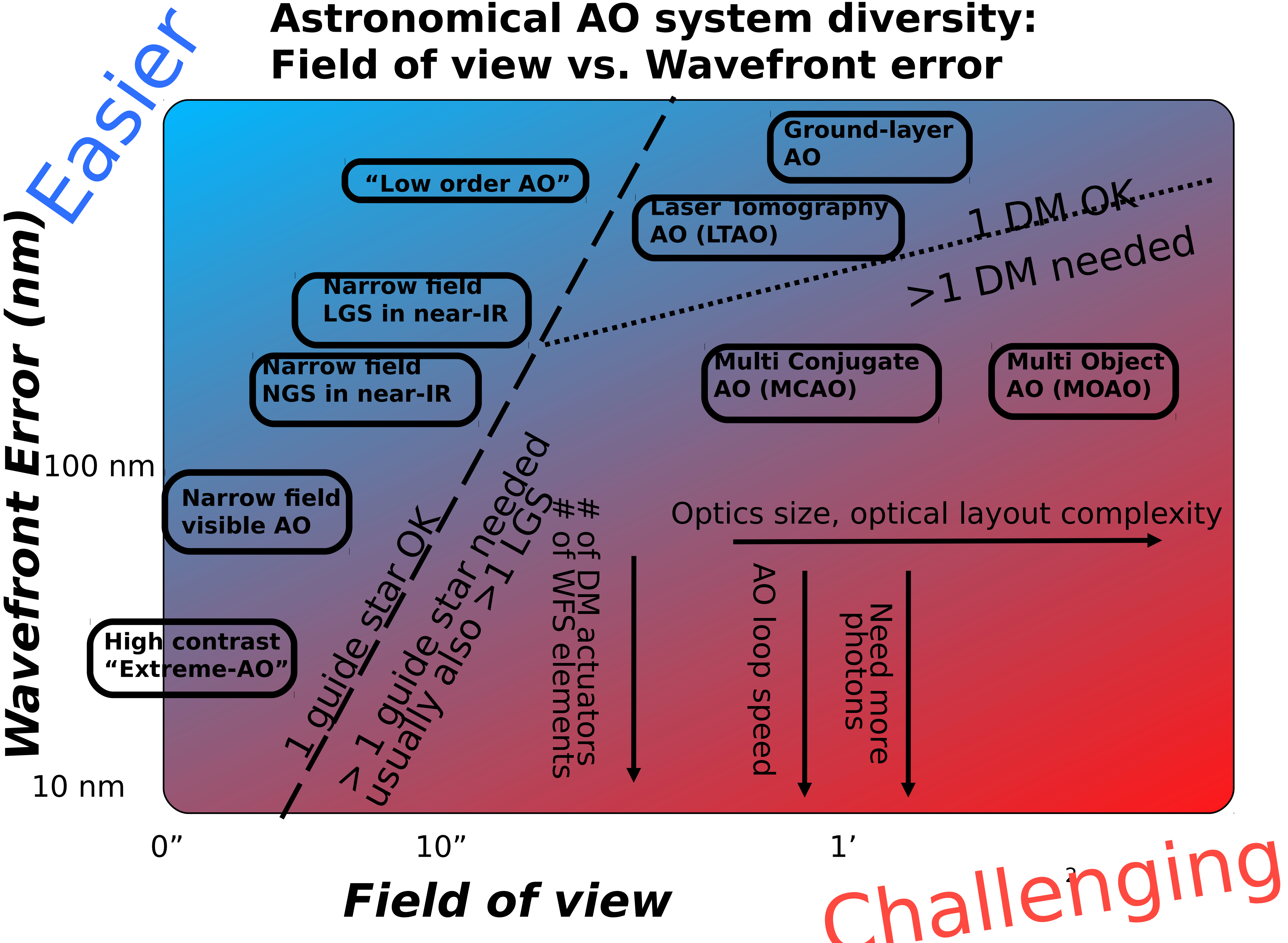
Adaptive Optics for Astronomy

Wavefront sensing
Natural and Laser Guide Stars
Types of WFS

Astronomical AO system diversity: Field of view vs. Wavefront error



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 the aberrated wavefront to allow correction with a deformable mirror (DM). Wavefront measurement is done by a Wavefront Sensor (hardware) + wavefront reconstructor (Software, translates WFS signal into DM language)

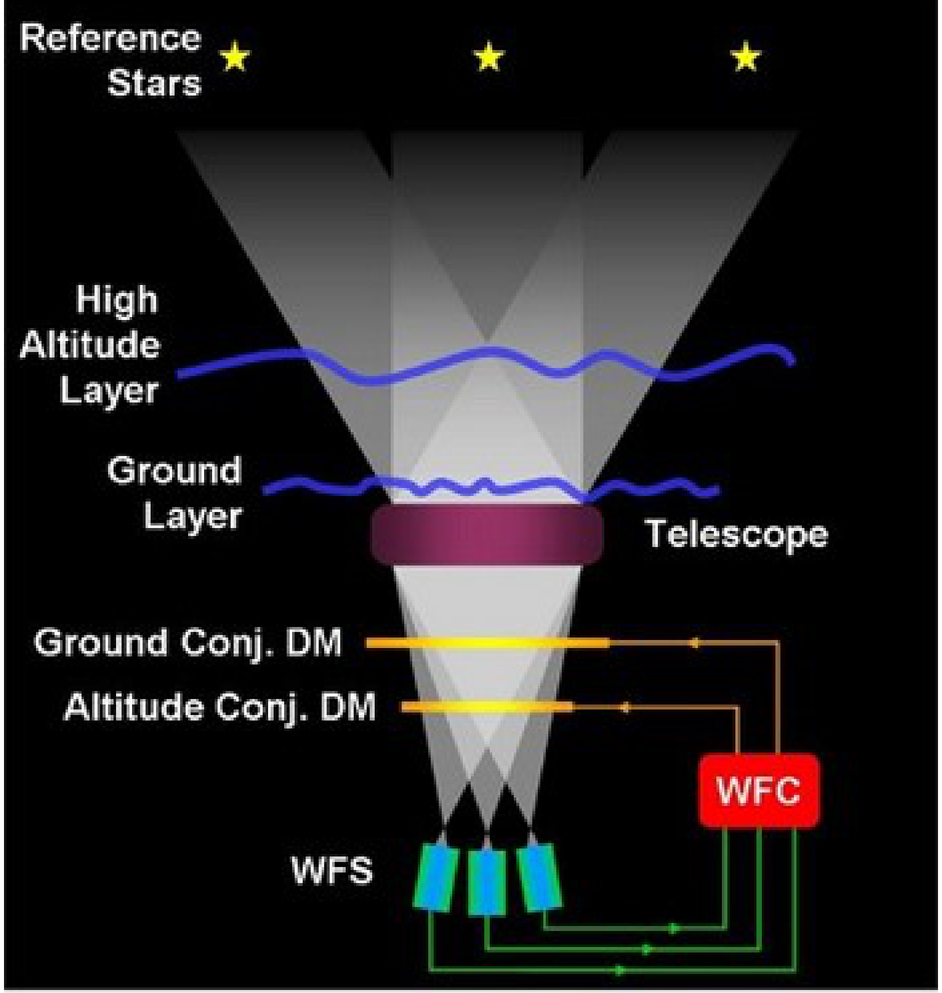
Requirements (need to be balanced in AO system design):

- **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)

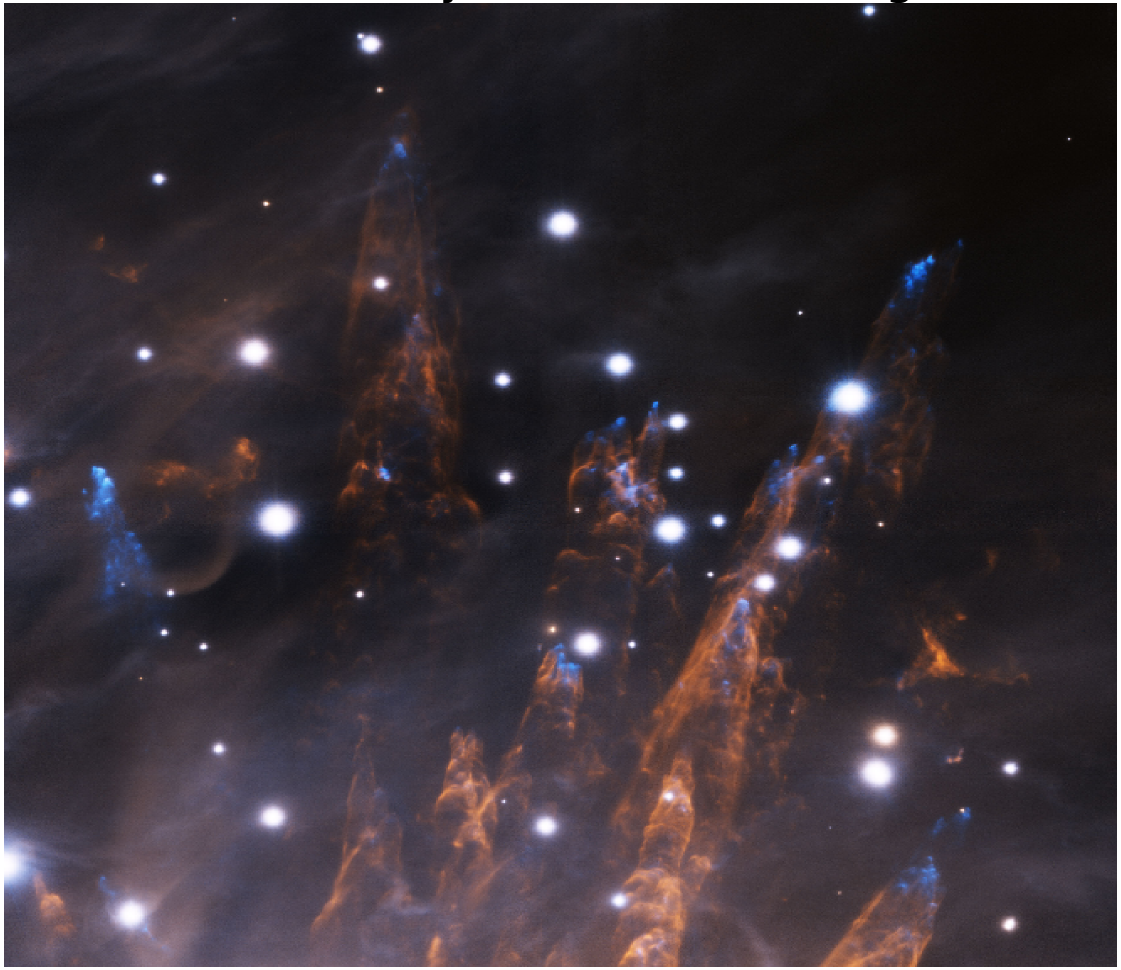
Multi-Conjugate AO (MCAO)

Uses several guide stars (NGS or/and LGS) to gain volumetric information of turbulence.

Uses several DMs to correct over wide field.

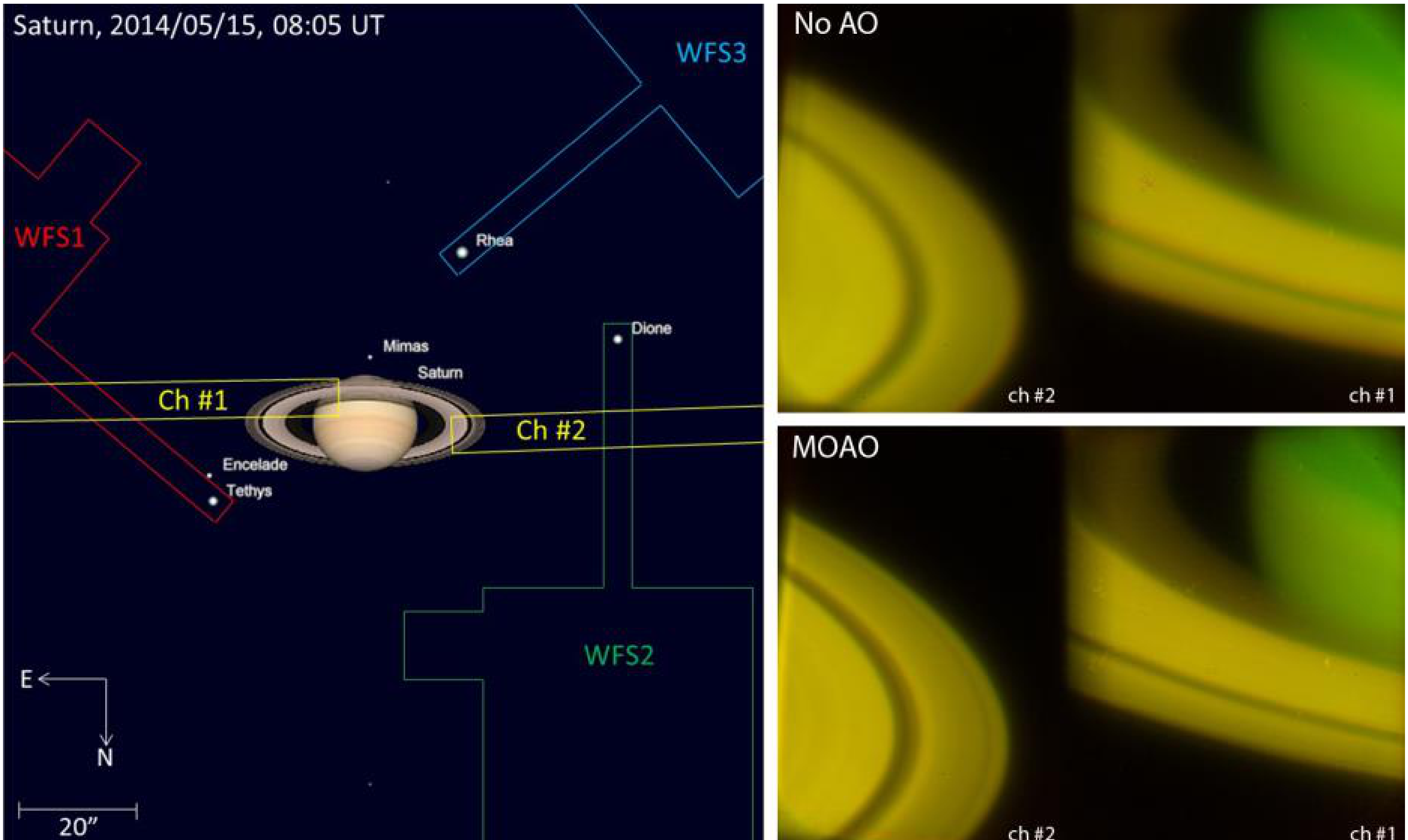


Gemini MCAO system (GEMS) image



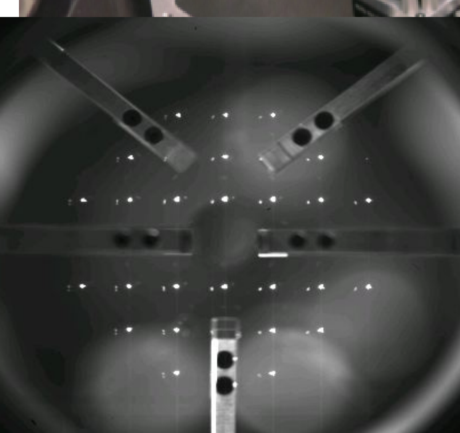
Multi-object WFS

3 natural guide stars → 2 fields corrected (each with a separate DM)

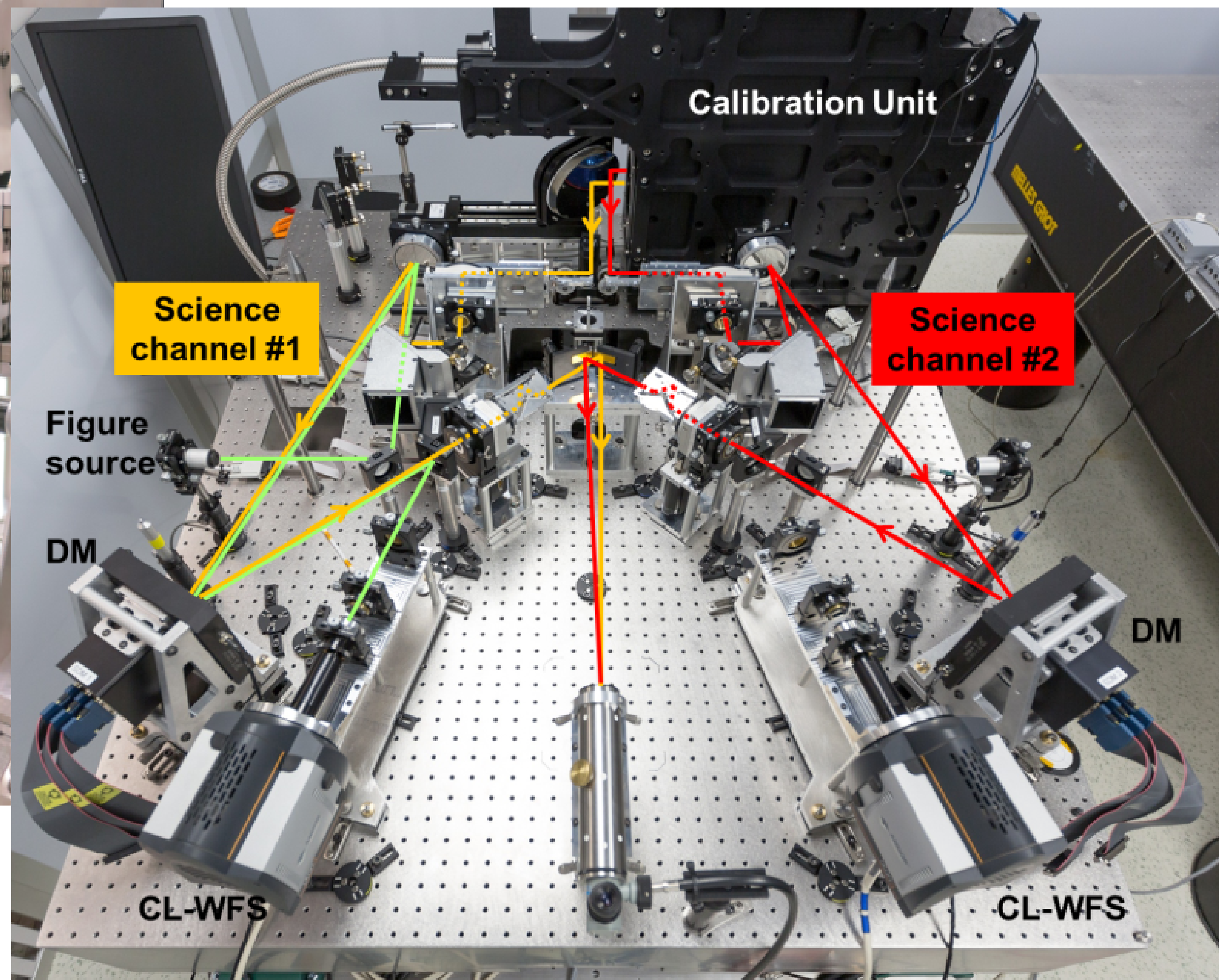


RAVEN optical bench (University of Victoria, Subaru Telescope)

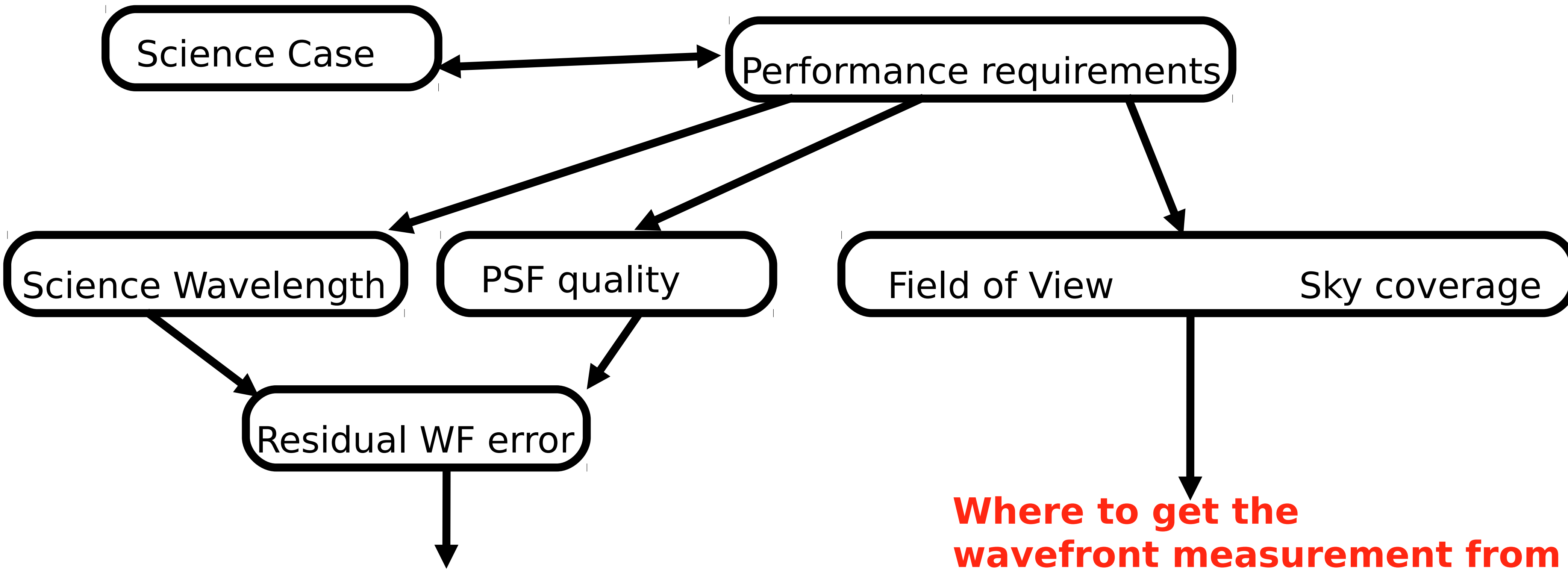
WFS and science fields acquisition



WF correction



Choosing the wavefront sensing strategy is the most fundamental step in the design of an AO system



Where to get the wavefront measurement from ?

NGS ? LGS ?
How many guide stars, where ?
WFS wavelength ?

Wavefront sensor(s) choice

SH, Curv, PYR, other ?
How many elements ?

It is important to understand the physics of WFS well, avoid bad/inefficient combinations

Where to get the wavefront measurement ?

(1) Are there suitable natural guide star(s) ?

If not -> **Laser Guide Star (LGS)**

which laser ?

- Rayleigh
  - low altitude (few km) Rayleigh scattering
  - same process makes the sky blue
  - works better at shorter wavelength
- Sodium
  - excitation of sodium layer at 90 km
- Polychromatic Sodium (not quite ready yet)
  - excitation of sodium layer to produce LGS
  - in 2 wavelengths -> can solve Tip/Tilt problem

LGS allows large (>50%) sky coverage

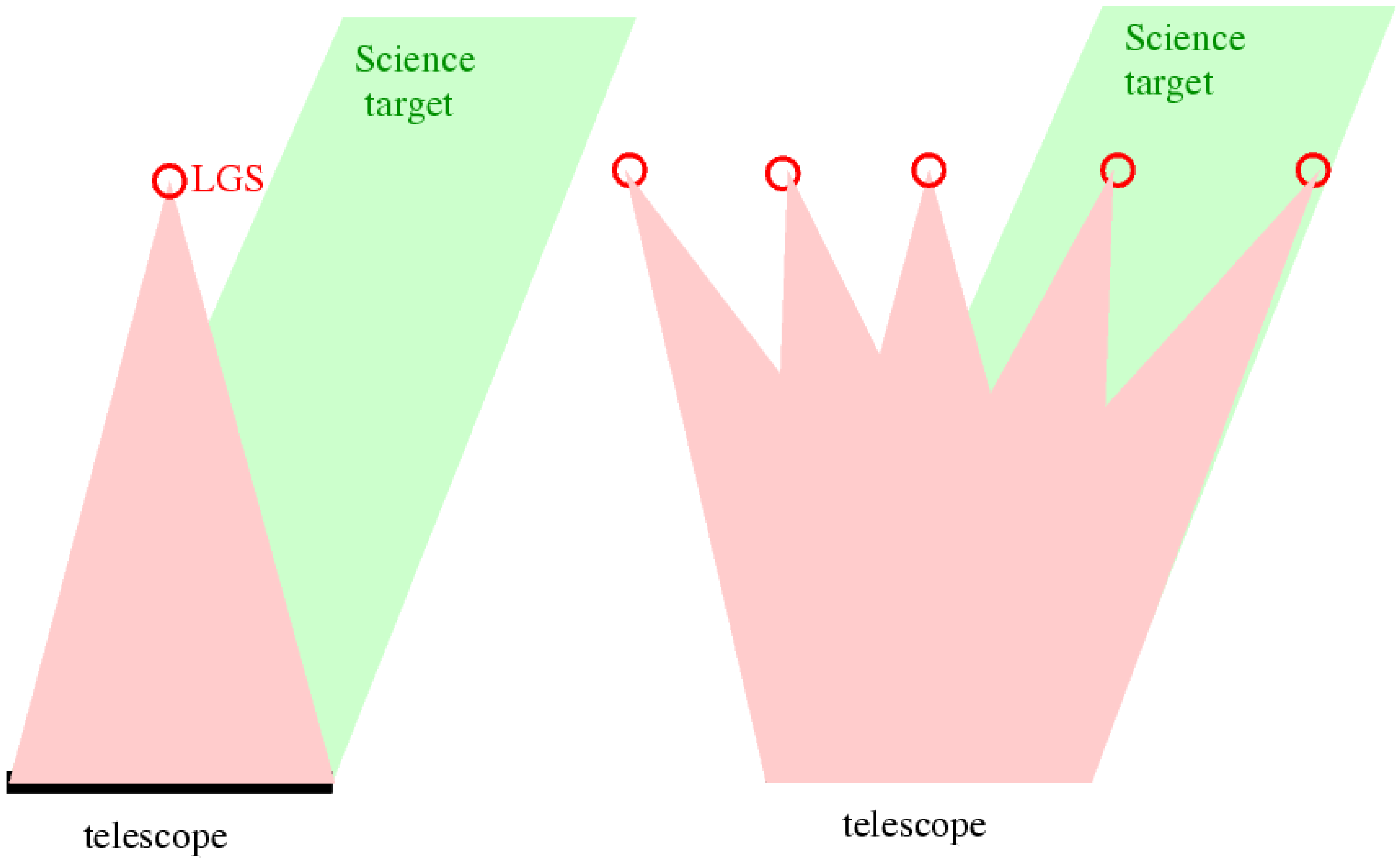
Where to get the wavefront measurement ?

(2) Need several guide stars ?

(for field of view, tomography ?)

Multiple LGS ?

Multiple NGS ?



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

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)

Focal plane Coronagraphic Mach-Zehnder interferometer (FPI)

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

Non-linear Curvature (nlCurv)

Non-linear Pyramid (nlPyr) ?

Wavefront sensor choice

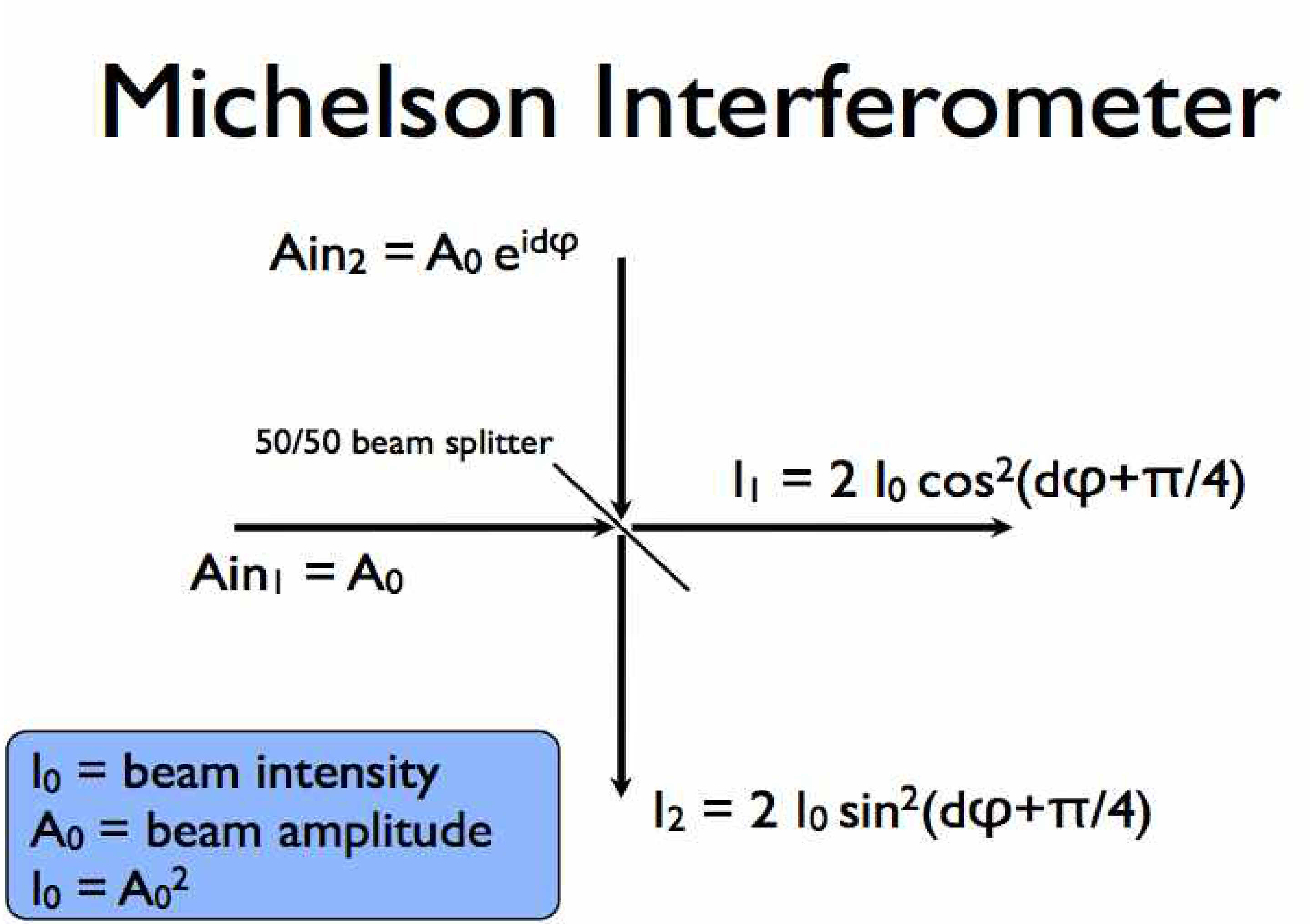
There is no such thing as a universally good (or bad) wavefront sensor

Wavefront sensor choice needs to take into account requirements:

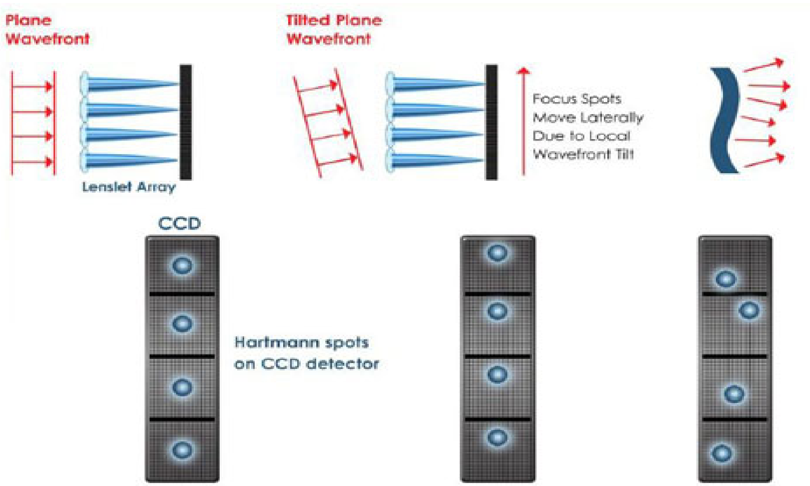
- is WFS used to initially close the AO loop ?
- Is WFS the main system WFS ?
- how many different things does the WFS need to do ?
- is input wavefront already cleaned by first stage AO correction ?
- is guide star extended (laser) or compact (natural star) ?
- is sensitivity a driving requirement ? Or is the AO system already limited by other components ?
- is reconstruction speed a concern ?

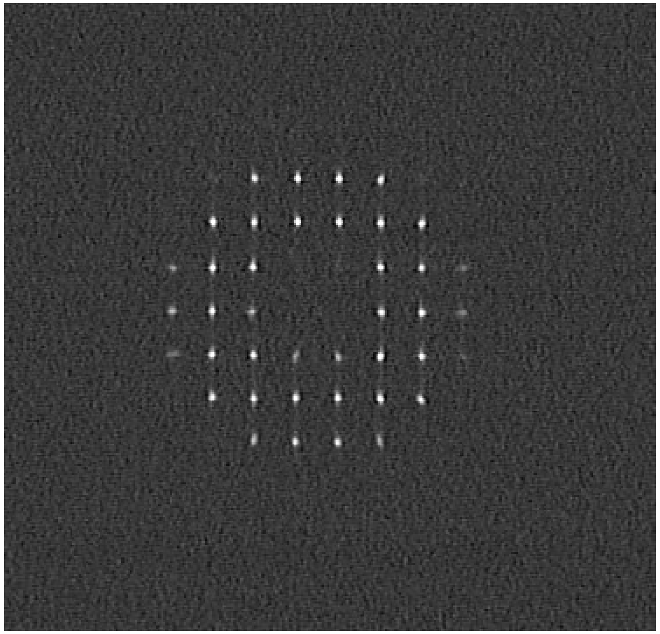
What is a WFS ? (simplest definition)

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-Hartman WFS





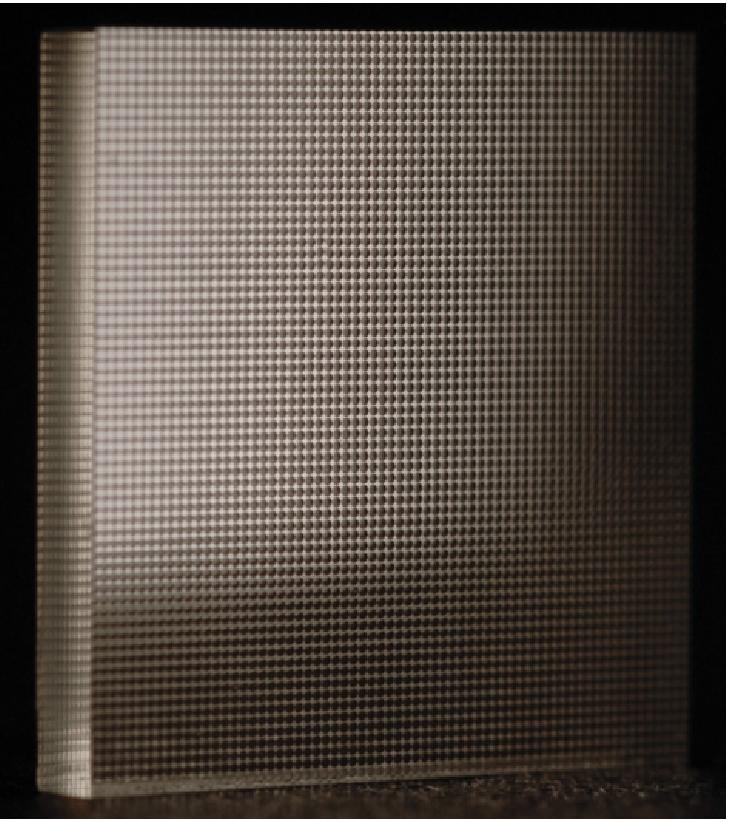
*courtesy:
Boston
Micromachines*

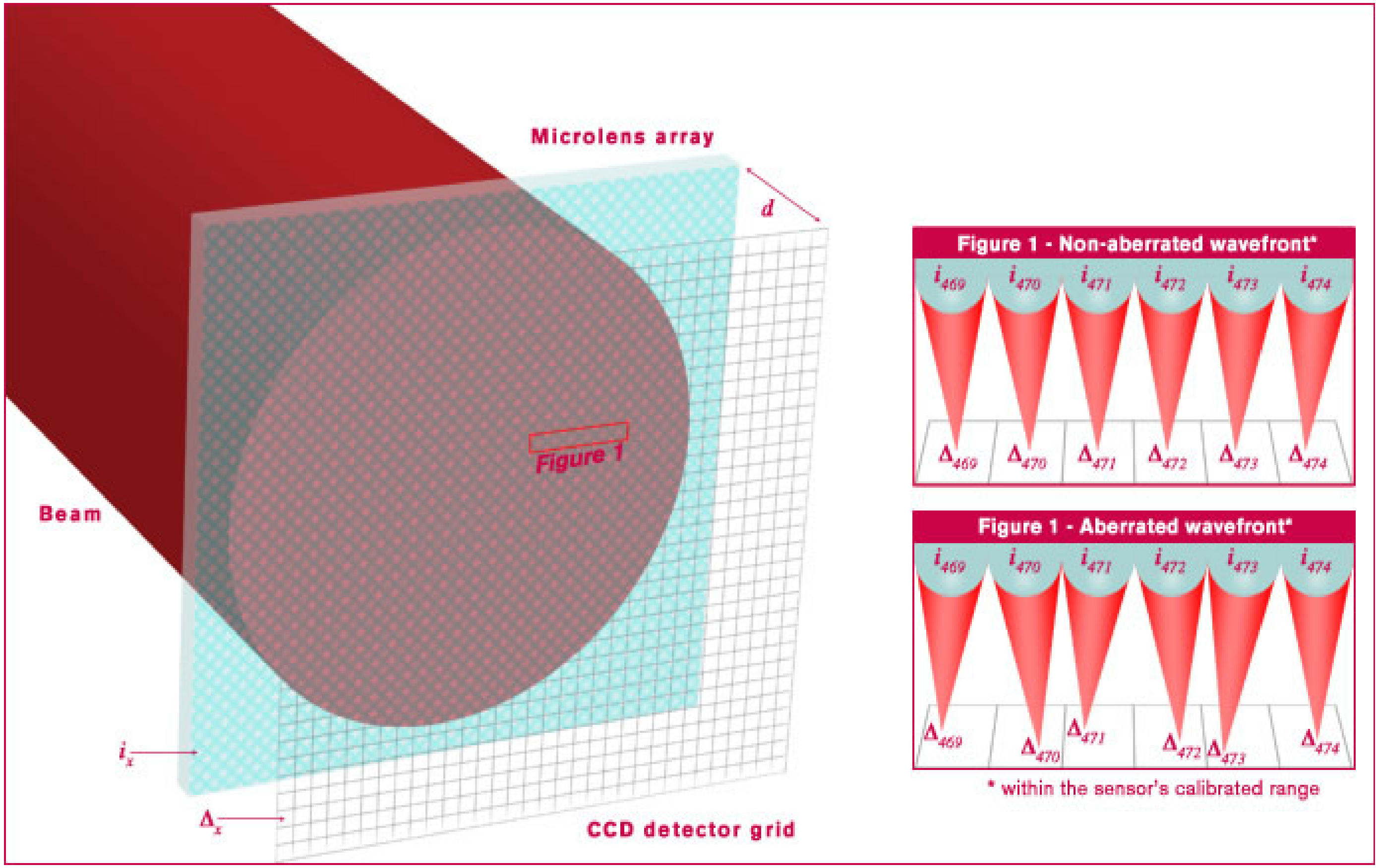
Most widespread WFS in astronomy:

- Able to work on extended source
- Linear over a very wide range
- Number of pixels per subaperture can be increased for capt. Range
- Lots of previous experience, well understood technique
- Straightforward relationship between WF and signal (easy to debug)

Shack-Hartmann WFS

Lenslet array + detector

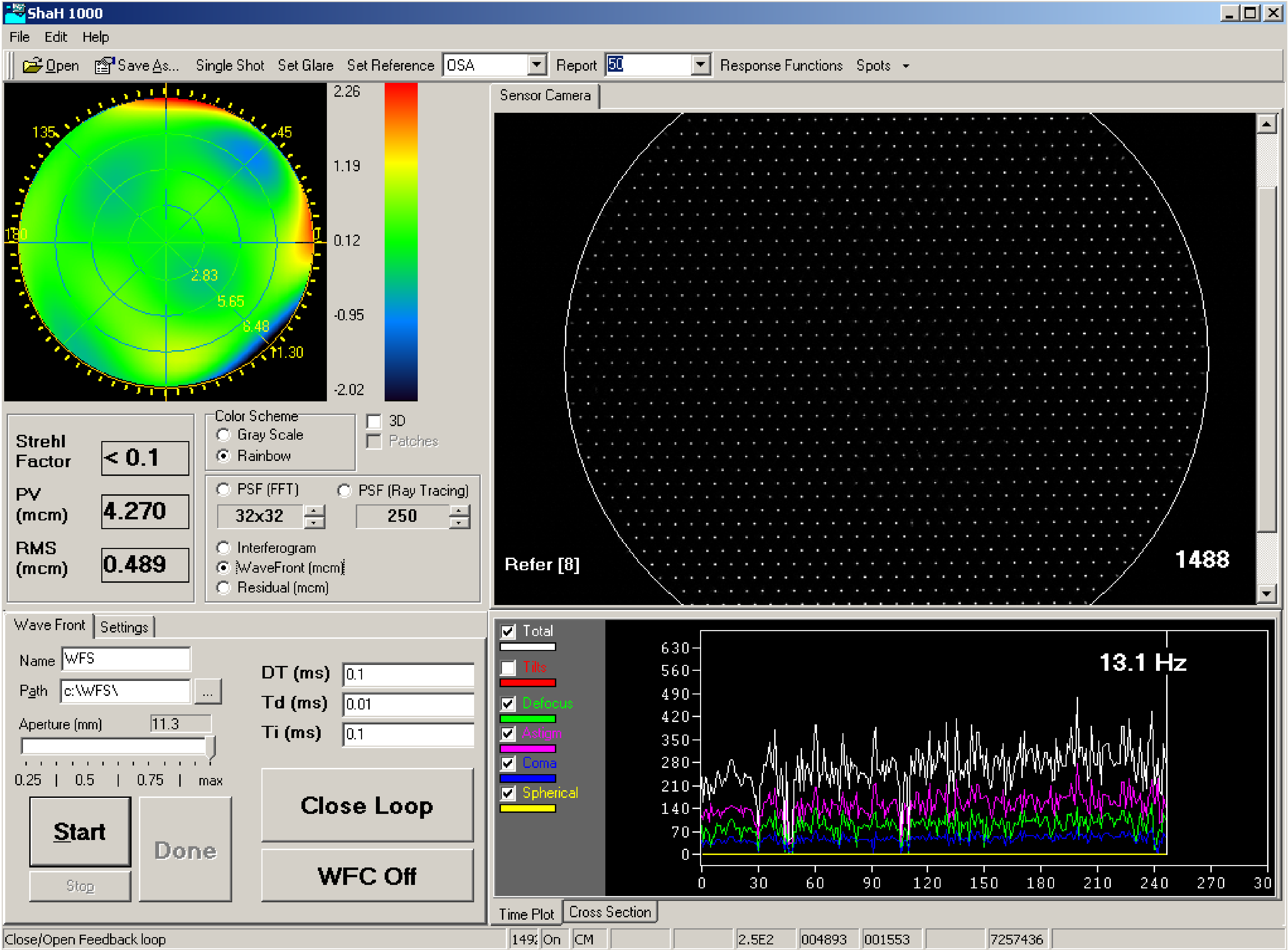




Shack-Hartmann WFS

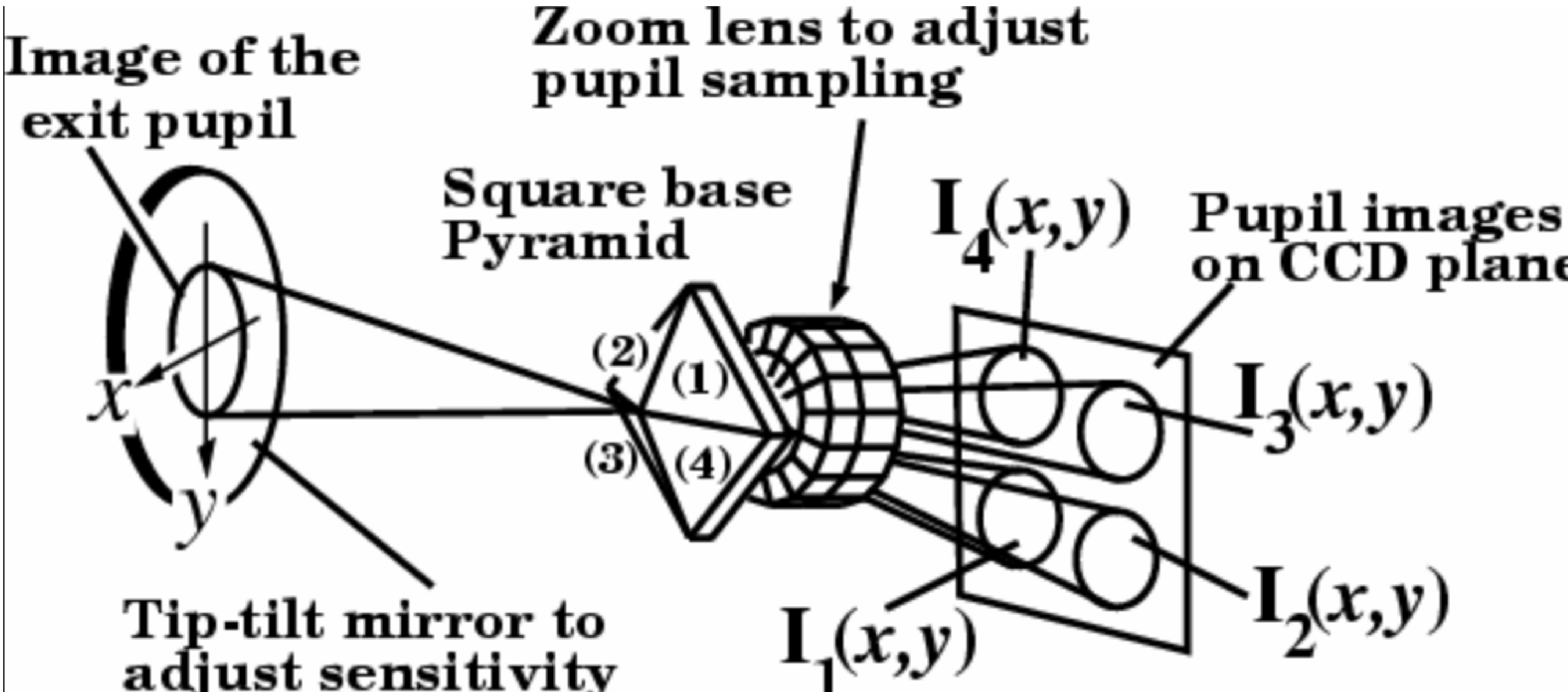
Software integrates slopes into wavefront

courtesy: Del Mar Photonics



Pyramid WFS (modulated)

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

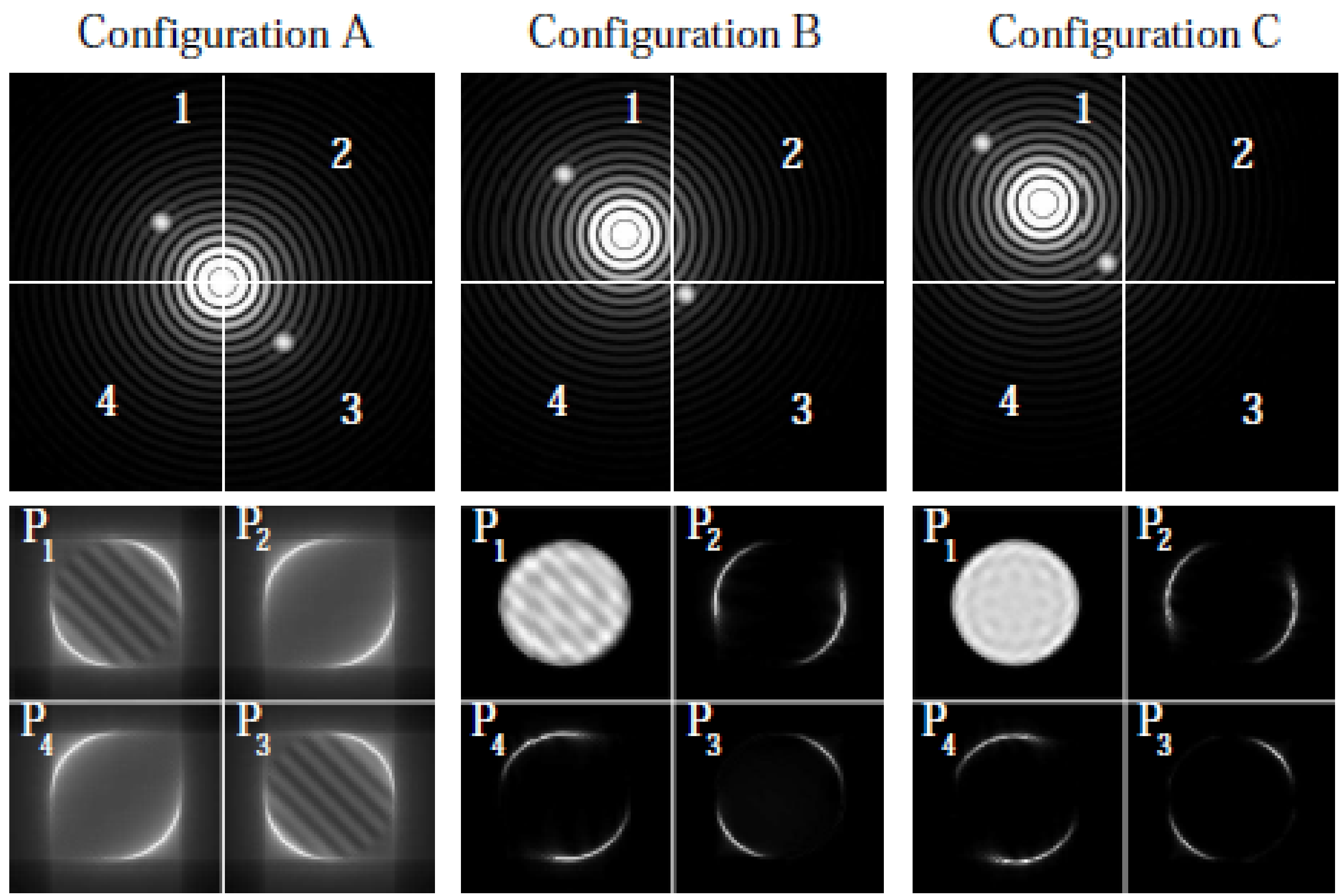
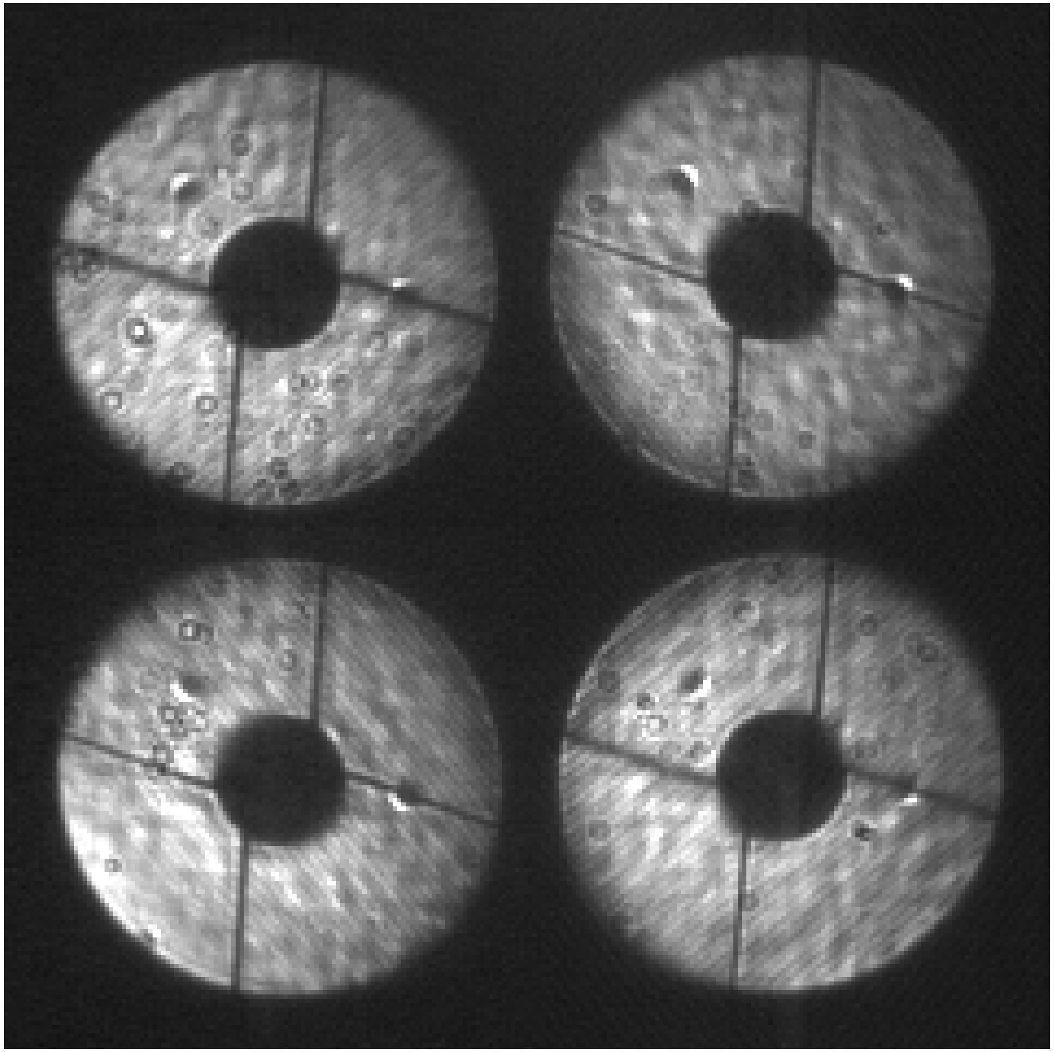


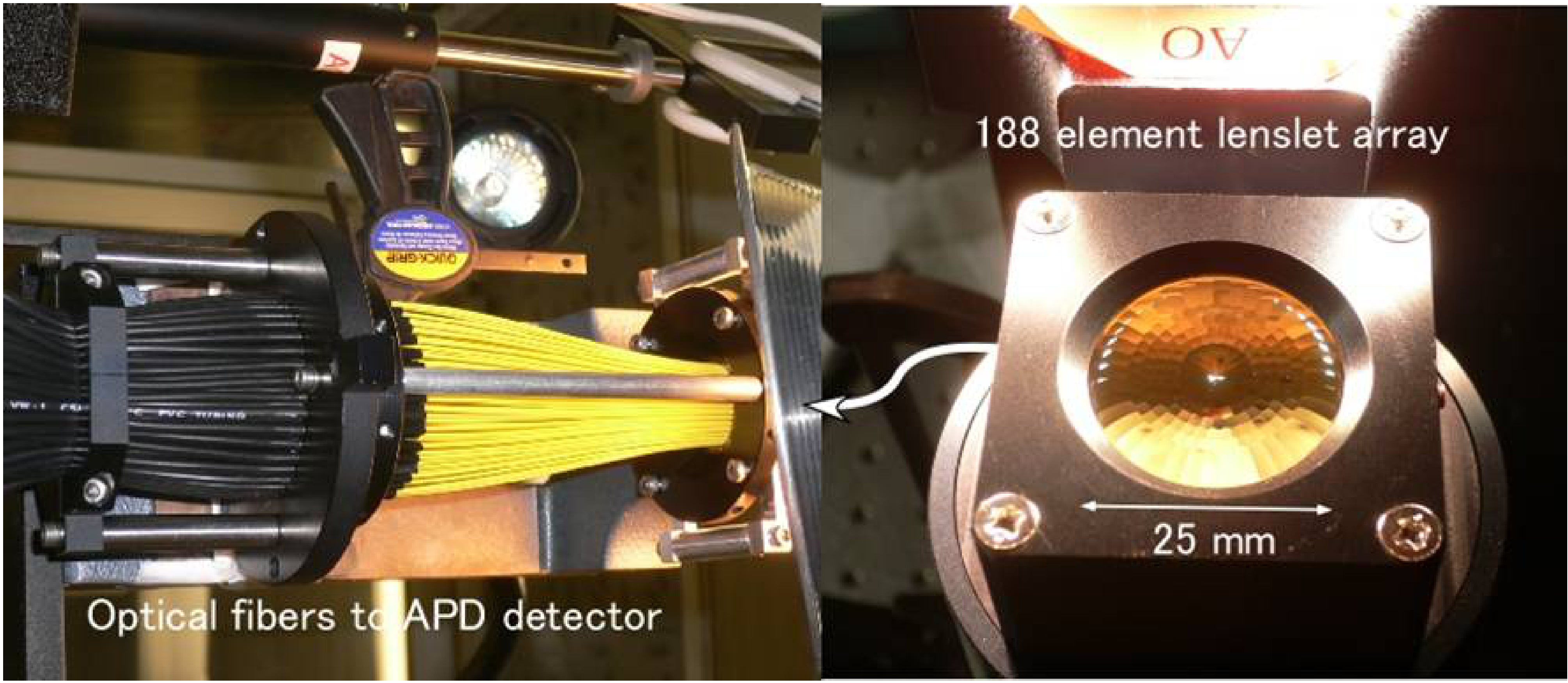
Fig. 5.— Focal plane images (top) and corresponding pupil images P_i (bottom) for a sine-wave pupil phase error (corresponding to 2 symmetric speckles in the focal plane). See text for details.

SCEXAO Pyramid WFS



Curvature WFS

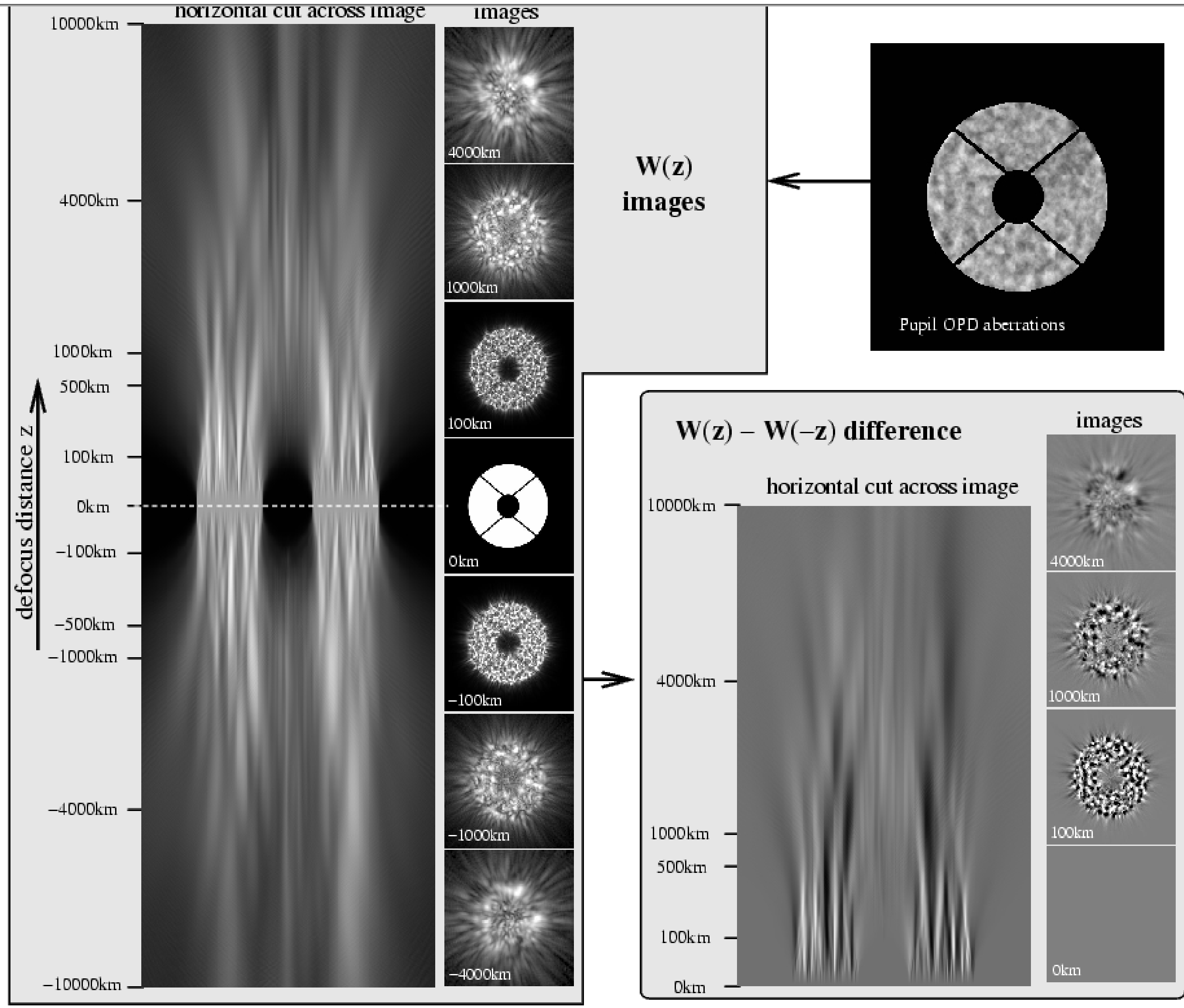
Subaru Telescope 188-element curvature WFS

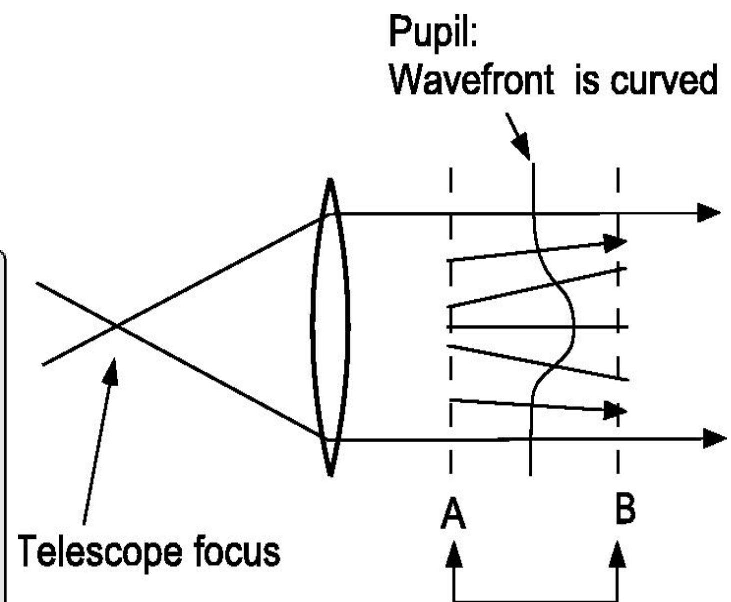


Lenslet array used to inject light into a series of fibers, which are connected to photon-counting Avalanche PhotoDiodes (APDs)

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)

Example 2:
What if sensitivity is the dominant requirement ?

This occurs in ExAO systems, where wavefront is already corrected by an upstream AO system (no requirement on capture range, WFS just needs to be good at one thing !).

Wavefront sensor sensitivity: definition

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)

IDEAL WFS:

Sensitivity Beta = 1 (1 ph = 1 rad of error)

At all spatial frequencies

Non-ideal WFS:

Beta > 1 (Beta x Beta ph = 1 rad of error)

Diffraction-limited wavefront sensors can be much more sensitive than seeing-limited wavefront sensors (such as SH, Curvature)

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, $\sigma^2 \sim 1/D^2$ (more photons)

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

SH, linear Curvature are widely used because they are linear over a wide range of WF errors

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**: 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 if there is more than ~ 1 rad of WF error ! -> poor dynamical range

Solutions exist with good dynamical range, but they are not linear (example: non-linear Curvature WFS – shown on next slide)

Operation of curvature WFS in non-linear regime, with large defocus distances, solves the noise propagation effect. Reconstruction algorithm is similar to phase retrieval (algorithm needs to be fast, with few iterations)

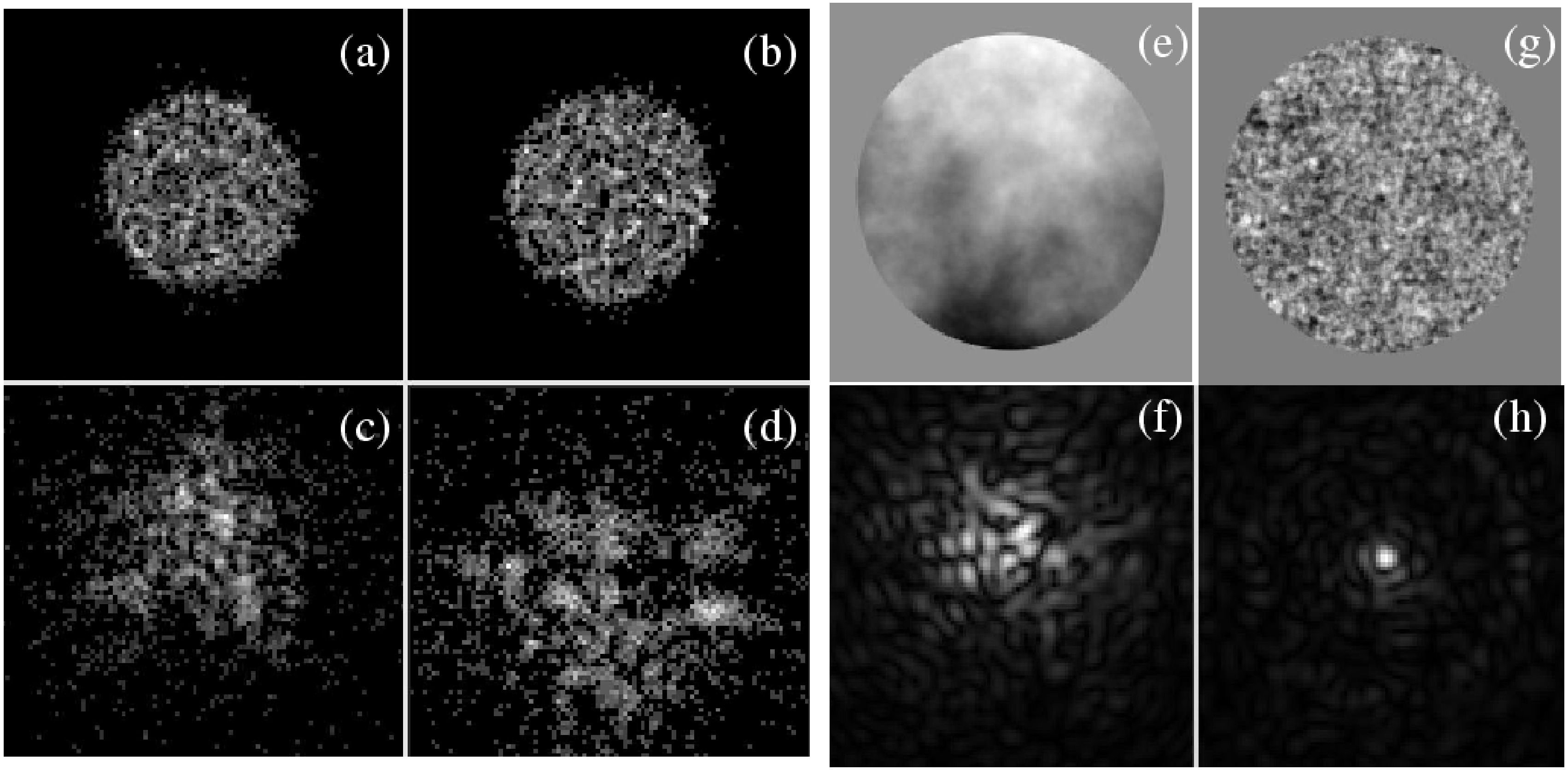


Fig. 9.— Wavefront reconstruction using the algorithm shown in fig. 8. Four noisy defocused pupil images (images (a), (b), (c) and (d)) are acquired to transform the pupil phase aberrations (e) into intensity signals. The input pupil phase is 609 nm RMS, yielding the PSF (f) before correction. After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

ref: Guyon, 2009

Example 3:
What if WF calibration is the dominant requirement ?

This occurs in ExAO systems, where the wavefront should be free of static errors which would look like planets.

Focal-plane wavefront sensing & correction addresses this requirement

Next 4 slides describe the technique

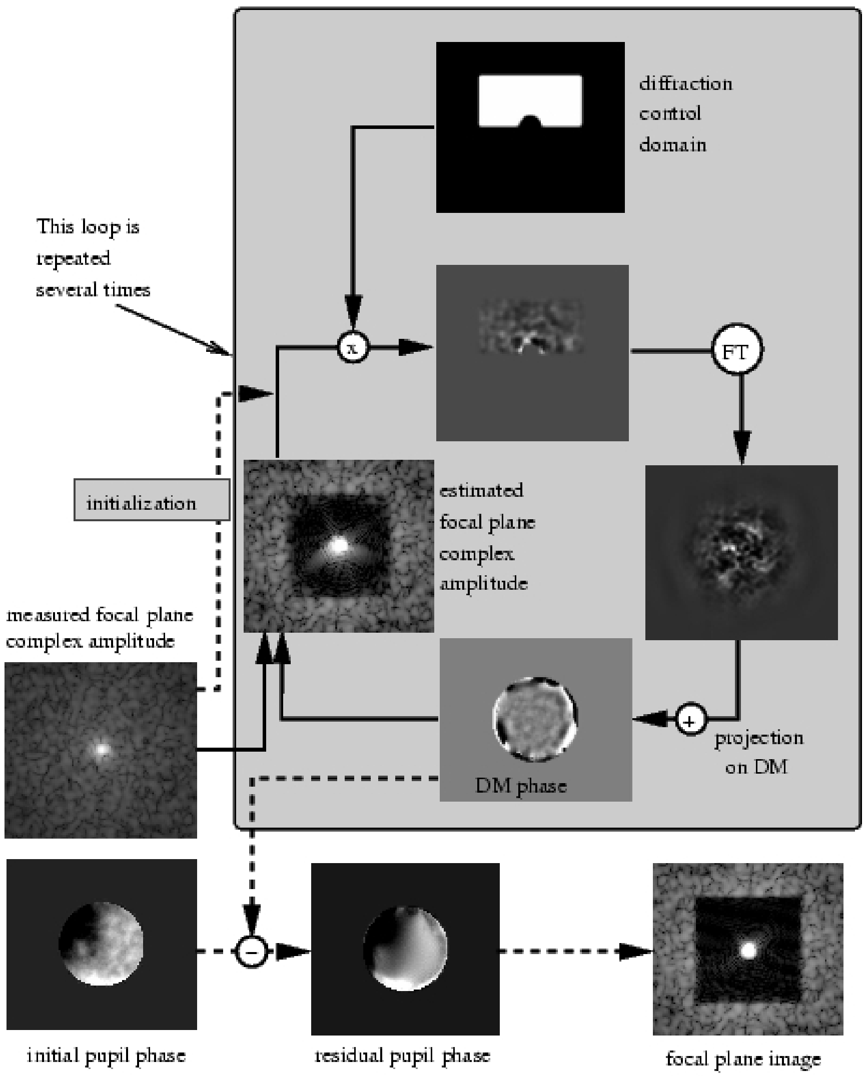
Focal plane WFS: a non-linear WFS well suited for Extreme AO

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

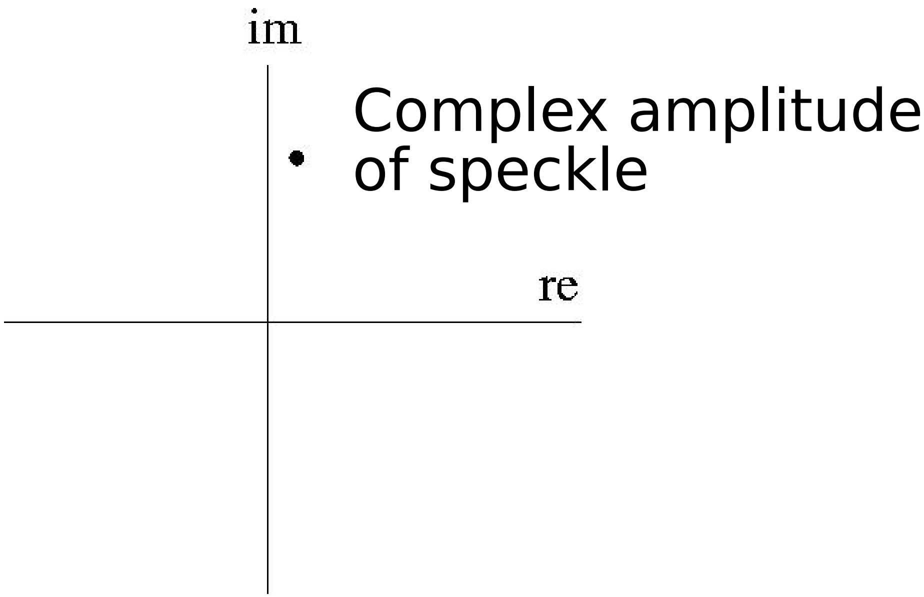
<u>Measure speckle field with no previous knowledge:</u>

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

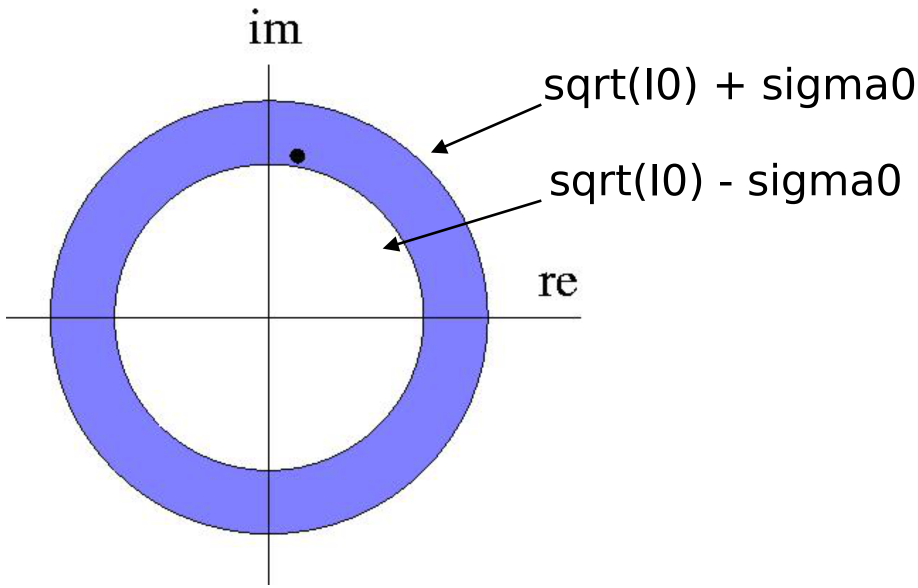
- compute 2 DM shapes which will add known speckles on top of existing speckles. These 2 “additive” speckle field have same amplitude as existing speckles, and the phase offset between the 2 additive speckle fields is PI/2

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

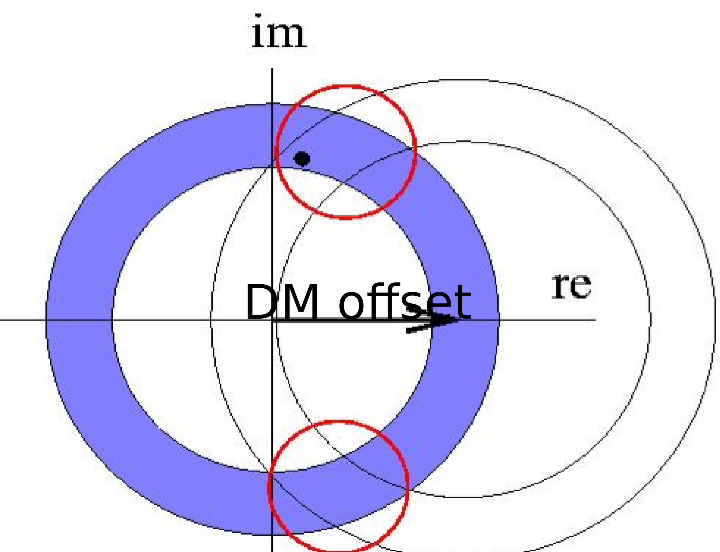
Initial problem

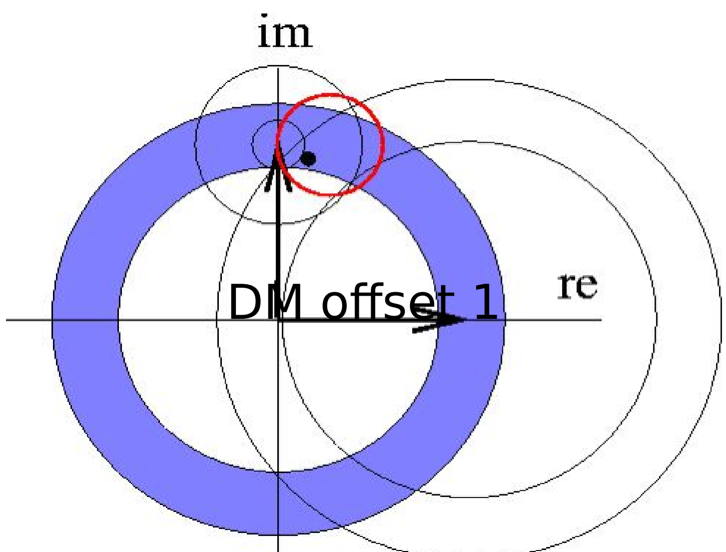


Take a frame -> measured speckle intensity = I0

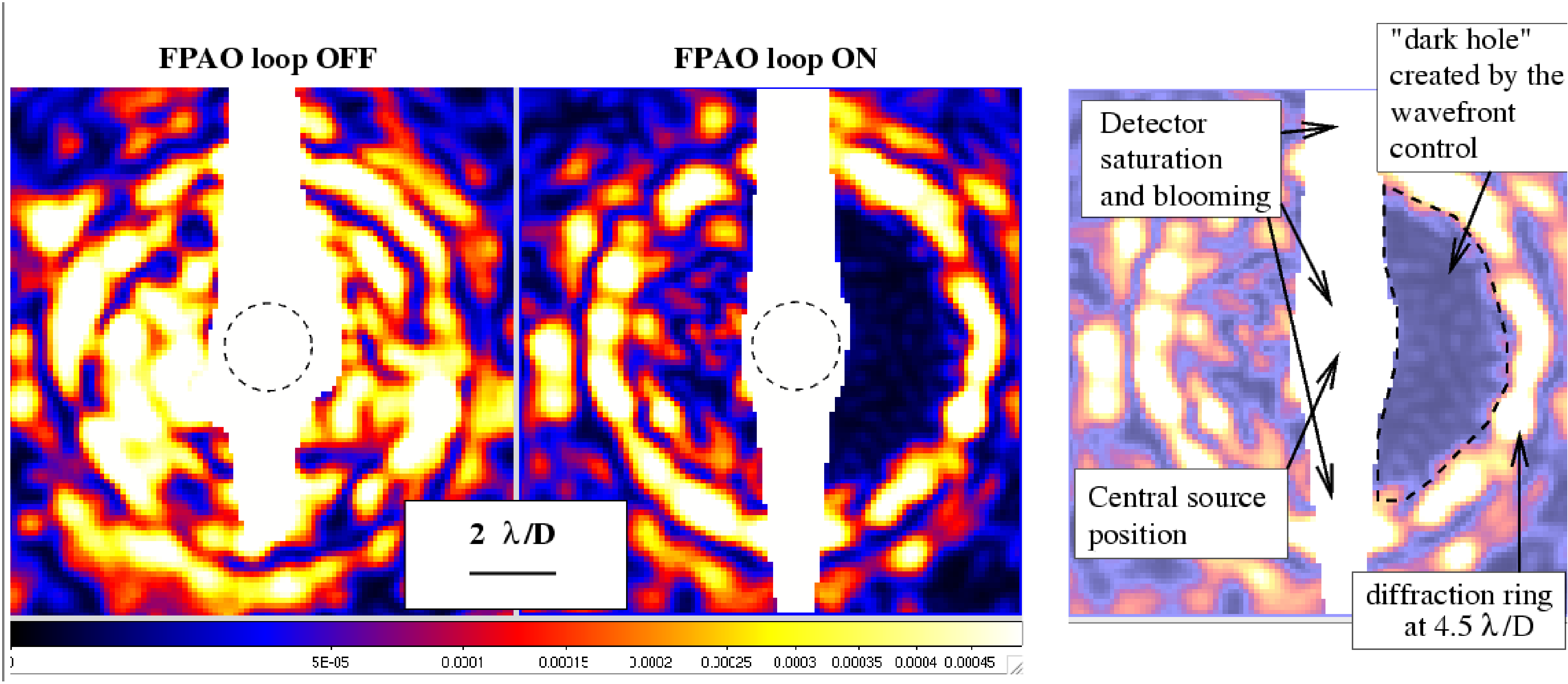


DM offset chosen to be ~ equal to speckle amplitude





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



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

Matching:

Wavefront quality in WFS — to — Wavefront sensor

<< 1 rad

Space Extreme-AO
(Terrestrial Planet Finder)

Second-stage of Extreme-AO
system in near-IR (“Tweeter”)

Interferometric

Focal plane

Not allowed

~ 1 rad

Extreme-AO Closed loop in Visible

Thermal IR AO on 8m telescope
open loop

“general purpose” AO system in
closed loop

Pyramid (fixed)

allowed

Pyramid (modulated)

>> 1 rad

LGS AO
GLAO

Open loop AO

Curvature

Shack-Hartmann

How to choose the best WFS(s) ? A few more guidelines…

- WFS for LGS should be SH, Curv (or modulated pyramid ?)
- For NGS AO, a multi-stage approach is attractive to combine advantages of several WFS options
  - this is especially attractive for Extreme-AO systems, for which the highest sensitivity WFS options would increase science return, but may not be able to close the loop if used alone

Example of sensible pairing: Possible Coronagraphic ExAO architecture

AO with visible WFS
(Curvature or
Shack Hartmann)

AO with high sensitivity
WFS in visible
(examples: Pyramid,
interferometer, focal plane WFS)

Near-IR

Coronagraph
Focal plane AO → Science frame acquired by the same camera as FPWFS

Fast camera for
focal plane WFS
after coronagraph

-The first step is used to clean the wavefront within ~ 1 rad in Visible
-The second step operates in the high coherence regime, and adopts a high sensitivity WFS.
-Last step uses focal plane WFS free of non-common path errors (Gemini Planet Imager (GPI) uses a similar strategy, with an interferometer WFS to measure coherent residuals)