Advancement of AO Technology for the Next Generation of Extremely Large Telescopes:
MEMS and Laser Guide Stars

Speaker: Donald Gavel

UCO/Lick Observatory, University of California, Santa Cruz

September, 26 2011

Collaborators:
Renate Kupke
Daren Dillon
Bruce Macintosh
Claire Max
Sandrine Thomas

Andrew Norton
Katie Morzinski
Rachel Rampy

Jay Dawson, Lawrence Livermore National Laboratory

Paul Bierden, Boston Micromachines

Outline of Presentation

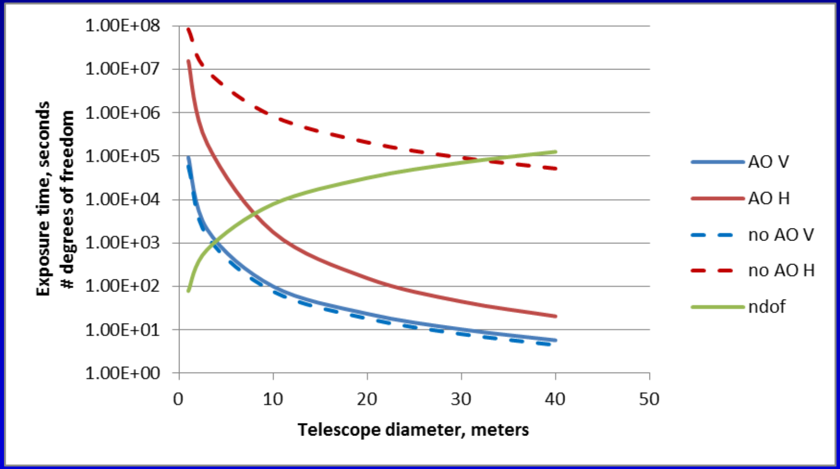
- **Context**
  - High contrast AO (exoplanet)
  - Diffraction limited astronomy with large apertures
  - AO for the visible bands
- **Overview of critical research**
  - Metrics for AO performance
  - Deformable mirrors (in particular, MEMS)
  - Guide star laser
- **AO systems under development**

Drivers for AO technology

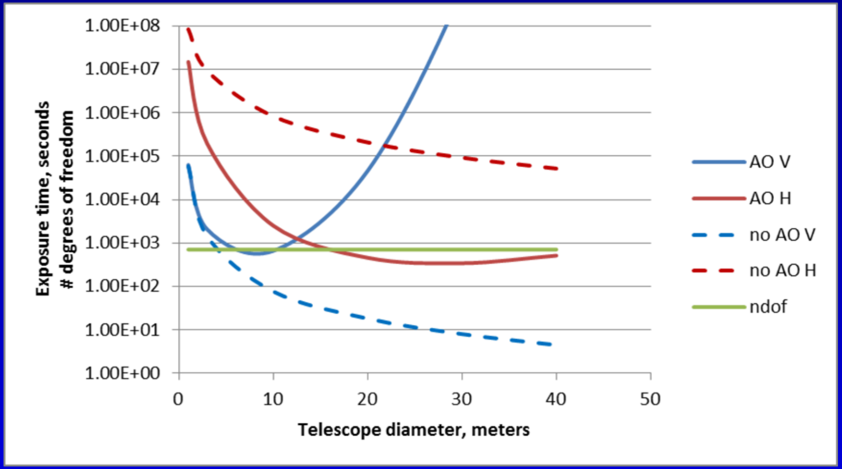
- **Exoplanets**
  - High contrast => high Strehl => finer sampling for the DM and WFS on the aperture.
  - Precision coronagraphy, scattered light suppression
- **Large Aperture AO**
  - Larger format actuator arrays
  - Higher stroke ($\sim D^{5/6}$)
  - Multiple copies of AO system for wide field coverage
  - Processing power
- **AO for the visible bands**
  - Spatial sampling $\sim(D/r_0)^2$; $r_0 \sim\lambda^{6/5}$
  - Guide stars $\sim(1/\theta_0)^2$; $\theta_0\sim\lambda^{6/5}$
  - Extraordinary precision and control of a number of additional error terms (calibration, non-common path error, drifts, flexure…)

Metric of AO: Speed

Speed ~ 1 / Exposure time to a given SNR



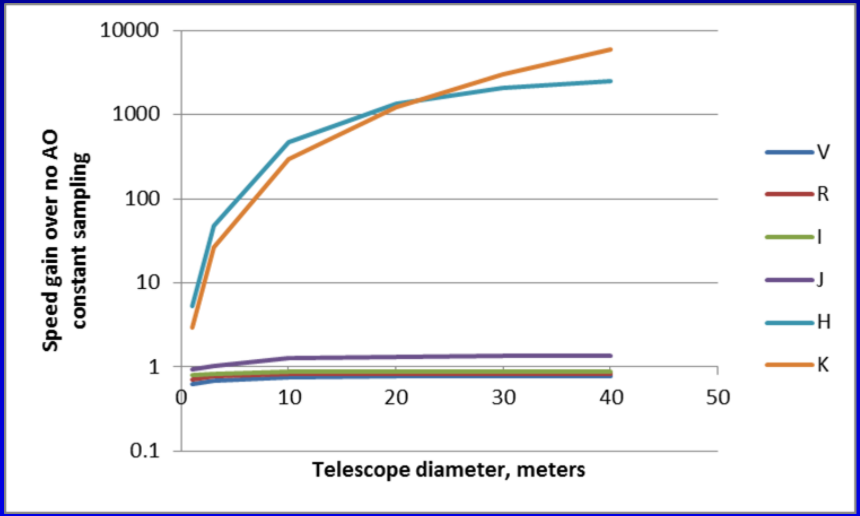
Constant sampling

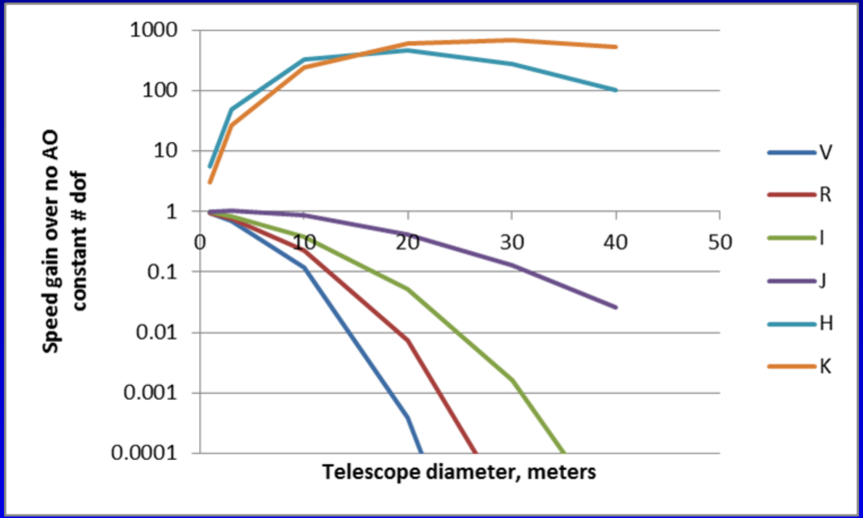


Constant # degrees of freedom

- Assumes pixels Nyquist sample in each situation
- Time to reach SNR=5 on m_V=30 star
- “Signal” is DL core (AO), or seeing disk (no AO)
- Noise …
- Strehl – idealized to spatial sampling term only
- AO throughput ~50%
- Warm AO system optics
- r0=10cm, d=10cm (nominal)
- Hi2RG detector with best/goal QE, read noise, dark current, well capacity

Speed gain with AO
relative to no AO





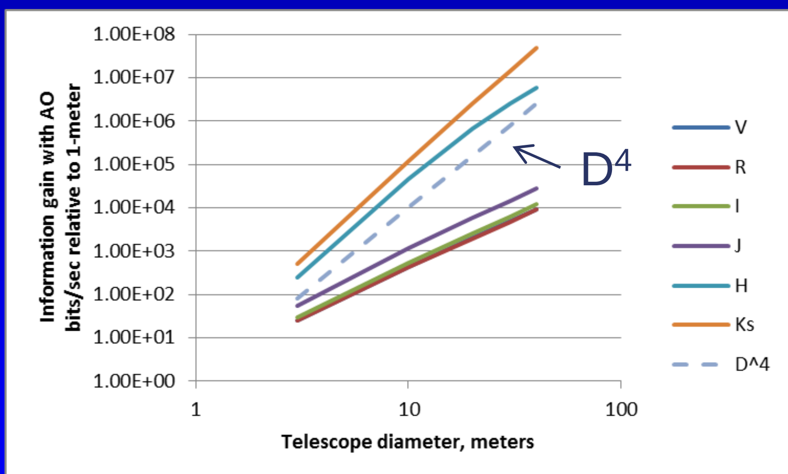
Constant sampling

Constant # degrees of freedom

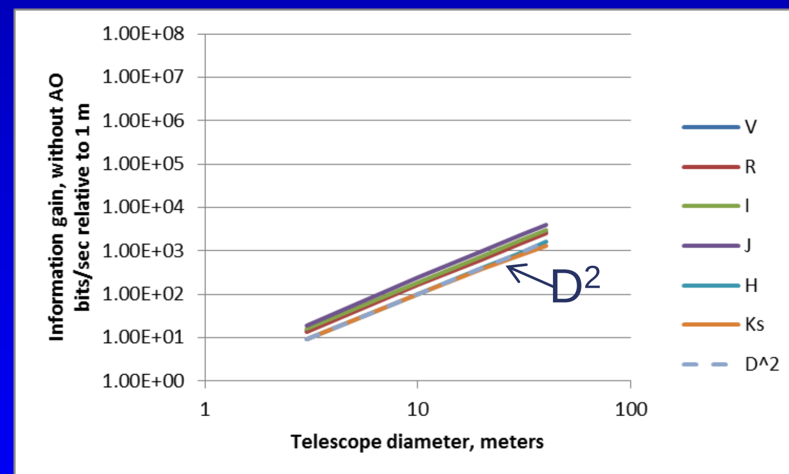
Metric of AO: Information rate

- **Speed measures only raw sensitivity**
- **Relative information accounts for increased resolution:**

$$I = \left[1 + 2log_2\left(\frac{\theta_{seeing}}{\theta_{DL}}\right)\right]\left(\frac{\tau_{noAO}}{\tau_{withAO}}\right)$$



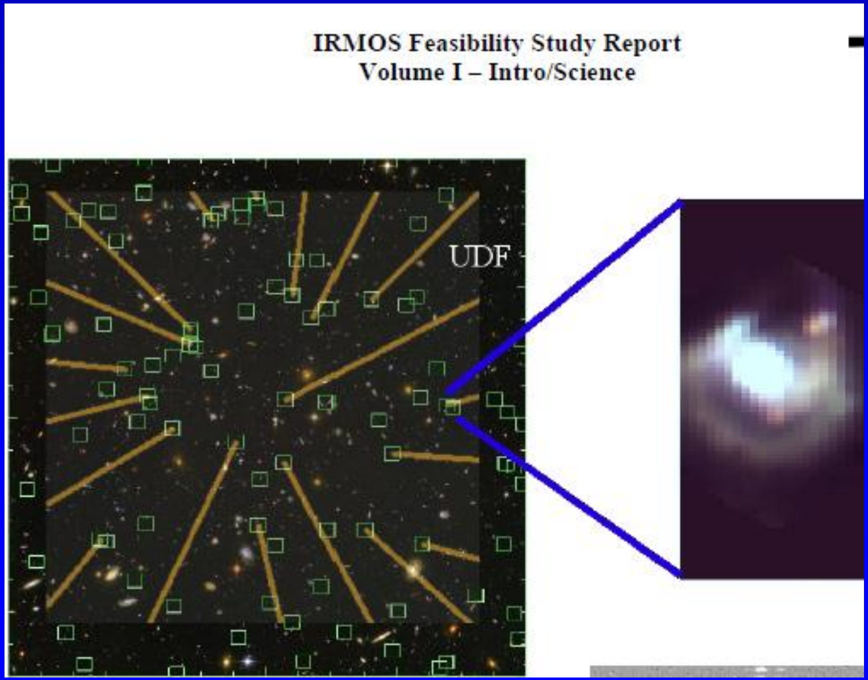
With AO
(constant sampling)



No AO

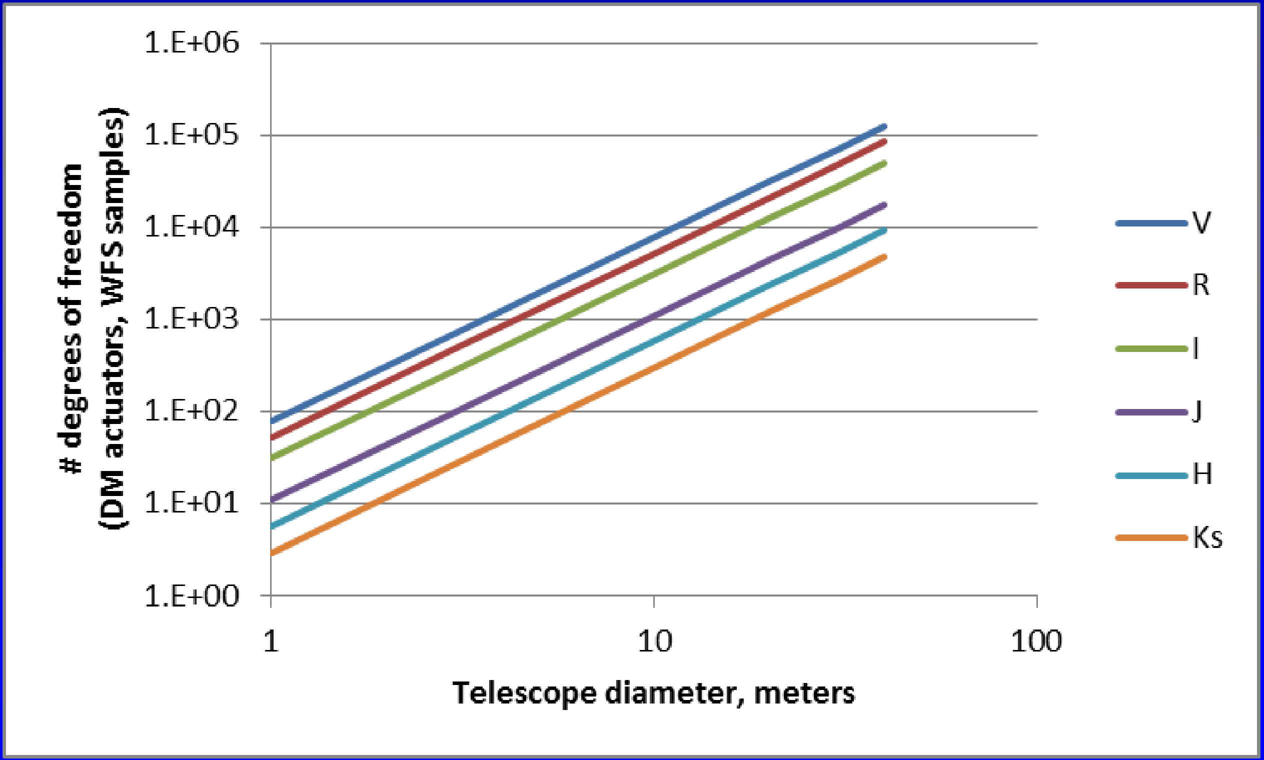
Metric of AO: AΩ

- Information rate increases ~linearly with multiplexing
- Wide field AO: MCAO, MOAO
- Hopefully, cost, complexity, etc. scale no more than linearly with Ω



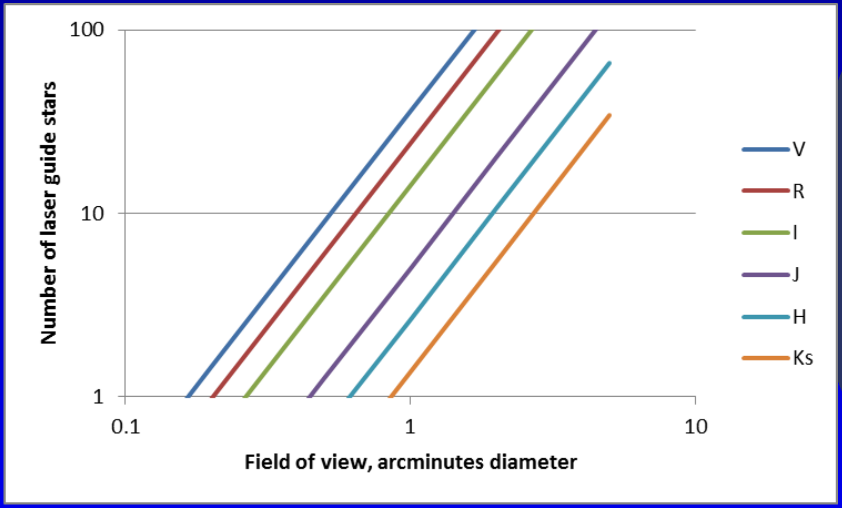
Big ticket items

- **Number of degrees of freedom:**
  - Deformable mirror
  - Wavefront sensor
  - Real-time processor



Big ticket items

- **Number of laser guide stars**

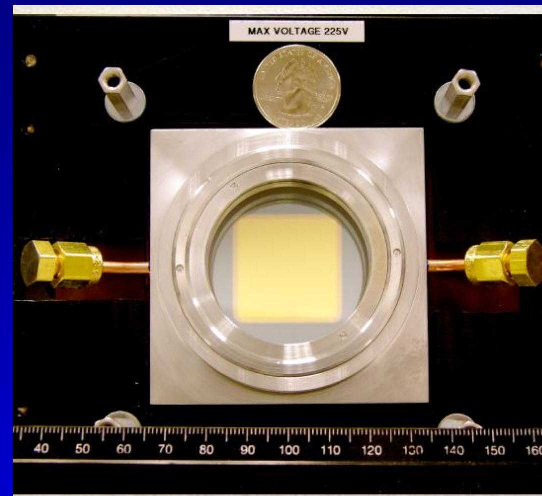


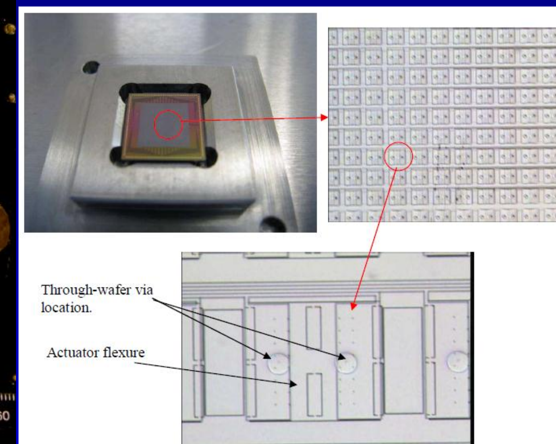
MCAO MOAO

and … power per laser guide star

MEMS Deformable Mirrors

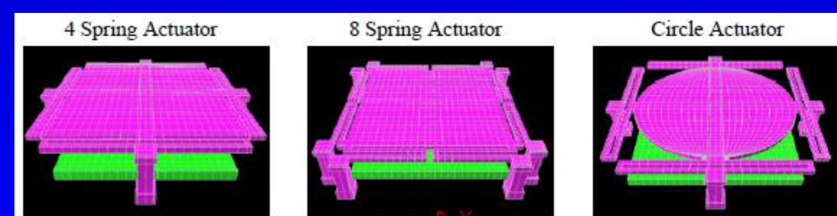
- **Consortium** to build 4,000 and develop 10,000 actuator devices (BMC)
  - Gemini Planet Imager
  - Keck Next Generation Adaptive Optics
  - Thirty Meter Telescope





Boston Micromachines

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

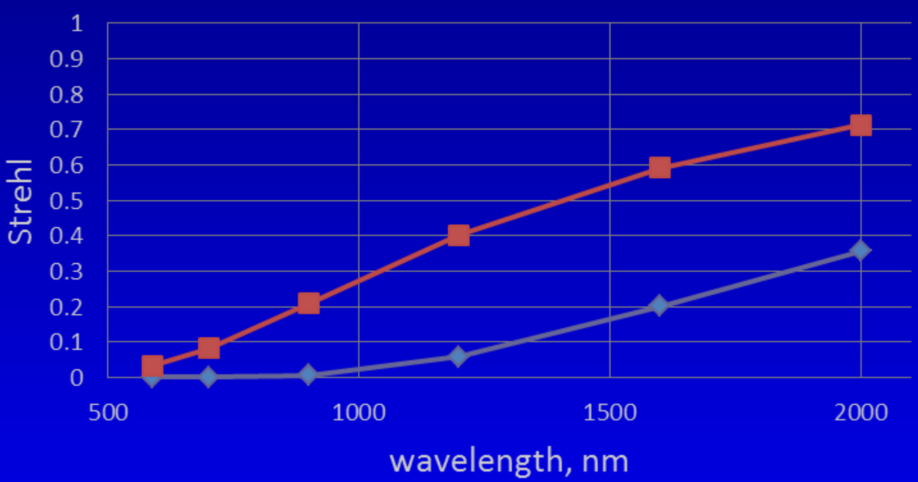


- **Higher stroke actuator** designs (UCSC)

ShaneAO implements a new 3-meter AO system with improved performance

using the latest technology and lessons-learned at LAO

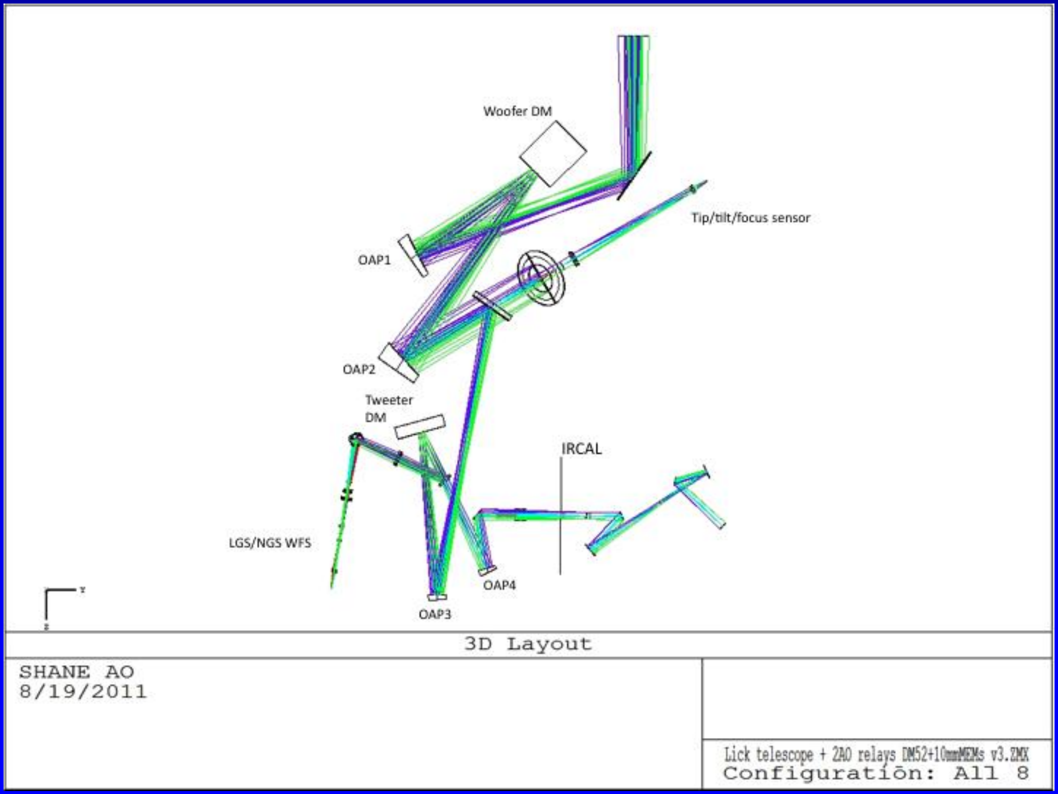
- Diffraction-limited I, J, H, K bands
- High Strehl
  - 32x32 MEMS DM
  - selection of subaps adjust to seeing and brightness of guidestar
  - New sodium guidestar laser, 5 – 10 x brighter than current



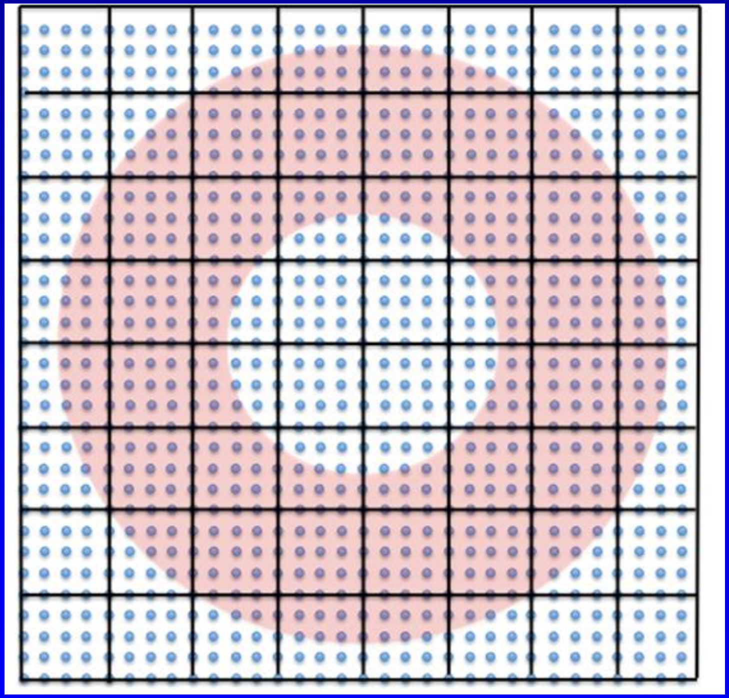
- High optical throughput
  - “Holy Grail” silver coatings
  - Note: we’re ignoring K-long for now, which would require cooling.
- Improved QE of Hawaii RG detector: 80% vs 62%, plus sensitivity into R band
- Improved opto-mechanical design stability
- Improved automation of setup and observing processes

AO optical design

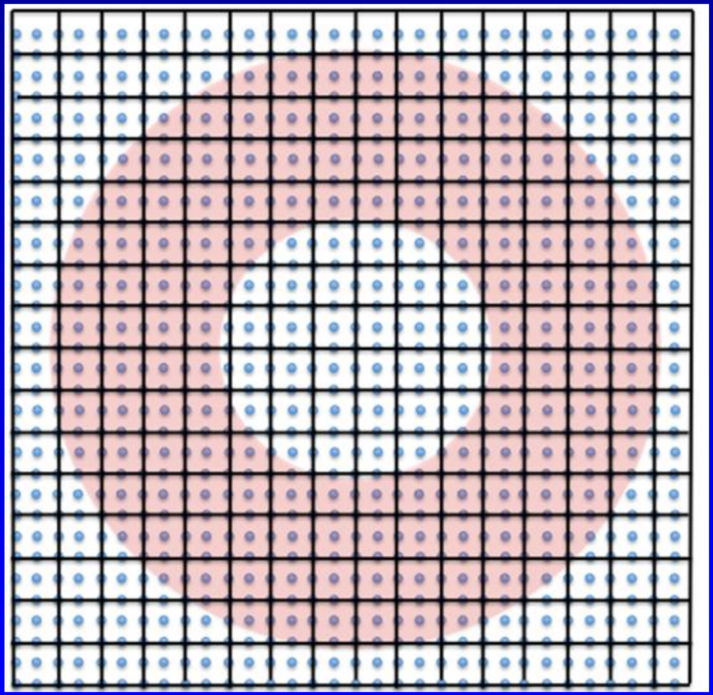
- AO system optical relay design is complete
- Woofer-Tweeter architecture, woofer performs tip/tilt
- Tip/tilt star Is partially corrected (by woofer) – improves sky coverage
- Tip/tilt sensor also senses slow focus – to track sodium layer height variation



AO pupil map

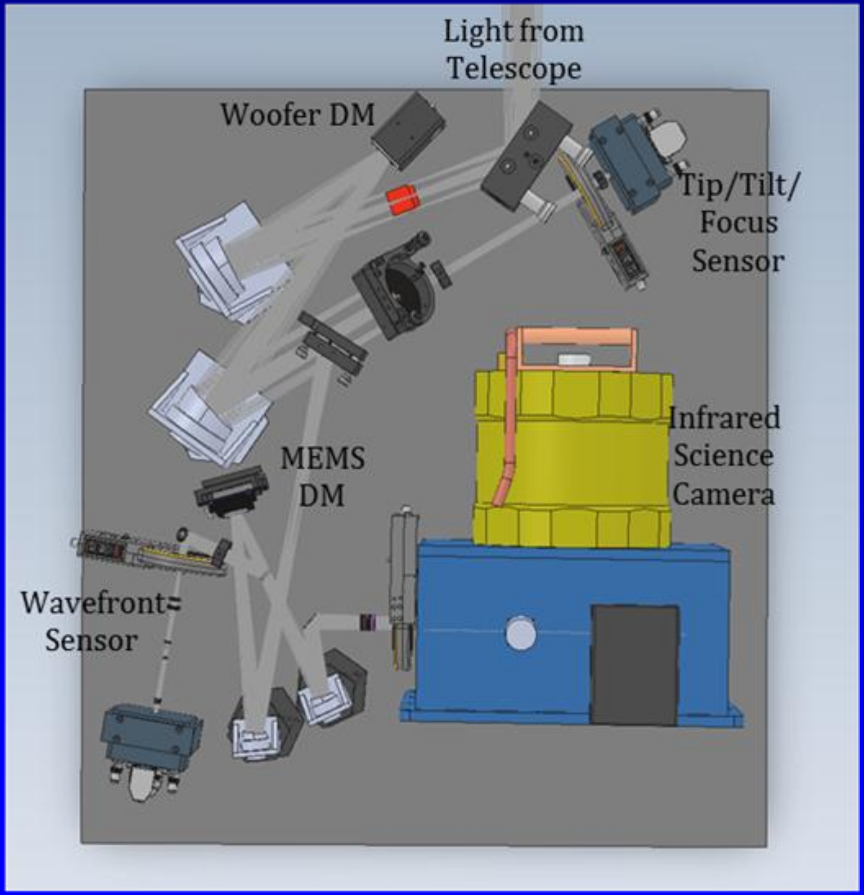


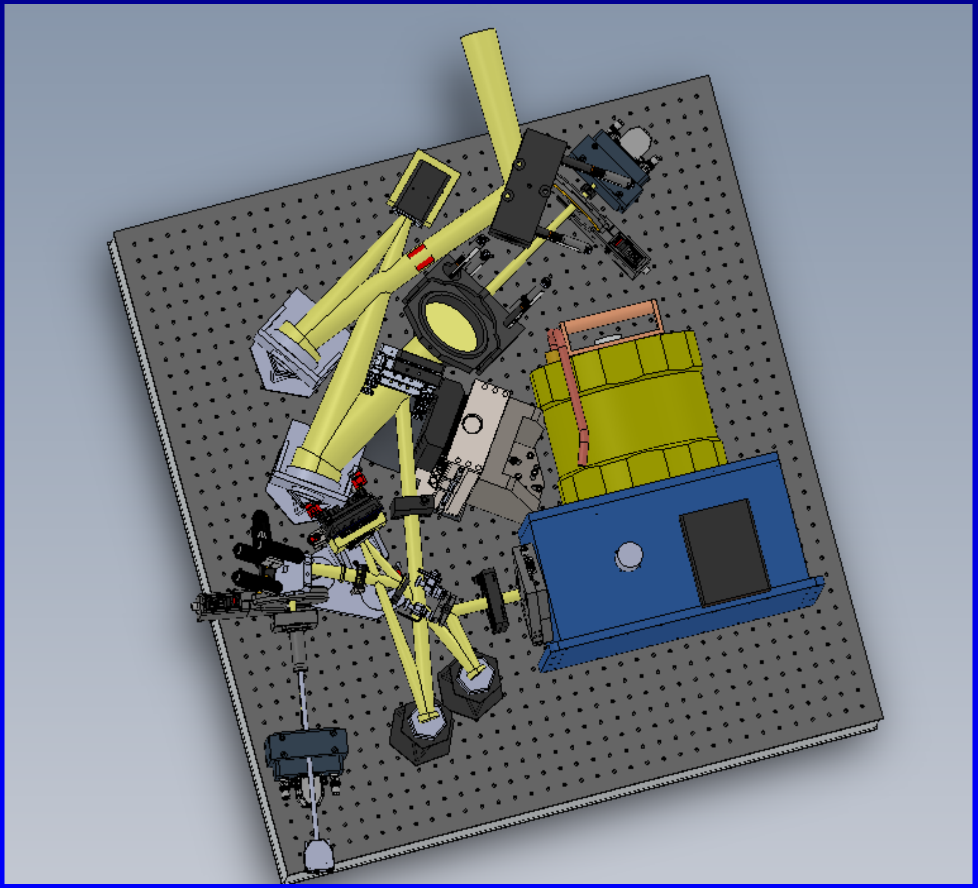
8x8 subaperture
(d=40 cm)



16x16 subaperture
(d=20 cm)

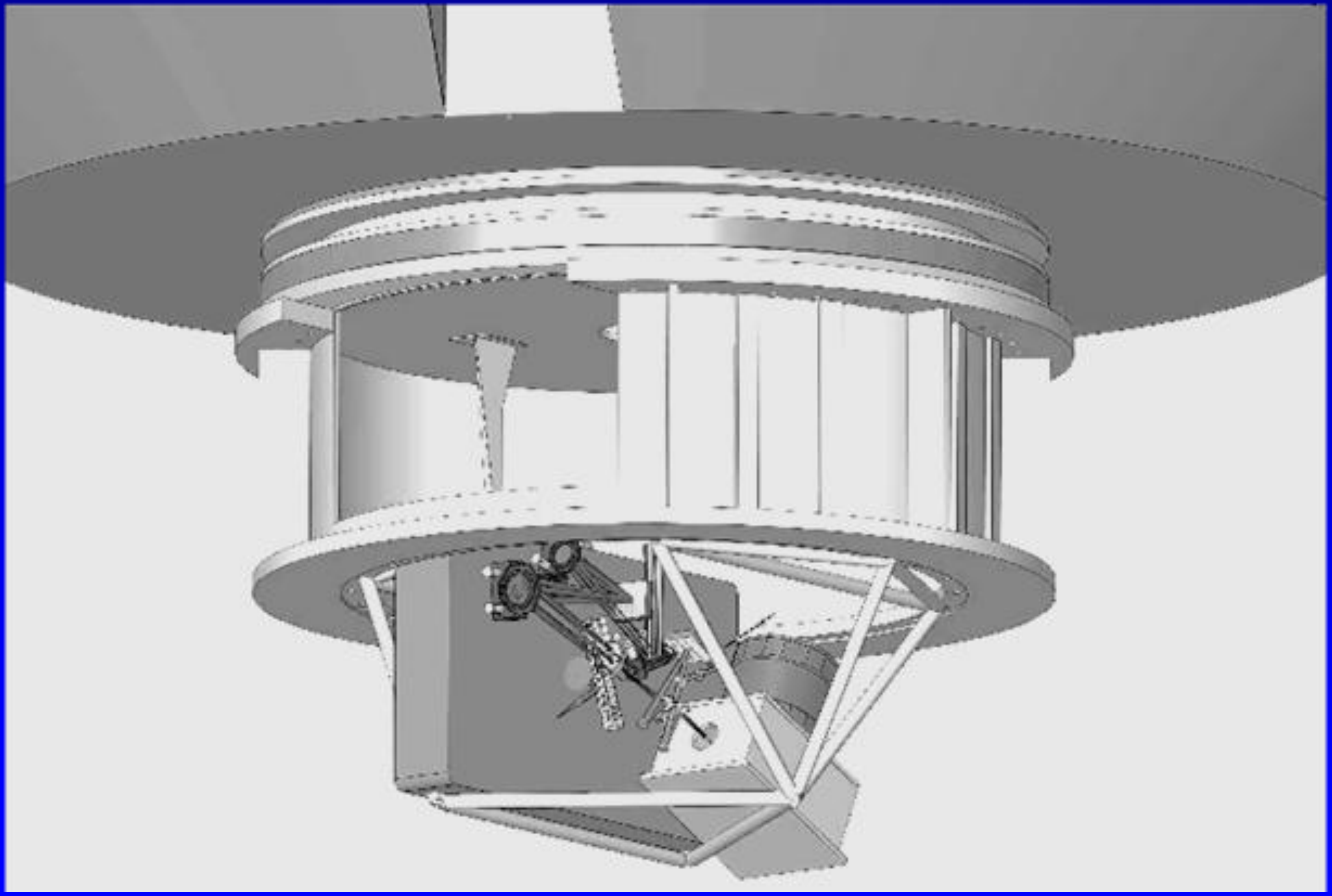
AO bench design





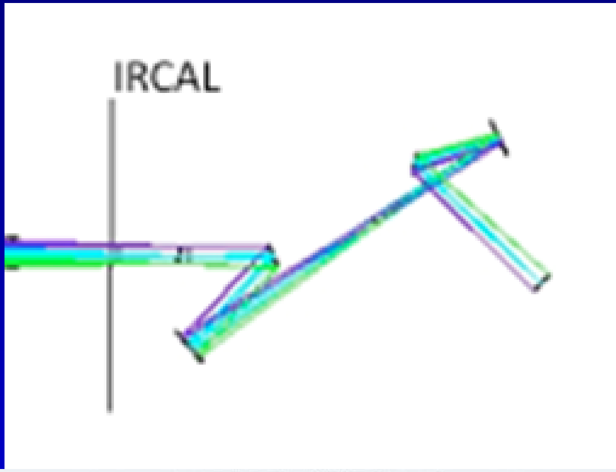
AO bench mounting to Shane Cassegrain focus

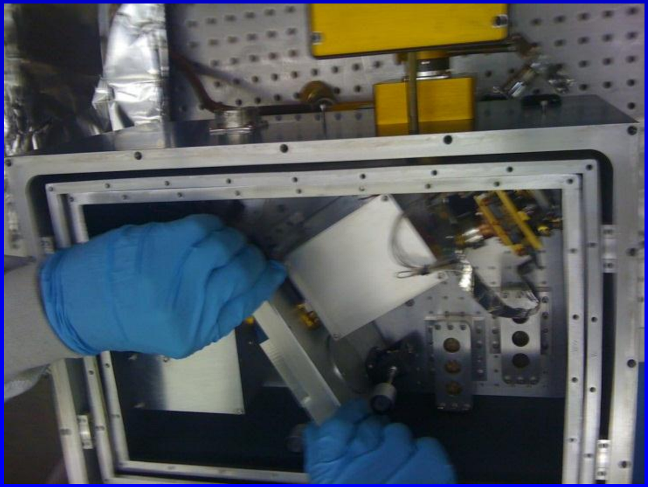
- Concept design at this point

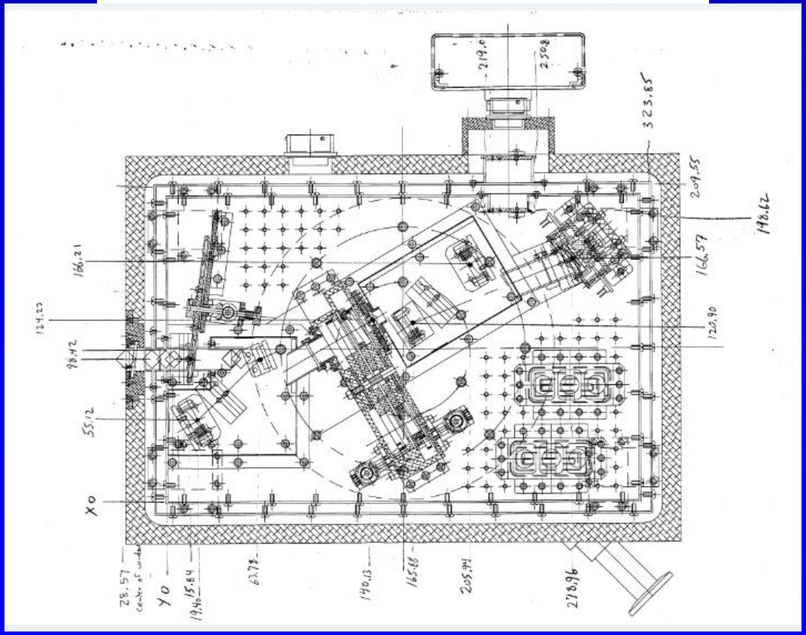


IRCAL optical design

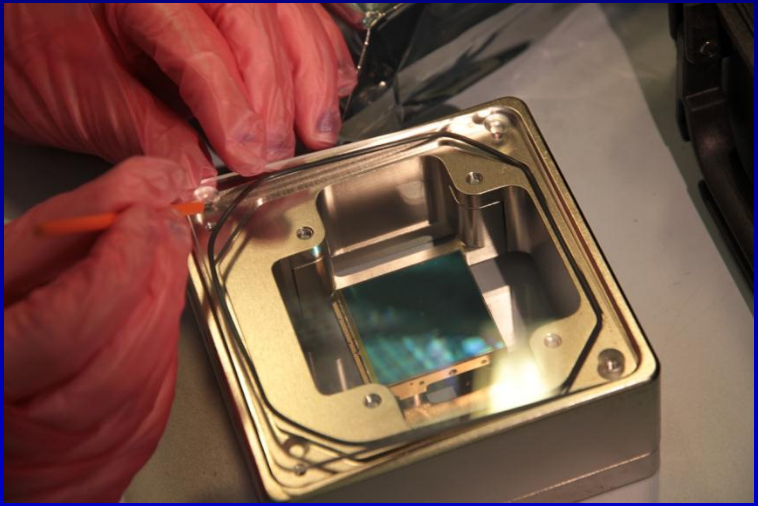
- Optical design mostly complete
- Location of detector changed
- Location of cold pupil changed
- 20 arcsec FOV
- R=700 spectroscopy mode, with grism

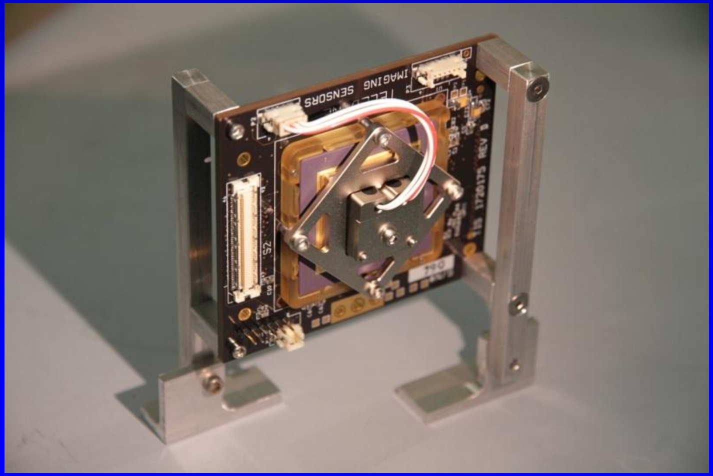






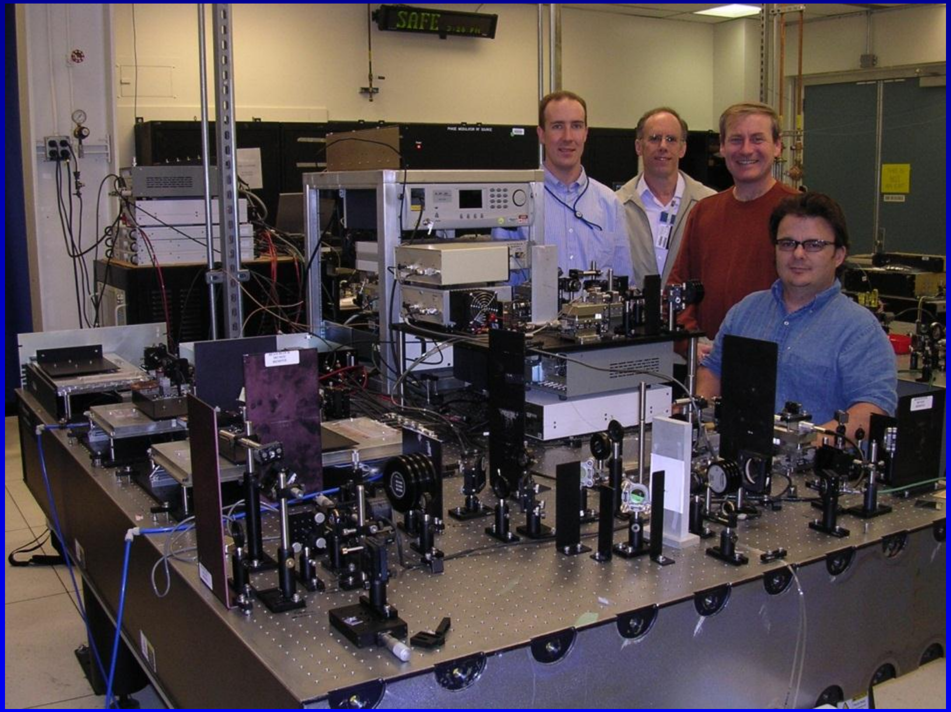
Hi2RG infrared detector and ASIC





Laser upgrade for ShaneAO

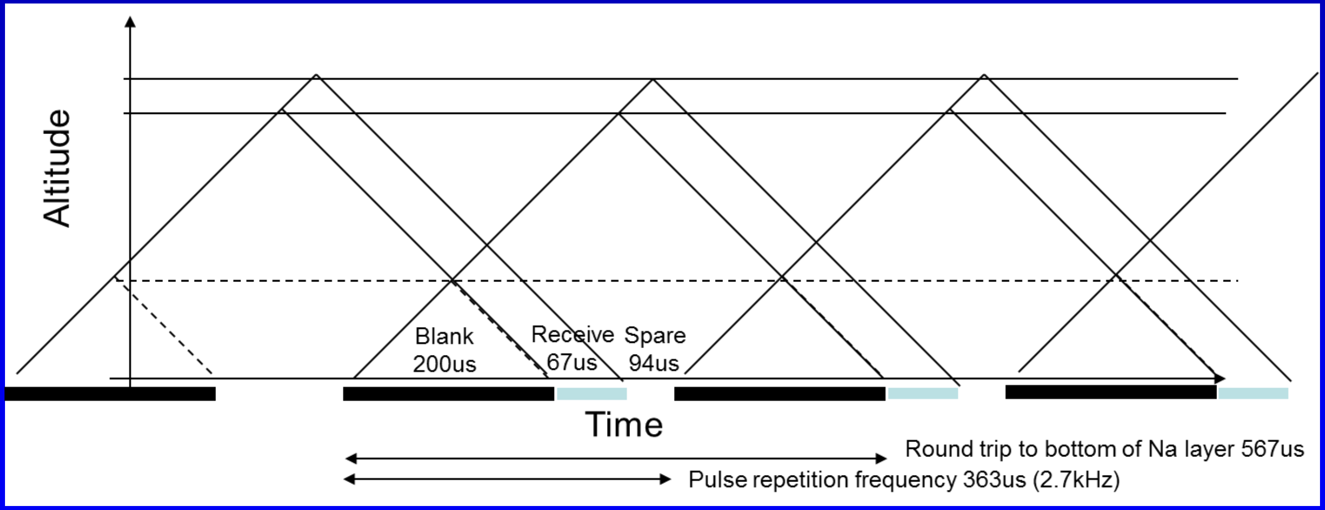
- **Old system:**
  - NG-YAG pumped dye laser
  - 150 ns pulse
  - Deliberately modulated to cover 1.2 GHz doppler-broadened line
- **New system:**
  - Solid state, sum-frequency 938+1532->589 (in PPSLT crystal)
  - Solid state fiber amplifiers for the two IR lines



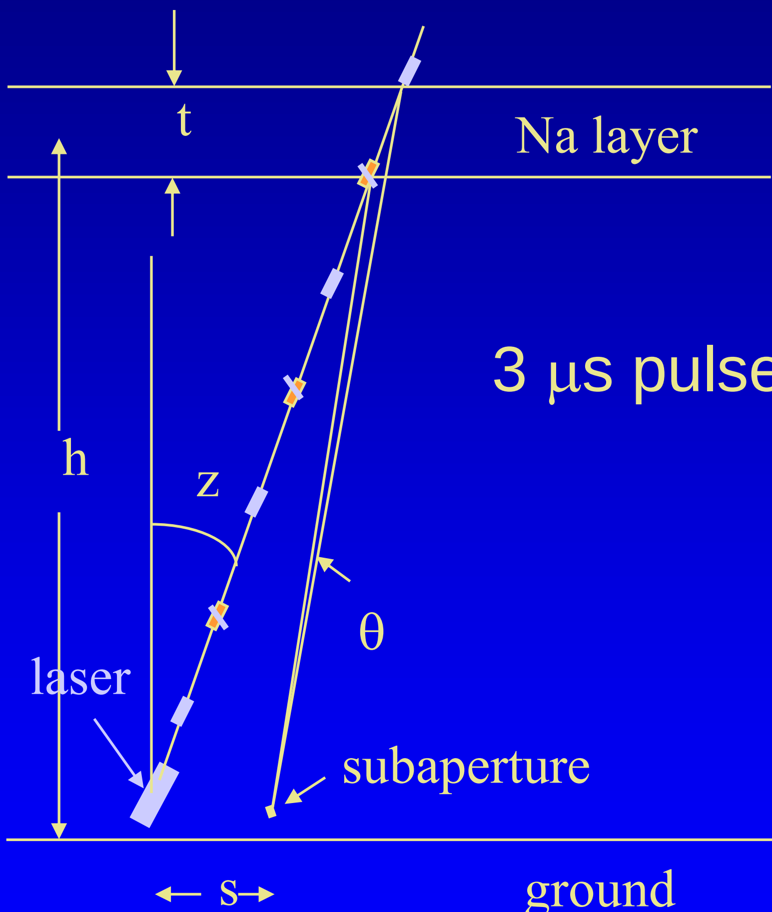
Both systems developed at Lawrence Livermore (LLNL)

Laser pulse format can be adjusted to optimize system performance

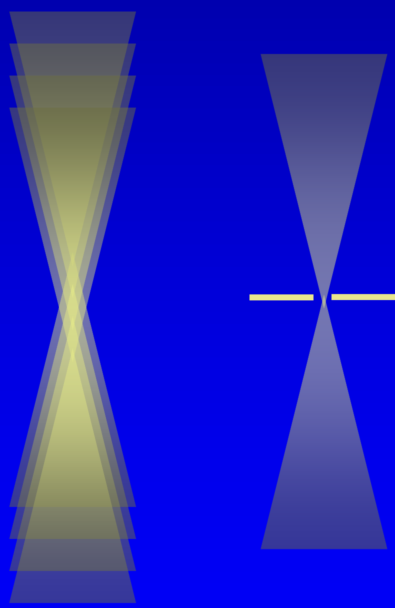
- Needs to "look" like narrow CW to the sodium atoms => narrow line width
- Rayleigh gate pulse ~30 μs pulse every 300 μs



Pulsing for Elongation Mitigation

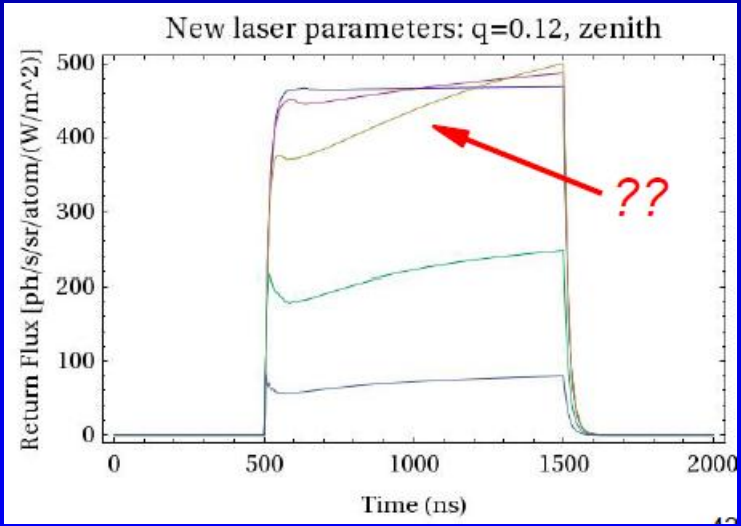


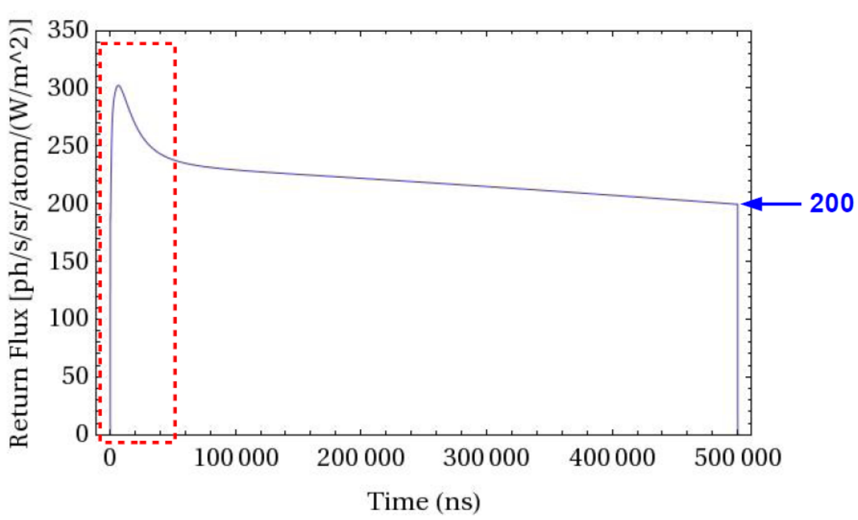
3 μs pulse



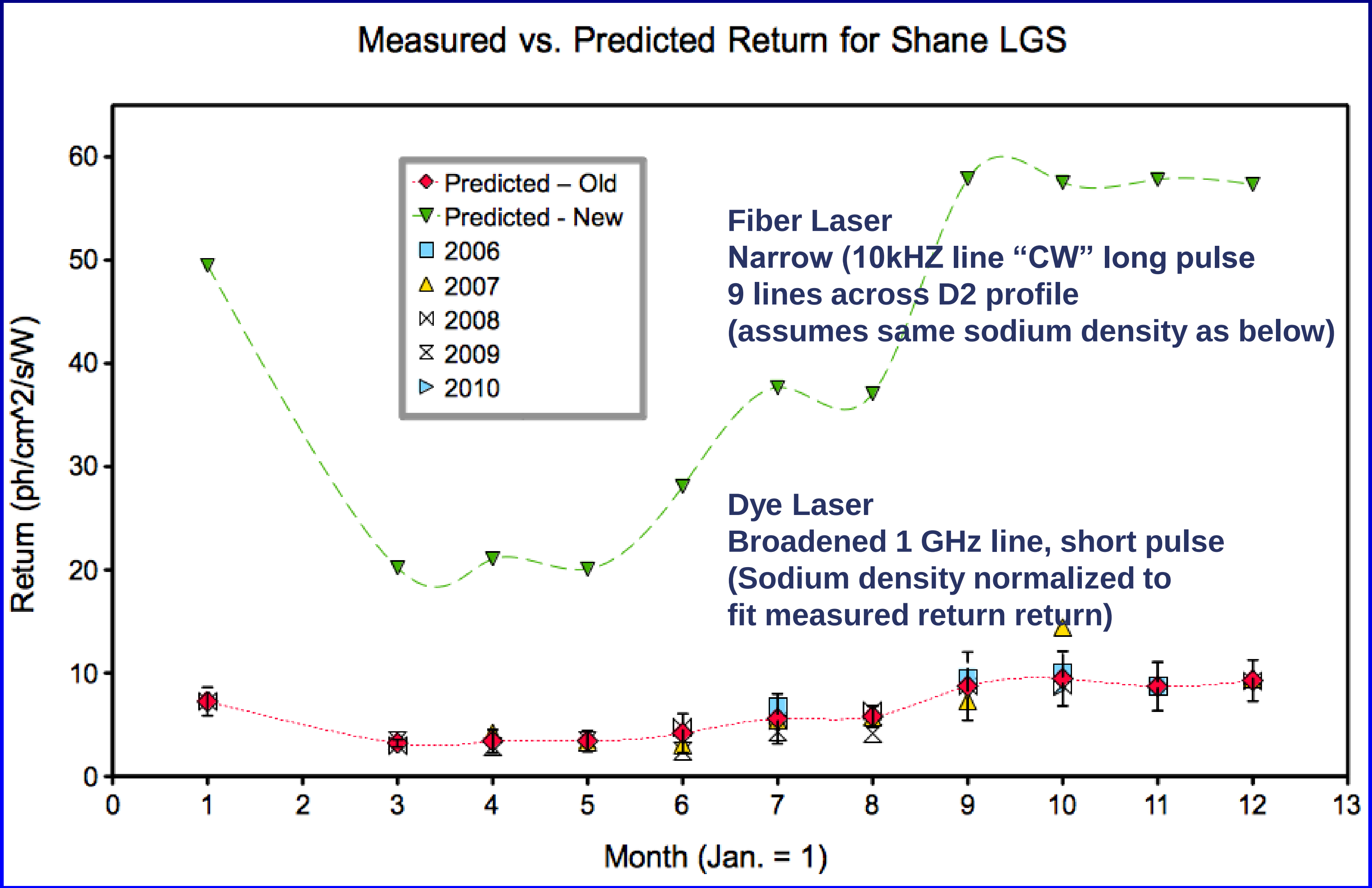
Modeling indicates an optical pumping advantage in optimzing CW pulse length

- **Intensity, linewidth, and "repumping" optimized to overcome the quenching due to Larmor precession caused by earth's magnetic field**





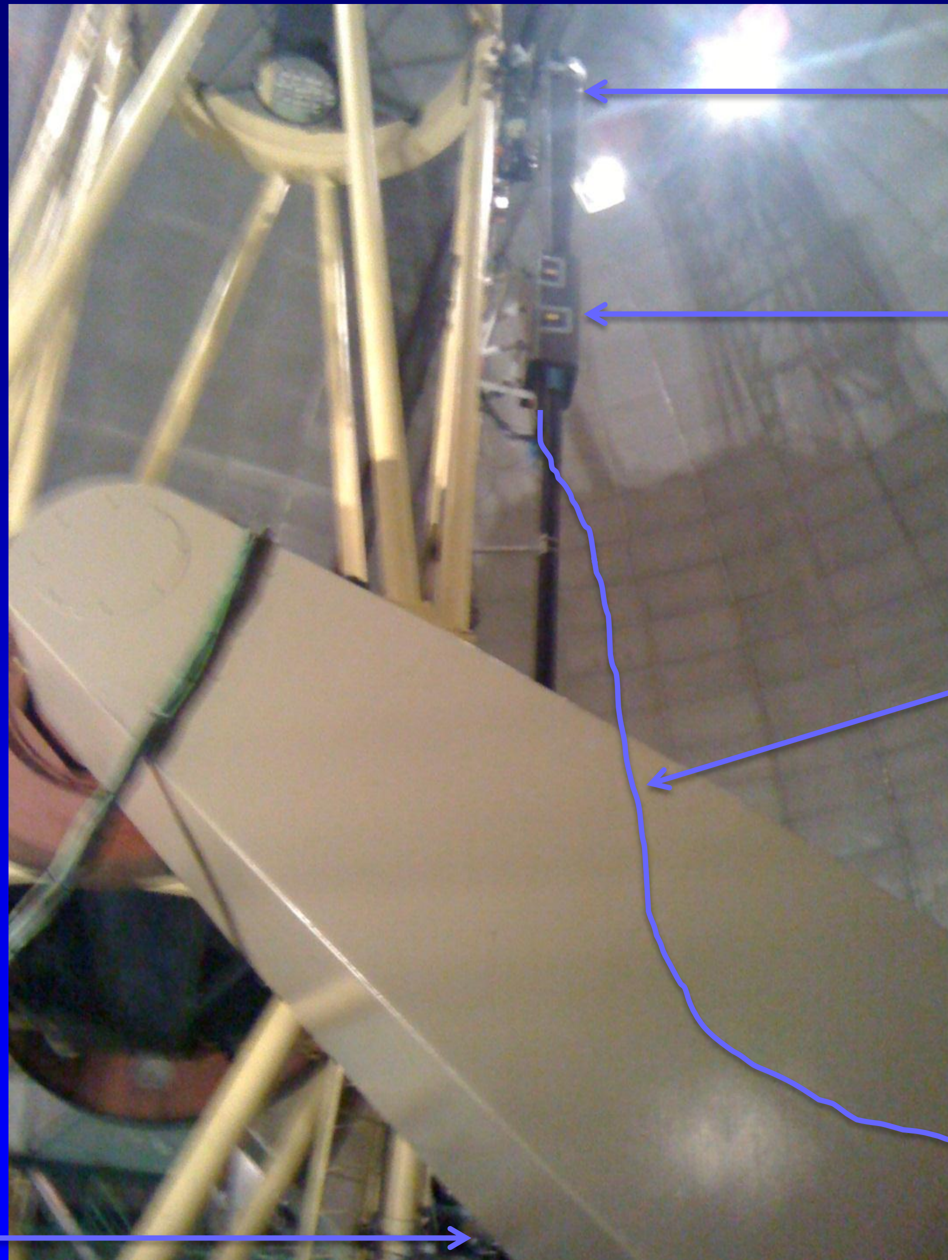
Return modeling indicates considerable improvement over existing dye laser system



Laser status

- **Laser is completed and tested at LLNL**
  - 10 watts output power
  - Pulsed, with programmable pulse format. Long pulse looks like CW to sodium => giant return gain
- **LLNL is contracted to deliver and set up laser at UCSC**
- **UCO to "harden" for mountaintop operation**

Laser Launch



Launch Telescope

Beam diagnostics

~ 30 m of photonics crystal fiber

Fiber laser enclosure

Existing Dye Laser

Summary

- **AO for ELTs => challenging cost and complexity**
- **Pathfinder work at LAO:**
  - MEMS
    - MEMS enables high # degrees of freedom
    - Issues of reliability, stroke
  - Guide Star Laser
    - High efficiency (return/watt) means less total power needed
- **Programs**
  - Gemini Planet Image – 4k MEMS DM
  - ShaneAO – 1k MEMS DM, pulsed fiber laser