Ultra high precision wavefront sensing for (Extreme-AO on) ELTs

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- ***Why not use "conventional" WFS for ExAO ?***
- ***Focal plane WFS + calibration***
- ***Non-linear Curvature: a robust WFS for ExAO and non-ExAO (all sky high Strehl AO?)***

Wavefront sensor sensitivity

Seeing-limited WFS vs Diffraction-limited (or "high coherence") WFS

Sensitivity = how well each photon is used

Ideally, for each WF mode: Error (rad rms on pupil) = 1 / sqrt(# of photons)
N photons, M modes : Error (rad) = sqrt(M/N)

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How well does a SH WFS do compared to this “ideal” limit ? ... quite bad !

Seeing-limited (at best !) instead of diffraction-limited (D^2 instead of D^4)
For Tip-Tilt (easiest mode to understand), SH requires $(D/r_0)^2$ more photons than ideal
 8m telescope, r_0 = 0.2m : Factor 1600 (8 mag)

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- 8m telescope, r_0 = 0.2m : Factor 1600 (8 mag)
- 42m telescope : Factor 44100 (12 mag)

For cycle per aperture (CPA) > 1: factor = $(D/(r_0 x CPA))^2$

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Do WFSs that reach this limit exist ? ... yes, but ...
Yes, several do, but they may not be as easy to use (this is the core of this talk)

What are these "ultra-high sensitivity WFSs" ?
How do they work ? (do they really work ???)
When can they be used ?
What does it mean for AO on ELTs (not just ExAO) ?

Wavefront Sensor Options...

Linear, large dynamical range, poor sensitivity [Easy to use in all conditions]
Shack-Hartmann (SH)
Curvature (Curv)
Modulated Pyramid (MPyr)

Linear, small dynamical range, high sensitivity [Won't work well if > 1 rad error - OK for ExAO]
Fixed Pyramid (FPyr)
Zernike phase constrast mask (ZPM)
Pupil plane Mach-Zehnder interferometer (PPMZ)

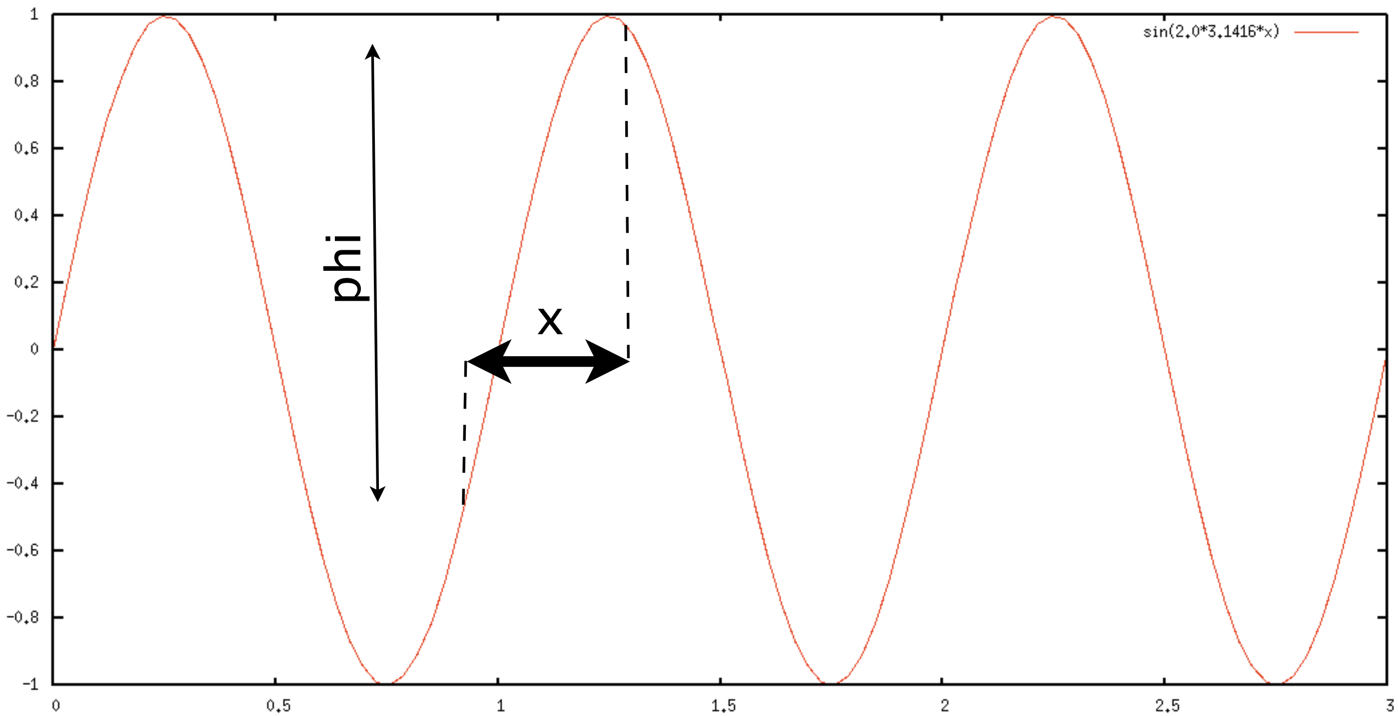
Non-linear, moderate to large dynamical range, high sensitivity [Should be used if possible, linear if < 1 rad]
Focal Plane (FP) - for ExAO
Non-linear Curvature (nlCurv)
Probably many others schemes ???

All this is well understood from theory...

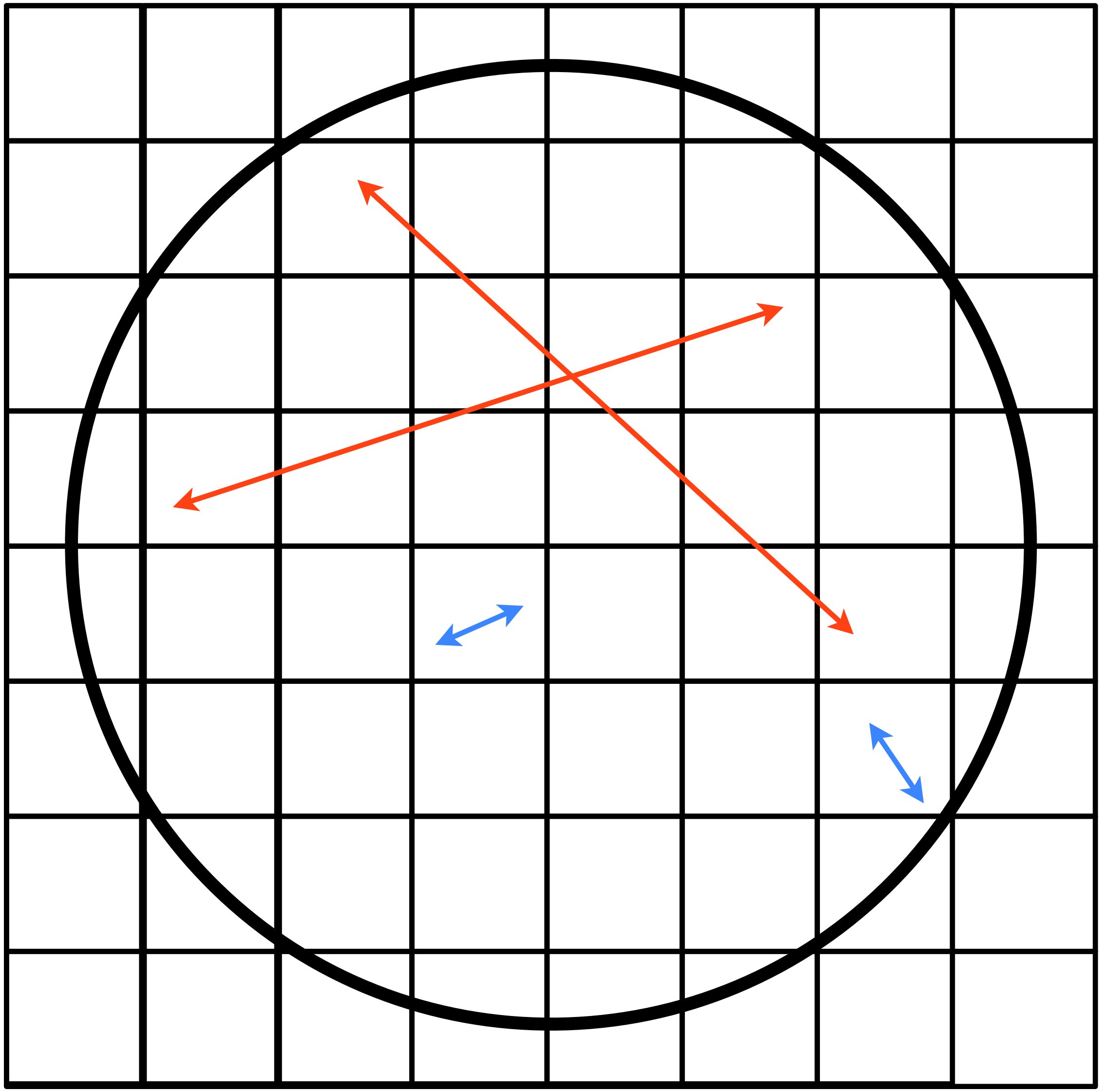
How to optimally convert phase into an intensity signal ?

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

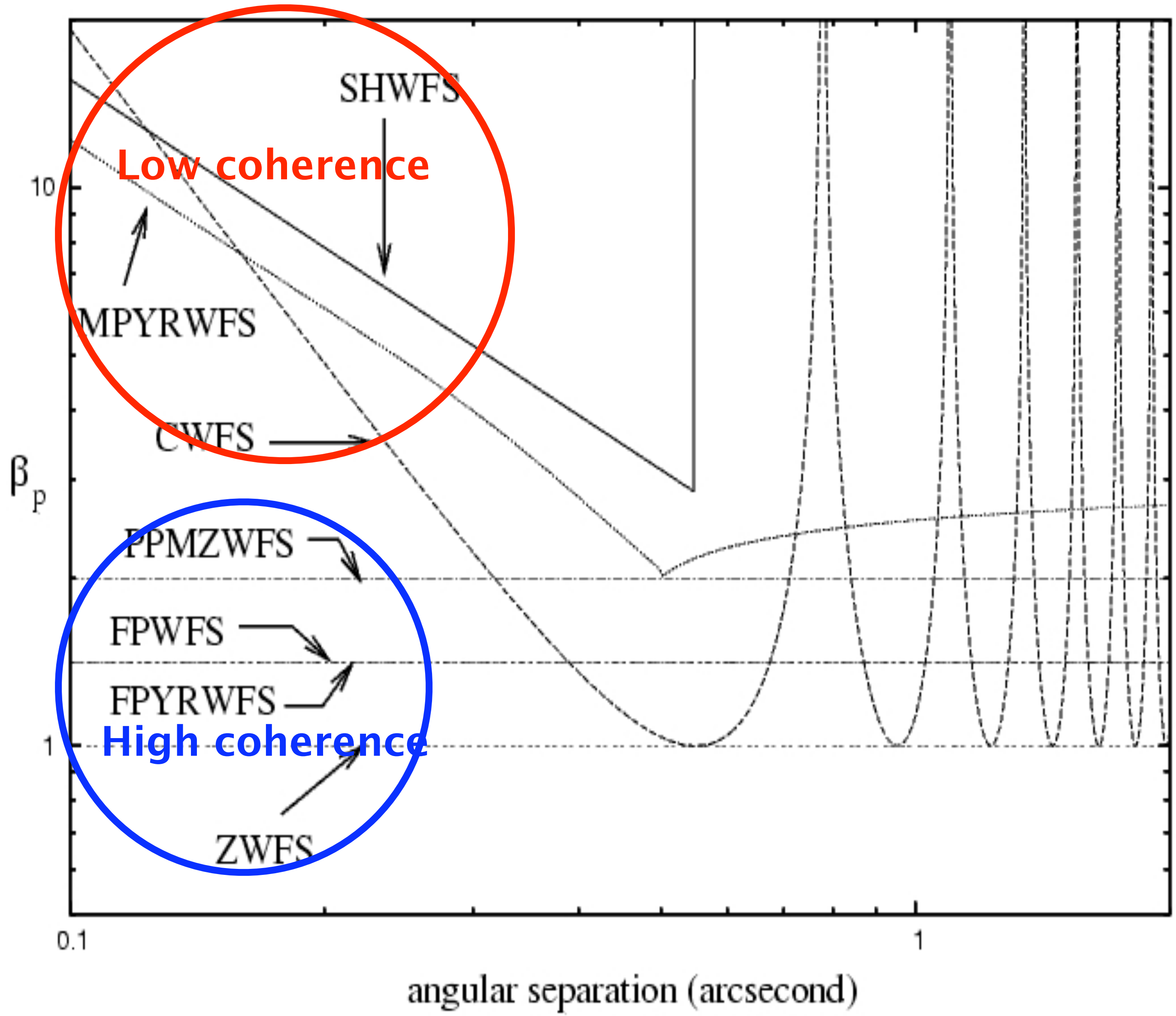


Problem:
SH does not allow interferences between points of the pupil separated by more than subaperture size

-> Poor sensitivity to low order modes (“noise propagation” effect)

This gets worse as the number of actuators increases !!!

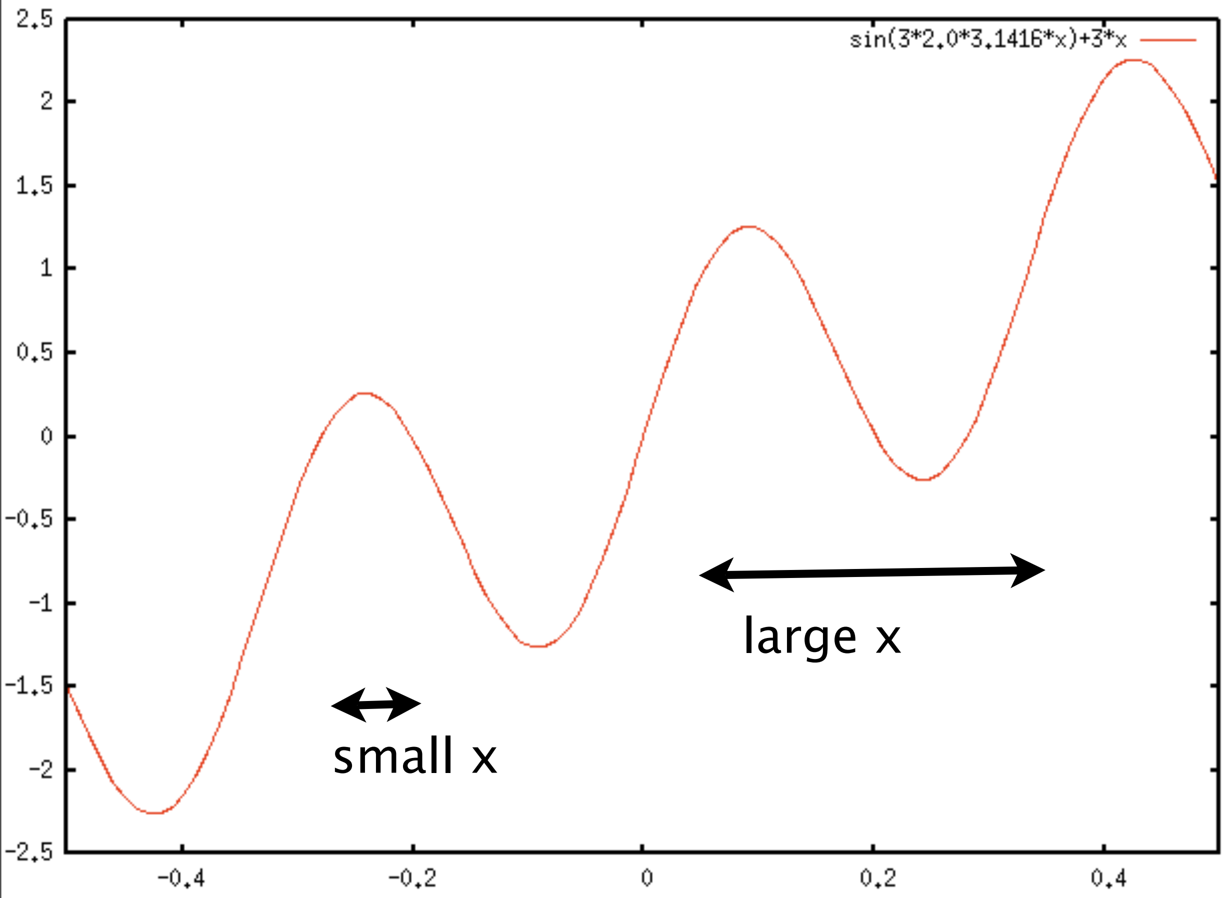
Wavefront sensors "sensitivities" in **linear regime** with full coherence (Guyon 2005, perturbation analysis)



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

plotted here for phase aberrations only, 8m telescope. Tuned for 0.5" separation.

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

	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

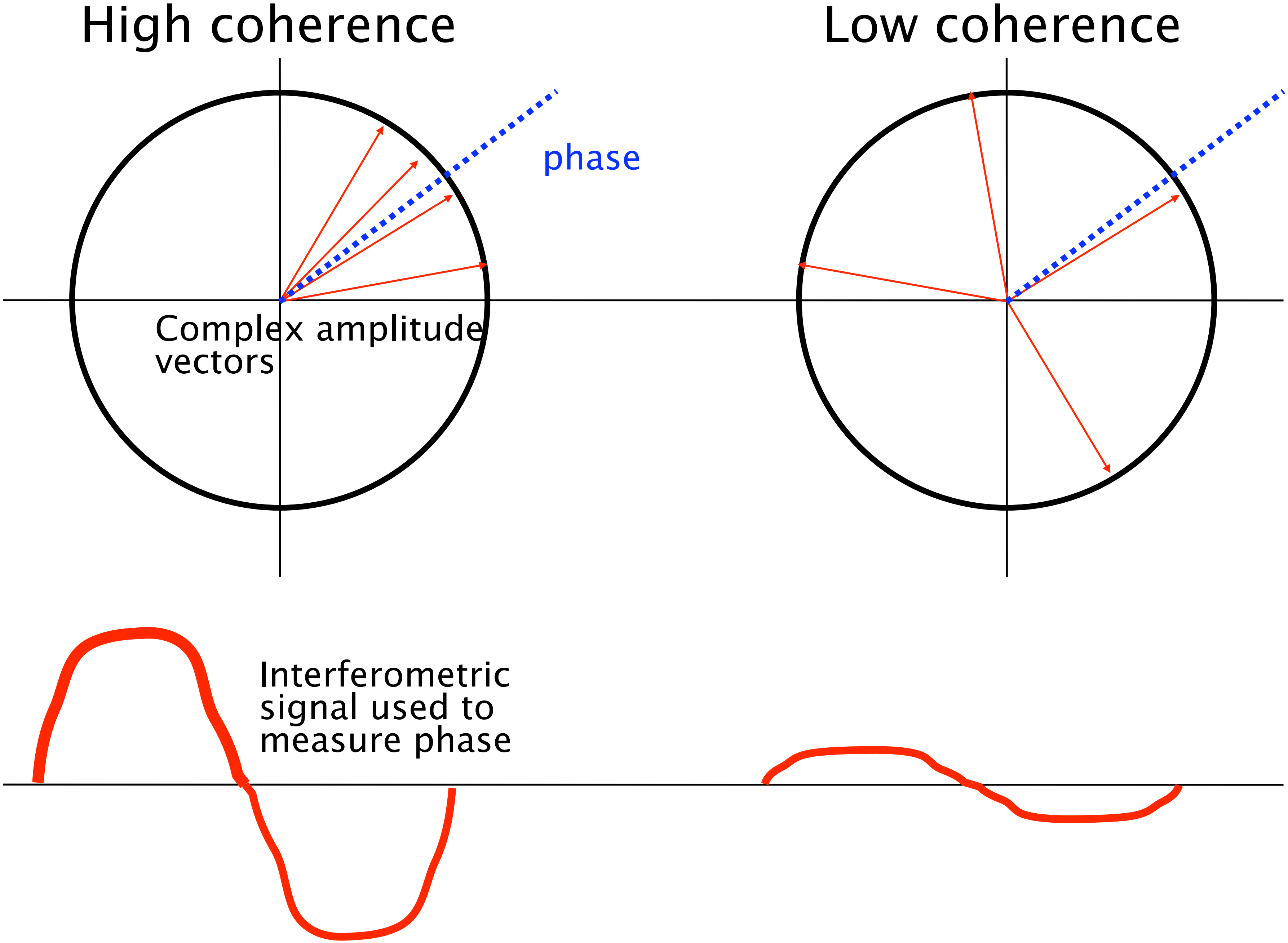
Wavefront coherence on large spatial scales must be maintained for high-sensitivity WFS

Temporal coherence:
"long WFS exposure" will greatly attenuate the signal if > 1rad variation in WF
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

Extreme AO has both temporal and spatial coherence, especially if there is a front AO system

“interferometer” representation of temporal coherence in WFS

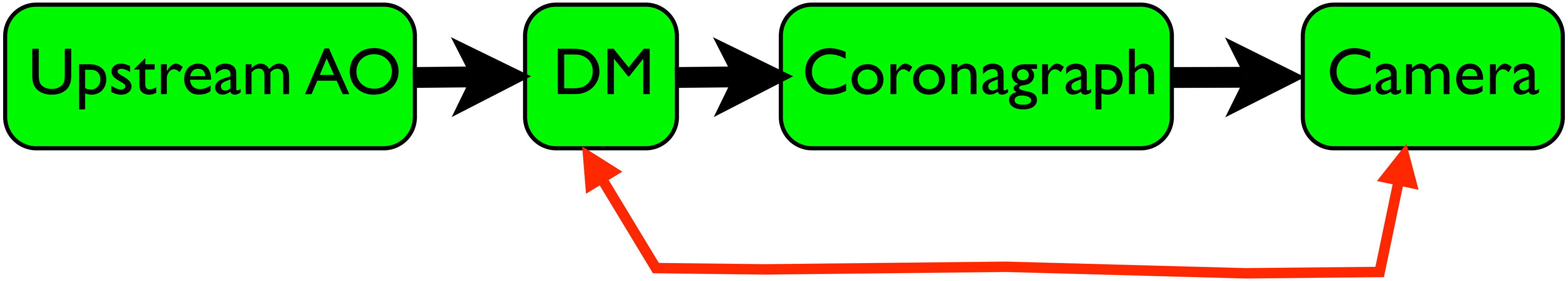


Focal plane WFS

It is easy to add known speckles in the coronagraph focal plane (need model of DM + coronagraph)

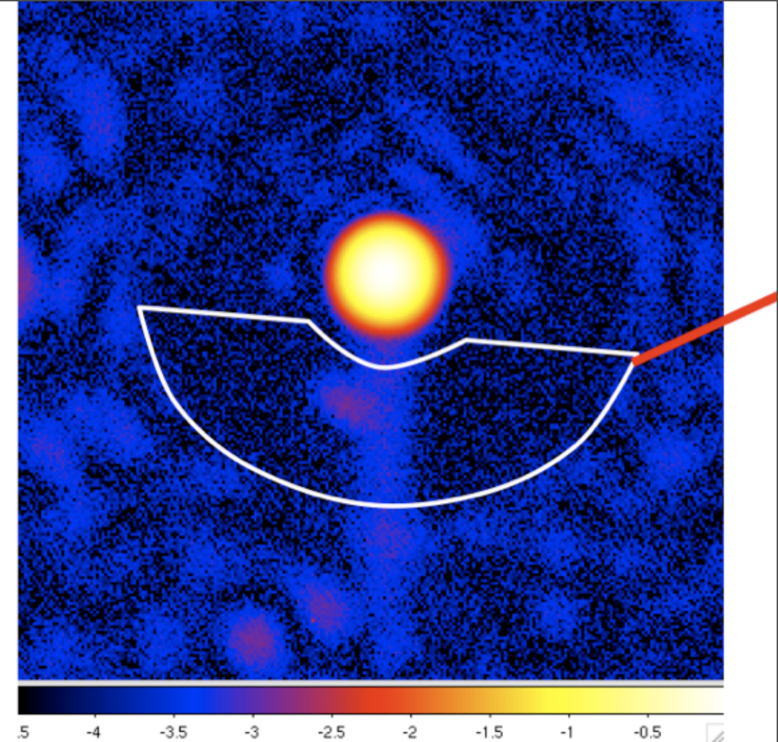
-> Add speckles in an optimal way to simultaneously
(1) **Measure** residual WF aberrations with ZERO non-common path error ("what you see is EXACTLY what you need to kill")
(2) **Remove** known WF errors
(3) **Calibrate** speckles vs. incoherent (=planet !) light

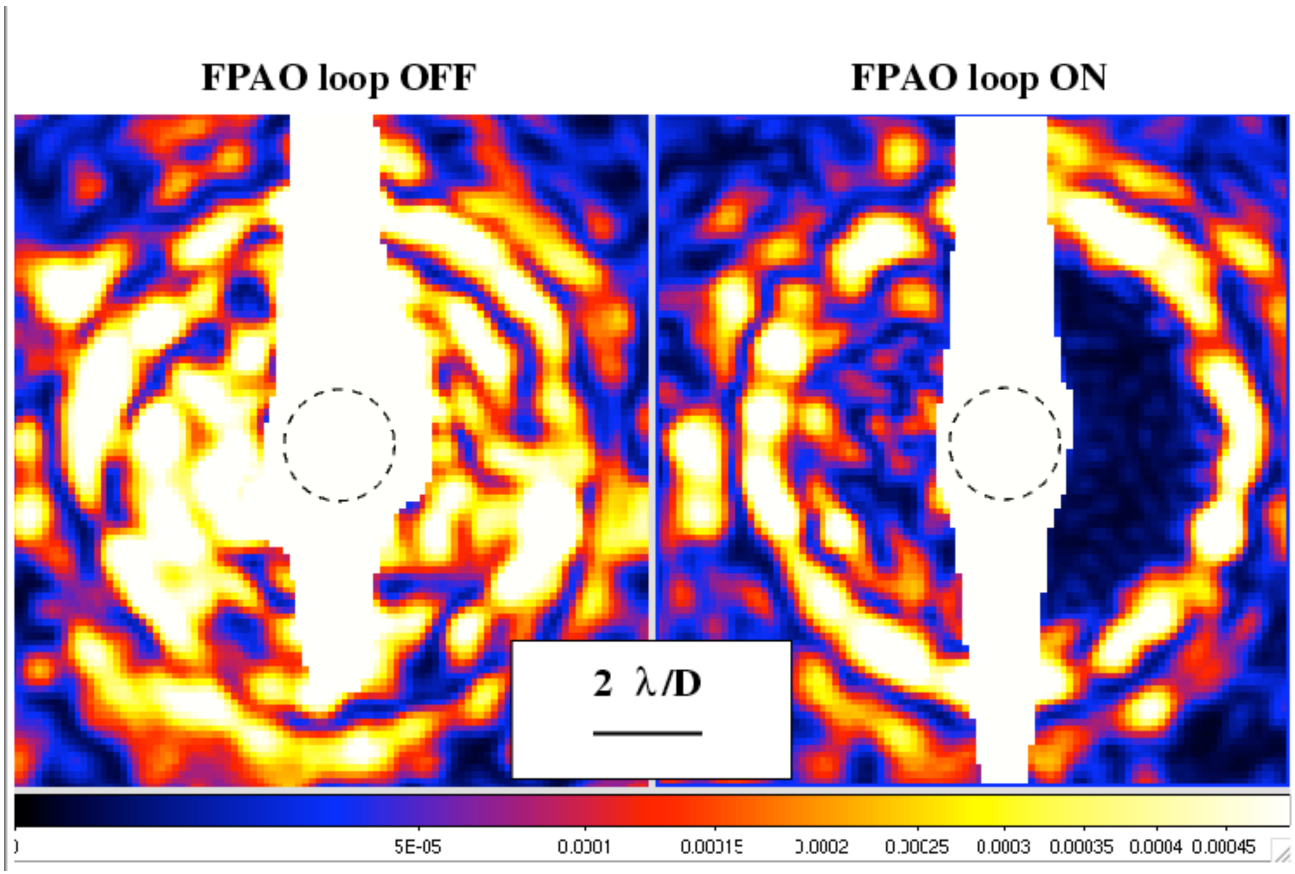
Error budget is only time lag & photon noise, and well calibrated residuals

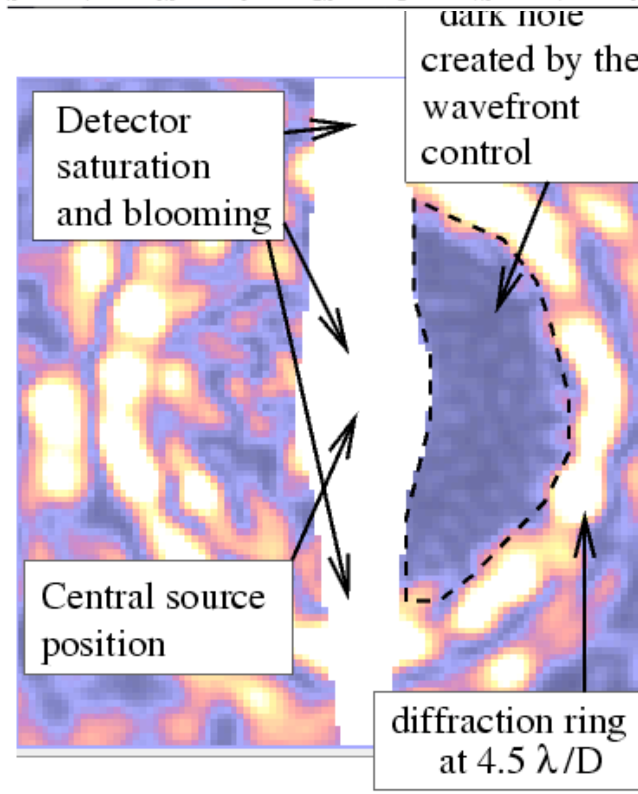


Lab results with PIAA coronagraph + FPAO with 32x32 MEMs DM

Prototype of Subaru Coronagraphic Extreme-AO (SCExAO) system to be deployed on the sky after Subaru AO188 system.

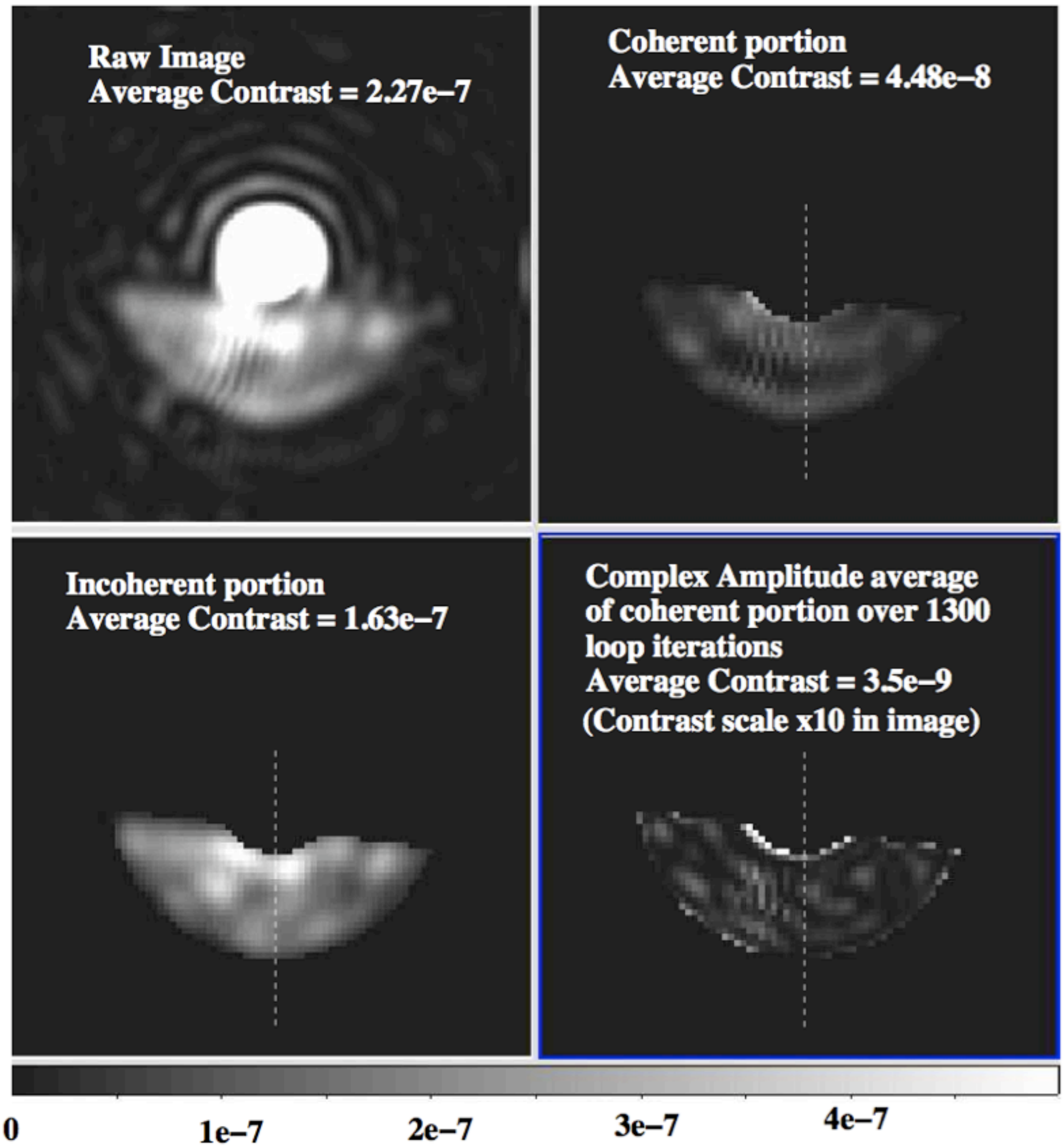






Lab demo of coherent light calibration to < 3.5e-9 contrast level

Demonstration to 100x below raw contrast



Self-tuning FPAO system finds its own response matrix

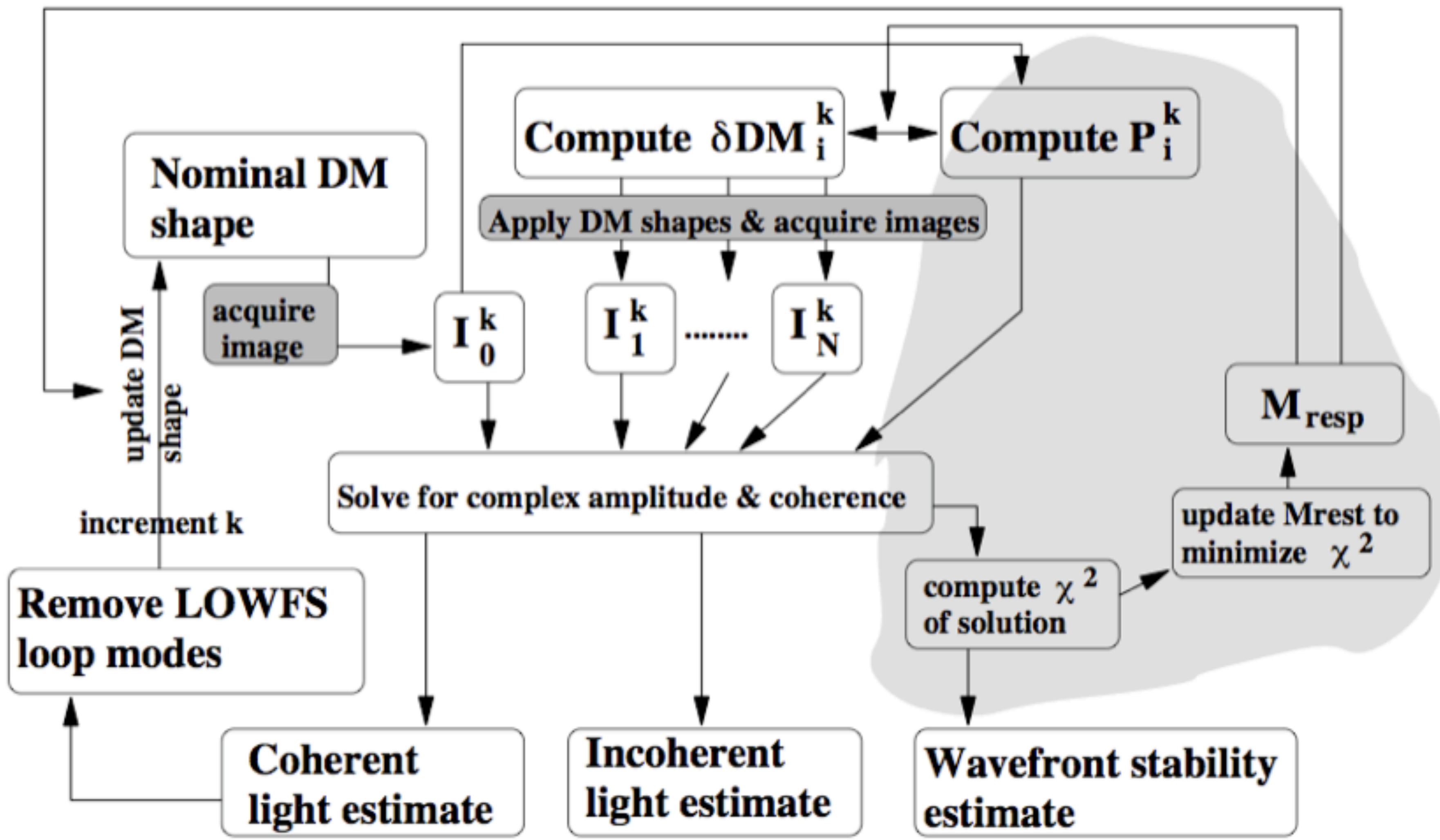
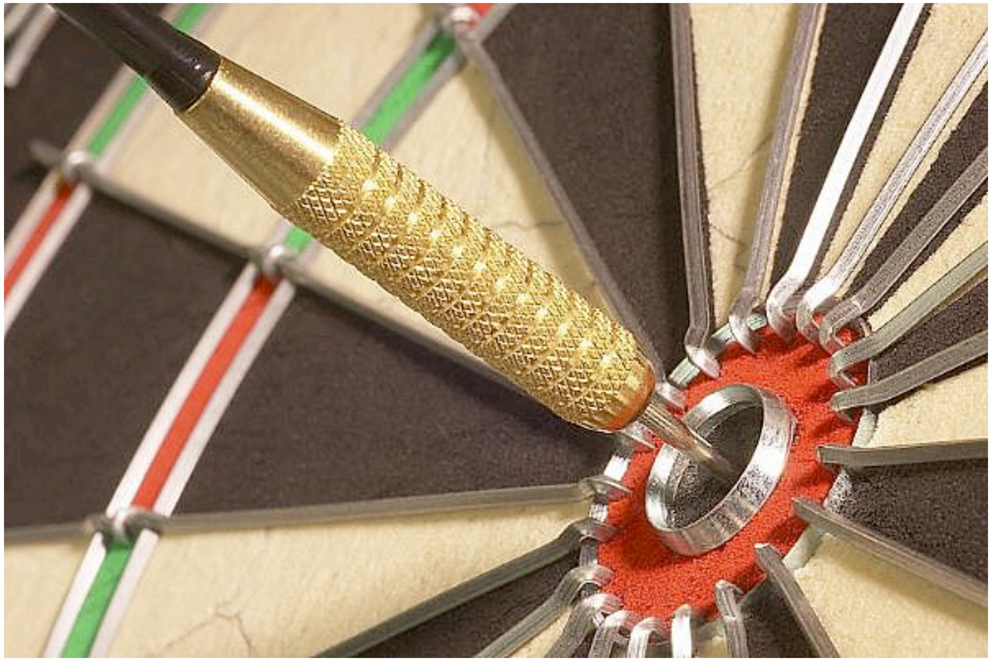


Fig. 9.— High order wavefront control loop, showing both the main loop and the system response matrix optimization loop (light shaded area). The two dark shaded boxes indicate image acquisition, which in the "simulation" mode, can be replaced with a simulated image acquisition using a model of the experiment and DM response.

Coronagraphic low order WFS (Guyon et al. 2009)



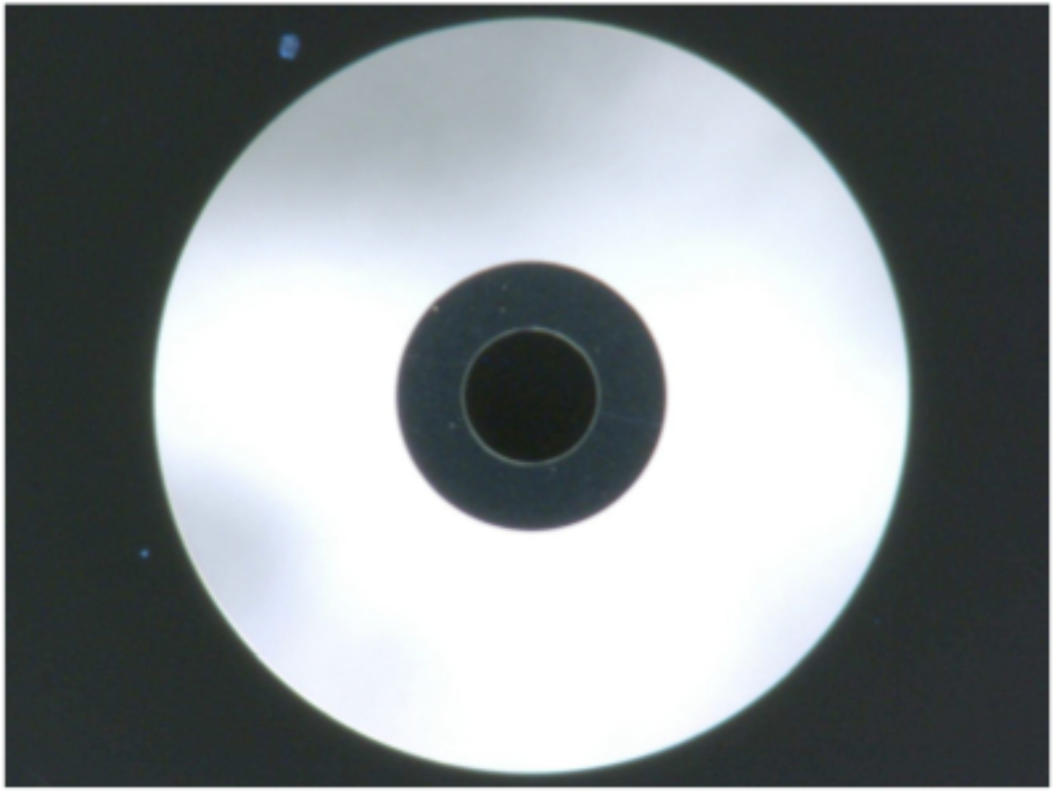
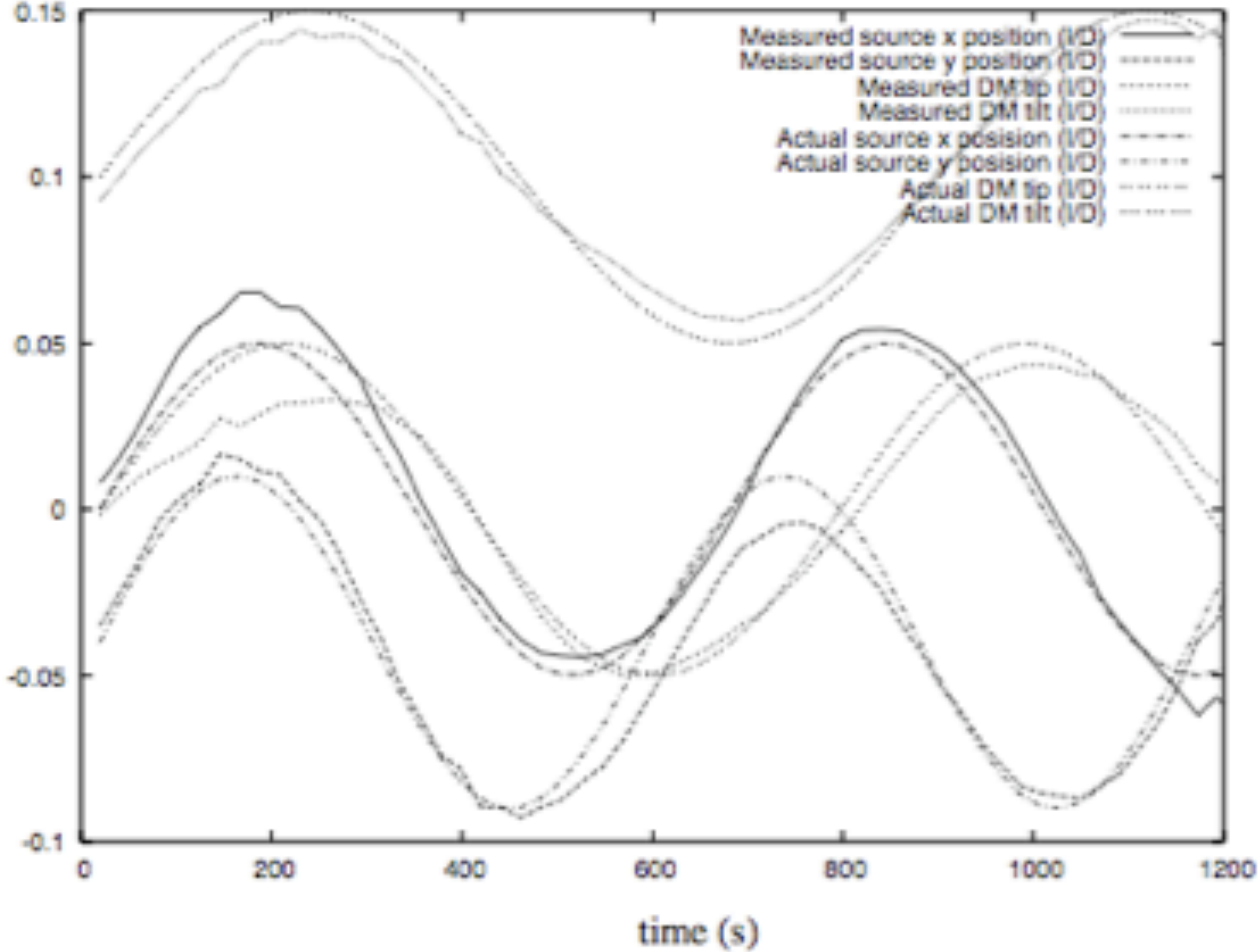


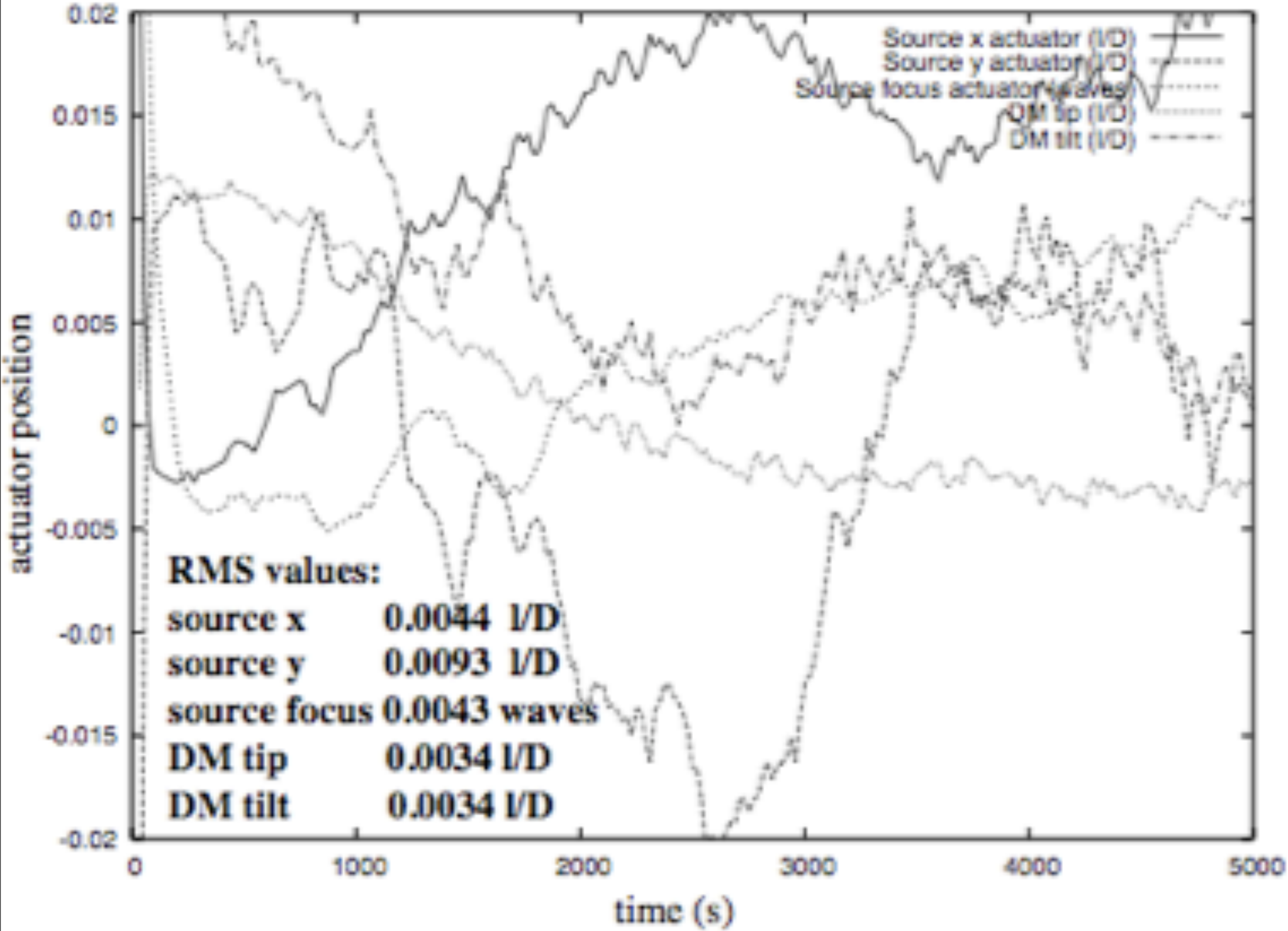
Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from 200 micron to 550 micron radius.

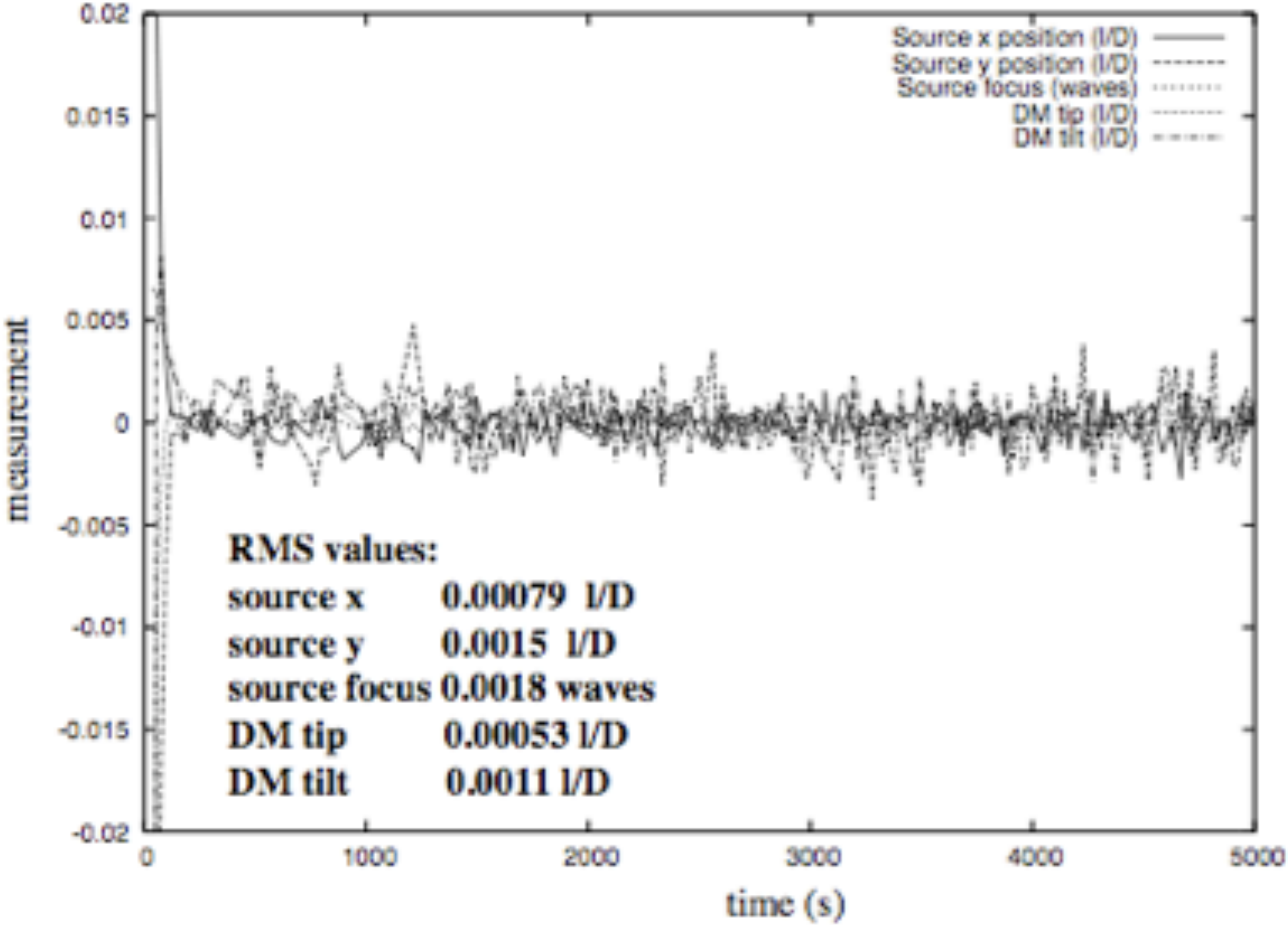
Why a central dark spot?

(1) Signal amplification
(2) Accurate reference



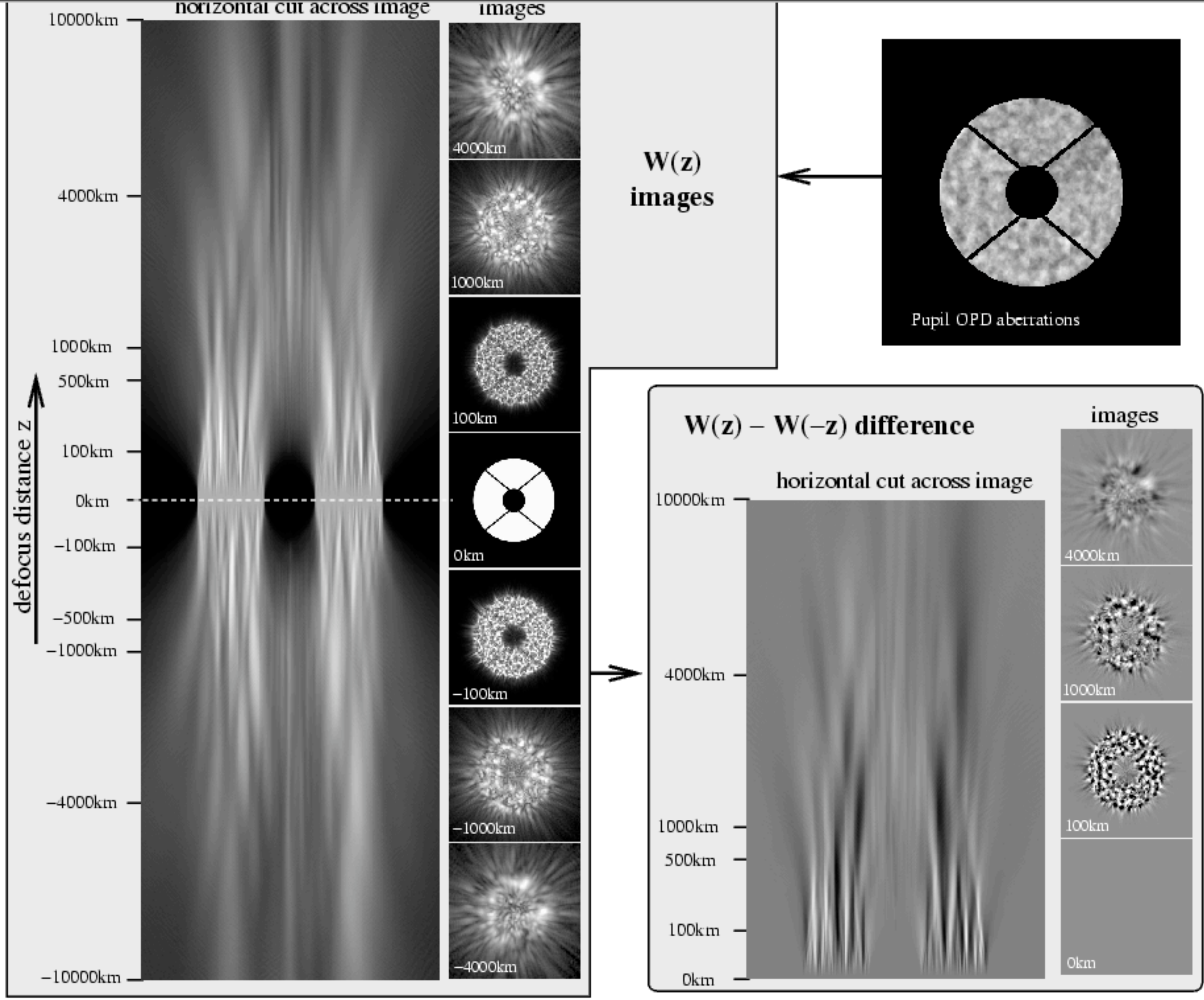
Measured source x position (l/D)
Measured source y position (l/D)
Measured DM tip (l/D)
Measured DM tilt (l/D)
Actual source x posision (l/D)
Actual source y posision (l/D)
Actual DM tip (l/D)
Actual DM tilt (l/D)
0.15
0.1
0.05
0
-0.05
-0.1
0
200
400
600
800
1000
1200
time (s)


Source x actuator (l/D)
Source y actuator (l/D)
Source focus actuator (waves)
DM tip (l/D)
DM tilt (l/D)
RMS values:
source x 0.0044 l/D
source y 0.0093 l/D
source focus 0.0043 waves
DM tip 0.0034 l/D
DM tilt 0.0034 l/D
actuator position
time (s)
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
0
1000
2000
3000
4000
5000



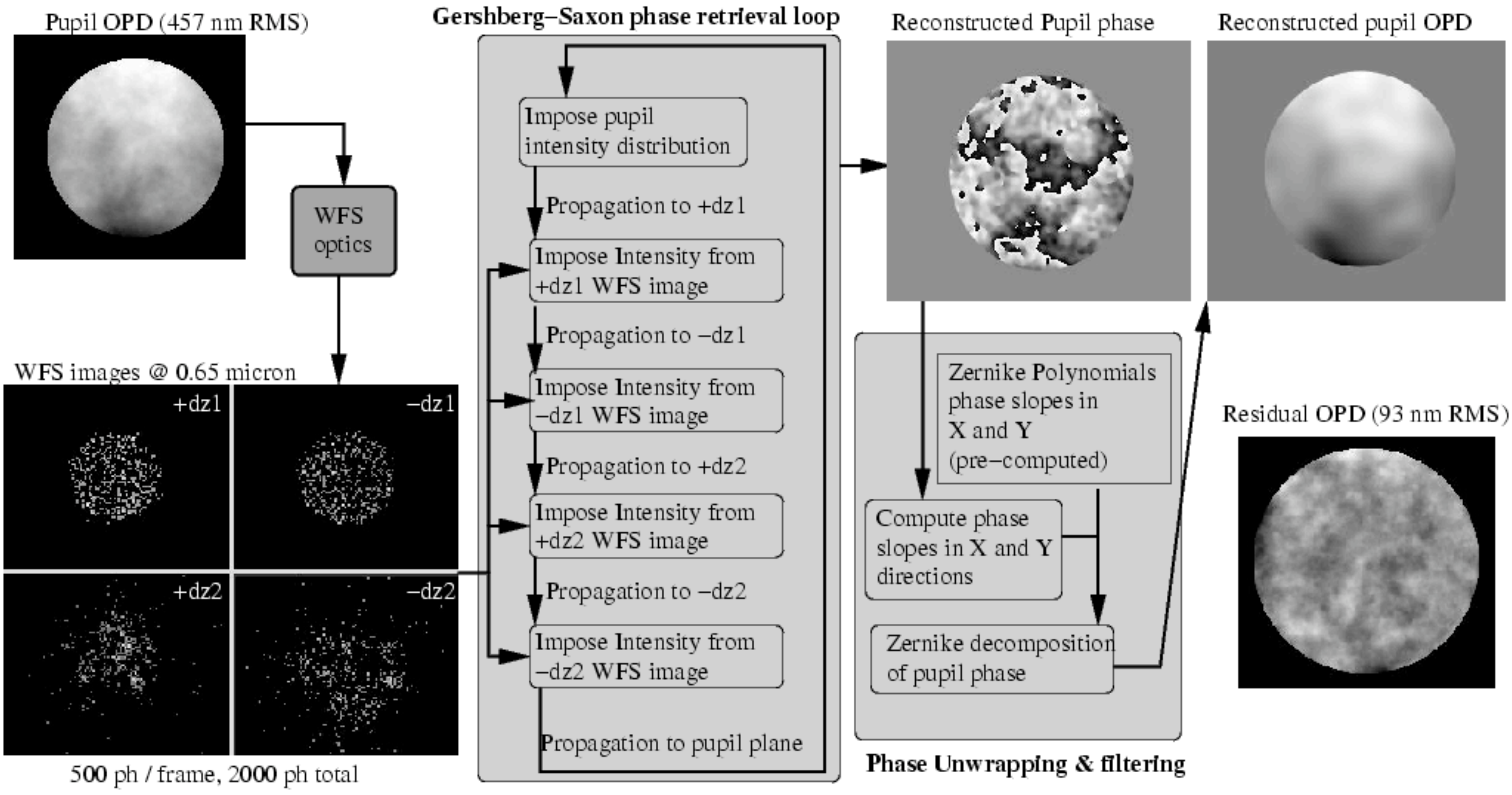
Source x position (l/D)
Source y position (l/D)
Source focus (waves)
DM tip (l/D)
DM tilt (l/D)
RMS values:
source x 0.00079 l/D
source y 0.0015 l/D
source focus 0.0018 waves
DM tip 0.00053 l/D
DM tilt 0.0011 l/D
measurement
time (s)
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
0
1000
2000
3000
4000
5000

Non-linear Curvature WFS



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
horizontal cut across image
images
10000km
4000km
1000km
500km
100km
0km
4000km
1000km
100km
0km

kHz operation appears to be possible with current chips for few 100s actuators system (100 32x32pix FFT = 0.2ms on single CPU)
FFT-based reconstruction scales well to larger # of pixels



Why is is so good ??? -> uses HSF to infer LSF

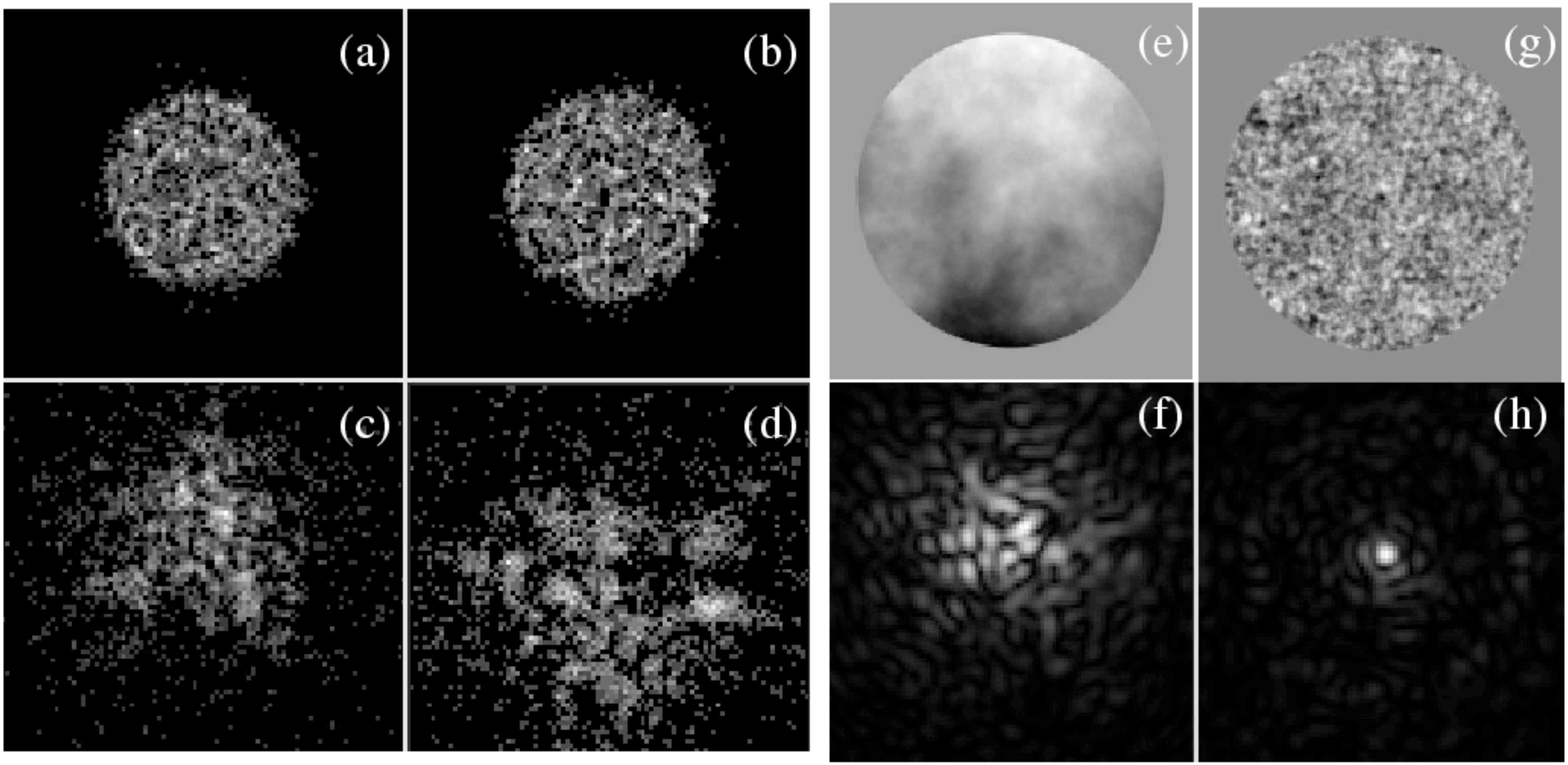
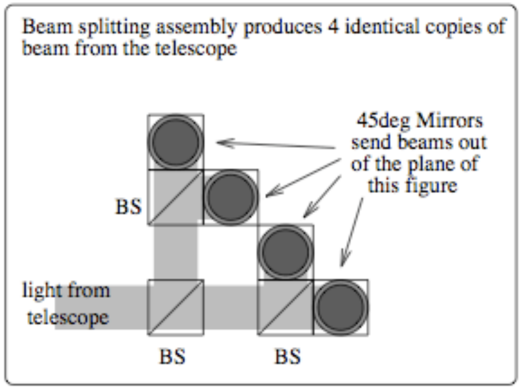
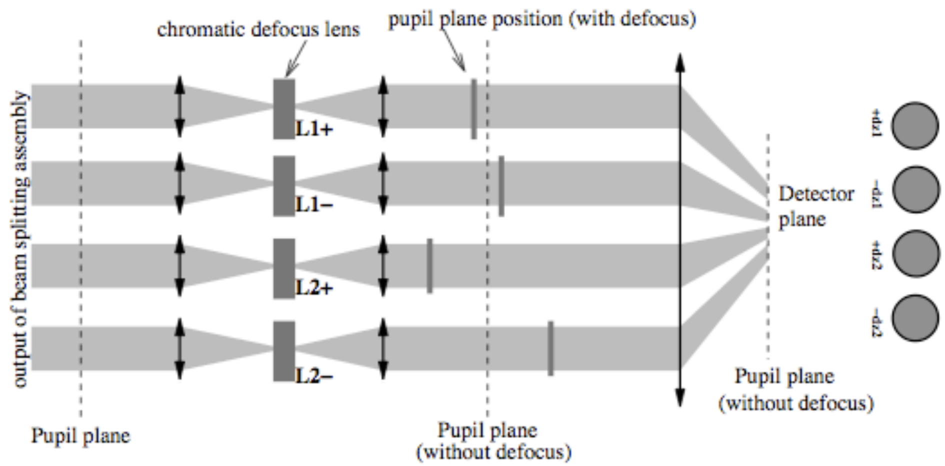
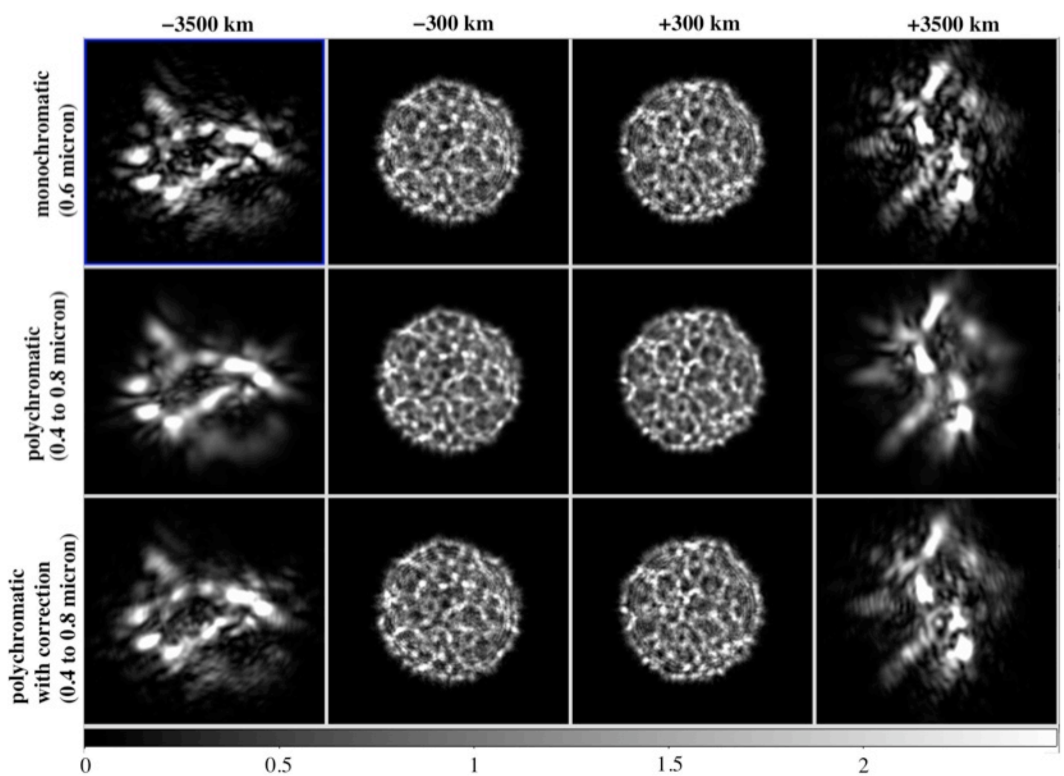


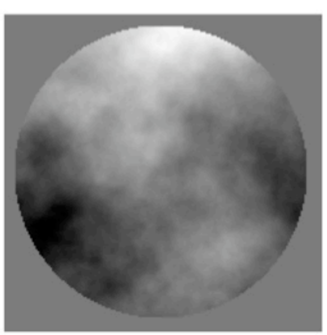
Fig. 9.— Wavefront reconstruction using the algorithm shown in fig. 8. Four noisy defocused pupil images (images (a), (b), (c) and (d)) are acquired to transform the pupil phase aberrations (e) into intensity signals. The input pupil phase is 609 nm RMS, yielding the PSF (f) before correction. After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

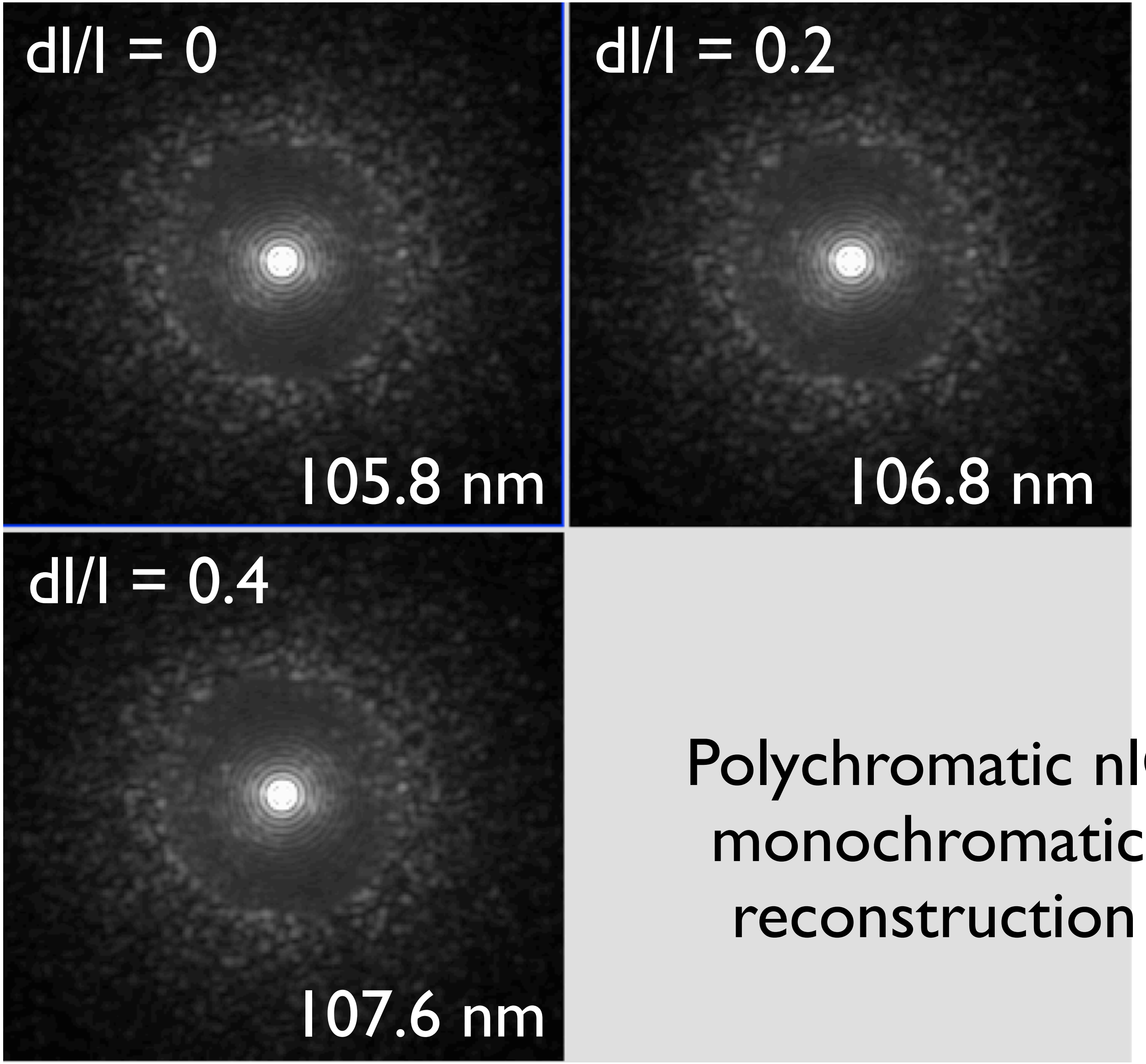
Using chromatic lenses for defocus is key to polychromatic operation





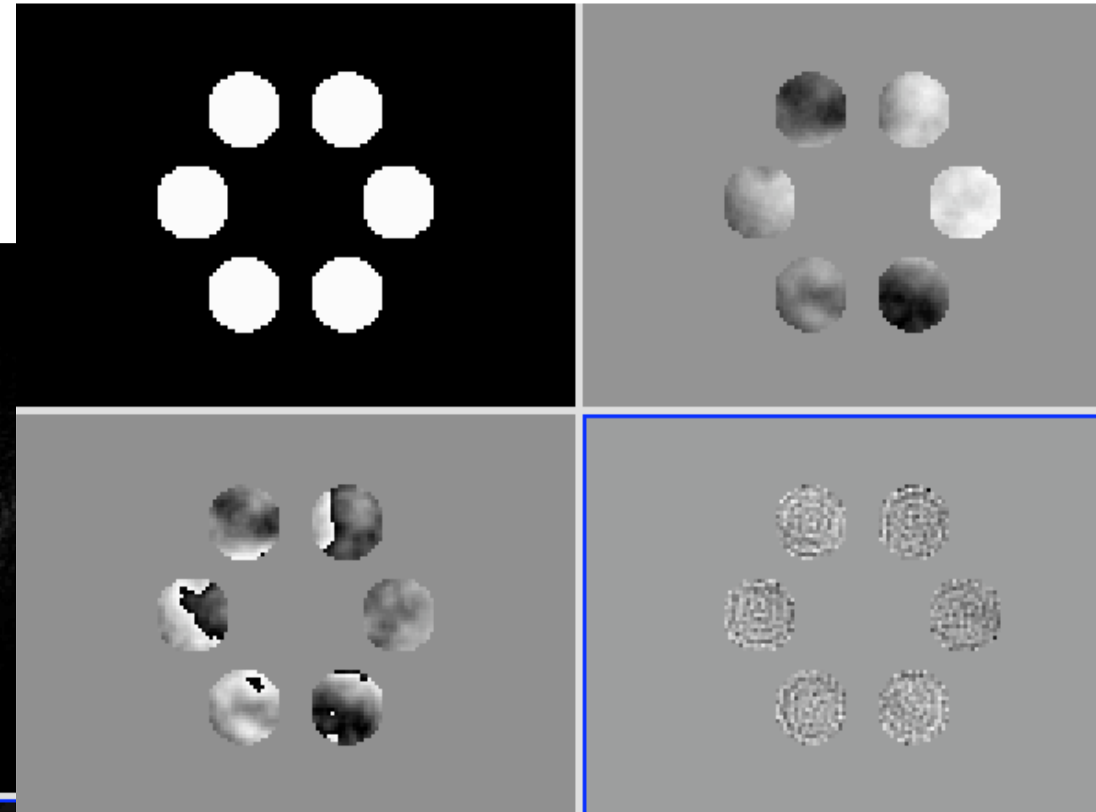


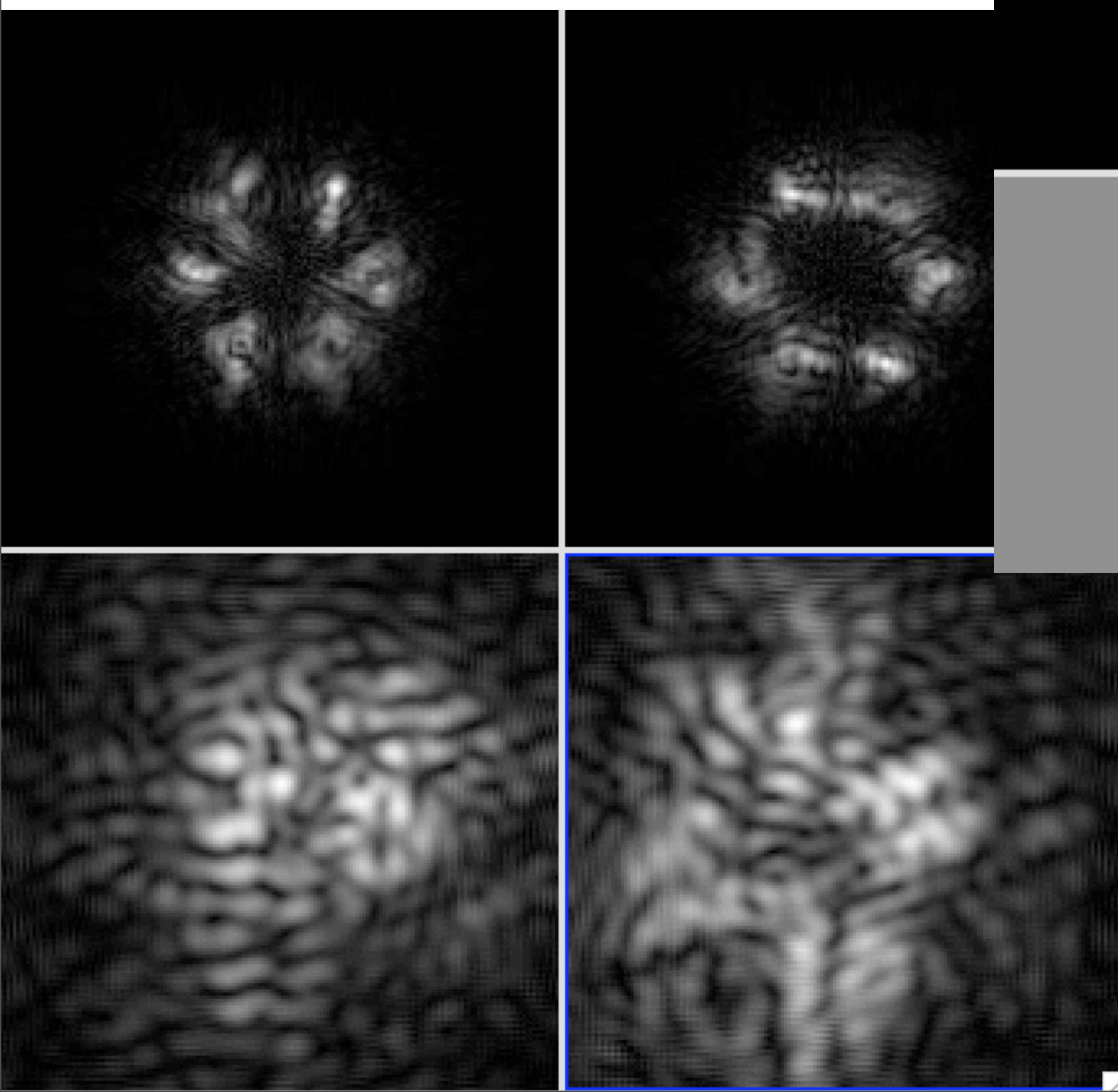




Polychromatic nlCWFS with monochromatic wavefront reconstruction algorithm

Very good for Sparse pupil or thick spiders

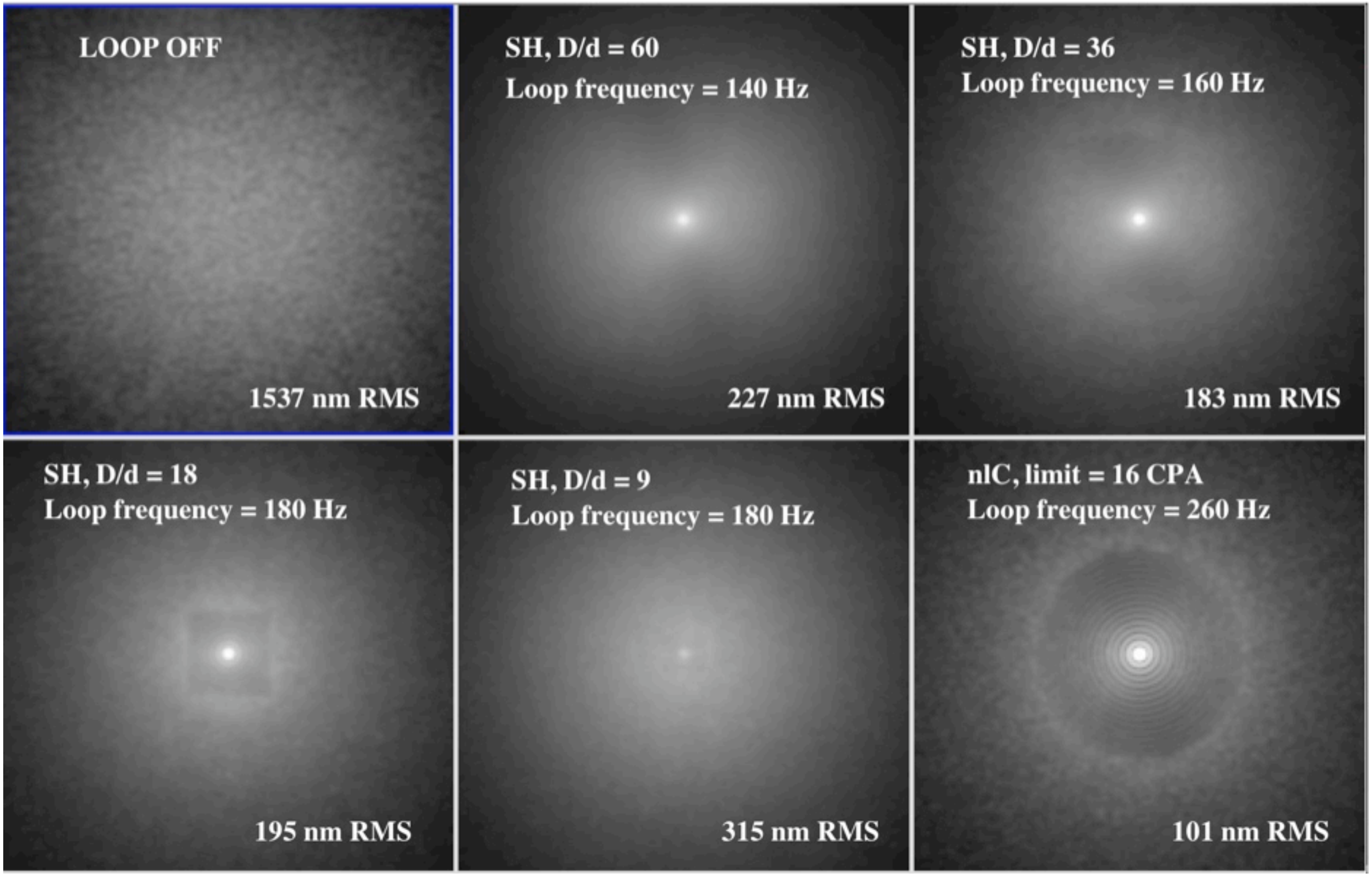




13nm RMS

2e8 ph

m ~ 13
D=8m
H band



WFS	Loop frequ	RMS	SR @ 0.85 mu	SR @ 1.6 mu
nlCurv	260 Hz	101 nm	57%	85%
SH - D/d=9	180 Hz	315 nm	~4%	22%
SH - D/d=18	180 Hz	195 nm	~13%	56%
SH - D/d=36	160 Hz	183 nm	~16%	60%
SH - D/d=60	140 Hz	227 nm	~6%	45%

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

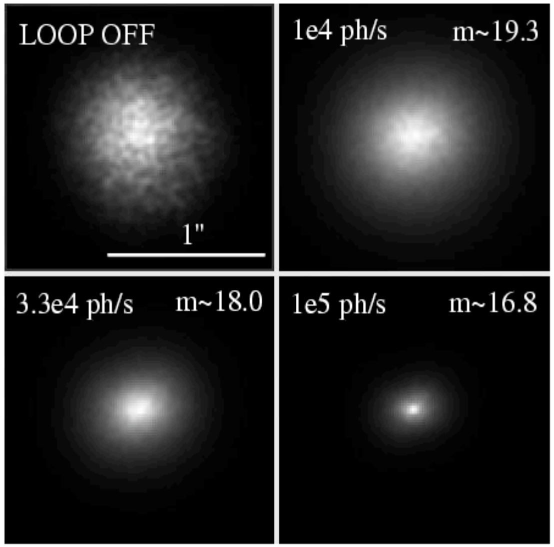


Fig. 12.— Simulated long exposure 1.6 μm PSFs obtained with a non-linear Dual stroke Curvature-based AO system. The sensing wavelength was 0.85 μm for this simulation.

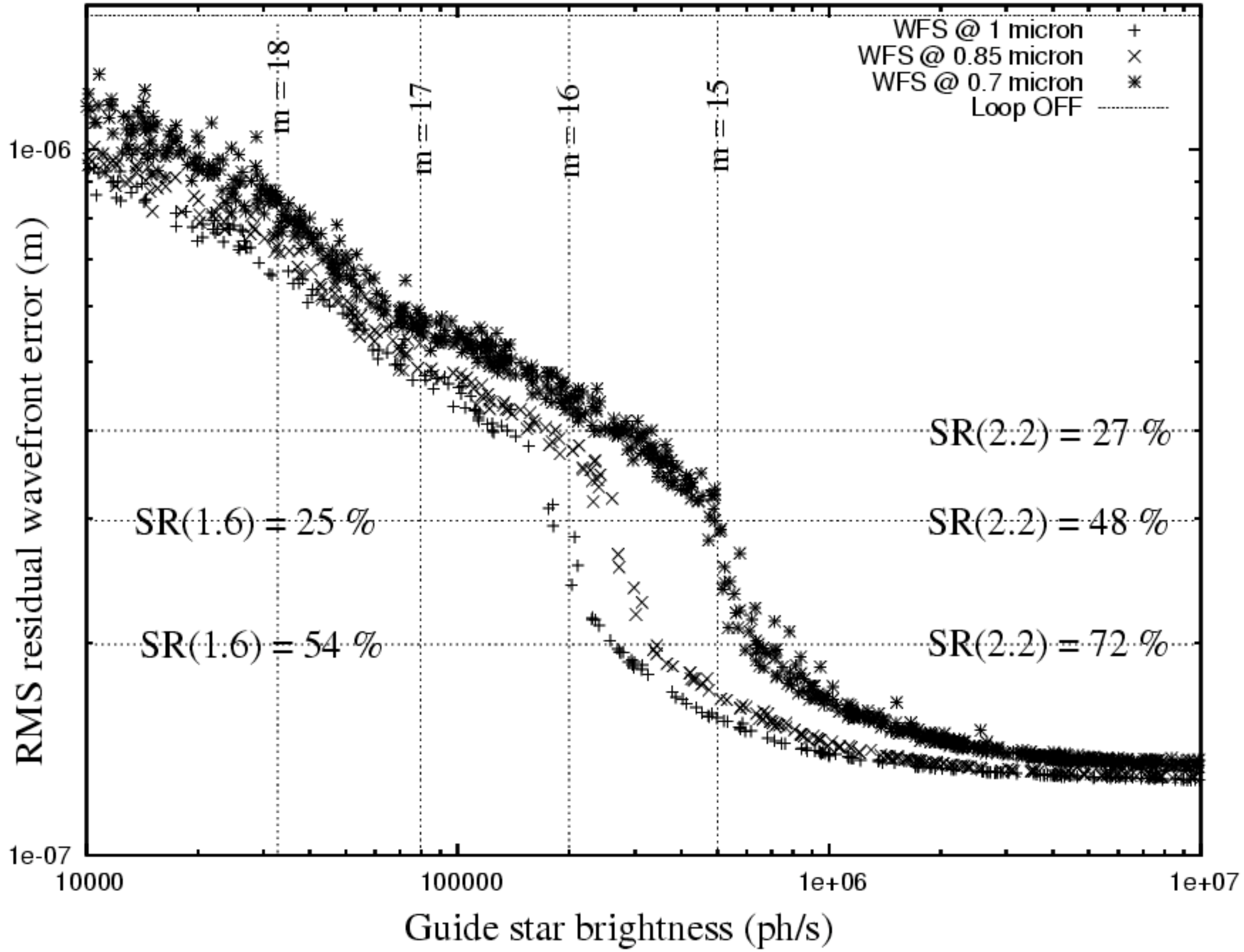
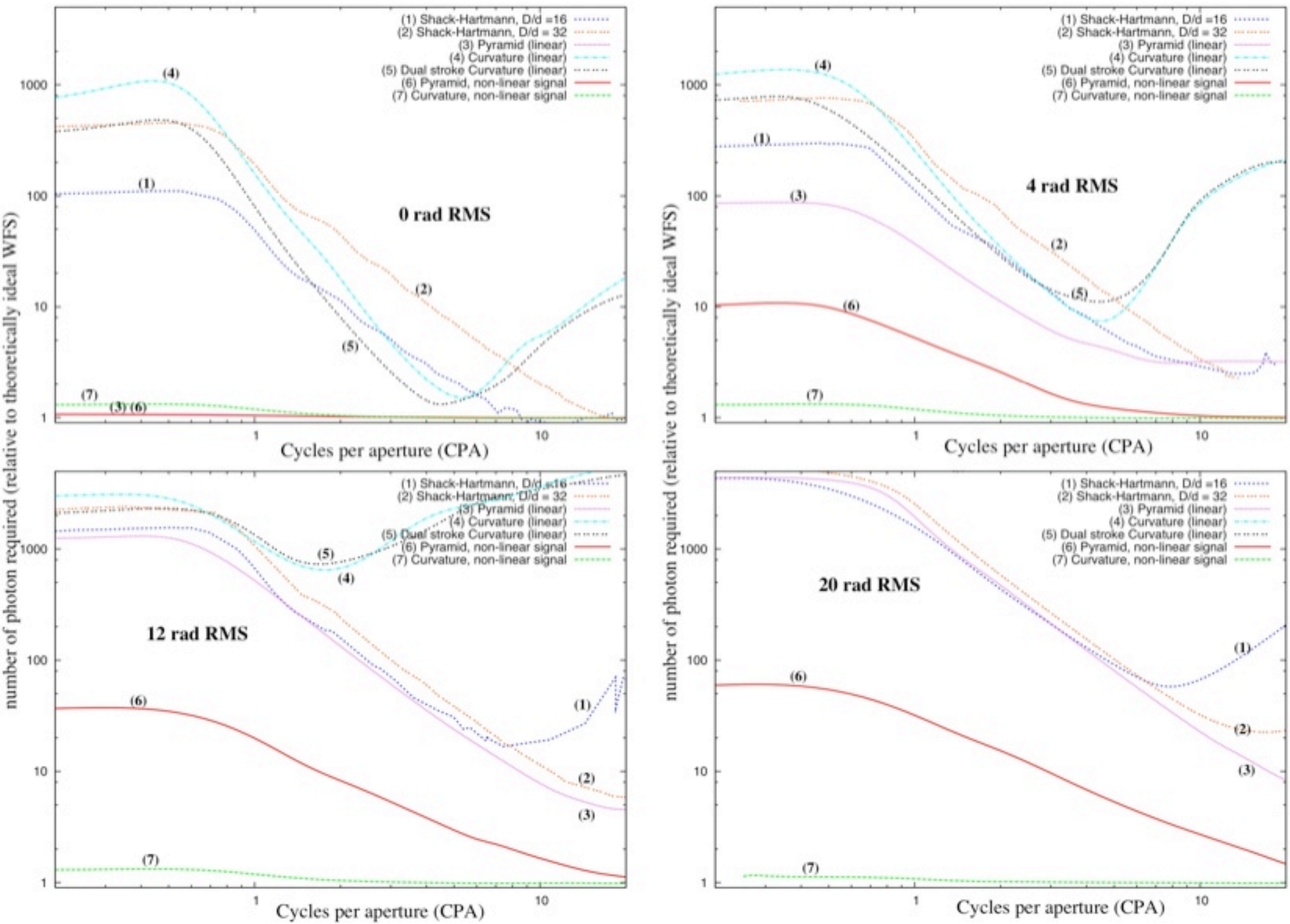


Fig. 11.— Simulated performance of a non-linear Dual stroke Curvature as a function of sensing wavelength (0.7, 0.85 and 1.0 μm) and guide star brightness. The stellar magnitudes given in this figure assume a 20% efficiency in a 0.5μm wide band. See text for details.



0 rad RMS
4 rad RMS
12 rad RMS
20 rad RMS
(1) Shack-Hartmann, D/d =16
(2) Shack-Hartmann, D/d = 32
(3) Pyramid (linear)
(4) Curvature (linear)
(5) Dual stroke Curvature (linear)
(6) Pyramid, non-linear signal
(7) Curvature, non-linear signal
number of photon required (relative to theoretically ideal WFS)
Cycles per aperture (CPA)
1
10
100
1000

NGS vs LGS in wide field AO systems

On 30m telescope, assuming LGS size = 1”, 589nm, sensitivity gain factor = 6.1E4/CPA^2 (12 mag for CPA=1)
[reminder: gain factor bigger for larger telescope, smaller for higher spatial frequencies]

For single star, no other knowledge on turbulence, coherence limit is at m~15.
nlCWFS does not need closed loop operation -> simple system architecture.
At m=15, star every 140” (~2’) for galactic pole

- Encouraging for high quality GLAO
- GLAO -> enable fainter than m=15 NGS -> all sky high performance AO ?
- Wide field AO system where NGS are the main GS and LGS used for bootstrapping ?

Conclusions

- ***Why not use "conventional" WFS for ExAO ?***

  Conventional WFSs have **very low efficiency**. Using SHWFS is equivalent to throwing away 99.8% of photons (8m telescope, CPA=2) or 99.99% of photons (42m telescope, CPA=2).

  At least two full sensitivity options exit:

- ***Focal plane WFS + calibration***

  Ideally suited for ExAO, proven in lab to 3.5e-9 contrast control. Simultaneously measures, controls and calibrates speckles. Self-tuning AO control.

- ***Non-linear Curvature WFS***

  Much more robust than focal plane WFS, hardware & software solutions identified.

  full sensitivity down to m~15 in (semi-?)open & closed loop

  Potentially high performance (& large sky coverage?) GLAO/MCAO/TAO with NGSs

  Ongoing effort to deploy nlCWFS on Subaru Telescope & MMT