Putting the non-linear Curvature Wavefront Sensor on the 6.5m MMT telescope

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Outline

Wavefront sensing sensitivity fundamentals

Non-linear Curvature Wavefront Sensor (nlCWFS) principle

Lab development

MMT system

Some fundamental desirable WFS properties

Linearity:

The WFS response should be a linear function of the input phase

- simplifies control algorithm
- minimizes computation time -> important for fast systems

Capture range:

The WFS should be able to measure large WF errors

- the loop can be closed on natural seeing
- possible to use the WFS in open loop
- possible to “dial in” large offset aberrations

Sensitivity:

The WFS should make efficient use of the incoming photons

- the AO system can then maintain high performance on fainter sources
- the AO system can run faster

Wavefront Sensor Options…

Linearity, dynamical range and sensitivity

Linear, large dynamical range, poor sensitivity:

Shack-Hartmann (SH)

Curvature (Curv)

Modulated Pyramid (MPyr)

Linear, small dynamical range, high sensitivity:

Fixed Pyramid (FPyr)

Zernike phase constrast mask (ZPM)

Pupil plane Mach-Zehnder interferometer (PPMZ)

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

Non-linear Curvature (nlCurv)

Non-linear Pyramid (nlPyr) ?

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

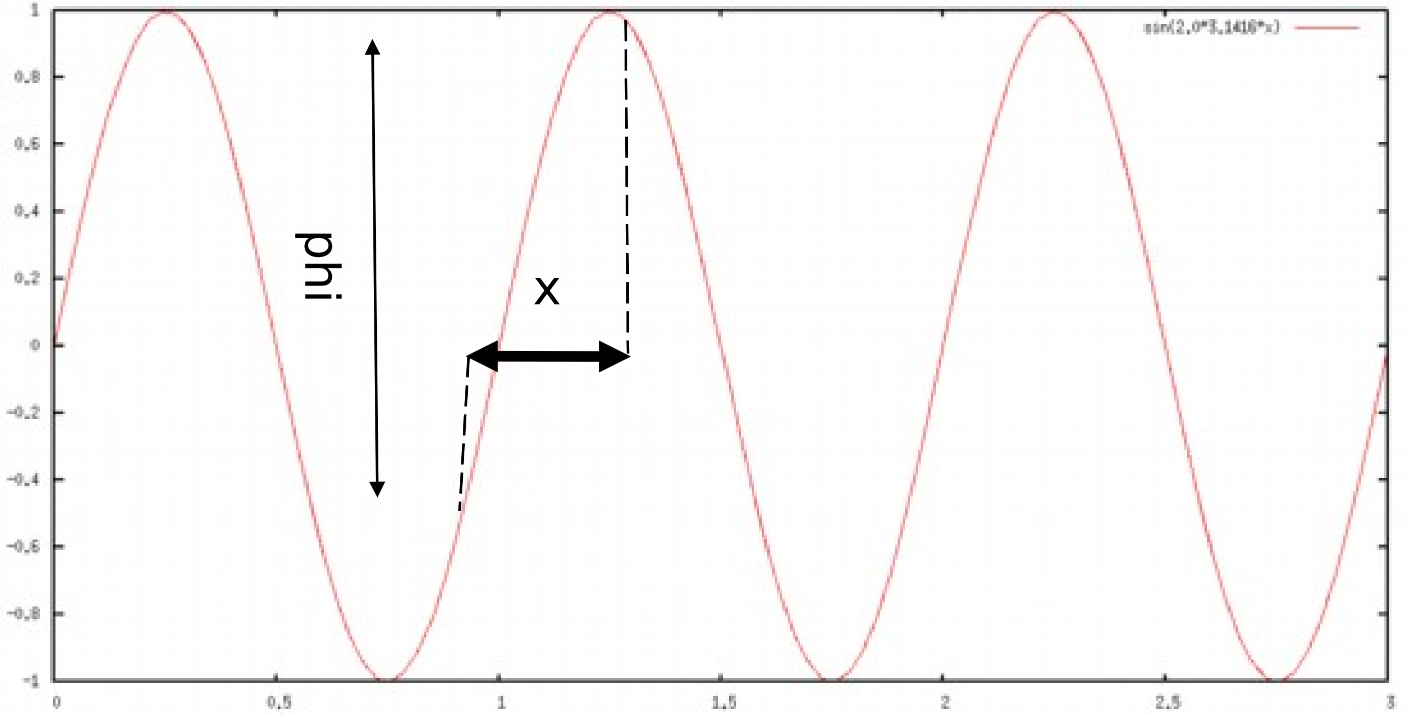
Example: a sine wave phase aberration of C cycles across the pupil, amplitude = a rad (in figure below, C = 3, a = 1 rad)

Interferences between points separated by x (2xC PI in “phase” along the sine wave)

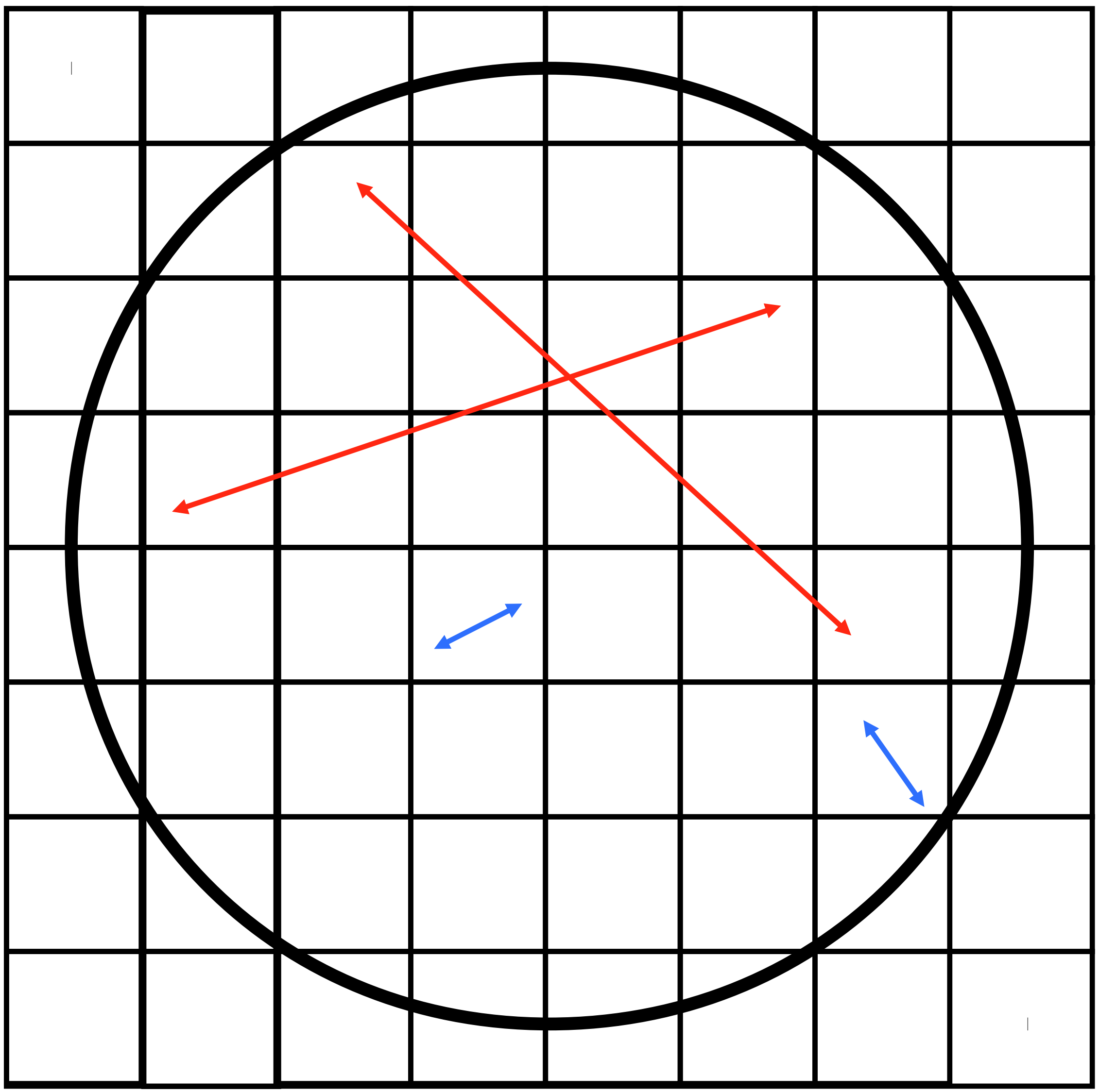
Phase difference between 2 points: phi = 2 a sin(xC PI)

Intensity signal is linear with phi (small aberrations approximation)

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

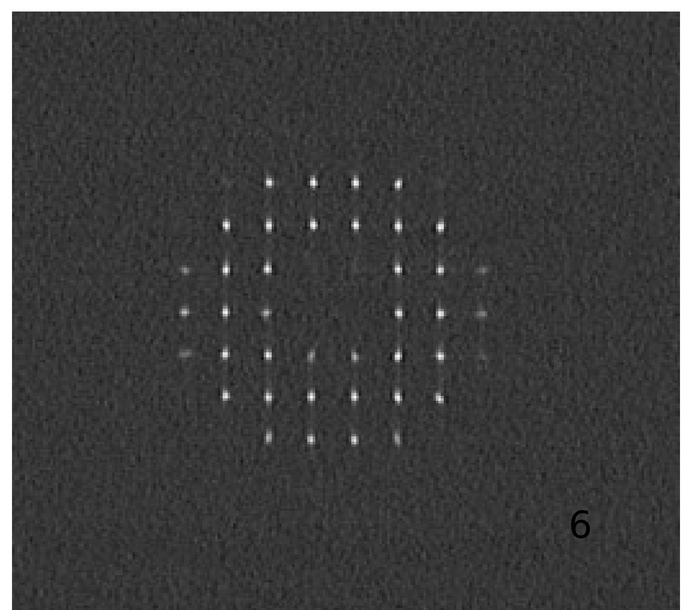


SH WFS : sensitivity issue for low spatial frequencies

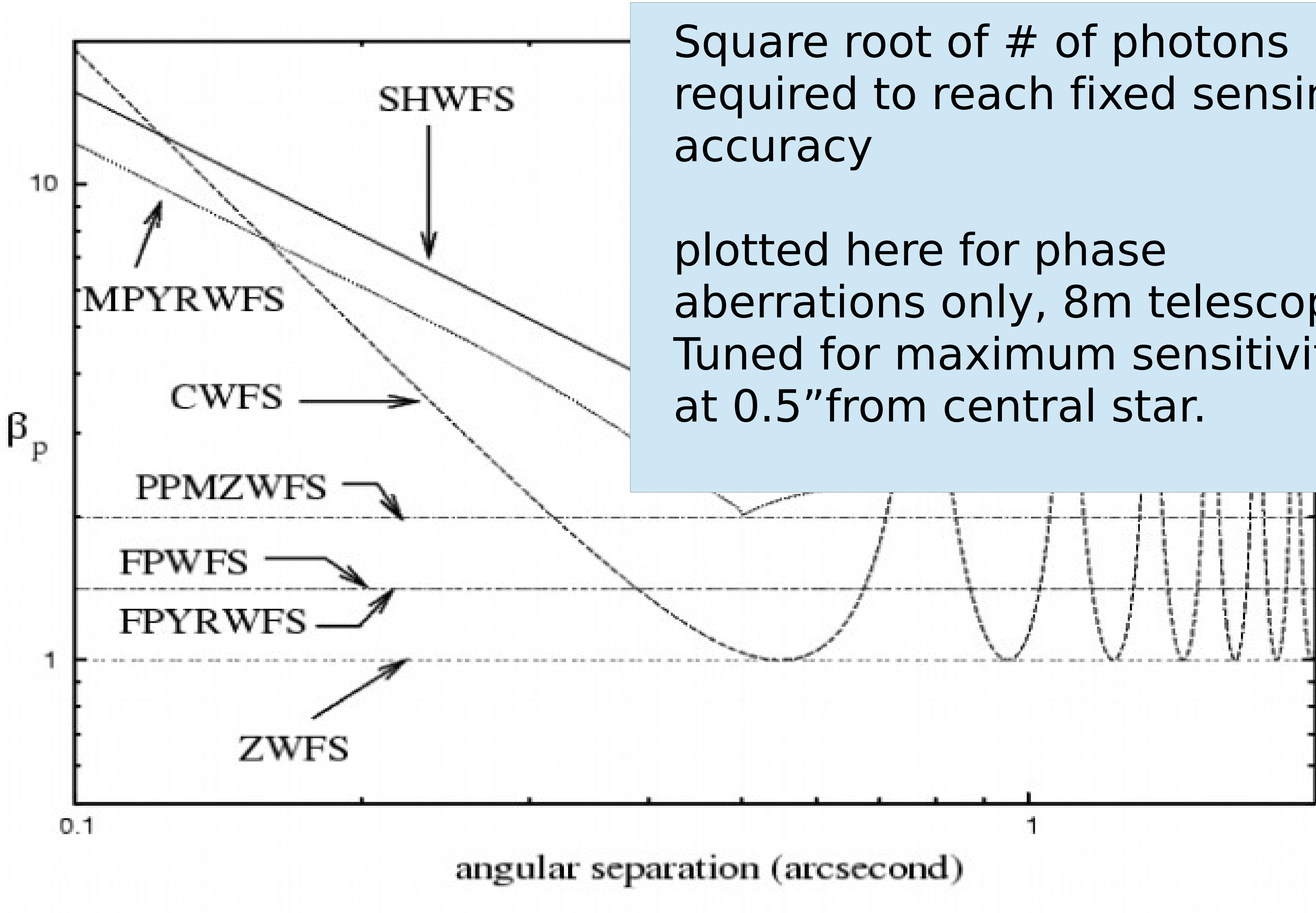


Problem:
SH does not allow interferences between points of the pupil separated by more than subaperture size

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



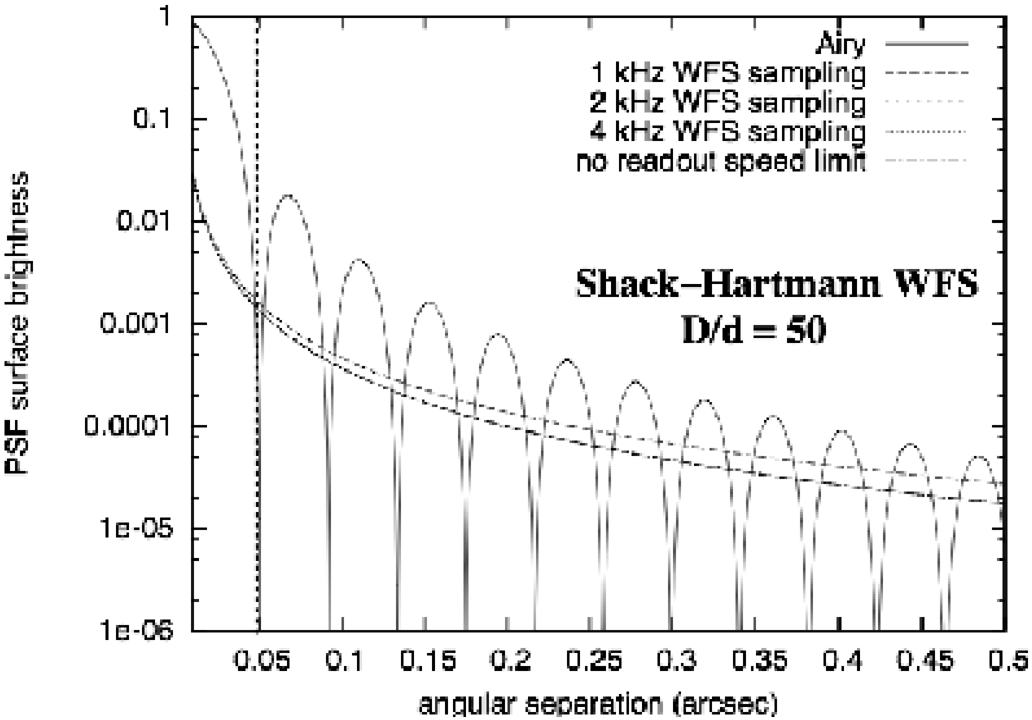
Wavefront sensors ''sensitivities'' in linear regime with full coherence (Guyon 2005)

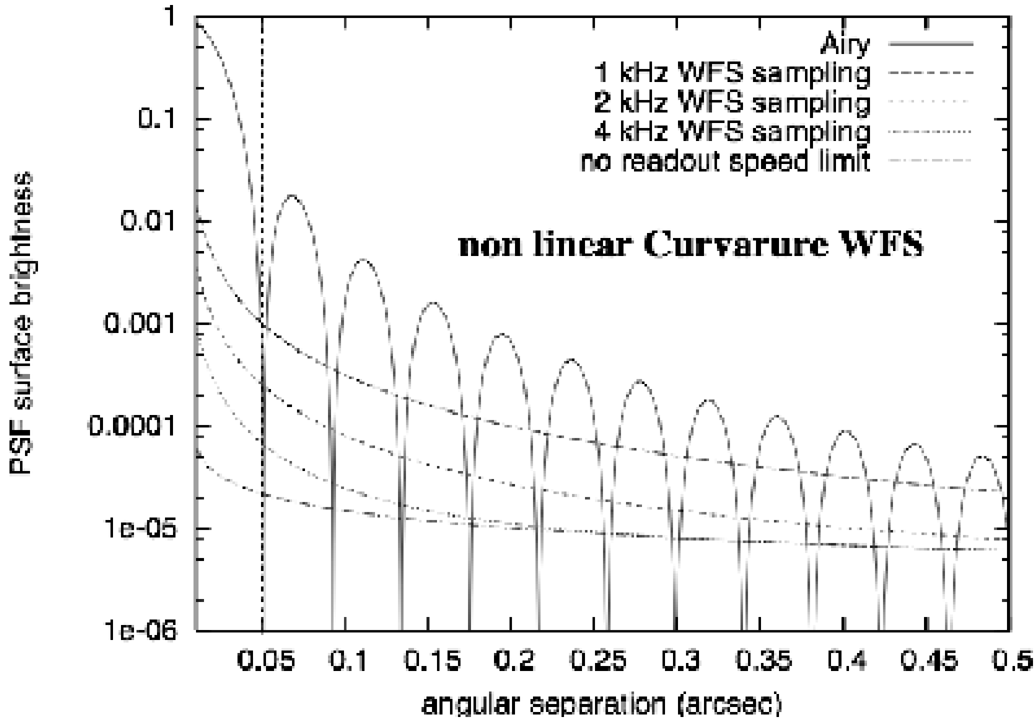


Square root of # of photons required to reach fixed sensing accuracy

plotted here for phase aberrations only, 8m telescope. Tuned for maximum sensitivity at 0.5”from central star.

Performance gain for ExAO on 8-m telescopes





"High Sensitivity Wavefront Sensing with a non-linear Curvature Wavefront Sensor", Guyon, O. PASP, 122, pp.49-62 (2010)

Large gain at small angular separation: ideal for ExAO

Wavefront sensing at the sensitivity limit imposed by the telescope diffraction limit

Seeing limited wavefront sensing (what we do now)

Example: SH WFS

Diffraction limited wavefront sensing (what needs to be done for ExAO)

Examples: Pyramid (non-modulated), non-linear curvature

Tip-tilt example :

With low coherence seeing-limited WFS, $\sigma^2 \sim 1/D^2$ (more photons)

Ideally, one should be able to achieve: $\sigma^2 \sim 1/D^4$ (more photons + smaller λ/D)

This makes a big difference for Extreme-AO on large telescopes

For Tip-Tilt, SHWFS on ELT is 40000x less sensitive than diffraction-limited WFS (11.5 mag)

Large gain on other low order modes

Sensitivity: Which WFS to use ?

LGS: sensitivity limited by spot size.
SHWFS is suitable, better WFSs will not do significantly better

NGS: Don't use SHWFS, try to take advantage of WF coherence across the pupil

Pyramid WFS with small modulation is excellent choice

If you really want the optimal sensitivity for low-order modes:
Non-modulated Pyramid WFS, but requires very good WF quality in the WFS (see C. Clergeon poster)

If WF is > 1 rad RMS, nlCWFS maintains full sensitivity
→ can use shorter wavelength
→ open loop NGS sensing for wide-field AO systems

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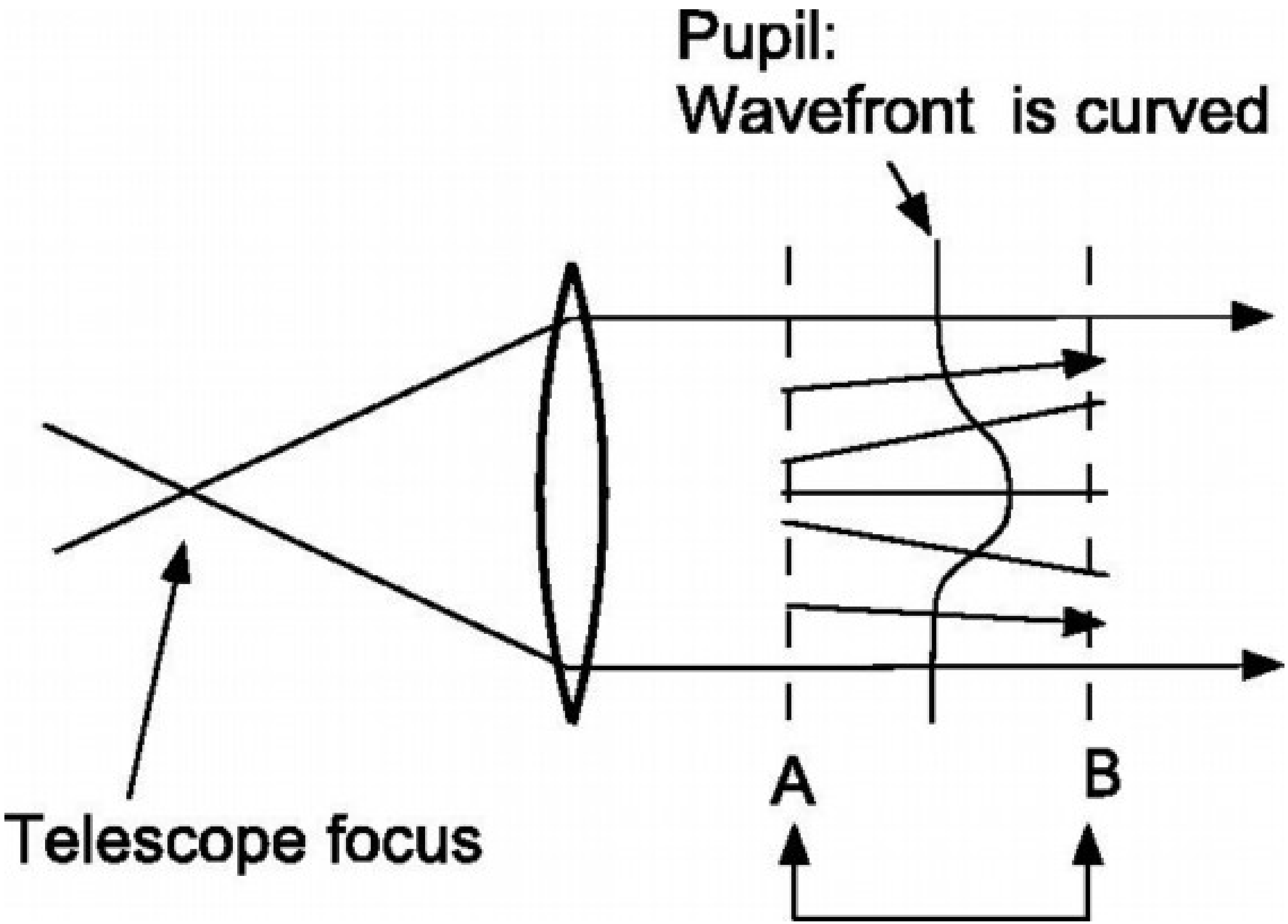
Curvature WFS

Light propagation turns phase into amplitude (similar to scintillation)

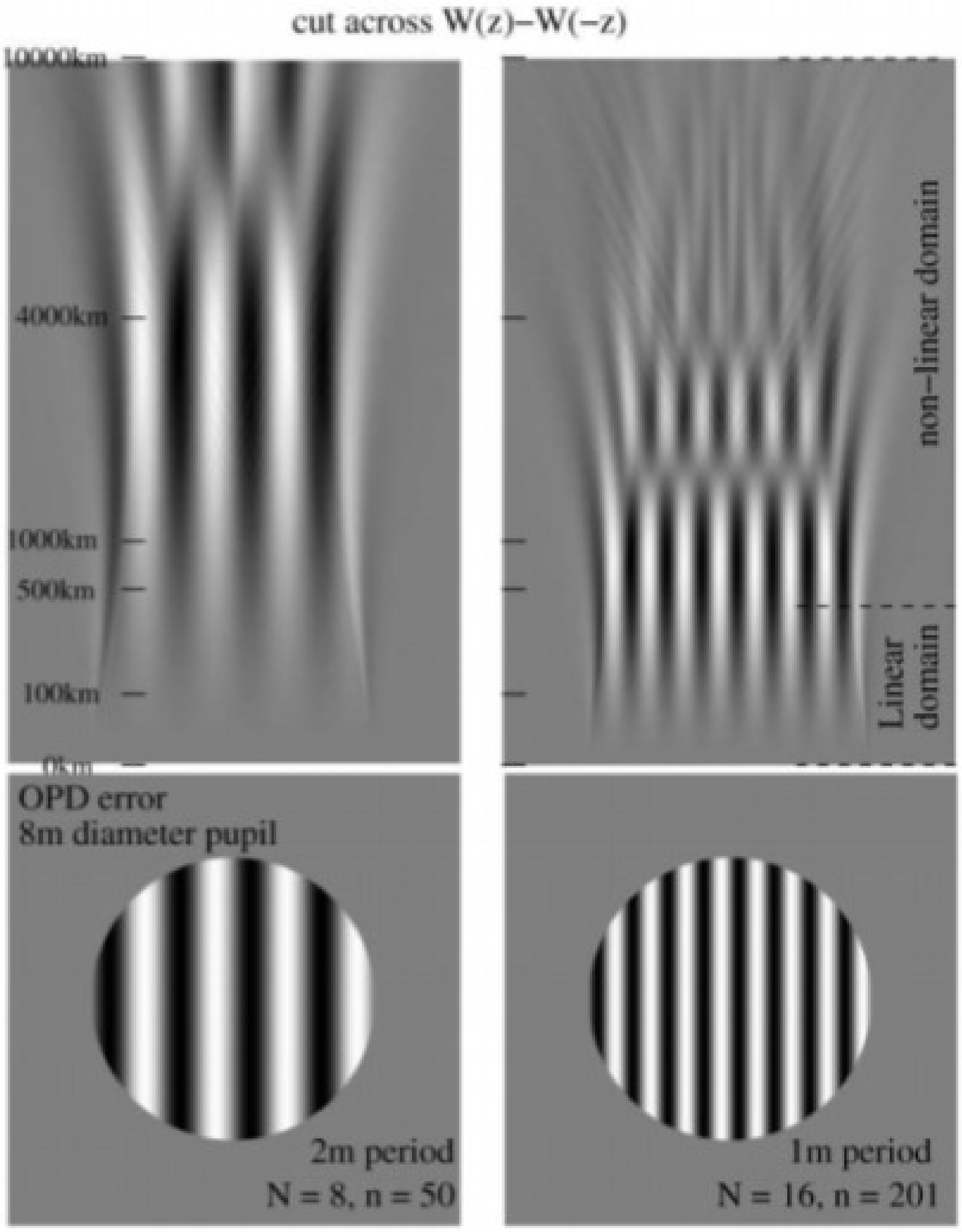


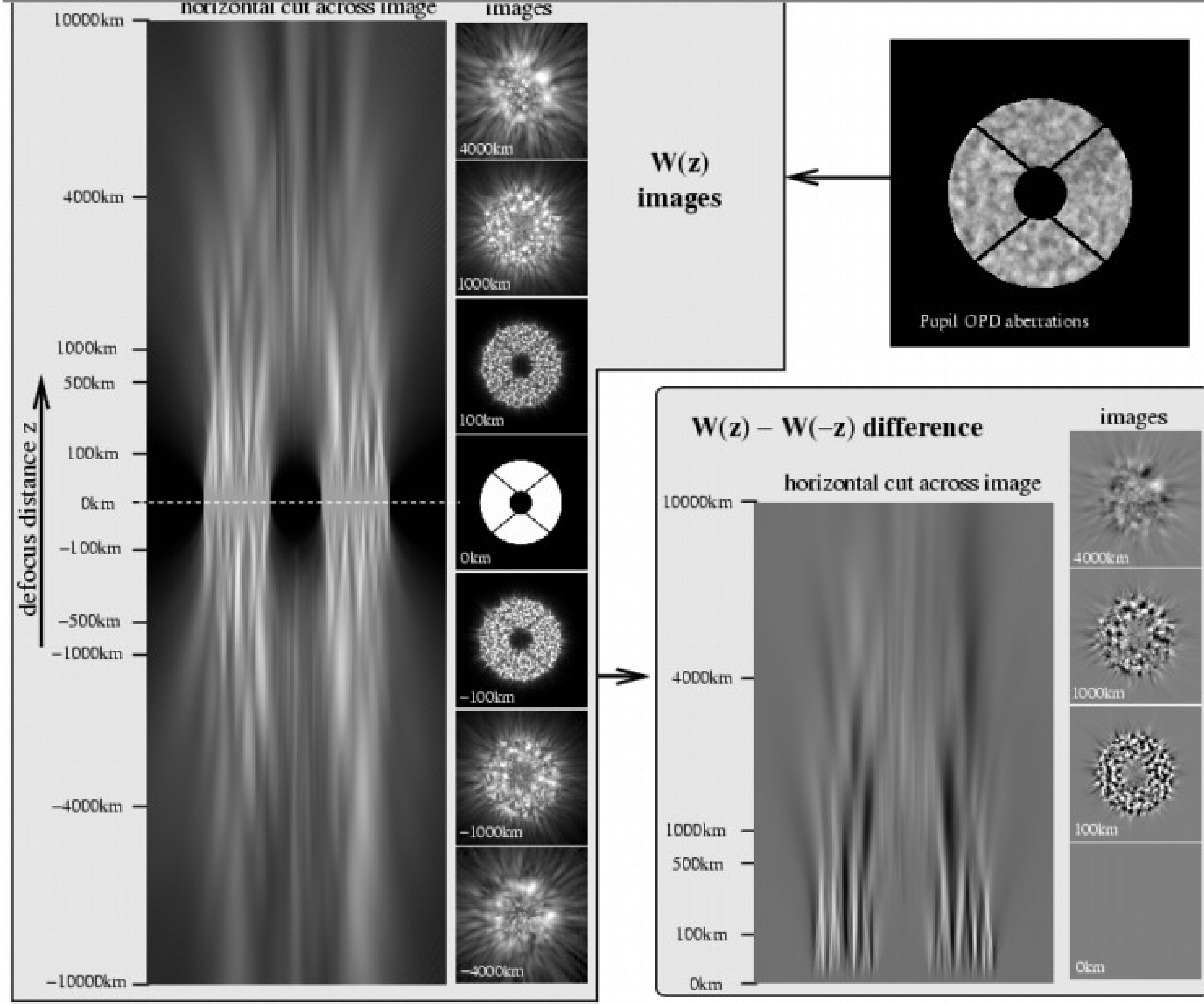
Lenslet array used to inject light into a series of fibers, which are connected to photon-counting Avalanche PhotoDiodes (APDs)

Curvature WFS

Wavefront Signal.

The optimal defocus distance at which the measured signal is strongest, is larger for lower spatial frequencies. For high spatial frequencies the linear domain extends to ~ 500 km.





horizontal cut across image
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Pupil OPD aberrations
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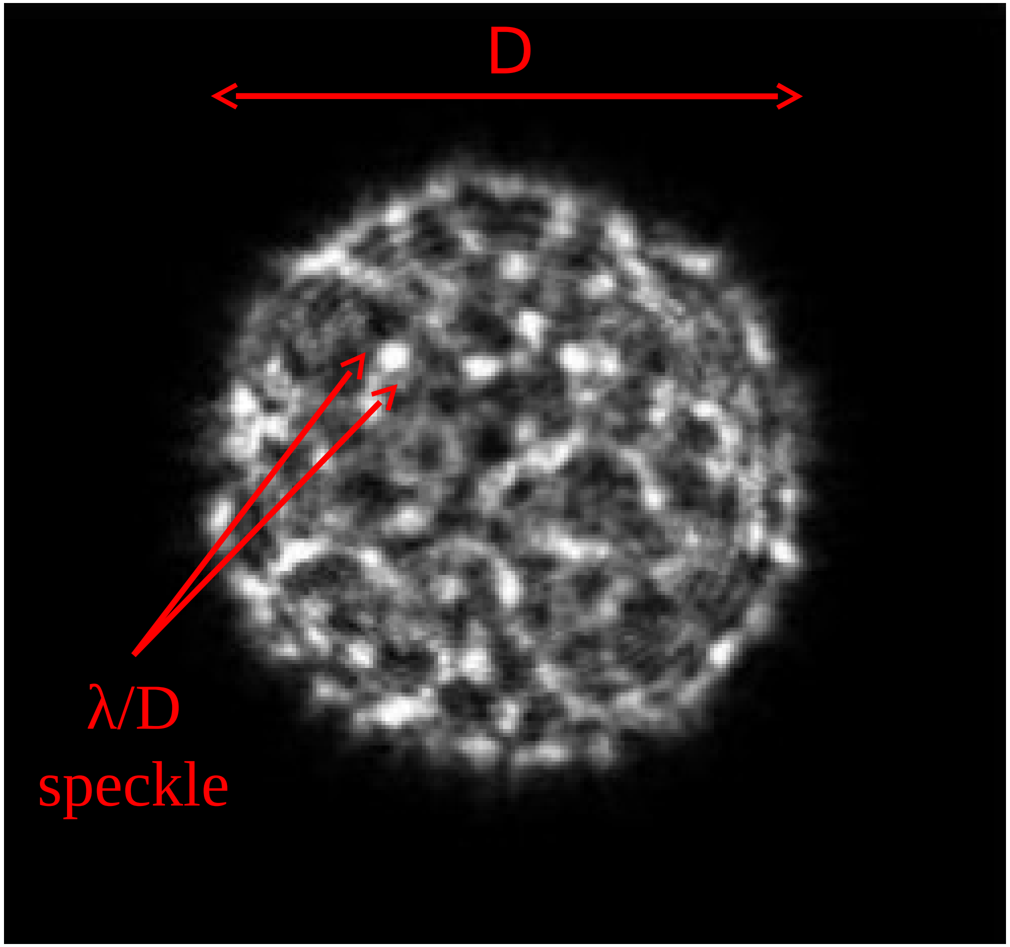
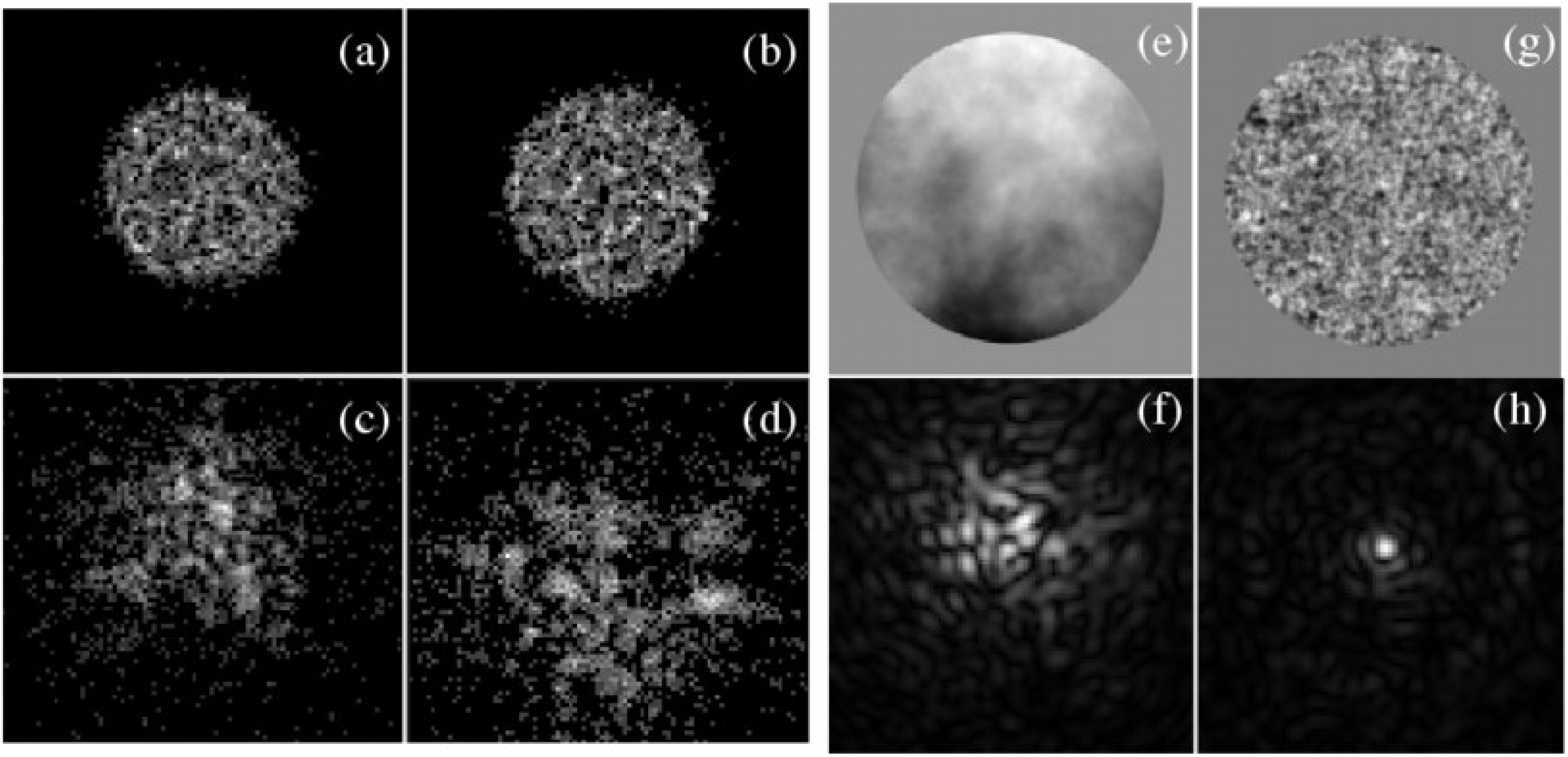


We want to utilize the D4 gain offered by ELTs

Simulated reconstruction
20,000 ph total
609nm → 34.4nm RMS



Non-linear Reconstruction Algorithm: Iterative Gerchberg-Saxton

Intensity recorded in the defocused pupil planes ±dz.

↓

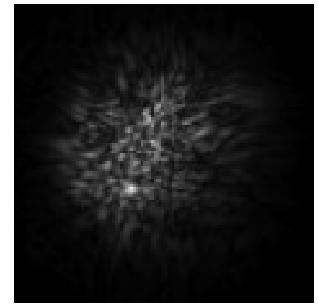
Wavefront is propagated to the pupil plane via Fourier Transform.

↓

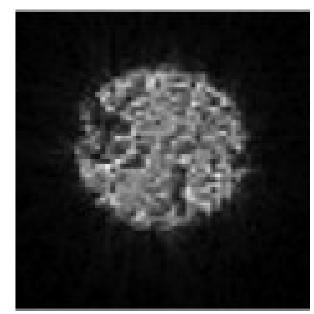
Phase preserved at pupil plane and the measured pupil plane intensity is applied.

↓

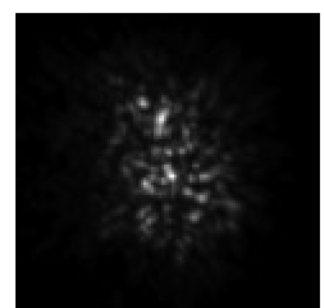
Wavefront is reverse propagated to the defocus planes via Fourier Transform.



Defcoused plane + dz



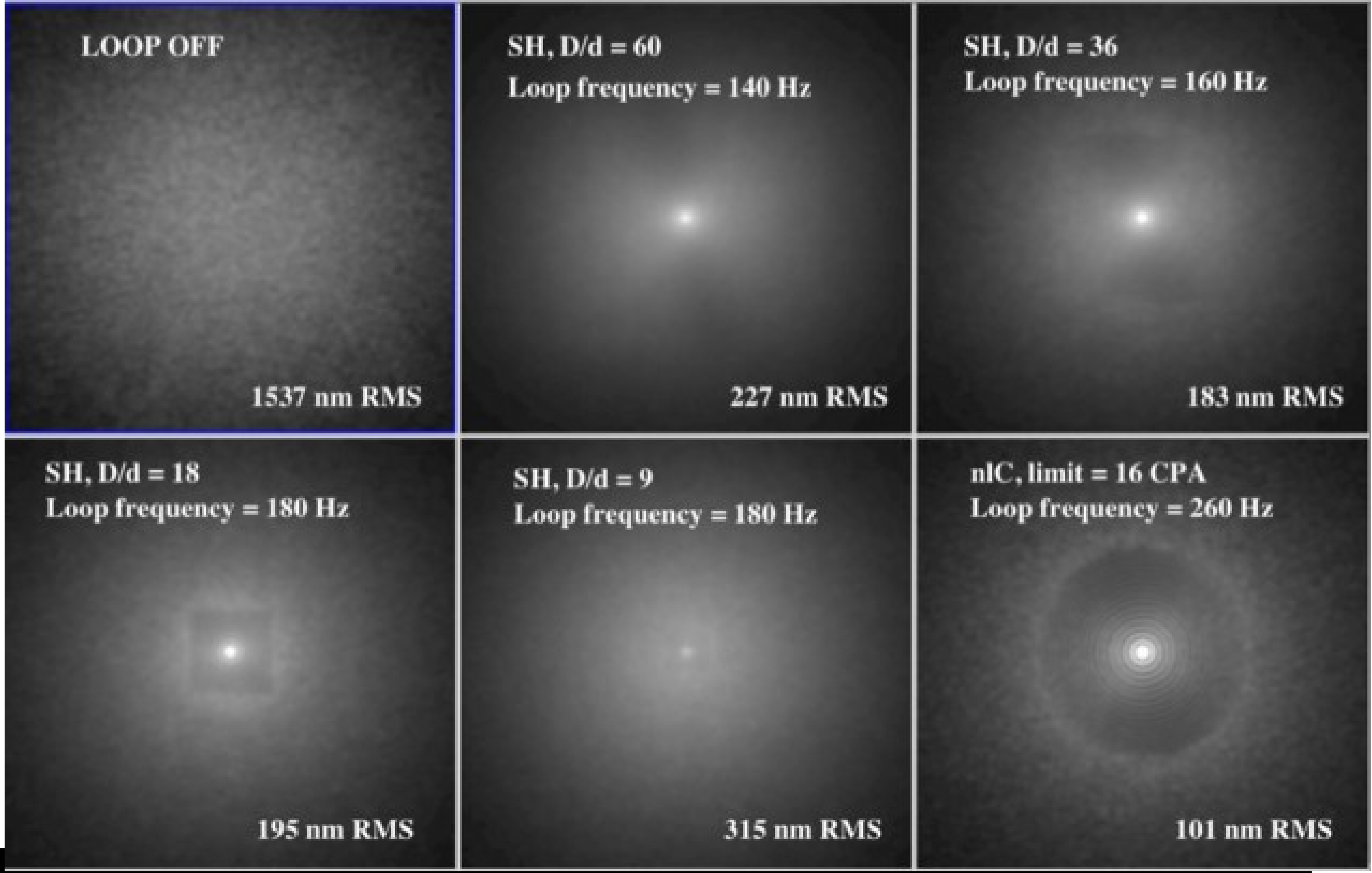
Pupil Plane



Defcoused plane - dz

Optical axis - z

Computer Simulations showing contrast gain with high sensitivity WFS (non-linear curvature)



m ~ 13

WFS	Loop frequ	RMS	SR @ 0.85 um	SR @ 1.6 um
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%

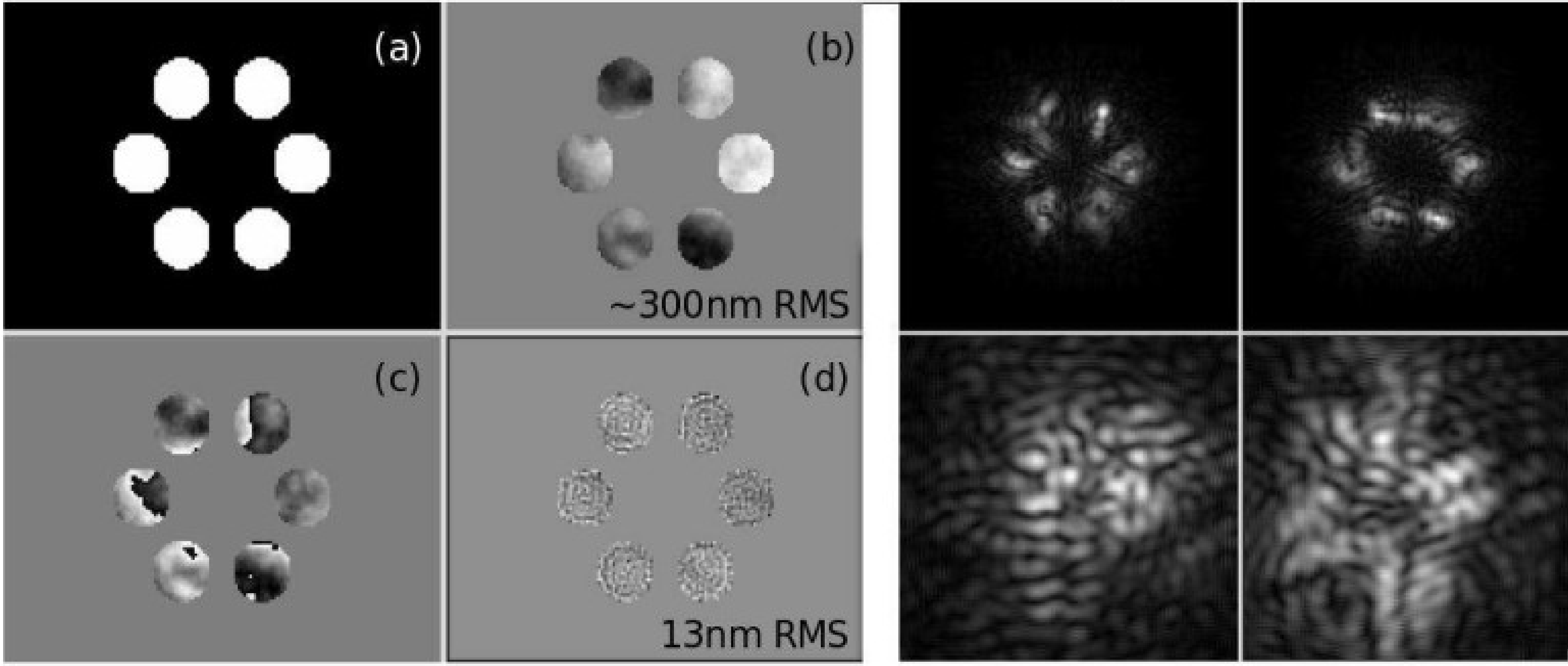
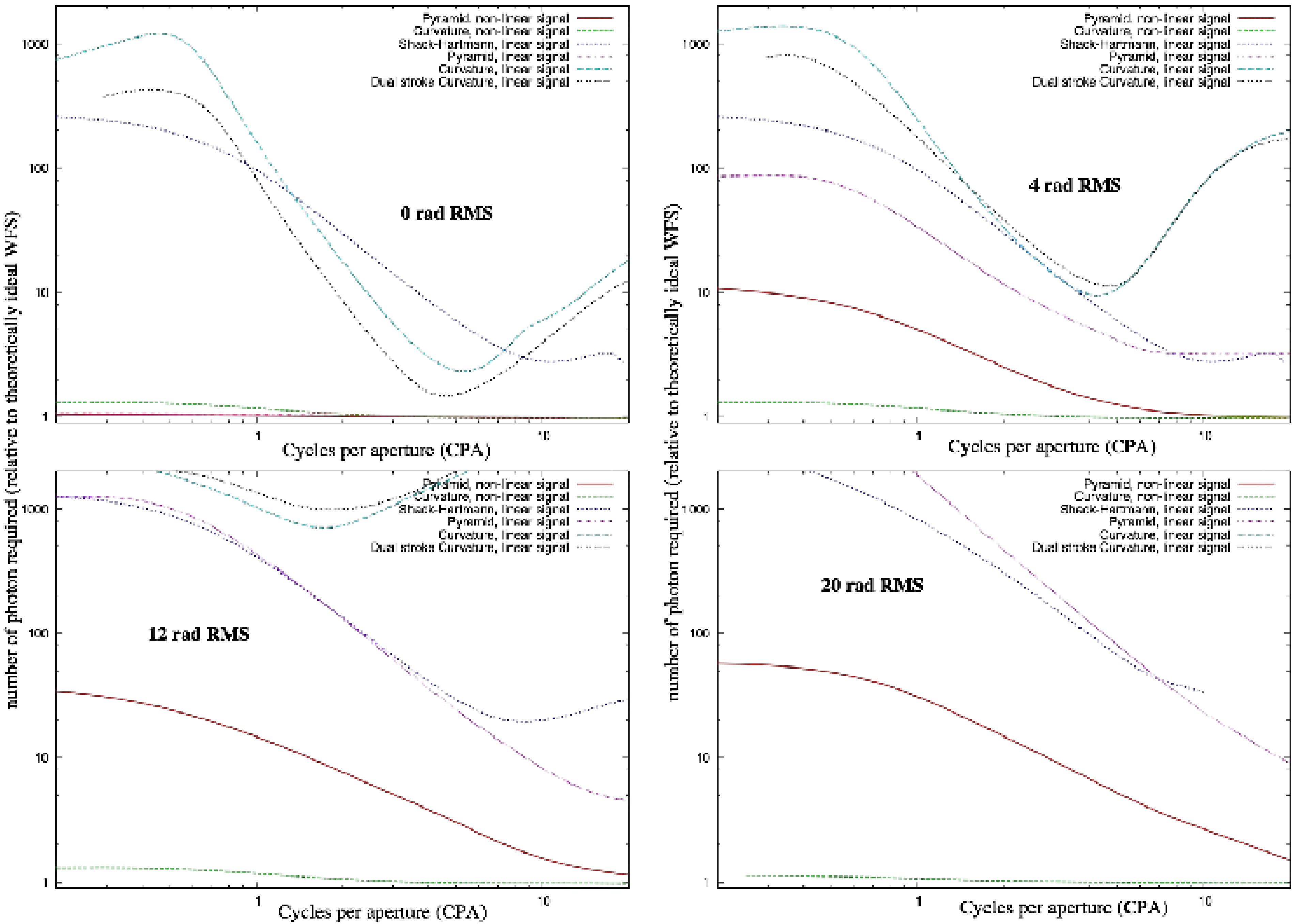


Fig. 9.— Wavefront reconstruction with dual stroke non-linear CWFS on a sparse pupil. The pupil amplitude (a) and phase (b) yield the four defocused pupil images shown on the right. The recovered pupil phase (c) and the residual phase error (d) demonstrate that dual stroke non-linear CWFS can simultaneously measure OPD within and across segments. This polychromatic simulation was performed with 2e8 photons in a $d\lambda/\lambda = 0.5$ wide band centered at 0.65 μm.

"High Sensitivity Wavefront Sensing with a non-linear Curvature Wavefront Sensor", Guyon, O. PASP, 122, pp.49-62 (2010)

Sensitivity compared with other schemes



Faint source regime (8m telescope)

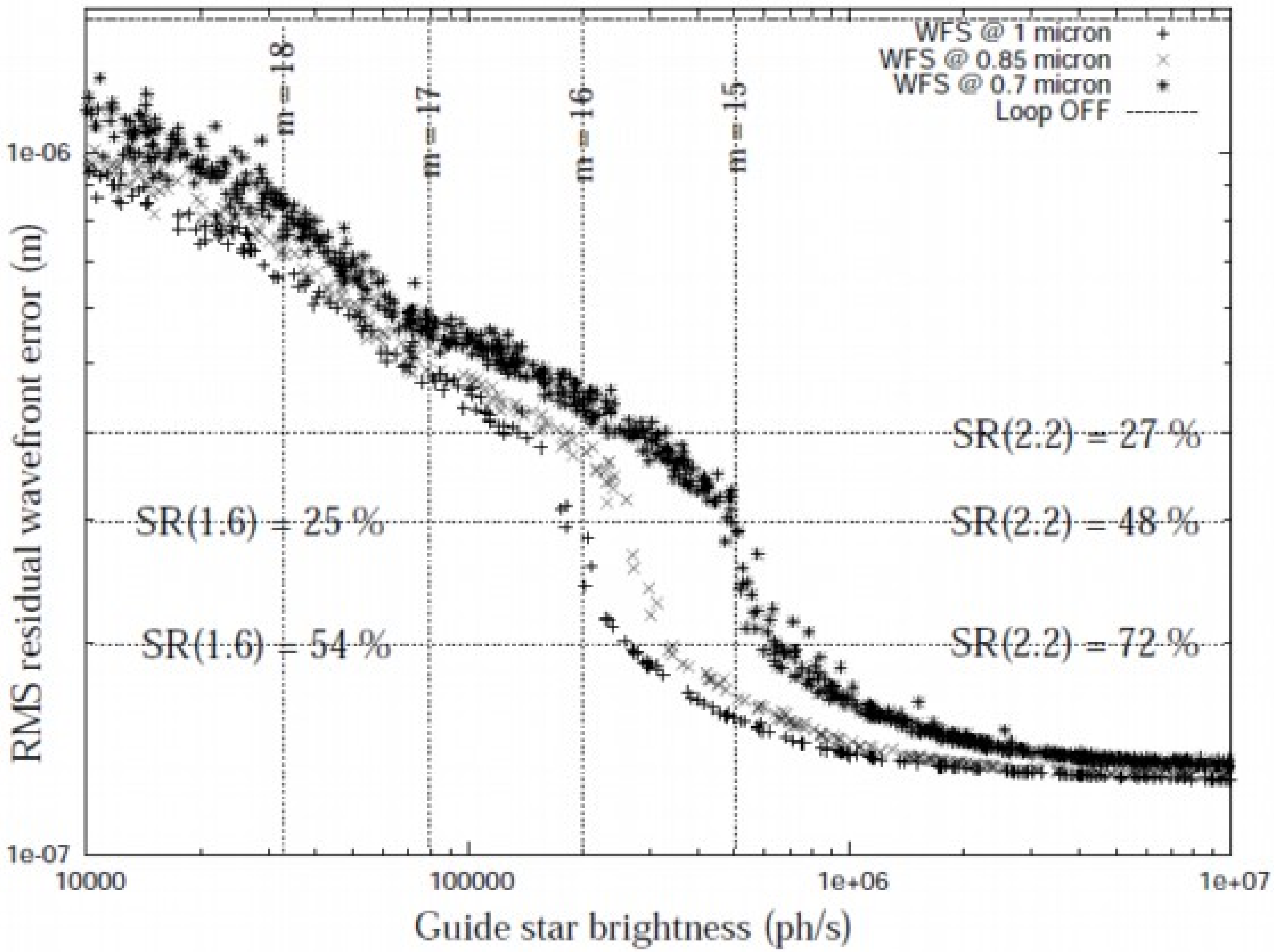


Fig. 8.— Simulated performance of a low order nlCWFS-based system (first 200 Zernike modes corrected) as a function of sensing wavelength (0.7, 0.85 and 1.0 μm) and guide star brightness. The stellar magnitudes given in this figure assume a 20% efficiency in a 0.5μm wide band. Each point in this figure is a 1-second average of the RMS residual wavefront error. See text for details.

Faint source regime (8m telescope)

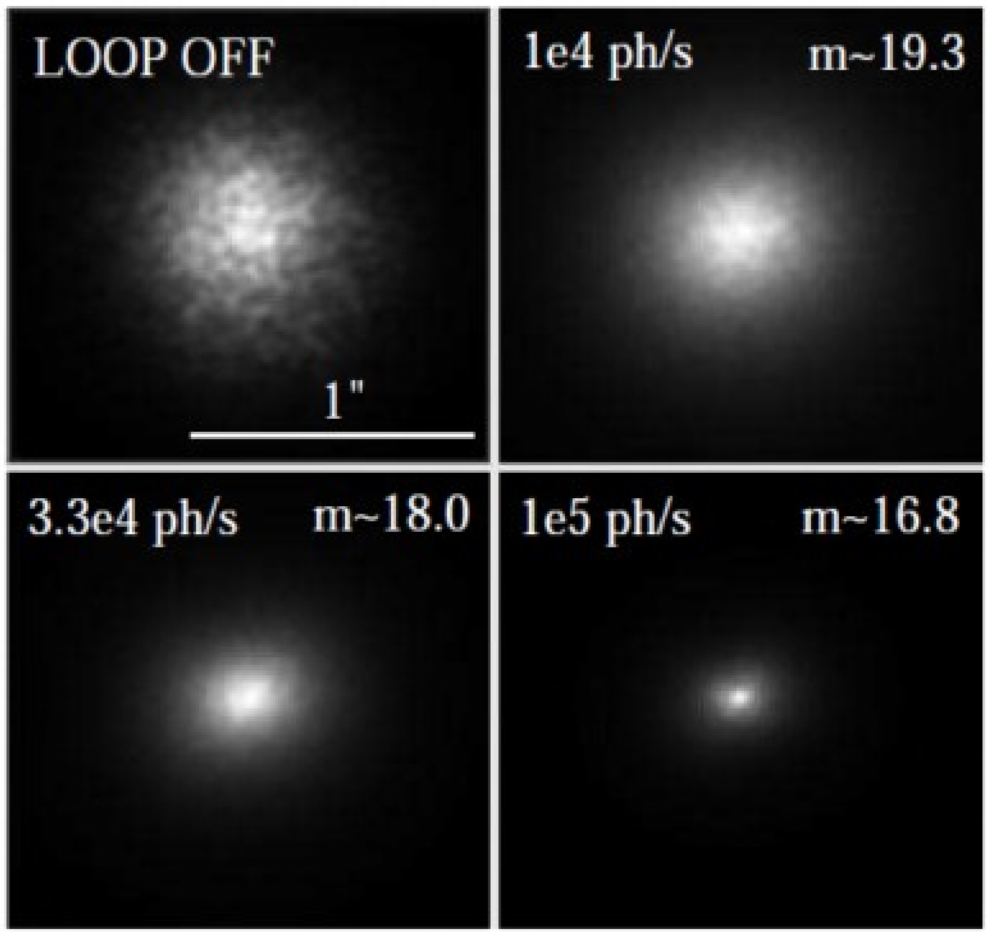


Fig. 7.— Simulated long exposure 1.6 μm PSFs obtained with a non-linear Dual stroke Curvature-based AO system. The sensing wavelength is 0.85 μm for this simulation.

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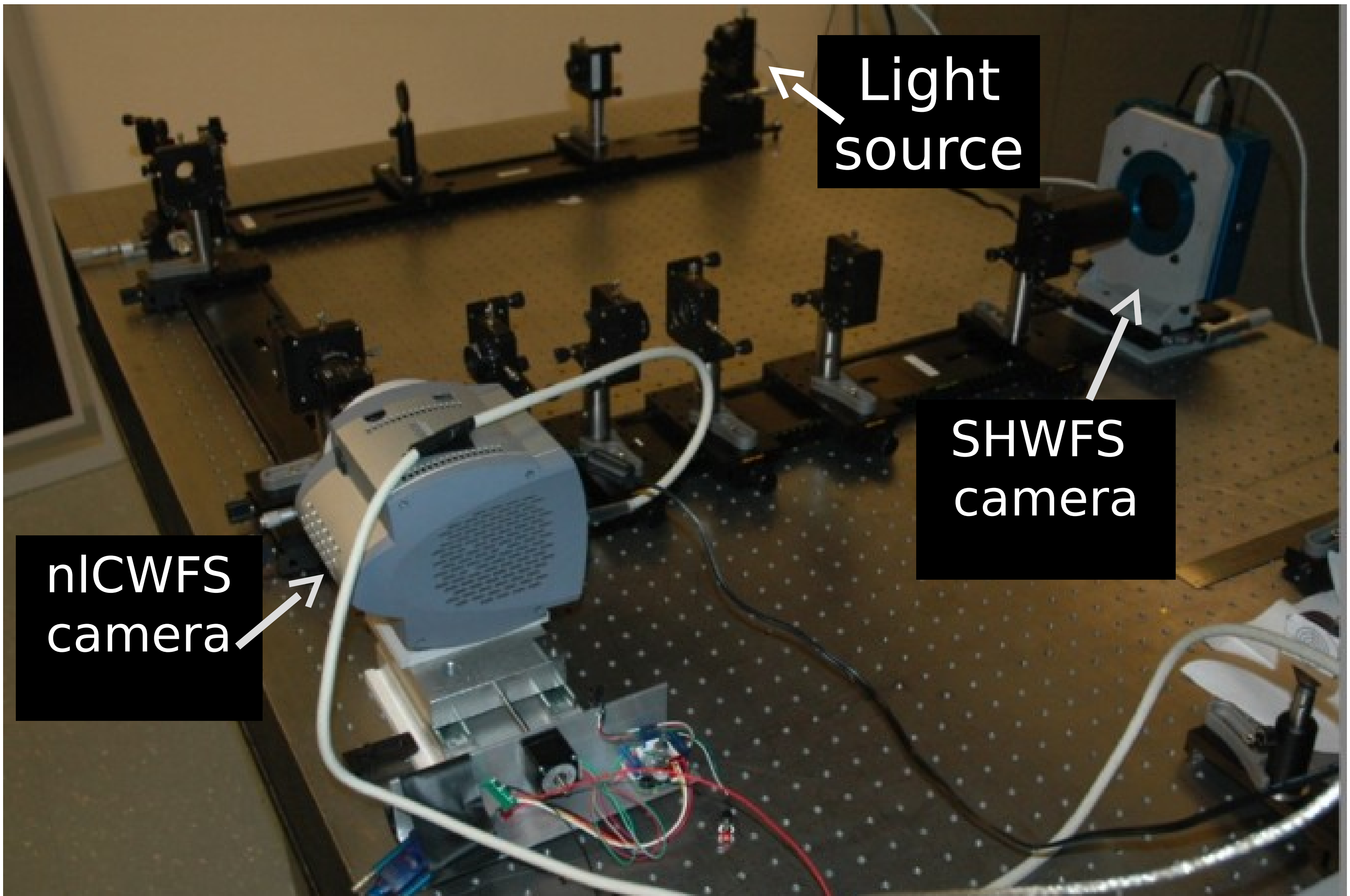
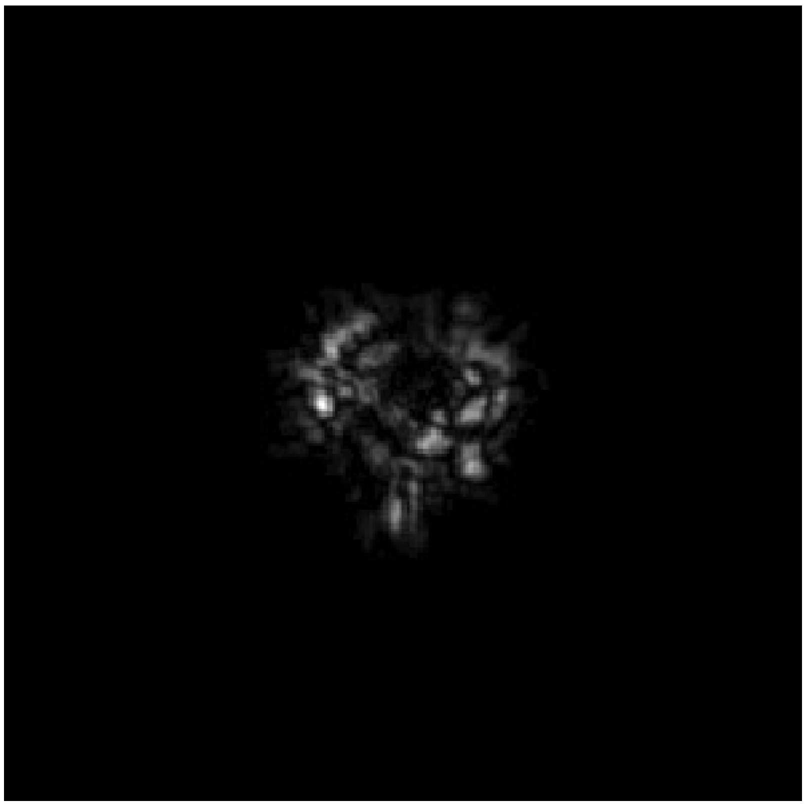
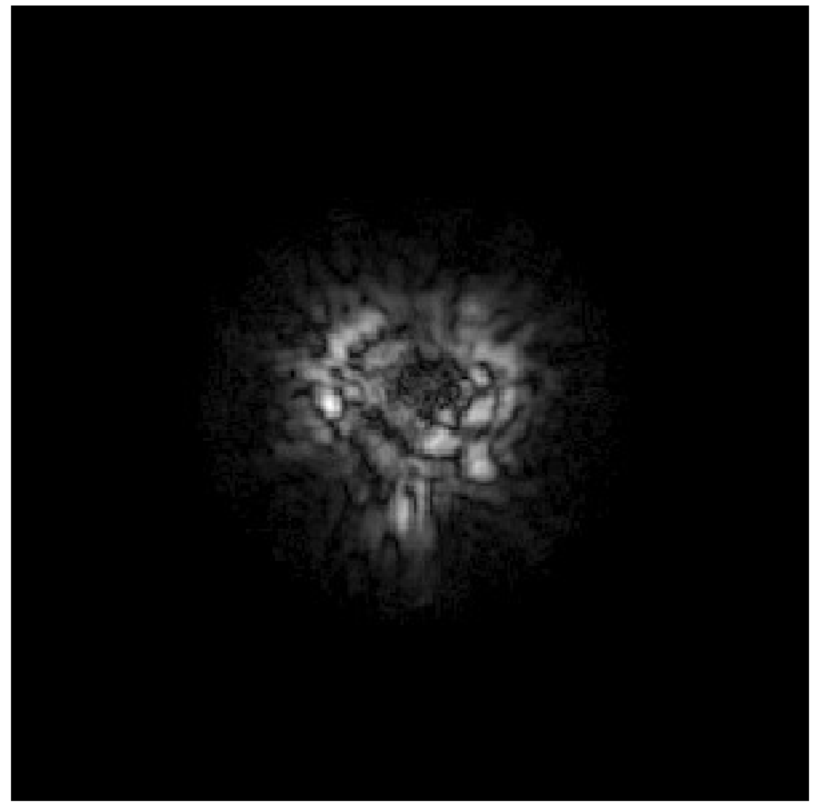
Experiment Setup



Wavefront reconstruction in lab



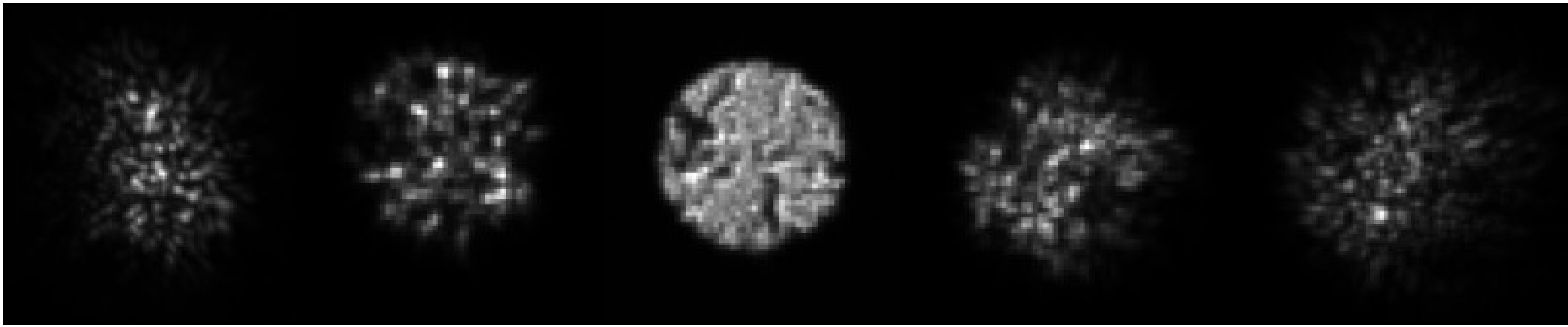
Data acquired in the lab



Gerchberg-Saxton solution

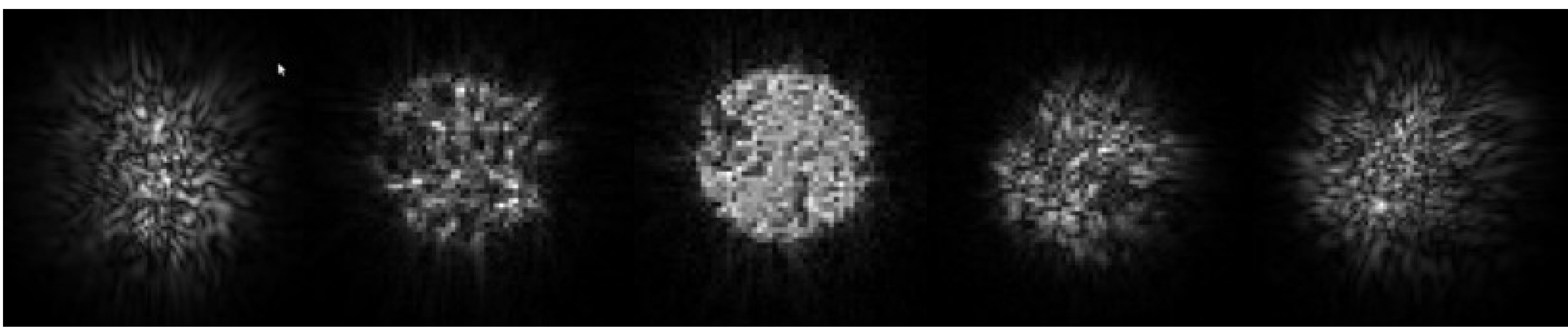
Wavefront reconstruction

Data acquired in the lab



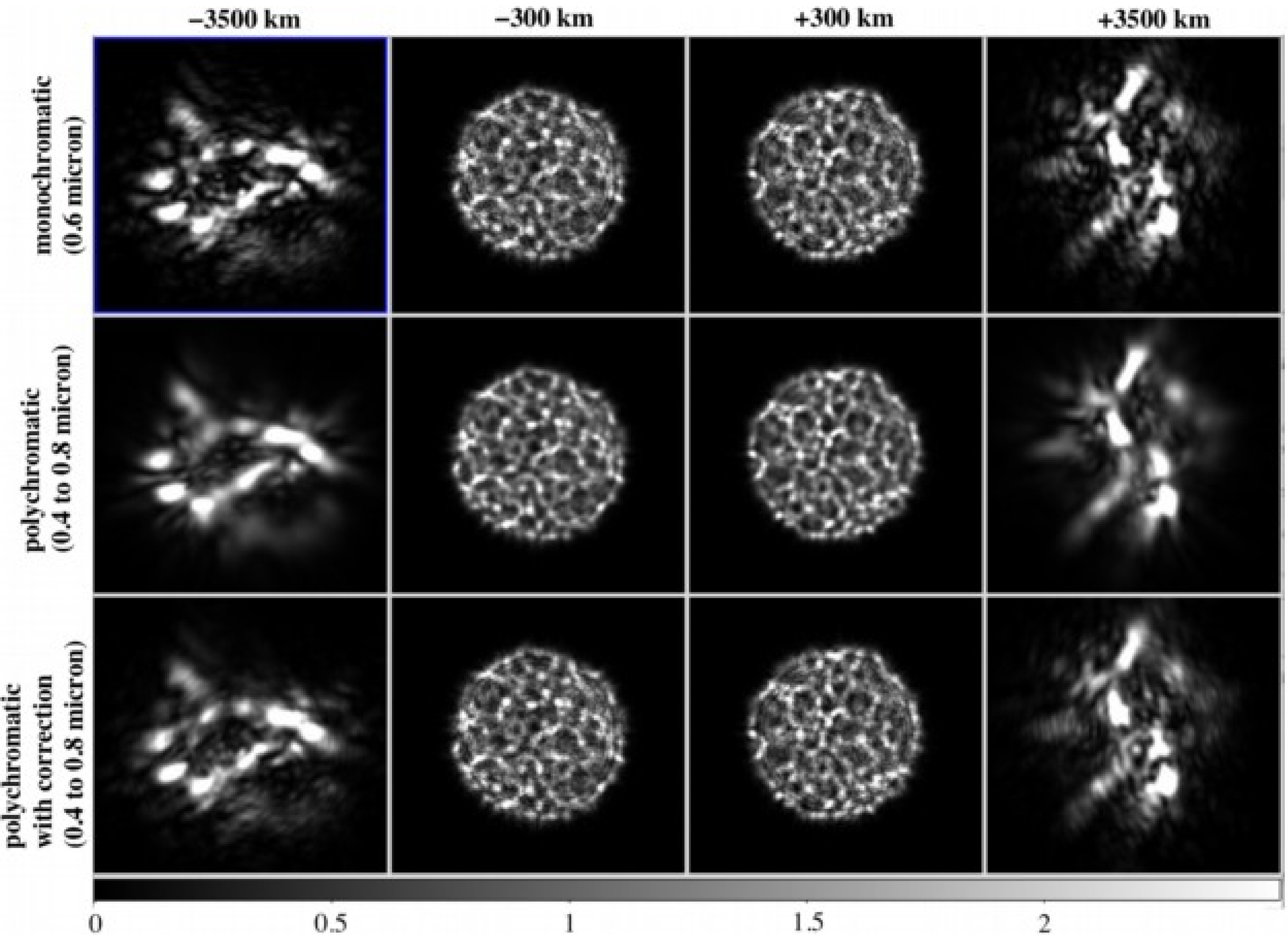
-dz2 -dz1 pupil +dz1 +dz2

Gerchberg-Saxton solution



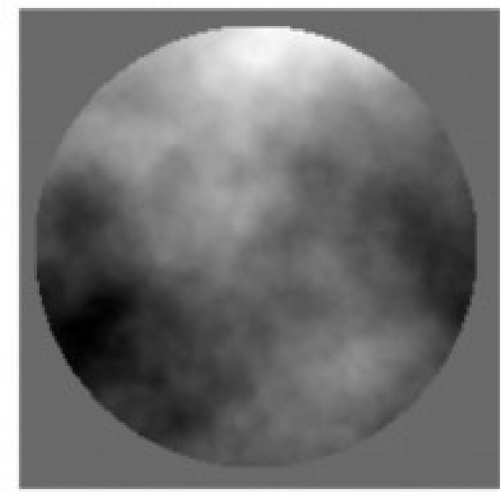
-dz2 -dz1 pupil +dz1 +dz2

Chromaticity

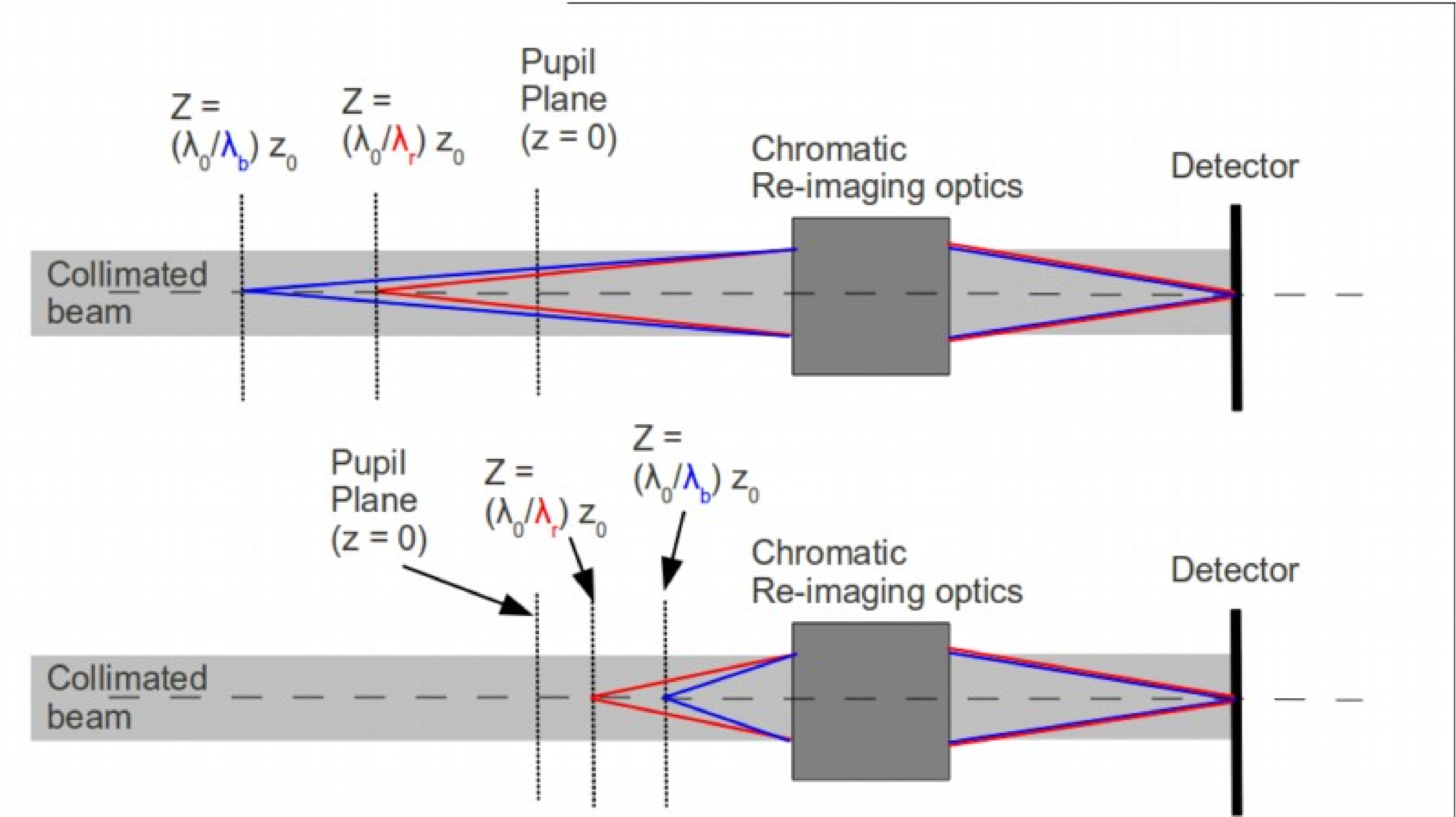


8 m diameter pupil

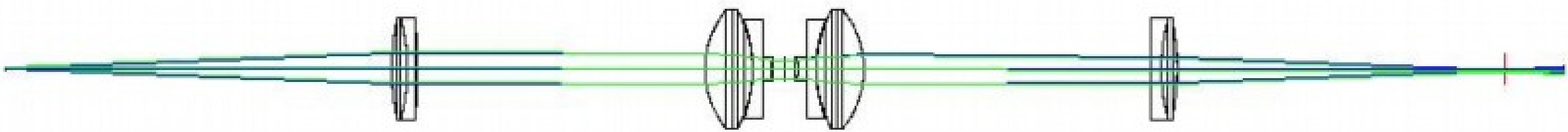
371 nm RMS

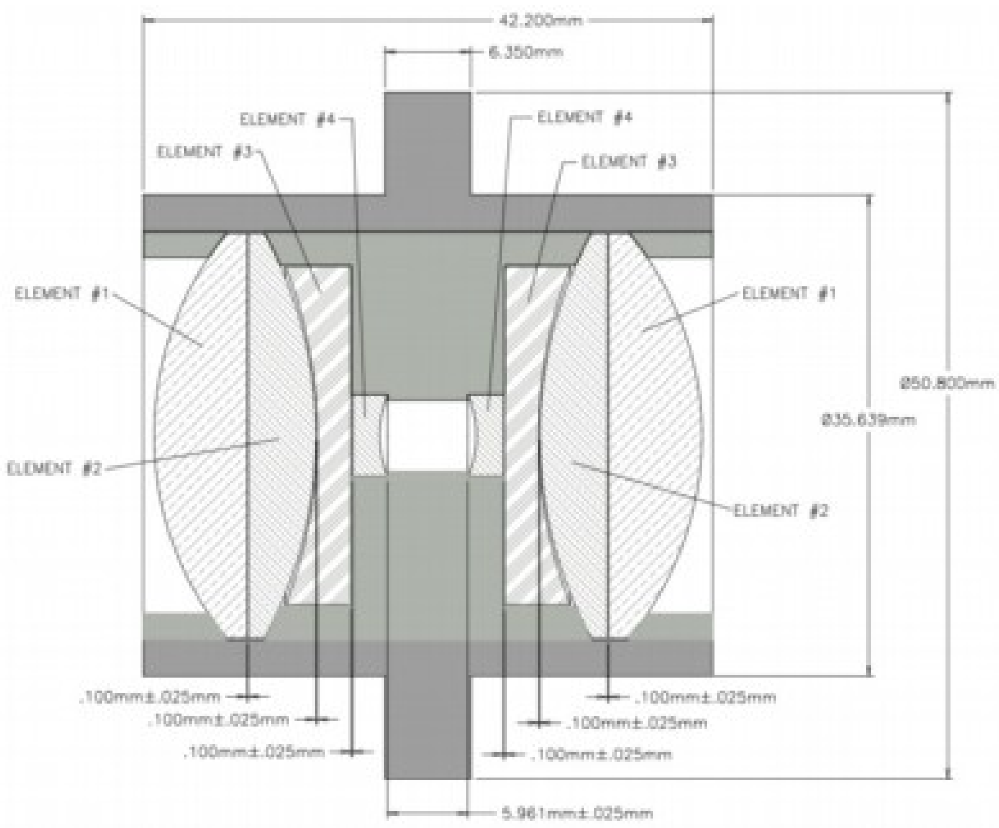


Chromaticity



Chromaticity compensation with chromatic optics





Chromaticity compensation

Simulation results

Monochromatic algorithm
Polychromatic data

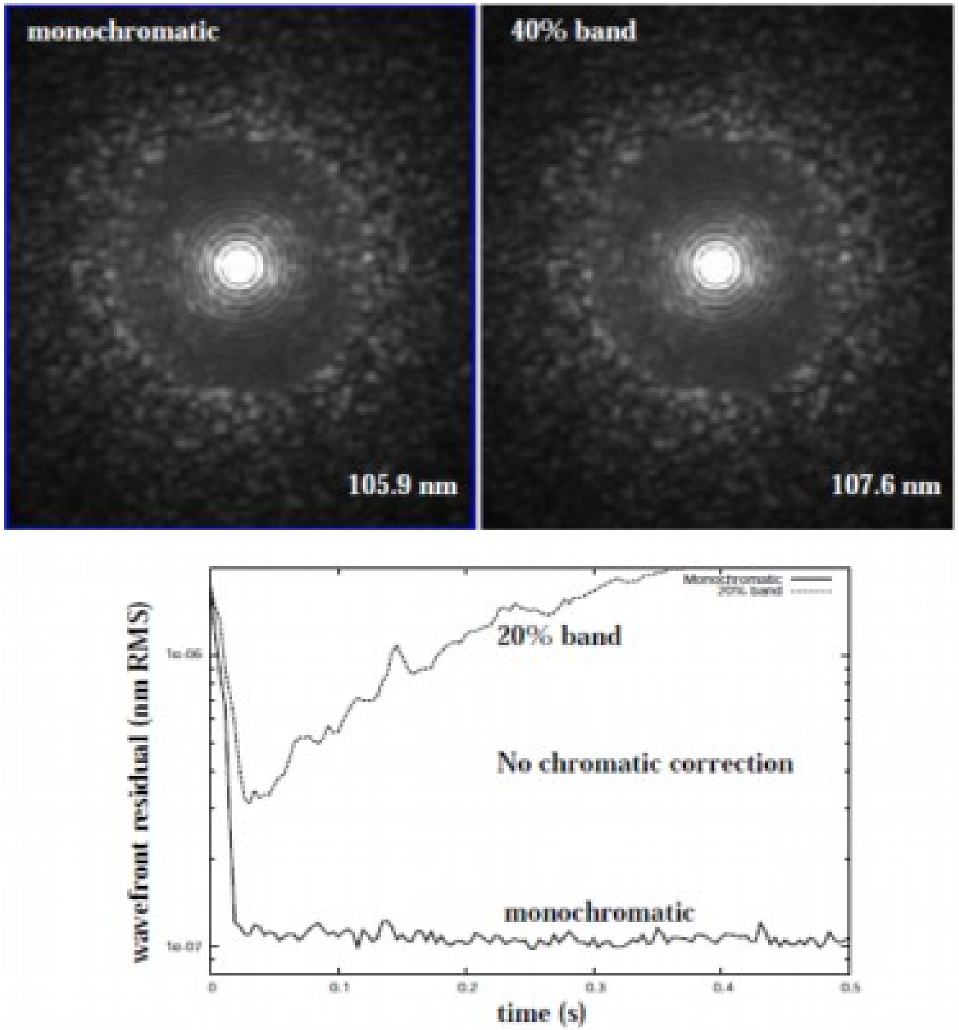


Fig. 6.— Top: Closed loop 1 second exposure PSFs at 0.85 μm with a nlCWFS working in monochromatic and broadband ($d\lambda/\lambda$ = 40%) light. In both simulations, the total number of photons in the nlCWFS is 3e6 ph/s. Bottom: Without chromatic correction within the nlCWFS (replacing the chromatic lenses by achromatic lenses in Figure 1), the loop would be unstable with $d\lambda/\lambda$=0.2.

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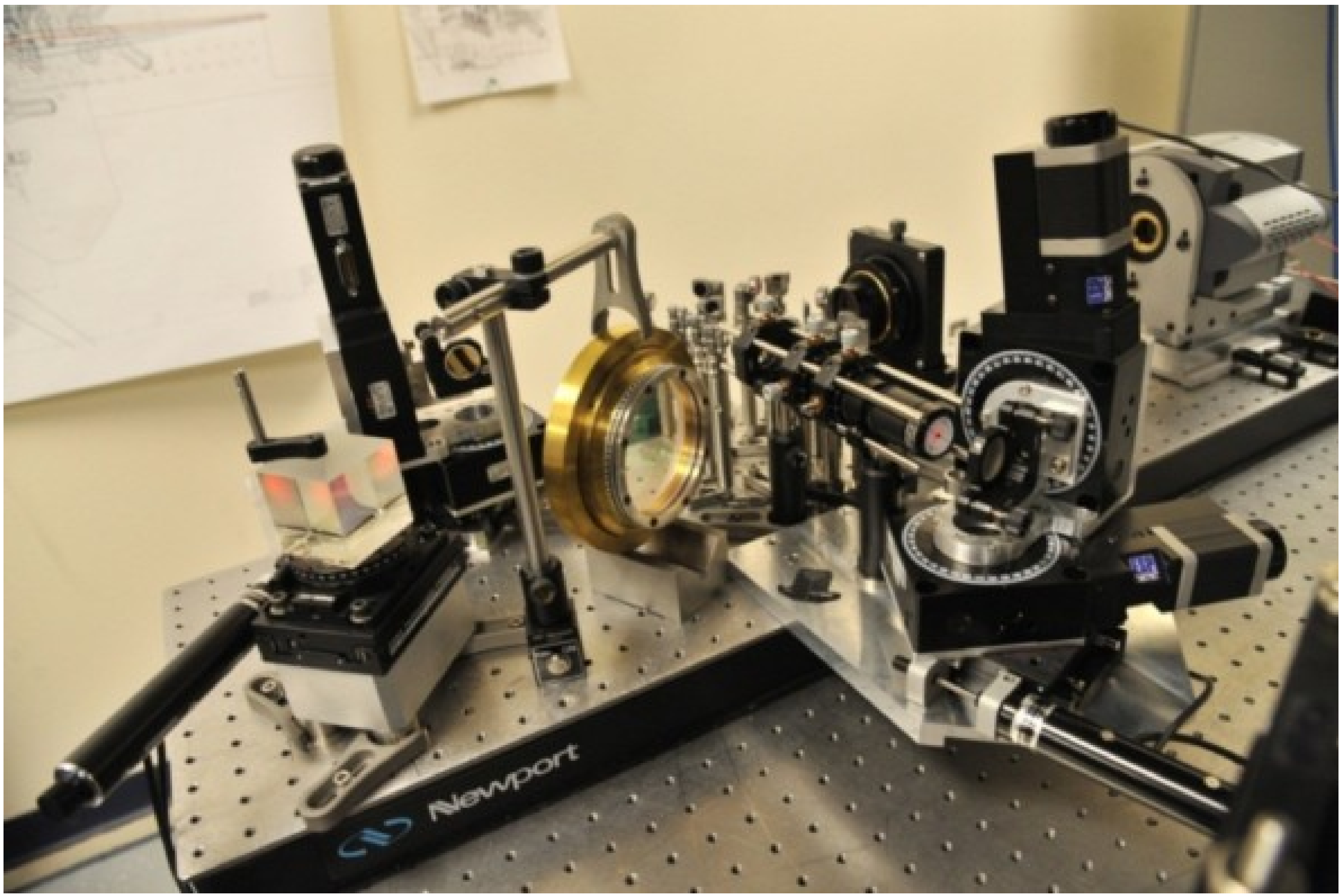
nlCWFS for 6.5m MMT



nlCWFS built for 6.5 m MMT

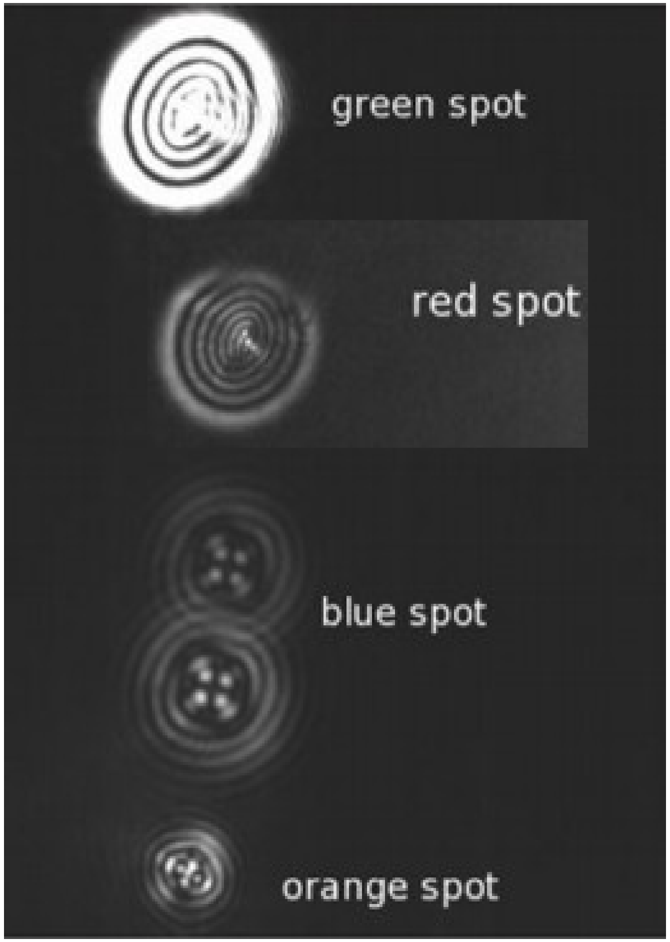


Fig. The four plane imaged on to a single detector.

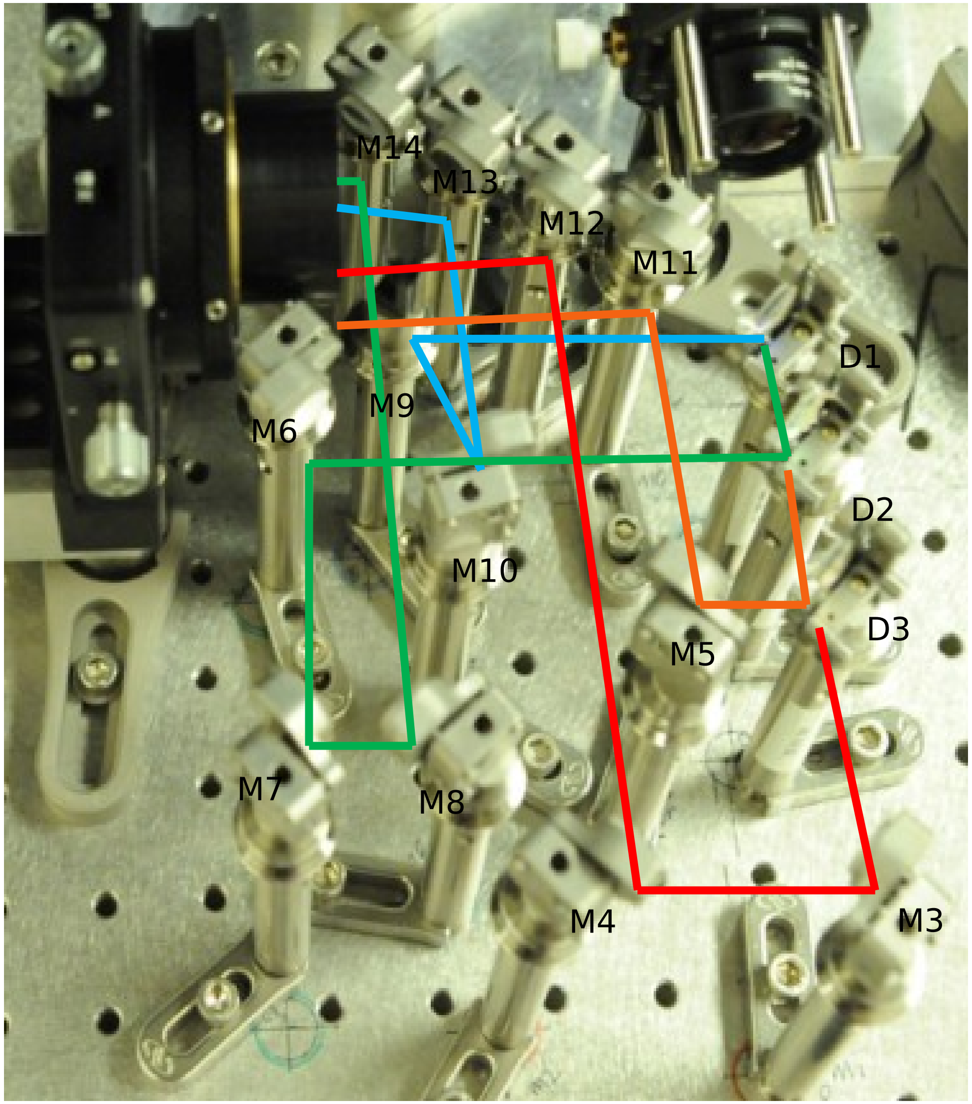
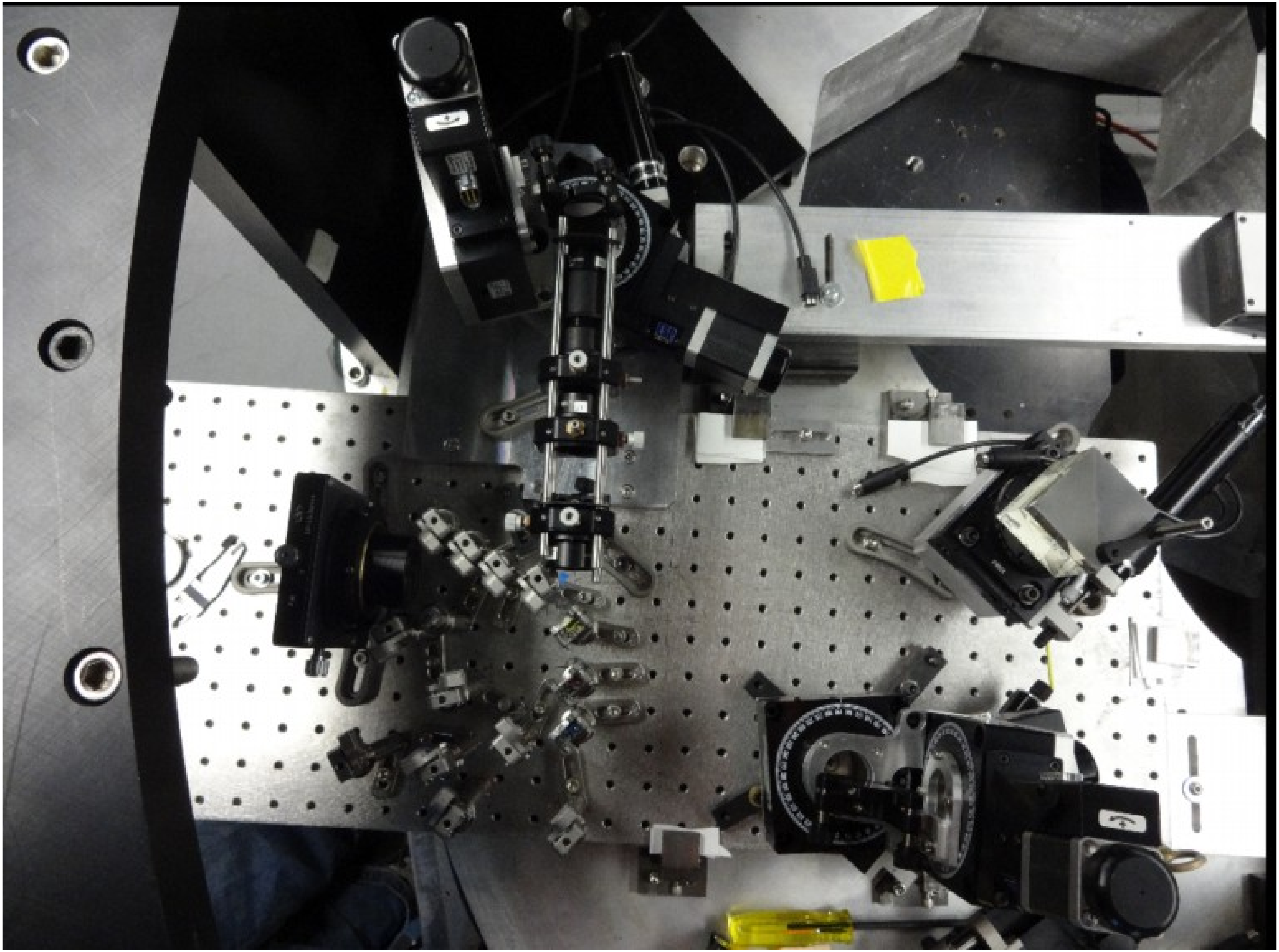
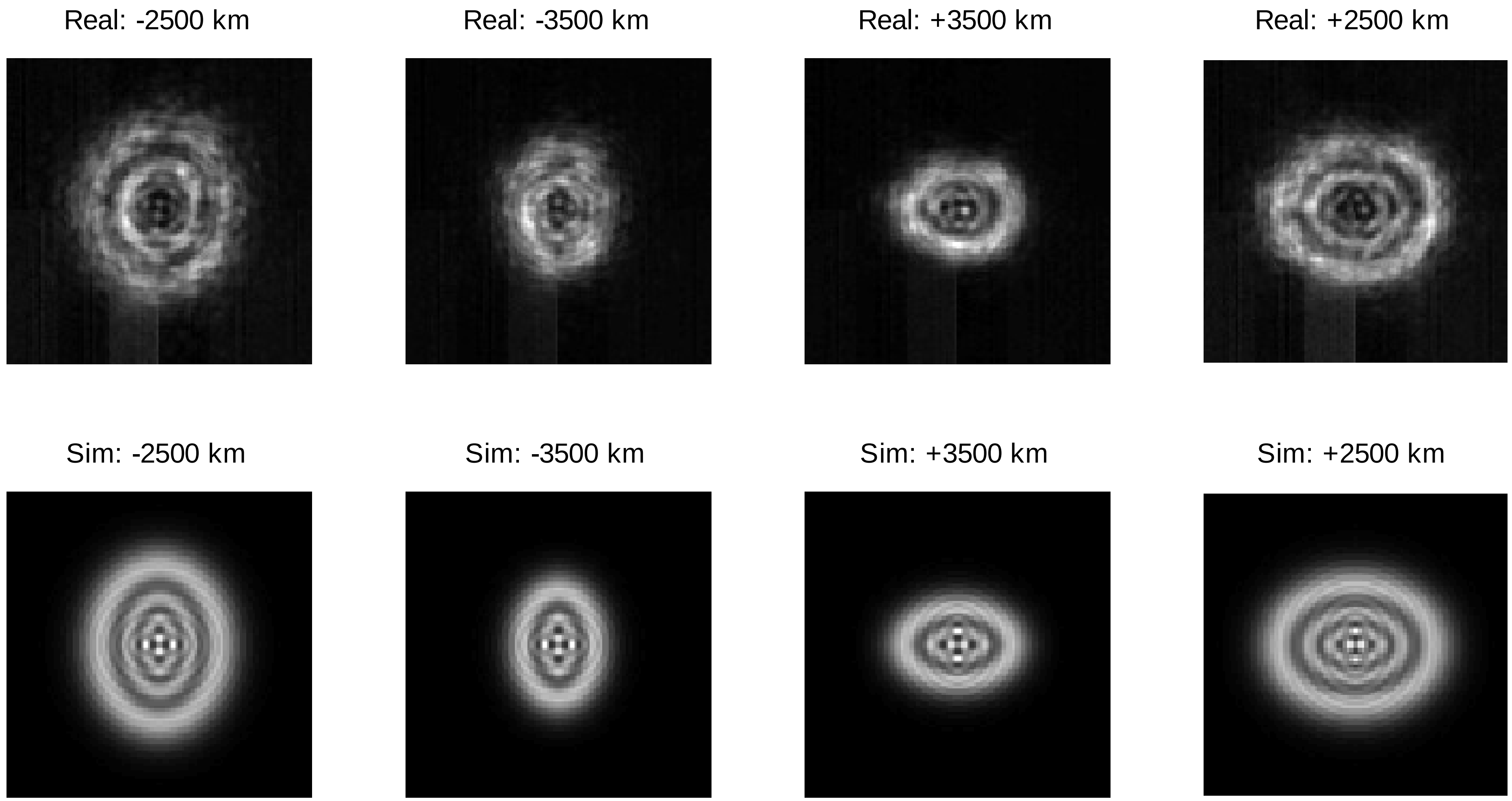


Fig. The four Fresnel planes have been created by using dichroics to split the light into four wavelength bands.



DM Generated 4 Plane Test with the 3.5 m SOR Telescope



Conclusion

nlCWFS enables high sensitivity WFS without requiring diffraction limited PSF in the WFS

On-sky data will soon be collected

- MMT: nlCWFS + SHWFS
- Subaru: nlCWFS + non-modulated pyramid
- SOR: DM modulation within SHWFS-based system
- AOLI: closing loop with nlCWFS + lucky imaging

Faster algorithm/hardware for WF reconstruction is a major challenge

Related work presented here:

- nlCWFS + pyramid effort at Subaru (C. Clergeon)
- Fast reconstruction for nlCWFS (C. Correia)
- AOLI system (J. Crass)
- DM+PyrWFS (Magrin, Raazzoni)