Adaptive Optics

Introduction to Adaptive Optics

Brief introduction to adaptive optics: why, how ?
AO for high contrast imaging
Components of an AO system
Types of AO systems

<u>Useful references:</u>
Adaptive Optics in Astronomy (2004), by Francois Roddier (Editor), Cambridge University Press
Adaptive Optics for Astronomical Telescopes (1998), by John W. Hardy, Oxford University Press

Why Adaptive Optics ?

Gains offered by AO :

Angular resolution:
Resolve small features on Sun, Moon, planets, disks, galaxies

Improved sensitivity for faint objects:
Detection of faint objects is a background-limited problem. By making the image smaller, the AO system limits amount of background mixed with image, and improves sensitivity. Efficiency with AO goes as D^4 instead of D^2 without AO.
This is especially important in infrared, as sky glows, and AO work well.

Astrometry:
Measuring the position of a source.
For example: measuring the mass of the black hole in the center of our galaxy.

Confusion limit:
Astronomical imaging of sources is often confusion limited. Better angular resolution helps !
For example: studying stellar populations in nearby galaxies.

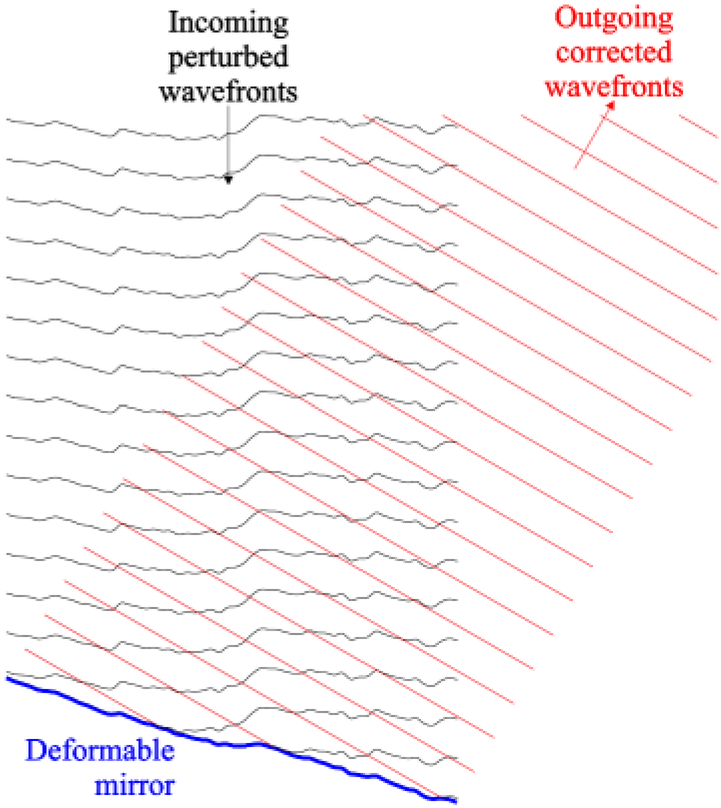
High contrast imaging (Extreme-AO)
Direct imaging of exoplanets and disks

What is Adaptive Optics ?

Atmospheric turbulence limits size of images to ~1” (1/3600 of a degree)
Diffraction limit of large telescopes is 0.1” to 0.01” → 10x to 100x smaller !

Without AO

With AO



AO uses a deformable mirror to correct atmospheric turbulence

Wavefront control for High contrast imaging

pupil plane complex amplitude

$$W(\vec{u}) = \mathcal{A}(\vec{u})\, e^{i\phi(\vec{u})}$$

Cosine aberration in pupil phase

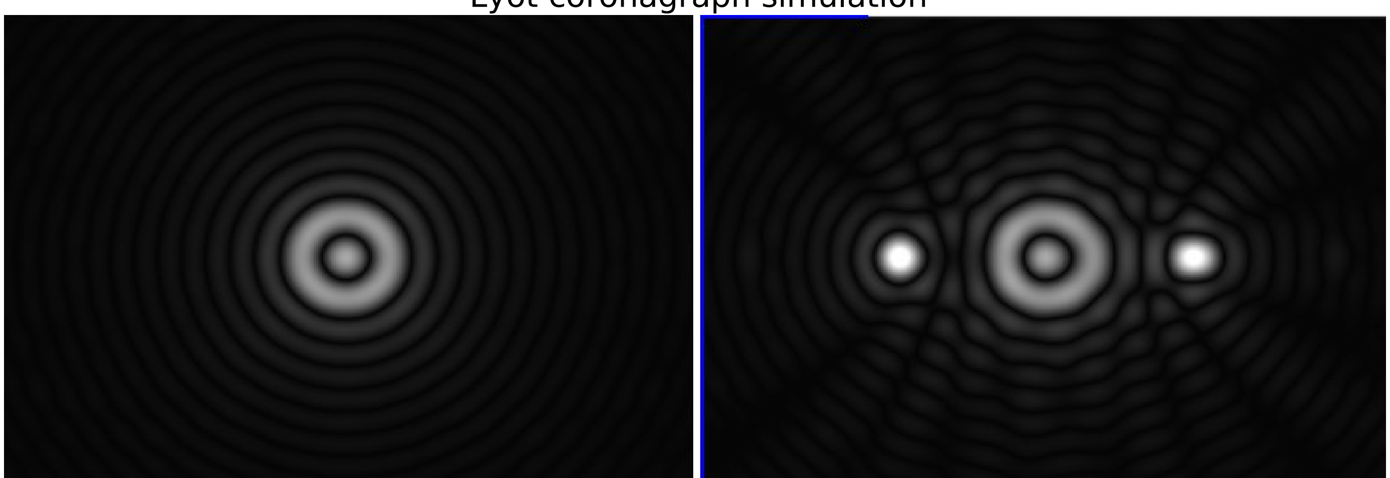
$$\phi(\vec{u}) = \frac{2\pi h}{\lambda} \cos\left(2\pi \vec{f}\vec{u} + \theta\right)$$

… creates 2 speckles

$$I(\vec{\alpha}) = PSF(\vec{\alpha}) + \left(\frac{\pi h}{\lambda}\right)^2 \left[PSF(\vec{\alpha}+\vec{f}\lambda) + PSF(\vec{\alpha}-\vec{f}\lambda)\right]$$

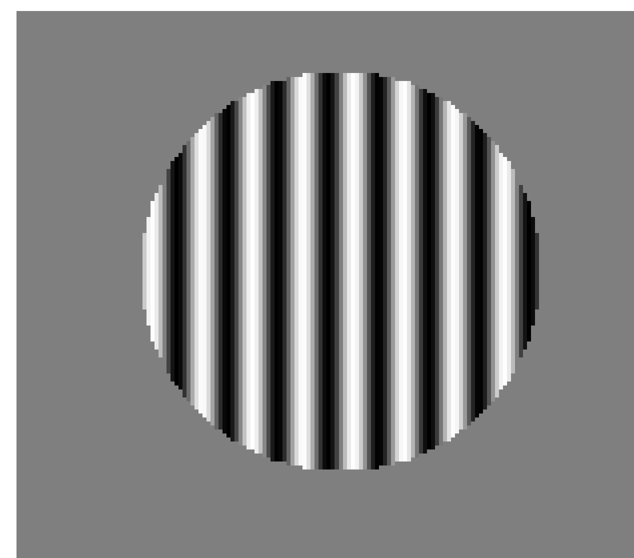
Earth-like planet around Sun-like star is ~1e-10 contrast
In visible light, h=1.6e-12 m (0.0012 nm) = 1e-10 speckle

Lyot coronagraph simulation



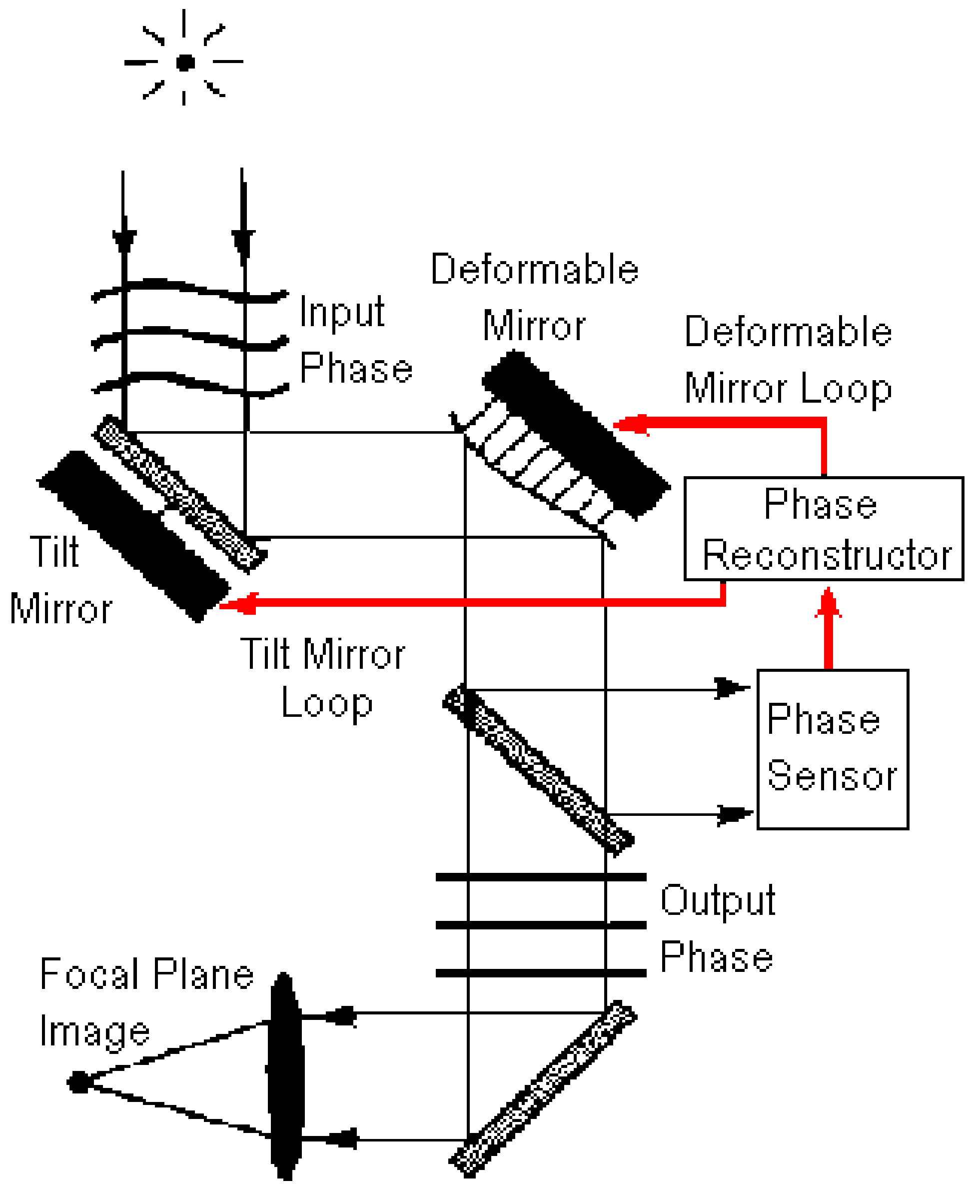
No phase error

pupil sine wave phase error



0.1 rad (1/63 wave) amplitude

What is Adaptive Optics ?



Main components of an AO system:

Guide star(s): provides light to measure wavefront aberrations, can be natural (star in the sky) or laser (spot created by laser)

Deformable mirror(s) (+ tip-tilt mirror): corrects aberrations

Wavefront sensor(s): measures aberrations

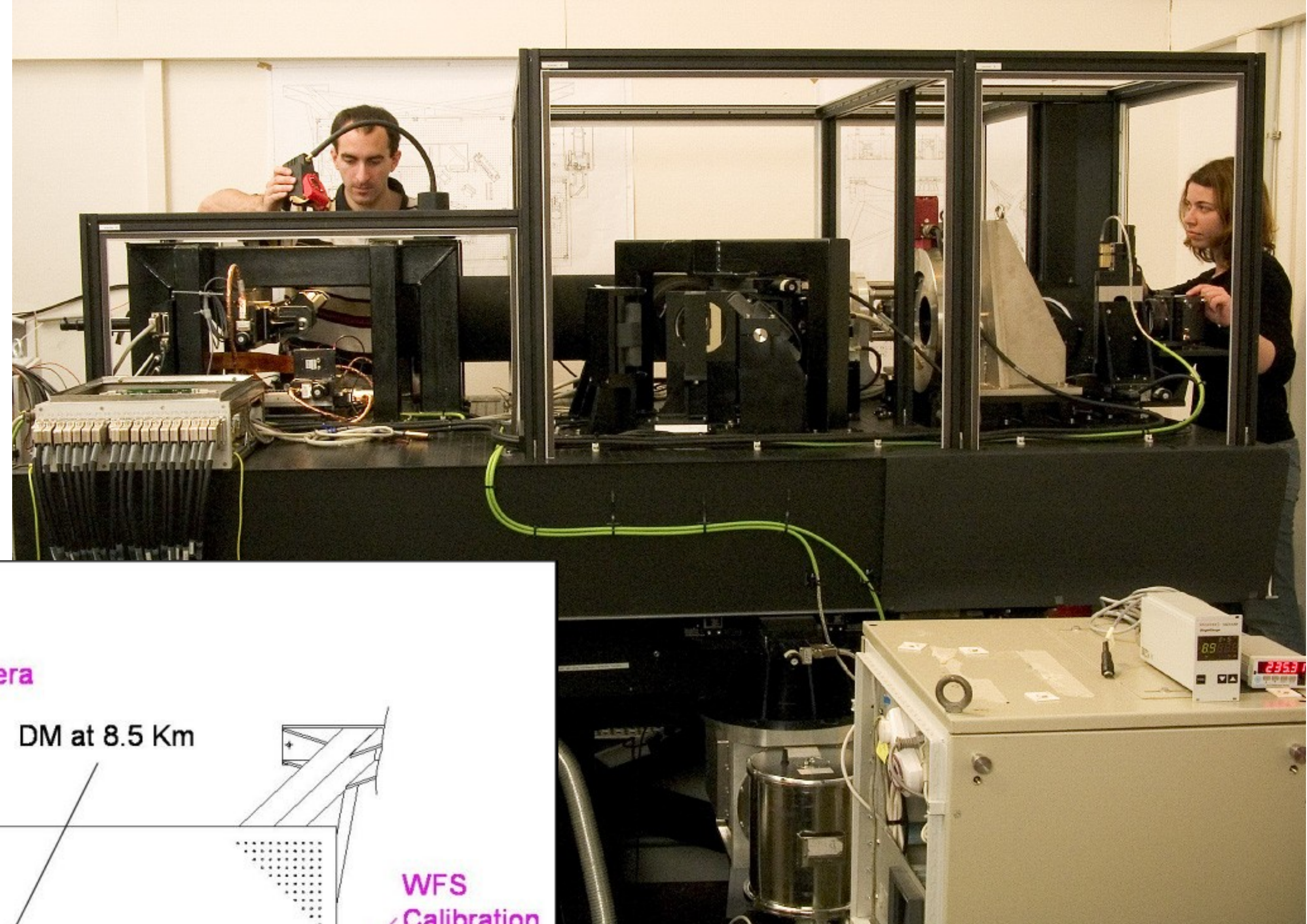
Computer, algorithms: converts wavefront sensor measurements into deformable mirror commands

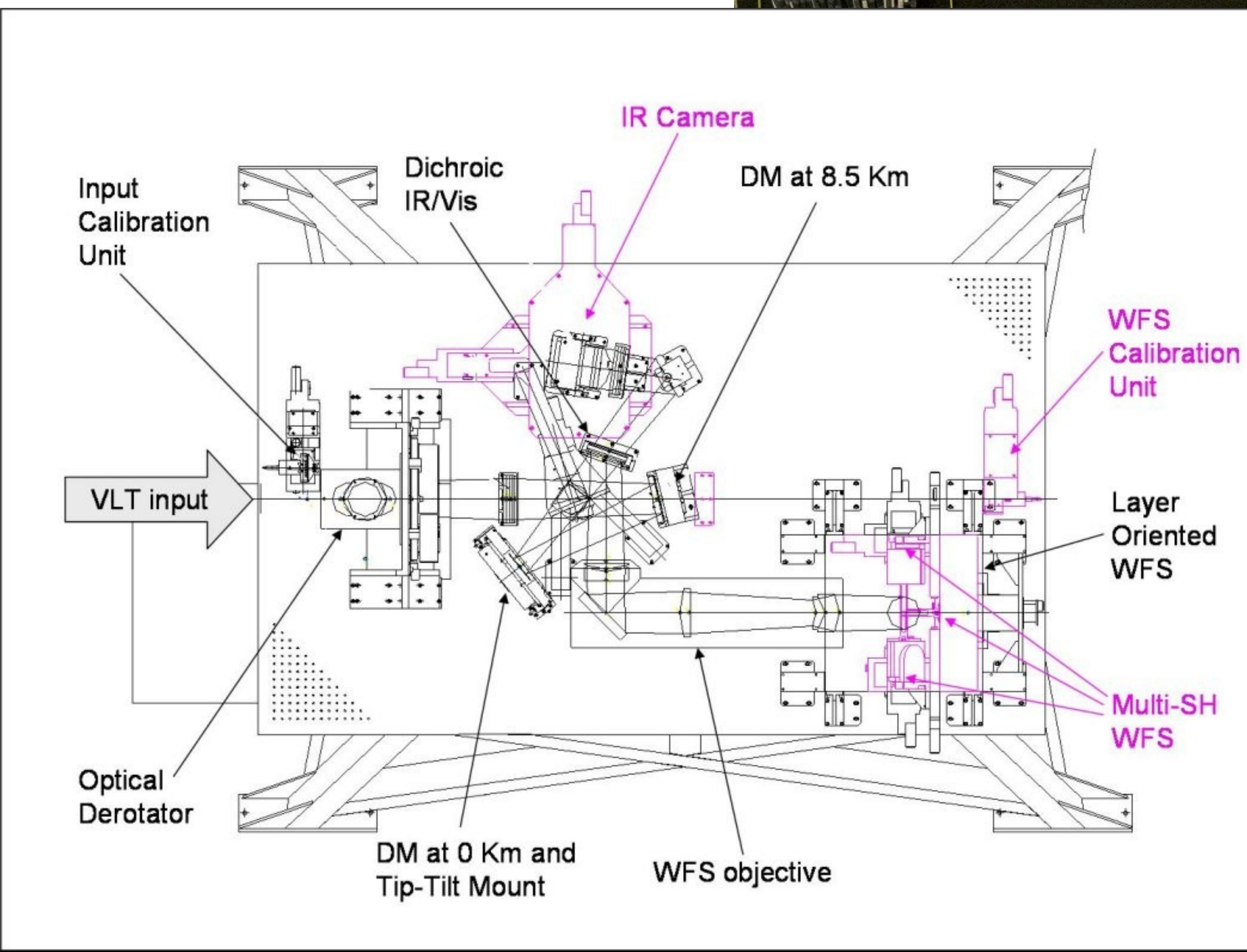
What is Adaptive Optics ?

Altair Optics bench (for Gemini)

What is Adaptive Optics ?

Multi Conjugate AO Demonstrator (MAD, ESO)





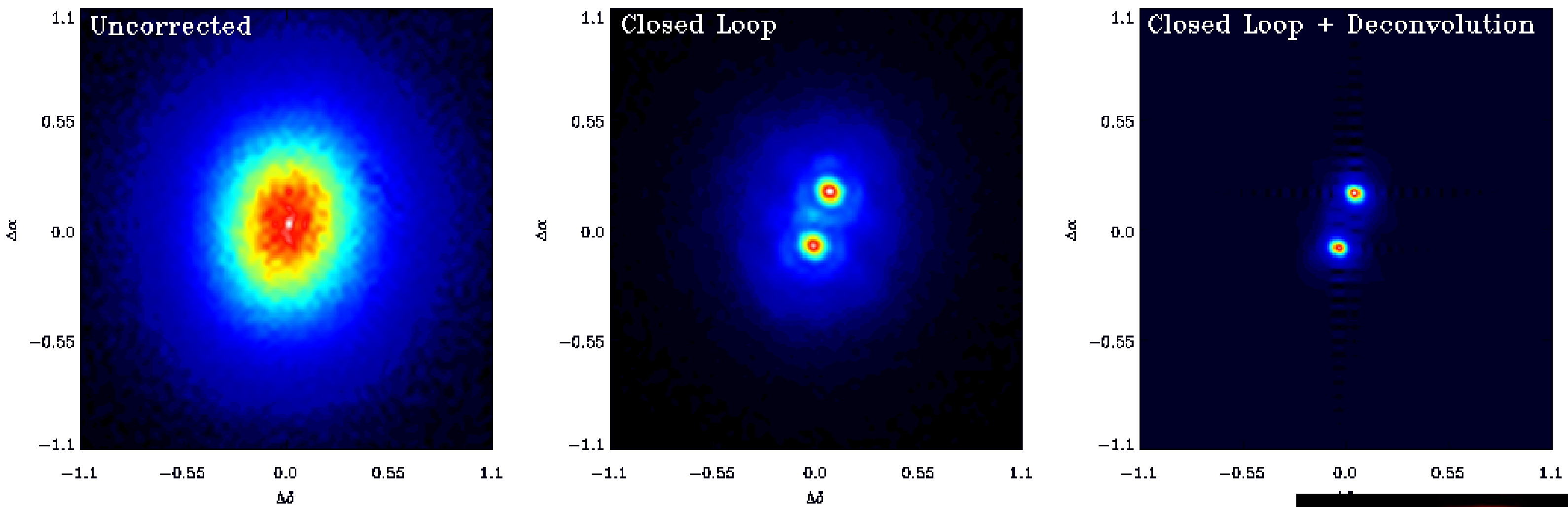
Why Adaptive Optics ?

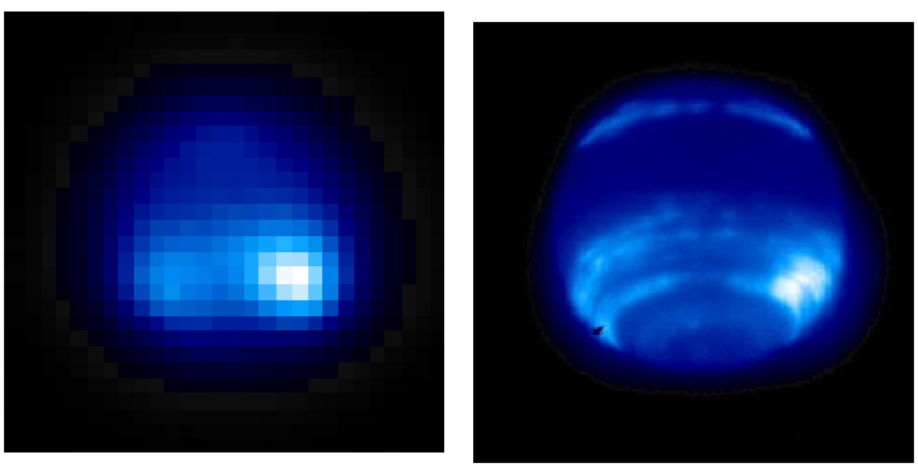
CFHT Adaptive Optics Bonnette & Monica

Double star, separation=0.276″
Seeing=0.7″ @ 0.5mic

Magnitude=10.7
Strehl Ratio=30%

H band, Integration=40 sec
Maximum likelihood



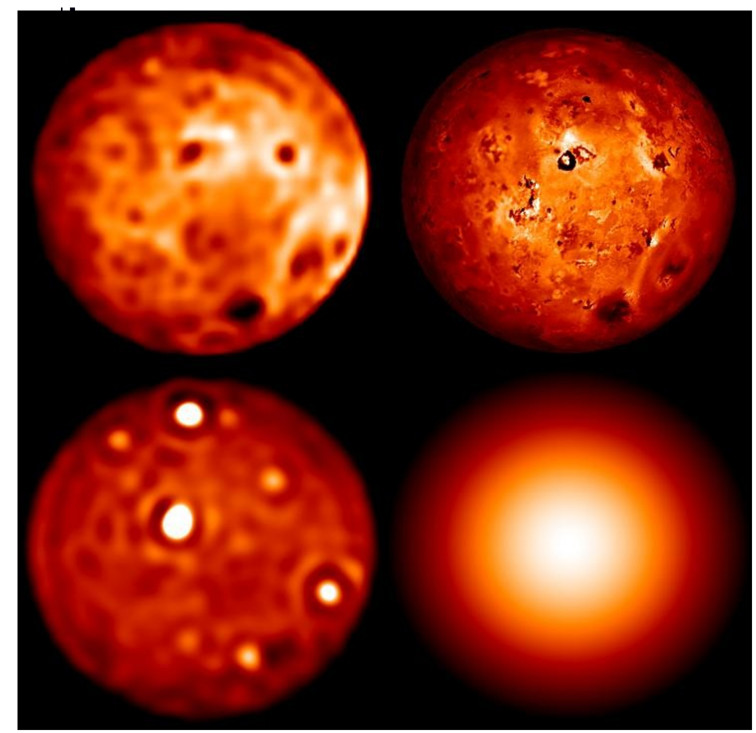


without AO

with AO

Neptune imaged by Keck AO

Io (Keck)



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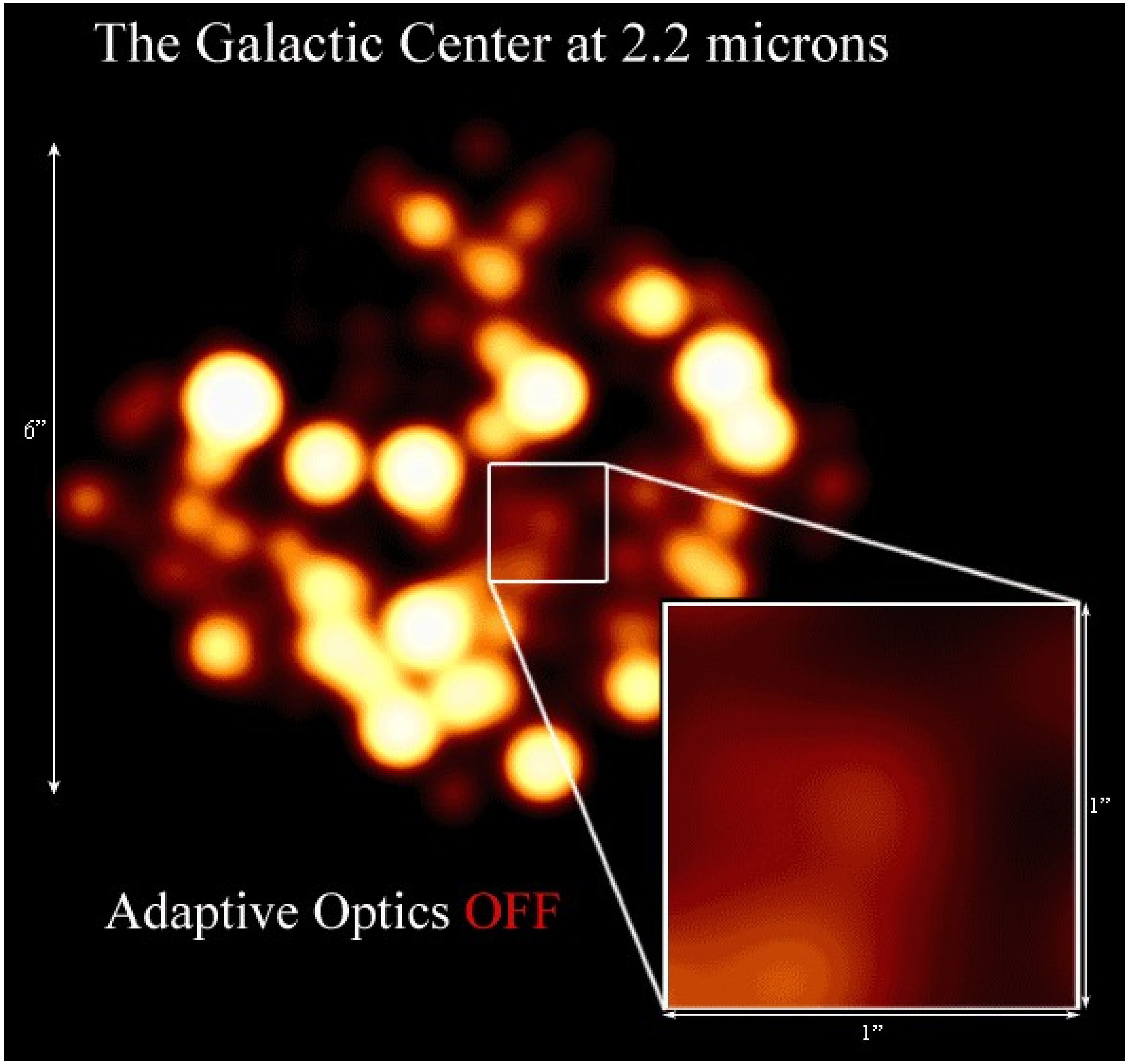
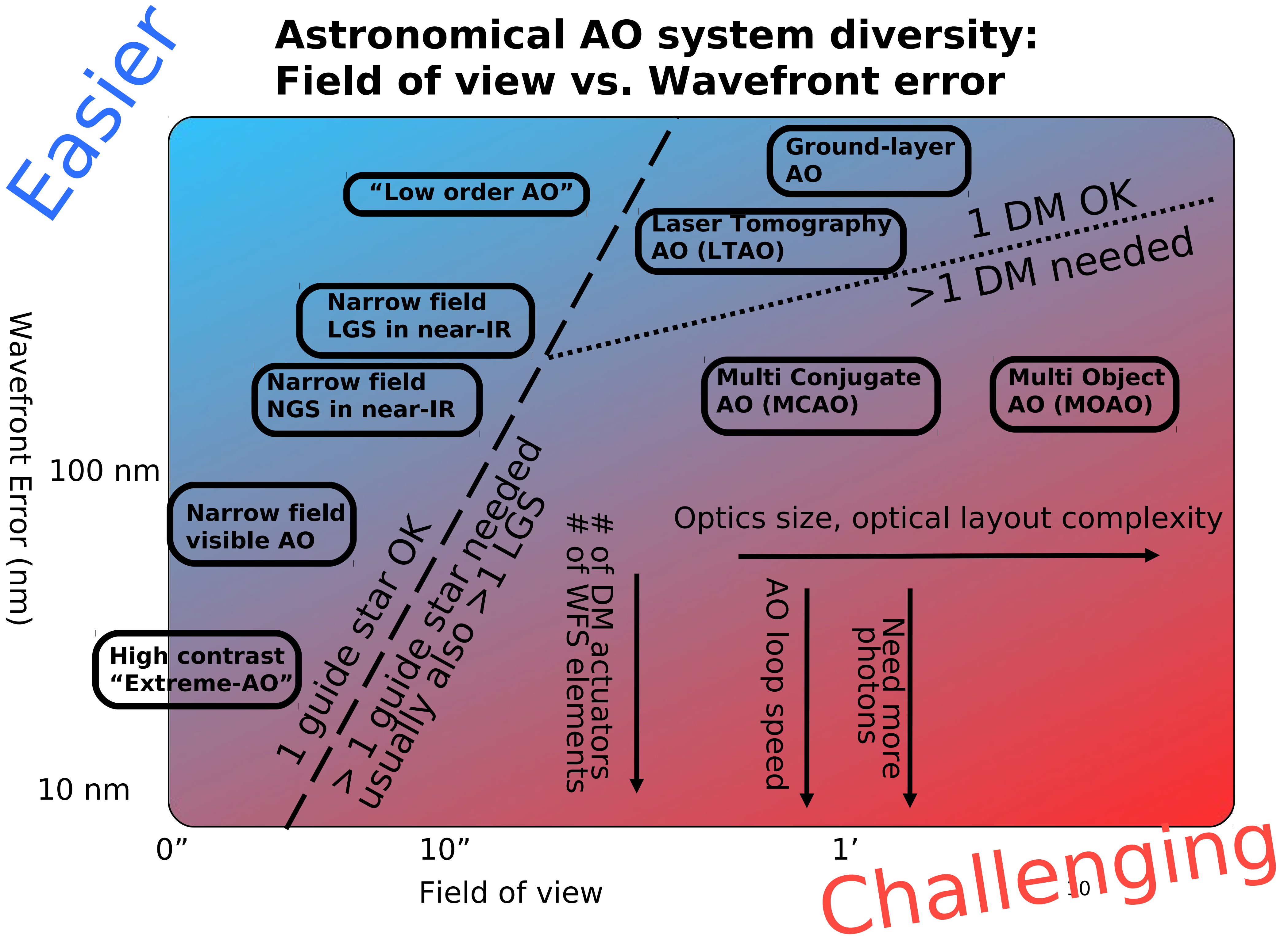


UCLA Galactic Center Group

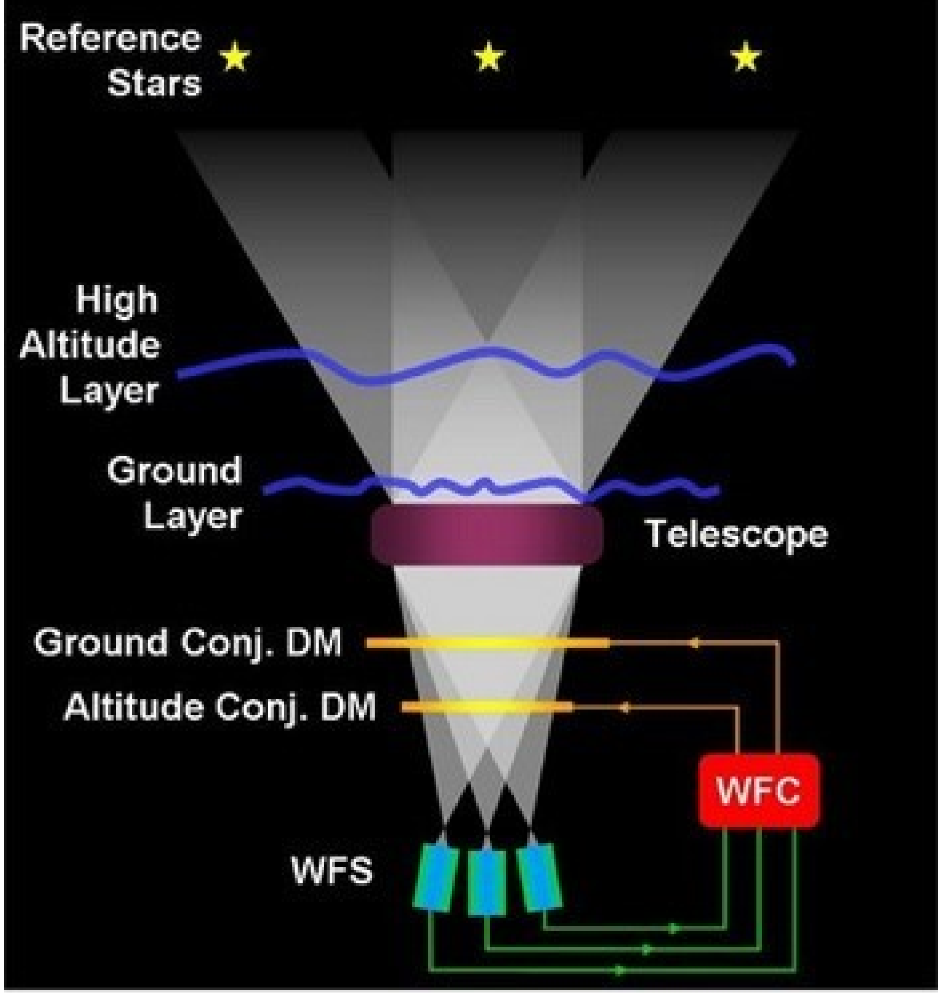
Astronomical AO system diversity: Field of view vs. Wavefront error



Example #1: Multi-Conjugate AO (MCAO)

Uses several guide stars (NGS or/and LGS) to gain volumetric information of turbulence.

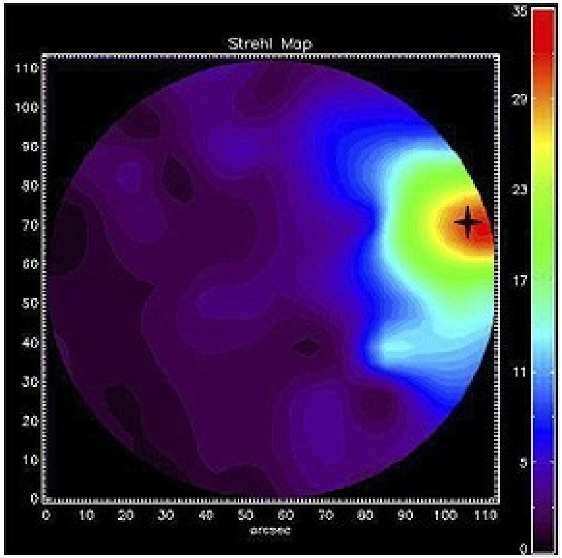
Uses several DMs to correct over wide field.

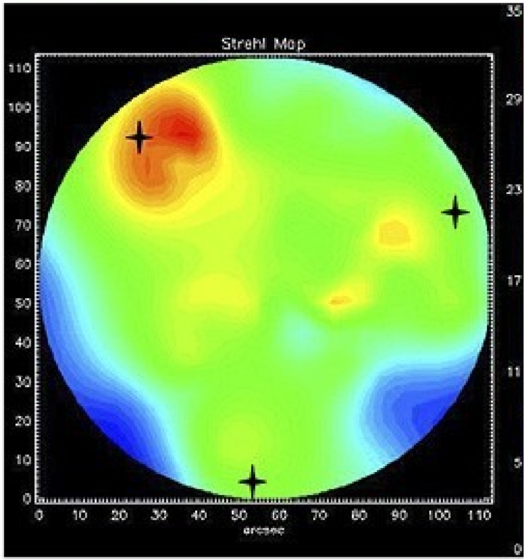


Results from ESO’s MCAO demonstrator (MAD)

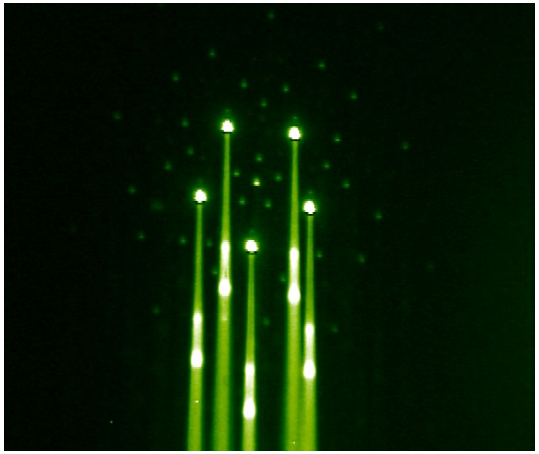
Gemini currently developing MCAO system

Strehl maps on the right show image quality is high over a wide field of view (black crosses show position of guide stars)





Example #2: The MMT multi-laser Ground Layer AO (GLAO) system

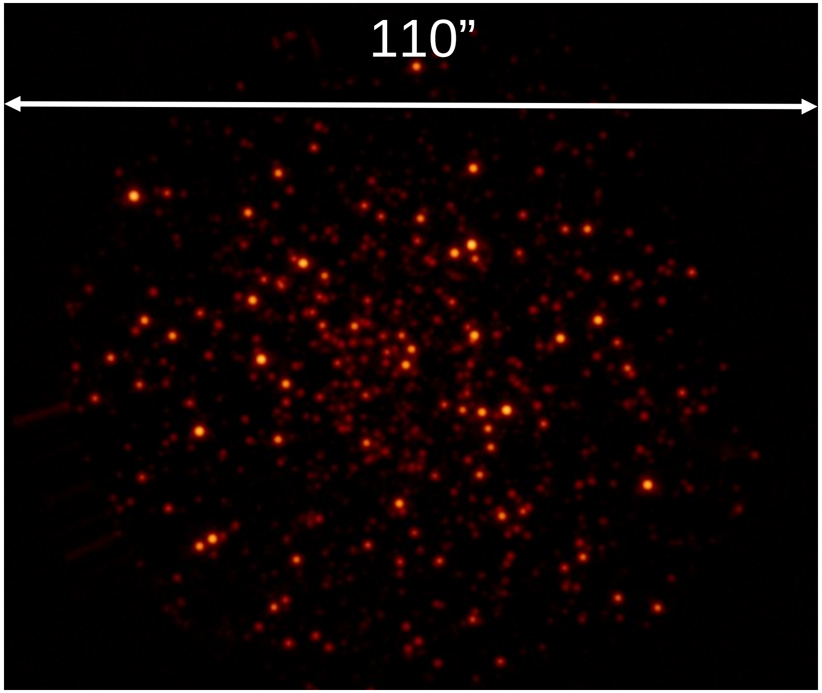


5 laser guide stars → 5 wavefront measurements
Reconstructor keeps only ground layer, common to the 5 wavefronts
Single DM corrects for the ground layer: correction is valid over a large field

MMT results: M3 globular cluster

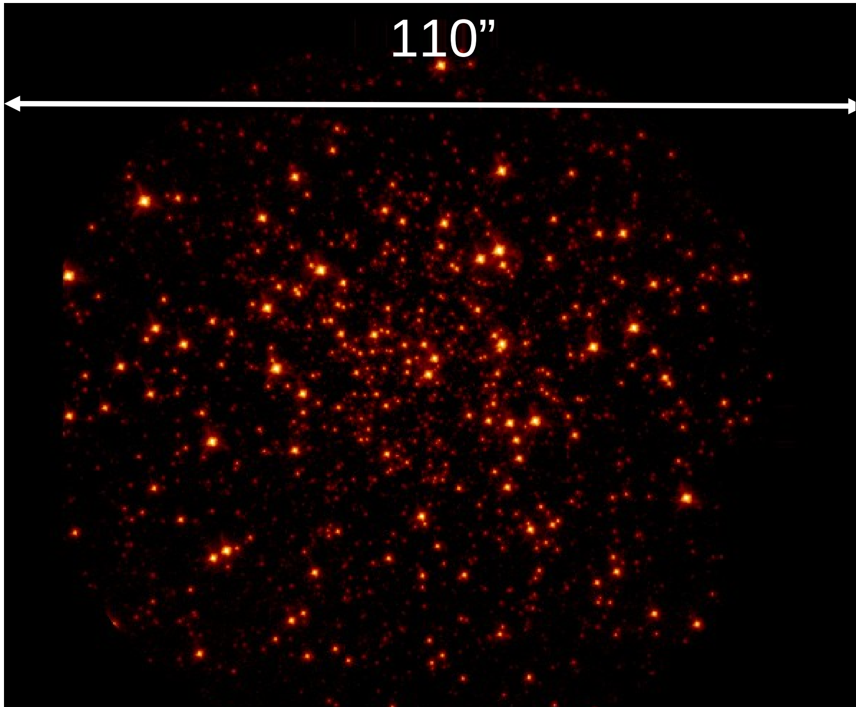
Open loop, K_s filter, FWHM 0.70”

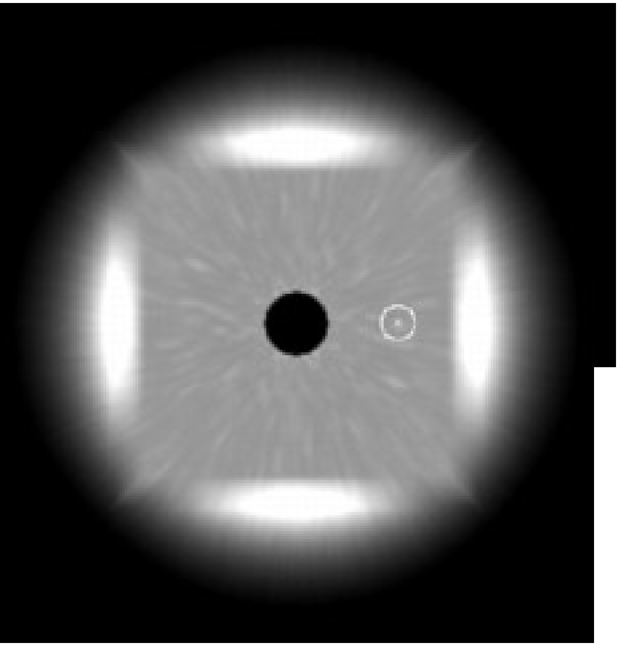
Logarithmic scale



Closed loop GLAO, K_s filter, FWHM 0.30”

Logarithmic scale

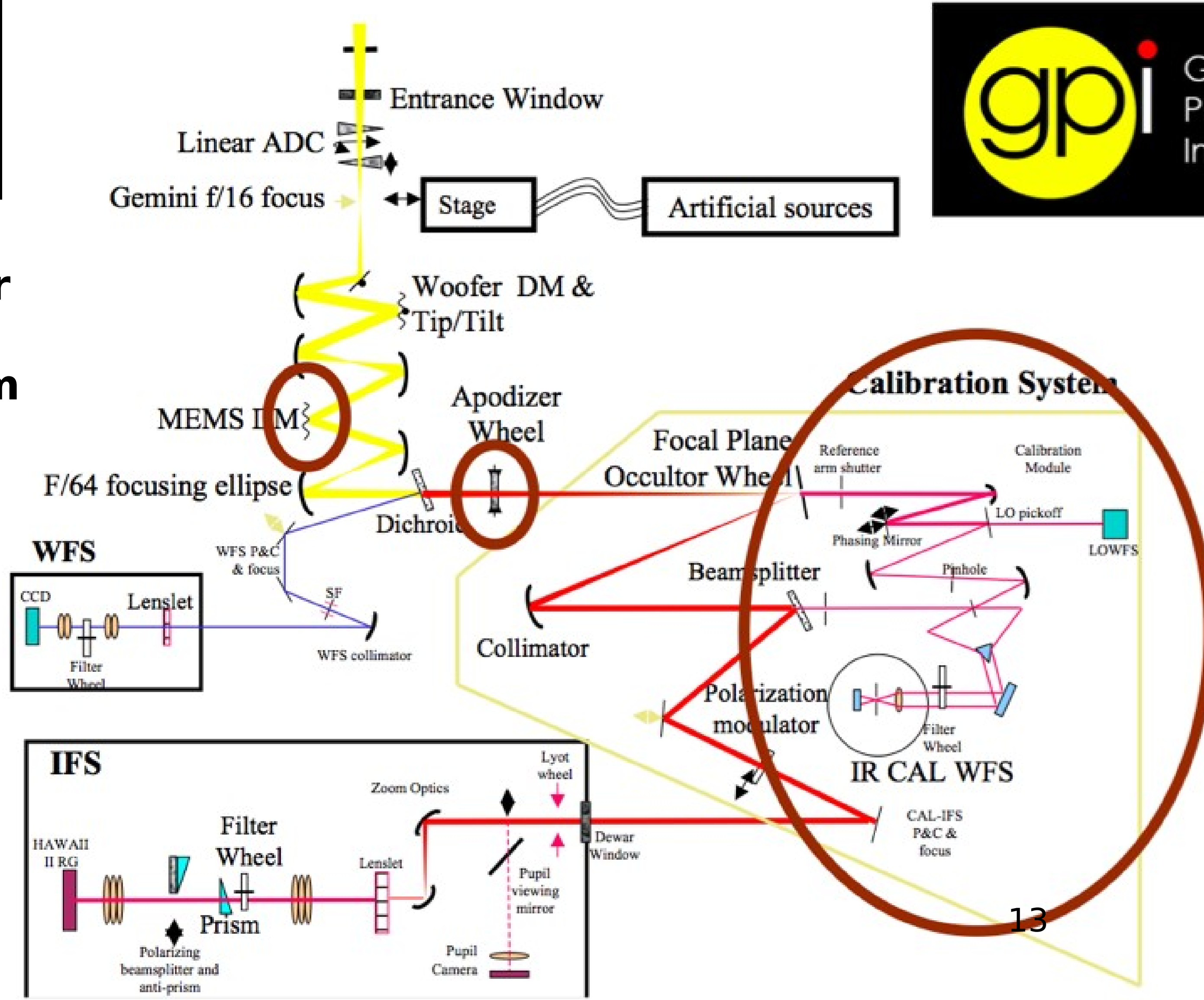




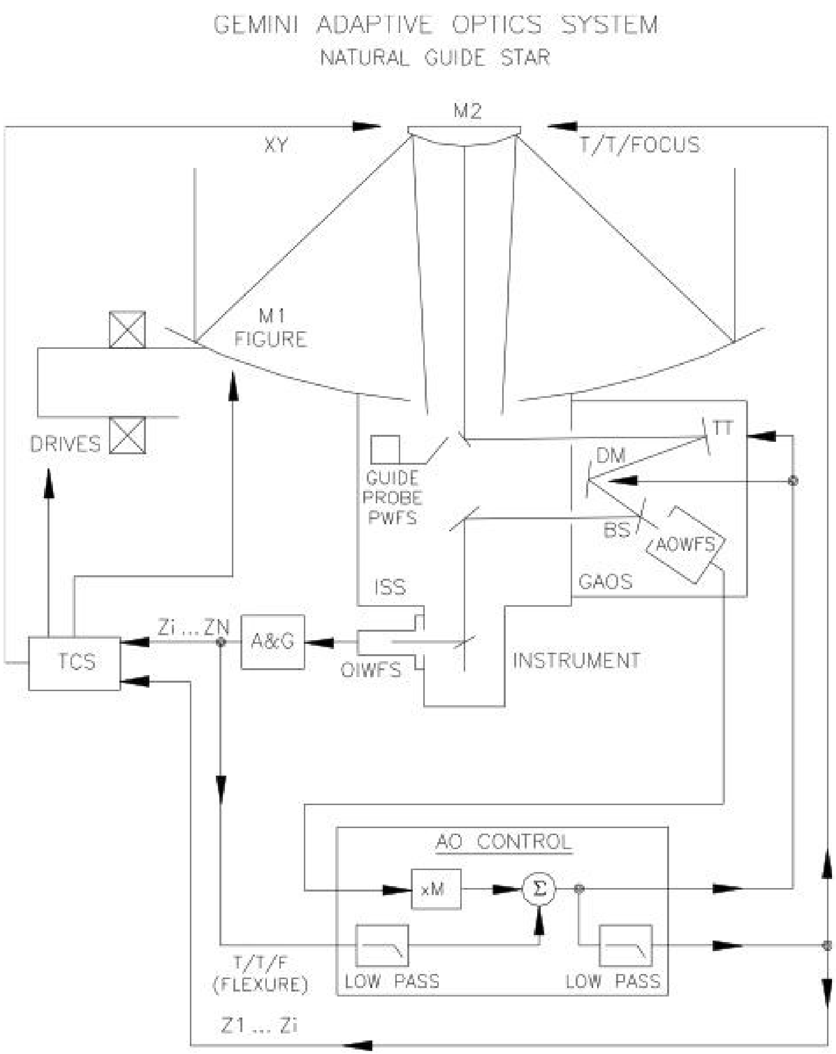
Example #3: The Gemini Planet Imager Extreme-AO system

Gemini Planet Imager
SPHERE (ESO)
Subaru CExAO system

Also under study: space-based ExAO systems

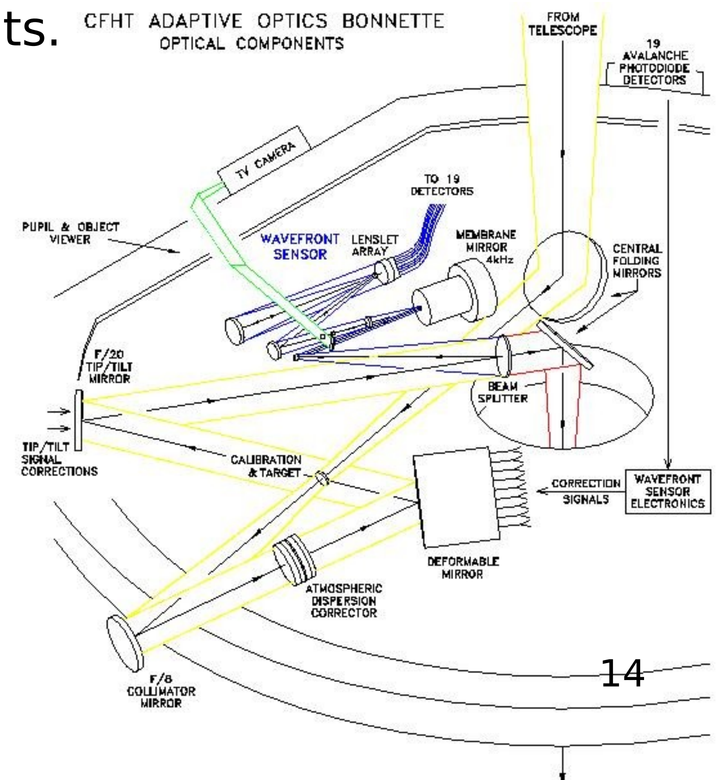


Communication between telescope/instruments and AO system



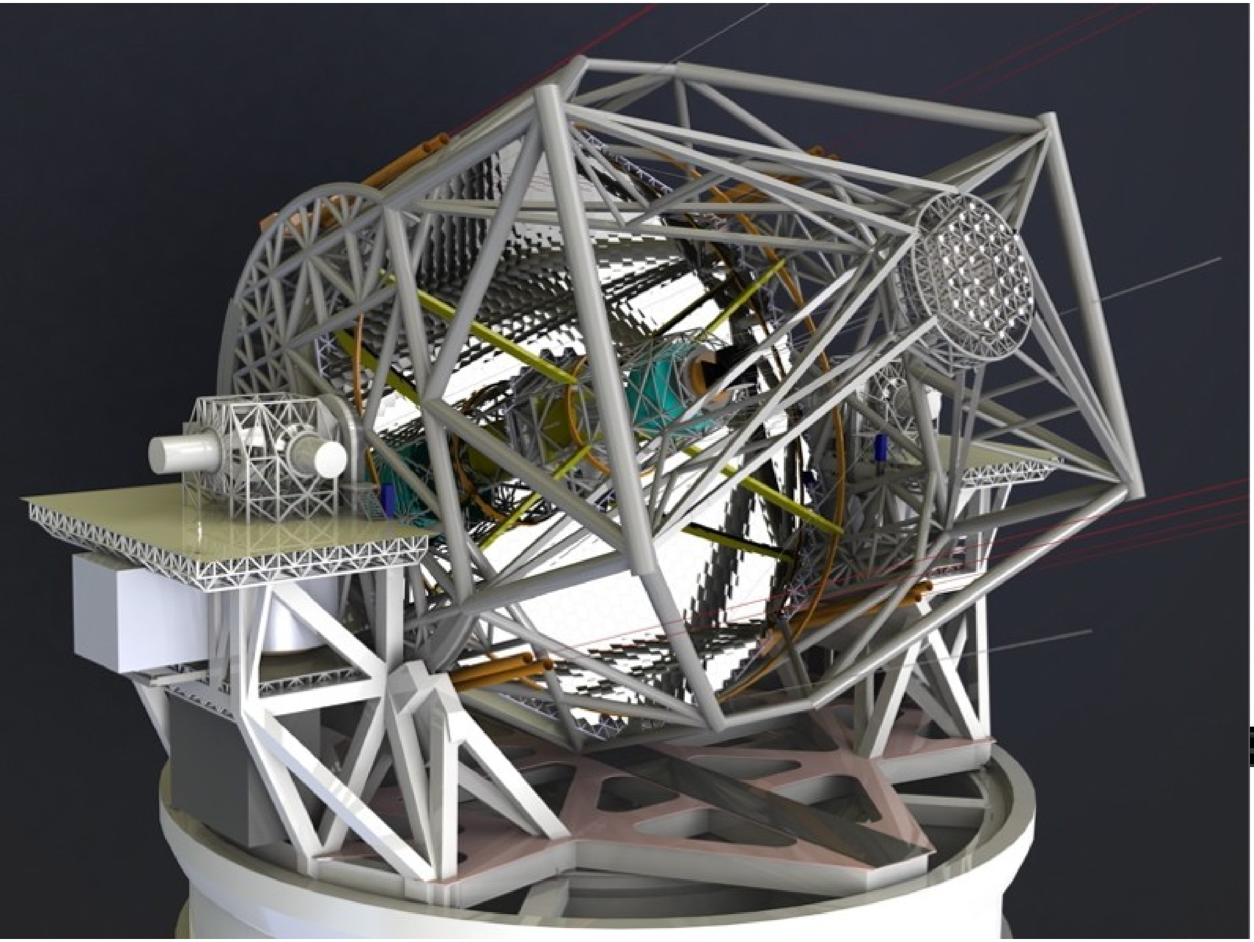
On modern telescopes, the AO system can "offload" wavefront aberrations to primary mirror, tip/tilt/focus secondary mirror and telescope pointing. The AO system "drives the telescope".

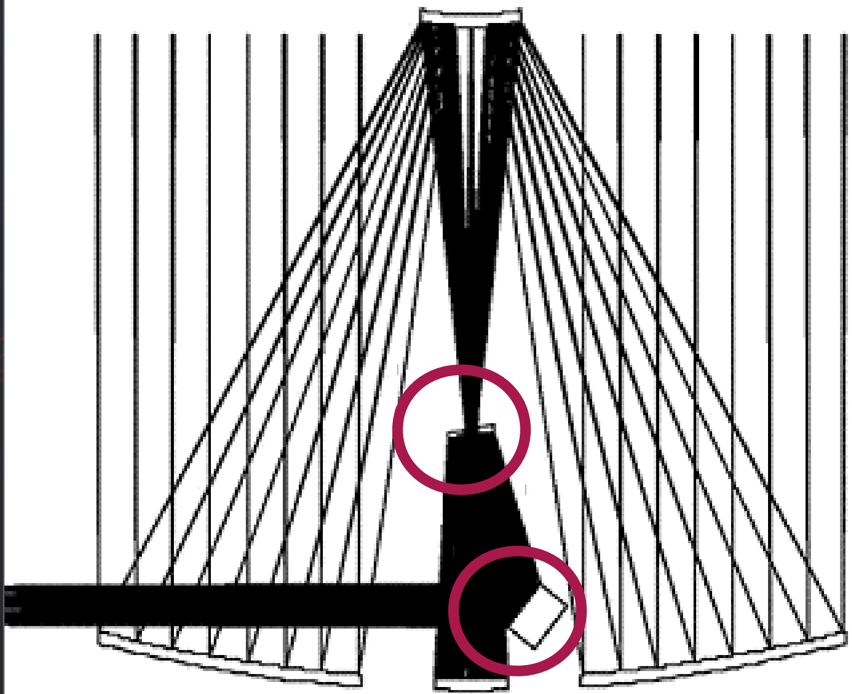
"Facility" AO systems can feed several instruments, and can be a "layer" which processes the beam prior to sending it to instruments.

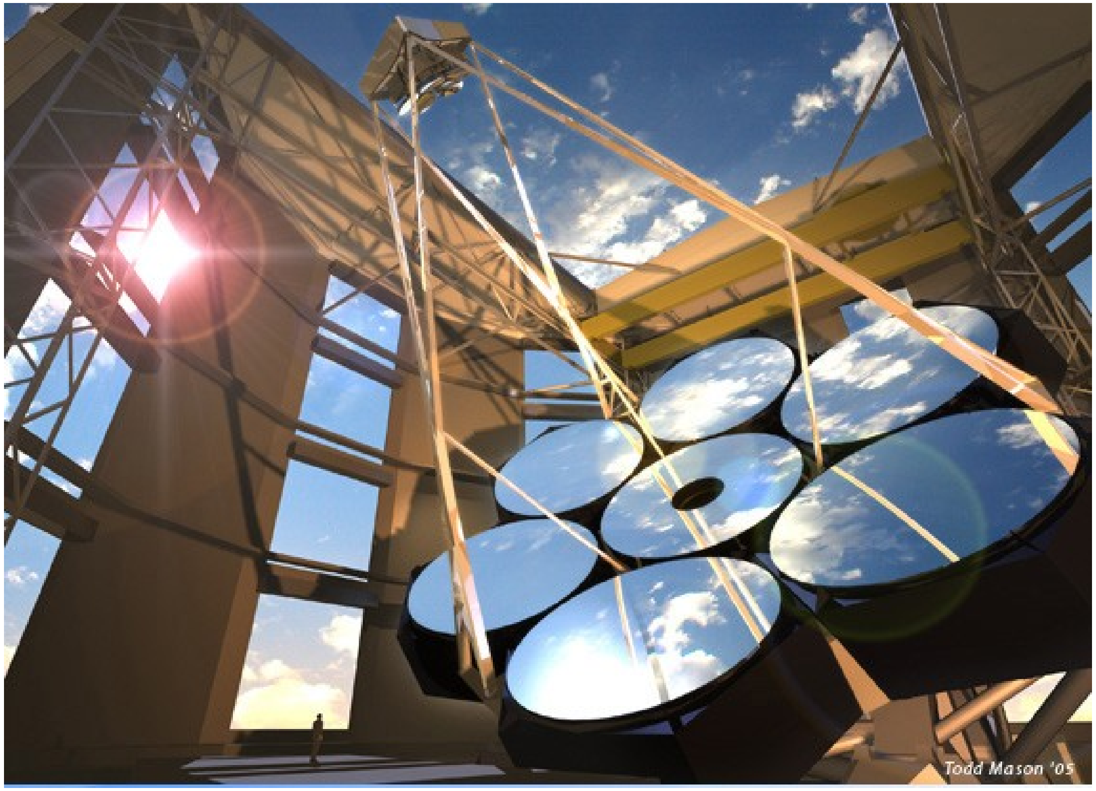


The next generation of large telescopes combine AO with telescope design

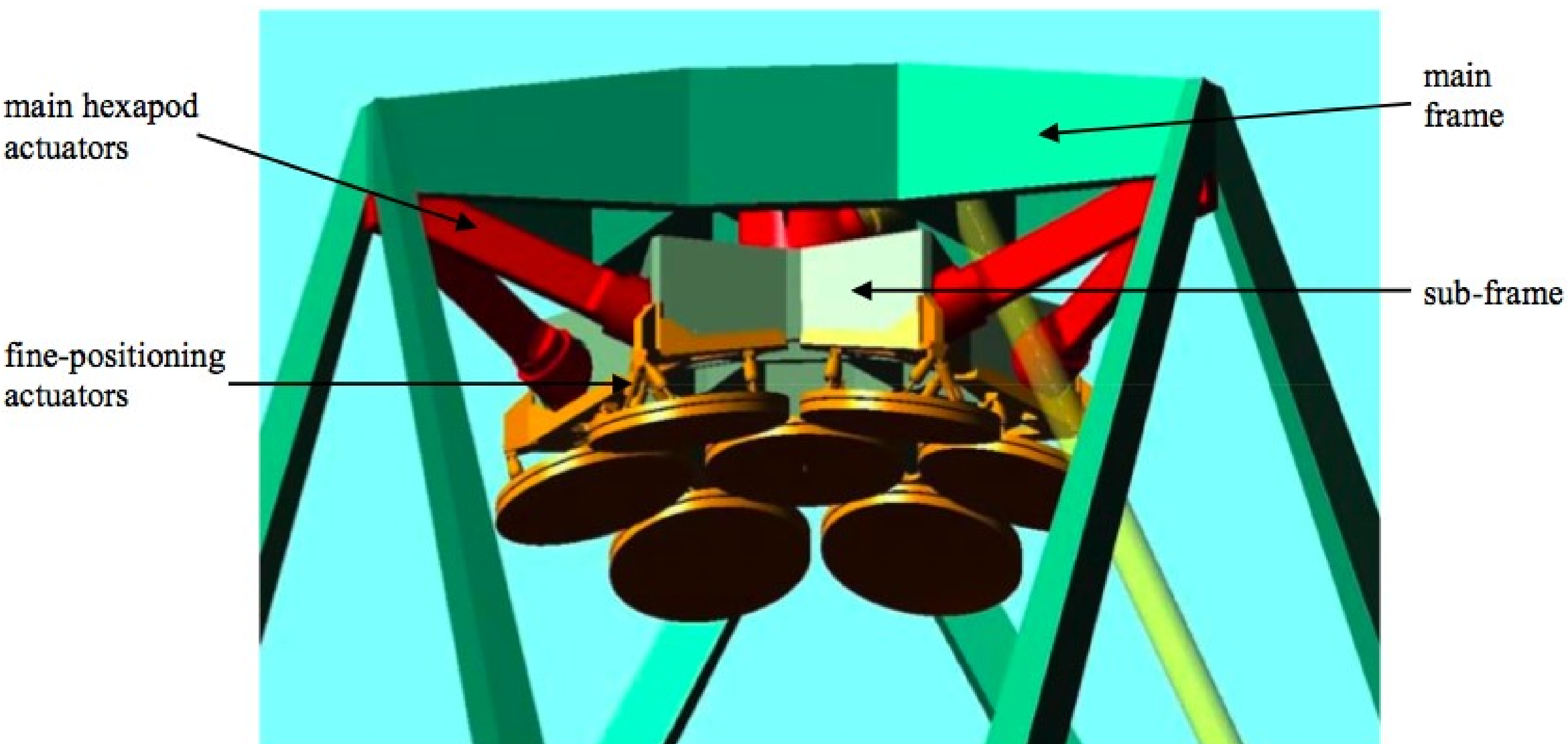
The 42m diameter European Extremely Large Telescope (EELT) optical design includes DMs as large fold mirrors (2.5m and 2.7m diameter).

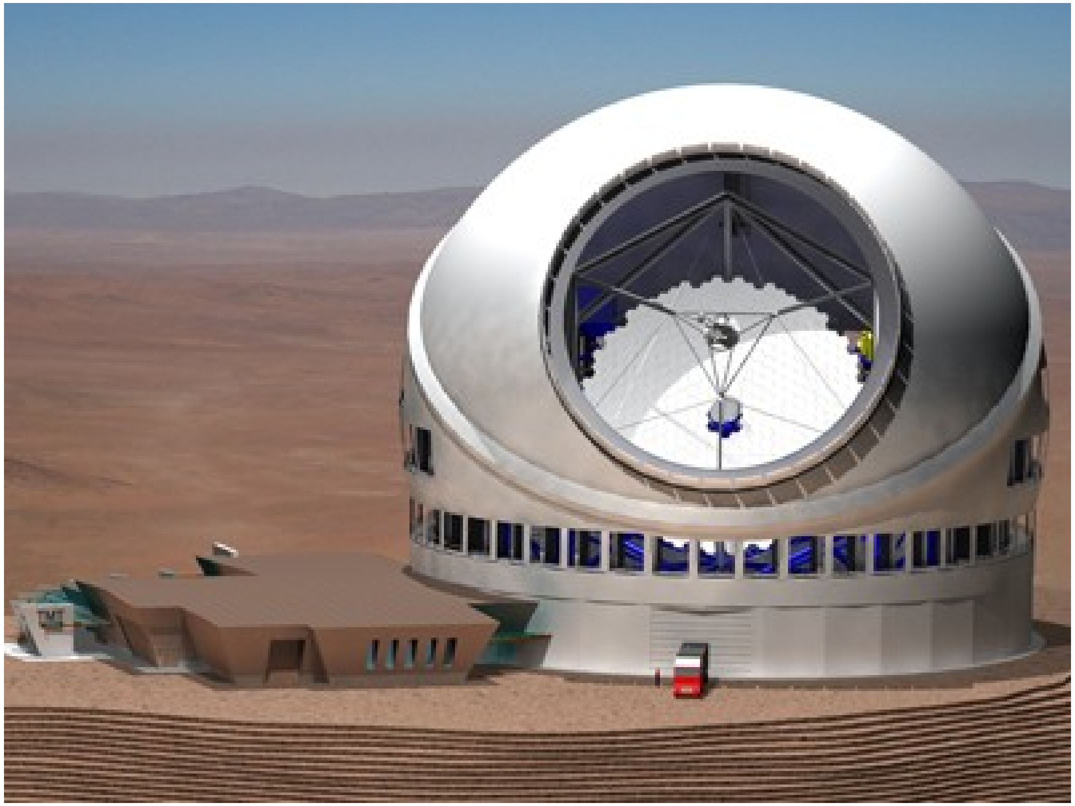






The Giant Magellan Telescope (GMT) secondary mirrors are adaptive and serve as DMs for the AO system(s).





The Thirty Meter Telescope (TMT), just like GMT and ELT, includes adaptive optics for first generation instruments.