Astronomical Observing Techniques 2019

Lecture 13: Twinkle, twinkle little star ... No more!

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Overview

1. The Power of Adaptive Optics
2. Seeing
3. Resolution & Sensitivity Improvements
4. Adaptive Optics Principles
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15. Laser Guide Stars
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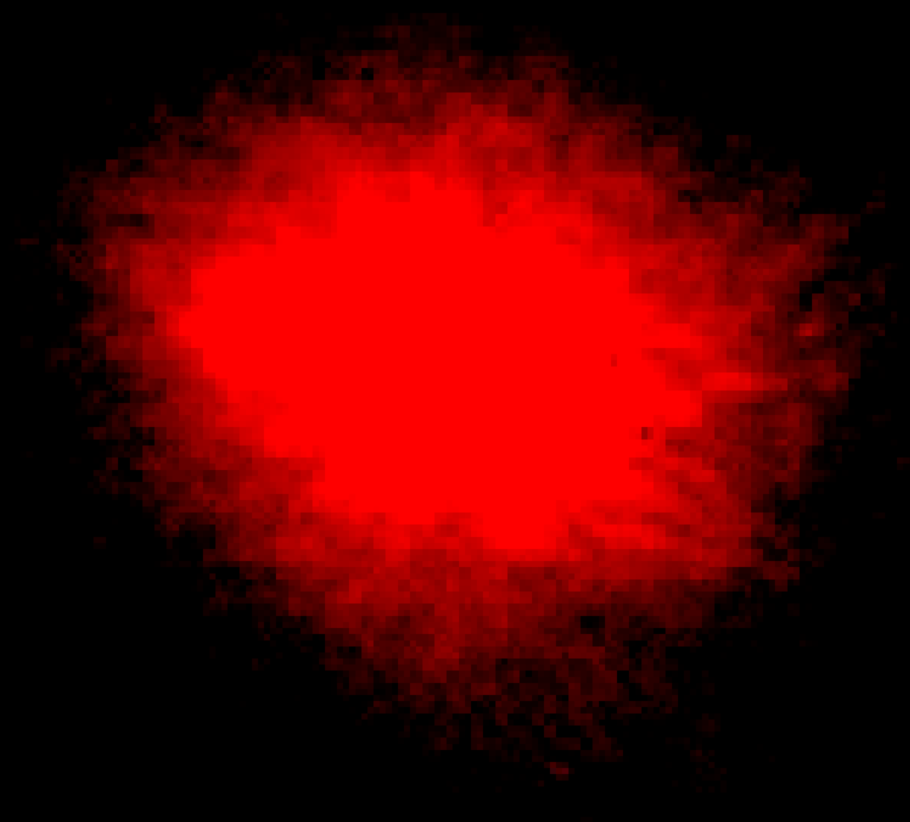
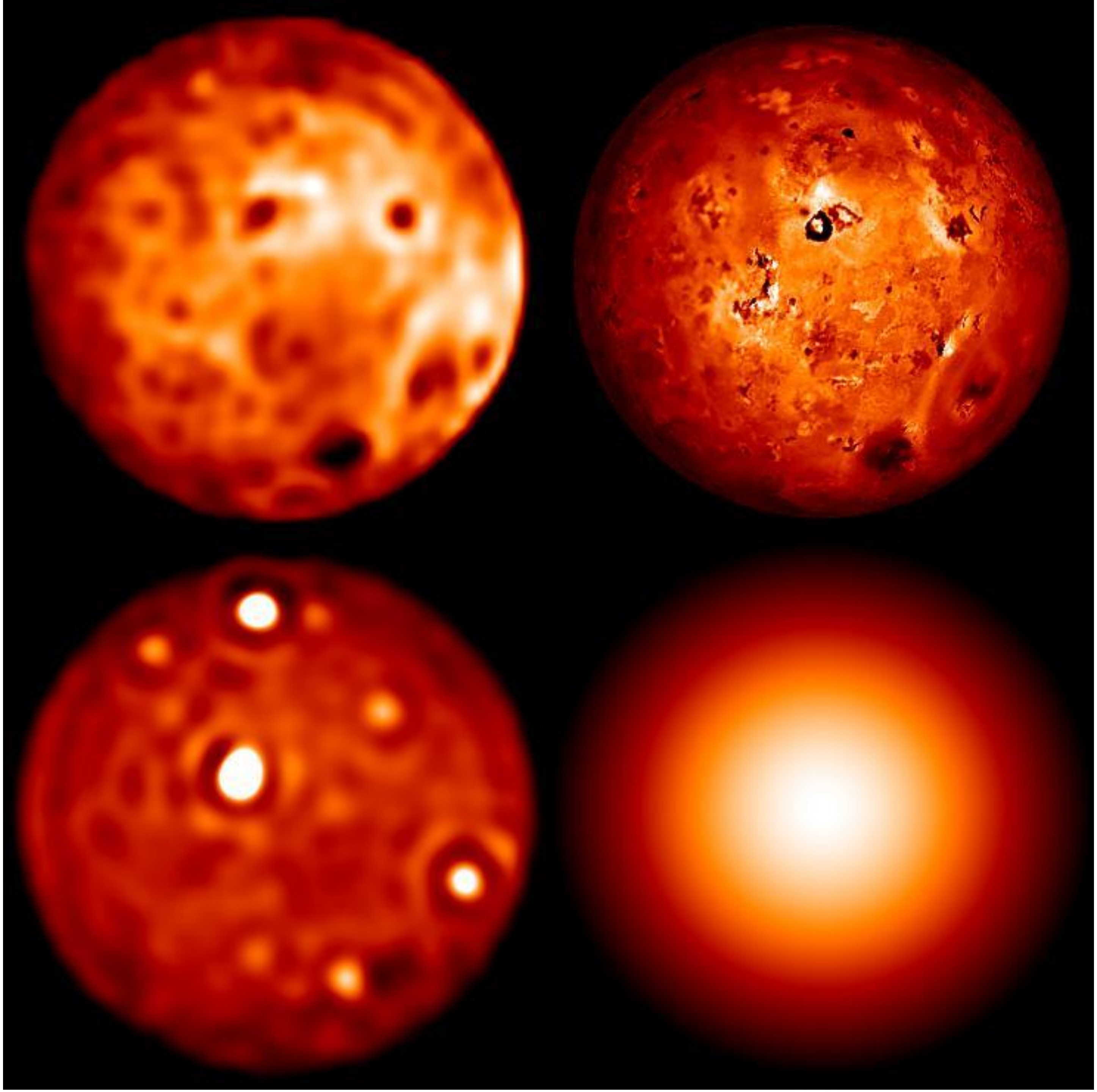
17. Multi-Conjugate Adaptive Optics
18. Extreme Adaptive Optics

The Power of Adaptive Optics

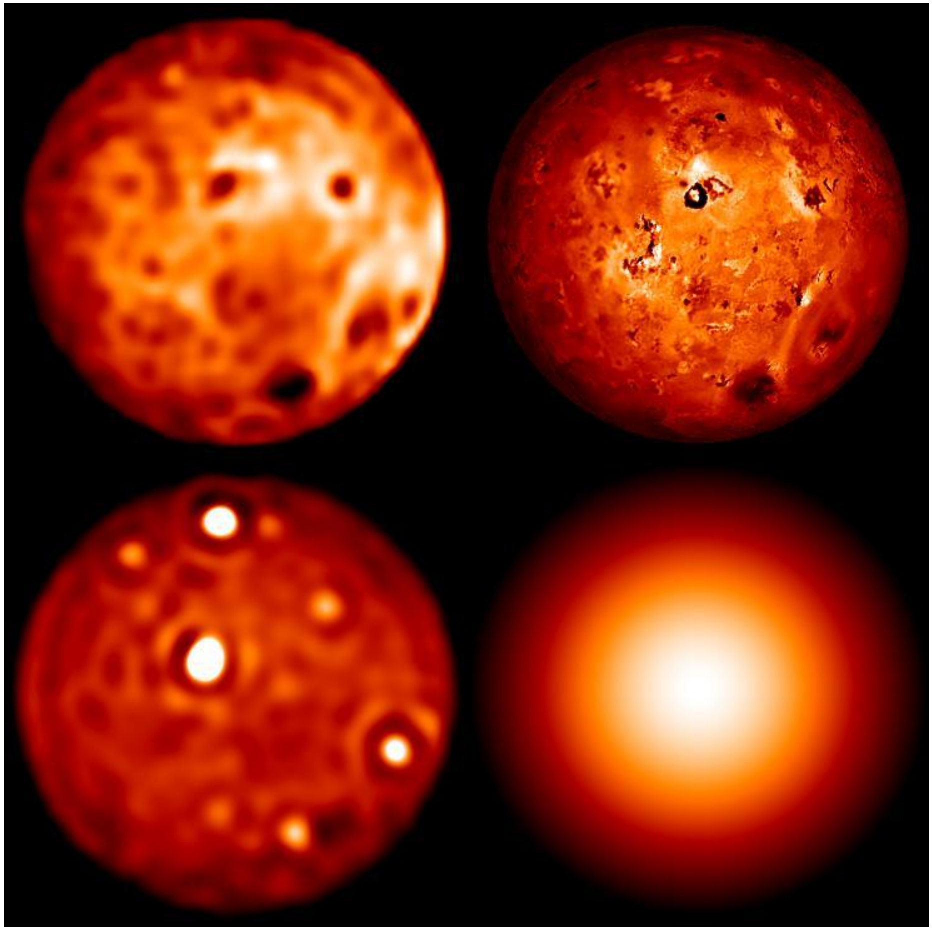


oldweb.lbto.org/AO/AOpressrelease.htm



Io with and without Keck AO

Io image taken with Keck adaptive optics; K-band, **2.2micron**



Io image based on visible light taken with **Galileo** spacecraft orbiter.

Io image taken with Keck adaptive optics; L-band, **3.5micron**

Io image taken **without** Keck adaptive optics.

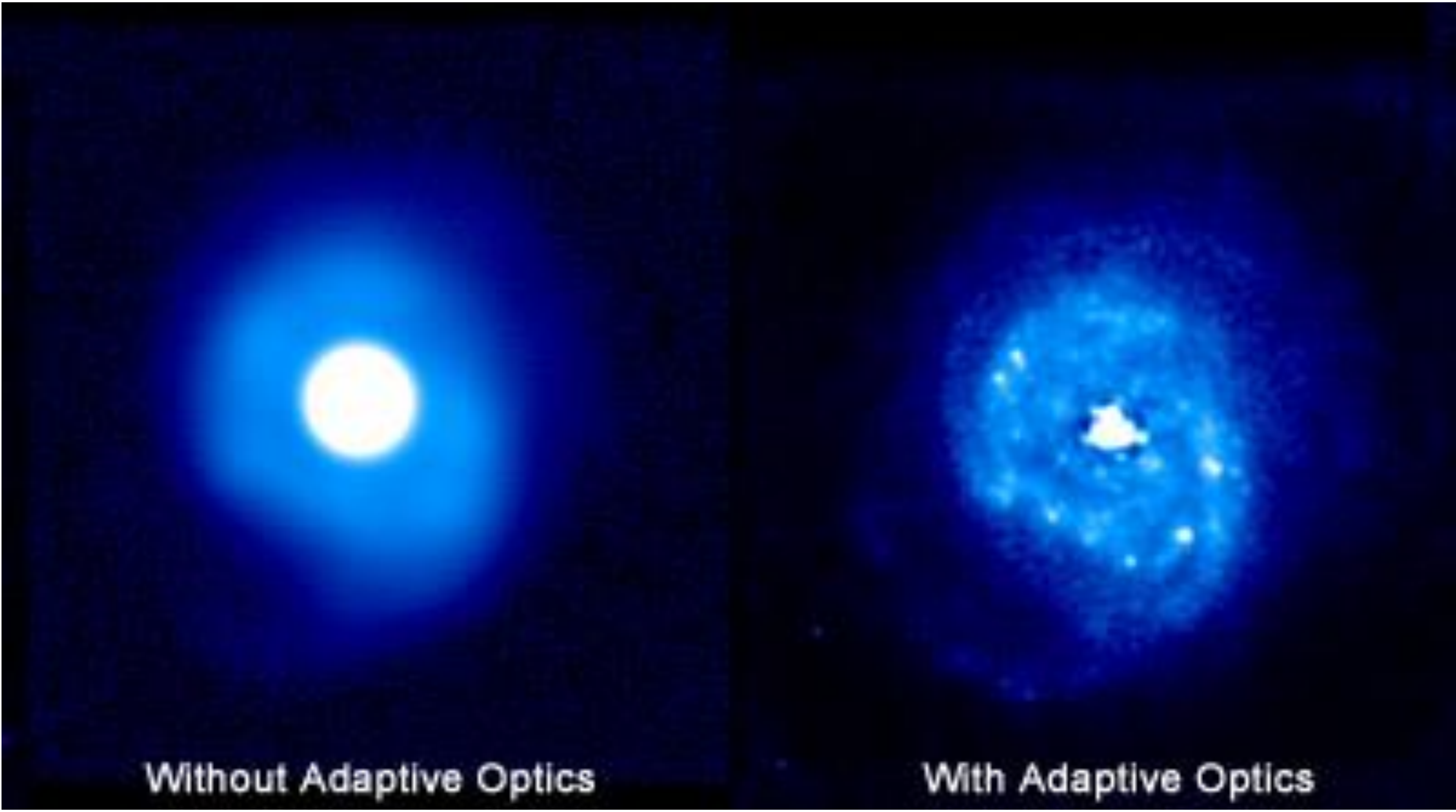
cfao.ucolick.org/pgallery/io.php

Io, vulcanic moon of Jupiter

- Observations of Io by passing spacecrafs (the *Voyagers*, *Galileo*, *Cassini*, and *New Horizons*) and Earth-based astronomers have revealed more than 150 active volcanoes.
- The heat source for Io's volcanism comes from tidal heating produced by its forced orbital eccentricity.
- Lava flows on Io, tens or hundreds of kilometres long, have primarily basaltic composition, similar to lavas seen on Earth at shield volcanoes such as Kīlauea in Hawaii.
- Ionian lava lakes are depressions partially filled with molten lava covered by a thin solidified crust. These lava lakes are directly connected to a magma reservoir lying below. The largest volcanic depression on Io is Loki Patera at 202 kilometres across.

https://en.wikipedia.org/wiki/Volcanology_of_Io

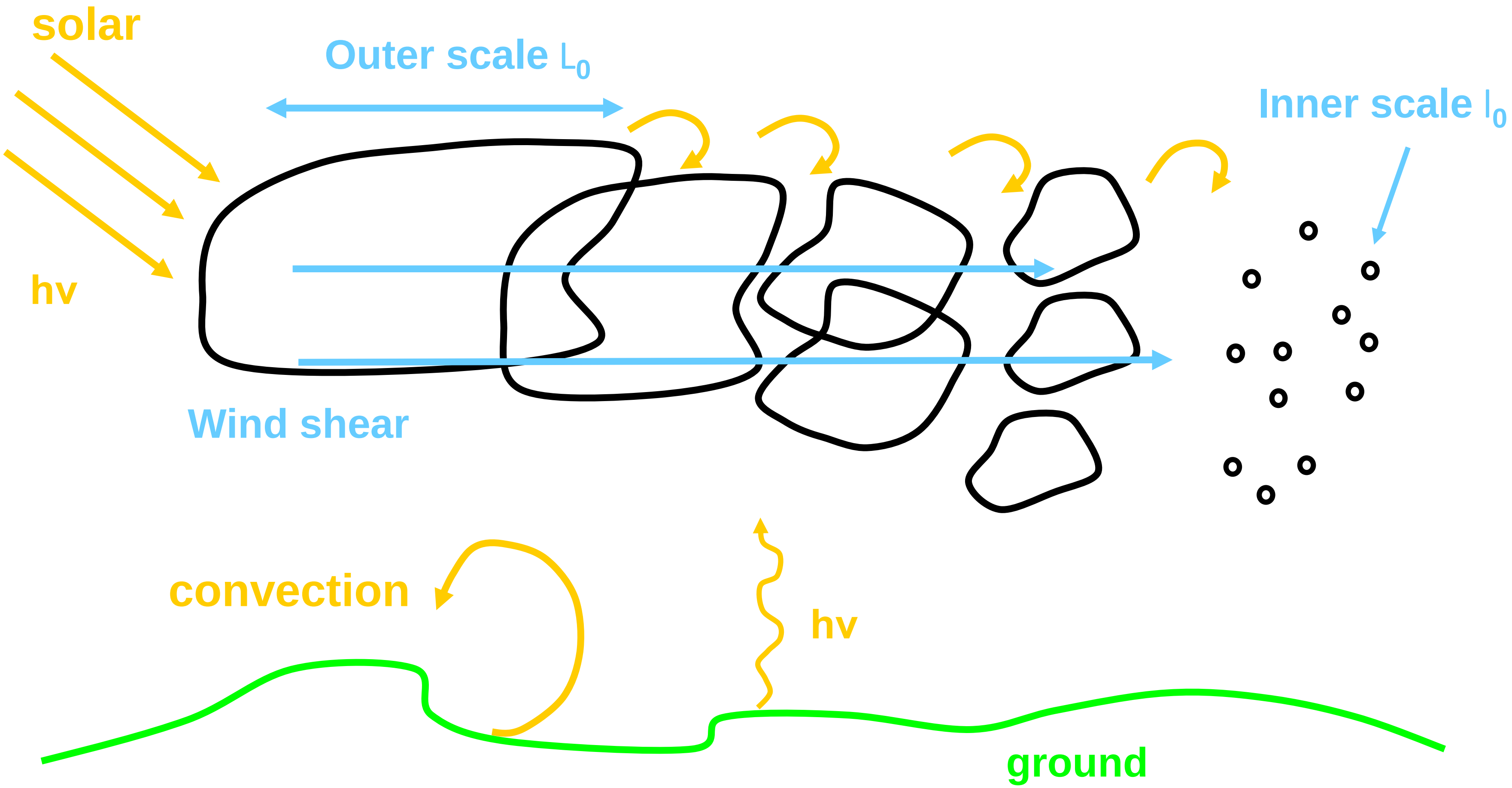
NGC 7469

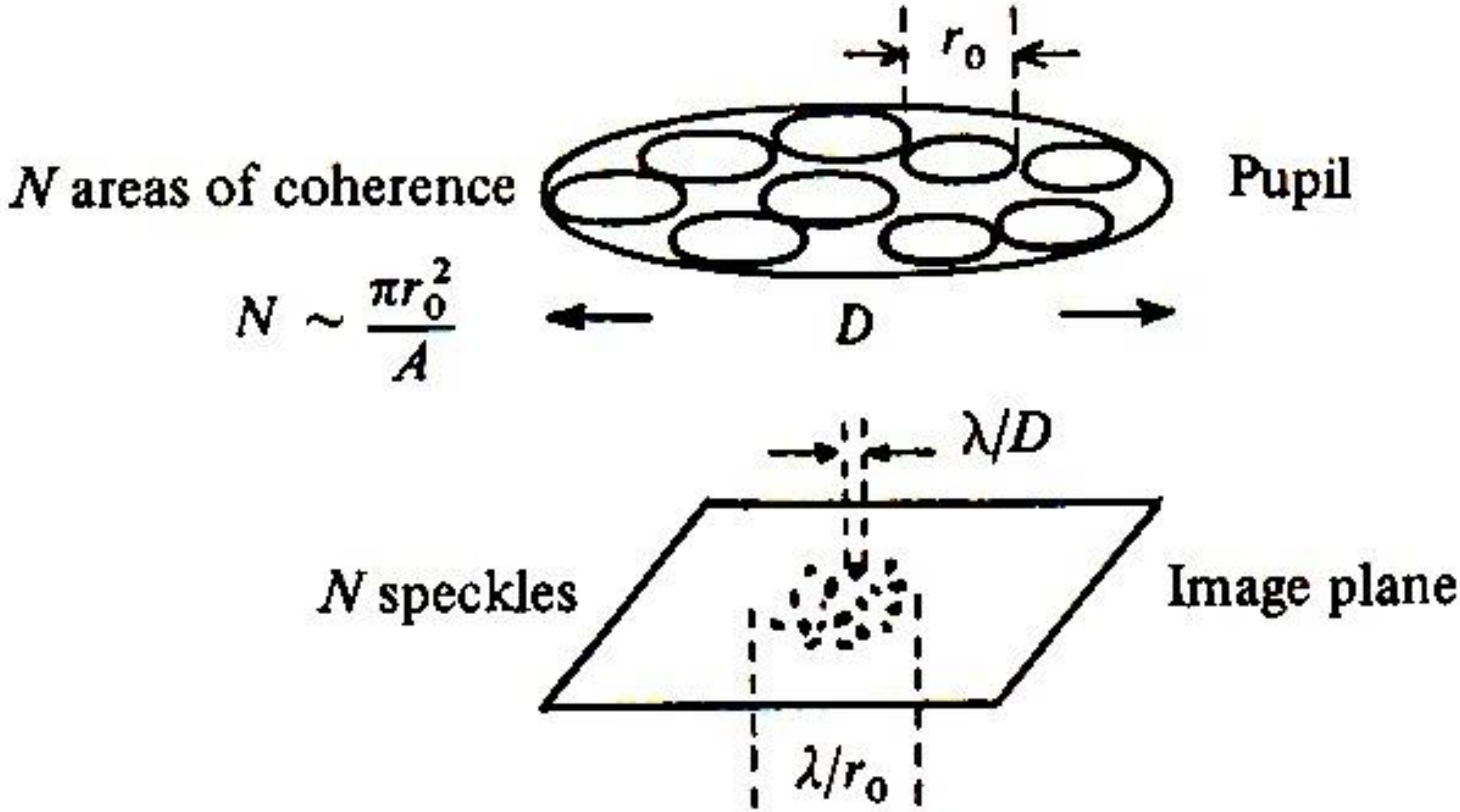


cfao.ucolick.org/ao/why.php

Lecture 8

Atmospheric Turbulence: Origin




r_0
N areas of coherence
Pupil
$N \sim \frac{\pi r_0^2}{A}$
D
λ/D
N speckles
Image plane
λ/r_0

Lecture 8

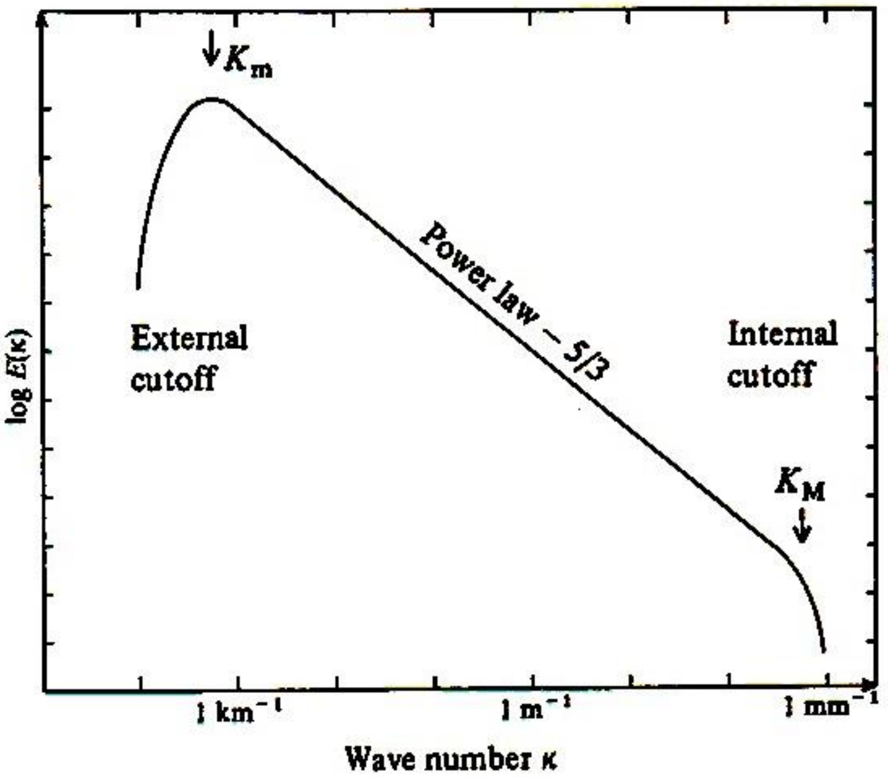
Kolmogorov Turbulence

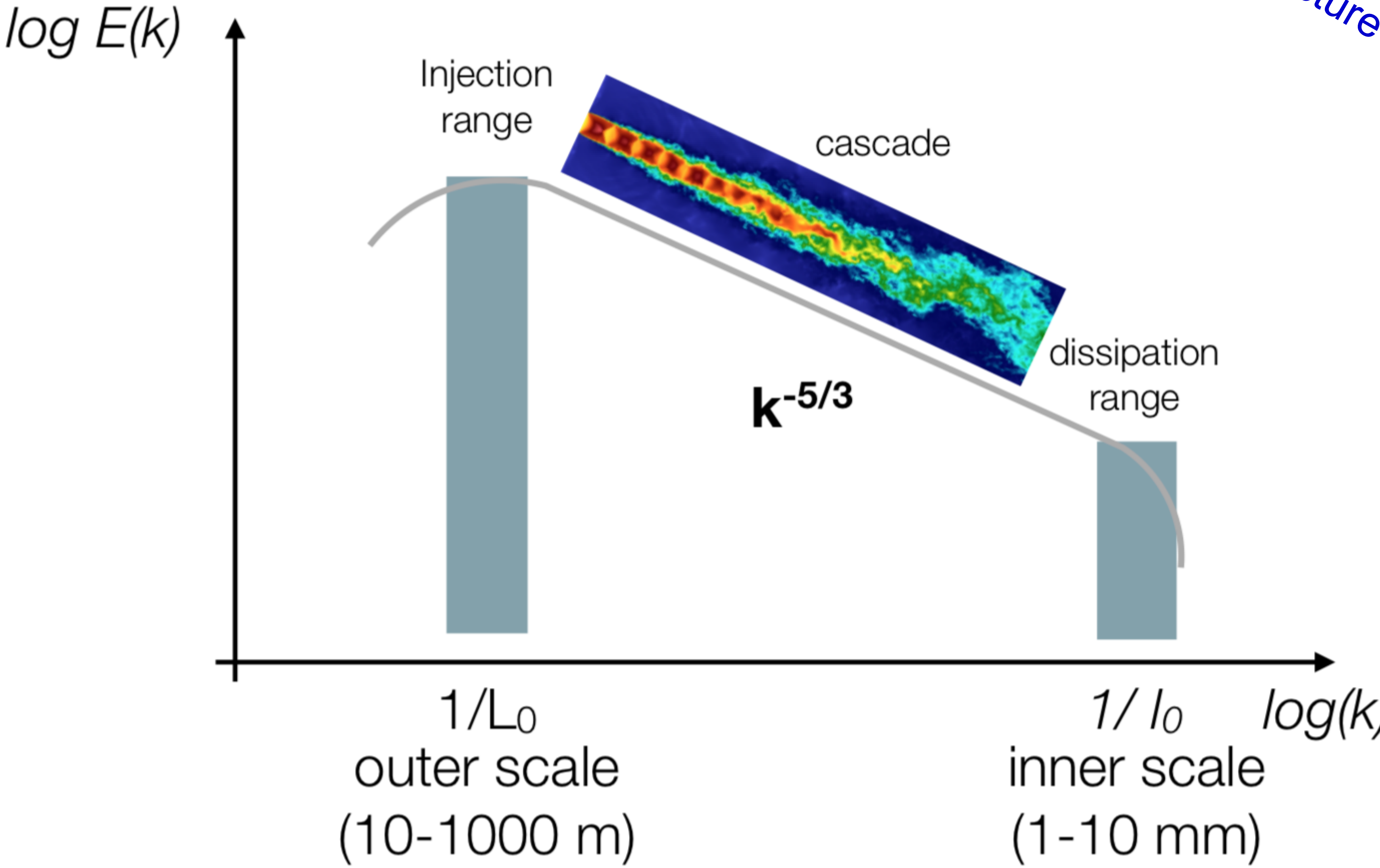
- kinetic energy of large scale (~*L*) movements transferred to smaller and smaller scales, down to minimum scale length l_0, where energy is dissipated by viscous friction
- local velocity field decomposed into spatial harmonics of wave vector κ (Fourier domain)
- $1/\kappa$ is considered length scale
- mean spectrum of kinetic energy (Kolmogorov spectrum)

$$E(\kappa) \propto \kappa^{-5/3}$$

- l_0 = inner scale, L_0 = outer scale

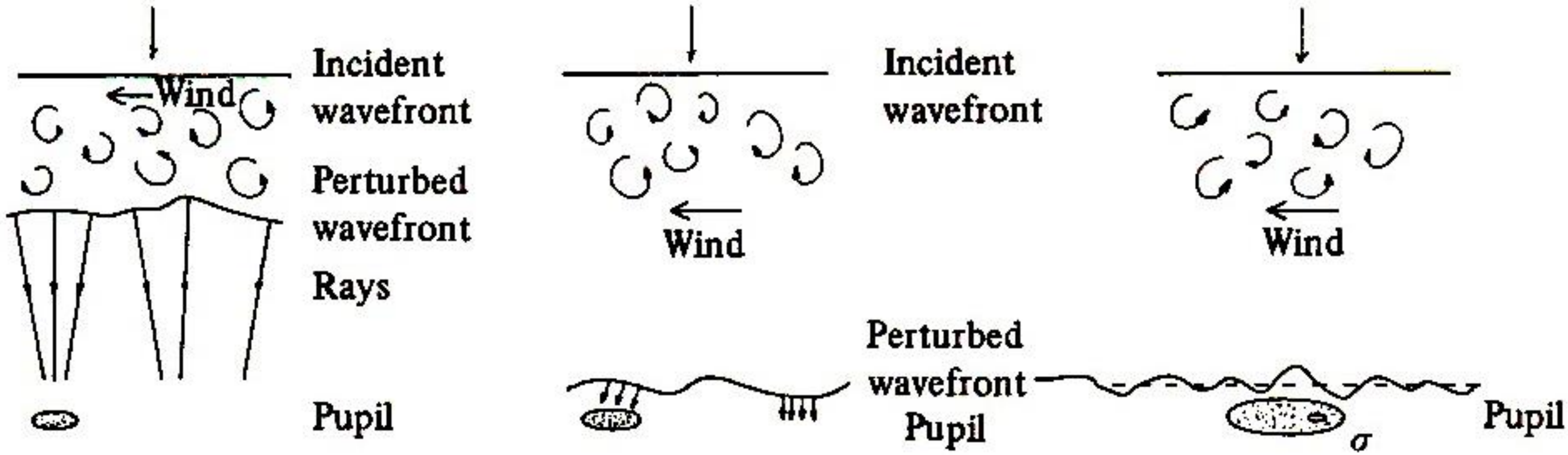
$$L_0^{-1} < \kappa < l_0^{-1}$$





http://www.astro.caltech.edu/~dmawet/teaching/ay122a_atmosphericphysics-3.pdf

Aspects of Image Degradation

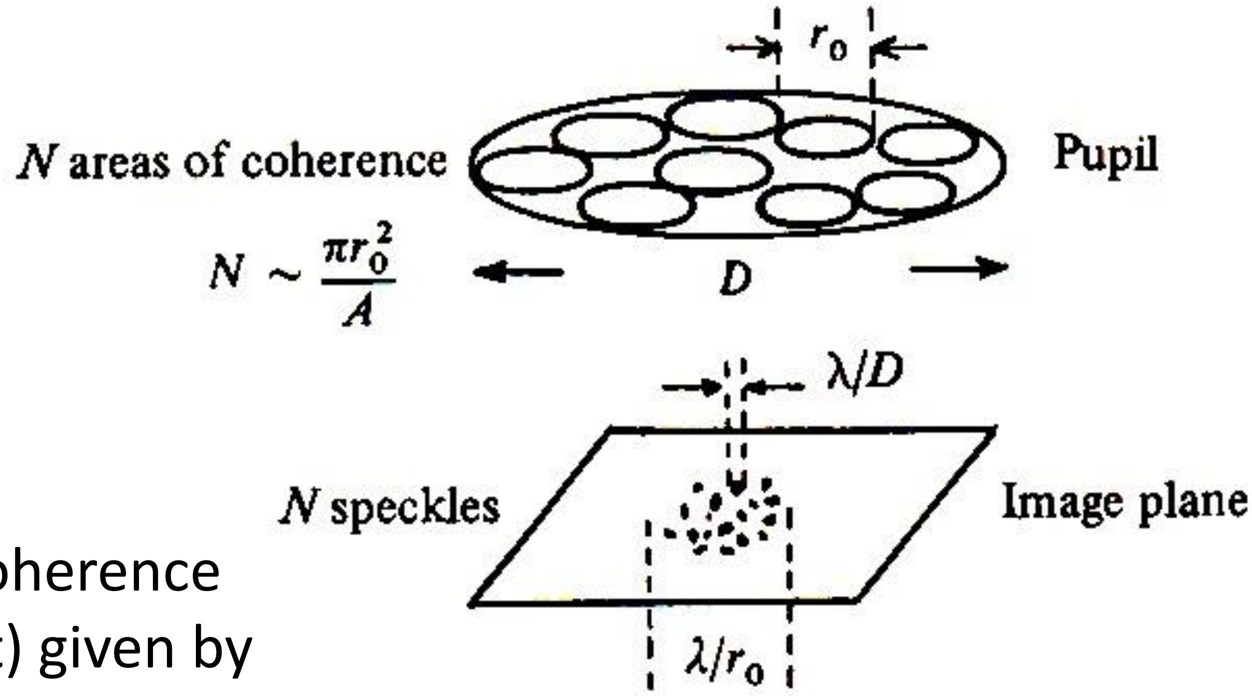


Scintillation
energy received by pupil varies in time (stars flicker)

Image Motion
average slope of wavefront at pupil varies ("tip-tilt", stars move around)

Image Blurring
wavefront is not flat ("seeing")

Fried Parameter r_0



- radius of spatial coherence area (of wavefront) given by Fried parameter r_0 :

$$r_0(\lambda) = 0.185\,\lambda^{6/5}\left[\int_0^{\infty} C_n^2(z)\,dz\right]^{-3/5}$$

- With C_n^2 the atmospheric turbulent strength as function of altitude z

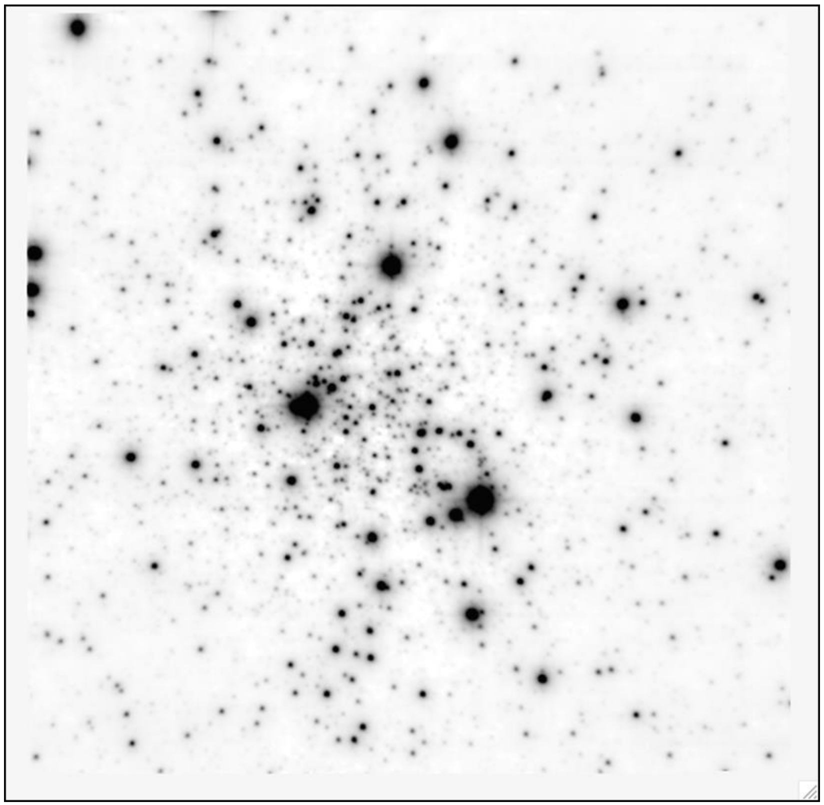
Lecture 8

Seeing: τ_0, θ_0

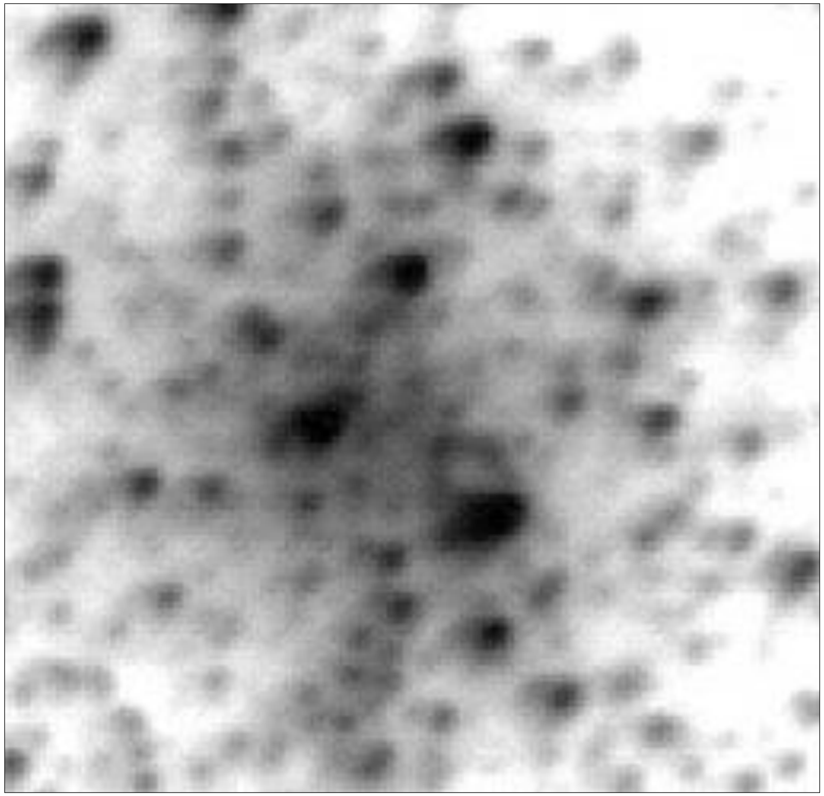
- Seeing $\Delta\theta$ at good sites at 0.5μm: 10 - 30 cm $\Delta\theta = \frac{\lambda}{r_0} \sim \lambda^{-1/5}$
- atmospheric coherence time: maximum time delay for RMS wavefront error to be < 1 rad ($\bar{v}$ is mean propagation velocity/wind) $t_0 = 0.314 \frac{r_0}{\bar{v}}$
- Isoplanatic angle θ_0: angle over which RMS wavefront error is smaller than 1 rad, with $\bar{h}$ the average height of the turbulence $\theta_0 = 0.314 \cos\zeta \frac{r_0}{\bar{h}}$

Resolution & Sensitivity Improvement

1. Angular resolution: $\theta = \frac{\lambda}{r_0} \rightarrow \theta = \frac{\lambda}{D} \quad \Rightarrow \text{gain} = \frac{D}{r_0}$
2. Point source sensitivity: $S/N \sim \mathrm{D}^2 \quad \Rightarrow \text{gain in } t_{\text{int}} \sim \frac{1}{D^4}$



PHARO Ks image using laser guide stars
500s integ., 40" FOV, 150 mas FWHM

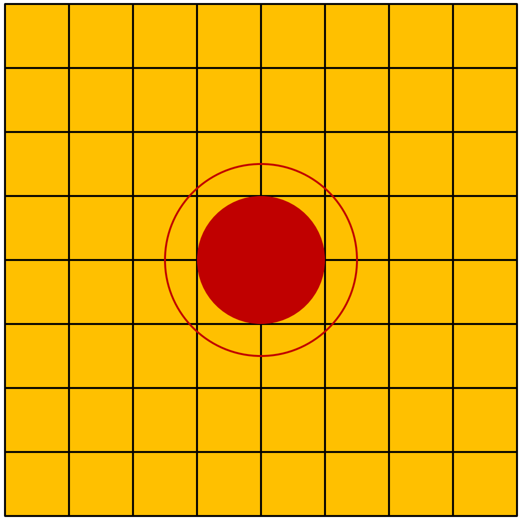


WIRO H image
Kobulnicky et al. 2005, AJ 129, 239-250

Lecture 5

Case 3: Diffraction-limited "Point Source"

Signal* = S; Background* = B; Noise = N; Telescope diameter = D



"$S/N = (S/N)_{\text{light bucket}} \cdot (S/N)_{\text{pixel scale}}$"

(i) Effect of telescope aperture: → $S/N \sim D$

- Signal $S \sim D^2$
- Background $B \sim D^2$ → $N \sim D$

(ii) Effect of pixel FOV (if Nyquist sampled to θ_{diff}): → $S/N \sim D$

- $S \sim$ const (pixel samples PSF = all source flux)
- $B \sim D^{-2}$ → $N \sim D^{-1}$

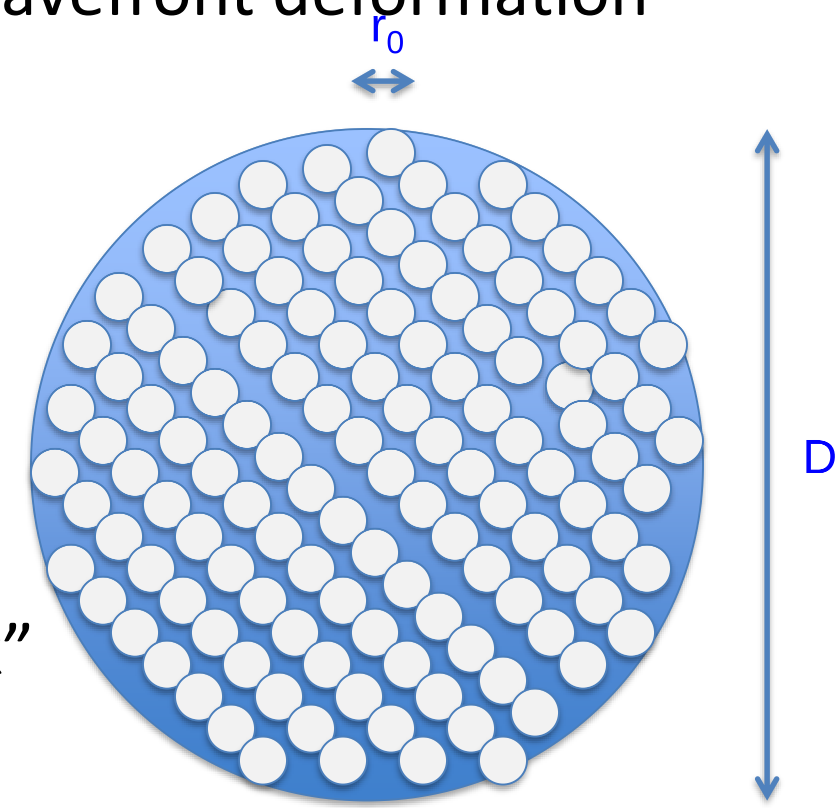
(i) and (ii) combined $S/N \sim D^2$ → $t_{int} \sim D^{-4}$

→ *huge gain: 1hr ELT = 3 months VLT*

*per pixel

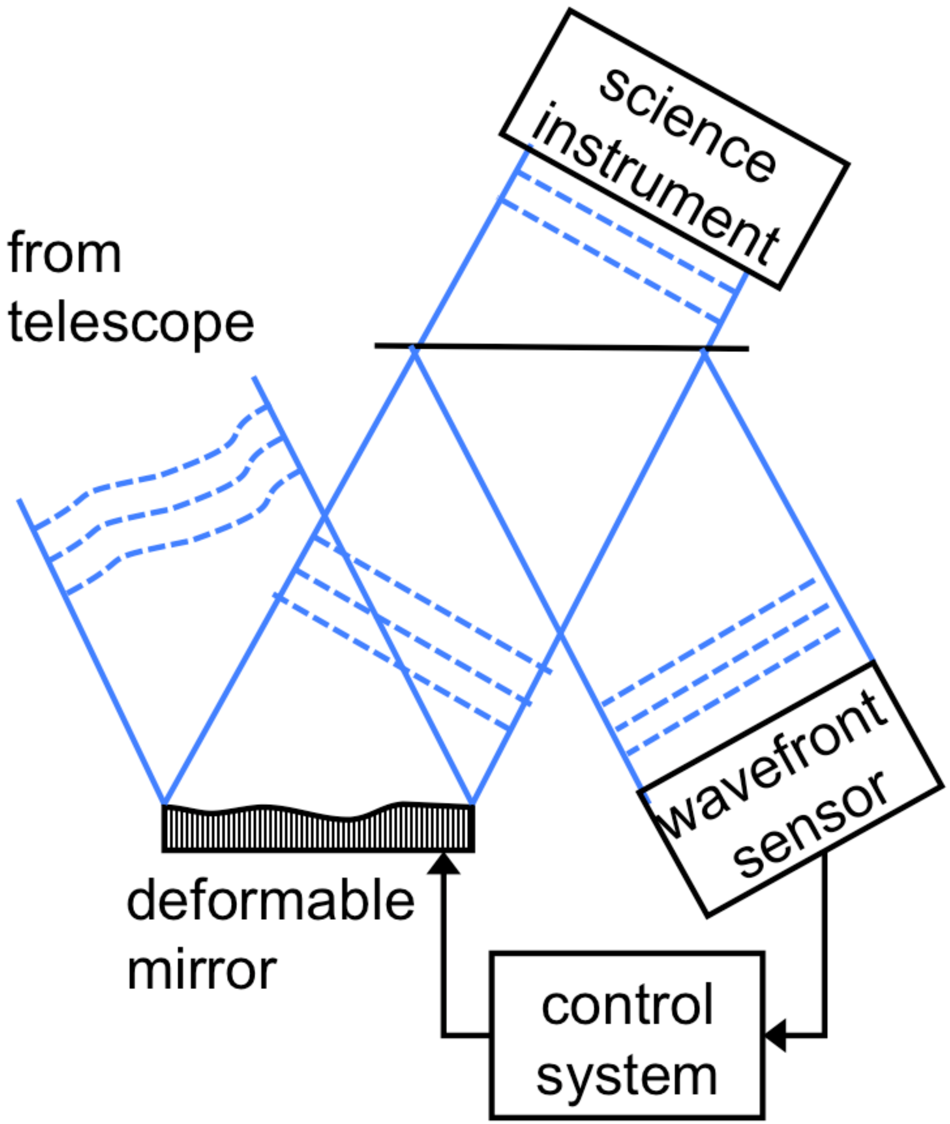
Adaptive Optics Principle

- Maximum scale of tolerated wavefront deformation is r_0 → subdivide telescope into apertures with diameter r_0
- Measure wavefront deformation
- Correct wavefront deformation by "bending back" patches of size r_0



- Number of subapertures is $(D/r_0)^2$ at observing wavelength → requires hundreds to thousands of actuators for large telescopes

Adaptive Optics Scheme



Wavefront Description: Zernike Polynomials

They are a sequence of polynomials $Z_n^m(\rho,\phi)$ that are orthogonal on the unit disk: $\sum a_{m,n} Z_n^m(\rho,\phi)$

There are even and odd Zernike polynomials. The even ones are defined as

$$Z_n^m(\rho,\varphi) = R_n^m(\rho)\,\cos(m\,\varphi)$$

and the odd ones as

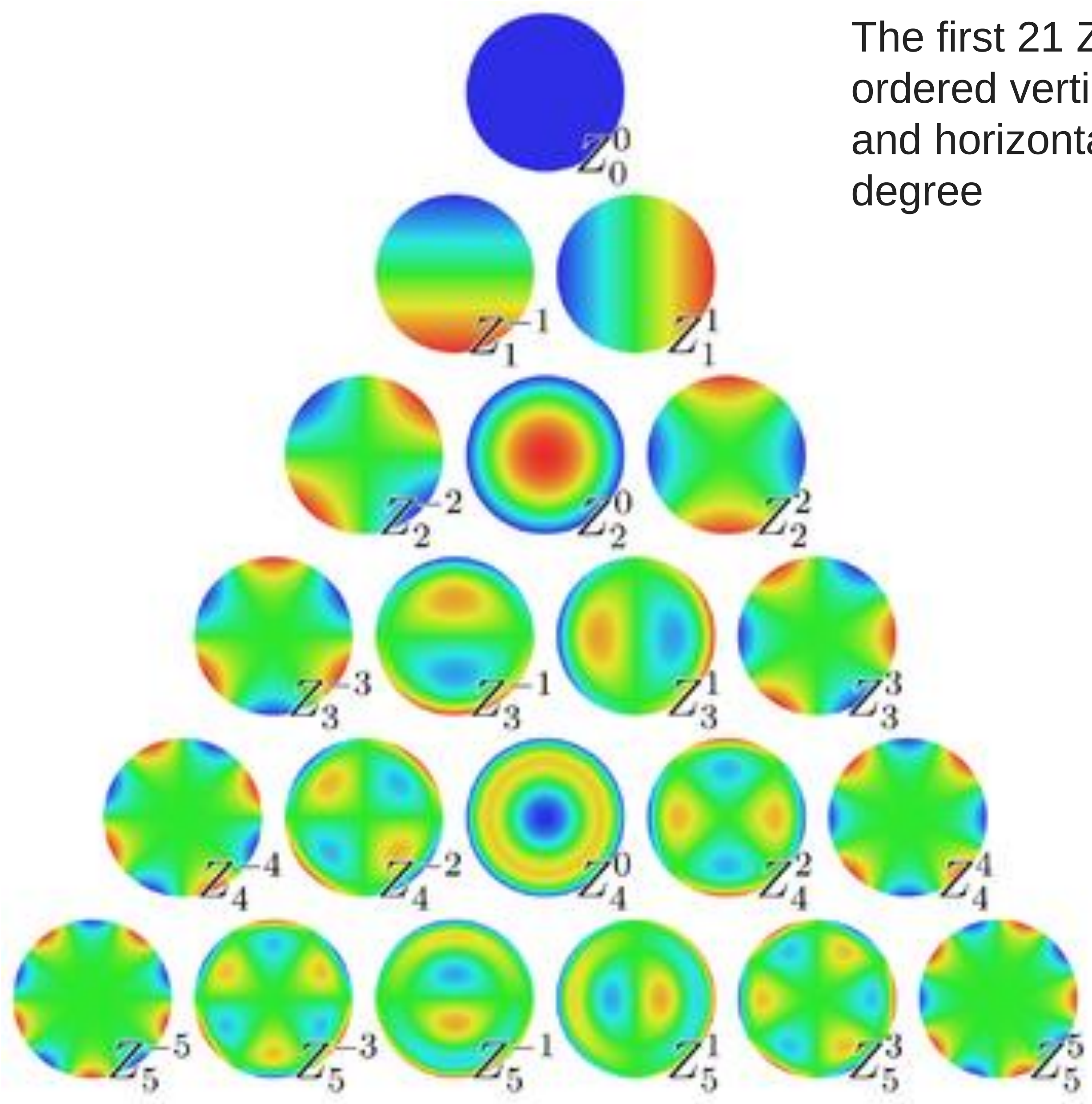
$$Z_n^{-m}(\rho,\varphi) = R_n^m(\rho)\,\sin(m\,\varphi),$$

where m and n are nonnegative integers with $n \geq m$, ϕ is the azimuthal angle, ρ is the radial distance $0 \leq \rho \leq 1$, and $R^m{}_n$ are the radial polynomials defined below. Zernike polynomials have the property of being limited to a range of −1 to +1, i.e. $|Z_n^m(\rho,\varphi)| \leq 1$. The radial polynomials $R^m{}_n$ are defined as

$$R_n^m(\rho) = \sum_{k=0}^{\frac{n-m}{2}} \frac{(-1)^k\,(n-k)!}{k!\,\left(\frac{n+m}{2}-k\right)!\,\left(\frac{n-m}{2}-k\right)!}\;\rho^{n-2\,k}$$

for $n - m$ even, and are identically 0 for $n - m$ odd.

https://en.wikipedia.org/wiki/Zernike_polynomials



The first 21 Zernike polynomials, ordered vertically by radial degree and horizontally by azimuthal degree

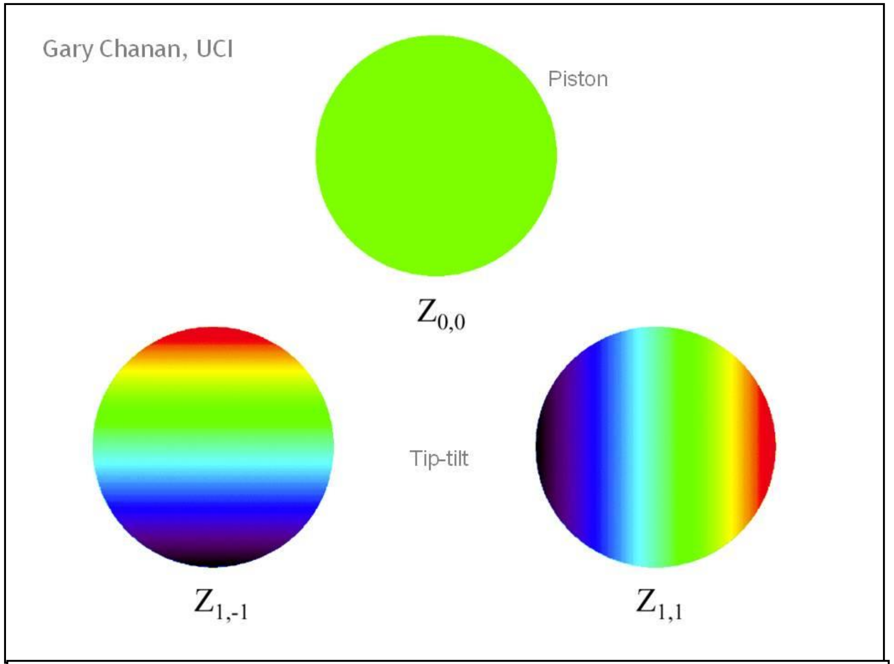
$$Z_{0,0} = 1$$ piston

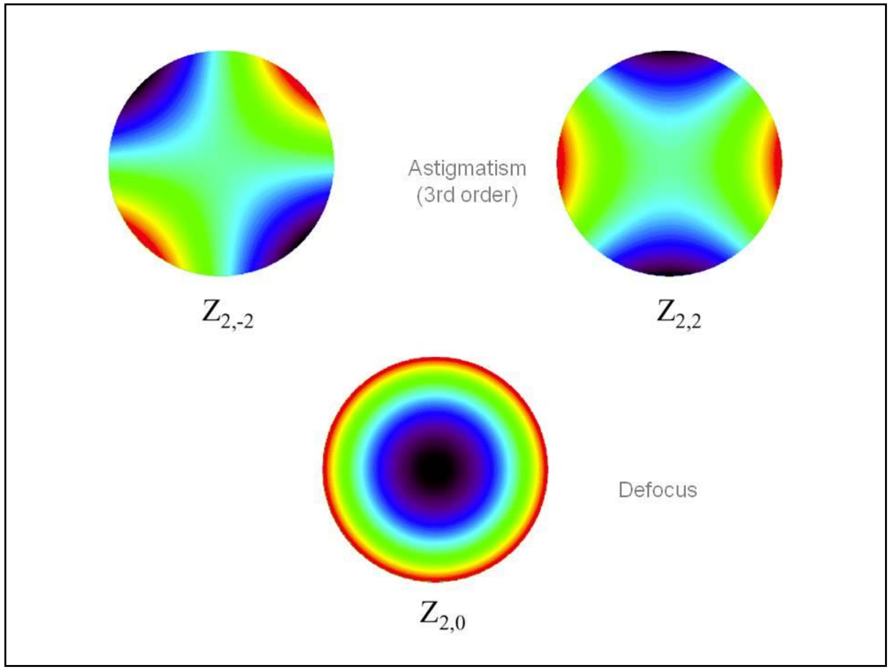
$$Z_{1,-1} = 2\, r \sin\theta$$
$$Z_{1,1} = 2\, r \cos\theta$$
tip/tilt

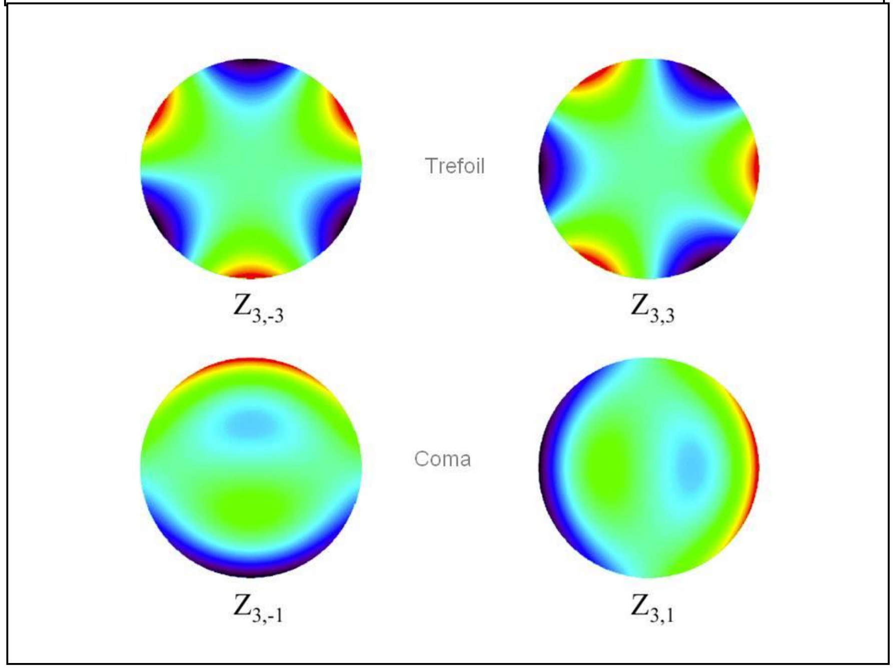
$$Z_{2,-2} = \sqrt{6}\, r^2 \sin 2\theta$$ astigmatism

$$Z_{2,0} = \sqrt{3}\, (2r^2 - 1)$$ focus

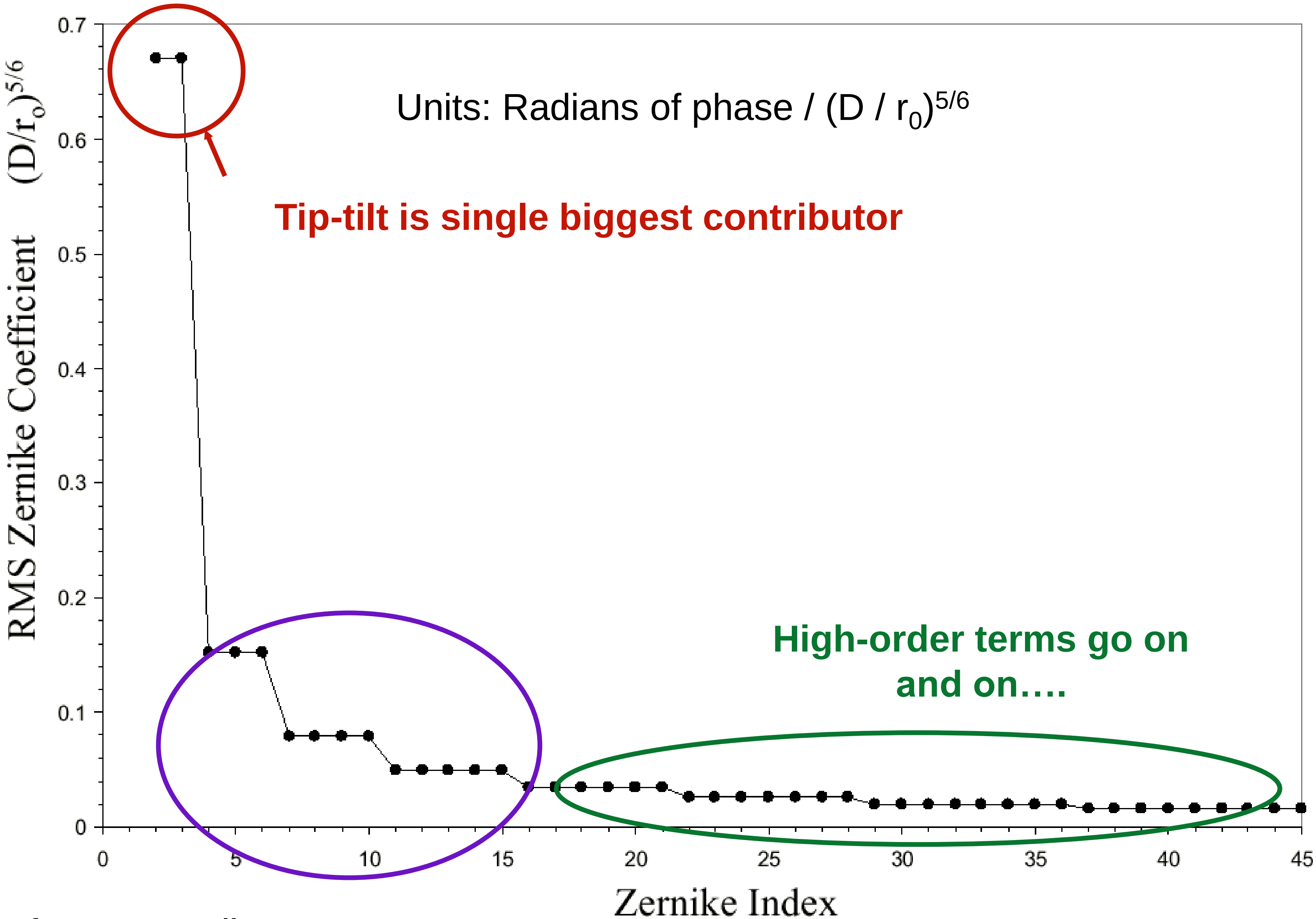
$$Z_{2,2} = \sqrt{6}\, r^2 \cos 2\theta$$ astigmatism







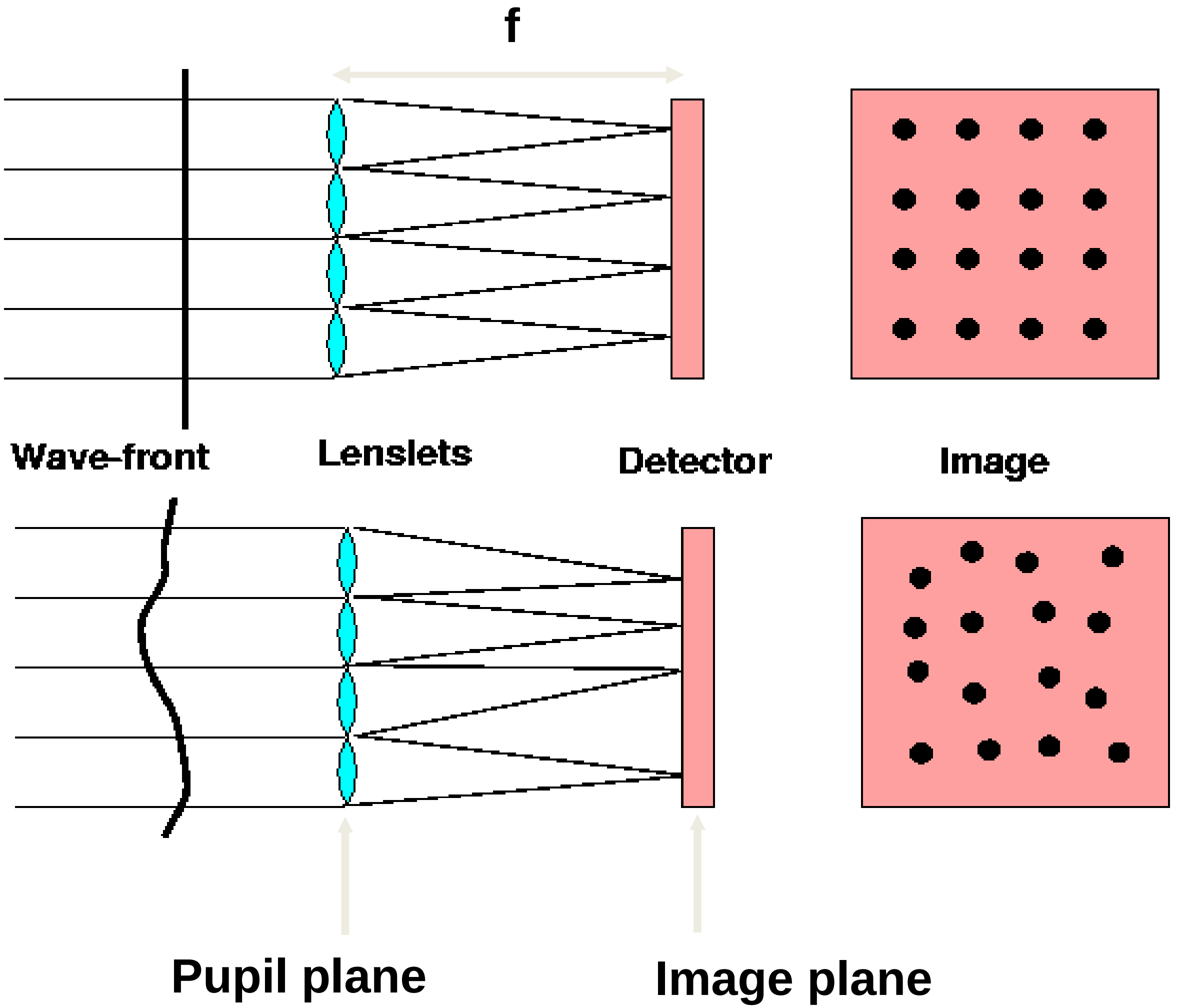
Zernike Amplitudes for Kolmogorov Turbulence

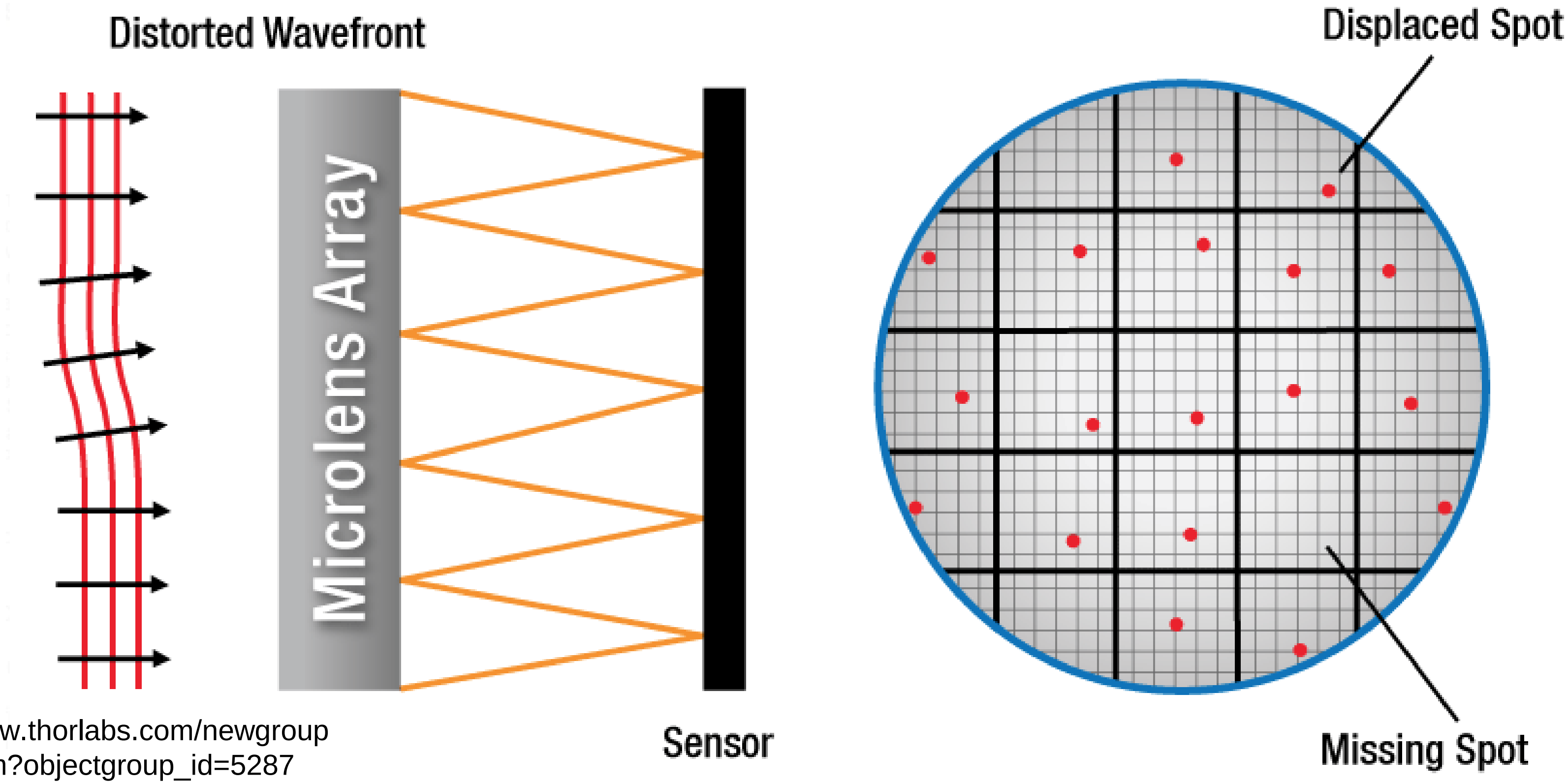


Reference: Noll

Wavefront Sensors – Shack Hartmann

Most common principle is the Shack Hartmann wavefront sensor measuring sub-aperture tilts:



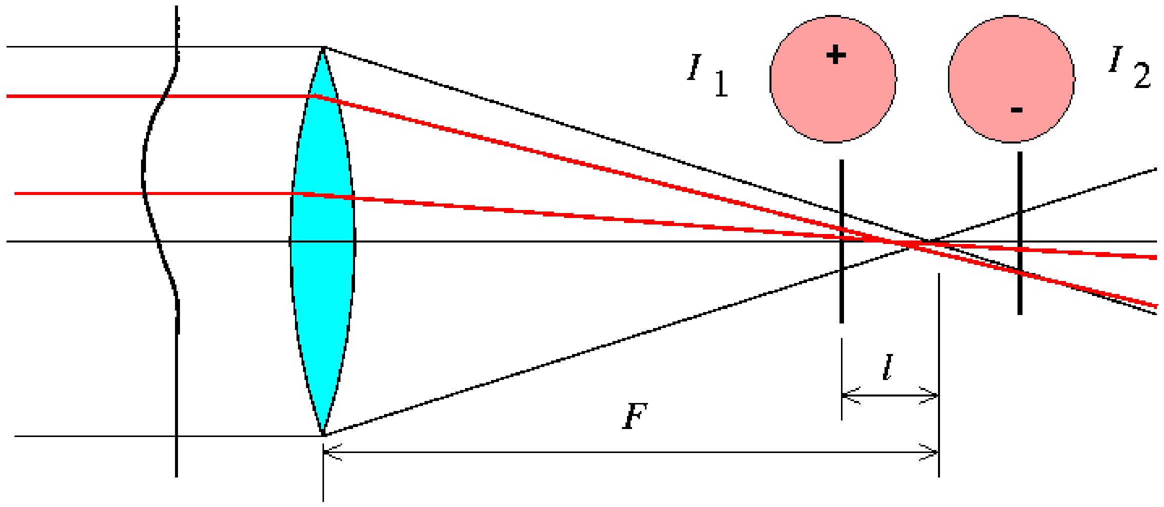


https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=5287

A **Shack–Hartmann wavefront sensor** (**SHWFS**) is an optical instrument commonly used in adaptive optics systems. It consists of an array of lenses (called lenslets) of the same focal length. Each is focused onto a photon sensor (typically a CCD). The local tilt of the wavefront across each lens can then be calculated from the position of the focal spot on the sensor. Any phase aberration can be approximated by a set of discrete tilts. By sampling an array of lenslets, all of these tilts can be measured and the whole wavefront approximated.

https://en.wikipedia.org/wiki/Shack–Hartmann_wavefront_sensor

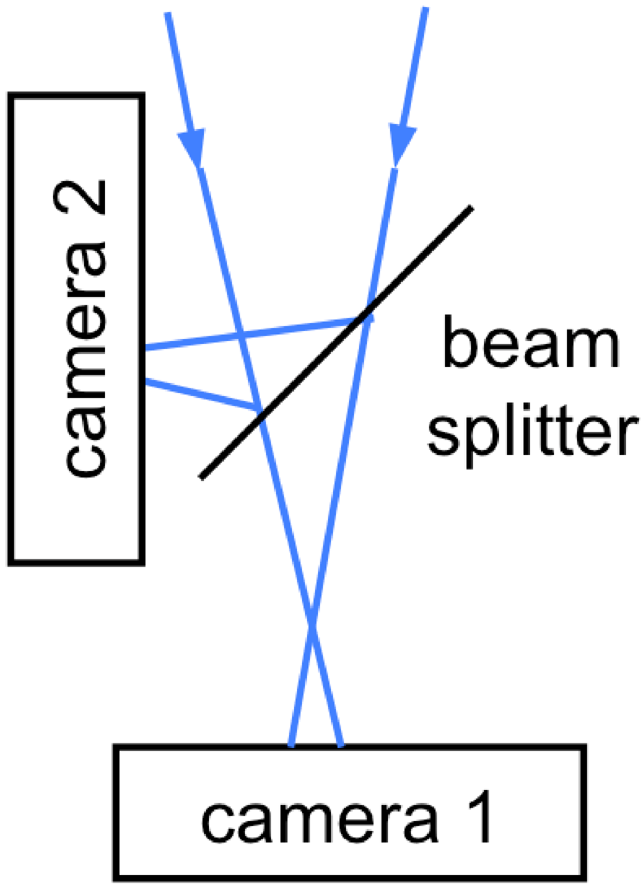
Curvature Wavefront Sensor



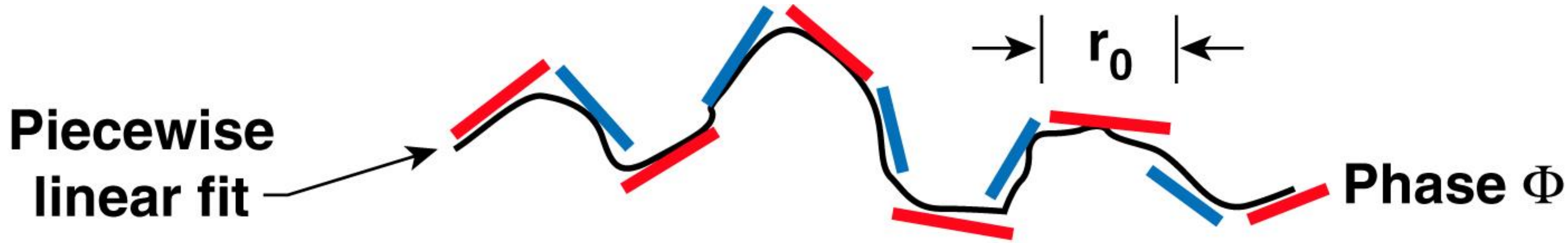
http://www.ctio.noao.edu/~atokovin/tutorial/part3/wfs.html

- two images, one on each side of the focus
- difference of images is proportional to wavefront <u>curvature</u>

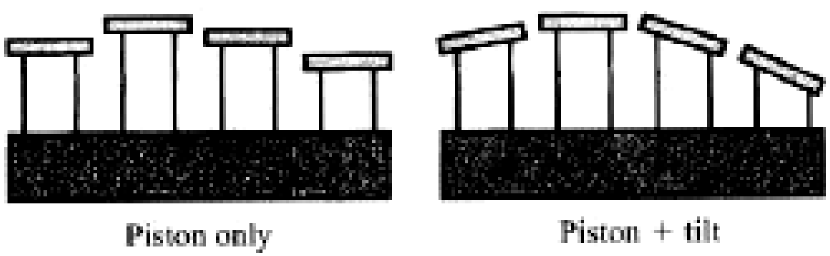
An implementation
Curvature Wavefront Sensor

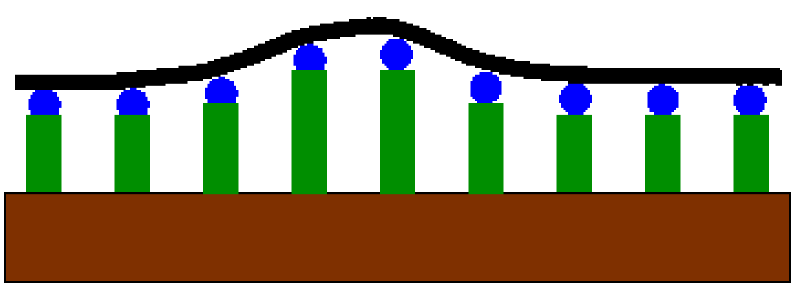


Deformable Mirrors (DM)

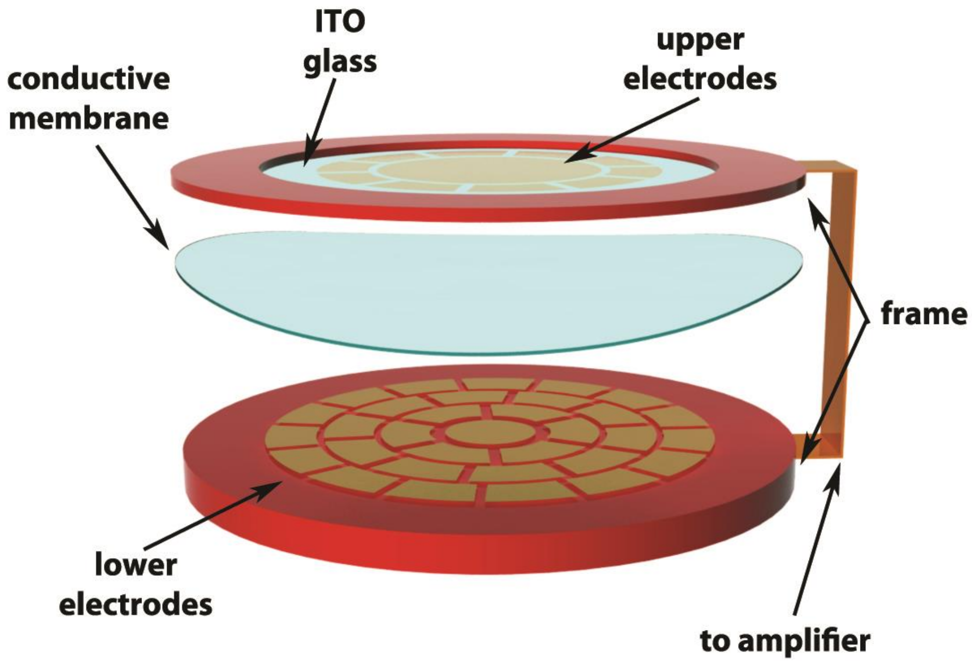


- Fit mirror surface to wavefront
- r_0 sets number of degrees of freedom
- segmented mirrors rarely used anymore
- mostly continuous face-sheet mirrors

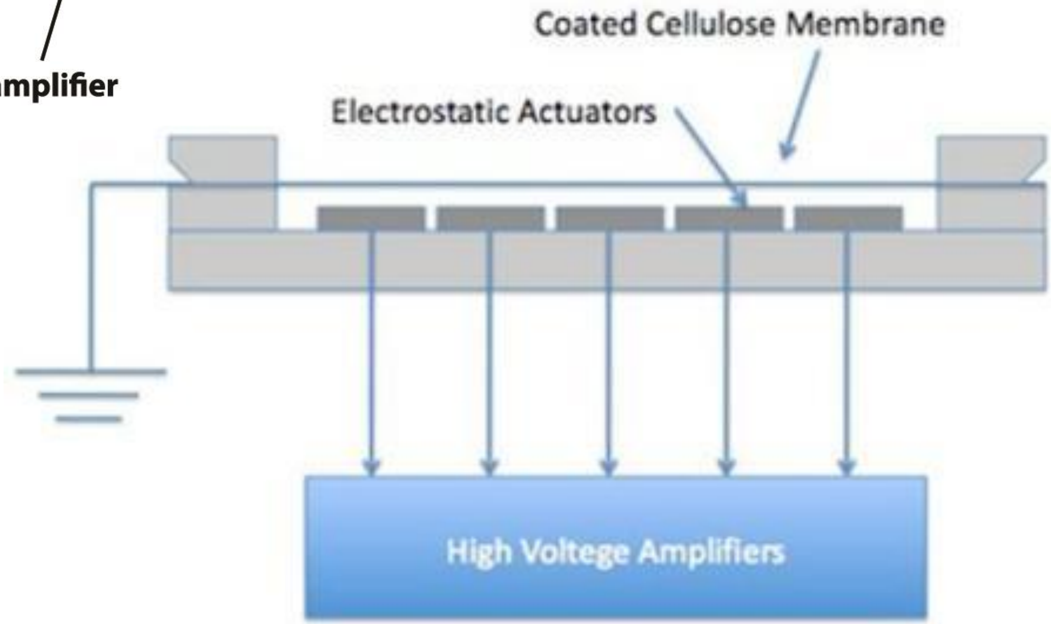




Membrane Deformable Mirror



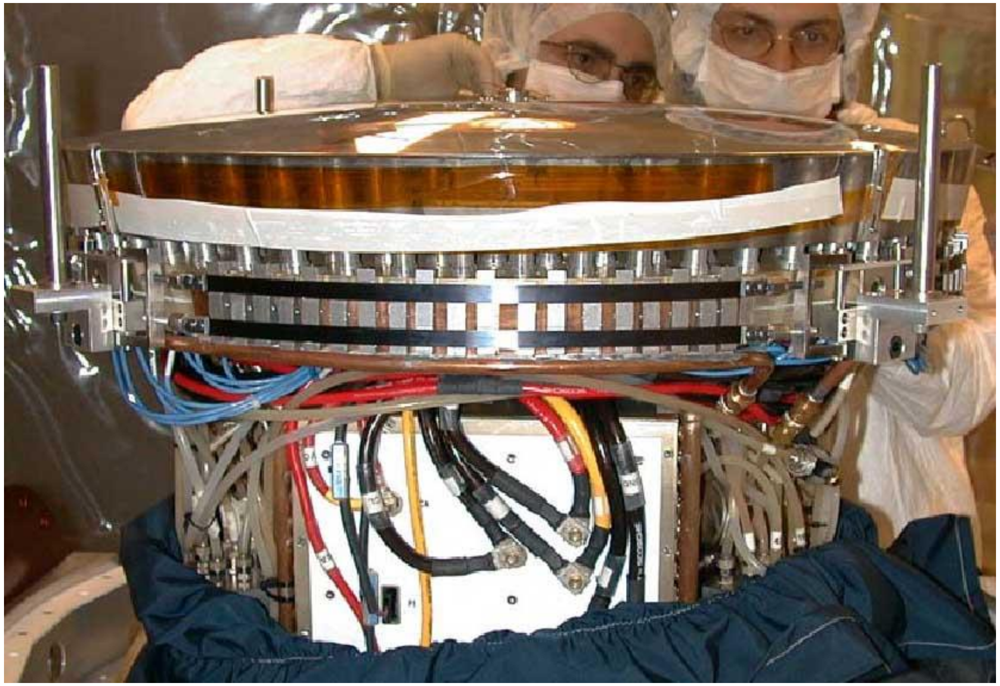
ıttps://optica.weblog.tudelft.nl/2012/
.2/14/new-publication-on-method-to-
:ontrol-deformable-mirrors/

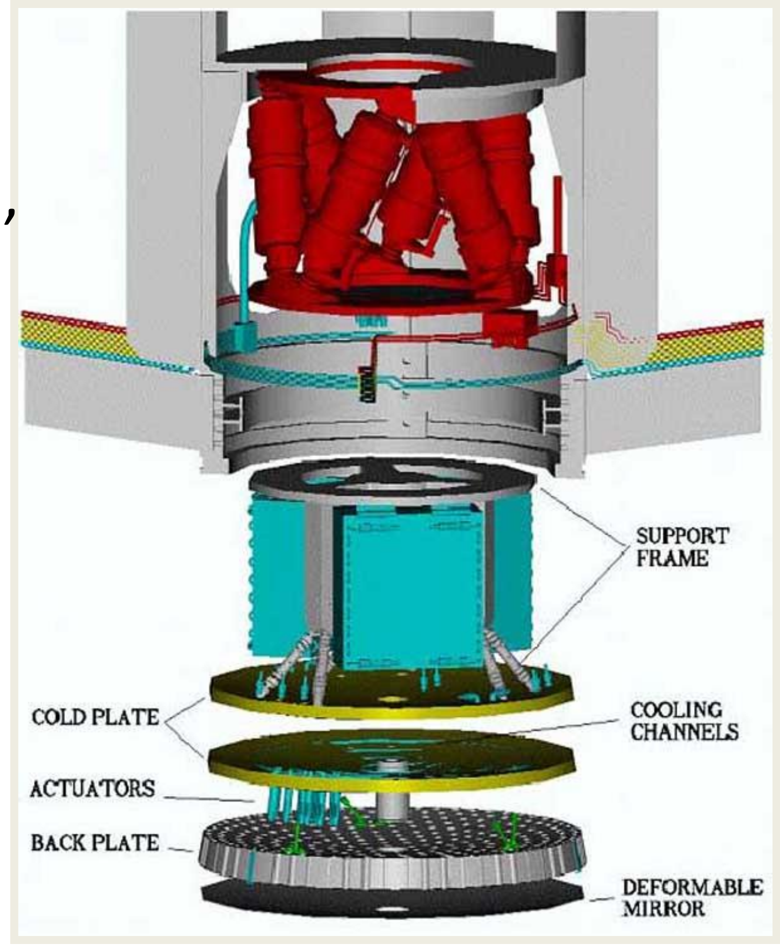


https://www.azooptics.com/Article.aspx?ArticleID=353

Adaptive Secondary Mirrors

- DM part of telescope → adaptive secondary mirrors
- no additional optics → lower emission, higher throughput
- more difficult to build, control, and handle



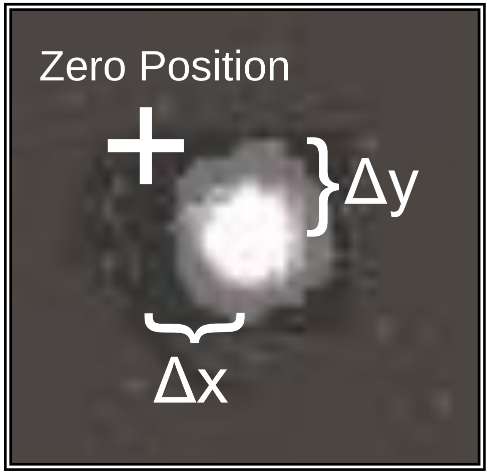


DM for MMT Upgrade

Shack-Hartmann in practice
Wavefront Analysis

- centroid (center of gravity) calculation on each subaperture:

$$\Delta x = \frac{\sum_{i=i_{\min}}^{i_{\max}} \sum_{j=j_{\min}}^{j_{\max}} I(i,j)\cdot i}{\sum_{i=i_{\min}}^{i_{\max}} \sum_{j=j_{\min}}^{j_{\max}} I(i,j)} \qquad \Delta y = \frac{\sum_{i=i_{\min}}^{i_{\max}} \sum_{j=j_{\min}}^{j_{\max}} I(i,j)\cdot j}{\sum_{i=i_{\min}}^{i_{\max}} \sum_{j=j_{\min}}^{j_{\max}} I(i,j)}$$



Influence Matrix

- slope of local wave front *and* Shack-Hartmann star positions are proportional to actuator position
- linear relationship between position actuators a_k and star positions c_n as determined by the x- and y-offsets

$$c_n = \sum_{k=1}^{N} a_k b_{nk}$$

- combine equations for each spot position *n* into matrix equation:

$$C = BA$$

C = star positions

A = control vector determining actuator positions

B = influence matrix describing influence of specific actuator position on star positions

Determining the Control Vector

- Find control vector A to correct for error in wavefront

$$A = B^{-1}C$$

- Overdetermined system
  - More centroid measurements than actuators
  - No exact solution A exists for given set of centroids
  - No exact B^{-1} exists (B is rectangular)
- Approximate B^{-1} in best possible way to minimizes wave front errors

Typical AO Error Terms

- Fitting errors from insufficient approximation of wavefront by deformable mirror due to finite number of actuators (*d*: actuator spacing)

$$s_{fit}^{2} \approx 0.3\left(\frac{d}{r_0}\right)^{5/3}$$

- Temporal errors from time delay between measurement and correction, mostly due to exposure and readout time

$$\sigma_{temp}^{2} \approx \left(\frac{t}{\tau_0}\right)^{5/3}$$

- Measurement errors from wavefront sensor

$$\sigma_{measure}^{2} \sim S/N$$

- Calibration errors from non-common aberrations between wavefront sensing optics and science optics

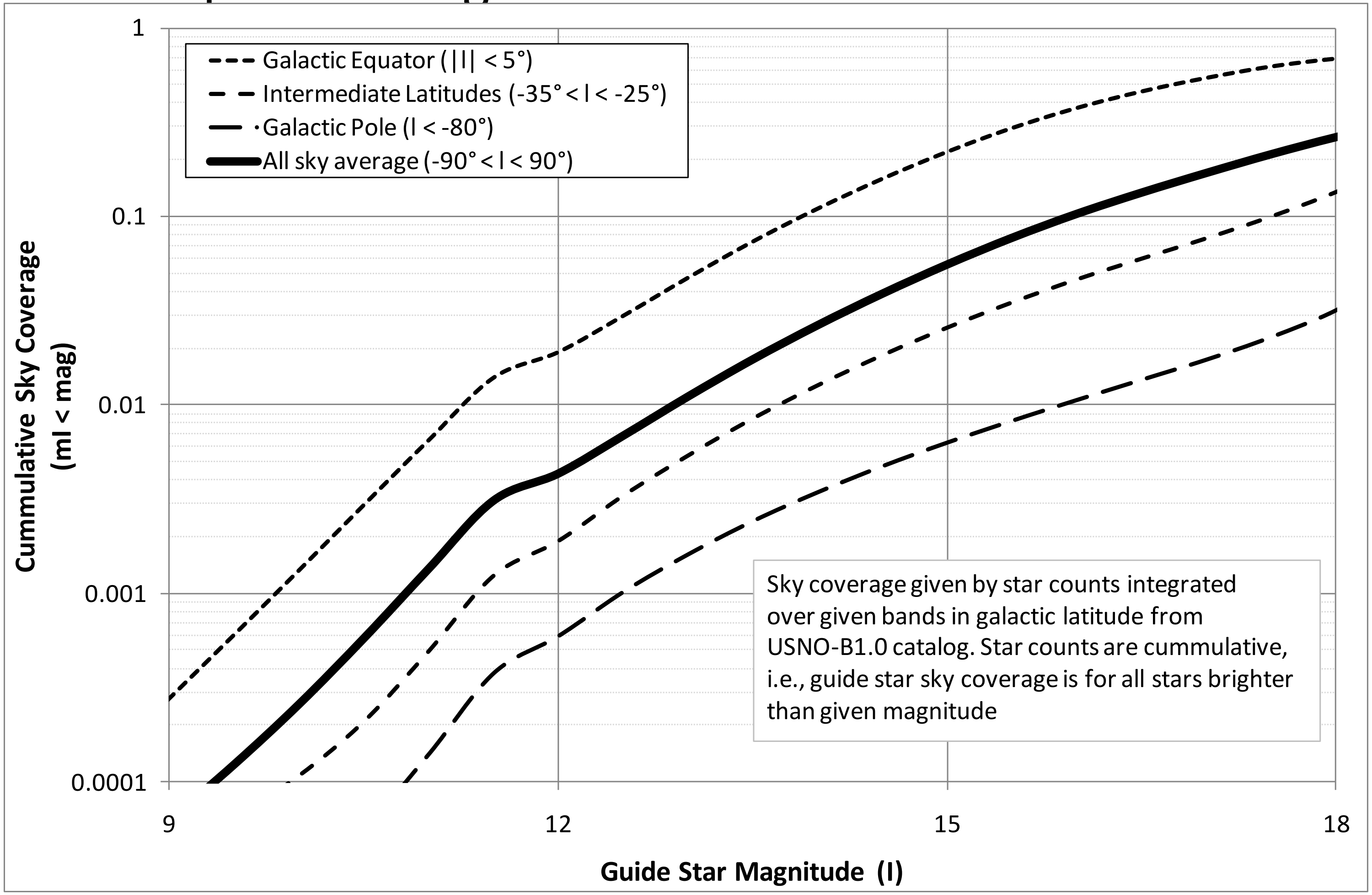
$$s_{calibration}^{2} \sim ???$$

- Angular anisoplanatism from sampling different lines of sight through the atmosphere, mostly limits field of view

$$\sigma_{aniso}^{2} \approx \left(\frac{\theta}{\theta_0}\right)^{5/3}$$

Sky Coverage

To sense the wavefront one needs a bright reference/guide star within the isoplanatic angle.



Cumulative sky coverage, i.e., the chance of finding stars brighter than given magnitude, for a random target as a function of I-band magnitude using the USNO-B1.0 catalogue.

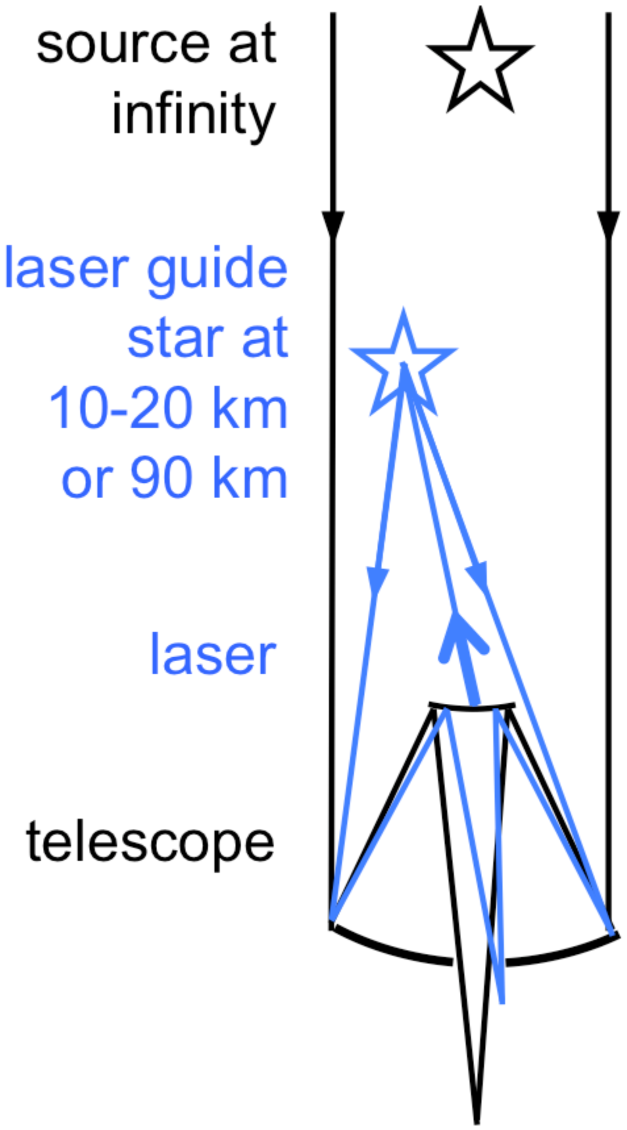
Laser Guide Stars (LGSs)

Solution to the sky coverage problem:

create your own guide star

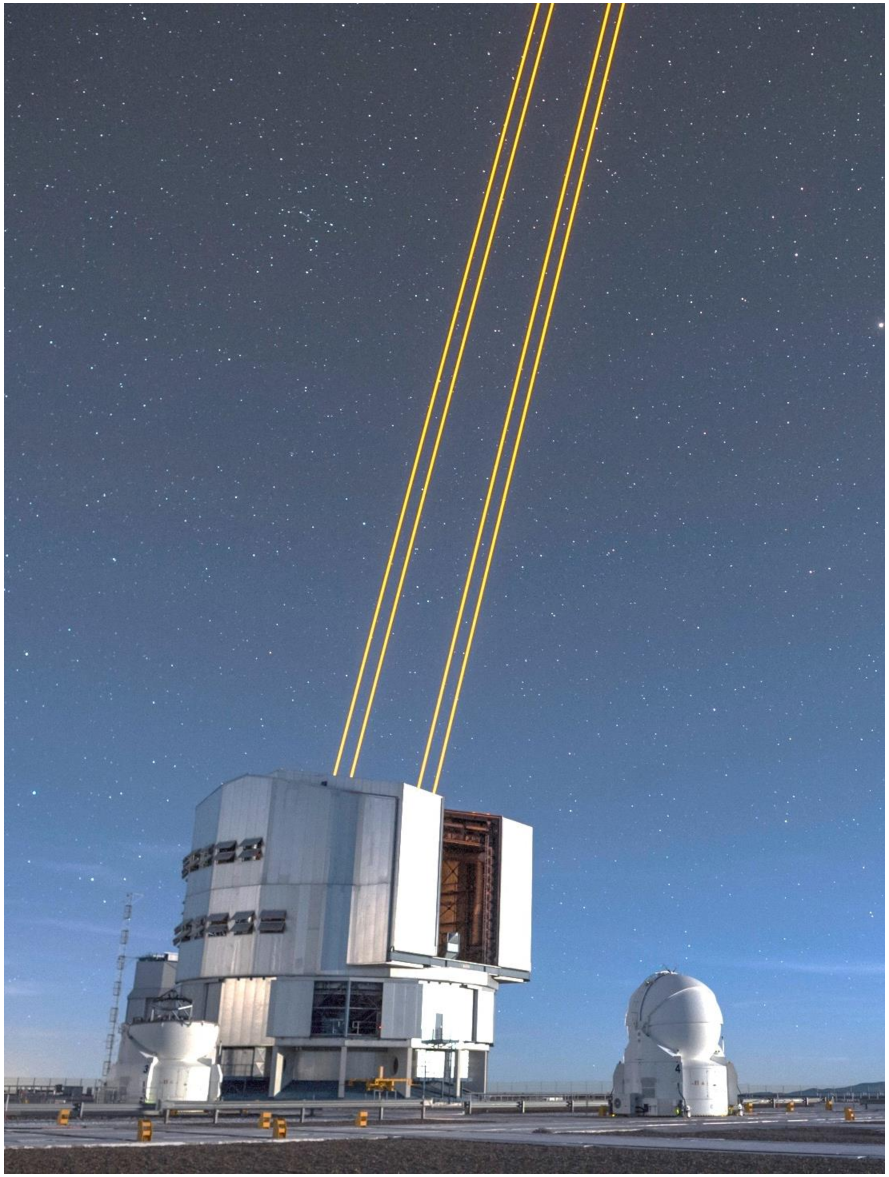
- Sodium LGS – excite atoms in "sodium layer" at altitude of ~ 95 km.
- Rayleigh beacon LGS – scattering from air molecules sends light back into telescope, h ~ 10 km

Since the beam travels twice (up and down) through the atmosphere, tip-tilt cannot be corrected → LGS-AO still needs a natural guide star, but this one can be much fainter (~18mag) as it is only needed for tip-tilt sensing



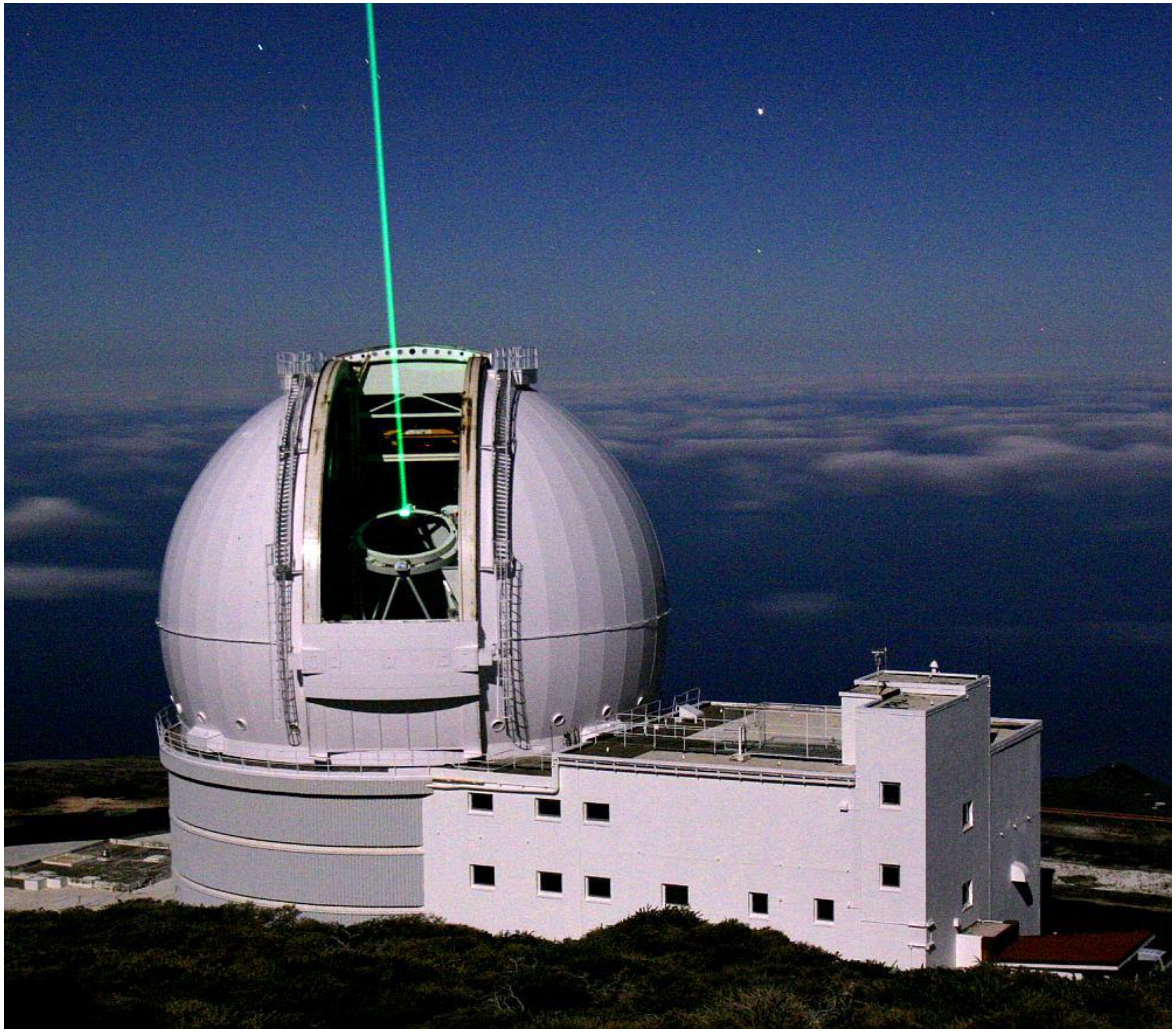
Sodium Beacons

- Layer of neutral sodium atoms in mesosphere (height ~ 95 km, thickness ~10km) from smallest meteorites
- Resonant scattering occurs when incident laser is tuned to D2 line of Na at 589 nm.



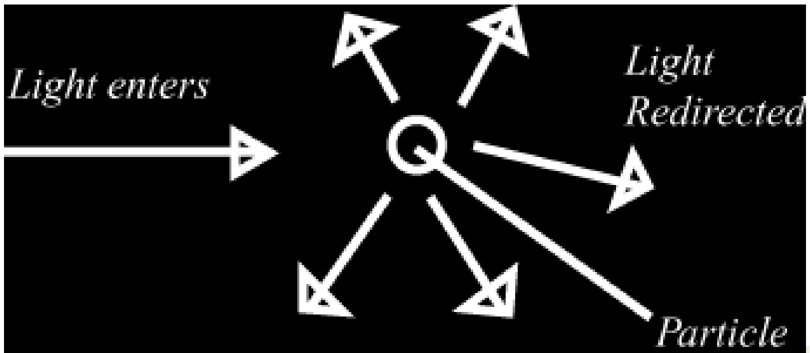
www.eso.org/public/images/eso1613n/

WHT Rayleigh Guide Star



Rayleigh Beacons

Due to interactions of the electromagnetic wave from the laser beam with molecules in the atmosphere.



Advantages:

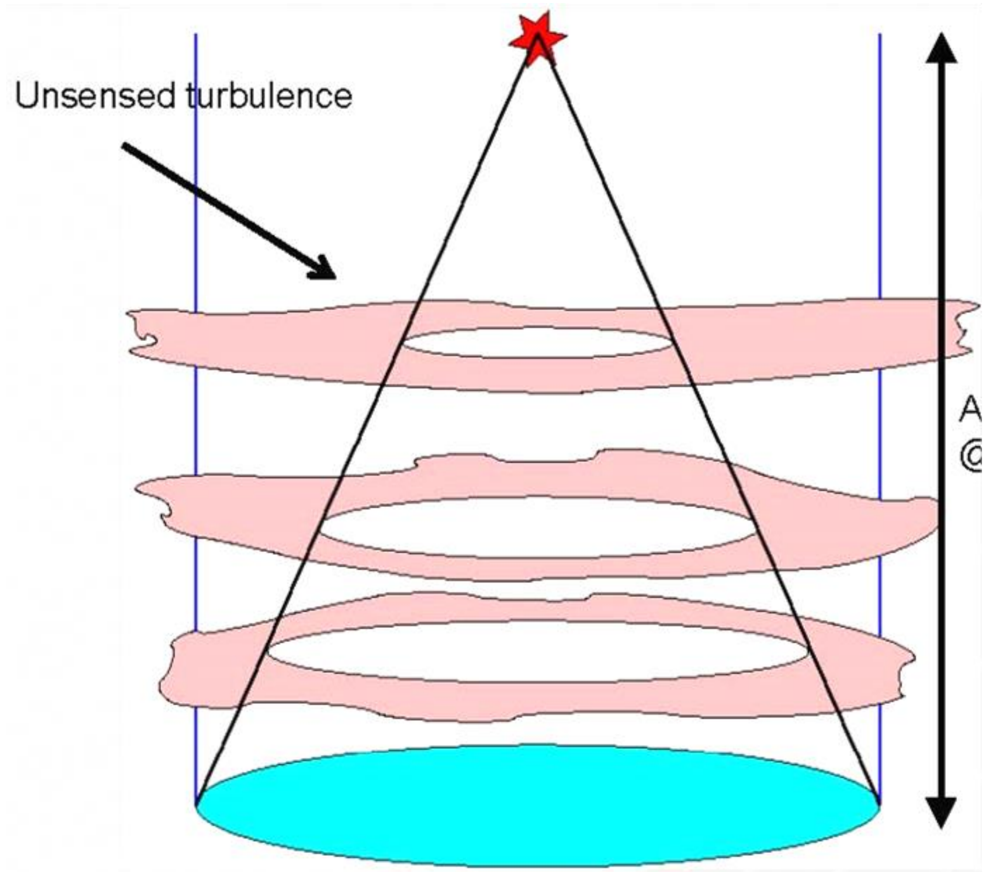
- cheaper and easier to build
- higher power
- independent of Na layer

Disadvantages:

- larger focus anisoplanatism
- laser pulses → timing

Focus Anisoplanatism

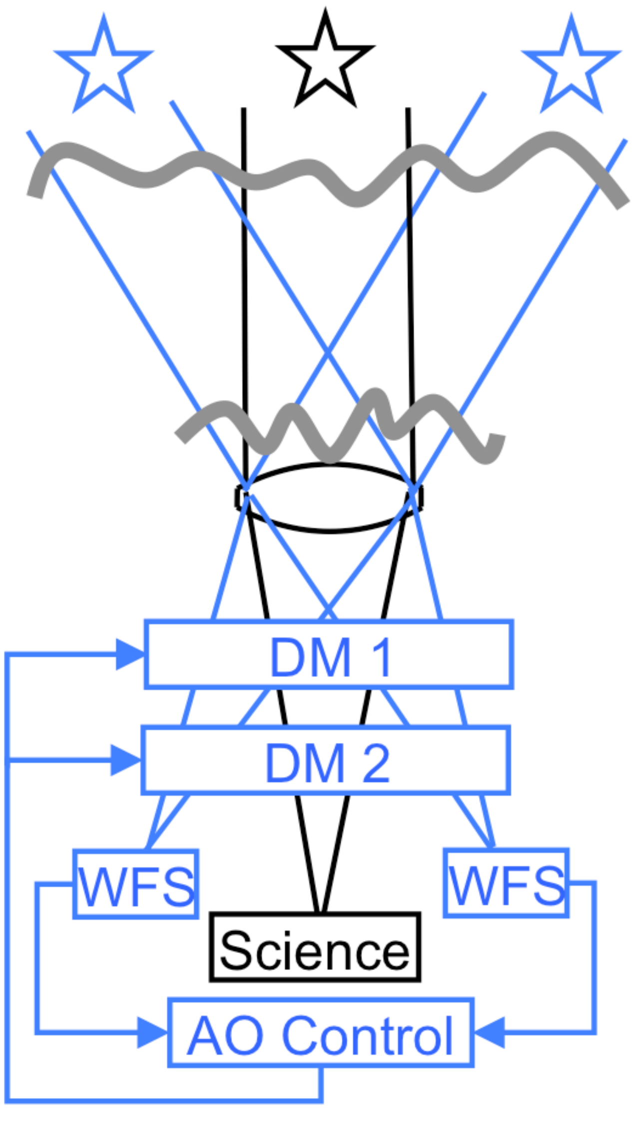
The LGS is at finite distance H above the telescope and does not sample all turbulence and not the same column of turbulent atmosphere ("cone effect"):



→ very large telescopes need multiple LGSs due to this cone effect.

Multi-Conjugate AO – MCAO

- to overcome anisoplanatism, the basic limitation of single guide star AO
- MCAO uses multiple natural guide stars or laser guide stars
- MCAO controls several DMs
- each DM is conjugated to a different atmospheric layer at a different altitude
- at least one DM is conjugated to the ground layer
- best approach to larger corrected FOV



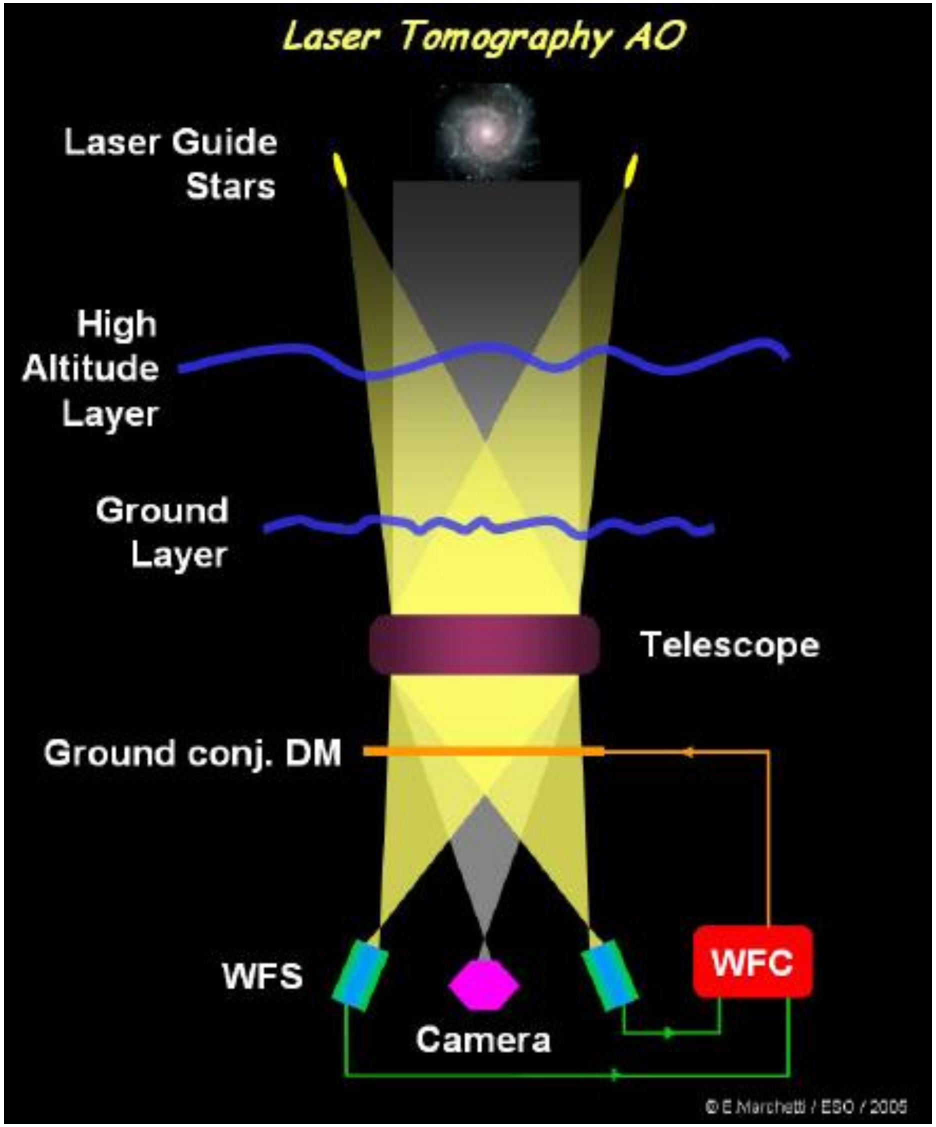
Tomography AO

- Uses multiple laser beacons or reference star

- combined information is used to optimize the correction by one DM on-axis.

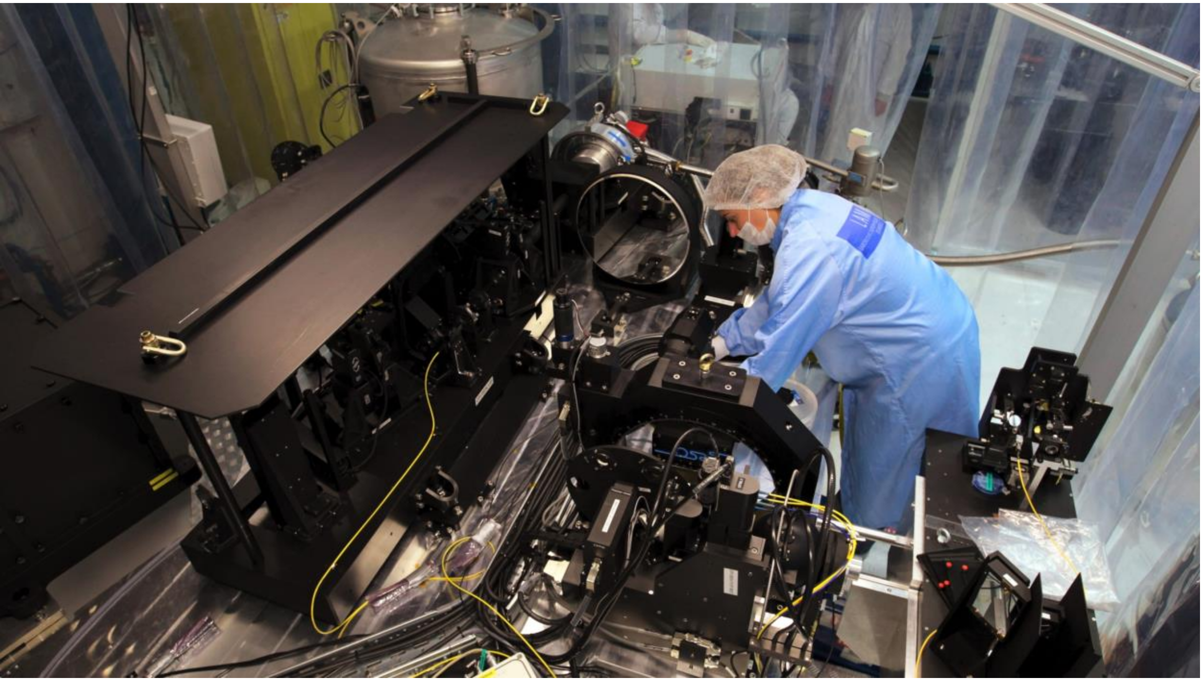
- reduces the cone effect

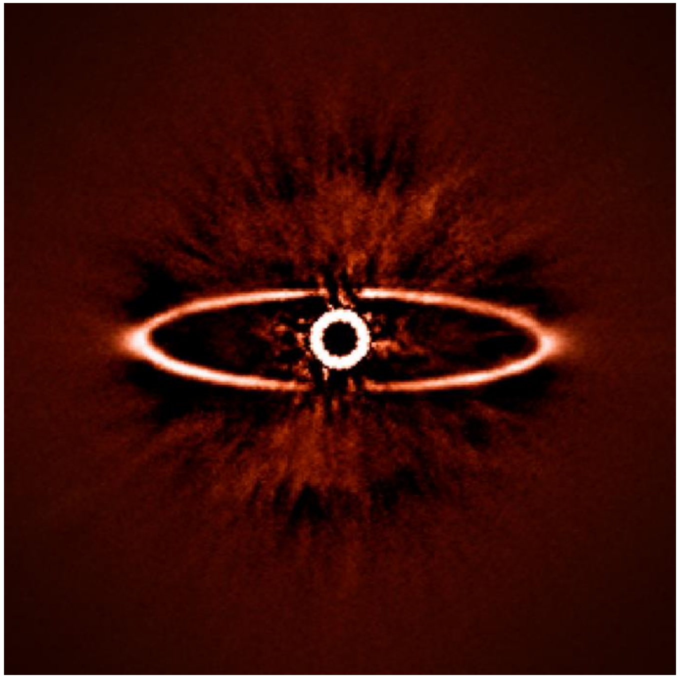
- system performance similar to natural guide star AO but at much higher sky coverage.



Extreme AO – XAO

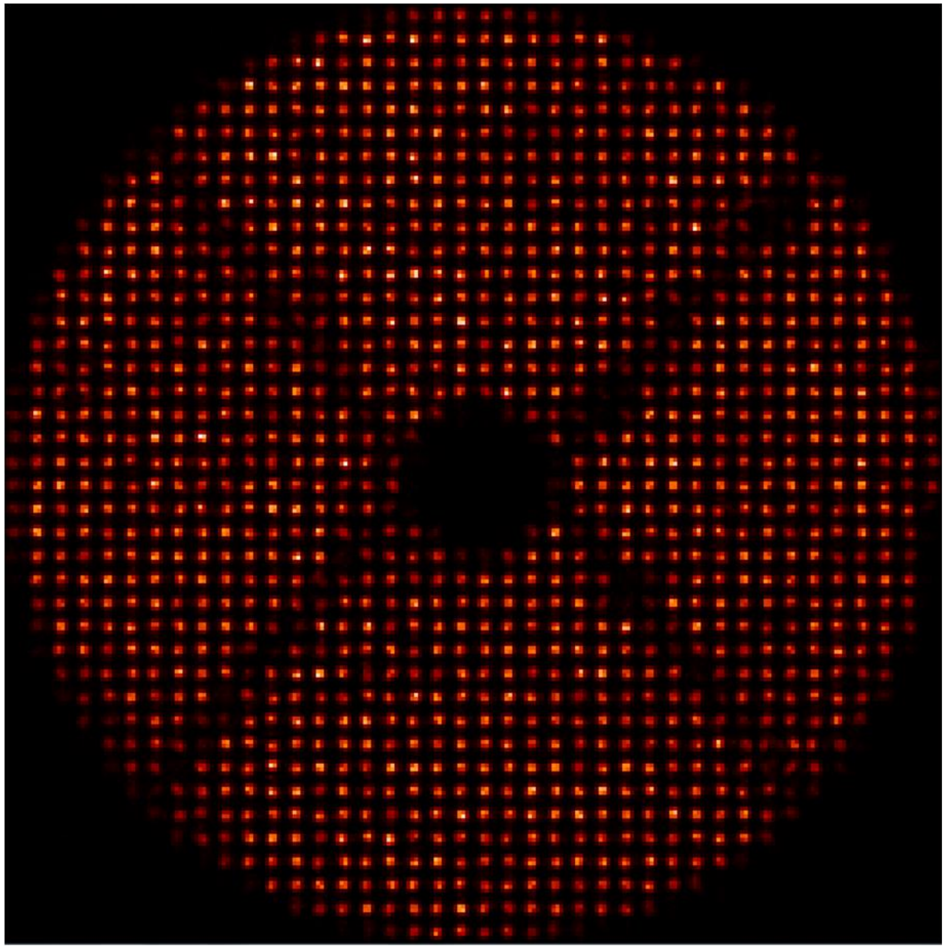
- high Strehl ratio on-axis and small corrected FOV
- requires thousands of DM actuators
- requires minimal optical and alignment errors
- main application: search for exoplanets, SPHERE on VLT, GPI on Gemini



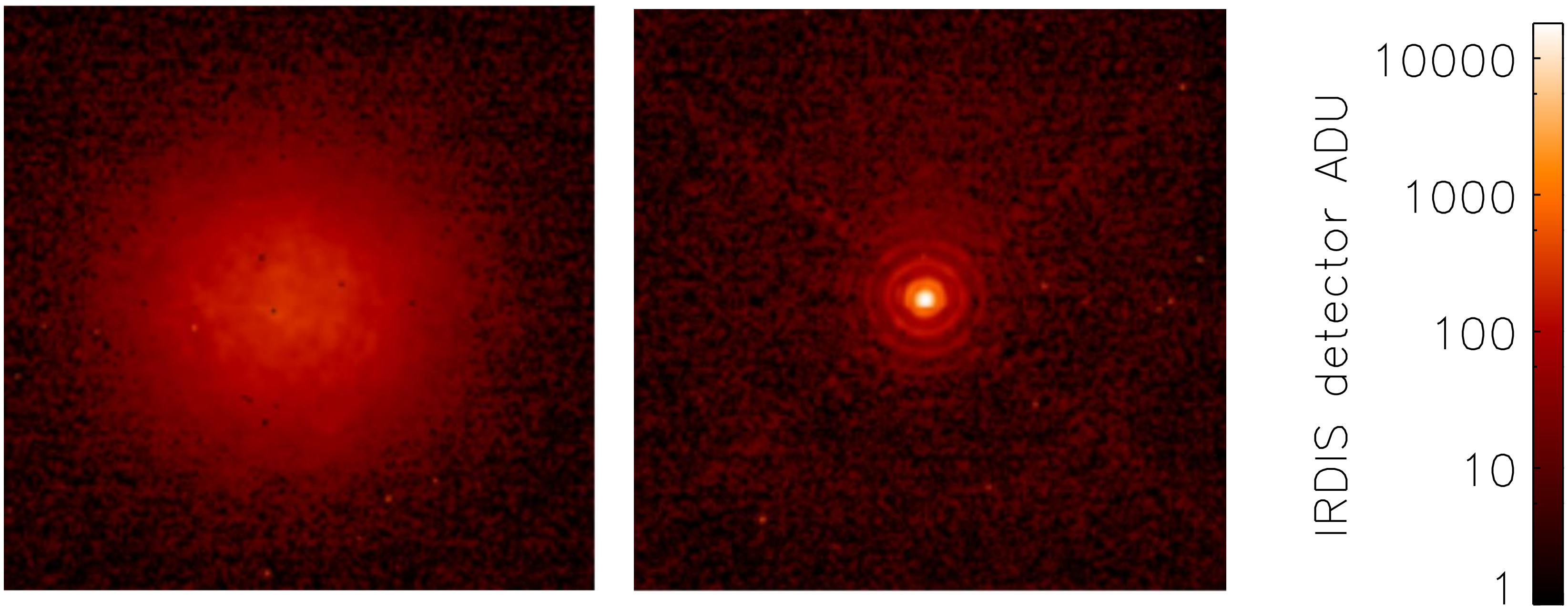


SPHERE Extreme AO

- Piezo-electric deformable mirror with 41 by 41 actuators
- Shack-Hartmann wavefront sensor with 40 by 40 subapertures
- EMCCD with 240 by 240 pixels, >1200Hz frame rate, <0.1e$^-$ readout noise



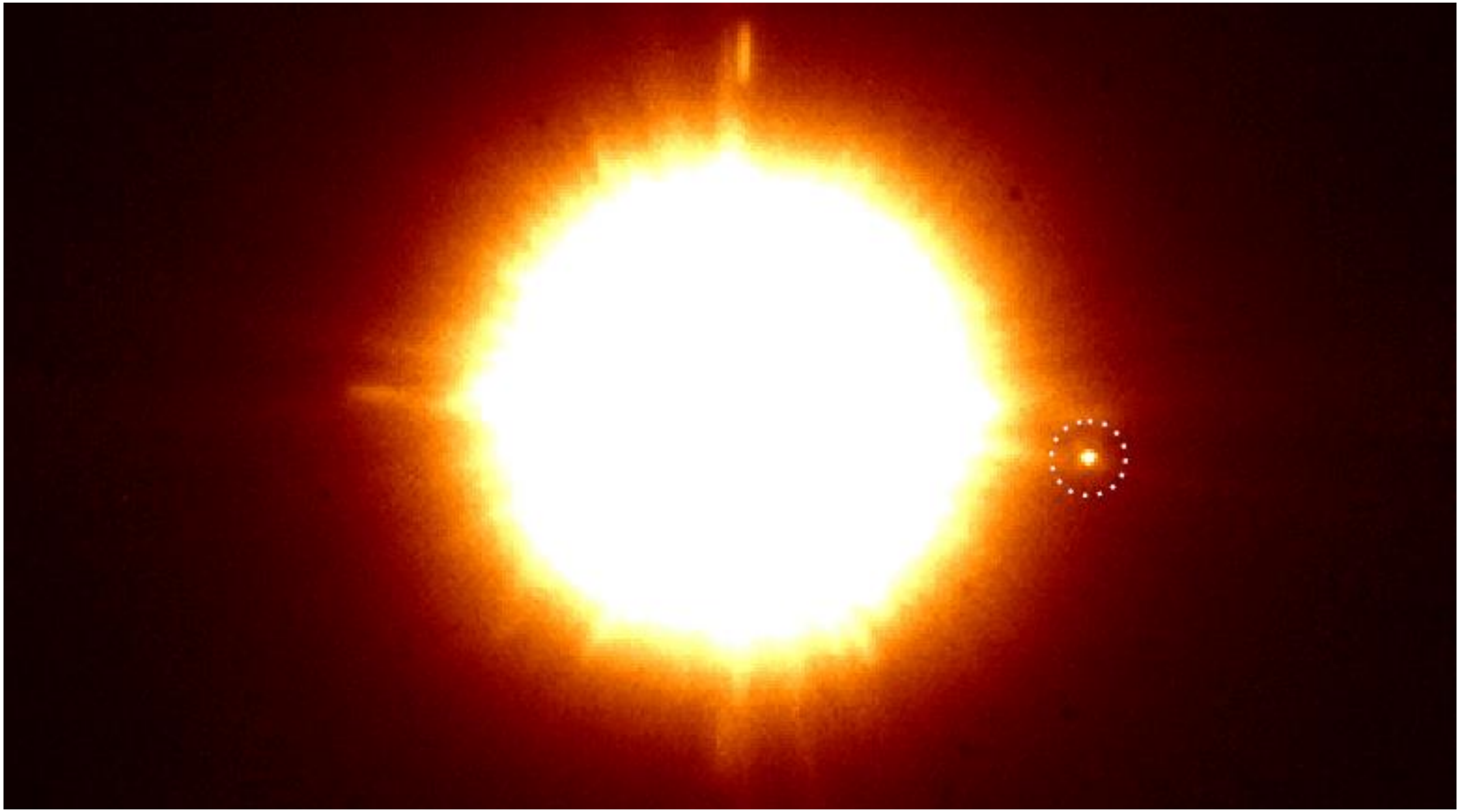
SPHERE



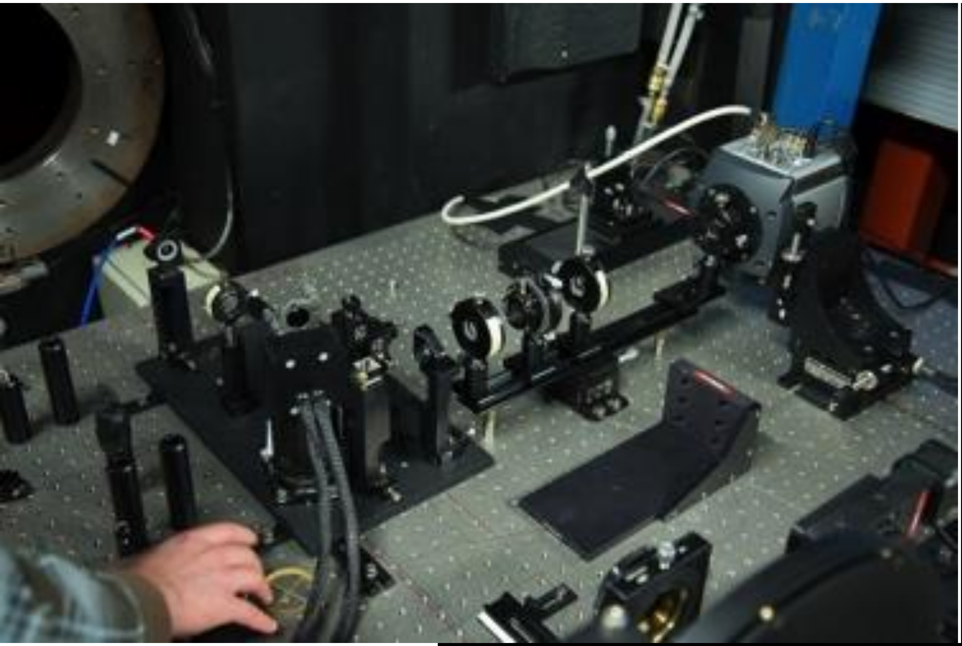
Seeing limited image
$5.2 \pm 2\%$ SR

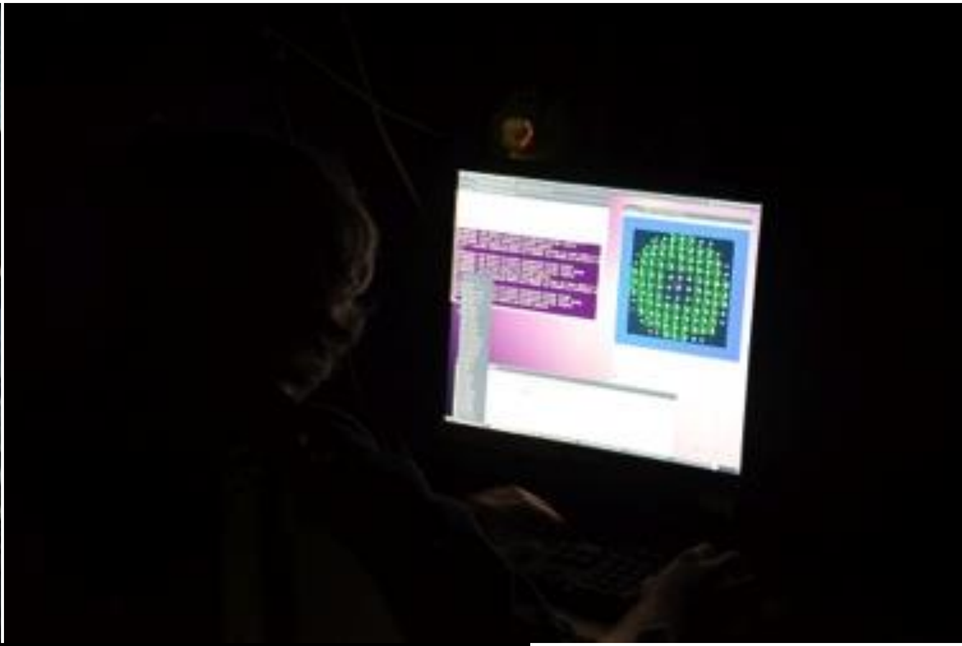
AO corrected image
$90.3 \pm 2\%$ SR

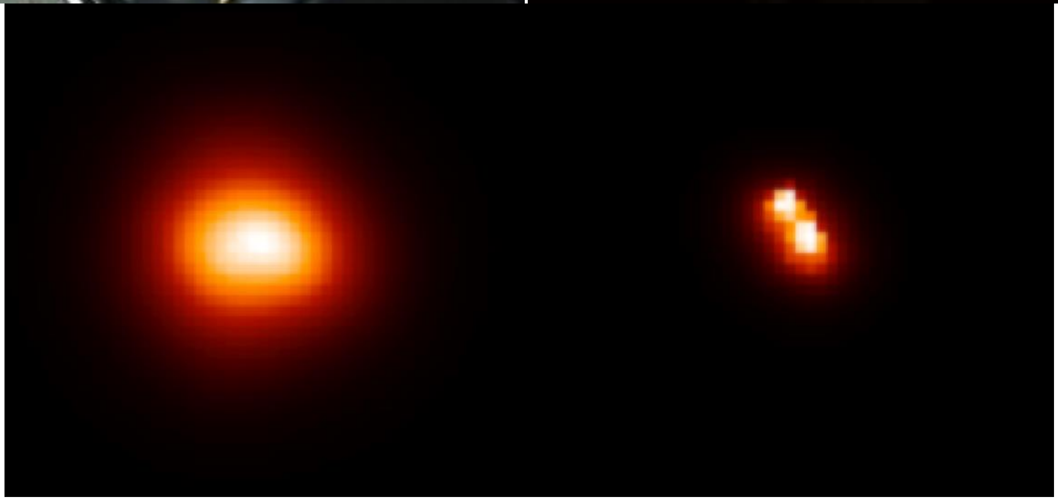
CS Cha (Ginski et al. 2018)



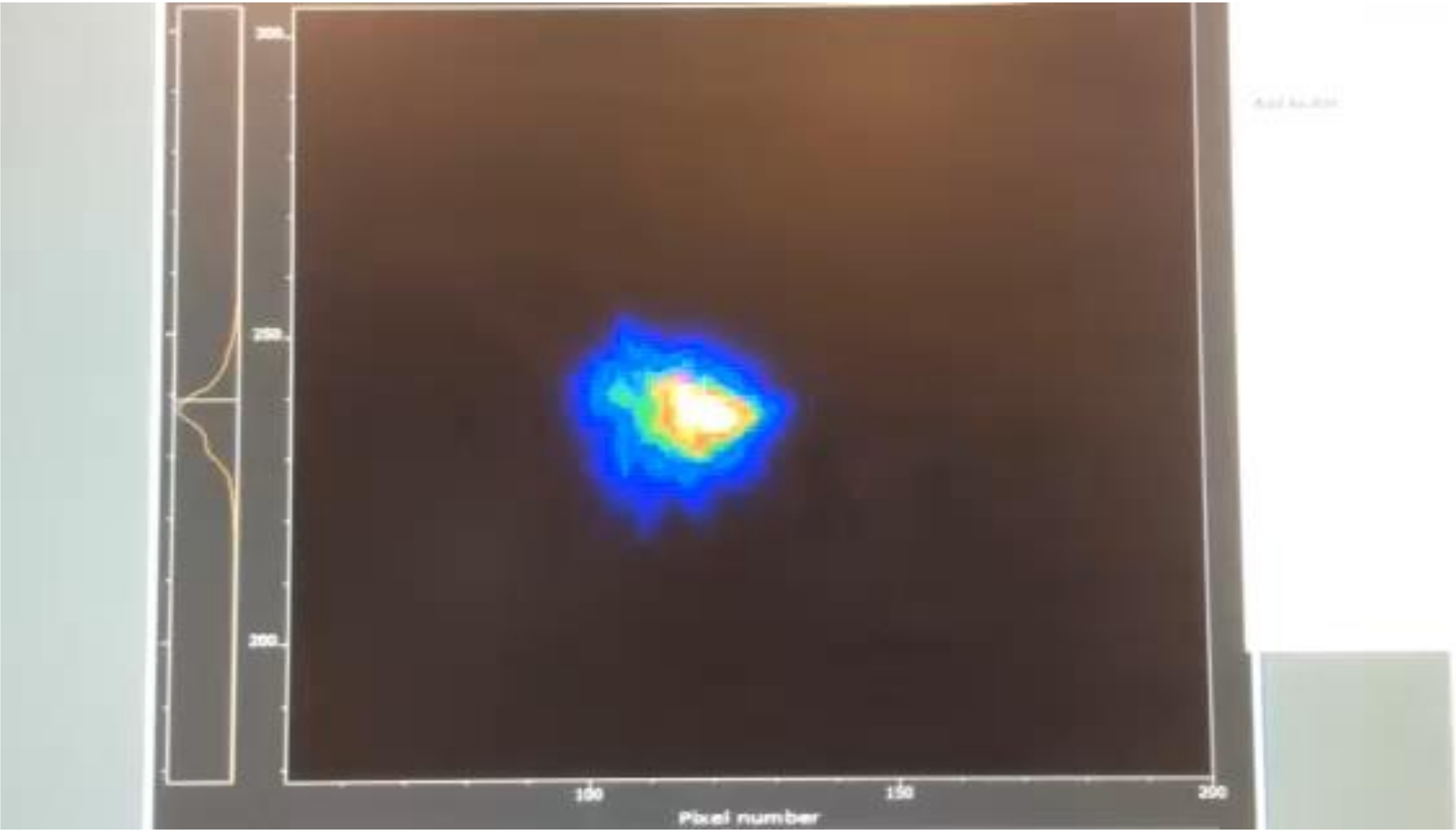
Student-Built ExPo Adaptive Optics







ExPo Adaptive Optics at WHT



MSc Astronomy & Instrumentation

- lectures:
  - Astronomical Telescopes and Instruments
  - Detection of Light
  - High Contrast Imaging
  - Project Management
- option to take courses at TU Delft (not required)
- option for major research thesis in industry

www.astroinstrumentation.nl