AO system Design: Astronomy

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Center for Adaptive Optics Summer School, Aug 2017

This lecture:

Will not discuss detailed optical designs, mechanical designs, hardware choices, computer algorithms

(covered in other lectures, often specific to some AO systems, easy to get lost in details and miss big picture...)

The main goals are to **explore fundamental AO strategies**, compare them, understand how/why/when they work or don't work, explore Telescope / AO system / instruments relationships

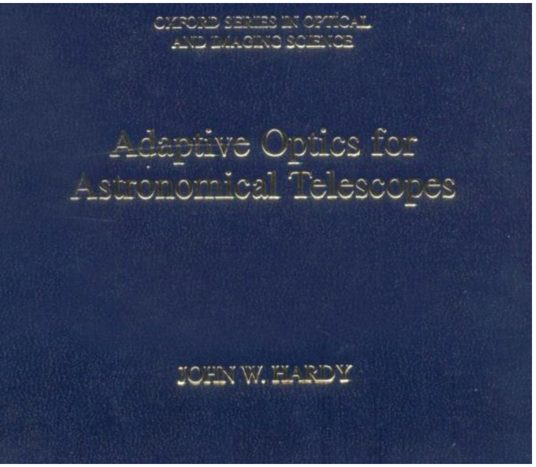
This lecture won't teach you how to build an AO system, but it will help you figure out what kind of AO system you might build for a specific application & what kind of problems will need to be solved

This lecture will show that there are **many different types of AO systems,** requiring different architectures and hardware

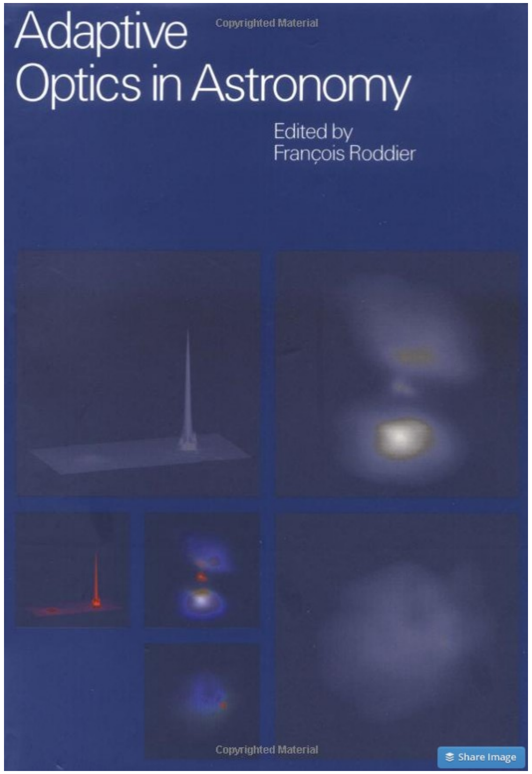
Useful references

… in addition to this school

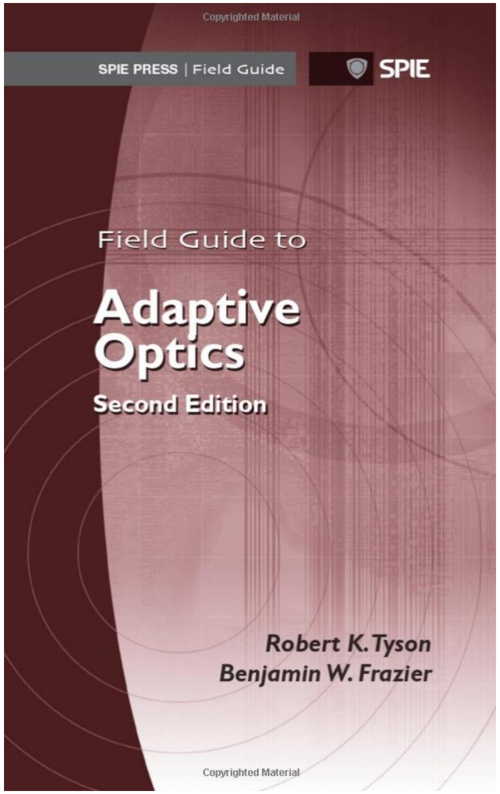
[1998]



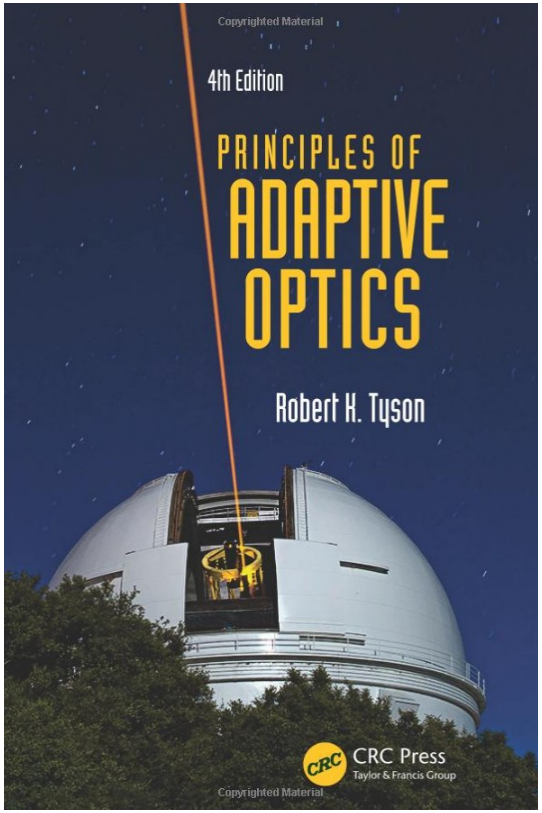
[1999]



[2012]



[2016]



Outline

Astronomical AO system diversity

Main challenges / error budget terms in astronomical AO systems

Wavefront sensing strategies

Large field of view AO systems

Optical/mechanical design considerations

From photons to DM commands: making it all work nicely together

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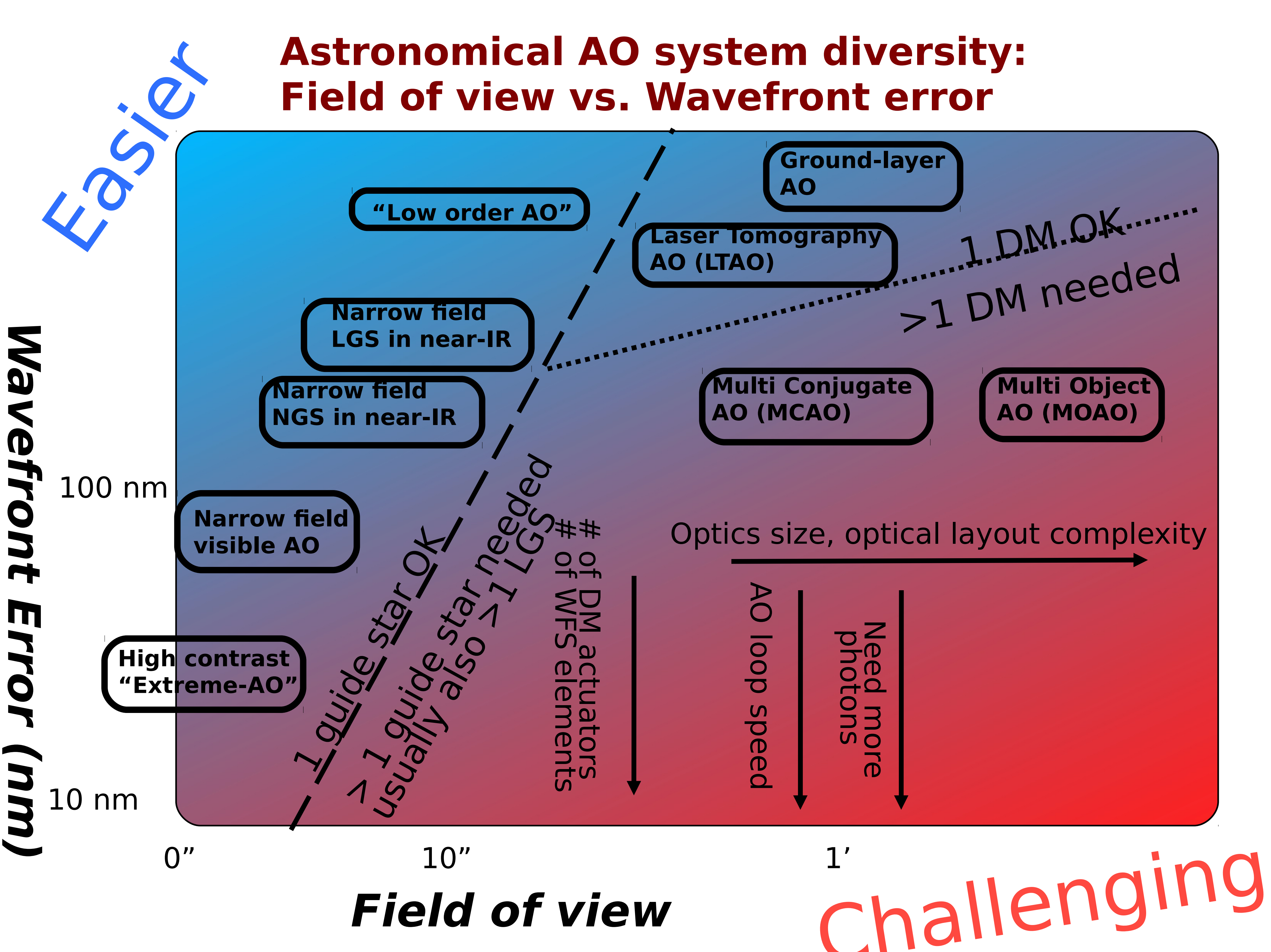
Why build an Astronomical Adaptive Optics System ?

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

Improved sensitivity (detecting 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 works well.

Astrometry:
Measuring the position of a source: small PSF helps !
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.

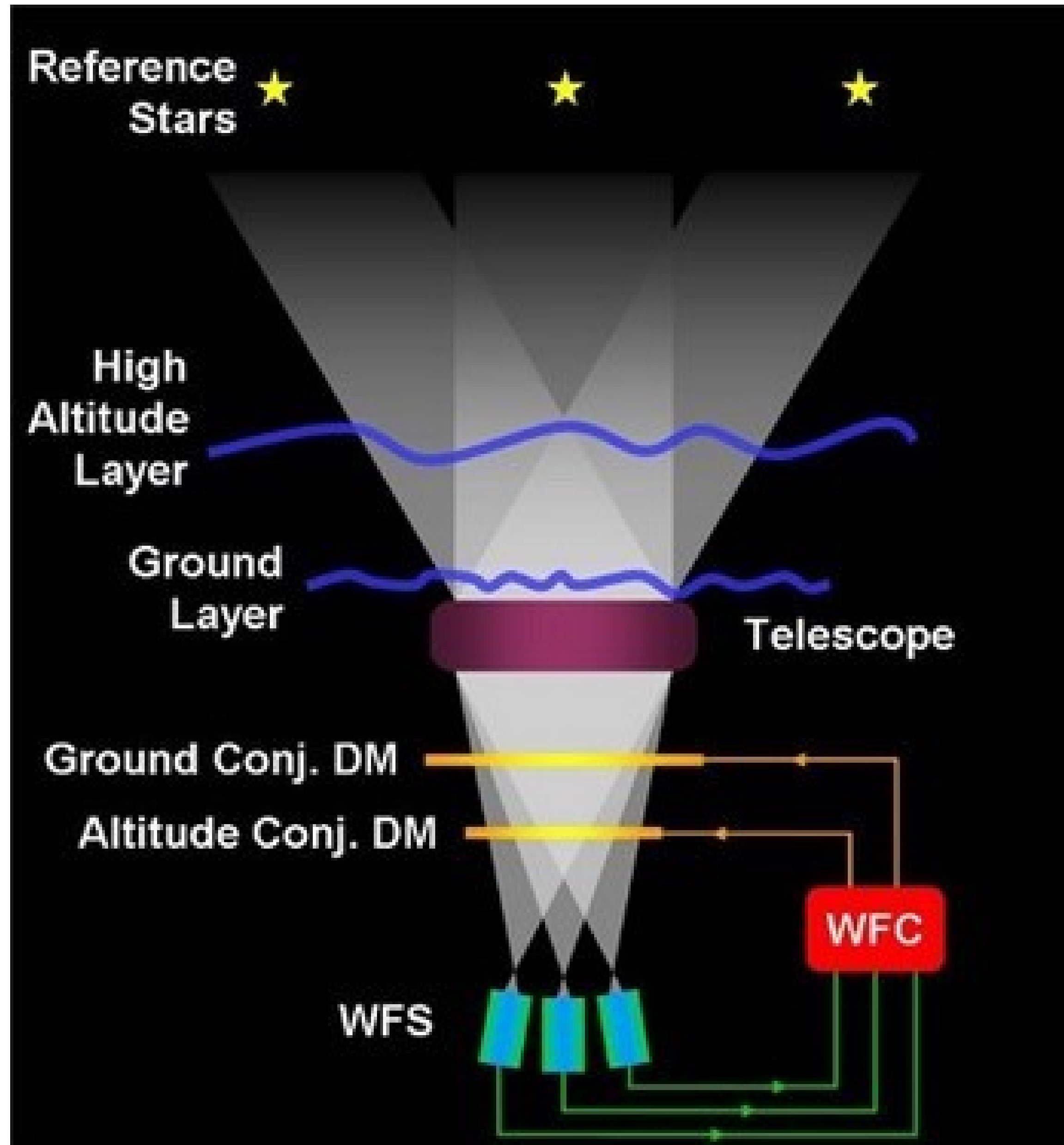


Astronomical AO system diversity:
Field of view vs. Wavefront error
Easier
Challenging
Wavefront Error (nm)
100 nm
10 nm
Field of view
0”
10”
1’
“Low order AO”
Ground-layer AO
Laser Tomography AO (LTAO)
1 DM OK
>1 DM needed
Narrow field LGS in near-IR
Narrow field NGS in near-IR
Multi Conjugate AO (MCAO)
Multi Object AO (MOAO)
Narrow field visible AO
High contrast “Extreme-AO”
1 guide star OK
> 1 guide star needed
usually also >1 LGS
Optics size, optical layout complexity
of DM actuators
of WFS elements
AO loop speed
Need more photons

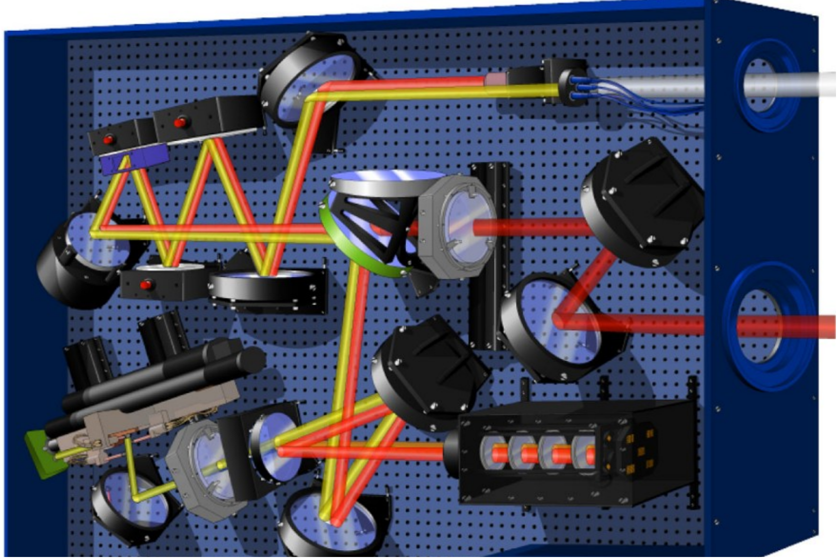
Example #1:
Multi-Conjugate AO (MCAO)

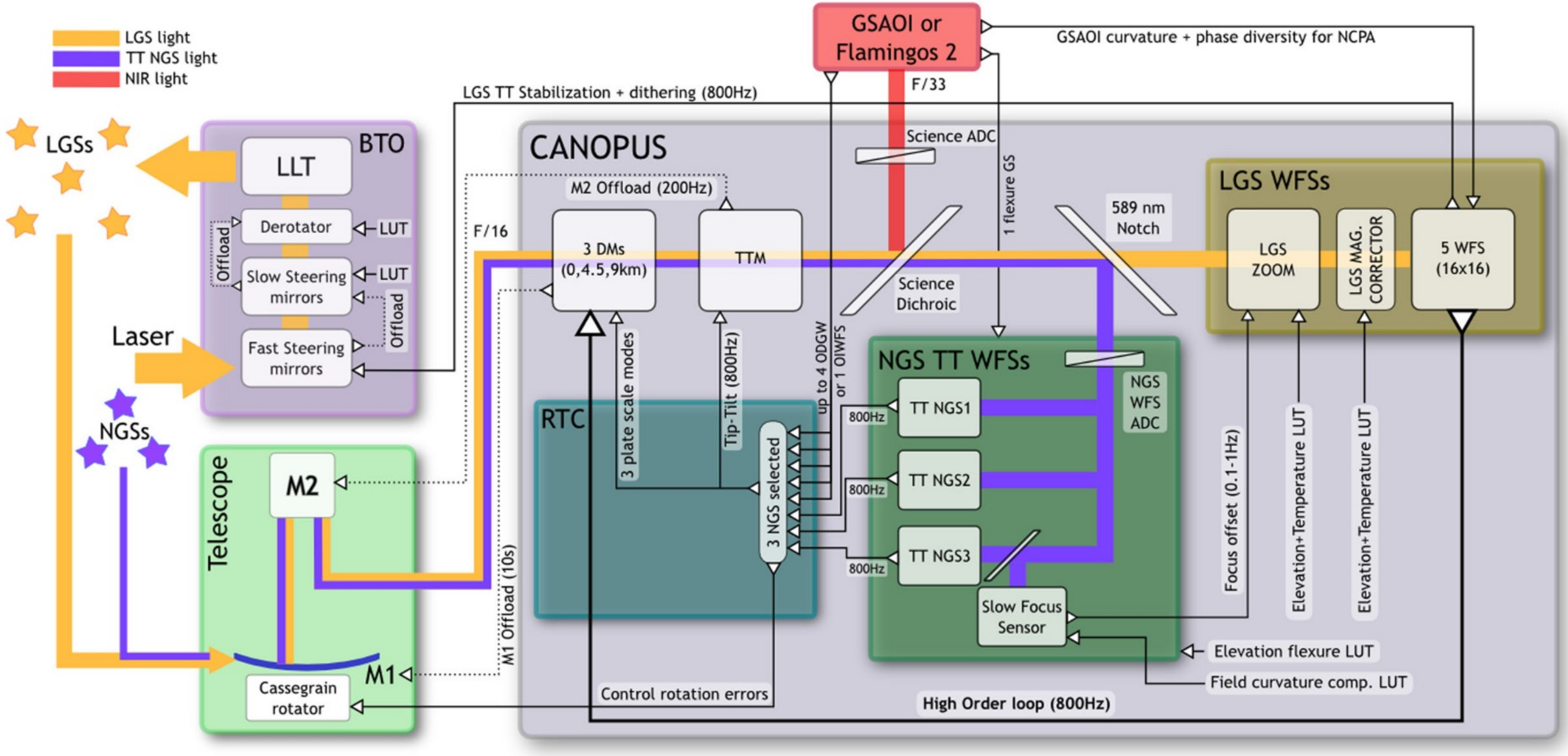
Uses several guide stars
(NGS or/and LGS)
to gain volumetric
information of turbulence.

Uses several DMs to correct
over wide field.



Gemini multiconjugate adaptive optics system (GeMS)



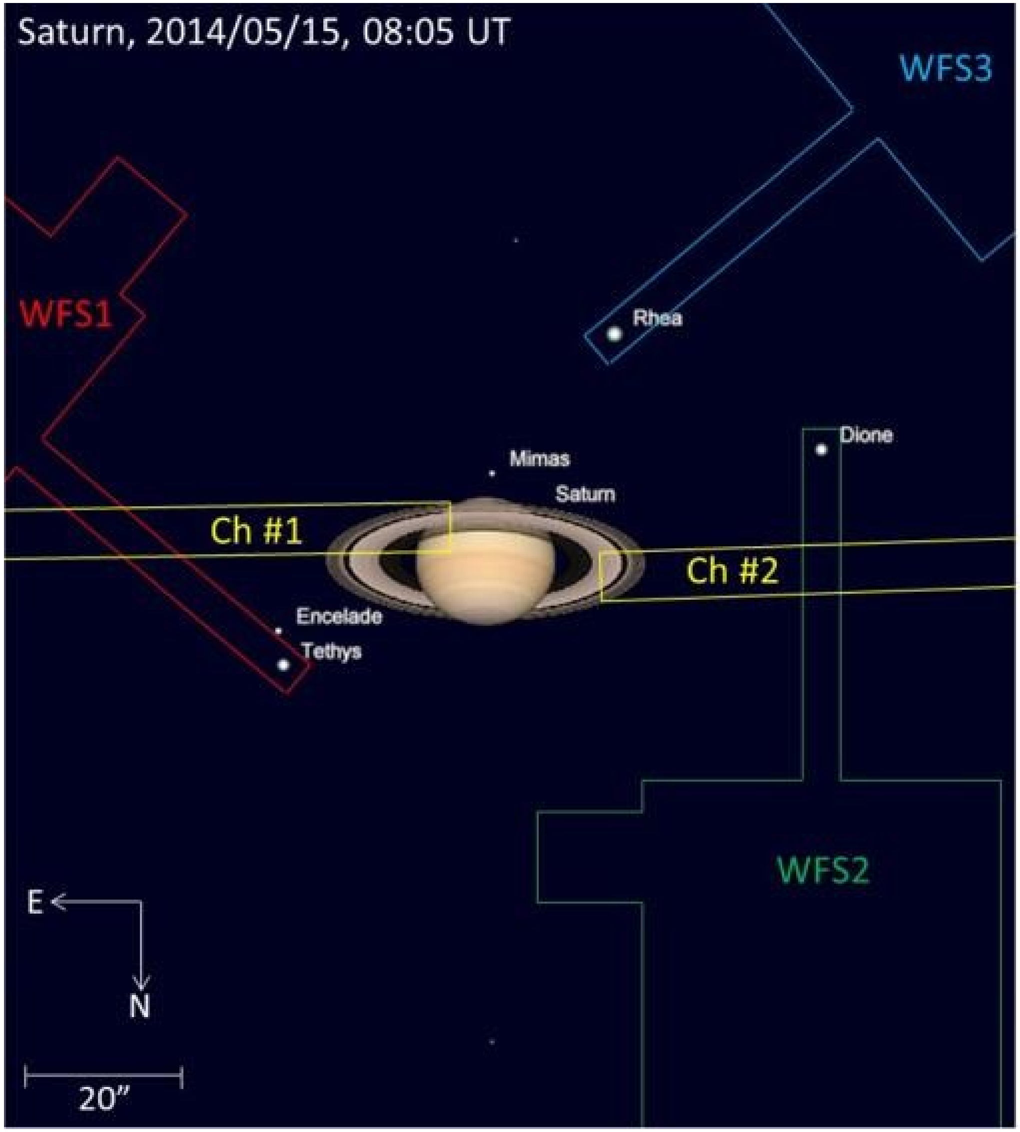


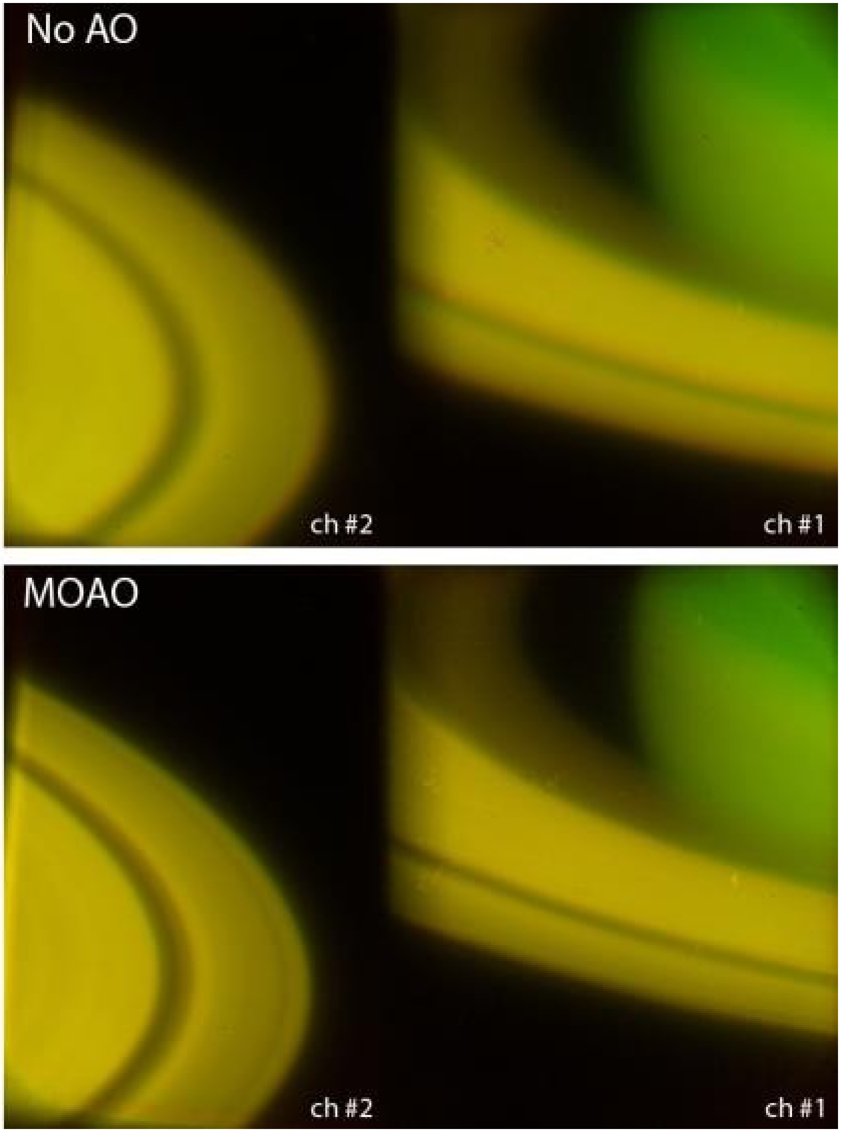
Credit: Gemini Observatory / AURA

Gemini Observatory Legacy Image

Example #2: The RAVEN MOAO system

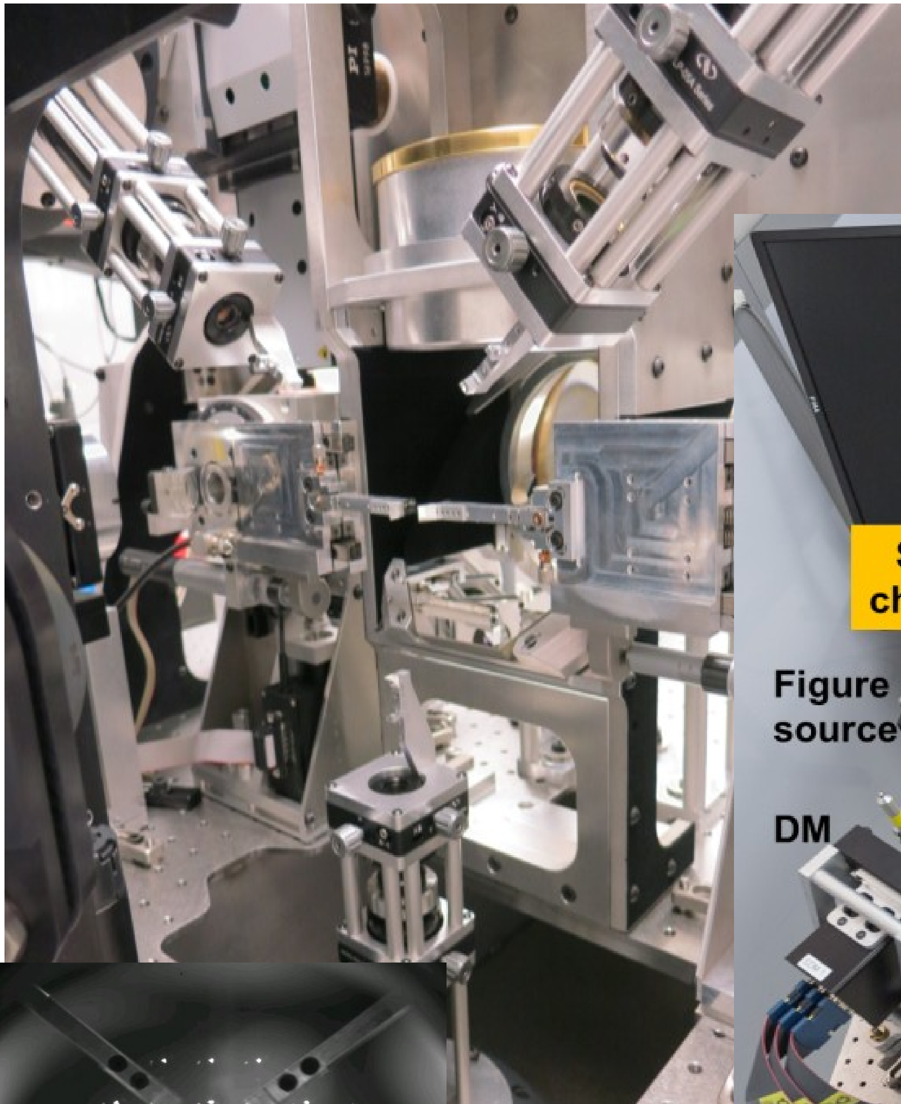
3 natural guide stars → 2 fields corrected (each with a separate DM)

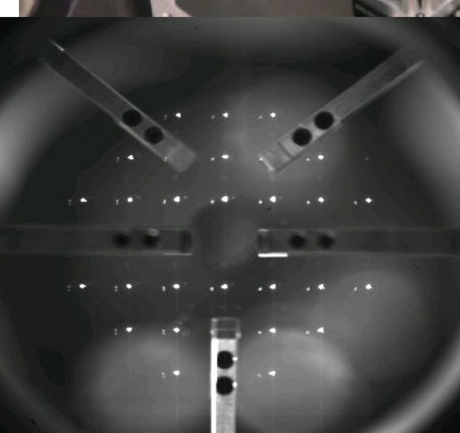




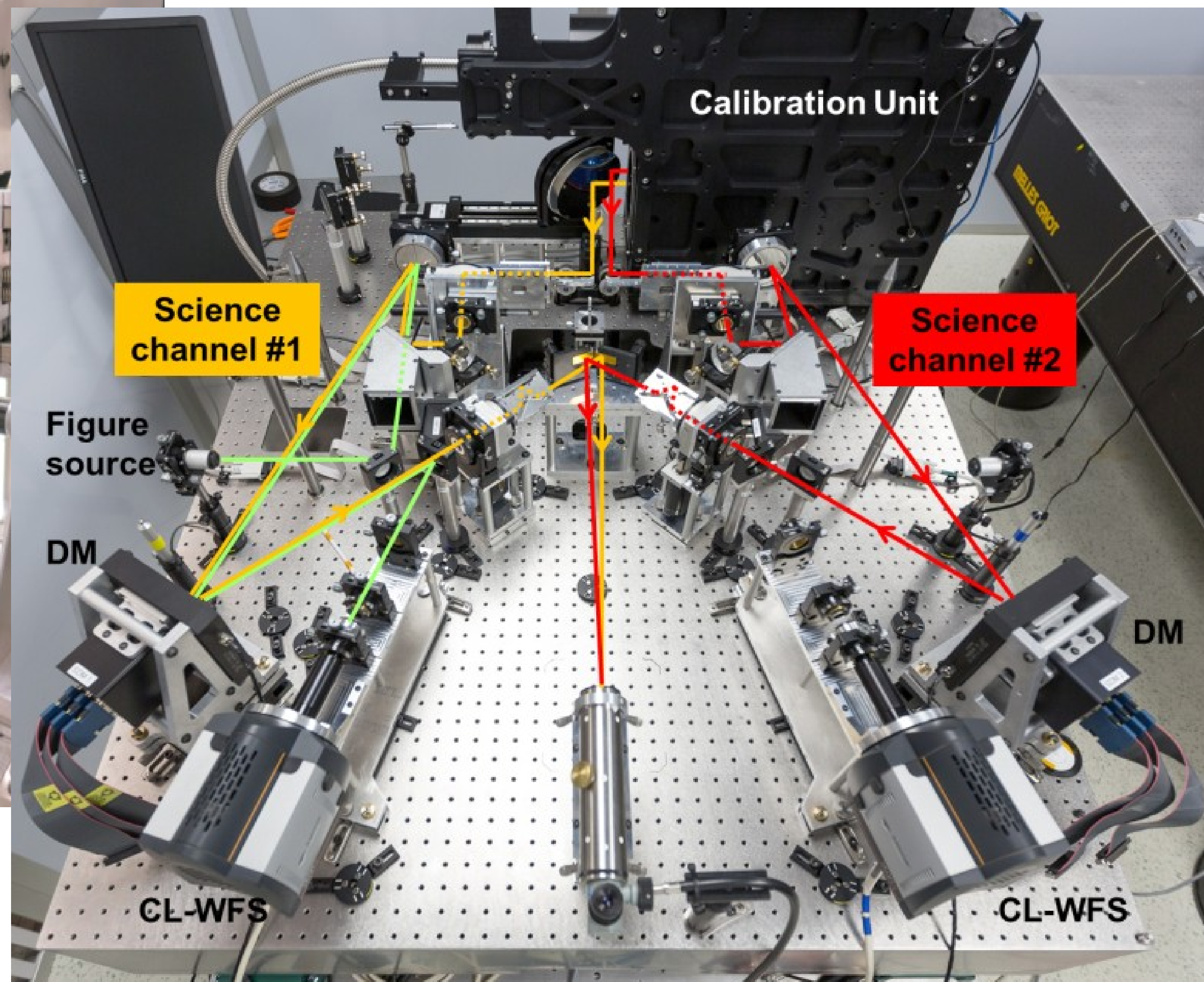
RAVEN optical bench (University of Victoria and Subaru Telescope)

WFS and science fields acquisition

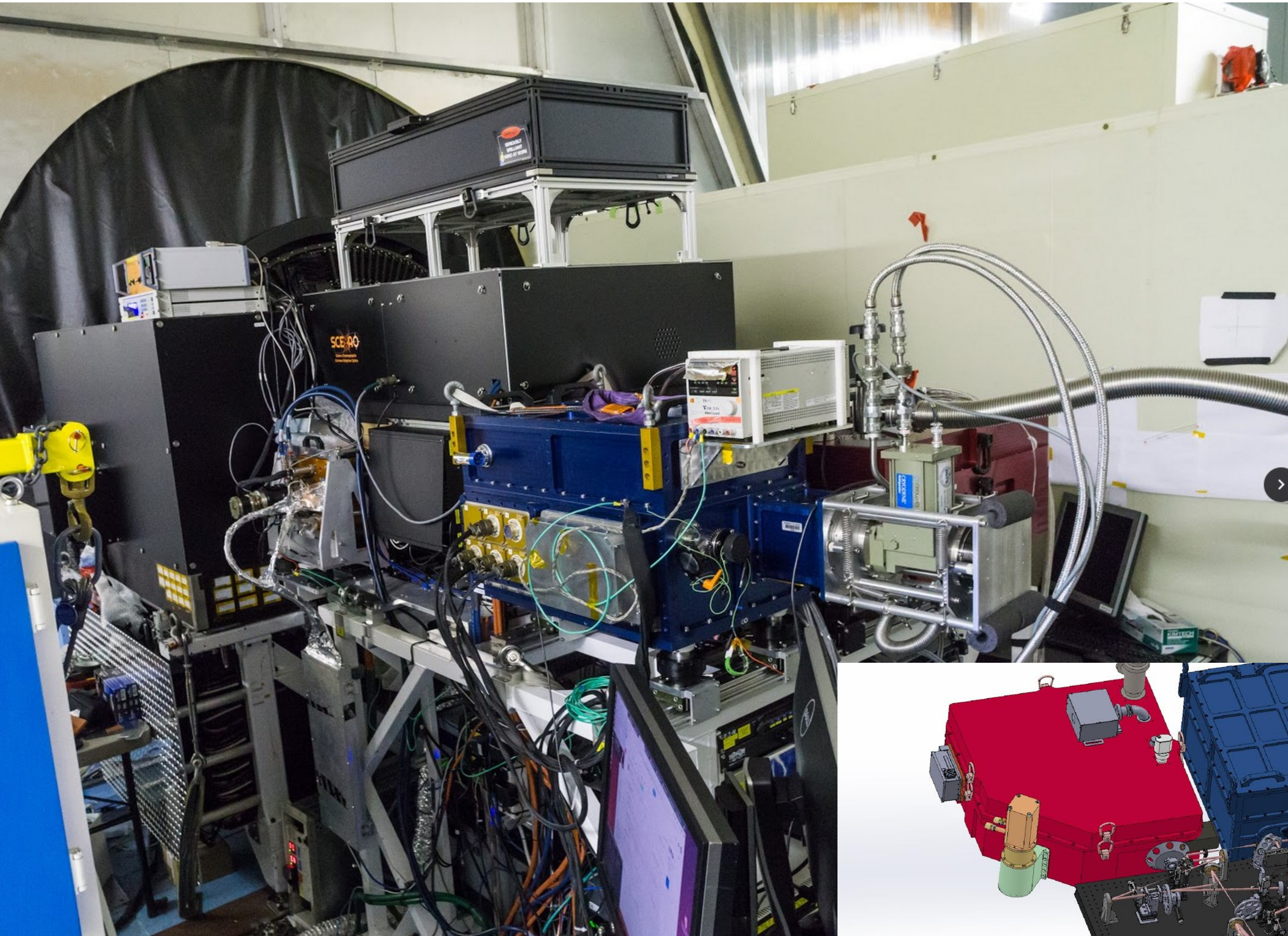




WF correction



Example #3: Extreme-AO system

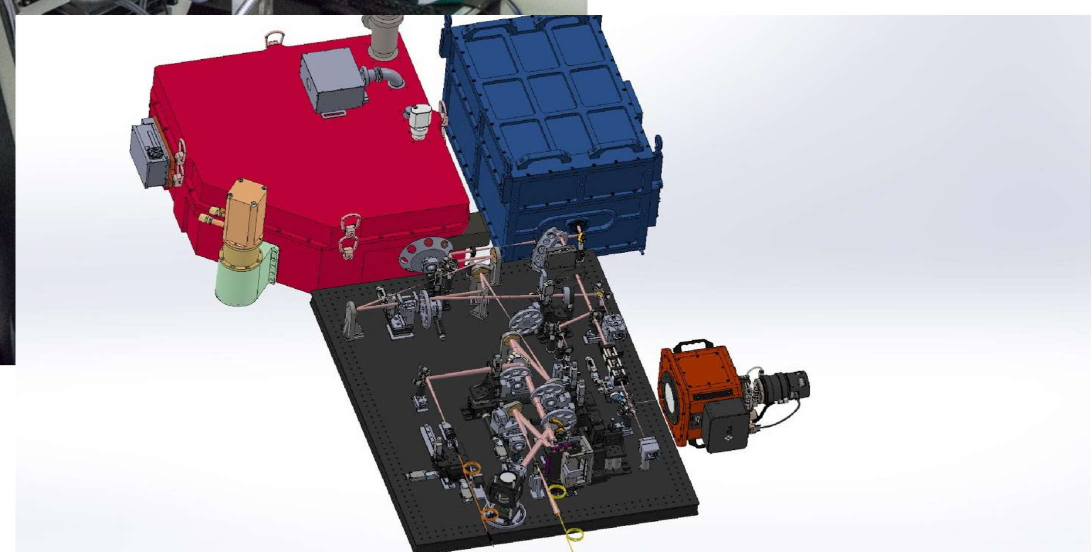


4 wavefront sensors:

- Coarse correction (visible WFS)
- Extreme-AO (visible pyramid)
- Low-order (near-IR)
- Speckles (near-IR)

3 deformable mirrors:

- 188 element bimorph
- 2000 element MEMs
- 37 segments MEMs



SCExAO modules

SCExAO Subaru Coronagraphic Extreme Adaptive Optics

The wavefront control feeds a high Strehl PSF to various modules, from 600 nm to K band.

Visible (600 – 950 nm):

VAMPIRES, non-redundant masking, polarimetry, with spectral differential imaging capability (h-alpha, SII)

FIRST, non-redundant remapping interferometer, with spectroscopic analysis

RHEA, single mode fiber injection, high-res spectroscopy, high-spatial resolution on resolved stars

IR (950-2400 nm):

HiCIAO - high contrast image (y to K-band)

SAPHIRA - high-speed photon counting imager, (H-band for now)

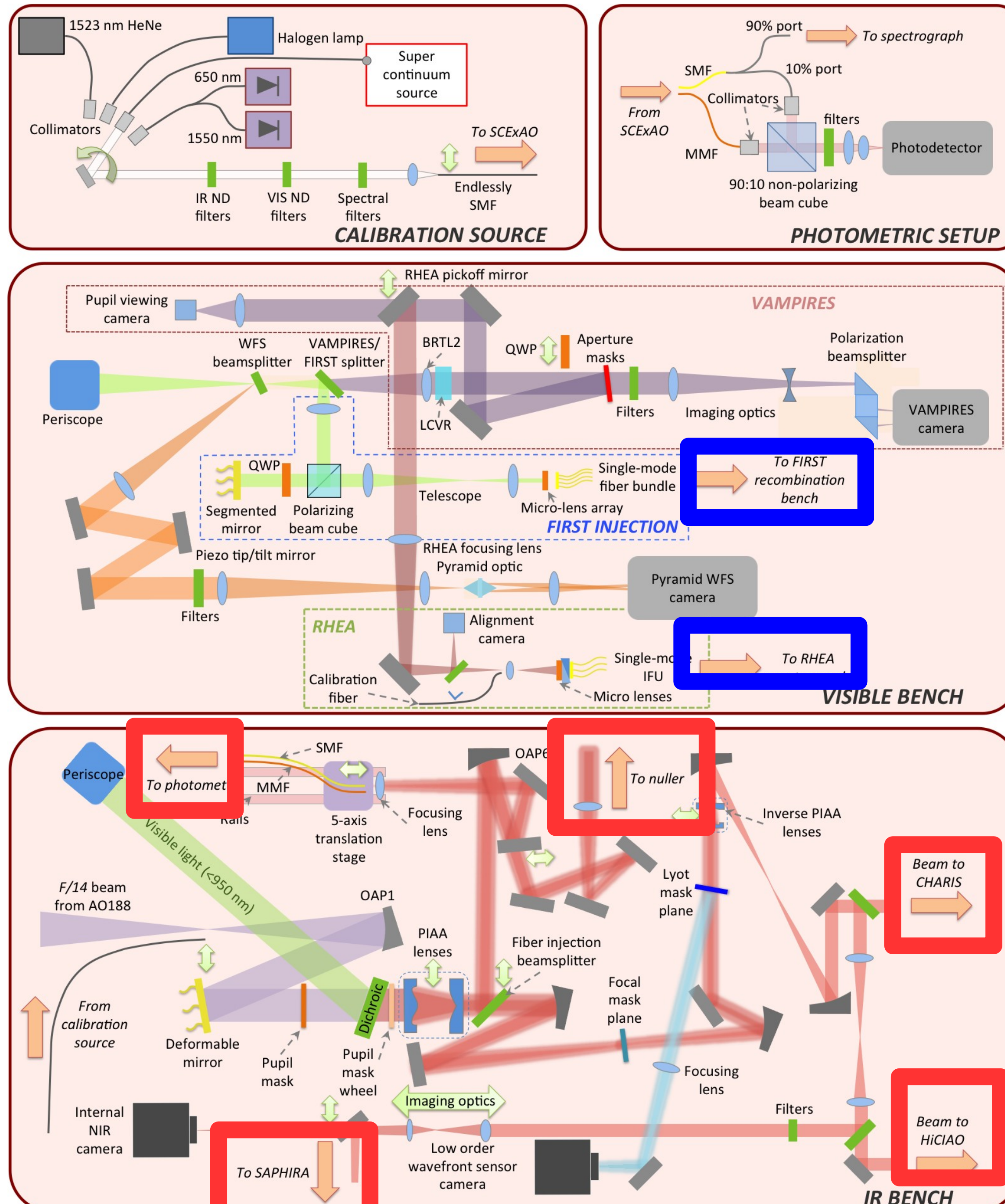
CHARIS - IFS (J to K-band)

MEC - MKIDs detector, high-speed, energy discriminating photon counting imager (y to J-band)

NIR single mode injection, high throughput high resolution spectroscopy. Soon will be connected to the new IRD

Various small IWA (1-3 l/D) coronagraphs for high contrast imaging – PIAA, vector vortex, 8OPM

GLINT - NIR nulling interferometer based on photonics

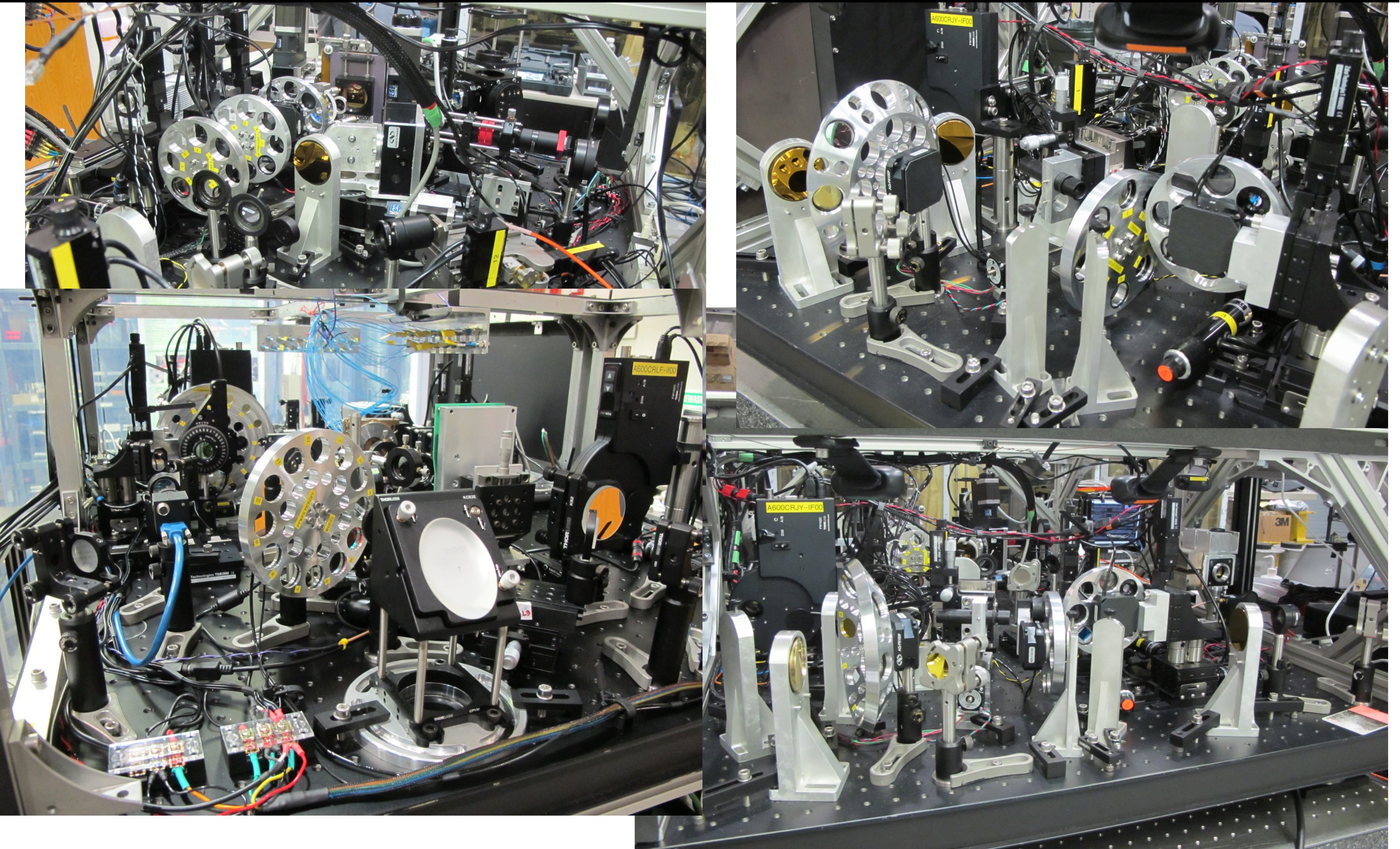


Jovanovic et al, PASP, 127, 890 (2015)

Altair Optics bench (Gemini North Telescope)

SCExAO

Subaru Coronagraphic Extreme Adaptive Optics



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Wavefront sensing strategy

Large field of view AO systems

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From photons to DM commands: making it all work nicely together

Fundamental wavefront error budget terms :

1 Fitting error

2 Speed

3 Limited # of photons

These 3 fundamental errors usually need to be traded against each other

4 AO guide “star” size & structure, sky background

5 Non-common path errors

- chromaticity
- cone effect (LGS) & anisoplanetism

6 Calibration, nasty “practical” things

- vibrations, instabilities between control loops
- DM hysteresis / poor calibration (generally not too serious in closed loop)

Useful references:

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

Wavefront error budget

Wavefront error (std deviation) σ is in radian in all equations.

Wavefront variance σ^2 is additive (no correlation between different sources), and the wavefront error budget is built by adding σ^2 terms.

Wavefront error (m) = λ x $\sigma/(2\pi)$

Strehl ratio ~ $e^{-\sigma^2}$
(Marechal approximation, valid for Strehl ratio higher than ~0.3)

1. Fitting error

Assuming that the wavefront error is perfectly known, how well can (the) deformable mirror(s) correct it ?

Wavefront errors from atmospheric turbulence in sq. radian

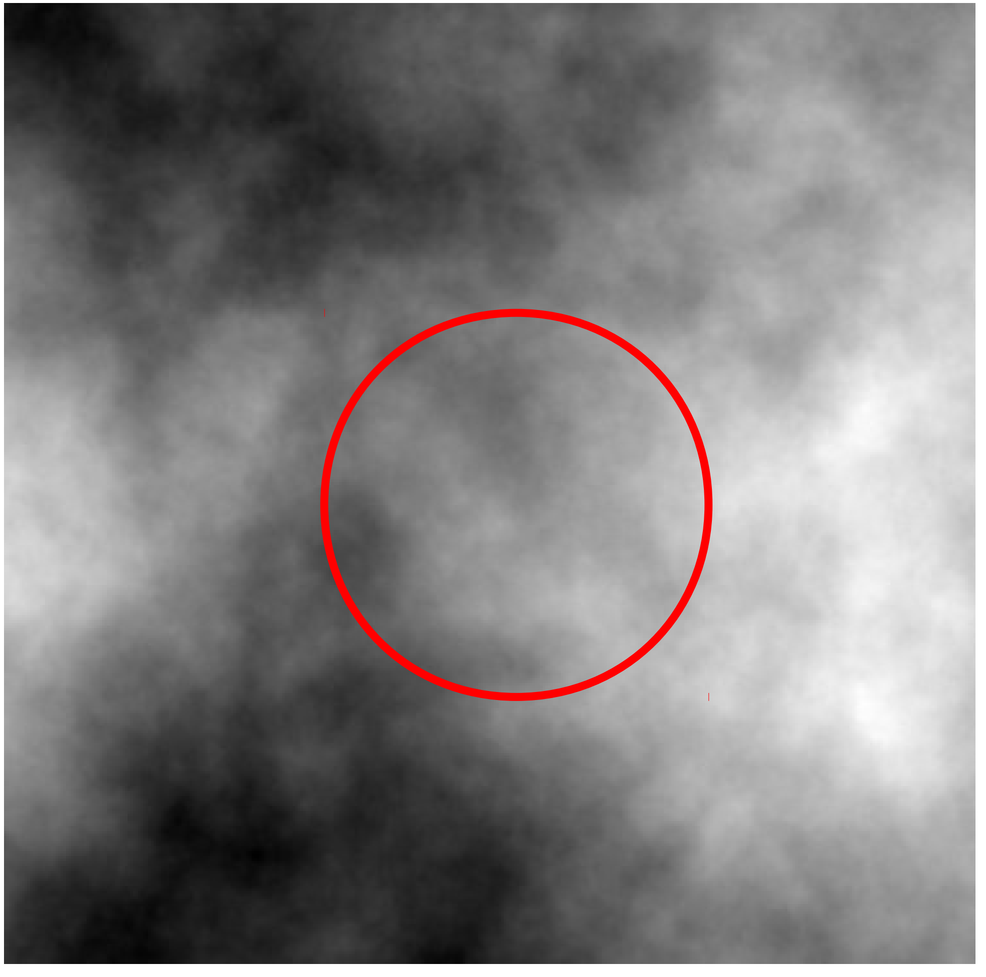
$\sigma^2 = 1.03\ (D/r_0)^{5/3}$

+ Vibrations, telescope guiding errors

+ Aberrations from optical elements (primary mirror, large number of small mirrors)

+ DM shape at rest

Kolmogorov turbulence



1. Fitting error

Need enough stroke on the actuators

$\sigma^2 = 1.03\ (D/r_0)^{5/3}$

(unit = radian)

Larger D -> more stroke needed

(also: faster system -> more stroke needed)

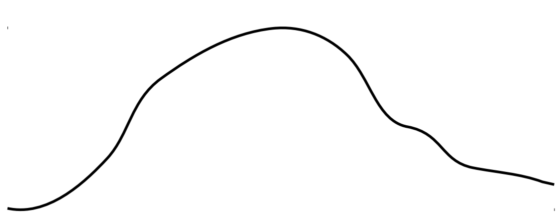
Most of the power is in tip-tilt:

It is helpful to have a dedicated tip-tilt mirror, or mount the DM on a tip-tilt mount

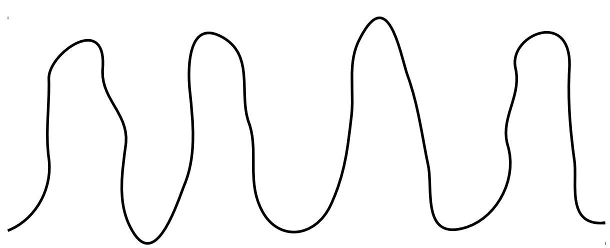
On many DMs, interactuator stroke < overall stroke

DM stroke needs to be looked at as a function of spatial frequency

eg: in a curvature DM, radius of curvature decreases as the number of actuators increases



Is easier than



1. Fitting error

Need enough actuators to fit the wavefront

D = telescope diameter, N = number of actuators

d = sqrt(D^2/N) = actuator size

If we assume each actuator does perfect piston correction (but no tip/tilt), WF error variance in sq. radian is:

$\sigma^2 = 1.03\,(d/r_0)^{5/3} = 1.03\,(D/r_0)^{5/3}\,N^{-5/6}$

If we assume continuous facesheet,

$\sigma^2 \sim 0.3\,(D/r_0)^{5/3}\,N^{-5/6}$

D = 8 m, r_0 = 0.8 m (0.2 m in visible = 0.8 m at 1.6 μm)

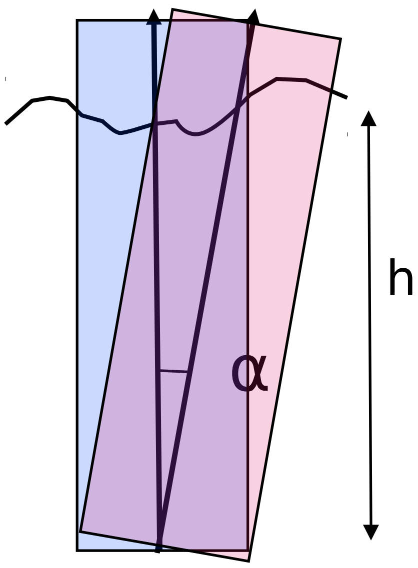
Diffraction limit requires ~ N = 24

In fact, exact DM geometry & influence functions are needed to estimate fitting error

1. Fitting error & field of view

Need enough actuators to fit the wavefront for over a non-zero field of view

Two equivalent views of the problem:
- Wavefront changes across the field of view (MOAO)
- Several layers in the atmosphere need to be corrected (MCAO)



If we assume perfect on-axis correction, and a single turbulent layer at altitude h, the variance (sq. radian) is :

$\sigma^2 = 1.03\ (\alpha/\theta_0)^{5/3}$

Where α is the angle to the optical axis,
θ_0 is the isoplanatic angle:

$\theta_0 = 0.31\ (r_0/h)$

D = 8 m, r_0 = 0.8 m, h = 5 km -> θ_0 = 10”

To go beyond the isoplanatic angle: more DMs needed (but no need for more actuators per DM).

2. Speed

Assuming perfect DMs and wavefront knowledge, how does performance decrease as the correction loop slows down ?

Assuming pure time delay t

$\sigma^2 = (t/t_0)^{5/3}$

t_0 = coherence time "Greenwood time delay"= 0.314 r_0/v

v = 10 m/s

r_0 = 0.15 m (visible)   0.8 m (K band)

t_0 = 4.71 ms (visible)   25 ms (K band)

Assuming that sampling frequency should be ~ 10x bandwidth

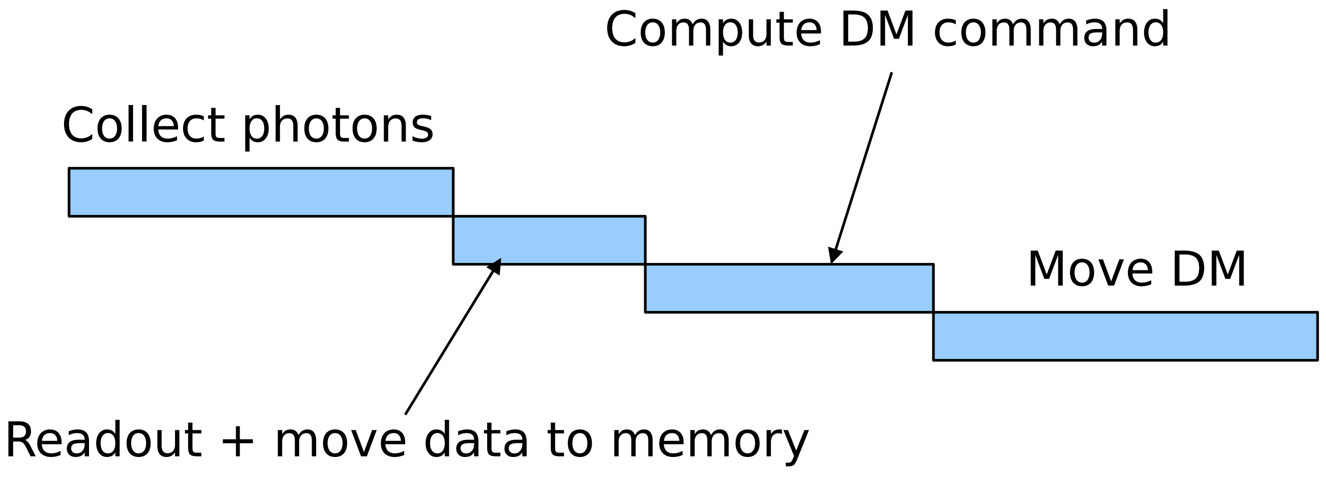
for "diffraction-limited" system (1 rad error in wavefront):
sampling frequency = 400 Hz for K band

for "extreme-AO" system (0.1 rad error):
sampling frequency = 6 kHz for K band

High speed means fewer photons / sample
→ need high SNR in WFS (optimal use of photons)

→ need fast hardware (see below)
- DM: good time response, low vibration
- Detector: fast readout / low readout noise
- computer, software & electronics

→ Clever, predictive control can help a lot
“anything that could be predicted should be !”



3. Limited # of photons from stars (per unit of time)

With a fixed finite photon arrival rate, how well can I measure the wavefront (speed vs. SNR) ?

Longer WFS "exposure time" -> better SNR but more time lag

m_V=15 -> 400 ph/ms on 8m pupil in 0.5 µm band (20% efficiency)

Example 1: **General purpose NGS system**

Goal: achieve diffraction limited performance over much of the sky

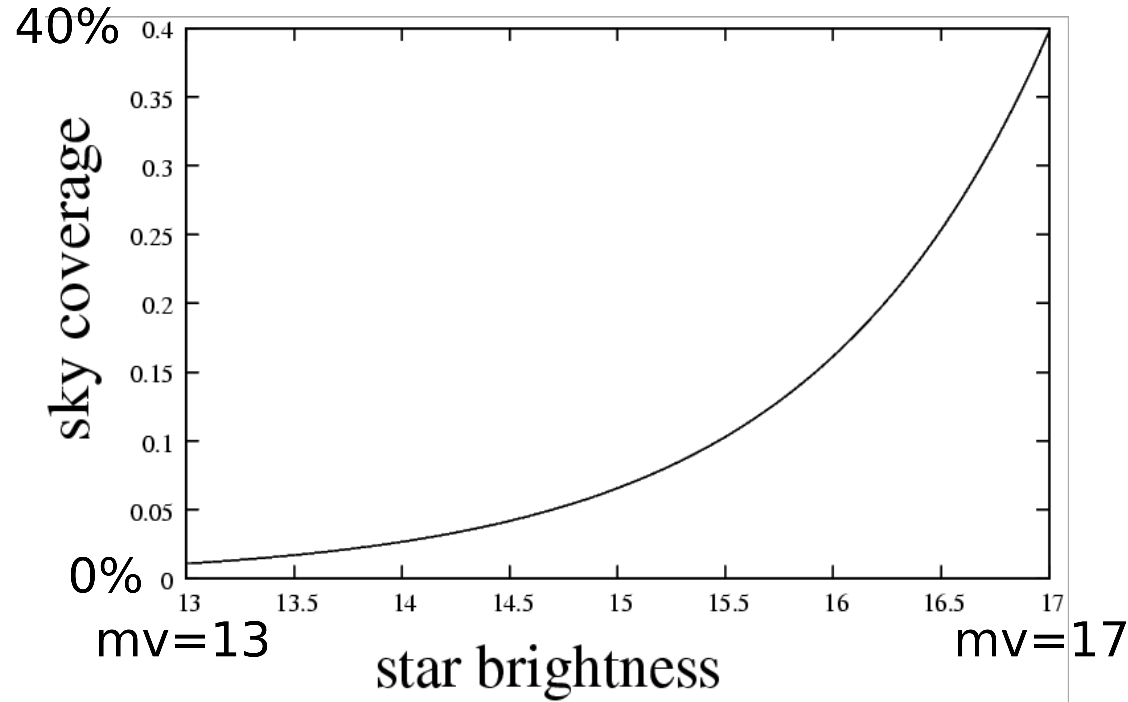
Star brighter than m_V density

~ 9e-4 exp(0.9 m_V) per

sq. deg (galactic pole)

ref: Parenti & Sasiela, 1994

Within a 20" radius:



NGS system has much higher changes of finding suitable guide star(s) in dense milky way than at high galactic latitude

Credit & Copyright: Alex Cherney (Terrastro)

Example 2: Extreme-AO system
Goal: Achieve exquisite wavefront correction on selected bright stars

m_V=8 → 2.5e5 ph/ms on 8m pupil in 0.5 µm band
& 20% efficiency

Running speed = 5 kHz (see speed section before)
2000 actuators

25 photons / actuators / sampling time
6 photon / pixel if 2x2 Shack Hartmann cells are used
with no readout noise, ~ 0.2 rad phase error per actuator
at best.

ExAO systems can easily be photon-starved due to high speed and large number of actuators

Limited # of photons will push system design into:

→ high efficiency WFS: good at converting OPD error into signal
(if possible, choose shorter wavelength)

→ high throughput (fewer optics), good detector (low readout noise)

→ WFS which works in broad band for NGS

→ bright laser for LGS, small angular size LGS

→ multiple guide stars

4. AO guide "star" size & structure, sky background

Extended targets means lower WFS efficiency and/or WFS failure

This problem is very WFS-dependent (some WFSs cannot deal with extended sources)

- Laser guide star is typically 1" or more, and elongated
- NGS: atmospheric refraction can be serious
  -> Atmospheric Dispersion Compensator (ADC) is often essential in the WFS
- frequent problem in Solar system observations
- double stars can be a problem

Sky background:

for faint guide stars, moonlight is a concern

5. Non-common path errors

- anisoplanatism (also discussed earlier in fitting error)

Due to angular separation between guide star and science target, guide star WF is different from science WF

-> minimize distance between guide star & science field

-> use several guide stars & perform tomographic rec.

-> if FOV is needed, use several guide stars (NGS or LGS)

- chromaticity

AO correction is optimal for WFS wavelength, not for science wavelength (non negligible for Extreme-AO)

- cone effect (for LGS)

-> tomographic reconstruction

- instrumental non-common path errors

Due to optics in WFS only or in science camera only

-> may need to be measured (for example, phase diversity daytime calibration) and offset to AO loop

6. Calibration, nasty “practical” things

- vibrations
  - -> good mechanical design
  - -> beware of cryocoolers (pumps), fans

- DM hysteresis / poor calibration (generally not too serious in closed loop)

- instabilities between control loops

Just because the AO system works in the lab, doesn't mean that it will work when it is on the telescope

Physical environment can be quite different (temperature, humidity, pressure, gravity orientation change, vibration environment)

Input wavefront may not be what is expected (telescope vibration, larger than expected telescope wavefront error)

Science wavelength choice:
IR is "easy", visible is "very very hard"

Things that get worse as lambda gets small:

- r_0 gets small: more actuators needed

  r_0 goes as $\lambda^{6/5}$ -> N goes as $\lambda^{-12/5}$

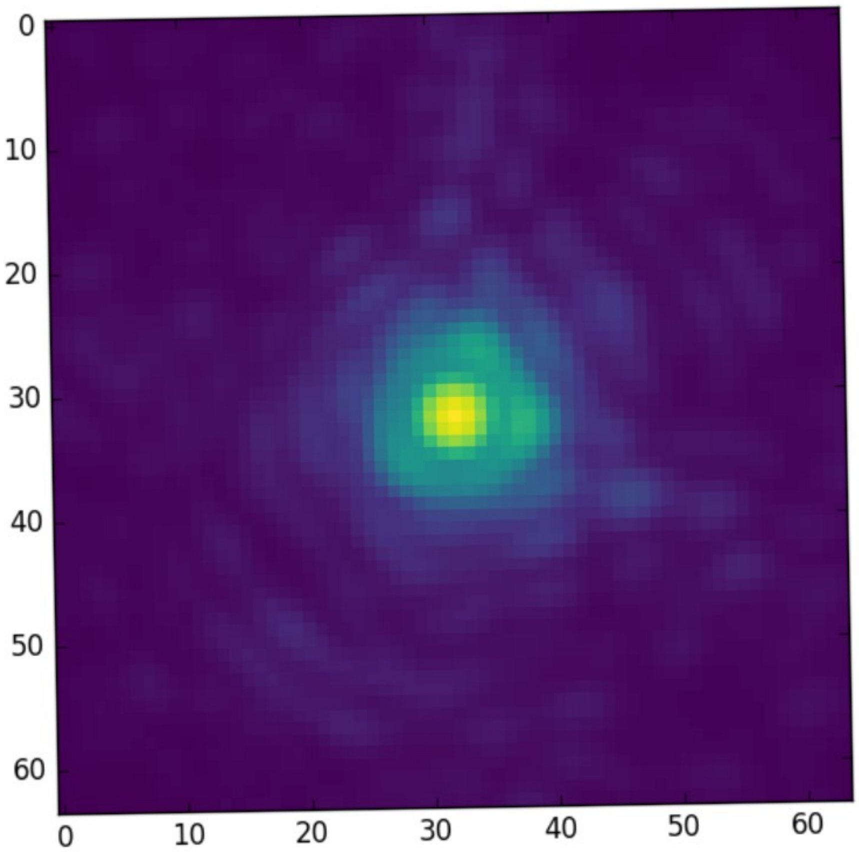
- speed gets high ($\tau_0 = 0.314\ r_0/v$) -> τ_0 goes as $\lambda^{6/5}$
- anisoplanatism gets small (FOV, sky coverage go down)

  θ_0 goes as $\lambda^{6/5}$

- chromaticity gets worse (refraction index of air varies more in visible than near-IR), ADC is needed
- instrumental non-common path errors get more serious

But diffraction limit is small in visible

Visible AO imaging: excellent angular resolution



VAMPIRES image @ SCExAO, 750nm, 1kHz imaging (summed)
log scale

FWHM = 20mas

(diffraction limit of 8m telescope at 750nm)

See also:

MagAO (dual-band visible camera)

ZIMPOL/SPHERE at ESO's VLT

Number of actuators should be very carefully chosen

Resist temptation of having more actuators than needed:
Systems with too many actuators are:
- not very sensitive (don't work well on faint stars)
- Harder to run at high speed
- demanding on hardware, more complex & costly
- less tolerant (alignment, detector readout noise...)

See also “noise propagation” section of this lecture

There is usually little motivation to have much more than ~1 actuator per r0.

Exception:
Extreme-AO, where actuator # is driven by the size of the high contrast “dark hole”

PSF quality: metric**S**

PSF quality metrics are driven by the science goals, and different metrics are used for different science goals/instruments/AO systems.

Example or PSF quality metrics:

- Full Width at Half Maximum (FWHM)
- Encircled energy (50 % of light in 0.xx” diameter)
- Strehl ratio
- astrometric accuracy
- photometric accuracy
- PSF contrast (for Extreme-AO)
- Correction radius (for Extreme-AO)
- residual jitter (for Extreme-AO + coronagraphy)

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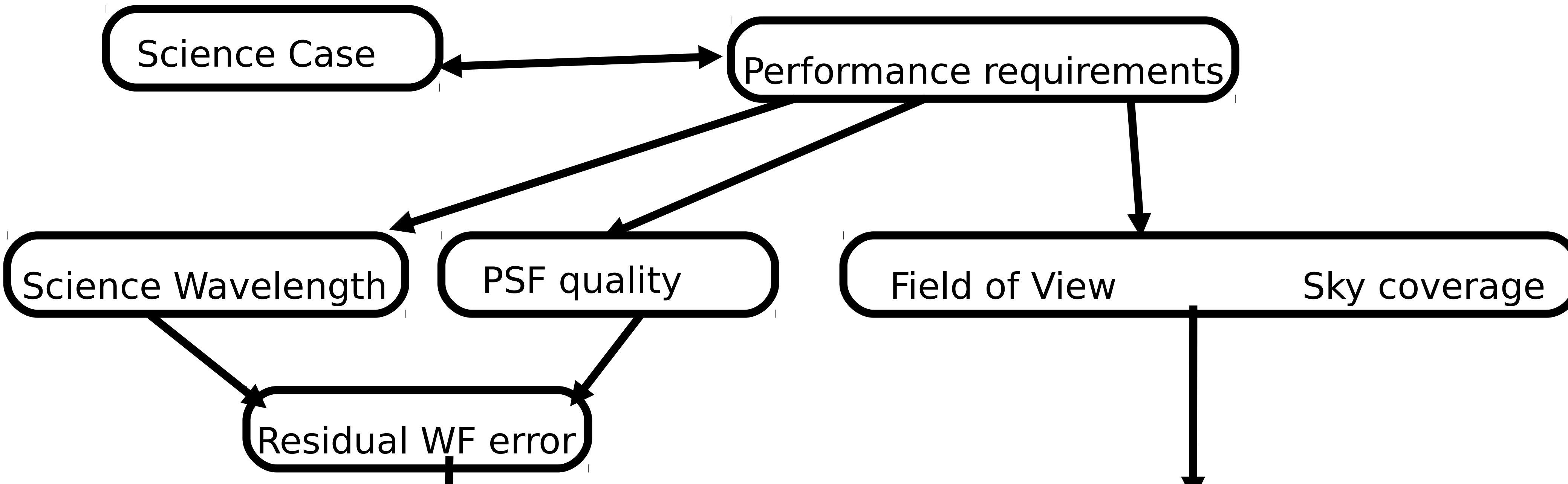
Choosing the wavefront sensing strategy is the most fundamental step in the design of an AO system



Where to get the wavefront measurement from ?

NGS ? LGS ?
How many guide stars, where ?
WFS wavelength ?

Wavefront sensor(s) choice

SH, Curv, PYR, other ?
How many elements ?

It is important to understand the physics of WFS well, avoid bad/inefficient combinations

Where to get the wavefront measurement ?

(1) Are there suitable natural guide star(s) ?

If not -> **Laser Guide Star (LGS)**

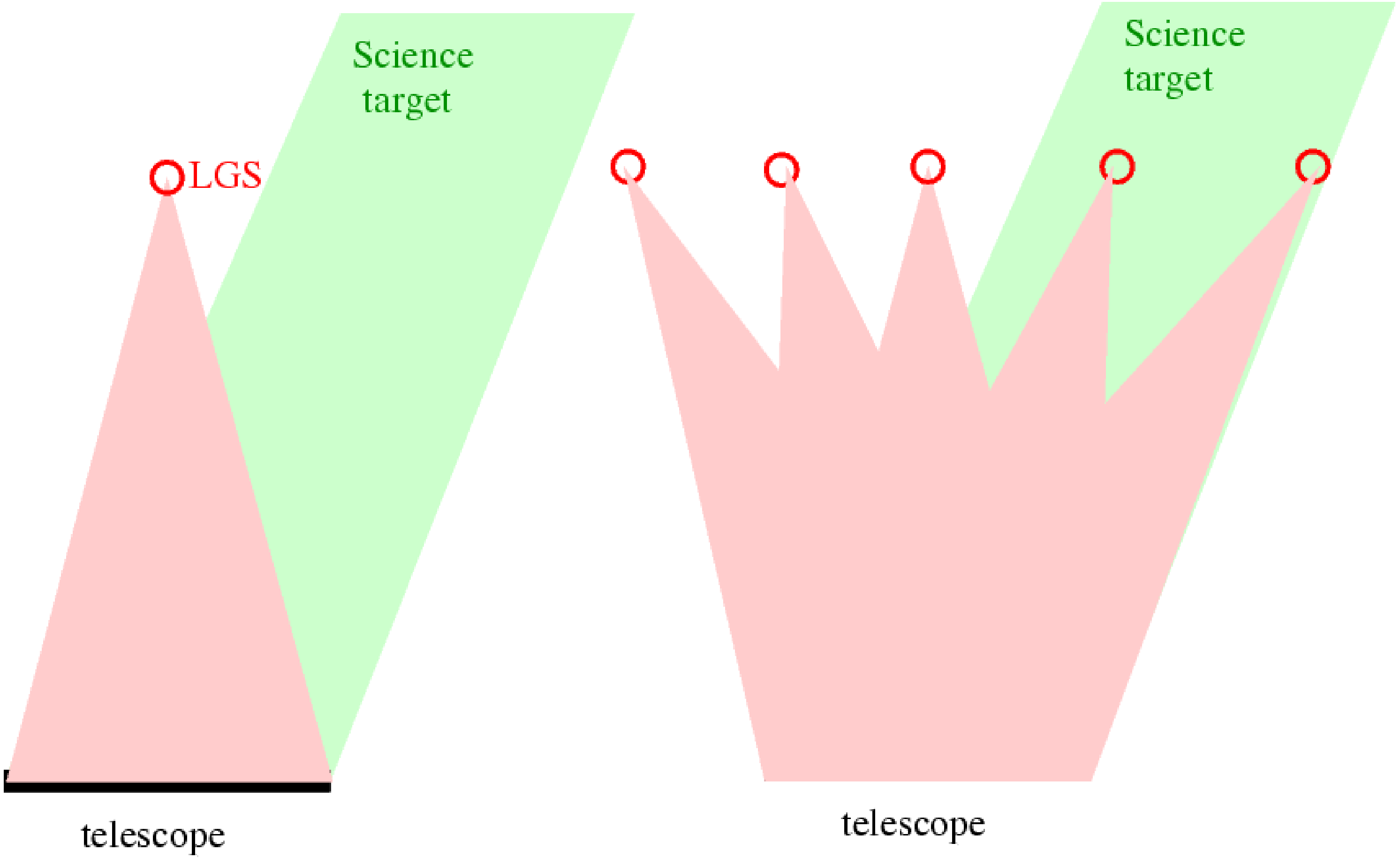
which laser ?

- Rayleigh
  - low altitude (few km) Rayleigh scattering
  - same process makes the sky blue
  - works better at shorter wavelength
- Sodium
  - excitation of sodium layer at 90 km
- Polychromatic Sodium (not quite ready yet)
  - excitation of sodium layer to produce LGS
  - in 2 wavelengths -> can solve Tip/Tilt problem

LGS allows large (>50%) sky coverage

Where to get the wavefront measurement ?

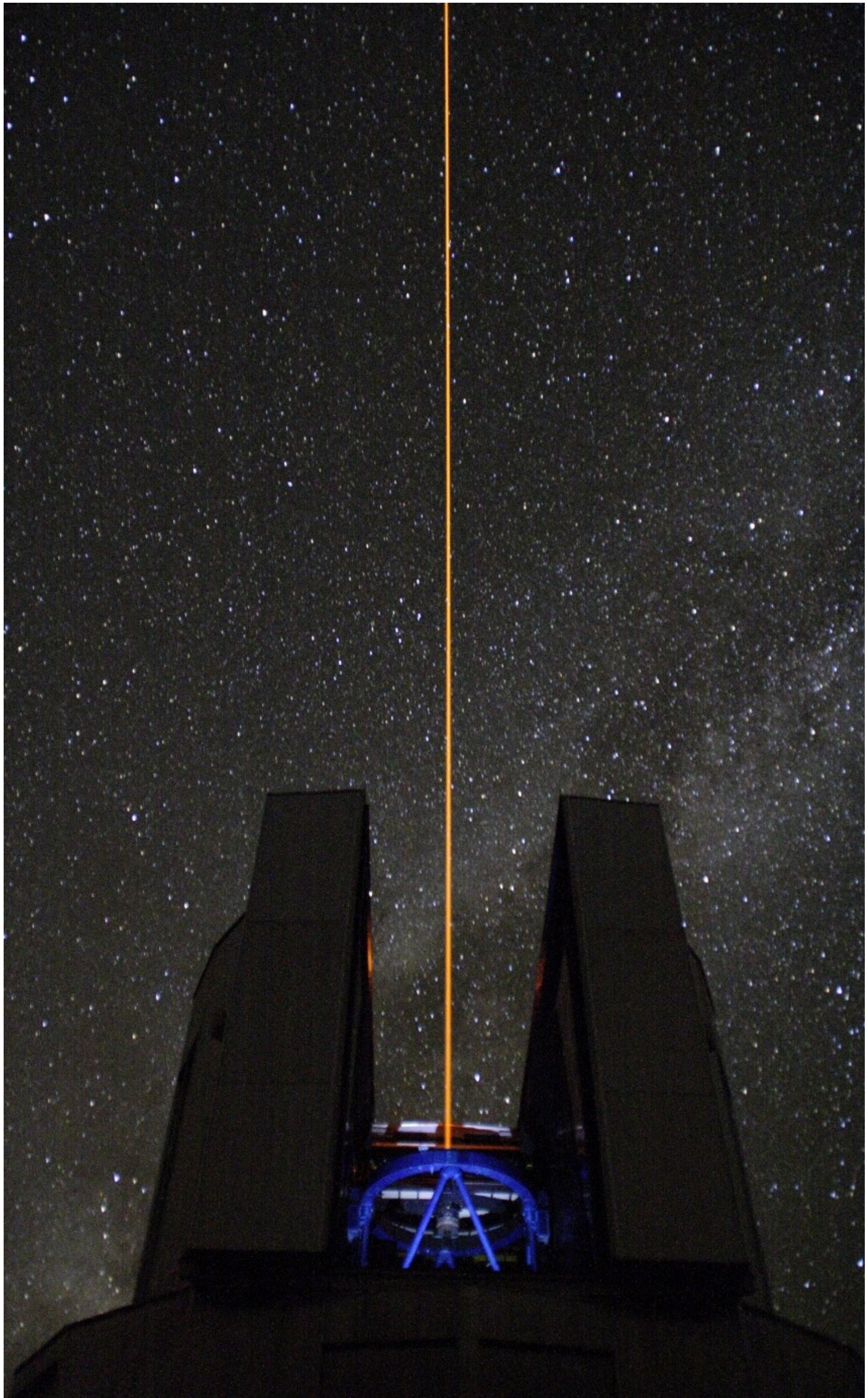
(2) Need several guide stars ?
(for field of view, tomography ?)
Multiple LGS ?
Multiple NGS ?



Some challenges of LGS AO

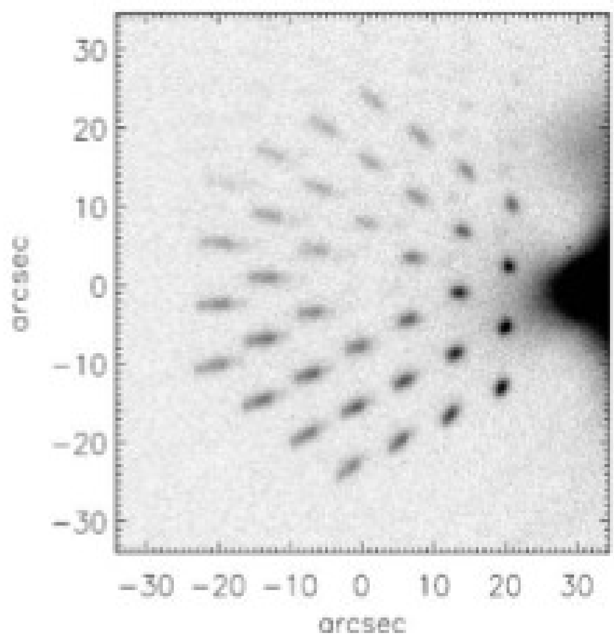
Cone effect due to finite altitude of LGS (90km sodium, few km for Rayleigh)
-> can be solved by using several lasers and tomography

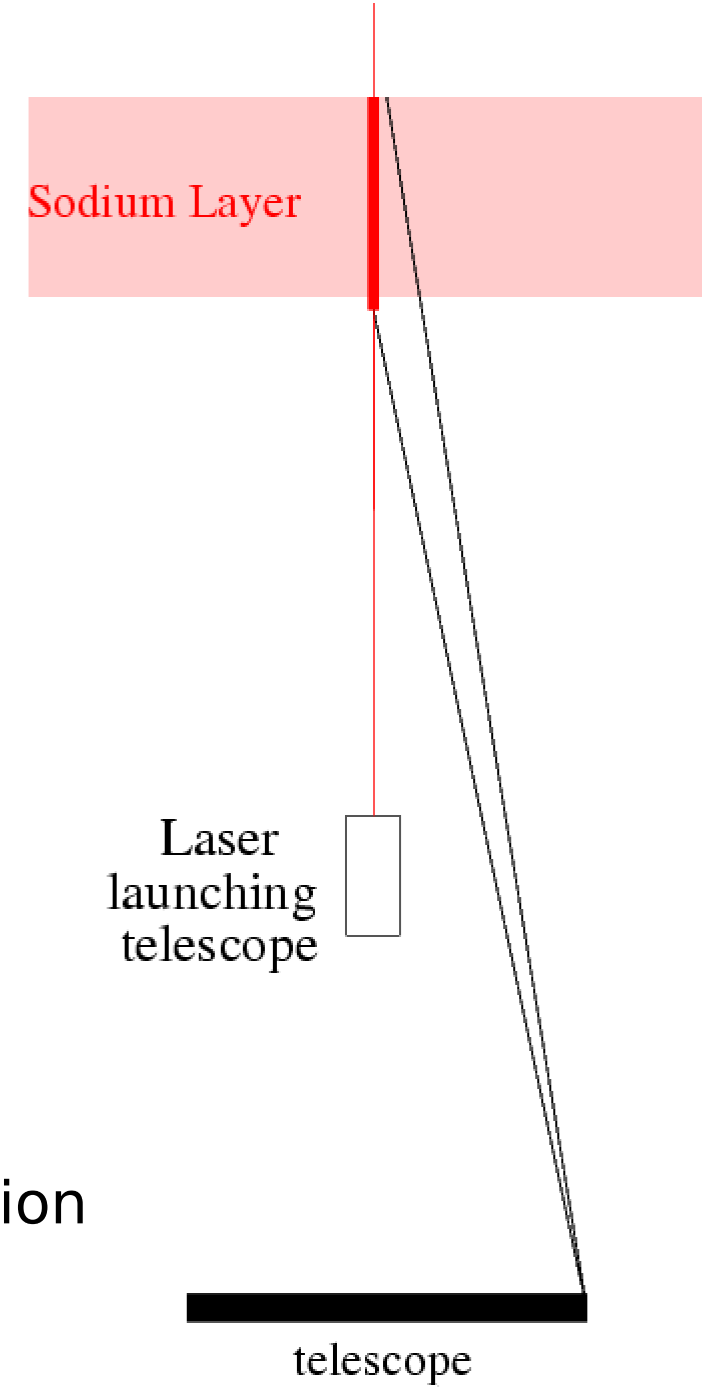
Tip/Tilt & Focus sensing
Upstream & downstream paths are the same: tip/tilt not seen
Sodium layer altitude not fixed: LGS focus info is incomplete (can be used to sense fast focus)
→ **Still need NGS(s) for tip/tilt & Focus**
→ **polychromatic laser (not quite mature yet)**



Some challenges of LGS AO

Spot elongation
Sodium layer
is ~10km thick





4m off-axis = 1” elongation
15m off-axis = 4” elongation
→ if single LGS, better to launch from the center of pupil than the edge
→ if multiple LGSs, can launch from edges and combine signal to mitigate spot elongation
→ dynamic refocusing + pulsed laser can remove spot elongation

LGS spot extended due to:

- Laser light has to go up through turbulence
- Diffraction from laser launching telescope aperture (usually << full telescope aperture)

-> it is very difficult to create a small size LGS

Spot size excludes some high sensitivity WFS options (discussed later)

Cone effect

Cone effect due to finite altitude of LGS (90km sodium, ~10-20 km for Rayleigh)

$$\sigma^2 = 1.03 \left(D / (2.91\theta_0 H) \right)^{5/3}$$

θ_0: isoplantic angle

H : LGS altitude

D : Telescope diameter

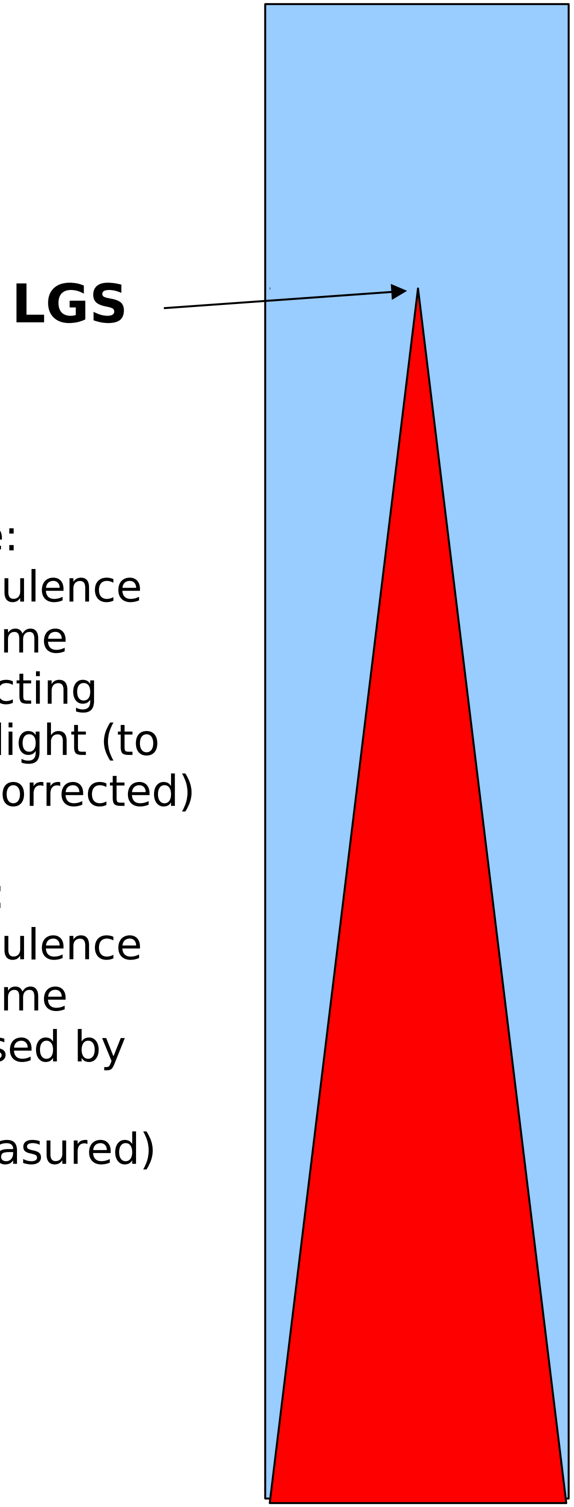
→ impact is smaller for sodium LGS

→ larger effect for large telescopes

Mitigated by using several LGSs

Blue: Turbulence volume affecting starlight (to be corrected)

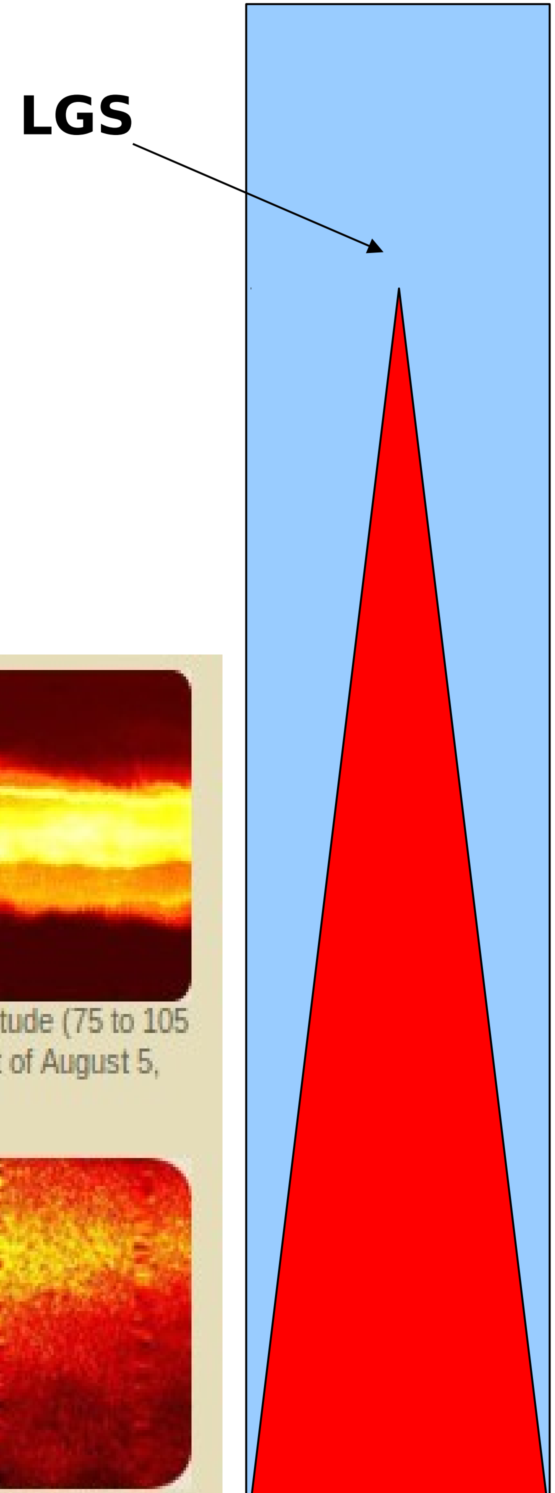
Red: Turbulence volume sensed by LGS (measured)



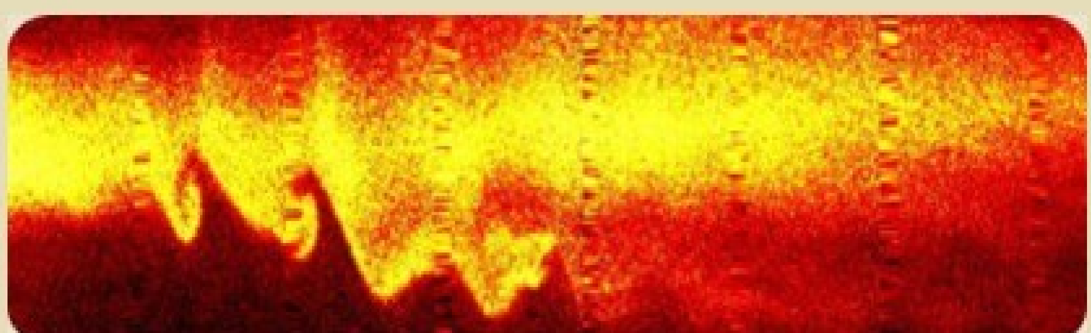
Focus sensing

Altitude of LGS is variable
(~90km sodium layer)
-> slow variations in measured
focus are introduced by sodium layer

Natural guide star is required to
measure slow focus
(fast focus can be measured by LGS)



This image shows sodium density above the facility as a function of altitude (75 to 105 km) and time (horizontal direction, covering about 5 hours) on the night of August 5, 2008.



Here we see a layer of sodium atoms becoming unstable and developing vortices. The vertical extent is 5 km and the elapsed time is 20 min.

LIDAR measurements
Pfrommer & Hickson 2009

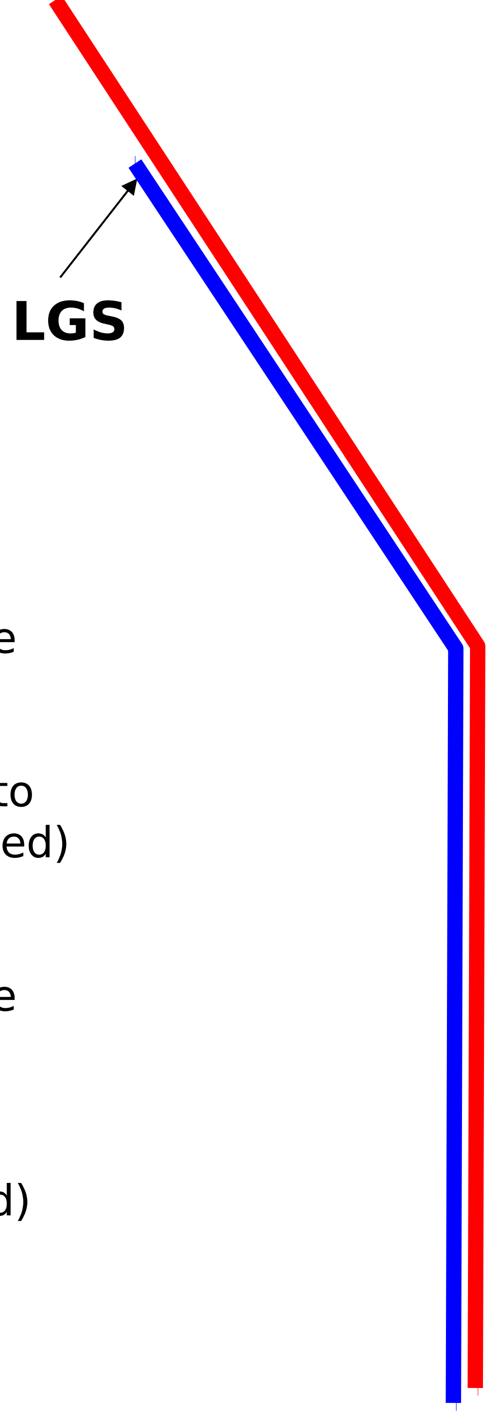
Tip-tilt sensing

LGS light goes from telescope to LGS, and then back from LGS to telescope (double pass)

NGS light goes from star to telescope (single pass)

→ tip-tilt is not sensed by LGS

Solutions:
- use natural guide star(s) to measure tip-tilt
- polychromatic LGS (under dev.)



Blue: Turbulence volume affecting starlight (to be corrected)

Red: Turbulence volume sensed by LGS (measured)

LGS AO system

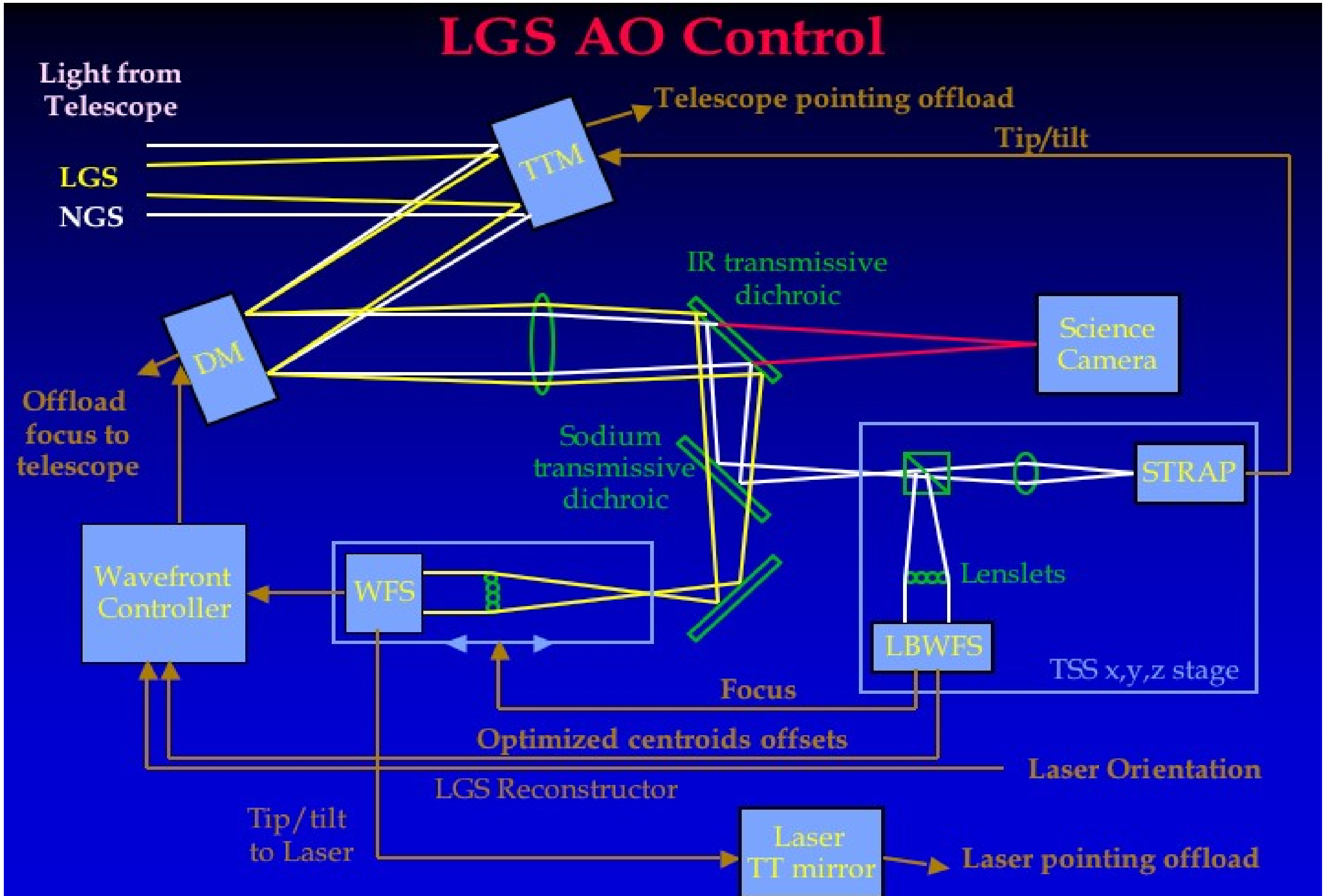
Must combine signals from several WFS sensors:

- Tip-tilt from NGS(s)
- Fast focus from LGS, slow focus from NGS
- High order modes from LGS
- (slow offset to some modes from NGS)

Needs mechanical focus stage for LGS

May need independent tip-tilt stage for LGS

Keck LGS system
Block diagram



Laser beam transport

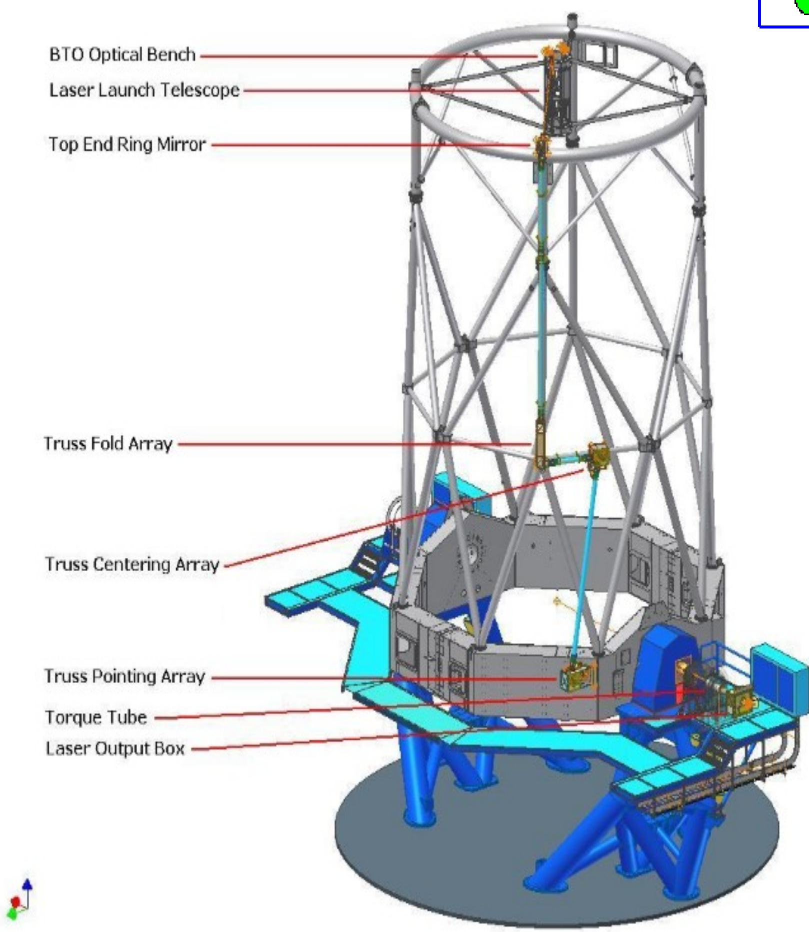
Lasers are too large to be mounted at the top of the telescope
Need to launch beam from behind secondary mirror
→ laser beam has to be transported

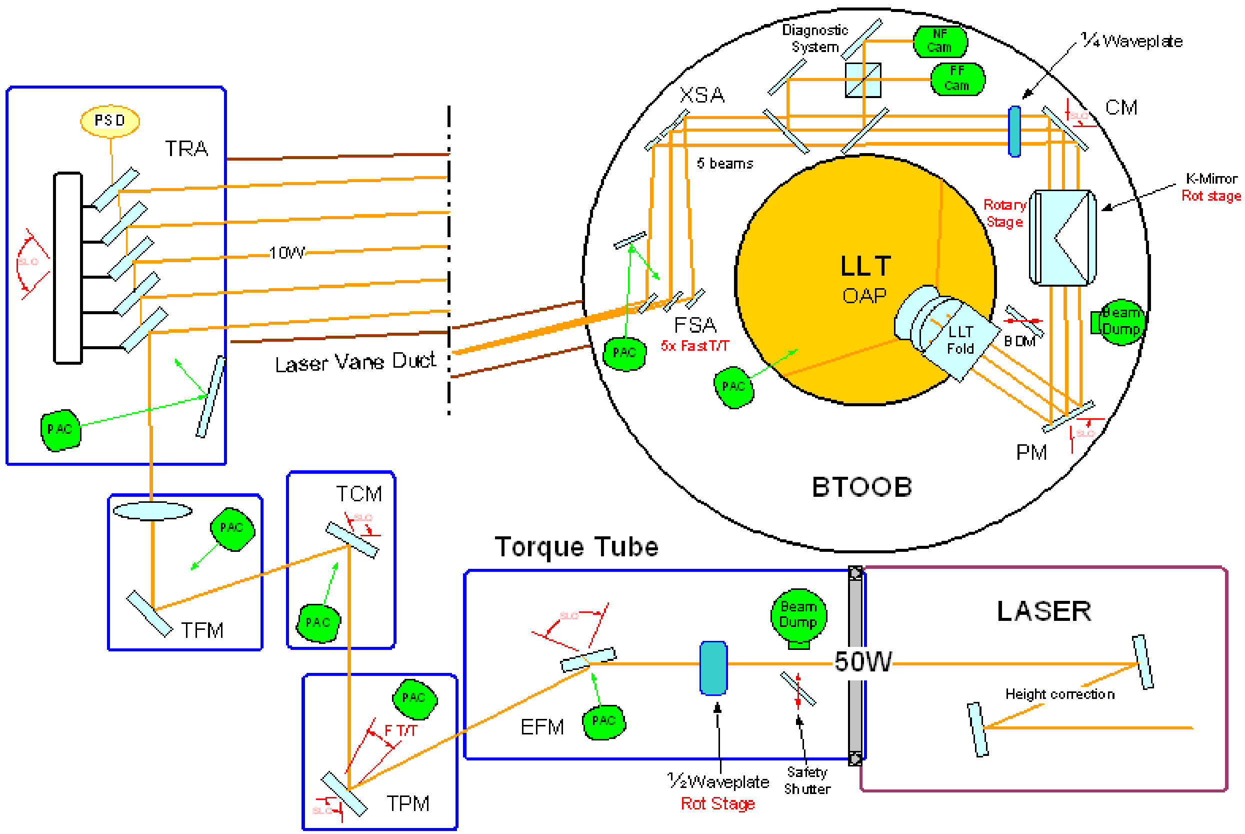
Two options:

Relay optics (mirrors)
Difficult to align, needs active compensation of flexures
(eg: Gemini, laser beam behind telescope spider)

Fiber transport
High power density in fiber: new fiber technologies
Fiber injection is critical
(eg: Subaru, laser in dedicated room, fiber runs to top of telescope)

Laser beam transport: GeMS system





Fundamental desirable WFS properties

Linearity:

The WFS response should be a linear function of the input phase

- simplifies control algorithm
- minimizes computation time -> important for fast systems

Capture range:

The WFS should be able to measure large WF errors

- the loop can be closed on natural seeing
- possible to use the WFS in open loop
- possible to "dial in" large offset aberrations

Sensitivity:

The WFS should make efficient use of the incoming photons

- the AO system can then maintain high performance on fainter sources
- the AO system can run faster

It is not possible to get all 3 properties simultaneously, and the WFS needs to be carefully chosen to fit the AO system requirements.

Wavefront Sensor Options

Linearity, dynamical range and sensitivity

Linear, large dynamical range, poor sensitivity:

Shack-Hartmann (SH)

Curvature (Curv)

Modulated Pyramid (MPyr)

Linear, small dynamical range, high sensitivity:

Fixed Pyramid (FPyr)

Zernike phase constrast mask (ZPM)

Pupil plane Mach-Zehnder interferometer (PPMZ)

Non-linear, moderate to large dynamical range, high sensitivity:

Non-linear Curvature (nlCurv)

Non-linear Pyramid (nlPyr) ?

Wavefront sensor choice

There is no such thing as a universally good (or bad) wavefront sensor

Wavefront sensor choice needs to take into account requirements:

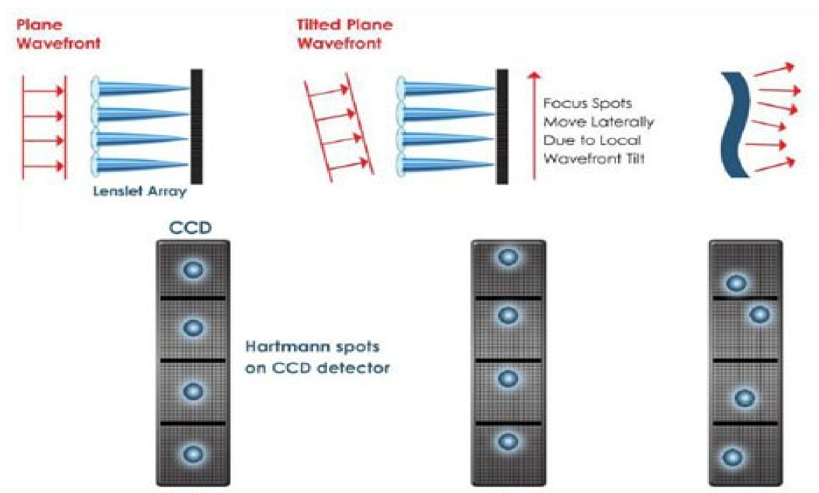
- is WFS used to initially close the AO loop ?
- Is WFS the main system WFS ?
- how many different things does the WFS need to do ?
- is input wavefront already cleaned by first stage AO correction ?
- is guide star extended (laser) or compact (natural star) ?
- is sensitivity a driving requirement ? Or is the AO system already limited by other components ?
- is reconstruction speed a concern ?

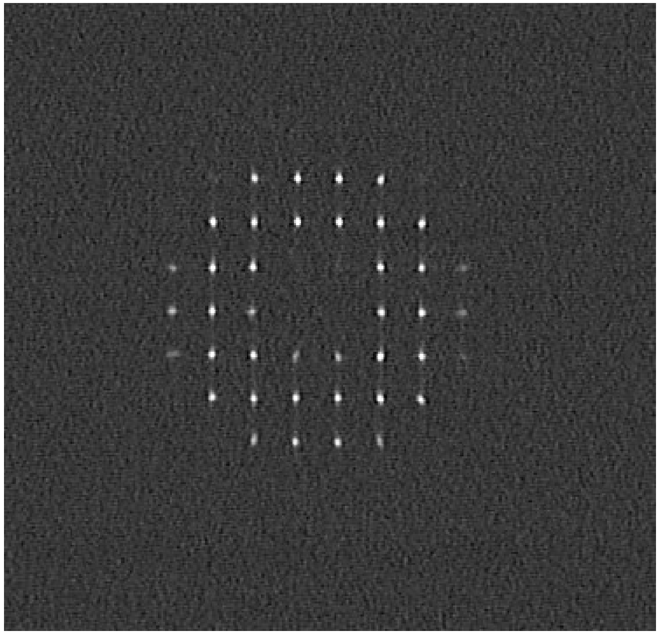
Example 1:
What if robustness is the dominant requirement ?

This occurs in most AO systems which must close the loop on bad wavefronts and work over a wide range of aberrations. For example, general purpose facility AO system must have a very robust WFS.

Ideally, WFS should be linear and have a large capture range

courtesy: Boston Micromachines





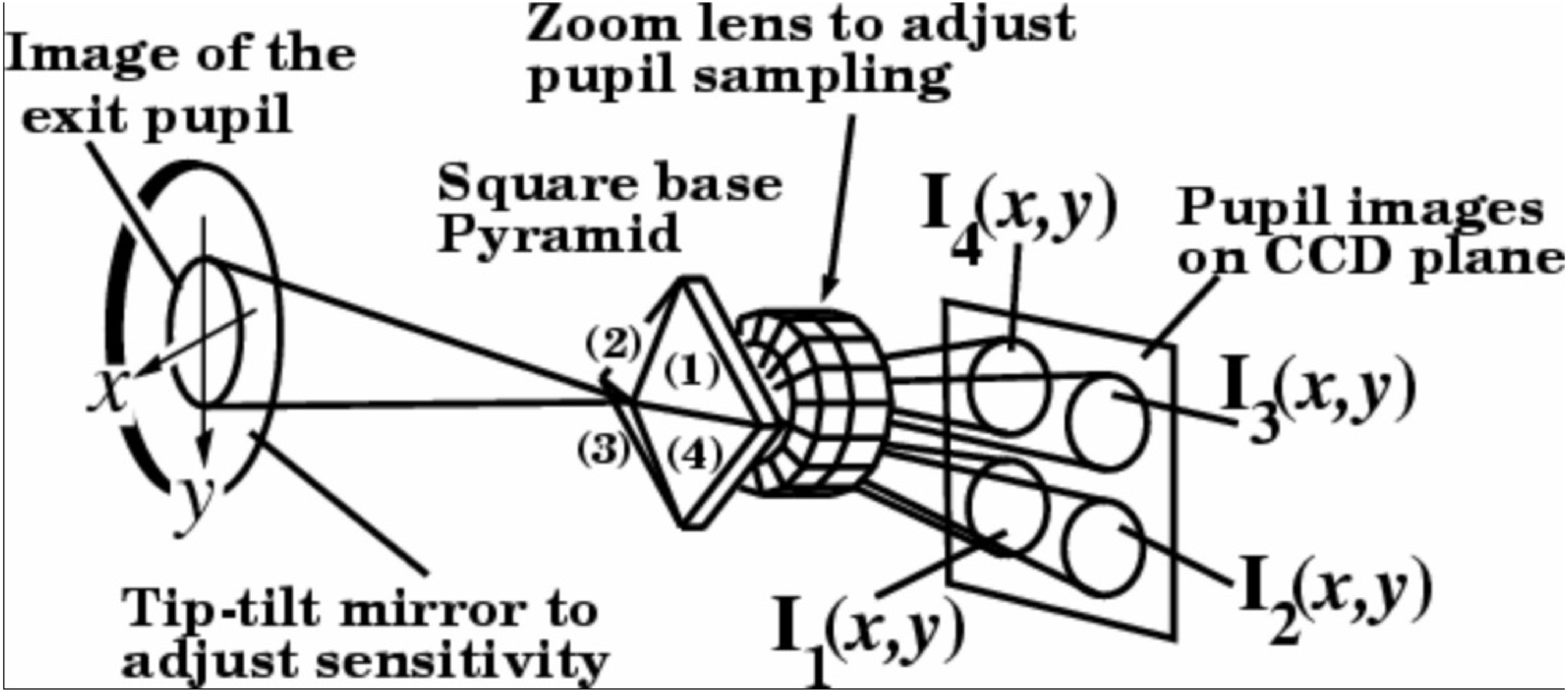
SH type WFS is then the ideal choice:

- Able to work on extended source
- Linear over a very wide range
- Number of pixels per subaperture can be increased for capt. Range
- Lots of previous experience, well understood technique
- Straightforward relationship between WF and signal (easy to debug)

Curvature and Pyramid may also be chosen

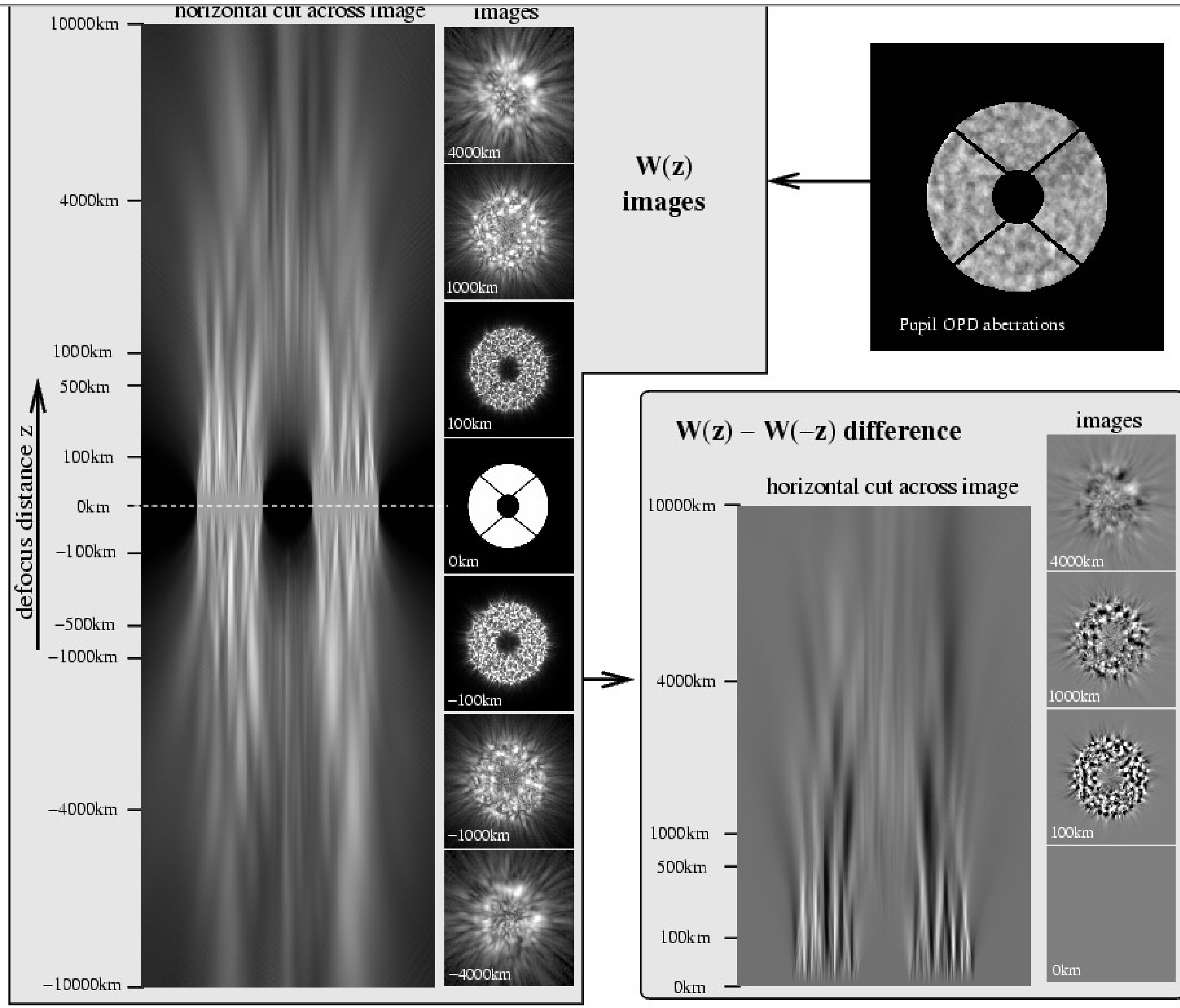
Pyramid WFS (modulated)

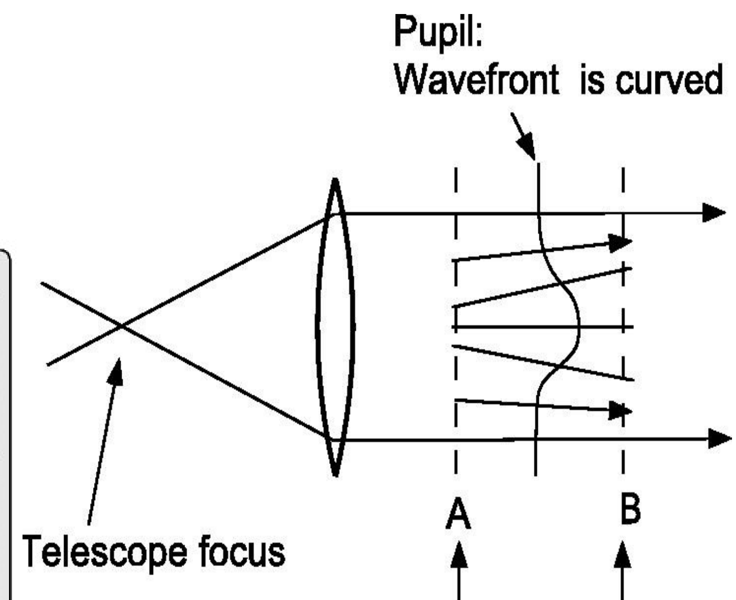
Separates focal plane into 4 quadrants, each quadrant re-imaged in pupil plane
Geometrical optics explanation: parts of the pupil with a given slope correspond to light in the corresponding focal plane quadrant



Curvature WFS

Light propagation turns phase into amplitude (similar to scintillation)





Lenslet array used to inject light into a series of fibers, which are connected to photon-counting Avalanche PhotoDiodes (APDs)

Example 2:
What if sensitivity is the dominant requirement ?

This occurs in ExAO systems, where wavefront is already corrected by an upstream AO system (no requirement on capture range, WFS just needs to be good at one thing !).

Wavefront sensor sensitivity: definition

Sensitivity = how well each photon is used

For a single spatial frequency (OPD sine wave in the pupil plane, speckle in the focal plane):

Error (rad) = Sensitivity / sqrt(# of photons)

IDEAL WFS:

Sensitivity Beta = 1 (1 ph = 1 rad of error)

At all spatial frequencies

Non-ideal WFS:

Beta > 1 (Beta x Beta ph = 1 rad of error)

Diffraction-limited wavefront sensors can be much more sensitive than seeing-limited wavefront sensors (such as SH, Curvature)

Good measurement of low order aberrations requires interferometric combination of distant parts of the pupil FPWFS does it, but
- SH chops pupil in little pieces → no hope !
- Curvature has to keep extrapupil distance small
(see previous slides) → same problem

Things get worse as # of actuators go up → **This makes a big difference for ELTs**

Tip-tilt example (also true for other modes):
With low coherence WFS, $\sigma^2 \sim 1/D^2$ (more photons)
Ideally, one should be able to achieve: $\sigma^2 \sim 1/D^4$ (more photons + smaller λ/D)

SH, linear Curvature are widely used because they are linear over a wide range of WF errors

High sensitivity WFS : Three examples

- **Fixed Pyramid WFS**: A pyramid is placed in the focal plane. The starlight hits the tip of the pyramid
- **Zernike phase contrast**: A small phase shifting mask is placed in the focal plane. Roughly 1/2 of the light goes through, 1/2 goes around. The two halves interfere to give an intensity signal
- **Mach-Zehnder**: An interferometer is assembled by splitting the beam in 2 and recombining the two halves. On one of the arms, a spatial filter (pinhole) is placed to create the “reference” beam which interferes with the wavefront

These 3 options are Linear but will fail if there is more than ~ 1 rad of WF error ! → poor dynamical range

Solutions exist with good dynamical range, but they are not linear (example: non-linear Curvature WFS – shown on next slide)

Operation of curvature WFS in non-linear regime, with large defocus distances, solves the noise propagation effect. Reconstruction algorithm is similar to phase retrieval (algorithm needs to be fast, with few iterations)

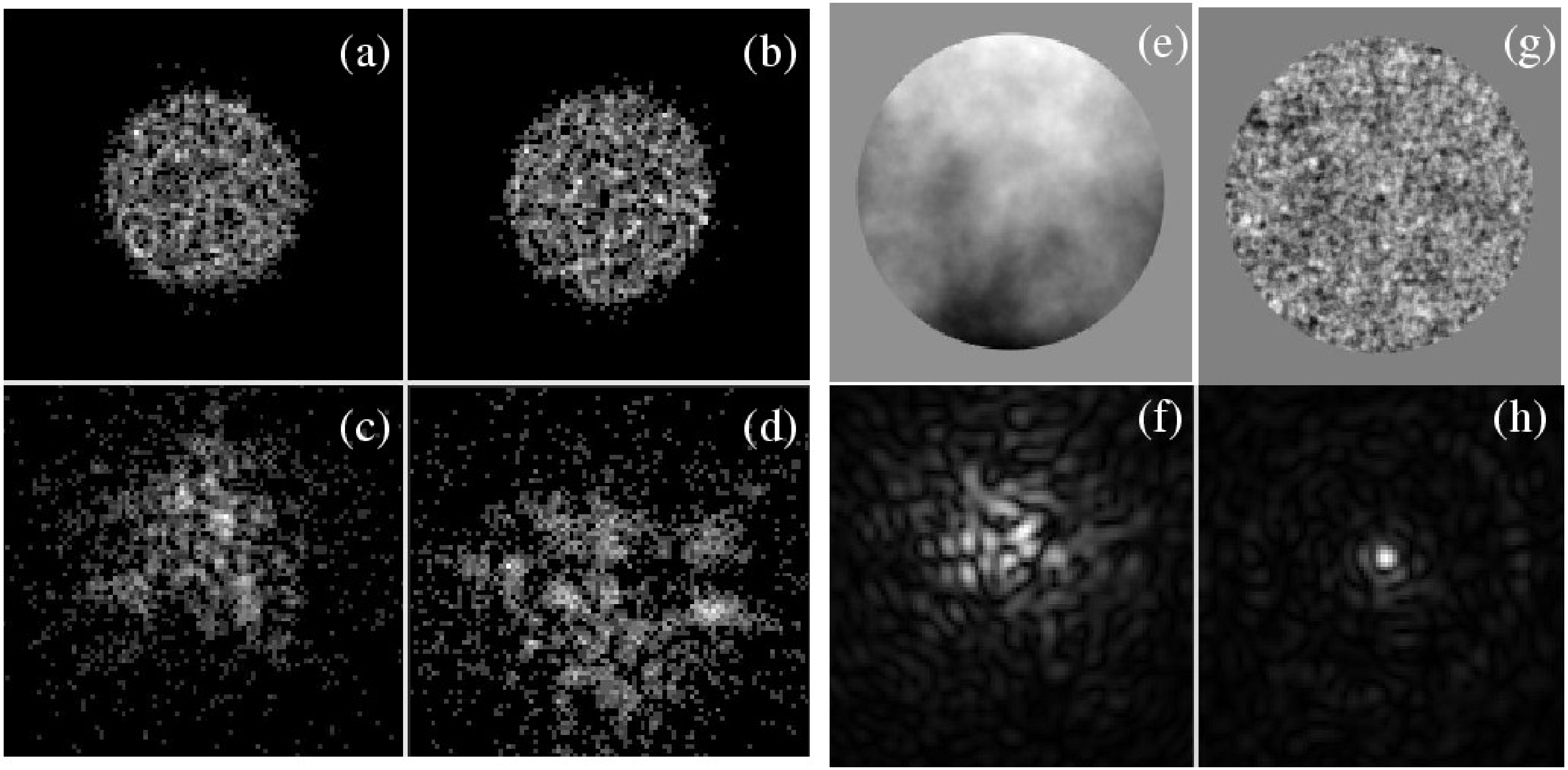


Fig. 9.— Wavefront reconstruction using the algorithm shown in fig. 8. Four noisy defocused pupil images (images (a), (b), (c) and (d)) are acquired to transform the pupil phase aberrations (e) into intensity signals. The input pupil phase is 609 nm RMS, yielding the PSF (f) before correction. After correction, the residual pupil phase aberration (g) is 34.4 nm RMS, allowing high Strehl ratio imaging (h). All images in this figure were obtained at 0.65 μm. The total number of photons available for wavefront sensing in 2e4.

ref: Guyon, 2009

Example 3:
What if WF calibration is the dominant requirement ?

This occurs in ExAO systems, where the wavefront should be free of static errors which would look like planets.

Focal-plane wavefront sensing & correction addresses this requirement

Next 4 slides describe the technique

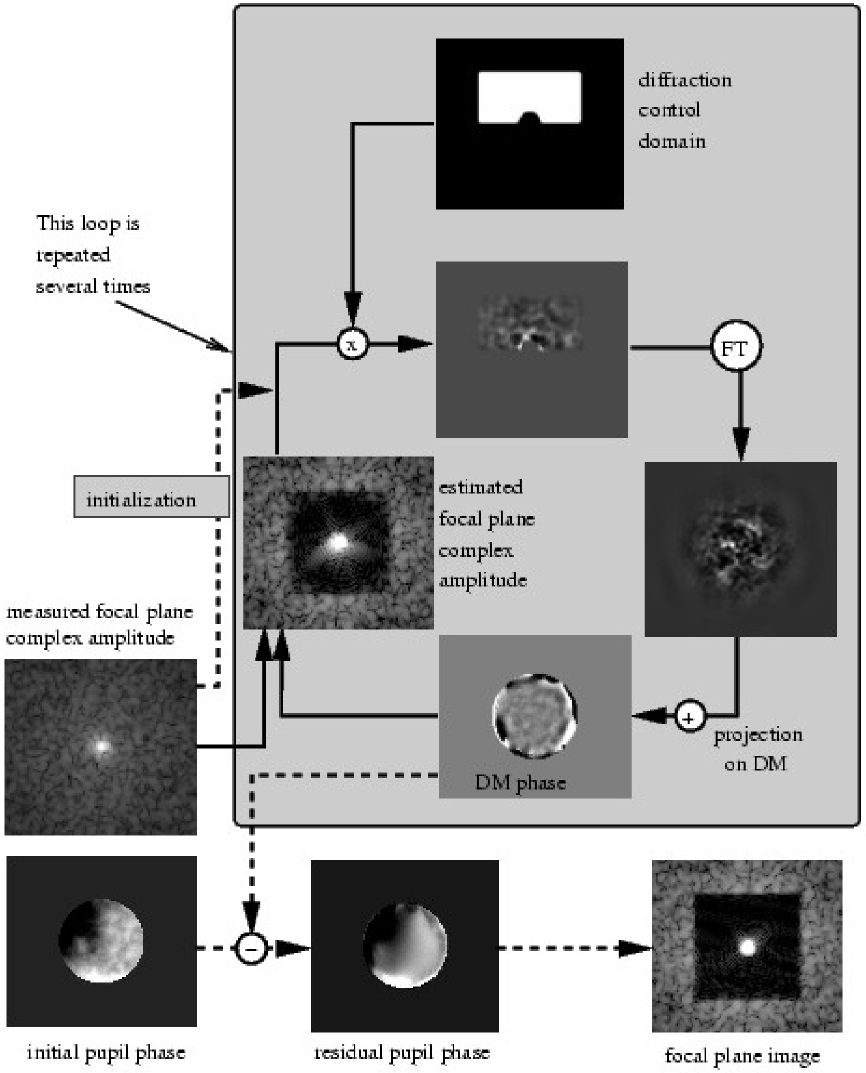
Focal plane WFS: a non-linear WFS well suited for Extreme AO

If speckle field Complex amplitude is known, **DM(s) can be controlled to "perfectly" cancel speckles**

DM can be also be asked to **create "arbitrary" speckle field for WFS**

Key advantages:
- no non-common path errors
- high sensitivity

Malbet, Yu & Shao (1995)
Guyon (2005)
Give'on (2003-2006)
Borde & Traub (2006)



How to **optimally** measure speckle field complex amplitude ?

Use upstream DM to introduce phase diversity.
Conventional phase diversity: focus
With DM: freedom to tune the diversity to the problem

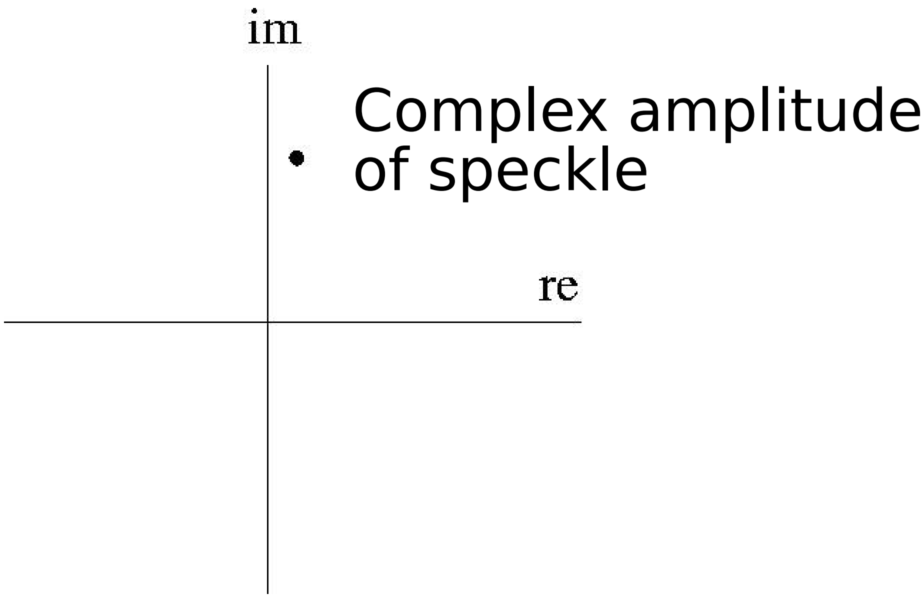
Measure speckle field with no previous knowledge:

- take one frame – this gives a noisy measure of the speckle field amplitude, but not phase

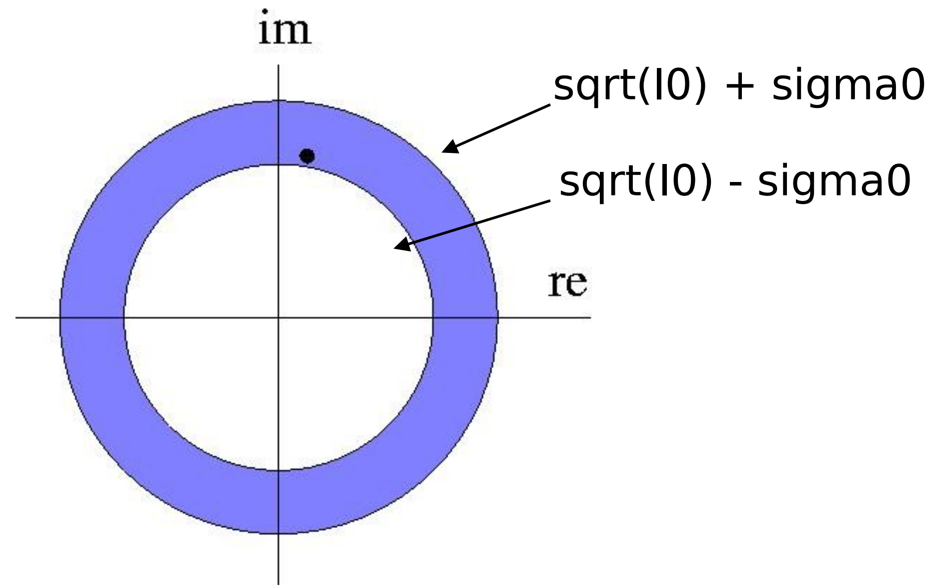
- compute 2 DM shapes which will add known speckles on top of existing speckles. These 2 “additive” speckle field have same amplitude as existing speckles, and the phase offset between the 2 additive speckle fields is PI/2

-> for each point in the focal plane, 3 intensities -> single solution for phase & amplitude of speckle field

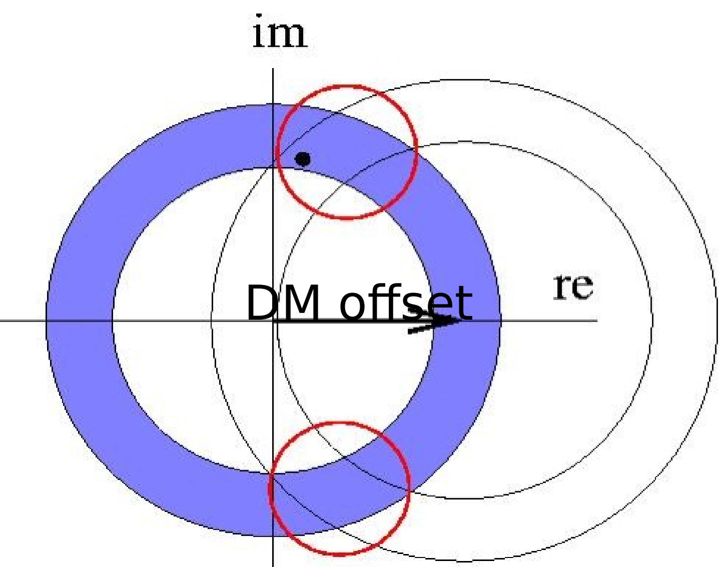
Initial problem

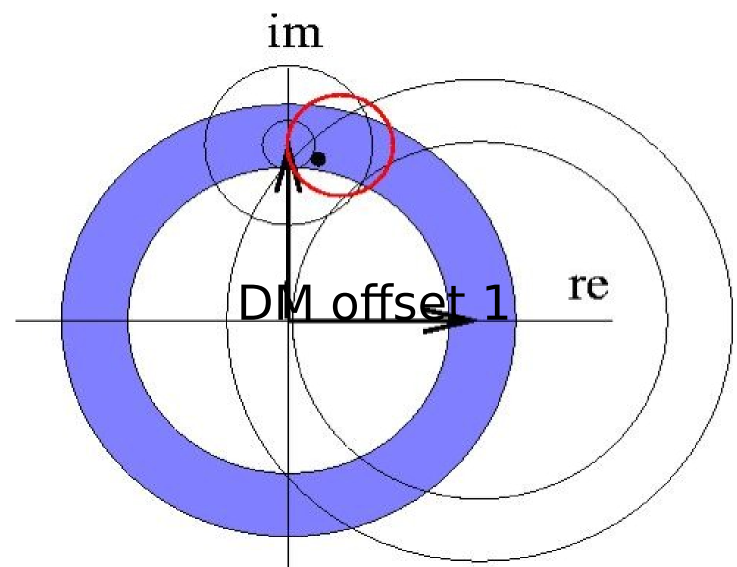


Take a frame -> measured speckle intensity = I0

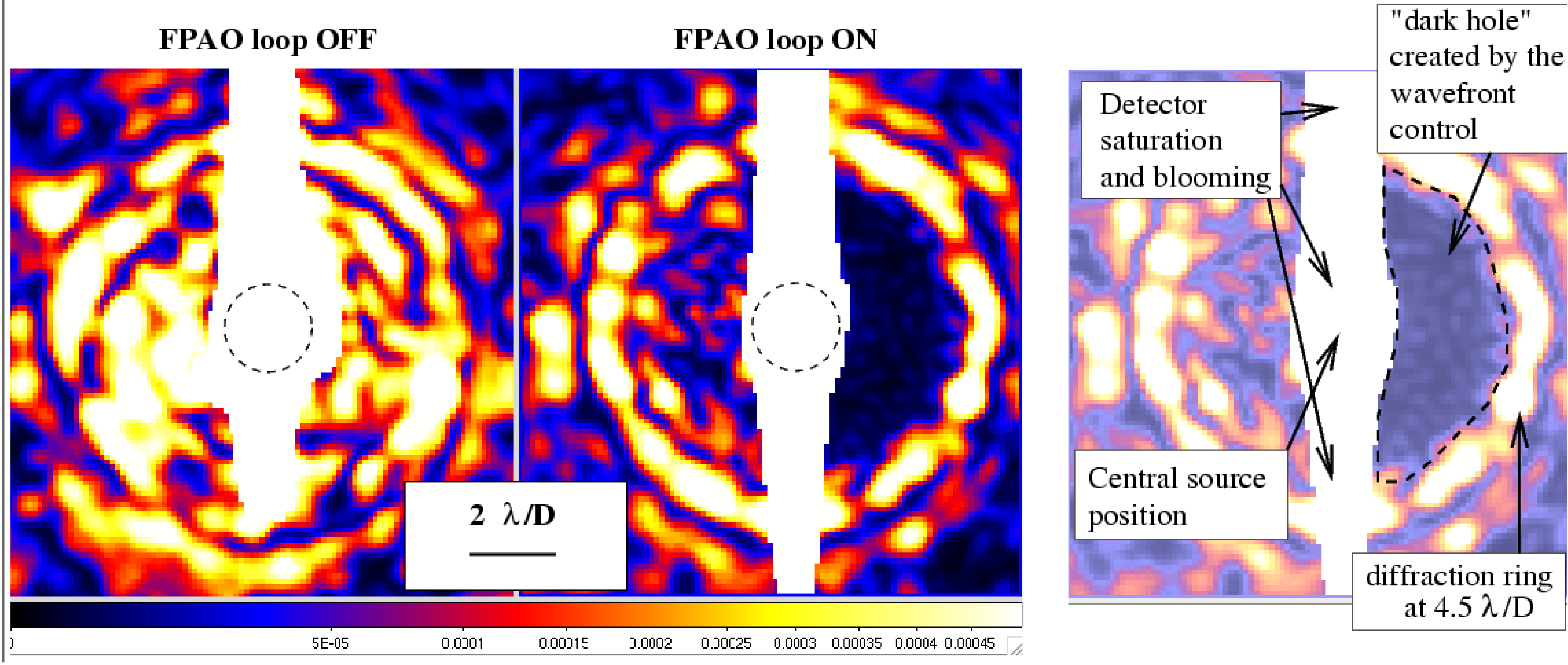


DM offset chosen to be ~ equal to speckle amplitude





Lab results with PIAA coronagraph + FPAO with 32x32 MEMs DM



See also results obtained at JPL HCIT, NASA Ames & Princeton lab

Matching:

Wavefront quality in WFS to Wavefront sensor

<< 1 rad

Space Extreme-AO
(Terrestrial Planet Finder)

Second-stage of Extreme-AO
system in near-IR (“Tweeter”)

~ 1 rad

Extreme-AO Closed loop in Visible

Thermal IR AO on 8m telescope
open loop

“general purpose” AO system in
closed loop

>> 1 rad

LGS AO
GLAO

Open loop AO

Not allowed

allowed

Interferometric

Focal plane

Pyramid (fixed)

Pyramid (modulated)

Curvature

Shack-Hartmann

How to choose the best WFS(s) ? A few more guidelines...

- WFS for LGS should be SH, Curv (or modulated pyramid ?)
- For NGS AO, a multi-stage approach is attractive to combine advantages of several WFS options
  - this is especially attractive for Extreme-AO systems, for which the highest sensitivity WFS options would increase science return, but may not be able to close the loop if used alone

Example of sensible pairing: Possible Coronagraphic ExAO architecture

AO with visible WFS
(Curvature or
Shack Hartmann)

AO with high sensitivity
WFS in visible
(examples: Pyramid,
interferometer, focal plane WFS)

Near-IR

Coronagraph
Focal plane AO

Fast camera for
focal plane WFS
after coronagraph

Science frame
acquired by the
same camera
as FPWFS

-The first step is used to clean the wavefront within ~ 1 rad in Visible
-The second step operates in the high coherence regime, and adopts a high sensitivity WFS.
-Last step uses focal plane WFS free of non-common path errors (Gemini Planet Imager (GPI) uses a similar strategy, with an interferometer WFS to measure coherent residuals)

Outline

Astronomical AO system diversity

Main challenges / error budget terms in astronomical AO systems

Wavefront sensing strategy

Large field of view AO systems

Optical/mechanical design considerations

From photons to DM commands: making it all work nicely together

Types of systems

Single conjugate AO (**SCAO**)	~ 30 arcsecond	1 DM, usually conjugated to ground	1 (LGS or NGS)	Easiest, traditional AO architecture
Laser Tomography AO (**LTAO**)	~30 arcsecond	1 DM	>3 (LGS or NGS)	Overcomes cone effect (LGS) and isoplanatic limitation (NGS)
Ground Layer AO (**GLAO**)	very wide – up to ~degree	1 DM, conjugated to ground	> 3	Optically challenging for wide field. Demonstrated on moderate (few arcmin) fields. Larger systems under active development
Multi Conjugate AO (**MCAO**)	wide, > arcmin	2 to 3	> 3, can be LGS or NGS	Working systems: MAD (ESO) and GEMS (Gemini), more to come
Multi Object AO (**MOAO**)	wide but fragmented	1 DM per object (+ 1 DM in common path?)	about 1 GS per field	Under active development. Demonstrators working (see RAVEN on Subaru, CANARY on WHT, development of EAGLE for E-ELT)

Fundamental problem to solve: Isoplanatic Angle

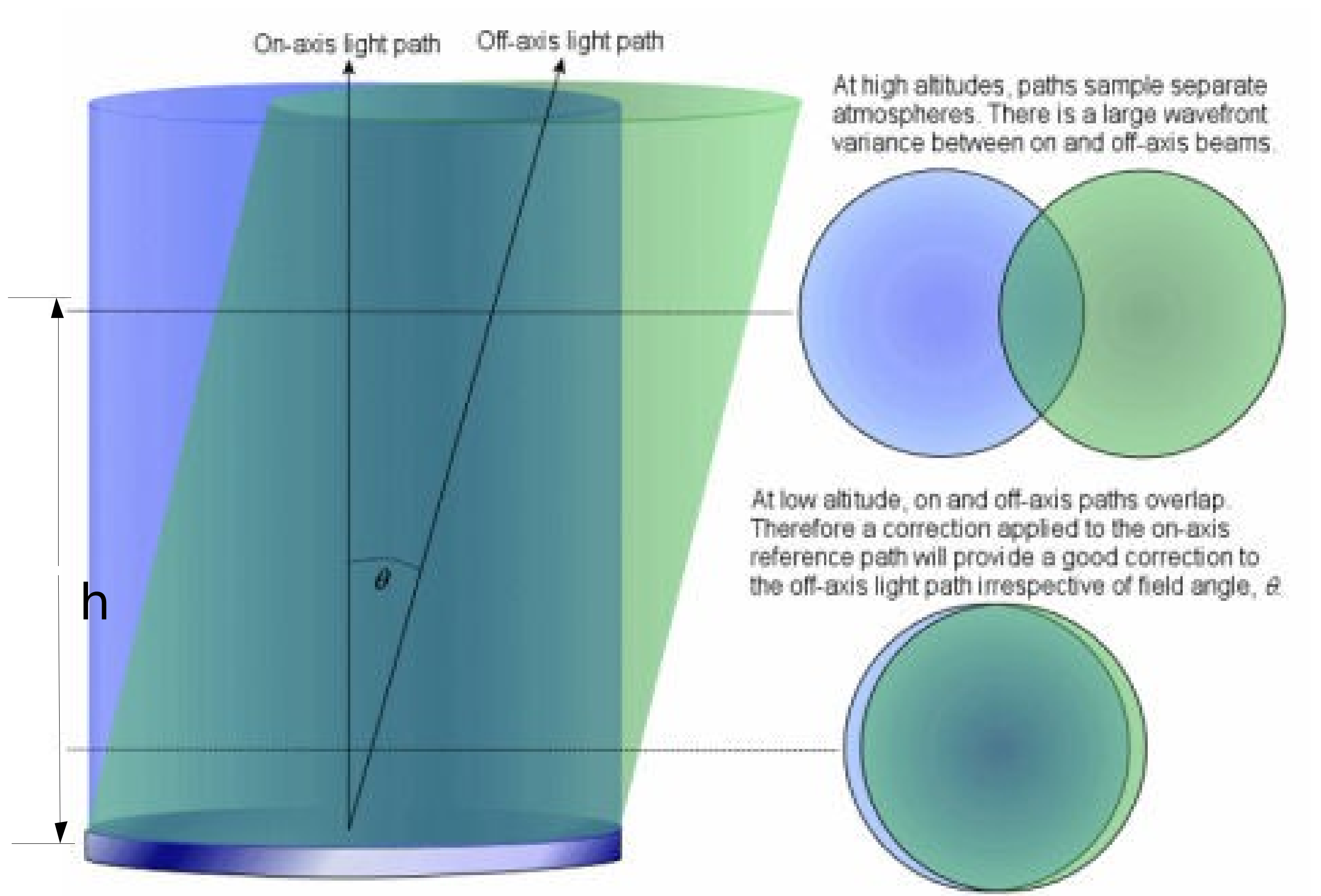
If we assume perfect on-axis correction,
and a single turbulent layer at altitude h,
the variance (sq. radian) is :

$\sigma^2 = 1.03\ (\theta/\theta_0)^{5/3}$

Where α is the angle to the optical axis,
θ_0 is the isoplanatic angle:

$\theta_0 = 0.31\ (r_0/h)$

D = 8 m, r_0 = 0.8 m,
h = 5 km -> θ_0 = 10



Solution:

Wavefront mesurement:
Several guide stars needed

Several guide stars
(Laser and/or natural)
→ volumetric knowledge
of atmospheric turbulence,
instead of simply collapsed
turbulence

GeMS (Gemini)

Wavefront correction:
Several DMs if good correction over a large FOV
Or, single DM driven to correct average wavefront error over wide FOV
(Ground-layer AO, partial correction)

With single DM, there is a fundamental limit in the wavefront error vs. FOV tradeoff. Multiple DMs is the only way to break this limit.

The required field of view & field “format” drives the AO system optical design (& more)

MCAO: System offering wide FOV over full continuous field
→ large optics, several large Deformable Mirrors (MCAO)
→ AO system works in closed loop, with several WFSs and several DMs
→ Multiple guide stars needed, with required positioning devices (NGS) or several laser beacons.

MOAO: Several small individual FOVs spread over a large field
→ The instrument could have small independent wavefront correction units (1 per small field) to minimize optical size/complexity
→ These small units should be fed by a smaller number of WFSs using tomographic reconstruction.
→ The WFSs would be running in open loop, and do not see the correction by the DMs.
→ The DMs would therefore need to be very well calibrated

Cone effect

Cone effect due to finite altitude of LGS (90km sodium, ~10-20 km for Rayleigh)

$\sigma^2 = 1.03 \; (D / (2.91\theta_0 H))^{5/3}$

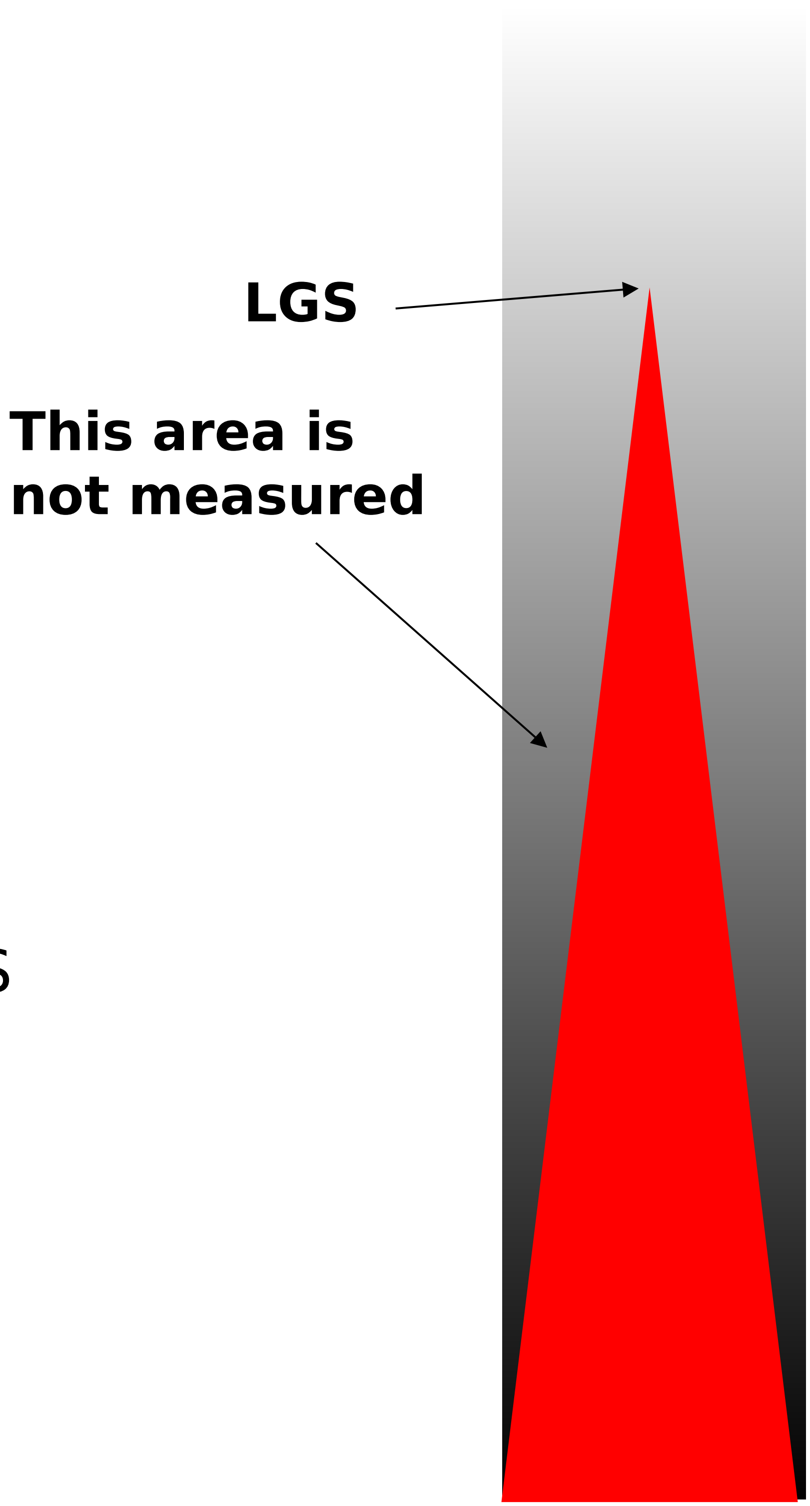
θ_0: isoplantic angle

H : LGS altitude

D : Telescope diameter

→ impact is smaller for sodium LGS

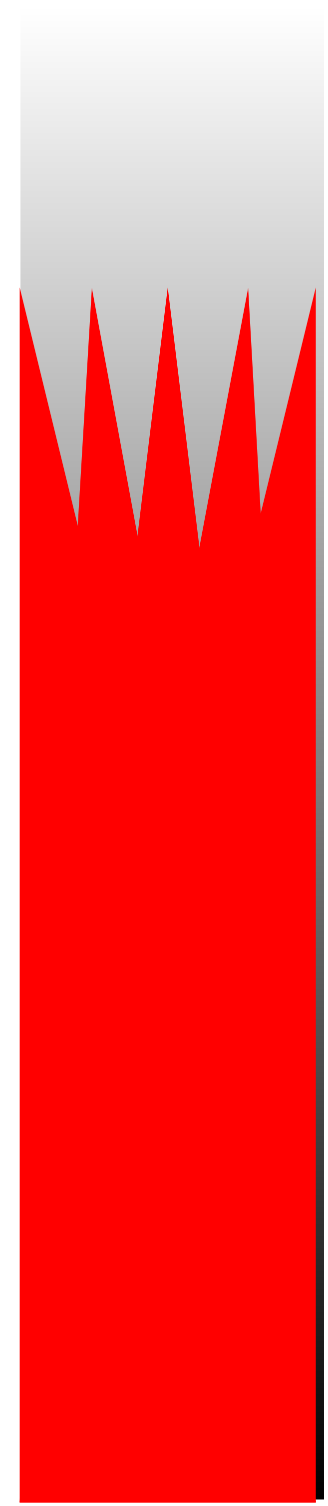
→ larger effect for large telescopes



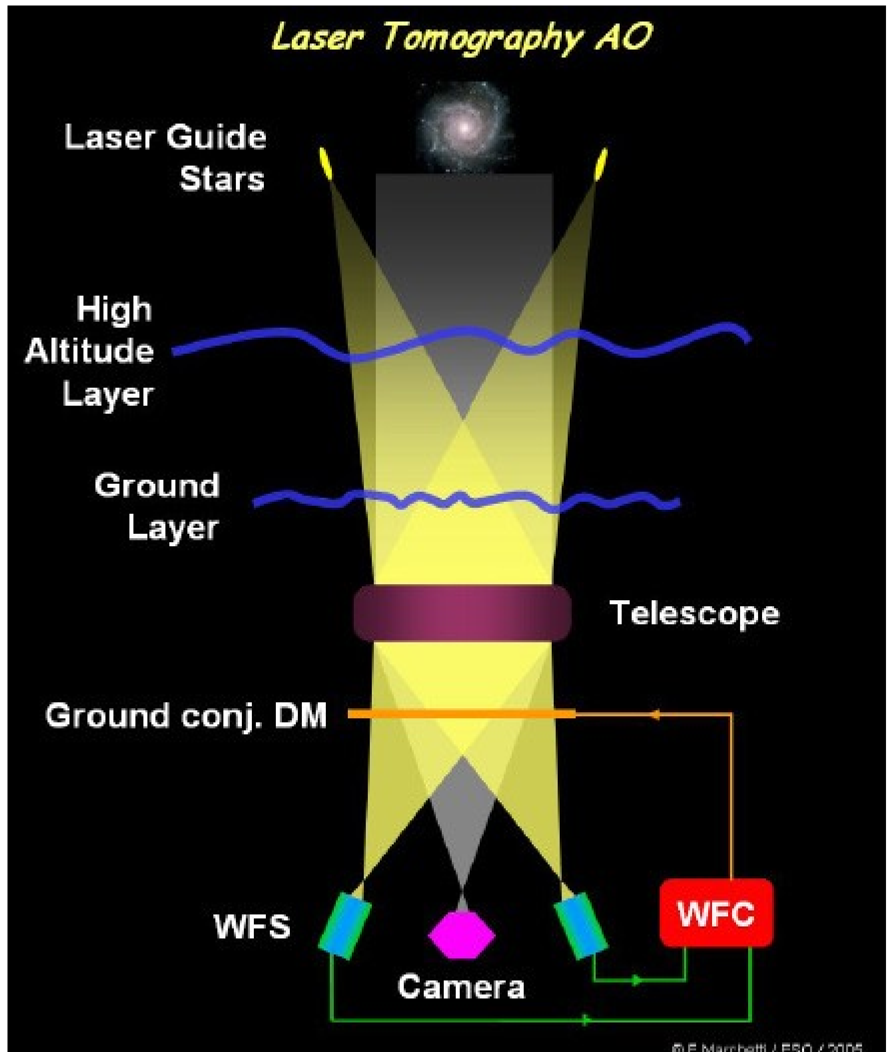
Laser Tomography AO (LTAO)

Tomography (usually with LGSs, but can also use NGSs) can mitigate cone effect by combining wavefront information from several guide stars.

LGSs

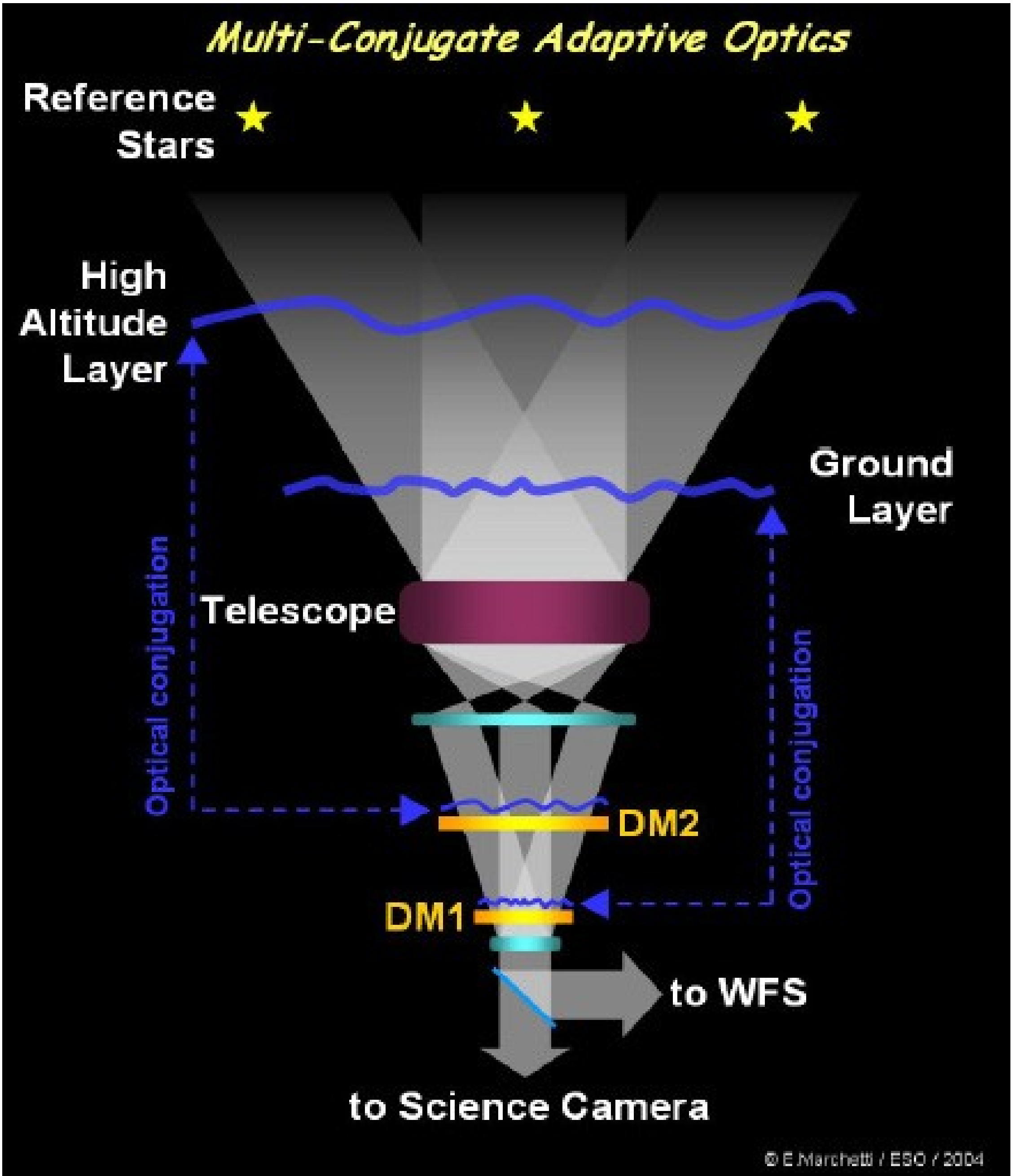


This technique used with a single DM to reduce cone effect error (no increase of FOV)

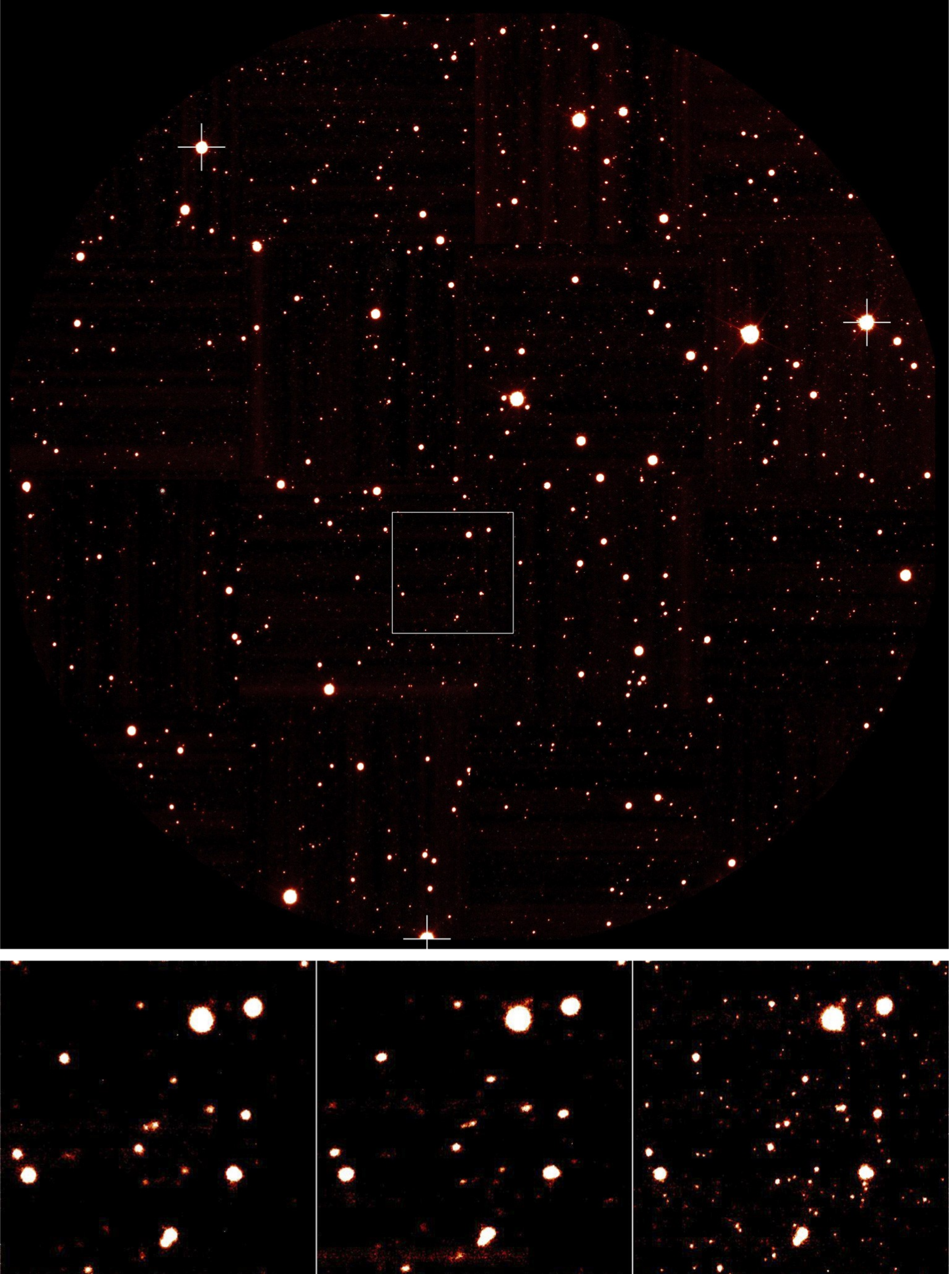


Multi-Conjugate Adaptive Optics (MCAO)

Concept: Use several DMs conjugated at different altitudes to perform correction over a wide fielf of view



Gemini South MCAO system

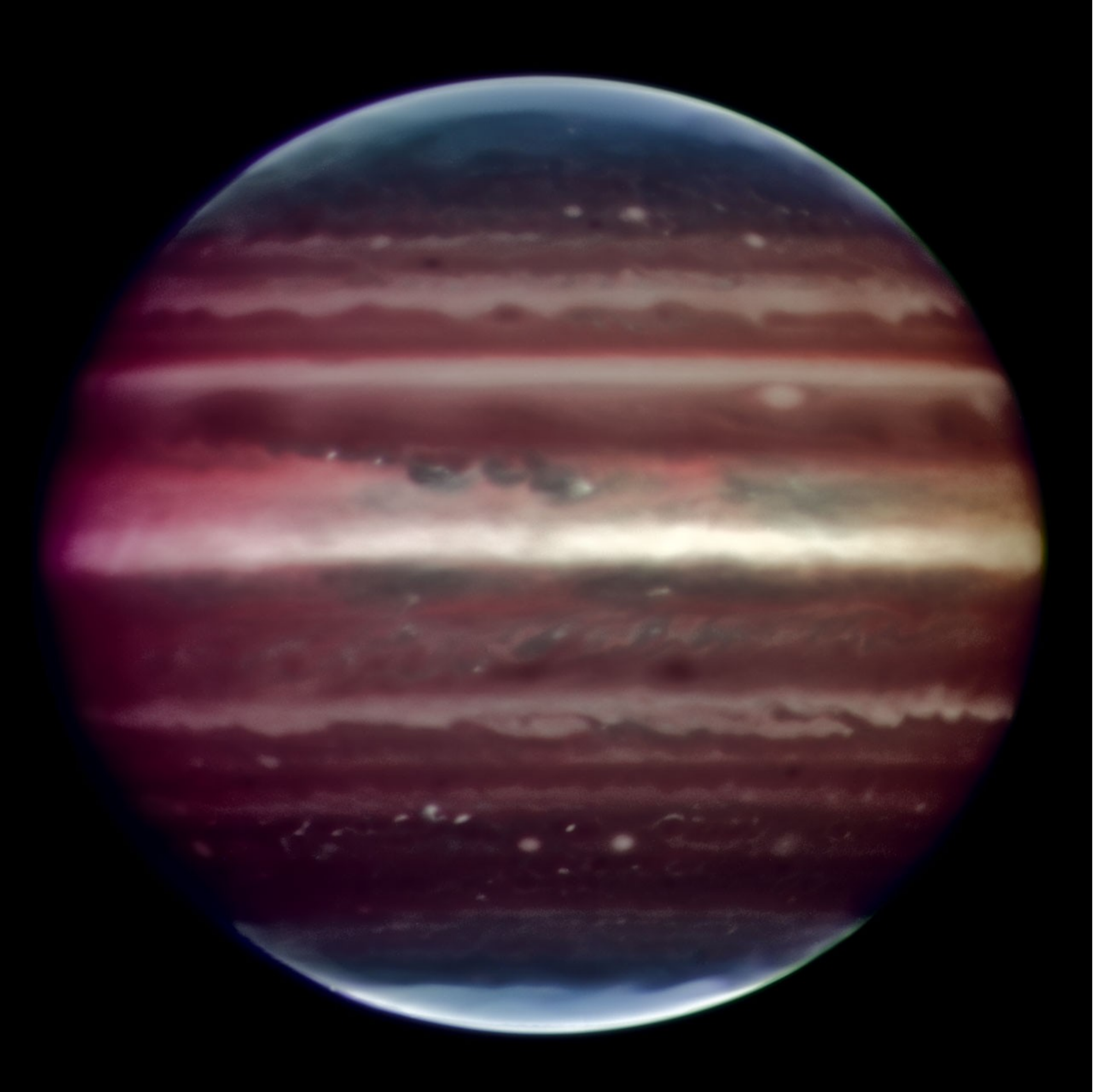


MCAO on-sky performance

MCAO improves image quality where there is no single nearby bright guide star

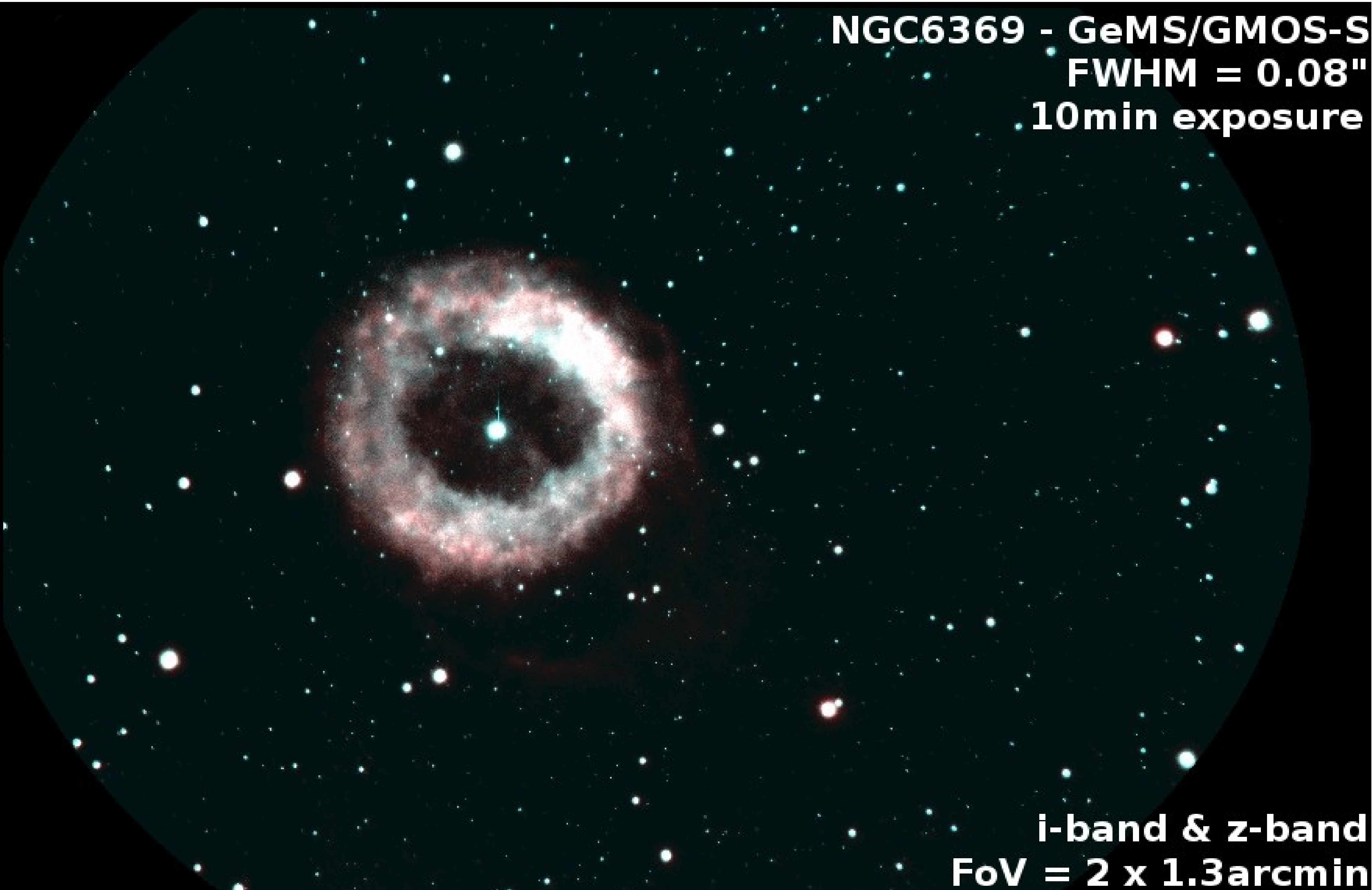
Central parts of the globular cluster Omega Centauri, as seen using different adaptive optics techniques. The upper image is a reproduction of ESO Press Photo eso0719, with the guide stars used for the MCAO correction identified with a cross. A box shows a 14 arcsec area that is then observed while applying different or no AO corrections, as shown in the bottom images. From left to right : No Adaptive Optics, Single Conjugate and Multi-Conjugate Adaptive Optics corrections. SCAO has almost no effect in sharpening the star images while the improvement provided by MCAO is remarkable.

Credit: ESO



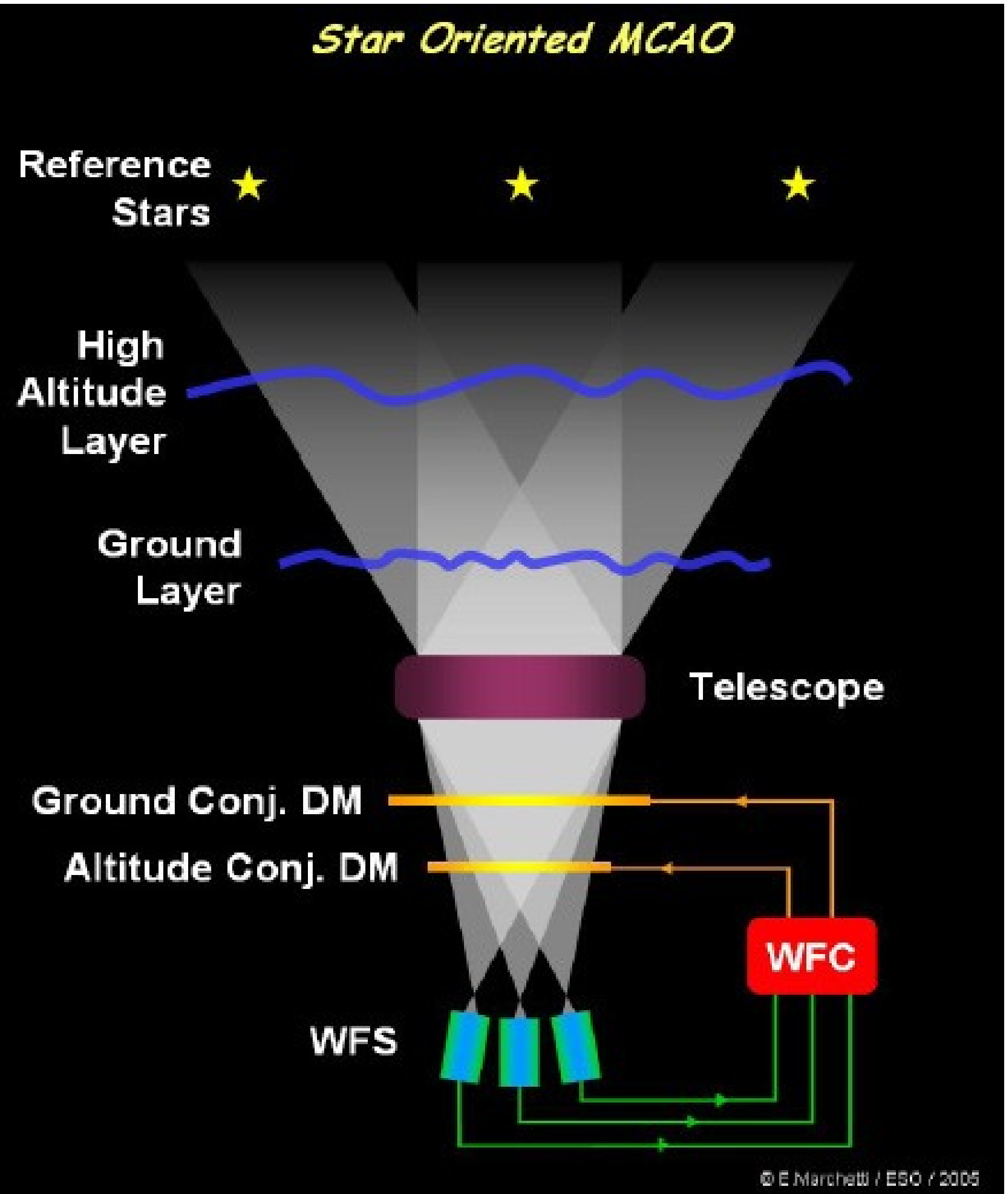
MCAO

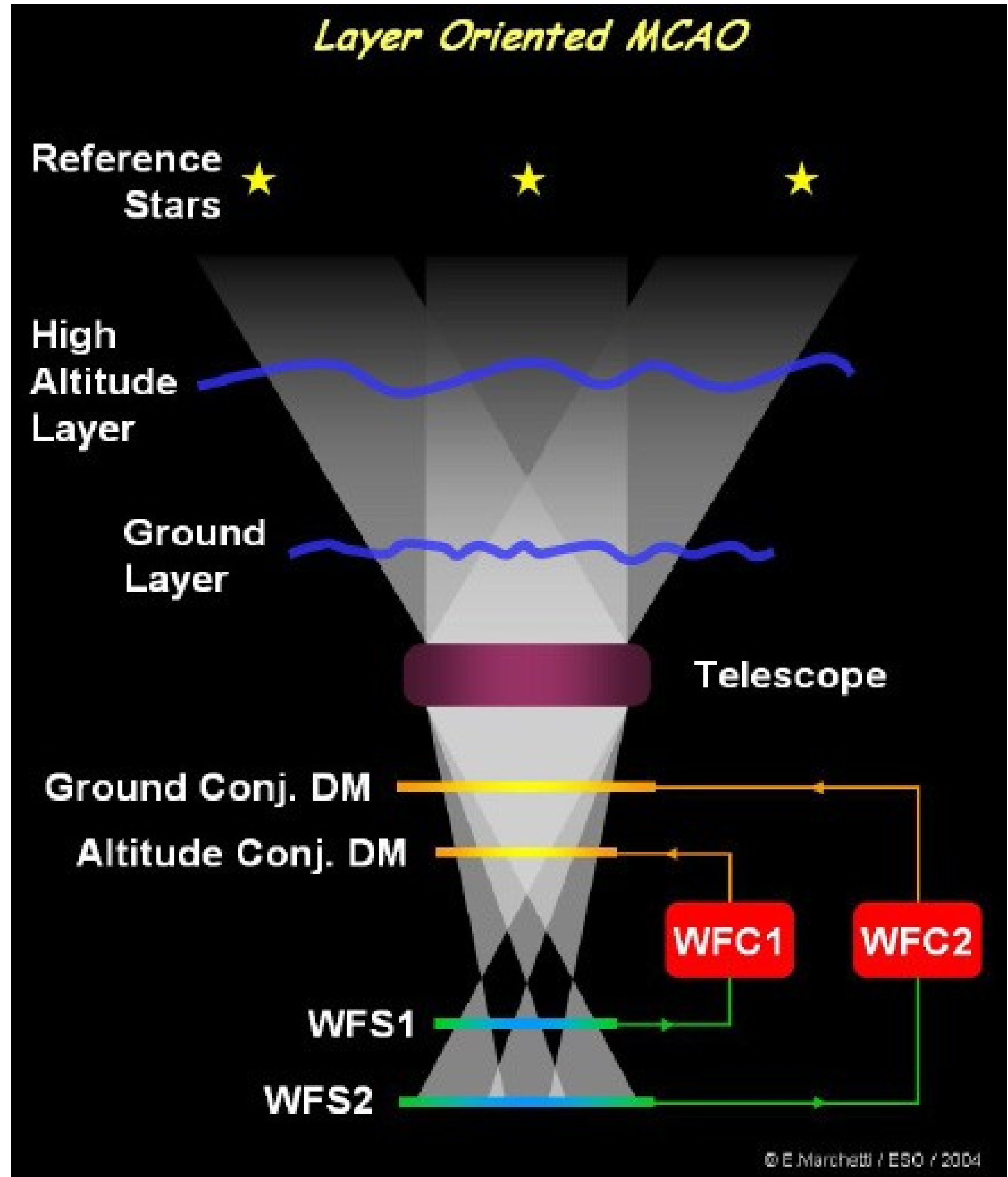
Jupiter imaged with ESO's Multi-conjugate Adaptive Optics Demonstrator (MAD)


NGC6369 - GeMS/GMOS-S
FWHM = 0.08"
10min exposure
i-band & z-band
FoV = 2 x 1.3arcmin

MCAO wavefront sensing

Star-oriented: 1 WFS per star
Layer-oriented: 1 WFS per layer

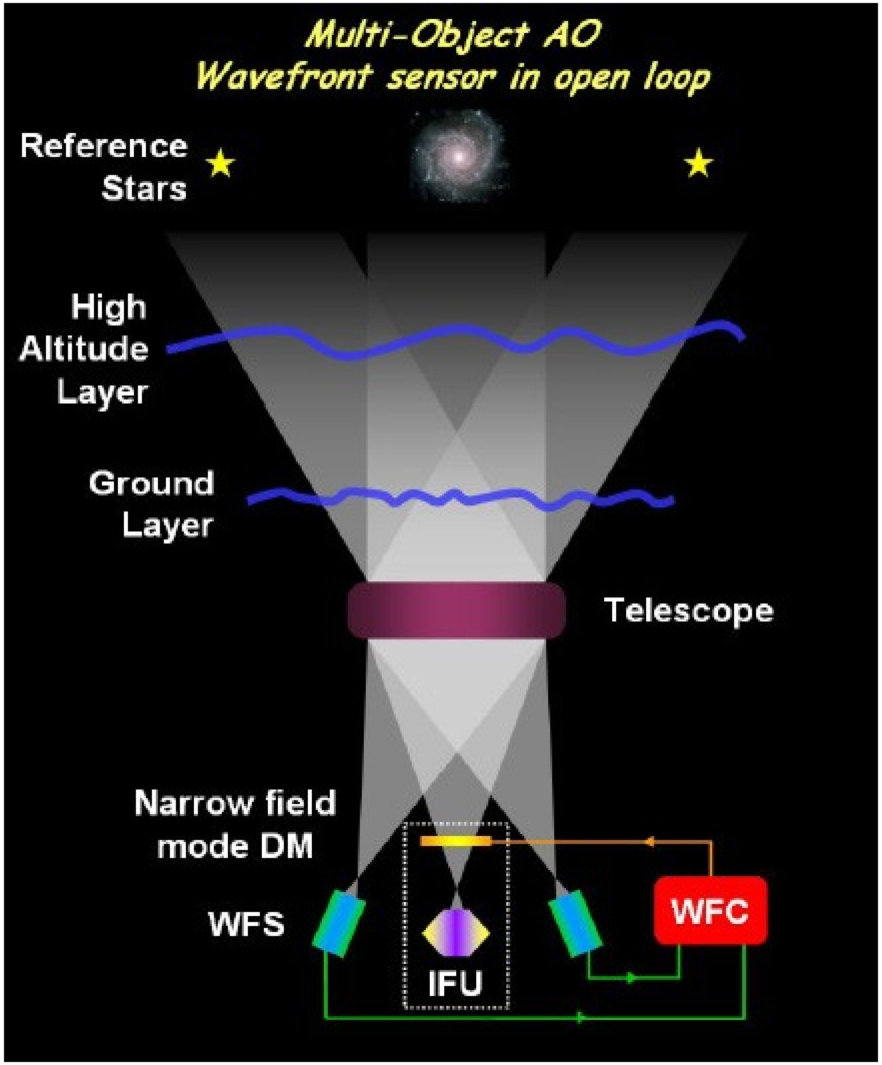


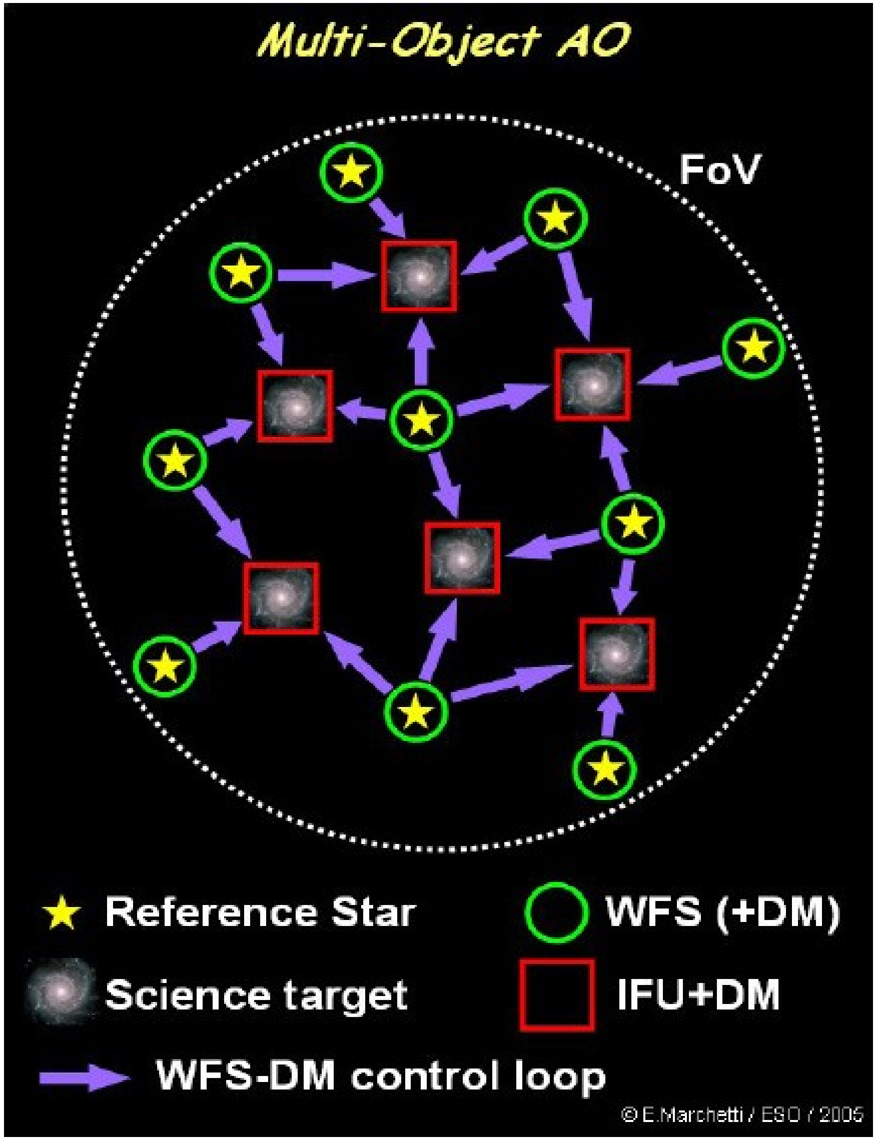


Multi Object Adaptive Optics (MOAO)

Can be visualized as several tomographic AO systems sharing the same set of wavefront sensors: 1 DM per object of interest

MOAO runs DMs in open loop → need for good DM calibration (WFSs do not see DMs)

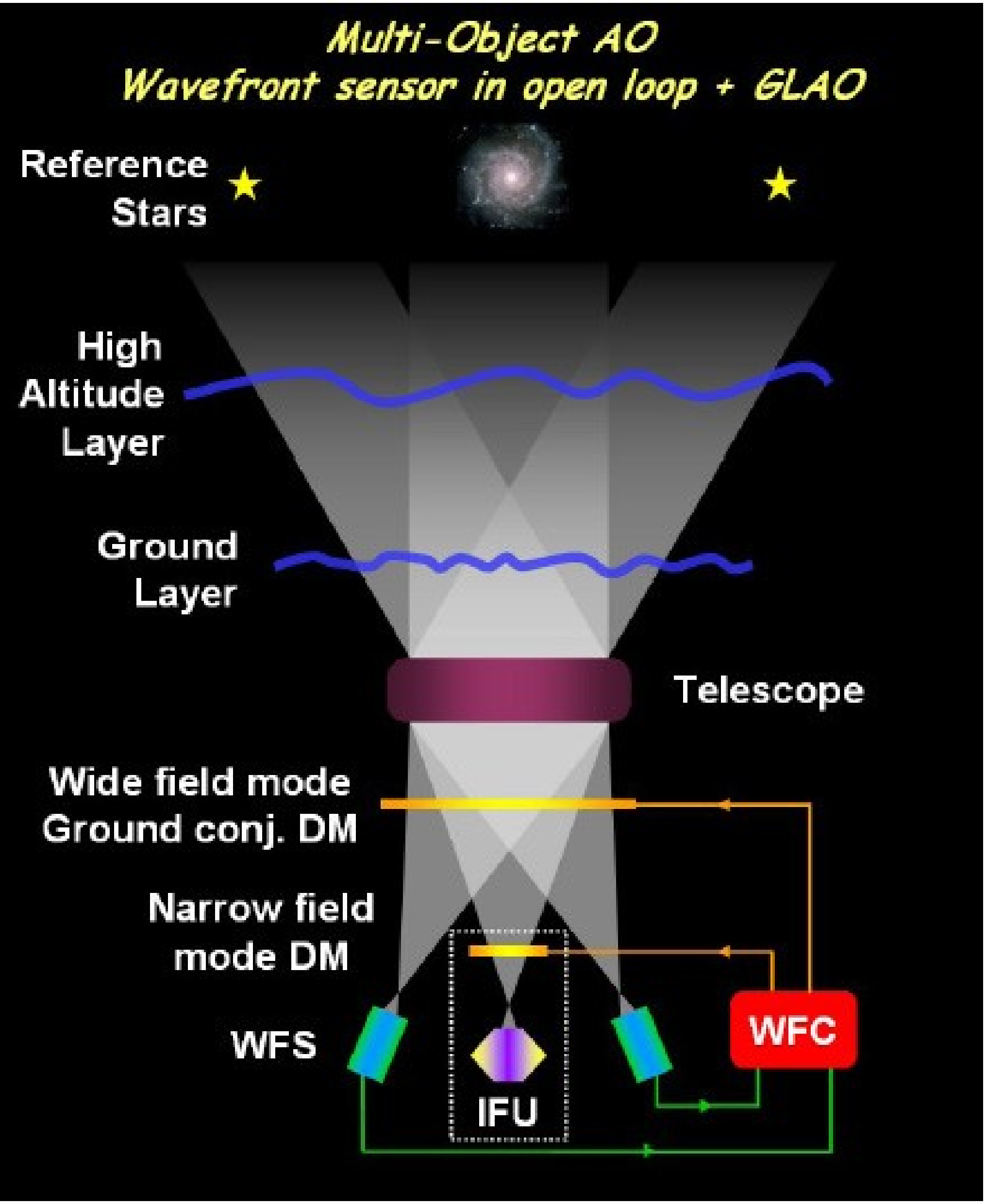


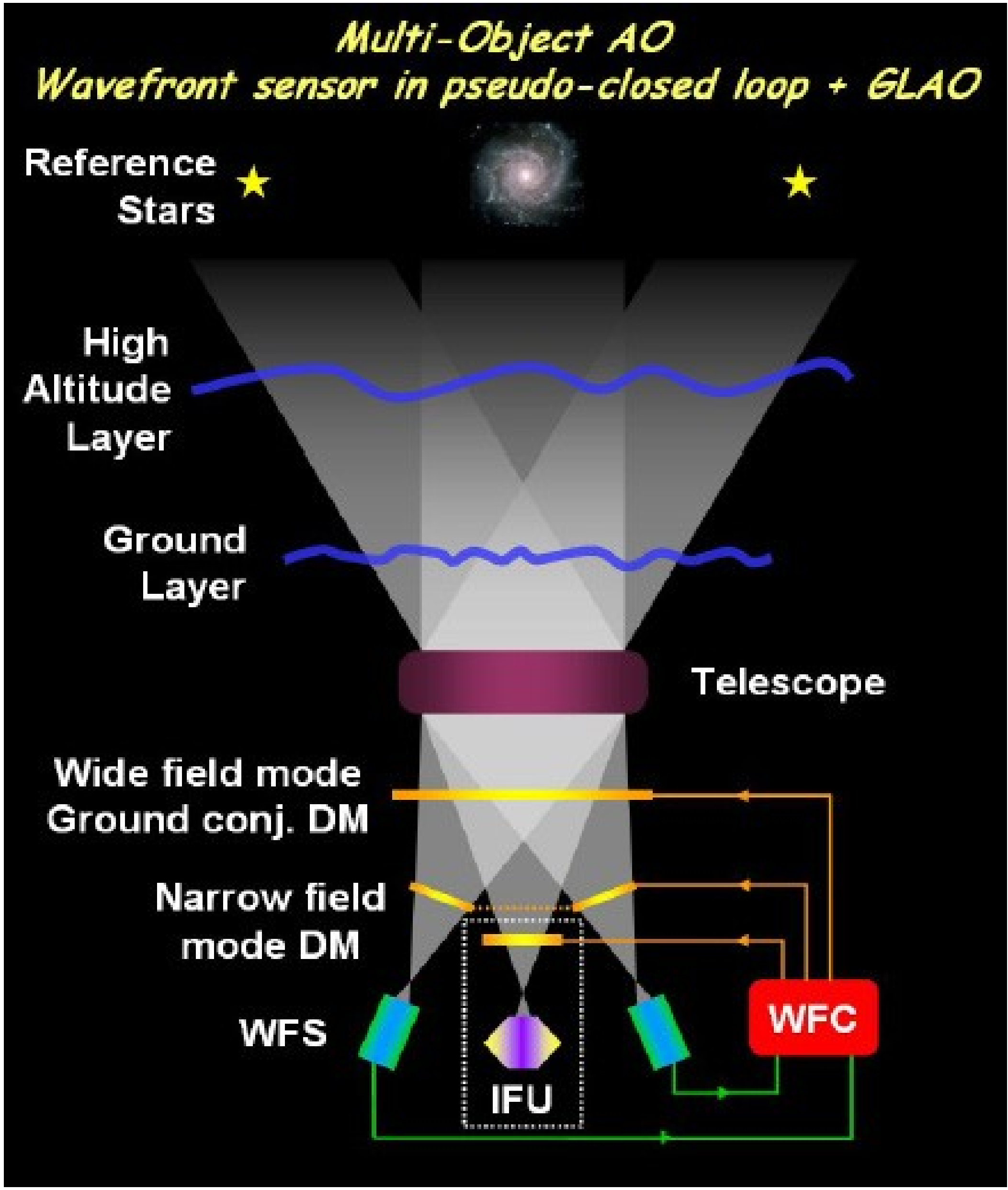


MOAO: hybrid correction schemes

Offload part of the correction to a common DM

Perform correction in individual WFSs to gain sensitivity





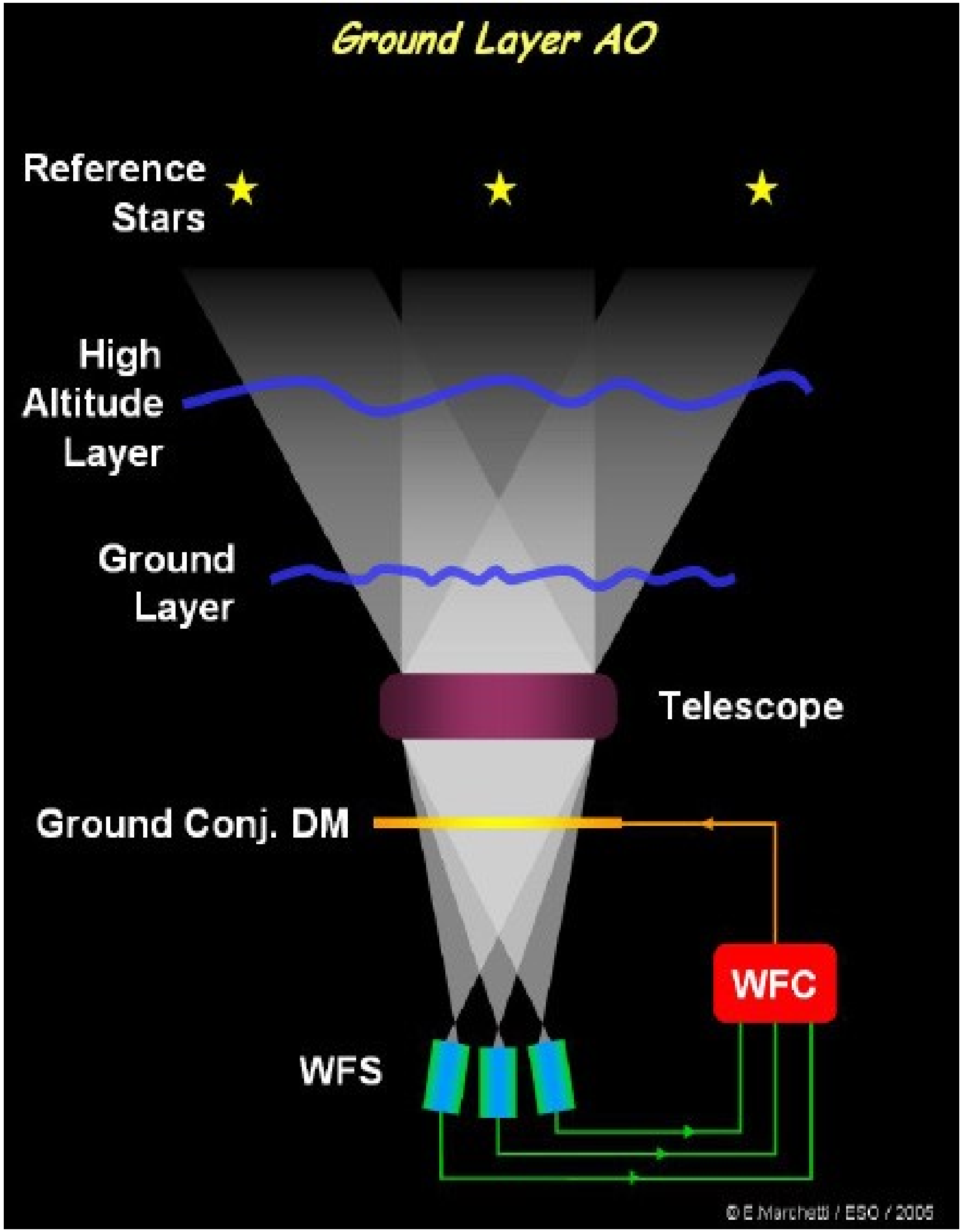
Ground Layer Adaptive Optics (GLAO)

- Significant part of turbulence (~50% or more) is located near ground level
- Ground layer turbulence is common to sources in a wide field of view

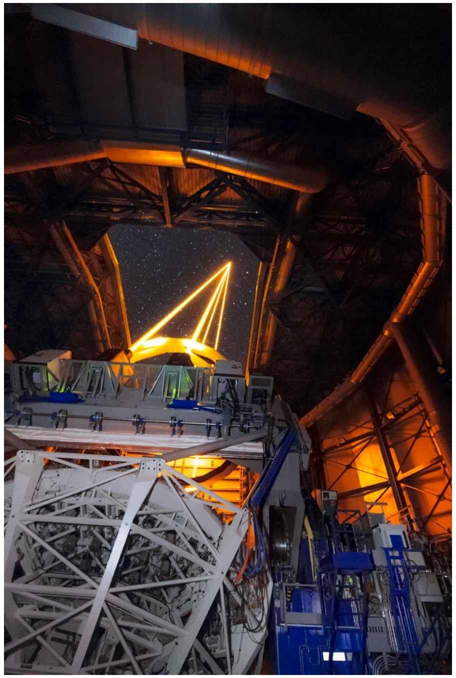
→ With correction of ground layer, image quality is improved over a wide field of view

Problem: how to isolate ground layer turbulence from high altitude turbulence.

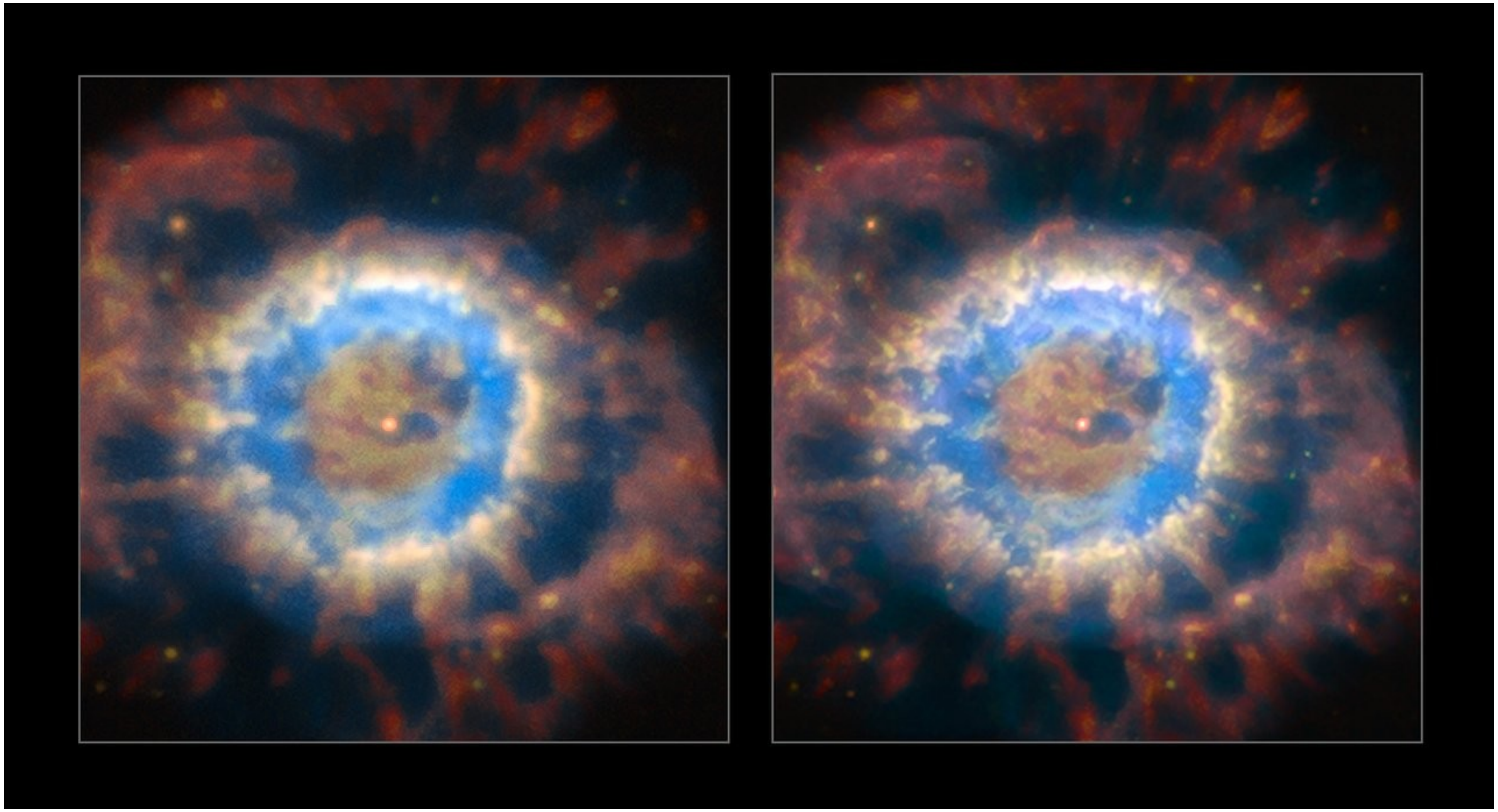
Solution: use several WFSs. The part of the wavefront common to all WFSs is the ground layer



Ground Layer Adaptive Optics (GLAO)



Natural seeing GLAO



MUSE @ ESO

MCAO, MOAO & GLAO bring huge efficiency gain, But are more complex than single guide star systems

They require **several natural guide stars**:
- Tip-tilt and focus not measured by LGSs
- Tip-tilt & Focus change across the field of view

Systems are quite complex, as they combine several NGS WFSs and often several LGS WFSs.
- LGS pattern on the sky can be fixed or variable (emphasis on FOV vs. image quality)
- LGS WFSs need variable focus stage (for Sodium), as altitude of LGS is function of pointing and varies with time due to Sodium Layer variations
- NGS pattern on the sky is different for each pointing: need for moving optics to acquire NGSs

Outline

Astronomical AO system diversity

Main challenges / error budget terms in astronomical AO systems

Wavefront sensing strategy

Large field of view AO systems

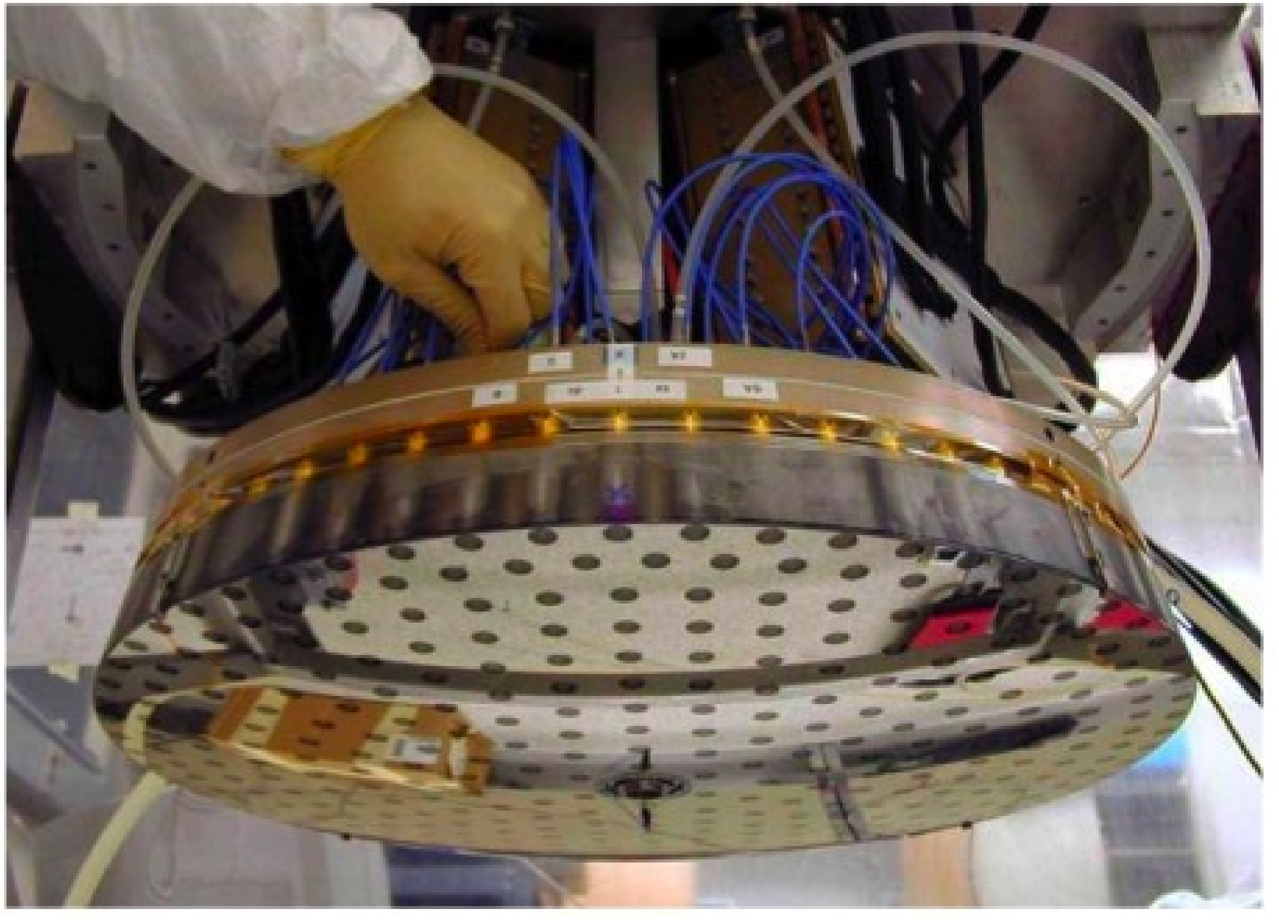
Optical/mechanical design considerations

From photons to DM commands: making it all work nicely together

Thermal IR instruments need low thermal background

-> fewer warm optics

adaptive secondary mirror (MMT, LBT)



Thermal IR instruments may need “chopping” (on source / off source images to calibrate background)

AO system then needs to be compatible with chopping (this is not easy)

The required field of view & field "format" drives the AO system optical design (& more)

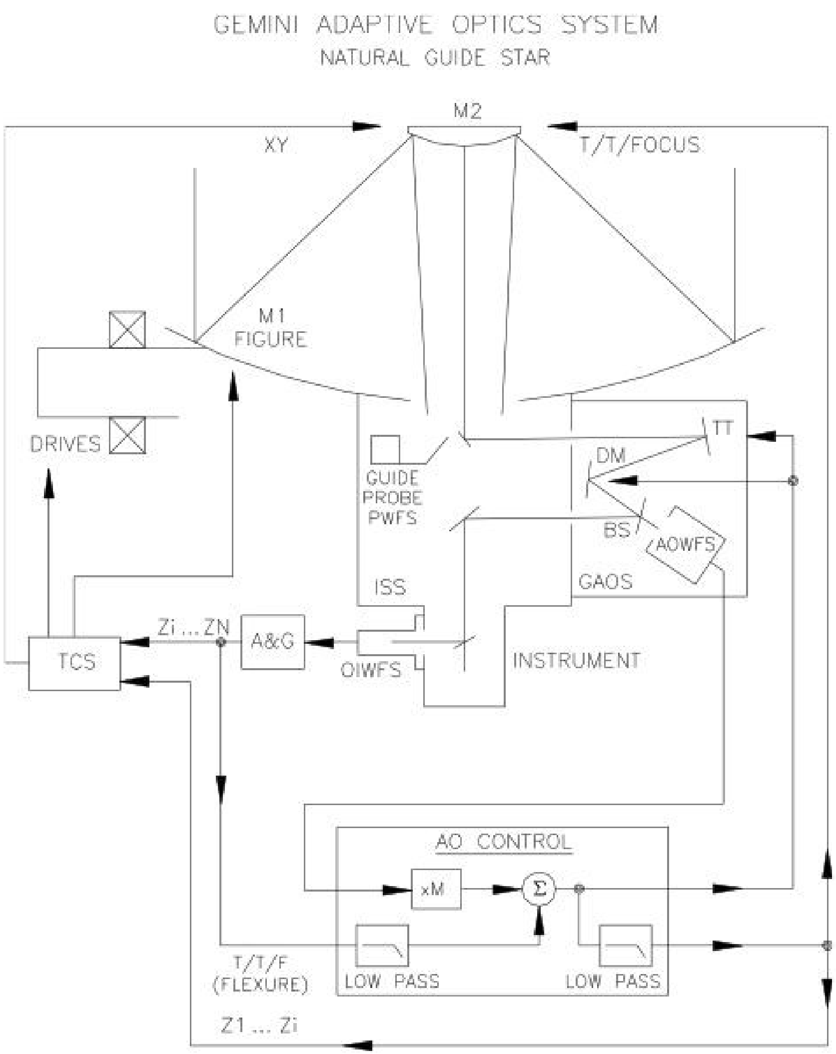
Example 1: System offering wide FOV over full continuous field
-> large optics, several large Deformable Mirrors (MCAO)
-> AO system works in closed loop, with several WFSs and several DMs
-> Multiple guide stars needed, with required positioning devices (NGS) or several laser beacons.

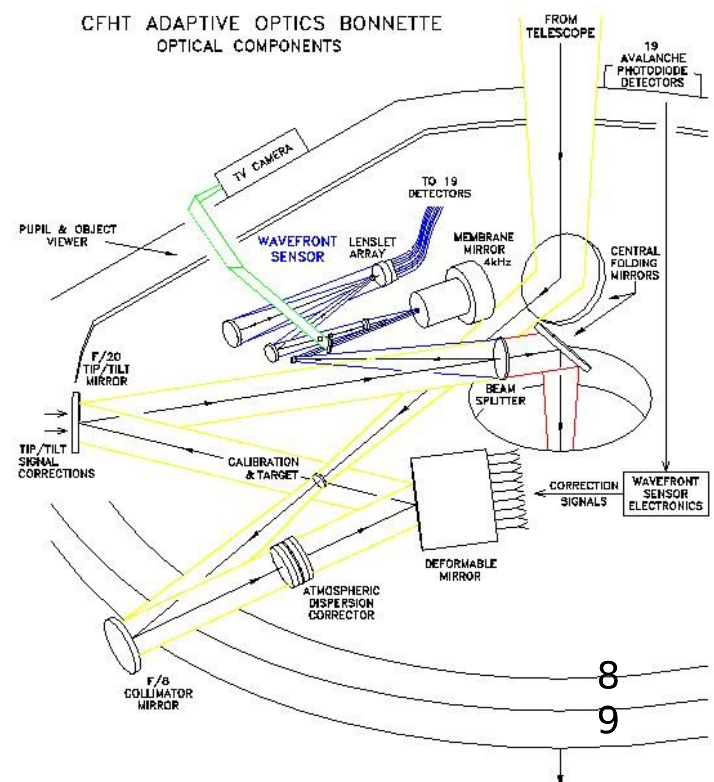
Example 2: Several small individual FOVs spread over a large field
-> The instrument could have small independent wavefront correction units (1 per small field) to minimize optical size/complexity
-> These small units should be fed by a smaller number of WFSs using tomographic reconstruction.
-> The WFSs would be running in open loop, and do not see the correction by the DMs.
-> The DMs would therefore need to be very well calibrated

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".

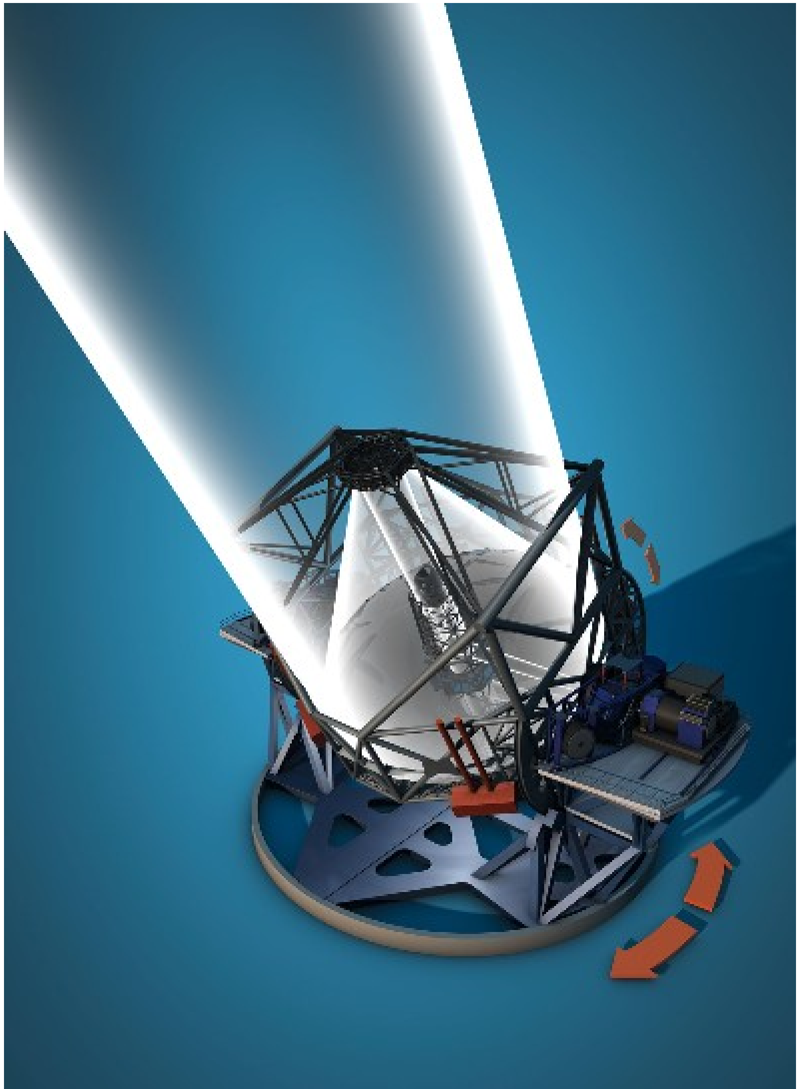
"Facility" AO systems can feed several instruments, and can be a "layer" which processes the beam prior to sending it to instruments.

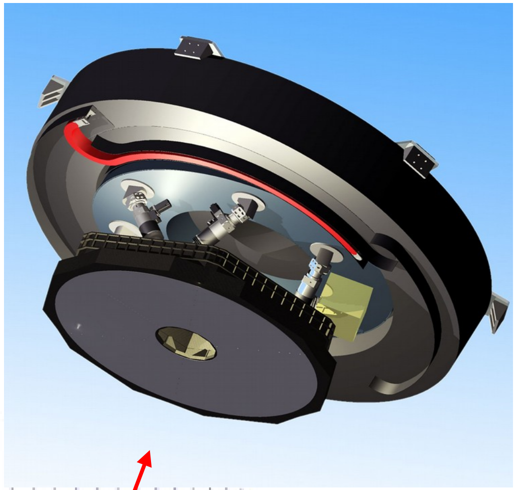


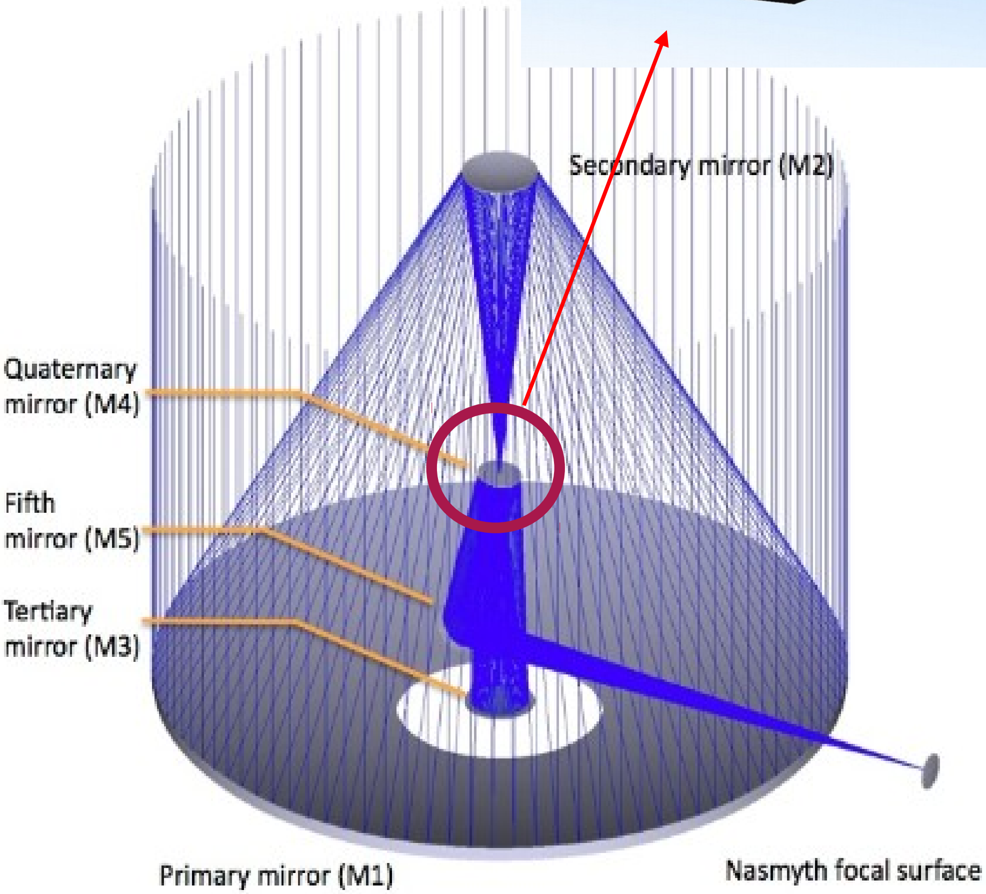


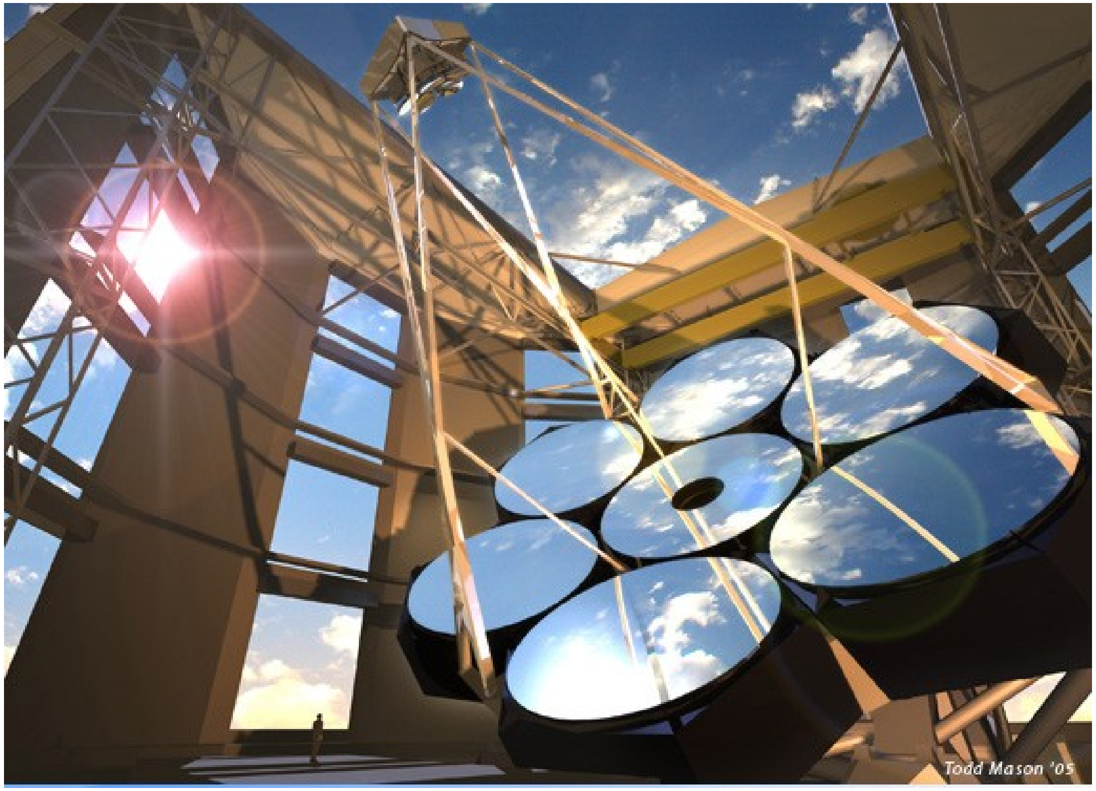
The next generation of large telescopes combine AO with telescope design

The 39m diameter European Extremely Large Telescope (EELT) optical design includes DM as large fold mirrors (M4: 2.4m diameter, 8000 actuators).

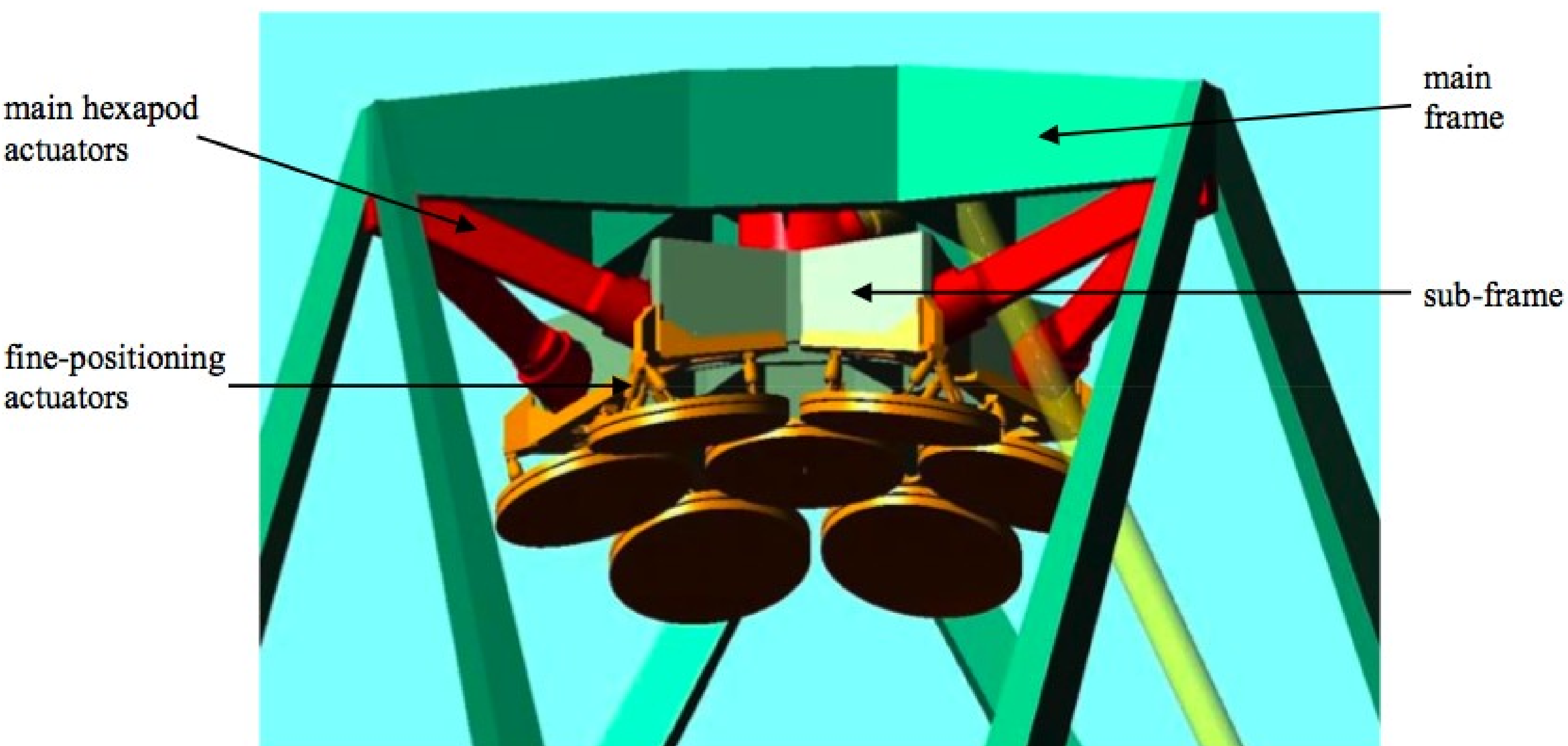


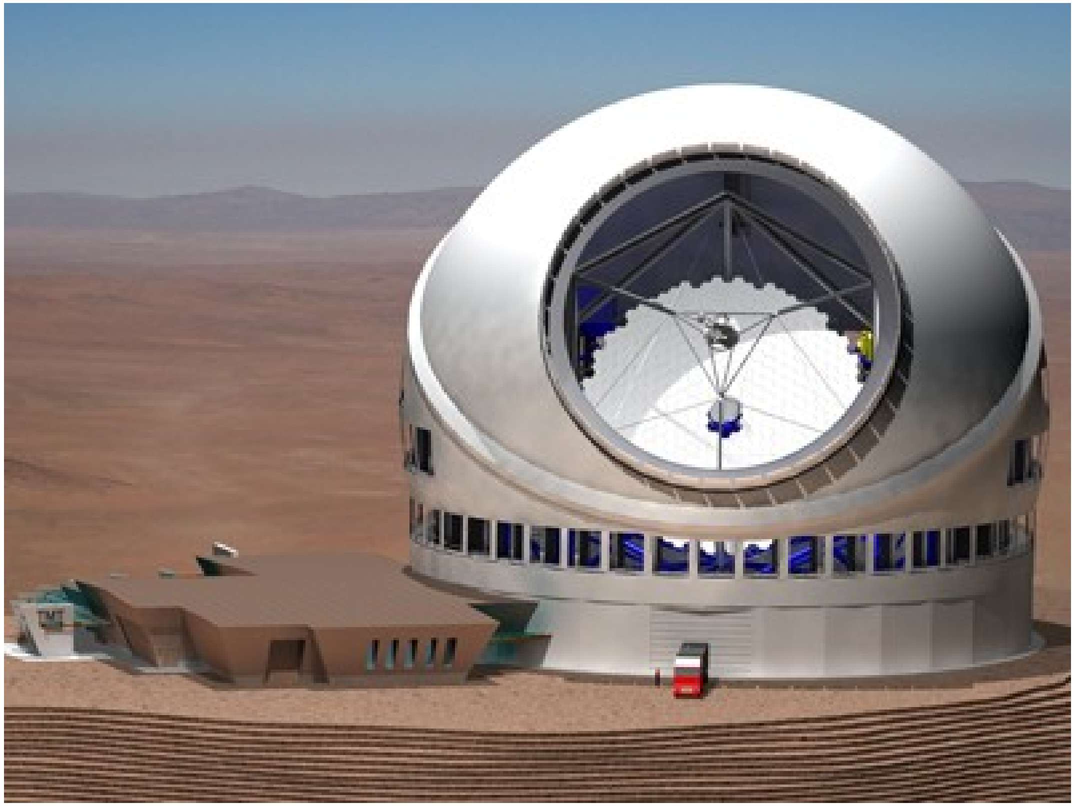




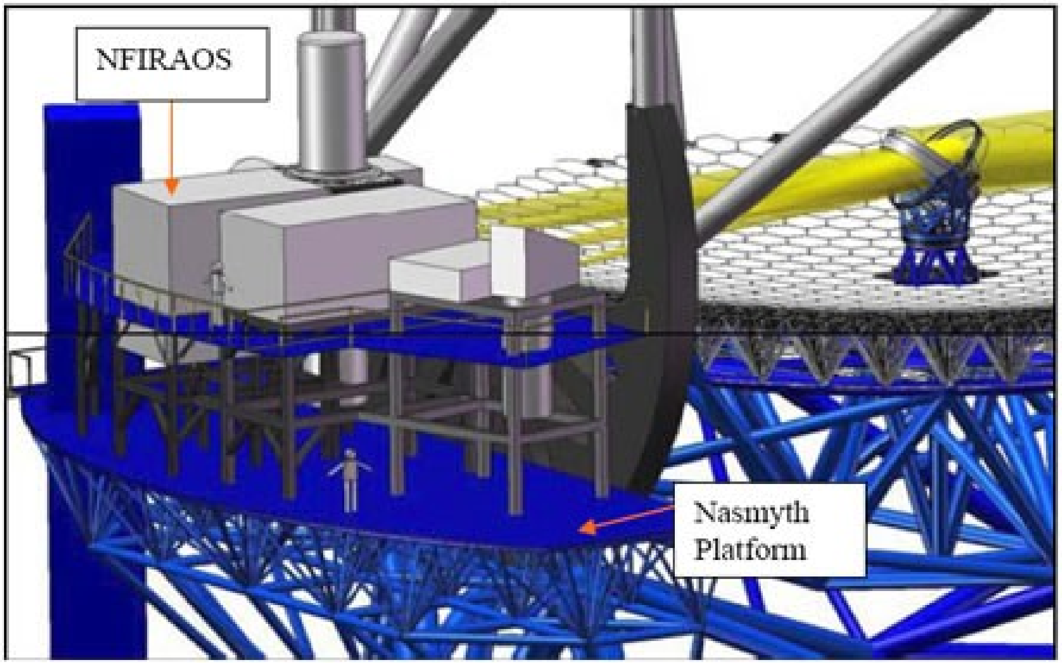


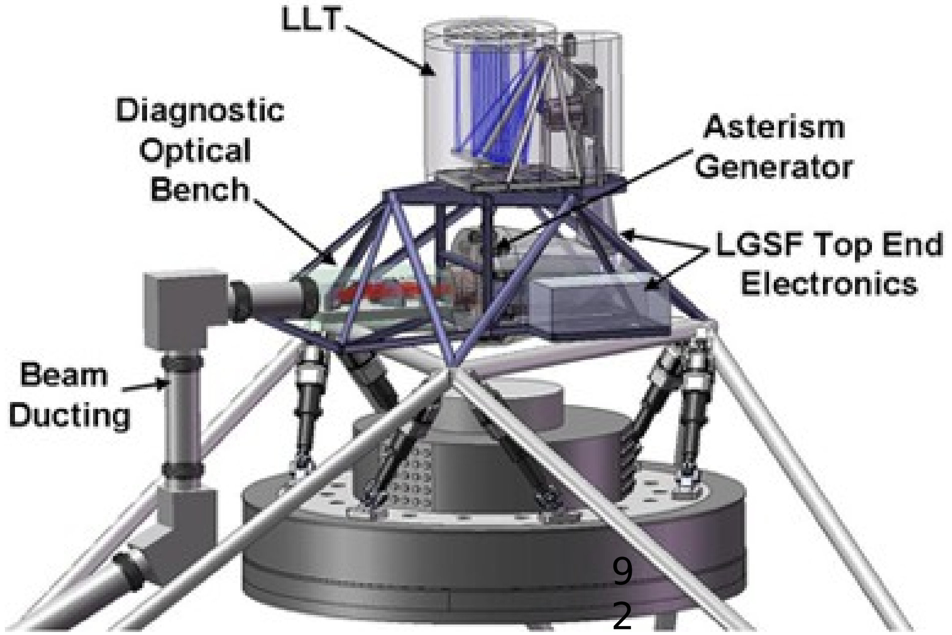
The Giant Magellan Telescope (GMT) secondary mirrors are adaptive and serve as DMs for the AO system(s).





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





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AO control

How should the AO system drive the DM from WFS measurements ?

“standard” solution (fast, linear):

- Measure/model how WFS measures DM commands
- If relationship is linear, this is stored as a “response matrix” “response matrix” is inverted → “control matrix” (this step usually includes some filtering – see next slide)
- WFS measurements x control matrix = DM commands

This could also be done by computing explicitly the wavefront:

WFS measurements → wavefront → DM commands

Good AO control now allows to separate WFS choice from DM choice: example: Curvature WFS could run with a MEMs DM

Linear control of AO system: response and control matrix

Wavefront sensor response to DM commands is linear:

If DM command increased by factor x, WFS signal multiplied by x
WFS signal to sum of 2 DM commands = sum of the 2 WFS signals

→ Relationship can be written as matrix multiplication:

$A = M_{resp}\ B$

Assuming m actuators, n sensing elements
$A_{i=0...n-1}$: WFS signal vector (for example, x,y centroids for SH)
$B_{j=0...m-1}$: DM commands (can be voltages, displacements)
M_{resp}: m x n Response matrix (usually not a square matrix !)

AO control problem:
Given A (WFS measurement), and knowing M_{resp}, what is the DM command B which will produce the WFS signal -A ?
How to do this in a robust way, in the presence of noise, and with M_{resp} which is generally not inversible ?

Linear control of AO system: response and control matrix

Wavefront sensor response to DM commands is linear
→ DM commands to produce a given WFS signal is obtained by multiplication of A (WFS signal) by the control matrix M_{contr}

$B = M_{contr} A$

With M_{contr} the pseudo-inverse of $M_{resp} = M_{resp}^{+} = (M_{resp}^{T} M_{resp})^{-1} M_{resp}^{T}$

If M_{resp} is an inversible square matrix, $M_{contr} = M_{resp}^{-1}$

M_{contr} can be computed by Singular Value Decomposition (SVD) of M_{rest}

Singular Value Decomposition:

$M = U \Sigma V^{*}$

U: Unitary matrix

Σ: diagonal matrix (Eigenvalues a_i)

V: Unitary matrix, V^{*} its conjugate transpose ($=V^{T}$ if V real)

Pseudo-inverse :

$M^{+} = V \Sigma^{+} U^{*}$

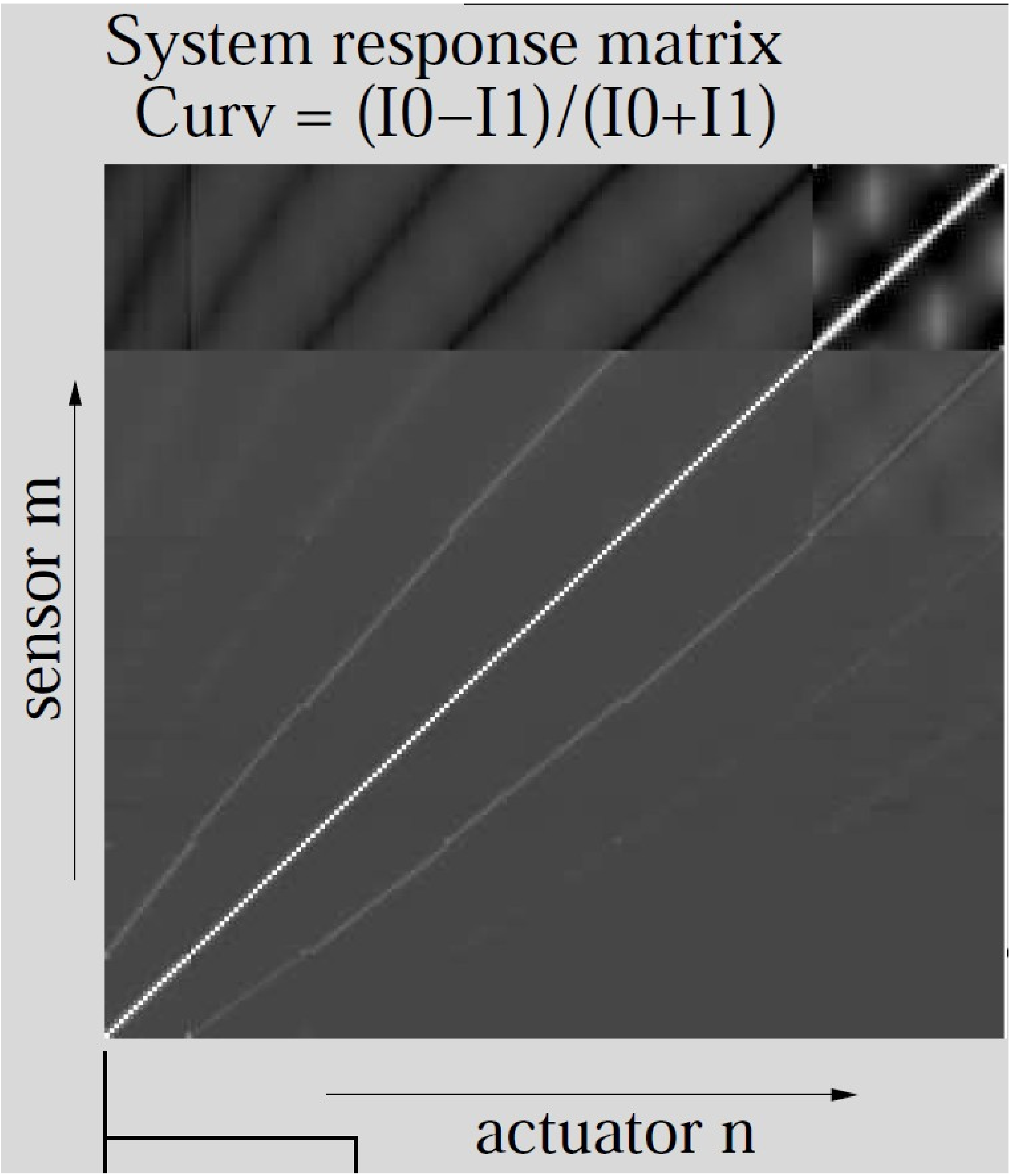
With $\Sigma^{+} = 1/a$ if $|a|>0$, and 0 if $a=0$

Linear control of AO system: response and control matrix

In practice:

- Although M_{resp} could be in theory computer, M_{resp} is usually measured by poking DM actuators and measuring the corresponding change in the WFS signal
- M_{resp} can be mesured quickly by driving simultaneously several actuators if M_{resp} is a sparse matrix (each DM actuator has an effect on a small number of sensors)
- M_{contr} is usually computed by SVD, and presence of noise in the measurement forces modes of M_{resp} with small eigenvalues to be discarded from the control loop (their eigeinvalue considered =0 in the pseudo-inverse computation)

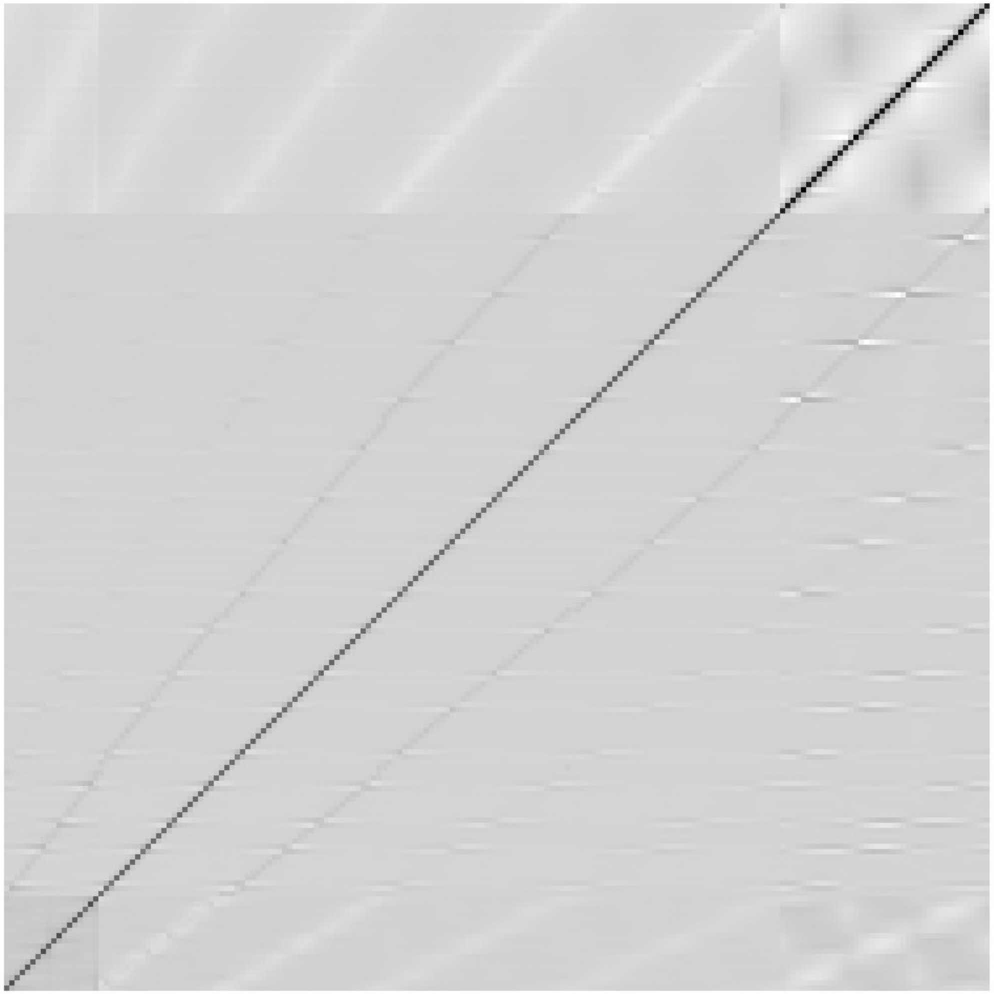
System response matrix: example (simulation)



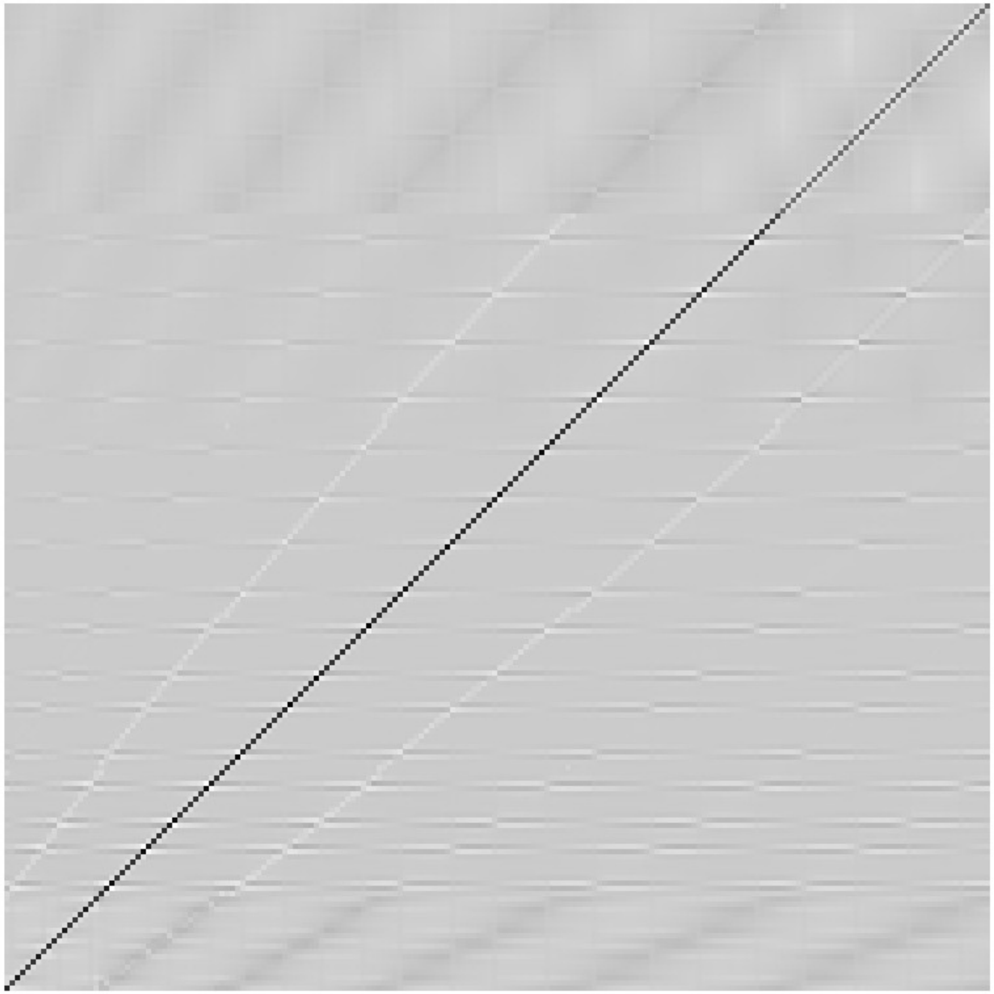
Measured response matrix includes system defects/imperfections, such as :
- alignment errors
- defective sensor(s)
- defective actuator(s)
- crosstalk

Mesuring response matrix is very good system diagnostics

System response and control matrix: example (simulation)



Response matrix



Control matrix

AO loop control: loop gain

At each step of the loop, offset dDM (= $-M_{contr}$ A) required to cancel WFS signal is computed. Ideally, with k the loop step (= time) :

$DM_k = DM_{k-1} + dDM$

Problem: with above equation, loop would likely be unstable

Effective time lag in the measurement is 1/sampling time

→ some temporal frequencies are amplified

Measurement is noisy, and several consecutive measurements should be averaged

Solution: use loop gain < 1:

$DM_k = DM_{k-1} + g\, dDM$

With $0<g<1$

Noisy WFS measurement (faint guide star) → small g

High quality WFS measurement (bright guide star) → large g

AO control: Modal control/filtering

Concept: Run AO loop at different speed for each mode, depending upon mode strength & WFS sensitivity for the mode
Gain becomes different for each mode

$M_{contr} = M_{resp}{}^{+} = V\ \Sigma^{+}\ U^{*}$
With $\Sigma^{+} = g_i/a_i$ if $|a_i|>0$, and 0 if $a_i=0$
Modal gains = g_i

Instead of thinking about AO control as relationship between individual sensors and actuators ("zonal" control), AO control is done mode per mode ("modal" control). Choice of modes is very important.

If $|a_i|$ is small (= WFS is not very sensitive to mode I), then $1/a_i$ is large → noise can be amplified (noise/a_i is big)
If $|a_i|$ is small and corresponding mode in atmosphere is weak, then g_i should be small

AO control: Modal control/filtering

Modal control is very useful to:

- reject “bad modes” which can be produced by DM but not well sensed by WFS
- attenuate known vibrations
- powerful tool for system diagnostic

Modes poorly seen (noisy) by WFS & weak in the atmosphere should be prevented from feeding strong signals to DM. Powerful & well sensed mode should be rapidly driving the DM.

Modal control can continuously tune the system for optimal performance, adjusting gains g_i in real time (see next slide for transfer function description).

Transfer function $H_g(f)$ known as a function of g_i, and WFS signals measures $WFS(f) = H_g(f)*Atm(f)$, with Atm(f) the input disturbance. Simplified description (without noise):

→ Atm(f) can be computed (= $WFS(f)/H_g(f)$)

→ WFS(f) can be estimated for other values of g_i

→ best g_i is adopted to minimize WFS(f)

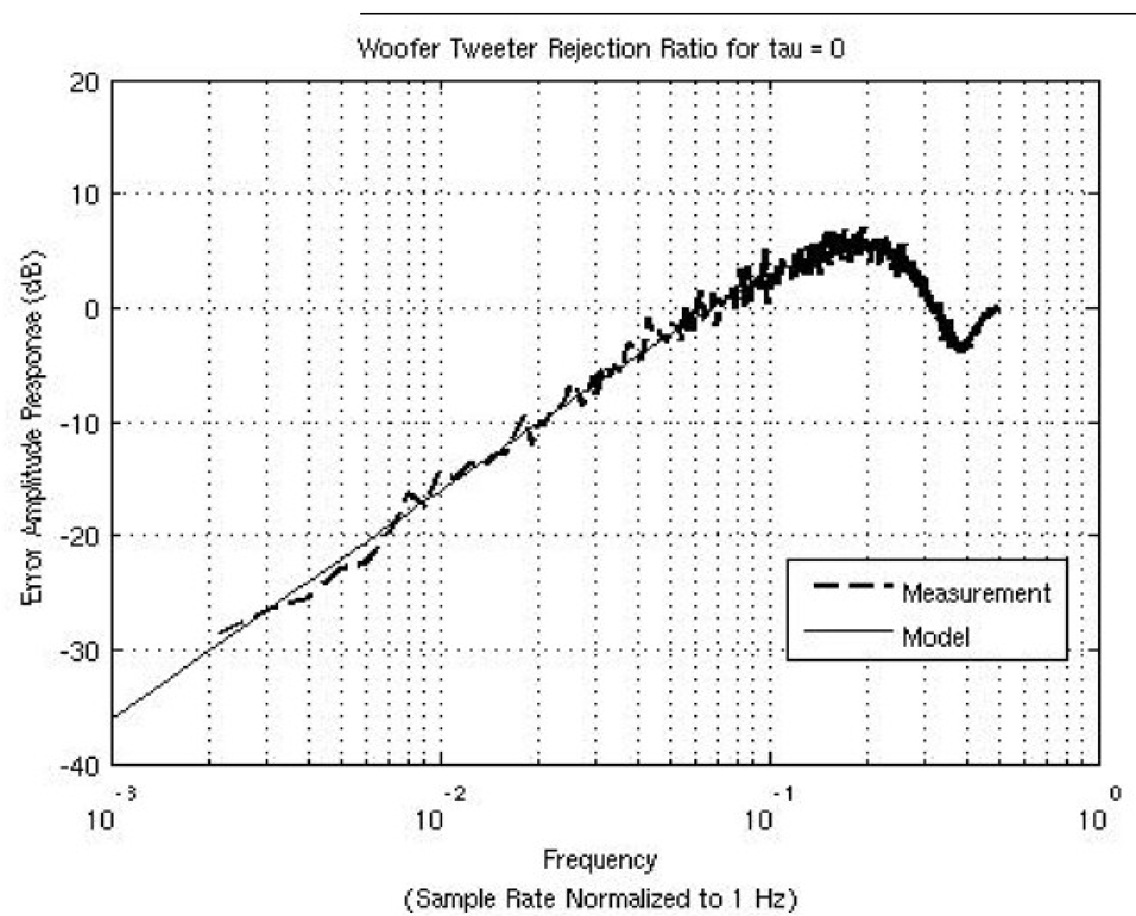
AO control: transfer function

AO control loop can be considered as a linear temporal filter. For each mode and each temporal frequency f, the AO system attenuates incoming errors by H(f), the AO error transfer function

H(f) < 1 : attenuation
H(f) > 1 : amplification

H(f) → 0 for f → 0 in a closed loop system

Notes:
- H(f) is complex :
    ampl = attenuation
    phase = delay
- analytical tools can express H(f) in amplitude and phase according to loop characteristics (gain, delay)



Hampton et al. (University of Victoria)

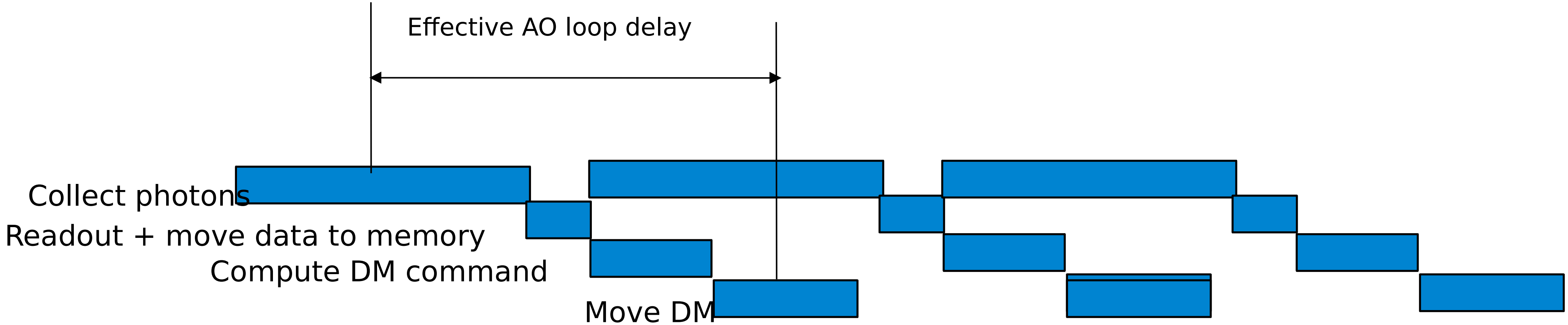
Optimizing AO control speed

→ High speed means fewer photons / sample need high SNR in WFS (optimal use of photons)

→ need fast hardware (see below)

- DM: good time response, low vibration
- Detector: fast readout / low readout noise
- computer, software & electronics need to be fast

→ Clever, predictive control can help a lot: anything that could be predicted should be !



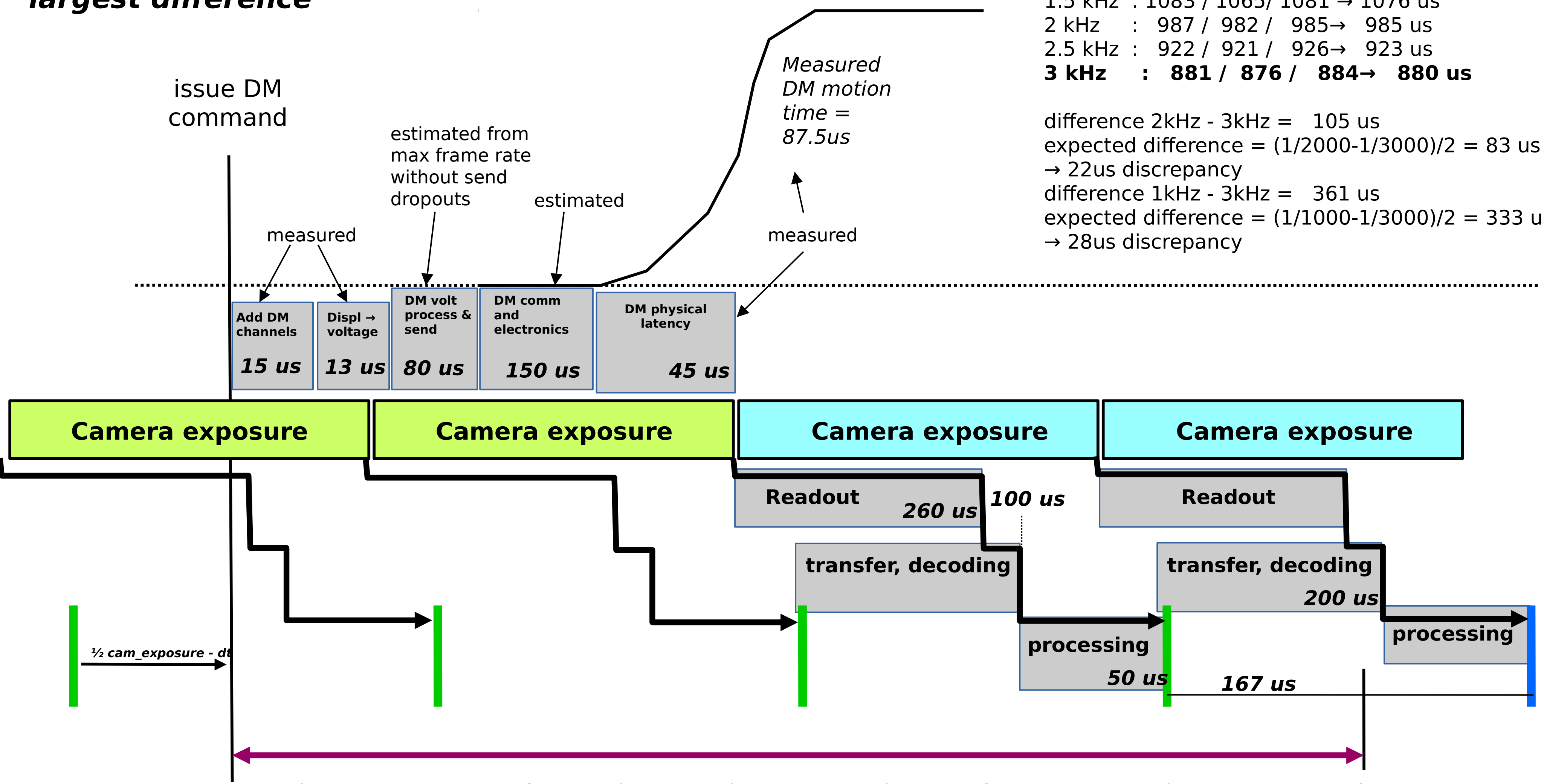
Example: Hardware Latency measured on SCExAO

Definition:
Time offset between ***DM command issued****, and* ***mid-point between 2 consecutive WFS frames with largest difference***

SCExAO measured hardware latencies:

1 kHz : 1253 / 1260/ 1269 → 1261 us
1.5 kHz : 1083 / 1065/ 1081 → 1076 us
2 kHz : 987 / 982 / 985→ 985 us
2.5 kHz : 922 / 921 / 926→ 923 us
3 kHz : 881 / 876 / 884→ 880 us

difference 2kHz - 3kHz = 105 us
expected difference = (1/2000-1/3000)/2 = 83 us
→ 22us discrepancy
difference 1kHz - 3kHz = 361 us
expected difference = (1/1000-1/3000)/2 = 333 us
→ 28us discrepancy



HardwareLatency = DM soft + DM elec + DM phys + CAM readout/transfer + CAM processing + ½ exposure time
HardwareLatency = N x cam_exposure + dt

Realistic simulations of AO systems are extremely useful

AO simulations are relatively accurate, as input and outputs are well known:

- seeing properties are fairly well known (Kolmogorov layers)
- WFS behavior & properties are usually very well known
- Control algorithm identical in simulations & on the sky

AO simulations can investigate:

→ performance vs. # of actuators, DM type/geometry
→ loop instabilities & mode filtering
→ hardware trade-off:
  WFS detector readout noise
  DM hysteresis
  speed of electronics & computer
  Laser power for LGS
  On-axis vs. off-axis LGS
→ alignment tolerance

Telemetry is also very important

Recording WFS and DM data allows:

- seeing estimation & logging
- self-tuning of system
- diagnostics

If a strange behaviour is observed in the AO loop, it is very hard to identify it without being able to “play back” the time when it occurs.

Issues:

Disk space

File management, archiving