

# **AO system Design: Astronomy**

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*Center for Adaptive Optics Summer School, Aug 2012*

# 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

**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

## 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**

## Outline

### **Astronomical AO system diversity**

Main challenges / error budget terms in astronomical AO systems

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

# What gains are offered by Astronomical Adaptive Optics Systems ?

## **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.

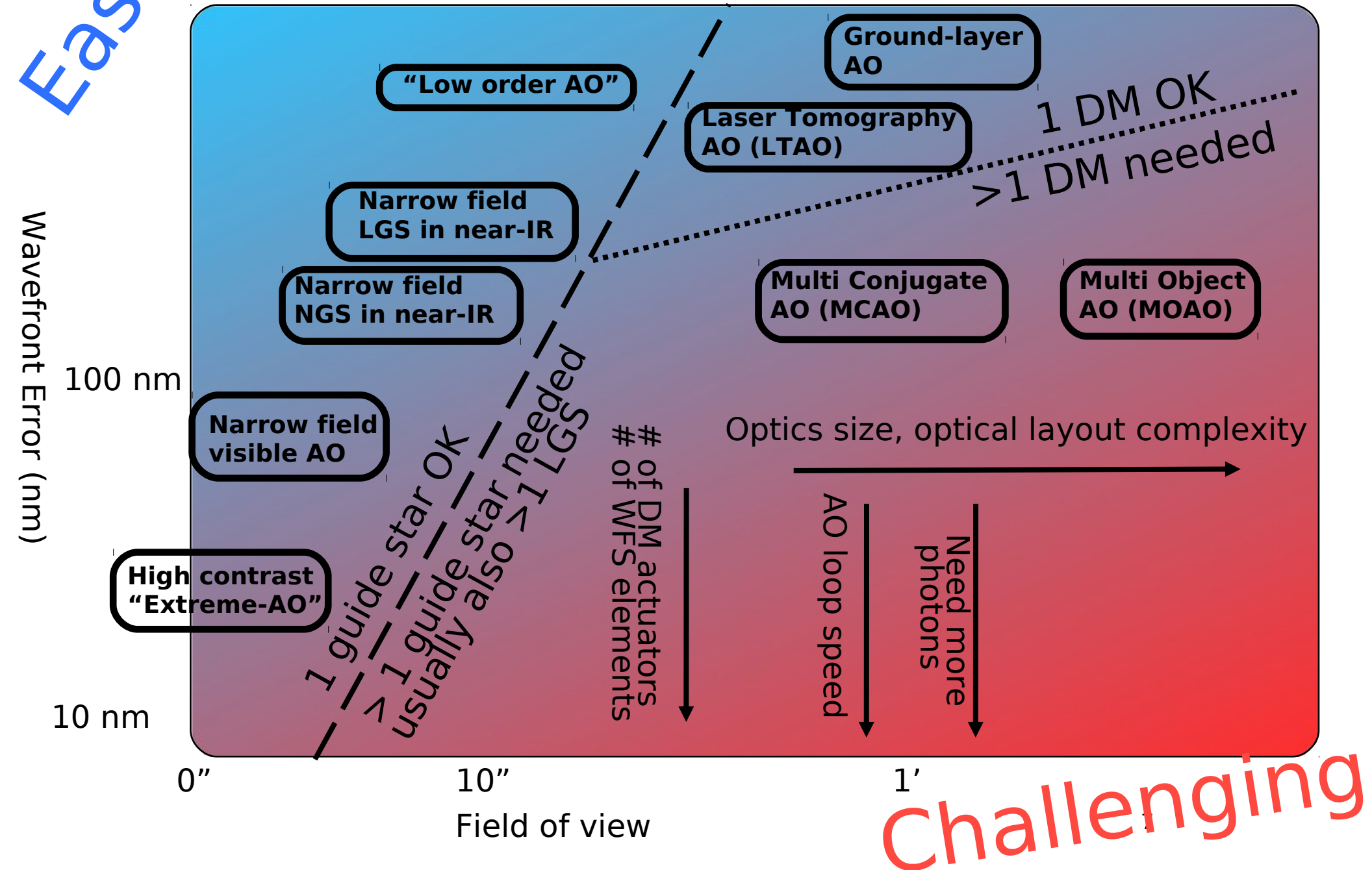
## **Confusion limit:**

Astronomical imaging of sources is often confusion limited. Better angular resolution helps !

For example: studying stellar populations in nearby galaxies.

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

Easier

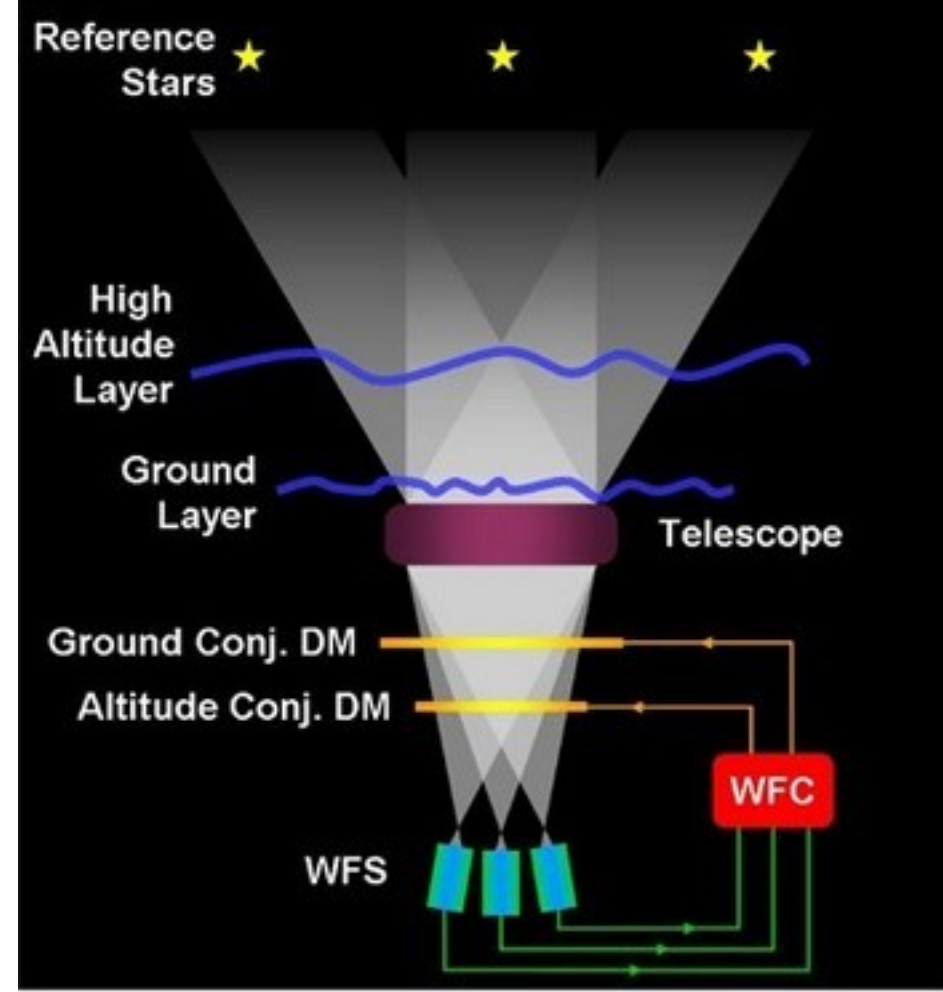


# Example #1: Multi-Conjugate AO (MCAO)

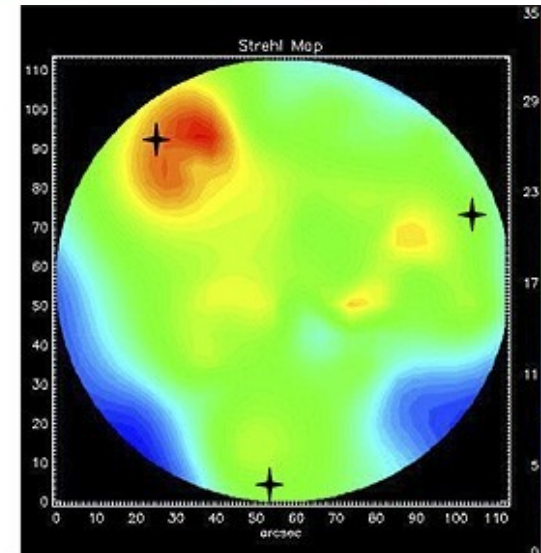
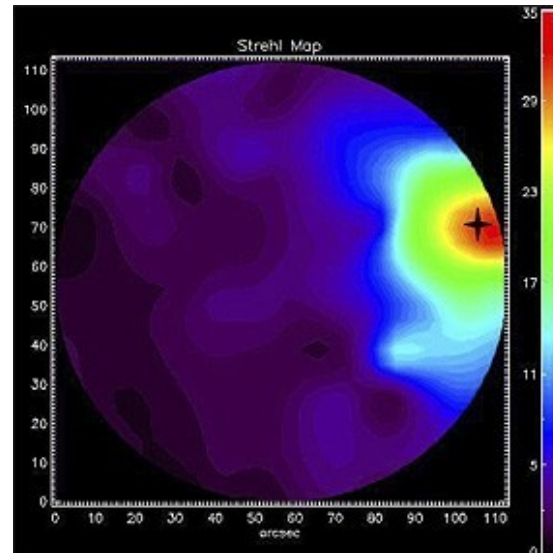
Uses several guide stars (NGS or/and LGS) to gain volumetric information of turbulence.

Uses several DMs to correct over wide field.

Results from ESO's MCAO demonstrator (MAD)  
and Gemini MCAO system (GEMS)

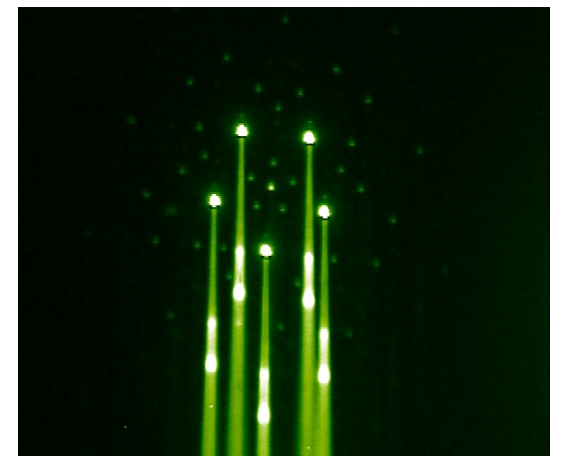


Strehl maps on the right show image quality is high over a wide field of view (black crosses show position of guide stars)





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



5 laser guide stars  $\rightarrow$  5 wavefront measurements

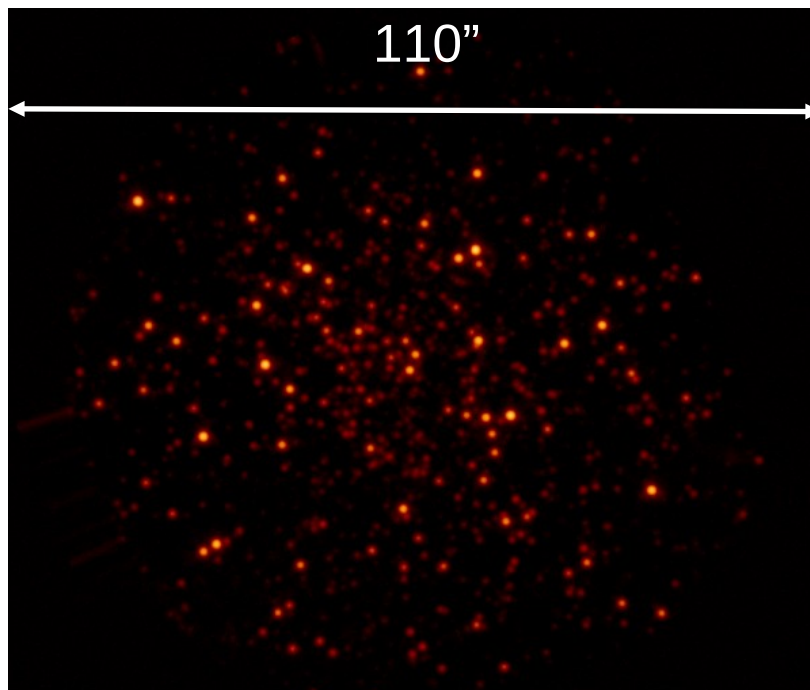
Reconstructor keeps only ground layer, common to the 5 wavefronts

Single DM corrects for the ground layer: correction is valid over a large field

### MMT results: M3 globular cluster

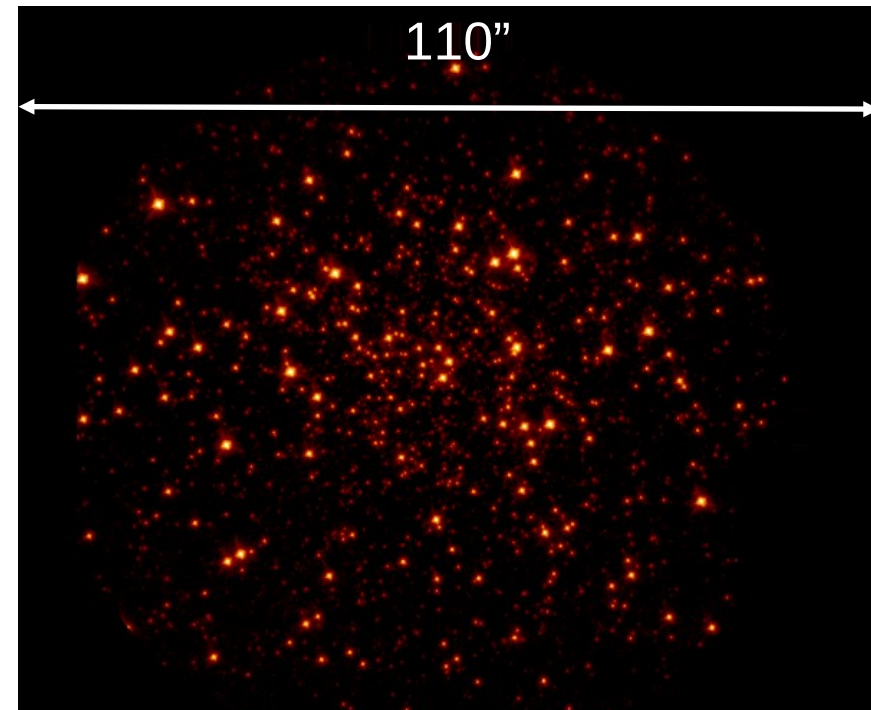
Open loop,  $K_s$  filter, FWHM  $0.70''$

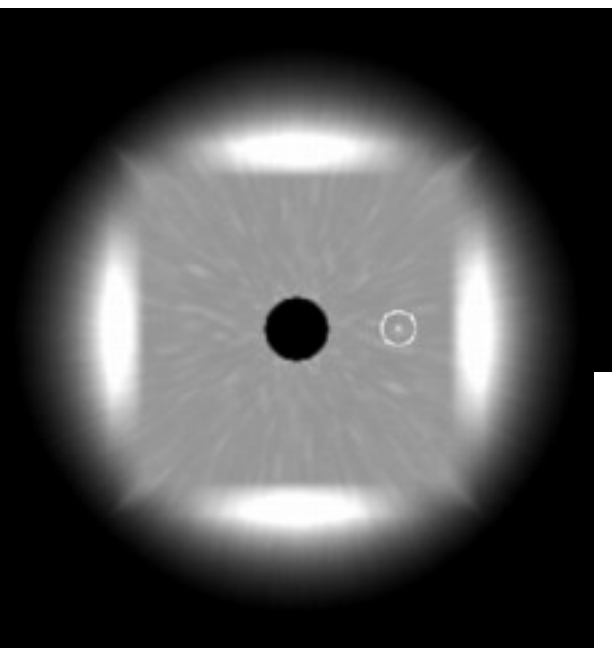
Logarithmic scale



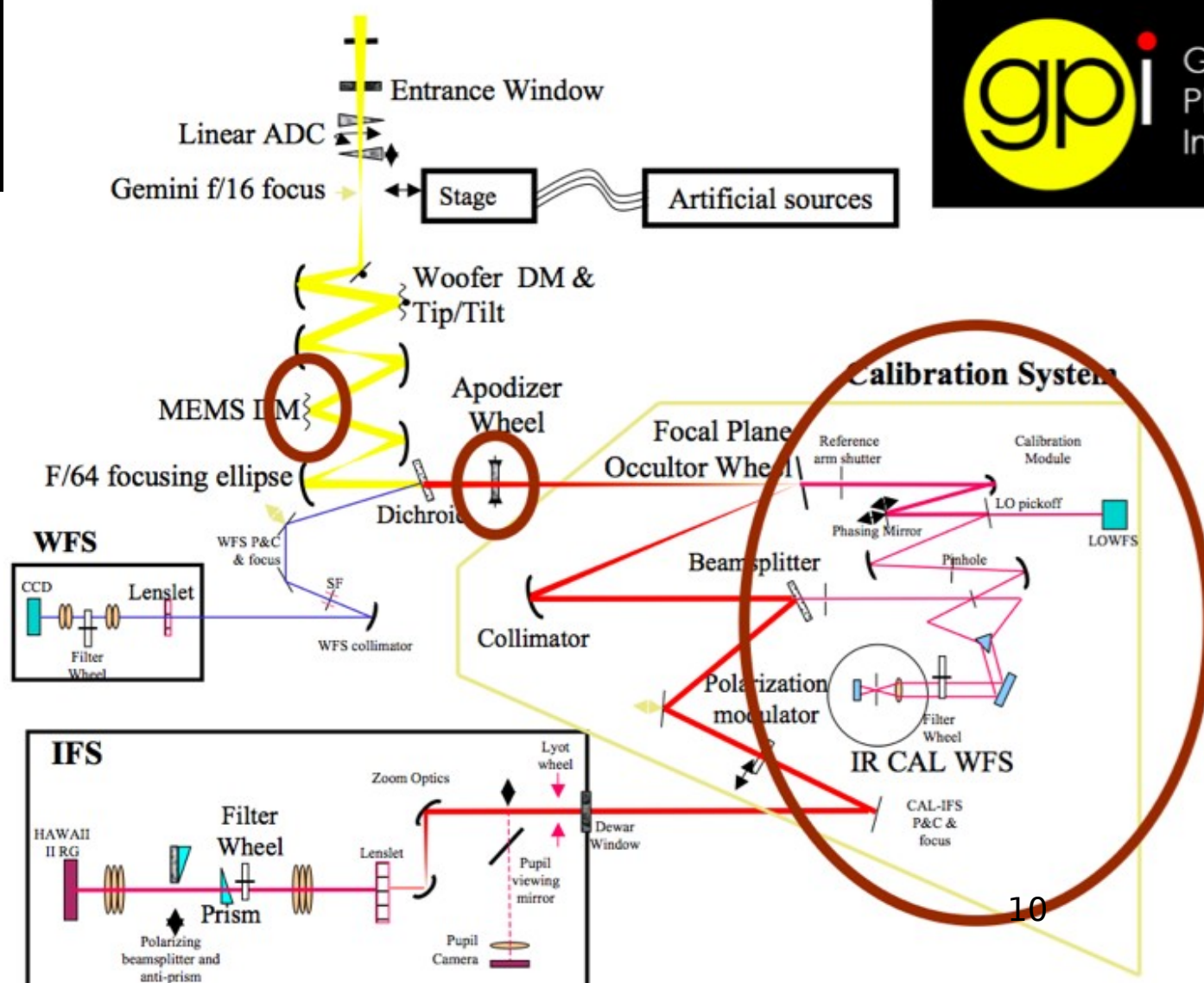
Closed loop GLAO,  $K_s$  filter, FWHM  $0.30''$

Logarithmic scale





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

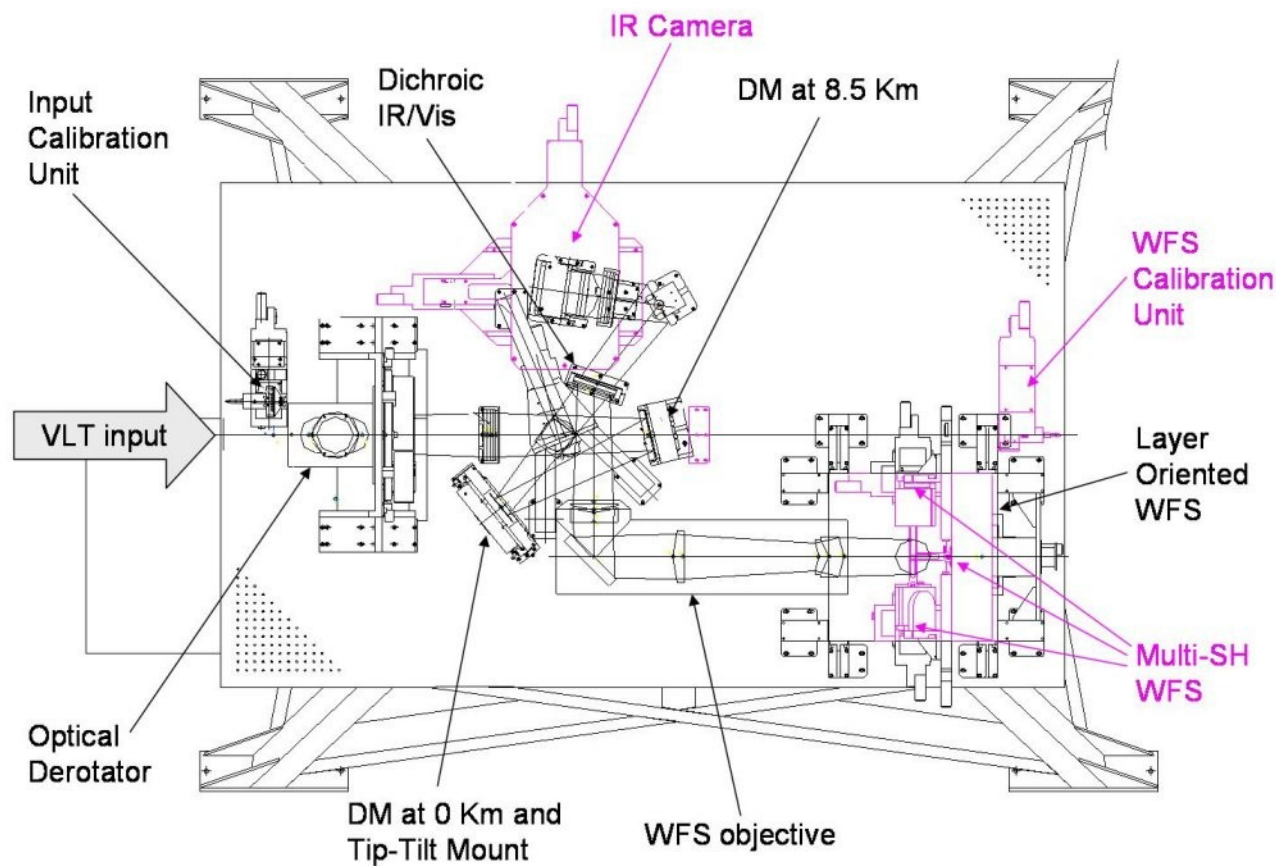
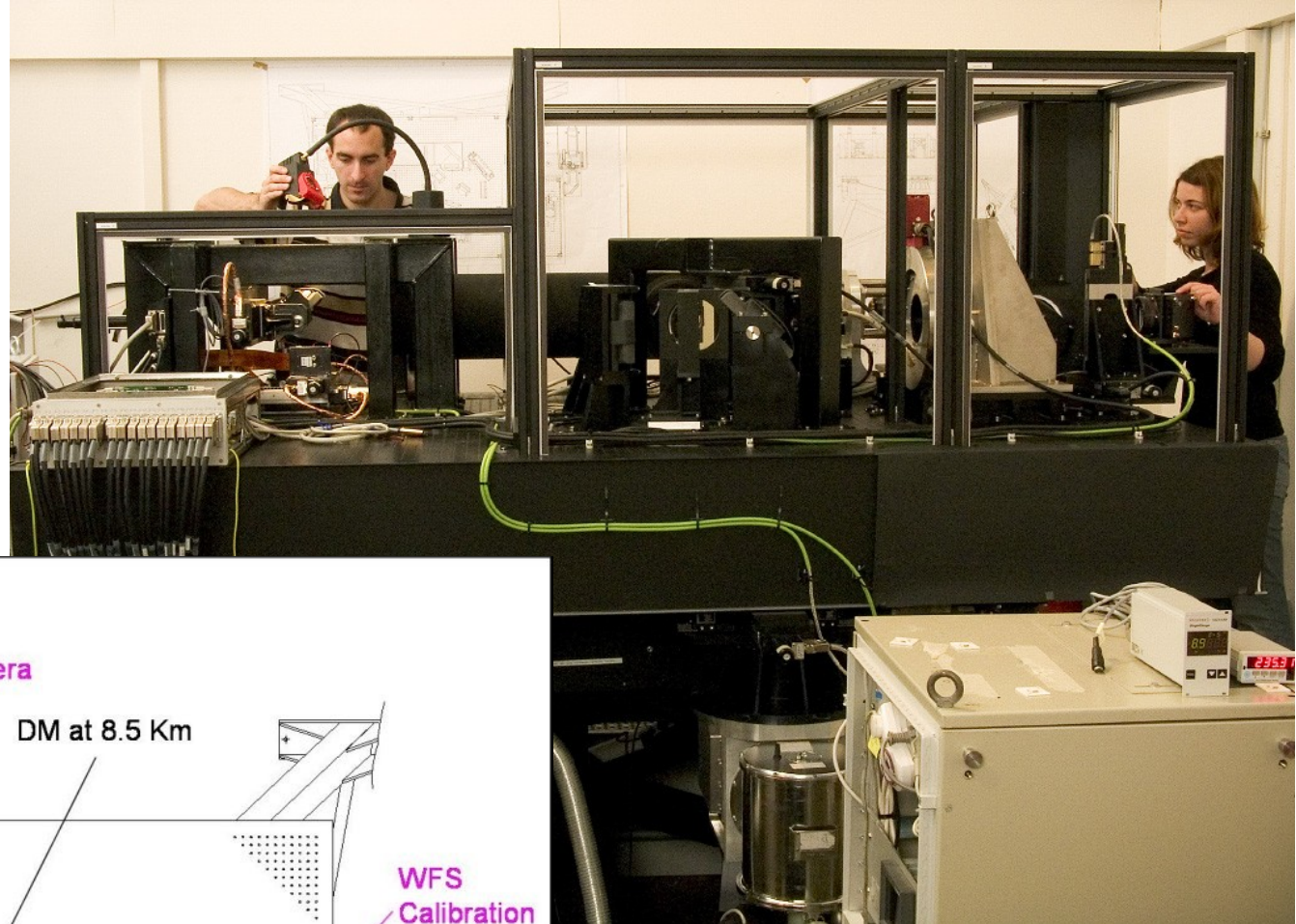


# Altair Optics bench (for Gemini North Telescope)





# Multi Conjugate AO Demonstrator (MAD, ESO)



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


## 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:**

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**Adaptive Optics for Astronomical Telescopes (1998)**, by John W. Hardy, Oxford University Press

# Wavefront error budget

Wavefront error  $\sigma$  is in radian in all equations.

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

Wavefront error (m) =  $\lambda \times \sigma / (2\pi)$

Strehl ratio  $\sim e^{-\sigma^2}$

(Marechal approximation, valid for Strehl ratio higher than  $\sim 0.3$ )

## 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

# 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

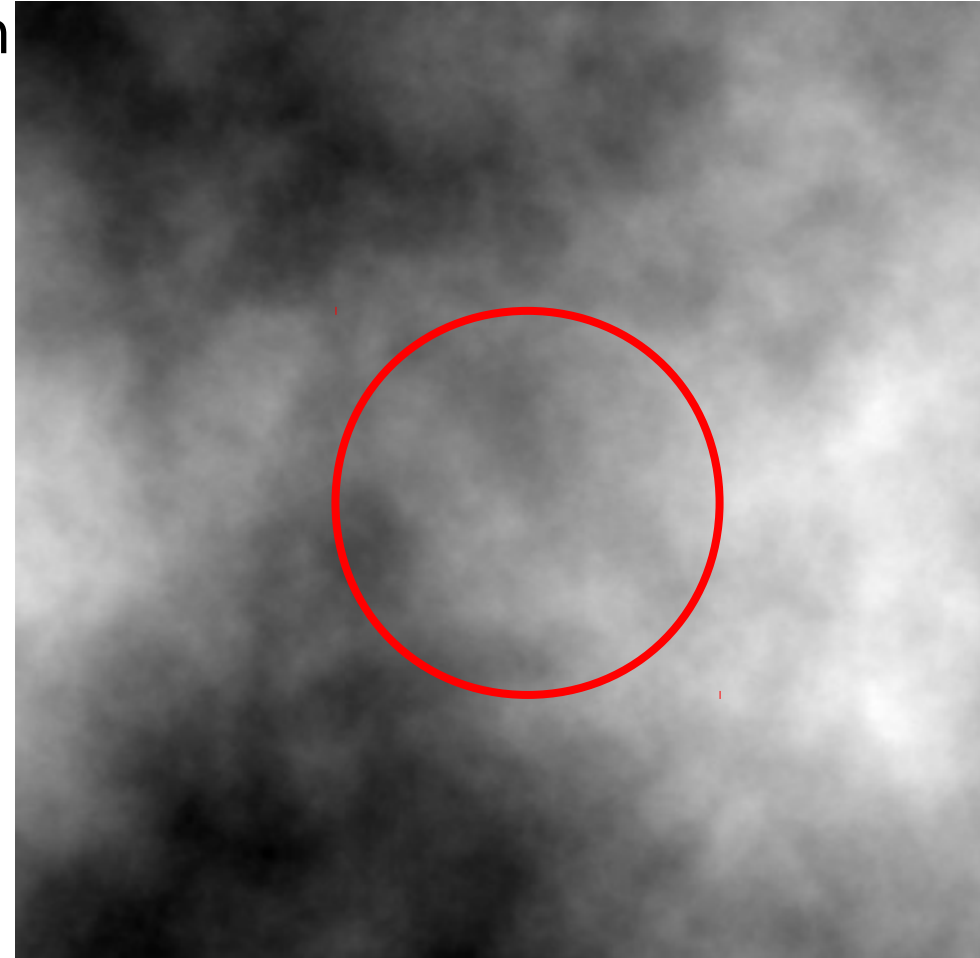
$$\sigma^2 = 1.03 (D/r_0)^{5/3}$$

+ 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)

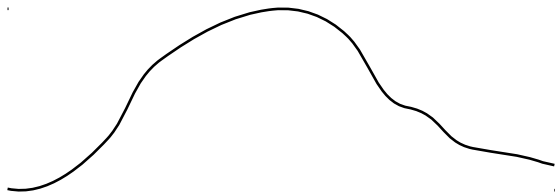
Most of the power is in tip-tilt:

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

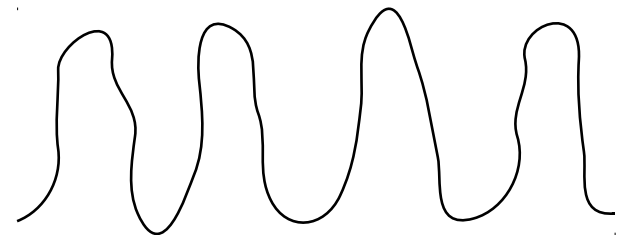
On many DMs, interactor stroke < overall stroke

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  $\mu\text{m}$ )

Diffraction limit requires  $\sim N = 24$

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 :

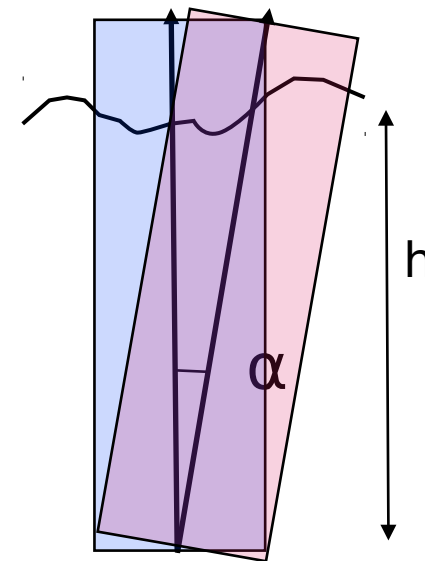
$$\sigma^2 = 1.03 (\alpha/\theta_0)^{5/3}$$

Where  $\alpha$  is the angle to the optical axis,  $\theta_0$  is the isoplanatic angle:

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

$$D = 8 \text{ m}, r_0 = 0.8 \text{ m}, h = 5 \text{ km} \rightarrow \theta_0 = 10''$$

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  $\sim 10\times$  bandwidth

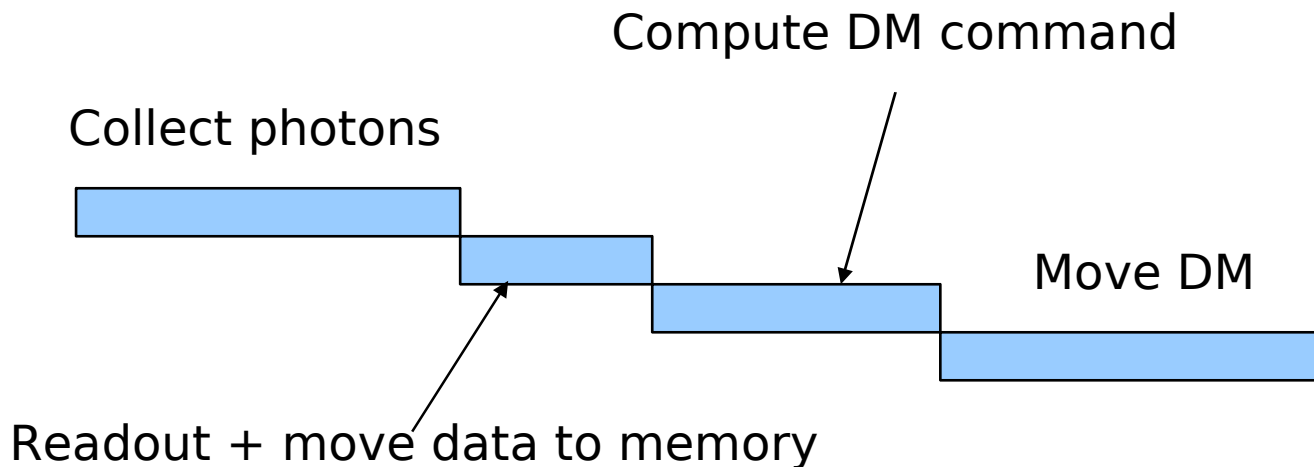
for “diffraction-limited” system (1 rad error in wavefront):

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  $\mu\text{m}$  band (20% efficiency)

Example 1: **General purpose NGS system**

**Goal: achieve diffraction limited performance over much of the sky**

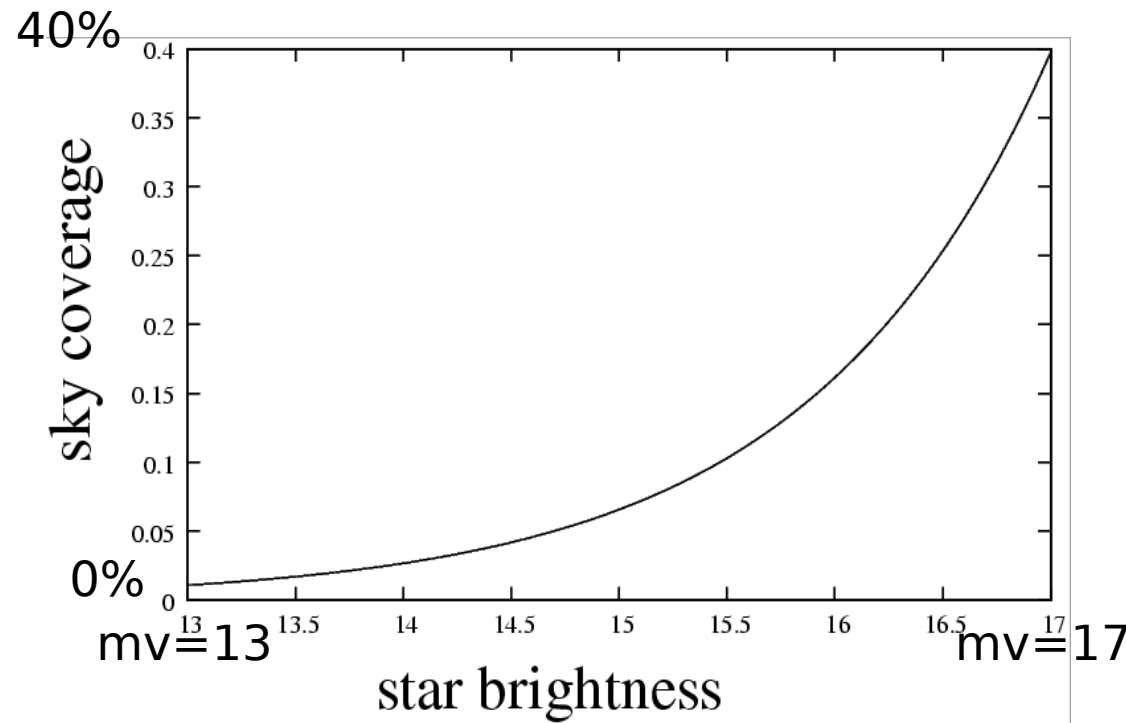
Star brighter than  $m_v$  density

$\sim 9e-4 \exp(0.9 m_v)$  per

sq. deg (galactic pole)

ref: Parenti & Sasiela, 1994

Within a 20" radius:







**$m_v=8 \rightarrow 2.5e5 \text{ ph/ms}$  on 8m pupil in 0.5  $\mu\text{m}$  band  
& 20% efficiency**

**Example 2: Extreme-AO system**

**Goal: Achieve exquisite wavefront correction on selected bright stars**

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,  $\sim 0.2$  rad phase error per actuator  
at best.



## 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  $\lambda^{6/5}$   $\rightarrow$   $N$  goes as  $\lambda^{-12/5}$

- speed gets high ( $\tau_0 = 0.314 r_0/v$ )  $\rightarrow \tau_0$  goes as  $\lambda^{6/5}$
- anisoplanatism gets small (FOV, sky coverage go down)  
 $\theta_0$  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

## **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  $\sim 1$  actuator per  $r_0$ .

Exception:

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

# PSF quality: metricS

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

**Example of 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)

## Outline

Astronomical AO system diversity

Main challenges / error budget terms in astronomical AO systems

## **Wavefront sensing strategy**

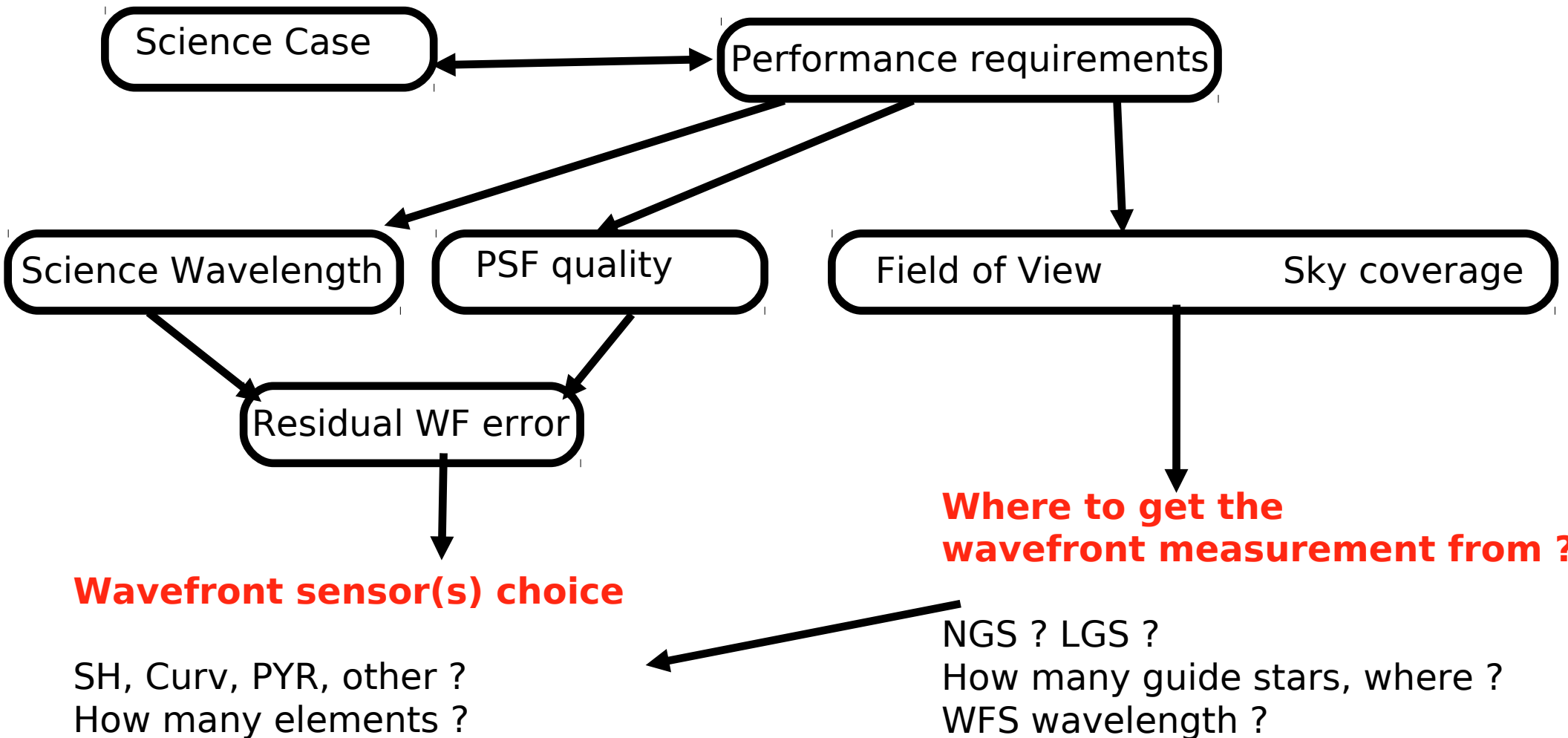
Large field of view AO systems

Optical/mechanical design considerations

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



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



## 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

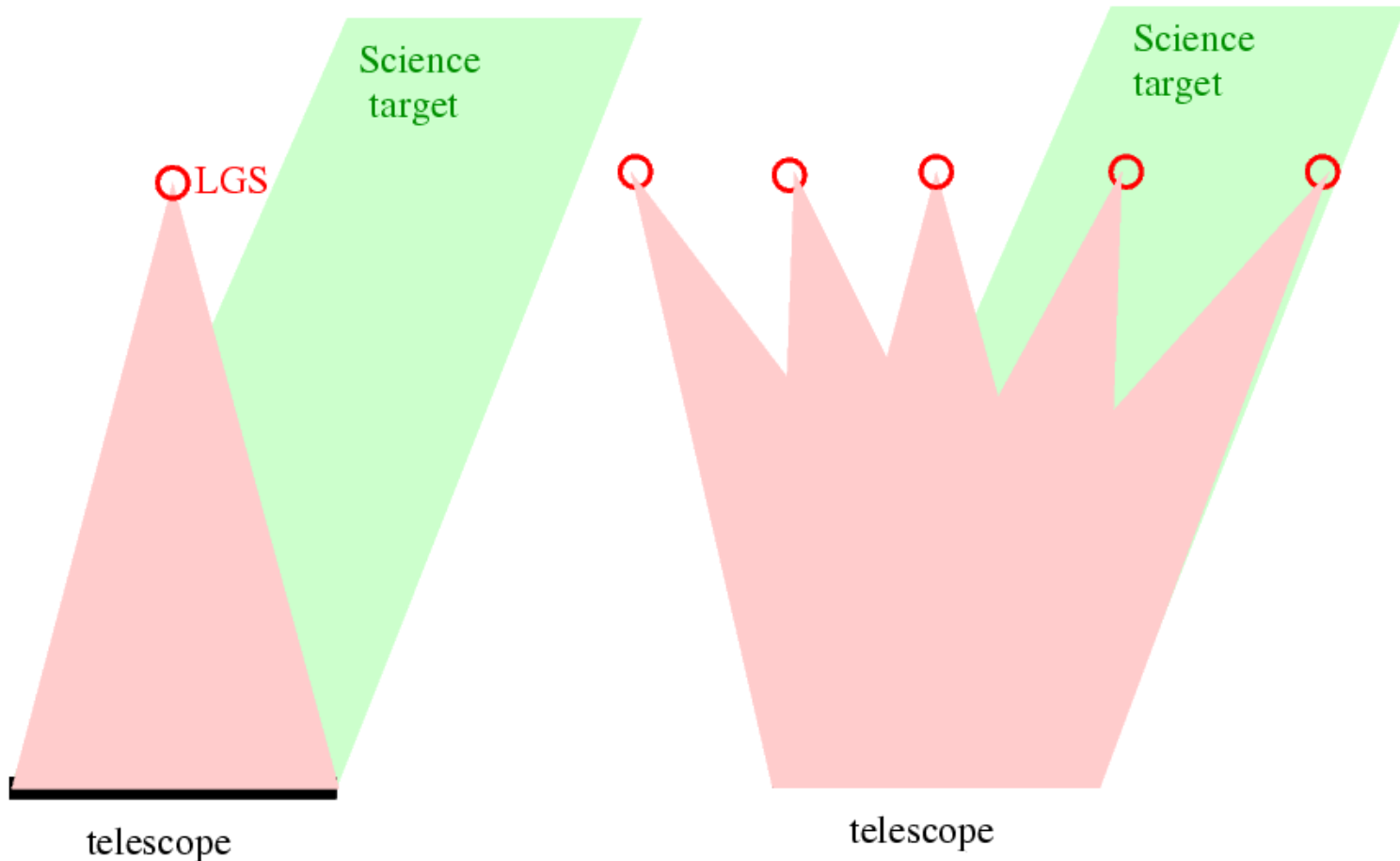
- in 2 wavelengths -> can solve Tip/Tilt problem

**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

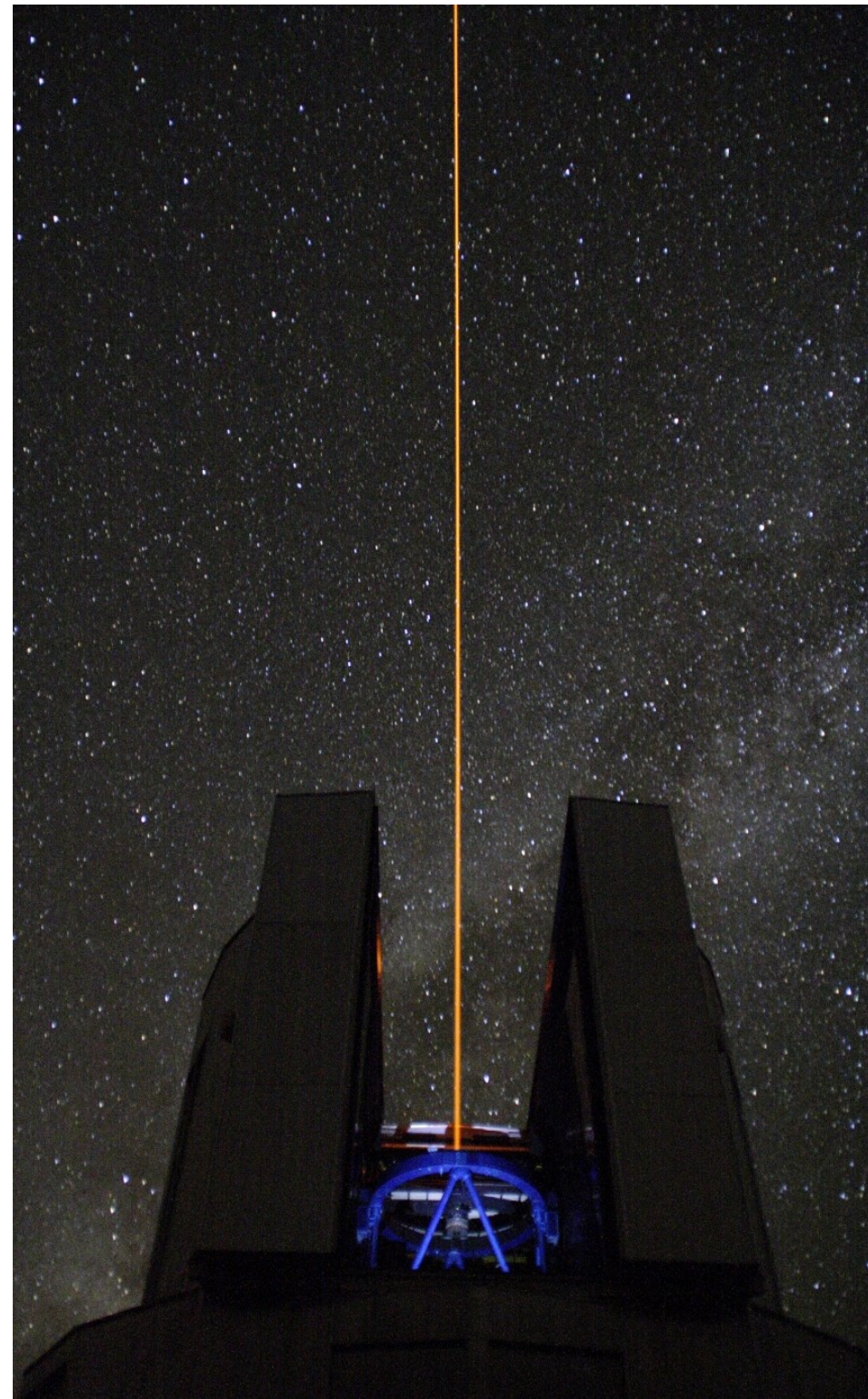
**Cone effect** due to finite altitude of LGS (90km sodium, few km for Rayleigh)  
-> can be solved by using several lasers and tomography

### **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**

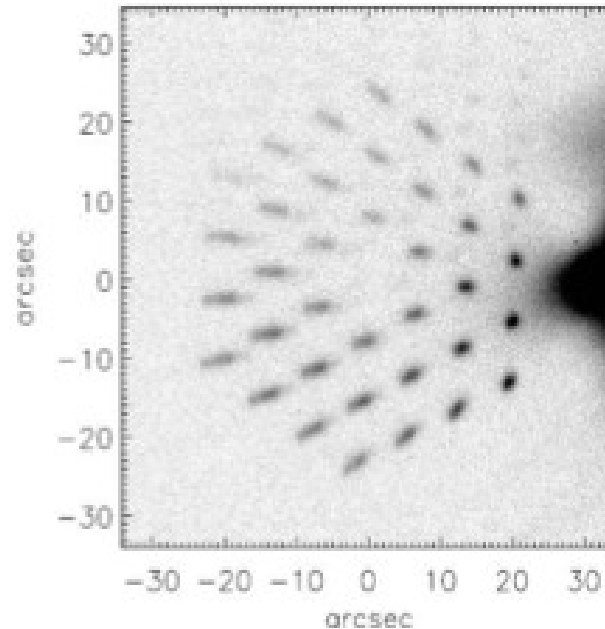
-> **polychromatic laser (not quite mature yet)**



## Some challenges of LGS AO

### Spot elongation

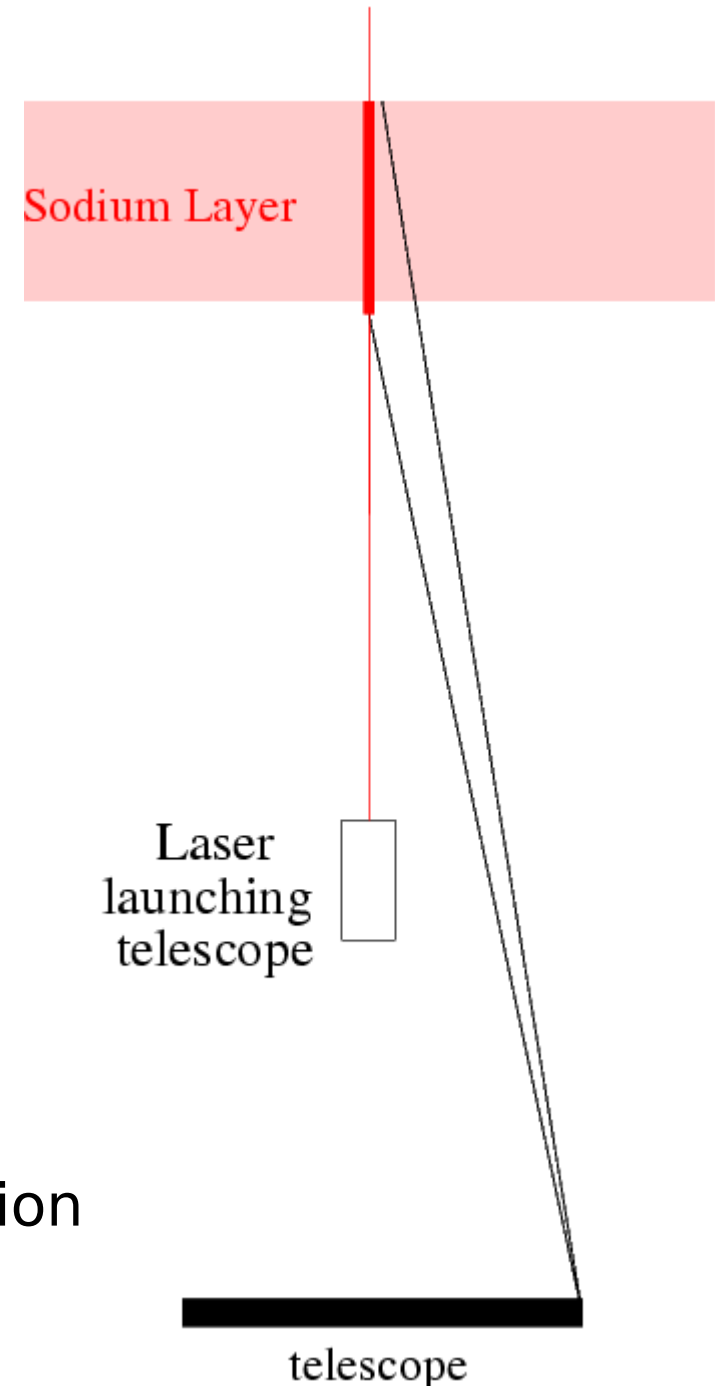
Sodium layer  
is  $\sim 10\text{km}$  thick



**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  $\ll$  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)

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

$\theta_0$ : isoplanatic angle

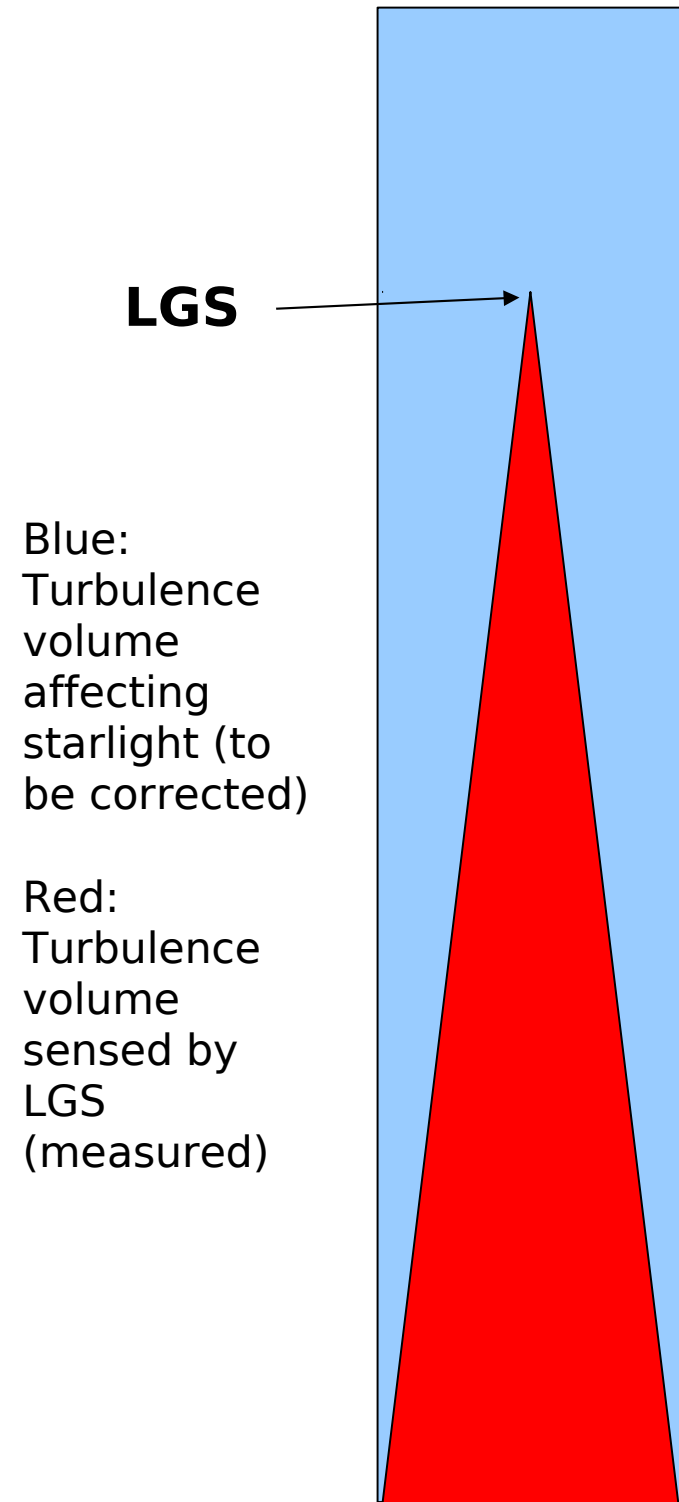
H : LGS altitude

D : Telescope diameter

→ impact is smaller for sodium LGS

→ larger effect for large telescopes

Mitigated by using several LGSs





## Focus sensing

Altitude of LGS is variable  
(~90km sodium layer)

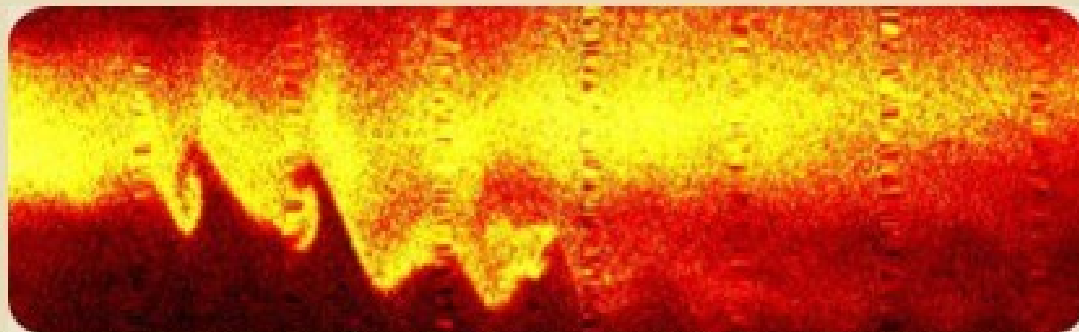
-> slow variations in measured  
focus are introduced by sodium layer

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

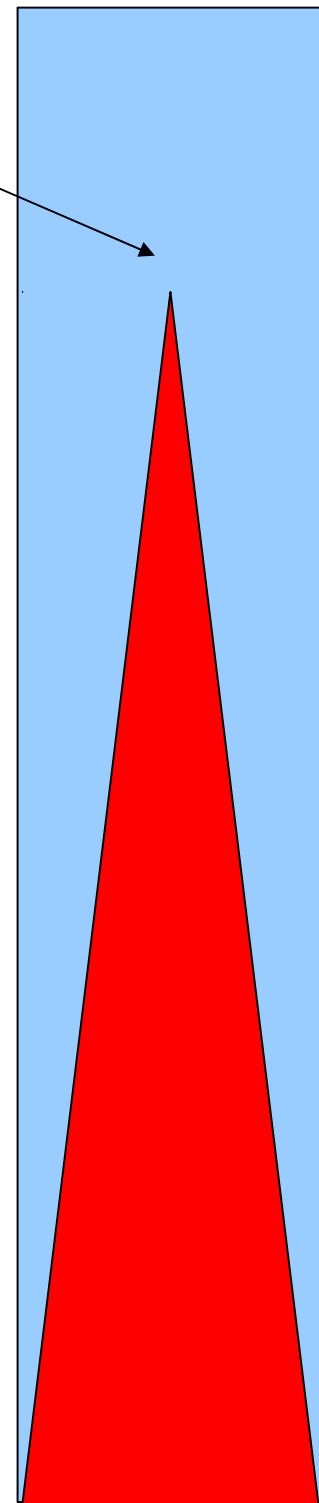
**LGS**



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

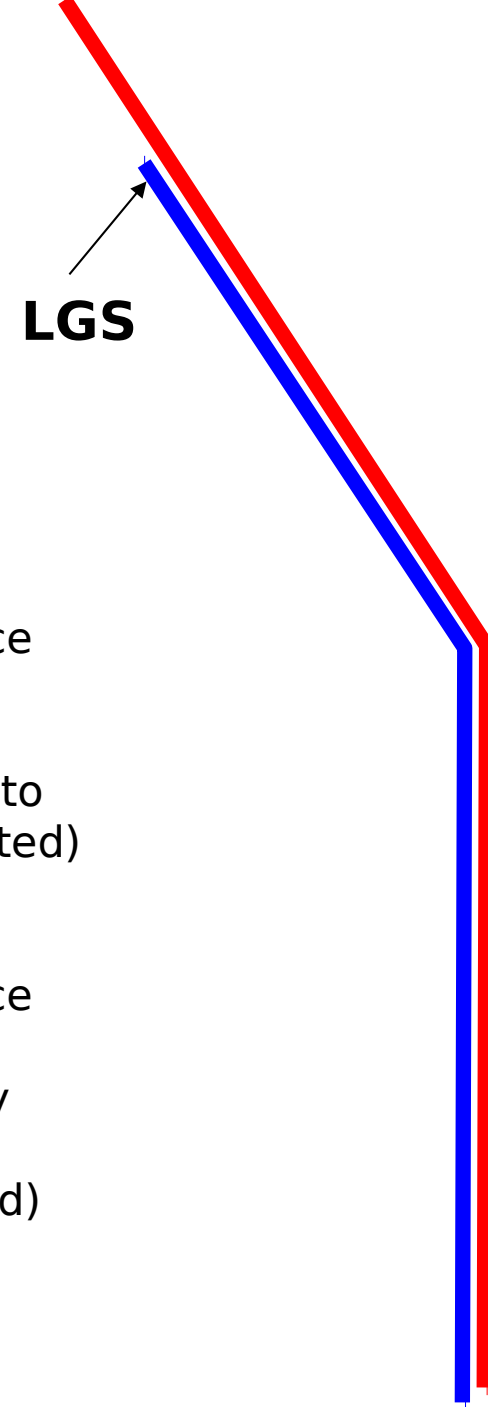
LGS light goes from telescope to LGS, and then back from LGS to telescope (double pass)

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.)



# LGS AO system

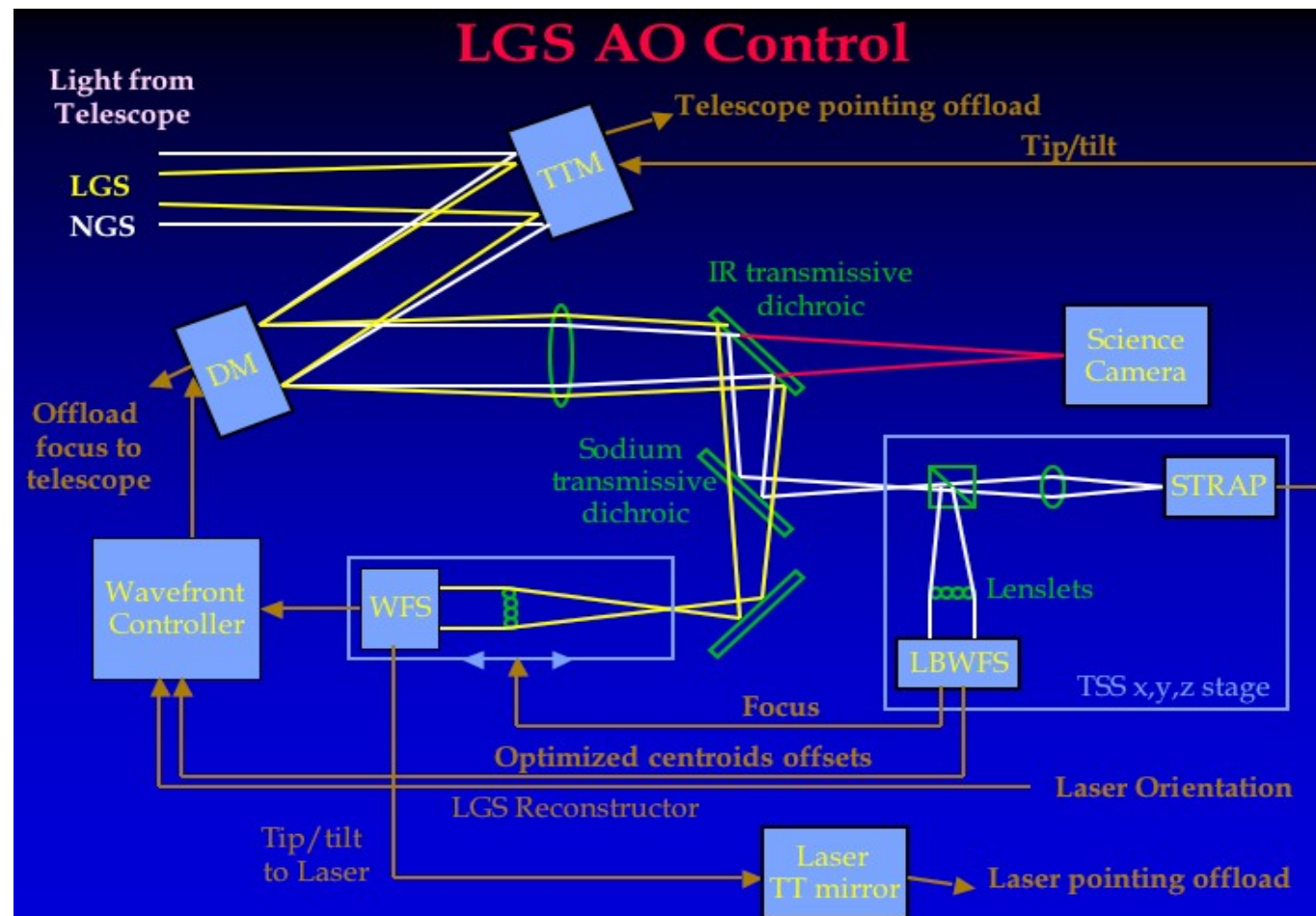
Must combine signals from several WFS sensors:

- 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)



## Some 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

I will show in the next slides that 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 contrast 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:**

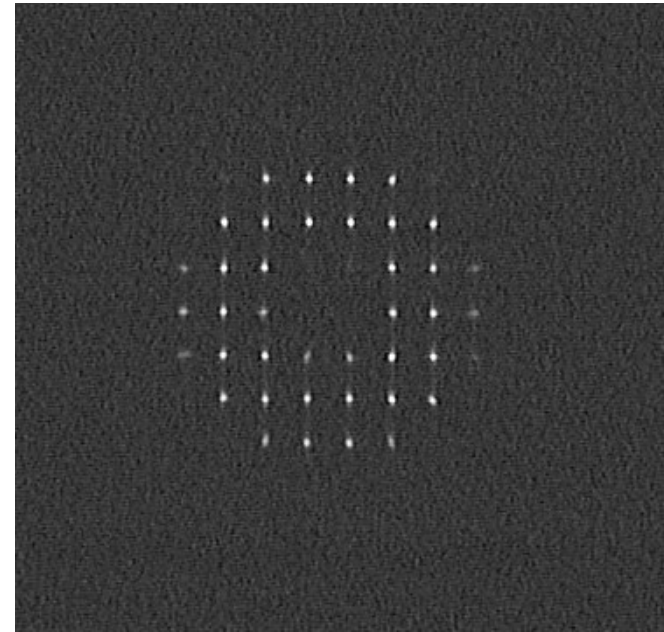
- is WFS used to initially close the AO loop ?
- Is WFS the main system WFS ?
- how many different things does the WFS need to do ?
- is input wavefront already cleaned by first stage AO correction ?
- is guide star extended (laser) or compact (natural star) ?
- is sensitivity a driving requirement ?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



SH type WFS is then the ideal choice:

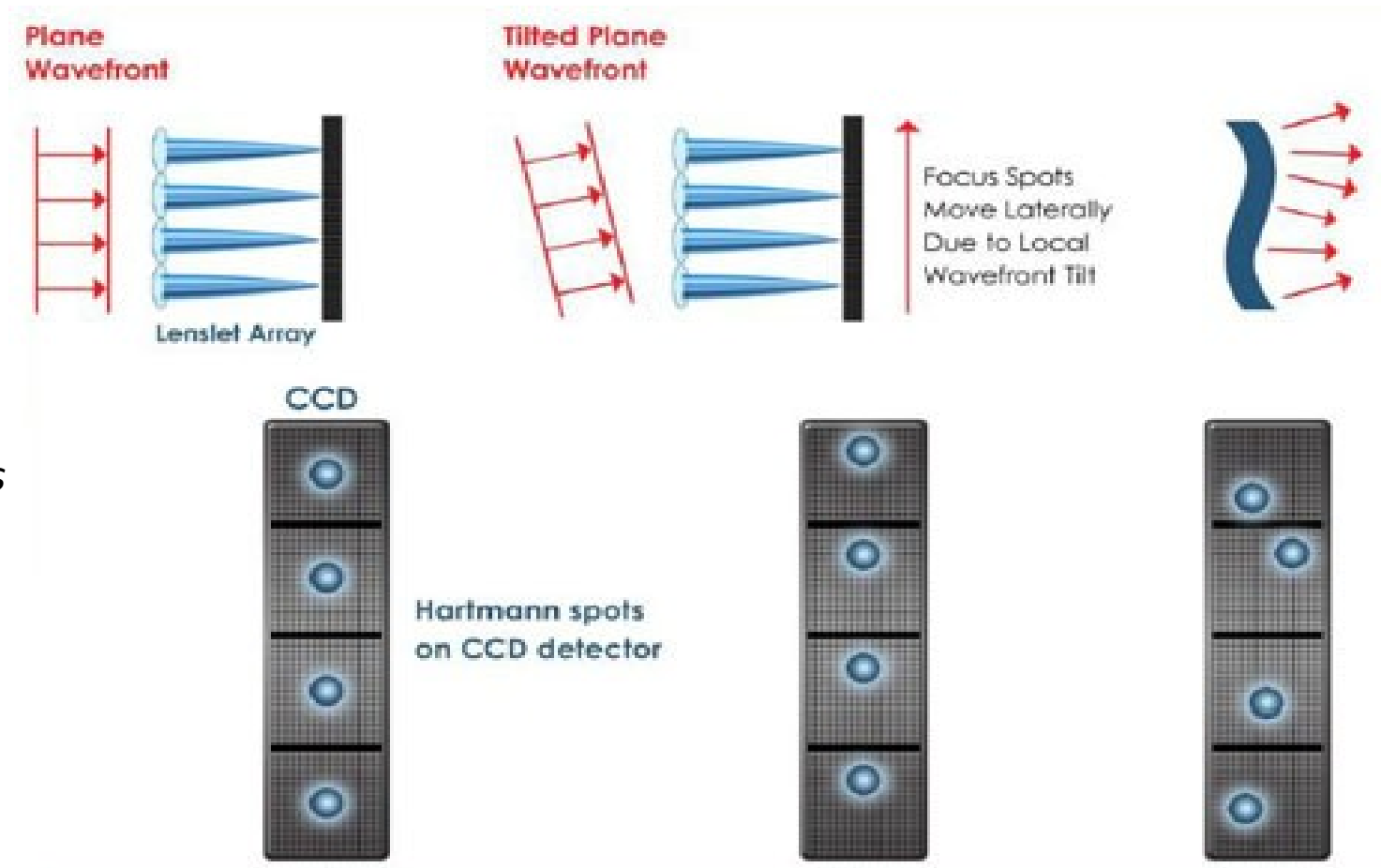
- Able to work on extended source
- Linear over a very wide range
- Number of pixels per subaperture can be increased for capt. Range
- Lots of previous experience, well understood technique
- Straightforward relationship between WF and signal (easy to debug)

Curvature and Pyramid may also be chosen



# Shack-Hartmann WFS

Measures wavefront slope in front of each subaperture

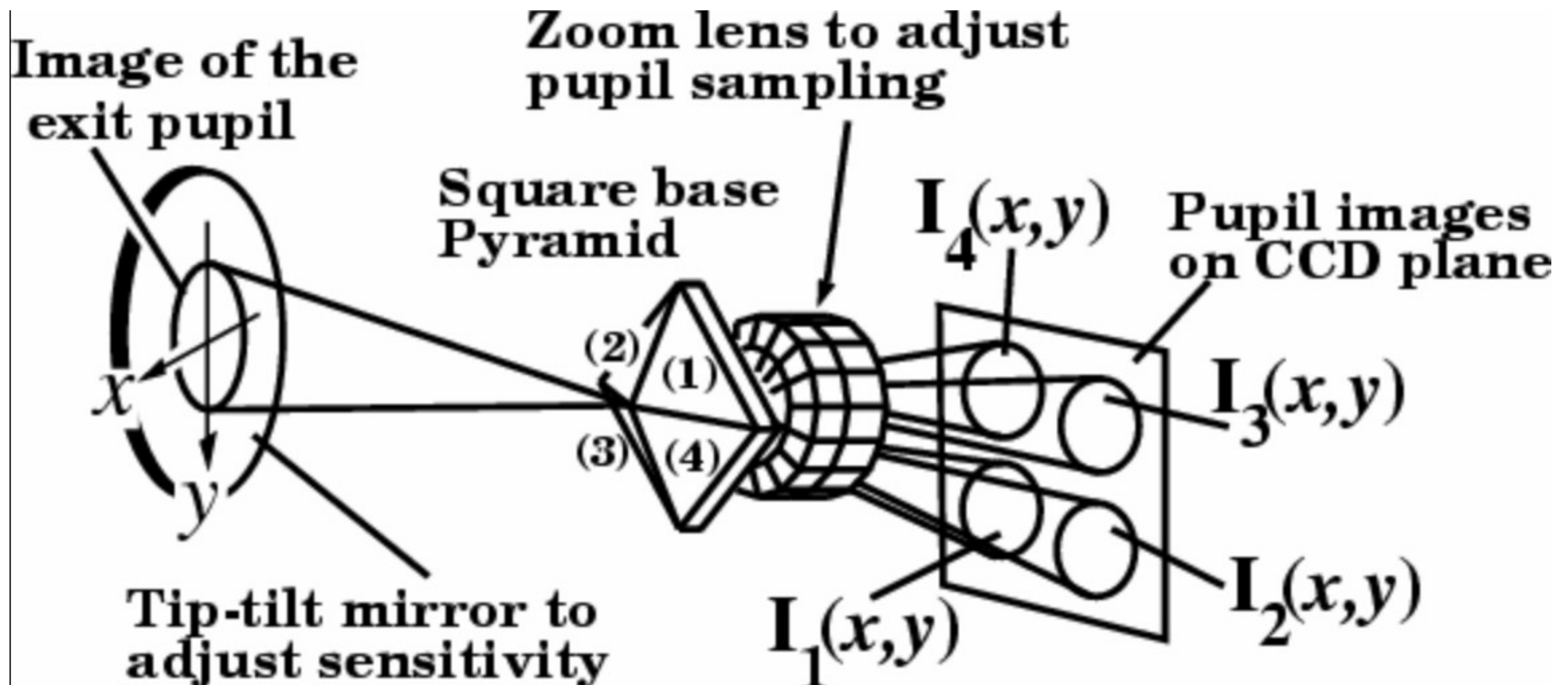


courtesy:  
Boston  
Micromachines

# Pyramid WFS (modulated)

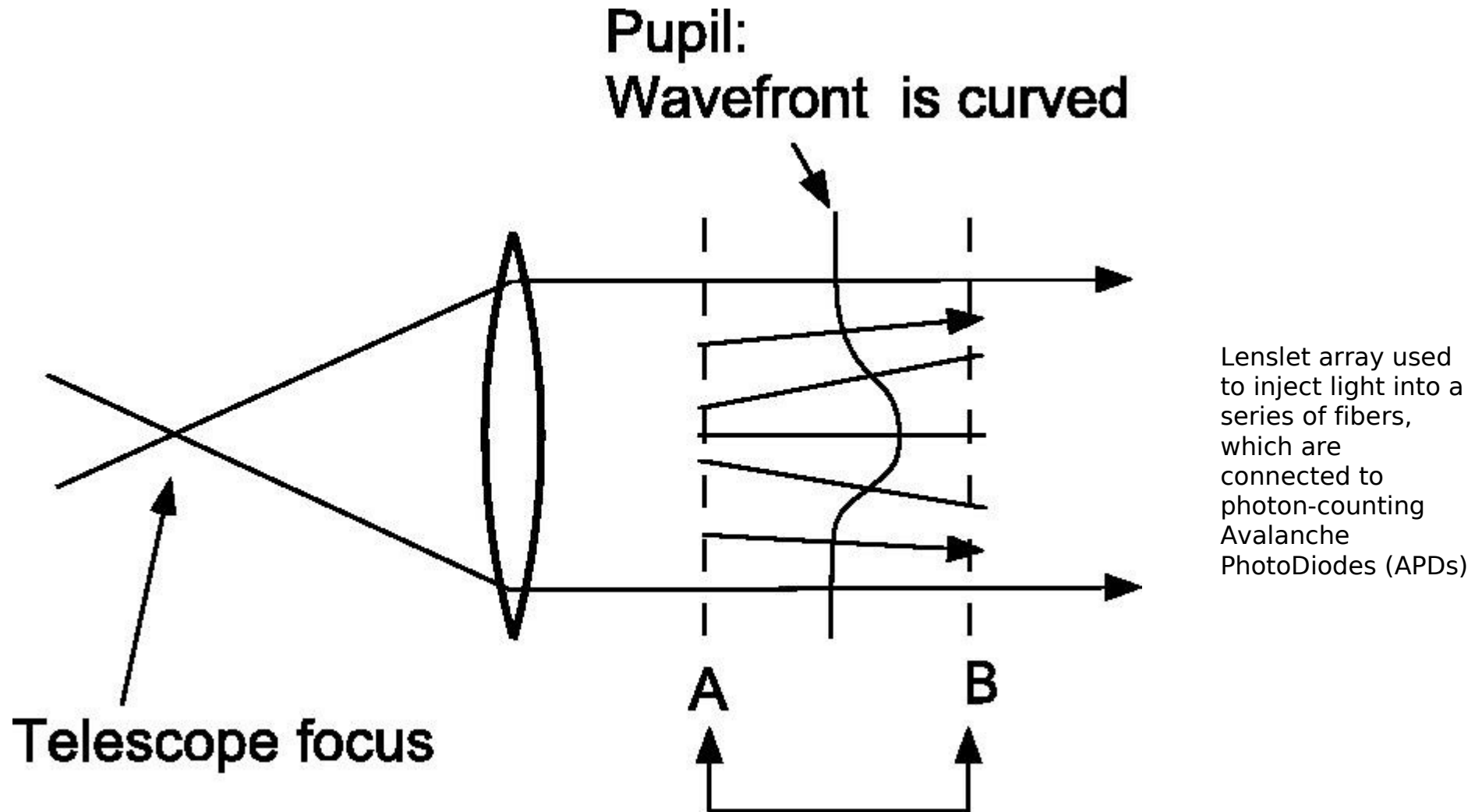
Separates focal plane into 4 quadrants, each quadrant re-imaged in pupil plane

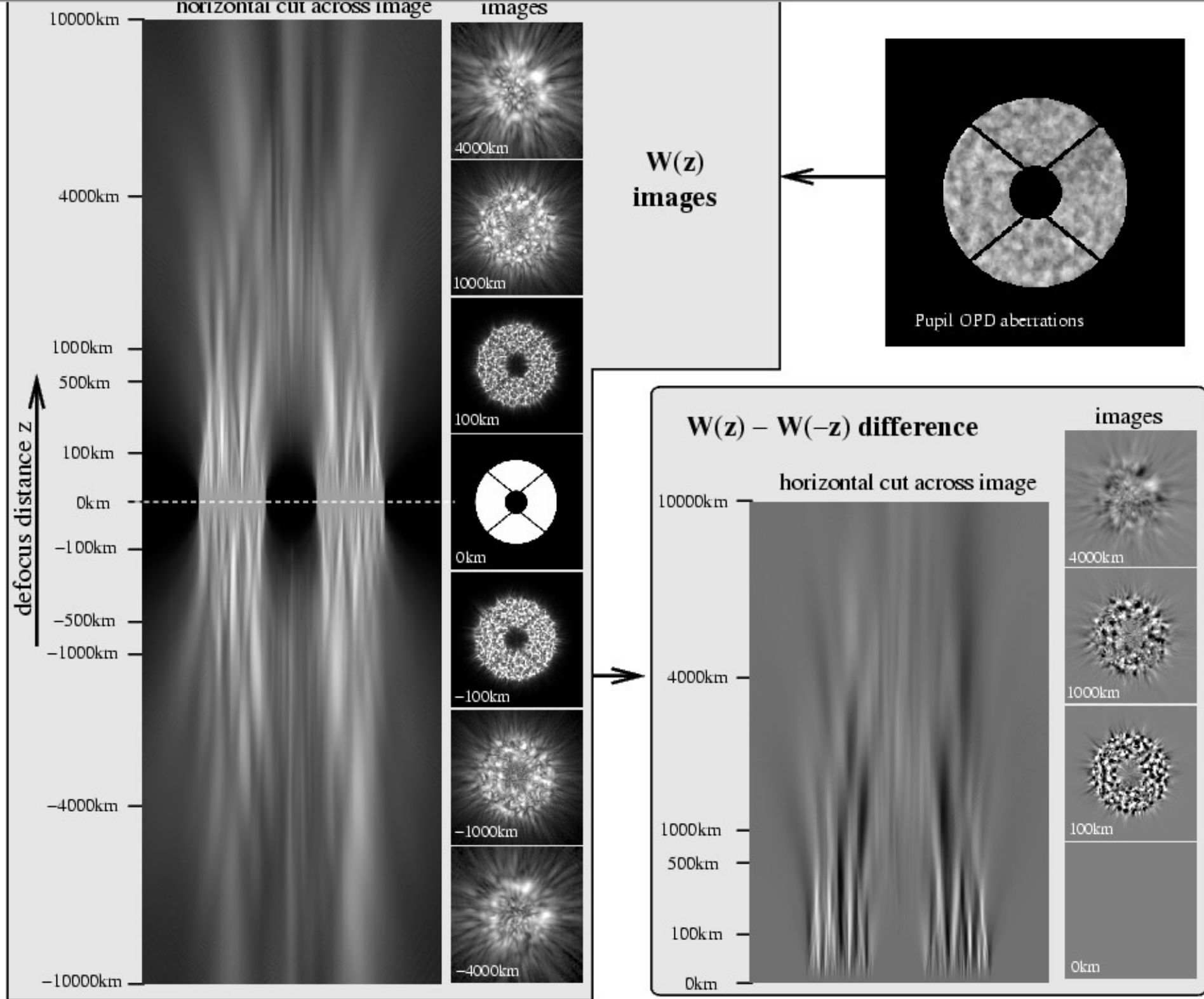
Geometrical optics explanation: parts of the pupil with a given slope correspond to light in the corresponding focal plane quadrant



# Curvature WFS

Light propagation turns phase into amplitude (similar to scintillation)





## **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:**

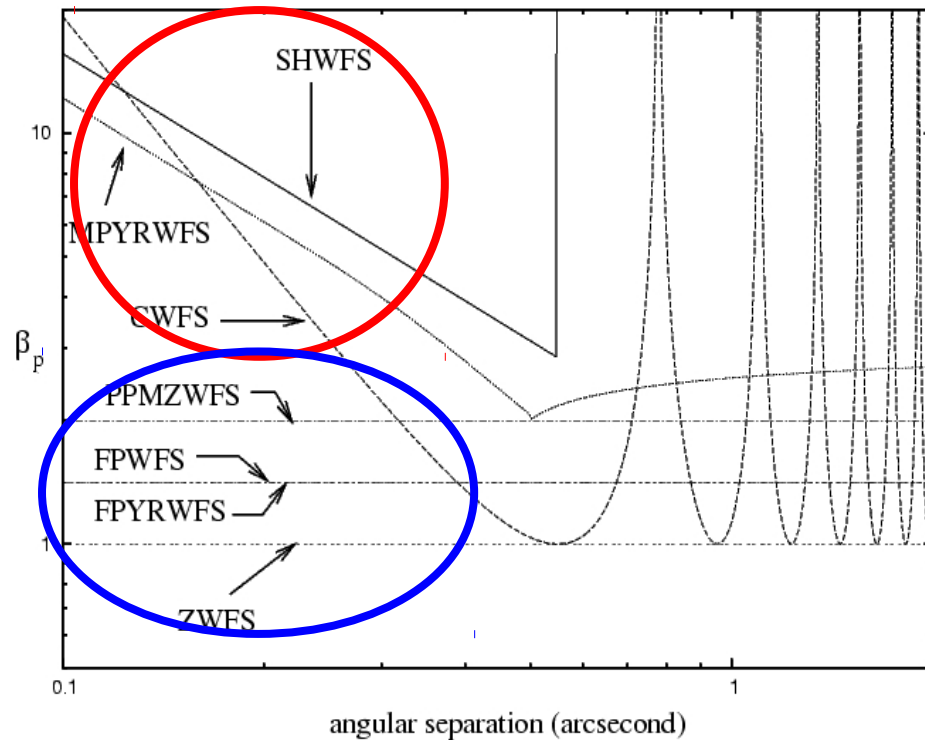
**Sensitivity Beta = 1 (1 ph = 1 rad of error)**

**At all spatial frequencies**

### **Non-ideal WFS:**

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

# Wavefront sensors "sensitivities" in linear regime with full coherence (Guyon 2005)



Square root of # of photons required to reach fixed sensing accuracy

plotted here for phase aberrations only, 8m telescope. Tuned for maximum sensitivity at 0.5'' from central star.

Figure above shows sensitivity (y axis) as a function of pupil spatial frequency (x axis). Pupil spatial frequency = angular separation in focal plane.

ALL wavefront sensor options have very good sensitivity at the spatial frequency defined by the WFS sampling

SOME wavefront sensors loose sensitivity at low spatial frequencies (red), other do not (blue)

# Why do SH, Curvature (& modulated pyramid) have sub-optimal sensitivity for low order aberrations ?

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  $\lambda/D$ )

**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)

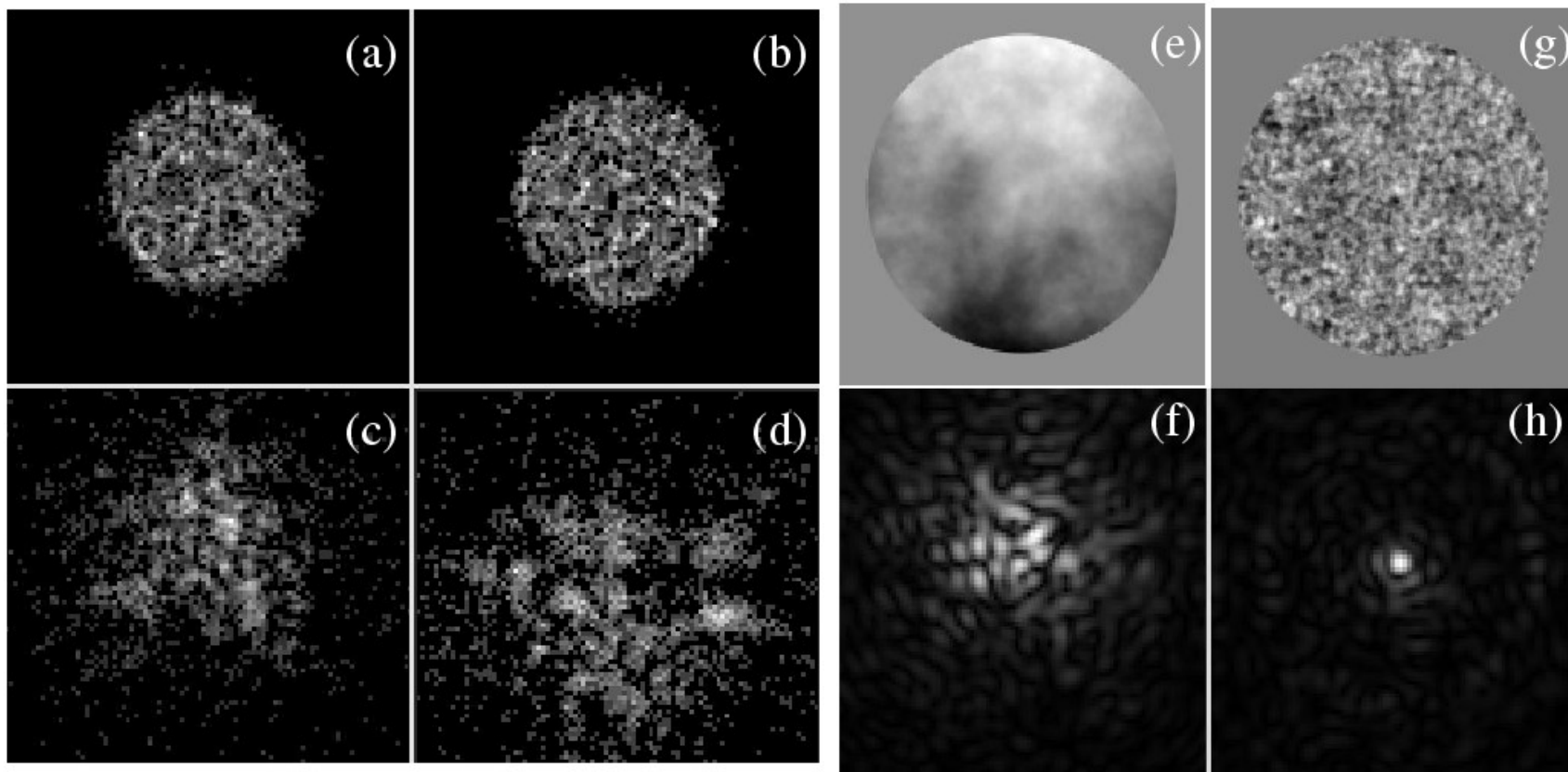


Fig. 9.— Wavefront reconstruction using the algorithm shown in fig. 8. Four noisy defocused pupil images (images (a), (b), (c) and (d)) are acquired to transform the pupil phase aberrations (e) into intensity signals. The input pupil phase is 609 nm RMS, yielding the PSF (f) before correction. After 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  $0.65 \mu\text{m}$ . The total number of photons available for wavefront sensing is  $2e4$ .

## **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:**

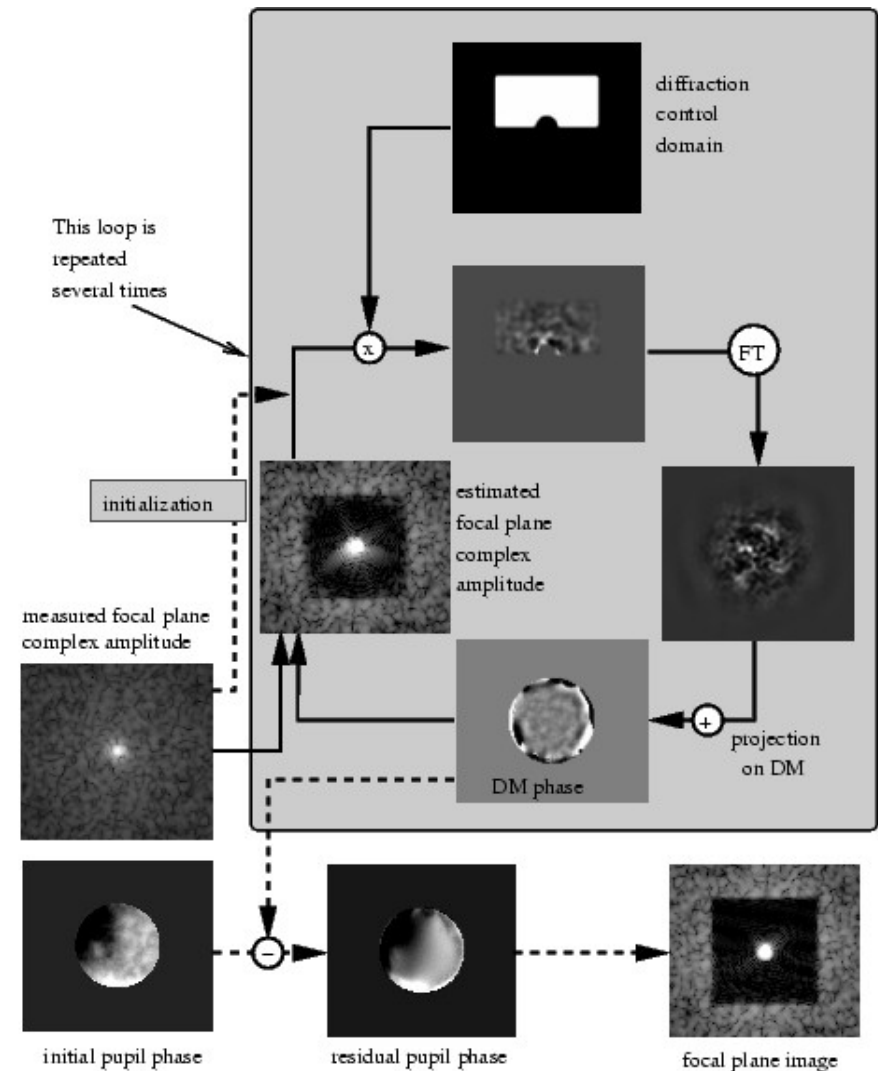
- no non-common path errors
- high sensitivity

*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.**

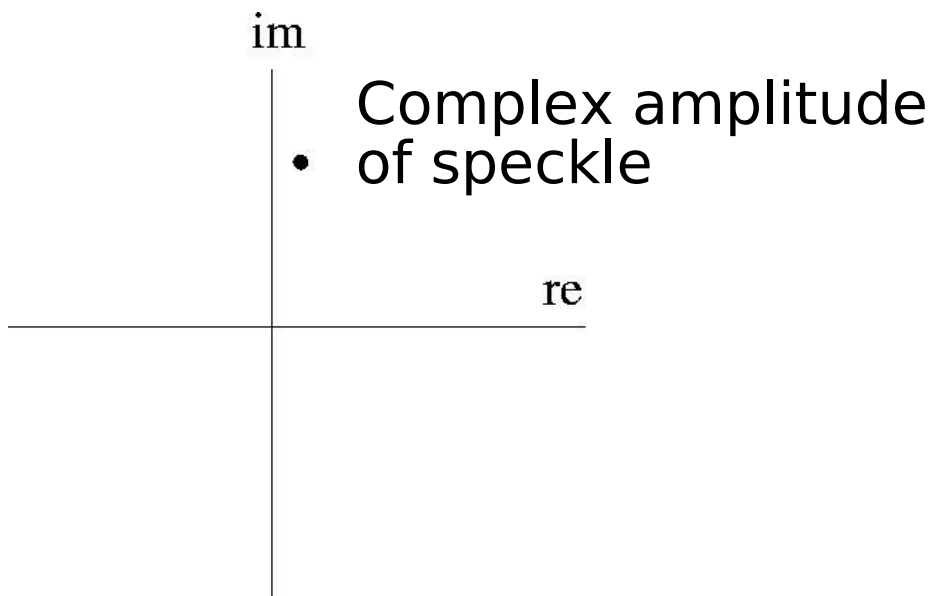
Conventional phase diversity: focus

With DM: **freedom to tune the diversity to the problem**

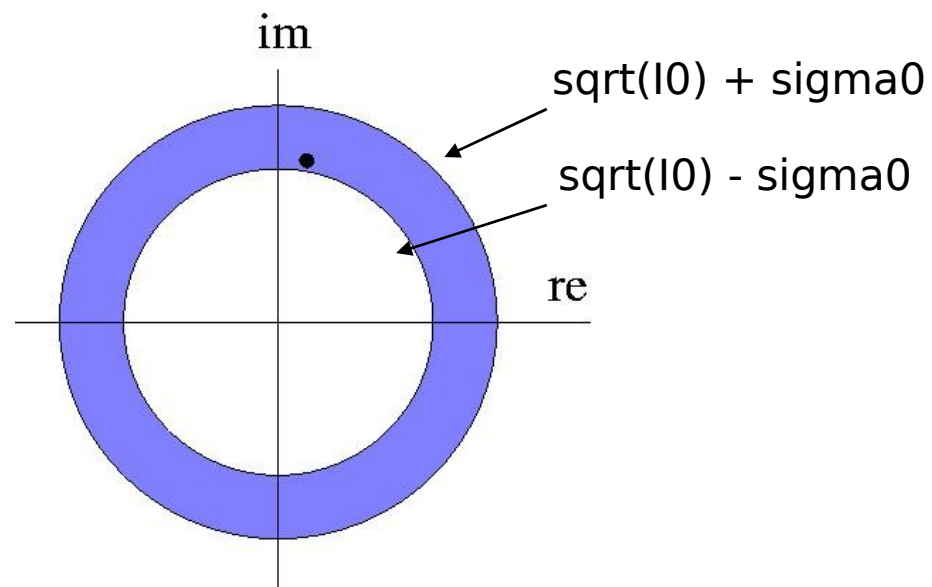
Measure speckle field with no previous knowledge:

- 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

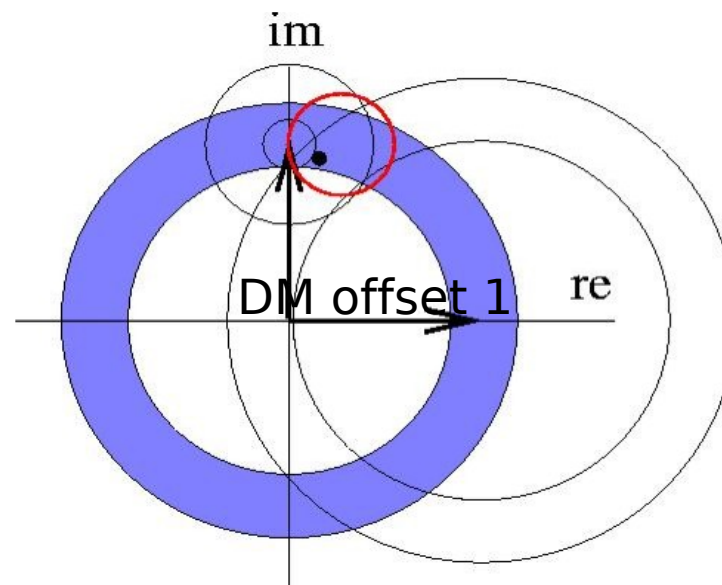
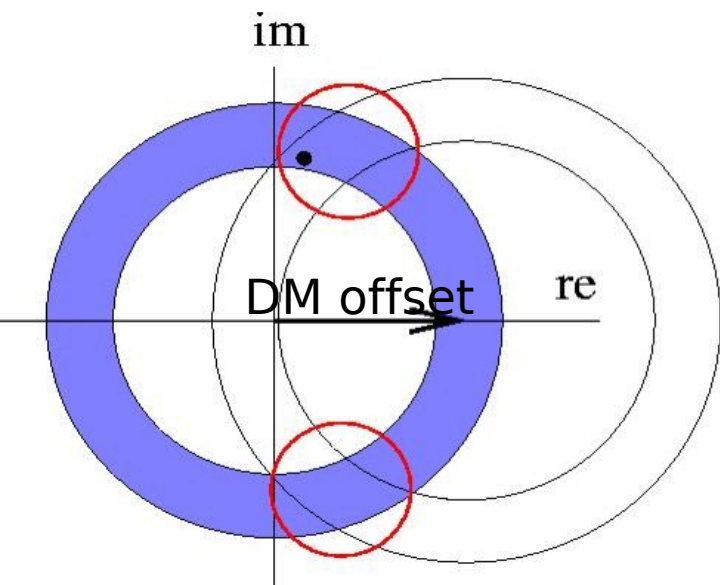
## Initial problem



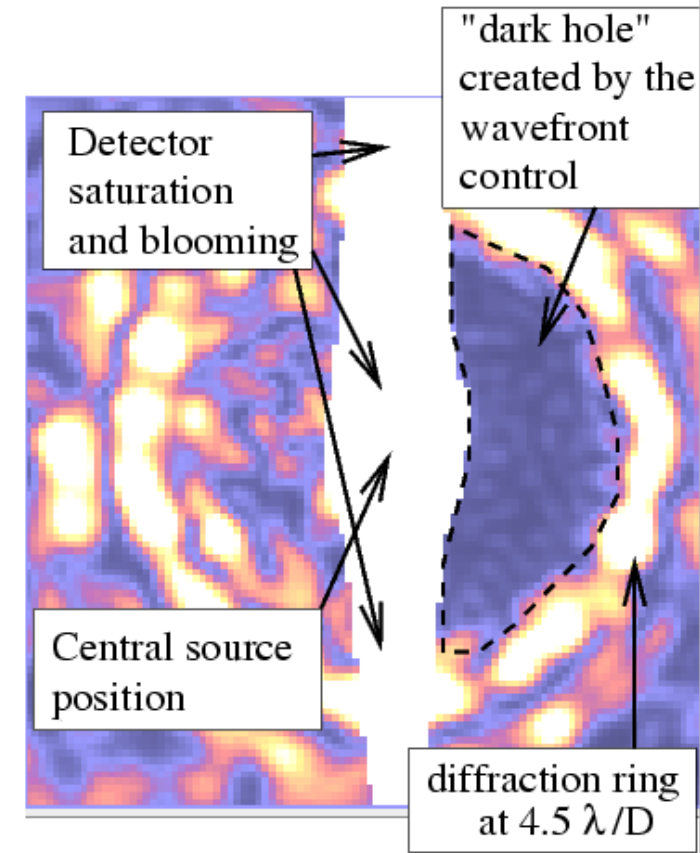
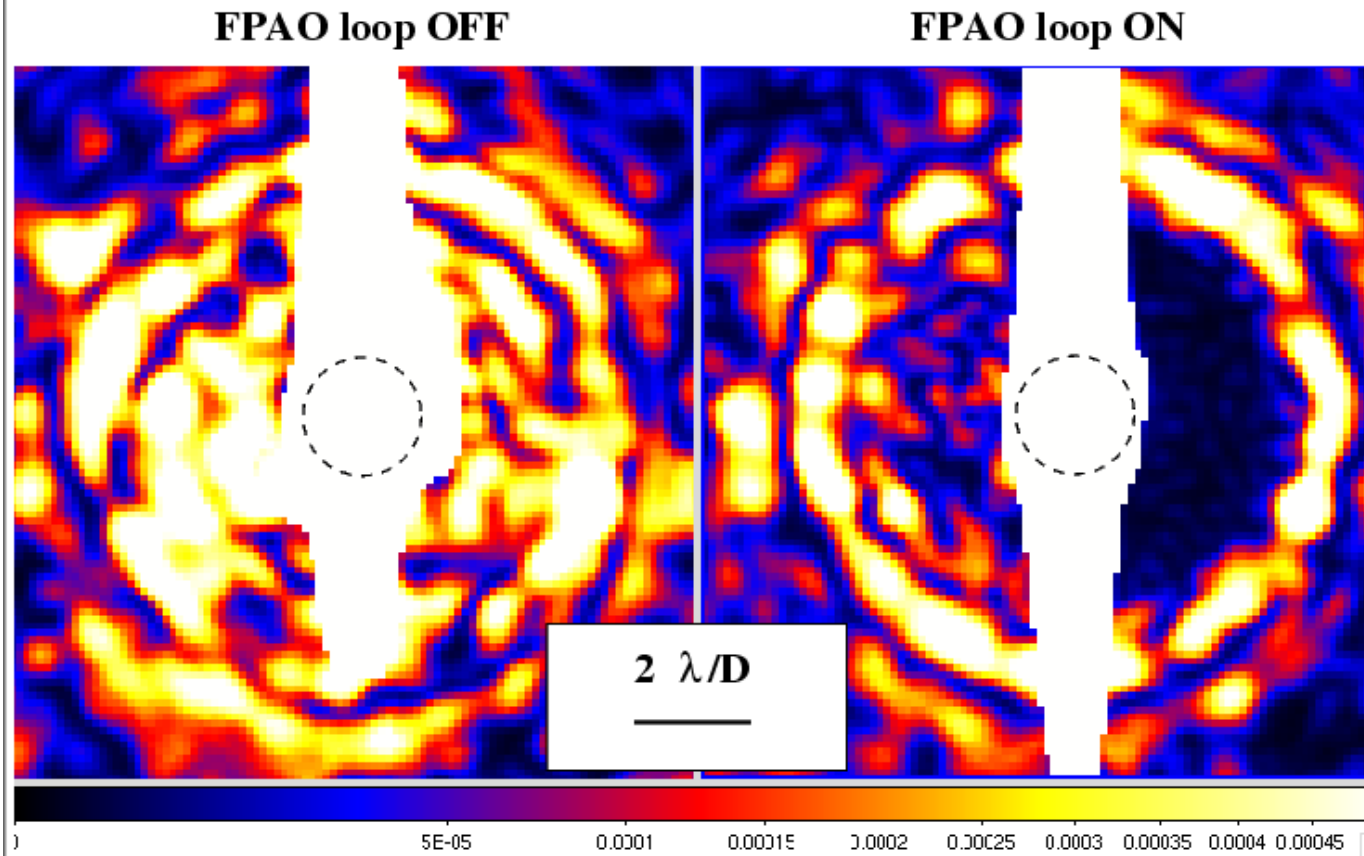
Take a frame  $\rightarrow$  measured speckle intensity =  $I_0$



DM offset chosen to be  $\sim$  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



	sensitivity	range	Extended target ? (LGS)	chromaticity	maturity	detector use
SH	serious noise propagation	Very good	Yes	Low	on sky	at least 4 pixels per subaperture
Curvature	serious noise propagation	Very good	Somewhat LGS OK	Low	on sky	1 pix/subaperture 2 reads
Pyramid (modulated)	noise propagation	very good	Somewhat LGS OK	Low	on sky	4 pix/subaperture
Pyramid (fixed)	Excellent	limited to $< 1$ rad in closed loop	No	Low	closed loop lab AO w turbulence	4 pix/subaperture
Zernike phase contrast	Excellent	limited to $< 1$ rad in closed loop	No	mask manufacturing	?	1 pix/subaperture
Mach-Zehnder	Excellent	limited to $< 1$ rad in closed loop	No	low if near zero OPD	?	2 pix/subaperture
Focal plane	Excellent	Good, can have $> 1$ rad error, but needs coherence	No	serious	closed loop lab AO w turbulence	4 pix/speckle
Non-linear curvature	Excellent	Good, can have $> 1$ rad error, but needs coherence	No	Low	in lab with no turbulence	4 pix/subaperture

**Good range/linearity but poor sensitivity**

**Good sensitivity over a small range**

**Non-linear reconstruction algorithm allows good sensitivity and larger range, but requires high coherence**

# 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")

Interferometric

Focal plane

**~ 1 rad**

Extreme-AO Closed loop in Visible

Thermal IR AO on 8m telescope  
open loop

"general purpose" AO system in  
closed loop

Not allowed

Pyramid (fixed)

allowed

Pyramid (modulated)

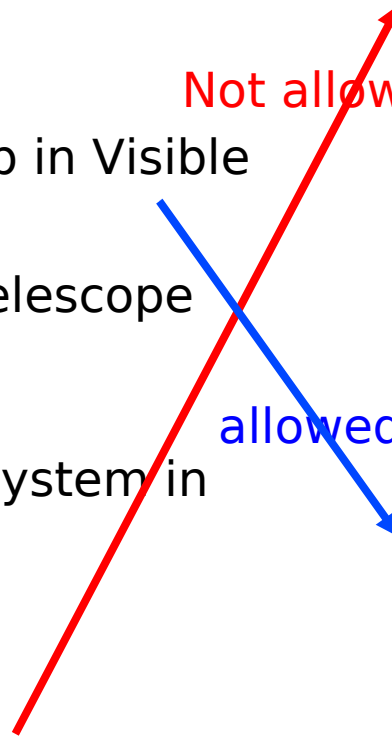
**>> 1 rad**

LGS AO  
GLAO

Open loop AO

Curvature

Shack-Hartmann



	sensitivity	range	Extended target ? (LGS)	chromaticity	maturity	detector use
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# 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)

Near-IR

AO with high sensitivity  
WFS in visible

(examples: Pyramid,  
interferometer, focal plane WFS)

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  $\sim 1$  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

	Field of view	# of DMs	# of guide stars	Notes
Single conjugate AO ( <b>SCAO</b> )	~ 30 arcsecond	1 DM, usually conjugated to ground	1 (LGS or NGS)	Easiest, traditional AO architecture
Laser Tomography AO ( <b>LTAO</b> )	~30 arcsecond	1 DM	>3 (LGS or NGS)	Overcomes cone effect (LGS) and isoplanatic limitation (NGS)
Ground Layer AO ( <b>GLAO</b> )	very wide – up to ~degree	1 DM, conjugated to ground	> 3	Optically challenging for wide field. Demonstrated on MMT (U of Arizona). Larger systems under active development
Multi Conjugate AO ( <b>MCAO</b> )	wide, > arcmin	2 to 3	> 3, can be LGS or NGS	Two working systems: MAD (ESO) and GEMS (Gemini), more to come
Multi Object AO ( <b>MOAO</b> )	wide but fragmented	1 DM per object (+ 1 DM in common path?)	about 1 GS per field	Under active development (for example: EAGLE for E-ELT)



# Fundamental problem to solve: Isoplanatic Angle

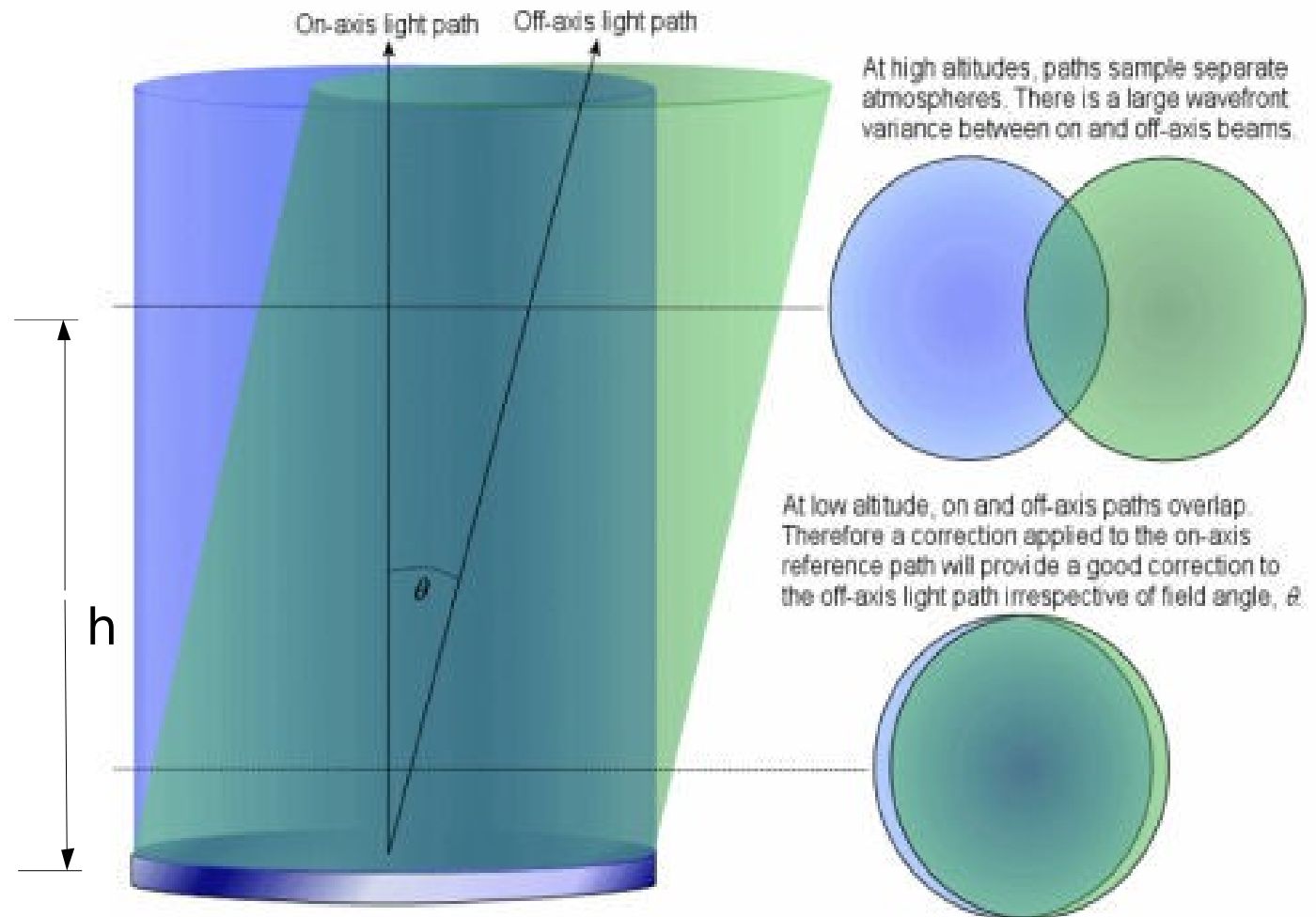
If we assume perfect on-axis correction,  
and a single turbulent layer at altitude  $h$ ,  
the variance (sq. radian) is :

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

Where  $\alpha$  is the angle to the optical axis,  
 $\theta_0$  is the isoplanatic angle:

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

$$D = 8 \text{ m}, r_0 = 0.8 \text{ m}, \\ h = 5 \text{ km} \rightarrow \theta_0 = 10''$$



## **Solution:**

### **Wavefront measurement: Several guide stars needed**

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

### **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)

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

$\theta_0$ : isoplanctic angle

H : LGS altitude

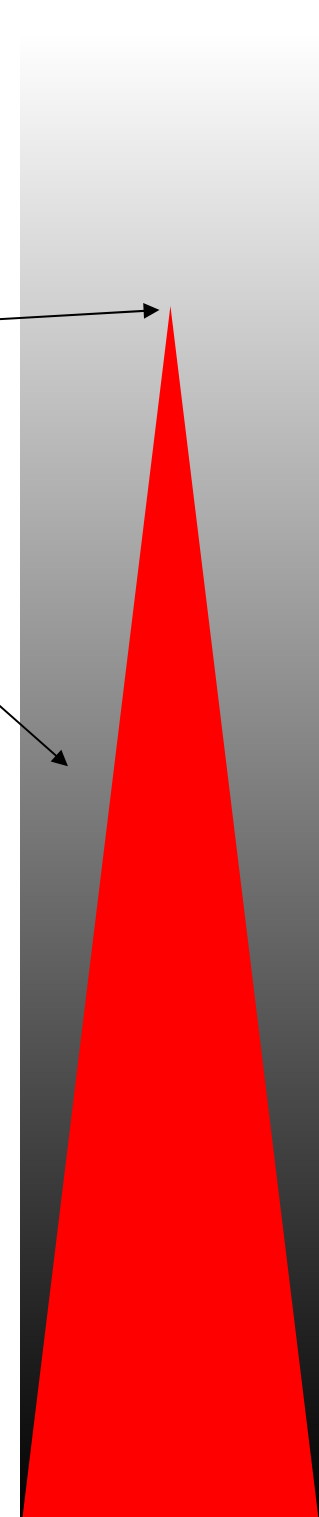
D : Telescope diameter

→ impact is smaller for sodium LGS

→ larger effect for large telescopes

**LGS**

**This area is not measured**

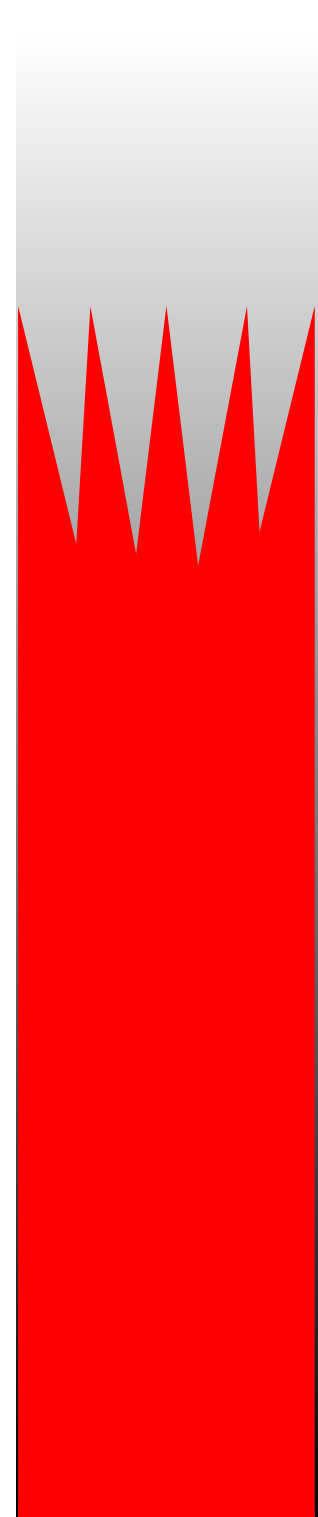
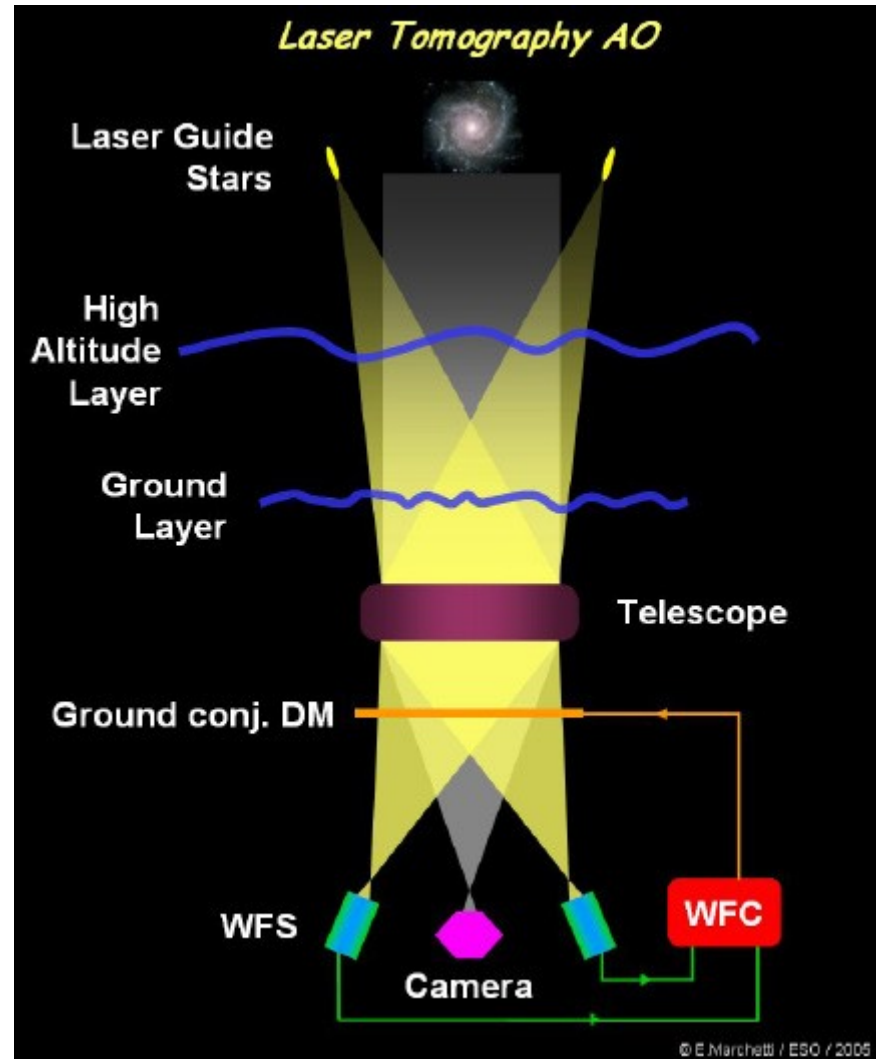


# Laser Tomography AO (LTAO)

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

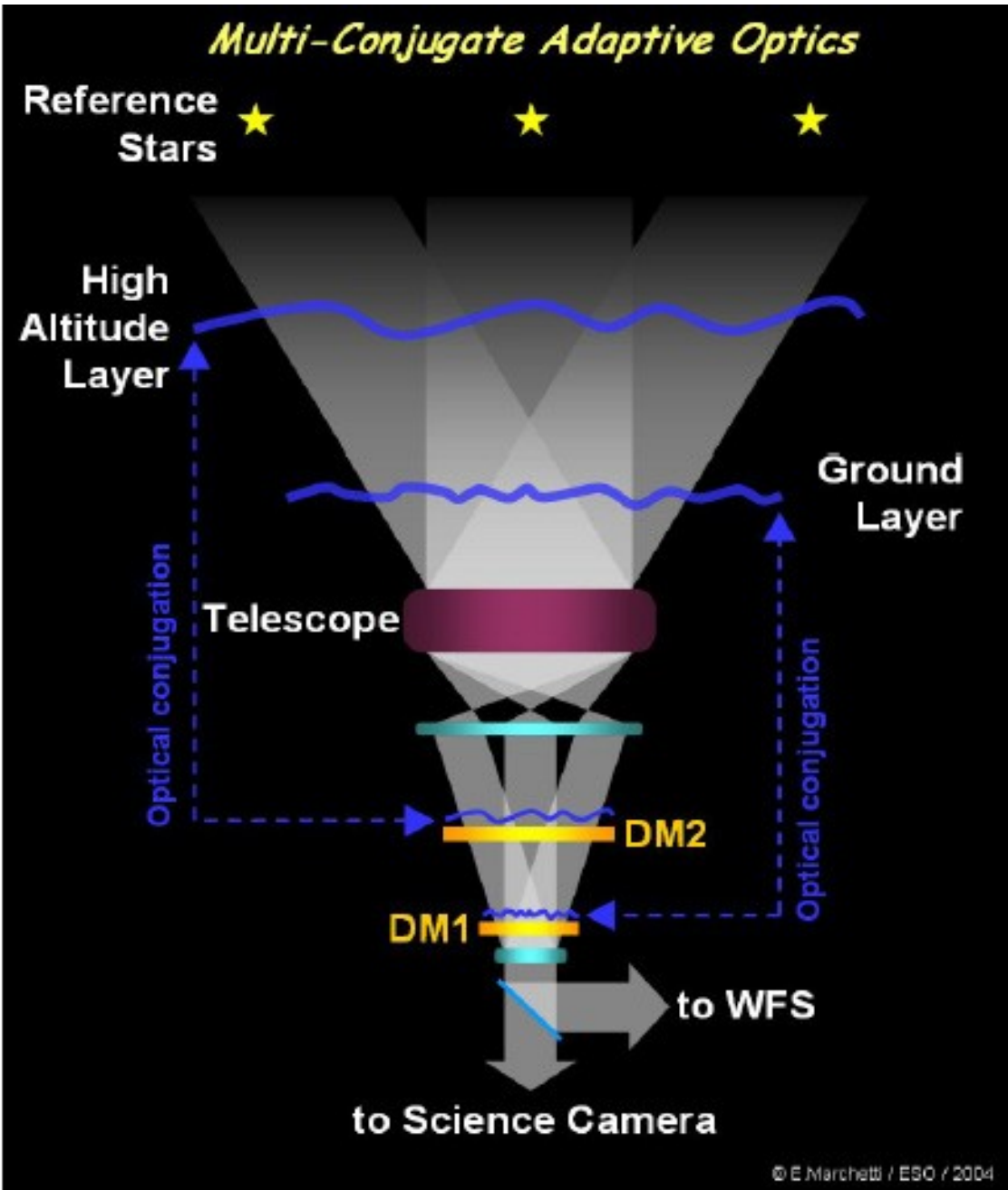
This technique used with a single DM to reduce cone effect error (no increase of FOV)

**LGSs**



# Multi-Conjugate Adaptive Optics (MCAO)

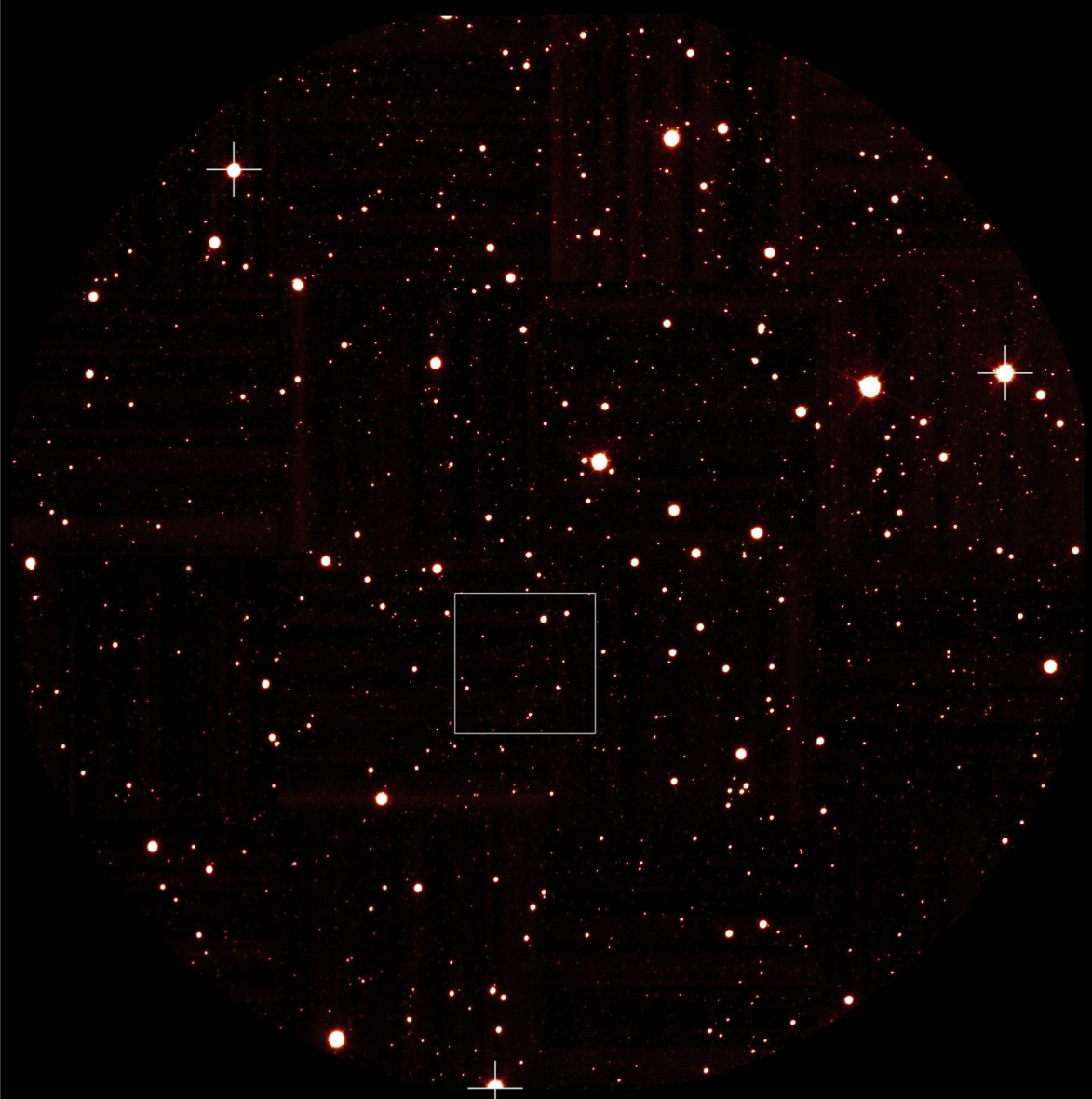
Concept: Use several DMs conjugated at different altitudes to perform correction over a wide field of view



Gemini South MCAO system



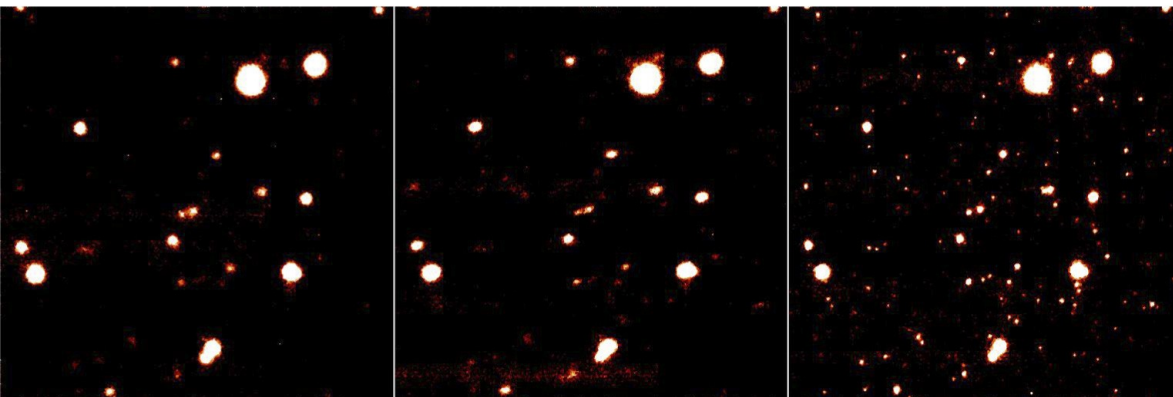




## MCAO on-sky performance

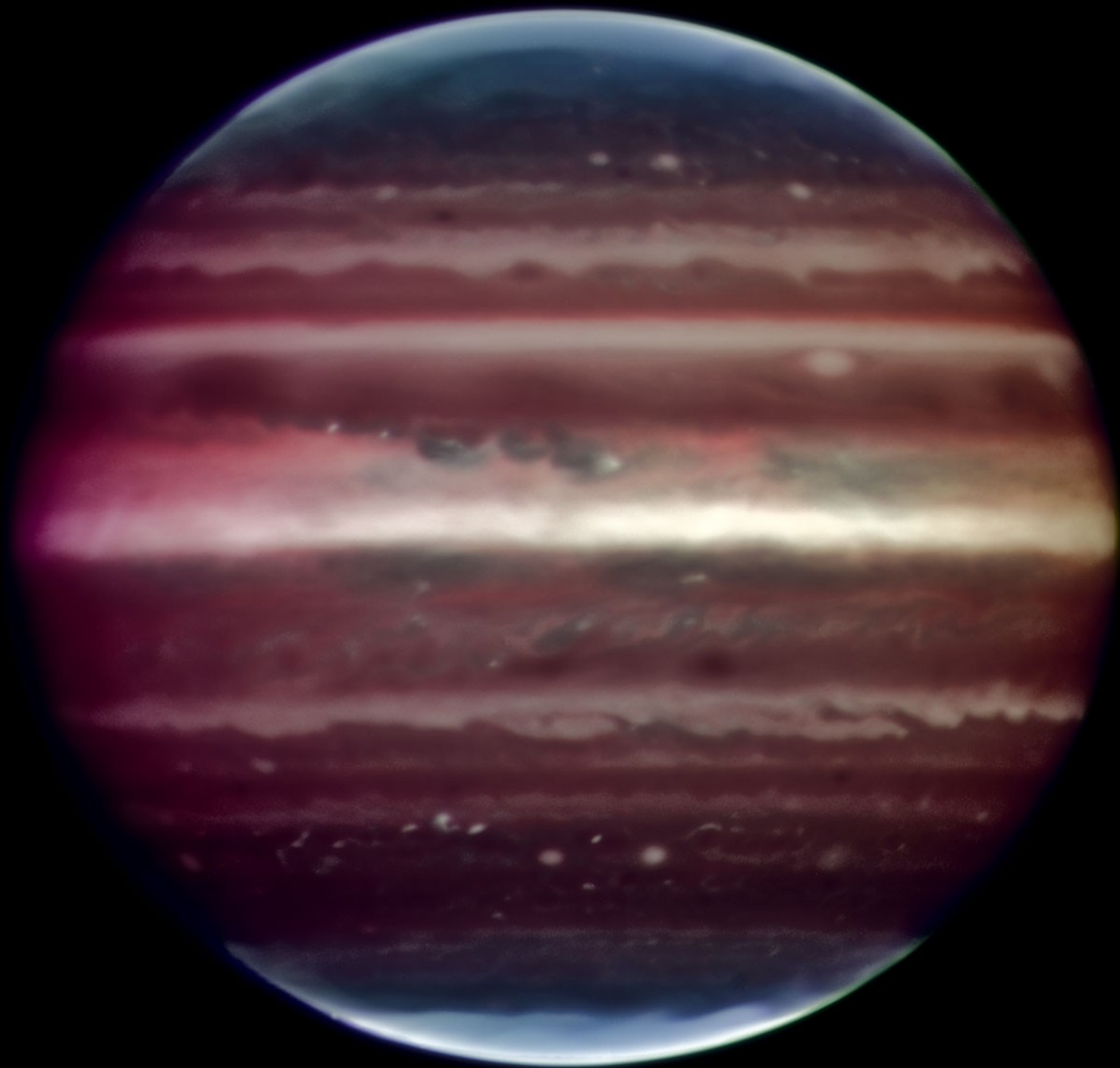
MCAO improves image quality where there is no single nearby bright guide star

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

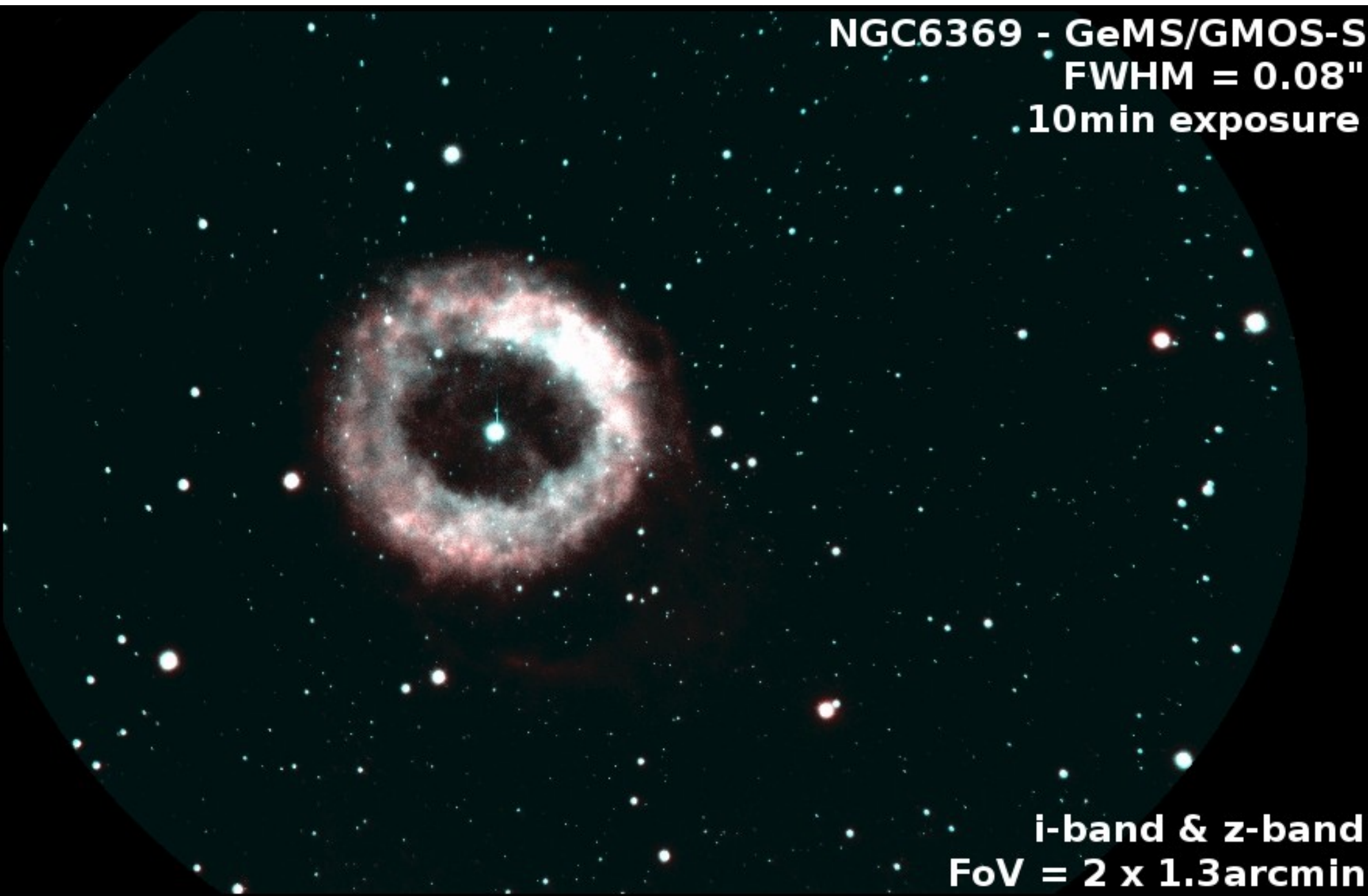




## MCAO

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

**NGC6369 - GeMS/GMOS-S**  
**FWHM = 0.08"**  
**10min exposure**



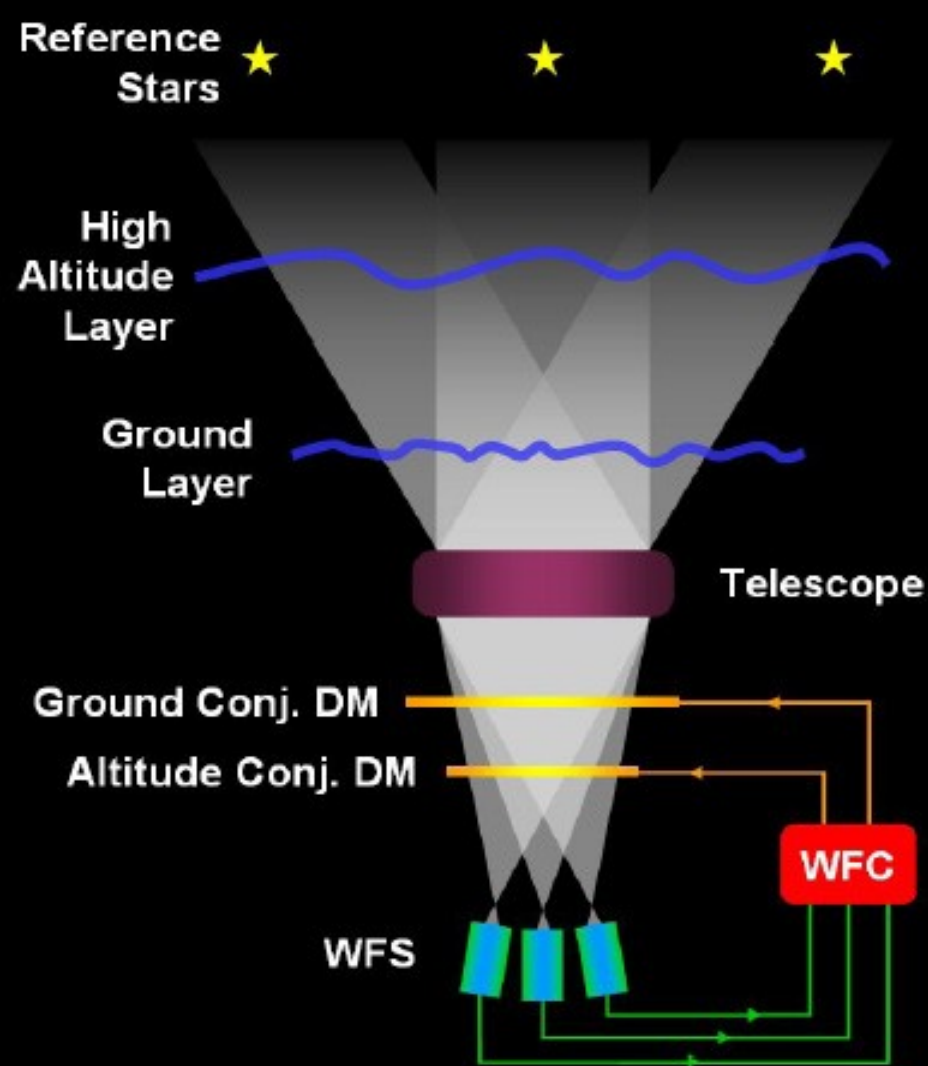
**i-band & z-band**  
**FoV = 2 x 1.3arcmin**

# MCAO wavefront sensing:

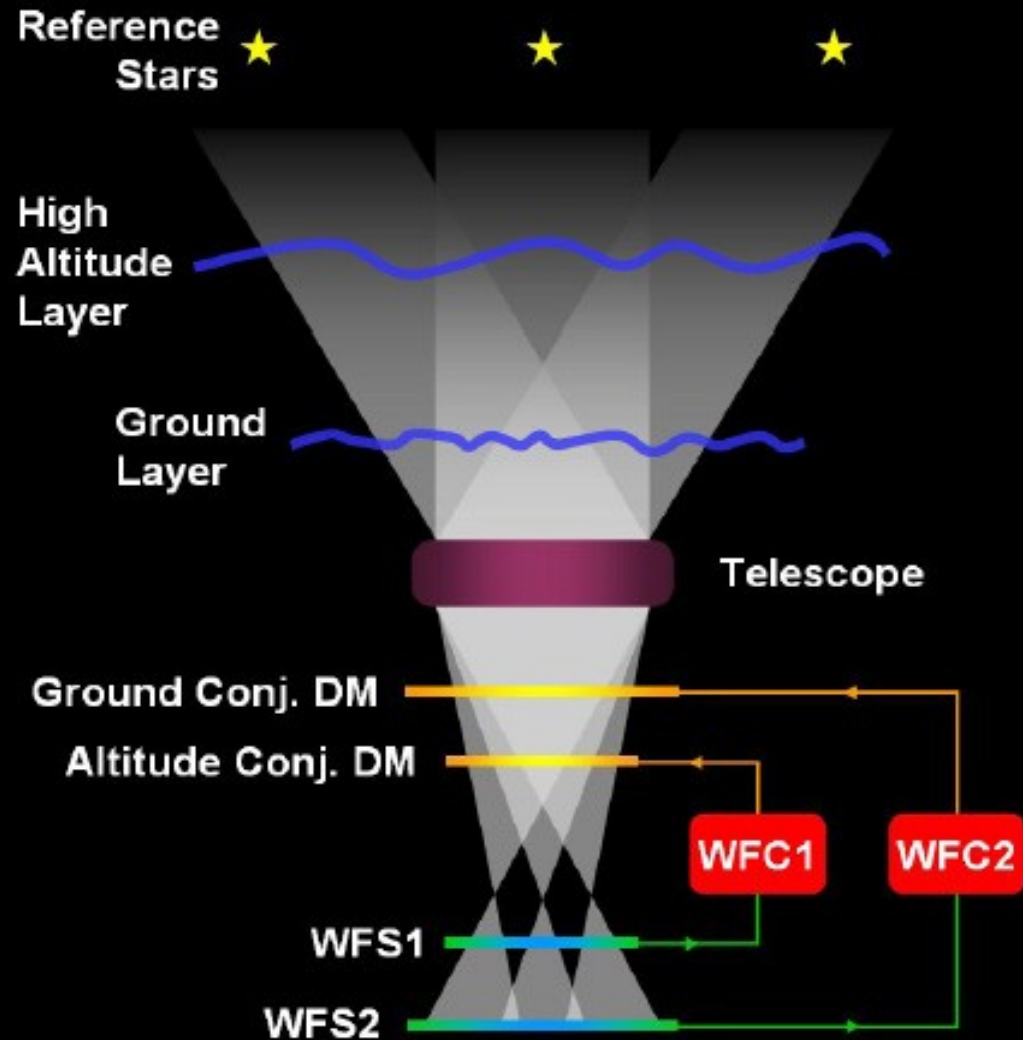
Star-oriented: 1 WFS per star

Layer-oriented: 1 WFS per layer

*Star Oriented MCAO*



*Layer Oriented MCAO*

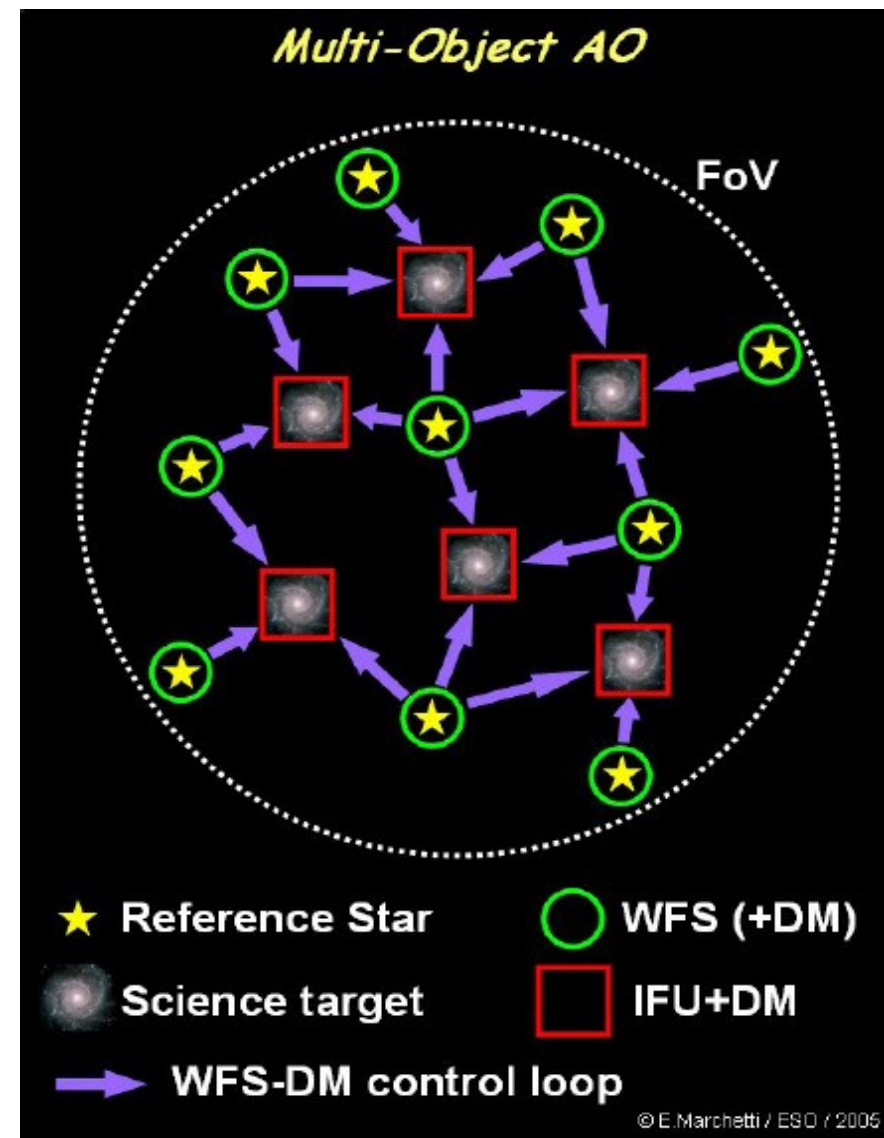
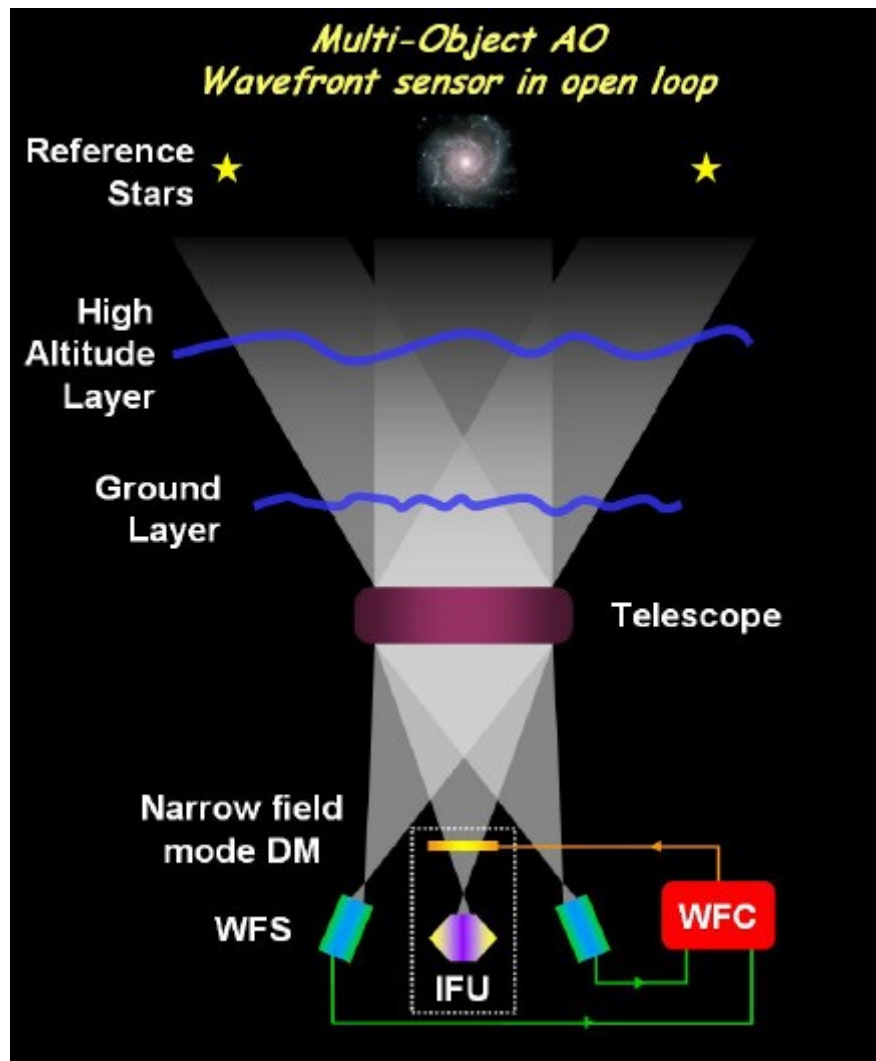




# Multi Object Adaptive Optics (MOAO)

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

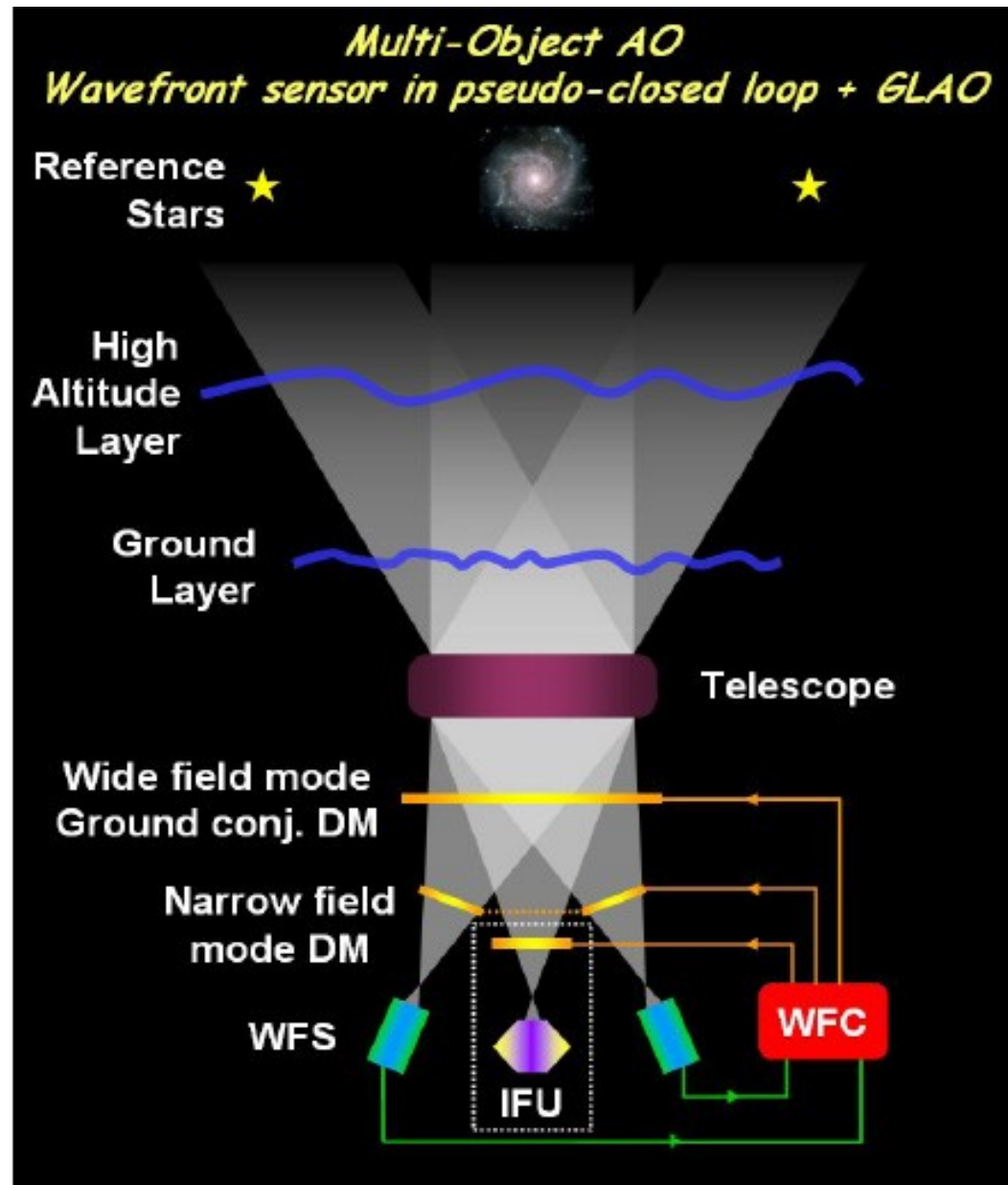
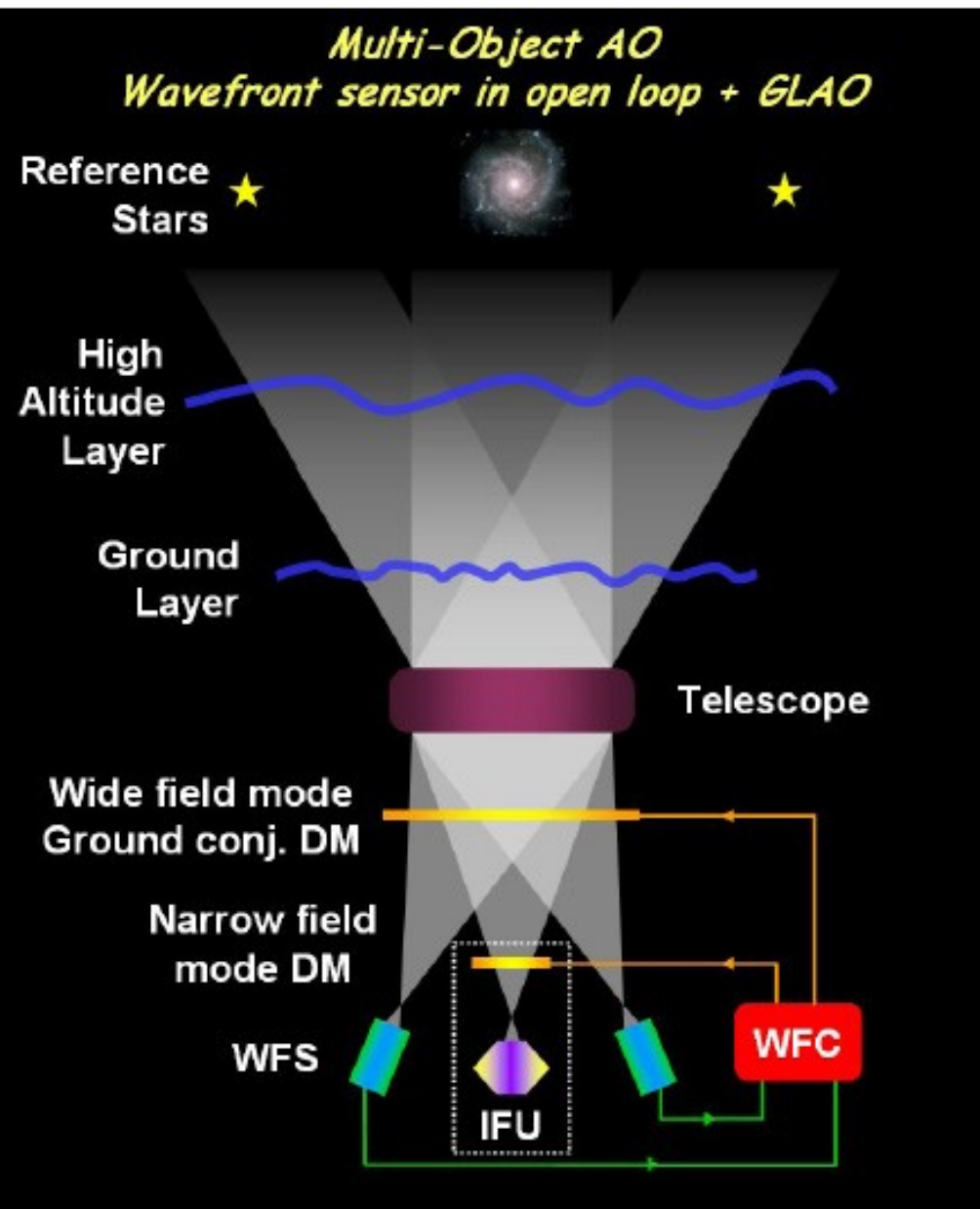
**MOAO runs DMs in open loop → need for good DM calibration (WFSs do not see DMs)**



# MOAO: hybrid correction schemes

Offload part of the correction to a common DM

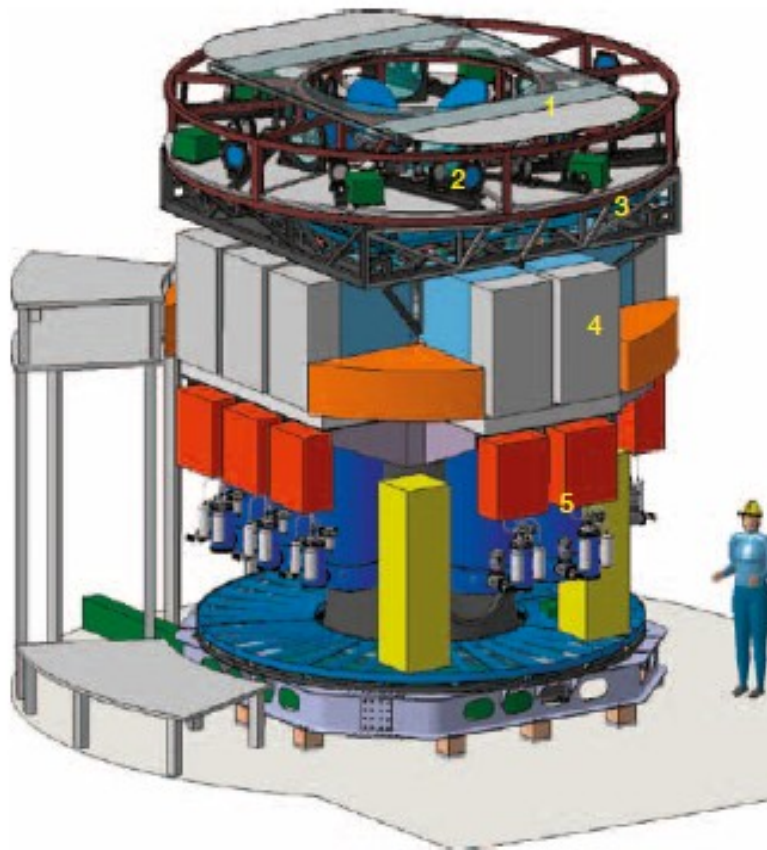
Perform correction in individual WFSs to gain sensitivity



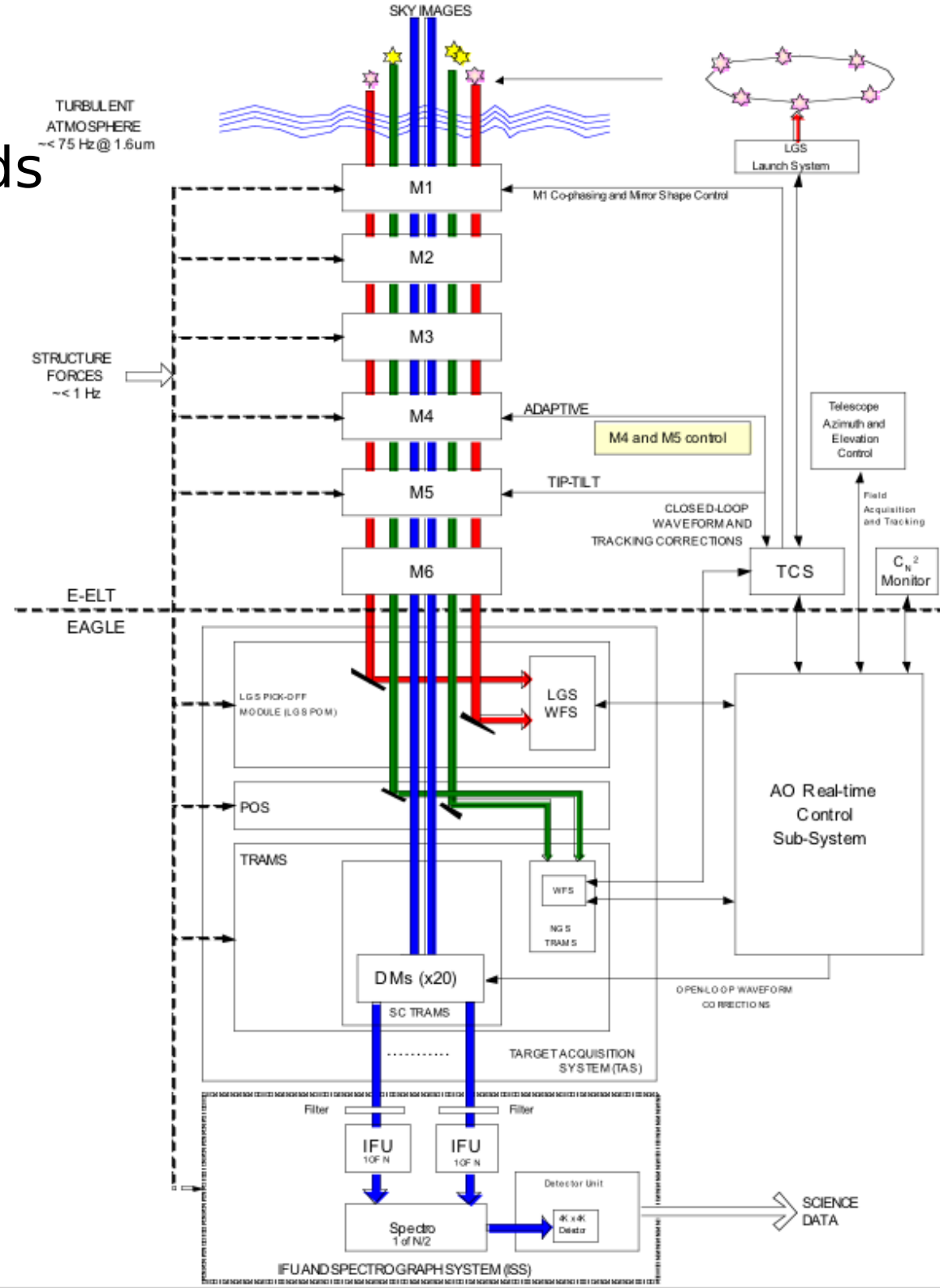
# EAGLE

## (ESO E-ELT project)

### MCAO system with 20 fields



- 1 Shutter
- 2 Laser Guide Star Sensing System
- 3 Pick-off System (Focal Plane)
- 4 Target Reimaging and Magnification System (including Deformable Mirror)
- 5 Integral Field Unit and Spectrograph System



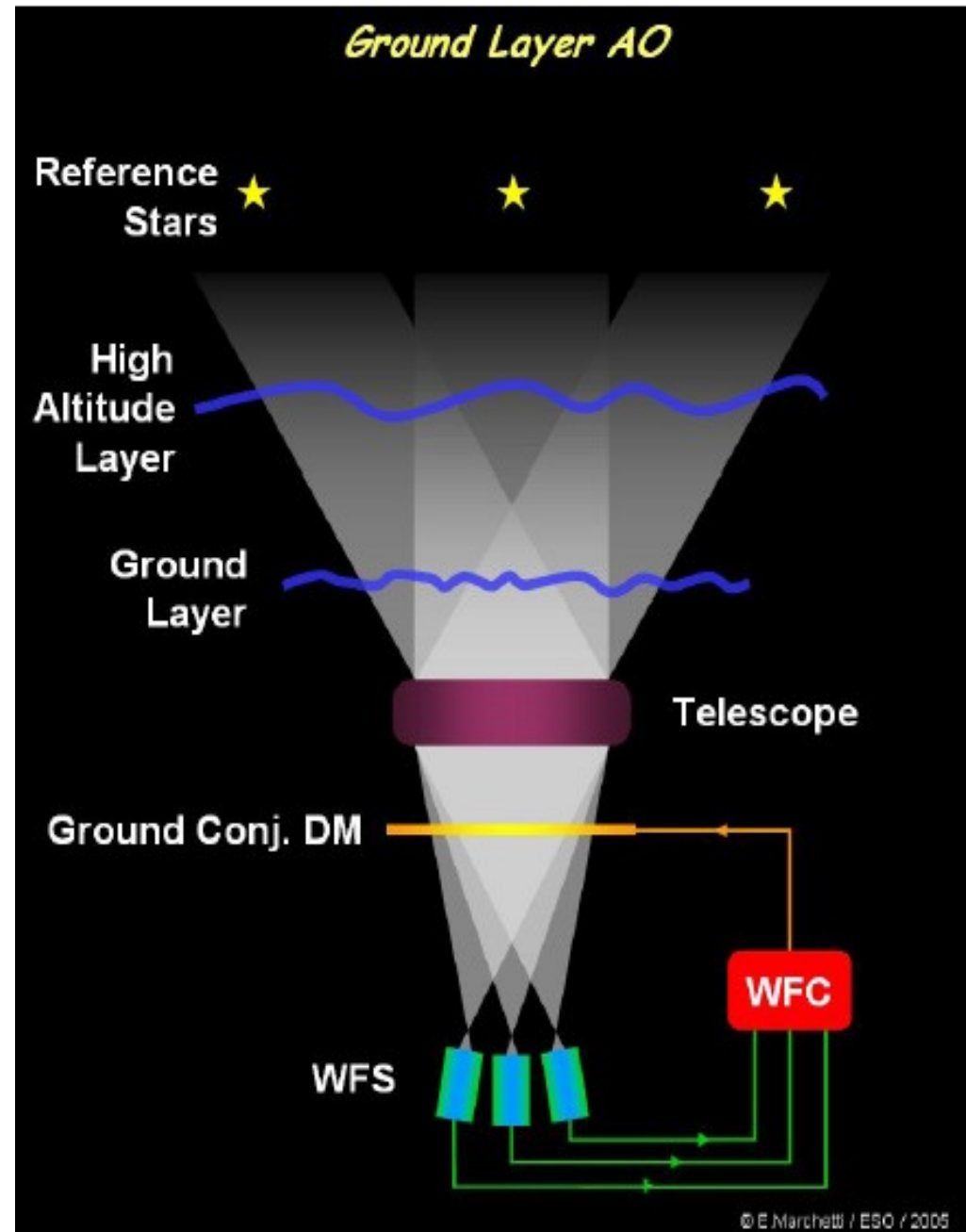
# Ground Layer Adaptive Optics (GLAO)

- 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





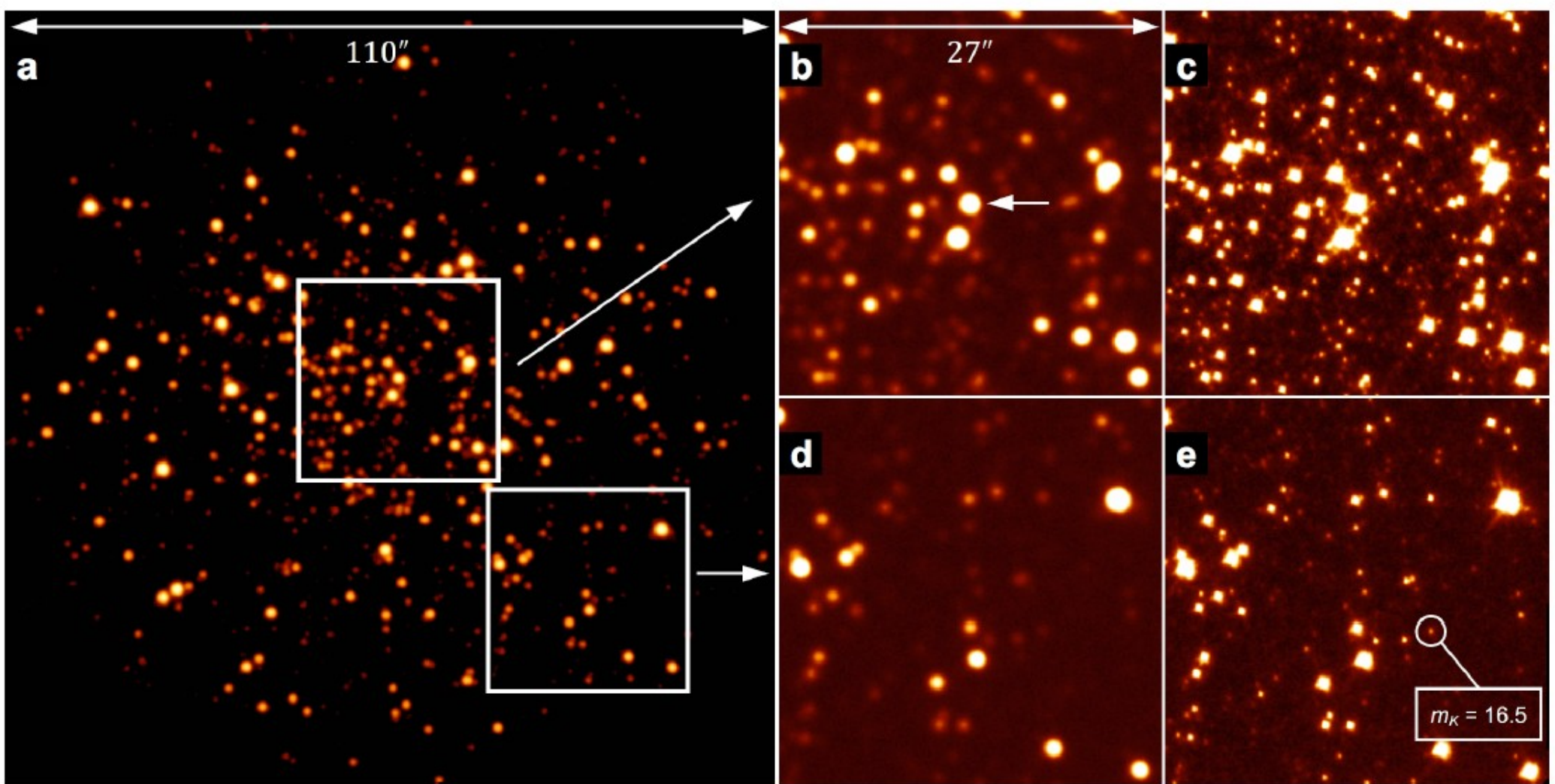


Fig. 8. The core of M3 imaged at  $2.2\ \mu\text{m}$  in two 60 s exposures. a) The full 110 arc sec field of the IR camera in the native seeing limit of 0.7 arc sec, on a logarithmic intensity scale. b,d) Two smaller 27 arc sec regions of the same image, indicated by the boxes in a) shown on a truncated linear scale in which bright stars appear saturated but which reaches the noise floor and brings out the faintest observable stars. c,e) In a second 60 s exposure of the same two regions, taken with GLAO running at 400 Hz and shown on the same linear scale as b) and d), the stellar image width is reduced to 0.3 arc sec and has a very similar PSF morphology across the whole field of view. For reference, we highlight a star in the corrected image with K band magnitude of 16.5, detected at a SNR of 26. In the uncorrected image, stars must be 2 mag brighter to be seen at the same SNR.

# **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

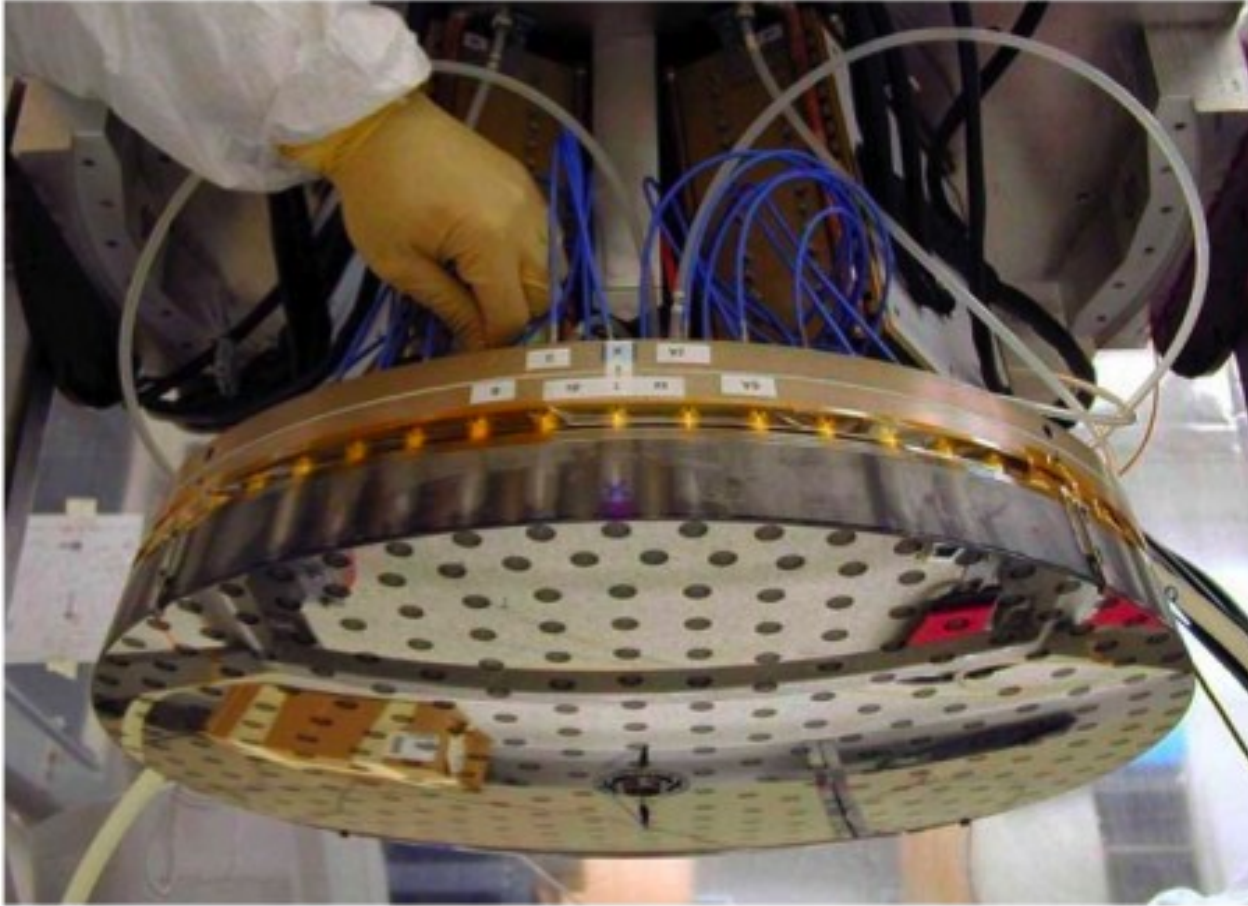
Large field of view AO systems

## **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**

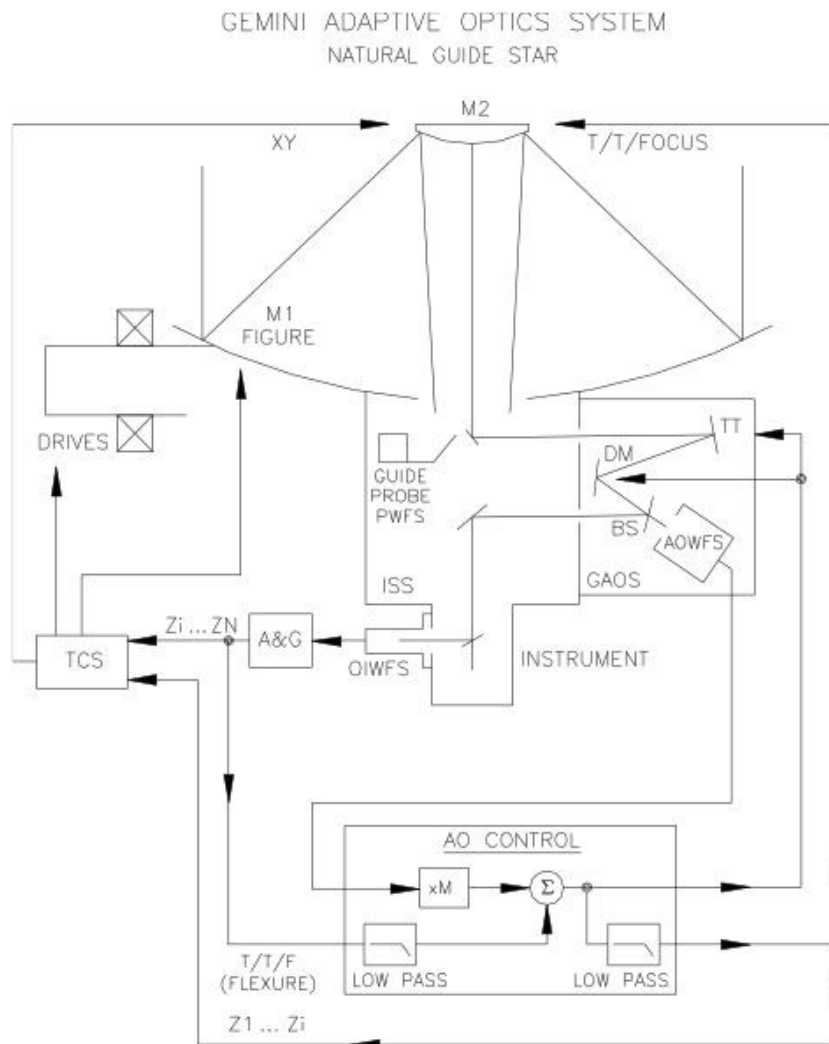
- > large optics, several large Deformable Mirrors (MCAO)
- > AO system works in closed loop, with several WFSs and several DMs
- > Multiple guide stars needed, with required positioning devices (NGS) or several laser beacons.

## **Example 2: Several small individual FOVs spread over a large field**

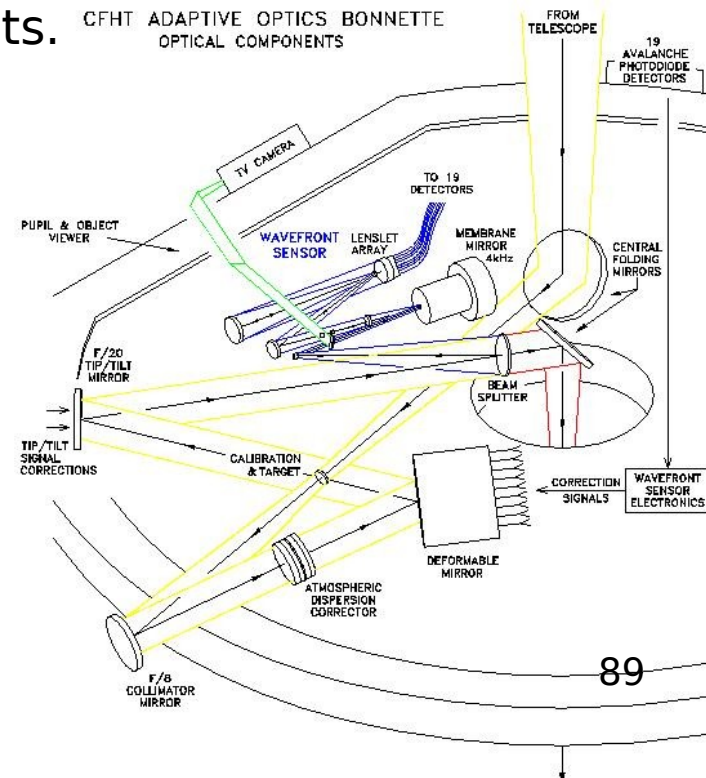
- > The instrument could have small independent wavefront correction units (1 per small field) to minimize optical size/complexity
- > These small units should be fed by a smaller number of WFSs using tomographic reconstruction.
- > The WFSs would be running in open loop, and do not see the correction 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”.

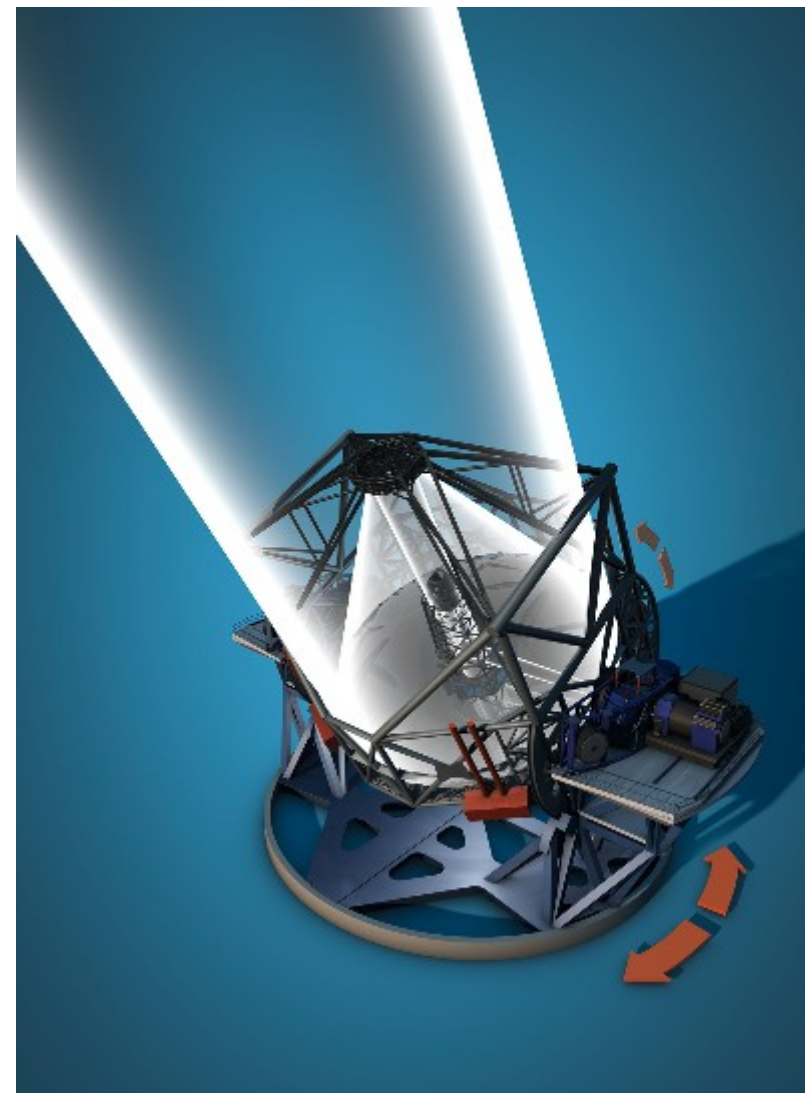
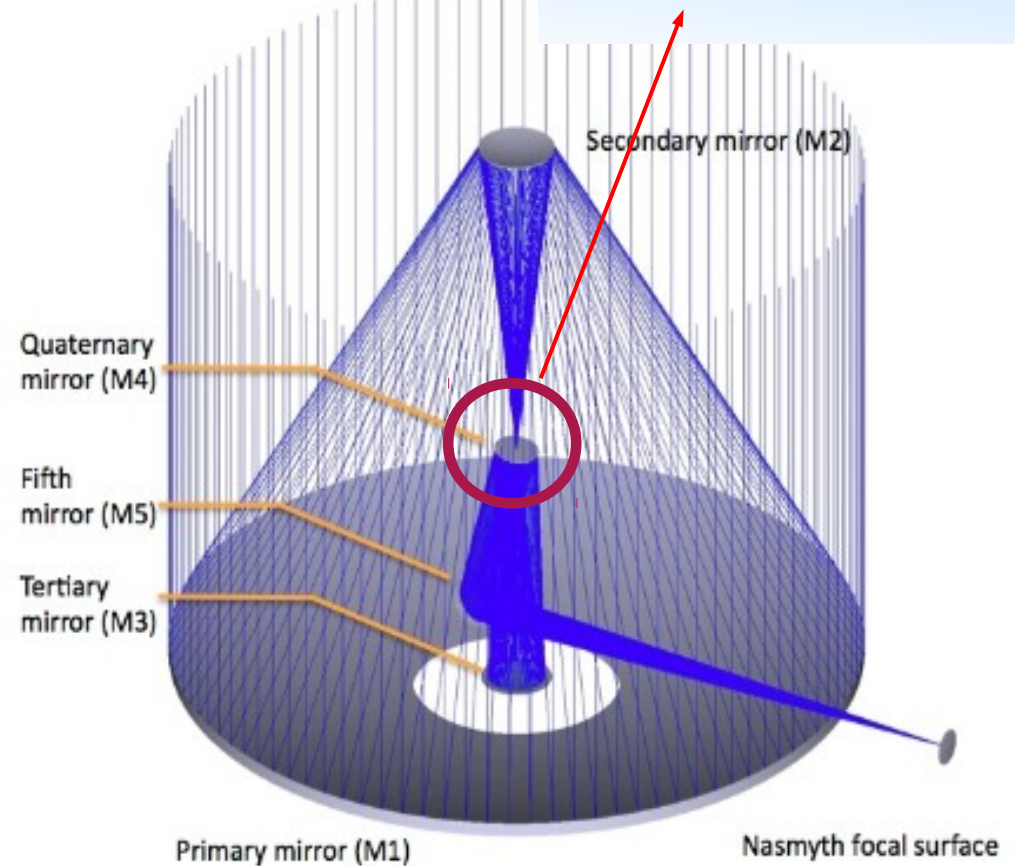
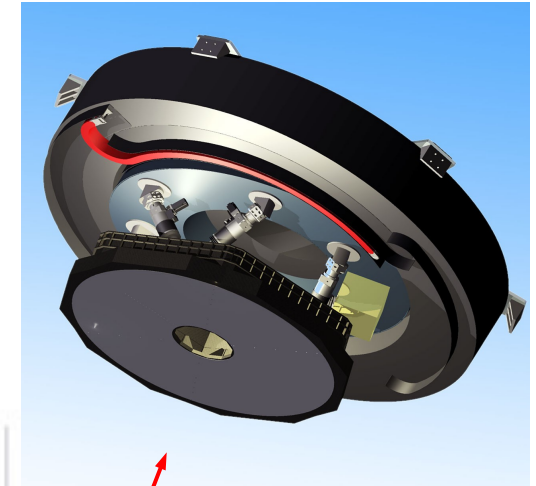


“Facility” AO systems can feed several instruments, and can be a “layer” which processes the beam prior to sending it to instruments.

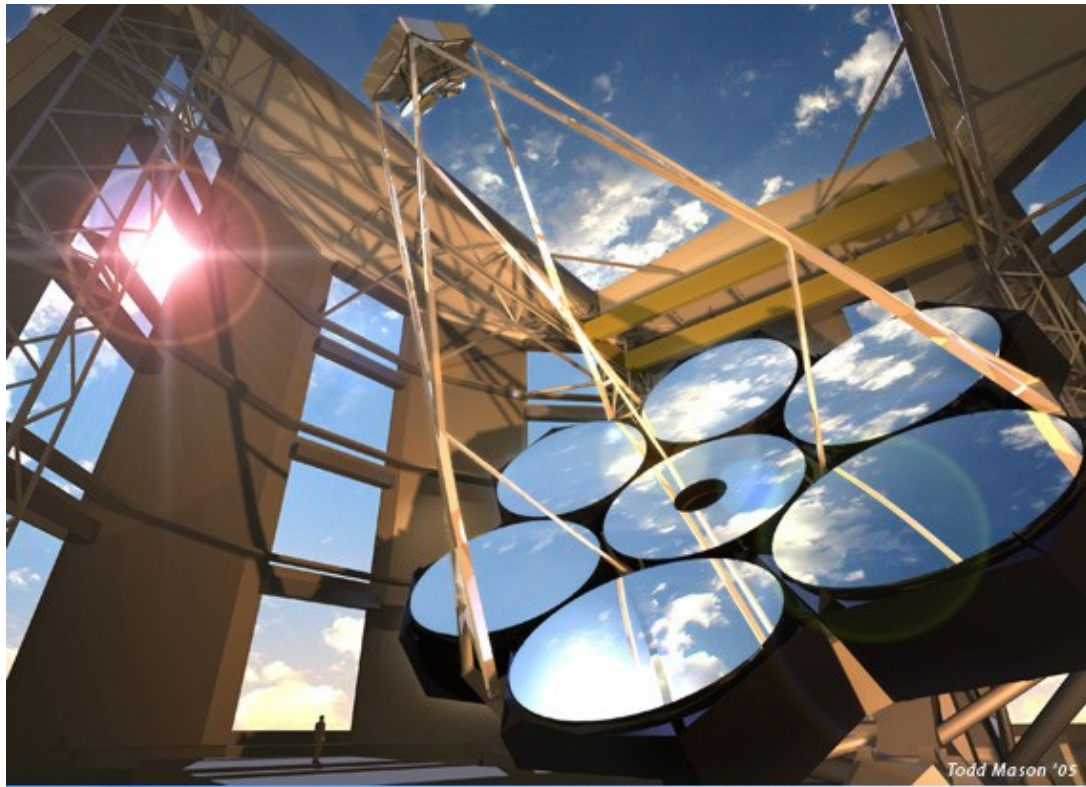


# The next generation of large telescopes combine AO with telescope design

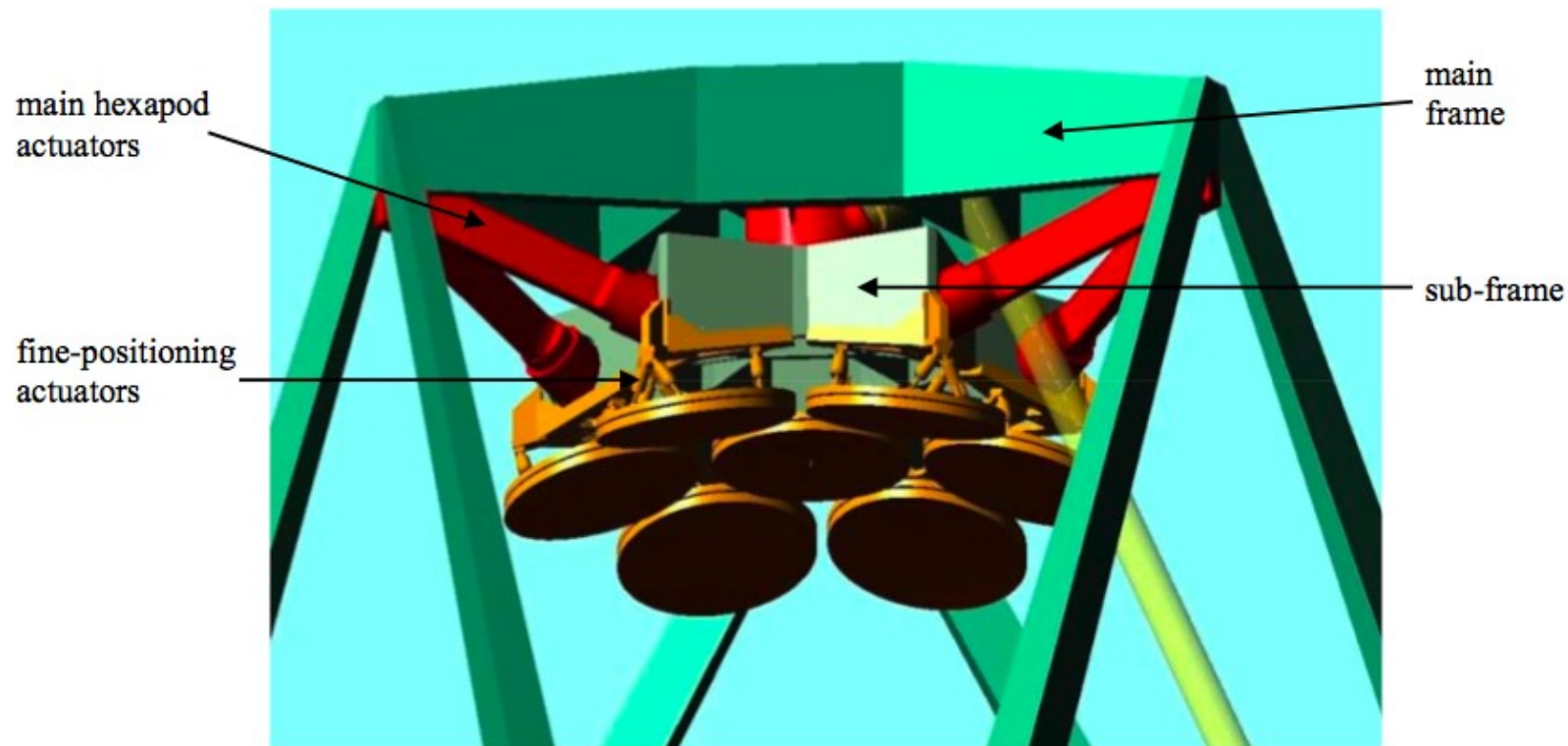
The 39m diameter European Extremely Large Telescope (EELT) optical design includes DM as large fold mirrors (M4: 2.4m diameter, 8000 actuators).

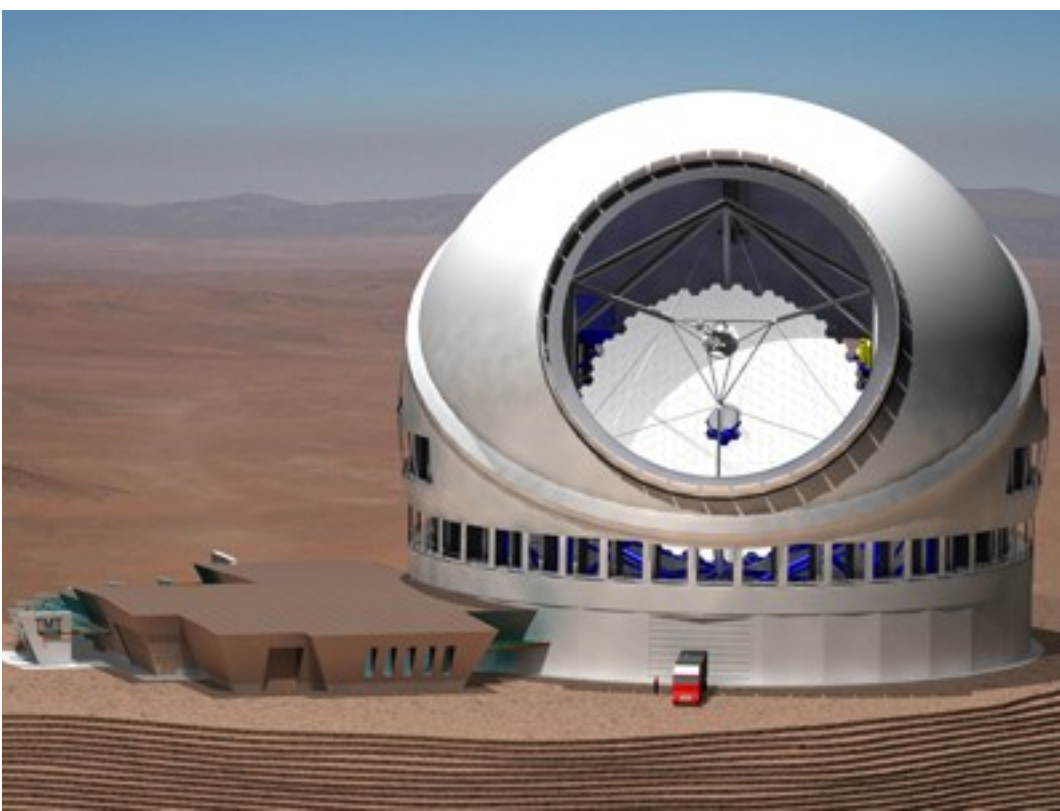




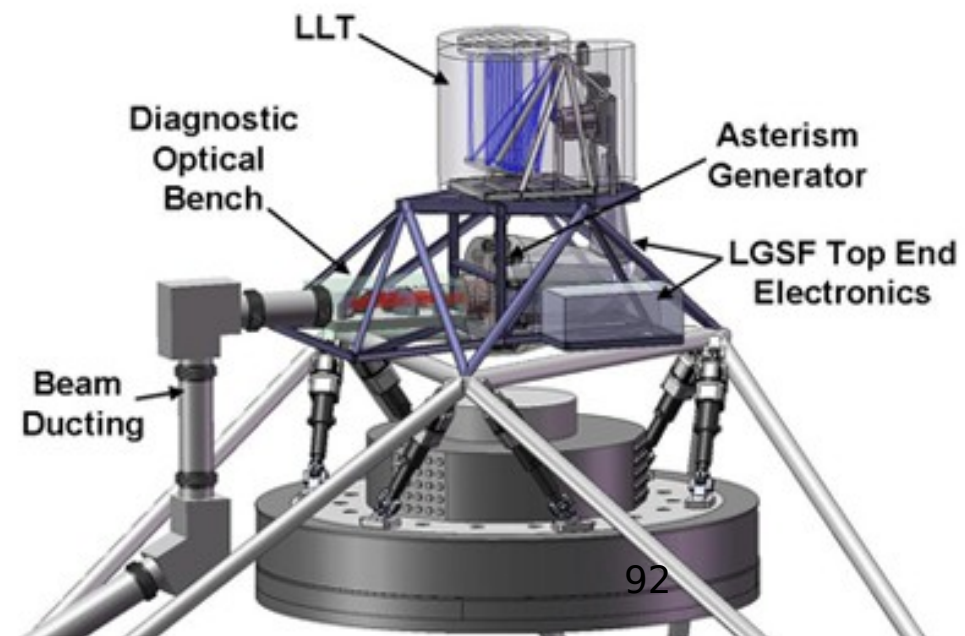
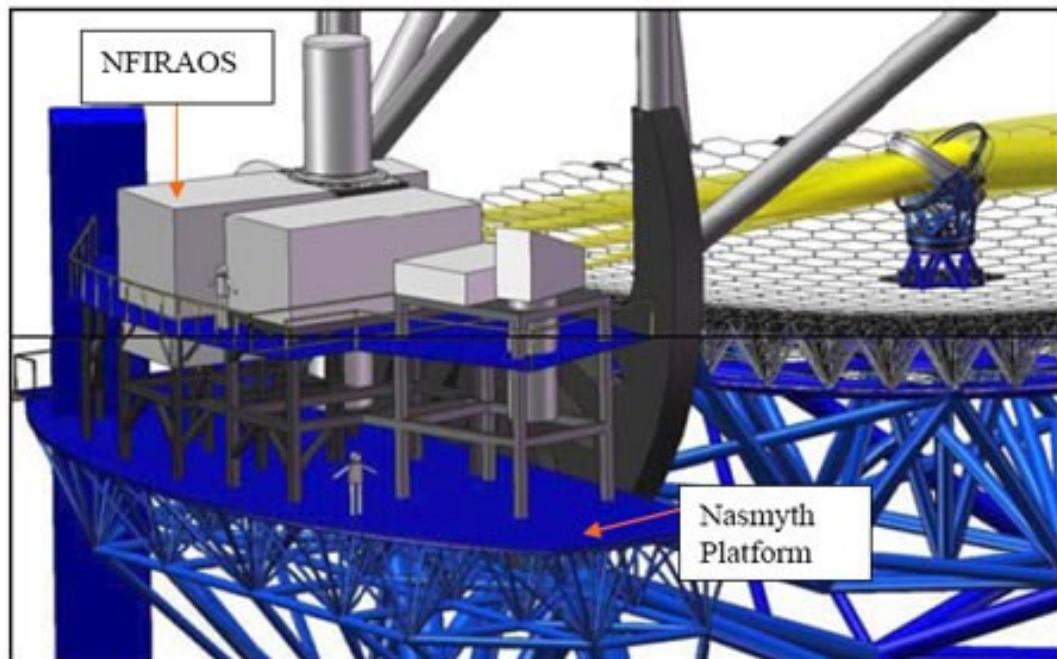


The Giant Magellan Telescope (GMT) secondary mirrors are adaptive and serve as DMs for the AO system(s).





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



## 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**

# 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  $\rightarrow$  “control matrix” (this step usually includes some filtering – see next slide)
- WFS measurements  $\times$  control matrix = DM commands

### **This could also be done by computing explicitly the wavefront:**

WFS measurements  $\rightarrow$  wavefront  $\rightarrow$  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:

$$A = M_{\text{resp}} B$$

Assuming  $m$  actuators,  $n$  sensing elements

$A_{i=0\dots n-1}$ : WFS signal vector (for example,  $x,y$  centroids for SH)

$B_{j=0\dots m-1}$ : DM commands (can be voltages, displacements)

$M_{\text{resp}}$ :  $m \times n$  Response matrix (usually not a square matrix !)

## AO control problem:

Given  $A$  (WFS measurement), and knowing  $M_{\text{resp}}$ , 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  $M_{\text{resp}}$  which is generally not invertible ?

# 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  $M_{\text{contr}}$

$$B = M_{\text{contr}} A$$

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

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

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

Singular Value Decomposition:

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

U: Unitary matrix

$\Sigma$ : 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

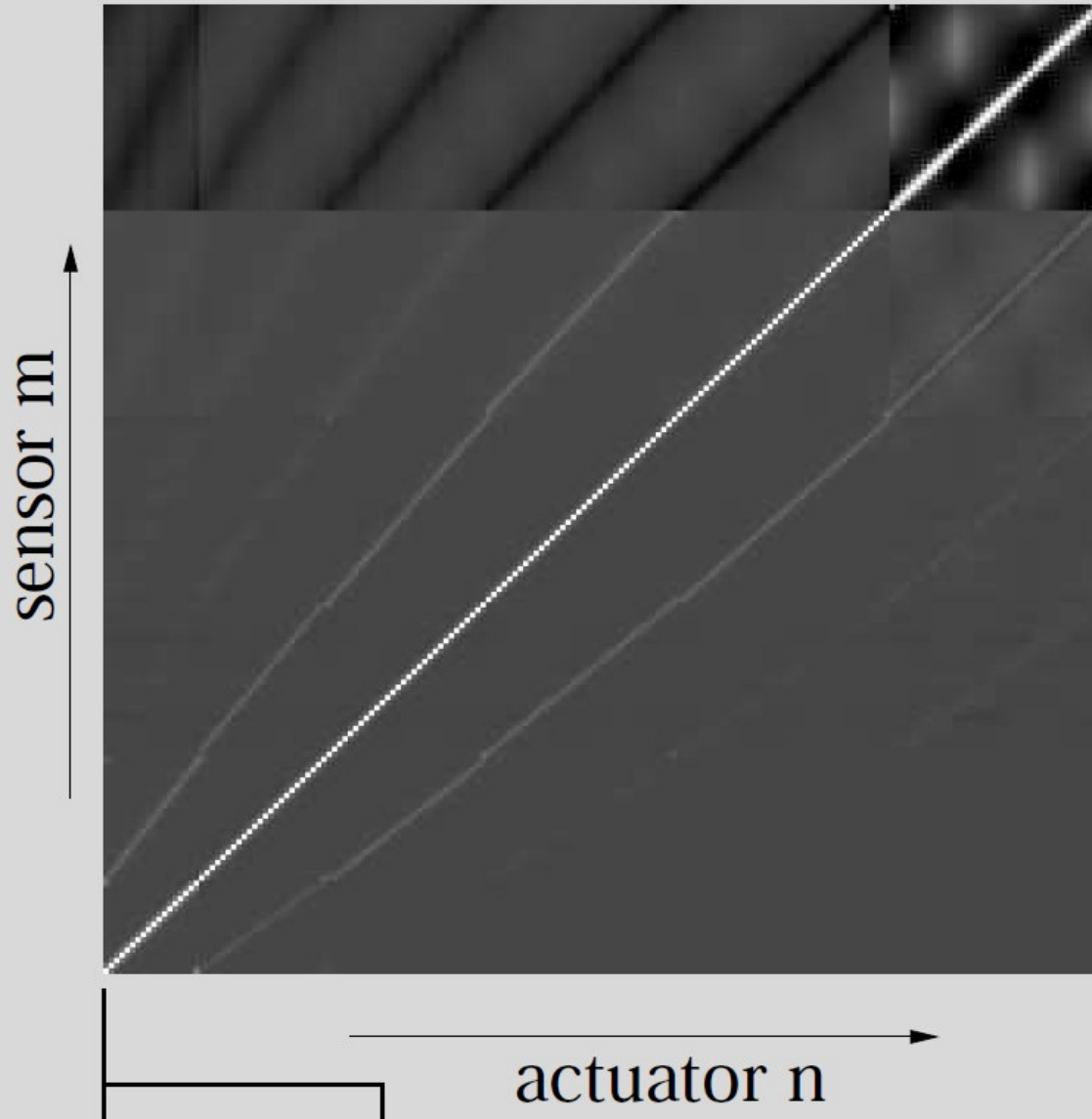
In practice:

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

# System response matrix: example (simulation)

System response matrix

$$\text{Curv} = (I_0 - I_1) / (I_0 + I_1)$$



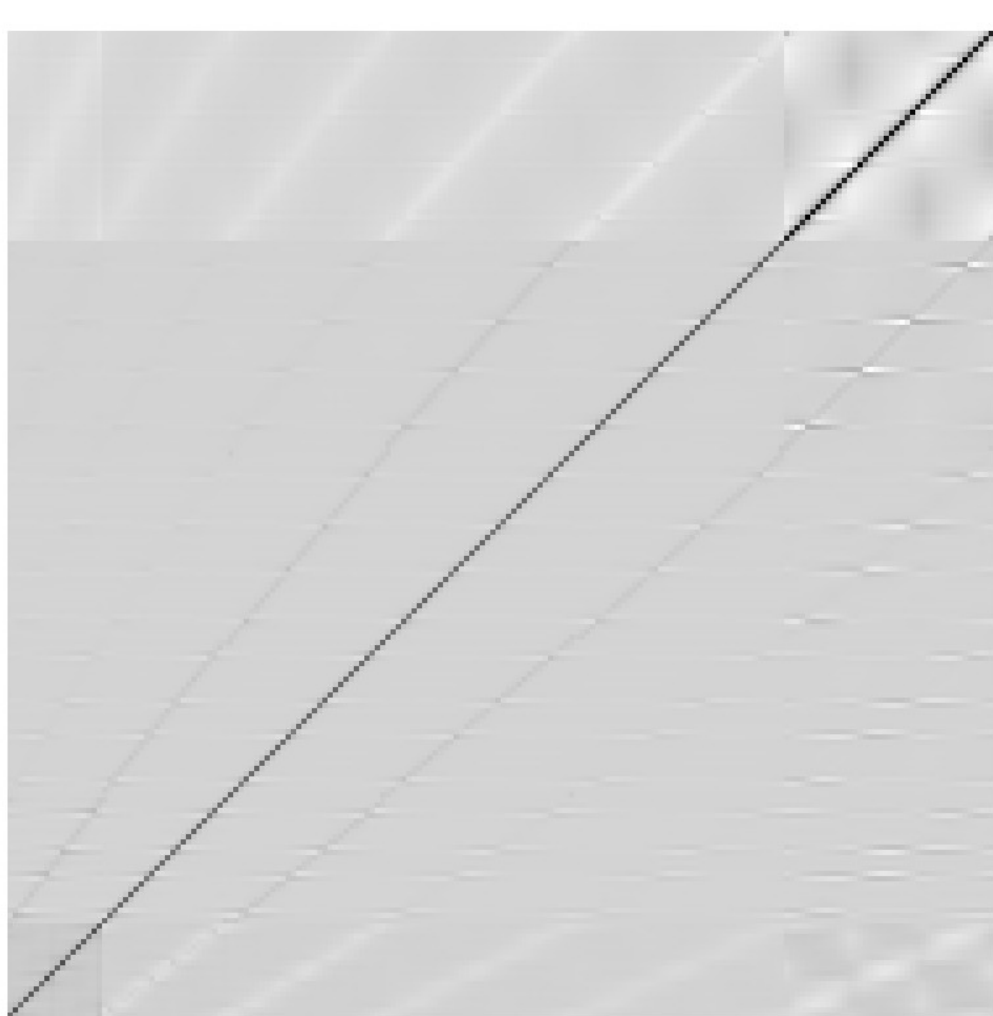
Measured response matrix includes system defects/imperfections, such as :

- alignment errors
- defective sensor(s)
- defective actuator(s)
- crosstalk

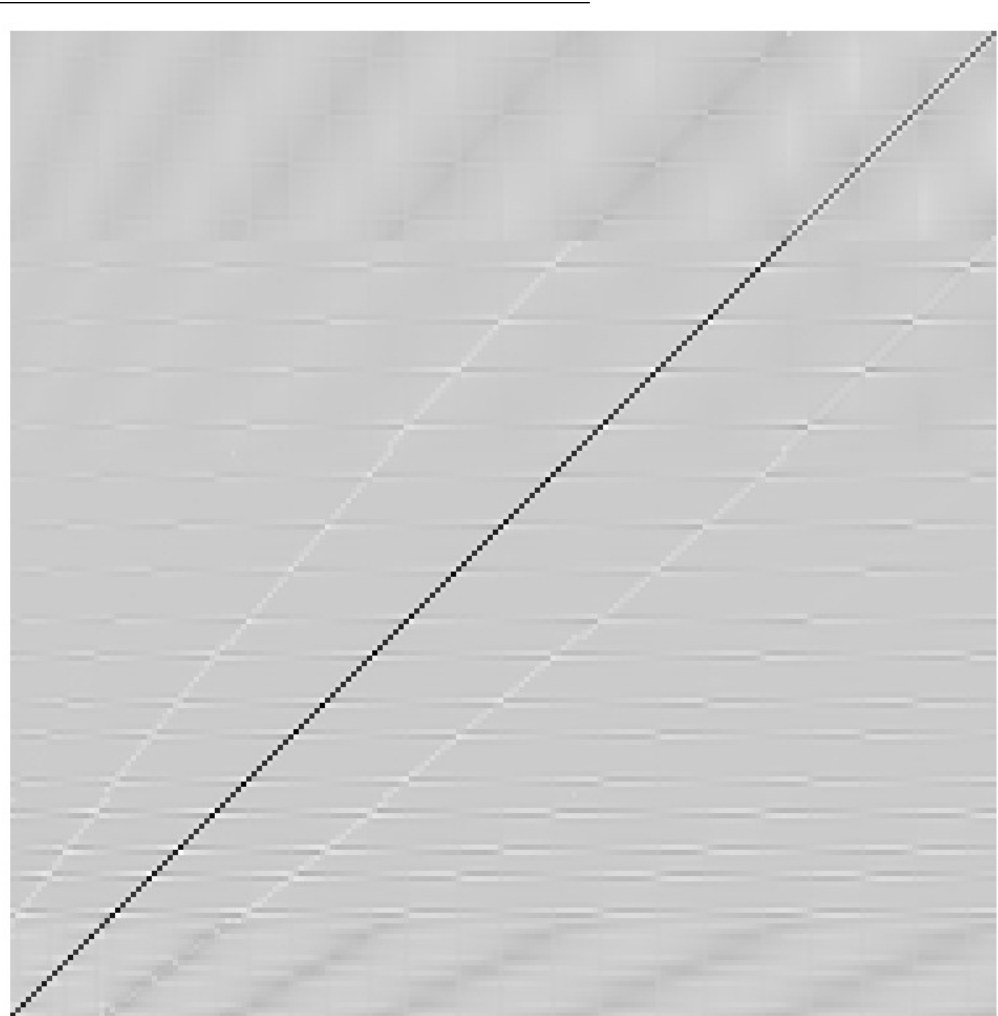
Mesuring response matrix is very good system diagnostics



# System response and control matrix: example (simulation)



Response matrix



Control matrix

## AO loop control: loop gain

At each step of the loop, offset  $dDM (= -M_{\text{contr}} A)$  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

$$M_{\text{contr}} = M_{\text{resp}}^+ = V \Sigma^+ U^*$$

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  $\rightarrow$  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

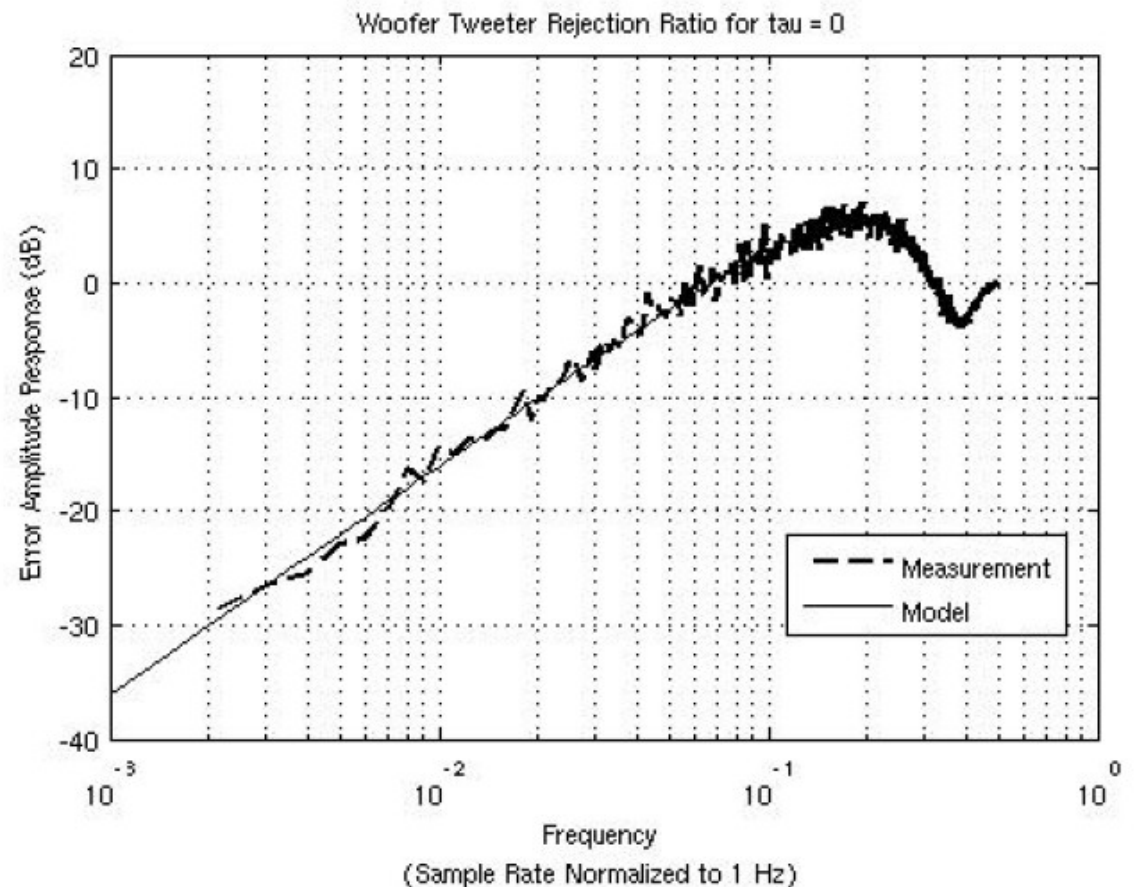
$H(f) < 1$  : attenuation

$H(f) > 1$  : amplification

$H(f) \rightarrow 0$  for  $f \rightarrow 0$  in a closed loop system

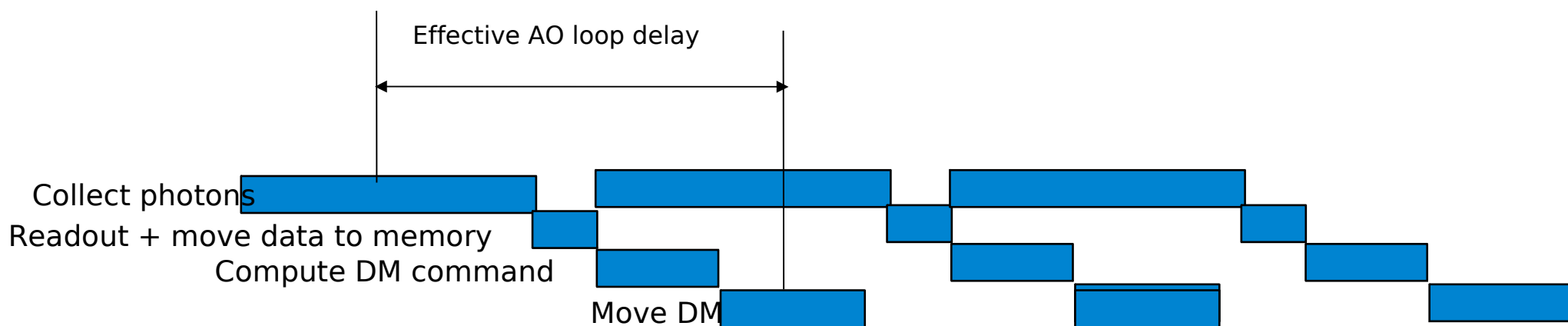
Notes:

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



# 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 !



# **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