Introduction to Adaptive Optics

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Why Adaptive Optics ?

Imaging through ideal telescope (reminder)

Imaging through atmospheric turbulence

Wave propagation (diffraction, geometrical)
Atmospheric turbulence: Fried Parameter and seeing
Modeling atmospheric turbulence and its effect on image quality

How does adaptive optics work ?

Adaptive optics principle

What is an Adaptive Optics loop ?
Identification of main components in AO system

Deformable mirrors

Wavefront sensing

Types of wavefront sensors: SH, Curvature, Pyramid
Laser guide stars

Making it all work together: control algorithms

Types of AO systems for Astronomy

Wide field systems: GLAO, MCAO
Extreme-AO for high contrast imaging

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*

Imaging through an ideal telescope (reminder)

Diffraction by an aperture – telescope diffraction limit

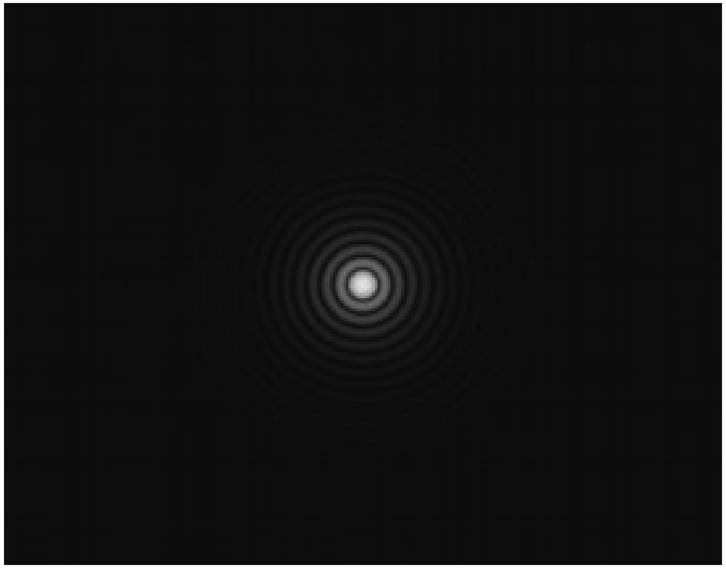
Fresnel diffraction integral: $$E(x,y,z) = \frac{e^{ikz}}{i\lambda z} \iint E(x',y',0) e^{\frac{ik}{2z}[(x-x')^2+(y-y')^2]} dx' dy'$$

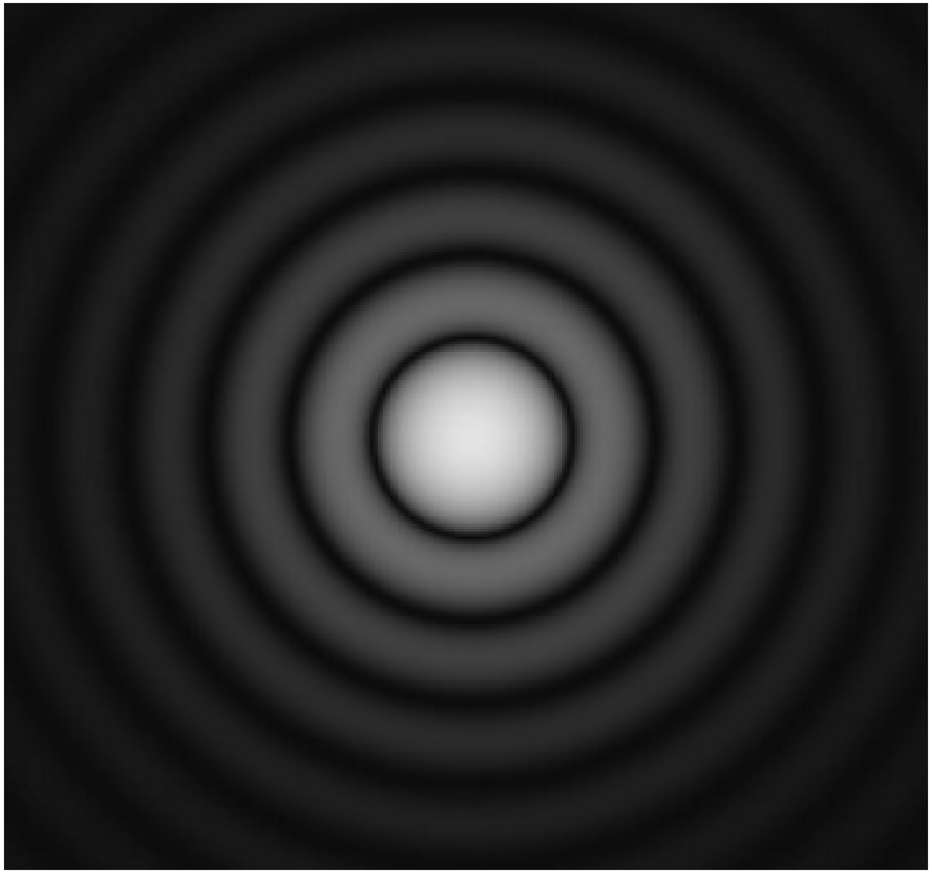
In imaging telescope, focal plane is conjugated to infinity (far field)
Fraunhofer is far field approximation of the Fresnel diffraction integral – and can easily be computed as a Fourier transform.

For circular aperture without obstruction : Airy pattern
First dark ring is at ~1.22 λ/D
Full width at half maximum ~ 1 λ/D
The "Diffraction limit" term = 1 λ/D

D=10m, λ=0.55 μm → λ/D = 0.011 arcsec

On large telescopes, image angular resolution is limited by atmospheric turbulence on the ground, at about 1 arcsecond
→ Adaptive optics required for < arcsecond imaging

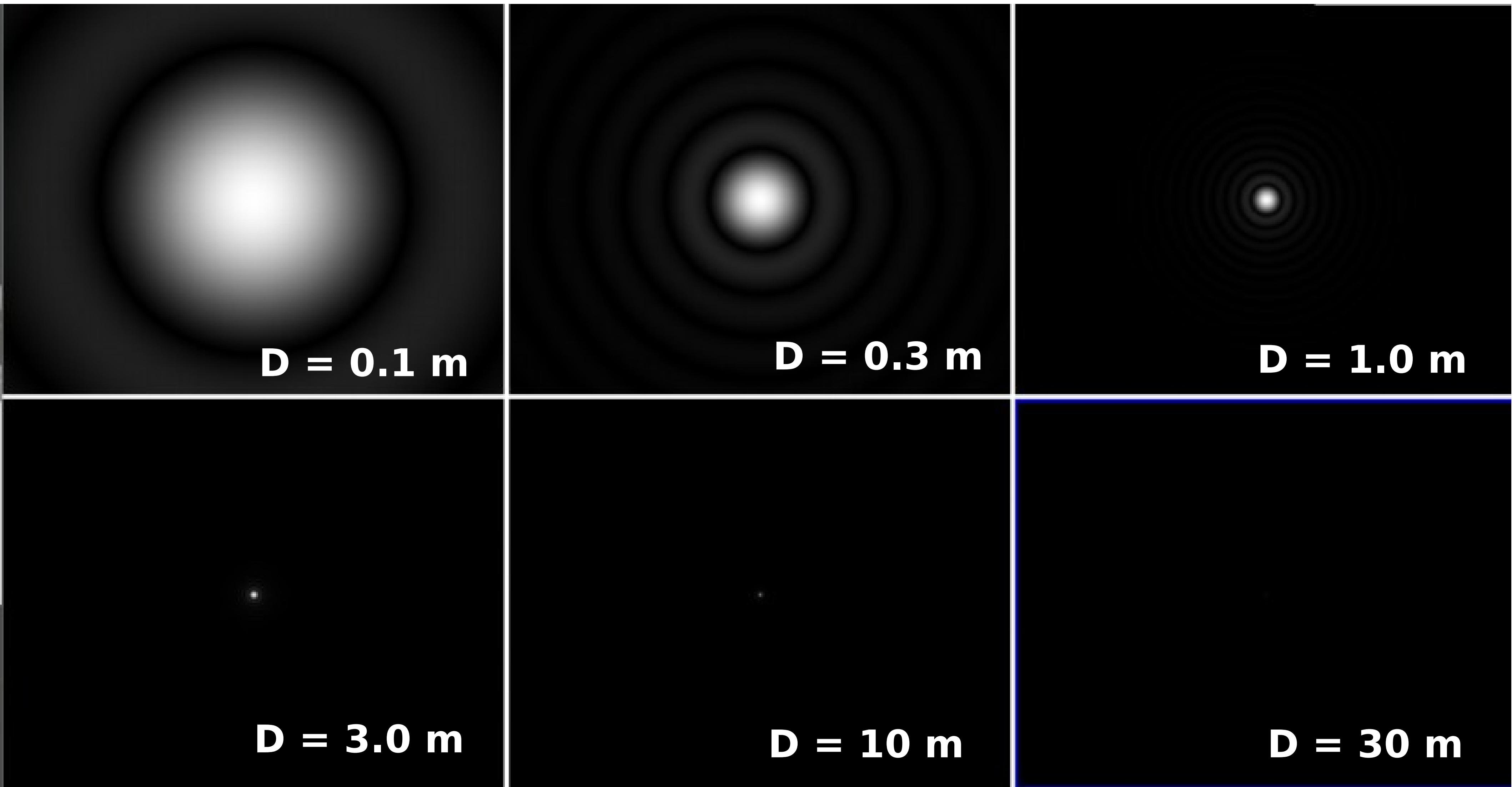




Imaging through Atmospheric turbulence

Diffraction by an aperture → Images should get sharper as telescope size increases (angular resolution ~λ/D)

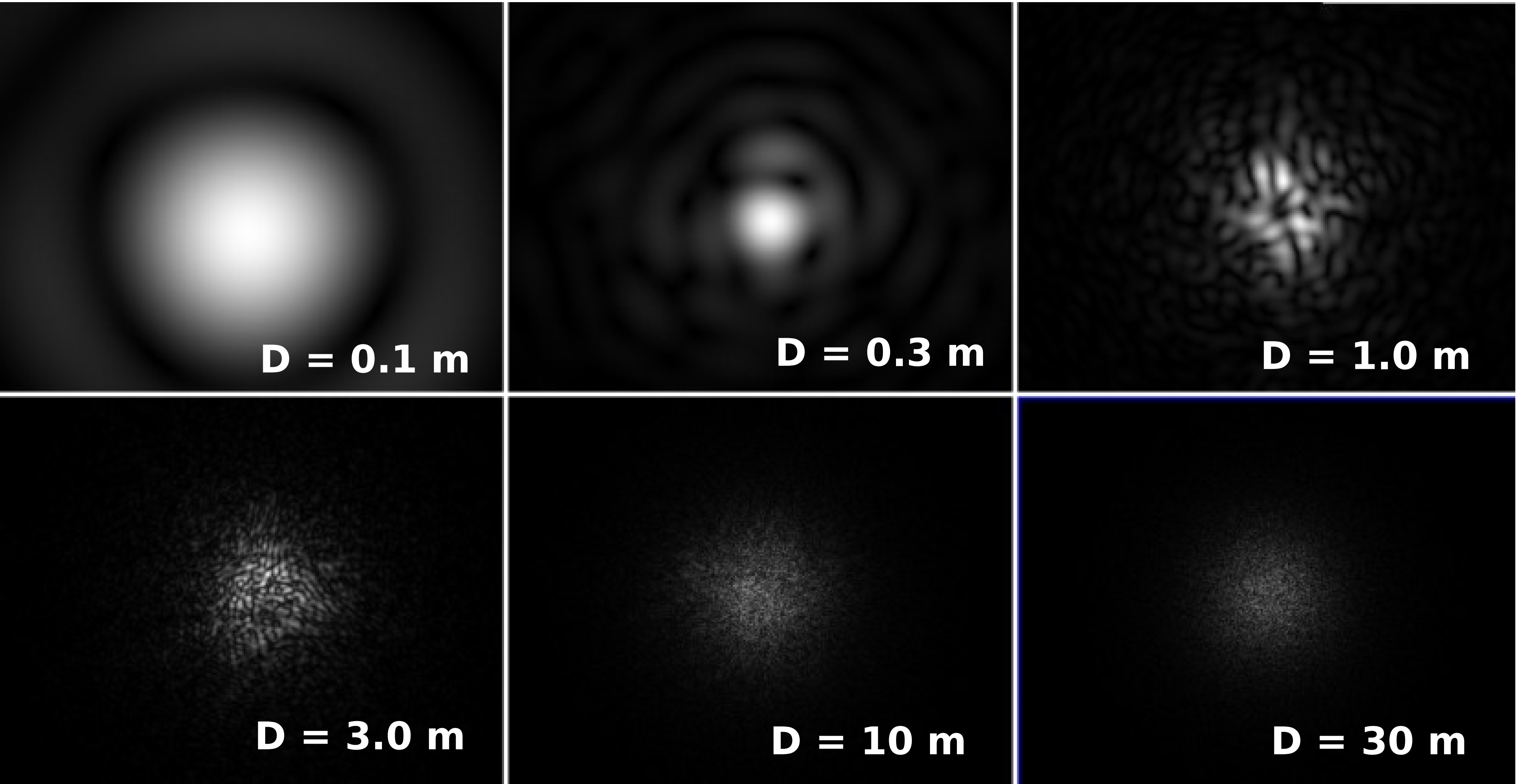
Below: Images of a point source at infinity at $\lambda = 0.6\ \mu m$



Imaging through Atmospheric turbulence

Unfortunately, atmospheric turbulence dominates angular resolution of telescope for D > ~0.2m in the visible (unless AO is used)

Below: Images of a point source at infinity at $\lambda = 0.6\ \mu m$ **with turbulence**



What is Atmospheric Turbulence ?

Spatial variations in refractive index → poor image quality

Turbulence is energy dissipation effect :
Large motions → breaks down into smaller turbulence cells → friction (heat dissipation) at inner scale

Strength of Turbulence : C_N^2

Refractive index spatial structure function (3D):

$D_N(\rho) = <|n(r)-n(r+\rho)|^2> = C_N^2 \rho^{2/3}$ (equ 1)

Equation is valid between inner scale (~mm) and outer scale (few m)

Taylor approximation: turbulence is a frozen wavefront pushed by the wind (frozen flow)

Between inner and outer scale, turbulence is well described by this power law.

Refractive index temporal structure function under Taylor approximation:

$D_N(\tau) = <|n(r,t)-n(r,t+\tau)|^2> = C_N^2 |v\tau|^{2/3}$

From C_N^2 (3D concept) to wavefront structure function (2D)

Wavefront phase spatial structure function (2D):

$$D_{\phi_a}(\rho) = \left\langle \left| \phi_a(\mathbf{r}) - \phi_a(\mathbf{r}+\rho) \right|^2 \right\rangle_{\mathbf{r}}$$

Can be obtained by integrating equ 1 over light path:

$$D_{\phi_a}(\rho) = 6.88 \left(\frac{|\rho|}{r_0} \right)^{5/3} \qquad \text{(equ 2)}$$

With r_0 = Fried Parameter [unit = m]

$$r_0 = \left(16.7 \lambda^{-2} (\cos\gamma)^{-1} \int_0^{\infty} dh C_N^2(h) \right)^{-3/5}$$

Wavelength

Elevation (=0 for Zenith)

Fried Parameter & Seeing

Wavefront phase error over a circular aperture of diameter d:

$$\sigma^2 = 1.0299 \left(\frac{d}{r_0} \right)^{5/3}$$

r_0 = Fried Parameter [unit = m] = diameter of telescope for which atmospheric wavefront ~ 1 rad^2

Seeing = λ/r_0 = angular size of PSF in long exposure

In this "collapsed" treatment of turbulence (what is the wavefront in a single direction in the sky), turbulence is fully described by r_0 and wind speed v

If variation of wavefront over small angles is important, the **turbulence profile** becomes important

Atmospheric turbulence, wavefront variance, Image quality

D = telescope diameter

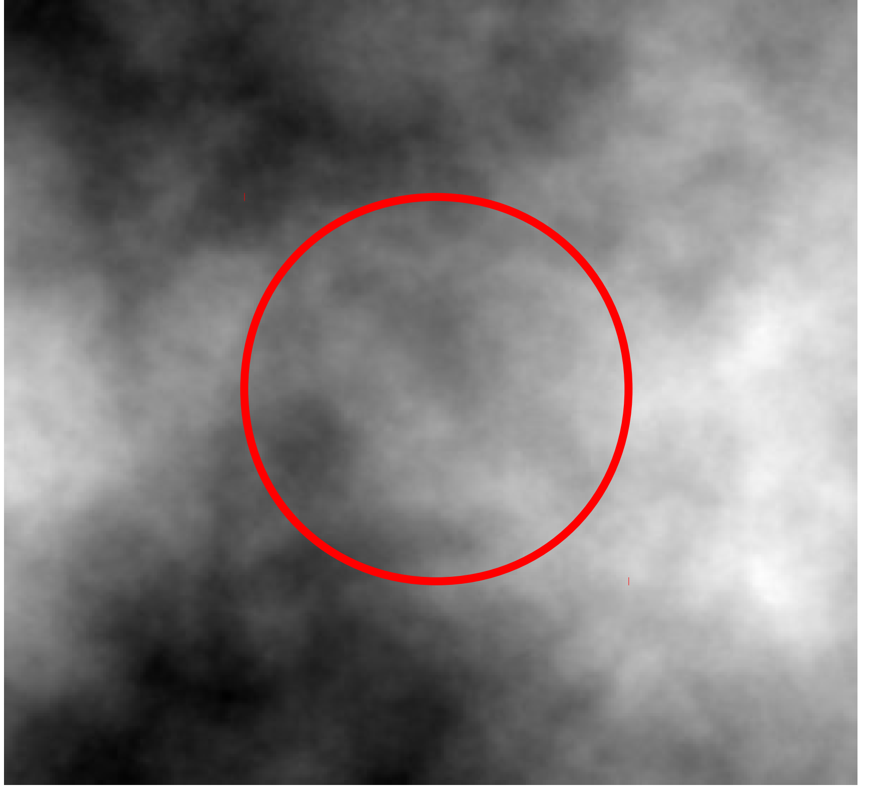
$\sigma^2 = 1.03\,(D/r_0)^{5/3}$

Seeing = λ/r_0

Number of speckles = $(D/r_0)^2$

D = 8 m, r_0 = 0.8 m

(0.2 m in visible = 0.8 m at 1.6 µm)



Kolmogorov turbulence

Wavefront error 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.

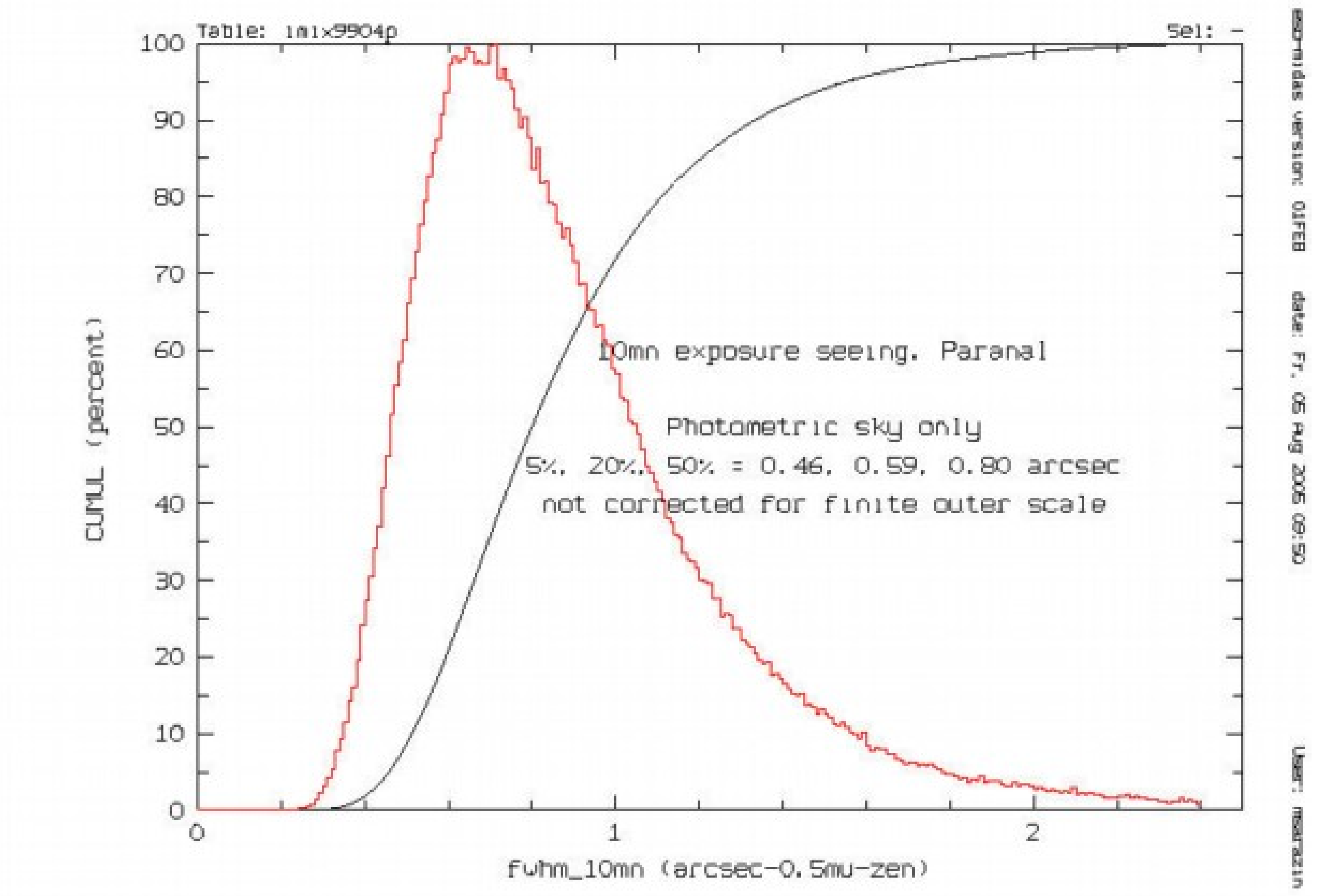
Wavefront error (m) = $\lambda \times \sigma/(2\pi)$

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

(Marechal approximation, valid for Strehl ratio higher than ~0.3)

Seeing (or its equivalent r_0) is the most used metric to quantify atmospheric turbulence

WITHOUT AO (and with long exposures), this is the only relevant quantity to describe atmospheric turbulence



ESO VLT seeing statistics, 1999-2004

With AO, **isoplanatic angle** and **coherence time** become important

How quickly does the wavefront change with location on the sky is quantified by **isoplanatic angle**

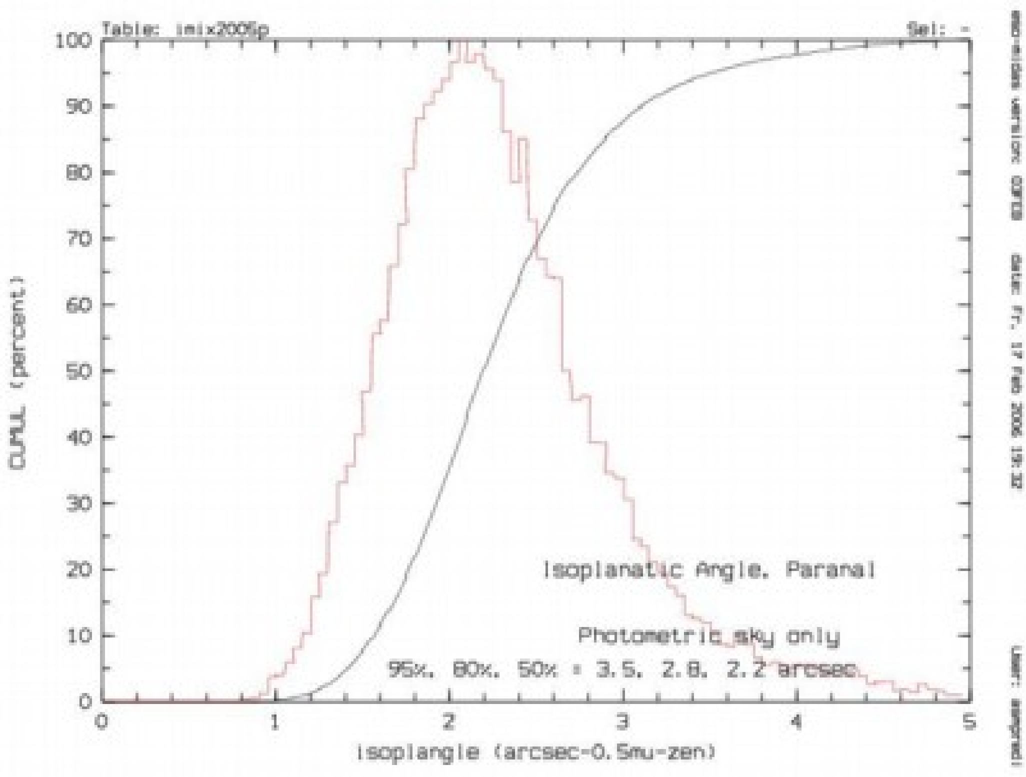
→ field of view of corrected image

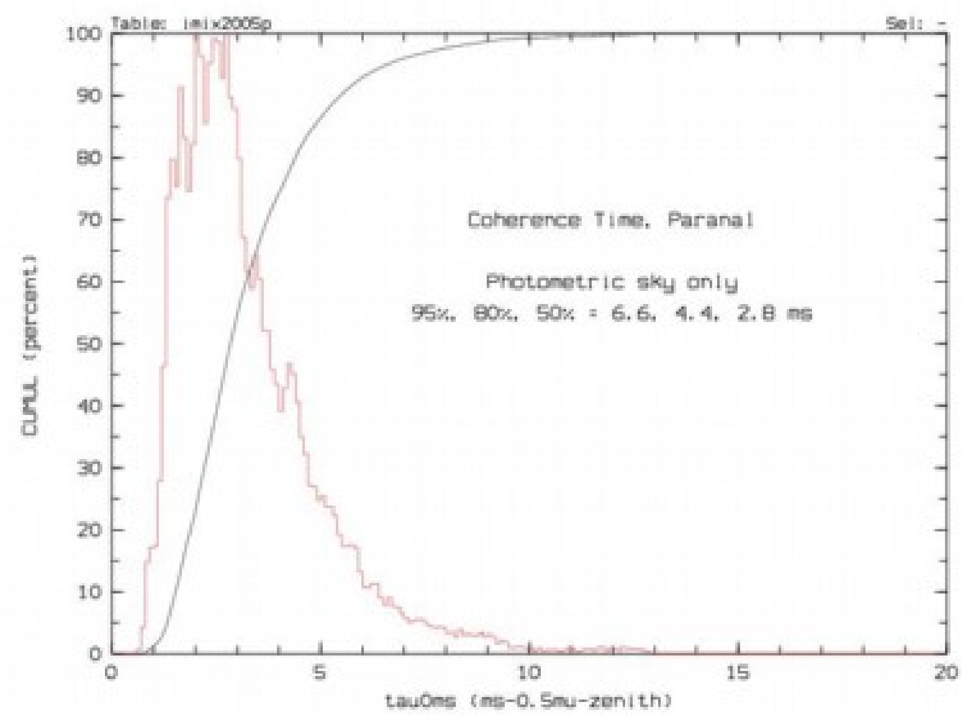
→ how far from science target can the guide star be

Speed at which wavefront changes is quantified by **coherence time**

→ how fast should the AO system run ?

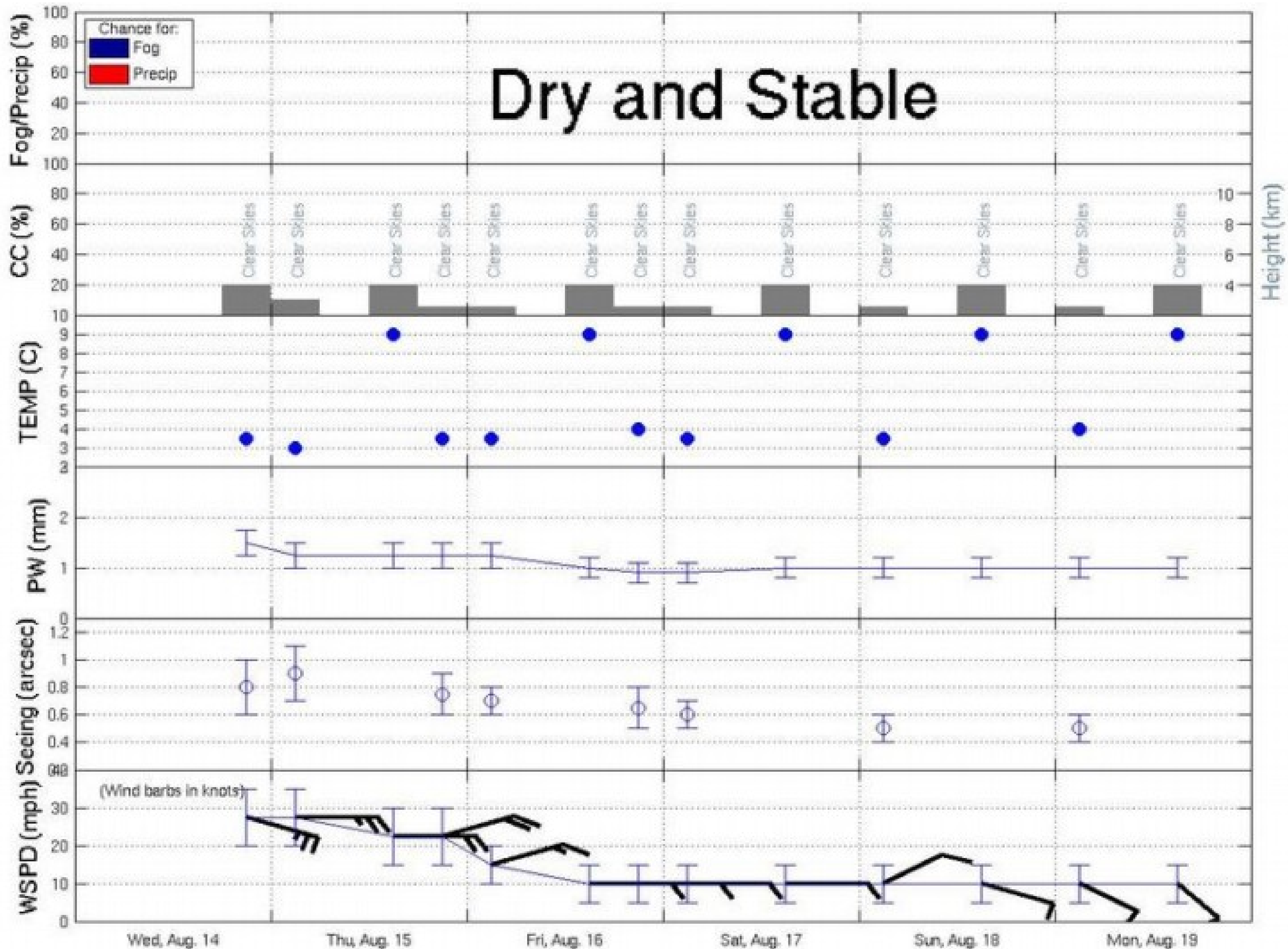
→ how faint a guide star can be used ?



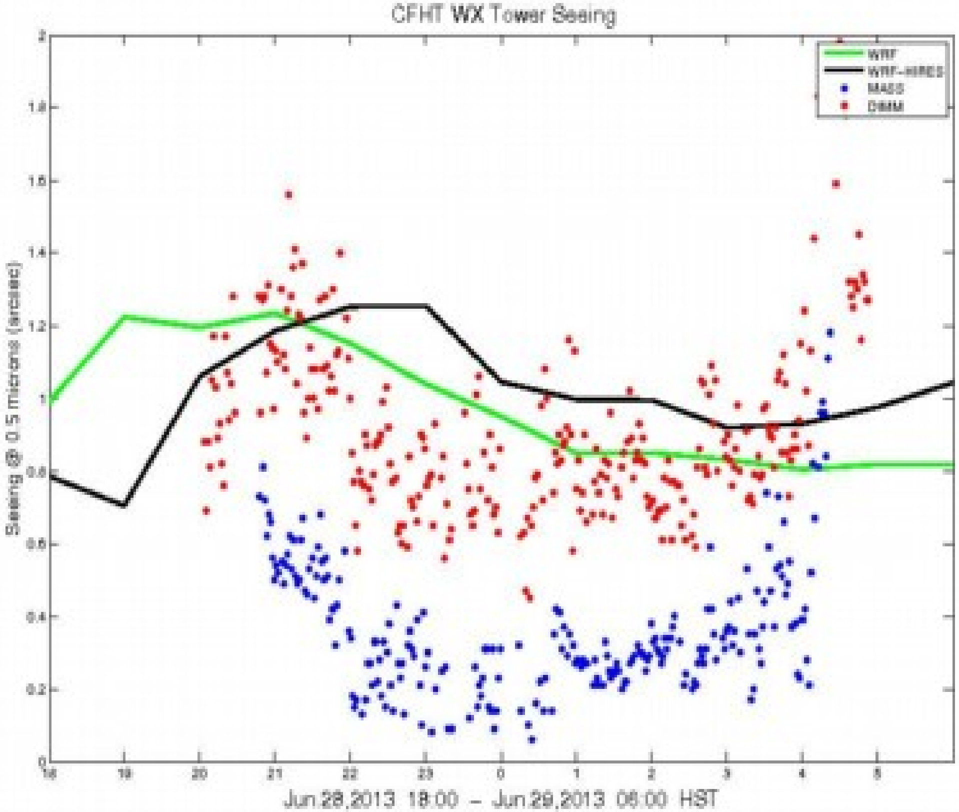


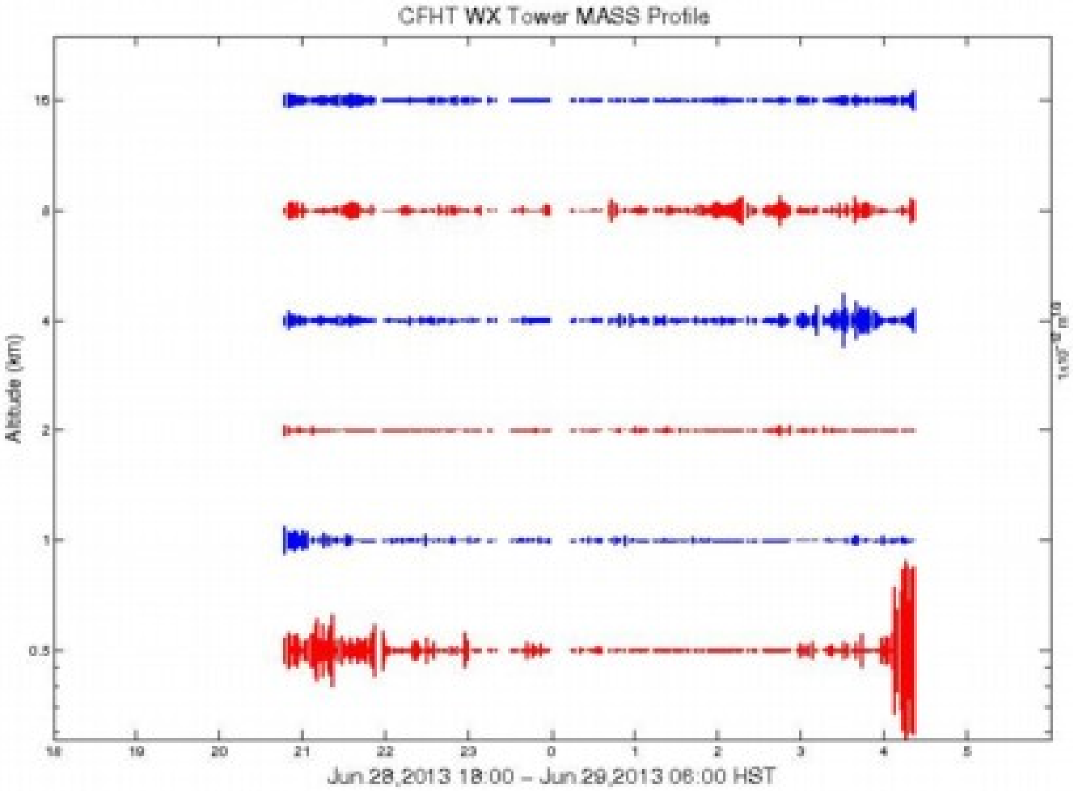
ESO VLT seeing statistics, 2005

Example: Mauna Kea observatory forecast



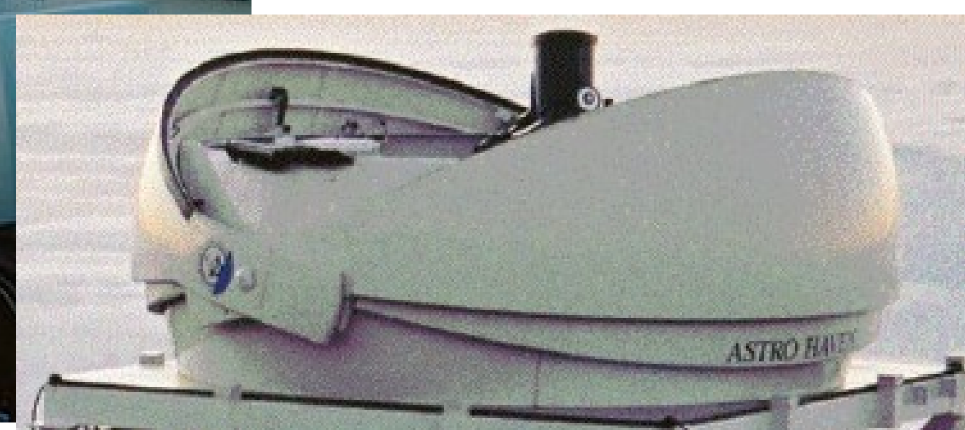
C_N^2 profile


CFHT WX Tower Seeing
WRF
WRF-HIRES
MASS
DIMM
Seeing @ 0.5 microns (arcsec)
Jun.28,2013 18:00 – Jun.29,2013 06:00 HST


CFHT WX Tower MASS Profile
Altitude (km)
Jun.28,2013 18:00 – Jun.29,2013 06:00 HST

Differential Image Motion Monitor (DIMM)

Concept: measure differential motion, for a single star, between images formed by different subapertures of a single telescope



RoboDIMM for Isaac Newton group of Telescope (LaPalma, Canary islands, Spain)

What gains are offered by Astronomical Adaptive Optics Systems ?

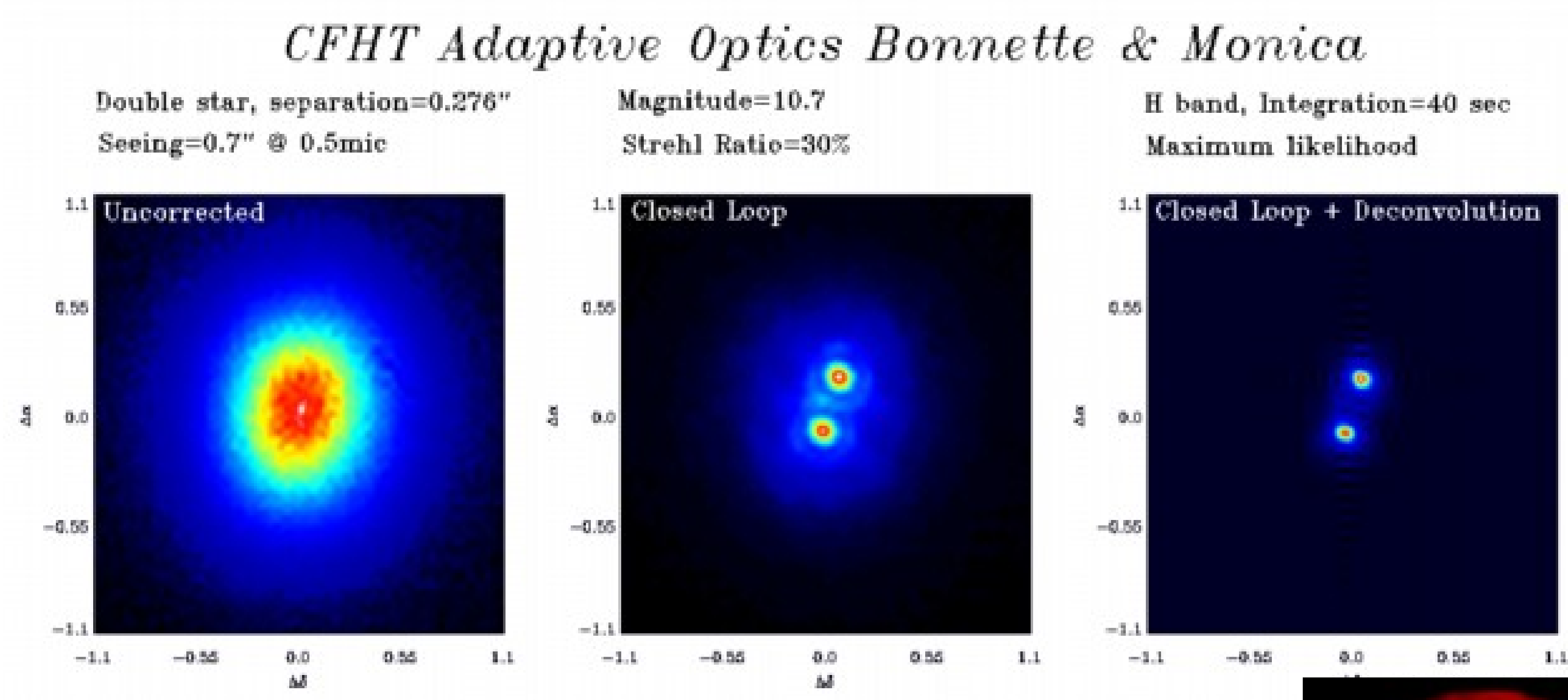
Angular resolution:
Resolve small features on Sun, Moon, planets, disks, galaxies

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.

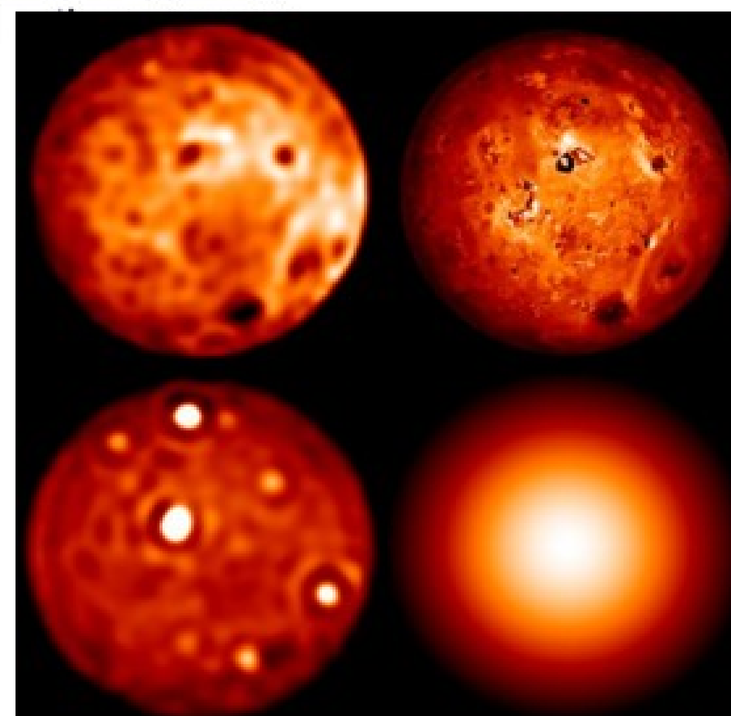
Astrometry:
Measuring the position of a source.
For example: measuring the mass of the black hole in the center of our galaxy.

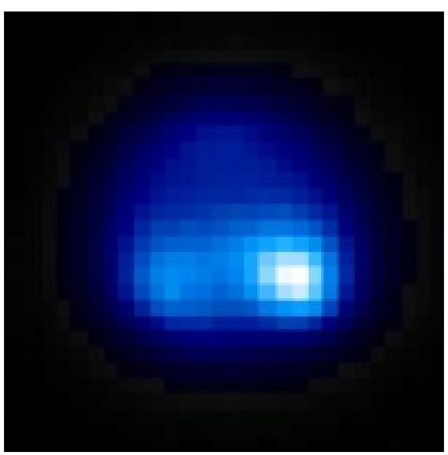
Confusion limit:
Astronomical imaging of sources is often confusion limited. Better angular resolution helps !
For example: studying stellar populations in nearby galaxies.

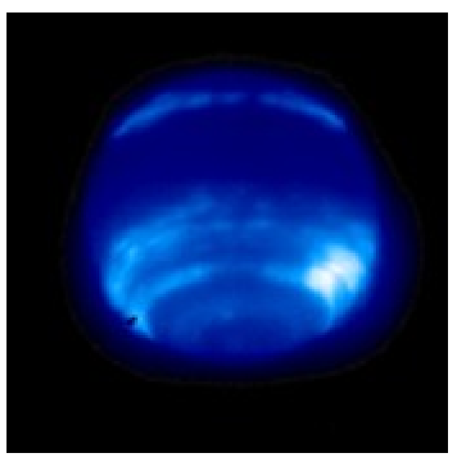
Why Adaptive Optics ?



Io (Keck)





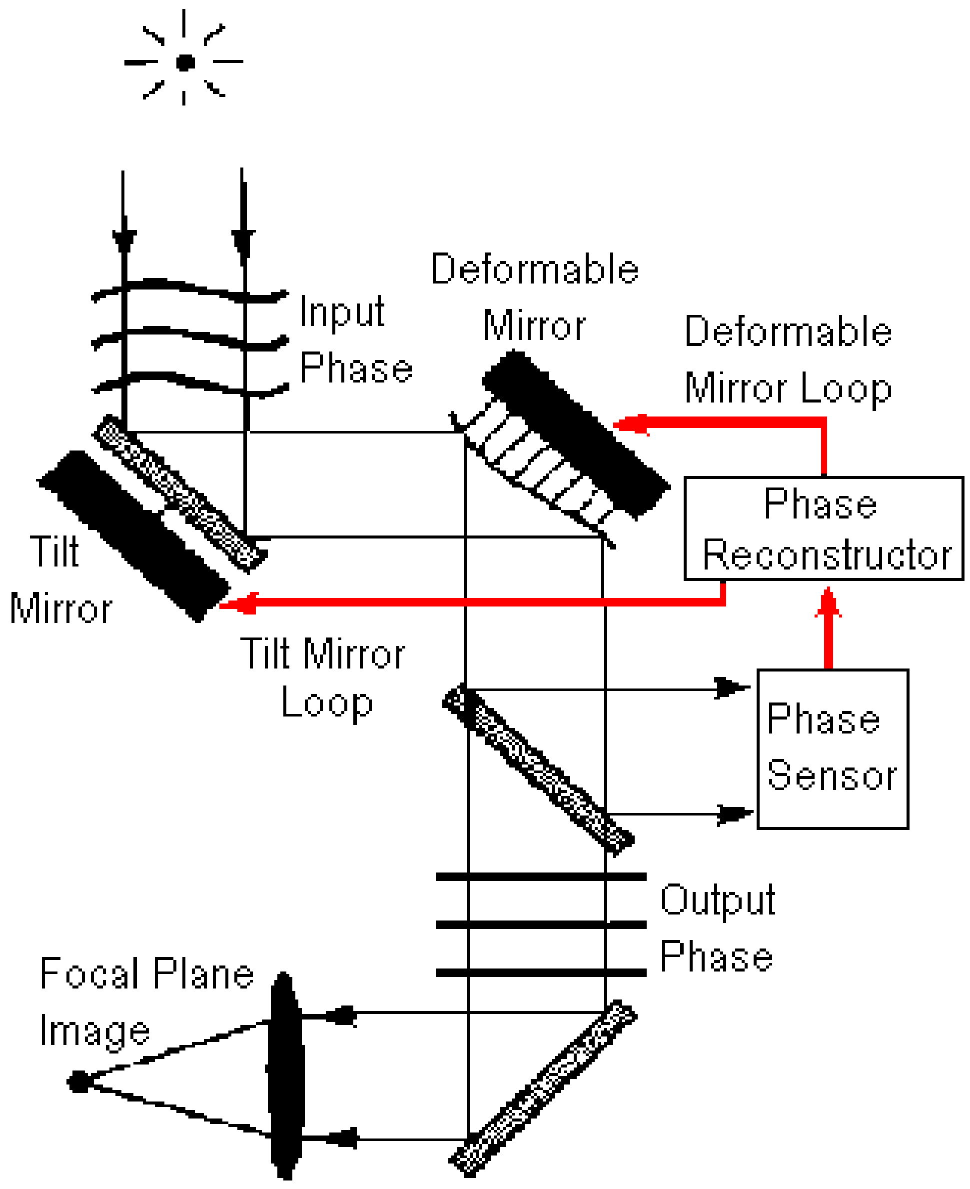


without AO

with AO

Neptune imaged by Keck AO

What is Adaptive Optics ?



Main components of an AO system:

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

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

Wavefront sensor(s): measures aberrations

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

What does an Adaptive Optics system look like ?

Altair Optics bench (for Gemini)

Deformable Mirror

Requirements and issues

Stroke: how much can the DM surface move (need few µm)
Number of actuators: 100s, 1000s
Speed: How fast does the DM respond (need ~kHz), vibrations
Stability: Does the surface drift with time ? are the actuator responses stable in time ? sensitivity to temperature, humidity, pressure

Hysteresis should be low (<30%, ideally less)
Backlash should be low
Wavefront quality
- Shape when not driven
- Non-correctable surface errors

Heat output
Reliablility

Piezoelectric effect

Coupling between electric field and mechanical strain

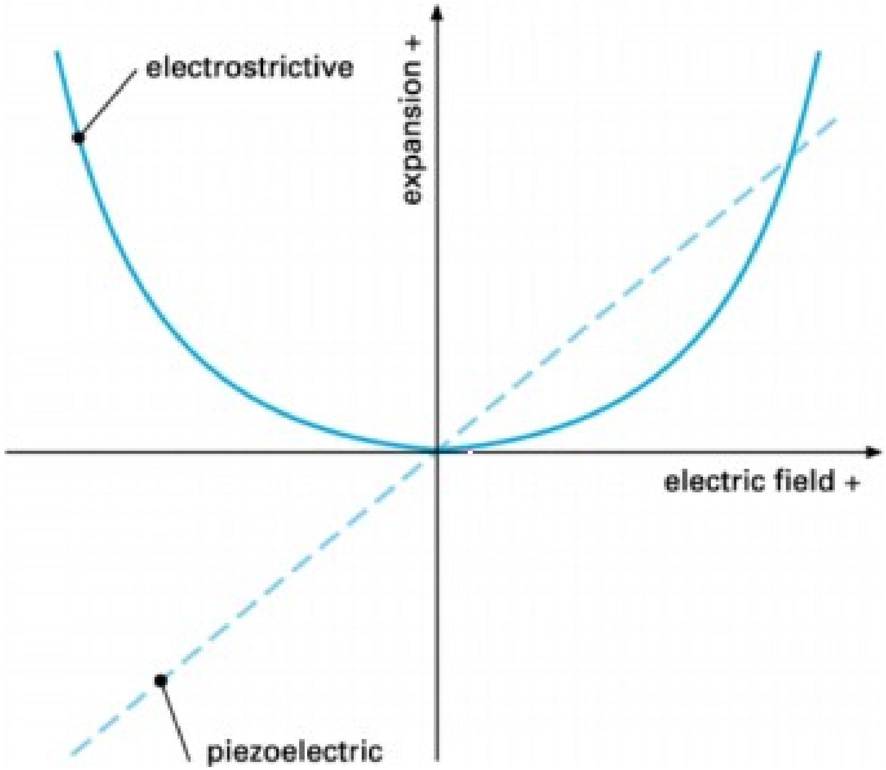
Applied electric field ↔ dimension

Relation is approximately linear, but:

- Hysteresis (~10%)
- Small drifts (temperature, exitation history)

Requires high voltage (typically > 100V)
Bipolar (voltage can be positive or negative)

Electrostrictive materials



Quadratic relationship between Electric field and displacement

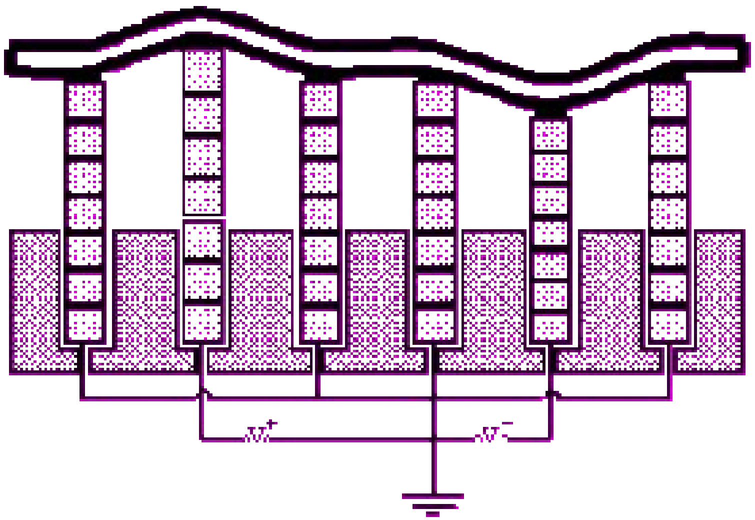
Smaller hysteresis, but more temperature dependance than piezoelectric materials.

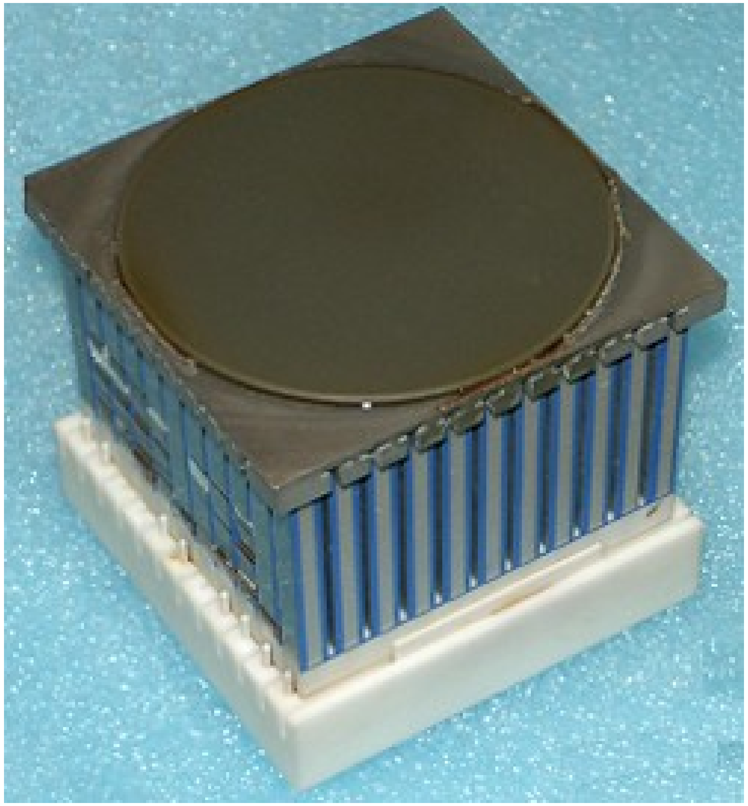
Higher capacitive load
→ requires higher currents

Piezo stack DM

Displacement is proportional to electric field
Large displacement = high electric field over long length of material

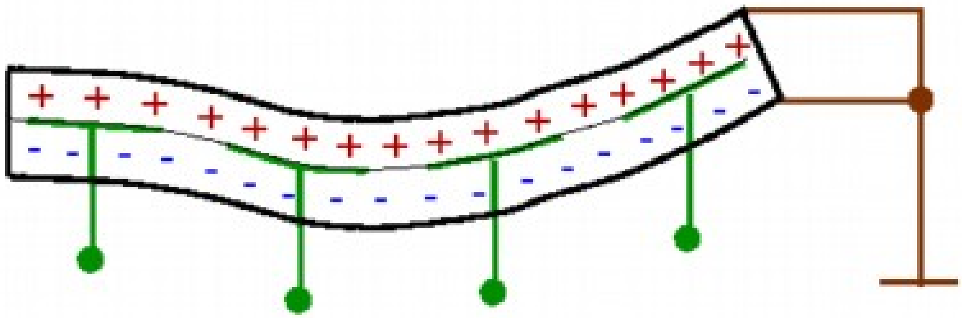
To avoid unreasonably high voltages, stack of piezo layers is used
Voltage is applied across each layer

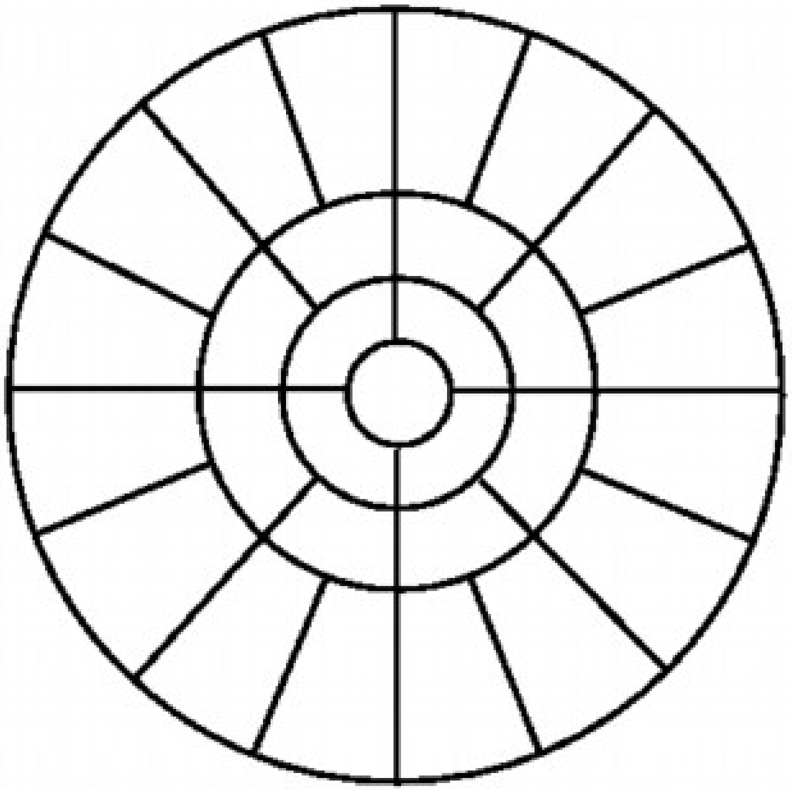




Piezo actuated mirror (Cilas)

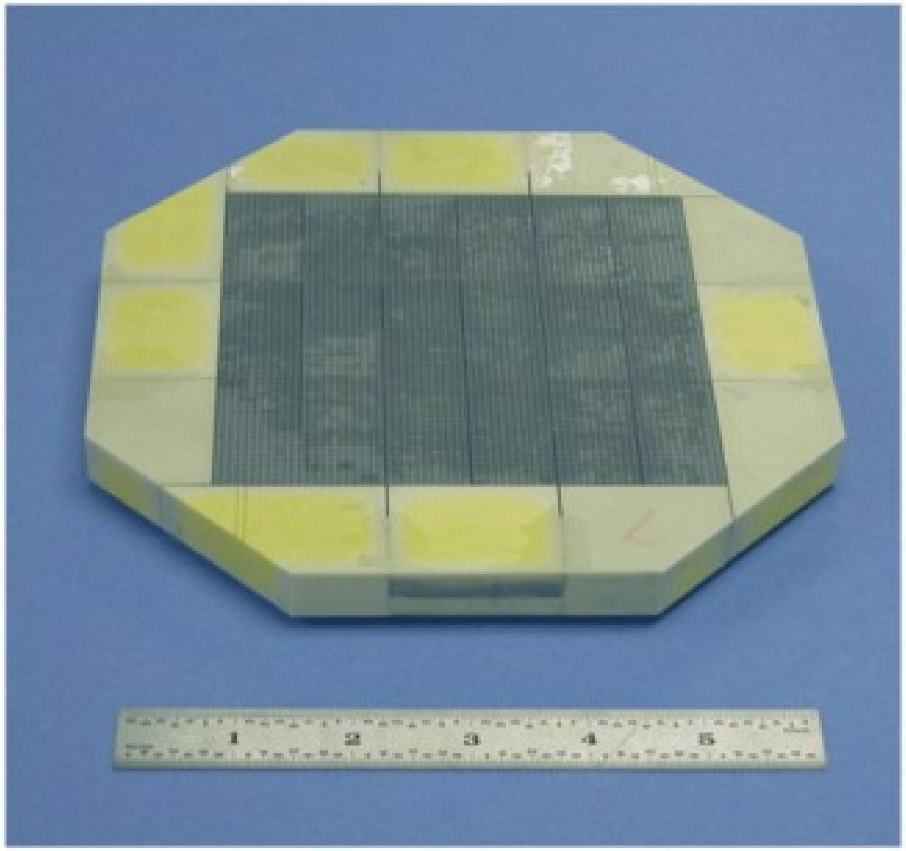
Bimorph DMs

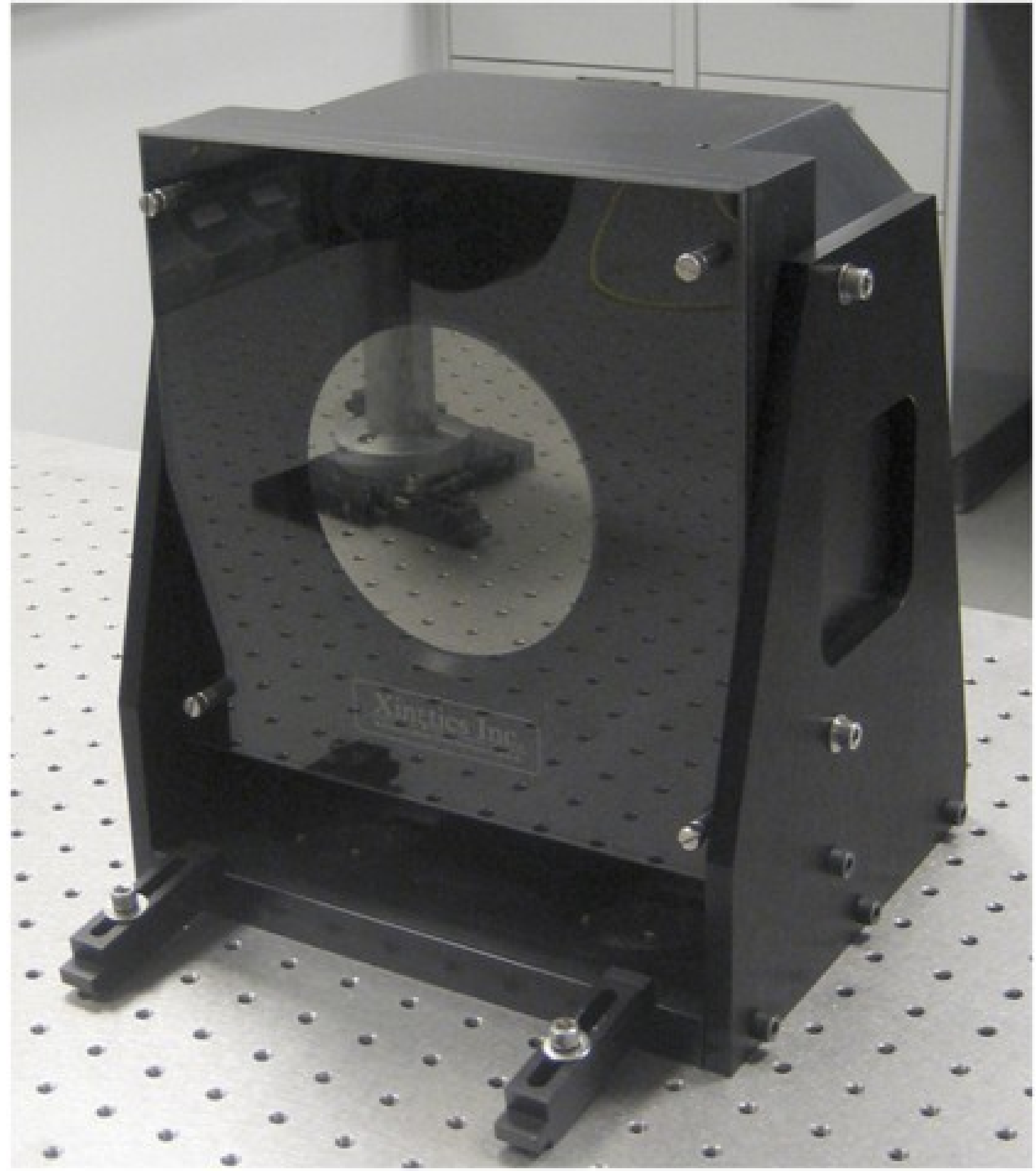




Curvature DM made by IfA, University of Hawaii

Electrostrictive DM

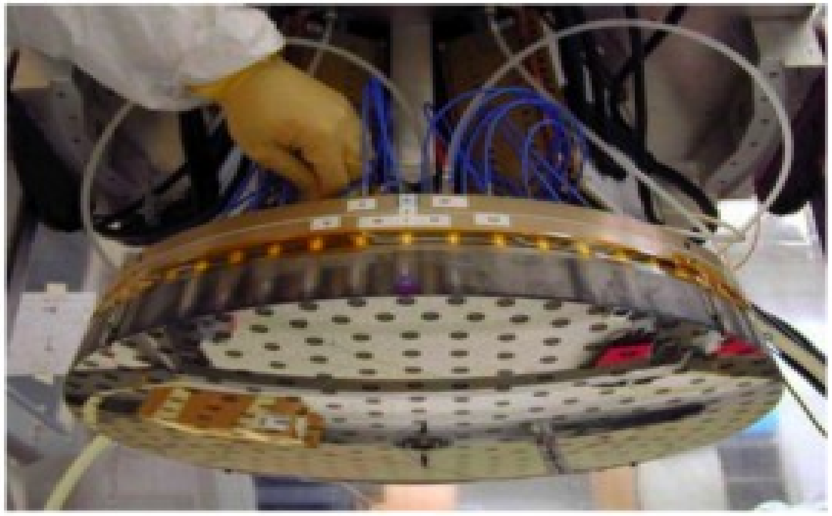


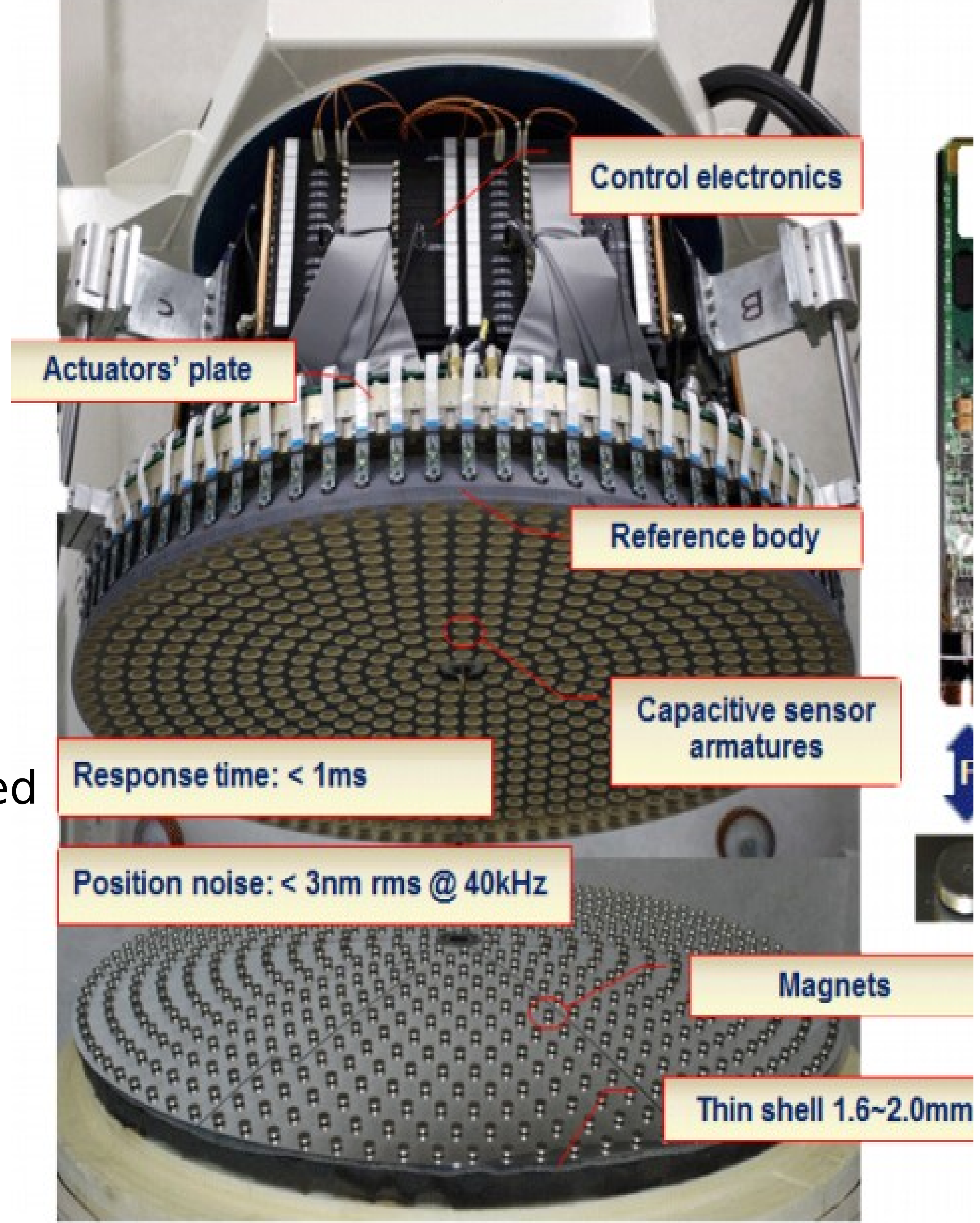


The 4356-actuator deformable mirror for PALM-3000 (Xinetics Inc.).

Magnetic force

Adaptive secondary Mirror



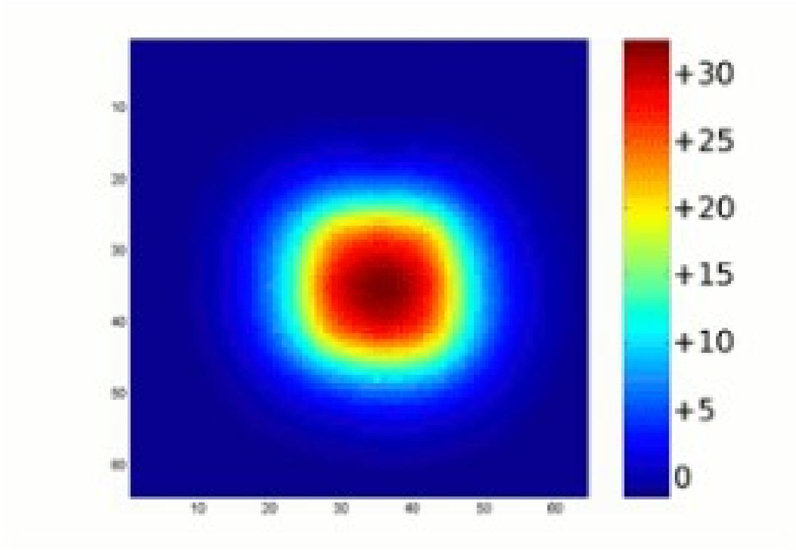


Thermal IR instruments need low thermal background
-> fewer warm optics

adaptive secondary mirror (MMT, LBT, Magellan)

Magnetic force

Small magnetic DMs
Key advantage is large stroke

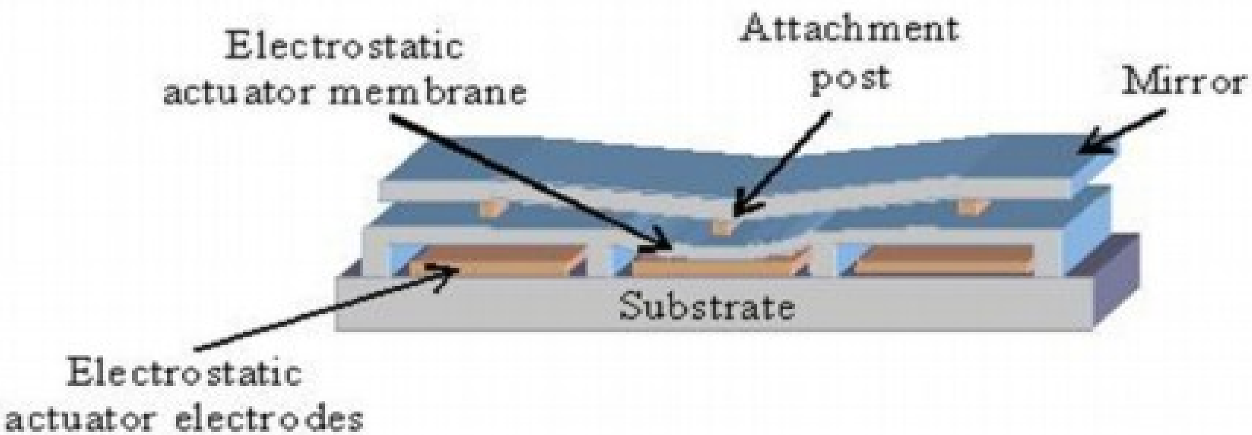


Typical stroke obtained while applying currents on 3x3 actuators (wavefront value, twice the mirror surface)

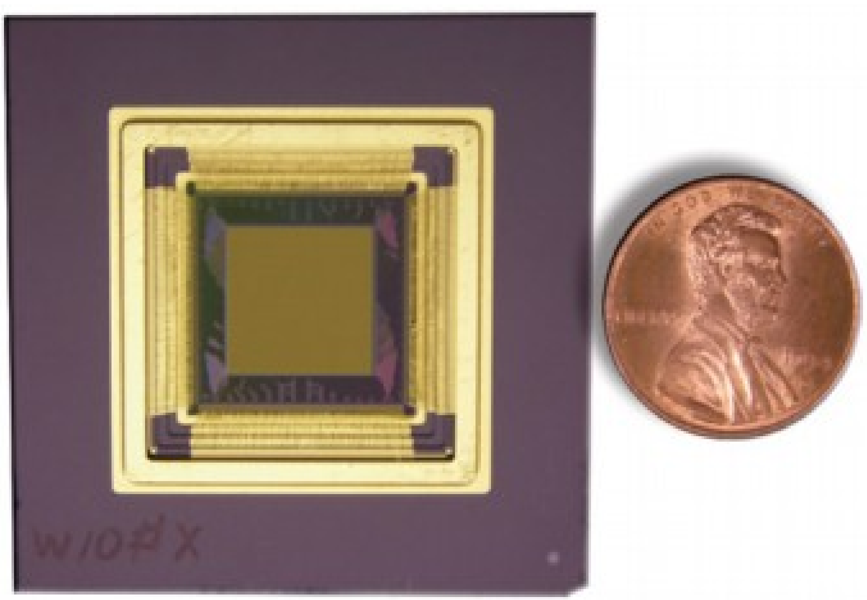
> 20 micron stroke
(high speed DM97, Alpao)

241 actuators magnetic DM
(Alpao)

Electrostatic DMs
large number of actuators in a small space



Small electrostatic MEMS mirror (Boston Micromachines, 1024 act)



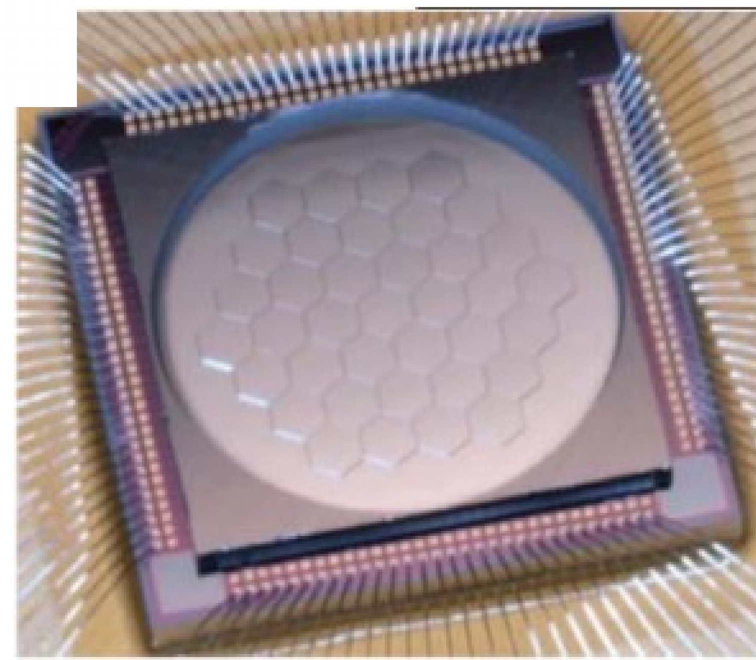


Figure 1. Photograph of an Iris AO PTT111-X deformable mirror.

WFS: Role & Requirements

Problem: Detectors measure light intensity, not phase → an optical trick is required to convert wavefront phase into intensity.

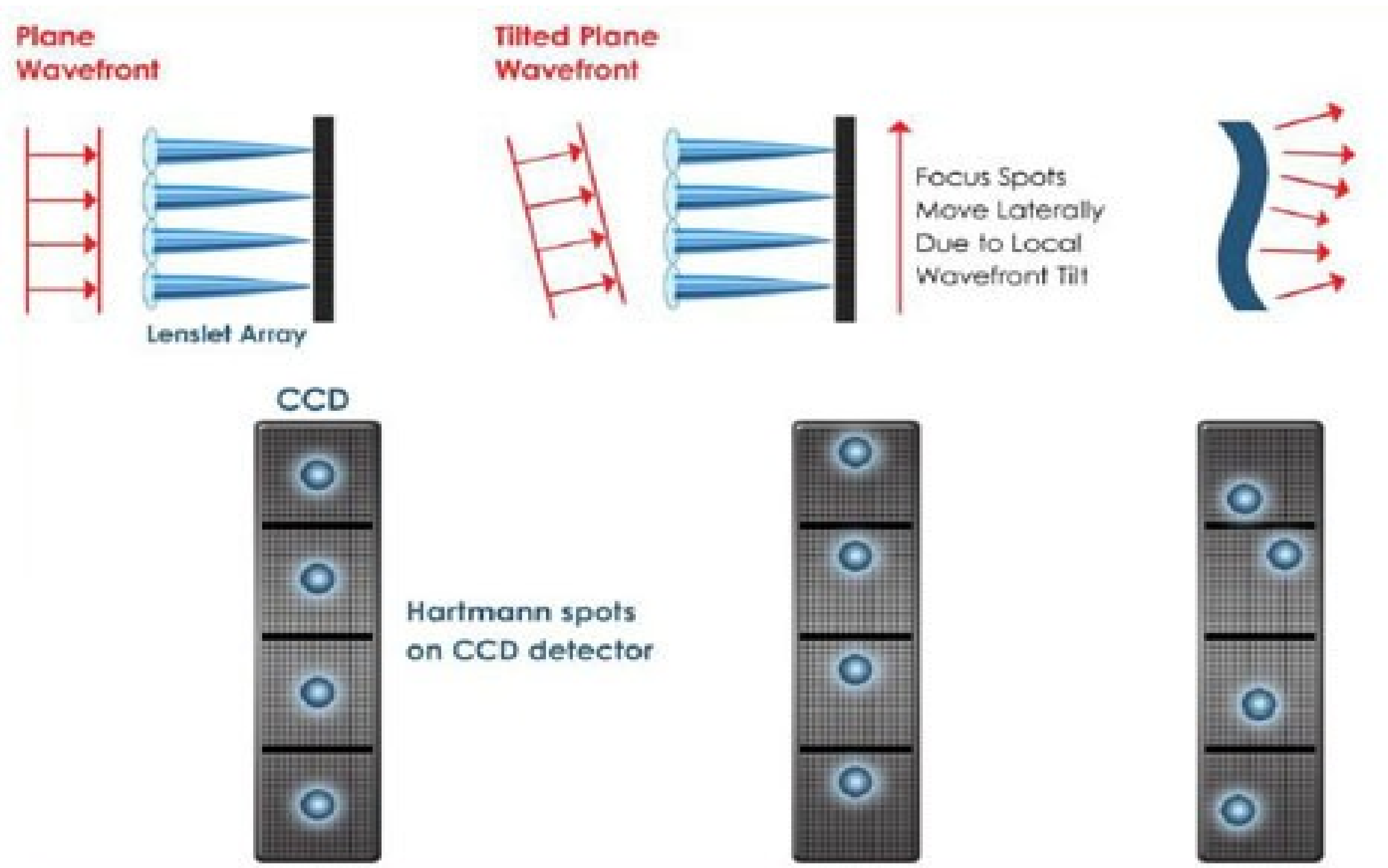
Wavefront sensor must measure wavefront to allow correction with Deformable mirror. Wavefront measurement is done by Wavefront Sensor (hardware) + wavefront reconstructor (Software, translates WFS signal into DM language)

Requirements (need to be balanced in AO system design):

- **Accuracy**
- **Spatial resolution** (number of modes measured – ideally as many as can be corrected by DM)
- **Efficiency** (good use of photons)
- **Speed** (coupled with accuracy and efficiency)
- ***Linearity*** (faster reconstruction → helps with speed)
- **Range** (ability to measure large wavefront errors)
- **Robustness** (chromaticity, ability to work on extended sources, etc …)
- **Match with DM** (WFS must see what DM can correct)

Shack-Hartmann WFS

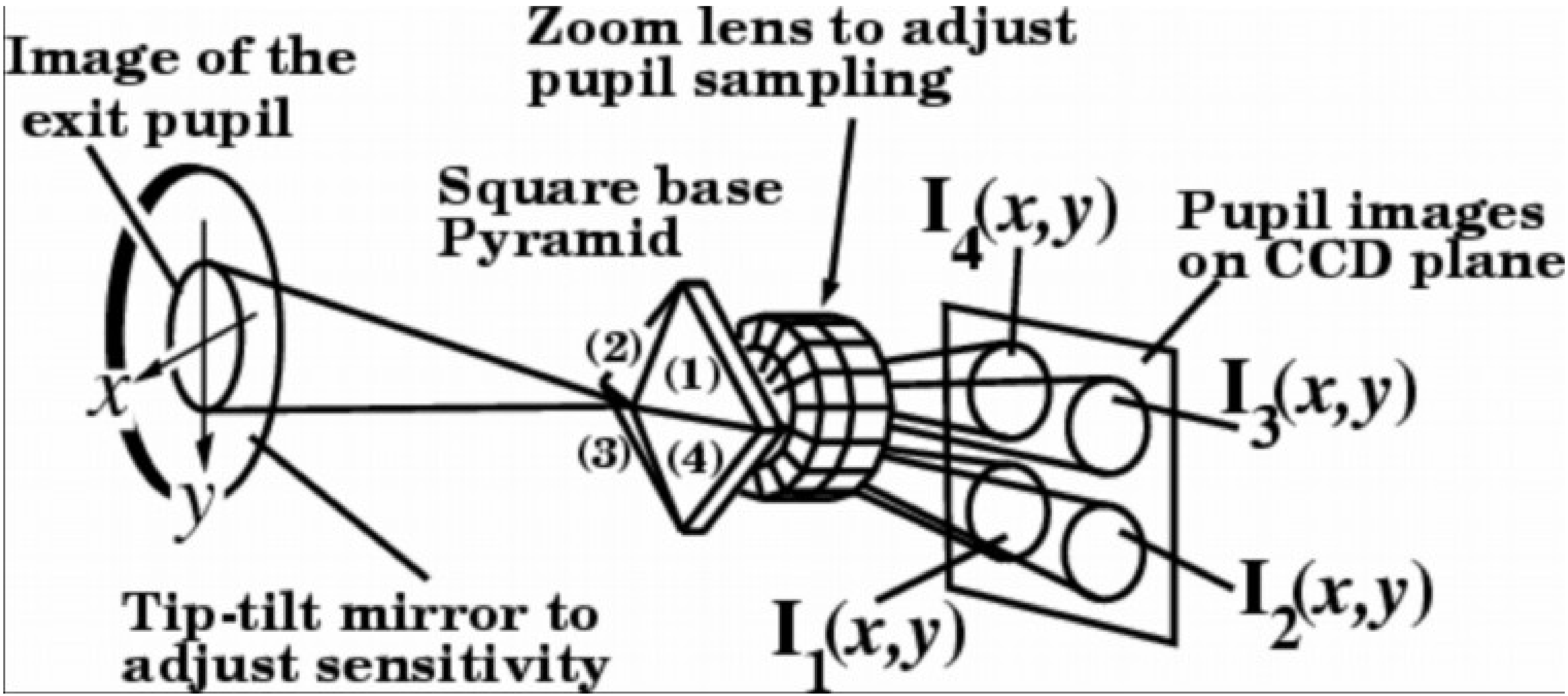
Measures wavefront slope in front of each subaperture



courtesy: Boston Micromachines

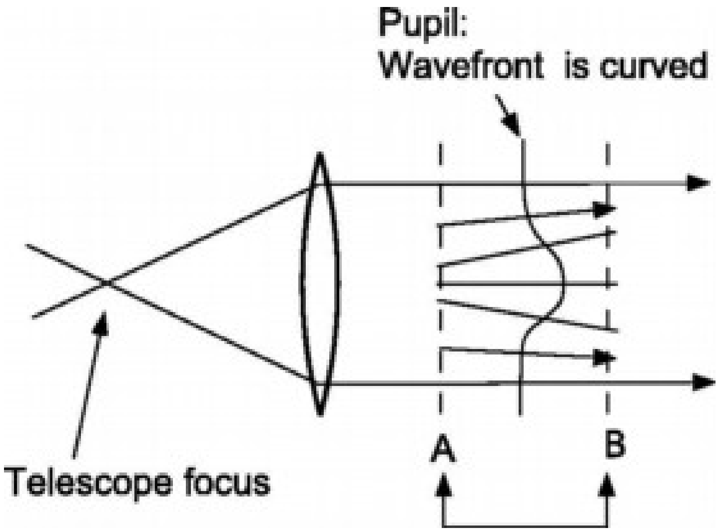
Pyramid WFS

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

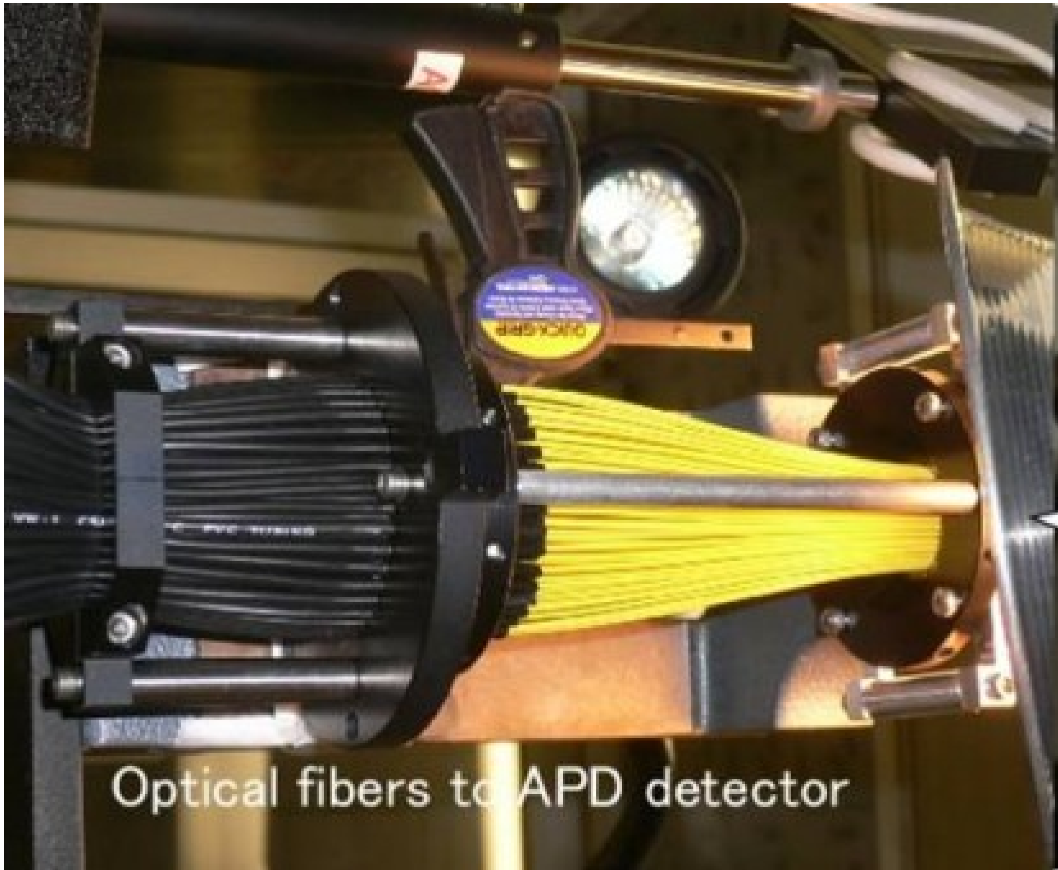


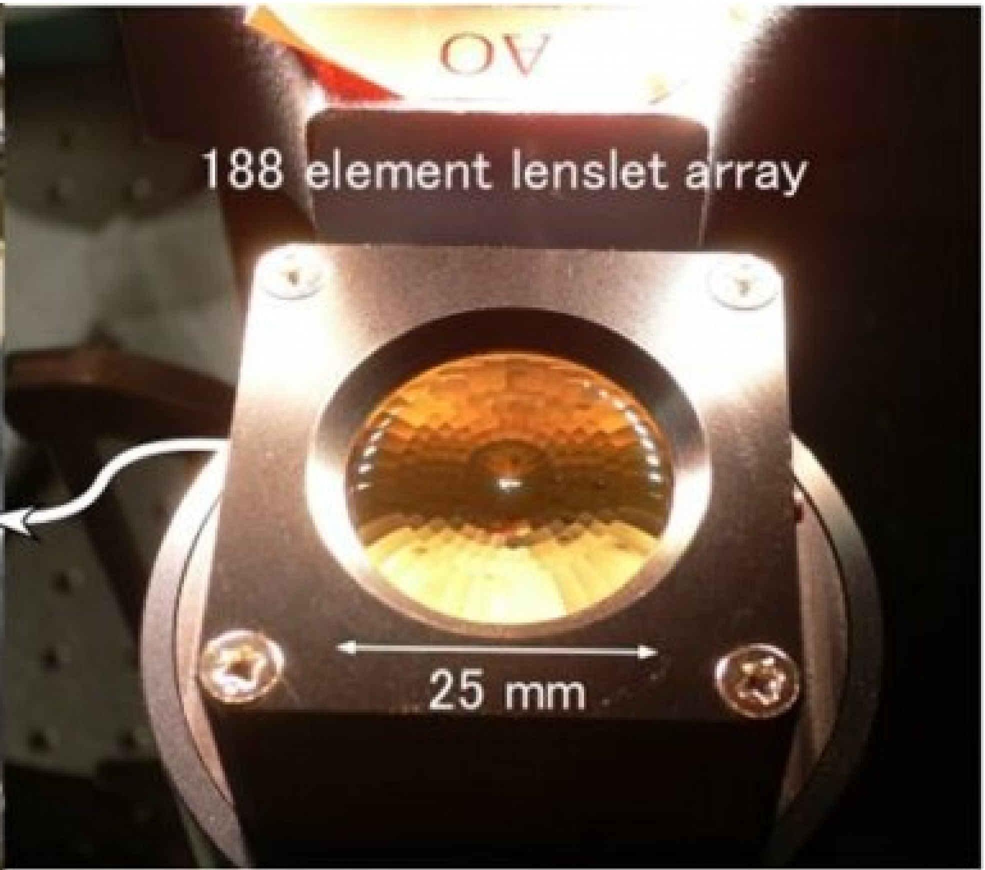
Curvature WFS

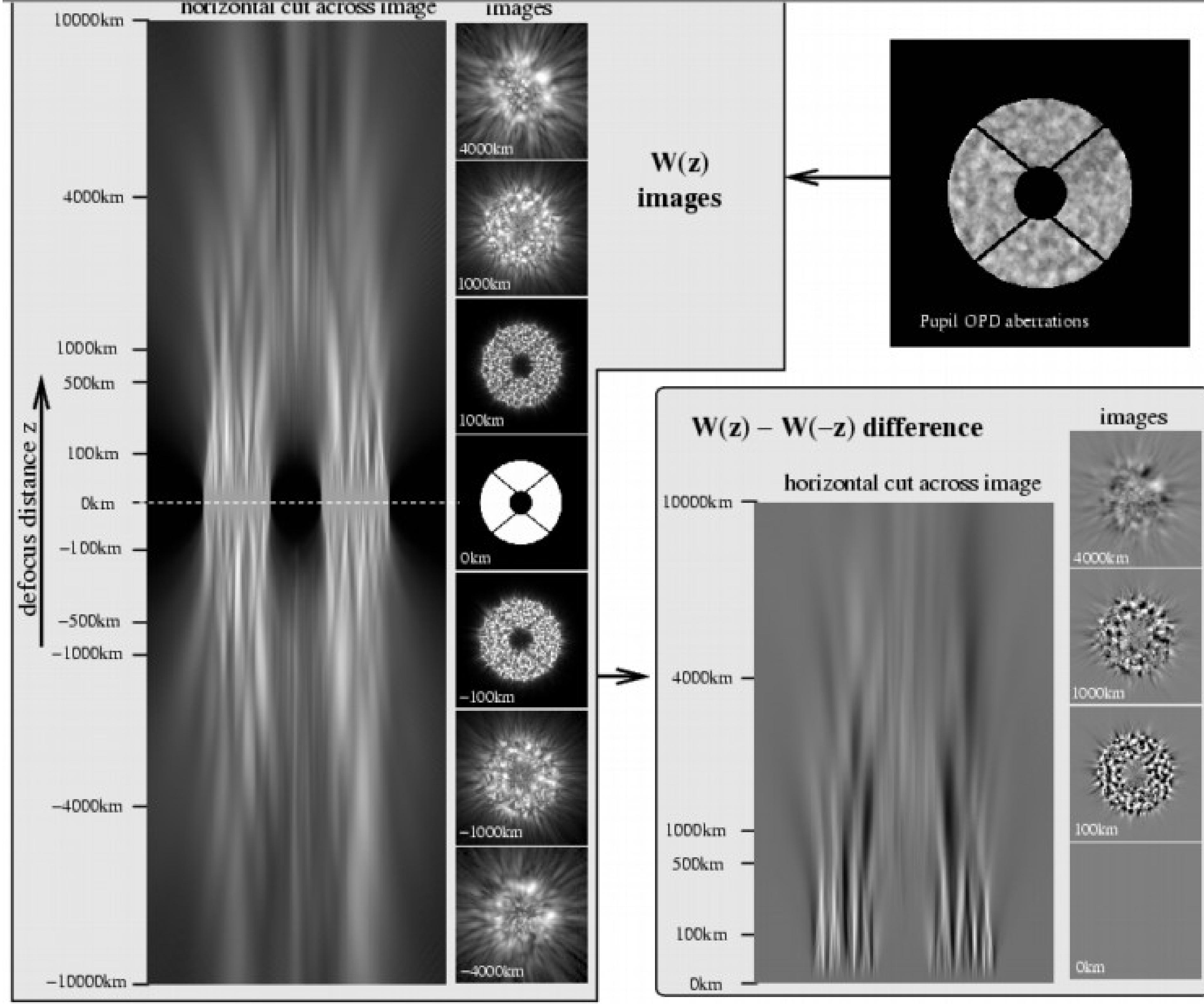
Light propagation turns phase into amplitude (similar to scintillation)



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







horizontal cut across image
images
10000km
4000km
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-500km
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-100km
-1000km
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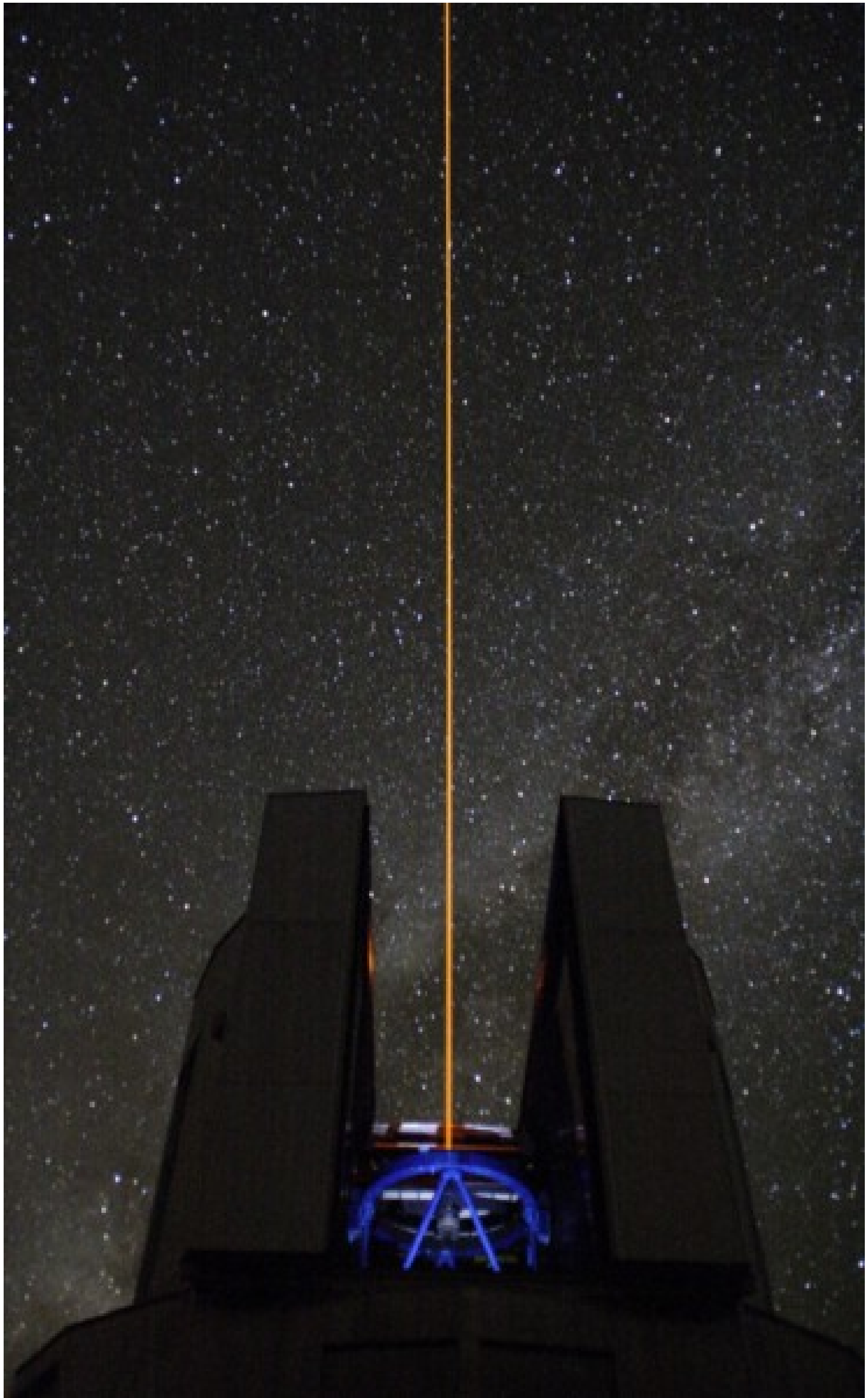
Pupil OPD aberrations
W(z) – W(–z) difference
images
horizontal cut across image
10000km
4000km
1000km
500km
100km
0km
4000km
1000km
100km
0km

Laser Guide stars can create a spot in the atmosphere for the WFS to measure the WF

Allows quasi-complete sky coverage

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**



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

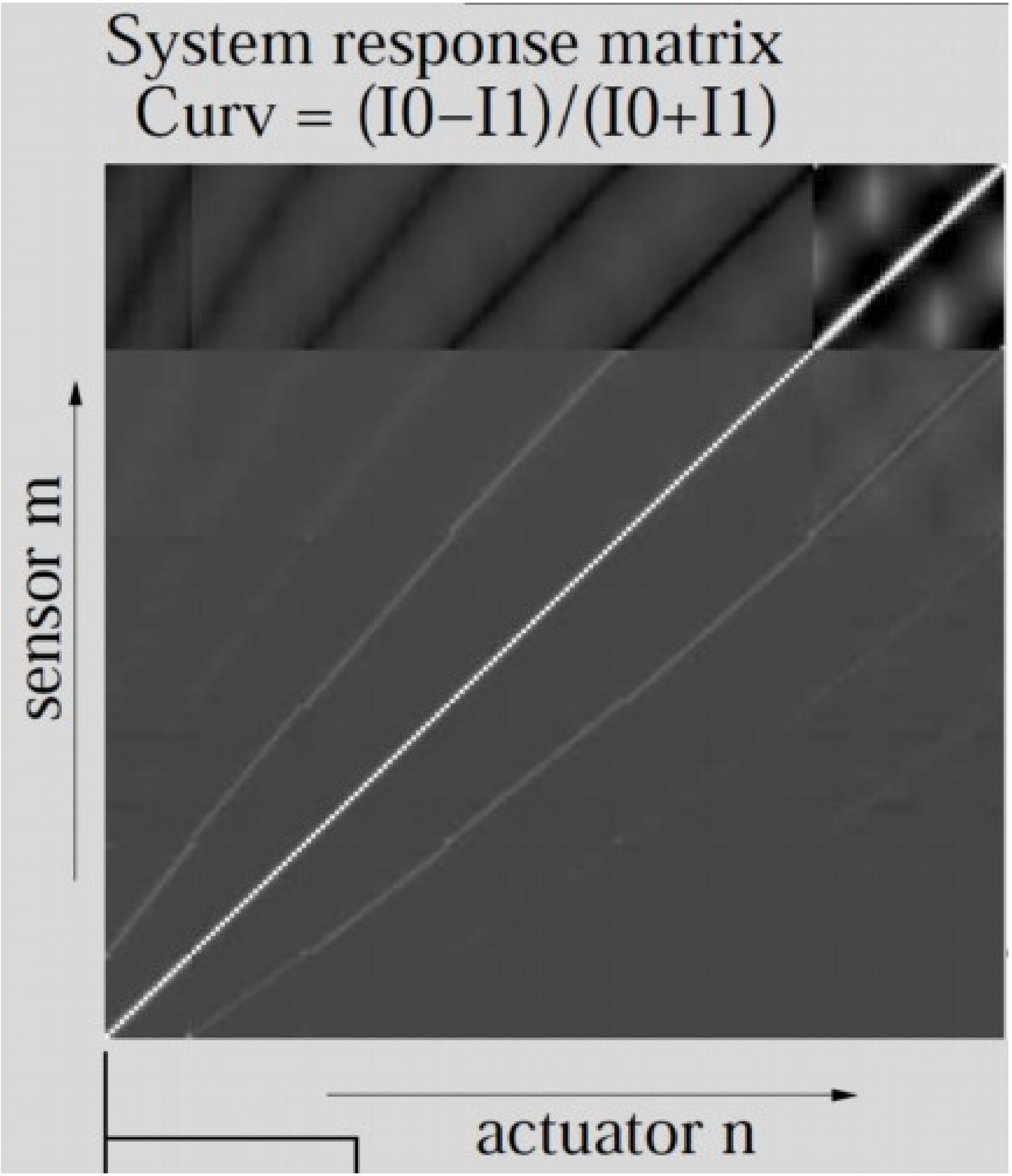
In practice:

- 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

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:

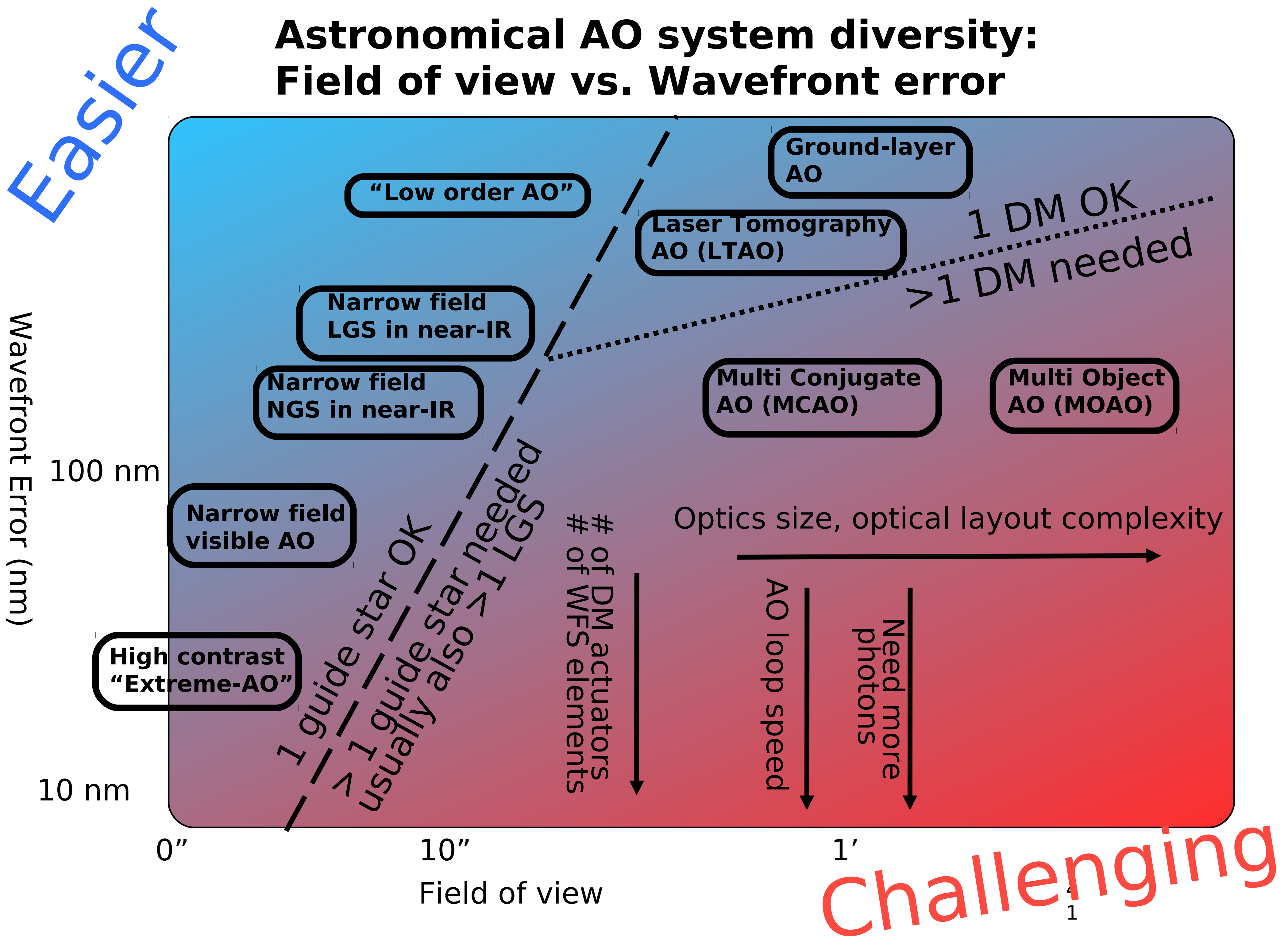
$DM_k = DM_{k-1} + g\, dDM$
With $0<g<1$
Noisy WFS measurement (faint guide star) → small g
High quality WFS measurement (bright guide star) → large g

Loop gain can be different for different modes (Modal control)
Predictive control can improve AO system performance

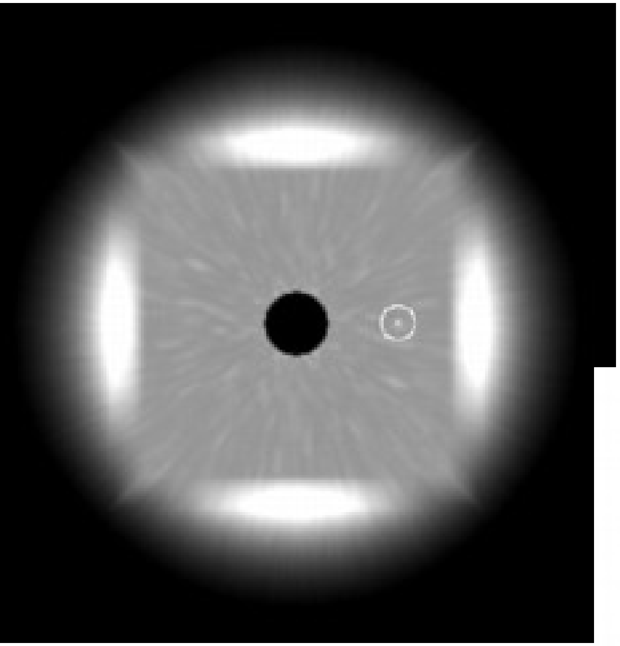
Types of AO systems

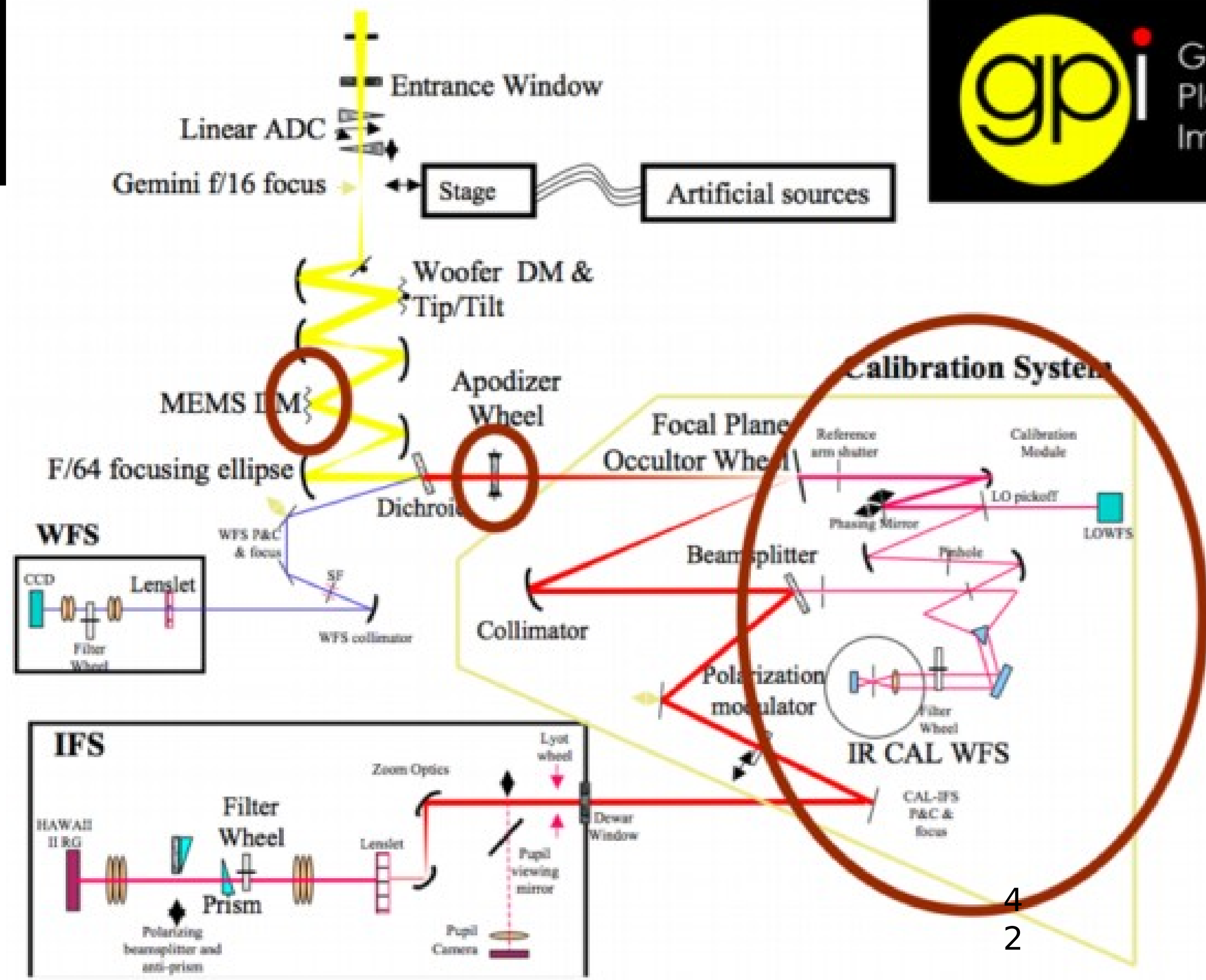
	Field of view	# of DMs	# of guide stars	Notes
Single conjugate AO (**SCAO**)	~ 30 arcsecond	1 DM, usually conjugated to ground	1 (LGS or NGS)	Easiest, traditional AO architecture
Extreme AO (**ExAO**)	~1 arcsecond	1 DM, or 2 DMs in woofer/tweeter	1 (on-axis NGS)	Extremely high precision AO to image exoplanets
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 MMT (U of Arizona). Larger systems under active development
Multi Conjugate AO (**MCAO**)	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 (**MOAO**)	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)

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



ExAO example: The Gemini Planet Imager Extreme-AO system

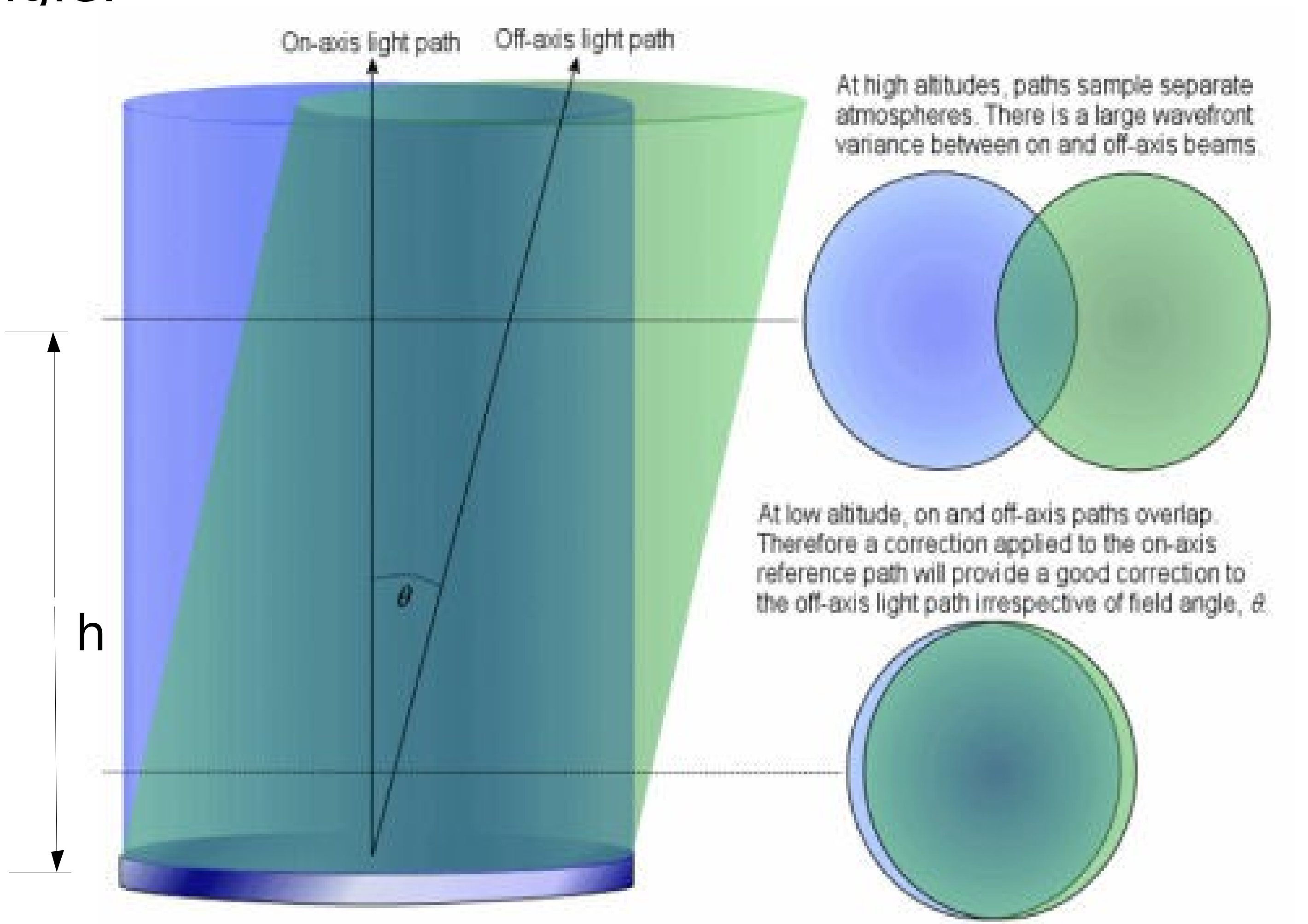




Fundamental problem to solve: Isoplanatic Angle

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 $\rightarrow \theta_0 = 10''$



Solution:

Wavefront mesurement: Several guide stars needed

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

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.

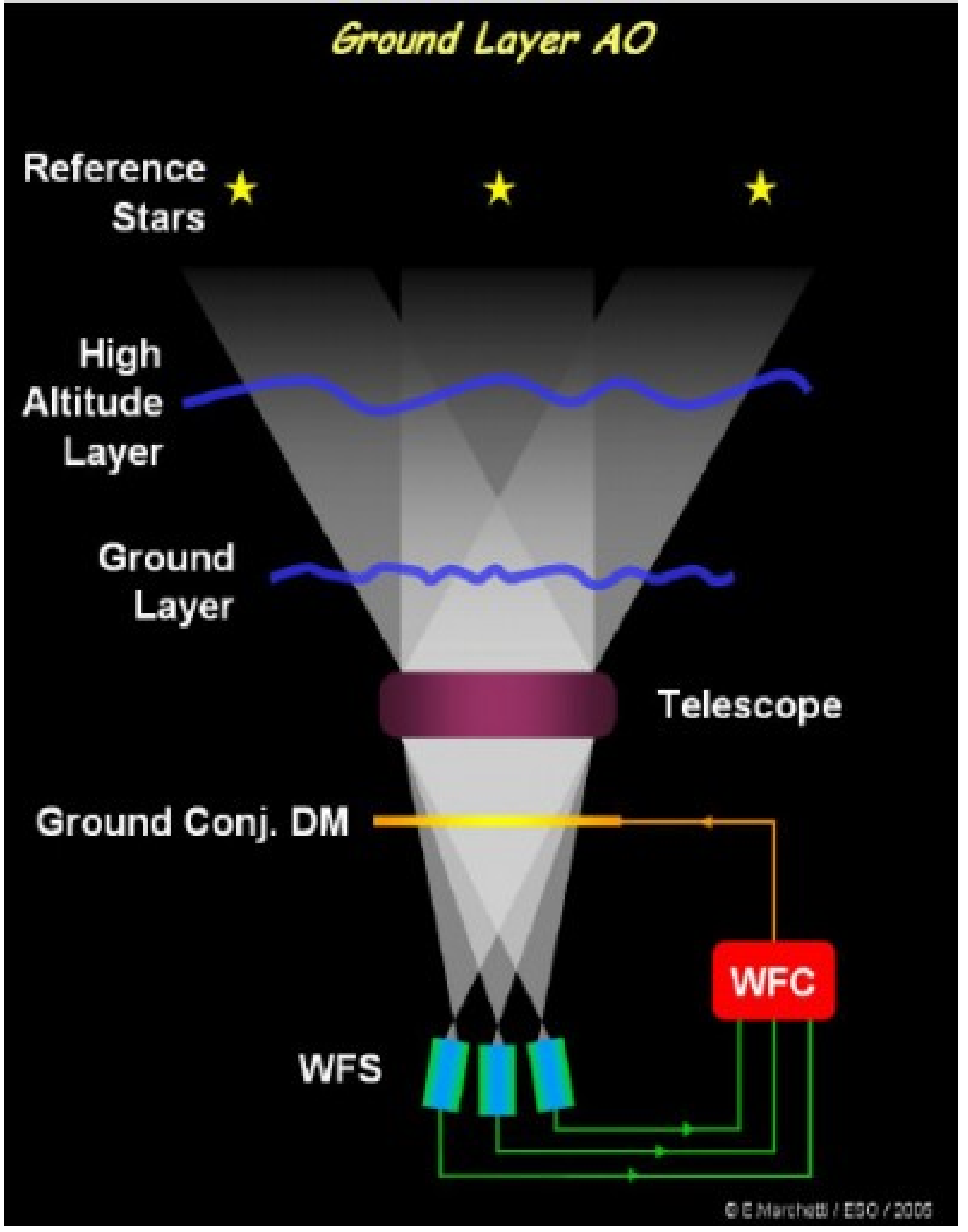
Ground Layer Adaptive Optics (GLAO)

•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



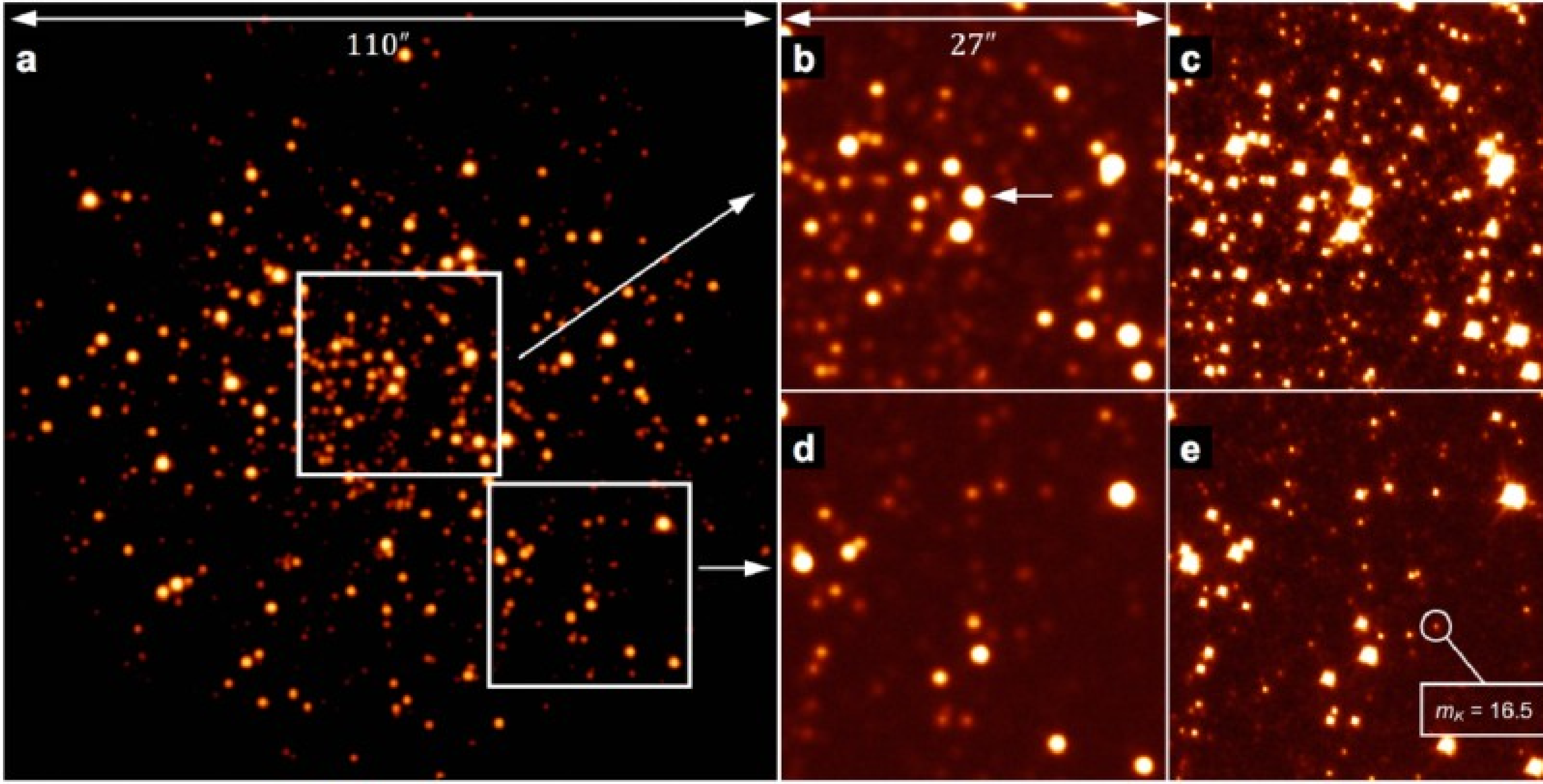
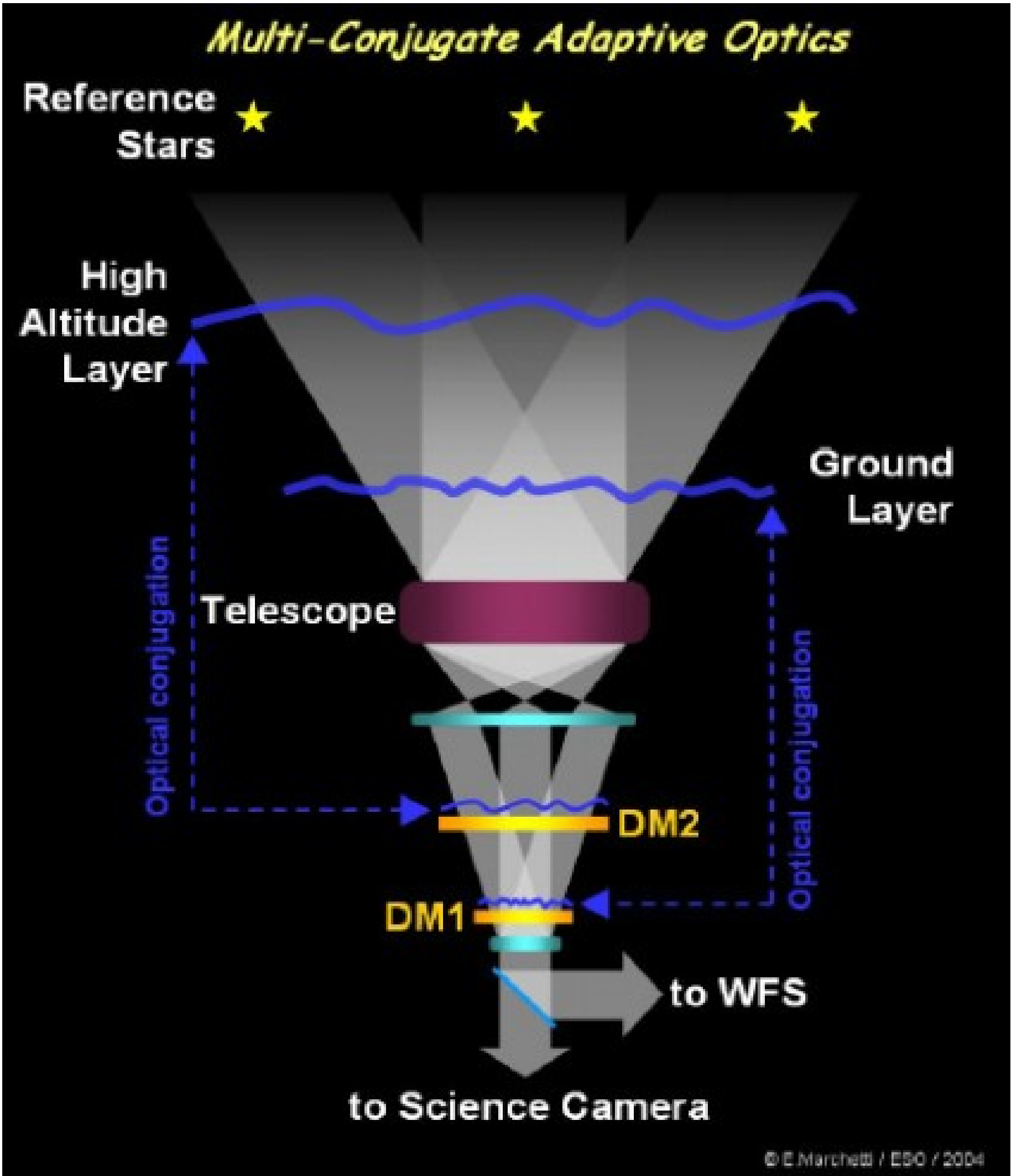


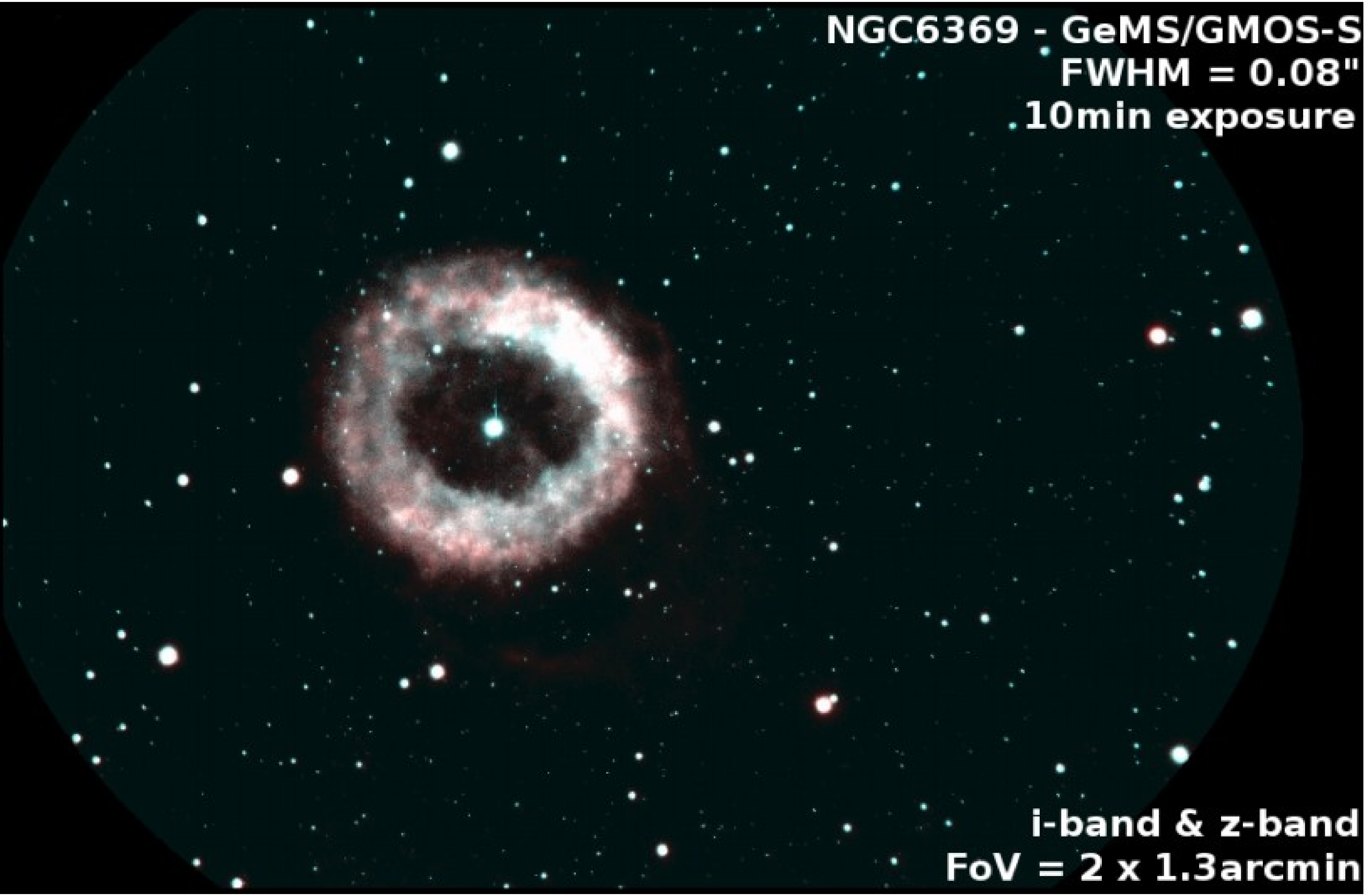
Fig. 8. The core of M3 imaged at 2.2 μm in two 60 s exposures. a) The full 110 arc sec field of the IR camera in the native seeing limit of 0.7 arc sec, on a logarithmic intensity scale. b,d) Two smaller 27 arc sec regions of the same image, indicated by the boxes in a) shown on a truncated linear scale 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.

GLAO @ MMT, Hart et al., 2010

Multi-Conjugate Adaptive Optics (MCAO)
Concept: Use several DMs conjugated at different altitudes to perform correction over a wide fielf of view



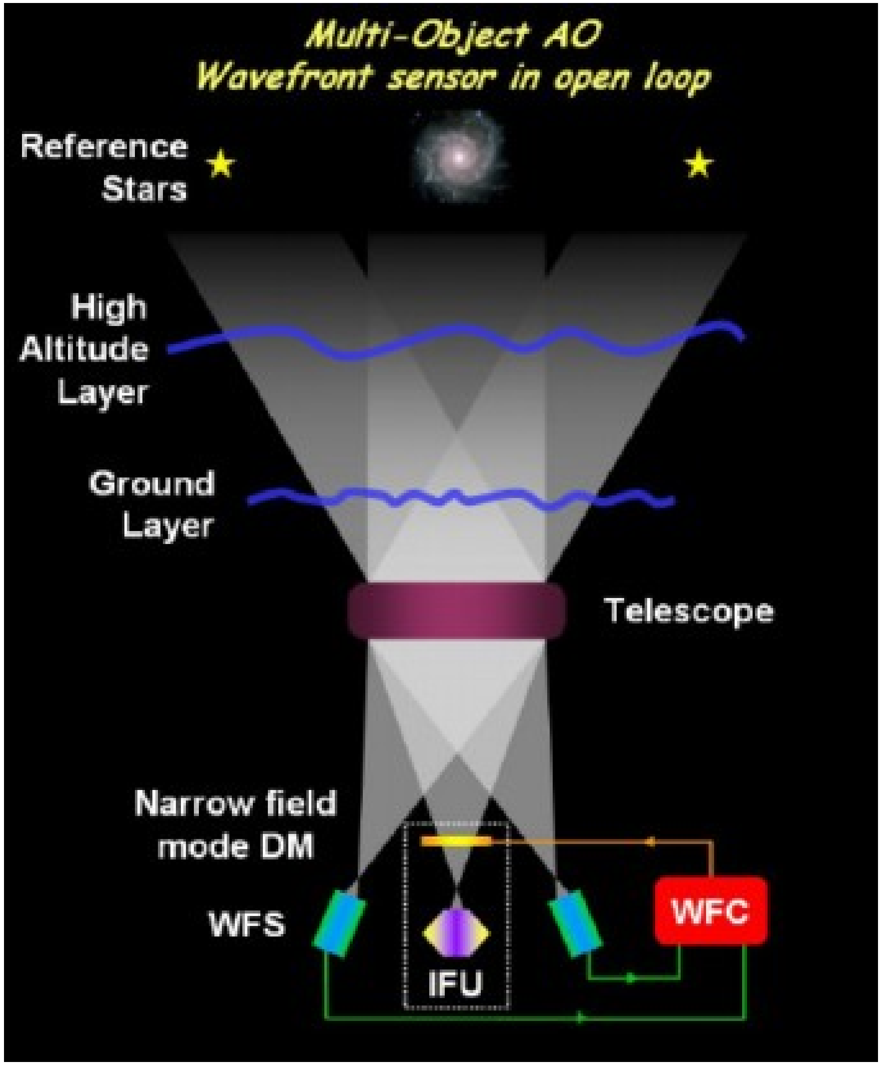
Gemini South MCAO system

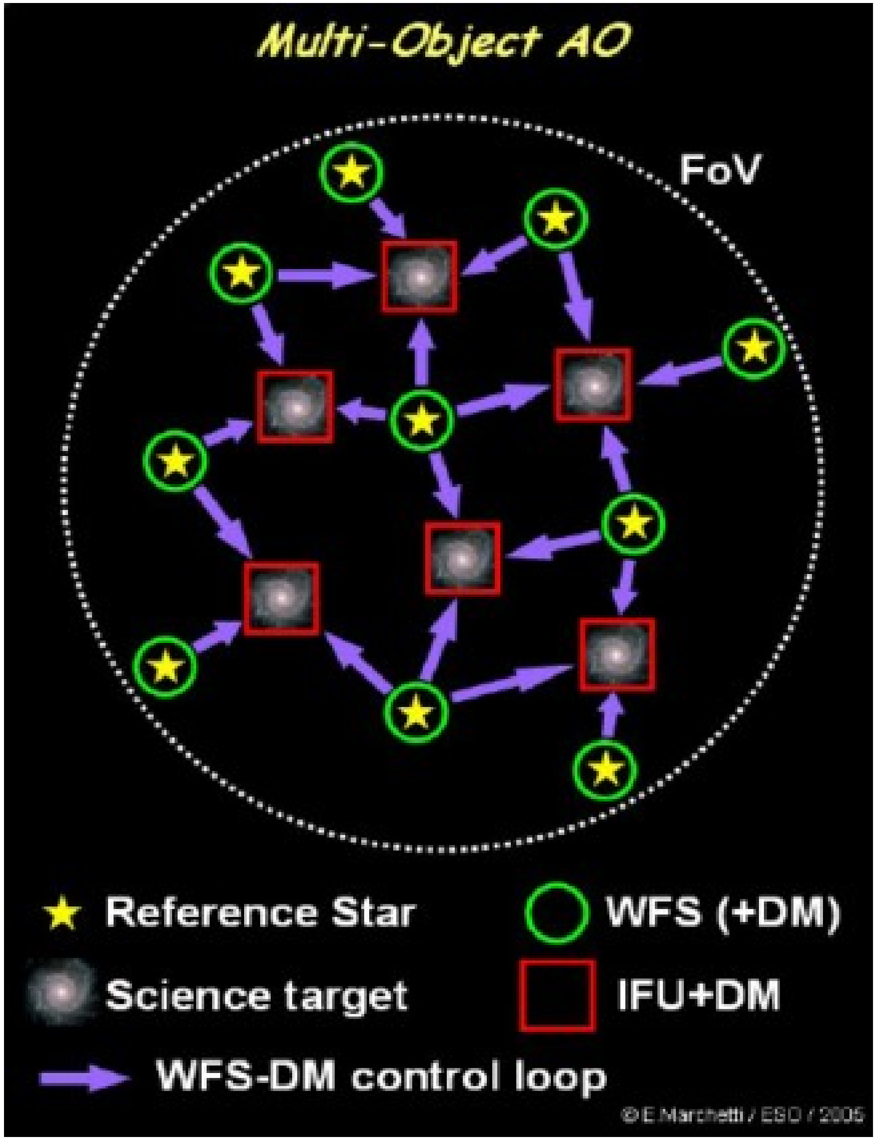

NGC6369 - GeMS/GMOS-S
FWHM = 0.08"
10min exposure
i-band & z-band
FoV = 2 x 1.3arcmin

Multi Object Adaptive Optics (MOAO)

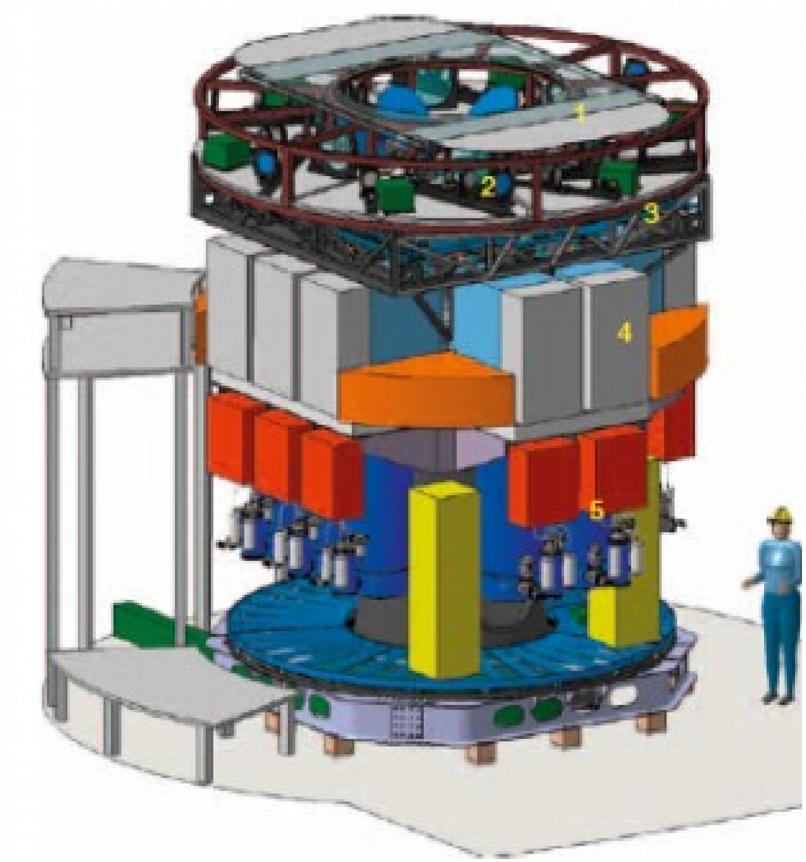
Can be visualized as several tomographic AO systems sharing the same set of wavefront sensors: 1 DM per object of interest

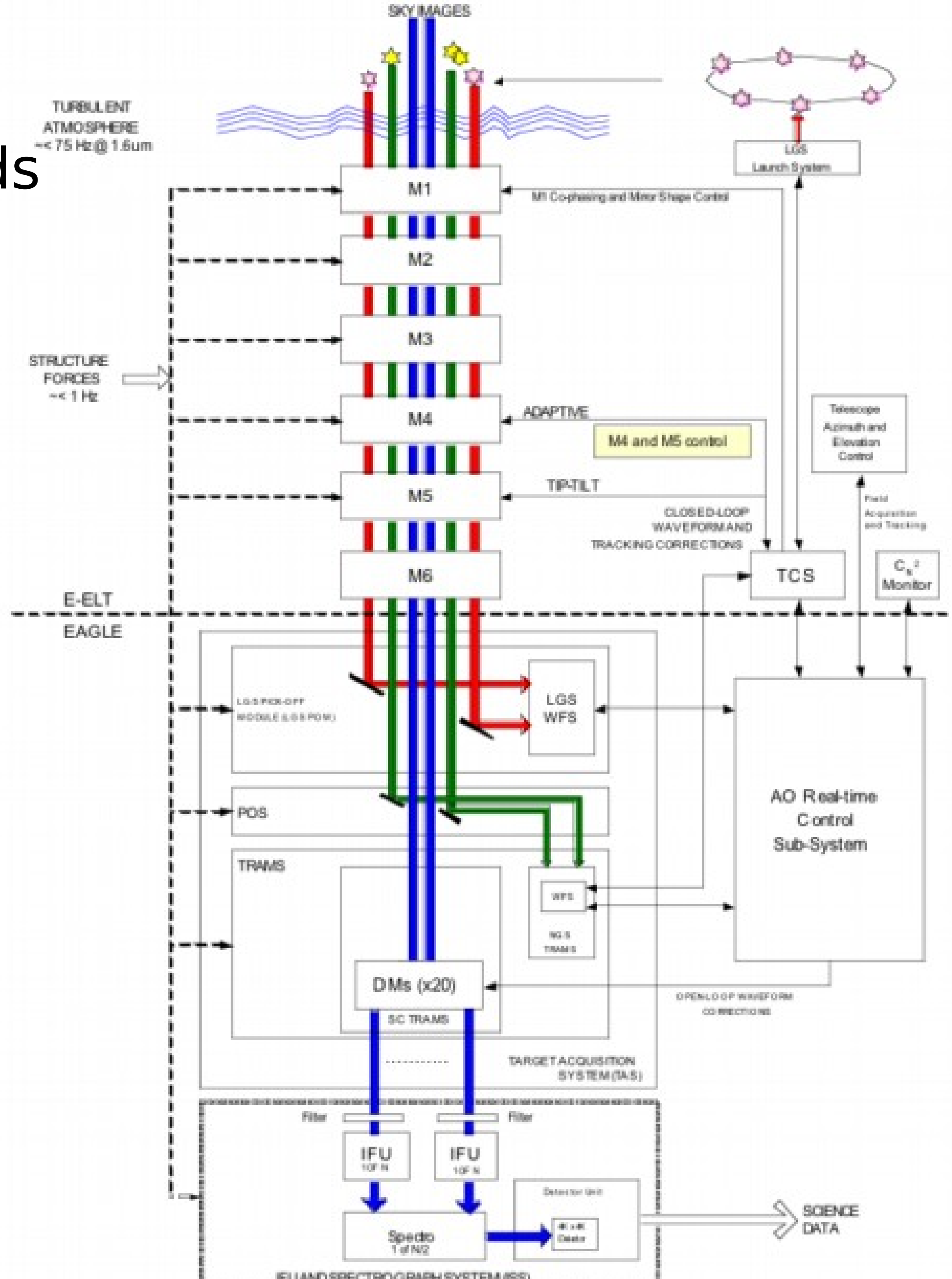
MOAO runs DMs in open loop → need for good DM calibration (WFSs do not see DMs)





EAGLE
(ESO E-ELT project)
MCAO system with 20 fields

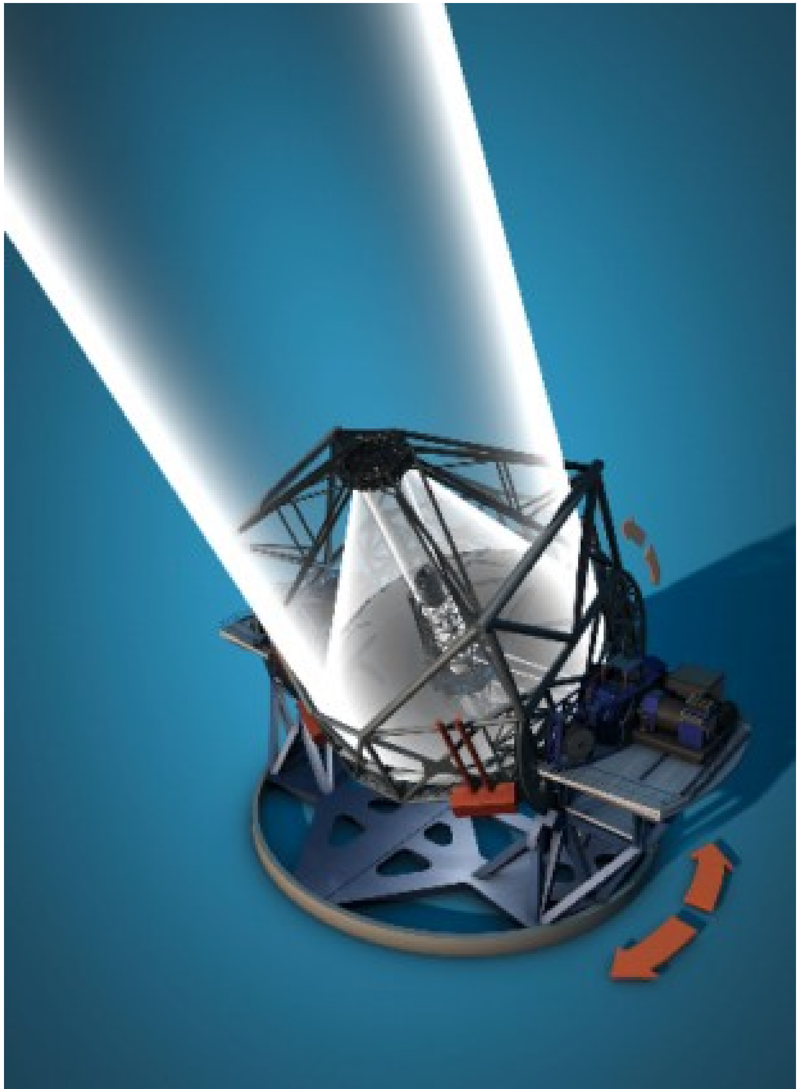


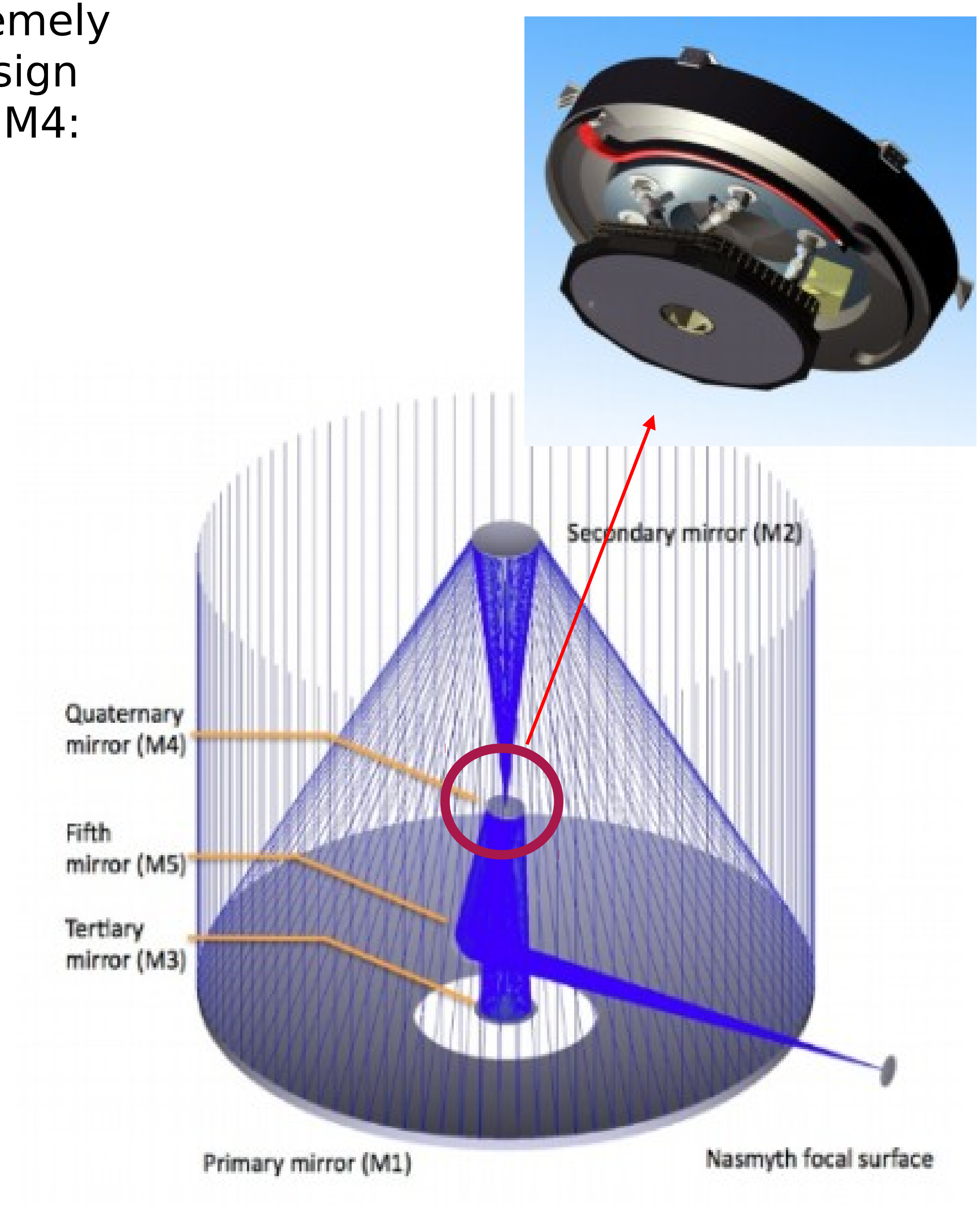


1 Shutter
2 Laser Guide Star Sensing System
3 Pick-off System (Focal Plane)
4 Target Reimaging and Magnification
System (including Deformable Mirror)
5 Integral Field Unit and Spectrograph
System

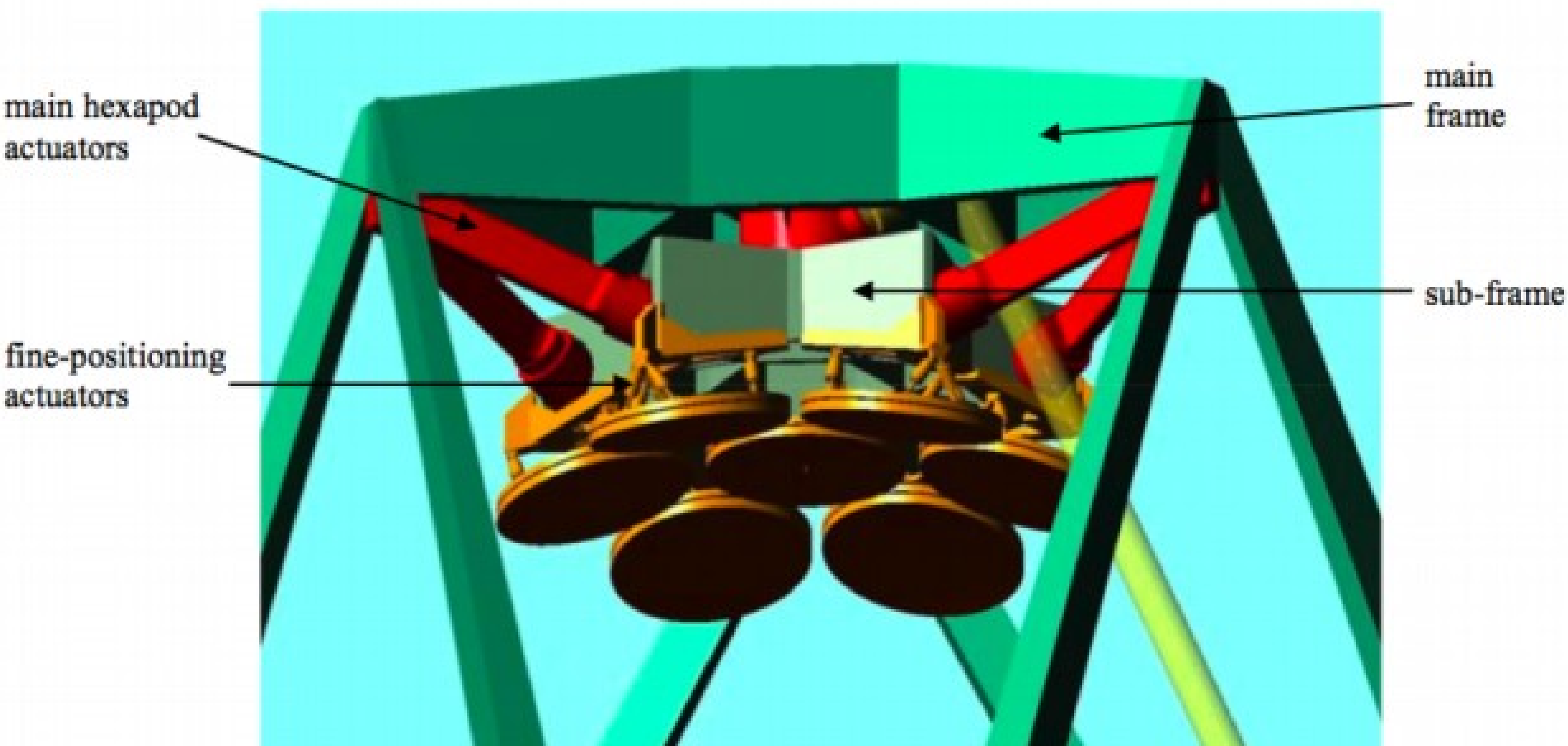
The next generation of large telescopes combine AO with telescope design

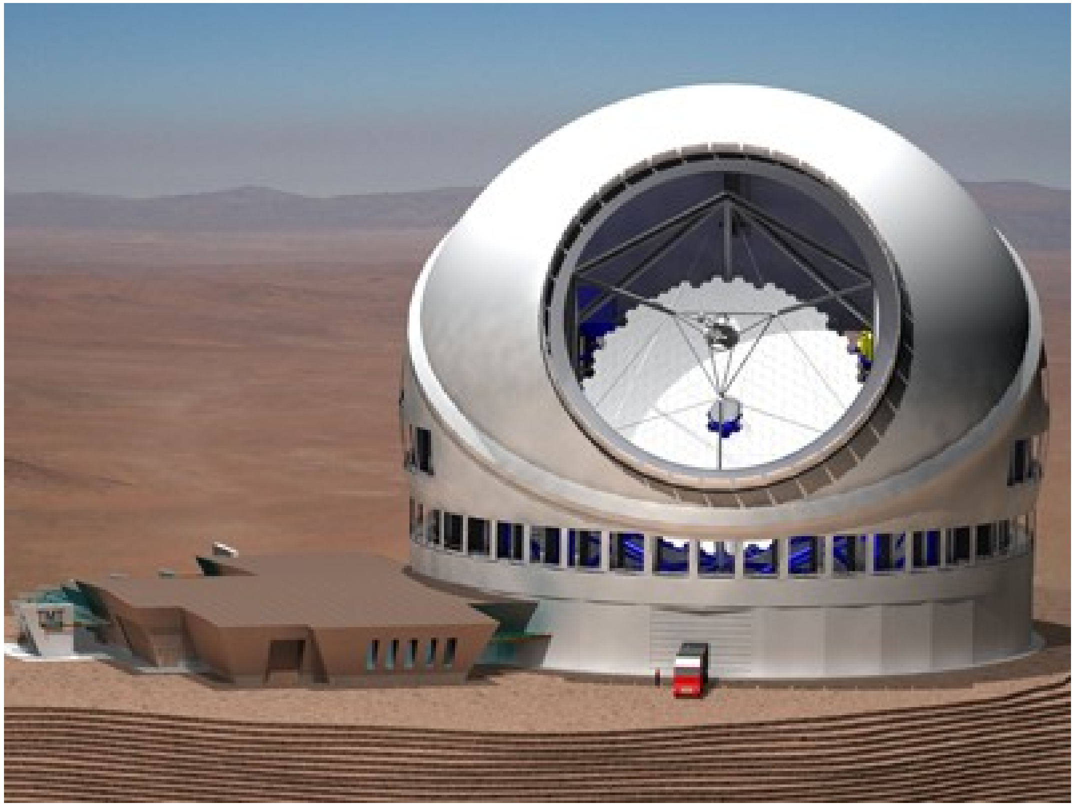
The 39m diameter European Extremely Large Telescope (EELT) optical design includes DM as large fold mirrors (M4: 2.4m diameter, 8000 actuators).





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.