6. Adaptive Optics

Introduction to Adaptive Optics

Brief introduction to adaptive optics: why, how ?

- AO for high contrast imaging
- Components of an AO system
- Types of AO systems

Atmospheric Turbulence

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

Why Adaptive Optics ?

Gains offered by AO :

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

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

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

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

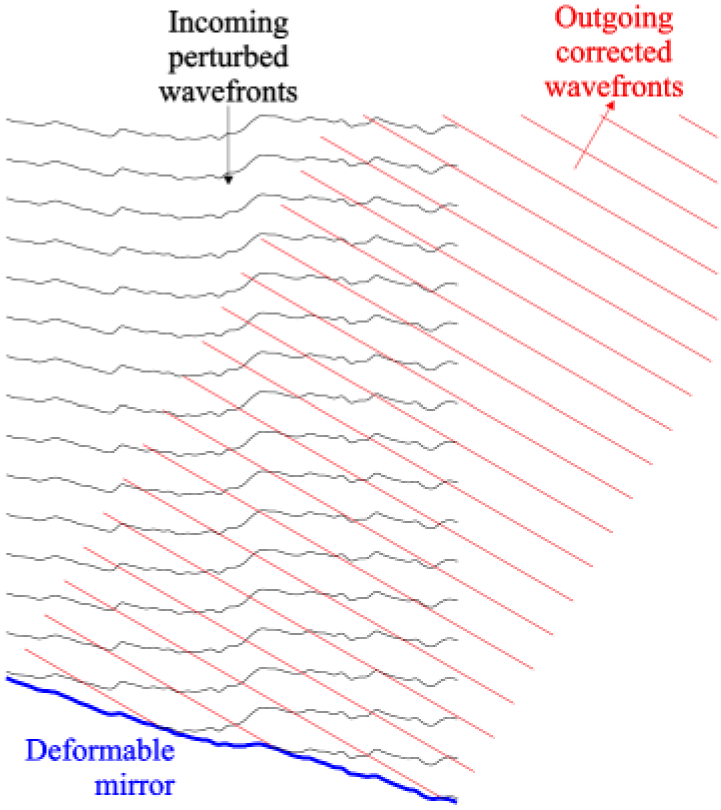
High contrast imaging (Extreme-AO)
Direct imaging of exoplanets and disks

What is Adaptive Optics ?

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

Without AO

With AO



AO uses a deformable mirror to correct atmospheric turbulence

Wavefront control for High contrast imaging

pupil plane complex amplitude

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

Cosine aberration in pupil phase

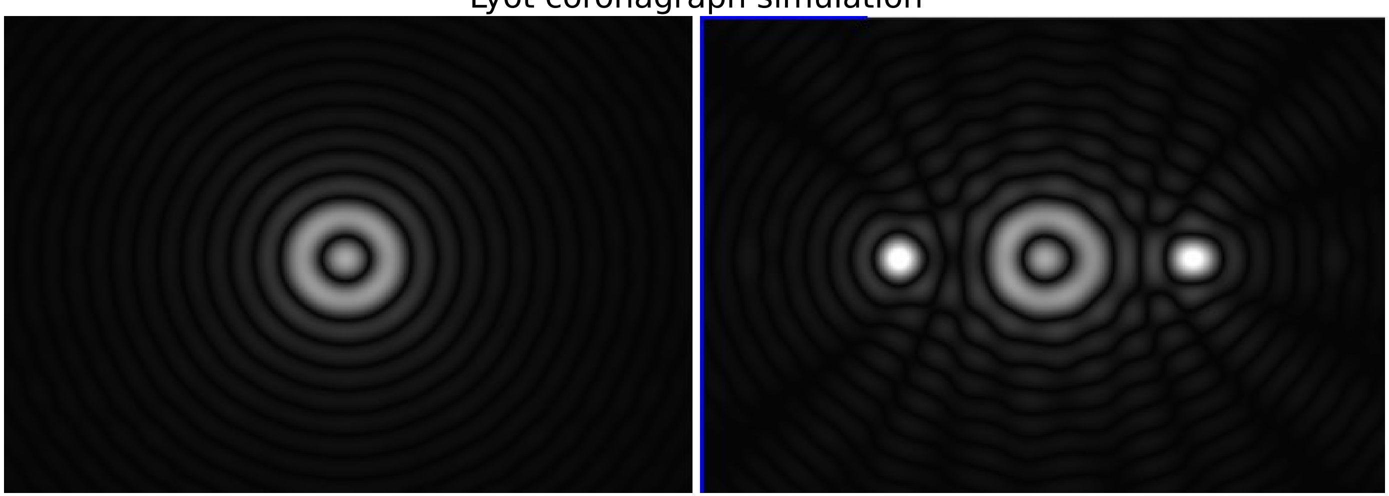
$$\phi(\vec{u}) = \frac{2\pi h}{\lambda} \cos\left(2\pi \vec{f}\vec{u} + \theta\right)$$

… creates 2 speckles

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

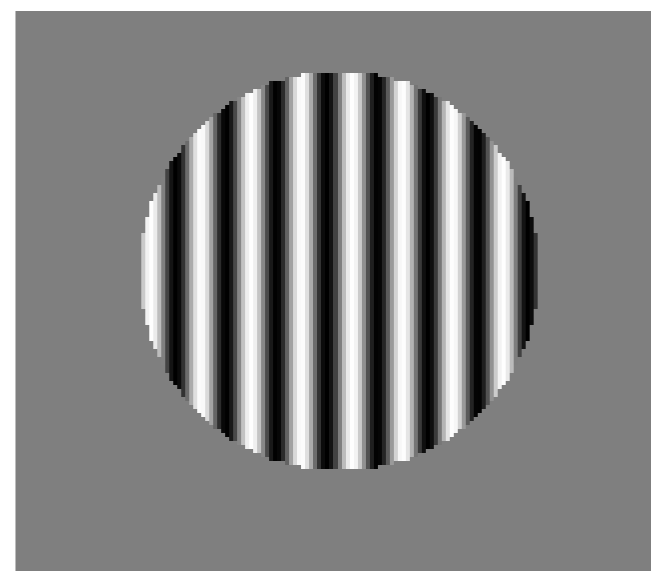
Earth-like planet around Sun-like star is ~1e-10 contrast
In visible light, h=1.6e-12 m (0.0012 nm) = 1e-10 speckle

Lyot coronagraph simulation



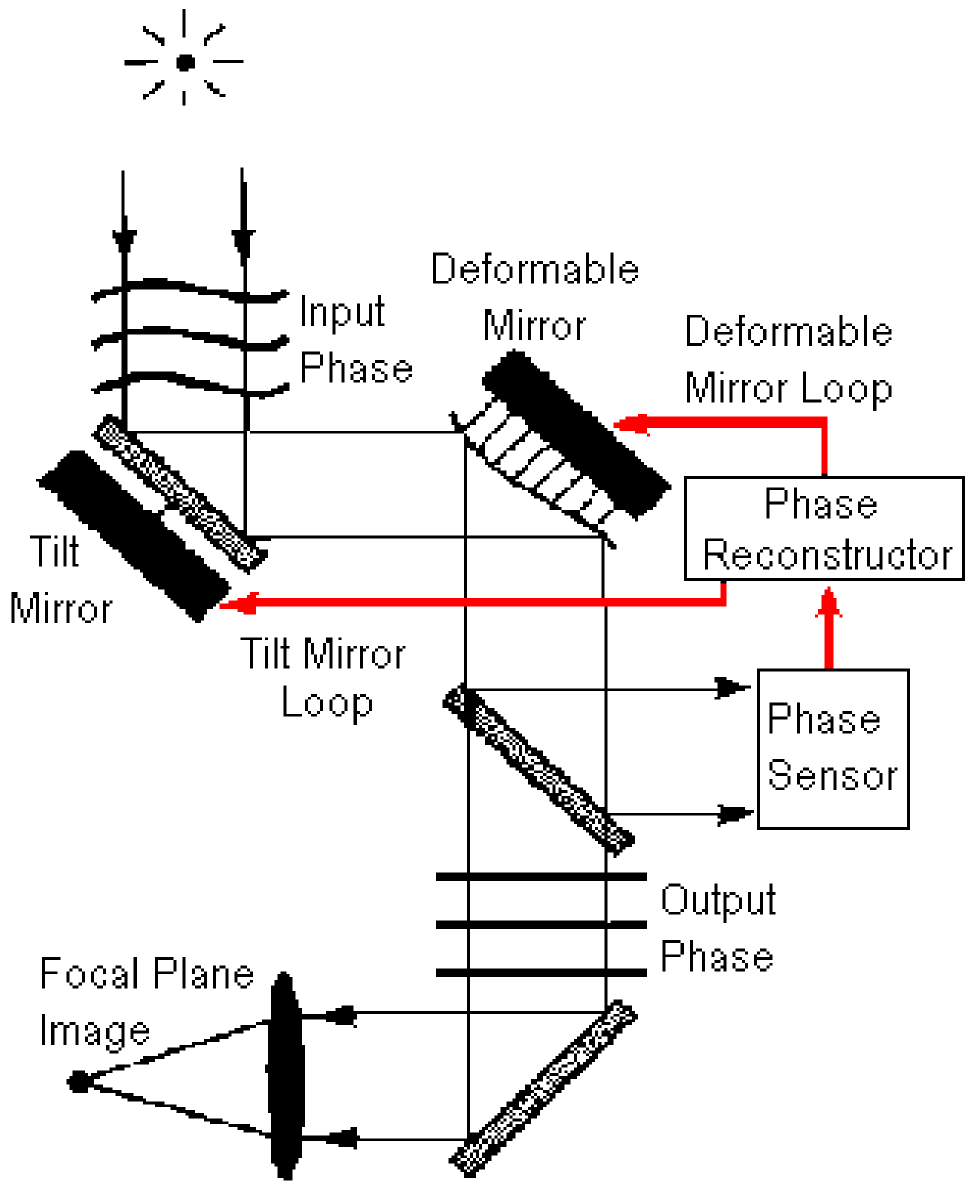
No phase error

pupil sine wave phase error



0.1 rad (1/63 wave) amplitude

What is Adaptive Optics ?



Main components of an AO system:

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

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

Wavefront sensor(s): measures aberrations

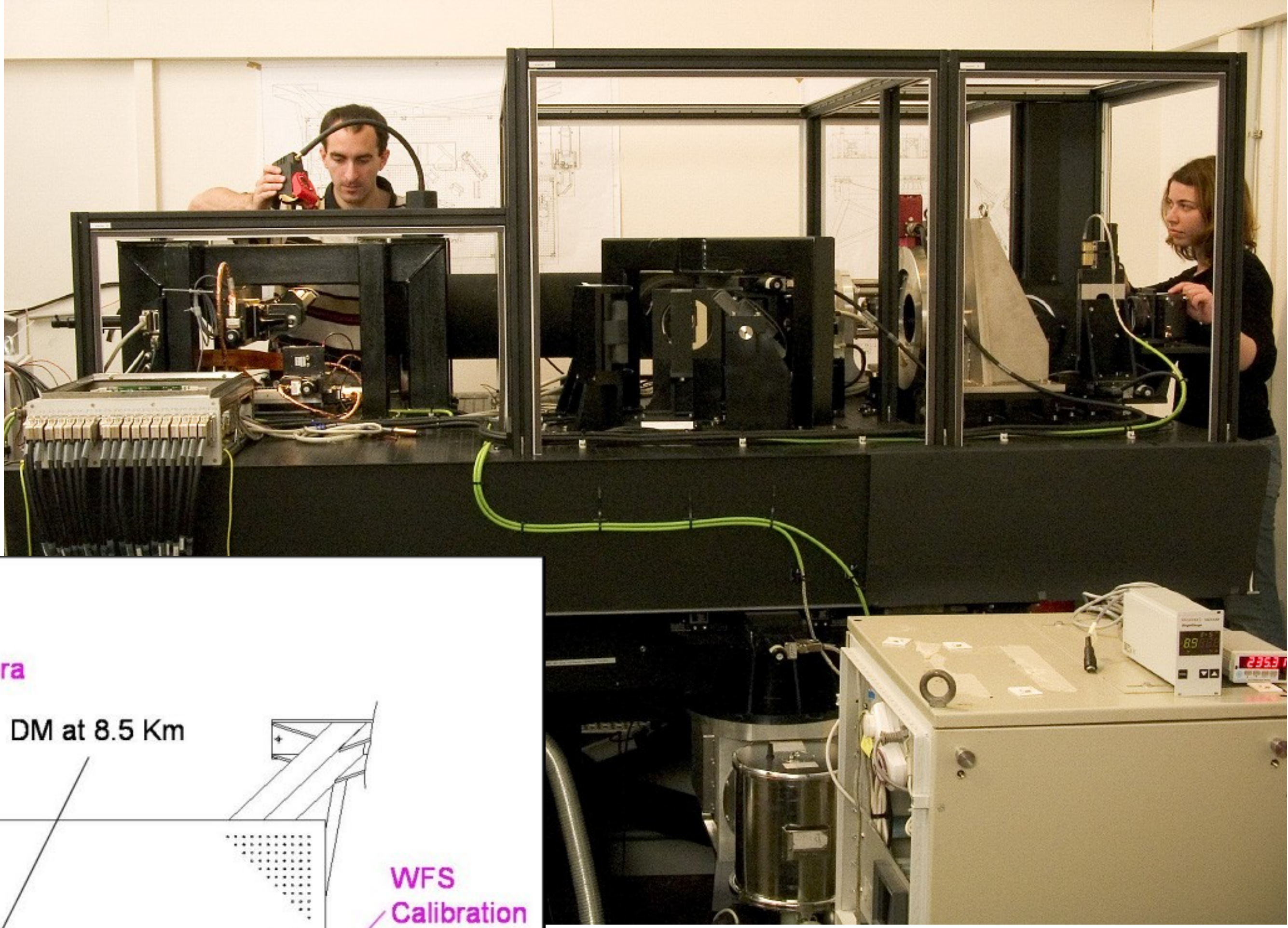
Computer, algorithms: converts wavefront sensor measurements into deformable mirror commands

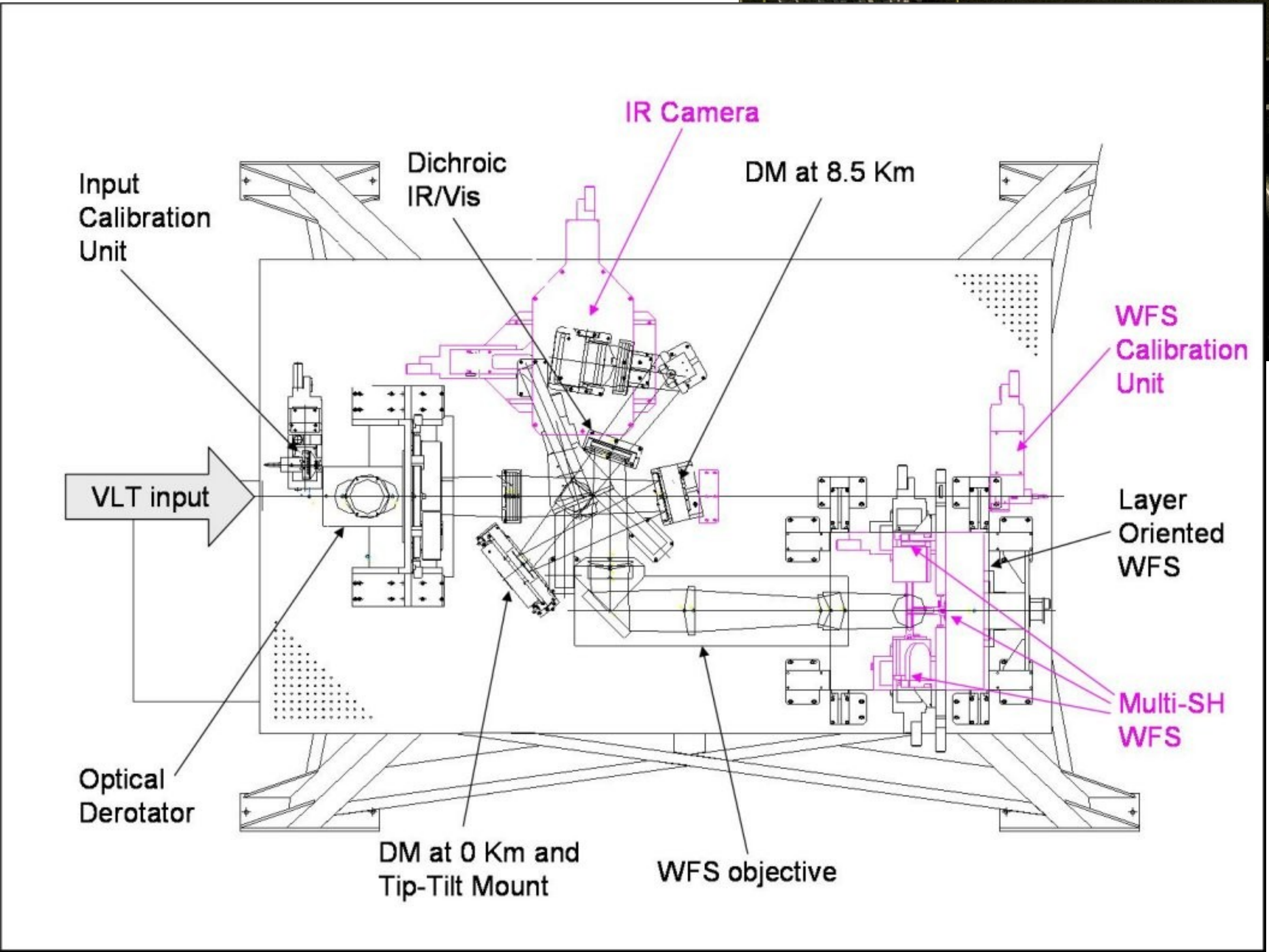
What is Adaptive Optics ?

Altair Optics bench (for Gemini)

What is Adaptive Optics ?

Multi Conjugate AO Demonstrator (MAD, ESO)



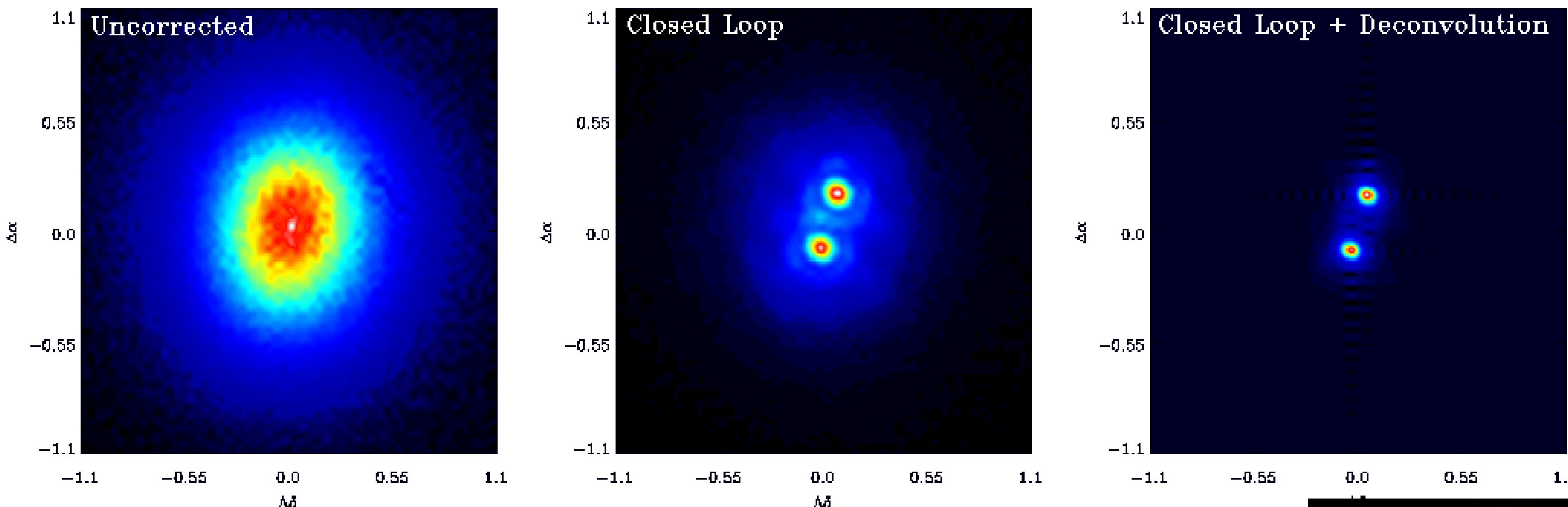


Why Adaptive Optics ?

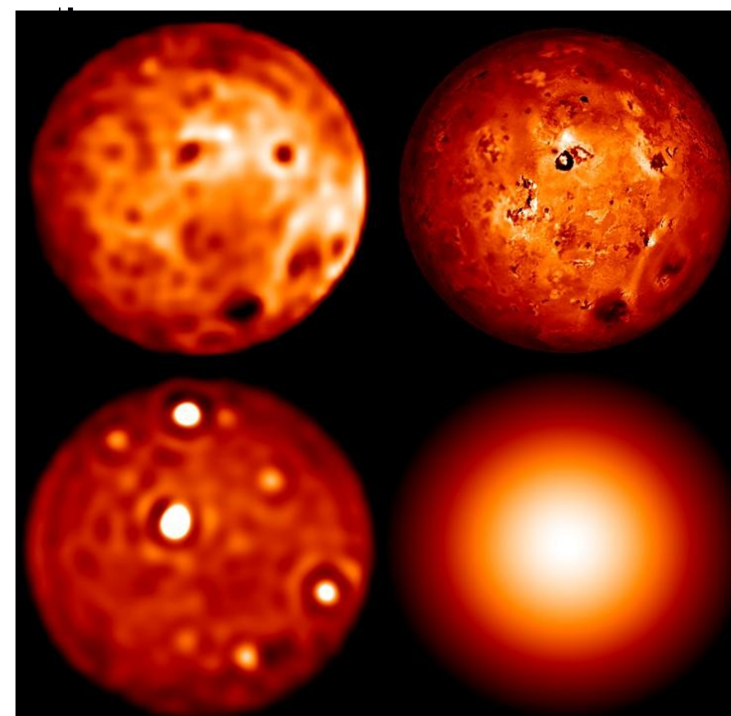
CFHT Adaptive Optics Bonnette & Monica

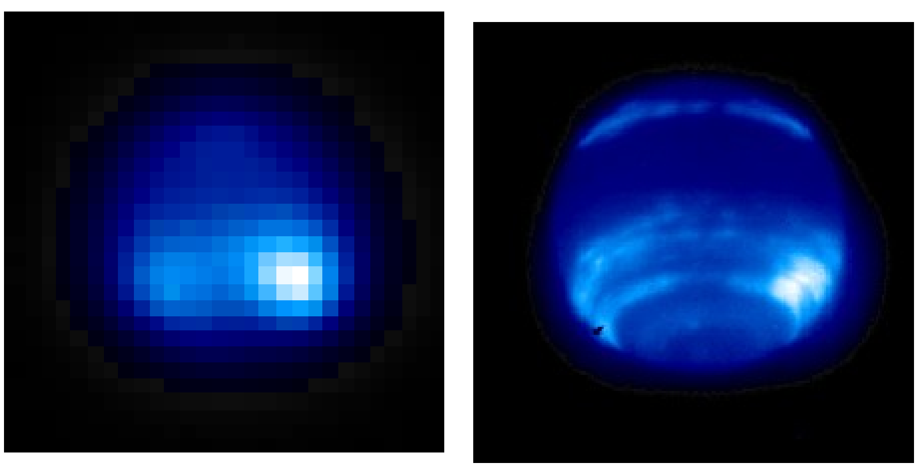
Double star, separation=0.276″ Magnitude=10.7 H band, Integration=40 sec

Seeing=0.7″ @ 0.5mic Strehl Ratio=30% Maximum likelihood



Io (Keck)





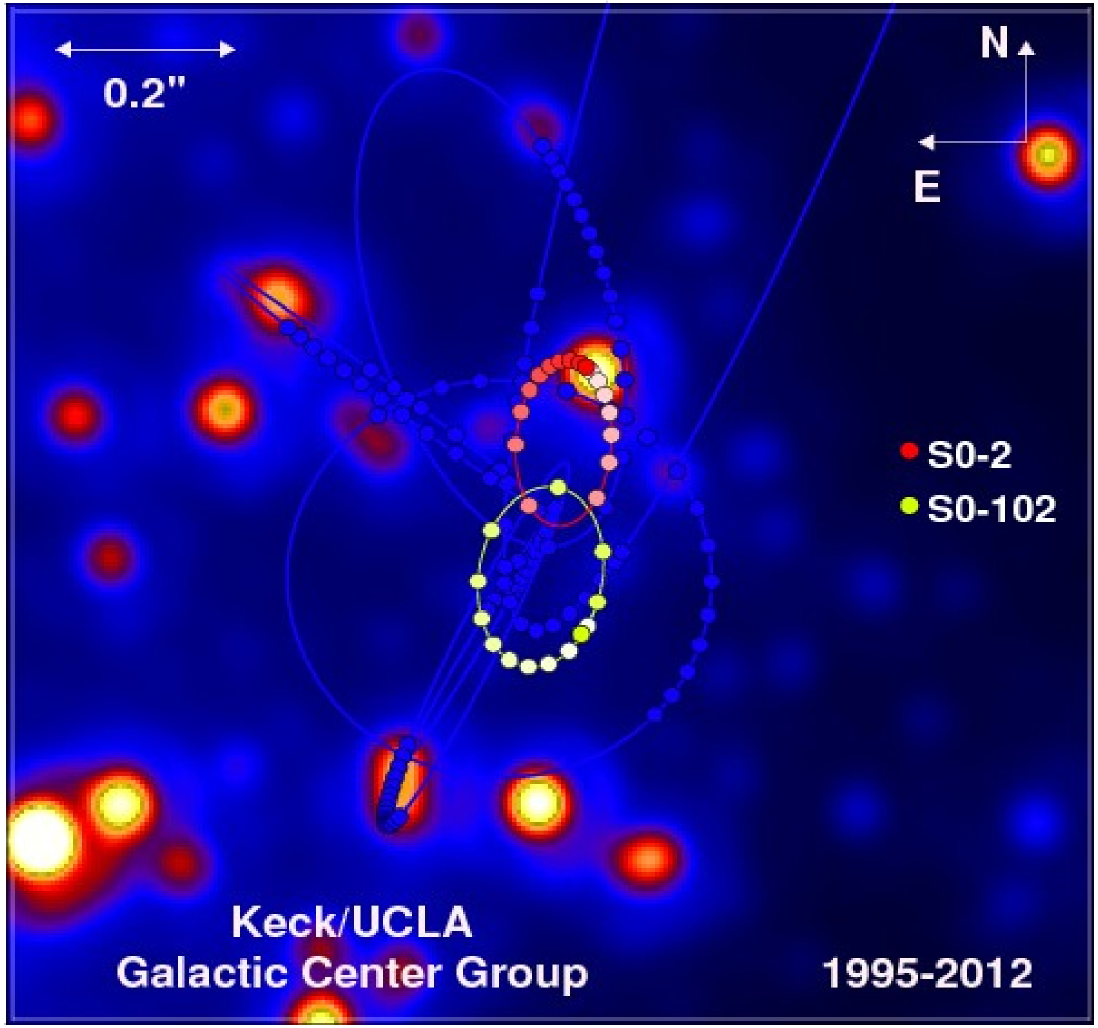
without AO

with AO

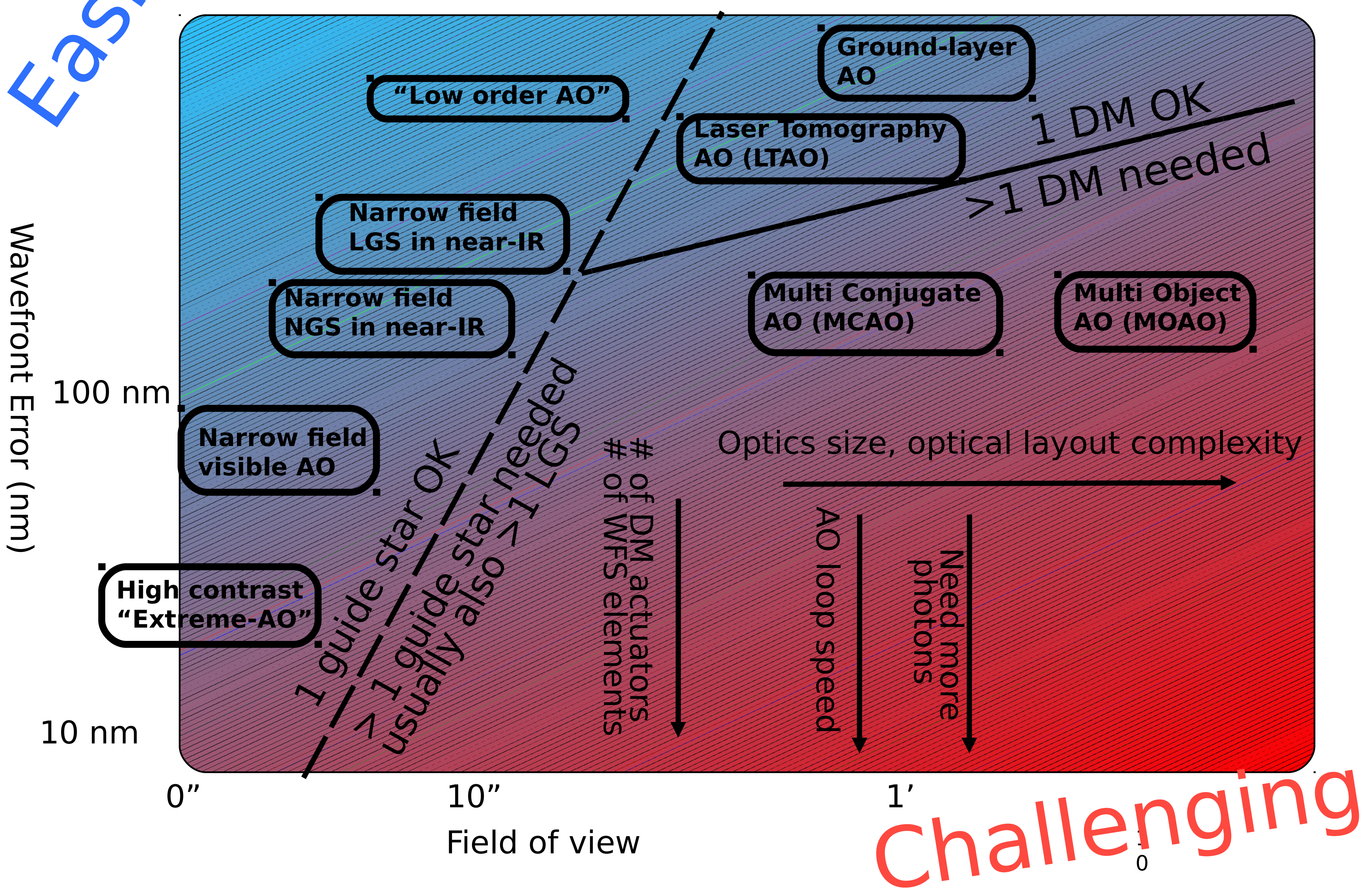
Neptune imaged by Keck AO

Why Adaptive Optics ?
Galactic center

Gemini AO image



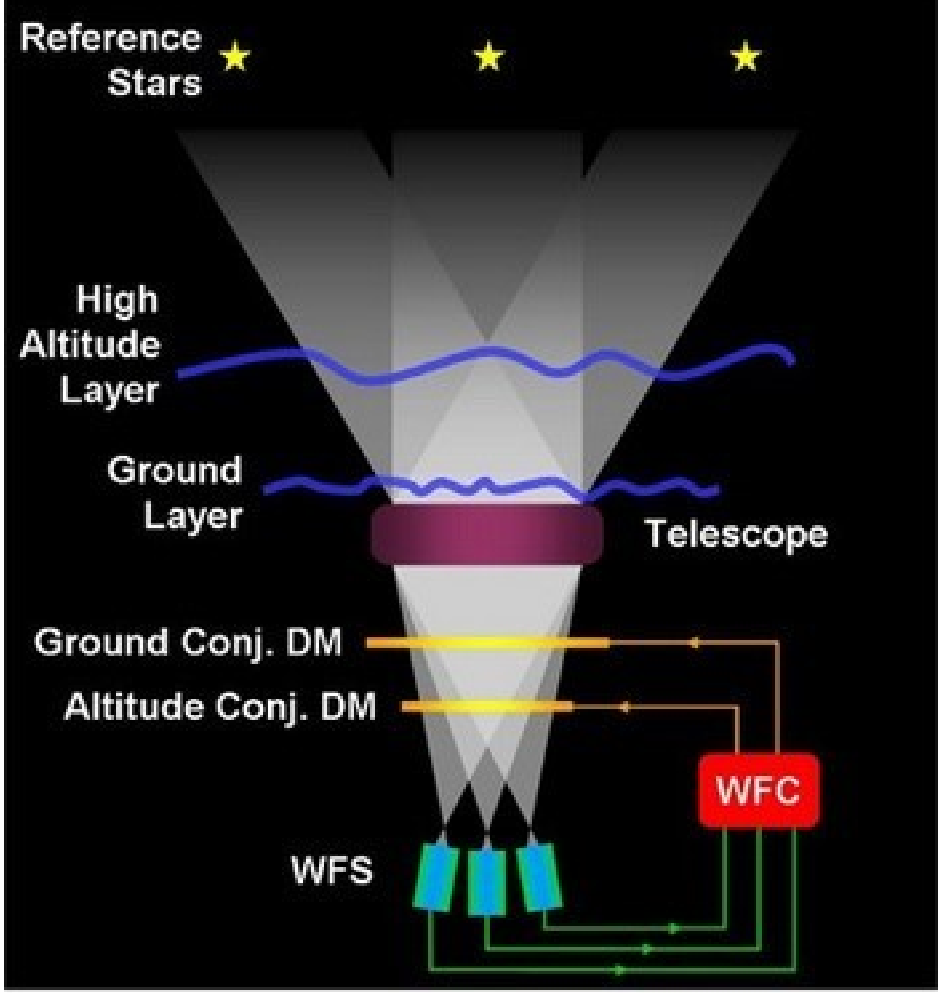
Astronomical AO system diversity:
Field of view vs. Wavefront error



Example #1:
Multi-Conjugate AO (MCAO)

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

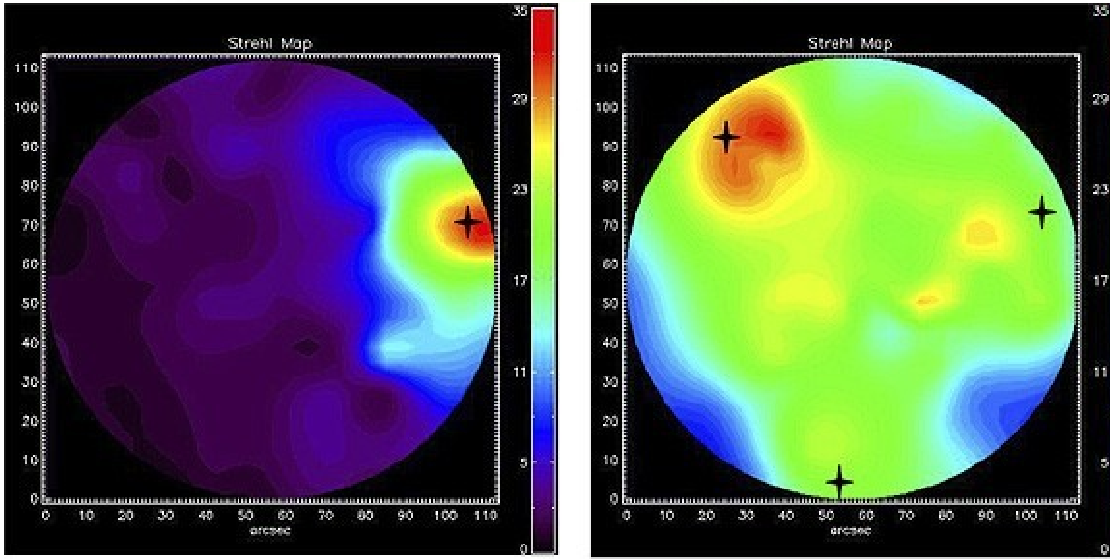
Uses several DMs to correct over wide field.



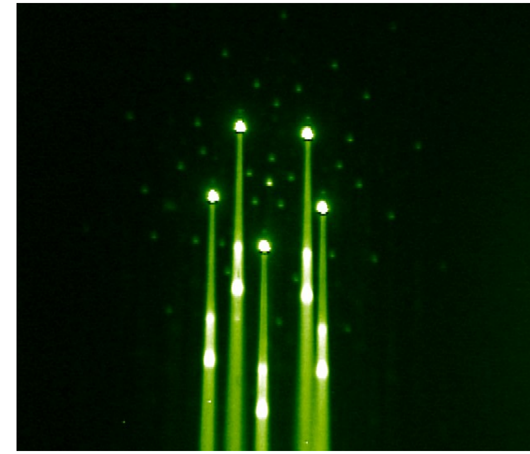
Results from ESO’s MCAO demonstrator (MAD)

Gemini currently developing MCAO system

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



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

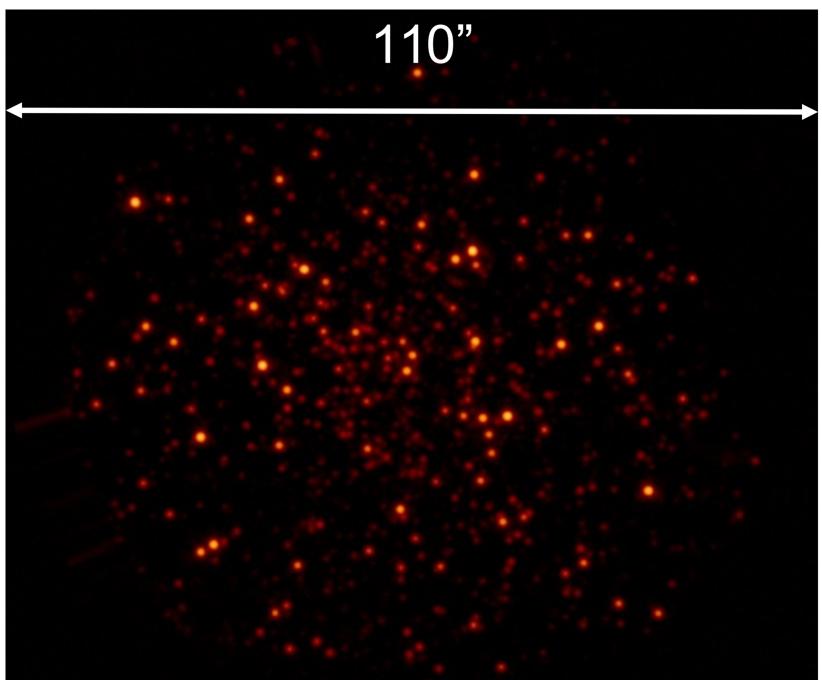


5 laser guide stars → 5 wavefront measurements
Reconstructor keeps only ground layer, common to the 5 wavefronts
Single DM corrects for the ground layer: correction is valid over a large field

MMT results: M3 globular cluster

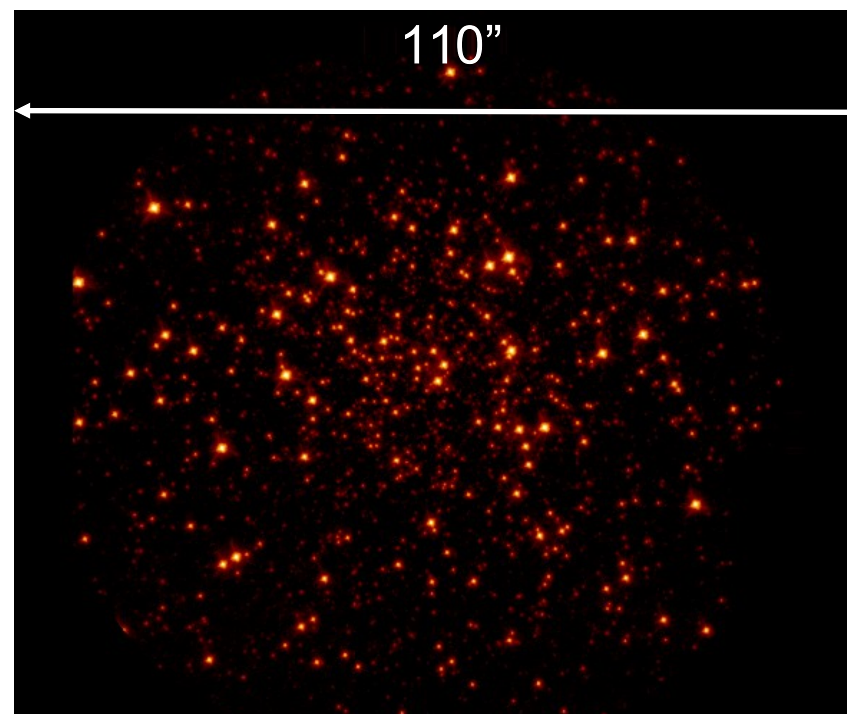
Open loop, K_s filter, FWHM 0.70”

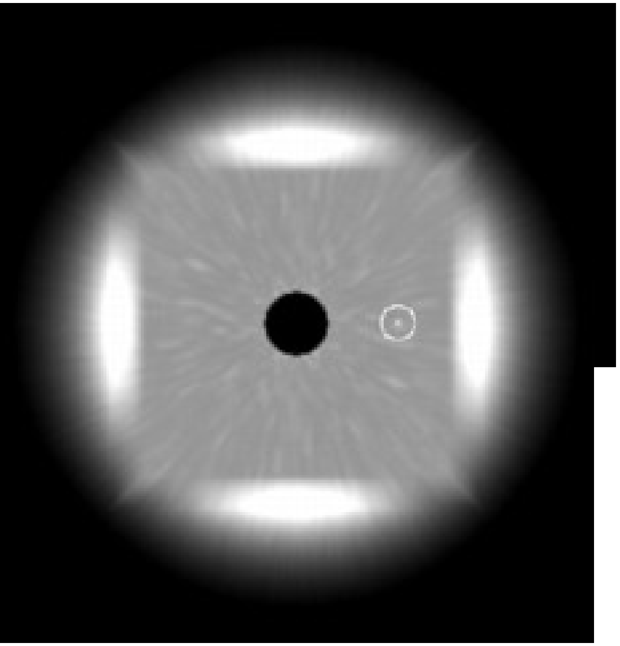
Logarithmic scale



Closed loop GLAO, K_s filter, FWHM 0.30”

Logarithmic scale

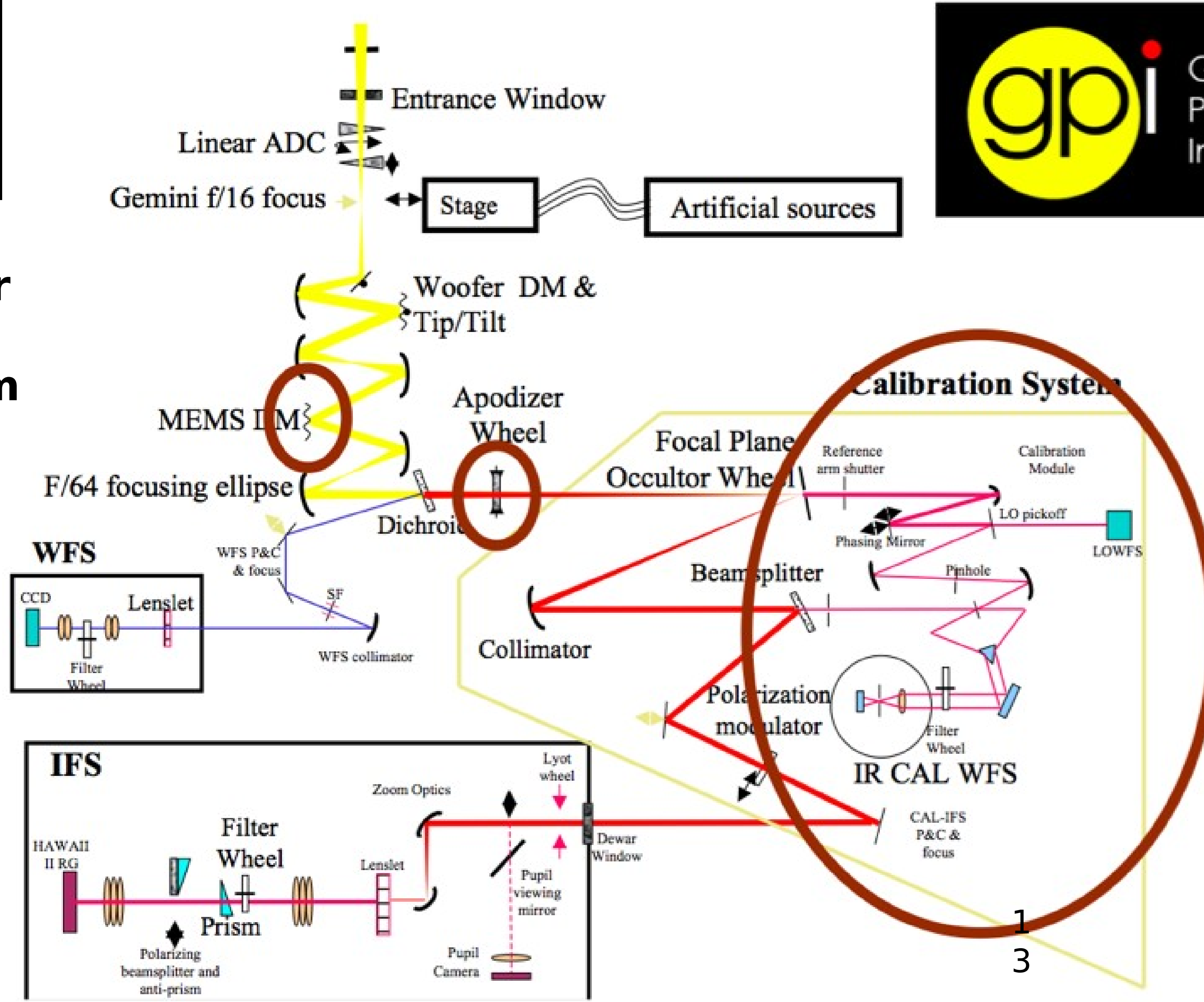




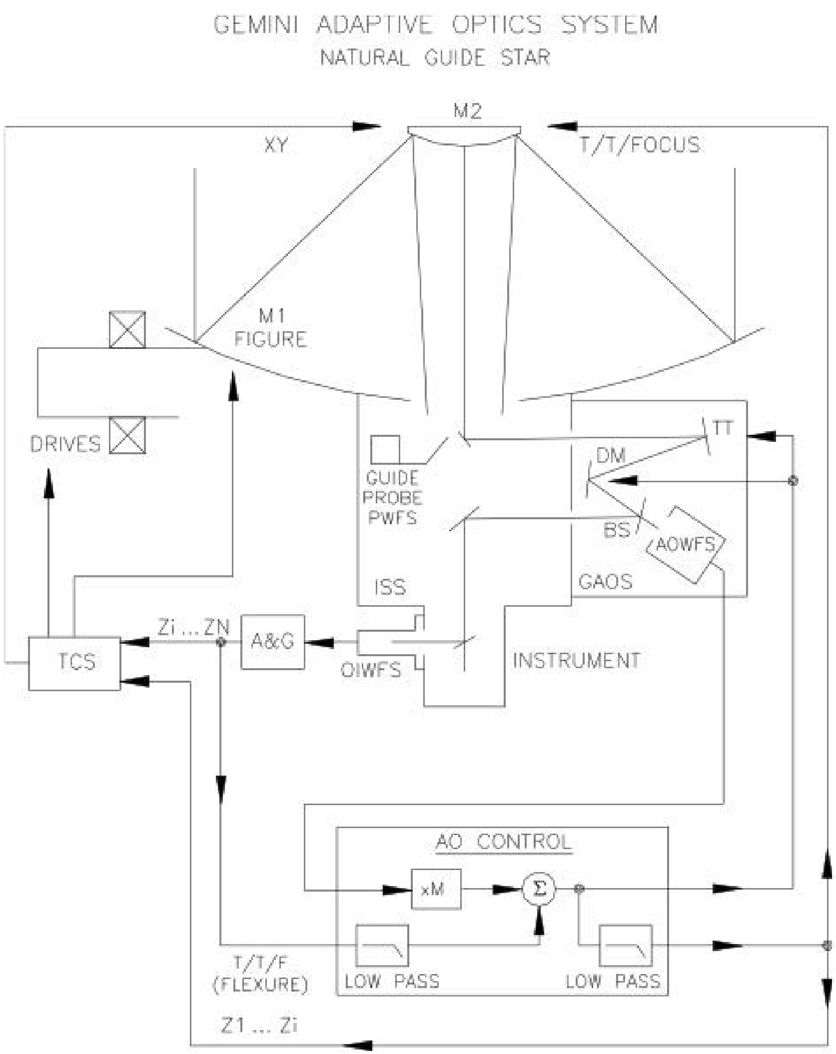
Example #3: The Gemini Planet Imager Extreme-AO system

Gemini Planet Imager
SPHERE (ESO)
Subaru CExAO system

Also under study: space-based ExAO systems

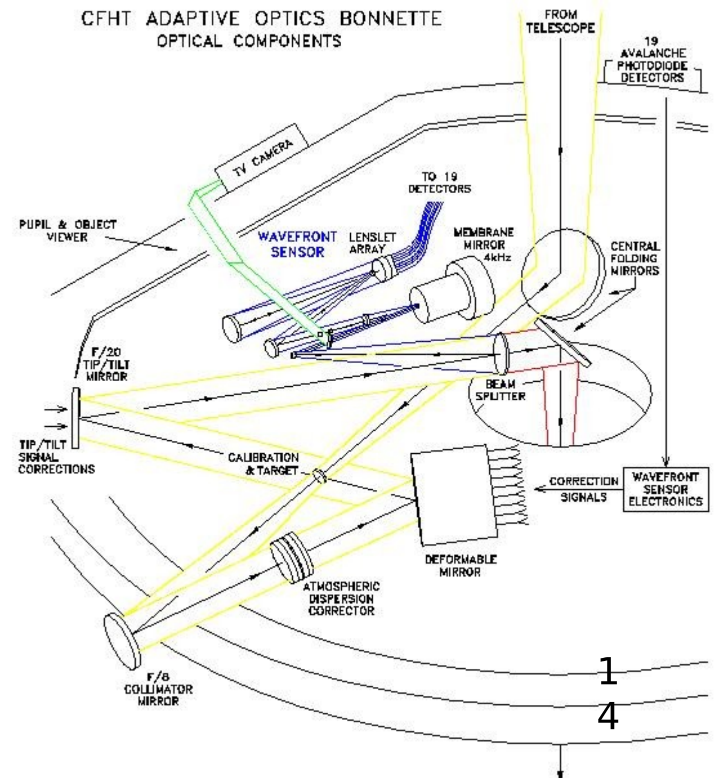


Communication between telescope/instruments and AO system



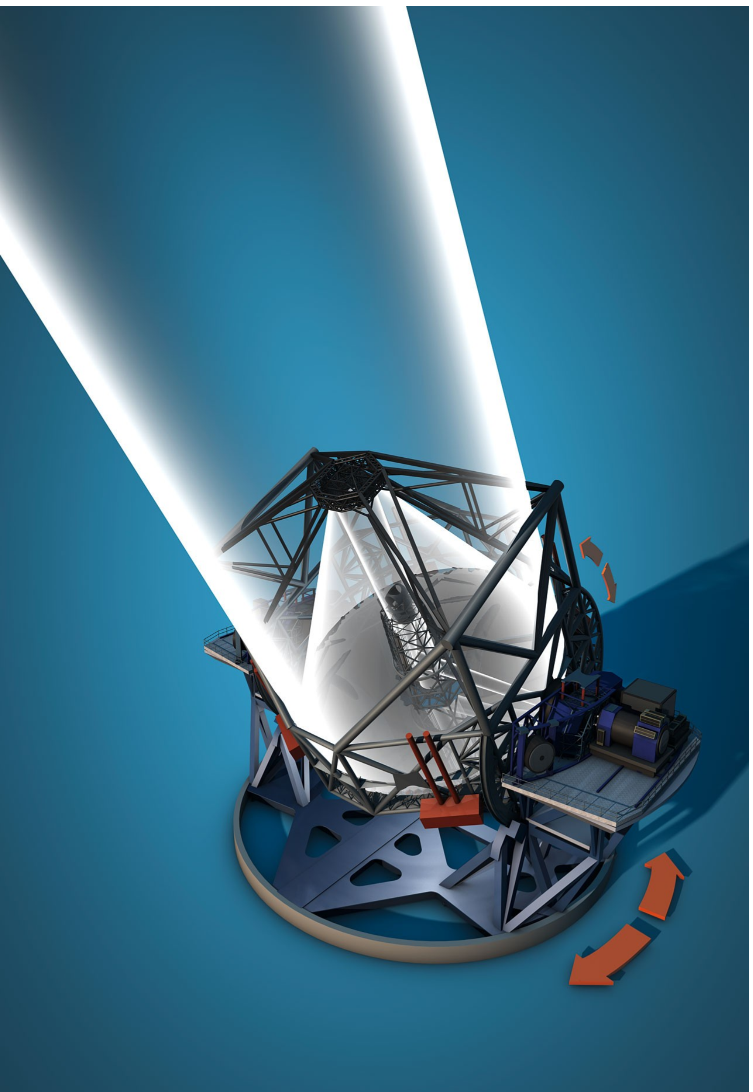
On modern telescopes, the AO system can “offload” wavefront aberrations to primary mirror, tip/tilt/focus secondary mirror and telescope pointing. The AO system “drives the telescope”.

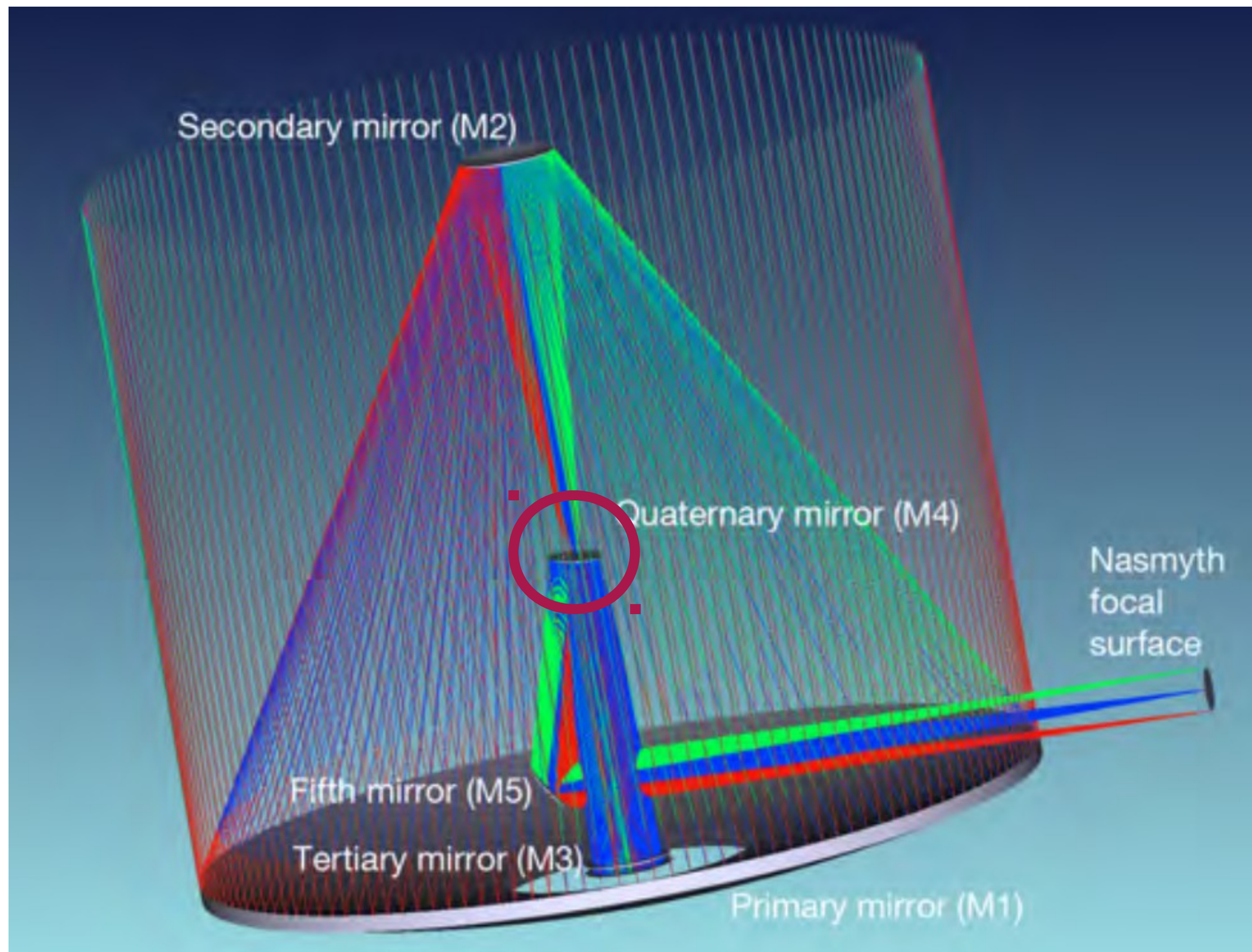
“Facility” AO systems can feed several instruments, and can be a “layer” which processes the beam prior to sending it to instruments.

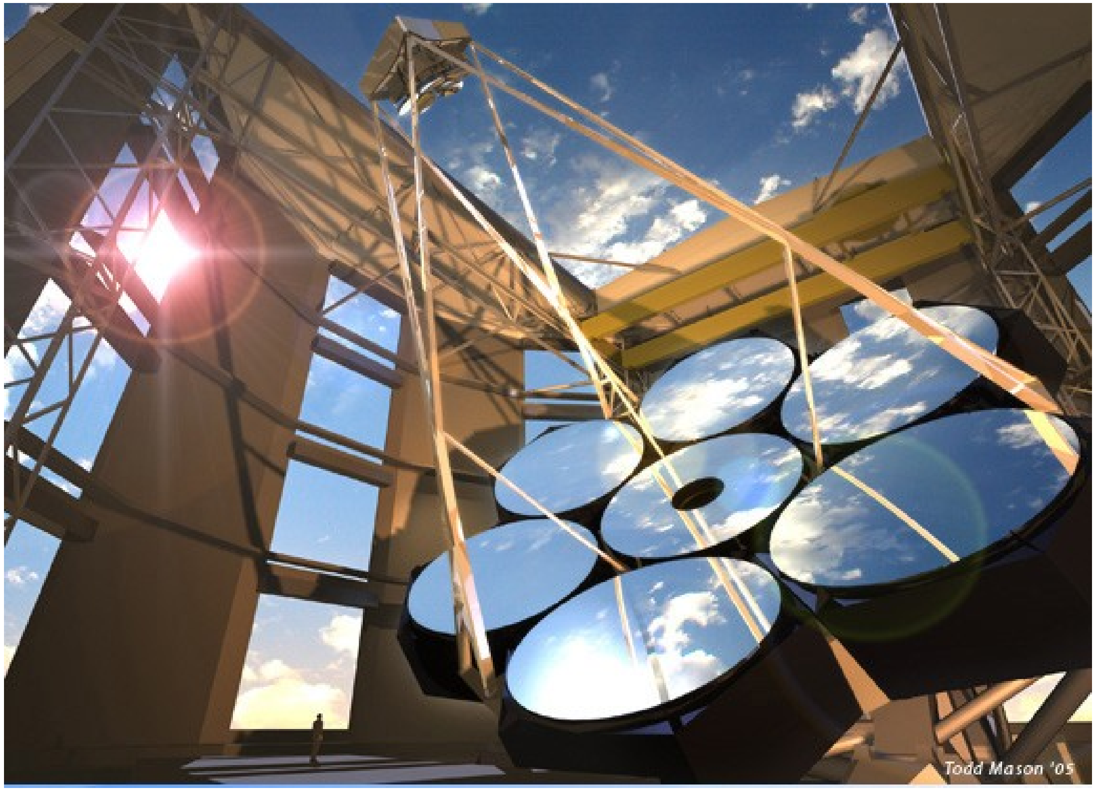


The next generation of large telescopes combine AO with telescope design

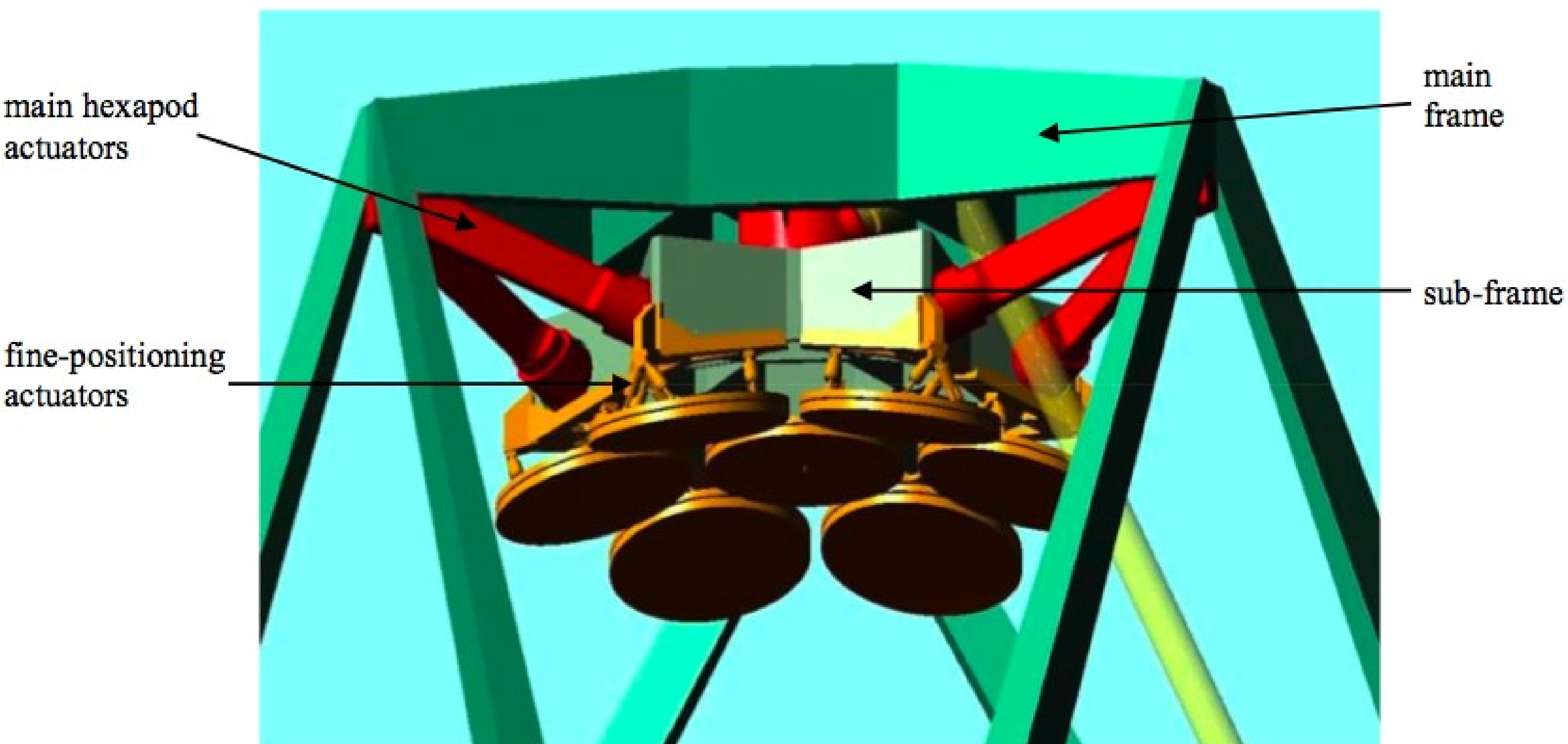
The 39m diameter European Extremely Large Telescope (EELT) optical design includes a large deformable mirror (2.4m diameter).

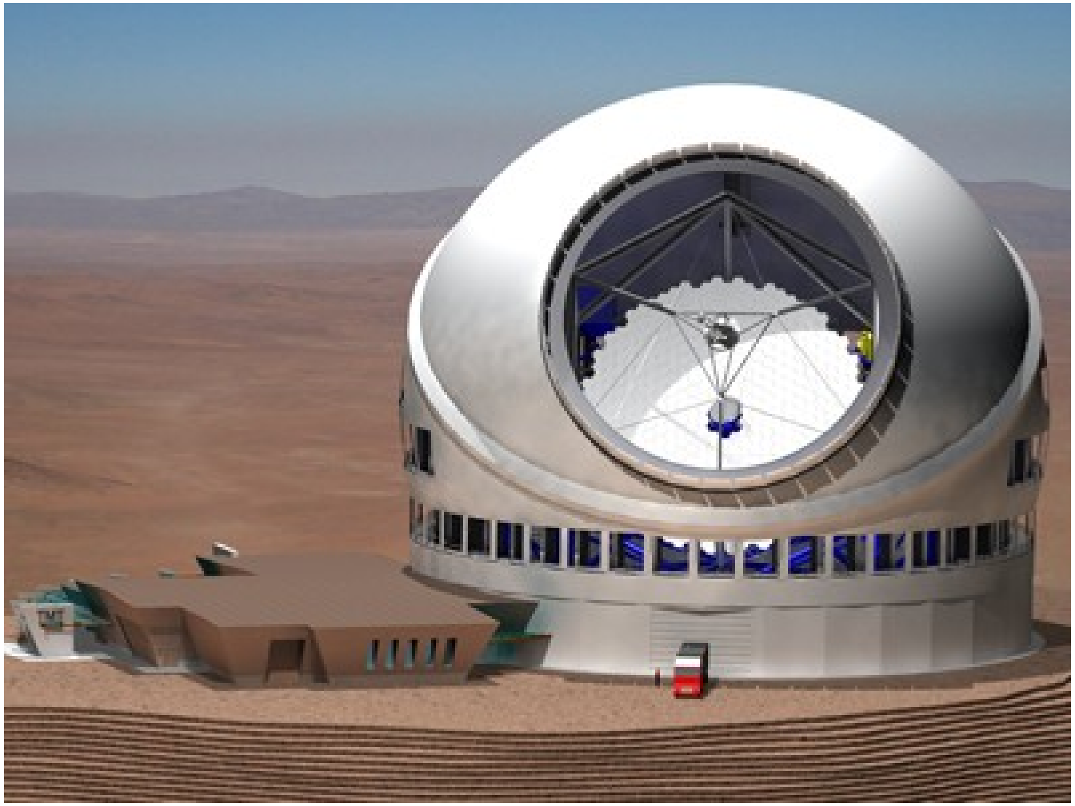




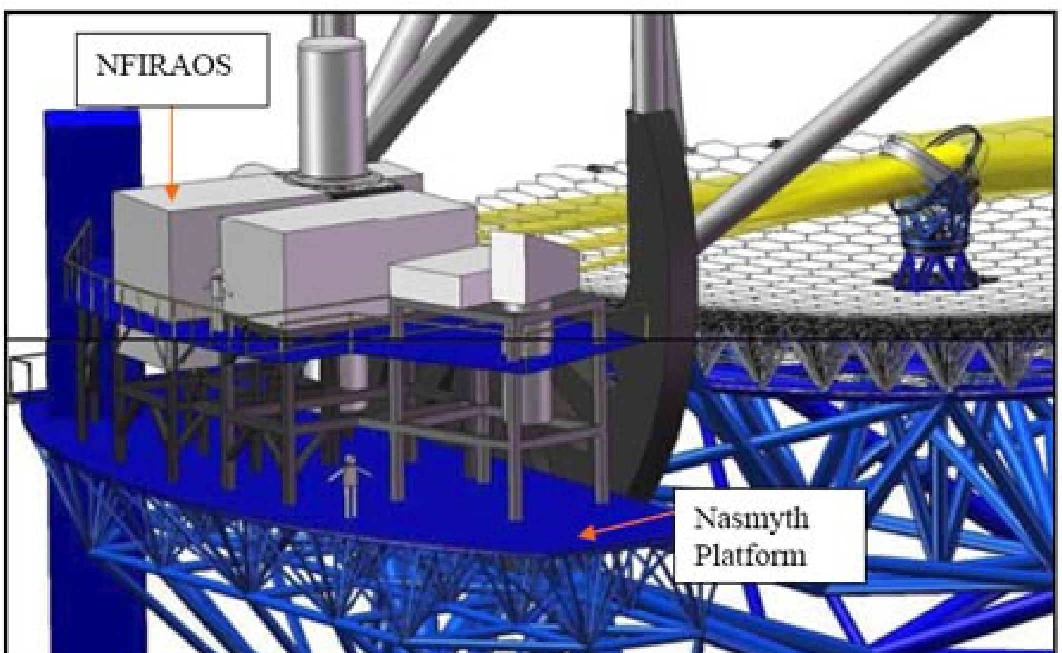


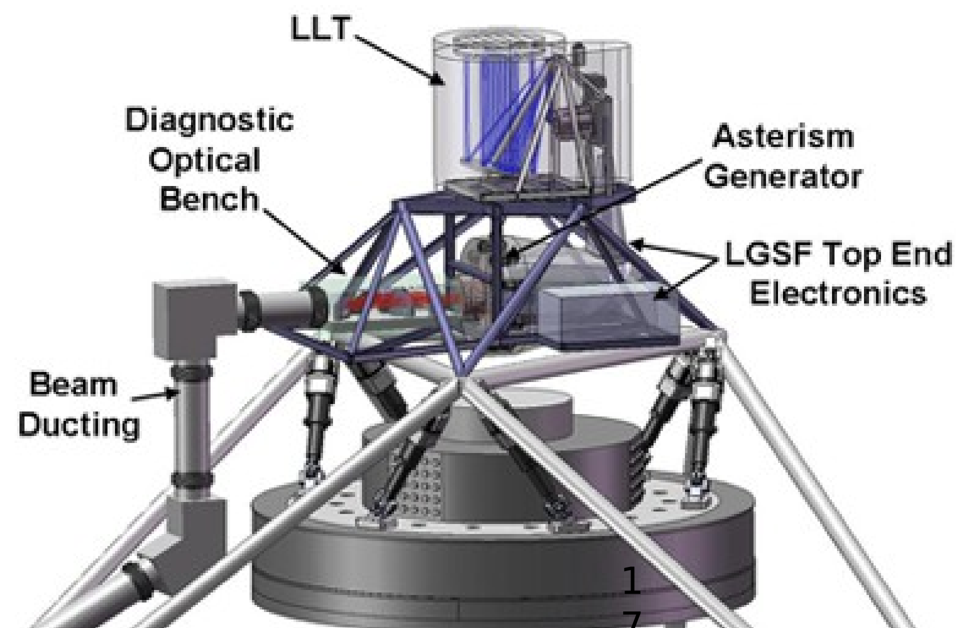
The Giant Magellan Telescope (GMT) secondary mirrors are adaptive and serve as DMs for the AO system(s).





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

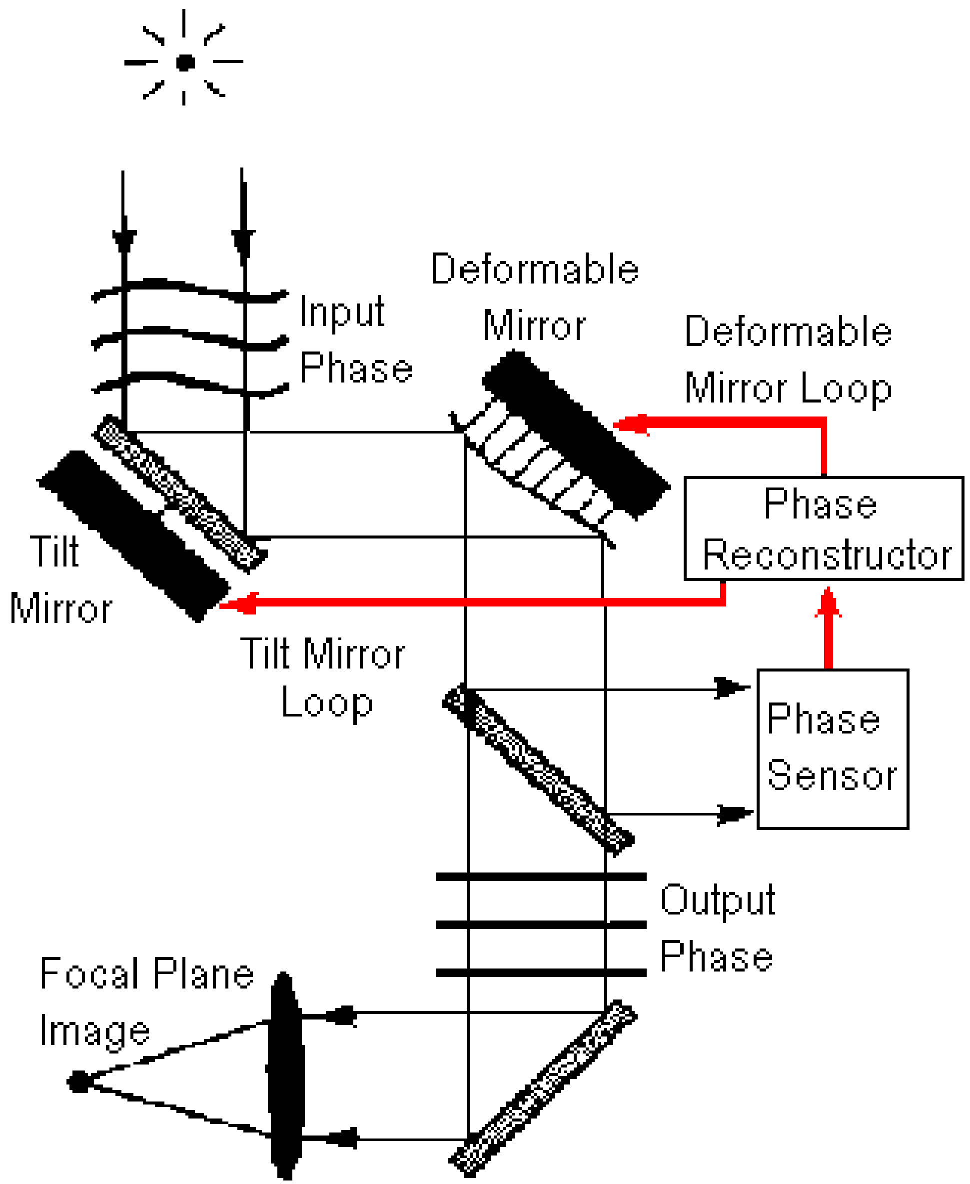




Atmospheric turbulence and its effect on image quality

Image quality metrics
Atmospheric turbulence
Wavefront phase
Measuring important turbulence parameters
Wavefront phase error budget

What is Adaptive Optics ?



Main components of an AO system:

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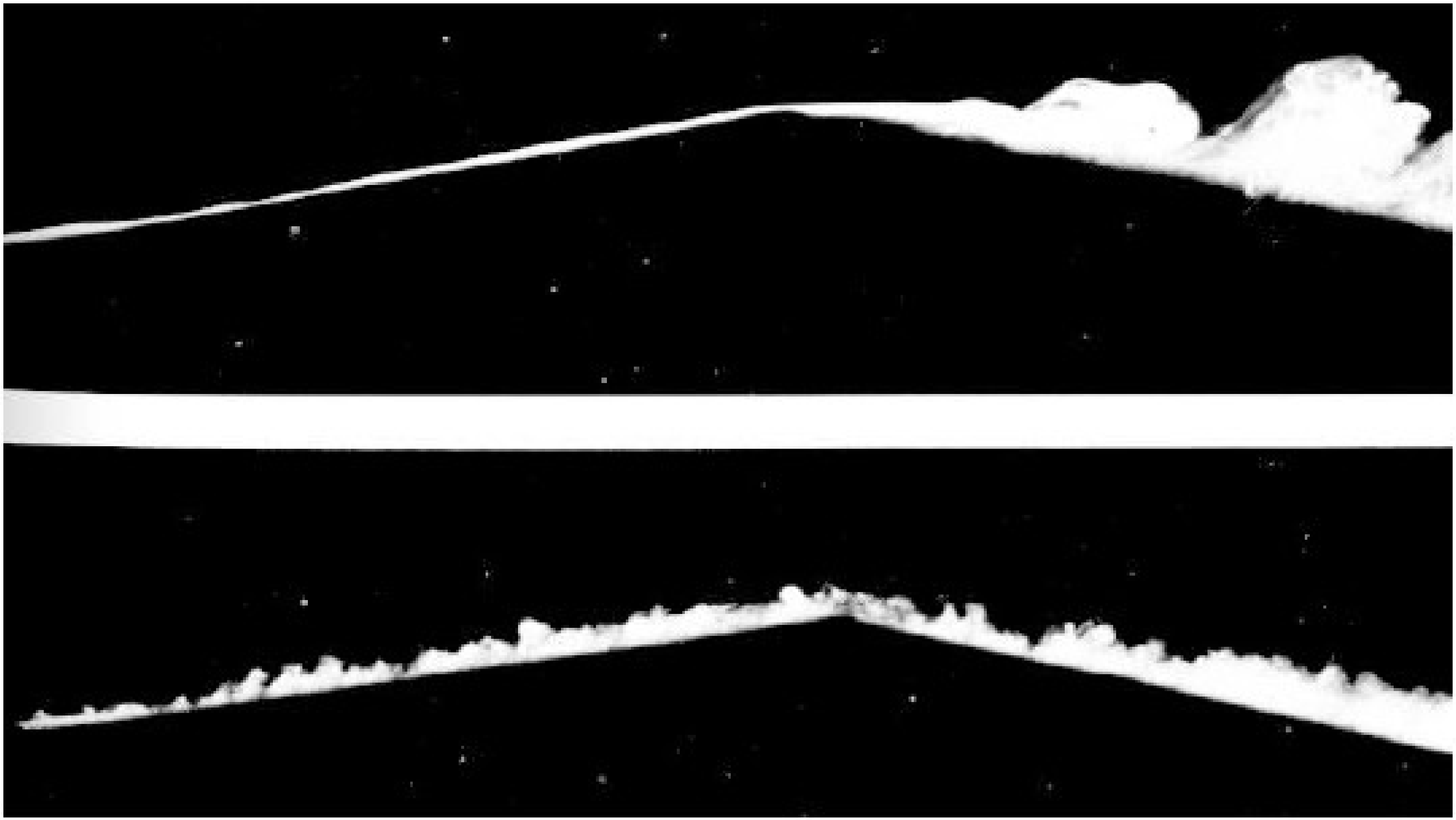
Computer, algorithms: converts wavefront sensor measurements into deformable mirror commands

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

Turbulence from a boundary layer



Bigger whirls have little whirls, Which feed on their velocity; Little whirls have smaller whirls, and so on to viscosity.

Atmospheric Turbulence

Temperature variations in the atmosphere result in index of refraction variations. This, in turn causes corrugations in wavefronts propagating through the atmosphere.

Large scale temperature variations create flow of air which will interact at boundary layers to create turbulence. Large scale eddies cascade into smaller scale turbulence. The resulting index variations have typical power spectra (strength versus spatial scale) which are characteristic of the turbulent process.

Strength of Turbulence : C_N^2

Refractive index spatial structure function (3D):

$D_N(\rho) = \langle|n(r)-n(r+\rho)|^2\rangle = C_N^2\ \rho^{2/3}$ (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)

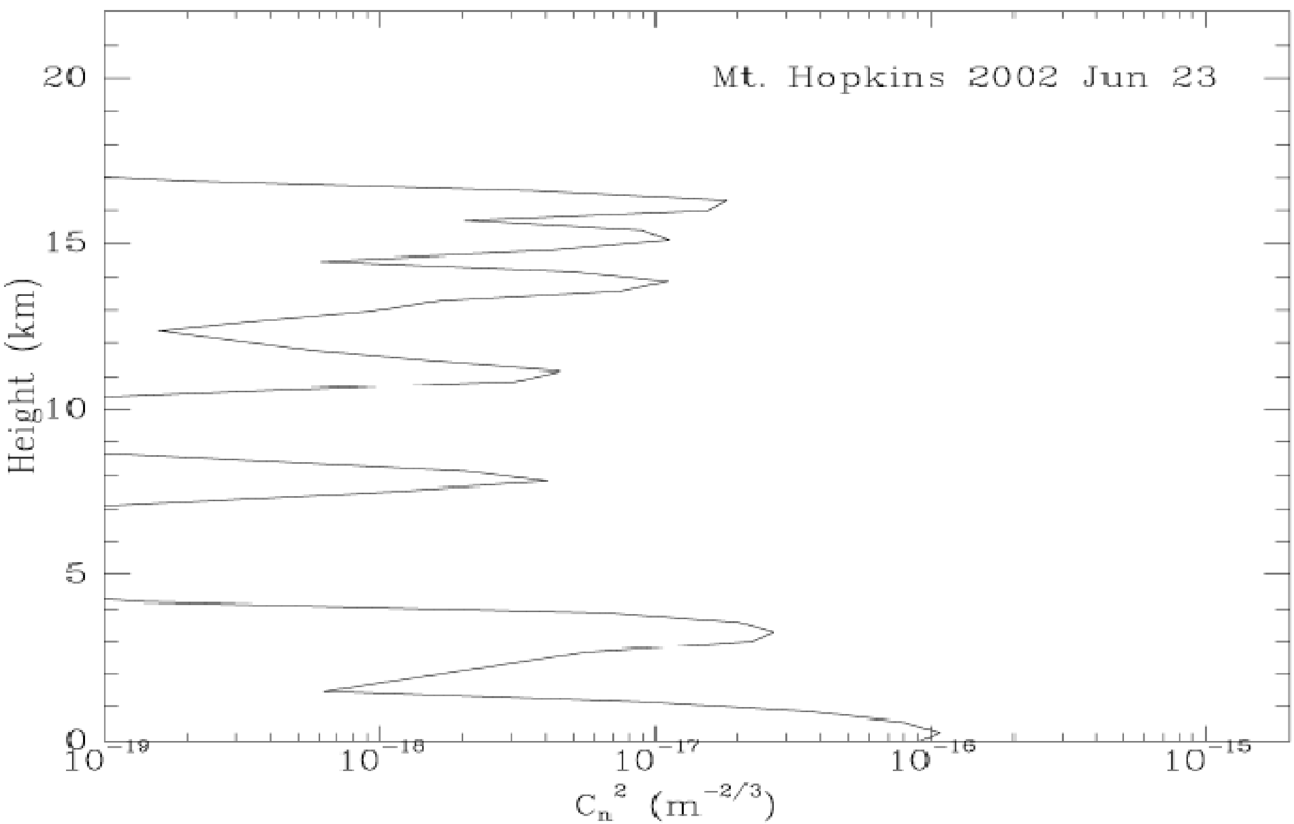
Between inner and outer scale, turbulence is well described by this power law.

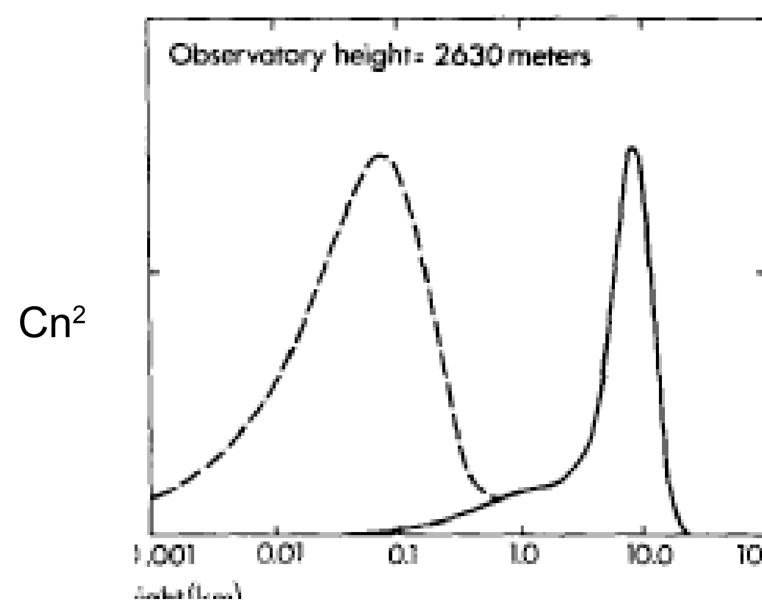
Refractive index temporal structure function under Taylor approximation:

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

Cn^2 profiles

- The strength of the turbulence is measured as an index of refraction variation (termed Cn^2).
- The turbulent layers are not limited to the ground, but extend well up into the troposphere.





From C_N^2 to wavefront structure function

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)

From C_N^2 to wavefront error

Wavefront phase error over a circular aperture of diameter d:

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

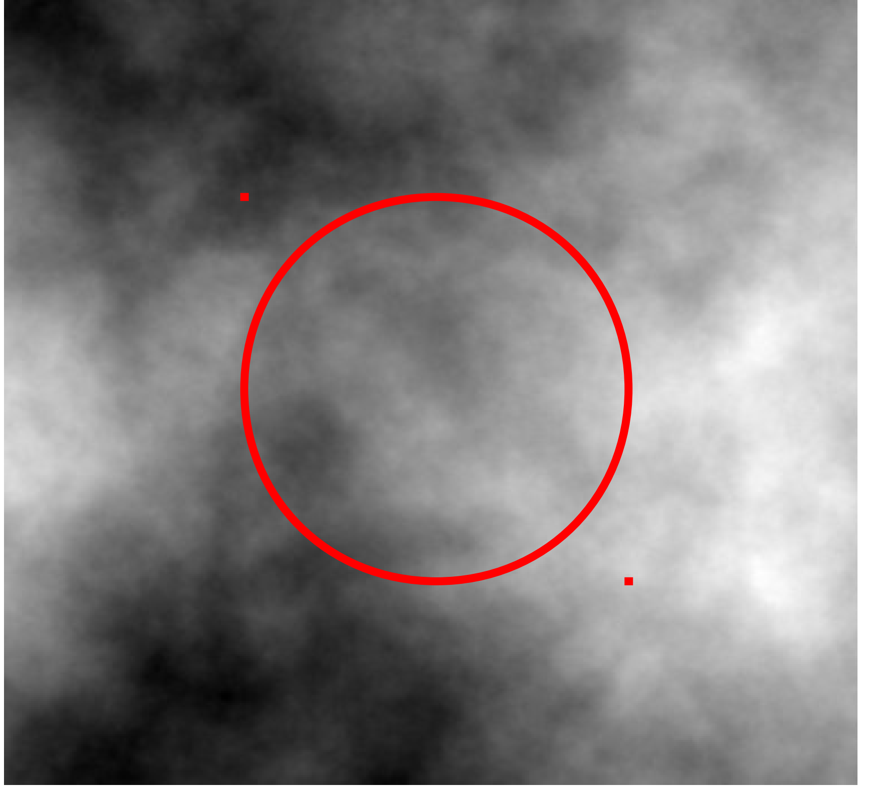
r_0 = Fried Parameter [unit = m] = diameter of telescope for which atmospheric wavefront ~ 1 rad^2

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.

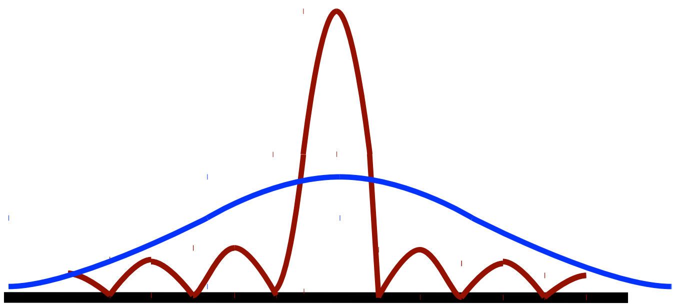
Wavefront variance σ^2 is additive (no correlation between different sources), and the wavefront error budget is built by adding σ^2 terms.

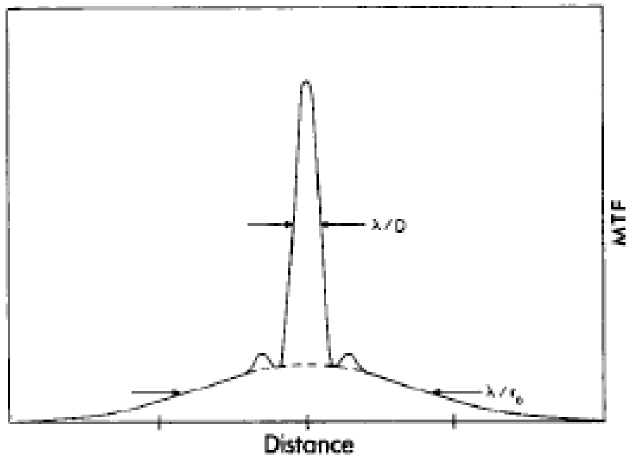
Wavefront error (m) = $\lambda \times \sigma/(2\pi)$

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

Image Structure

- The point spread function of an adaptive optics system is complicated by the fact that the light is only partially corrected.
- A portion of the total energy, S, is gathered into an Airy pattern.
- The remaining energy, 1-S, is spread into a halo with a characteristic size of the seeing disk.





Contribution to Strehl

Potential sources of wavefront error include

time delay,

fitting error,

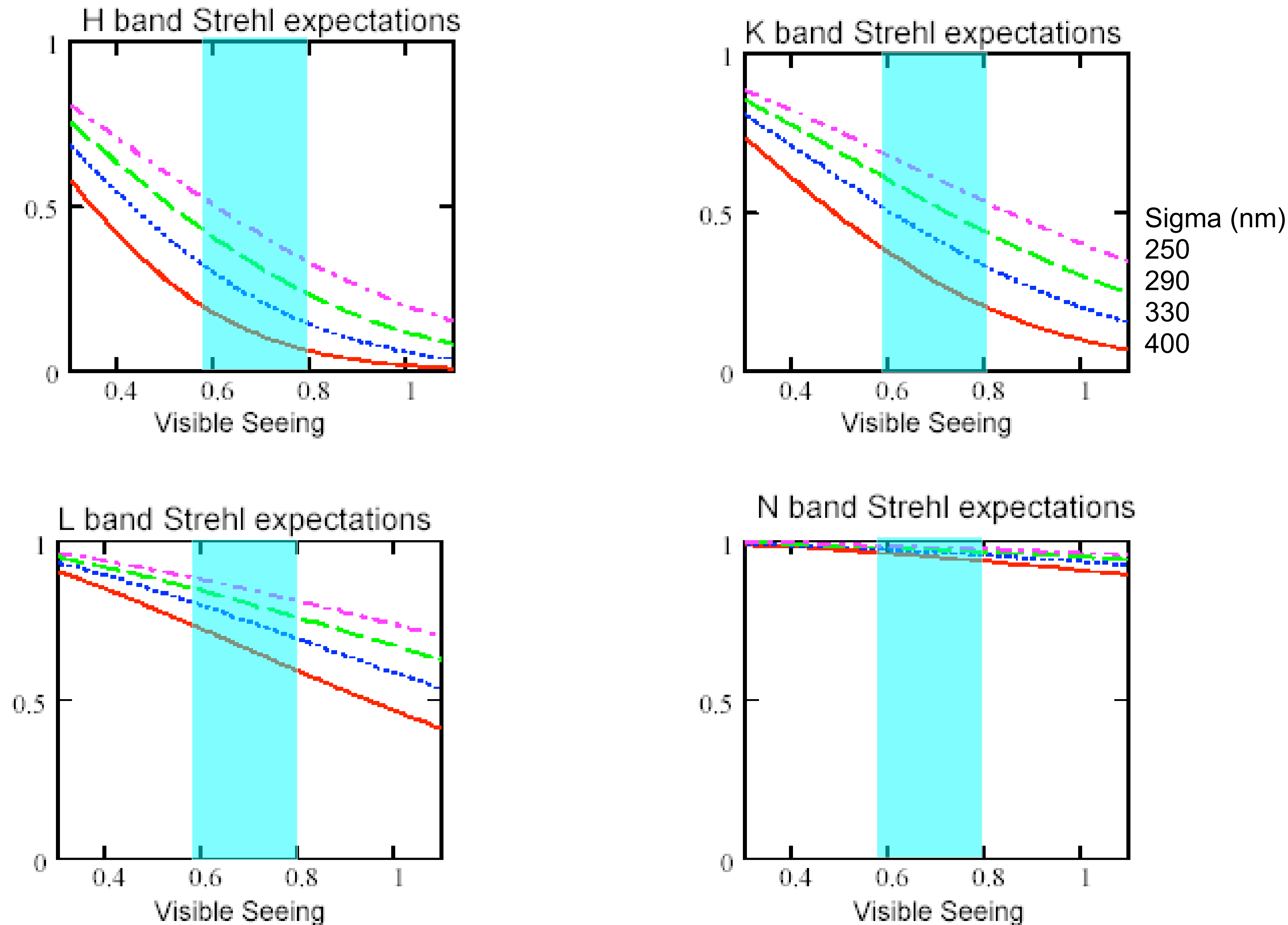
isoplanatic error,

photon noise error

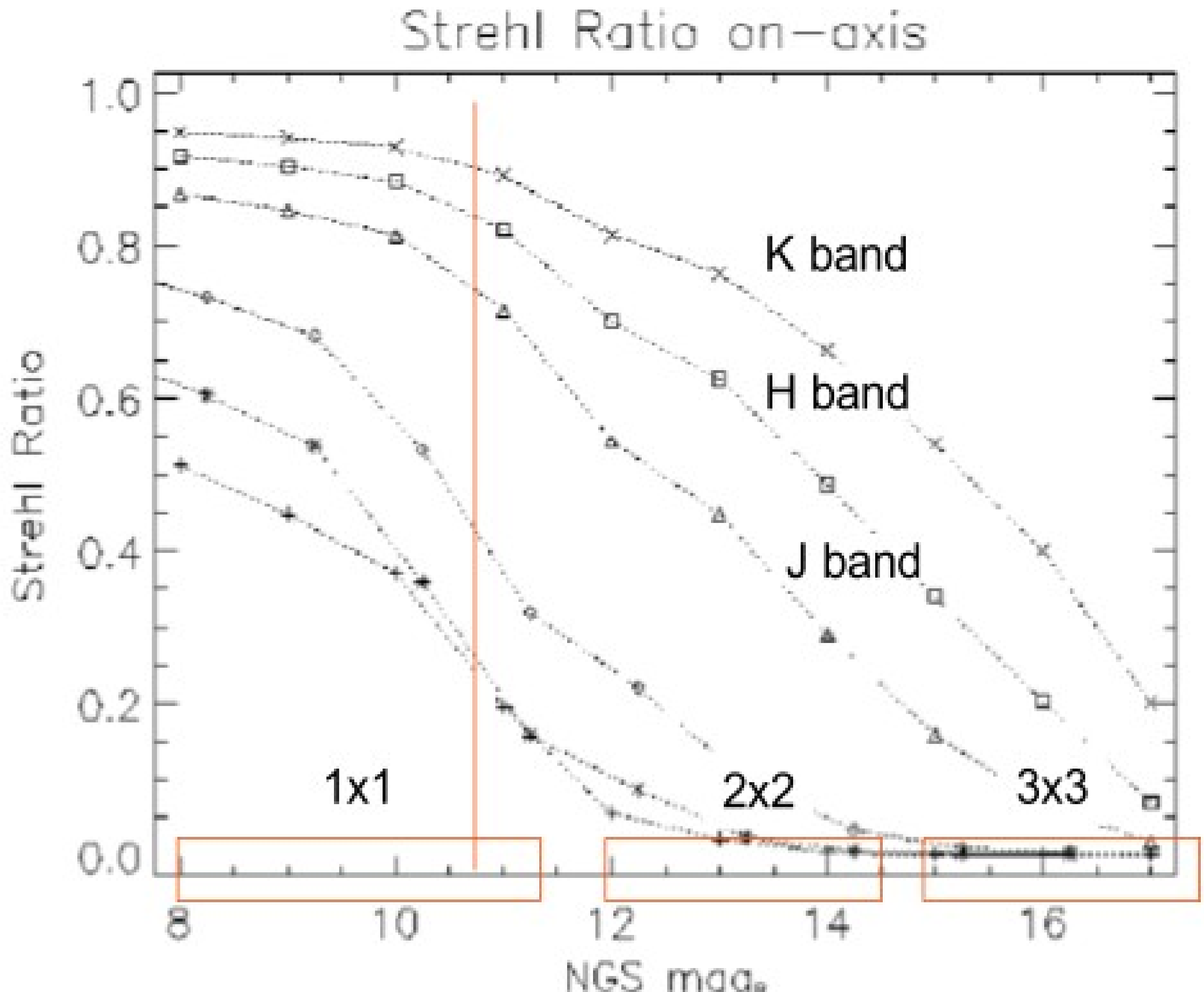
If we assume the wavefront error terms are independent we can write:

$$\sigma^2 = \sum \sigma_i^2$$

Strehl versus seeing

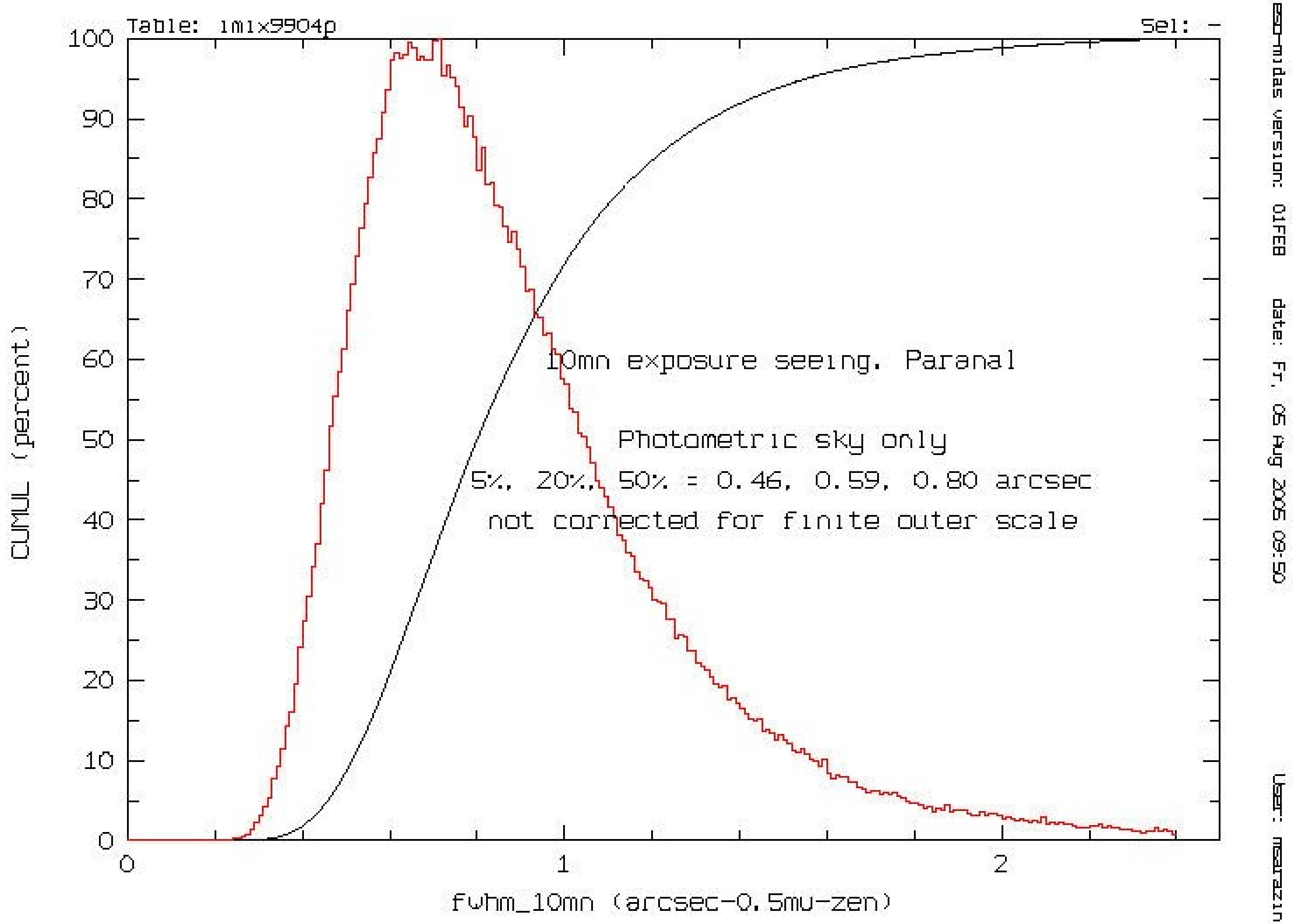


Predicted Strehl versus Guide Star



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**

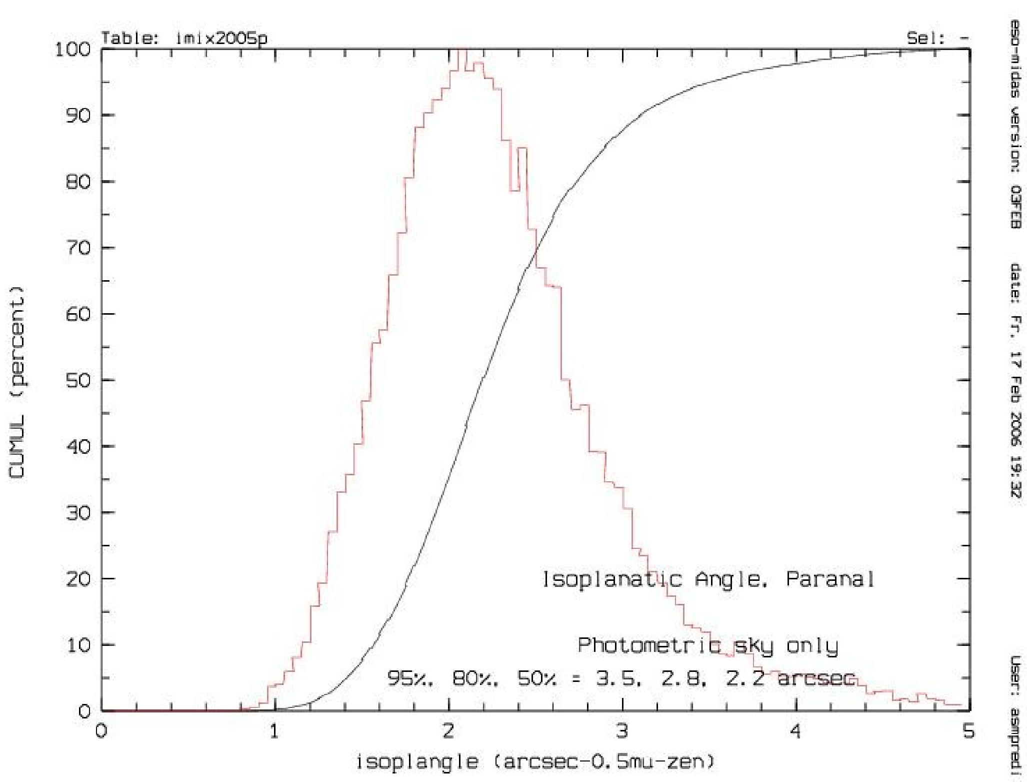
→ field of view of corrected image

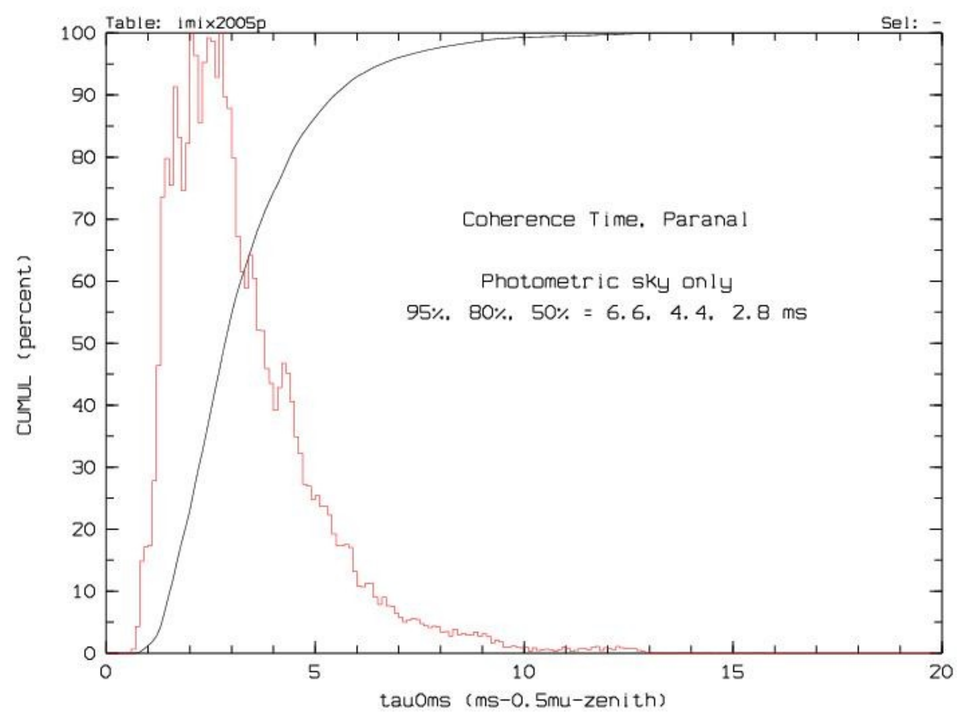
→ how far from science target can the guide star be

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

→ how fast should the AO system run ?

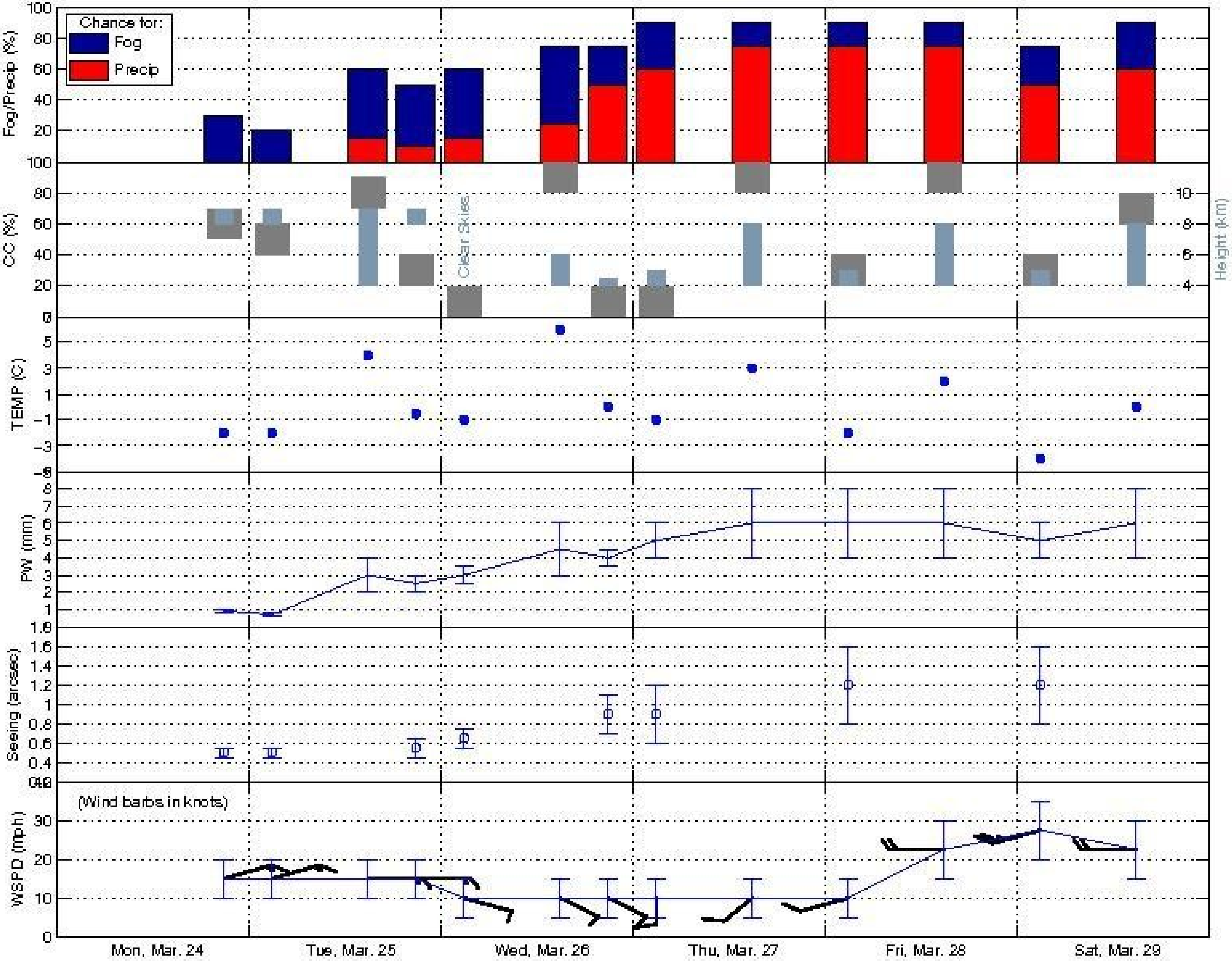
→ how faint a guide star can be used ?



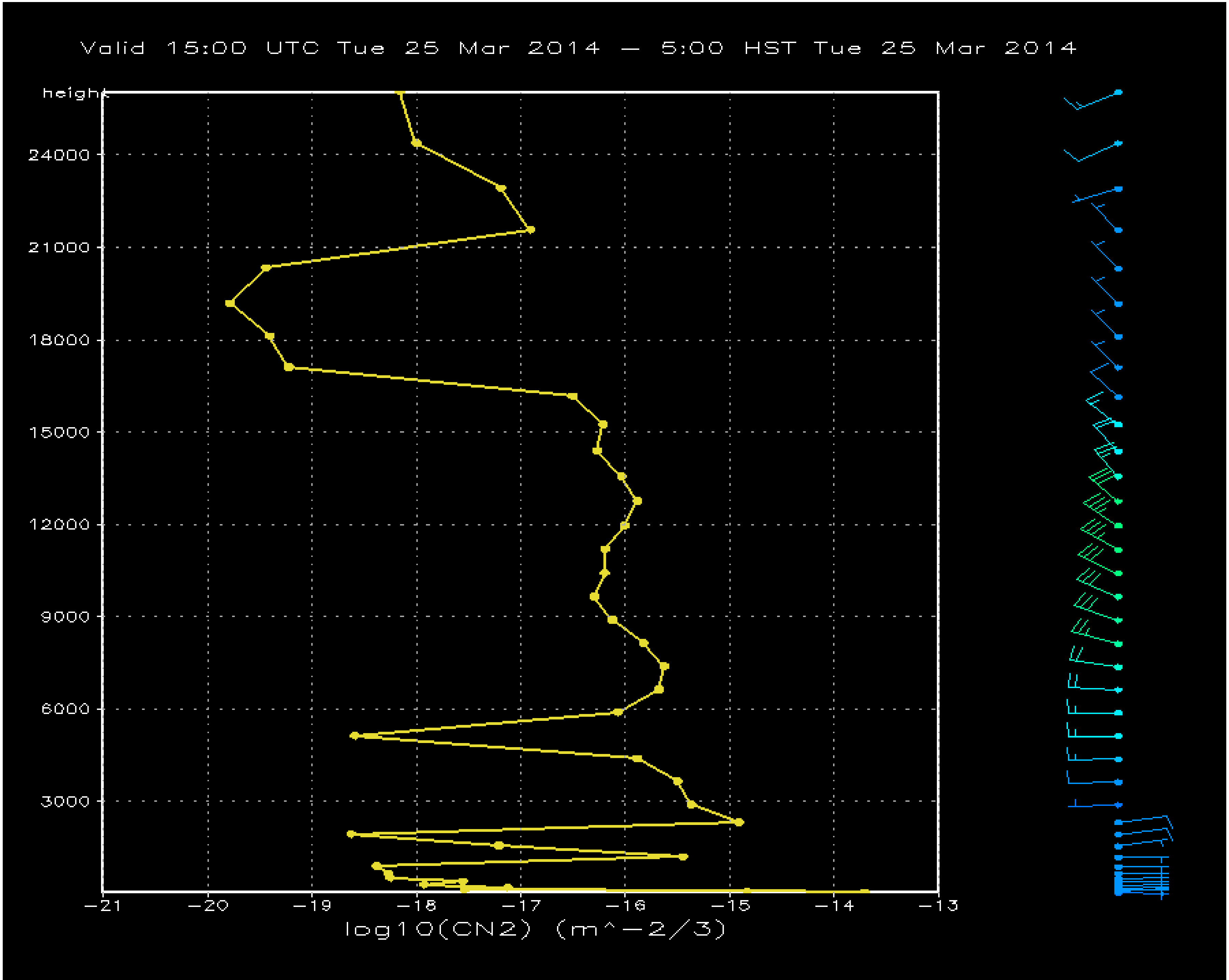


ESO VLT seeing statistics, 2005

Example: Mauna Kea observatory forecast



C_N^2 profile

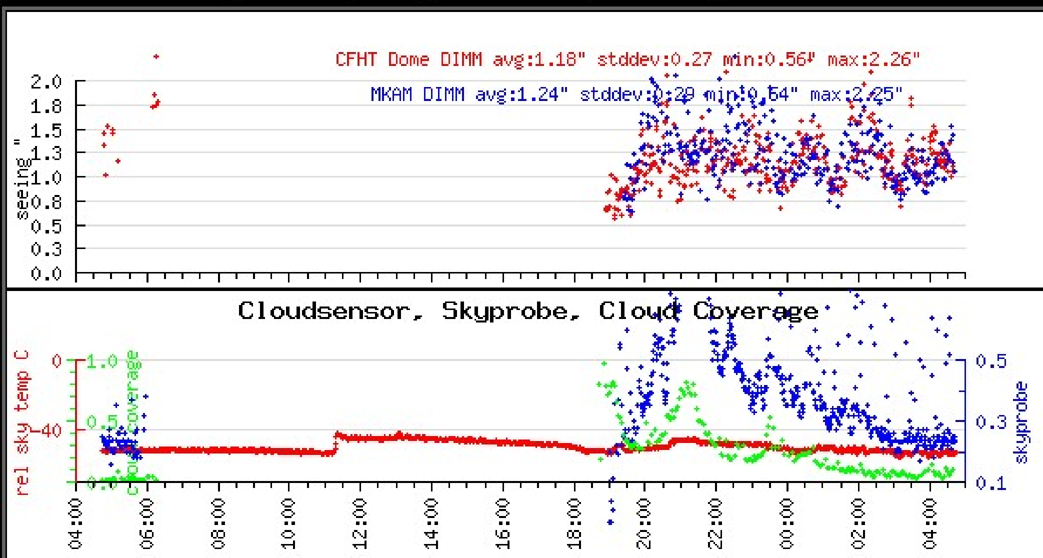


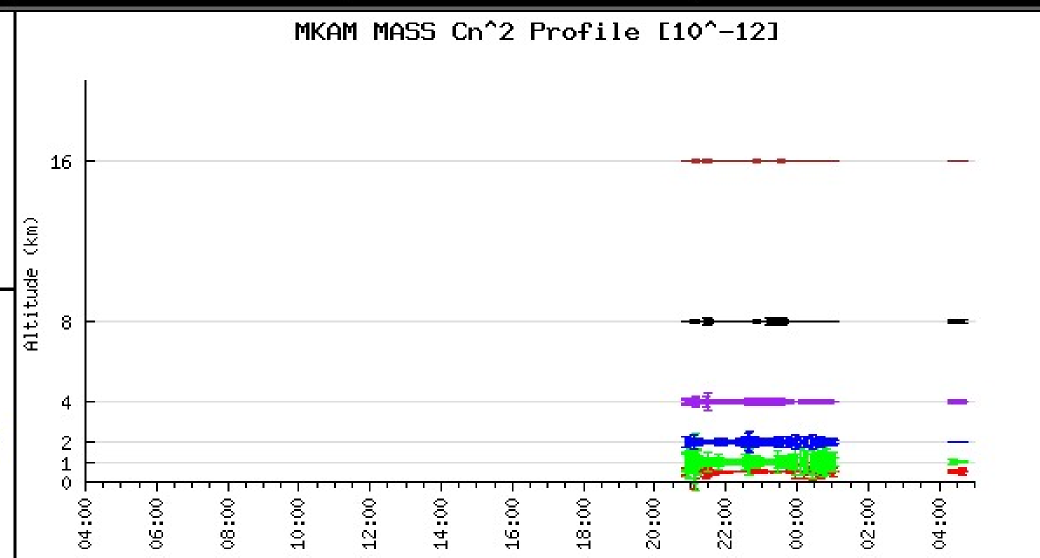
Valid 15:00 UTC Tue 25 Mar 2014 — 5:00 HST Tue 25 Mar 2014
height
24000
21000
18000
15000
12000
9000
6000
3000
−21
−20
−19
−18
−17
−16
−15
−14
−13
log10(CN2) (m^−2/3)

Canada France Hawaii Telescope (CFHT) weather summary page

DIMM: Differential Image Motion Monitor
MASS: Multiaperture Scintillation Sensor

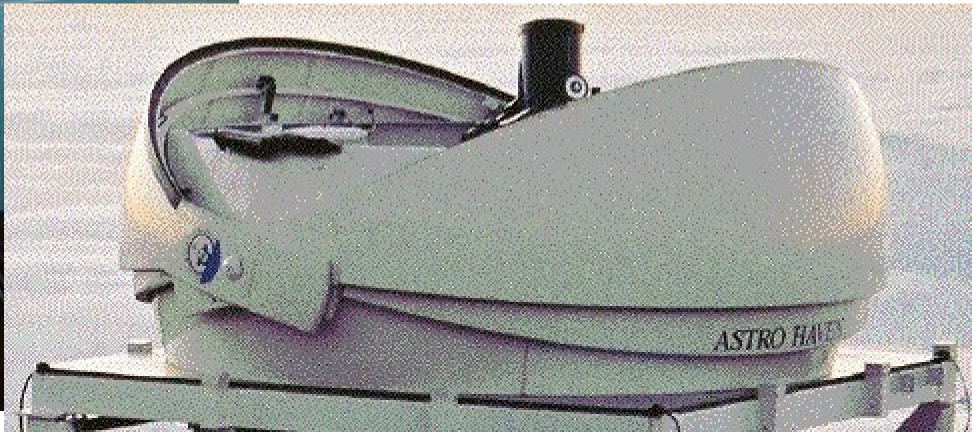
Currently	Ambient	RH %	Wind	Sky Temp	Last Cloud Coverage	Last Skyprobe	Last Dome DIMM seeing	Last Seeing Monitor Seeing
Mar 24 2011 4:43AM	0C	10%	6 @ 79deg	-53.01C	10% @ Mar 24 2011 4:39AM	0.23 @ Mar 24 2011 4:42AM	1.08" @ Mar 24 2011 4:37AM	1.06" @ Mar 24 2011 4:42AM





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)

Coherence time

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

Assuming pure time delay t

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

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

v = 10 m/s

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

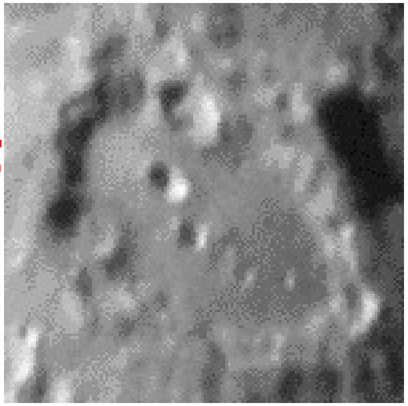
t_0 = 4.71 ms (visible)   25 ms (K band)

Assuming that sampling frequency should be ~ 10x bandwidth

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

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

Isoplanatic angle



Atmospheric wavefront not the same for different directions on the sky

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

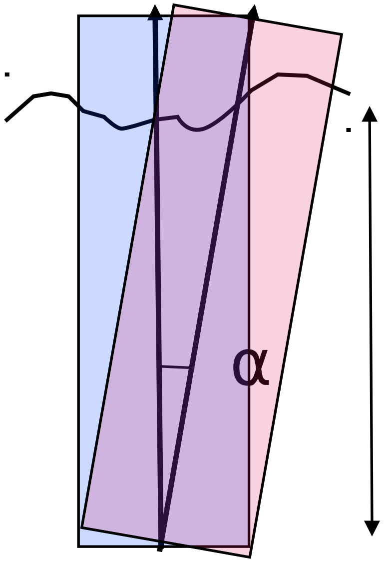
If we assume perfect on-axis correction, and a single turbulent layer at altitude h, the variance (sq. radian) is :

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

Where α is the angle to the optical axis,

θ_0 is the isoplanatic angle:

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



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

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

Amplitude effects (scintillation), chromaticity

Atmospheric wavefronts are chromatic (in optical path unit), and include amplitude modulation (scintillation)

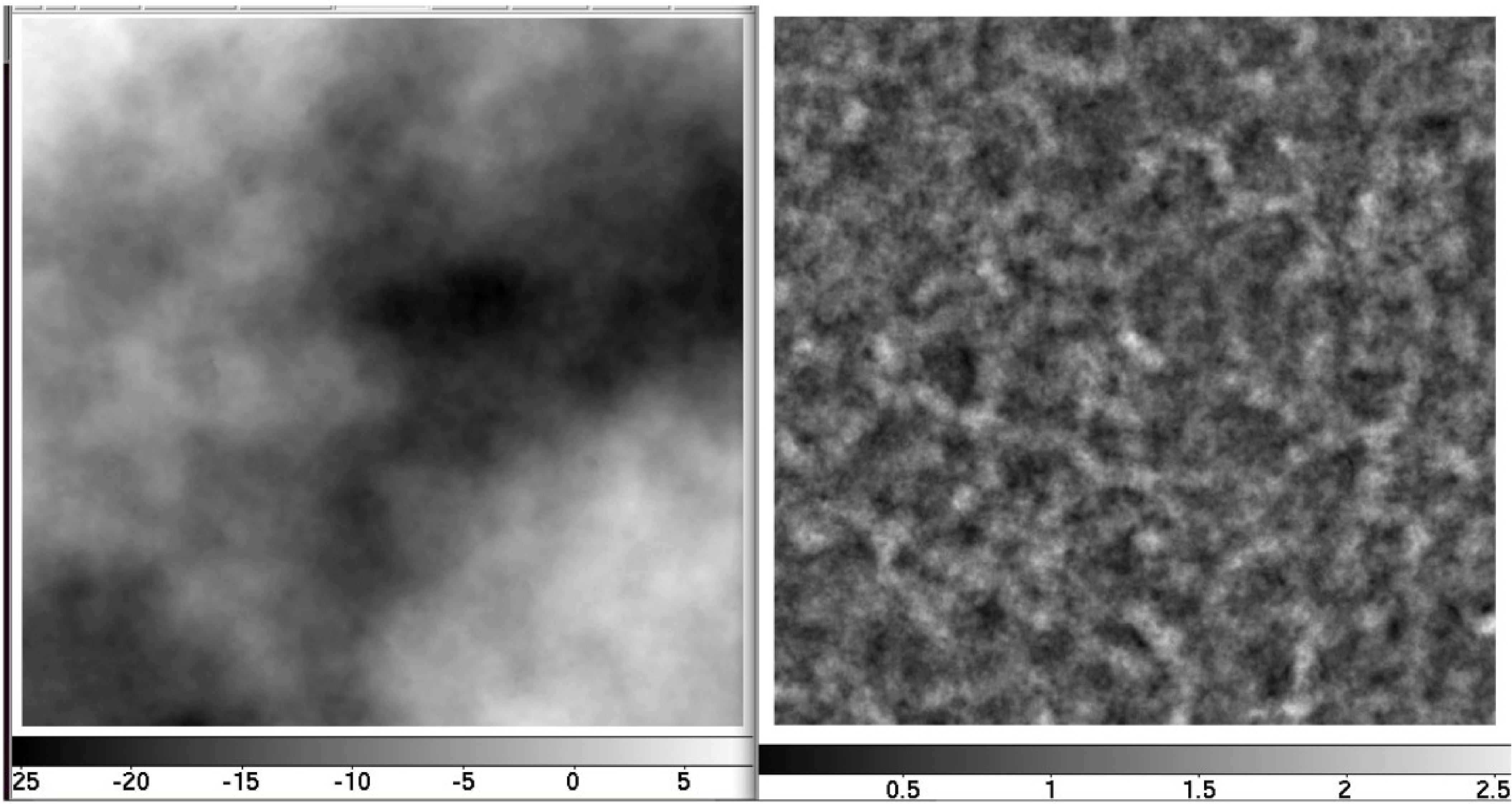
Several effects:

- Diffraction propagation converts phase into amplitude (scintillation)
- Diffraction propagation is chromatic → scintillation is partially chromatic
- Refraction index of air is chromatic
- Atmospheric dispersion → light path from source to telescope is slightly different for different colors (~cm offset between red and blue light at a few km altitude)

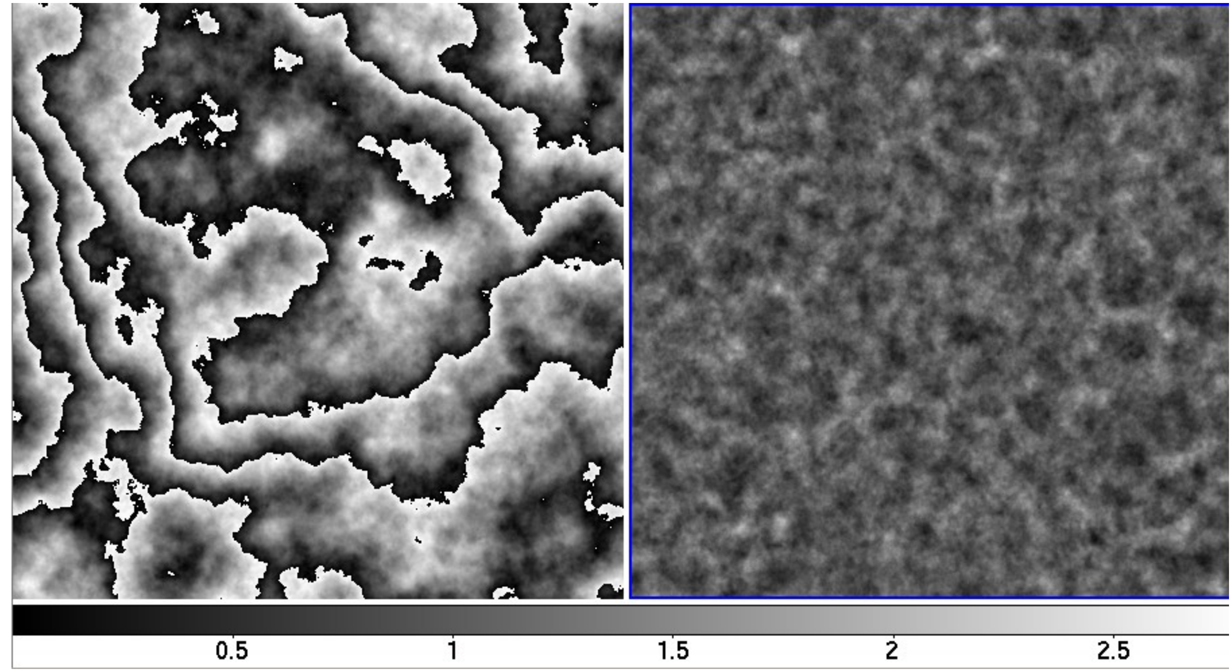
Amplitude and chromaticity effects << phase corrugations, but can be important in Extreme-AO systems aiming a very high quality correction
OR
High precision photometry

Scintillation example

2mm/pixel, 1024x1024 pix (~2m x 2m)
lambda=500nm, 30 deg zenith angle, 0.8” seeing at zenith
Site: Mauna Loa observatory (3500m altitude)



Photometry: Atmospheric Scintillation



Atmospheric phase

Atmospheric ampl (scintillation)

Scintillation noise (multiplicative)
= 0.004 airmass$^{3/2}$ D$^{-2/3}$ t$^{-1/2}$ exp$^{-h/h0}$

~ 1/cos(zenith angle) → airmass

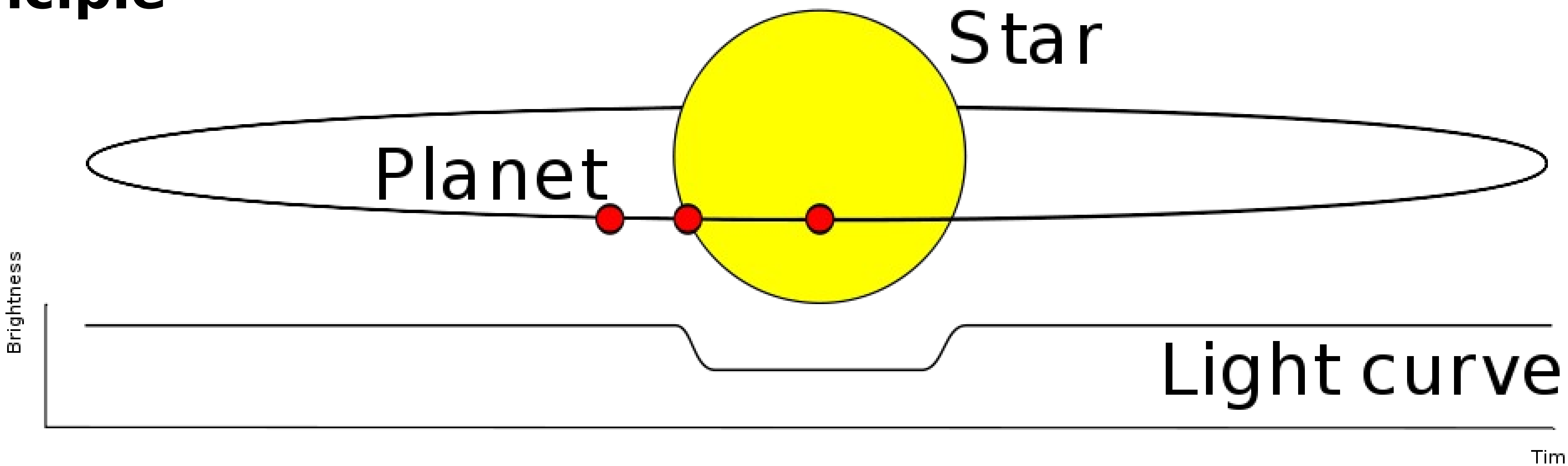
Tel diam [m] → D

exp time [sec] → t

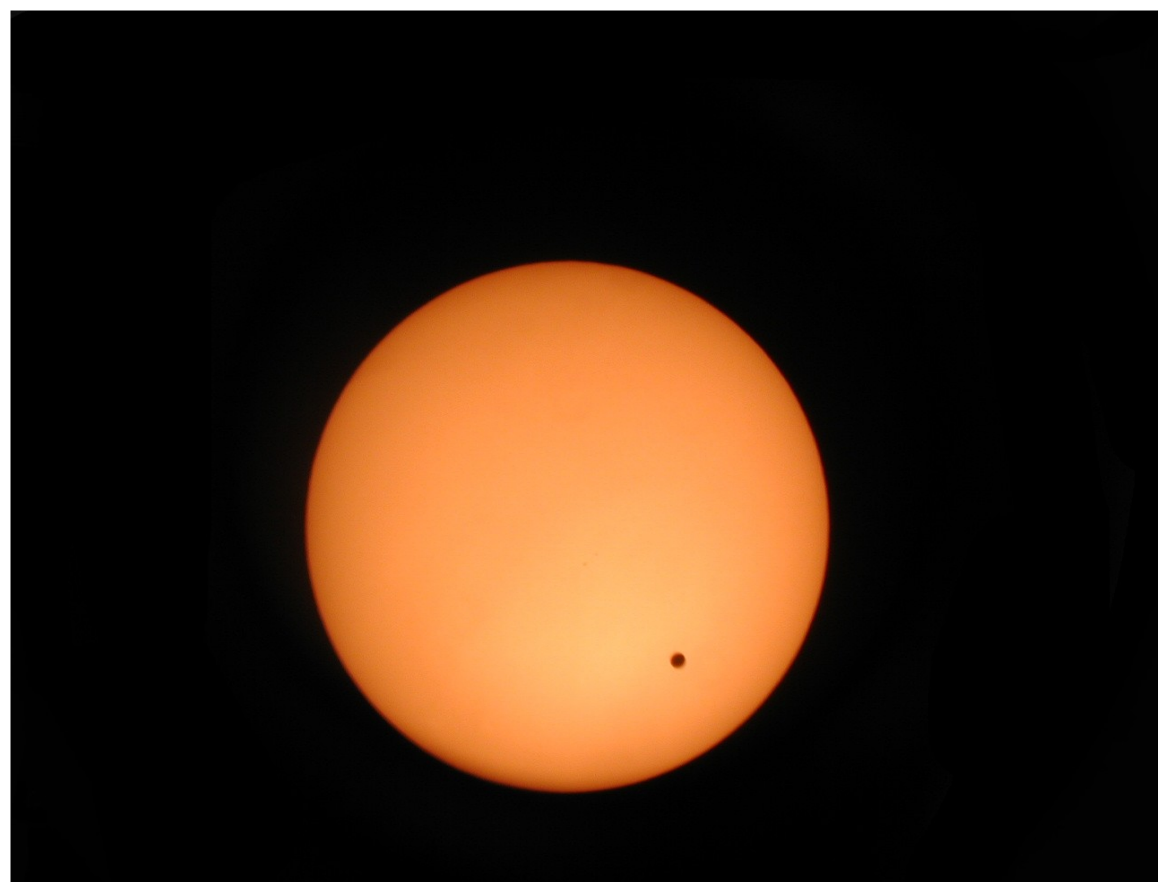
altitude / 8km → exp$^{-h/h0}$

Earth analog transit:
1m telescope, 1hr exposure → 7e-5 (similar to Earth transit depth)

Principle



2004 transit of Venus



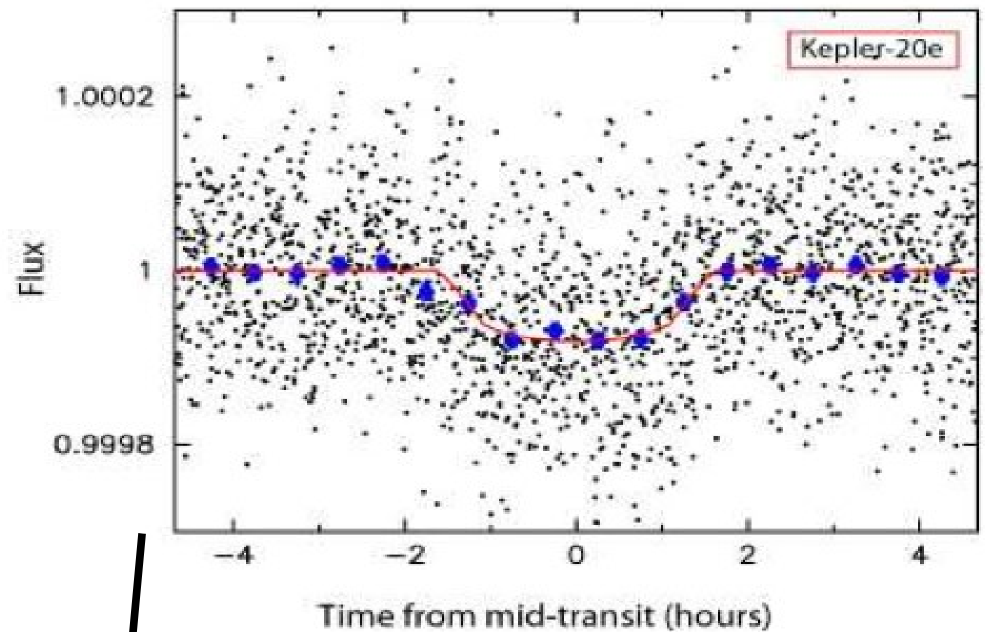
Transit depth

Transit depth = $(R_{planet} / R_{star})^2$

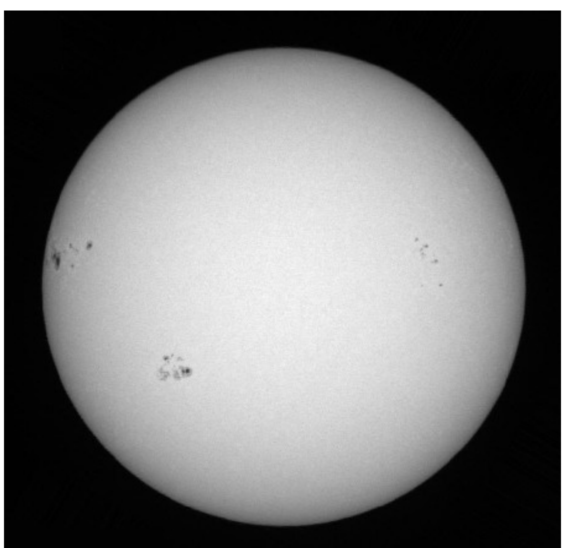
Earth radius = 6,371 km
Jupiter radius = 69,911 km
Sun radius = 696,000 km

→ Amplitude = 8e-5 (Earth)
→ Amplitude = 1% (Jupiter)

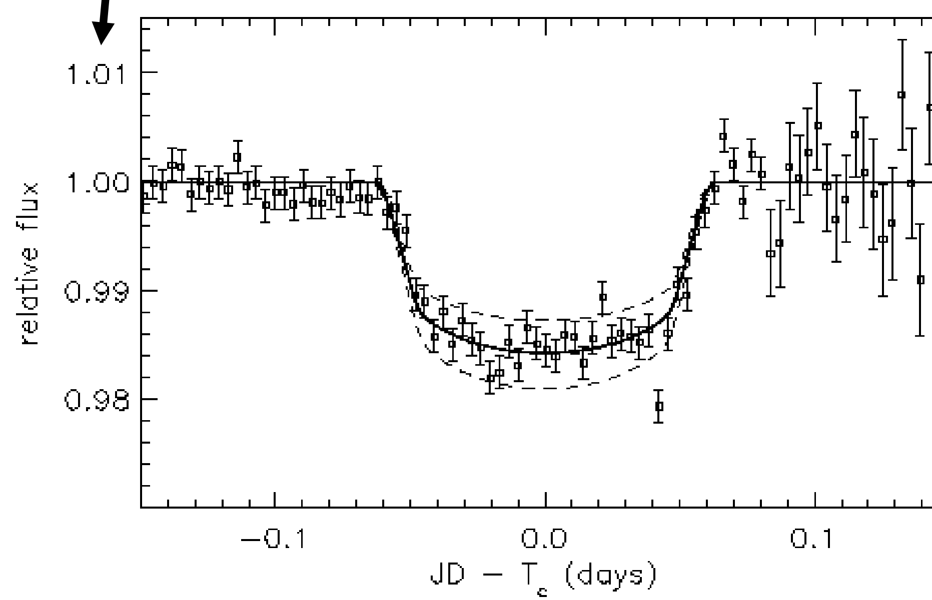
Kepler 20e: transit depth = 0.008 %
(similar to Earth transit depth)



~100x factor in scale



HD 209458: 1.7% deep transit



Note that transit is deeper at mid-transit
(limb darkening)

Error

Summary

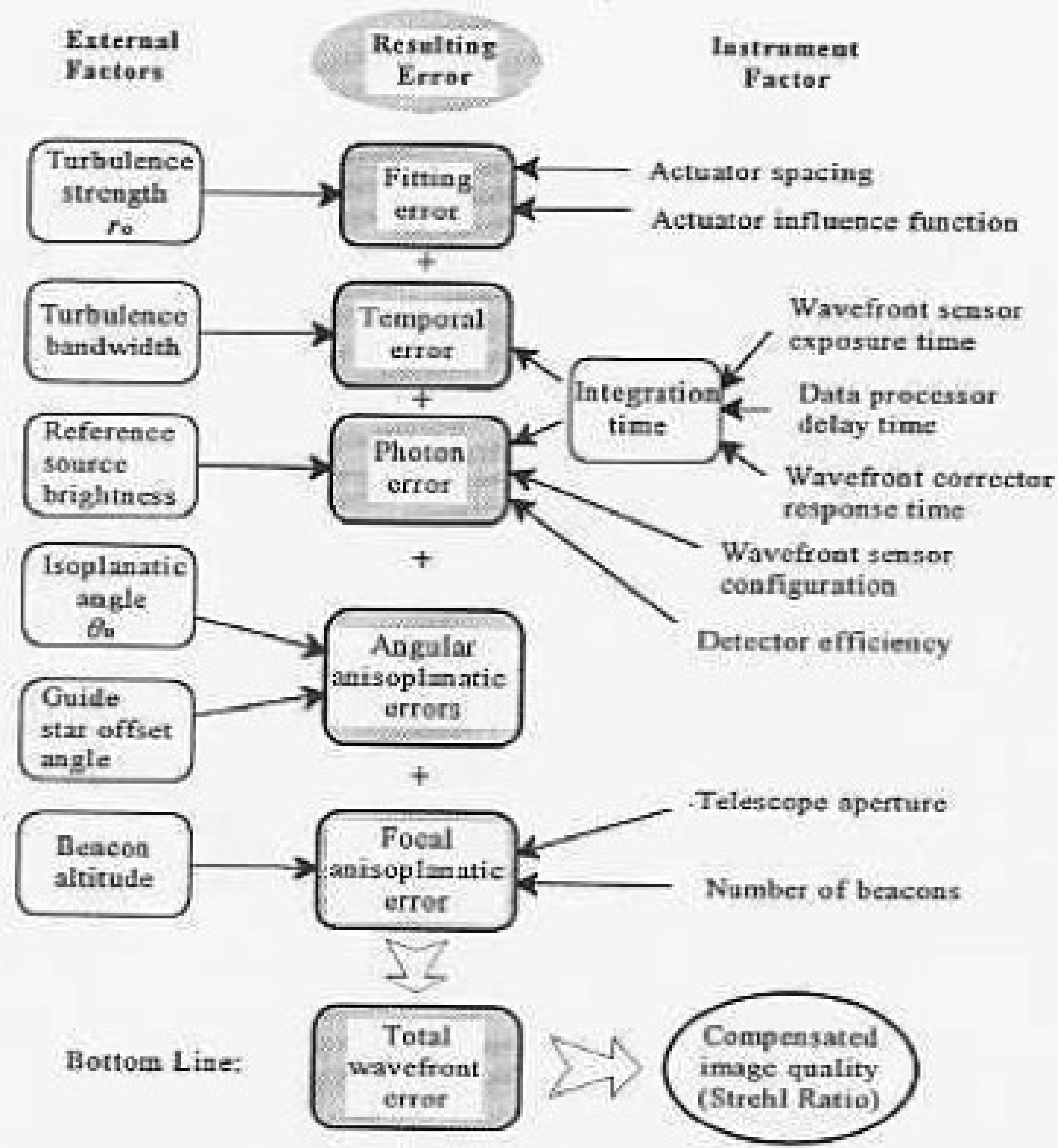


Figure 2.32 Main sources of wavefront error in adaptive optics.

How good a Strehl do you need?