AO system Design: Astronomy

Olivier Guyon (Subaru Telescope) guyon@naoj.org

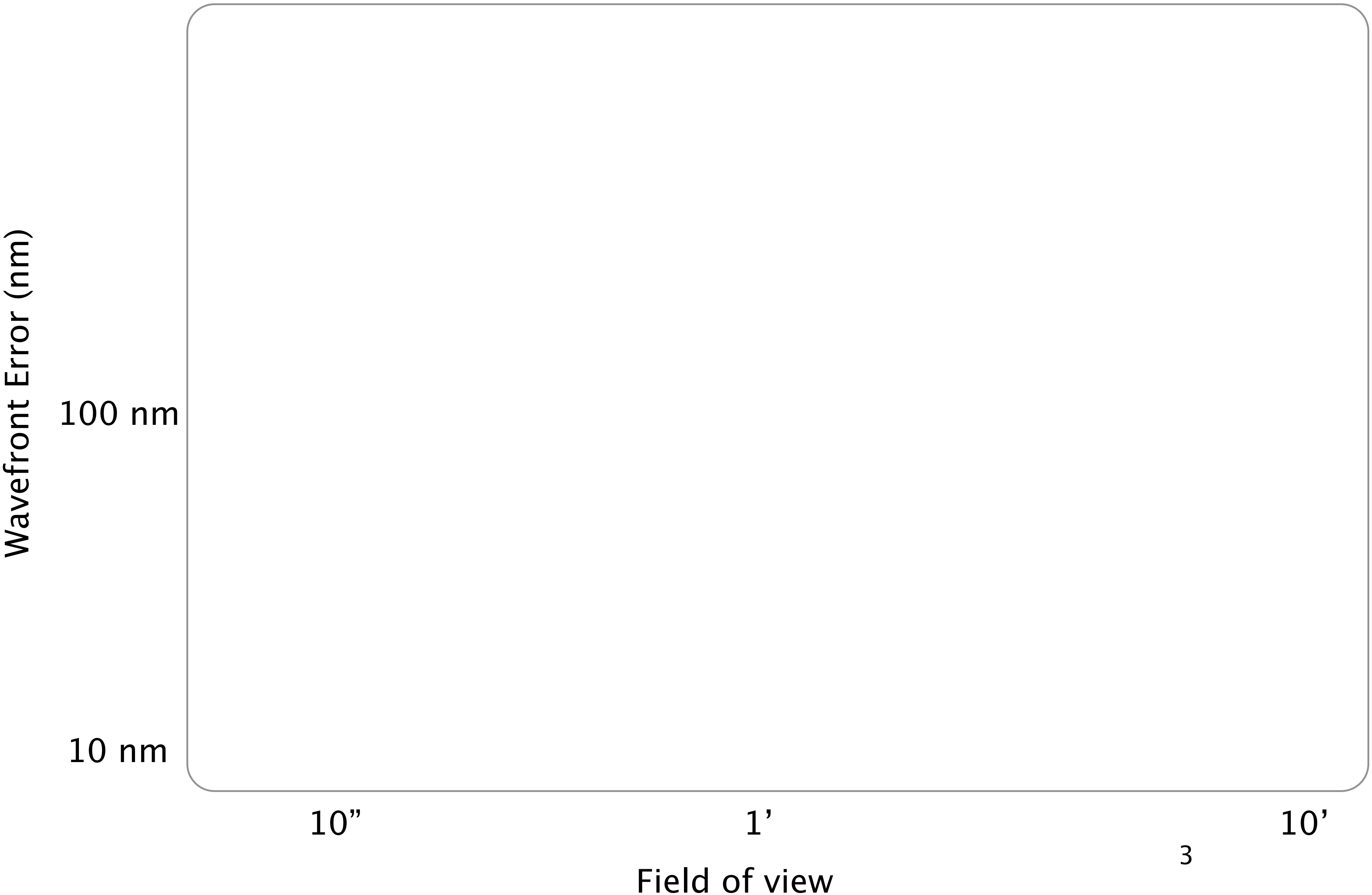
This lecture:

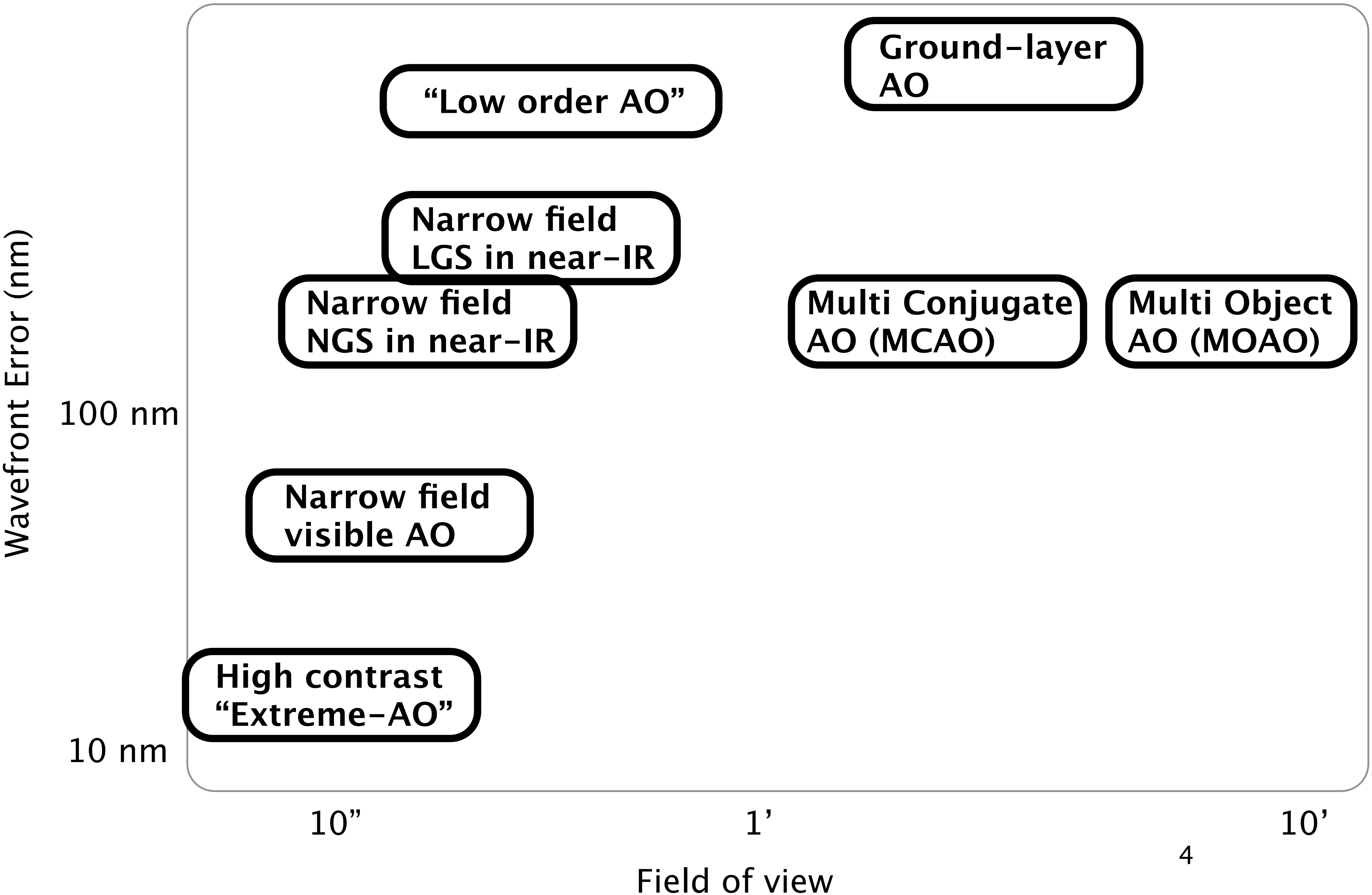
Will not discuss detailed optical designs, mechanical designs, hardware choices, computer algorithms
(often too specific to some AO systems, easy to get lost in details...)

Main goal is to explore fundamental AO strategies, compare them, understand how/why/when they work or don't work

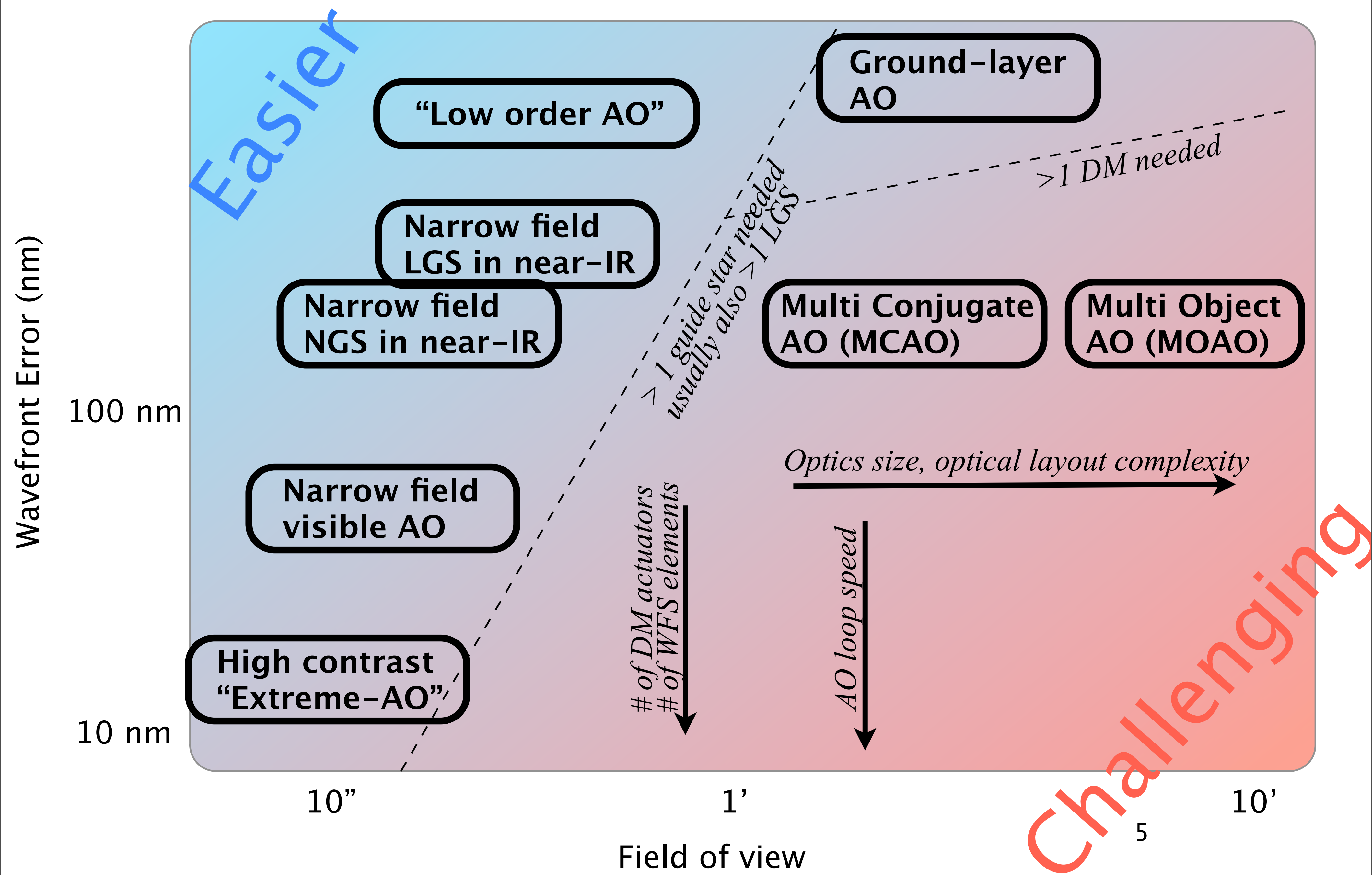
~1/2 of this lecture focuses on optimal WFS strategy - probably the most essential part of an astronomical AO system design

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


Wavefront Error (nm)
100 nm
10 nm
10”
1’
10’
Field of view



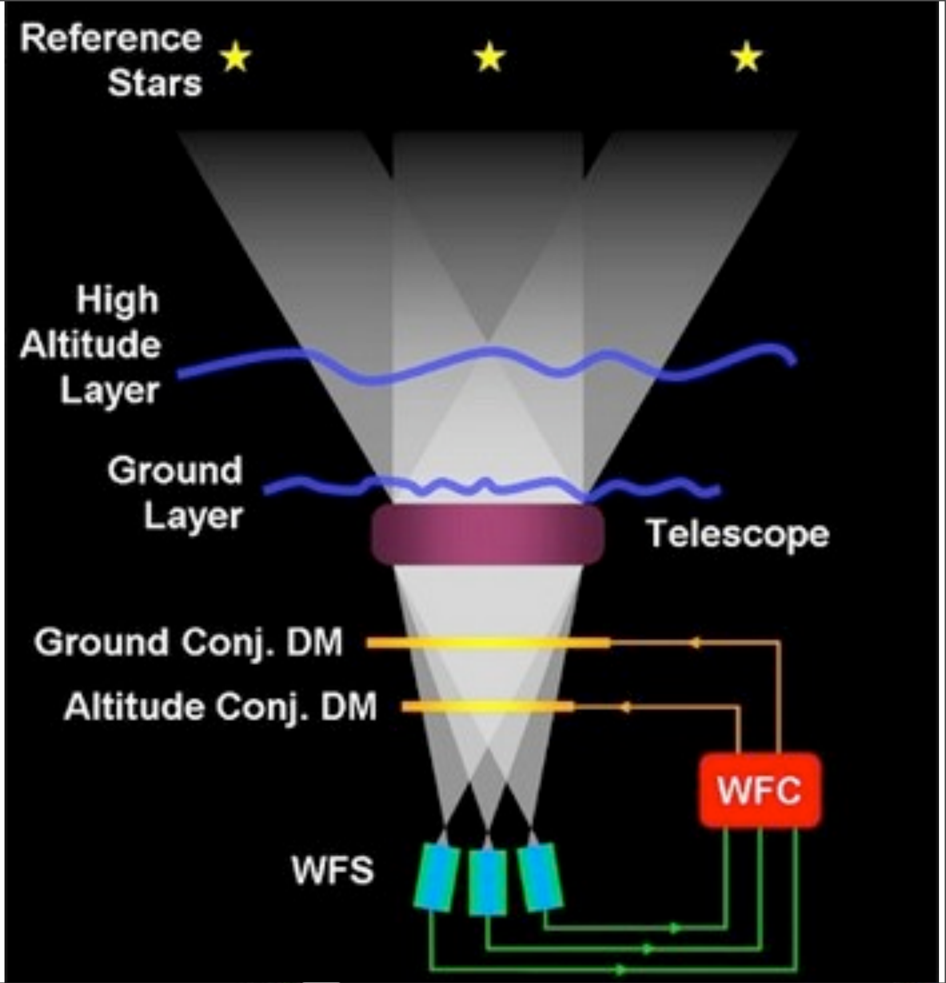
Ground-layer AO
"Low order AO"
Narrow field LGS in near-IR
Narrow field NGS in near-IR
Multi Conjugate AO (MCAO)
Multi Object AO (MOAO)
Narrow field visible AO
High contrast "Extreme-AO"
Wavefront Error (nm)
100 nm
10 nm
10"
1'
10'
Field of view

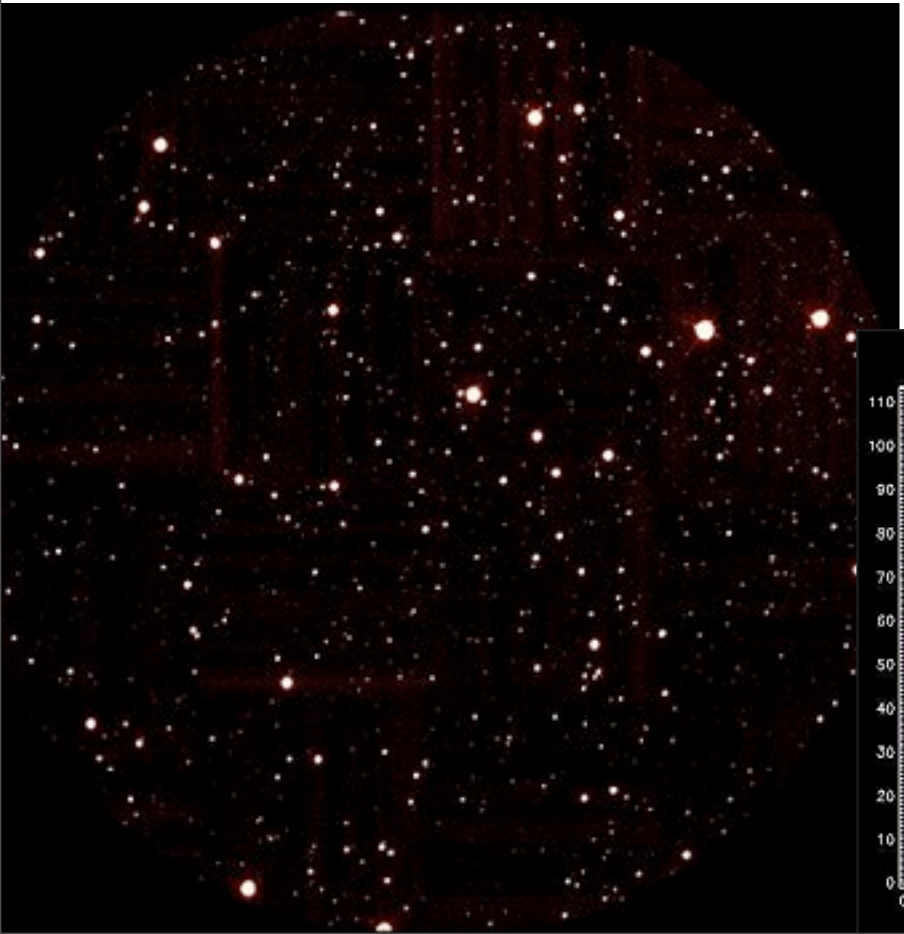

Easier
"Low order AO"
Narrow field LGS in near-IR
Narrow field NGS in near-IR
Narrow field visible AO
High contrast "Extreme-AO"
Ground-layer AO
> 1 guide star needed
usually also > 1 LGS
>1 DM needed
Multi Conjugate AO (MCAO)
Multi Object AO (MOAO)
Optics size, optical layout complexity
# of DM actuators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

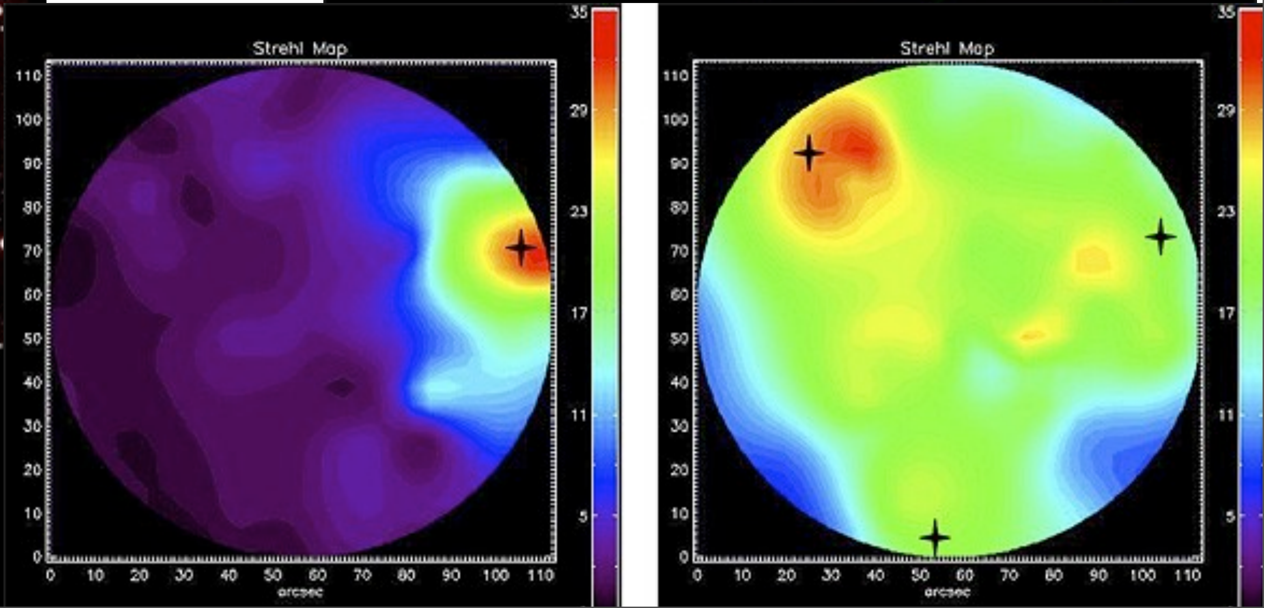
Multi-Conjugate AO (MCAO)

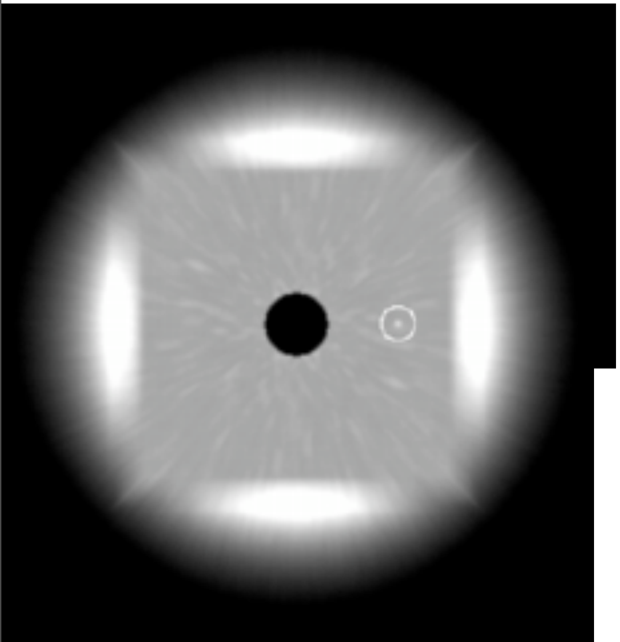
Early results from ESO's MCAO demonstrator (MAD)

Gemini currently developing MCAO system





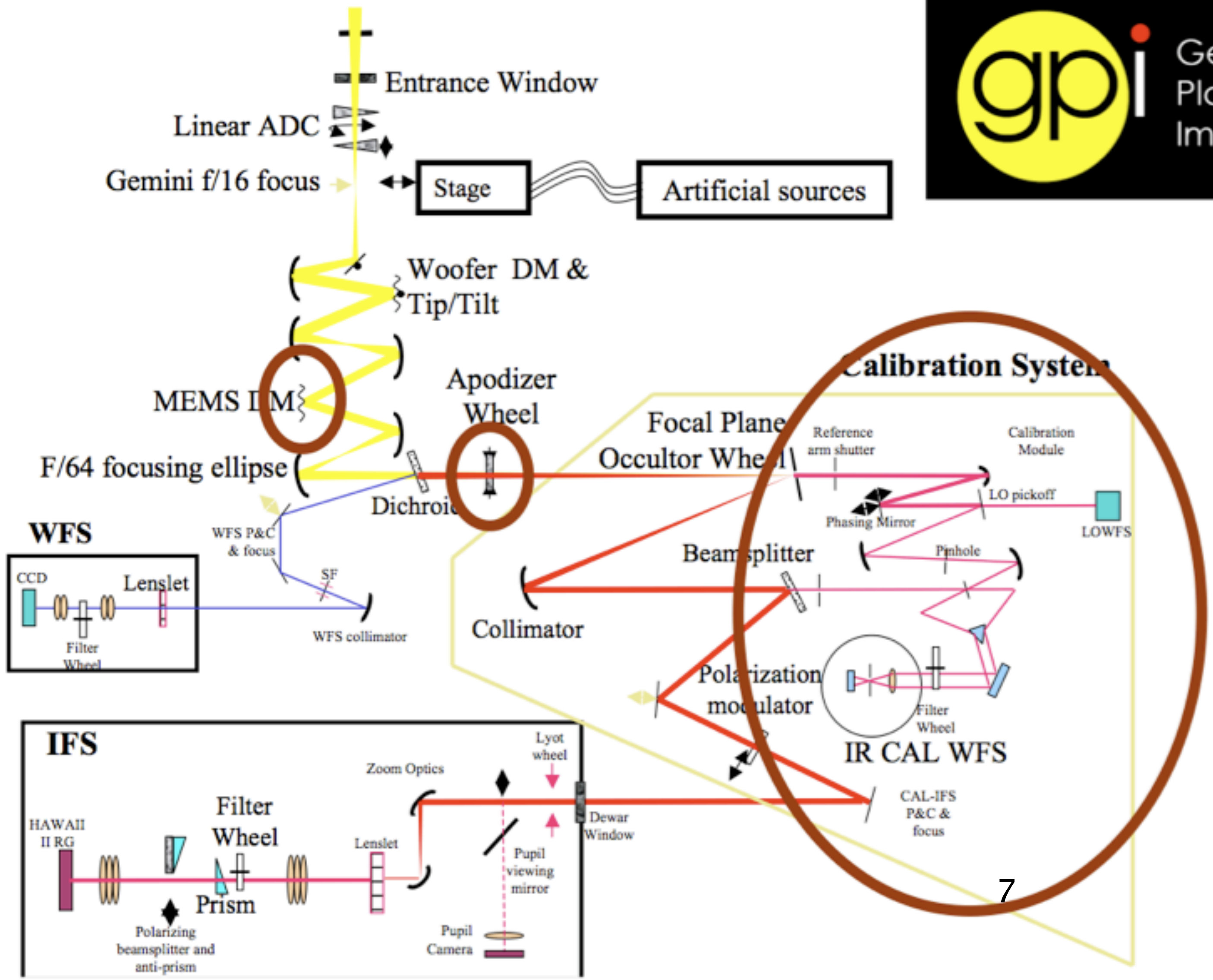




Extreme-AO

Gemini Planet Imager
SPHERE (ESO)
Subaru CEAO system

Also under study: space-based ExAO systems



Outline

1. Main challenges / error budget terms in astronomical AO systems

How to design an AO system which meets science requirements & reduces overall error budget ?

- The answer strongly depends on the science objective
  - Solar AO, Extreme AO, MOAO, GLAO, LGS vs. NGS ...

2. Wavefront sensing strategy

- AO guide star:
  - LGS, NGS ? Multiple sources ? Sensing wavelength ?
- Choosing the right Wavefront Sensor

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

1. Main challenges / error budget terms in astronomical AO systems

How to design an AO system which meets science requirements & reduces overall error budget ?

- The answer strongly depends on the science objective
  - Solar AO, Extreme AO, MOAO, GLAO, LGS vs. NGS ...

2. Wavefront sensing strategy

- **AO guide star:**
  - **LGS, NGS ? Multiple sources ? Sensing wavelength ?**
- **Choosing the right Wavefront Sensor**

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

Fundamental AO challenges :

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)

1. Fitting error

Wavefront errors from atmospheric turbulence

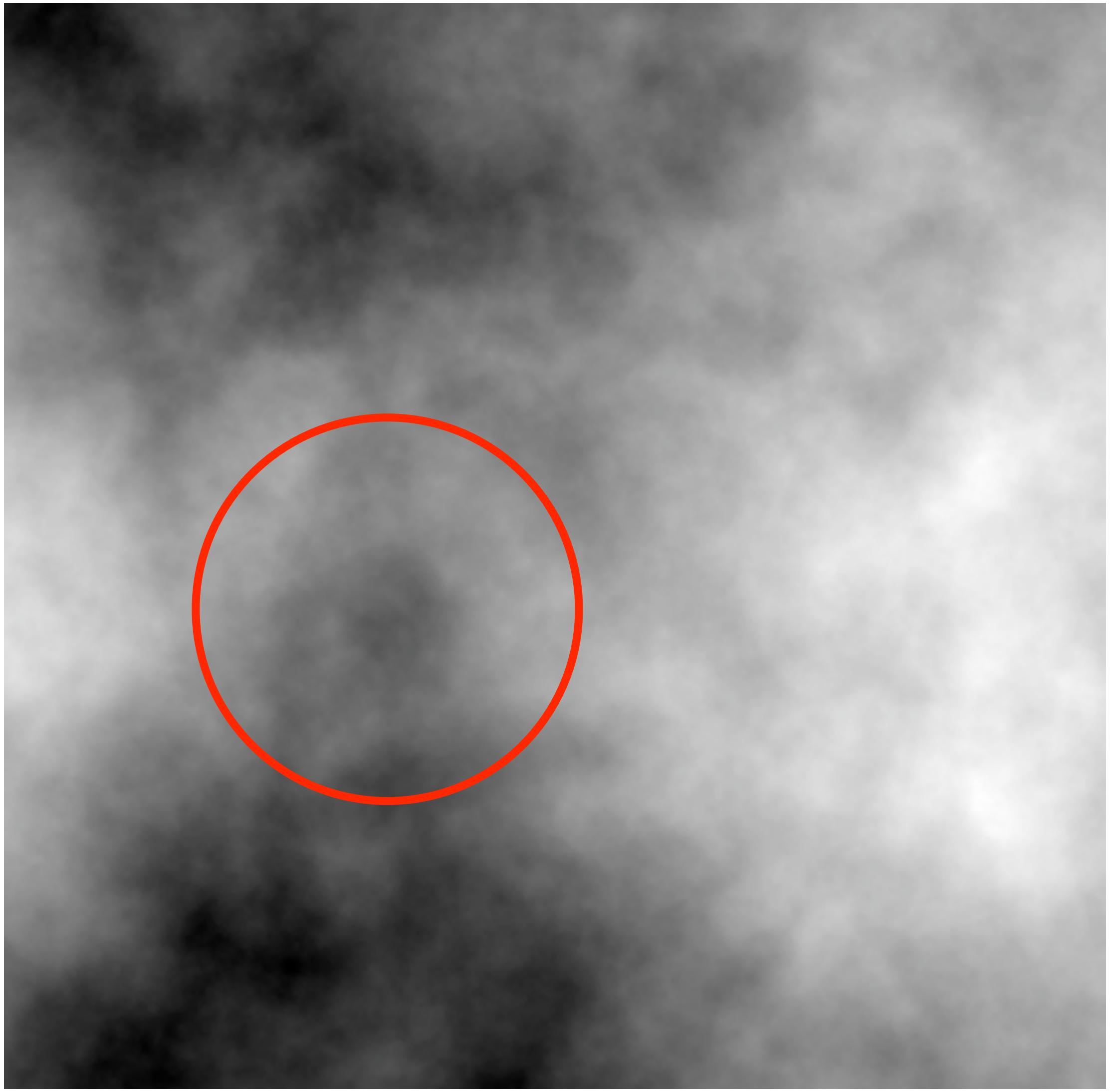
$$\sigma^2 = 1.03\ (D/r_0)^{5/3}$$

+ 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

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

Larger D -> more stroke needed

(also: faster system -> more stroke needed)

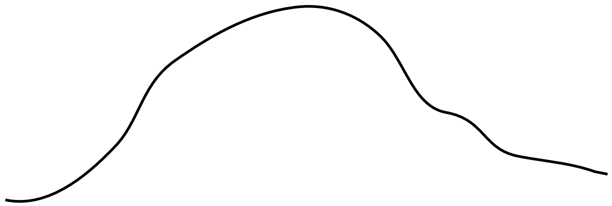
Most of the power is in tip-tilt:

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

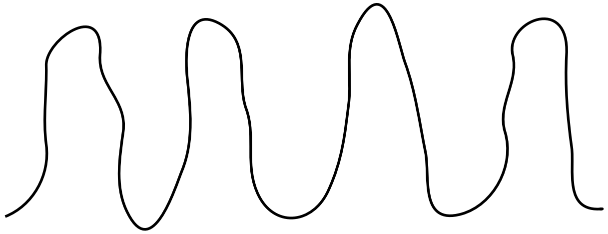
On many DMs, interactuator stroke < overall stroke

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

$d^2 = D^2/N$ = actuator size

If we assume each actuator does perfect piston correction (but no tip/tilt):

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

If we assume continuous facesheet (see Hardy, Roddier),

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

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

2. Speed

assuming pure time delay t

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

t_0 = coherence time "Greenwood time delay" (see Hardy)

$= 0.314\ r_0/v$

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)

sampling frequency ~ 10x bandwidth

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

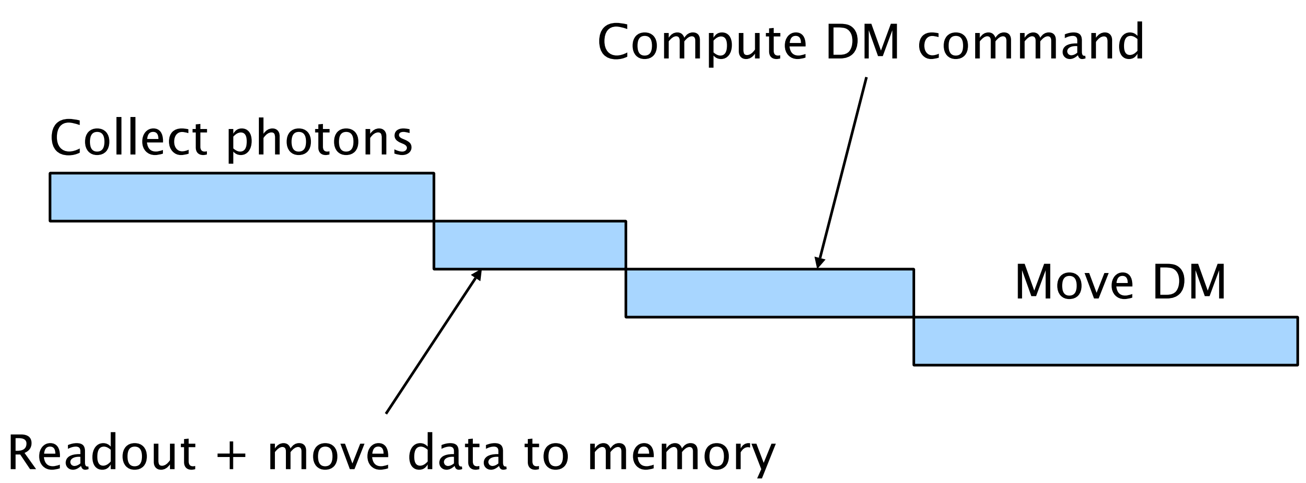
for "extreme-AO" system (0.1 rad error):
6 kHz for K band

-> 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 !"



<u>3. Limited # of photons from stars (per unit of time)</u>

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

Example 1: General purpose NGS system

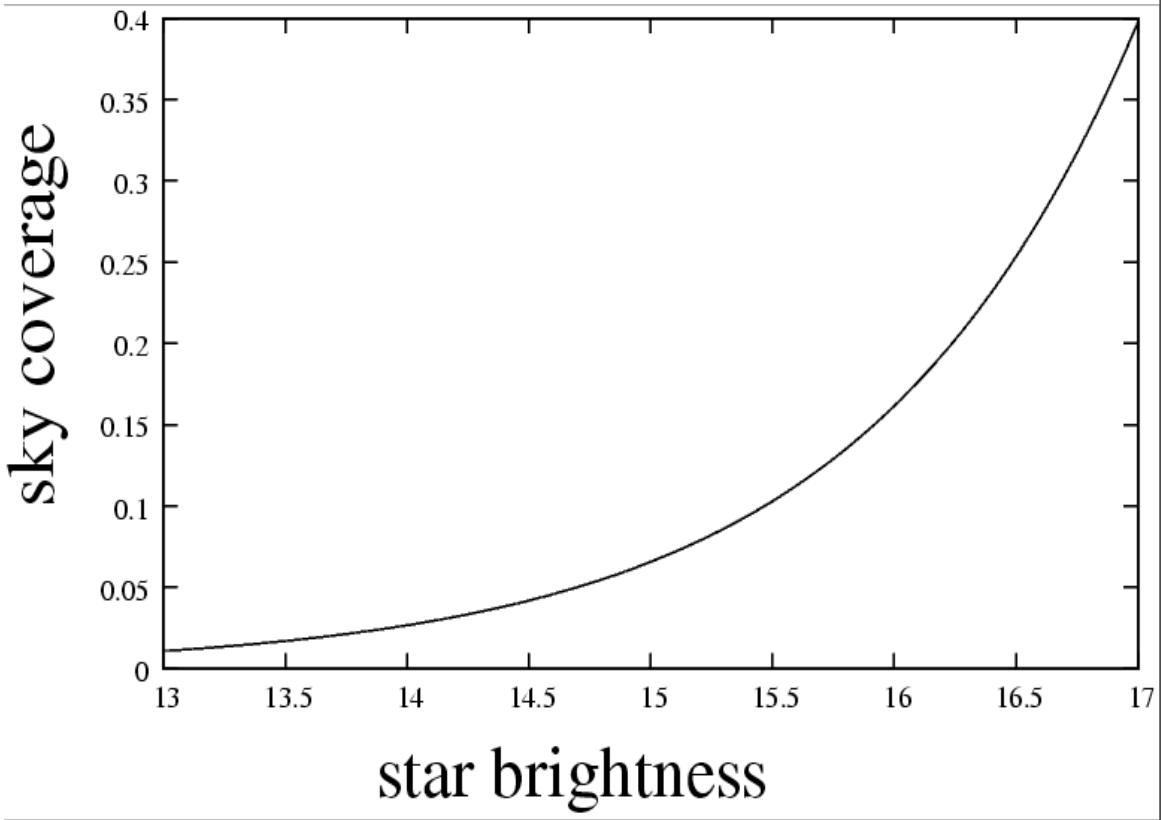
Goal: achieve diffraction limited performance over much of the sky

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 essential
- frequent problem in Solar system observations
- double stars

Sky background:
for faint guide stars, moonlight is a concern

5. Non-common path errors

- anisoplanatism

  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 (LGS)

  -> tomographic reconstruction

- instrumental non-common path errors

  Due to optics in WFS only or in science camera only

  -> may need to be measured (phase diversity works well for this) and offset to AO loop

6. Calibration, nasty “practical” things

– vibrations, instabilities between control loops
-> good mechanical design
-> beware of cryocoolers (pumps), fans, wind, telescope mounts, tip-tilt mirrors

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

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
  $r_0 \alpha \lambda^{6/5}$ -> $N \alpha \lambda^{-12/5}$
- speed gets high ($\tau_0 = 0.314\ r_0/v$) -> $\tau_0 \alpha \lambda^{6/5}$
- anisoplanatism gets small (FOV, sky coverage go down)
  $\theta_0 \alpha \lambda^{6/5}$
- chromaticity gets worse (refraction index of air varies more in visible than near-IR)
- 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)
- 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 # driven by field of view.

PSF quality: metric<u>**S**</u>

- **Low order AO, ground-layer AO:**
  - Full Width at Half Maximum (FWHM)
  - Encircled energy (50 % of light in 0.xx" diameter)
- **NGS narrow field AO, MCAO, MOAO**
  - Strehl ratio
  - FWHM and Encircled energy
- **Extreme-AO**
  - PSF contrast
  - Correction radius
  - residual jitter (coronagraphy)

Questions ???

1. Main challenges / error budget terms in astronomical AO systems

How to design an AO system which meets science requirements & reduces overall error budget ?

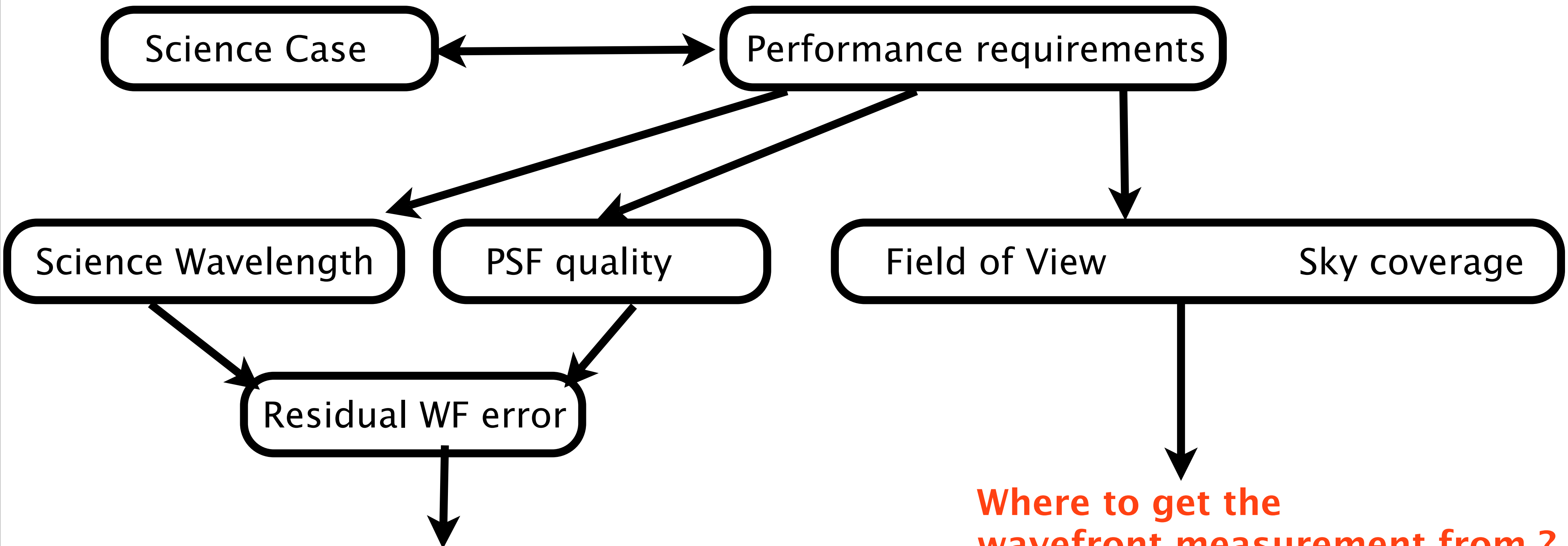
- The answer strongly depends on the science objective
  - Solar AO, Extreme AO, MOAO, GLAO, LGS vs. NGS ...

2. Wavefront sensing strategy

- **AO guide star:**
  - **LGS, NGS ? Multiple sources ? Sensing wavelength ?**
- **Choosing the right Wavefront Sensor**

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

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



Wavefront sensor(s) choice

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

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

Where to get the wavefront measurement from ?

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

Where to get the wavefront measurement ?

(1) Are there suitable natural guide stars ?

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

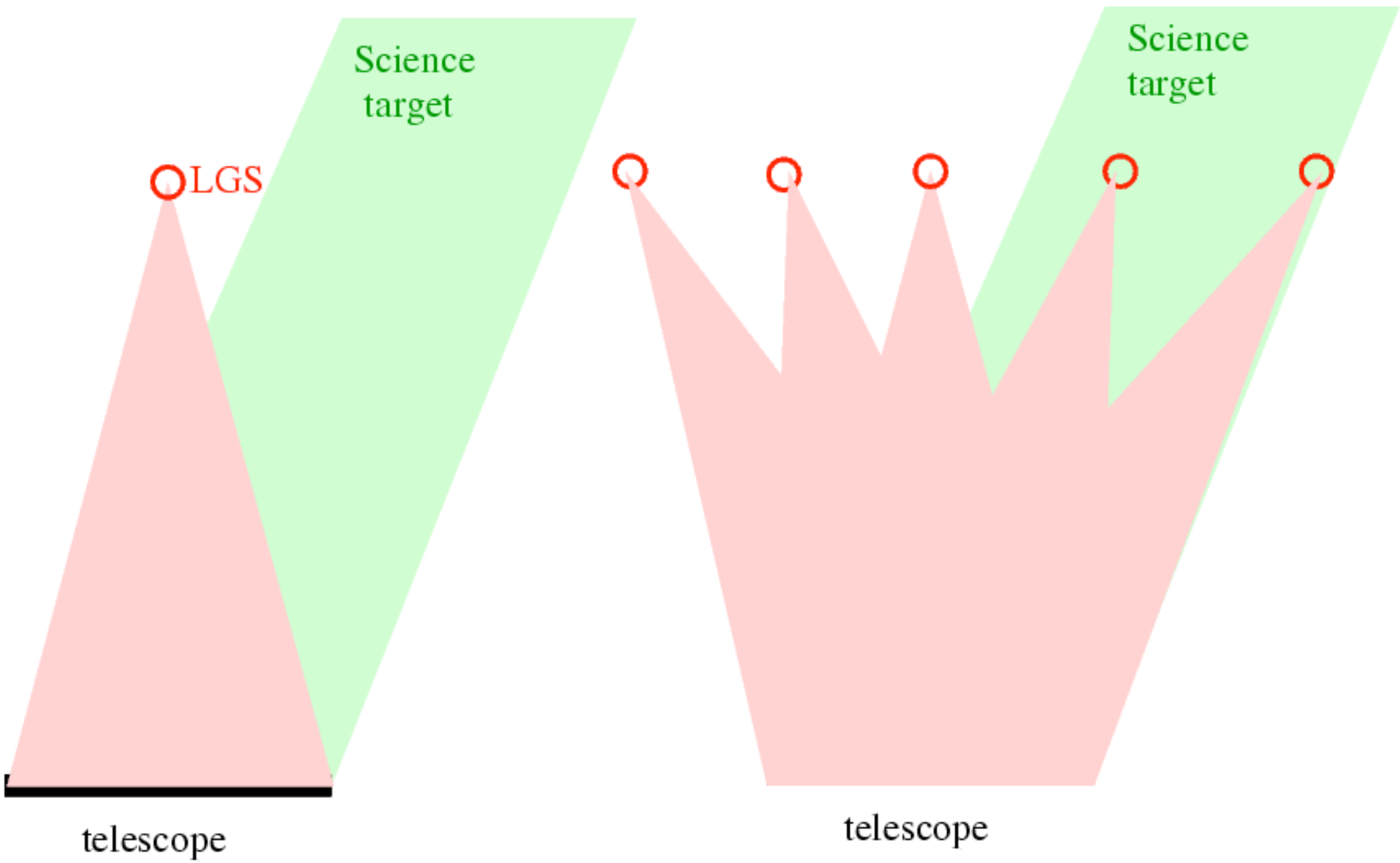
Where to get the wavefront measurement ?

(2) Need several guide stars ?

(for field of view, tomography ?)

Multiple LGS ?

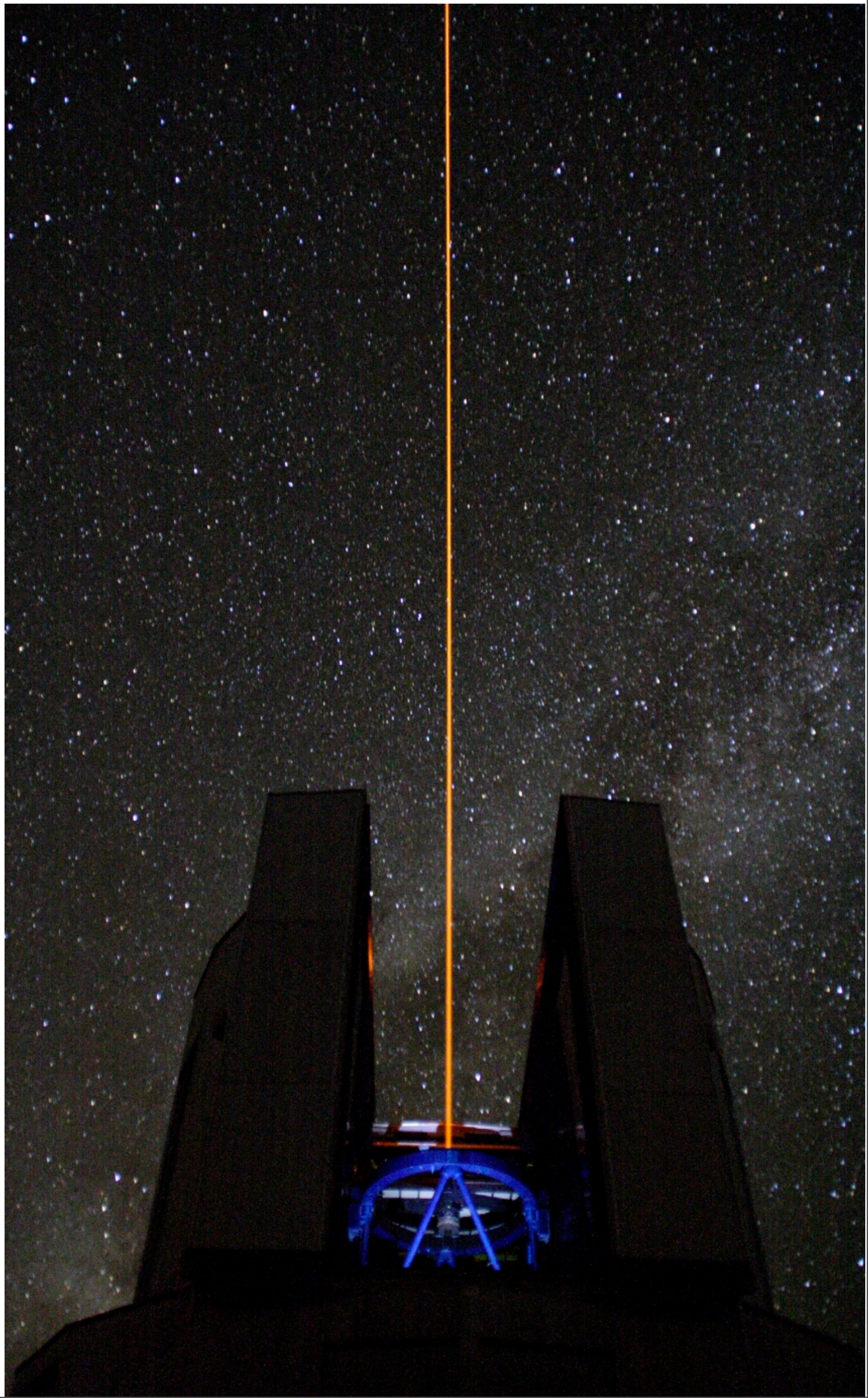
Multiple NGS ?



Some challenges of LGS AO

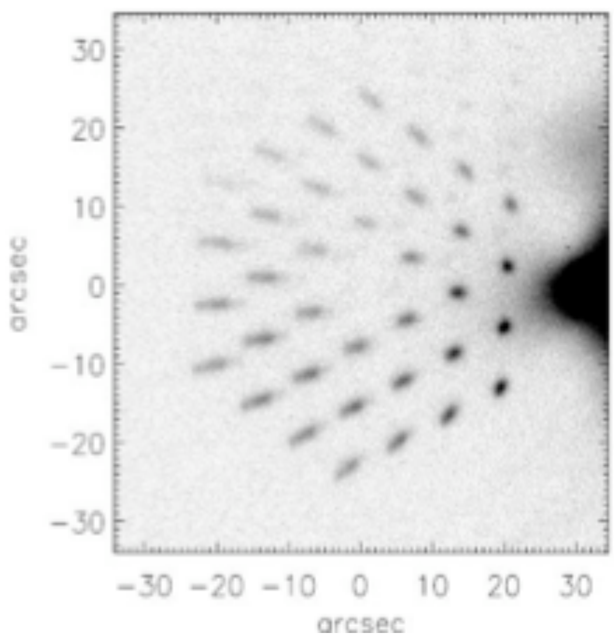
Cone effect due to finite altitude of LGS (90km sodium, few km for Rayleigh)
-> can be solved by using several lasers and tomography

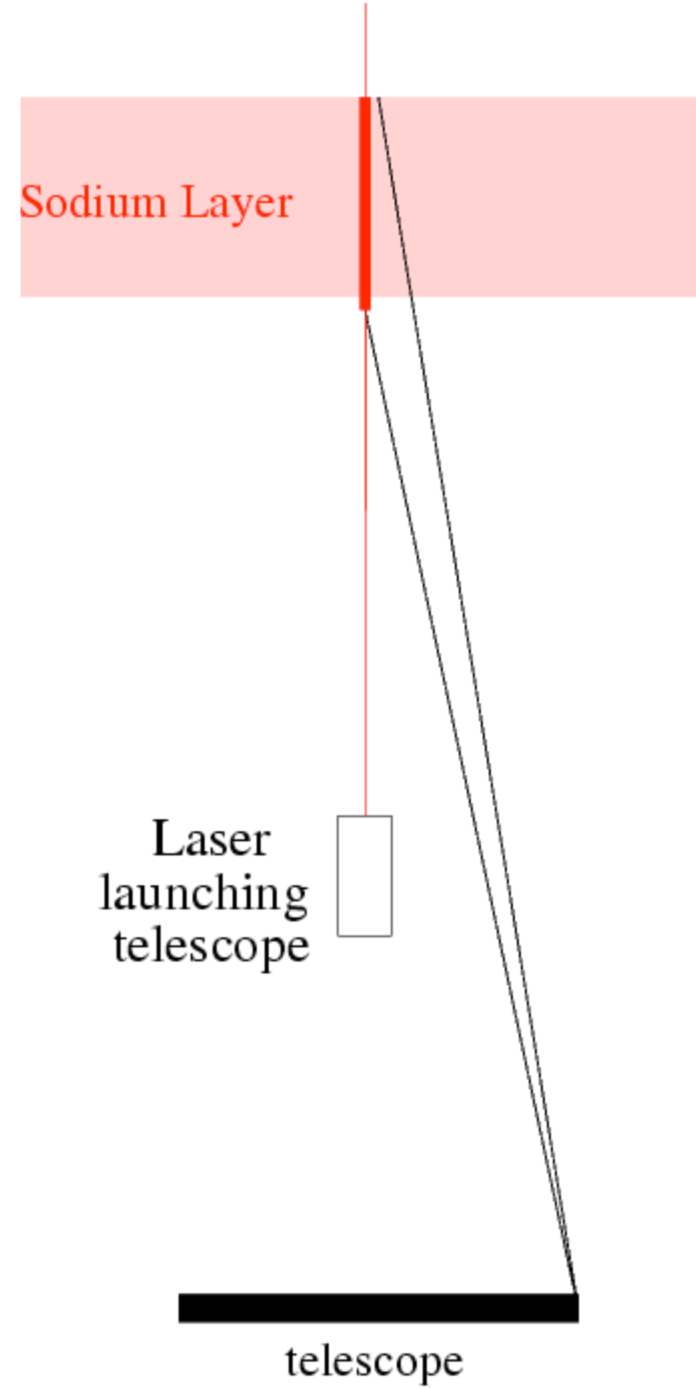
Tip/Tilt & Focus sensing
Upstream & downstream paths are the same: tip/tilt not seen
Sodium layer altitude not fixed: LGS focus info is incomplete (can be used to sense fast focus)
-> **Still need NGS(s) for tip/tilt & Focus**
-> polychromatic laser (not quite mature yet)



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

Wavefront Sensor Options...

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:
Focal Plane (FP)
Non-linear Curvature (nlCurv)
Non-linear Pyramid (nlPyr) ?

Next slide compiles strengths and weaknesses of WFS options, and will be explained with simple but fundamental physics ...

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

Wavefront sensor sensitivity

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

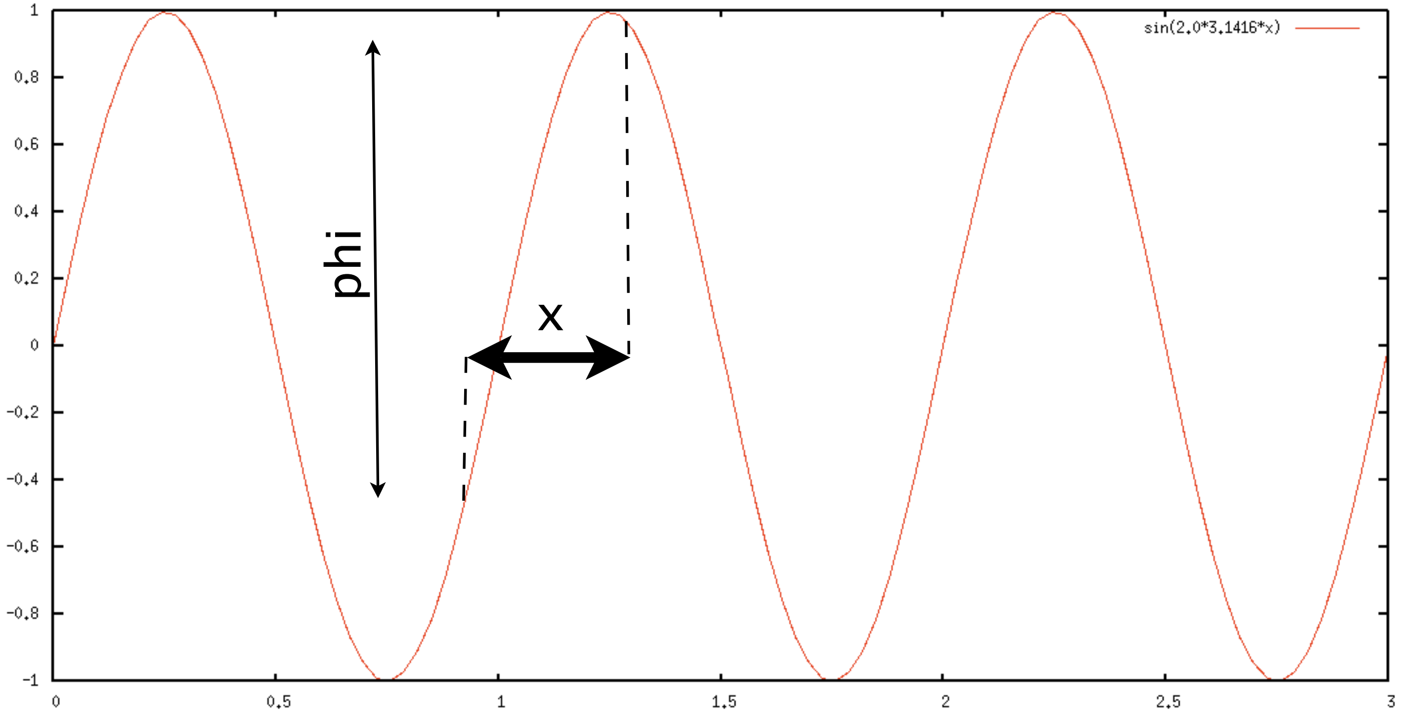
Non-ideal WFS:

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

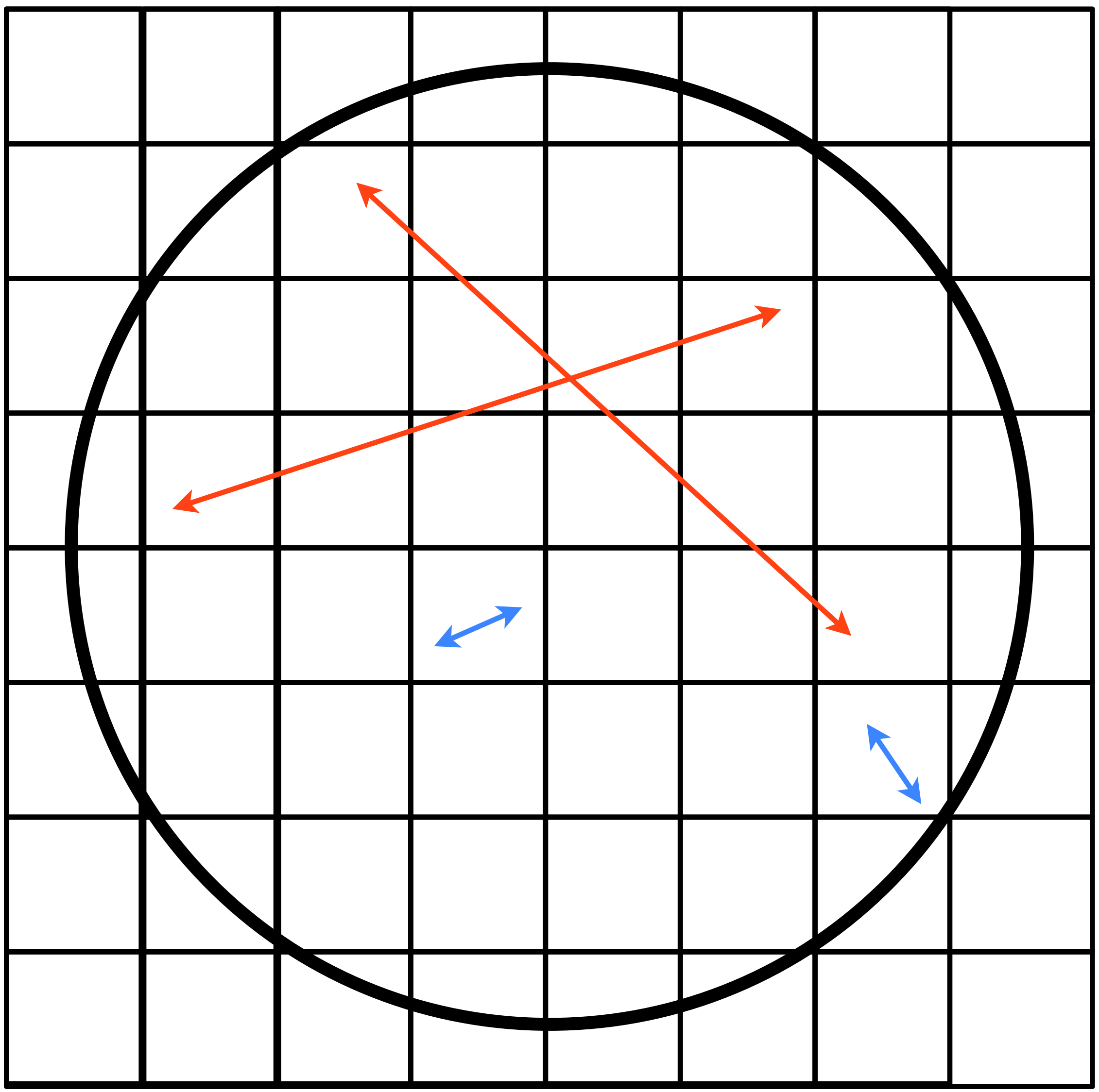
How to optimally convert phase into an intensity signal ?

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



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 !!!

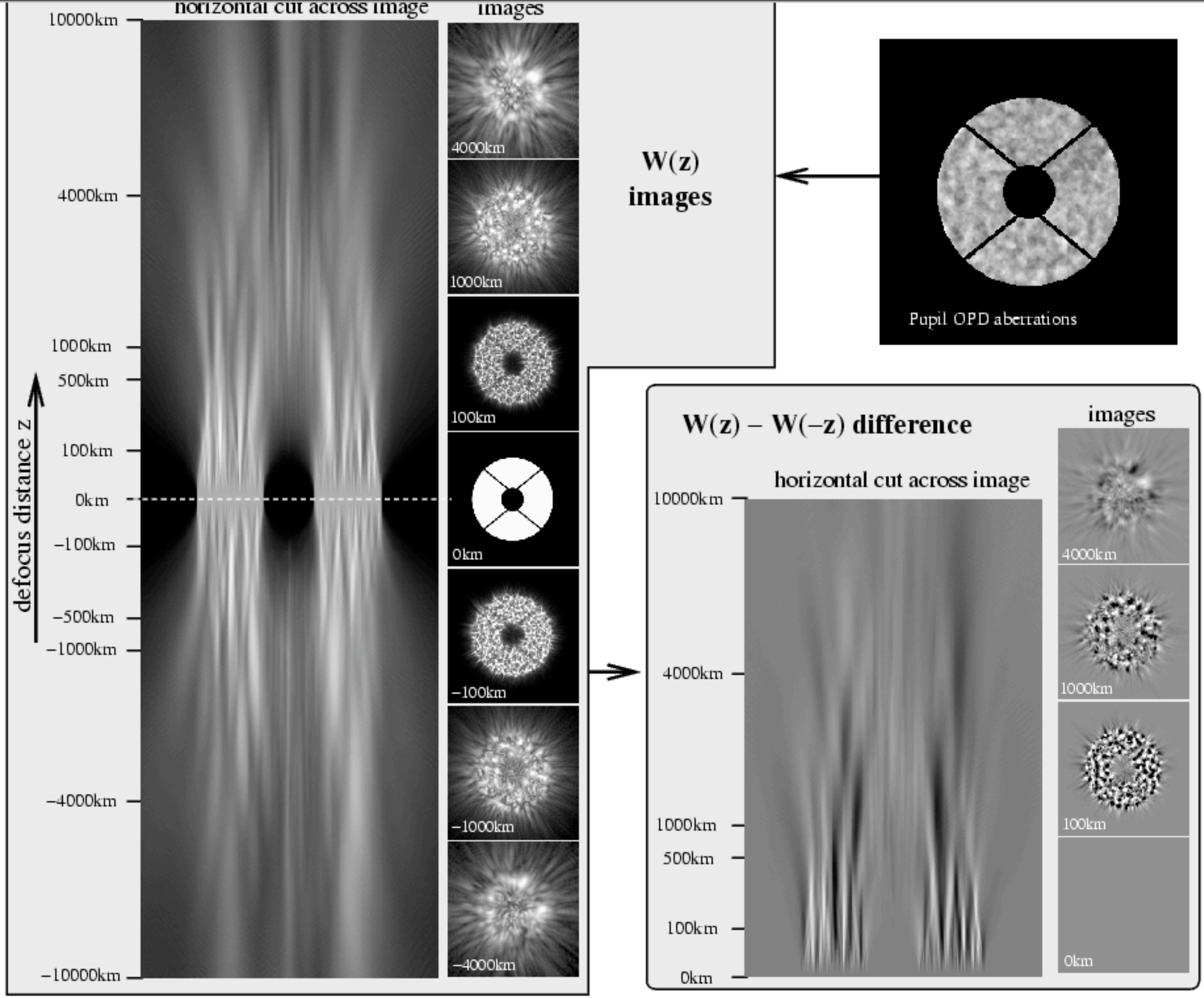
Curvature WFS

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

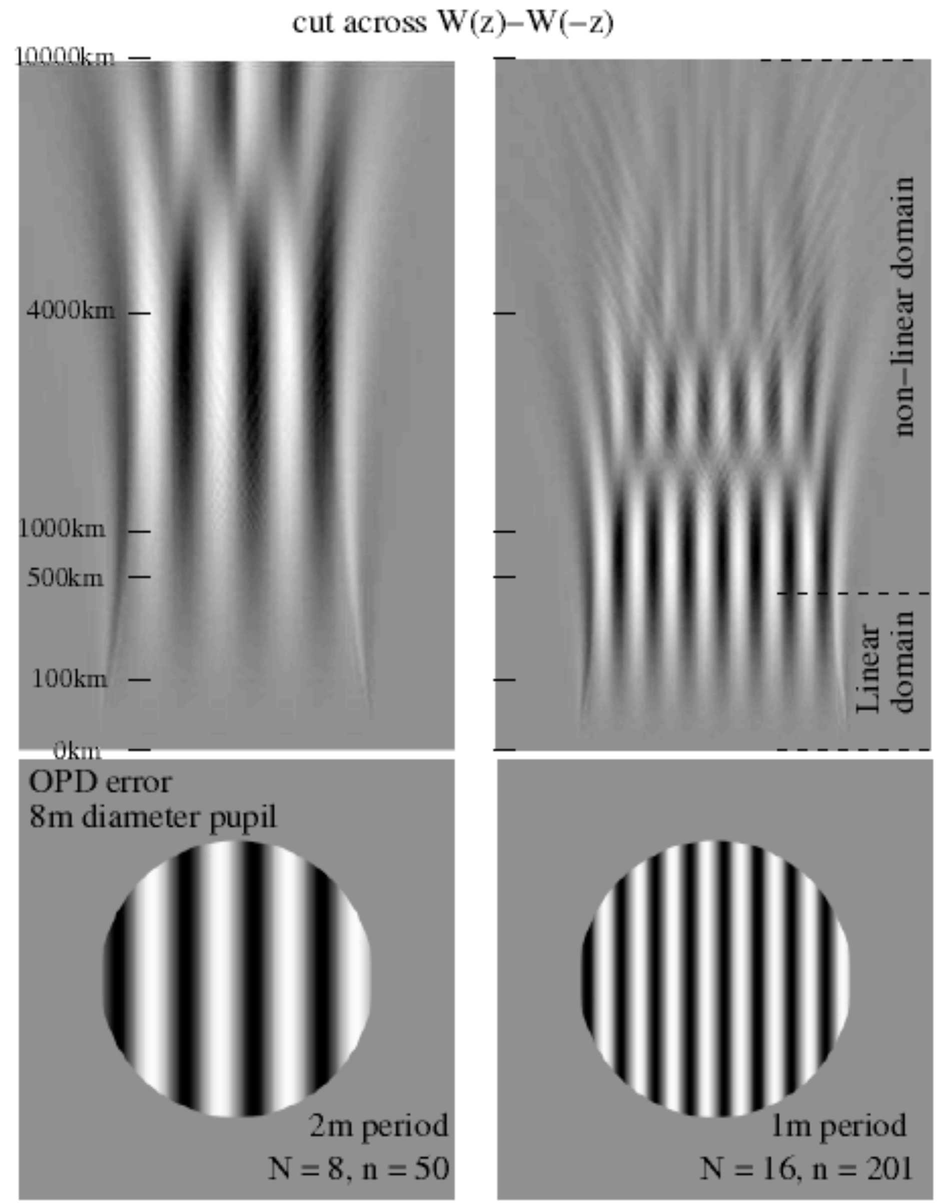

horizontal cut across image
images
10000km
4000km
1000km
500km
100km
0km
−100km
−500km
−1000km
−4000km
−10000km
defocus distance z
4000km
1000km
100km
0km
−100km
−1000km
−4000km
W(z)
images
Pupil OPD aberrations
W(z) − W(−z) difference
images
horizontal cut across image
10000km
4000km
1000km
500km
100km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

Problem #1:

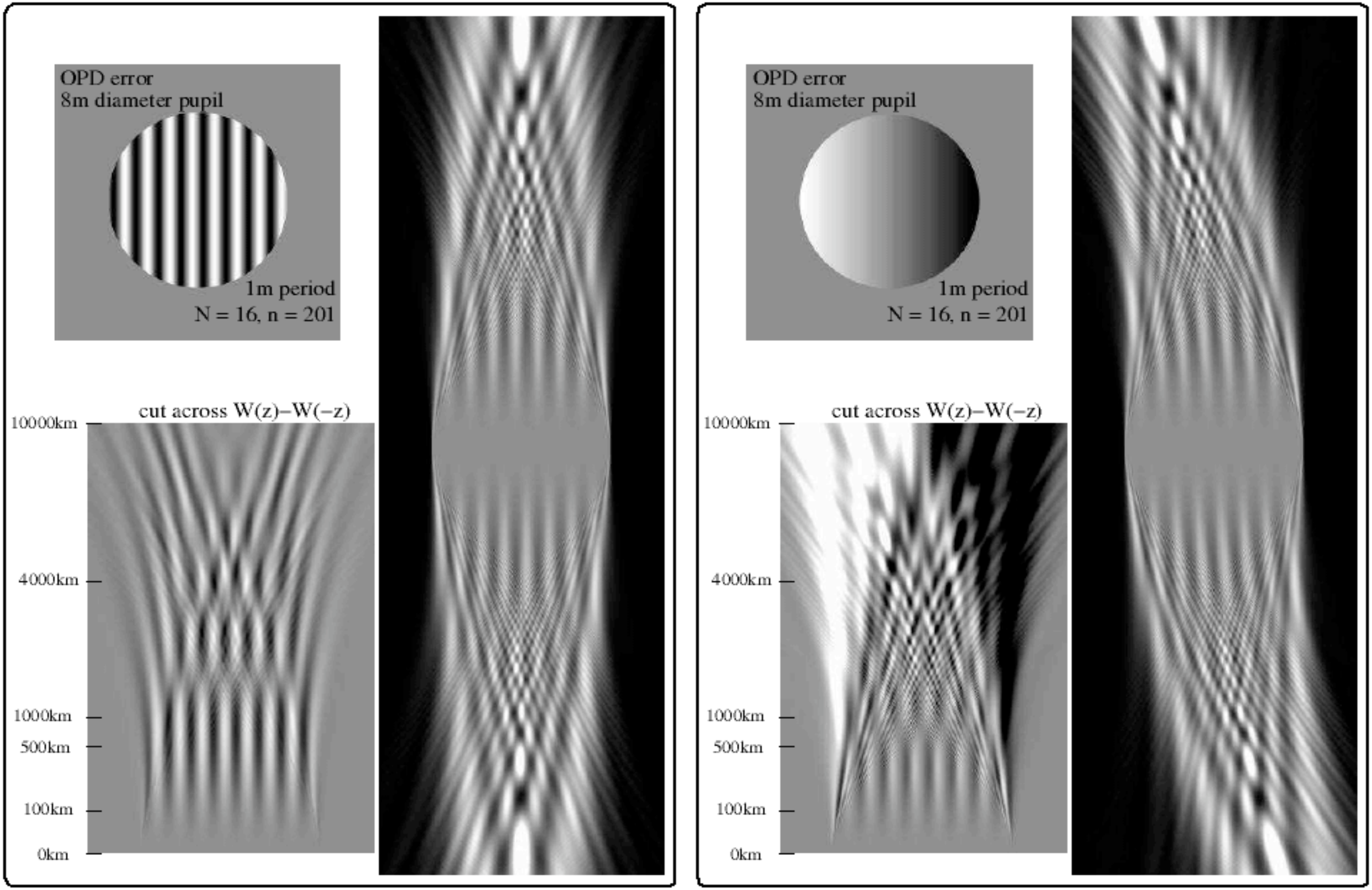
The “Linear” domain of curvature wavefront sensing (= defocus range within which wavefront curvature is linearly transformed into intensity modulation) becomes smaller as the # of actuators increases.

-> defocus distance must be kept small

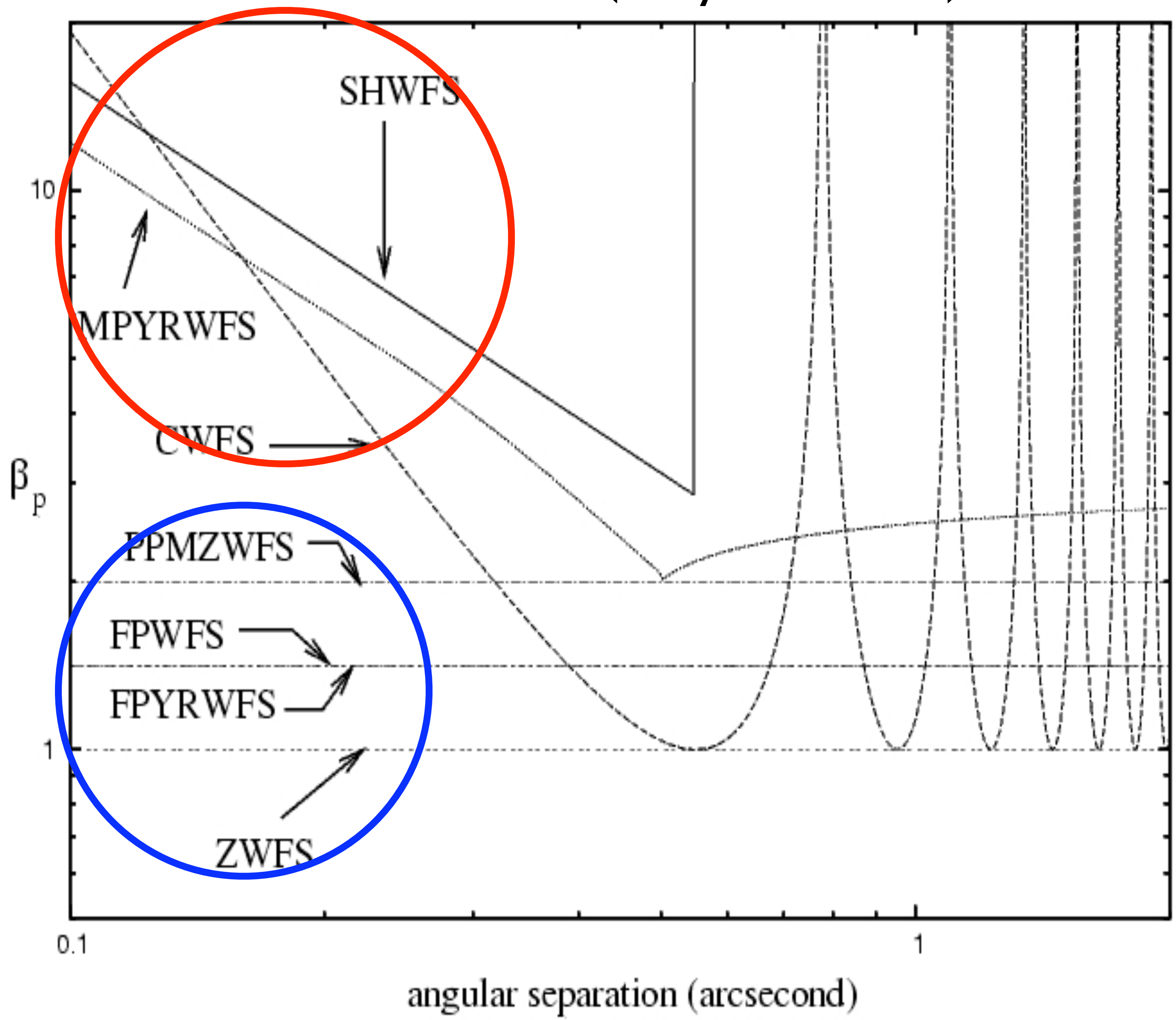
-> this forces low spatial frequencies to be poorly sensed



Problem #2: Low order aberrations "scramble" high spatial frequencies
-> defocus distance must be kept small



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.

Why do SH, Curvature (& modulated pyramid) have bad sensitivity for low order aberrations ?

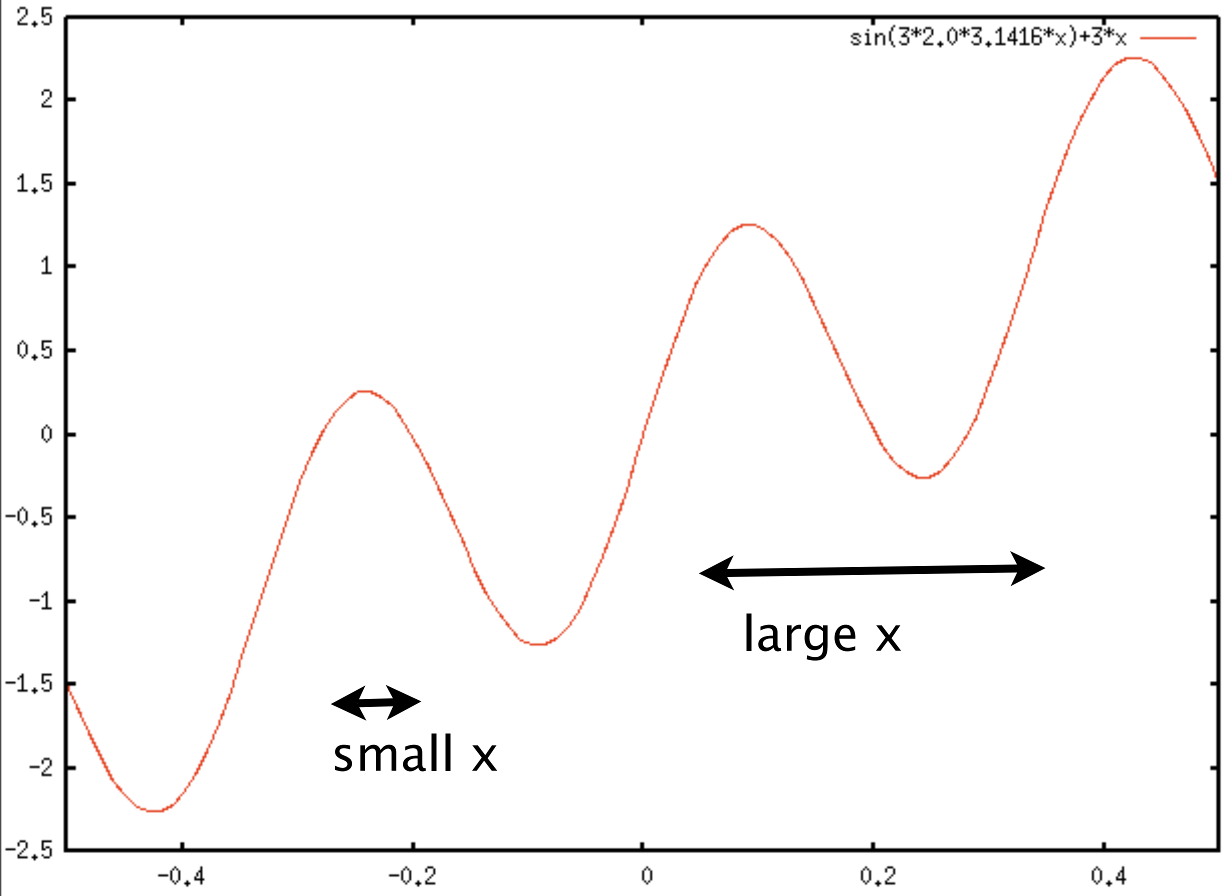
Good measurement of low order aberrations requires interferometric combination of distant parts of the pupil
FPWFS does it, but:
___- SH chops pupil in little pieces -> no hope !
- Curvature has to keep extrapupil distance small (see previous slides) -> same problem

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)

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

WFS range / linearity



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

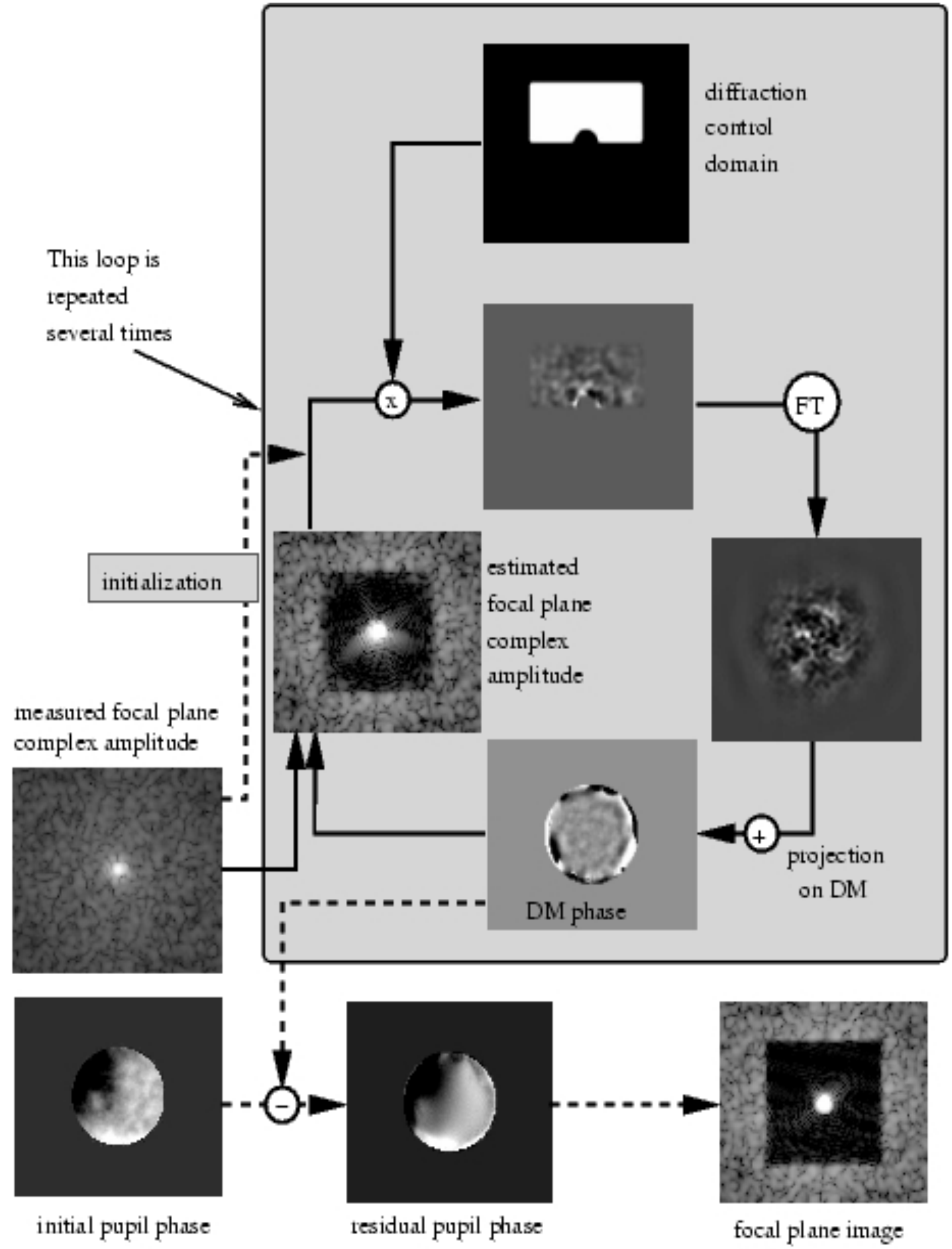
Solution:
Non-linear reconstruction allows a large dynamical range measurement on a high-sensitivity WFS

Focal plane WFS

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

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



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

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

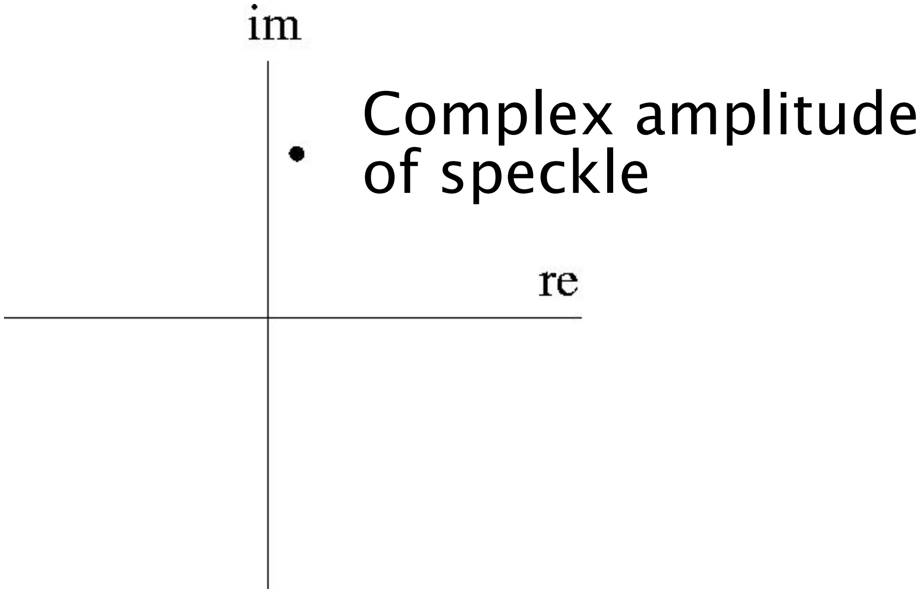
Measure speckle field with no previous knowledge:

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

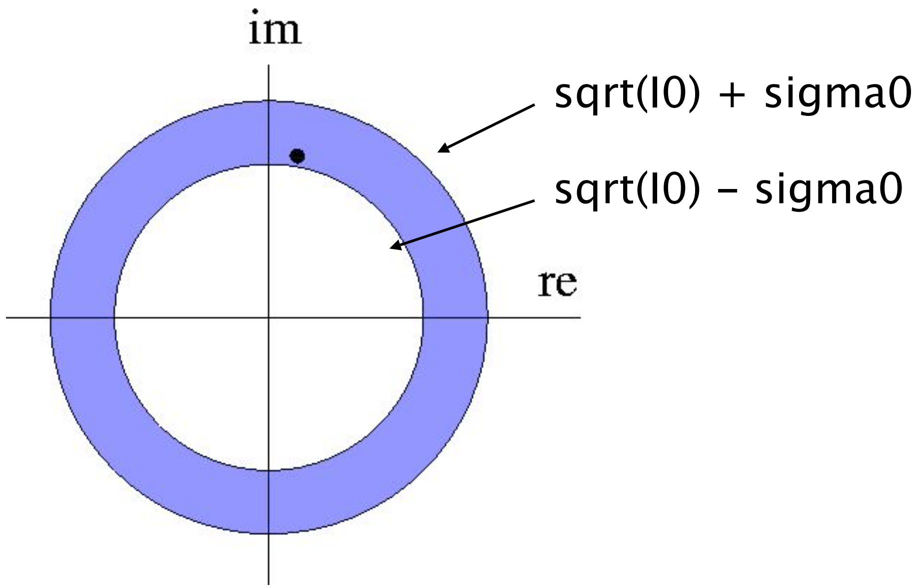
- compute 2 DM shapes which will add known speckles on top of existing speckles. These 2 “additive” speckle field have same amplitude as existing speckles, and the phase offset between the 2 additive speckle fields is PI/2

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

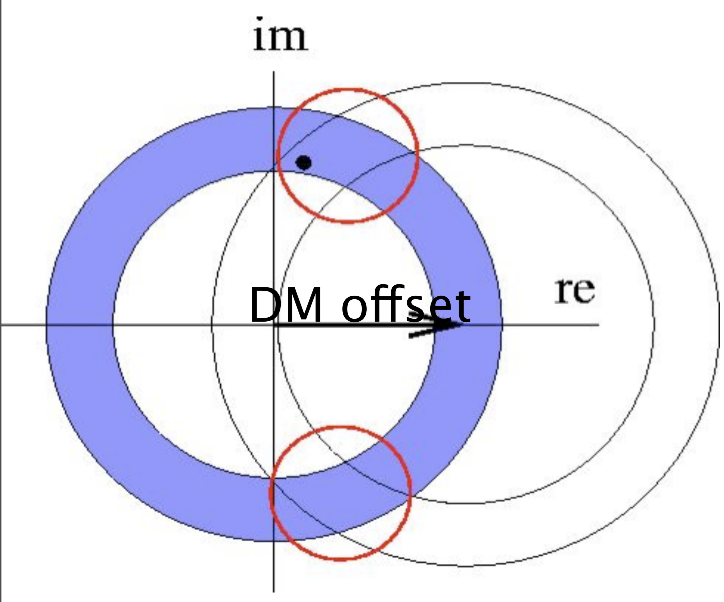
Initial problem

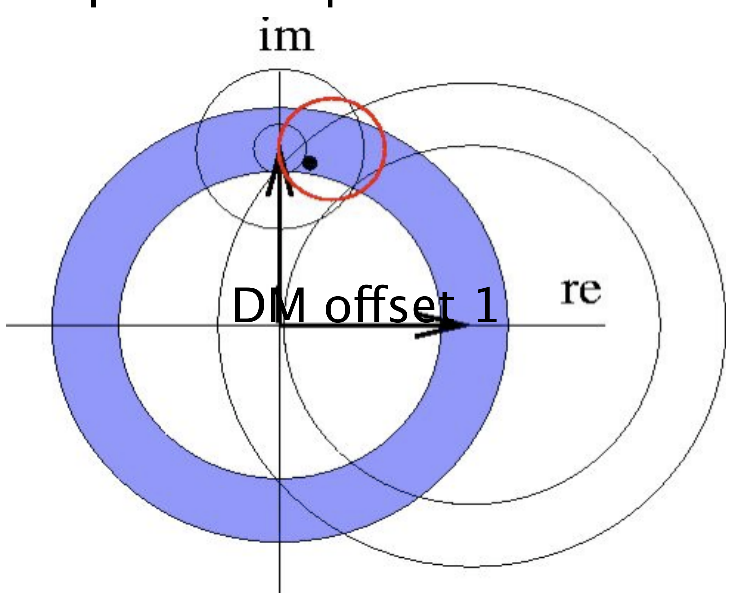


Take a frame -> measured speckle intensity = I0

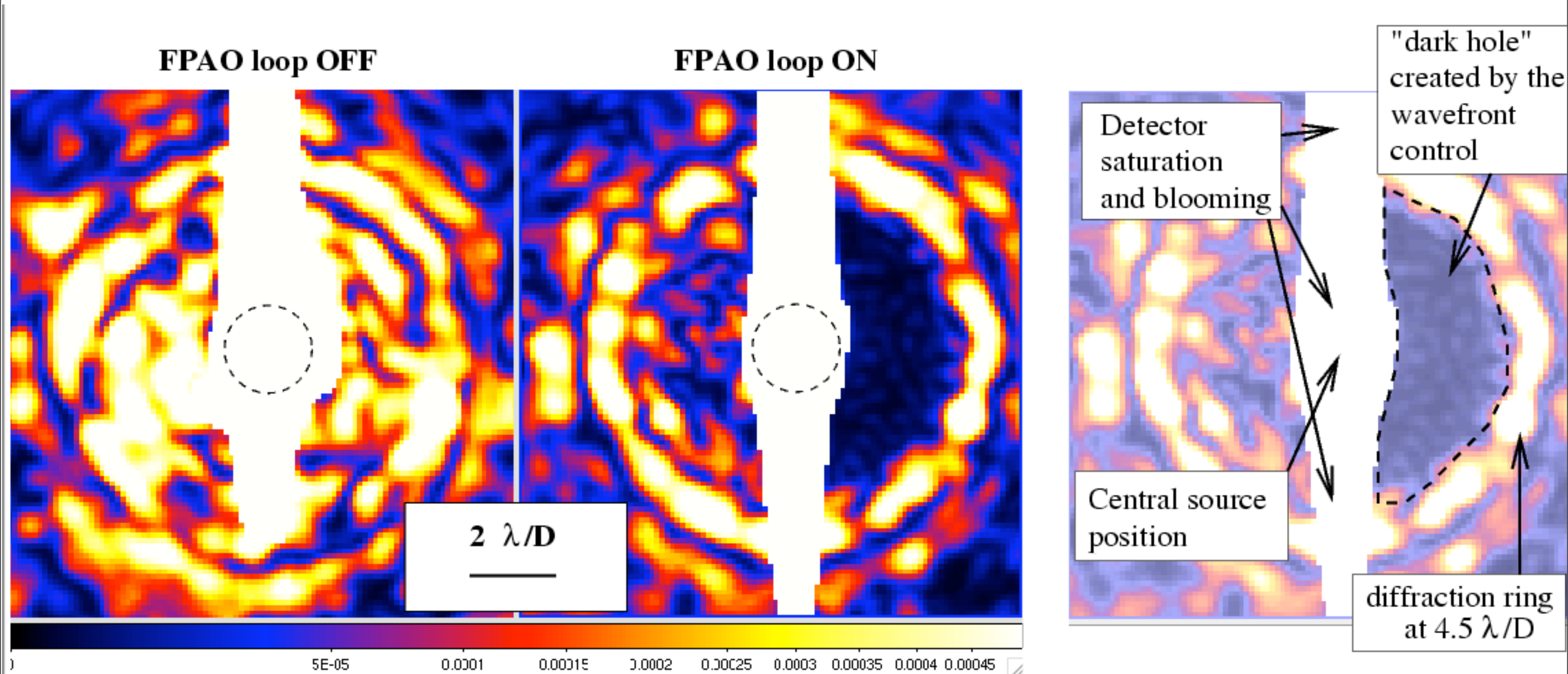


DM offset chosen to be ~ equal to speckle amplitude

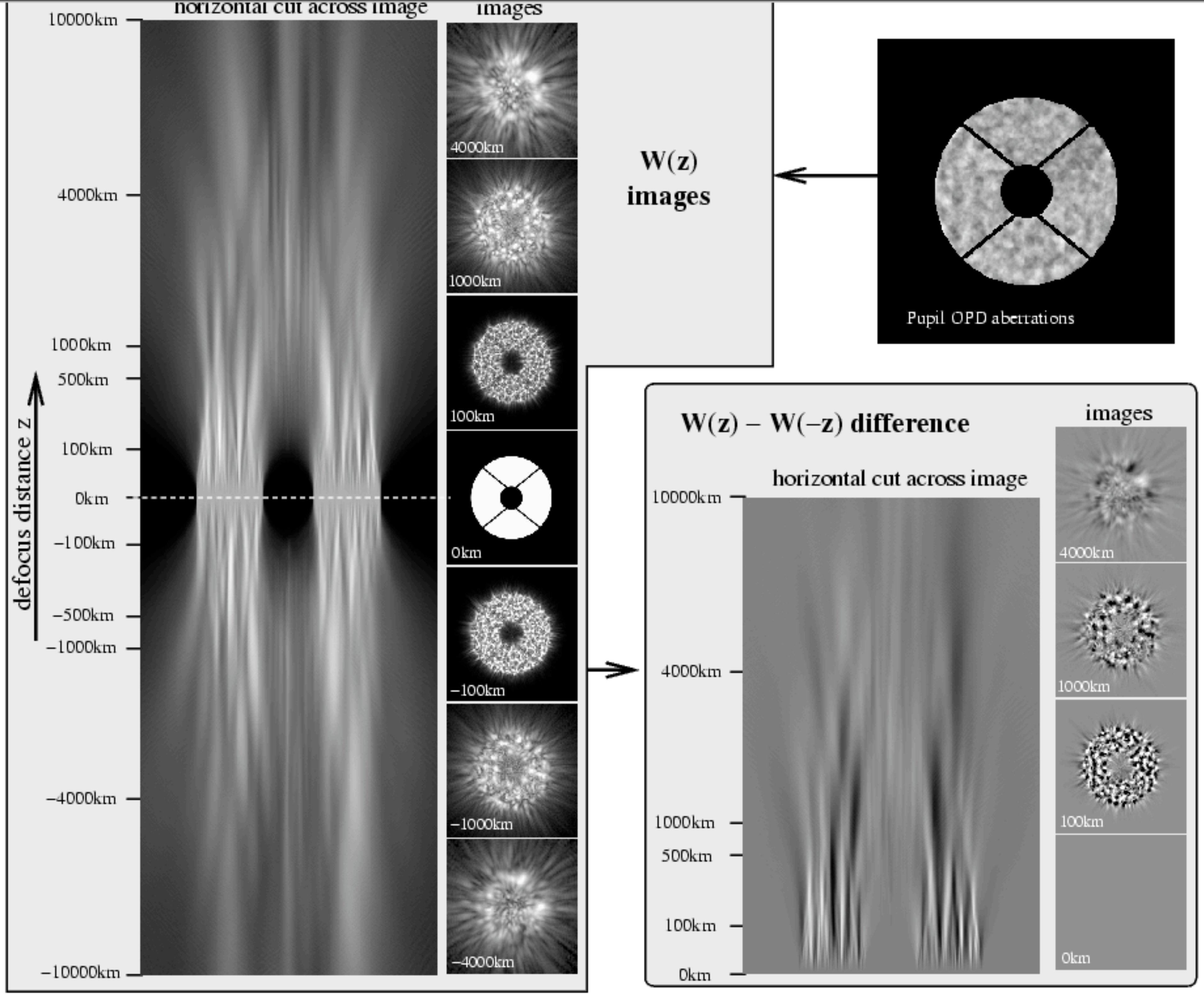




Lab results with PIAA coronagraph + FPAO with 32x32 MEMs DM



See also results obtained at JPL HCIT & Princeton
So far, these results are obtained at <1 Hz: making FPAO run at ~kHz is challenging (detector, algorithms)



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

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)

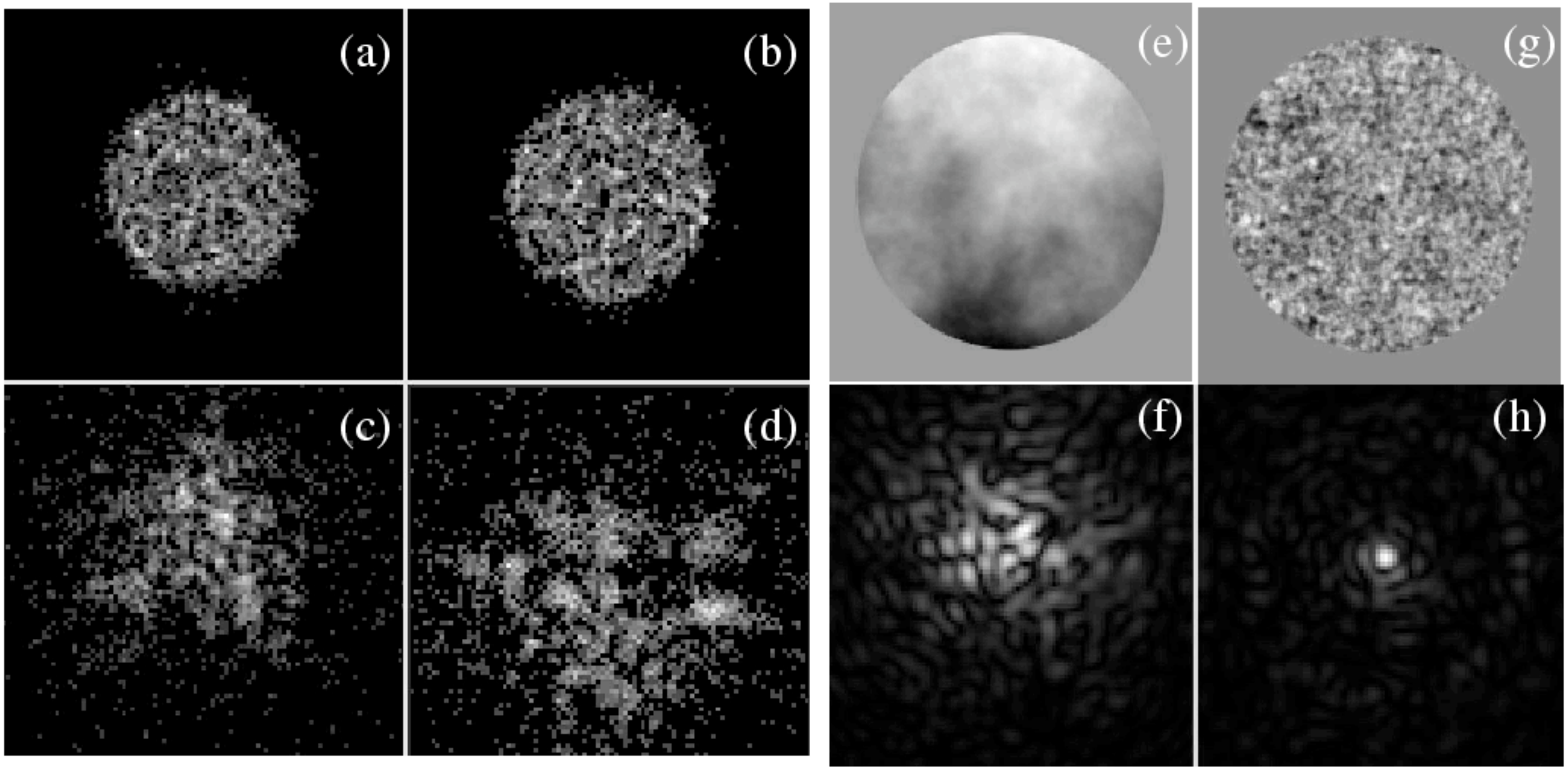


Fig. 9.— Wavefront reconstruction using the algorithm shown in fig. 8. Four noisy defocused pupil images (images (a), (b), (c) and (d)) are acquired to transform the pupil phase aberrations (e) into intensity signals. The input pupil phase is 609 nm RMS, yielding the PSF (f) before correction. After 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.

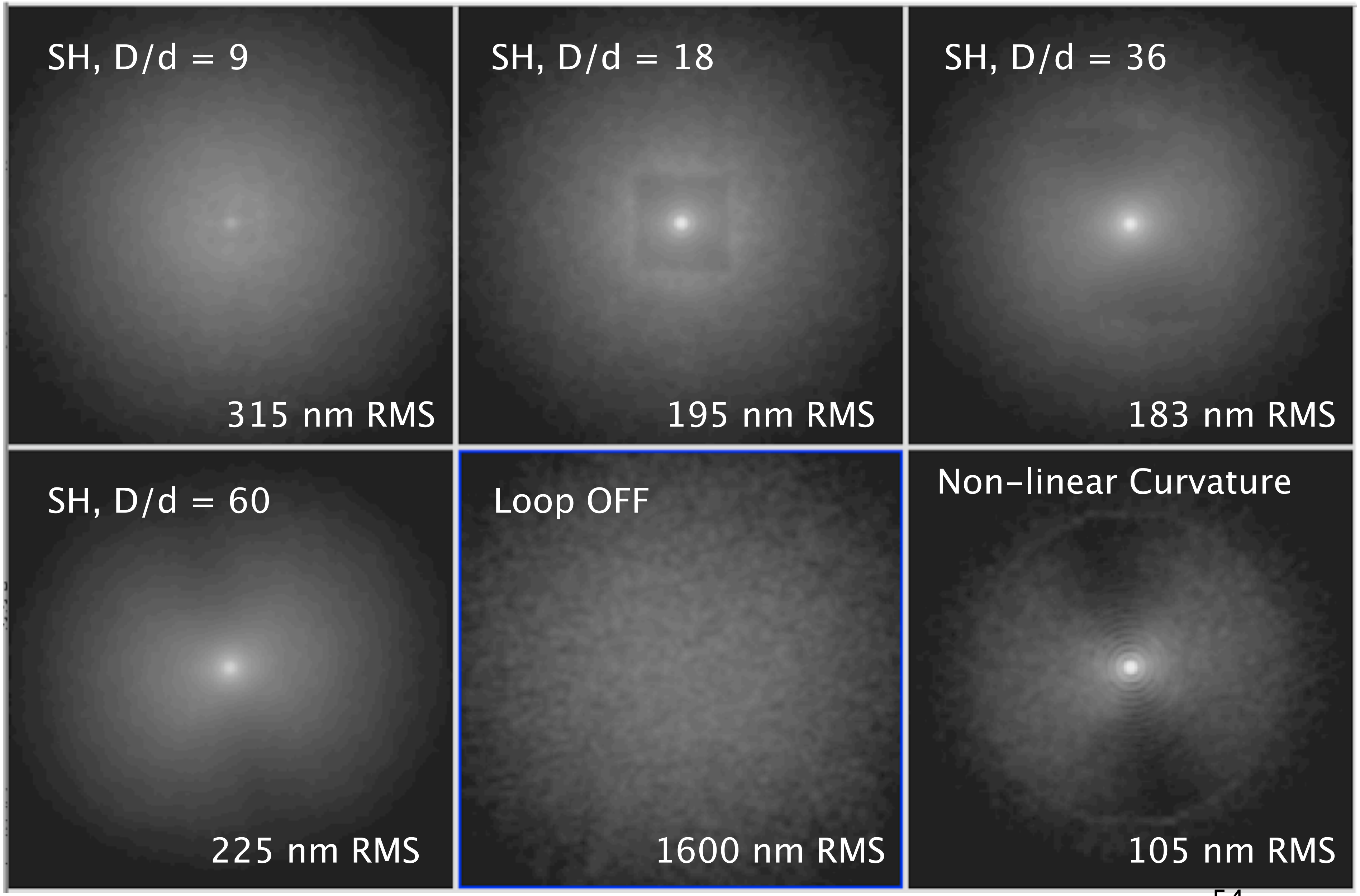
	sensitivity	range	Extended target ? (LGS)	chromaticity	maturity	detector use
SH	serious noise propagation	Very good	Yes	Low	on sky	at least 4 pixels per subaperture
Curvature	serious noise propagation	Very good	Somewhat LGS OK	Low	on sky	1 pix/subaperture 2 reads
Pyramid (modulated)	noise propagation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

Good range/linearity but poor sensitivity

Good sensitivity over a small range

Non-linear reconstruction algorithm allows good sensitivity and larger range

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



Guide “star” for WFS: COHERENCE

COHERENCE = ability to make coherent interferences between different 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

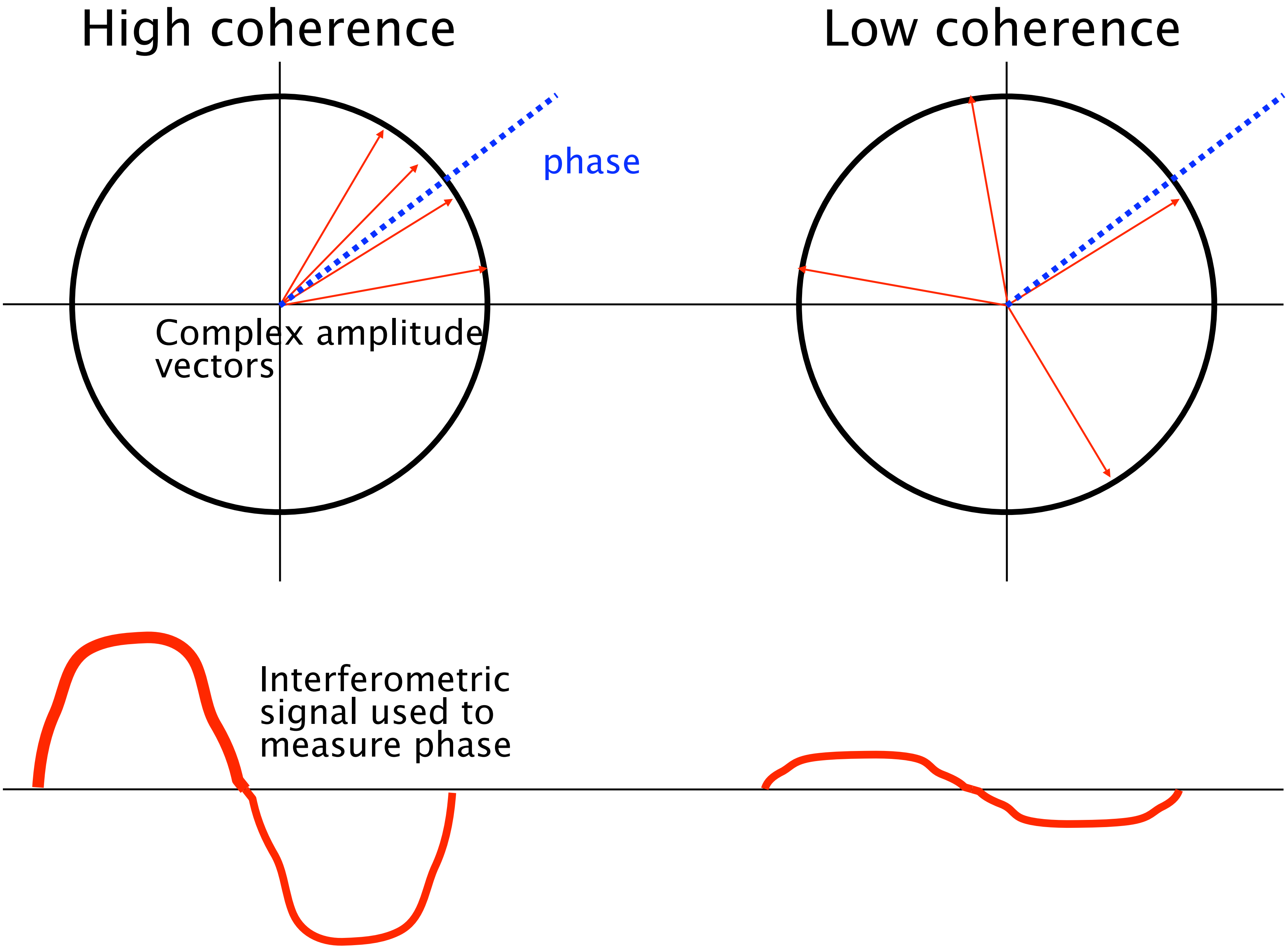
Wavefront coherence on large spatial scales must be maintained for high-sensitivity WFS

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



Example of loss due to temporal coherence.
Note how choosing longer sensing wavelength helps by increasing wavefront coherence (even though phase signal gets smaller !!!)

Closed loop simulations

WFS:
non-linear phase retrieval on curvature wavefront sensor

Same behaviour would be obtained with fixed pyramid

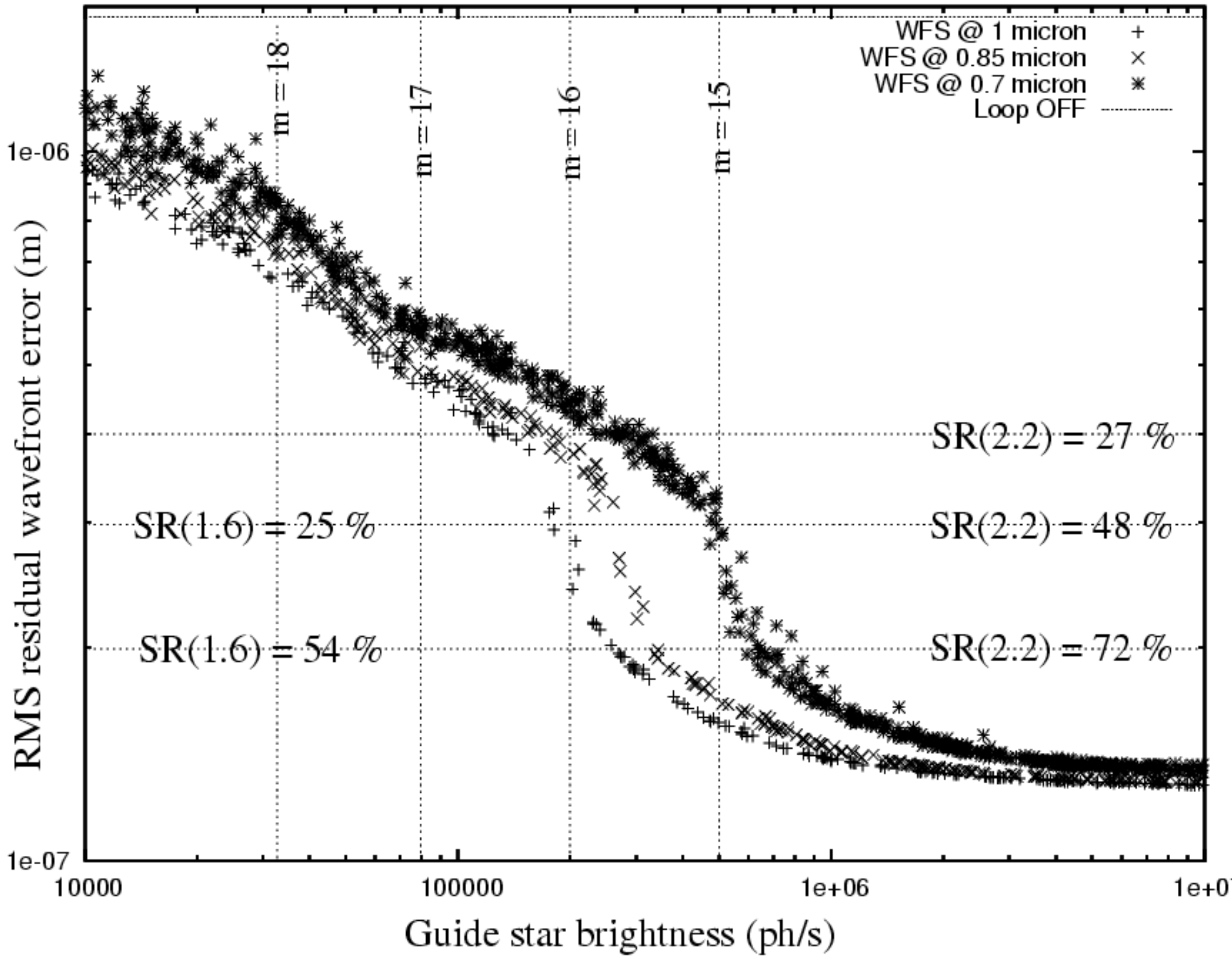


Fig. 11.— Simulated performance of a non-linear Dual stroke Curvature as a function of sensing wavelength (0.7, 0.85 and 1.0 μm) and guide star brightness. The stellar magnitudes given in this figure assume a 20% efficiency in a 0.5μm wide band. See text for details.

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")

Interferometric

Focal plane

Not allowed

~ 1 rad

Extreme-AO Closed loop in Visible

Thermal IR AO on 8m telescope open loop

"general purpose" AO system in closed loop

Pyramid (fixed)

allowed

Pyramid (modulated)

>> 1 rad

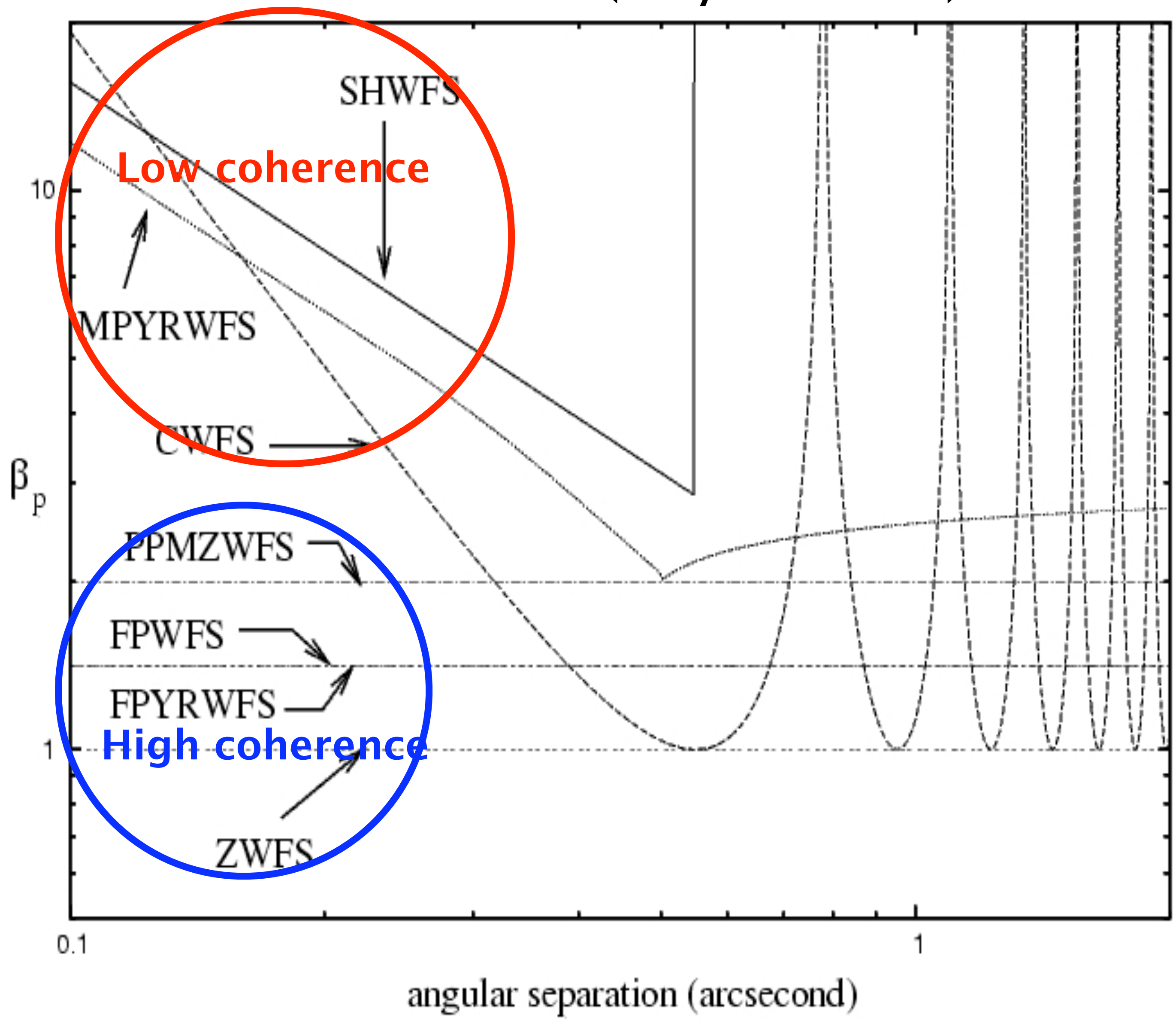
LGS AO
GLAO

Open loop AO

Curvature

Shack-Hartmann

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 0.5" separation.

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

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

Example: Possible Coronagraphic ExAO architecture

High speed AO in visible

non linear curvature
Pyramid
Shack Hartmann

→

Near-IR

Coronagraph
Focal plane AO →

Fast camera for
focal plane WFS
after coronagraph

Science frame
acquired by the
same camera
as FPWFS

The first step is used to clean the wavefront within ~ 1 rad in Visible

The second step operates in the high coherence regime, and adopts the FPWFS.

Gemini Planet Imager (GPI) uses a similar strategy, with an interferometer to measure coherent residuals

Questions ???

1. Main challenges / error budget terms in astronomical AO systems

How to design an AO system which meets science requirements & reduces overall error budget ?

The answer strongly depends on the science objective

Solar AO, Extreme AO, MOAO, GLAO, LGS vs. NGS ...

2. Wavefront sensing strategy

AO guide star:

LGS, NGS ? Multiple sources ? Sensing wavelength ?

Choosing the right Wavefront Sensor

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

AO control

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

“standard” solution (fast, linear):

- Measure/model how WFS measures DM commands
- If relationship is linear, this is stored as a “response matrix”
“response matrix” is inverted -> “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 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.

AO system & science instrument

Other ways science instrument can drive AO design:

IR instruments need low thermal background
-> fewer warm optics
example: adaptive secondary mirror

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)

Science instrument can perform its own wavefront sensing
- This is especially true for Extreme-AO
Science instrument measures non-common path errors
example: Focal plane wavefront sensing

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!)


We have them on the run. Finish the job Freelancer
Diminutions Attack Probe [LOCKED]
Velocity: 0.0
Frames: 30
Weapon: Prism Cannon [1399/1500]
Shields
Armor
Struct.
Energy
Fuel
Cargo
Destroy the Invading Probe
Probe Destroyed
Probe Destroyed
Probe Destroyed
Probe Destroyed
Galaxy
Options
Control
Status
Mission

(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

Thank you...

Questions ???