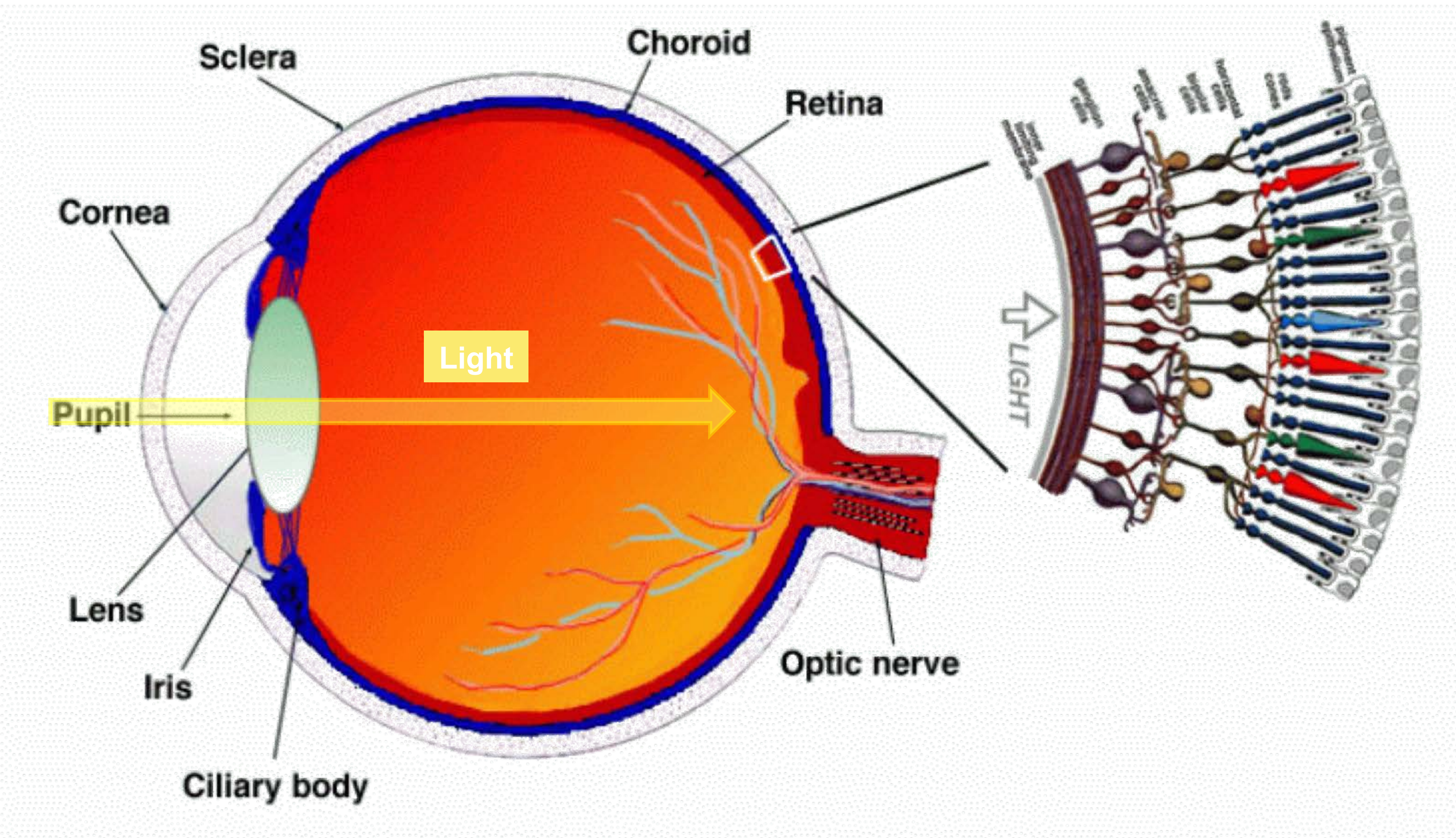
Adaptive Optics for Vision Science

Claire Max
Astro 289, UCSC

March 5, 2020

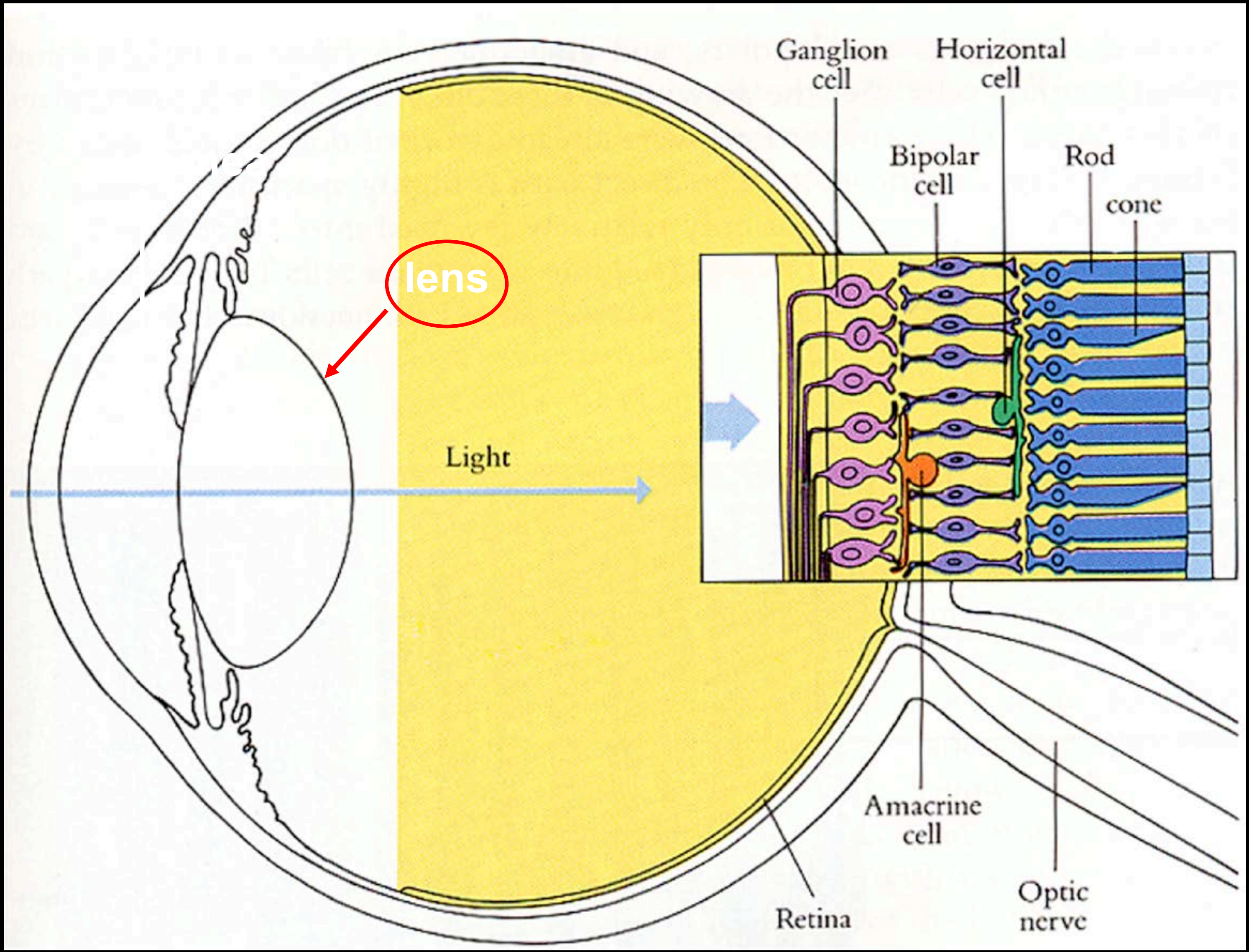
Based on lectures by
Jason Porter (U. Houston)
Austin Roorda (UC Berkeley)
Robert Zawadzki (UC Davis)

Human eye



http://www.ai.rug.nl/~lambert/projects/BCI/literature/misc

Anatomy of the human eye

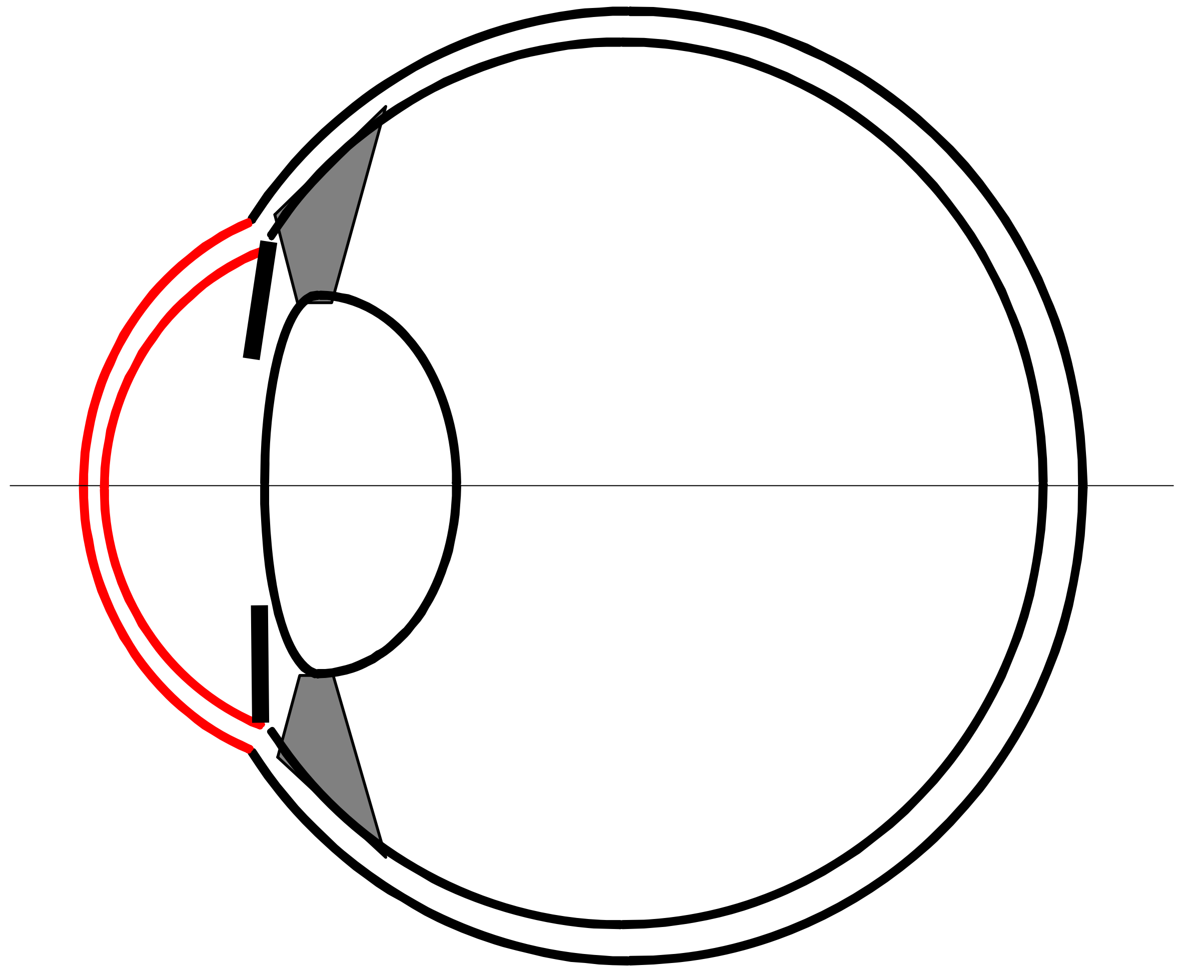


Retina is a 3D structure!

From Hubel - Eye, Brain & Vision

Optics of the eye: The Cornea

2/3 of total eye power



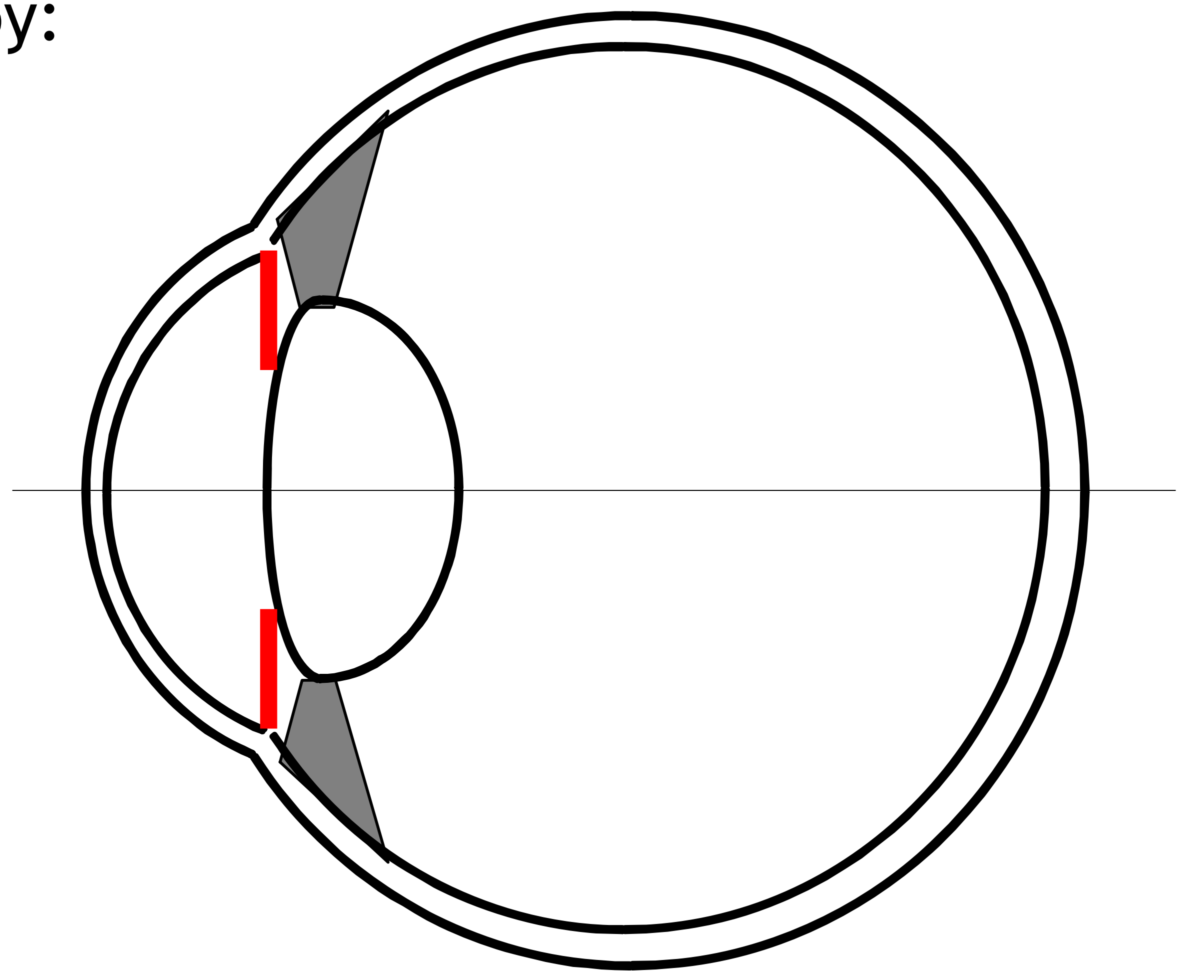
Optics of the eye: The Pupil

The Pupil is affected by:

light conditions
attention
emotion
age

Function:

govern image quality
depth of focus
control light level?



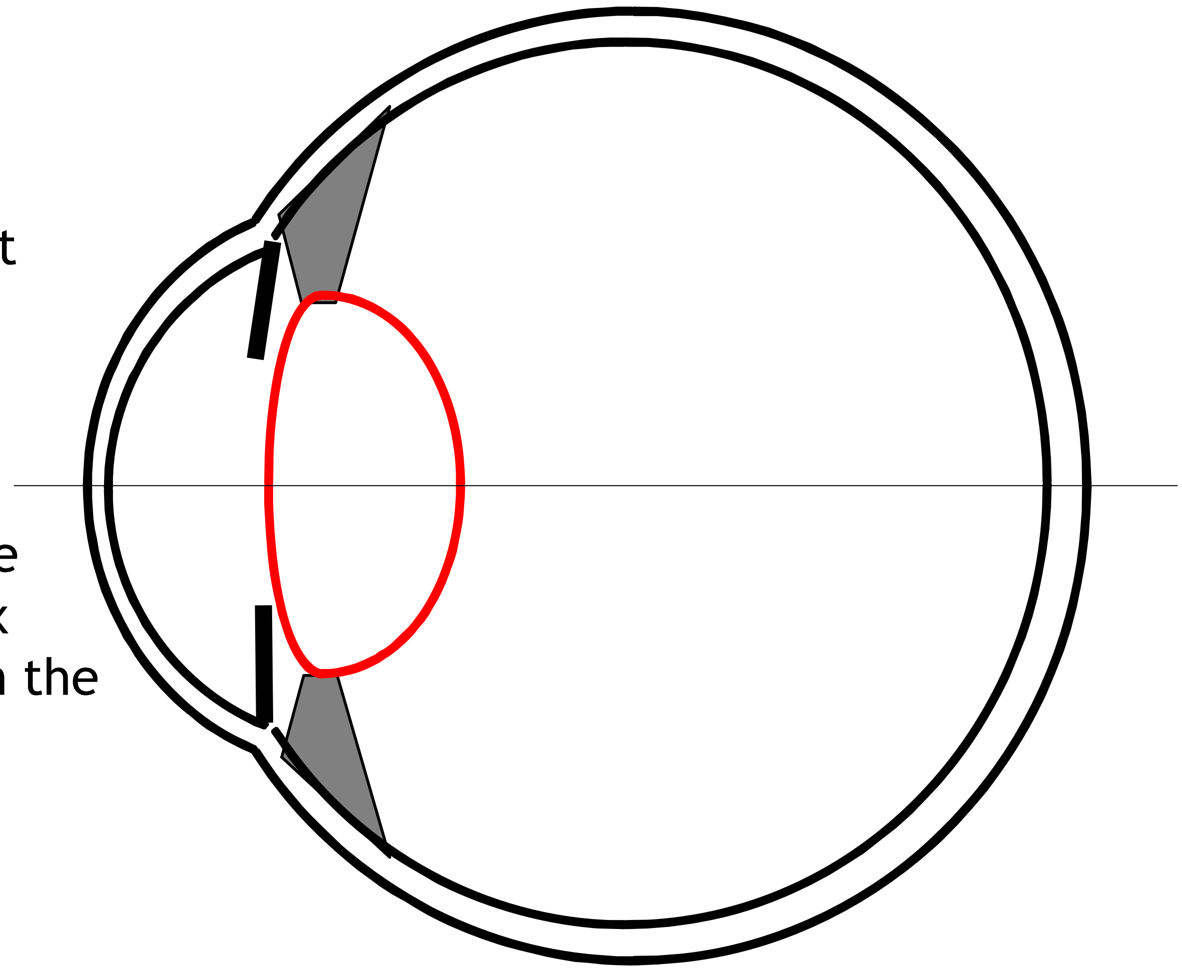
Optics of the Eye: The Crystalline Lens

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.

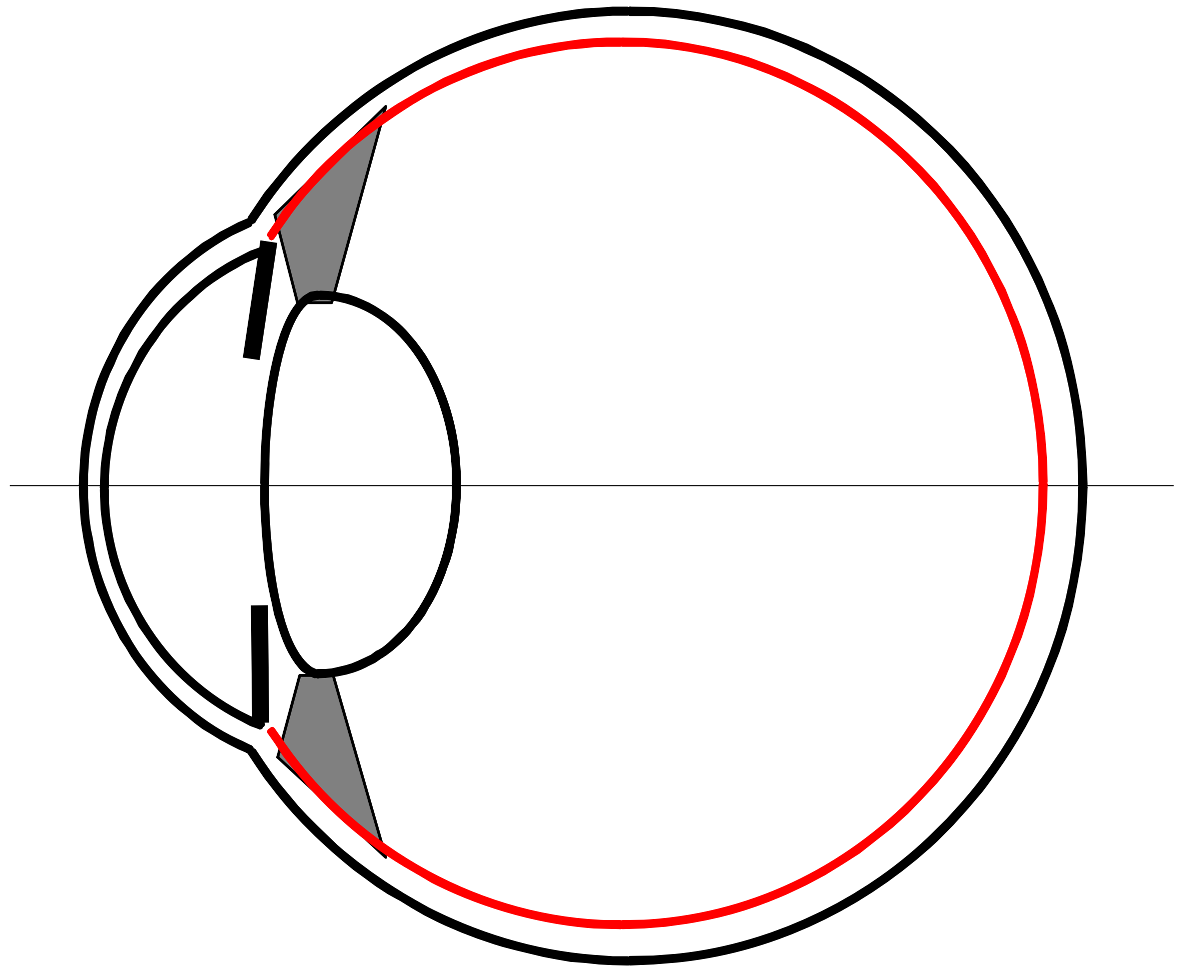
total power of lens ~= 21 D



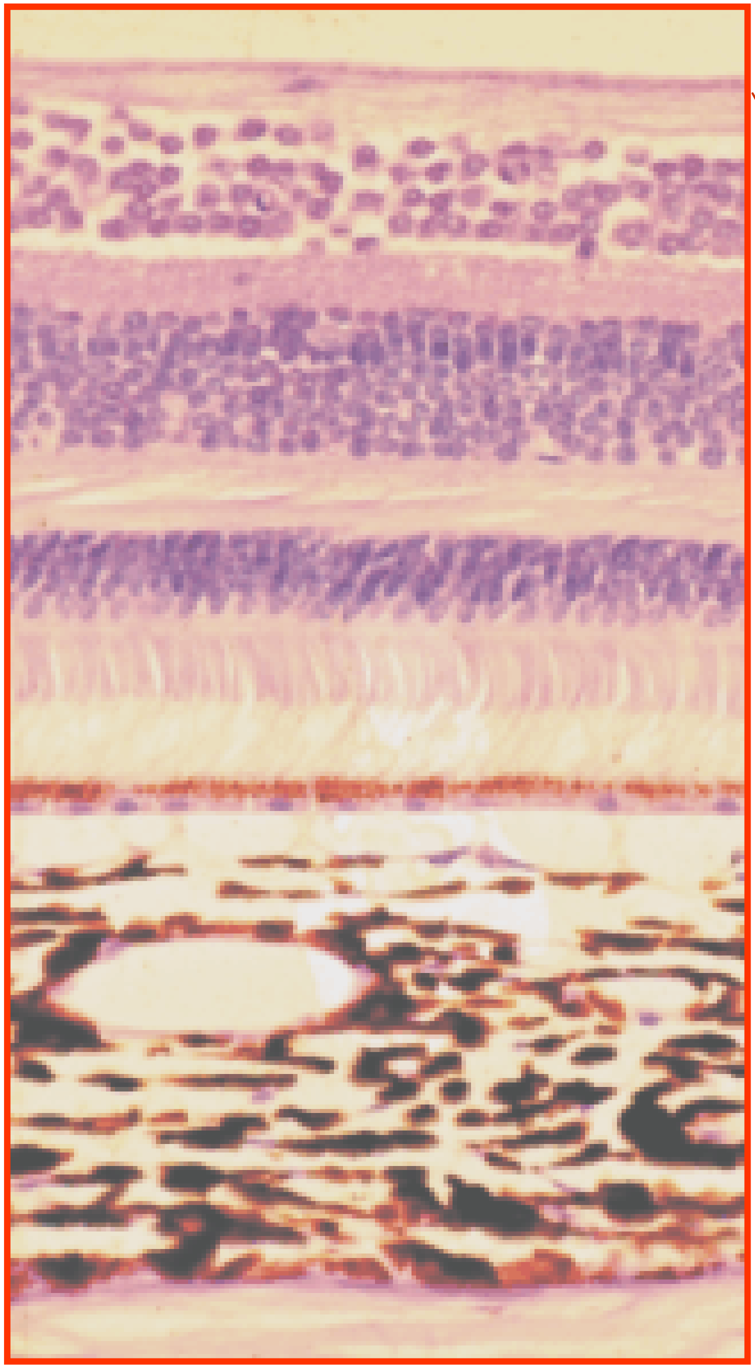
Optical power in diopters ≡ 1 / focal length in meters

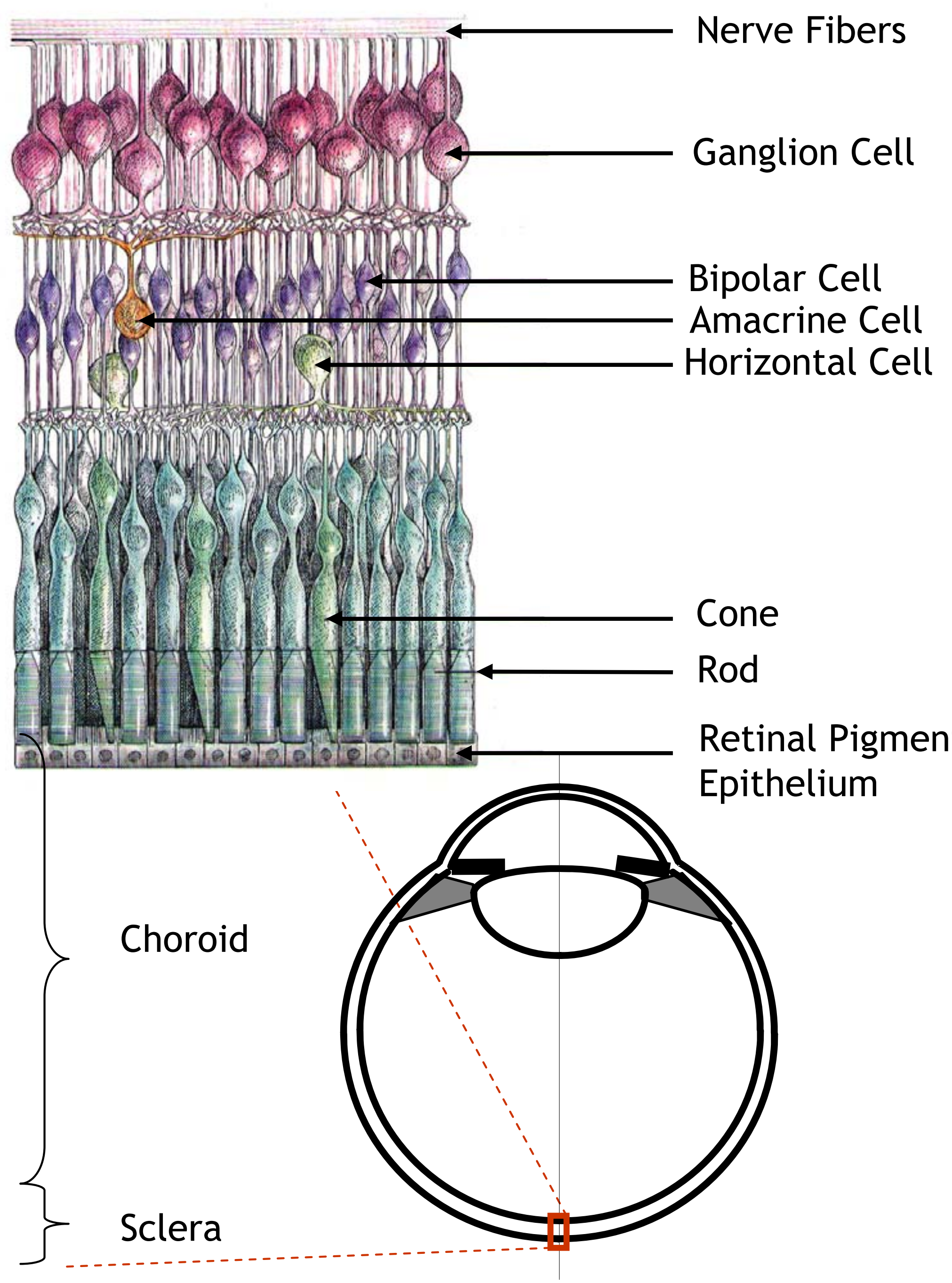
Optics of the Eye: The Retina

Images are sampled by
rods (>100 million)
and cones (~6 million).

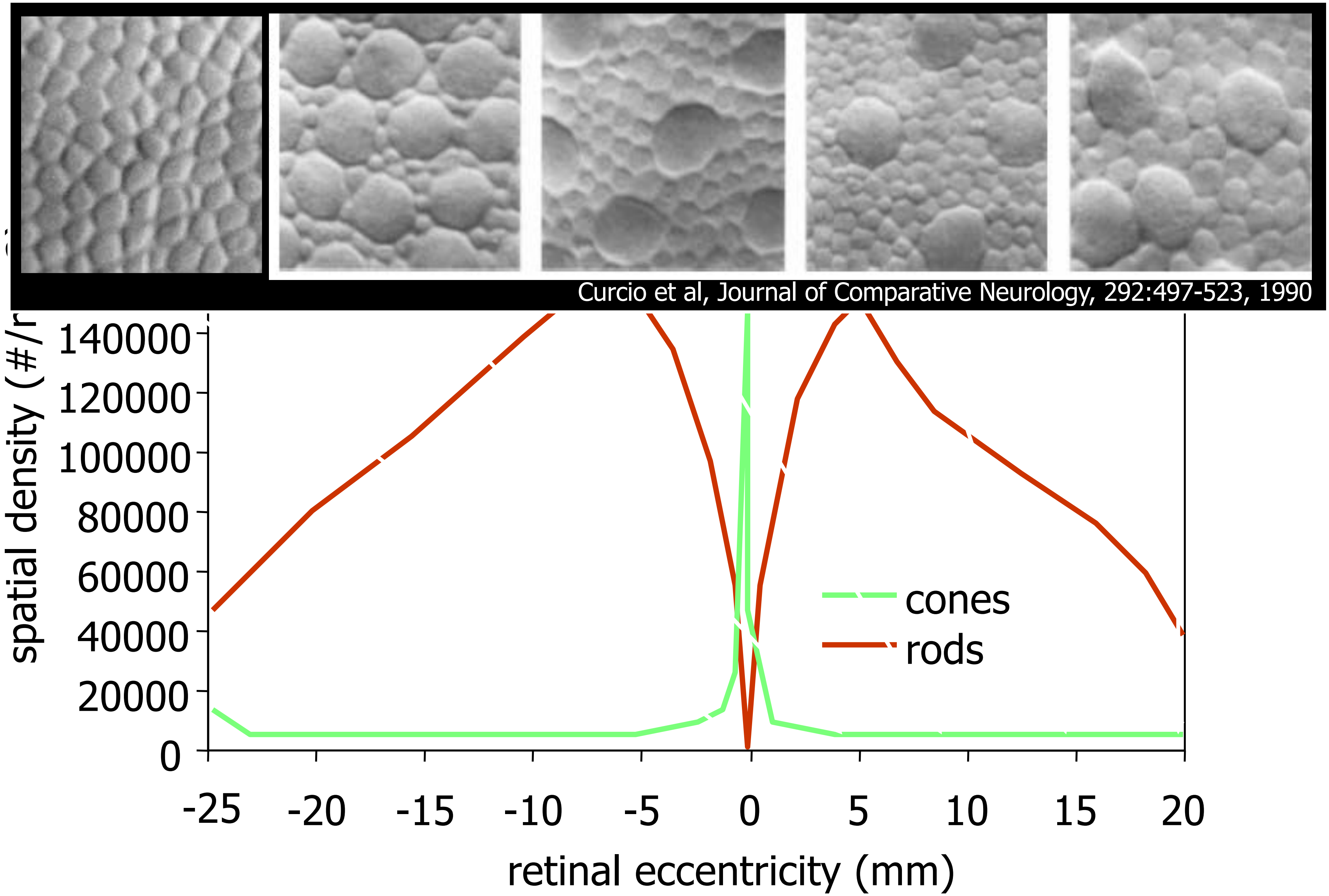


The retina is a thick-multilayered structure





Spatial Distribution of Rods and Cones



How bad is 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"

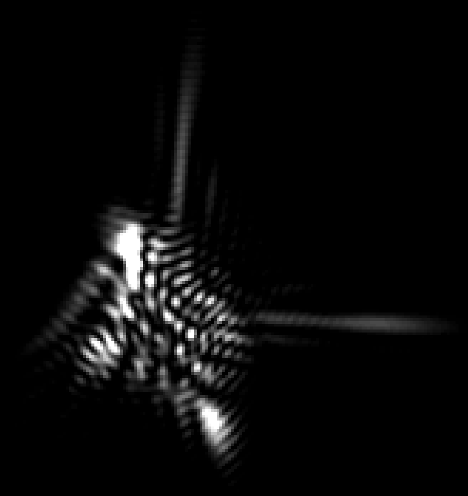
Helmholtz (1881) on the eye's optics.

How bad is the eye?

This is how a point source appears for a perfect eye

How bad is the eye?

This is how the same point source appears for a typical human eye

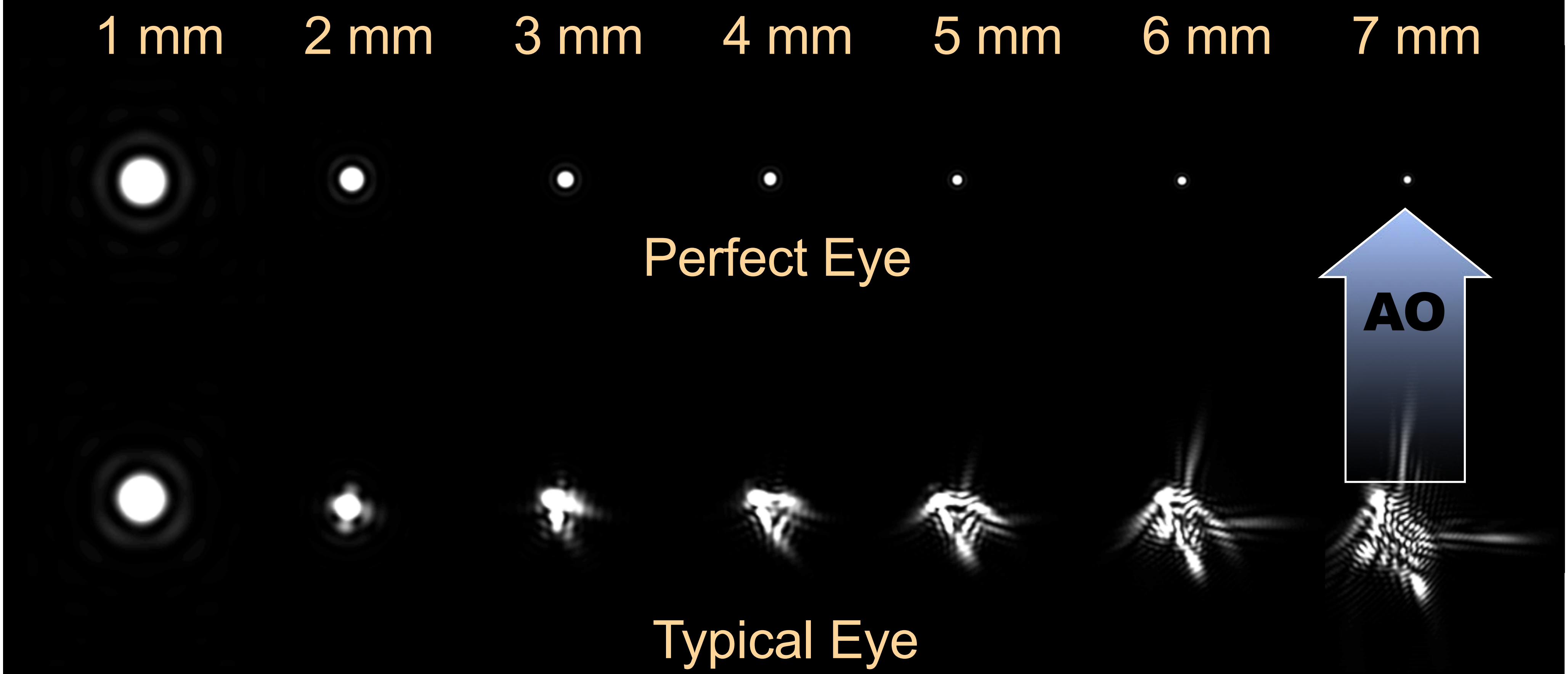


How bad is the eye?

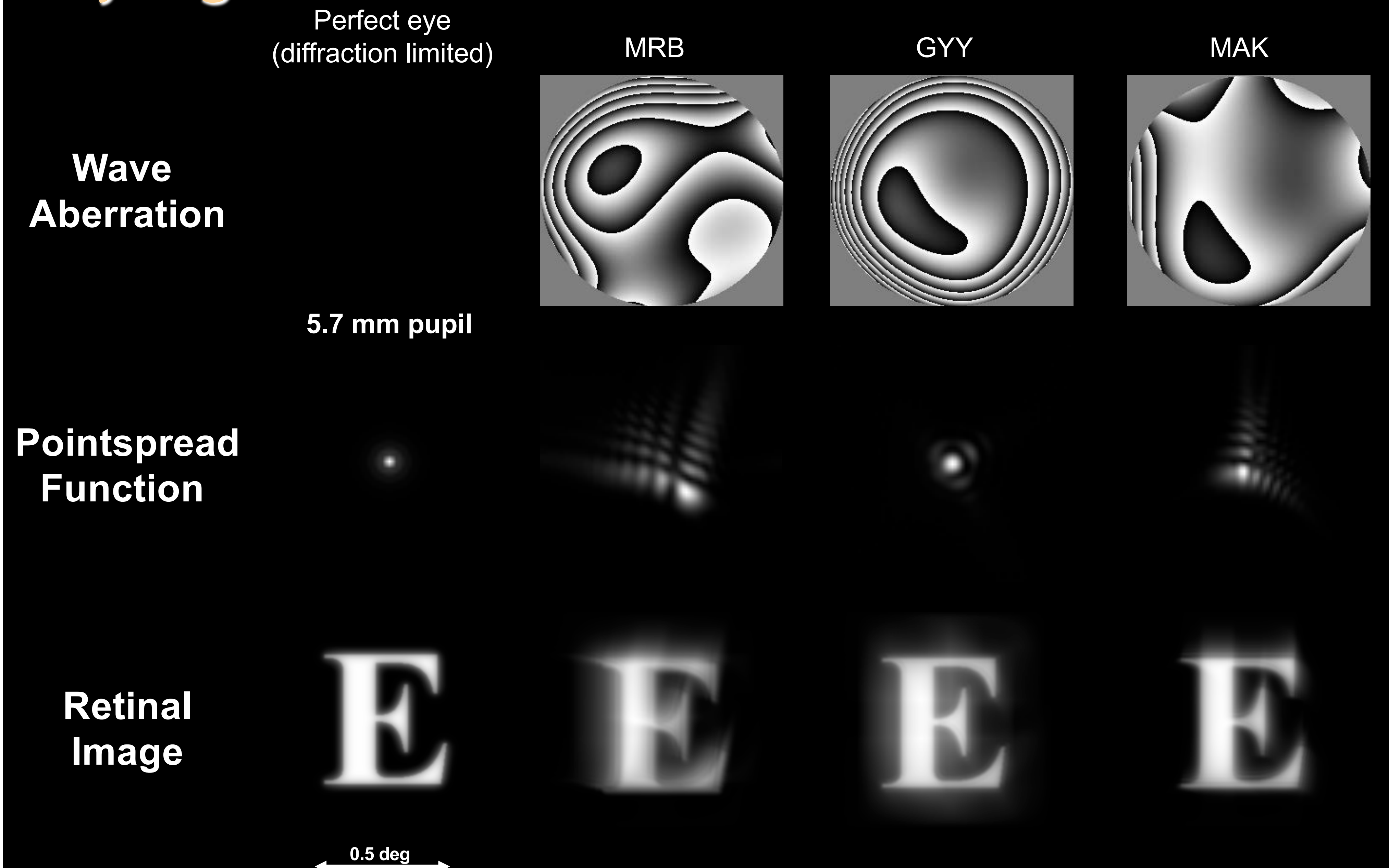
And how to correct it with AO

- Static Aberrations
  - statistics on human eye aberrations are used to determine the spatial density of actuators, maximum stroke etc.
- Dynamic Aberrations
  - statistics on human eye aberration dynamics are used to determine AO closed-loop frequency requirements

Point Spread Function vs. Pupil Size

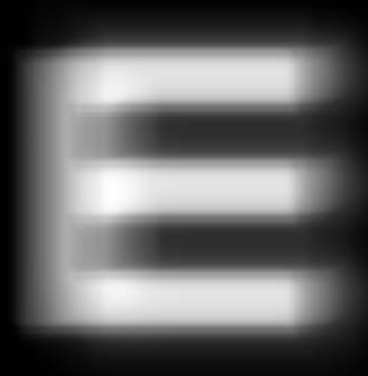


Every eye has a different pattern of high order aberrations

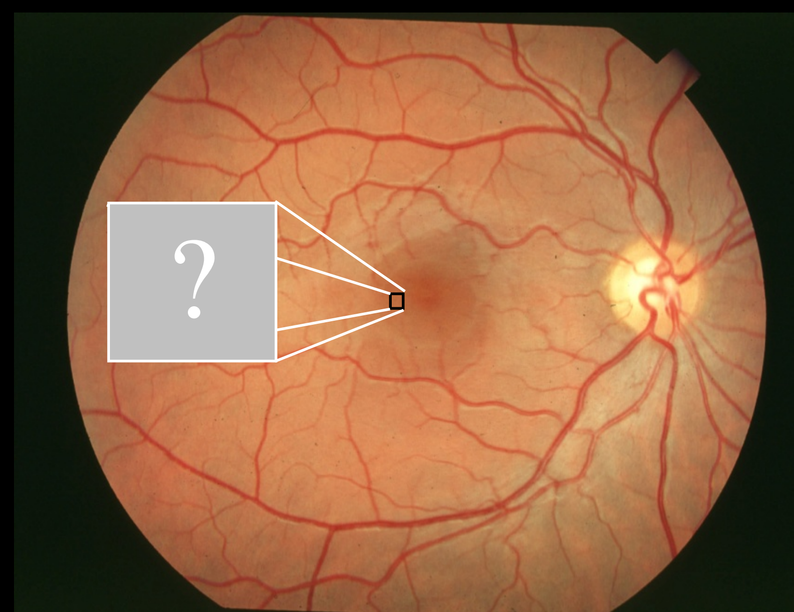


How can we use AO to improve

the quality of vision?



the resolution of
retinal images?



AO for astronomy and vision science are fundamentally similar, but face different challenges

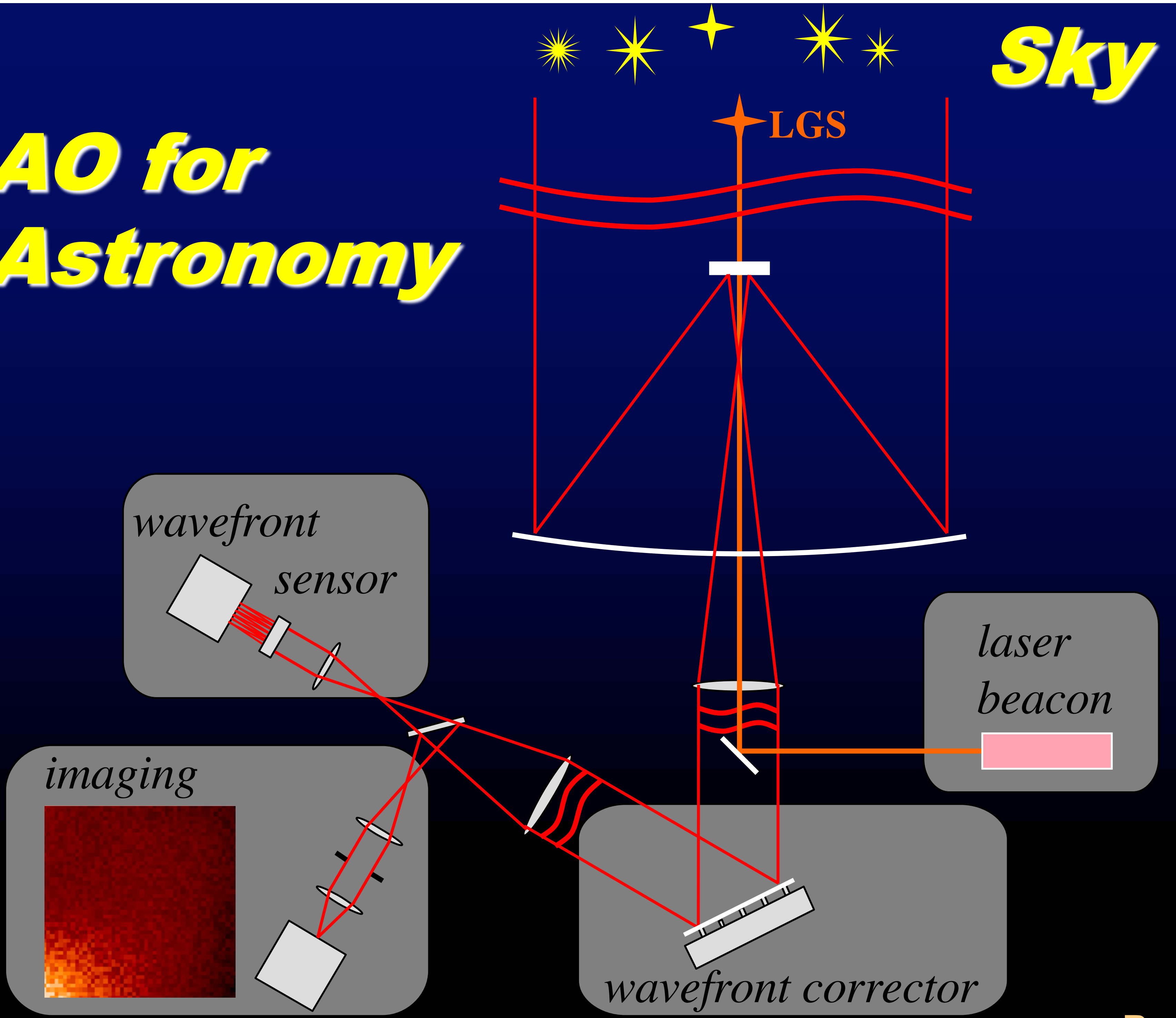
Sources of Retinal Image Blur

Diffraction

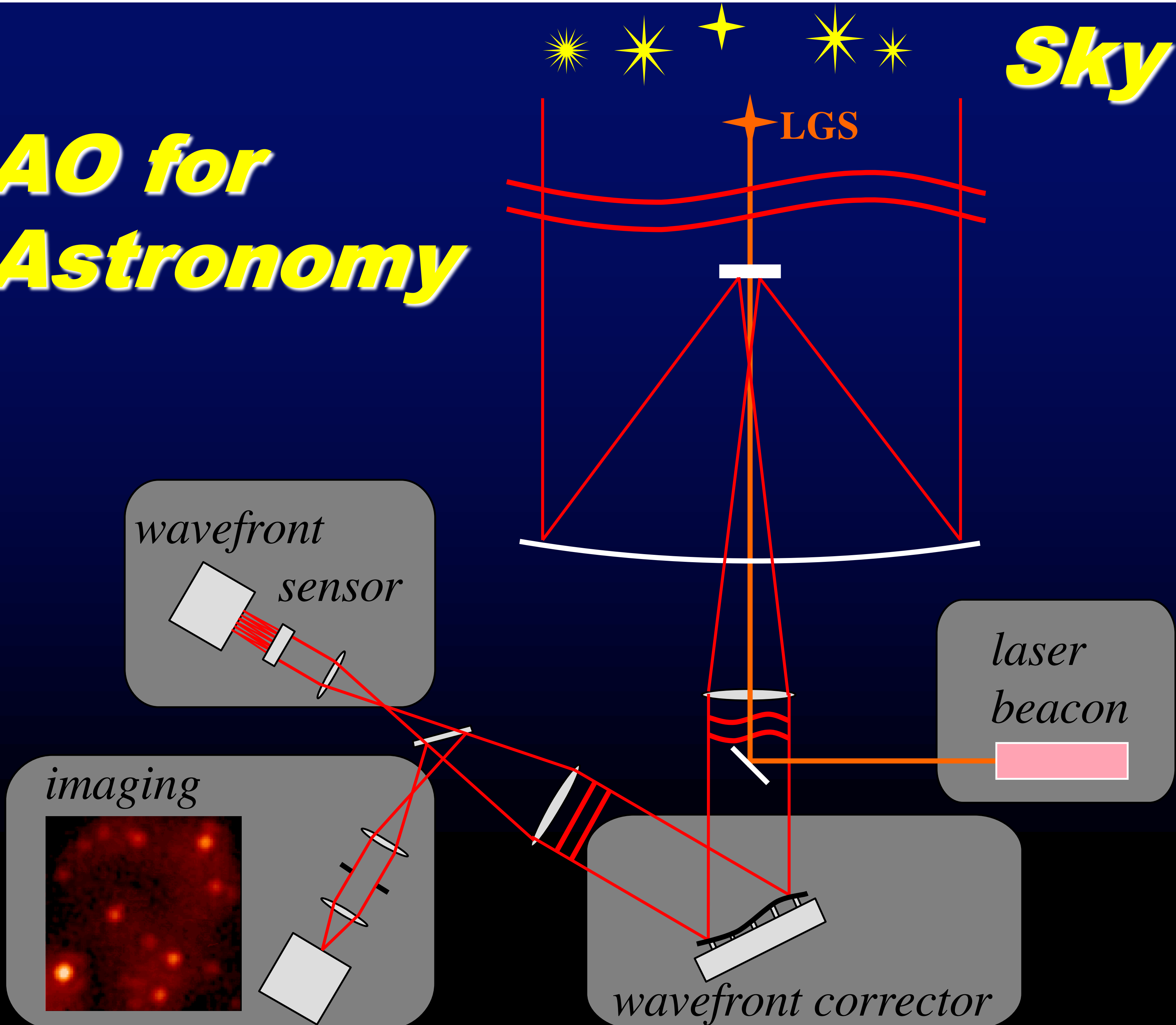
Aberrations

Light Scatter

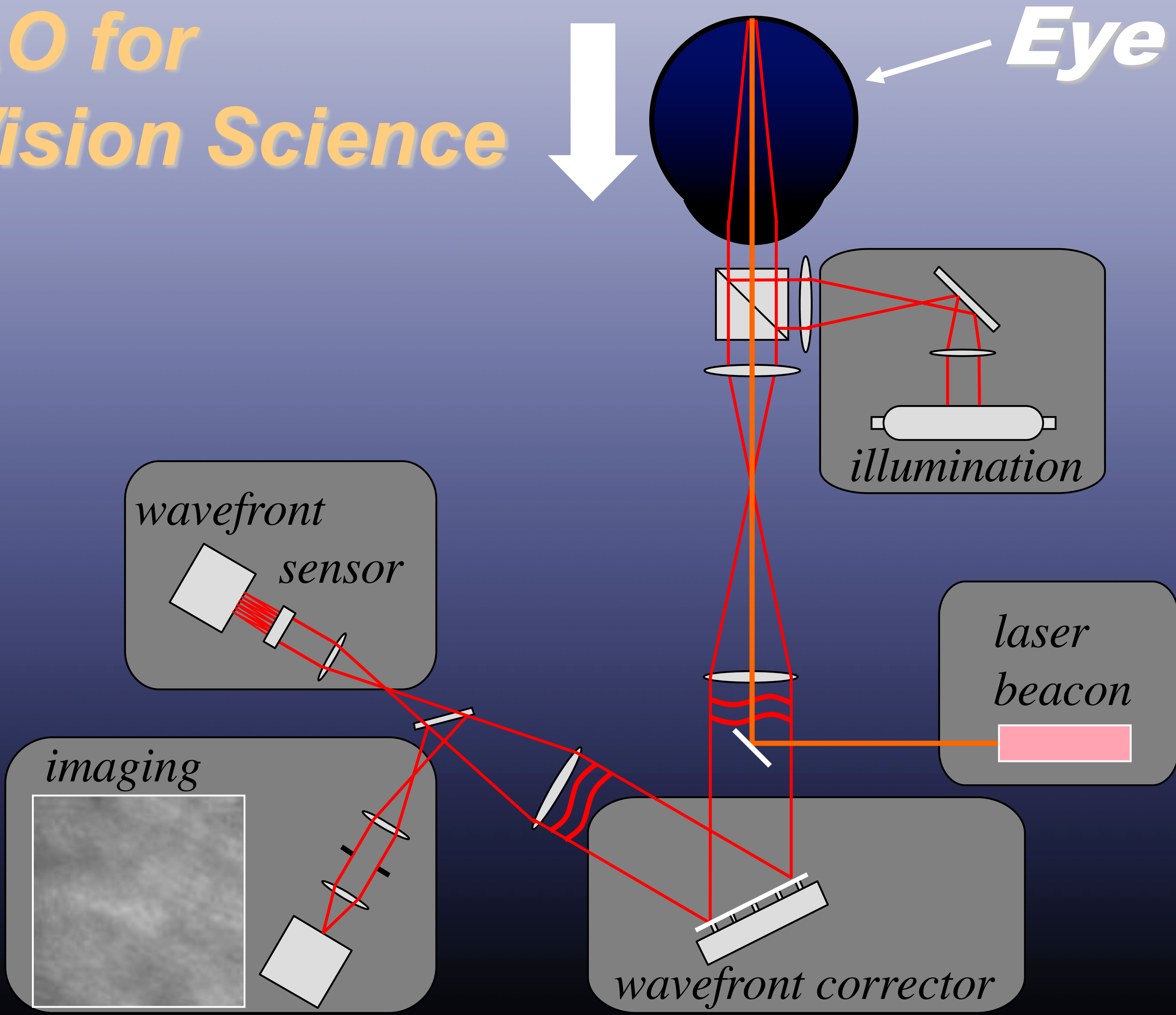
AO for Astronomy

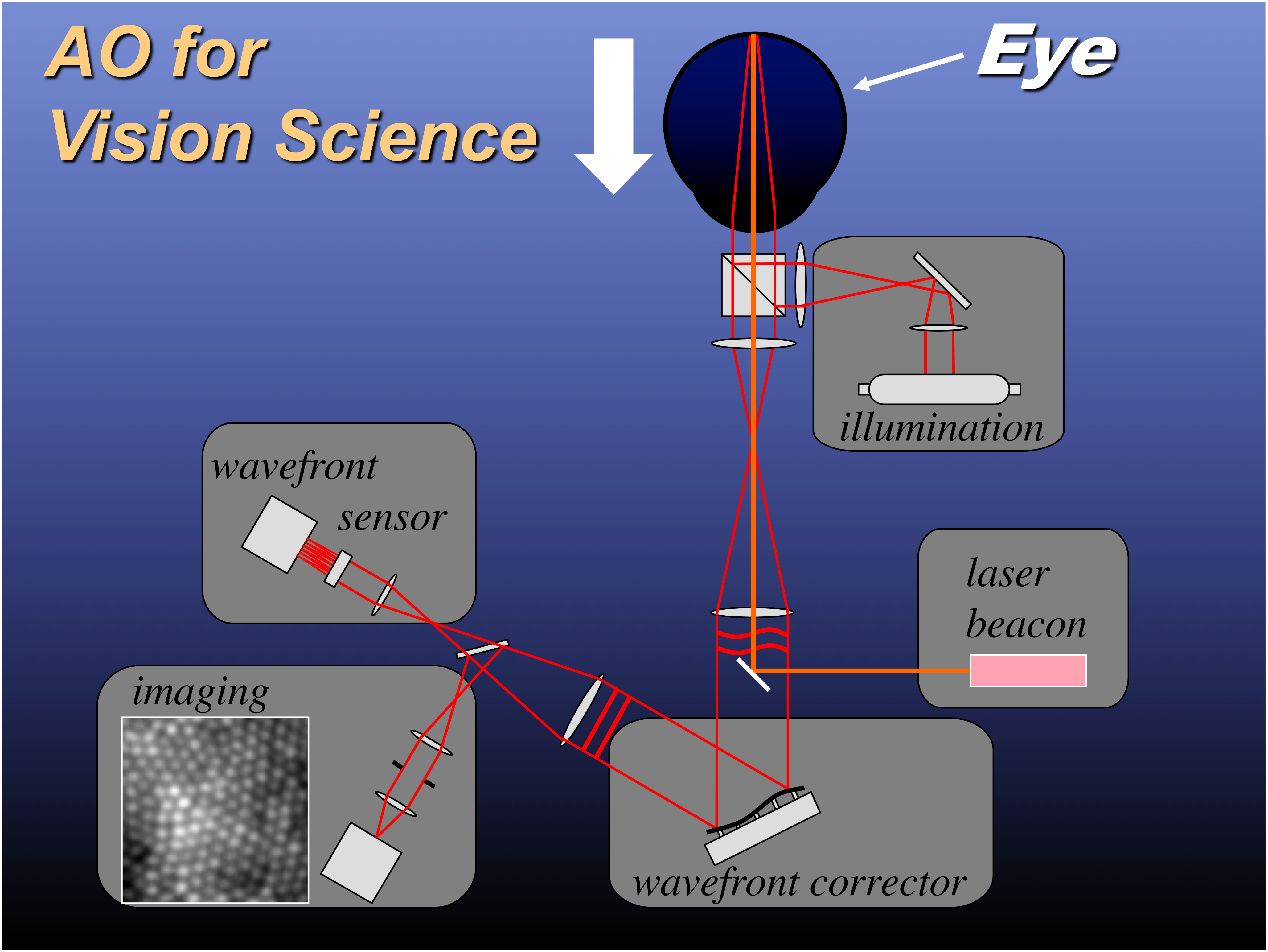


AO for Astronomy

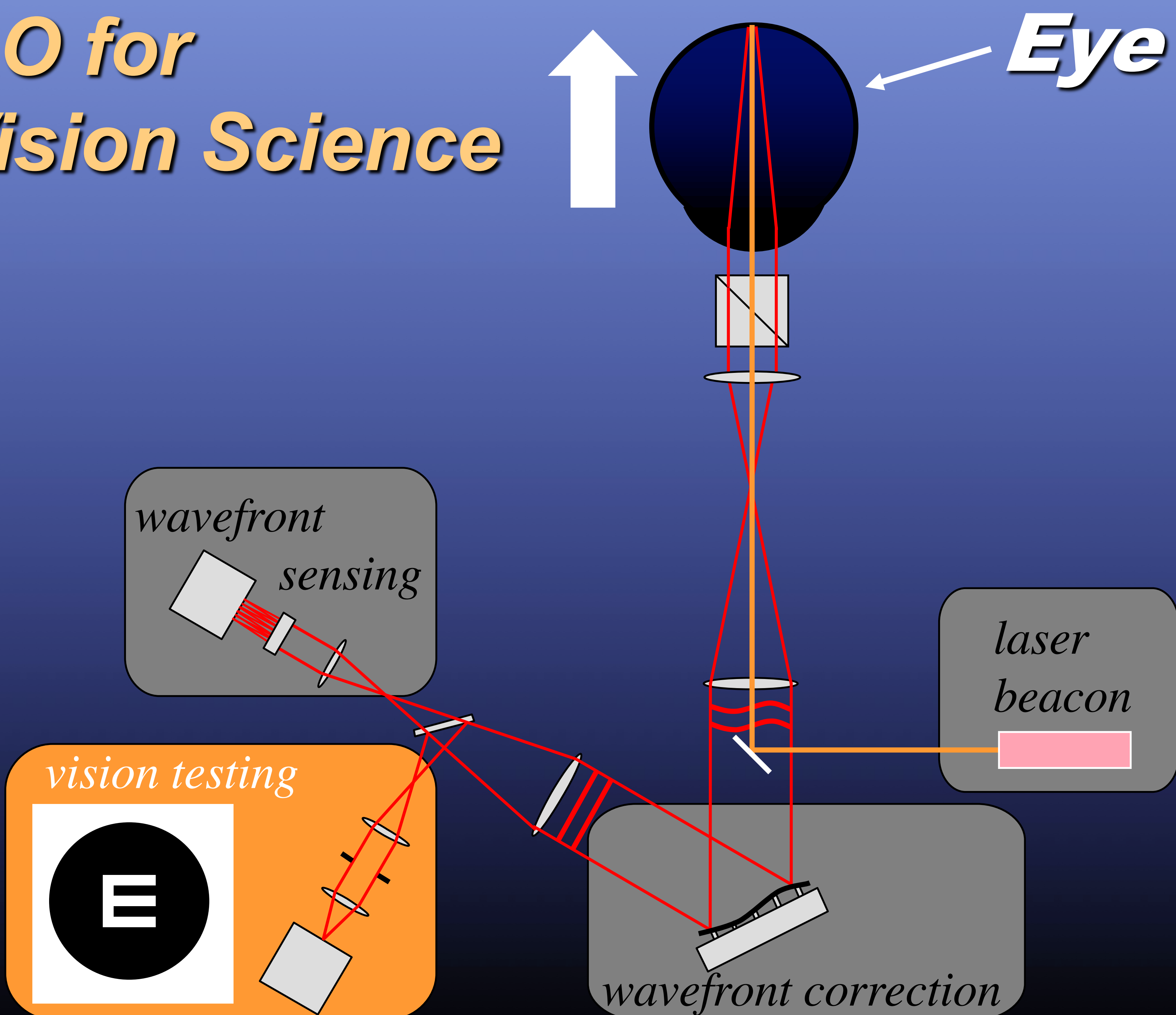


AO for Vision Science



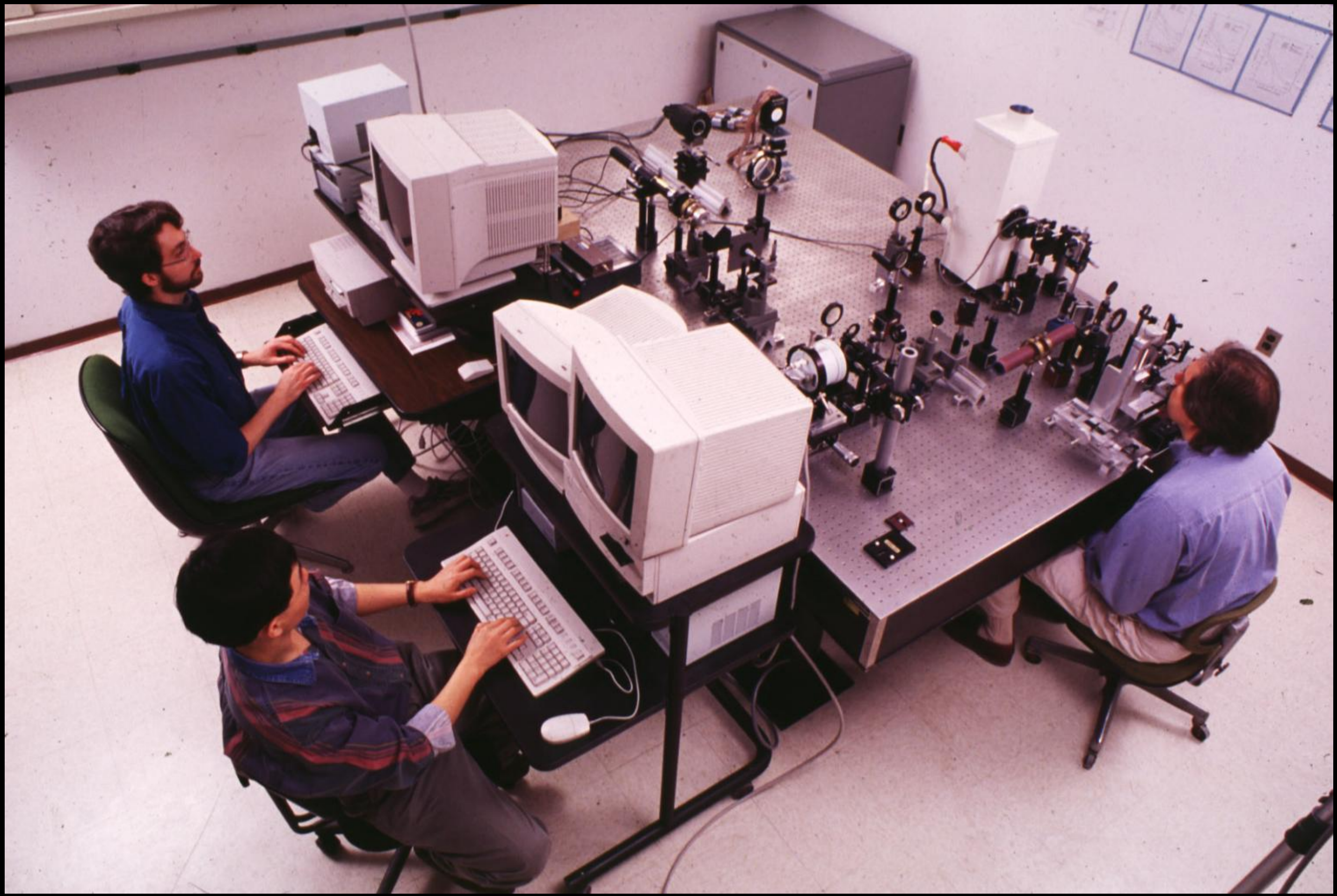

AO for
Vision Science
Eye
illumination
wavefront
sensor
laser
beacon
imaging
wavefront corrector

AO for Vision Science

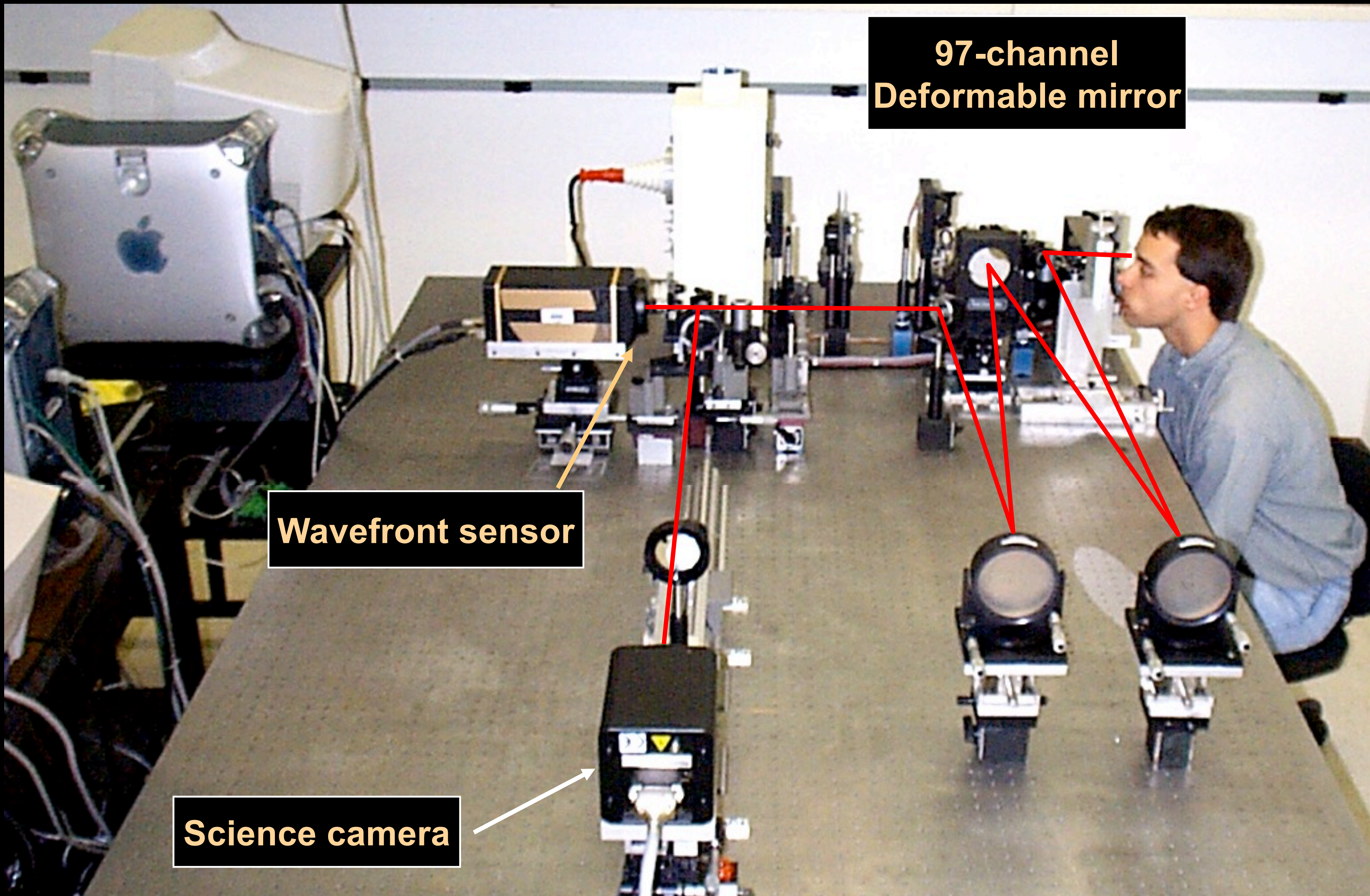


First demonstration of retinal imaging & vision improvement by correcting higher order aberrations

Liang J, Williams DR, and Miller DT. Supernormal vision and high resolution retinal imaging through adaptive optics. *J. Opt. Soc. Am. A.*, 1997;14:2884-2892.

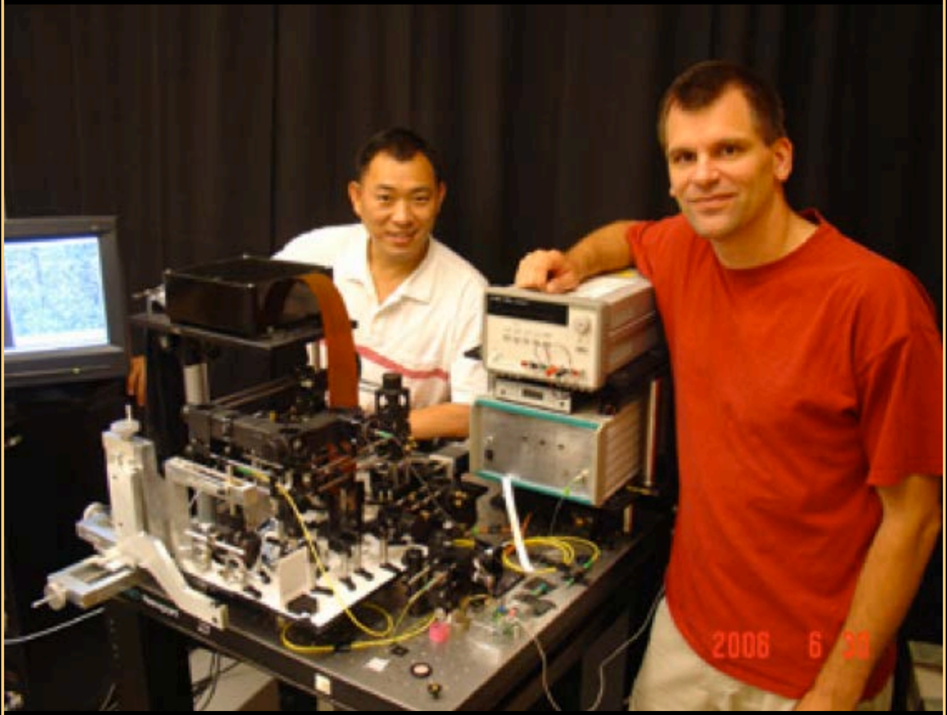


U Rochester: Early AO Ophthalmoscope



Recent instruments are compact: Roorda's compact scanning laser ophthalmoscope

- Can be rolled from room to room
- Not only imaging, but also a scanning confocal microscope

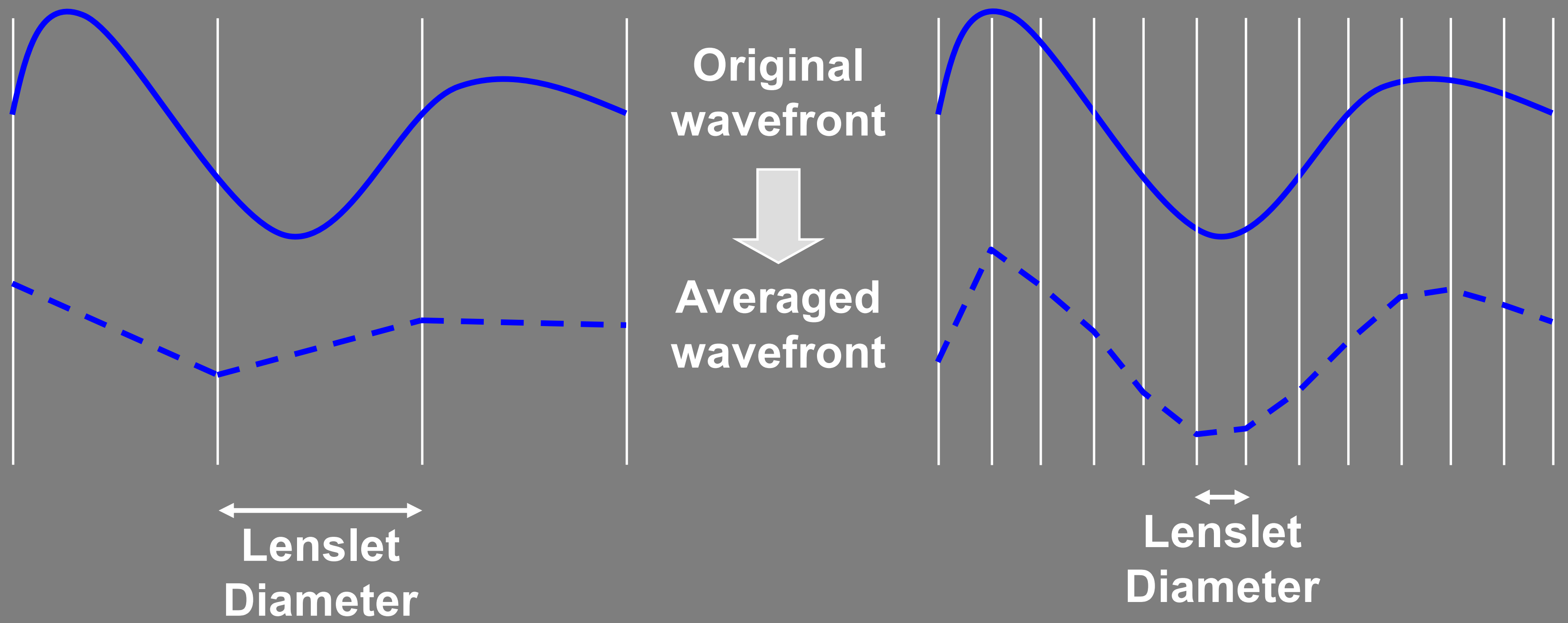


How many lenslets do I need to adequately sample and reconstruct the wavefront?

Will depend on several factors, including the complexity of (spatial frequencies contained in) the wavefront

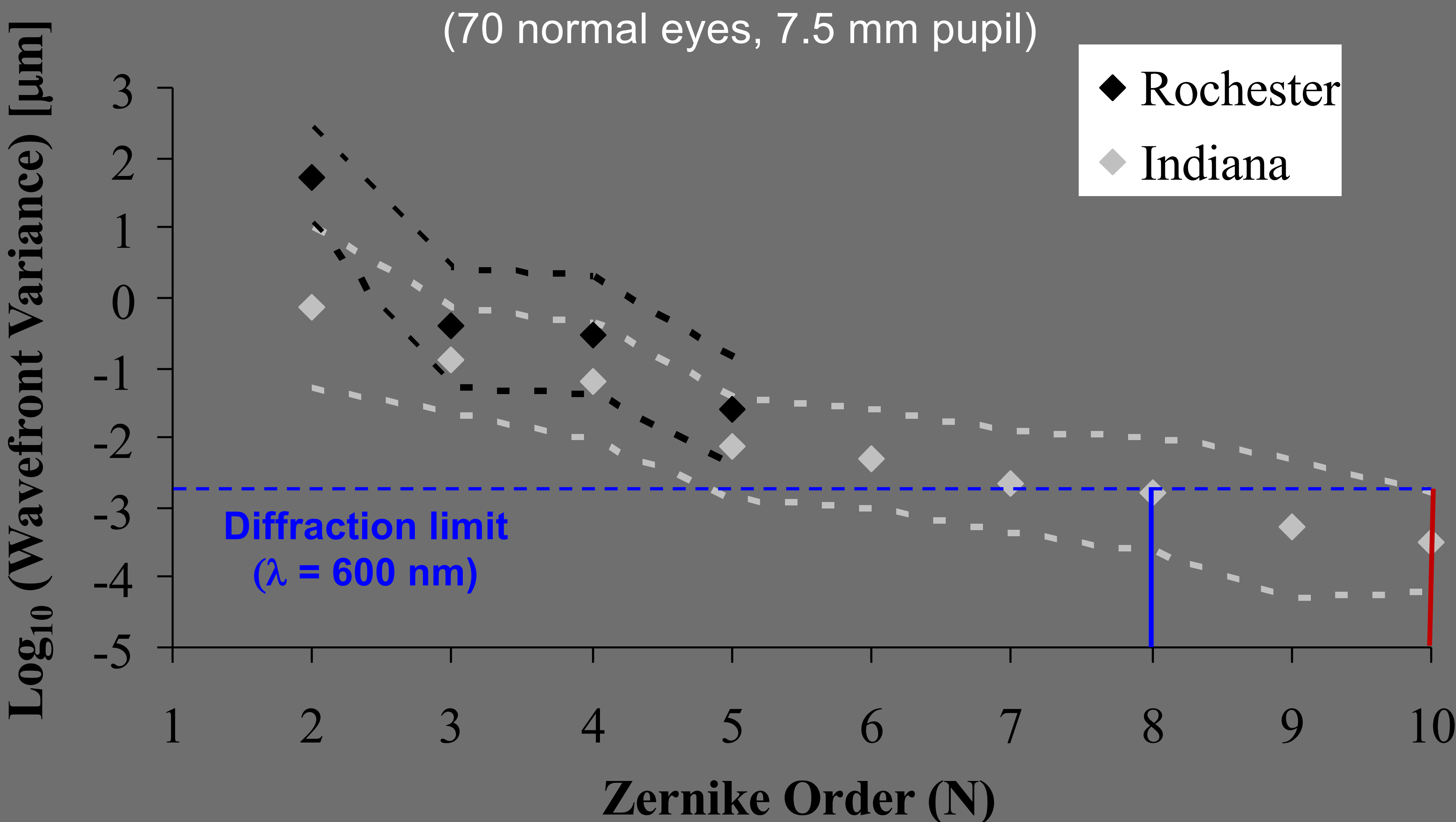
Fewer lenslets
Poor representation of the wavefront

More lenslets
More precise representation of the wavefront



G. Yoon, "Wavefront sensing and diagnostic uses," Chapter 3, Adaptive Optics for Vision Science (2006).

There is a measurable amount of aberration in normal eyes up to at least the 8th radial order



N. Doble & D.T. Miller, “Vision correctors for vision science,“ Chapter 4, Adaptive Optics for Vision Science (2006).

N. Doble, *et al.*, "Requirements for discrete actuator and segmented wavefront correctors for aberration compensation in two large populations of human eyes," *Appl. Opt.* 46, 4501-4514 (2007),

Typical Shack-Hartmann wavefront sensor parameters for the *normal* human eye

1. **Lenslet array parameters:**

   - **~200 for dilated pupil (15 x 15 to 20 x 20 arrays within 6-8 mm pupil)**

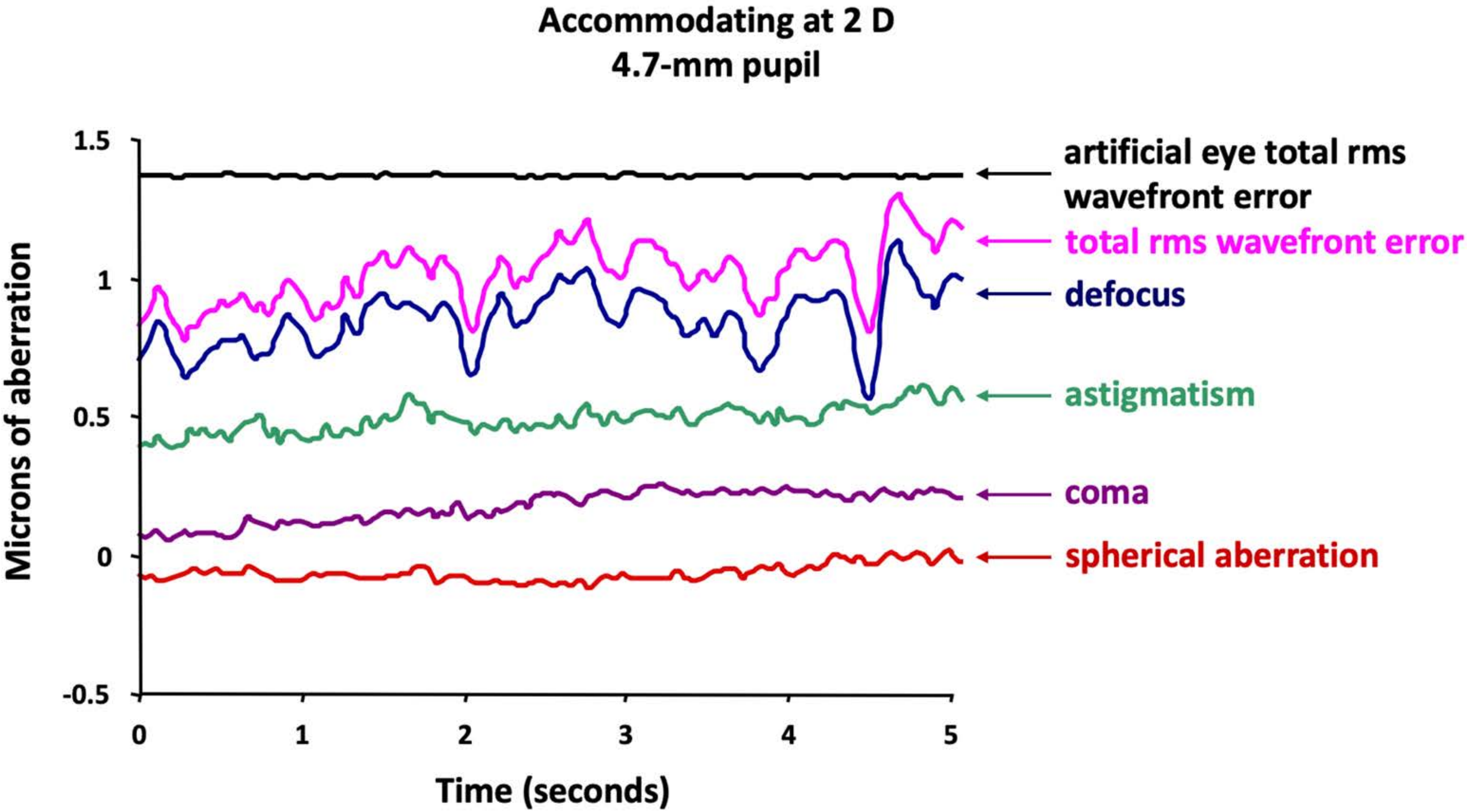
2. **# pixels across spot core:** **4 to 14**
   - **Note that vision science AO systems typically use many more pixels per subaperture than astronomy systems**

3. **Wavelength:** **633 – 850 nm**

4. **Other parameters to consider:**
   - **CCD pixel size**
   - **CCD frame rate (don't need super low read noise)**

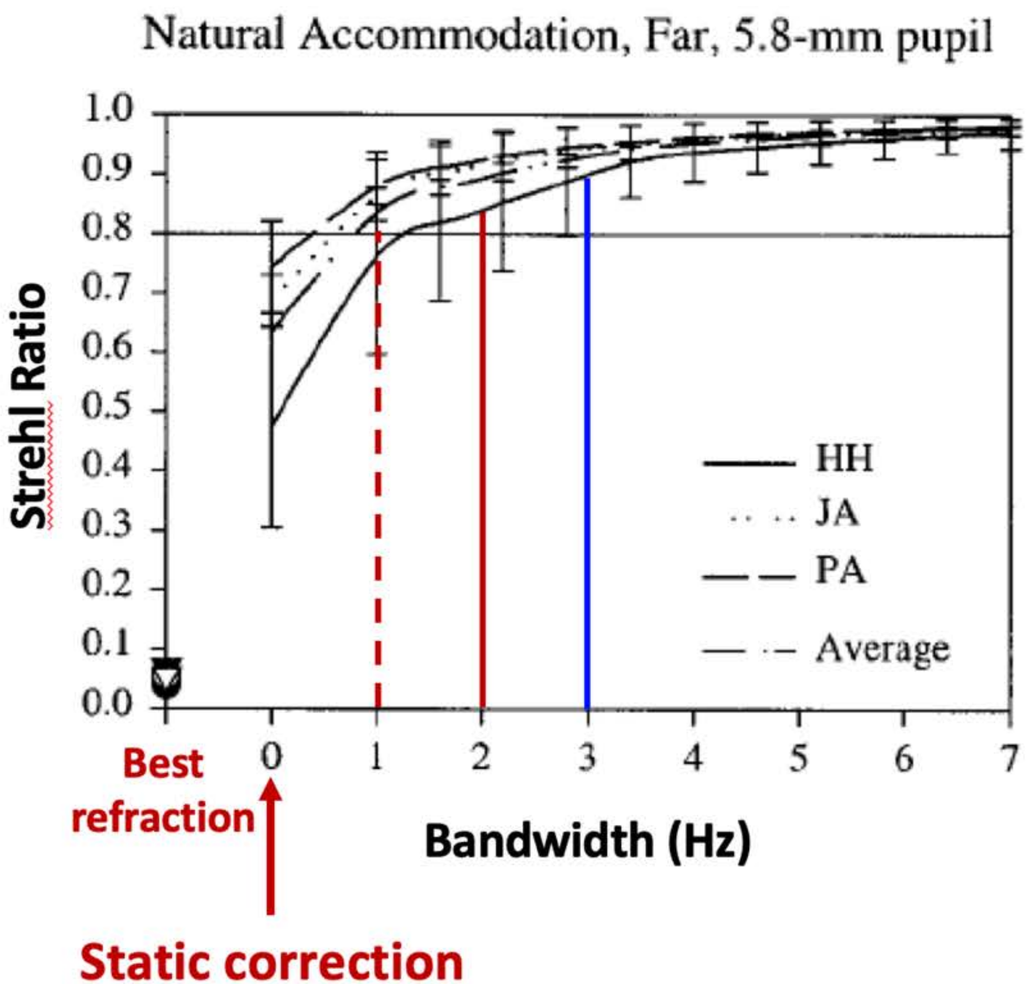
How fast does my vision AO system need to go?

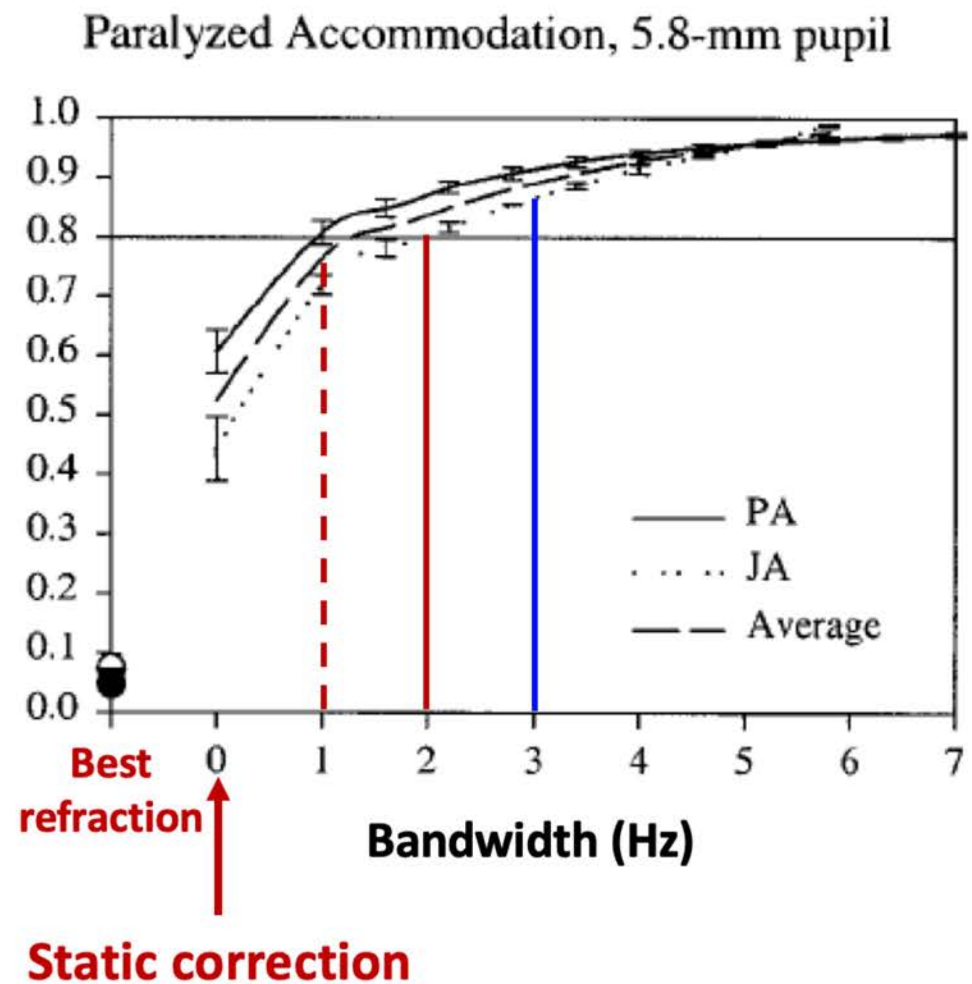
Temporal fluctuations exist in all of the eye's aberrations with natural accommodation



Hofer H et al. Dynamics of the eye's wave aberration. JOSA A. 2001;18:497-506.

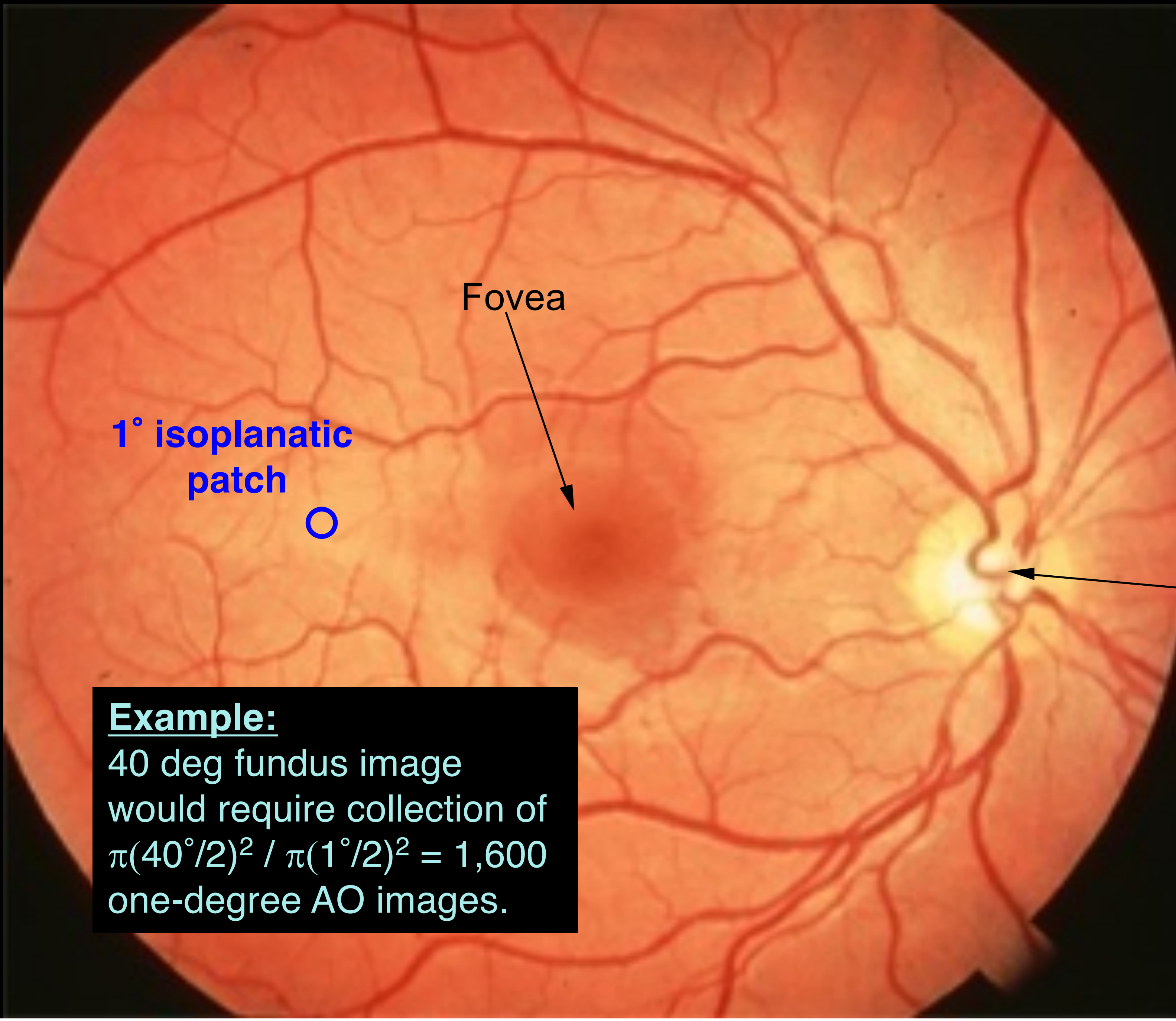
A closed-loop bandwidth of 1-3 Hz can ideally correct aberrations sufficiently to achieve a Strehl > 0.8





Hofer H et al. Dynamics of the eye's wave aberration. JOSA A. 2001;18:497-506.

Conventional fundus photograph – 40º FOV (~ 12mm)

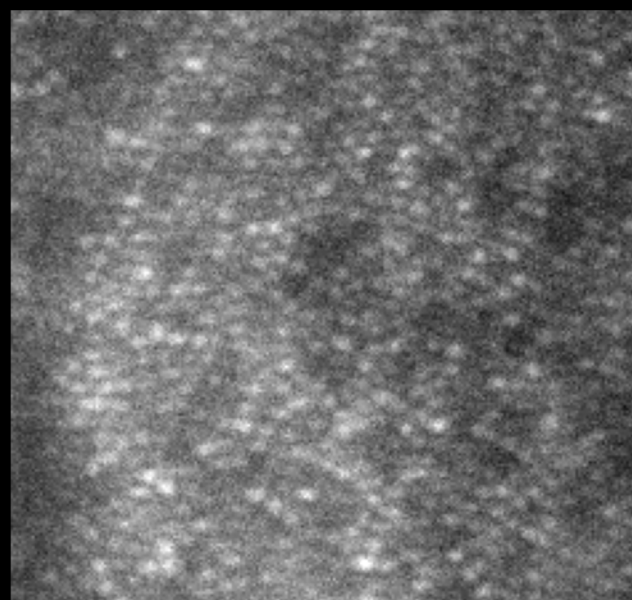


Example:
40 deg fundus image would require collection of $\pi(40^\circ/2)^2 / \pi(1^\circ/2)^2 = 1{,}600$ one-degree AO images.

Adaptive optics can resolve individual photoreceptors in the living eye

Without AO
(single image)

With AO
(single image)



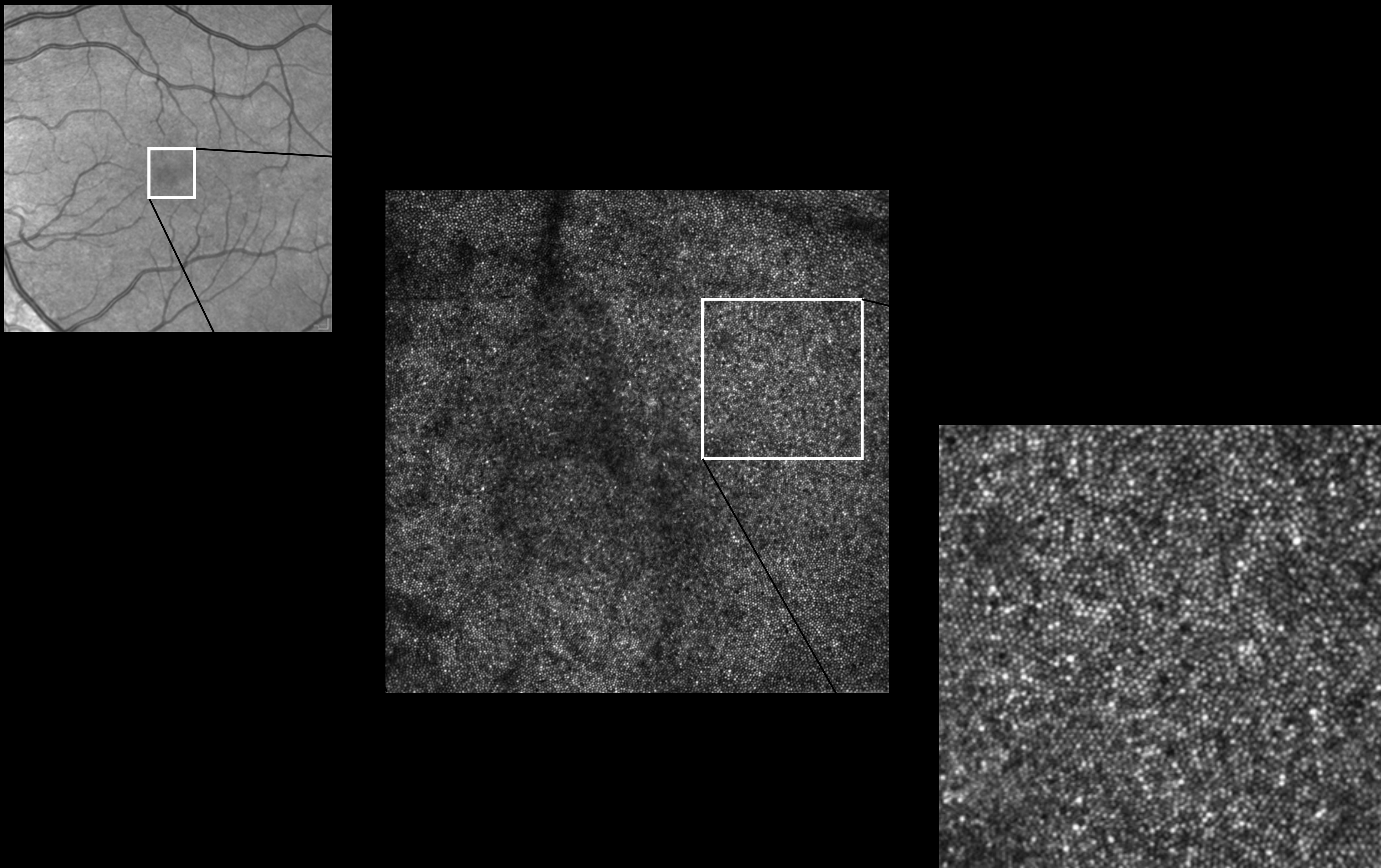
~ 50 µm

With AO
(registered sum)

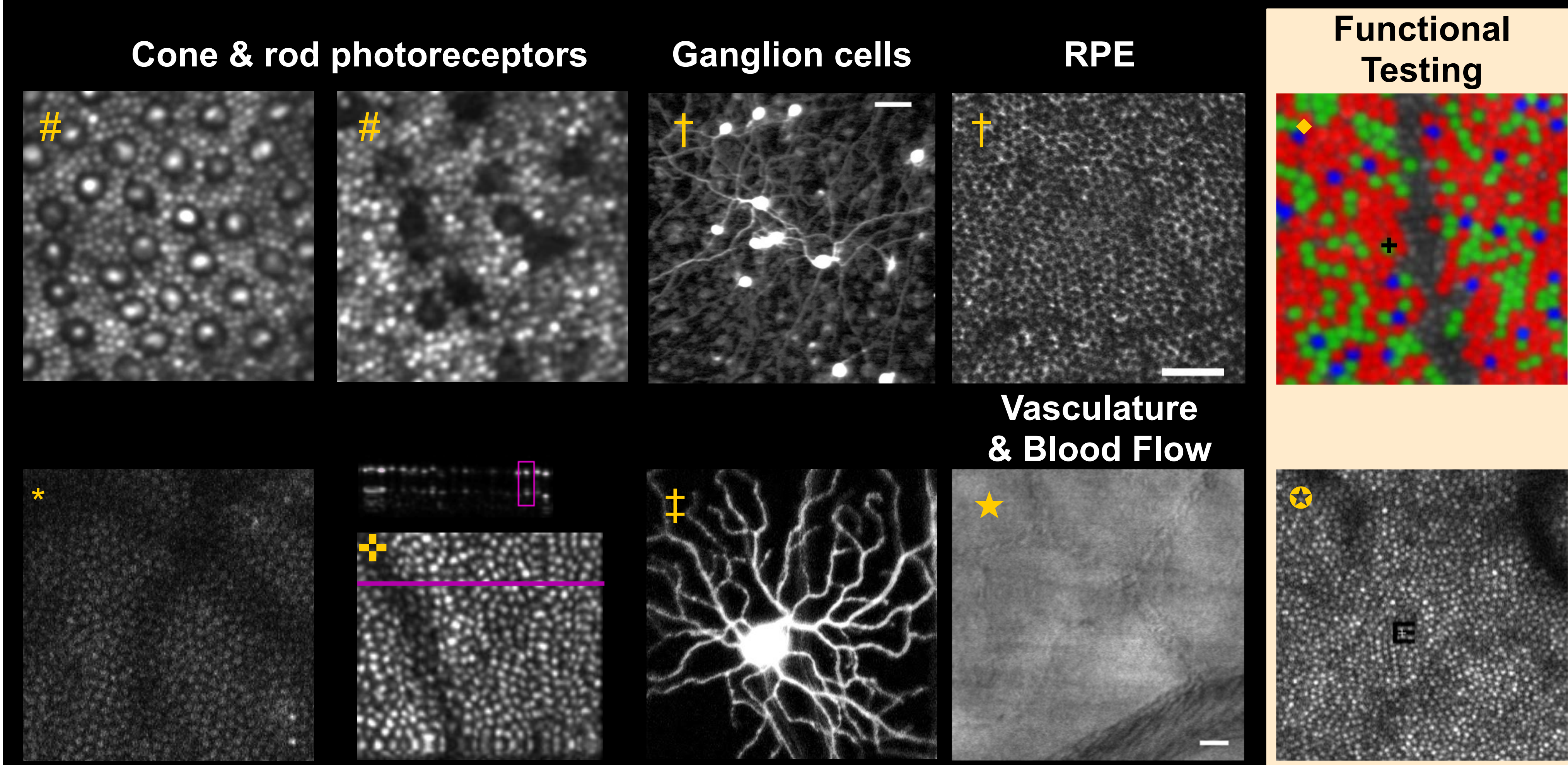
1 deg eccentricity

Heidi Hofer, David Williams

AO can "zoom in" to see single cells



AO allows visualization of different cell types and for visual psychophysics on a cellular scale

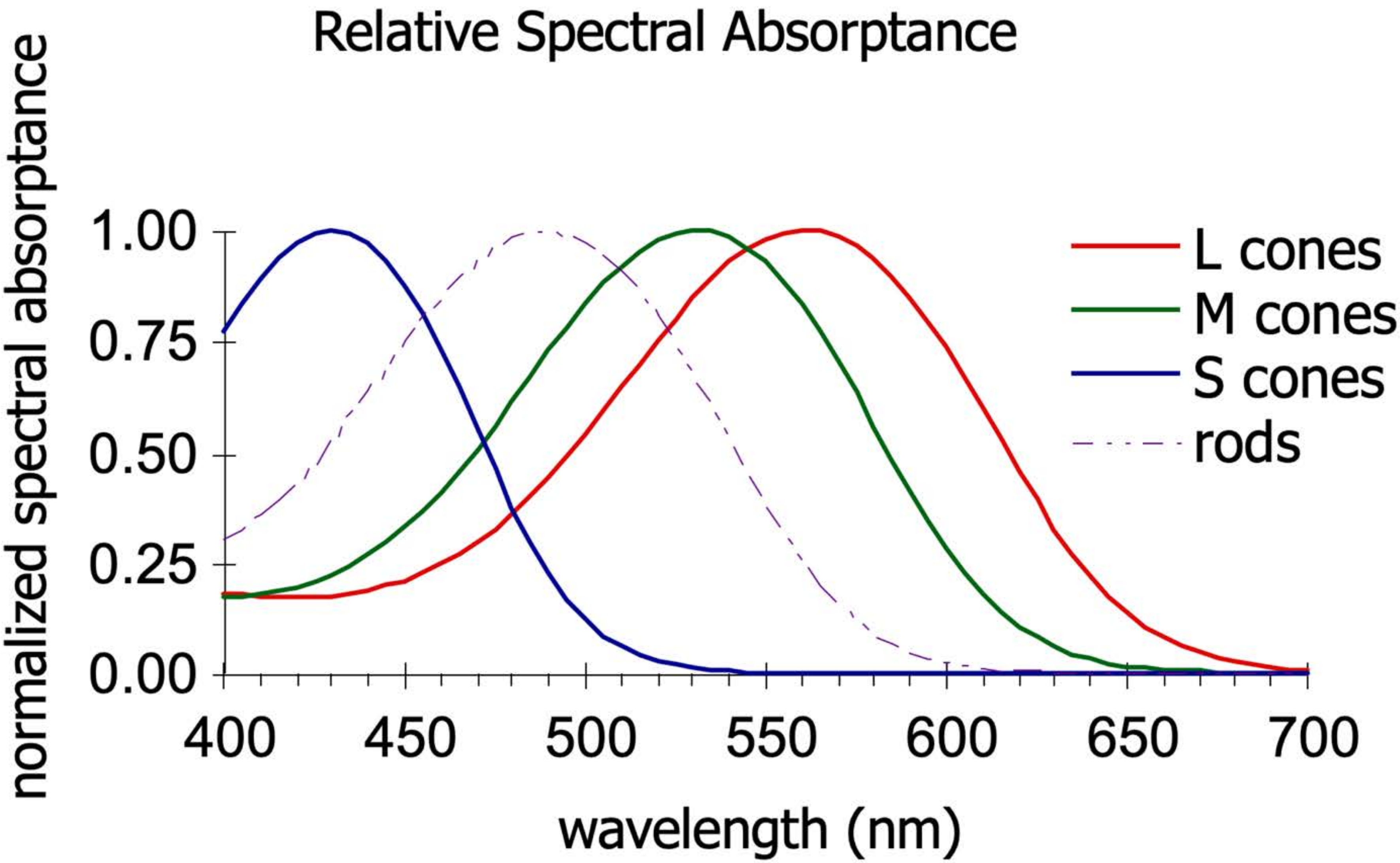


- # Joe Carroll, Alf Dubra
- * Jennifer Hunter, David Williams
- ✚ Donald Miller, Omer Kocaoglu
- † Dan Gray, Jessica Morgan, Jason Porter, Bill Merigan, David Williams
- ‡ Ying Geng, David Williams
- ★ Stephen Burns
- ◆ Heidi Hofer, Austin Roorda, Joe Carroll, D. Williams
- ✪ Austin Roorda, Curt Vogel, David Arathorn

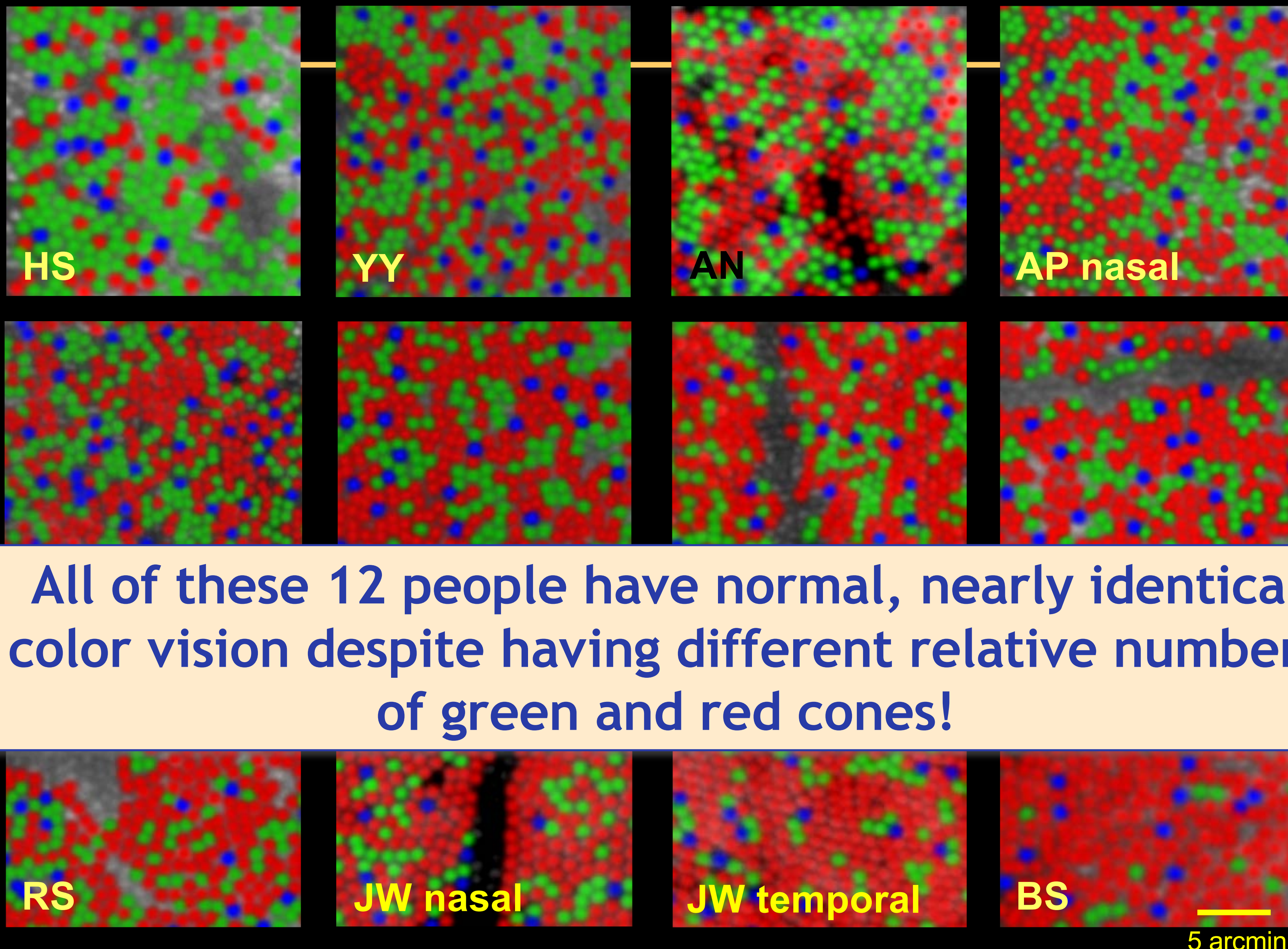
Applications of AO

- Basic science imaging
  - Properties of retinal cells
  - Color vision mechanisms
- Clinical applications
  - Early diagnosis of disease
  - Track disease progression, test efficacy of new drugs
- Functional imaging
  - Relation between structure and function
  - Study retinal circuitry
- Vision science
  - Vision benefits of aberration correction
  - Optical and neural limits of human vision
- Dynamical studies
  - Blood flow in the eye
  - Eye motion
- Precision light delivery
  - Stimulate single cells
  - Targeted laser treatment

Components of the human optical system



Mapping the trichromatic cone mosaic

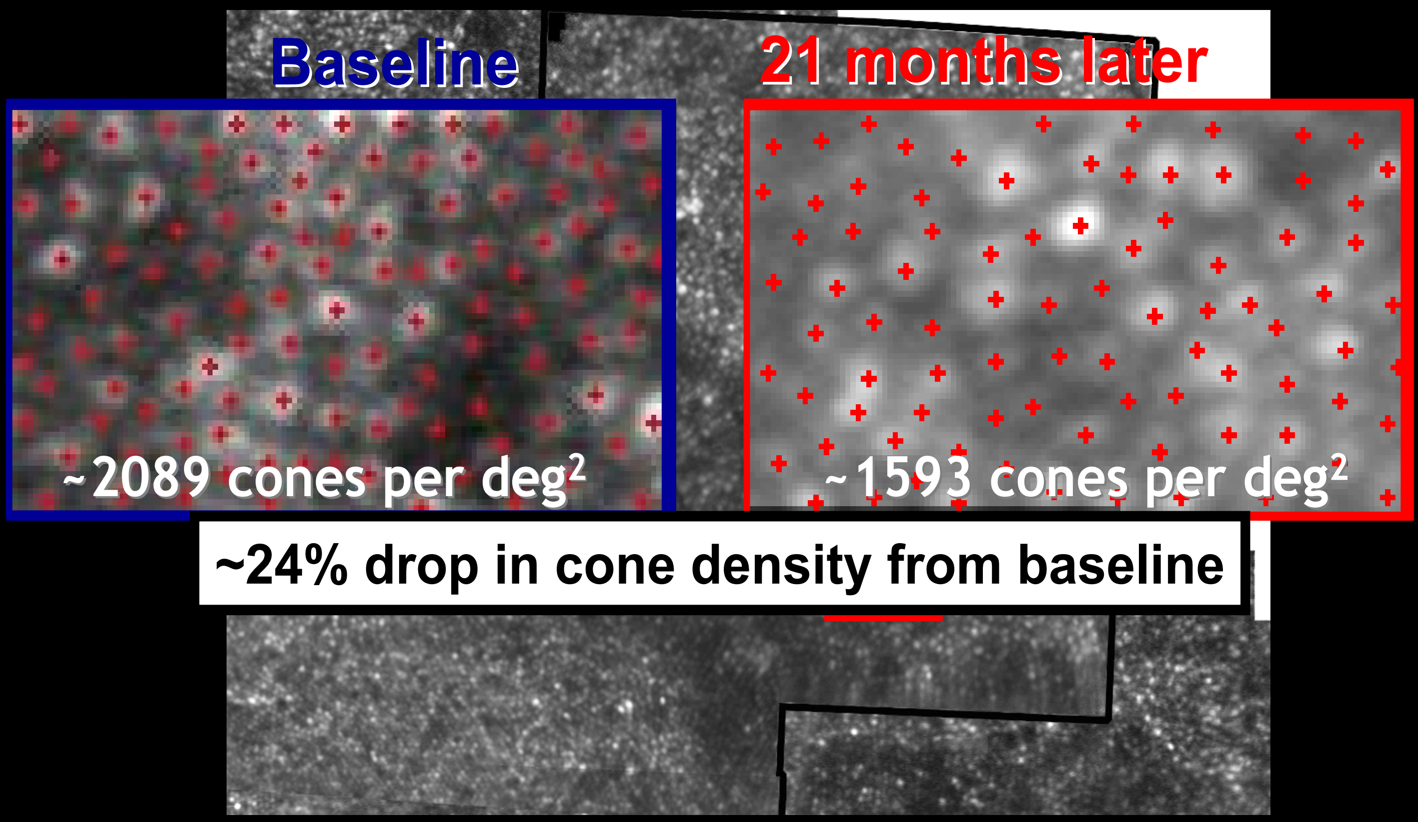


All of these 12 people have normal, nearly identical color vision despite having different relative numbers of green and red cones!

Roorda & Williams (1999) & Hofer (2003)

Clinical application: Cone tracking to follow progression of eye disease

Cone tracking in eye disease



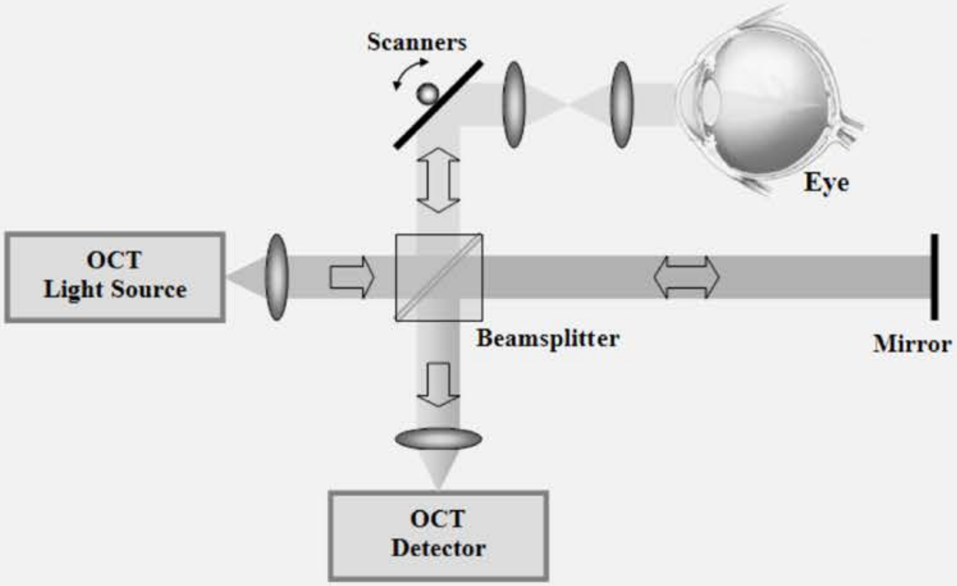
In a diseased eye (retinitis pigmentosa illustrated here), we can monitor changes in cone density over time.

Talcott et al, submitted (2010) (also 2010 ARVO abstract)

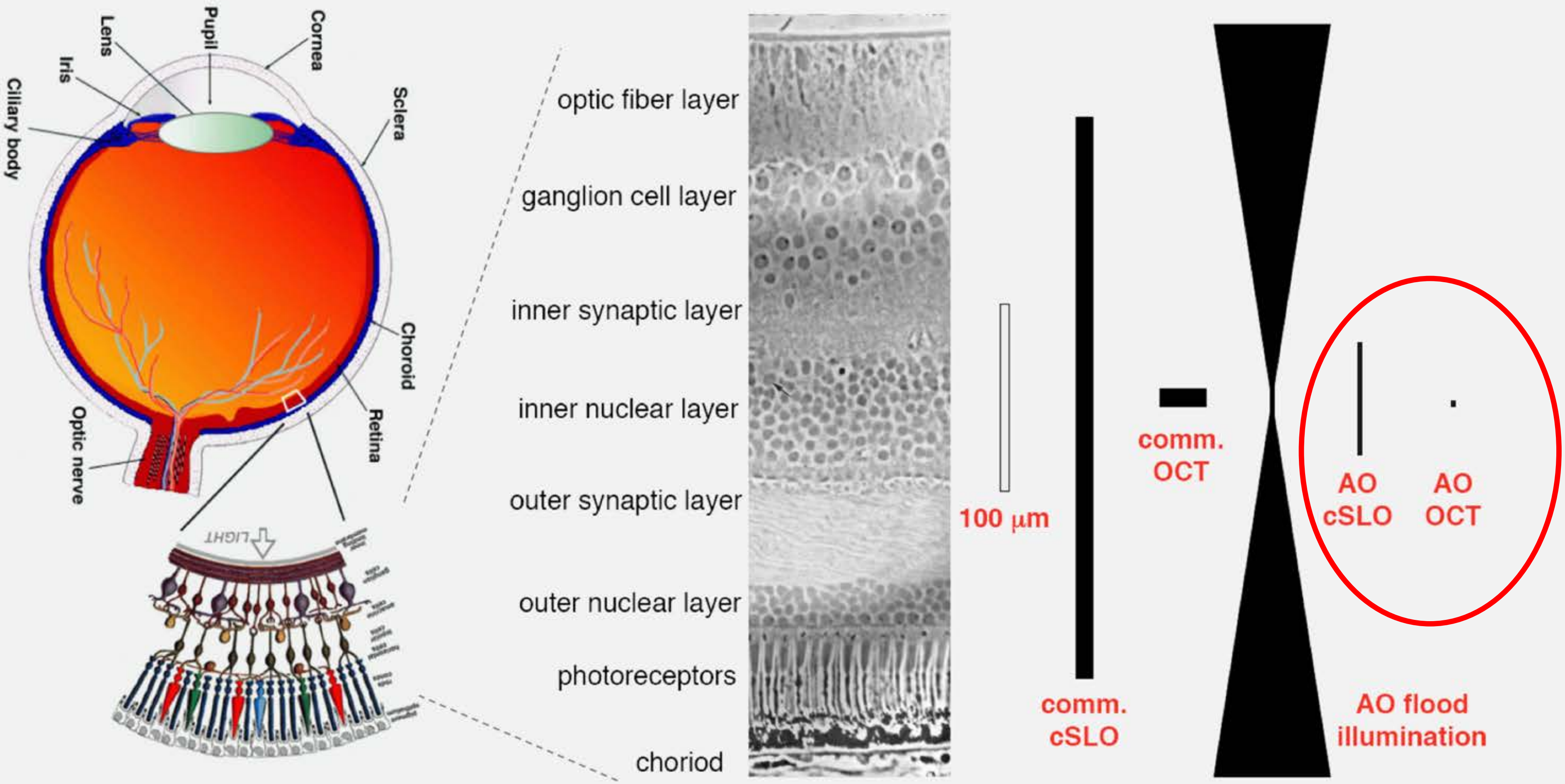
Optical Coherence Tomography

Optical Coherence Tomography is an an interferometric, non-invasive optical imaging method that offers very high axial resolution.

OCT relays on white light or low coherence interferometry. The optical setup typically consists of an interferometer (typically Michelson type) with a low coherence, broad bandwidth light source. Light is split into and recombined from reference and sample arm, respectively.



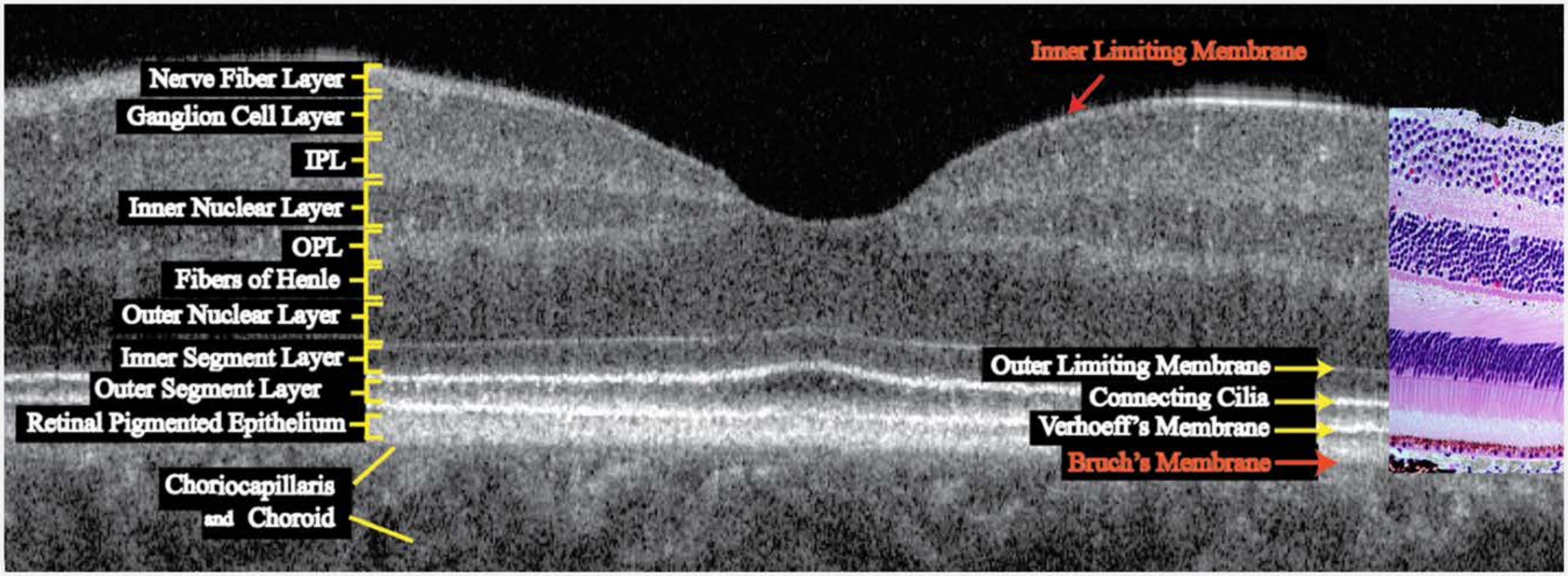
Resolution of retinal imaging instruments



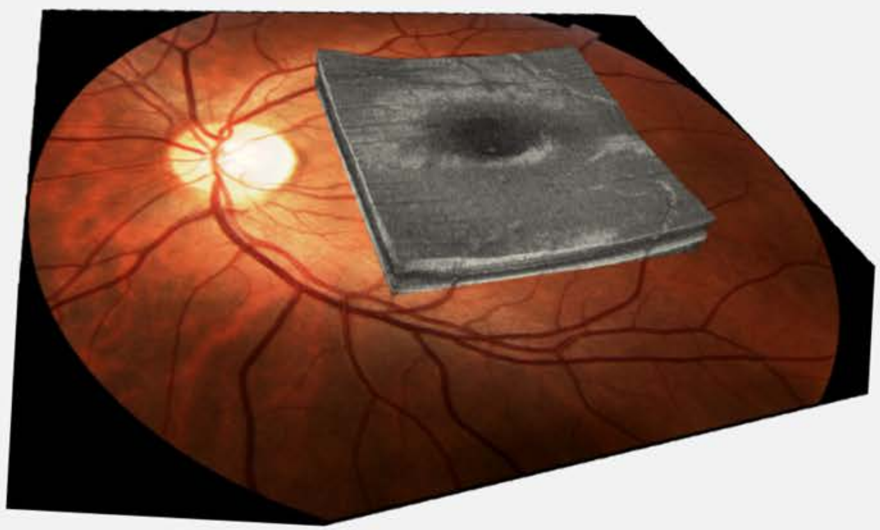
AO SLO = scanning laser ophthalmoscope
AO OCT = AO optical coherence tomography

Don Miller; Indiana University

AO OCT



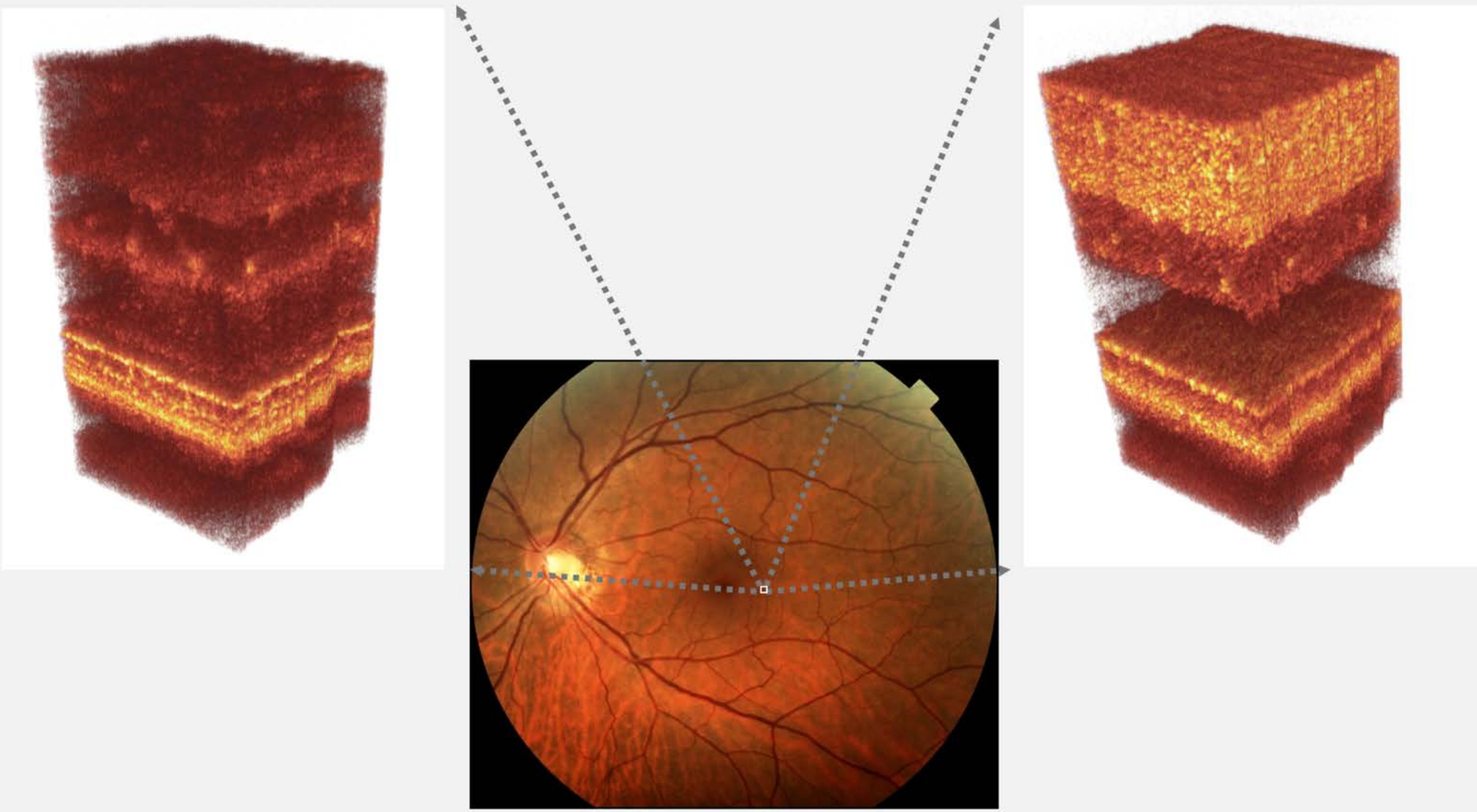
3000 A-scans; x = 6mm; Δz = 3.5 μm; Δx = 10-15 μm; dx = 1,5 μm τ = 50 μs; T=150 ms;



Slices through side view of retina

AO-OCT

Volume reconstruction

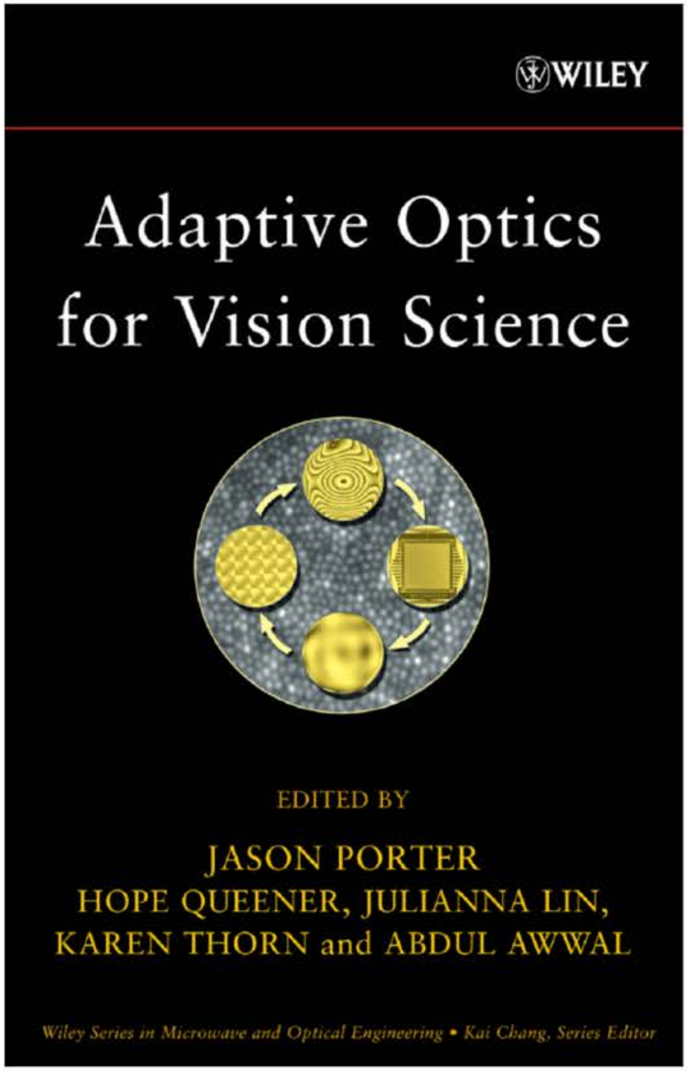


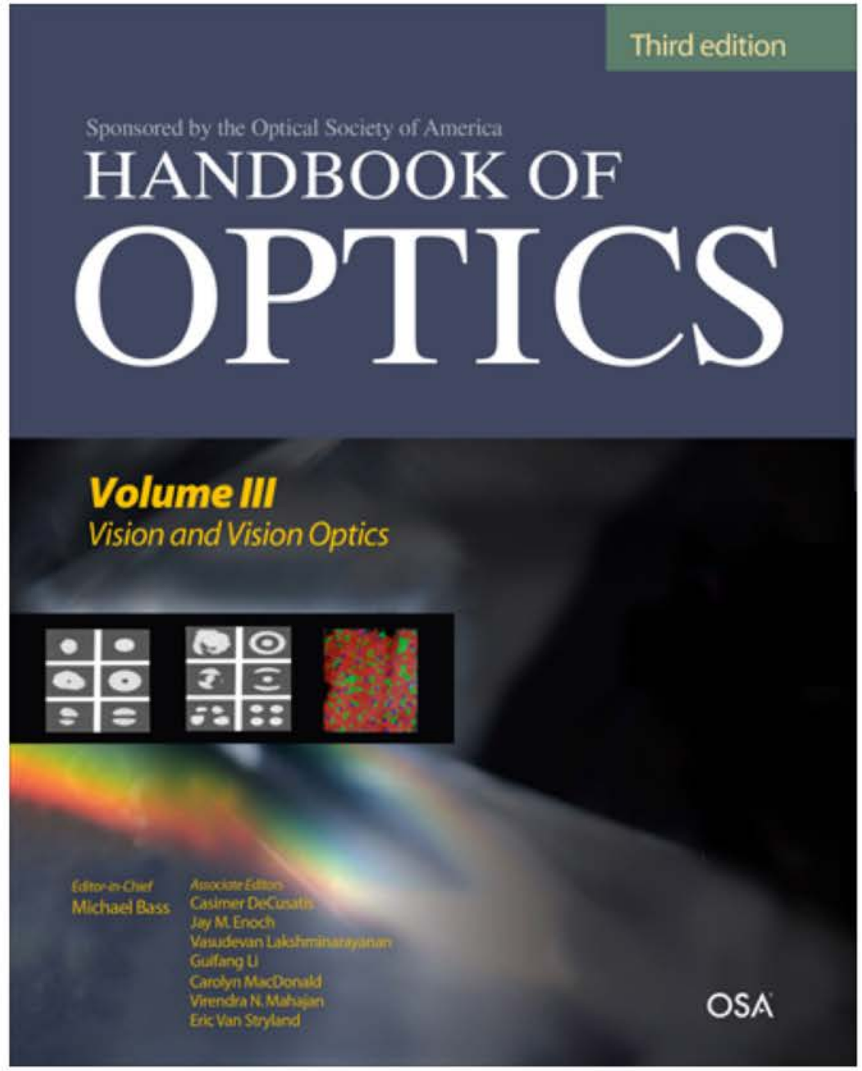
Summary

- Adaptive optics for imaging the living retina has many similarities with astronomical AO
  - "Laser guide star" for wavefront sensing
  - Similar wavefront sensors and DMs
- A key difference: retina is a 3D structure
  - Need both axial and lateral resolution
  - AO Scanning Laser Ophthalmoscopes, Optical Coherence Tomography
- Applications:
  - Physiology and psychology of vision
  - Clinical and medical applications

[No Title]

Want to learn more about AO for vision science?





Miller DT and Roorda A. *Adaptive optics in retinal microscopy and vision*, Chapter 17.