AO system Design: Astronomy

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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 course 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

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

Optical/mechanical design considerations

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

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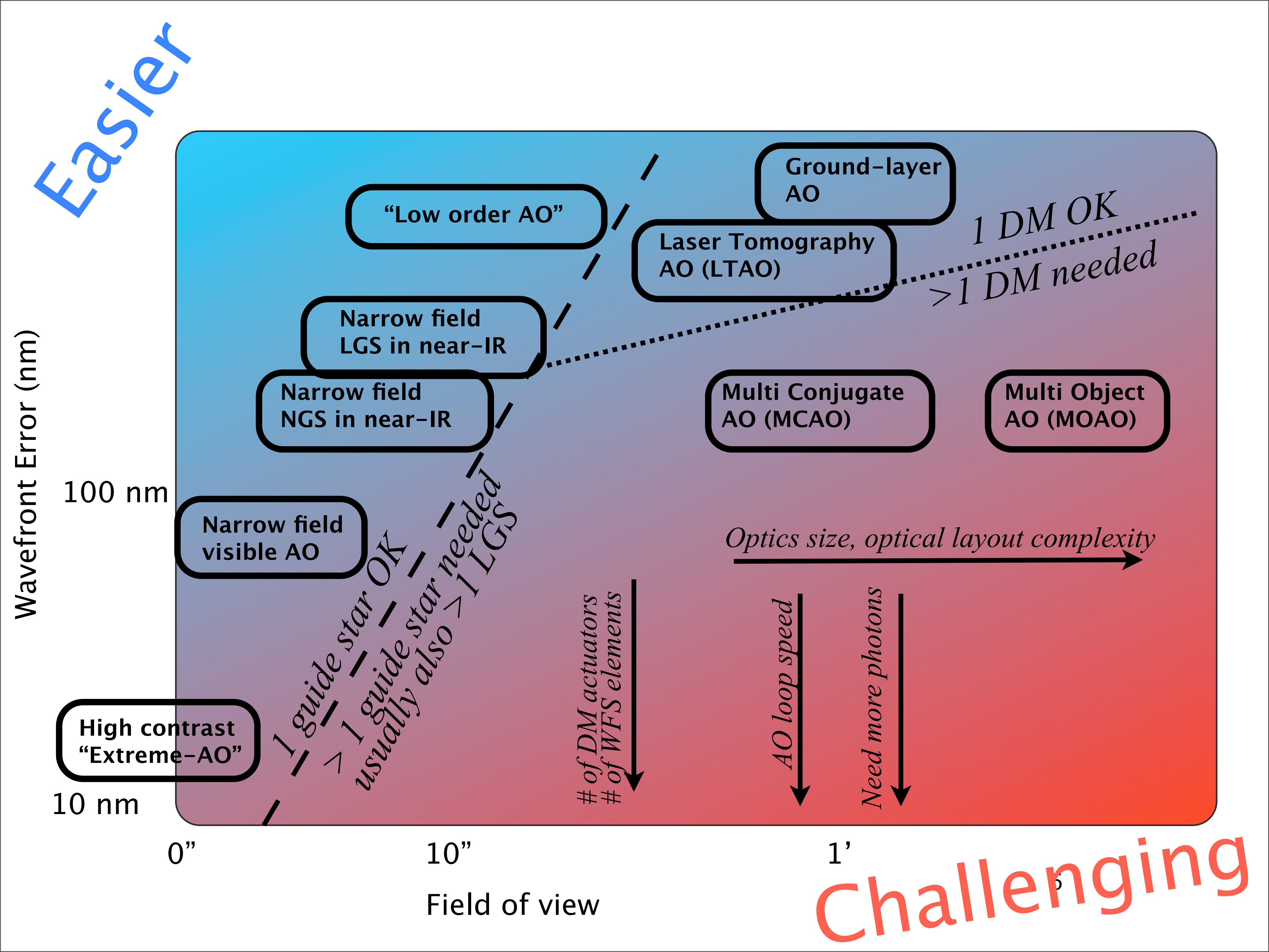
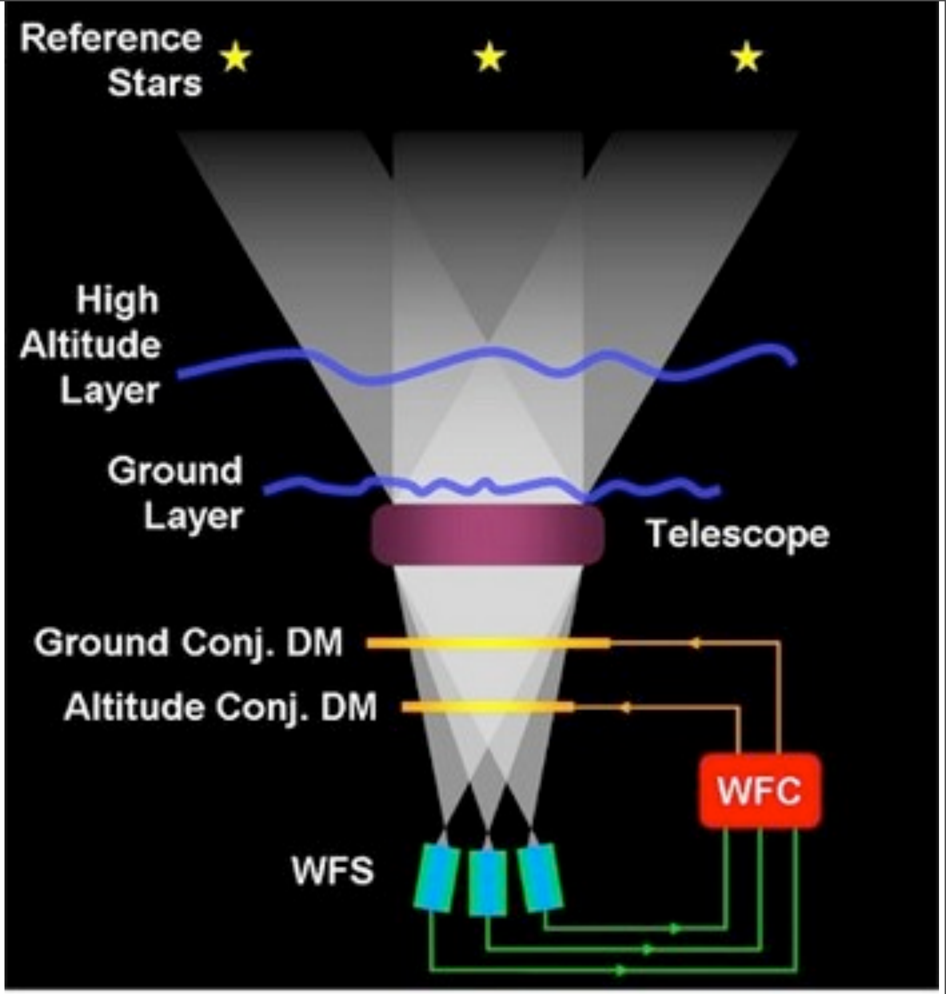


Easier
Challenging
Wavefront Error (nm)
100 nm
10 nm
Field of view
0"
10"
1'
"Low order AO"
Ground-layer AO
Laser Tomography AO (LTAO)
1 DM OK
>1 DM needed
Narrow field LGS in near-IR
Narrow field NGS in near-IR
Multi Conjugate AO (MCAO)
Multi Object AO (MOAO)
Narrow field visible AO
High contrast "Extreme-AO"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

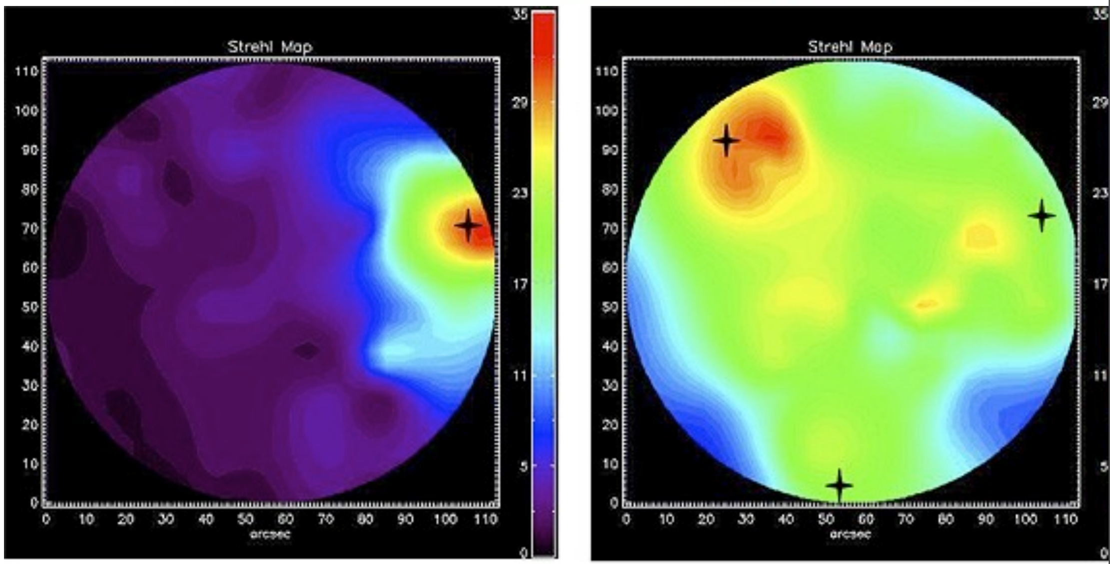
Multi-Conjugate AO (MCAO)



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)

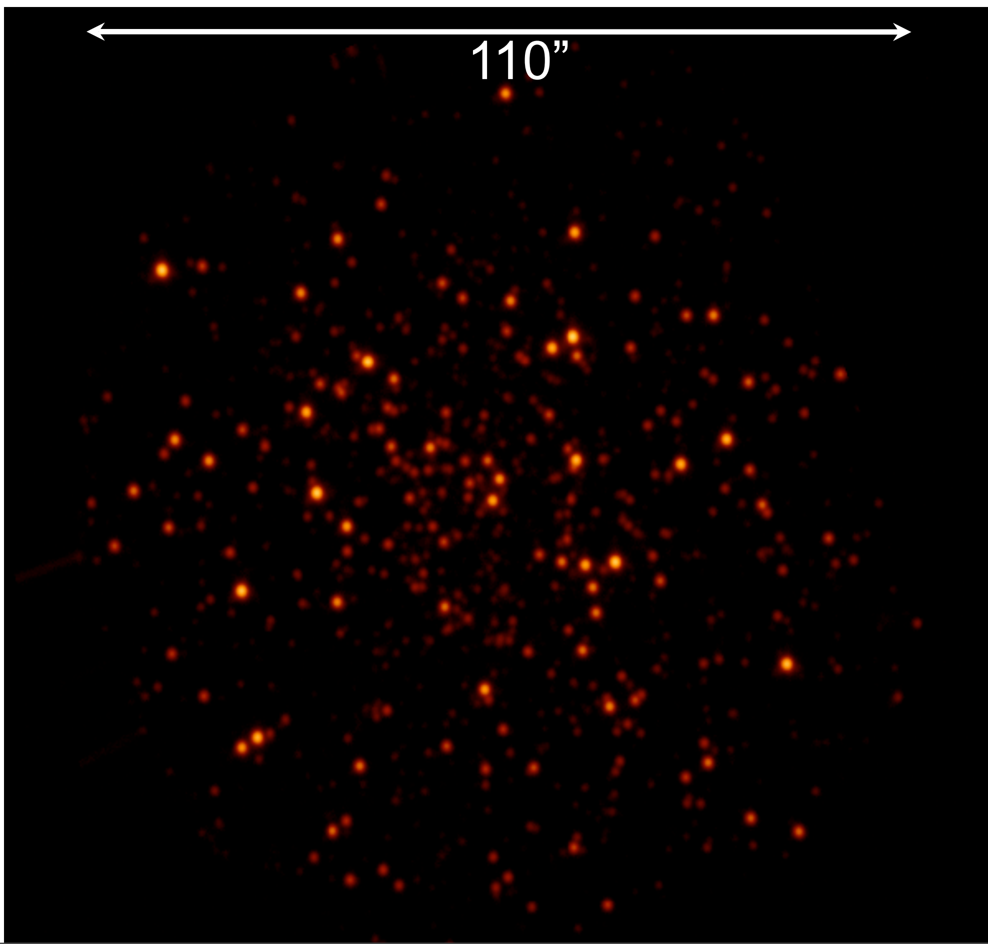


The MMT multi-laser Ground Layer AO (GLAO) system

MMT results: M3 globular cluster

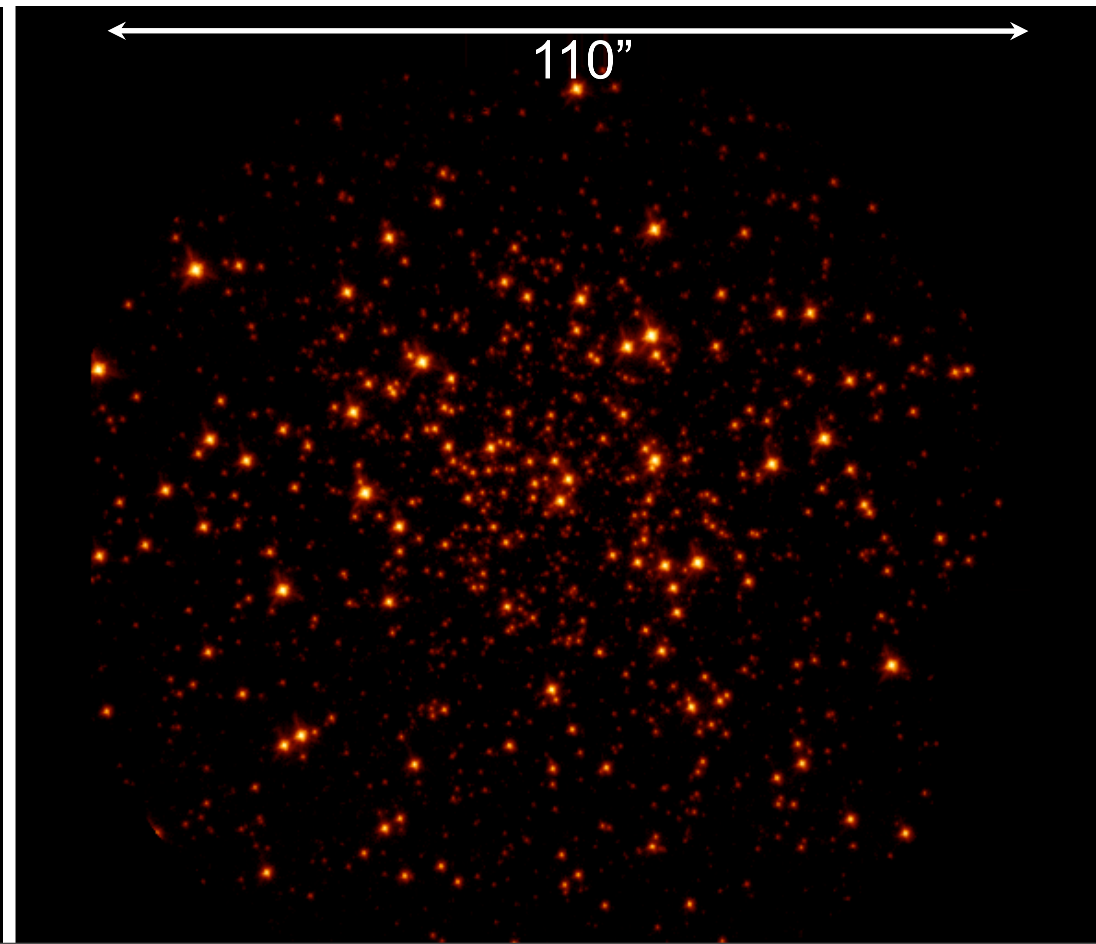
Open loop, K_s filter, seeing 0.70”

Logarithmic scale



Closed loop GLAO, K_s filter, seeing 0.30”

Logarithmic scale



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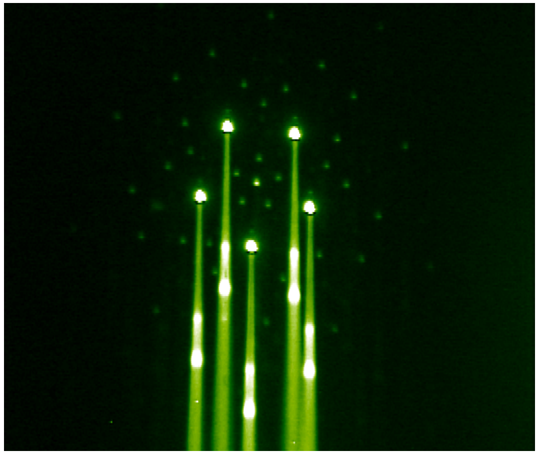

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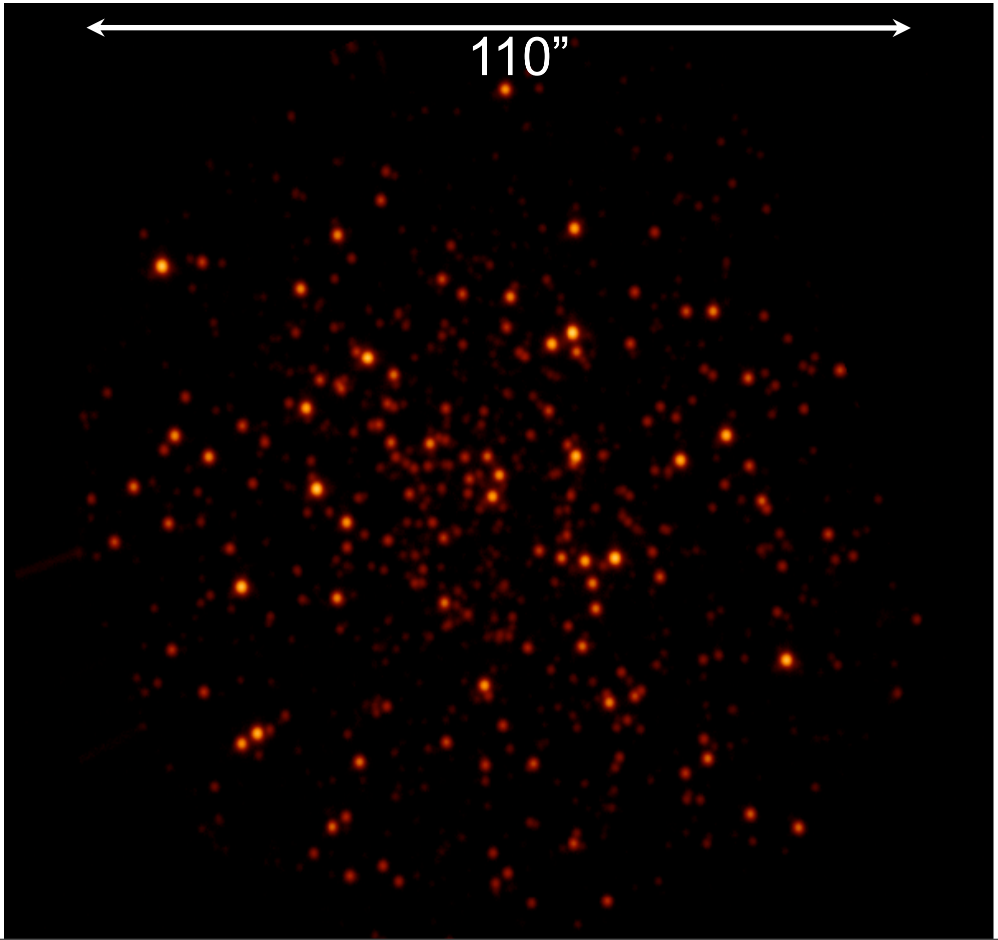
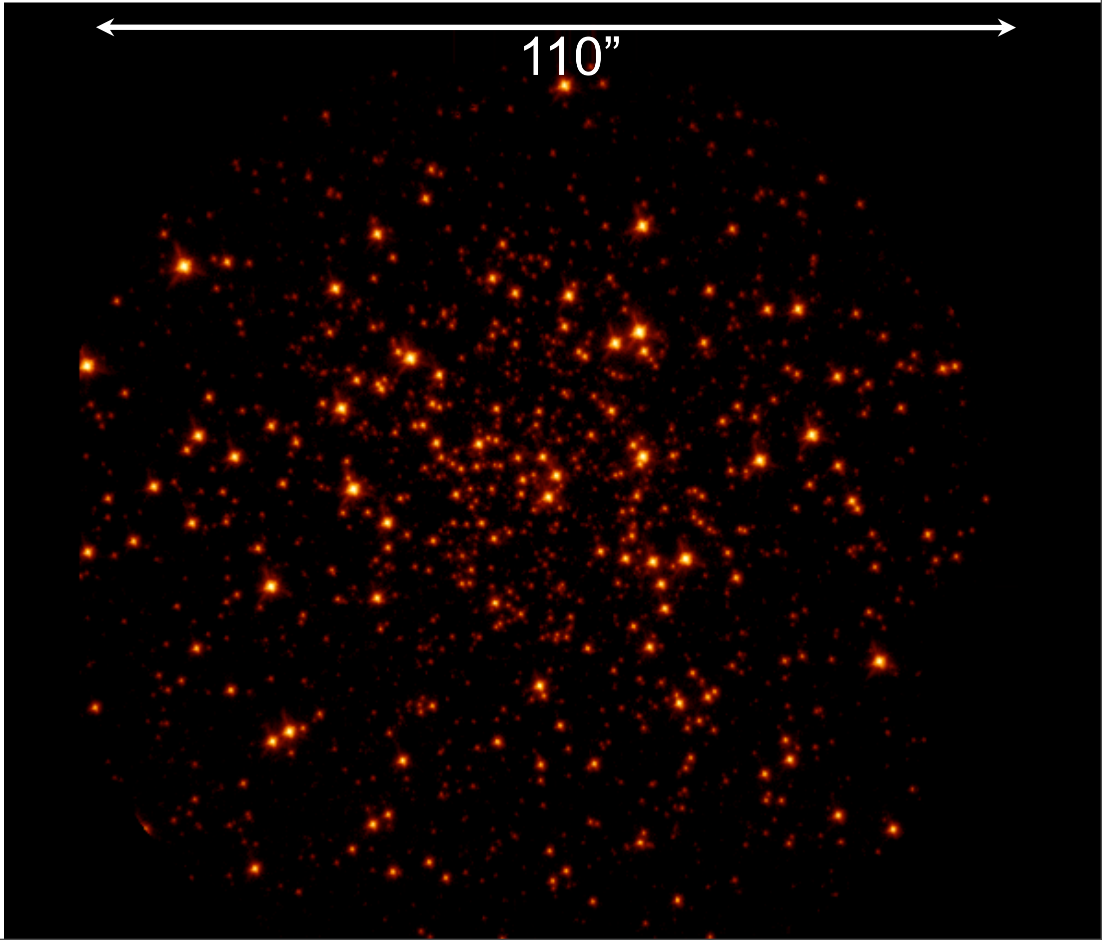
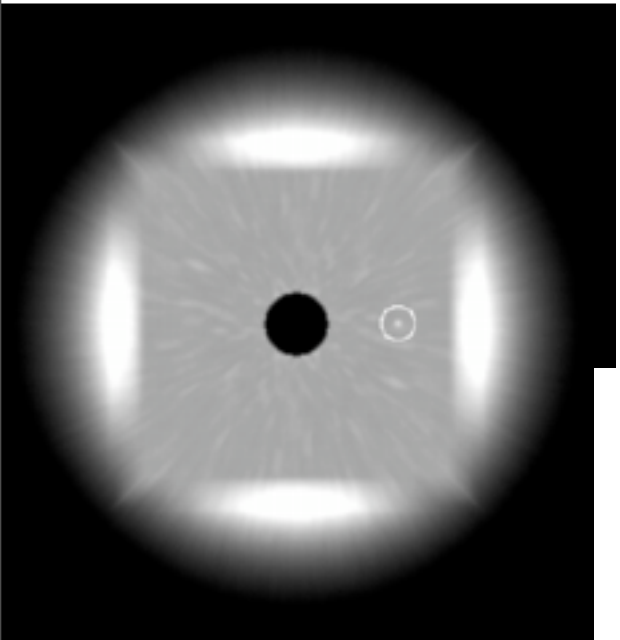


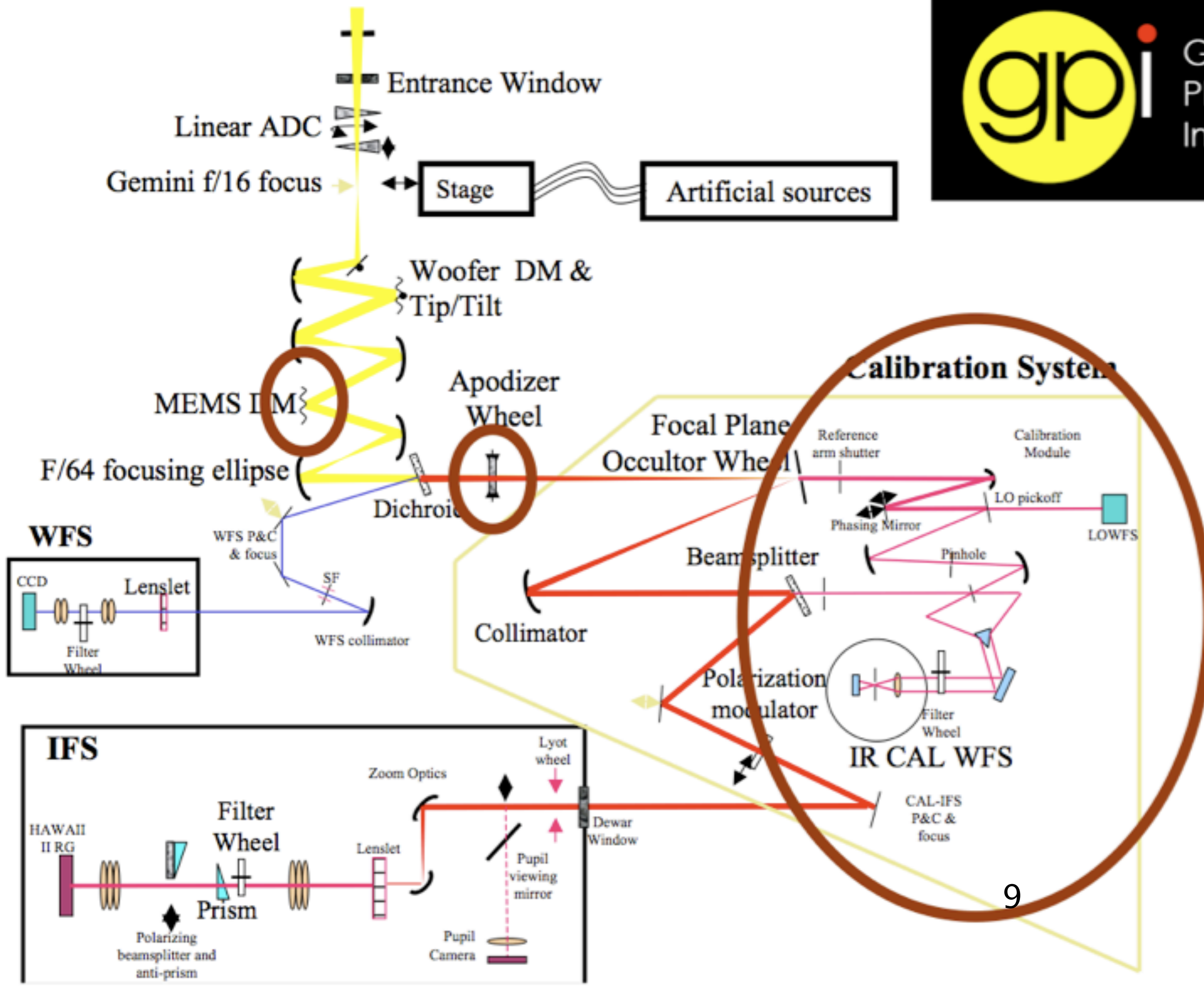
Closed loop GLAO, K_s filter, seeing 0.30”

Logarithmic scale



Extreme-AO





Gemini Planet Imager
SPHERE (ESO)
Subaru CExAO system

Also under study:
space-based ExAO systems

Outline

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Main challenges / error budget terms in astronomical AO systems

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References:

Fundamental wavefront error budget terms :

1 Fitting error

2 Speed

3 Limited # of photons

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)

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Wavefront error budget

Wavefront error σ is in radian in all equations.

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

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

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

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1. Fitting error

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

Wavefront errors from atmospheric turbulence in sq. radian

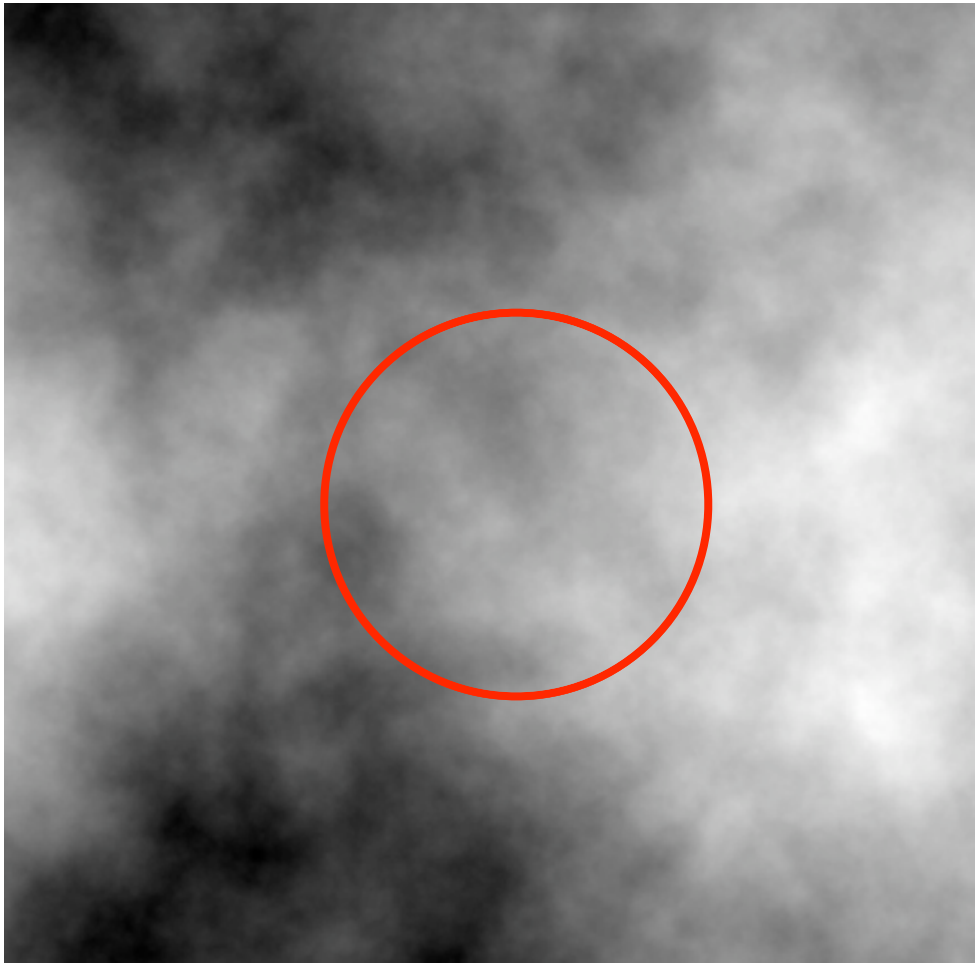
$\sigma^2 = 1.03\ (D/r_0)^{5/3}$

+ Vibrations, telescope guiding errors

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

+ DM shape at rest

Kolmogorov turbulence



1. Fitting error

Need enough stroke on the actuators

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

(unit = radian)

Larger D -> more stroke needed

(also: faster system -> more stroke needed)

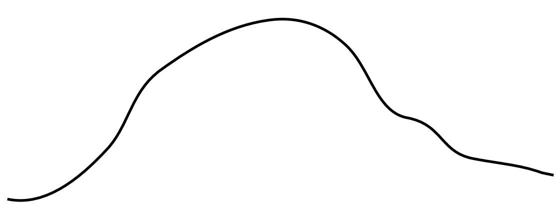
Most of the power is in tip-tilt:

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

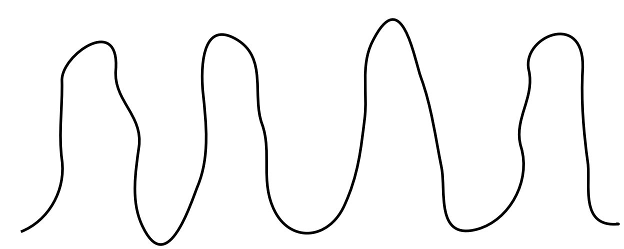
On many DMs, interactuator stroke < overall stroke

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

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



Is easier than



1. Fitting error

Need enough actuators to fit the wavefront

D = telescope diameter, N = number of actuators

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

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

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

If we assume continuous facesheet,

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

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

Diffraction limit requires ~ N = 24

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

1. Fitting error & field of view

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

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

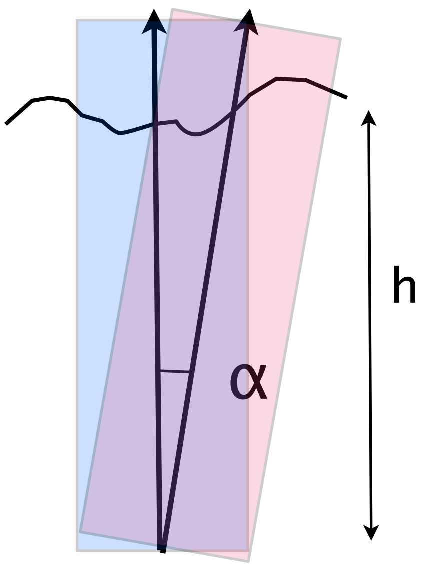
If we assume perfect on-axis correction, and a single turbulent layer at altitude h, the variance (sq. radian) is :

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

Where α is the angle to the optical axis,

θ_0 is the isoplanatic angle:

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



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

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

2. Speed

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

Assuming pure time delay t

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

t_0 = coherence time "Greenwood time delay"= $0.314\, r_0/v$

v = 10 m/s

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

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

Assuming that sampling frequency should be ~ 10x bandwidth

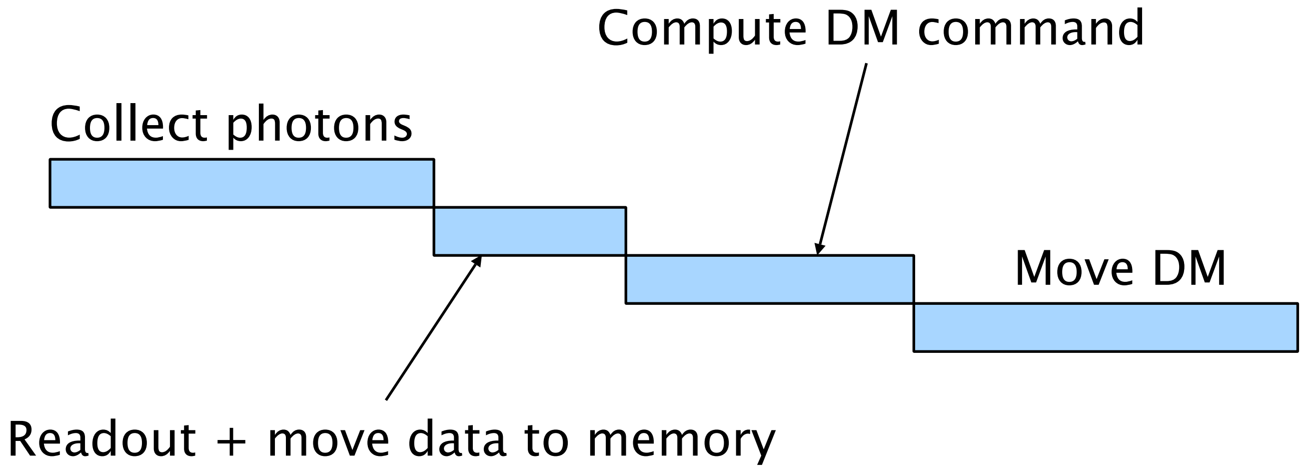
for "diffraction-limited" system (1 rad error in wavefront):
sampling frequency = 400 Hz for K band

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

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

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

-> Clever, predictive control can help a lot
"anything that could be predicted should be !"



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

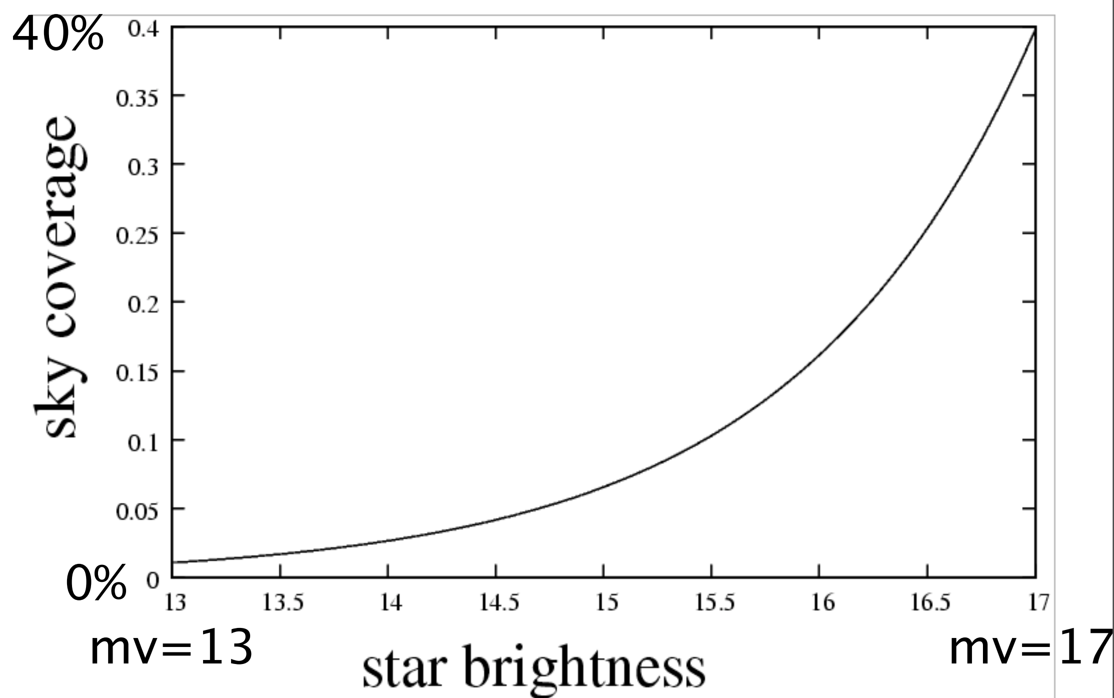
With a fixed finite photon arrival rate, how well can I measure the wavefront (speed vs. SNR) ?
Longer WFS "exposure time" -> better SNR but more time lag

mV=15 -> 400 ph/ms on 8m pupil in 0.5 μm band
& 20% efficiency

Example 1: General purpose NGS system
Goal: achieve diffraction limited performance over much of the sky

Star brighter than mV density
~ 9e-4 exp(0.9 mV) per
sq. deg (galactic pole)
ref: Parenti & Sasiela, 1994

Within a 20" radius:



mV=8 -> 2.5e5 ph/ms on 8m pupil in 0.5 micron 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, ~ 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:

- r0 gets small: more actuators needed
  r_0 goes as $\lambda^{6/5}$ -> N goes as $\lambda^{-12/5}$
- speed gets high ($\tau_0 = 0.314\ r_0/v$) -> τ_0 goes as $\lambda^{6/5}$
- anisoplanatism gets small (FOV, sky coverage go down)
  θ_0 goes as $\lambda^{6/5}$
- chromaticity gets worse (refraction index of air varies more in visible than near-IR), ADC is needed
- instrumental non-common path errors get more serious

But diffraction limit is small in visible

Number of actuators should be very carefully chosen

Resist temptation of having more actuators than needed:
Systems with too many actuators are:

- not very sensitive (don't work well on faint stars)
- Harder to run at high speed
- demanding on hardware, more complex & costly
- less tolerant (alignment, detector readout noise...)

See also "noise propagation" section of this lecture

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

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

PSF quality: metric**S**

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

Example or PSF quality metrics:

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

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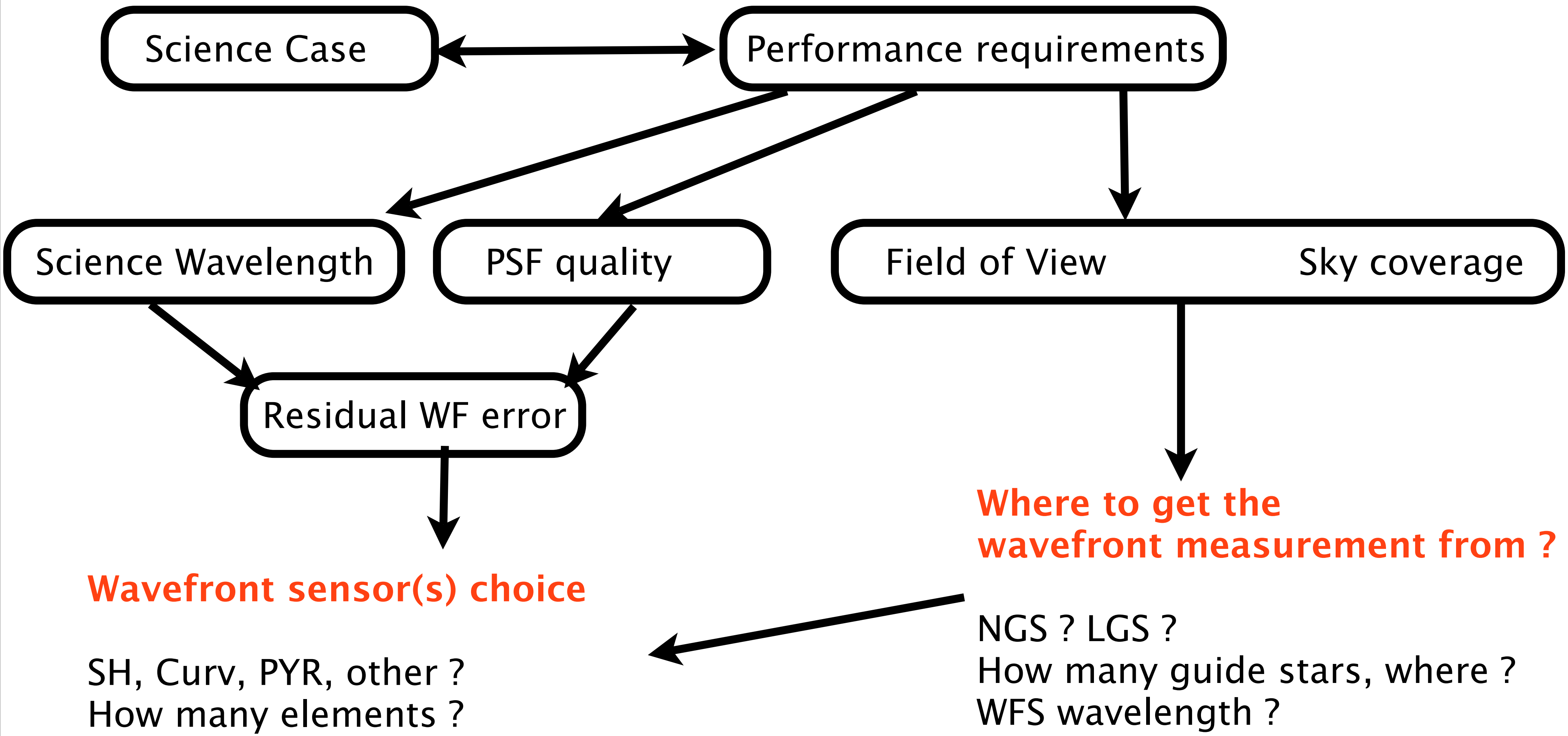
Optical/mechanical design considerations

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



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

Where to get the wavefront measurement ?

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

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

which laser ?

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

LGS allows large (>50%) sky coverage

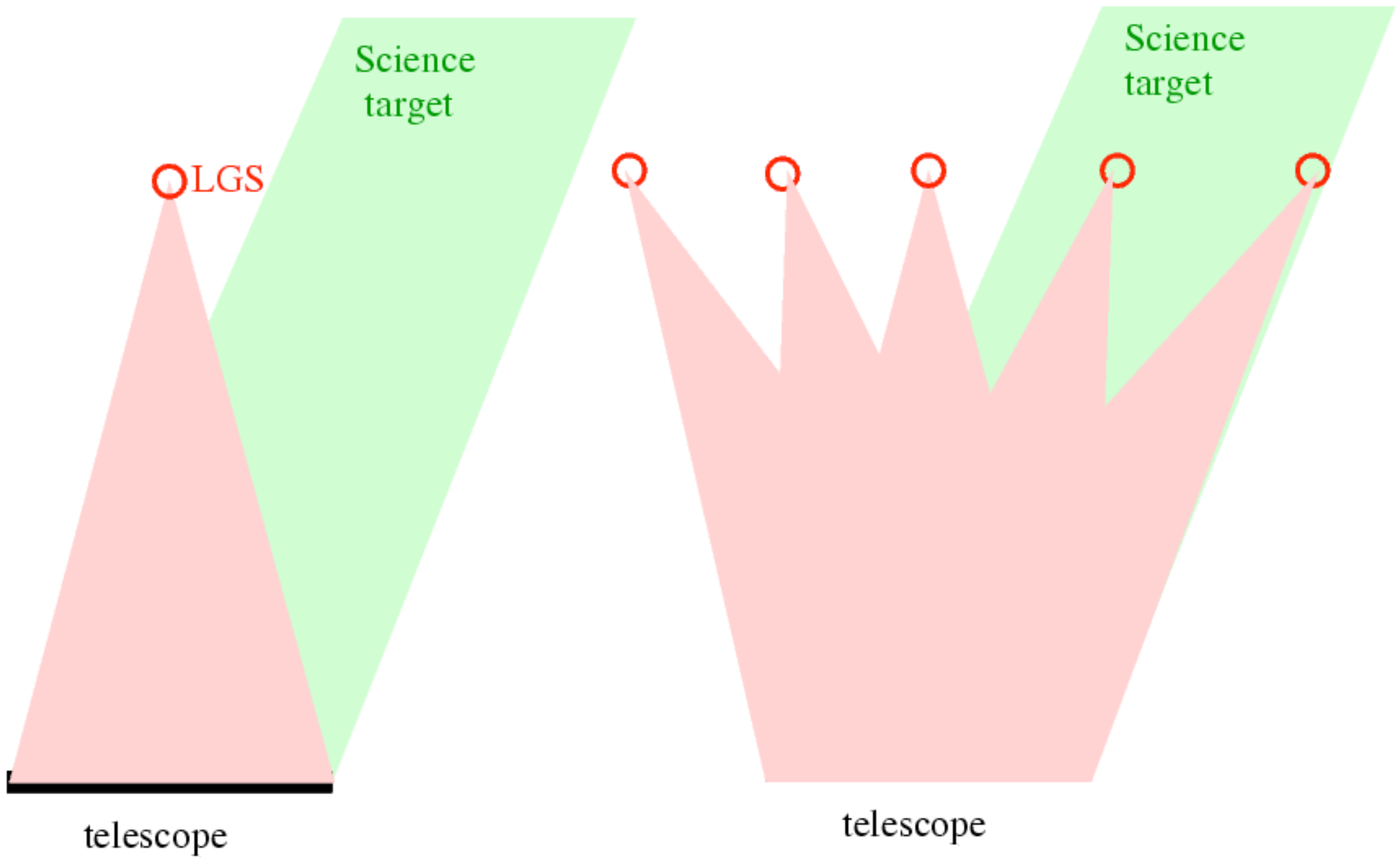
Where to get the wavefront measurement ?

(2) Need several guide stars ?

(for field of view, tomography ?)

Multiple LGS ?

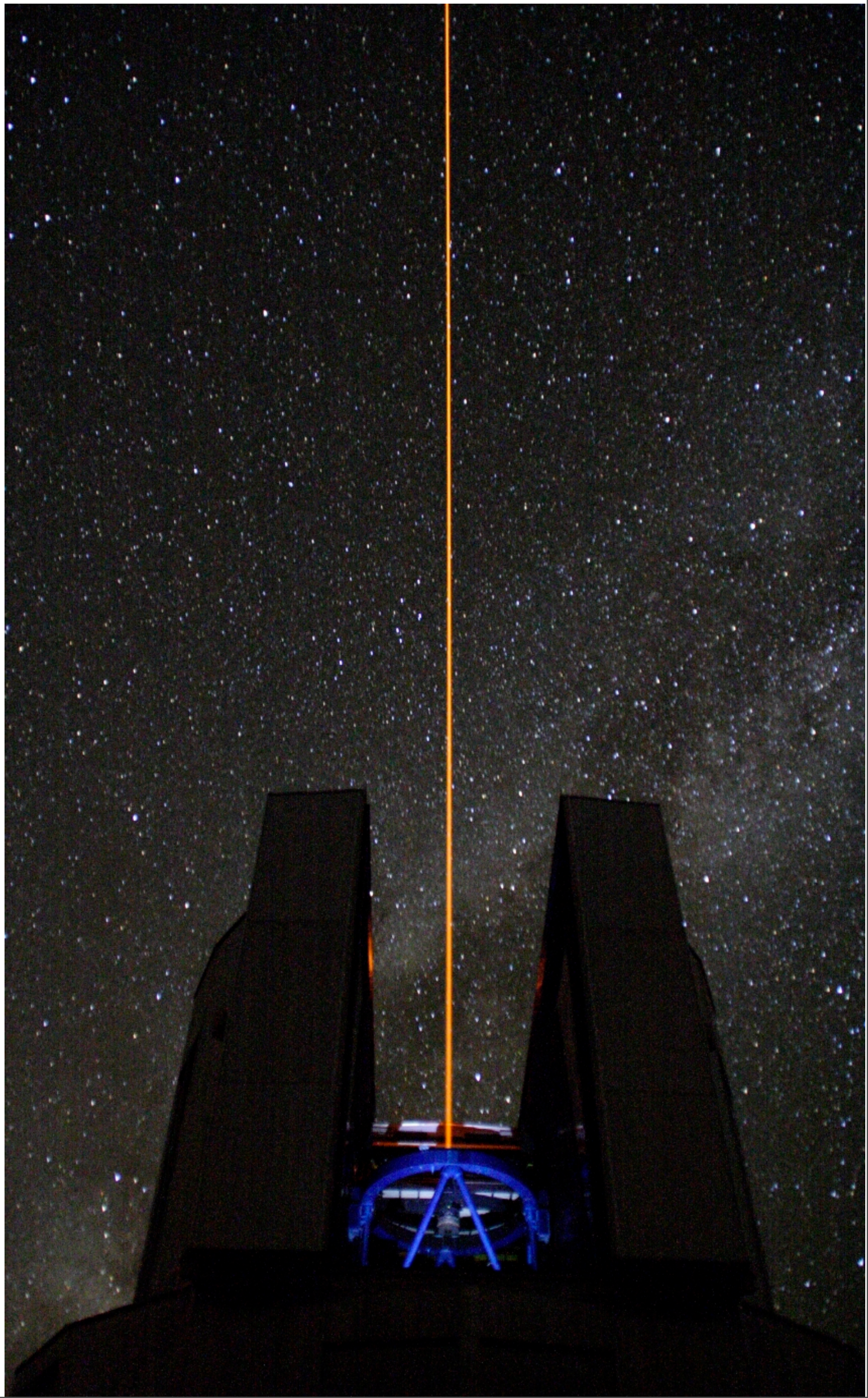
Multiple NGS ?



Some challenges of LGS AO

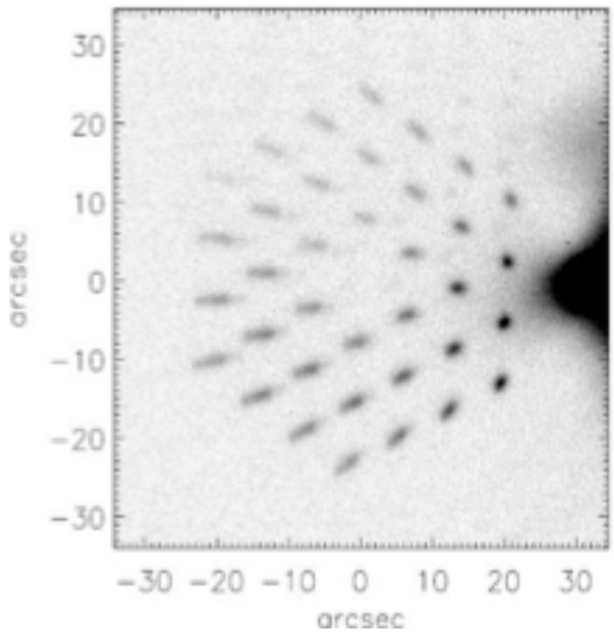
Cone effect due to finite altitude of LGS (90km sodium, few km for Rayleigh)
-> can be solved by using several lasers and tomography

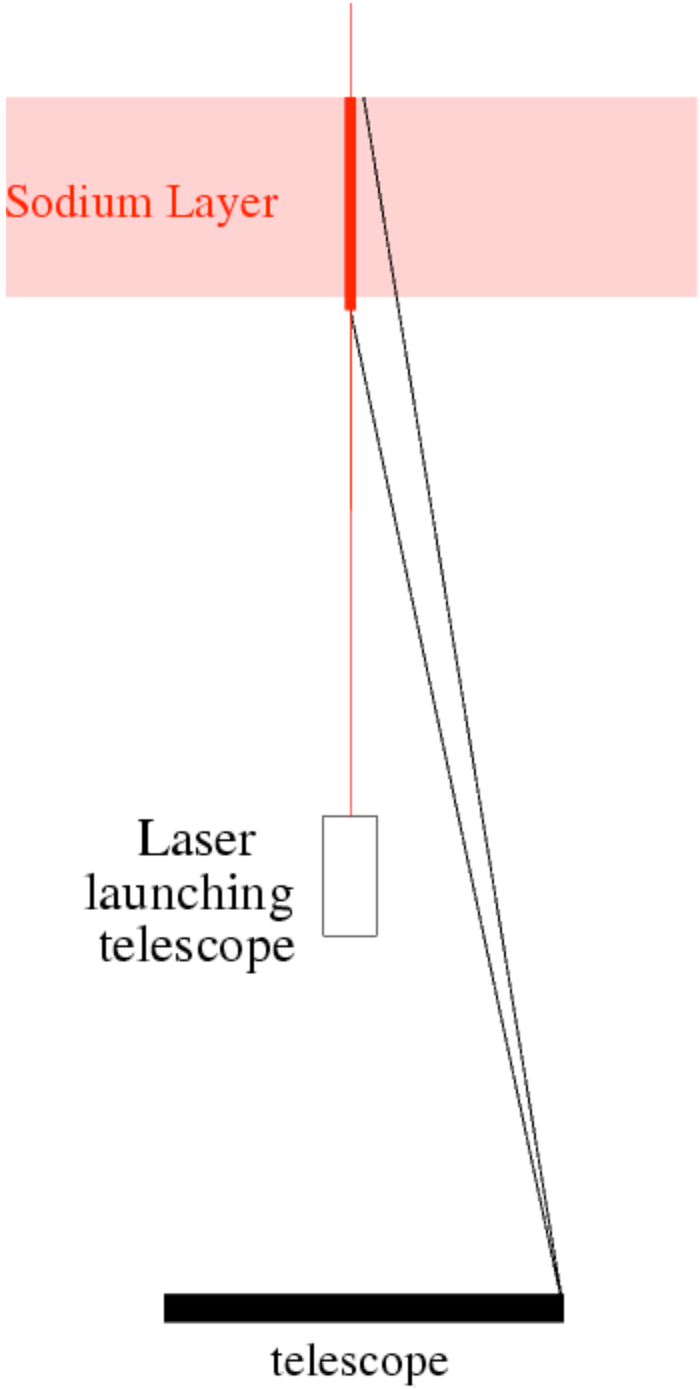
Tip/Tilt & Focus sensing
Upstream & downstream paths are the same: tip/tilt not seen
Sodium layer altitude not fixed: LGS focus info is incomplete (can be used to sense fast focus)
-> **Still need NGS(s) for tip/tilt & Focus**
-> polychromatic laser (not quite mature yet)



Some challenges of LGS AO

Spot elongation
Sodium layer
is ~10km thick





4m off-axis = 1” elongation
15m off-axis = 4” elongation
-> better to launch from the center of pupil than the edge
-> dynamic refocusing + pulsed laser

Upstream path / diffraction
Laser has to go through turbulence -> LGS is extended
Diffraction from laser launching telescope aperture

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

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

Some fundamental desirable WFS properties

Linearity, range and sensitivity

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 constrast mask (ZPM)
Pupil plane Mach-Zehnder interferometer (PPMZ)

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

Non-linear Curvature (nlCurv)
Non-linear Pyramid (nlPyr) ?

Wavefront sensor 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):

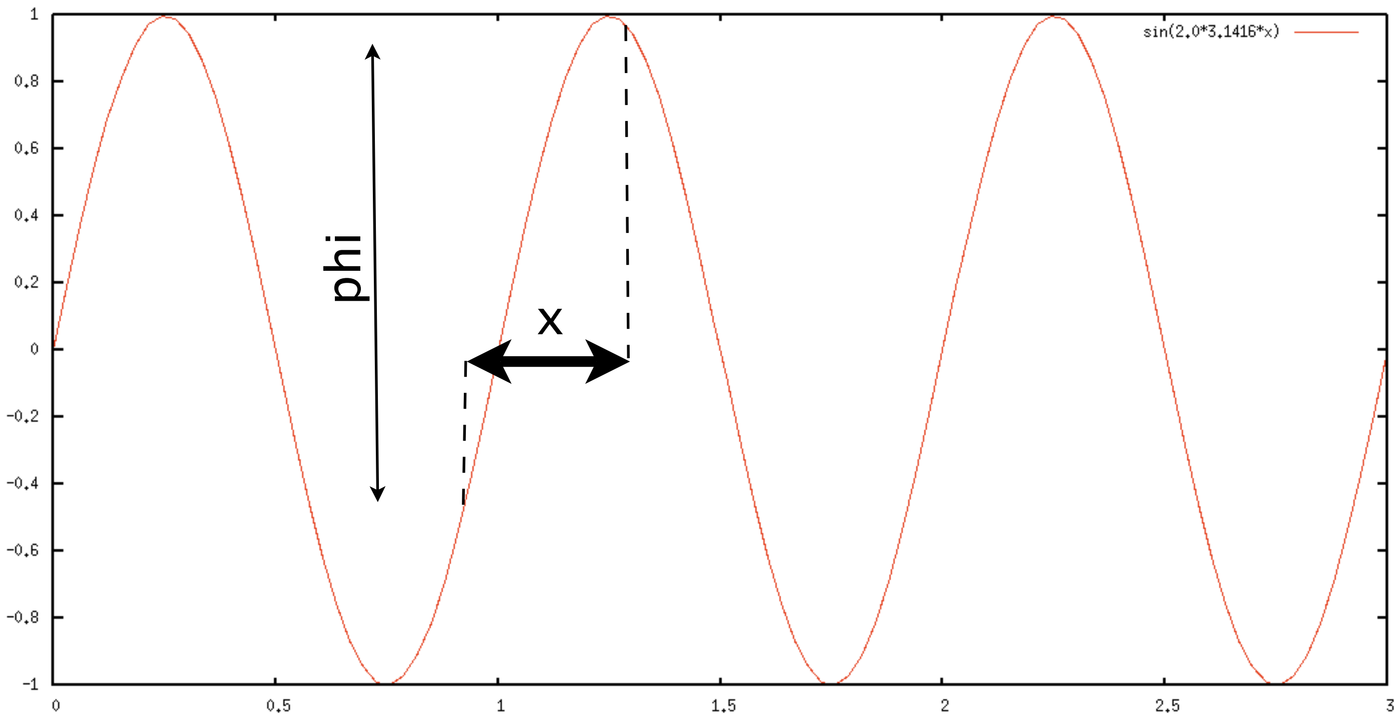
Error (rad) = Sensitivity / sqrt(# of photons)

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)

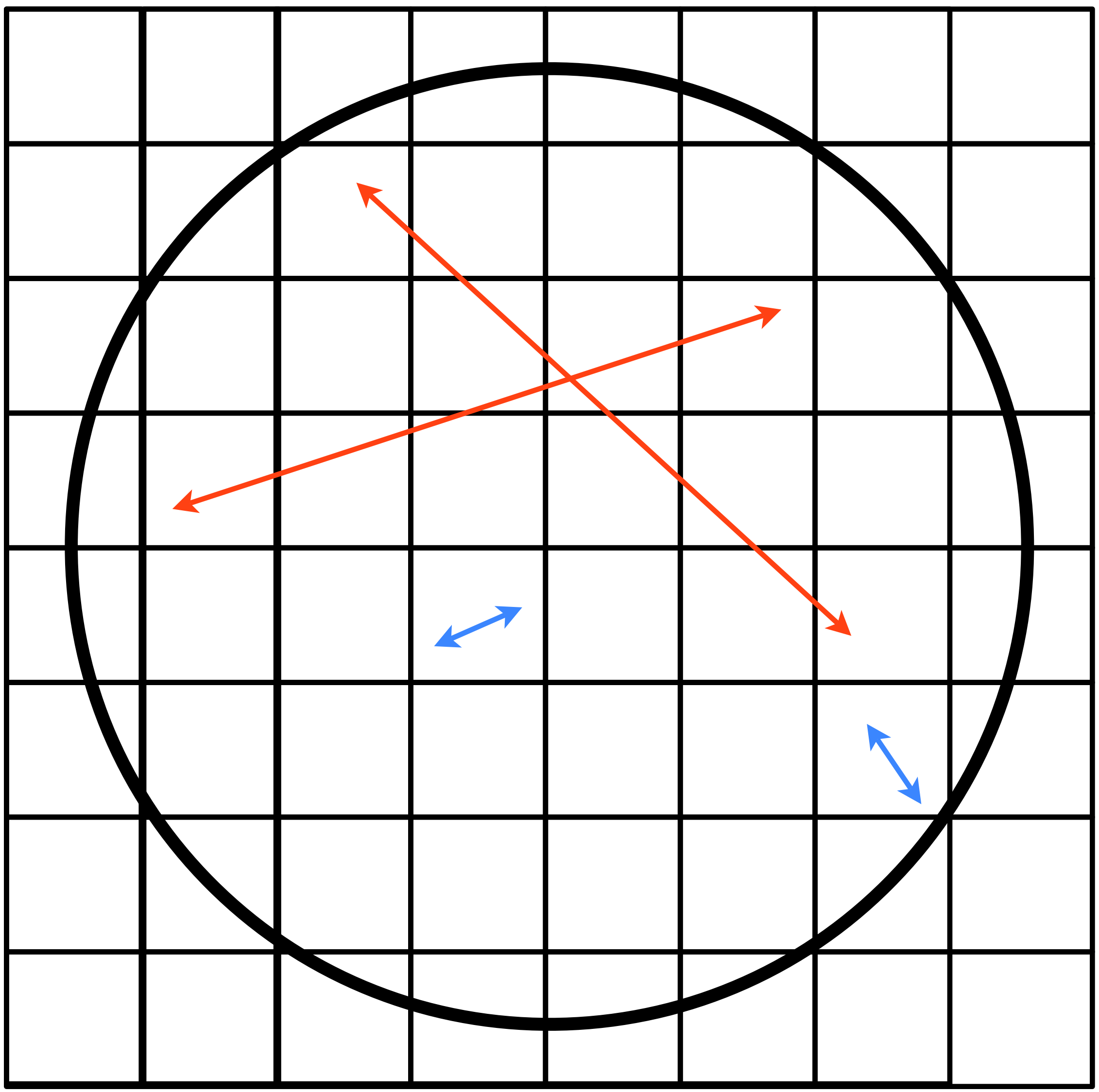
Sensitivity: how to optimally convert a phase error into an intensity signal ?

Example: a sine wave phase aberration of C cycles across the pupil, amplitude = a rad (in figure below, C = 3, a = 1 rad)
Interferences between points separated by x (2xC PI in “phase” along the sine wave)
Phase difference between 2 points: phi = 2 a sin(xC PI)
Intensity signal is linear with phi (small aberrations approximation)

For a sine wave aberration on the pupil, a good WFS will make interferences between points separated by ~ half a period of the sine wave

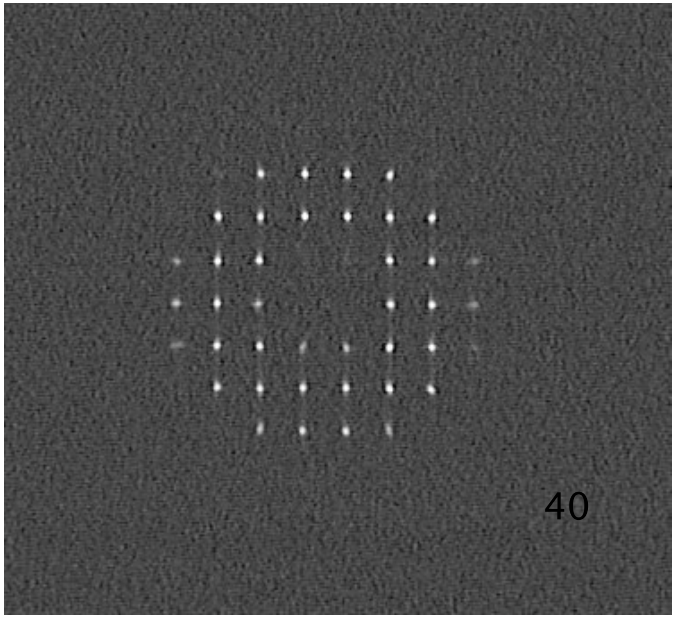


SH WFS : sensitivity issue for low spatial frequencies



Problem:
SH does not allow interferences between points of the pupil separated by more than subaperture size

-> Poor sensitivity to low order modes ("noise propagation" effect)
This gets worse as the number of actuators increases !!!



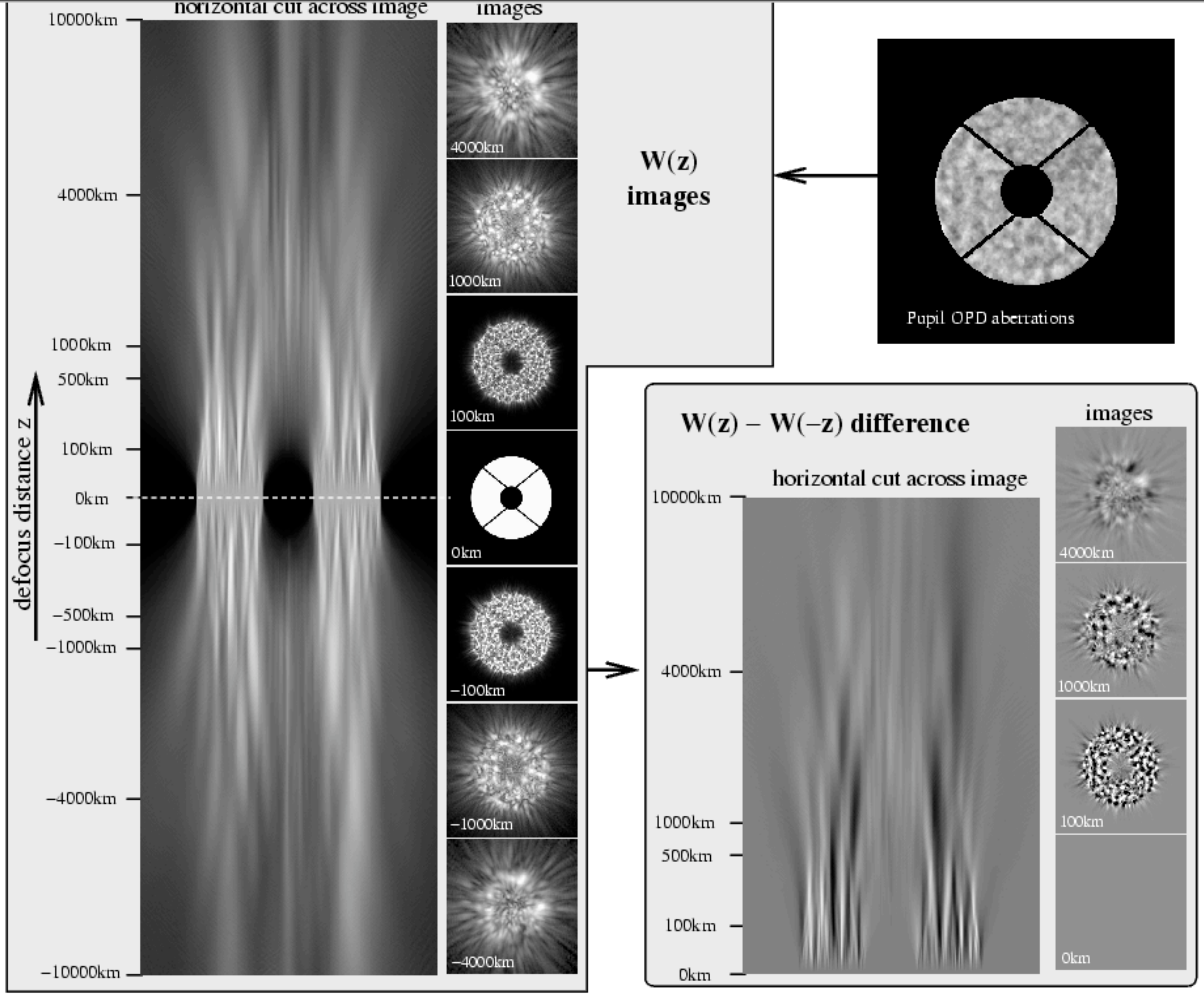
Linear Curvature WFS also suffers from the same poor sensitivity for low order aberrations

Uses **light propagation** to convert phase into intensity
-> measure intensity in at least 2 “defocused” pupil planes and compute phase.

Usually, planes at +dz and -dz, with dz ~ 1000km are imaged.

If dz “small” (~1000 km), **defocused images are linear function of wavefront curvature**

Next slide shows how phase is converted into intensity modulation in a CWFS



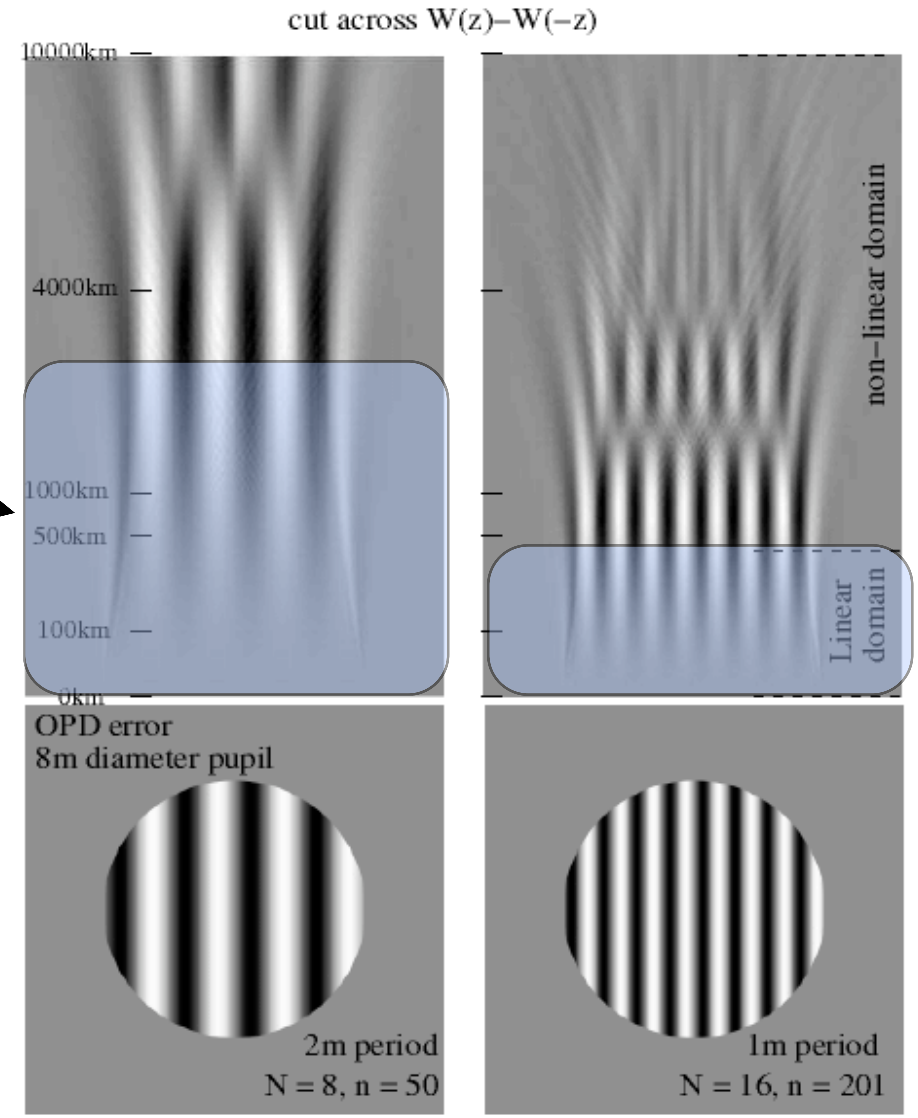
horizontal cut across image
images
10000km
4000km
1000km
500km
100km
0km
−100km
−500km
−1000km
−4000km
−10000km
defocus distance z
4000km
1000km
100km
0km
−100km
−1000km
−4000km
W(z)
images
Pupil OPD aberrations
W(z) − W(−z) difference
images
horizontal cut across image
10000km
4000km
1000km
500km
100km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

Problem #1:

The "Linear" domain of curvature wavefront sensing (= defocus range within which wavefront curvature is linearly transformed into intensity modulation) becomes smaller as the # of actuators increases.

-> defocus distance must be kept small

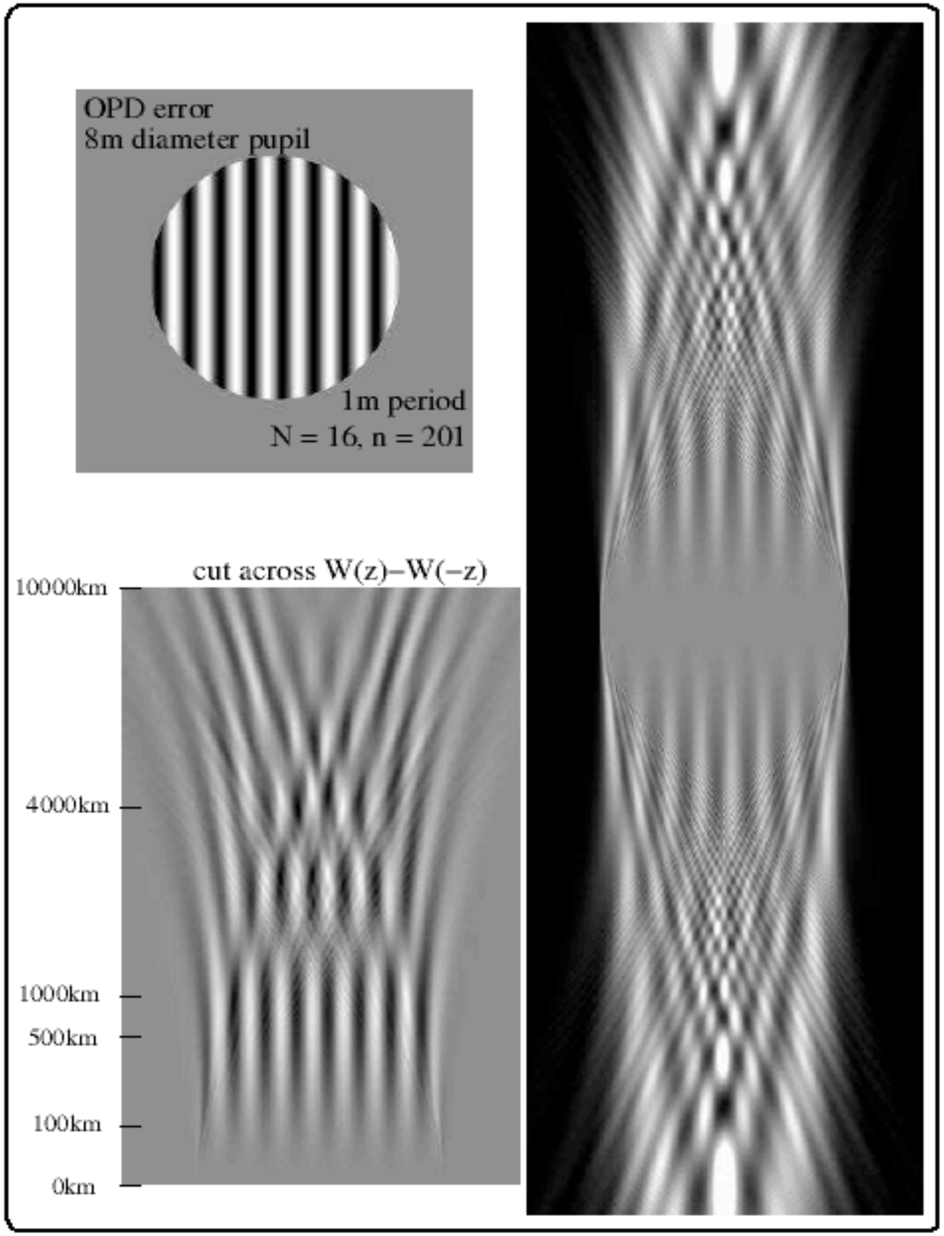
-> this forces low spatial frequencies to be poorly sensed on a high order system

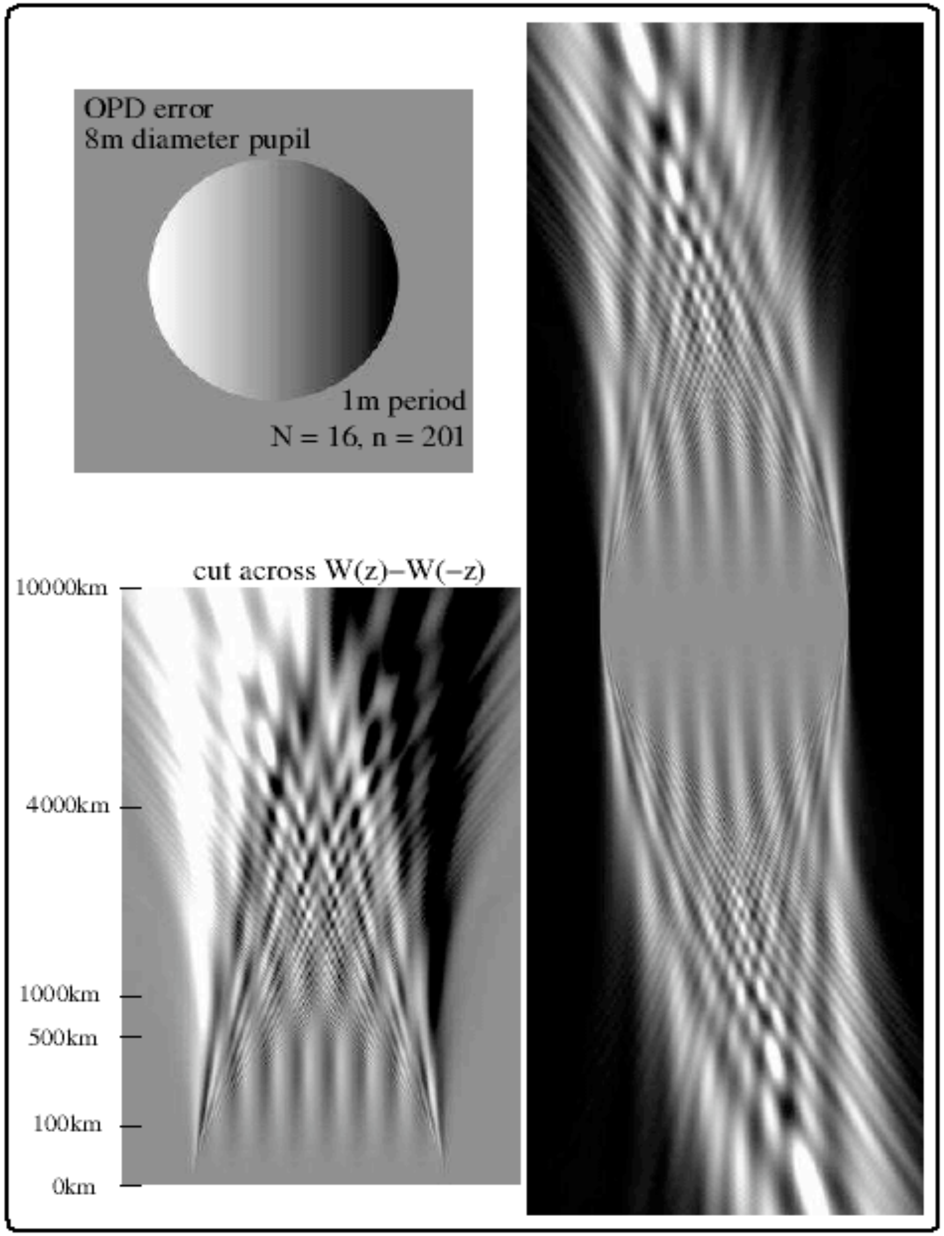


Low order system High order system

Note: This simulation does not telescope include central obstruction

<u>Problem #2</u>: Low order aberrations “scramble” high spatial frequencies
-> defocus distance must be kept small





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, sigma2 ~ 1/D^2 (more photons)
Ideally, one should be able to achieve: sigma2 ~ 1/D^4 (more photons + smaller l/D)

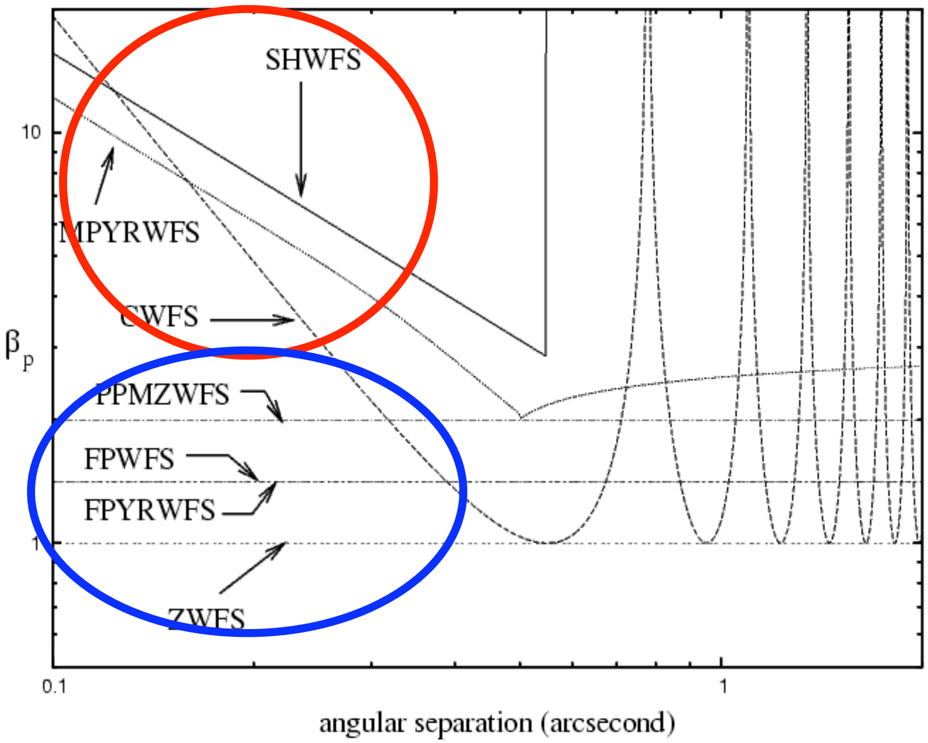
SH, linear Curvature are widely used because they are linear over a wide range of WF errors

How to build a 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 ! -> very poor dynamical range

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)

	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
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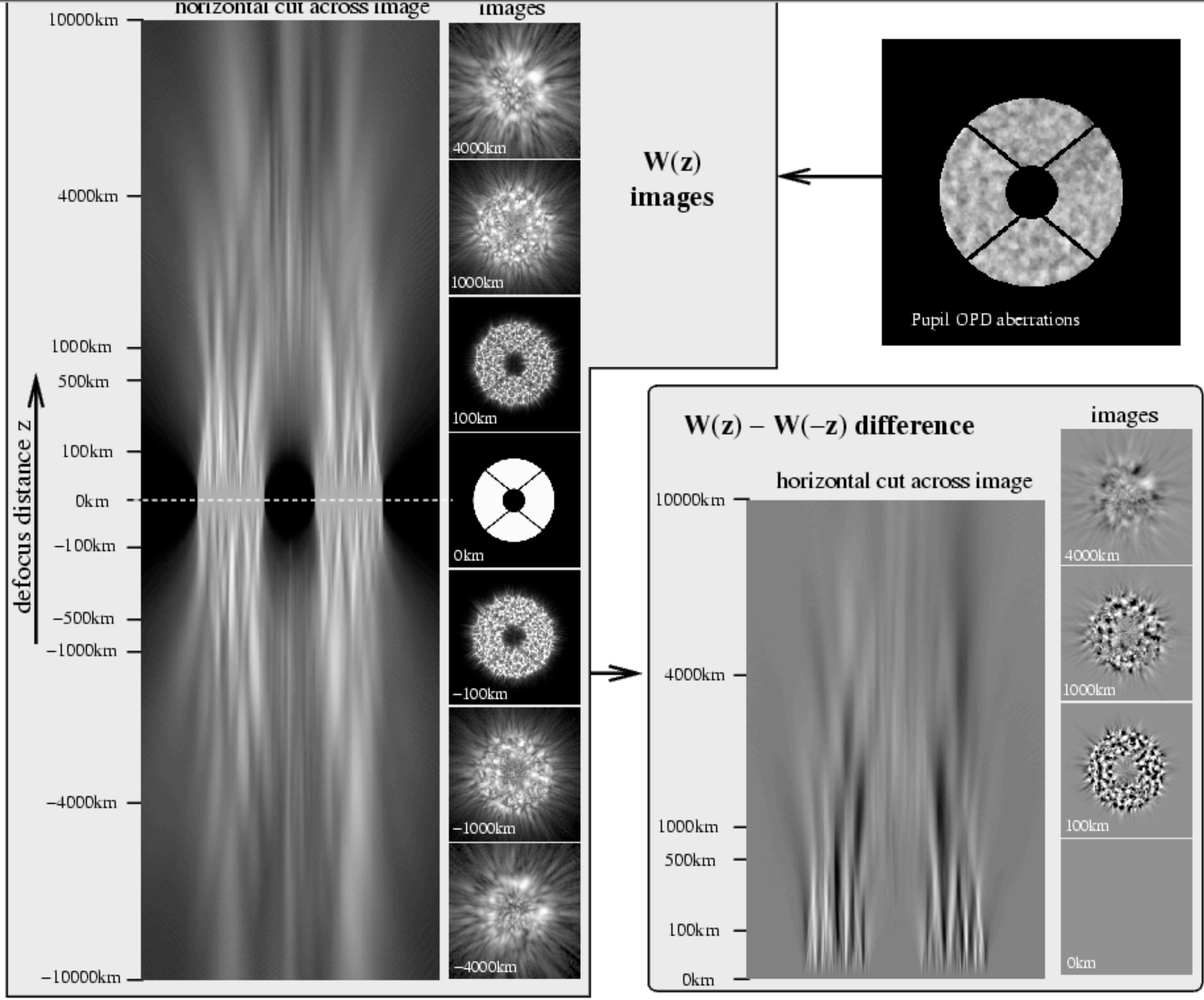
Can a WFS with good sensitivity and range be built ?

Yes, but it has to be non-linear

Next 3 slides describe one such concept, the non-linear curvature WFS (= phase diversity near pupil plane)



horizontal cut across image
images
10000km
4000km
1000km
500km
100km
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−100km
−500km
−1000km
−4000km
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W(z) − W(−z) difference
images
horizontal cut across image
10000km
4000km
1000km
500km
100km
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0km

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

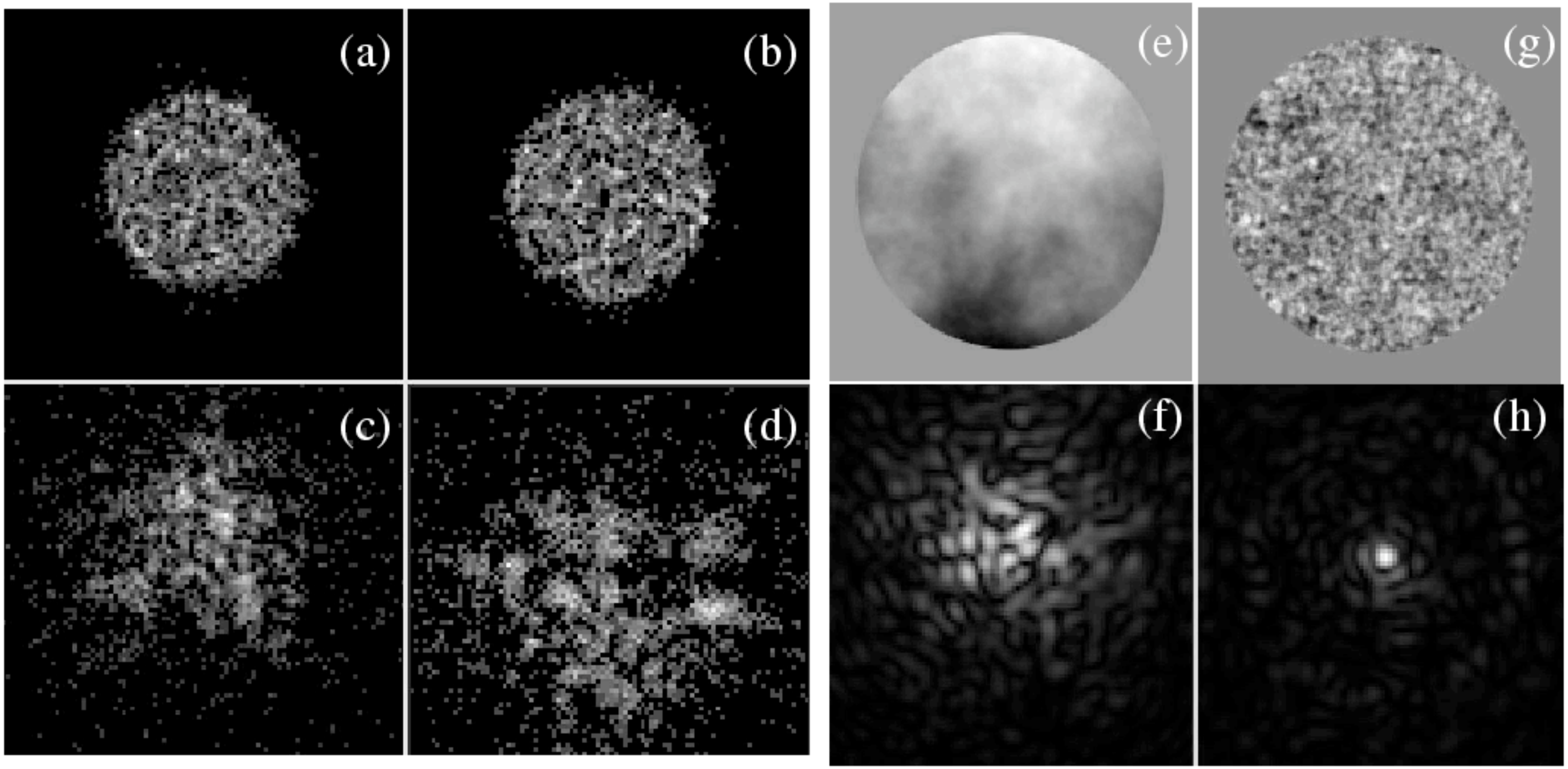
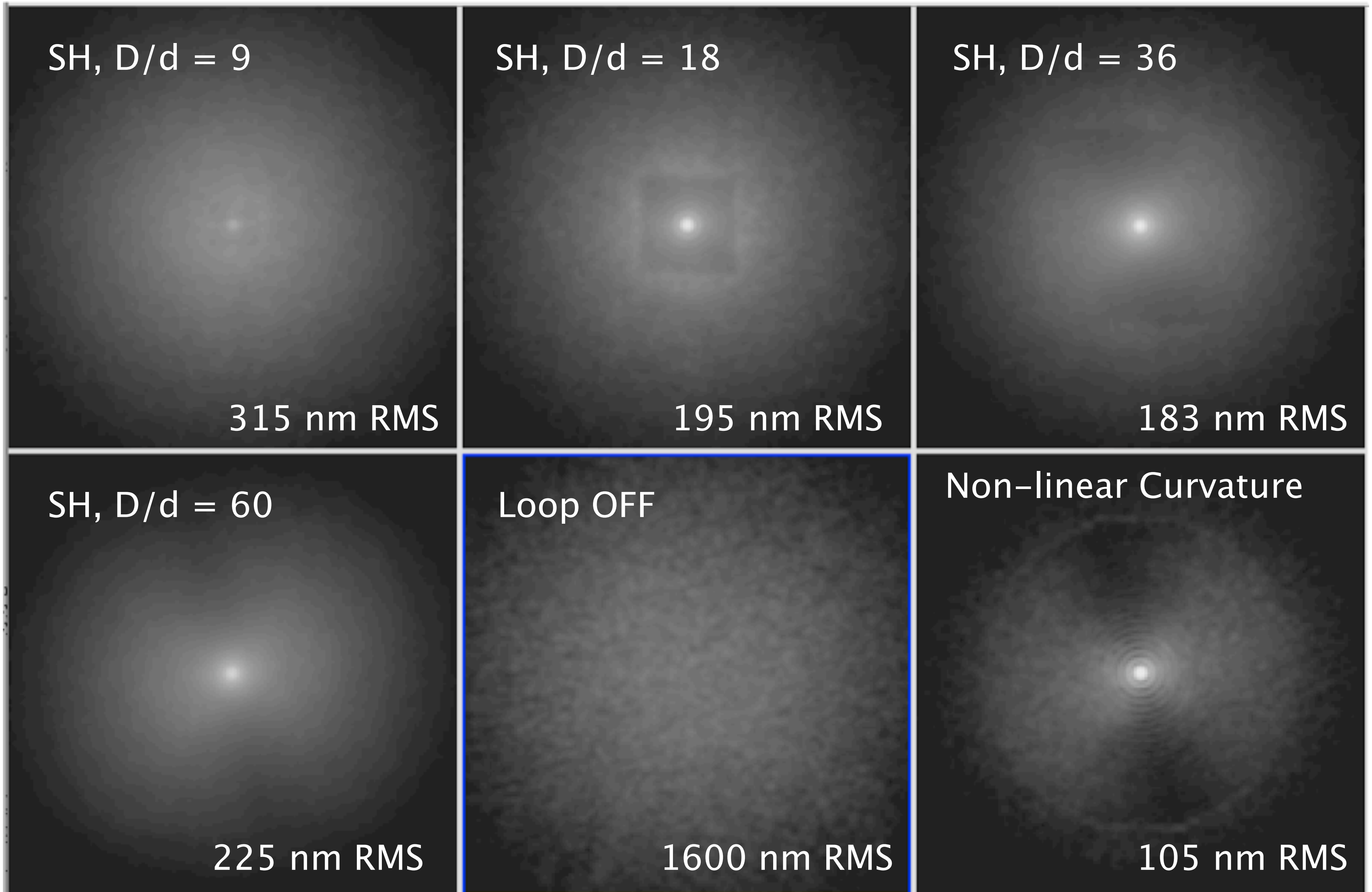


Fig. 9.— Wavefront reconstruction using the algorithm shown in fig. 8. Four noisy defocused pupil images (images (a), (b), (c) and (d)) are acquired to transform the pupil phase aberrations (e) into intensity signals. The input pupil phase is 609 nm RMS, yielding the PSF (f) before correction. After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

ref: Guyon, 2009 (submitted)

Closed loop simulated PSFs with “ideal” AO system
8m telescope, 0.85 micron, 3e6 ph/s



Note: “bow tie” is due to wind direction in this simple 1 layer turbulence model

Can a WFS with good sensitivity and range be built ?

Yes, but it has to be non-linear

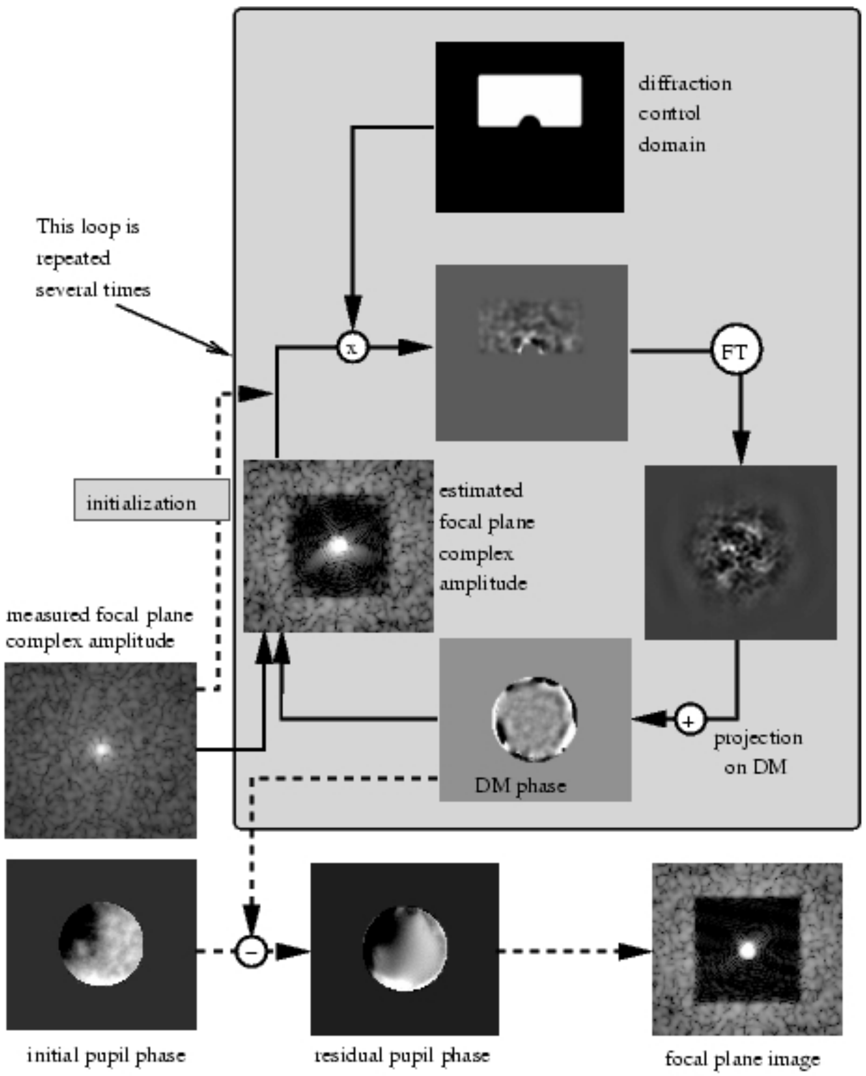
Next 4 slides describe another similar concept, the non-linear focal plane WFS (= phase diversity in focal plane)

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

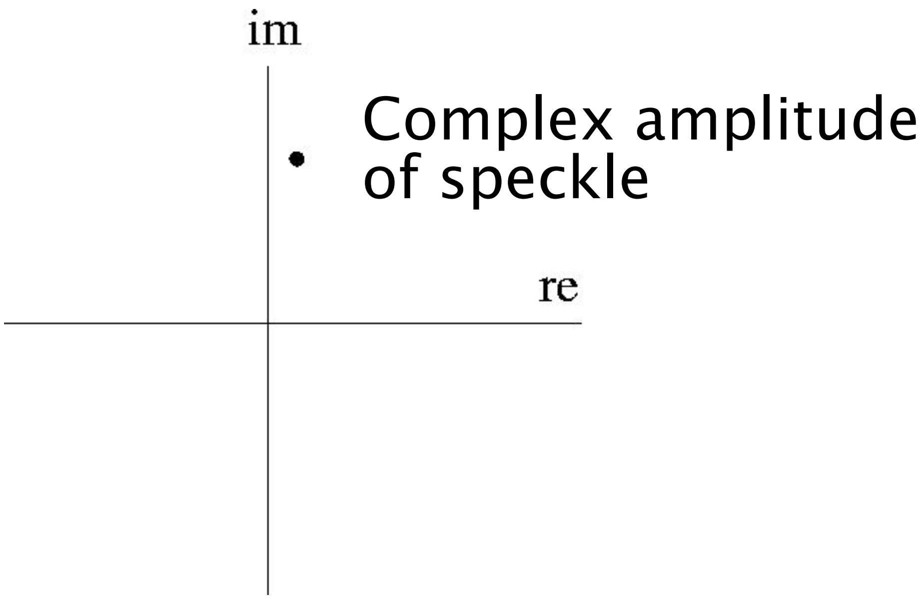
<u>Measure speckle field with no previous knowledge:</u>

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

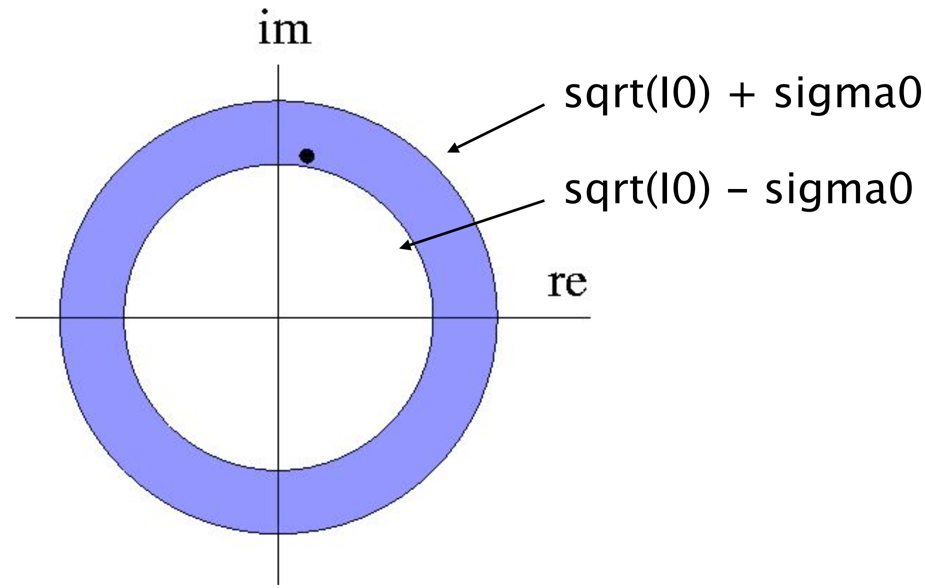
- compute 2 DM shapes which will add known speckles on top of existing speckles. These 2 “additive” speckle field have same amplitude as existing speckles, and the phase offset between the 2 additive speckle fields is PI/2

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

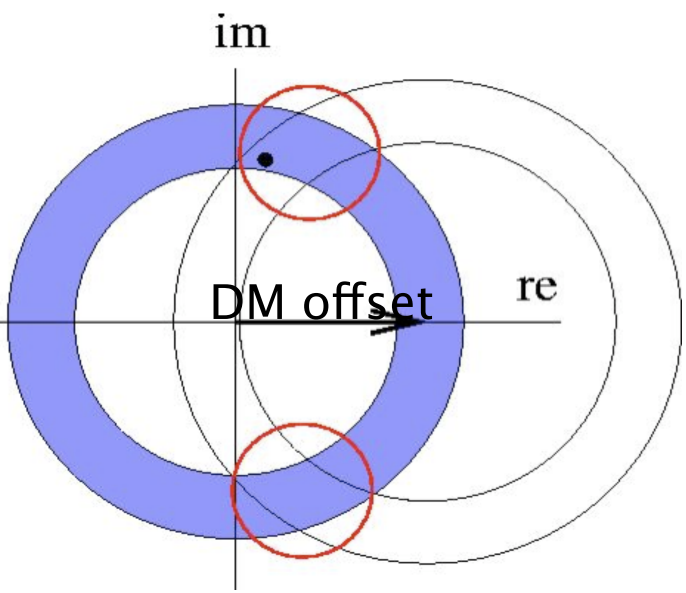
Initial problem

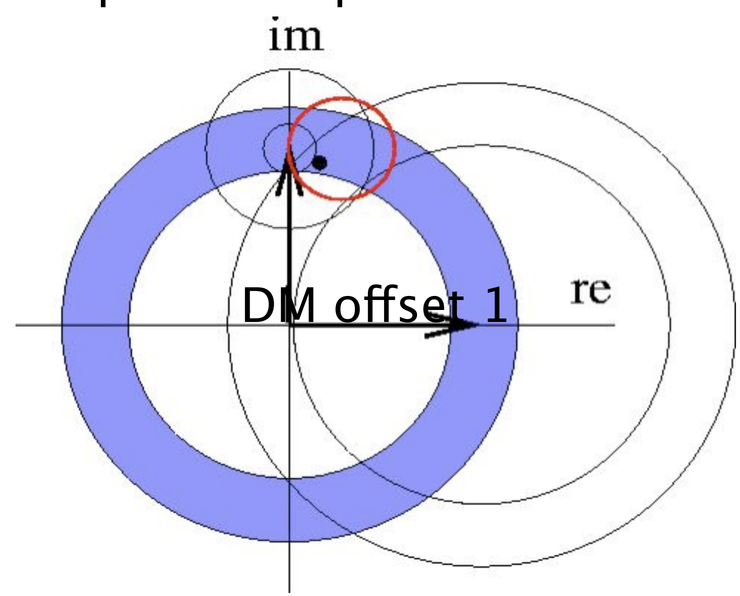


Take a frame -> measured speckle intensity = I0

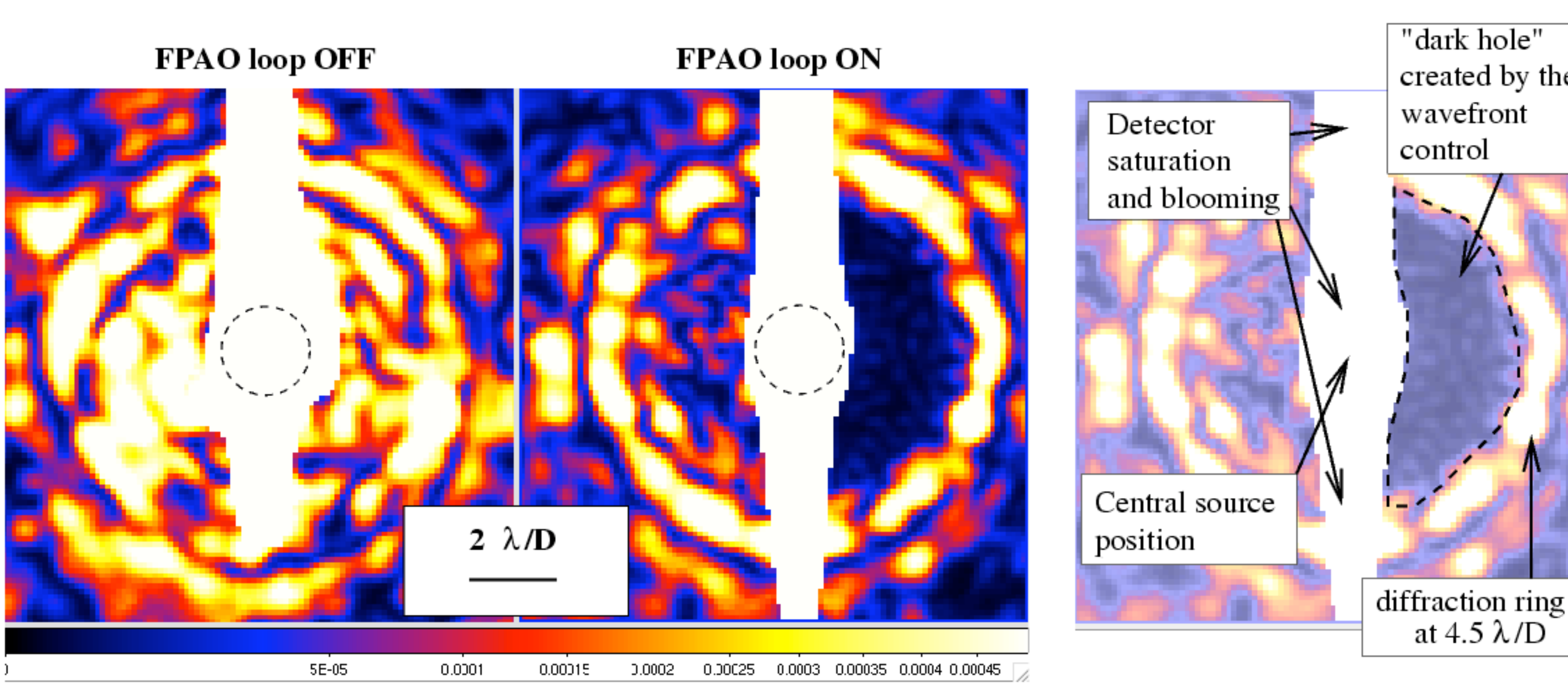


DM offset chosen to be ~ equal to speckle amplitude





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



See also results obtained at JPL HCIT & Princeton lab

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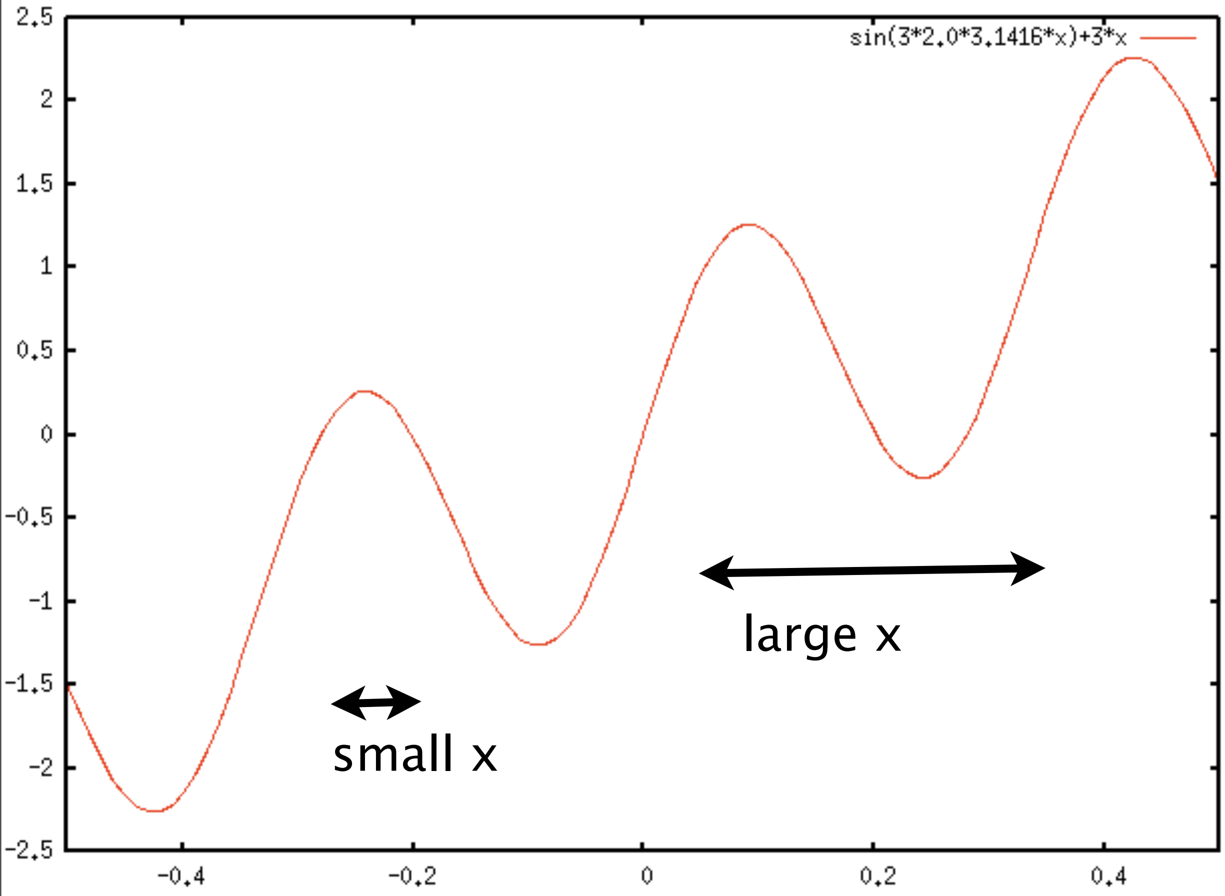
Good range/linearity but poor sensitivity

Good sensitivity over a small range

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

WFS range & linearity: why can't we get both simultaneously ?



small x:
phi < 1 rad
WFS signal is linear with phase aberrations

large x:
phi > 1 rad
WFS signal is non-linear with phase aberrations

WFS range, linearity and WFS sensitivity are pushing the WFS architecture in opposite directions

Solution:
Non-linear reconstruction allows a large dynamical range measurement on a high-sensitivity WFS

Guide "star" for WFS: COHERENCE

COHERENCE = ability to make coherent interferences between different parts of the pupil
For a high sensitivity WFS to work, coherence MUST be high across large parts of the pupil
Coherence is usually high across small parts of the pupil, low across large parts of the pupil

What makes the guide star "incoherent" ?

Wavefront stability during sampling time
- sampling time too long / turbulence too fast
- sensing wavelength too short
- vibrations

Large time-variable and/or unknown wavefront errors
- poor correction
- open loop wavefront sensing

Angular size of source
- Atmospheric dispersion
- source resolved > lambda/D

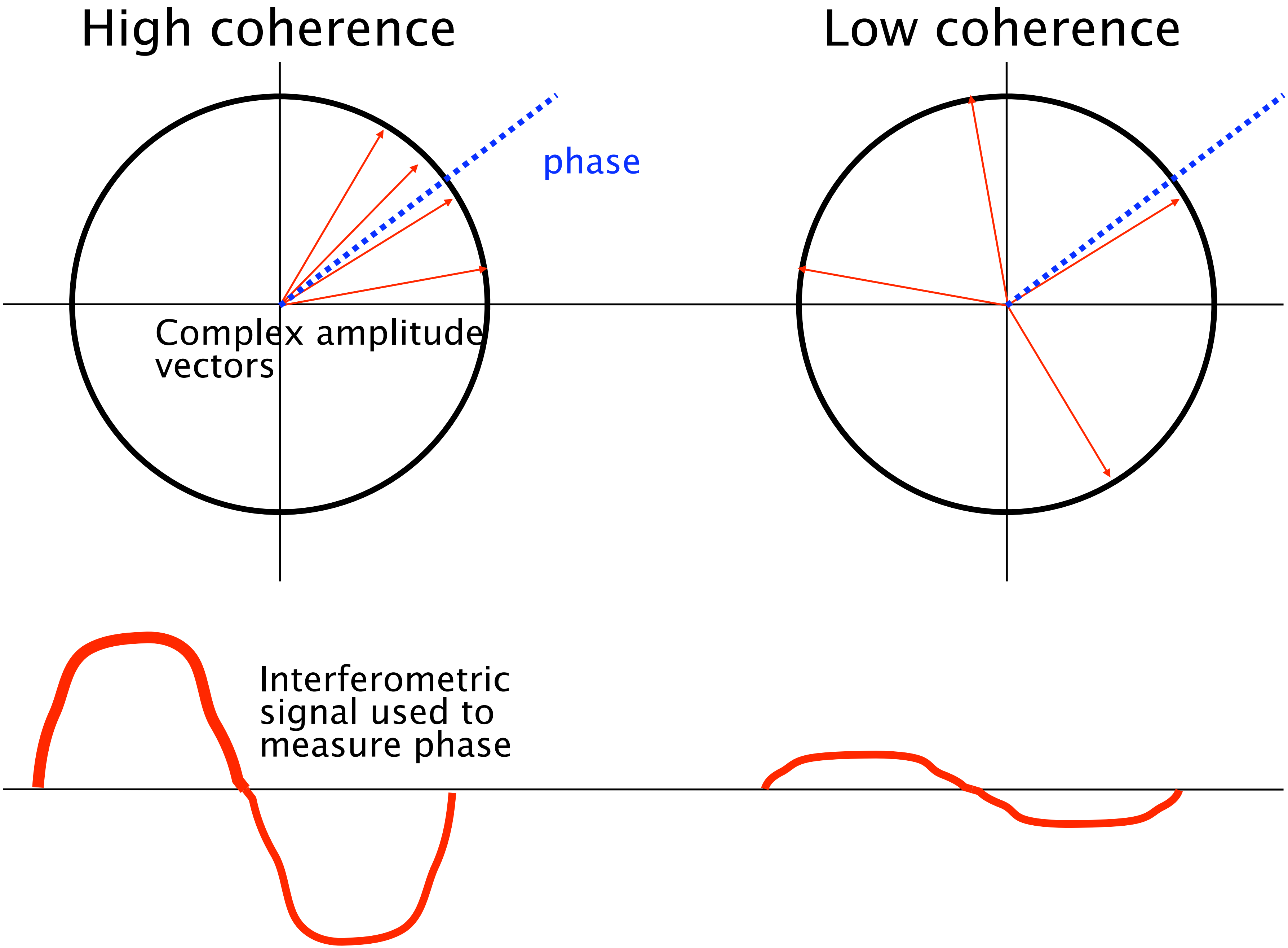
Chromaticity

Temporal coherence:
“long WFS exposure” will greatly attenuate the signal
Limits the WFS sensitivity in low light level, where long WFS exposure is required

Spatial coherence:
Sensitivity will not be achieved on extended targets
Extended target = points separated by large distance in the pupil plane will produce weak interference
This is fundamentally same thing as saying that TT on an extended target is less sensitive
Fundamental effect, will limit all WFS designs equally

Chromatic coherence:
WFS design must work in broadband
Problem for focal plane WFS, **other WFS concepts can work in broadband**

“interferometer” representation of temporal coherence in WFS



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Matching:

Wavefront COHERENCE in WFS **to** **Wavefront sensor**

<< 1 rad

Space Extreme-AO (Terrestrial Planet Finder)

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

~ 1 rad

Extreme-AO Closed loop in Visible

Thermal IR AO on 8m telescope open loop

“general purpose” AO system in closed loop

>> 1 rad

LGS AO
GLAO

Open loop AO

Interferometric

Focal plane

Not allowed

Pyramid (fixed)

allowed

Pyramid (modulated)

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 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: Possible Coronagraphic ExAO architecture

AO with visible WFS
(Curvature or
Shack Hartmann)

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

Near-IR

Coronagraph
Focal plane AO

Science frame
acquired by the
same camera
as FPWFS

Fast camera for
focal plane WFS
after coronagraph

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

Outline

Astronomical AO system diversity

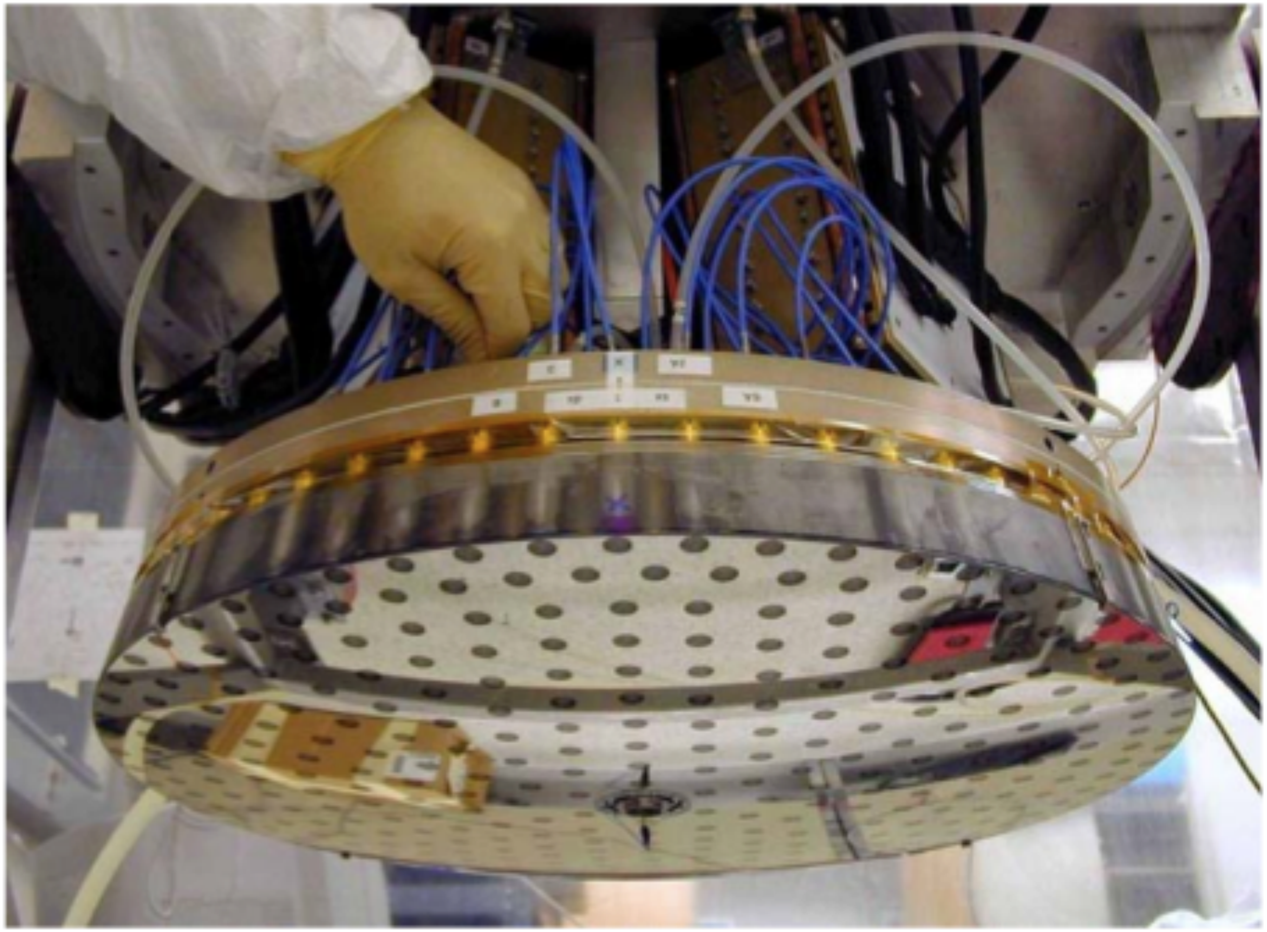
Main challenges / error budget terms in astronomical AO systems

Wavefront sensing strategy

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)

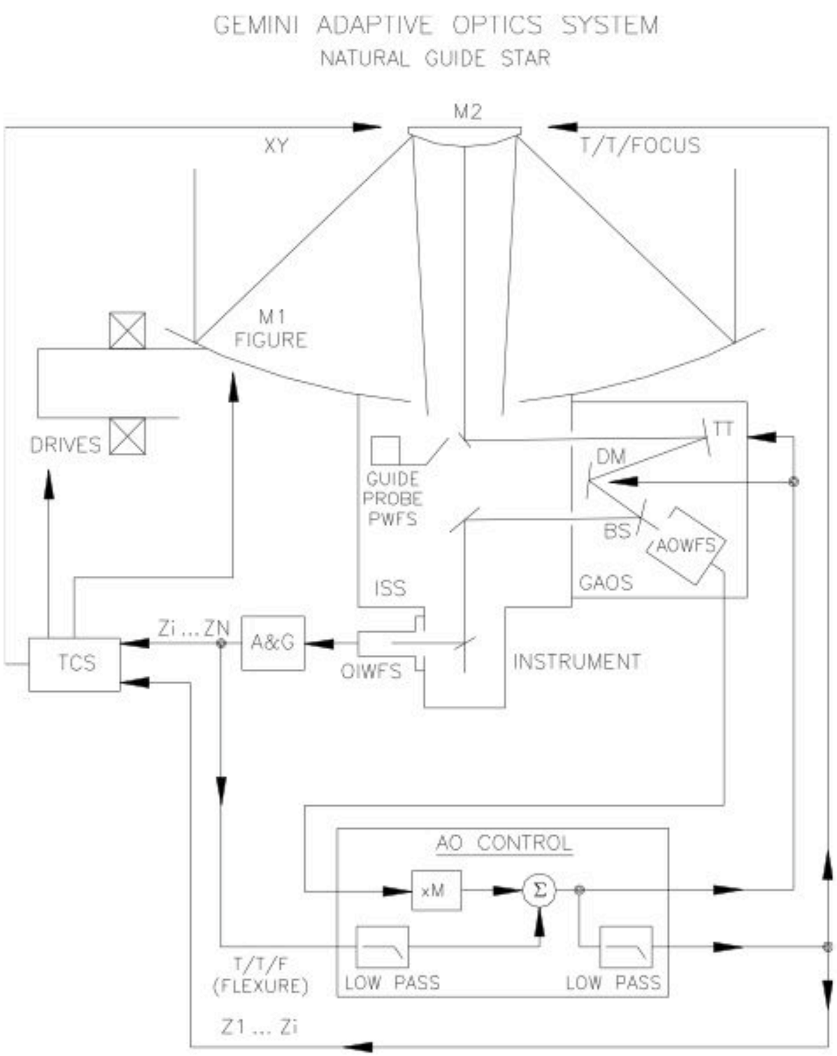
Example 1: System offering wide FOV over full continuous field
-> large optics, several large Deformable Mirrors (MCAO)
-> AO system works in closed loop, with several WFSs and several DMs
-> Multiple guide stars needed, with required positioning devices (NGS) or several laser beacons.

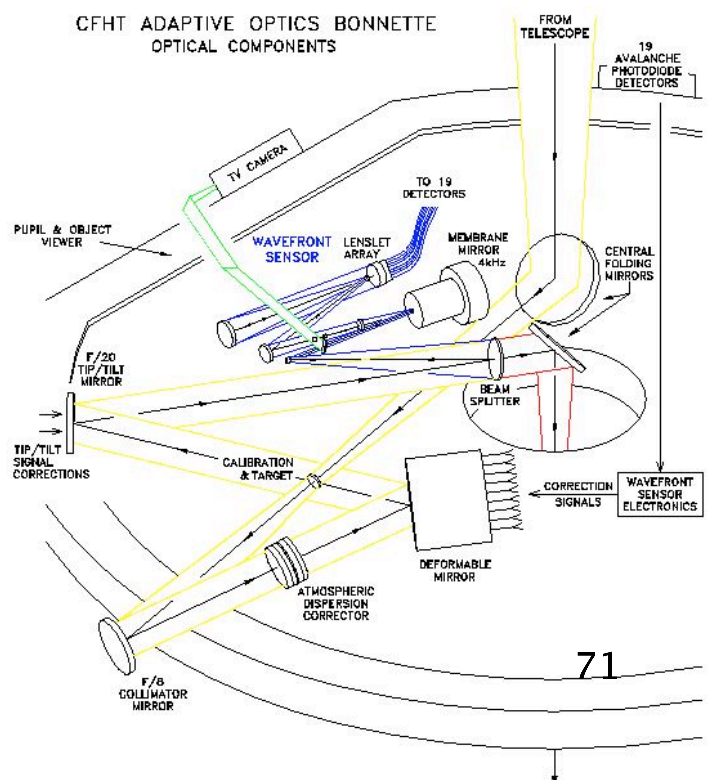
Example 2: Several small individual FOVs spread over a large field
-> The instrument could have small independent wavefront correction units (1 per small field) to minimize optical size/complexity
-> These small units should be fed by a smaller number of WFSs using tomographic reconstruction.
-> The 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".

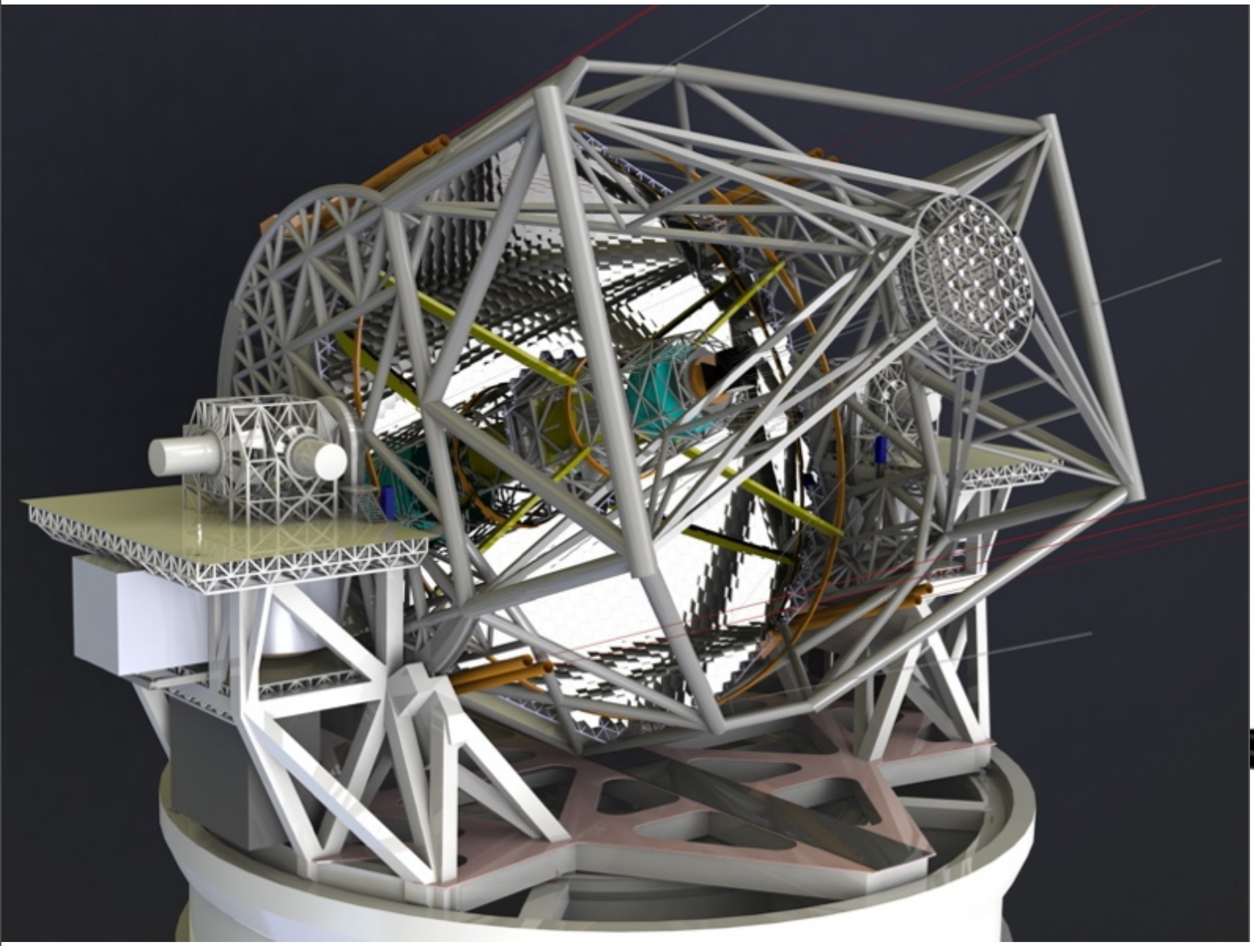
"Facility" AO systems can feed several instruments, and can be a "layer" which processes the beam prior to sending it to instruments.

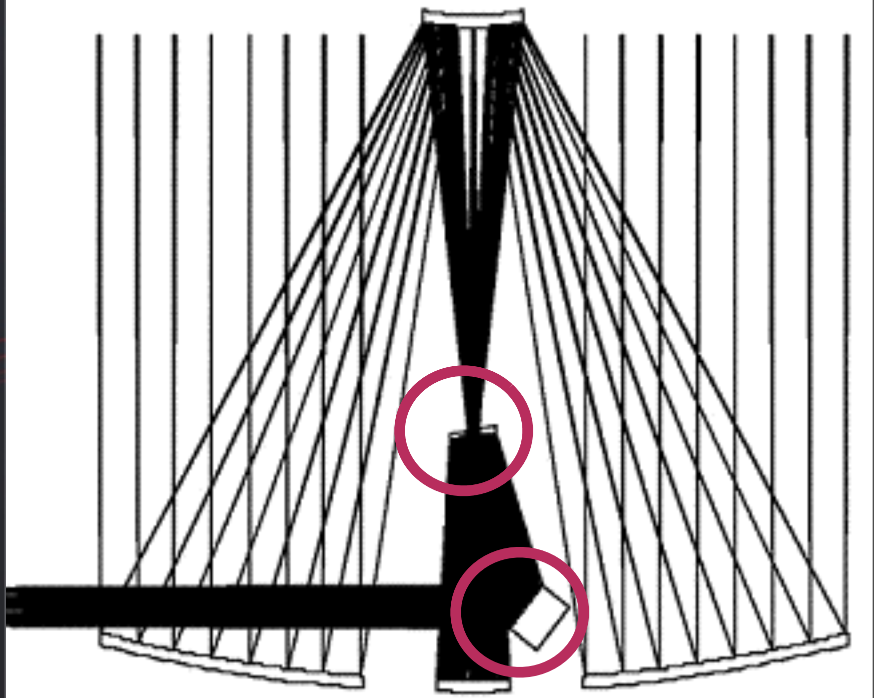


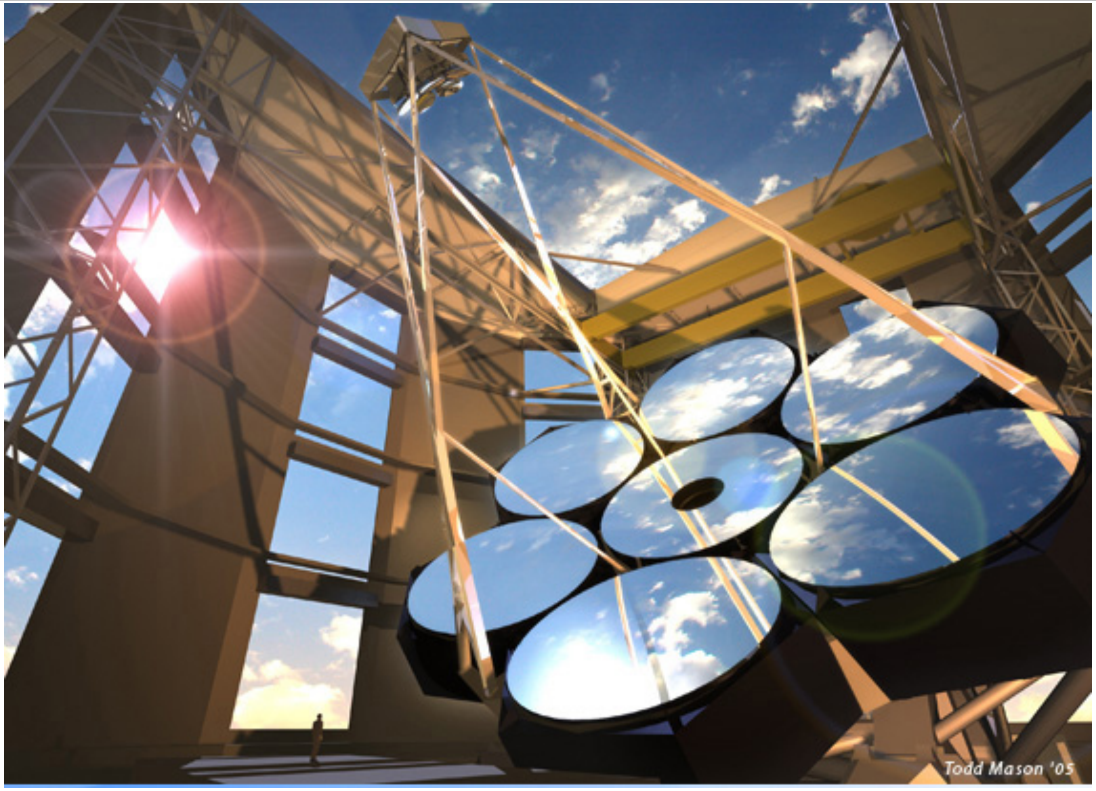


The next generation of large telescopes combine AO with telescope design

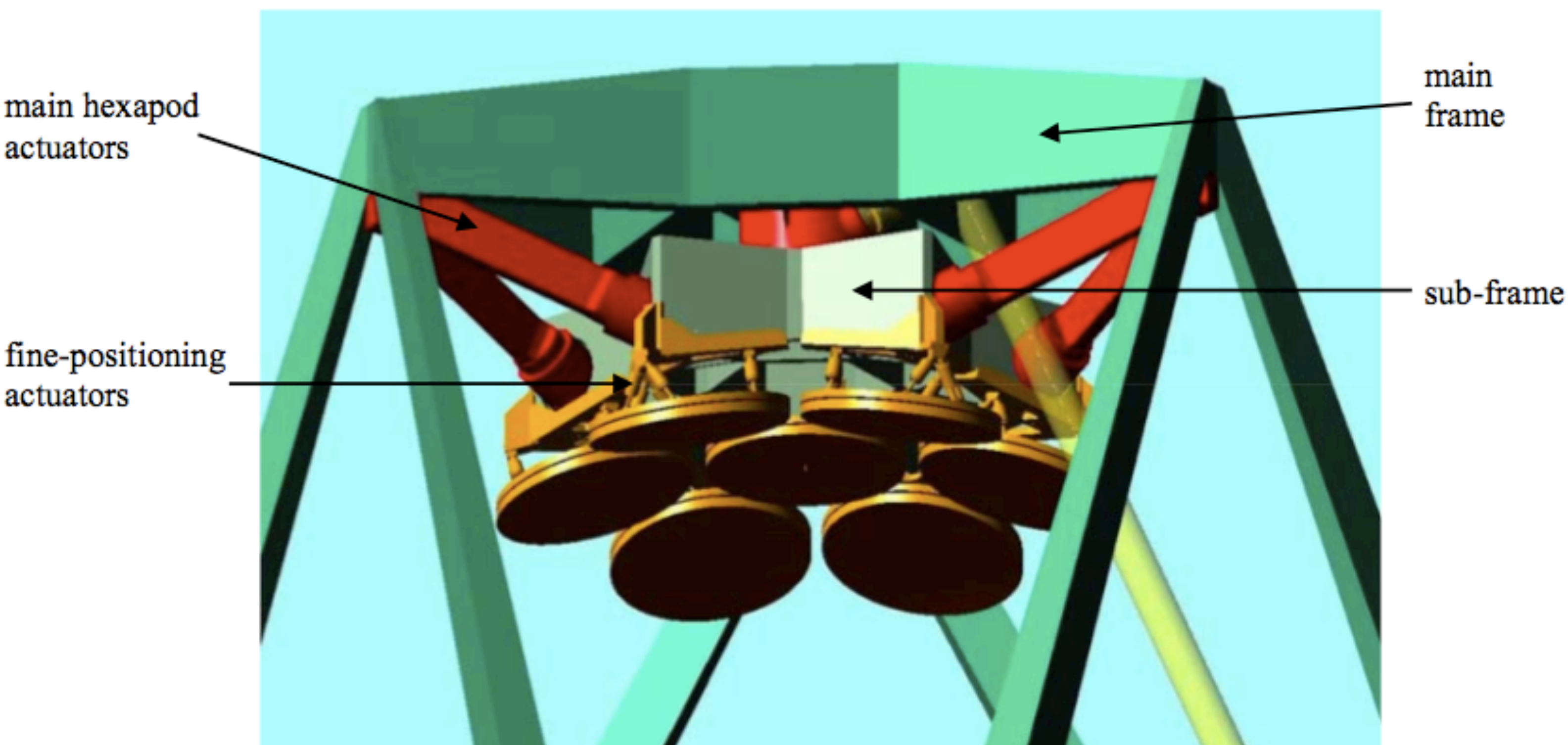
The 42m diameter European Extremely Large Telescope (EELT) optical design includes DMs as large fold mirrors (2.5m and 2.7m diameter).

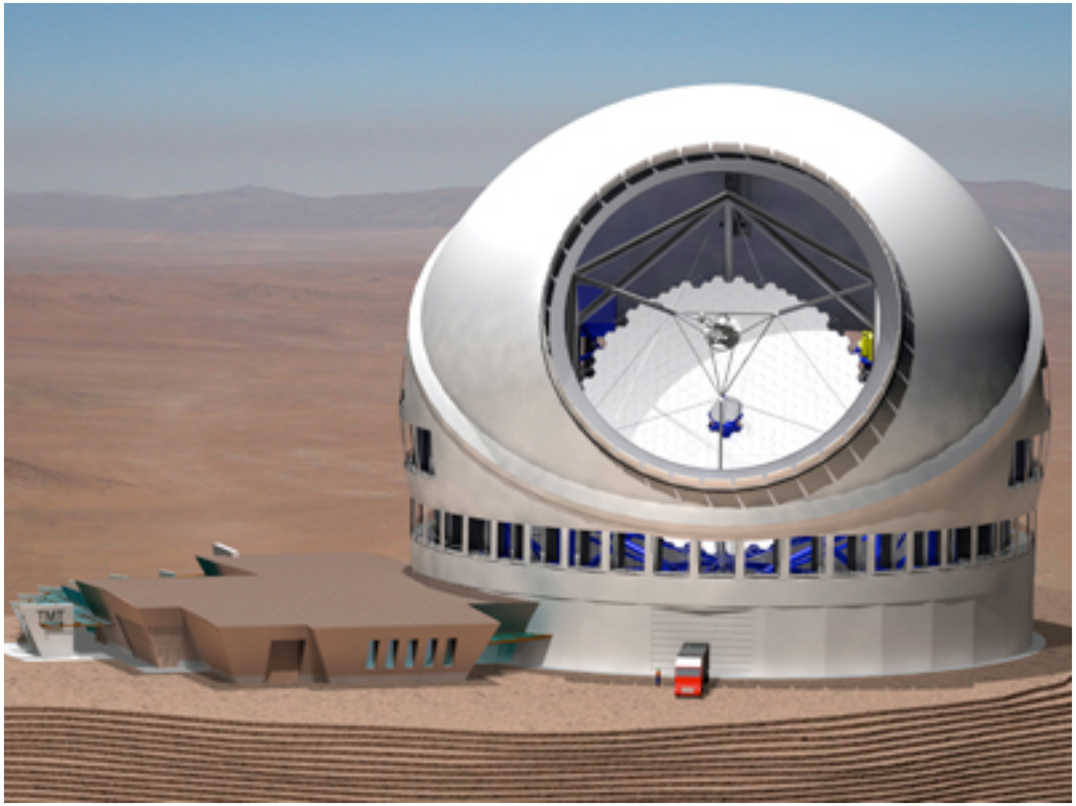




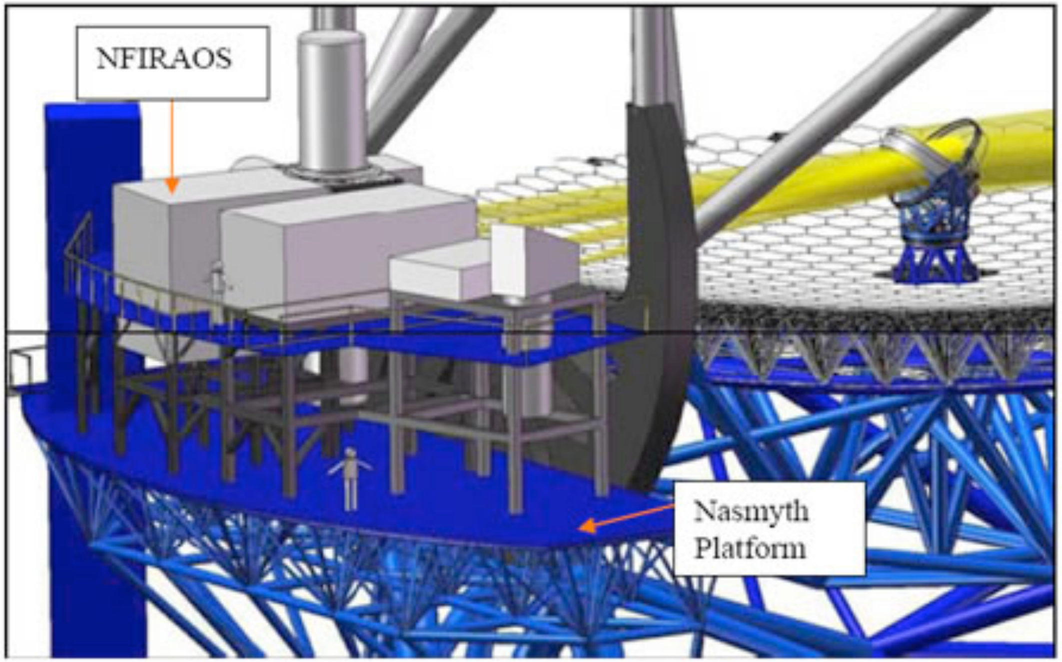


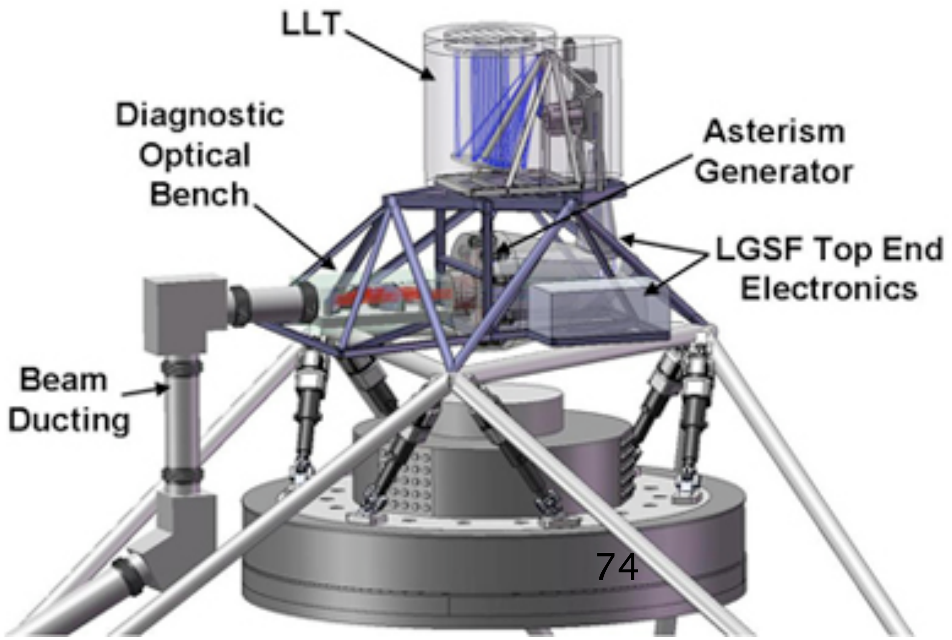
The Giant Magellan Telescope (GMT) secondary mirrors are adaptive and serve as DMs for the AO system(s).





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





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AO control

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

“standard” solution (fast, linear):

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

This could also be done by computing explicitly the wavefront:

WFS measurements -> wavefront -> DM commands

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

AO control

Modal control/filtering helps a lot

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

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

Example:

mode 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 continuously tunes the system for optimal perf.

Realistic simulation of AO system is 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

Top 10 things NOT TO DO in astronomical adaptive optics

(10) Build a 5000 actuator system stuck at ~100Hz because of limited computer power or hardware

(9) Build a LGS system (I really think lasers are cool) with a fixed pyramid wavefront sensor (I heard it's the best) for Extreme-AO on bright stars (seeing planets is cool!)

(8) Build a 5000 actuator SH NGS system for "general astrophysics" imaging

(7) Put a high order SH system in space for exoplanet imaging

(6) Start right now a 10 yr long very expensive project using "brand new" technology

(5) Forget about non-common path errors in an Extreme-AO system

(4) Forget about telescope vibration (wind, pumps)

(3) Mount a strong massive tip-tilt mount on a small flexible optical bench

(2) I have problems with turbulence on my AO bench ->

I'll mount big fans on an ExAO system bench for cooling components (cameras, motors)

(1) Build an AO system that can keep the loop closed to very high performance, but can't close the loop