UCO/Lick Laboratory for Adaptive Optics

Developing Adaptive Optics for the Next Generation of Astronomical Telescopes

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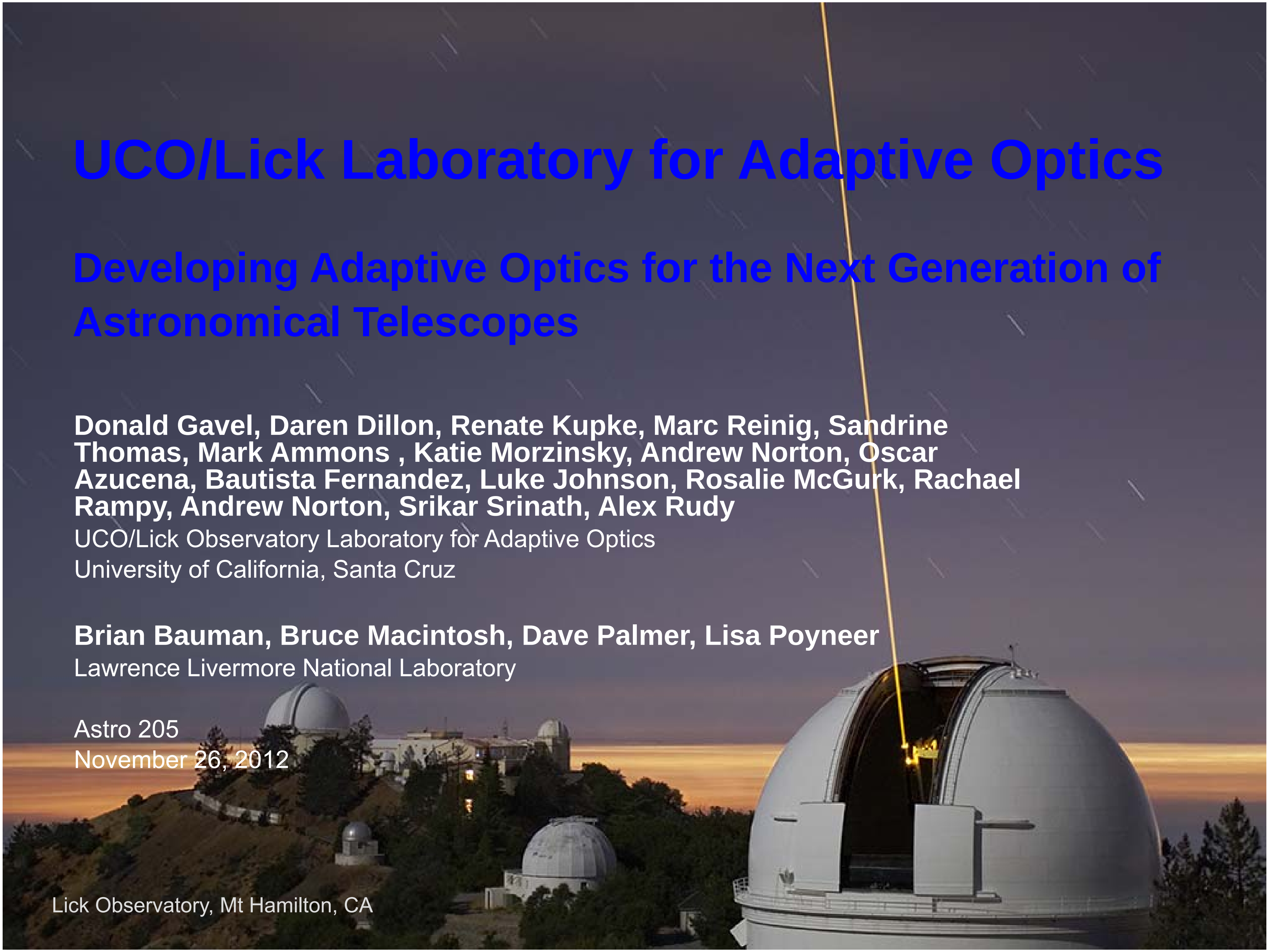
University of California, Santa Cruz

Brian Bauman, Bruce Macintosh, Dave Palmer, Lisa Poyneer

Lawrence Livermore National Laboratory

Astro 205
November 26, 2012



Lick Observatory, Mt Hamilton, CA

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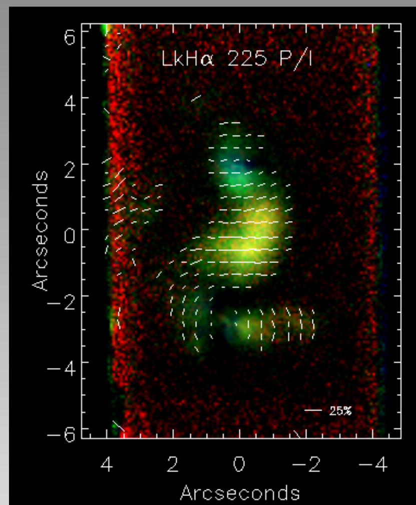
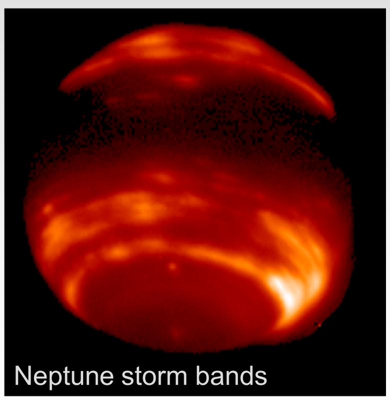
UCO/Lick Observatory: Pioneering Laser Guide Star Adaptive Optics

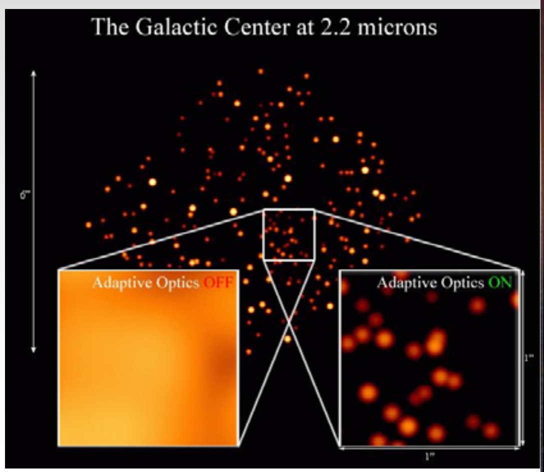
- **LGS AO facility at Lick 3-m telescope – routine science observing since 2001**
- **LGS AO at Keck 10-m telescope – science observing starting 2005A**

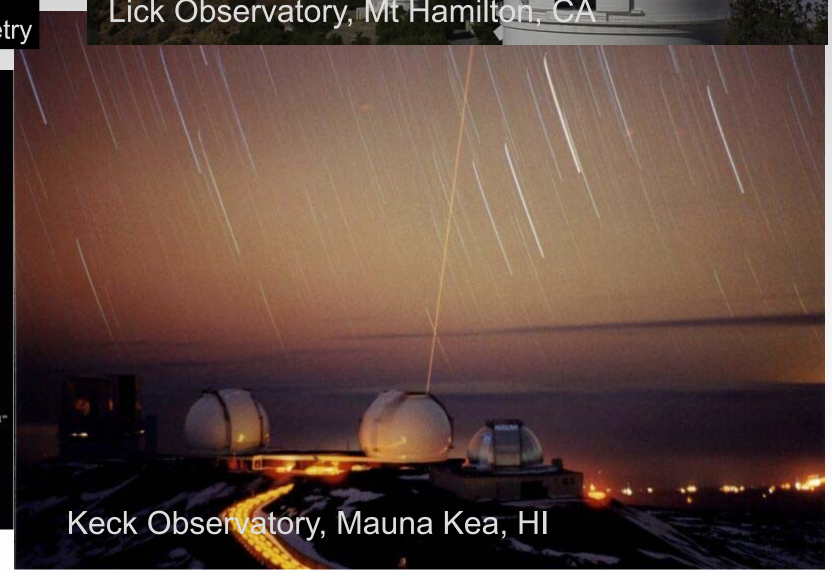


Star-forming regions - polarimetry


Lick Observatory, Mt Hamilton, CA


Neptune storm bands

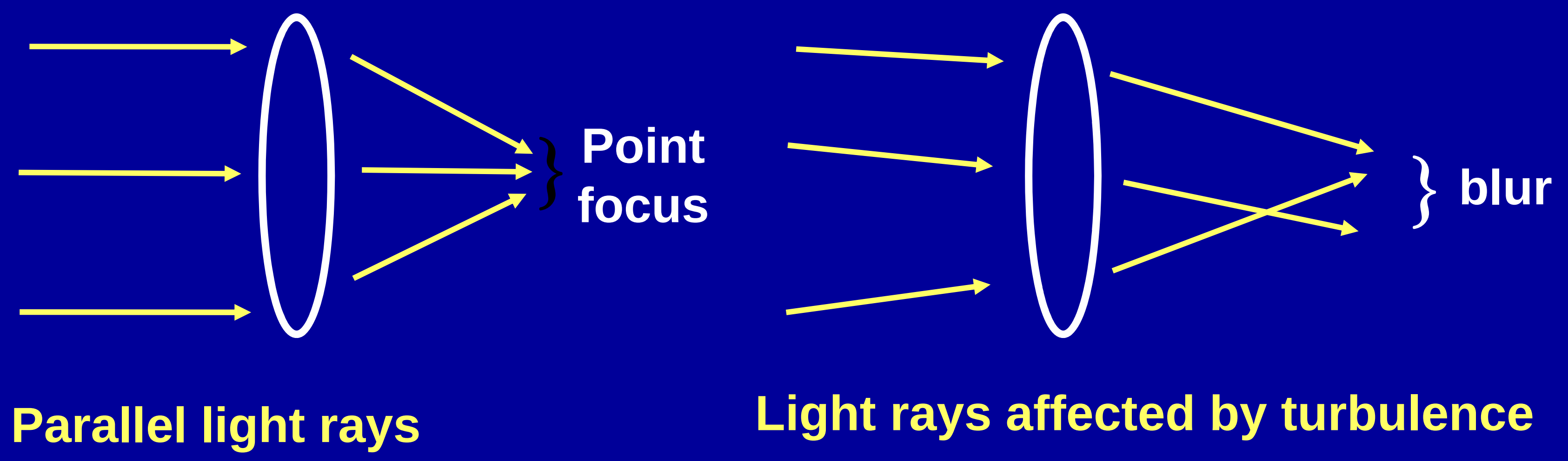



Keck Observatory, Mauna Kea, HI

Why Adaptive Optics?

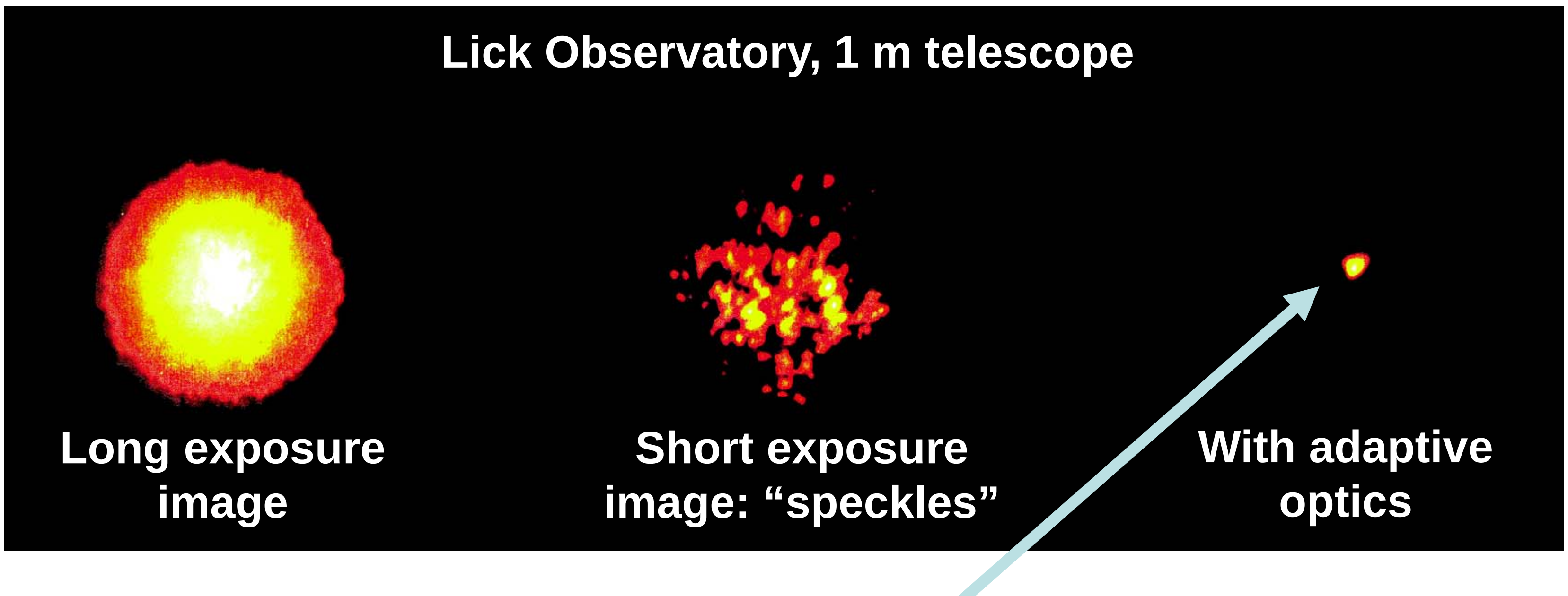
The Atmospheric Blurs Astronomical Images

- 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:



How AO improves astronomical imaging

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, …

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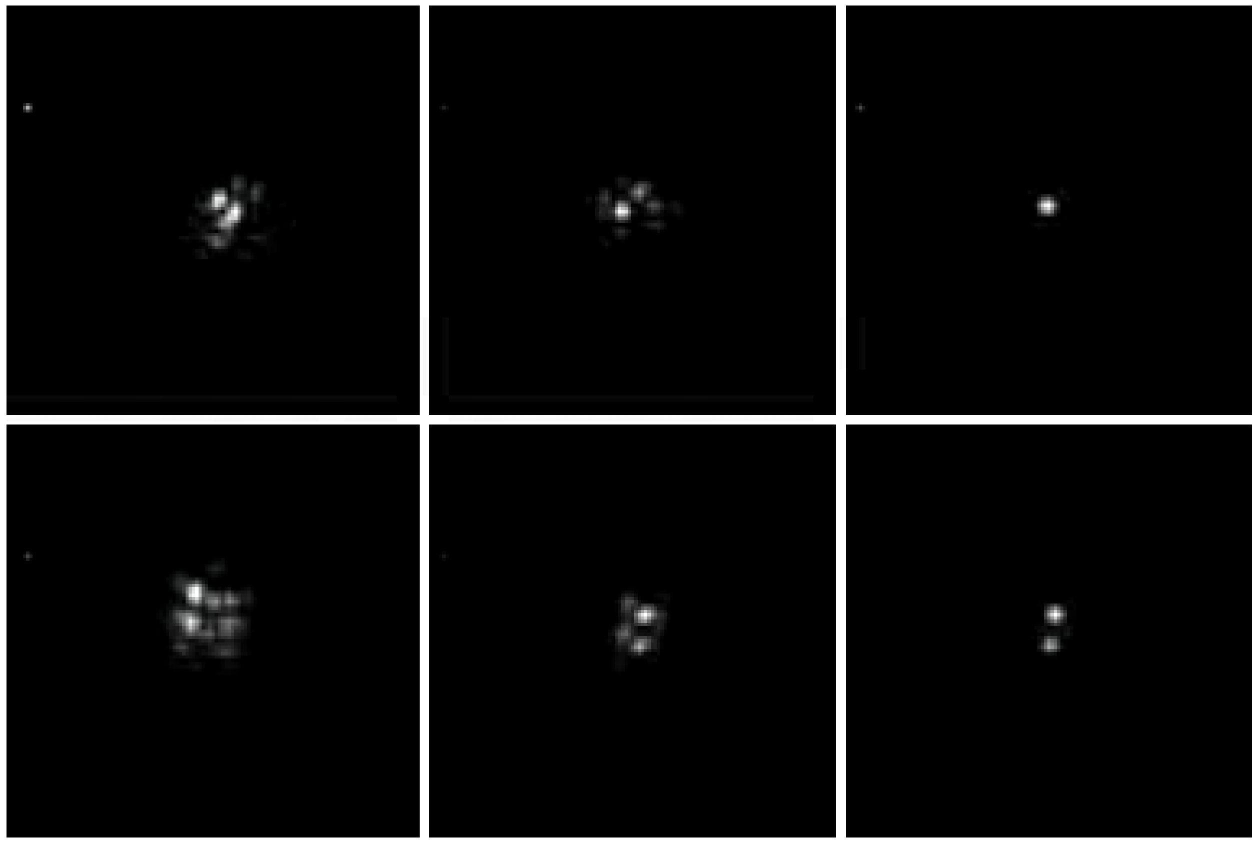
No AO | Tip/Tilt | AO

ν UMa

HIP 59386

Separation=0.38″



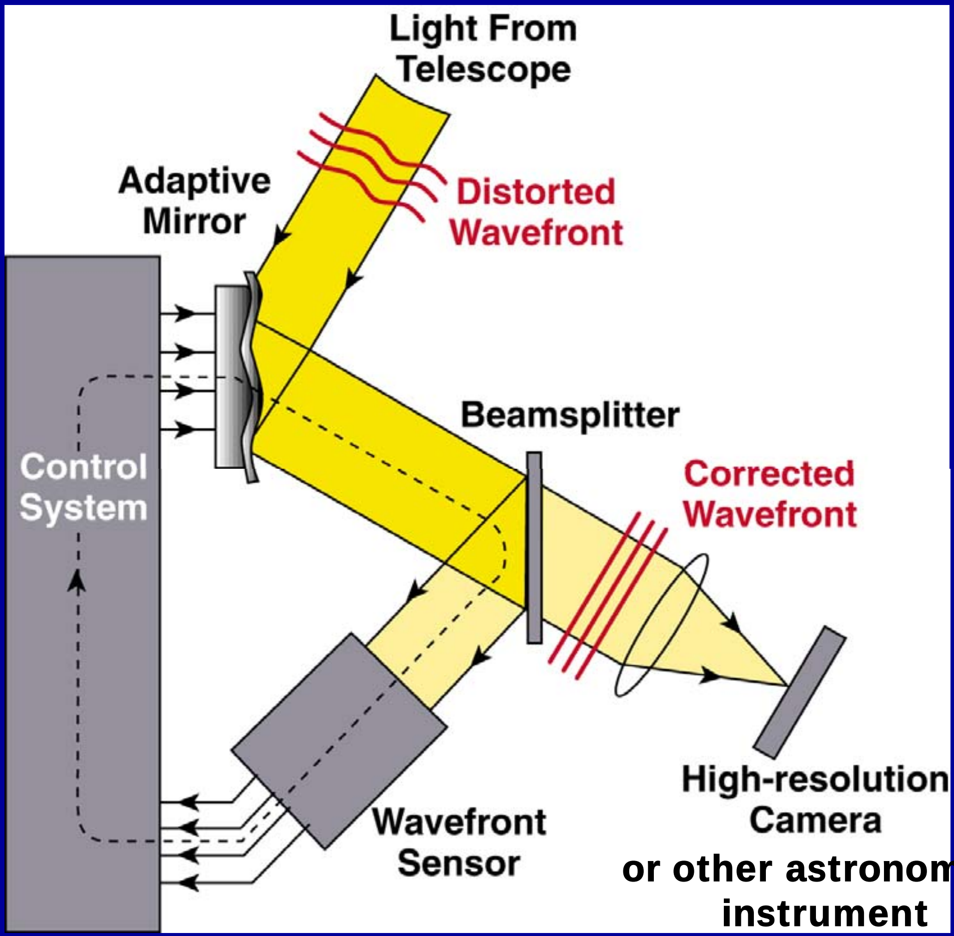
Closed loop Strehl=0.74, 2.2μm, r_0=18cm at 5500A

57ms exposures, 4.8″ field of view

How Adaptive Optics Works

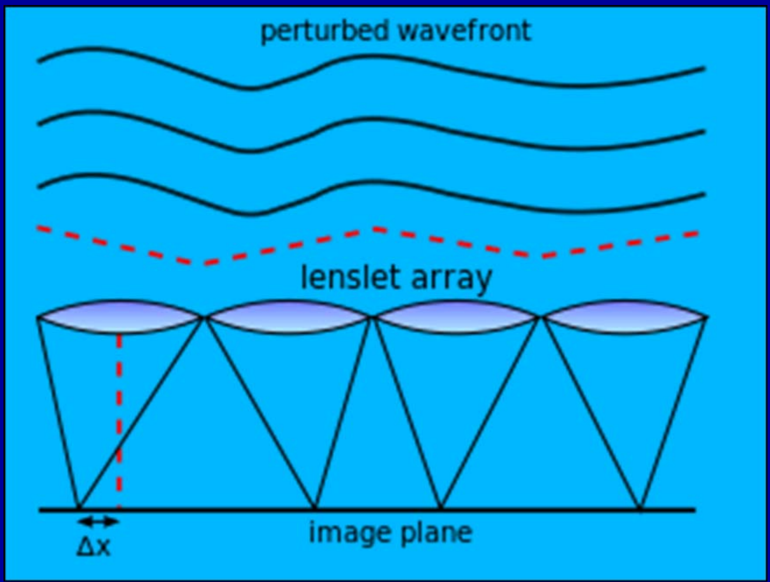
Invert the wavefront aberration with an "anti-atmosphere" (deformable mirror)

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

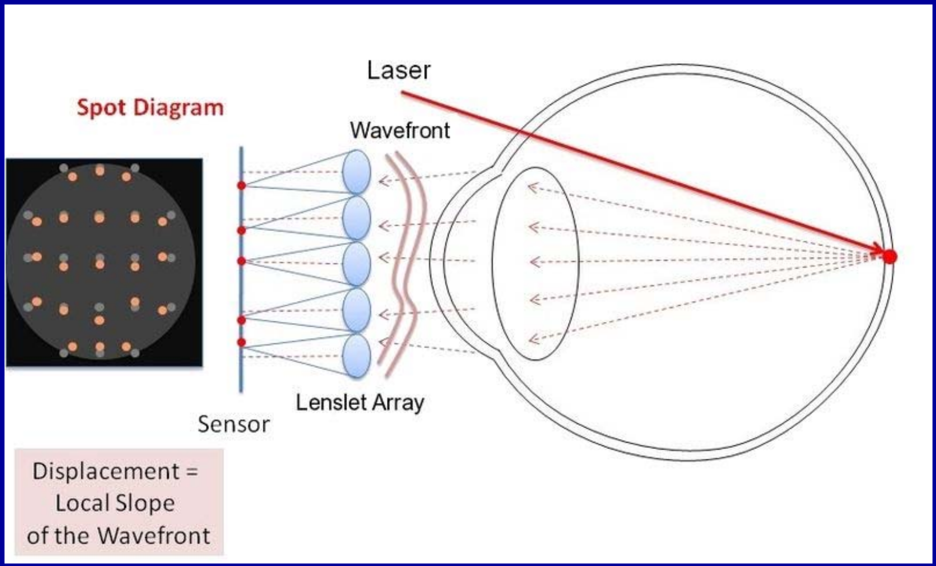


or other astronomical instrument

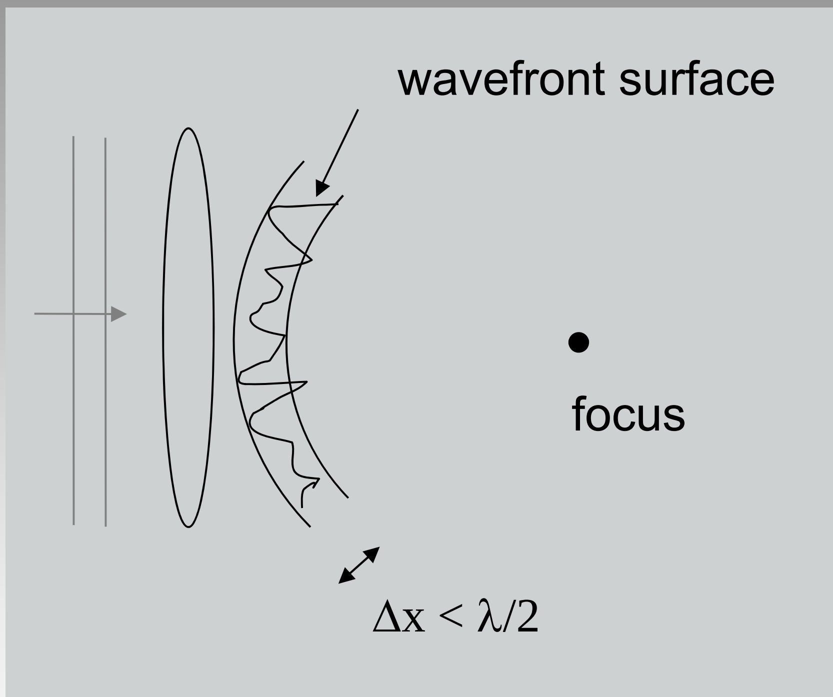
Wavefront sensing using a guide star: Hartmann sensor



Slope = spot displacements = Gradient (phase). Solve for phase



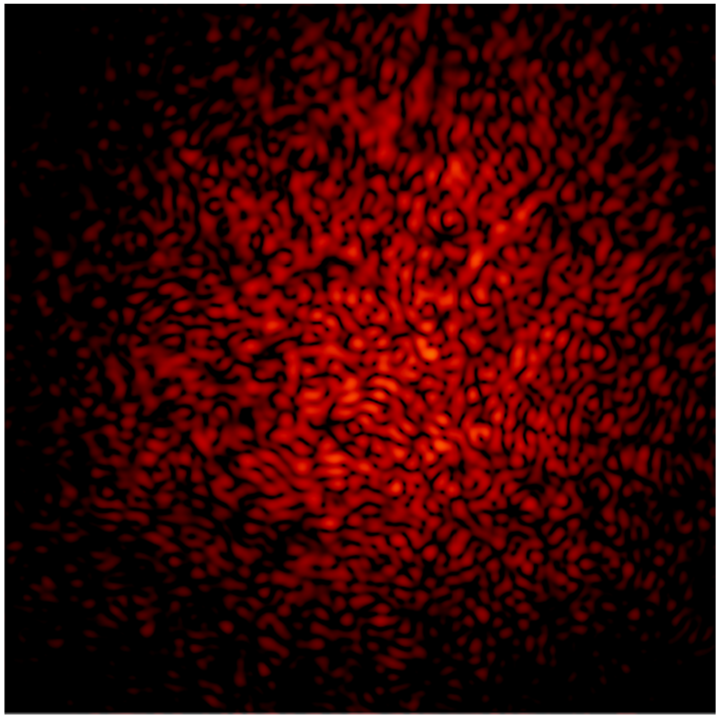
Diffraction-Limited Image Formation:
Marechal's Condition



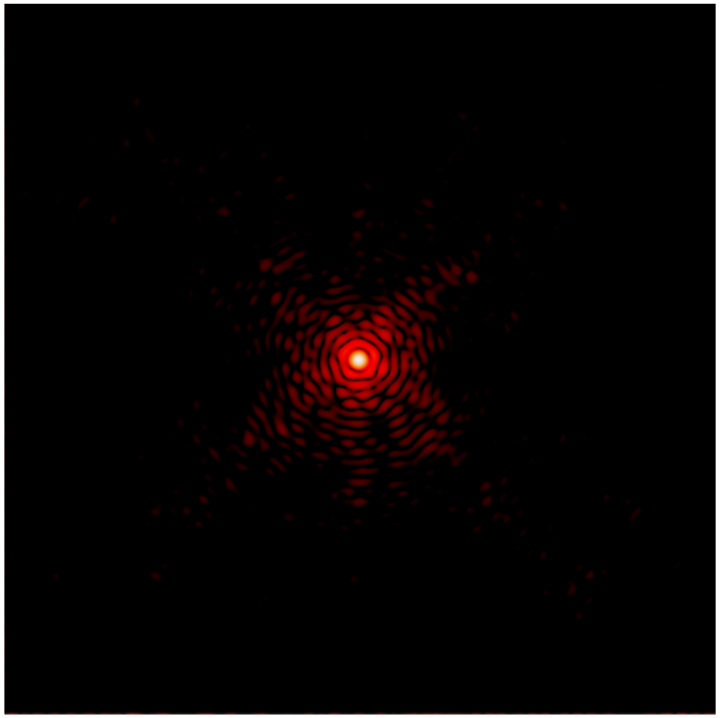
If the wavefront phase is contained within confocal spheres $\lambda/2$ apart everywhere where the intensity is significant

The waves will add up at the focus

AO correction of a star – 30 meter telescope

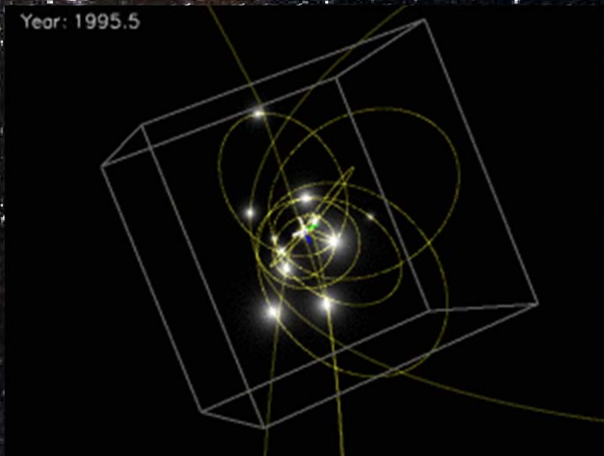


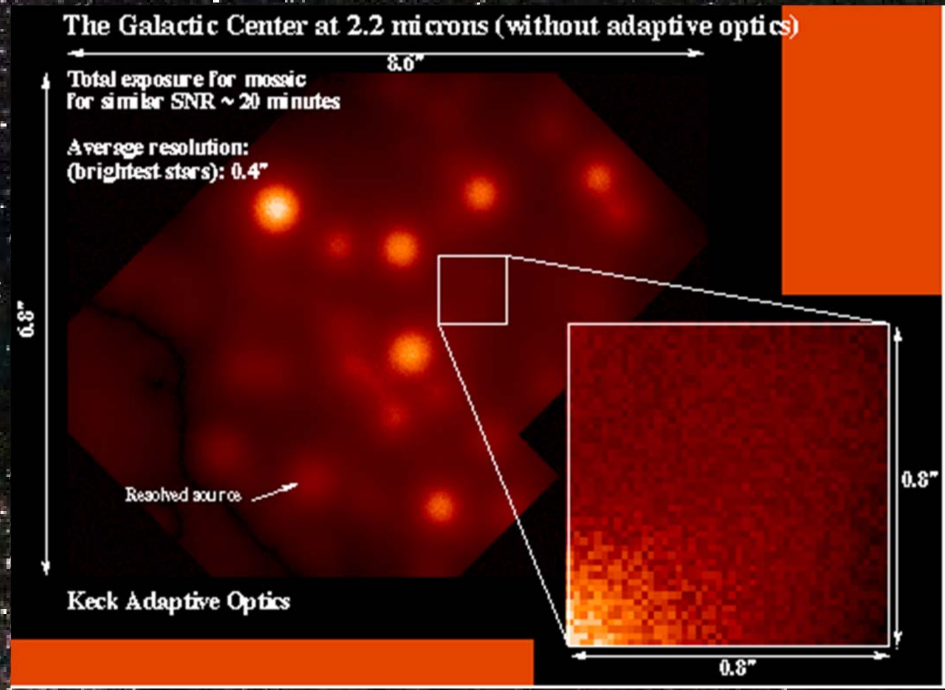
Uncorrected

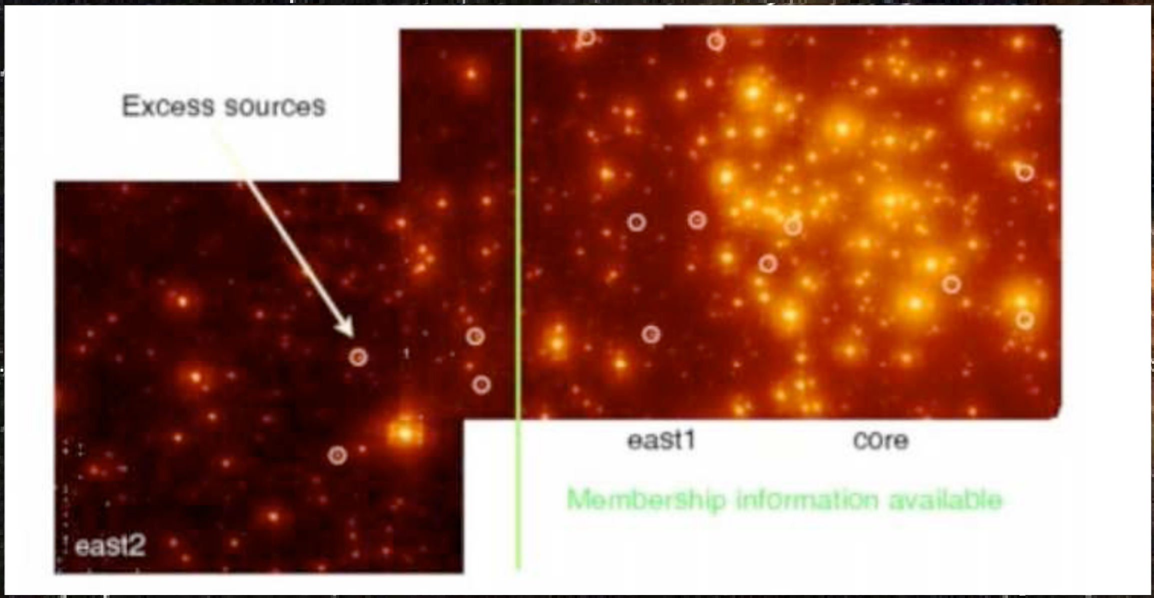


Corrected

Galactic Center



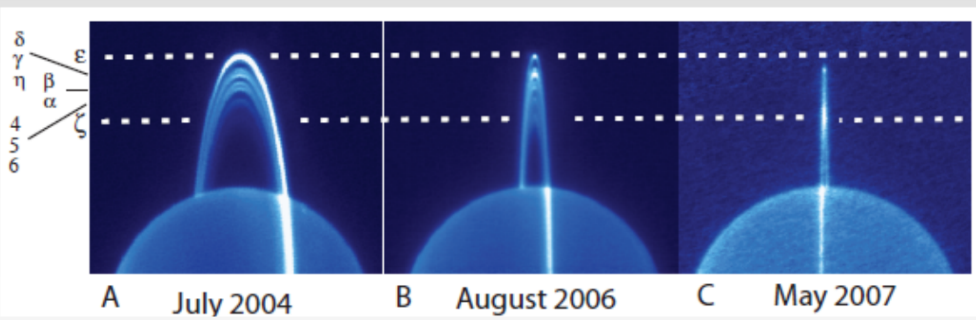




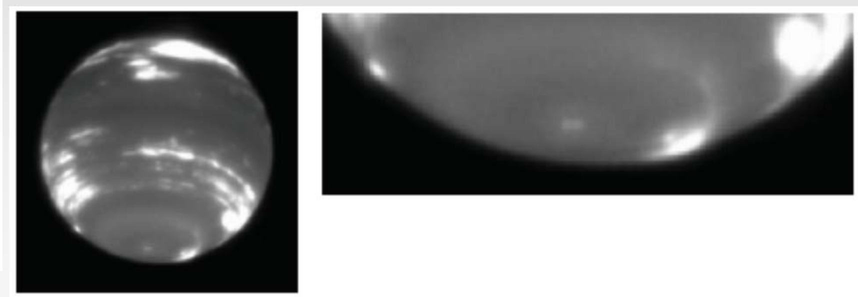
Left: **Arches cluster near the Galactic Center.** In the process of analyzing data collected to investigae the stellar mass function within the Arches cluster, we made the surprising discovery of finding many infrared excess sources. We have also expanded our astrometric coverage of the Arches to look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

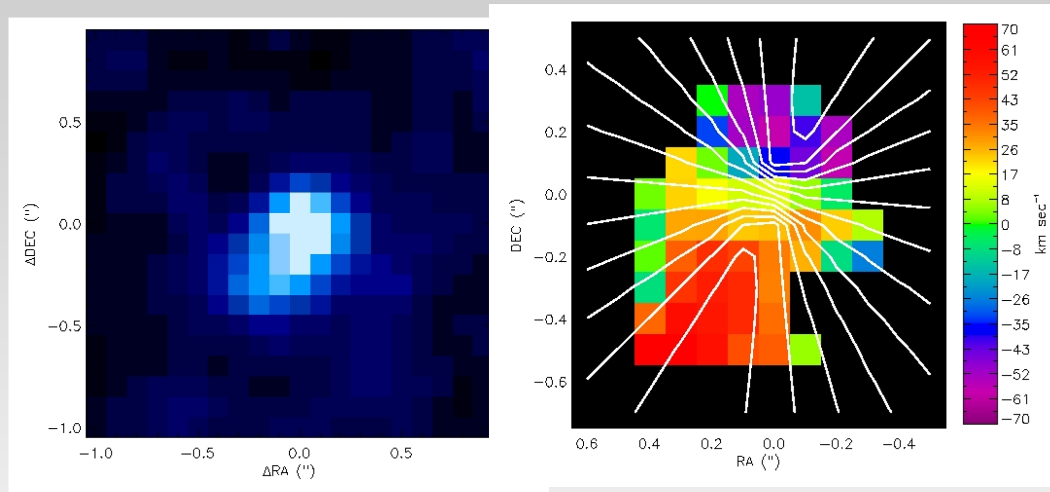


Keck AO image of **Neptune** in H band from 26 July 2007. On the right is an enlargement of the S. pole, showing the double spot. (Luszcz, de Pater, Hammel)

Extragalactic Research

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

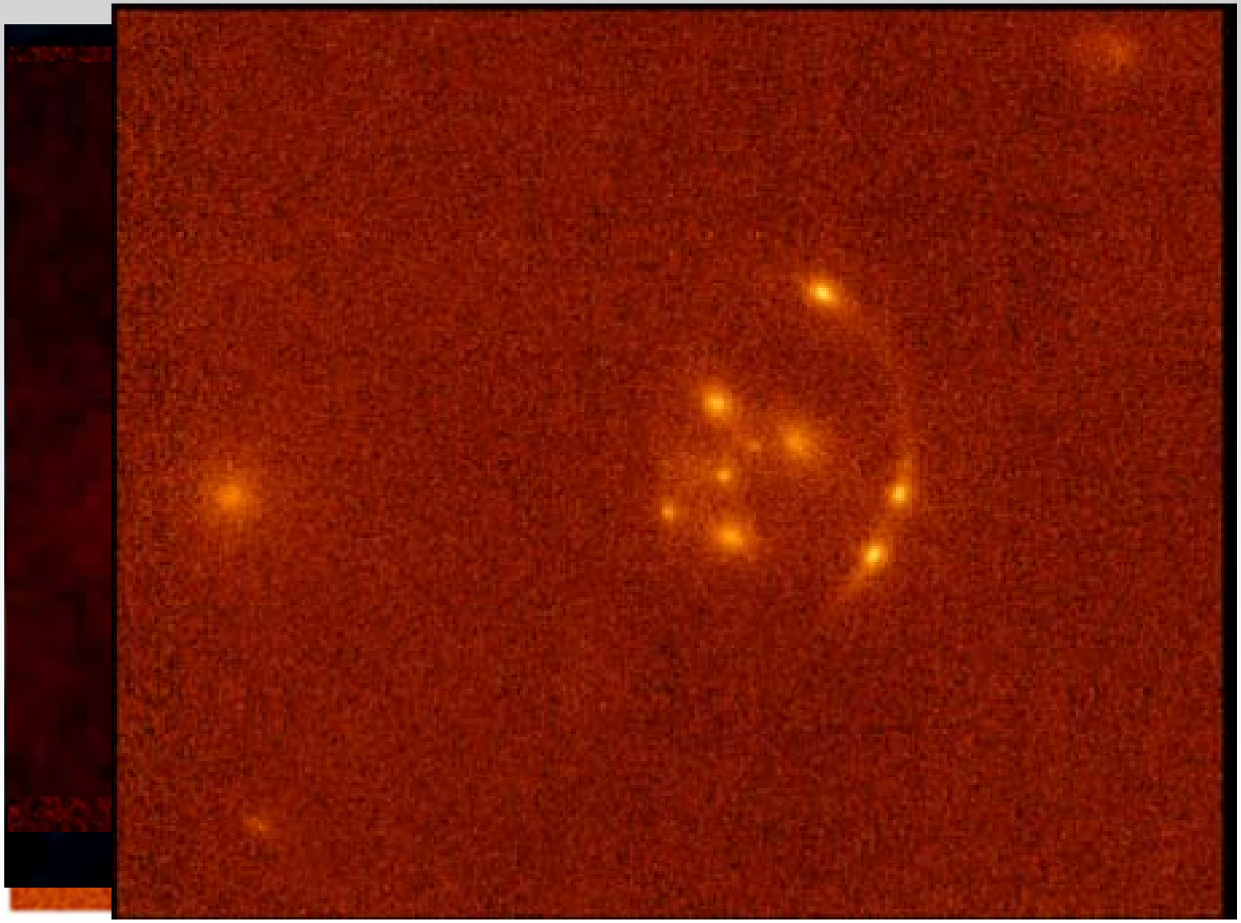
1. assembly of galaxies from smaller subunits to larger ones like our own Milky Way,
2. measure the rates of star formation and the evolution in stellar populations
3. discover the highest redshift supernovae
4. characterizing central active galactic nuclei (AGNs) throughout the past 10-12 Billion years



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

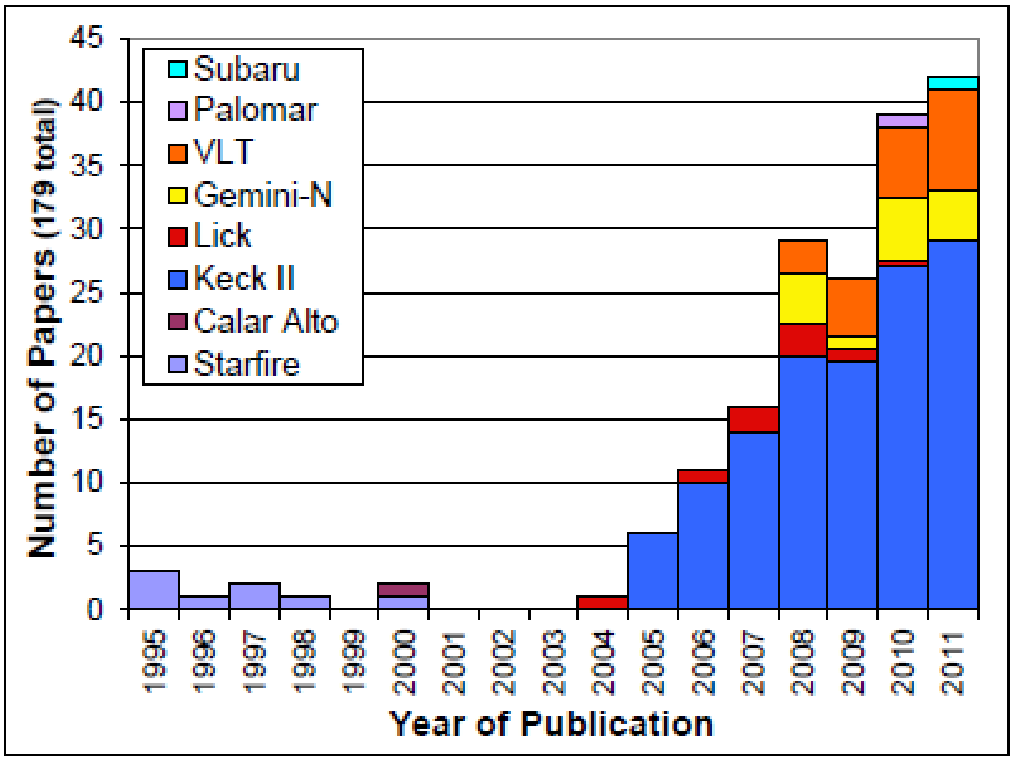
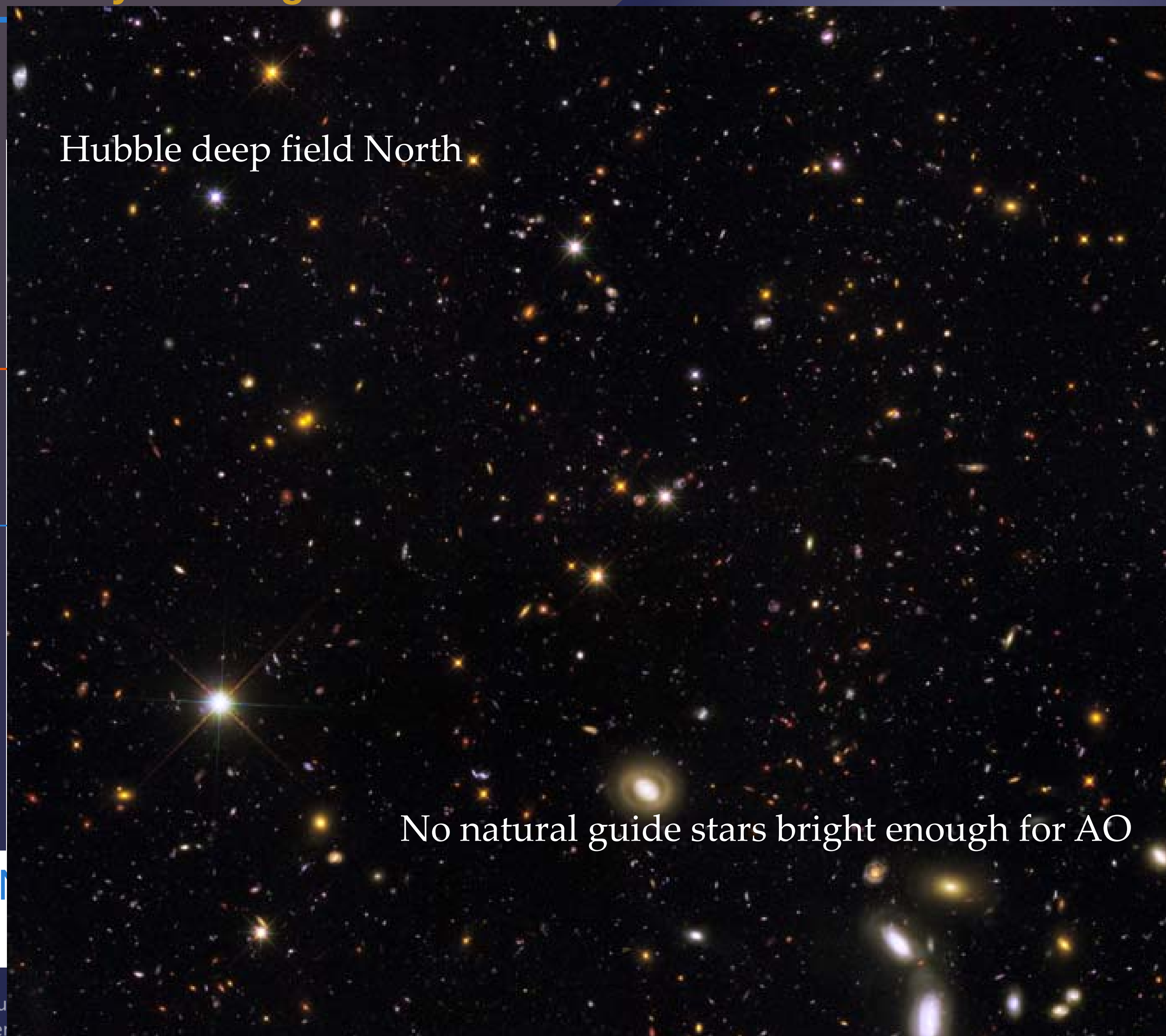


Figure 1: Refereed science publications by year and facility based on LGS AO data

Why laser guide stars?

“Sky coverage”



rage
0 %

Galactic
latitude

90°
45°
30°

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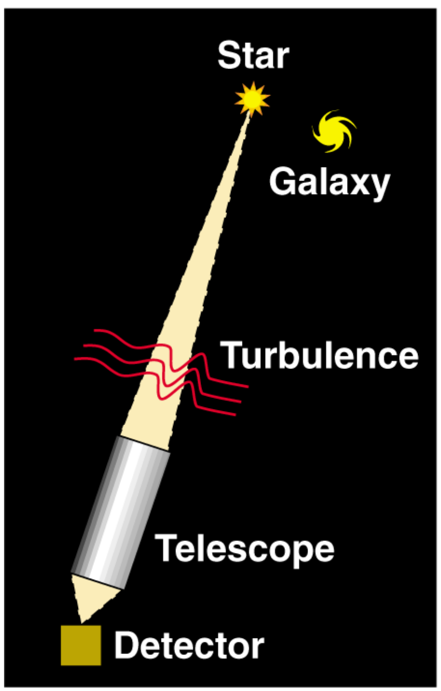
How Laser Guidestar AO Works

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

(a)

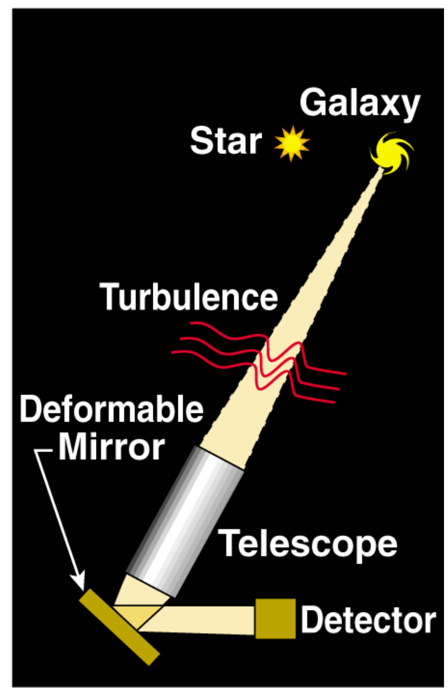


Calculate on a computer the shape to apply to a deformable mirror to correct blurring

(b)

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

(c)



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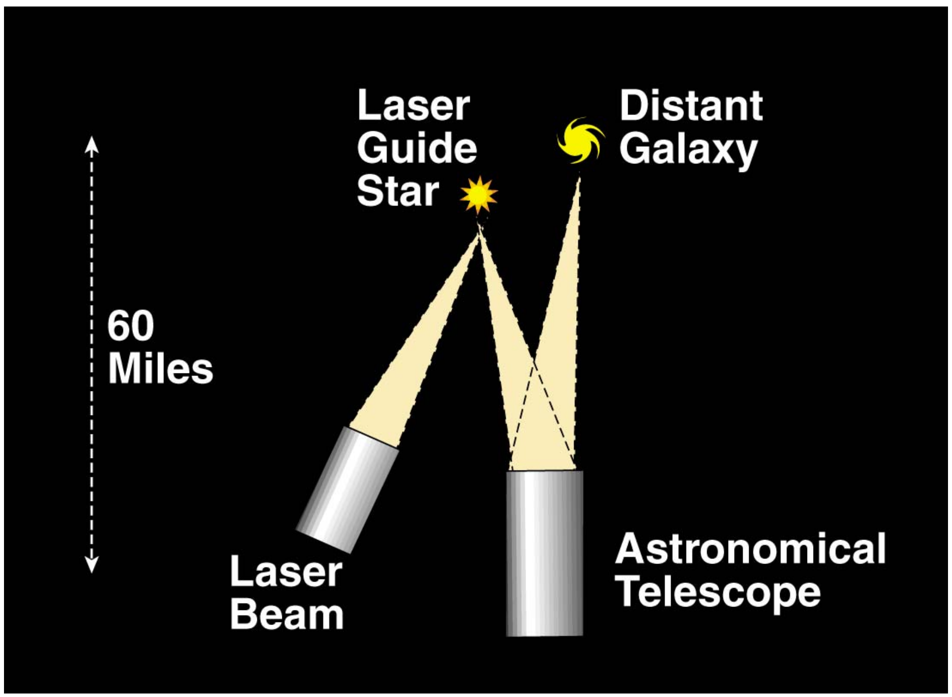
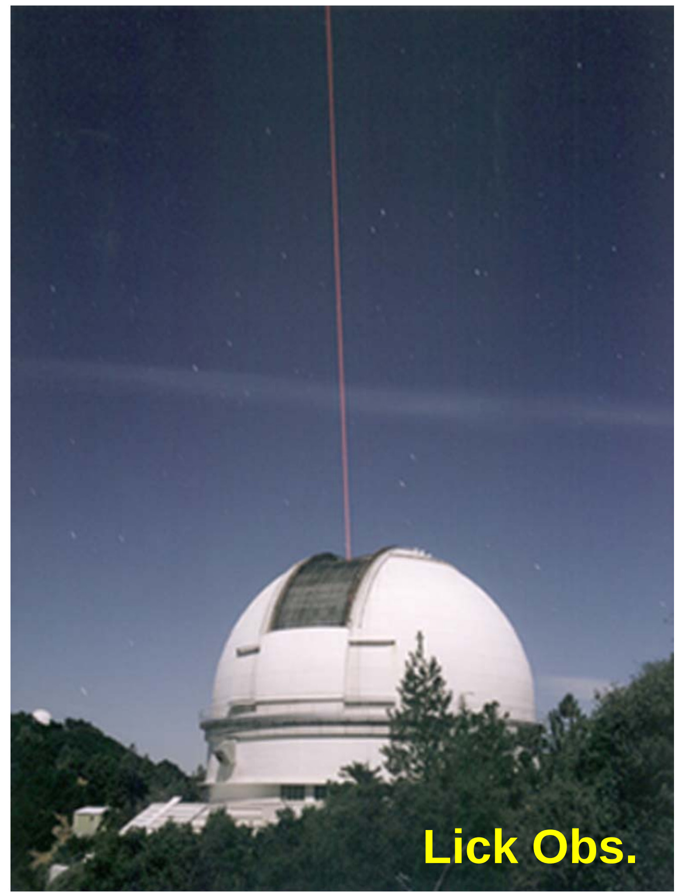
If there is no nearby star, make your own "star" using a laser

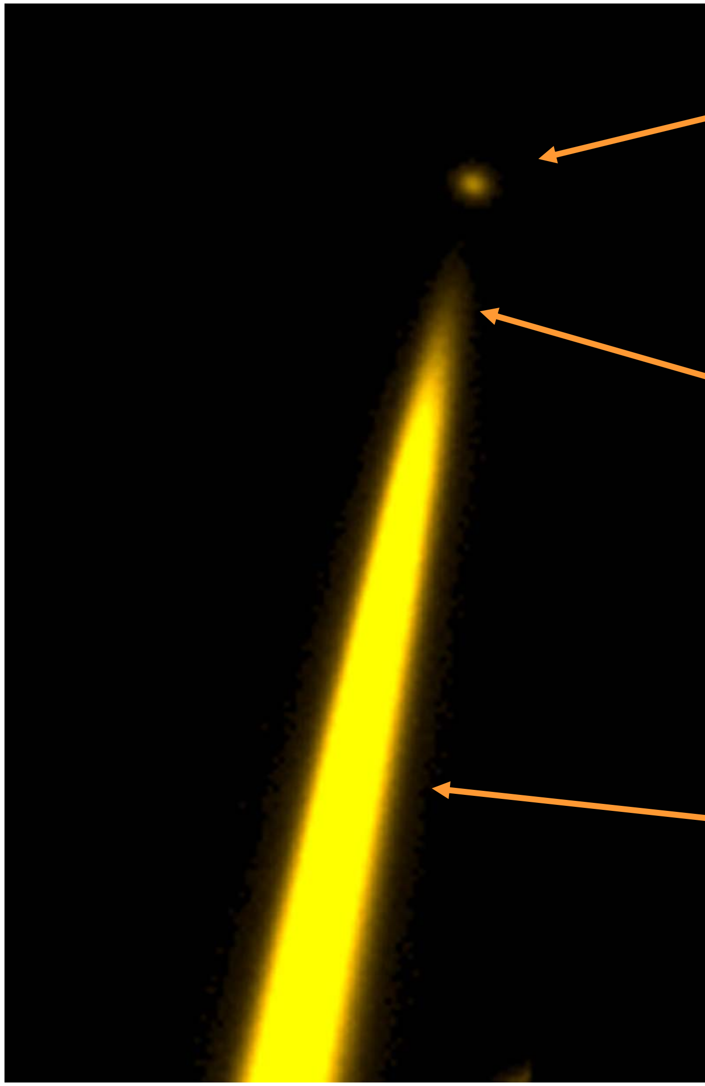
Concept



Implementation



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

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Laser Guidestar Structure in the Sodium Layer

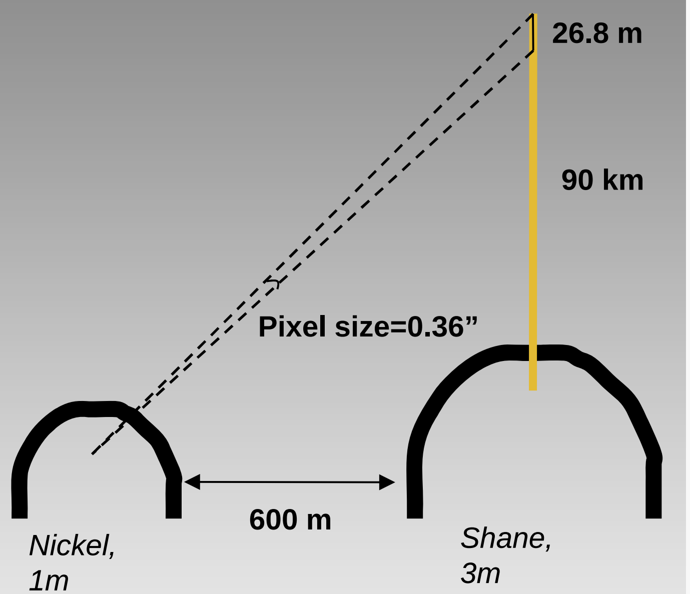
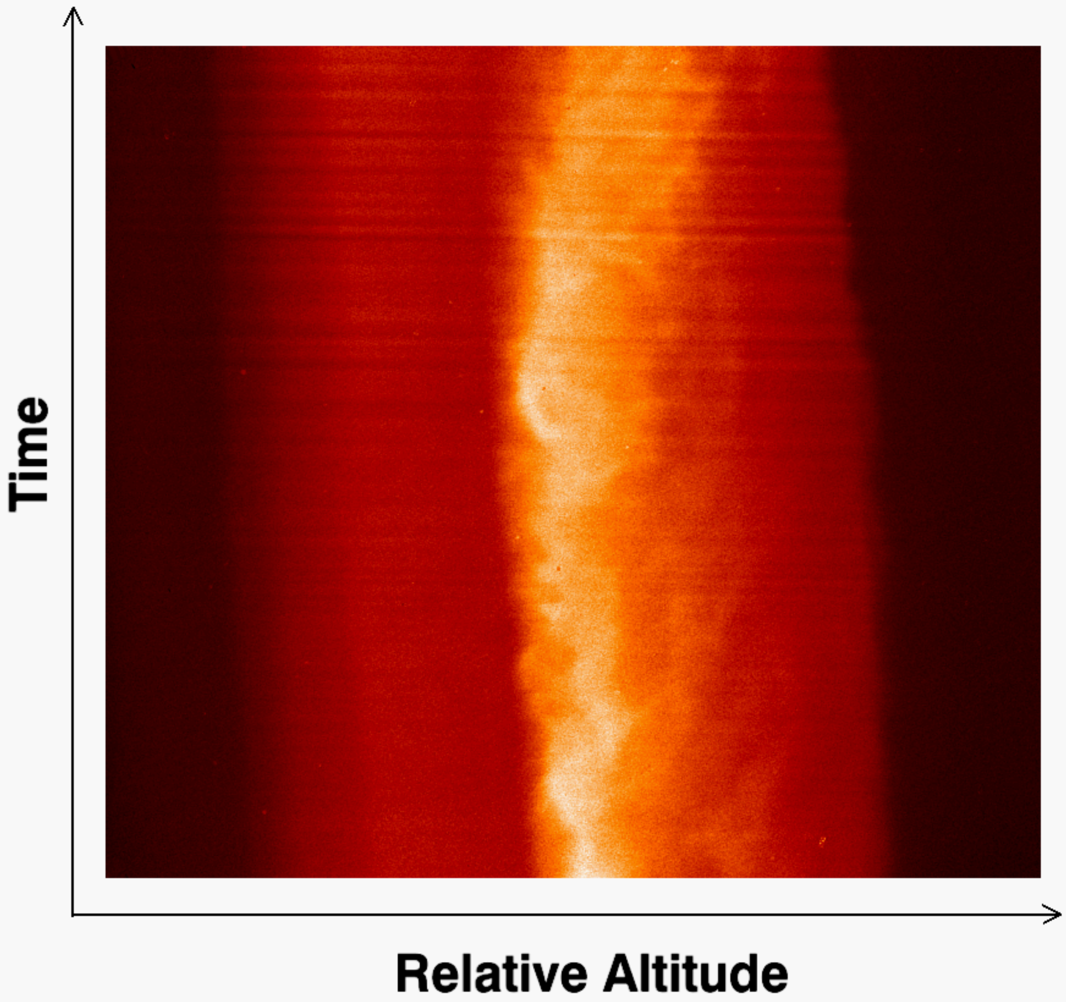
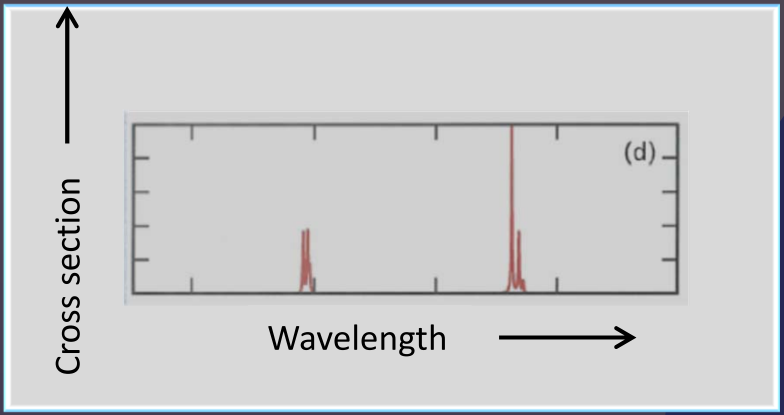
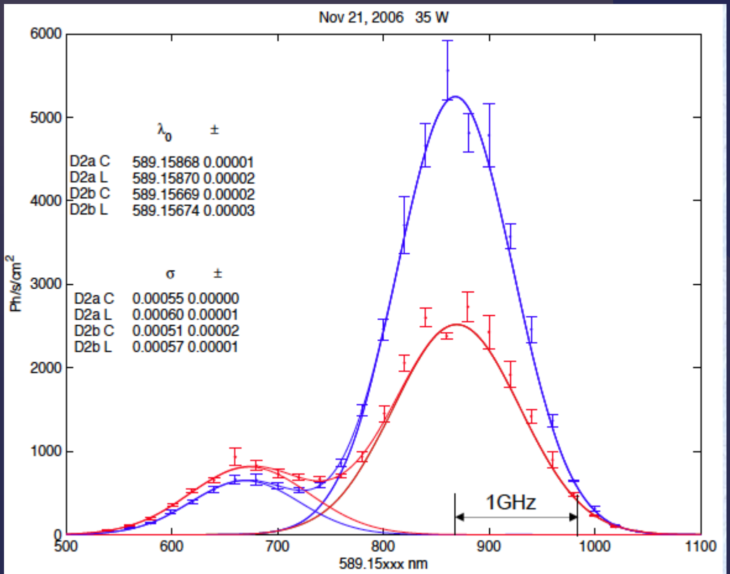


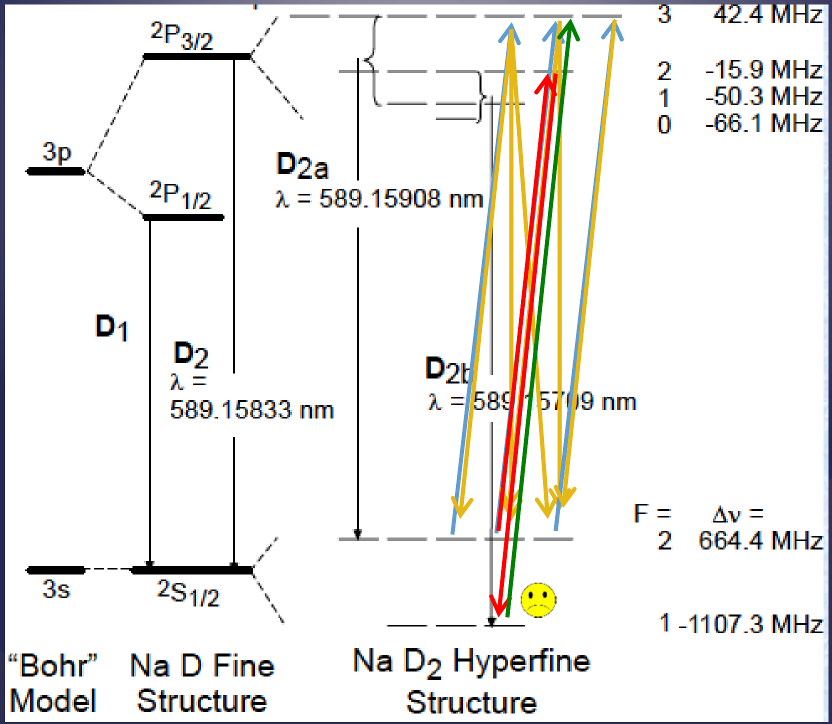
Figure 9. Variation of the mesospheric sodium density as a function of time and altitude was measured using the Lick Observatory Shane Telescope sodium laser. Drift-scan images from the Nickel, 600 meters to the west, enable us to resolve time and altitude dependence.



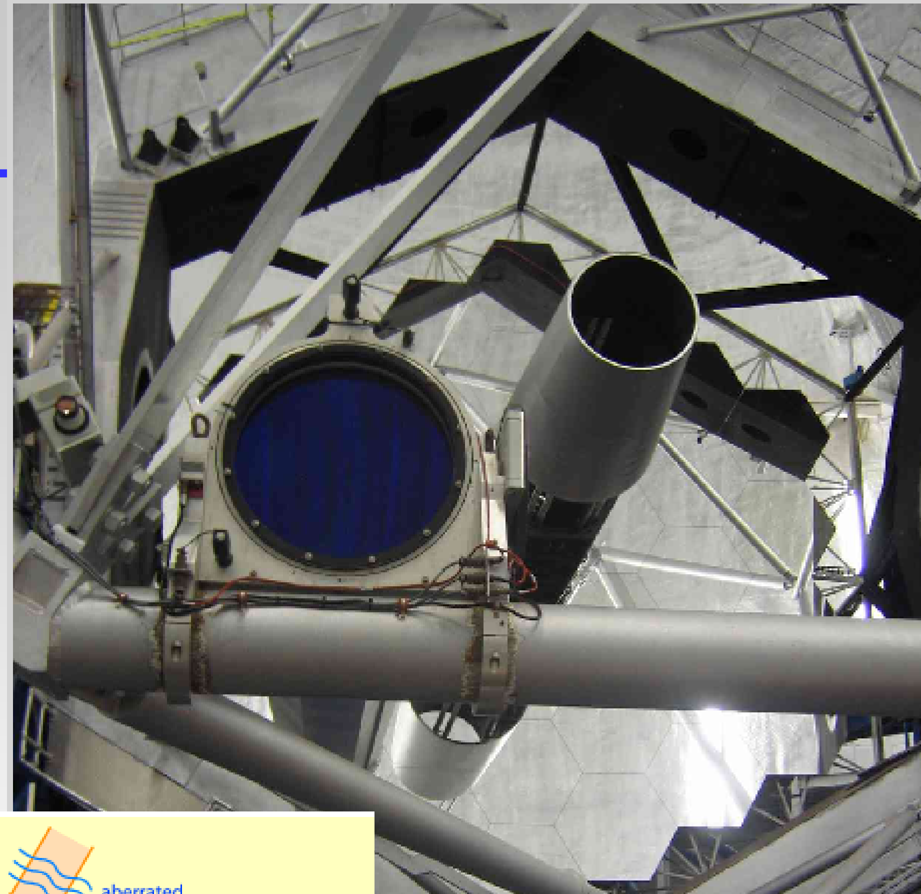
Optical pumping with circularly polarized light

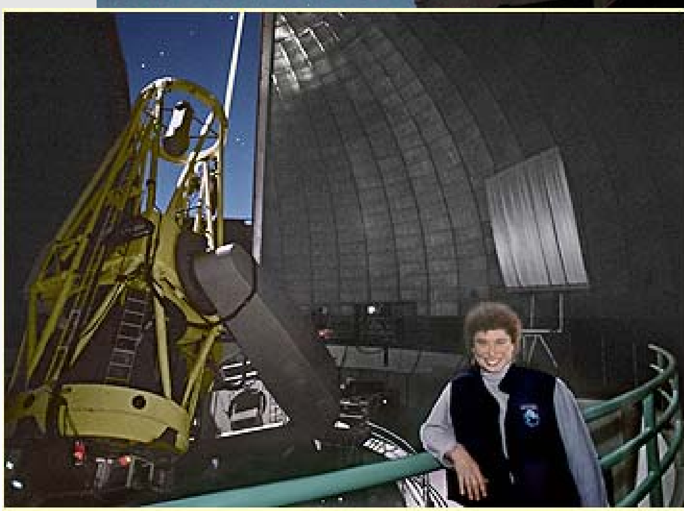




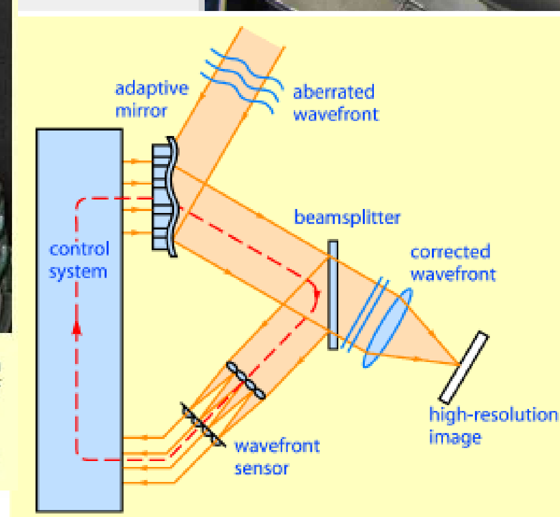


Keck II 36-Segment Primary



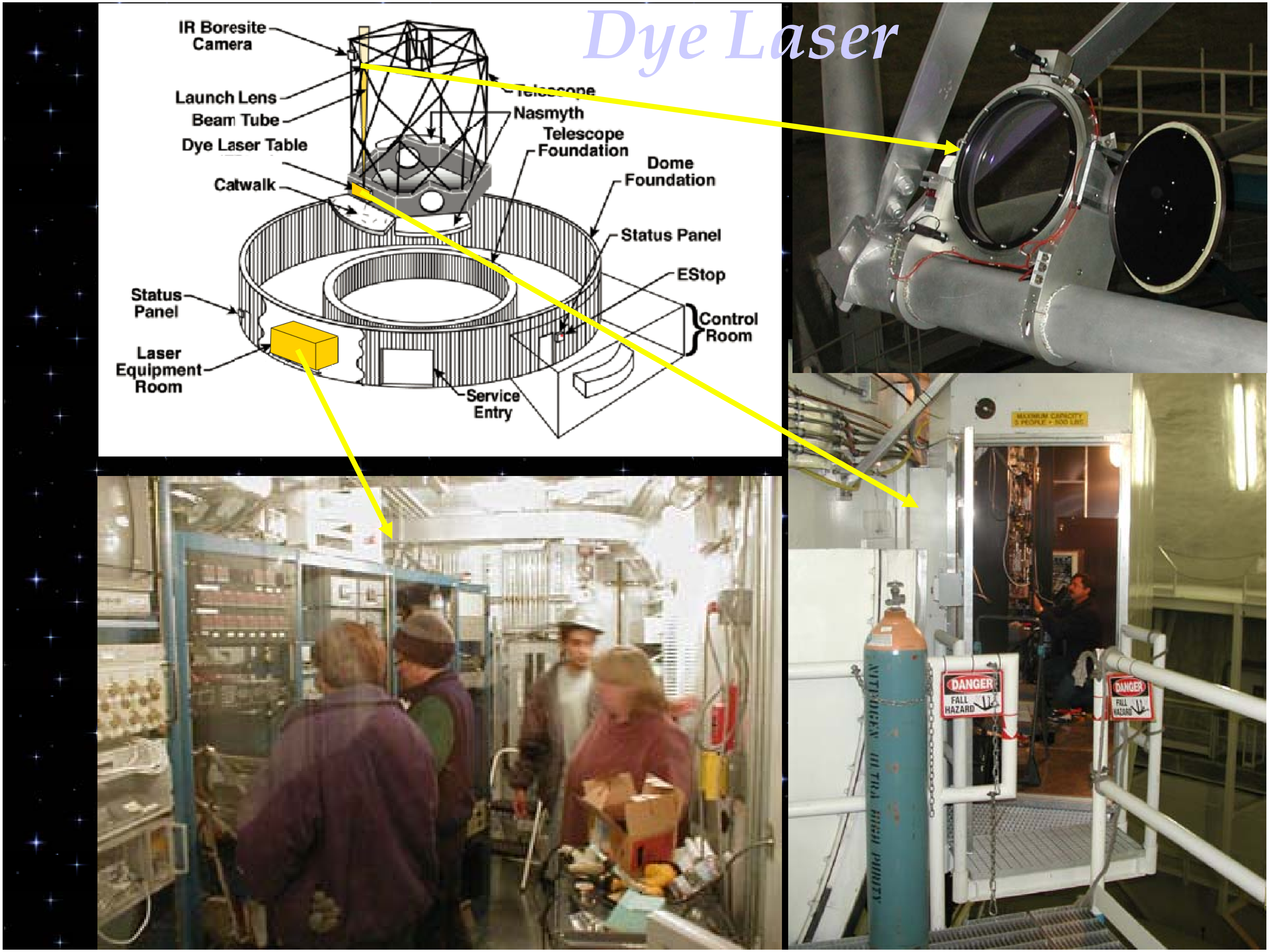


Claire Max stands next to the Shane Telescope at Lick Observatory on Mt. Hamilton. In the background, the bright straight line at the top of the photo is the laser beam from the laser guide star system Max designed as part of the telescope's adaptive optics system, which corrects for the blurring effect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



Deformable Mirror:

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

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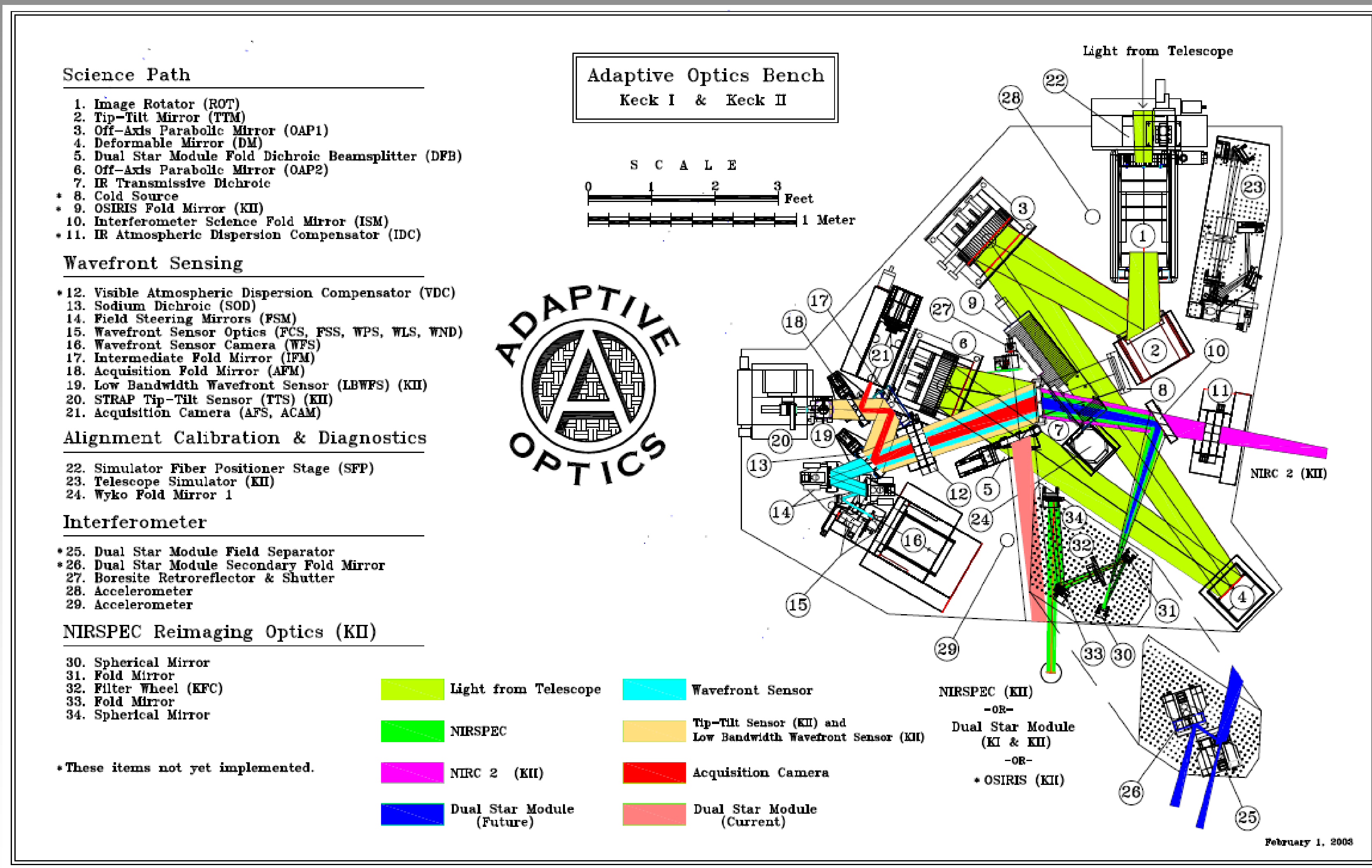
Keck Telescope Adaptive Optics



Laser system on the Shane Telescope

Lick Observatory, Mt Hamilton, CA

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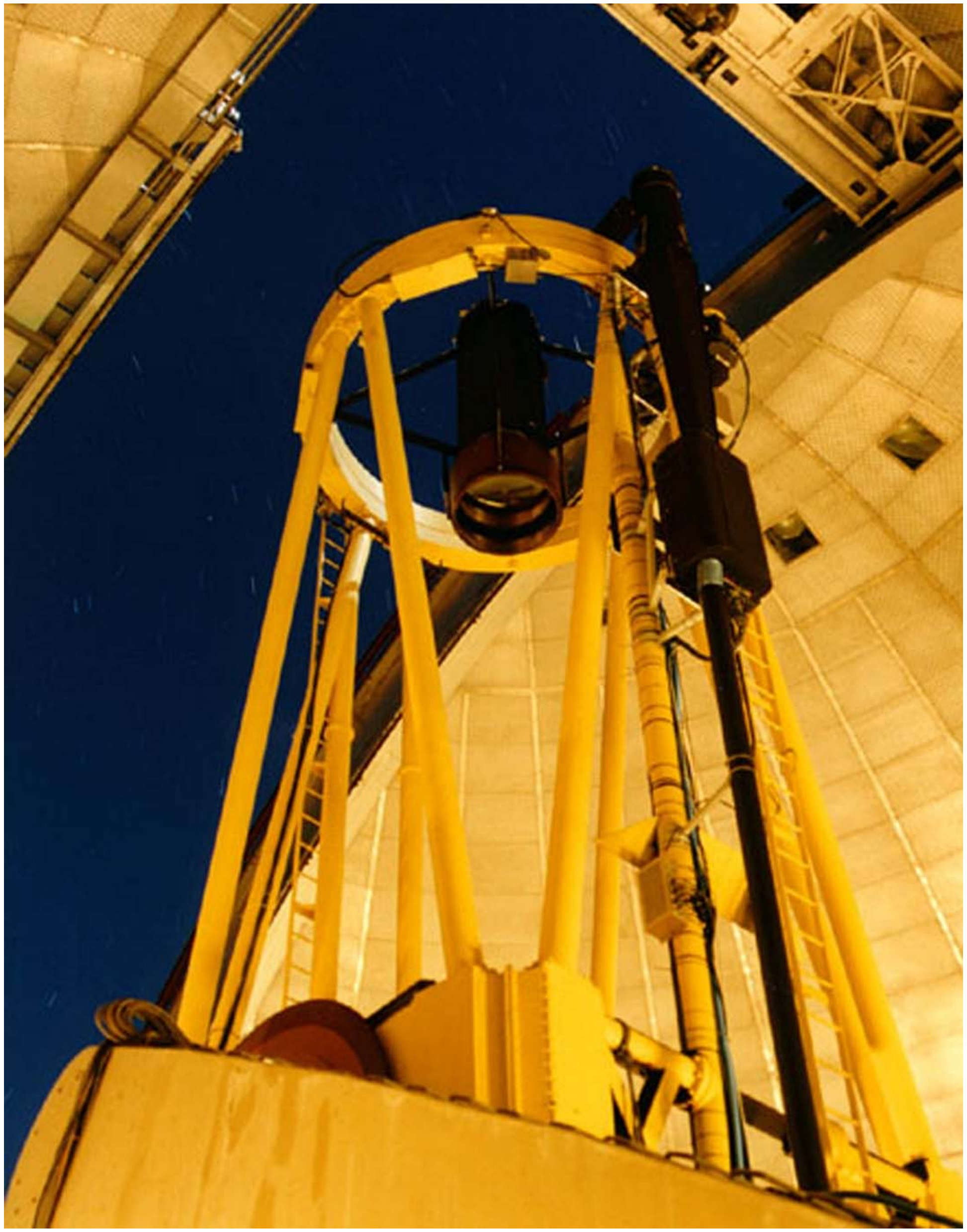
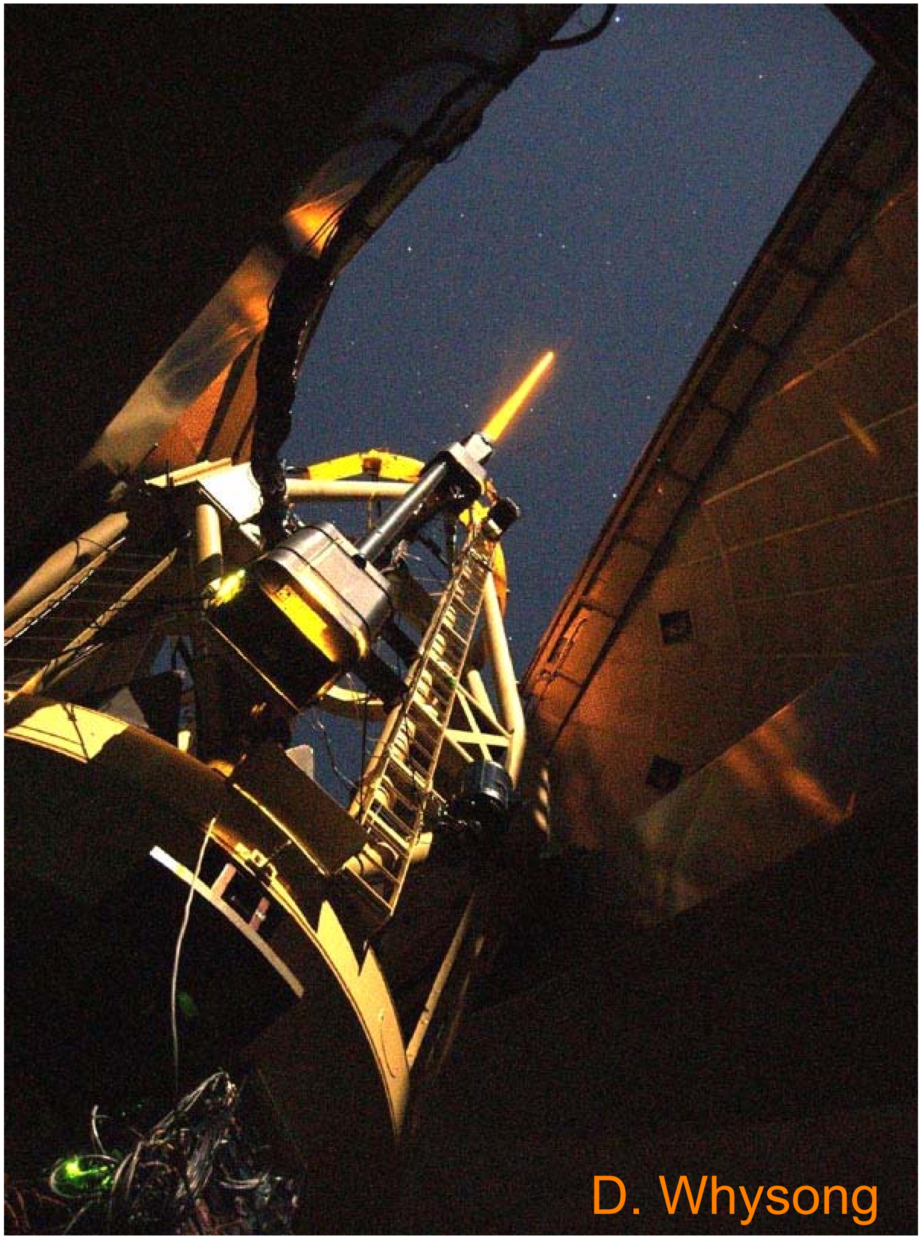


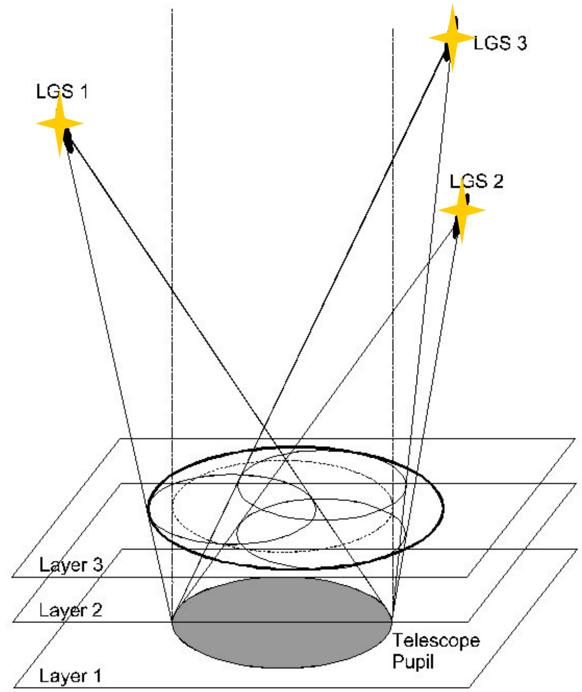


D. Whysong

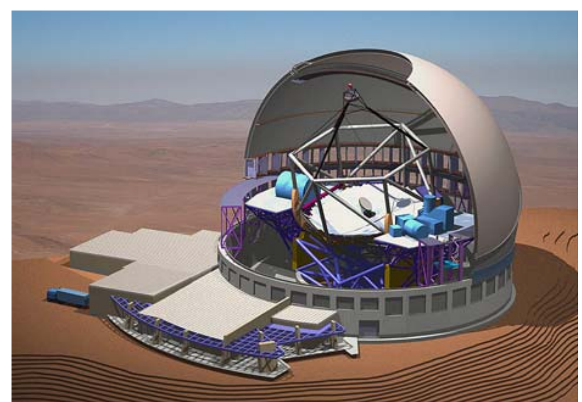

M. Perrin

AO 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

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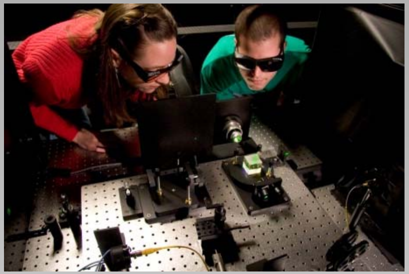
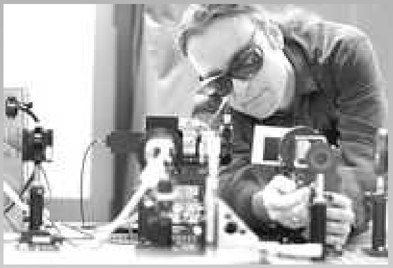
Laboratory for Adaptive Optics

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

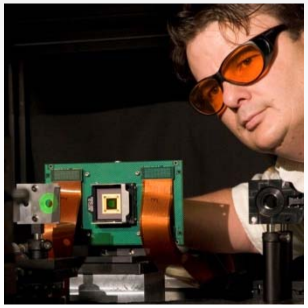




- A permanent facility within the UCO/Lick Observatory located at the UC Santa Cruz campus
- Presently funded by a grant from the Gordon and Betty Moore Foundation

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



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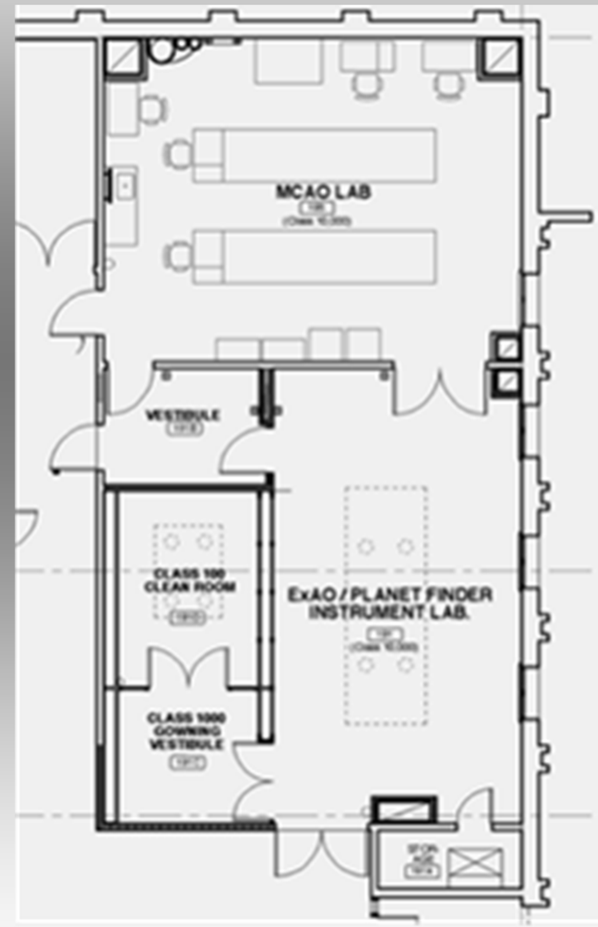
LAO Facility
in Thimann Labs Building, UCSC



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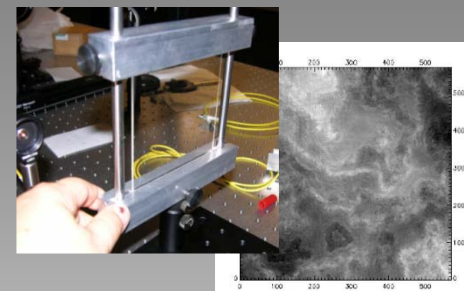
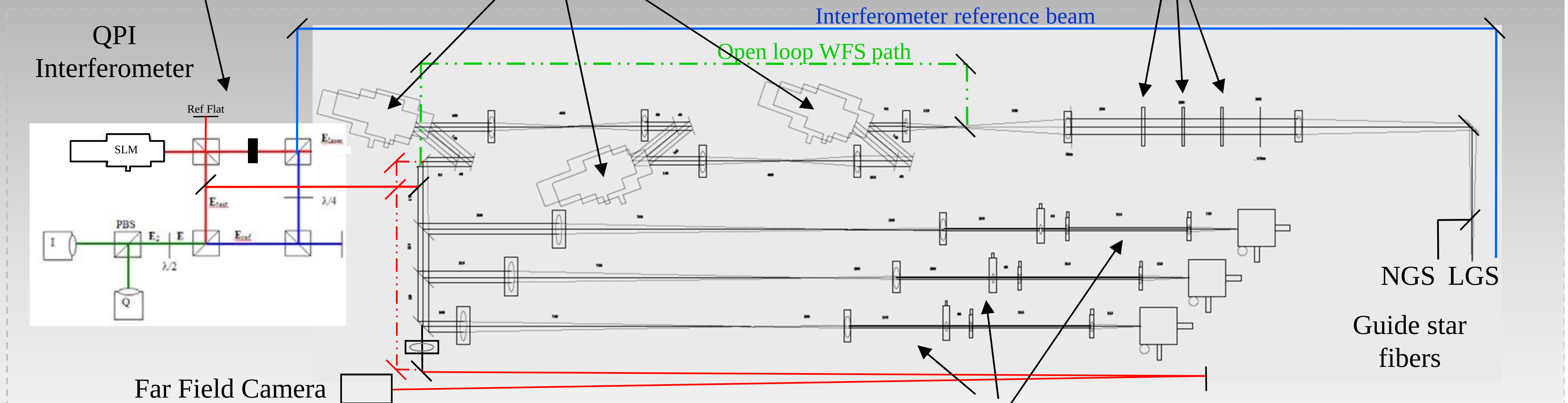
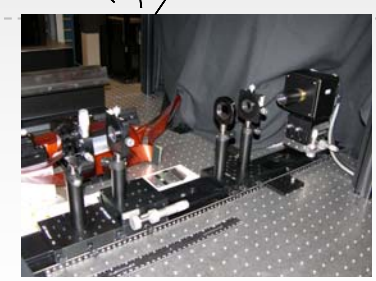
MCAO / MOAO Testbed

Deformable Mirrors (SLMs)

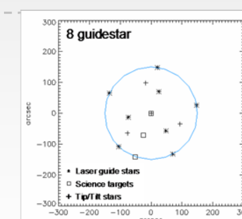


Kolmogorov Atmosphere phase aberrator plates





Hartmann Wavefront Sensors

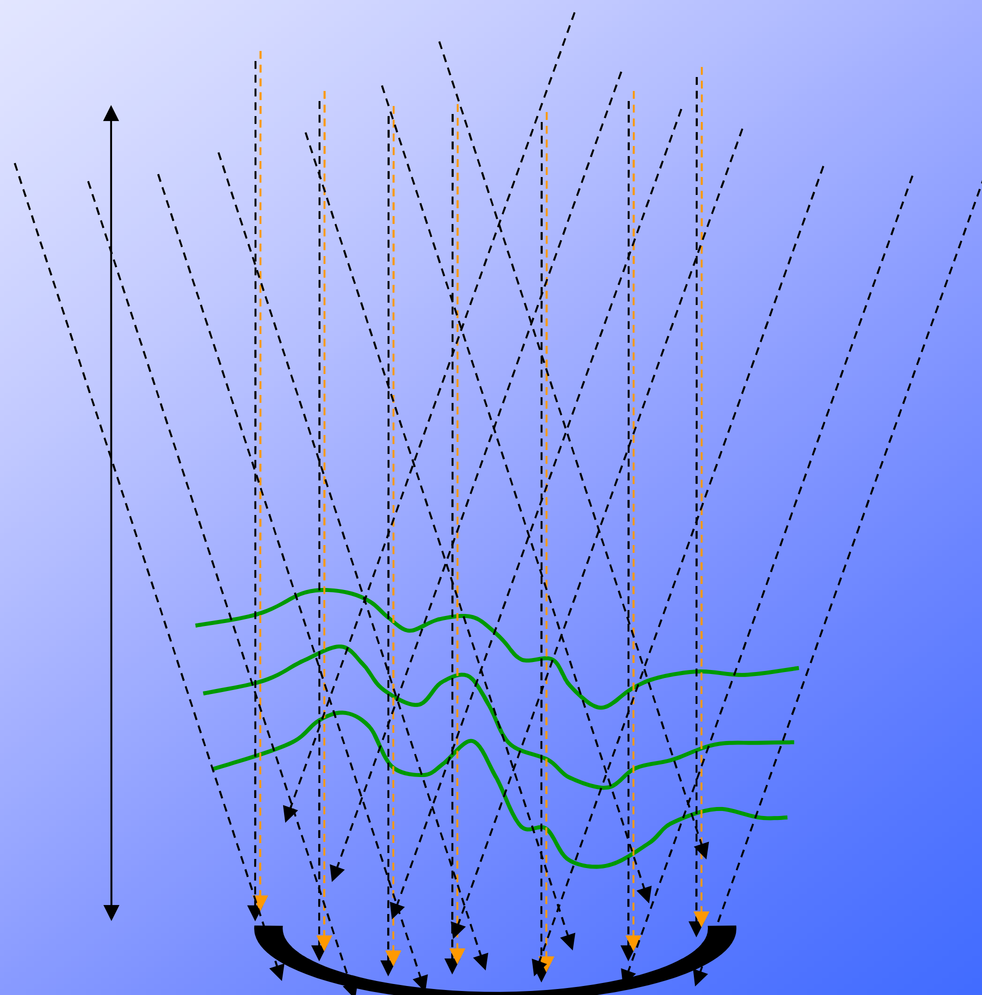


Configurable guide star constellation

- 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

Limitations for AO systems with one guide star

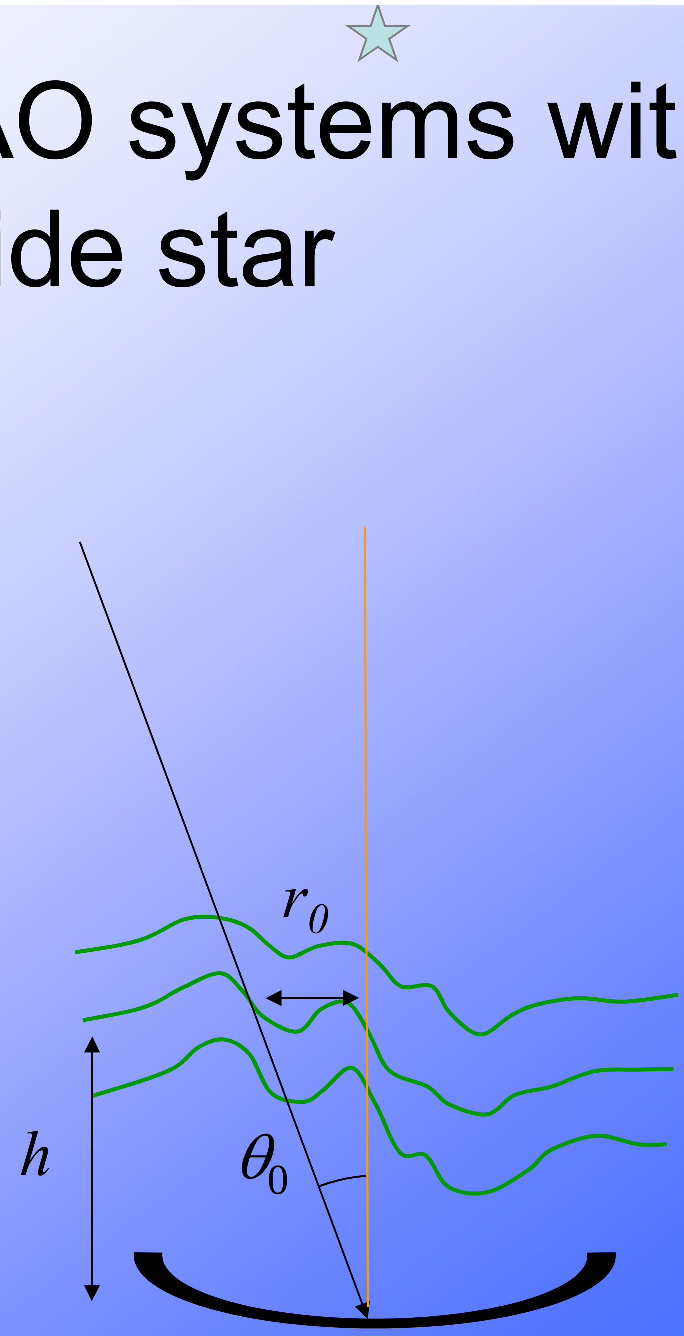
- Isoplanatic Angle



Limitations for AO systems with one guide star

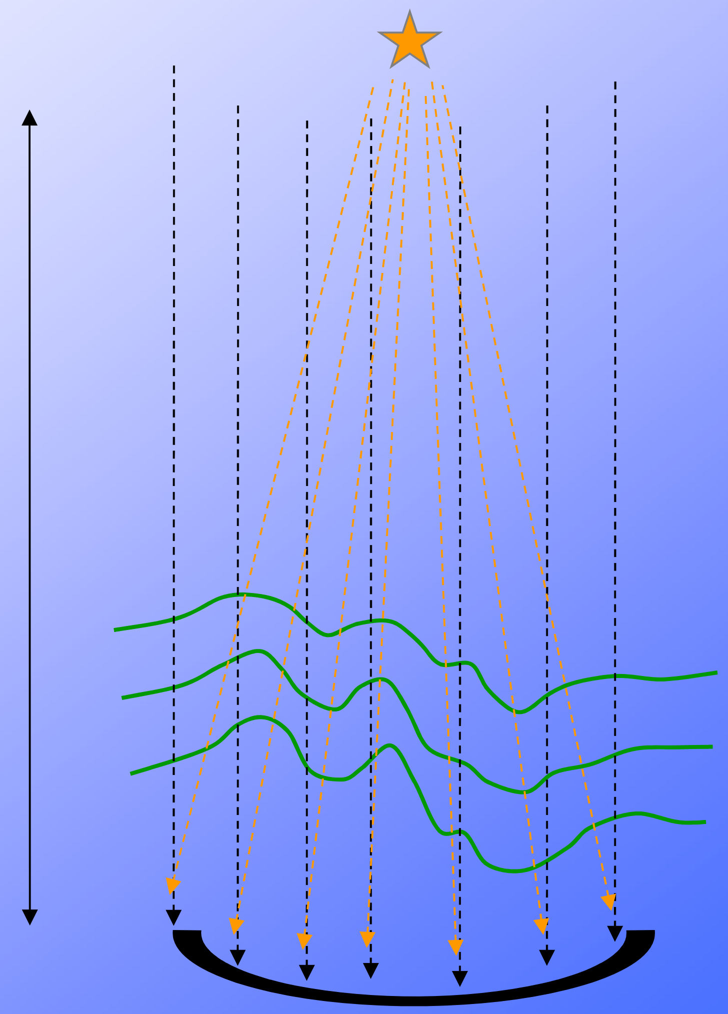
- Isoplanatic Angle

  Limits the corrected field



Limitations for AO systems with one guide star

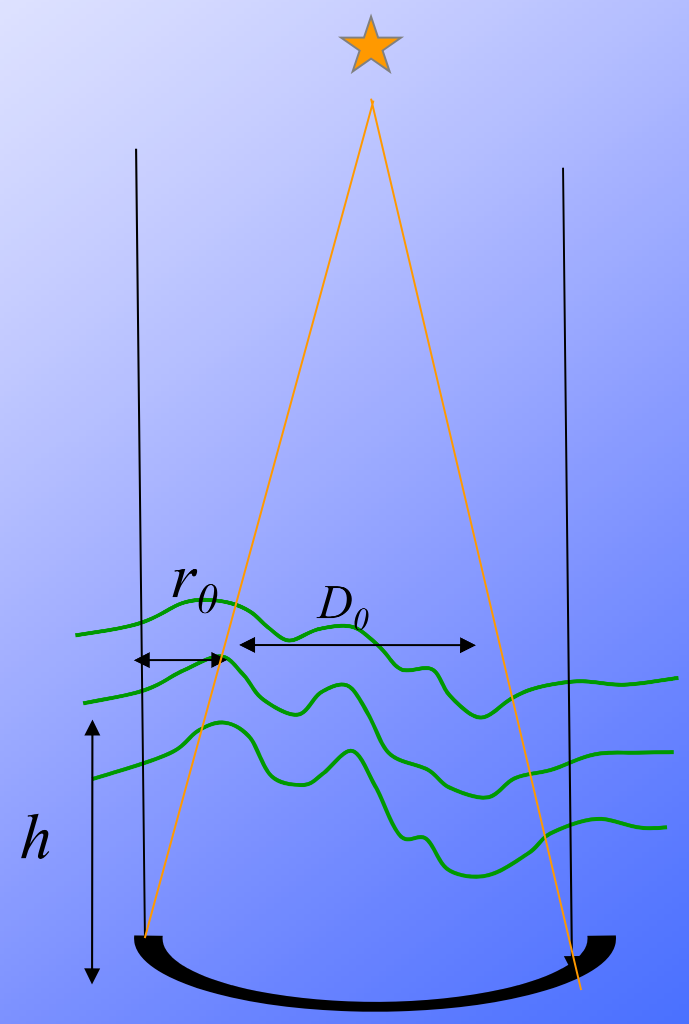
- Cone effect



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



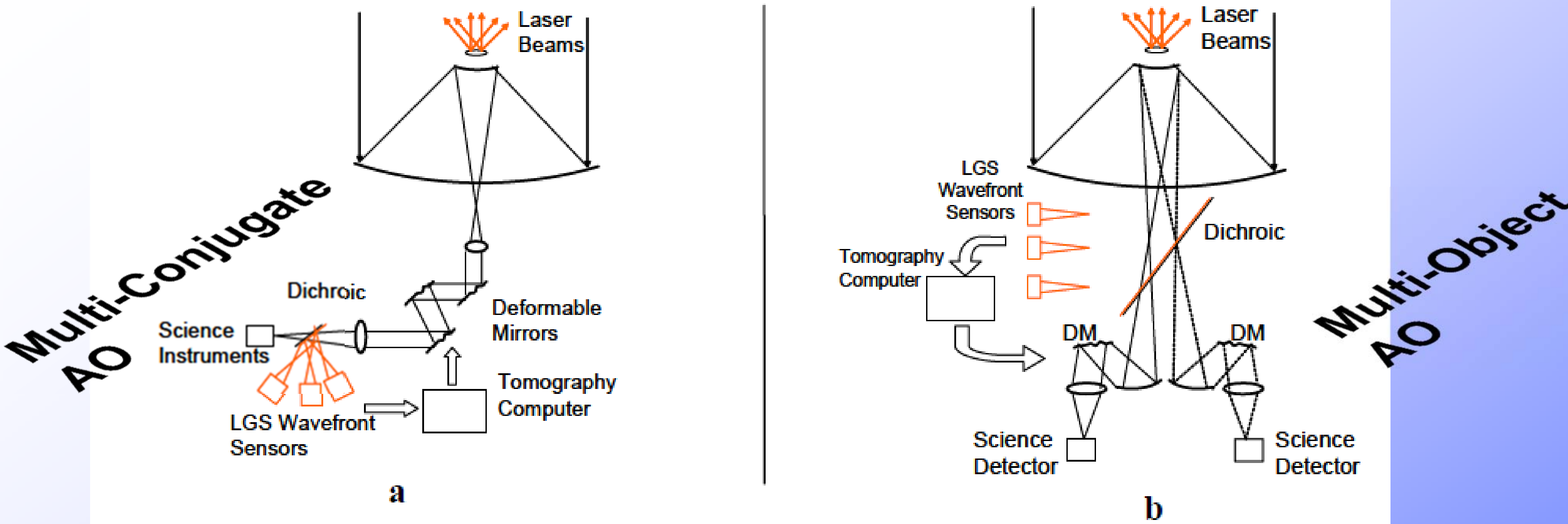


Figure 1 Configurations of astronomical adaptive optics systems: a) multiple conjugate, b) multiple object.

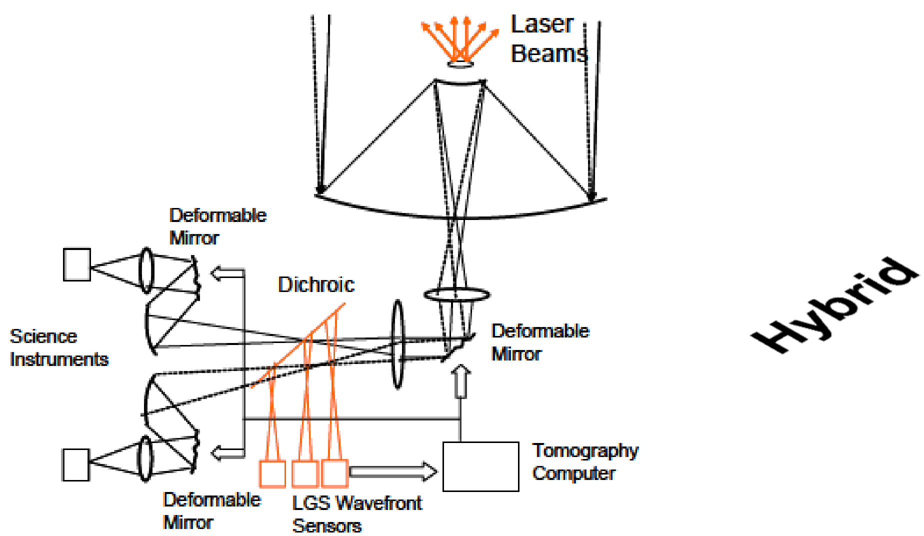


Figure 2 Hybrid MCAO/MOAO configuration.

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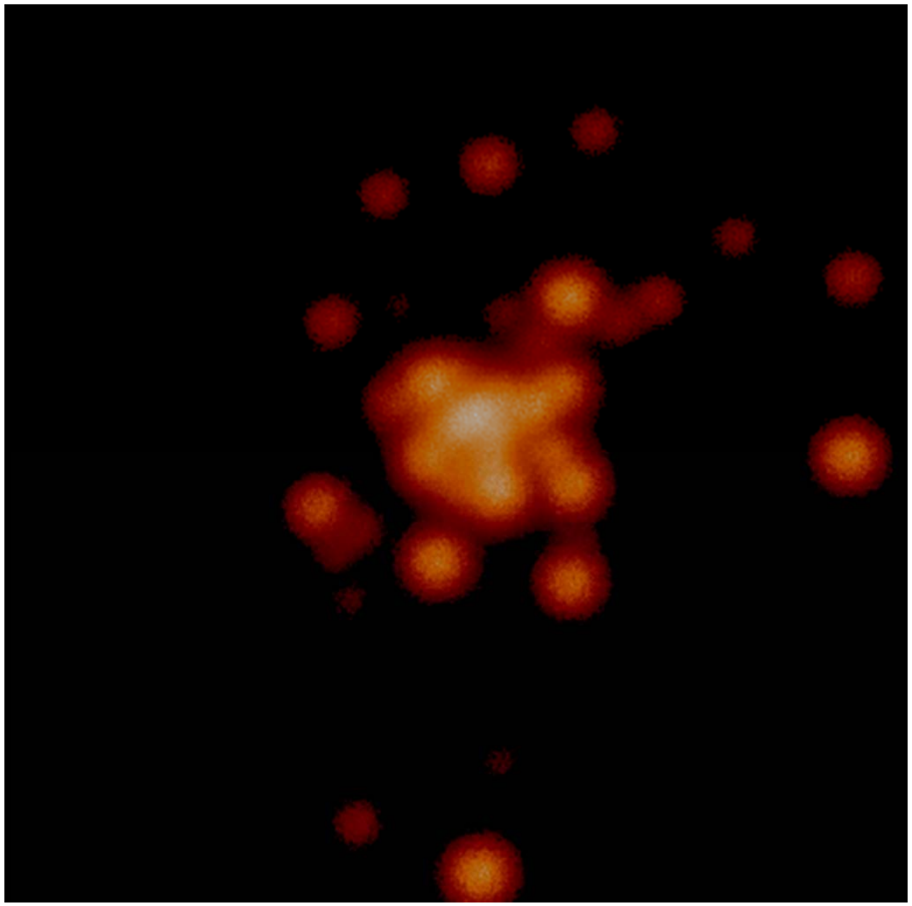
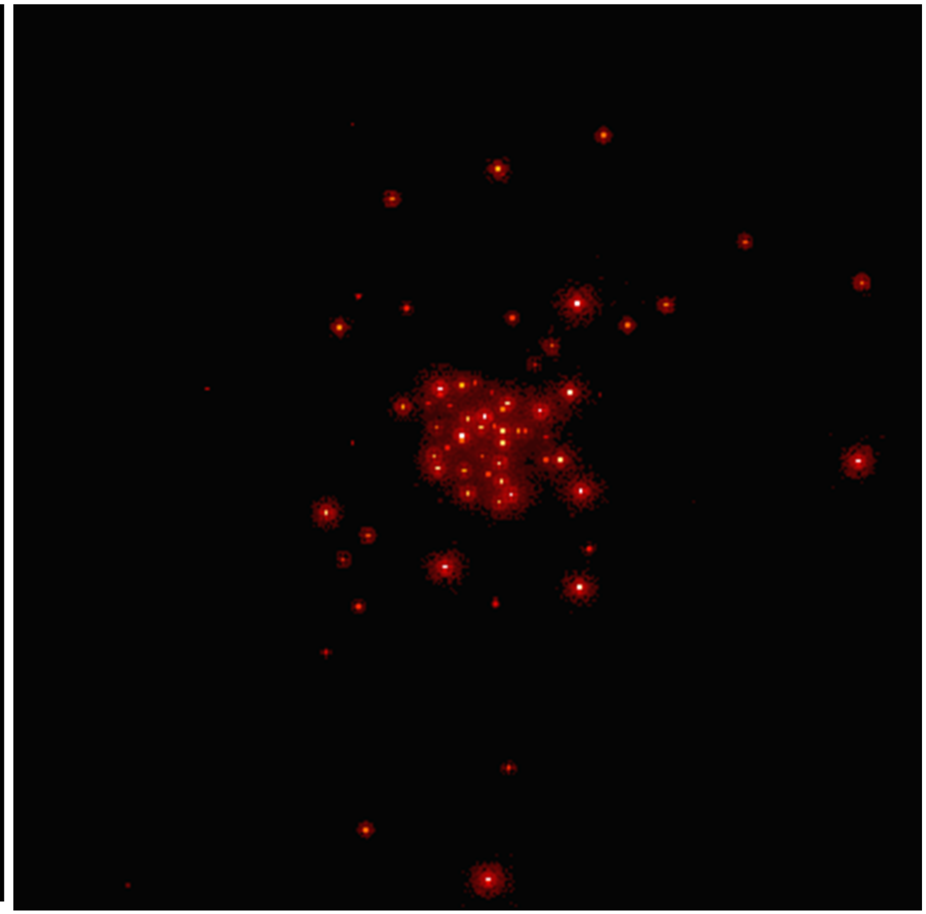
University of California, Santa Cruz

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

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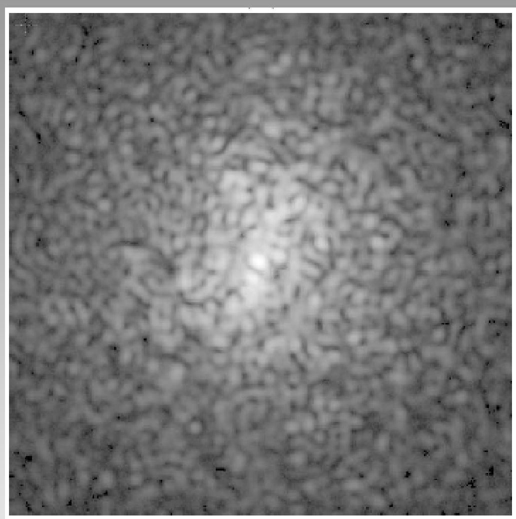
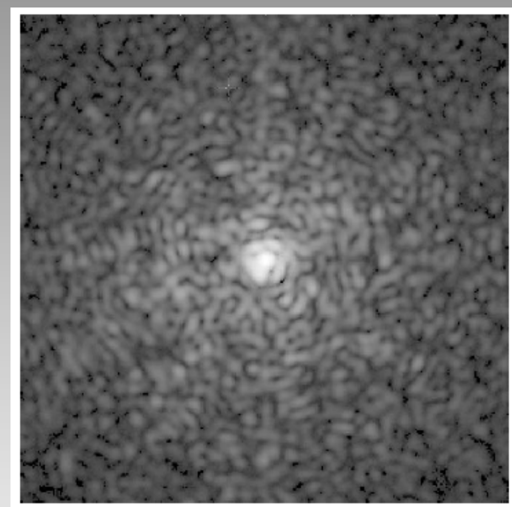
UCO/Lick Observatory
University of California, Santa Cruz

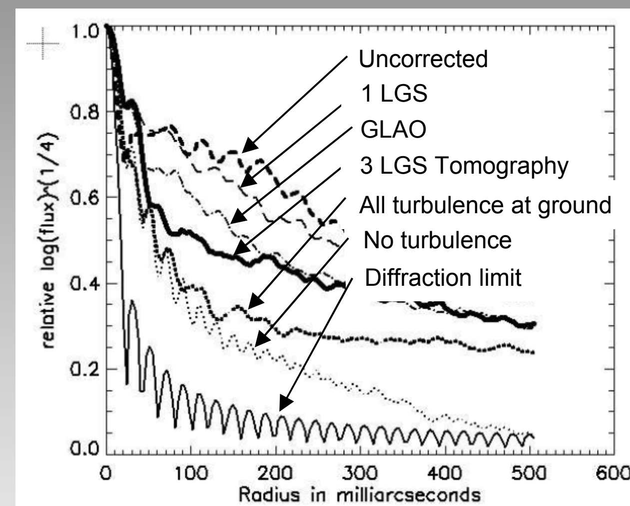
MCAO/MOAO Testbed in Operation

Ammons, et. al., SPIE 6272-175

Testbed "commissioning" results:







1 LGS (Anisoplanatic)

1.3′

3 LGS Tomography

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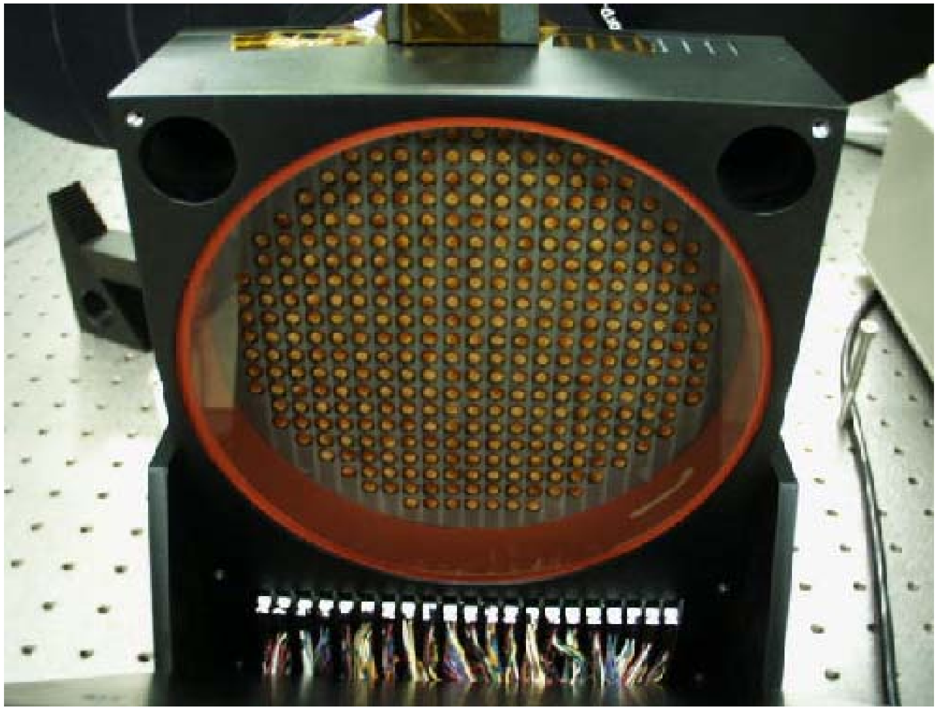
DM used on the Keck AO System

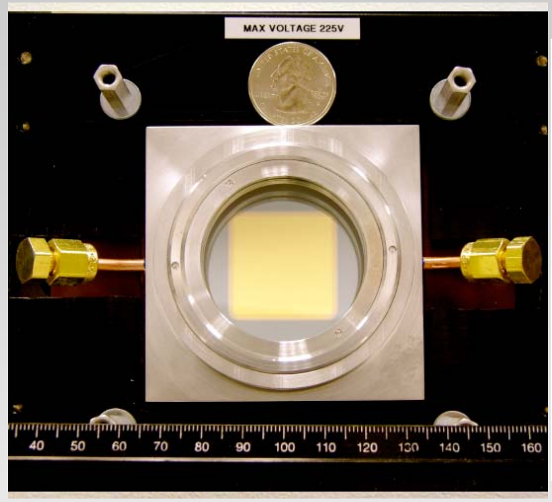
349 degrees of freedom

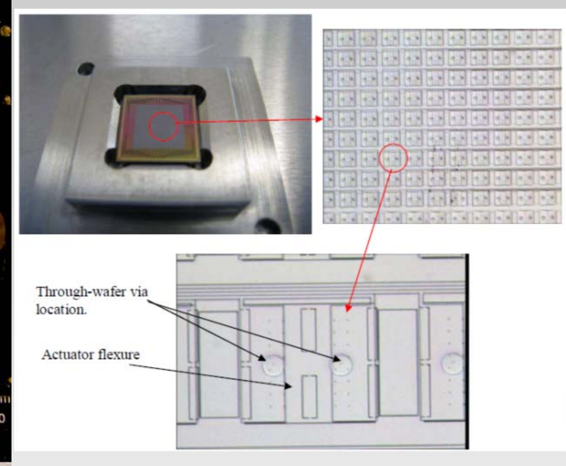
Front View


Back View

MEMS Deformable Mirrors

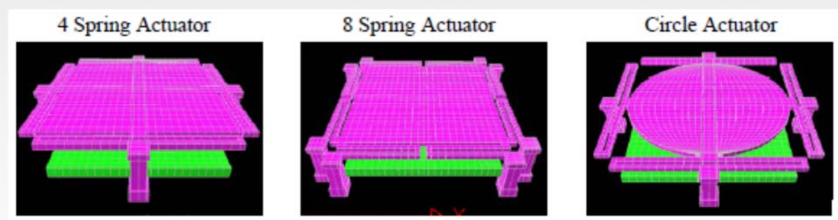
- **Consortium** to build 4,000 and develop 10,000 actuator devices (BMC)
  - Gemini Planet Imager
  - Keck Next Generation Adaptive Optics
  - Thirty Meter Telescope



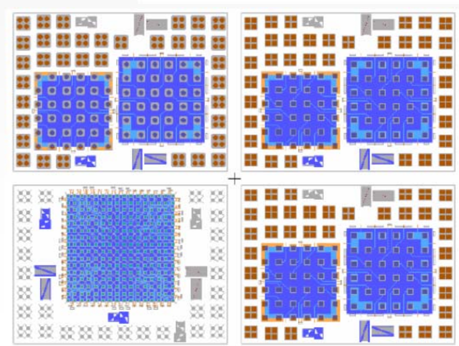


Boston Micromachines

- **High density** interconnect, packaging, & electronics (BMC)



- **Higher stroke actuator** designs (UCSC)



Joel Kubby, UCSC

Laboratory for Adaptive Optics
UCO/Lick Observatory
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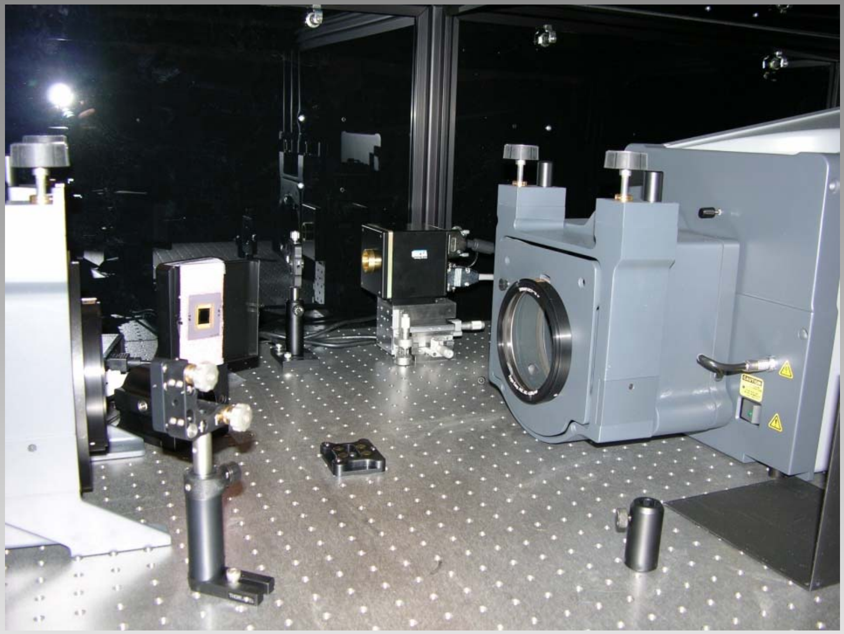
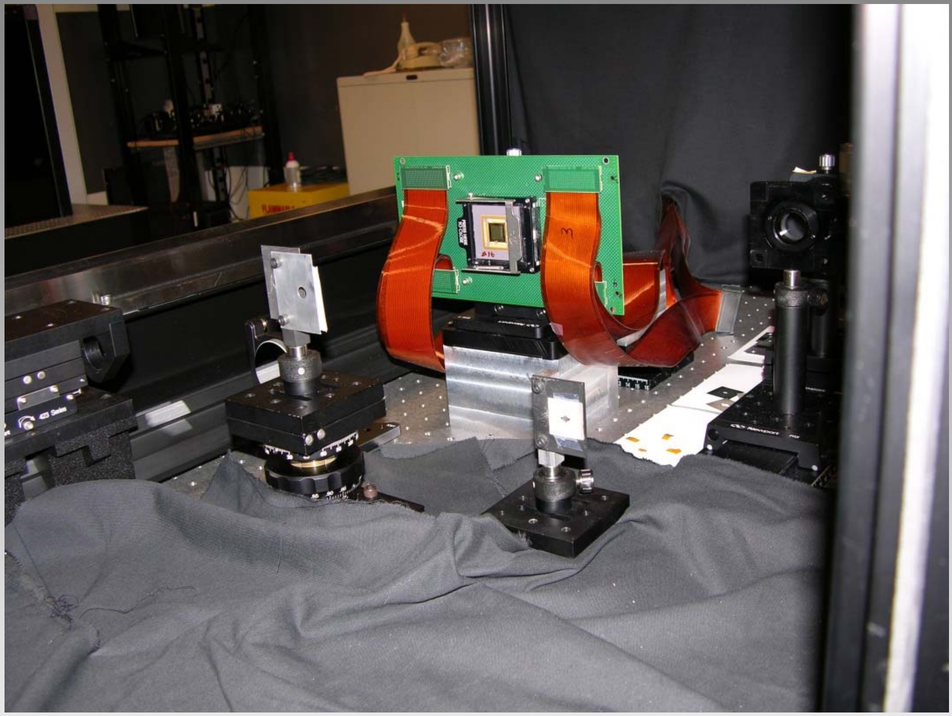
Micro-electo-mechanical System (MEMS) Deformable Mirror



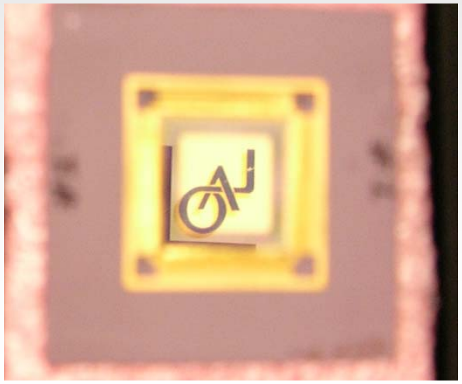


MEMS devices in the lab now:

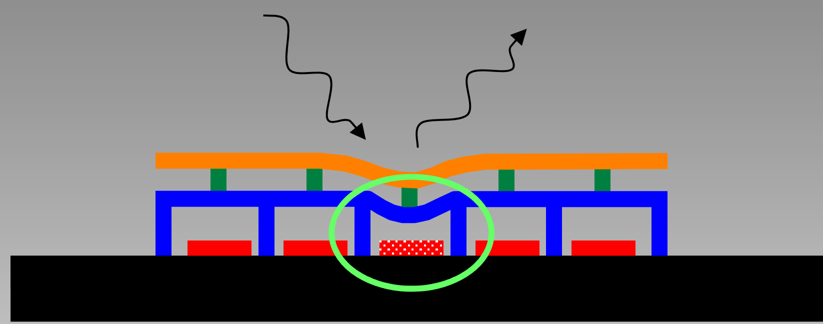
- 32x32 array
- 64x64 array

Goal:

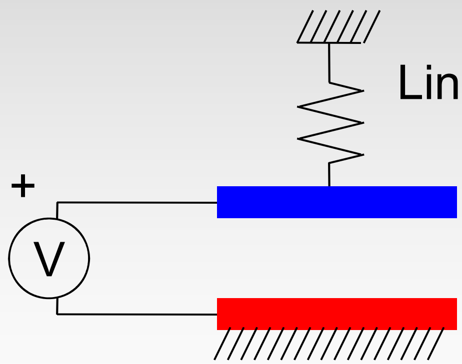
- 100x100 array – 30 m telescope general use



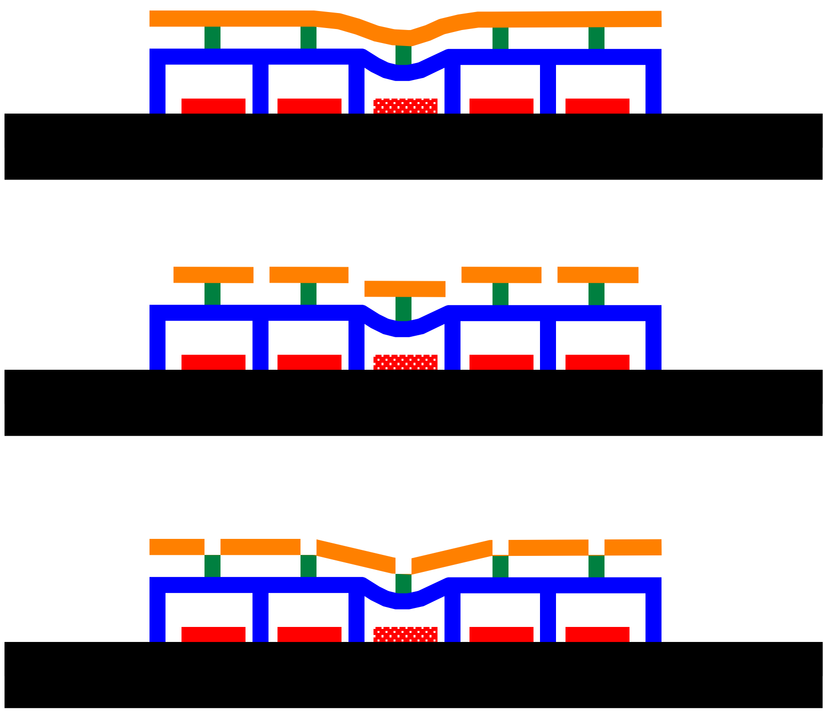
MEMS deformable mirror with electrostatic actuators



Simplified actuator model:



Boston University & Boston Micromachines Corporation Design



Continuous

Piston

Tip-Tilt

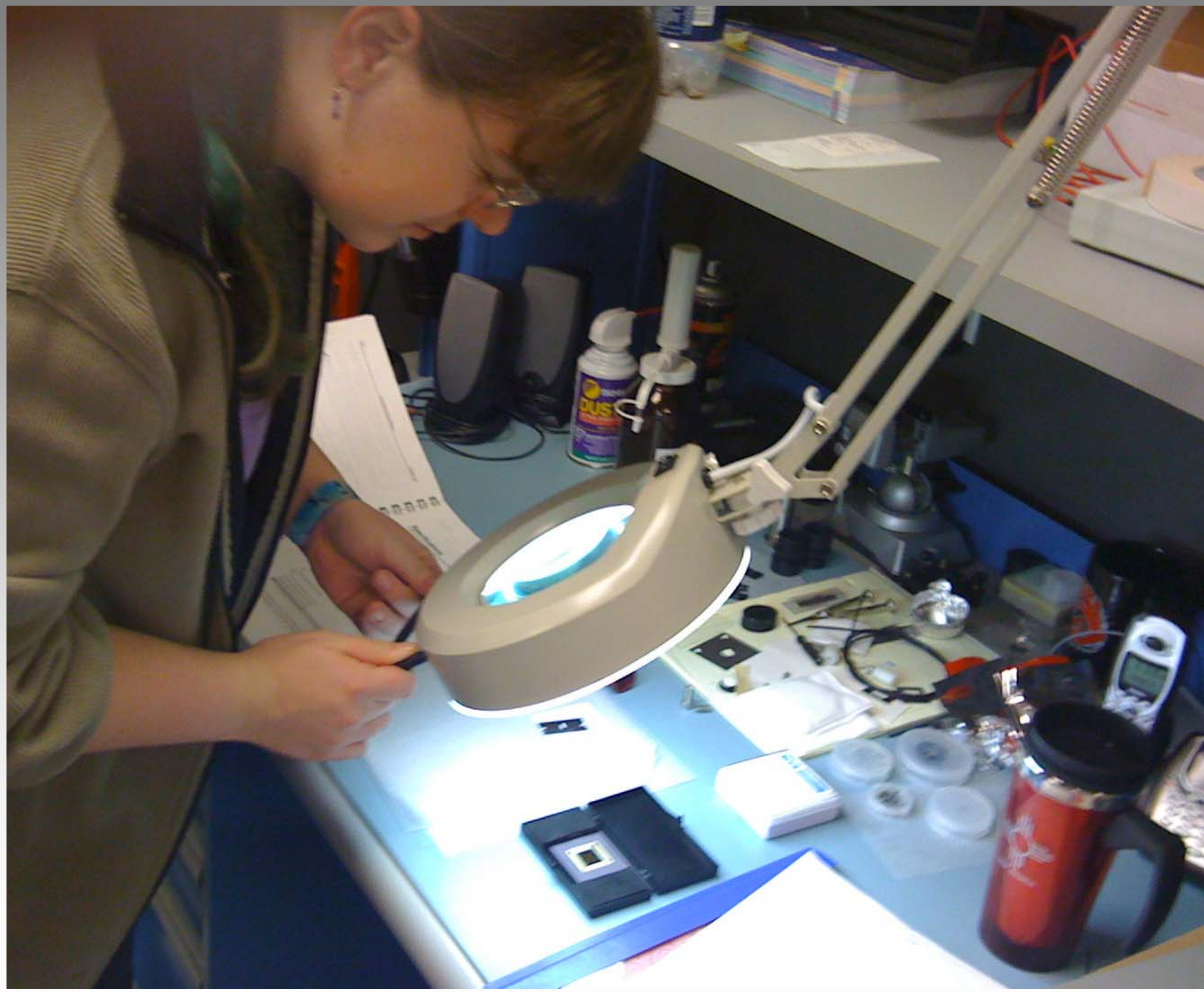
To get the same AO fitting error (Kolmogorov turbulence)

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

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

(C. Max, CfAO website)

BOSTON MICROMACHINES CORPORATION



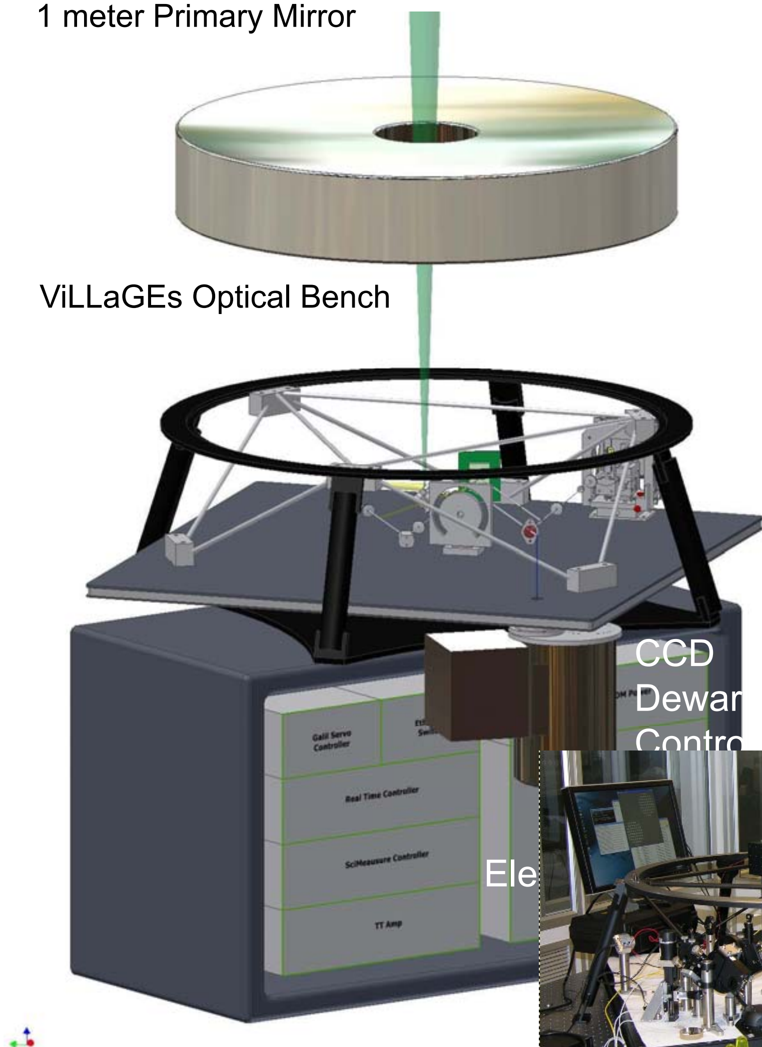
Visible Light Laser Guidestar AO System Experiments

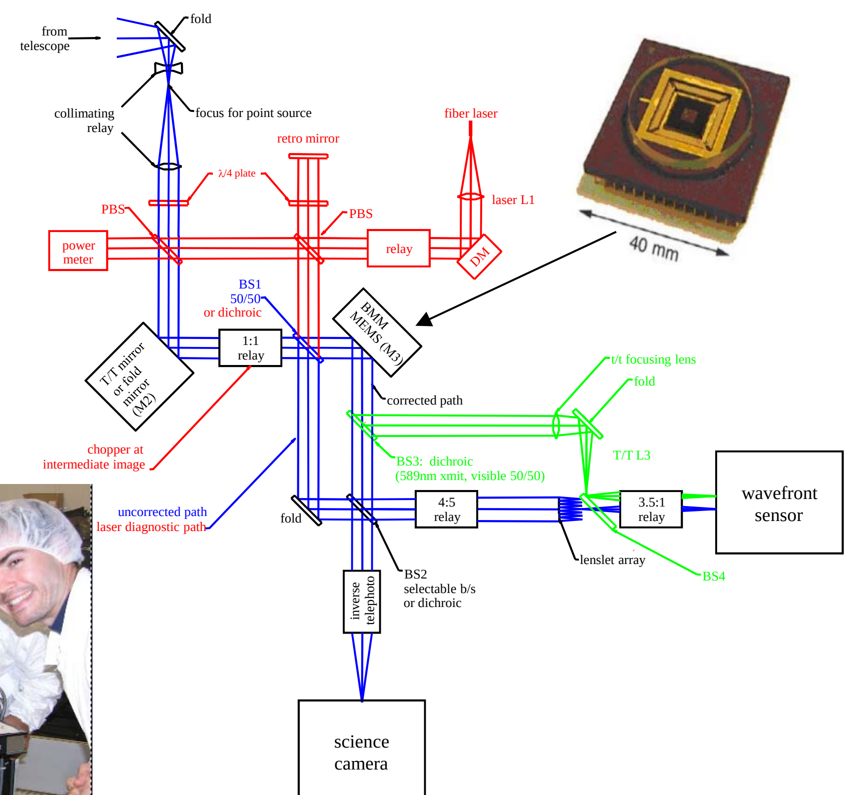
Laboratory for Adaptive Optics

Villages

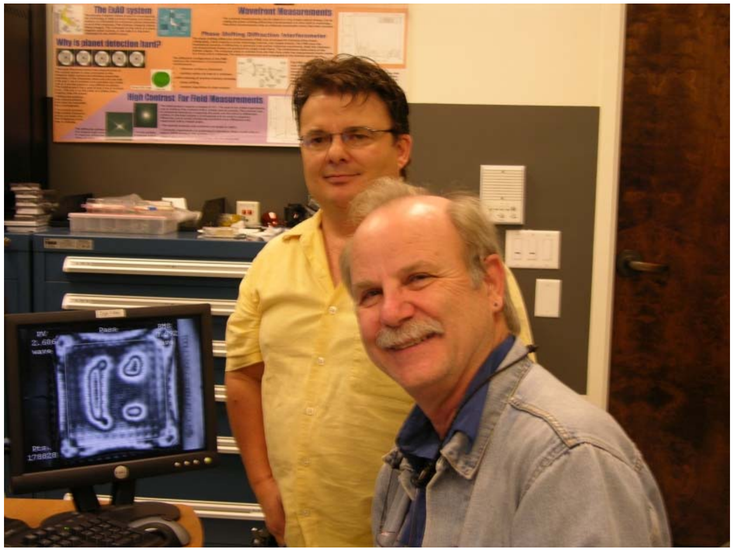
- Designed for Nickel 1-m Telescope, Mt. Hamilton
- Proof of concept for MEMS deformable mirrors in astronomical AO instruments
- PoC of AO uplink correction of laser beam
- Experiments at the telescope started mid 2007

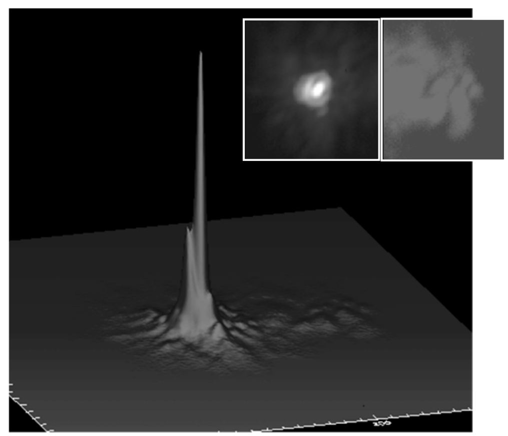
Nickel Telescope
1 meter Primary Mirror

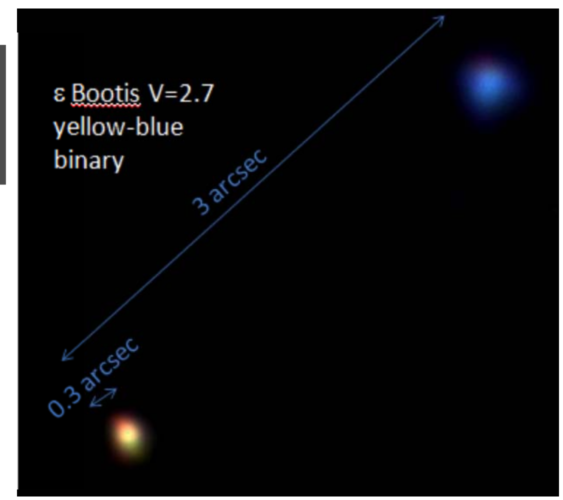




Villages On-sky
at the Nickel Telescope, Mt Hamilton







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.

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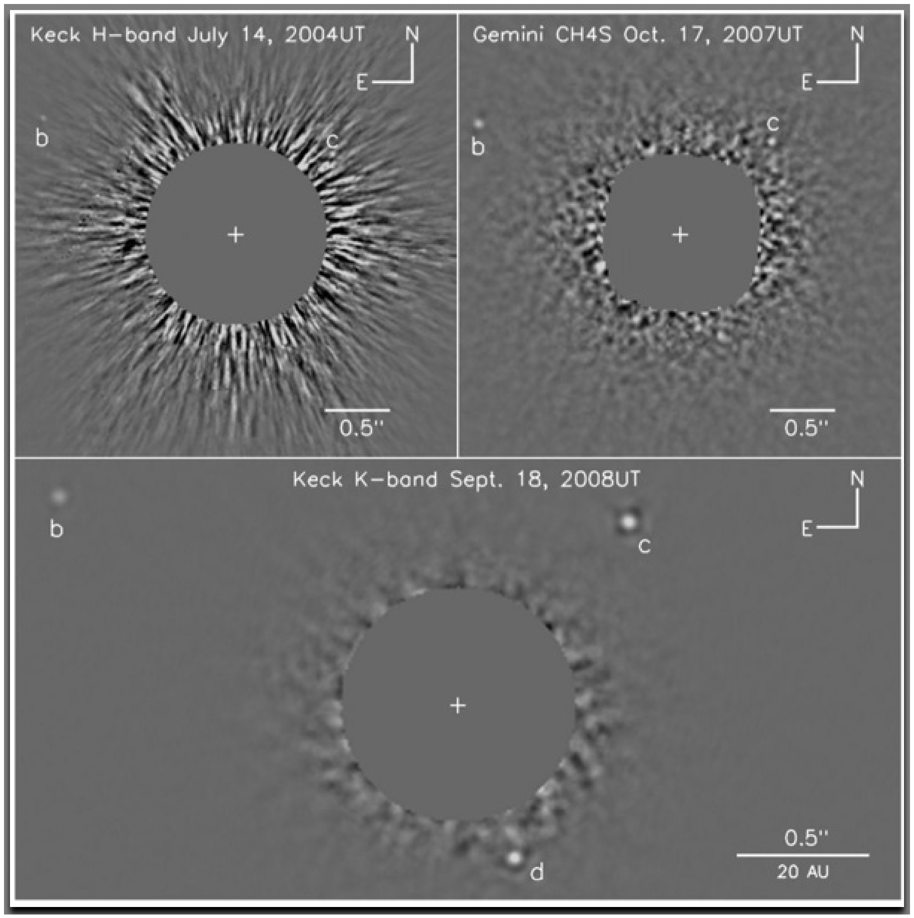
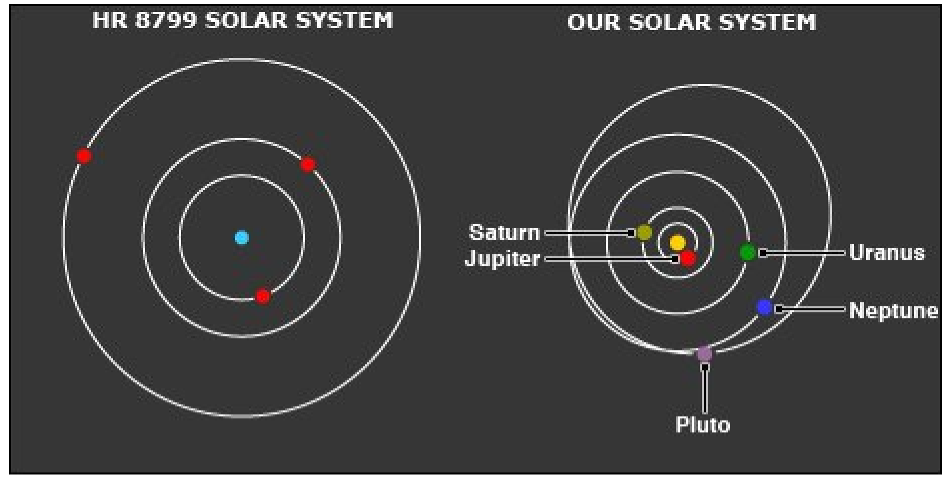
Gemini Planet Imager

Extreme Adaptive Optics: Imaging Extrasolar Planets





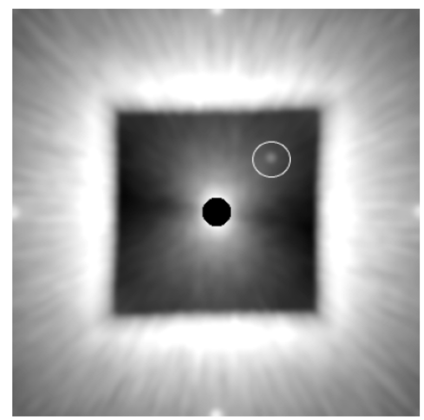


Figure 1: Simulated 20 second Gemini ExAOC integration showing a 5 Jupiter-mass extrasolar planet in a 6 AU orbit around a 200 Myr solar-type star at 10 pc. The star is located behind an occulting spot. The square "dark hole" region, 1.8" on a side, is produced by our spatially-filtered wave front sensor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

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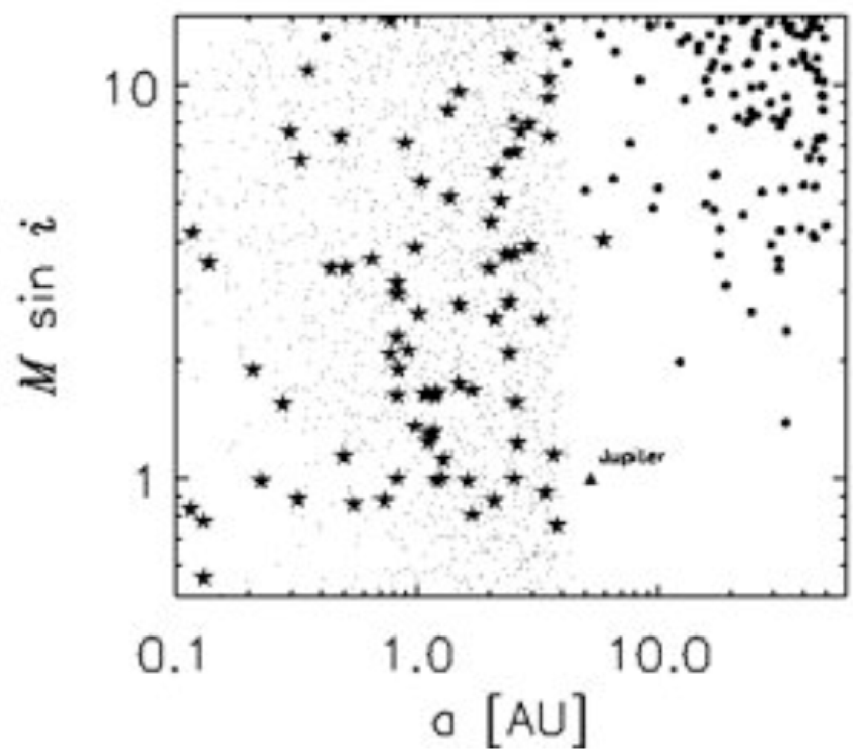
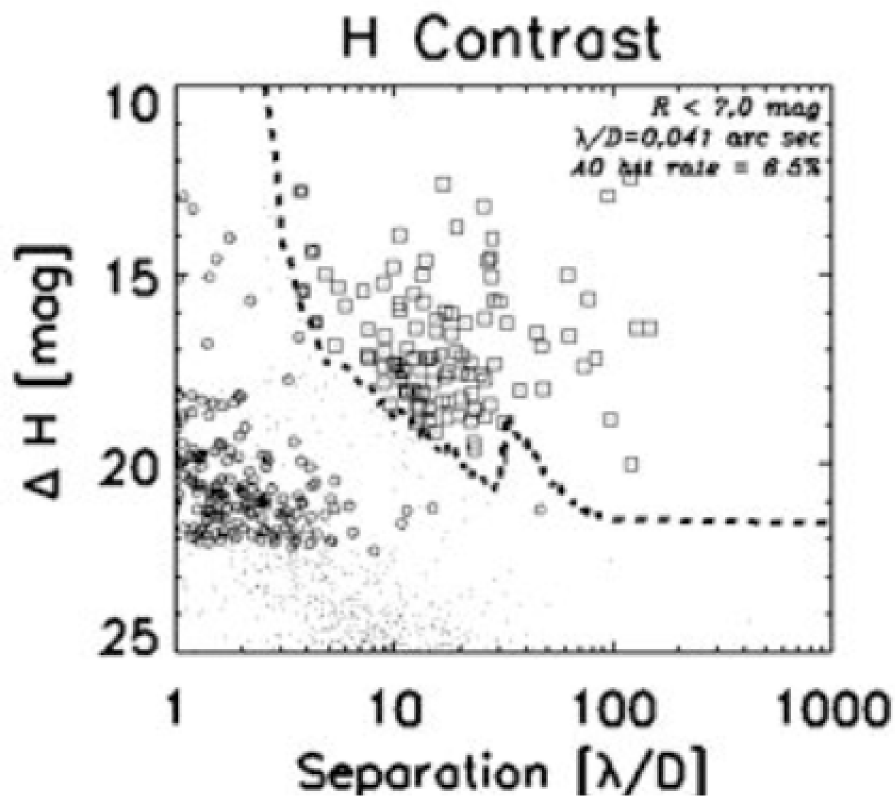
Gemini Planet Imager

Planet populations detectable with GPI based on simulations





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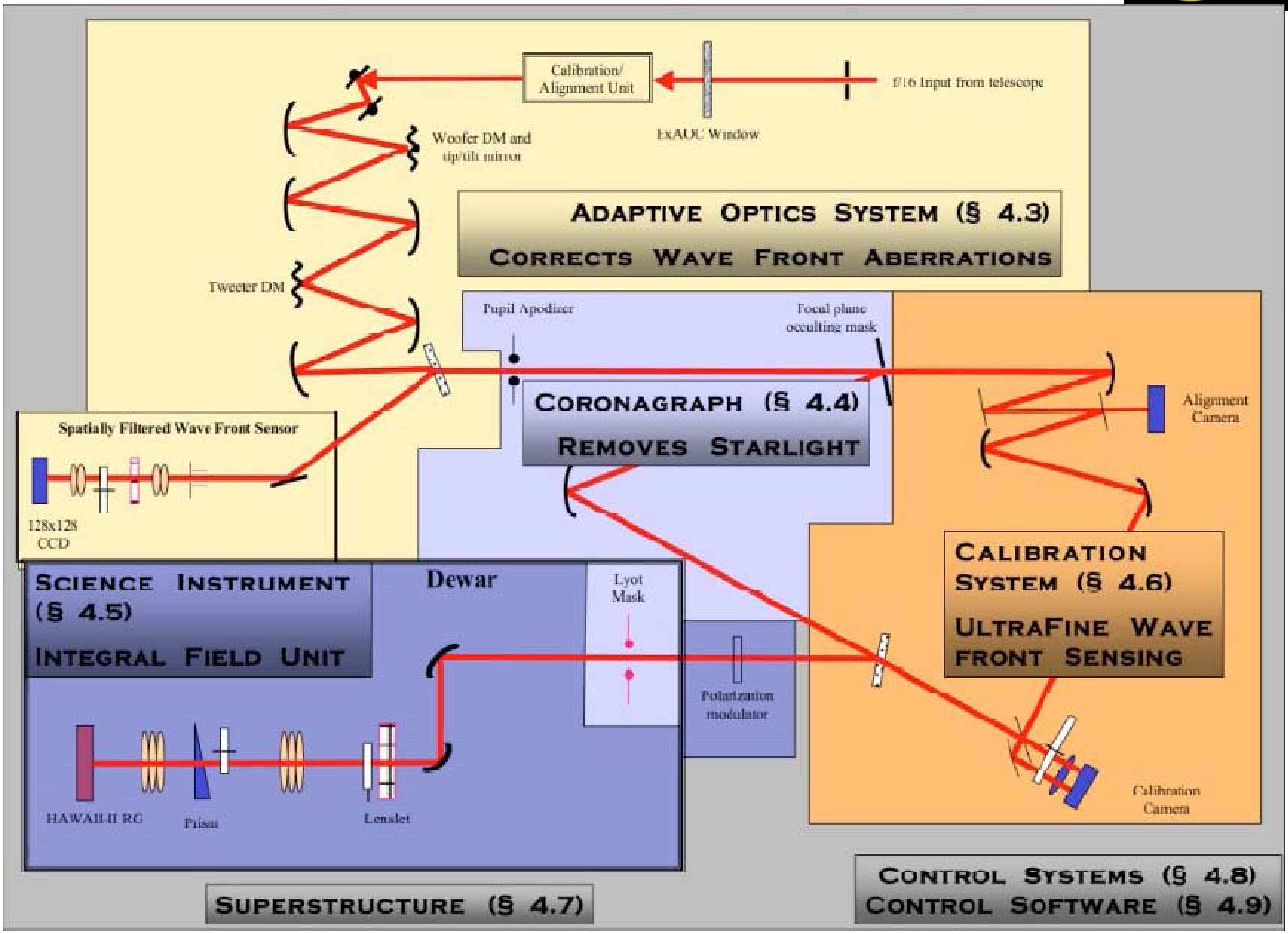
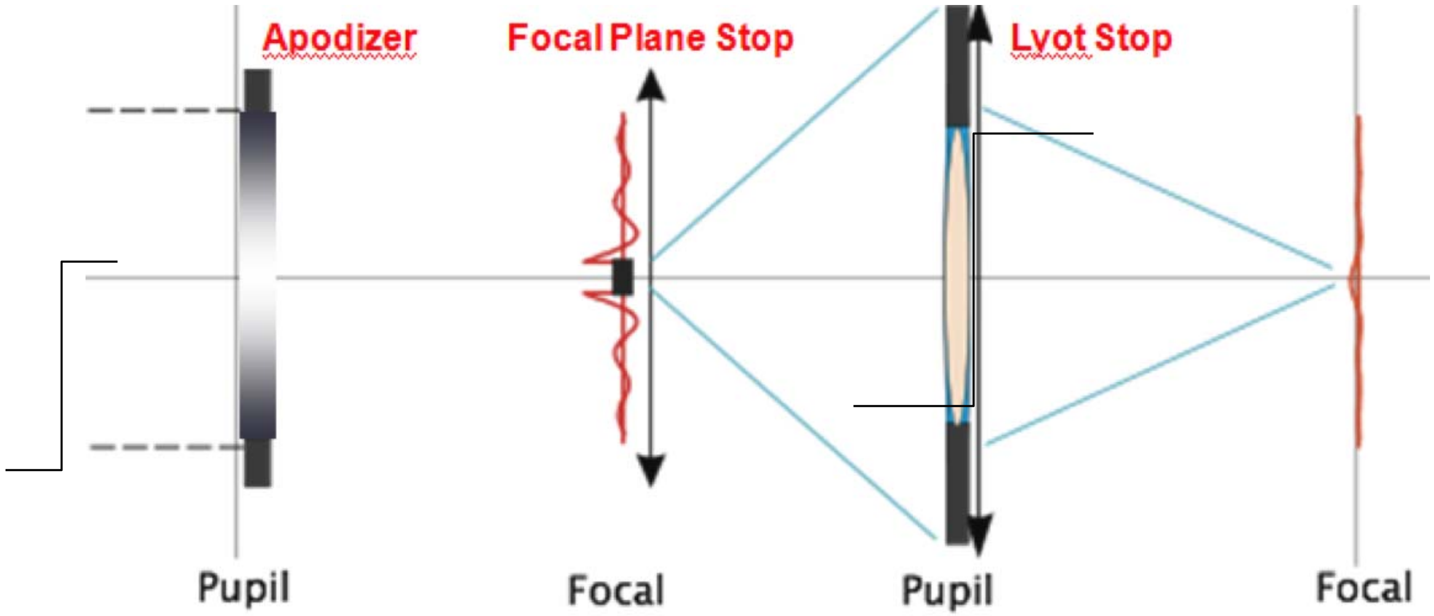
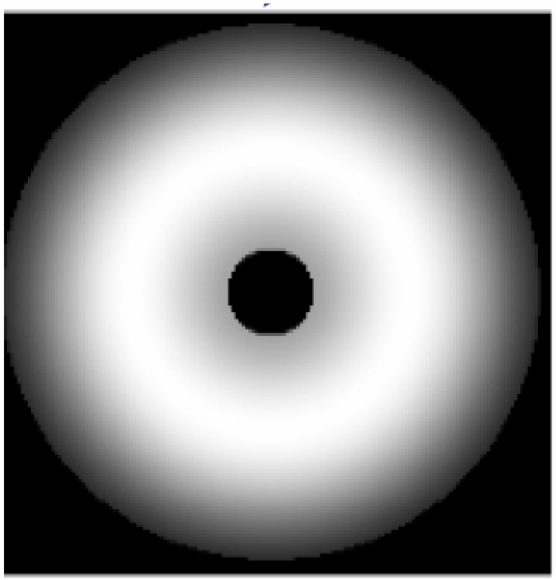
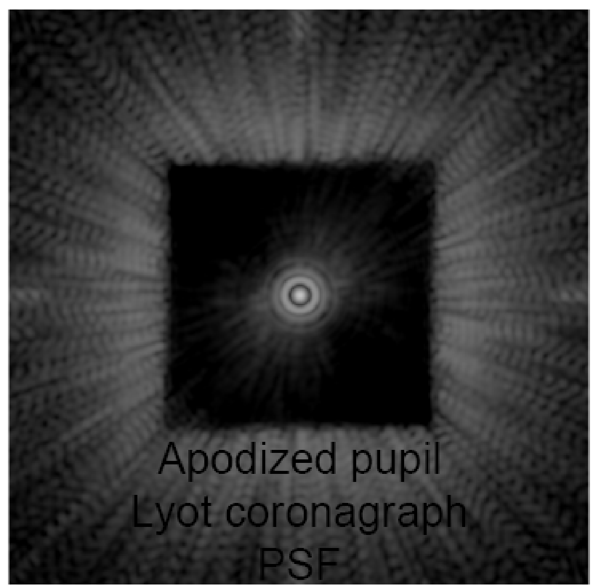
Gemini Planet Imager



Apodized-pupil Lyot coronagraph (Soummer 2005)







Soummer 2005

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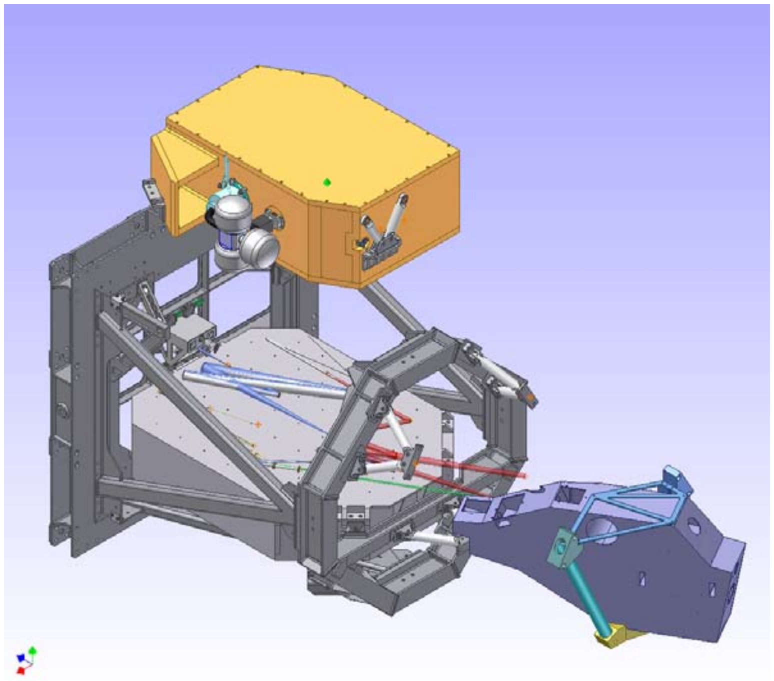
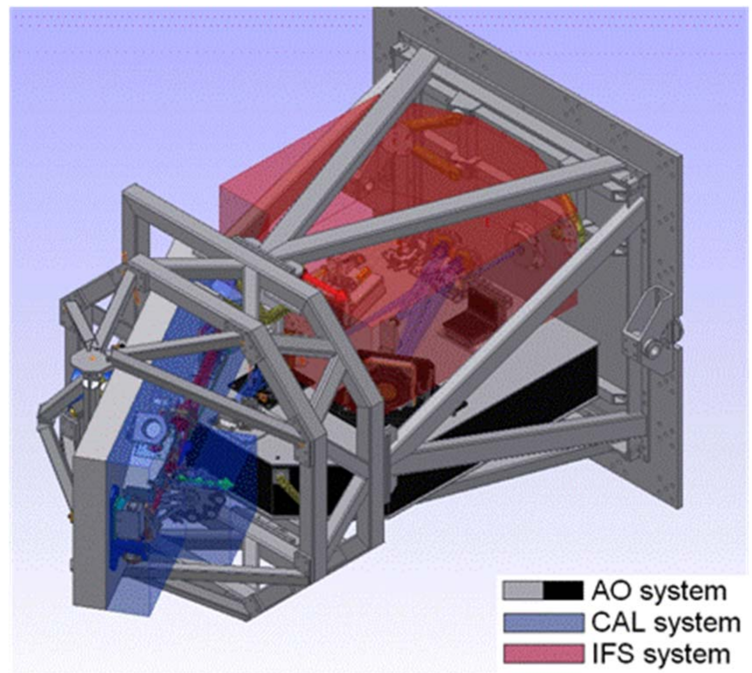
Gemini Planet Imager

GPI Assembly





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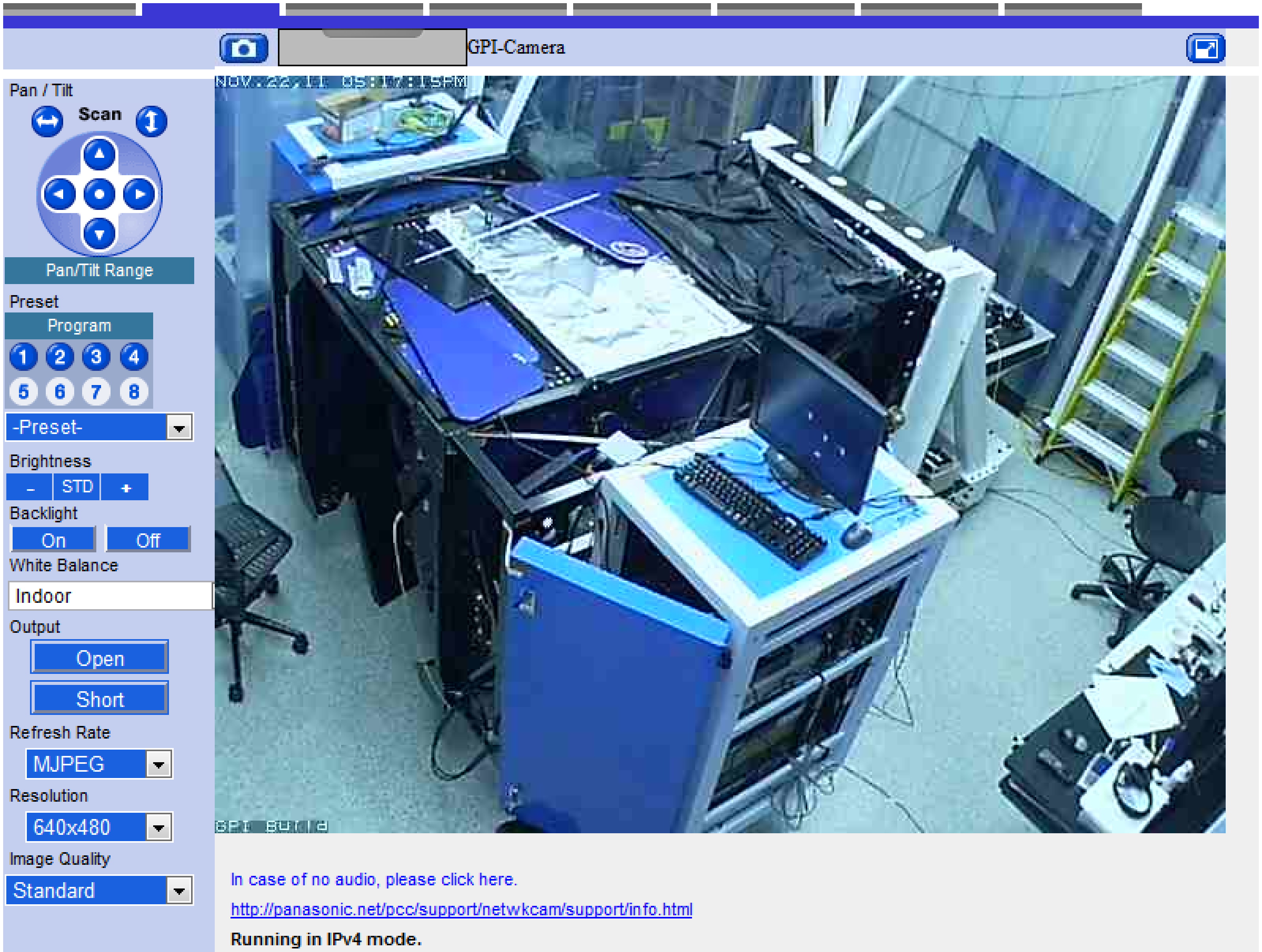
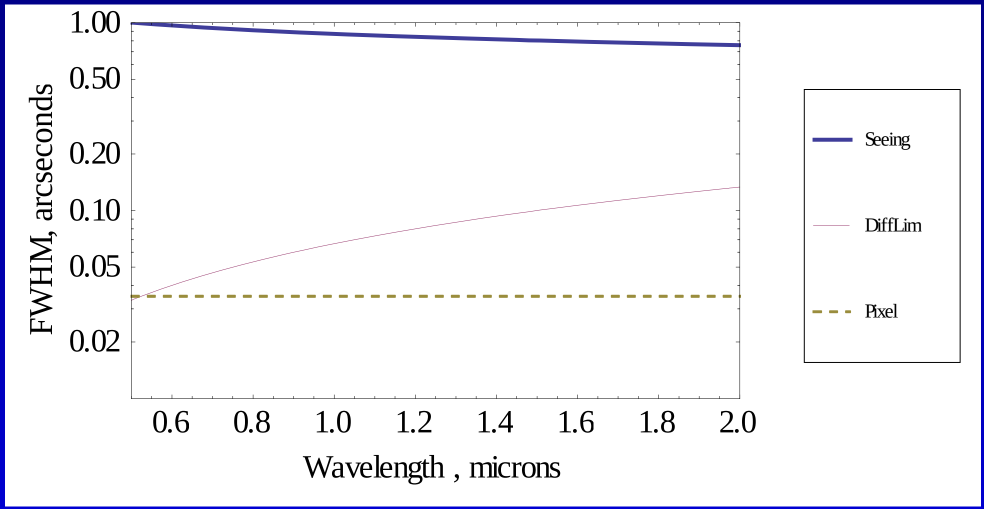
Gemini Planet Imager

Integration and Test

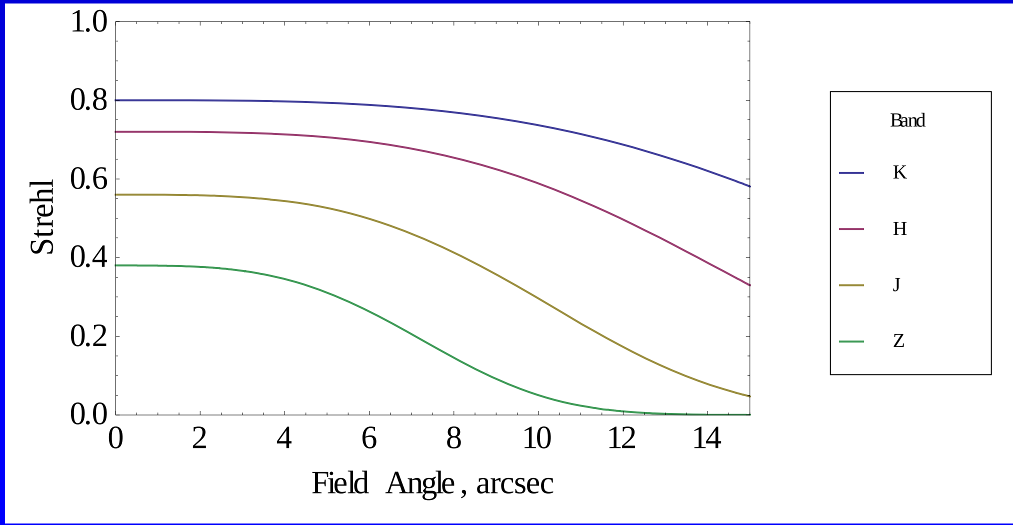


ShaneAO: New Adaptive Optics System at the Shane 3-meter Telescope

- ShaneAO is a diffraction-limited imager, spectrograph, and polarimeter for the visible and near-infrared science bands.



- Adaptive optics corrects for the nominally ~1 arcsecond seeing blur to the diffraction limit over a field of view known as the isoplanatic patch



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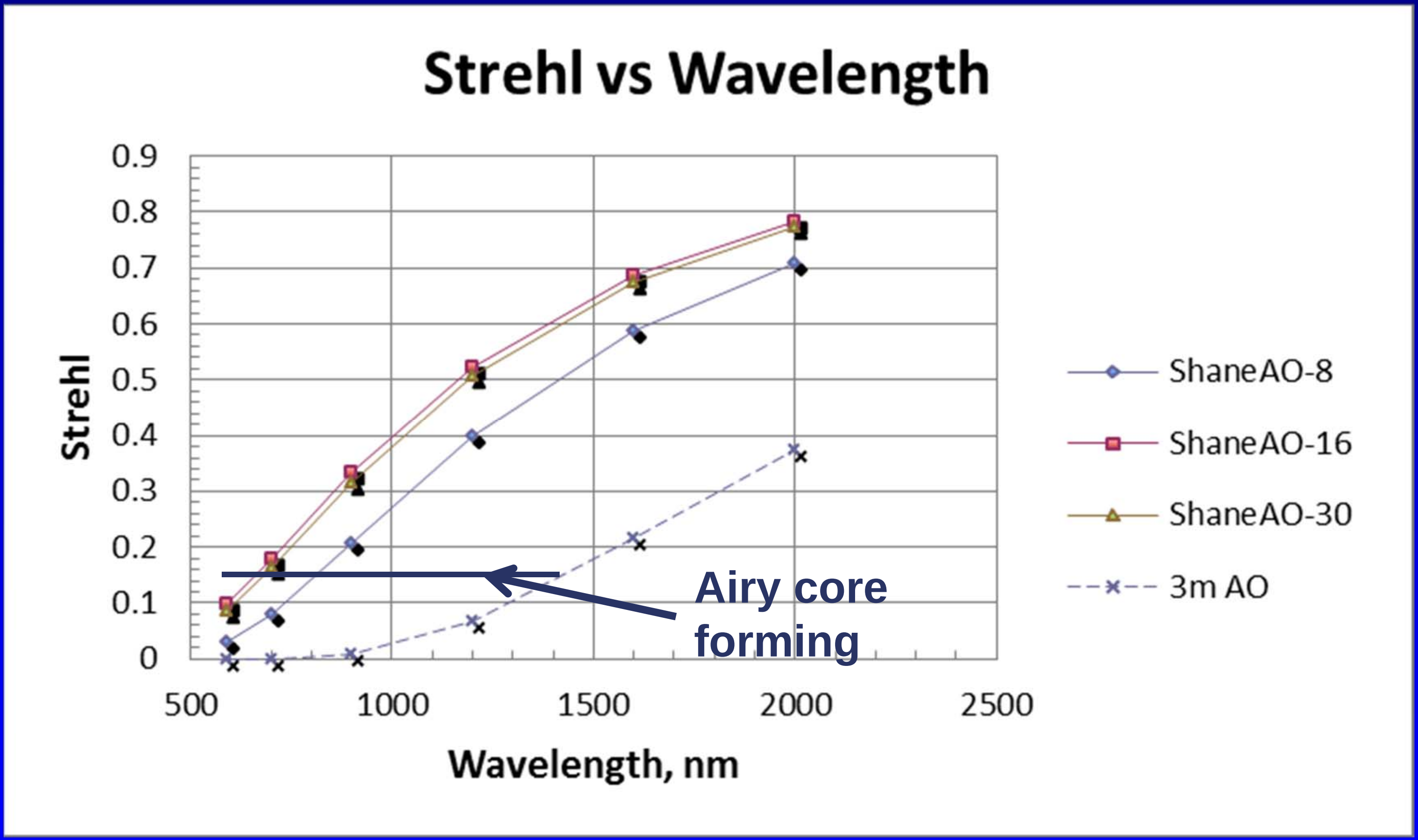
ShaneAO

ShaneAO Strehl curve predictions



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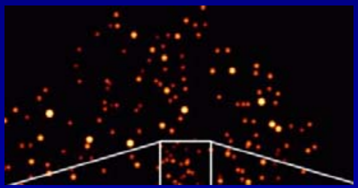
ShaneAO

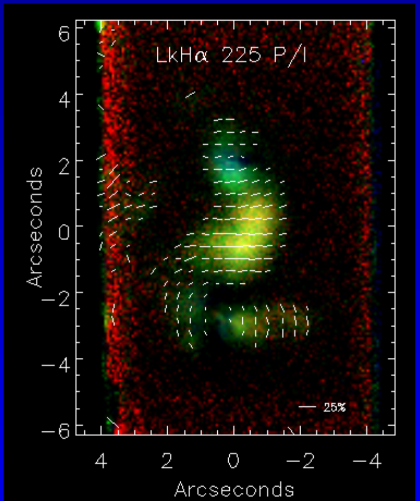
ShaneAO instrument characteristics

Detector sampling	0.035	arcsec/pixel
Field of view	20	arcsec square
Science detector: Hawaii2RG	Hawaii2RG	
Science wavelength coverage: 0.7 to 2.2 microns	0.7 to 2.2	microns
Spectral resolution	R = 500	
Slit width: 0.1 arcseconds	0.1	arcsec
Slit decker: 10 arcseconds (?)	10	arcsec
Slit angle on sky	adjustable 0-360°	
Long-exposure stability	hold to the diffraction-limit for one hour hold to ½ slit width for 4 hours	
Polarimitry mode:	polarization analyzer and variable angle waveplate	
Delta magnitude within seeing disk	Dm_K=10	
Minimum brightness tip/tilt star:	m_V=18	
Tip/tilt star selection field	120	arcsec
Sky coverage	~90%	LGS mode
Minimum brightness natural guide star	m_V=13	
Camera readout modes	Correlated double-sampling (CDS) up the ramp (UTR) sub-frame region of interest (ROI) quick take	
Exposure support:	Multiple frame co-added automated nod and expose coordinated with telescope (snap-i-diff, box-4, box-5) automated darks sequence based of history of science exposures	
Observations support	automatic data logging automatic data archiving	

ShaneAO Science Application

Crowded field imaging:
- Star counts, metallicity and ages in clusters within our Galaxy
- Star counts in Andromeda galaxy
- Astrometry – tracking the orbits of stellar companions
- Astrometry – tracking the orbits of stars around the Galactic center





Star-forming regions - polarimetry

Detailed imaging of nebula and galaxies
- Gas and dust disks around young stars
- Multiple star systems in star forming regions
- Velocity dispersion of galaxies hosting active galactic nuclei
- Morphological detail of quasar host galaxies
- Details of morphology of merging galaxies

Exoplanets and planet formation statistics
- Follow up to radial velocity planetary systems (stellar companions)
- Follow up to Kepler survey stars (companions)
- Precursory work for Gemini Planet Imager target stars

Solar system
- Composition and orbital parameters of Kuiper belt objects
- Composition and orbital parameters of asteroids and asteroid moons
- Details of gas-giant ring structure and positions of ring-shepherding moons
- Details and evolution of gas-giant weather

Construction Progress

- **AO**
  - Funded: NSF MRI + UCO cost-share
  - Optomechanics in fabrication, AO components set up in LAO testbed
  - AO system on telescope: Spring 2013
- **Laser**
  - CfAO + Moore Foundation + UCO funded
  - Delivered just recently from LLNL
  - Fiber laser goes to Mt. Hamilton: est. Late 2013
- **Upgrade** (-30 version = "Visible AO")
  - LabFees program funded
  - 2014

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ShaneAO

ShaneAO: New adaptive optics system for the Shane 3-meter telescope

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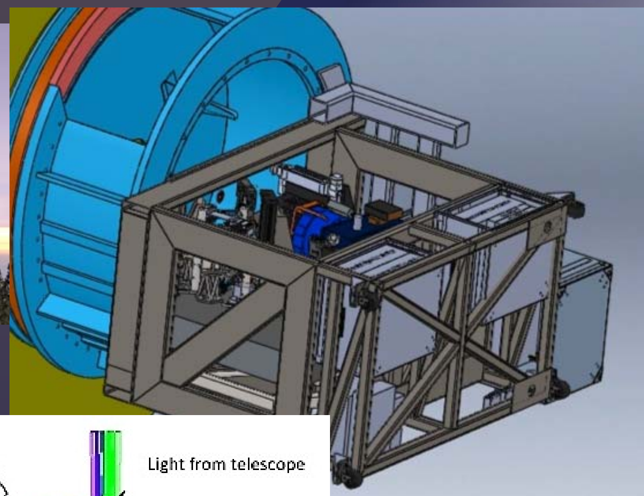
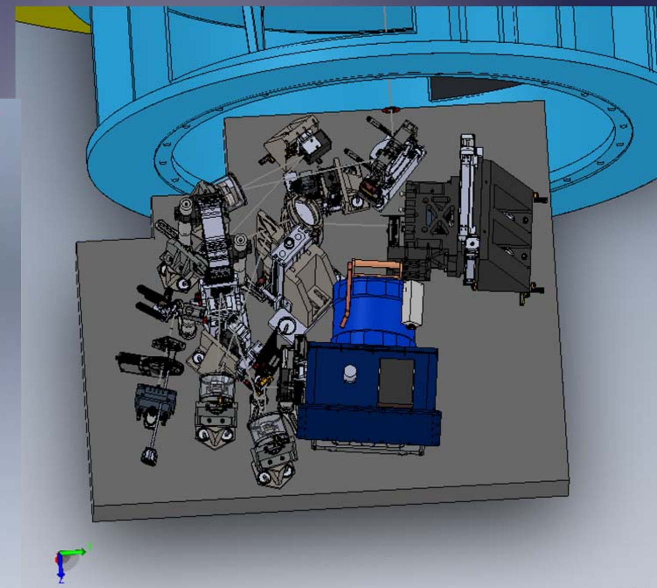
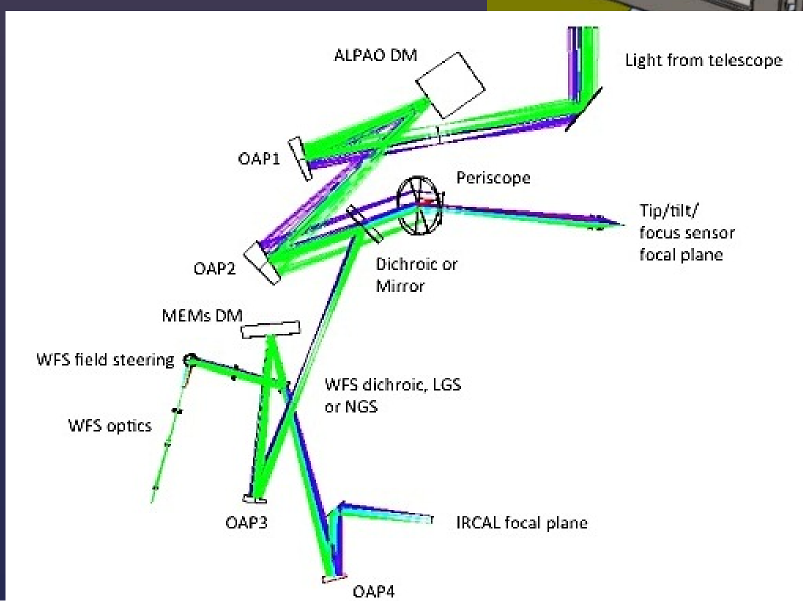
See poster by Kupke: 8447-125





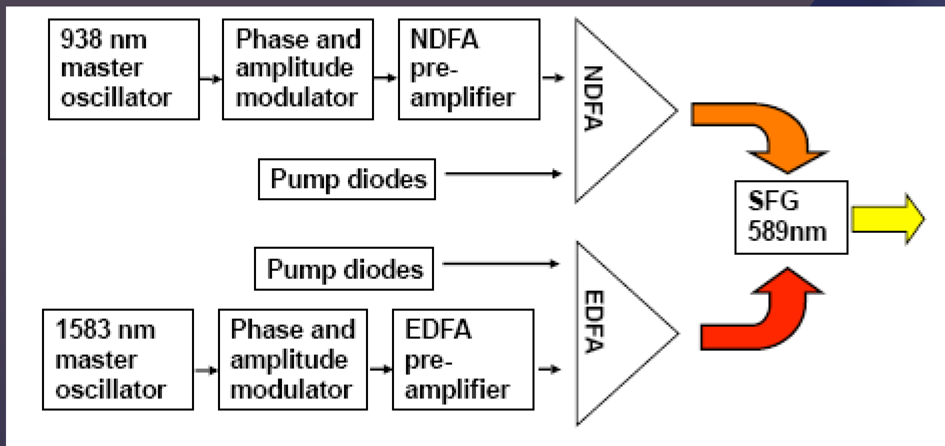


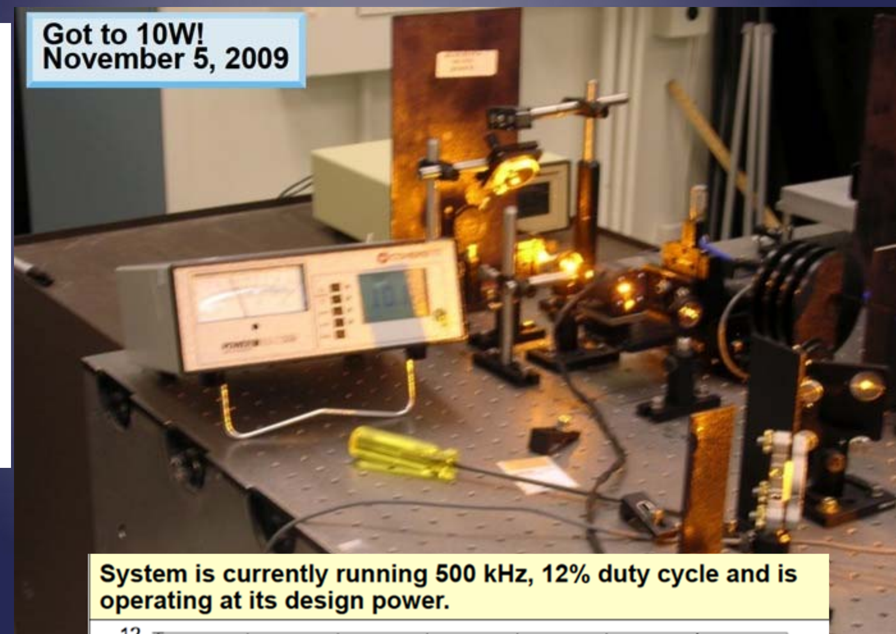
Old System	ShaneAO
High Strehl in K band J and H accessible	High Strehl in J, H, and K bands I band accessible
Diffraction-limited imaging in K 19 arcsec FOV 76 mas/pix	Diffraction-limited in J, H, and K 20 arcsec FOV 33 mas/pix more sensitive science detector
Limited to short exposures	4-hour exposures enables dim object spectra
Fixed on-sky orientation	Instrument can rotate to set the spectrograph slit angle

SPIE Astronomical Instrumentation

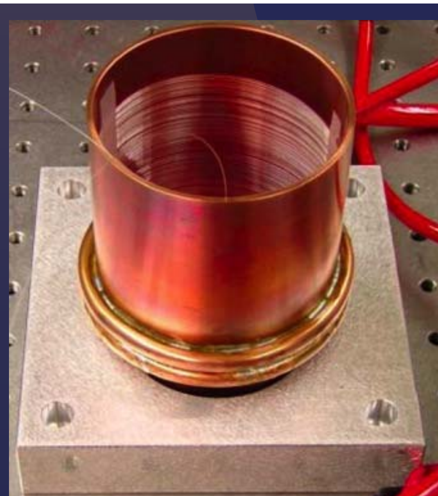
Guide Star Laser

- Gets to the sodium 589nm line by mixing two IR lines

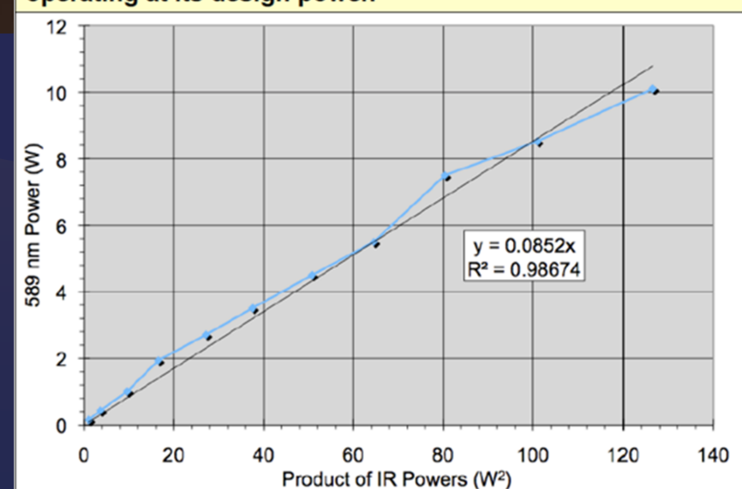




Nd^{3+} PM fiber amplifier chain

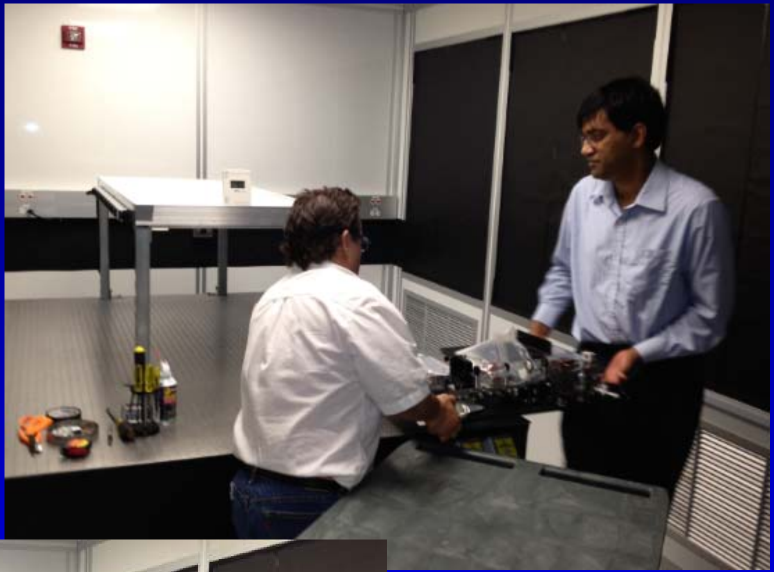


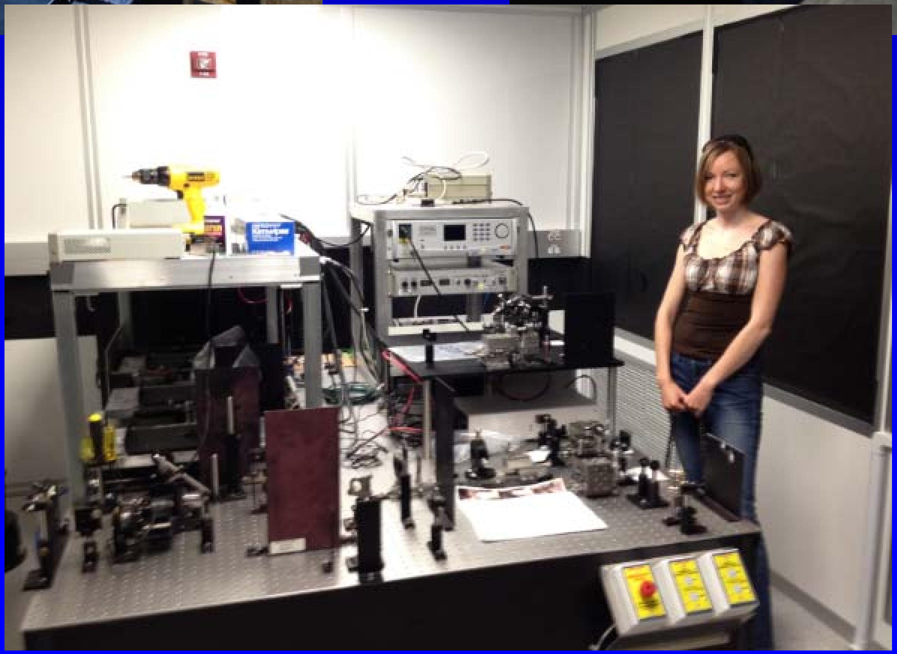
System is currently running 500 kHz, 12% duty cycle and is operating at its design power.



Jay Dawson, LLNL

Laser Arrival at UCSC





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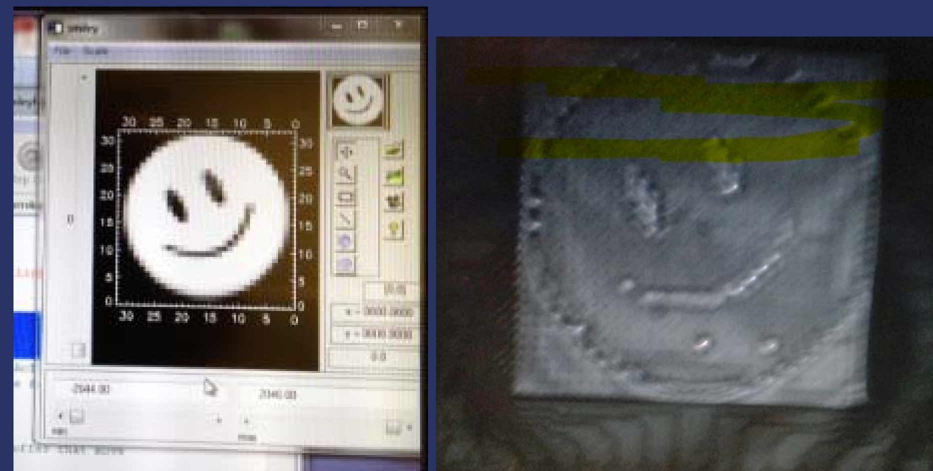
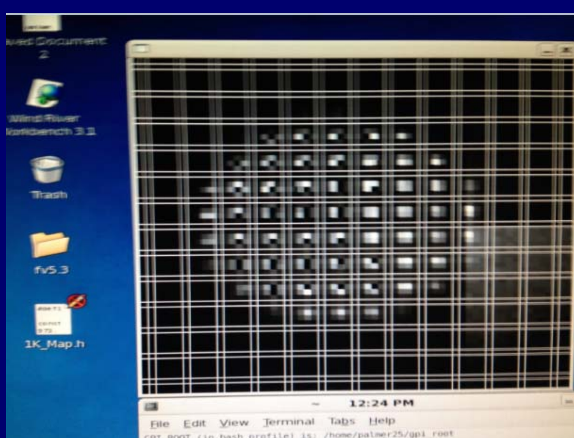
ShaneAO components in the lab

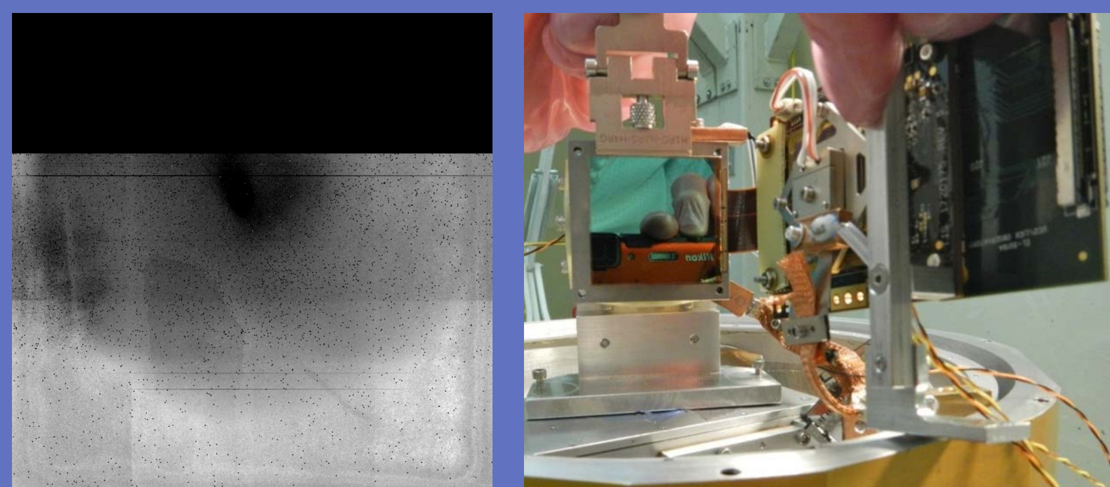


Deformable Mirror

Wavefront Sensor



Science Detector



More information

- http://lao.ucolick.org/ShaneAO
- Yearly Project Reports to the NSF: 2010 2011 2012
- Design Review Presentation (April, 2012
- ShaneAO Document

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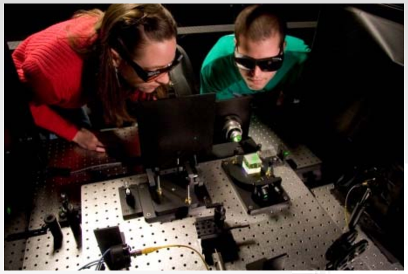

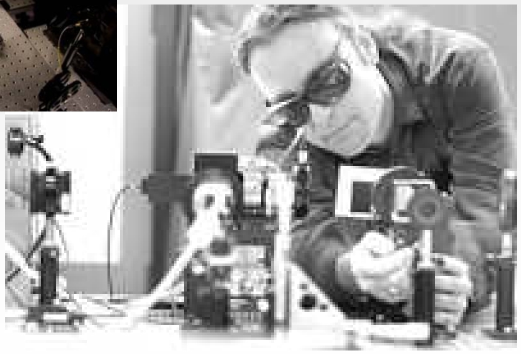

Thank you