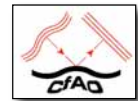


Introduction to AO and the Center for Adaptive Optics



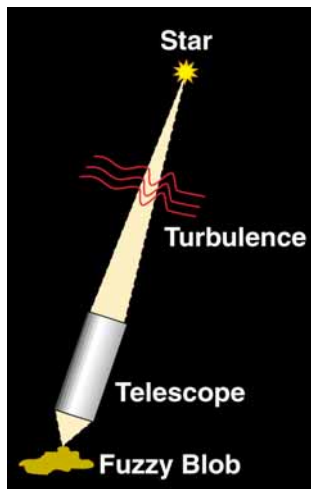
CfAO Summer School
2007
Claire Max
CfAO Director

Outline



- Principles of Adaptive Optics
 - Basic ideas
 - AO for Astronomy
 - AO for Vision science
 - Other applications
 - AO systems and components
- The Center for Adaptive Optics
 - CfAO Organization and Mission
 - Thematic structure
- Throughout I will highlight **summer school talks to come**

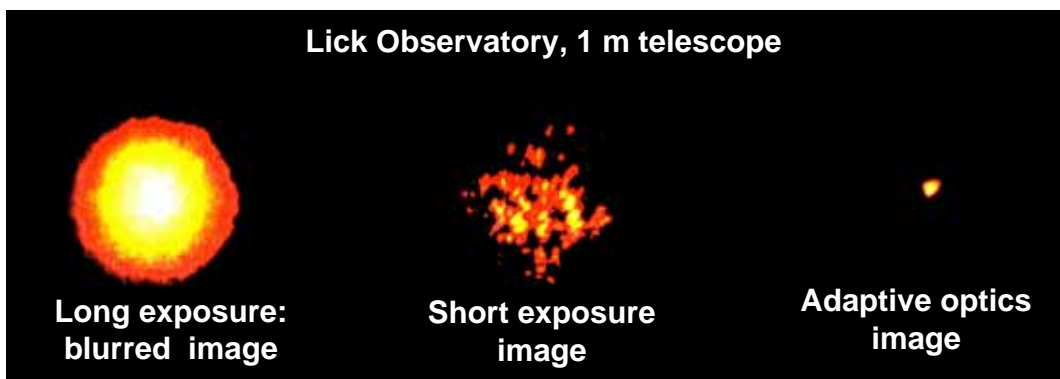
Turbulence in the Earth's atmosphere limits the performance of astronomical telescopes



- 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

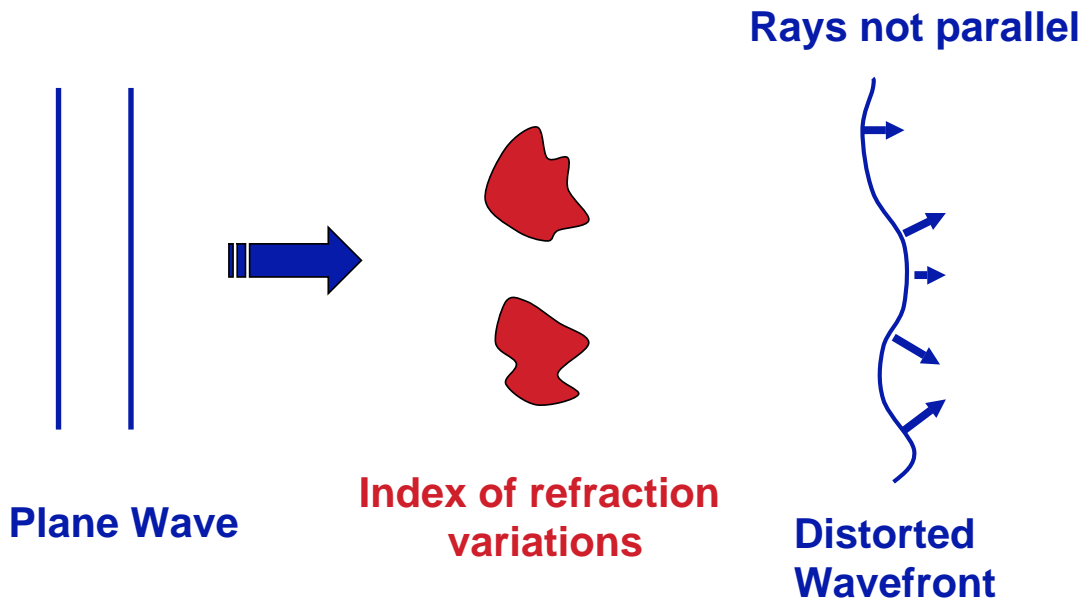
Even the largest ground-based astronomical telescopes have no better resolution than an 8" backyard telescope!

What is Adaptive Optics?



- A technique for correcting optical distortions to dramatically improve image quality.
- Useful in astronomy, vision science, laser eye surgery, communications, remote sensing, high-powered lasers, ...

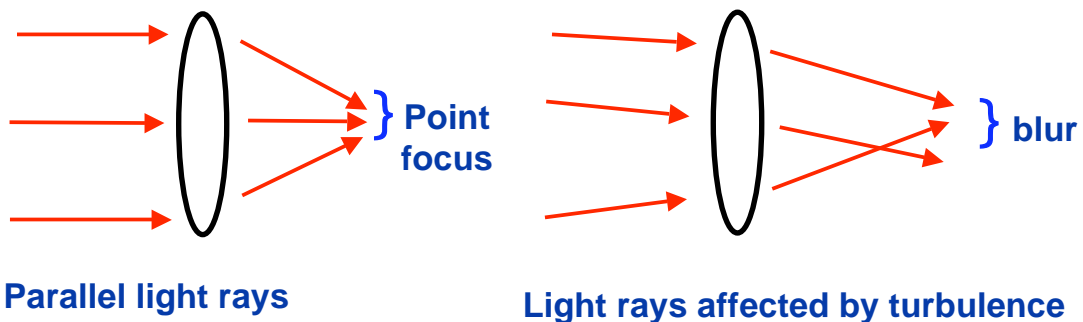
Atmospheric perturbations cause distorted wavefronts



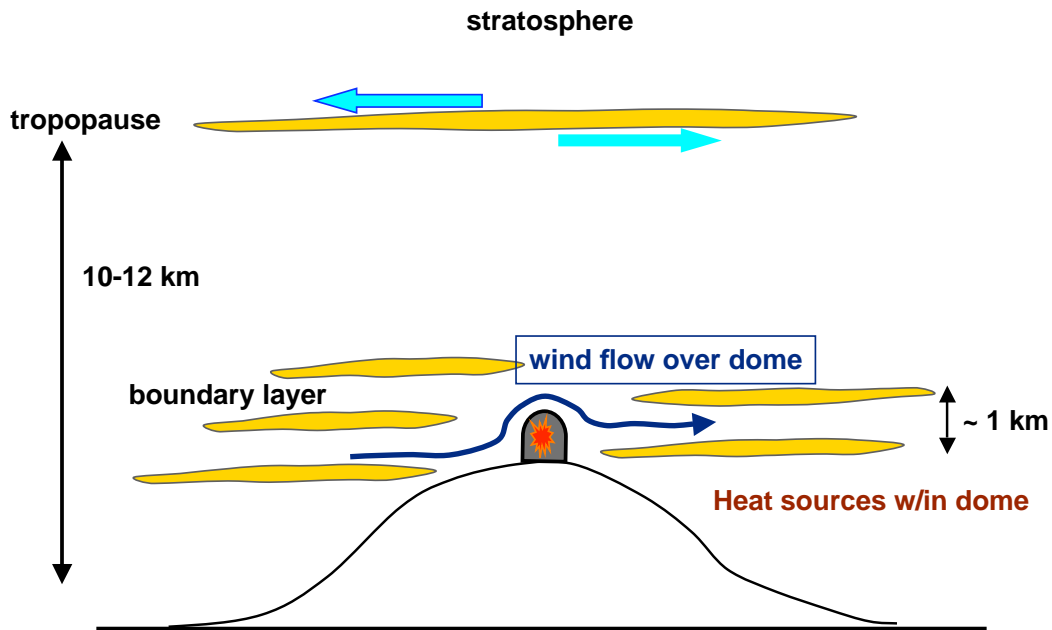
Optical consequences of turbulence: blurring



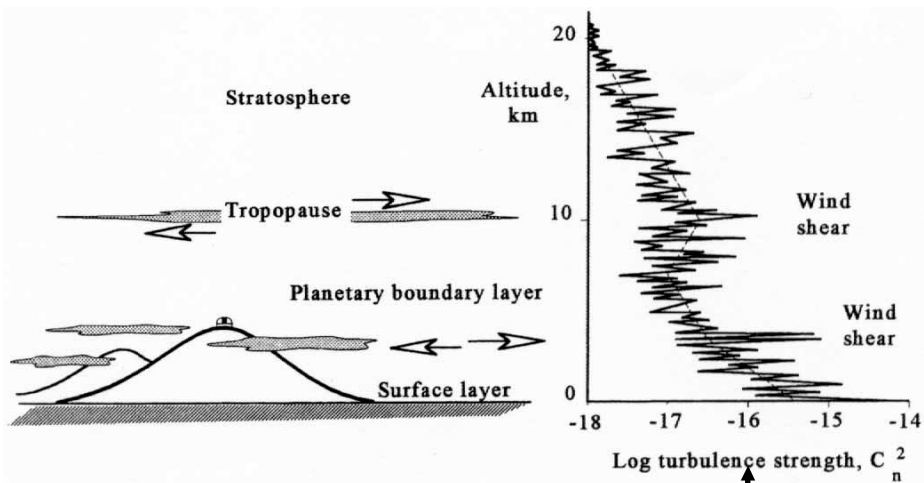
- Temperature fluctuations in small patches of air cause changes in index of refraction of the air (like many little lenses)
- Light rays are refracted many times (by small amounts each time).
- When they reach the telescope they are no longer exactly parallel with each other
- Hence rays can't be focused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



Turbulence arises in several places

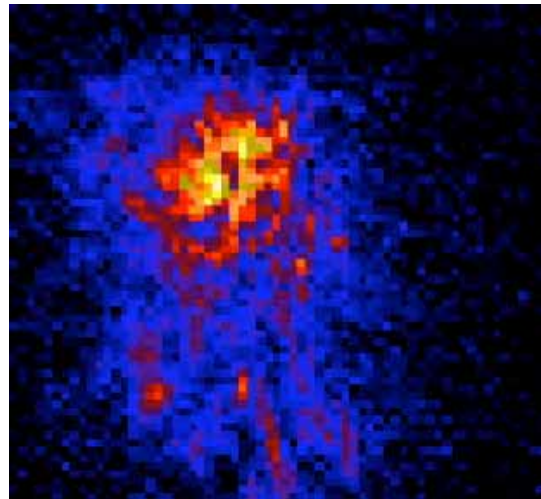


Vertical profile of turbulence



Measured from a balloon rising through various atmospheric layers

Movie of "real" turbulence (vastly slowed down)



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

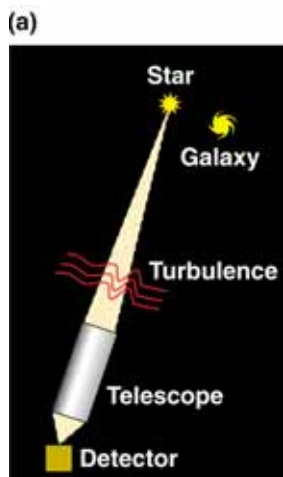
Adaptive Optics can correct for atmospheric blurring



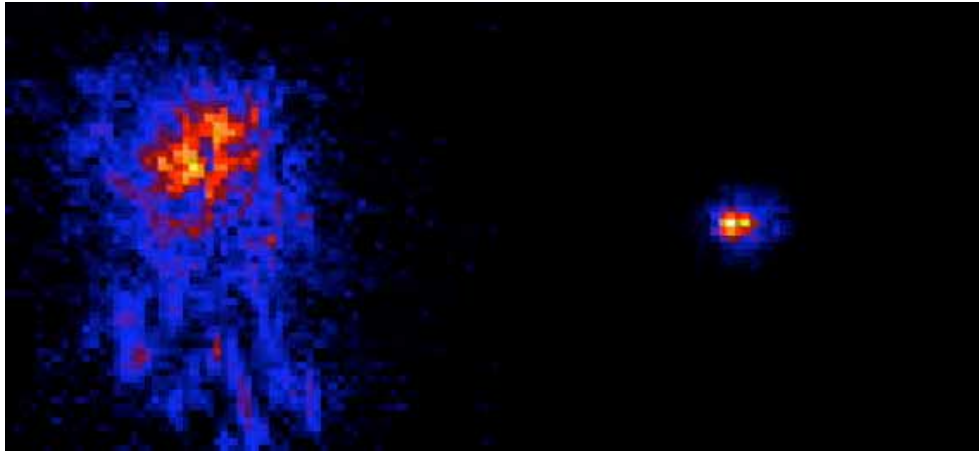
Measure details of blurring from "guide star" near the object you want to observe

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



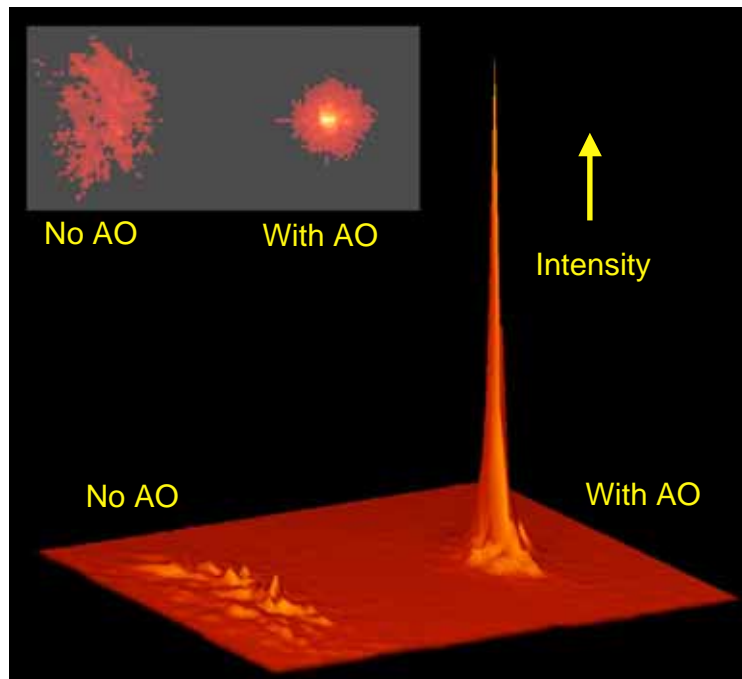
Infra-red images of a star, from Lick Observatory adaptive optics system



No adaptive optics

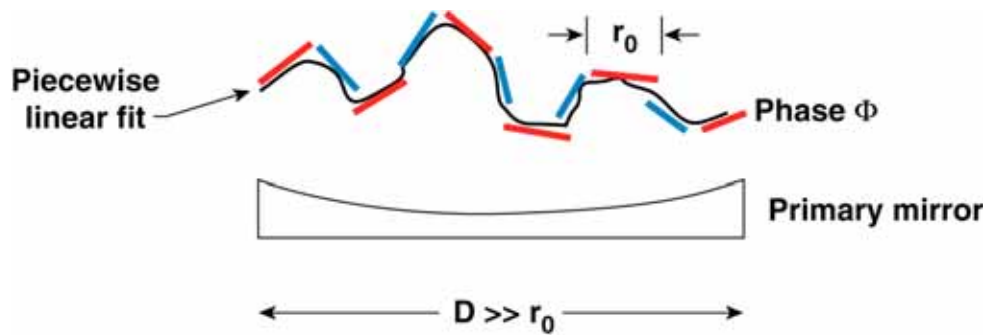
With adaptive optics

Adaptive optics increases peak intensity of a point source



Lick
Observatory

Strength of turbulence is often described by the "Fried Parameter" r_0

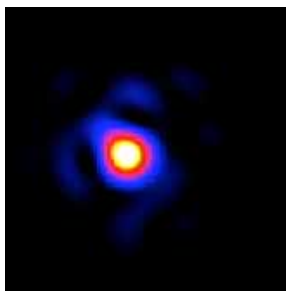


- r_0 is defined as largest distance (on telescope mirror) over which phase of incoming wave is well-correlated
- Typical values: at good site, $r_0 \sim 10 - 15$ cm, $\lambda = 0.5 \mu\text{m}$

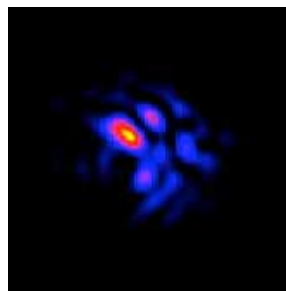
Effects of turbulence depend on size of telescope



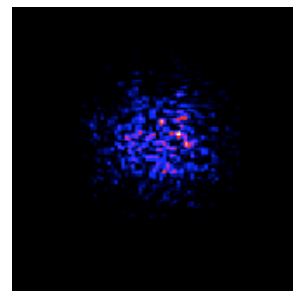
- For telescope diameter $D < \text{a few } \times r_0$:
Dominant effect is "image wander"
- As D becomes $\gg r_0$:
Many small "speckles" develop.
Each speckle is $\sim \lambda / D$; overall envelope is $\sim \lambda / r_0$ ("seeing disk")
- Computer simulations by Nick Kaiser:



$D = 1$ m

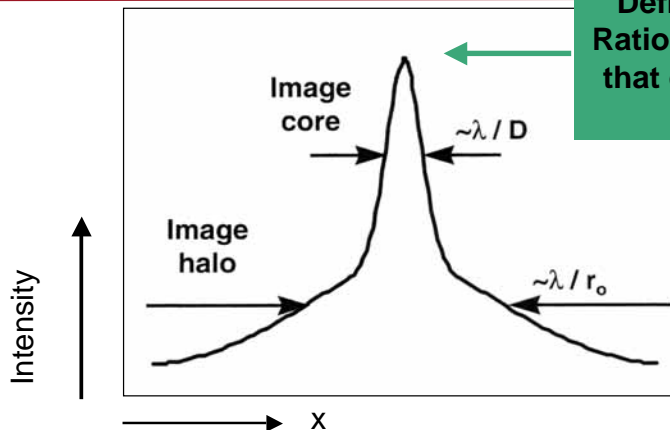


$D = 2$ m



$D = 8$ m

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 $\sim r_0$)
- Ratio between core and halo varies during night

Outline

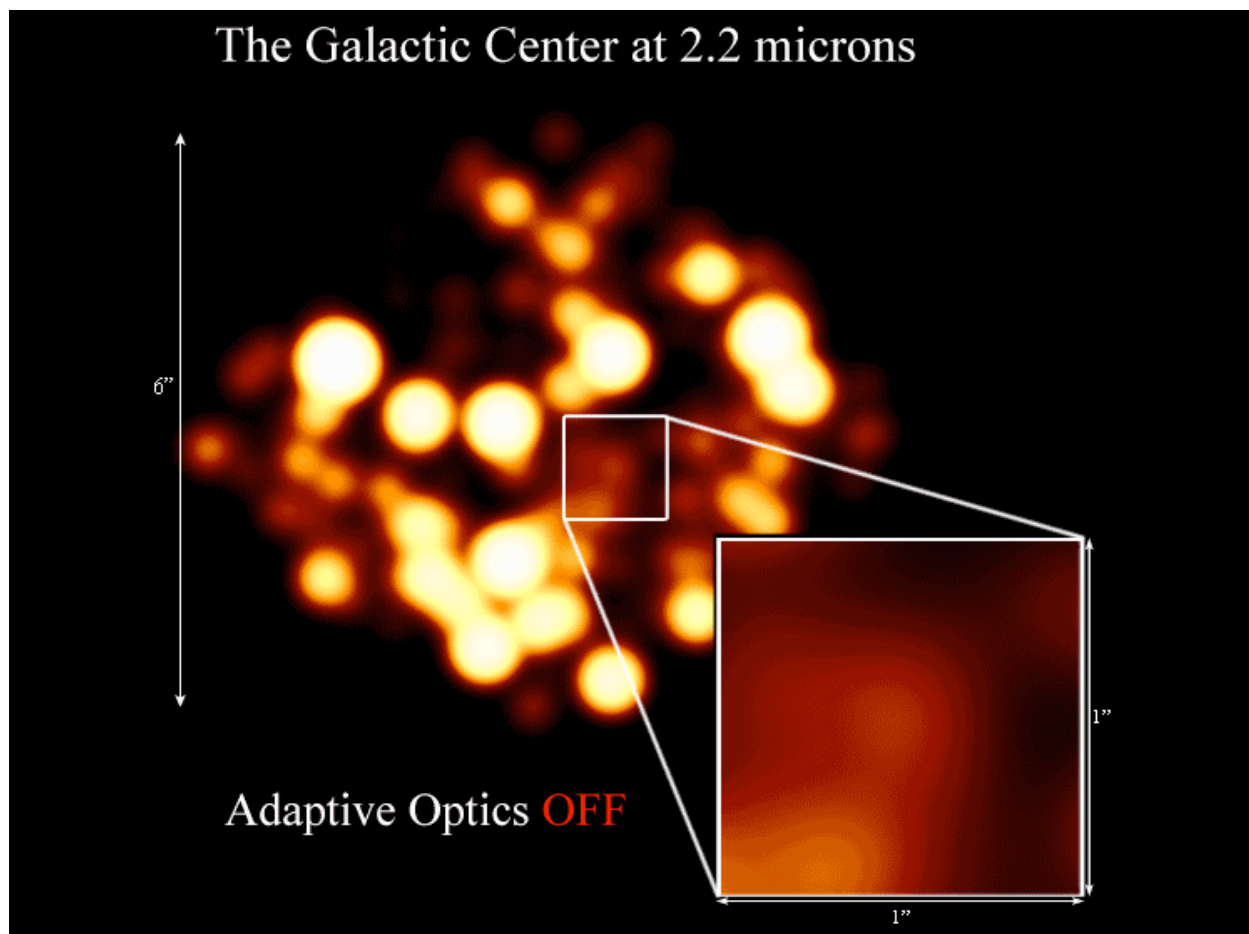


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AO Science in Astronomy



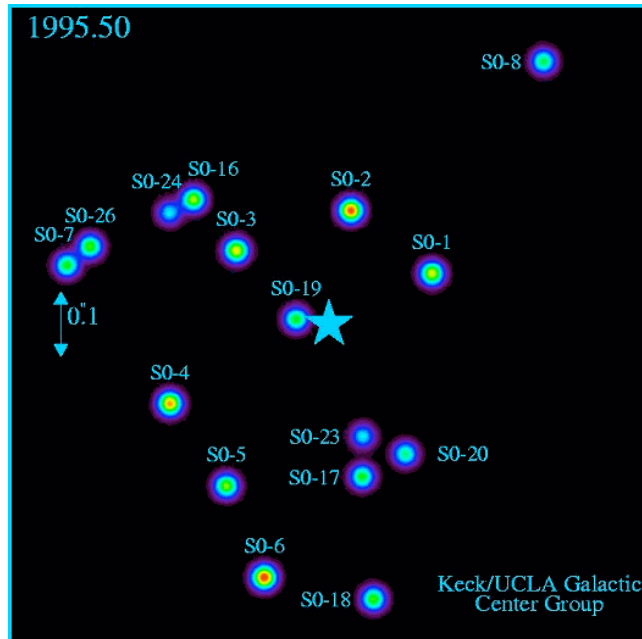
- AO systems are currently in use at many observatories
- We want AO systems on all future large telescopes
- Science examples: the black hole at the center of our Galaxy; the atmosphere of Neptune; atmosphere and rings of Uranus; solar physics
- James Graham will talk about instruments for astronomical AO
- Olivier Guyon will talk about designing AO systems for astronomy



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



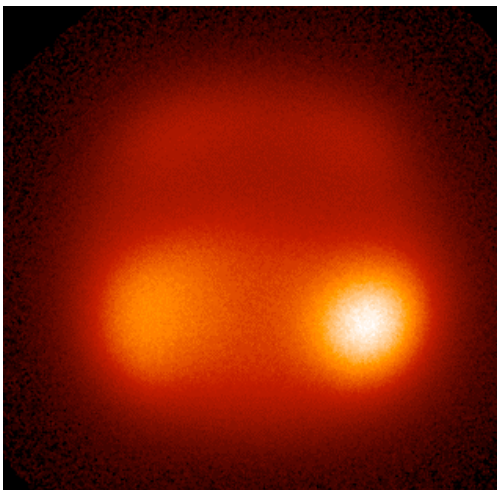
- Orbits of stars around xray source called Sag A*
- Kepler's laws of motion allowed Ghez and Genzel to solve for mass of central black hole
- Several million times the mass of the Sun



Neptune at 1.65 microns

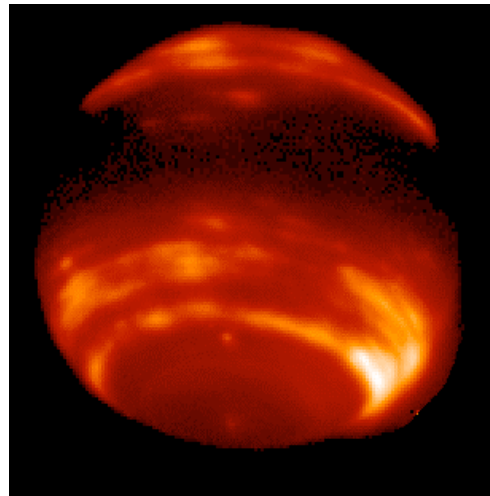


Without adaptive optics



May 24, 1999

With adaptive optics



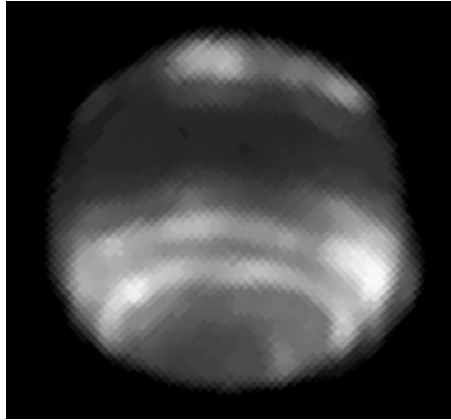
June 28, 1999

2.3 arc sec

Neptune at 1.6 microns: Hubble Space Telescope compared with Keck AO

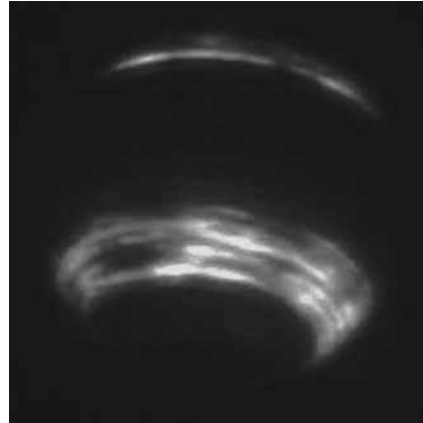


HST - NICMOS



2.4 meter telescope

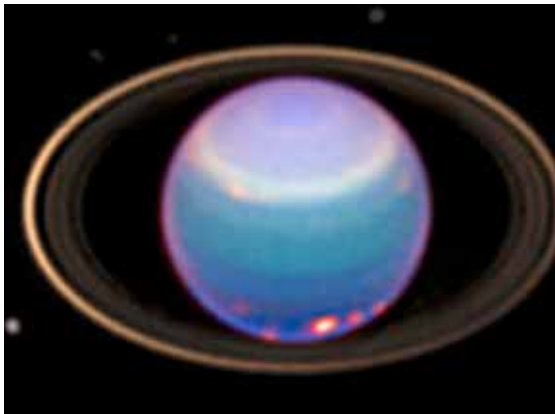
Keck AO



10 meter telescope

(Two different dates and times)

Uranus with Hubble Space Telescope and Keck AO



HST, Visible



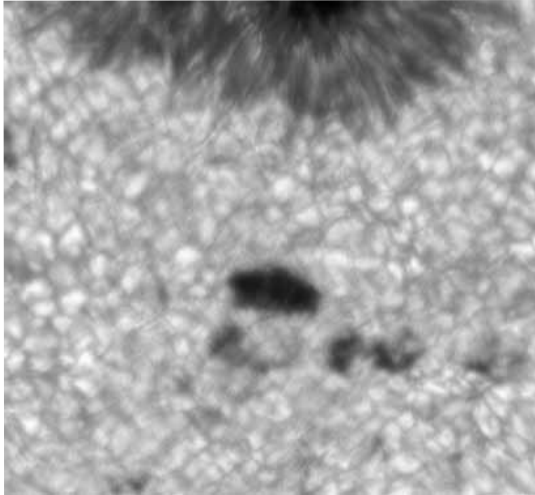
Keck AO, IR

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

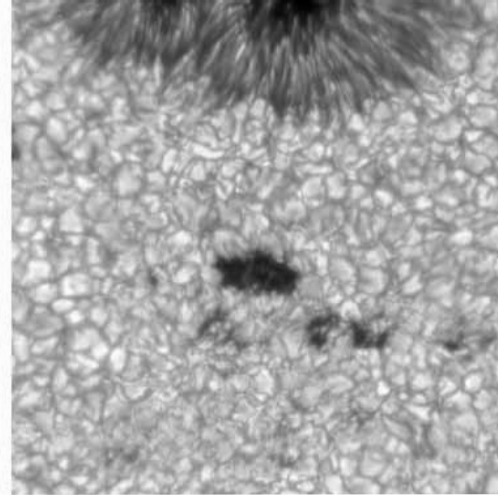
Adaptive optics for solar physics



Solar active region, Dunn Solar Telescope, NSO



No adaptive optics



With adaptive optics

Outline

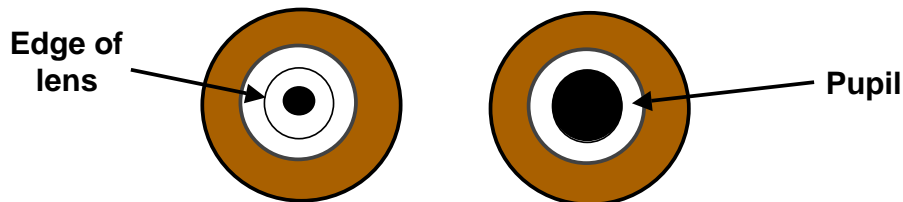


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Why is adaptive optics needed for the human eye?

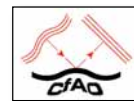


- Around edges of lens and cornea, imperfections cause distortion
- In bright light, pupil is much smaller than size of lens, so distortions don't matter much
- But when pupil is large, incoming light passes through the distorted regions



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

Role of AO in vision science



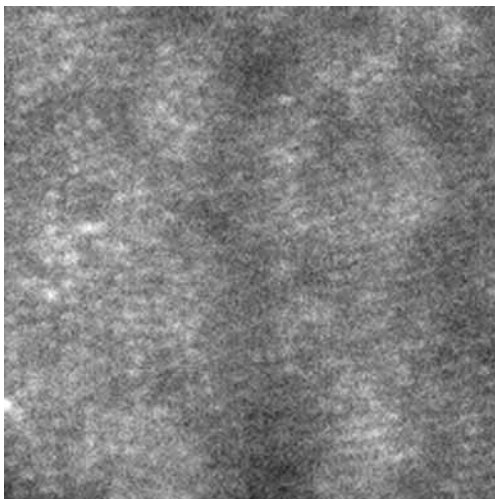
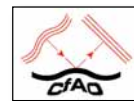
- Human eye is limited by aberrations when pupil is dilated
- AO can restore the resolution
 - Potential for improving human vision
- At the diffraction limit, images of the retina reveal individual cones
 - Basic science of retinal imaging
 - Color vision
 - Retinal structure (nerves, blood vessels,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

AO for vision science

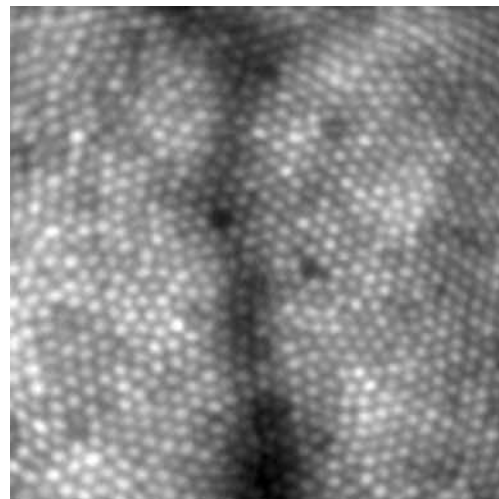


- Vision science AO systems are closely similar to astronomical AO systems
- But with very sophisticated back-end instruments, for example aimed at imaging the 3D structure of the living retina
- Don Miller will talk about designing vision science AO systems
- Austin Roorda will talk about AO instrumentation for vision science

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



Without AO



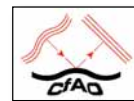
With AO: resolve individual cones

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Other Applications of AO



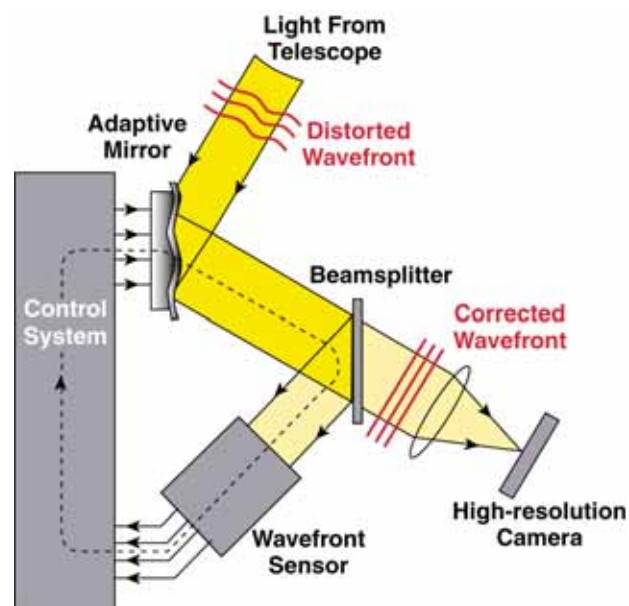
- Astronomy has the longest history of using AO and has the most technically challenging systems.
- Vision science applications promise great practicality for human vision improvements, science, and medicine.
- AO is useful in horizontal path or scene imaging.
- AO has applications in free-space laser communications.
- Principles of wavefront measurement and correction are increasingly being used for space telescopes too.
 - Large-diameter space telescopes must be light-weighted and deployable
 - Hence “floppy”, can benefit from AO

Outline

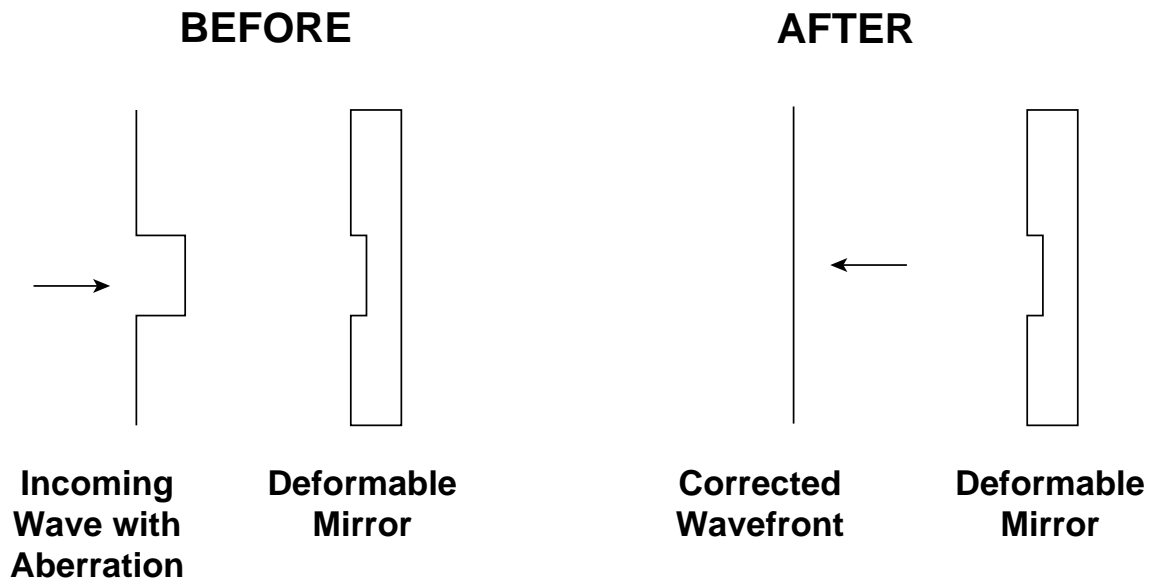


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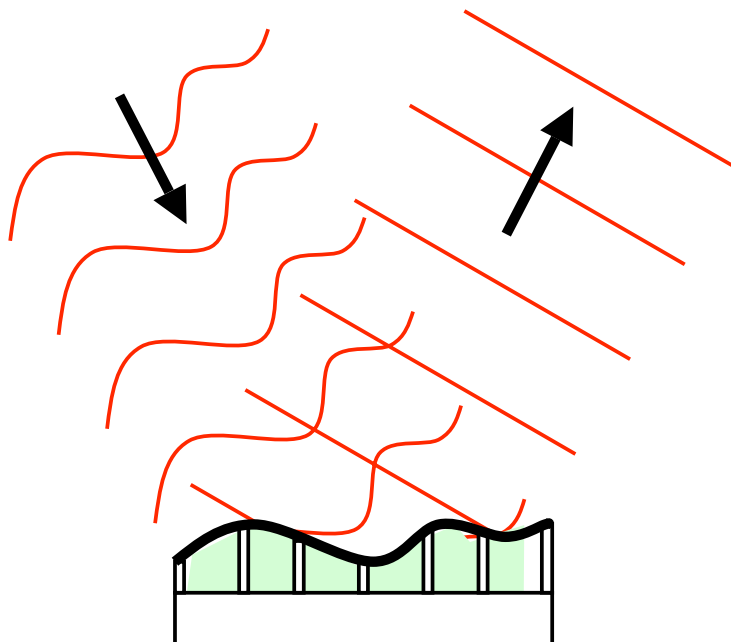
Optical schematic of adaptive optics system



How a Deformable Mirror Works

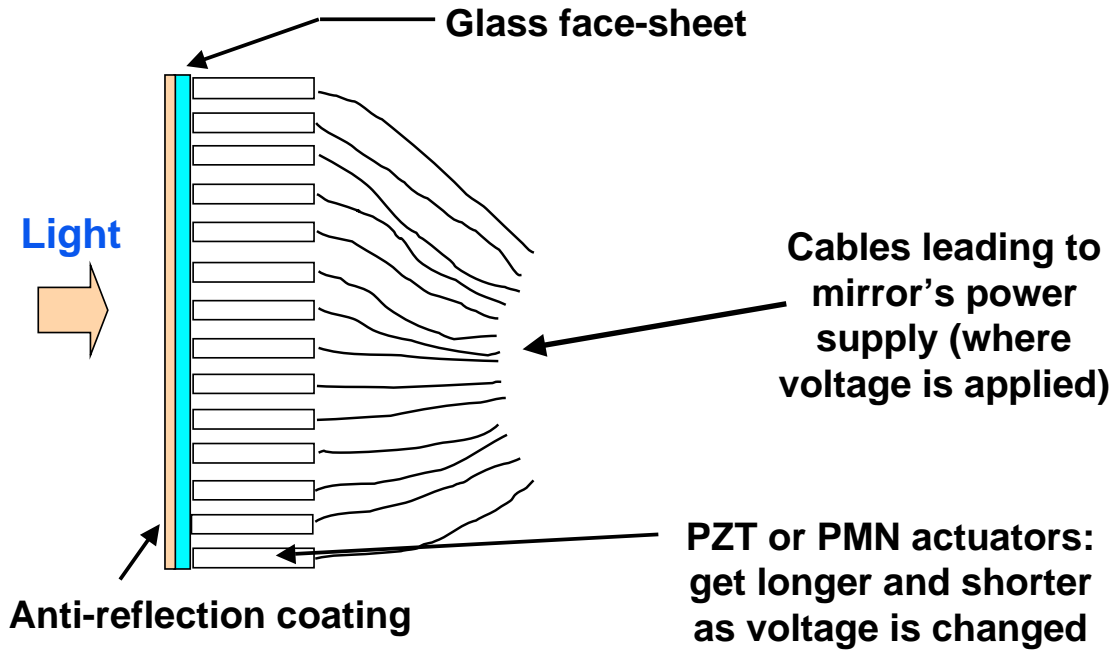


The Deformable Mirror



Joel Kubby will discuss wavefront correction at the Summer School

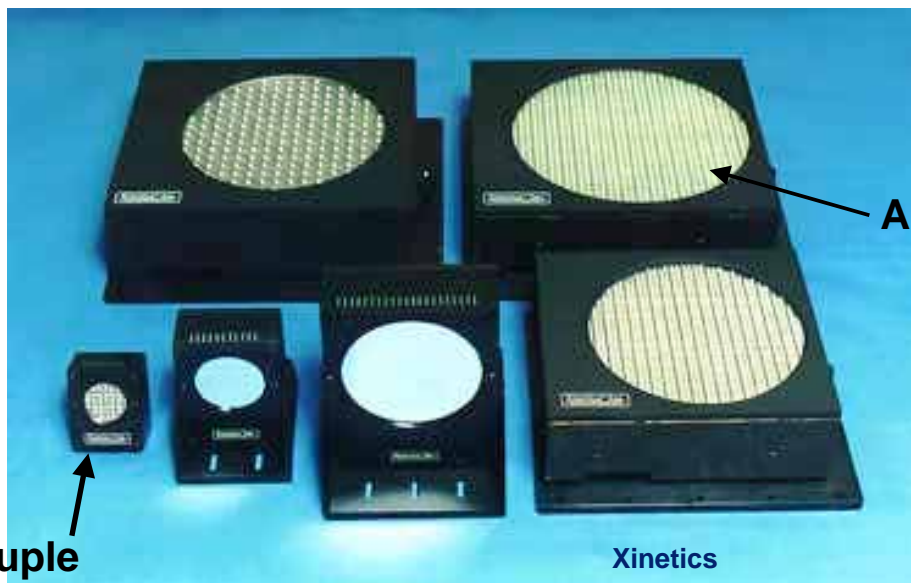
Most deformable mirrors today have thin glass face-sheets



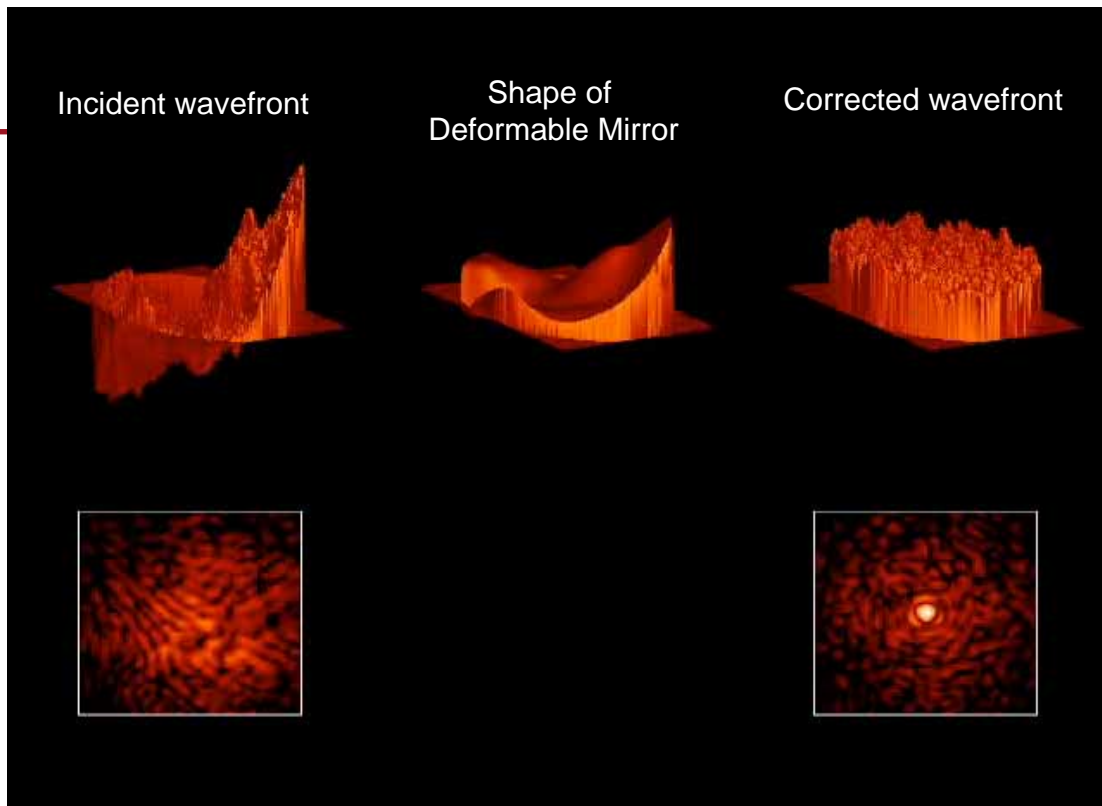
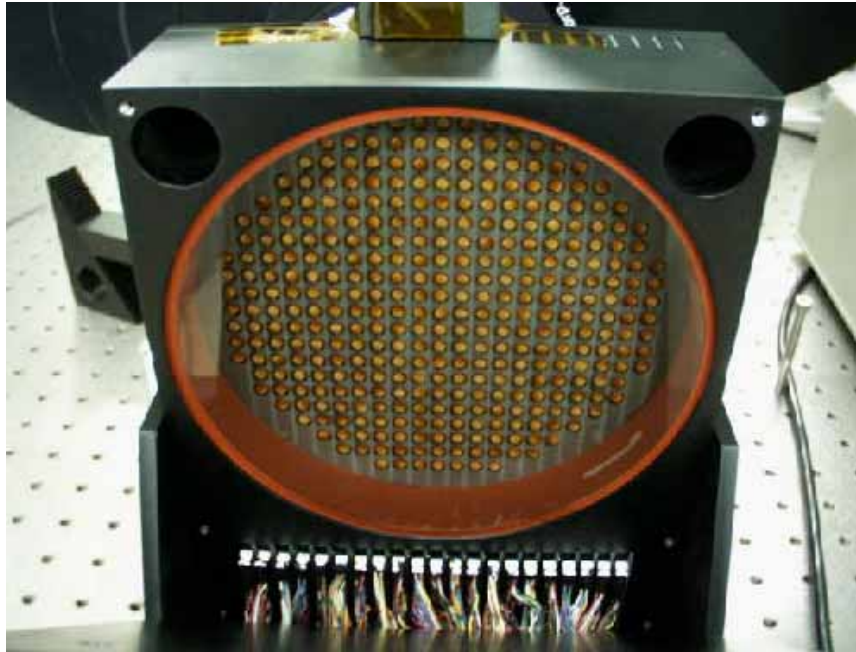
Deformable mirrors come in many sizes

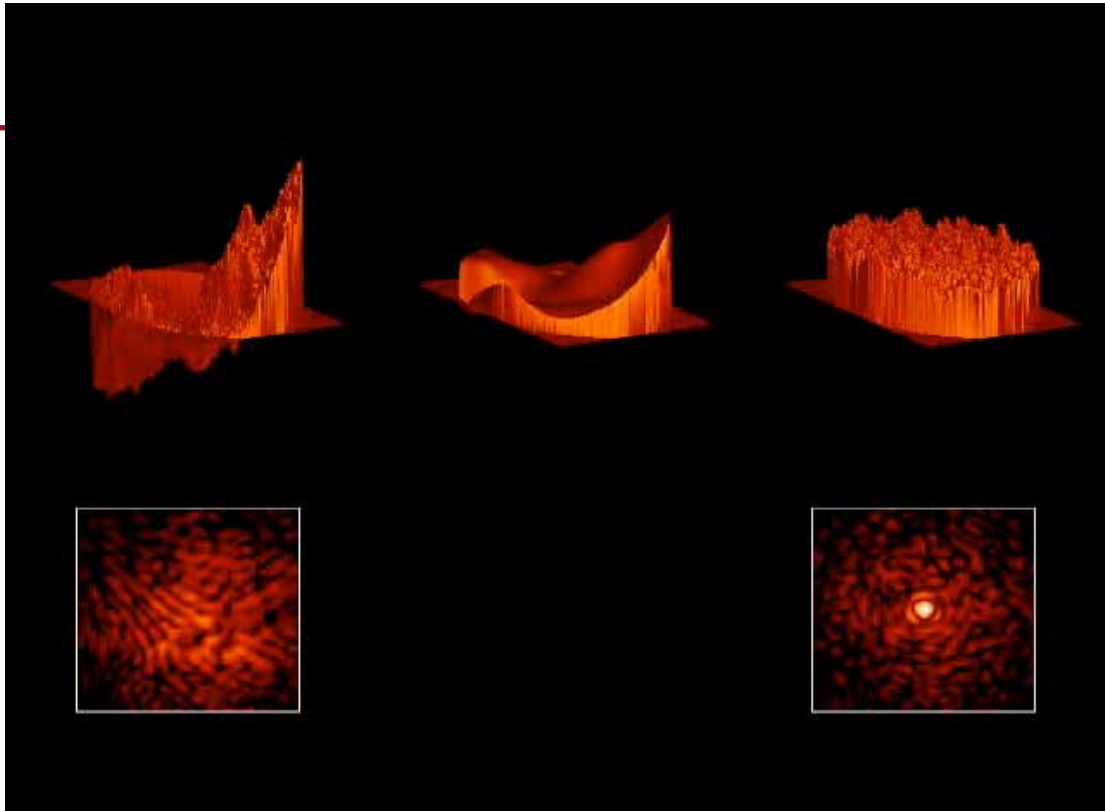


- Range from 13 to > 900 actuators (degrees of freedom)

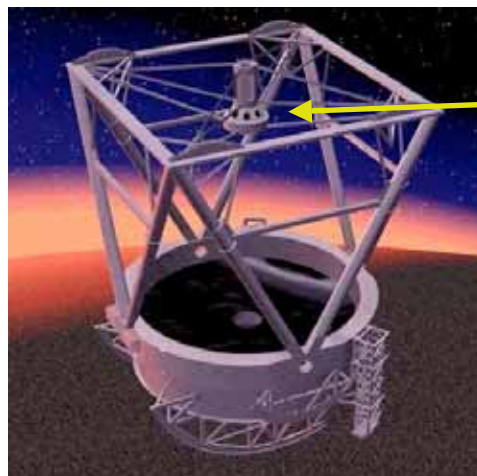


Rear view of Xinetics 349 actuator DM used in Keck Telescope AO system





Cassegrain telescope concept



Adaptive secondary deformable mirror lives here

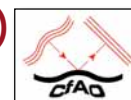
Adaptive Secondary Mirrors



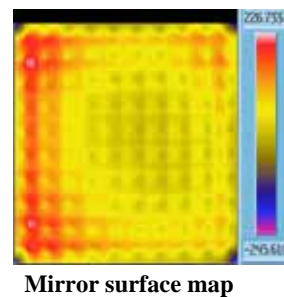
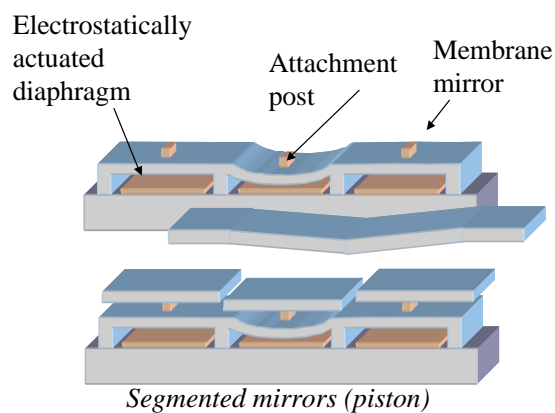
- U. Arizona + Arcetri Observatory (Italy)
- 336 actuators, 642 mm diameter, 2mm facesheet



MEMS (micro-electro-mechanical systems) deformable mirrors



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

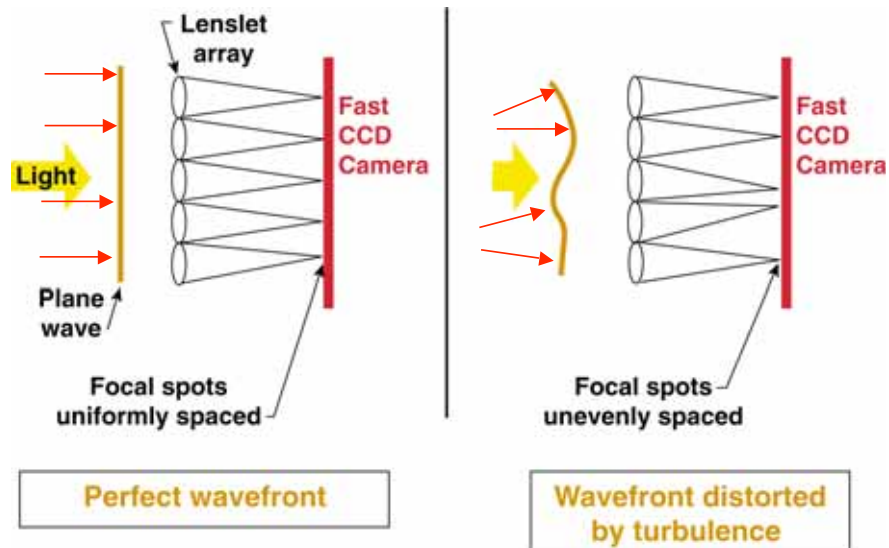


- Joel Kubby will discuss MEMS deformable mirrors at the Summer School

How to measure turbulent distortions (one method among many)

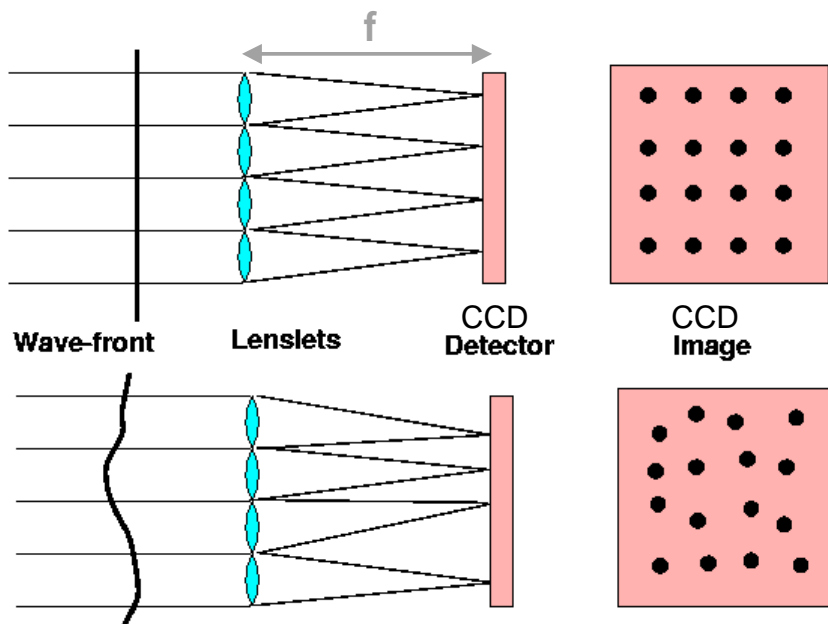


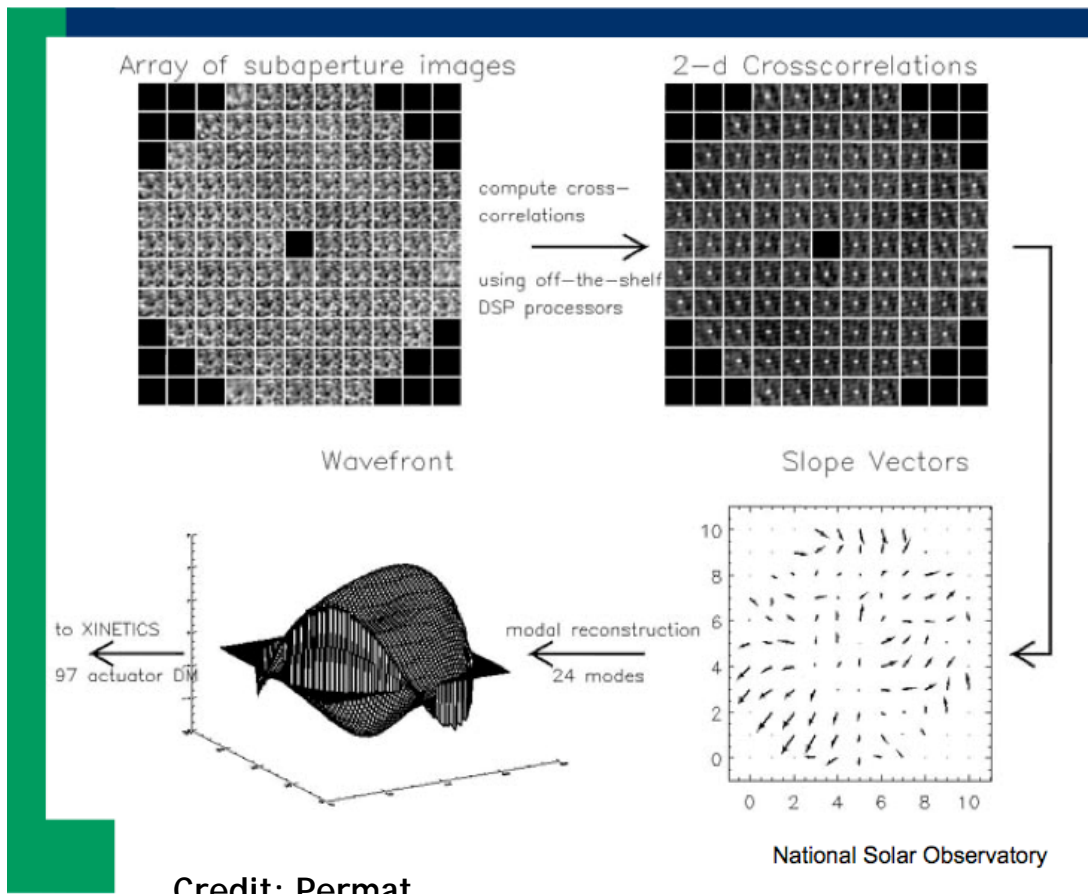
Shack-Hartmann wavefront sensor



Marcos van Dam and Matthew Britton will discuss wavefront sensing and reconstruction

Shack-Hartmann wavefront sensor concept - measure subaperture tilts





Wavefront Reconstruction



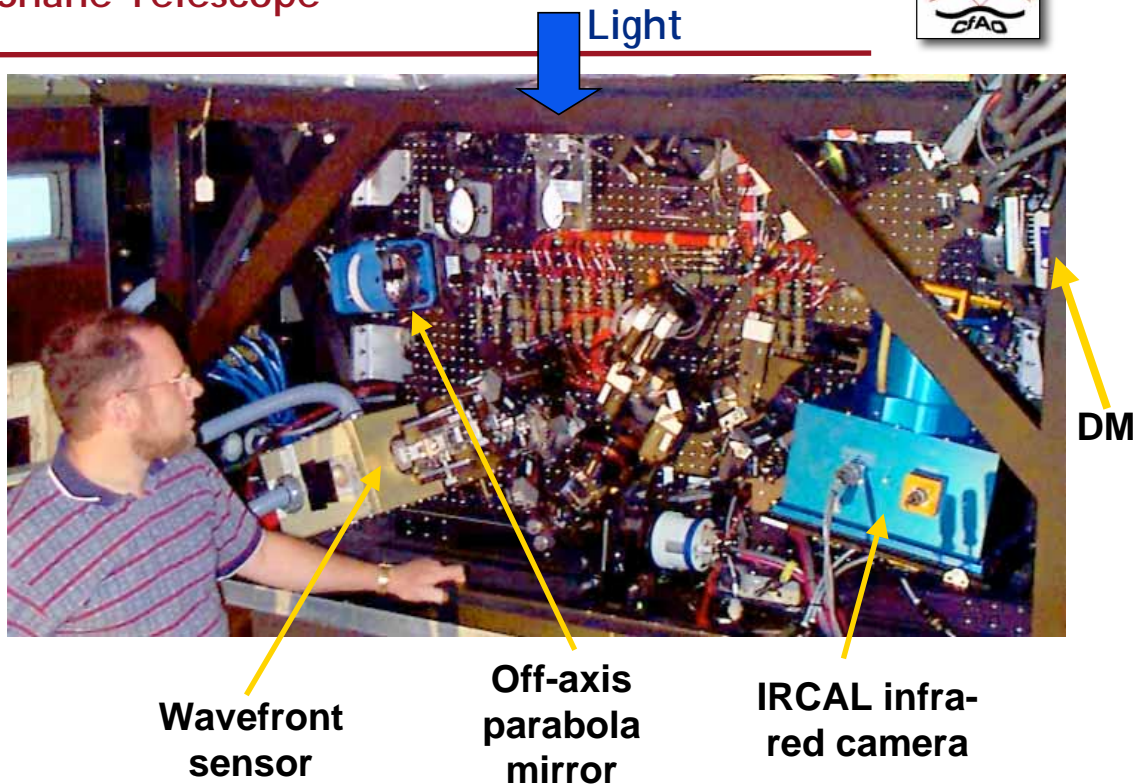
- Most wavefront sensing methods do not directly measure the wavefront error
- The measurements need to be processed to find the best estimate of the wavefront. In practice the DM actuator commands are what is usually sought.
- Don Wiberg, Marcos van Dam, and Matthew Britton will discuss aspects of wavefront control and reconstruction

Building and using AO systems



- Astronomical AO systems are complex
- Because the atmosphere is statistically describable, its possible to model AO system performance
- Don Gavel will discuss the optics needed for AO system design, and will also discuss how to characterize AO system performance

Lick adaptive optics system at 3m Shane Telescope



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What is the 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
- Headquarters at the University of California Santa Cruz
- 11 other universities, plus national laboratories and industrial partners



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)



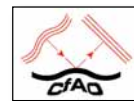
- 5) Integrating education with our research
- 6) Building a Center community that is supportive of diversity through vigorous recruiting, retention, and training activities
- 7) Encouraging the interaction of vision scientists and astronomers to promote the emergence of new science and technology
- 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 our 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 (winter quarter next year)
 - Taught by Max; some videoconference participation is possible

Some basic reference materials



- Web:
 - Max's graduate course
<http://www.ucolick.org/~max/289C/>
 - Tokavinin's course
<http://www.ctio.noao.edu/~atokovin/tutorial/intro.html>
 - Laird Close's course at U of Arizona
<http://athene.as.arizona.edu/~lclose/a519/>
 - Jennifer Lotz's AO tutorial
<http://www.pha.jhu.edu/~jlotz/aoptics/empaper2.html>
- 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