# High performance wavefront sensing with non-linear curvature

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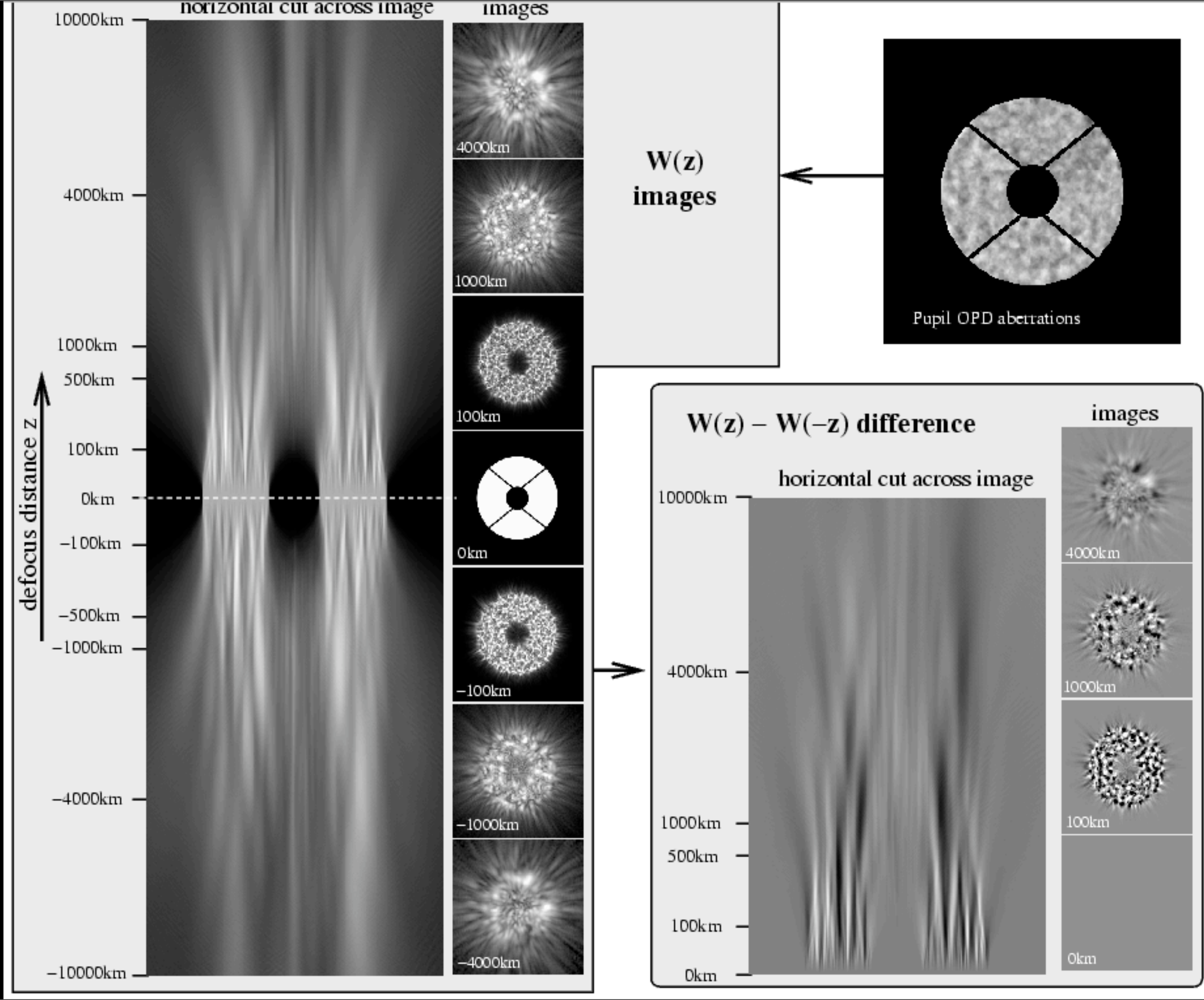
horizontal cut across image
images
10000km
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W(z)
images
Pupil OPD aberrations
W(z) – W(–z) difference
horizontal cut across image
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10000km
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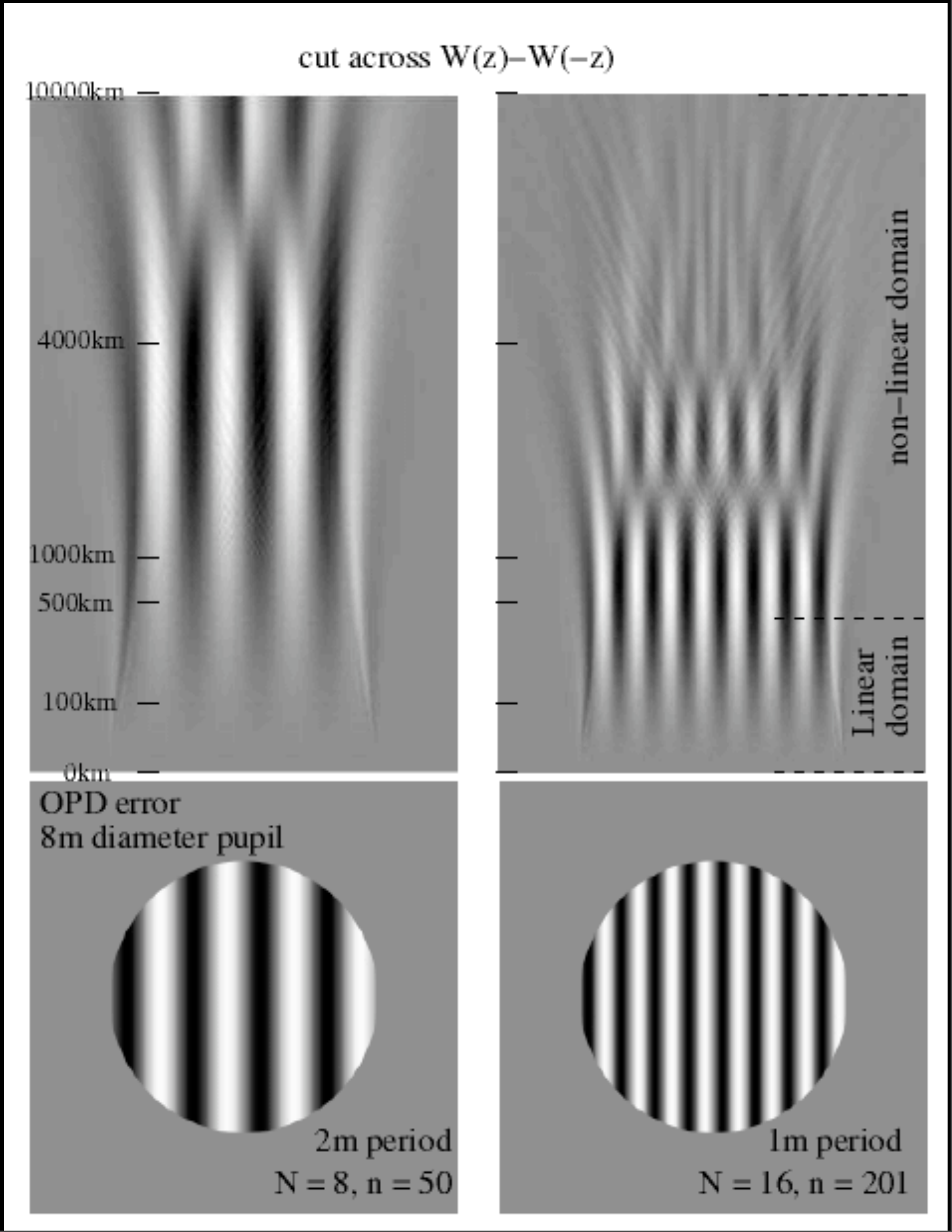
# Traditional CWFS assumes linear relationship between WFS signals and WF

Problem #1:

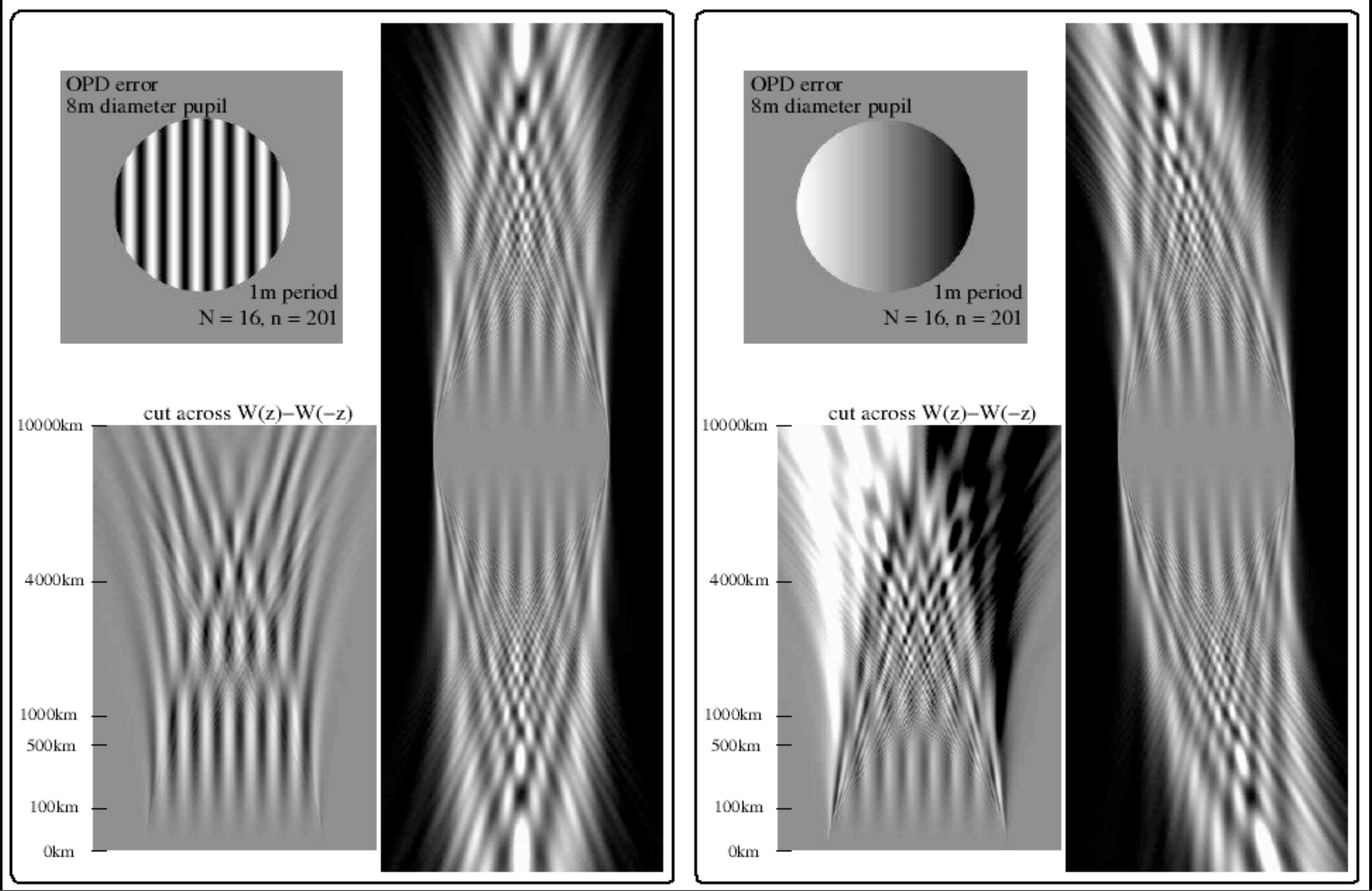
The "Linear" domain of curvature wavefront sensing (= defocus range within which wavefront curvature is linearly transformed into intensity modulation) becomes smaller as the # of actuators increases.

-> defocus distance must be kept small

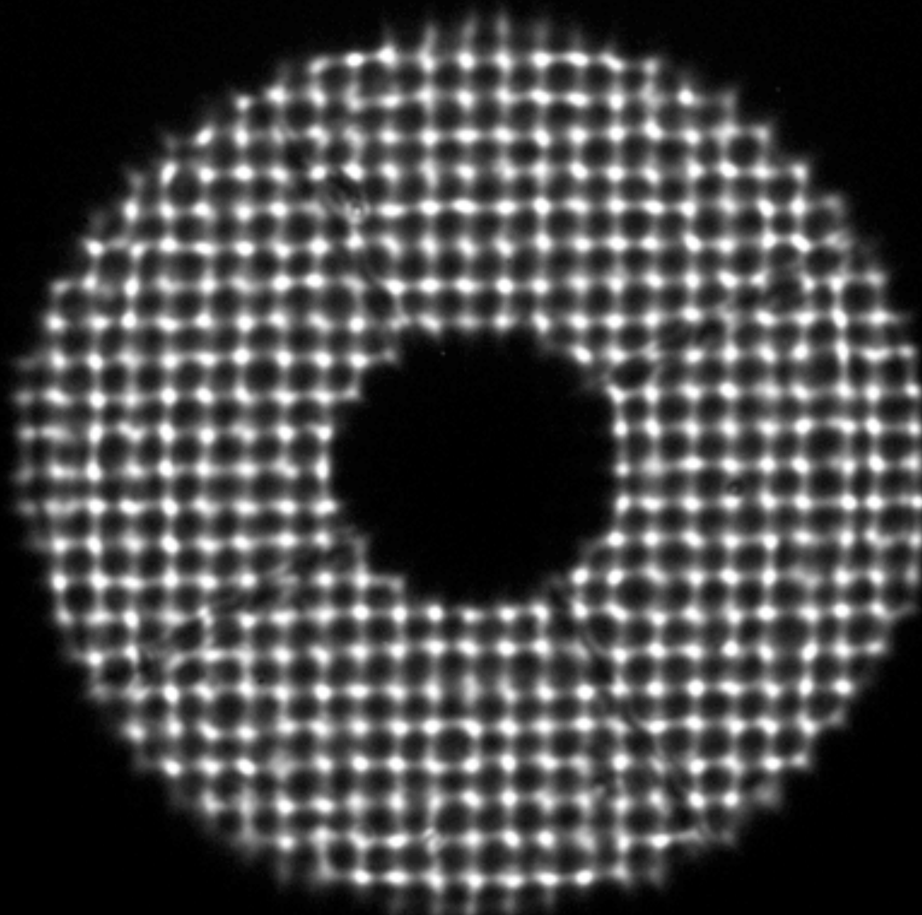
-> this forces low spatial frequencies to be poorly sensed



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



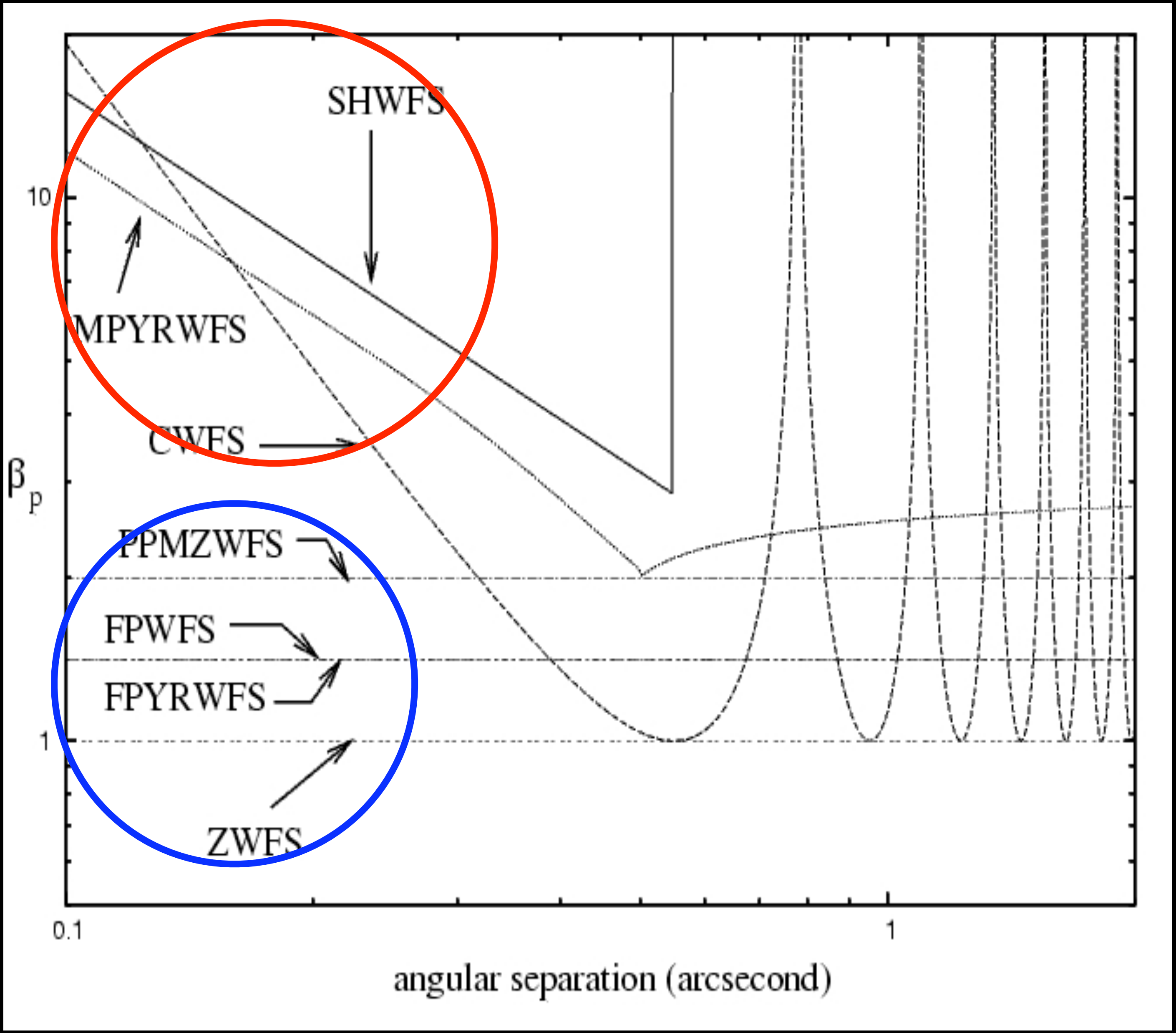
# SH WFS is also suffering from noise propagation



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

Low order modes suffer from very poor SNR

# 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

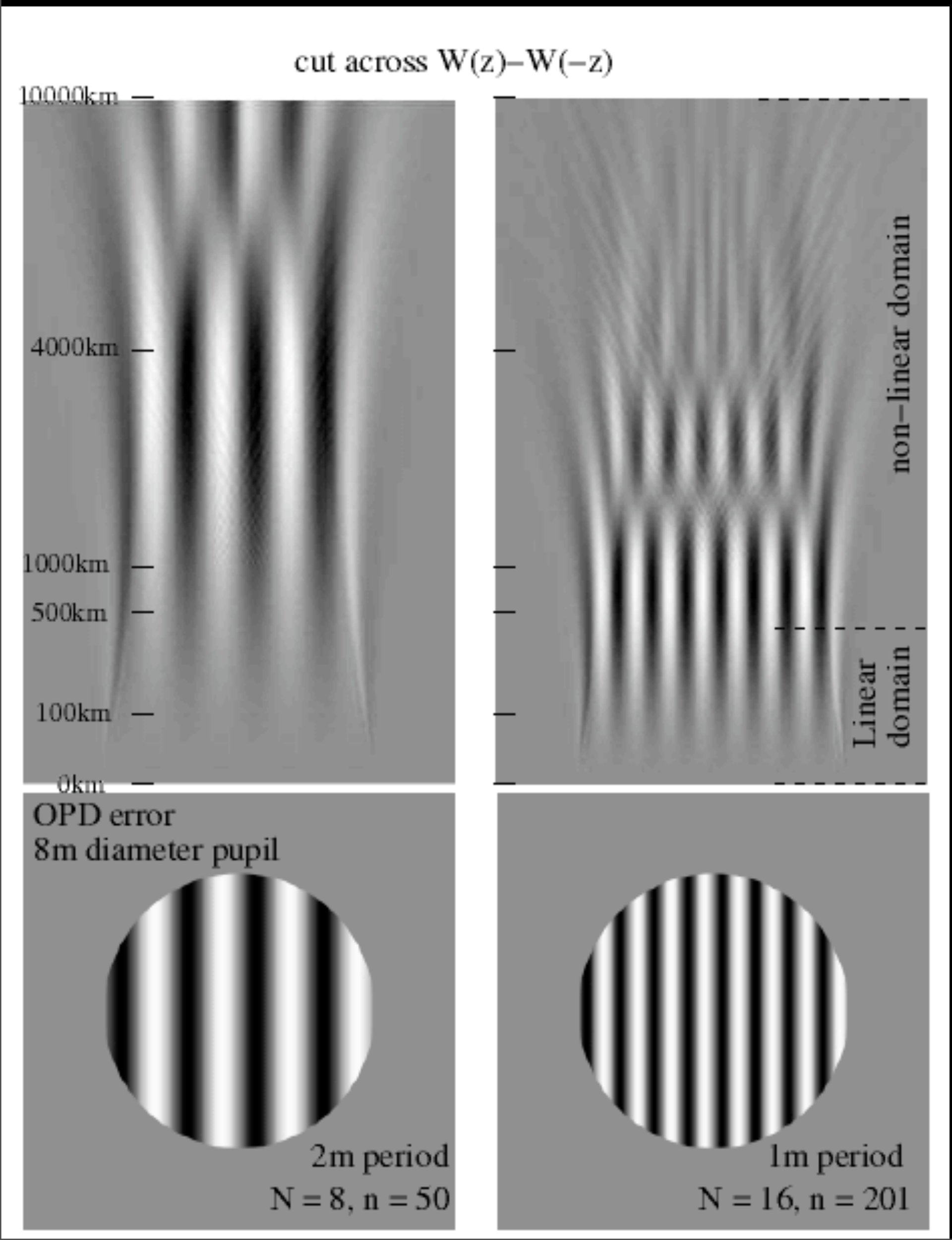
Things get worse as # of actuators go up.
-> **This makes a big difference for ELTs**

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)

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

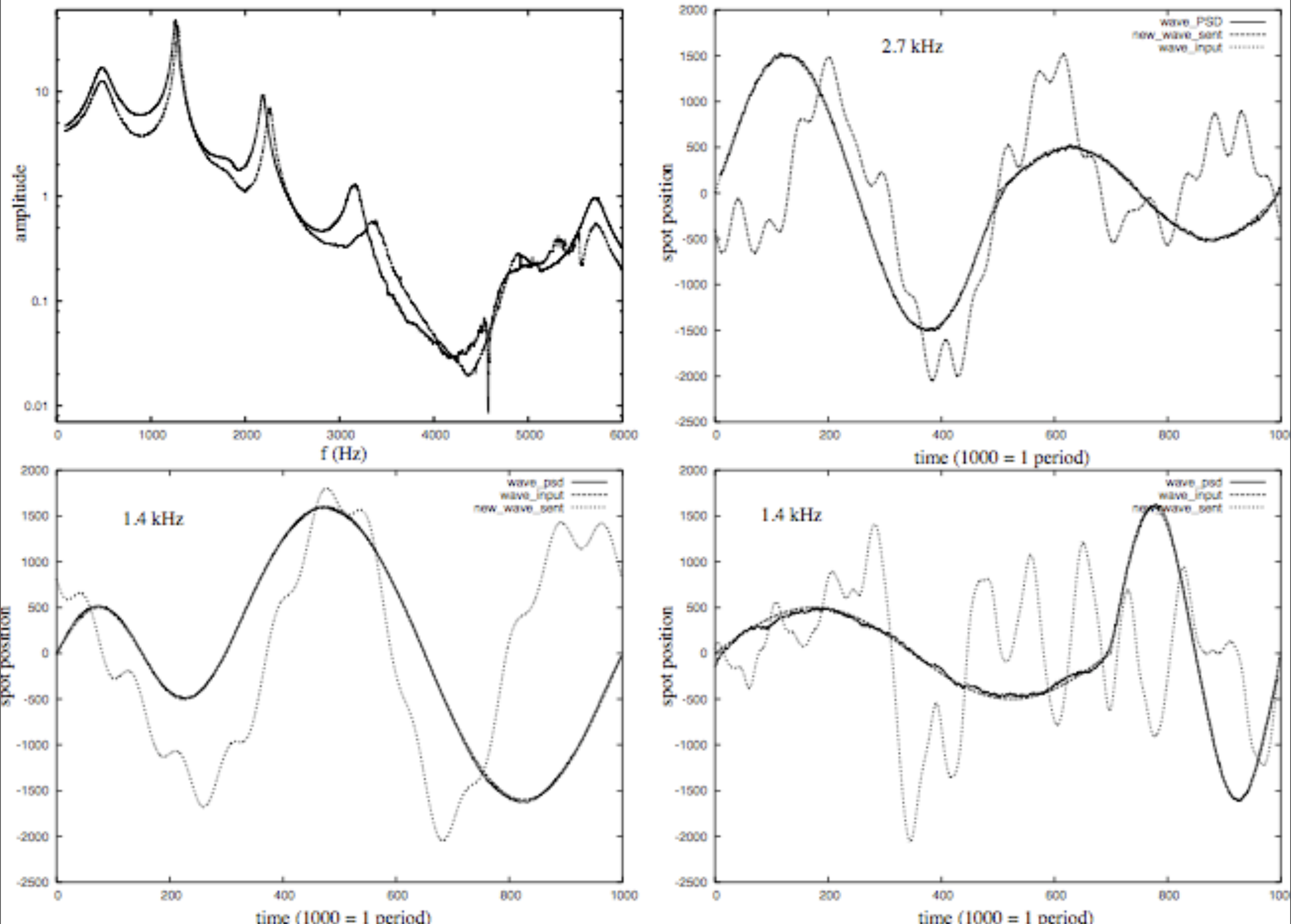
Curvature: Noise propagation comes from processing of WFS frames, which imposes linearity
-> possible to mitigate / solve ?

# “Dual stroke” curvature



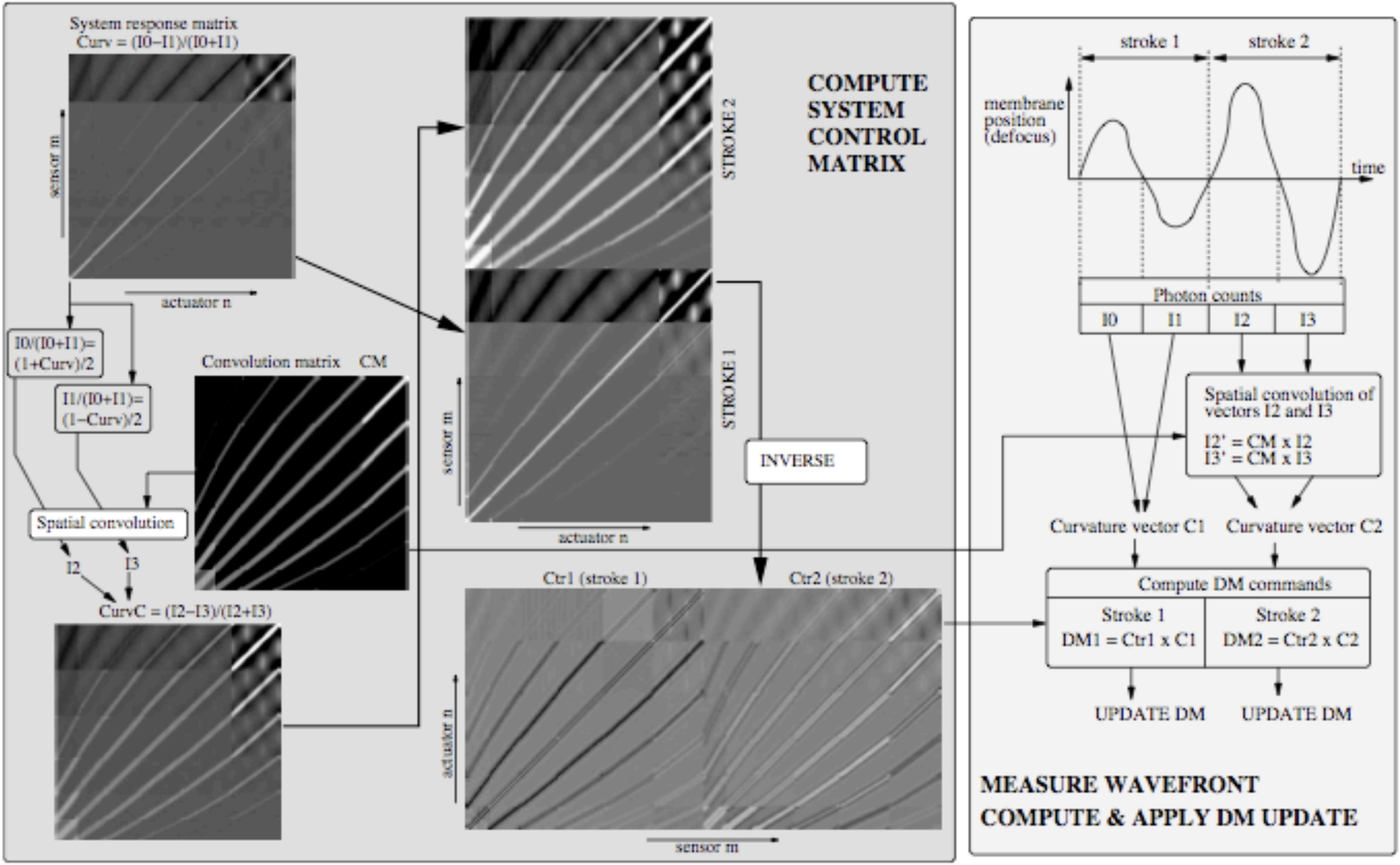

Get low order aberration from
2 “large stroke” frames
+
Get high spatial frequencies from
2 “small stroke” frames

On 188 elements system, gain in
SR is 1.5 mag
Biggest gain is for tip-tilt and low order
aberrations:
Especially good for coronagraphy

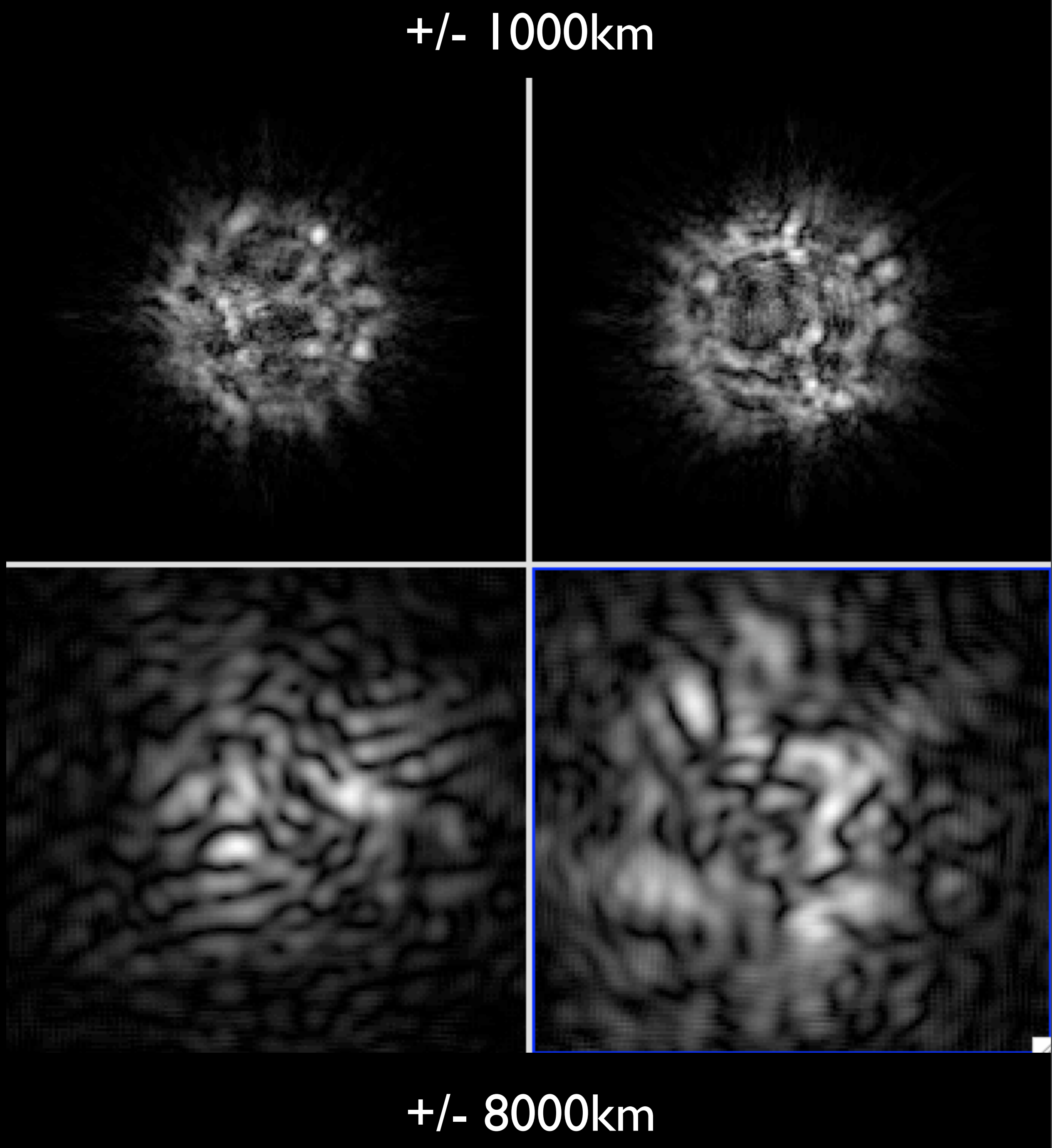


amplitude
f (Hz)
2.7 kHz
wave_PSD
new_wave_sent
wave_input
spot position
time (1000 = 1 period)
1.4 kHz
wave_psd
wave_input
new_wave_sent
spot position
time (1000 = 1 period)
1.4 kHz
wave_psd
wave_input
new_wave_sent
spot position
time (1000 = 1 period)

# Linear control for dual stroke curvature

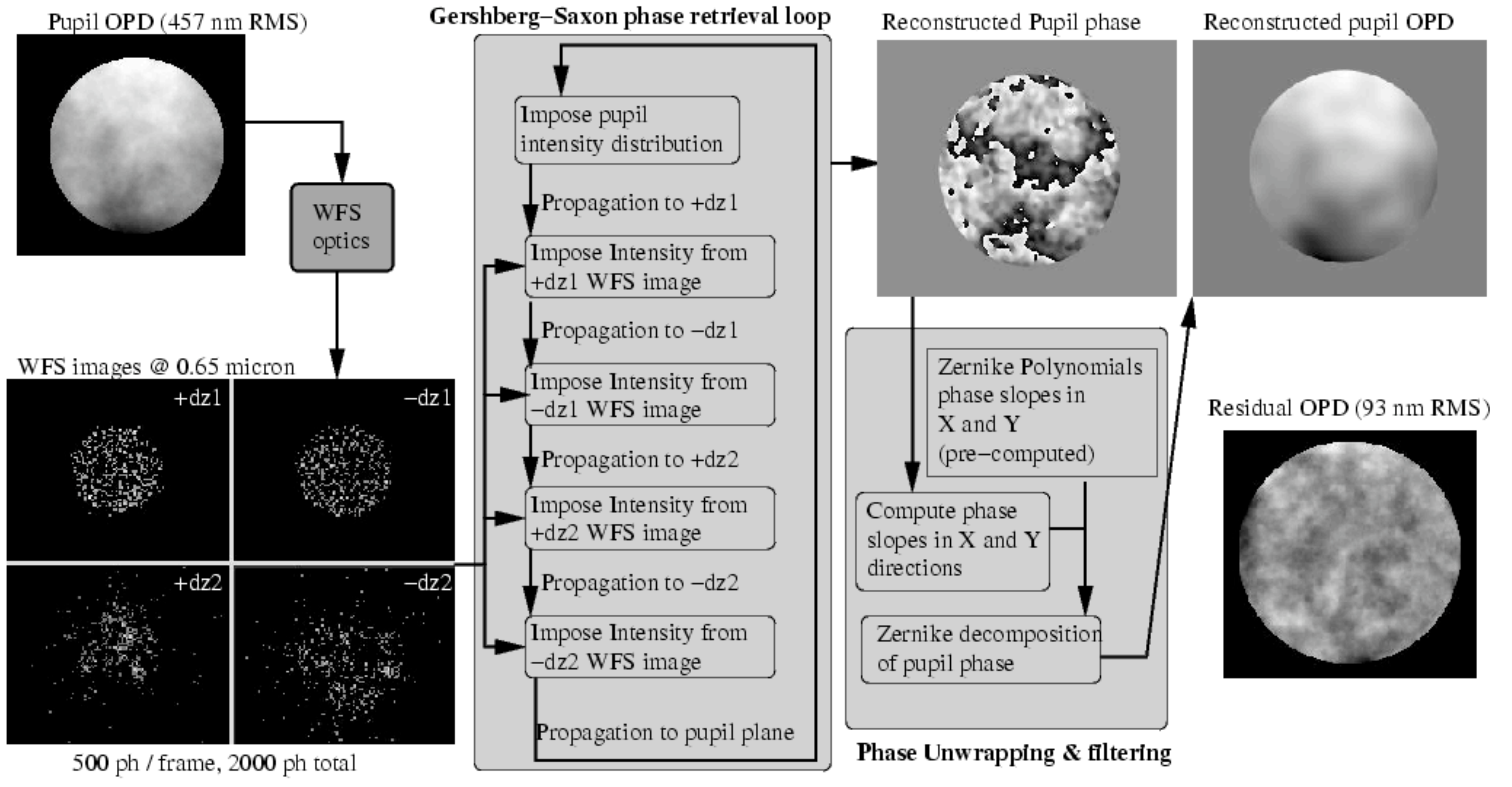


Defocused pupil images are full of lambda/D speckles

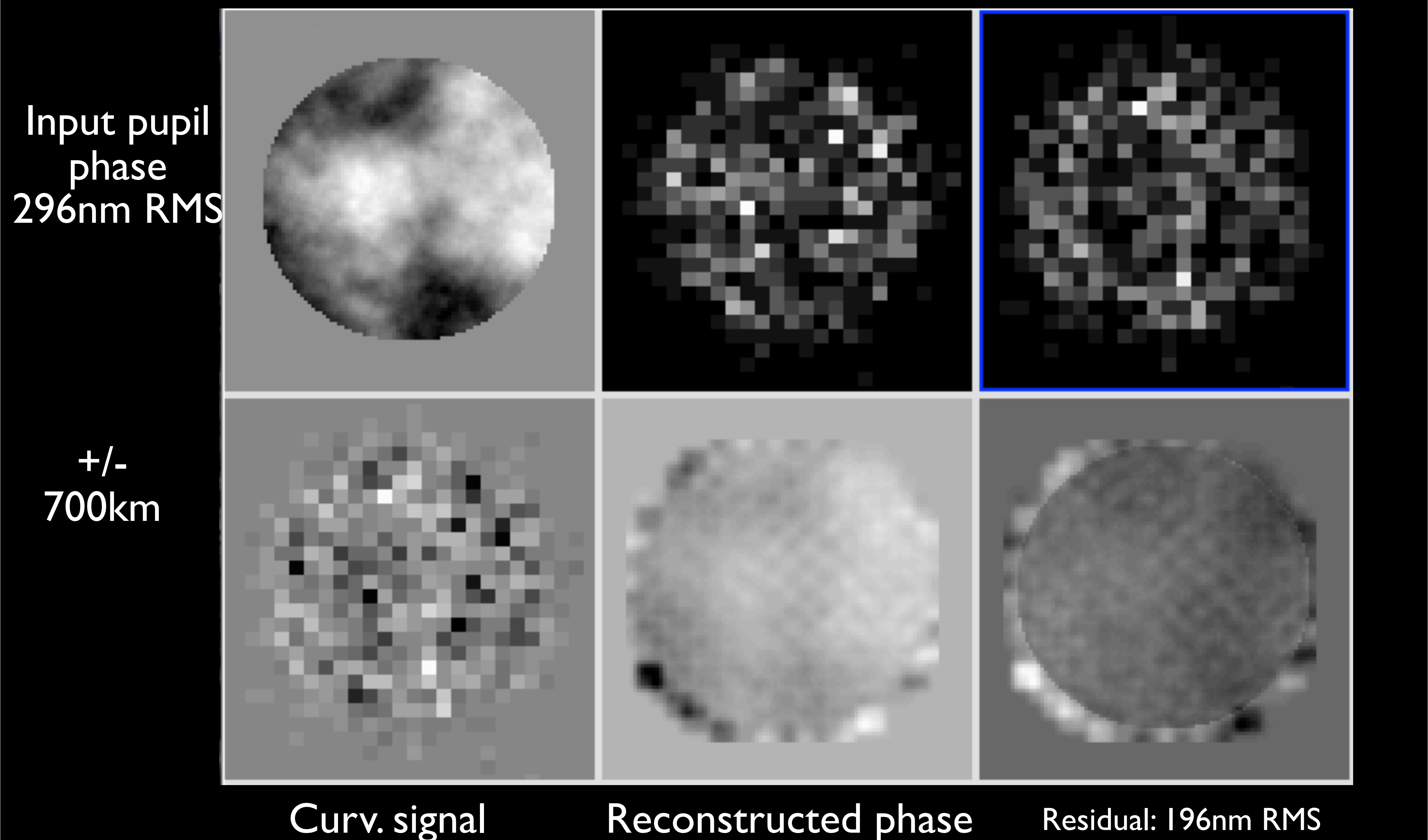


Standard phase diversity algorithm, working around pupil plane. There are probably better/faster algorithms (see for example:  van Dam & Lane 2002, JOSA vol. 19)

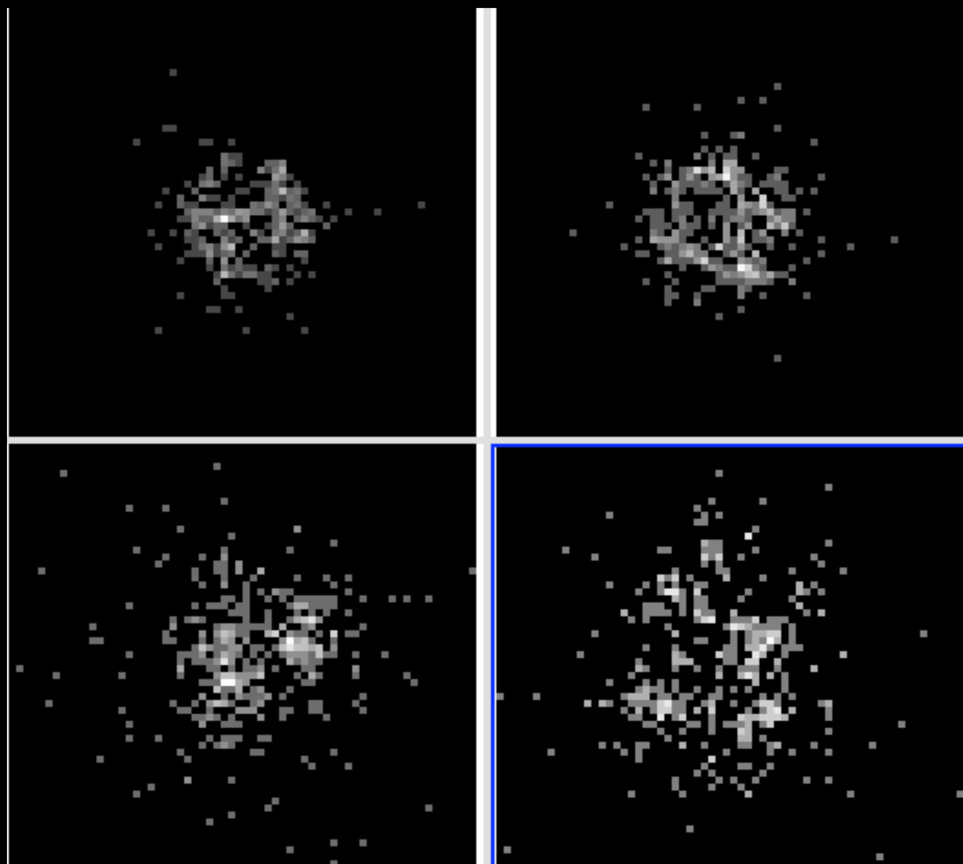
**kHz operation appears to be possible with current chips for few 100s actuators system (100 32x32pix FFT = 0.2ms on single CPU)**



# 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.

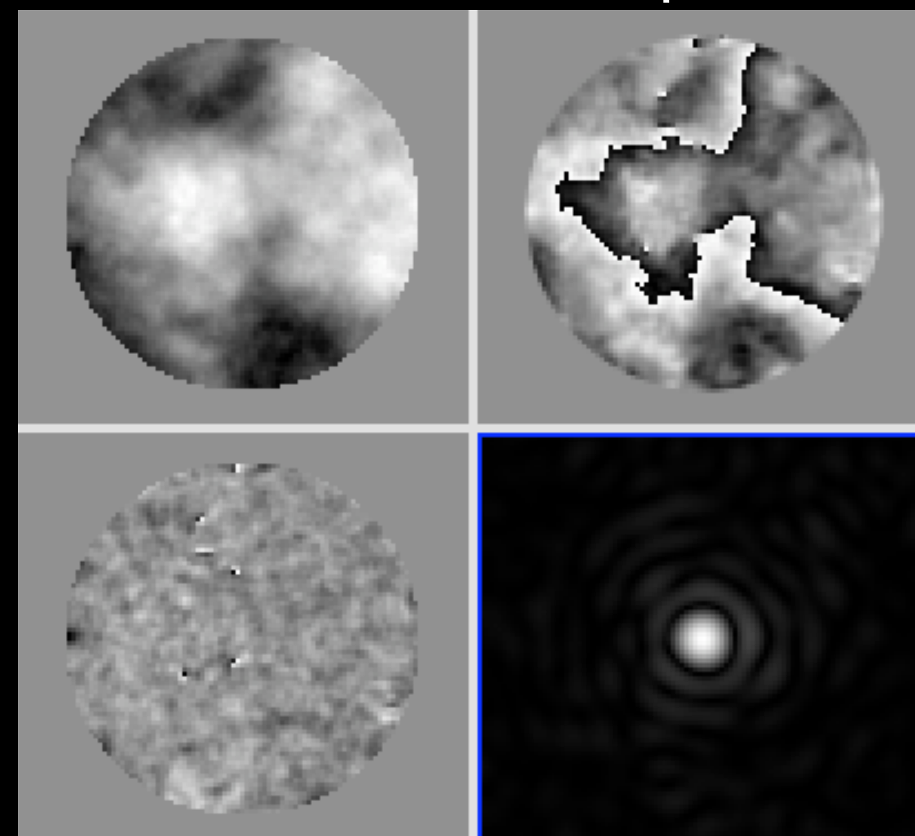


Defocused pupil images

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

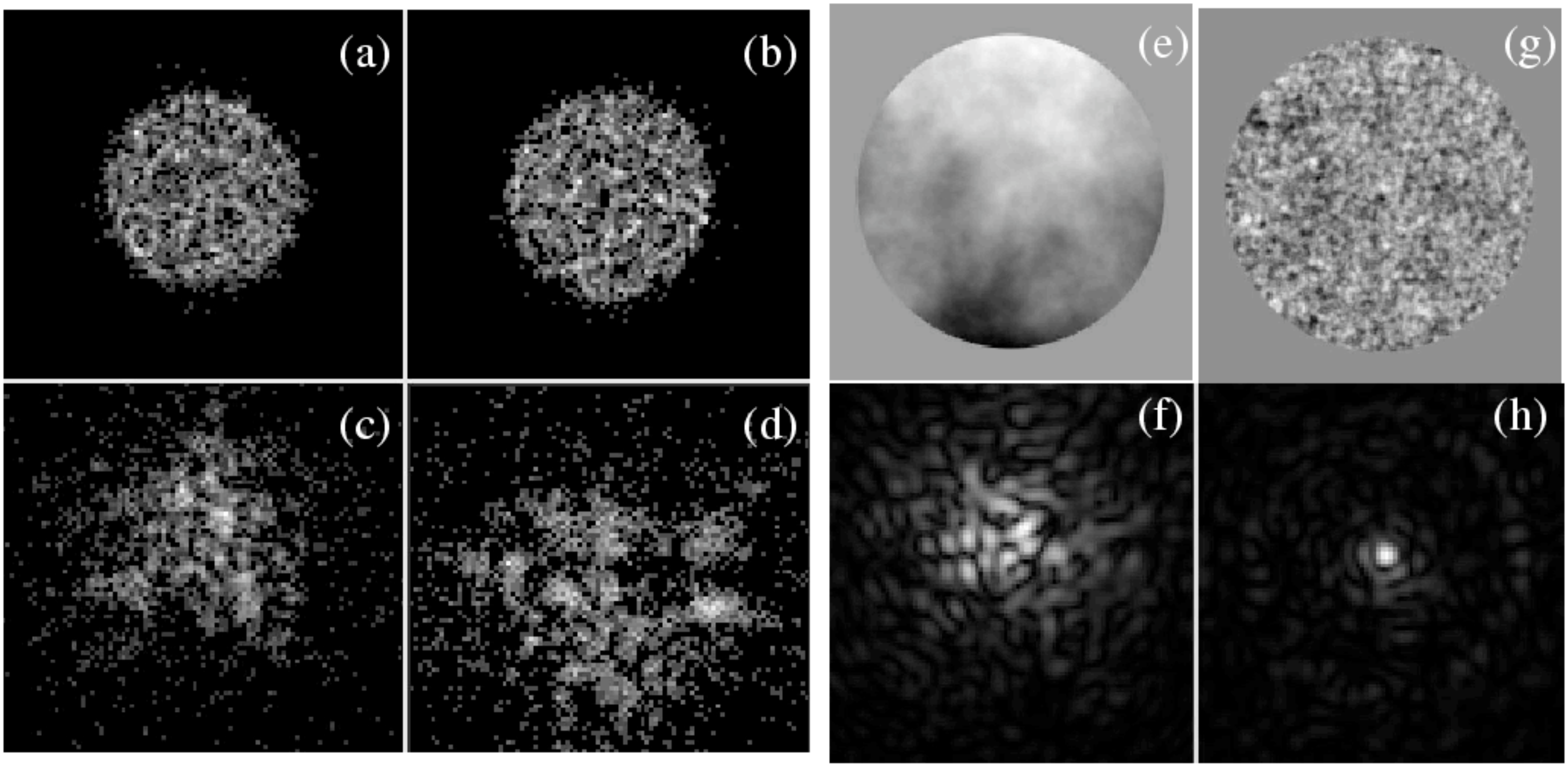



Fig. 9.— Wavefront reconstruction using the algorithm shown in fig. 8. Four noisy defocused pupil images (images (a), (b), (c) and (d)) are acquired to transform the pupil phase aberrations (e) into intensity signals. The input pupil phase is 609 nm RMS, yielding the PSF (f) before correction. After 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 $\mu$m. The total number of photons available for wavefront sensing in 2e4.

**6073 ill.**
**elements**

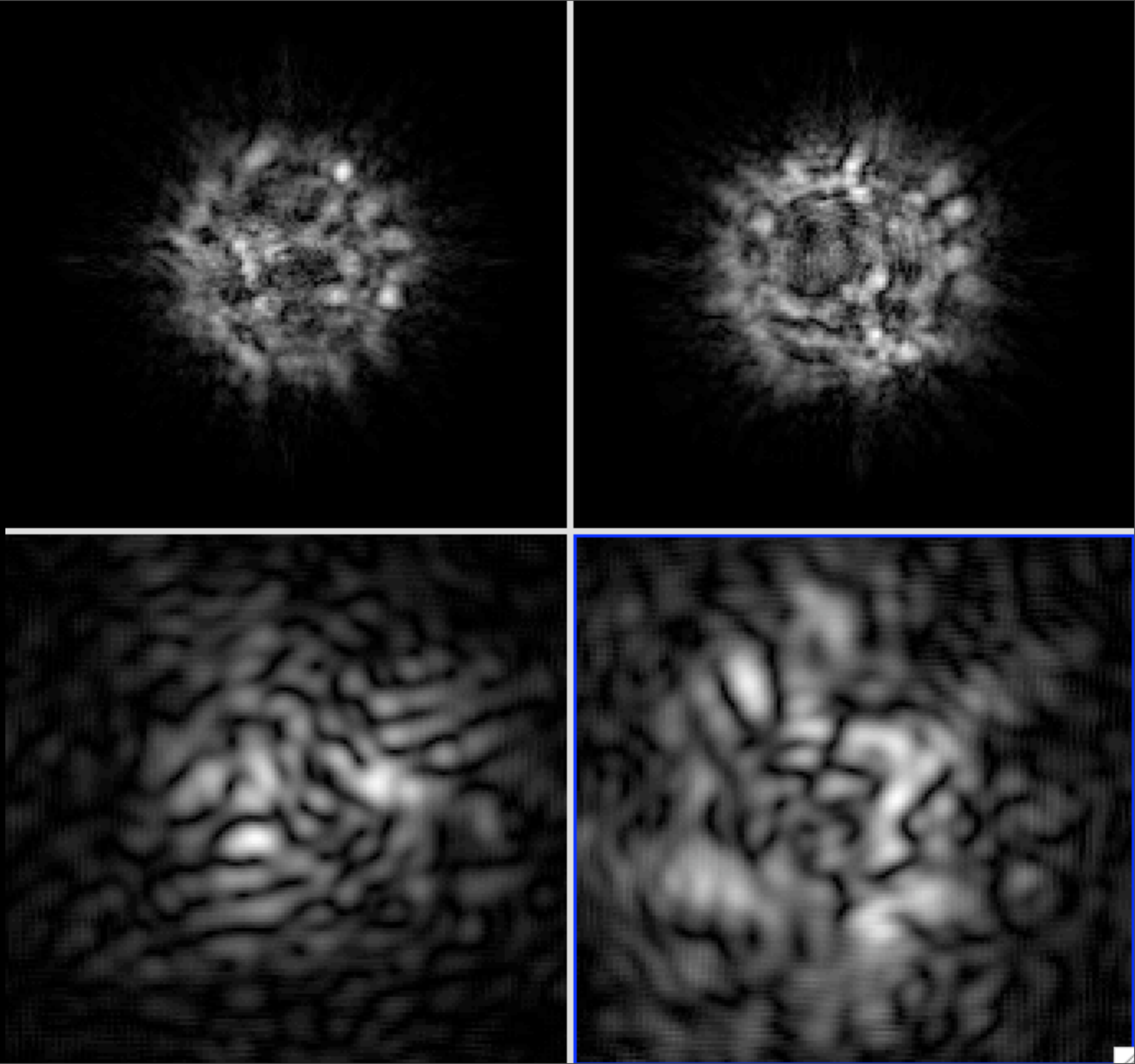
+/- 1000km

dl/l = 0.0

Nph = 2e8

After
Correction:

SR = 99.3
RMS = 8nm
+/- 8000km

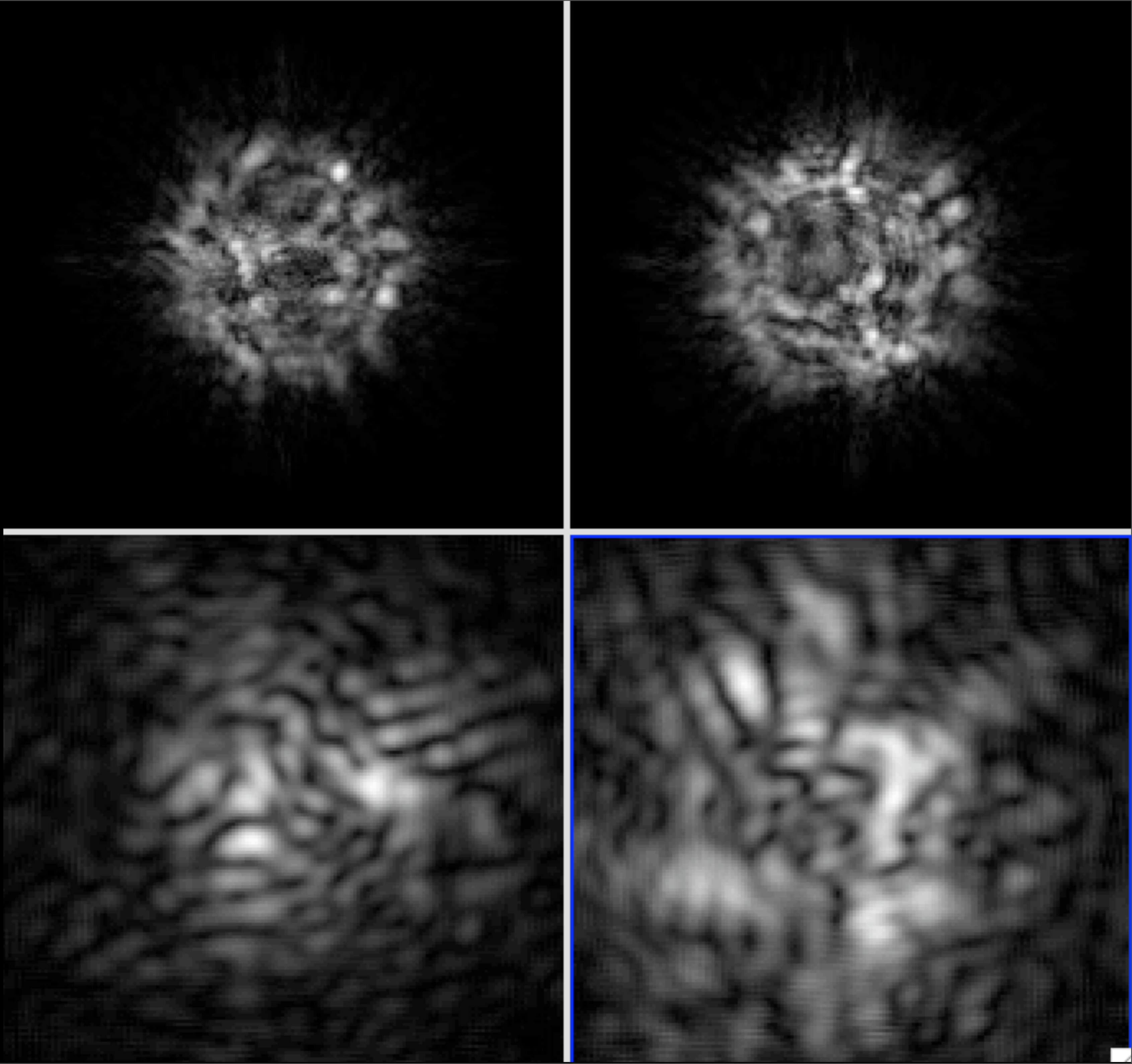


dI/I = 0.5

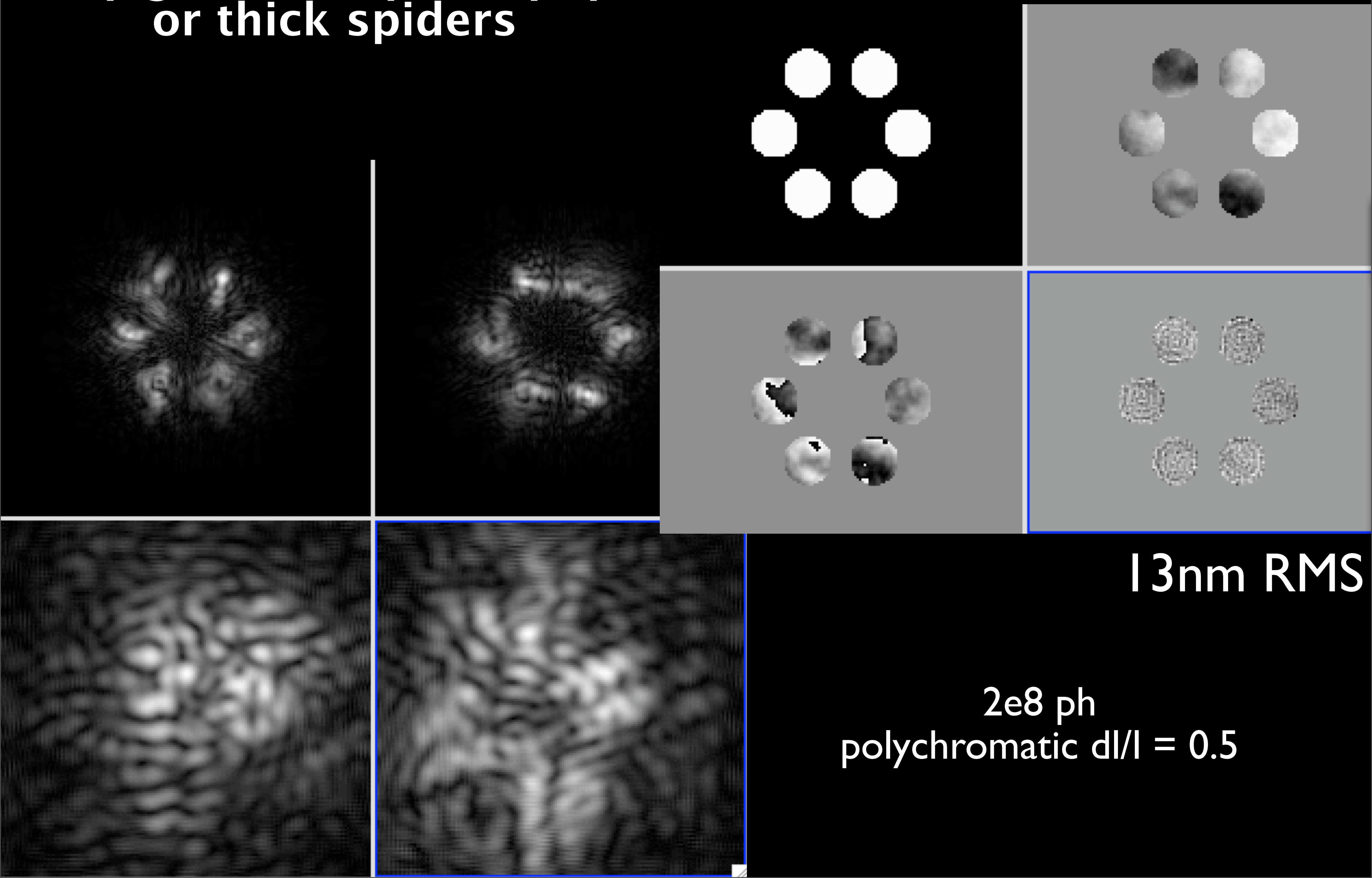
Nph = 2e8

After Correction :

SR = 98.6
RMS = 12nm



## Very good for Sparse pupil or thick spiders



13nm RMS

2e8 ph
polychromatic dl/l = 0.5

# Closed loop simulations

WFS: non-linear phase retrieval on curvature wavefront sensor

Same behaviour would be obtained with fixed pyramid

Example of how choosing longer sensing wavelength helps by increasing wavefront coherence (even though phase signal gets smaller !!!)

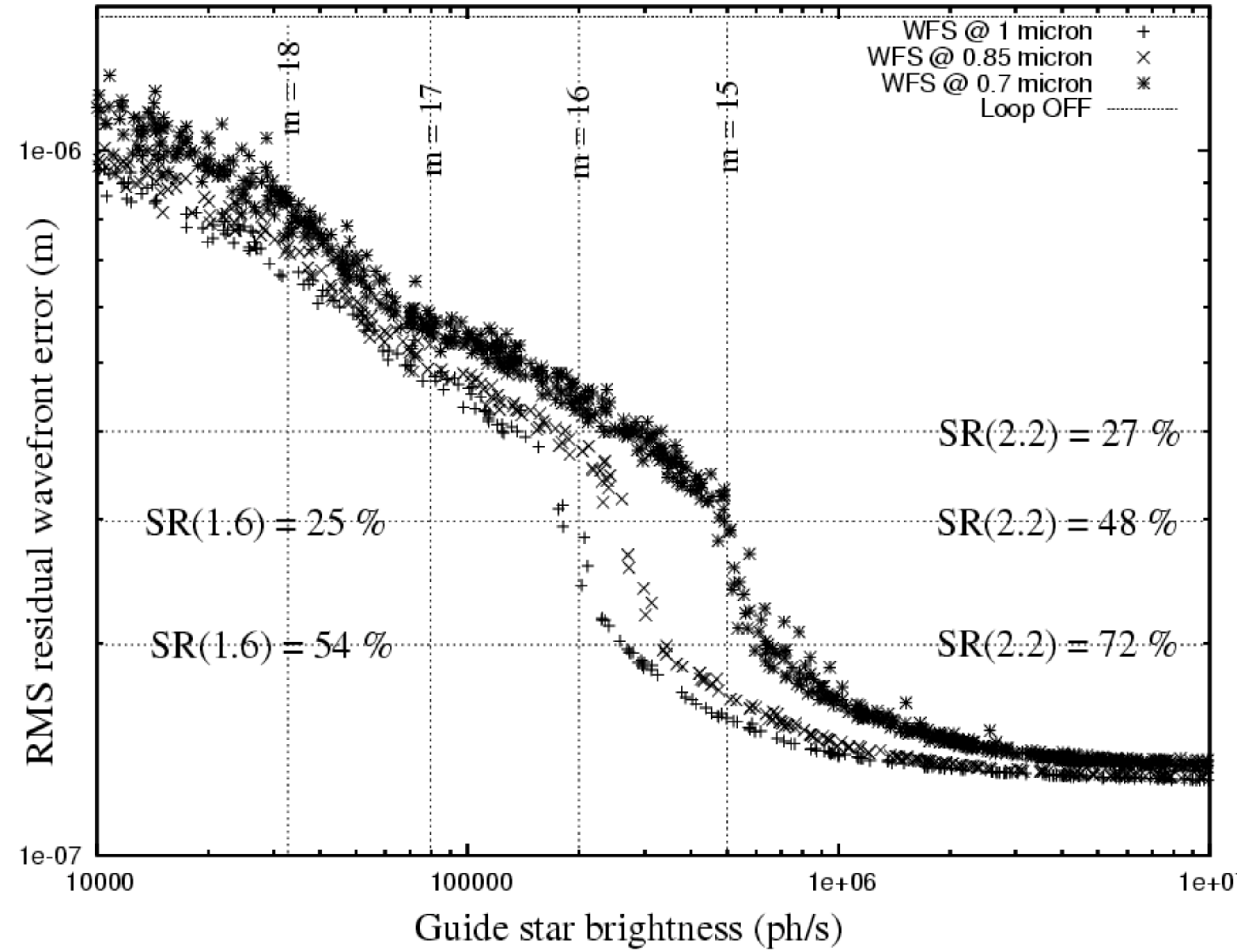



Fig. 11.— Simulated performance of a non-linear Dual stroke Curvature as a function of sensing wavelength (0.7, 0.85 and 1.0 $\mu$m) and guide star brightness. The stellar magnitudes given in this figure assume a 20% efficiency in a 0.5$\mu$m wide band. See text for details.

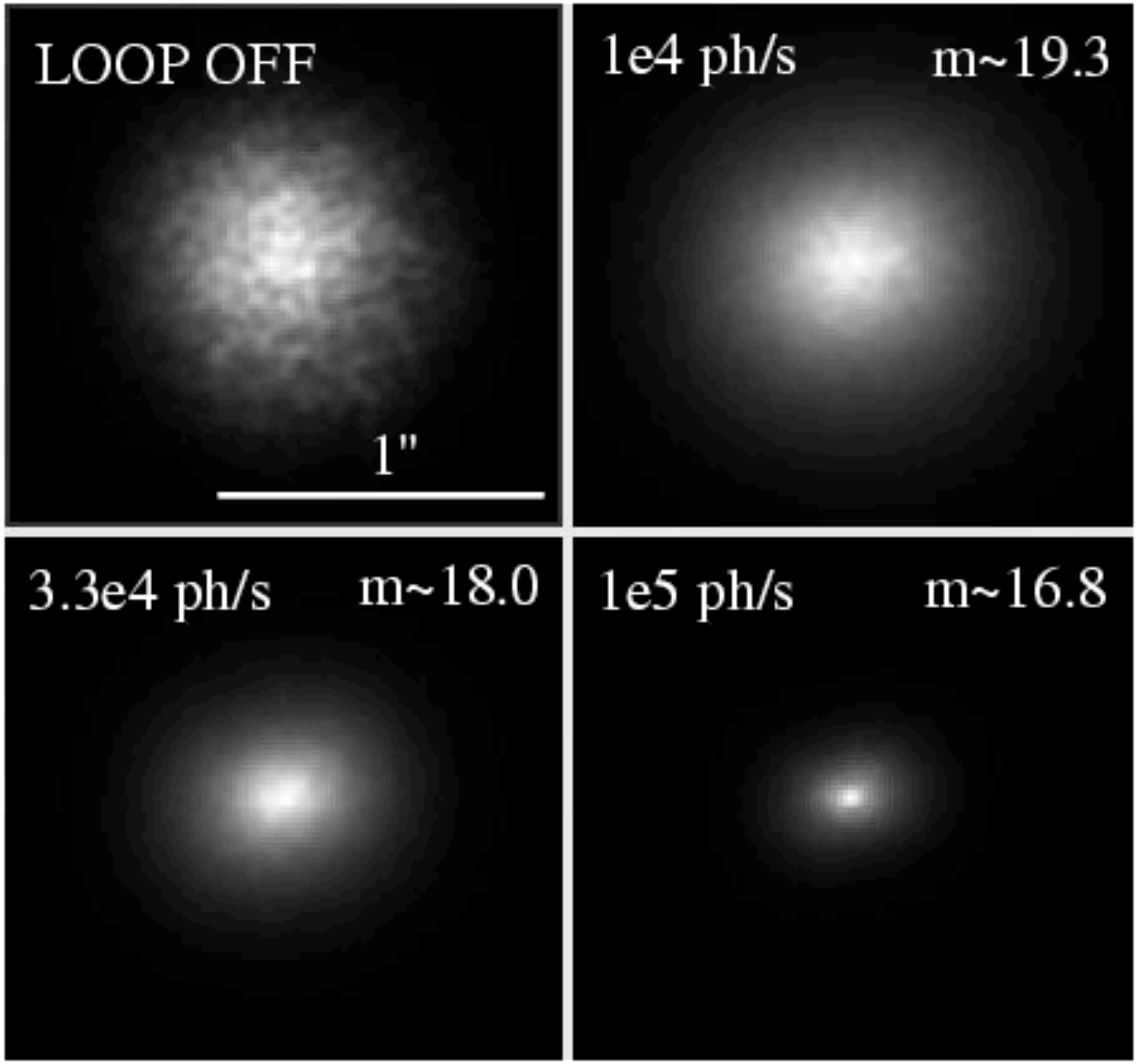



Fig. 12.— Simulated long exposure 1.6 $\mu$m PSFs obtained with a non-linear Dual stroke Curvature-based AO system. The sensing wavelength was 0.85 $\mu$m for this simulation.

# SH / nlCWFS comparison

PERFORMANCE COMPARISON BETWEEN SH AND NON-LINEAR CWFS

| | $\beta(SH)$ | Flux gain | Contrast gain |
|---|---|---|---|
| 8m telescope, tip/tilt sensing | 40.0 | 1600 (8.0 magn) | - |
| 8m telescope, 2 l/d (41 mas) | 19.0 | 180 (5.6 magn) | 31.8 (3.8 magn) |
| 8m telescope, 5 l/d (103 mas) | 7.6 | 29 (3.6 magn) | 9.4 (2.4 magn) |
| 30m telescope, tip/tilt sensing | 150.0 | 22500 (10.9 magn) | - |
| 30m telescope, 2 l/d (11 mas) | 71.1 | 2525 (8.5 magn) | 185.4 (5.7 magn) |
| 30m telescope, 5 l/d (28 mas) | 28.4 | 404 (6.5 magn) | 54.7 (4.3 magn) |
| 30m telescope, 10 l/d (55 mas) | 14.2 | 101 (5.0 magn) | 21.7 (3.3 magn) |

**Larger telescope / smaller separation ->bigger gain.**

Within linearity range of pyramid, performance is identical

nlCWF has extended stability range (same may be possible with non linear pyramid)

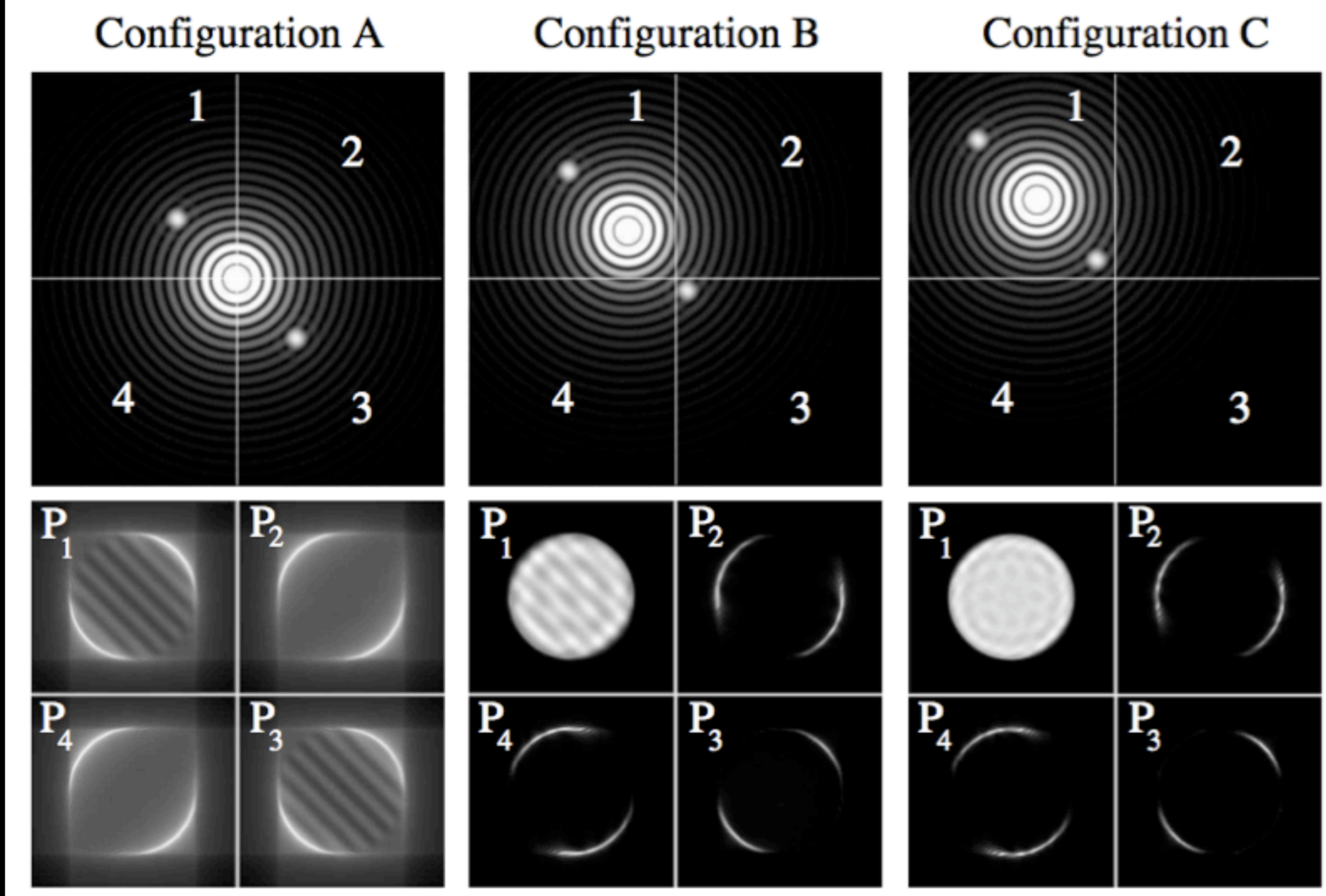



Fig. 5.— Focal plane images (top) and corresponding pupil images $P_i$ (bottom) for a sine-wave pupil phase error (corresponding to 2 symmetric speckles in the focal plane). See text for details.

*Guyon, 2005*

# Extreme-AO

- Huge gain for high contrast imaging, where key is low residual error on low order modes (this is where the planets are !)
- Visible detectors with << 1 e readout noise are here (photon-counting)
- Even if there is small readout noise (~ 2e), this is not a serious issue for Extreme AO as there is several e- per pixel

# Extreme-AO

**Problem:**

To fully take advantage of very high SNR for low order aberrations, need to have very fast loop (10 kHz to 100 kHz sampling)

note: even at low speed, high SNR offers large gain for PSF calibration

**Solution:**

computing: non-linear curvature WFS becomes linear if $<1$ rad in WFS

detector: no need for large number of pixels (20x20 pixels pupil still gives stable loop)

400 pixels at 40 MHz = 100 kHz

# Linear CWFS and high sensitivity ?

Yes if < 1 rad in WFS
But, may require to add known NCPE !

High contrast l/D speckles modulated/displaced by aberrations.

(1) pupil phase linear with pupil complex amplitude (<1rad)
(2) pupil complex amplitude linear with detector complex amplitude
(2) intensity linear with complex amplitude (intensity > 0 & small complex amplitude)

# Performance on intermediate brightness sources

3e6 ph/s on 8m telescope
(m~13 with 20% throughput and 0.5 micron wide band)

0.6" seeing at 0.5 micron
10 m/s wind speed, single layer

perfect detector
SH: large # of very small (<< l/d) pixels per cell to compute centroid
Curv: 90 pixels across pupil

No modal control
Control of "sine modes" up to 20 CPA for curv
Control of "sine modes" up to the SH sampling, least square minimization of centroids

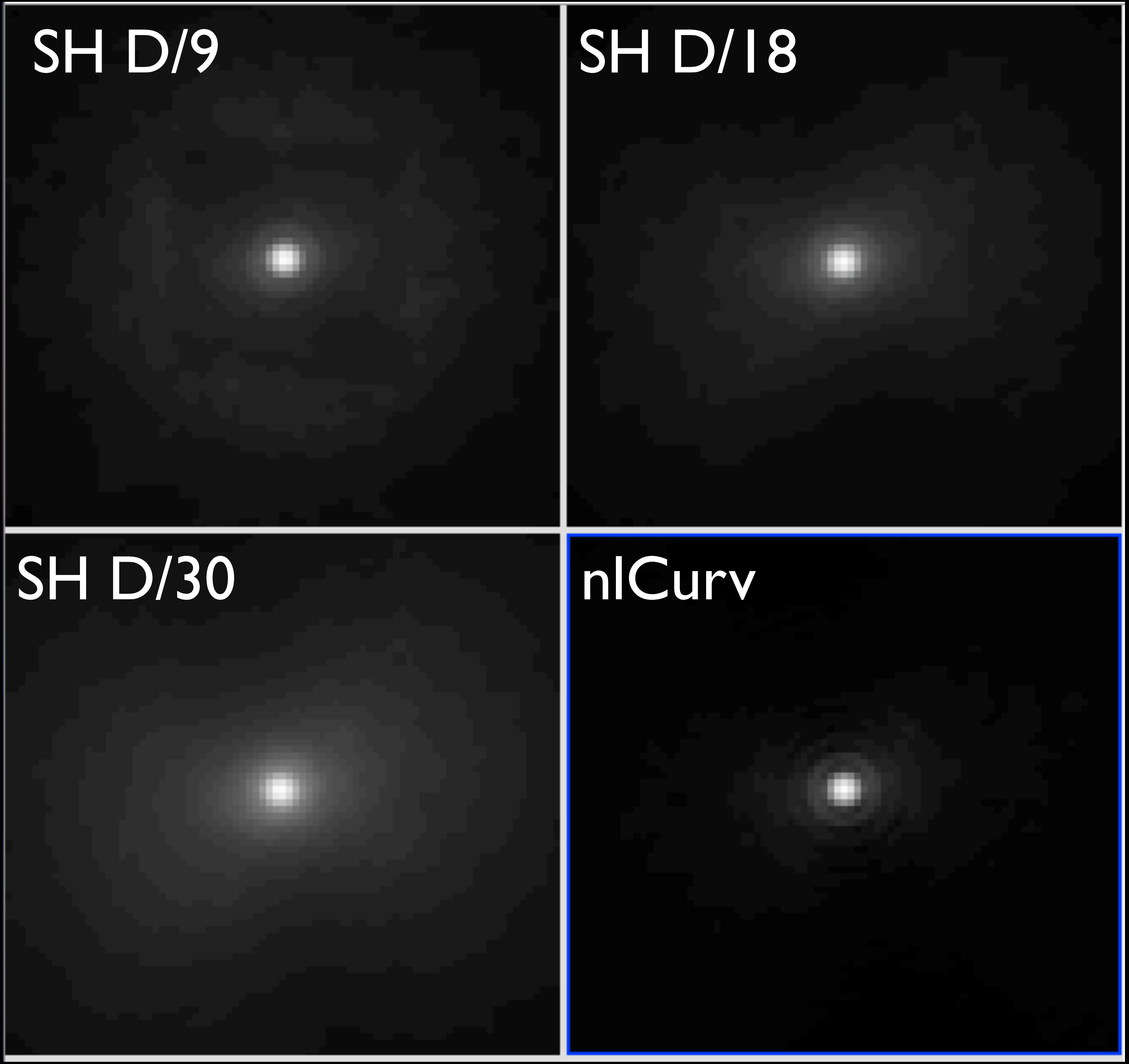
Perfect DM up to 20 CPA, no correction beyond 20 CPA
time delay (computation + DM) = 1/2 of sampling period

# DM fitting error = 59.6 nm

| WFS | Loop frequ | RMS | SR @ 0.85 mu | SR @ 1.6 mu |
|---|---|---|---|---|
| nlCurv | 210 Hz | 104 nm | 55% | 85% |
| | | | | |
| SH - D/9 | 164 Hz | 192 nm | 13% | 57% |
| SH - D/18 | 166 Hz | 182 nm | 16% | 60% |
| SH - D/30 | 141 Hz | 225 nm | 6% | 54% |

PSF @ 0.85 mu

20 sec simulations



# Non-linear Curvature does not require flat WF to deliver full sensitivity

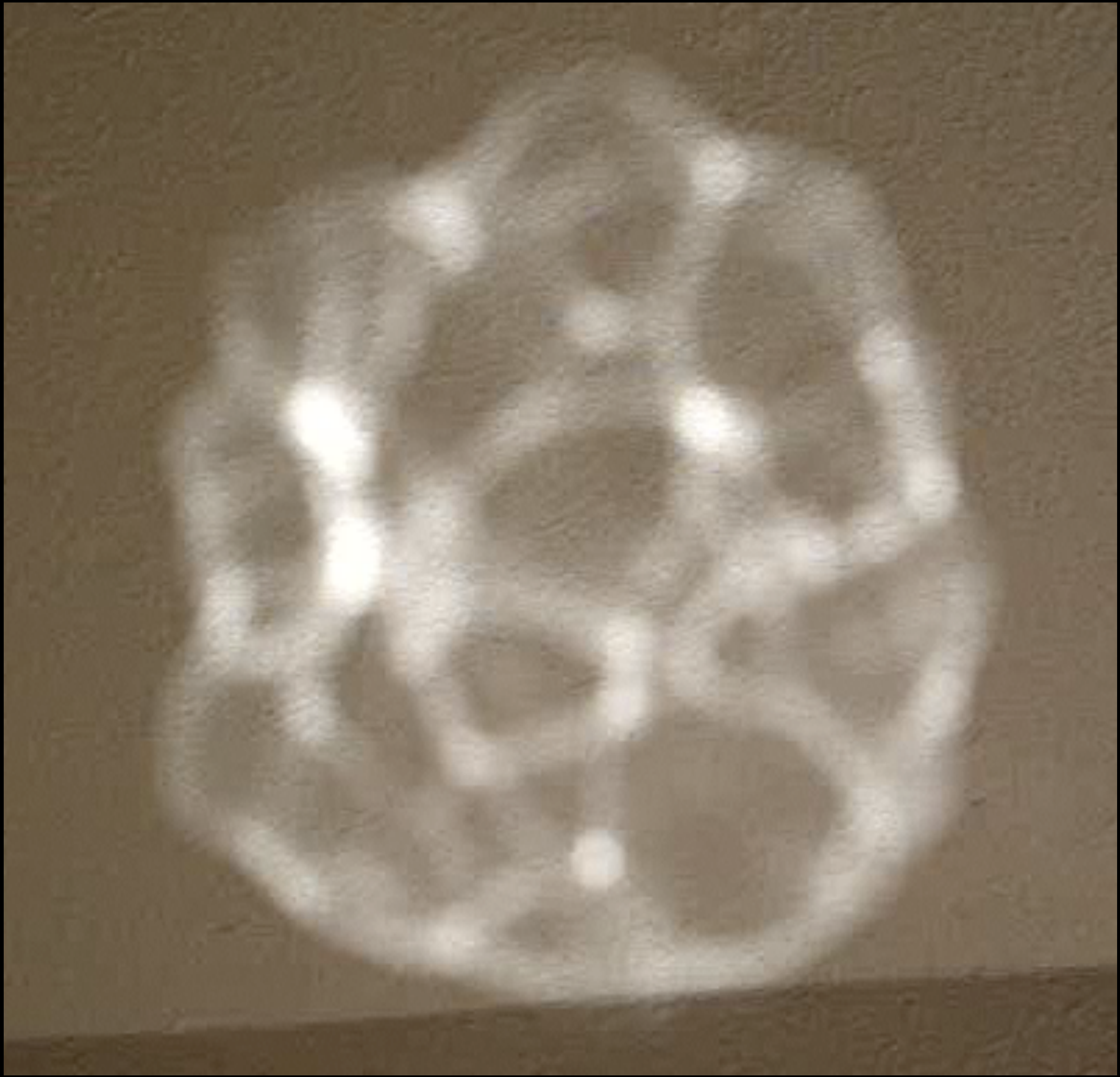
(1) Can work in open loop

(2) Can work with non-common path errors offset

(3) Can work at shorter wavelength

3.1. Increased sensitivity

3.2. better detectors in visible



# Source size

Number of photons required for given residual error is:

**N ~ 1+x^2**

**x = alpha/(m lambda/D)**

m = mode order (1 = tip/tilt)

alpha = source size

0 for ideal case

quadratic sum of lambda/r0 and lambda/D for SH

1” for LGS (x ~ 50/m)

-> for tip-tilt, LGS (~1”) will need 2500x more photons on ~10m (10x more for ELT)

-> Need good ADC in WFS

-> uplink AO on LGS and pulsed laser to mitigate cone effect could recover significant gain

# Conclusions

SH is wasting a lot of photons !
This is especially true for:

- low order aberrations
- ELTs
- coronagraphy

nlCWFS is a high performance alternative to SH and works efficiently down to m~15 guide star

We have built a prototype in Subaru Telescope. Starting to test in the lab...

**We are hiring !**