# High sensitivity wavefront sensing with the non-linear curvature WFS

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## 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

I will show in the next slides that it is not possible to get all 3 properties simultaneously, and the WFS needs to be carefully chosen to fit the AO system requirements.

# 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) ?

# High sensitivity WFS : Three examples

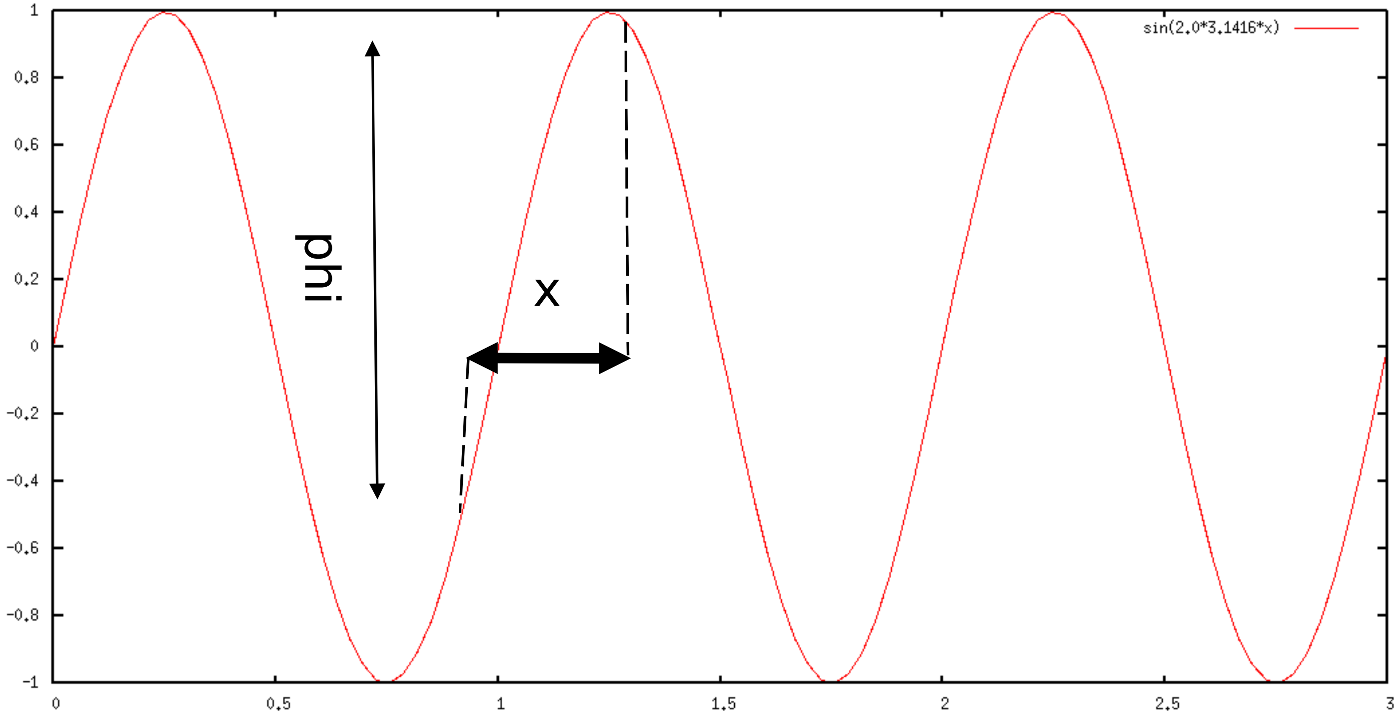
- **Fixed Pyramid WFS**: A pyramid is placed in the focal plane. The starlight hits the tip of the pyramid
- **Zernike phase contrast**: A small phase shifting mask is placed in the focal plane. Roughly 1/2 of the light goes through, 1/2 goes around. The two halves interfere to give an intensity signal
- **Mach-Zehnder / Self-referencing interferometer / point diffraction interferometer**: An interferometer is assembled by splitting the beam in 2 and recombining the two halves. On one of the arms, a spatial filter (pinhole) is placed to create the “reference” beam which interferes with the wavefront

**These 3 options are Linear but will fail (or loose sensitivity) if there is more than ~ 1 rad of WF error ! -> poor dynamical range**

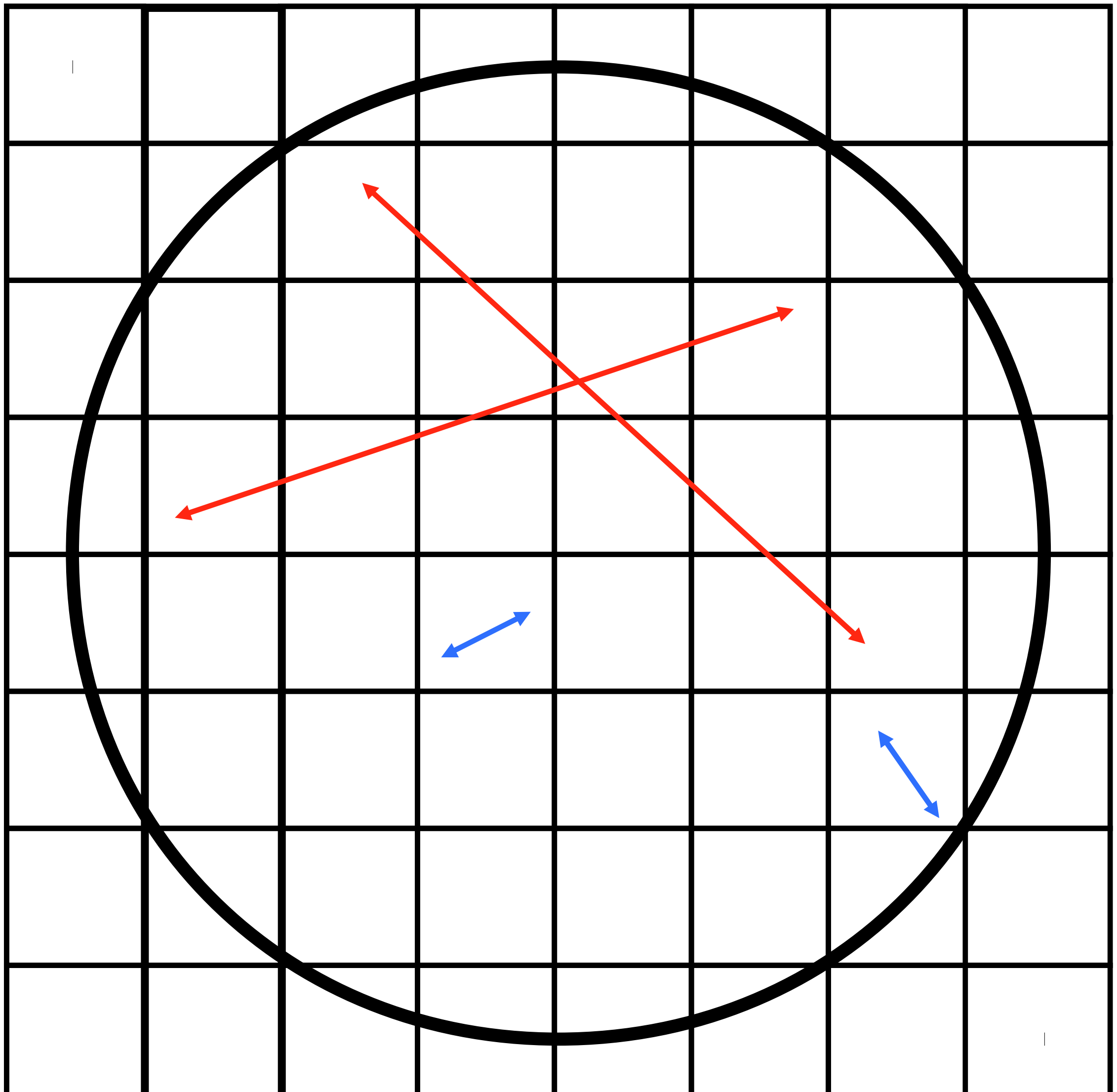
# Sensitivity: how to optimally convert a phase error into an intensity signal ?

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**

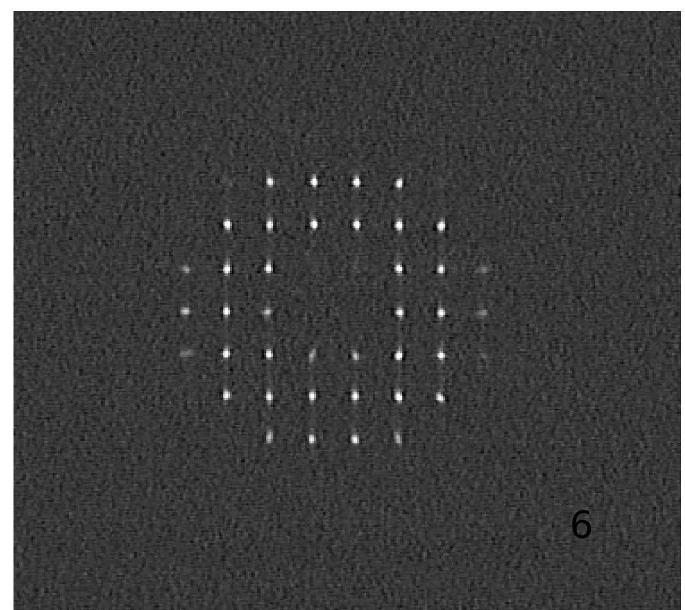


# SH WFS : sensitivity issue for low spatial frequencies



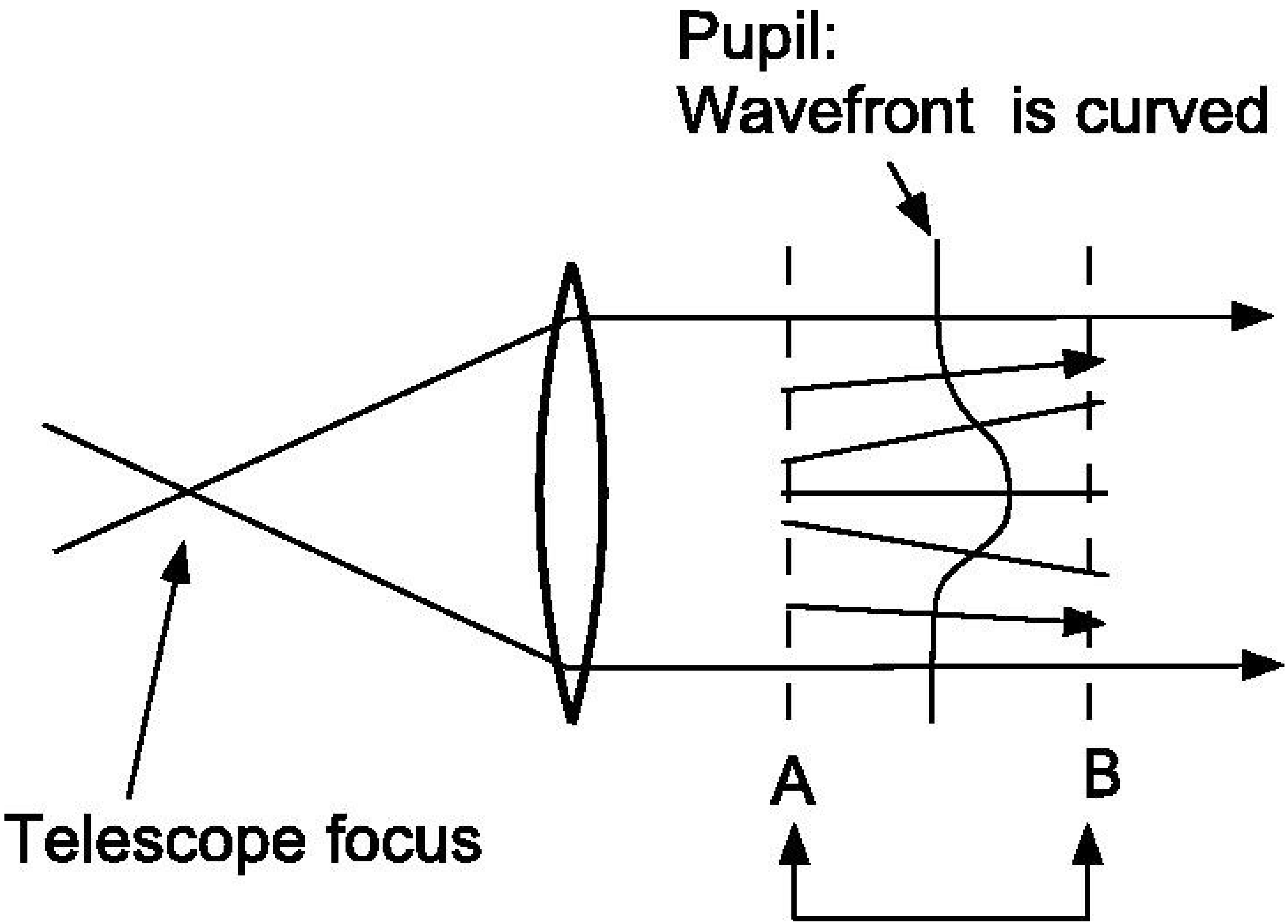
Problem:
SH does not allow interferences between points of the pupil separated by more than subaperture size

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



# Curvature WFS

Light propagation turns phase into amplitude (similar to scintillation)

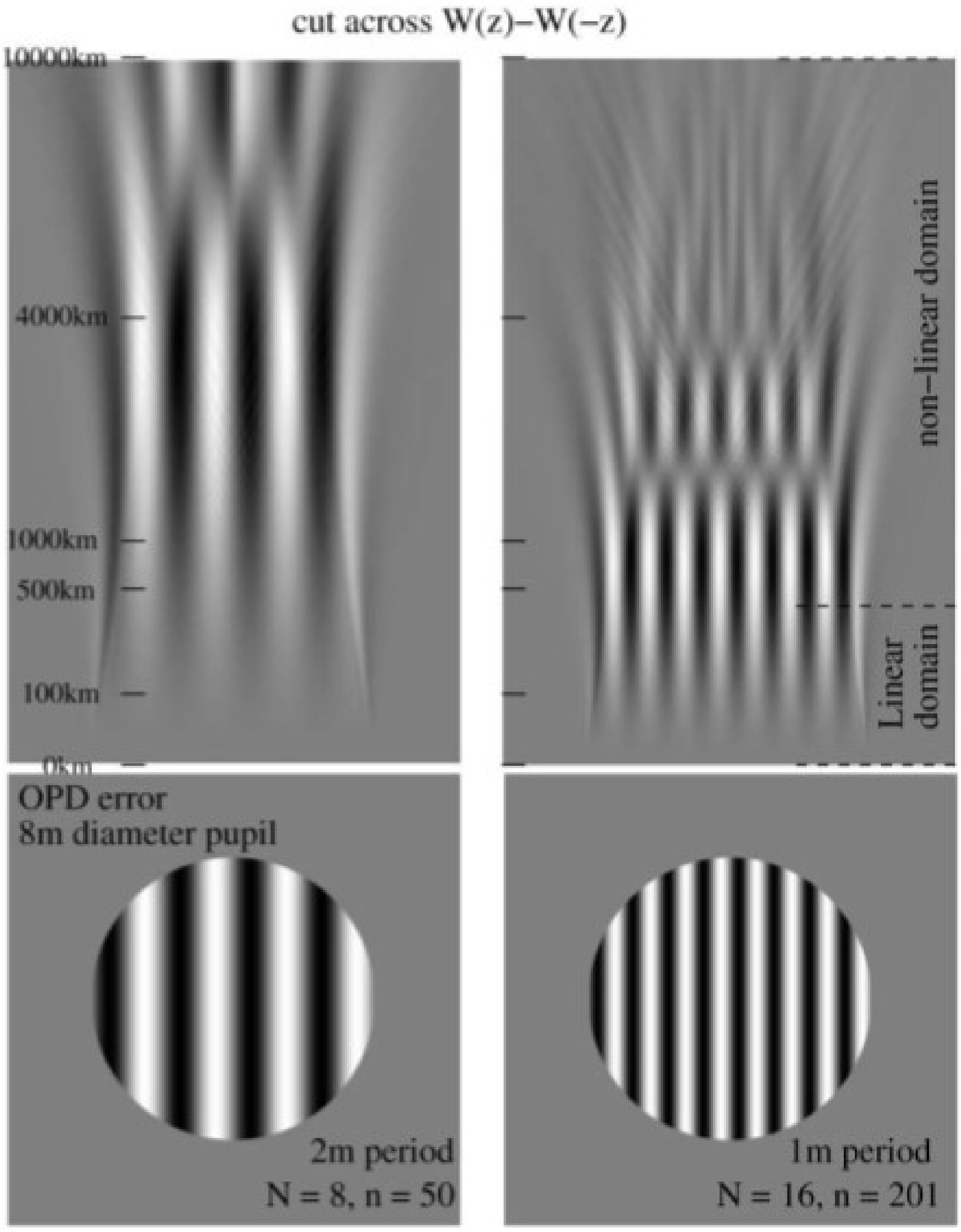


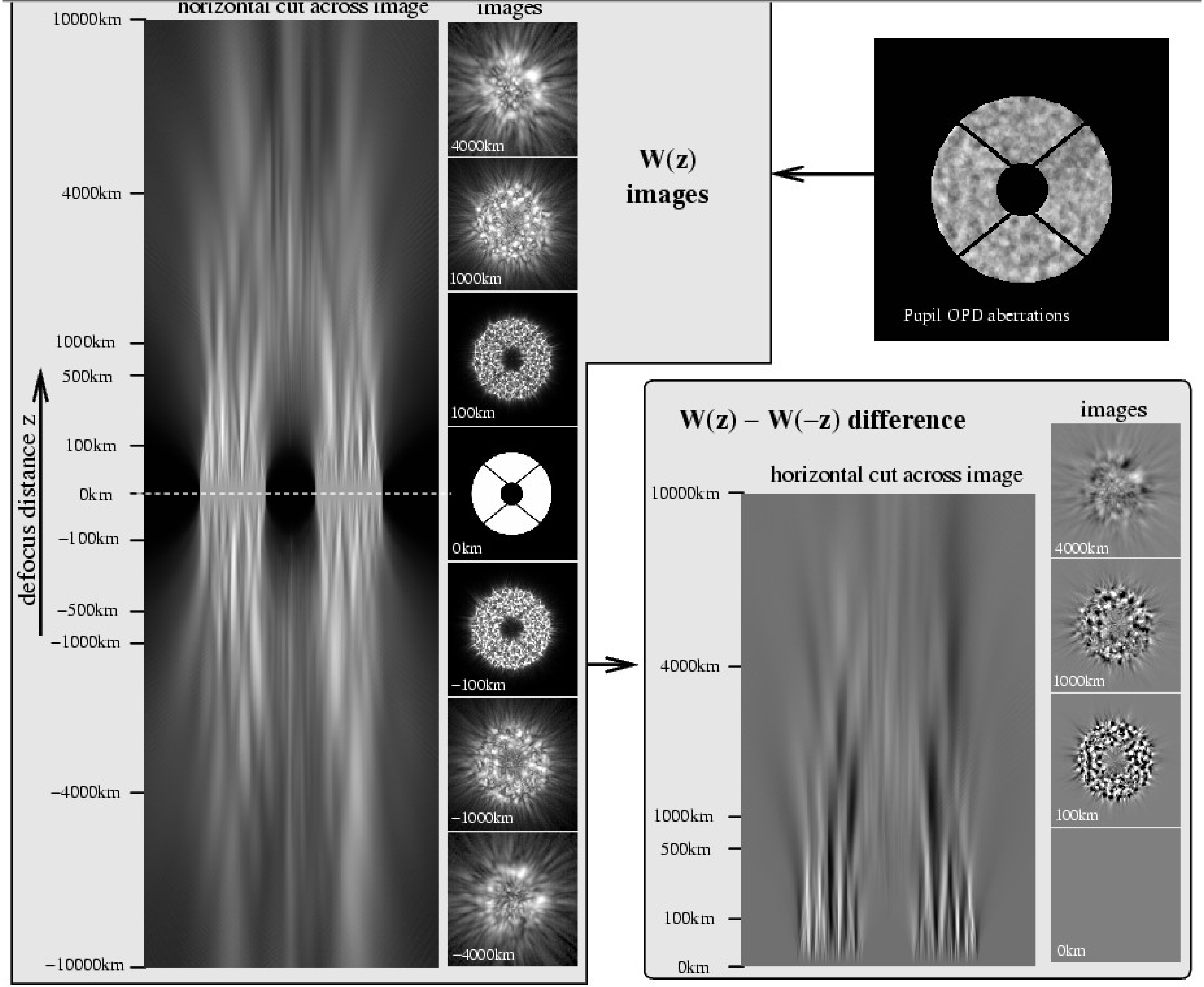

Lenslet array used to inject light into a series of fibers, which are connected to photon-counting Avalanche PhotoDiodes (APDs)

# 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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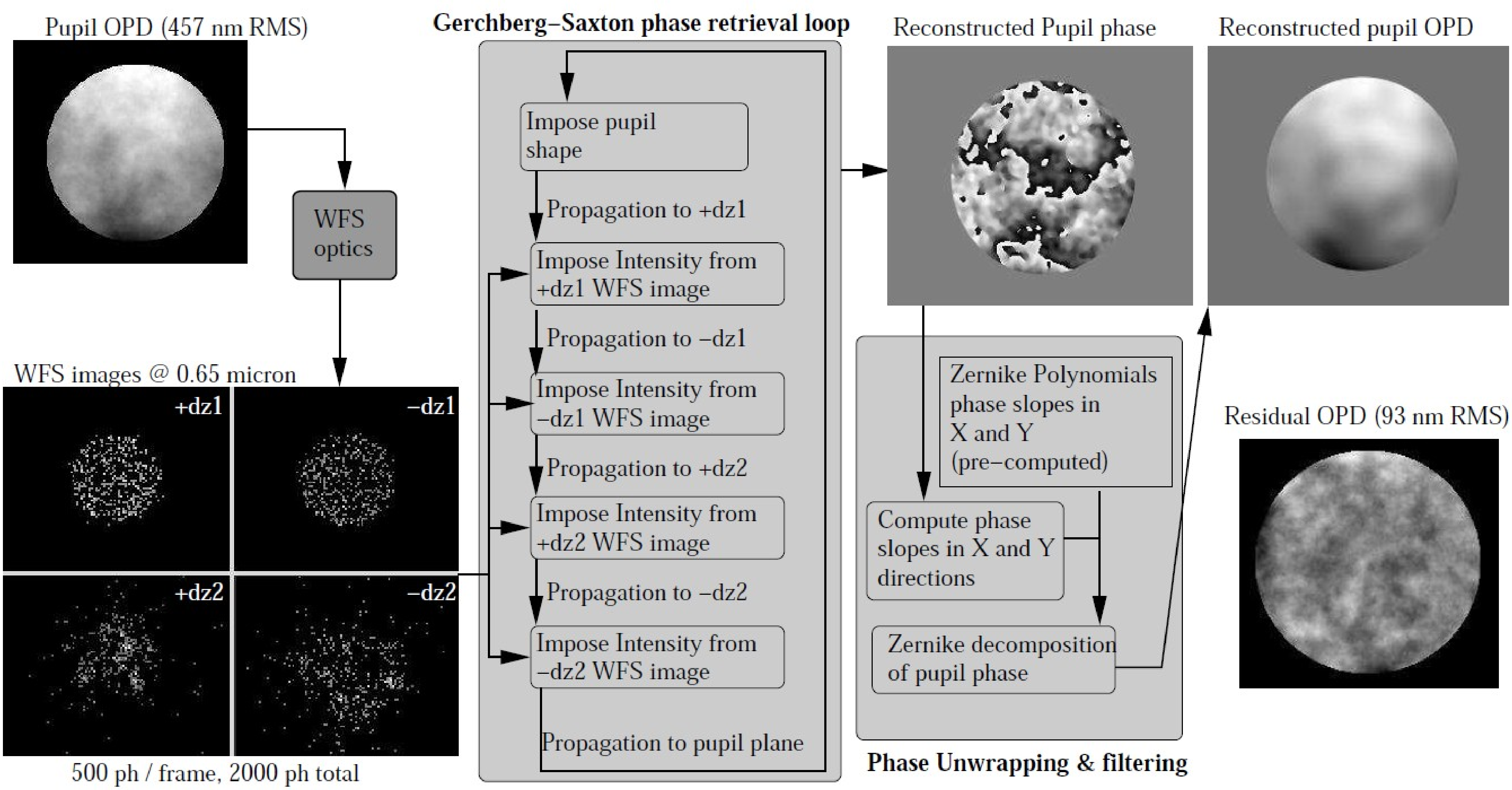
# Reconstruction Algorithm



# Reconstruction Algorithm

For faster reconstruction:
(1) bin down data to low resolution and run iterative algorithm
(2) expand solution to full resolution and run a small number of iterations
(3) Speed up convergence by injecting derivative between iterations

Iterative loop is slow, but:

- Linear algorithm can give fast low sensitivity estimate used as starting point
- Locally linear (within 1 rad)
- Becomes linear if aberration < 1 rad (valid for high performance AO closed loop)

Faster hardware coming online (GPUs)

# Wavefront sensing at the diffraction limit of the telescope

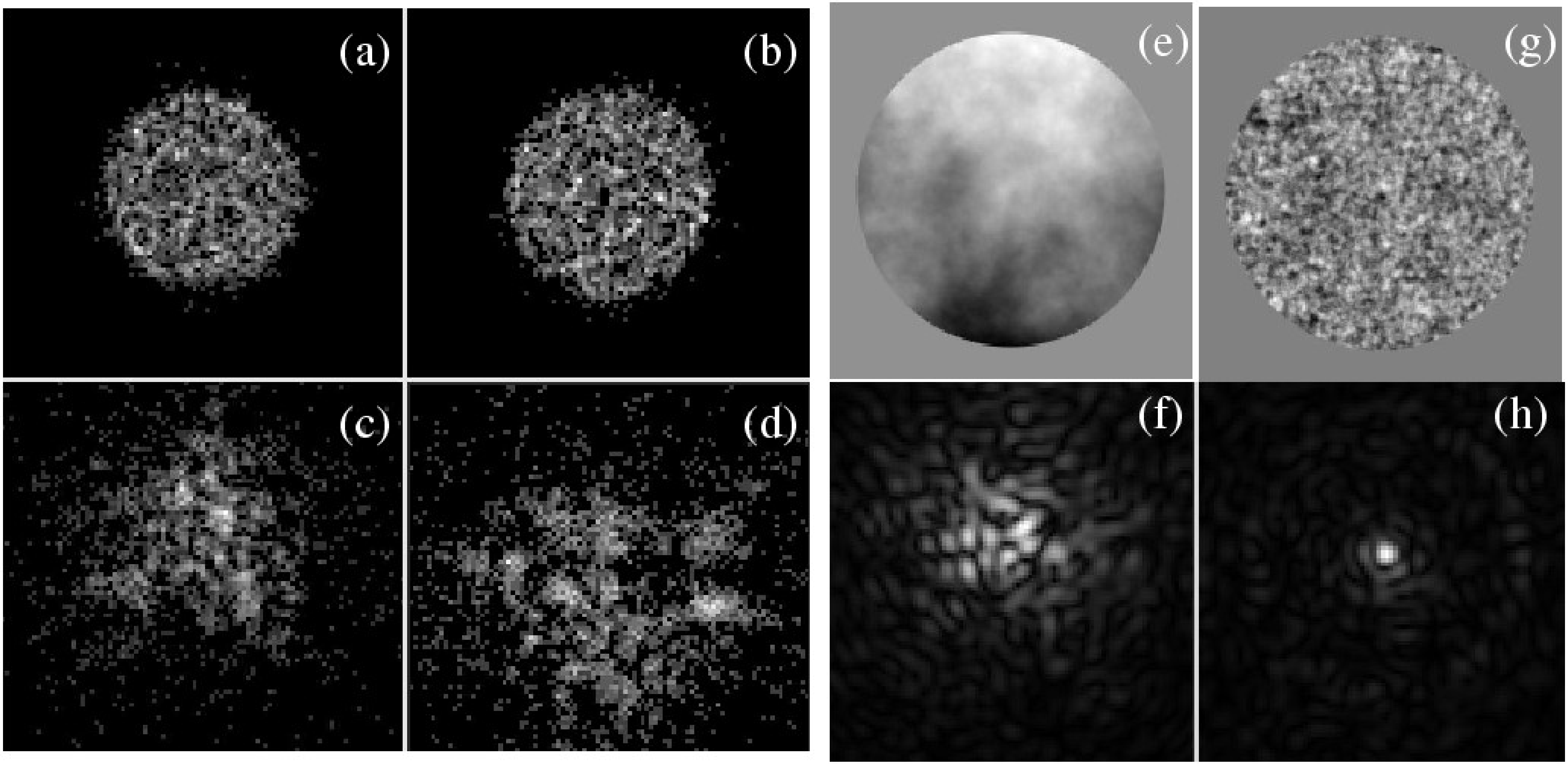
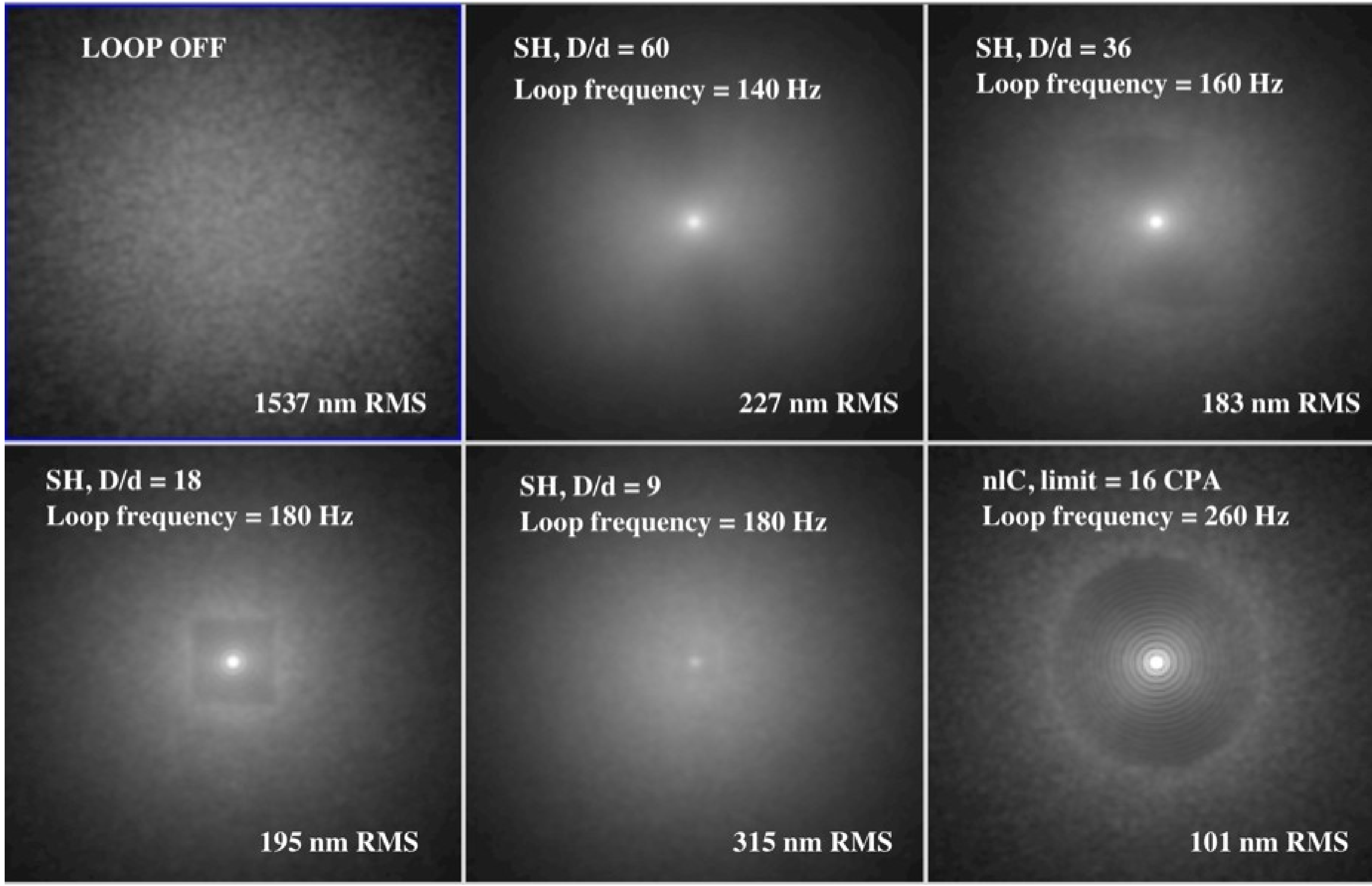



Fig. 9.— Wavefront reconstruction using the algorithm shown in fig. 8. Four noisy defocused pupil images (images (a), (b), (c) and (d)) are acquired to transform the pupil phase aberrations (e) into intensity signals. The input pupil phase is 609 nm RMS, yielding the PSF (f) before correction. After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

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% |

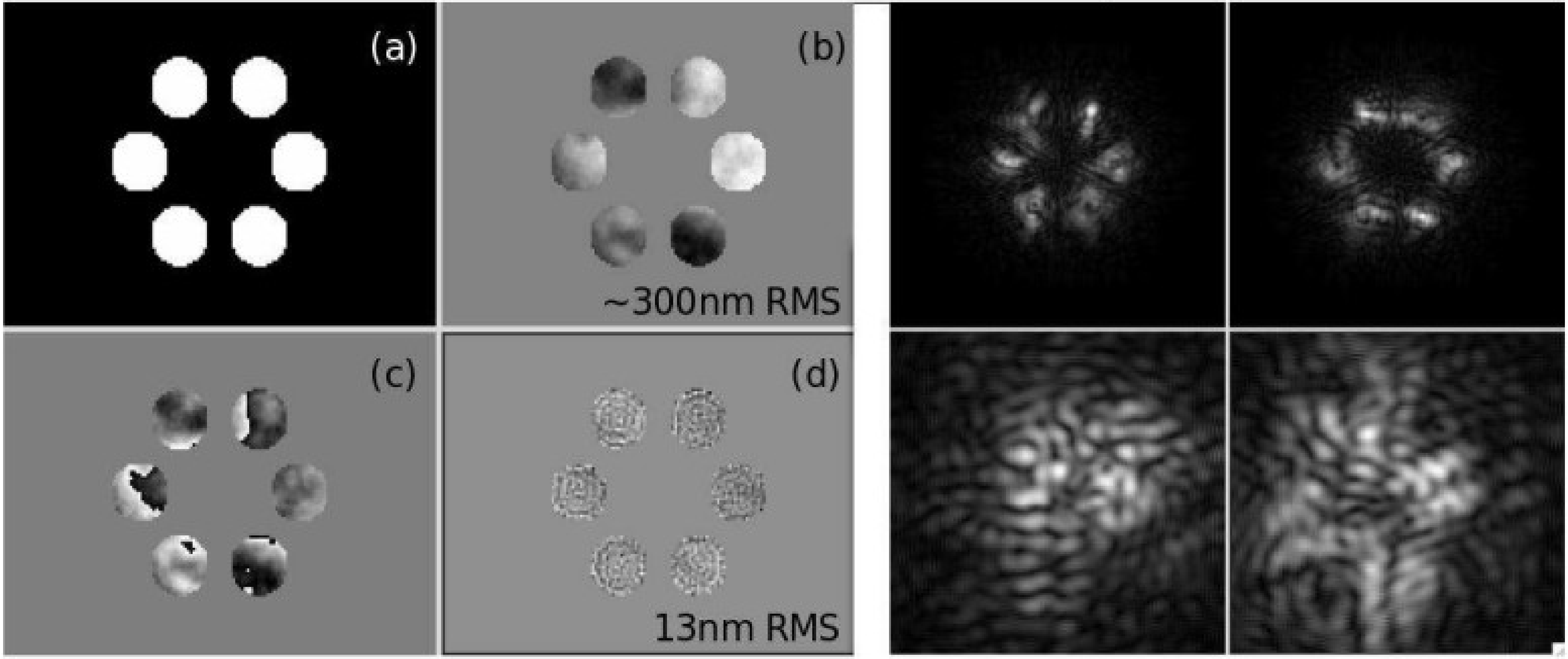



Fig. 9.— Wavefront reconstruction with dual stroke non-linear CWFS on a sparse pupil. The pupil amplitude (a) and phase (b) yield the four defocused pupil images shown on the right. The recovered pupil phase (c) and the residual phase error (d) demonstrate that dual stroke non-linear CWFS can simultaneously 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 $0.65\ \mu m$.

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

# Sensitivity

**<u>Wavefront sensor sensitivity: definition</u>**

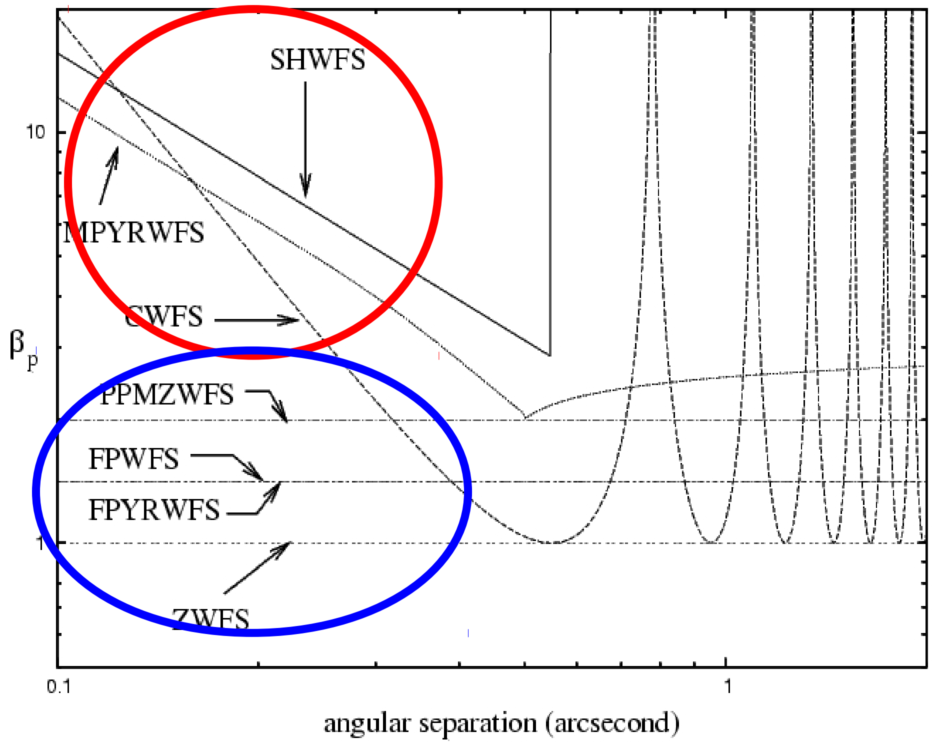
Sensitivity = how well each photon is used

For a single spatial frequency (OPD sine wave in the pupil plane, speckle in the focal plane):

Error (rad) = Sensitivity / sqrt( # of photons)

**<u>IDEAL WFS:</u>**
**Sensitivity Beta = 1   (1 ph = 1 rad of error)**
**At all spatial frequencies**
**<u>Non-ideal WFS:</u>**
**Beta > 1  (Beta x Beta ph = 1 rad of error)**

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



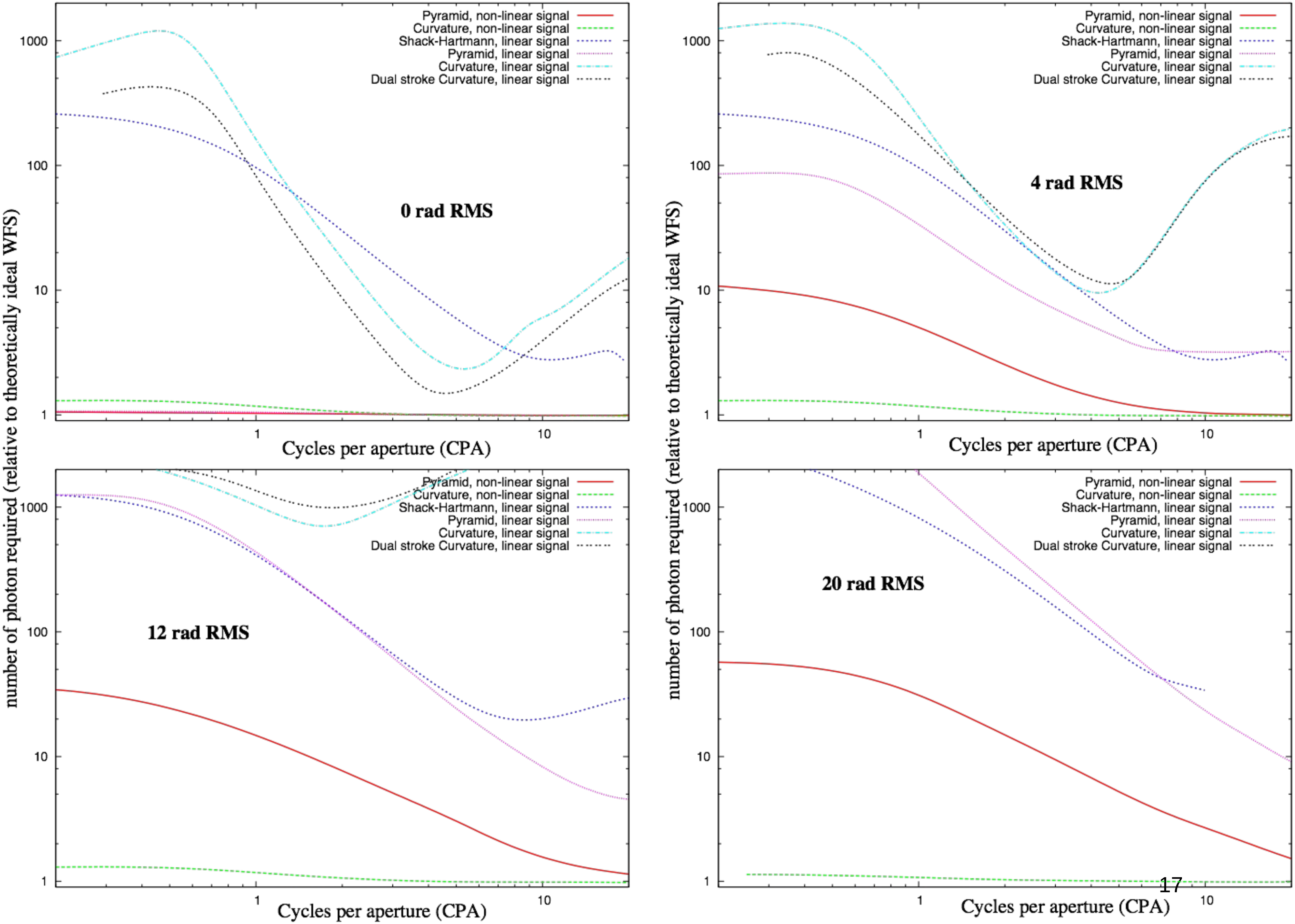

Square root of # of photons required to reach fixed sensing accuracy

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

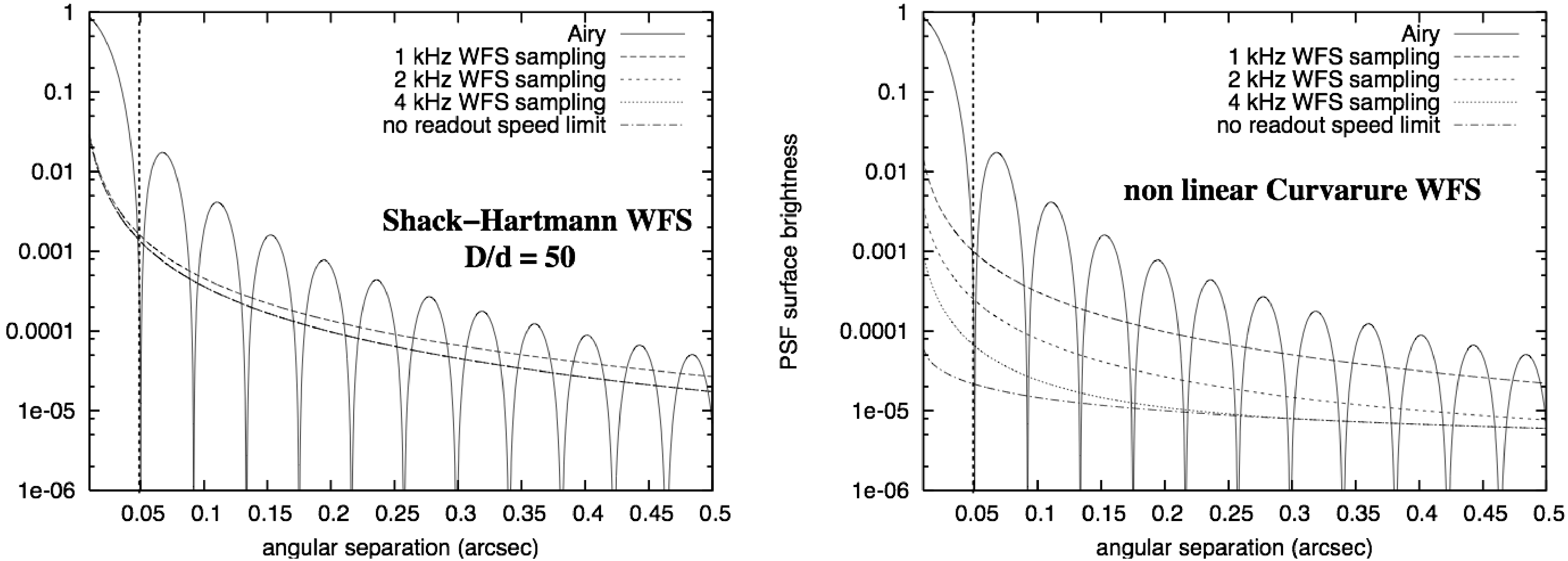
Figure above shows sensitivity (y axis) as a function of pupil spatial frequency (x axis). Pupil spatial frequency = angular separation in focal plane.

ALL wavefront sensor options have very good sensitivity at the spatial frequency defined by the WFS sampling
SOME wavefront sensors loose sensitivity at low spatial frequencies (red), other do not (blue)

# Sensitivity compared with other schemes



# 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)**

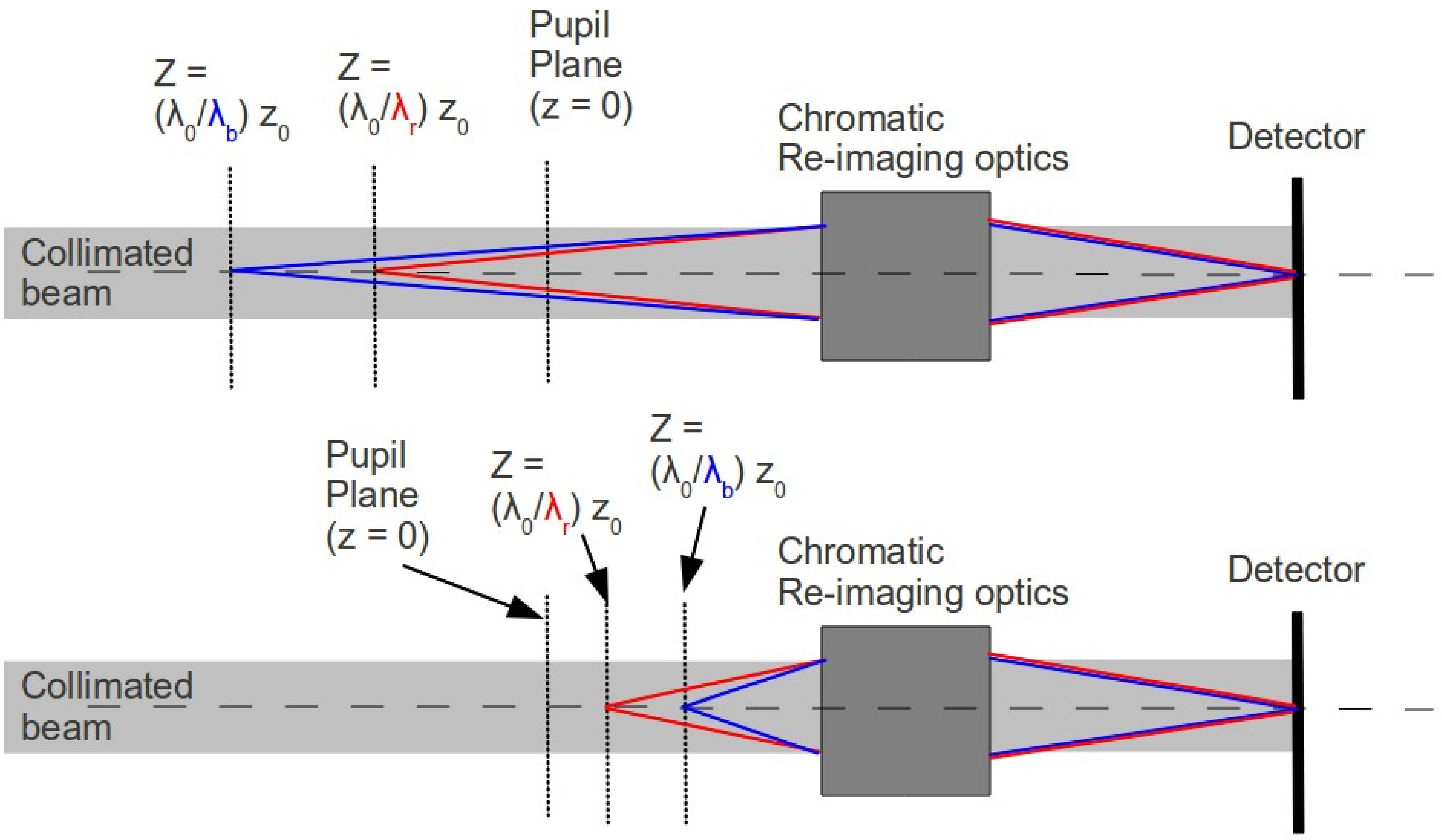
*Examples: Pyramid (non-modulated), non-linear curvature*

Tip-tilt example (same argument applicable to other modes):
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 $\lambda/D$)

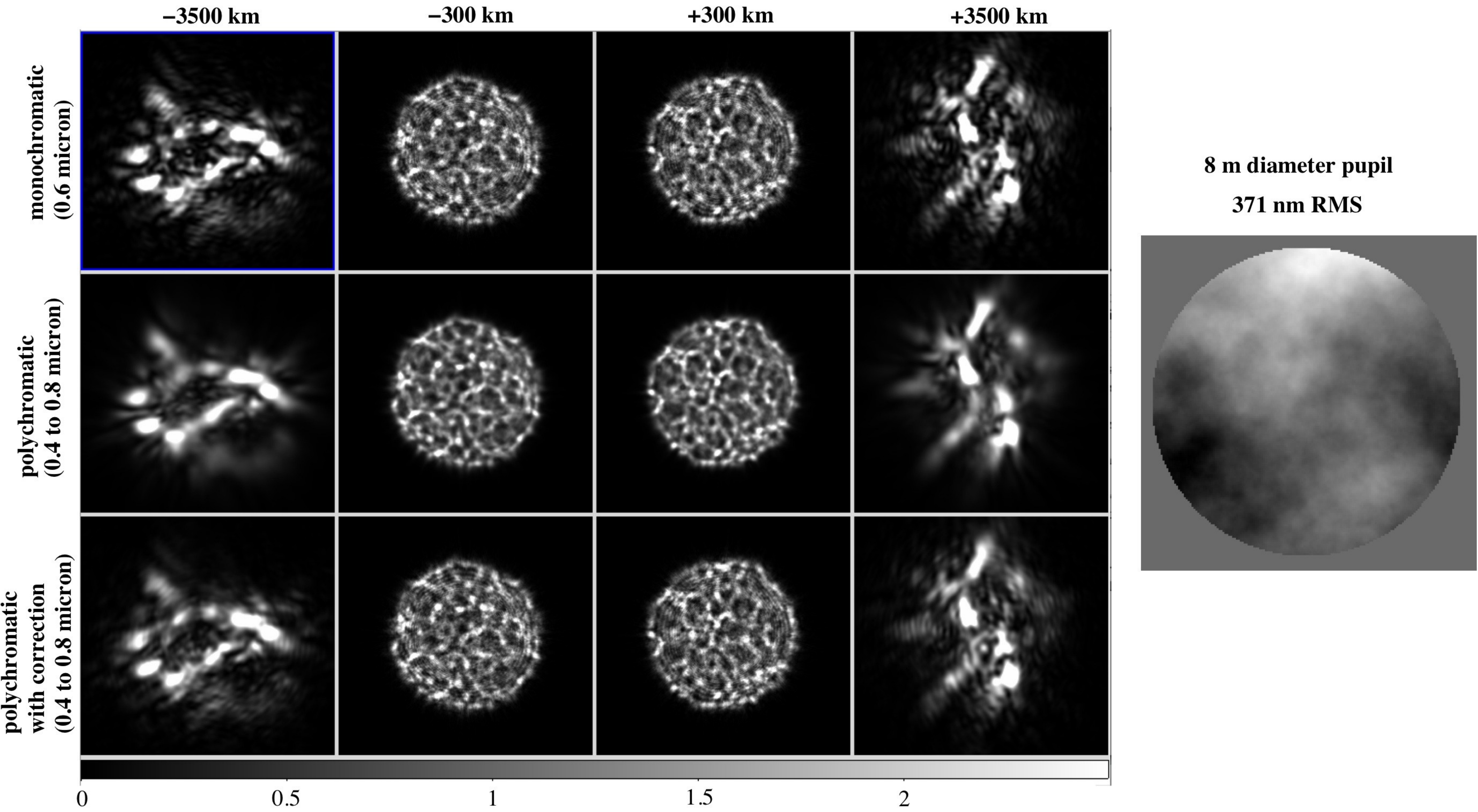
**This makes a big difference for Extreme-AO on large telescopes**

**For Tip-Tilt, SHWFS on ELT is 40000x less sensitive than diffraction-limited WFS (11.5 mag)**
**Similar gain on other low order modes**

# Chromaticity



# Chromaticity



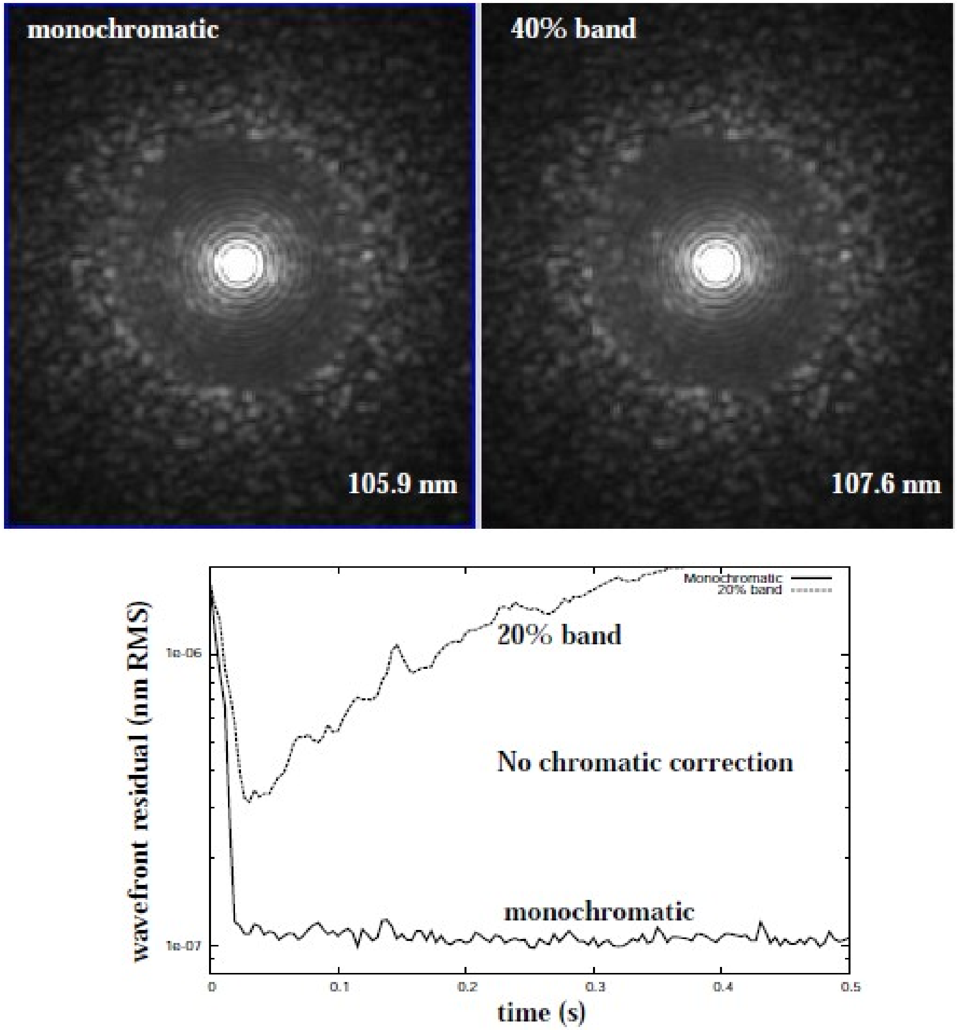


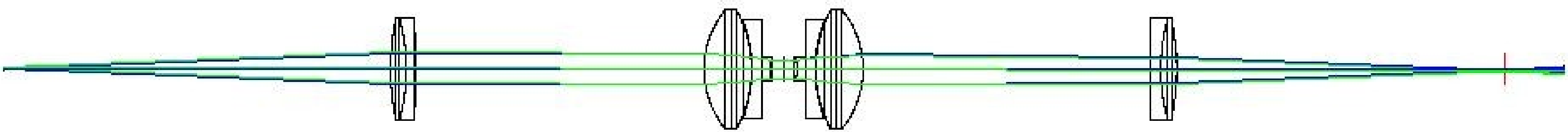

Fig. 6.— Top: Closed loop 1 second exposure PSFs at 0.85 $\mu$m with a nlCWFS working in monochromatic and broadband ($d\lambda/\lambda$ = 40%) light. In both simulations, the total number of photons in the nlCWFS is 3e6 ph/s. Bottom: Without chromatic correction within the nlCWFS (replacing the chromatic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

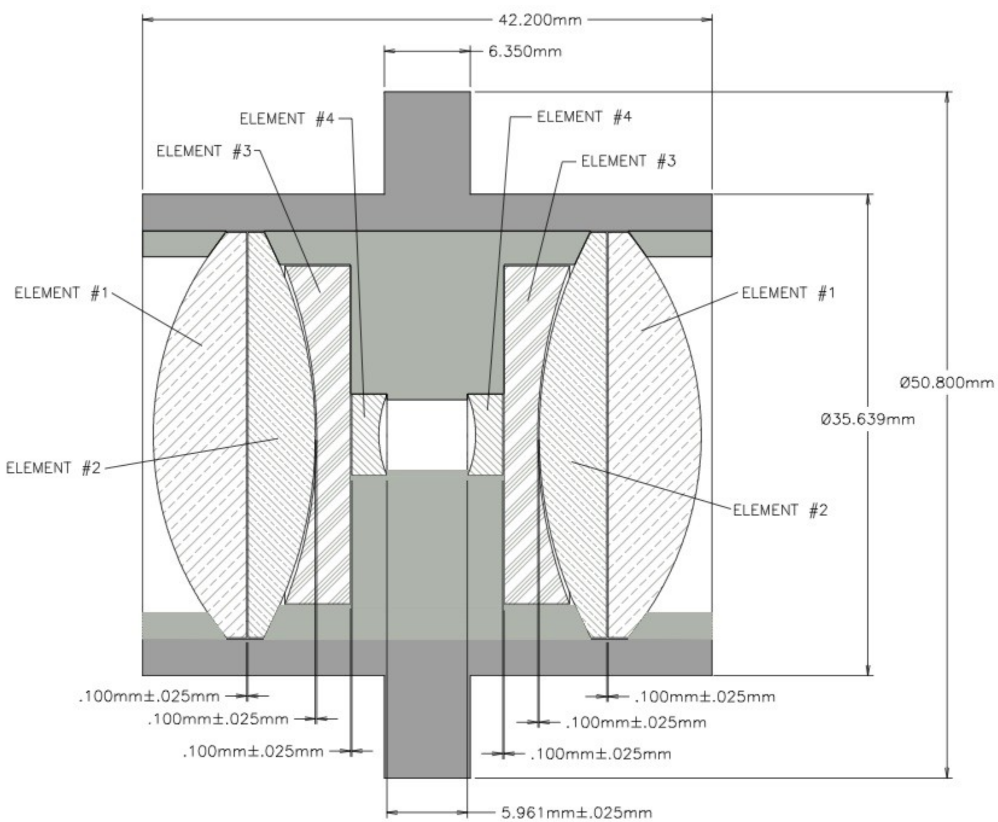
# Chromaticity compensation

Simulation results

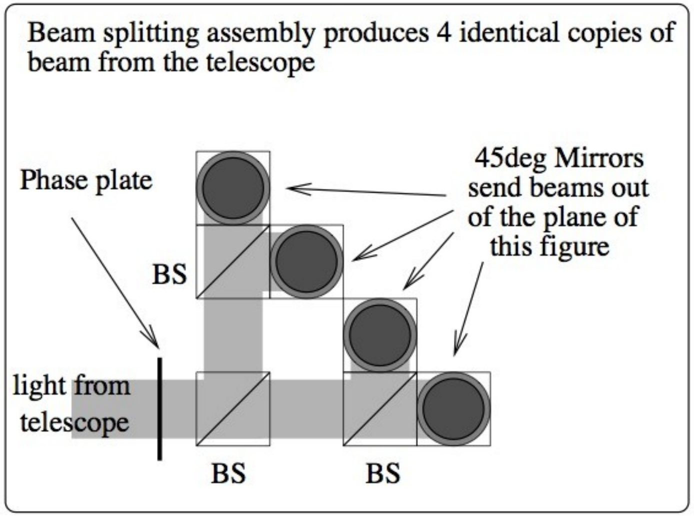
Monochromatic algorithm
Polychromatic data

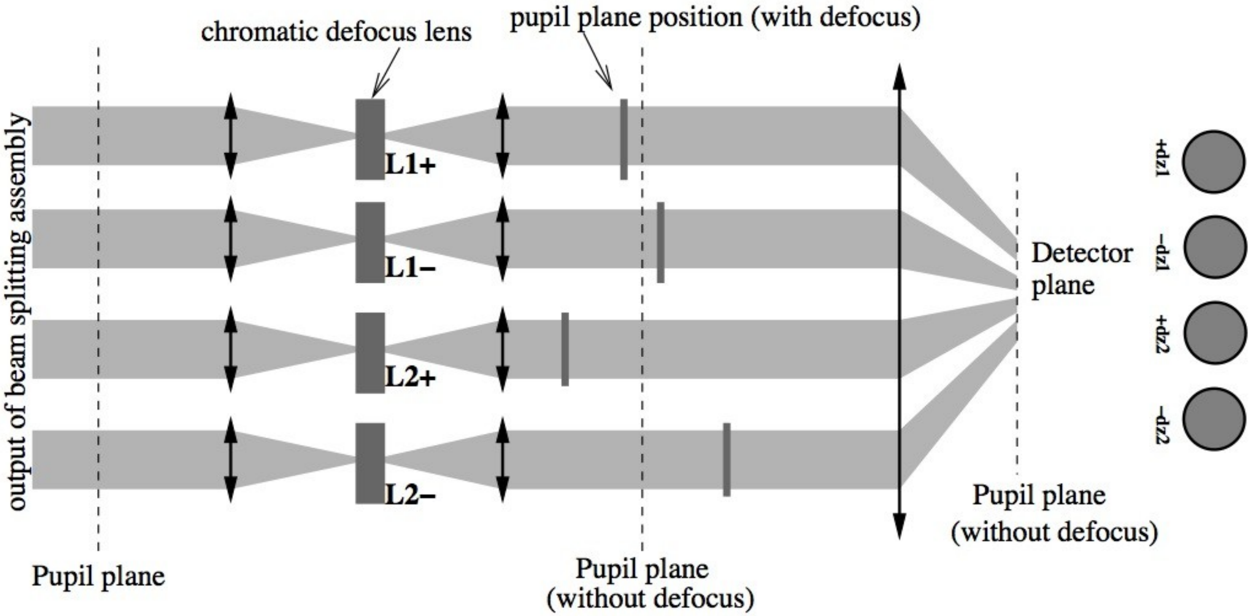
# Chromaticity compensation with chromatic optics






# Optical implementation




Better solution (suggested by Marcos Van Dam):
split 4 beams according to wavelength with dichroics

→ mitigates (solves ?) chromaticity issue (to be simulated and validated)

# Faint source regime

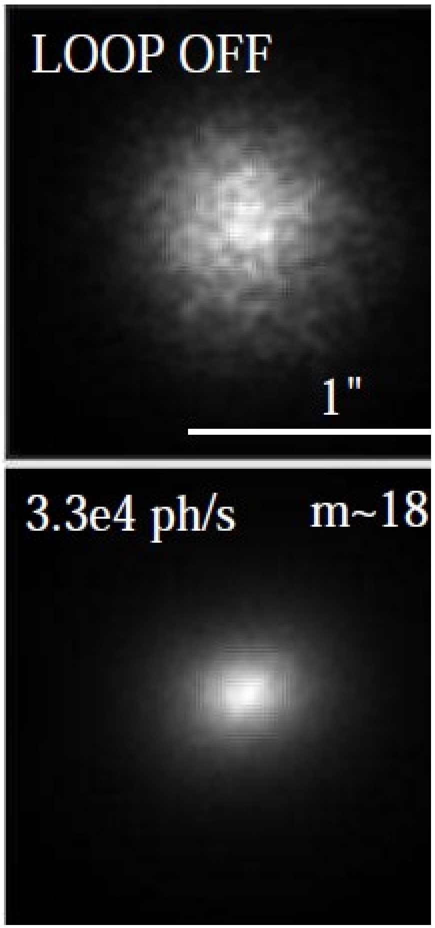



Fig. 7.— Simulated
obtained with a non-li
based AO system. Th
$\mu$m for this simulatio

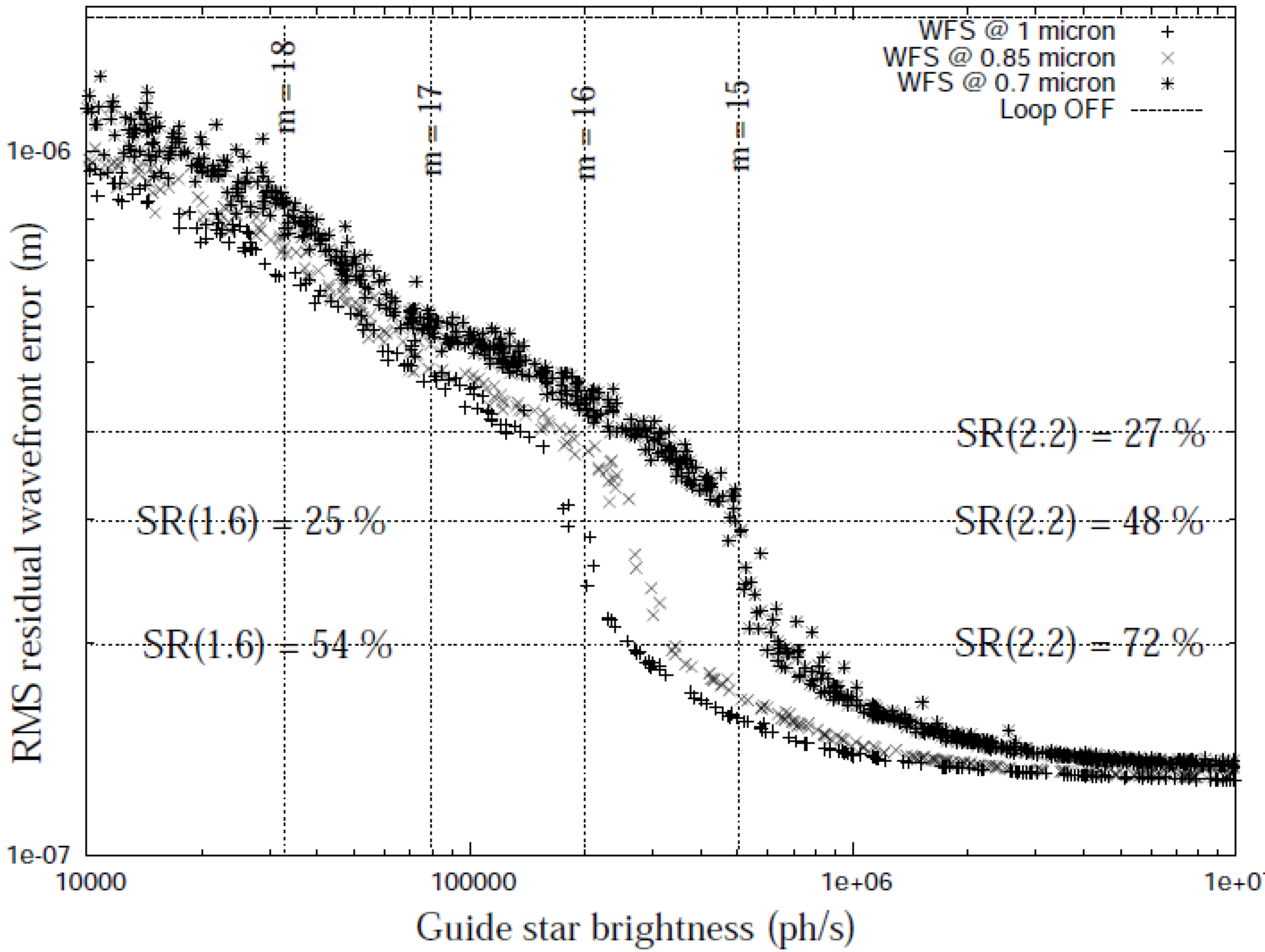
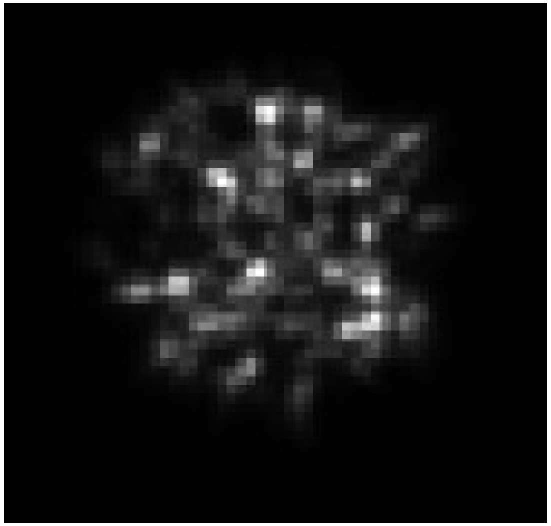



Fig. 8.— Simulated performance of a low order nlCWFS-based system (first 200 Zernike modes corrected) as a function of sensing wavelength (0.7, 0.85 and 1.0 $\mu$m) and guide star brightness. The stellar magnitudes given in this figure assume a 20% efficiency in a 0.5$\mu$m wide band. Each point in this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

# Extended sources



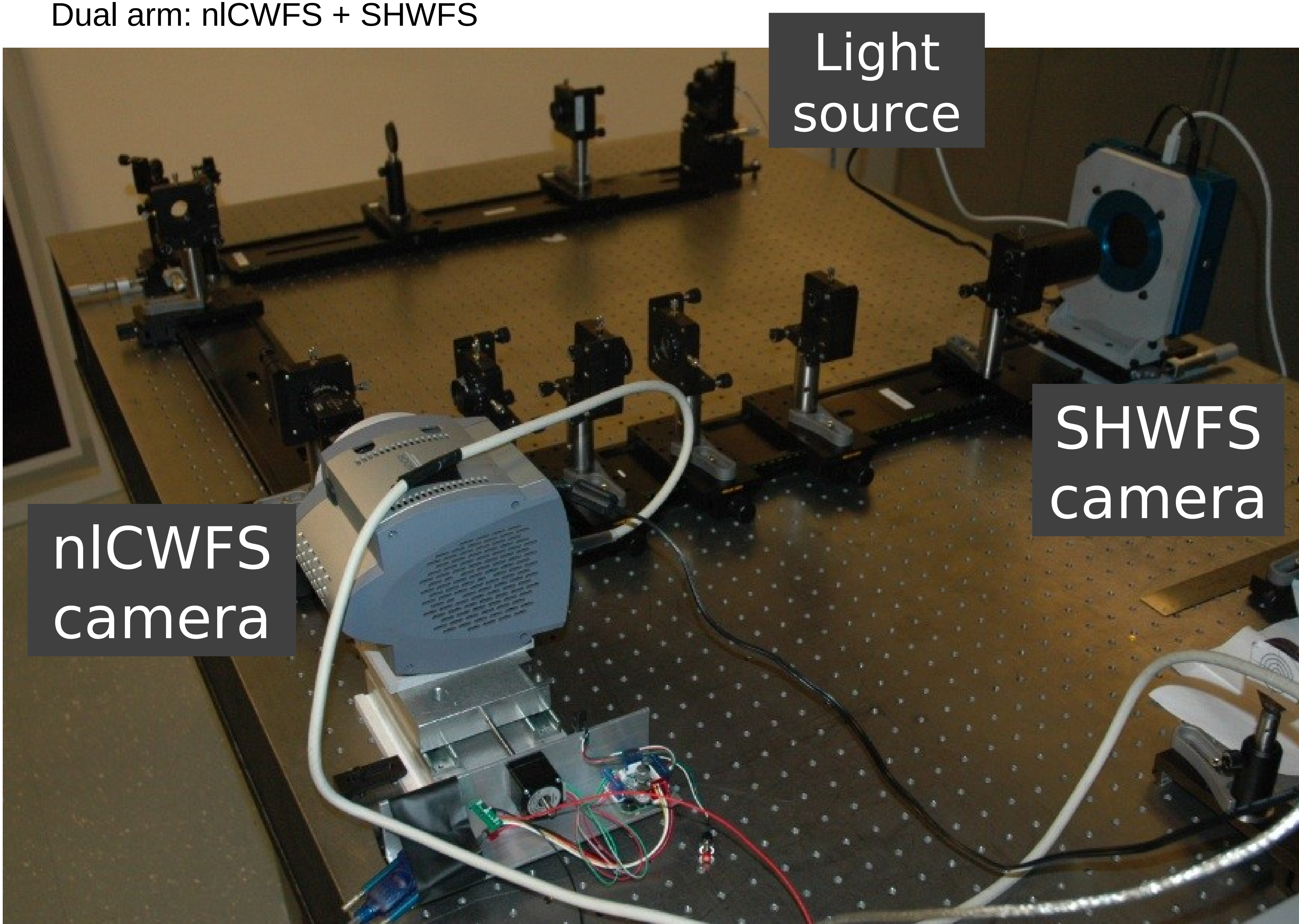
Extended source:
→ no diffraction limited speckles
→ sensitivity loss

Example: seeing-limited source (Laser Guide Star)
→ no gain beyond SH WFS

However, nlCWFS should be beneficial for extended source with fine structure
→ simultaneous wavefront + source estimation required

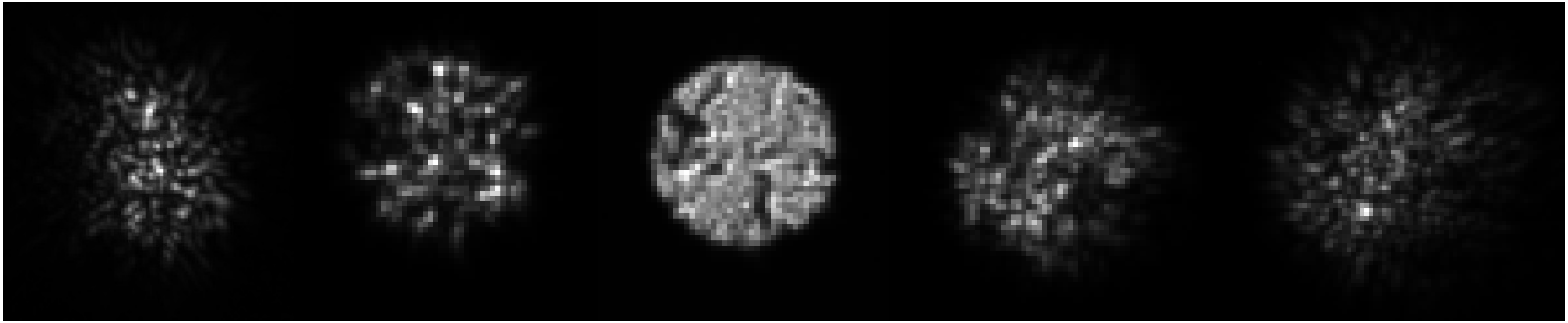
# Lab validation

Dual arm: nlCWFS + SHWFS



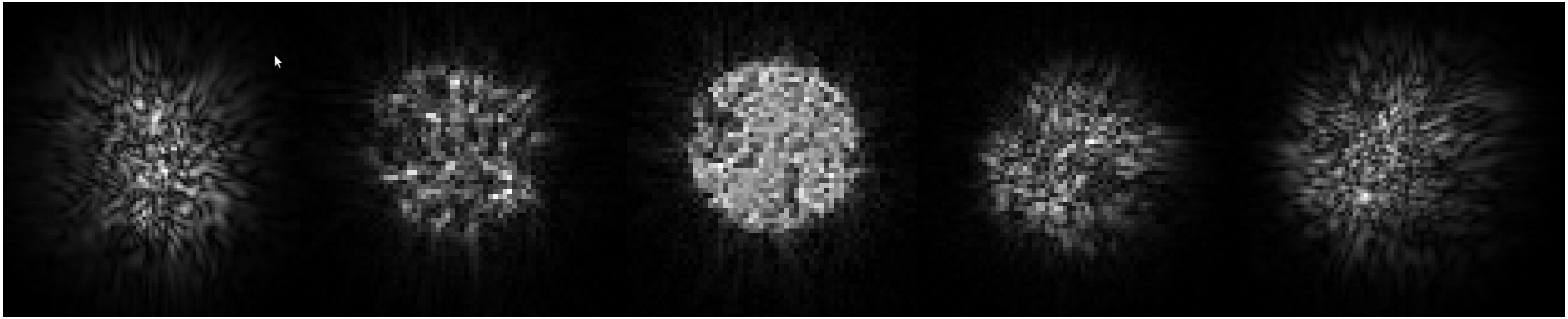
# Wavefront reconstruction

Data acquired in the lab



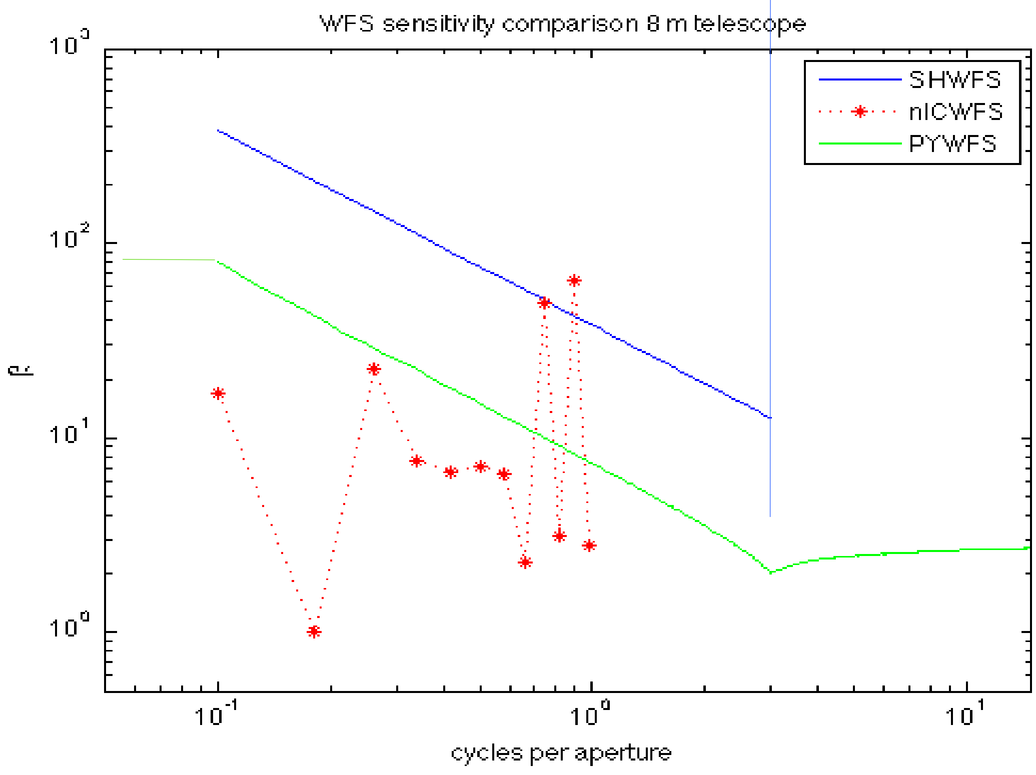
-dz2 -dz1 pupil +dz1 +dz2

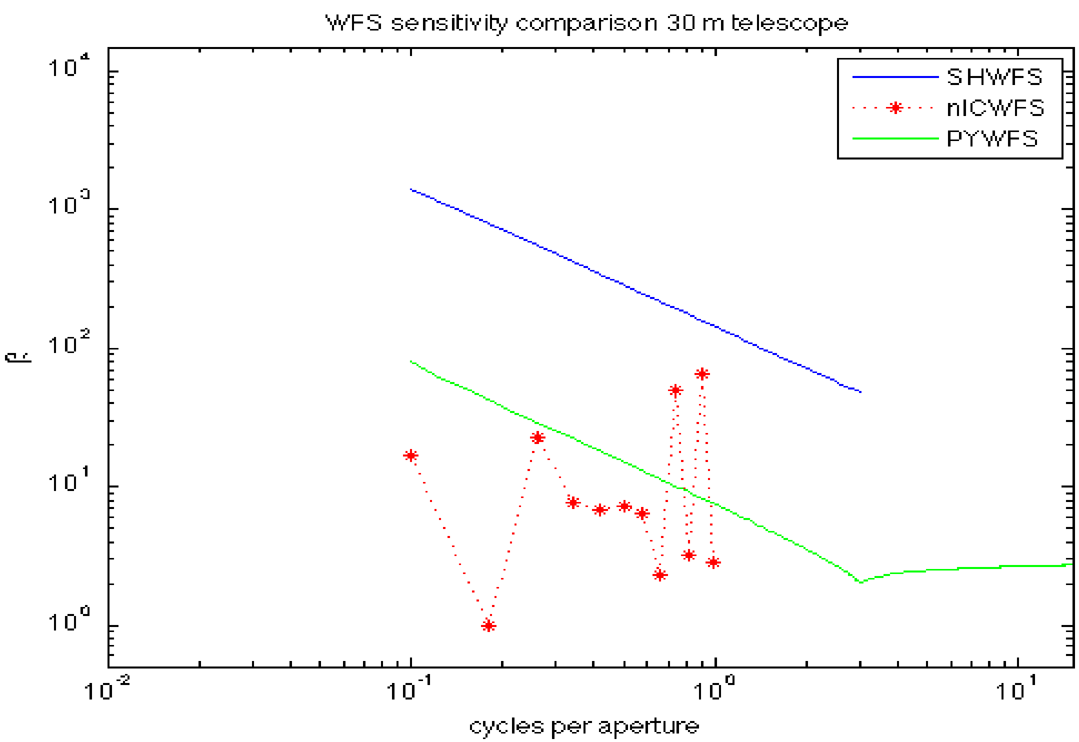
Gerchberg-Saxton solution



-dz2 -dz1 pupil +dz1 +dz2

# Sensitivity measurement using lab data



# Conclusions

The nlCWFS concept offers **high sensitivity without requiring high quality wavefront** → attractive for adaptive optics

Can **fully exploit the telescope diffraction limit** in a wide range of conditions

- Star brighter that mV~15
- Natural guide star (or possibly extended object with structure)

→ nlCWFS greatly improves sensitivity for NGS, and for low-order aberrations, makes NGS as good a target as LGS ~1000x to 10000x brighter on large telescopes

Challenges are **computing power** for reconstruction and chromaticity

**Lab demonstration ongoing, plans to install on ground-based telescope**

*For more info on the concept:*

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