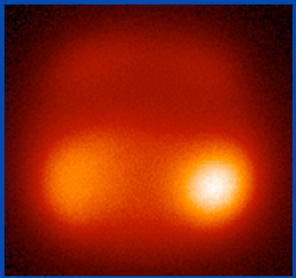
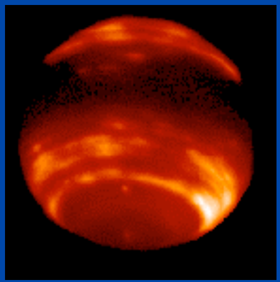
# *Adaptive Optics and its Applications Lecture 1*

Neptune



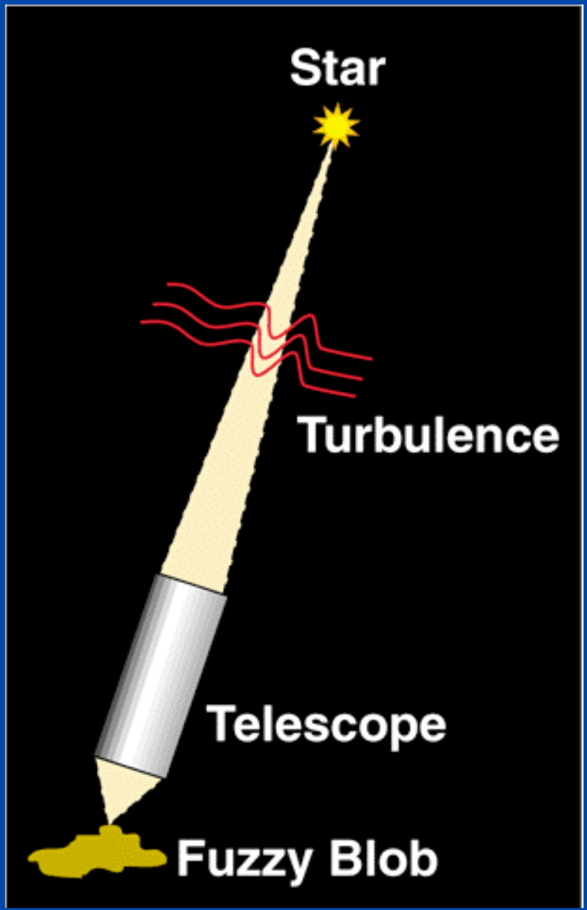


Claire Max

UC Santa Cruz

January 8, 2008

# *Why is adaptive optics needed?*



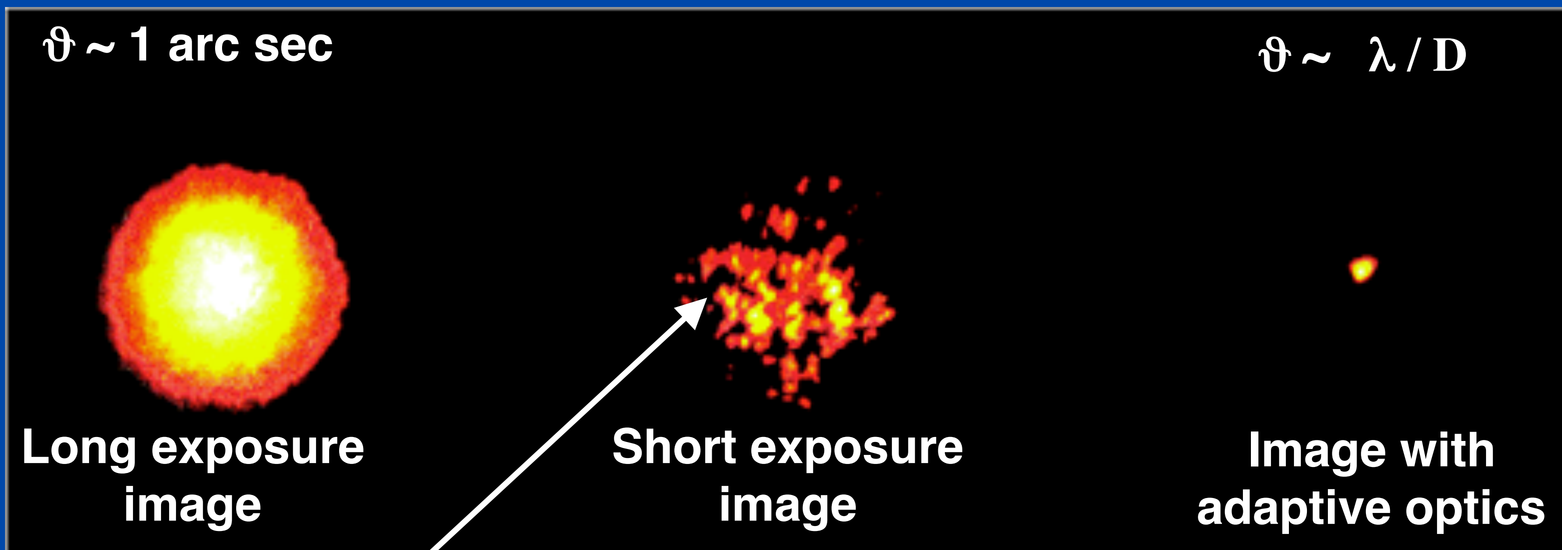

Turbulence in earth's atmosphere makes stars twinkle

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!**

# *Images of a bright star, Arcturus*

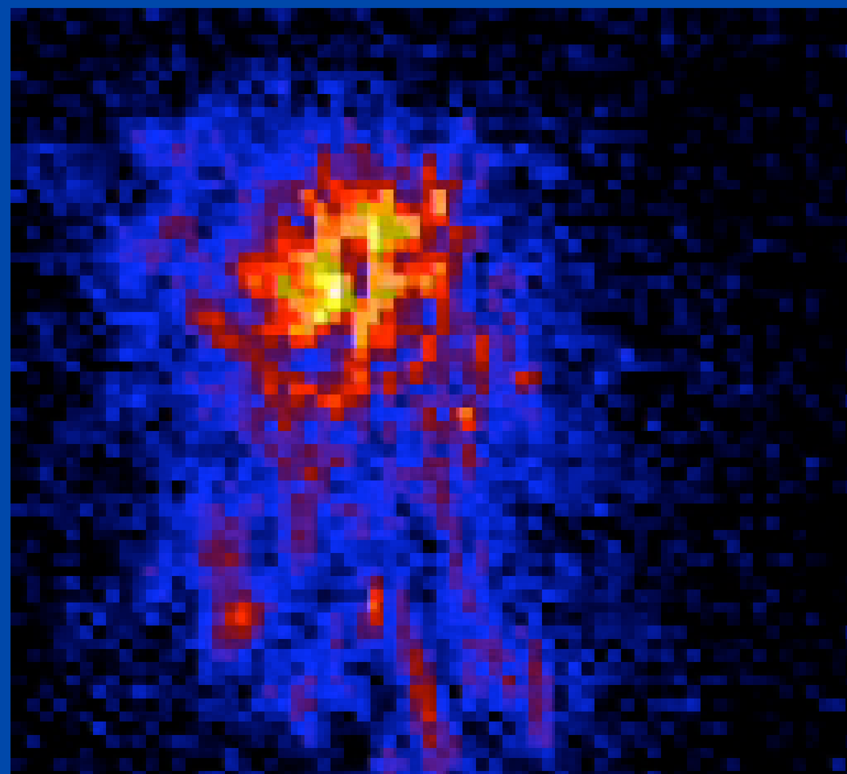
Lick Observatory, 1 m telescope




Speckles (each is at diffraction limit of telescope)

# *Turbulence changes rapidly with time*

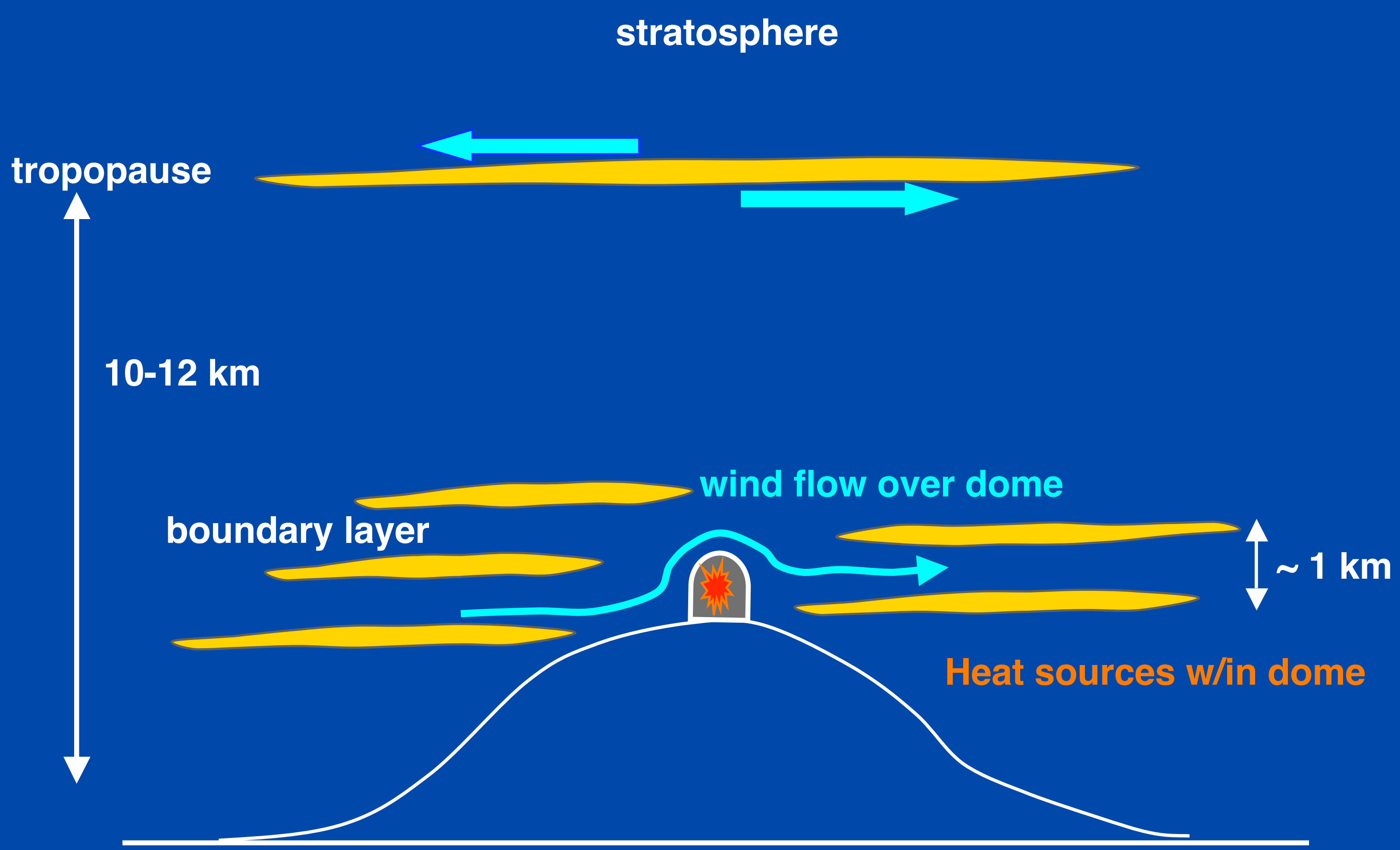
Image is spread out into speckles



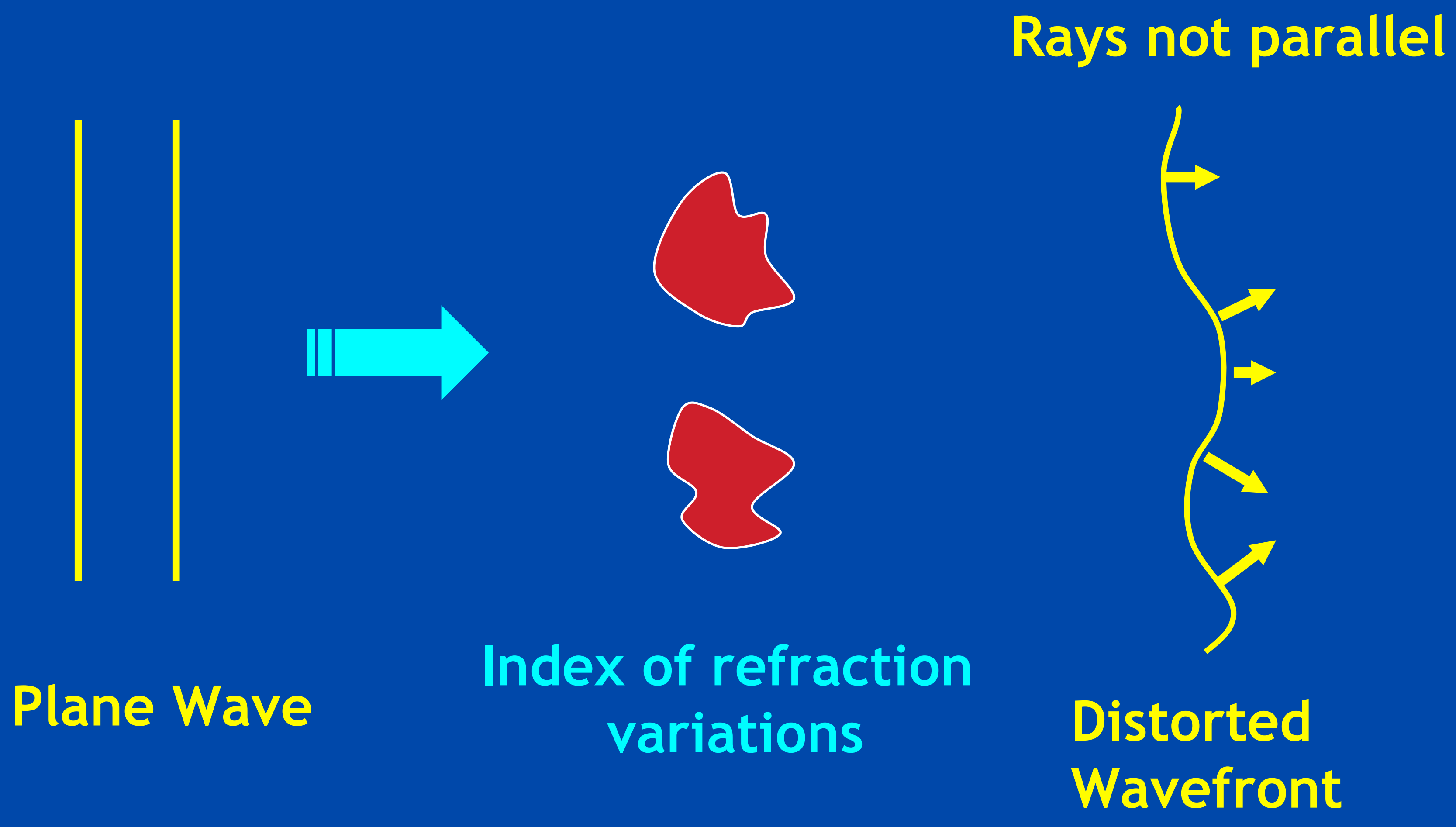
Centroid jumps around (image motion)

"Speckle images": sequence of short snapshots of a star, taken at Lick Observatory using the IRCAL infra-red camera

# Turbulence arises in many places

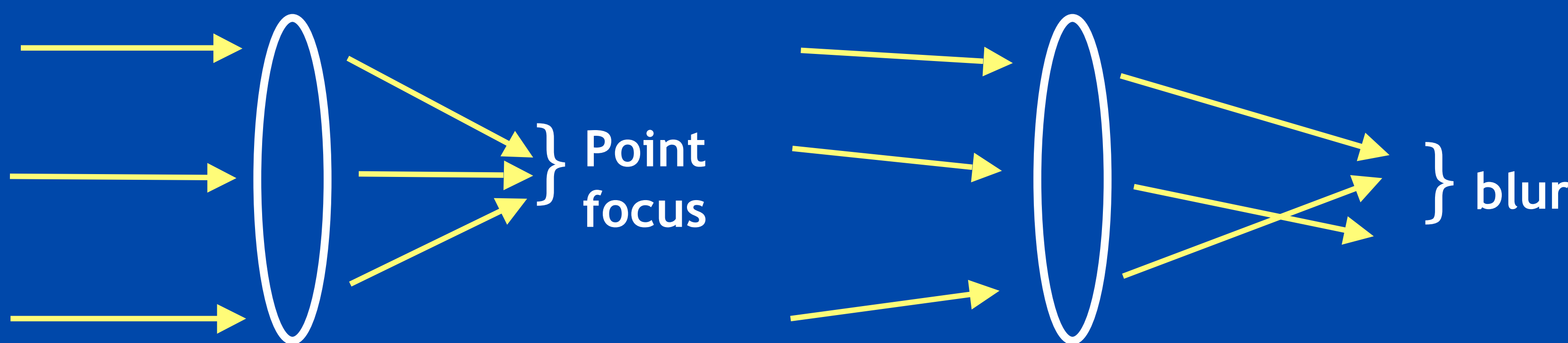


# *Atmospheric perturbations cause distorted wavefronts*



# *Optical consequences of turbulence*

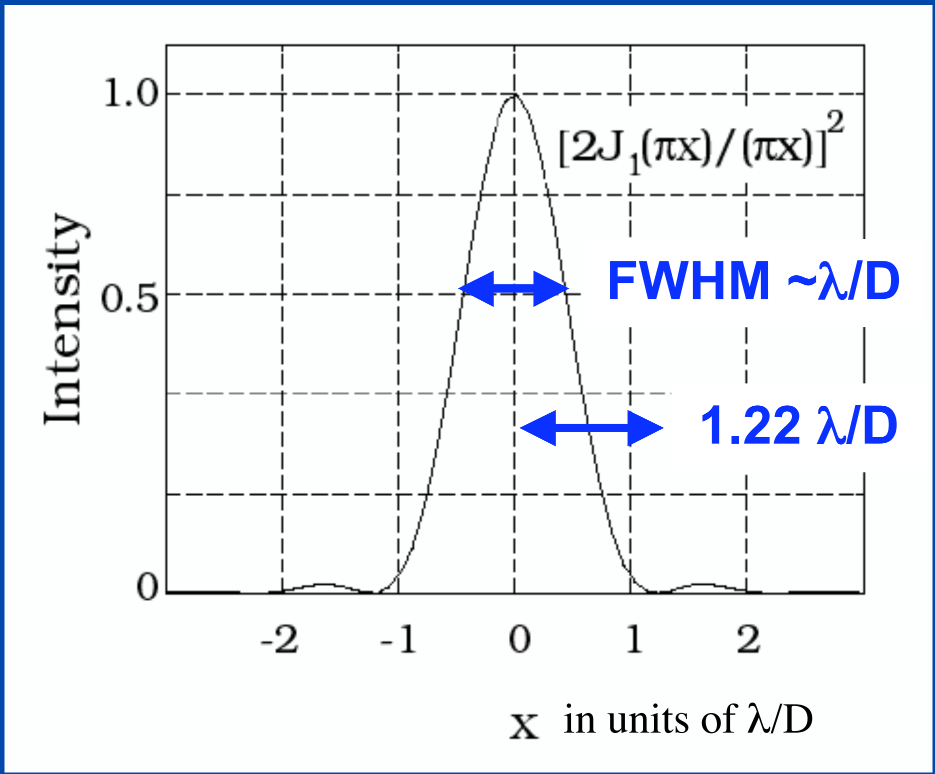
- Temperature fluctuations in small patches of air cause changes in index of refraction (like many little lenses)
- Light rays are refracted many times (by small amounts)
- When they reach telescope they are no longer parallel
- Hence rays can't be focused to a point:




Parallel light rays

Light rays affected by turbulence

# *Imaging through a perfect telescope*




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

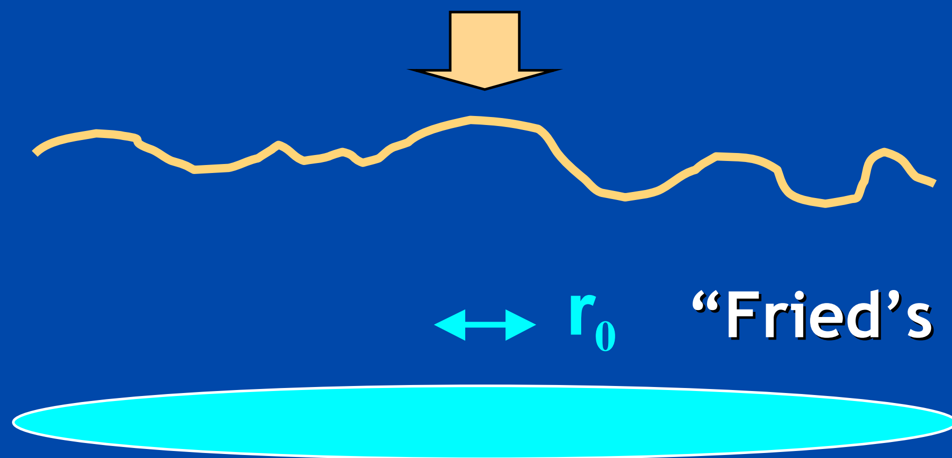
With no turbulence, FWHM is diffraction limit of telescope, $\vartheta \sim \lambda / D$

Example:

$\lambda / D = 0.02$ arc sec for $\lambda = 1\ \mu m$, $D = 10$ m

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

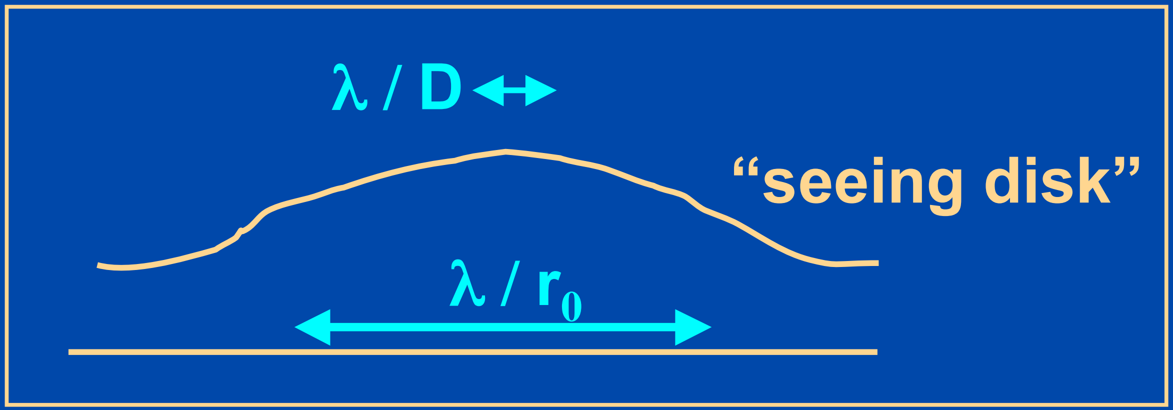
# *Characterize turbulence strength by quantity $r_0$*




- "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: $r_0$ = 10 cm ⇔ FWHM = 1 arc sec at $\lambda = 0.5\mu m$

# *Effect of turbulence on image size*

- If telescope diameter D >> $r_0$ , image size of a point source is $\lambda / r_0$ >> $\lambda / D$



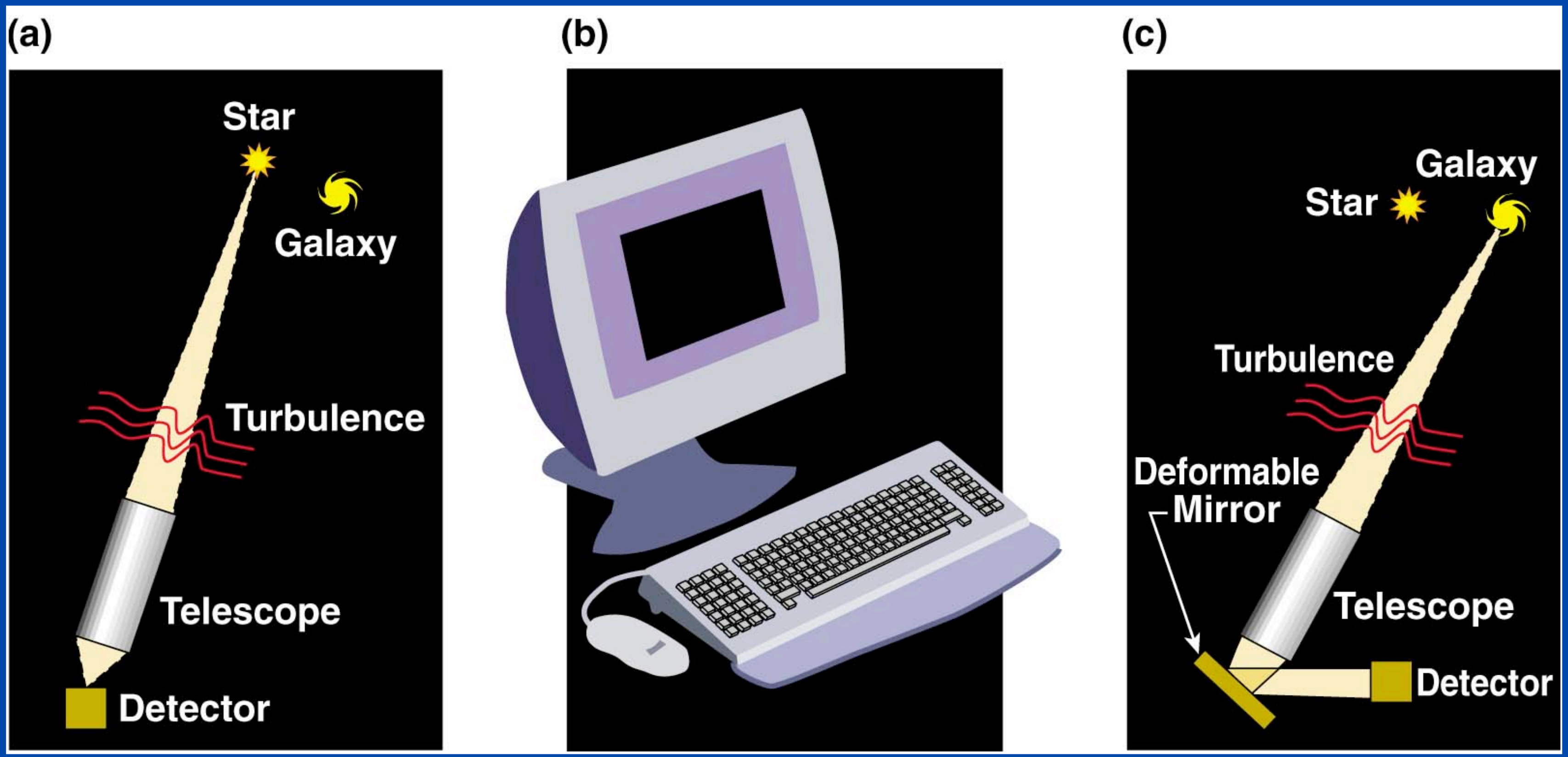

- $r_0$ is diameter of the circular pupil for which the diffraction limited image and the seeing limited image have the same angular resolution.
- $r_0 \approx$ 10 inches at a good site. So any telescope larger than this has no better spatial resolution!

# How does adaptive optics help? (cartoon approximation)

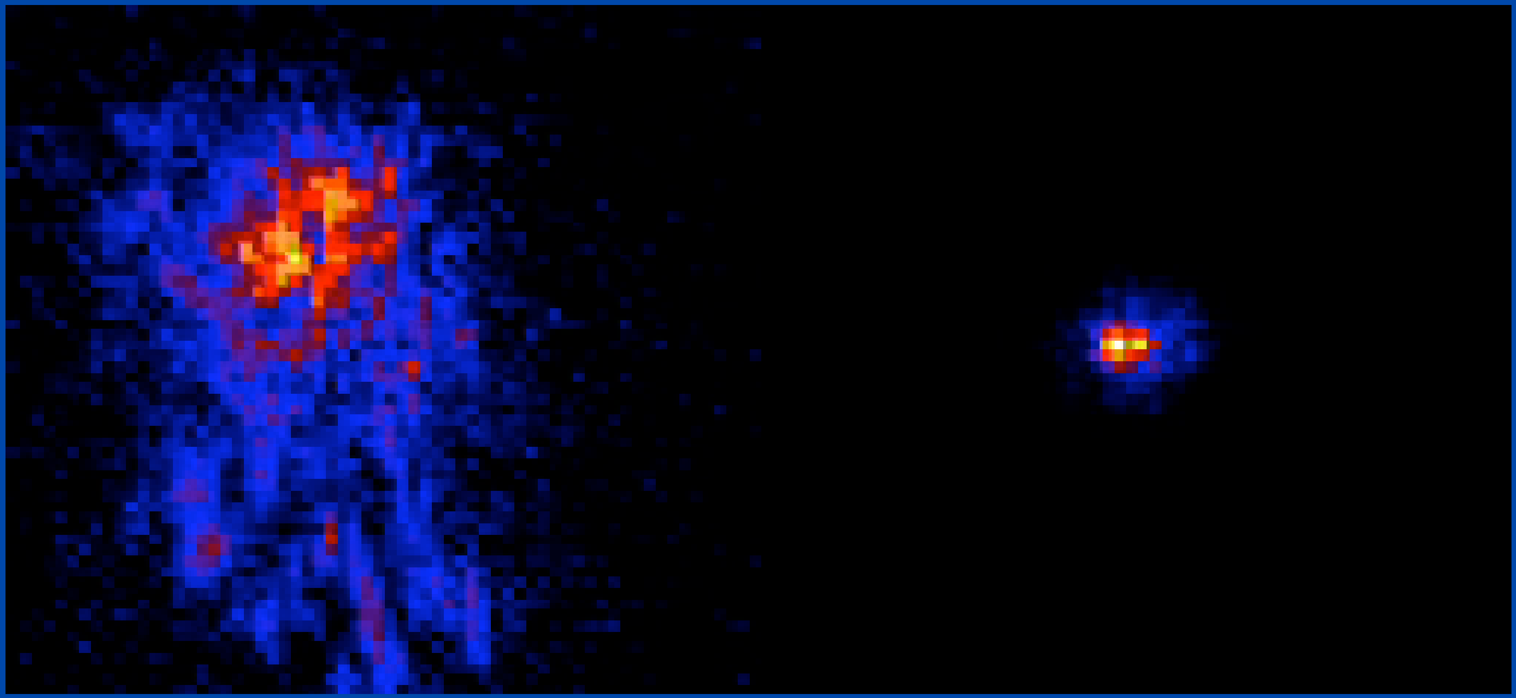
*Measure details of blurring from "guide star" near the object you want to observe*

*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*



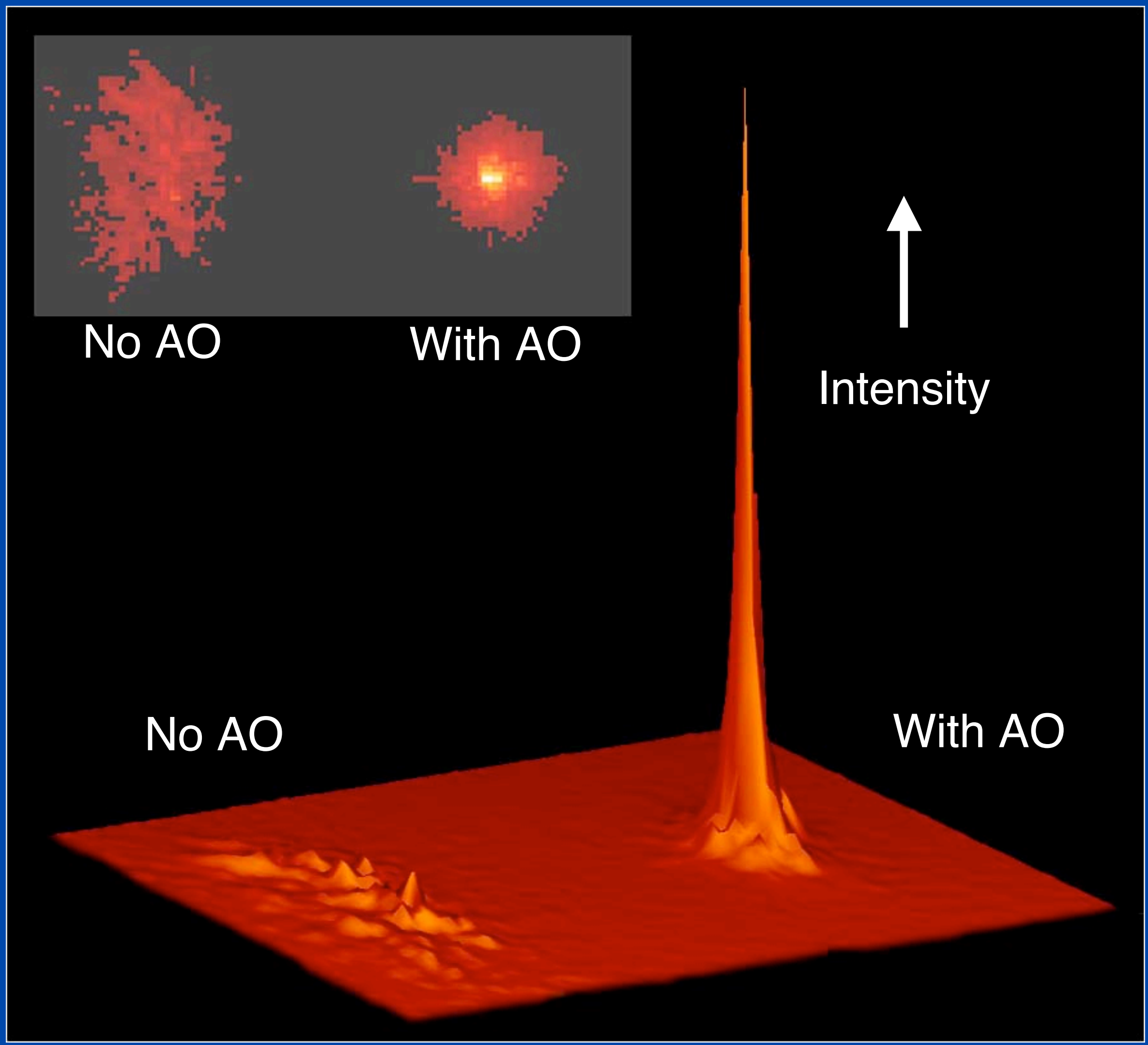
# *Infra-red images of a star, from Lick Observatory adaptive optics system*



**No adaptive optics** **With adaptive optics**

**Note: "colors" (blue, red, yellow, white) indicate increasing intensity**

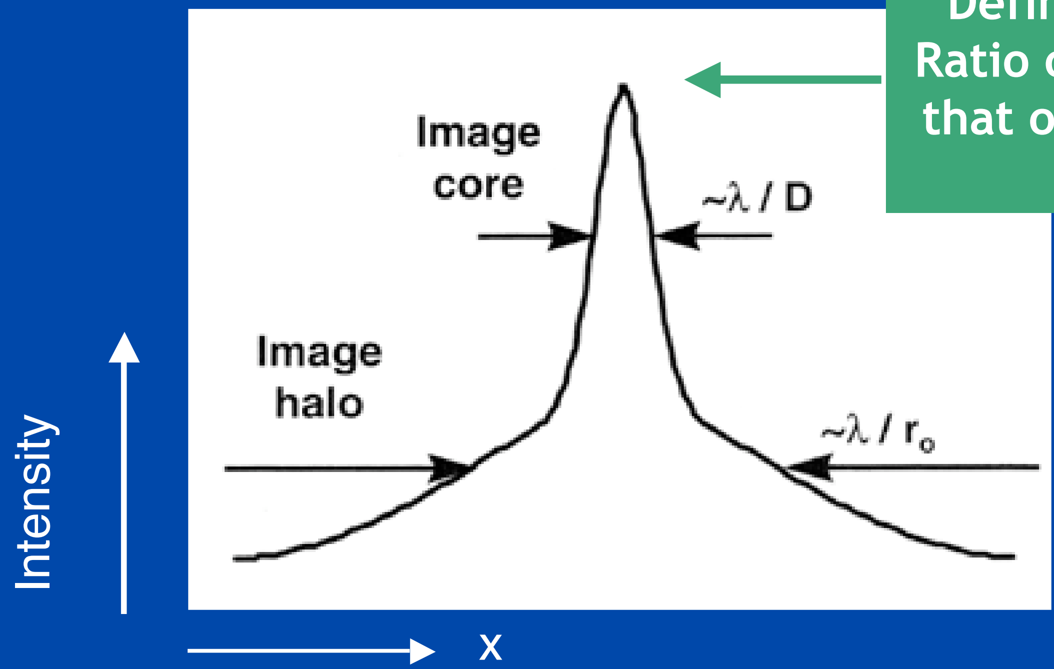
# *Adaptive optics increases peak intensity of a point source*




**Lick Observatory**

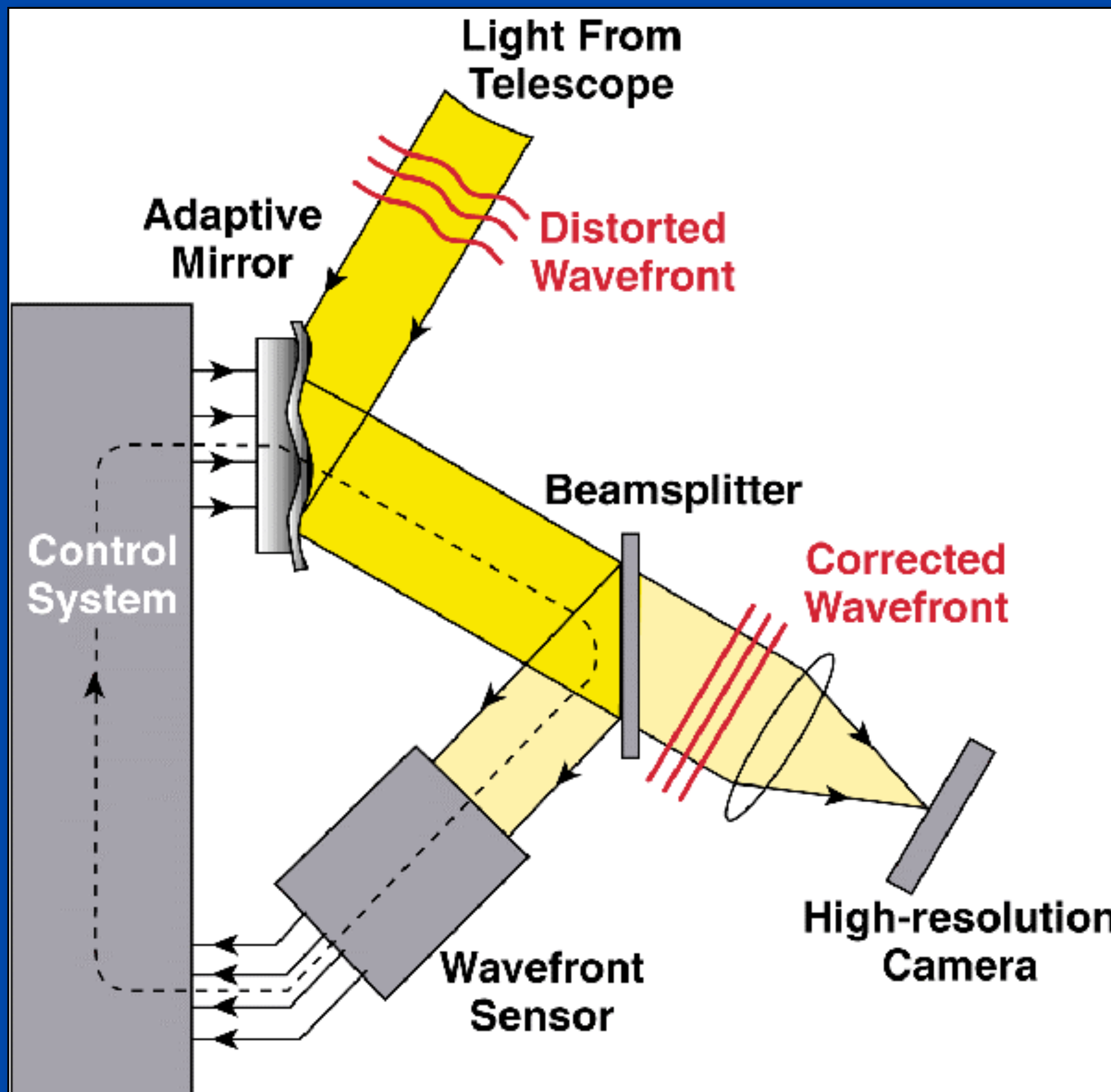
# *AO produces point spread functions with a "core" and "halo"*

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



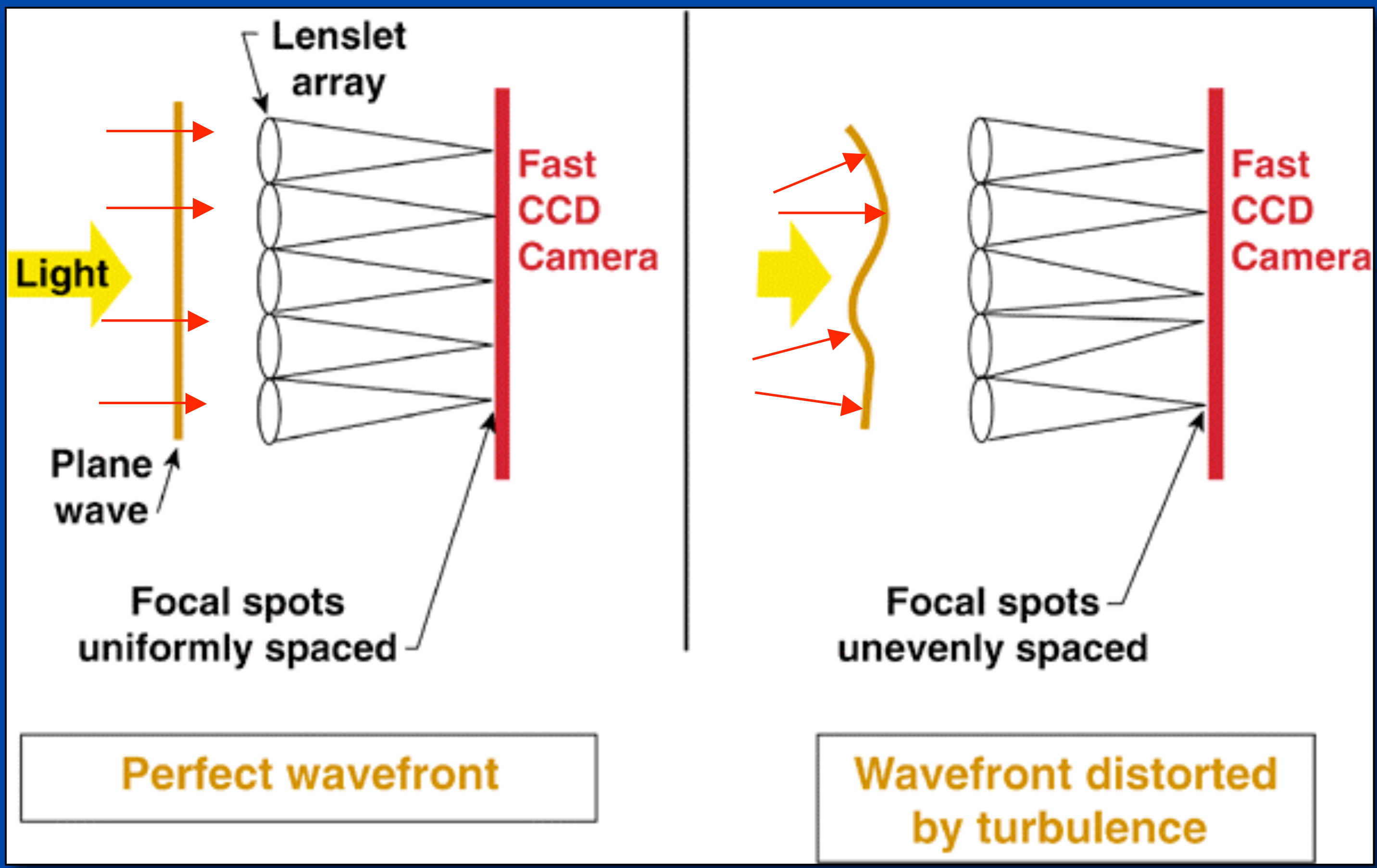

- When AO system performs well, more energy in core
- When AO system is stressed (poor seeing), halo contains larger fraction of energy (diameter ~ $r_0$)
- Ratio between core and halo varies during night

# Schematic of adaptive optics system




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

# *How to measure turbulent distortions (one method among many)*




Shack-Hartmann wavefront sensor

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

- Divide pupil into subapertures of size ~ $r_0$
  - Number of subapertures $\alpha$ $(D / r_0)^2$

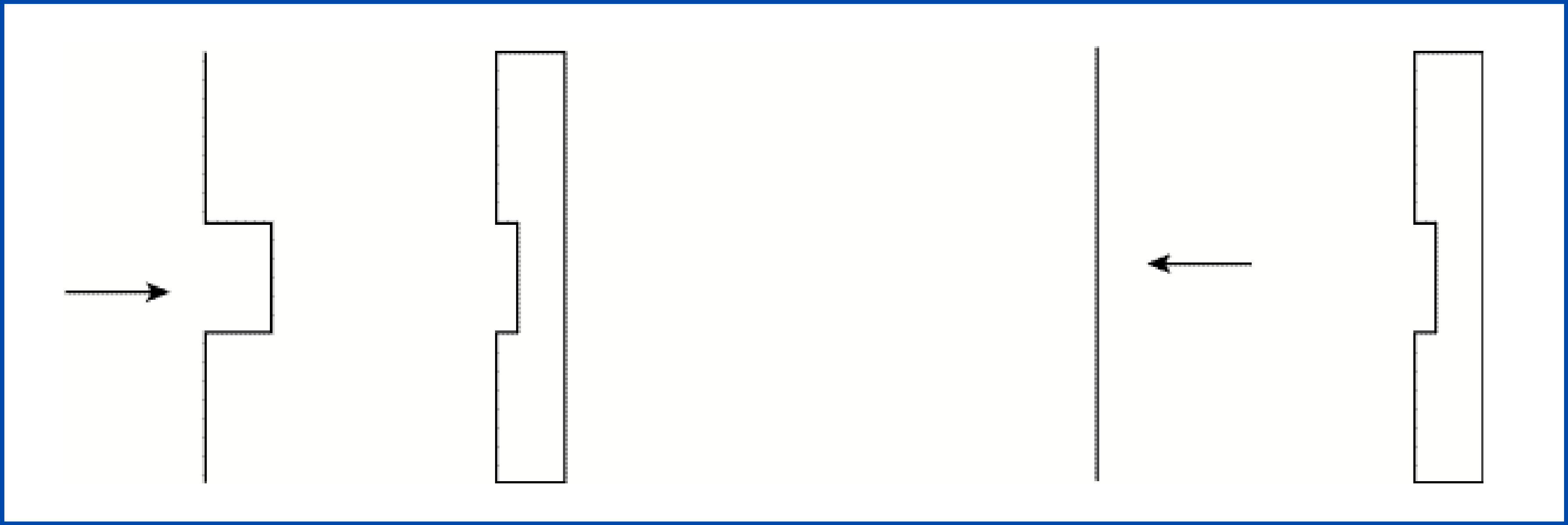
- Lenslet in each subaperture focuses incoming light to a spot on the wavefront sensor's CCD detector

- 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

# *How a deformable mirror works (idealization)*

**BEFORE** **AFTER**

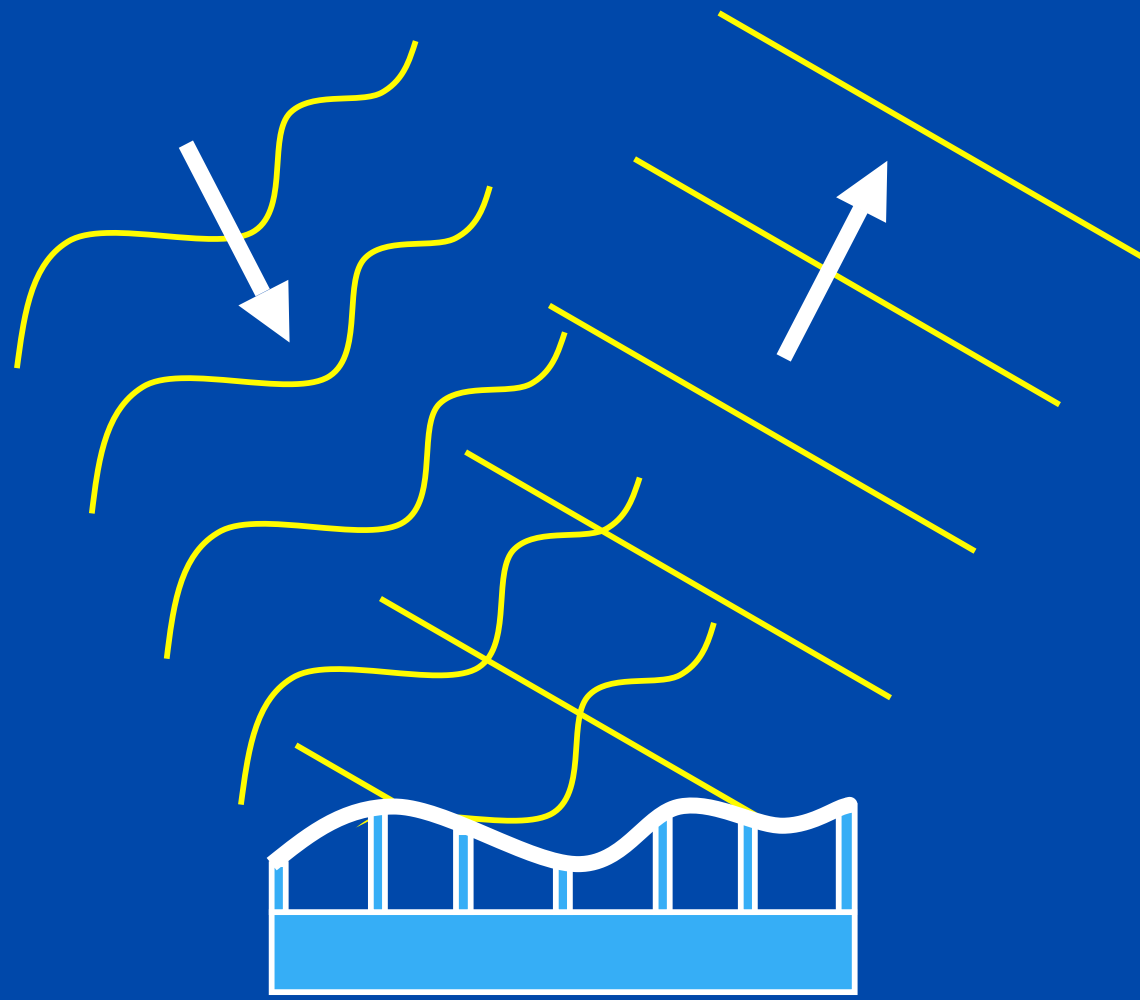


**Incoming Wave with Aberration**

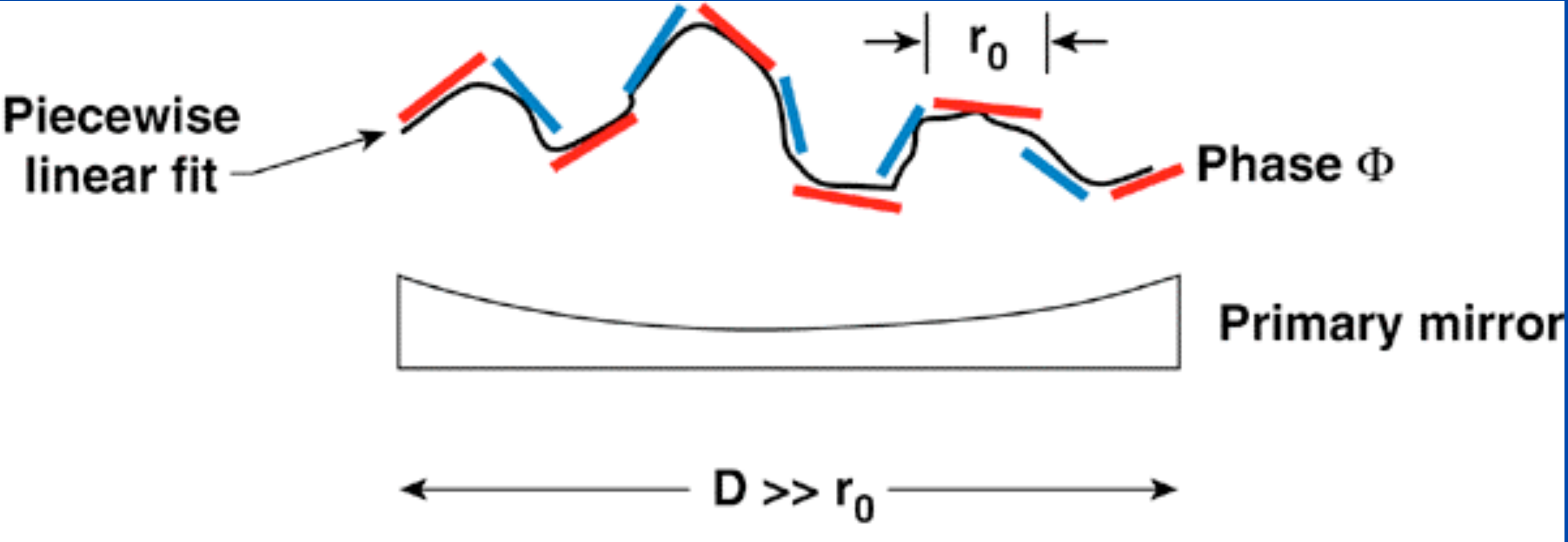
**Deformable Mirror**

**Corrected Wavefront**

# Deformable Mirror for real wavefronts

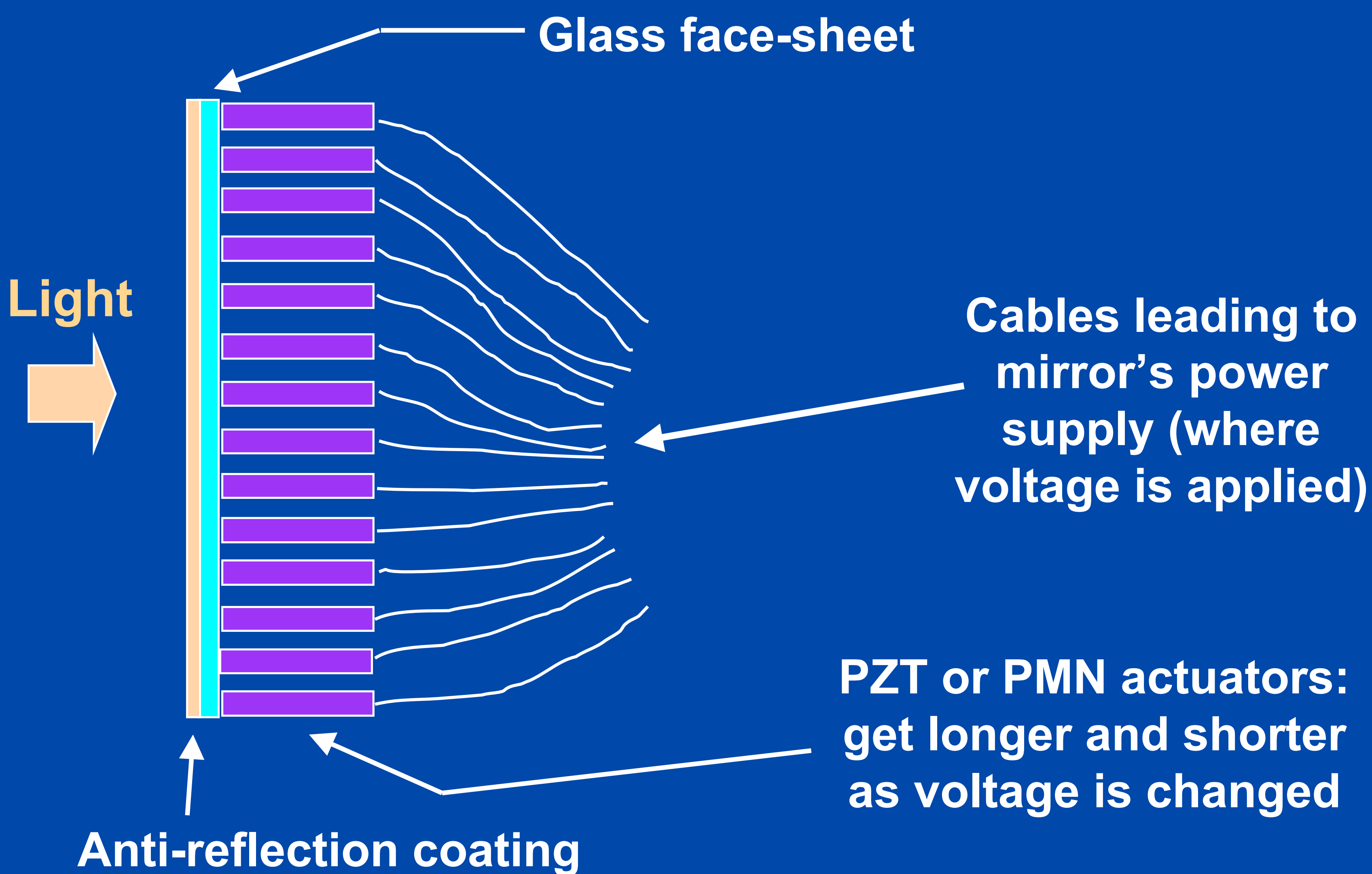


# *Real deformable mirrors have smooth surfaces*



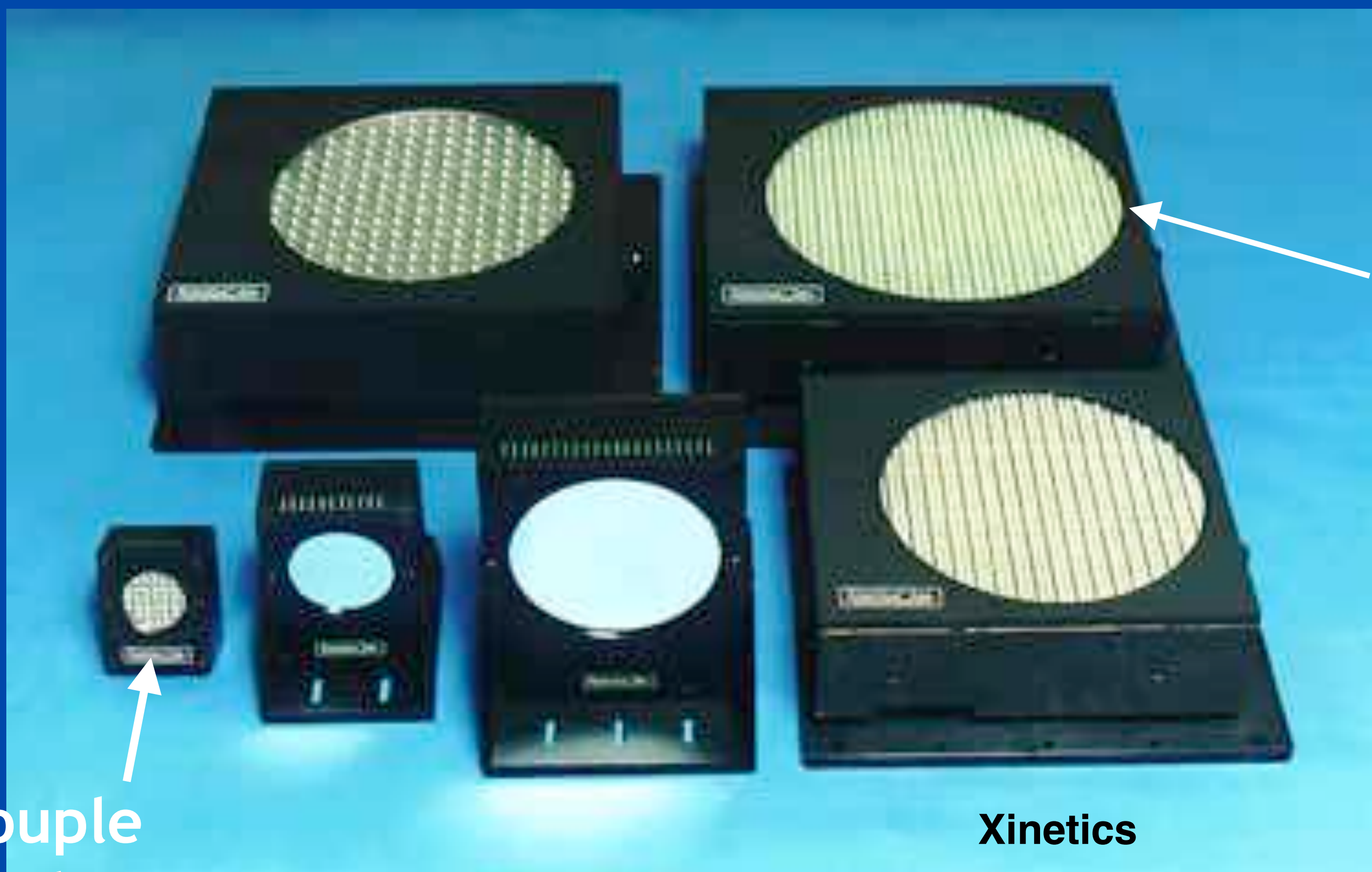

- In practice, a small deformable mirror with a thin bendable face sheet is used
- Placed <u>after</u> the main telescope mirror

# *Most deformable mirrors today have thin glass face-sheets*



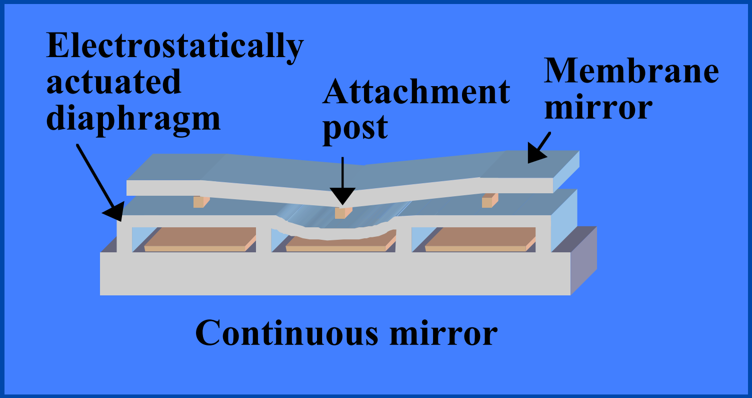
# *Deformable mirrors come in many sizes*

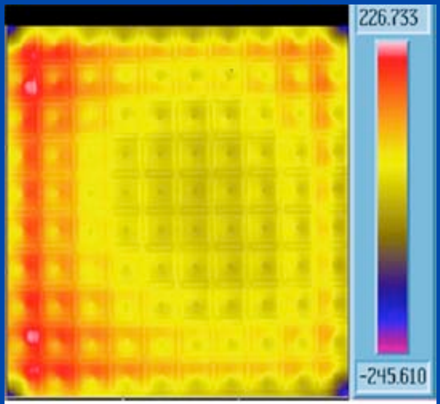
- Range from 13 to > 900 actuators (degrees of freedom)



# *New developments: tiny deformable mirrors*

- Potential for less cost per degree of freedom
- Liquid crystal devices
  - Voltage applied to back of each pixel changes index of refraction locally (not ready for prime time yet)
- MEMS devices (micro-electro-mechanical systems) - very promising today

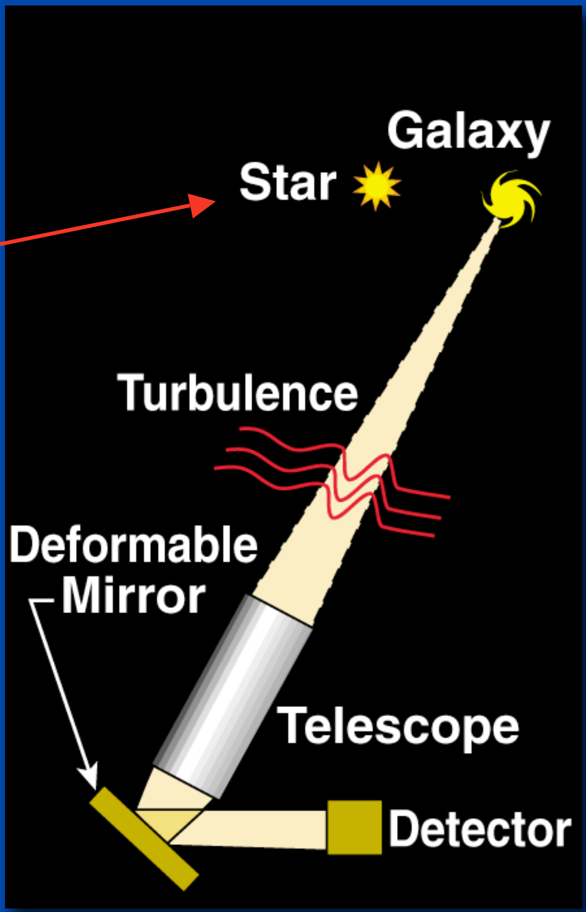


Mirror surface map

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

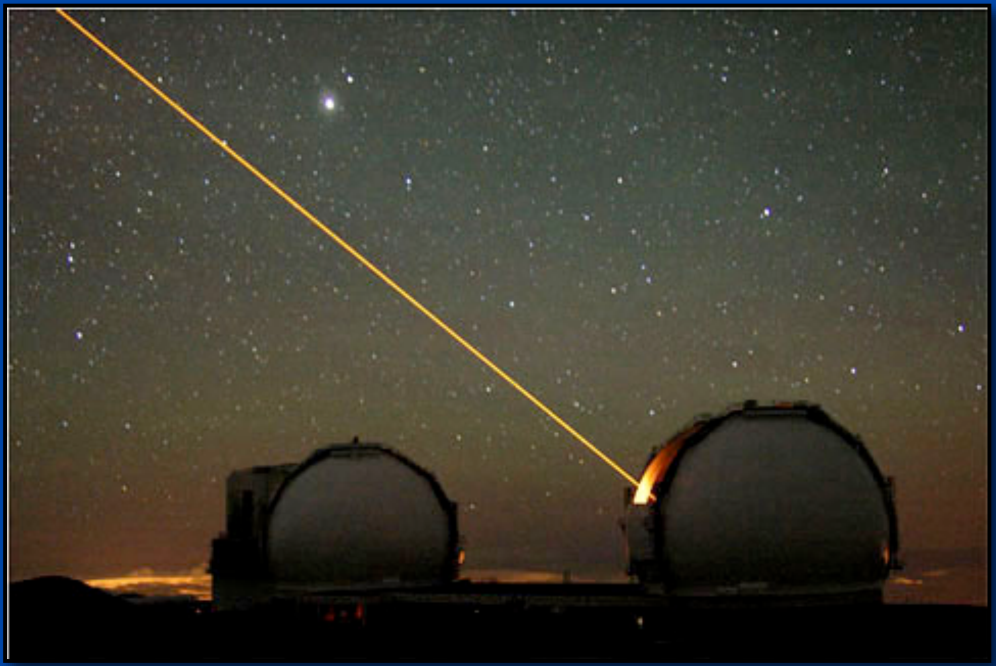
- Use a laser beam to create artificial "star" at altitude of 100 km in atmosphere



# *Laser guide stars are operating at Lick, Keck, Gemini North, VLT Observatories*

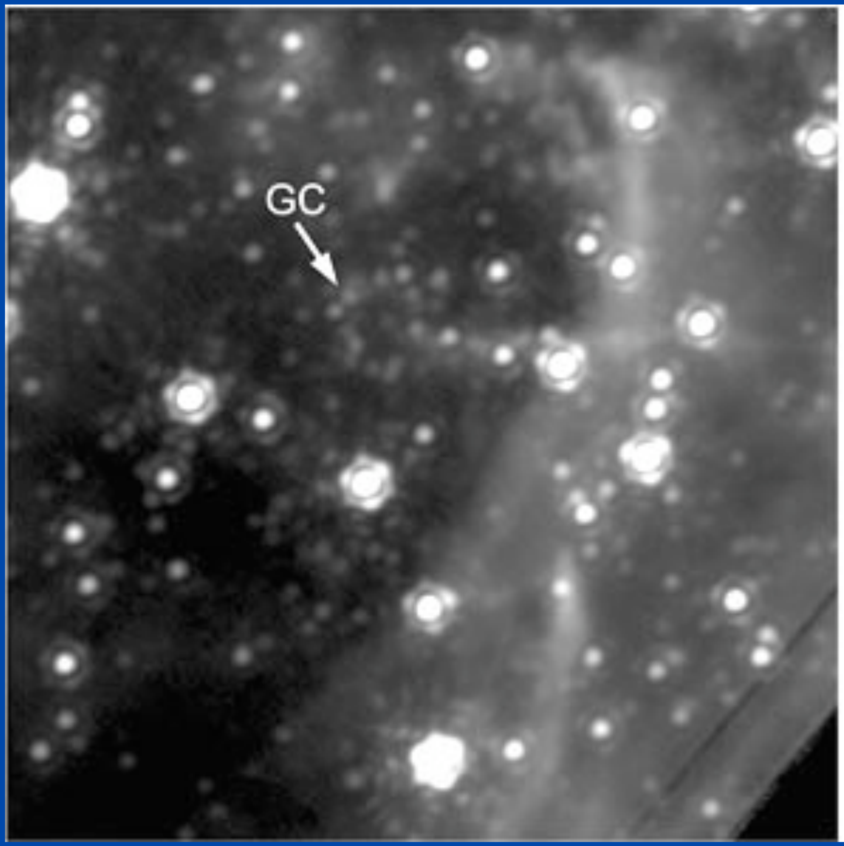
Lick Observatory

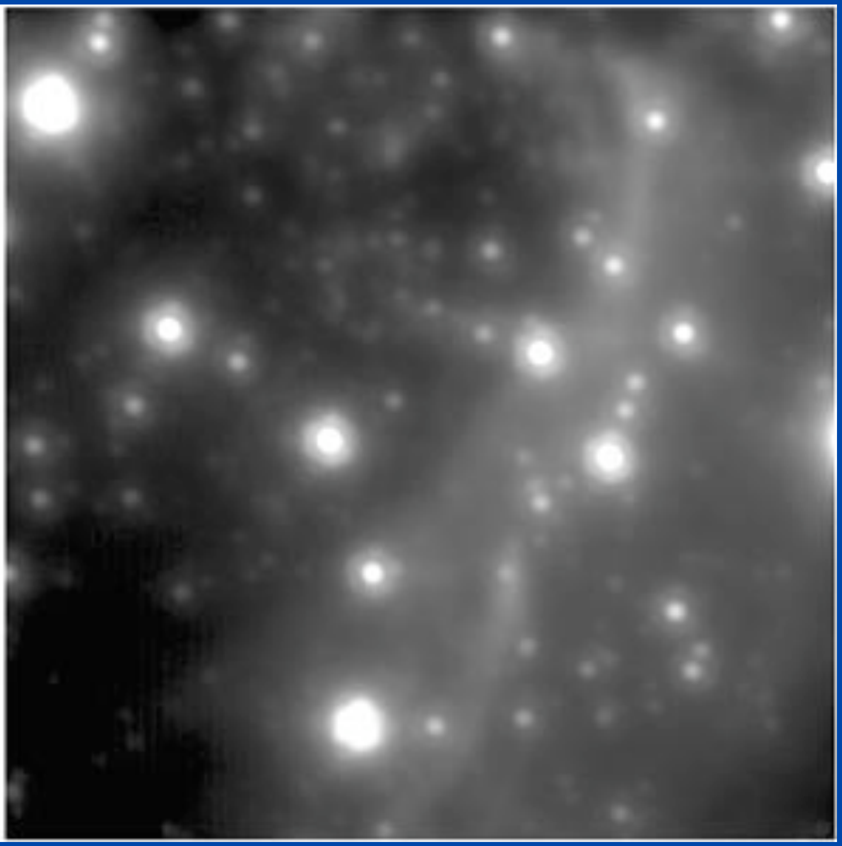
Keck Observatory



# Galactic Center with Keck laser guide star

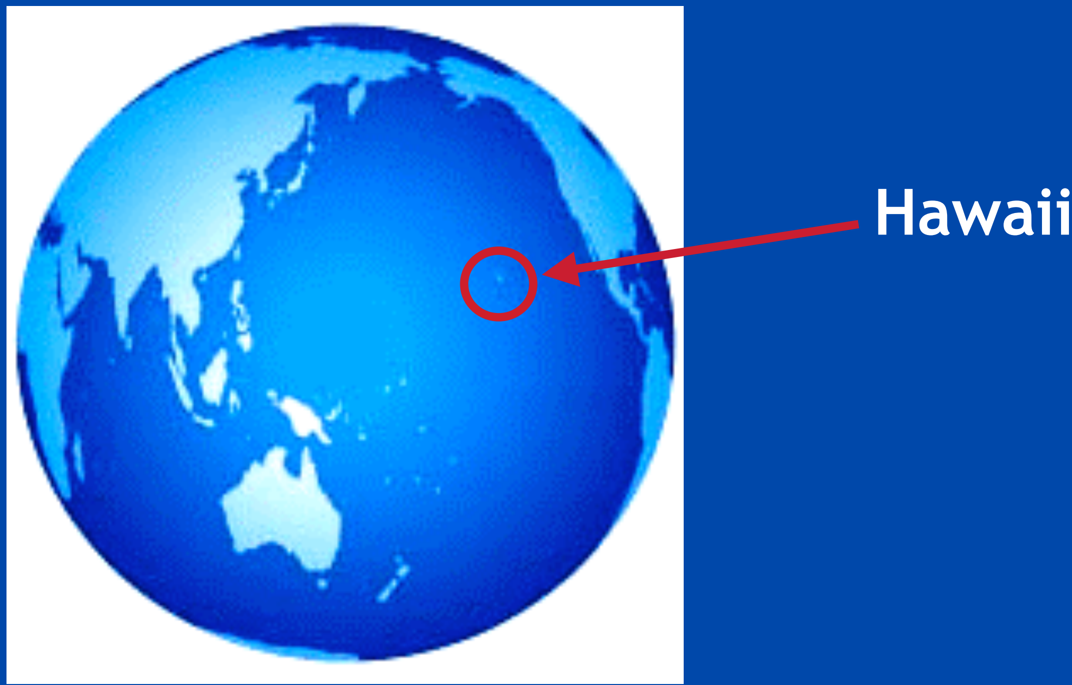
**Keck laser guide star AO** | **Best natural guide star AO**



# *Astronomical Adaptive Optics: World Tour*

# *Astronomical Adaptive Optics World Tour (2nd try)*



# *Summit of Mauna Kea volcano in Hawaii*

## *Astronomical observatories with AO on 6 - 10 m telescopes*

- Keck Observatory, Hawaii
  - 2 telescopes
- European Southern Observatory (Chile)
  - 4 telescopes
- Gemini North Telescope, Hawaii
- Subaru Telescope, Hawaii
- MMT Telescope, Arizona

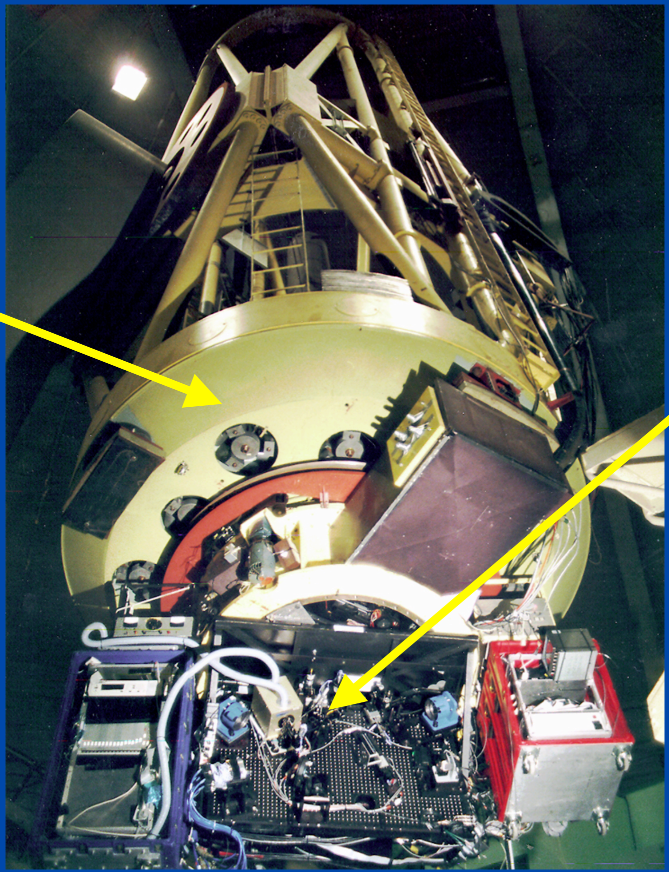
- Soon:
  - Gemini South Telescope, Chile
  - Large Binocular Telescope, Arizona

# *European Southern Observatory: four 8-m Telescopes in Chile*

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

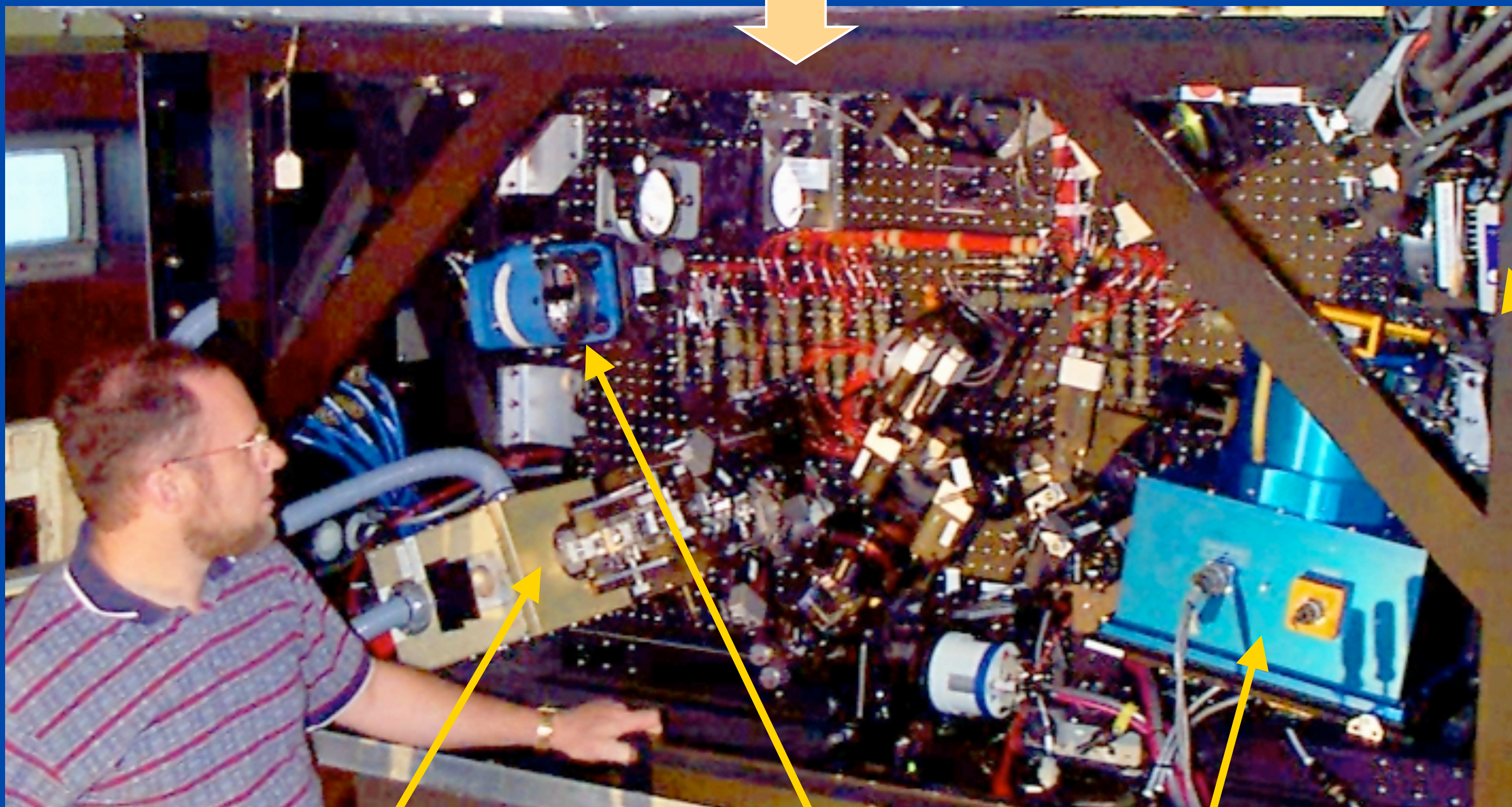
- Example: AO system at Lick Observatory's 3 m telescope

Support for main telescope mirror



Adaptive optics package below main mirror

# *Lick adaptive optics system at 3m Shane Telescope*



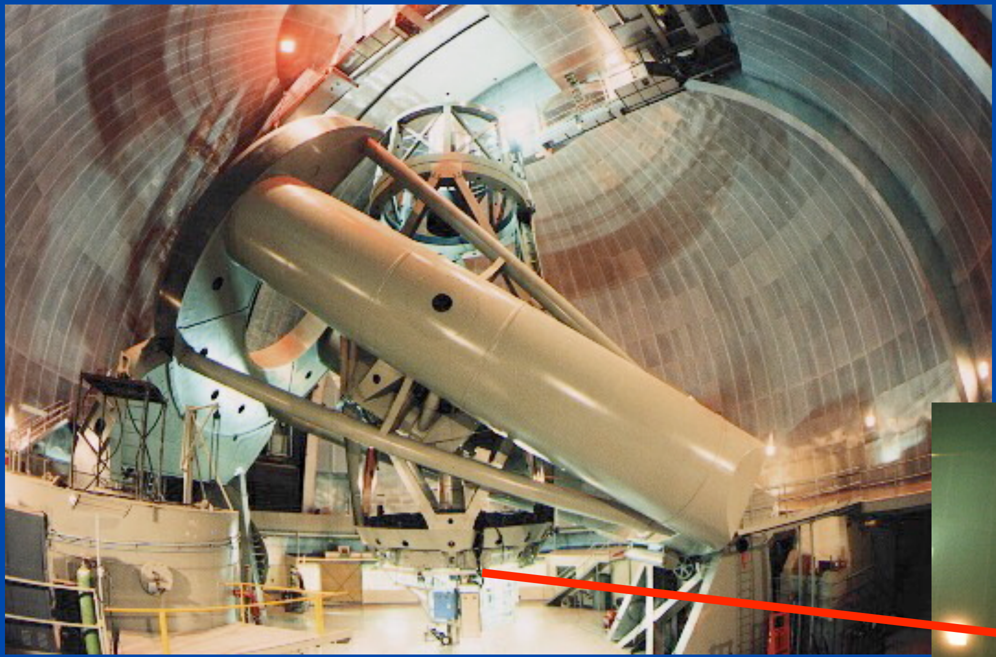
DM

Wavefront sensor

Off-axis parabola mirror

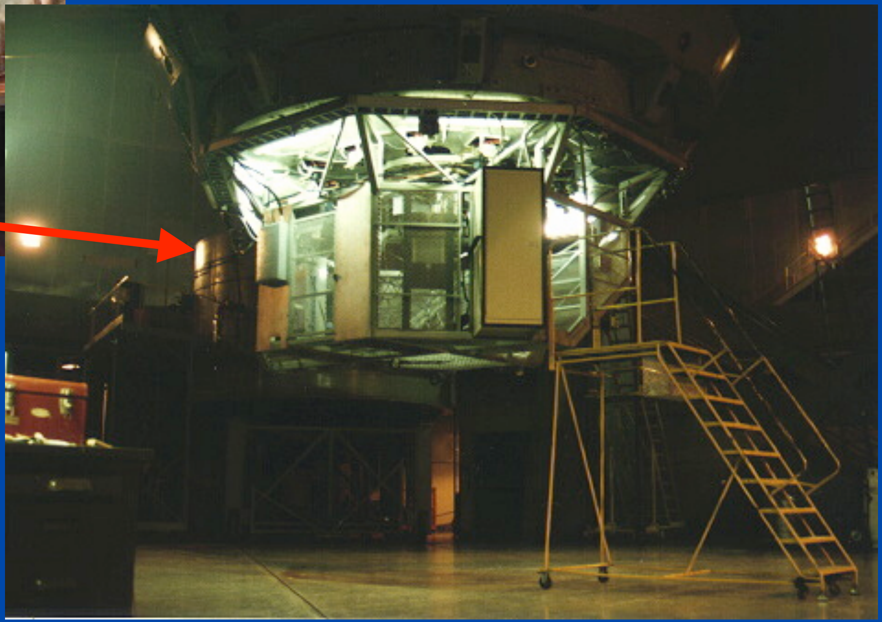
IRCAL infra-red camera

# *Palomar adaptive optics system*



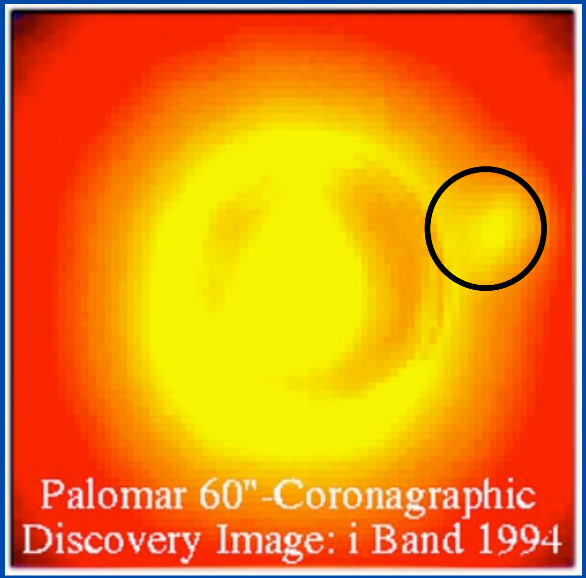
200” Hale telescope

AO system is in Cassegrain cage

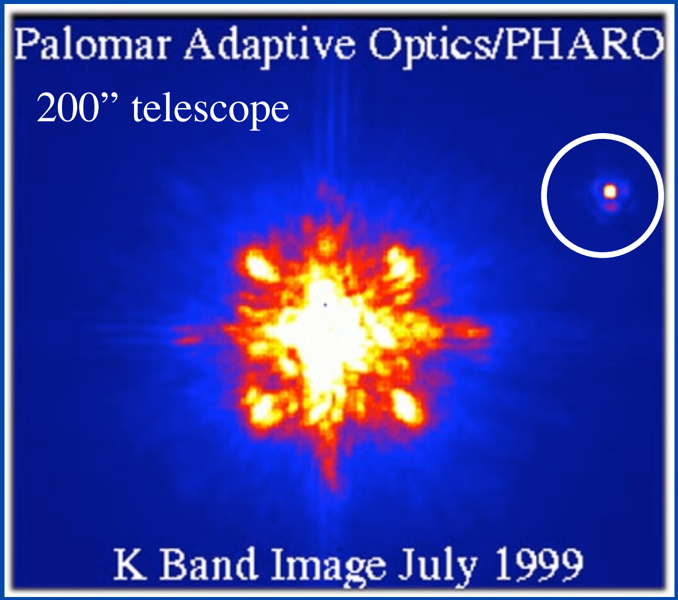


# *Adaptive optics makes it possible to find faint companions around bright stars*

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




**No AO**

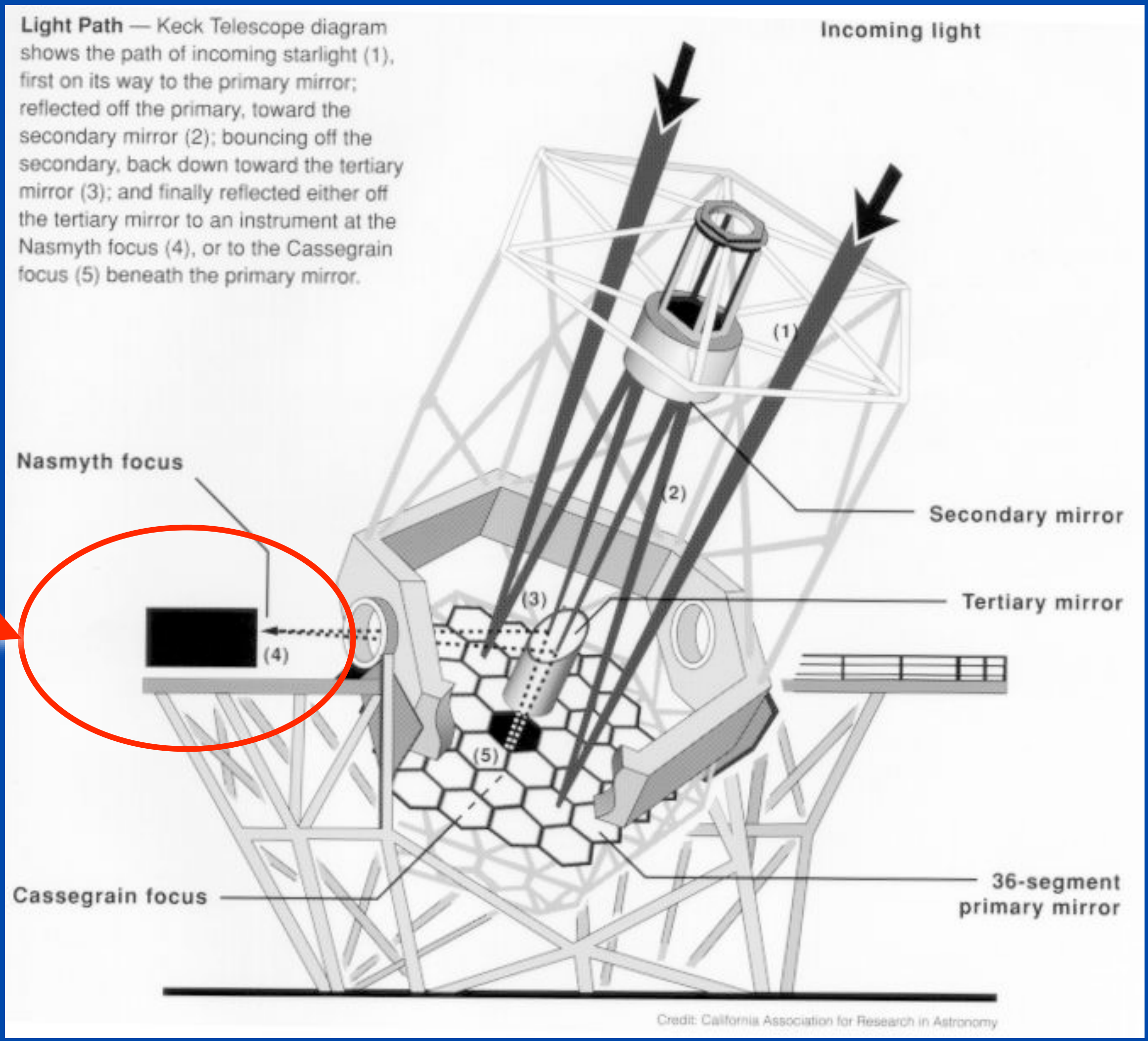



**With AO**

**Credit: David Golimowski**

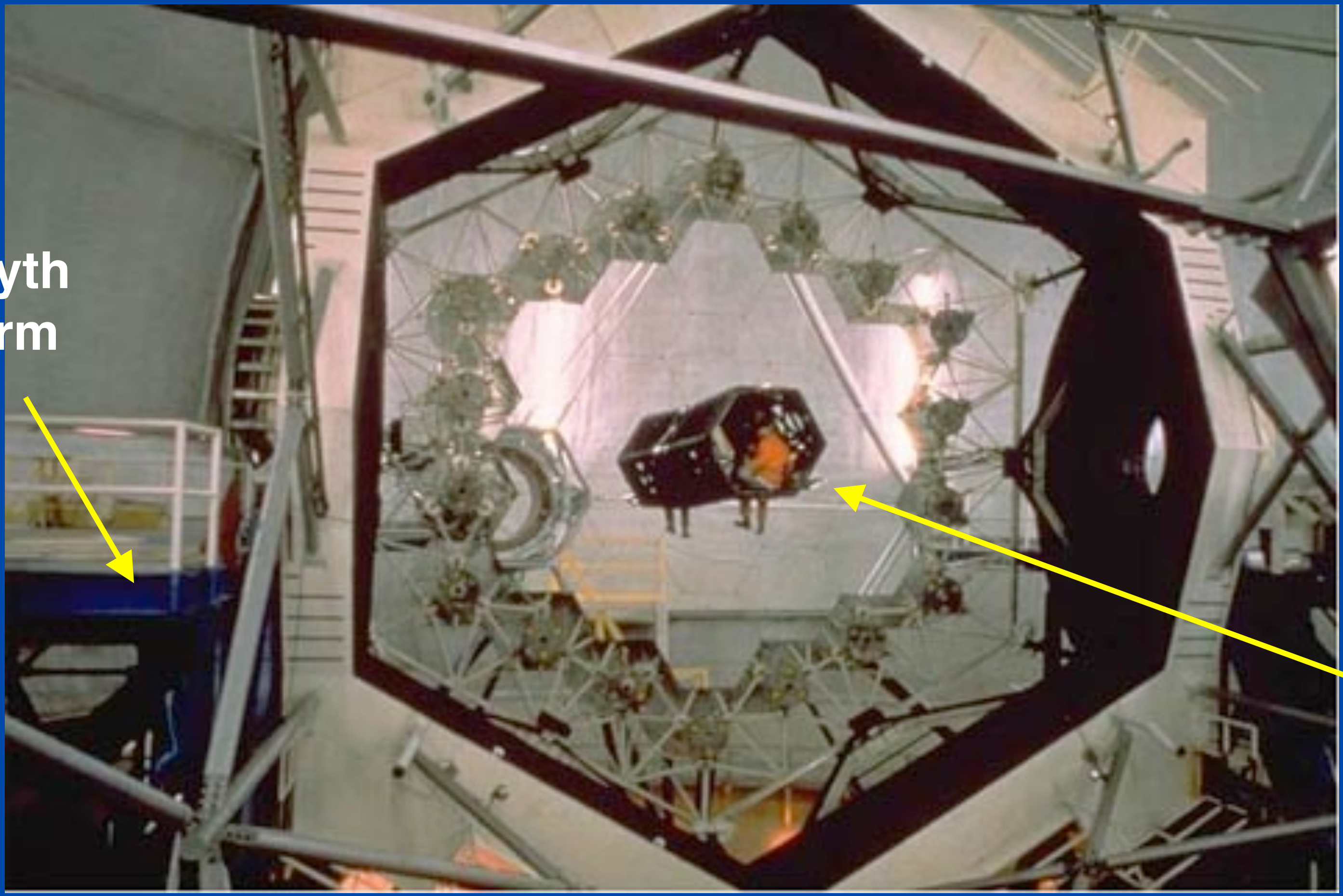
# The Keck Telescopes

Adaptive optics lives here



# *Keck Telescope's primary mirror consists of 36 hexagonal segments*

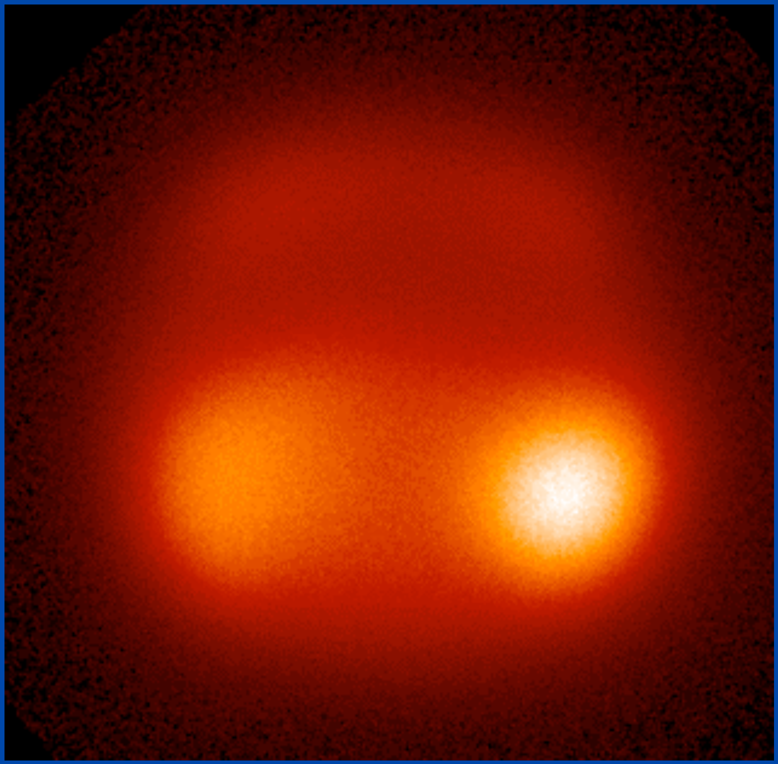
Nasmyth platform



Person!

# *Neptune in infra-red light (1.65 microns)*

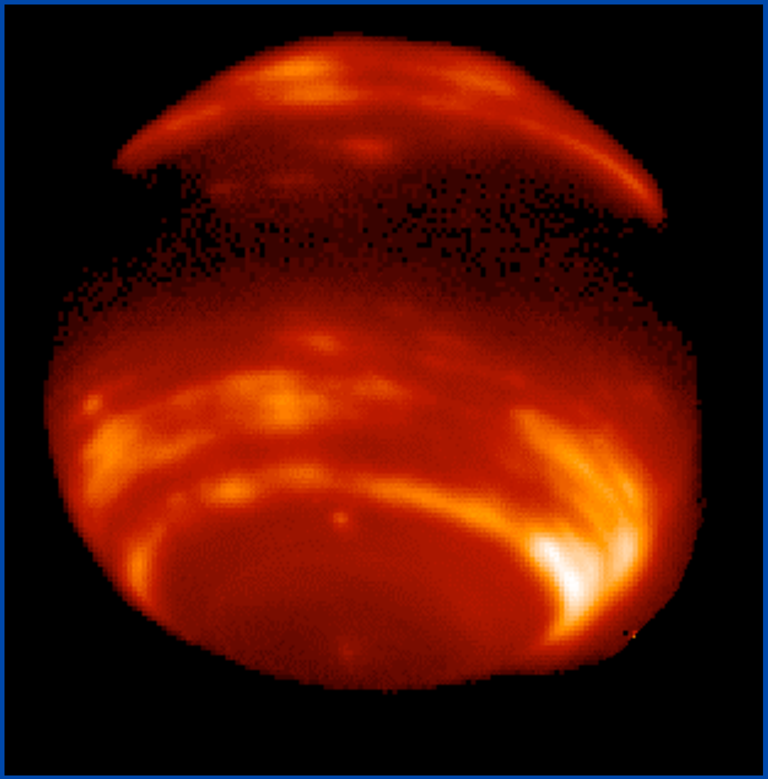
**Without adaptive optics**



**May 24, 1999**

2.3 arc sec

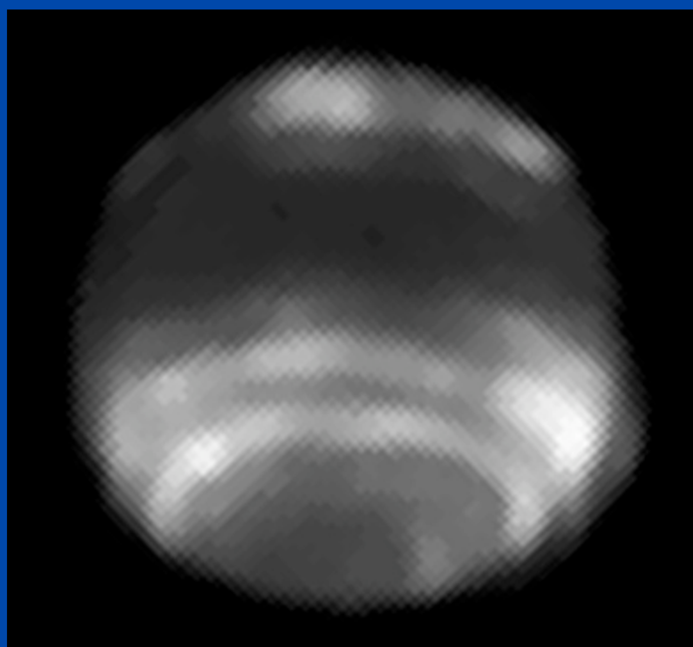
**With Keck adaptive optics**



**June 27, 1999**

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

**HST - NICMOS**



**2.4 meter telescope**

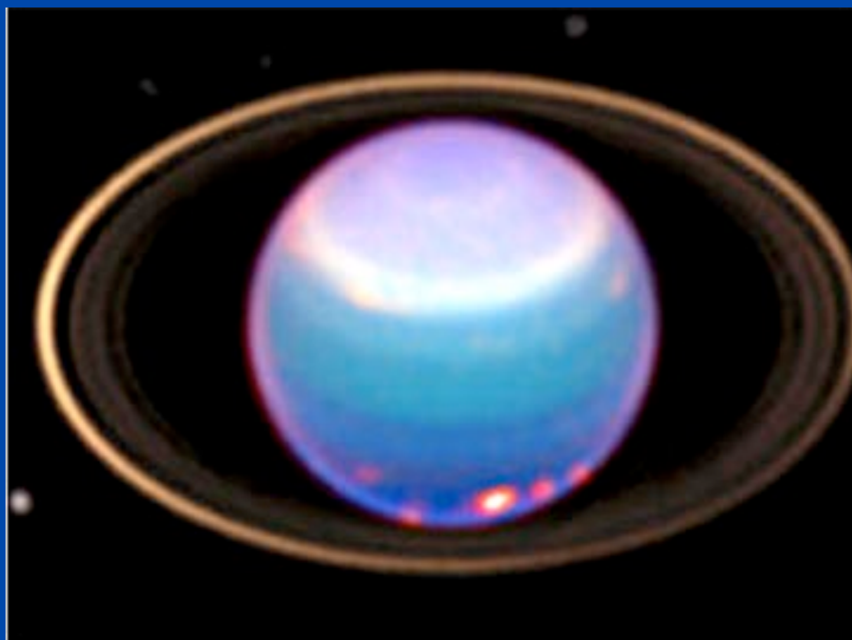
**Keck AO**

**10 meter telescope**

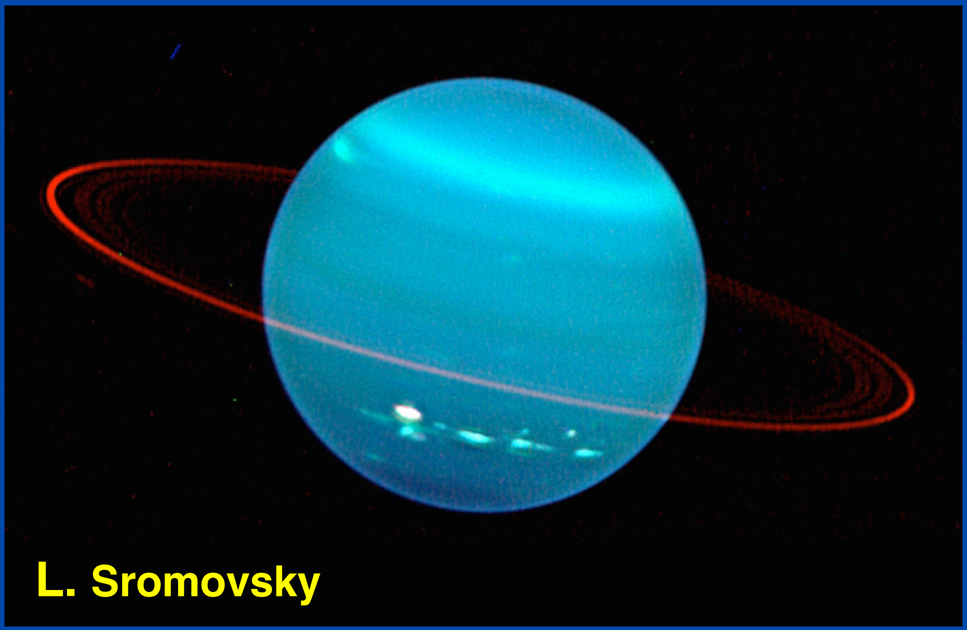
**~2 arc sec**

**(Two different dates and times)**

# Uranus with Hubble Space Telescope and Keck AO



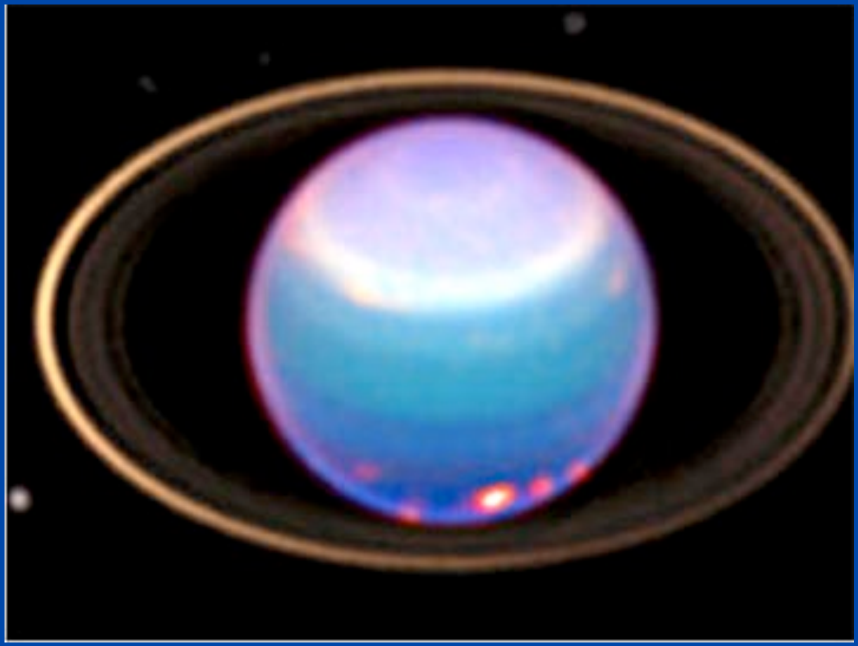
HST, Visible

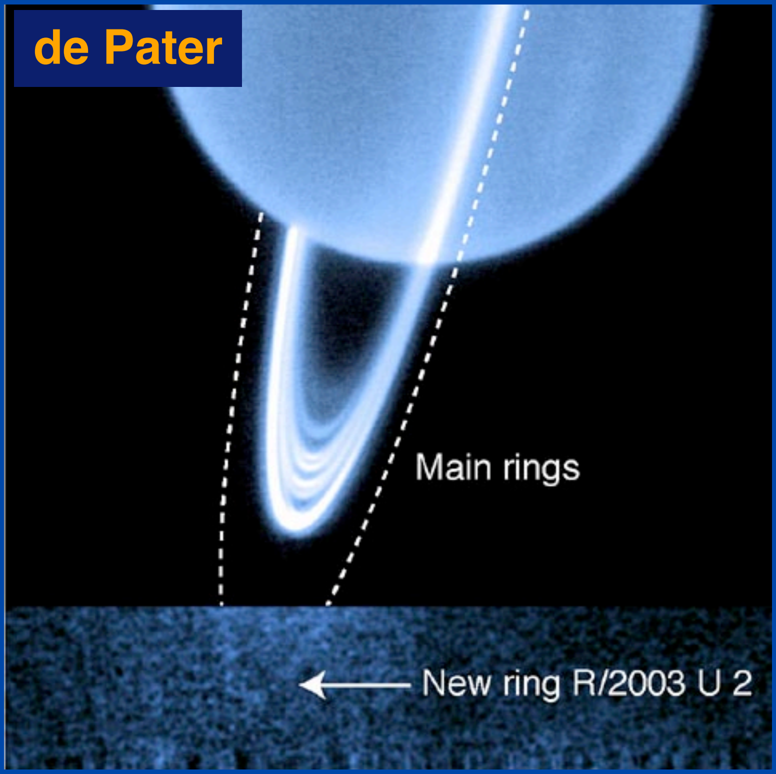



Keck AO, IR

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

# *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**

# *Some frontiers of astronomical adaptive optics*

- Current systems (natural and laser guide stars):
  - How can we measure the Point Spread Function while we observe?
  - How accurate can we make our photometry? astrometry?
  - What methods will allow us to do high-precision spectroscopy?
- Future systems:
  - Can we push new AO systems to achieve very high contrast ratios, to detect planets around nearby stars?
  - How can we achieve a wider AO field of view?
  - How can we do AO for visible light (replace Hubble on the ground)?
  - How can we do laser guide star AO on future 30-m telescopes?

# *Frontiers in AO technology*

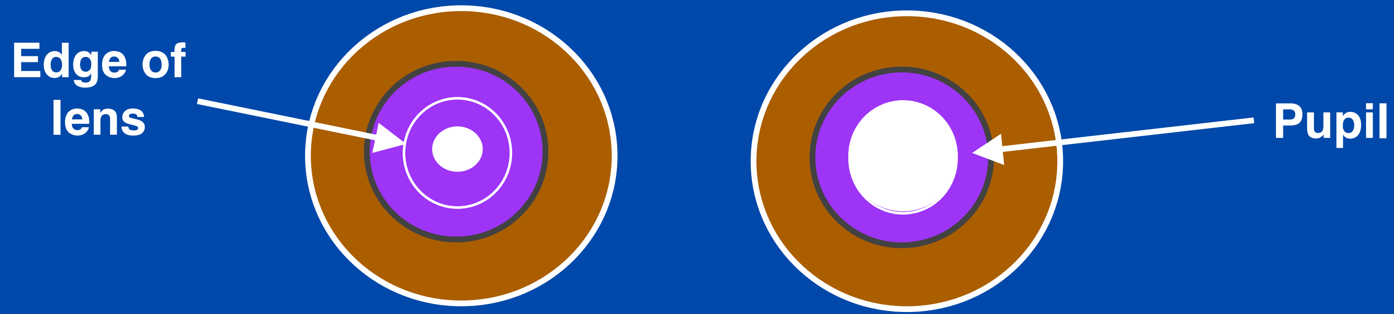
- New kinds of deformable mirrors with > 5000 degrees of freedom
- Wavefront sensors that can deal with this many degrees of freedom
- Innovative control algorithms
- "Tomographic wavefront reconstuction" using multiple laser guide stars
- New approaches to doing visible-light AO

# *Ground-based AO applications*

- Biology
  - Imaging the living human retina
  - Improving performance of microscopy (e.g. of cells)
- Free-space laser communications (thru air)
- Imaging and remote sensing (thru air)

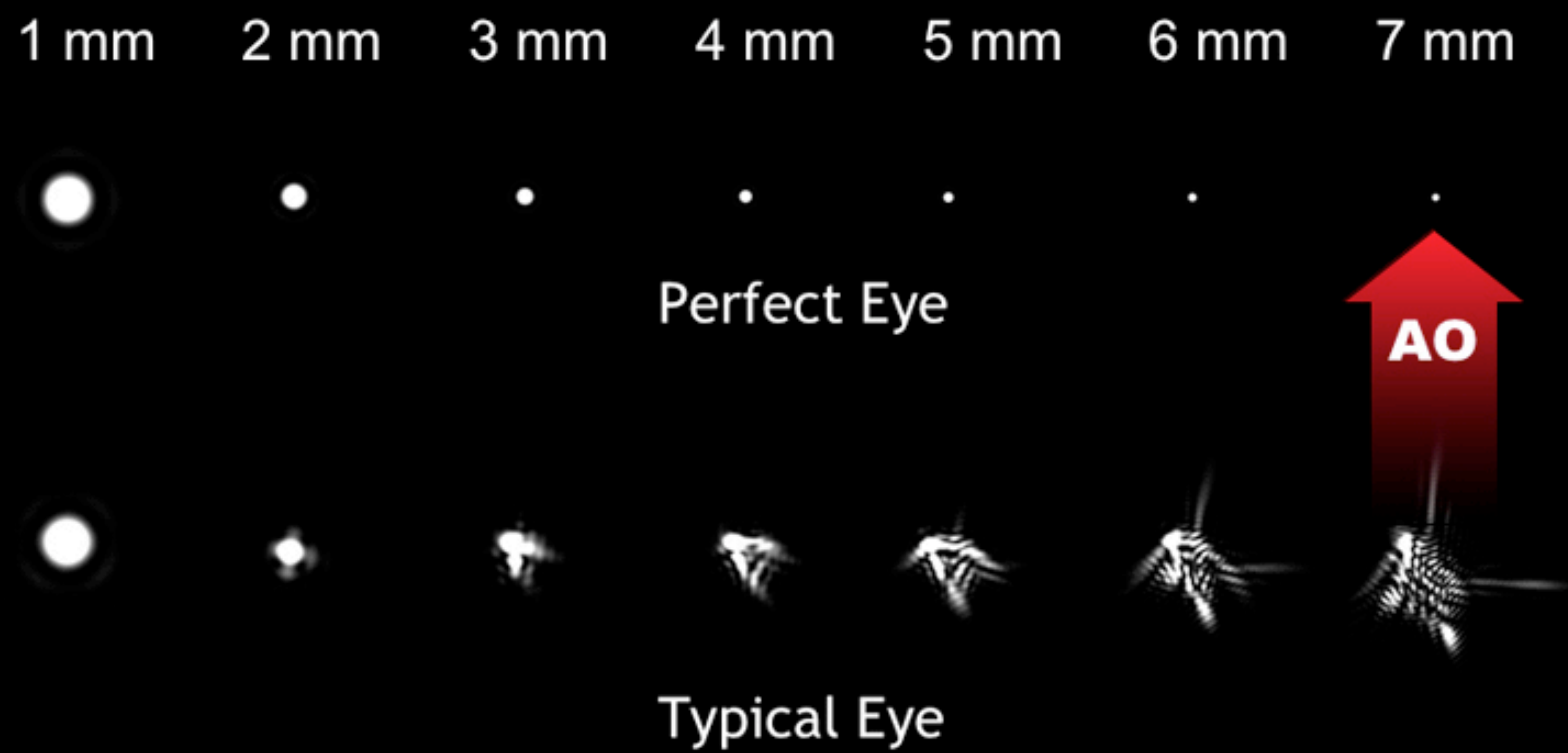
# *Why is adaptive optics needed for imaging the living human retina?*

- Around edges of lens and cornea, imperfections cause distortion
- In bright light, pupil is much smaller than size of lens, so distortions don't matter much
- But when pupil is large, incoming light passes through the distorted regions




- Results: Poorer night vision (flares, halos around streetlights). Can't image the retina very clearly (for medical applications)

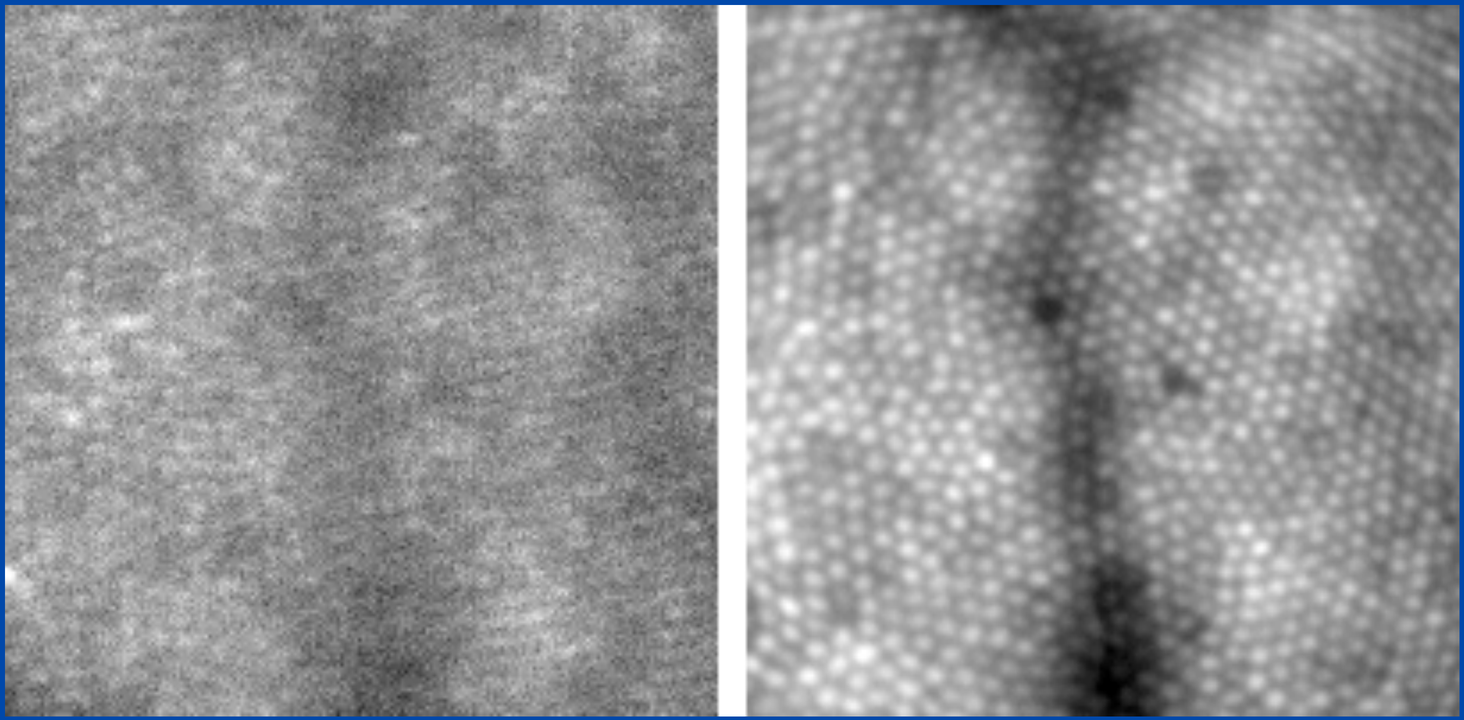
# Point Spread Function vs. Pupil Size




*C. of Austin Roorda*

# Adaptive optics provides highest resolution images of living human retina

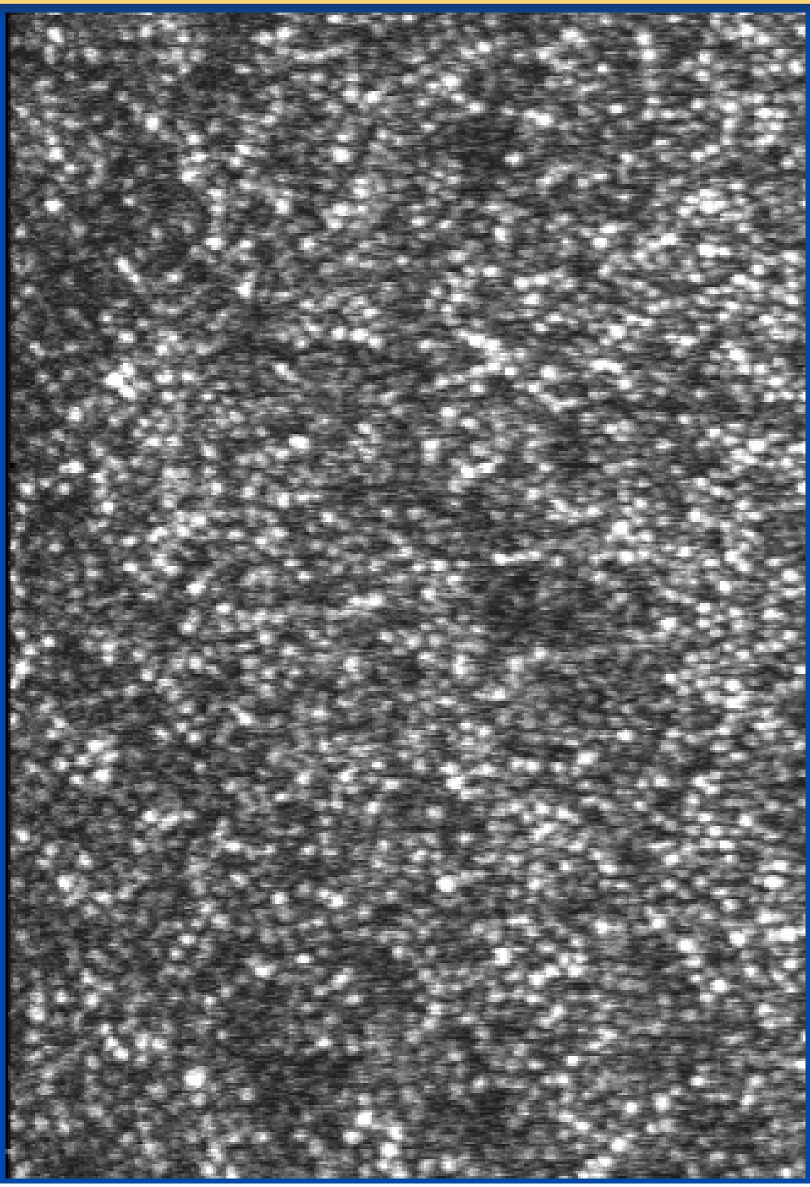
Austin Roorda, UC Berkeley



Without AO

With AO:
Resolve individual cones
(retina cells that detect color)

# *Watch individual blood cells flow through capillaries in the eye*



# *Horizontal path applications*

- Horizontal path thru air: $r_0$ is tiny!
  - 1 km propagation distance, typical daytime turbulence: $r_0$ can easily be only 1 or 2 cm
- So-called "strong turbulence" regime
  - Turbulence produces "scintillation" (intensity variations) in addition to phase variations
- Isoplanatic angle also very small
  - Angle over which turbulence correction is valid
  - $\vartheta_0 \sim r_0 / L \sim$ (1 cm / 1 km) ~ 2 arc seconds (10 μrad)

# *AO Applied to Free-Space Laser Communications*

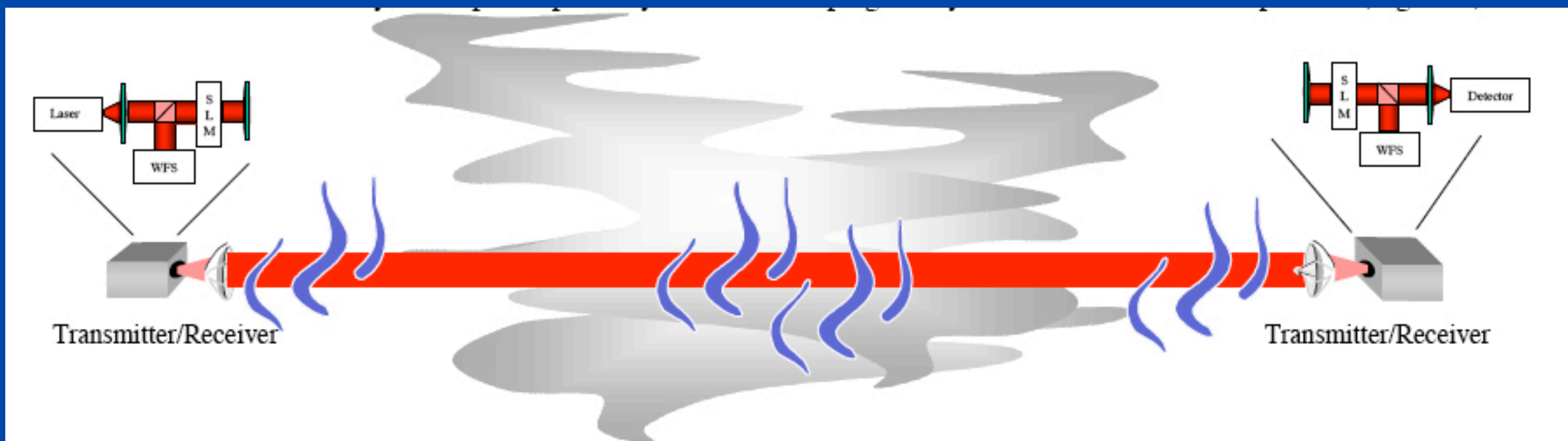



**Figure 1.** Stylized diagram of horizontal-path optical communications through a turbulent atmosphere.

- 10's to 100's of gigabits/sec
- Example: AOptix
- Applications: flexibility, mobility
  - HDTV broadcasting of sports events
  - Military tactical communications
    - Between ships, on land, land to air