

# Adaptive Optics

## Wavefront sensing

### Requirements

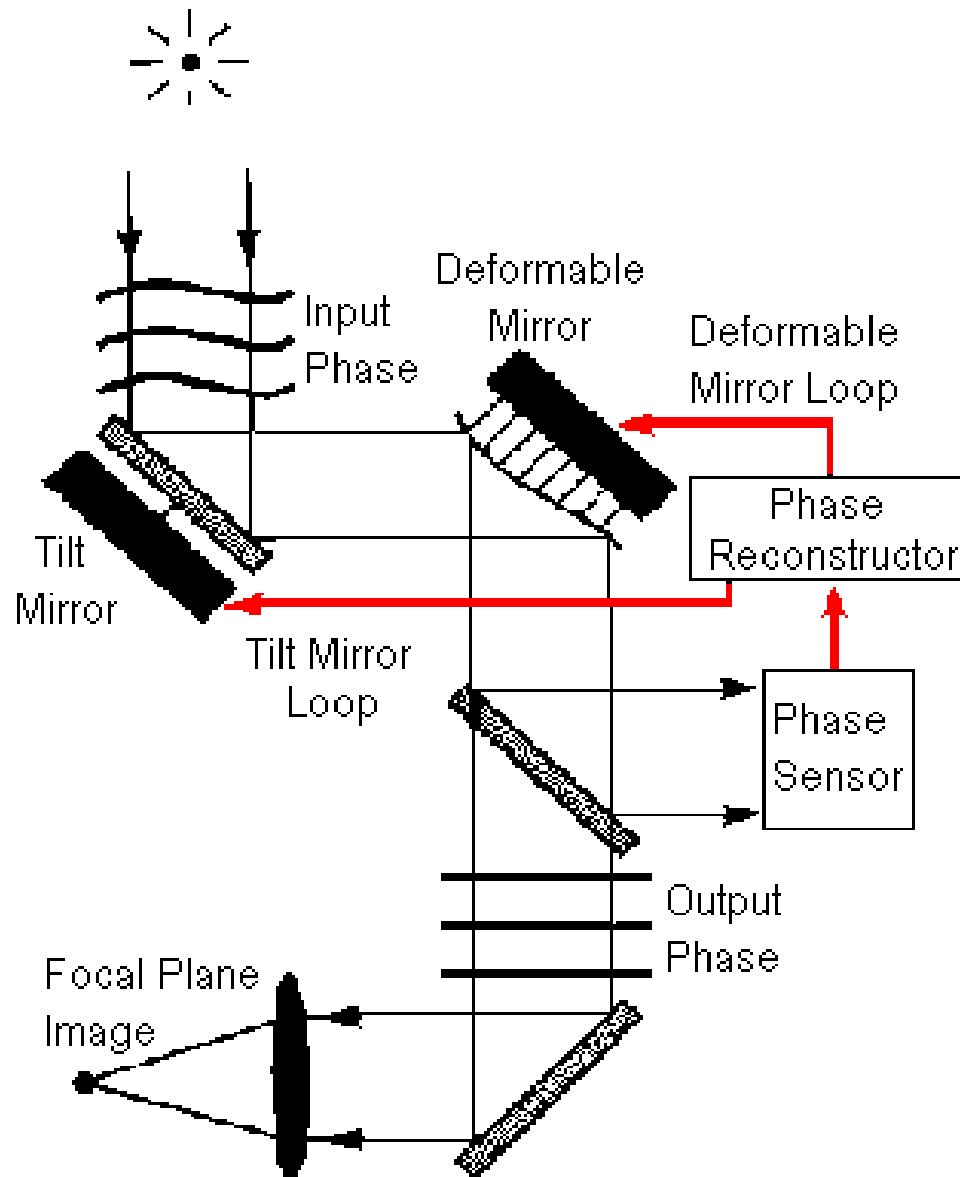
#### Main types of wavefront sensors (WFS):

- 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)

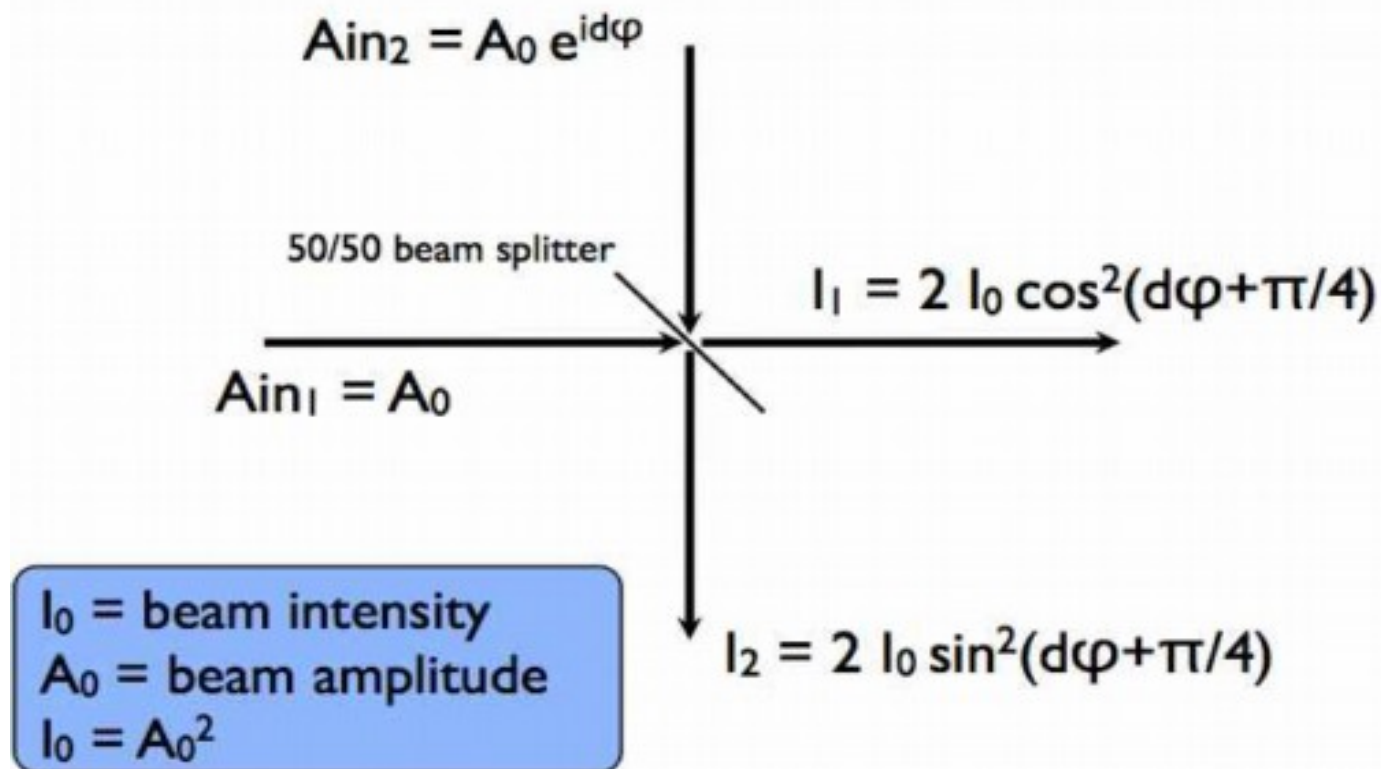
Requirements (need to be balanced in AO system design):

- **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)

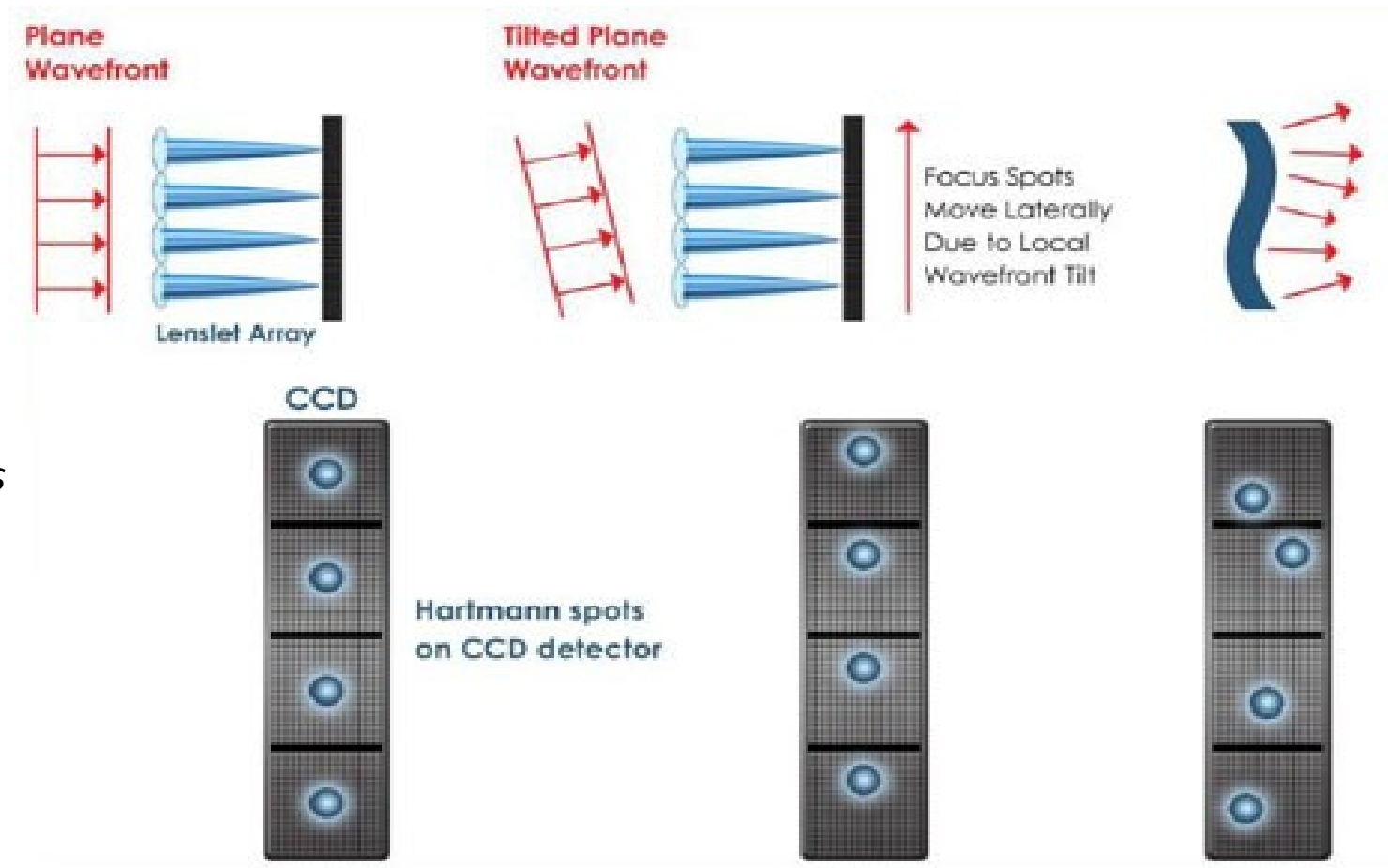
A WFS performs coherent interferences between parts of the input wavefront to convert phase into intensity. The simplest WFS is a 2-beam interferometer, measuring the phase offset between the 2 beams.

## Michelson Interferometer



# Shack-Hartmann WFS

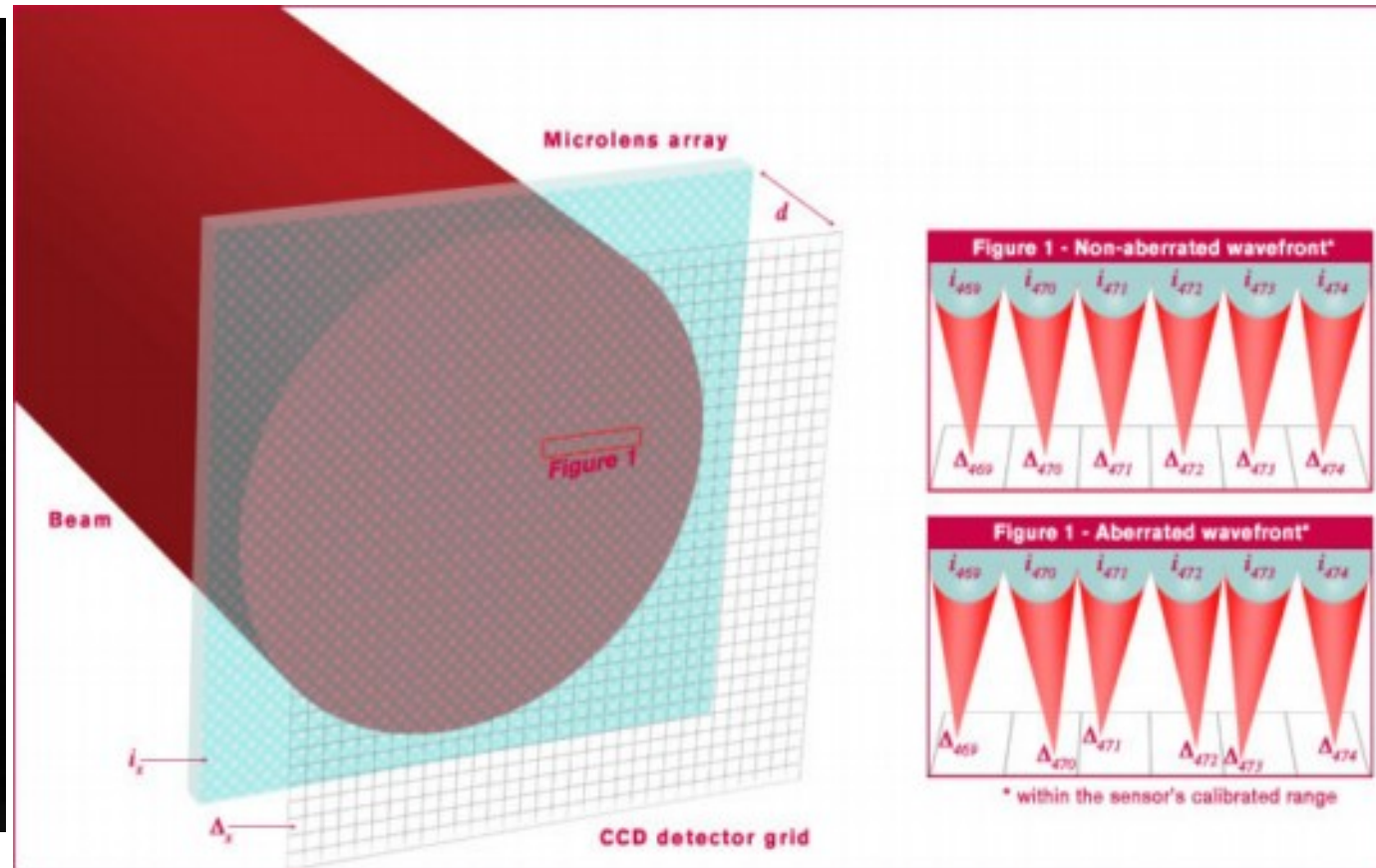
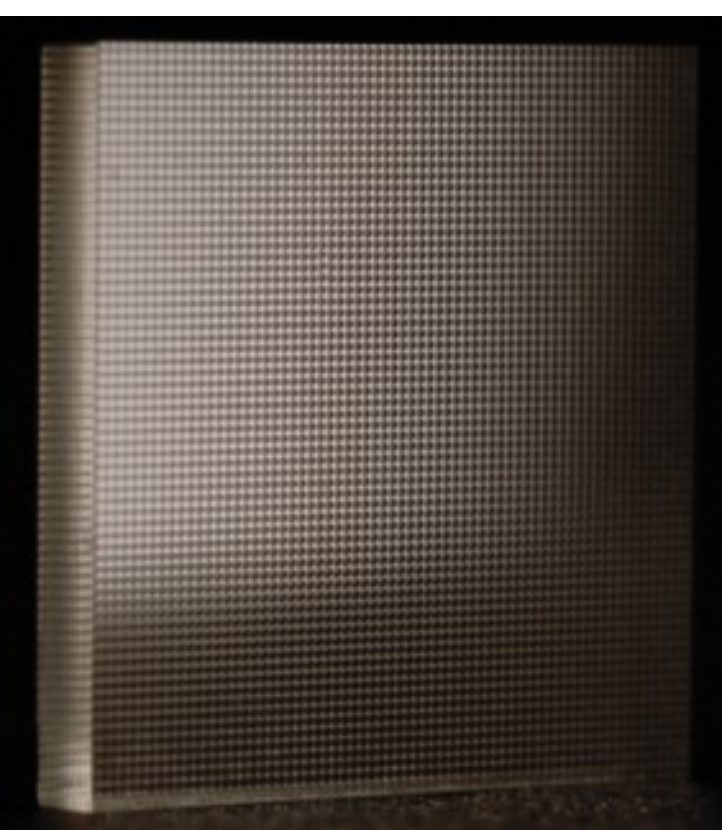
Measures wavefront slope in front of each subaperture



courtesy:  
Boston  
Micromachines

# Shack-Hartmann WFS

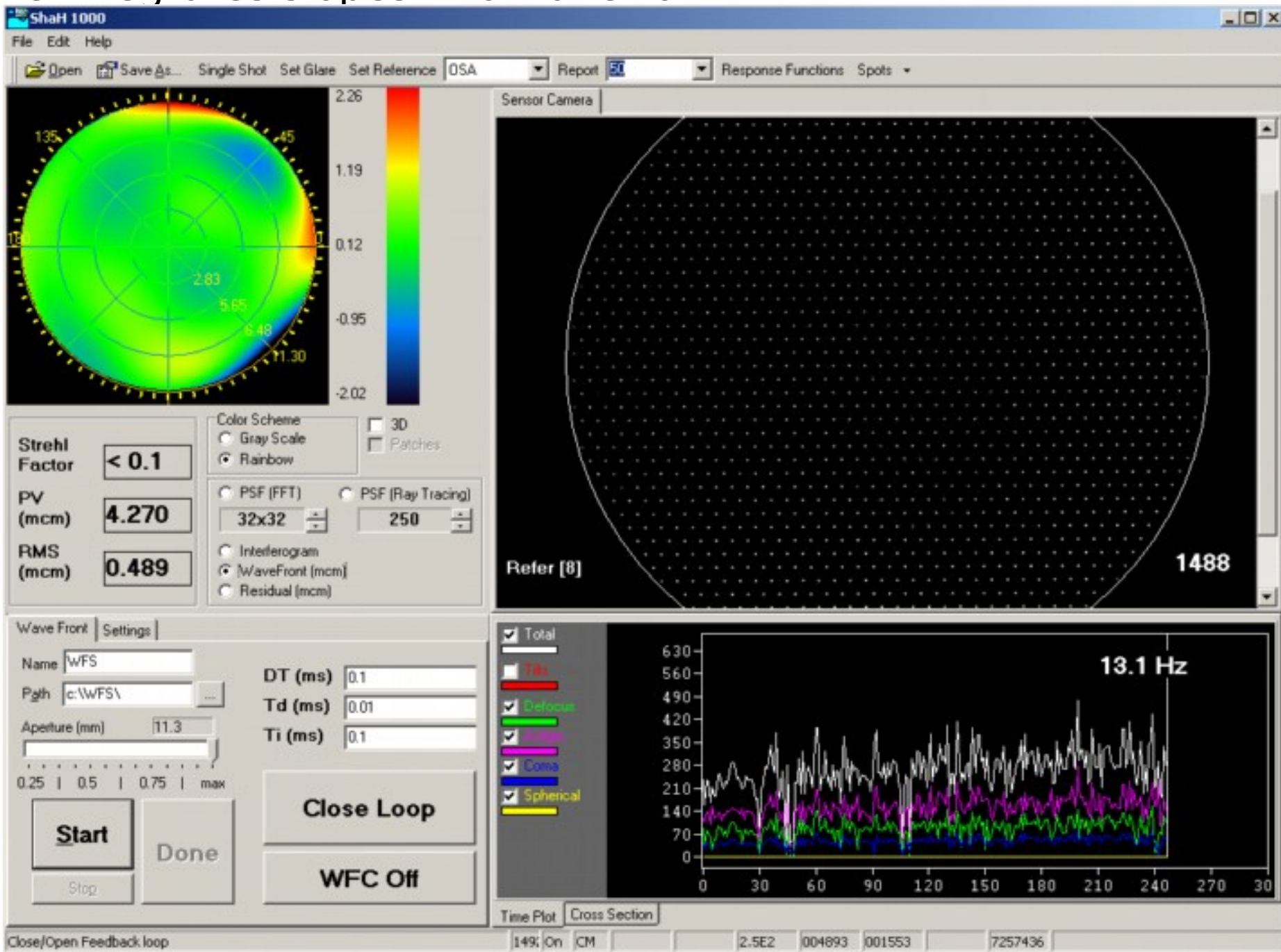
Lenslet array + detector





# Shack-Hartmann WFS

Software integrates slopes into wavefront

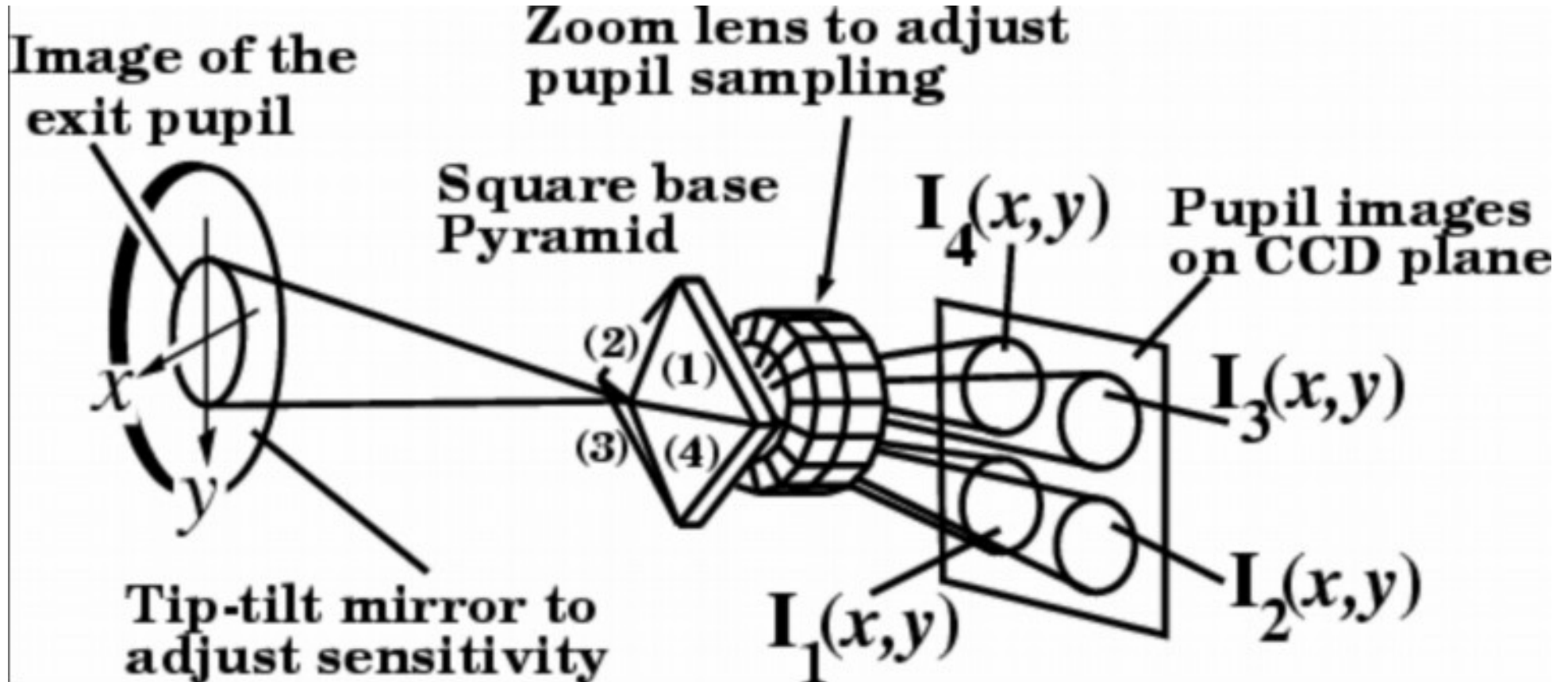


courtesy:  
Del Mar  
Photonics

# 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

Diffraction analysis

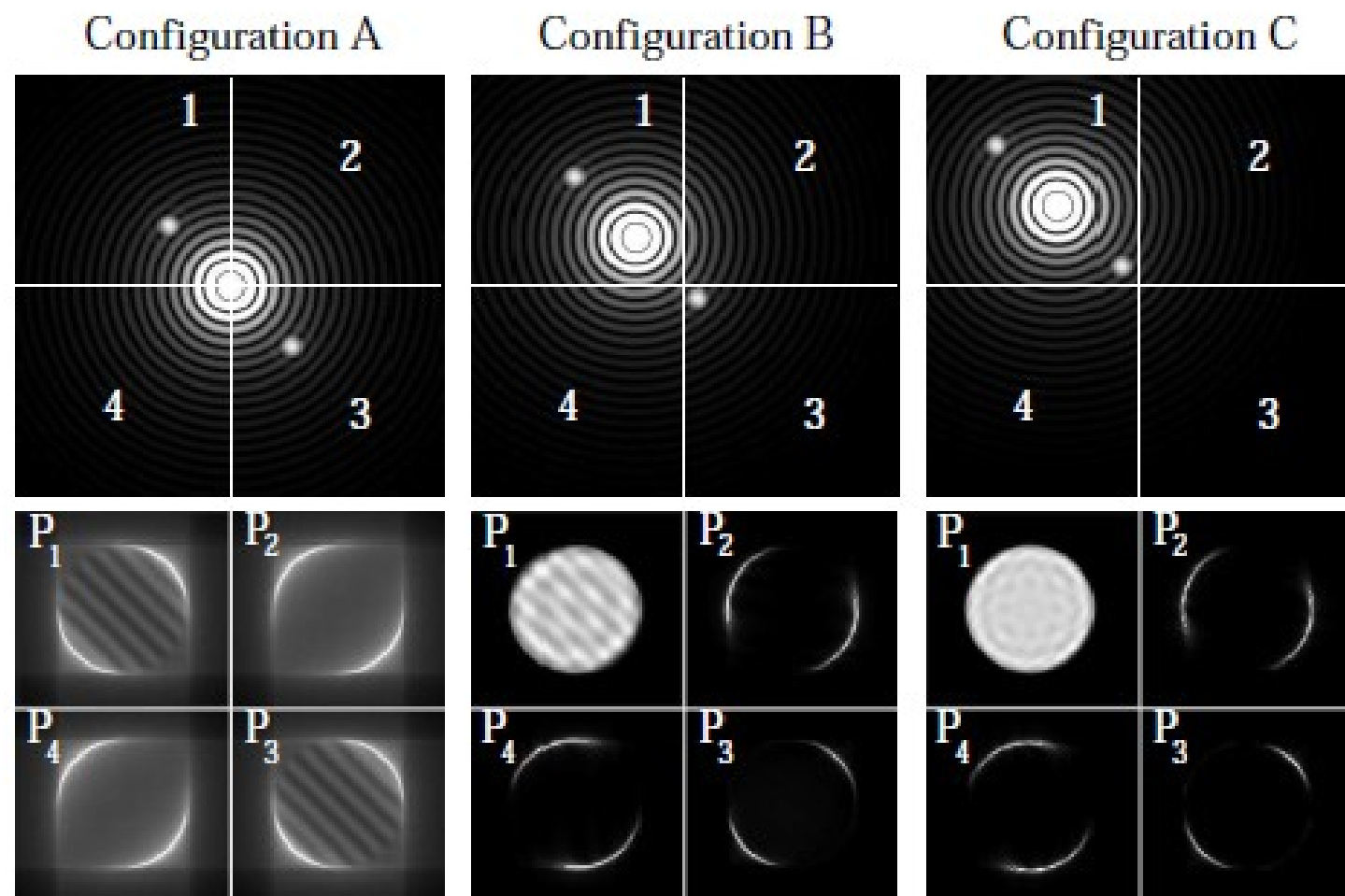
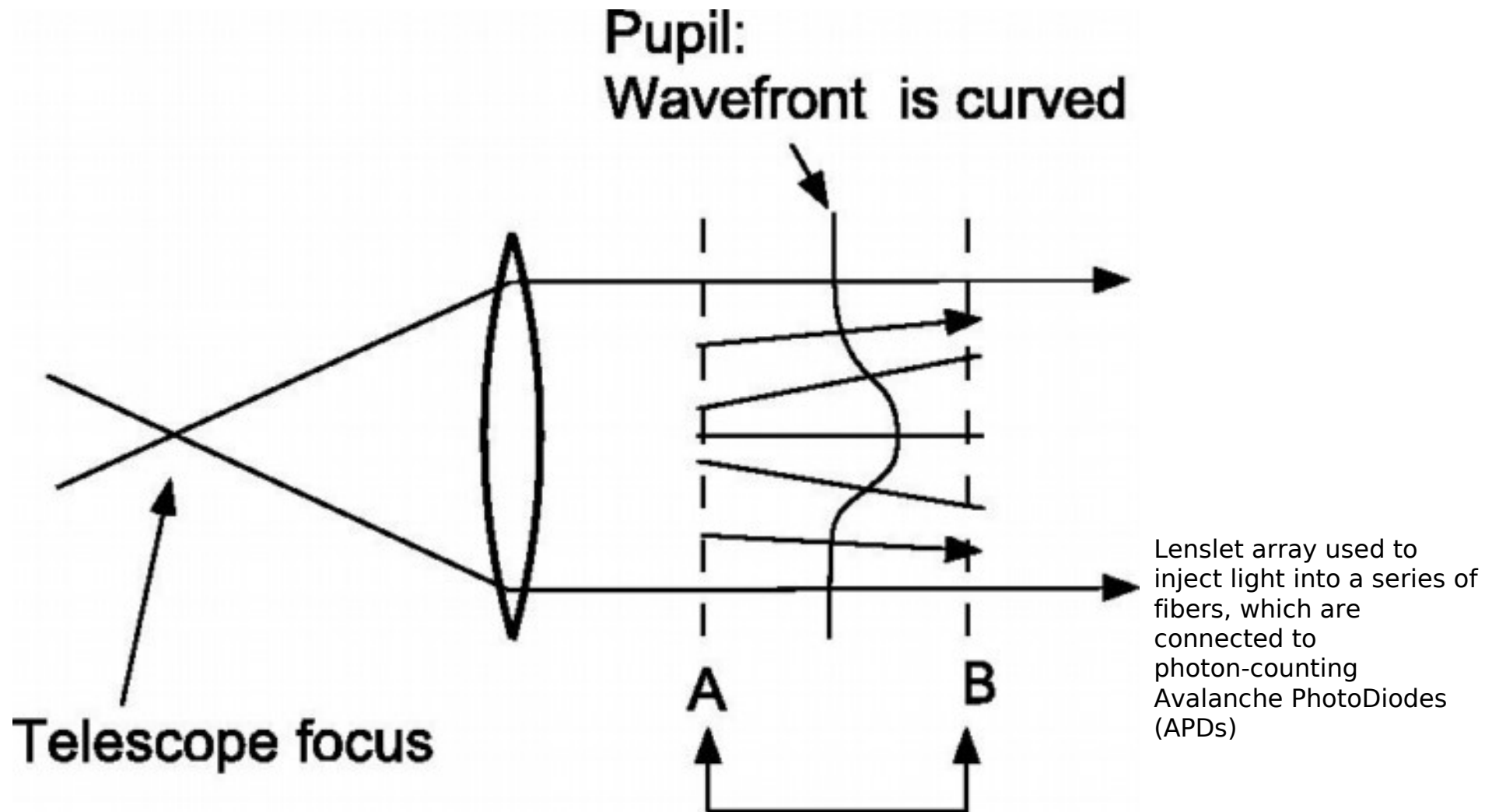


Fig. 5.— Focal plane images (top) and corresponding pupil images  $P_i$  (bottom) for a sine-wave pupil phase error (corresponding to 2 symmetric speckles in the focal plane). See text for details.

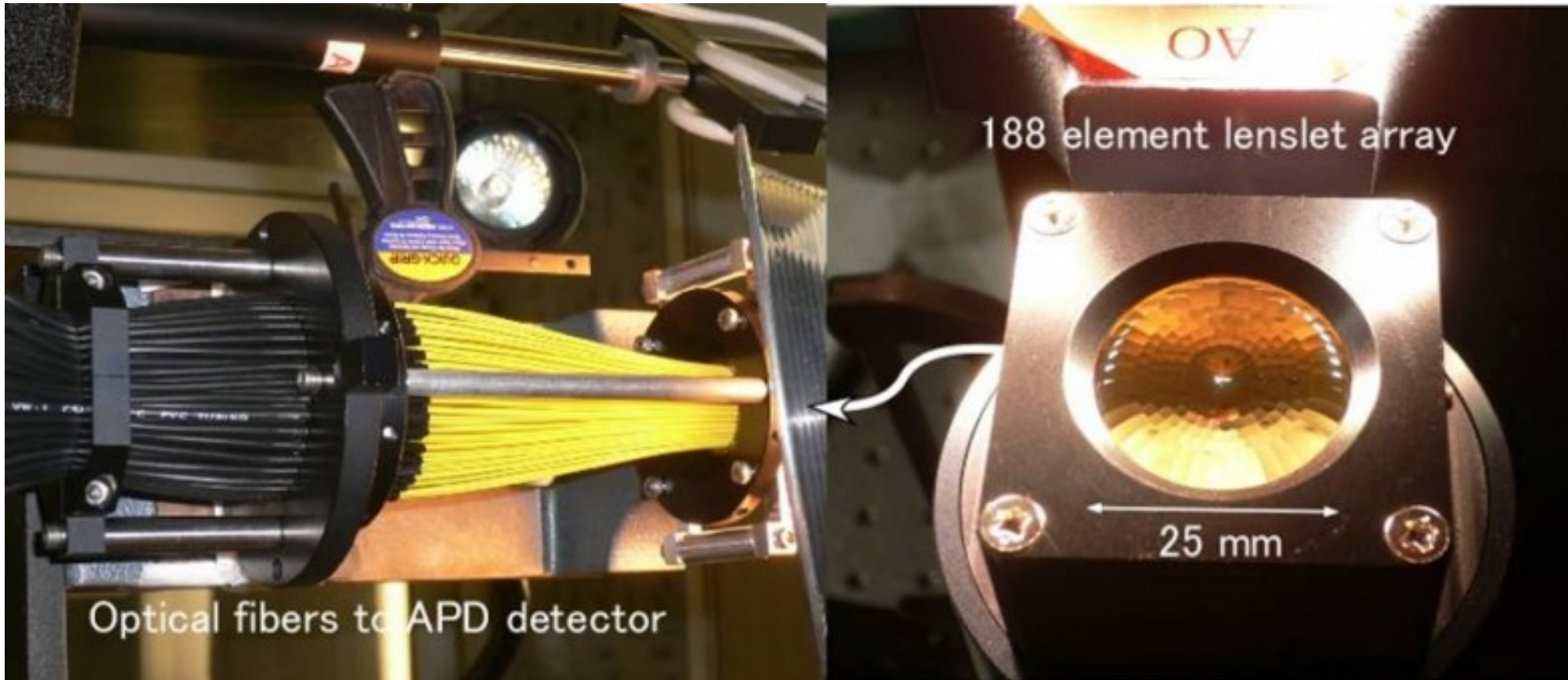
# Curvature WFS

Light propagation turns phase into amplitude (similar to scintillation)

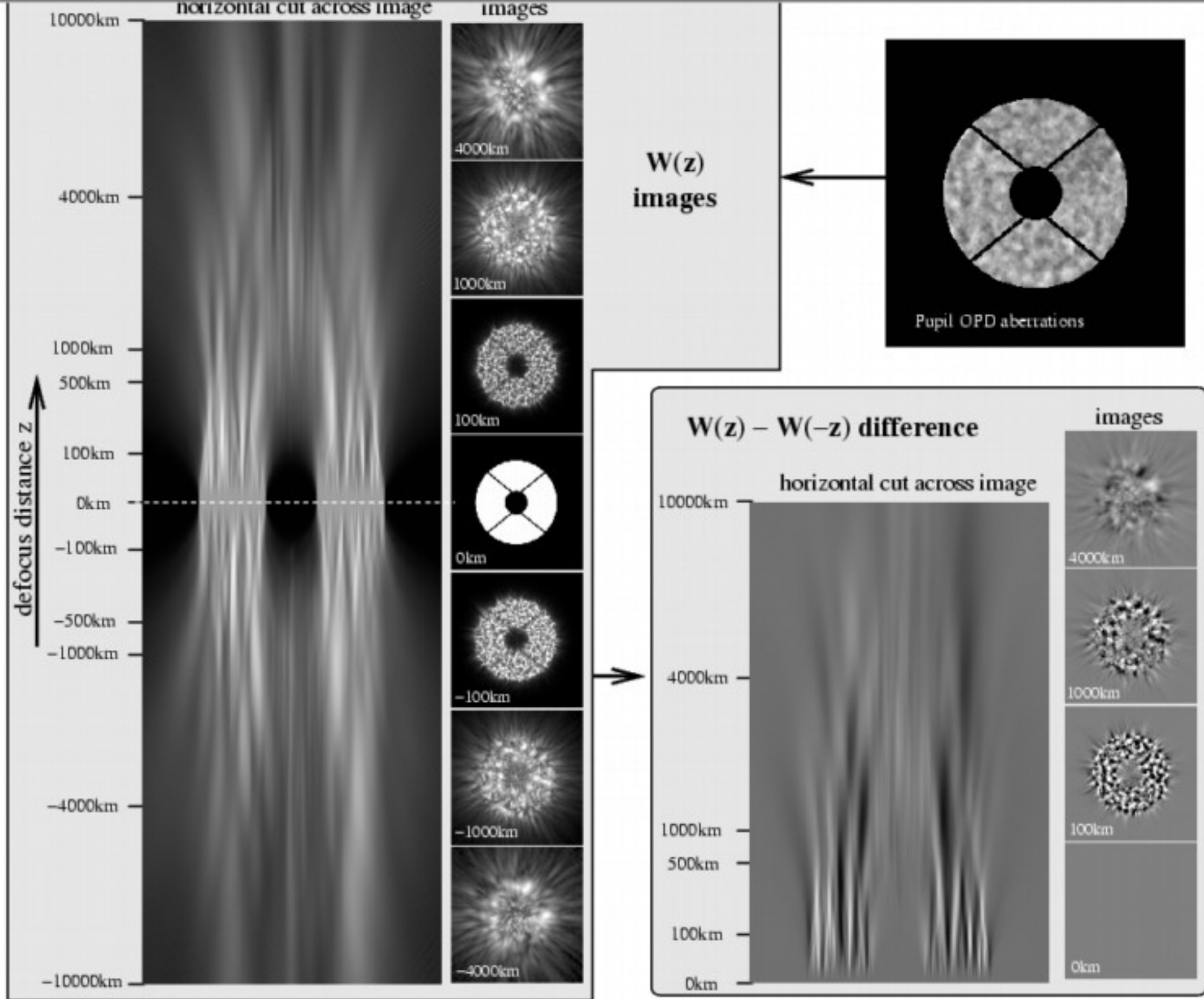


# Curvature WFS

## 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)



# 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:**

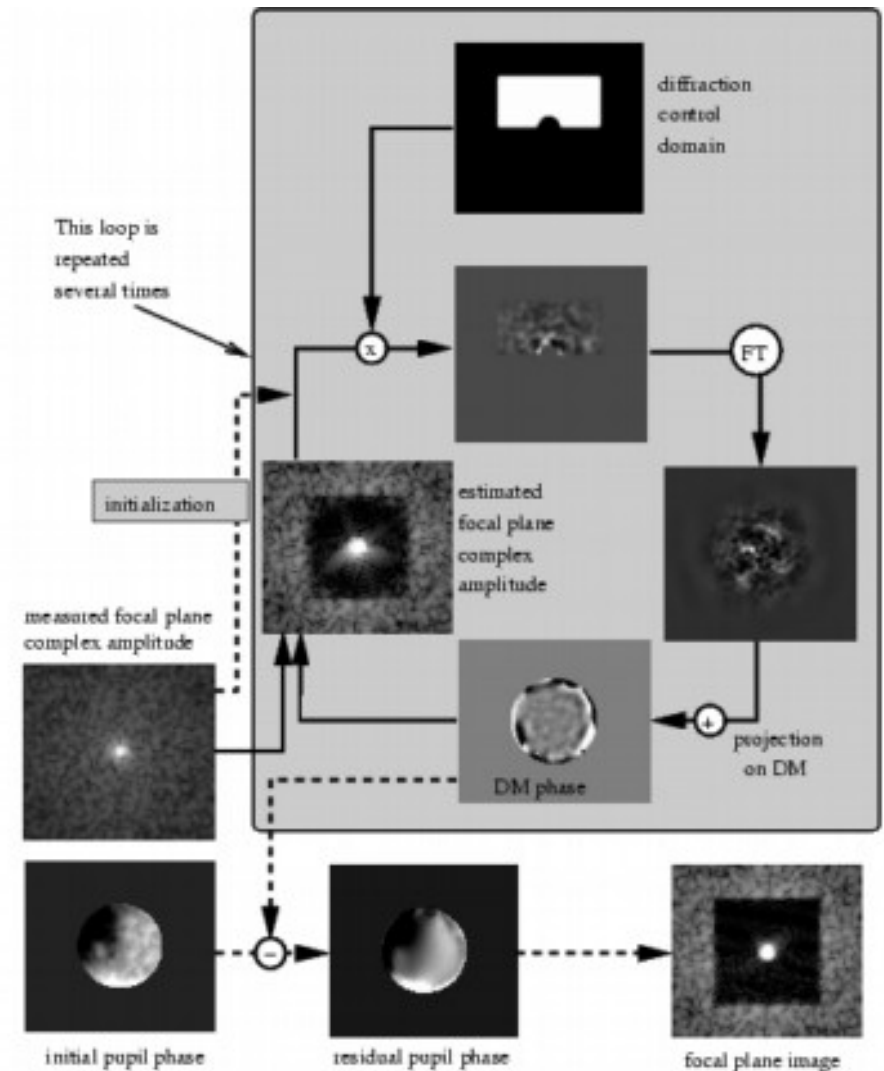
- no non-common path errors
- high sensitivity

*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.**

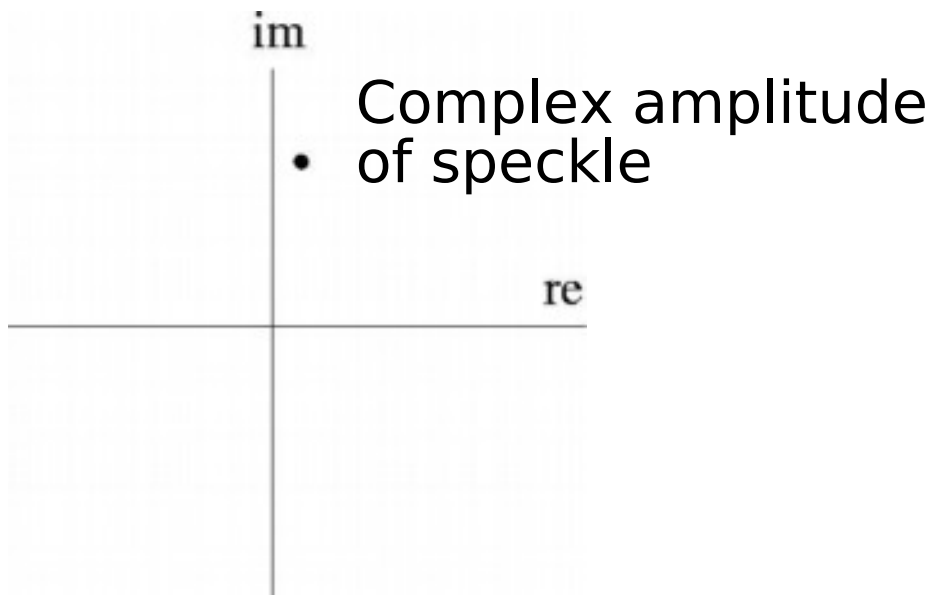
Conventional phase diversity: focus

With DM: **freedom to tune the diversity to the problem**

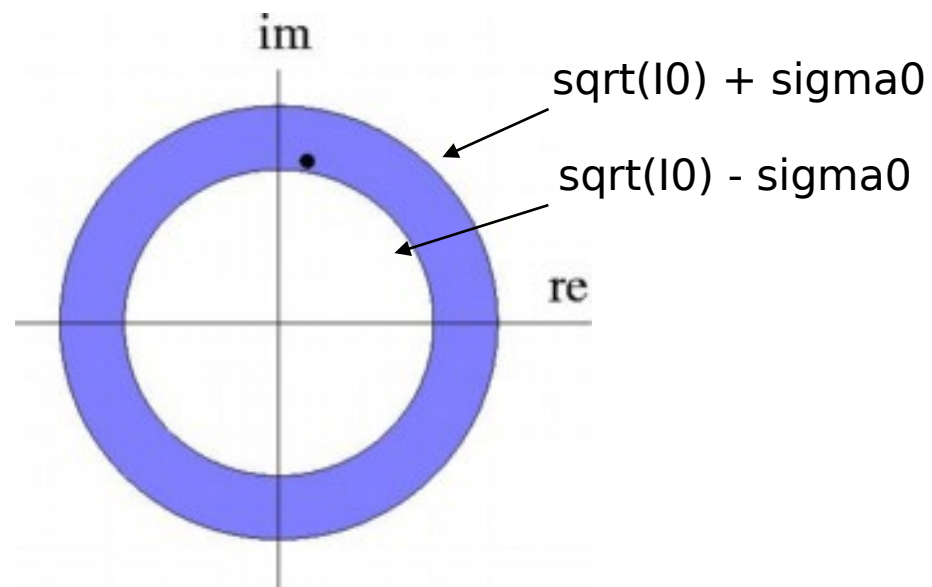
Measure speckle field with no previous knowledge:

- 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

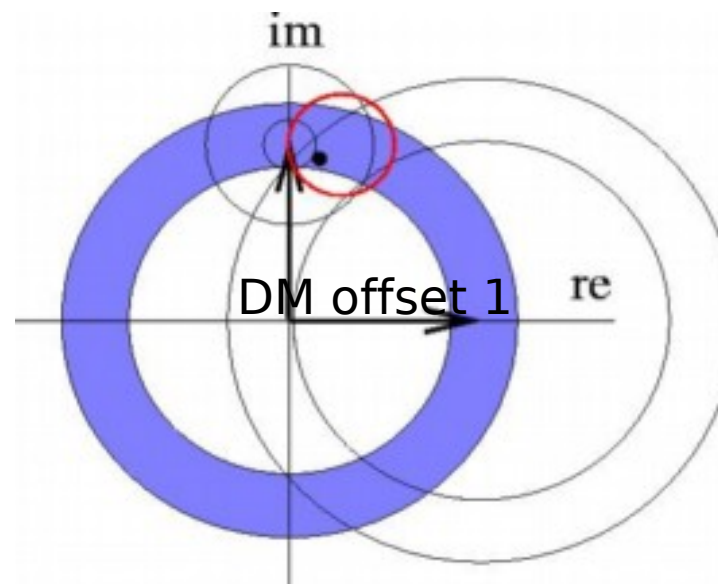
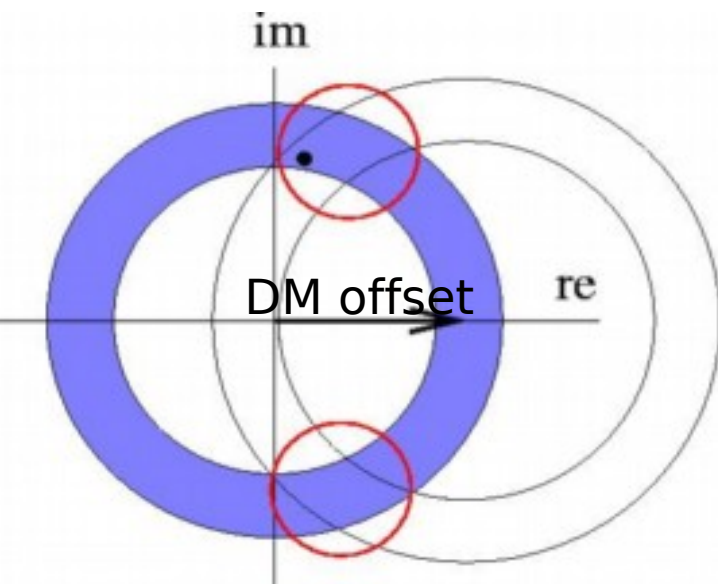
## Initial problem



Take a frame  $\rightarrow$  measured speckle intensity =  $I_0$

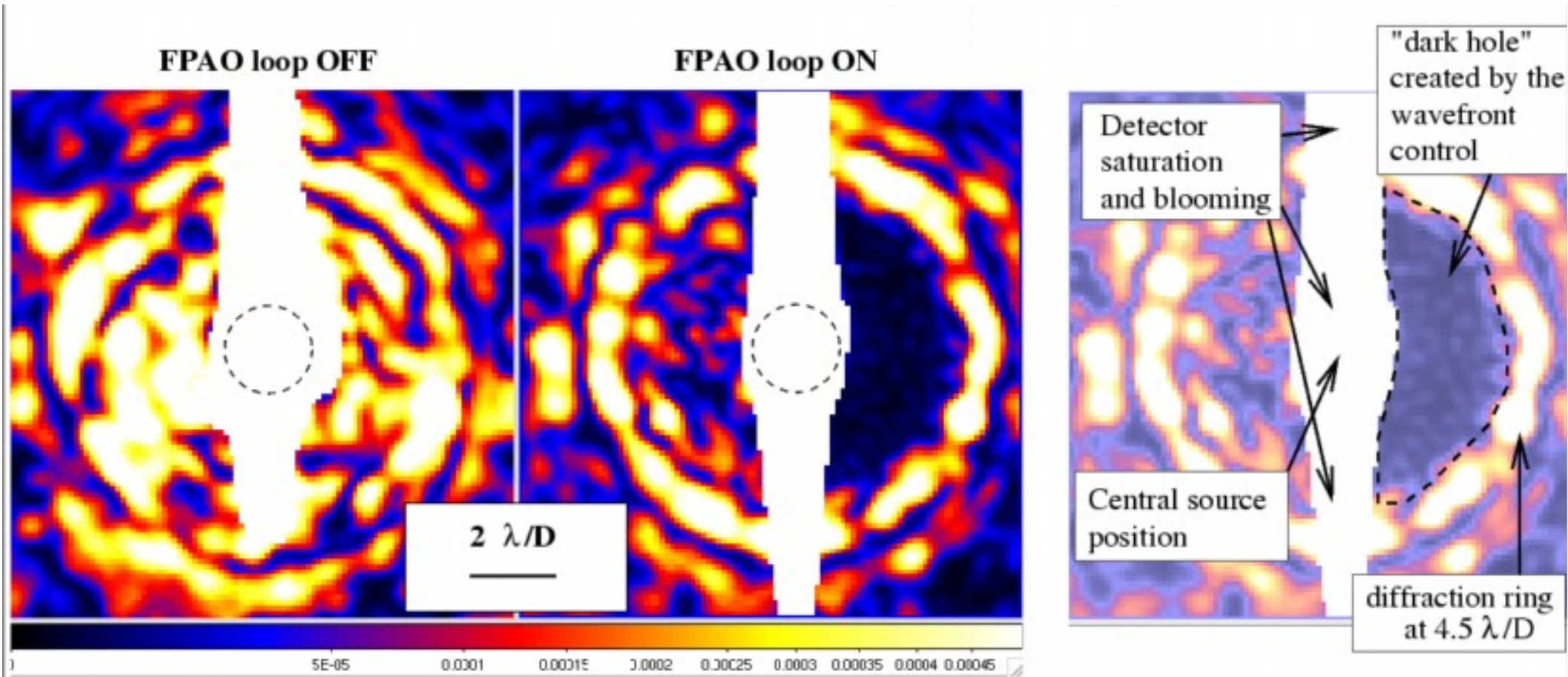


DM offset chosen to be  $\sim$  equal to speckle amplitude





## 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 frequencies:

Shack-Hartmann (SH)

Curvature (Curv)

Modulated Pyramid (MPyr)

Linear, small dynamical range, high sensitivity:

Fixed Pyramid (FPyr)

Zernike phase contrast 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) ?