Introduction to AO and the Center for Adaptive Optics

CfAO Summer School
August 5, 2006
Claire Max
CfAO Director

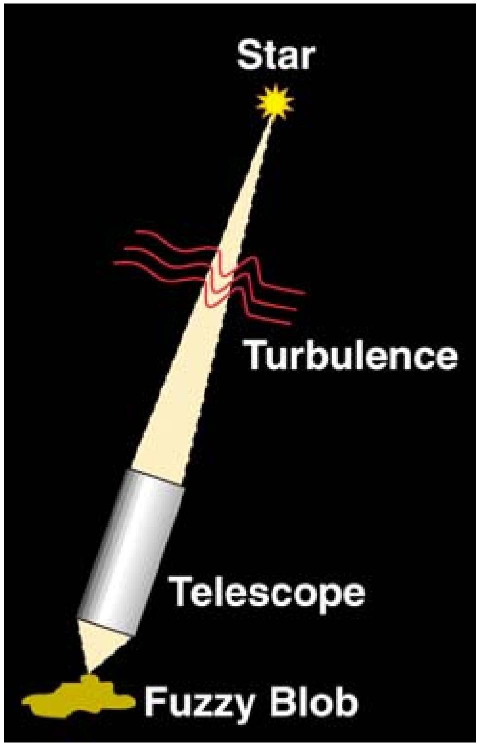
Outline

- Principles of Adaptive Optics
  - Basic ideas
  - Components of AO systems
  - AO for Astronomy and Vision Science (brief)
- The Center for Adaptive Optics
  - CfAO Organization and Mission
  - Thematic structure
  - Education activities

What is adaptive optics?

- A method of measuring and then removing distortions in optical systems
- Distortions due to:
  - Turbulence in the earth's atmosphere
    - Astronomy
    - Laser free-space communications
  - Biological structures and tissues
    - Vision science
    - Confocal microscopy of cells
  - Thermal distortions
    - Inside high-powered lasers
    - Space telescopes
  - Many others as well

Turbulence in the Earth's atmosphere limits the performance of astronomical telescopes

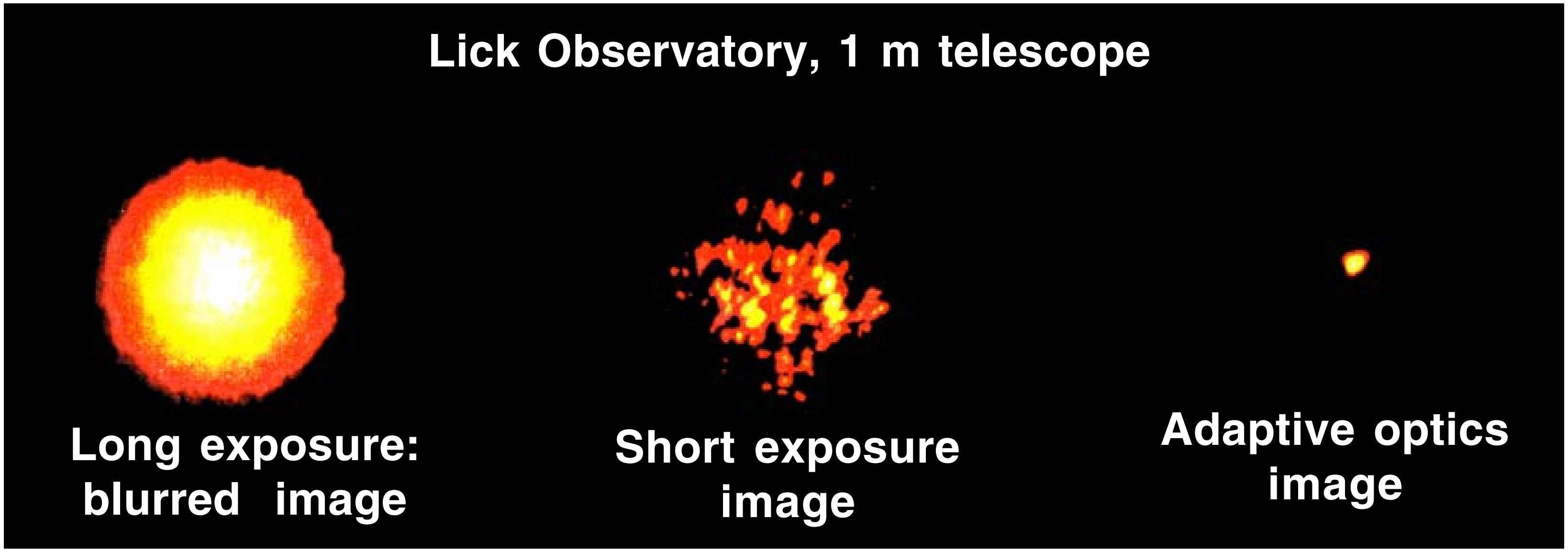


- Turbulence is the reason why stars twinkle
- More important for astronomy, turbulence spreads out the light from a star; makes it a fuzzy blob rather than a point

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

Adaptive optics gives big improvements

- **Three images of the bright star Arcturus**



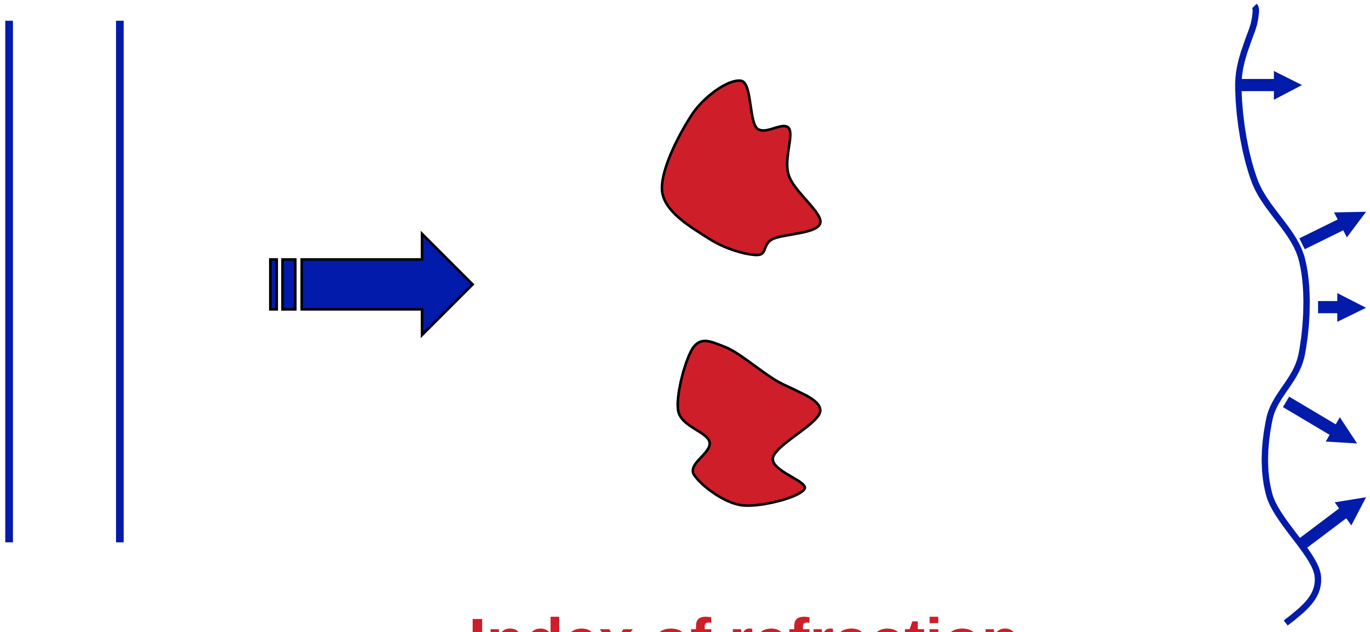
Lick Observatory, 1 m telescope

Long exposure:
blurred image

Short exposure
image

Adaptive optics
image

How do atmospheric perturbations cause distorted wavefronts?



Rays not parallel

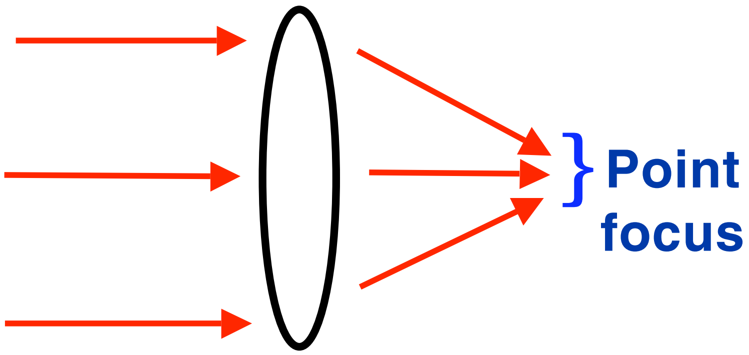
Plane Wave

Index of refraction variations

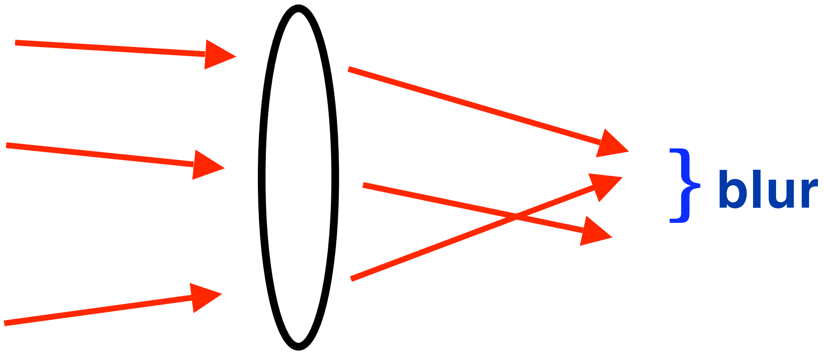
Distorted Wavefront

Optical consequences of turbulence: blurring

- Temperature fluctuations in small patches of air cause changes in index of refraction of the air (like many little lenses)
- Light rays are refracted many times (by small amounts each time).
- When they reach the telescope they are no longer exactly parallel with each other
- Hence rays can’t be focused to a point by a lens (or a mirror):

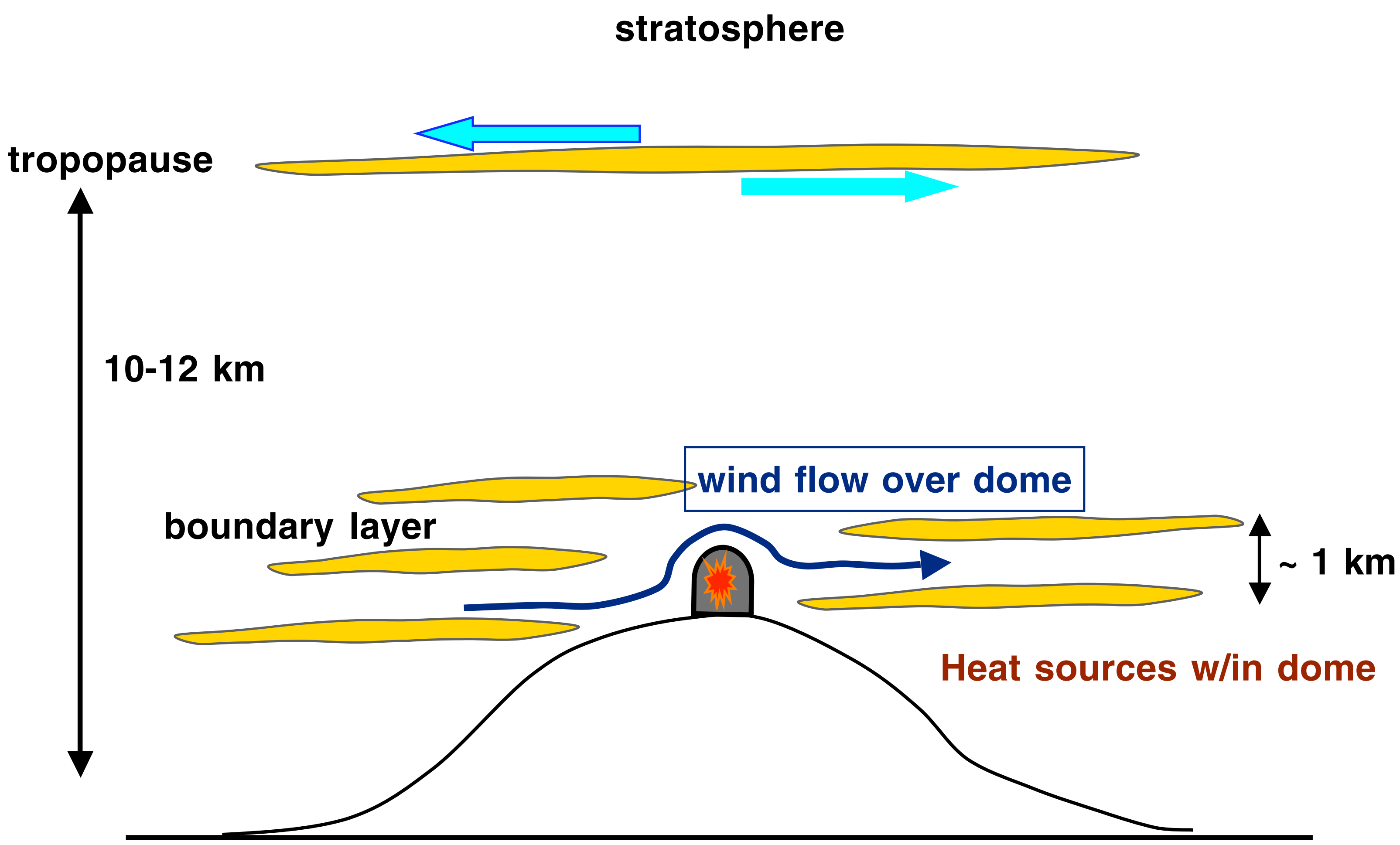


Parallel light rays

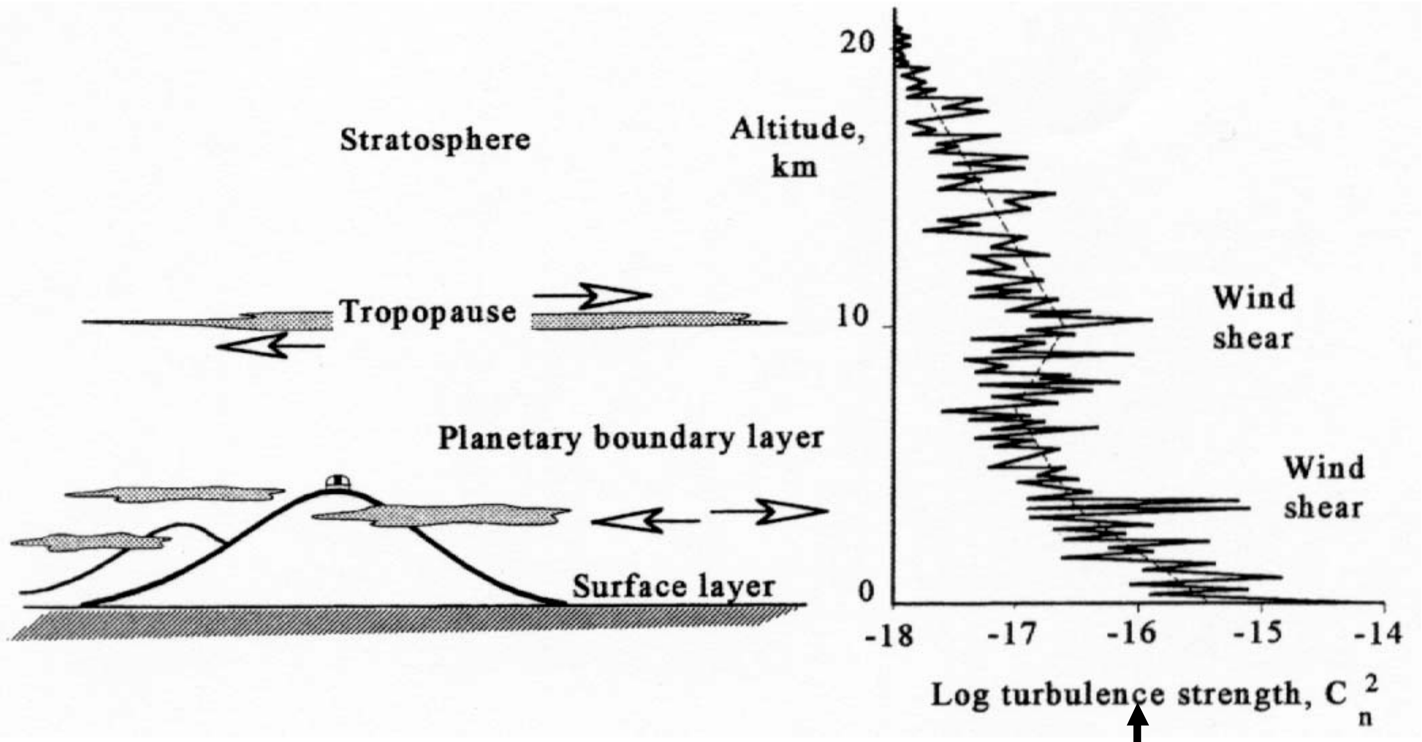


Light rays affected by turbulence

Atmospheric turbulence arises in several places

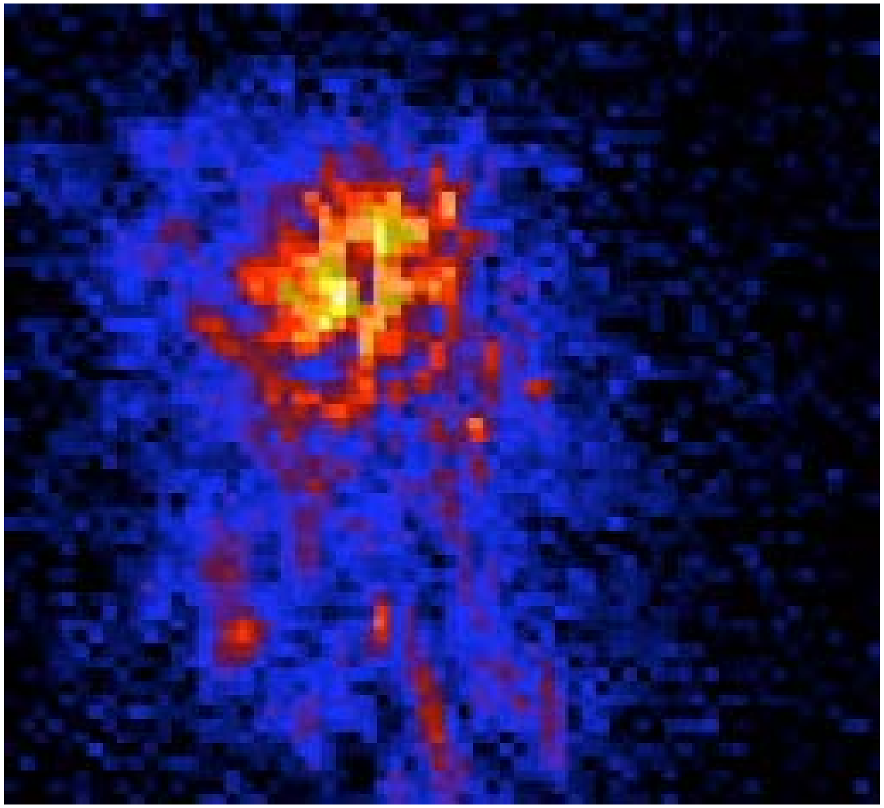


Vertical profile of turbulence



Measured from a balloon rising through various atmospheric layers

Movie of "real" turbulence (slowed down): what a star looks like without AO



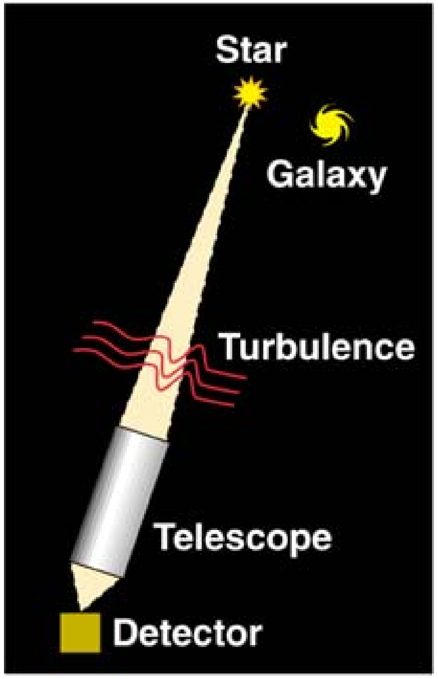
Credit: James Lloyd

Sequence of short snapshots of a star, taken at Lick Observatory using the IRCAL infra-red camera

Adaptive Optics can correct for atmospheric blurring

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

(a)

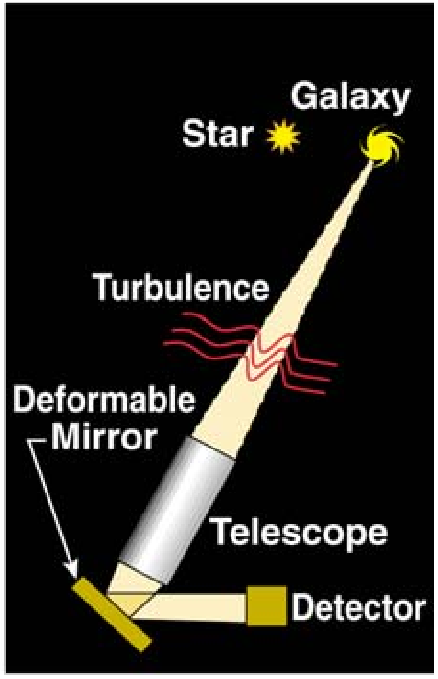


Calculate (on a computer) the shape to apply to deformable mirror to correct blurring

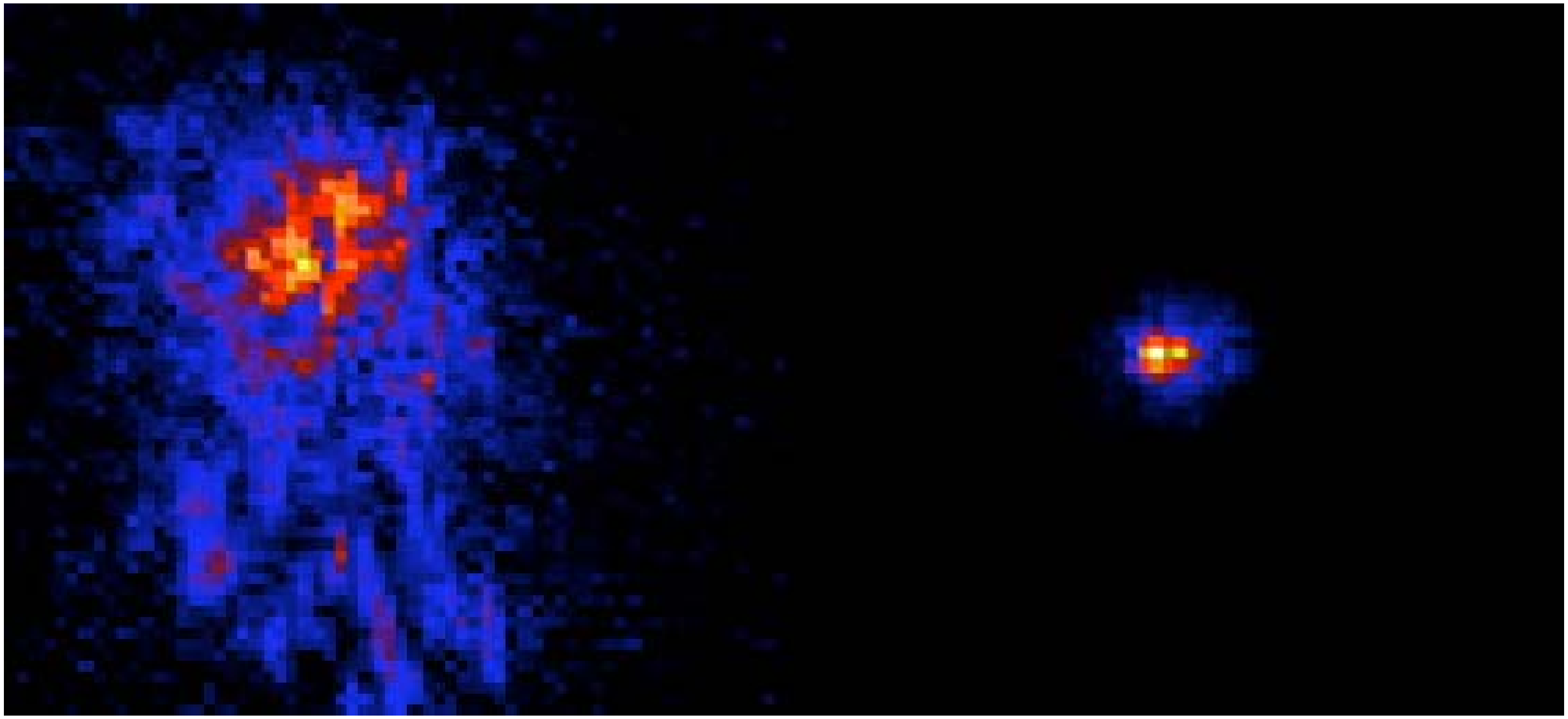
(b)

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

(c)



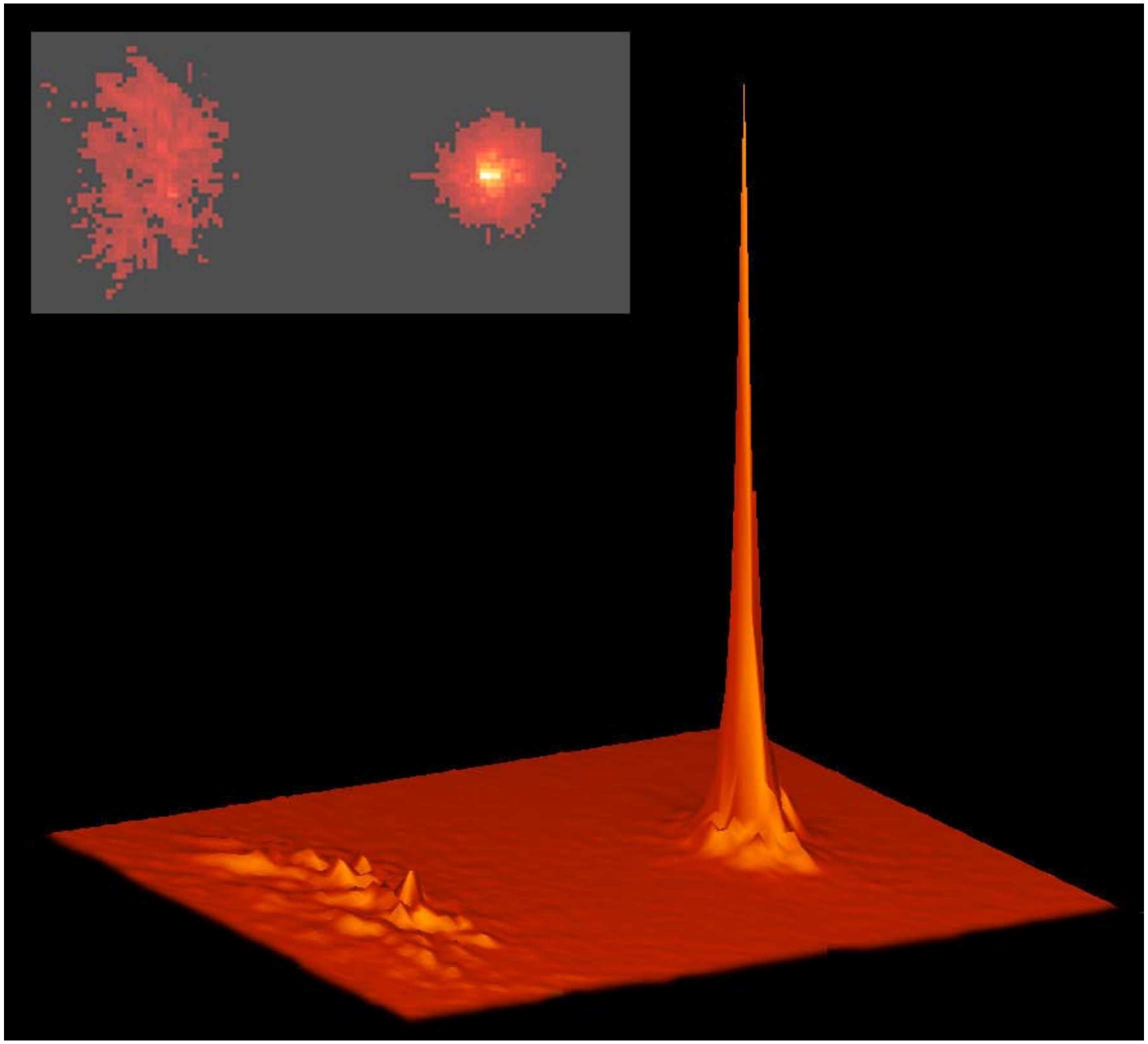
Movie of real turbulence: a star with and without adaptive optics



No adaptive optics **With adaptive optics**

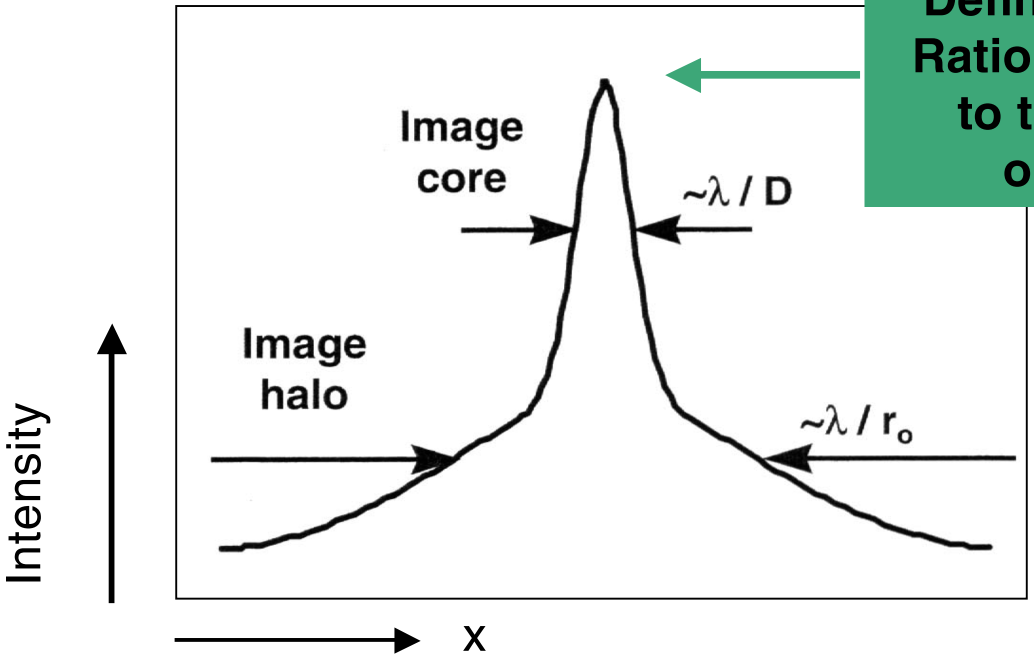
Credit: James Lloyd

Adaptive optics increases peak intensity of a point source



Credit:
James Lloyd

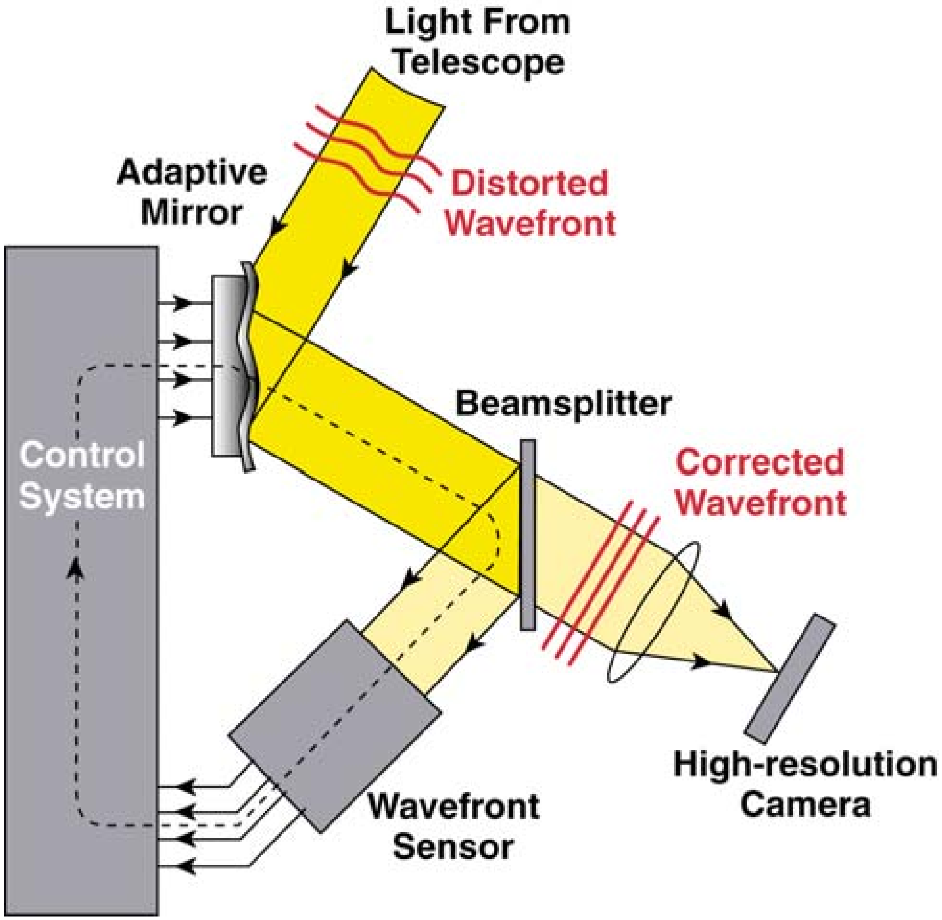
Astronomical AO produces point spread functions with a "core" and "halo"



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
- Ratio between core and halo varies during night

Optical schematic of adaptive optics system



How a Deformable Mirror Works

BEFORE

AFTER

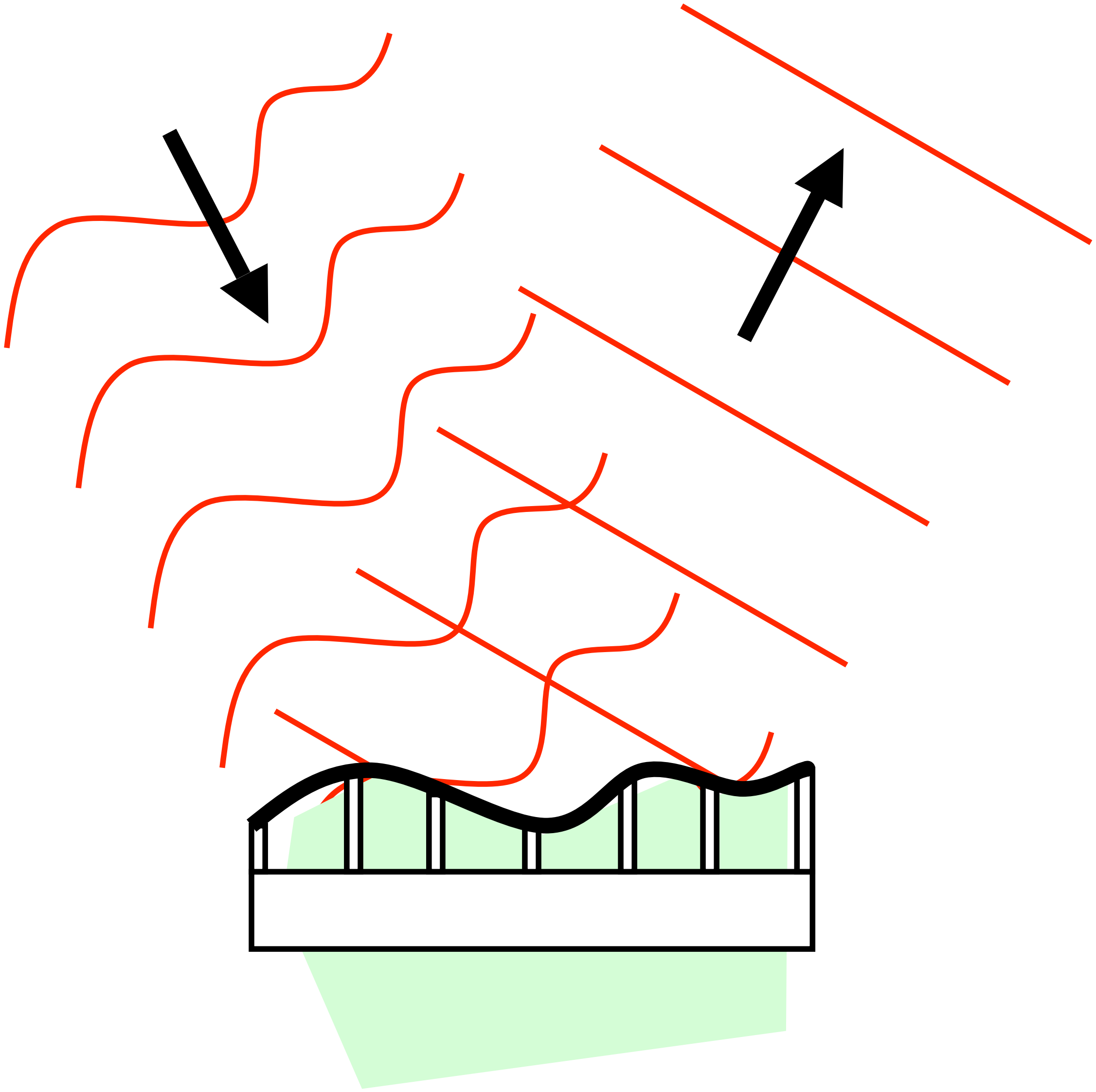
Incoming Wave with Aberration

Deformable Mirror

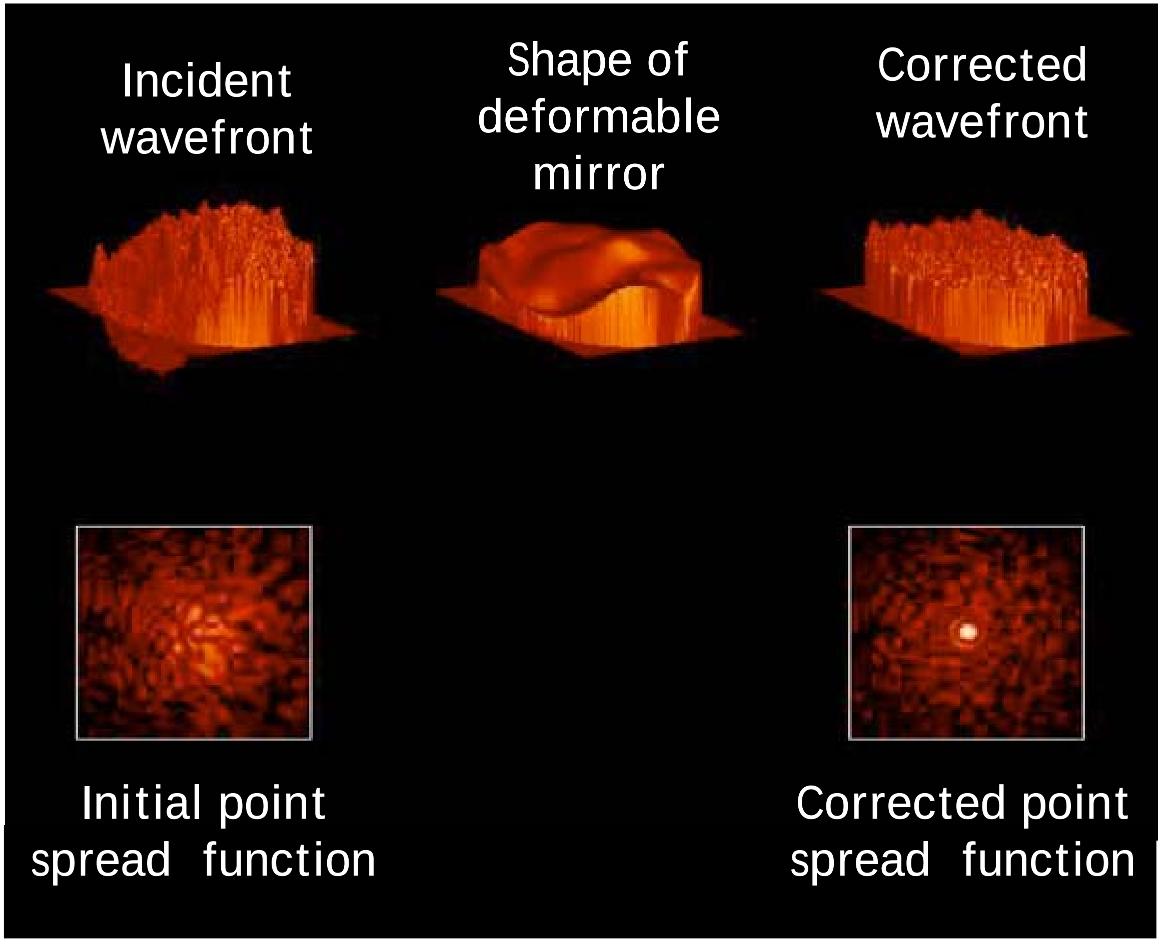
Corrected Wavefront

Deformable Mirror

A more realistic deformable mirror

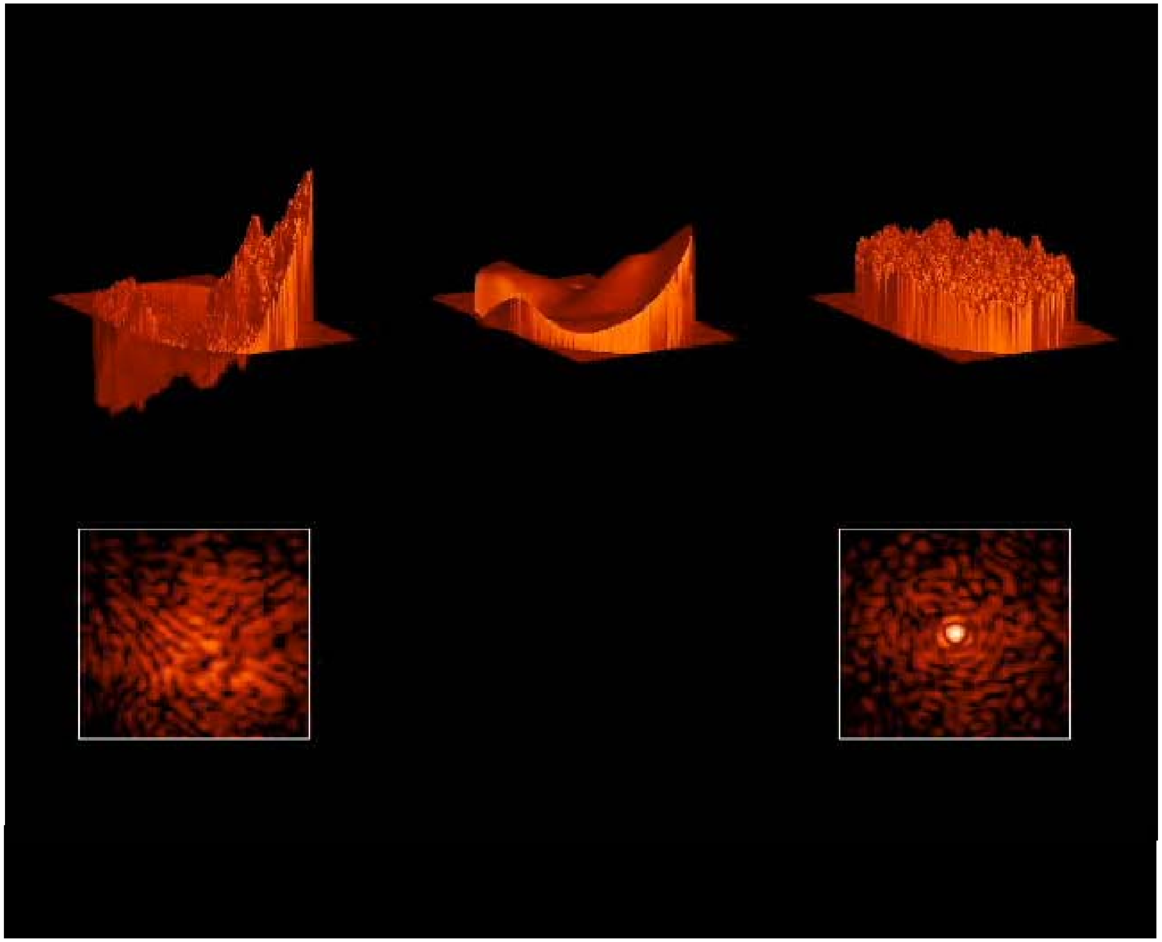


Simulation of a deformable mirror’s effects



Credit: James Lloyd, Cornell University

Simulation of a deformable mirror's effects

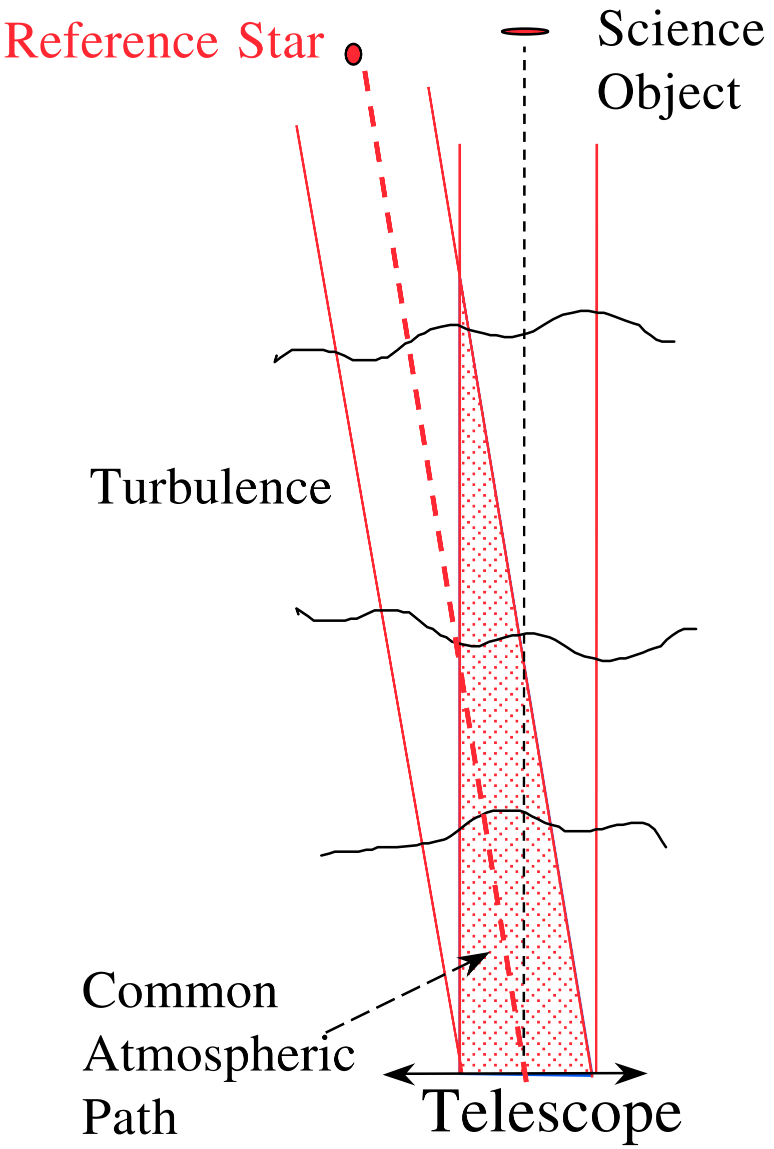


Credit: James Lloyd, Cornell University

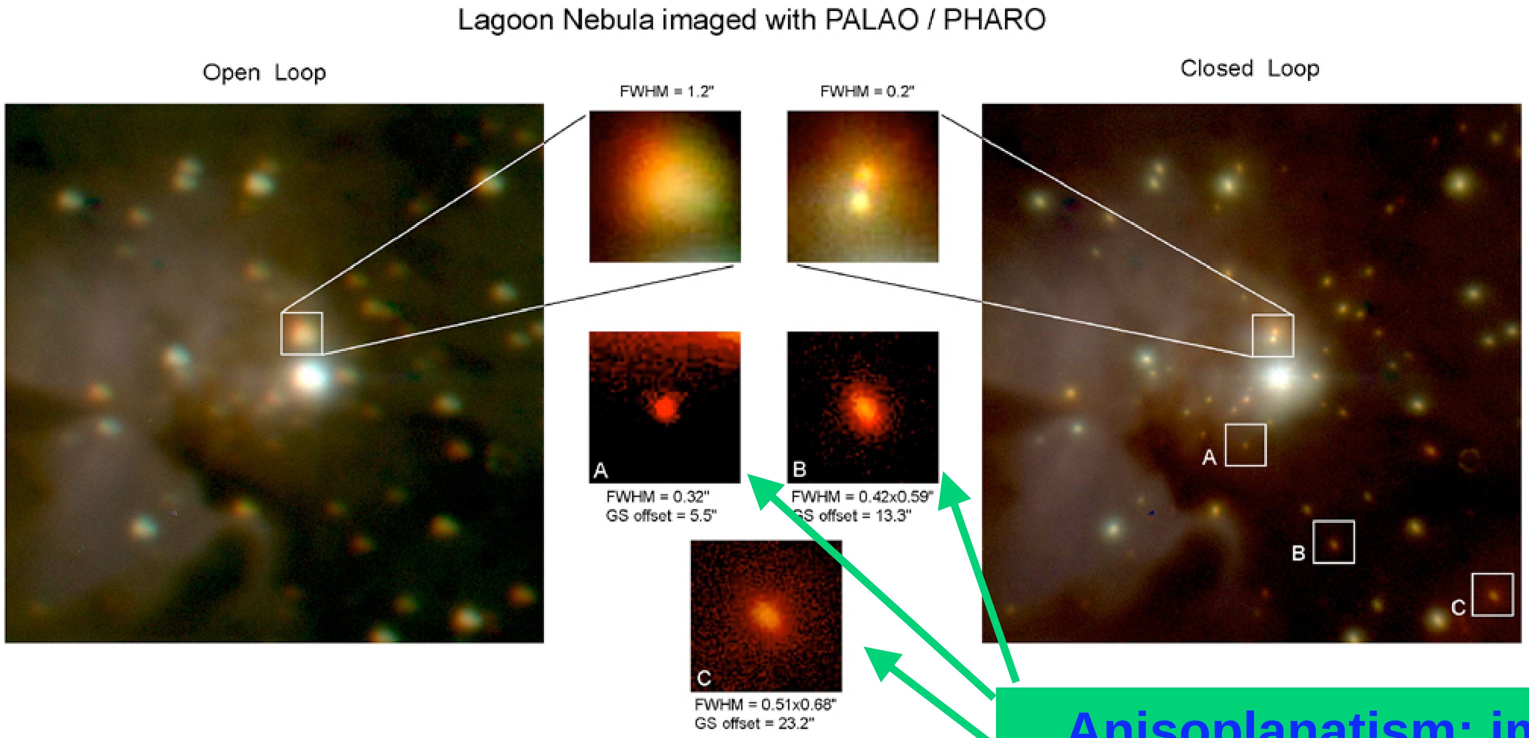
Effect of having reference star separated from science object

Anisoplanatism

sets a limit to the distance of the reference star from the science object



Palomar: anisoplanatism with AO


Lagoon Nebula imaged with PALAO / PHARO

Anisoplanatism: image quality deteriorates farther from guide star

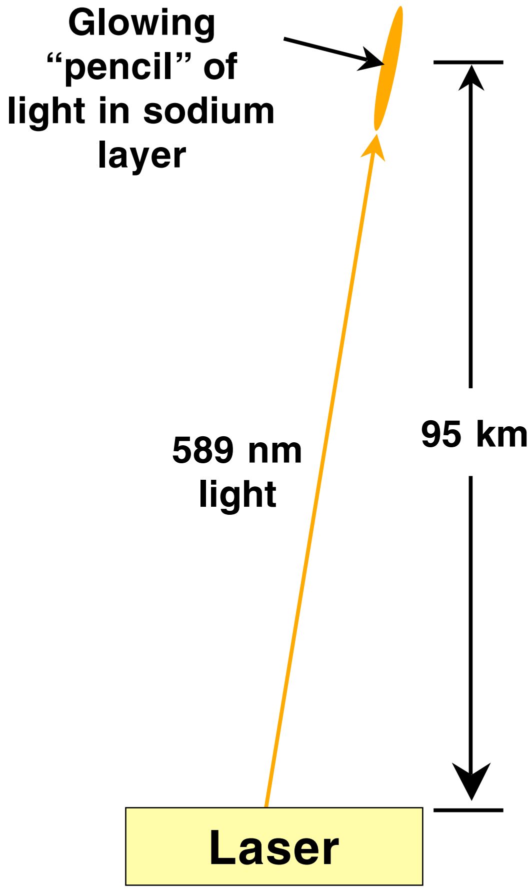
- Composite J, H, K band image
- Field of view 40"x40" (at 0.04 arc sec
- On-axis K-band Strehl ~ 40%, falls to 25% at corner

Sky coverage

- Because the field of view around a single bright star is limited, generally only a small portion of the sky can be viewed with AO
- Astronomy needs artificial beacons to increase sky coverage
- Laser beacons act as artificial stars, and can be pointed very near the science object of interest
- Na laser beacons are best (furthest away), due to fact that a layer of Na atoms exists 90 km above us

How to make a sodium-layer laser guide star

- Sodium layer: region of increased density of atomic sodium at altitude of 95 to 105 km in earth's atmosphere
- Excite resonance line of sodium (D_2 line) by shining 589 nm light onto sodium layer
- Makes a "pencil" of yellow light
- If you look at it from the bottom, it is small and round



Laser guide stars at Gemini and Keck Observatories, Mauna Kea HI

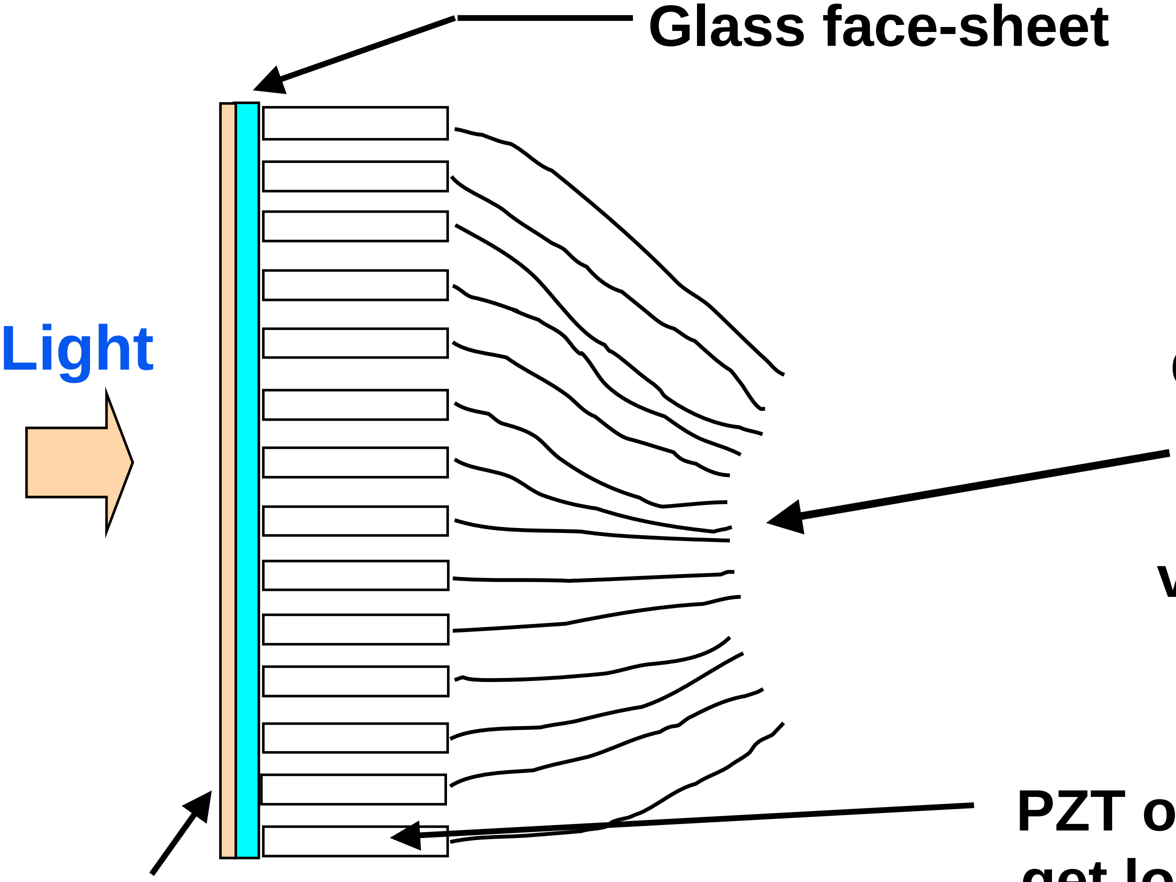
Keck Observatory

Gemini Observatory

Components of AO systems

- Deformable mirrors
- Wavefront sensors
- Science instruments

Most deformable mirrors until now have had thin glass face-sheets



Glass face-sheet

Light

Cables leading to mirror’s power supply (where voltage is applied)

PZT or PMN actuators: get longer and shorter as voltage is changed

Anti-reflection coating

Deformable mirrors come in many sizes

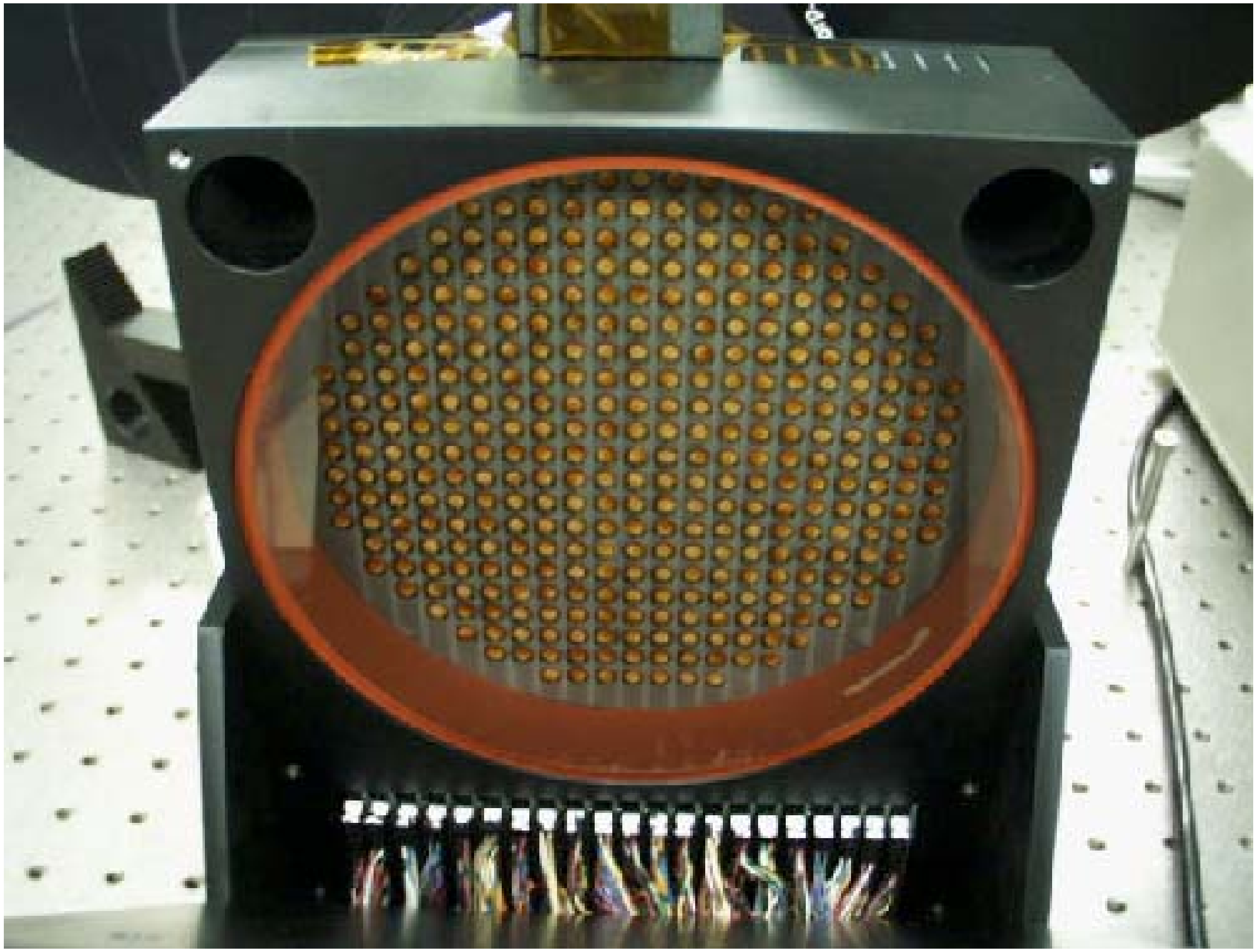
- Range from 13 to > 900 actuators (degrees of freedom)

About 12”

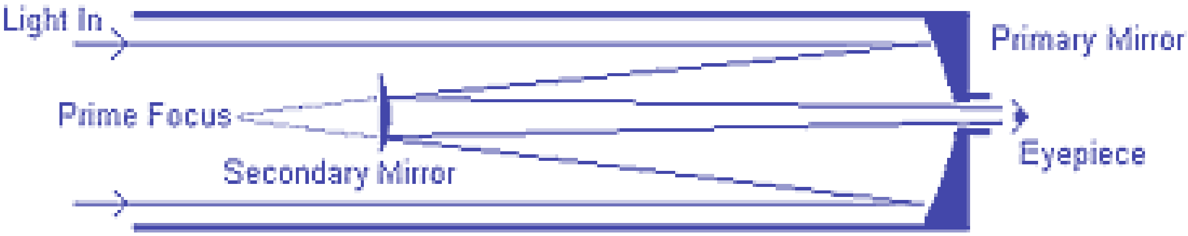
A couple of inches

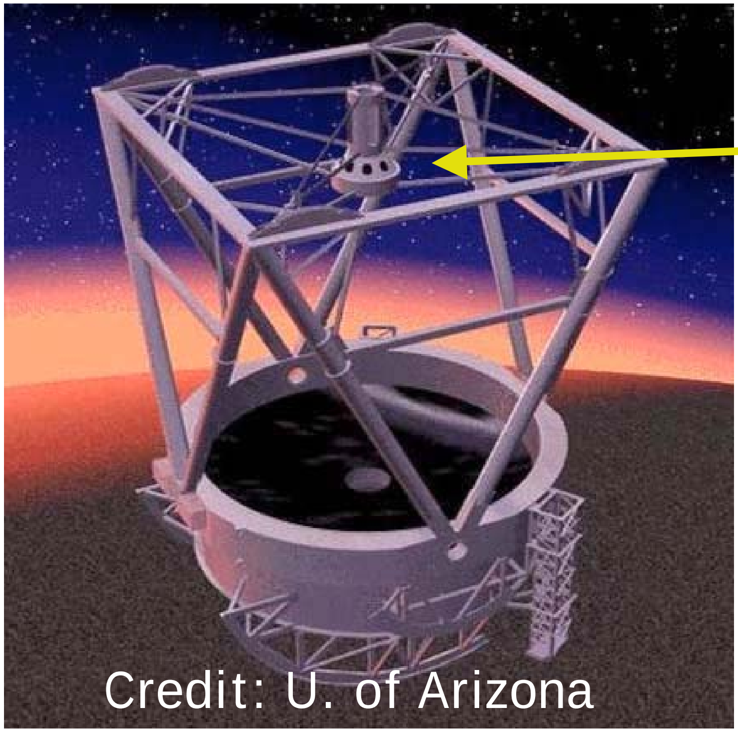
Credit: Xinetics

Rear view of Xinetics 349 actuator DM used in Keck Telescope AO system



Adaptive secondary mirrors for telescopes




Credit: U. of Arizona

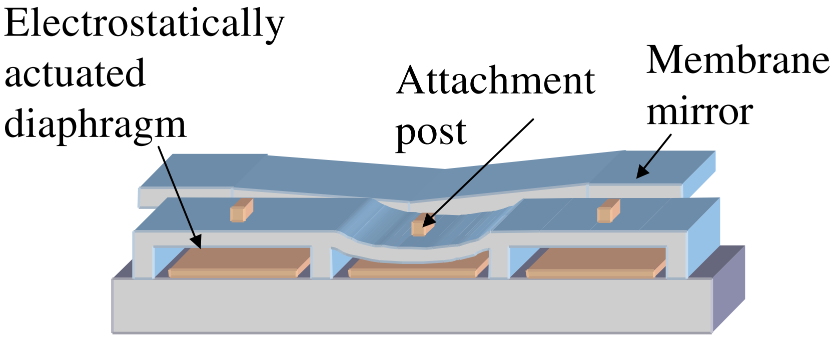
Adaptive secondary deformable mirror lives here

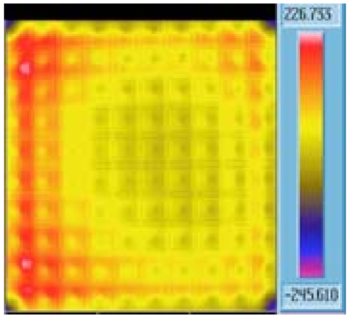
Adaptive Secondary Mirrors: MMT

- U. Arizona + Arcetri Observatory (Italy)
- 336 actuators, 642 mm diameter, 2mm facesheet

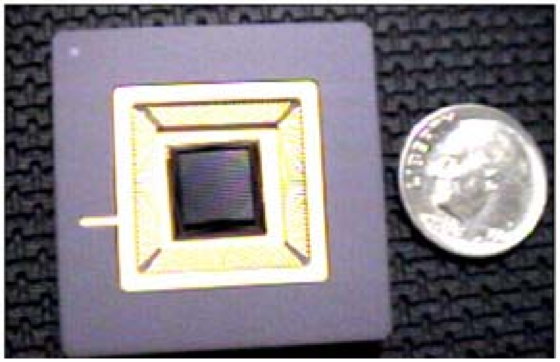
MEMS (micro-electro-mechanical systems) deformable mirrors

- Potential for lower cost per degree of freedom
- Ideal for compact systems such as vision science AO





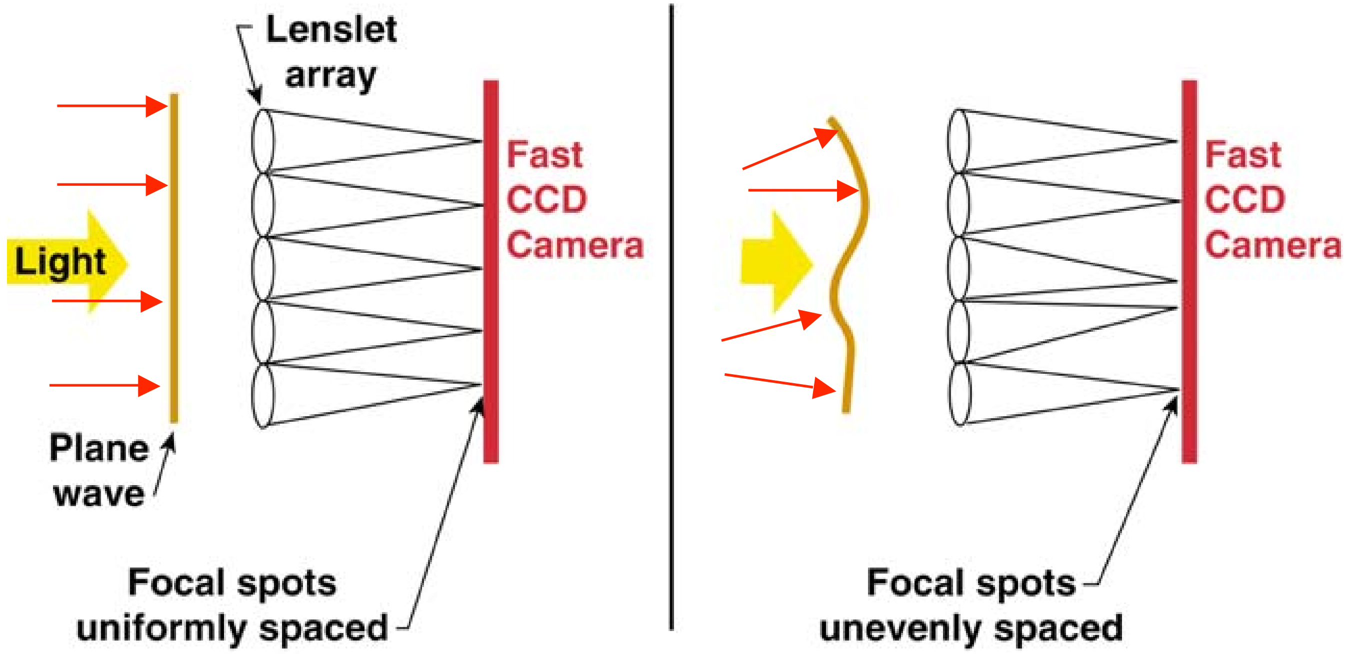
Mirror surface map



Boston Micromachines

Wavefront sensing:
How to measure turbulent distortions

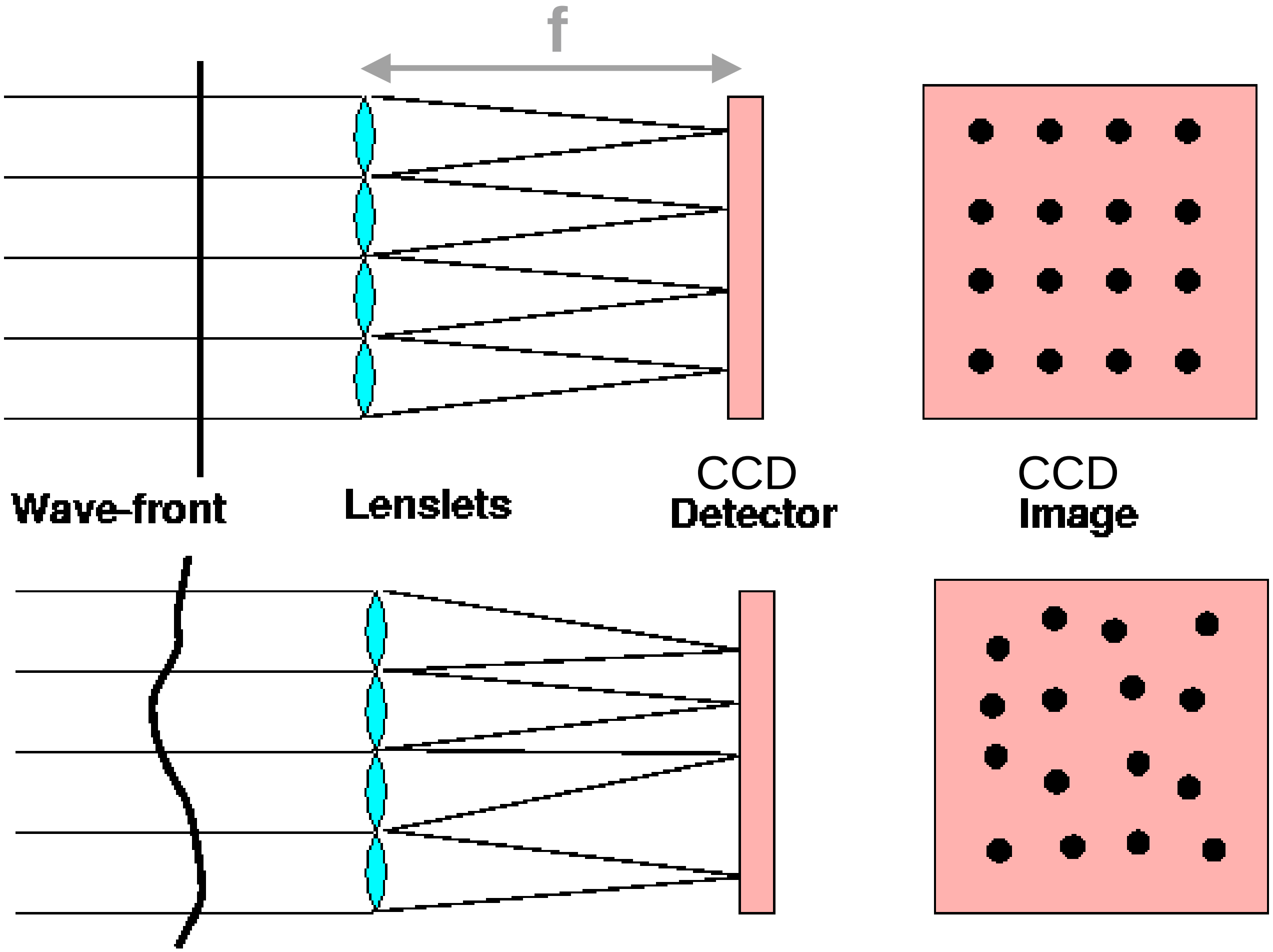
One method: Shack-Hartmann wavefront sensor



Perfect wavefront

Wavefront distorted by turbulence

Shack-Hartmann wavefront sensor - view of patterns on the CCD camera

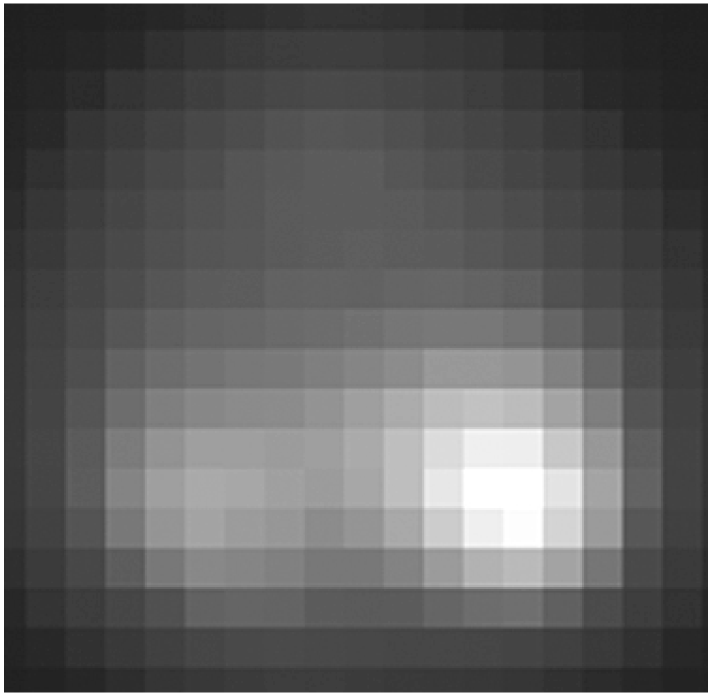


Instruments to use behind AO systems

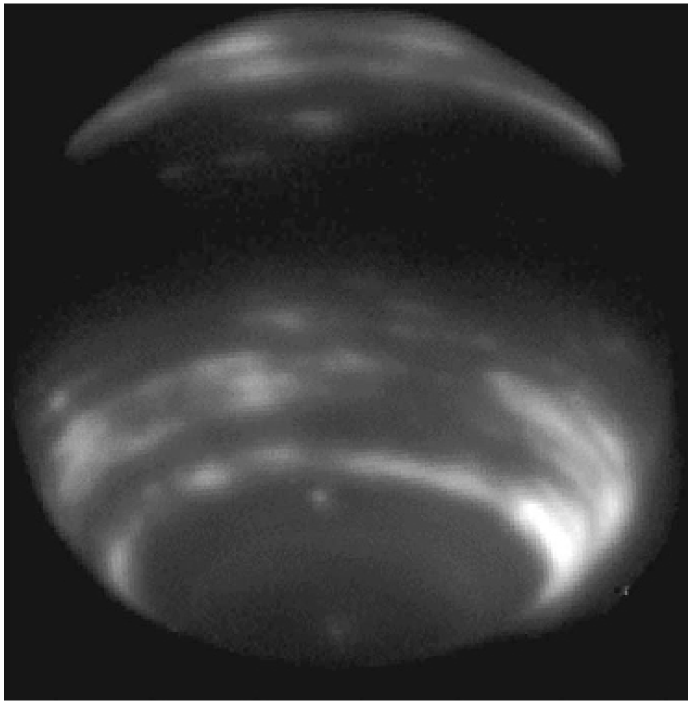
- Usually can’t just re-use non-AO instruments
  - Better optical quality needed
    - Don’t want the optics in the instrument to ruin the new images!
  - Final spatial scales needed
    - Usually implies using finer pixel sampling, with more pixels
  - Higher peak intensities imply -
    - Shorter exposure times to reach same signal to noise ratio
    - Requirement for higher dynamic range detector

Need finer pixel scale to take advantage of sharper AO images

- Example: Two images of Neptune from Keck Observatory, infrared light (1.65 microns)



Typical without AO

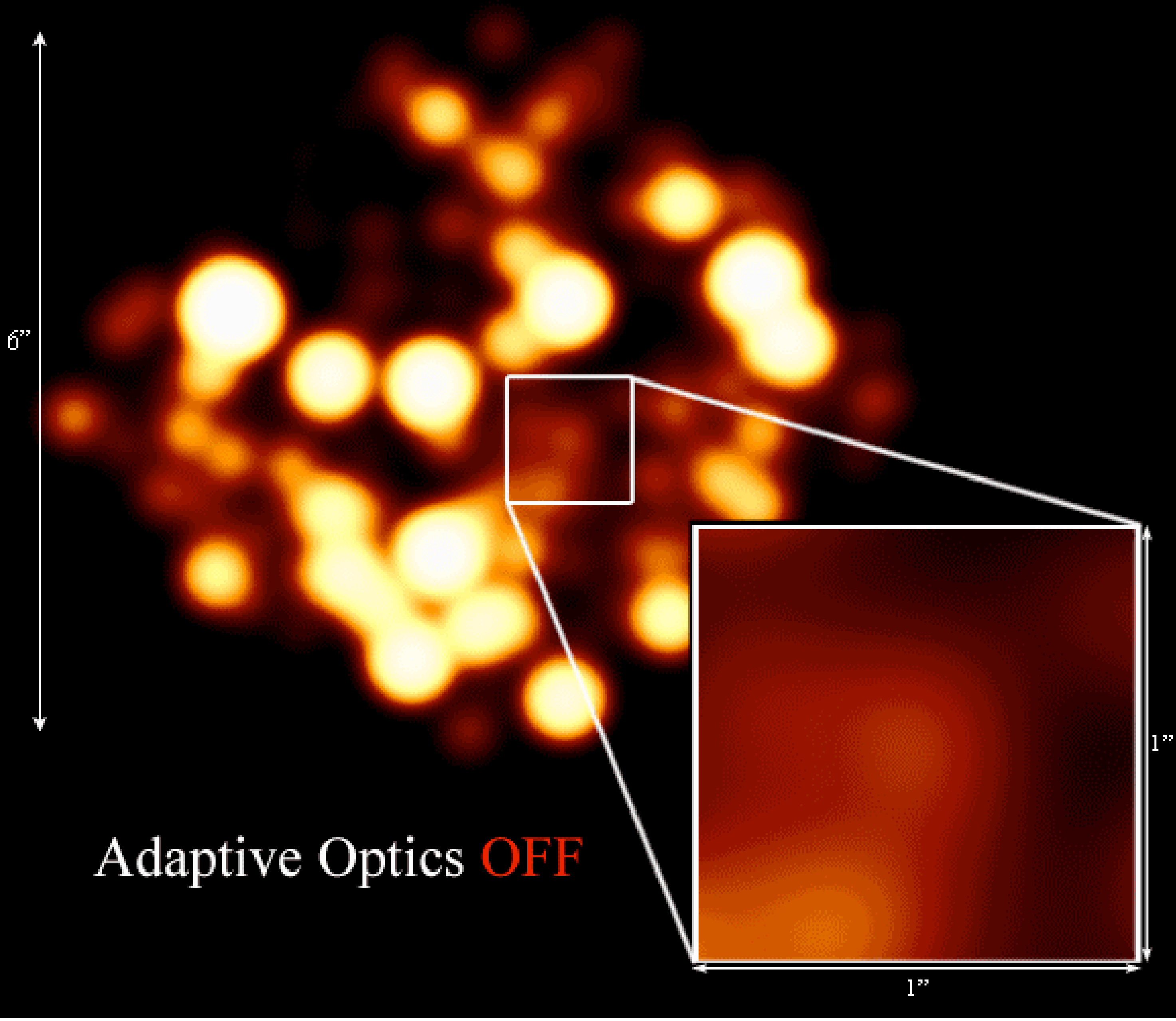


Typical with AO

AO Science in Astronomy

- AO systems are currently in use at many observatories
- We want AO systems on all future large telescopes
- Science examples: (see Jerry Nelson’s talk for more)
  - The black hole at the center of our Galaxy
  - Finding planets around nearby stars

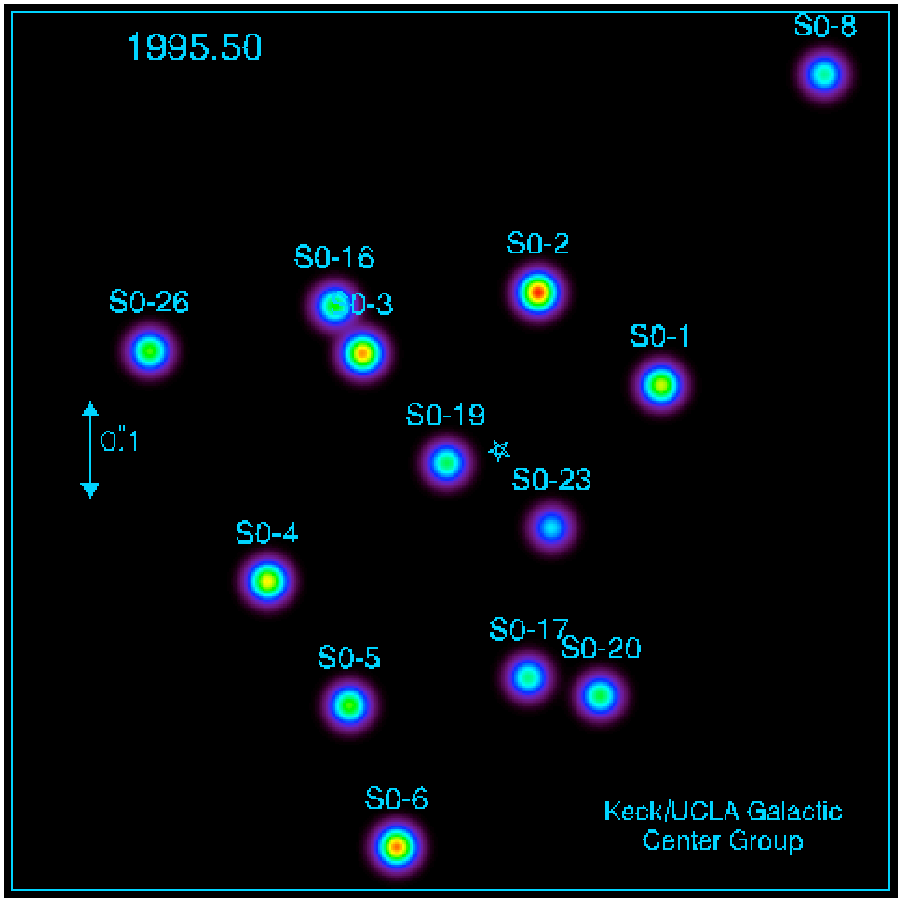
The Galactic Center at 2.2 microns



Adaptive Optics OFF

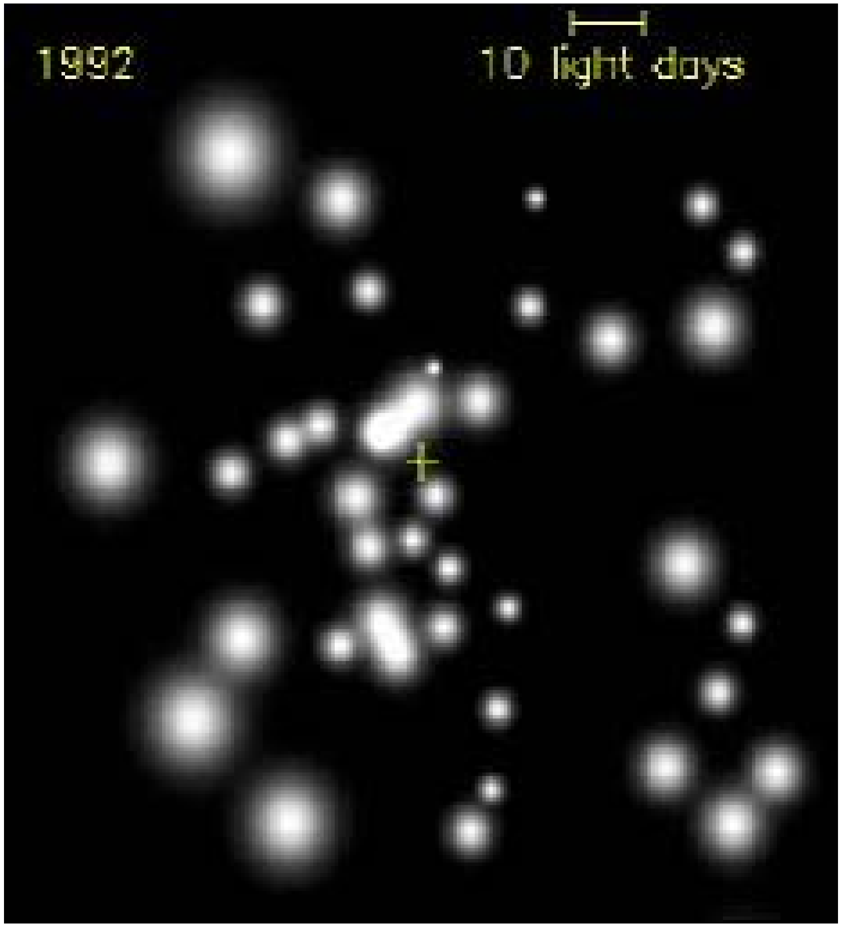
We have a big black hole at the center of our Milky Way Galaxy (!)

- **Orbits of stars around xray source called Sag A***
- **Kepler's laws of motion allowed Ghez and Genzel to solve for mass of central black hole**
- **Several million times the mass of the Sun (!)**



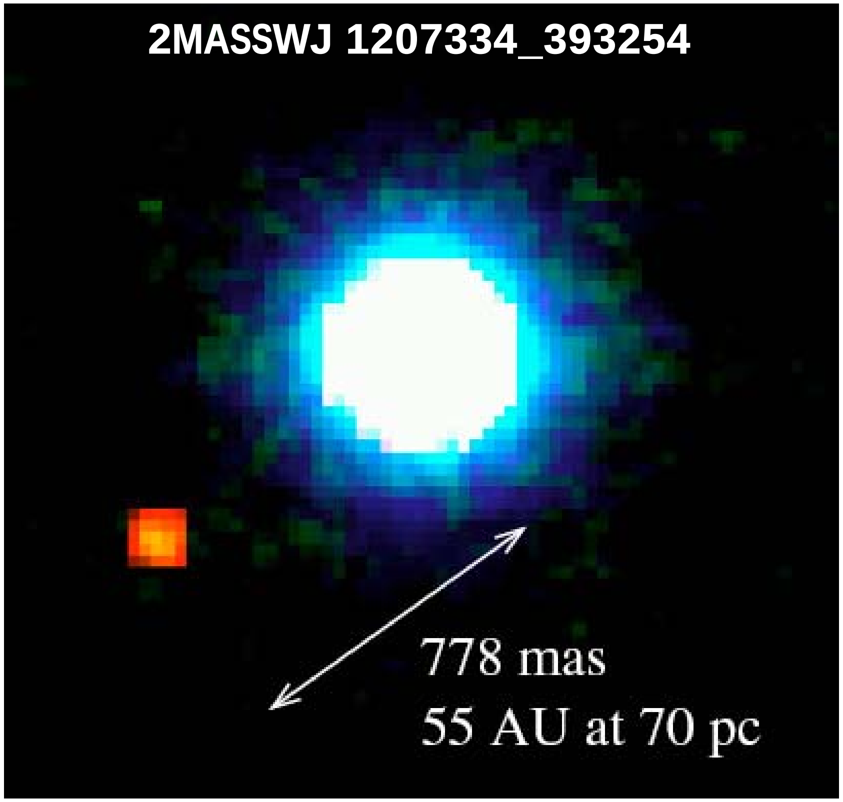
Keck/UCLA Galactic Center Group

Galactic Center stellar orbit movie, Max-Planck Garching



Planets are now being found around stars besides the Sun, using AO

- Very faint red object at r ~55 AU (Pluto is at 40 AU from Sun)
- Evolutionary models suggest a planet, with mass = $5 \pm 2\ M_{\mathrm{Jupiter}}$
- The parent star is rather faint. Finding planets around brighter stars requires extreme measures to eliminate the scattered starlight and hence see the planet.
- "Extreme" AO systems give images in very high contrast situations.

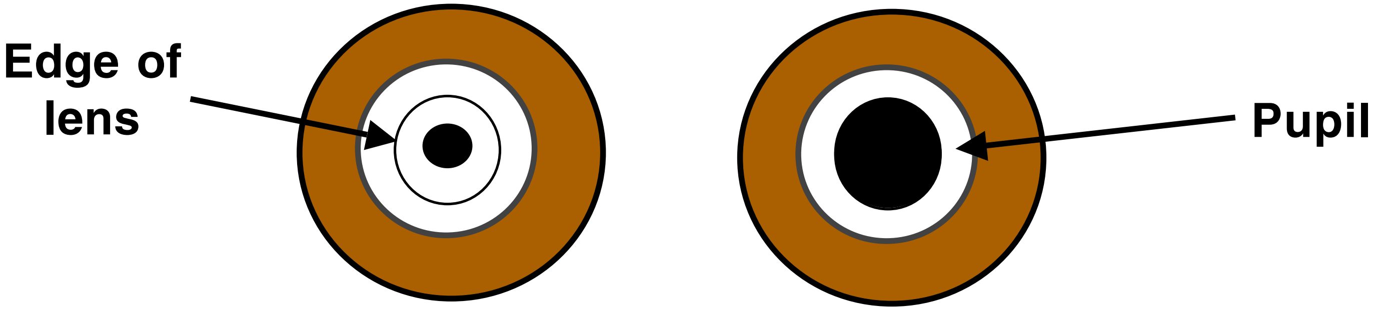


blue 1.2 μm, green 1.6 μm, red 2.2 μm

Chauvin et al., ESO NAOS AO system on VLT Telescope

Vision Science: Why is adaptive optics needed when looking into the human eye?

- 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

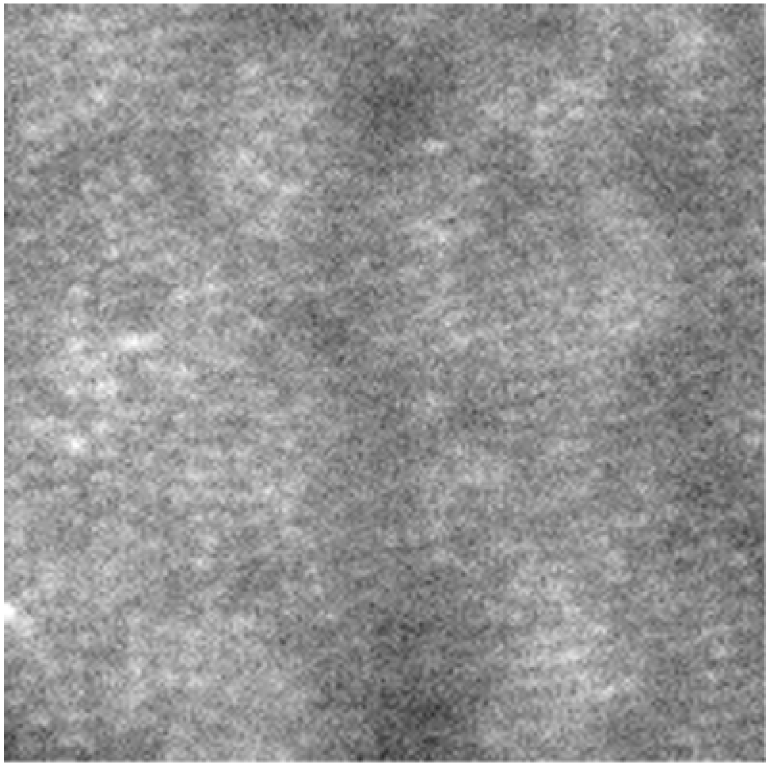


- Results: Poorer night vision (flares, halos around streetlights). Can't image the retina very clearly (for medical applications)

Role of AO in vision science

- Human eye is limited by aberrations when pupil is dilated
- AO can restore the resolution
  - Potential for improving human vision
- At the diffraction limit, images of the retina reveal individual cones (color receptors)
  - Basic science of retinal imaging
  - Color vision
  - Retinal structure (nerves, blood vessels, cones, etc)
  - Retinal diseases

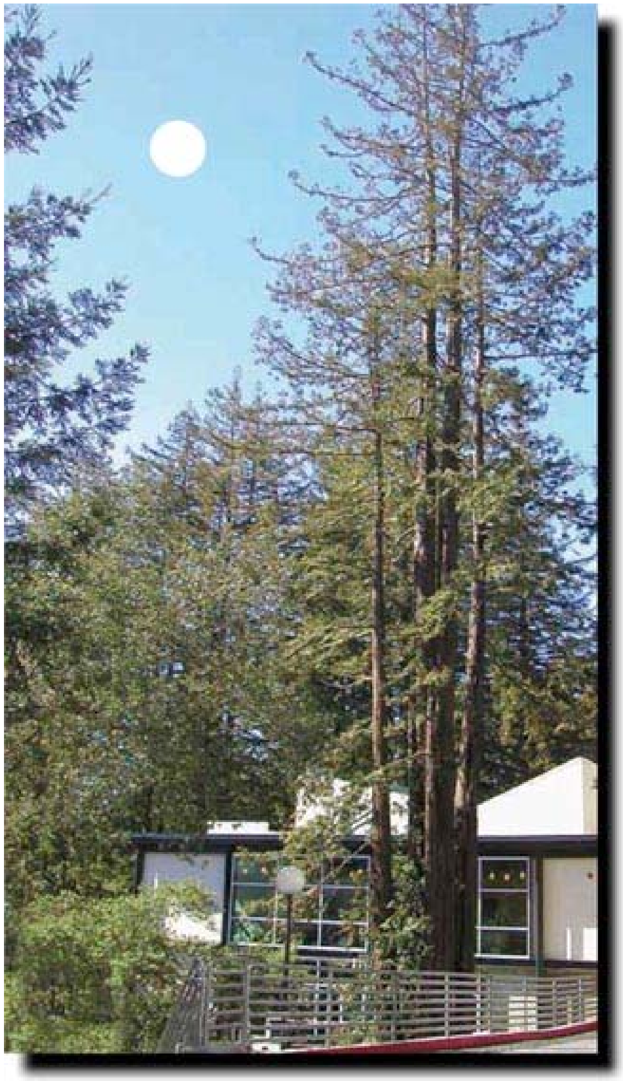
AO yields a major improvement in retinal imaging of the human eye



Without AO

With AO: resolve individual cones

The CfAO Today



- Adaptive optics for astronomy and vision science
- A dozen universities, 8 labs and research institutes, 10 industrial associates
- Headquarters at UCSC
- CfAO Themes:
    1. Education
    2. AO for Extremely Large Telescopes
    3. Extreme AO for Planet-finding
    4. AO for Vision Science

Center for Adaptive Optics: an NSF Science and Technology Center

- NSF periodically supports Science and Technology Centers
  - Innovative, cross disciplinary programs
  - 10 years (1999-2009)
  - $4M/yr
- Embark upon long-term, multi-disciplinary science and technology research
- Explore more effective ways to educate students
- Develop mechanisms to ensure timely transition of research and education advances into service to society

CfAO Mission and Strategies

- CfAO Mission : Advance and Disseminate Adaptive Optics knowledge in service to science, health care, industry, and education

- CfAO will pursue its purpose and achieve its goal by:
  1) Demonstrating the power of AO by doing forefront science
  2) Increasing the accessibility of AO to the scientific community
  3) Developing and deploying highly capable AO systems and laser beacons
  4) Coordinating and combining research efforts to take advantage of the synergies afforded by the Center mode of operations

Strategies (cont)

5) Integrating education with our research

6) Building a Center community that is supportive of diversity through vigorous recruiting, retention, and training activities

7) Encouraging the interaction of vision scientists and astronomers to promote the emergence of new science and technology

8) Leveraging our efforts through industry partnerships and cross-disciplinary collaborations

The CfAO is organized into four Themes

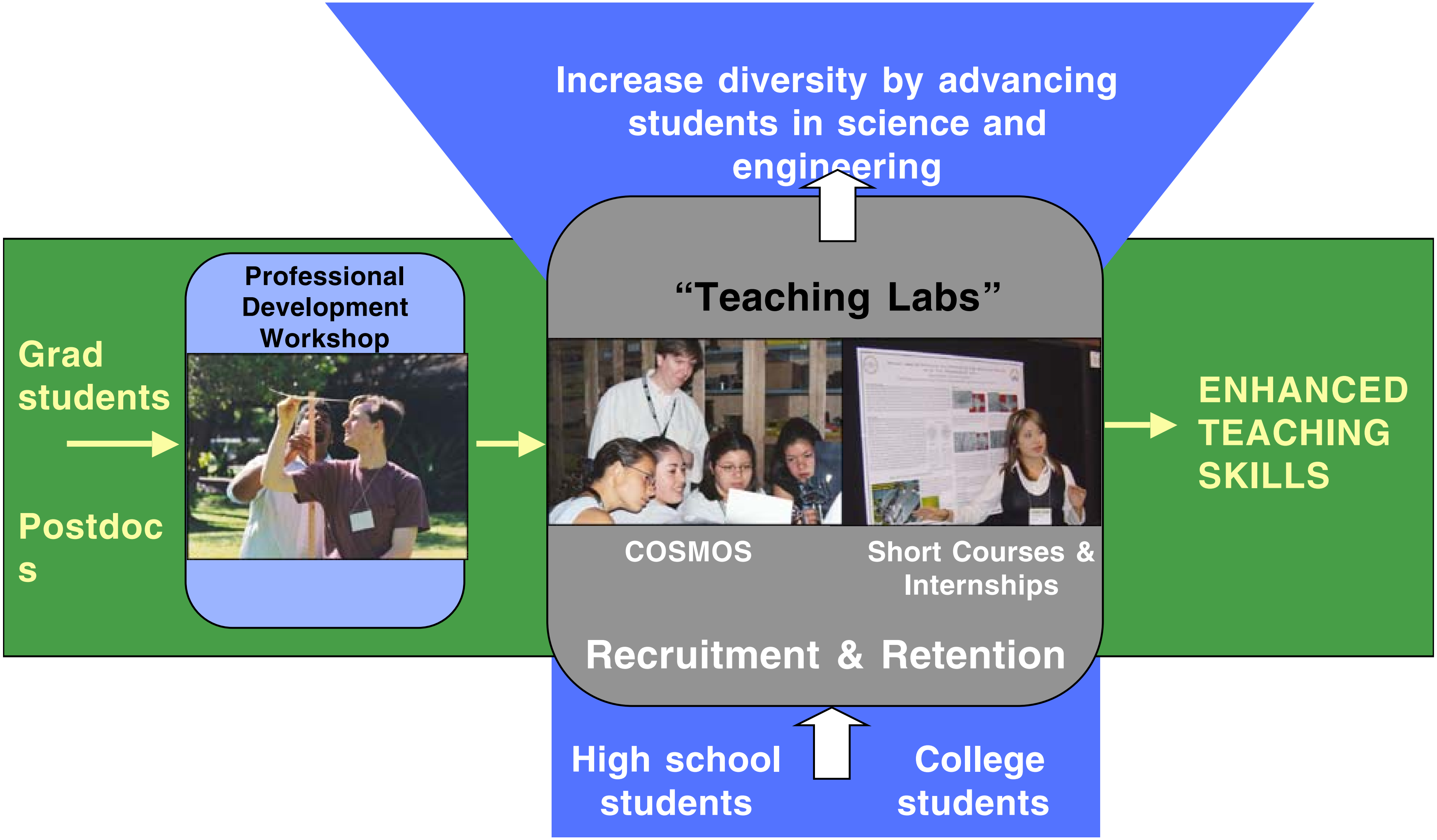
- Designed to focus efforts, foster Center-wide collaborations toward common goals (Themes), and to leave valued “monuments” as a legacy

- Themes
  - Theme 1: Education and Human Resources
  - Theme 2: AO for Extremely Large Telescopes
  - Theme 3: “Extreme AO” (ultra high contrast)
  - Theme 4: Compact Vision Science Instrumentation for Clinical and Scientific Use

How CfAO works

- Research projects
  - Annual proposal process among CfAO members
- Education programs
  - Grad students and postdocs learn modern teaching methods such as "inquiry based learning"
  - Use these methods in CfAO-sponsored short courses (college level) and summer programs (high school students)
  - Emphasis on increasing the participation of students from groups that are under-represented in science and technology
- Retreats, workshops, conferences
- Graduate course in AO every two years
  - Taught by Max; some videoconference participation is possible

CfAO Education Program:
Two Integrated Strands



Increase diversity by advancing students in science and engineering

Grad students

Postdocs

Professional Development Workshop

“Teaching Labs”

COSMOS

Short Courses & Internships

Recruitment & Retention

High school students

College students

ENHANCED TEACHING SKILLS

Example: Two Hawaii internships preceded by "Short Courses"

Maui Akamai Program:

Industry/Gov

Started 2003

Big Island Akamai Program:

Observatories

Started 2005

CfAO Summer School 2006

- CfAO sponsors a summer school in adaptive optics each year
  - Participants include
    - Astronomers
    - Vision scientists
    - Technologists
    - Engineers
    - Students
    - from industry, academia, observatories

Basic reference materials

- Web:
  - Max's graduate course
    http://www.ucolick.org/~max/289C/
  - Tokavinin's shorter course
    http://www.ctio.noao.edu/~atokovin/tutorial/intro.html

- Introduction to Adaptive Optics (SPIE Tutorial Texts in Optical Engineering Vol. TT41) by Robert K. Tyson
- Field Guide to Adaptive Optics (SPIE Vol. FG03) (Benjamin W. Frazier) by Robert K. Tyson
- Adaptive Optics for Astronomical Telescopes (Oxford Series in Optical and Imaging Sciences) by John W. Hardy
- Adaptive Optics in Astronomy (Cambridge University Press) edited by François Roddier