Laser Guide Star Adaptive Optics for Astronomy

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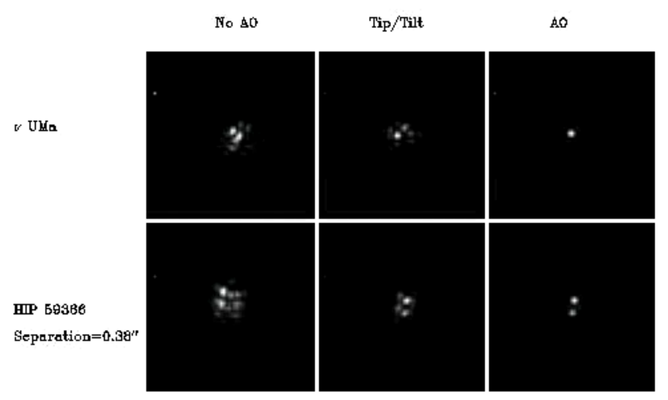
Lick Observatory
Mount Hamilton, California

Why AO?

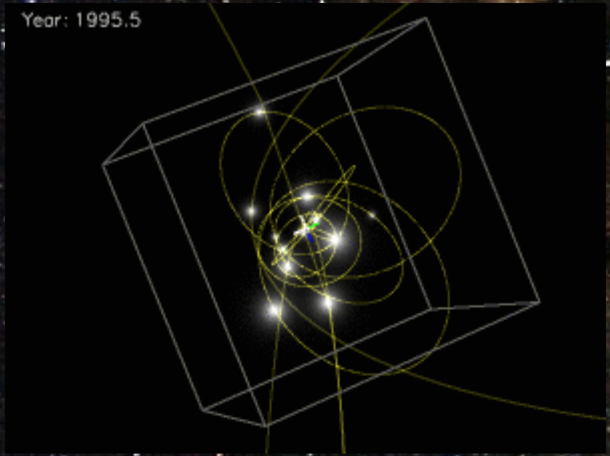
- AO improves resolution by correcting for the atmospheric aberration
- AO improves SNR over background (IR In particular)
- AO enables science from the ground:
  - Planet imaging
  - Details of Galactic center
  - Galaxy mergers – growth of the universe
- AO can take advantage of large telescope diameter

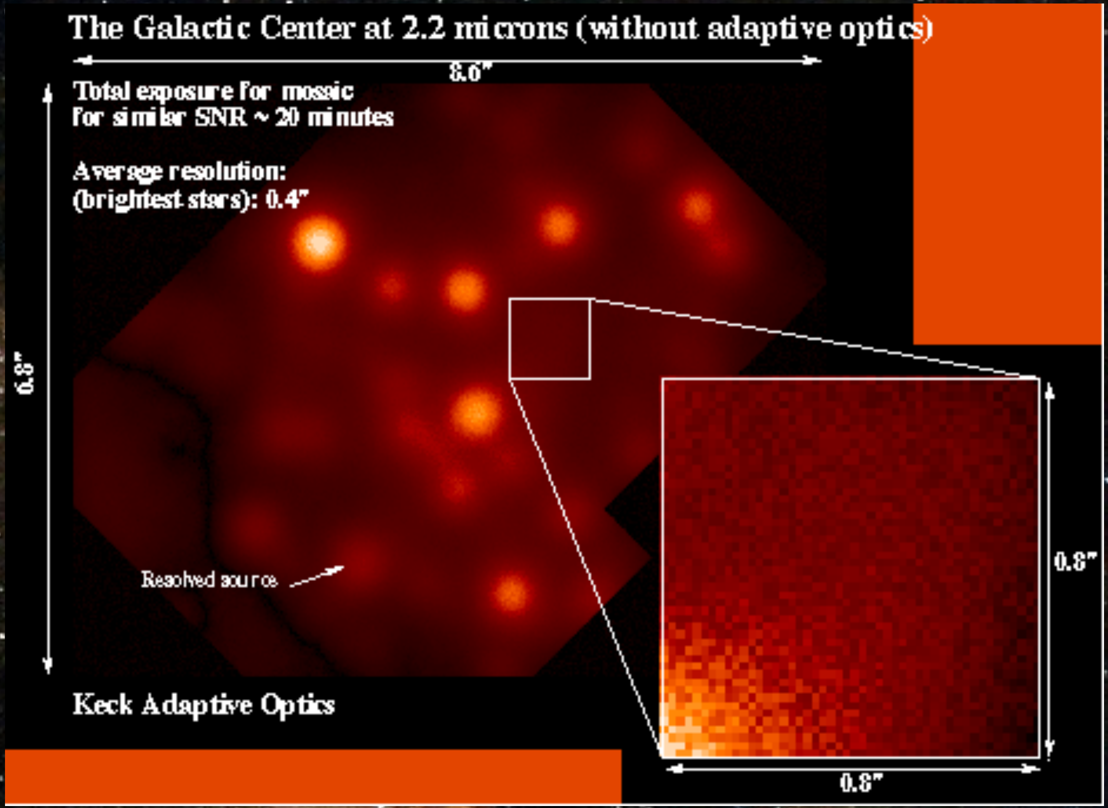


Closed loop Strehl=0.74, 2.2μm, r_0=18cm at 5500A
57ms exposures, 4.8″ field of view

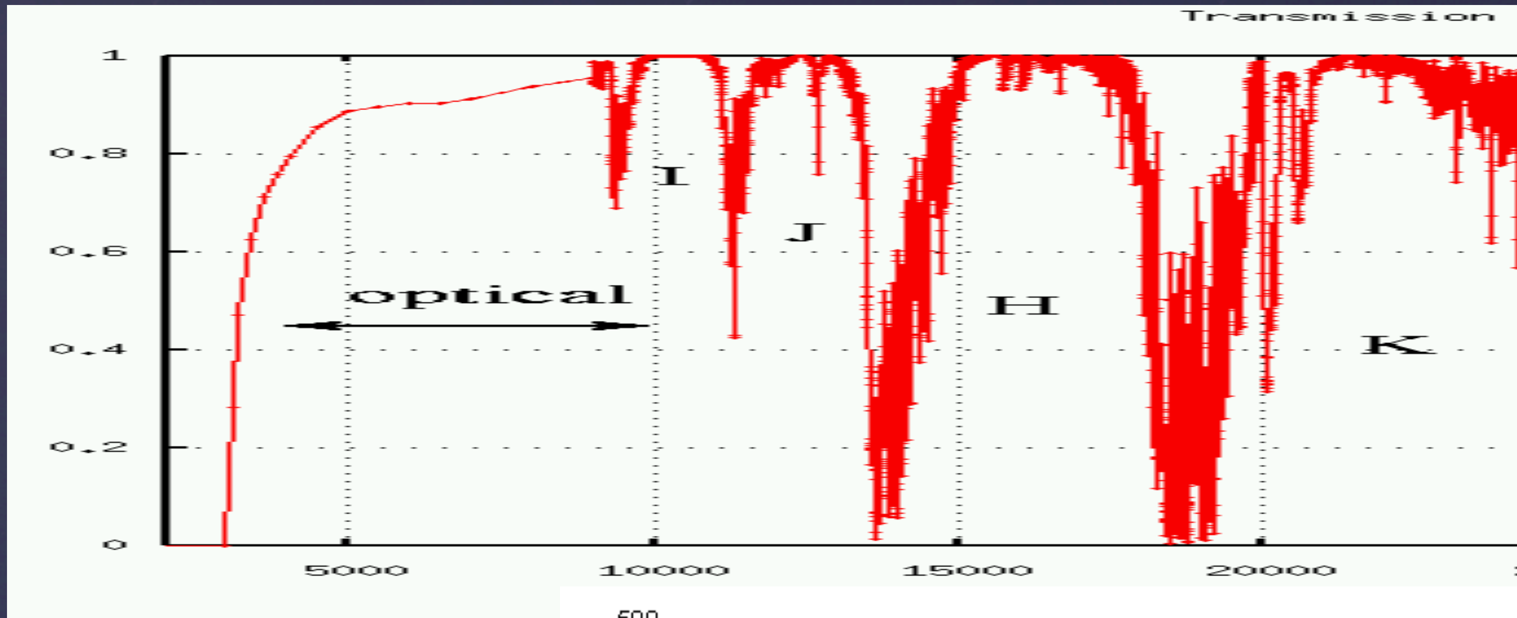
Galactic Center

Prof. Andrea Ghez
Galactic Center Group, UCLA



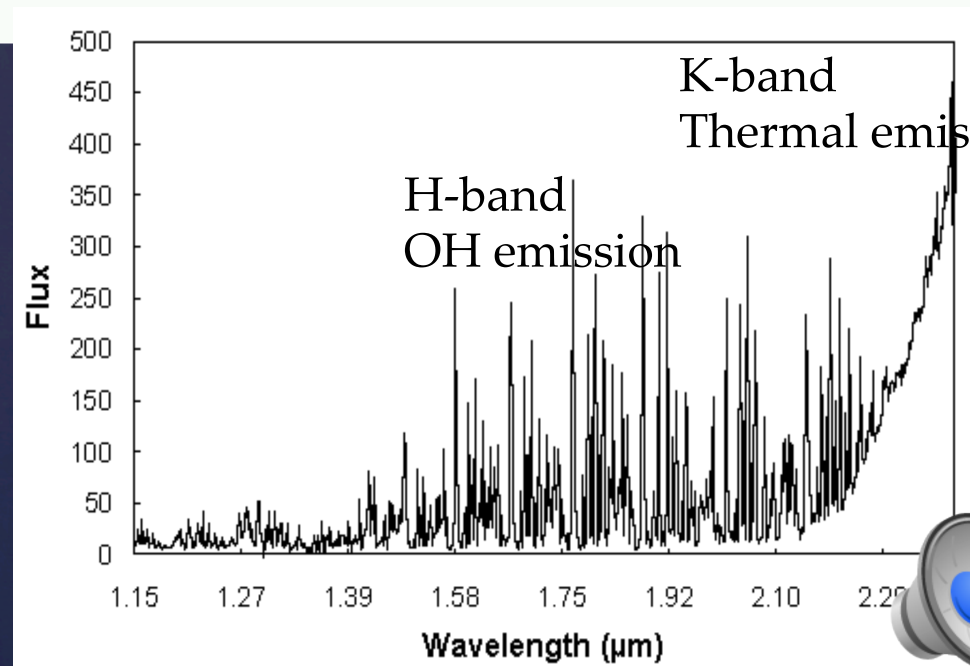


The Night Sky

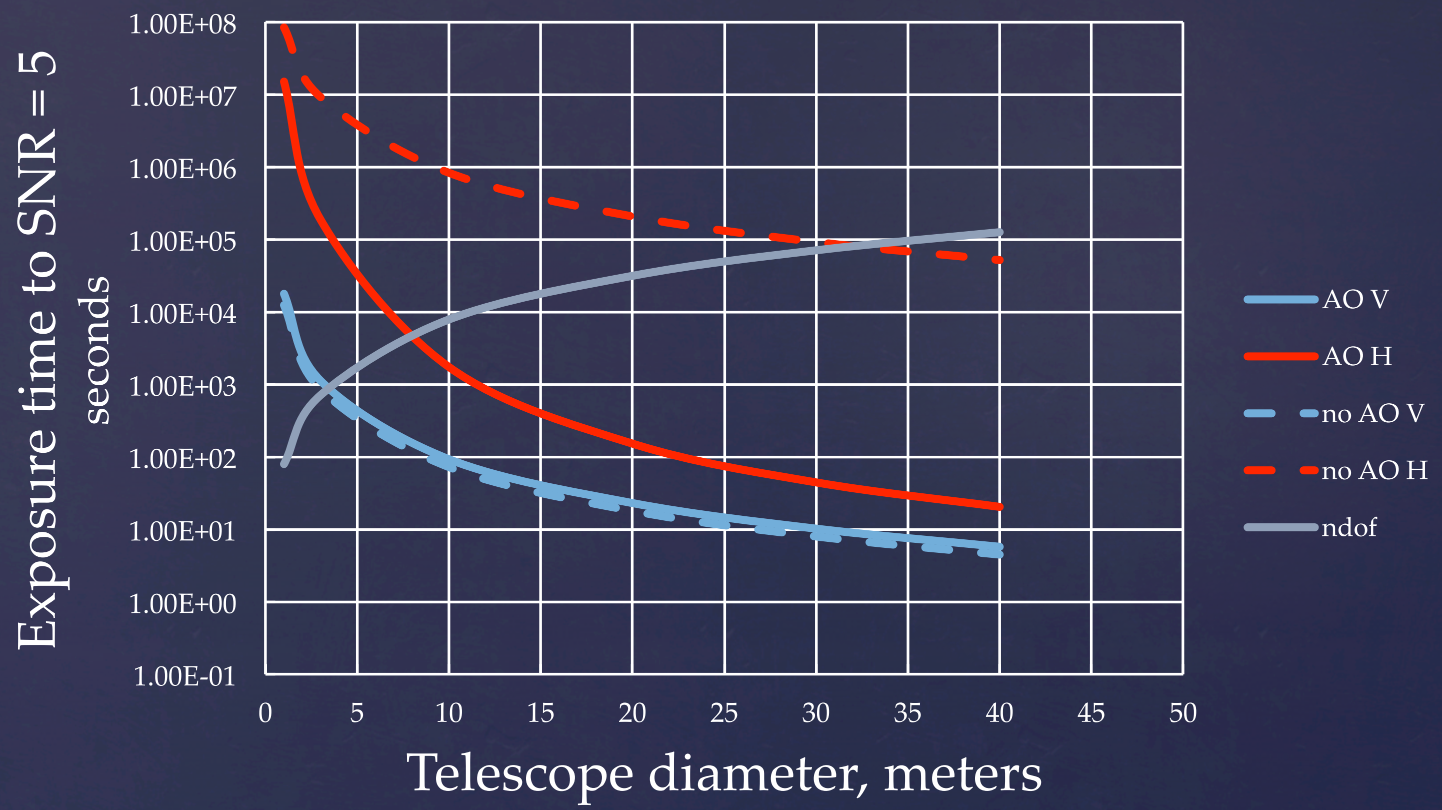


Sky Transmivity

Sky Background



AO Speed Improvement

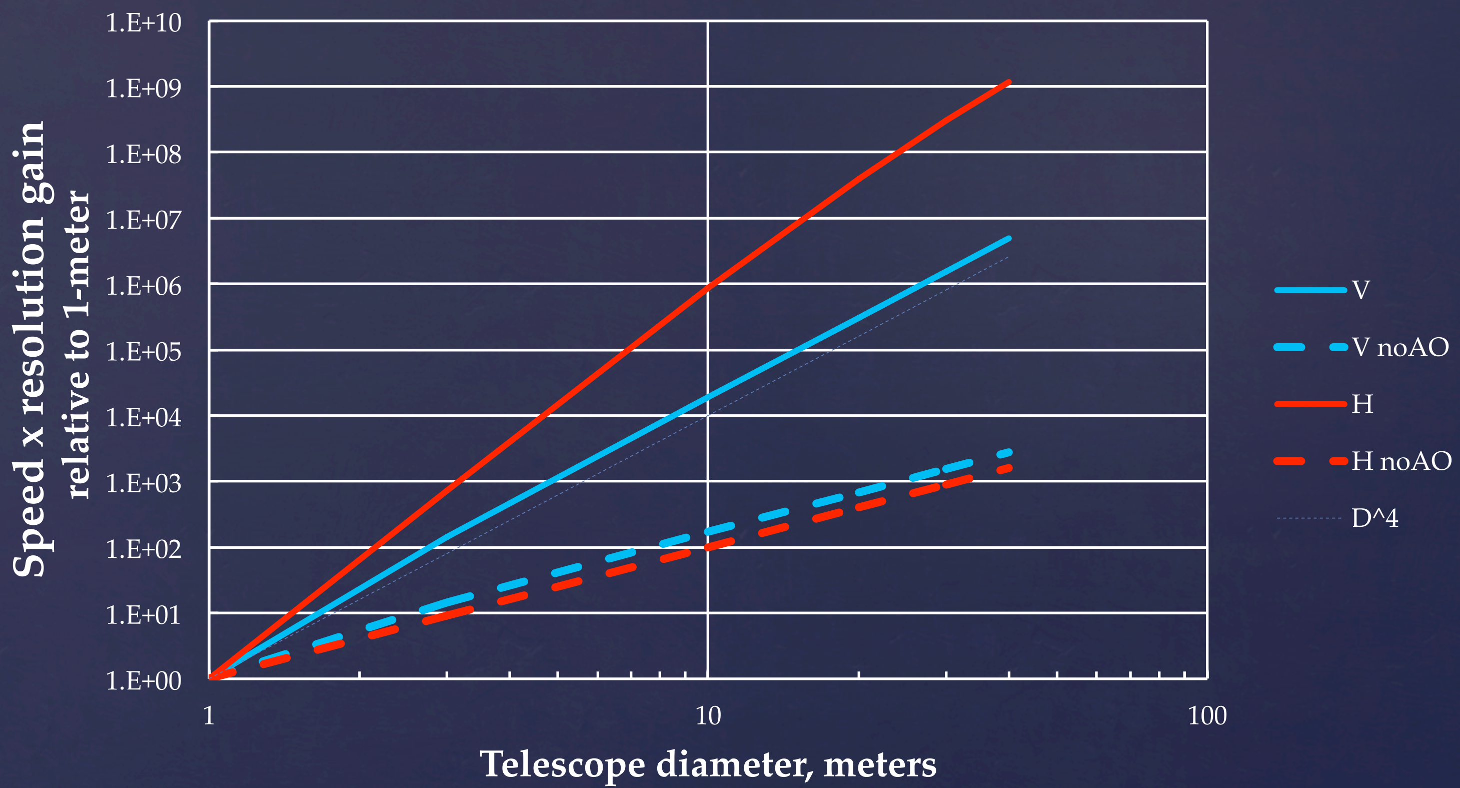


Exposure time to a given SNR as a function of telescope diameter and science band, with and without AO. "Signal" is counted in the diffraction-limited core (AO case) or seeing disk (no AO case). Noise is a combination of background, thermal emission, dark current and read noise, with backgrounds and emission counted only in the pixel region of the signal photons. Assumptions are r_0 = actuator spacing = 10 cm, warm fore-optics, throughput = 50%.

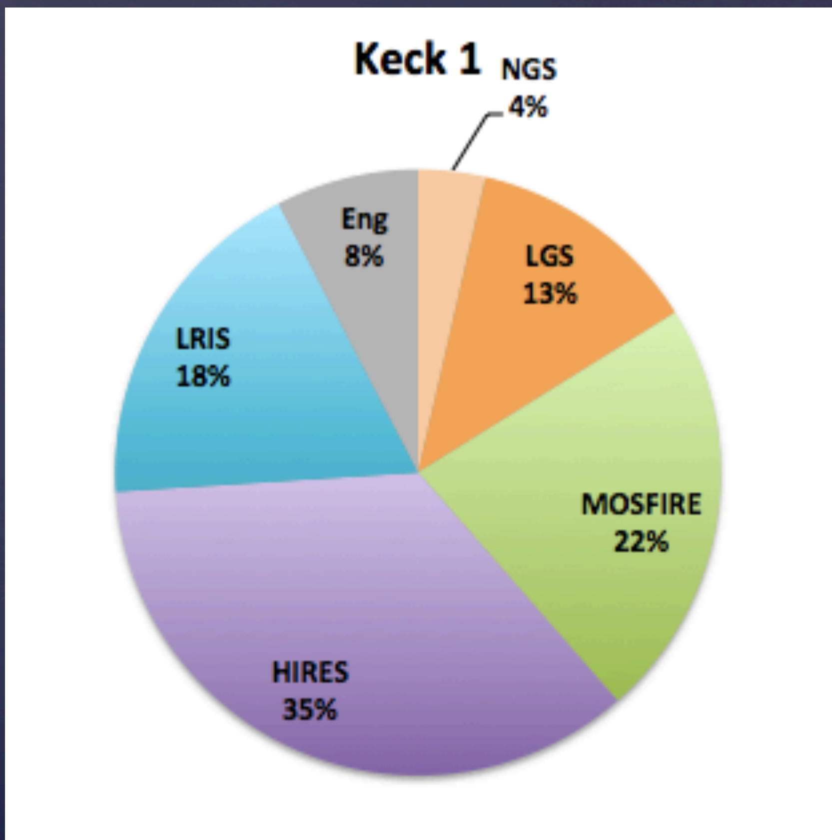
When there is sky background, point-source SNR improves as sources poke above the noise

Speed-Resolution Product

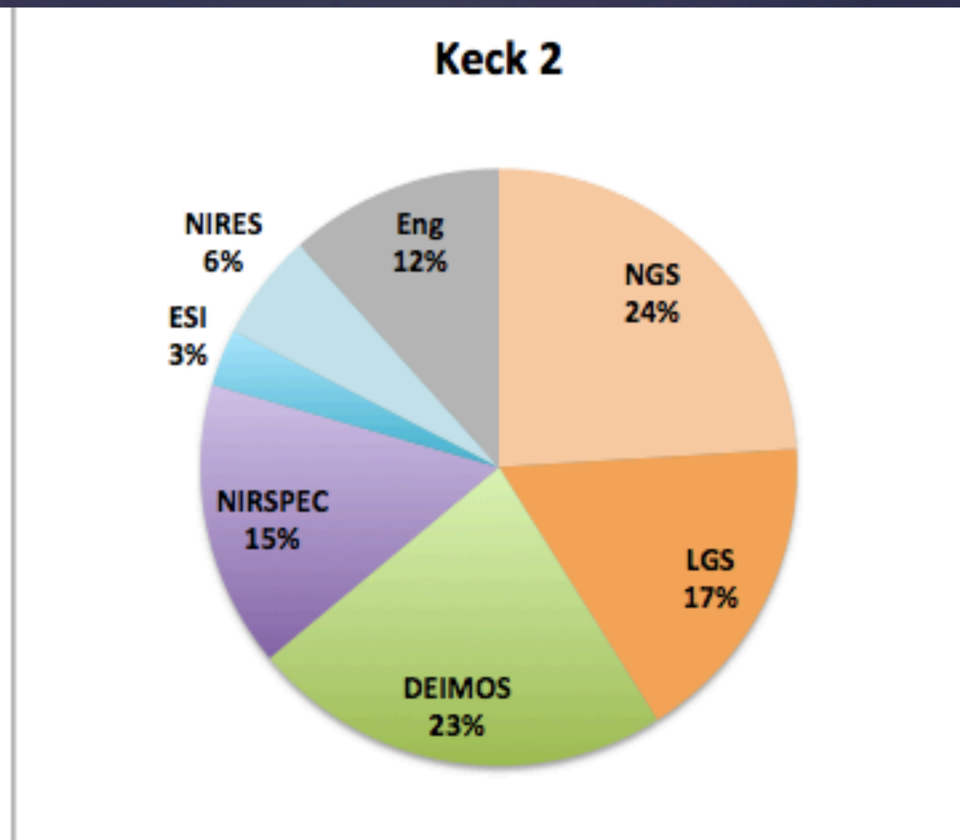
$$I=(\tau_{noAO}/\tau_{withAO})\,(\theta_{seeing}/\theta_{DL})^2$$



Keck AO Use



17%



41%

Gemini AO Use

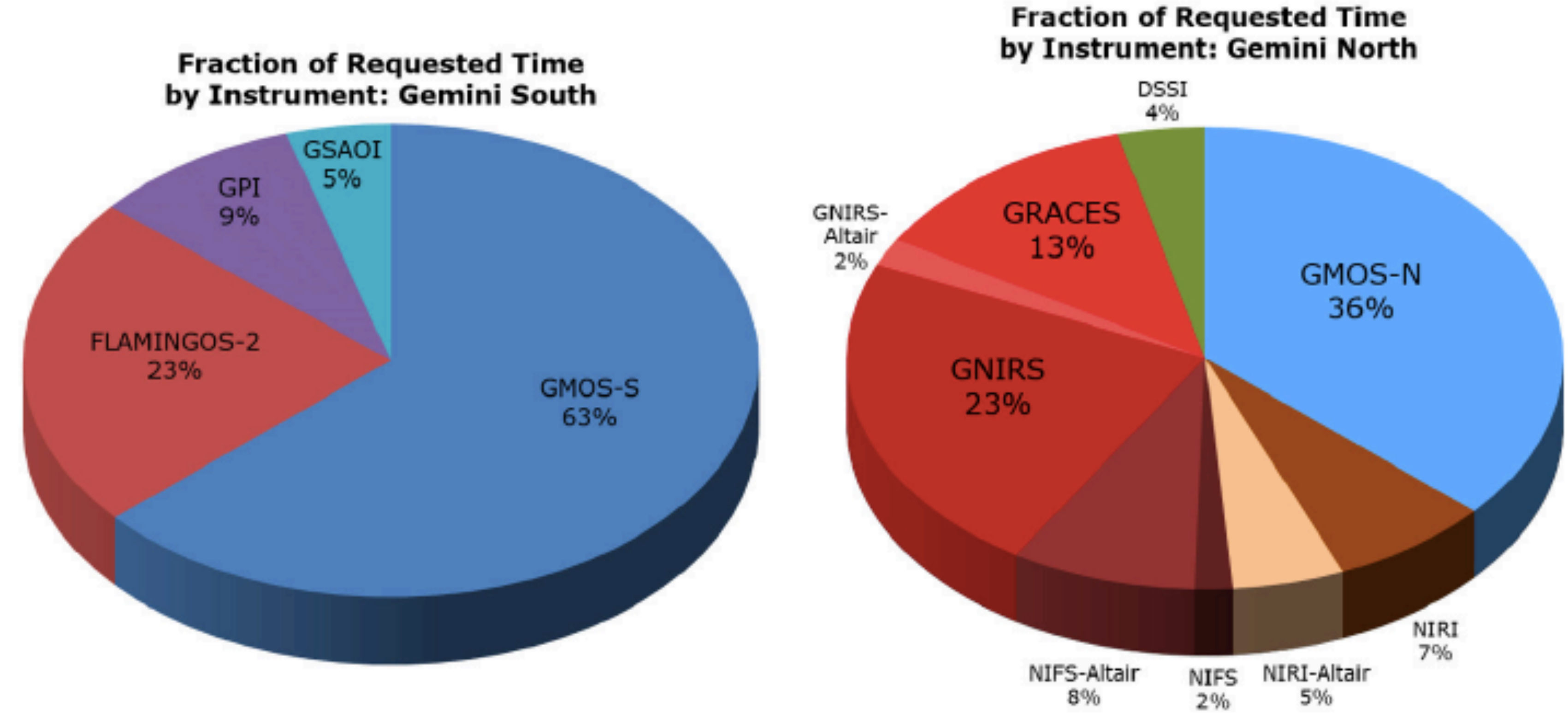
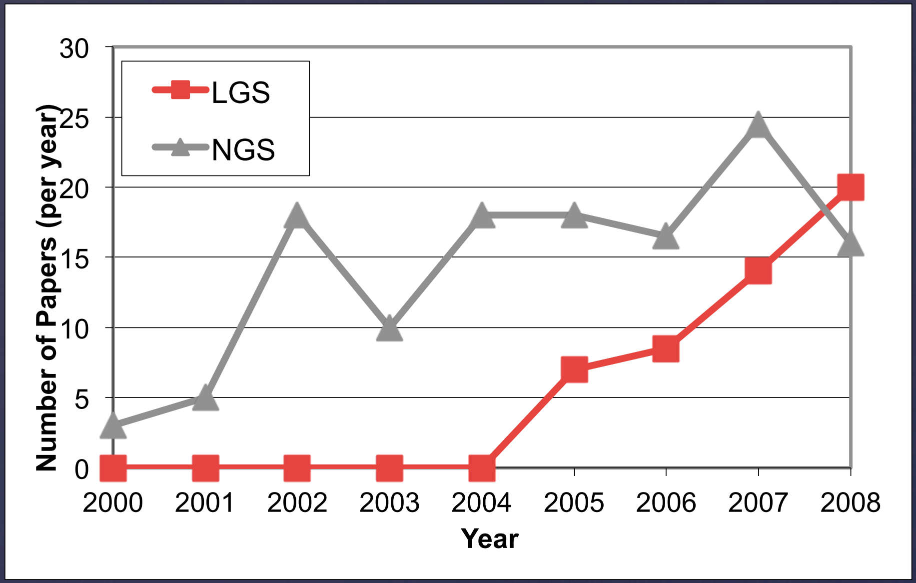
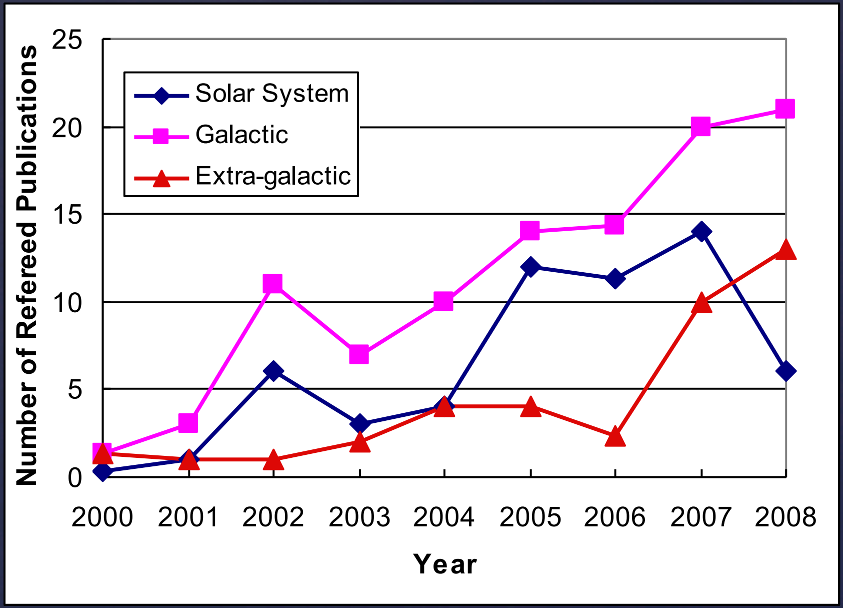


Figure 6 – Semester 2015B demand by instrument.

15%

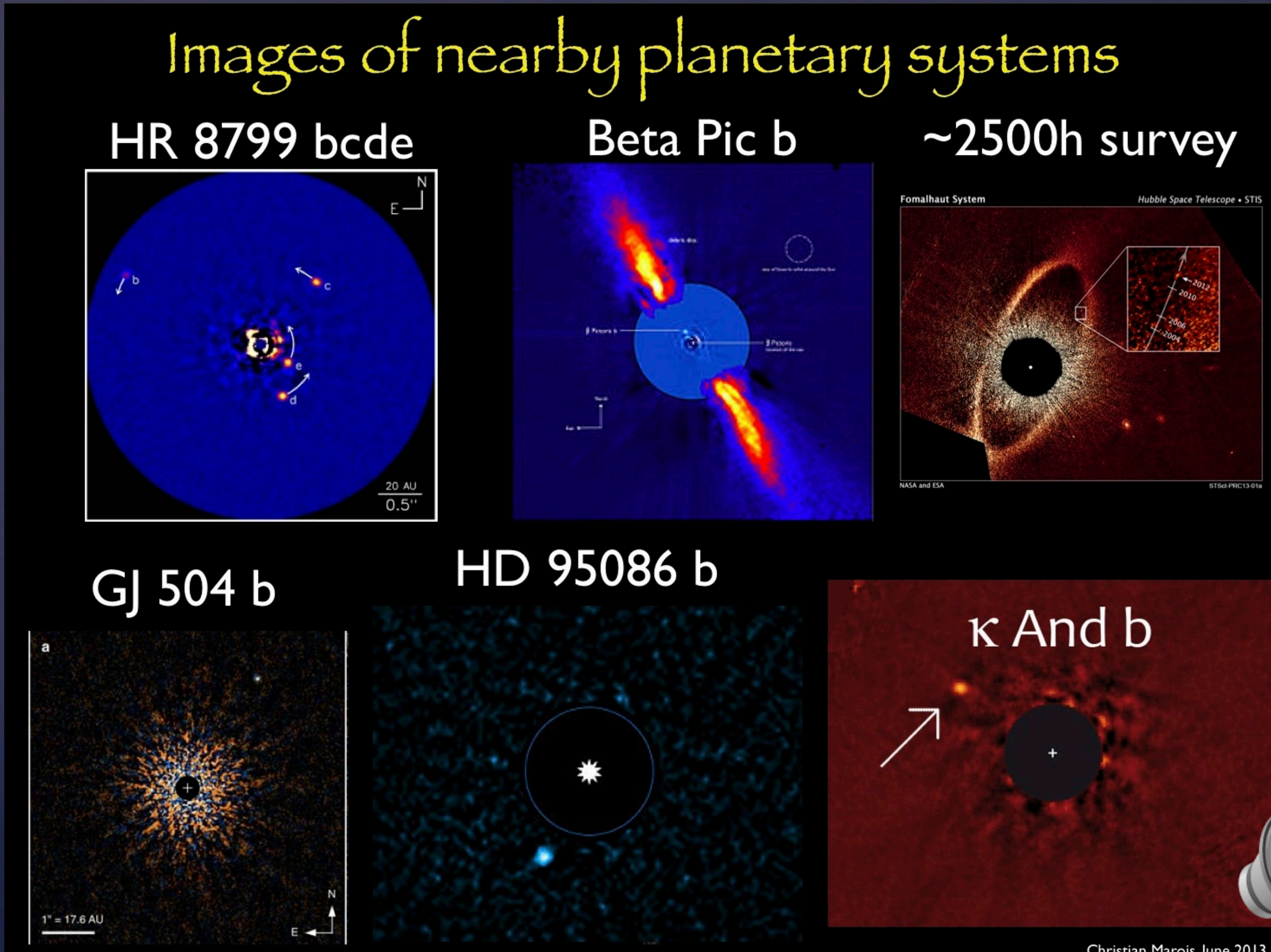
Introduction of Laser to AO has a growing impact on science with AO





Data from Keck Observatory

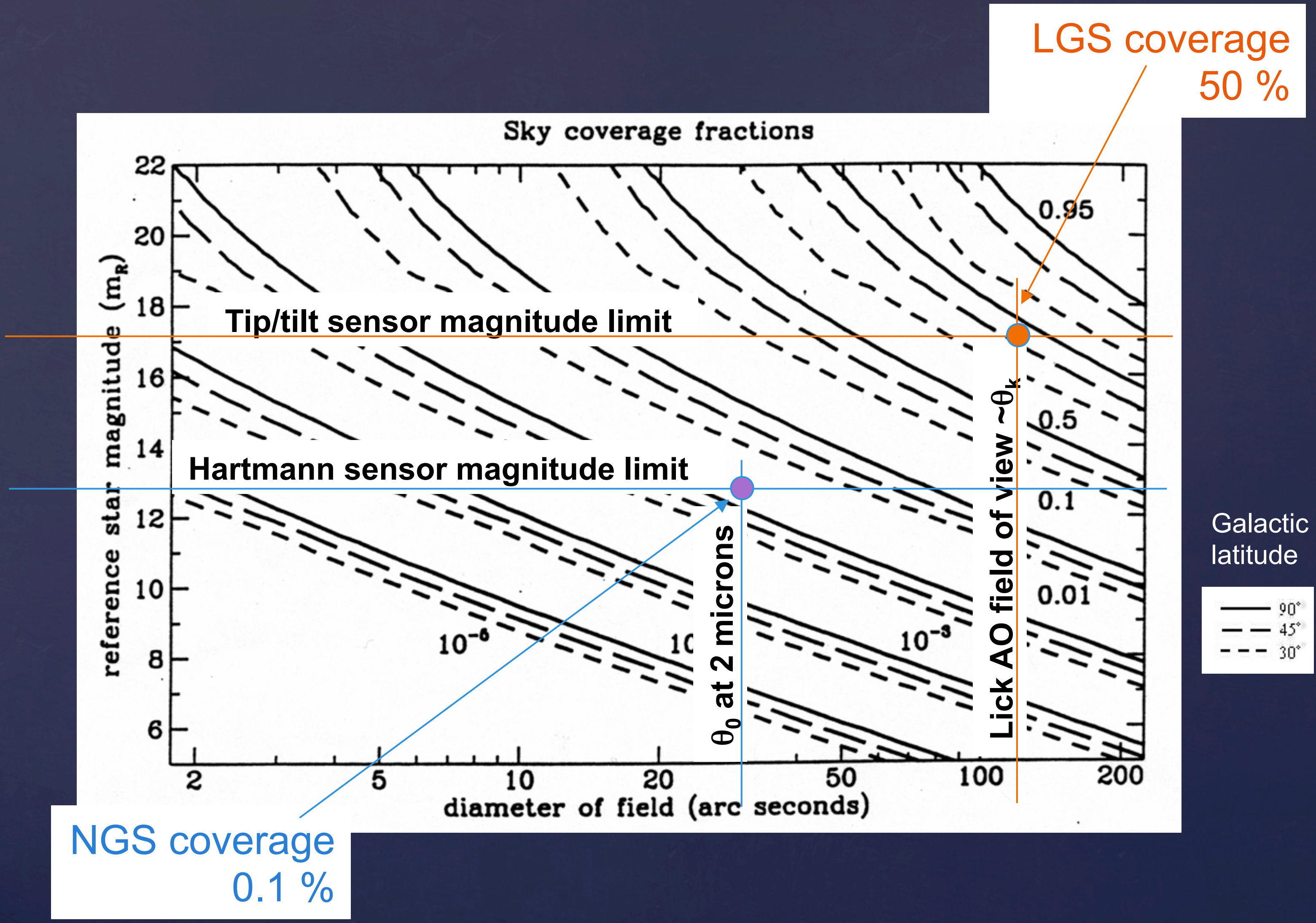
Gemini Planet Imager



Bottom line

- AO has highest payoff in the near infrared
  - OH lines, and thermal emission starting at 2μ
  - Visible?
  - MidIR?
- Wide field AO
- All-sky – Laser Guide Stars

Why Laser Guide Stars?
AO Science on the Whole Sky



Why Laser Guide Stars?

AO Science on the Whole Sky

rage
50 %

Galactic latitude

90°
45°
30°

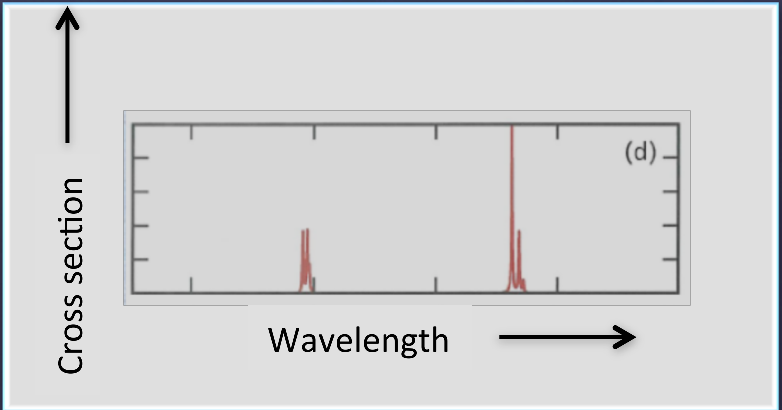
Mauna Kea Heavens 2 4K – Sean Goebel
https://www.youtube.com/watch?v=H1JOU2iDKeM

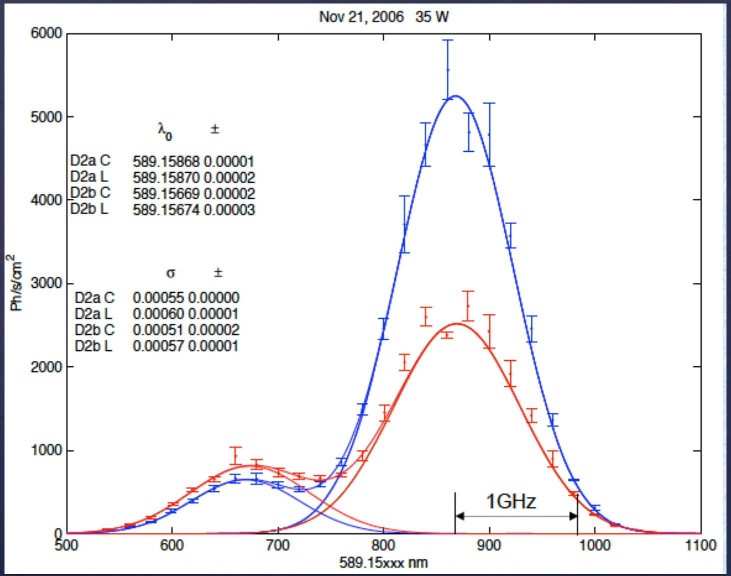
What makes an ideal laser guide star?

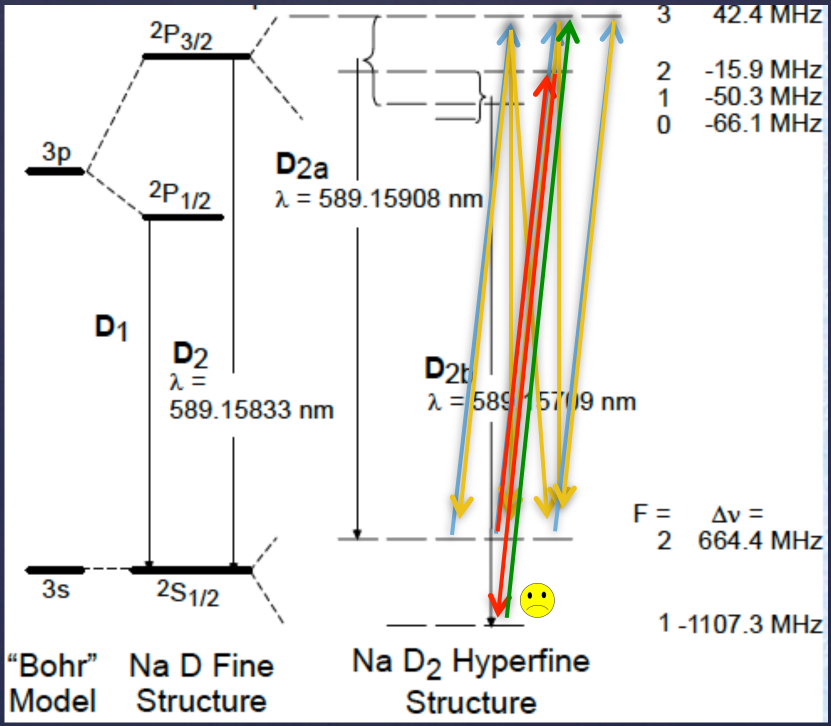
- As close to infinity as possible
- As close to a point source as possible
- As bright as possible

- ------- Particulars for a Sodium layer beacon: -------
- Sodium layer at 90km – the highest beacon possible using natural terrestrial phenomena – much higher than Rayleigh (atmosphere) scatter at ~30km
- Sodium has high cross-section
- Sodium can be optically pumped
- System issues favor pulsing
  - Blanking Rayleigh background return
  - Pulse tracking to counter elongation – reduces spot size

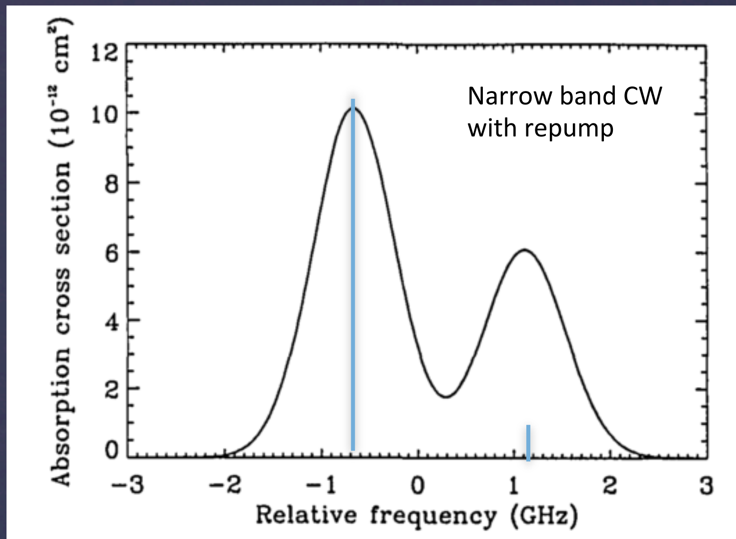
Optical pumping with circularly polarized light

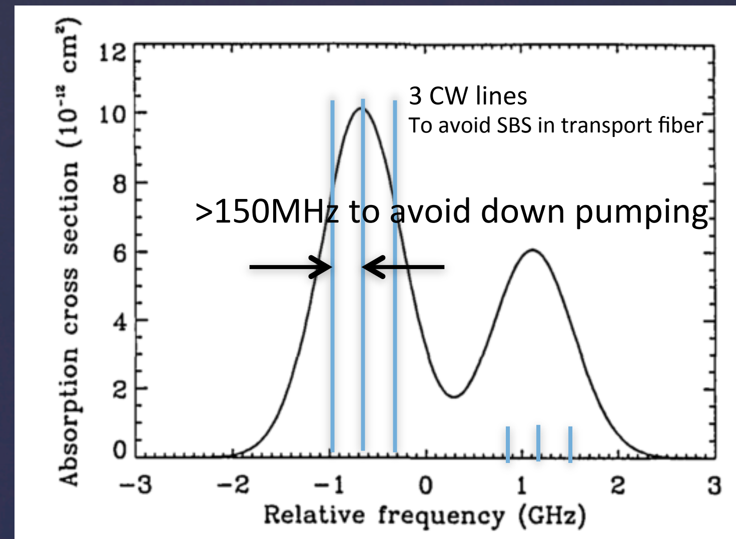


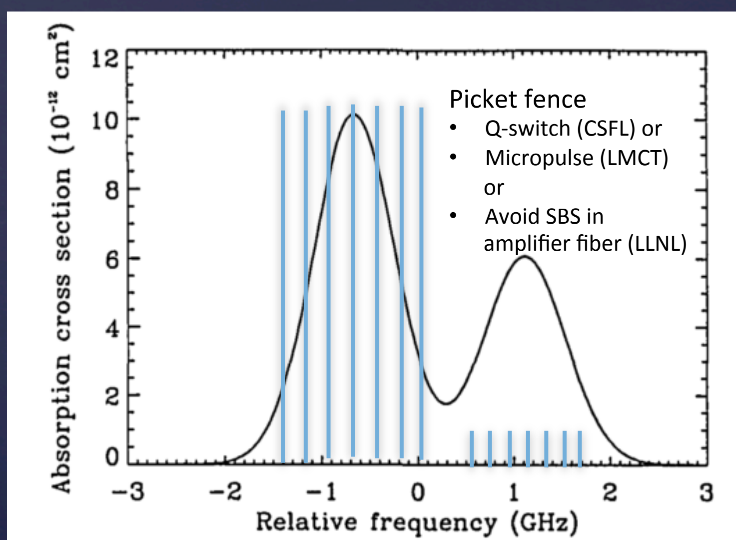


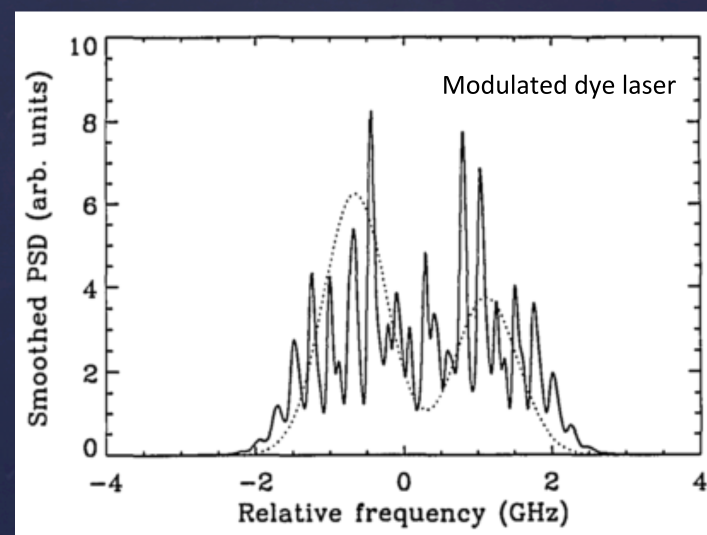


Spectral Formats are driven by AO system considerations and laser technology

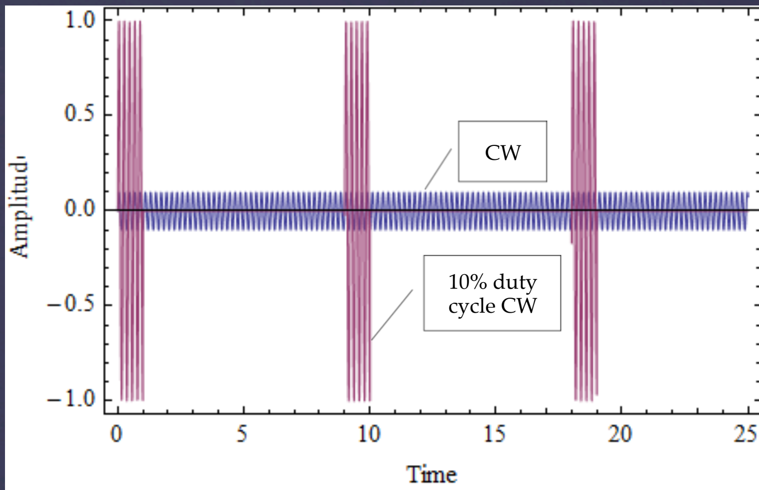






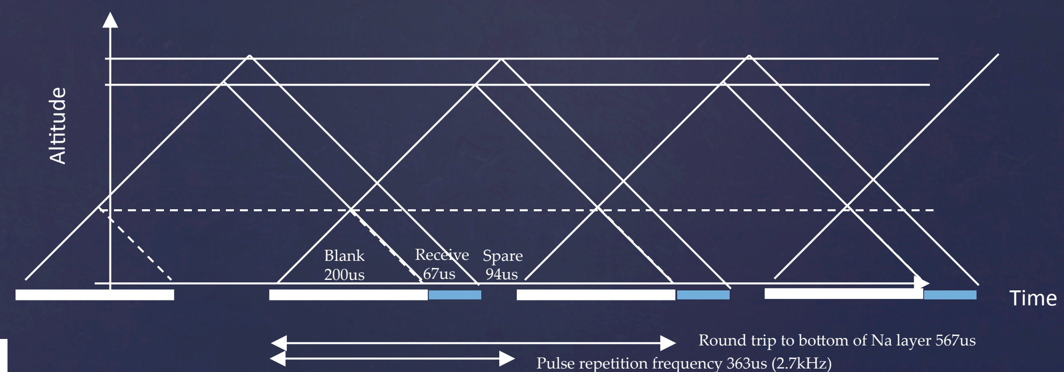


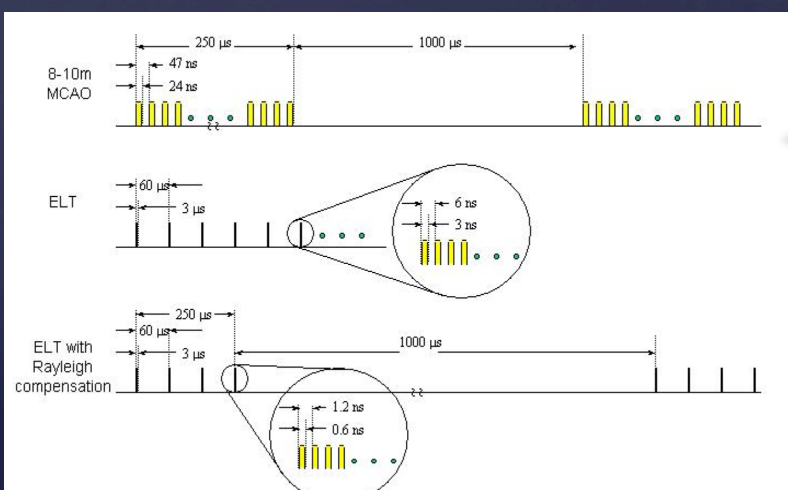
Pulse formats are also driven by AO system considerations and laser technology



Rayleigh-blank

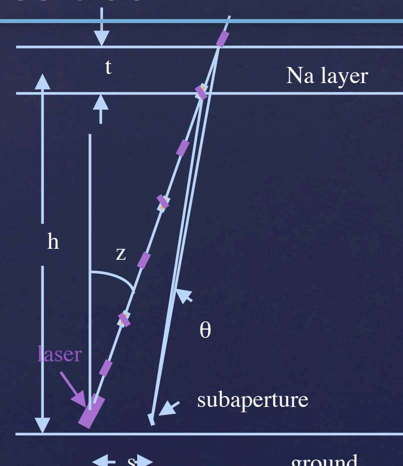
- Receiver is blanked while pulse is <30 km from telescope
  - Important when projecting out the receiver aperture
- Pulse width can be $0 < t_p < 60$us due to spare time in the cycle
  - $t_p < 3$us pulse for pulse tracking, but duty cycle is < 1%
  - Slight variation to this solution for $t_p = 30$us, 10% duty cycle (2.9kHz rep)
- All times scale with sec(z), preserving duty cycle





Graphic courtesy Alan Hankla, Lockheed Martin Coherent Technology

Pulse-track

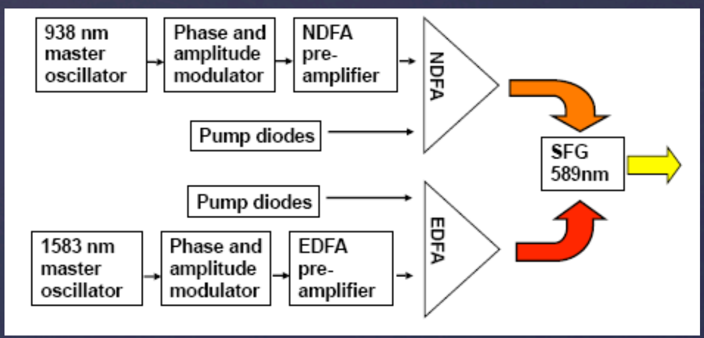


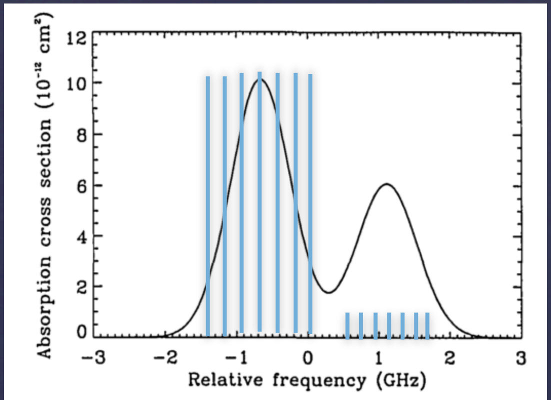
$\sigma_{\text{wavefront measurement}} \propto (\text{spot size}) \times \frac{1}{\sqrt{\ }}$

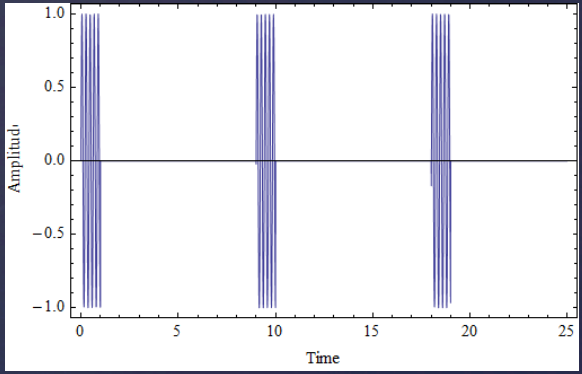
ShaneAO Guide Star Laser

UC Observatories Laboratory for Adaptive Optics ShaneAO

- 7-9 spectral lines, 10-20% duty cycle
- Variable pulse repetition frequency, goal is Rayleigh blank format







	Current dye laser	New fiber laser	
		Lab tested format	*"Goal" format*
Output power	9 W	10 W	10 W
Polarization	Linear	Circular	Circular
Spectral format	~2 GHz FWHM bandwidth	9 lines with 200 MHz spacing	Fewer lines and/or smaller spacing
Pulse duration	150 ns	200 ns	30 µs
Duty cycle	0.16 %	10 %	20 %
Fraction of light tuned to D2b	None	None	10%

- Also: goal is to transport to launch telescope via fiber

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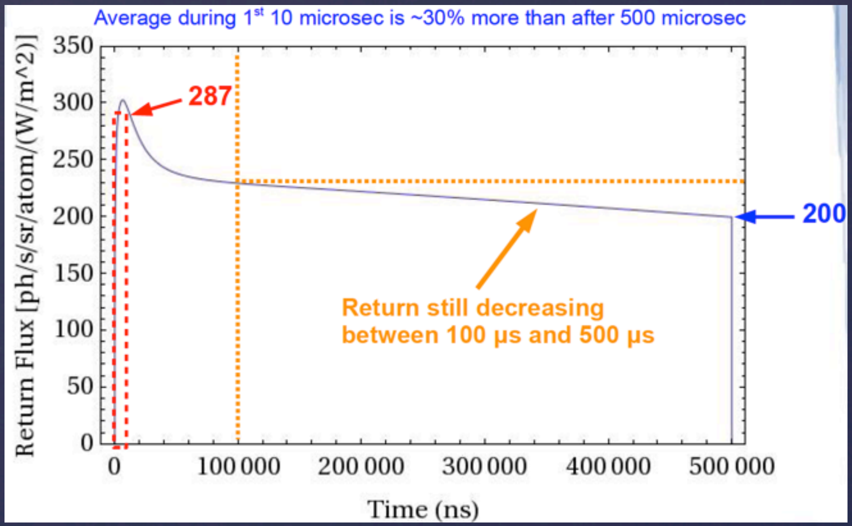
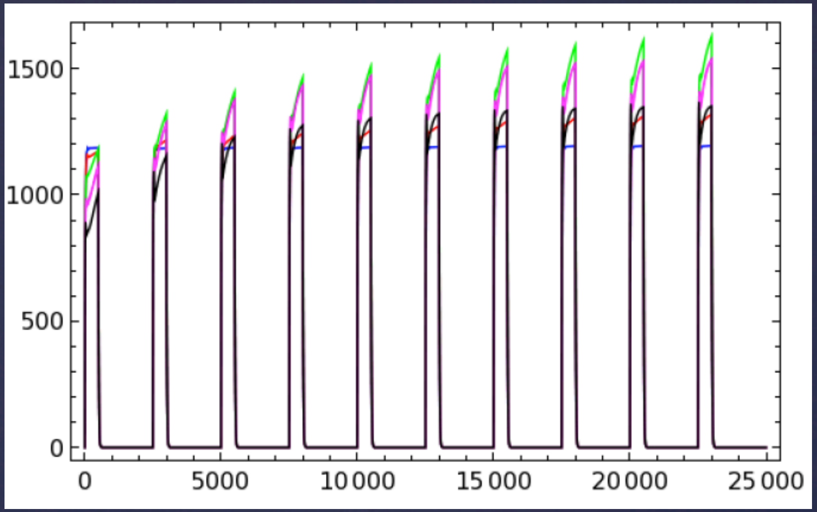
Modeling of laser pulse format interaction with sodium atom

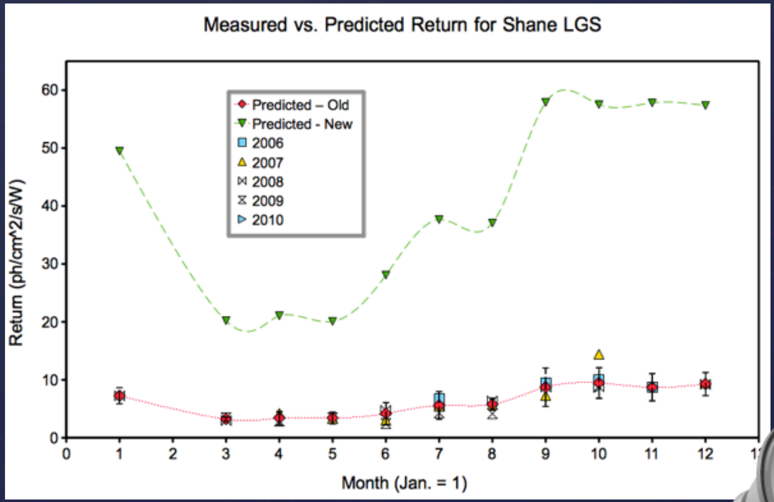
Rampy, 2012



Some advantage to pulses < 100 μs



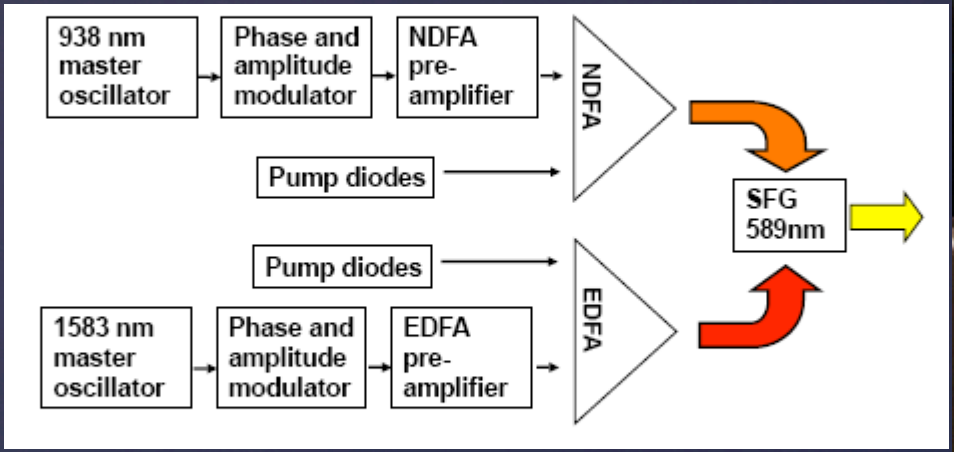
Pulse format of fiber laser (400 ns, 500 kHz, 20% duty cycle) shows inter-pulse optical pumping

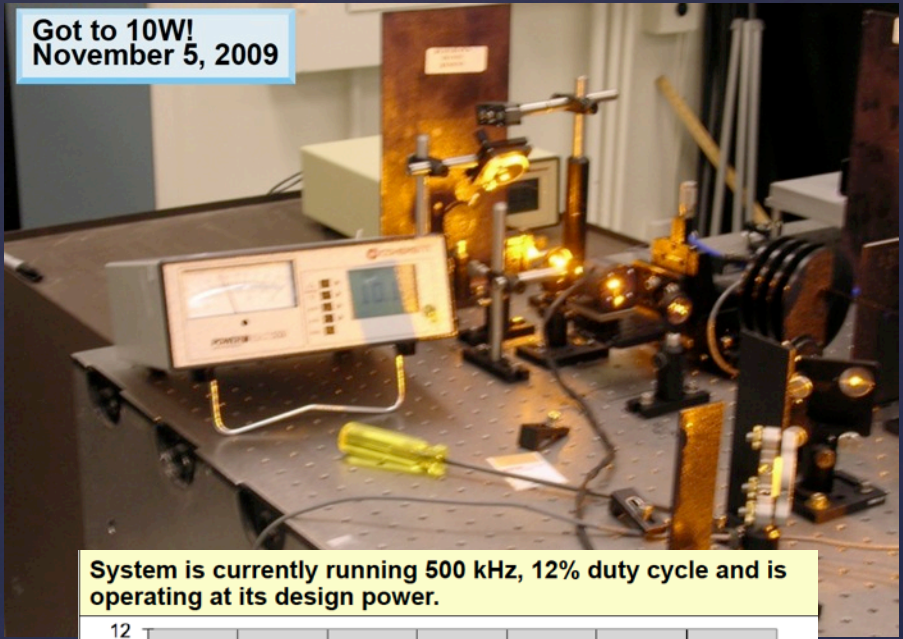


Predicted return of new laser: 5 – 10 x the [illegible] the current dye laser at Lick

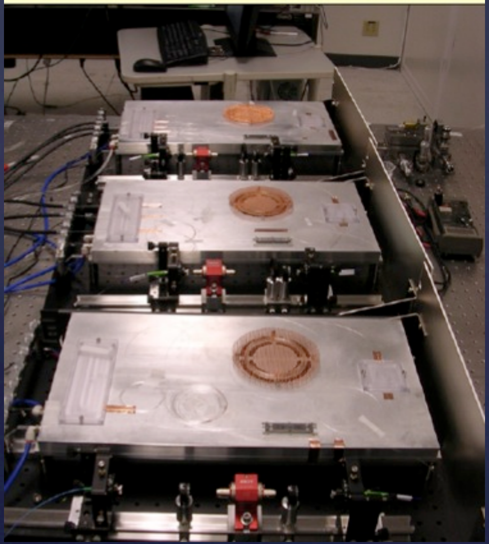
Guide Star Laser

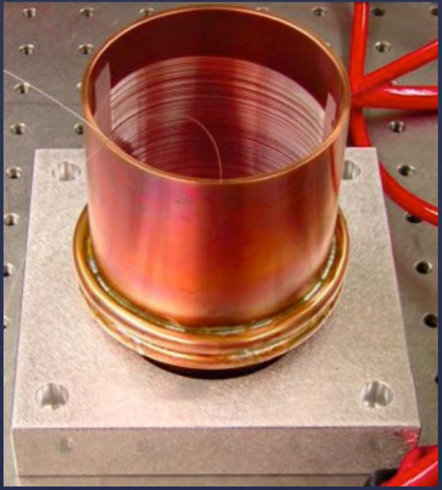
- Gets to the sodium 589nm line by mixing two IR lines



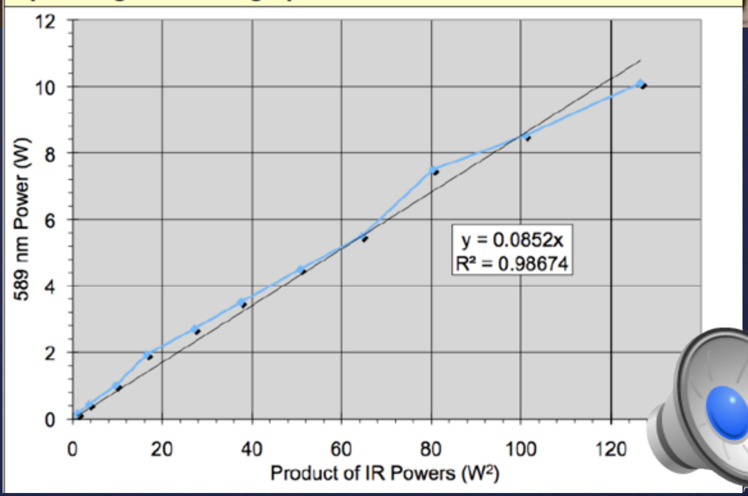


Nd^{3+} PM fiber amplifier chain





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



Jay Dawson, LLNL

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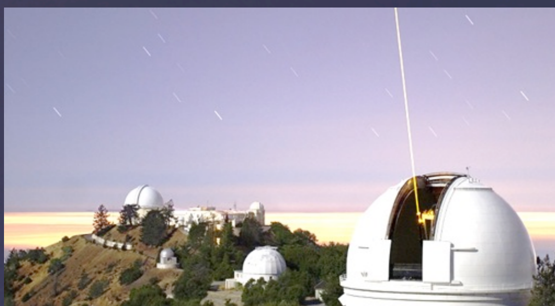
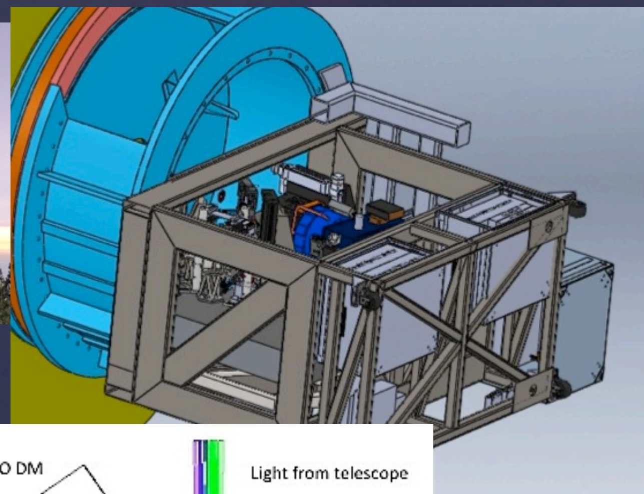
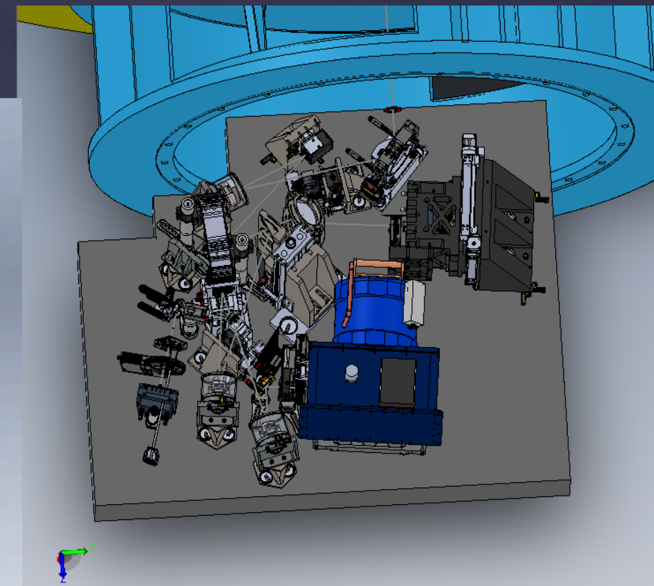
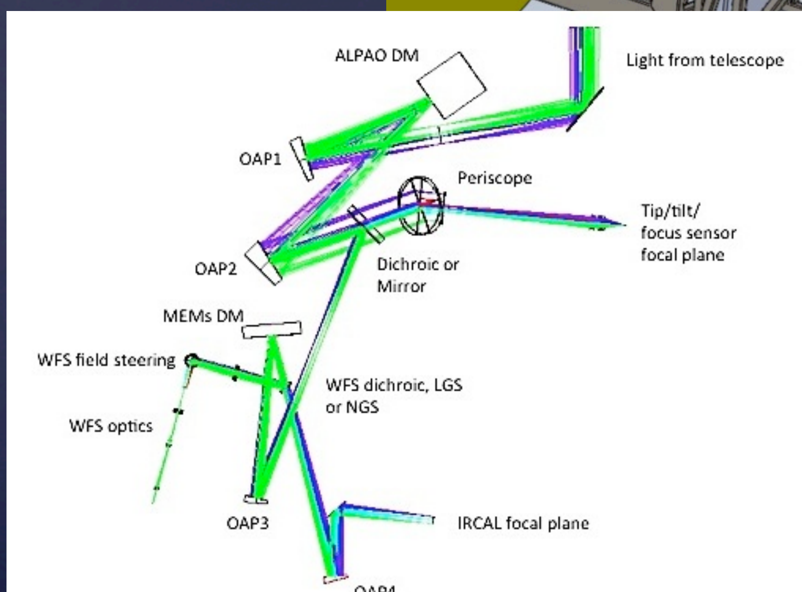
ShaneAO: New adaptive optics system for the Shane 3-meter telescope

UC Observatories
Laboratory for Adaptive Optics
ShaneAO



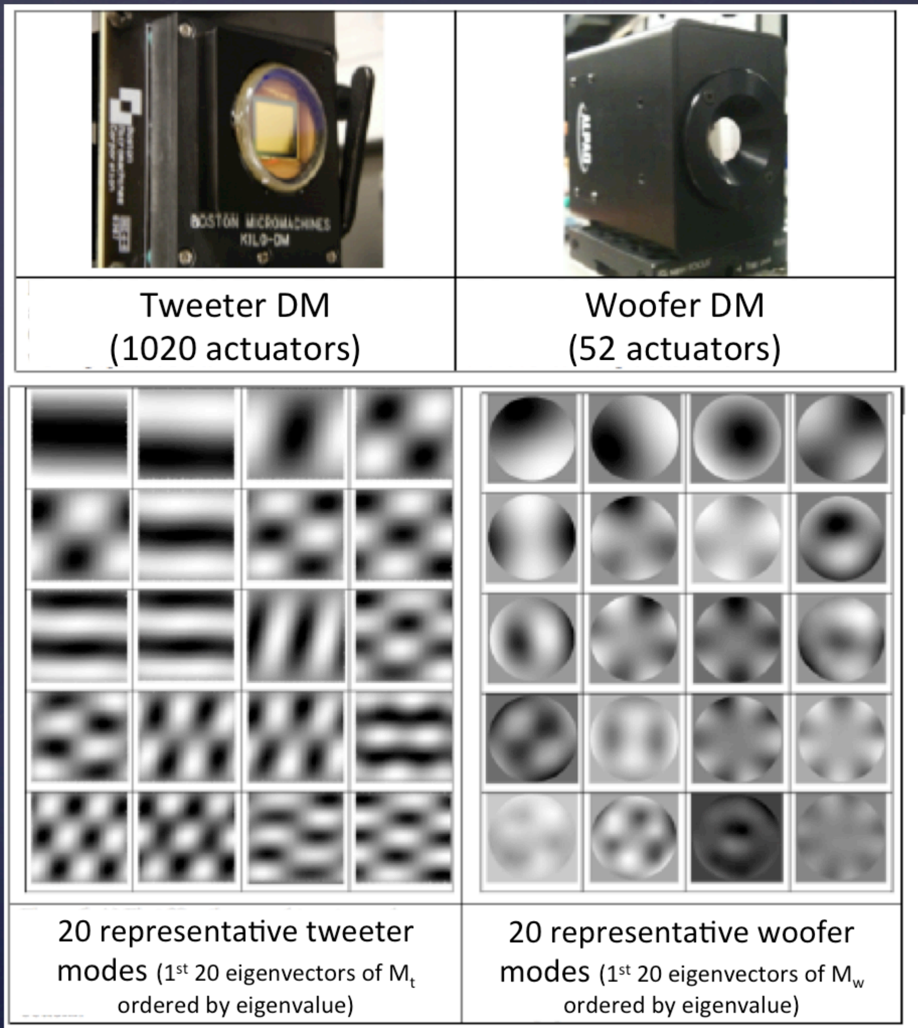


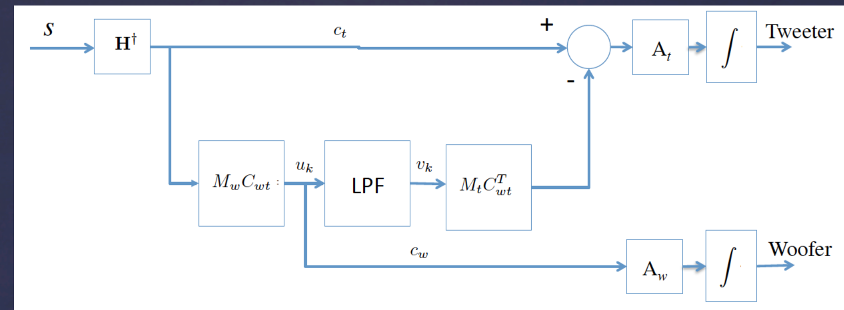


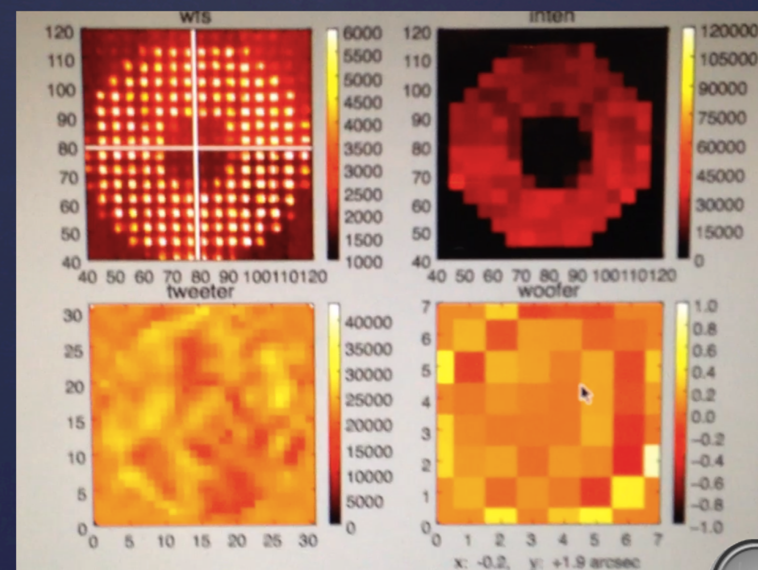


Old System	ShaneAO
High Strehl in K band J and H accessible	High Strehl in J, H, and K bands I band accessible
Diffraction-limited imaging in K 19 arcsec FOV 76 mas/pix	Diffraction-limited in J, H, and K 20 arcsec FOV 33 mas/pix more sensitive science detector
Limited to short exposures	4-hour exposures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

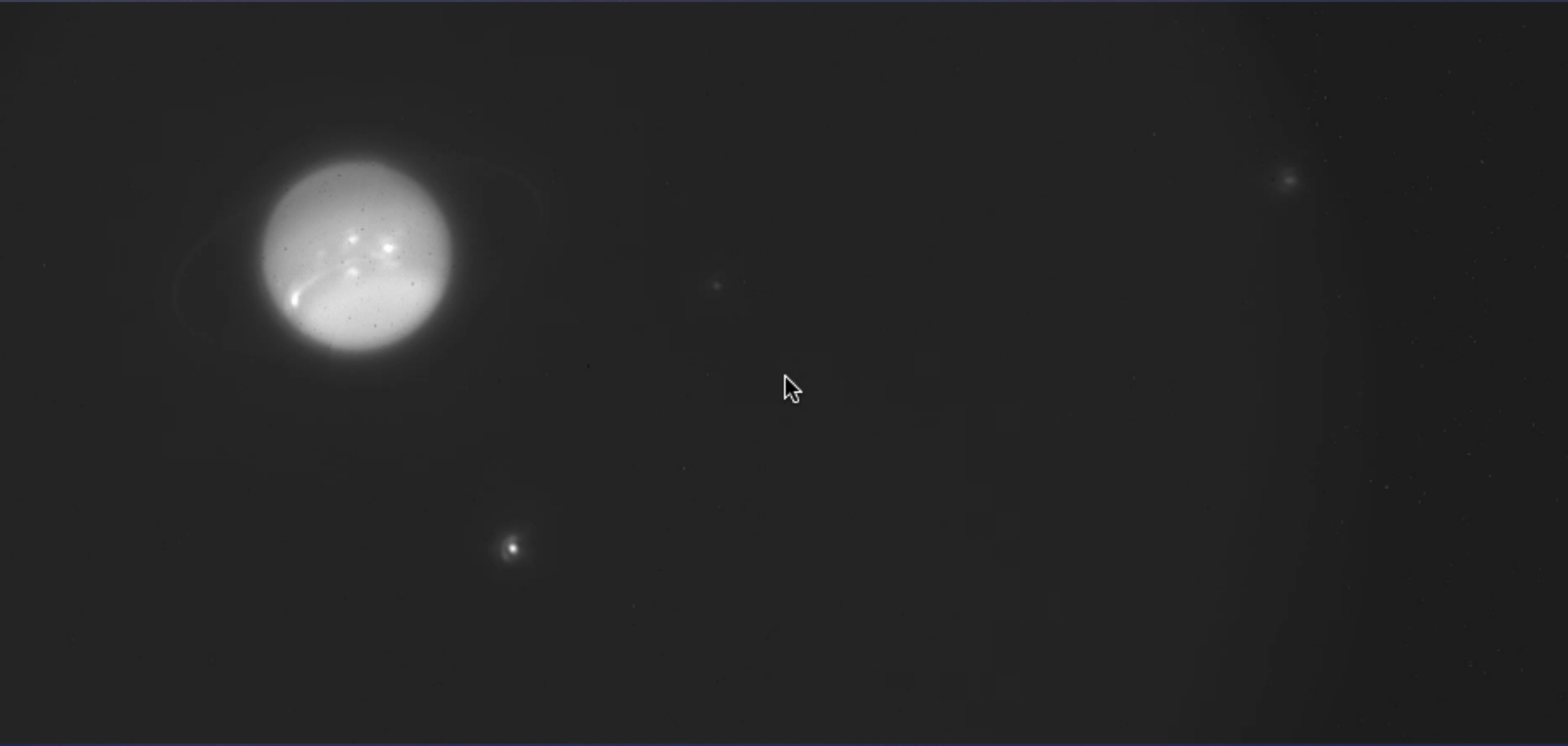
Woofer-tweeter control







Uranus, Rings, Moons



Click on the image - it's a movie

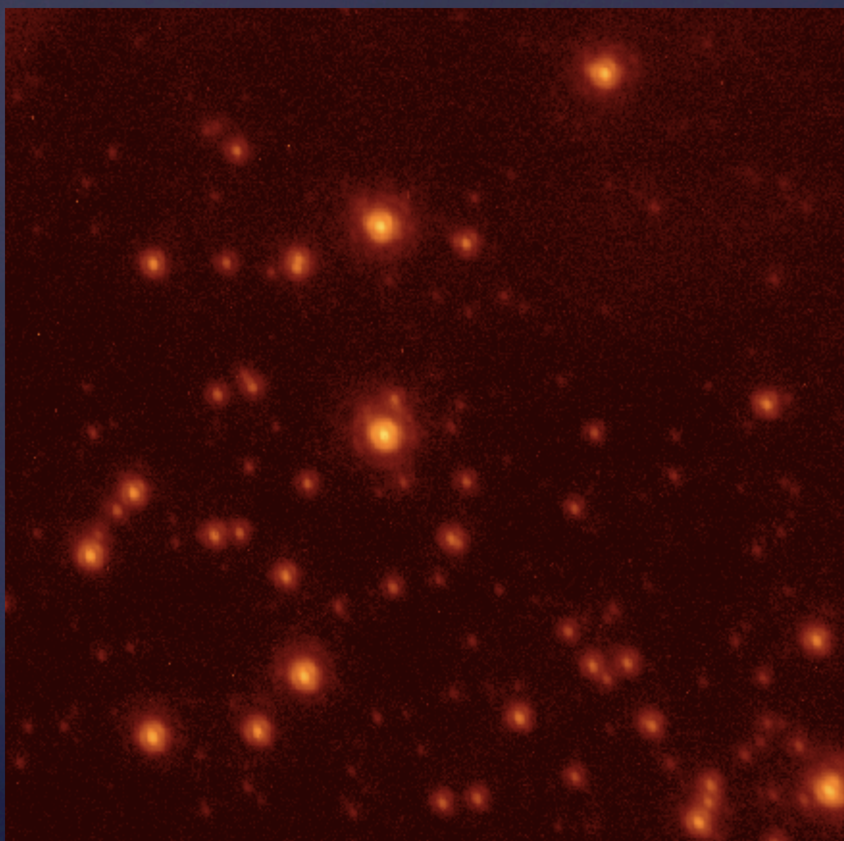
Note the motion: rotating planet and orbiting moons

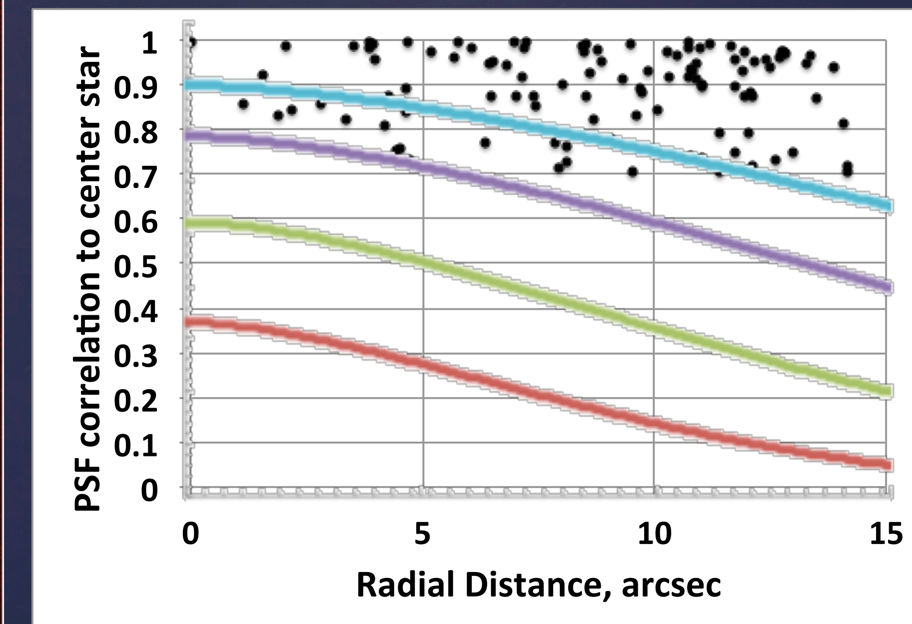
3 rings are resolved

Diffraction-limit (note the Airy rings) everywhere in this 28 arcsec field
Hundreds of stars

Also, Isoplanatic angle

may be much larger than expected





This implies we can have AO correction on a wider field

Mt Hamilton Seeing

- Mt Hamilton seeing is anecdotally 1.25 to 1.5 arcseconds FWHM of star in mid visible (V-band)
- Years of data collection (from telescope guider cameras) seem to support this

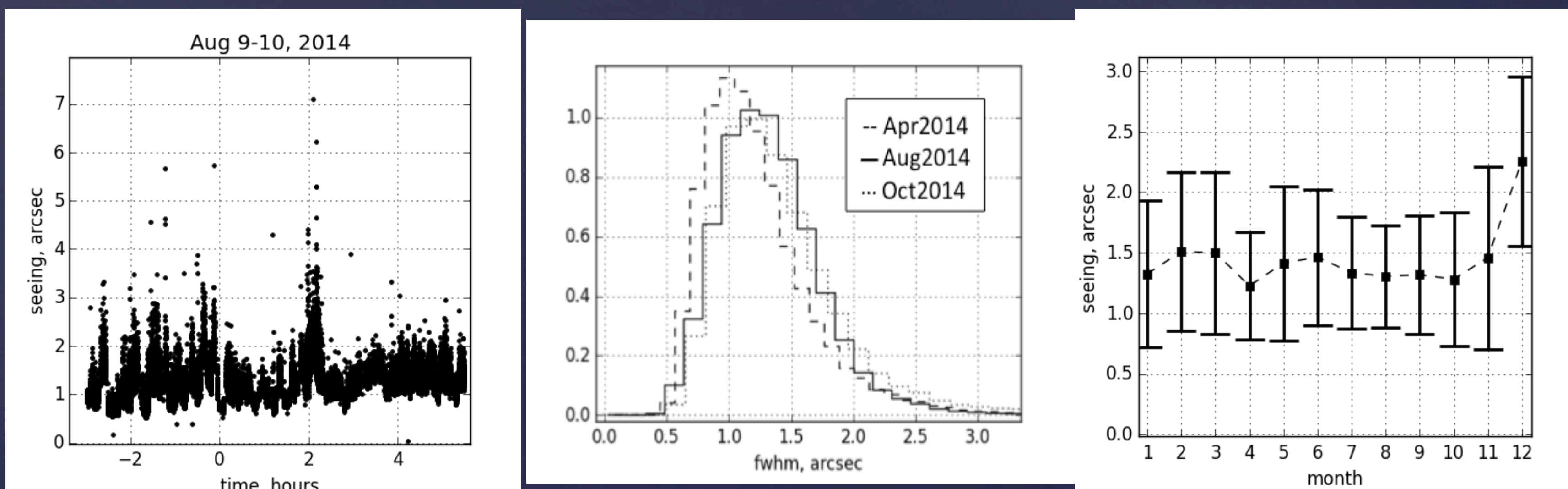
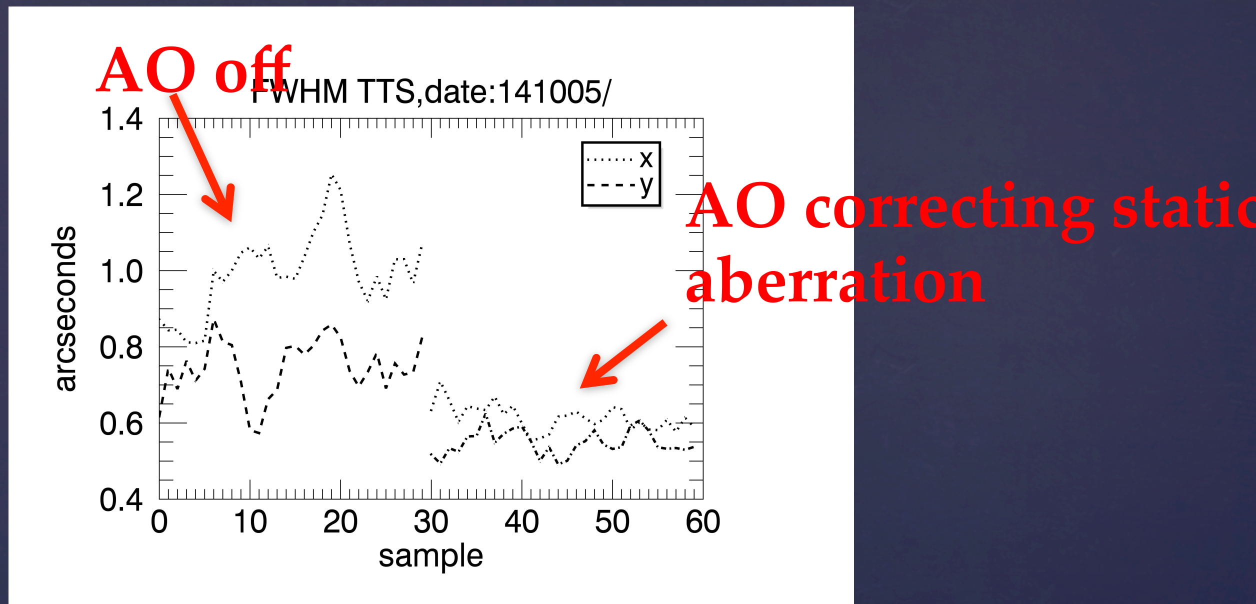


Figure 1 Seeing data from the APF guider. Left, time series from one night's observing with data taken every few seconds. Histogram of seeing for several months. Right average seeing on a monthly basis over the past year.

ShaneAO can measure “free-seeing”
independent of telescope and dome



- There is evidence that free seeing of the Mt. Hamilton site is ***much better*** than 1.25 arcsec, more like 0.7 arcsec
- We will be collecting seeing data every AO night
- Submitted a proposal to construct a seeing monitor – this will complement observing programs (e.g. PSF estimator)
- Future AO development at Lick may be impacted by results
- Future Mt Ham site use may be impacted by results

Conclusions

- Laser guide stars will bring AO-fed instrumentation into high-use at large telescopes
- 2nd generation technology enables unprecedented science discoveries
- Even slow AO (“ao” – “active” optics), can improve science productivity of all instruments - ASM

Acknowledgements

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  - The National Science Foundation Science and Technology Center for Adaptive Optics managed by the University of California at Santa Cruz under cooperative agreement No. AST-9876783
  - The National Science Foundation Major Research Instrumentation program
  - The Gordon and Betty Moore Foundation.