Adaptive Optics

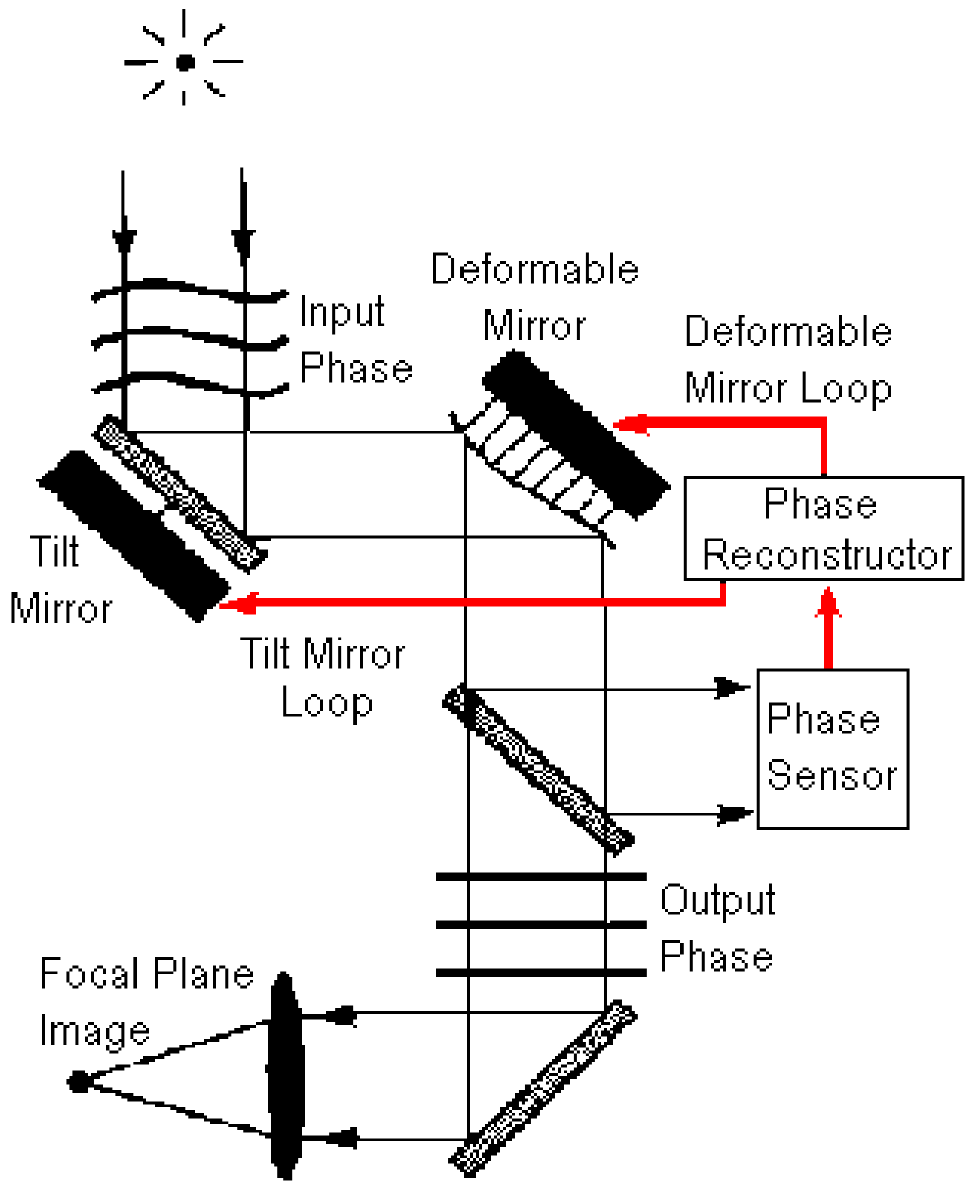
Wavefront sensing

Requirements

Main types of wavefront sensors (WFS):
- Shack-Hartmann
- Curvature
- Pyramid
- Focal plane WFS (for coronagraphs)

Fundamentals of wavefront sensing
- Sensitivity
- Range
- linearity

What is Adaptive Optics ?



Main components of an AO system:

Guide star(s): provides light to measure wavefront aberrations, can be natural (star in the sky) or laser (spot created by laser)

Deformable mirror(s) (+ tip-tilt mirror): corrects aberrations

Wavefront sensor(s): measures aberrations

Computer, algorithms: converts wavefront sensor measurements into deformable mirror commands

WFS: Role & Requirements

Problem: Detectors measure light intensity, not phase → an optical trick is required to convert wavefront phase into intensity.

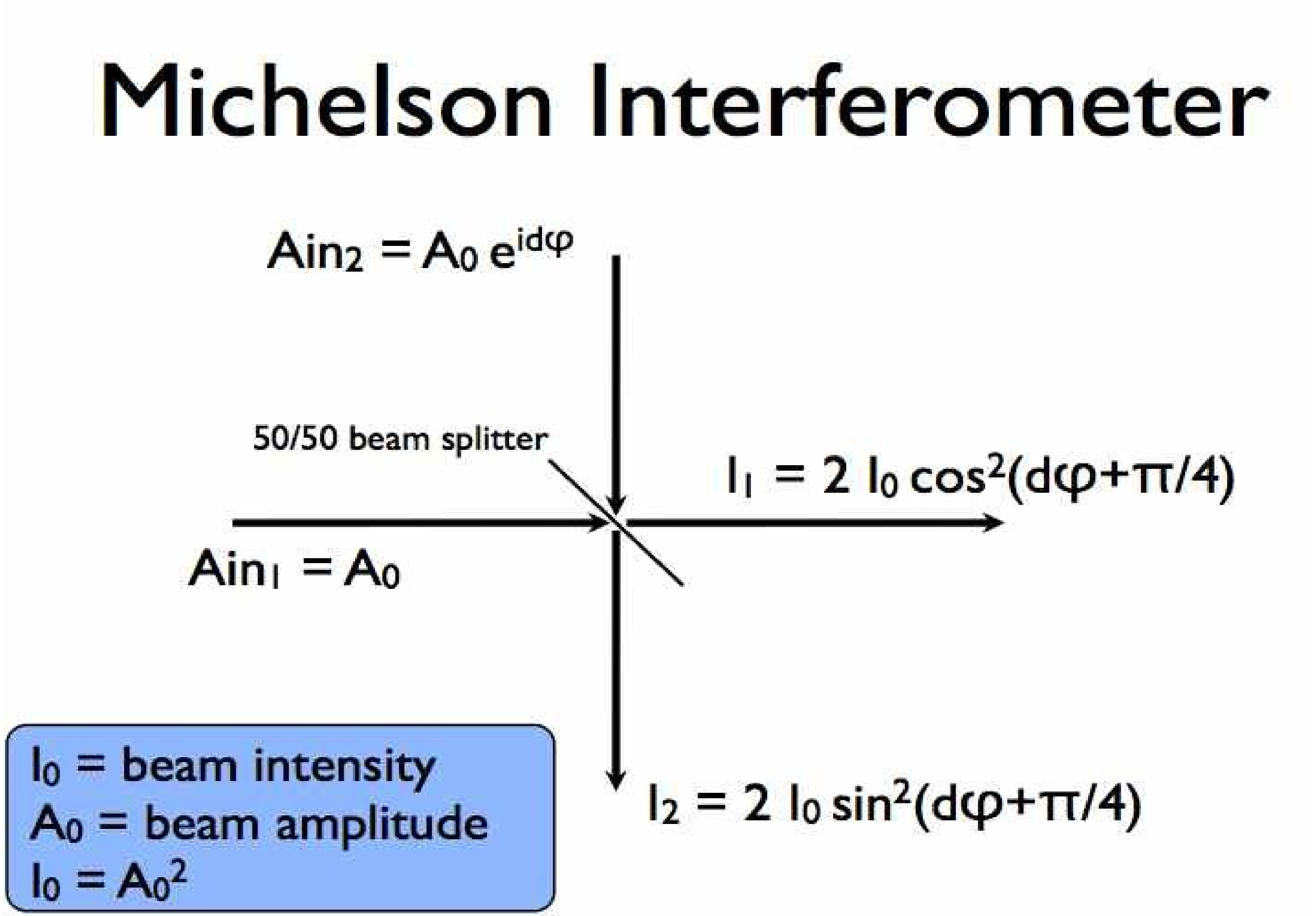
Wavefront sensor must measure wavefront to allow correction with Deformable mirror. Wavefront measurement is done by Wavefront Sensor (hardware) + wavefront reconstructor (Software, translates WFS signal into DM language)

Requirements (need to be balanced in AO system design):

- **Accuracy**
- **Spatial resolution** (number of modes measured – ideally as many as can be corrected by DM)
- **Efficiency** (good use of photons)
- **Speed** (coupled with accuracy and efficiency)
- ***Linearity*** (faster reconstruction → helps with speed)
- **Range** (ability to measure large wavefront errors)
- **Robustness** (chromaticity, ability to work on extended sources, etc …)
- **Match with DM** (WFS must see what DM can correct)

What is a WFS ? (simplest definition)

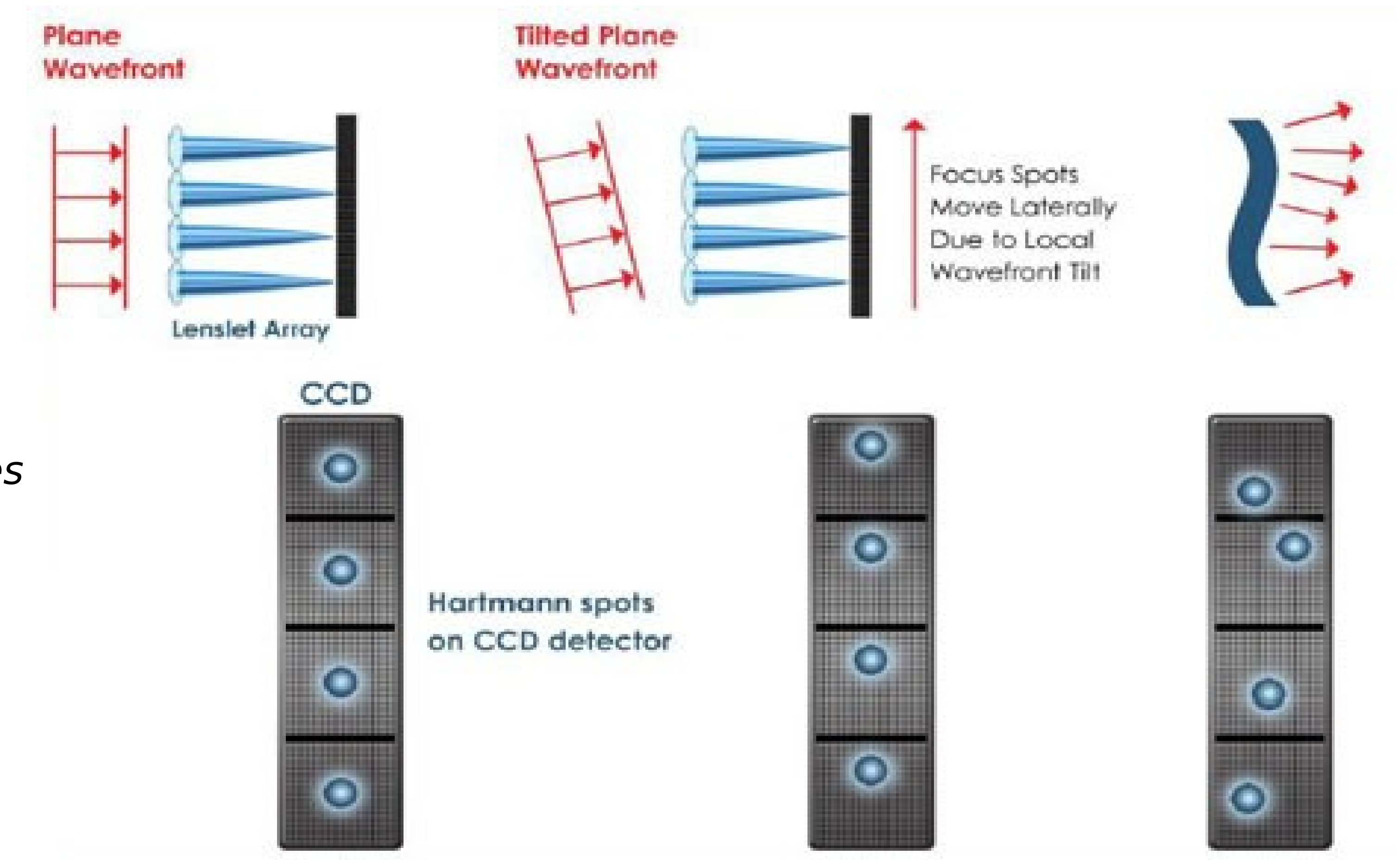
A WFS performs coherent interferences between parts of the input wavefront to convert phase into intensity. The simplest WFS is a 2-beam interferometer, measuring the phase offset between the 2 beams.



Shack-Hartmann WFS

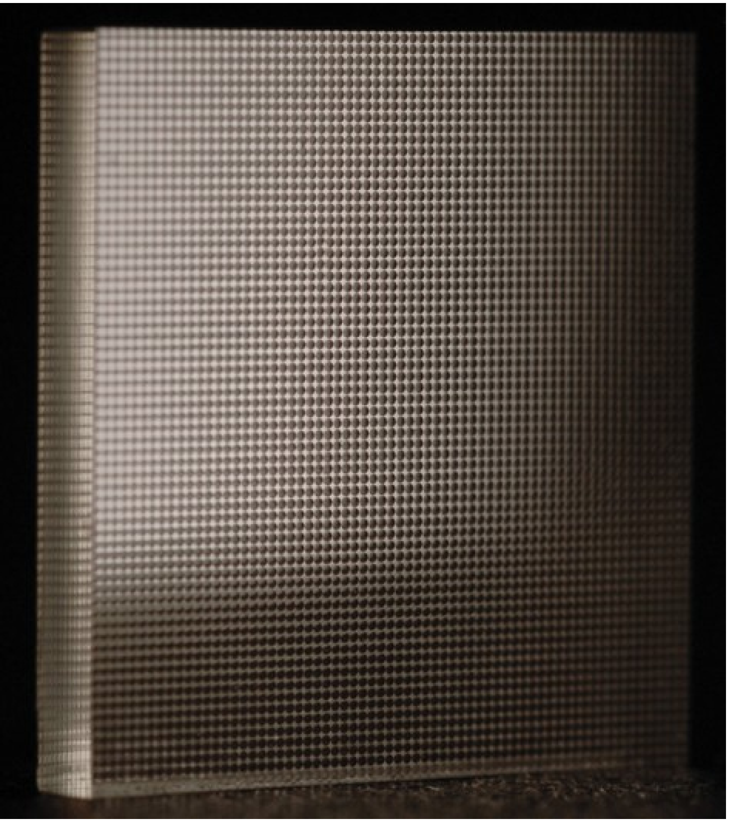
Measures wavefront slope in front of each subaperture

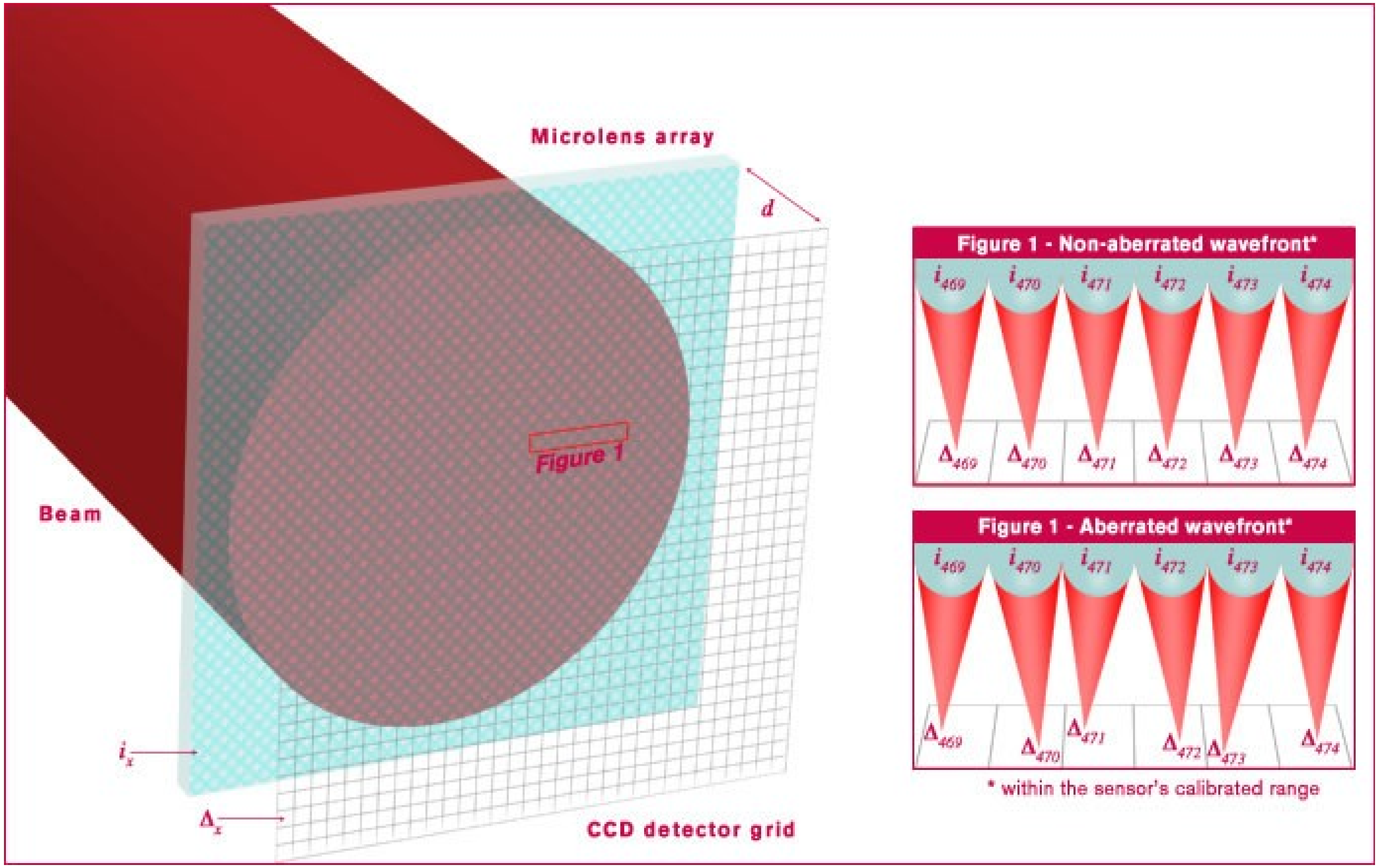
courtesy: Boston Micromachines



Shack-Hartmann WFS

Lenslet array + detector

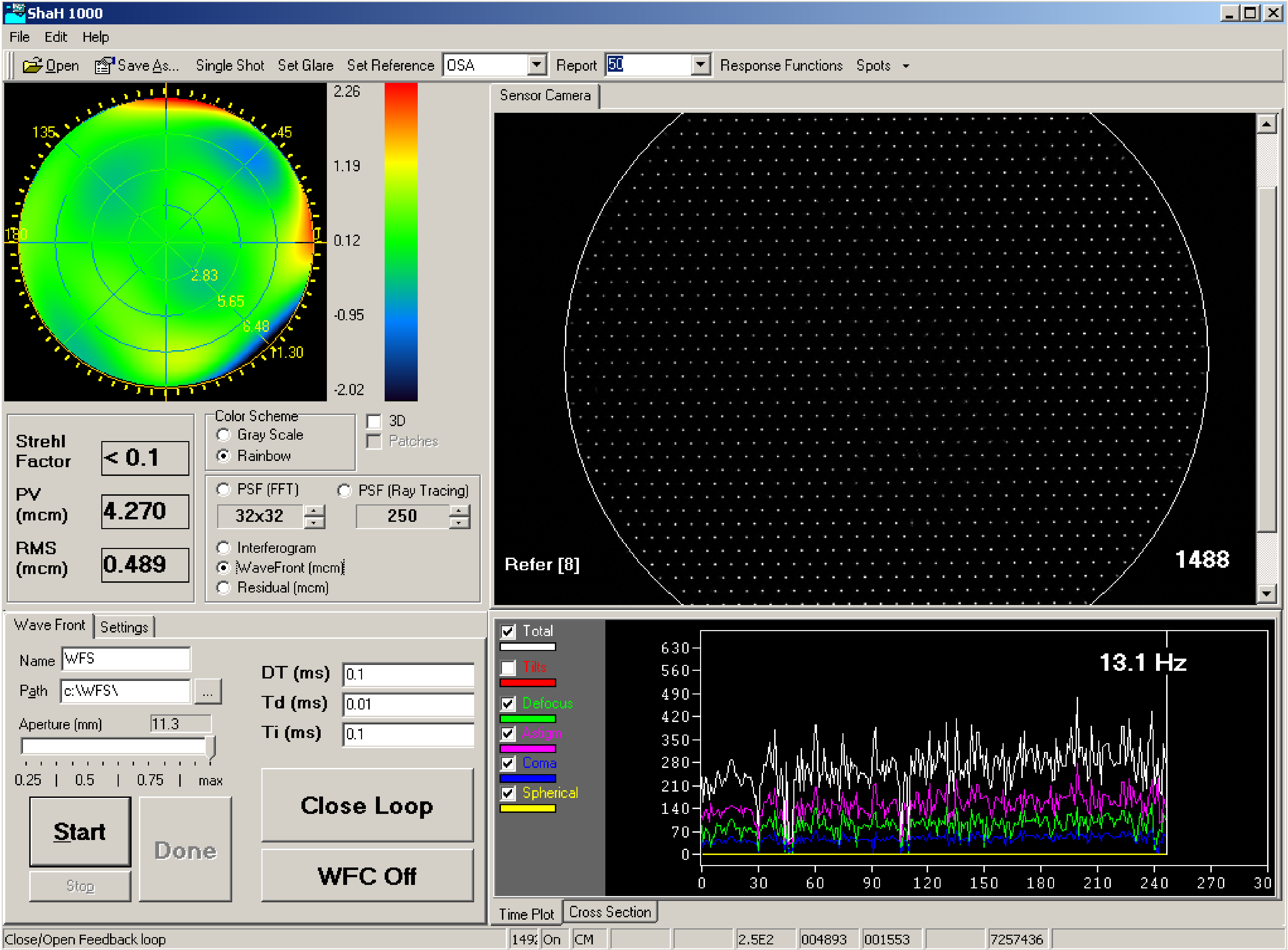




Shack-Hartmann WFS

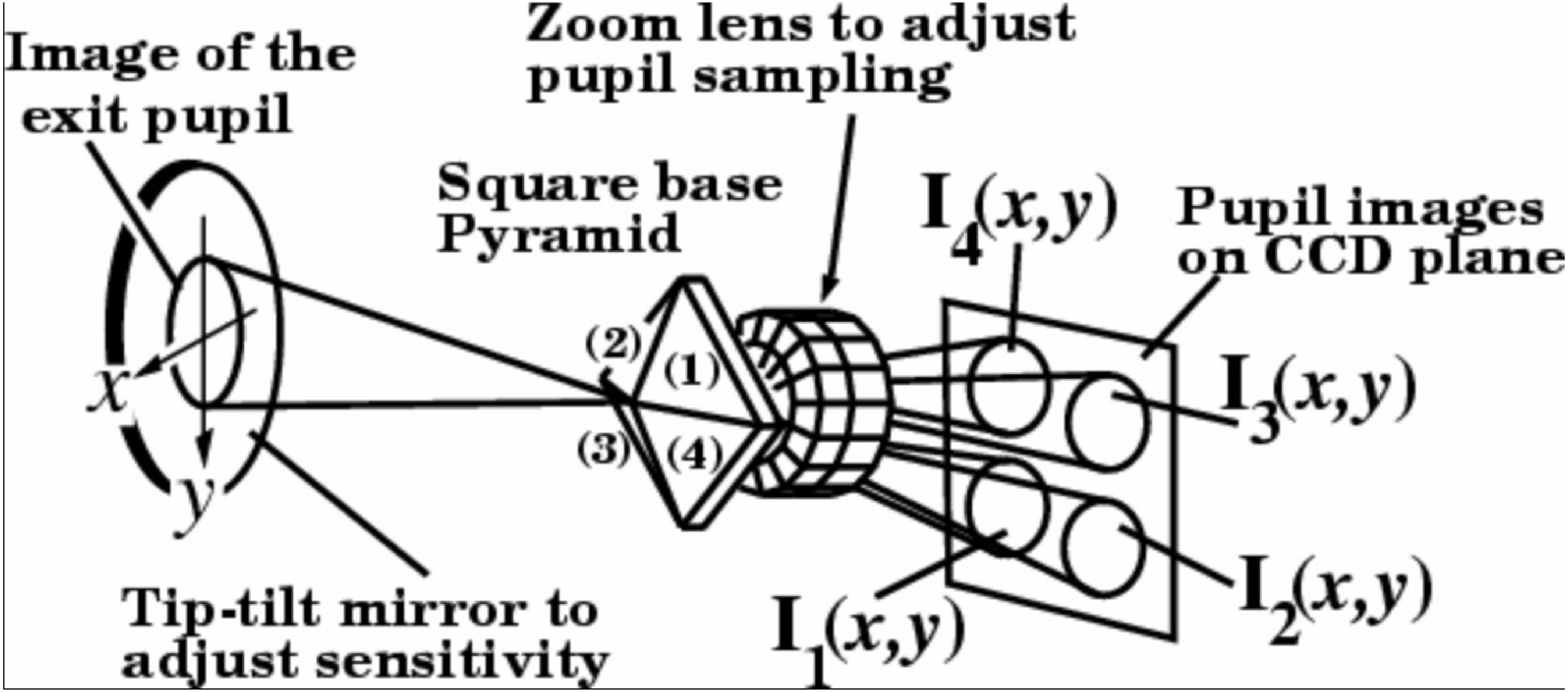
Software integrates slopes into wavefront

courtesy: Del Mar Photonics



Pyramid WFS

Separates focal plane into 4 quadrants, each quadrant re-imaged in pupil plane
Geometrical optics explanation: parts of the pupil with a given slope correspond to light in the corresponding focal plane quadrant



Pyramid WFS

Diffractive analysis

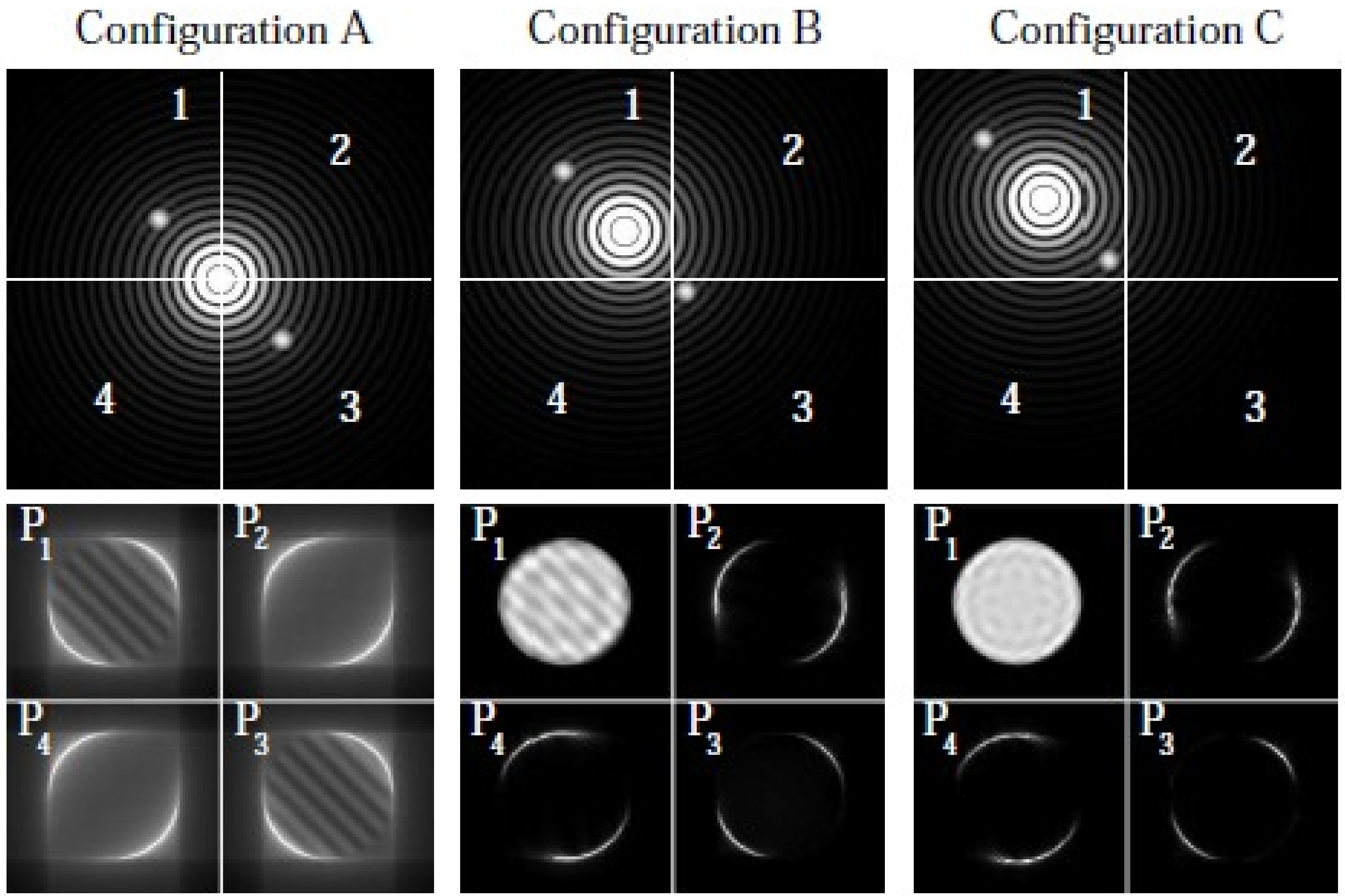
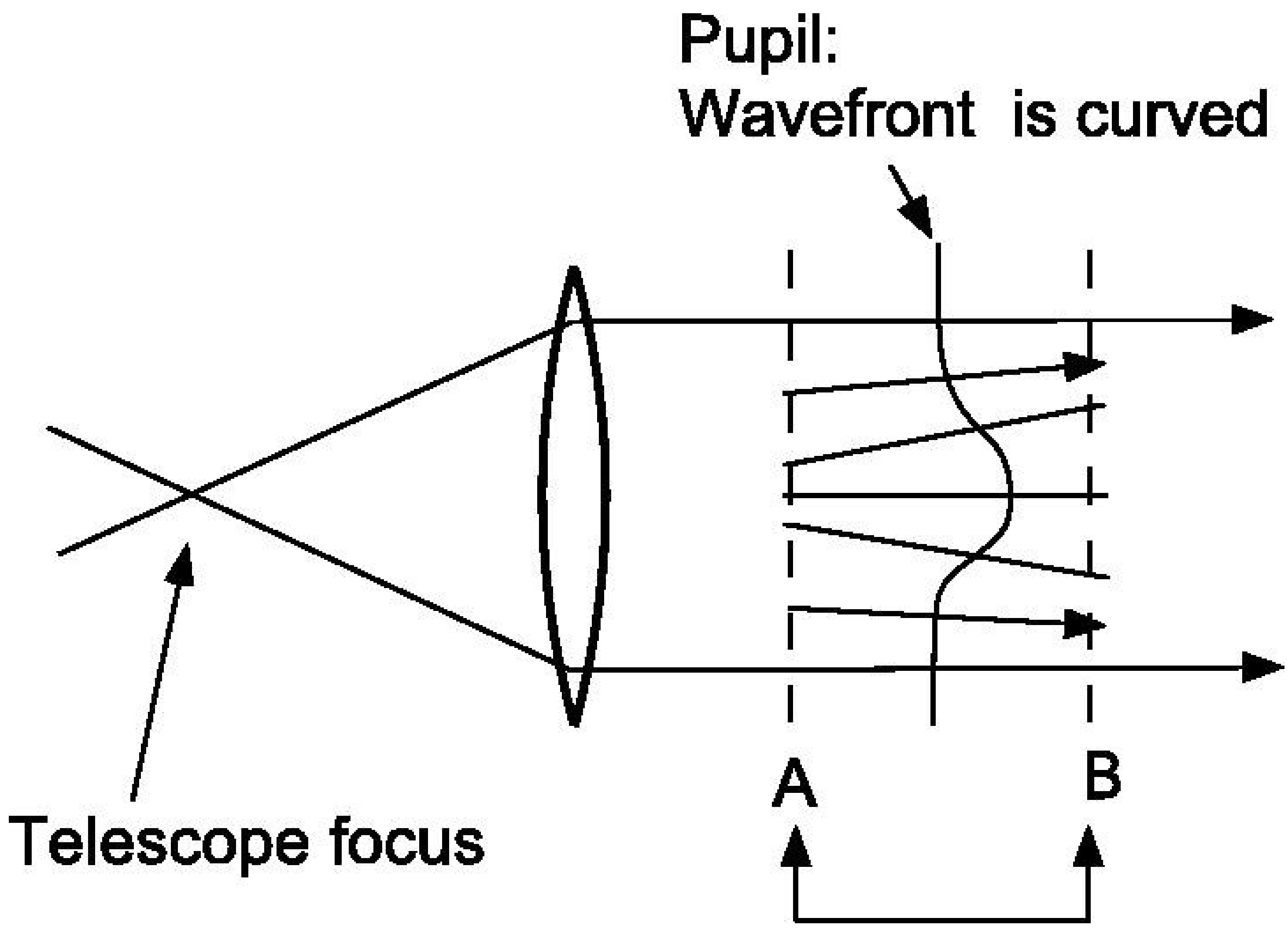


Fig. 5.— Focal plane images (top) and corresponding pupil images P_i (bottom) for a sine-wave pupil phase error (corresponding to 2 symmetric speckles in the focal plane). See text for details.

Curvature WFS

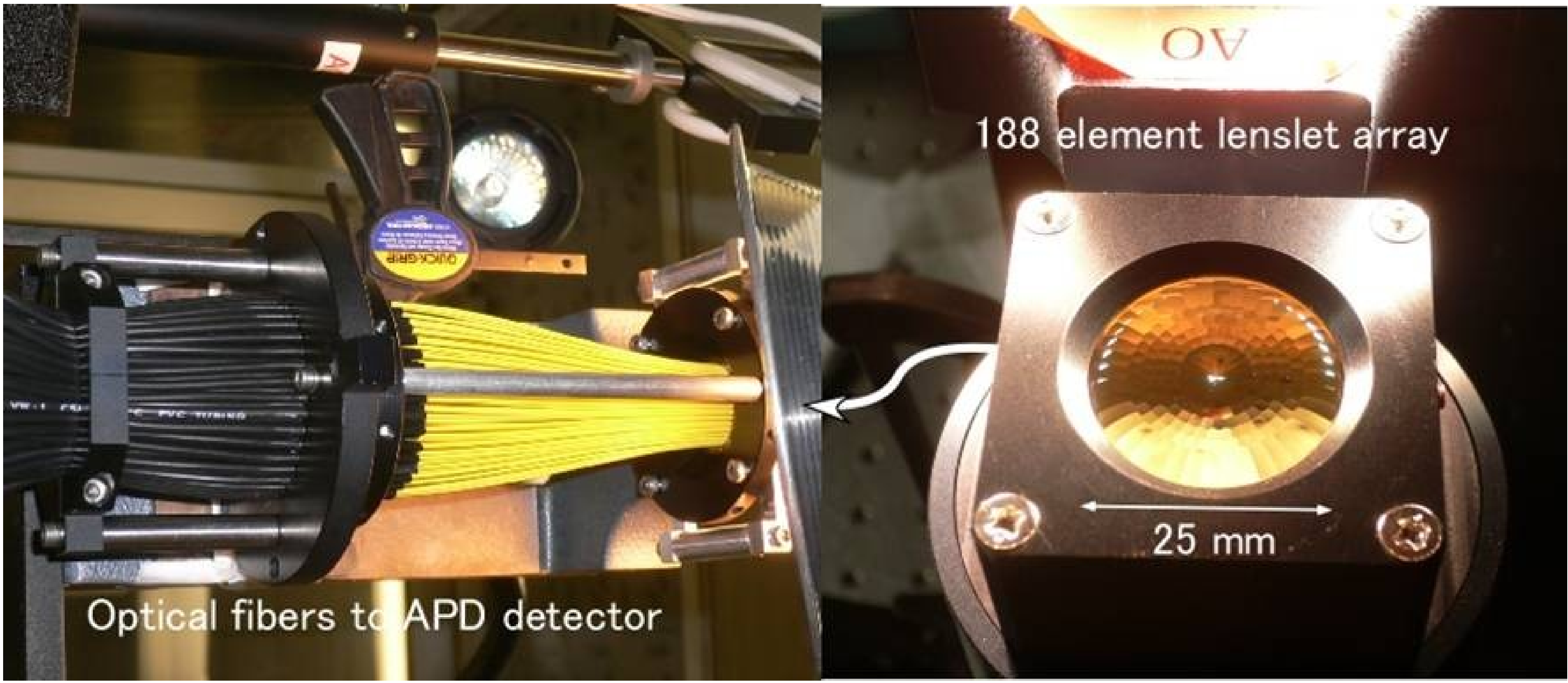
Light propagation turns phase into amplitude (similar to scintillation)



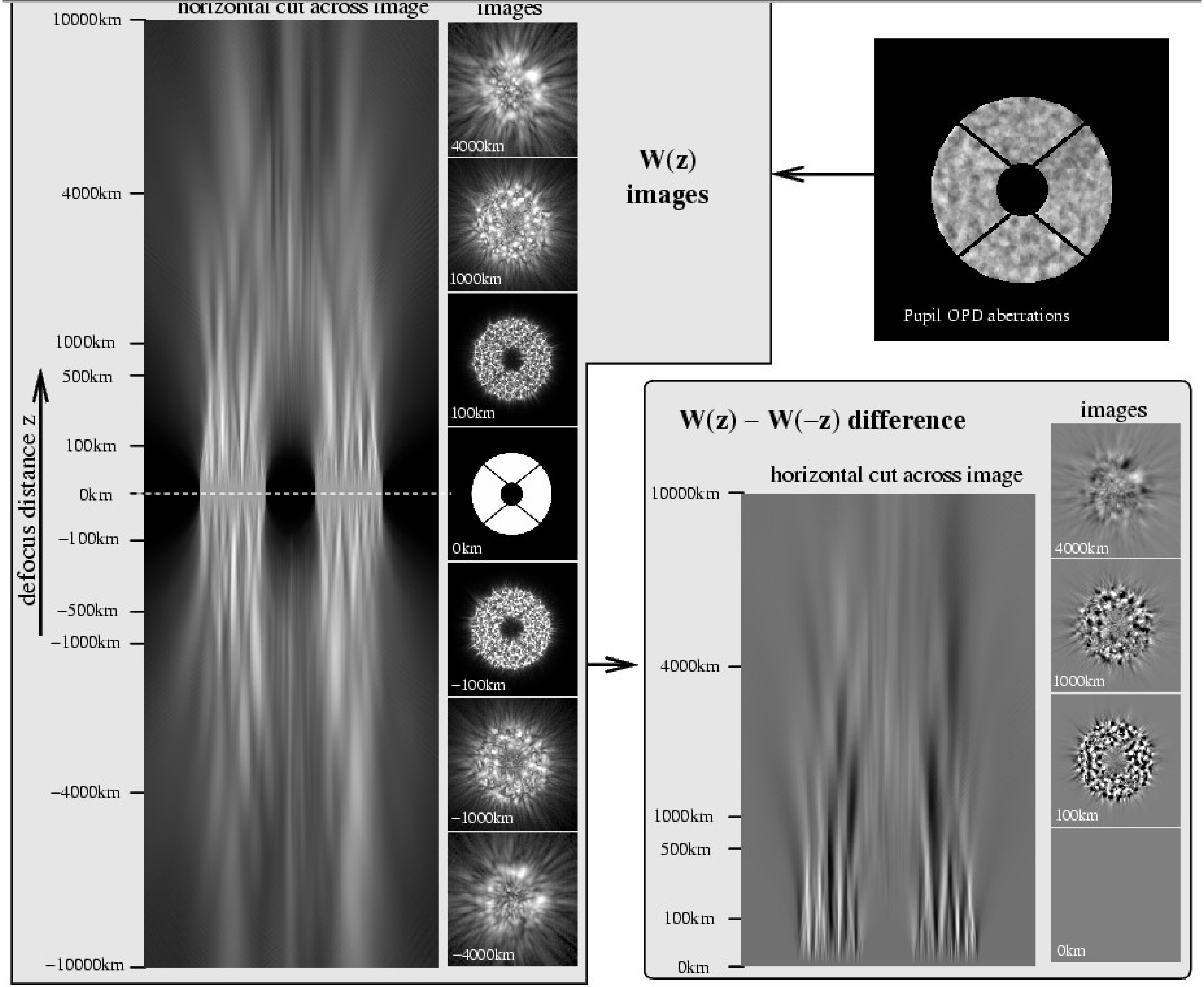
Lenslet array used to inject light into a series of fibers, which are connected to photon-counting Avalanche PhotoDiodes (APDs)

Curvature WFS

Subaru Telescope 188-element curvature WFS



Lenslet array used to inject light into a series of fibers, which are connected to photon-counting Avalanche PhotoDiodes (APDs)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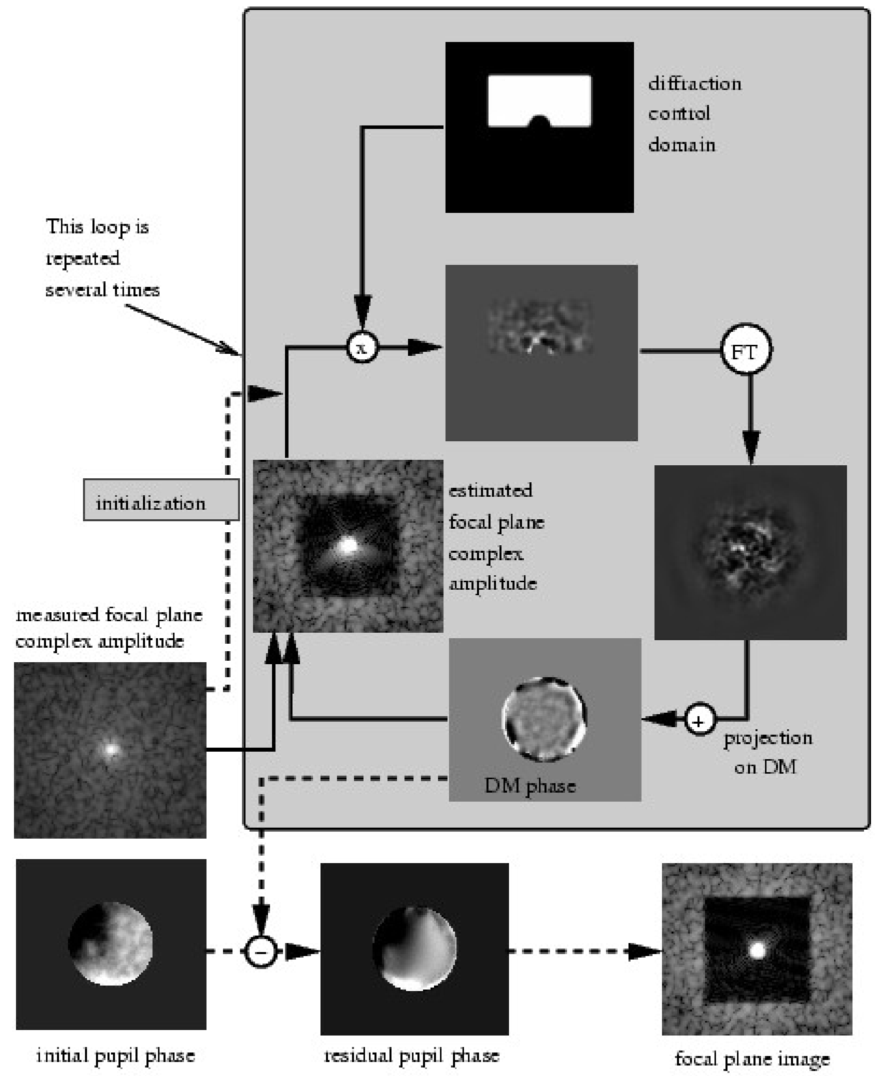
Focal plane WFS: a non-linear WFS well suited for Extreme AO

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

Key advantages:
- no non-common path errors
- high sensitivity

Malbet, Yu & Shao (1995)
Guyon (2005)
Give'on (2003-2006)
Borde & Traub (2006)



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

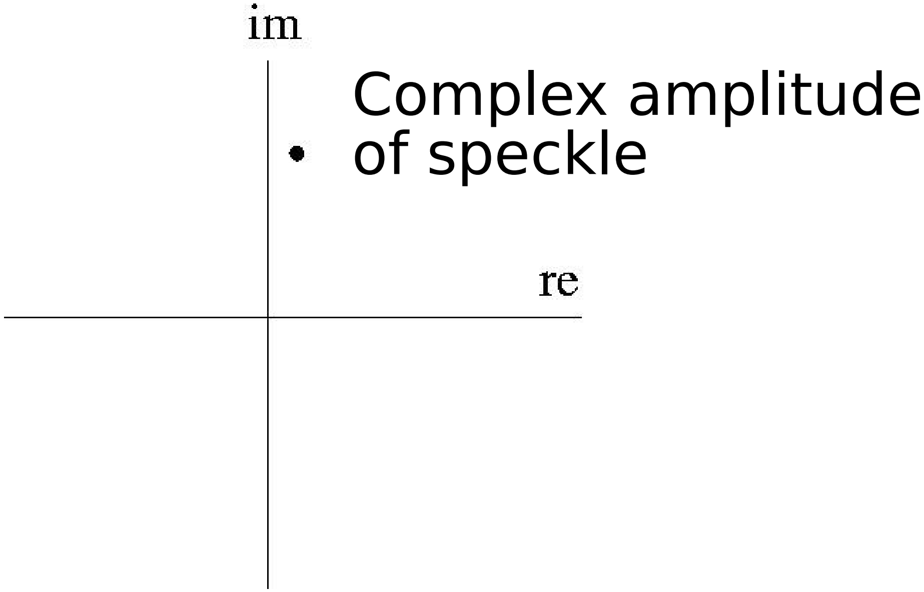
Measure speckle field with no previous knowledge:

- take one frame – this gives a noisy measure of the speckle field amplitude, but not phase

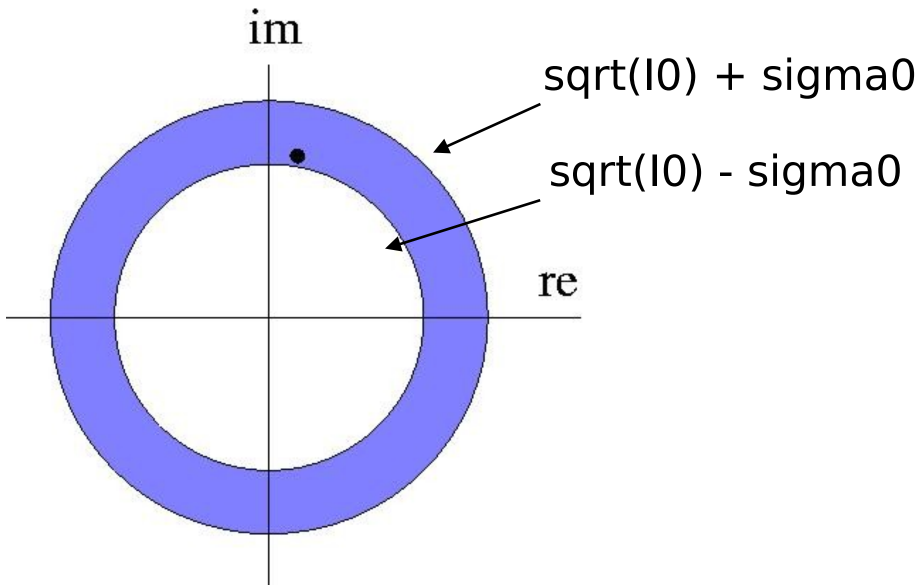
- compute 2 DM shapes which will add known speckles on top of existing speckles. These 2 “additive” speckle field have same amplitude as existing speckles, and the phase offset between the 2 additive speckle fields is PI/2

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

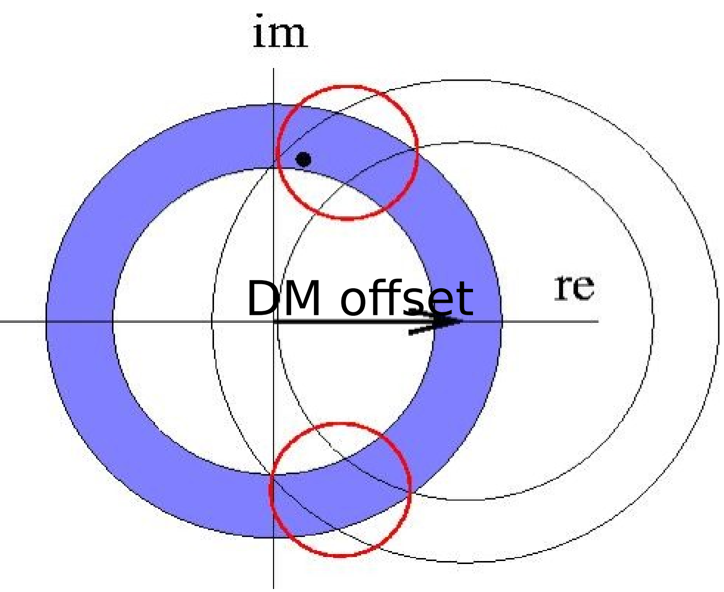
Initial problem

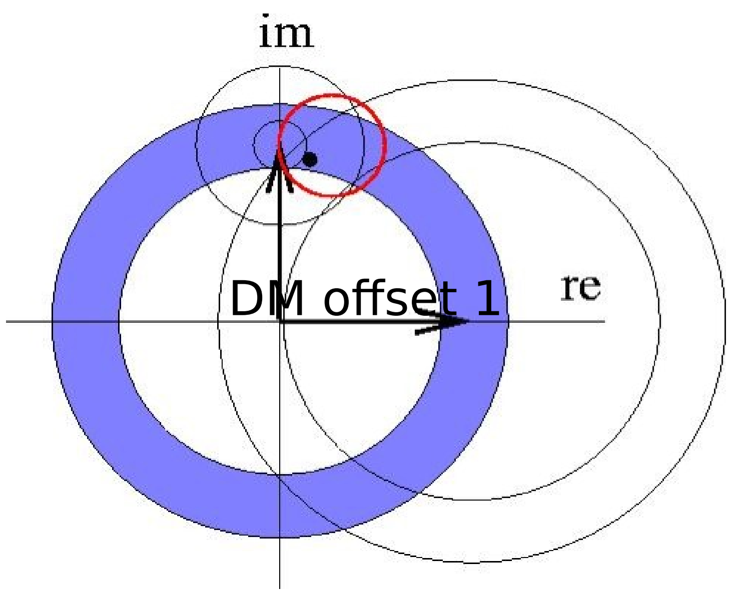


Take a frame -> measured speckle intensity = I0

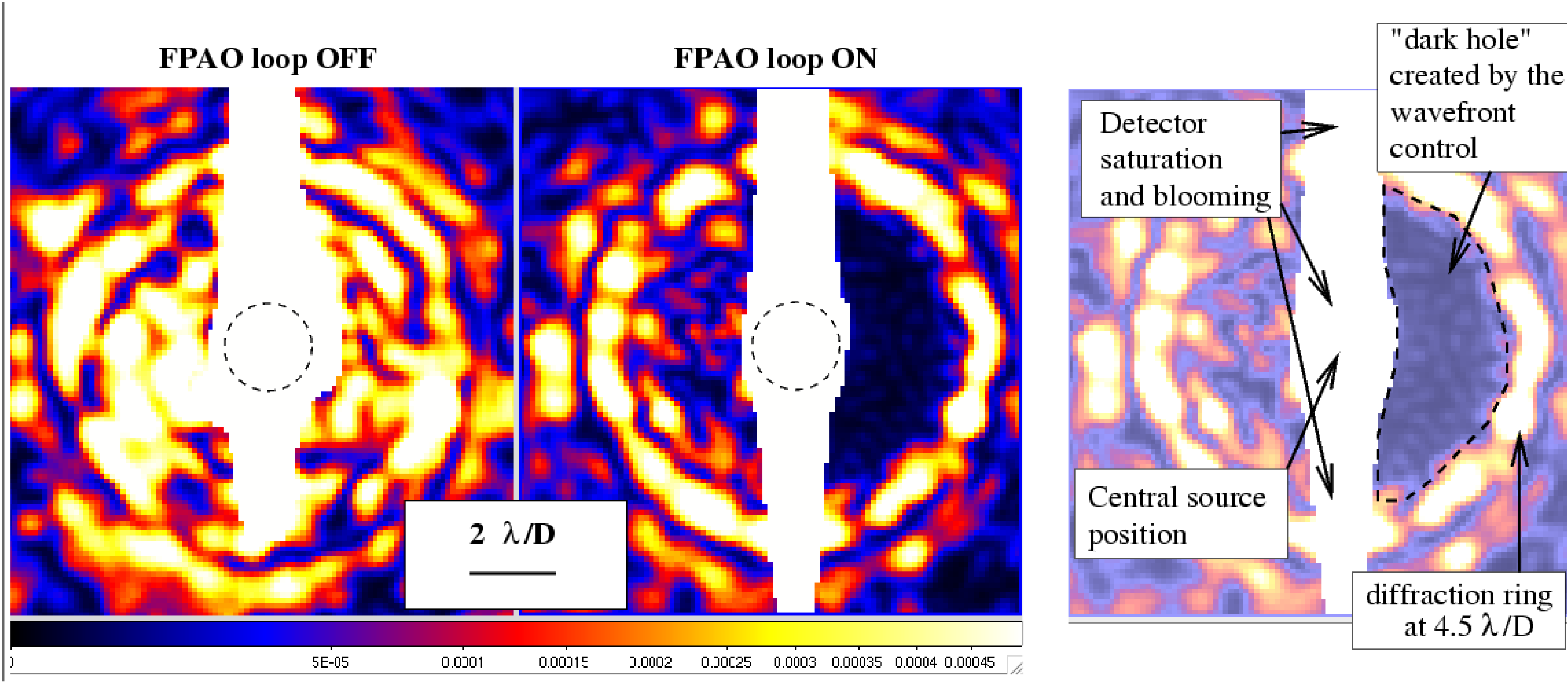


DM offset chosen to be ~ equal to speckle amplitude





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



See also results obtained at JPL HCIT, NASA Ames & Princeton lab

Some fundamental desirable WFS properties

Linearity, range and sensitivity

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

We 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 at low spatial frencies:

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) ?