Efficient WFS technologies for direct imaging of exoplanets from ground and space

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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
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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

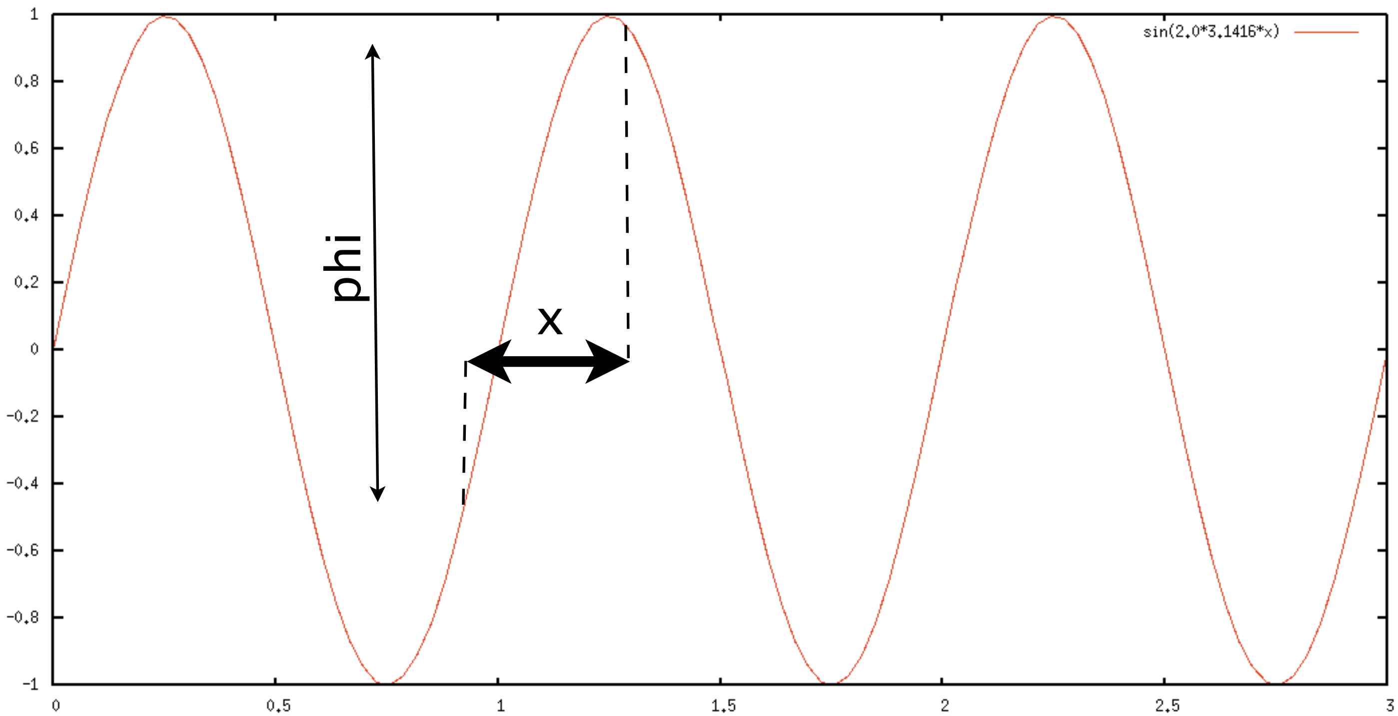
Non-ideal WFS:

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

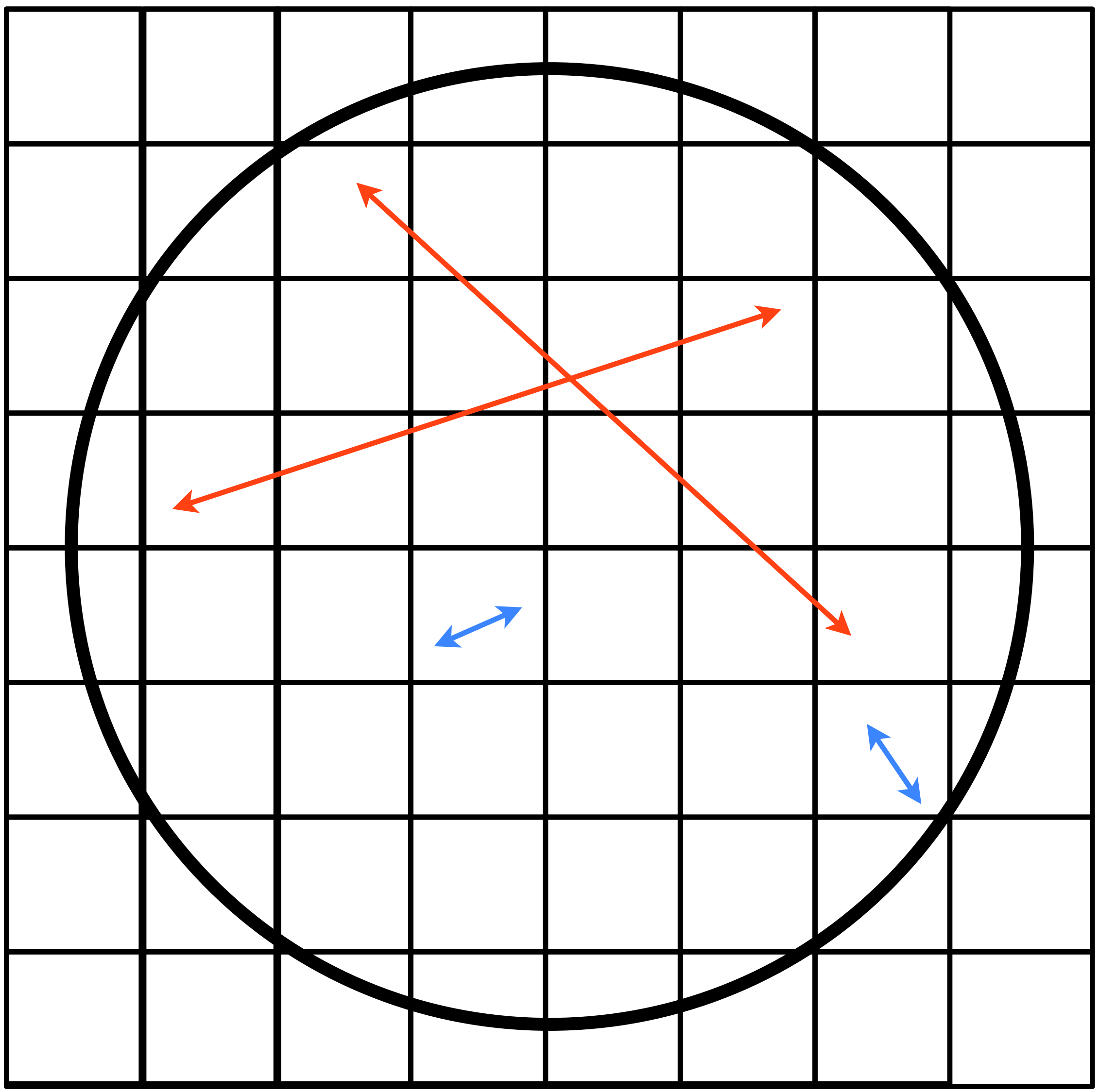
How to optimally convert phase into an intensity signal ?

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

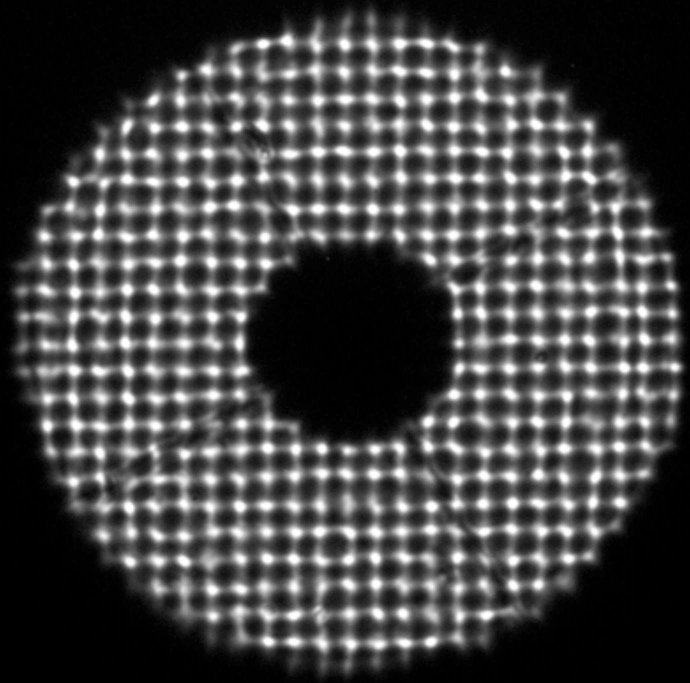


Problem:
SH does not allow interferences between points of the pupil separated by more than subaperture size

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

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

SH WFS is also suffering from noise propagation



Spot sizes is lambda/r0 at best (lambda/d if d<r0) >> lambda/D

Low order modes suffer from very poor SNR

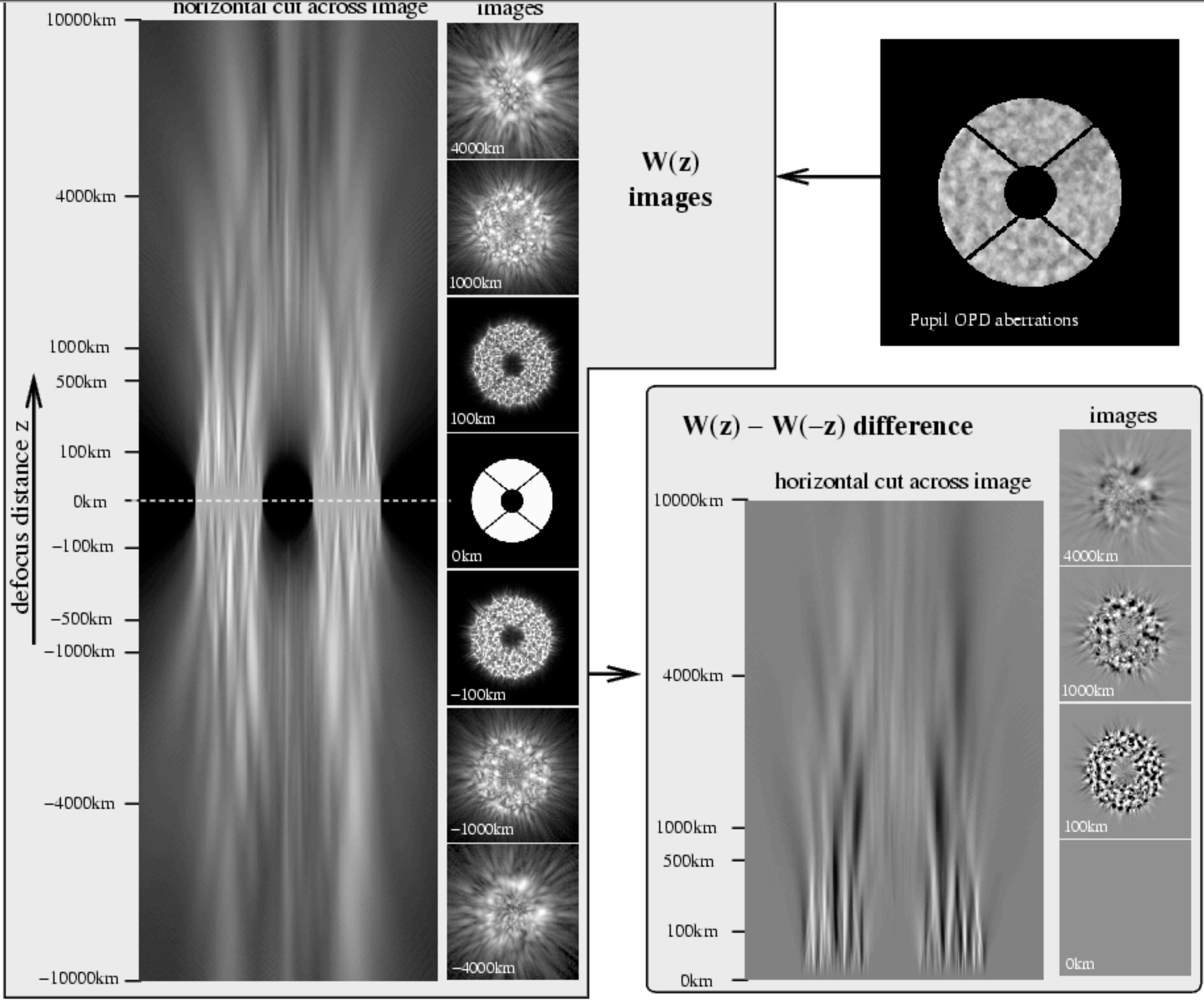
Curvature WFS

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

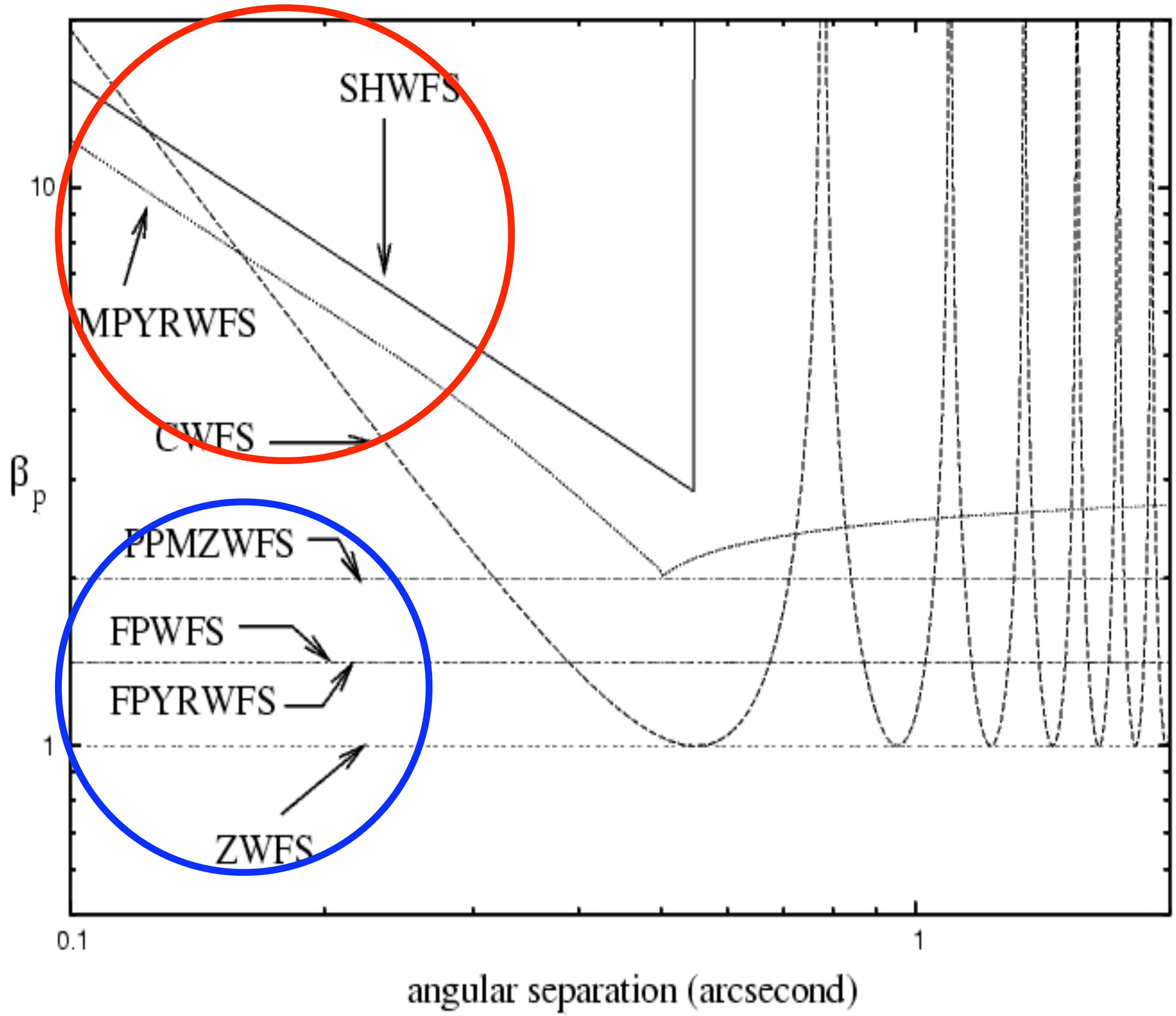
Usually, planes at +dz and -dz, with dz ~ 1000km are imaged.

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

Future slides will 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

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)

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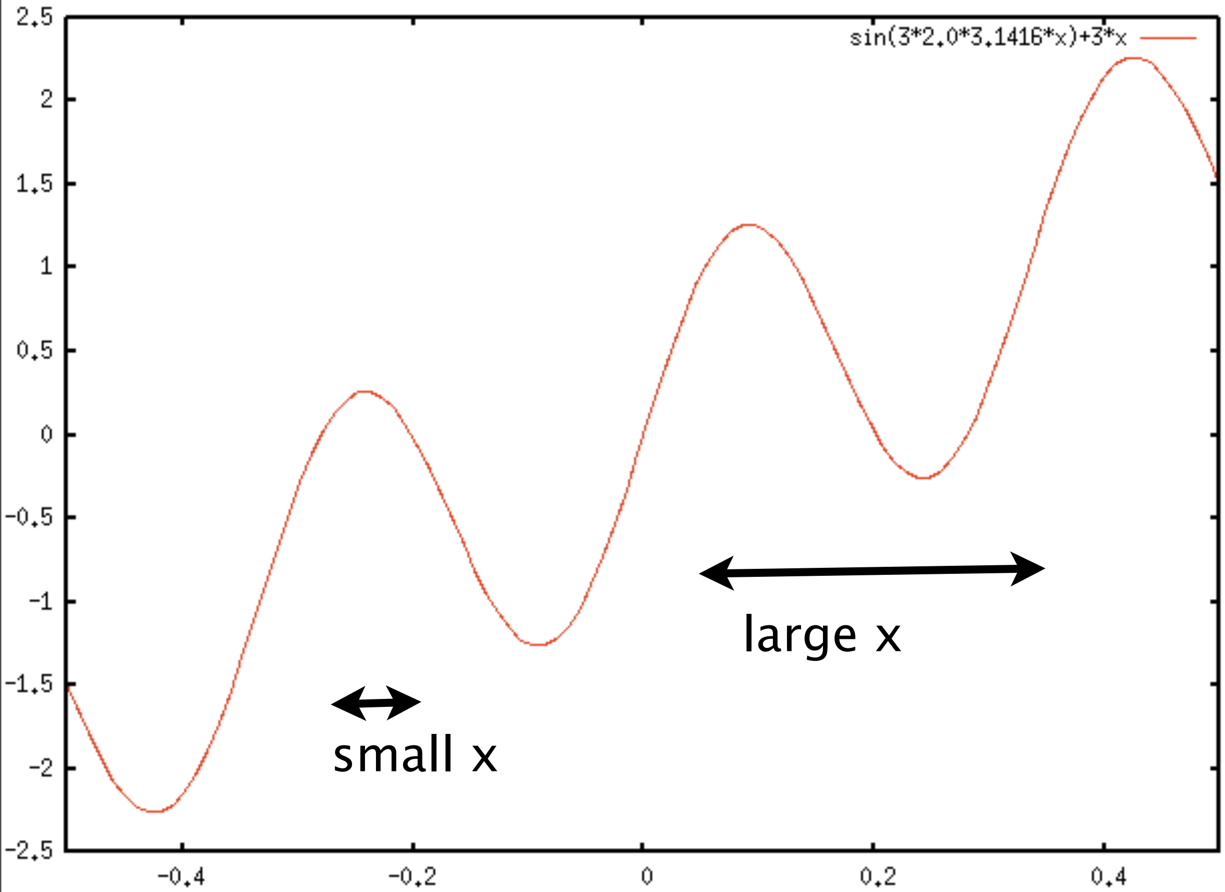
WFS range / linearity



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

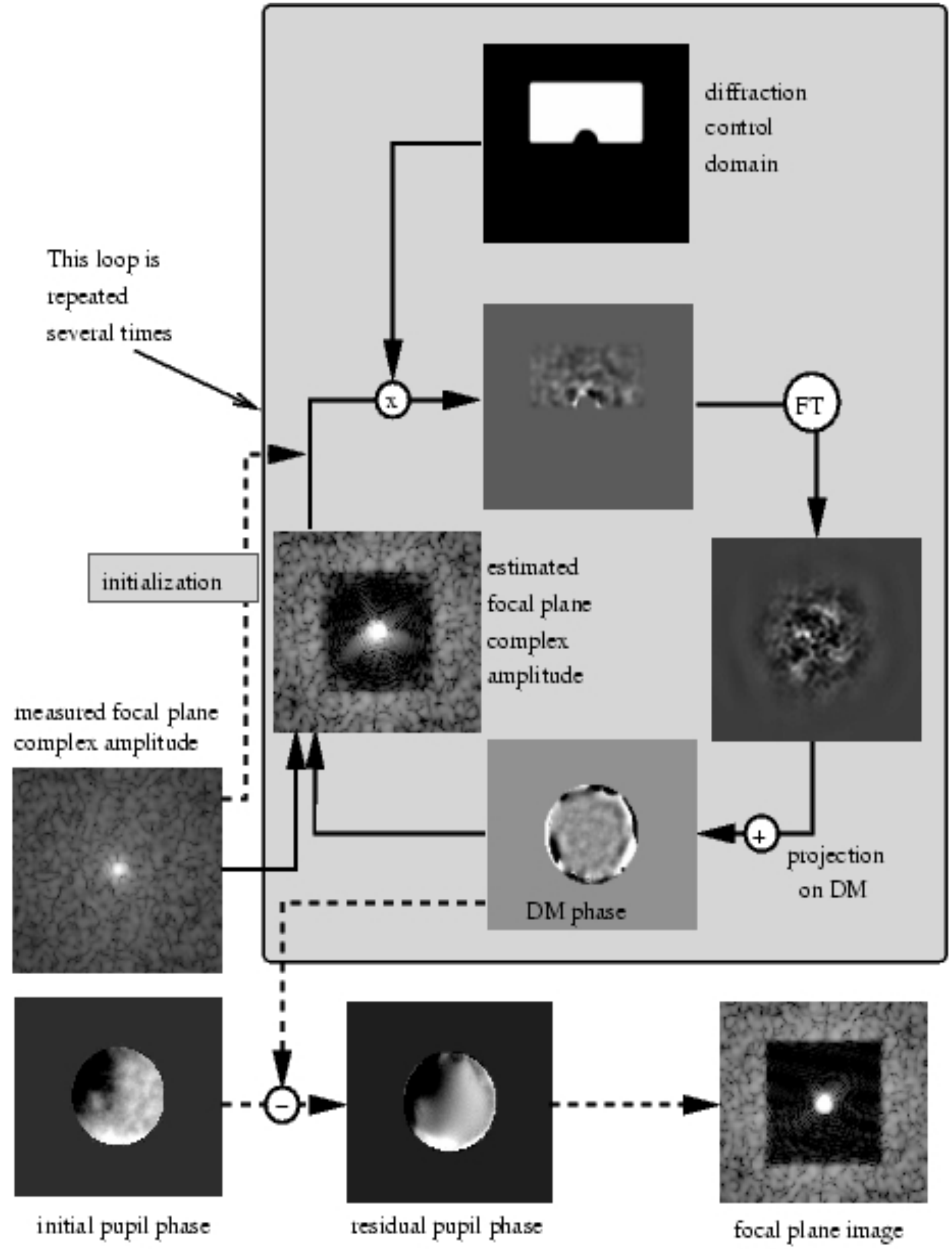
Solution:
Non-linear reconstruction allows a large dynamical range measurement on a high-sensitivity WFS

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)



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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

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

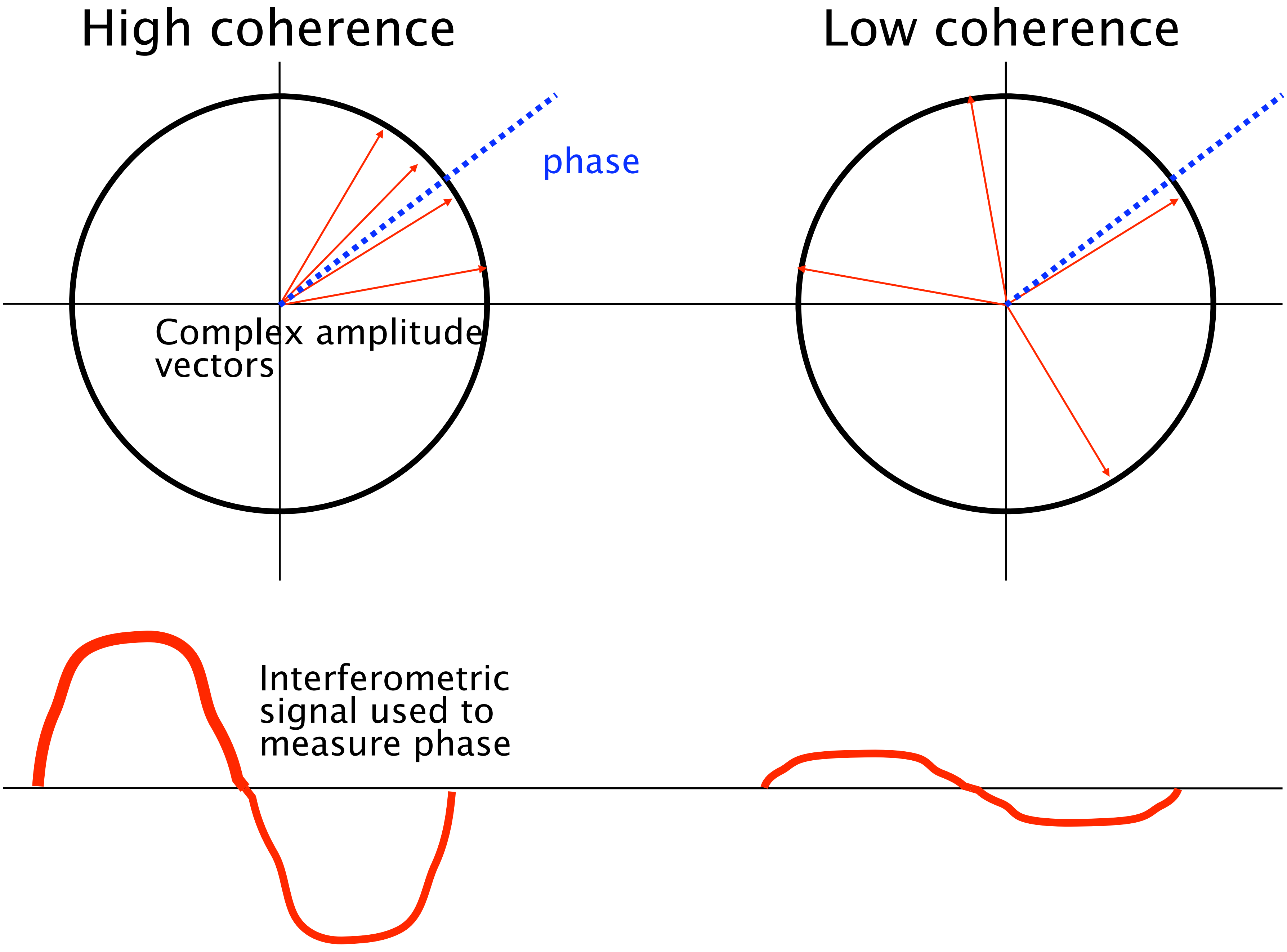
Wavefront coherence on large spatial scales must be maintained for high-sensitivity WFS

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



Matching:

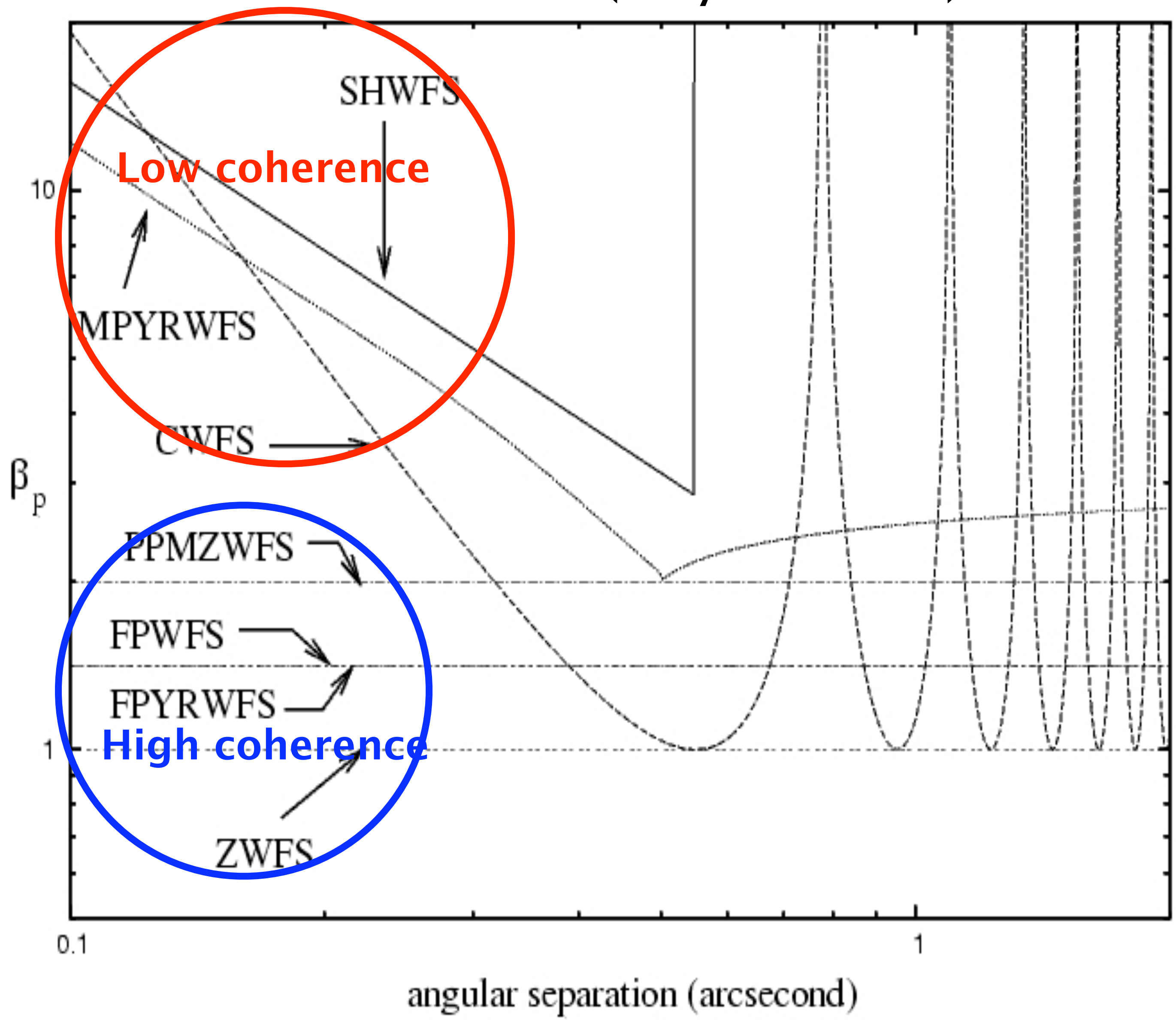
Wavefront COHERENCE in WFS — **to** — **Wavefront sensor**

Wavefront COHERENCE in WFS		Wavefront sensor
<< 1 rad	Space Extreme-AO (Terrestrial Planet Finder) Second-stage of Extreme-AO system in near-IR ("Tweeter")	Interferometric Focal plane
~ 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) Pyramid (modulated)
>> 1 rad	LGS AO GLAO Open loop AO	Curvature Shack-Hartmann

Not allowed

allowed

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.

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Example: Possible Coronagraphic ExAO architecture

High speed AO in visible

non linear curvature
Pyramid
Shack Hartmann

→

Near-IR

Coronagraph
Focal plane AO →

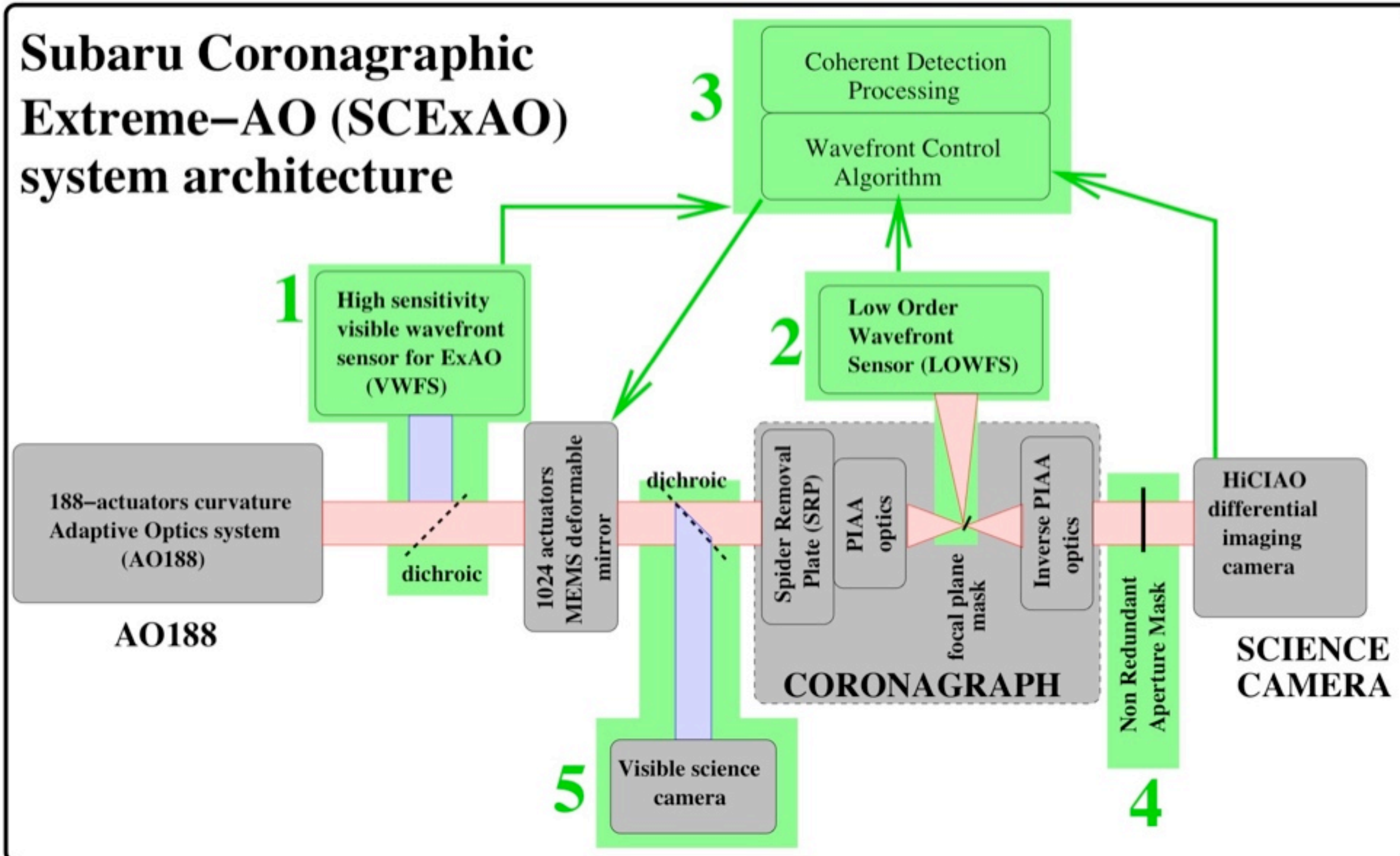
Fast camera for
focal plane WFS
after coronagraph

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



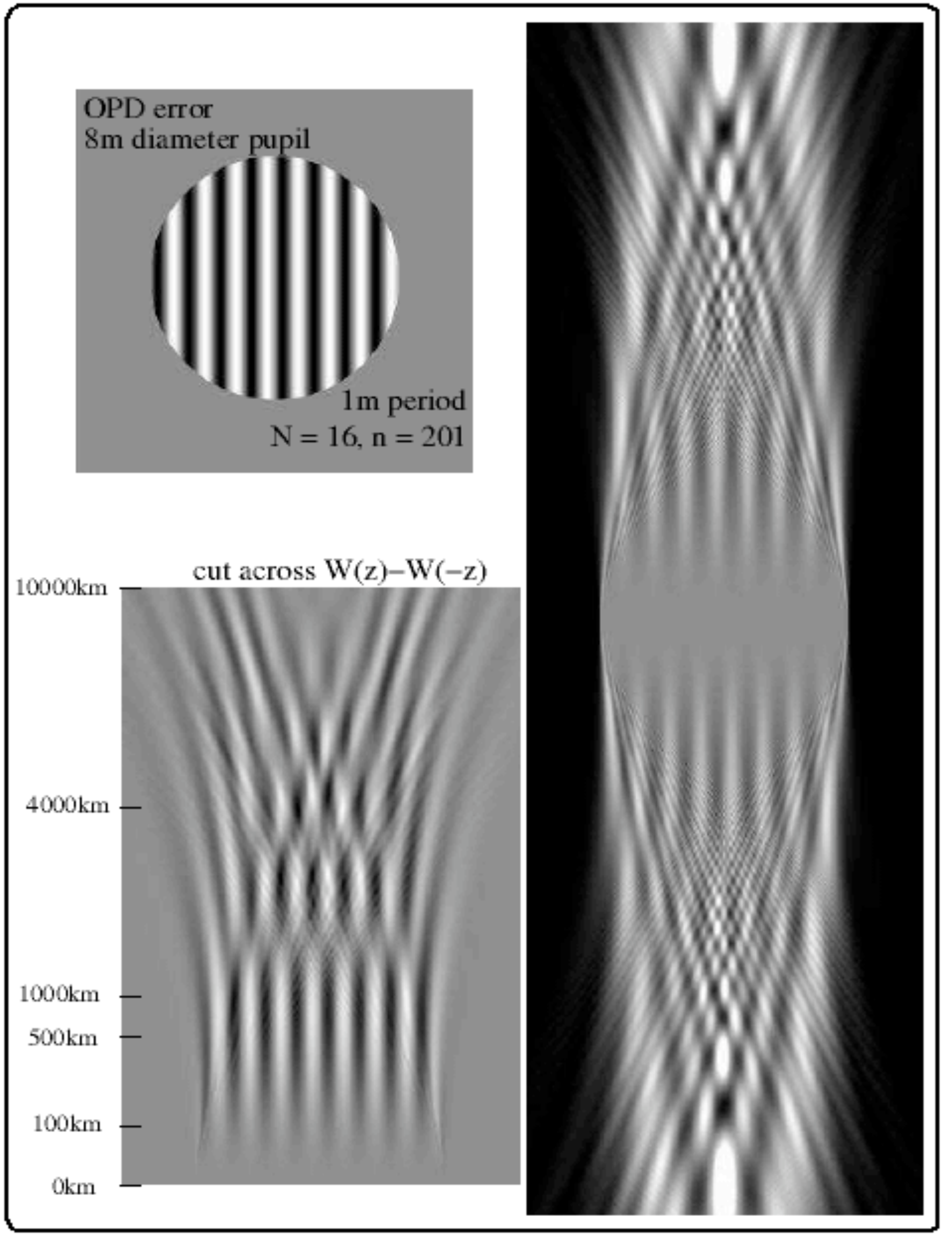
Subaru Coronagraphic Extreme−AO (SCExAO) system architecture
3
Coherent Detection Processing
Wavefront Control Algorithm
1
High sensitivity visible wavefront sensor for ExAO (VWFS)
2
Low Order Wavefront Sensor (LOWFS)
188−actuators curvature Adaptive Optics system (AO188)
dichroic
1024 actuators MEMS deformable mirror
dichroic
Spider Removal Plate (SRP)
PIAA optics
focal plane mask
Inverse PIAA optics
Non Redundant Aperture Mask
HiCIAO differential imaging camera
AO188
CORONAGRAPH
SCIENCE CAMERA
5
Visible science camera
4

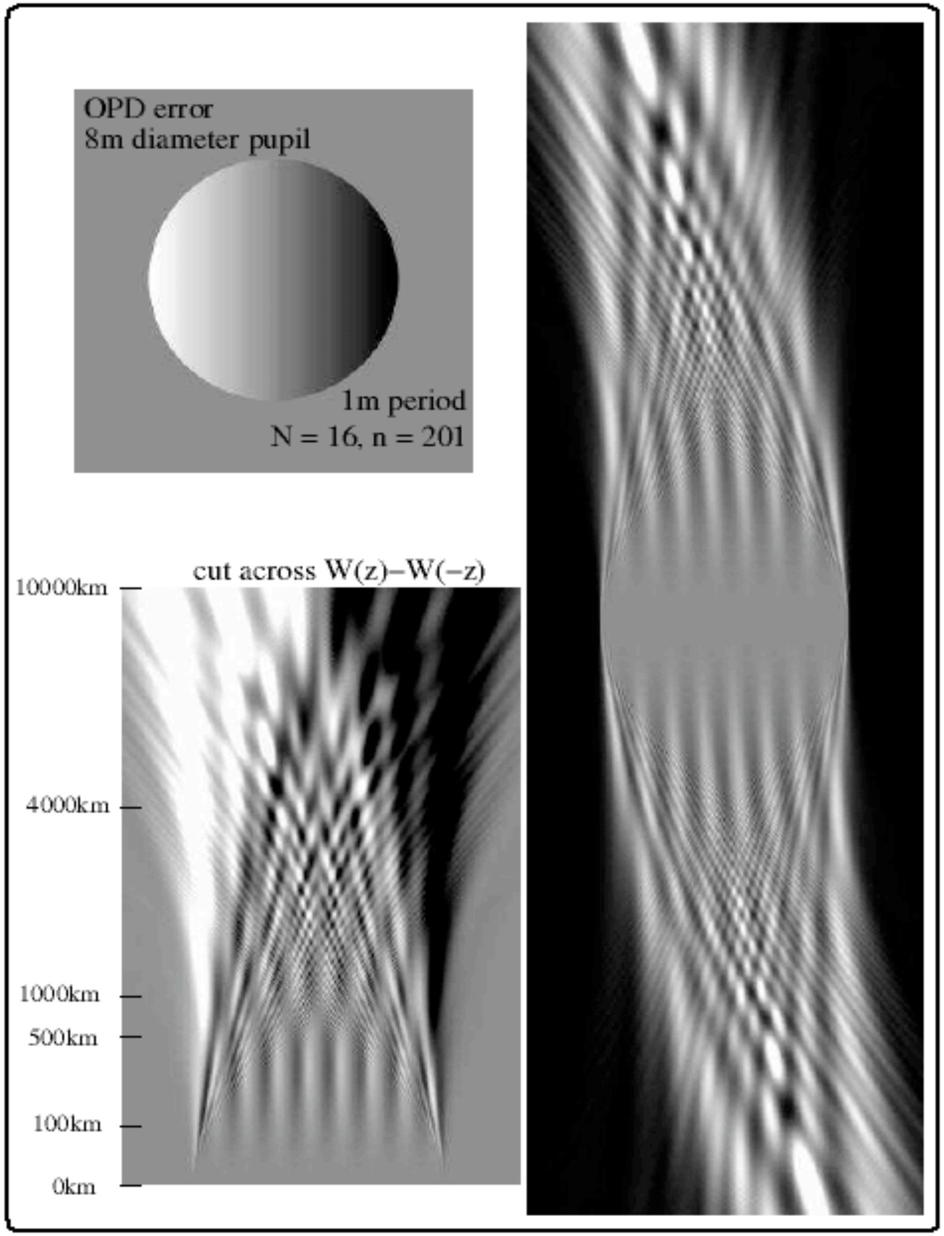
Non-linear Curvature WFS

SH: Noise propagation limitation is introduced at the optical level (chopping the pupil in small pieces)

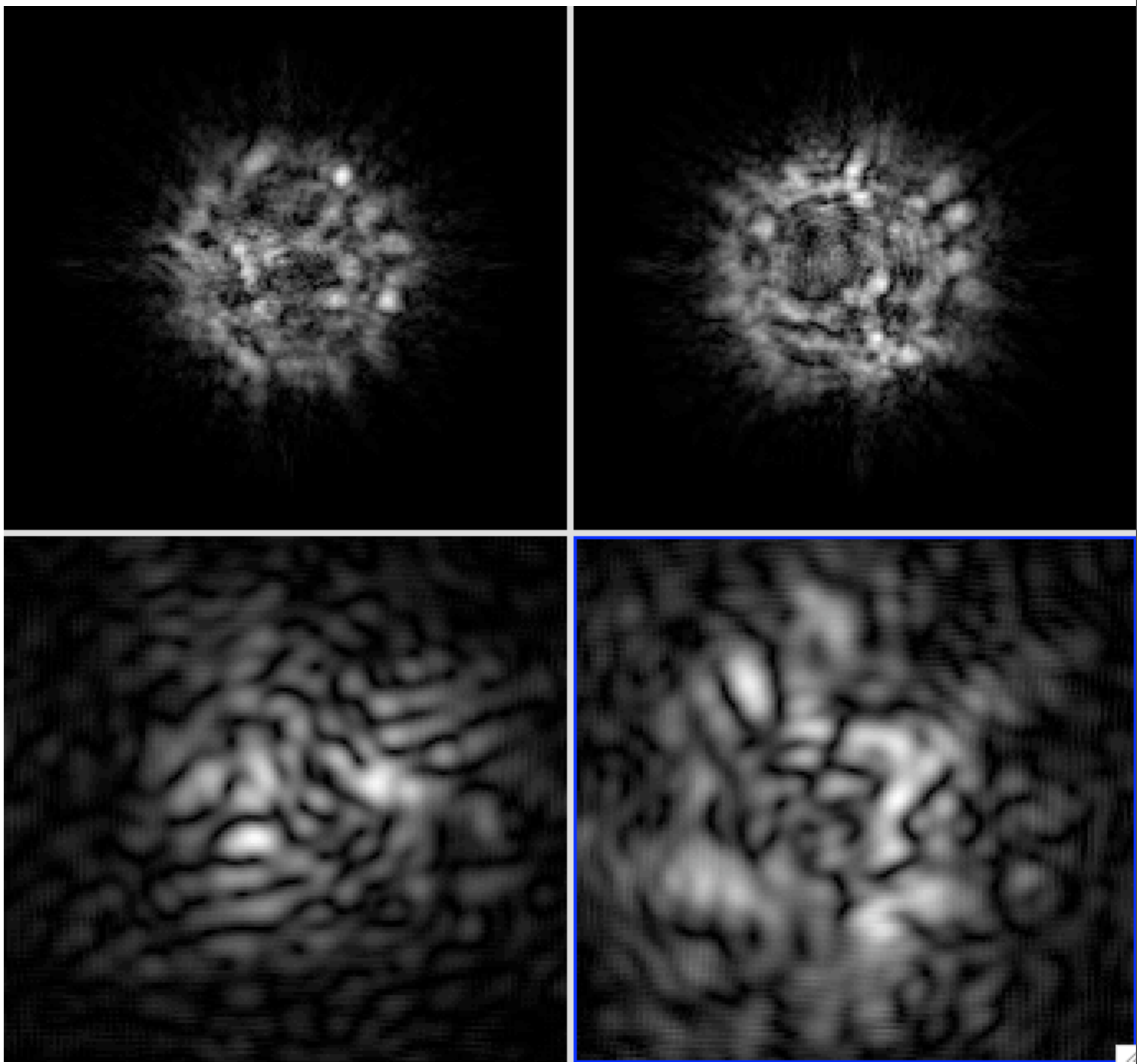
Curvature: Noise propagation comes from processing of WFS frames, which imposes linearity
-> possible to mitigate / solve ?

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



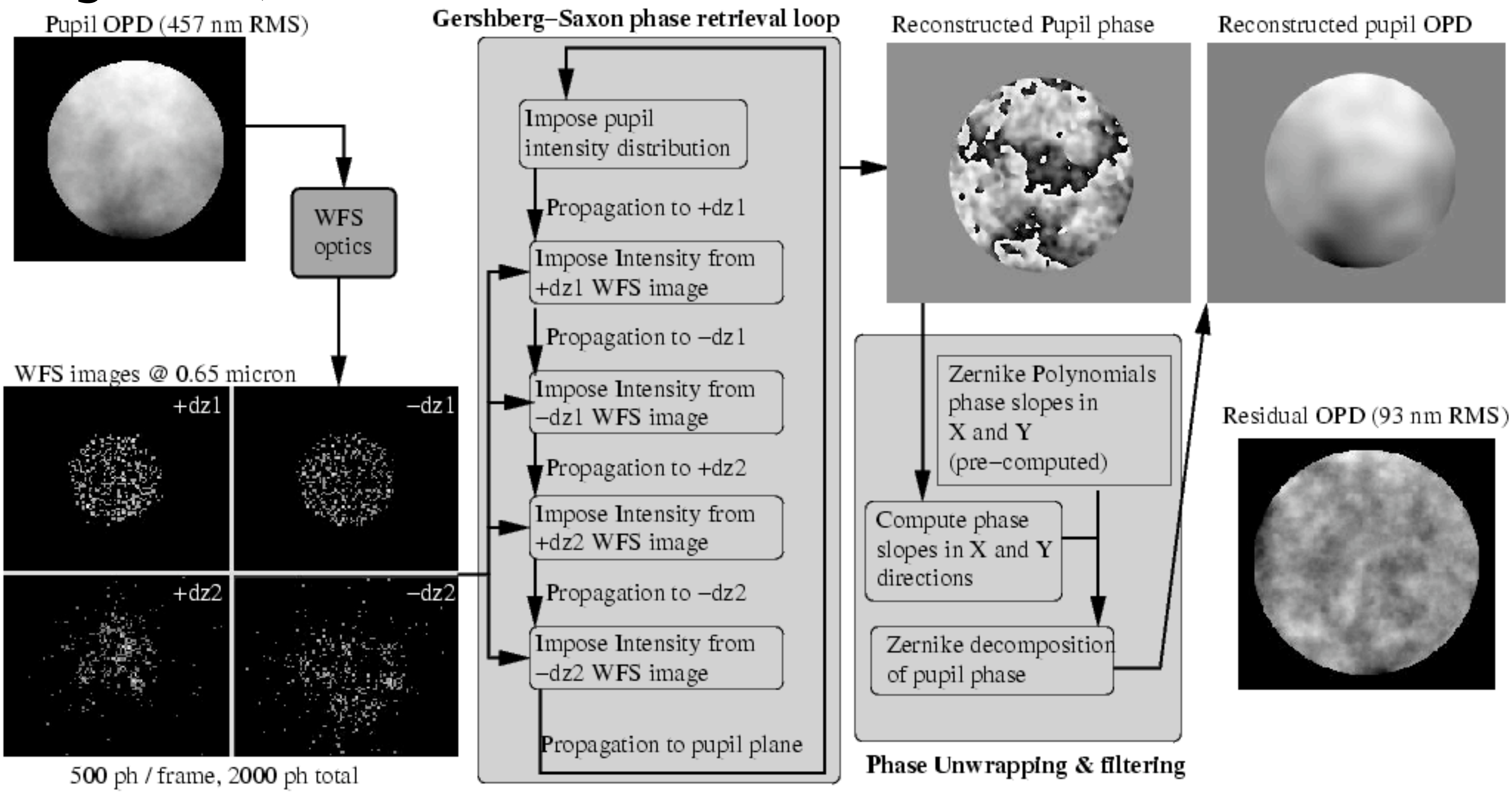


Defocused pupil images are full of lambda/D speckles

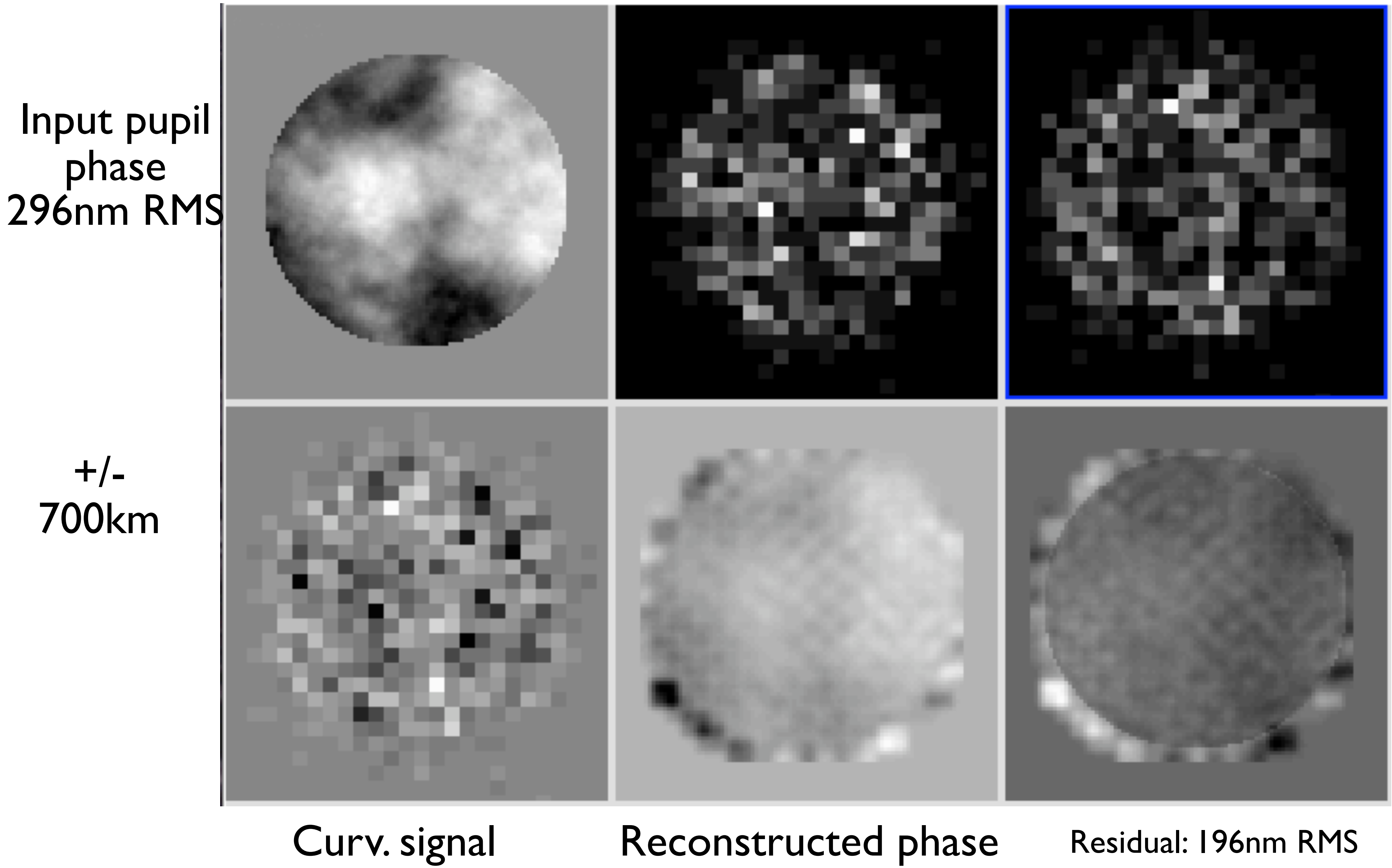


Standard phase diversity algorithm, working around pupil plane. There are probably better/faster algorithms (see for example: van Dam & Lane 2002, JOSA vol. 19)

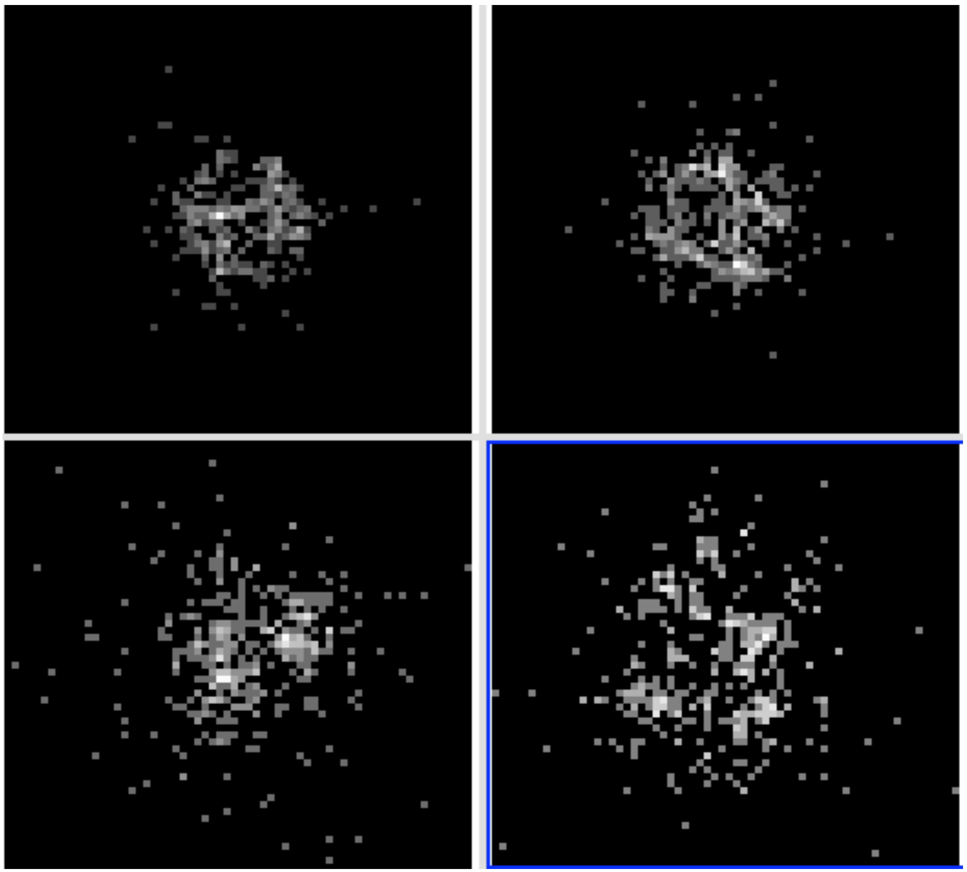
kHz operation appears to be possible with current chips for few 100s actuators system (100 32x32pix FFT = 0.2ms on single CPU)



Linear single stroke WFS, 2000 ph total
8m telescope, 0.65 mu, 373 ill. subapert.



Non linear dual stroke WFS, 2000 ph total
8m telescope, 0.65 mu, 373 ill. subapert.

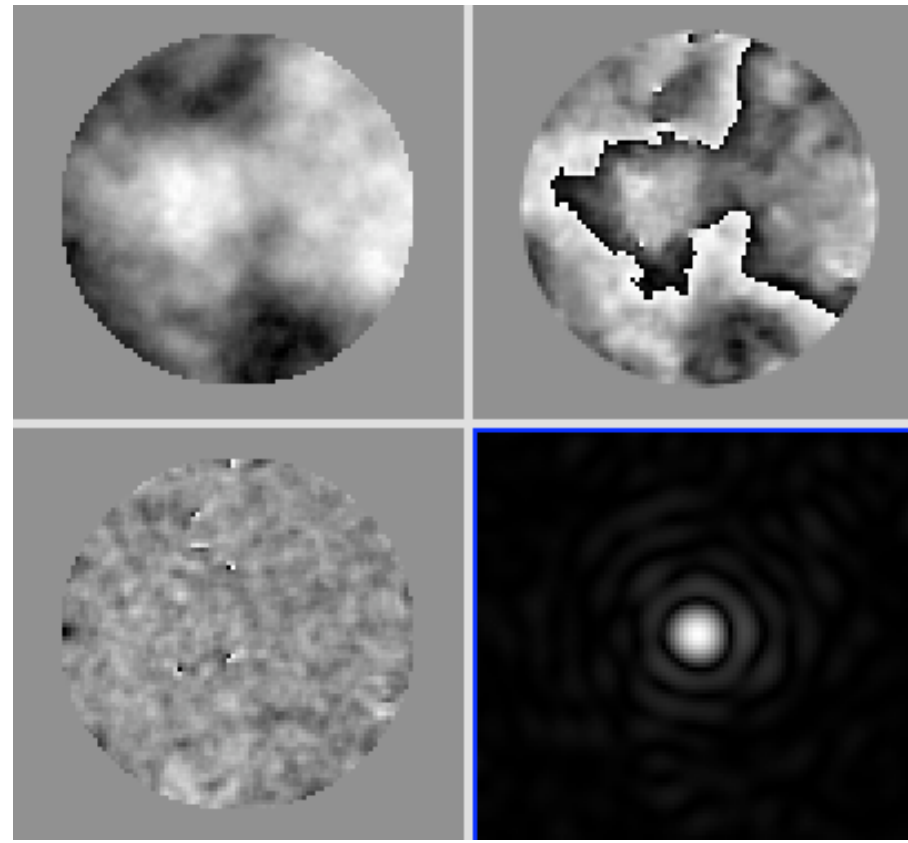


Defocused pupil images

500 ph / frame
Top : +/- 2000km
Bottom: +/- 8000km

Input pupil phase 296nm RMS

Reconstructed phase



Residual: 55nm RMS

SR = 0.763 at 0.65 micron

Magn 16 source -> 2000 ph/ms on 8m telescope

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

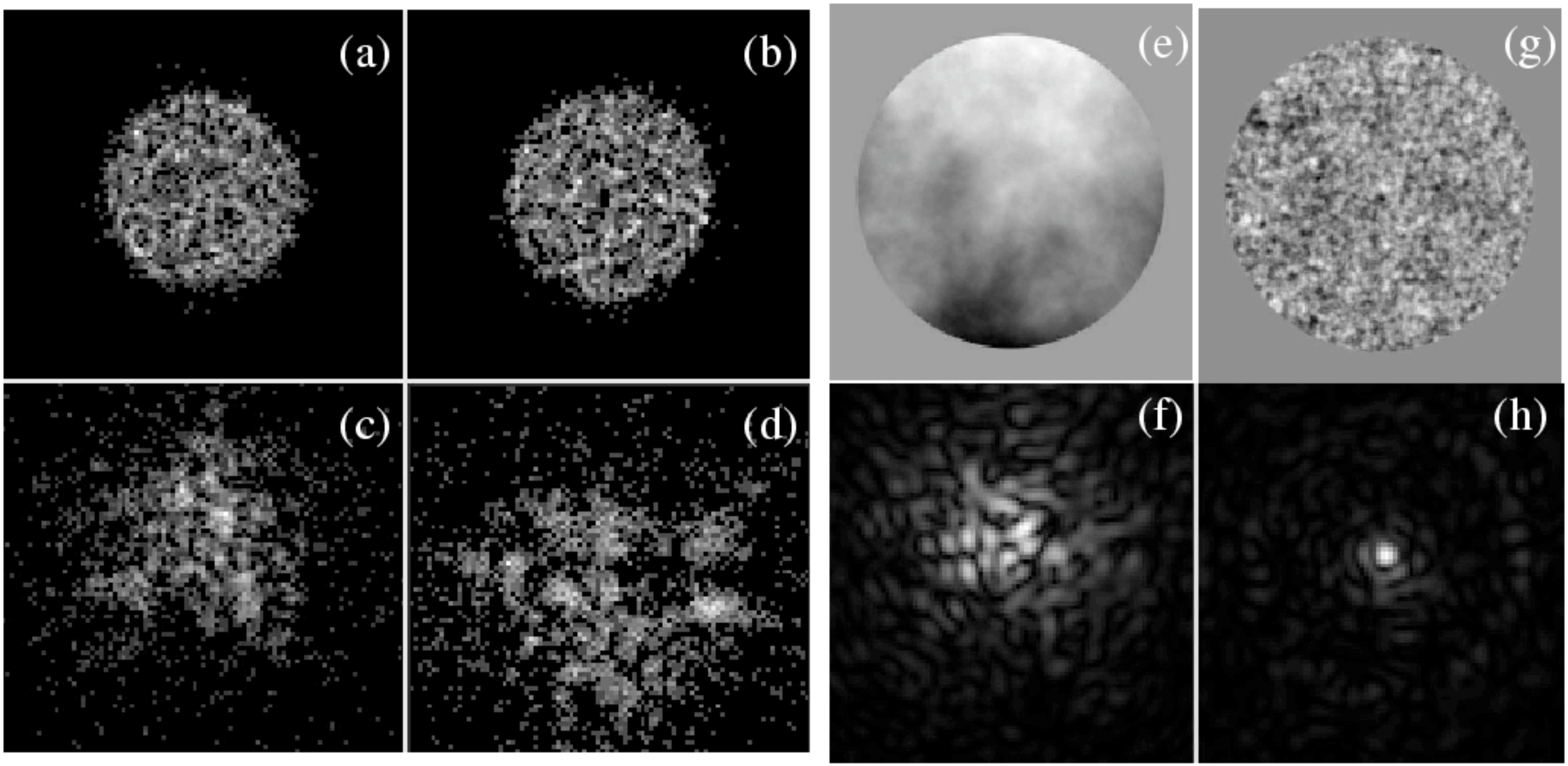
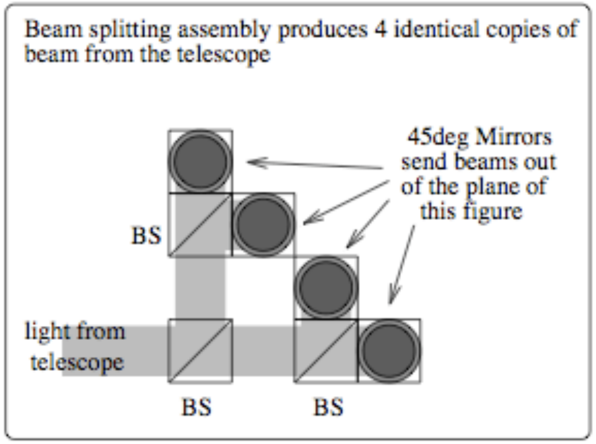
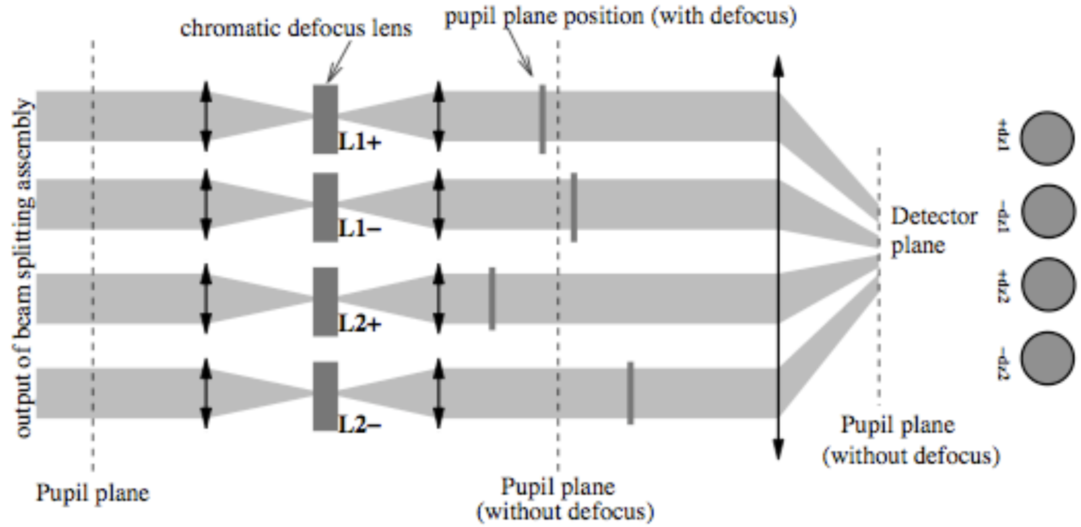
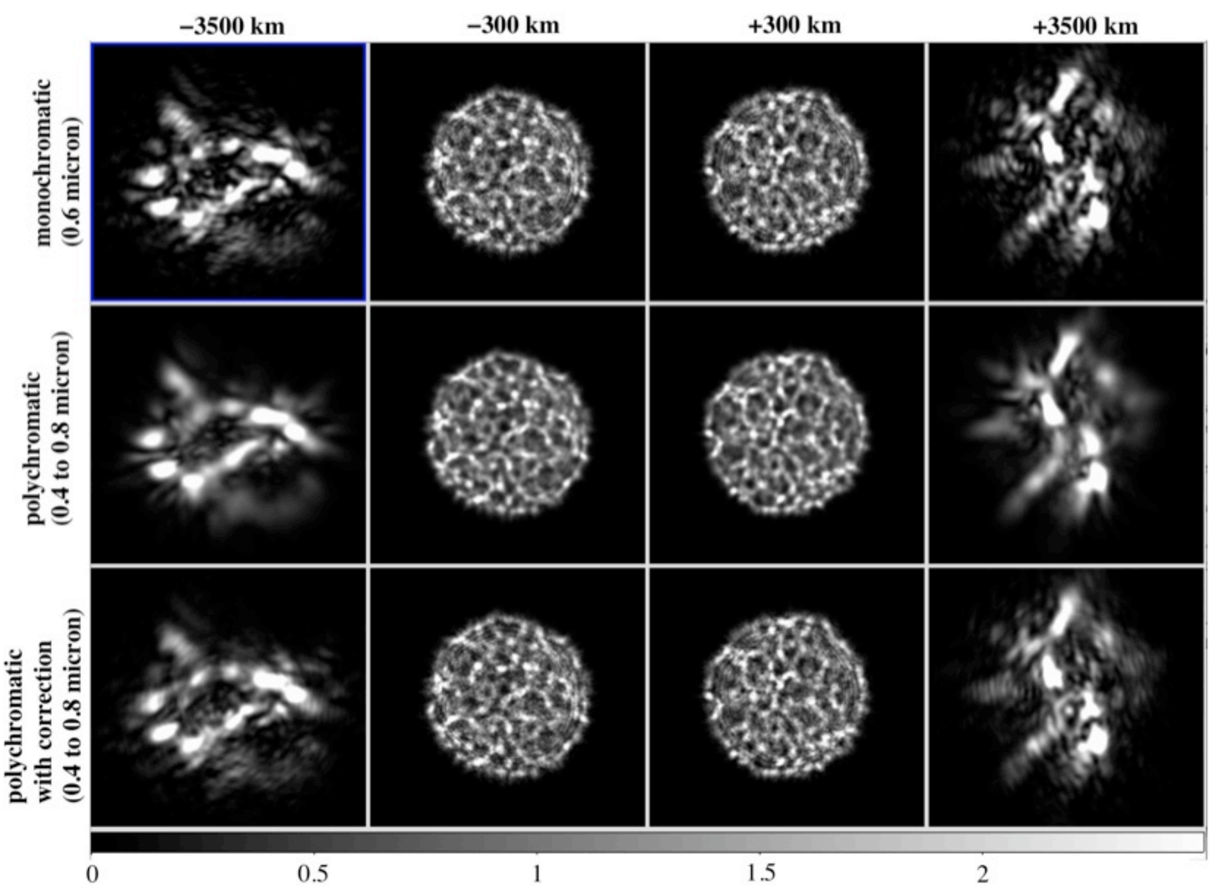


Fig. 9.— Wavefront reconstruction using the algorithm shown in fig. 8. Four noisy defocused pupil images (images (a), (b), (c) and (d)) are acquired to transform the pupil phase aberrations (e) into intensity signals. The input pupil phase is 609 nm RMS, yielding the PSF (f) before correction. After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

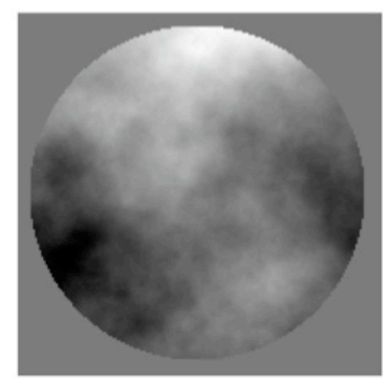


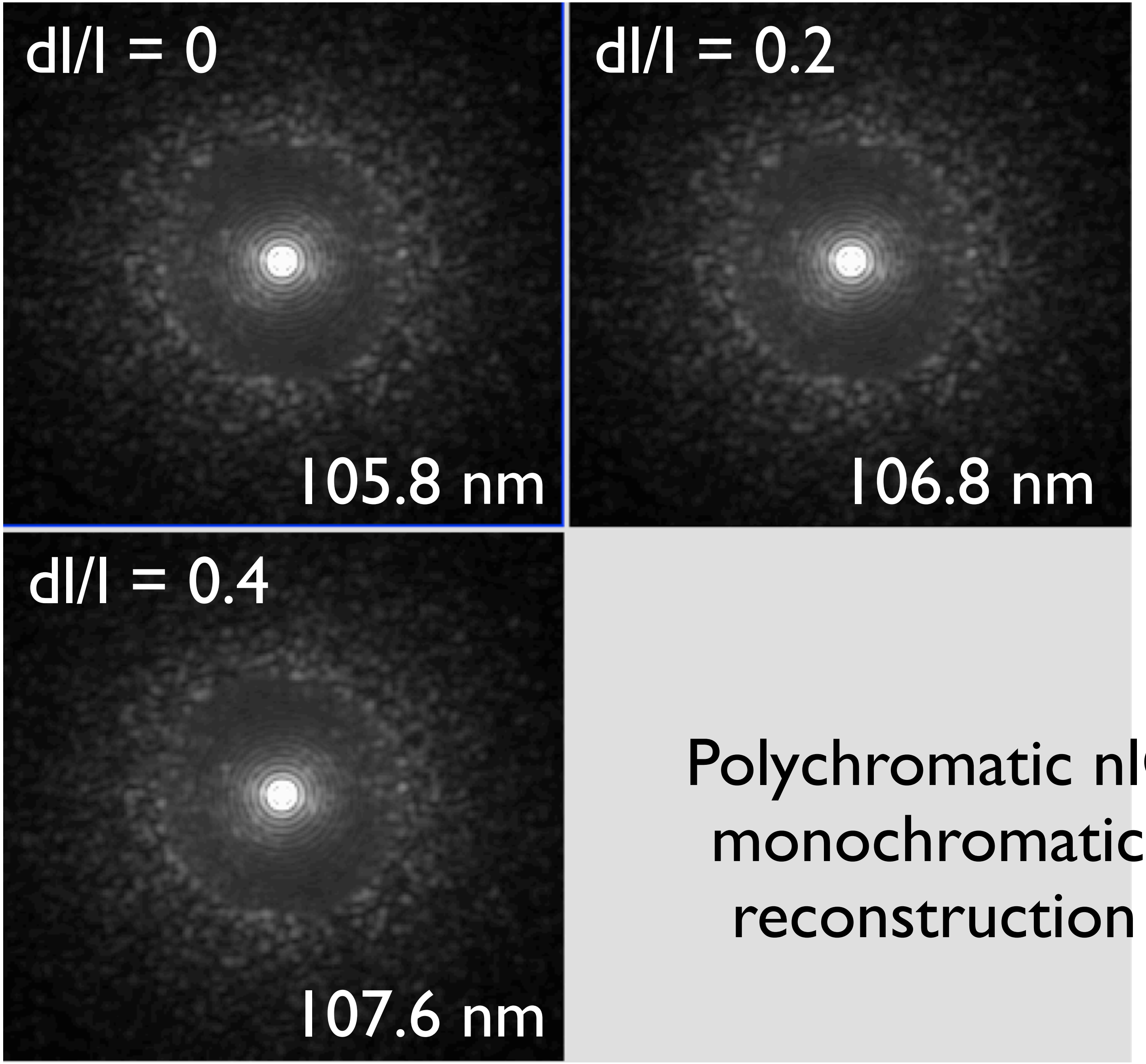




8 m diameter pupil

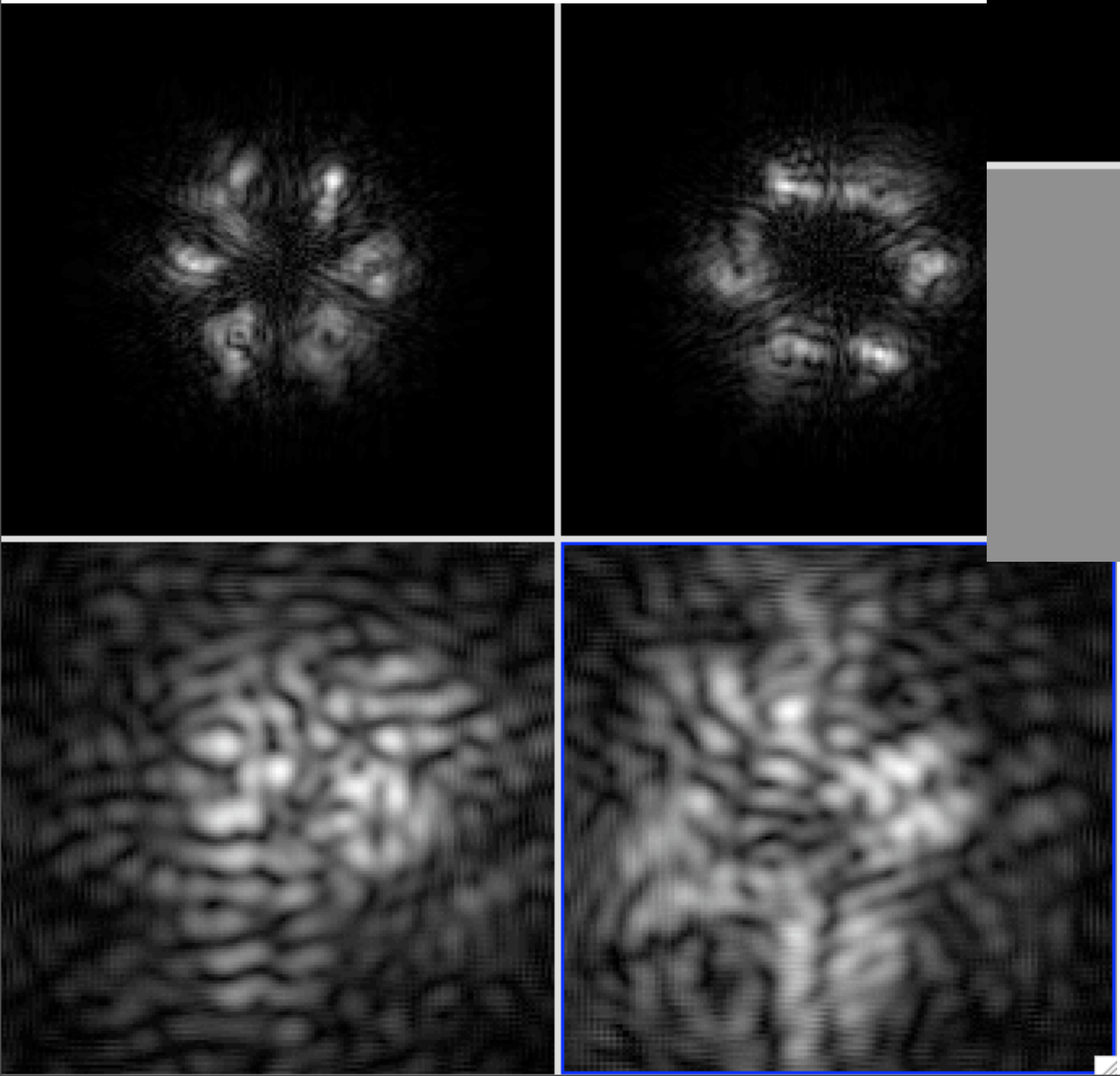
371 nm RMS

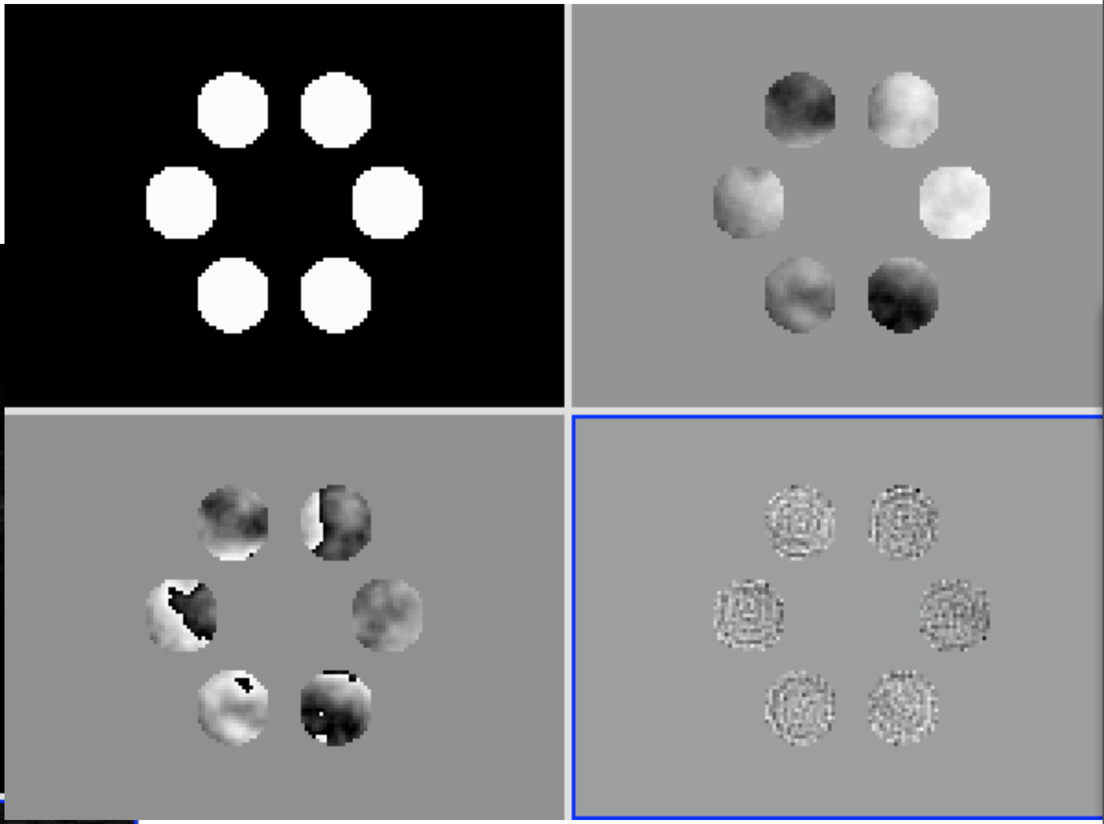




Polychromatic nlCWFS with monochromatic wavefront reconstruction algorithm

Very good for Sparse pupil or thick spiders

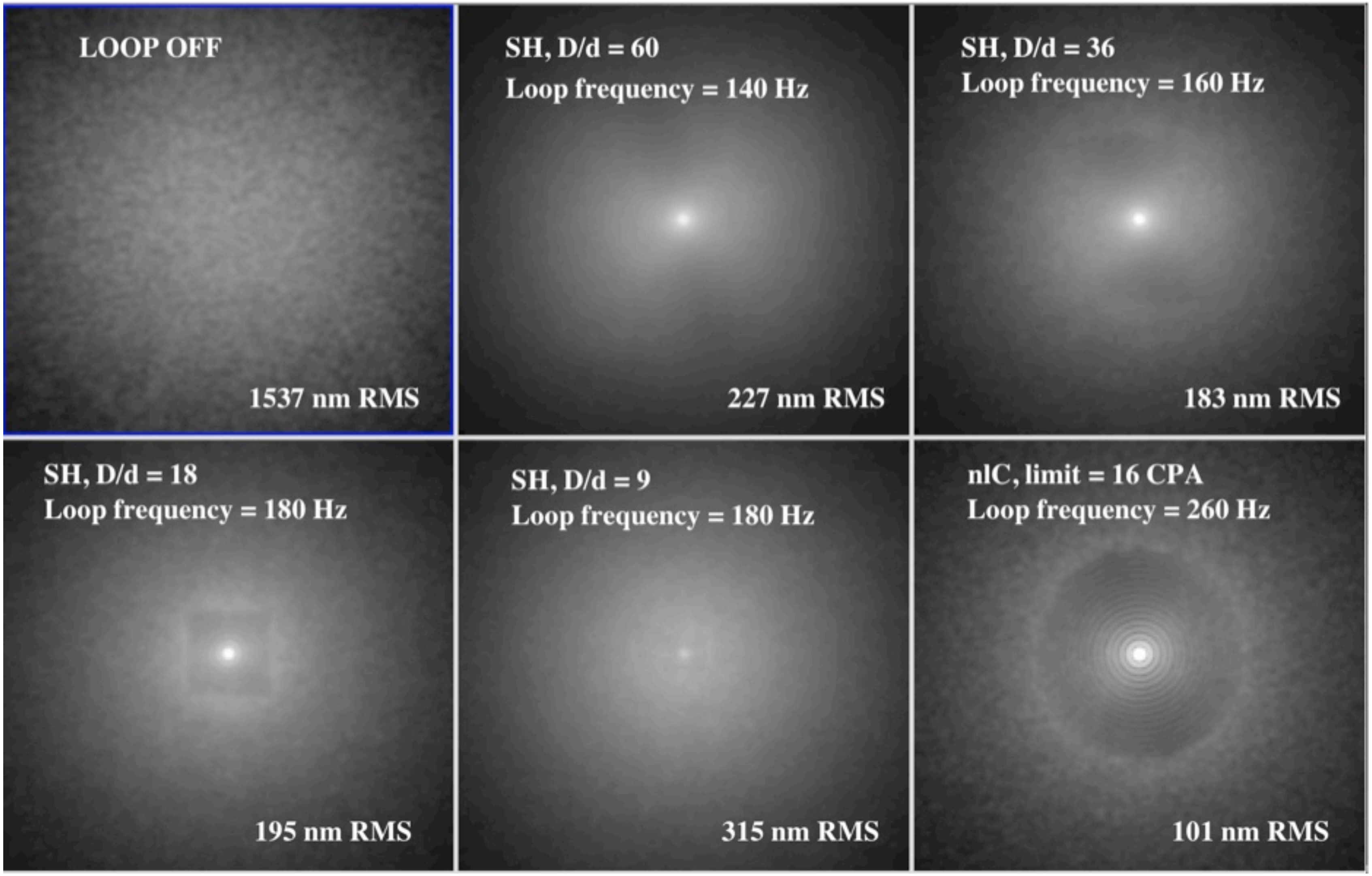




13nm RMS

2e8 ph

m ~ 13



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

Closed loop simulations

WFS:
non-linear phase retrieval on curvature wavefront sensor

Same behaviour would be obtained with fixed pyramid

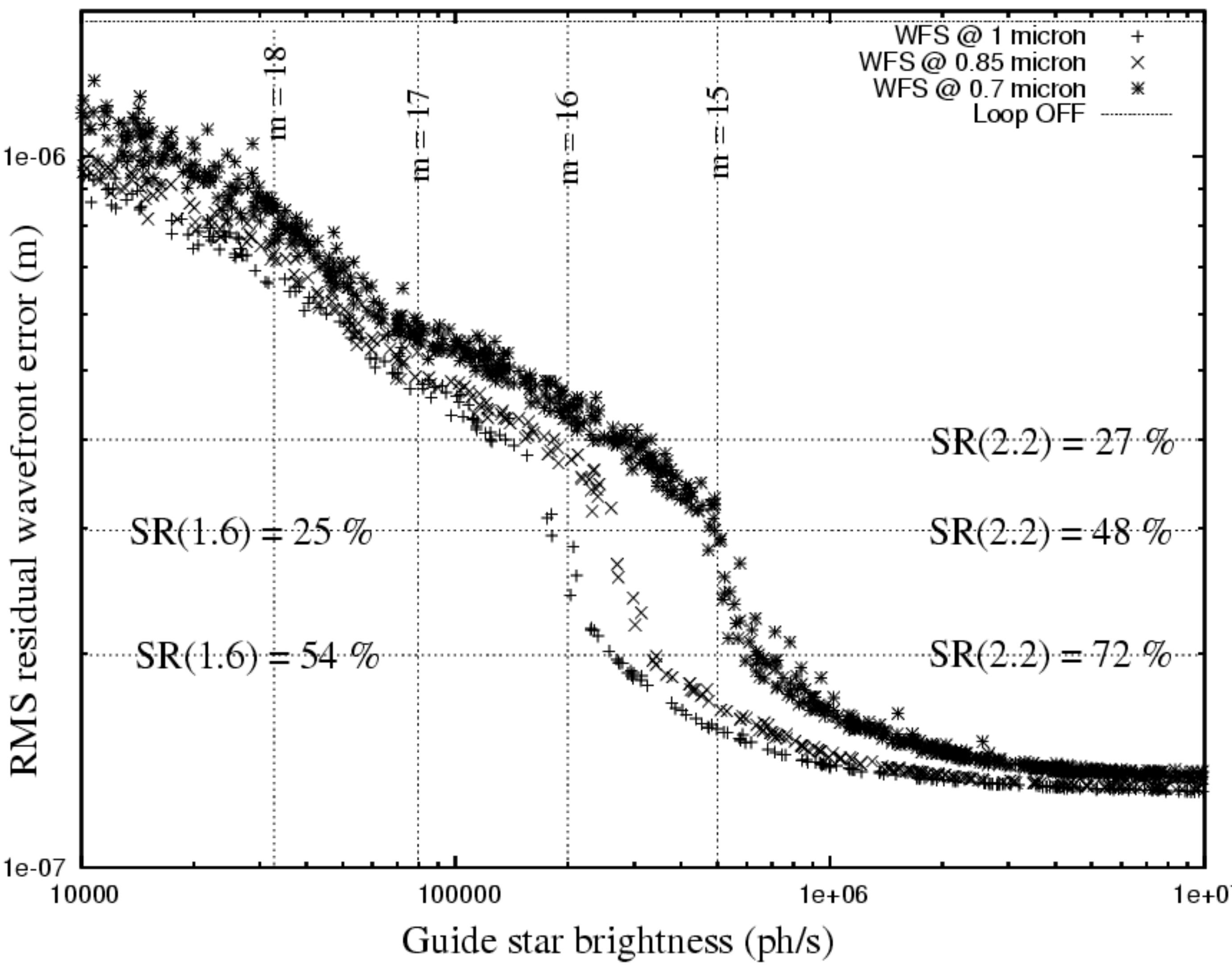


Fig. 11.— Simulated performance of a non-linear Dual stroke Curvature as a function of sensing wavelength (0.7, 0.85 and 1.0 μm) and guide star brightness. The stellar magnitudes given in this figure assume a 20% efficiency in a 0.5μm wide band. See text for details.

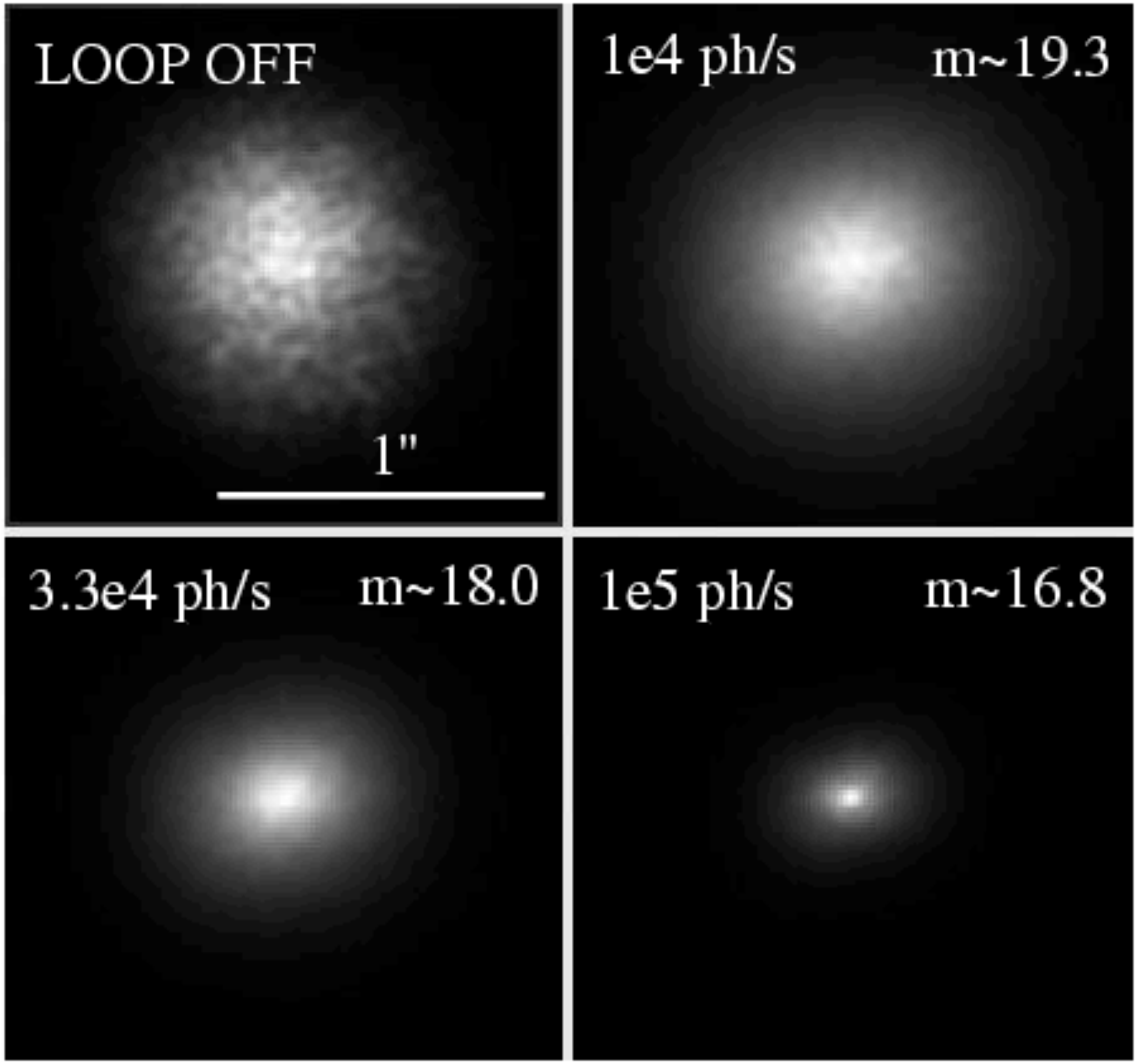
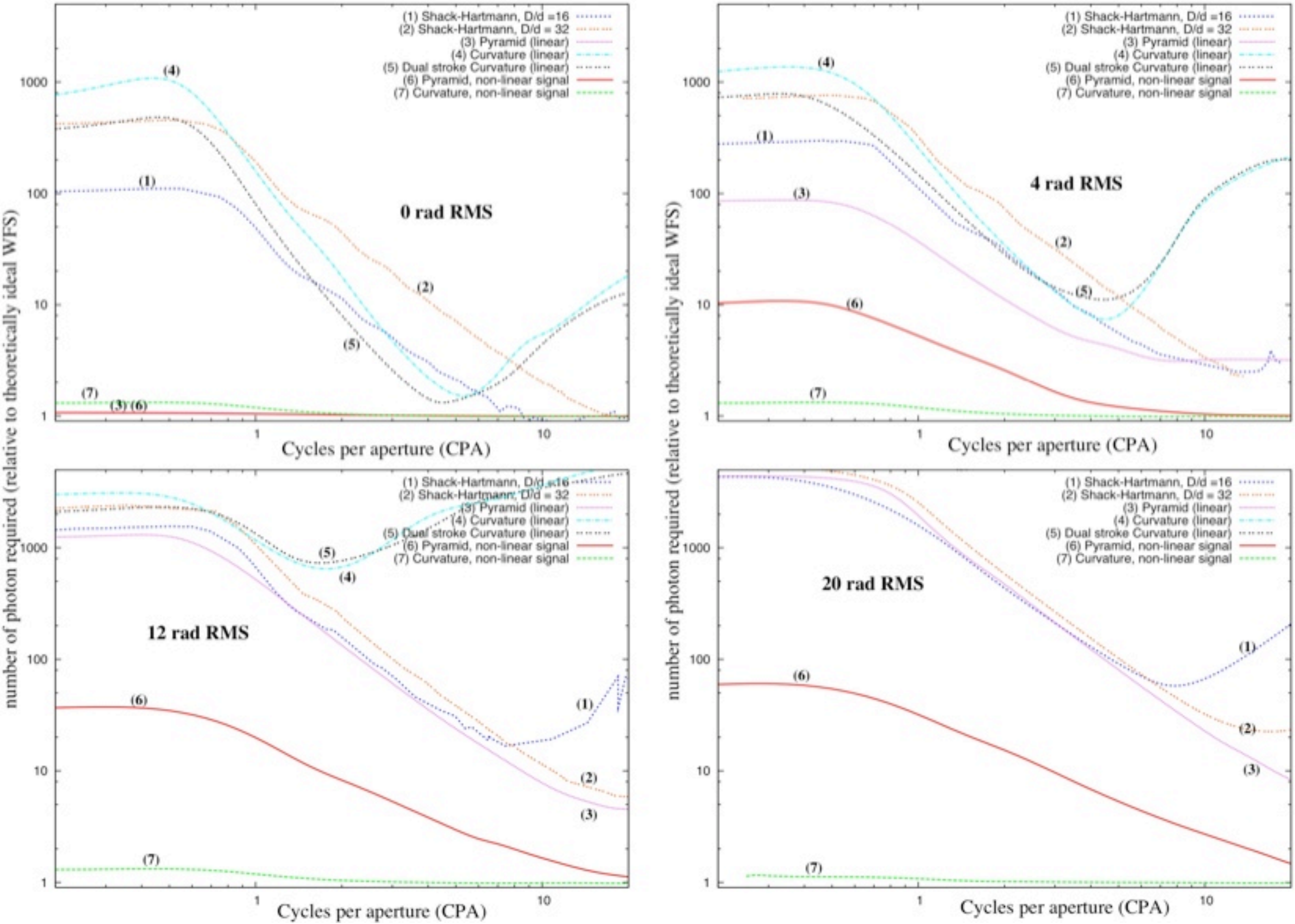


Fig. 12.— Simulated long exposure 1.6 μm PSFs obtained with a non-linear Dual stroke Curvature-based AO system. The sensing wavelength was 0.85 μm for this simulation.


number of photon required (relative to theoretically ideal WFS)
Cycles per aperture (CPA)
(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
0 rad RMS
4 rad RMS
12 rad RMS
20 rad RMS
1000
100
10
1
1
10

Focal plane WFS

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

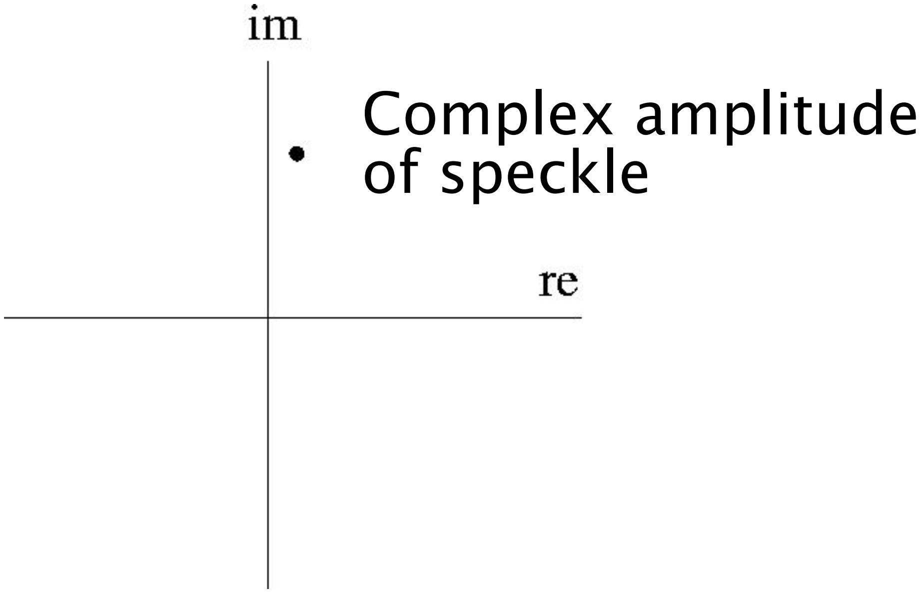
-> for each point in the focal plane, 3 intensities -> single solution for phase & amplitude of speckle field

Speckles vs. planet

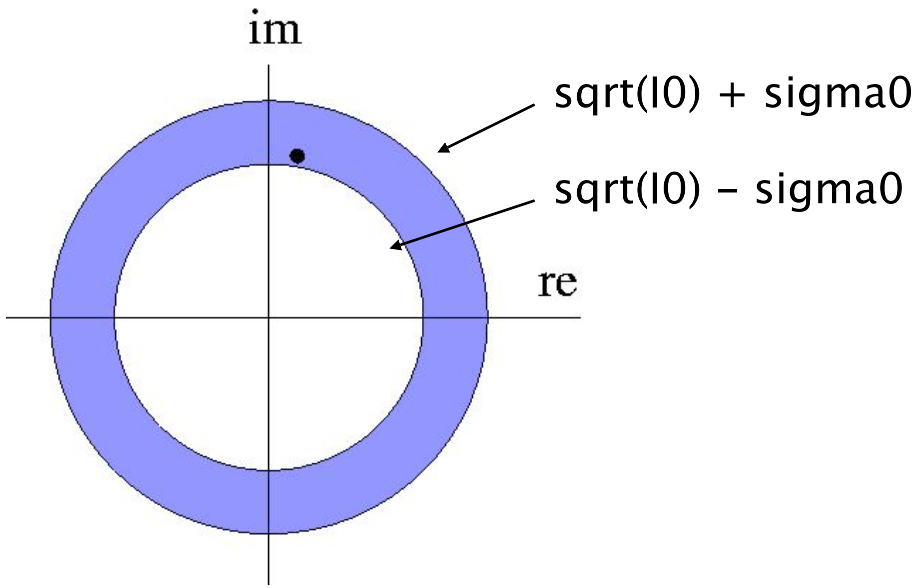
Spectra differential imaging (SDI)
Optimized for methane-bearing giant planets
Will only detect planets with a given spectral feature
Polarization differential imaging (PDI)
Degree of polarization may be low (few %)
Only works on reflected light
Angular differential imaging (ADI)
Performs well if static speckles are strong
Does not work well at small angular separations

Coherent differential imaging (CDI)
Use DM to introduce a know variation in the WF to modulate speckle intensity
Can reach photon noise limit if system is very well calibrated and CDI is performed quickly (or simultaneously)

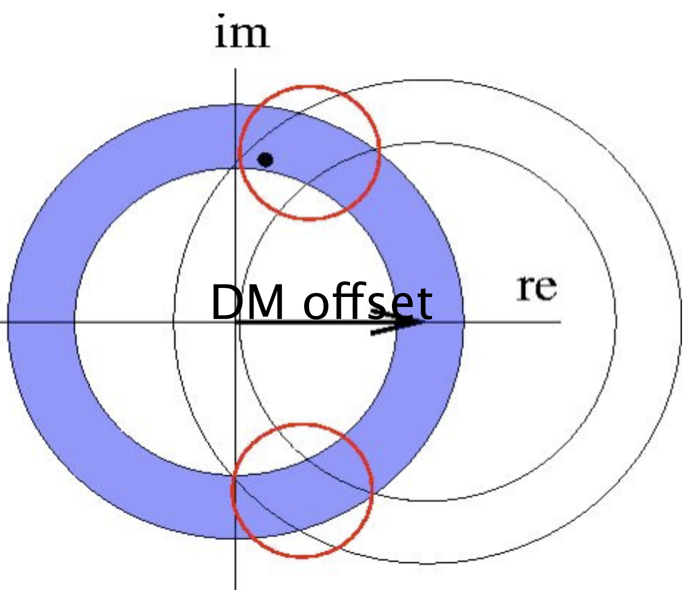
Initial problem

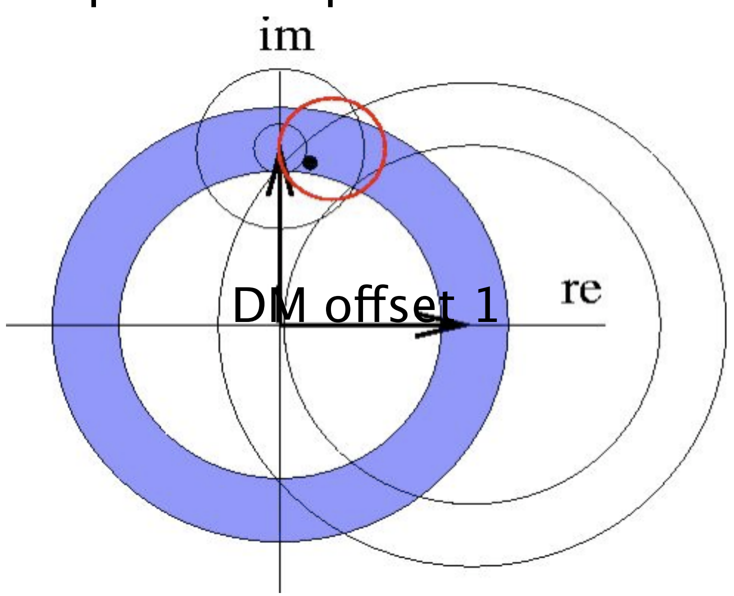


Take a frame -> measured speckle intensity = I0

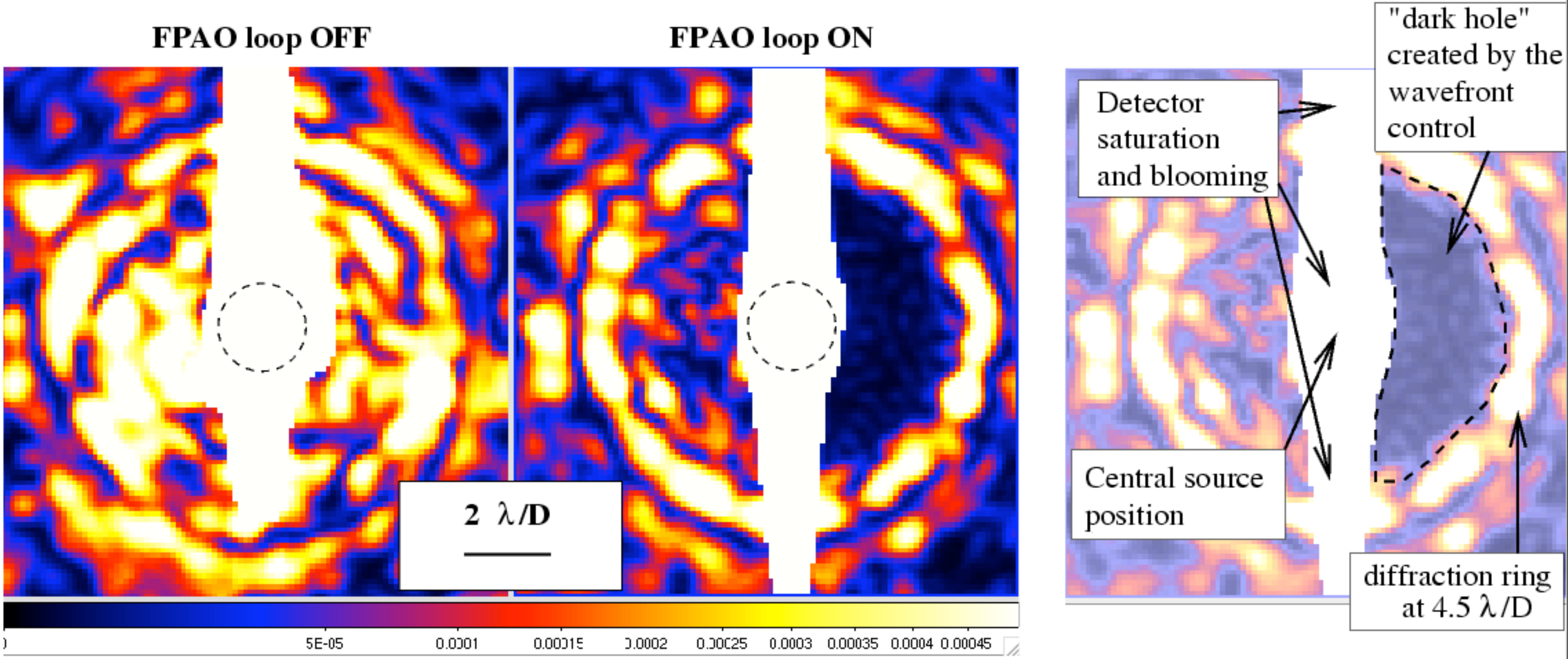


DM offset chosen to be ~ equal to speckle amplitude



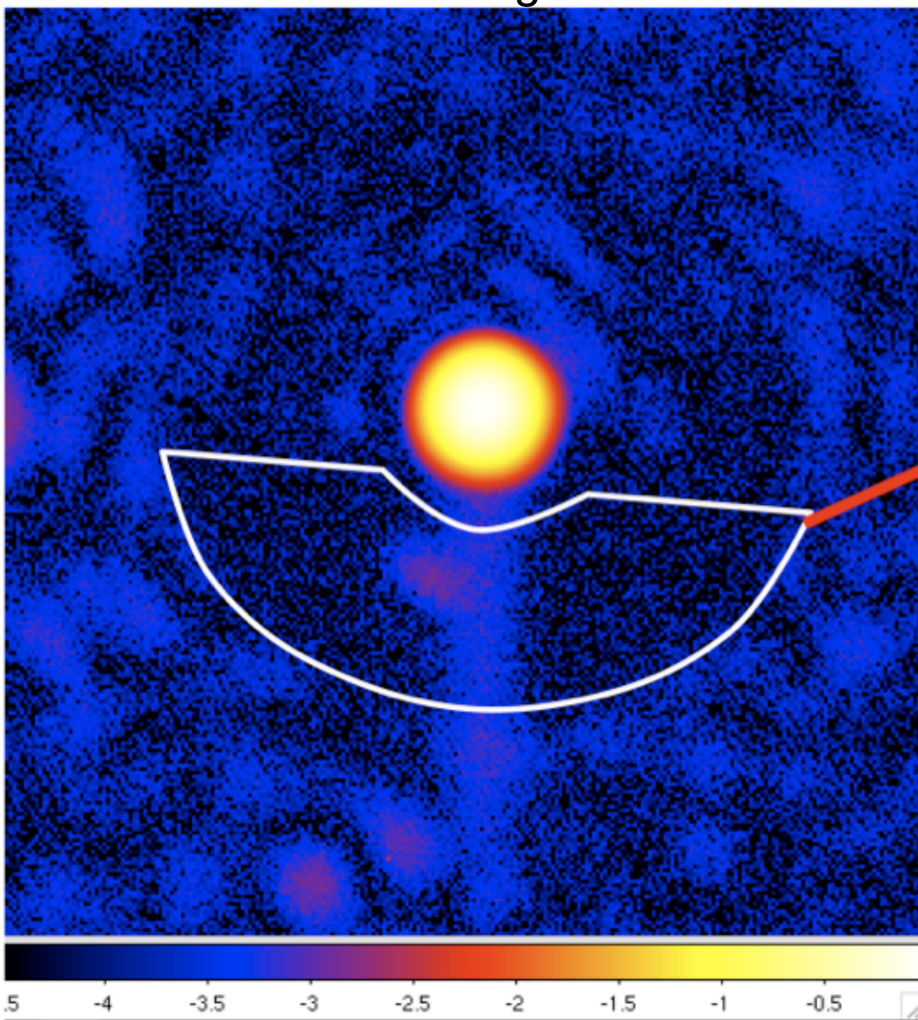


Lab results with PIAA coronagraph + FPAO with 32x32 MEMs DM

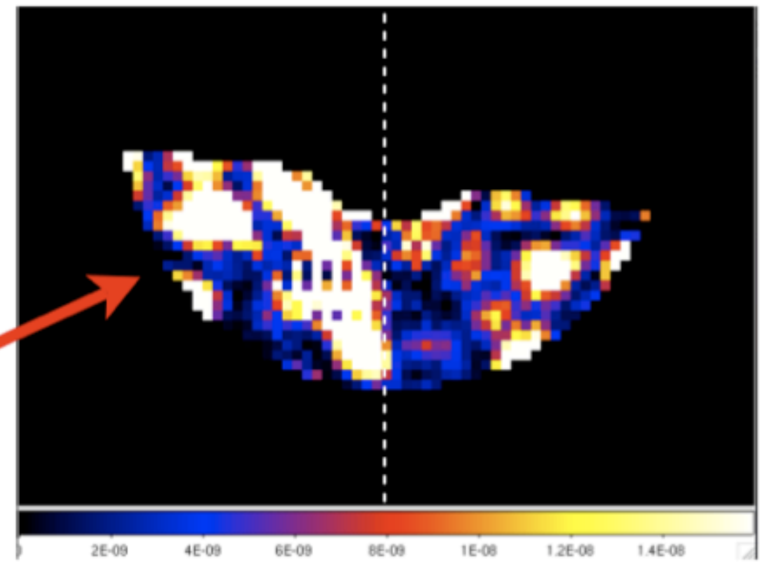


Recent lab results demonstrate PIAA coronagraph + Focal plane AO + coherent differential imaging

Raw image



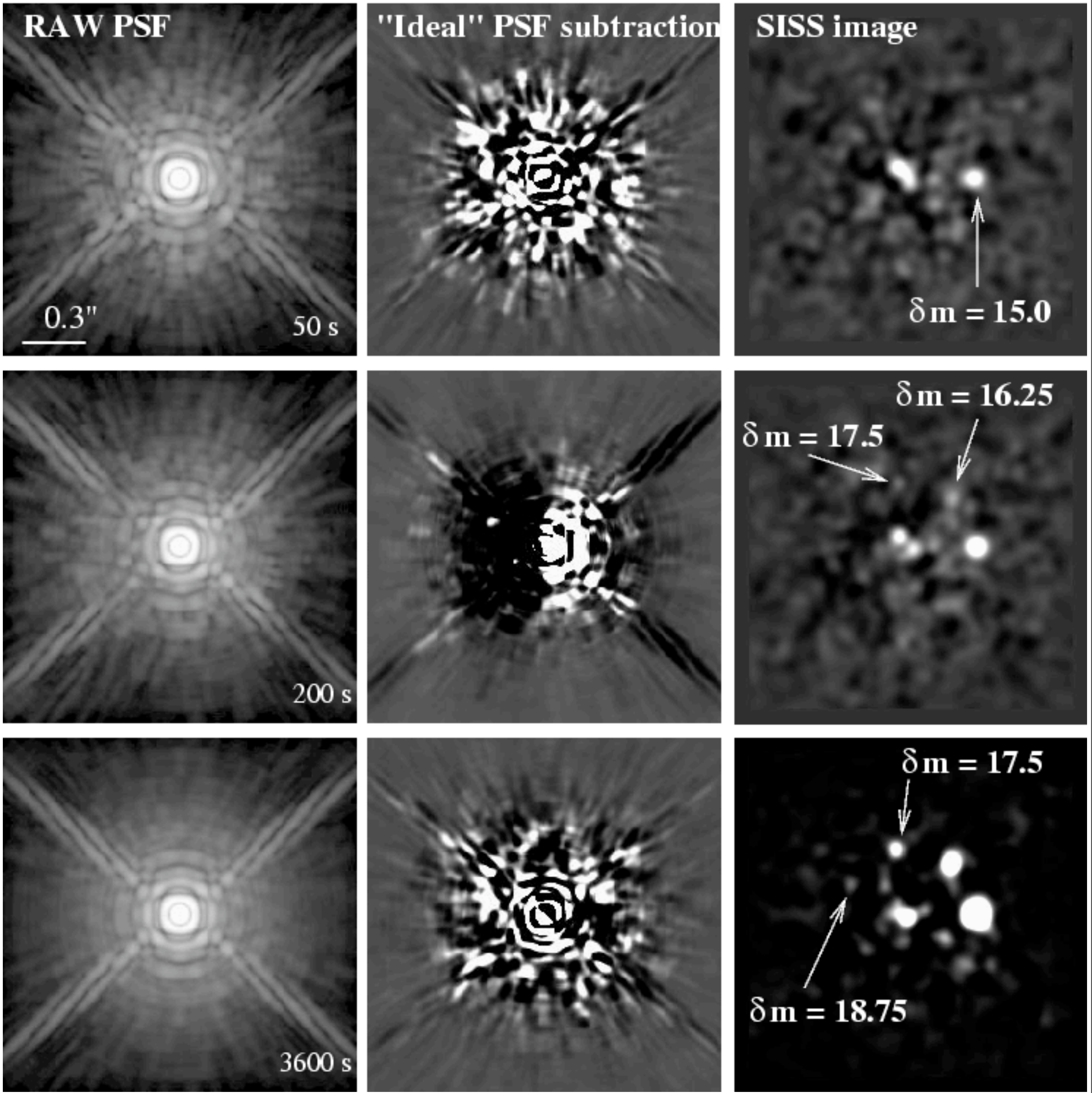
Coherent starlight



Average contrast in right half of the science field shown above (excludes the ghost on the left) = 7e-9

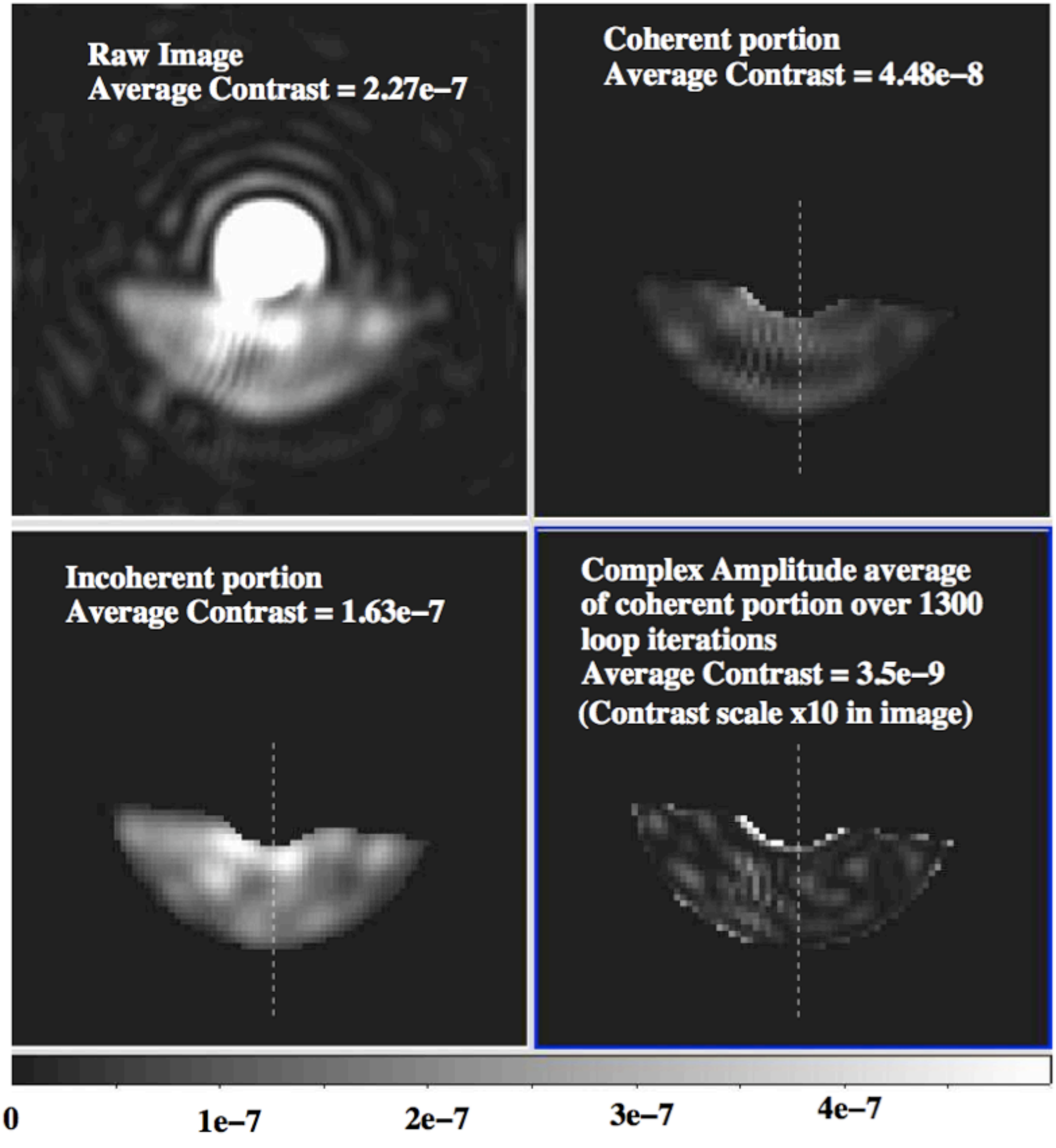
Contrast achieved in 1.6 to 4.5 l/D zone:
1.5e-7 incoherent halo ghost (equivalent to exozodi)
7e-9 coherent starlight speckles (turbulence, vibrations)

Speckle calibration with active coherent modulation



Coherent detection works in the lab alongside FPAO

Extremely powerful for ExAO:
- Optically simple
- Non NCPE
- on-the fly diagnostics
- CDI post-processing



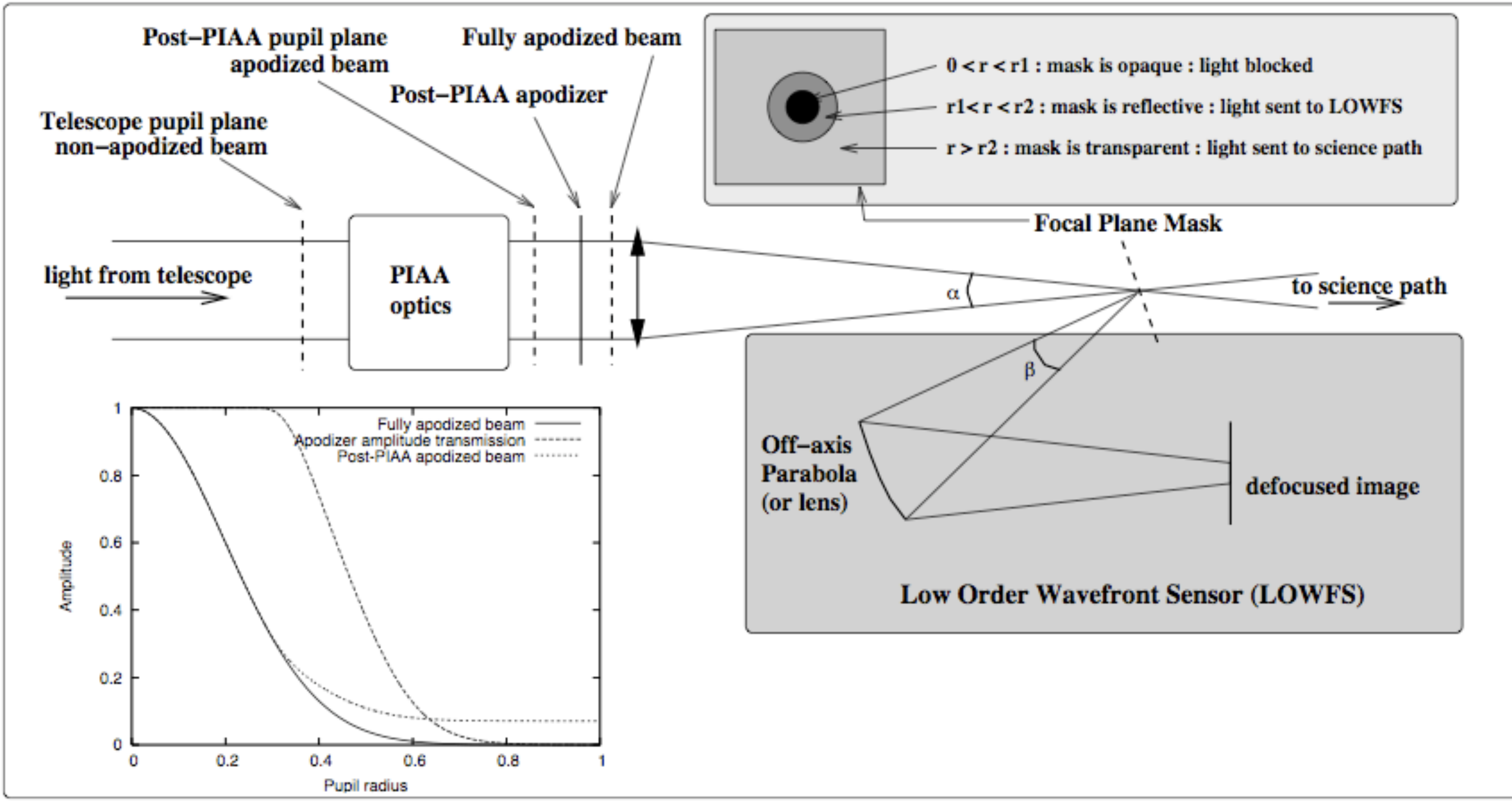


Fig. 1.— Optical layout of a coronagraphic low order wavefront sensor system, shown here with a PIAA coronagraph. See text for details.

Guyon, Matsuo, Angel, 2008 - in press

Can also be applied to phase mask type coronagraphs (Matsuo & Guyon, in preparation)

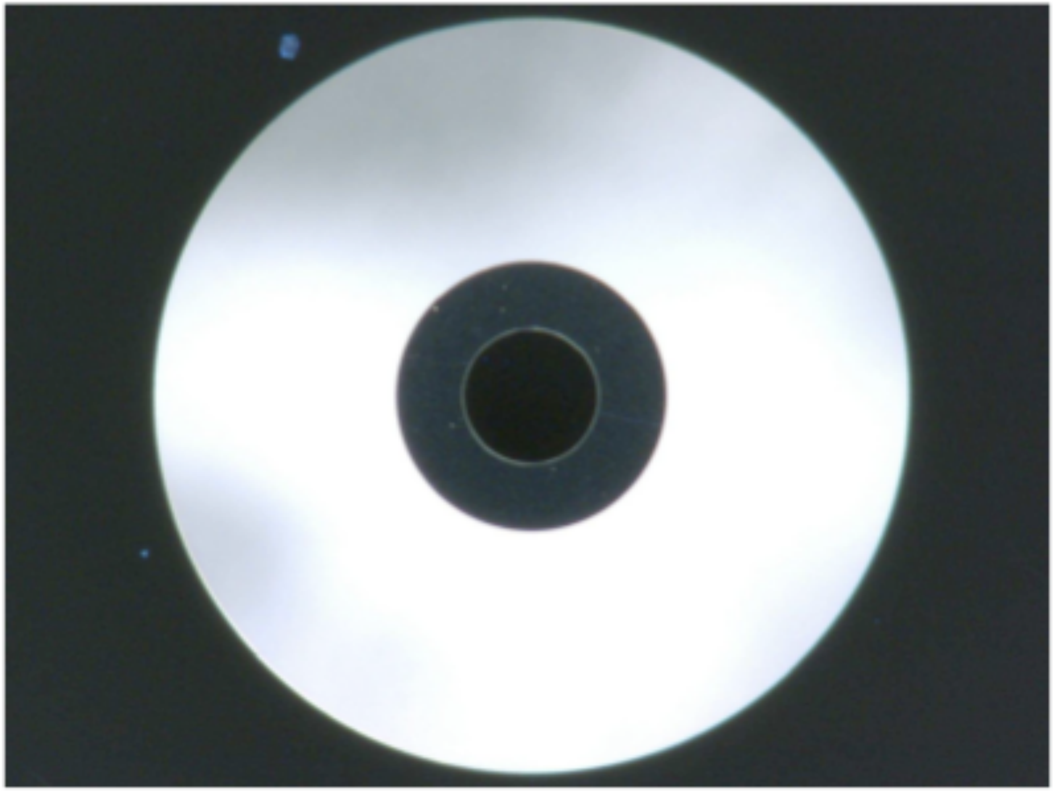
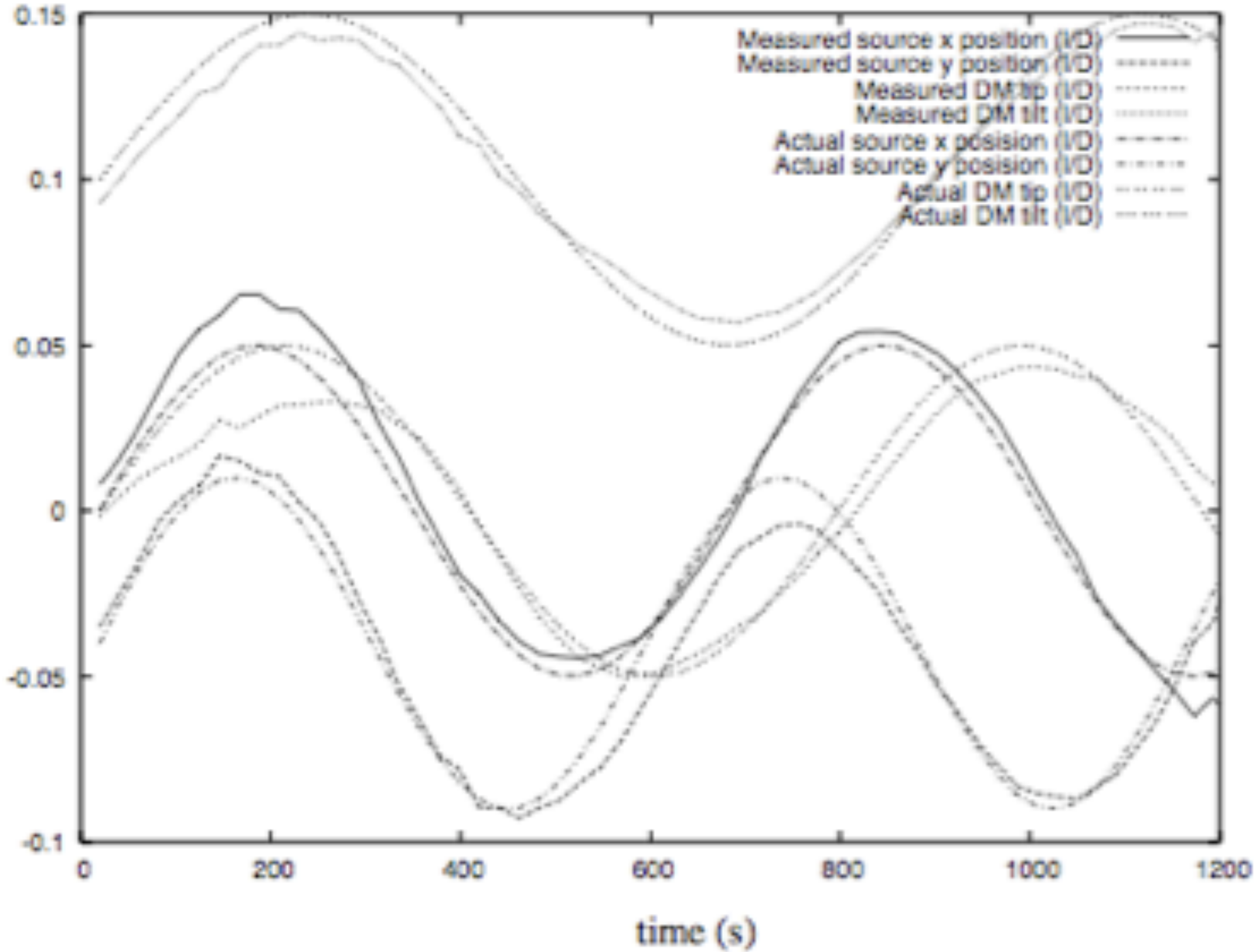
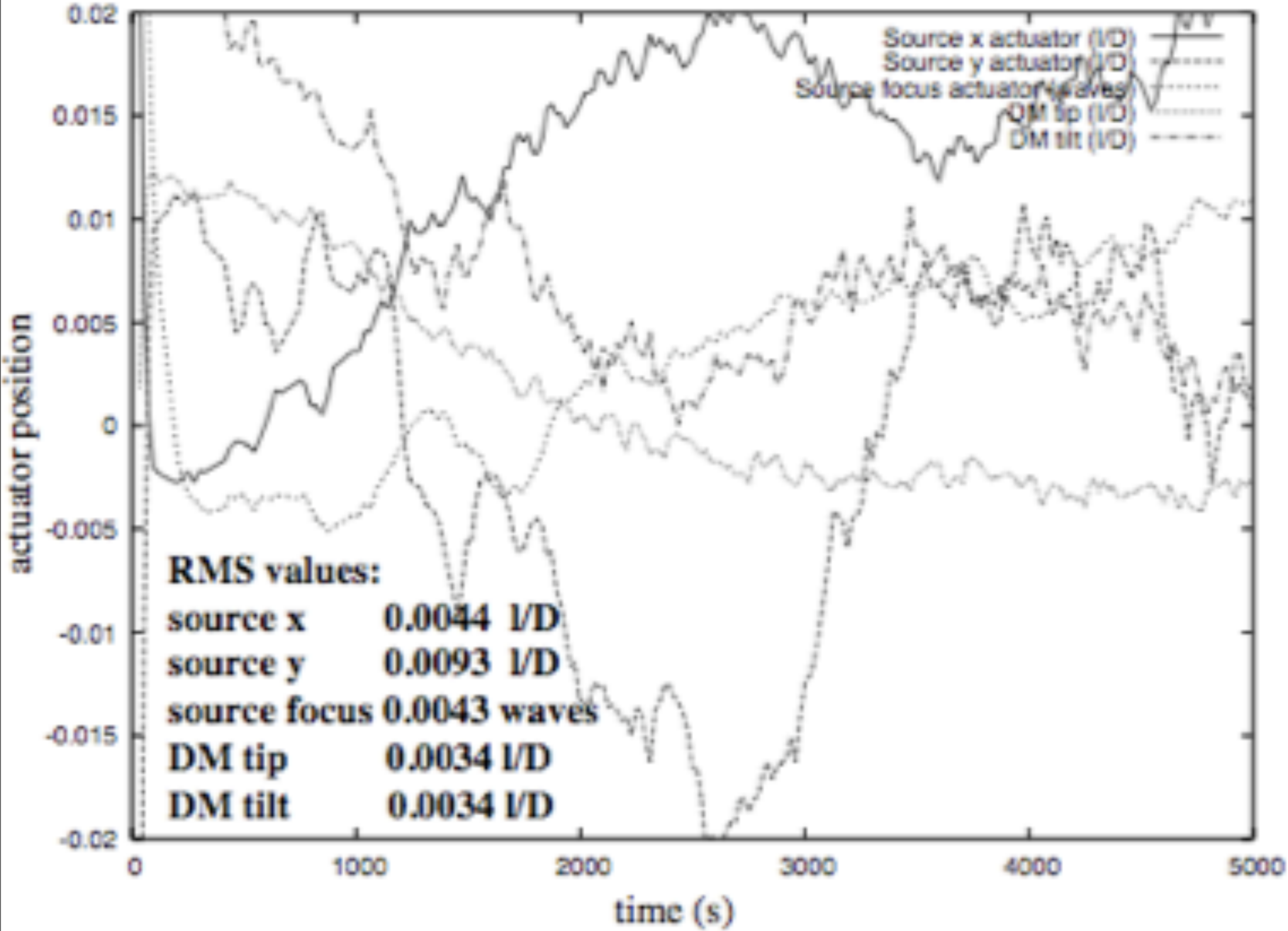


Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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

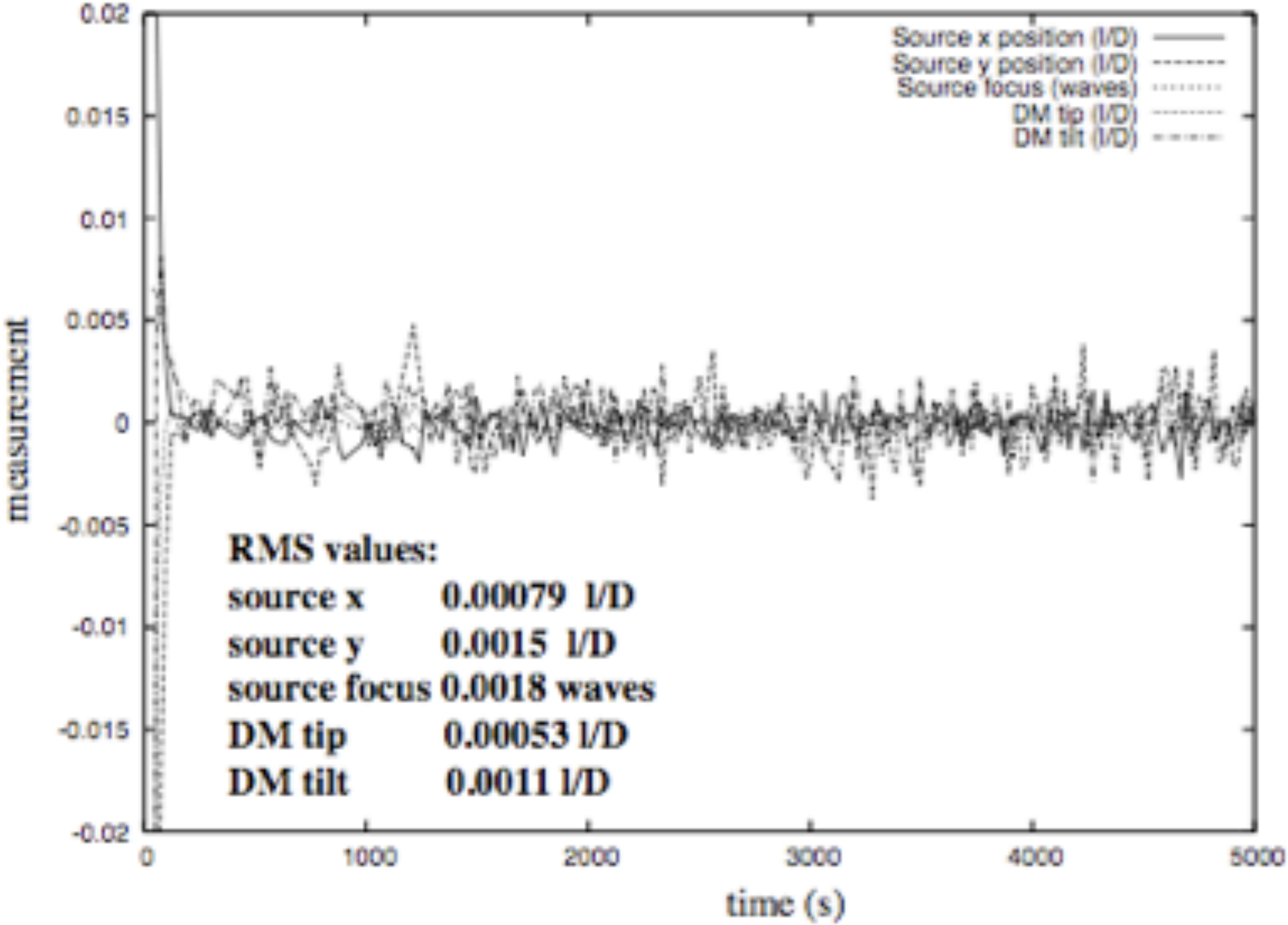
Why a central dark spot?

(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)
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
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

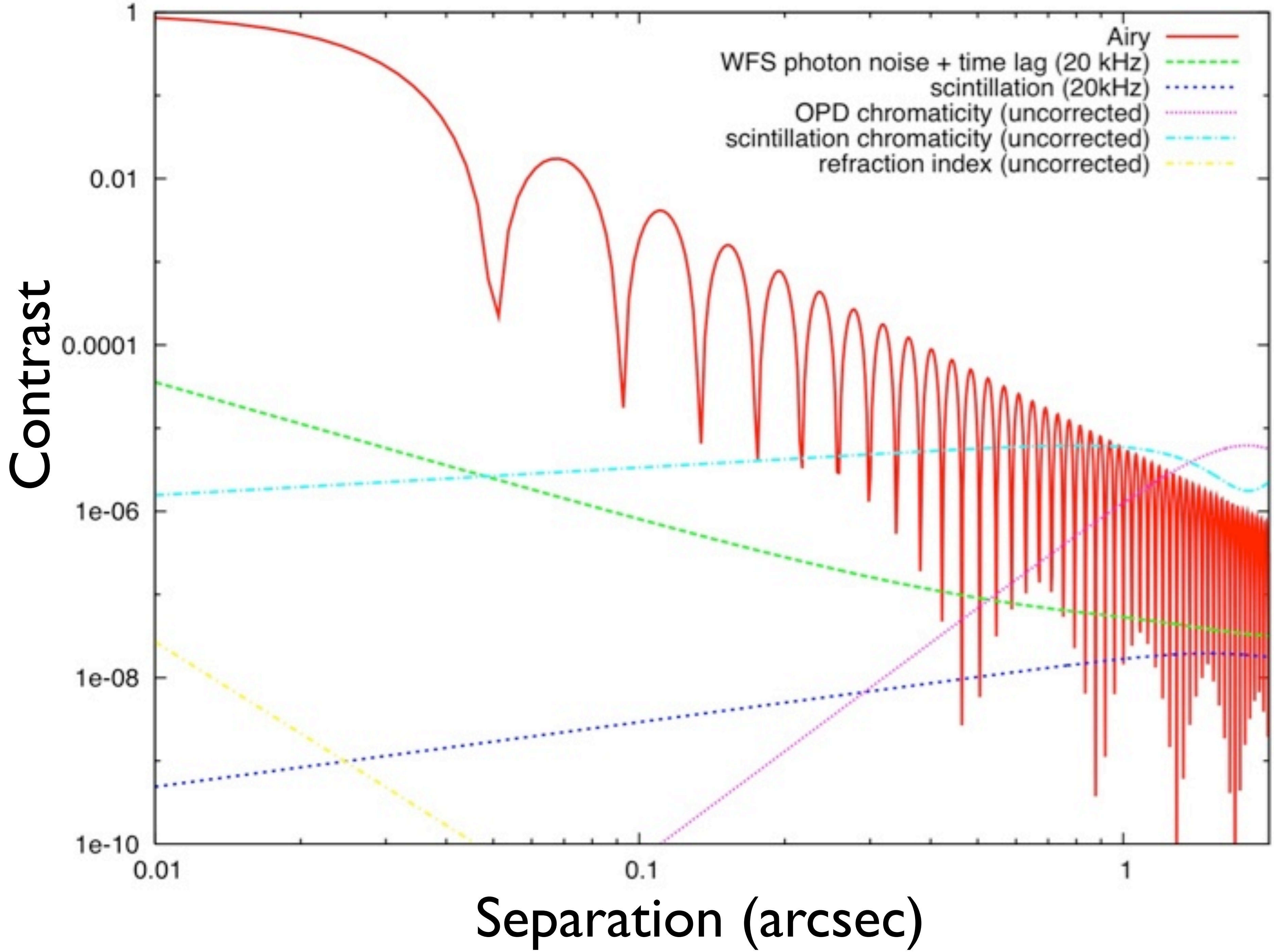

Source x position (l/D)
Source y position (l/D)
Source focus (waves)
DM tip (l/D)
DM tilt (l/D)
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
measurement
0
1000
2000
3000
4000
5000
time (s)
RMS values:
source x 0.00079 l/D
source y 0.0015 l/D
source focus 0.0018 waves
DM tip 0.00053 l/D
DM tilt 0.0011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

Can we image Earths with ground-based telescopes ?

Reflected light:

- Earth/Sun contrast ~ 1e-9
- SuperEarth ~ 4e-9
- Jupiter @ 1 AU: 2.5e-8

8-m telescope

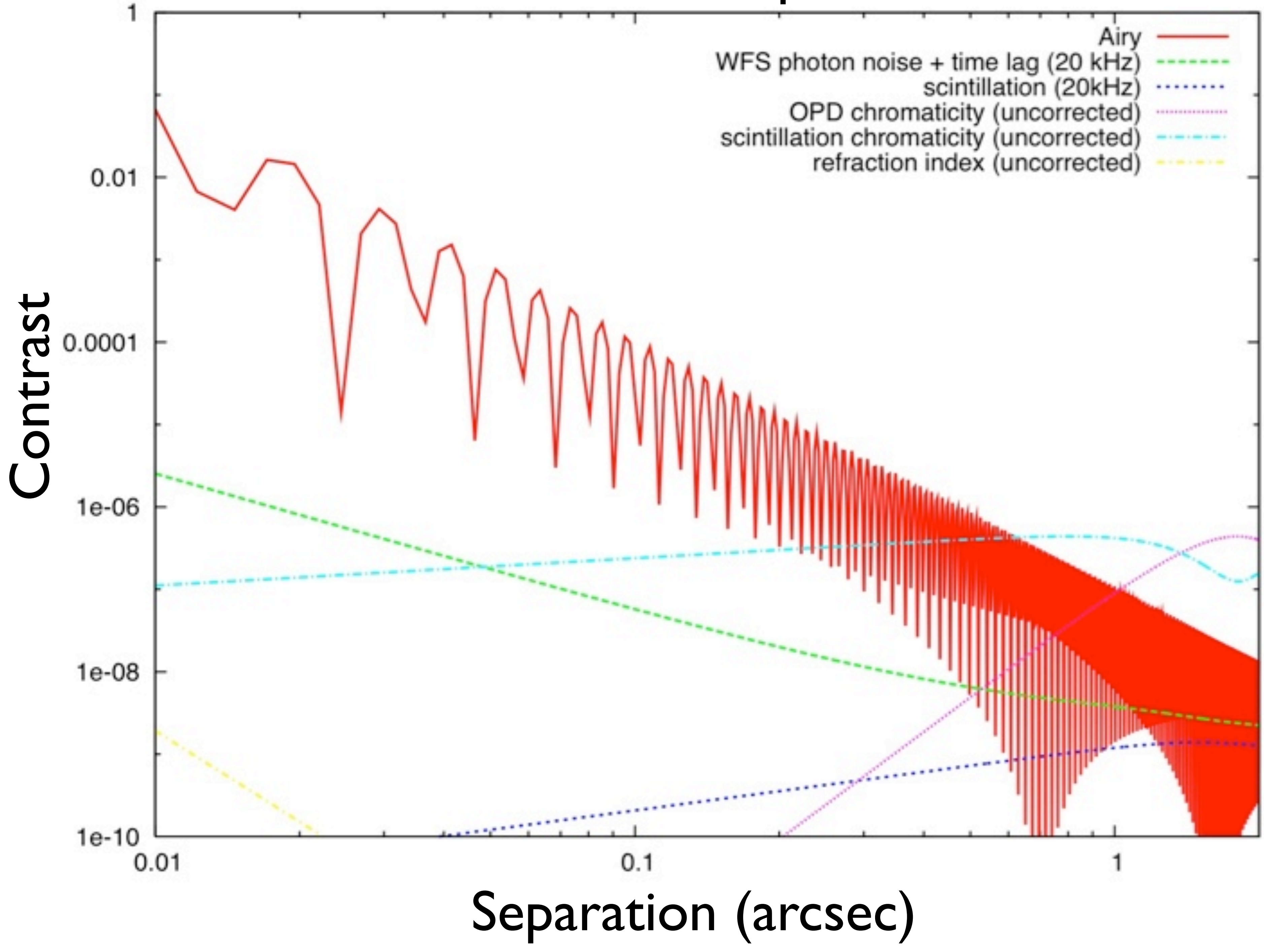


8m telescope, very good ExAO + slow near-IR correction

mV = 5, mH = 5
Contrast in H ~ 1e-5 ~ 1e4 ph/s/speckle (H band background ~1/2 of this)
with ~10 Hz residual speckle timescale
Photon noise from Halo = 1e-7 x 1/sqrt(t(s))
Speckle noise from Halo = 3e-6 x 1/sqrt(t(s))

in 1hr, 3-sigma detection limit =
1.5e-7 (no differential detection)
1e-8 (differential detection, 1/4 photons)

30-m telescope



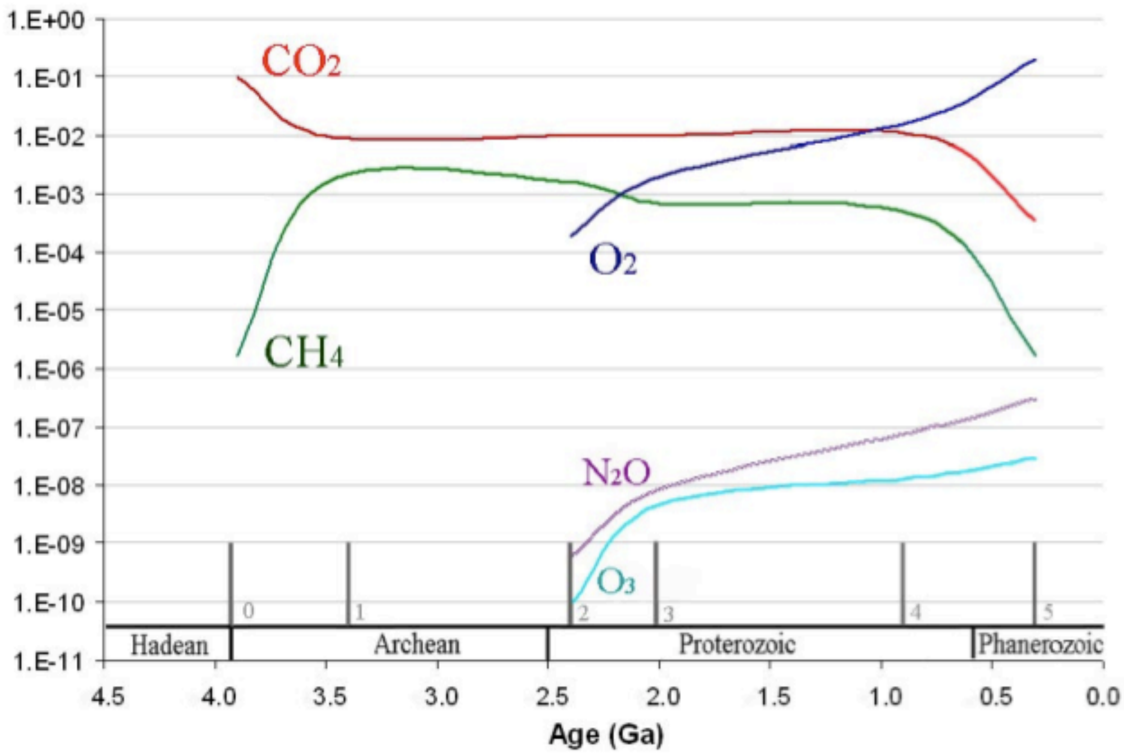
30m telescope, very good ExAO + slow near-IR correction

14x more photons in planet and star, contrast 14x better
still ~1e4 ph/s/speckle (7e-7 contrast)
Photon noise from Halo = 7e-9 x 1/sqrt(t(s))
Speckle noise from Halo = 2e-7 x 1/sqrt(t(s))

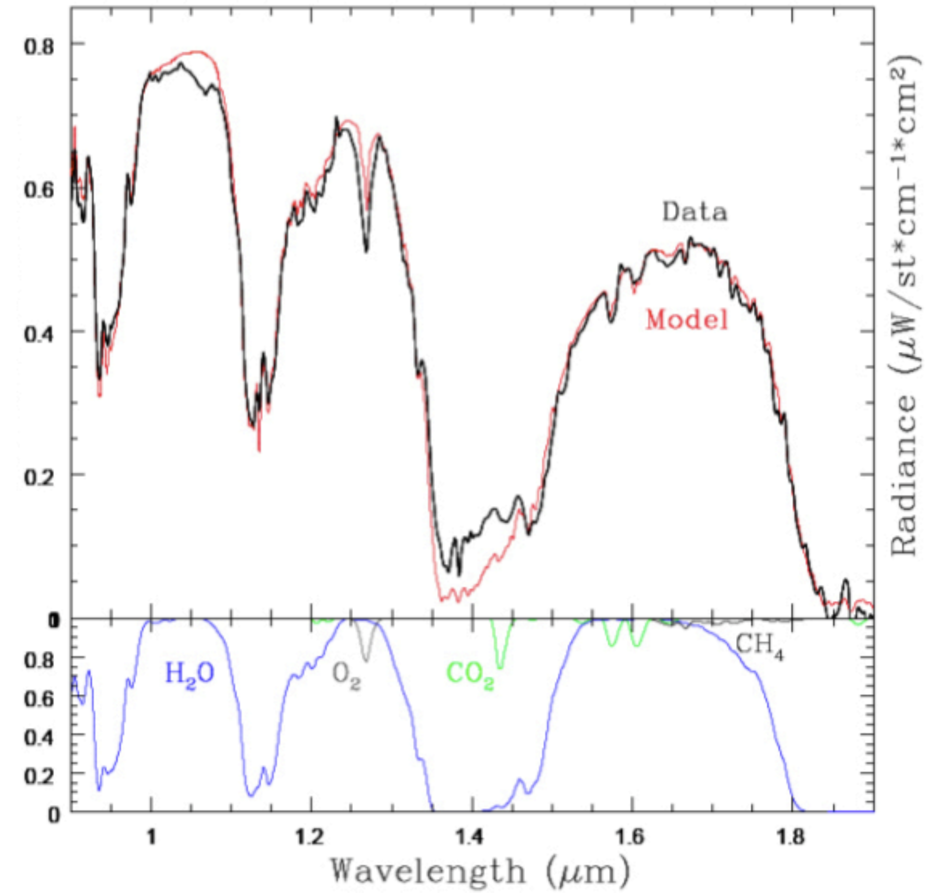
in 1hr, 3-sigma detection limit =
1.1e-8 (no differential detection)
7e-10 (differential detection, assuming 1/4 photons)

Near-IR Earth spectra

- Water is easiest to detect
- CO_2, CH_4, O_2



Kasting 2004



Turnbull et al 2006