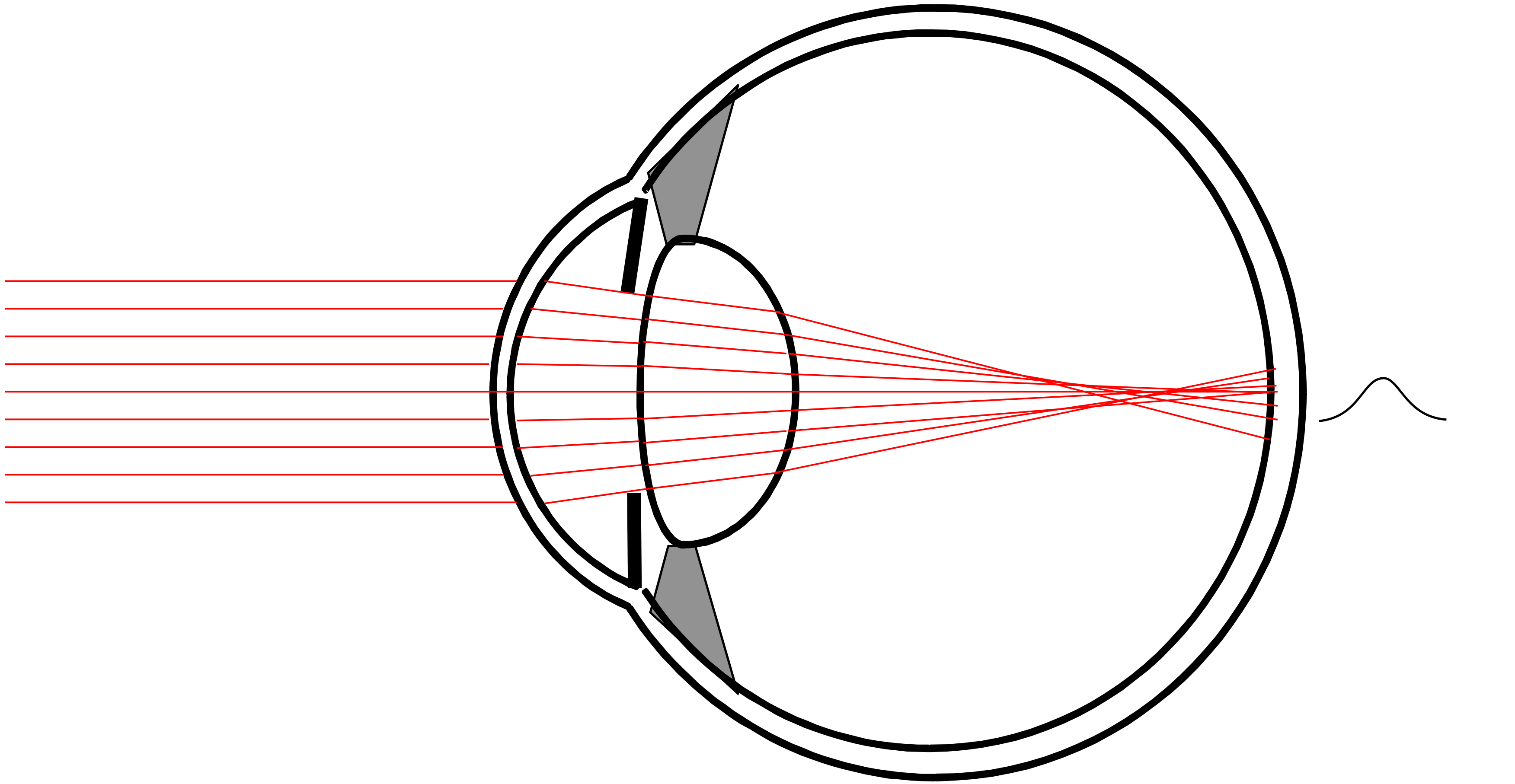
2.7 Monochromatic Aberrations

Perfect Eye
(limited only by diffraction)



2.7 Monochromatic Aberrations

Aberrated Eye



2.8 The Total Aberrations of the Eye

"*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.

2.8 The Total Aberrations of the Eye

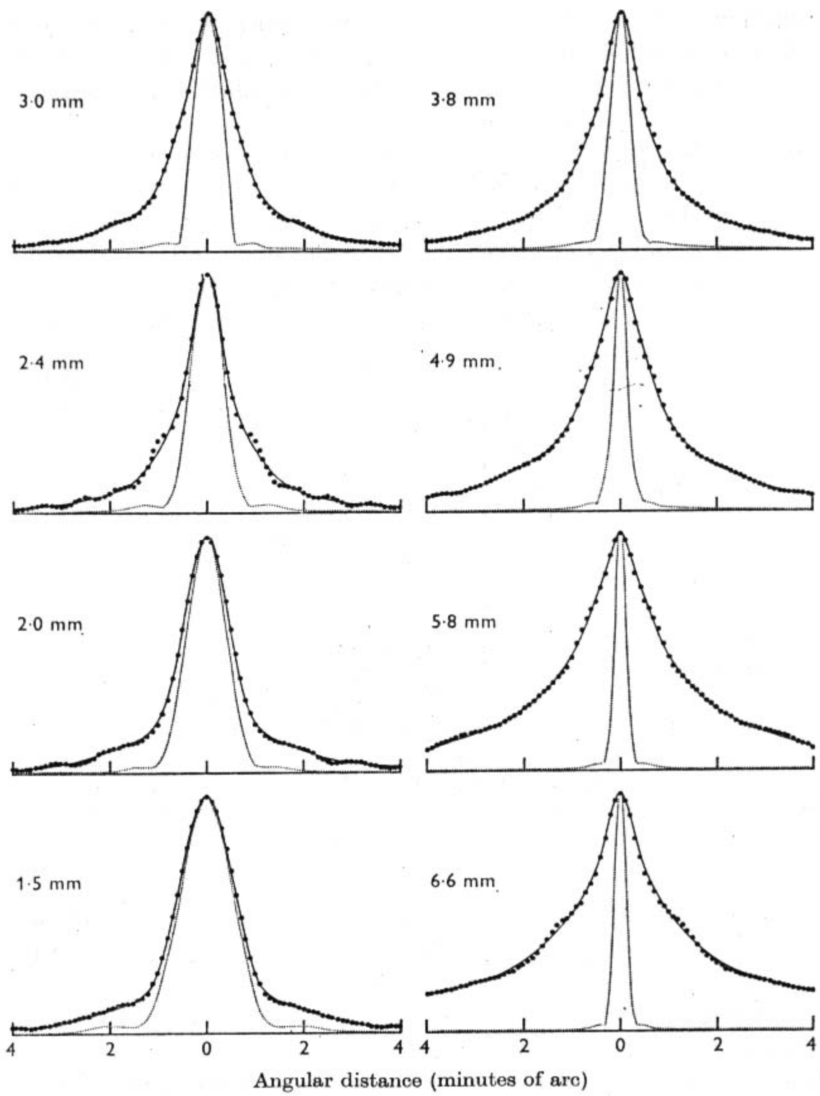
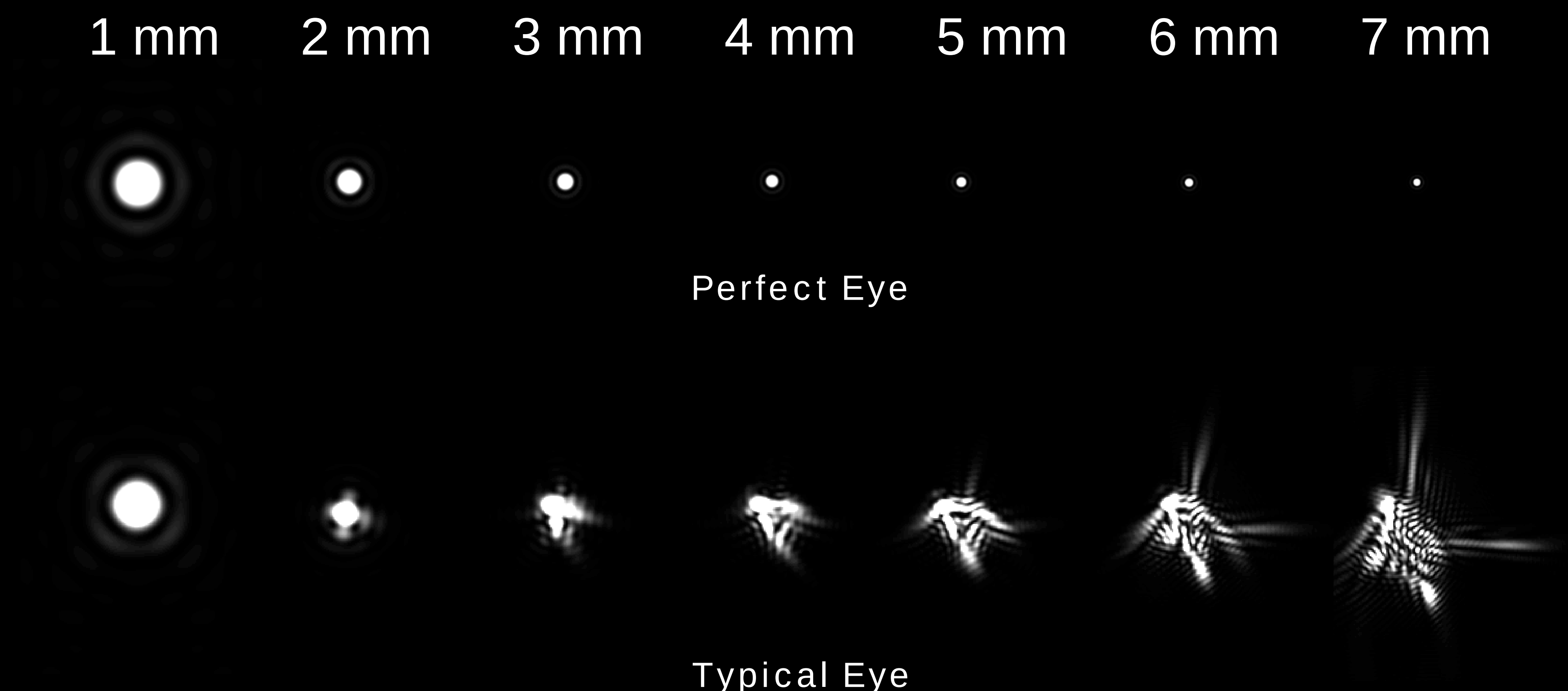


Fig. 10. Optical linespread functions of the human eye. Each curve represents the normalized distribution of illuminance occurring on the fundus for a thin line source of light. Dots occur at 0·1 min increments. Narrower curve indicates the diffraction image of a line at the given pupil diameter.

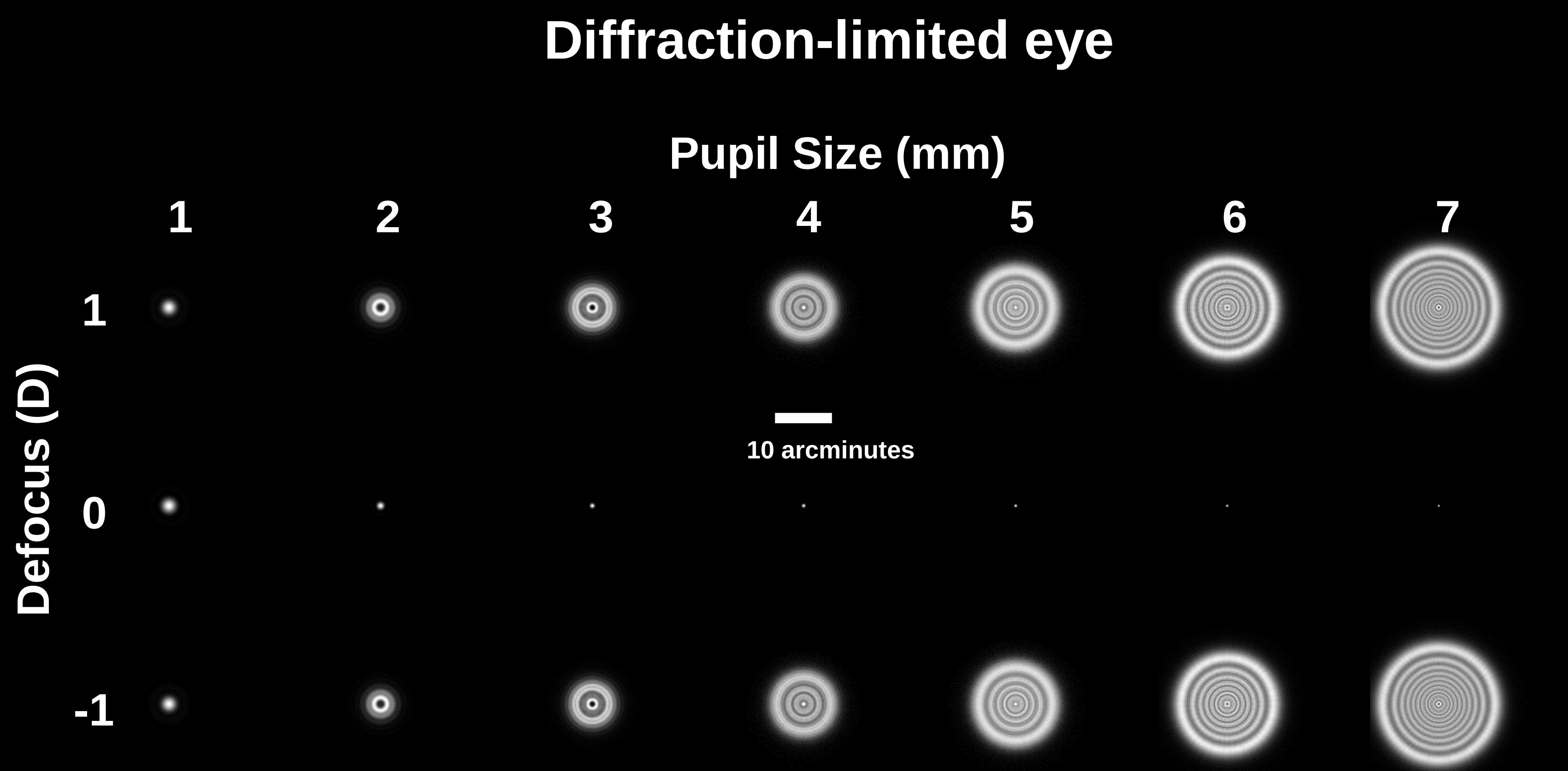
Change in the line spread function with pupil size

Campbell & Gubisch, 1966

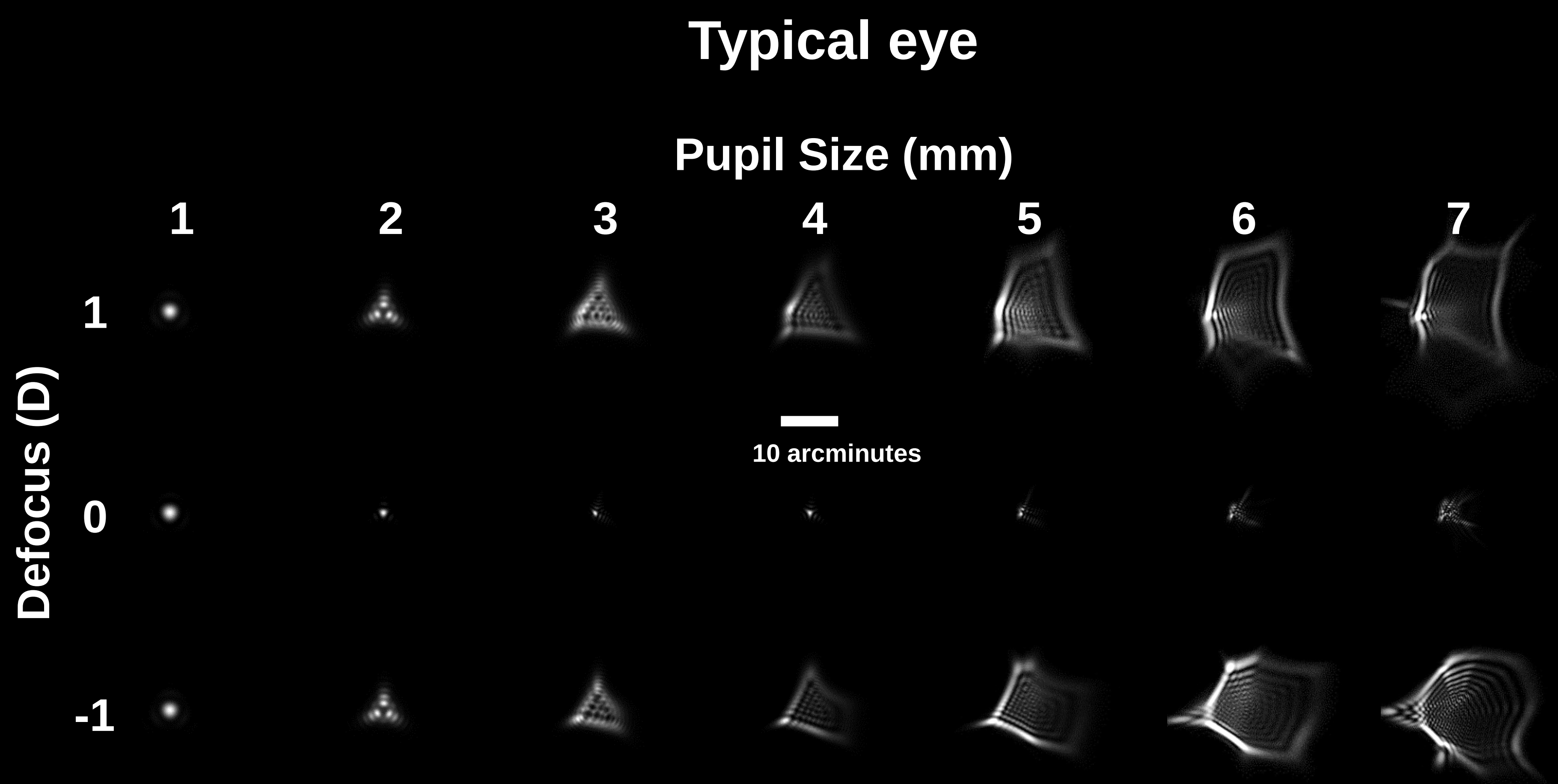
2.8 The Total Aberrations of the Eye



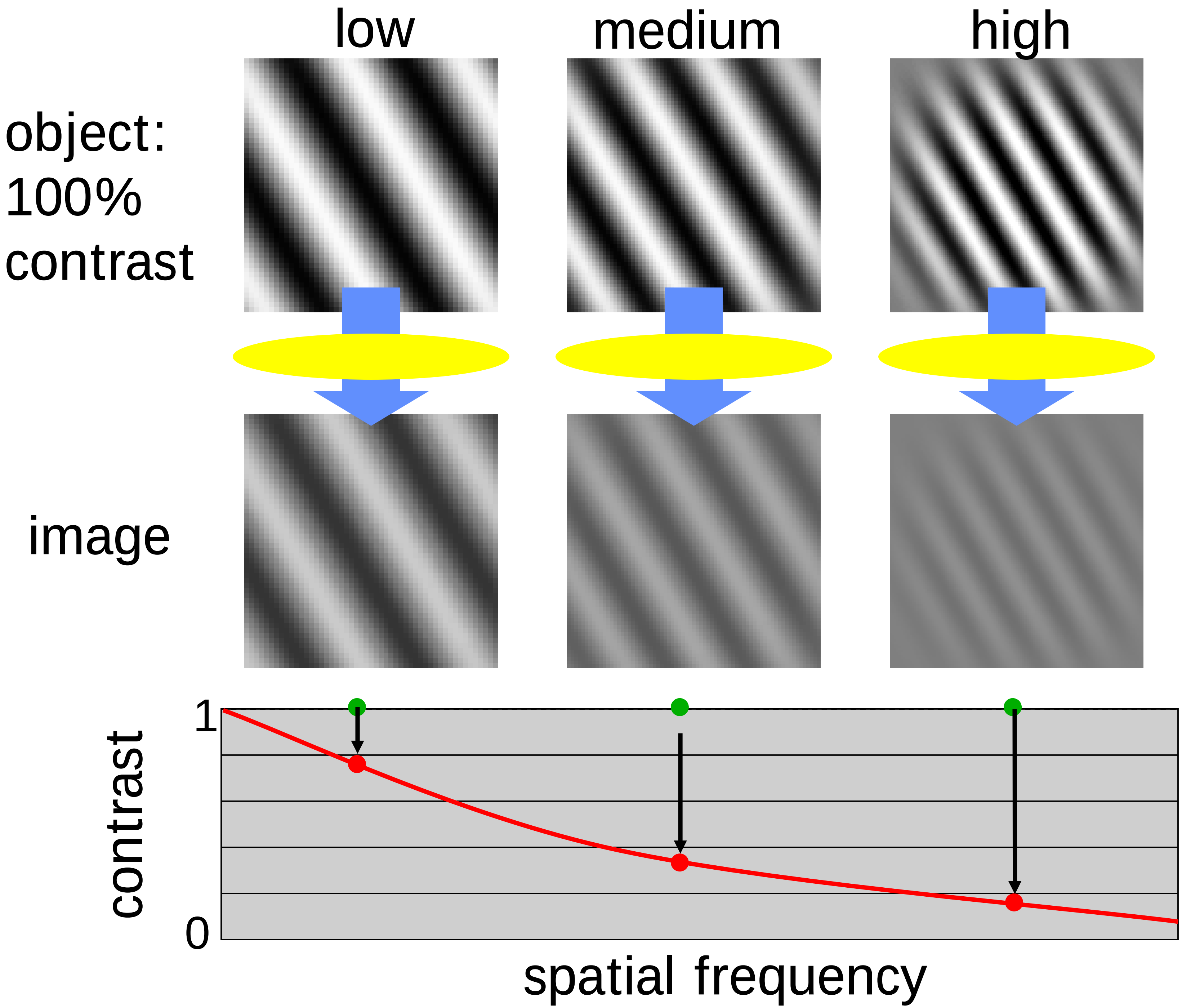
2.8 The Total Aberrations of the Eye



2.8 The Total Aberrations of the Eye



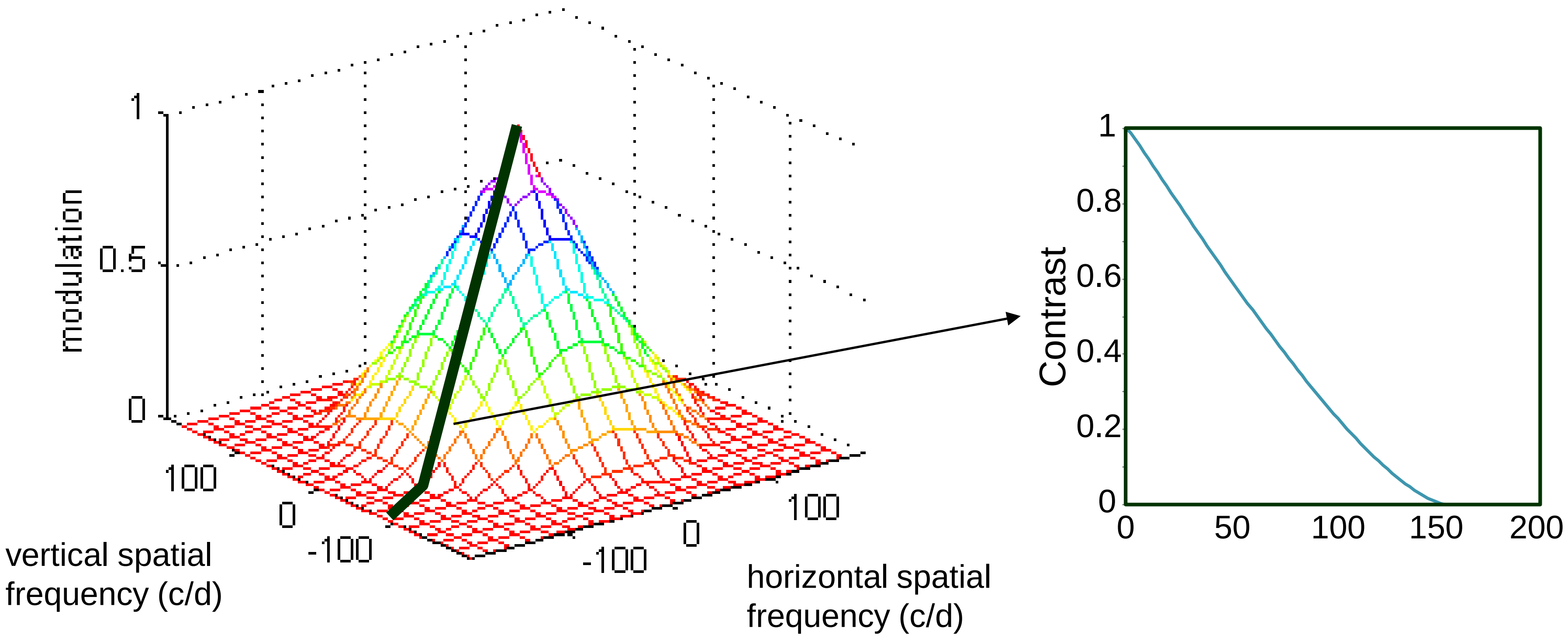
2.9 The Modulation Transfer Function, or MTF



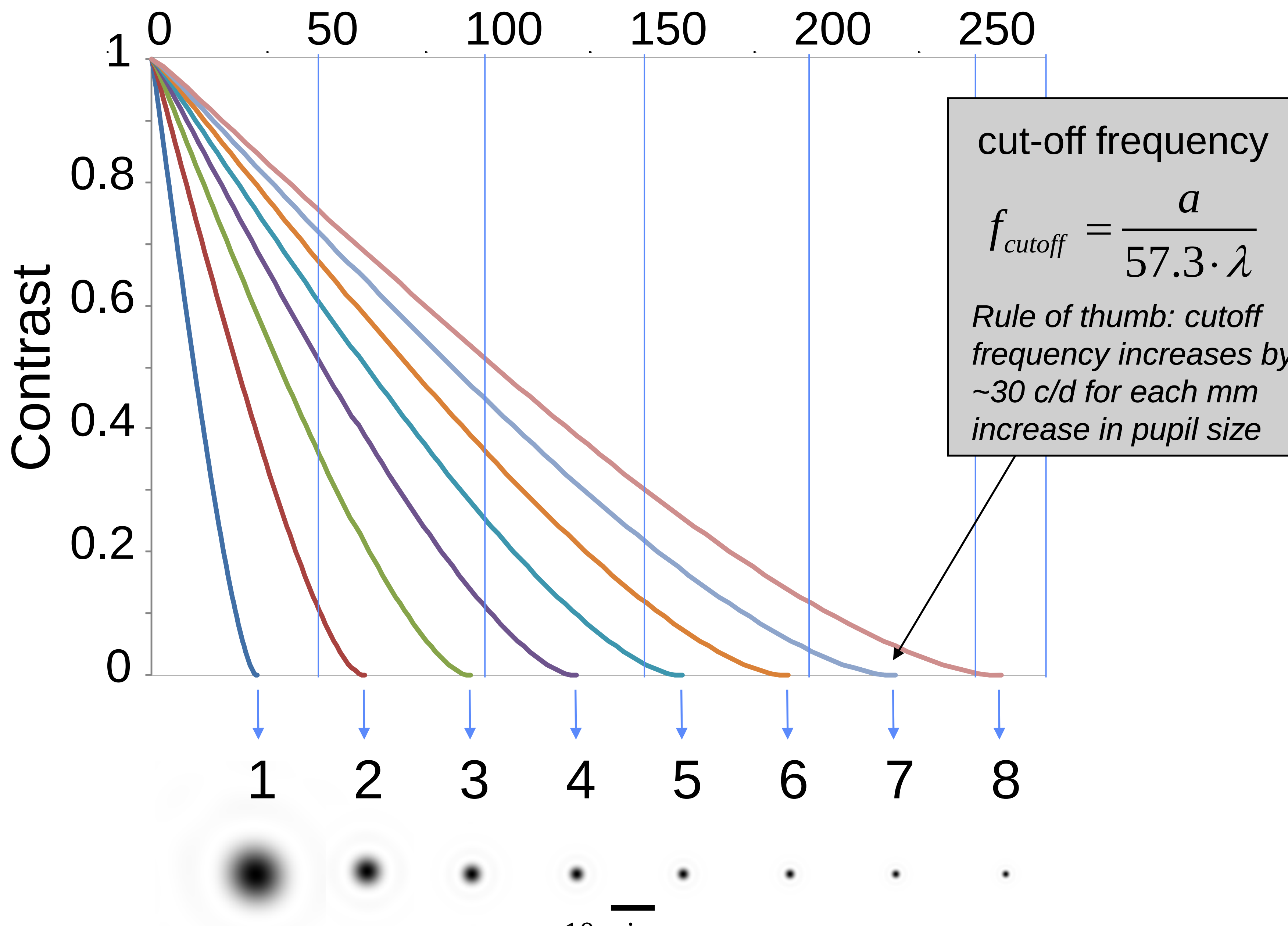
low
medium
high
object:
100%
contrast
image
1
0
contrast
spatial frequency

2.9 The Modulation Transfer Function

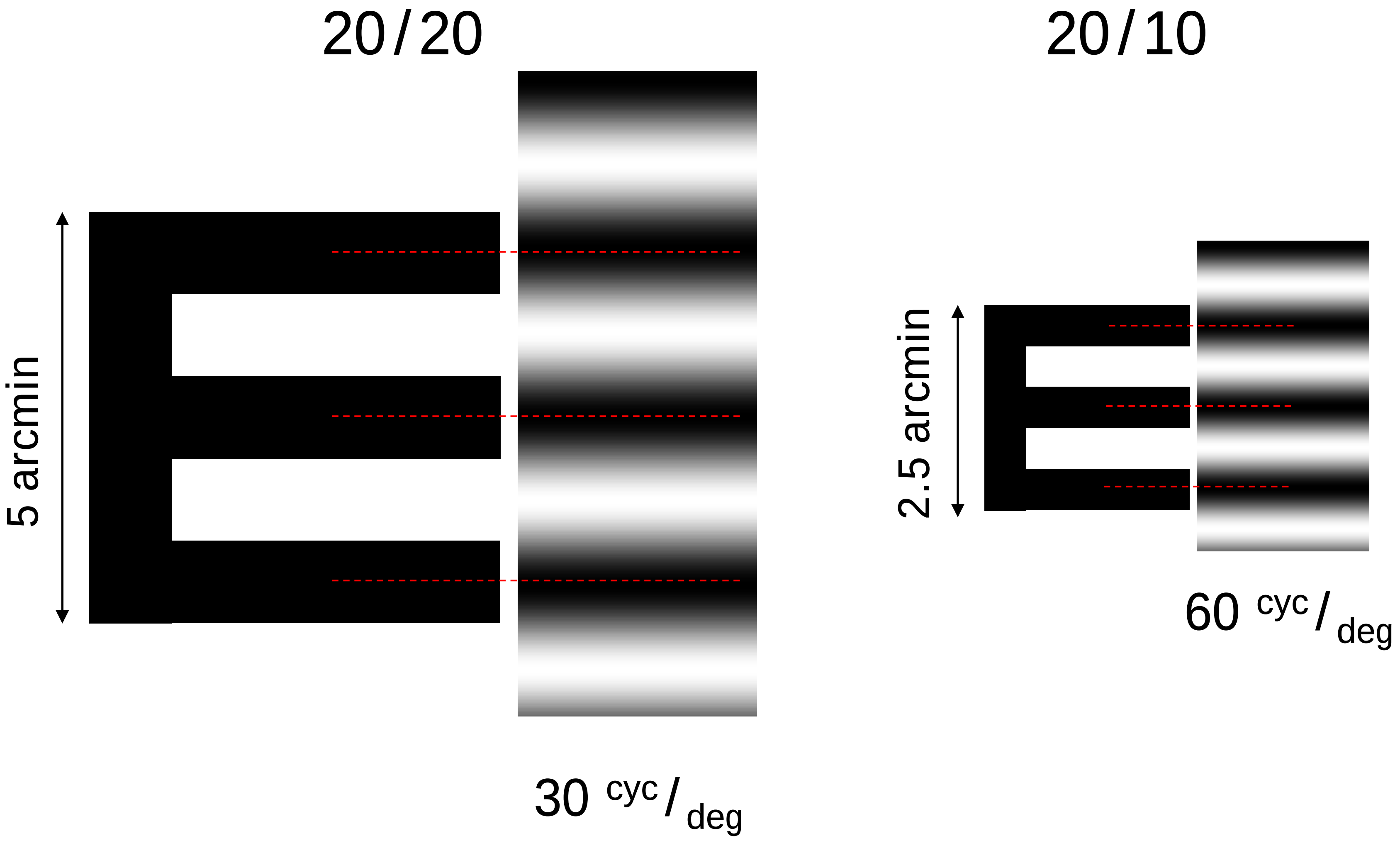
3D MTF



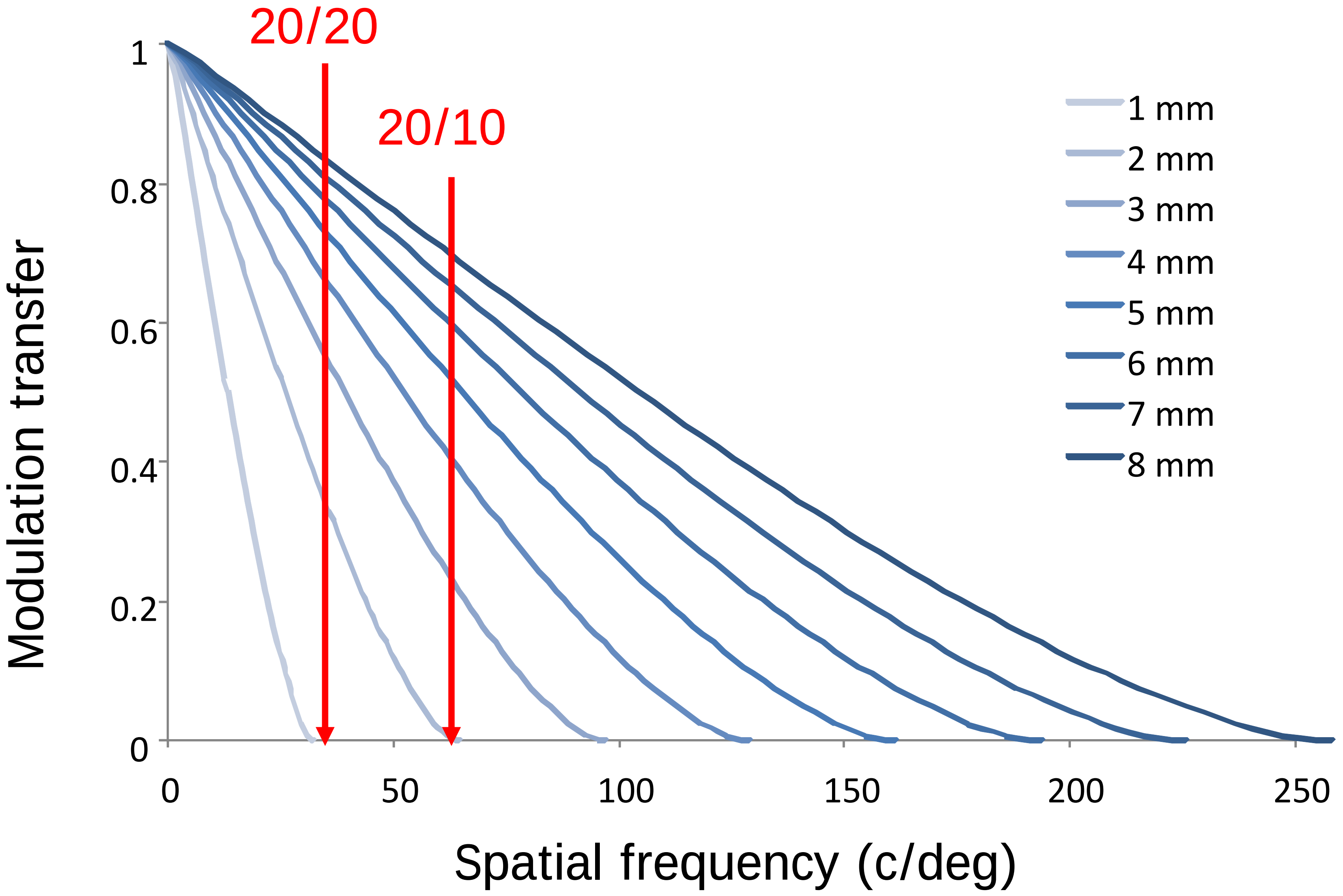
2.9 The Modulation Transfer Function



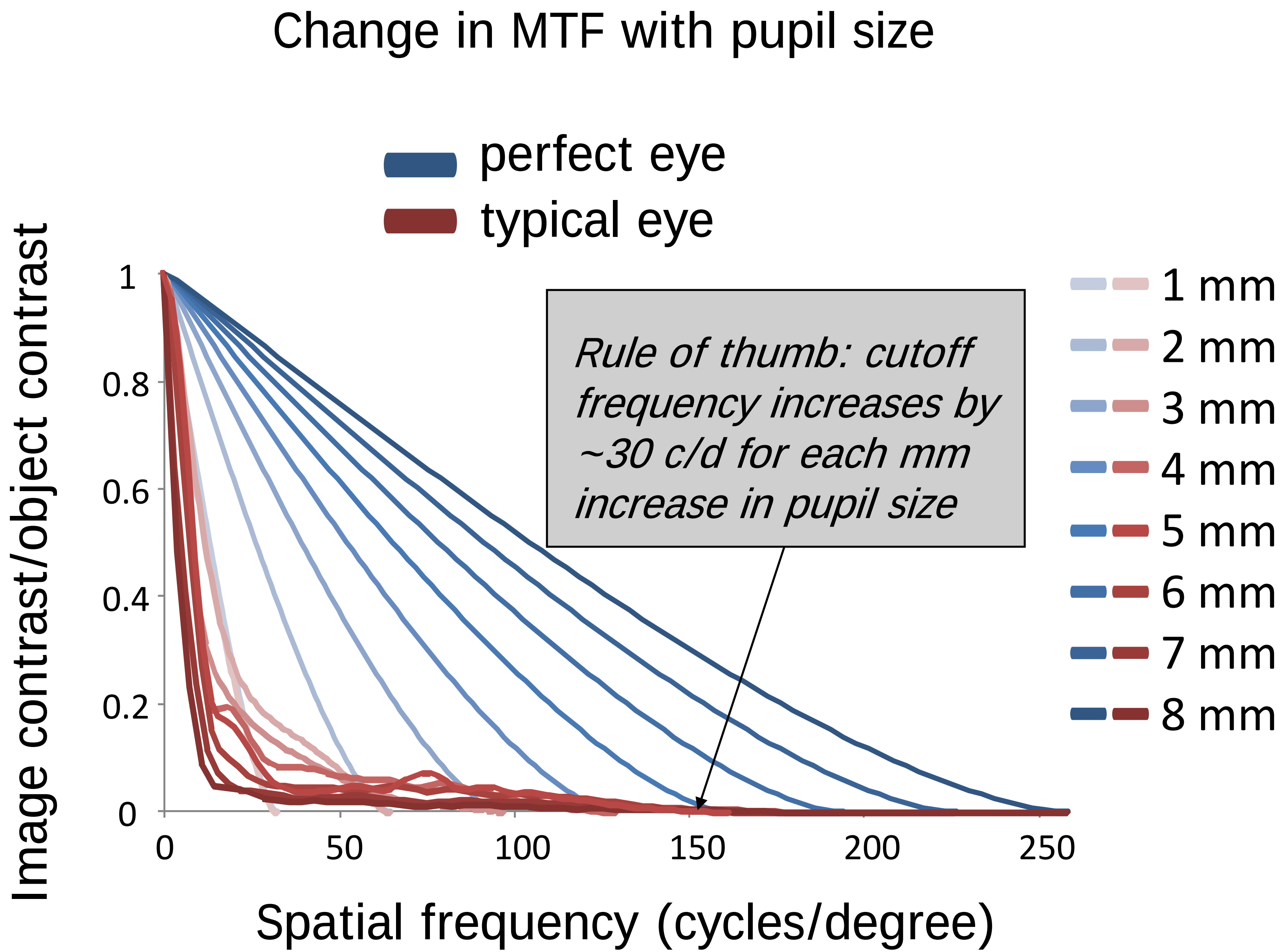
2.9 The Modulation Transfer Function



2.9 The Modulation Transfer Function

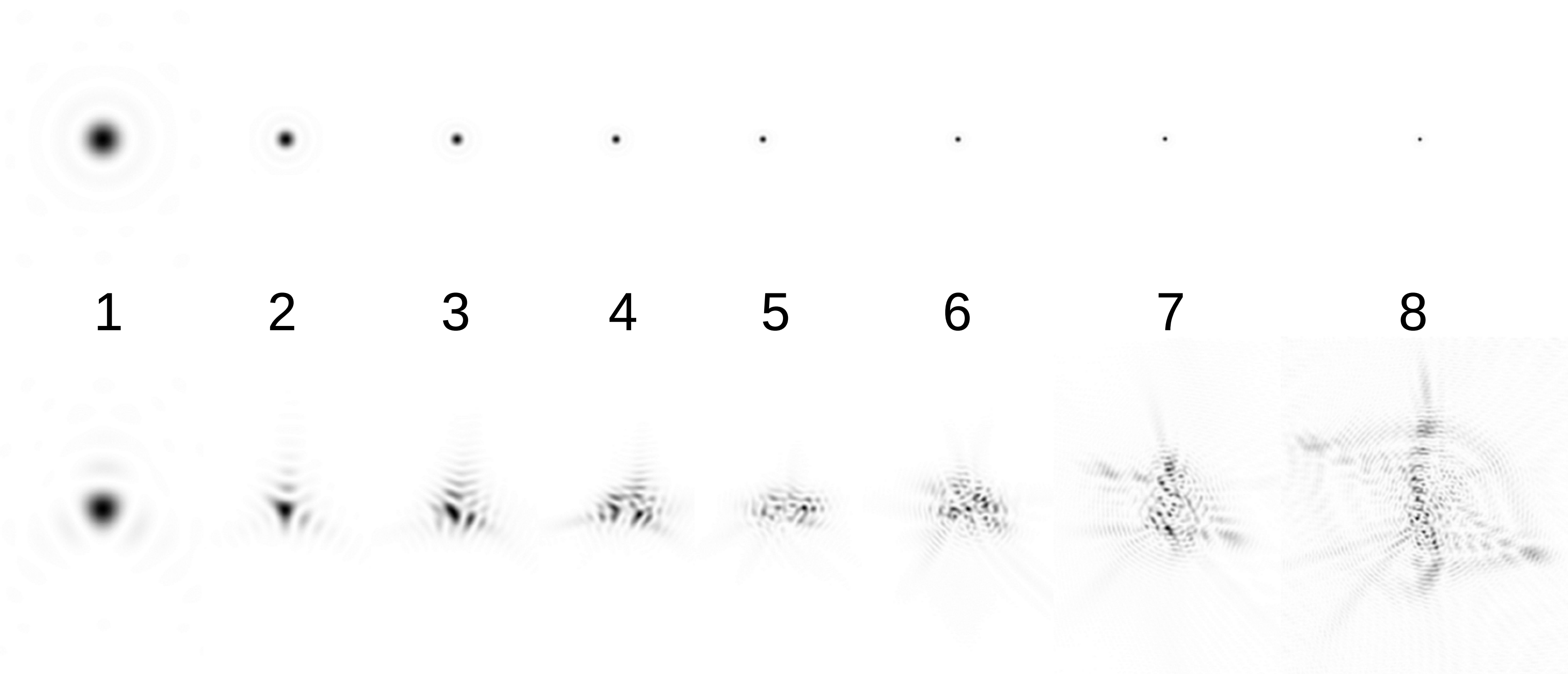


2.9 The Modulation Transfer Function

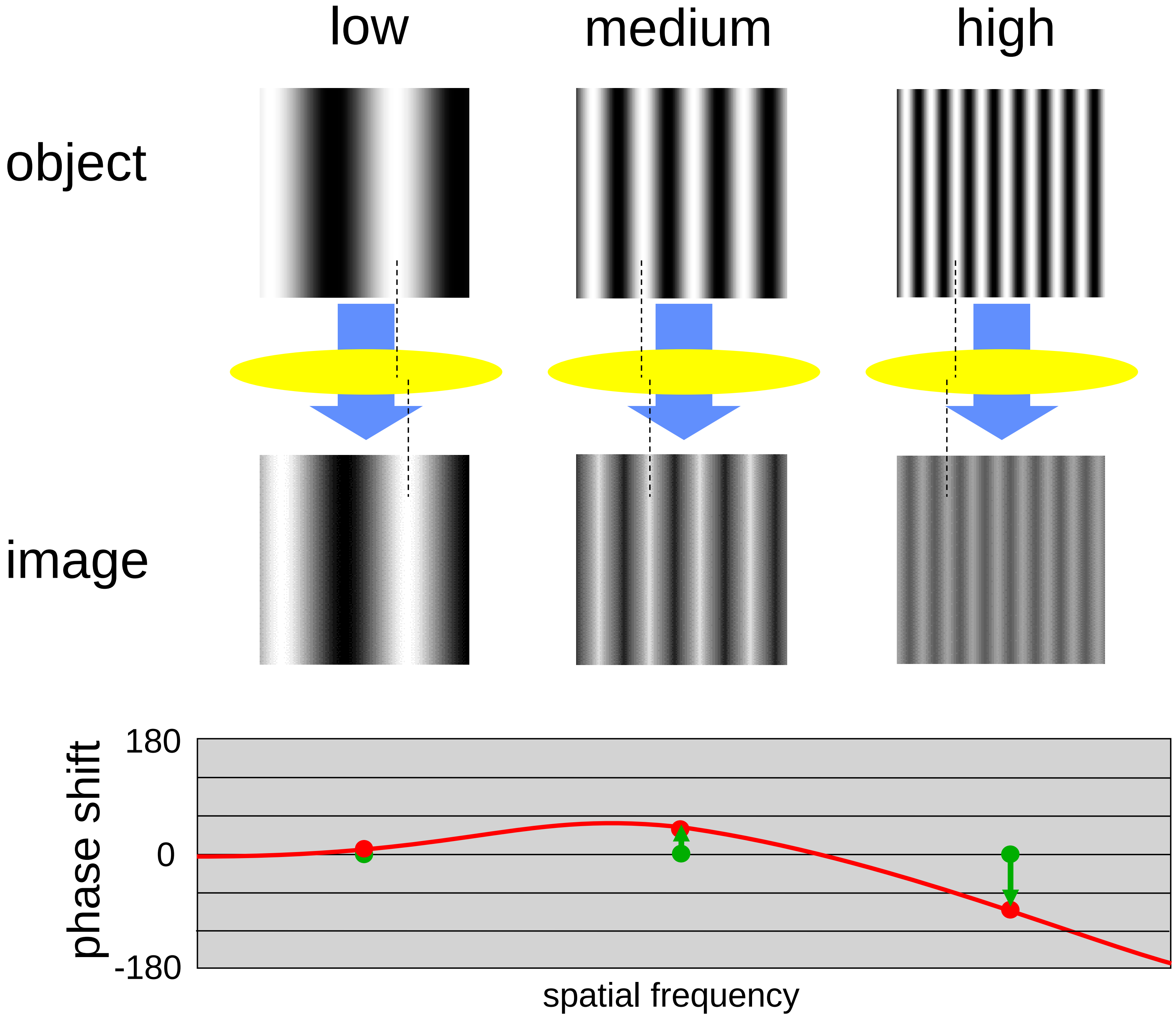


2.9 The Modulation Transfer Function

PSFs for the same eye



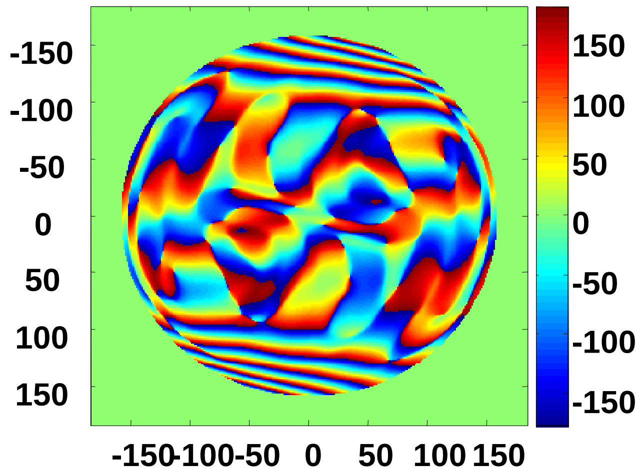
2.10 The Phase Transfer Function, or PTF

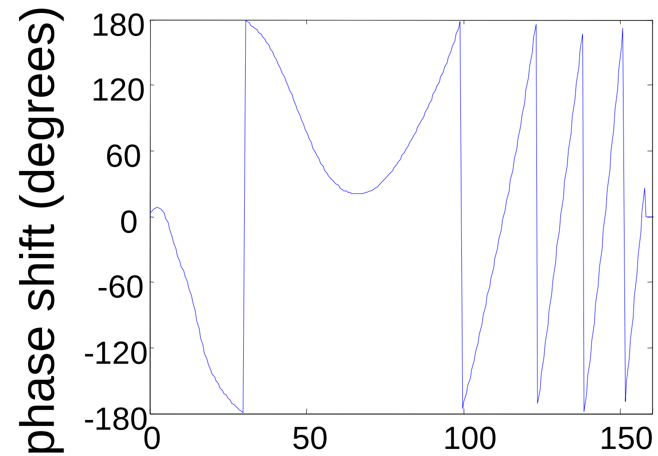


low
medium
high
object
image
phase shift
180
0
-180
spatial frequency

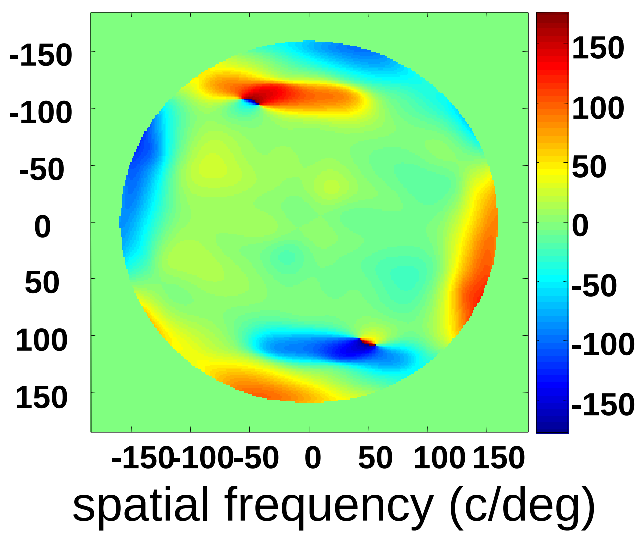
Phase Transfer Function

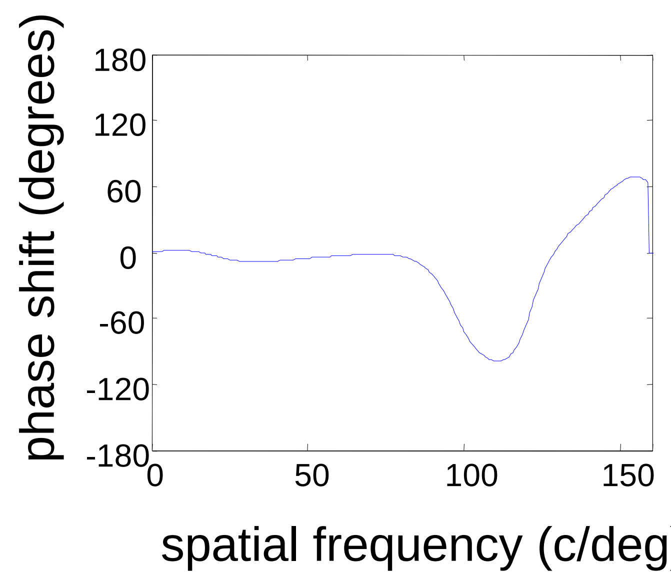
No AO
rms: 0.29 μm





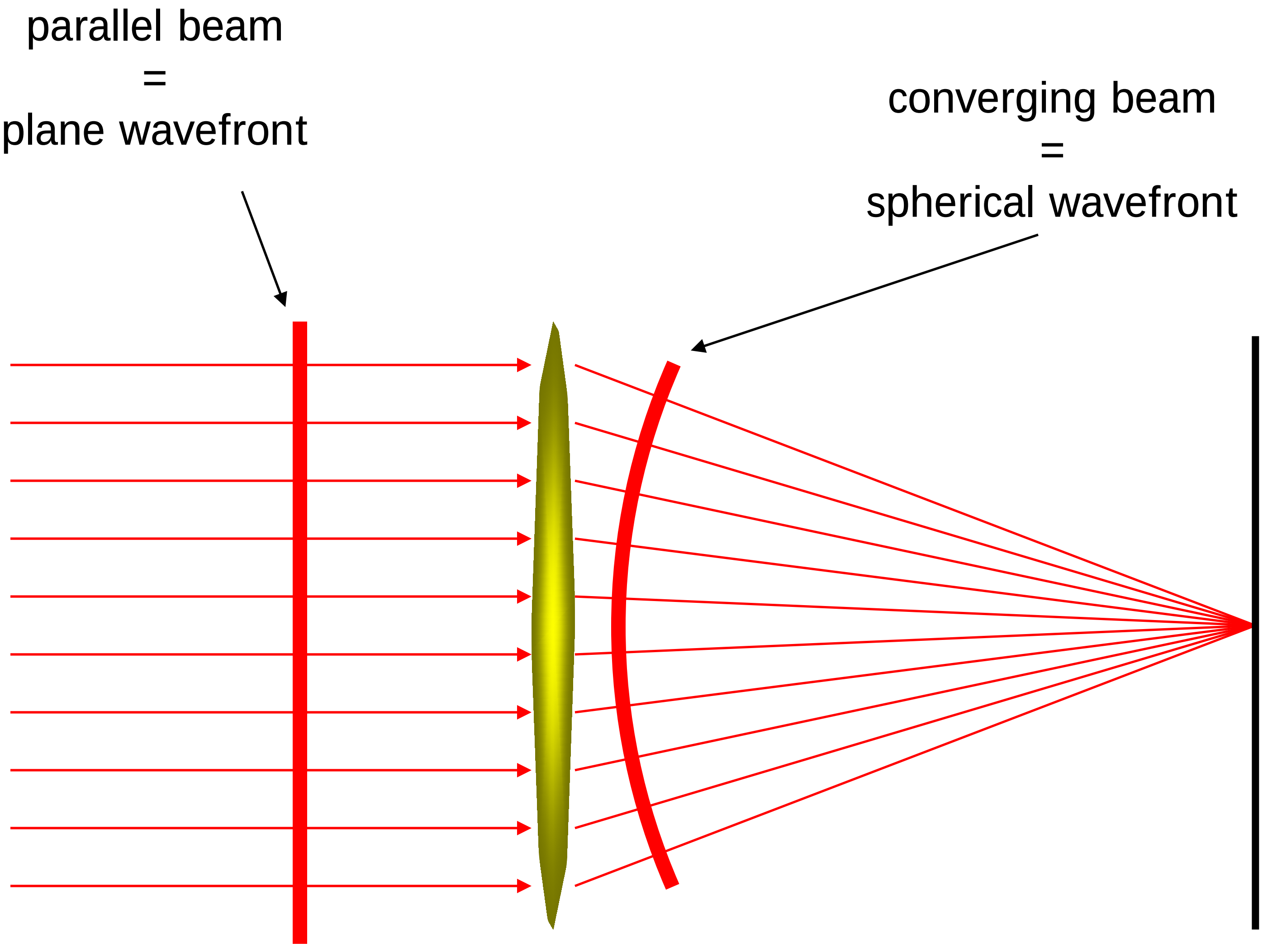
AO corrected
rms: 0.09 μm



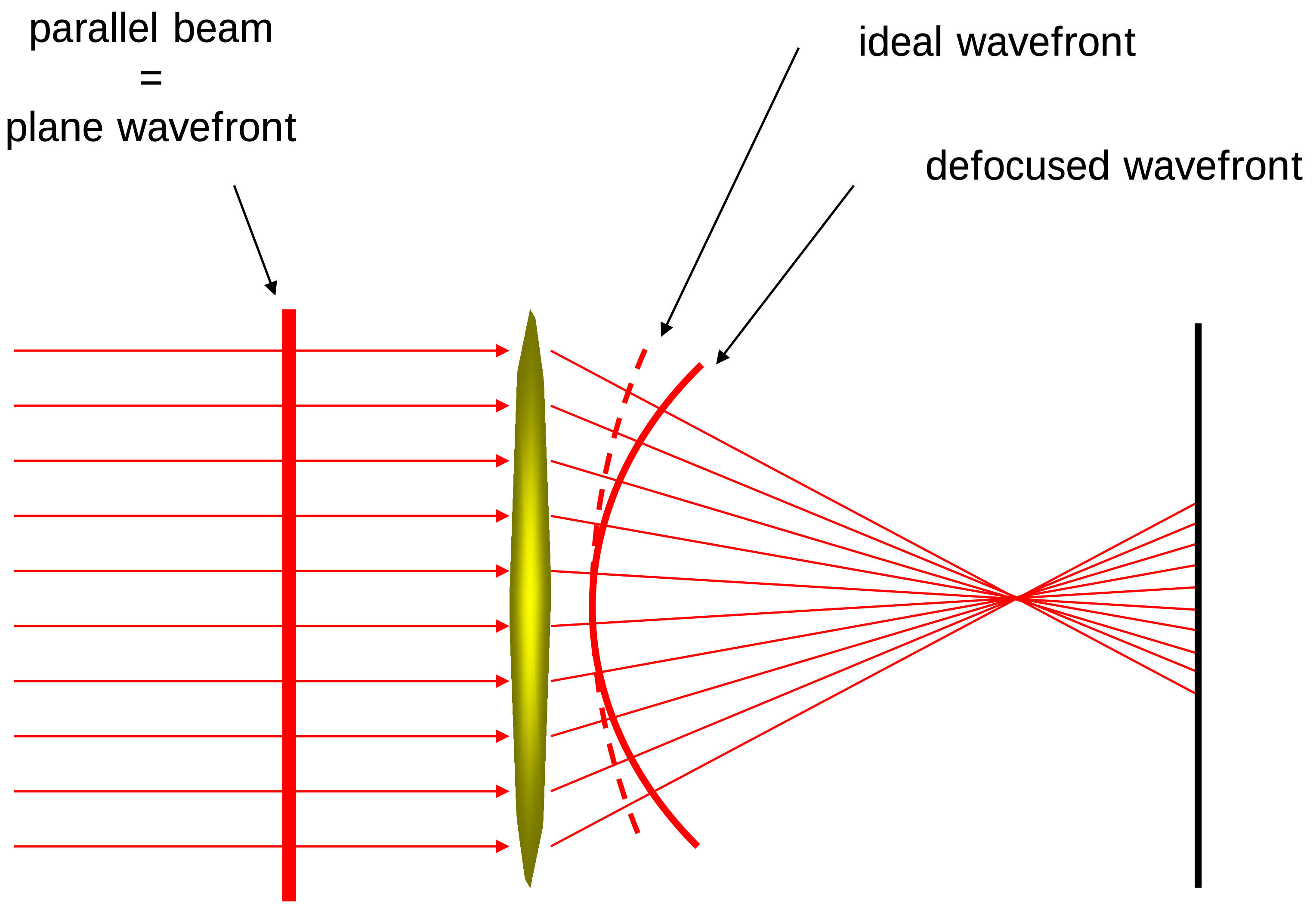


2.11 Measurement of the wave aberrations of the eye

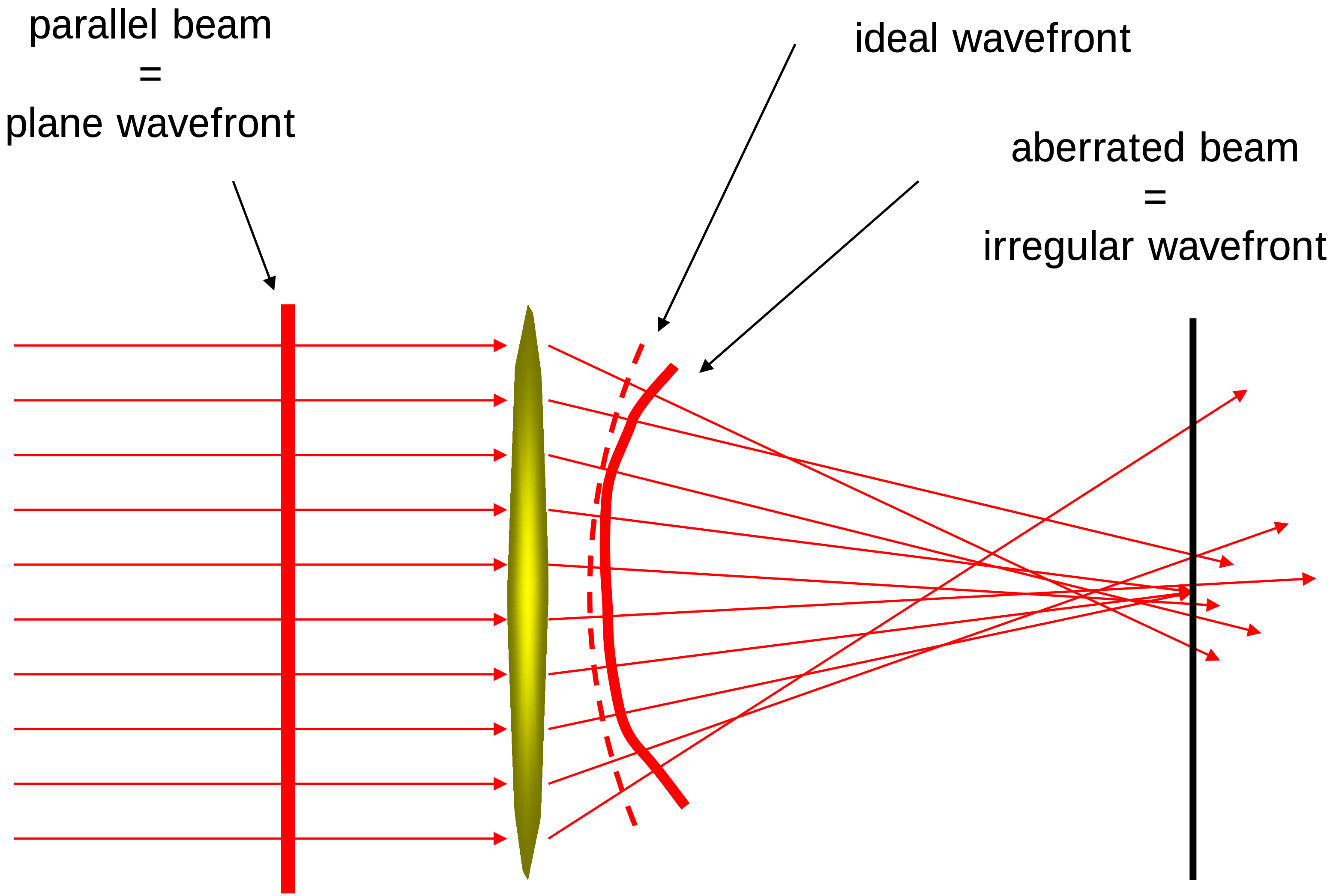
2.11 What is the Wavefront?



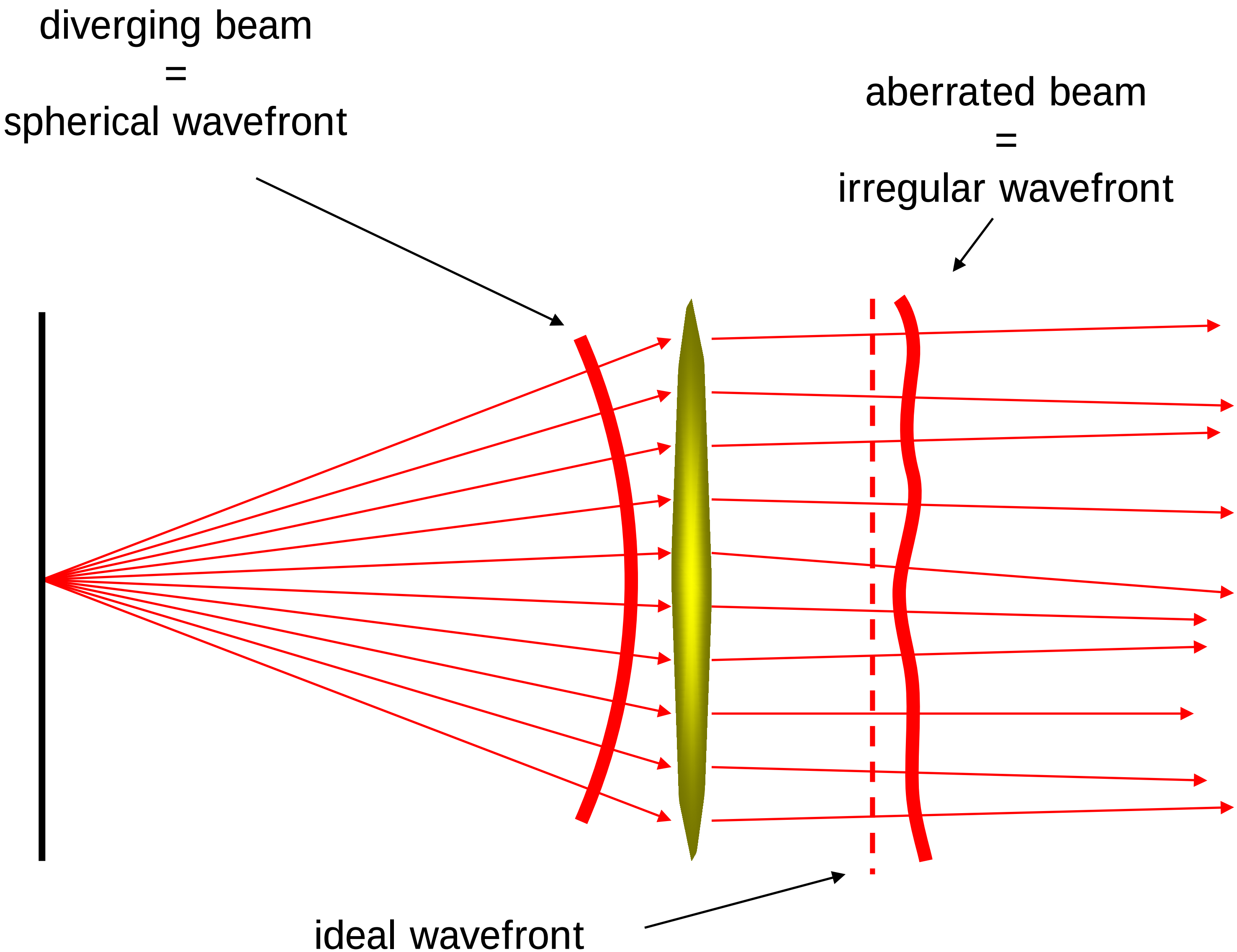
2.11 What is the Wavefront?



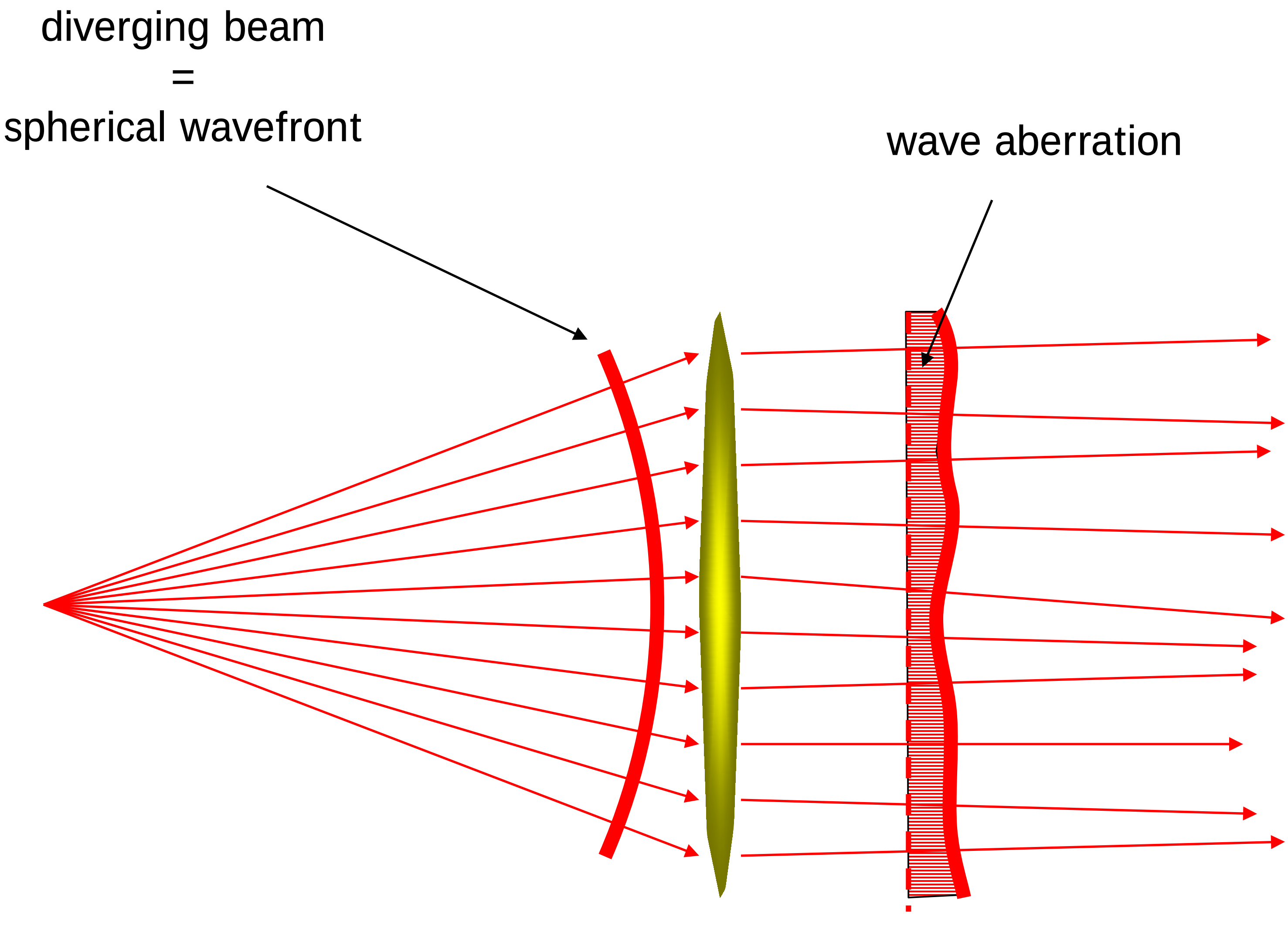
2.11 What is the Wavefront?



2.11 What is the Wavefront?

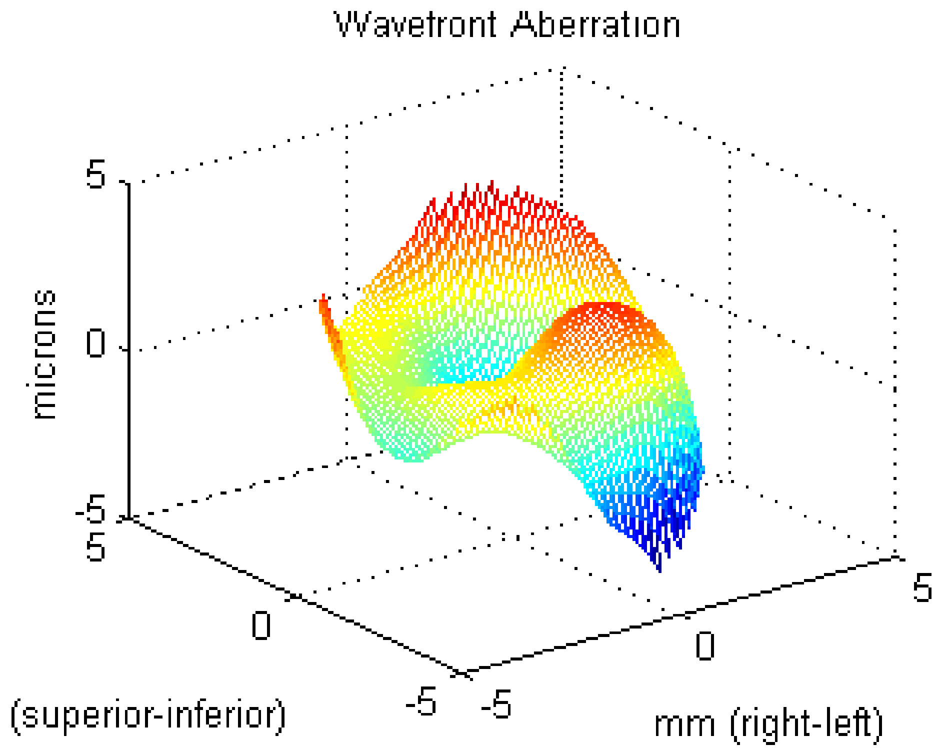


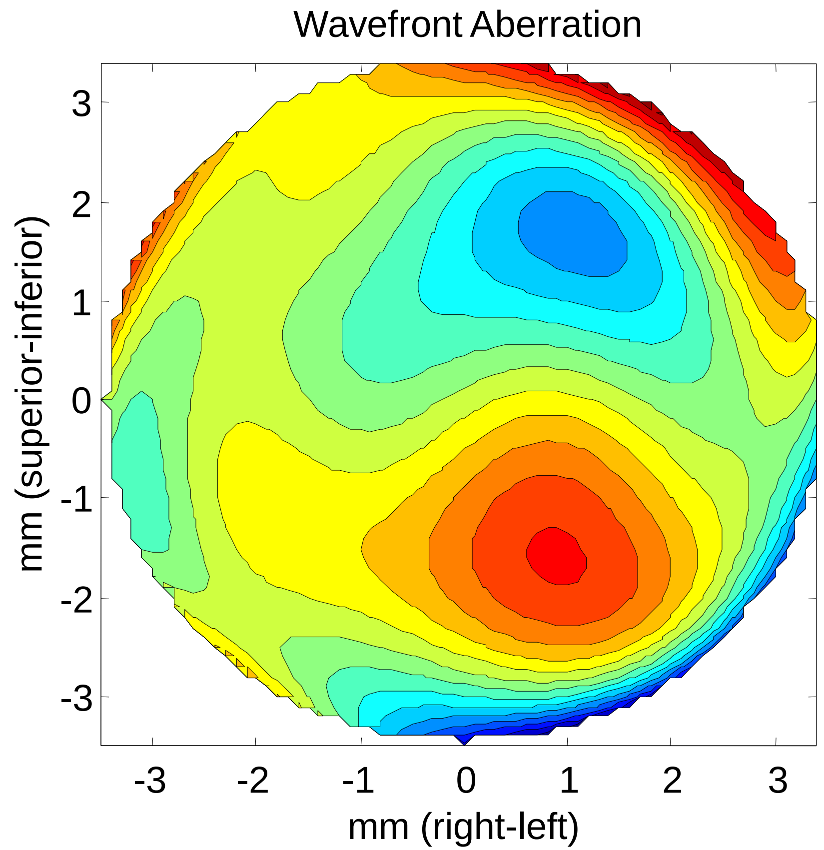
2.11 What is the *Wave Aberration*?



2.11 What is the Wave Aberration?

Wave Aberration of a Surface





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

Zernike Polynomials

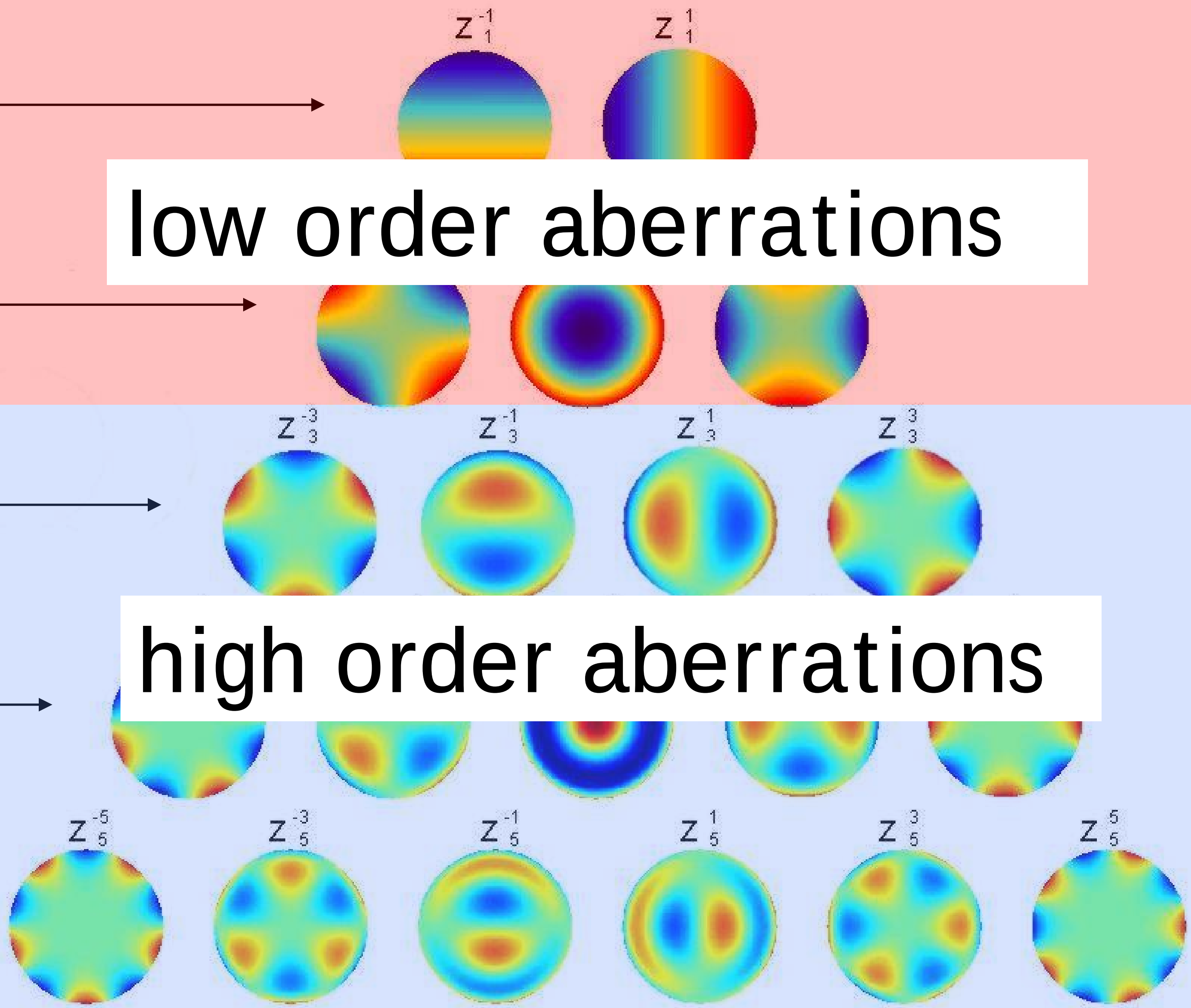
1st order

2nd order

3rd order

4th order

5th order



low order aberrations

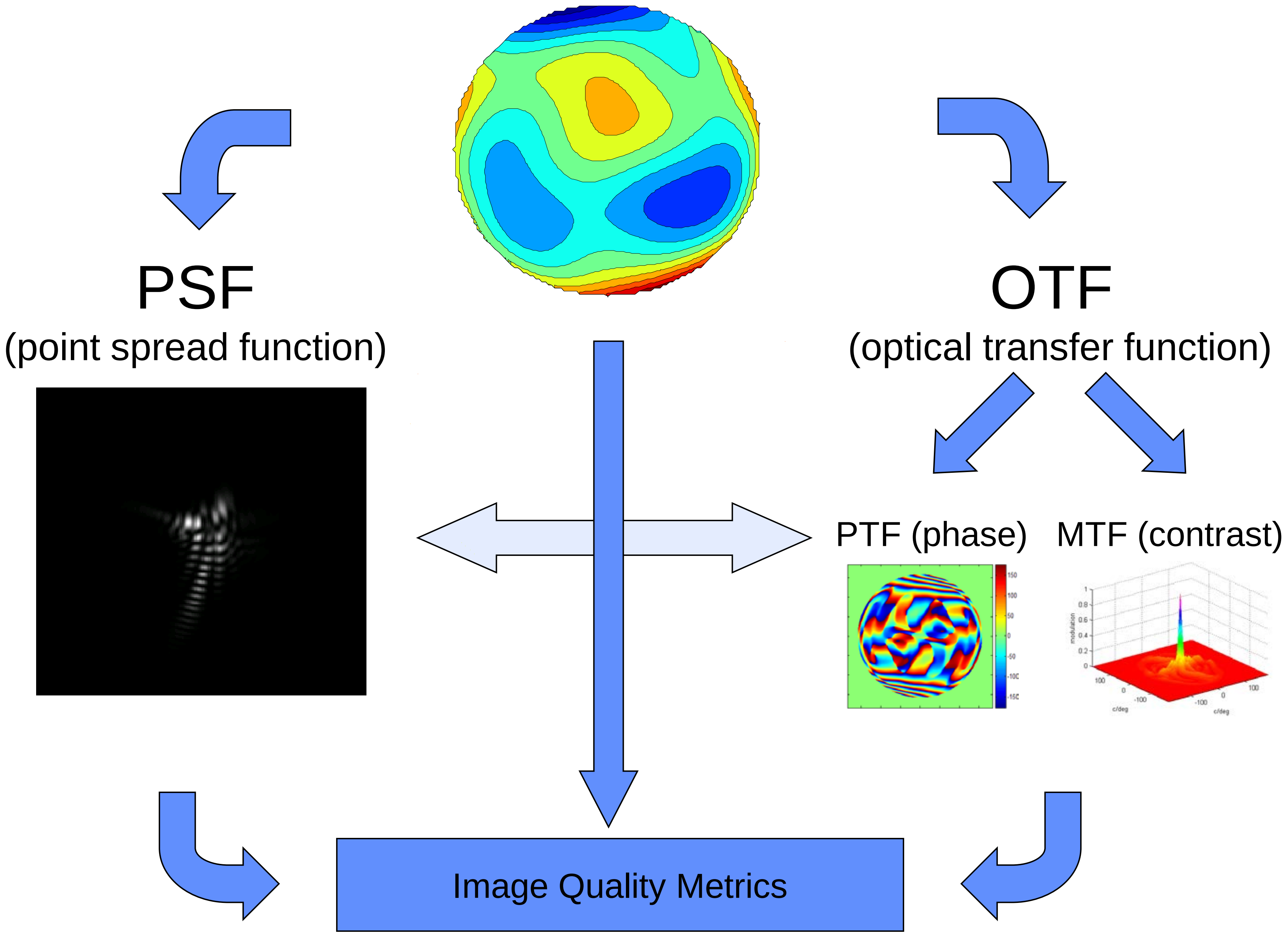
high order aberrations

Properties of Zernike Polynomials

- orthogonal
  - terms are not similar in any way, so the weighting of one term 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

2.11.3 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

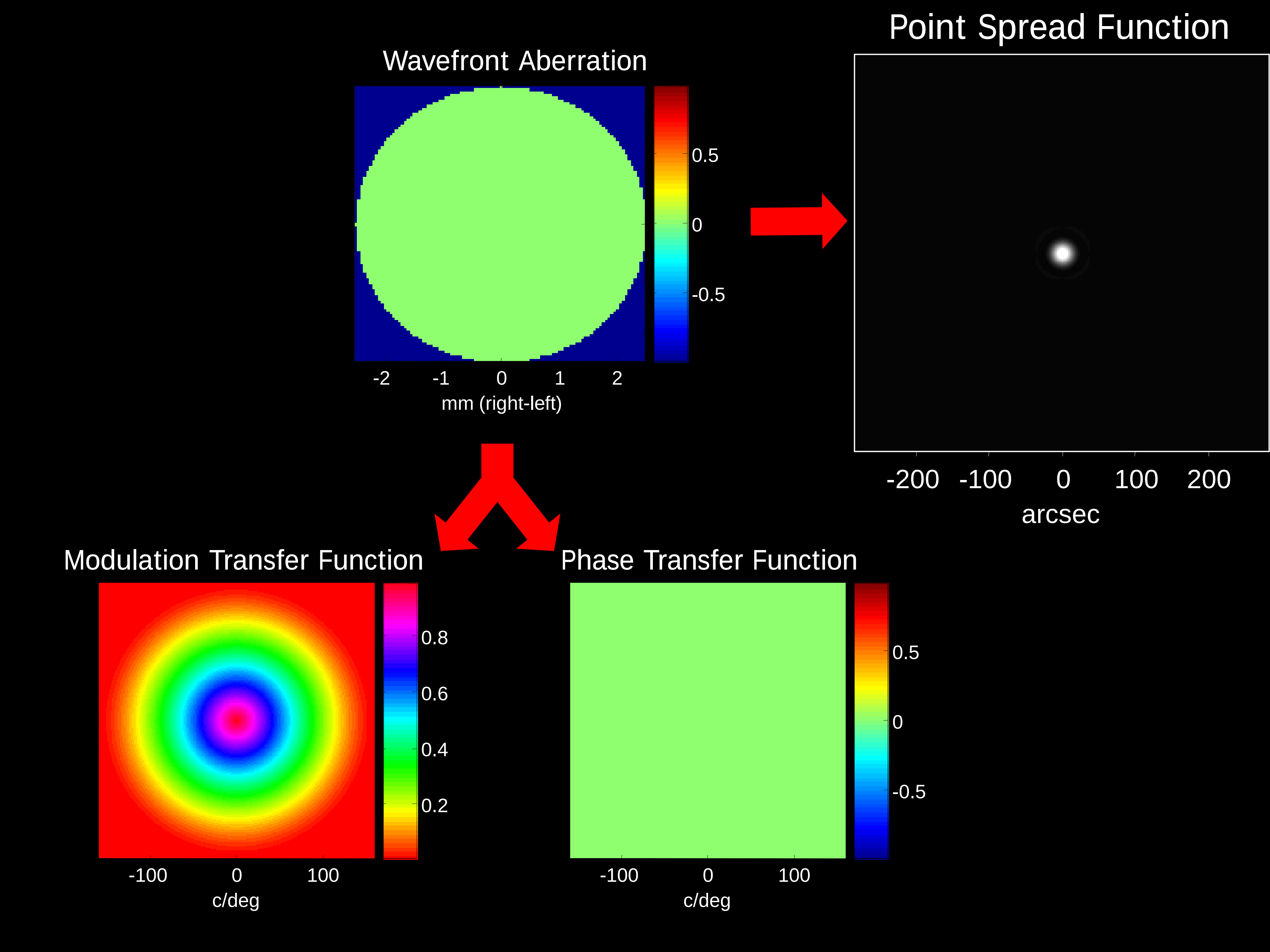
$$PSF\left(x_i, y_i\right) = FT\left\{P(x,y)e^{-i\frac{2\pi}{\lambda}W(x,y)}\right\}$$

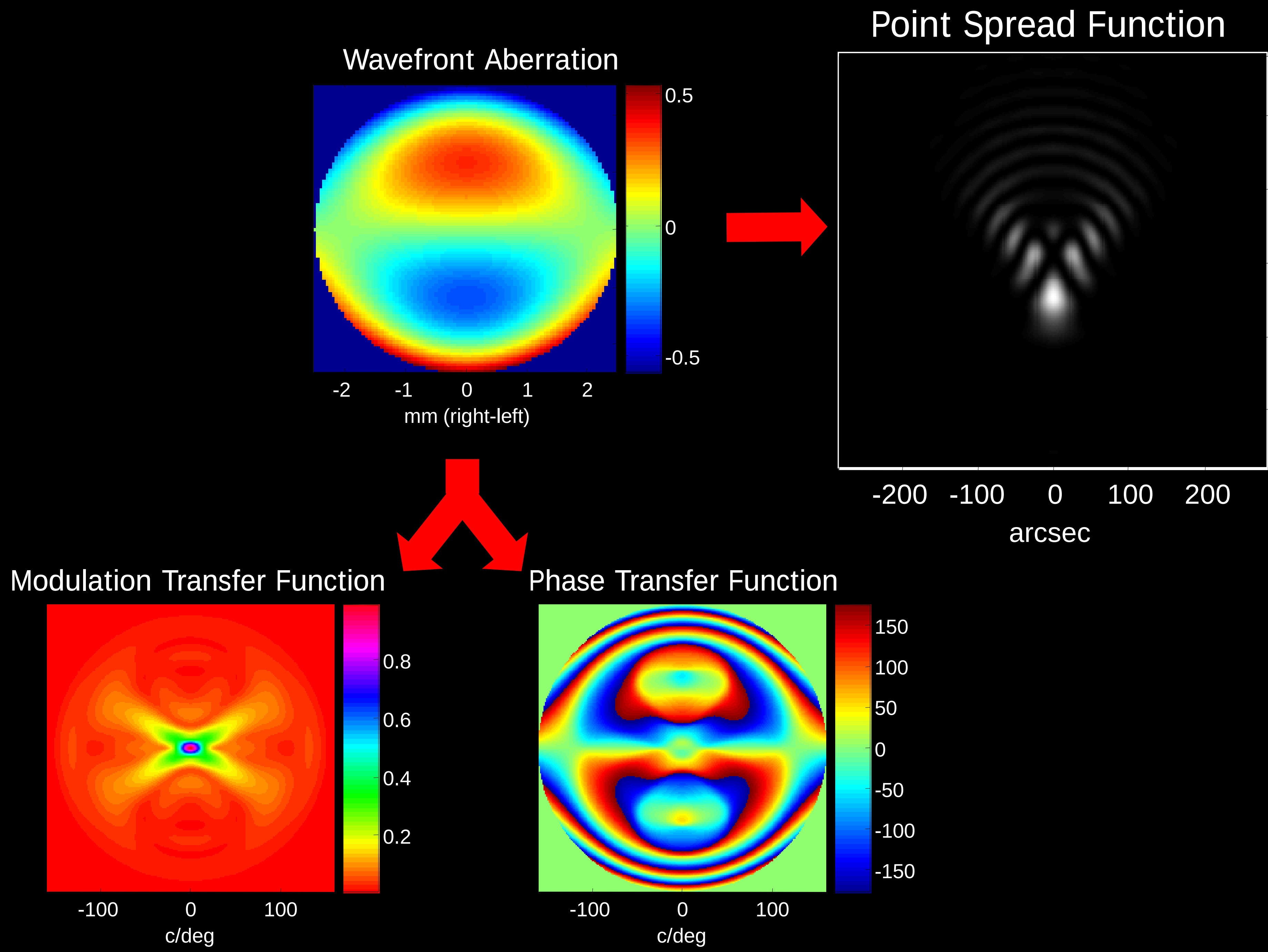
The MTF is the amplitude component of the FT of the PSF

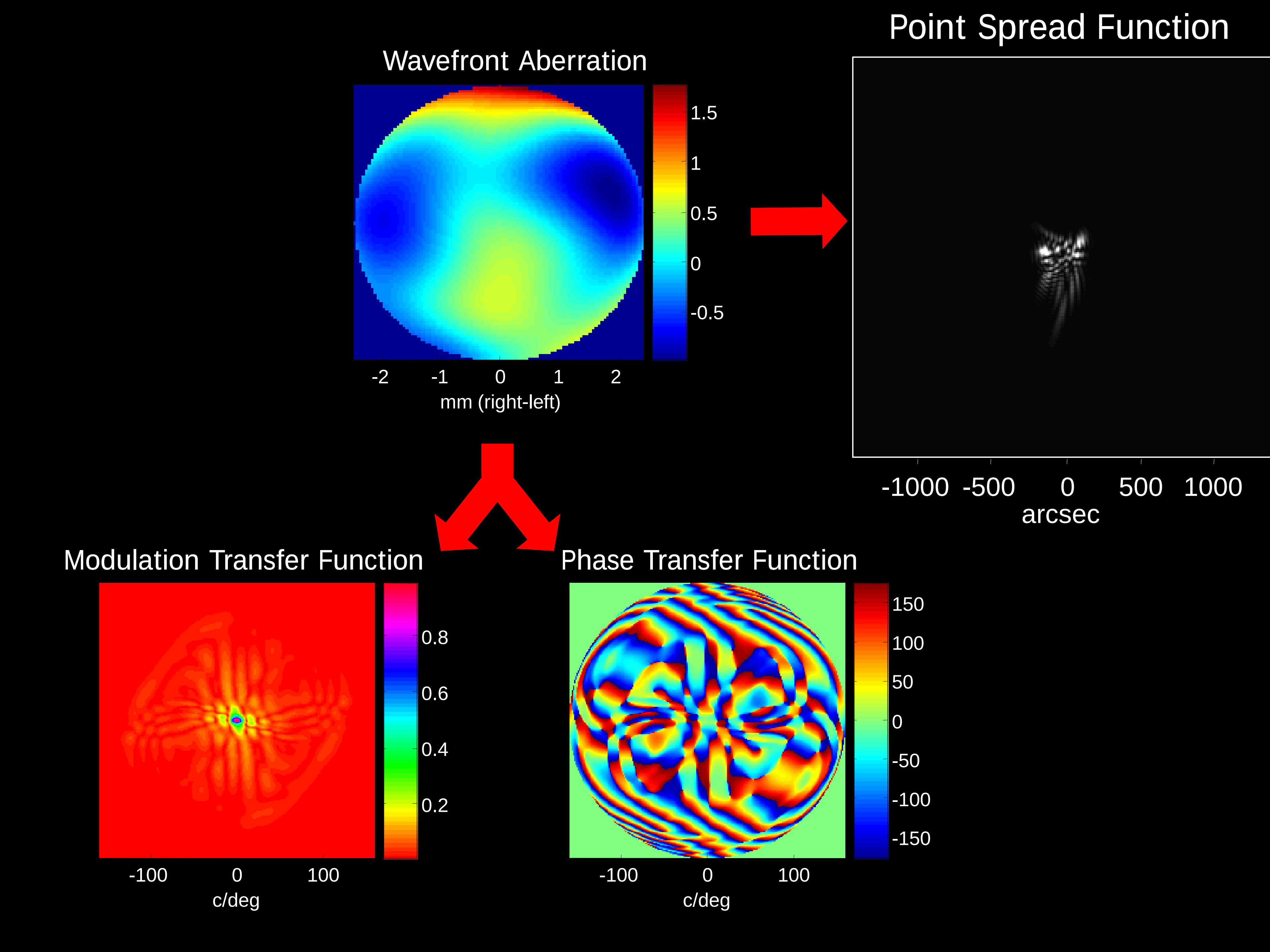
$$MTF\left(f_x, f_y\right) = Amplitude\left[FT\left\{PSF(x_i, y_i)\right\}\right]$$

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

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


Point Spread Function
Wavefront Aberration
0.5
0
-0.5
-2
-1
0
1
2
mm (right-left)
-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

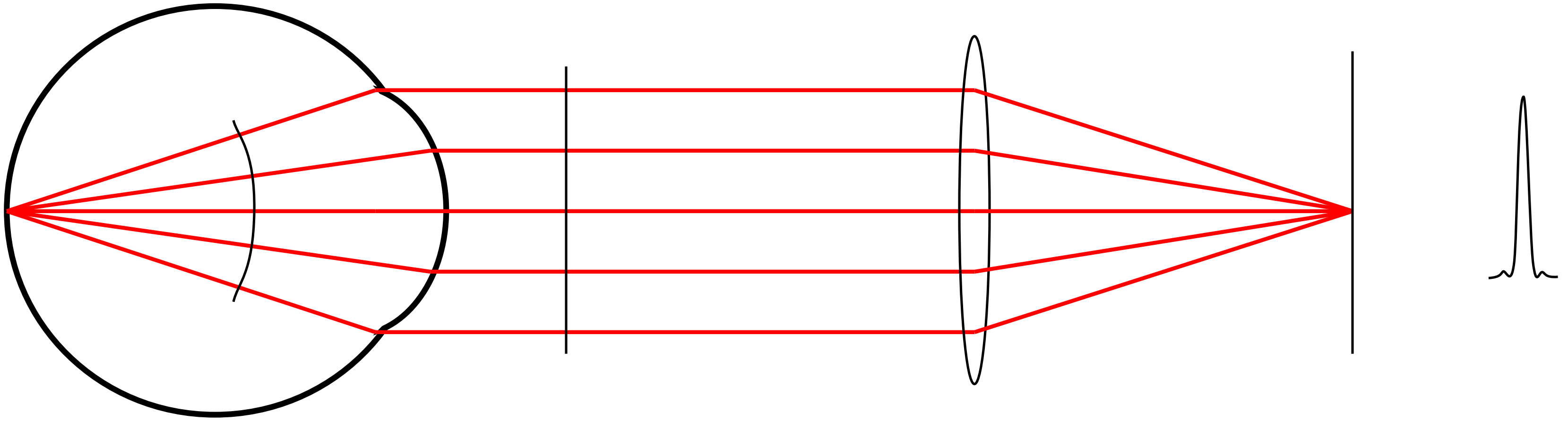

Wavefront Aberration
0.5
0
-0.5
-2
-1
0
1
2
mm (right-left)
Point Spread Function
-200
-100
0
100
200
arcsec
Modulation Transfer Function
0.8
0.6
0.4
0.2
-100
0
100
c/deg
Phase Transfer Function
150
100
50
0
-50
-100
-150
-100
0
100
c/deg



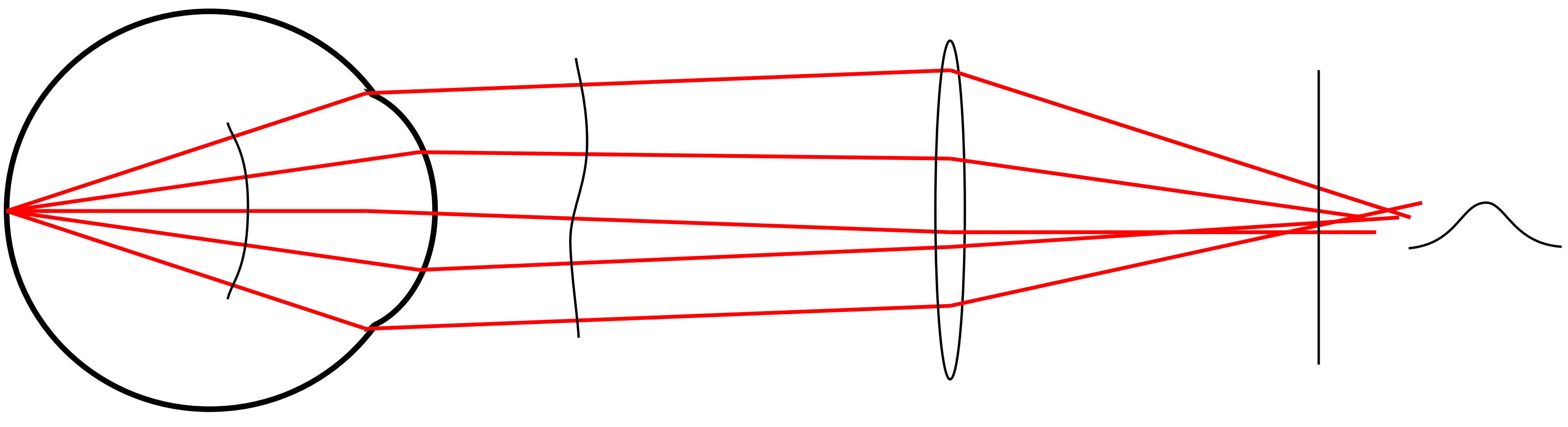
Wavefront Aberration
1.5
1
0.5
0
-0.5
-2
-1
0
1
2
mm (right-left)
Point Spread Function
-1000
-500
0
500
1000
arcsec
Modulation Transfer Function
0.8
0.6
0.4
0.2
-100
0
100
c/deg
Phase Transfer Function
150
100
50
0
-50
-100
-150
-100
0
100
c/deg

2.11.4 Principles of the Shack-Hartmann Wavefront Sensor

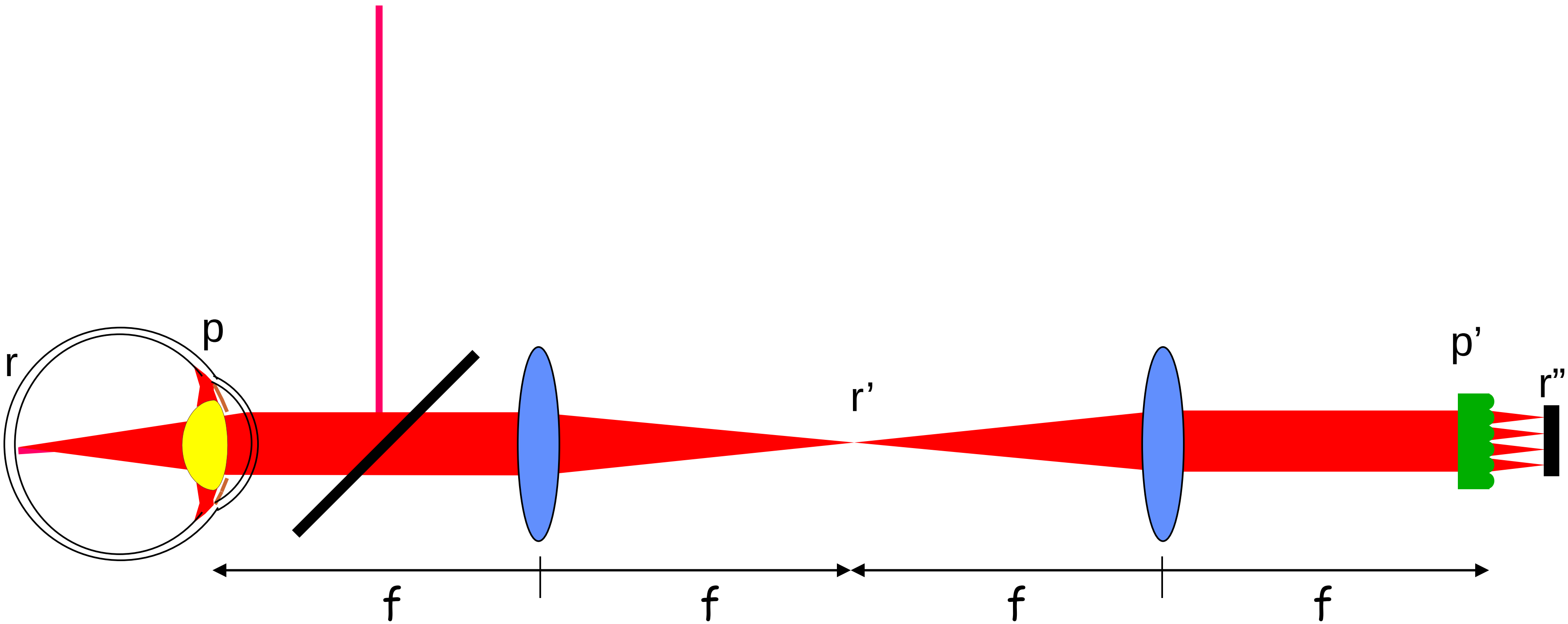
Perfect Eye



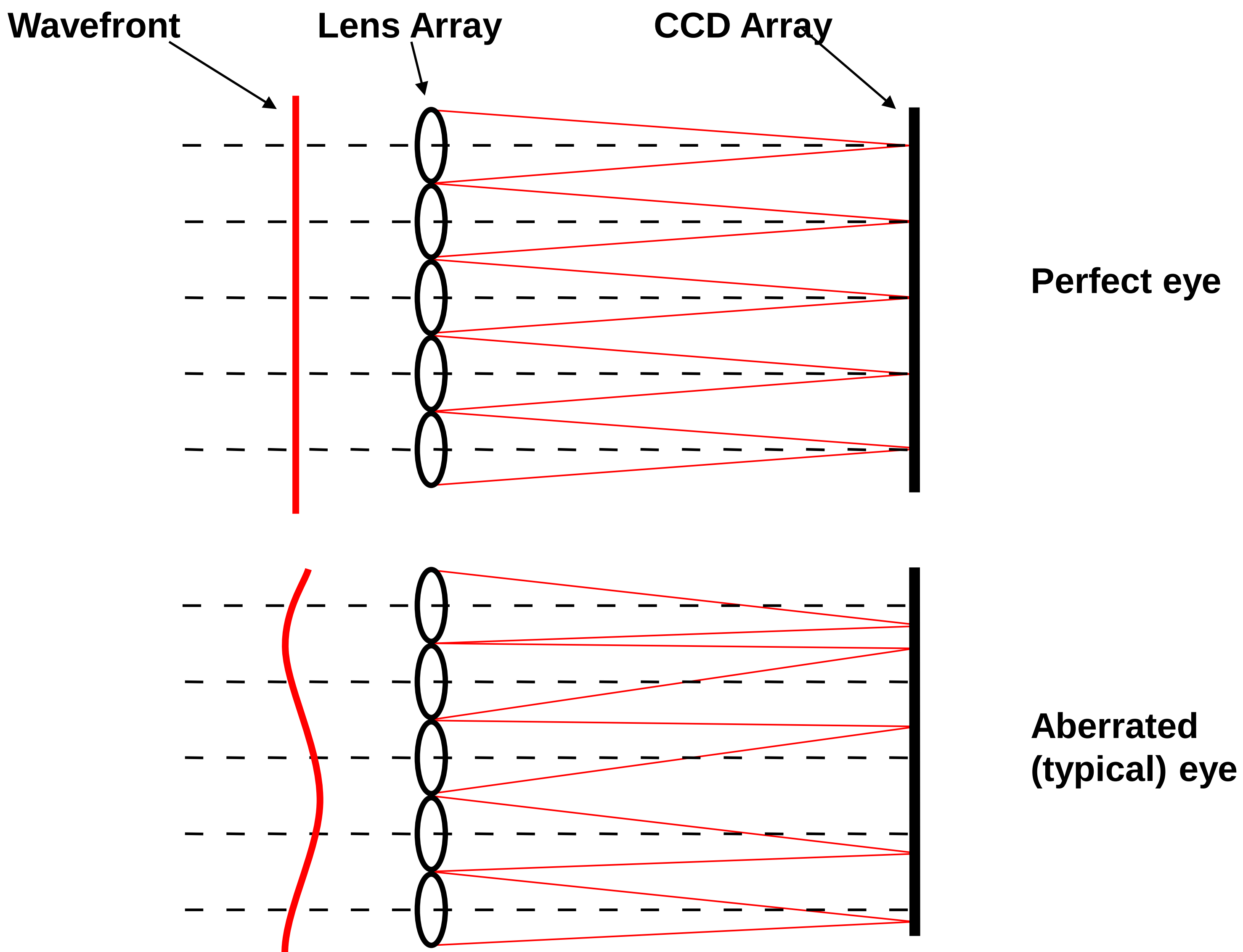
Aberrated Eye



2.11.4 Principles of the Shack-Hartmann Wavefront Sensor



2.11.4 Principles of the Shack-Hartmann Wavefront Sensor



2.11.4 Principles of the Shack-Hartmann Wavefront Sensor

Fitting the Wavefront

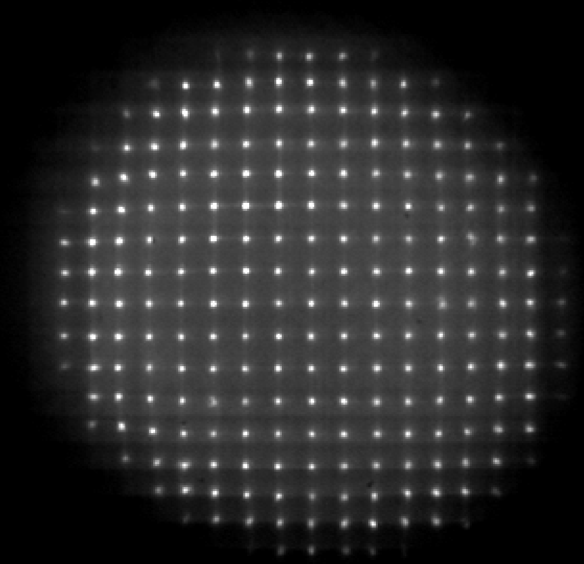
- The local slope (or the first derivative) of the wavefront is determined at each lenslet location
- The corresponding wavefront is determined by a least squares fitting of the slopes to the derivative of a polynomial selected to fit the wavefront
- Zernike polynomial is the most commonly used

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

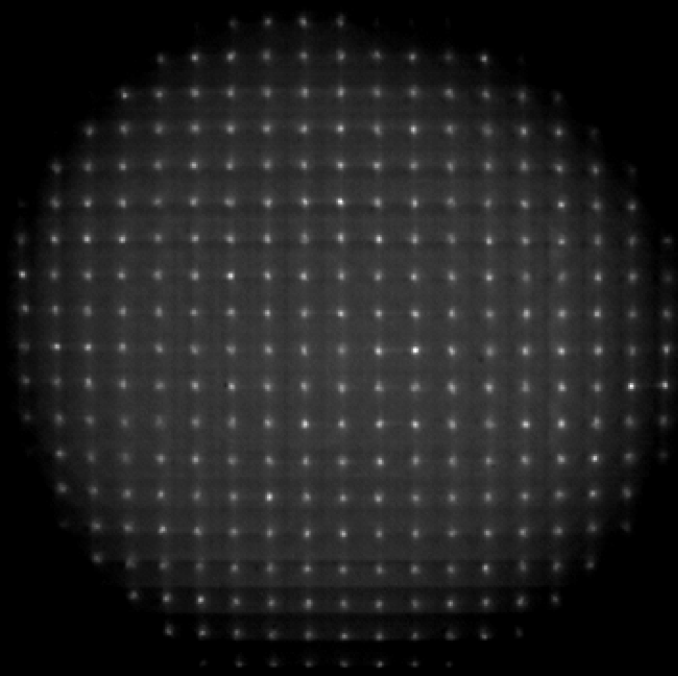
2.11.4 Principles of the Shack-Hartmann Wavefront Sensor

Shack-Hartmann Images

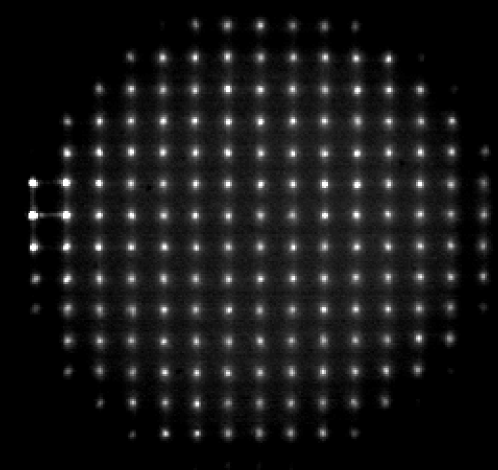
BD



KW



SM

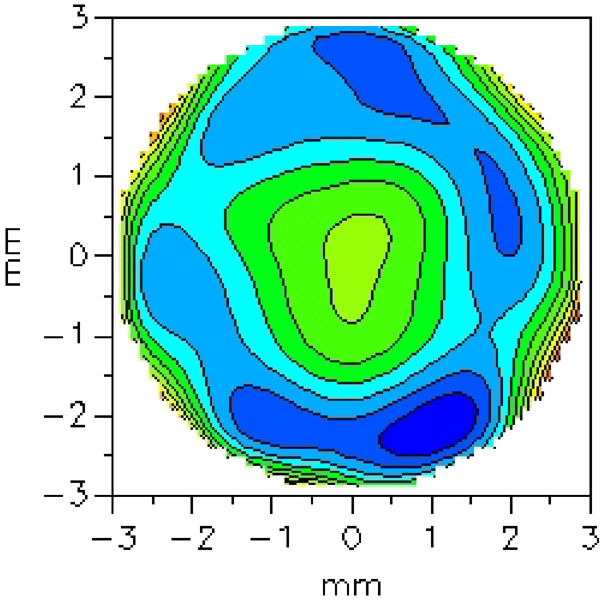


2.11.4 Principles of the Shack-Hartmann Wavefront Sensor

Wavefront Maps

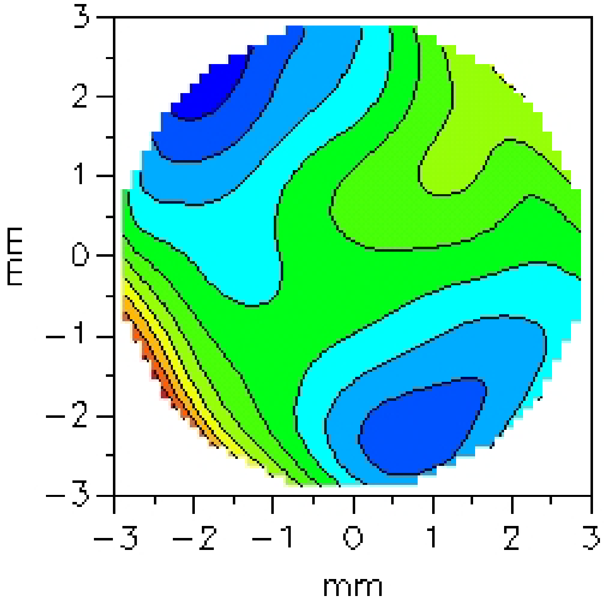
(at best focal plane)

BD



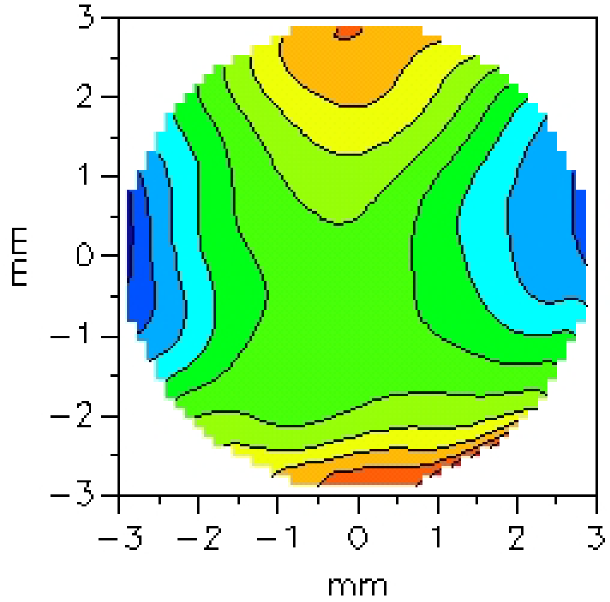
0.33 DS
–0.17 DC X 87

KW



6.42 DS
–0.6 DC X 126

SM

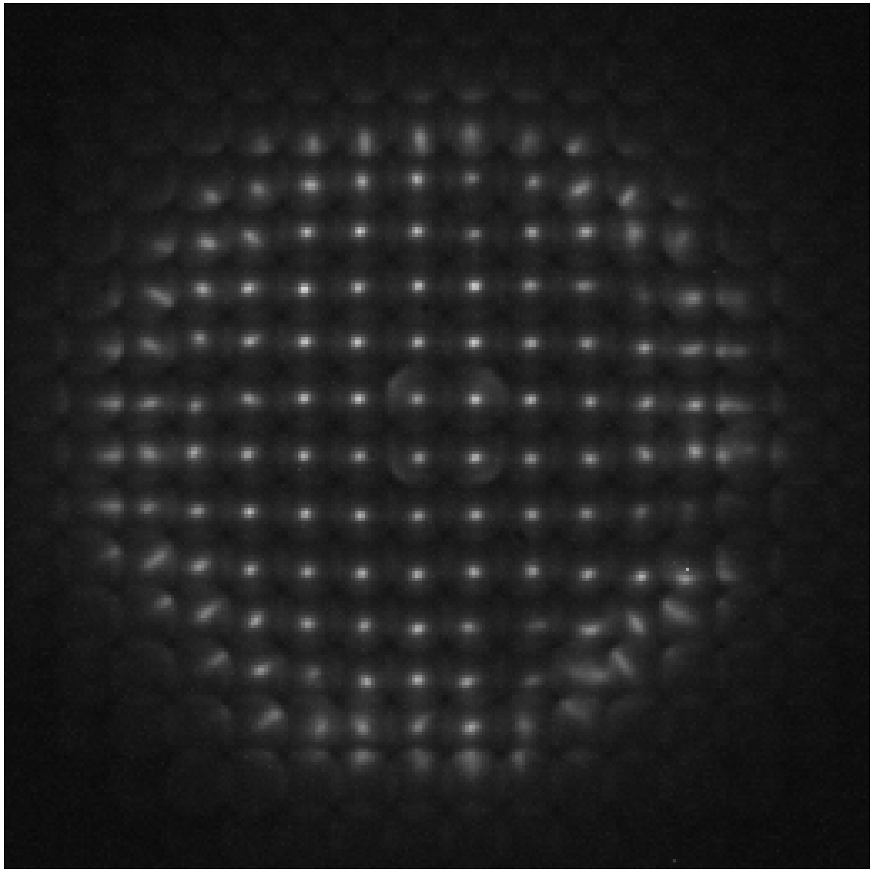


0 DS
–1 DC X 3

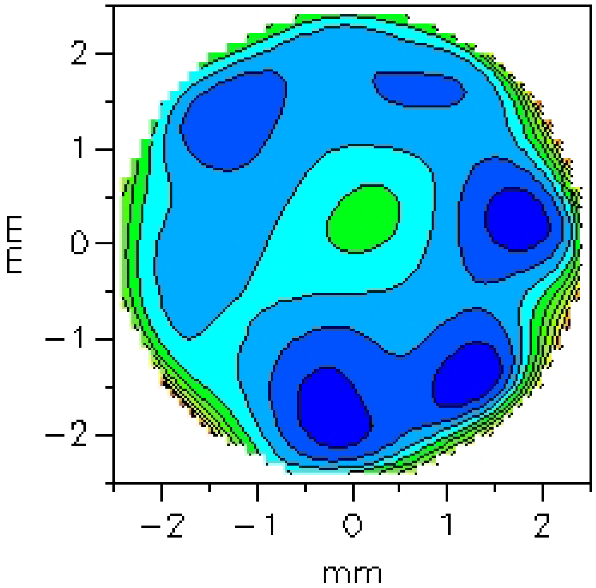
2.11.4 Principles of the Shack-Hartmann Wavefront Sensor

Aberrations of an RK patient

Wavefront sensor image



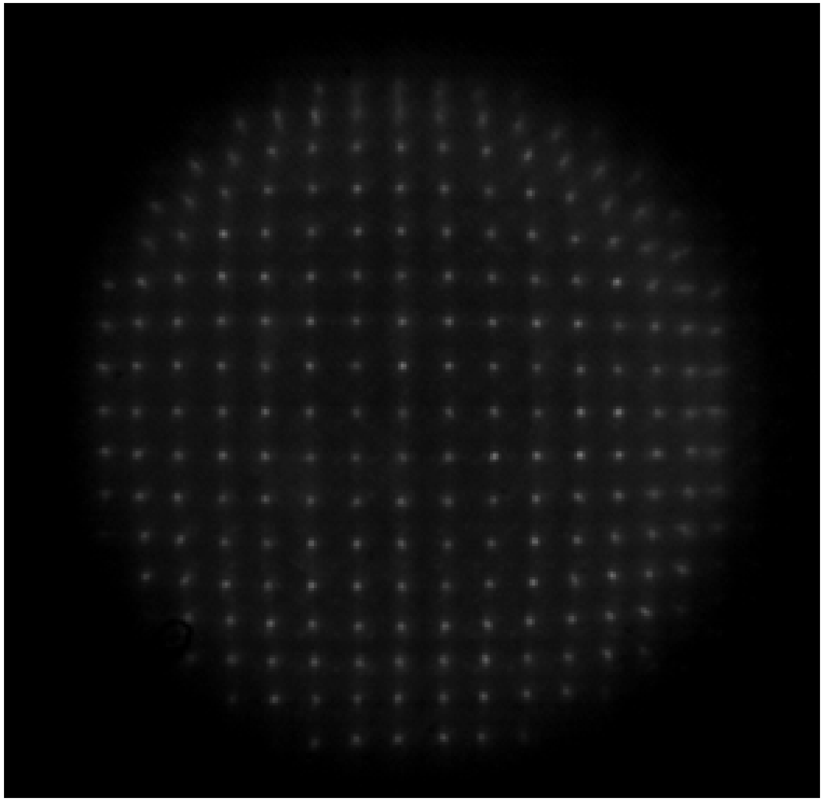
Wavefront aberration



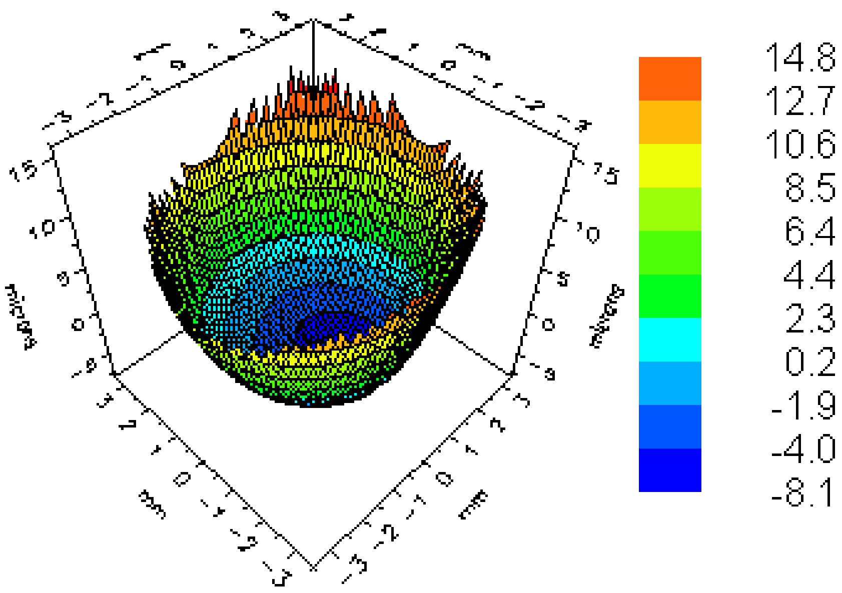
2.11.4 Principles of the Shack-Hartmann Wavefront Sensor

Aberrations of a LASIK patient

Wavefront sensor image

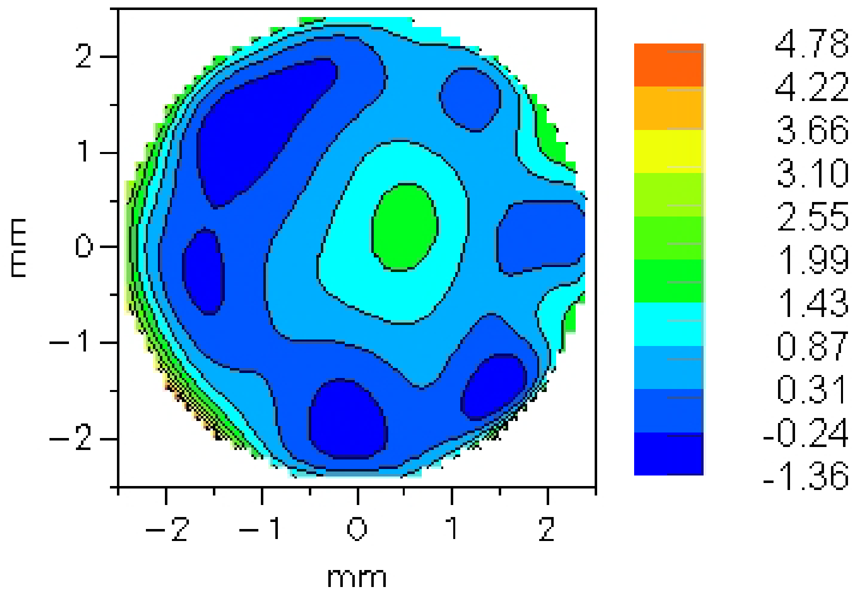


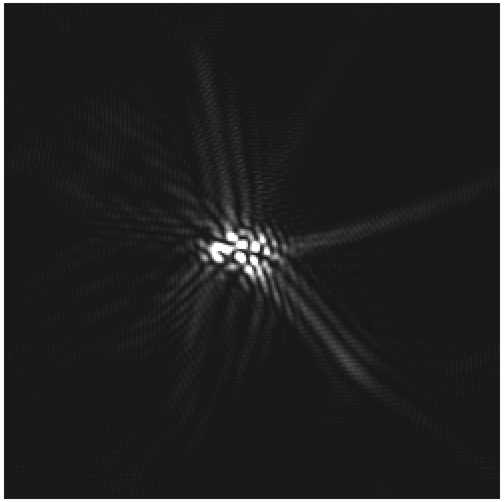
Wavefront aberration



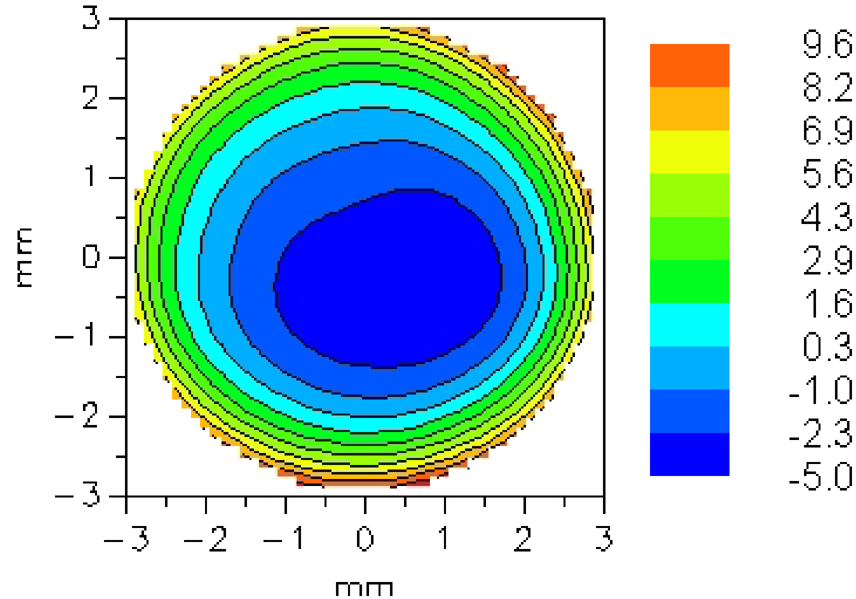
2.11.4 Principles of the Shack-Hartmann Wavefront Sensor

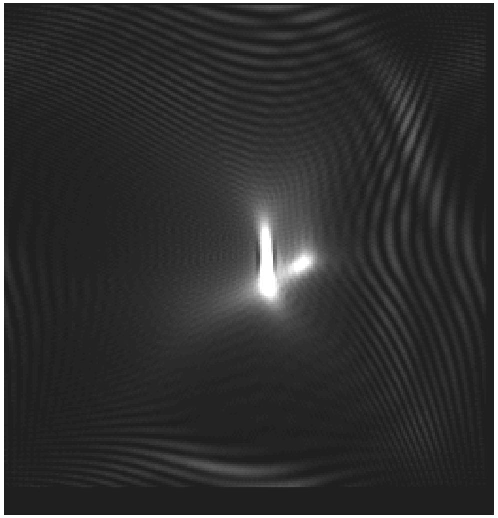
Post - RK





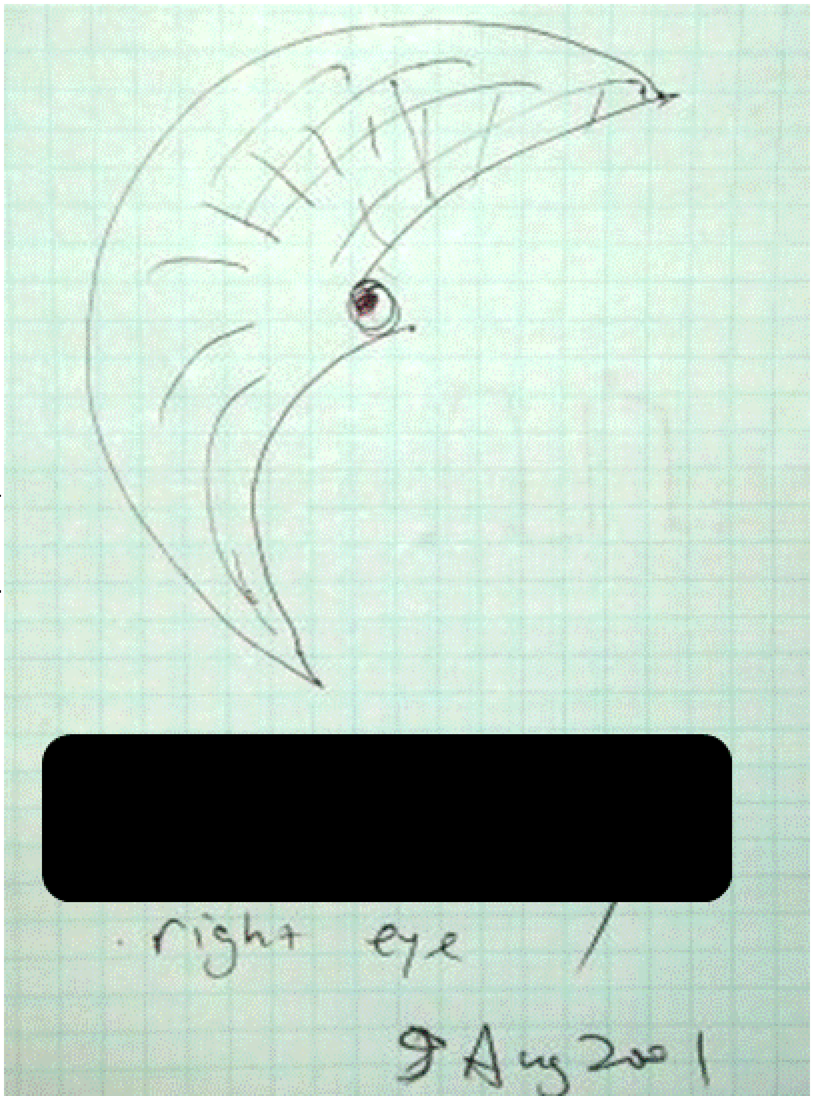
Post - LASIK

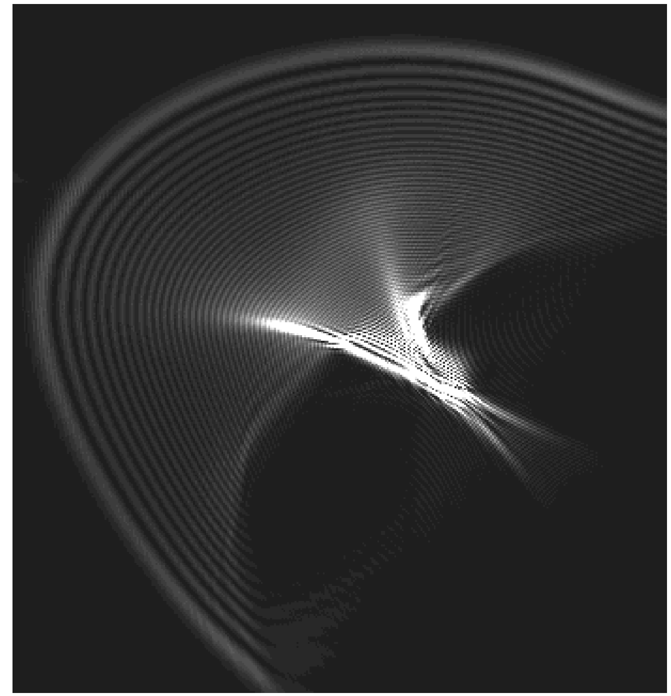




2.11.4 Principles of the Shack-Hartmann Wavefront Sensor

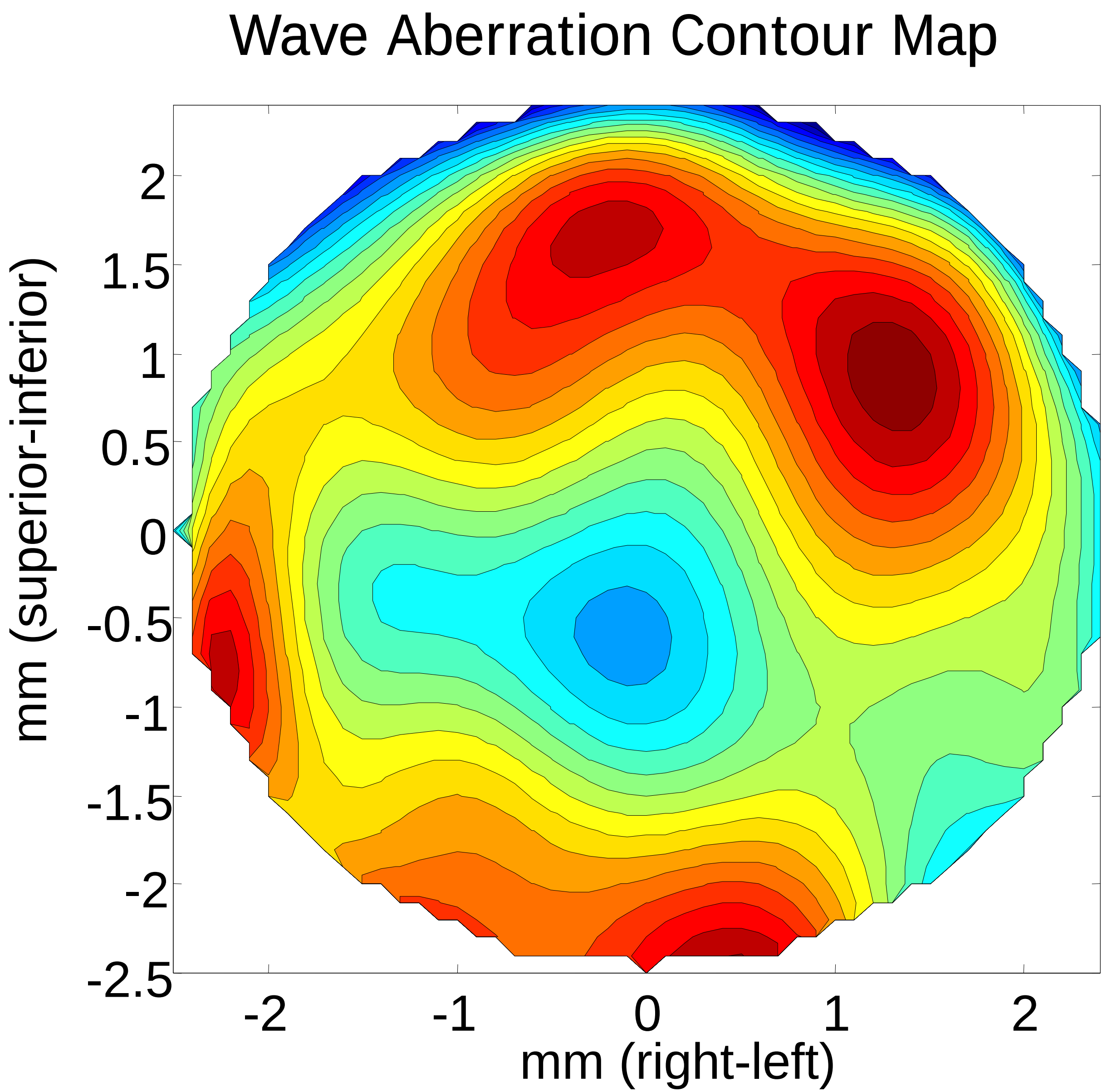
Keratoconus



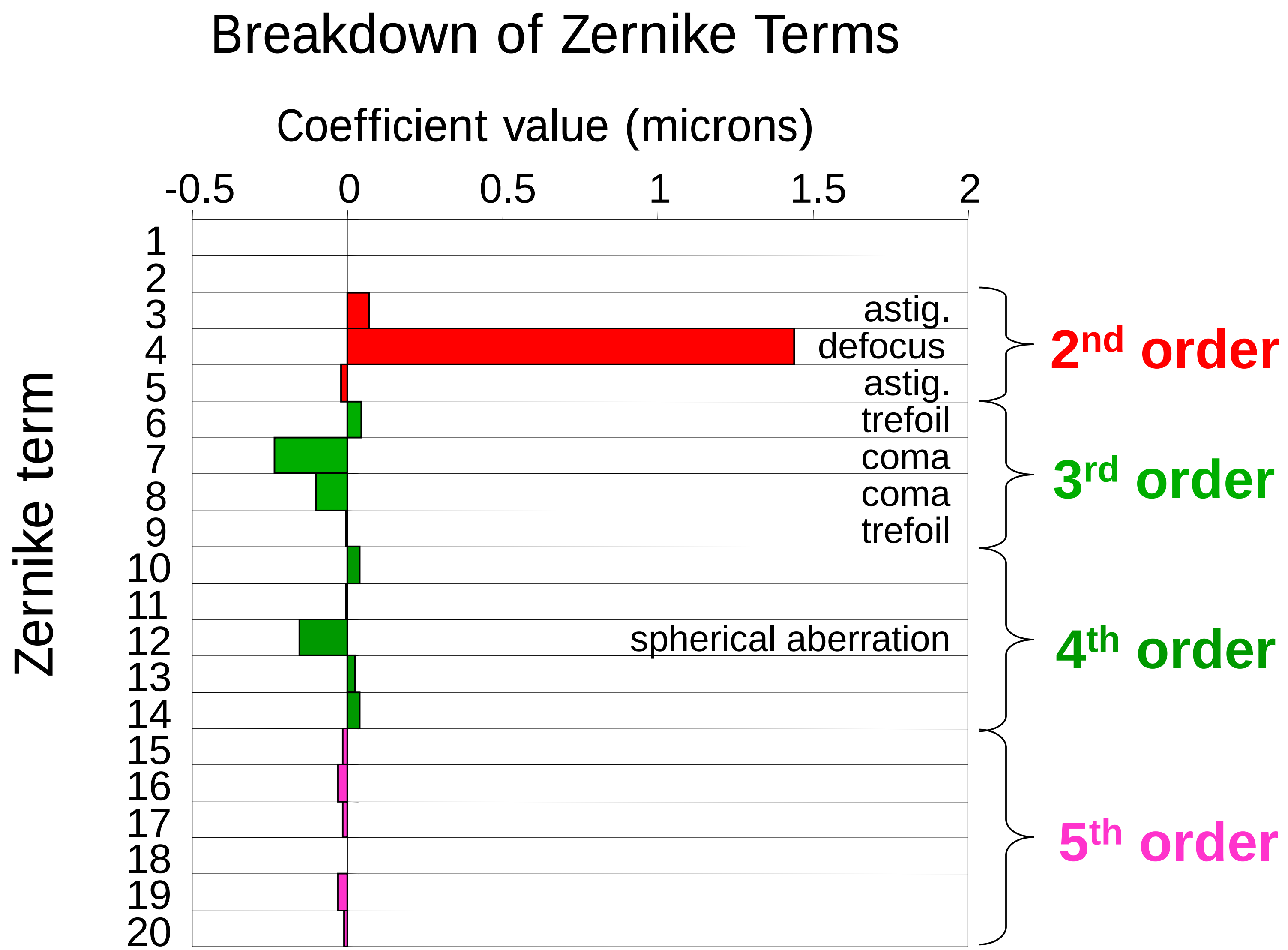


2.11.5 Metrics to Define Image Quality

2.11.5 Metrics to Define Image Quality



2.11.5 Metrics to Define Image Quality



2.11.5 Metrics to Define Image Quality

Root Mean Square Wave Aberration

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

$A-$ pupil area

$W(x,y)-$ wave aberration

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

2.11.5 Metrics to Define Image Quality

Root Mean Square Wave Aberration

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

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.)

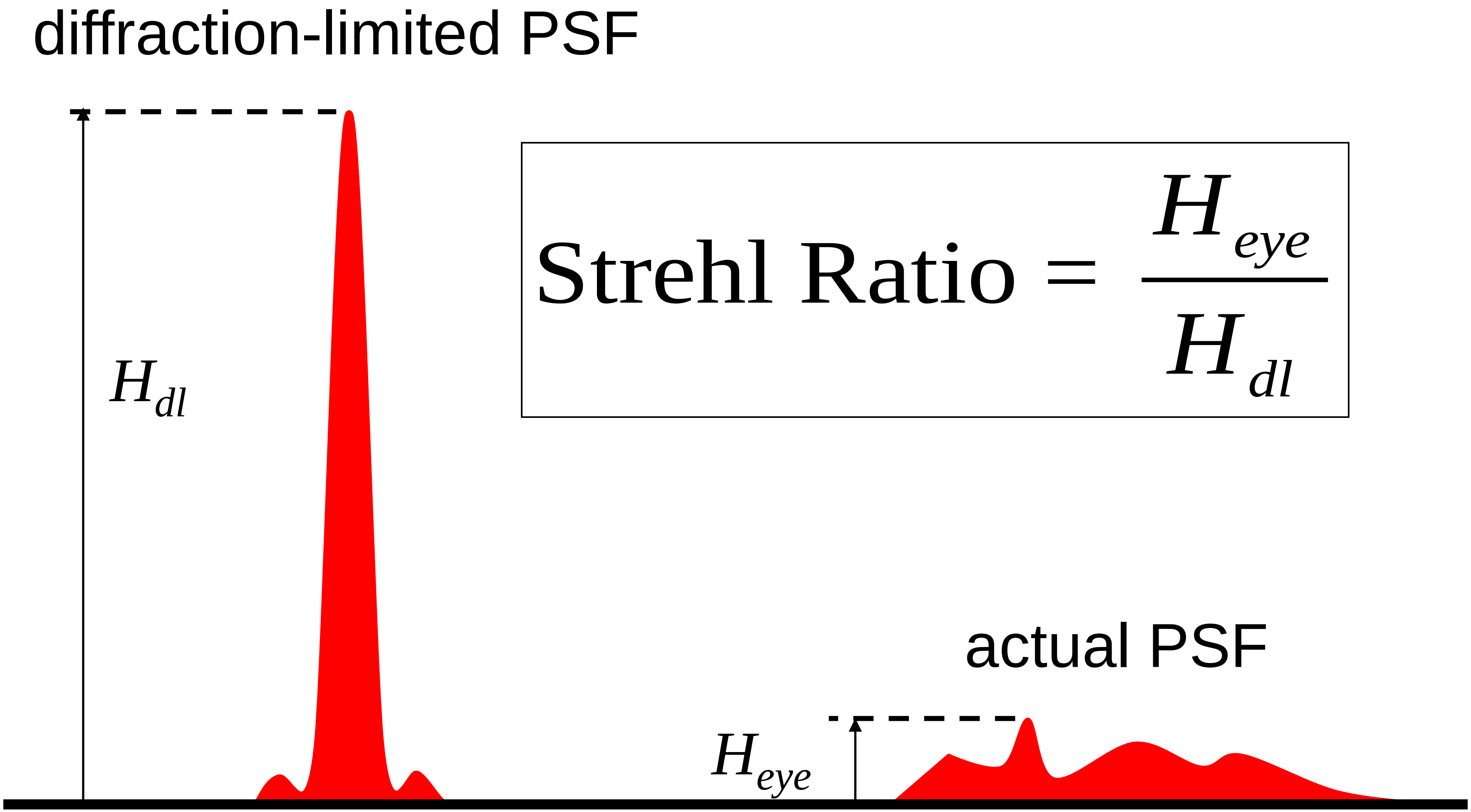
2.11.5 Metrics to Define Image Quality

Point Spread Function

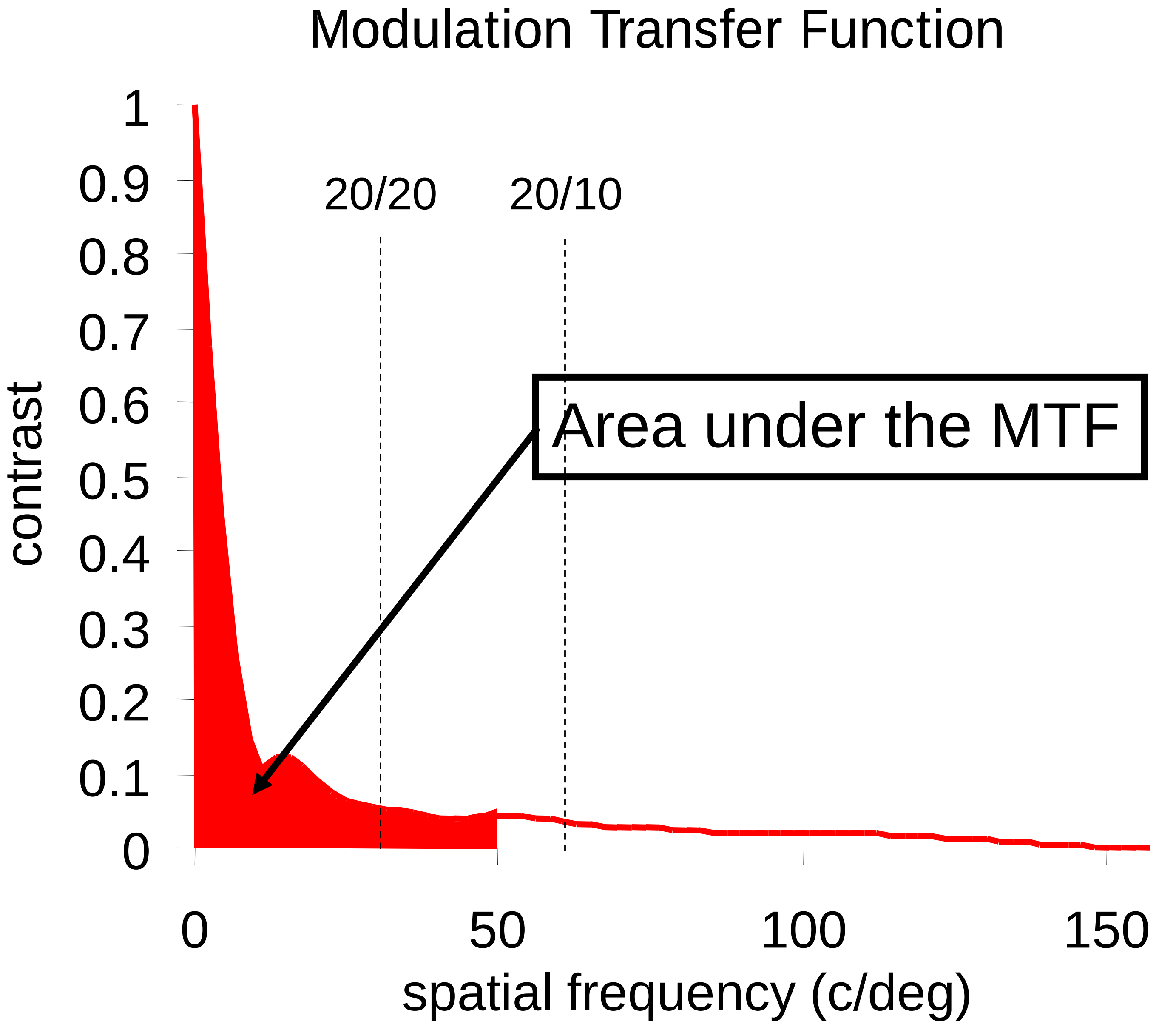
2.11.5 Metrics to Define Image Quality

Strehl Ratio

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



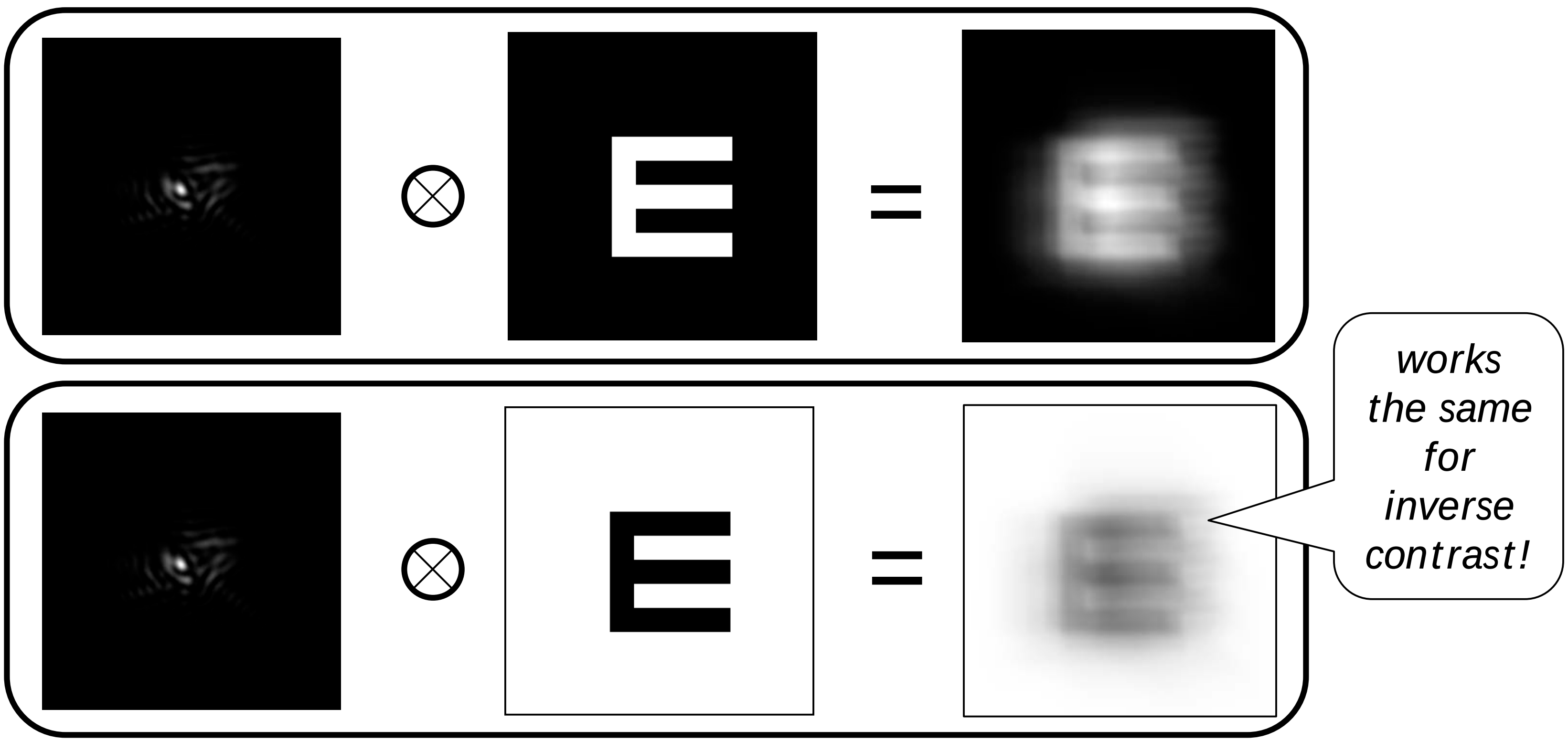
2.11.5 Metrics to Define Image Quality



2.12 Metrics to Define Image Quality

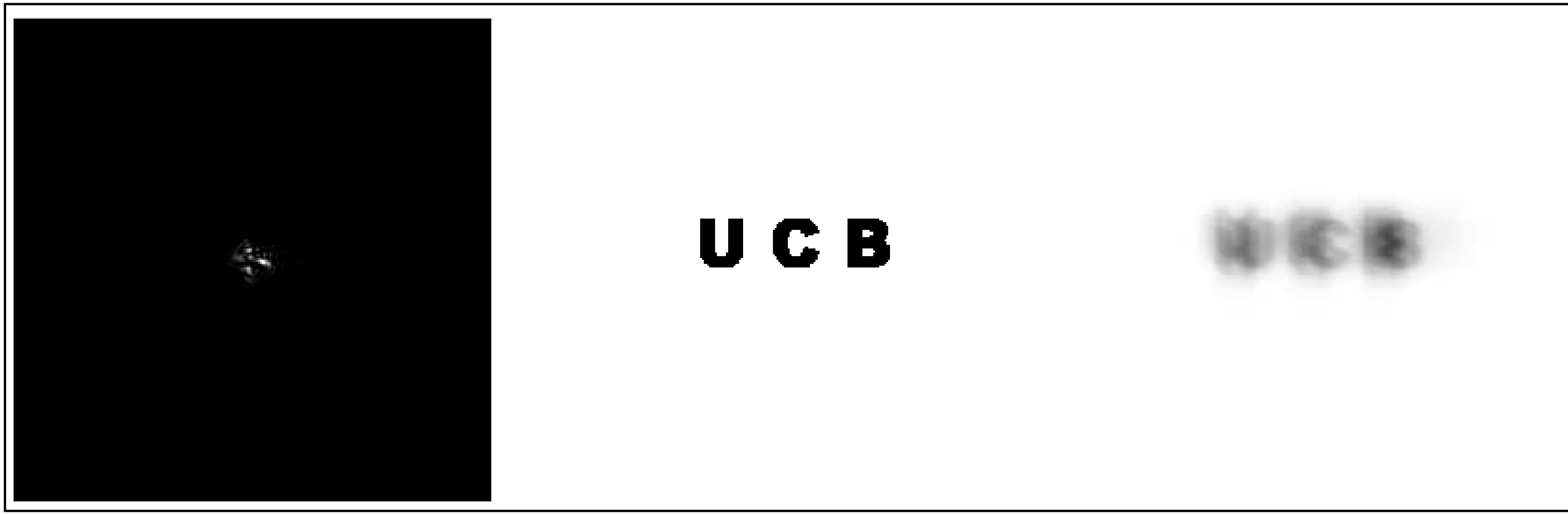
Convolution

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



2.11.5 Metrics to Define Image Quality

20/20 letters



20/40 letters

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

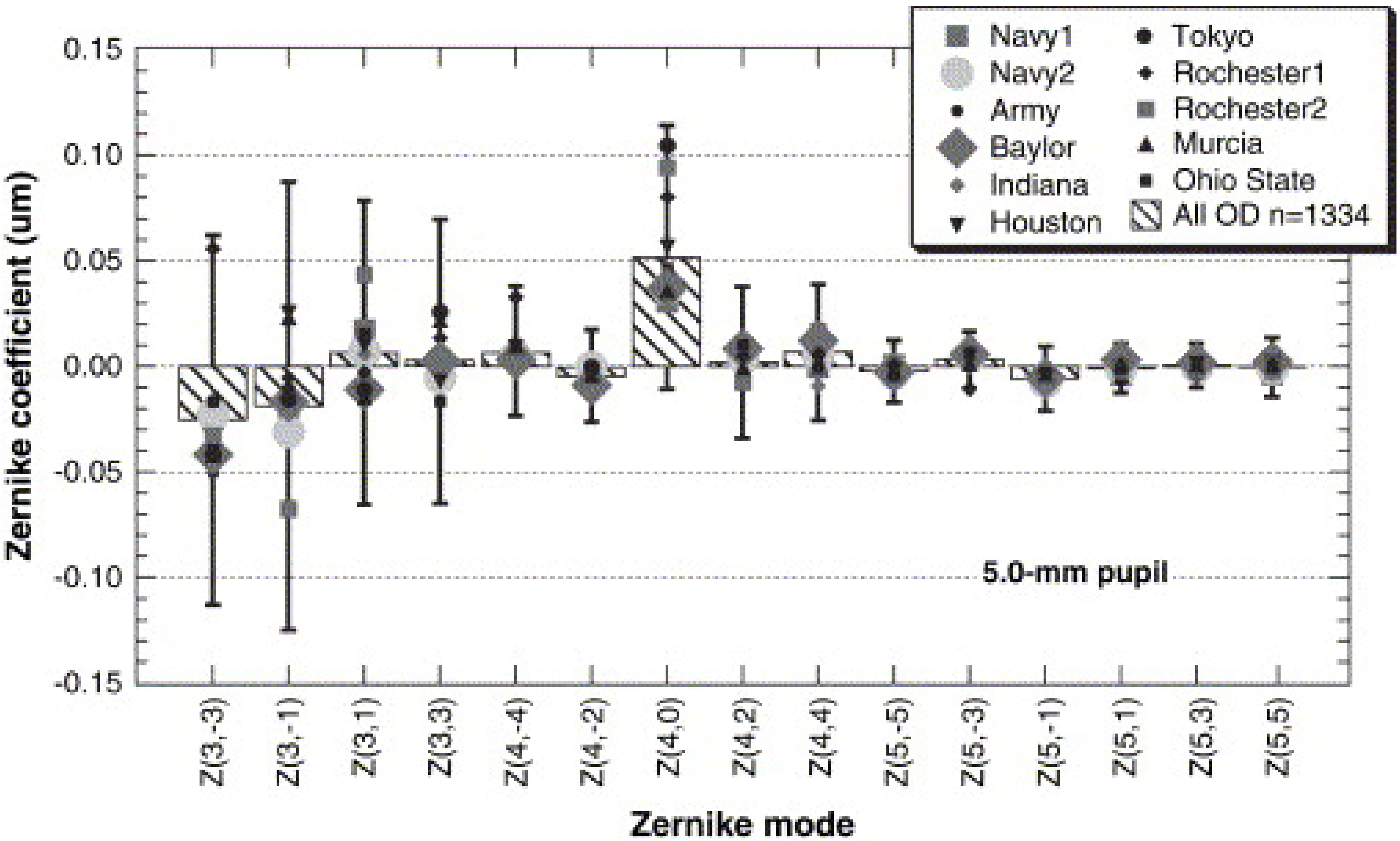
J CATARACT REFRACT SURG - VOL 32, DECEMBER 2006

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

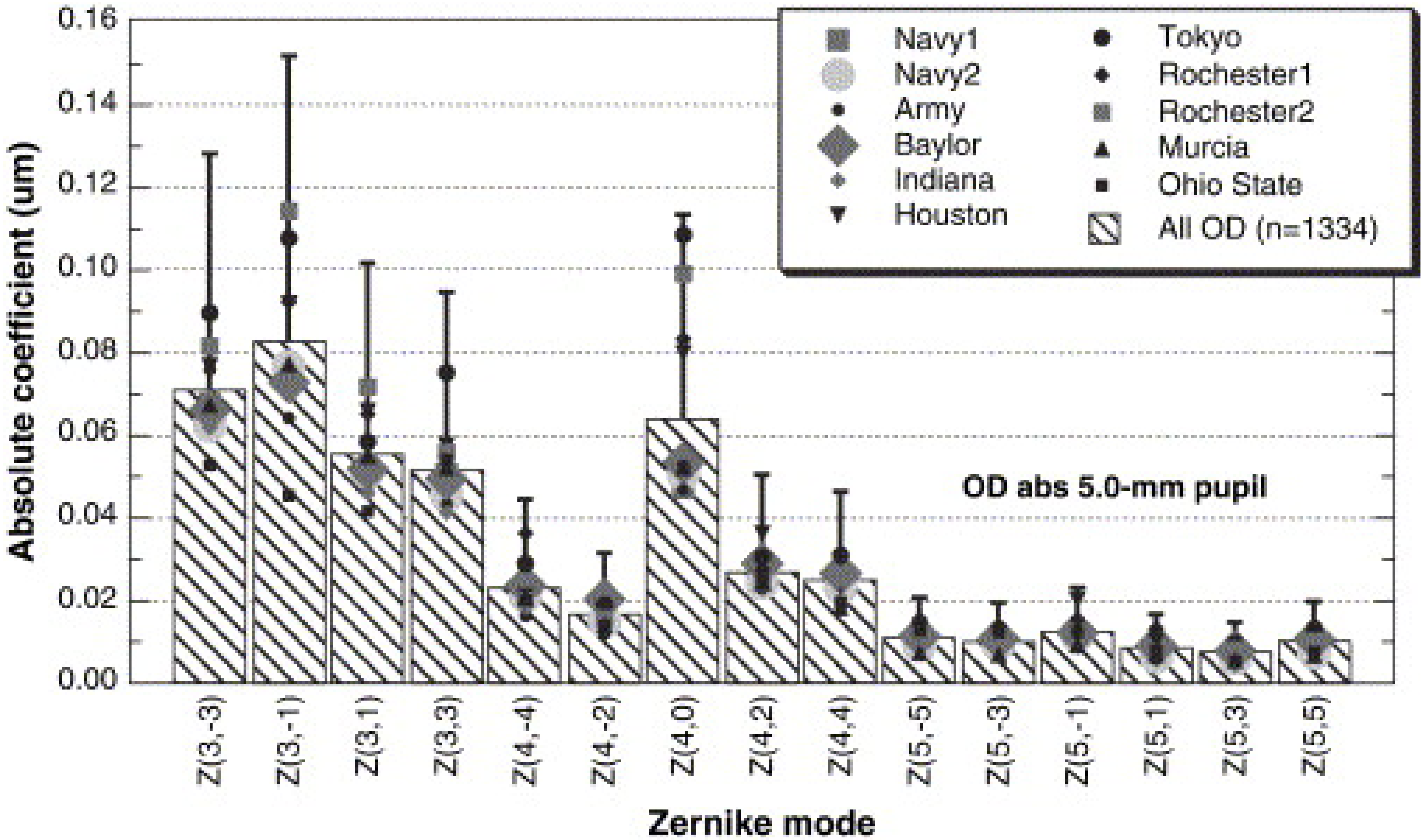
How bad is the eye?: Static Aberrations



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

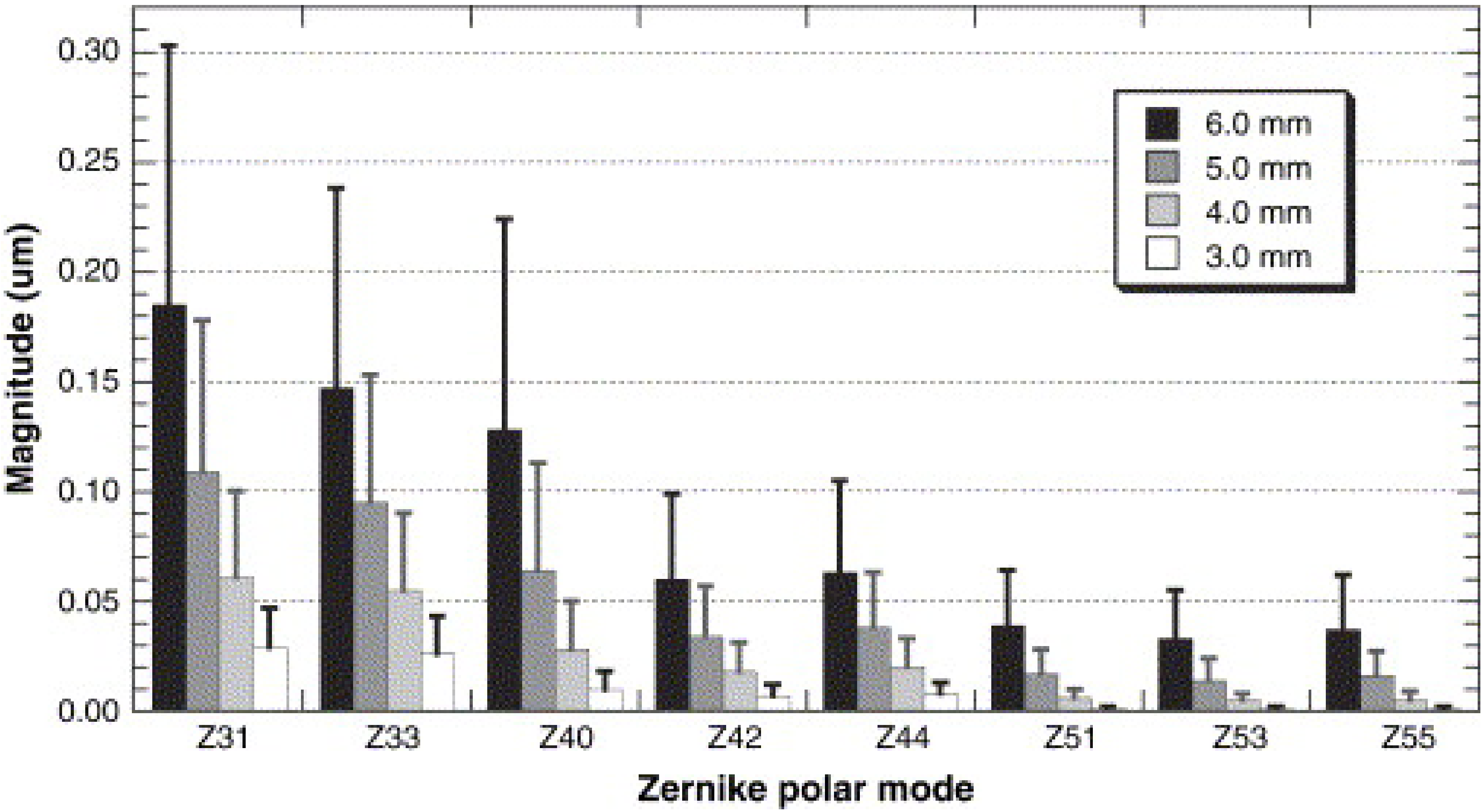
How bad is the eye?: Static Aberrations



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

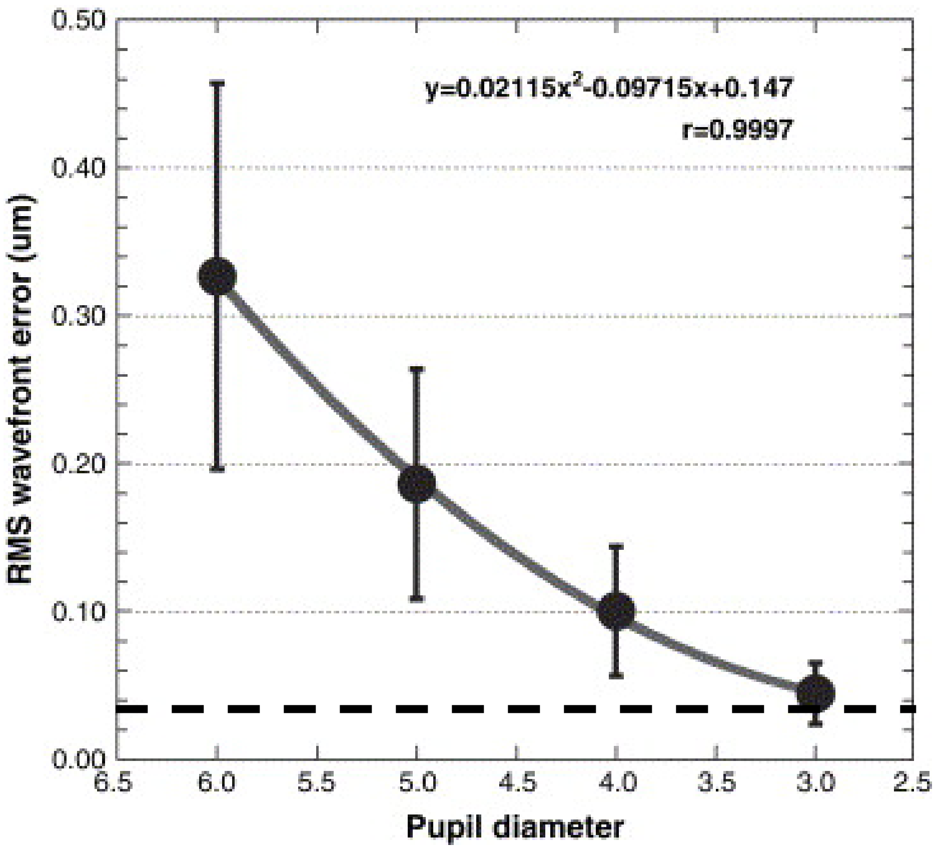


Like most optical systems, the aberrations diminish as the aperture is reduced.

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

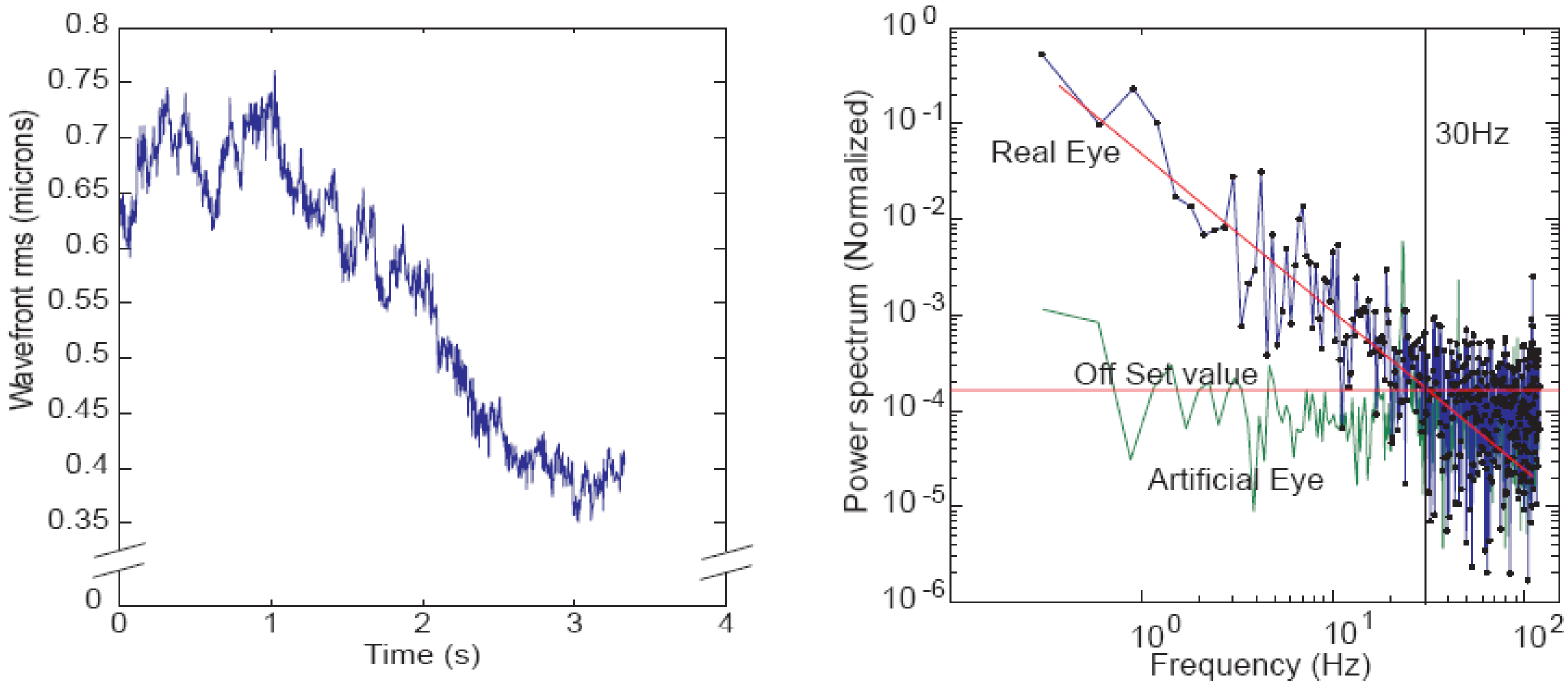


Fig. 2. Dynamics of ocular aberrations. (a) Wavefront rms measured at 240 Hz over approximately 4 s. (b) Power spectrum of the signal in (a) showing dynamic behaviour in excess of 30 Hz.

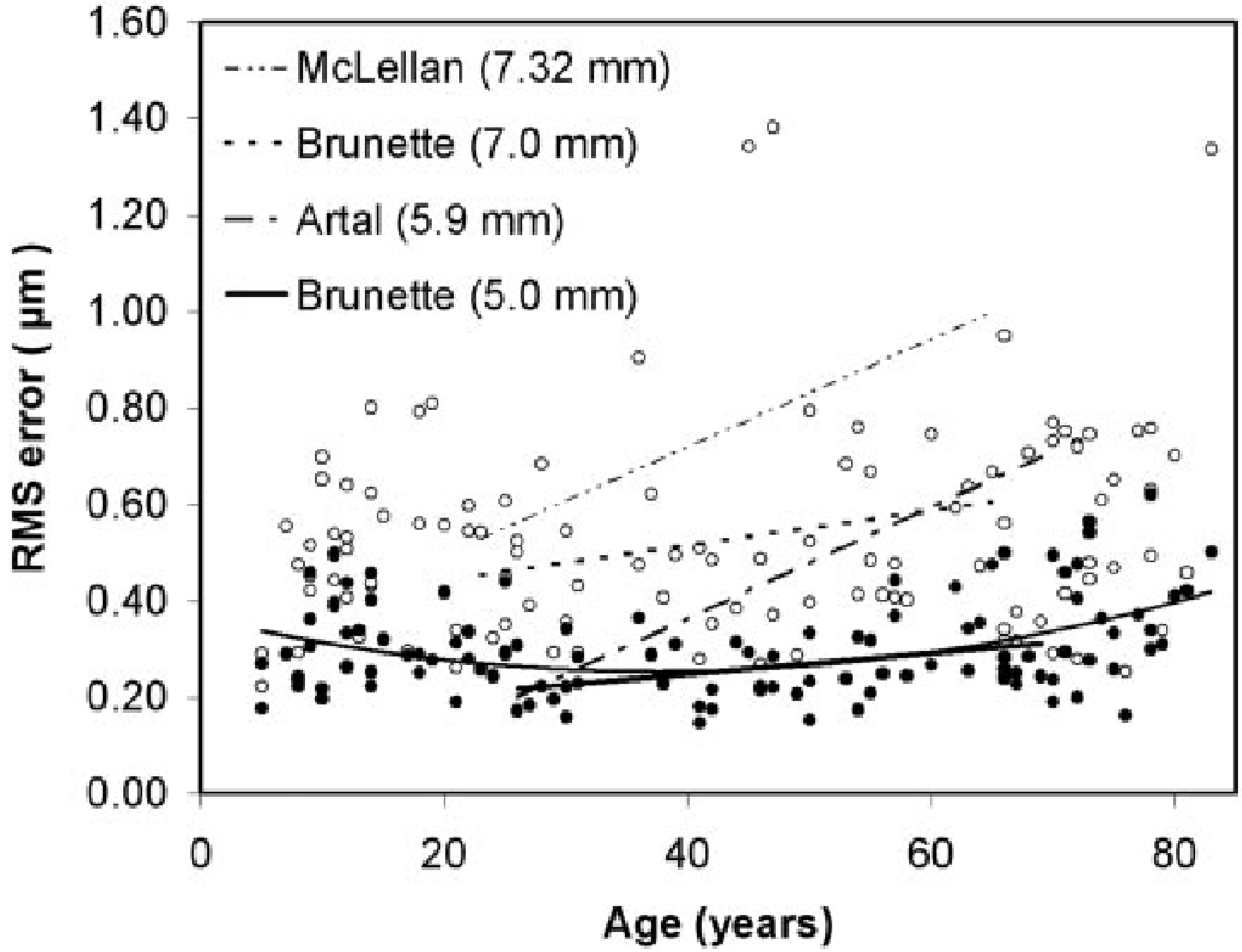
Diaz-Santana et al. Benefit of higher closed-loop bandwidths in ocular adaptive optics, Opt Express, 11: (2003)

2.12 Typical Values for Wave Aberration

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

2.12 Typical Values for Wave Aberration

Change in aberrations with age

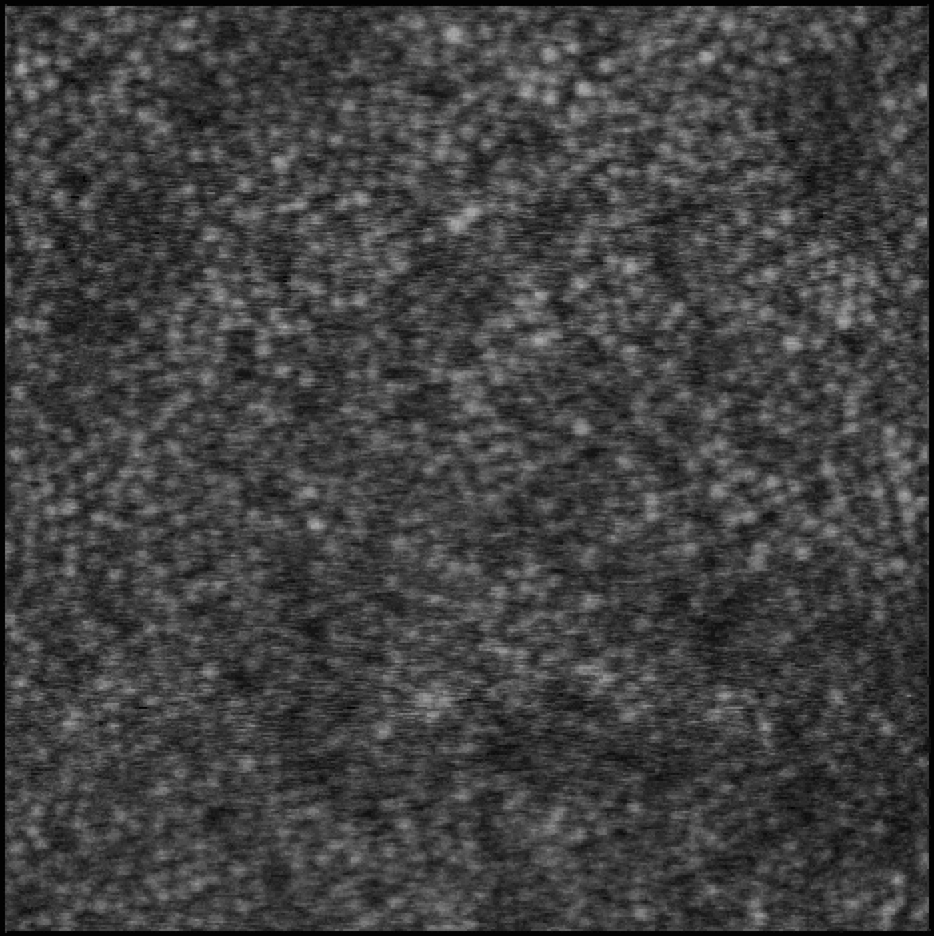


Monochromatic Aberrations as a Function of Age, from Childhood to Advanced Age

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

Localizing the Receptive Field

the black spot indicates where a dim red laser has been turned on



40 microns
0.2 deg

Sincich et al, Nature Neuroscience, 2009

Summary

- geometrical optics
- physical optics
- optical quality in the eye
- metrics for determining visual image quality
- measurement of optical quality in the eye

THANKS FOR YOUR ATTENTION!