Astronomie et astrophysique pour physiciens
CUSO 2012

Instruments and observational techniques – Adaptive Optics

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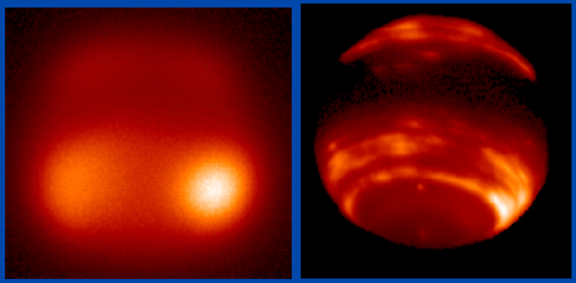
Adaptive Optics in the VLT and ELT era

basics of AO

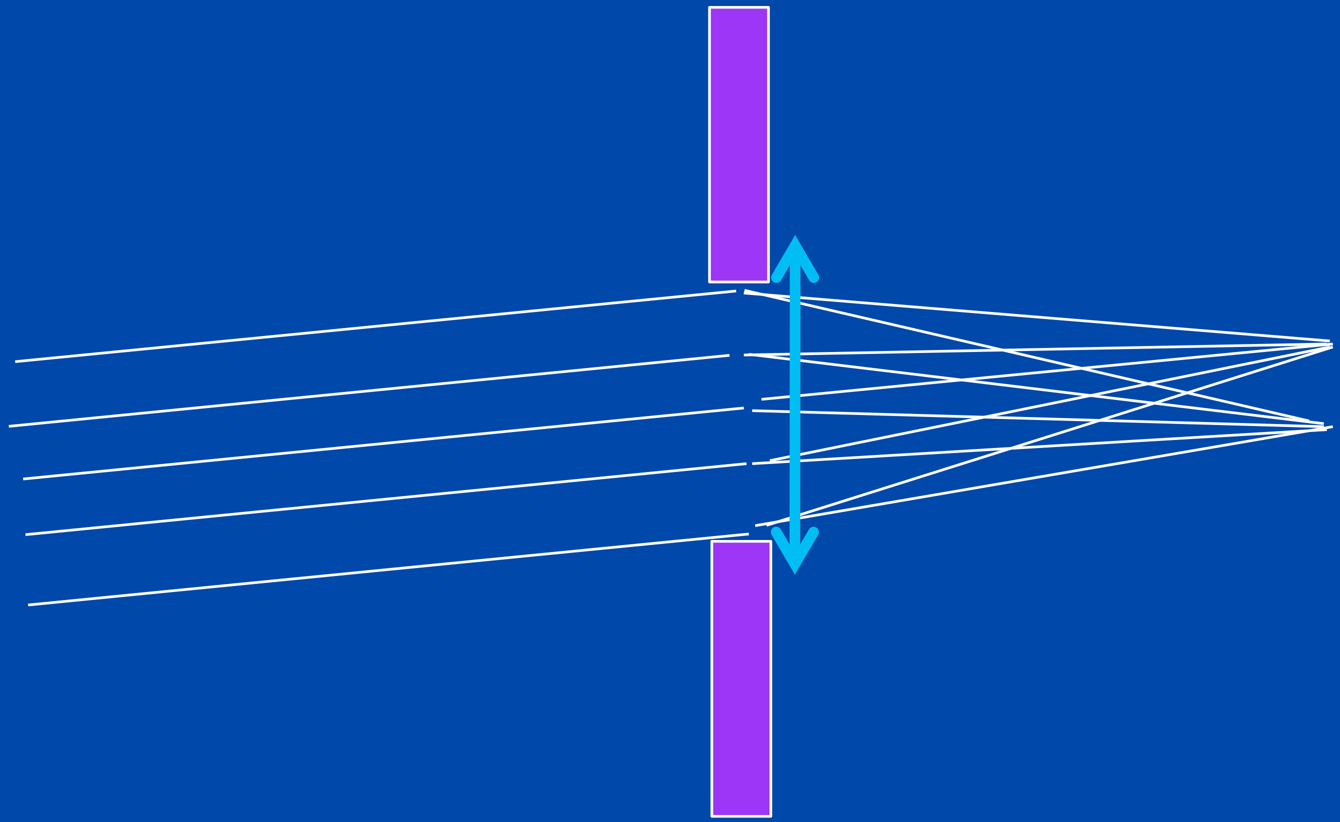
Neptune



Adapted from: François Wildi
Observatoire de Genève

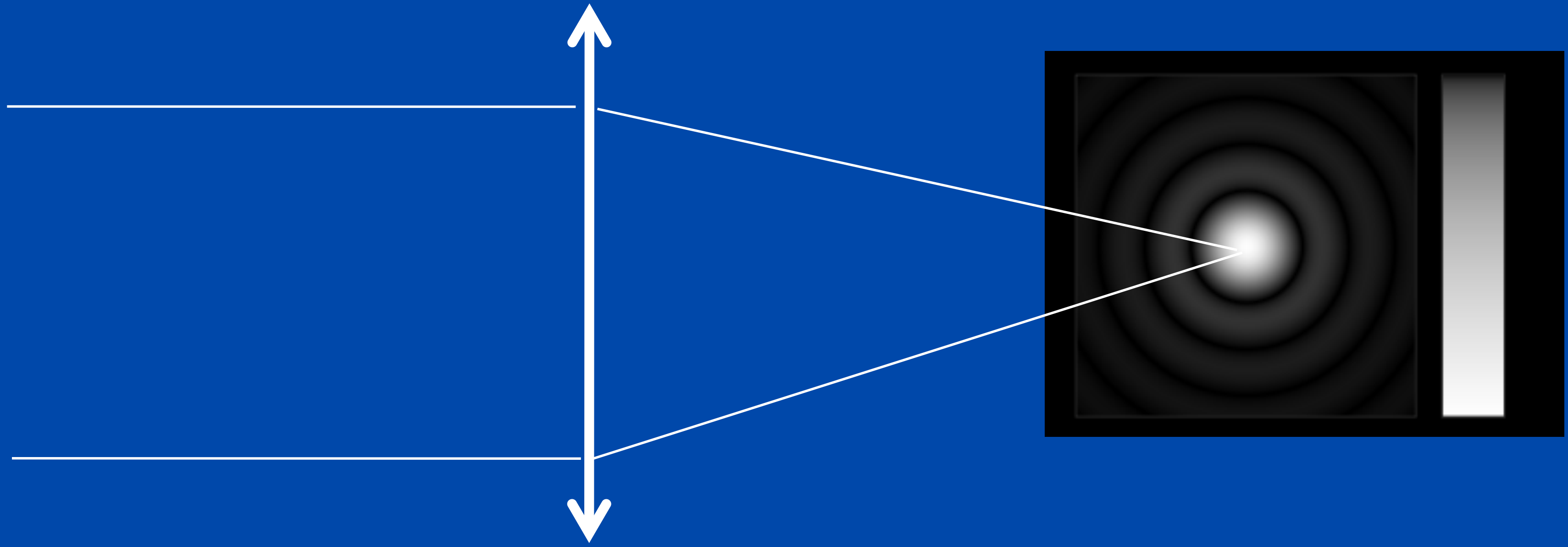
Credit for most slides : Claire Max (UC Santa Cruz)

Looking at the far field (step 2)



What is the 'ideal' PSF?

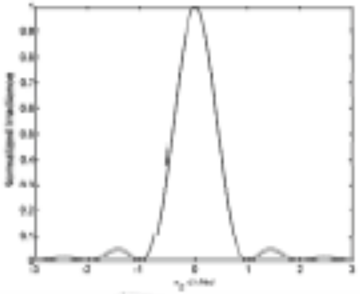
- The image of a point source through a round aperture and no aberrations is an Airy pattern



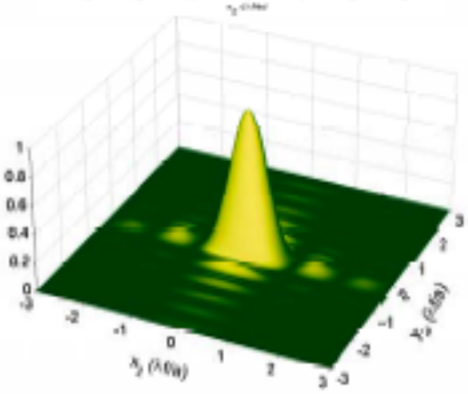
Rectangular Aperture

$$E_2(x_2,y_2)=\frac{E_o\,a^2 d^2}{\lambda^2 f^2}\,\mathrm{sinc}^2\!\left(\frac{x_2}{\lambda f/a},\frac{y_2}{\lambda f/d}\right)$$

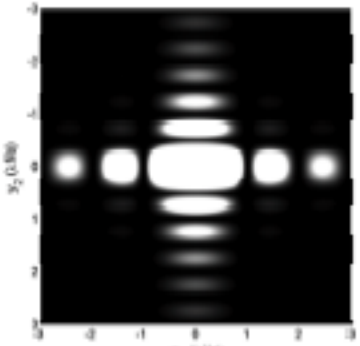
a.)



b.



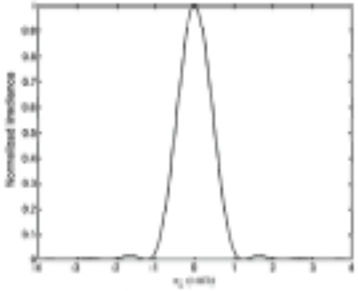
c.)



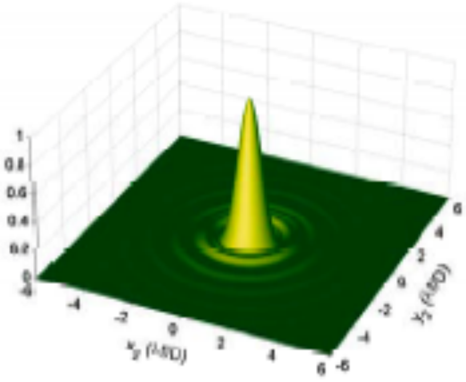
Circular Aperture

$$E_2(x_2,y_2)=E_o\left(\frac{\pi D^2}{4\lambda f}\right)^2\mathrm{somb}^2\!\left(\frac{r_2}{\lambda f/D}\right)$$

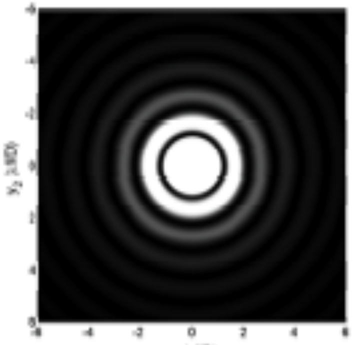
a.)



b



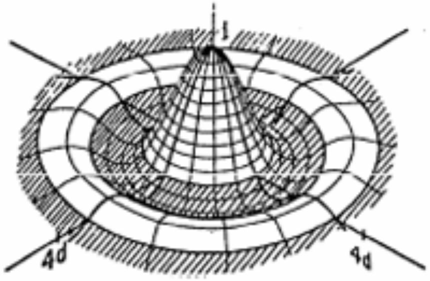
c.)

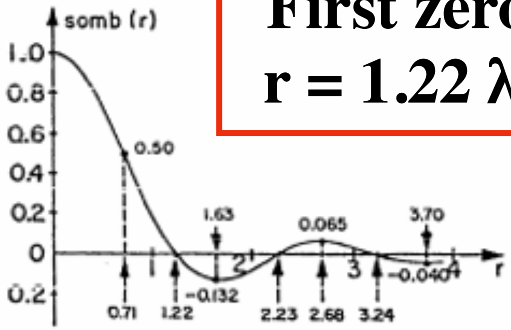


Details of diffraction from circular aperture and flat wavefront

1) Amplitude

$\mathrm{somb}(r) = 2\,J_1(\pi r)/(\pi r)$



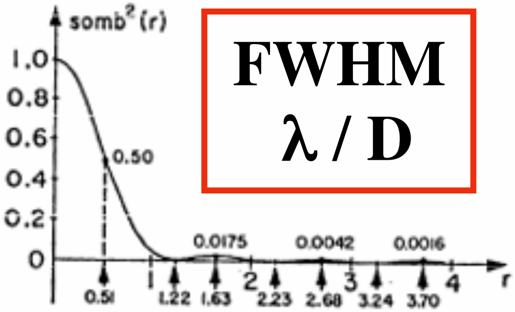


First zero at
r = 1.22 λ / D

2) Intensity

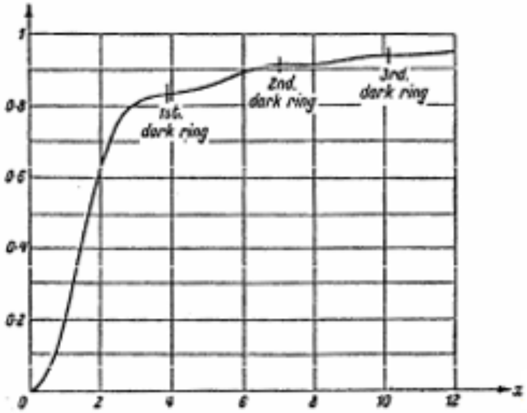
Airy Pattern

$\mathrm{somb}^2(r)$

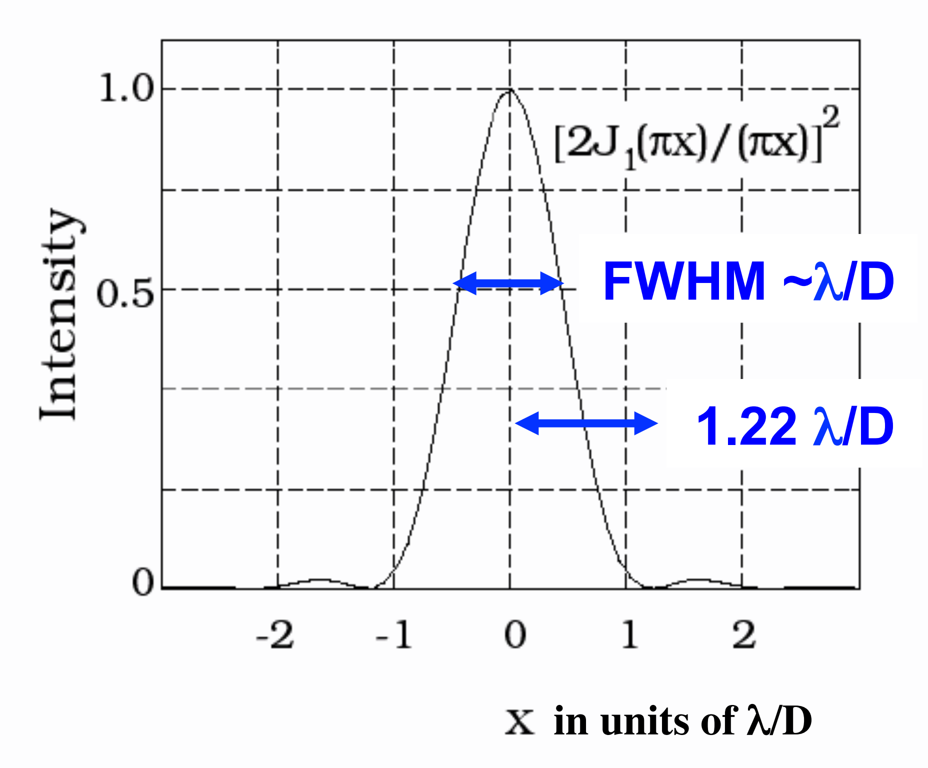


FWHM
λ / D

Fractional Encircled Energy



Imaging through a perfect telescope (circular pupil)



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

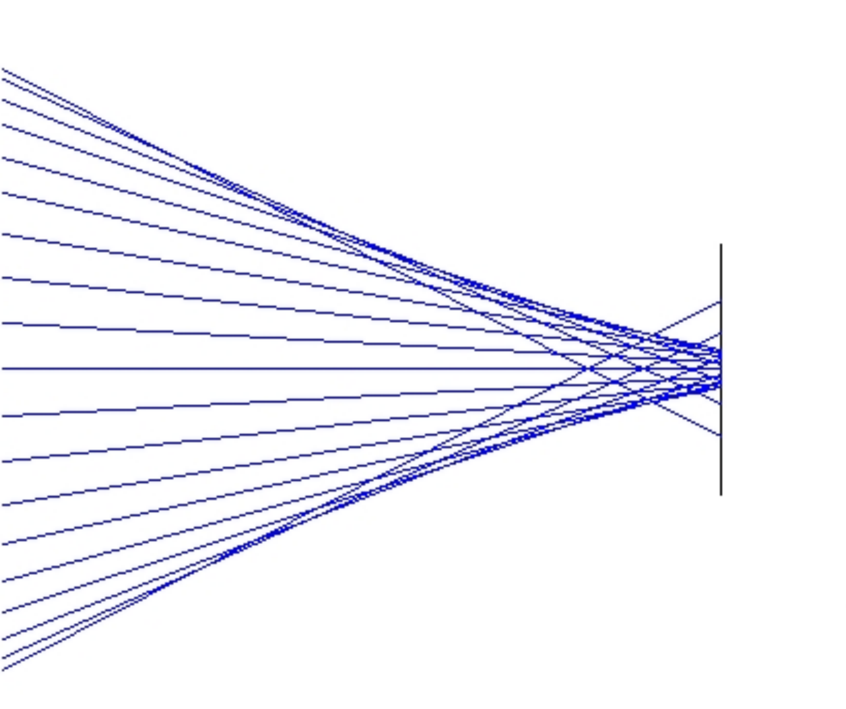
With **no turbulence**, FWHM is diffraction limit of telescope, $\vartheta \sim \lambda / D$

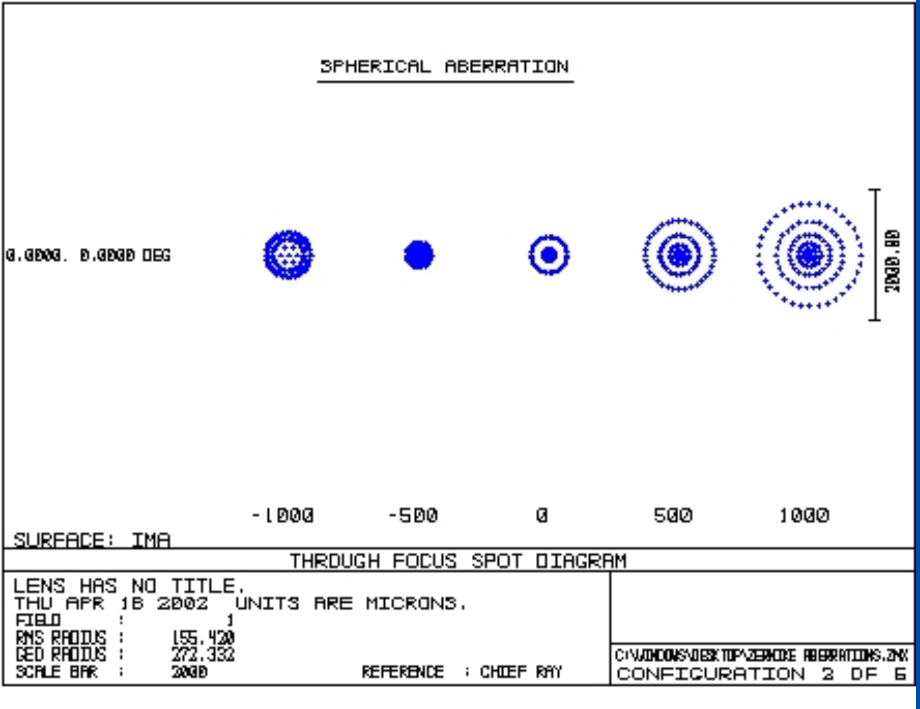
Example:

$\lambda / D = 0.02$ arc sec for $\lambda = 1\ \mu\text{m}$, $D = 10$ m

With turbulence, image size gets much larger (**typically 0.5 - 2 arc sec**)

Spherical aberration





THROUGH FOCUS SPOT DIAGRAM

LENS HAS NO TITLE.
THU APR 18 2002 UNITS ARE MICRONS.
FIELD : 1
RMS RADIUS : 155.420
GEO RADIUS : 272.332
SCALE BAR : 2000 REFERENCE : CHIEF RAY

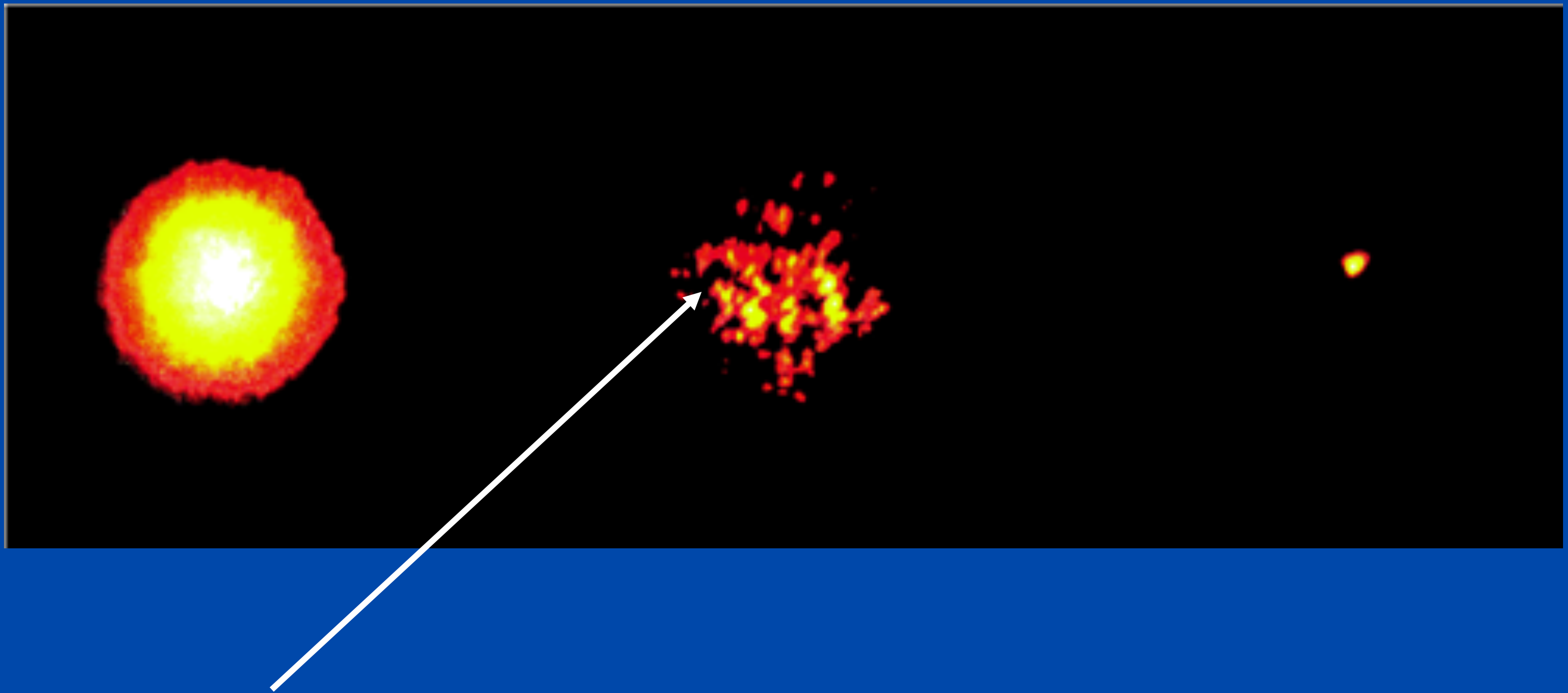
C:\WINDOWS\DESKTOP\ZERNIKE ABERRATIONS.ZMX
CONFIGURATION 2 OF 6

Rays from a spherically aberrated wavefront focus at different planes

Through-focus spot diagram for spherical aberration

Images of a bright star

1 m telescope



Speckles (each is at diffraction limit of telescope)

Goals of lecture

- To understand the main concepts behind adaptive optics systems
- To understand how important AO is for a VLT and how indispensible for an ELT
- To get an idea what is brewing in the AO field and what is store for the future

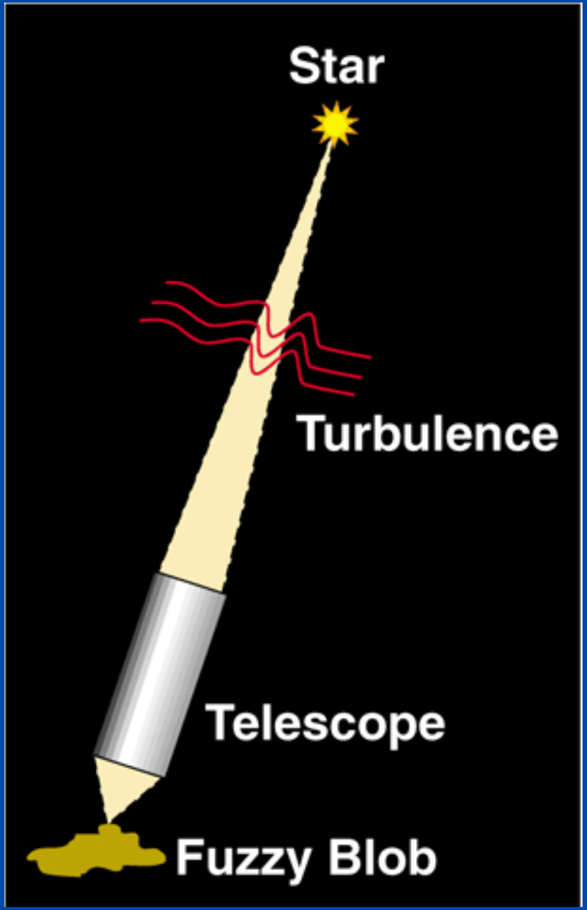
Content

- Intro to AO systems
- Basic optics, diffraction, Fourier optics, image structure

- High contrast AO (VLT SPHERE, E-ELT)
- Sky coverage, Laser guide stars

- Wide field AO, Multi-Conjugate Adaptive Optics (Gemini GLAO, VLT MAD, Gemini MCAO)
- Multi-Object Adaptive Optics (TMT IRMOS, E-ELT Eagle)

Why is adaptive optics needed?

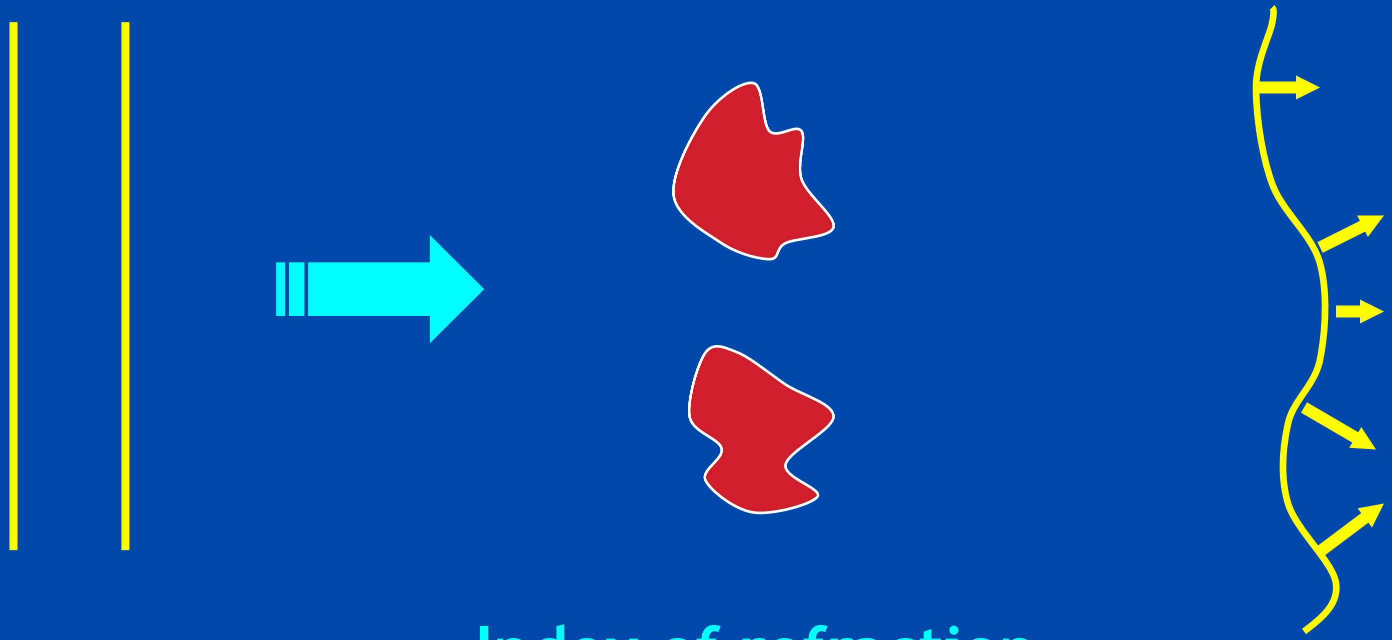


Turbulence in earth's atmosphere makes stars twinkle

More importantly, turbulence spreads out light; makes it a blob rather than a point. This blob is a lot larger than the Point Spread Function (PSF) that would be limited by the size of the telescope only

Even the largest ground-based astronomical telescopes have no better resolution than an 20cm telescope

Atmospheric perturbations cause distorted wavefronts



Rays not parallel

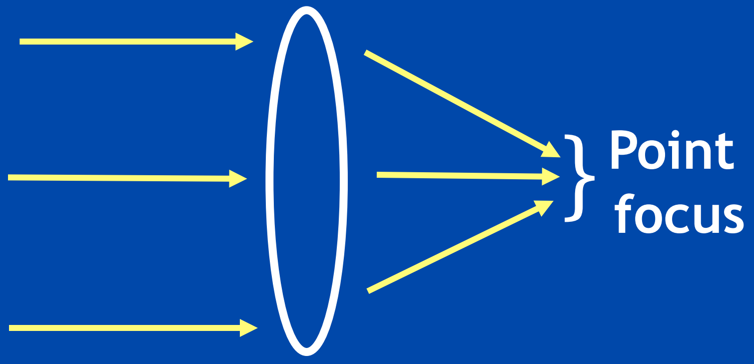
Plane Wave

Index of refraction variations

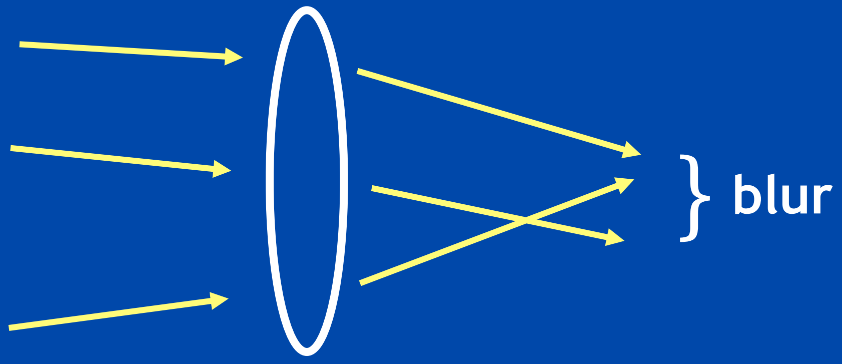
Distorted Wavefront

Optical consequences of turbulence

- Temperature fluctuations in small patches of air cause changes in index of refraction (like many little lenses)
- Light rays are refracted many times (by small amounts)
- When they reach telescope they are no longer parallel
- Hence rays can't be focused to a point:



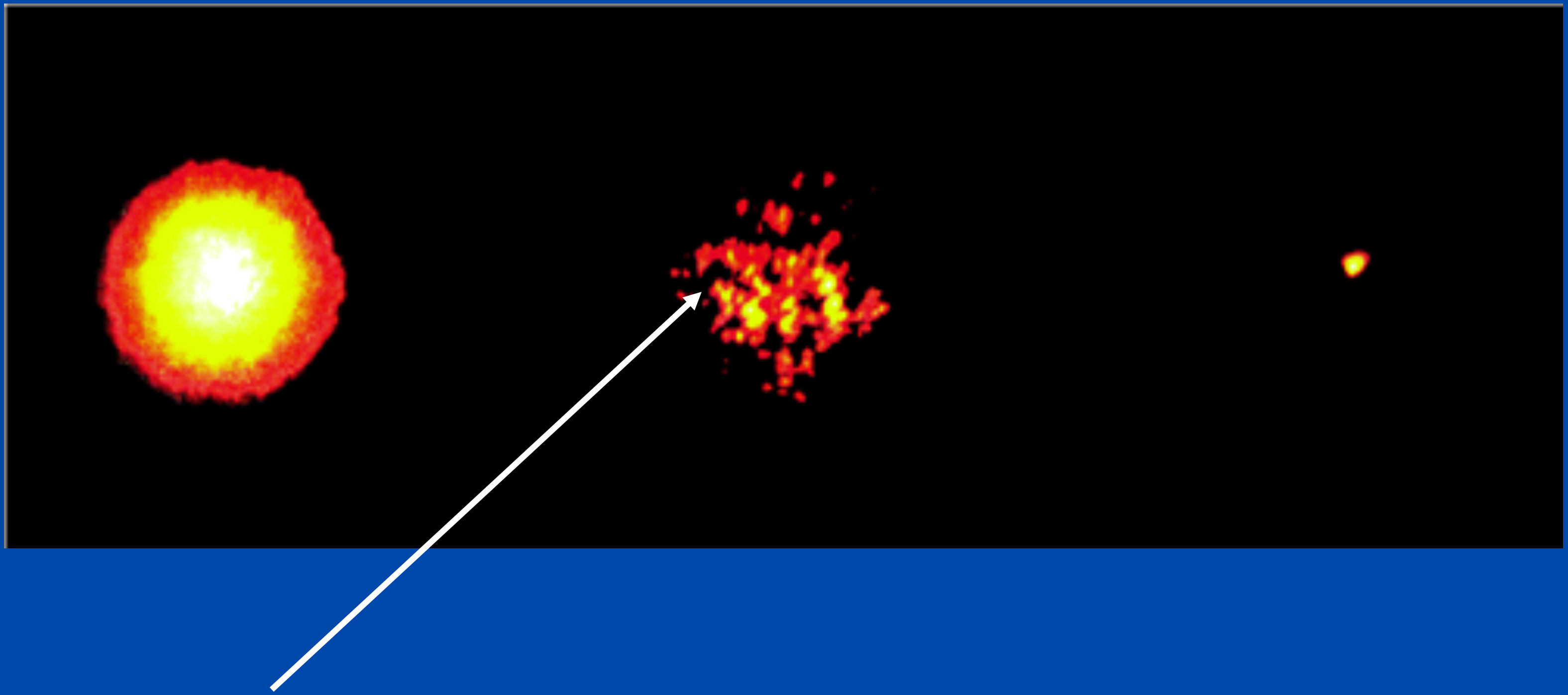
Parallel light rays



Light rays affected by turbulence

Images of a bright star

1 m telescope



Speckles (each is at diffraction limit of telescope)

Turbulence changes rapidly with time

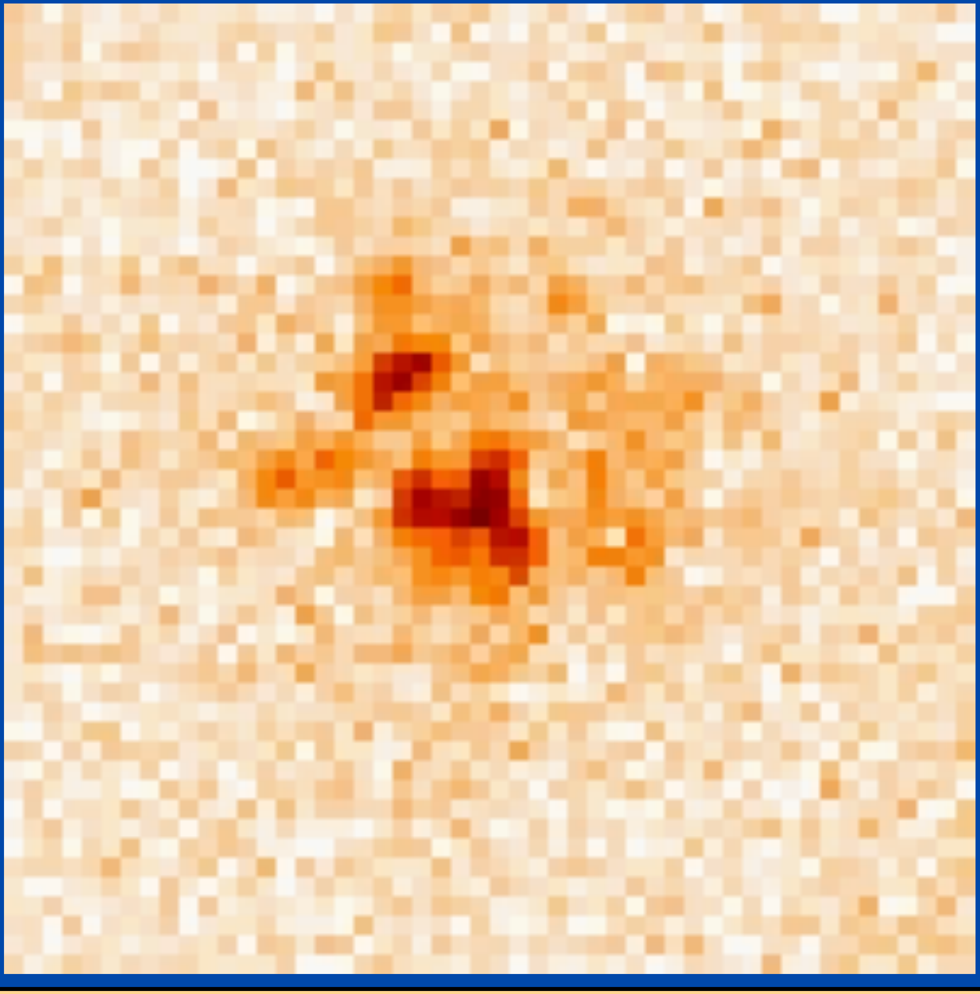
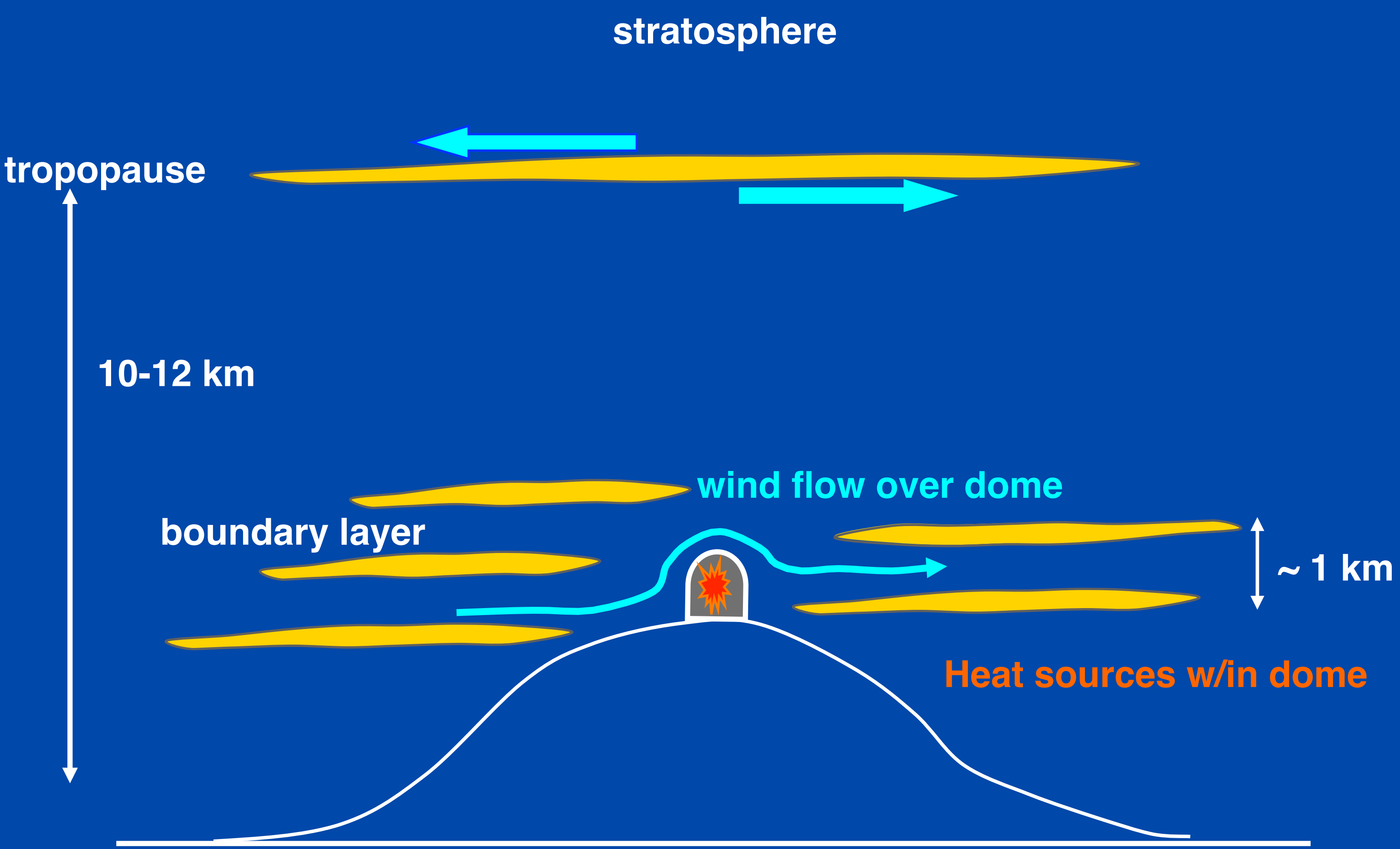


Image is
spread out
into speckles

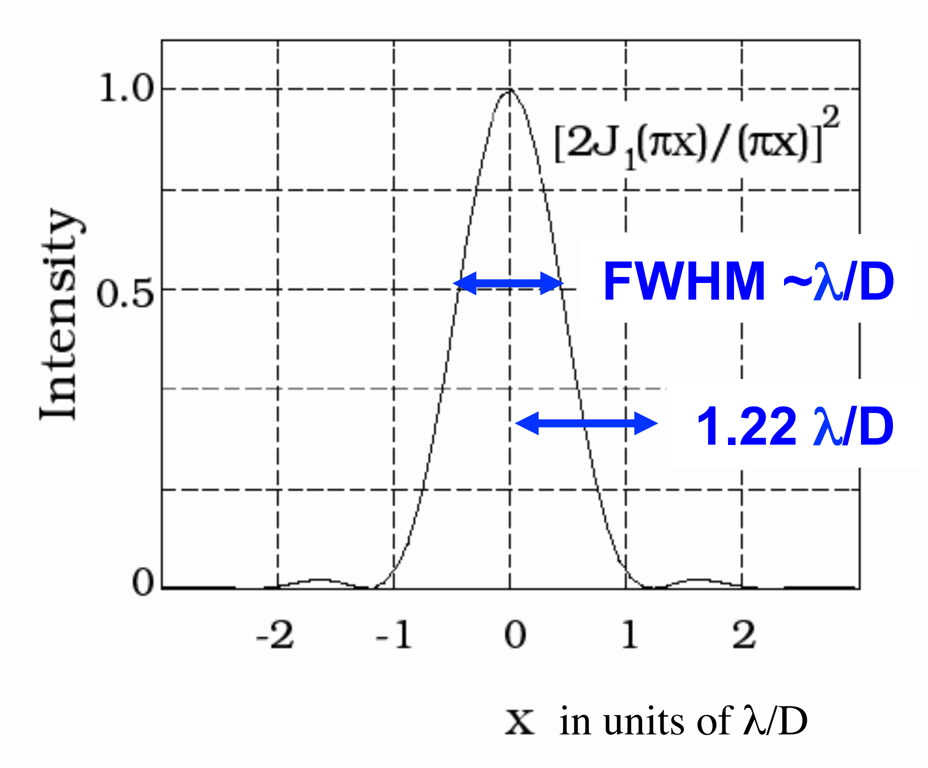
Centroid jumps
around
(image motion)

"Speckle images": sequence of short snapshots of a star, taken at MMT Observatory using a commercial H-band camera

Turbulence arises in many places



Imaging through a perfect telescope (circular pupil)



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

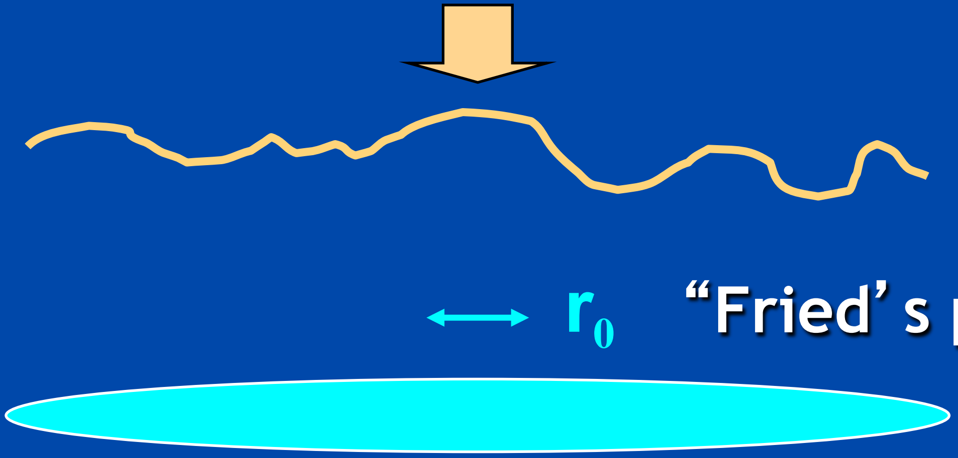
With **no turbulence**, FWHM is diffraction limit of telescope, $\vartheta \sim \lambda / D$

Example:

$\lambda / D = 0.02$ arc sec for $\lambda = 1\ \mu m$, $D = 10$ m

With turbulence, image size gets much larger (**typically 0.5 - 2 arc sec**)

Turbulence strength is characterized by quantity r_0



Wavefront of light

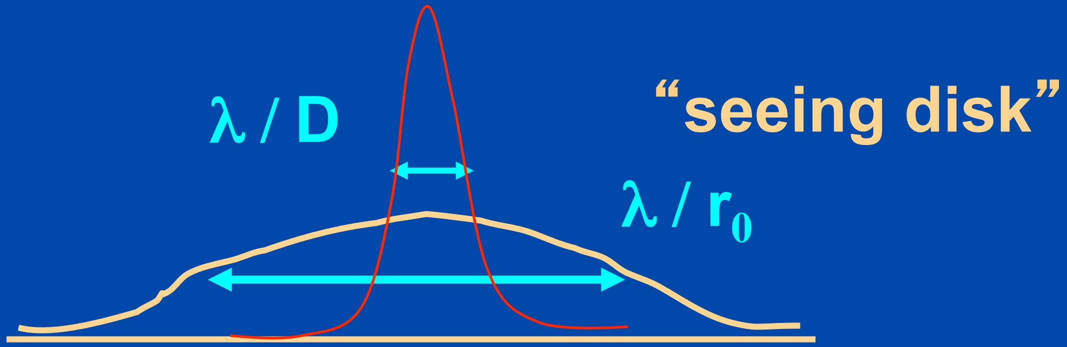
r_0 “Fried’s parameter”

Primary mirror of telescope

- “Coherence Length” r_0 : distance over which optical phase distortion has mean square value of 1 rad^2 (r_0 ~ 15 - 30 cm at good observing sites)
- Easy to remember: r_0 = 10 cm ⇔ FWHM = 1 arc sec at $\lambda = 0.5 \mu m$

Effect of turbulence on image size

- If telescope diameter D >> r_0 , image size of a point source is $\lambda / r_0 \; >> \; \lambda / D$



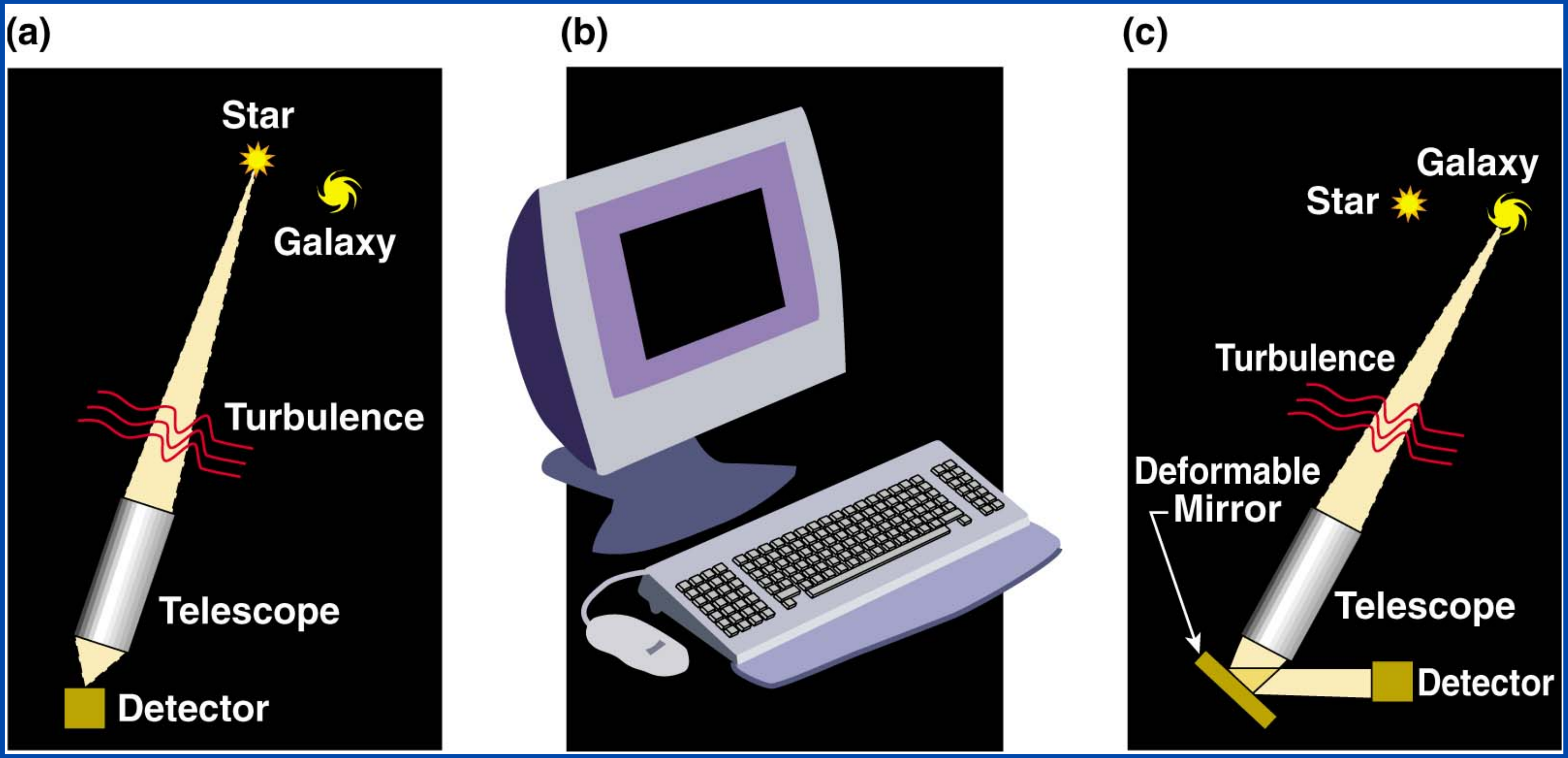
- r_0 is diameter of the circular pupil for which the diffraction limited image and the seeing limited image have the same angular resolution.
- $r_0 \approx$ 25cm at a good site. So any telescope larger than this has no better spatial resolution!

How does adaptive optics help?

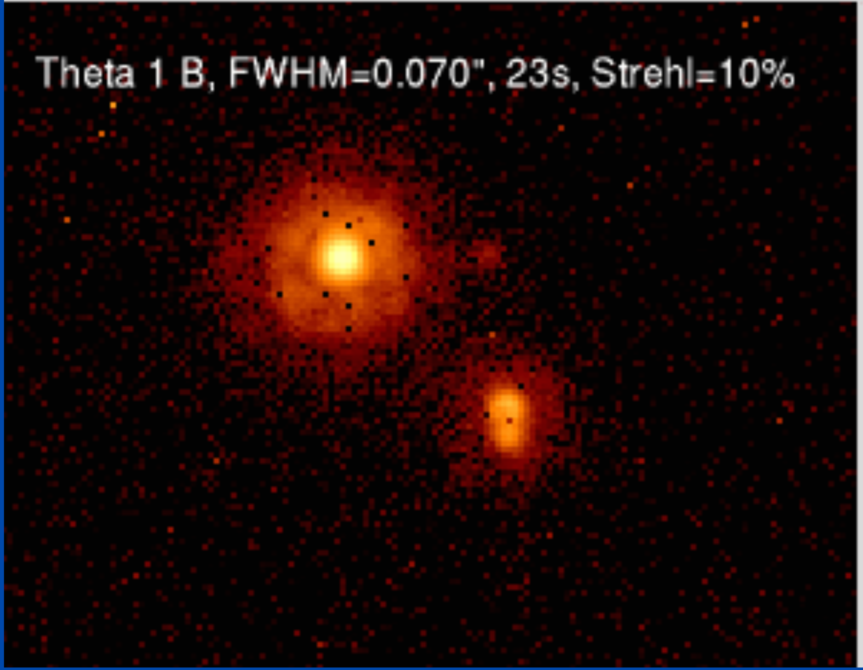
Measure details of blurring from "guide star" near the object you want to observe

Calculate (on a computer) the shape to apply to deformable mirror to correct blurring

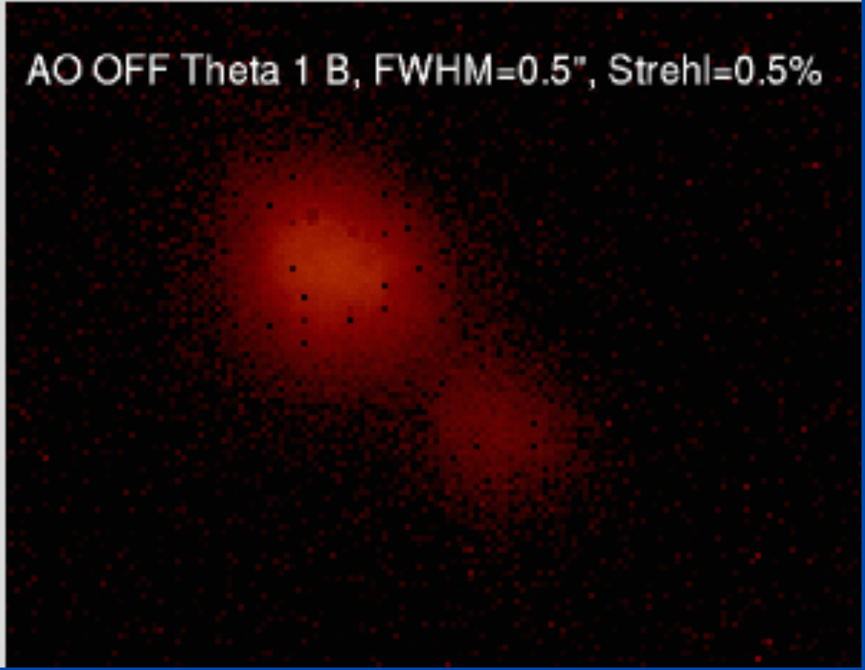
Light from both guide star and astronomical object is reflected from deformable mirror; distortions are removed



H-band images of a star system, from MMT AO

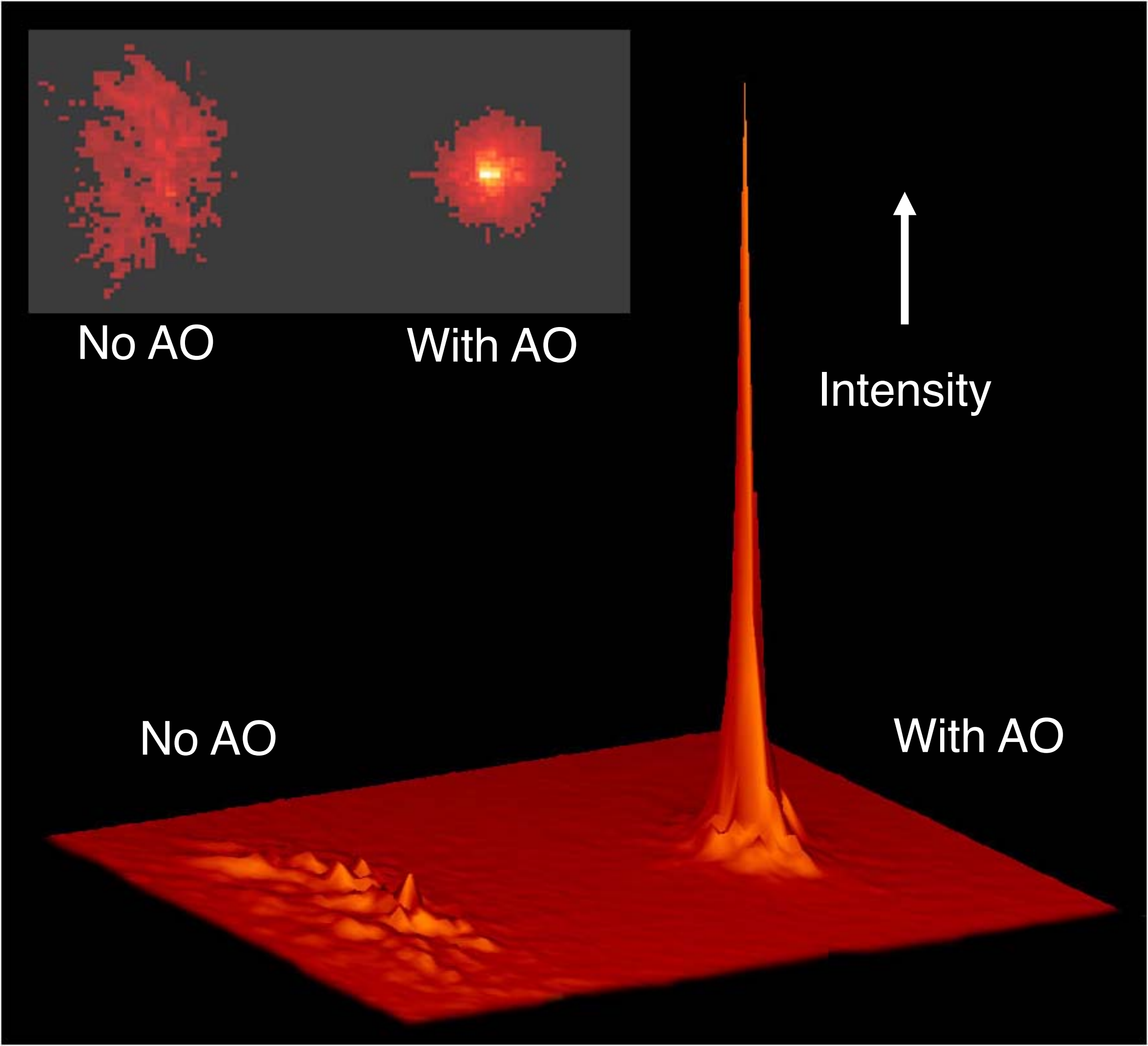


With adaptive optics

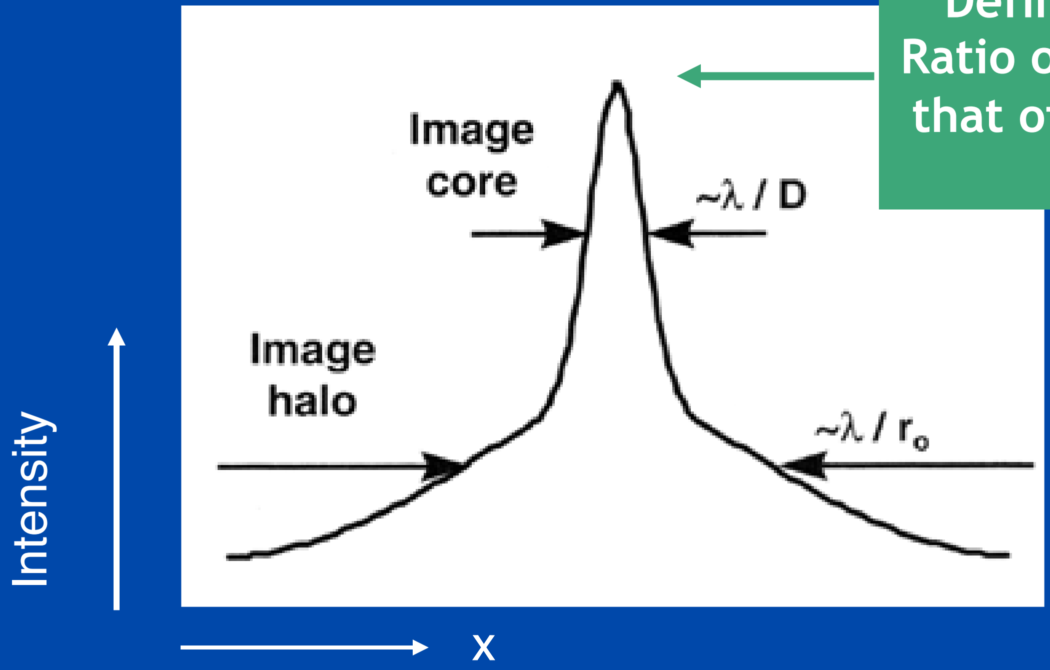


No adaptive optics

Adaptive optics increases peak intensity of a point source



AO produces point spread functions with a "core" and "halo"

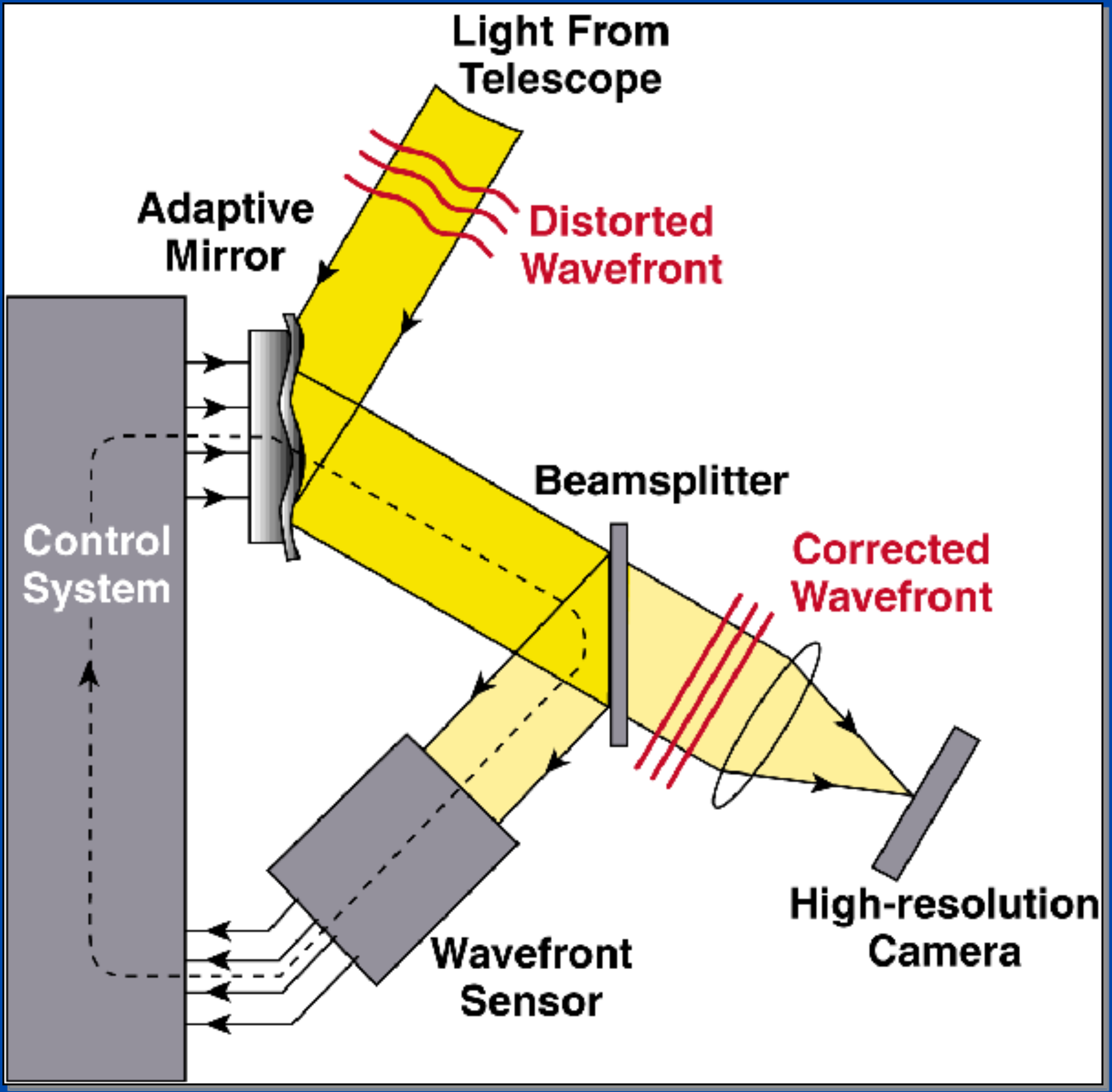


Definition of "Strehl": Ratio of peak intensity to that of "perfect" optical system

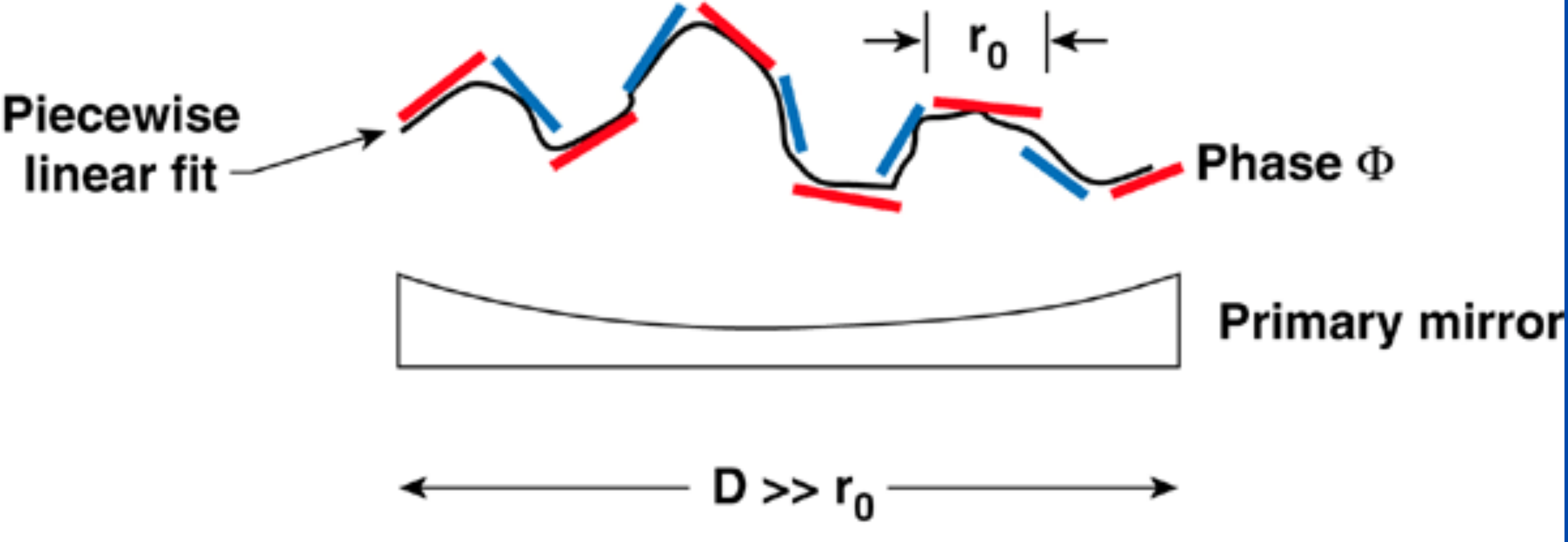
- When AO system performs well, more energy in core
- When AO system is stressed (poor seeing), halo contains larger fraction of energy (diameter ~ r_0)
- Ratio between core and halo varies during night

Schematic of adaptive optics system

Feedback loop: next cycle corrects the (small) errors of the last cycle

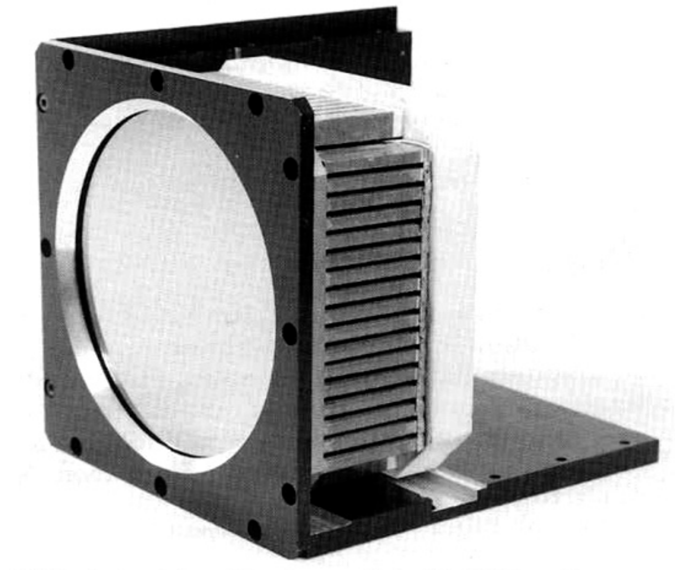


Real deformable mirrors have smooth surfaces

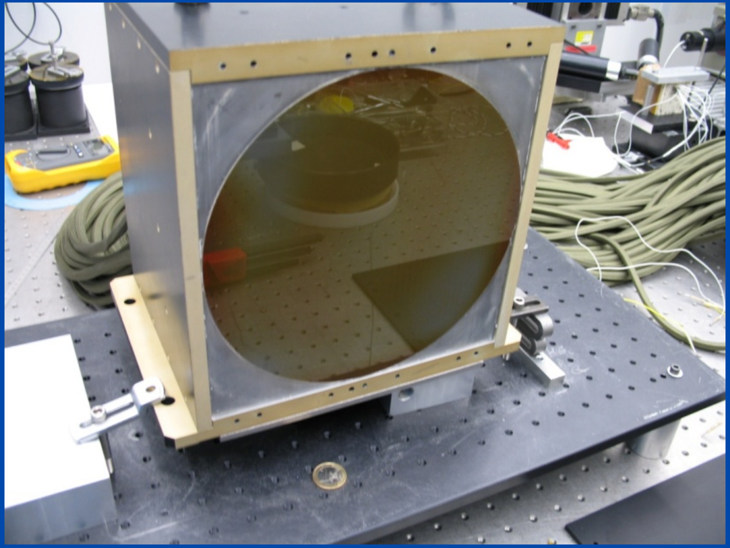


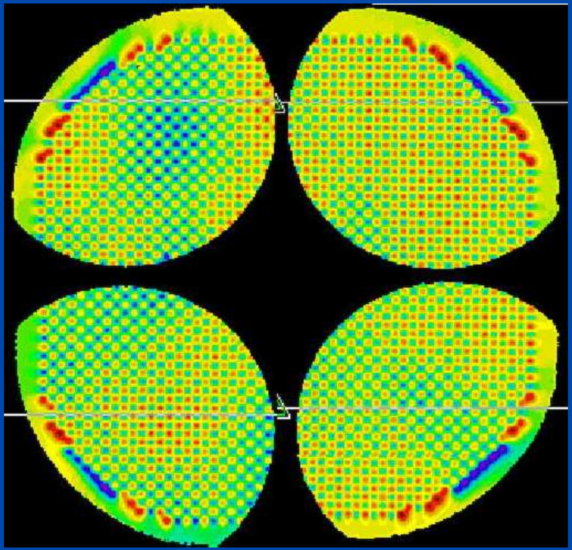
- In practice, a small deformable mirror with a thin bendable face sheet is used
- Placed <u>after</u> the main telescope mirror

Classical PIEZO actuators

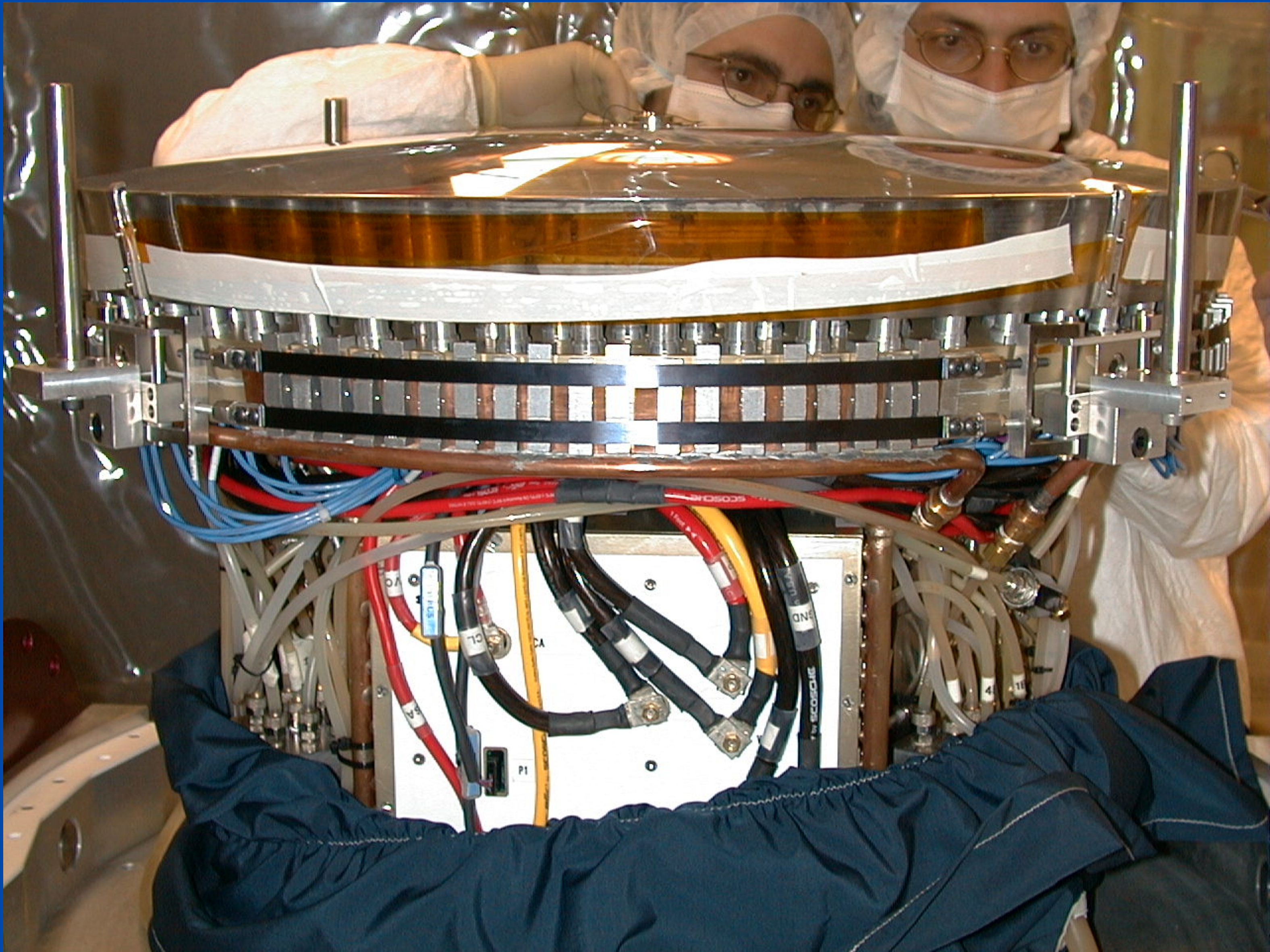


A 249 actuator deformable mirror made by CILAS (France)

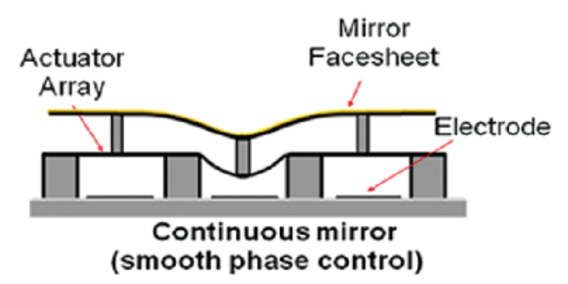


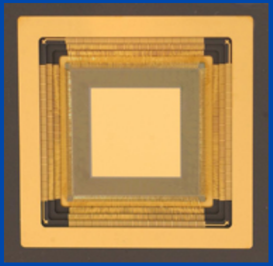


Large DM's are on every ELT technological roadmap

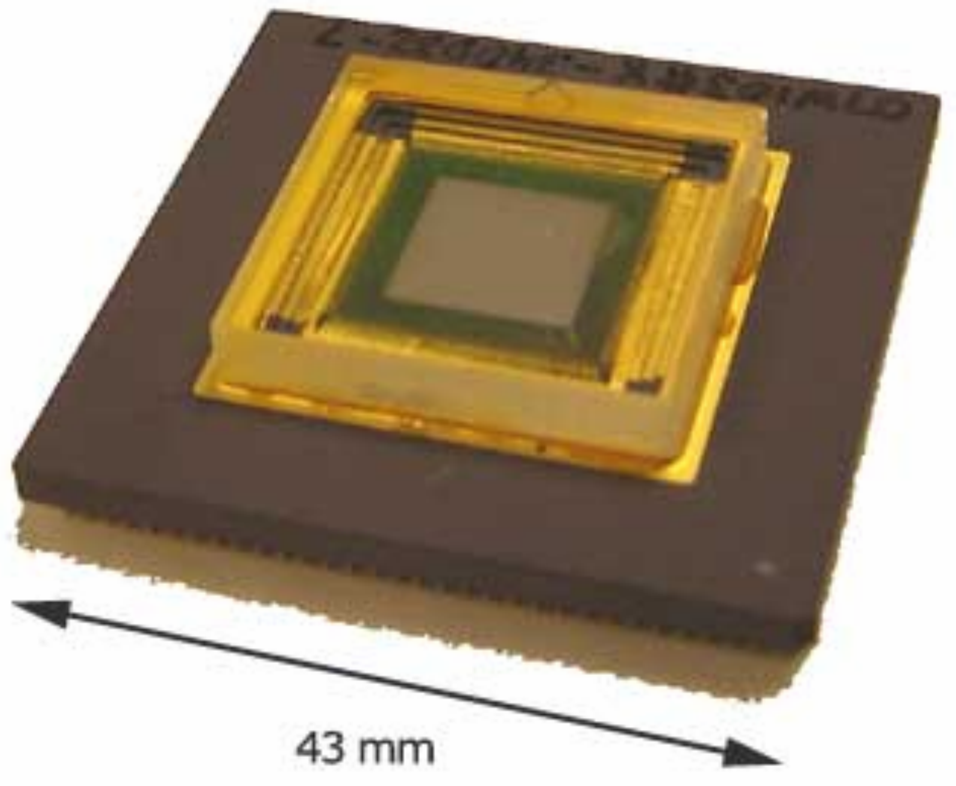


Existing MEMS mirror (sufficient for Hybrid-MOAO)



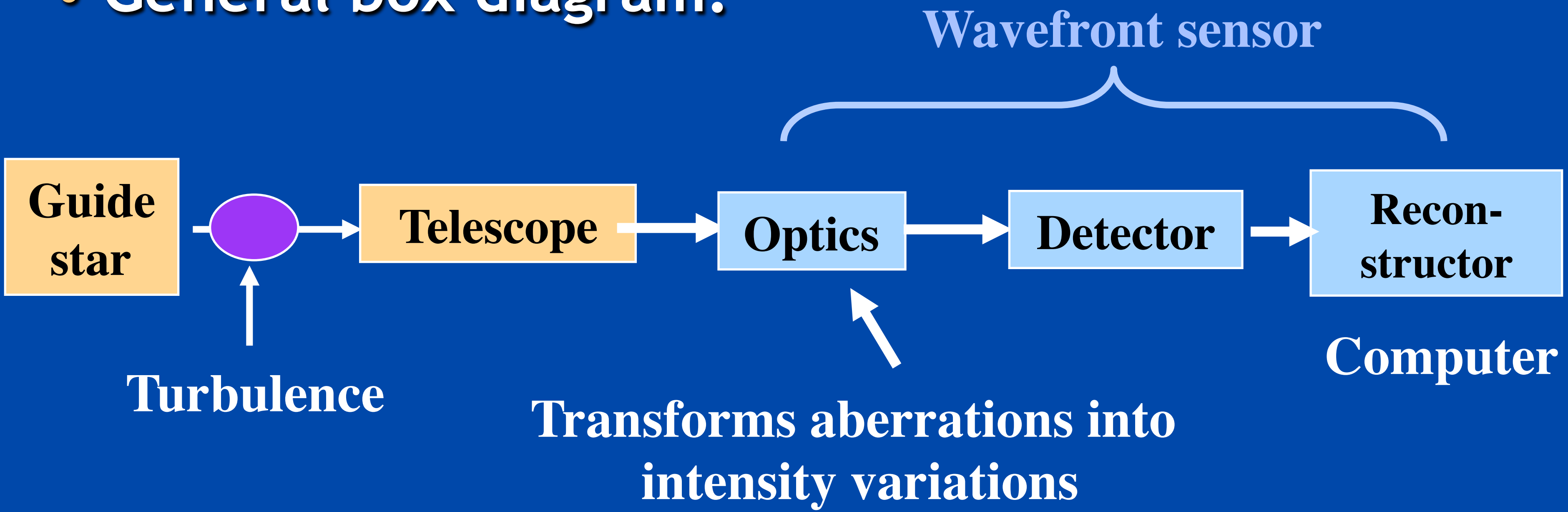


Boston Micromachines 32x32 actuator, 1.5 um MEMS device.
(In Stock)



Basics of wavefront sensing

- Measure phase by measuring intensity variations
- Difference between various wavefront sensor schemes is the way in which phase differences are turned into intensity differences
- General box diagram:



Wavefront sensor

Guide star

Telescope

Optics

Detector

Recon-structor

Turbulence

Transforms aberrations into intensity variations

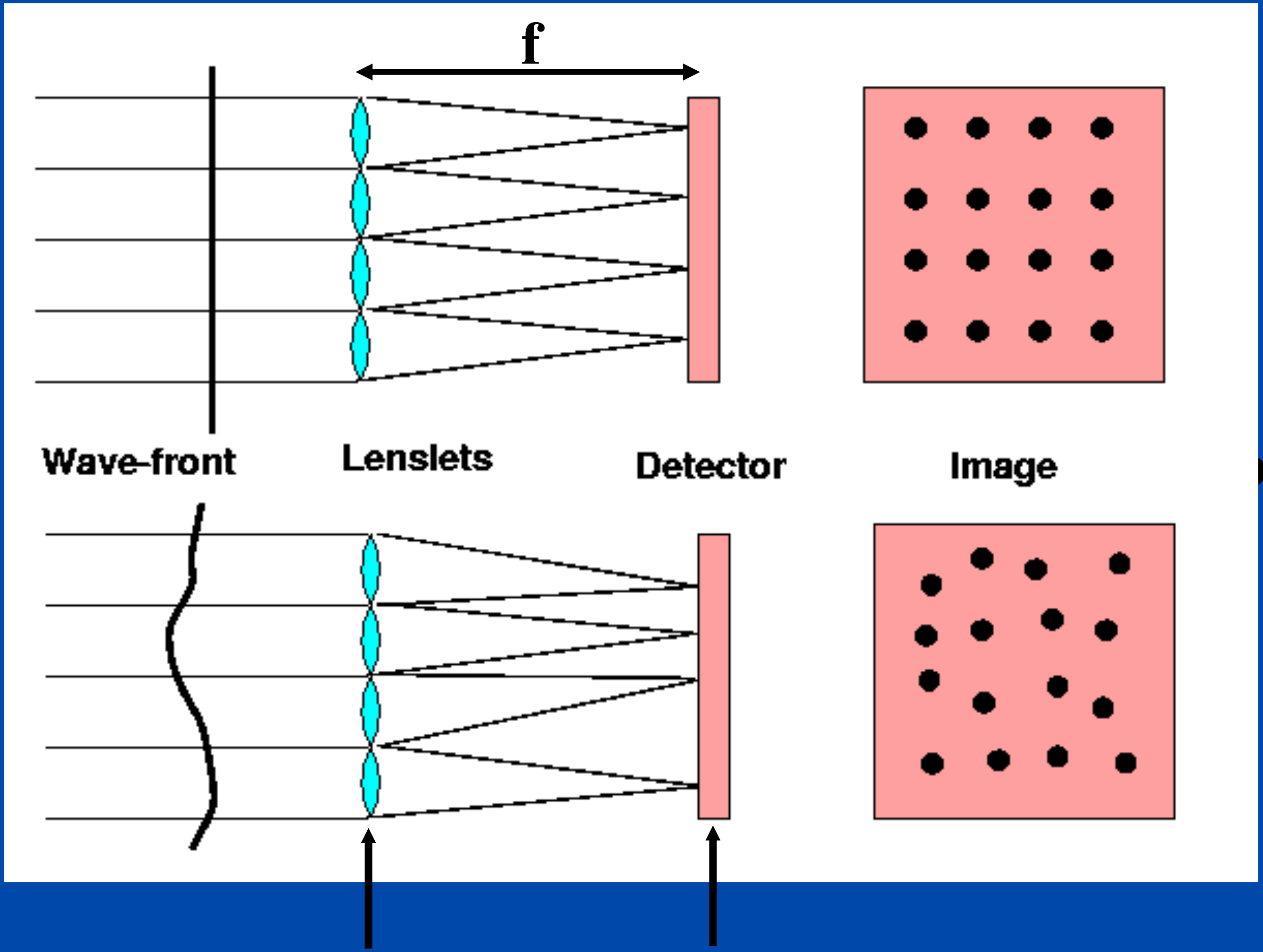
Computer

Types of wavefront sensors

- **“Direct” in pupil plane:** split pupil up into subapertures in some way, then use intensity in each subaperture to deduce phase of wavefront. **REAL TIME**
  - Slope sensing: Shack-Hartmann, pyramid sensing
  - Curvature sensing

- **“Indirect” in focal plane:** wavefront properties are deduced from whole-aperture intensity measurements made at or near the focal plane. Iterative methods - **take a lot of time**.
  - Image sharpening, multi-dither
  - Phase diversity

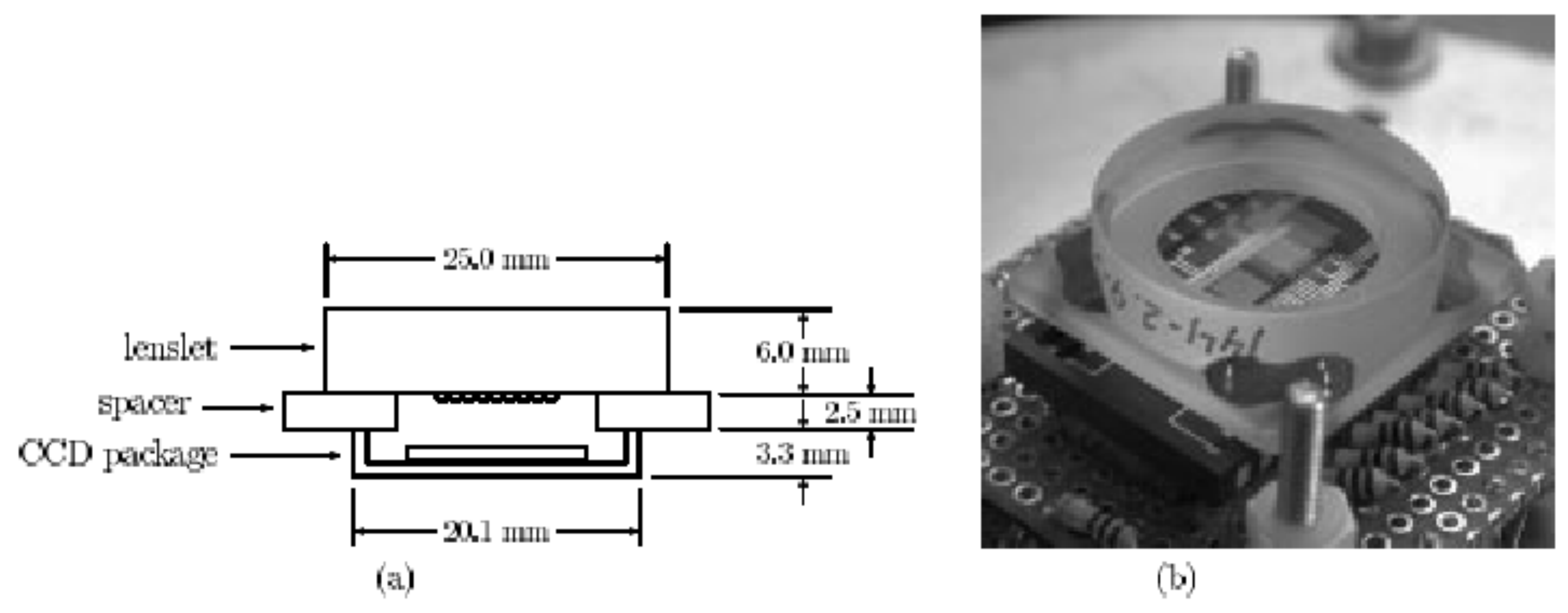
Shack-Hartmann wavefront sensor concept - measure subaperture tilts



Pupil plane

Image plane

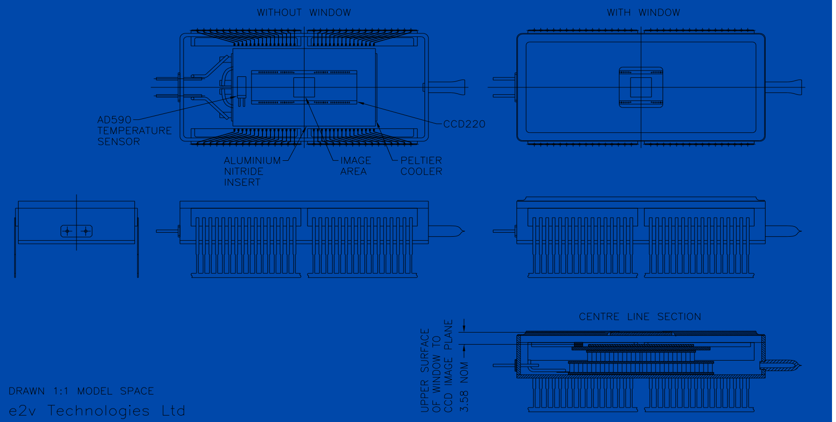
WFS implementation

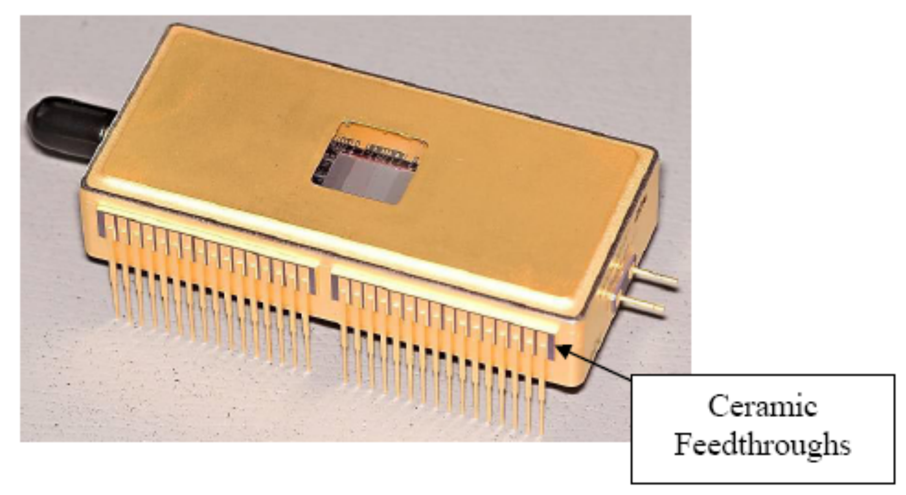


- Compact
- Time-invariant

CCD rapide

- CCD design complete
- 64 pins
  - 256x256 pixels
  - 1200 trames/s
  - < 1e bruit
  - Refroidissment Peltier



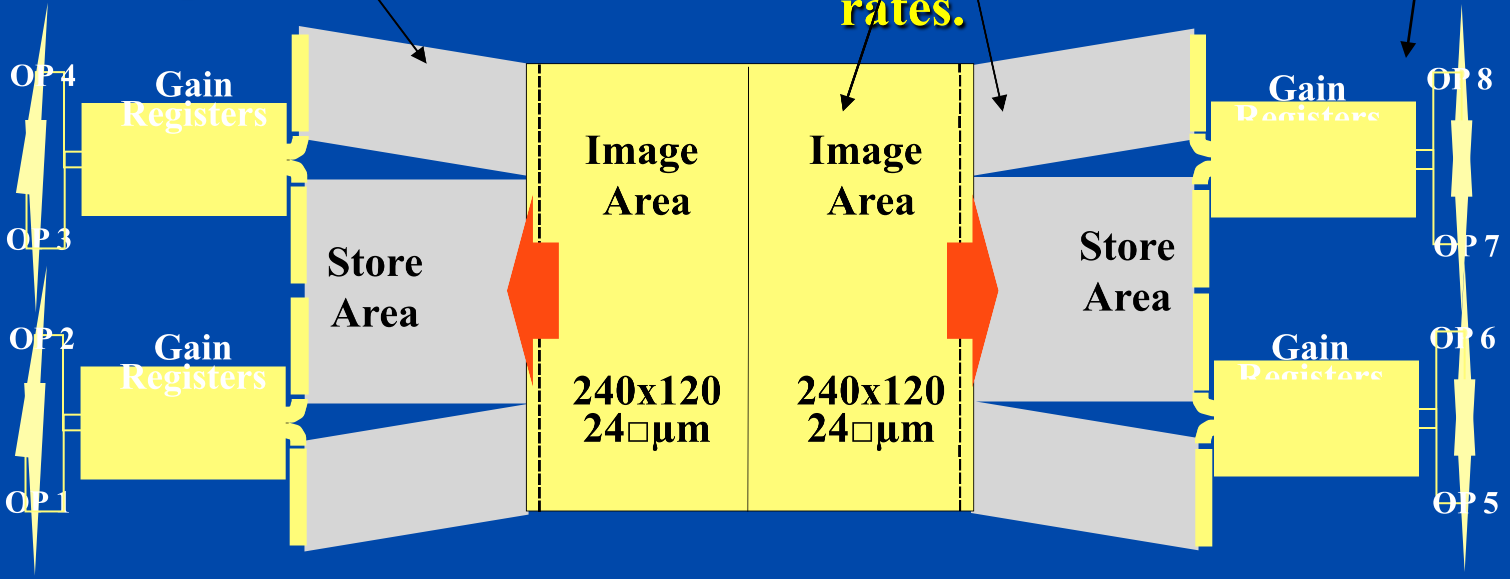


Split frame transfer 8-output back-illuminated e2v L3Vision CCD for WFS.

Store slanted to allow room for multiple outputs.

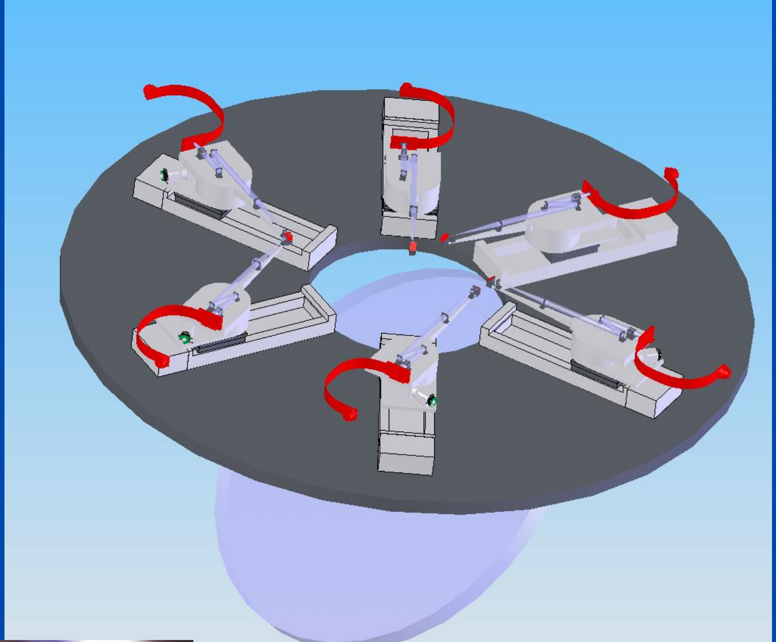
Metal Buttressed 2Φ 10 Mhz Clocks for fast image to store transfer rates.

8 L3Vision Gain Registers/Outputs. Each 15Mpix./s.

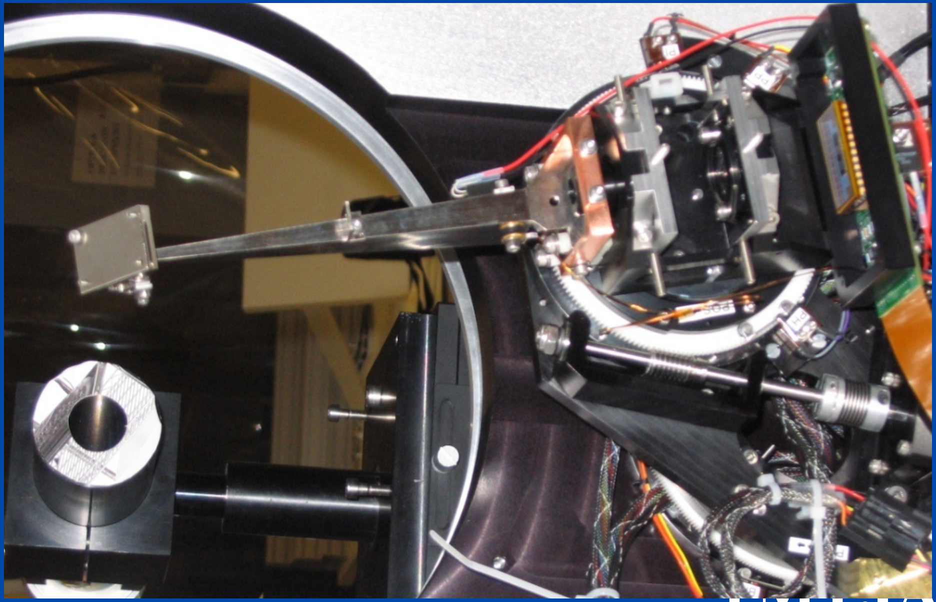


3. NGS WFS

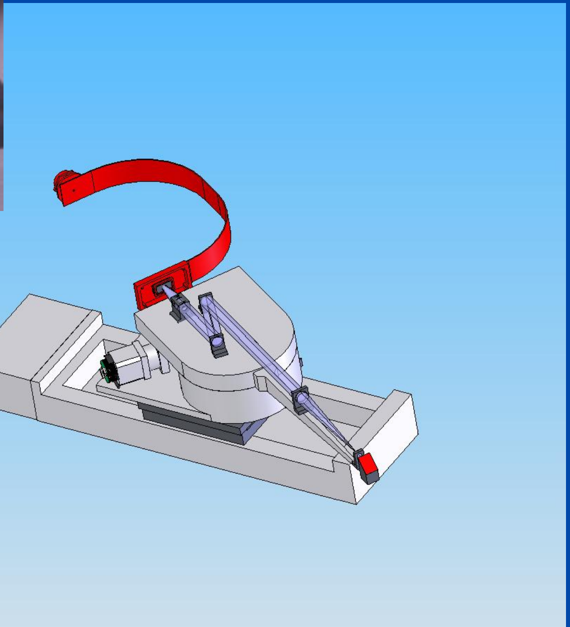
- Radial+Linear stages with encoders offer flexile design with min. vignetting
- 6 probe arms operating in “Meatlocker” just before focal plan
- 2x2 lenslets



EEV CCD60



Flamingos2 OIWFS



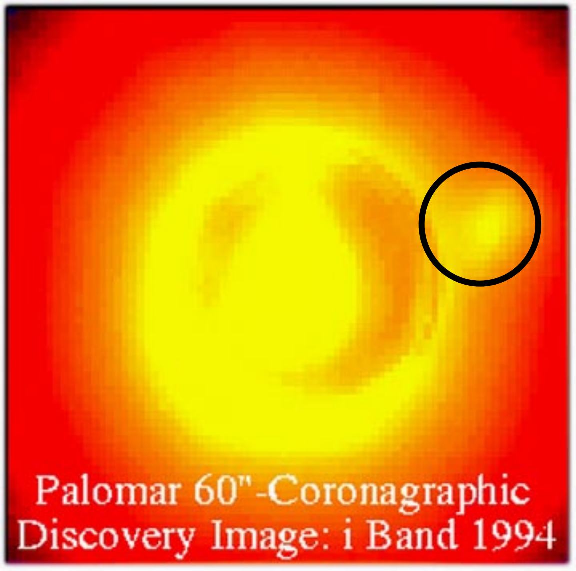
Astronomical observatories with AO on 6 - 10 m telescopes

- European Southern Observatory (Chile)
  - 4 telescopes (MACAO, NAOS, CRIRES, SPIFFI, MAD)
- Keck Observatory, (Hawaii)
  - 2 telescopes
- Gemini North Telescope (Hawaii), ALAIR + LGS
- Subaru Telescope, Hawaii
- MMT Telescope, Arizona

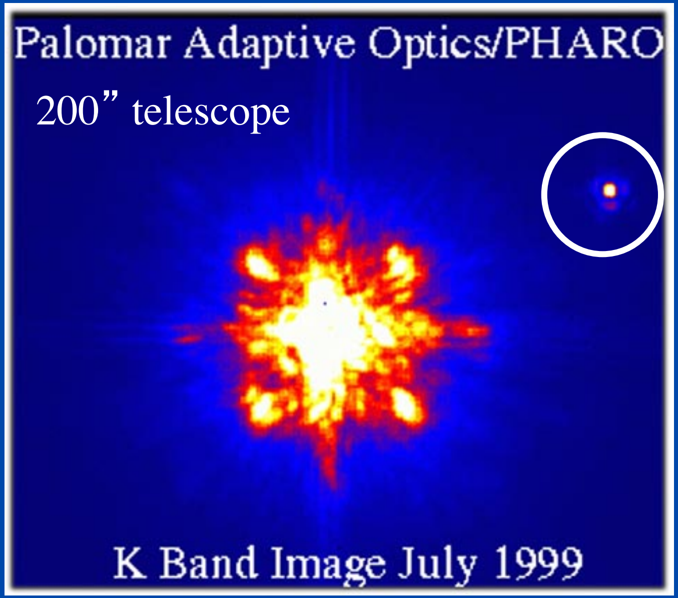
- Soon:
  - Gemini South Telescope, Chile (MCAO)
  - Large Binocular Telescope, Arizona

Adaptive optics makes it possible to find faint companions around bright stars

Two images from Palomar of a brown dwarf companion to GL 105



No AO

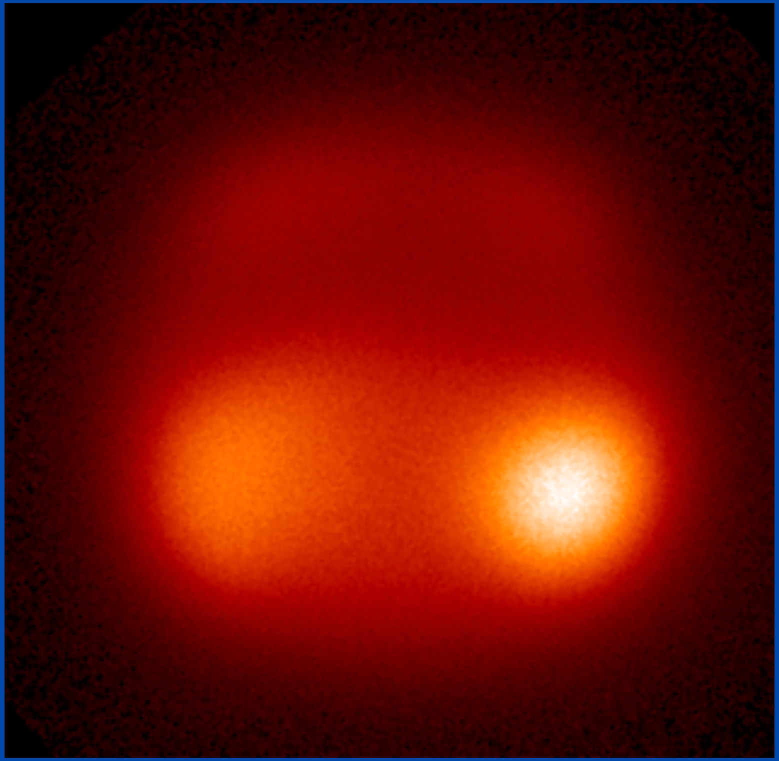


With AO

Credit: David Golimowski

Neptune in infra-red light (1.65 microns)

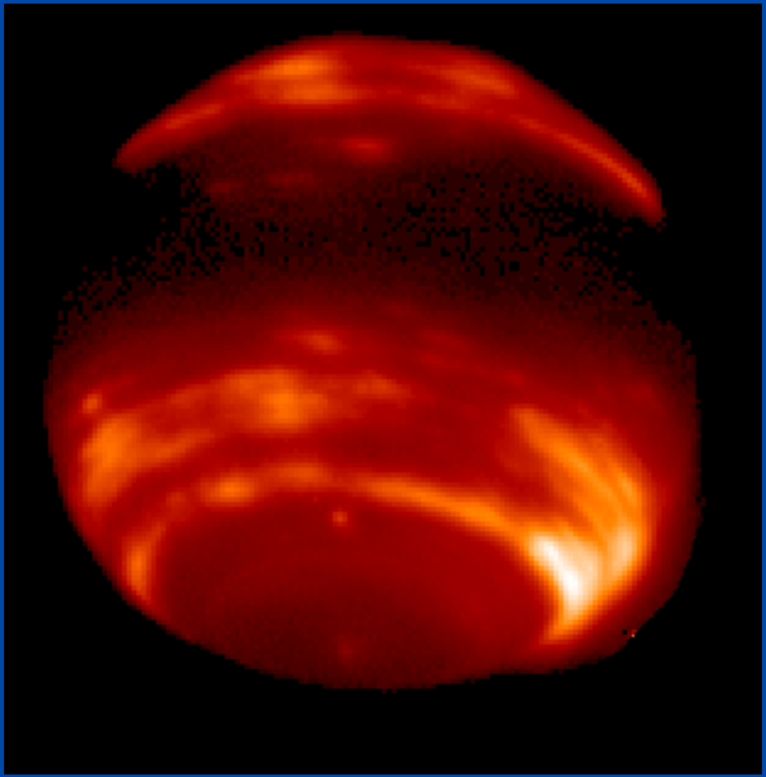
Without adaptive optics



May 24, 1999

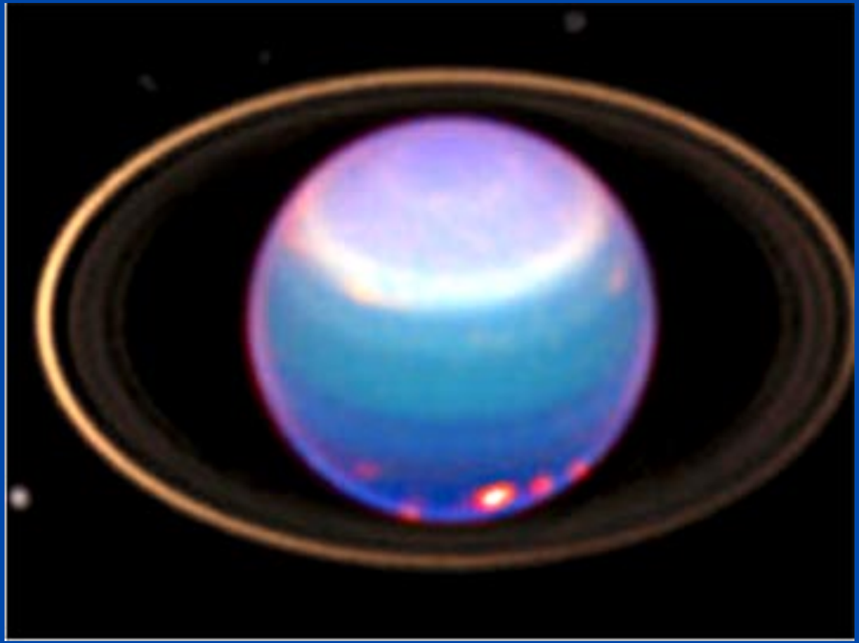
With adaptive optics

2.3 arc sec

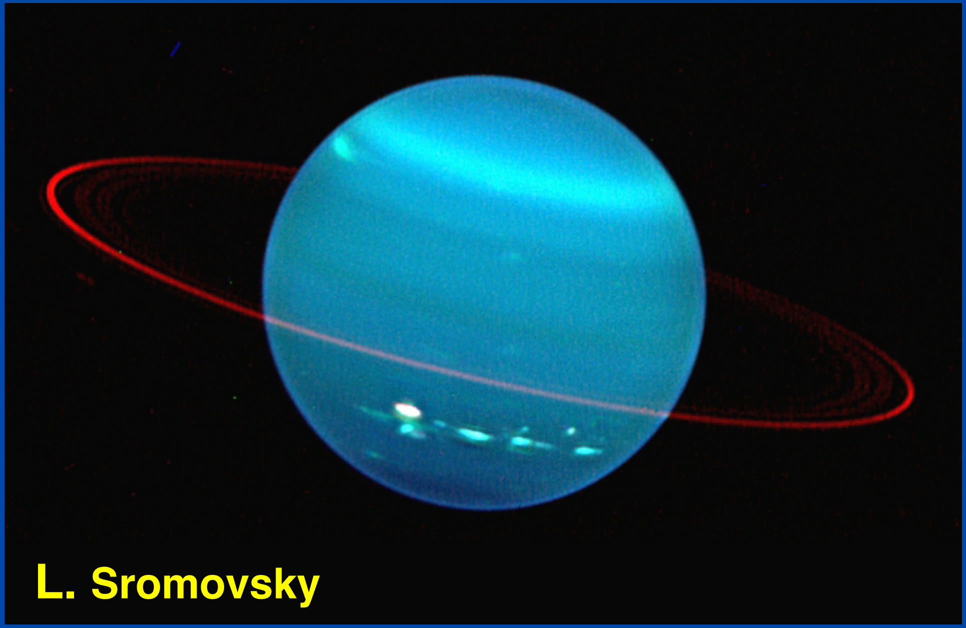


June 27, 1999

Uranus with Hubble Space Telescope and Keck AO



HST, Visible



Keck AO, IR

Lesson: Keck in near IR has ~ same resolution as Hubble in visible

Some frontiers of astronomical adaptive optics

- Current systems (natural and laser guide stars):
  - How can we measure the Point Spread Function while we observe?
  - How accurate can we make our photometry? astrometry?
  - What methods will allow us to do high-precision spectroscopy?

- Future systems:
  - Can we push new AO systems to achieve very high contrast ratios, to detect planets around nearby stars?
  - How can we achieve a wider AO field of view?
  - How can we do AO for visible light (replace Hubble on the ground)?
  - How can we do laser guide star AO on future 30-m telescopes?

Frontiers in AO technology

- New kinds of deformable mirrors with > 5000 degrees of freedom
- Wavefront sensors that can deal with this many degrees of freedom
- (ultra) Fast computers
- Innovative control algorithms
- "Tomographic wavefront reconstuction" using multiple laser guide stars
- New approaches to doing visible-light AO