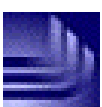
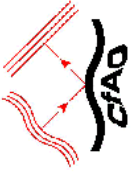


# Adaptive Optics Wavefront Control and Performance

Don Gavel  
LLNL

Center for Adaptive Optics  
Adaptive Optics Workshop  
U.C. Berkeley  
Feb. 4, 2000



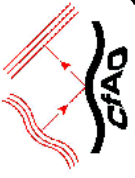
# Wavefront Control and AO Performance

*Now that I have (access to) an AO system...*

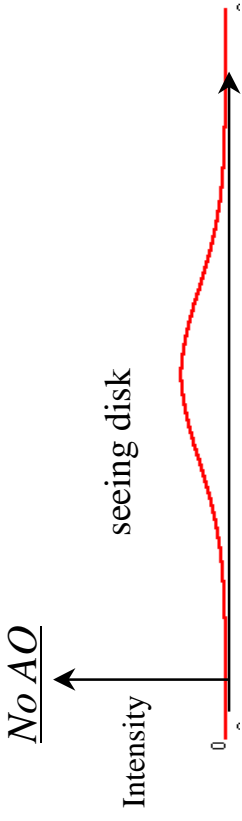
- What does an AO system do?
- What objects can I look at?
- How do I plan my observations?
- What PSF can I expect?

*and afterward...*

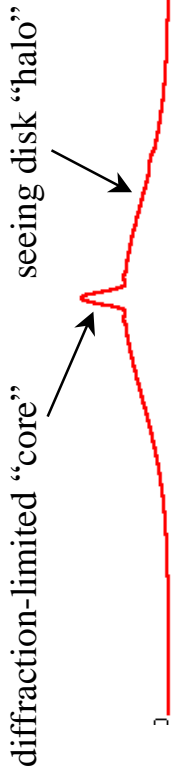
- What was the PSF?
- How do I reduce the data?



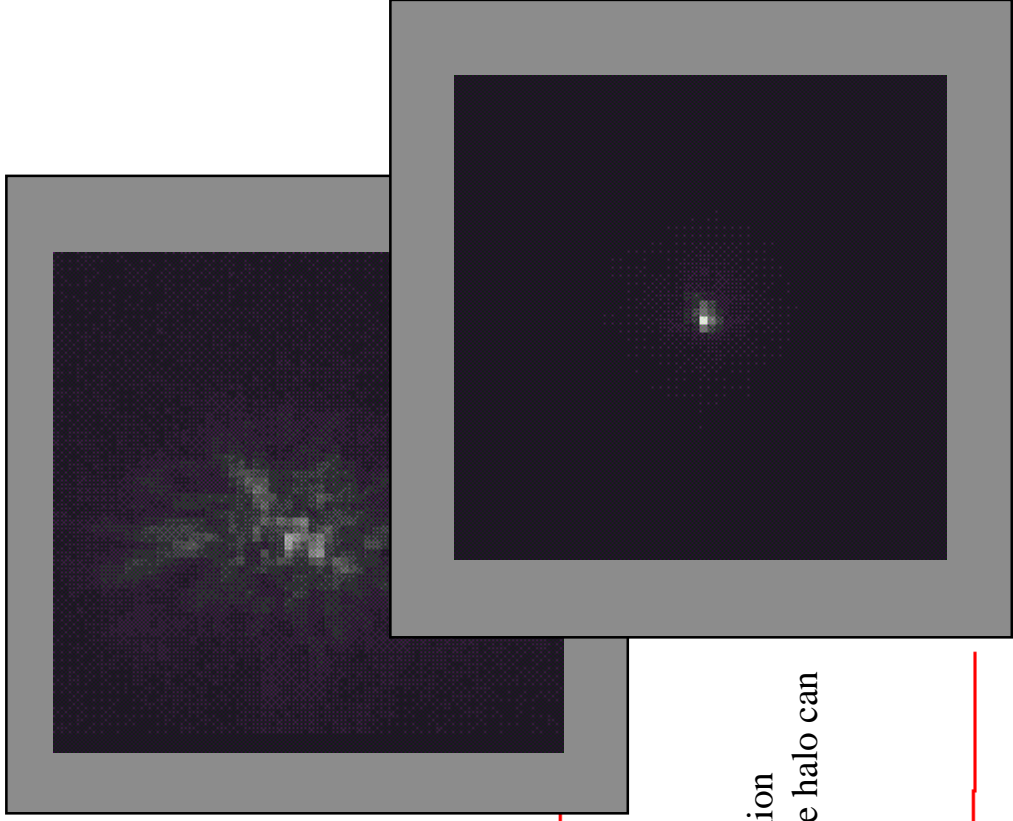
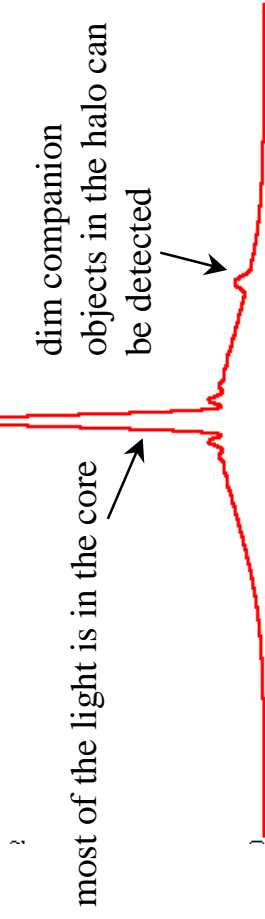
# AO Systems gather star light (point-sources) into a tighter area on the focal plane

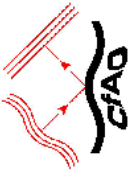


## AO on, moderate performance

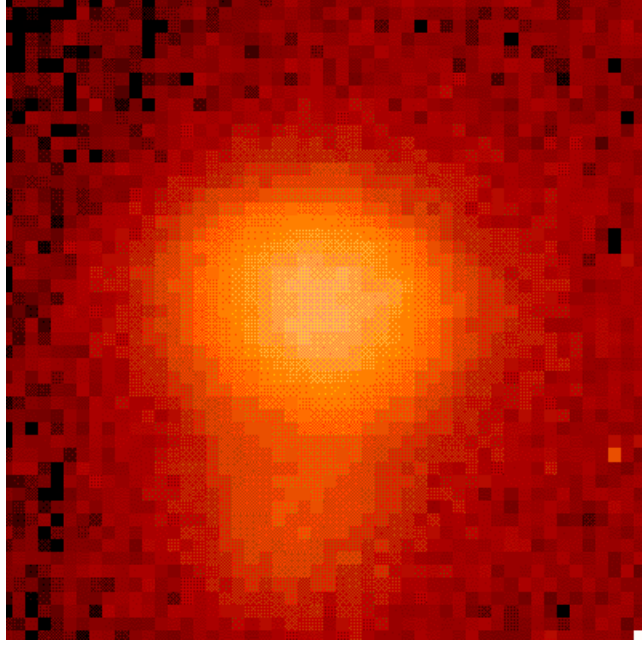
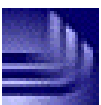


## AO on, high performance

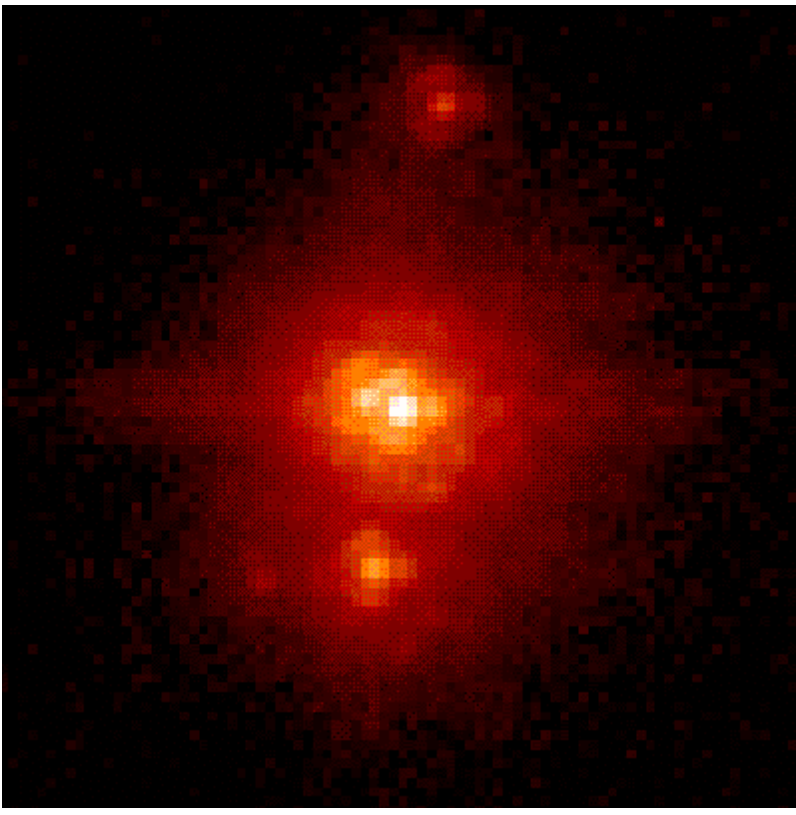




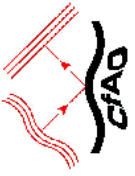
# LkH $\alpha$ 234 Lick Adaptive Optics



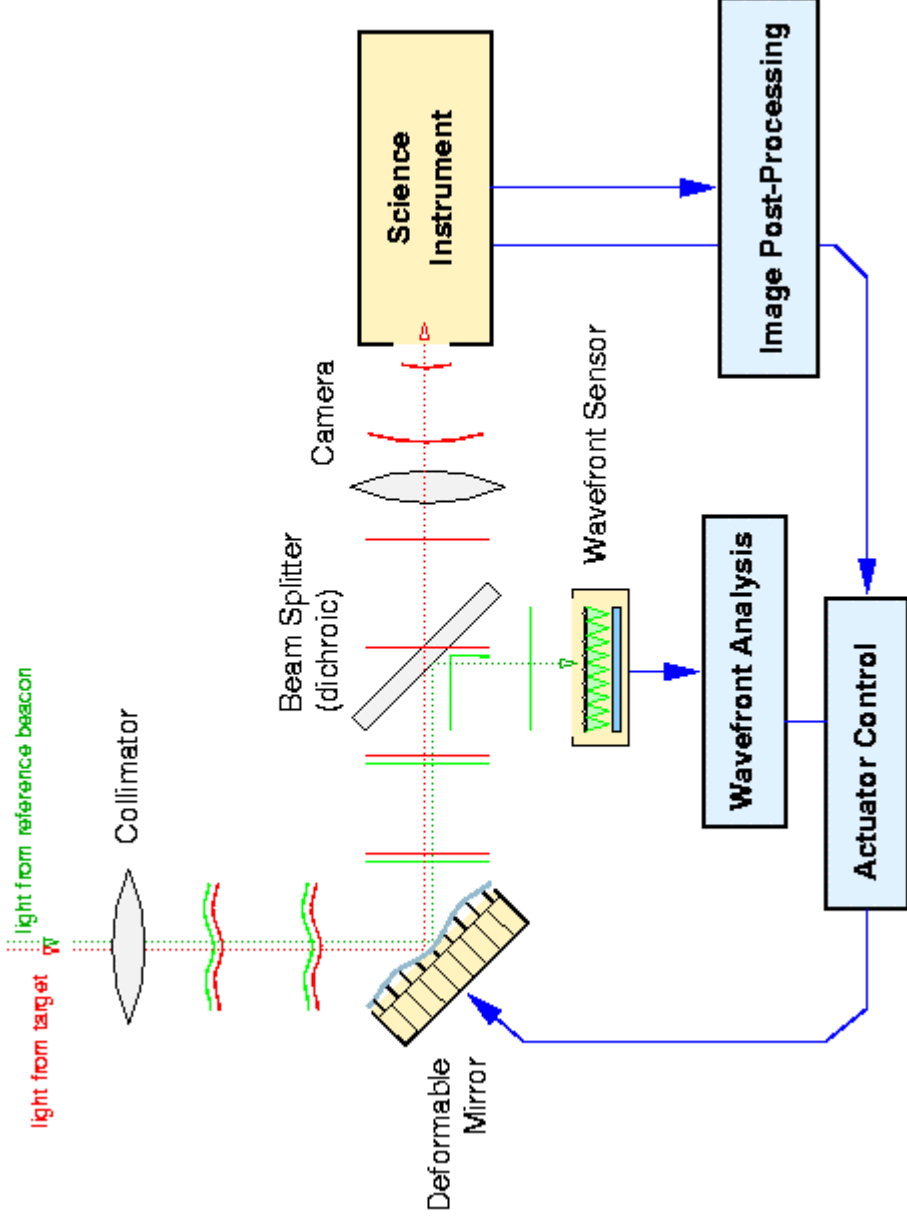
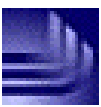
AO off



AO on

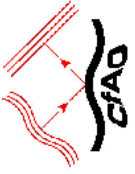


## What does an AO system do?

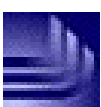


Note that the closed loop operation “null-seeks” so that, nominally, the wavefront sensor measures a nearly-flat wavefront, justifying perturbation analysis of performanc.

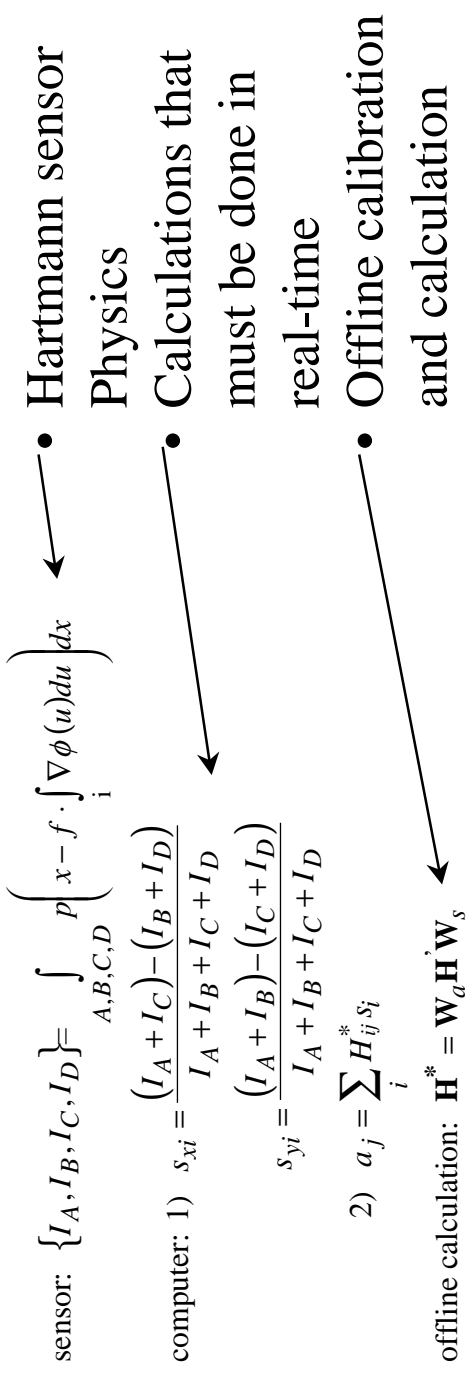
(from the CfAO web site <http://www.ucolick.org/~cfao/>)



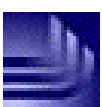
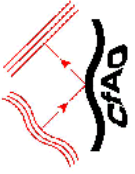
What does an AO system do?



# Wavefront reconstruction - in a nutshell



- H is the “push” matrix (sensor response per unit actuator motion) - it is pre-calibrated, typically the day before observing
- H\* is the pre-calculated “reconstructor matrix”
  - Zonal or Modal
  - Weighted least squares fit
  - “Waffle” mode removed

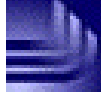


# What objects can I look at?

1. Make sure there is a science benefit to using AO
  - NGS
  - $m_r < \sim 12$  at Lick
  - $m_r < \sim 13$  at Keck
- 2\*. LGS-AO also uses a natural guide star, for tip-tilt correction
  - LGS tip-tilt
  - $m_r < \sim 16$  at Lick
  - $m_r < \sim 18$  at Keck

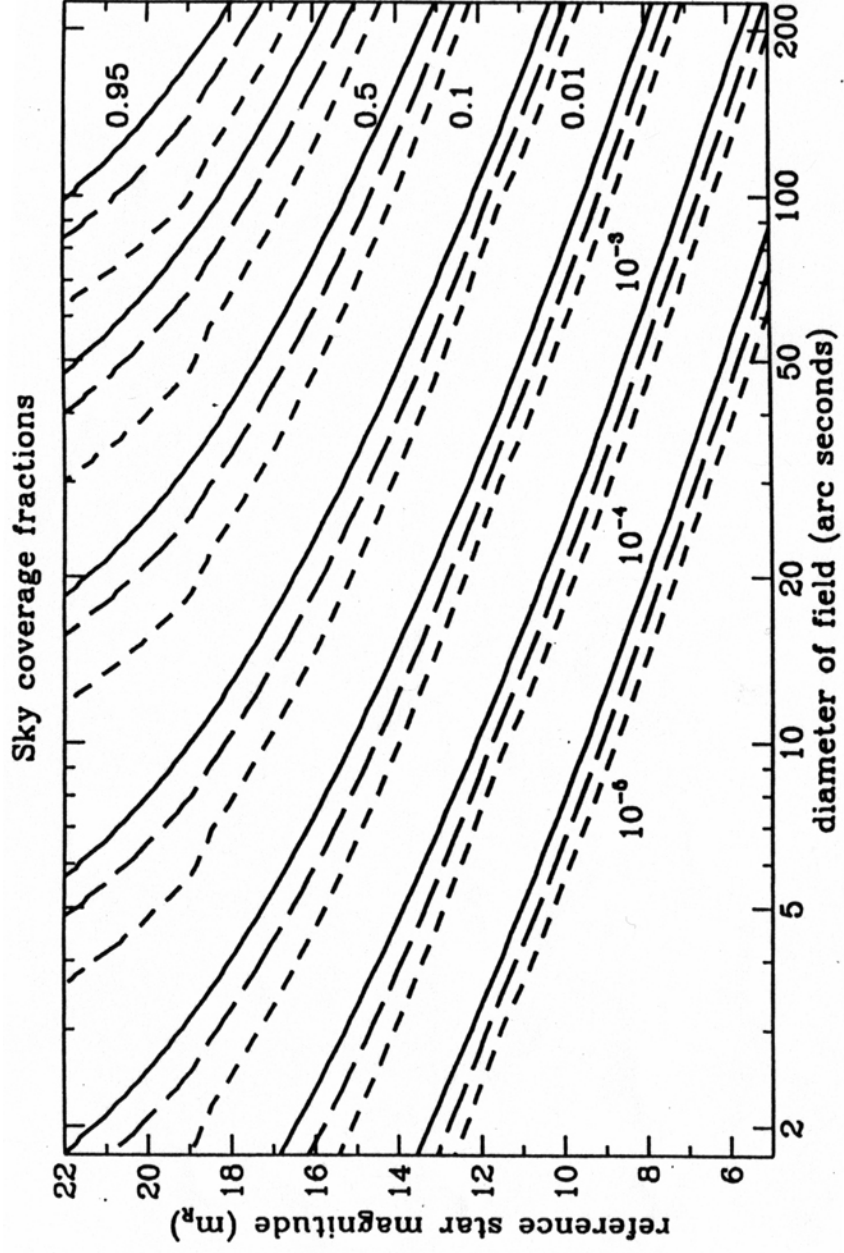
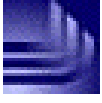
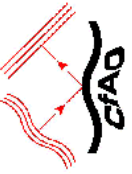


*What objects can I look at?*



## AO resolution of various science targets

	seeing	Lick AO	Keck AO
Moon	1.8 km	300 m	100 m
Jupiter (5 au)	3600 km	550 km	160 km
Solar neighbor (5pc)	5 au	0.7 au	0.2 au
T Tauri (200 pc)	200 au	30 au	9 au
M31 (670 kpc)	3 pc	0.5 pc	0.15 pc
NGC 1068 (11 Mpc)	53 pc	8 pc	2 pc
3C2 (Z=1)	24 kpc	3.6 kpc	1.1 kpc

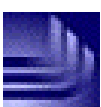


(sky coverage chart - contours of constant sky coverage vs separation & magnitude)



*What PSF can I expect?*

## AO performance measures



- **FWHM** - Full Width, Half Maximum -
  - AO systems typically produce diffraction-limited FWHM
  - Can separate 2 equally bright point sources  $\lambda/d$  apart
- **Contrast ratio** - ratio of the peak of a dimmer source within the halo to the brightness of the halo
  - Important for dim companion searches, brown dwarfs, extra-solar planets
- **Strehl ratio** - ratio of AO-corrected PSF peak to the diffraction-limited PSF peak
- **Encircled energy** - vs radius
  - Important for photometry, centroiding accuracy
- **Energy in a slit**
  - Spectroscopy

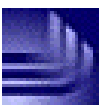


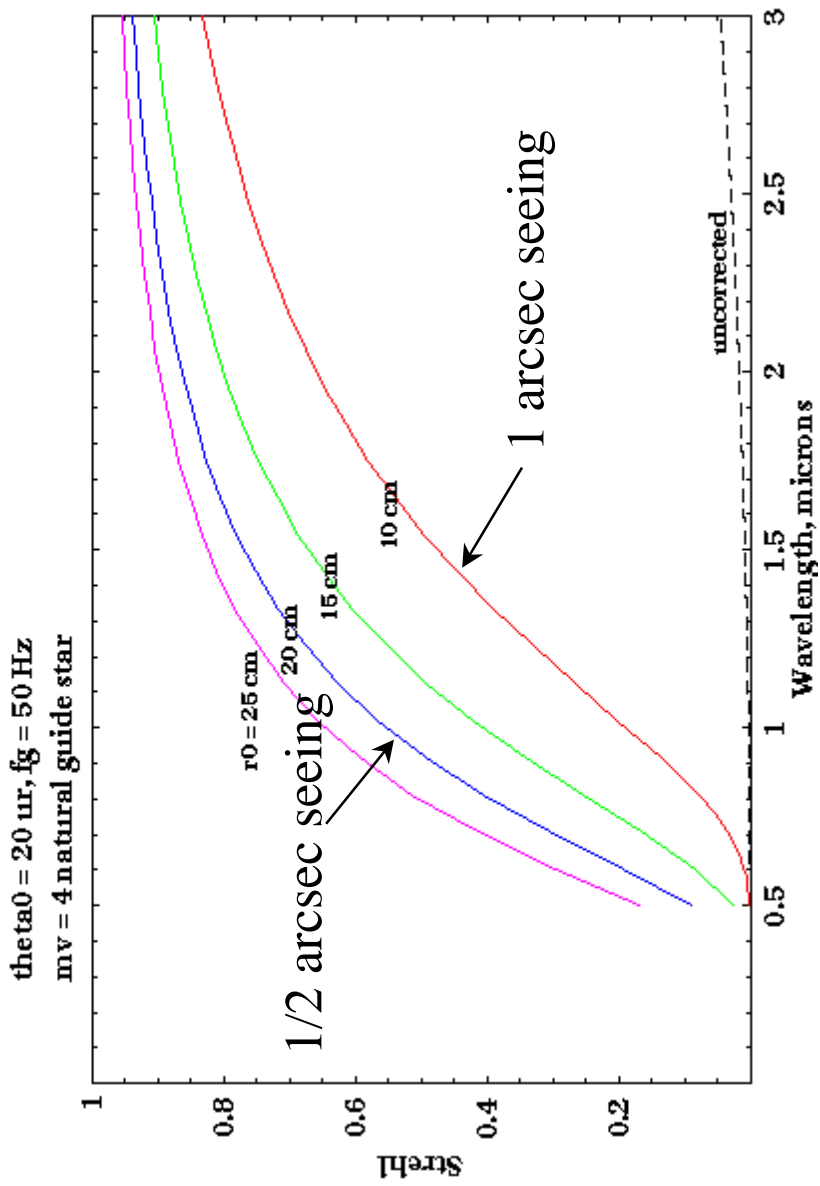
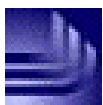
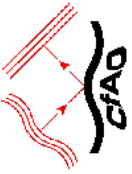
*What PSF can I expect?*

AO performance is affected by

- Seeing conditions ( $r_0$ ), wind ( $\tau_0$ )
- Number of DM actuators
- Controller bandwidth
- Separation of guide star from science target
- Brightness of guide star\*

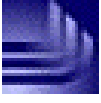
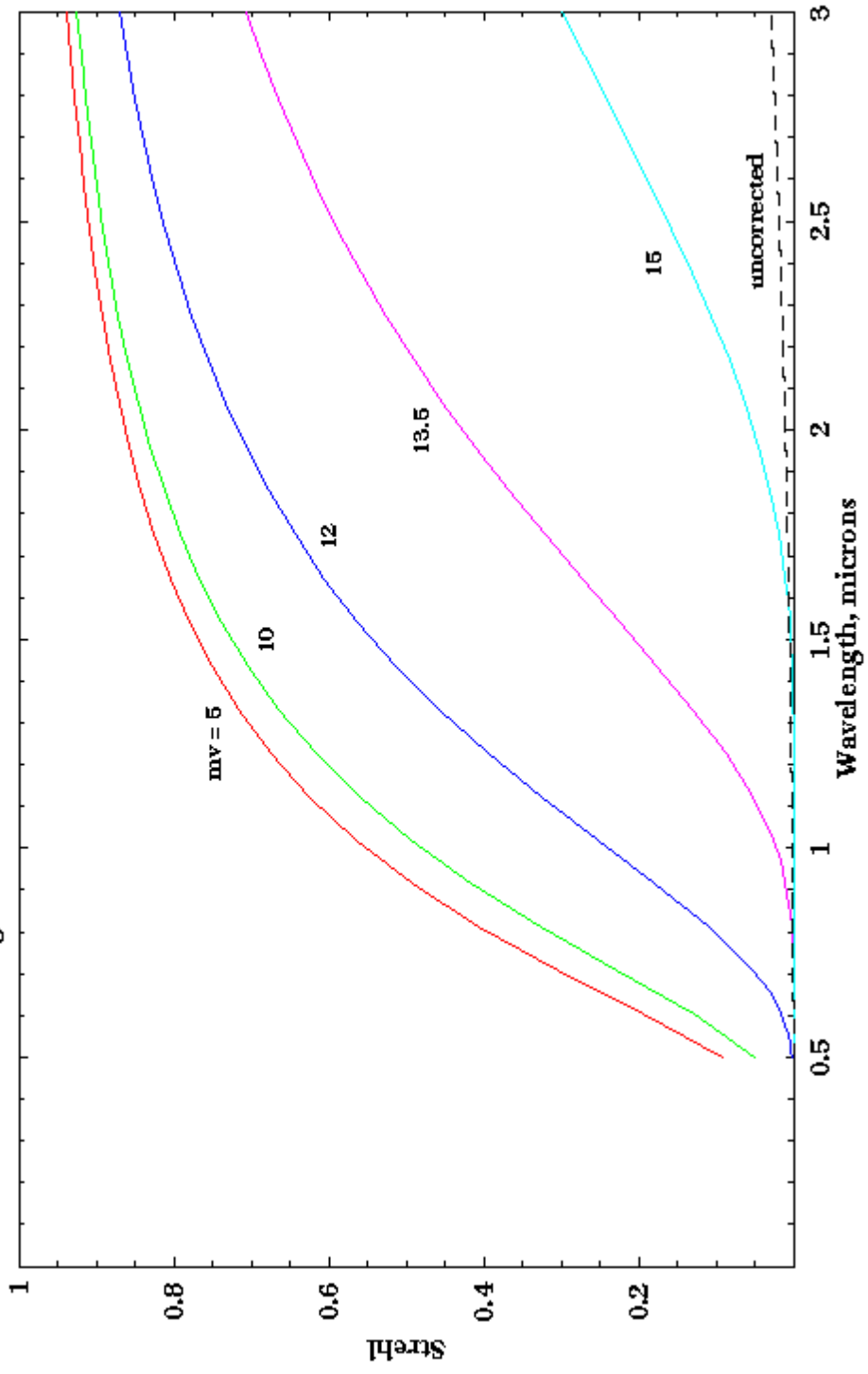
\*and extent (e.g. planet, nebula, LGS)

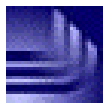
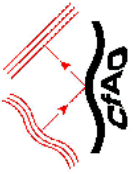




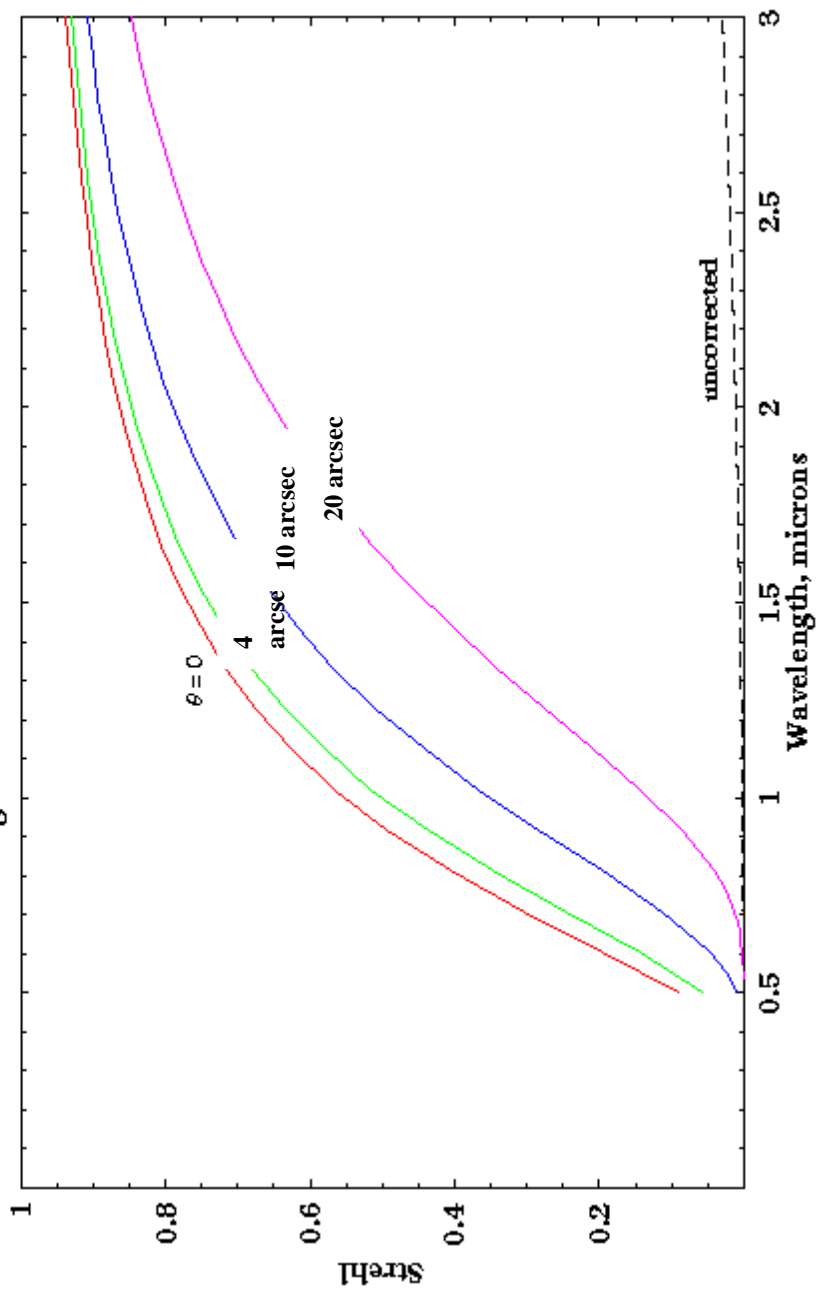


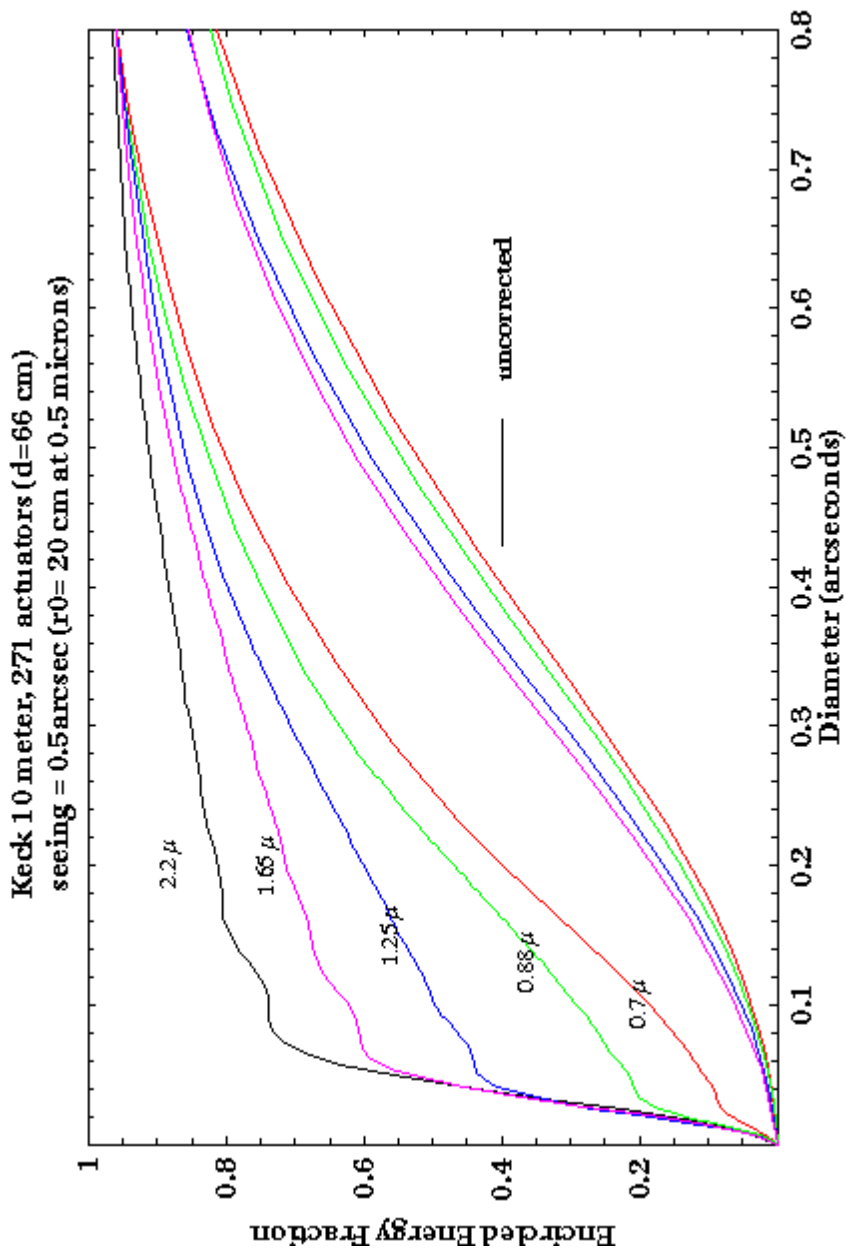
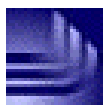
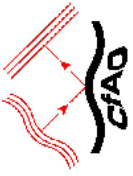
$r_0 = 20$  cm,  $\theta_{\text{ta}0} = 20$  ur,  $f_g = 50$  Hz  
natural guide star

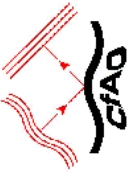




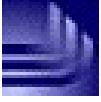
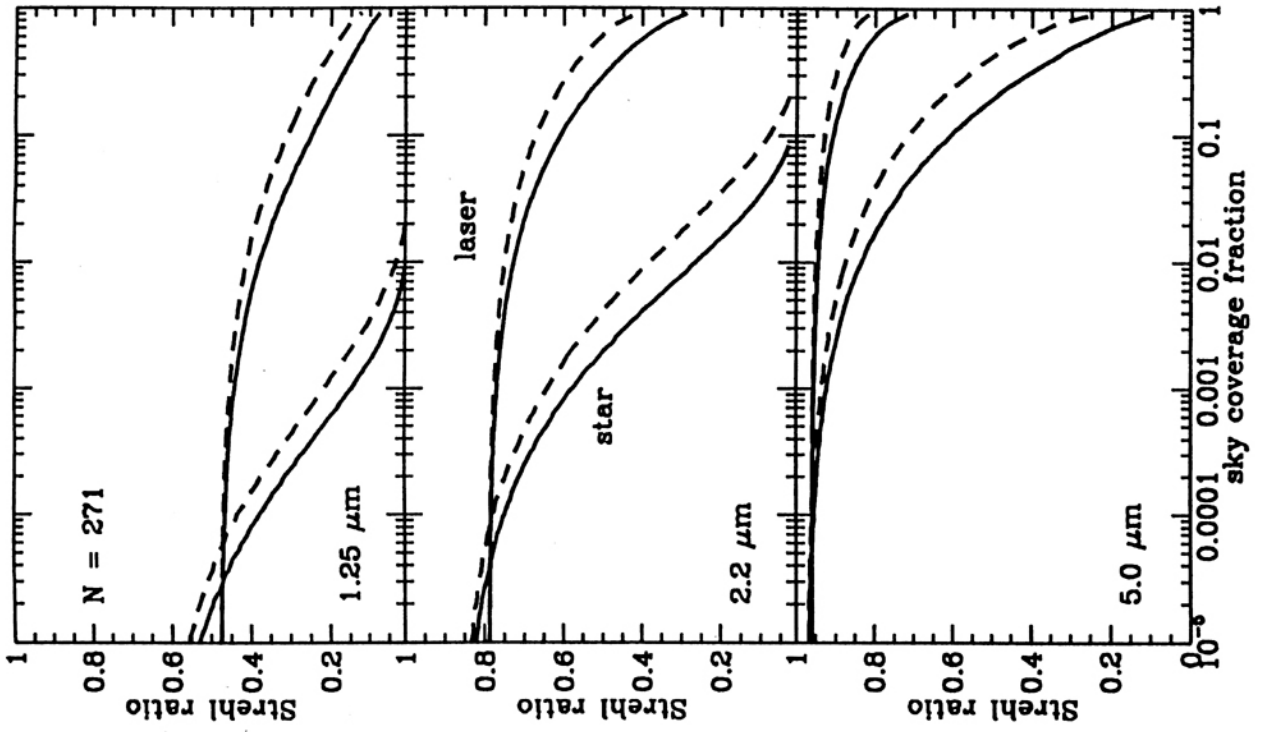
$r_0 = 20$  cm,  $\theta_{\text{ta}0} = 20$  ur,  $f_g = 50$  Hz  
 $m_v = 4$  natural guide star

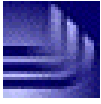
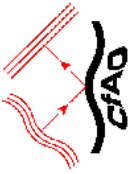






### Comparison of Laser and Natural Guide Stars





Planning AO Observations - Netscape

File Edit View Go Communicator Help

Back Forward Reload Home Search Netscape Print Security

Bookmarks Location: rGuideStar/LickAO/aoObservations.html

http://espnets Internet Lookup New&Cool www.hitachipc.c FC's

- Digital Sky Survey
- SIMBAD Astronomical Database

## ADAPTIVE OPTICS SYSTEM

Lawrence Livermore National I

### Planning your observation

Before applying for telescope time with the AO system, ask: Is there additional spatial resolution observation. The AO system improves resolution from typical diffraction-limit (0.12 arcseconds in K band). The IR camera plate scale is 0

- AO observations are best during the best seeing. Improvement is seen seeing occurs in the late summer and early fall.
- Schedule observations so targets are near zenith during exposures.
- Select a guide star near the science target. The guide star must be at brighter stars give better correction, especially in windy condition patch (m) of the science target. The system field of view for guide star diameter centered on the science target location.
- Point spread reference stars should have the same magnitude, color, star, so that AO system conditions duplicate, as nearly as possible,

Here is a [chart of sky coverage](#) (% of the sky near a guide star for a given guide star). Here is a [chart of model predicted Strehl vs separation from target for various guide stars](#).

Document Done

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### AO Performance Predictor

Strehl is a measure of the performance of the AO system. 1.0 = perfect correction. Higher Strehls give higher contrast images. Strehl of >0.1 is necessary to achieve diffraction-limited features in the images.

Here are [plots of binary companion detectability](#) as a function of AO system Strehl, delta-magnitude, and separation.

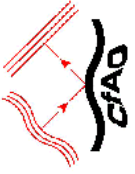
Seeing (arcsec):	Wind speed (m/sec):	Separation, target from guide star (arcsec):
Guide star magnitude (V=):	Zenith angle (degrees):	

Calculate (choose one):

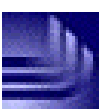
STREHL RATIO      POINT SPREAD FUNCTION

CONTRAST CURVE      EFFICIENCY CURVE

The highest Lick AO system Strehl was 0.65 in K' band, on a 4th magnitude star at zenith in 0.5 arcsecond seeing [Ref].



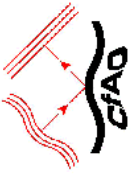
*How do I plan my observations?*



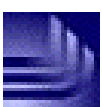
## Good planning is crucial to success with AO

- Guide stars near targets
- PSF calibrator stars, photometric standards...
- Observing wavelength (1-5 $\mu$  Keck, 1-2.5 $\mu$  Lick)
- Field of view, nodding
- Seeing conditions ( $r_0$ ), wind ( $\tau_0$ )
- Sodium abundance (!)
- Exposure time

The future of AO: Queue scheduling the observations for optimum conditions



*How do I reduce the data?*



- IR post-processing techniques (Bruce Macintosh's talk)
- Deconvolution
  - Iterative methods to solve

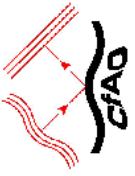
$$I = (P * O) + N$$

Image      PSF      True Object      Noise

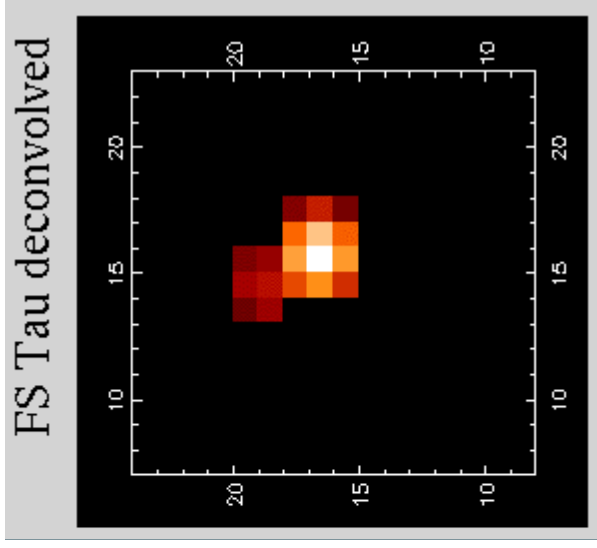
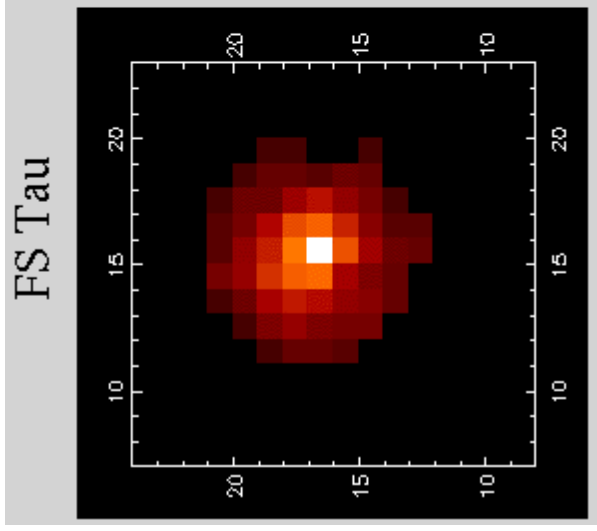
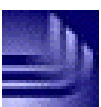
The equation  $I = (P * O) + N$  is shown with four arrows pointing to the terms: 'Image' points to  $I$ , 'PSF' points to  $P$ , 'True Object' points to  $O$ , and 'Noise' points to  $N$ .

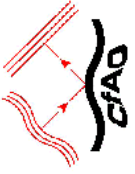
*.. and what was the PSF?*

- PSF determination
  - PSF calibrator stars (plan backups, many are double-stars)
  - J. P. Veran's algorithm: PSF determined "in-vivo" using the AO system telemetry data



# FS Tau with Lick Adaptive Optics and Laser Guide Star





# Conclusions

- AO is powerful instrumentation that can improve spatial resolution by factors of 10-50
- Sky coverage is limited with NGS AO
- LGS AO covers most of the sky at 1-2 $\mu$
- Calibration issues are much more demanding at these high resolutions
- PSF is variable, complicated, seeing dependent. Special techniques for PSF recovery are in progress. Developing AO data reduction pipelines is one charge of the CfAO.

