UCO/Lick Laboratory for Adaptive Optics

Developing Adaptive Optics for the Next Generation of Astronomical Telescopes

Donald Gavel, Daren Dillon, Renate Kupke, Marc Reinig, Sandrine Thomas, Mark Ammons , Katie Morzinsky, Andrew Norton, Oscar Azucena, Bautista Fernandez, Luke Johnson, Rosalie McGurk, Rachael Rampy

UCO/Lick Observatory Laboratory for Adaptive Optics
University of California, Santa Cruz

Brian Bauman, Bruce Macintosh, Dave Palmer, Lisa Poyneer

Lawrence Livermore National Laboratory

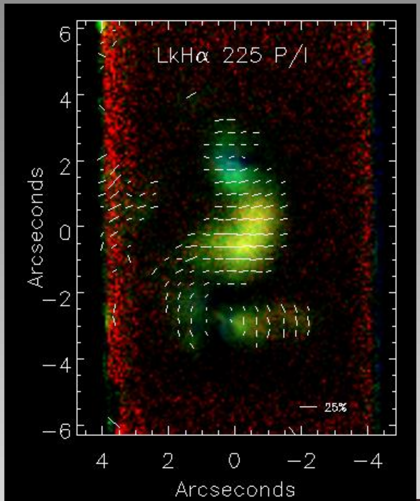
Astro 205
November 8, 2010

Lick Observatory, Mt Hamilton, CA

Laboratory for Adaptive Optics
UCO/Lick Observatory
University of California, Santa Cruz

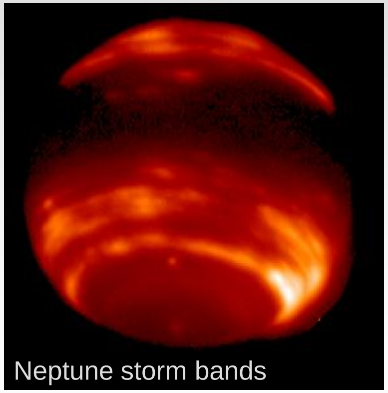
UCO/Lick Observatory: Pioneering Laser Guide Star Adaptive Optics

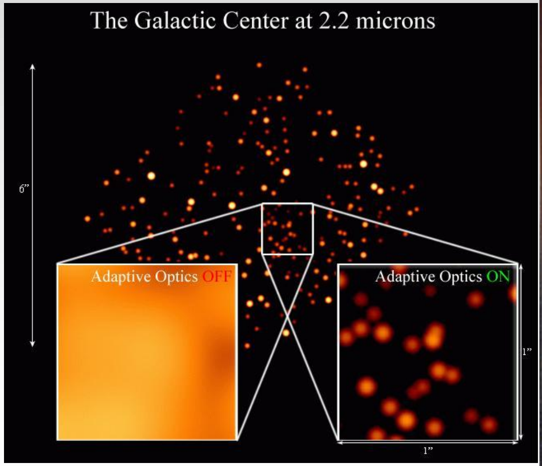
- LGS AO facility at Lick 3-m telescope – routine science observing since 2001
- LGS AO at Keck 10-m telescope – science observing starting 2005A

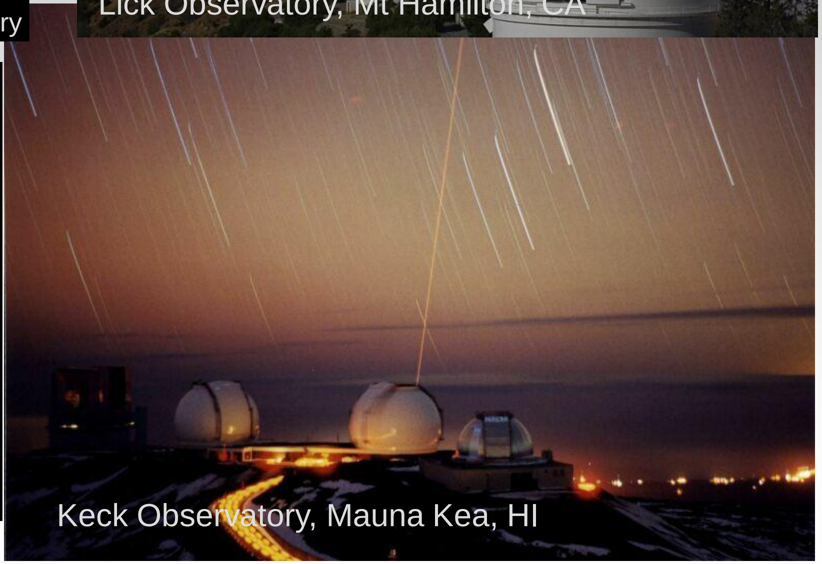


Star-forming regions - polarimetry


Lick Observatory, Mt Hamilton, CA

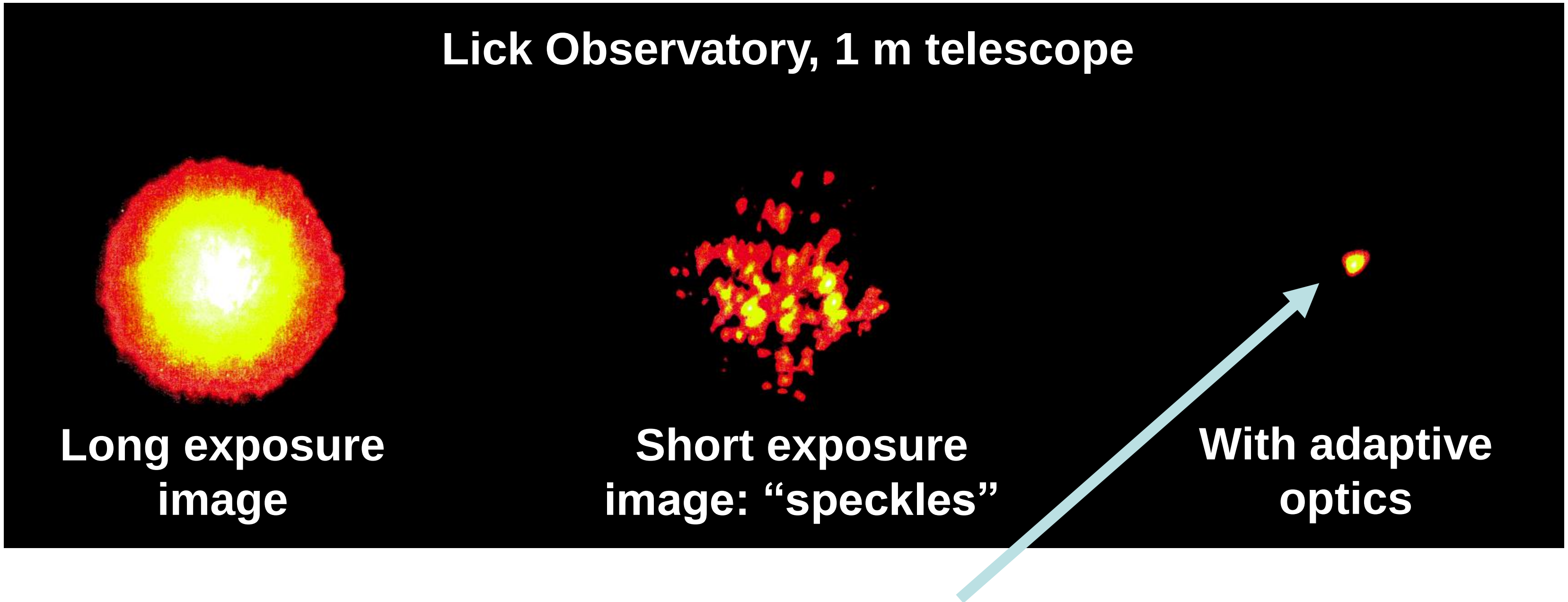

Neptune storm bands




Keck Observatory, Mauna Kea, HI

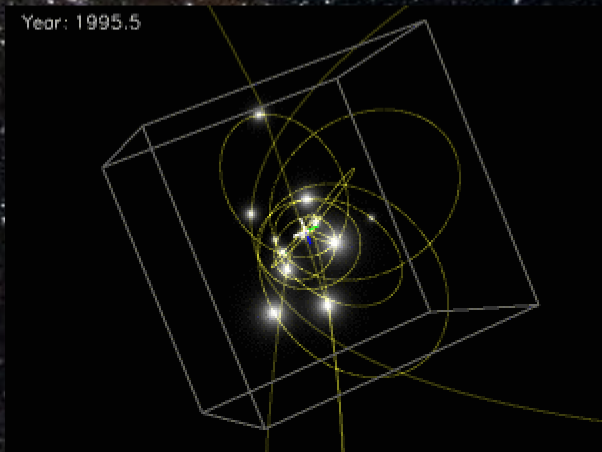
Why do astronomers need AO?

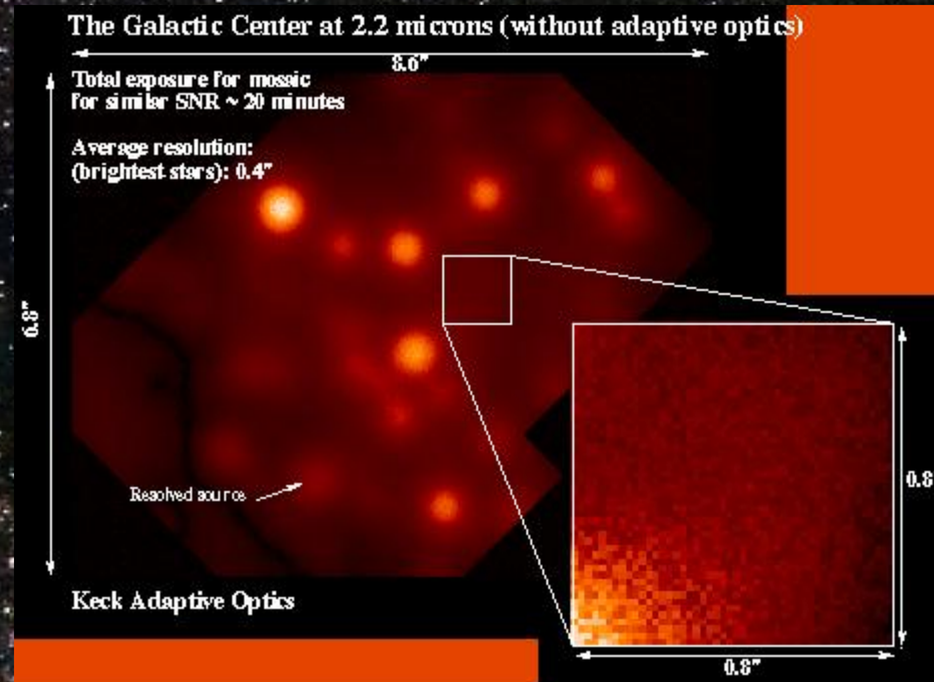
Three images of a bright star:

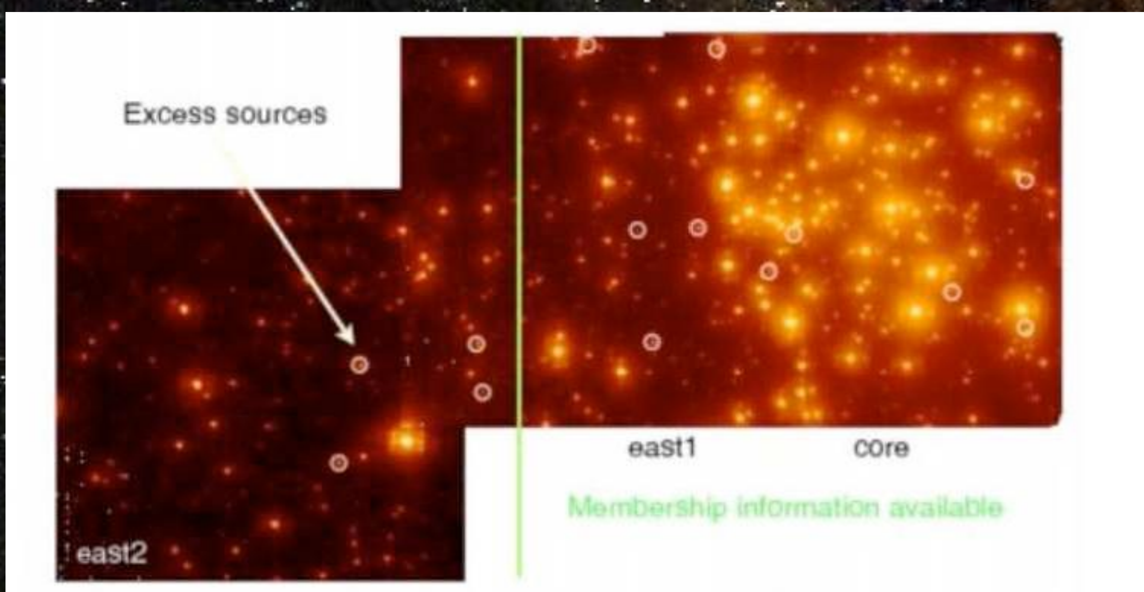


If image of a star is very small, your telescope will also be able to see fine details of galaxies, star clusters, ...

Galactic Center



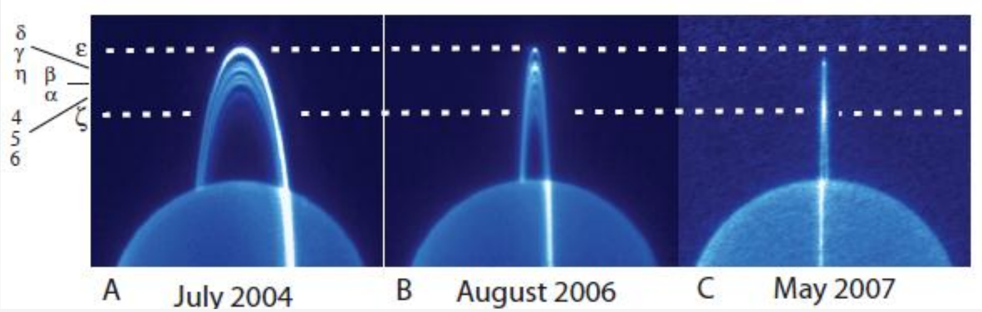




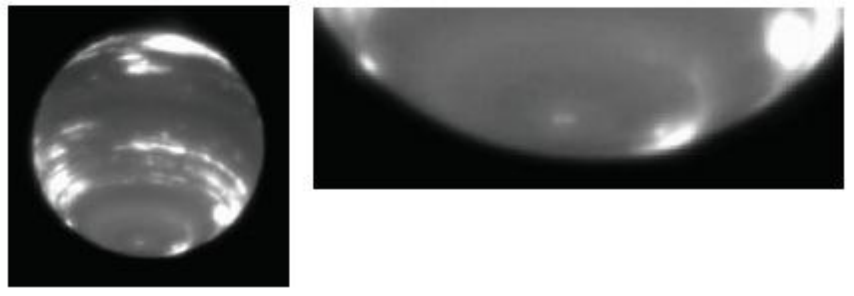
Left: **Arches cluster near the Galactic Center.** In the process of analyzing data collected to investigae the stellar mass function within the Arches cluster, we made the surprising discovery of finding many infrared excess sources. We have also expanded our astrometric coverage of the Arches to look for tidal effects (tidal radius and tidal tails).

Solar System Planetary Science

- Data from several of the currently available AO systems Keck, VLT, Gemini, Lick, and ESO-3.6 m
- Titan, Neptune, Uranus, Io, Jupiter's ring and Callisto, binary asteroids and transneptunian objects (TNO)



Comparison of the lit and unlit sides of the rings of **Uranus**. **(A)** The lit side in early July 2004, when the ring opening angle to Earth B = 11° , and the angle Bo to the Sun =13.2° . **(B)** The lit side on 1 August 2006 when B = 3.6° and Bo = 5.2° . **(C)** The unlit side on 28 May 2007 when B = 0.7° and Bo= 2.0° . The dotted lines show the position of rings e (upper line) and z (lower line). The pericenter of e was near the tip of the ring in 2006, at ~11 o'clock in 2004, and at ~ 2 o'clock position in 2007. (de Pater et al. 2007c)

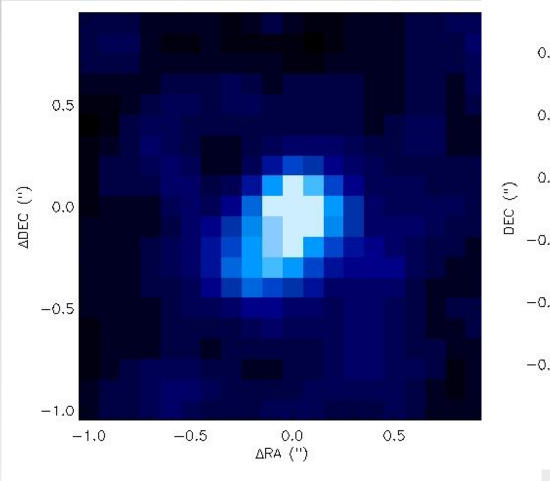


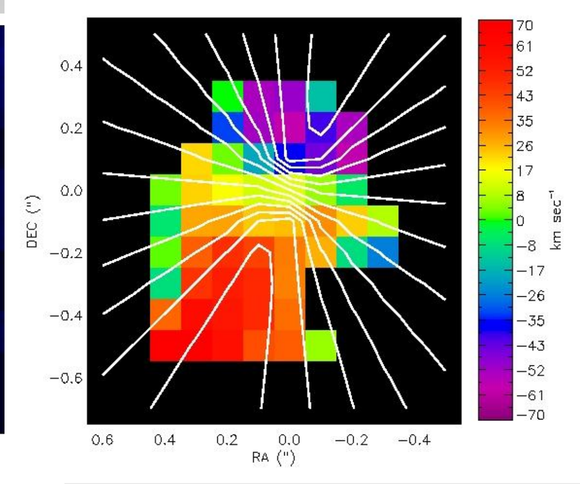
Keck AO image of **Neptune** in H band from 26 July 2007. On the right is an enlargement of the S. pole, showing the double spot. (Luszcz, de Pater, Hammel)

Extragalactic Research

Observe a large, deep sample of galaxies in the early universe

1. assembly of galaxies from smaller subunits to larger ones like our own Milky Way,
2. measure the rates of star formation and the evolution in stellar populations
3. discover the highest redshift supernovae
4. characterizing central active galactic nuclei (AGNs) throughout the past 10-12 Billion years

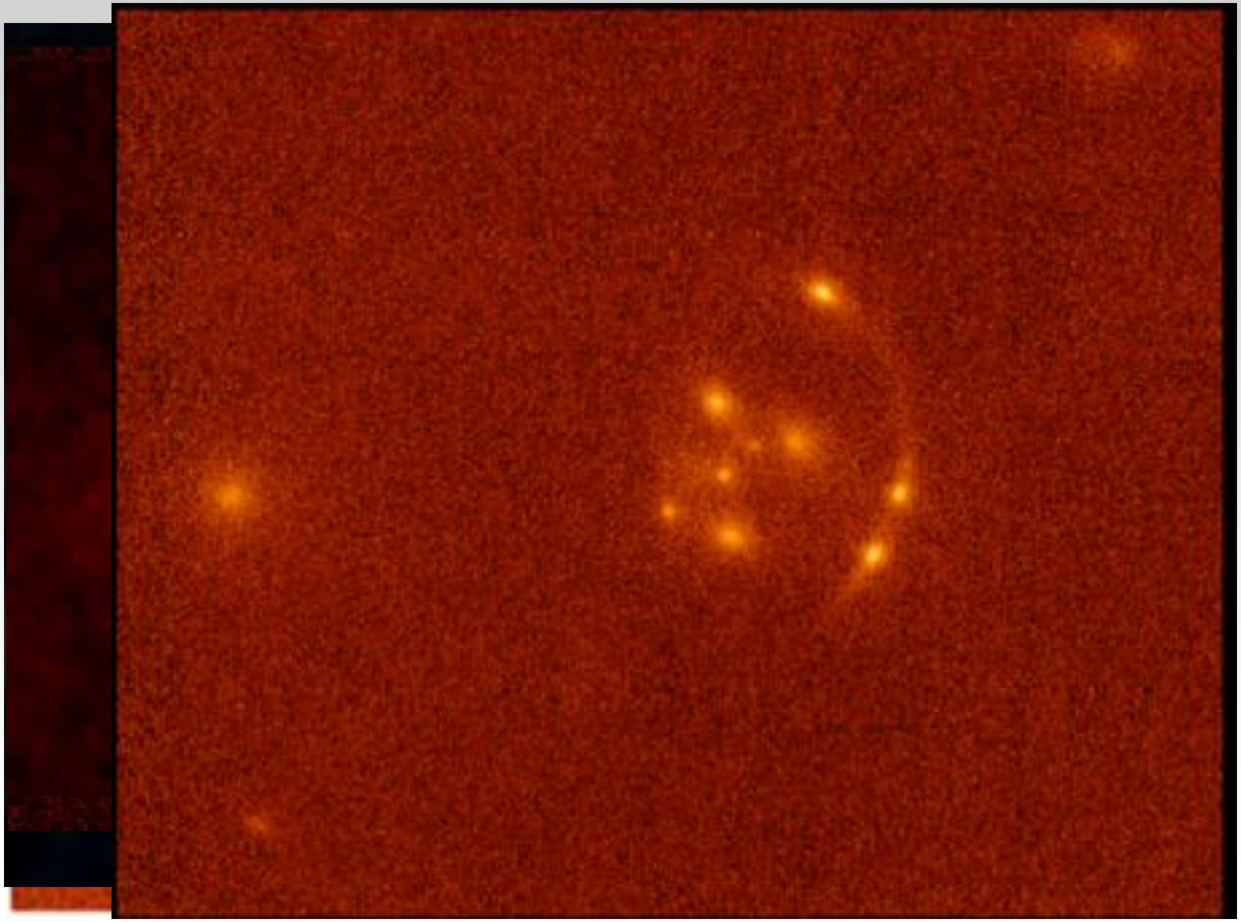




First successful OSIRIS LGS-AO detection of a high redshift star-forming galaxy (z=1.478). The image is a Gaussian smoothed (FWHM=0.2") mosaiced image of the Q2343 galaxy (Z=1.478) with a total exposure of 90 minutes collapsed around Hα ($\Delta\lambda$=0.0014 μm) with a spatial size of 2.0"x2.0". (BELOW) Two-dimensional Hα kinematics of Q2343-BM133 showing spatial distribution of velocity (km s^{-1}) relative to the measured systemic velocity. The two-dimensional velocity map for BM133 is indicative of a galaxy with a symmetrically rotating disk. Overlaid is the well-fit (reduced c^2 of 0.78) spider diagram for an inclined-disk model, with each contour representing 10 km s^{-1}. These results were recently published in Wright et al. 2007.

Gravitationally Lensed Galaxies

Hubble WFPC-2 to Keck II LGSAO comparison
Courtesy, Chris Fasnacht, UC Davis



Team: Chris Fasnacht, Matt Auger, John McKean, Dave Thompson, Keith Matthews, Tom Soifer, and Leon Koopmans
Presented at 2008 Keck Science Meeting

AO Impact on Astronomical Science

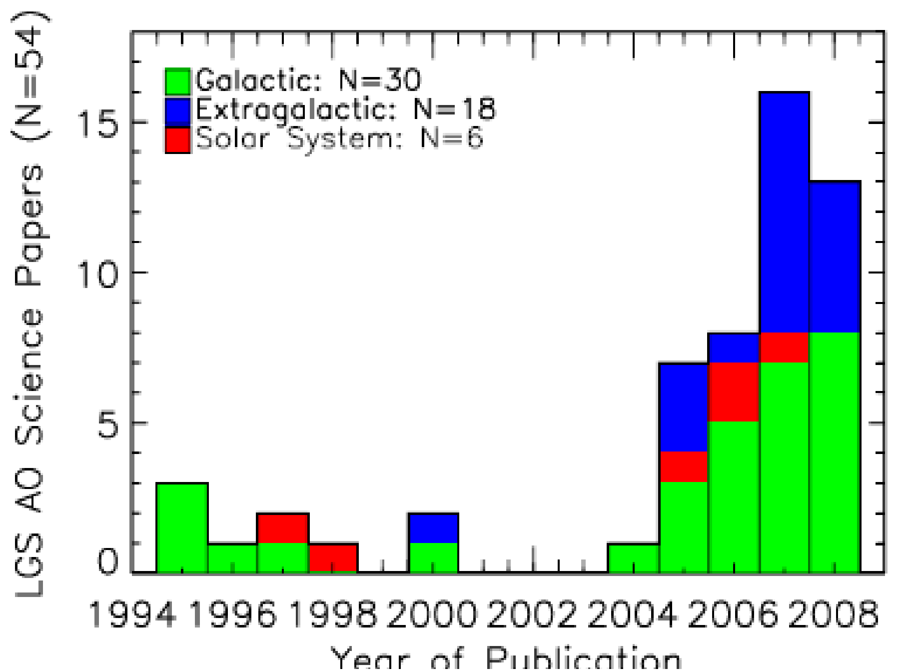


Figure 1. A summary of all refereed LGS AO science papers published as of June 2008, 54 in total. The colors represent different science areas. The large spike in publications since 2005 comes largely from the LGS AO system on the Keck II Telescope.

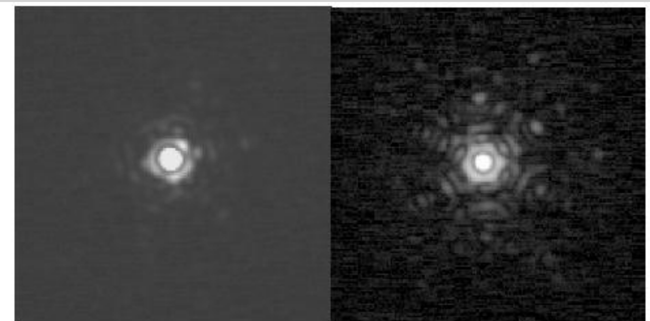
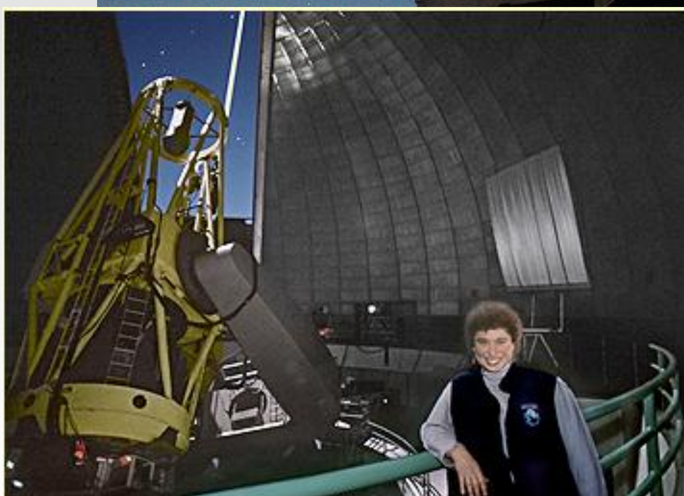


Figure 2: Some of the best images of a 7th magnitude star taken with the OWFC (left) and the NGWFC (right). The images have K-band Strehls of 58% and 66% respectively.

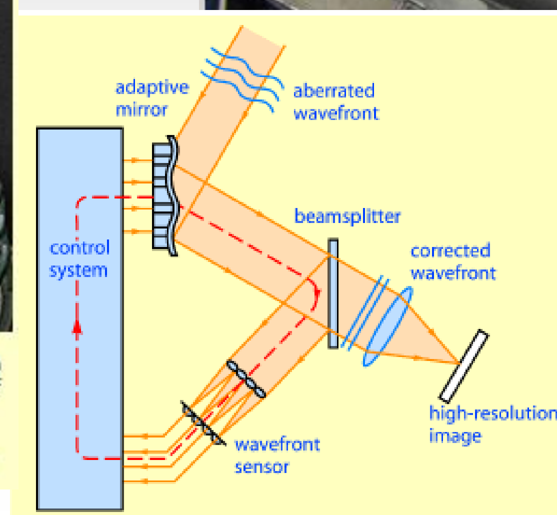
From van Dam et al, "**Performance of the Keck II AO System**," KAON 489

From Liu, "**LGS AO Science Impact: Present and Future Perspectives**," SPIE 7015, 2008.

Keck II 36-Segment Primary



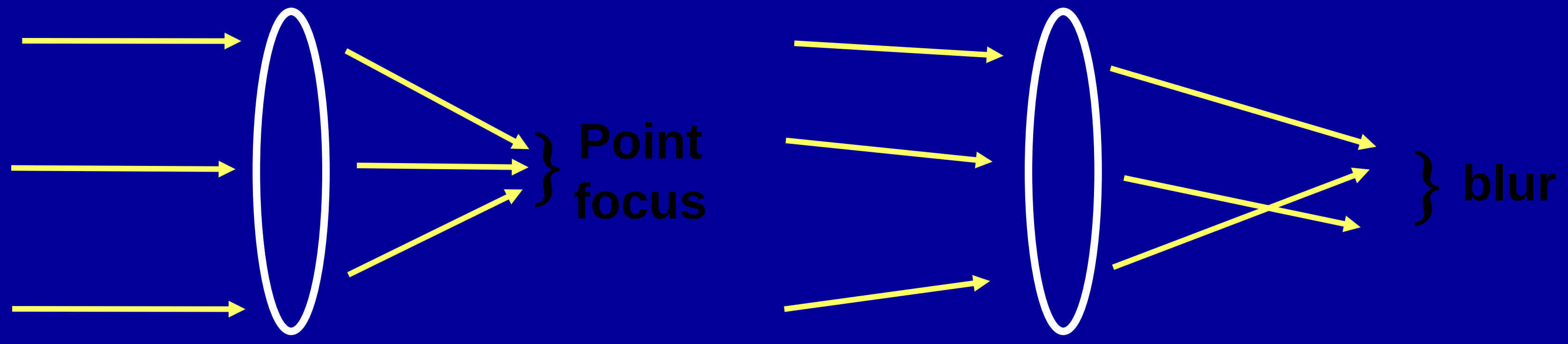
Claire Max stands next to the Shane Telescope at Lick Observatory on Mt. Hamilton. In the background, the bright straight line at the top of the photo is the laser beam from the laser guide star system Max designed as part of the telescope's adaptive optics system, which corrects for the blurring effect of the atmosphere. Photo by Laurie Hatch, Lick Observatory



Deformable Mirror:

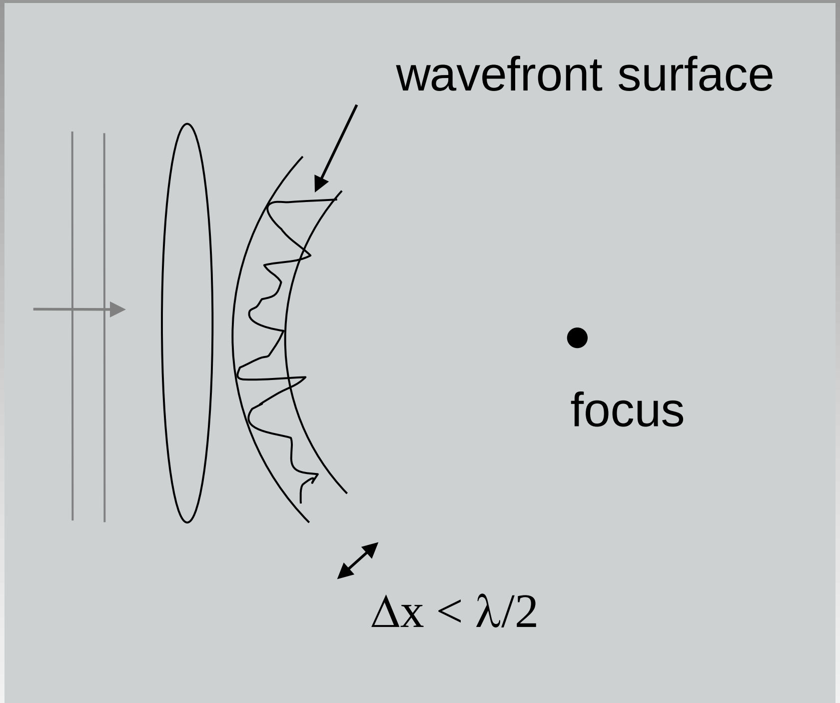
The Atmospheric Blurs Astronomical Images

- 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**

Diffraction-Limited Image Formation: Marechal's Condition

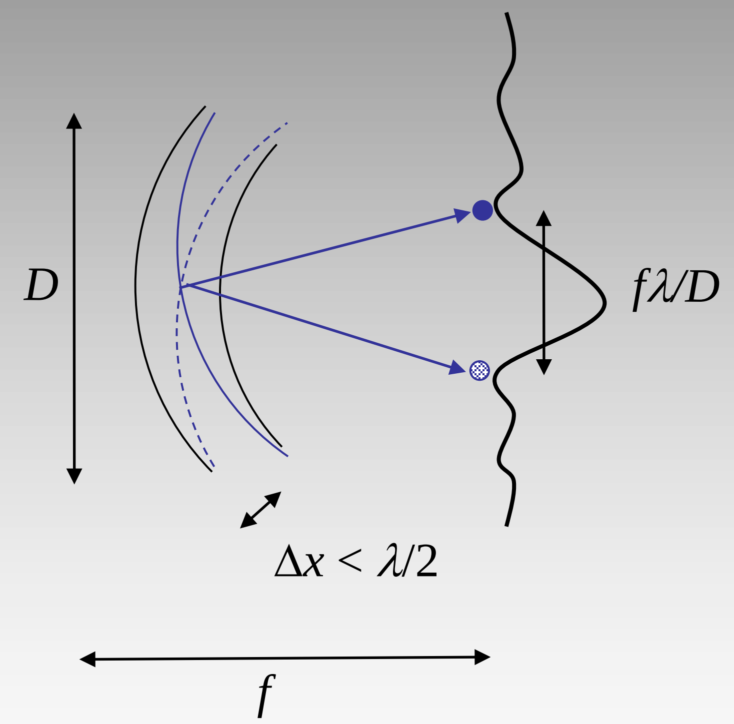


If the wavefront phase is contained within confocal spheres λ/2 apart everywhere where the intensity is significant

The waves will add up at the focus

Diffraction angle

- Tip/Tilt allowed by Marechal's condition



$$\theta = \frac{\lambda}{D}$$

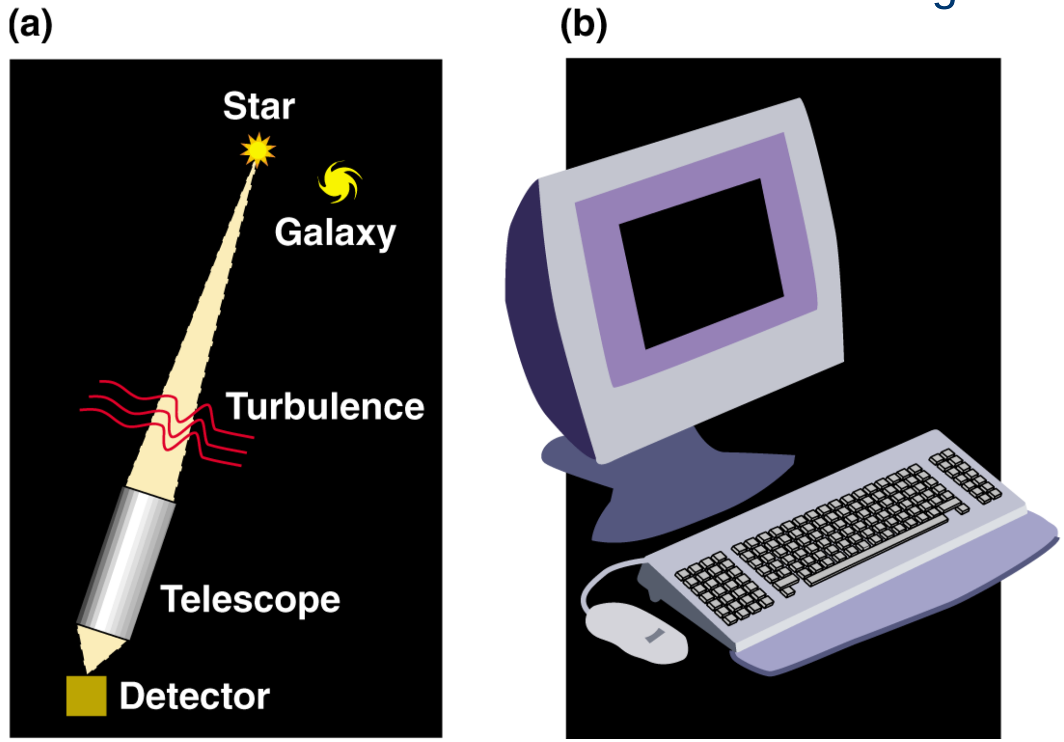
Laboratory for Adaptive Optics
UCO/Lick Observatory
University of California, Santa Cruz

How AO Works

Measure the wavefront from a “guide star” near the object you want to observe

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

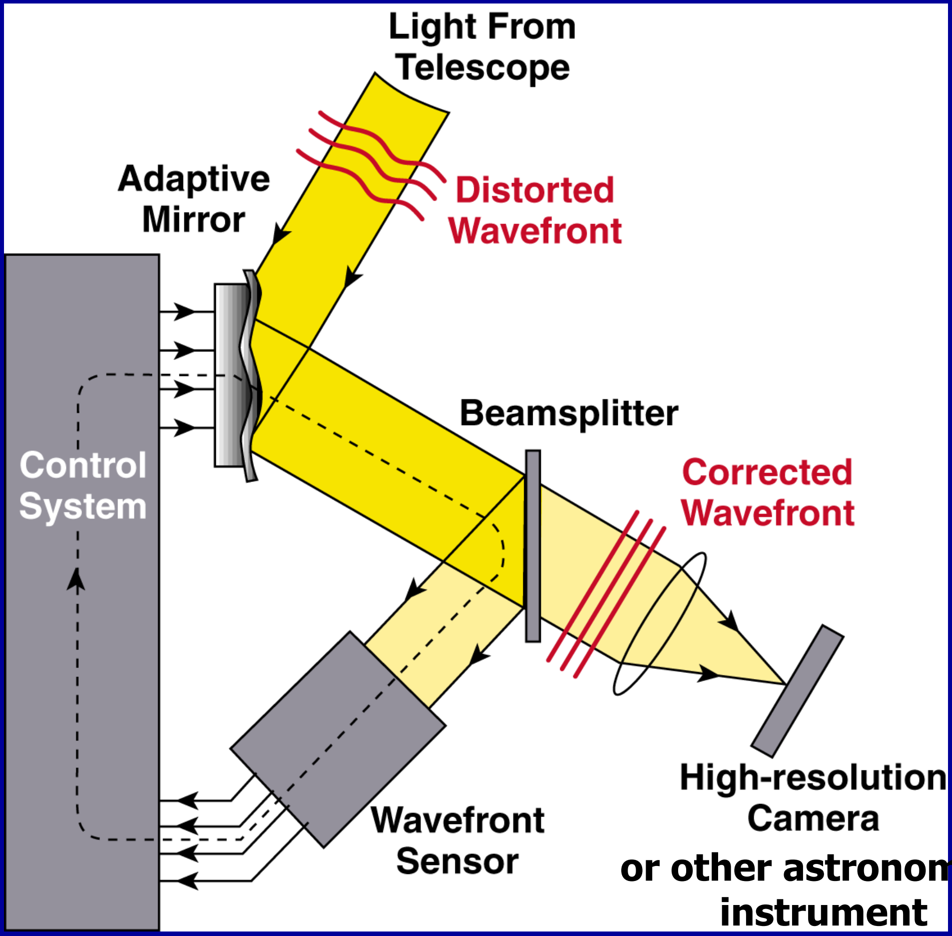
Light from both guide star and astronomical object is reflected from deformable mirror; distortions are removed



How Adaptive Optics Works

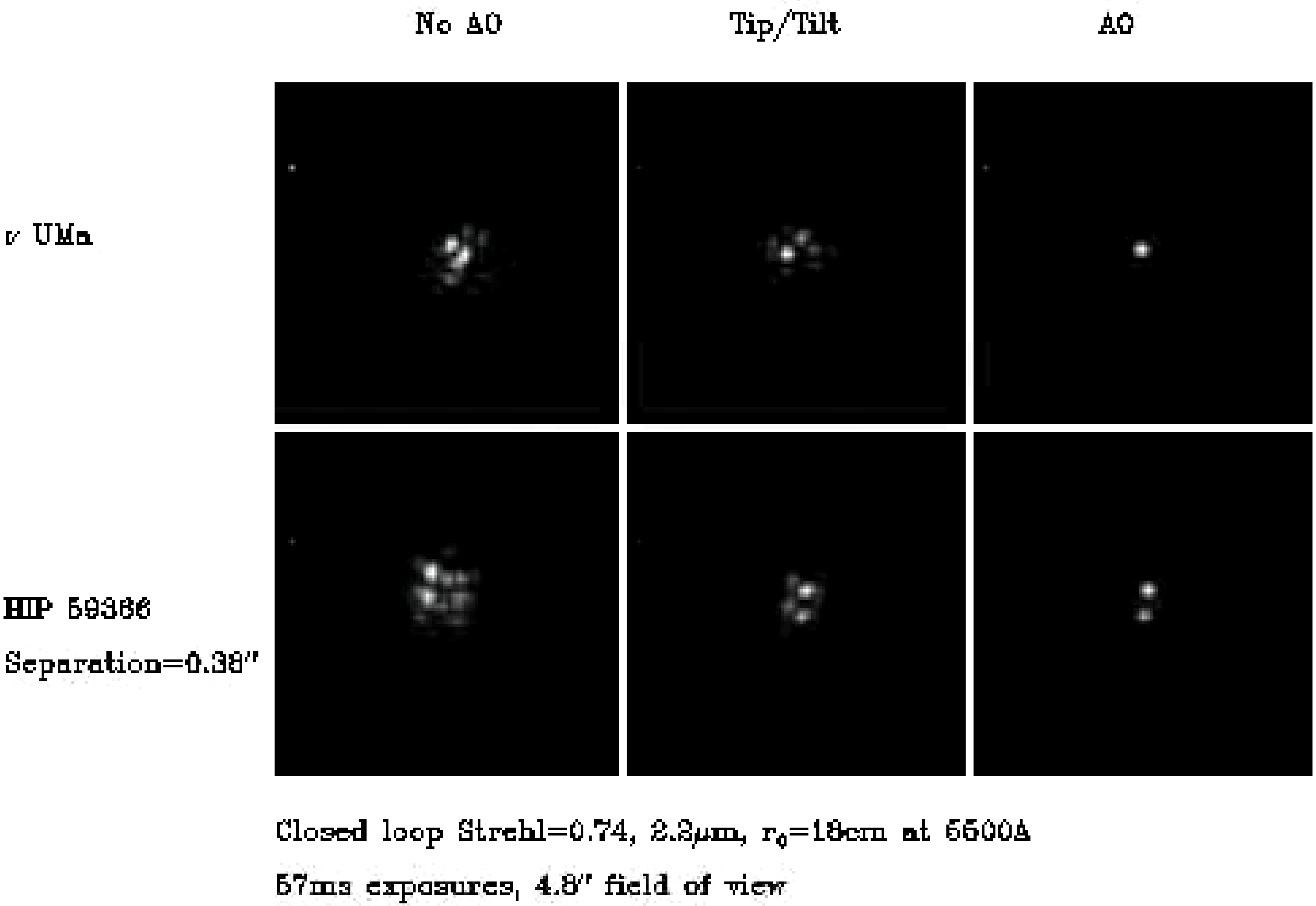
Invert the wavefront aberration with an "anti-atmosphere" (deformable mirror)

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



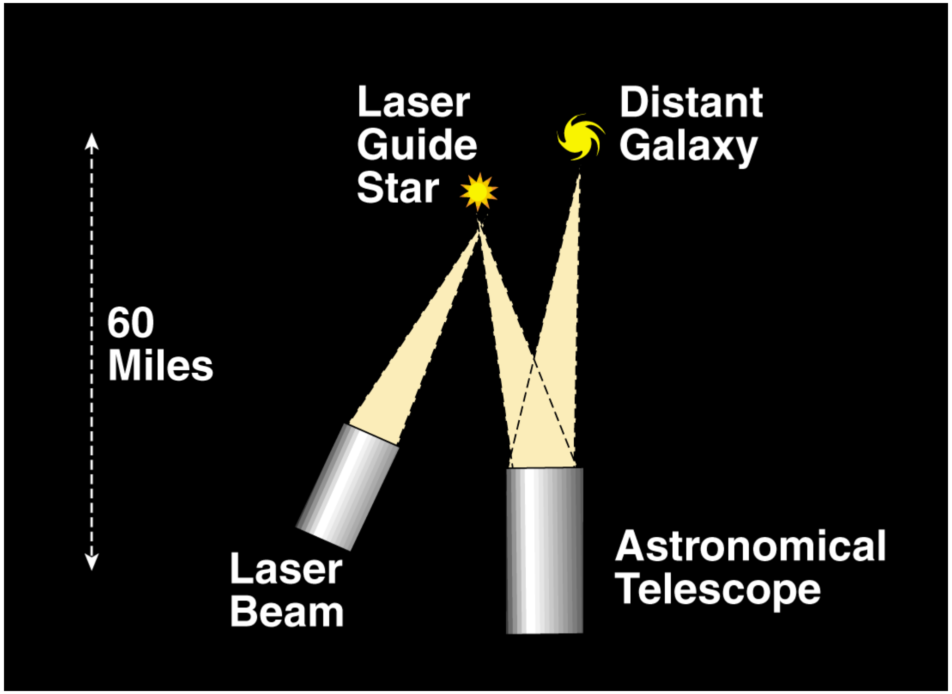
or other astronomical instrument

AO movie from Shane Telescope AO system

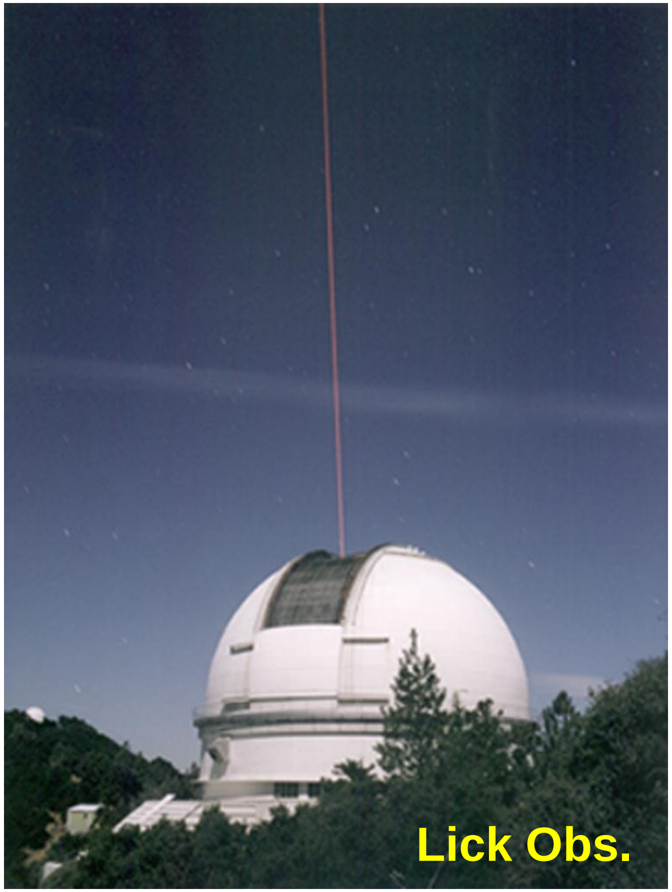


If there is no nearby star, make your own "star" using a laser

Concept

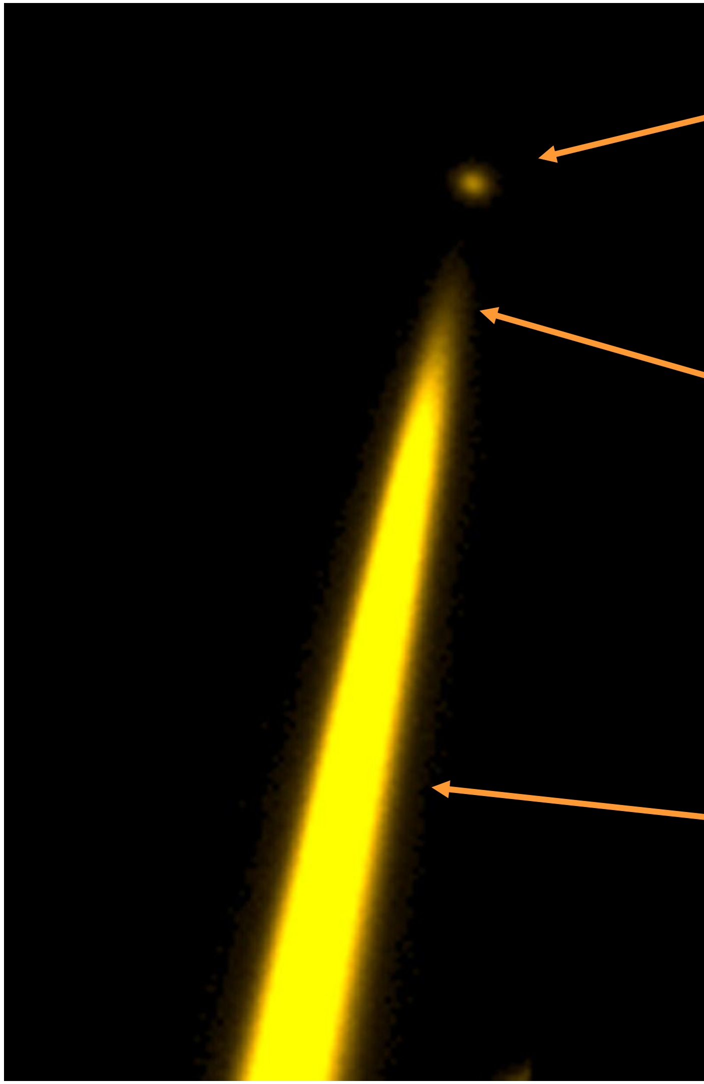


Implementation



Laboratory for Adaptive Optics
UCO/Lick Observatory
University of California, Santa Cruz

Anatomy of a Laser Guide Star



The Guide Star:
Fluorescent scattering by the mesospheric Sodium layer at ~ 95 km

Maximum altitude of (unwanted) backscatter from the air ~ 35 km

Back scatter from air molecules

Laboratory for Adaptive Optics
UCO/Lick Observatory
University of California, Santa Cruz

Laser Guidestar Structure in the Sodium Layer

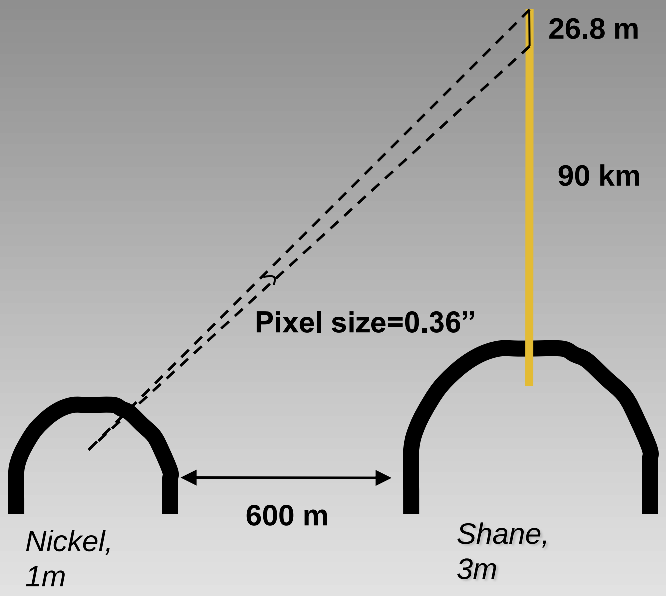
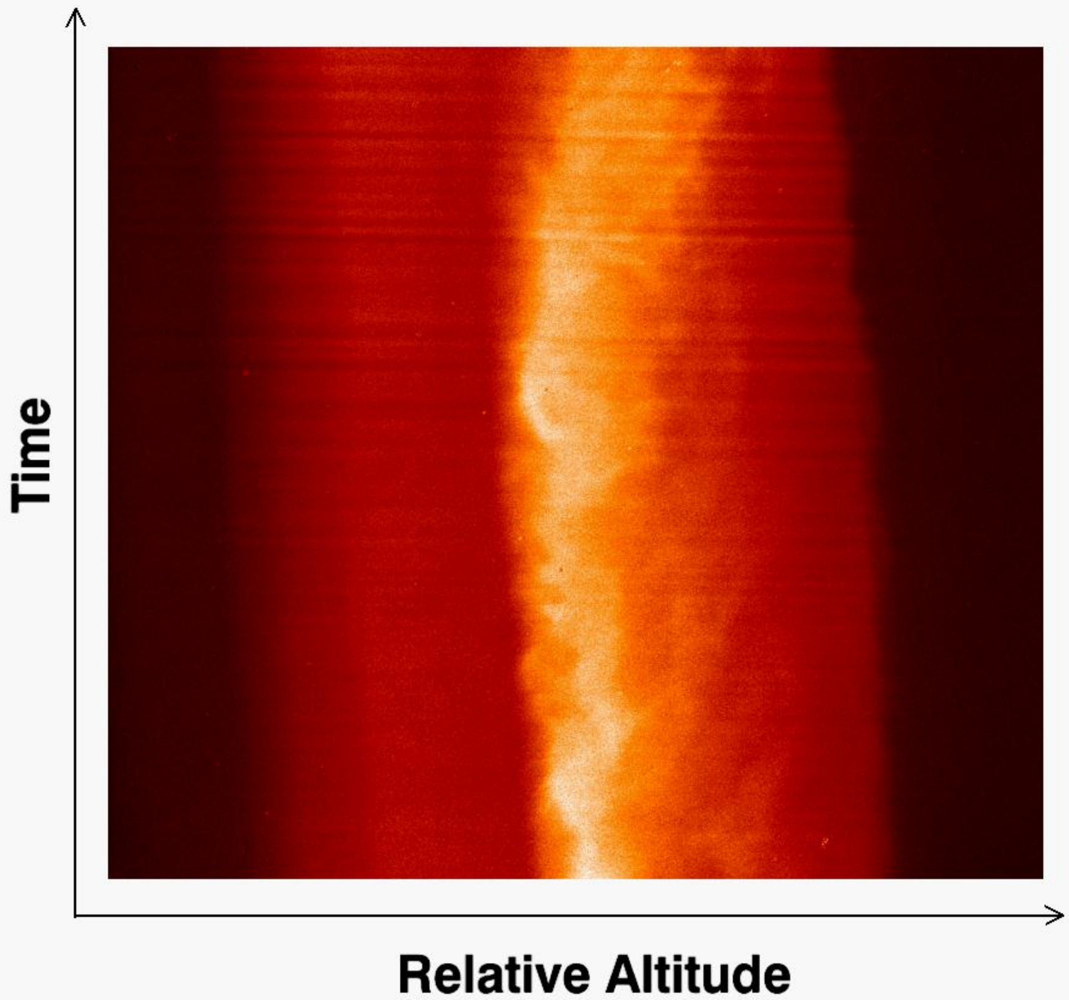


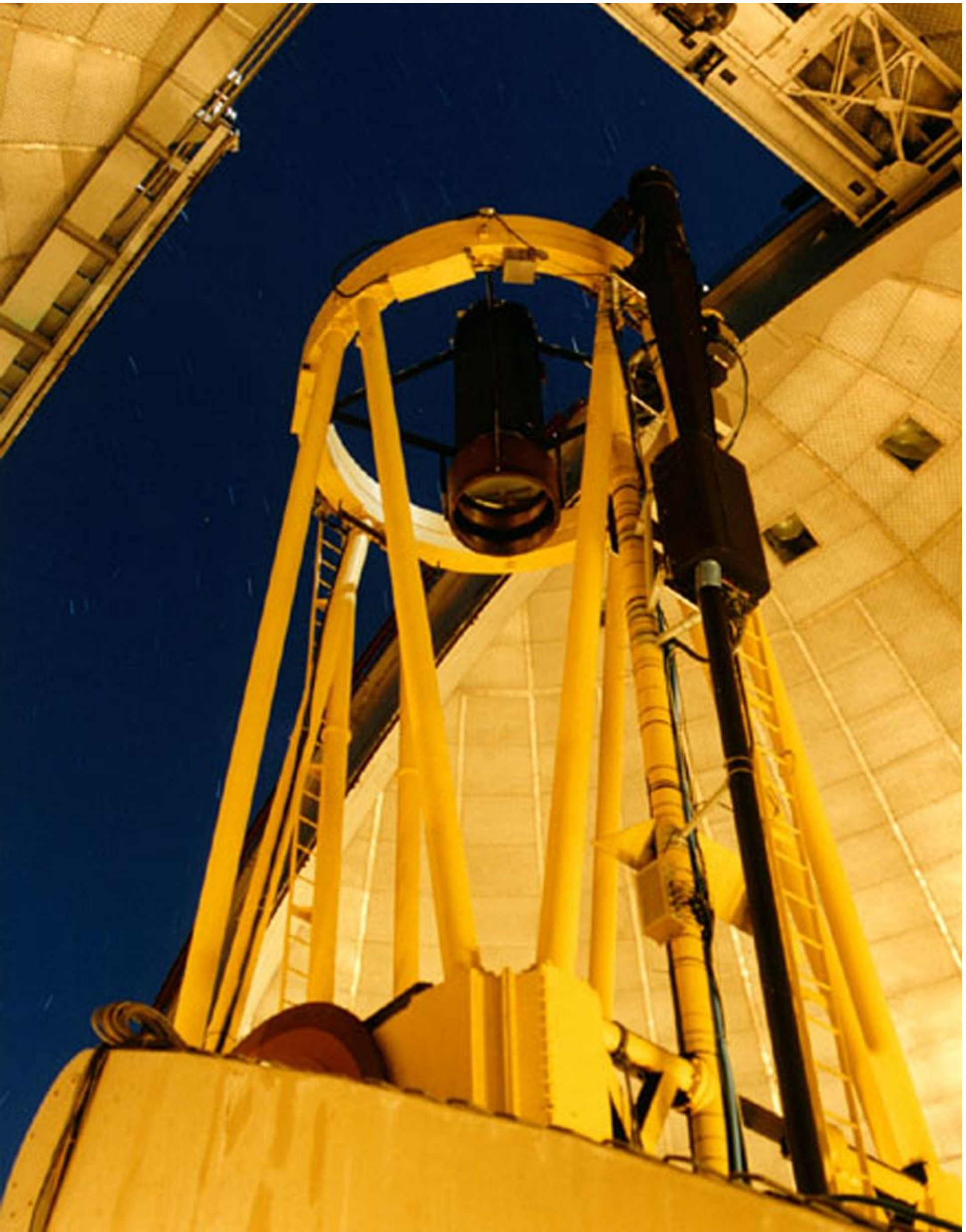
Figure 9. Variation of the mesospheric sodium density as a function of time and altitude was measured using the Lick Observatory Shane Telescope sodium laser. Drift-scan images from the Nickel, 600 meters to the west, enable us to resolve time and altitude dependence.

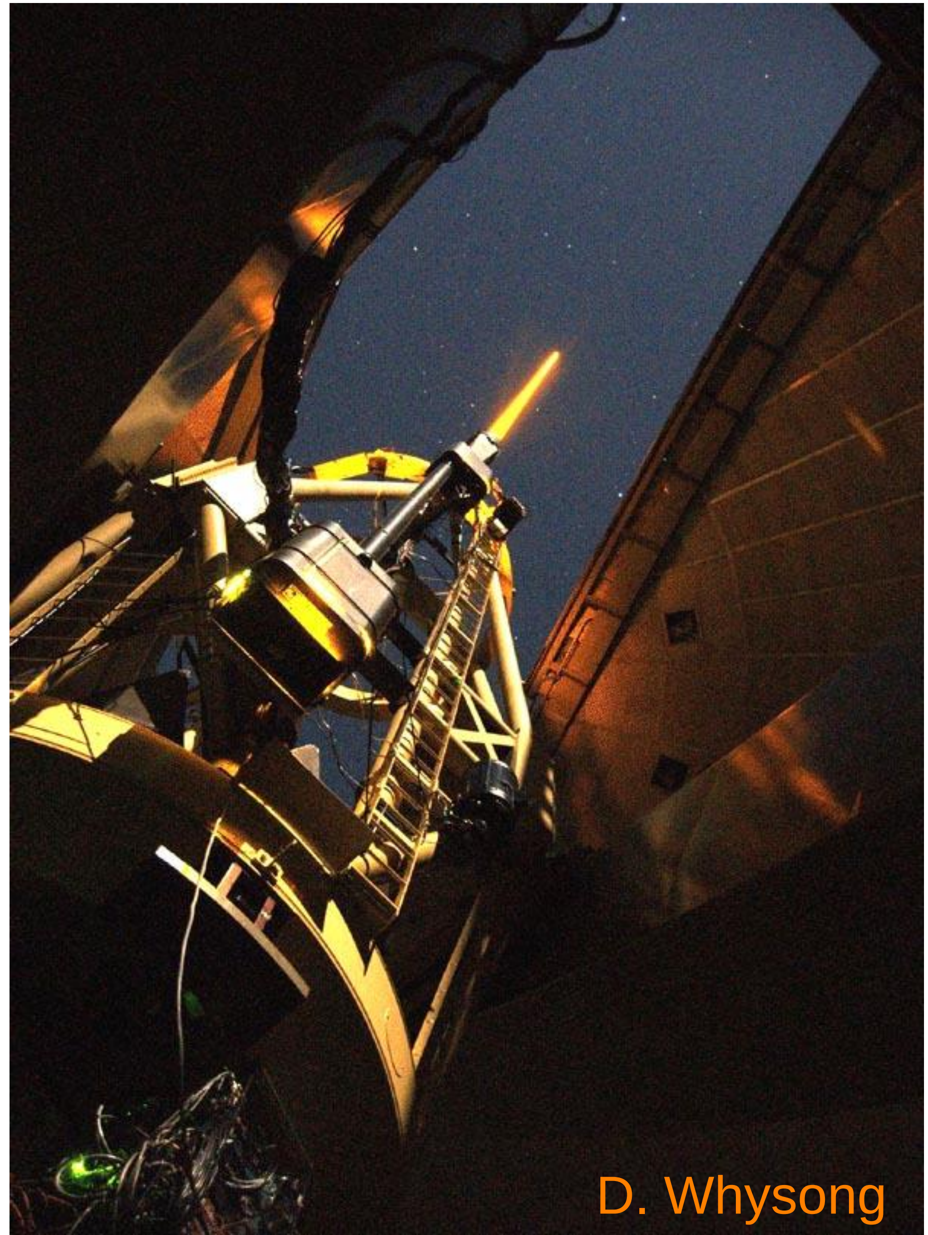


Laboratory for Adaptive Optics
UCO/Lick Observatory
University of California, Santa Cruz

Laser system on the Shane Telescope

Lick Observatory, Mt Hamilton, CA






M. Perrin

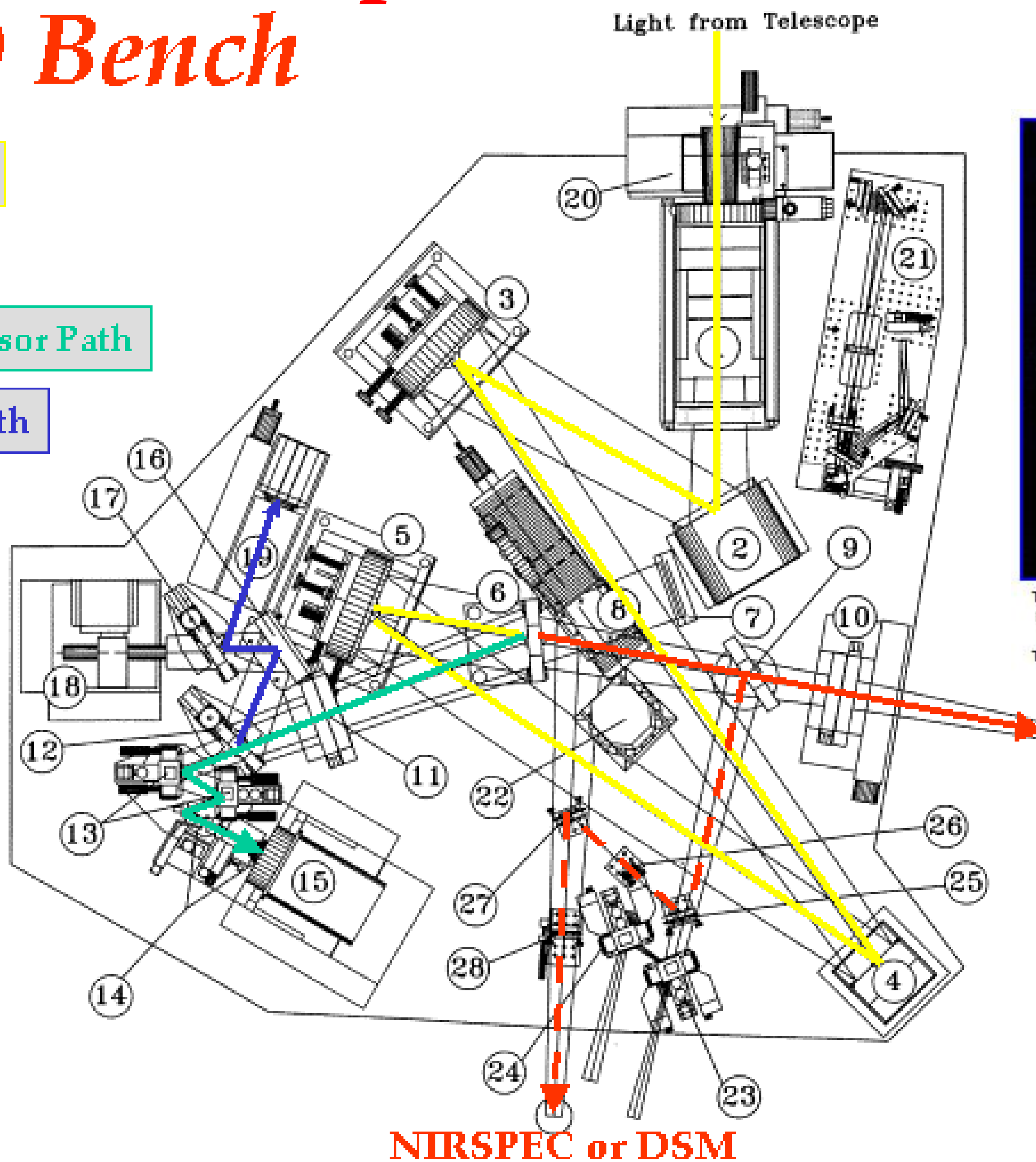
Keck Telescope
AO Bench

Common Path

Science Path

Wavefront Sensor Path

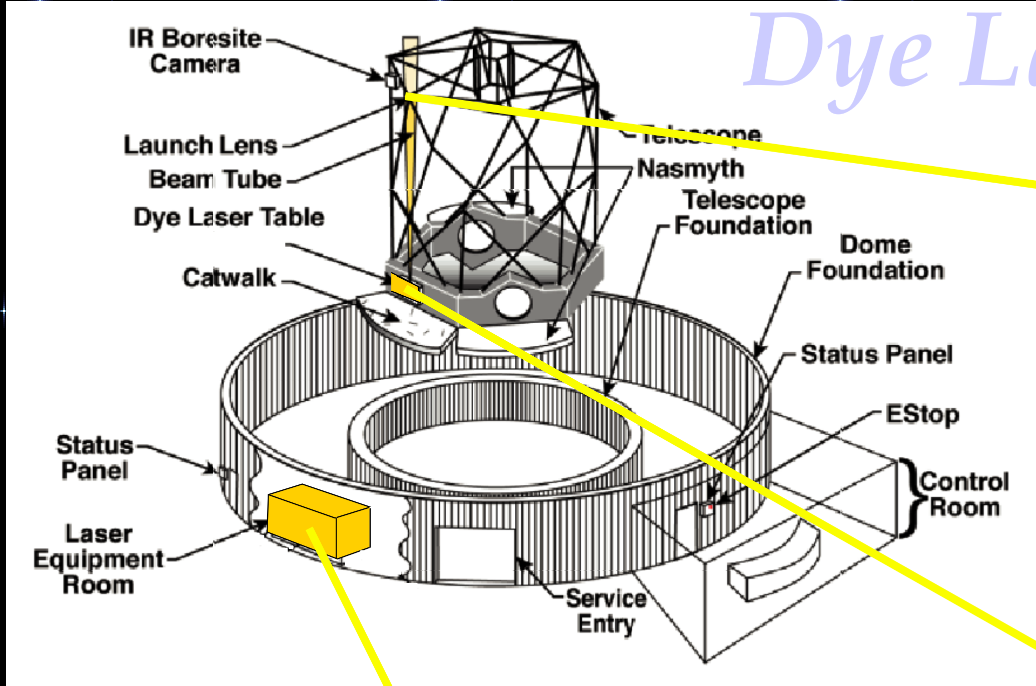
Acquisition Path

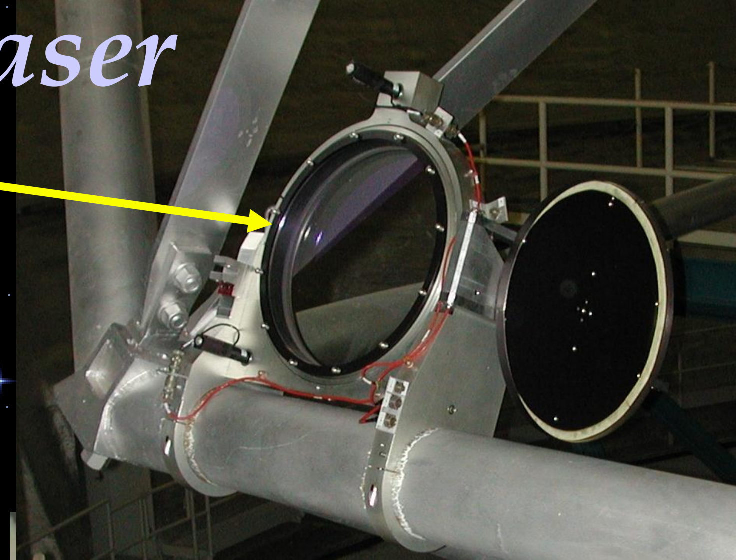


The Egg Nebula imaged on NIRC2 in H, H2 (2.12) and Kcont (2.29) bands on 07 Jul. 2004 UT - FOV: 15.8"x23.7"
TT ref. star: Rmag=14.3, sep=24.9arcsec

http://www2.keck.hawaii.edu/optics/ao/

Dye Laser


IR Boresite Camera
Launch Lens
Beam Tube
Dye Laser Table
Catwalk
Nasmyth
Telescope Foundation
Dome Foundation
Status Panel
EStop
Control Room
Status Panel
Laser Equipment Room
Service Entry

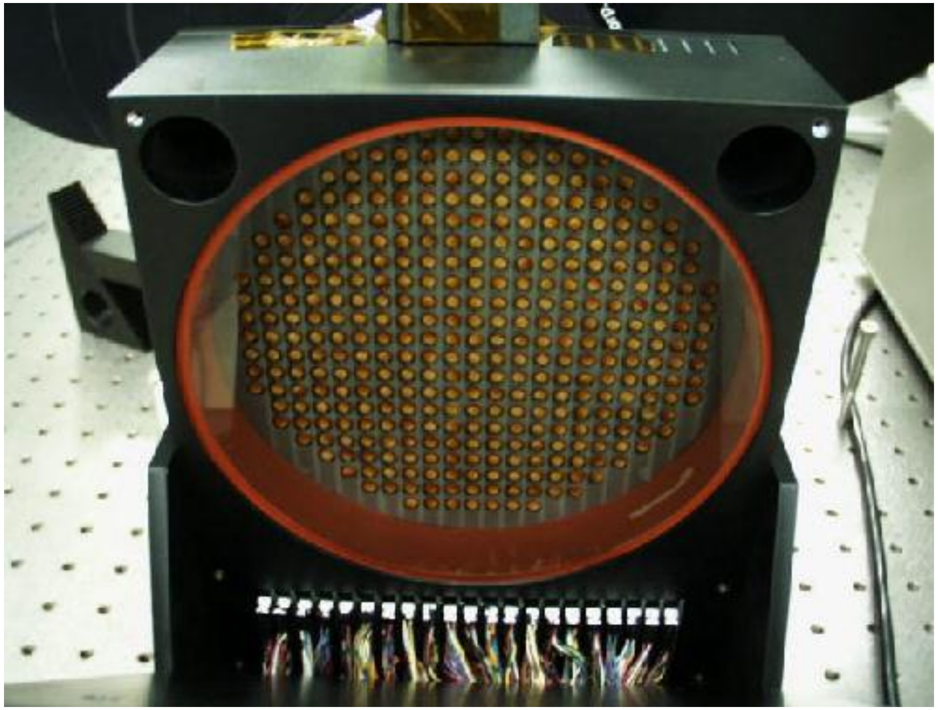



DANGER
FALL HAZARD
DANGER
FALL HAZARD

DM used on the Keck AO System

349 degrees of freedom

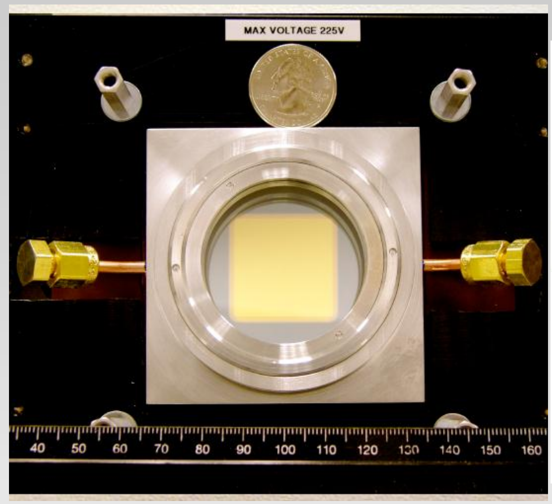
Front View

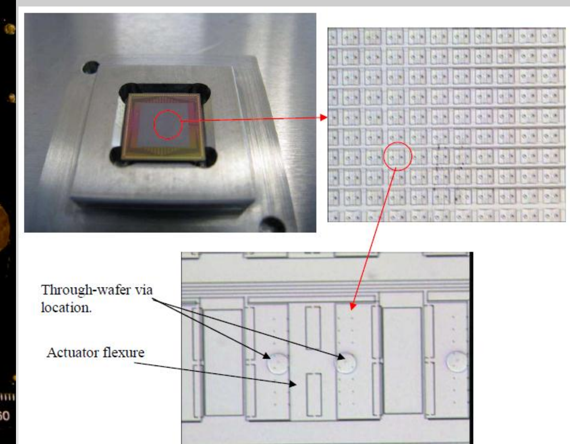


Back View

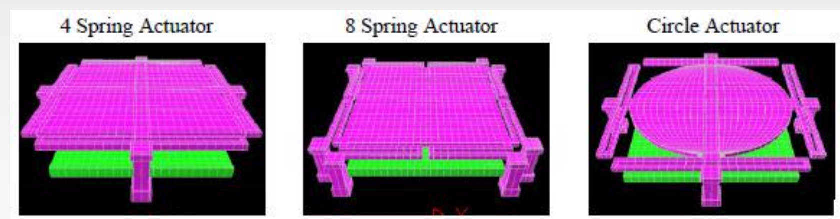
MEMS Deformable Mirrors

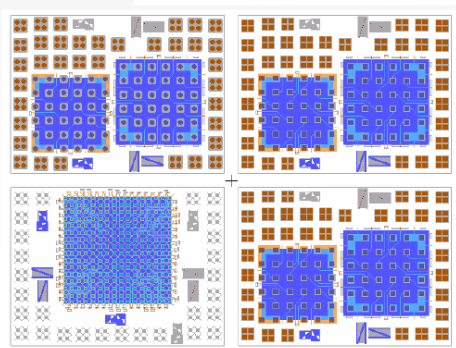
- **Consortium** to build 4,000 and develop 10,000 actuator devices (BMC)
  - Gemini Planet Imager
  - Keck Next Generation Adaptive Optics
  - Thirty Meter Telescope
- **High density** interconnect, packaging, & electronics (BMC)
- **Higher stroke actuator** designs (UCSC)





Boston Micromachines

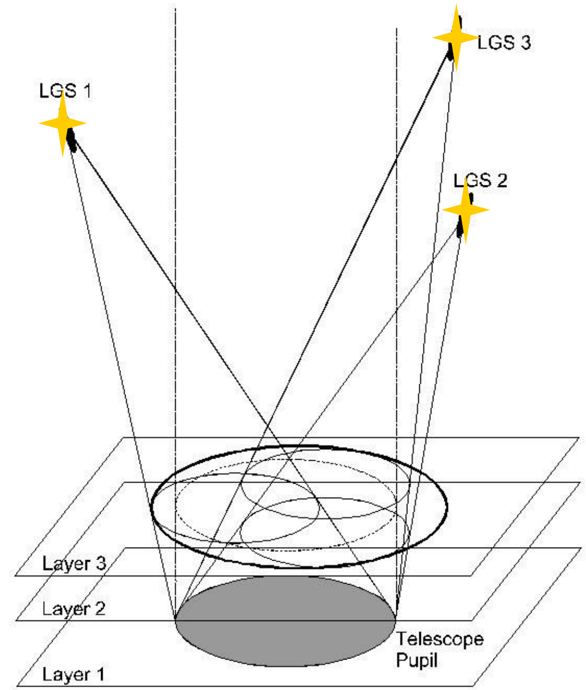




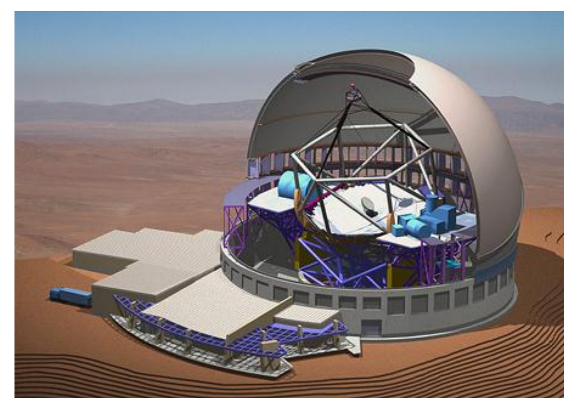
Joel Kubby, UCSC

Research Goals

1. Create **workable point designs** for wide field adaptive optics systems for future giant (30 meter class) telescopes
2. Develop long-range partnerships for developing **key AO technologies**:
    1. Deformable mirrors
    2. Wavefront sensor detectors
    3. Lasers to produce artifical guide stars
3. Develop techniques for doing **quantitative astronomy** given adaptive optically corrected data
4. Pursue **astronomical science** projects using existing laser guide star adaptive optics systems

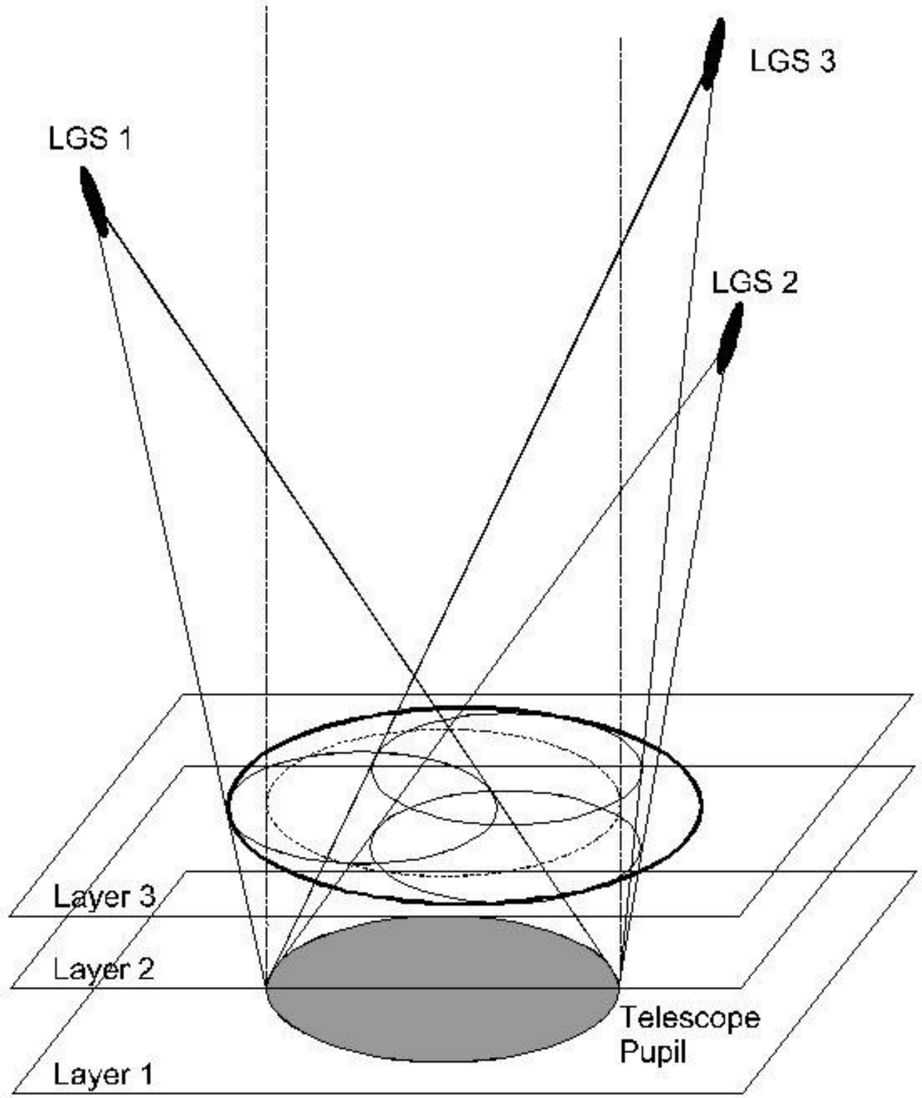



Keck Observatory

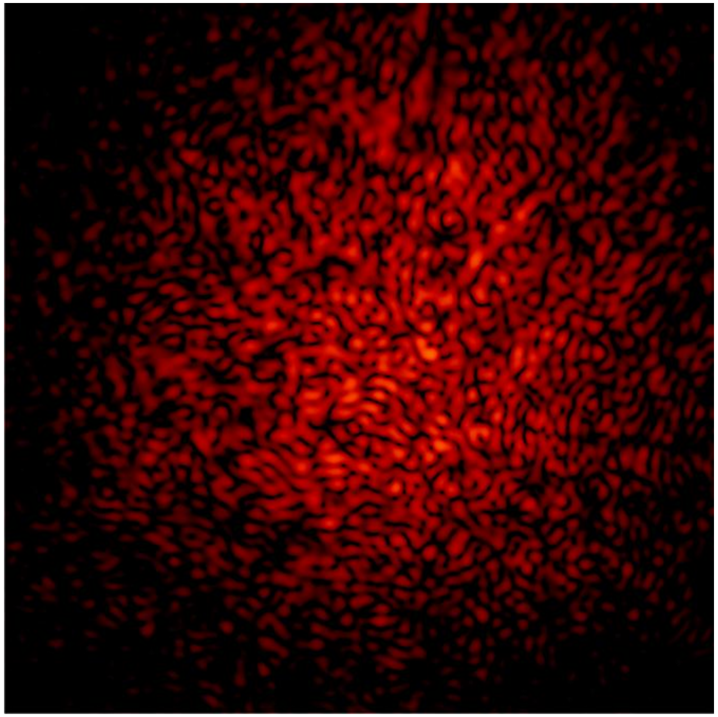

Thirty Meter Telescope

Next Generation Adaptive Optics

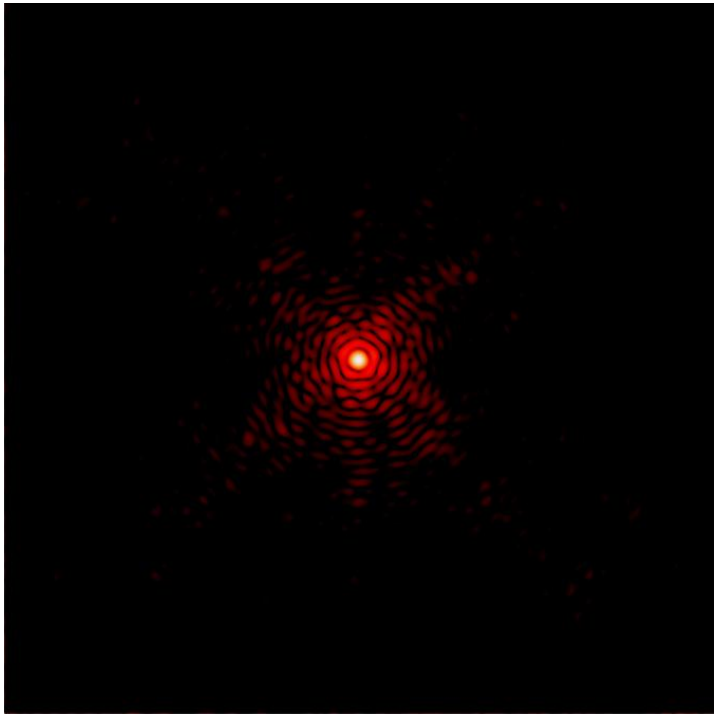
Multiple Guidestar Tomography + Volume Correction = MCAO



AO correction of a star – 30 meter telescope



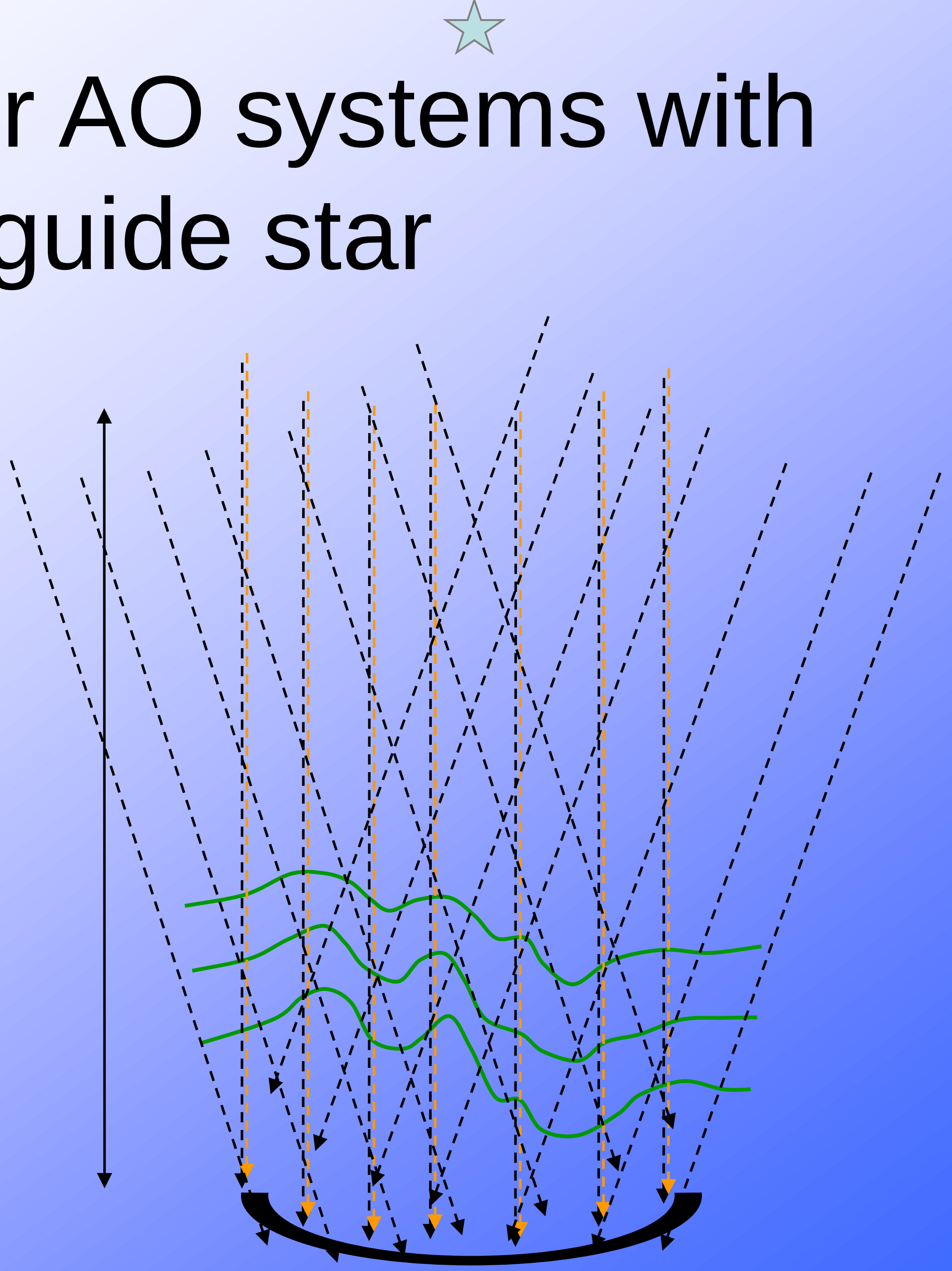
Uncorrected



Corrected

Limitations for AO systems with one guide star

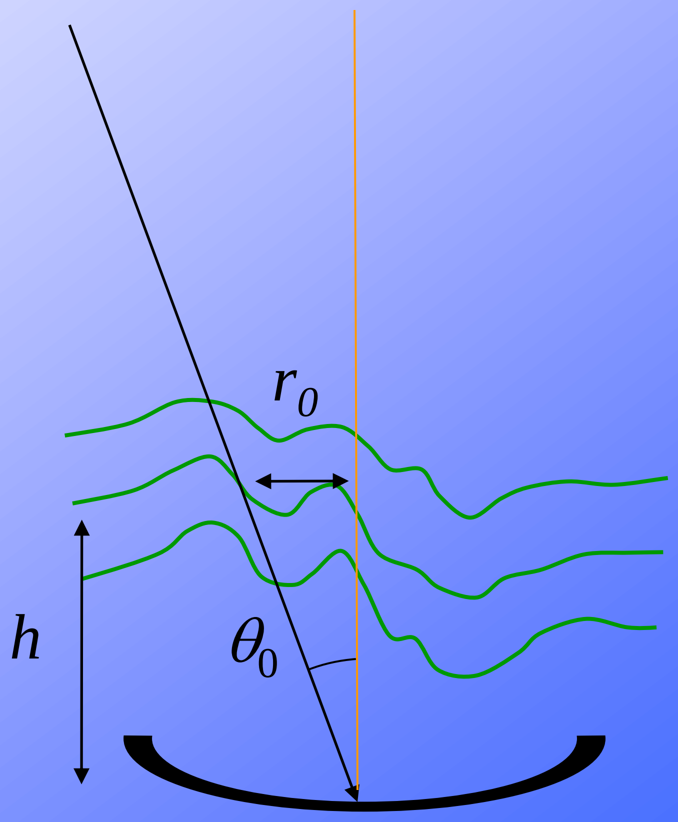
- Isoplanatic Angle



Limitations for AO systems with one guide star

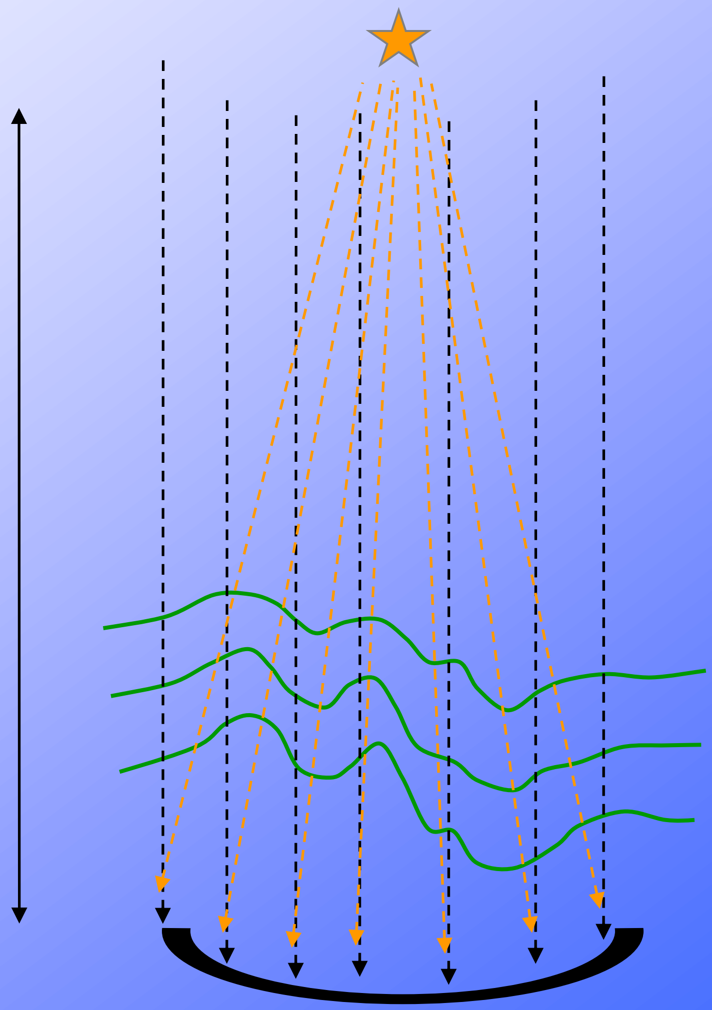
- Isoplanatic Angle

  Limits the corrected field



Limitations for AO systems with one guide star

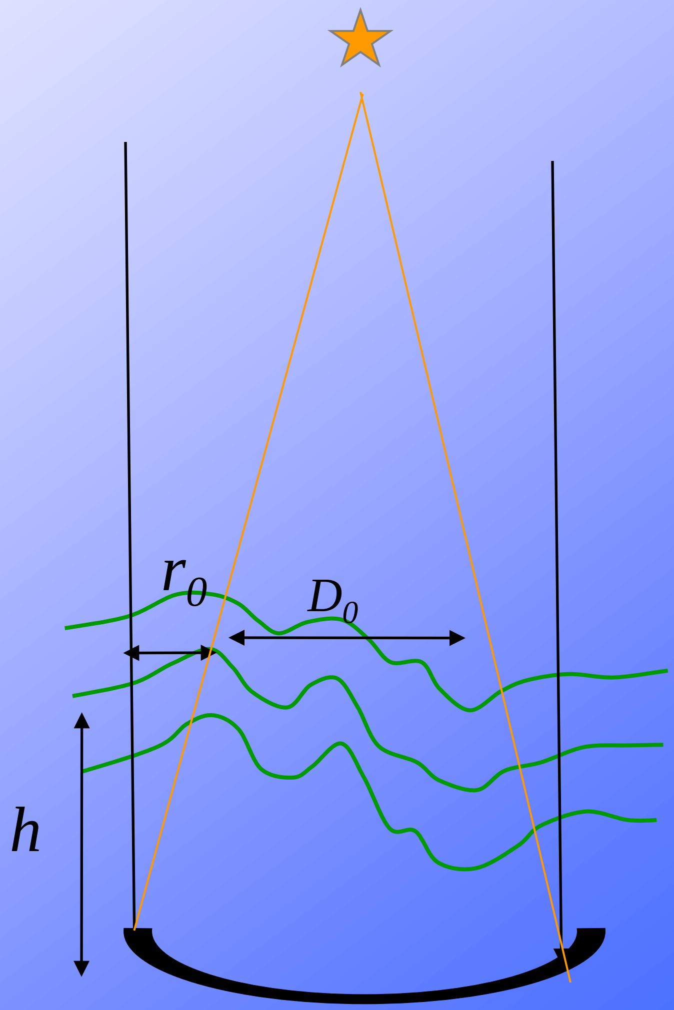
- Cone effect



Limitations for AO systems with one guide star

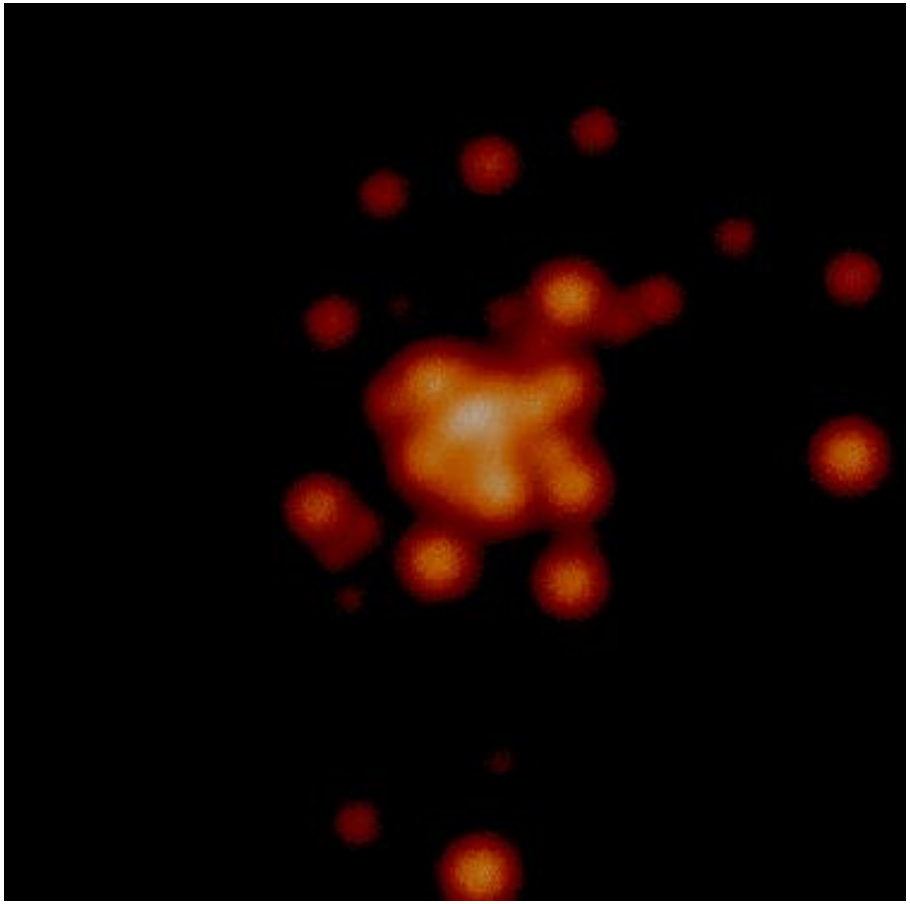
- Cone effect
  1. Missing turbulence outside cone
  2. Spherical wave “stretching” of wavefront

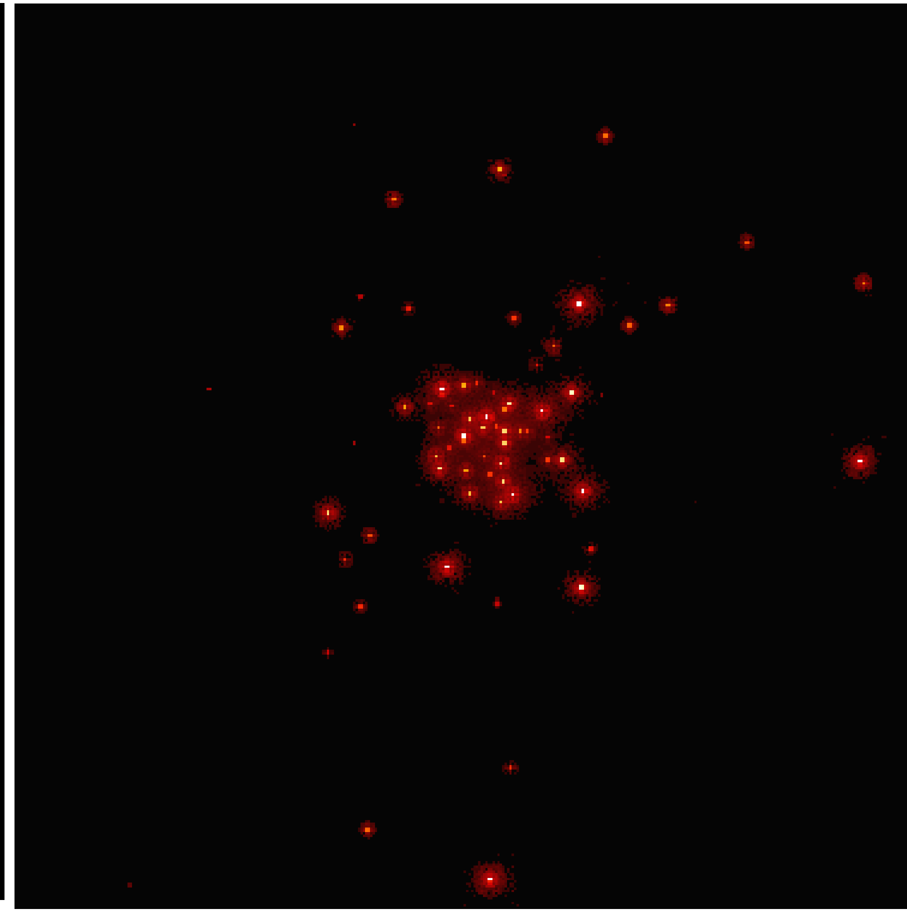
  Limits the telescope diameter



Laboratory for Adaptive Optics
UCO/Lick Observatory
University of California, Santa Cruz

MCAO correction of a field of stars
30 meter telescope





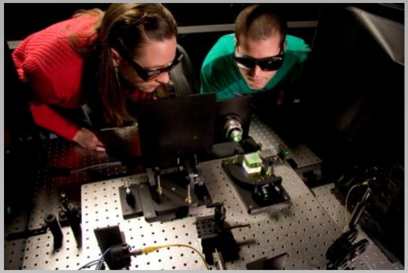
Uncorrected **Corrected**

Simulation performed by Jose Milovich on the MCR supercomputer cluster at Lawrence Livermore National Laboratory

Laboratory for Adaptive Optics
UCO/Lick Observatory
University of California, Santa Cruz

Laboratory for Adaptive Optics

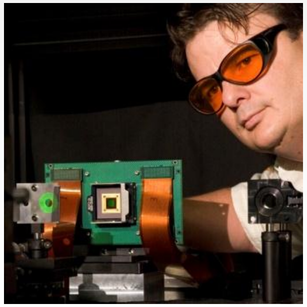
Claire Max, Principal Investigator
Joseph Miller, co-Investigator
Jerry Nelson, co-Investigator
Donald Gavel, Laboratory Director



- A permanent facility within the UCO/Lick Observatory located at the UC Santa Cruz campus
- Presently funded by a grant from the Gordon and Betty Moore Foundation

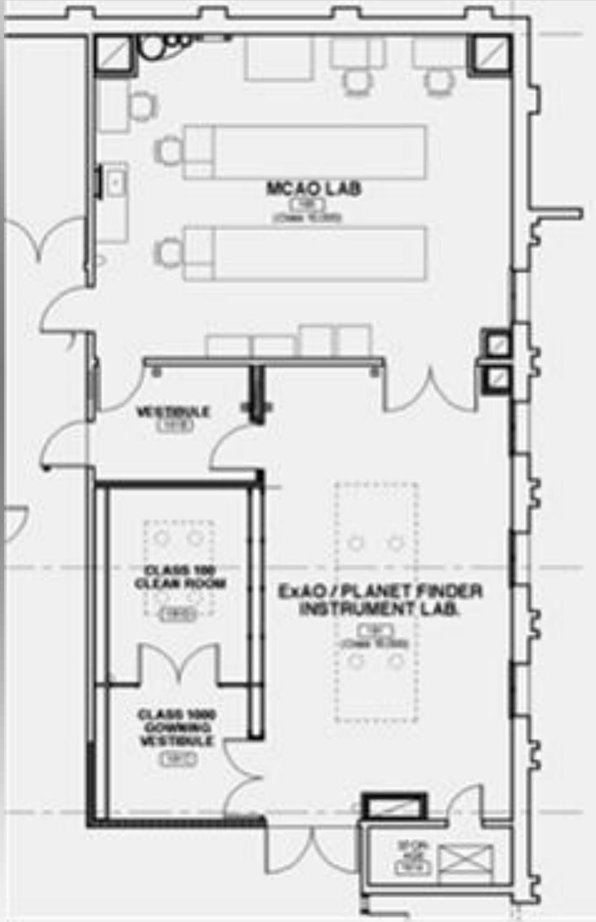
LAO Goals

1. Develop Adaptive optics technology and methods for the next generation of extremely large ground-based telescopes
2. Develop and build a planet finder instrument using “extreme” adaptive optics technology
3. Develop, test, and evaluate new components and key technologies for adaptive optics
4. Provide a laboratory where students and postdocs will be trained in adaptive optics design, modeling, and implementation



Laboratory for Adaptive Optics
UCO/Lick Observatory
University of California, Santa Cruz

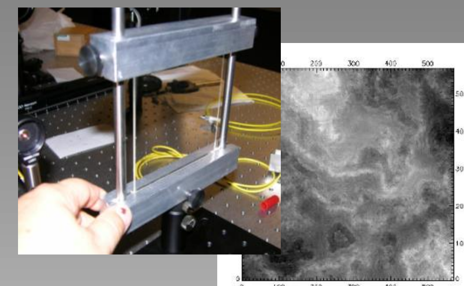
LAO Facility
in Thimann Labs Building, UCSC



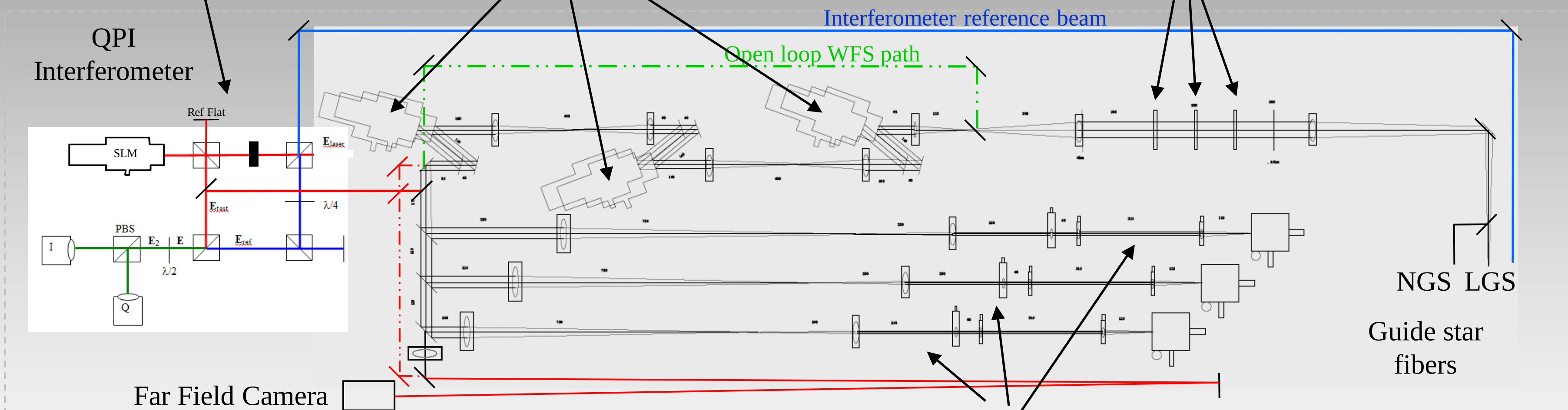
Laboratory for Adaptive Optics
UCO/Lick Observatory
University of California, Santa Cruz

MCAO / MOAO Testbed

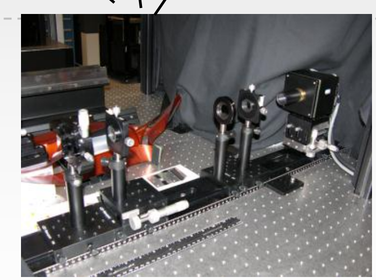
Deformable Mirrors (SLMs)



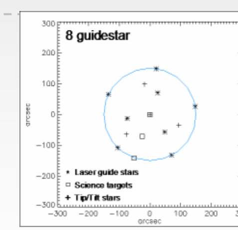
Kolmogorov Atmosphere phase aberrator plates



- Up to 8 wavefront guide stars and 4 tip/tilt stars
- 10,000 DOF per DM (100x100 subaperture Hartmann sensors)
- Up to 3 DMs (MCAO) or 1 DM and open loop WFS path (MOAO)
- 5 Hz sample & control rate
- Moving phase plates (wind)
- Moving LGS fibers in z to simulate LGS elongation, or laser pulse



Hartmann Wavefront Sensors

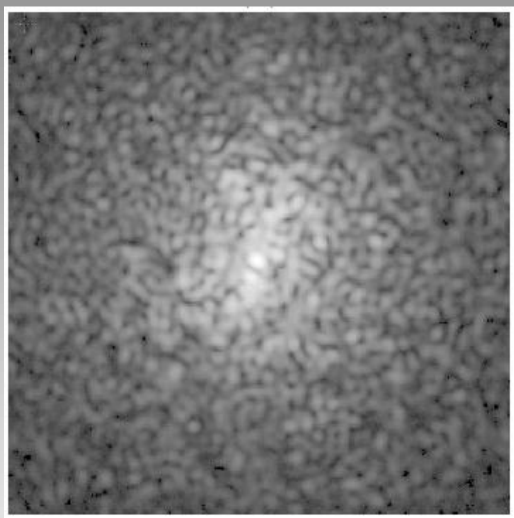


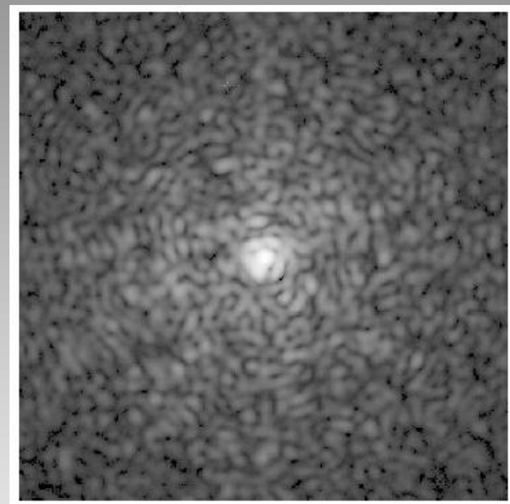
Configurable guide
star constellation

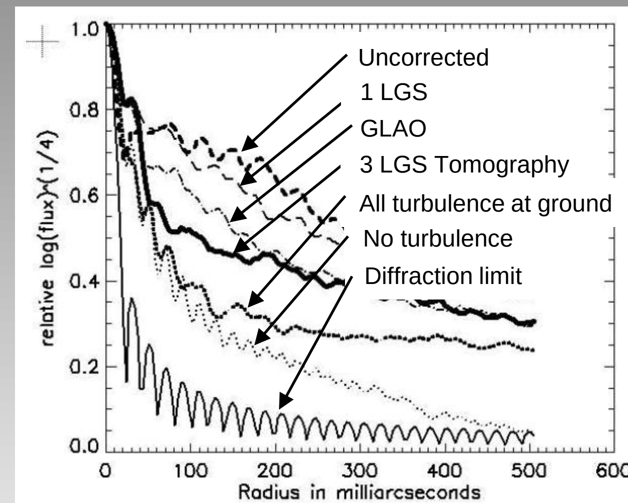
MCAO/MOAO Testbed in Operation

Ammons, et. al., SPIE 6272-175

Testbed "commissioning" results:



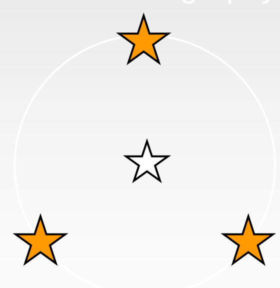




1 LGS (Anisoplanatic)

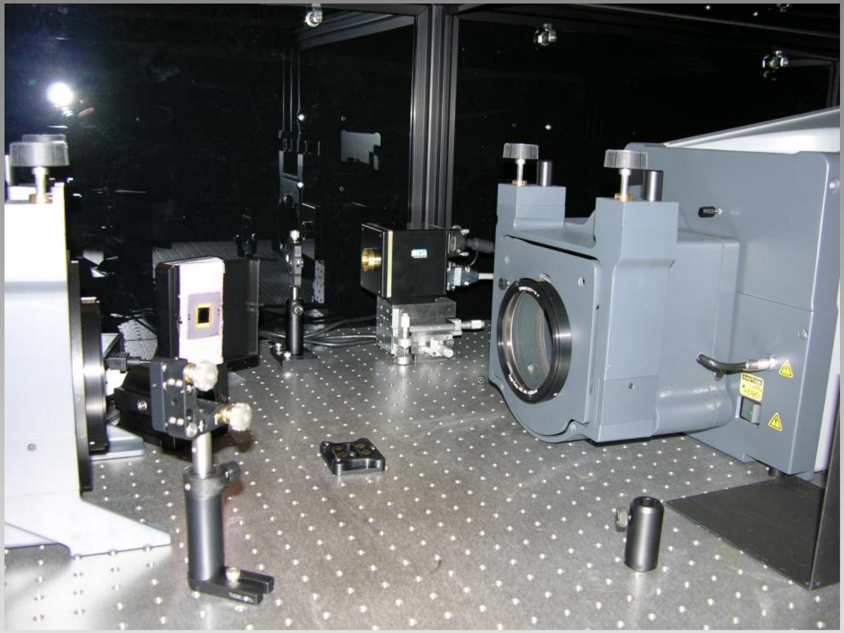
1.3'

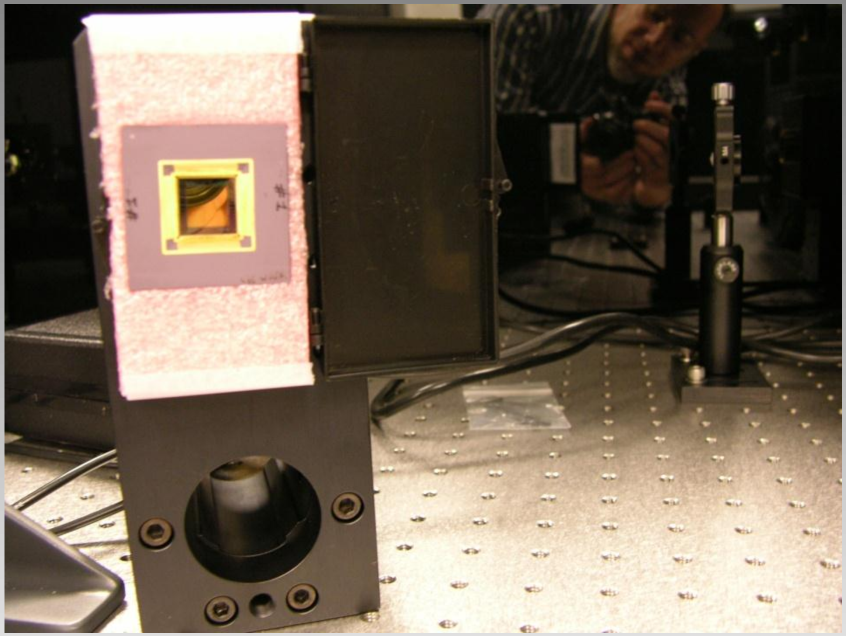
3 LGS Tomography

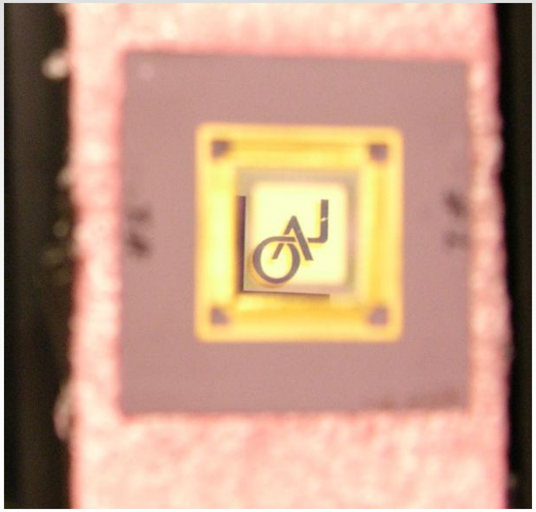


Laboratory for Adaptive Optics
UCO/Lick Observatory
University of California, Santa Cruz

Micro-electo-mechanical System (MEMS) Deformable Mirror







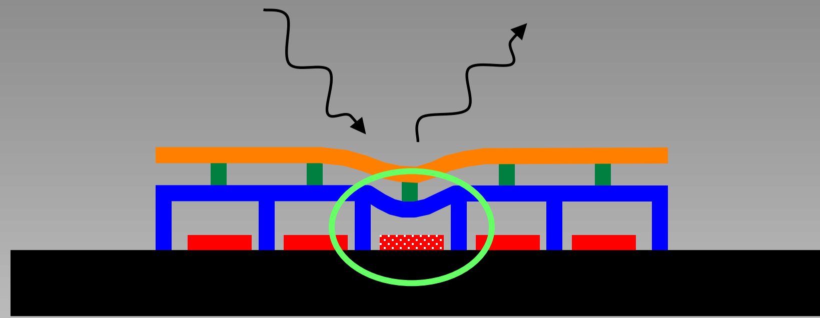
MEMS device in the lab now:

- 32x32 array
- 360μ actuator to actuator

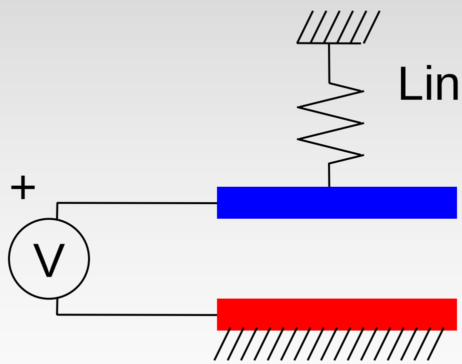
Goals:

- 64x64 array – planet finder for 8 m telescope
- 100x100 array – 30 m telescope general use

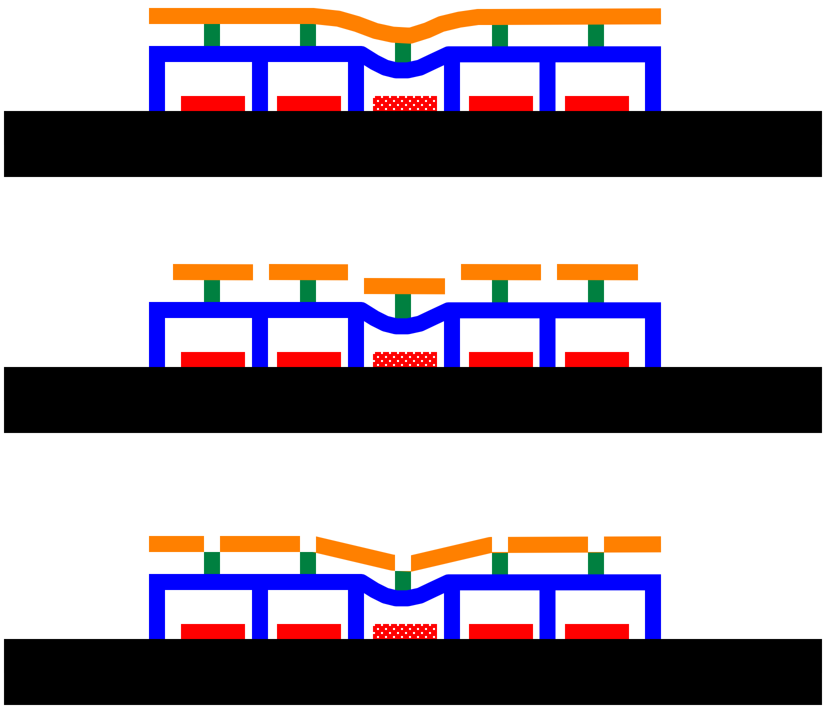
MEMS deformable mirror with electrostatic actuators



Simplified actuator model:



Boston University & Boston Micromachines Corporation Design



Continuous

Piston

Tip-Tilt

To get the same AO fitting error (Kolmogorov turbulence)

$N_{piston}/N_{continuous} = 6.2$

$N_{tip\text{-}tilt}/N_{continuous} = 1.8$

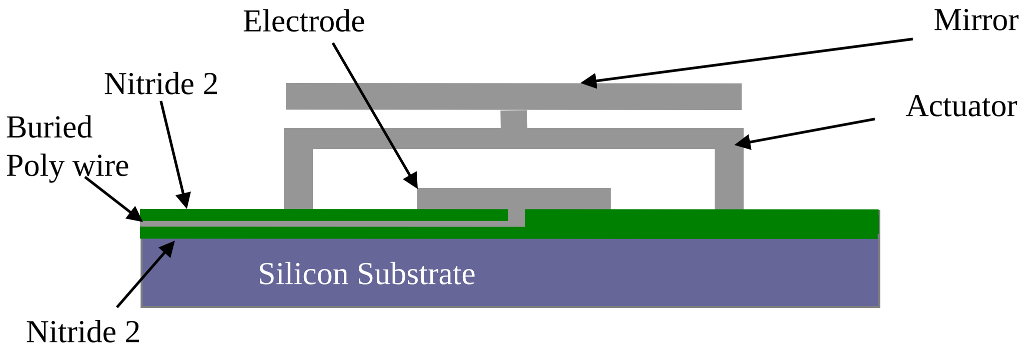
(C. Max, CfAO website)

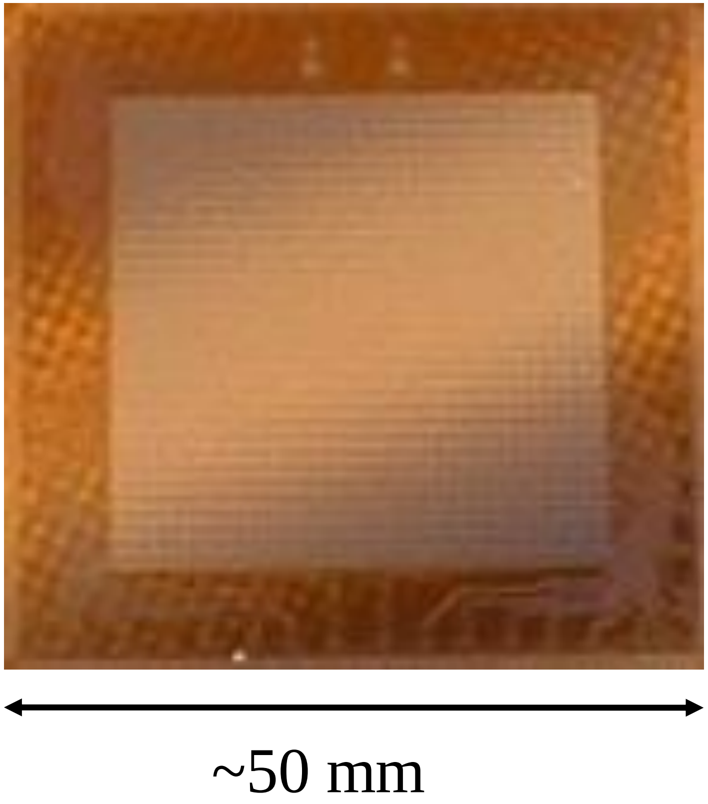
BOSTON MICROMACHINES CORPORATION

4k Element Mirror:

Straightforward Extension of Proven 1k Mirror Fabrication Process

- 64x64 element device
- High density wiring achieved through “buried” poly layer
- Wirebonding to off-chip electronics
- 1 device/100mm wafer
- Packaged in custom ceramic PGA chip carrier





BOSTON MICROMACHINES CORPORATION

Laboratory for Adaptive Optics
UCO/Lick Observatory
University of California, Santa Cruz

Extreme Adaptive Optics: Imaging Extrasolar Planets

Gemini Planet Imager

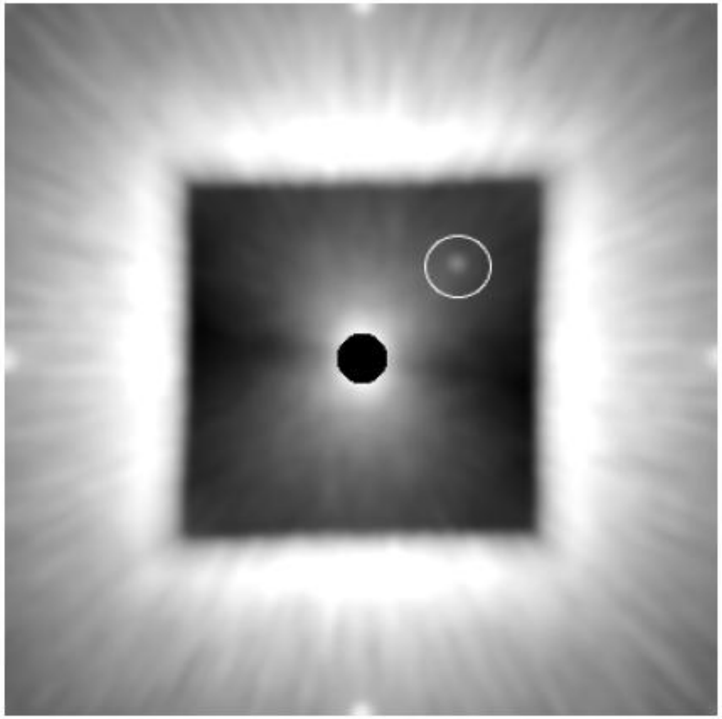
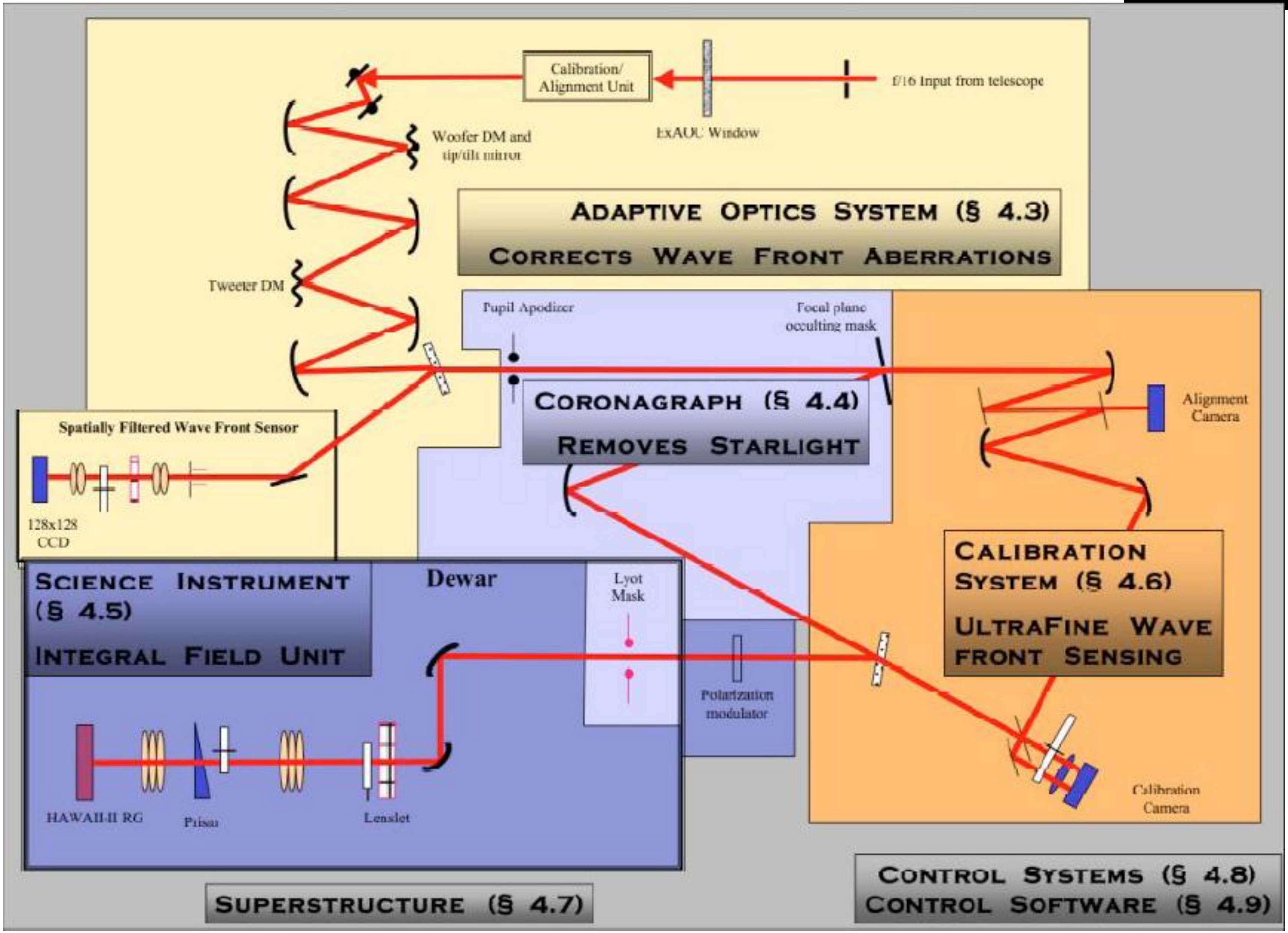


Figure 1: Simulated 20 second Gemini ExAOC integration showing a 5 Jupiter-mass extrasolar planet in a 6 AU orbit around a 200 Myr solar-type star at 10 pc. The star is located behind an occulting spot. The square "dark hole" region, 1.8" on a side, is produced by our spatially-filtered wave front sensor (SFWFS). This is a direct broadband image with no post-processing. In hourlong exposures ExAOC will be 13 times more sensitive.

Laboratory for Adaptive Optics
UCO/Lick Observatory
University of California, Santa Cruz

Gemini Planet Imager



Laboratory for Adaptive Optics
UCO/Lick Observatory
University of California, Santa Cruz

Gemini Planet Imager

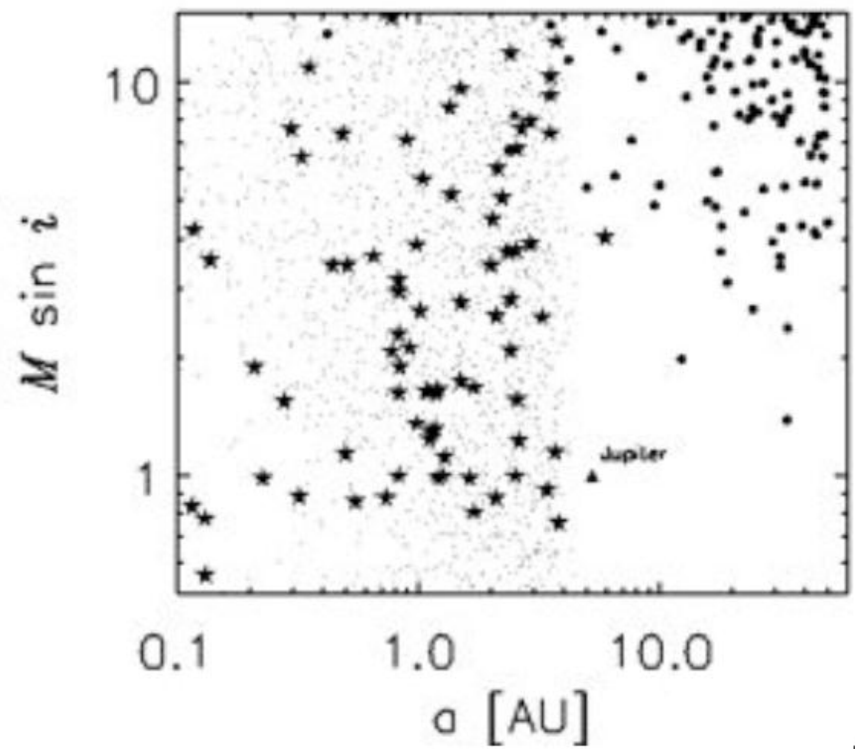
Planet populations detectable with GPI – based on simulations

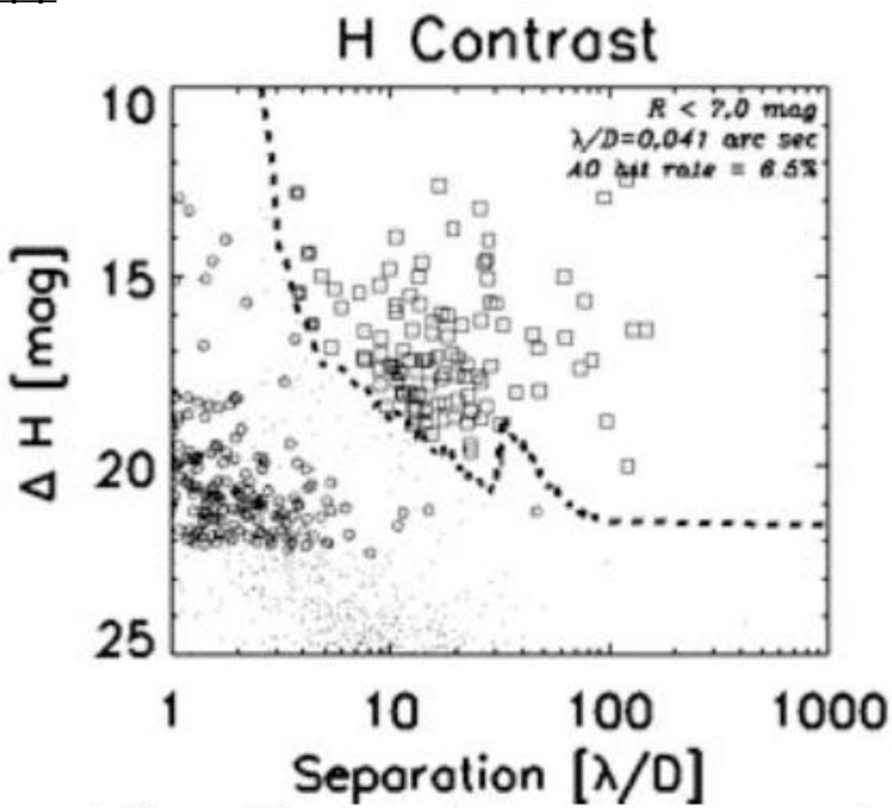
Keck/Lick Doppler Survey

GPI

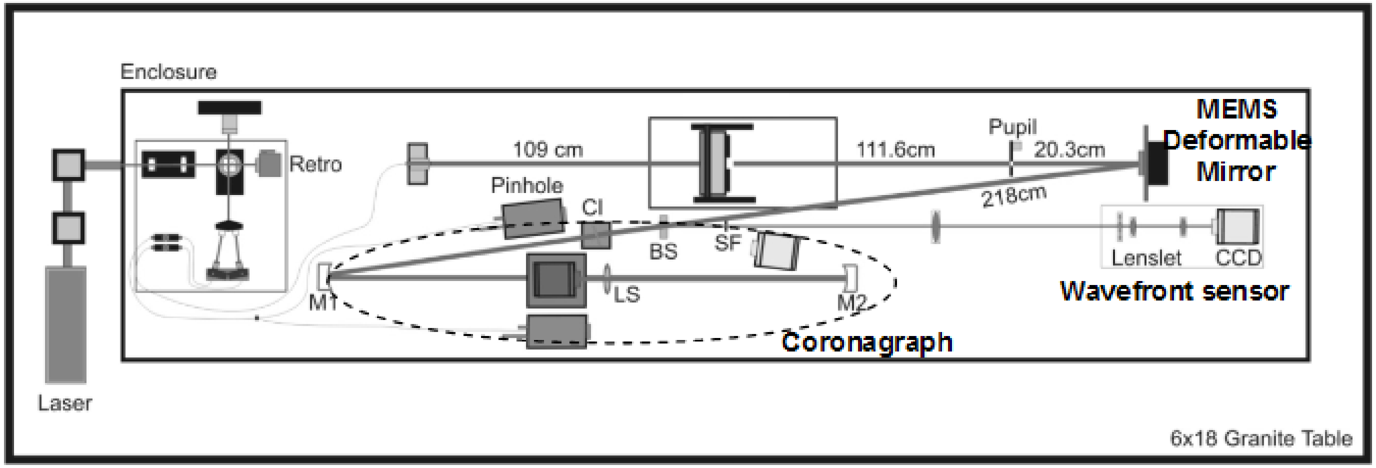
Doppler

GPI





ExAO Development and Instrument Prototype at the UCO/Lick Laboratory for Adaptive Optics



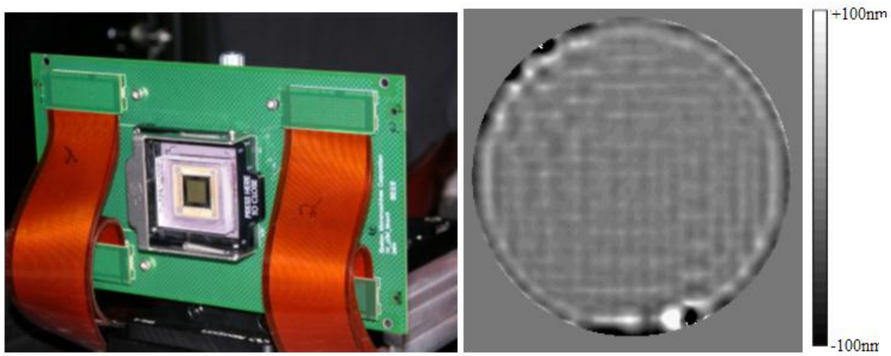


Figure 5. Left: the MEMS deformable mirror is shown in its mount. Right: grey-scale display of wavefront phase, as measured by PSDI, of a 9-mm diameter circular beam of light reflected off the central area of the MEMS. The MEMS device has a 10-mm square active area. An iterative algorithm using PSDI measurements determines the voltage commands required to achieve maximum flatness. The residual wavefront error visible, on the order of 5 nm rms, is mostly "print-through" of actuator mounting structure to the continuous mirror surface. This high spatial frequency ripple scatters light mostly outside of the discovery region in the final image.

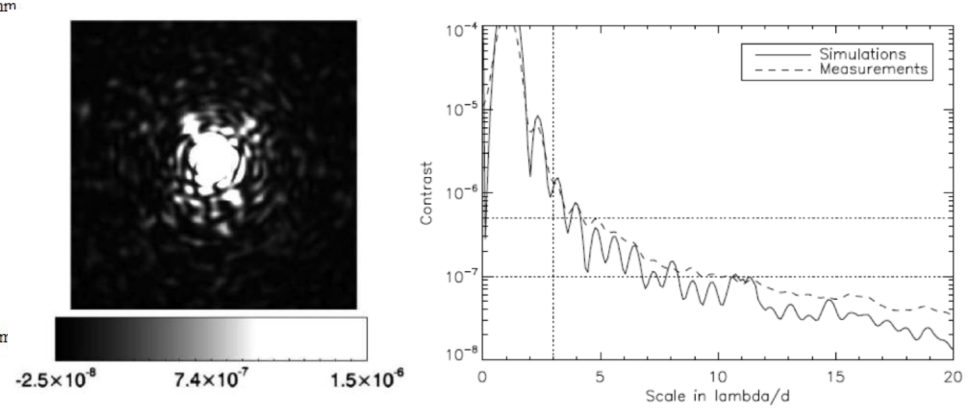
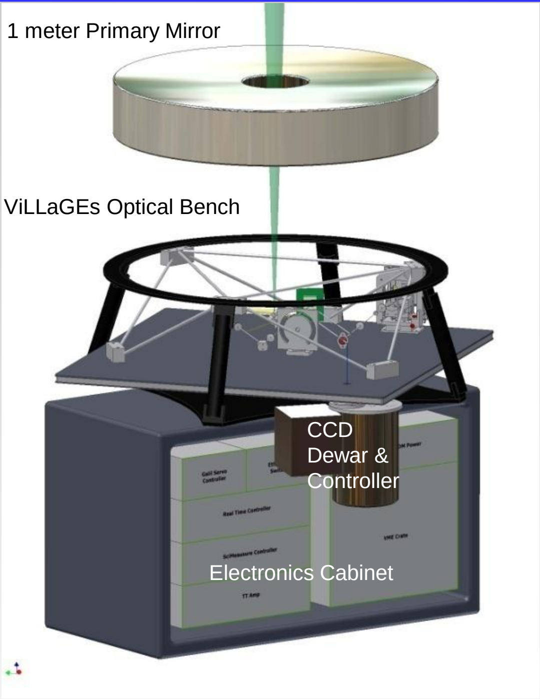


Figure 6. Left, image in the focal plane of the scattered light from the star leaking through the apodized pupil Lyot coronagraph. The scale is log-stretched. Right: lineout of contrast, showing that the coronagraph's suppression of diffracted light exceeds 10^6 at 3 l/D and $5x10^7$ at 5 l/D. These suppressions are two orders of magnitude more than that of the standard Lyot coronagraph (we reported results on this in our Sept. 2006 report).

MEMS AO/ ViLLaGEs* On-Sky Experiments

Experiment Goals are to demonstrate the latest generation of **new AO technologies developed under CfAO and LAO R&D efforts:**

- MEMS
- Open-loop control (MOAO)
- Spatially filtered Shack-Hartmann wavefront sensor
- Pyramid wavefront sensor
- Fiber laser
- Laser uplink correction



These technologies are critical stepping stones to **visible wavelength astronomy with laser guidestars**

*ViLLaGEs: Visible Light Laser Guidestar Experiments

Laboratory for Adaptive Optics

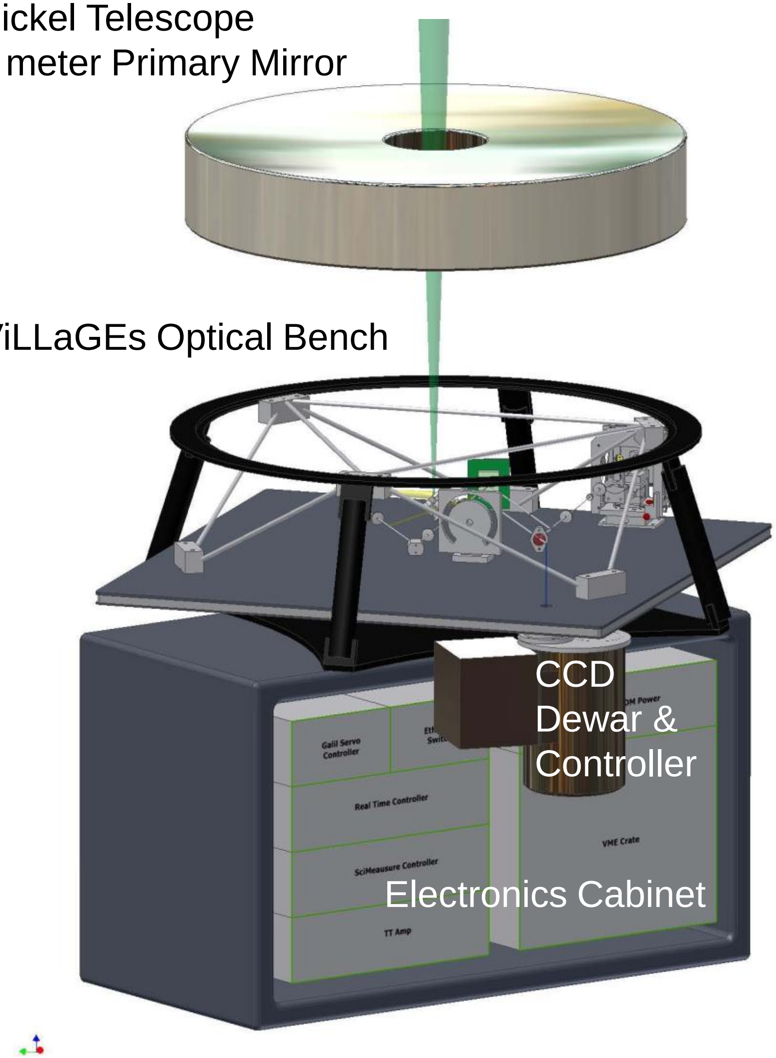
Villages

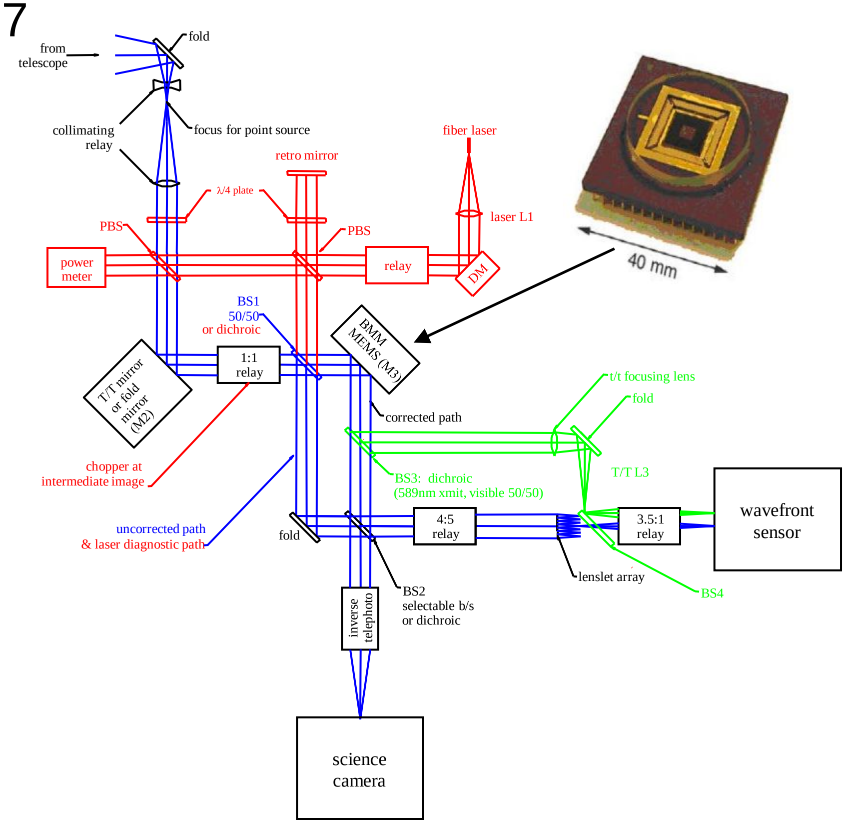
Visible Light Laser Guidestar AO System Experiments

- Designed for Nickel 1-m Telescope, Mt. Hamilton
- Proof of concept for MEMS deformable mirrors in astronomical AO instruments
- PoC of AO uplink correction of laser beam
- Experiments at the telescope started mid 2007

Nickel Telescope
1 meter Primary Mirror

ViLLaGEs Optical Bench



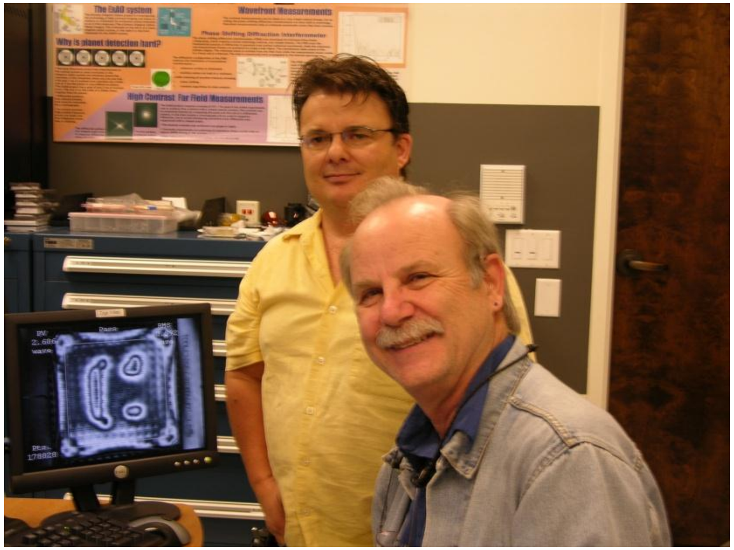


Laboratory for Adaptive Optics

Villages

Villages On-sky

at the Nickel Telescope, Mt Hamilton



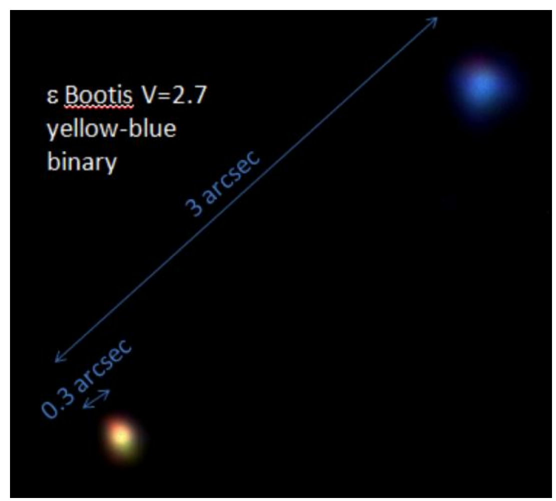
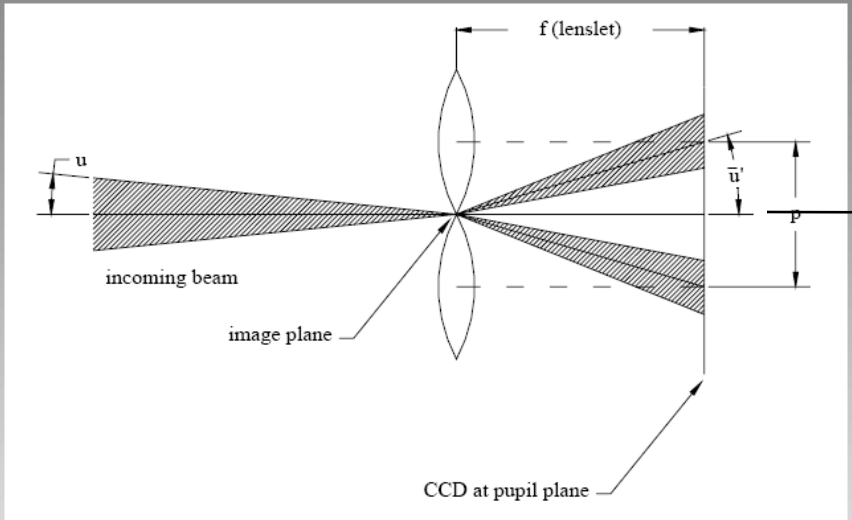


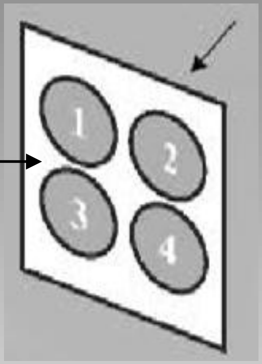
Figure 16. Colorful images of star clusters with the Villages system, demonstrating the sharpened images after adaptive optics correction. These are “true color”: red = R band, green = V band, blue = B band filter.

Laboratory for Adaptive Optics
UCO/Lick Observatory
University of California, Santa Cruz

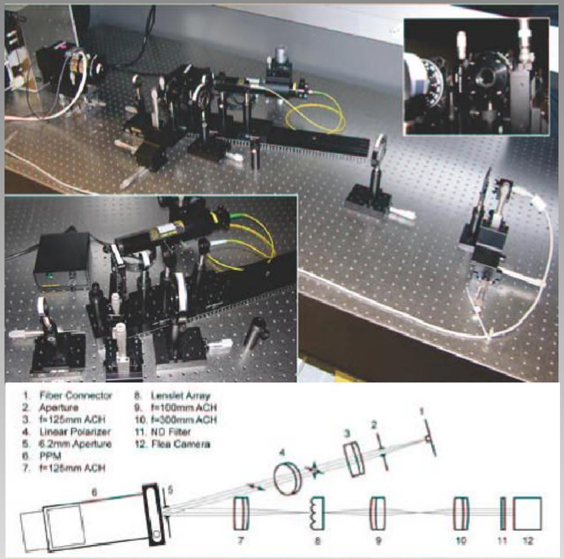
Pyramid-Lenslet Wavefront Sensor Development

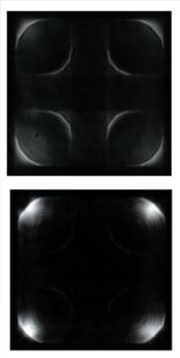
Johnson, et. al., SPIE 6272-165





Pupil images

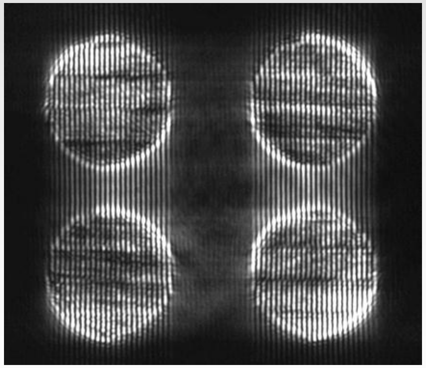


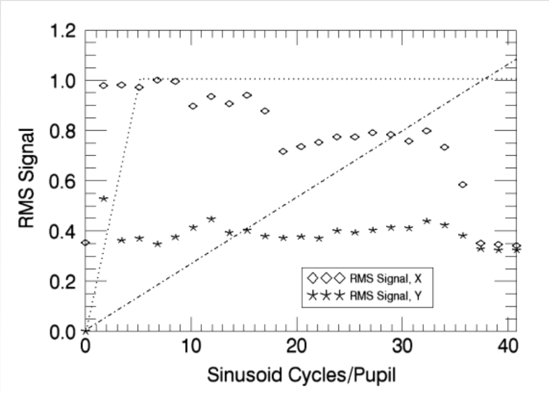


Unaberrated

Defocused

Sinusoidal phase



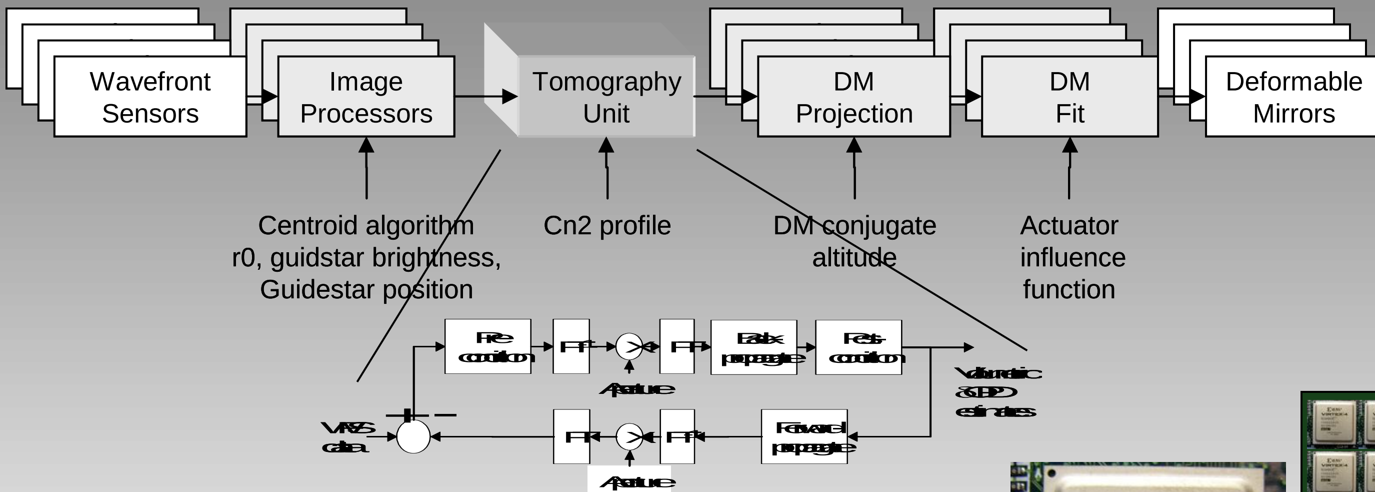


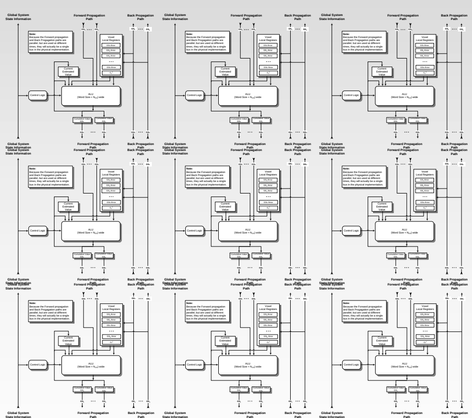
Direct Phase (Interferometric) Readout

Laboratory for Adaptive Optics
UCO/Lick Observatory
University of California, Santa Cruz

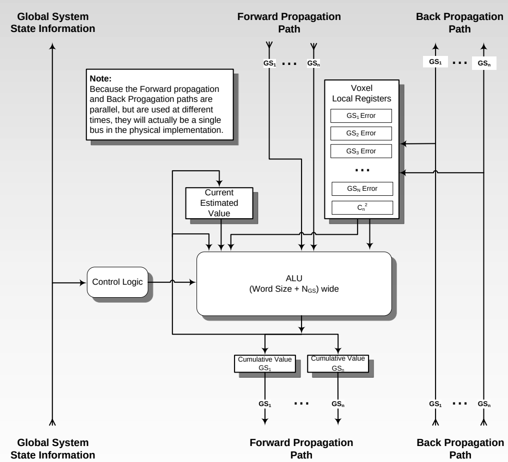
Prototype MCAO tomography reconstructor

Implementation with massive parallel processing for ELT AO





•An Array of Voxel Processors



•A Single Voxel Processor

Student-led design project won Best Senior Engineering Project award

Visit us on the web
http://lao.ucolick.org/