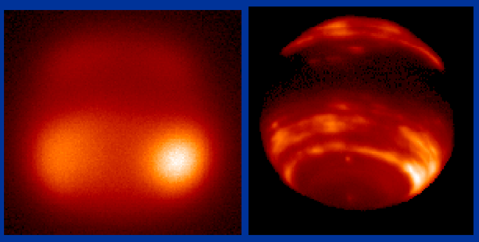
Adaptive Optics Overview

Adapted from presentations by
Prof. Claire Max, UC Santa Cruz
Director, Center for Adaptive Optics

With additional material from the MPE Garching AO group, ESO AO group, UCLA AO group, and GBT surface adjustment program

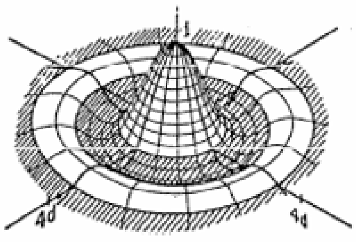
Neptune

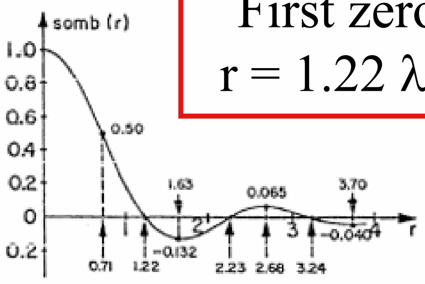


Details of diffraction from circular aperture

1) Amplitude

$\mathrm{somb}(r) = 2\, J_1(\pi r)/(\pi r)$



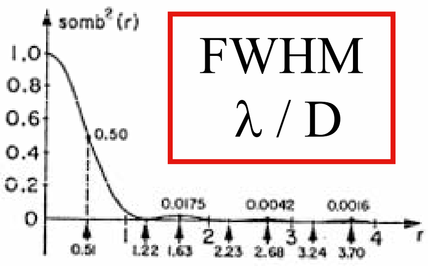


First zero at
$r = 1.22\ \lambda / D$

2) Intensity

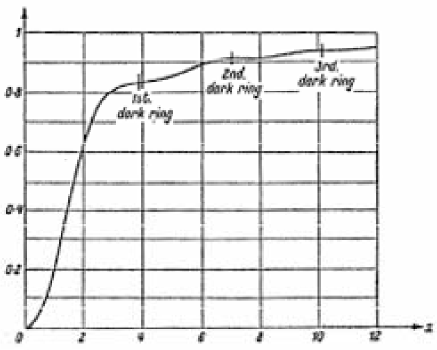
Airy Pattern

$\mathrm{somb}^2(r)$

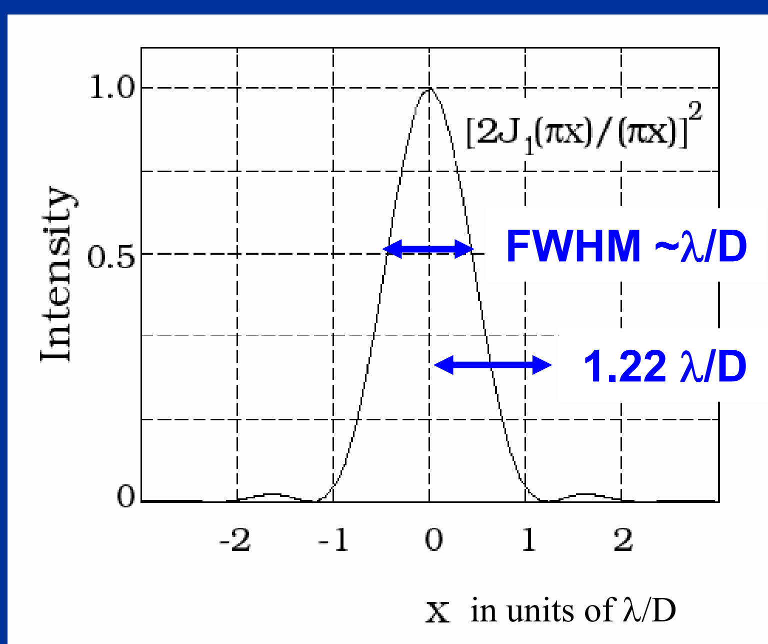


FWHM
λ / D

Fractional Encircled Energy



Imaging through a perfect telescope



Point Spread Function (PSF): intensity profile from point source

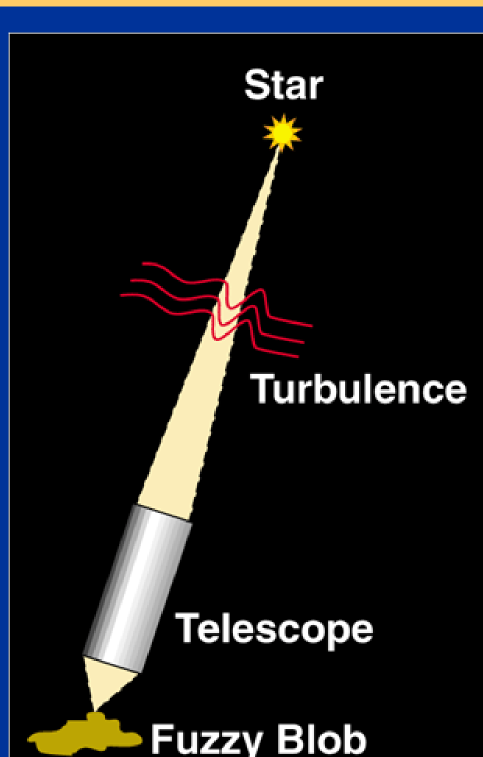
With no turbulence, FWHM is diffraction limit of telescope, $\vartheta \sim \lambda / D$

Example:

λ / D = 0.02 arc sec for λ = 1 μm, D = 10 m

With turbulence, image size gets much larger (typically 0.5 - 2 arc sec)

Why is adaptive optics needed?



Turbulence in earth's atmosphere makes stars twinkle

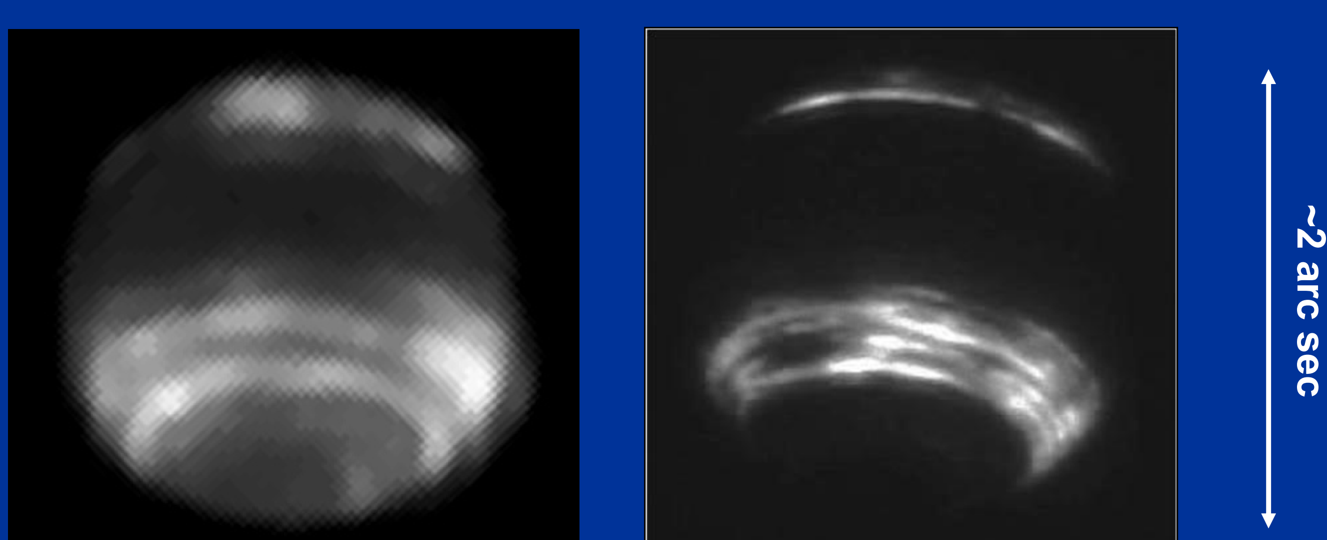
More importantly, turbulence spreads out light; makes it a blob rather than a point

Even the largest ground-based astronomical telescopes have no better resolution than an 8" telescope!

No atmosphere, no twinkle

Neptune at 1.6 μm: Keck AO exceeds resolution of Hubble Space Telescope

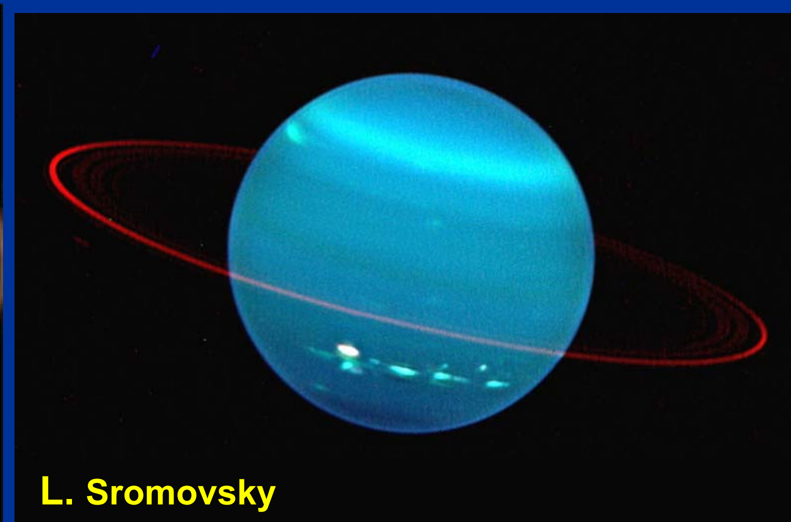
HST - NICMOS | **Keck AO**



2.4 meter telescope | **10 meter telescope**

(Two different dates and times)

Uranus with Hubble Space Telescope and Keck AO



HST, Visible

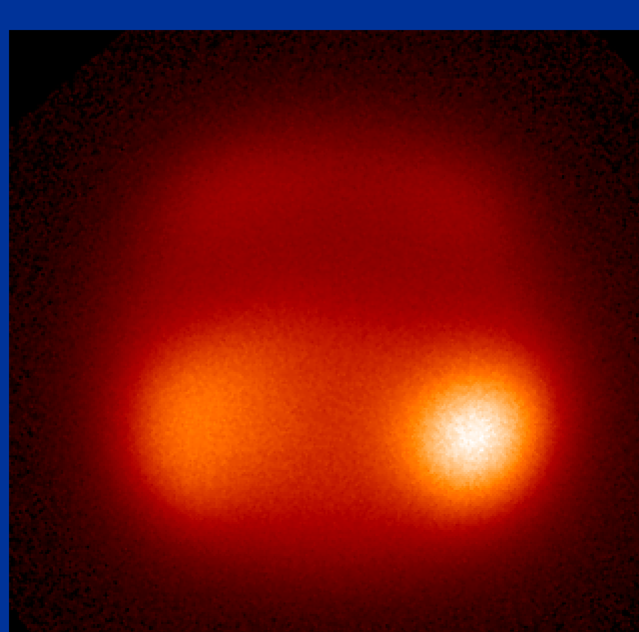
Keck AO, IR

Lesson: Keck in near IR has same resolution as Hubble in visible

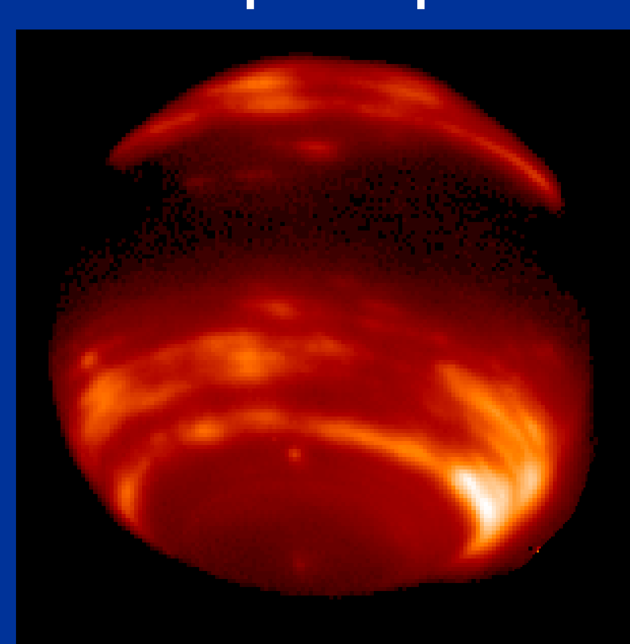
Neptune in infra-red light (1.65 microns)

Without adaptive optics

With Keck adaptive optics



2.3 arc sec

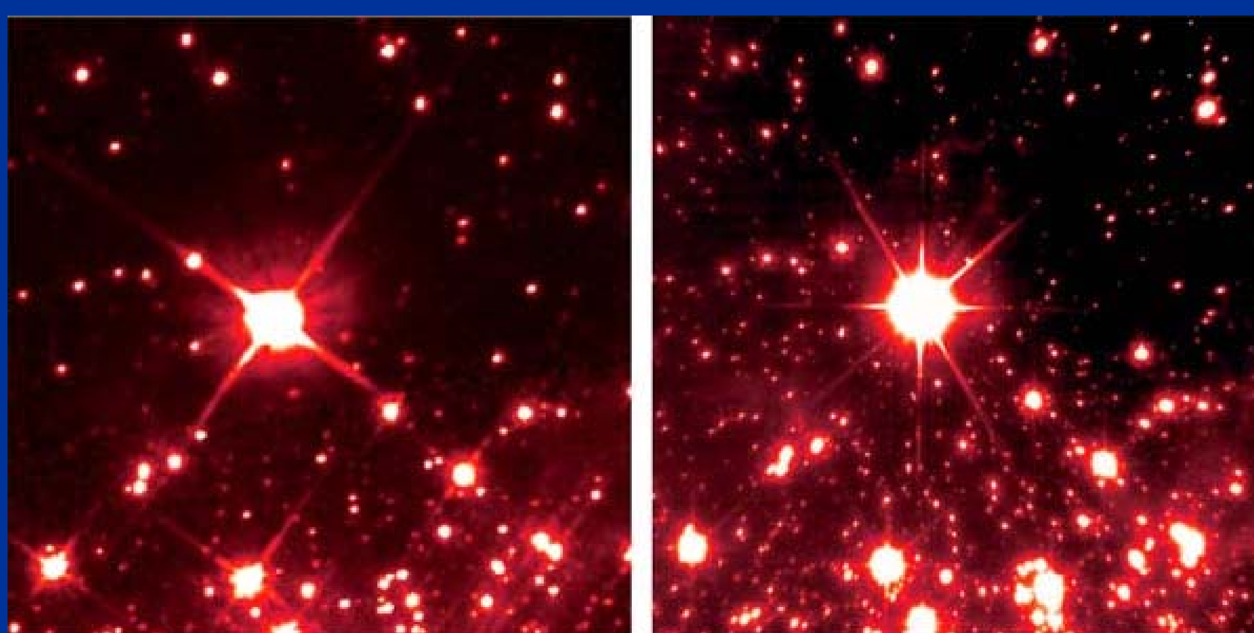


May 24, 1999

June 27, 1999

VLT NAOS AO first light

Cluster NGC 3603: IR AO on 8m ground-based telescope achieves same resolution as HST at 1/3 the wavelength

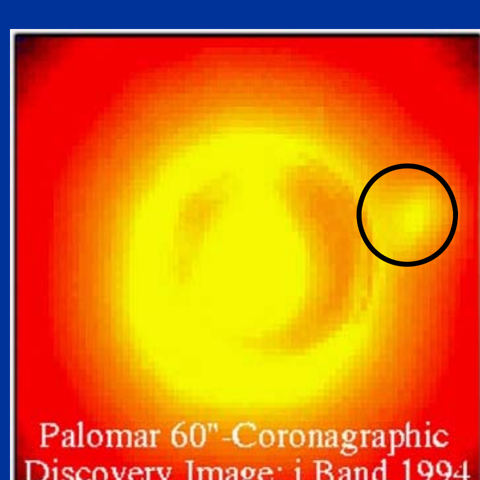


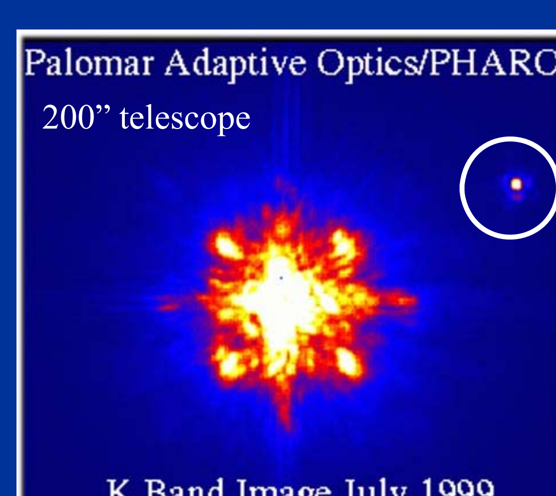
Hubble Space Telescope
WFPC2, λ = 800 nm

NAOS AO on VLT
λ = 2.3 microns

Adaptive optics makes it possible to find faint companions around bright stars

Two images from Palomar of a brown dwarf companion to GL 105

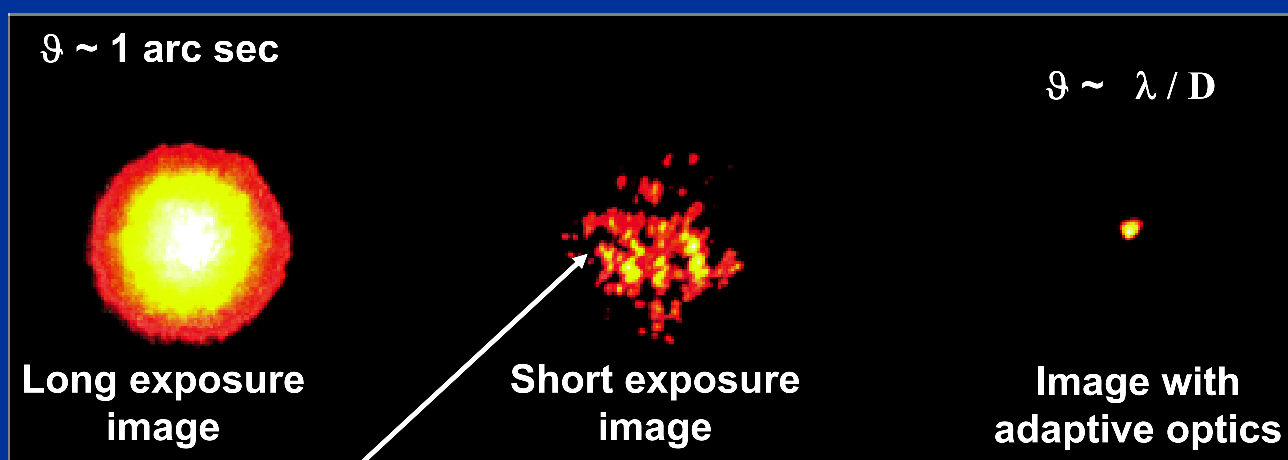




Credit: David Golimowski

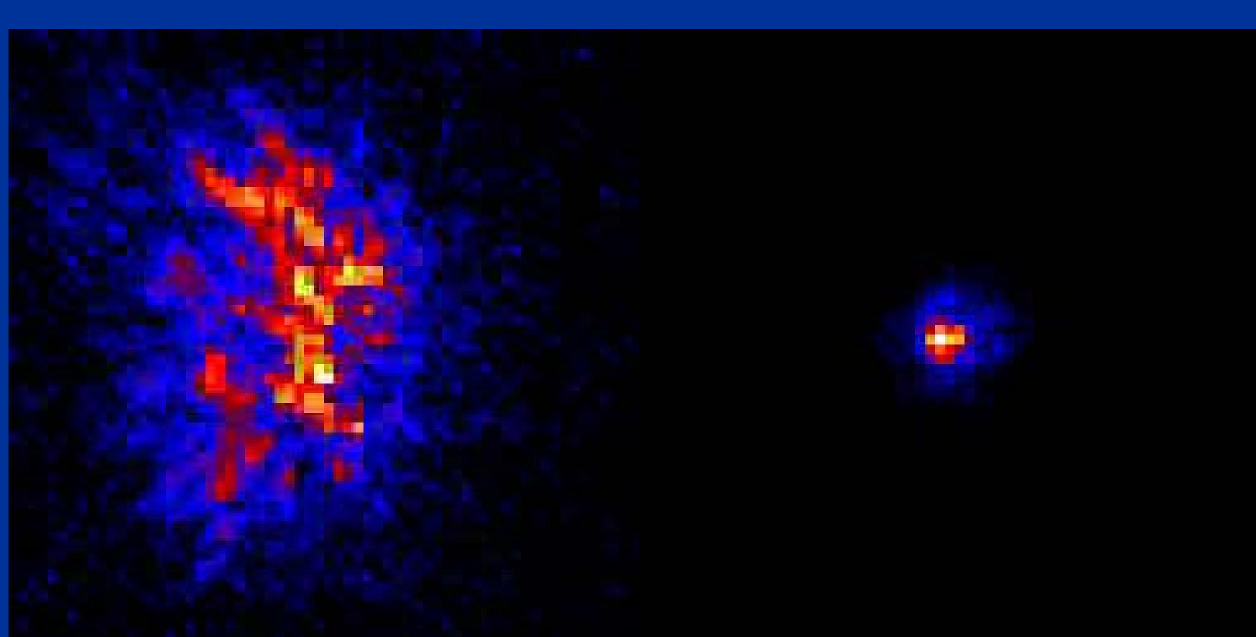
Images of a bright star, Arcturus

Lick Observatory, 1 m telescope



Speckles (each is at diffraction limit of telescope)

What does it really look like?



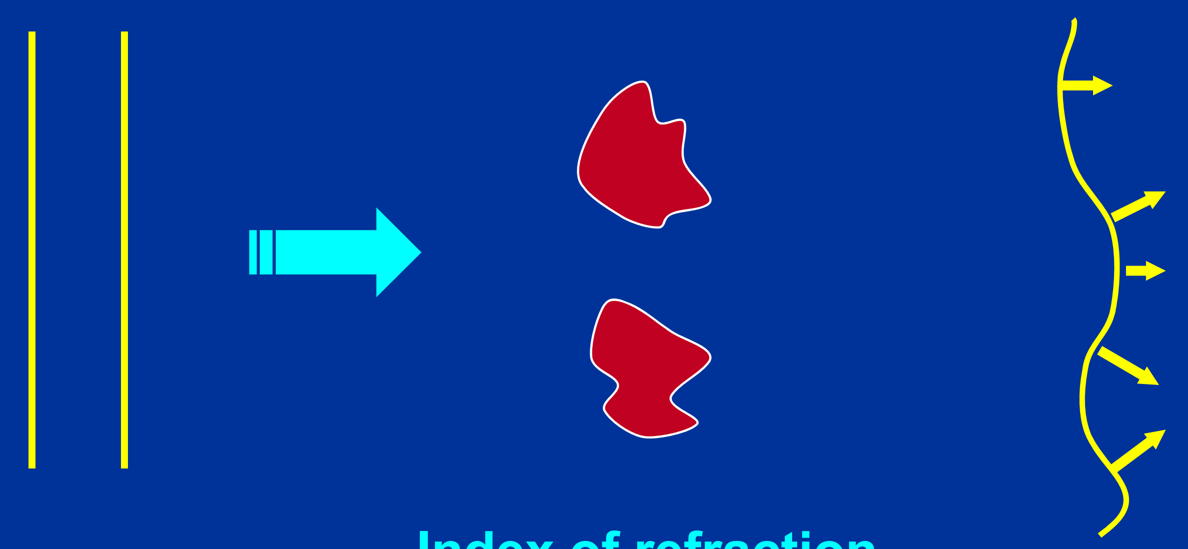
Speckles and the "Seeing disk"

With AO

Images from the MPE Garching AO group
http://www.mpe.mpg.de/ir/ALFA

Atmospheric perturbations cause distorted wavefronts

Rays not parallel



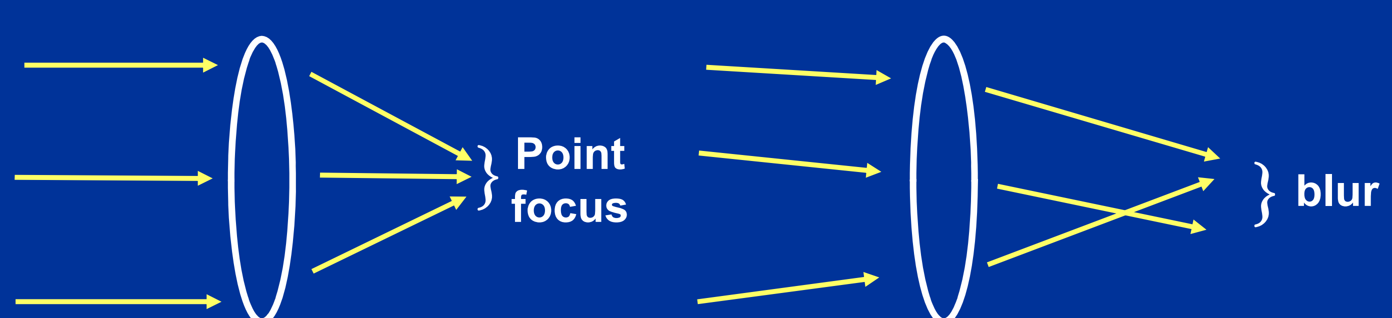
Plane Wave

Index of refraction variations

Distorted Wavefront

Optical consequences of turbulence

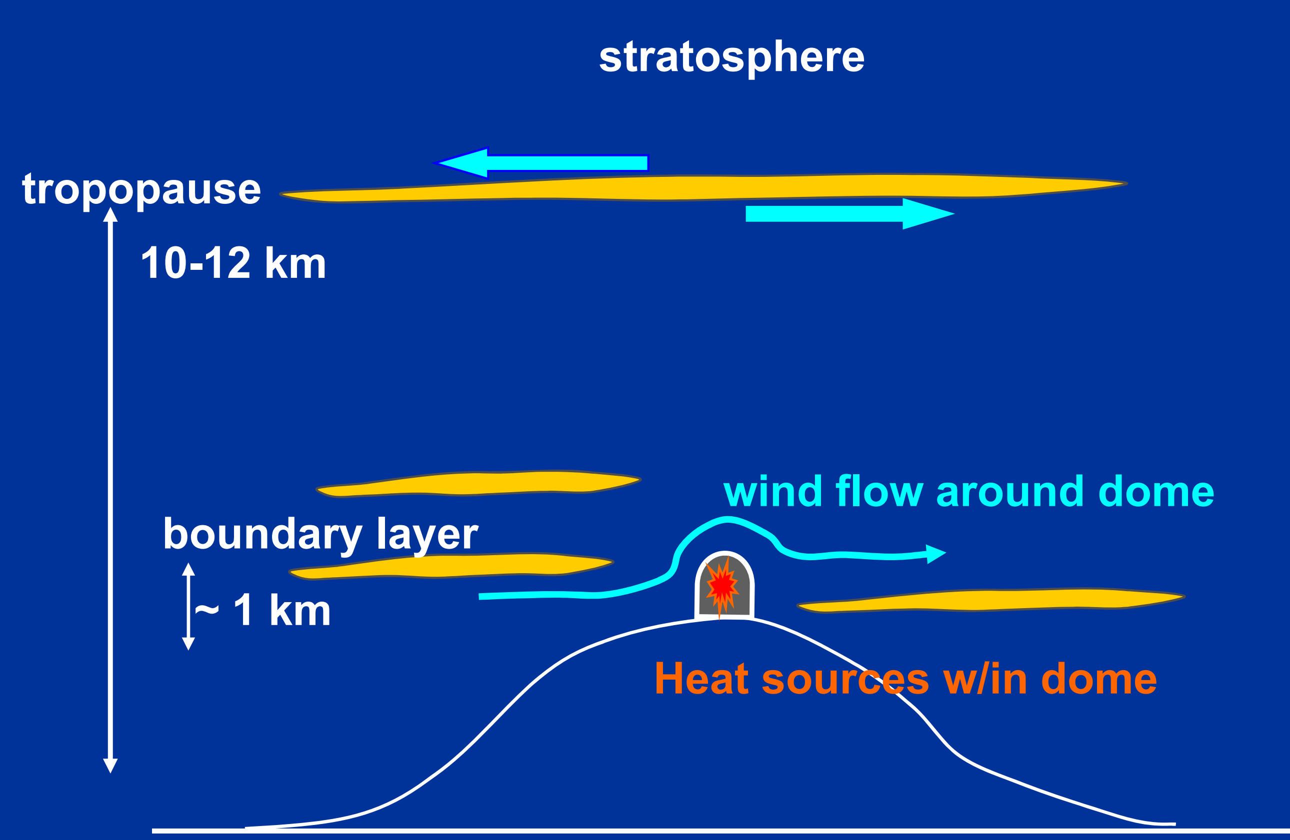
- **Temperature fluctuations in small patches of air cause changes in index of refraction (like many little lenses)**
- **Light rays are refracted many times (by small amounts)**
- **When they reach telescope they are no longer parallel**
- **Hence rays can't be focused to a point:**



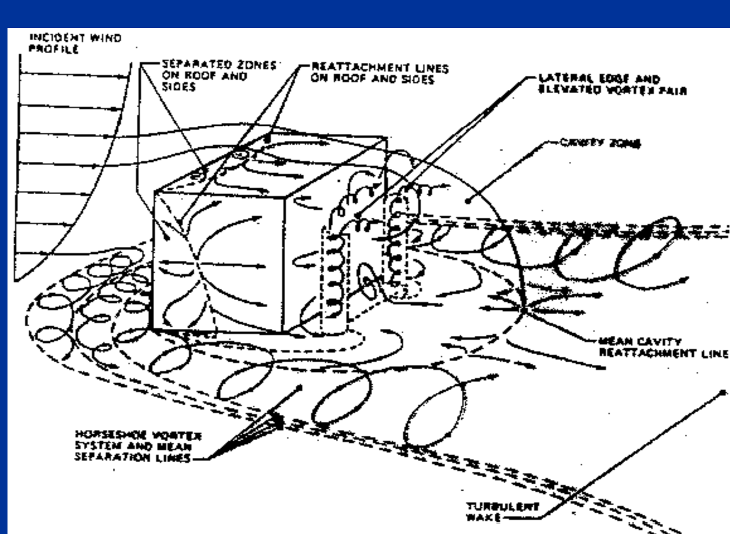
Parallel light rays

Light rays affected by turbulence

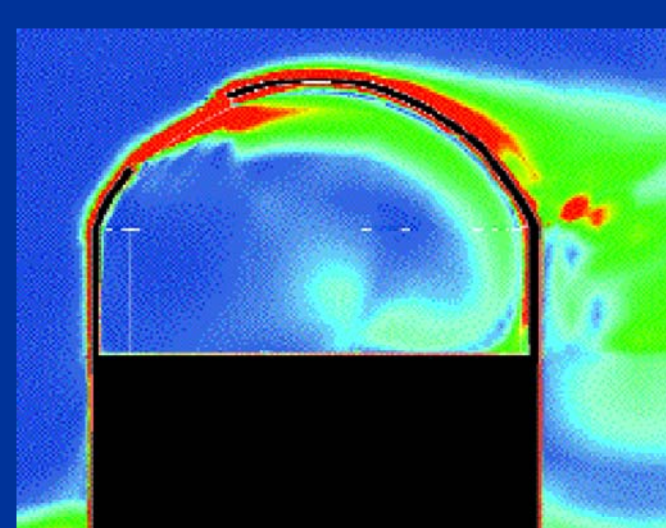
Turbulence arises in several places



Local "Seeing" - Flow pattern around a telescope dome



Cartoon (M. Sarazin): wind is from left, strongest turbulence on right side of dome



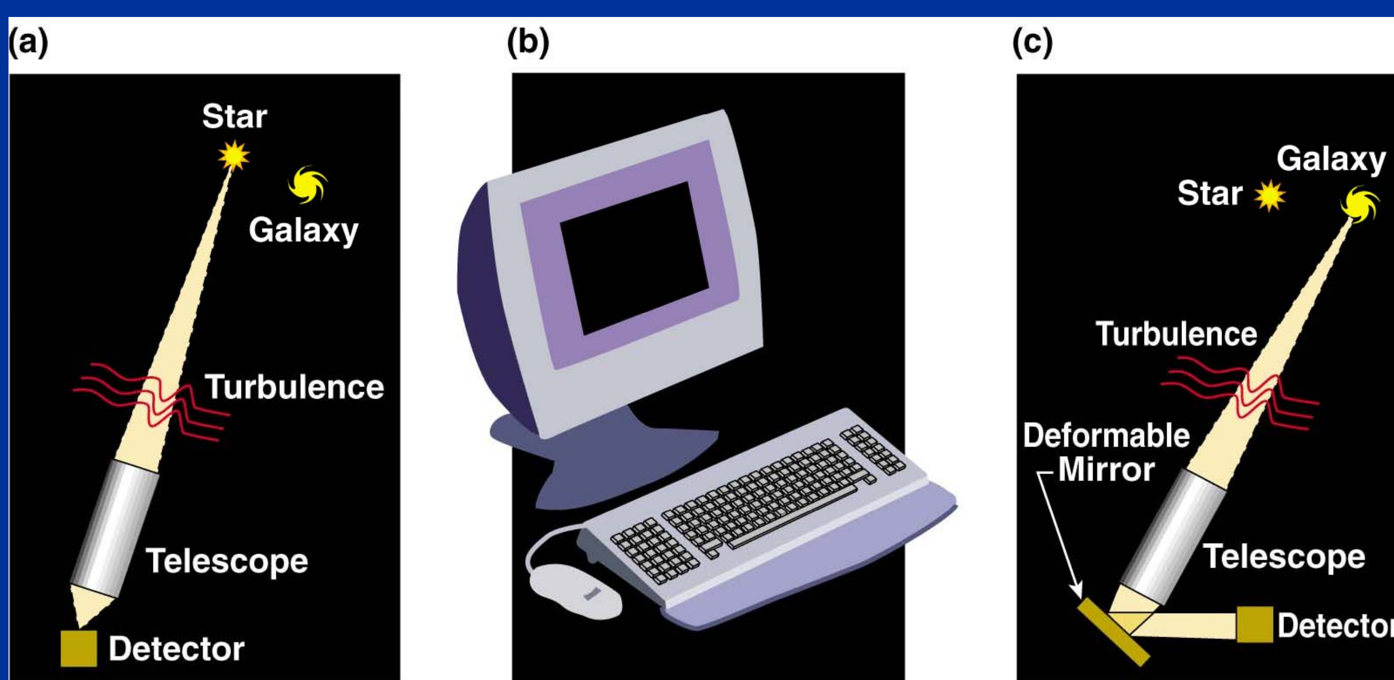
Computational fluid dynamics simulation (D. de Young) reproduces features of cartoon

How does adaptive optics help? (cartoon approximation)

Measure details of blurring from "guide star" near the object you want to observe

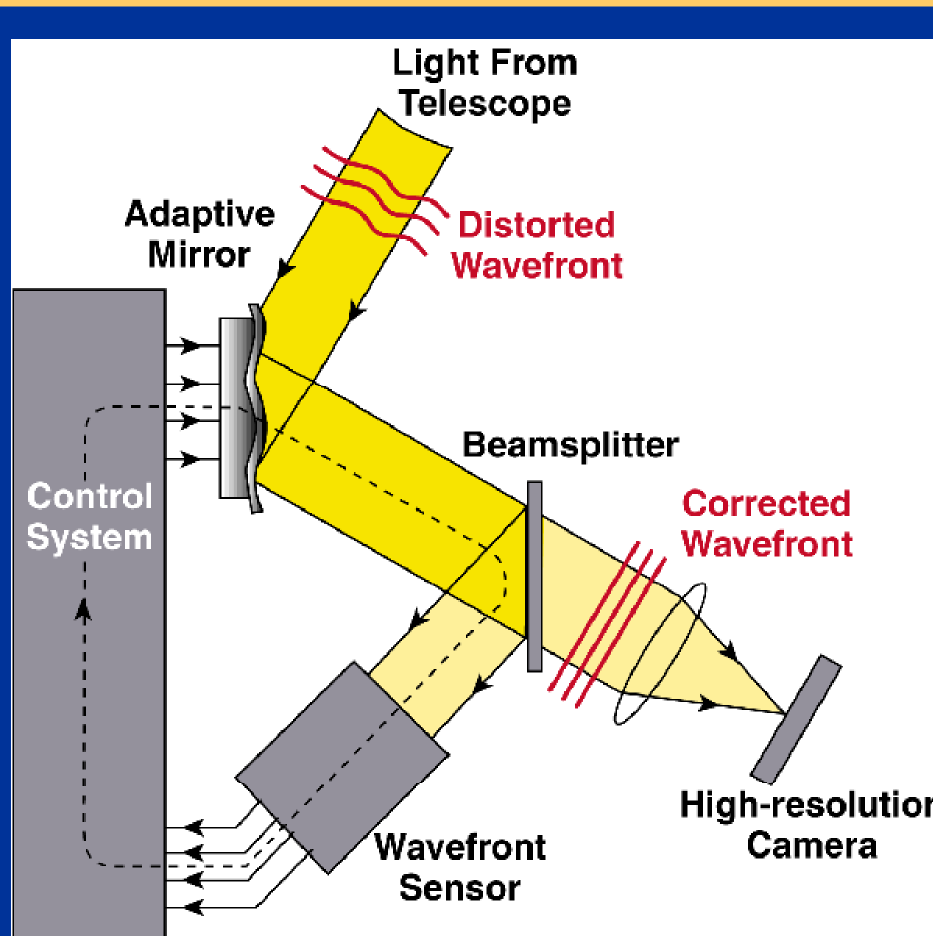
Calculate (on a computer) the shape to apply to deformable mirror to correct blurring

Light from both guide star and astronomical object is reflected from deformable mirror; distortions are removed

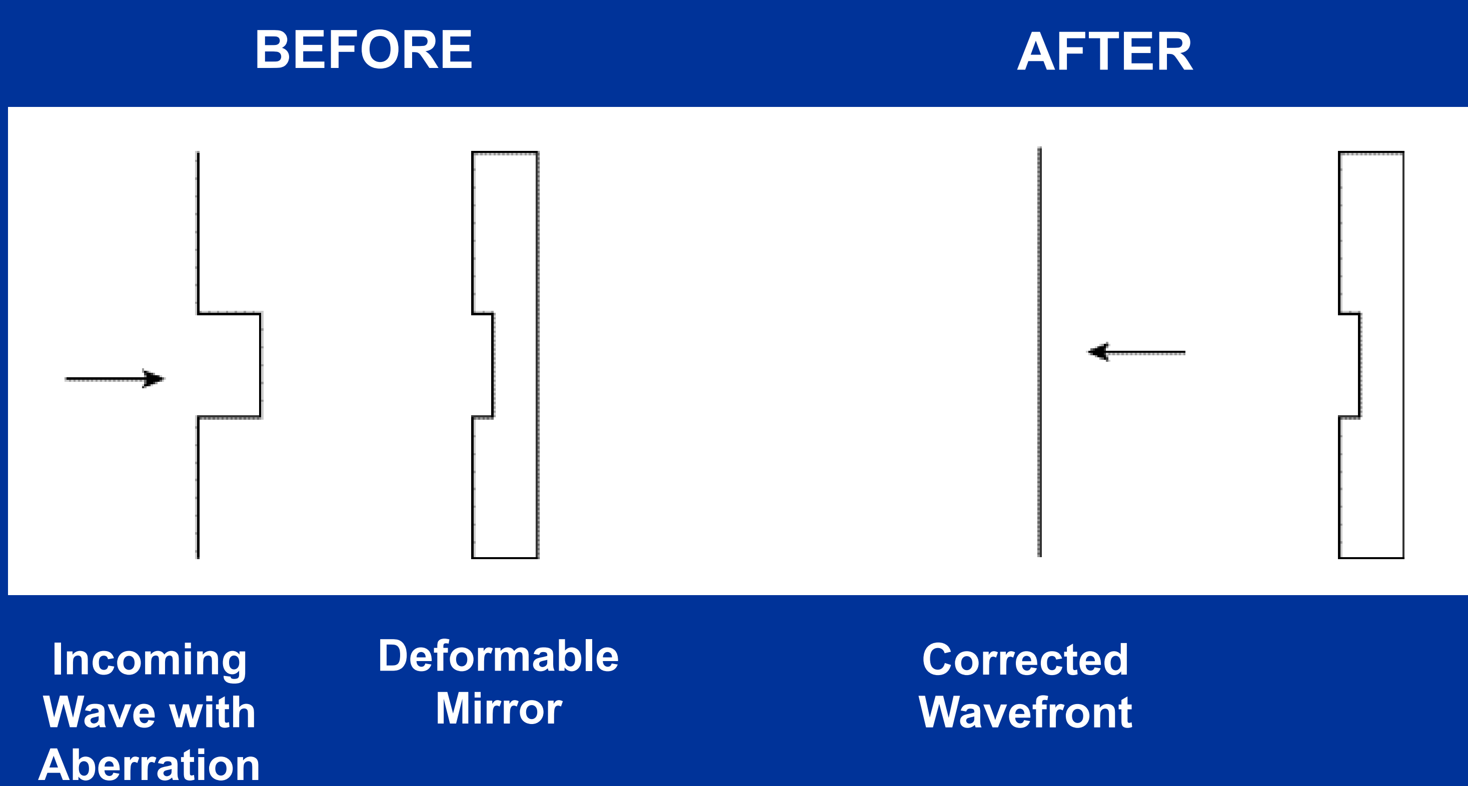


Schematic of adaptive optics system

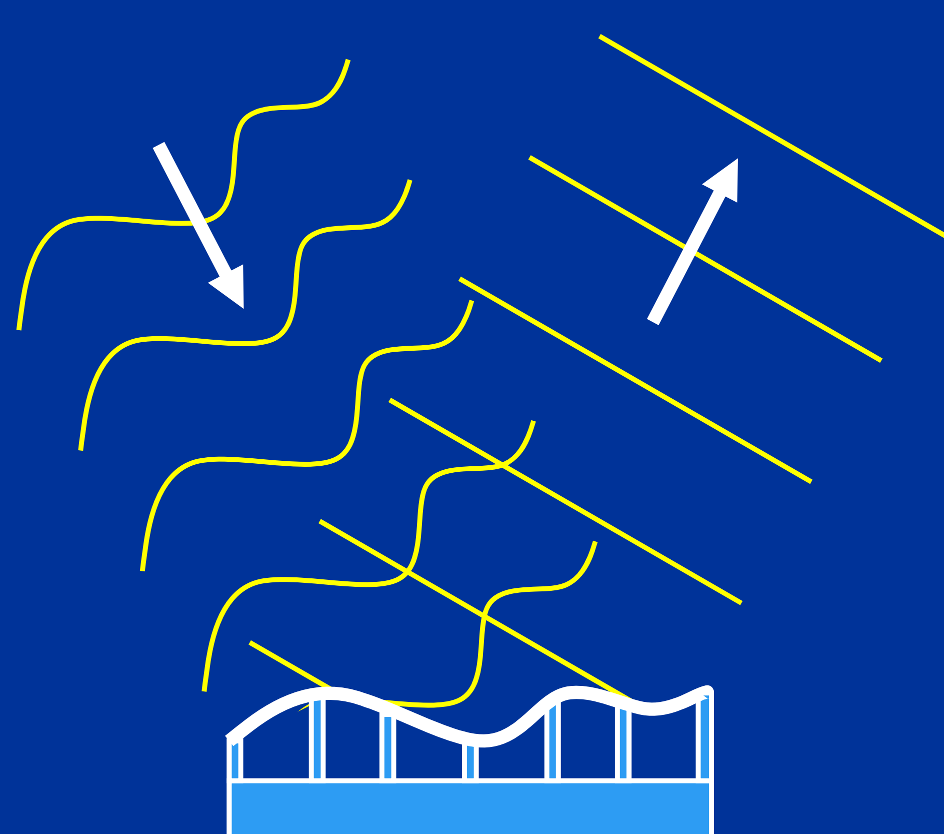
Feedback loop: next cycle corrects the (small) errors of the last cycle



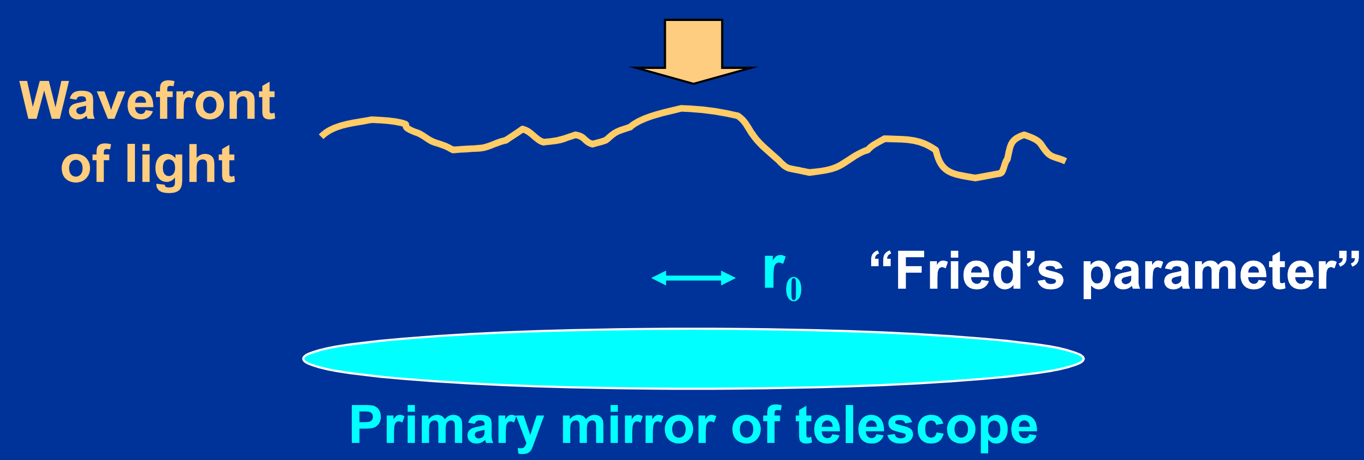
How a deformable mirror works (idealization)



Deformable Mirror for real wavefronts

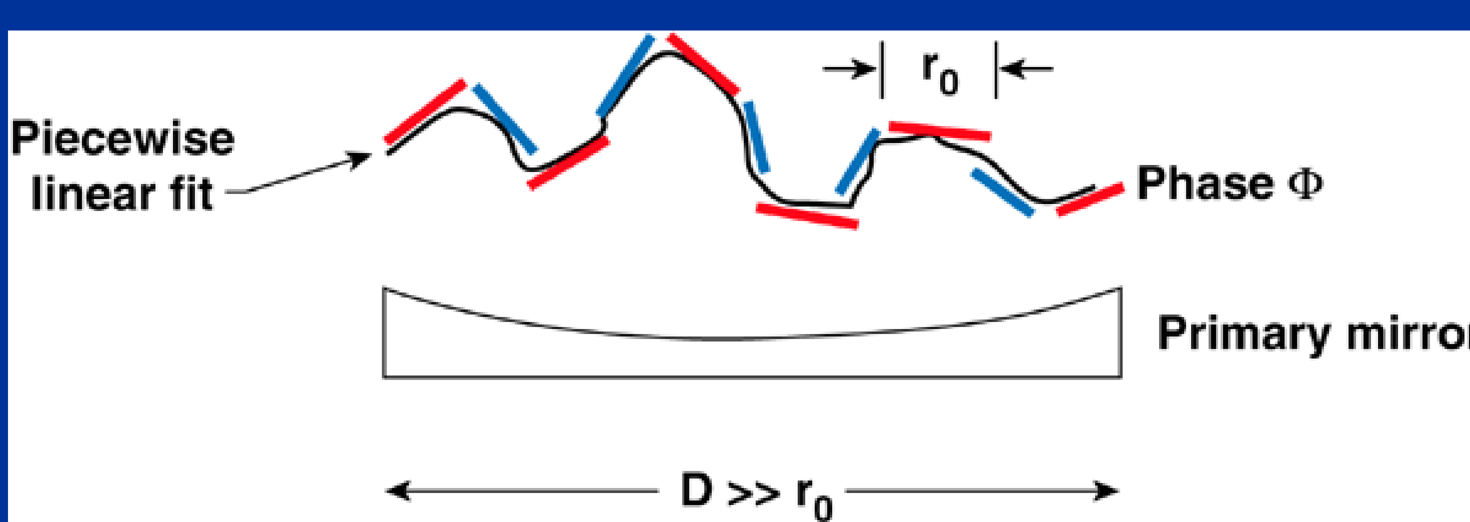


Characterize turbulence strength by quantity r_0



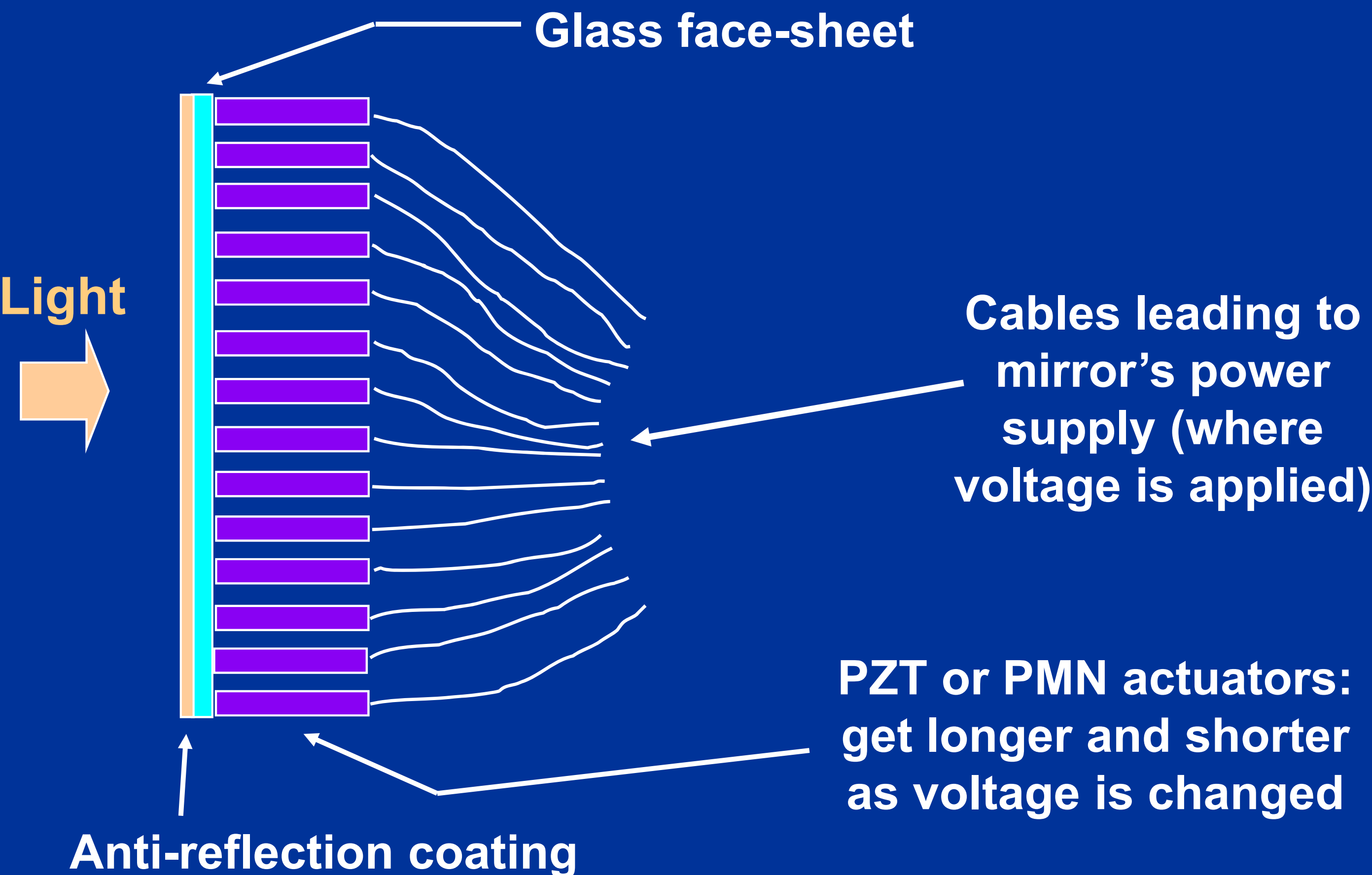
- "Coherence Length" r_0 : distance over which optical phase distortion has mean square value of 1 rad^2 (r_0 ~ 15 - 30 cm at good observing sites)
- Easy to remember: r_0 = 10cm ⇔ FWHM = 1" at λ = 0.5μm

Real deformable mirrors have continuous surfaces



- In practice, a small deformable mirror with a thin bendable face sheet is used
- Placed <u>after</u> the main telescope mirror

Most deformable mirrors today have thin glass face-sheets

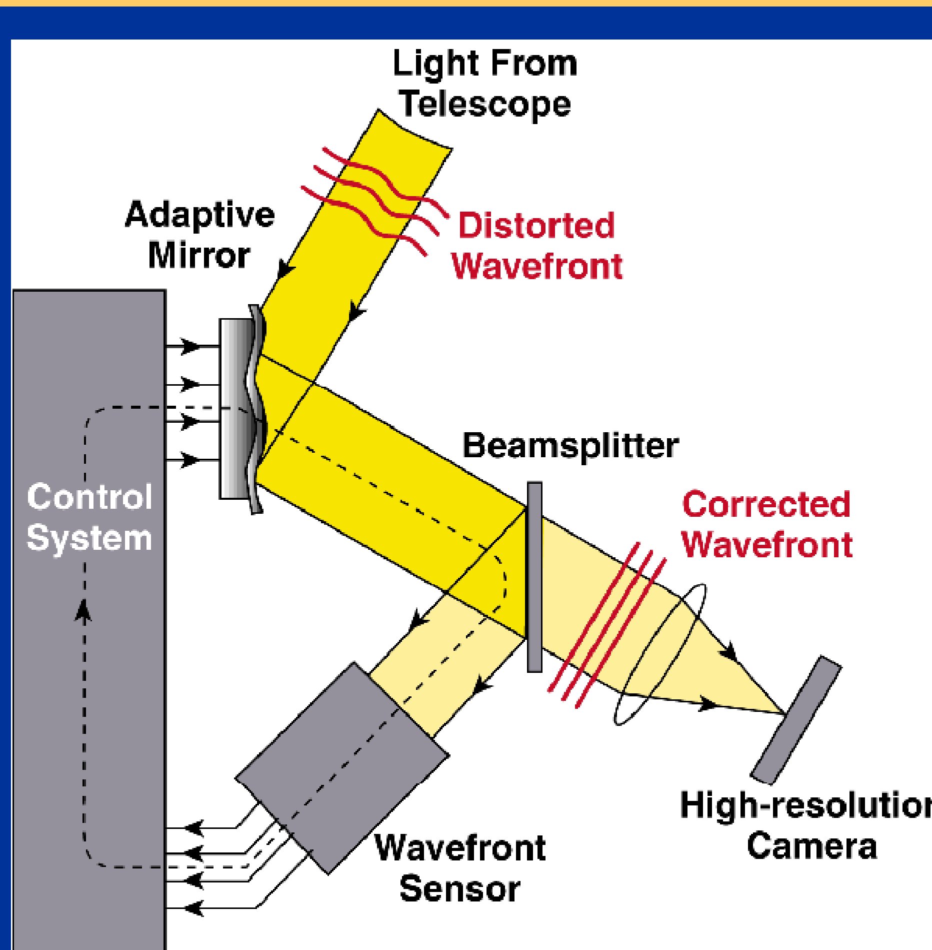


Deformable mirrors come in many sizes

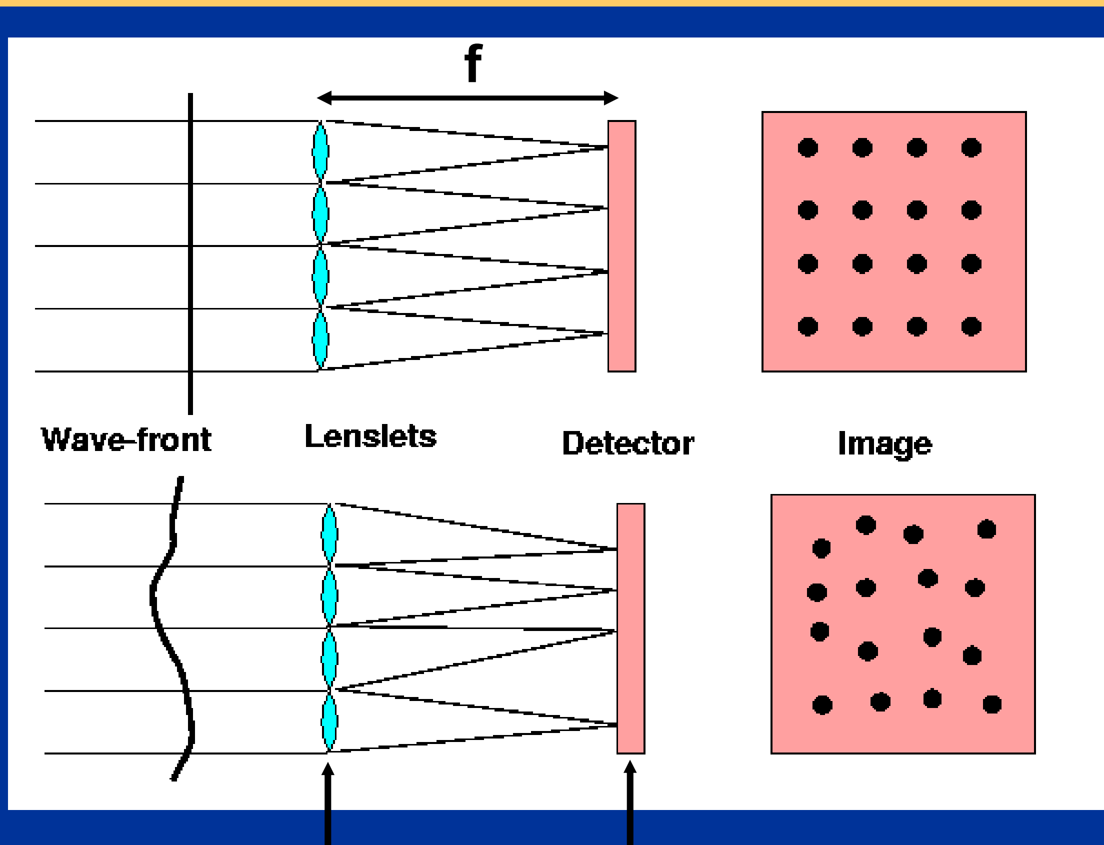
- Range from 13 to > 900 actuators (degrees of freedom)

Schematic of adaptive optics system

Feedback loop: next cycle corrects the (small) errors of the last cycle



Shack-Hartmann wavefront sensor concept - measure subaperture tilts



Pupil plane

Image plane

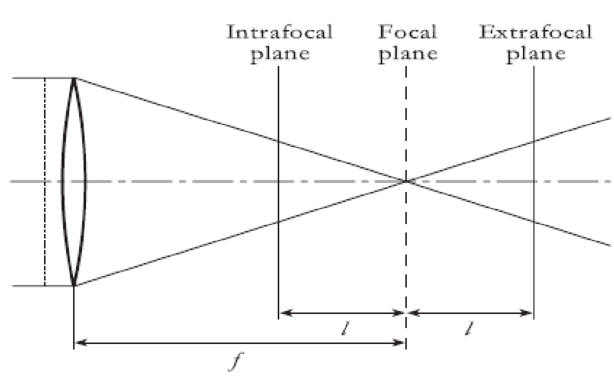
Shack-Hartmann wavefront sensor measures local "tilt" of wavefront

- **Divide pupil into subapertures of size ~ r_0**
  - **Number of subapertures α $(D / r_0)^2$**
- **Lenslet in each subaperture focuses incoming light to a spot on the wavefront sensor's CCD detector**
- **Deviation of spot position from a perfectly square grid measures shape of incoming wavefront**
- **Wavefront reconstructor computer uses positions of spots to calculate voltages to send to deformable mirror**

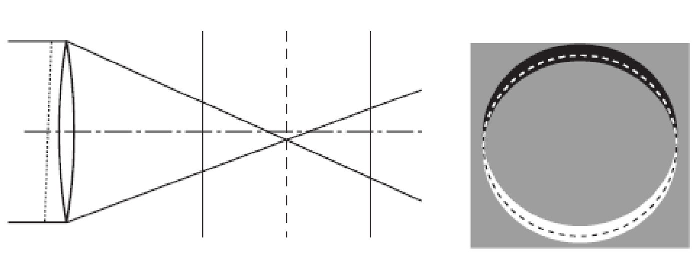
Page 27

Reinhold Dorn A CCD based curvature wavefront sensor

Curvature sensing (1)



- A flat wavefront focused by a lens, showing the **intrafocal** and **extrafocal** image planes on either side of the focal plane.

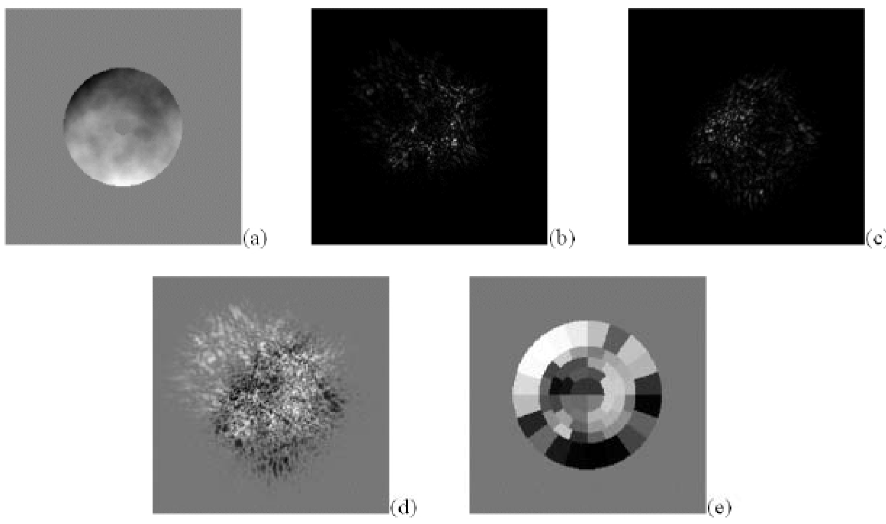


- Propagation of a flat but tilted wavefront and the resulting curvature signal.
- Grey is a curvature signal of zero, white is positive and black is negative.
- The dashed line shows the outline of the pupil.

7/2/01 6

8

Curvature sensing - Computer simulation of curvature wavefront sensing



- AO loop open:

(a) wavefront distortion,

(b) intrafocal image,

(c) extrafocal image

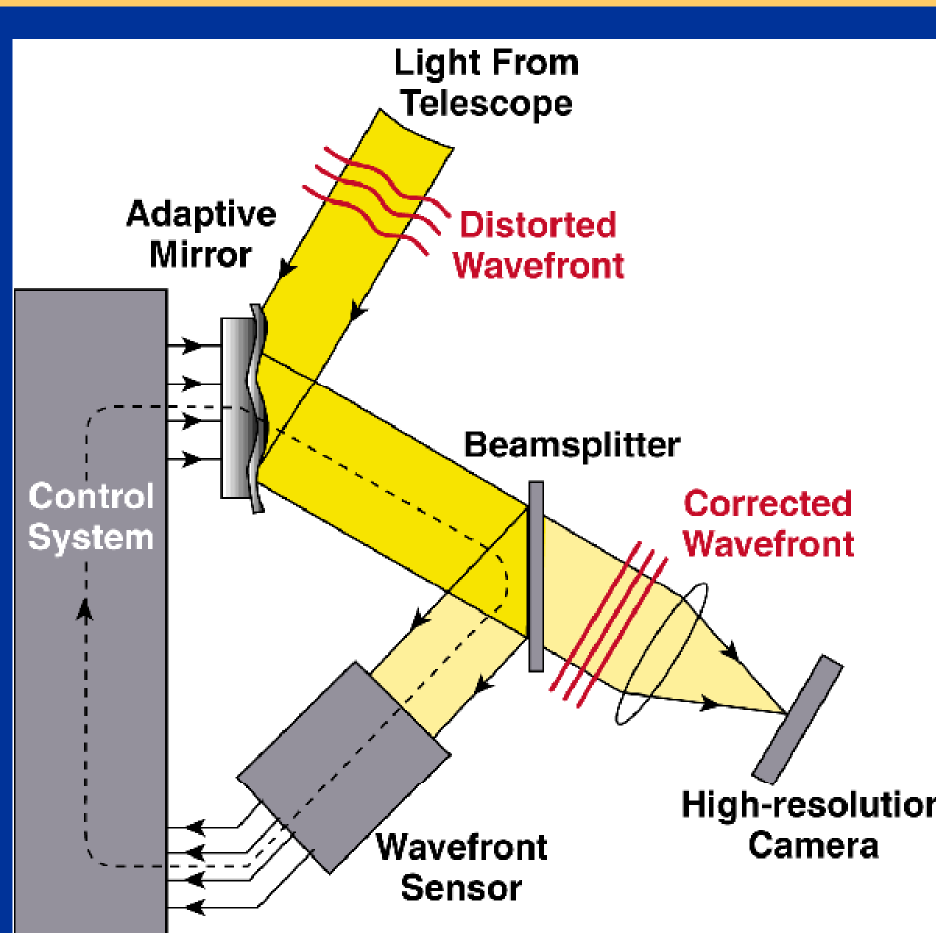
(d) curvature signal at high resolution,

(e) curvature signal binned into 60 subapertures.

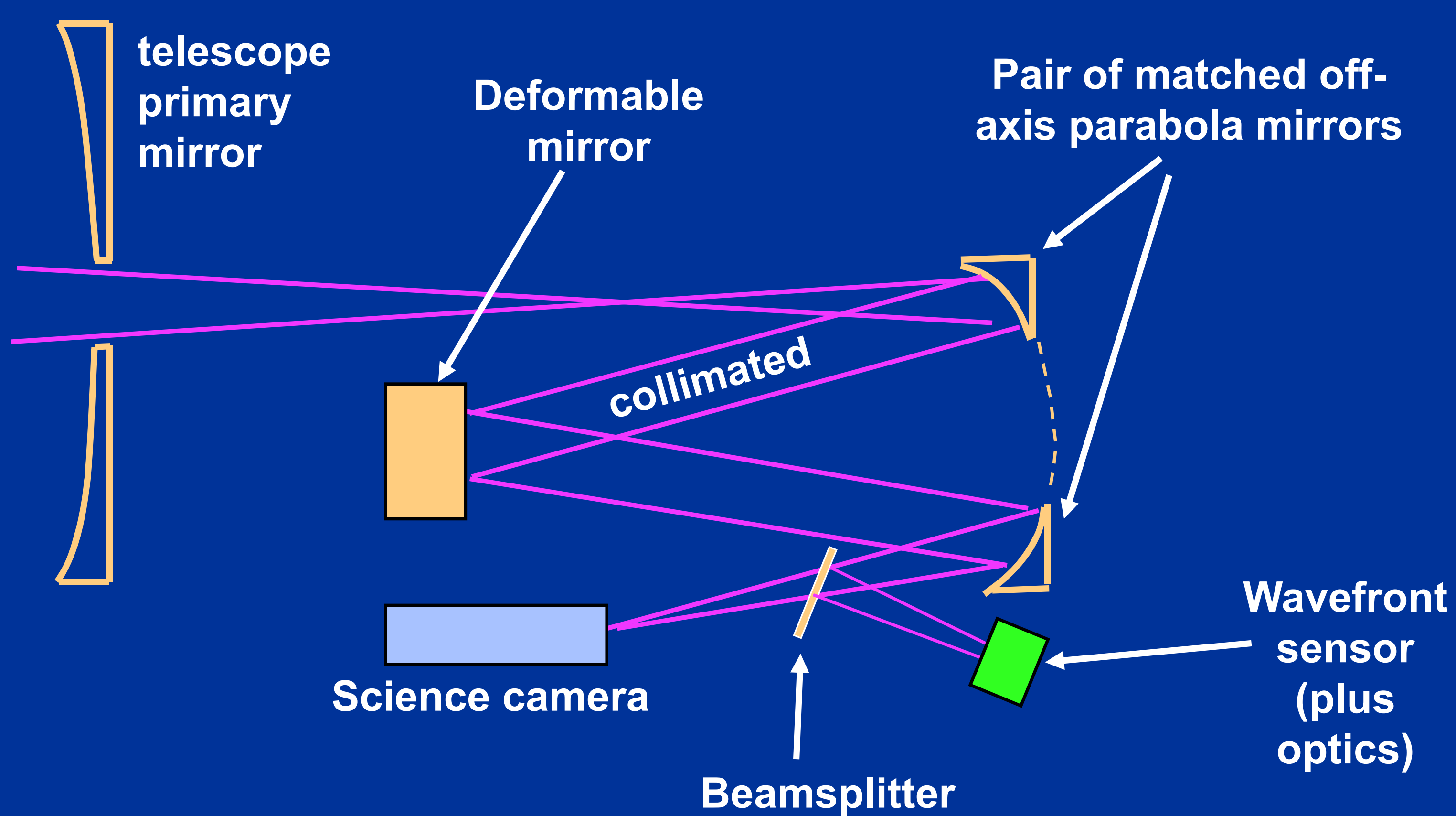
- Simulation parameters: 0.66 arc sec seeing (at 500 nm), sensing wavelength = 700 nm (monochromatic), infrared image wavelength = 2.2 µm, out of focus distance = 25 cm, telescope focal length = 400 m, telescope diameter = 8 m with 14% obscuration from 1.12 m diameter secondary. Photon noise has not been simulated – all signals are "infinite" light level.

Schematic of adaptive optics system

Feedback loop: next cycle corrects the (small) errors of the last cycle



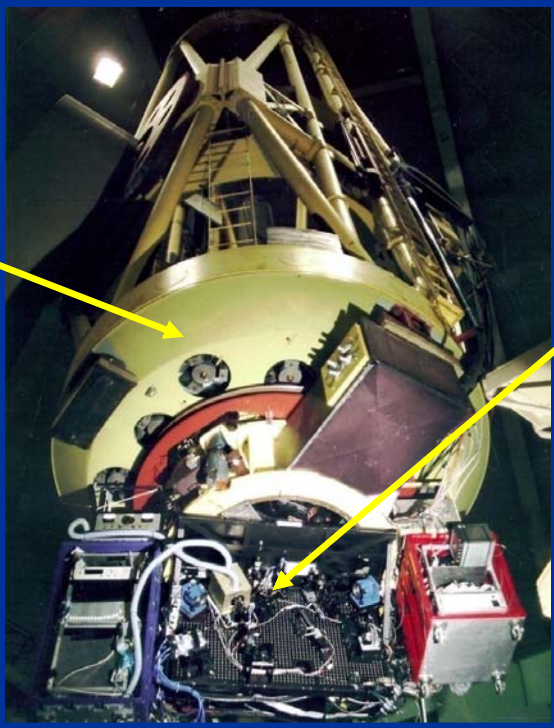
Typical optical design of AO system



Adaptive optics system is usually <u>behind</u> main telescope mirror

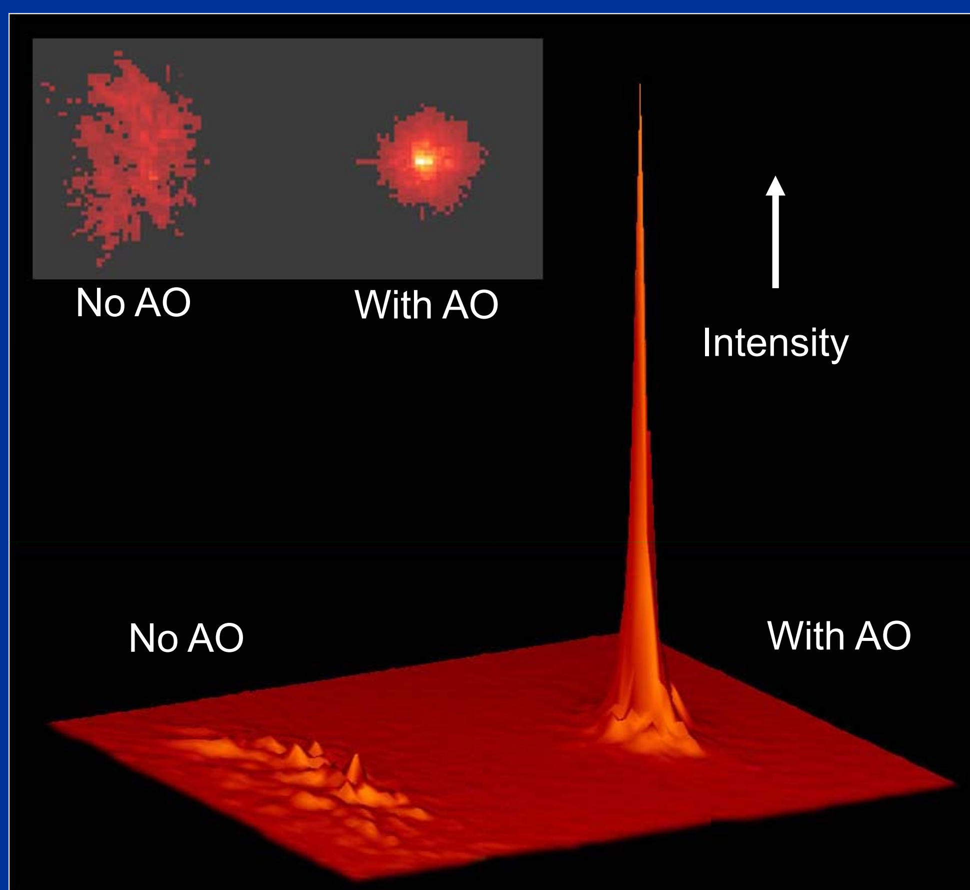
- Example: AO system at Lick Observatory's 3 m telescope

Support for main telescope mirror



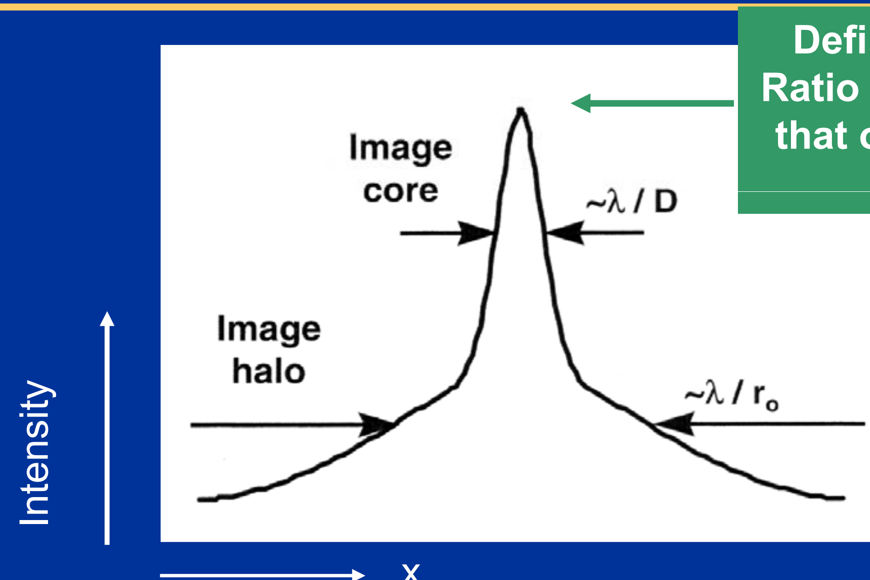
Adaptive optics package below main mirror

Adaptive optics increases peak intensity of a point source



Lick Observatory

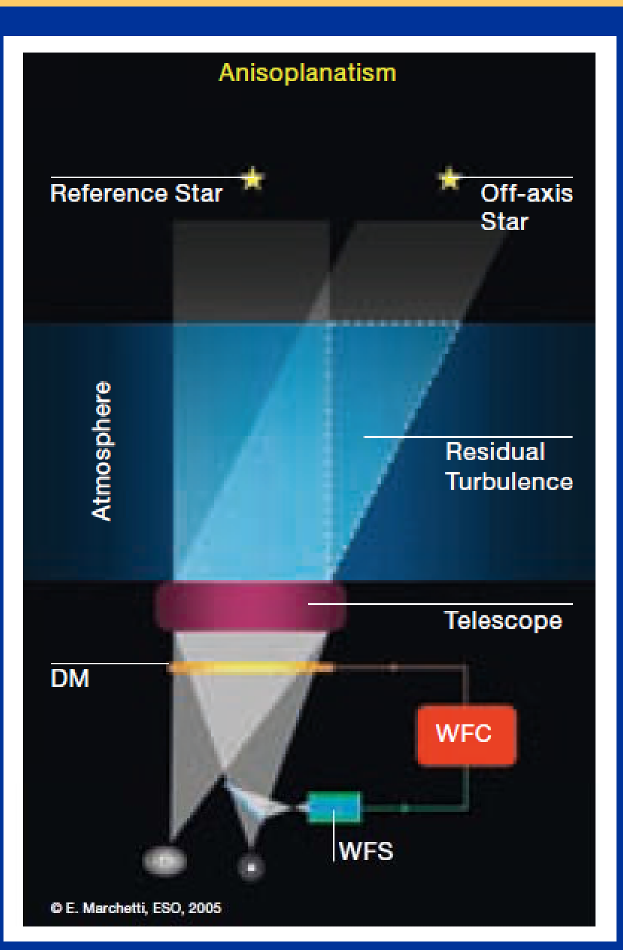
AO produces point spread functions with a "core" and "halo"



Definition of "Strehl": Ratio of peak intensity to that of "perfect" optical system

- **When AO system performs well, more energy in core**
- **When AO system is stressed (poor seeing), halo contains larger fraction of energy (diameter ~ r_0)**
- **Ratio between core and halo varies during night**

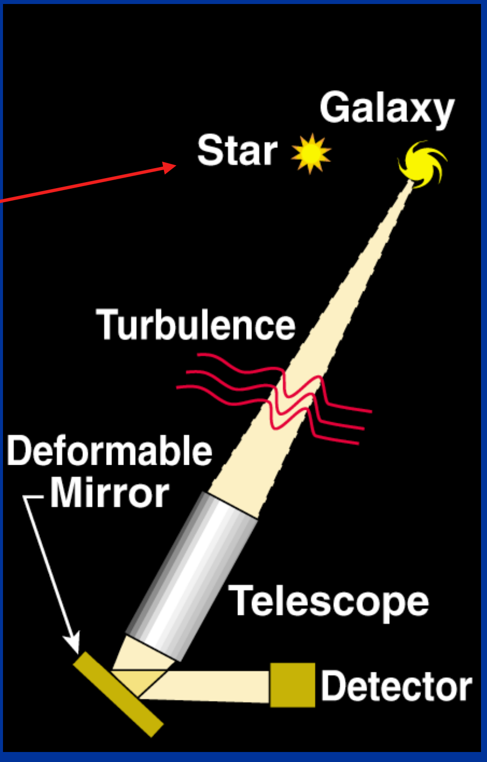
Classical AO in the isoplanatic patch



https://www.eso.org/sci/publications/messenger/archive/no.129-sep07/messenger-no129-8-13.pdf

If there's no close-by "real" star, create one with a laser

- Use a laser beam to create artificial "star" at altitude of 100 km in atmosphere



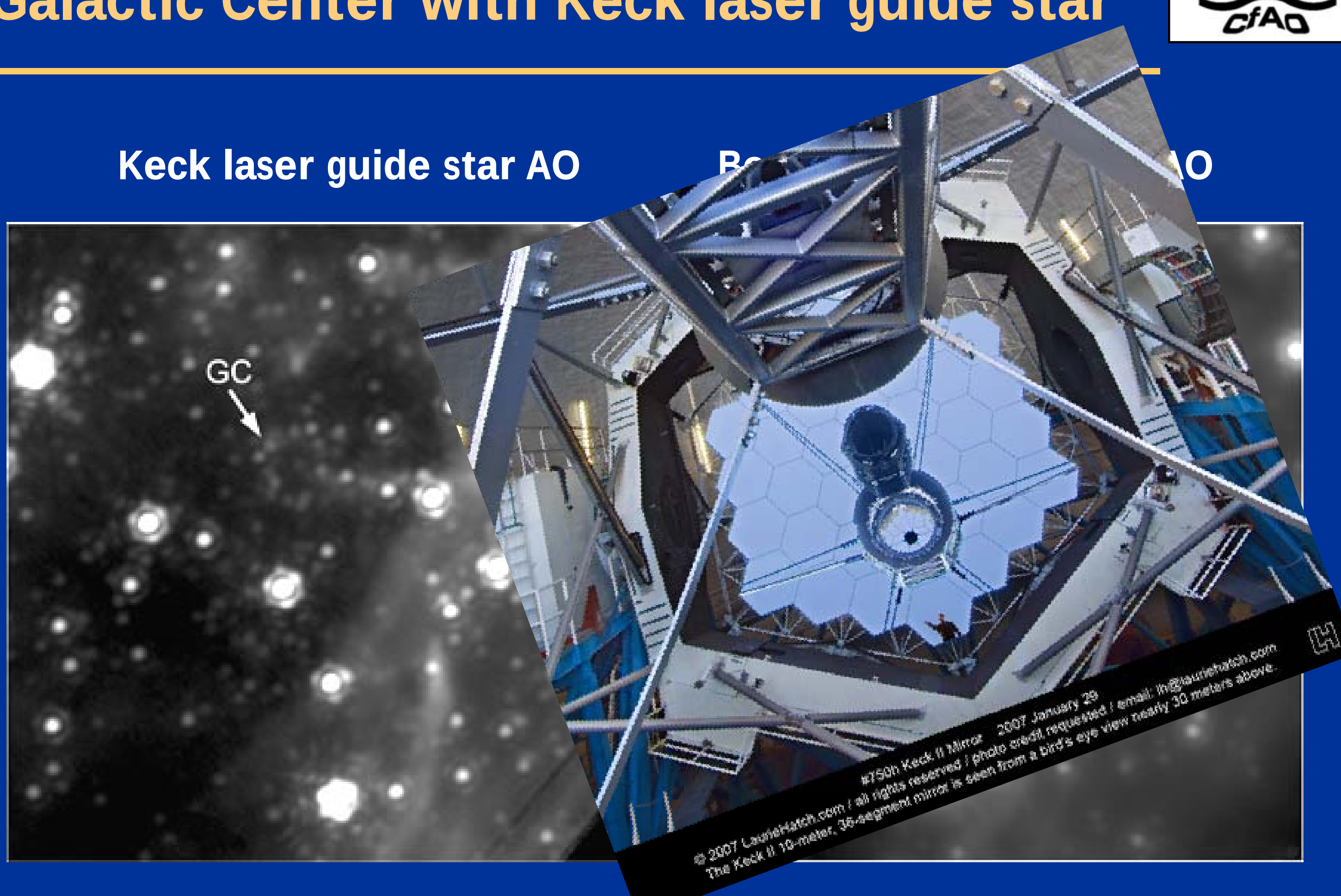
Laser "guide star" (or, here, guide stars)

Twin beams toward the Galactic center for AO with the Keck Interferometer

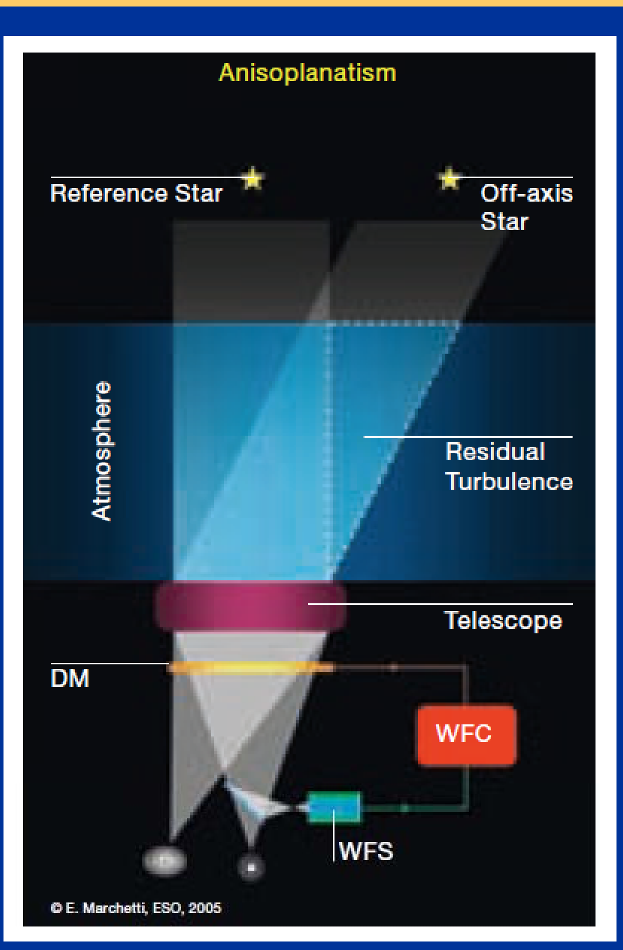
Photo credit Dan Birchall, UCLA

Galactic Center with Keck laser guide star

Keck laser guide star AO

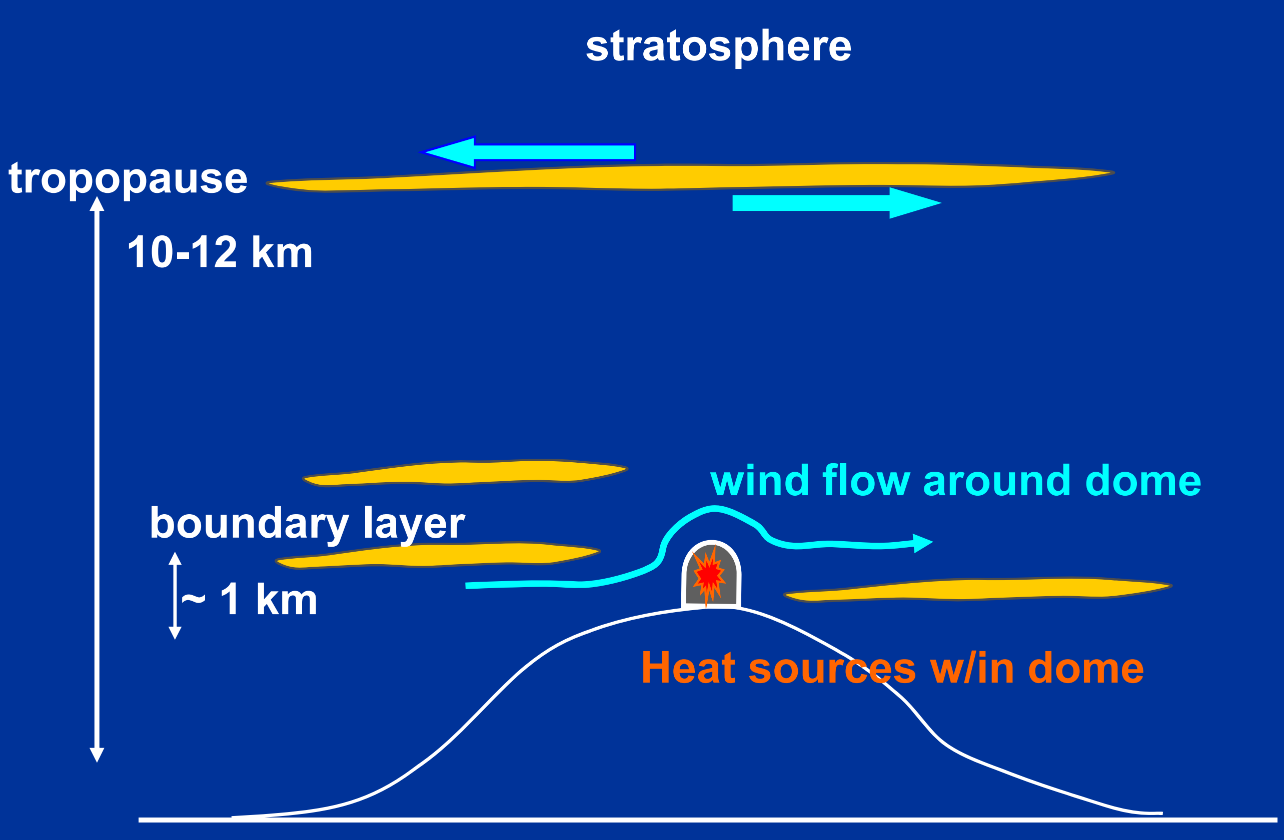


AO in the isoplanatic patch

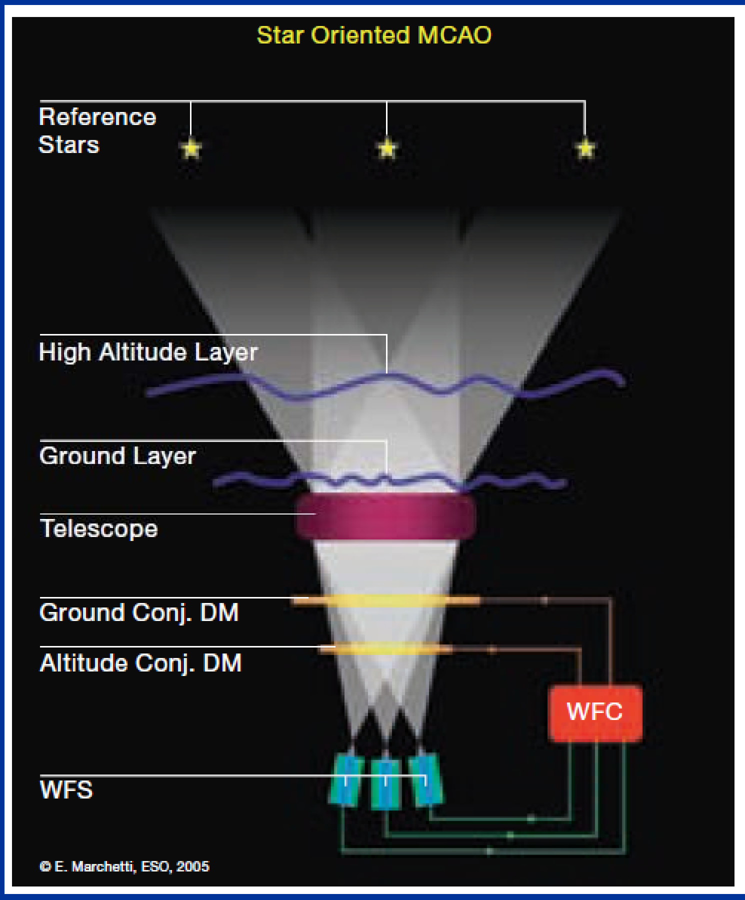


https://www.eso.org/sci/publications/messenger/archive/no.129-sep07/messenger-no129-8-13.pdf

Turbulence arises in several places



Multi-conjugate AO (MCAO)

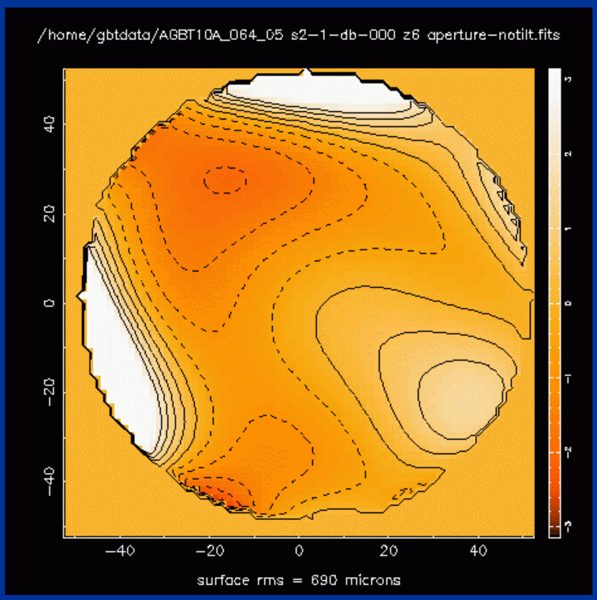


https://www.eso.org/sci/publications/messenger/archive/no.129-sep07/messenger-no129-8-13.pdf

Page 41

Active optics: reflector surface errors

- **Many telescopes have segmented surfaces: Keck, NGST, and radio telescopes are familiar examples**
- **Now deform the *aperture* to correct the phase errors**



Page 42

Zernike polynomials

- **The Zernike polynomials are orthogonal on a unit disk**
  - **First, piston (up-down)**
  - **Then tilts (R-L, up-down)**
  - **Then bends with one half cycle across aperture**
  - **Then more and more cycles**
- **Orthogonality simplifies computations; Zernike for circular apertures**

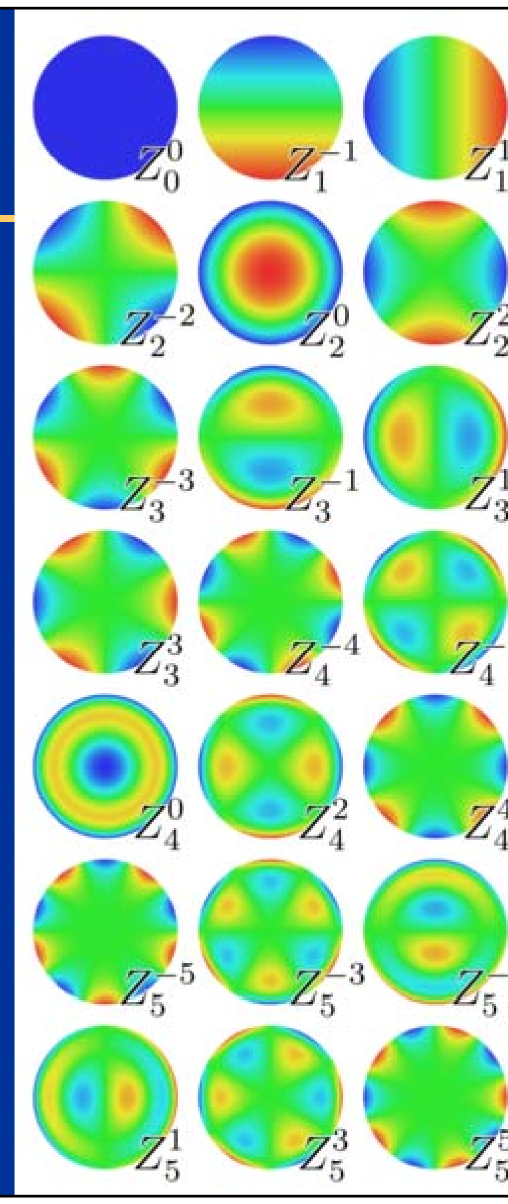


Image from Rocchini, Wikipedia commons

Surface improvement