GLAO, Palomar, and relationship to MK

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Caltech GLAO Workshop
September 14-15, 2014

Outline of GLAO topics

- Wide-field AO architectures
- Relevance to Palomar
  - Single-Laser GLAO (w/ and w/o TT guiding)
  - Hybrid LGS-NGS AO
    - Palomar Ultraviolet Laser for the Study of Exoplanets (PULSE)
  - Concept for 10’ GLAO at P200 prime focus
- Relevance to Mauna Kea
- Potential areas of collaboration

Wide Field Adaptive Optics

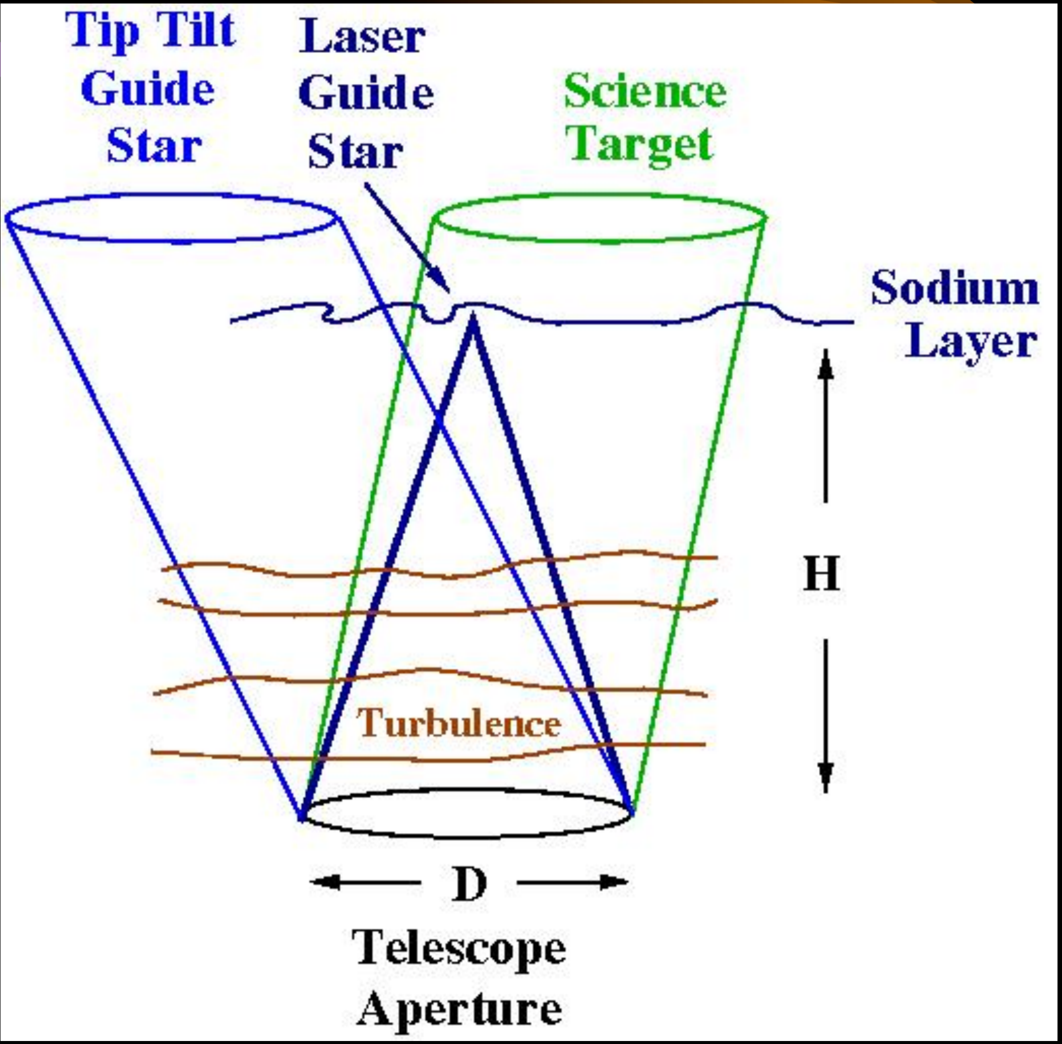
(w/ thanks to M. Britton)

A Preliminary Comment

Field dependence of the AO system performance is a function of:

- Aperture diameter
- Observing wavelength
- Guide star configuration
- How the adaptive mirrors are deployed
- Zenith angle
- Turbulence conditions (-> time)

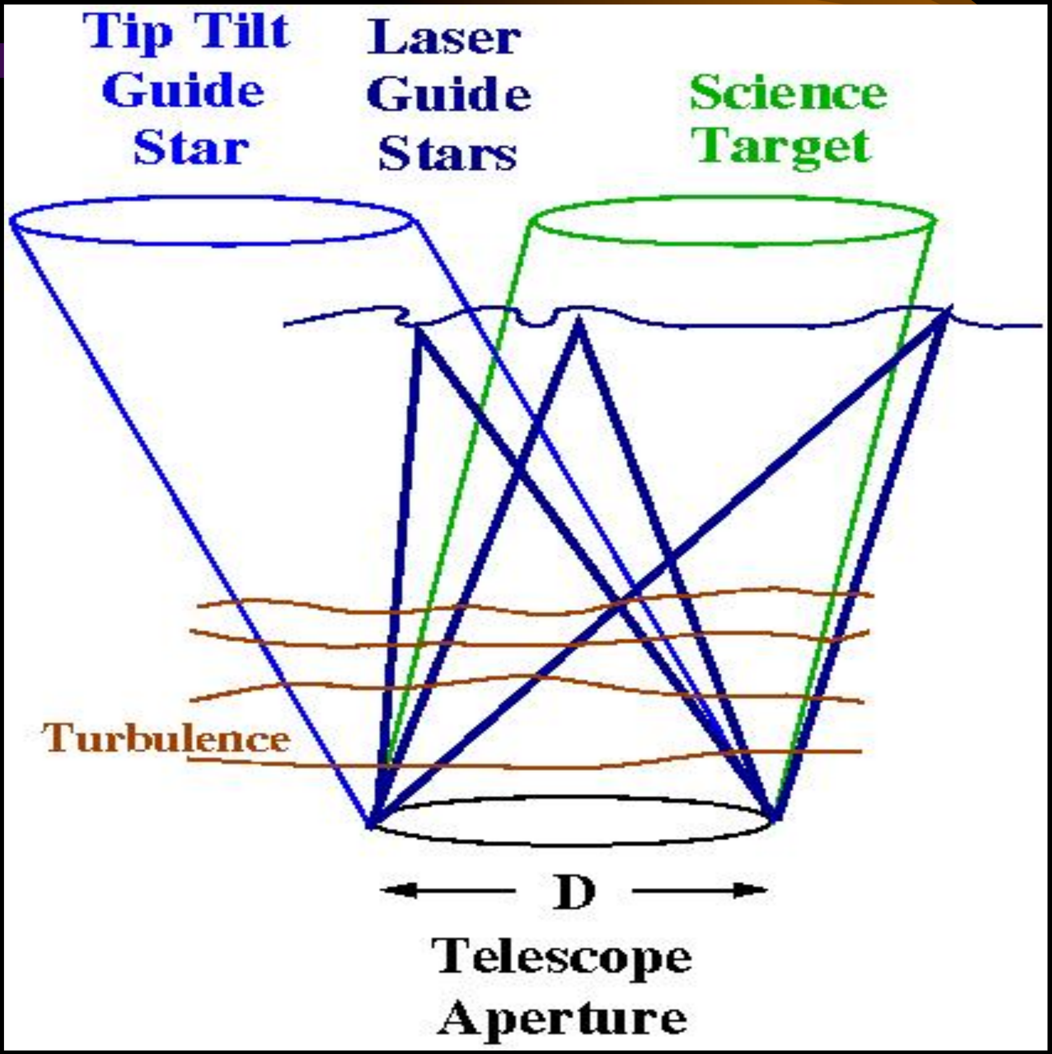
Single Laser AO (SLGLAO)



Poor to moderate performance over a modest field

FOV = 70” (D / 30 m)(90 km / h)

Ground Layer AO (GLAO)

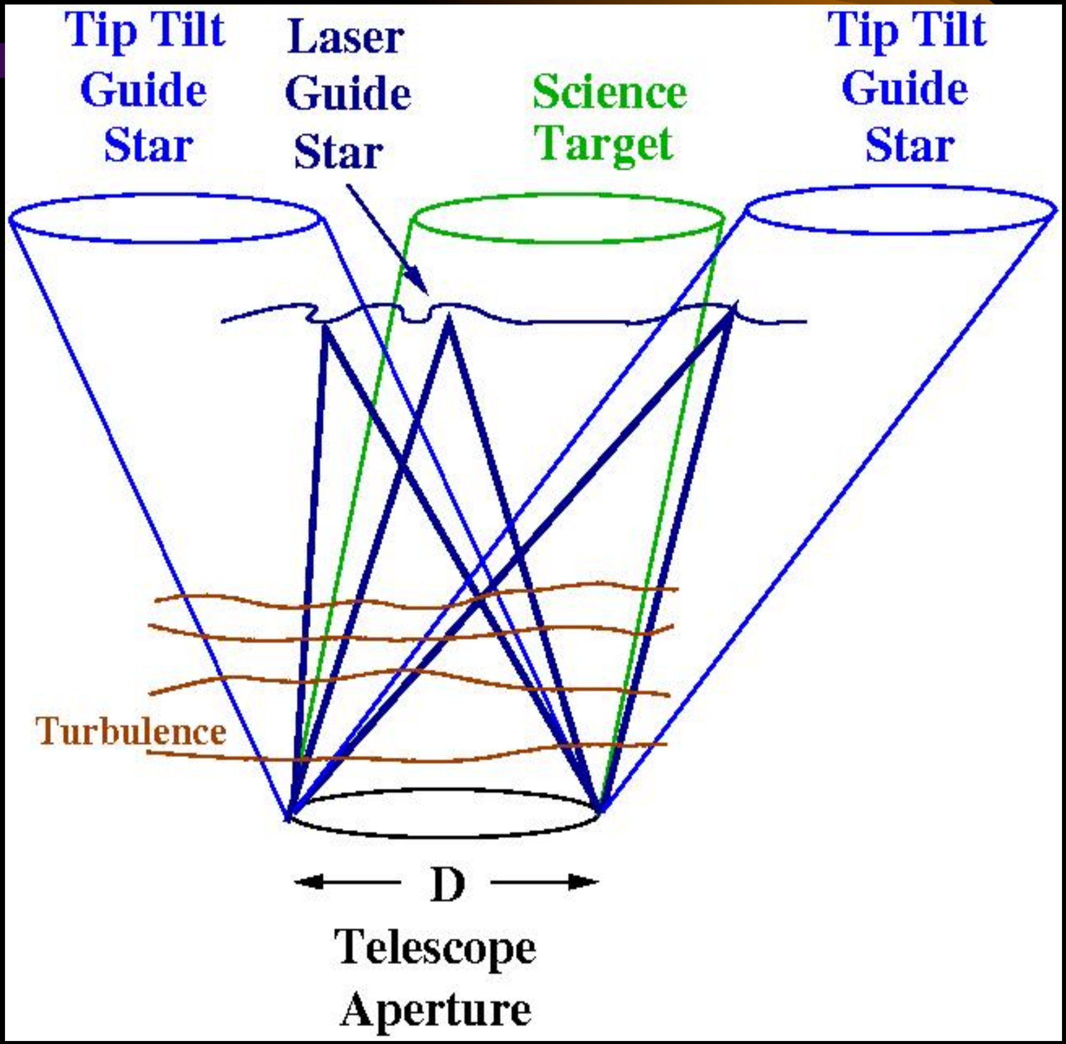


Poorer WFE performance

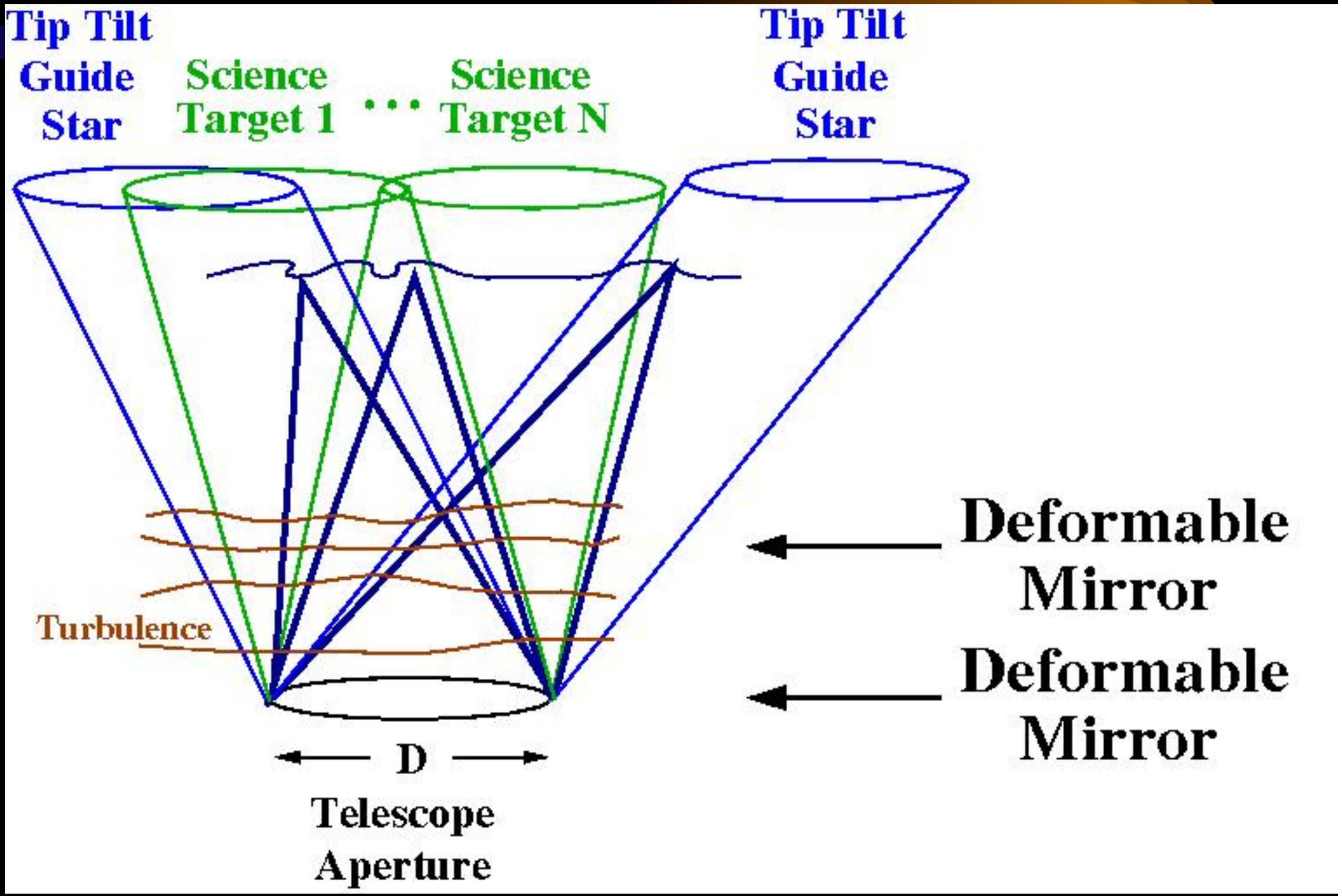
Improved uniformity

Laser Tomography AO (LTAO)

Excellent performance on axis



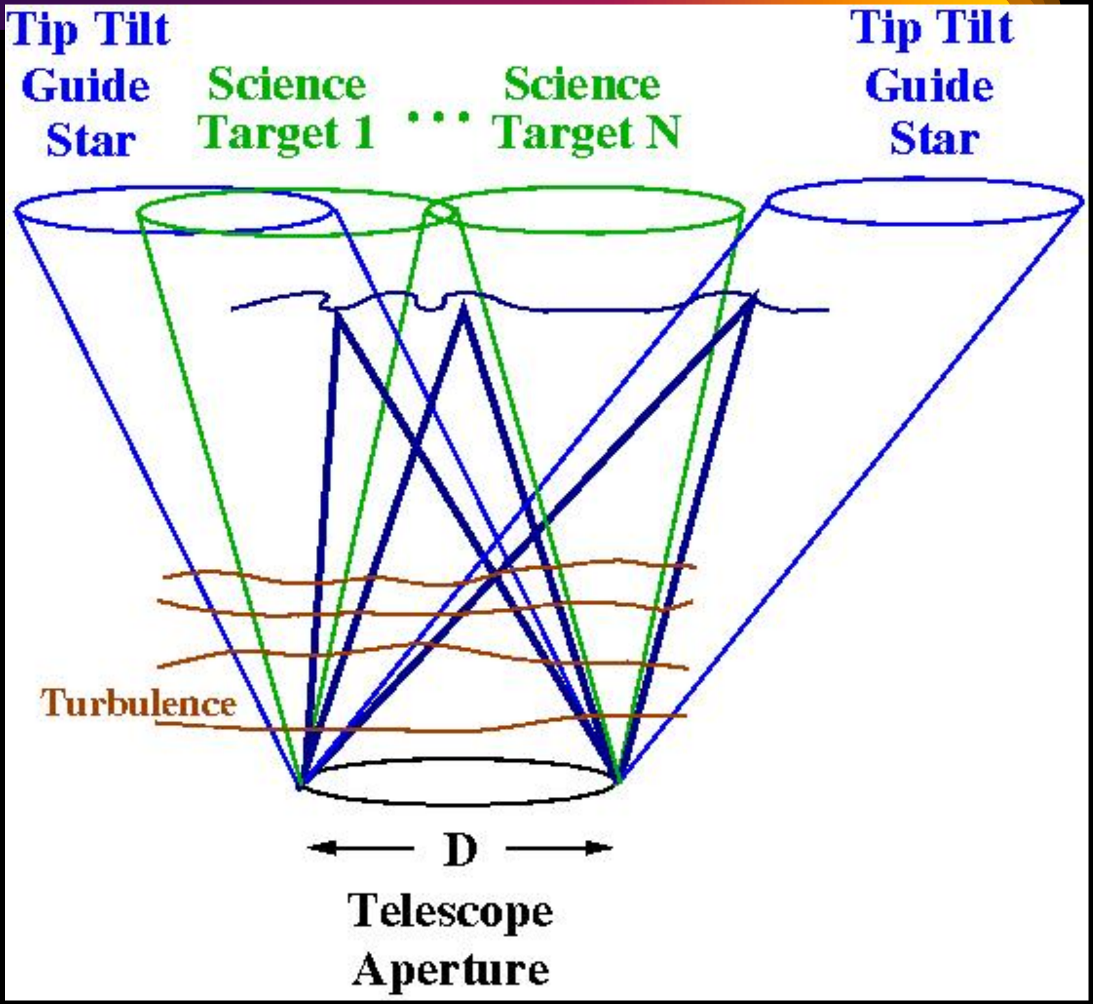
Multiconjugate AO (MCAO)



Good performance over 30” field

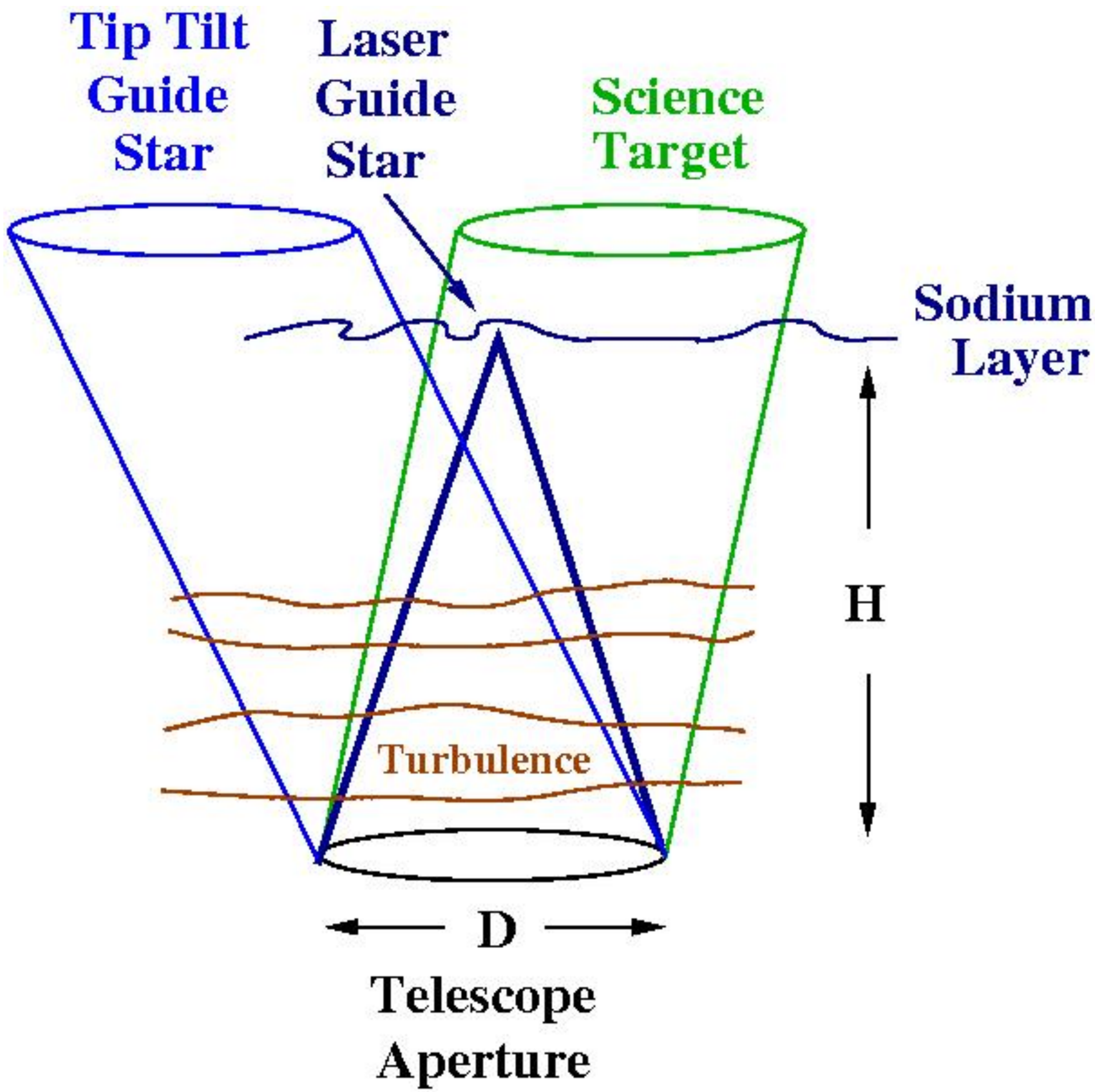
Multiobject AO (MOAO)

Intermediate performance over 5’ - 10’ field

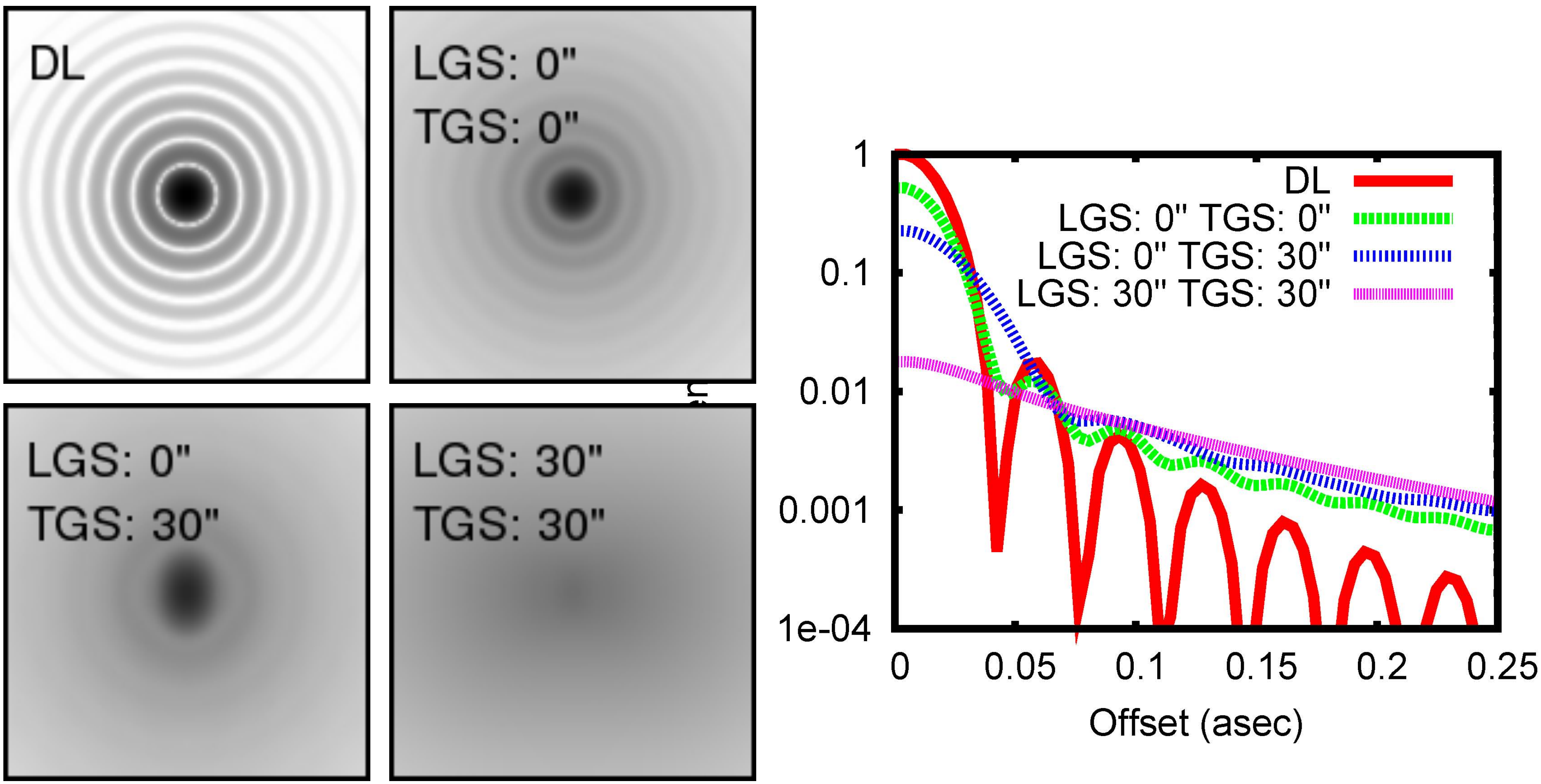


Single-laser GLAO

- Natural geometry of single LGS favors sampling of the ground-layer
  - Increasingly so for larger telescope aperture and lower beacon height


Tip Tilt
Guide
Star
Laser
Guide
Star
Science
Target
Sodium
Layer
H
Turbulence
D
Telescope
Aperture

LGS PSFs on a 10 m Aperture



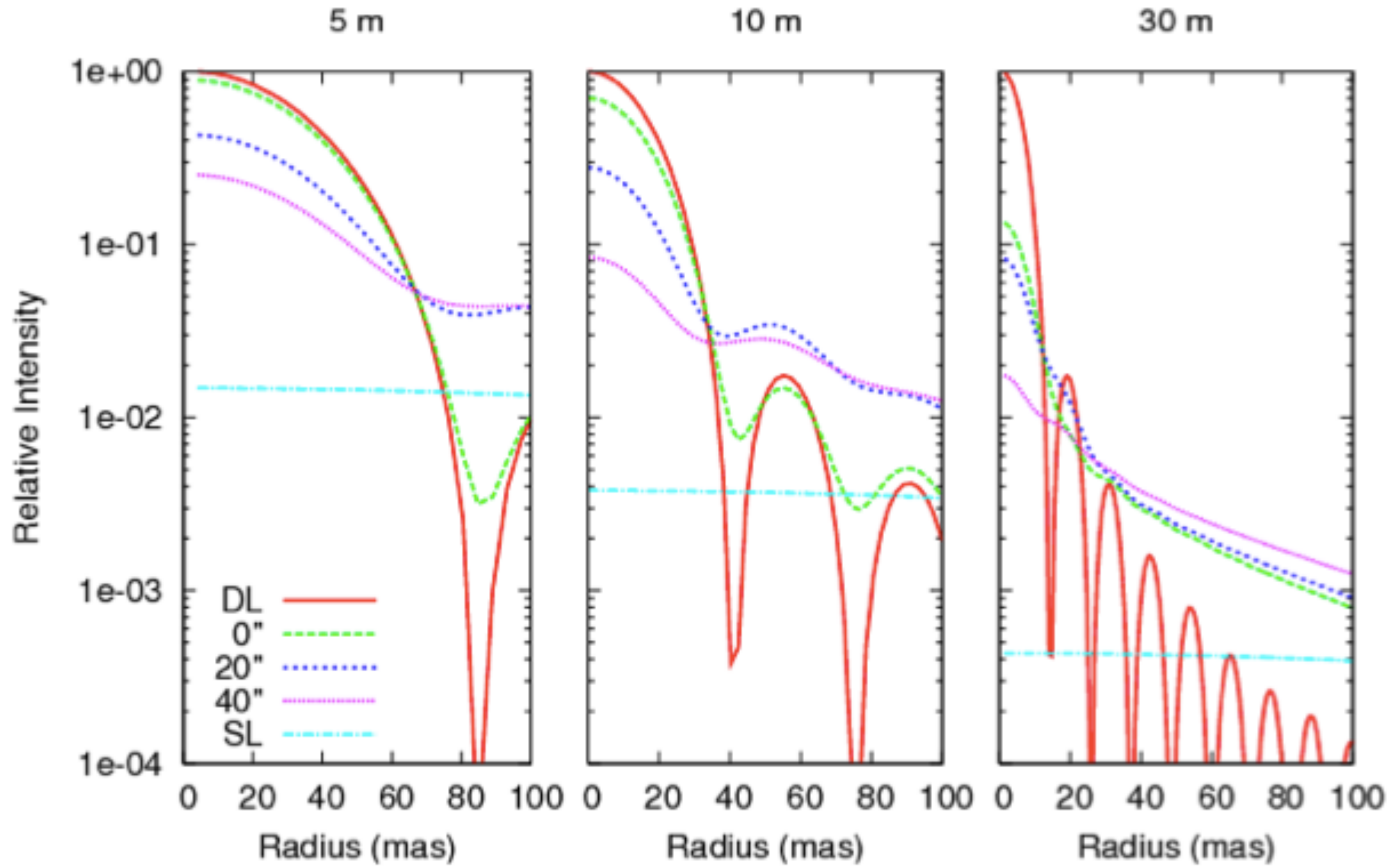


Figure 2. Radial cuts through the PSF for diffraction limited, seeing limited and SLGLAO architectures on 5 to 30 meter apertures. SLGLAO results are shown for angular offsets of 0", 20", and 40" from the laser beacon. A guide star altitude of 90 km has been used in the computation of the SLGLAO PSFs, and a typical astronomical turbulence profile was used. These results assume perfect tip tilt compensation.

Tip/tilt NGS with GLAO system?

- The contribution to delivered image quality (DIQ) from tip/tilt decreases as aperture increased (Hardy, 1998).
  - 10m aperture has less TT error than 8m at same site

- For DIQ in the 0.3” FWHM range, running w/o TT NGS may be viable observing mode
  - Robo-AO on Palomar 1.5m telescope has run this way for 3 years

PULSE

Extending high-contrast/visible-light adaptive optics to faint targets

PULSE will augment the 5.1-m Hale Telescope PALM-3000 exoplanet adaptive optics system (with the world's largest deformable mirror) with an ultraviolet Rayleigh laser guide star to enable science using much fainter, and more numerous, guide stars.

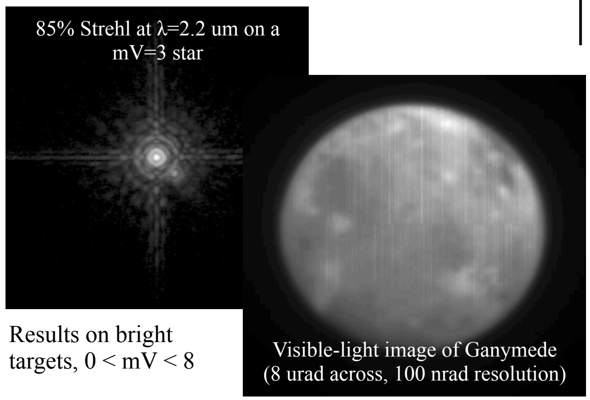
Benefits:
High infrared contrast ratios and excellent visible-light adaptive optics performance will be achieved with the PULSE upgrade on stars as faint as mV=15.

Science Enabled:
This will enable direct imaging searches for, and subsequent characterization of, companions around cool, low-mass stars for the first time, as well as routine visible-light imaging twice as sharp as HST for fainter targets.

Technology Heritage:

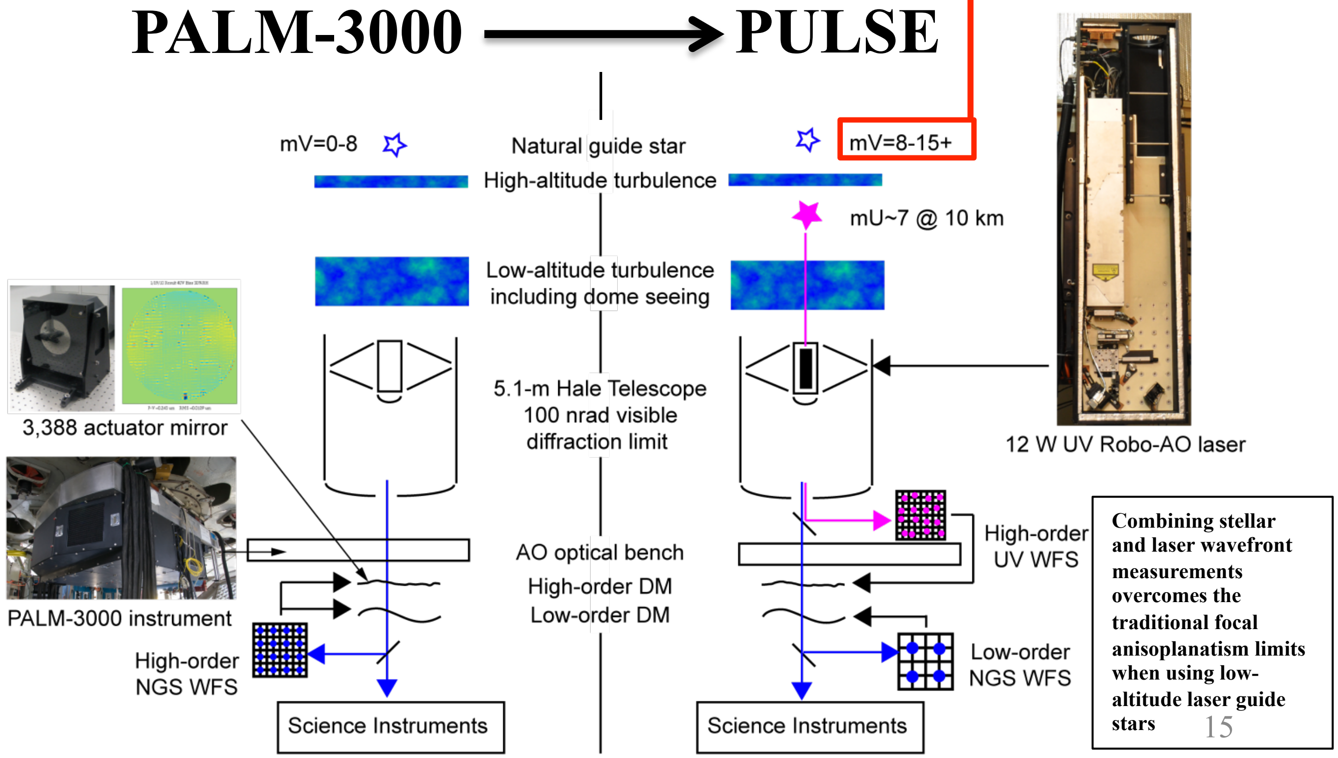
200" Telescope with PALM-3000 AO
- World's largest deformable mirror (3,388 active actuators)
- Visible-light capability on bright stars

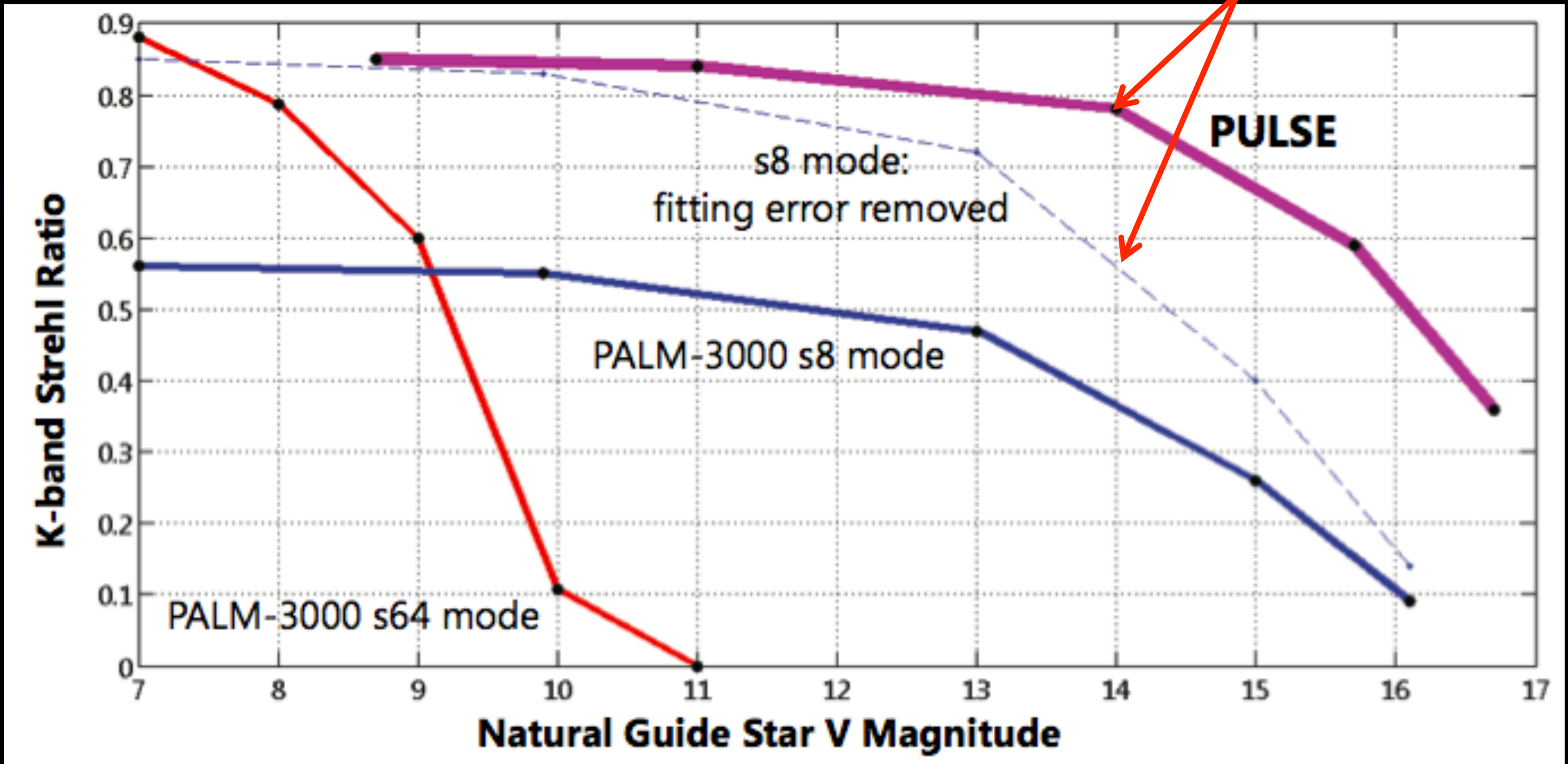
60" Telescope with Robo-AO
- Compact Rayleigh UV laser
- UV wavefront sensor
- Automated operation



Results on bright targets, 0 < mV < 8

First images of exoplanets in habitable zones around M-dwarf stars
(Visible-light correction using guide object brightness of 8 < mV < 15)





- Rayleigh LGS provides high-order wavefront corrector for HODM (s64 mode), eliminating ~230 nm fitting error (RMS), albeit w/some residual focal anisoplanatism error (as shown in simulations)
- Rayleigh LGS provides significant sharpening of NGS within a low-order WFS subaperture
  - Our model here is FWHM = 0.4” in an s8 SHWFS
  - Coherent NGS sensors may do even better (~1 mag fainter)

Conclusions: PULSE can provide 80% K-Strehl for V = 14-15
PULSE can provide 50% K-Strehl for V = 16-17

PULSE Heritage

- Successful Robo-AO RGS system operating autonomously on the Palomar 1.5 meter telescope
  - FAA approved as harmless to pilots
  - Automated STRATCOM predicts generated nightly
  - *Proven low / no impact to Observatory operations*
- Low-order NGS wavefront sensing already in PALM-3000 (currently 8 x 8 subap SH)

A (GLAO) NIR imager for 3-5 meter telescopes

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Palomar GLAO overview

- A 4k x 4k H2RG camera for P200?
  - Benefits and concerns
- Wide-field GLAO over 5-10' FoV enables science unique in the era of large synoptic surveys
  - Enables narrower, deeper high-angular resolution imaging
  - Example science cases emphasizing 100 μas astrometry
- Mid-sized telescopes are well suited for wide-FoV GLAO
  - Can reach DL over wider FoV than for larger telescopes
- One implementation concept
  - 10' FoV NIR GLAO Imager for P200 prime focus
  - Increment implementation of up to 12 Teledyne H2-RG detectors

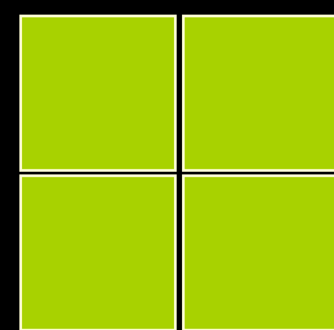
A 4k x 4k infrared array for P200

- Could replace WIRC (Cornell U., circa 2003)
  - A 8.7' x 8.7' Hawaii II HgCdTe
  - J ~ 22, Ks ~ 20.6 (SNR = 5, 3600 s, 1" seeing)
  - New system up to 17' x 17' FoV at the seeing limit

- Compliment to NEWFIRM
  - NEWFIRM could e.g. remain in Southern Hemisphere w/ community P200 access for Northern observations

3-5m GLAO seeing-limited imager focal plane

- 2 x 2 mosaic covering ~17' x 17'
  - ~0.25" / pixel
  - ~0.7" FWHM NIR PSF
- 4x successor to WIRC
- Existing PF Wynne corrector not designed for achromatic NIR operations



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- Compliment to NEWFIRM
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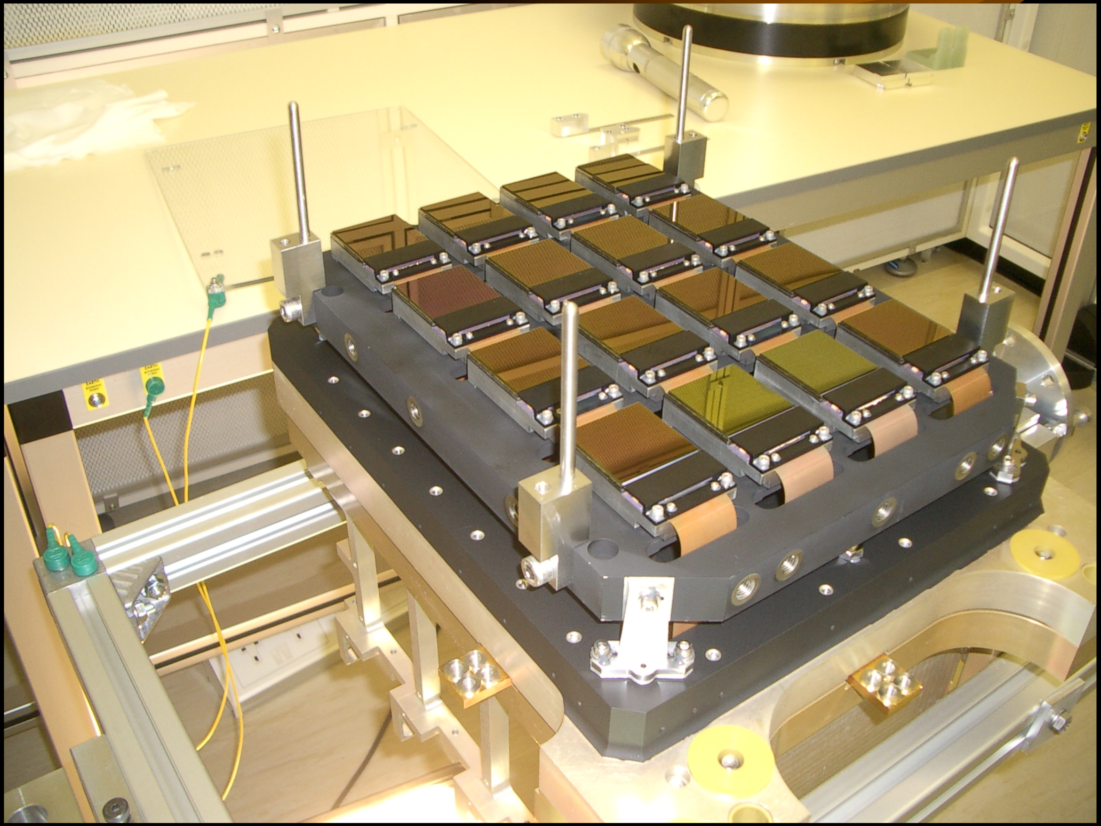
- However, wide-field *seeing-limited* NIR imaging to be dominated by VISTA
  - 0.6 sq. deg. with 0.55" FWHM on 4m telescope
  - Dedicated full time survey cannot be completed against on a general use facility

VISTA focal plane

4 x 4 sparse mosaic of
Raytheon VIRGO
2k x 2k HgCdTe
0.84 - 2.5 micron



GLAO aims to correct a ground-layer atmospheric slab common to a wide FoV

- AO correction applied to DM conjugated near the ground-layer improves image quality over wide FoV
  - Details depend on vertical turbulence profile
    - Potential time-variable performance
    - In classic form, IQ at the mercy of upper-altitude turbulence
- GLAO improves NIR sensitivity, overcomes crowding, and improves astrometry
  - P200 reaches J ~ 24, Ks ~22.6 (SNR=5, 3600s, 0.15" FWHM)
  - Equivalent to 6x increase in aperture for resolved, background-limited programs

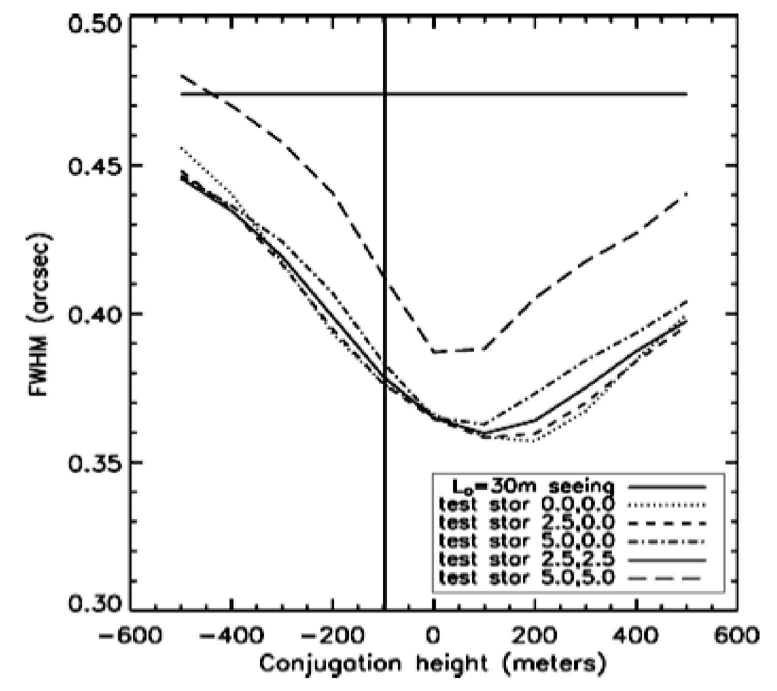


FIG. 18.—FWHM of five field positions plus the seeing-limited case (see the key), as a function of DM conjugation height. FWHMs were measured from the typical : typical profile at a wavelength of 1 μm. Considering the five field positions, the optimal conjugate altitude, depending on the image quality criteria, is around +100 m. The conjugation of the Gemini telescope secondary mirror is indicated by the vertical line at −97 m, which suffers only a 5% degradation in FWHM relative to the optimal FWHM for this case.

Andersen, et al., PASP, **118**, (2006)

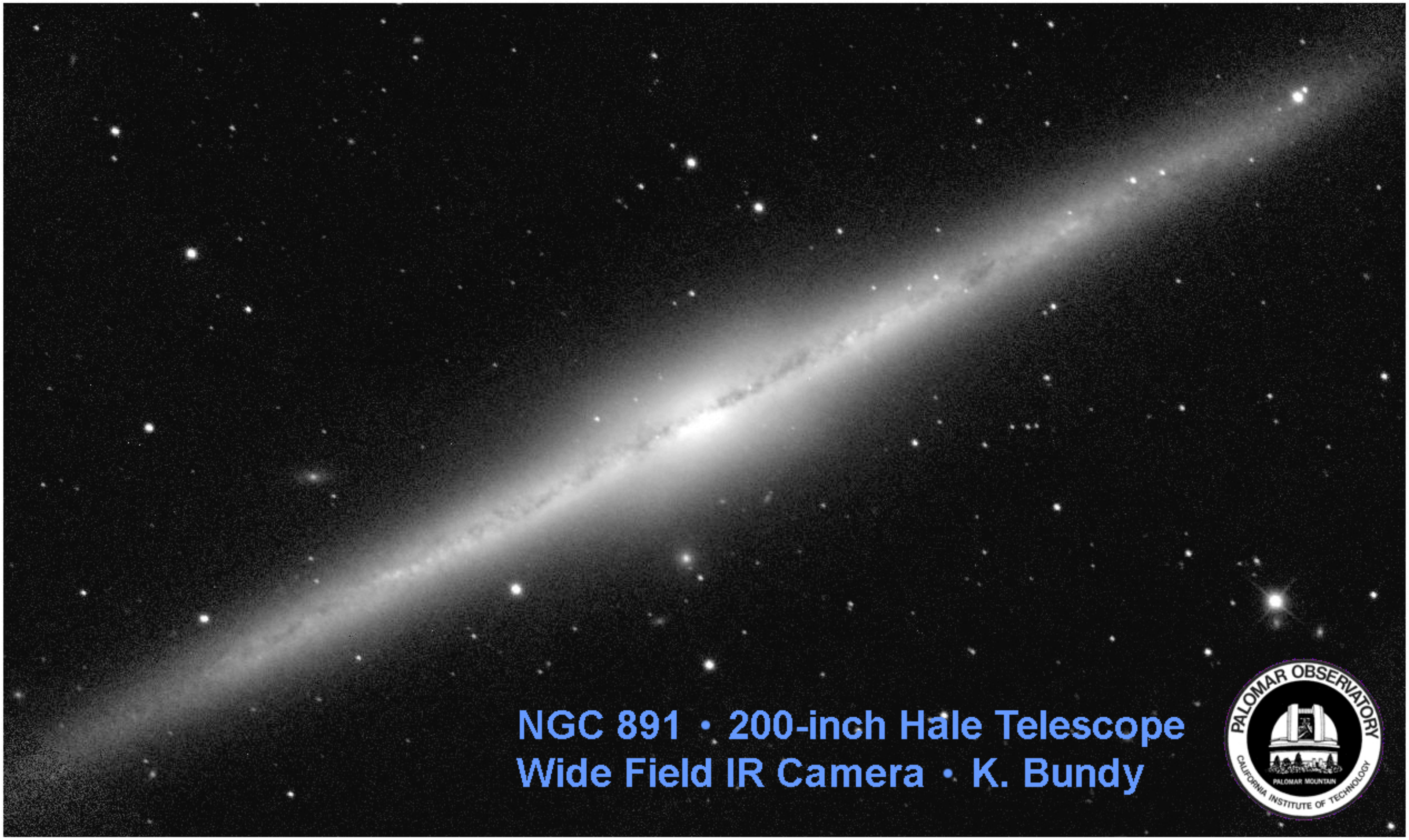
Wide-field GLAO science on mid-sized telescopes

- 5’ FoV Programs
  - Proper motion membership/internal dynamics of young stars/clusters in the Galactic plane
    - Infrared observation at high resolution needed
  - Search for intermediate mass black holes (IMBH) in globular clusters
    - Individual stars *must* be resolved; need > 2’ for advantage over HST/JWST
  - Matter distribution in the inner Galaxy
    - Bulge, inner disk, bar, etc. not well constrained
  - Galaxy formation for z > 2
    - Characteristic formation scale < 0.3”


Globular Cluster M92 • 200-inch Hale Telescope
Wide-field IR Camera • D. Thompson
PALOMAR OBSERVATORY
PALOMAR MOUNTAIN
CALIFORNIA INSTITUTE OF TECHNOLOGY

Wide-field GLAO science on mid-sized telescopes

- 10' FoV Programs
  - Nearby (<500pc) clusters; mosaicing of Orion
  - Distant clusters in outer galaxy
    - Low metallicity compared to other young Galactic clusters
  - Motions of peculiar objects in the Galactic plane
    - Anomalous X-ray pulsars, runaway OB stars
  - Astrometric exoplanet discovery (low-mass stars)
  - Proper motions in nearby galaxies
    - In the IR, you can see isolated AGB stars, whereas in the optical the bright OB or Wolf-Rayet sources tend to be clustered
  - Galaxy cluster strong-lens survey
    - Already mined with 1'-2' with HST - still worth doing?
    - LSST strong lens follow-up?


NGC 891 • 200-inch Hale Telescope
Wide Field IR Camera • K. Bundy
PALOMAR OBSERVATORY
PALOMAR MOUNTAIN
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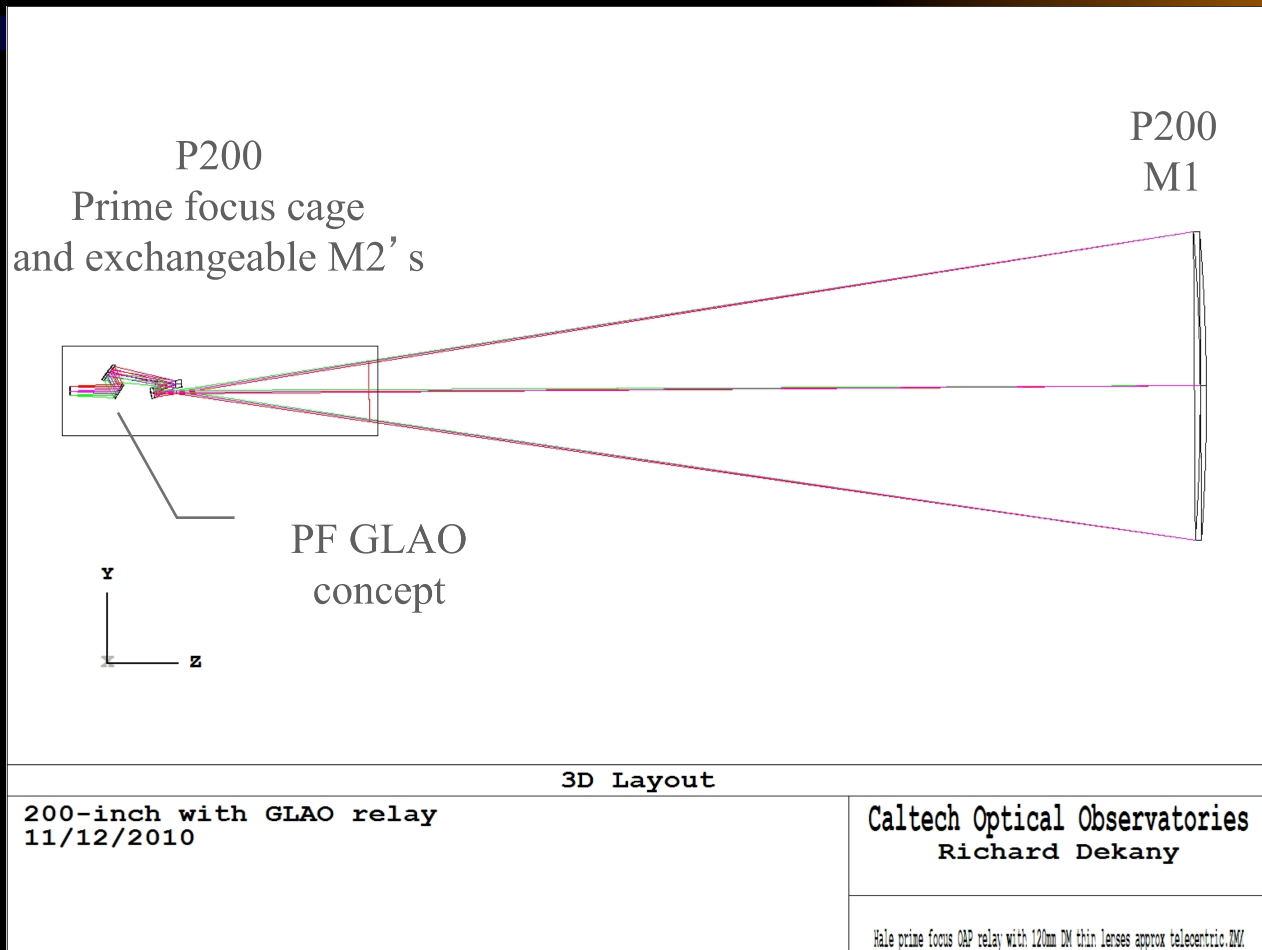
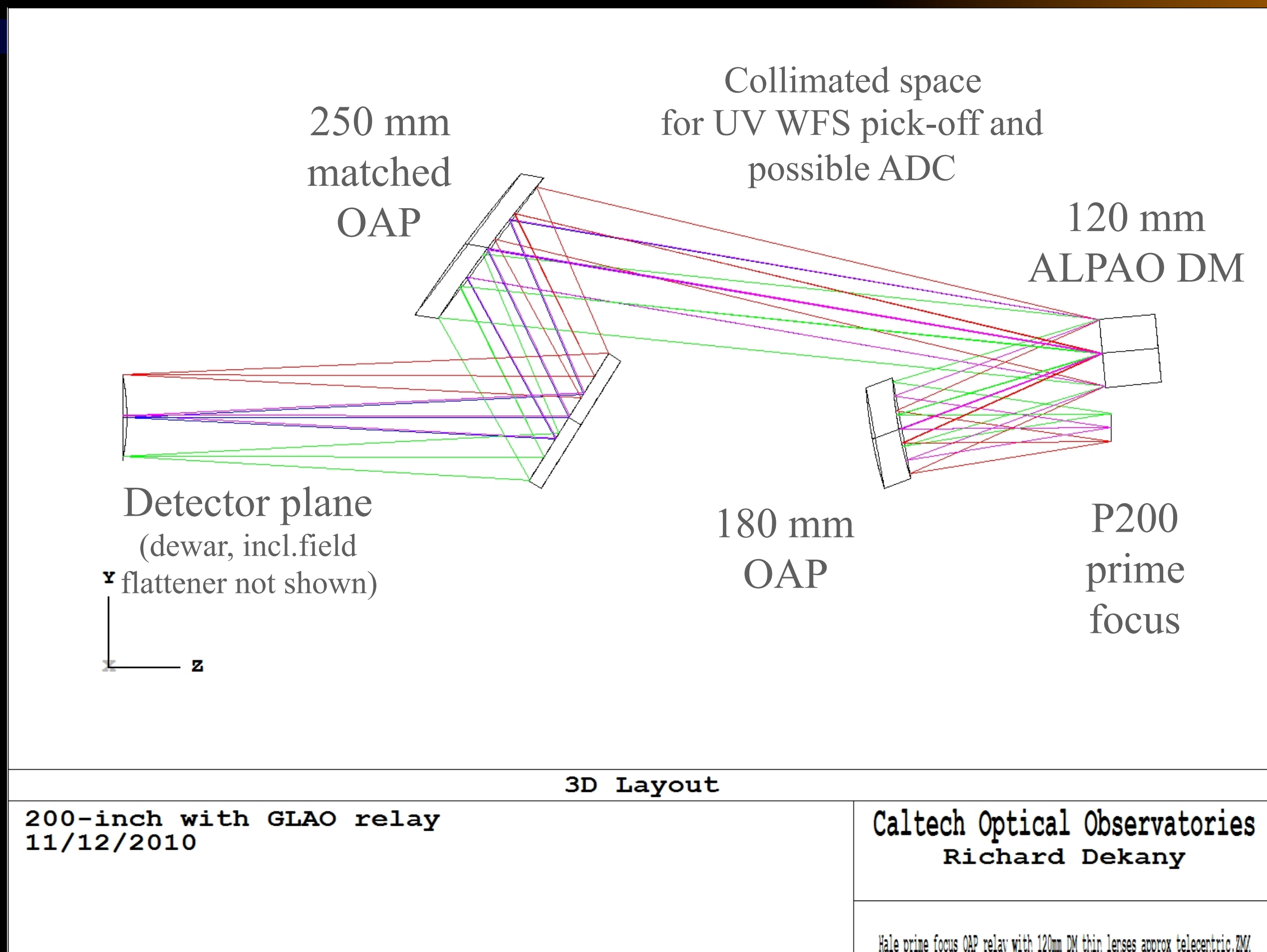
GLAO for 5’-10’ astrometry

- GLAO provides several unique benefits
  - Better SNR
    - Improves both astrometry of science targets, but also number of reference objects that can be used to establish precise motions
  - Better resolution
    - Provides strong advantage for crowded field astrometry (Cameron, et al., 2005)
- Mid-sized telescopes are well suited for wide-FoV GLAO
  - Can reach DL over wider FoV than for large telescopes
  - Correctable ground-layer speckles with residual tilt anisoplanatism

10’ FoV GLAO relay on P200

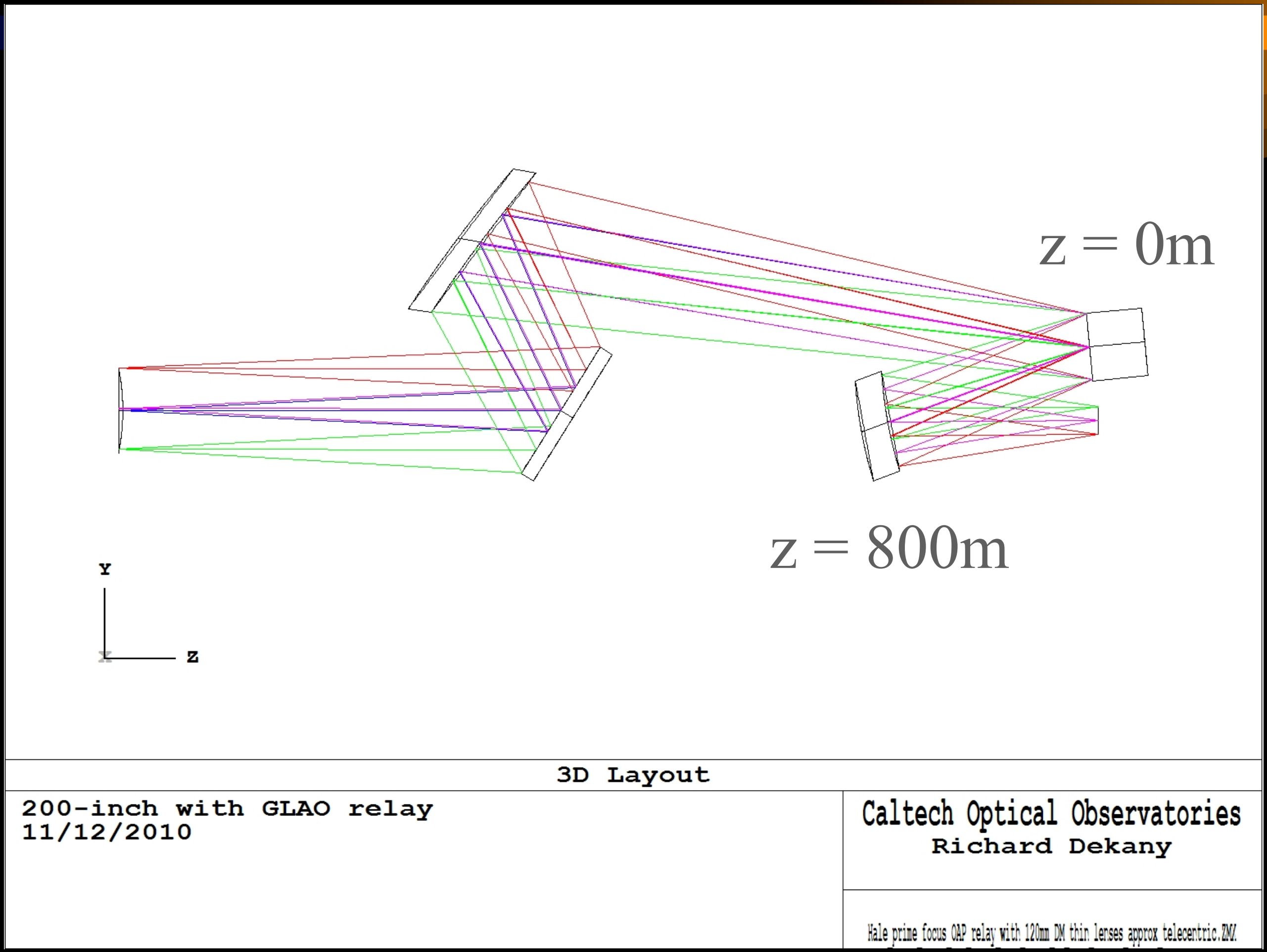


10' FoV GLAO relay on P200



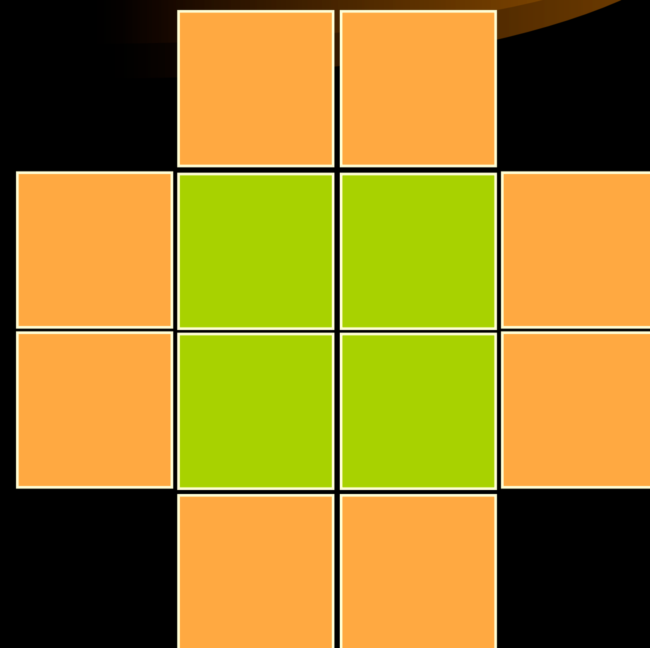
Design by
C. Baranec

10’ FoV GLAO relay on P200



3-5m GLAO imager focal plane

- Initial 2 x 2 mosaic covering 5’ x 5’ FoV
  - Teledyne H2-RG for rapid guiding mode (high altitude WFS)
  - ~0.075” / pixel
  - ~0.15” FWHM PSF
- Build-out to 75 square arcmin



Summary

- Wide-field NIR imaging on 3-5m telescopes has wide science application
  - Promise of 0.15" FWHM and 100 μas astrometry
  - Complimentary to visible GLAO and seeing-limited NIR systems
- Wide-field GLAO on mid-sized telescopes results in sharpened images with plate scale distortions due to tilt anisoplanatism
- A modest cost 5' FoV camera could be built quickly, based on Robo-AO technologies
  - Subsequent round funding can build out 3x the detector solid angle upon GLAO performance verification

Relevance to Mauna Kea?

SLGLAO and Hybrid LGS-NGS AO on Mauna Kea

- Thin boundary layer at Mauna Kea
  - SLGLAO correction improved (larger d_0)
  - Isoplanatism improved (larger θ_0)
  - Hybrid system requires fewer NGS modes
- Opens potential for wide-field architectures
  - Single Na LGS with or w/o NGS NIR PyWFS
  - Na LGS + Rayleigh LGS combinations
  - Need for simulations

LTAO Costs are Driven by Component Technology Development

- New technology needed on many parallel fronts
  - High stroke, high-spatial bandwidth DM's
  - High power 589 nm lasers
  - Low noise WFS detectors
  - Tomography
  - Precision calibration
- LTAO system cost is strong function of desired residual wavefront error ($100K's per nm RMS)

GLAO costs are increasingly driven by mature technologies

- Lower wavefront error ambition allows combinations of existing technologies
  - Modest spatial bandwidth DMs
    - Offset by large optical field of view
      - Adaptive secondary mirrors (ASM) or other large large diameter mirror for stroke and FoV
  - Wavefront sensing multiplex
    - But modest (Rayleigh?) laser and WFS detectors
      - TT and/or Truth WFS'ing may be unnecessary
  - Wide-field instrumentation becomes larger relative cost (so reuse is more advantageous)

Potential areas of collaboration

- Hybrid WFS and control
  - Robo-AO experience w/ and w/o TT
  - PULSE and PULSE-like systems for Keck
  - YAO simulations of different architectures
- GLAO instrumentation
  - Wide-field NIR imaging mosaic
  - Deployable NIR MOAO multi-object IFS