Wavefront Sensing & Control

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Slides based on material by Claire Max,
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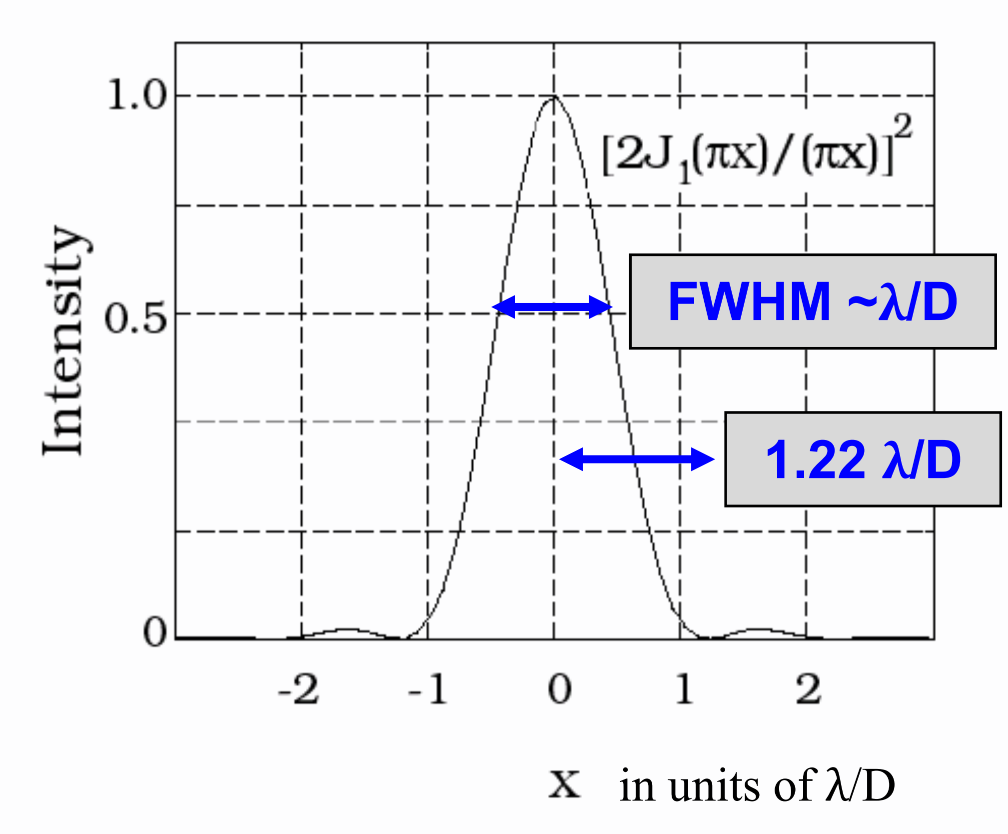
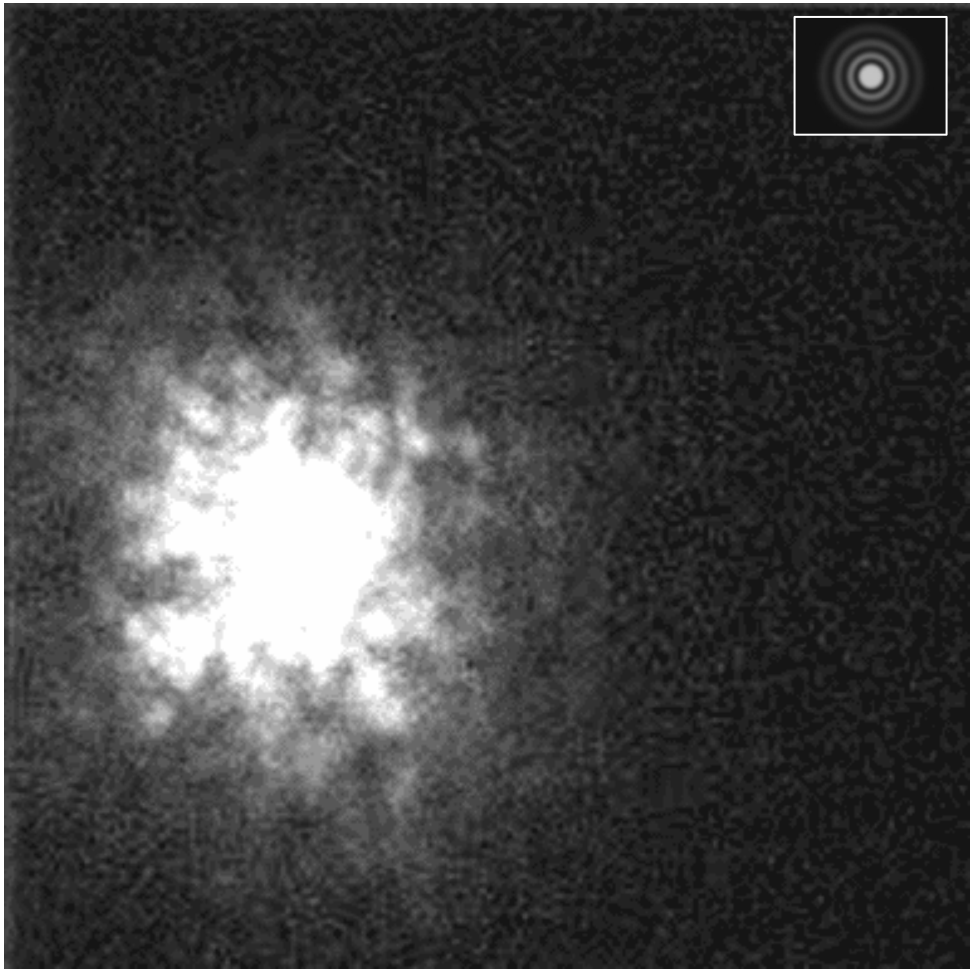
Imaging through a perfect telescope

Point Spread Function (PSF):
intensity profile from point source



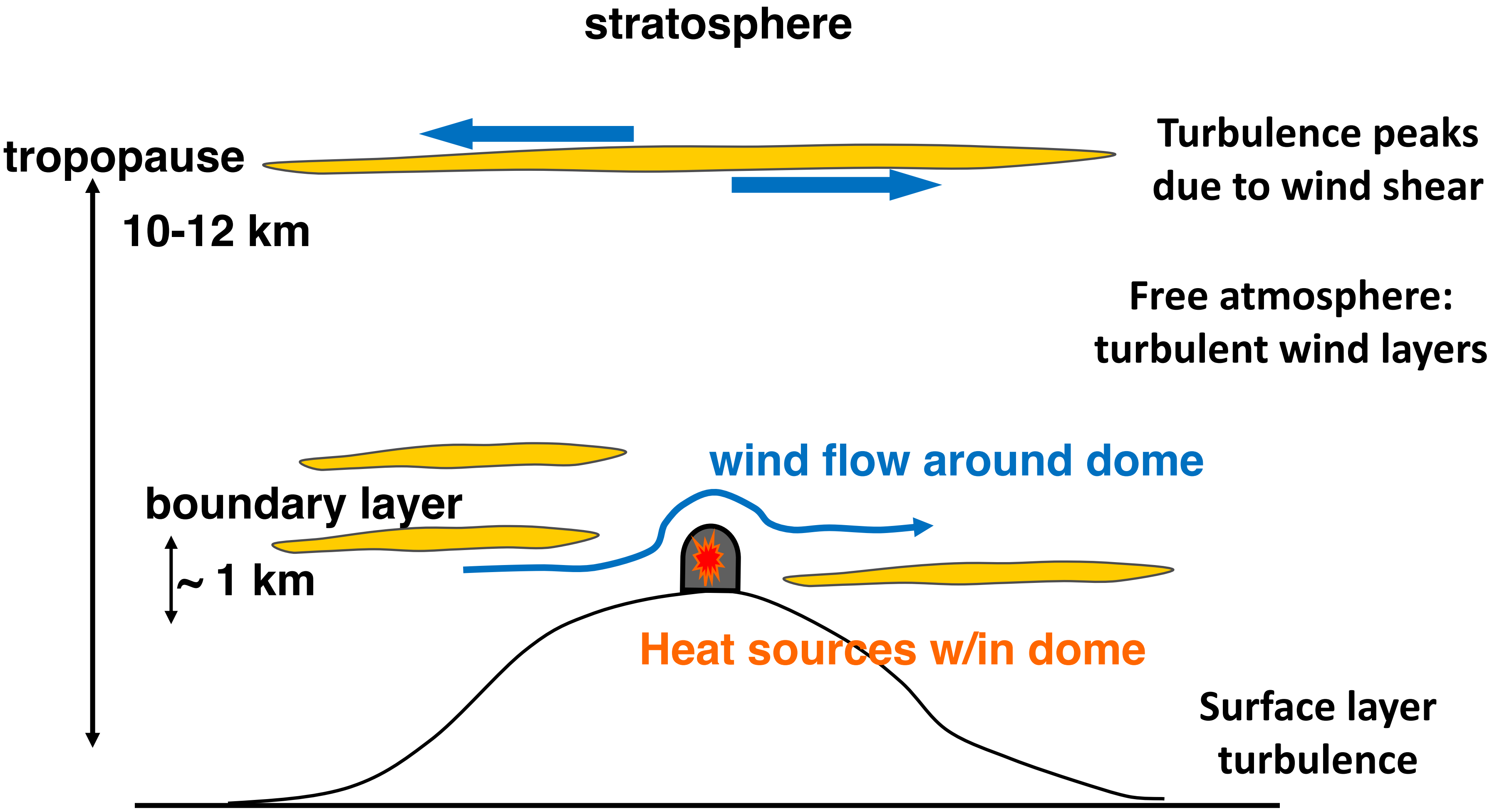
- With no turbulence, FWHM is the diffraction limit of telescope, $\theta \sim \lambda / D$
- With turbulence, the image size is much larger, typically 0.5 - 2 arcseconds

Turbulence changes rapidly with time



- Resulting images are a combination of many Airy discs at different locations, called speckles
- Each Airy disc is defined by the diffraction limit of the telescope
- Centroid jumps around (image motion)

Turbulence arises at many locations



stratosphere

tropopause

Turbulence peaks due to wind shear

10-12 km

Free atmosphere: turbulent wind layers

wind flow around dome

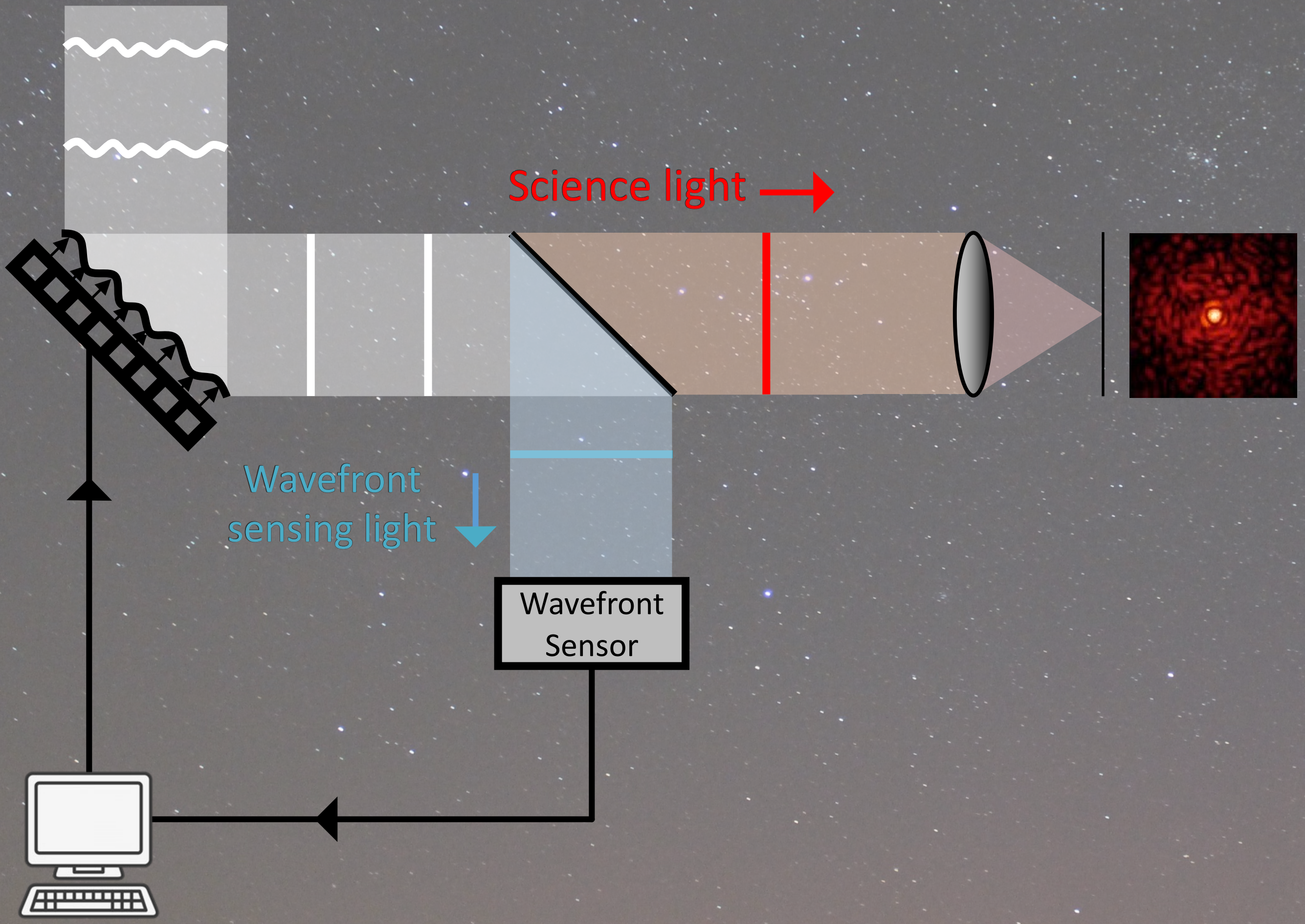
boundary layer

~ 1 km

Heat sources w/in dome

Surface layer turbulence

Cartoon Diagram of an Adaptive Optics System



Science light →

Wavefront sensing light ↓

Wavefront Sensor

An idealized deformable mirror

BEFORE

AFTER

Incoming Wave with Aberration

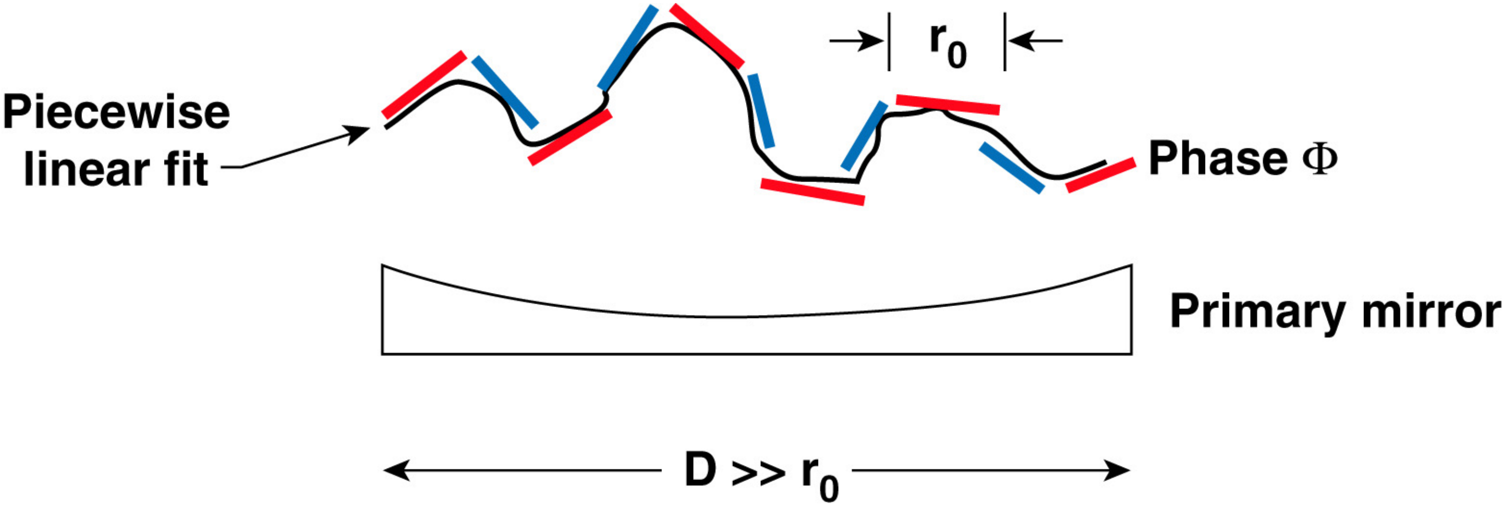
Deformable Mirror

Corrected Wavefront

Deformable mirror requirements: r_0 sets the required # of degrees of freedom

- The spatial scale of turbulence is described by the Fried parameter, r_0

$$r_0 \equiv \left[0.423k^2(\sec z)\int C_N^2 dh\right]^{-3/5}$$



- Number of subapertures is approximately $(D/r_0)^2$ where r_0 is evaluated at the desired observing wavelength

DM Requirements

- **Dynamic Range:** from turbulence theory, the variance across a wavefront is:

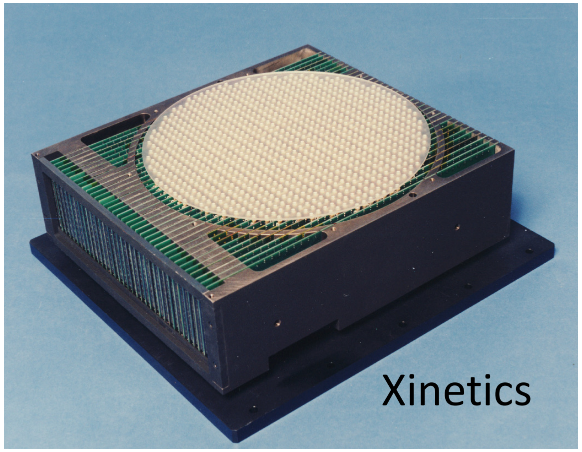
$$\sigma^2_{wavefront} = 6.88(D/r_0)^{5/3}\ [rad^2]$$

For Keck, σ ∼ 5.5 microns
For ELTs, σ ∼ 30 microns

- **Temporal Response:** should be much faster than the coherence time (∼1%) to avoid limiting the system's performance (1-2ms in the NIR)
  - The temporal scale of the atmosphere is given by $\tau_0 \sim \left(\frac{r_0}{\bar{V}}\right)$
- **Influence Function:** a continuous facesheet DM needs a good match between the facesheet thickness and actuator spacing
- **Other requirements:** surface quality, actuator hysteresis, power dissipation, and size

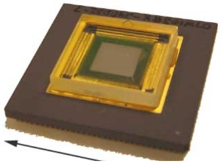
Deformable mirrors come in many genres and sizes

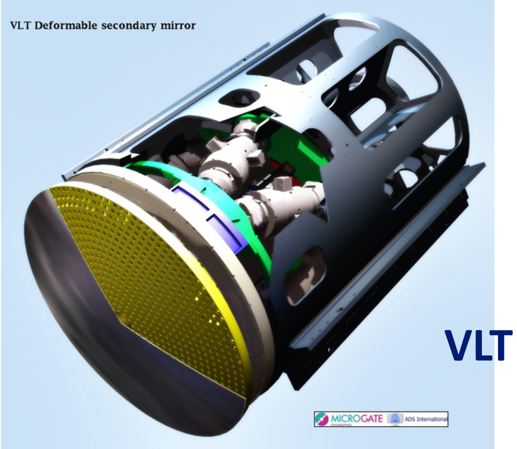
Glass facesheet DM
1000 actuators




LBT adaptive secondary
672 actuators

Boston Michromachins MEMS DM
1000 actuators

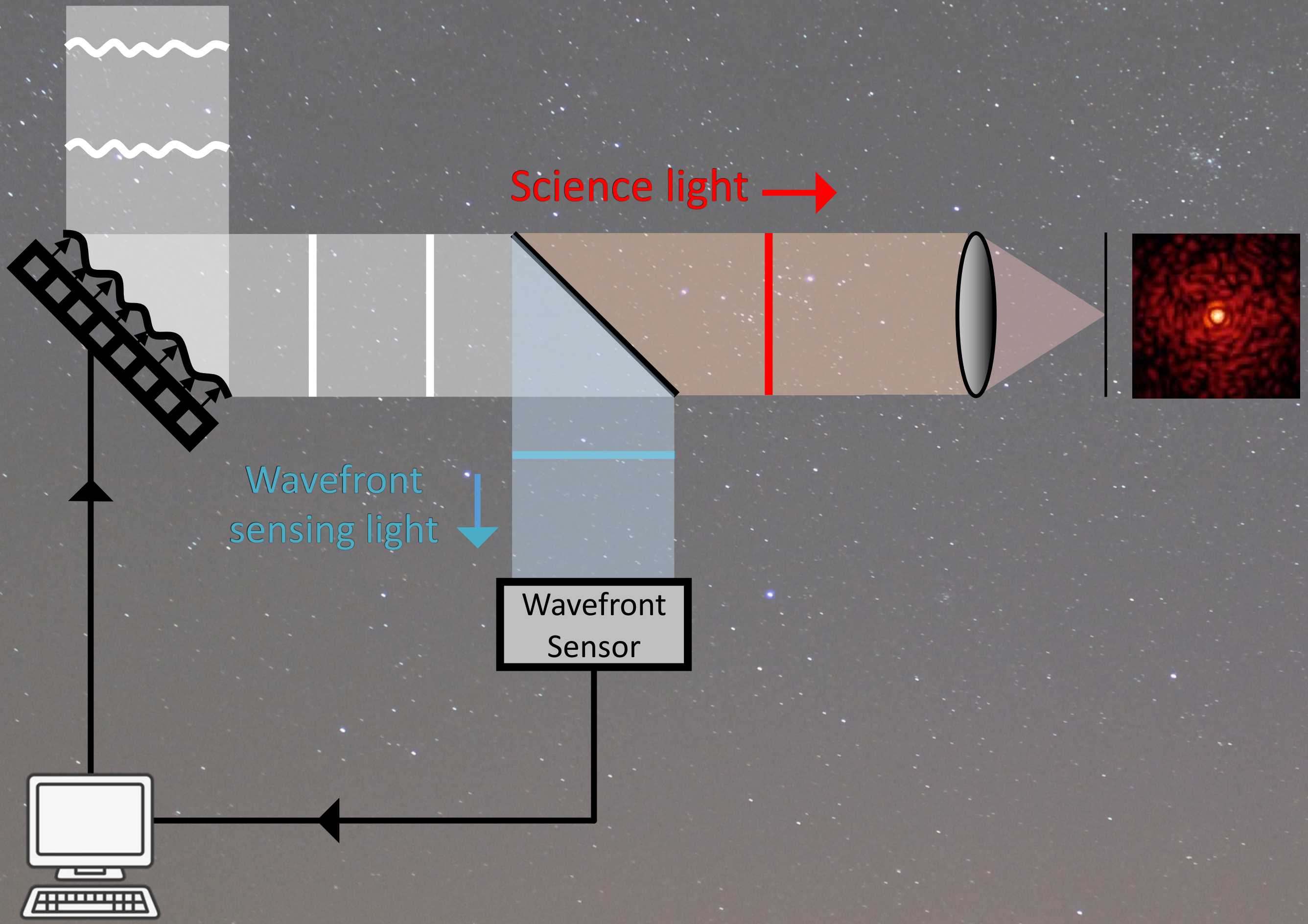

1 cm



VLT adaptive secondary

1170 actuators

Cartoon Diagram of an Adaptive Optics System



Wavefront Sensor Requirements

- **Spatial resolution:** should at least match what DM can correct
- **Dynamic range:** should be able to measure large amplitude aberrations
- **Sensitivity:** should be able to measure small amplitude aberrations
- **Temporal requirement**: AO loop needs to run on timescale of atmospheric turbulence (millisecond timescales)
- **Linear range:** linear relation between input phase variation and output intensity variation
- **Efficient use of photons: a**llows for use of faint light sources
- Ability to work on both **point sources and extended sources**, operate over **wide range of wavelengths**

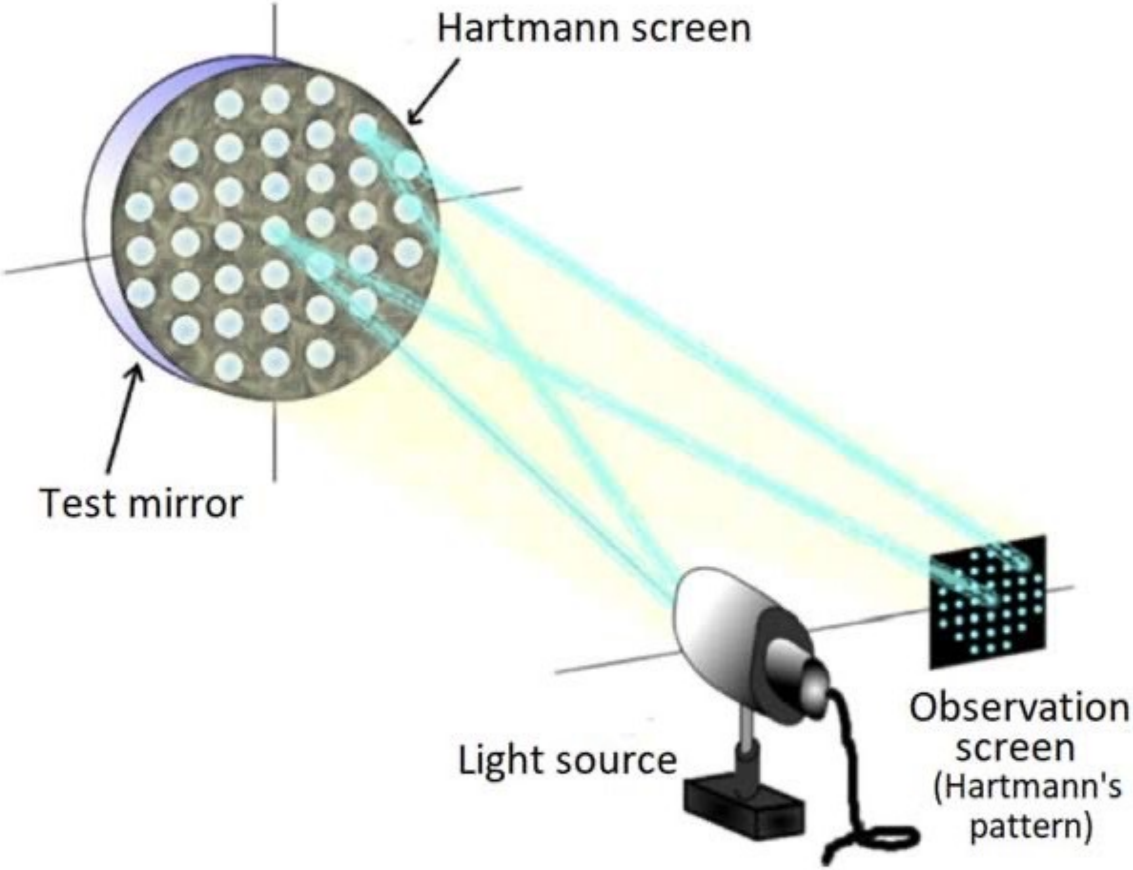
Types of Wavefront Sensors

- **Pupil plane:** wavefront properties are deduced by splitting the pupil into subapertures and measuring the intensity in each subaperture
    - Examples include Shack-Hartmann, Pyramid sensing

- **Focal plane:** wavefront properties are deduced from intensity measurements made at or near the focal plane.
    - Examples that are typically used to measure ~static aberrations:
        - Phase retrieval, e.g. Gerchberg-Saxton algorithm
        - Mostly iterative with long computation times compared to pupil plane
    - Examples that measure residual atmospheric aberrations as well:
        - Self-coherent camera

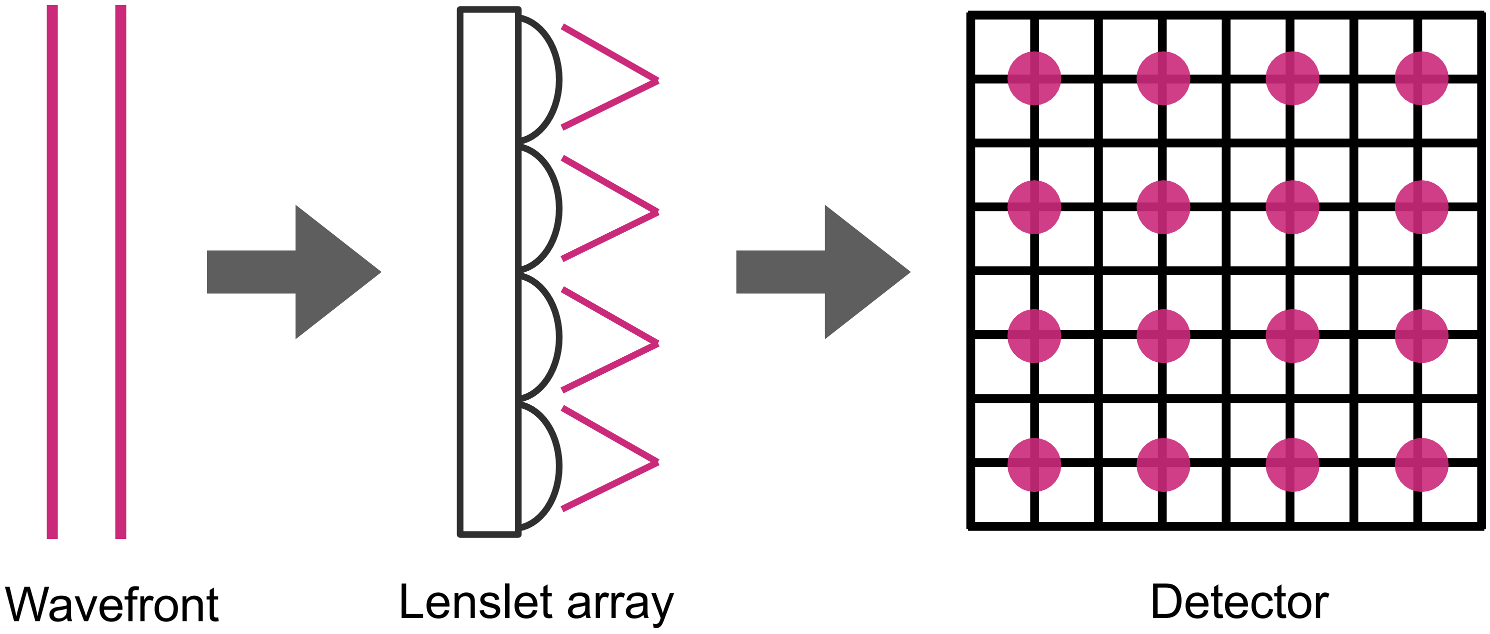
The Shack-Hartmann Wavefront Sensor

- Johannes Hartmann (1904): grid of holes mask placed to observe resulting dot pattern

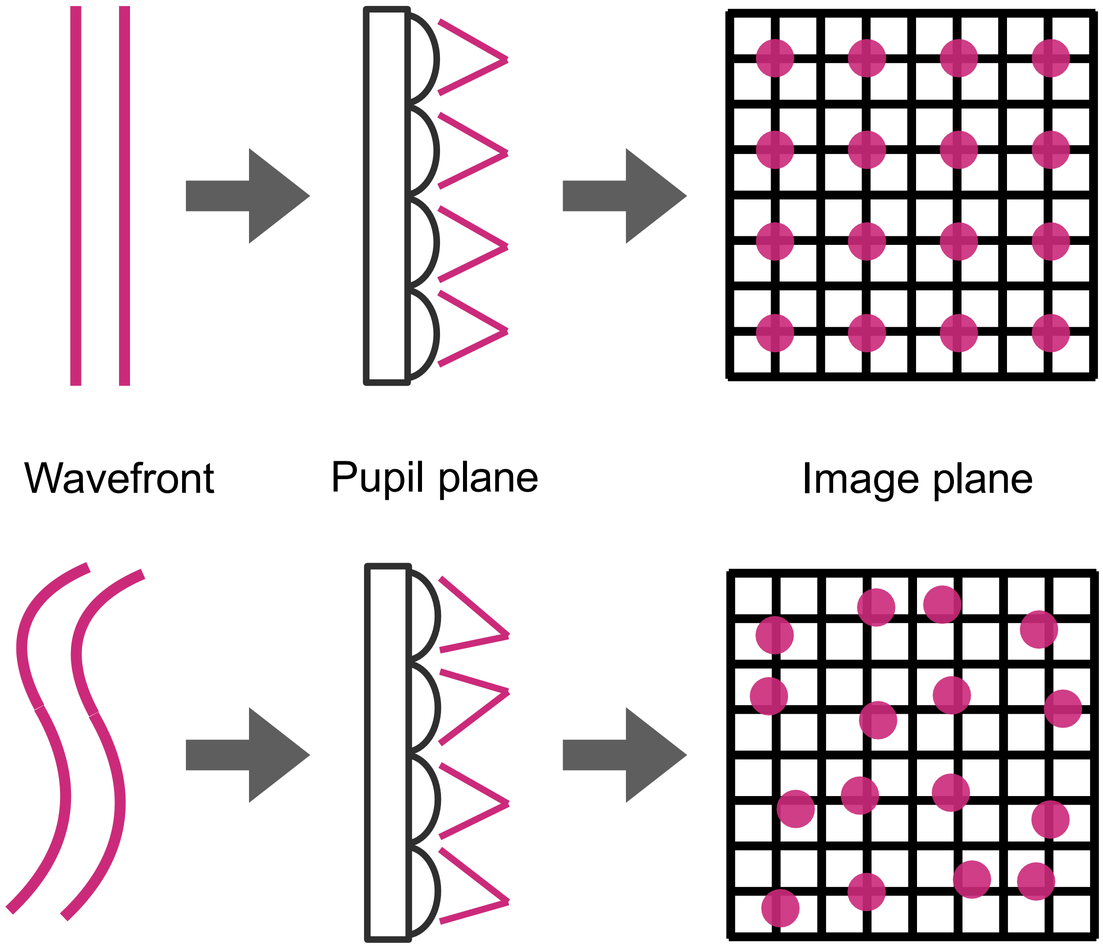


The Shack-Hartmann Wavefront Sensor

- Johannes Hartmann (1904): grid of holes mask placed to observe resulting dot pattern
- Roland Shack (1970s): replace holes with an array of lenses to improve light efficiency



The Shack-Hartmann Wavefront Sensor

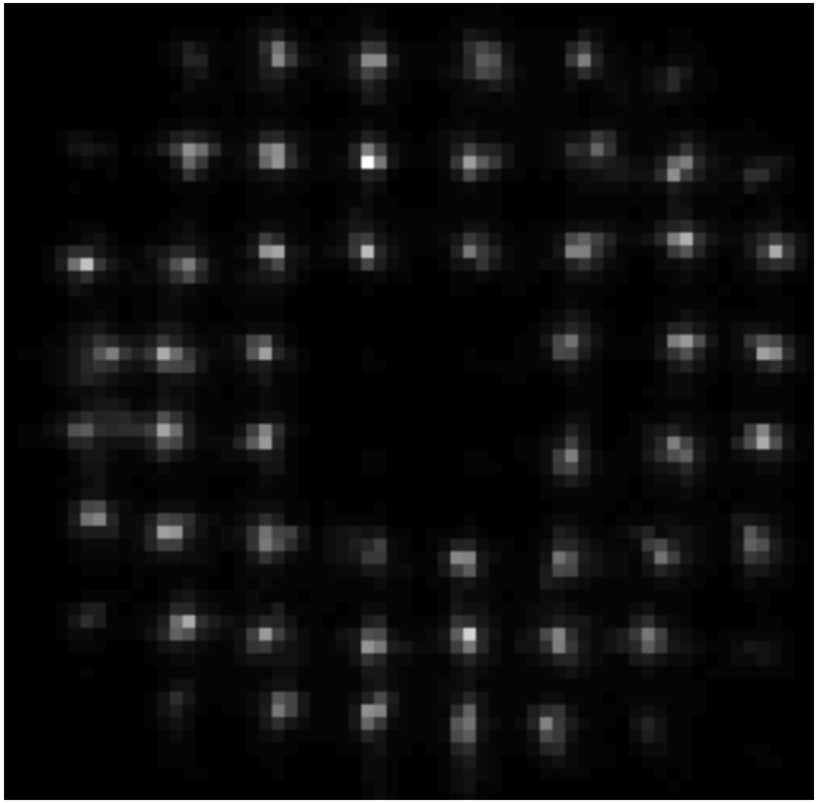


Wavefront

Pupil plane

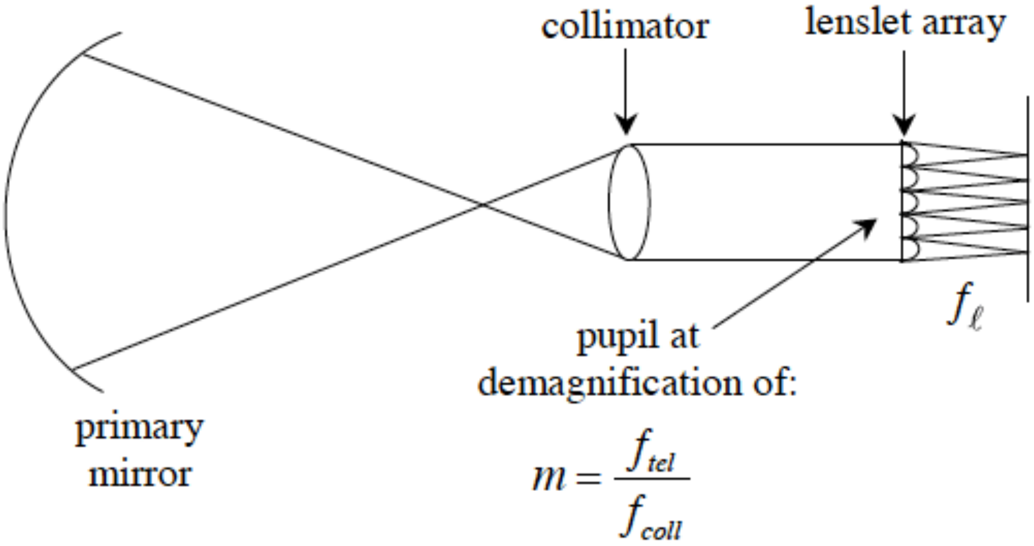
Image plane

Example: Shack-Hartmann Wavefront Signals



Credit: Cyril Cavadore

Quantitative description of Shack-Hartmann operation

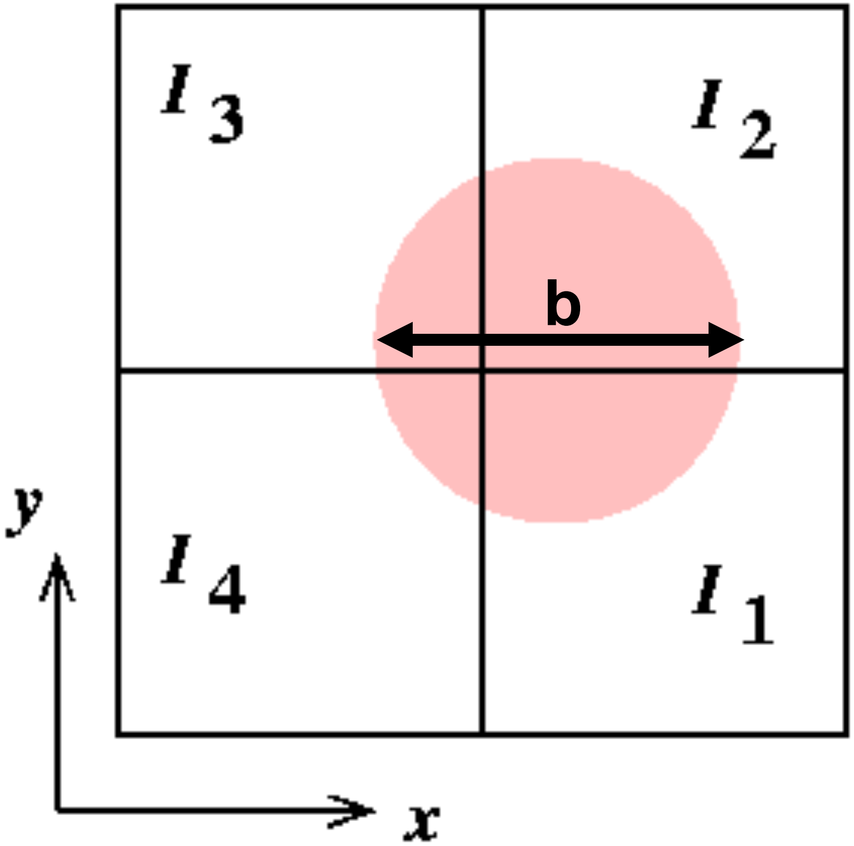


- The relationship between the displacement of Shack-Hartmann spots and the slope of wavefront:

$$k\Delta x = Mf\nabla\phi(x, y)$$

where $k = 2\pi\ /\lambda$, Δx is the lateral displacement of a subaperture image, M is the magnification of the system, f is the focal length of the lenslets in front of the Shack-Hartmann sensor

How do we measure $\Delta\vec{x}$: the distance a spot has moved on the detector? "Quad cell formula"

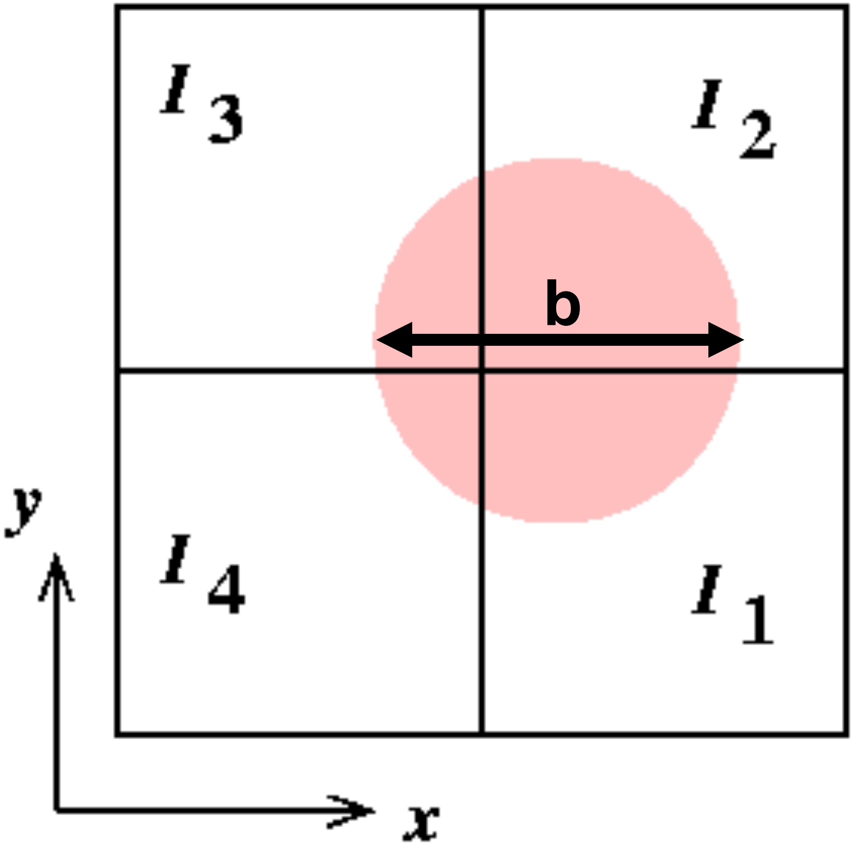


$$\delta_x \cong \frac{b}{2}\left\lfloor \frac{(I_2+I_1)-(I_3+I_4)}{(I_1+I_2+I_3+I_4)} \right\rfloor$$

$$\delta_y \cong \frac{b}{2}\left[\frac{(I_3+I_2)-(I_4+I_1)}{(I_1+I_2+I_3+I_4)} \right]$$

$$\boxed{\delta_{x,y} = \frac{b}{2}\frac{(difference\ \ of\ I's)}{(sum\,of\,I's)}}$$

How do we measure $\Delta\vec{x}$: the distance a spot has moved on the detector? “Quad cell formula”



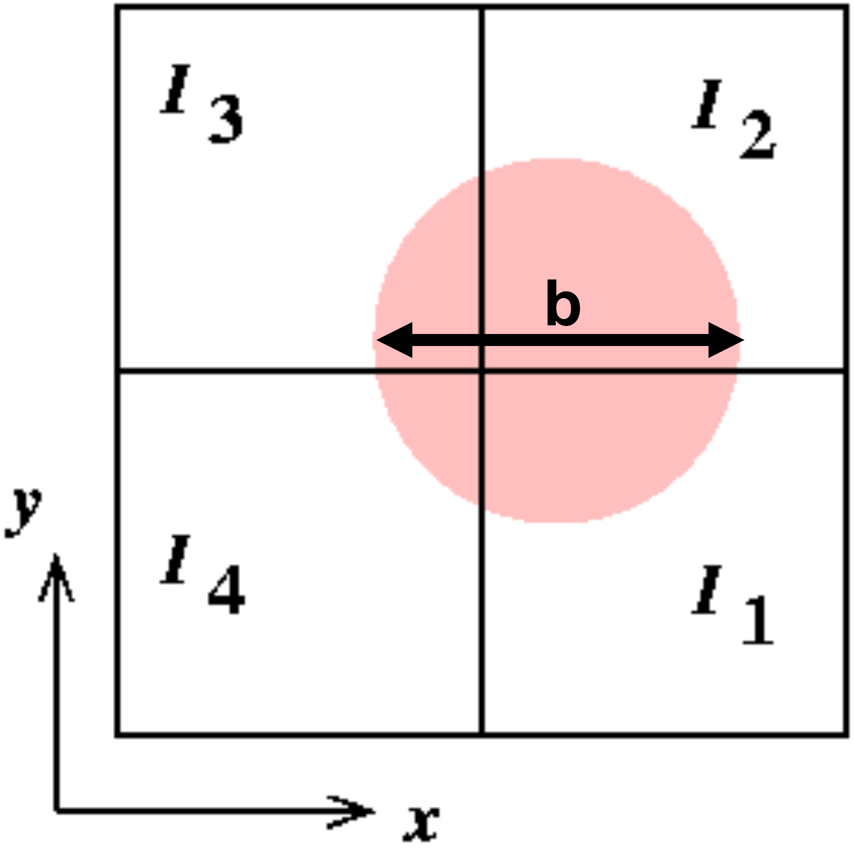
“Signal” in x

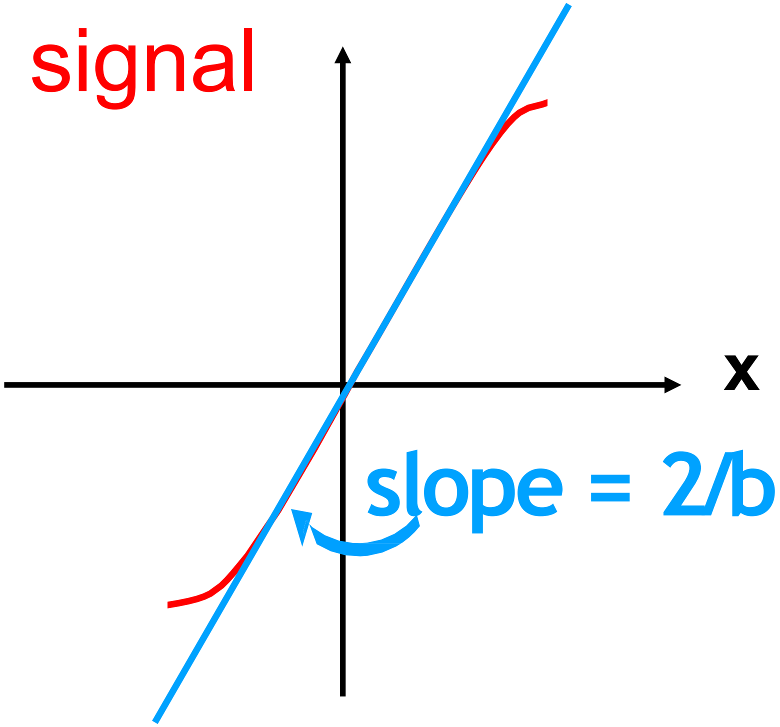
$$\delta_x \cong \frac{b}{2}\left[\frac{(I_2+I_1)-(I_3+I_4)}{(I_1+I_2+I_3+I_4)}\right]$$

$$\delta_y \cong \frac{b}{2}\left[\frac{(I_3+I_2)-(I_4+I_1)}{(I_1+I_2+I_3+I_4)}\right]$$

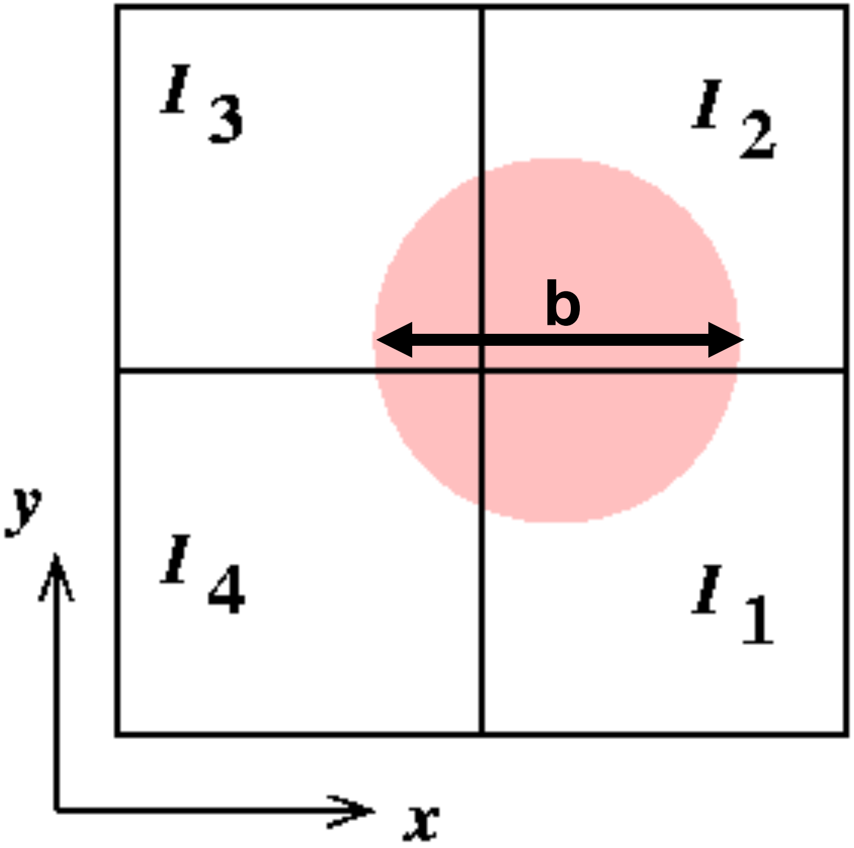
$$\boxed{\delta_{x,y} = \frac{b}{2}\,\frac{(difference\ \ of\ I's)}{(sum\, of\, I's)}}$$

How do we measure the distance a spot has moved on the CCD? “Quad cell formula”

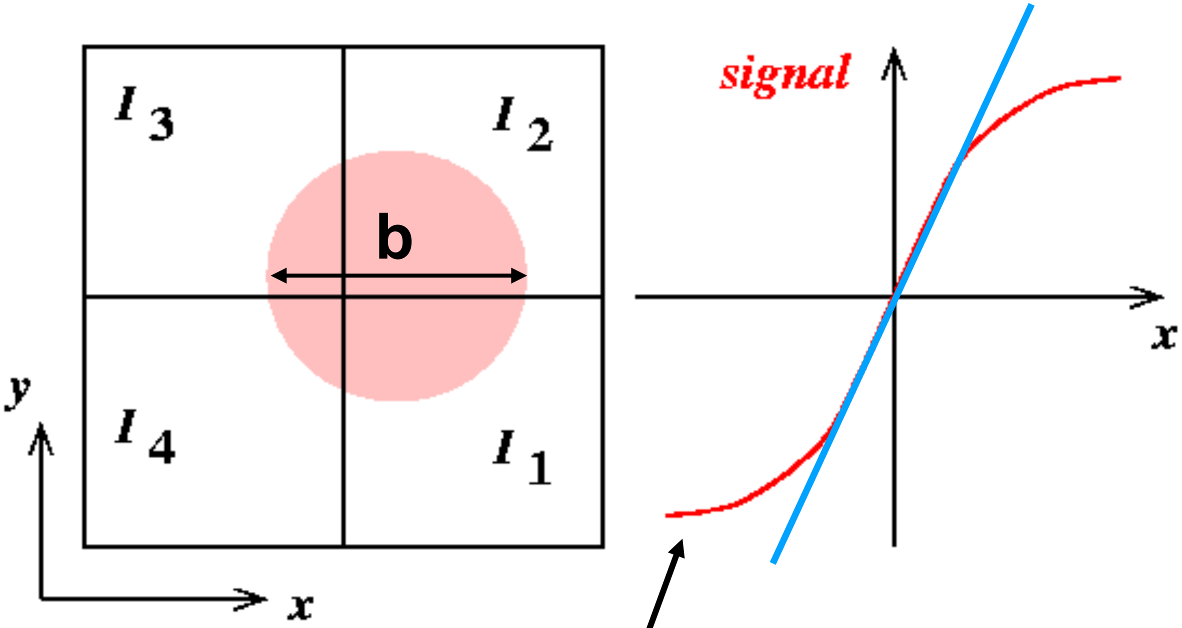




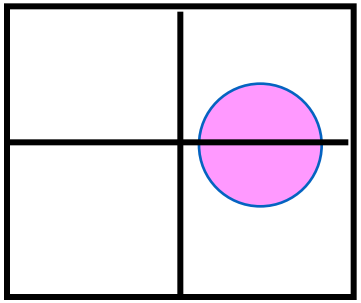
<u>Concept Question:</u> What might happen if the displacement of the spot is > radius of spot?



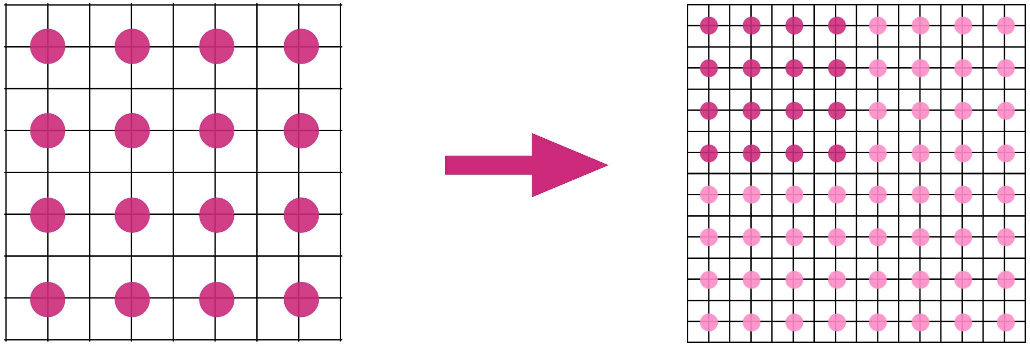
Signal becomes nonlinear and saturates for large angular deviations



“Rollover” corresponds to spot being entirely outside of 2 quadrants



SHWFS Sources of Error: # Lenslets

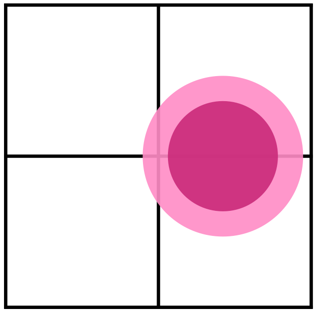


↑ Increase # of lenslets = ↑ Increase sampling of wavefront slopes = ↑ Increase spatial resolution

<u>But</u> photons are more spread out = ↓ decrease SNR = ↓ decrease sensitivity

Credit: Maissa Salama

SHWFS Sources of Error: spot size relative to the subaperture size

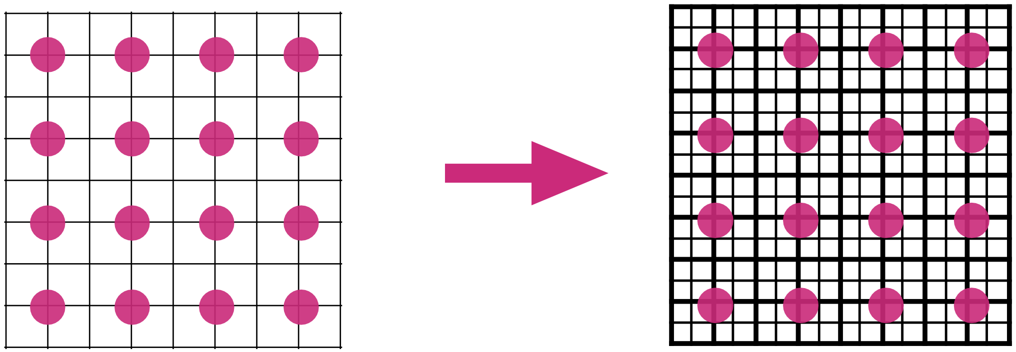


↑ Increase spot size (e.g. defocus) = ↑ Increase dynamic range

But less accurate centroiding = ↓ decrease sensitivity

Credit: Maissa Salama

SHWFS Sources of Error: # of pixels

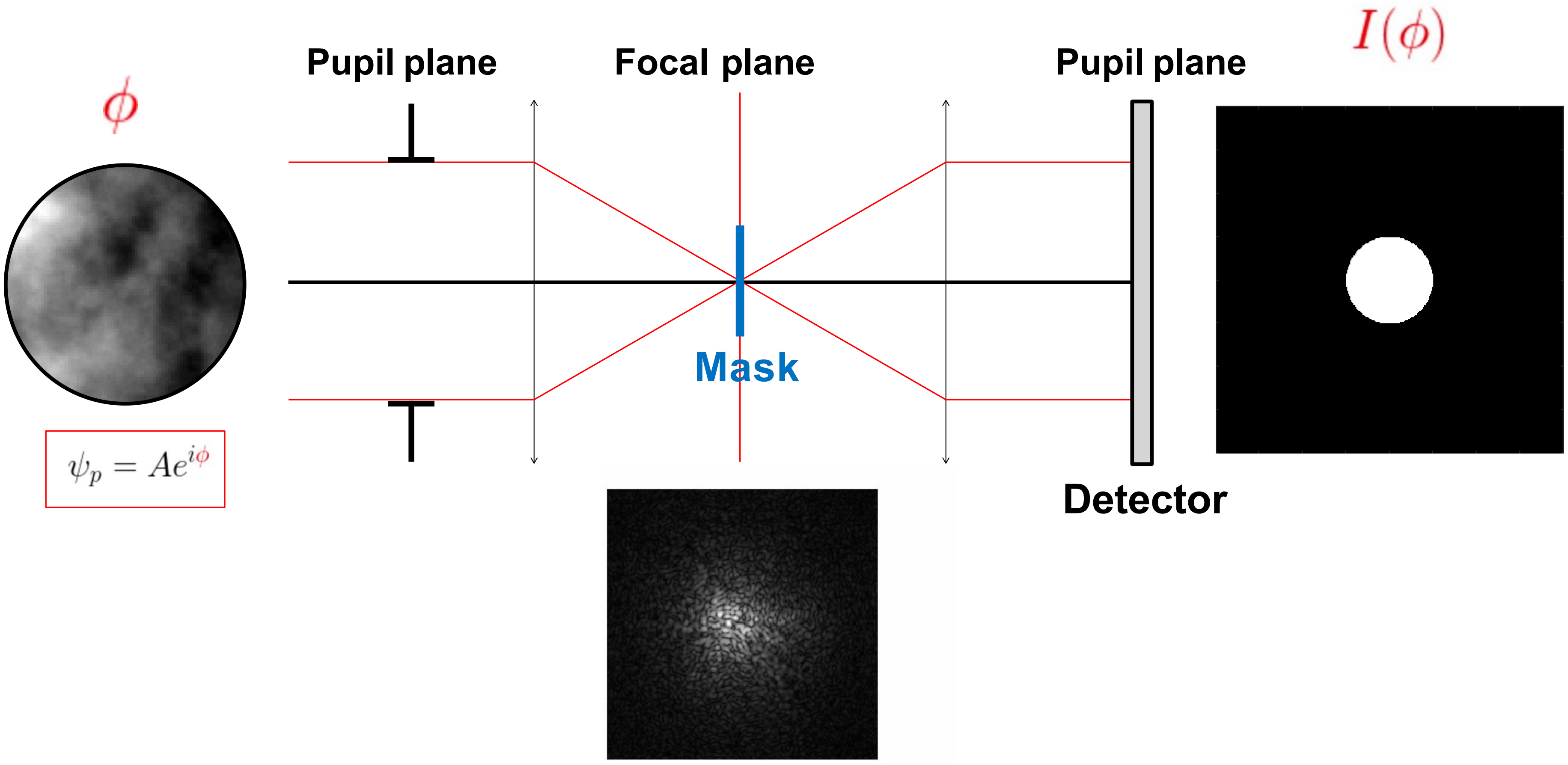


↑ Increase # pixels = ↑ Increase centroiding accuracy (Measure position of spots by estimating center of gravity positions instead of quad-cell)

<u>But</u> photons are spread out over more pixels = ↓ decrease SNR

Credit: Maissa Salama

Fourier-Filtering Wavefront Sensors



$I(\phi)$

Pupil plane

Focal plane

Pupil plane

ϕ

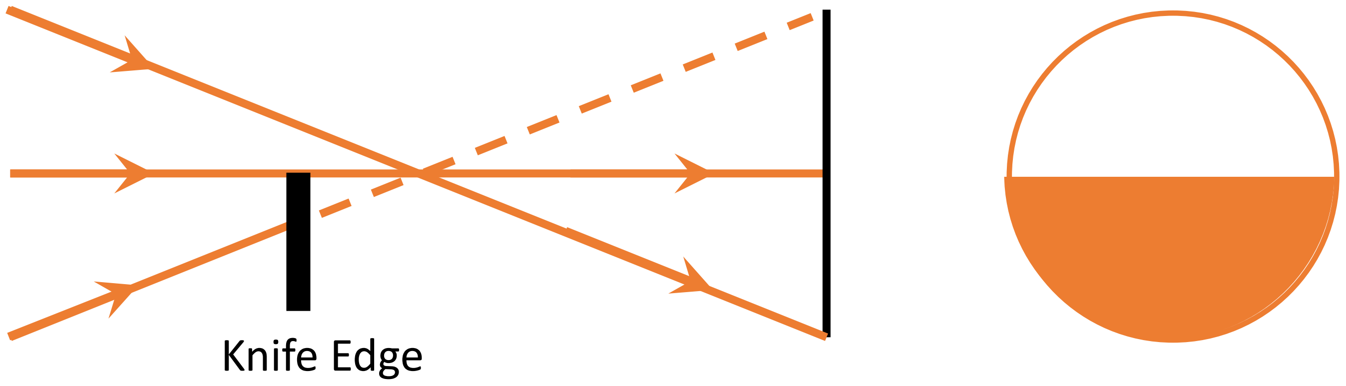
Mask

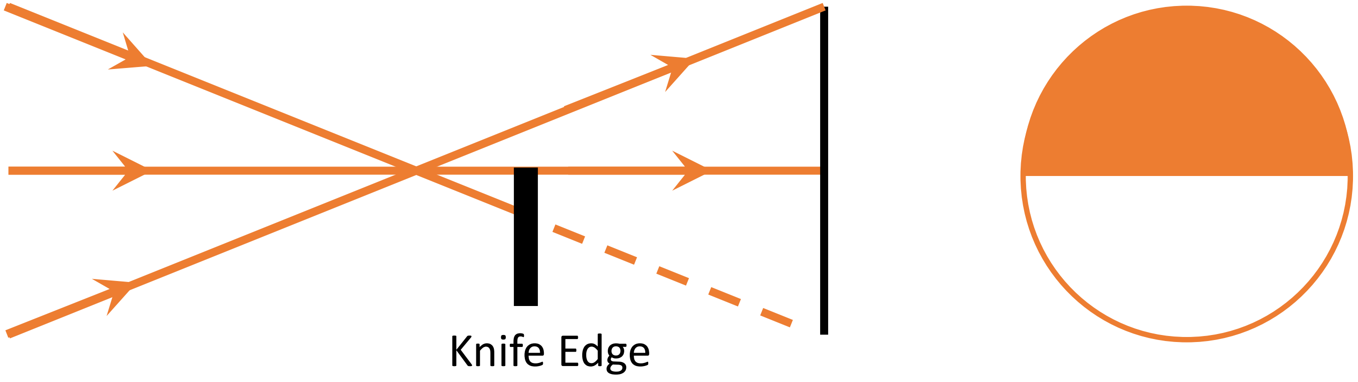
$\psi_p = Ae^{i\phi}$

Detector

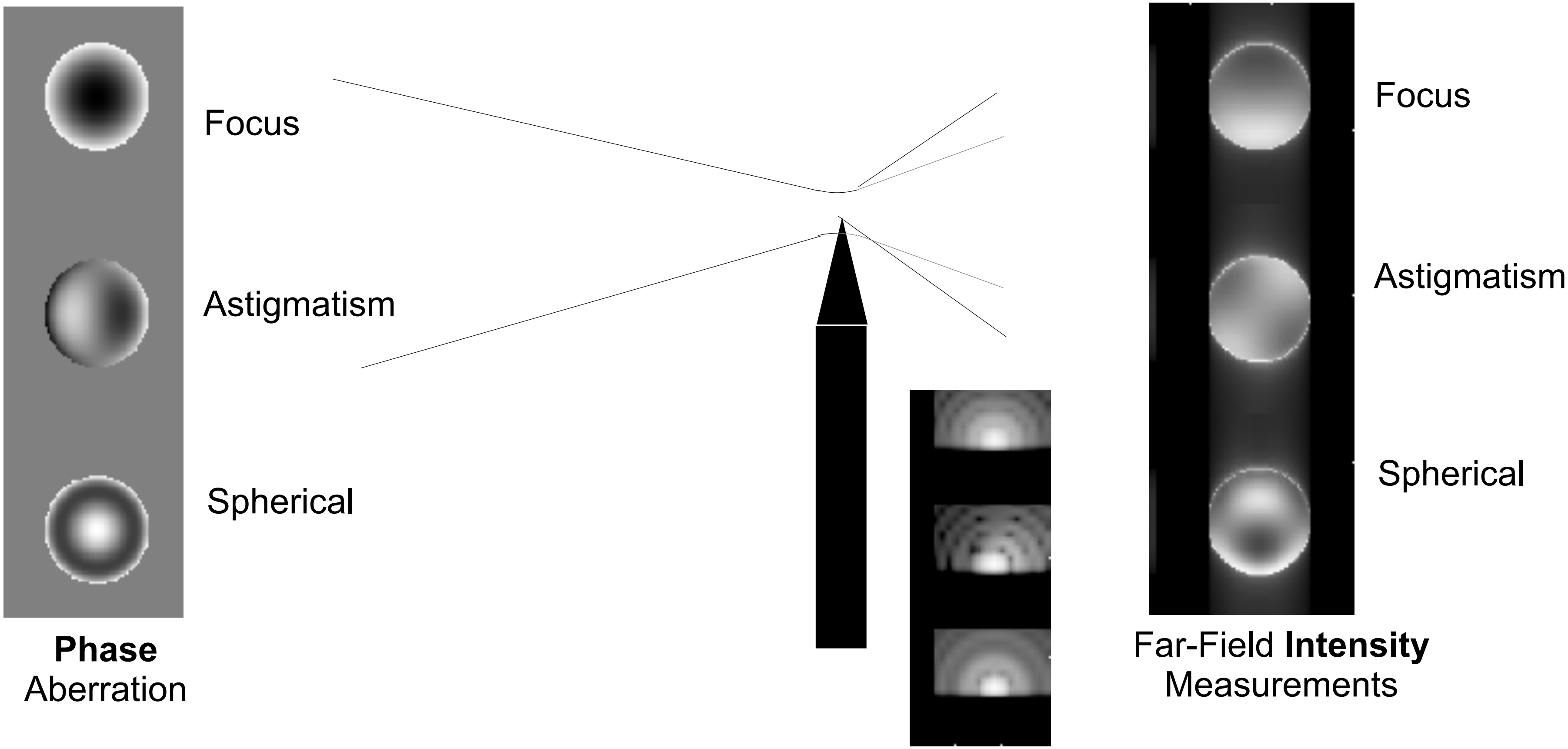
(Slide Credit: Vincent Chambouleyron)

Foucault Knife Edge Test: an early example of a Fourier-filtering WFS





Fourier-filtering WFS: Foucault Knife Edge Test



Focus

Astigmatism

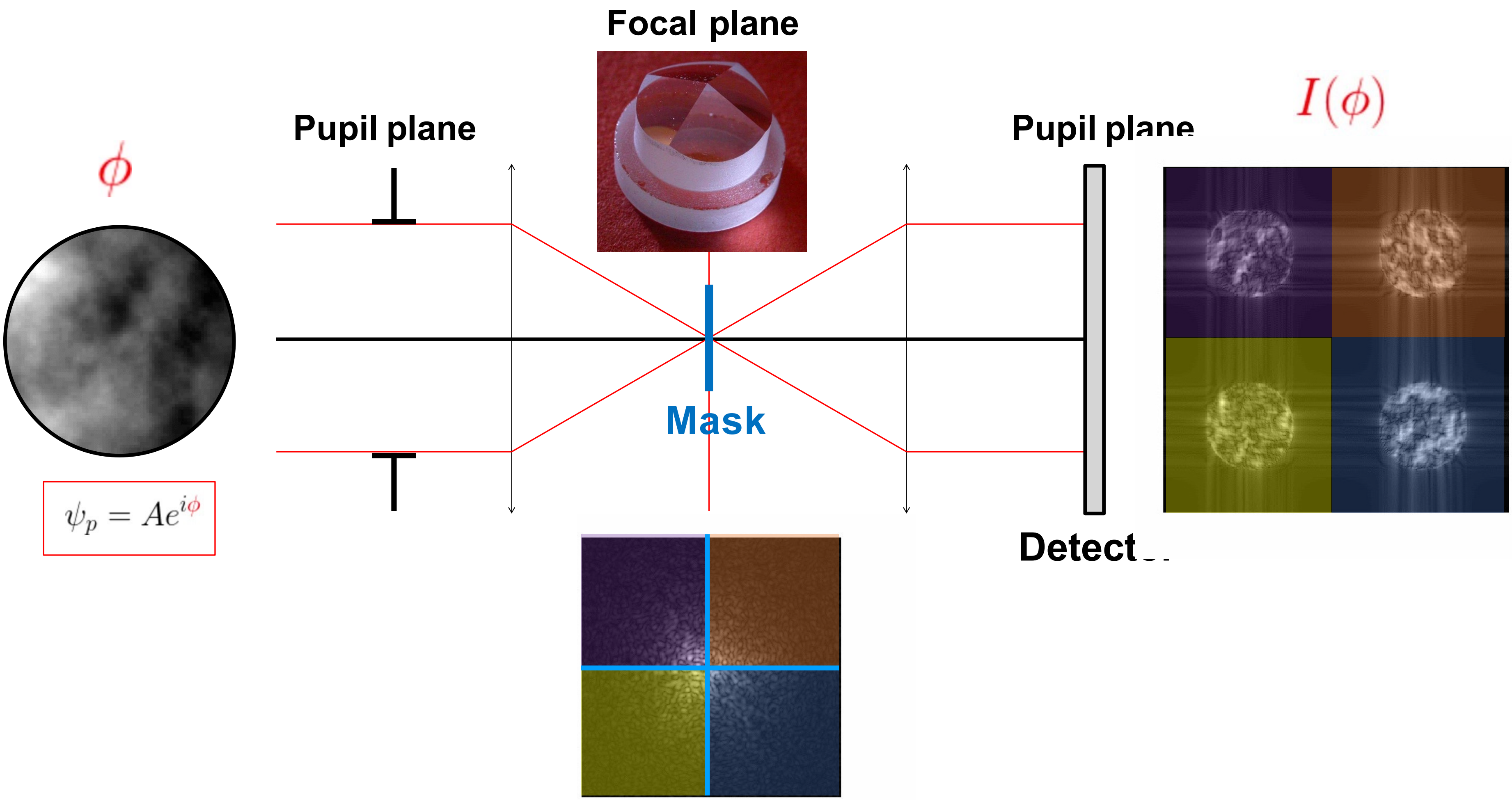
Spherical

Phase Aberration

At focal plane

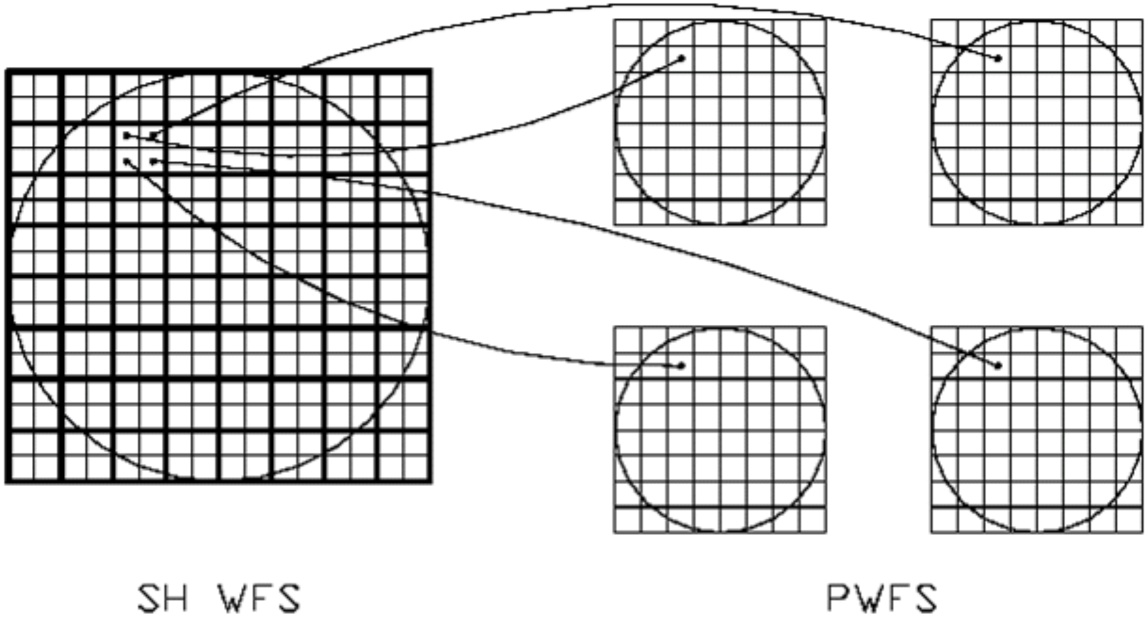
Far-Field **Intensity** Measurements

Fourier-filtering WFS: Pyramid Wavefront Sensor (Ragazzoni 1996)



(Slide Credit: Vincent Chambouleyron)

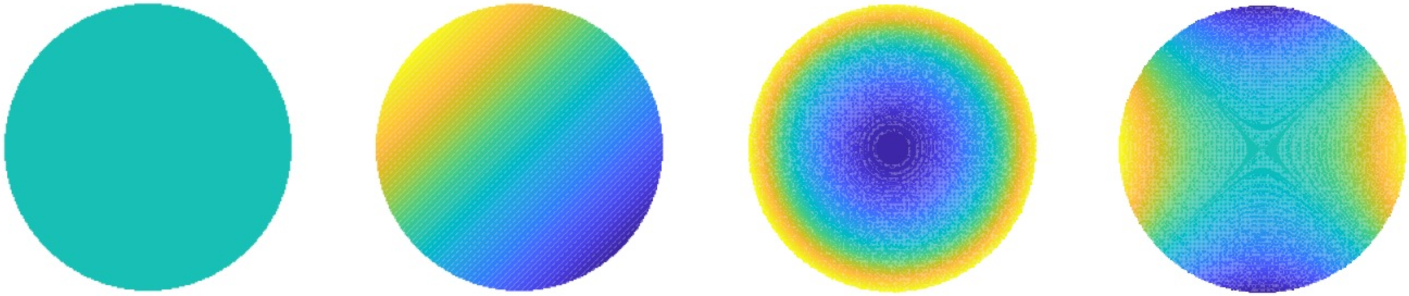
Pyramid sensor reverses order of operations in a Shack-Hartmann sensor



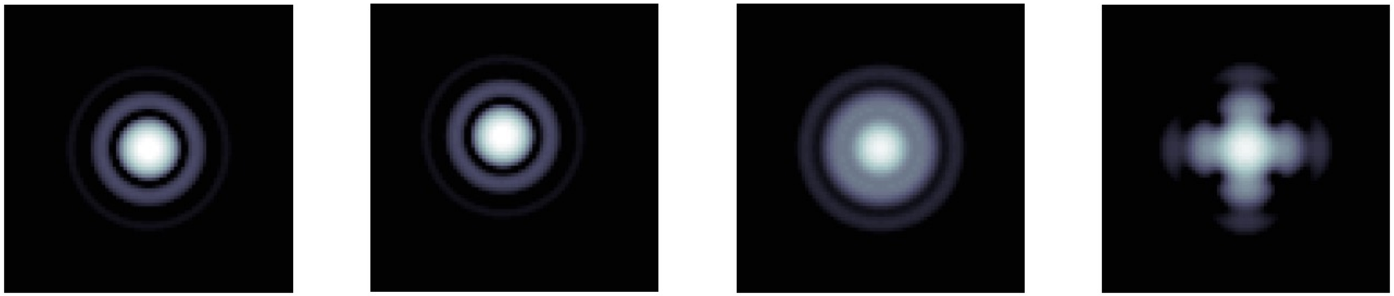
- Slope-like signal for each subaperture is given by:

$$S_x(x,y) = [(I_1(x,y) + I_2(x,y)) - (I_3(x,y) + I_4(x,y))]/I_0,$$
$$S_y(x,y) = [(I_1(x,y) + I_4(x,y)) - (I_2(x,y) + I_3(x,y))]/I_0,$$

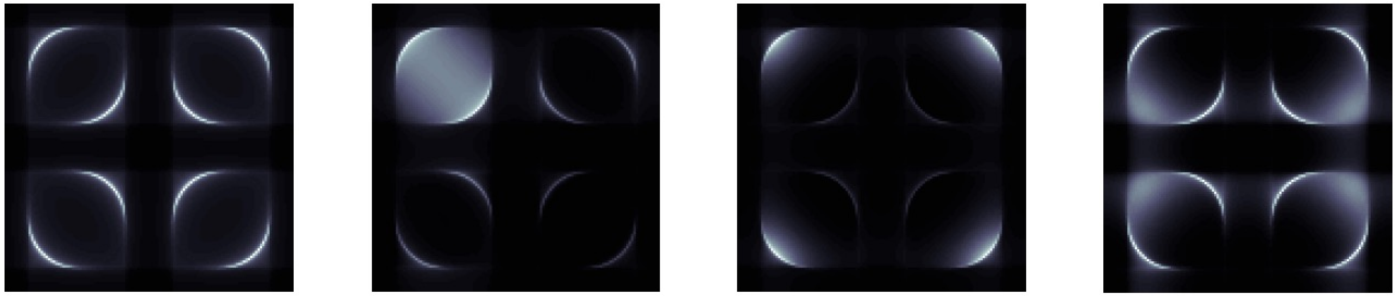
Typical intensity patterns for a Pyramid Sensor



(a) Low order wavefront aberrations.



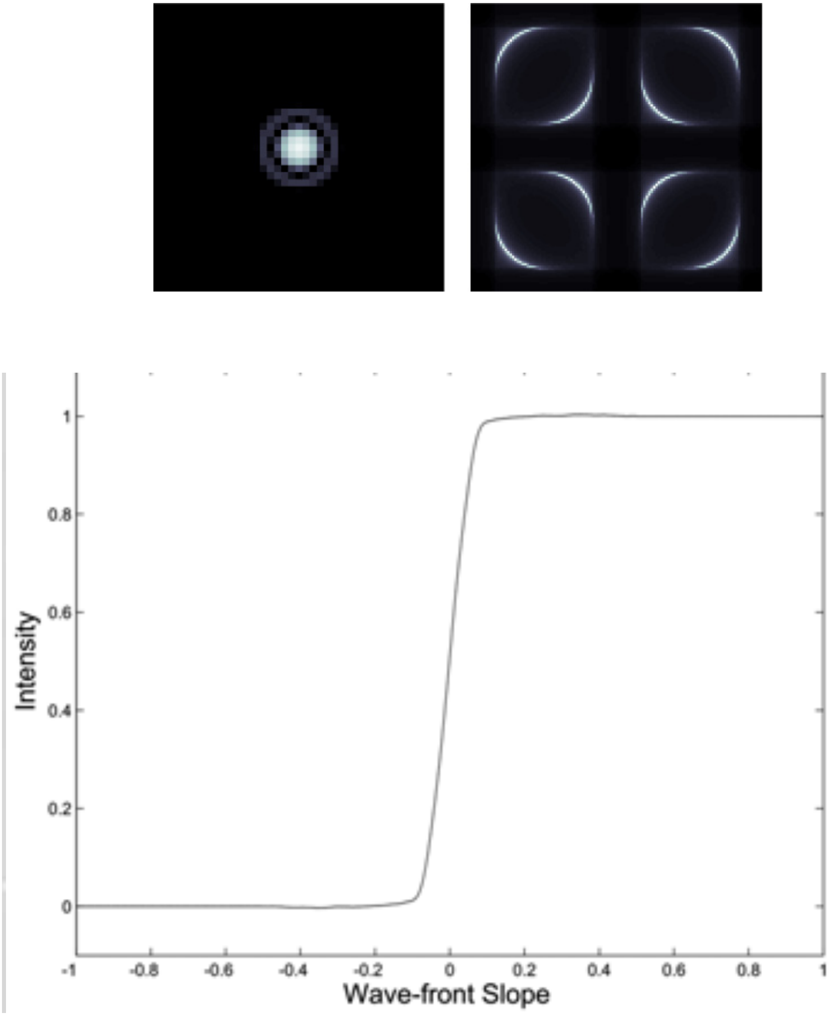
(b) Focal plane images for low order wavefront aberrations.



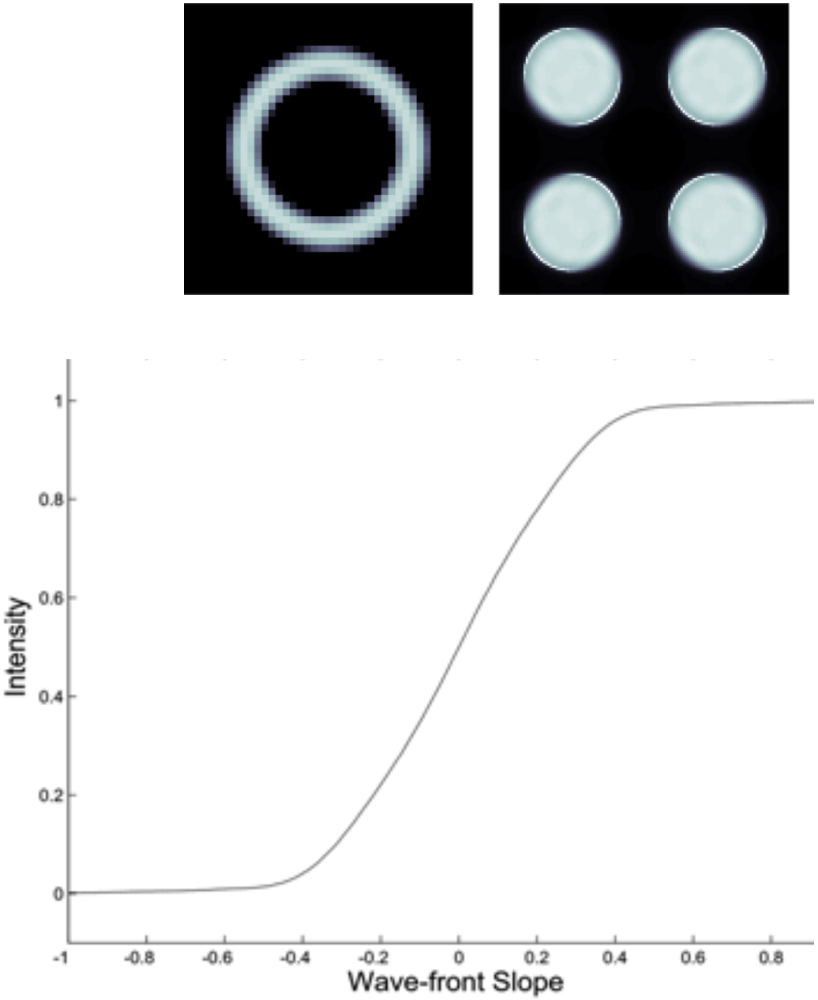
(c) Pyramid WFS signals for low order wavefront aberrations.

Credit:
Charlotte
Bond

The Modulated Pyramid Wavefront Sensor

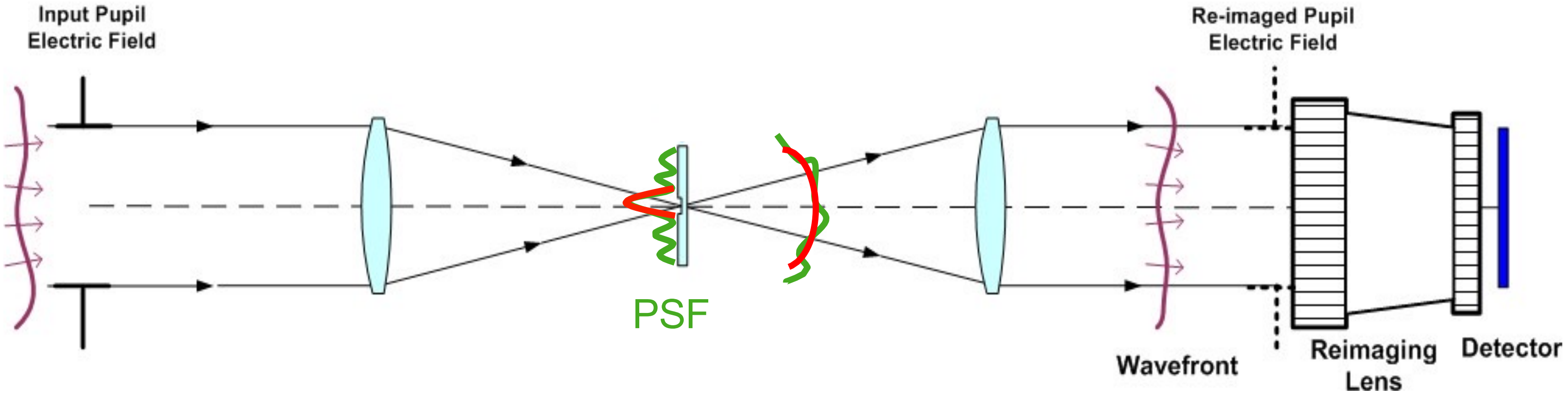


Without modulation:
linear over spot width



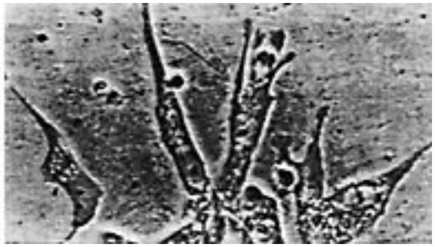
With modulation: linear
over modulation width

Zernike phase contrast technique: converting phase variations into intensity measurements imaged on a detector



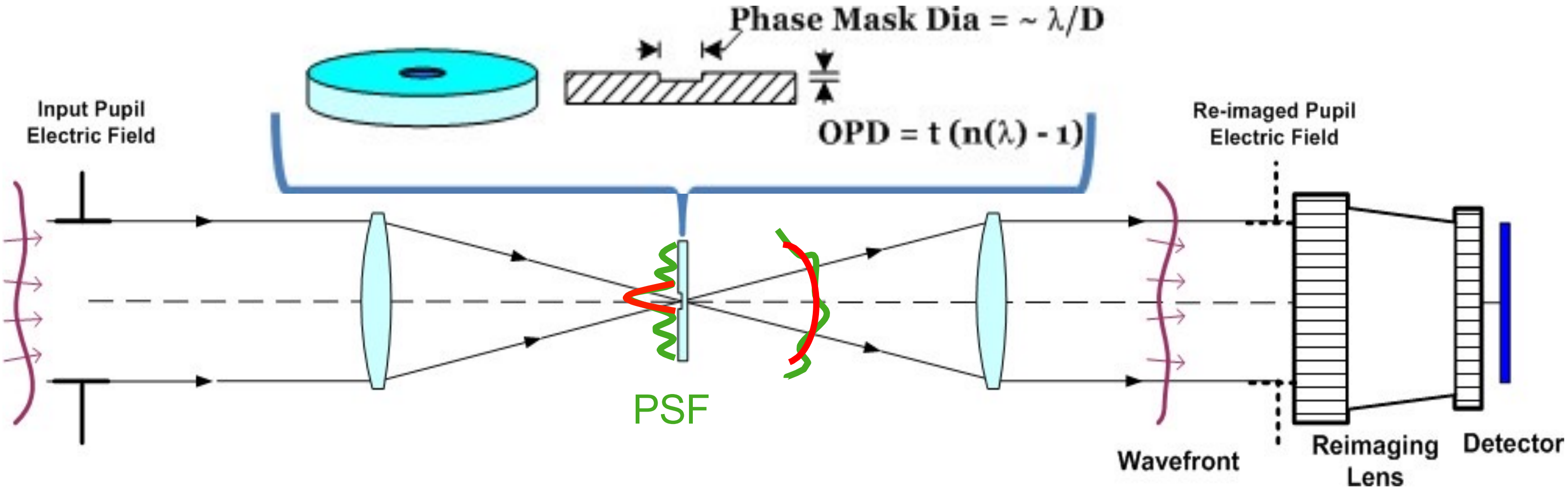
Brightfield

Original Phase Contrast Photomicrographs of Human Cells by Frits Zernike in 1930s



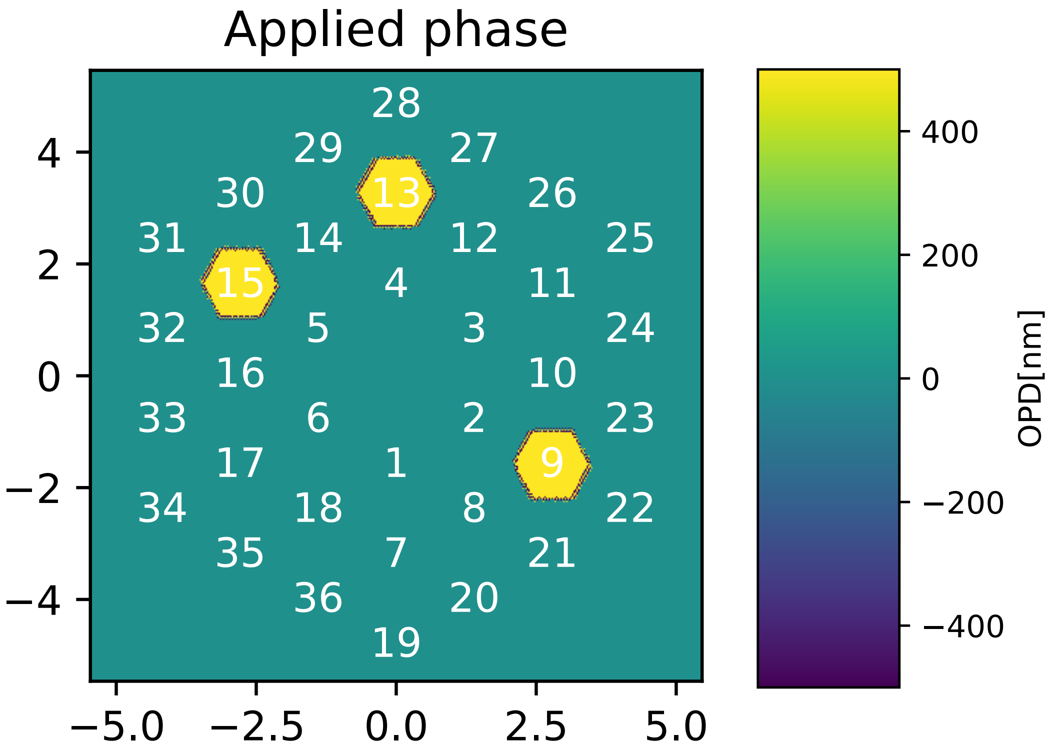
Phase Contrast

Zernike phase contrast technique: converting phase variations into intensity measurements imaged on a detector

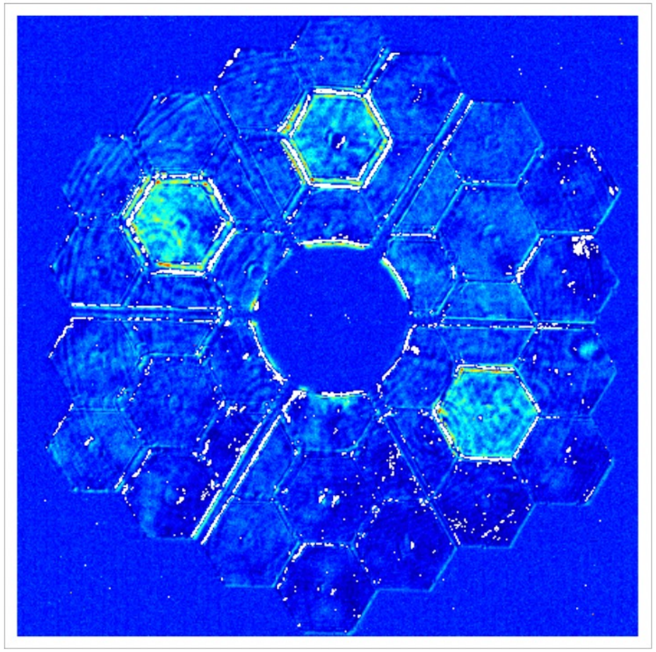


VERY sensitive but
SMALL dynamic range

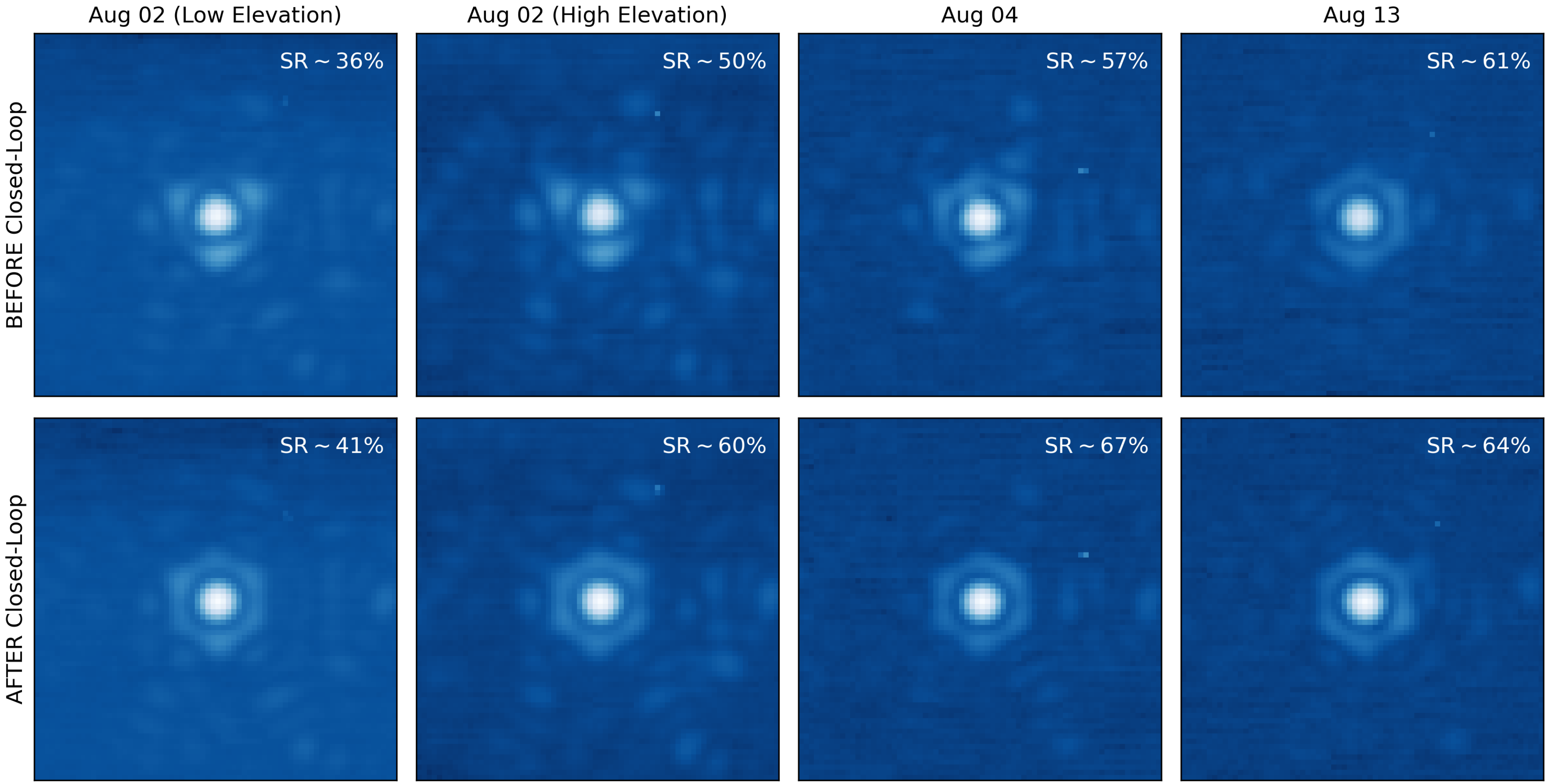
Using a ZWFS to characterize the cophasing of Keck's Segmented Primary Mirror: van Kooten et al. 2022



Zernike Image



Using a ZWFS to improve the cophasing of Keck's Segmented Primary Mirror: Salama et al. 2024



Focal Plane wavefront sensing

- Focal plane WFS: wavefront properties are deduced from intensity measurements made at or near the focal plane

- Why is focal plane wavefront sensing hard?
  - Recall that the intensity is $E \cdot E^{*}$, so when you look at e.g. an image of the PSF you've lost the sign information from the phase

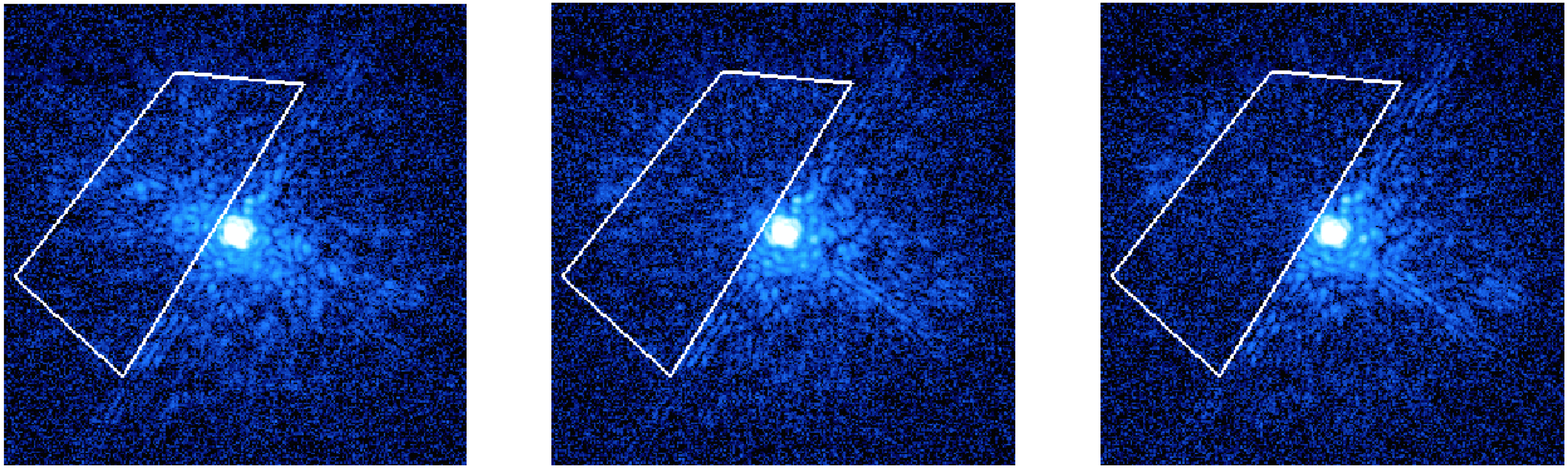
  - So, e.g. if your PSF is defocused you can't know which side of focus it's on

  - You need some kind of variation or "diversity" if you want to reconstruct the phase from an intensity image

- Jovanovic et al. 2018 is a nice overview of FPWFS techniques

Speckle Nulling

- Coronagraphs null the diffraction-limited component of the PSF
- Non-common path aberrations create slowly-evolving speckles
- By putting sine waves of the corresponding frequency on the DM, you can null these speckles



(a) Initial speckle field (b) Fourth iteration (c) Ninth iteration

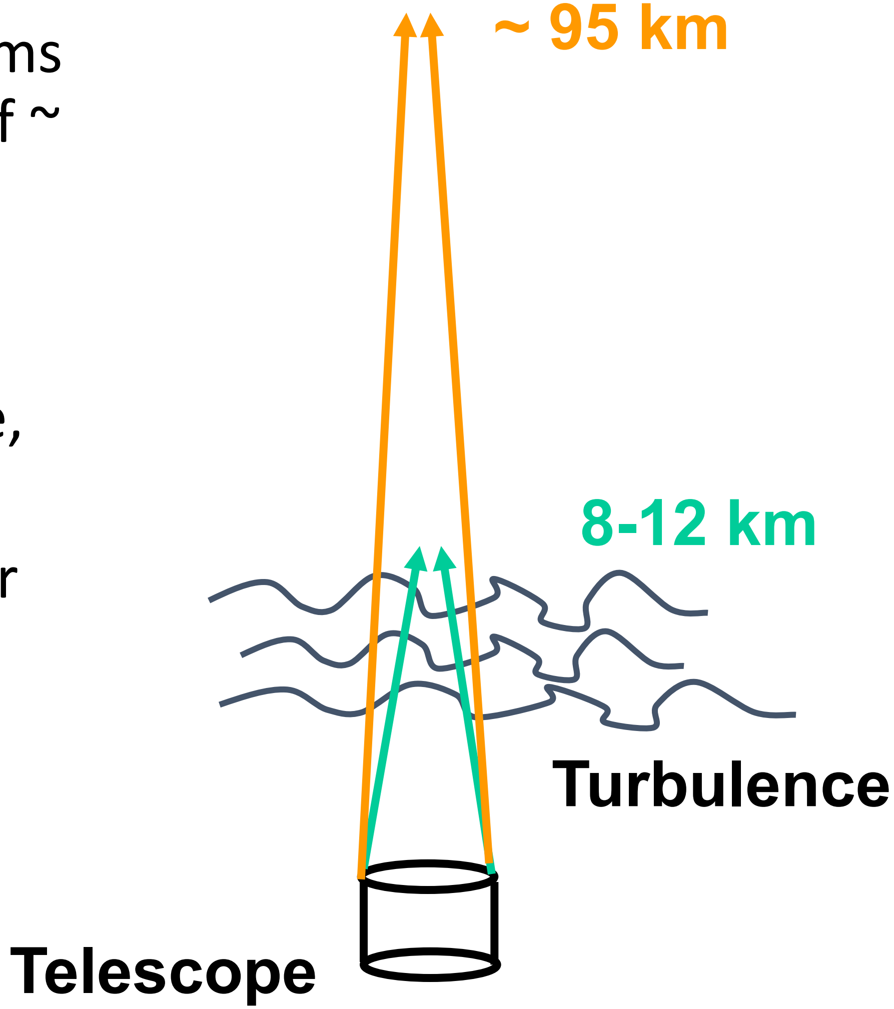
Bottom et al. 2019

Mauna Kea, Hawai’i

Video Credit: Andrew Cooper

Two types of laser guide stars in use today: "Rayleigh" and "Sodium"

- Sodium guide stars: excite atoms in "sodium layer" at altitude of ~ 95 km
- Rayleigh guide stars: Rayleigh scattering from air molecules sends light back into telescope, h ~ 10 km
- Higher altitude of sodium layer is closer to sampling the same turbulence that a star from "infinity" passes through



Summary

- Wavefront sensing and control is necessary for both ground and space-based telescopes
- A wavefront sensor is an optical device which transforms phase into intensity
- Wavefront sensors come in many genres, including pupil plane and focal plane sensors.
- Wavefront sensors and coronagraphs are two sides of the same coin
- To learn more, join us in Santa Cruz for the AO Summer School in August! Register here by the end of this week: cfao.science.ucsc.edu/ao-summer-school