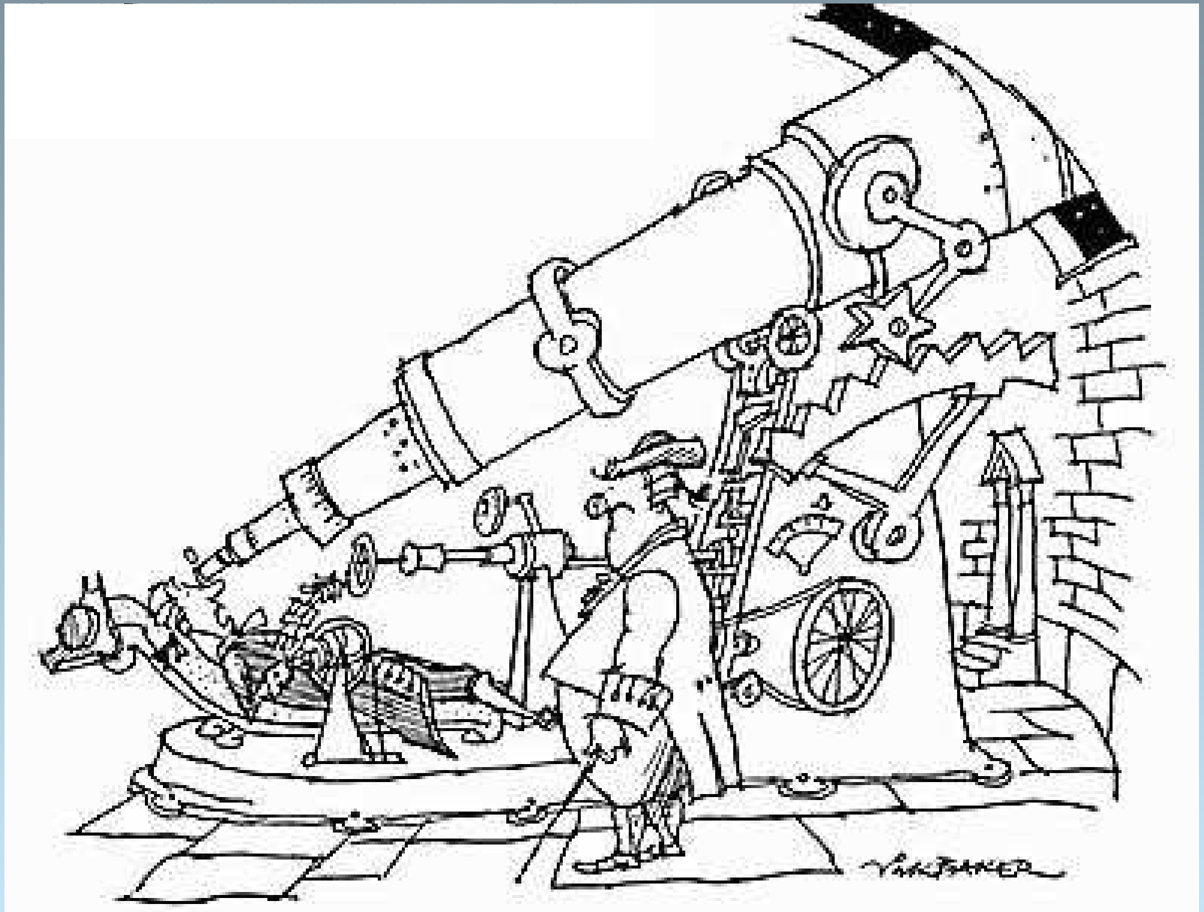
Optical/IR Observational Astronomy

Telescopes II: observing sites, the atmosphere & adaptive optics



"I just don't feel focussed or grounded these days."

David Buckley, SALT

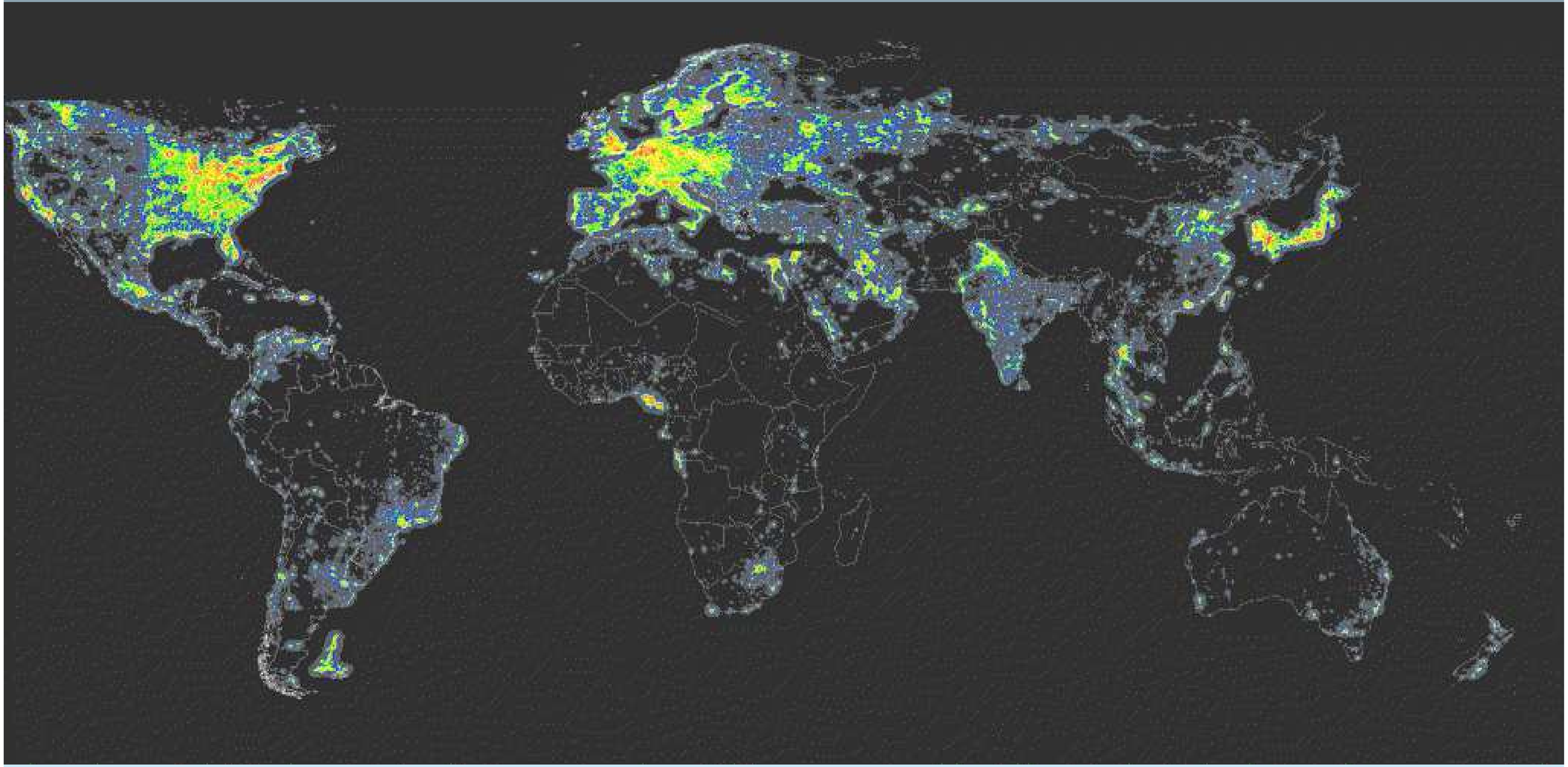
Optical/IR Observational Astronomy

Telescopes II: observing sites, the atmosphere & adaptive optics

Observatory Sites

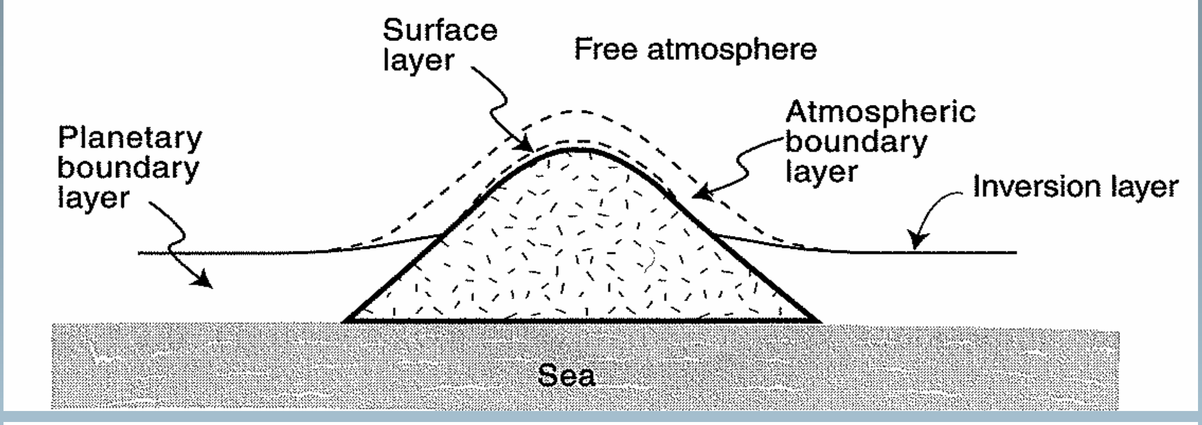
Requirements

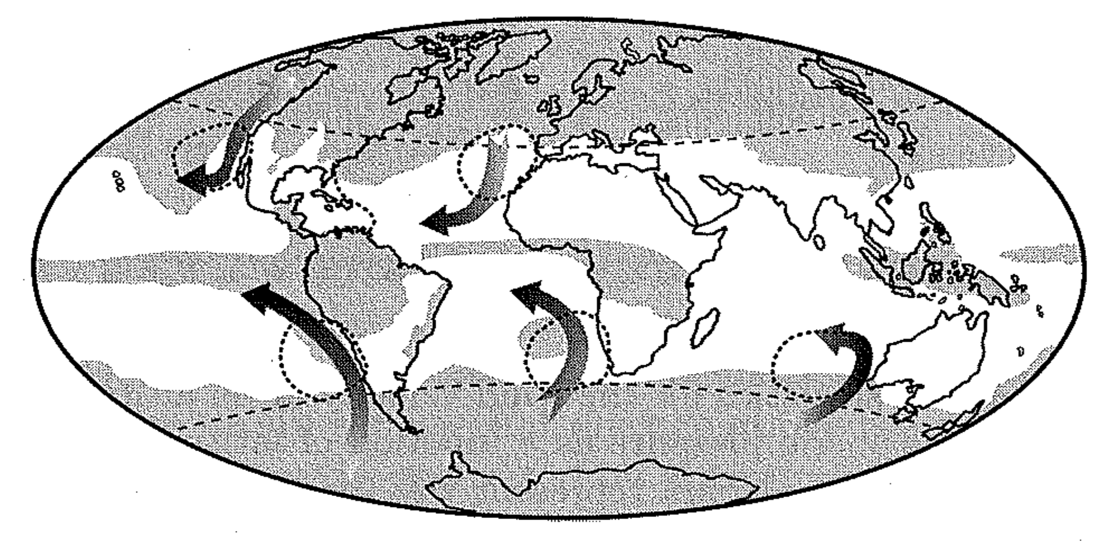
- **Dark: no light pollution**



Observatory Sites

- **High: above inversion layer**
  - **lower water vapour content**
  - **Less aerosols, so less absorption & scattering**
  - **Less turbulence, so better seeing**
- **Dry: less cloud cover and lower water vapour content**

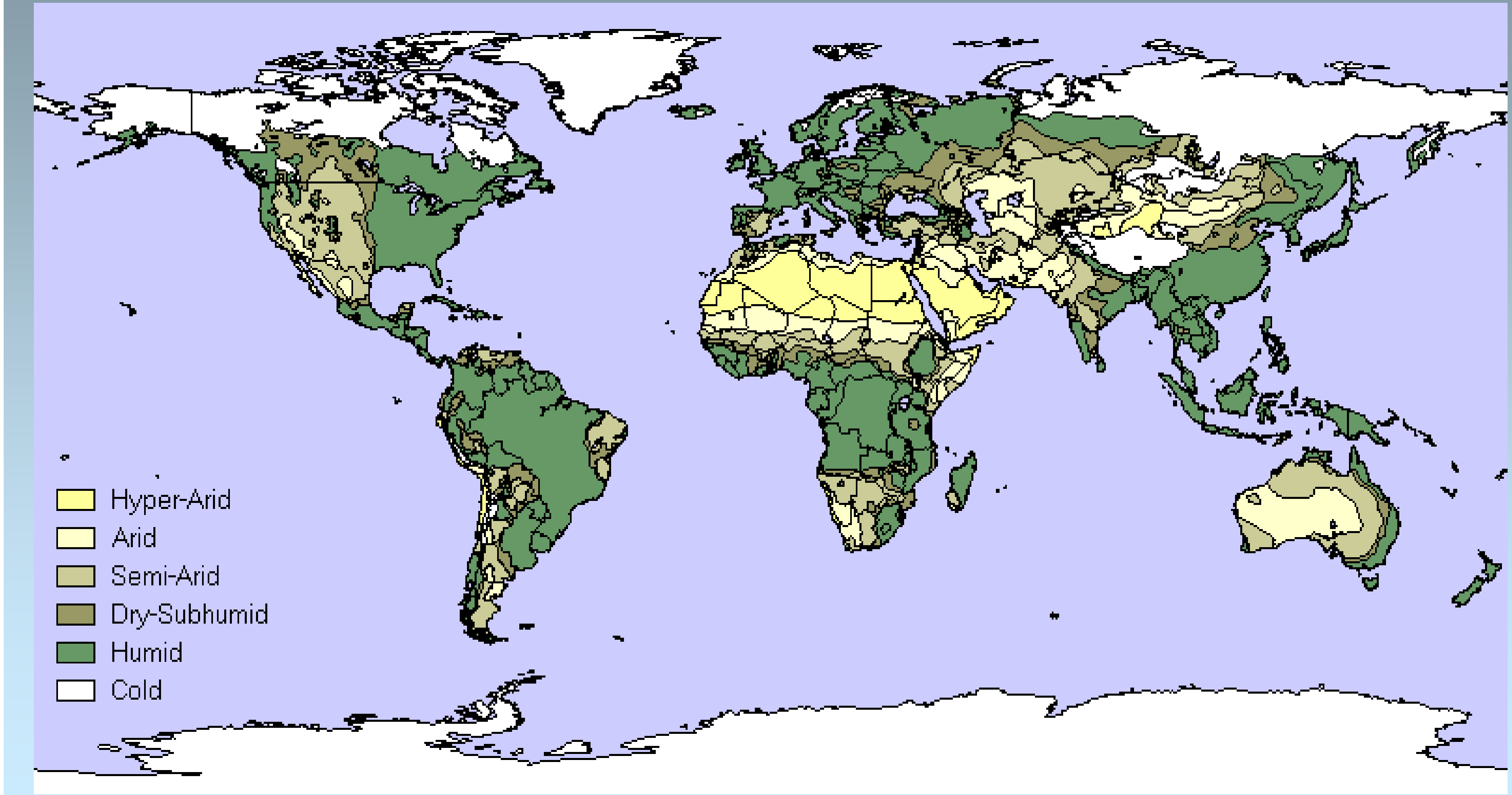




Shaded areas: >2/8ths cloud cover for 50% of the time; Arrows indicate cold ocean currents

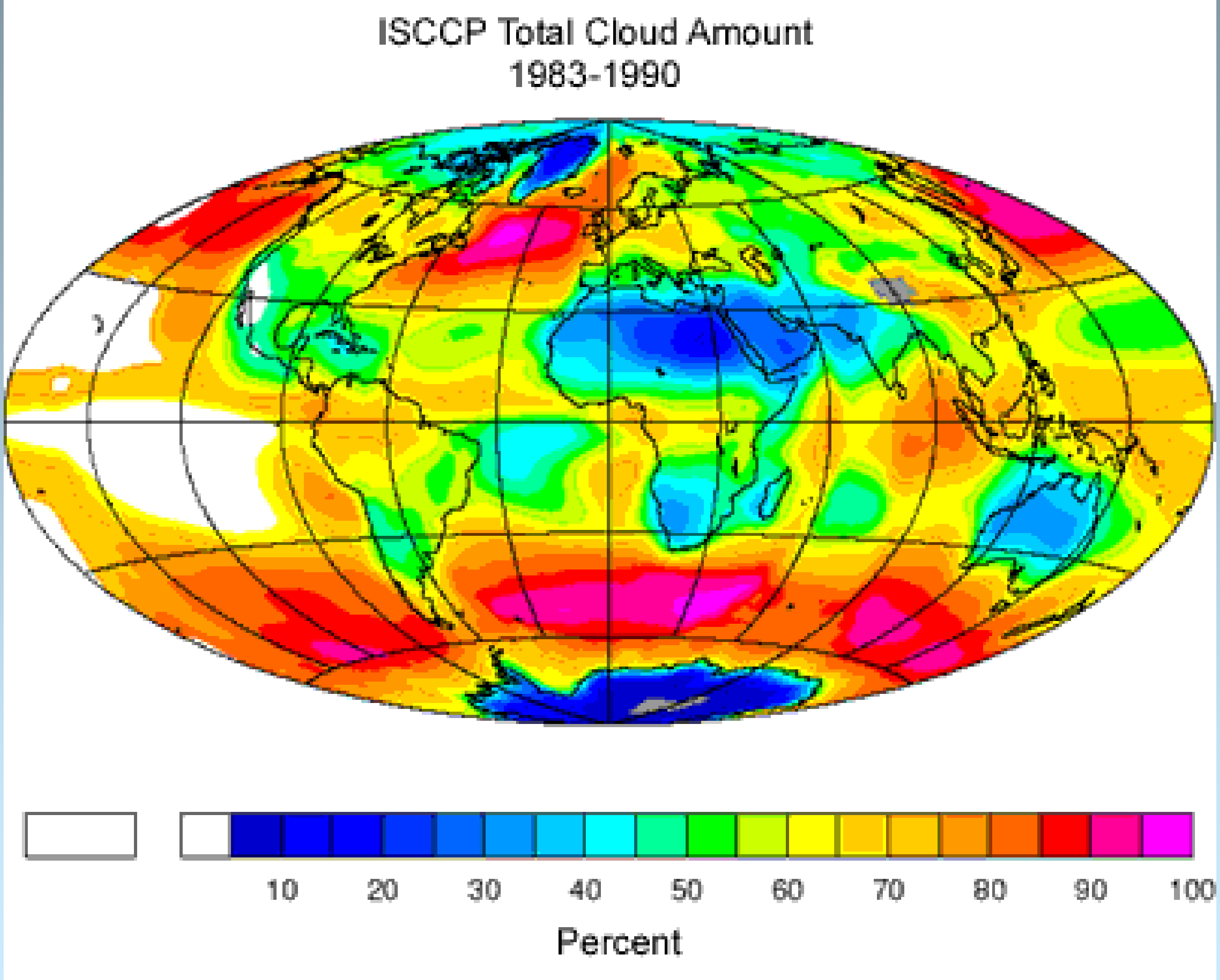
Observatory Sites

- **Low humidity / water vapour**



Observatory Sites

- **Low cloud cover**



Observatory Sites

“For the Air through which we look upon the Stars, is in a perpetual Tremor... Long Telescopes may cause Objects to appear brighter and larger than short ones can do, but they cannot be so formed as to take away that confusion of the Rays which arises from the Tremors of the Atmosphere. The only Remedy is a most serene and quiet Air, such as may perhaps be found on the tops of the highest Mountains above the grosser Clouds." **Sir Isaac Newton (1704)**

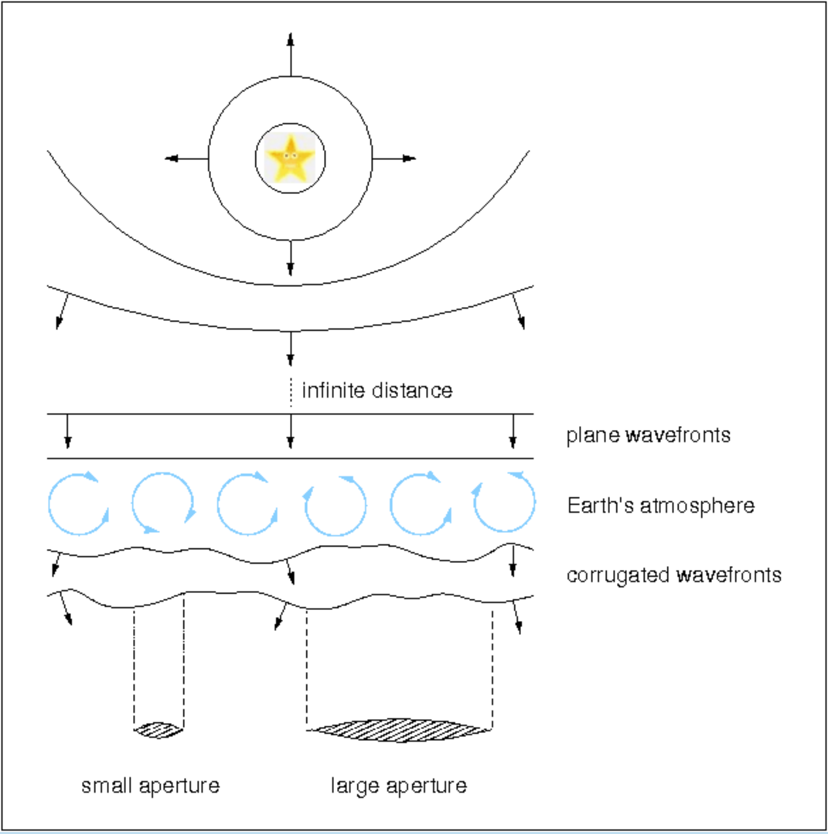
Mountain Top sites: Mauna Kea in Hawaii

VLT in Paranal (Chile)

Effects of the Atmosphere

- **Atmosphere can be treated layers of turbulent air moving with a group velocity: the wind speed and direction**
- **Turbulence results from air of different temperature, pressure and density moving as ensembles or "parcels" of air**
  - **These ensembles have slightly varying refractive index, *n(λ)***
  - **Because *n(λ)* is non-uniform, plane parallel wavefronts passing through the atmosphere undergo phase changes (velocity of light changes)**
  - **Degrades the image (the *Point Spread Function*)**
  - **Akin to small lenses moving across the telescope aperture**
  - **Air parcels move like a turbulent viscous compressible fluid, resulting in eddies, or vortices.**
  - **A wide range of physical sizes of the "parcel", from mm to m in size**
  - **Characterized mathematically by a spectrum of sizes obeying certain statistical properties: Kolmogorov theory (1941)**

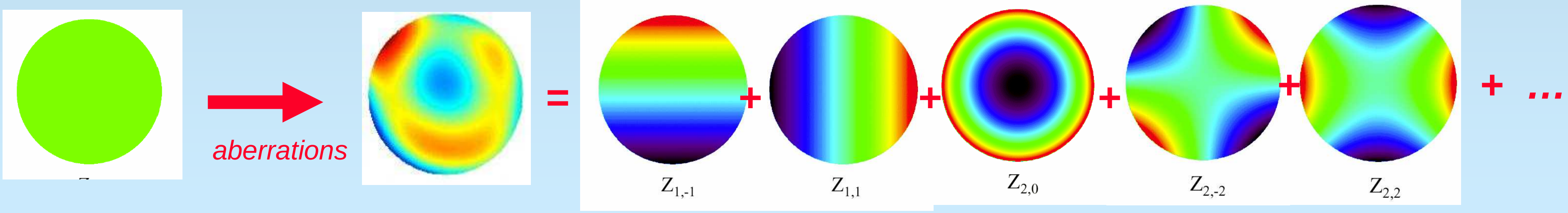
Wavefront Perturbations



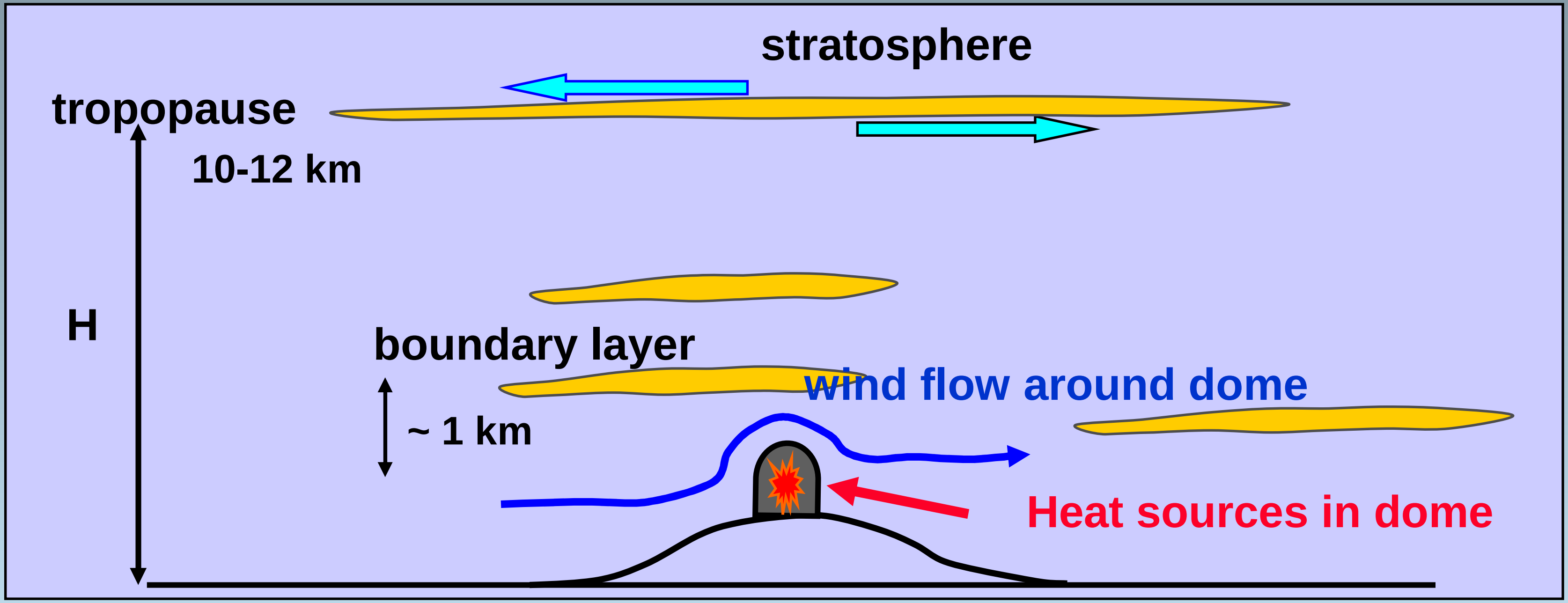
- **Turbulent cells of varying index of refraction distort the wavefront**
- **Phase changes occur**
- **Introduces aberrations which distort the ideal image ('near field'), the *point spread function (PSF)***

- **In the *pupil* plane ('far field'), phase variations can be deconvolved into the Zernike terms.**

Ideal pupil ***aberrated pupil*** ***pupil deconvolved into Zernike terms***

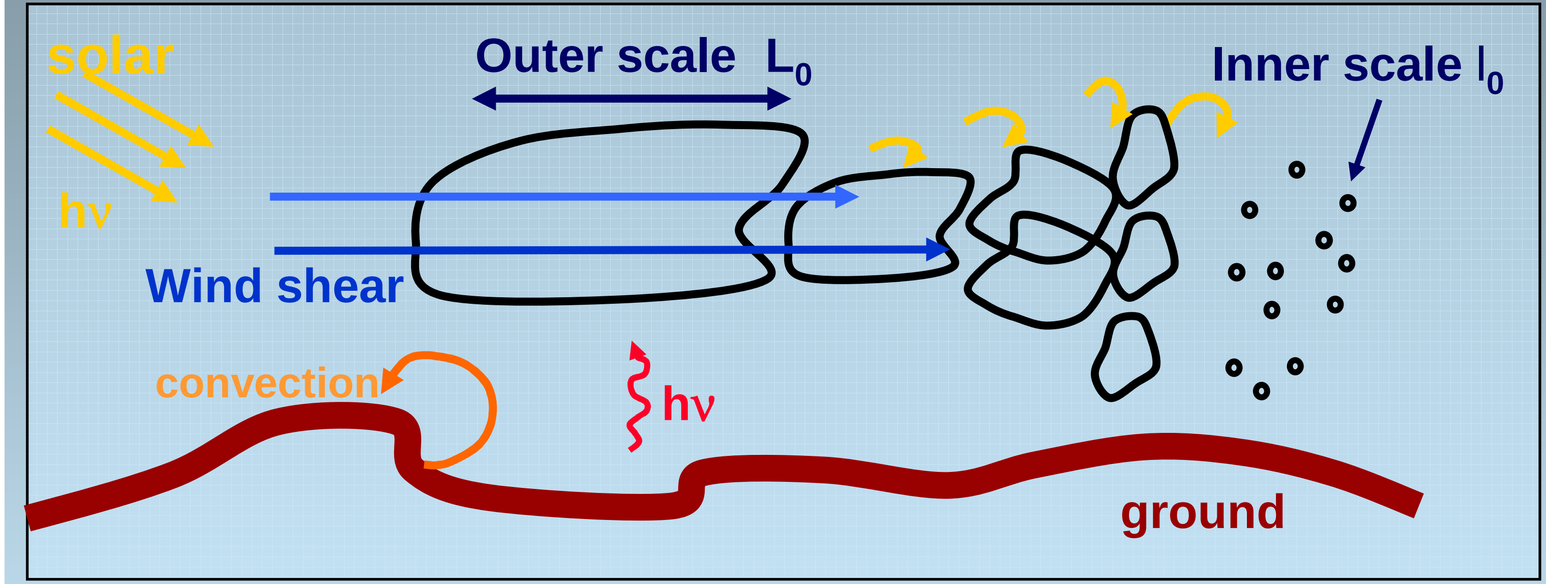


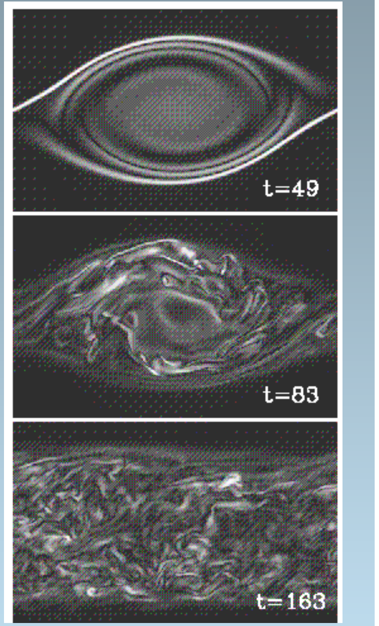
Turbulence arises in several places



- Wind speed = zero at ground; = v_{wind} at H =several hundred m (in the “free” atmosphere). The “boundary layer” is where this adjustment takes place and where atmosphere feels strong influence of surface
- Quite different between day and night
  - Daytime: boundary layer is thick (up to a km), dominated by convective plumes rising from hot ground. Quite turbulent.
  - Night-time: boundary layer collapses to a few hundred meters, is stably stratified. Perturbed if winds are high.

Atmospheric Kolmogorov turbulence





- Assume energy is added to system at largest scales - “outer scale” L_0
- Then energy cascades from larger to smaller scales (turbulent eddies “break down” into smaller and smaller structures).
- Size scales where this takes place is termed the “inertial range”.
- Finally, eddy size becomes so small that it is subject to dissipation from viscosity, at the “inner scale” l_0
- In regime $l_0 < r < L_0$, turbulence is homogeneous & isotropic (Kolmogorov regime)

Effects of the Atmosphere

<u>Critical parameters:</u>

V = flow velocity
l = scale length of vortex
k = wavenumber of vortex (= $2\pi/l$)
ν = kinematic viscosity

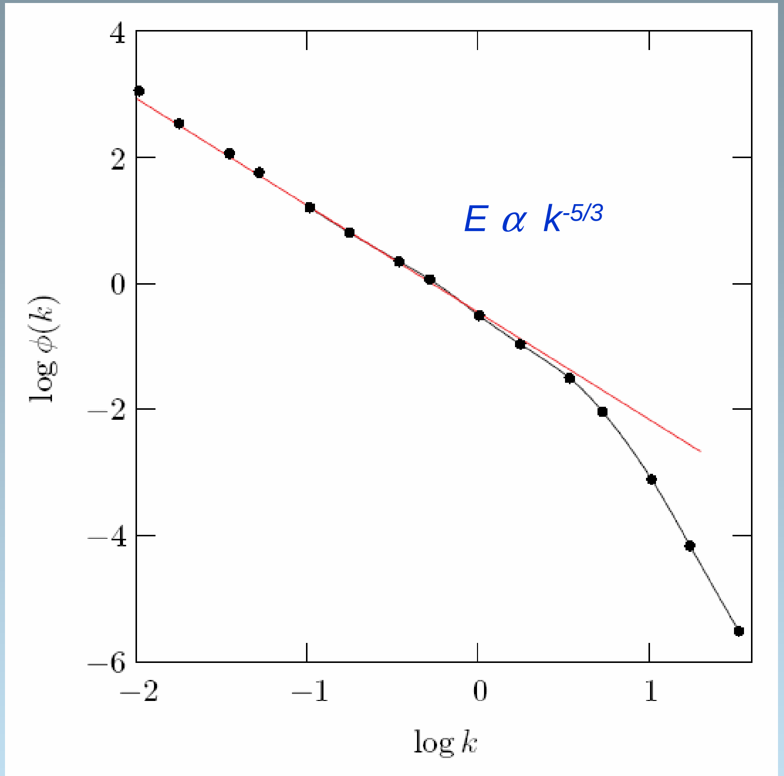
Reynolds number (ratio of inertial to viscous forces):

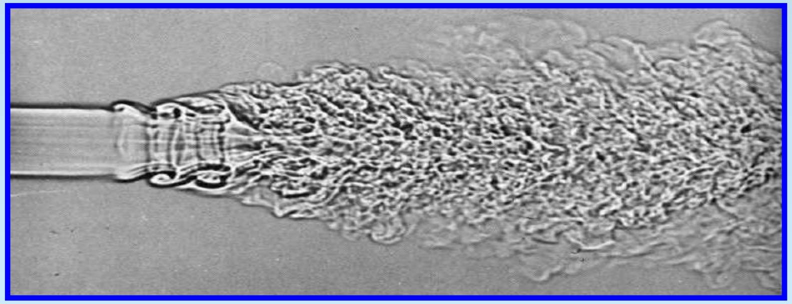
$$\boxed{R = \nu\, l\, /\, v}$$

Laminar flow occurs at R <2000, when viscous forces dominate.

For typical atmospheric values of V (1 m s^{-1}), L (15 m) & ν (1.5 x 10^{-5}), R ~10^6, implying a fully turbulent medium.

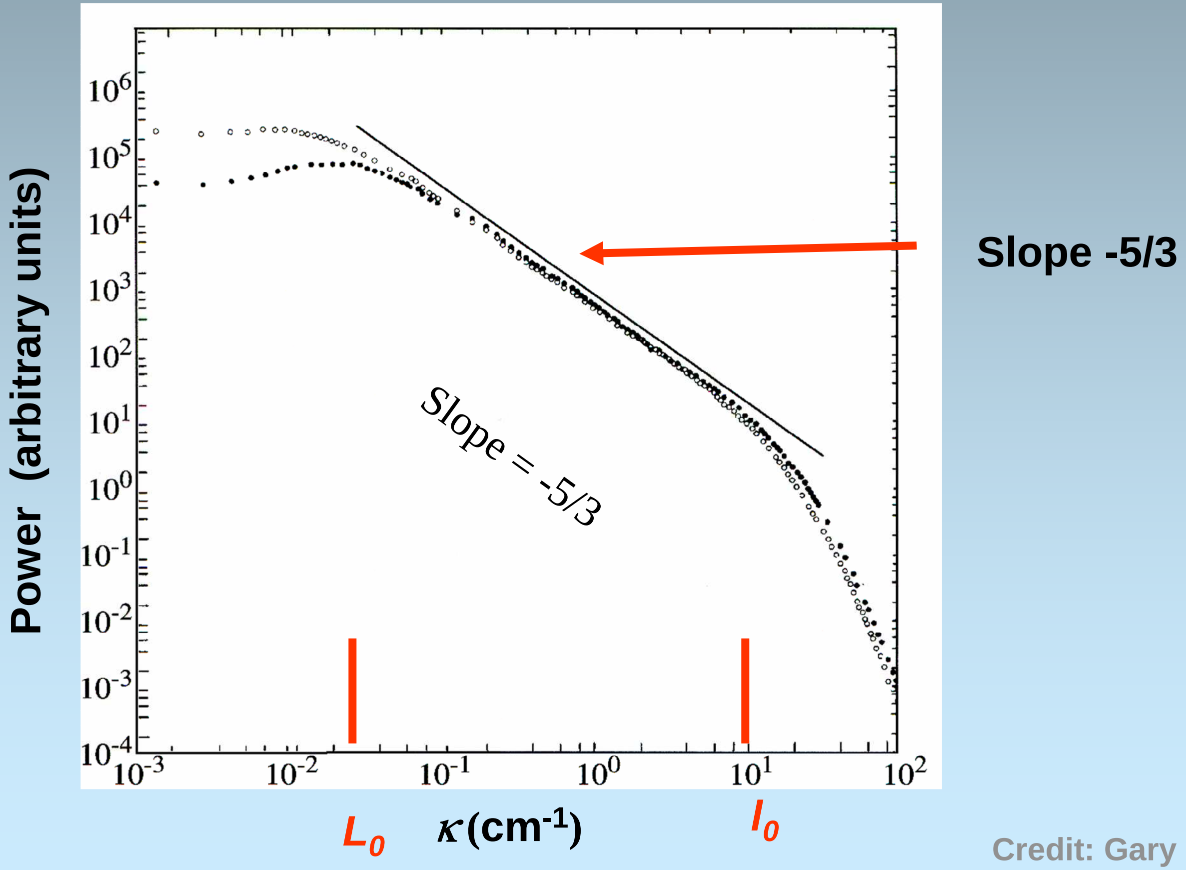
KE of larger scale motions is transferred to smaller scale motions – Kolmogorov theory. Kolmogorov envisioned a process in which mixing occurs over a range of wave numbers, say from k_{min} to k_{max}. The turbulent mixing transfers energy to the higher wave numbers.





Lab experiments agree with theory

- **Assumptions: turbulence is homogeneous, isotropic, stationary in time**



Credit: Gary Chanan, UCI

Effects of the Atmosphere

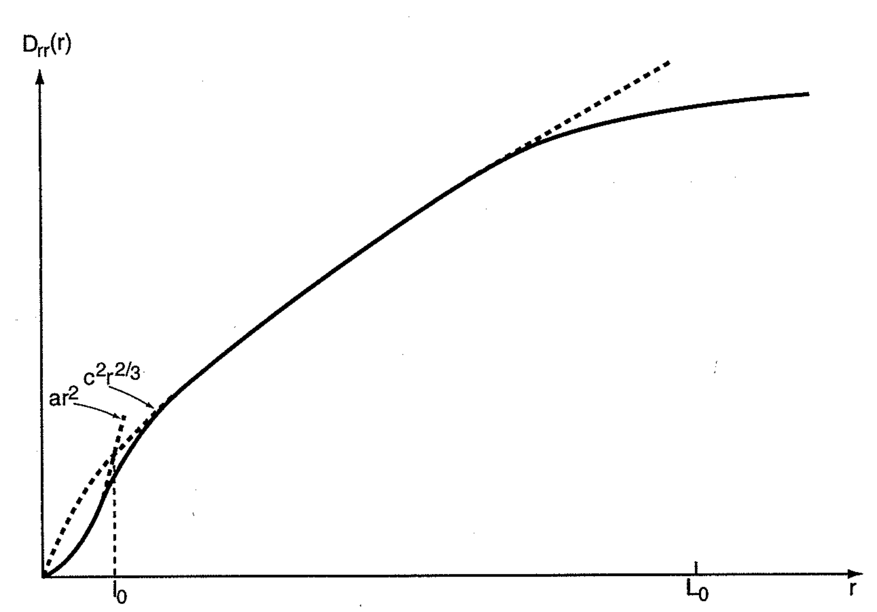
Strength of turbulence is related to the mean velocity *difference* squared of vortices:

$D_{rr} \propto \langle (v_1 - v_2)^2 \rangle \propto \varepsilon^{2/3} r^{2/3}$ *[Kolmogorov 2/3 law]*

ε = energy dissipation rate of turbulent K.E.
r = separation of interacting vortices

$\varepsilon \sim v^3/l$

Structure functions (tensors) can be defined in terms of velocity, temperature and refractive index (Tartarski 1961)



laminar

Non-isotropic

Kolmogorov theory holds for linear part of structure or energy dissipation functions, i.e. for $l_0 < r < L_0$

l_0 = inner (E dissipation) scale length ; laminar flow for $r < l_0$ (ranges from mm or less near ground level to ~1 cm at troposphere-stratosphere boundary)

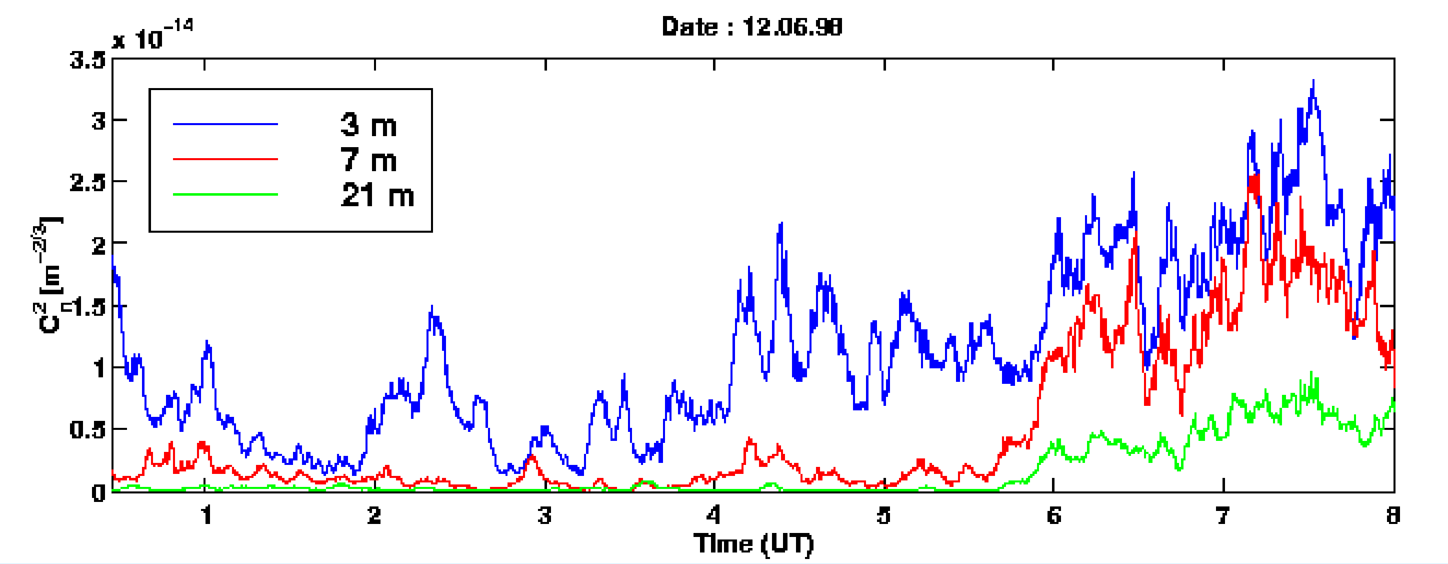
L_0 = outer (E injection) scale length; 10s to 100's metres

What about temperature and index of refraction fluctuations?

- **Temperature fluctuations are carried around passively by the velocity field (for incompressible fluids).**
- **So *T* (temp) and *N* (index of refraction) have structure functions similar to *v*:**

$$D_T (r) = < [T (x) - T(x + r)]^2 > = C_T^2 \ r^{2/3}$$
$$D_N (r) = < [N (x) - N (x + r)]^2 > = C_N^2 \ r^{2/3}$$

- **Night-time boundary layer: $C_N^2 \sim 10^{-13} - 10^{-15} \ m^{-2/3}$**



Atmospheric Turbulence: Main Points

- **The dominant locations for index of refraction fluctuations that affect astronomers are the atmospheric boundary layer and the tropopause**
- **Atmospheric turbulence (mostly) obeys Kolmogorov statistics**
- **Kolmogorov turbulence is derived from dimensional analysis (heat flux in = energy in turbulence)**
- **Structure functions derived from Kolmogorov turbulence are $\propto$ $r^{2/3}$**
- **All else will follow from these points!, plus:**
  - **Index of refraction:**

$$n-1=\frac{77.6\cdot 10^{-6}}{T}\left(1+7.52\cdot 10^{-3}\lambda^{-2}\right)\left(P+4810\frac{e}{T}\right)$$

T = temp, P = air pressure
e = water vapour pressure
λ = wavelength

Assuming constant pressure and humidity, n varies only due to temperature fluctuations, with the same structure function

  - **Conversion from C_T^2 to C_N^2**

$$C_n^2 = \left(80\cdot 10^{-6}\frac{P}{T^2}\right)^2 C_T^2 \quad at\ \lambda = 0.5\mu m$$

Parameters of Atmospheric Seeing

Fried's parameter: (metres, $\propto \lambda^{6/5}$)

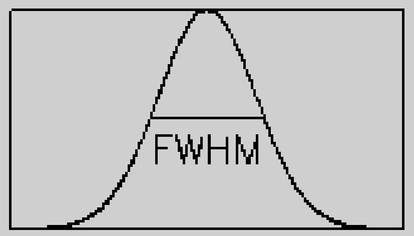
Coherence diameter: spatial scale of wavefront aberrations

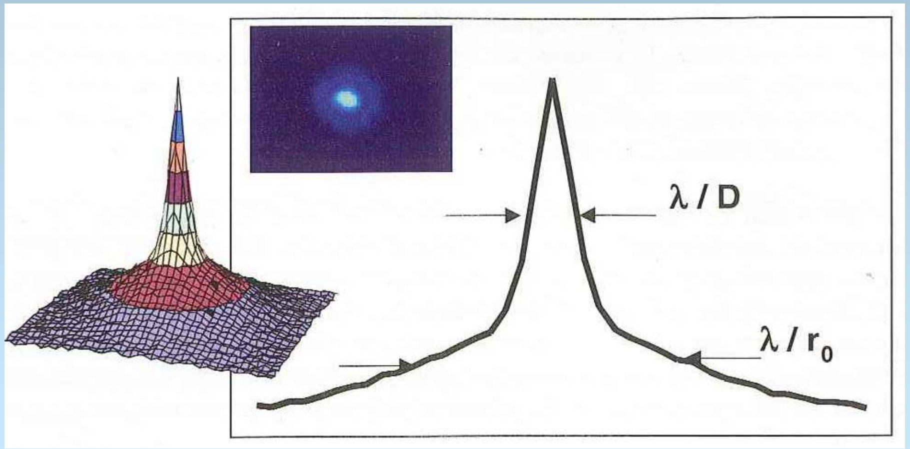
Dependent on the integrated index of refraction structure function

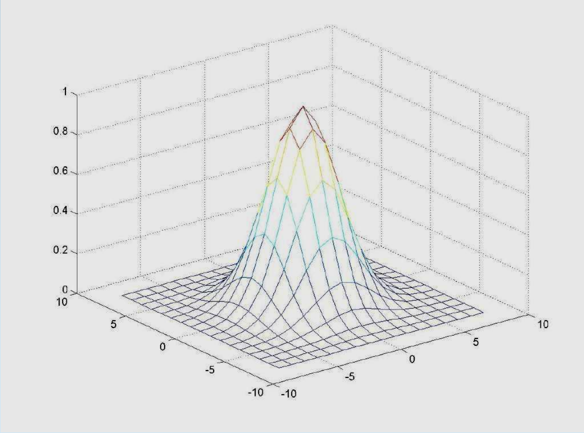
$$r_0(\lambda) = \left[0.423\left(\frac{2\Pi}{\lambda}\right)^2 \sec(\varsigma)\int_0^\infty C_n^2(h)\,dh\right]^{-3/5}$$

Seeing size: (radians, $\propto \lambda^{-1/5}$)

$$FWHM\ (\lambda) = 0.98\,\frac{\lambda}{r_0}$$







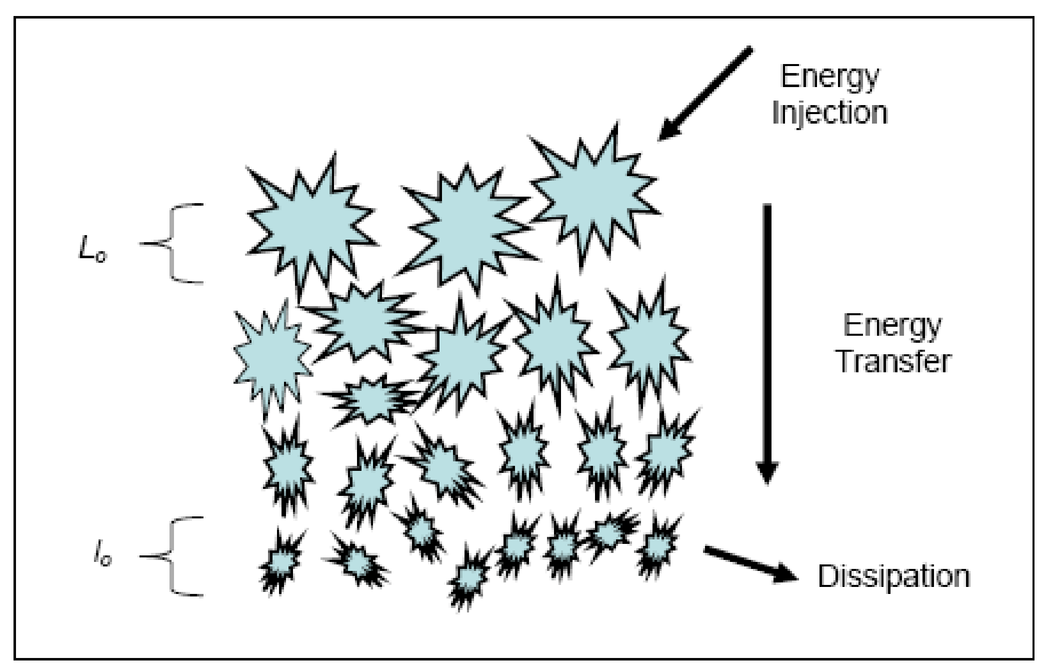
r_0 = 10 cm ⇔ FWHM = 1" in the visible (0.5μm)

Kolmogorov Turbulence

And now a little poem!

Big whorls have little whorls,
which feed on their velocity;
Little whorls have smaller whorls,
And so on unto viscosity.

Lewis Fry Richardson (1881-1953; FRS, mathematician, physicist & meteorologist, who pioneered weather forecasting.



According to an apocryphal story, Werner Heisenberg said on his deathbed

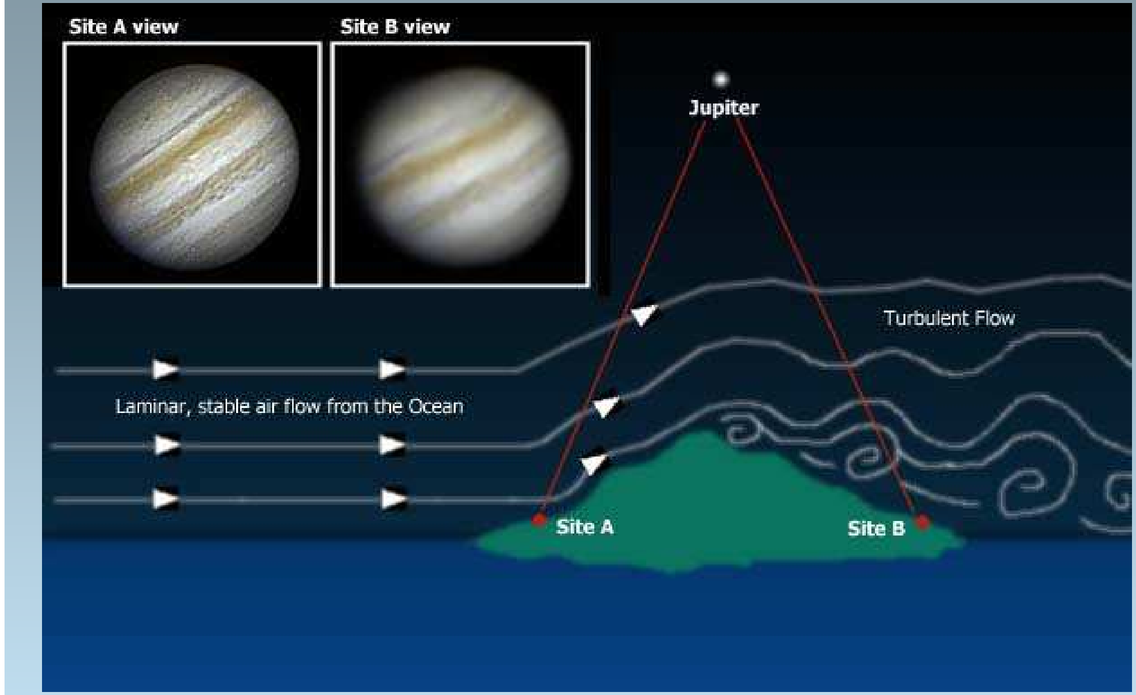
"When I meet God, I am going to ask him two questions:

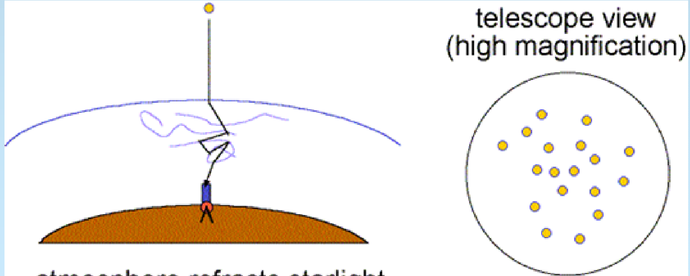
1. *Why relativity?*
2. *Why turbulence?*

I really believe he will have an answer for the first."

Atmospheric “Seeing”

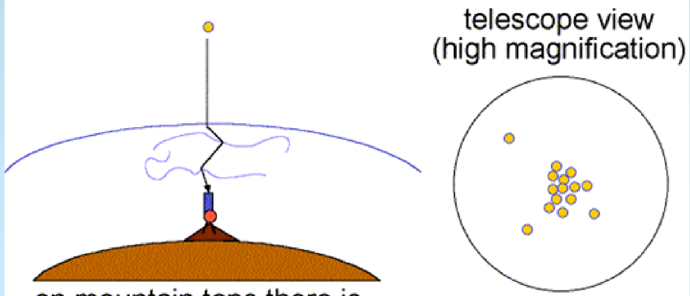
[Graphics copied from Nick Strobel’s Astronomy Notes: Go to www.astronomynotes.com for updates & corrections]





atmosphere refracts starlight in random directions very quickly—stars “twinkle”.

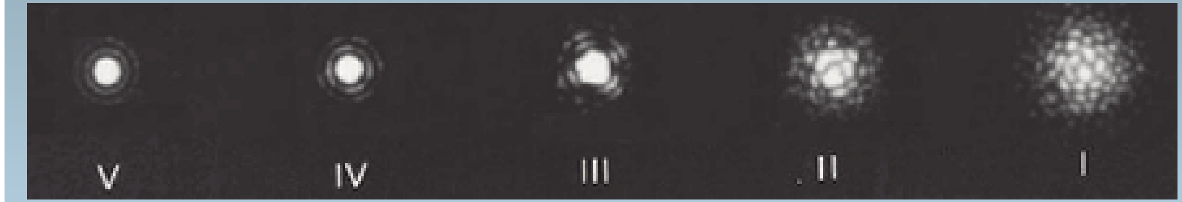
multiple images created



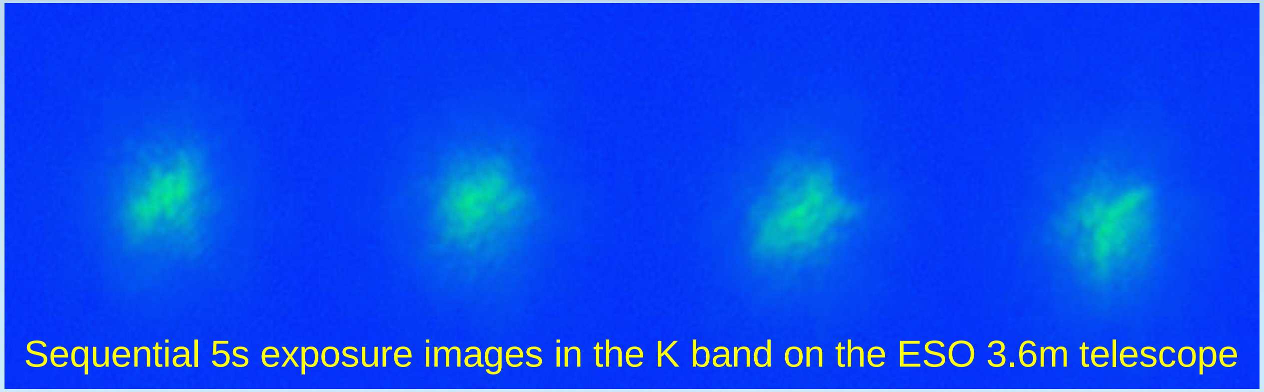
on mountain tops there is less atmosphere to look through—less distortion.

What does all of this mean in practice?

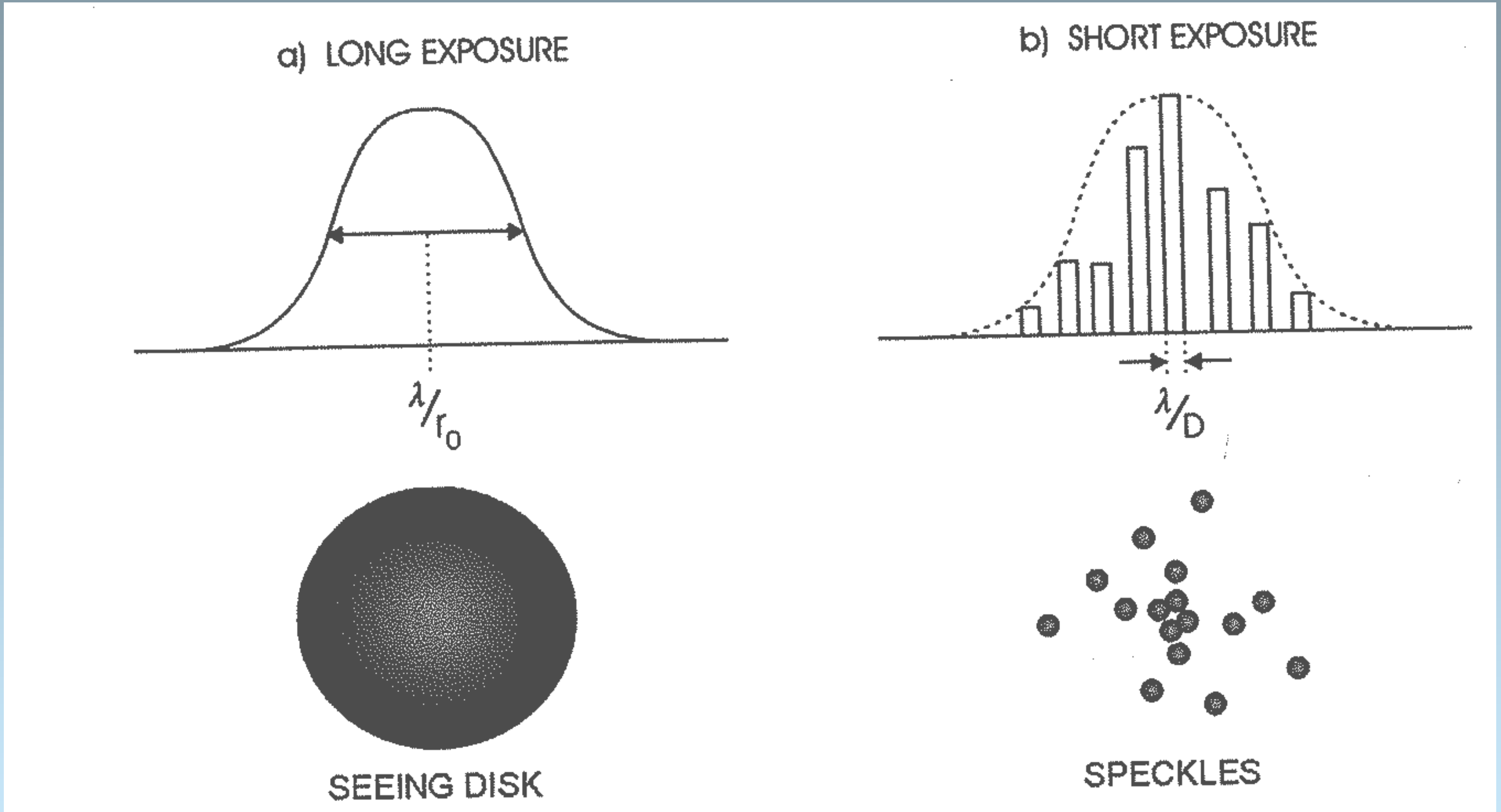
- **The atmosphere causes phase changes in wavefronts over the telescope's aperture: *atmospheric 'seeing' effects***
- **The Point Spread Function (PSF) of an image produced by the telescope is perturbed**
  - **PSF in convolved with atmopheric aberrations such that its Fourier power spectrum (the Optical Transfer Function) looses high frequency (fine structure) information**



Shorter exposures allow to freeze some atmospheric effects and reveal the spatial structure of the wavefront corrugation


Sequential 5s exposure images in the K band on the ESO 3.6m telescope

What does all of this mean in practice?

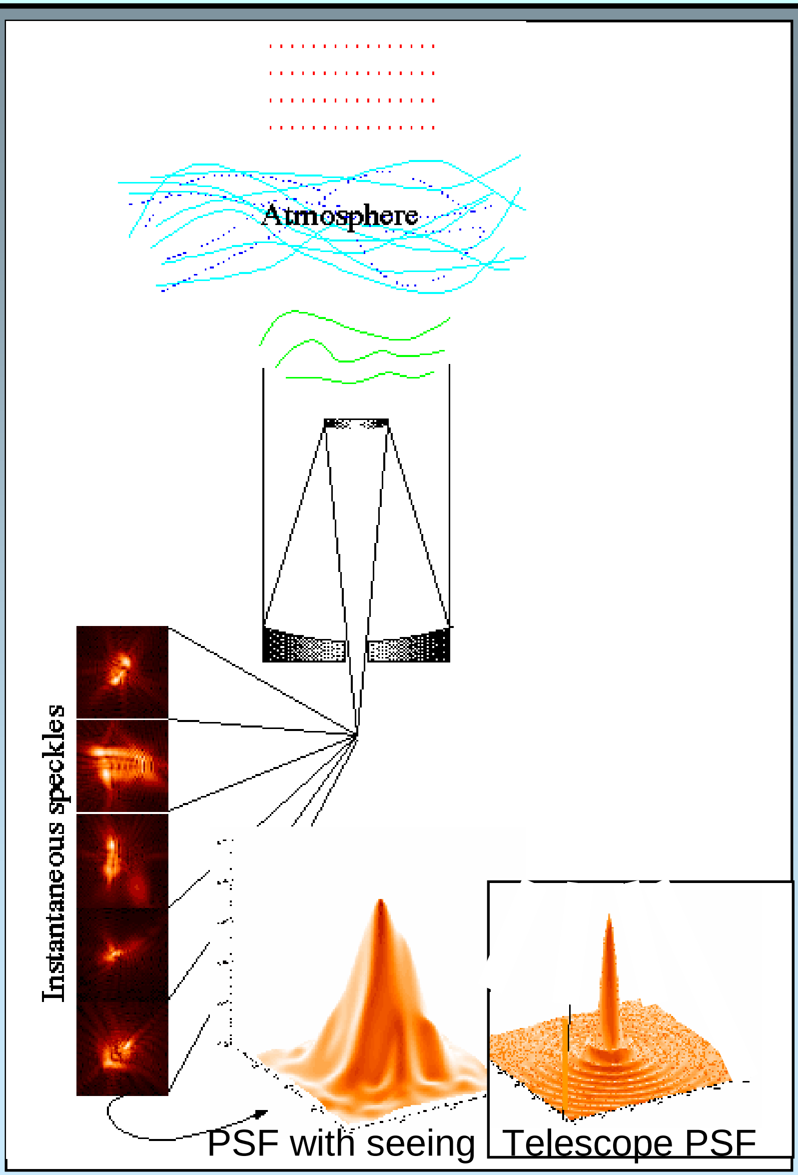


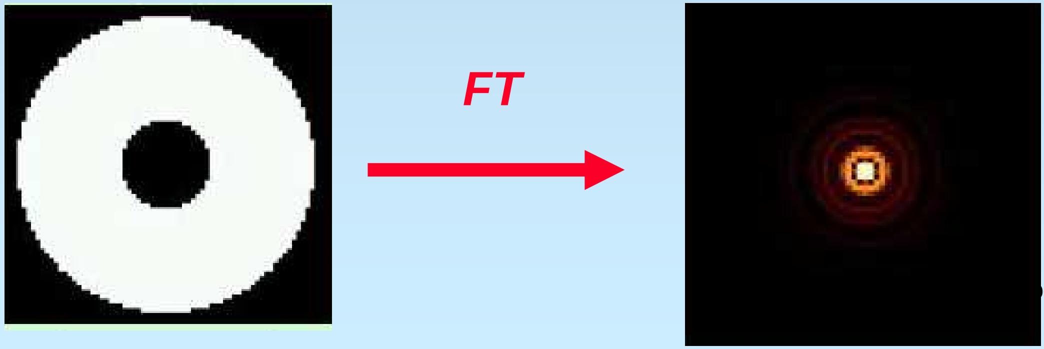
- ***And now some art…. (who says astronomers are without an aesthetic appreciation?)***

- ***So, on that starry night in Arles, was Vincent Van Gogh pondering about the bad seeing & atmospheric turbulence?***

PSF variations

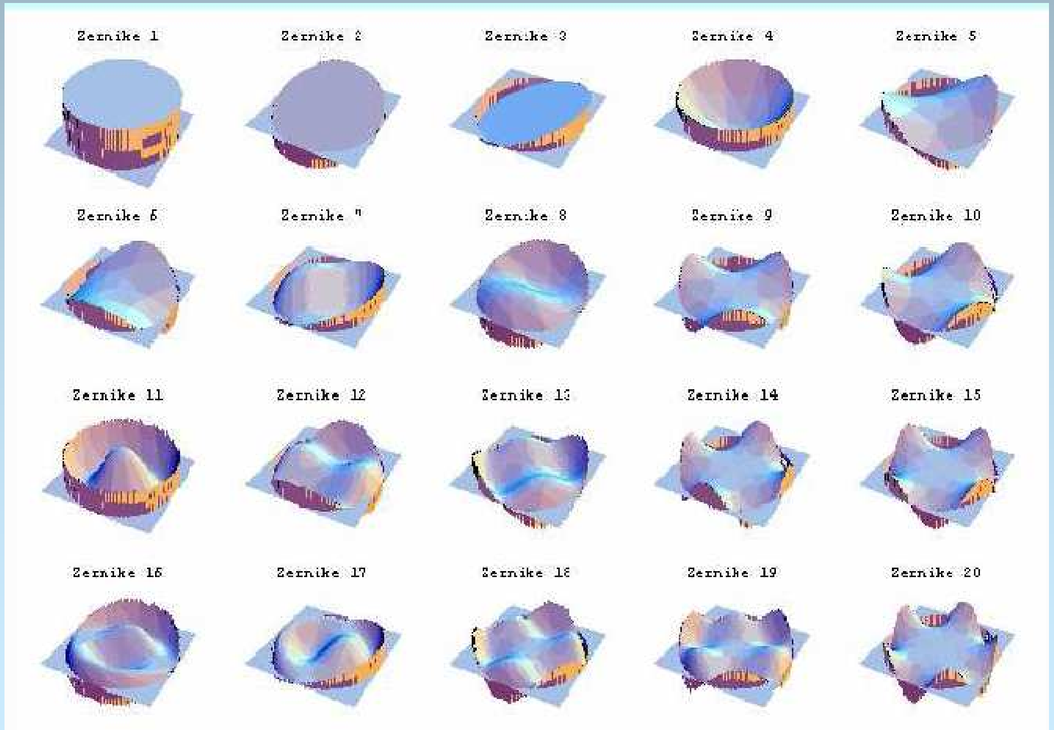
- **Wavefront perturbed by a Kolmogorov distribution of turbulent air cells of varying index of refraction**
- **Phase variations distorts the PSF**
  - **The telescope PSF is itself the convolution of the telescope's OTF with the ideal point source (Dirac delta function)**
- **Final observed PSF is a convolution of the OTFs of the telescope and atmosphere**
- **PSF is the modulus squared of the Fourier transform of the complex wavefront at the telescope pupil**

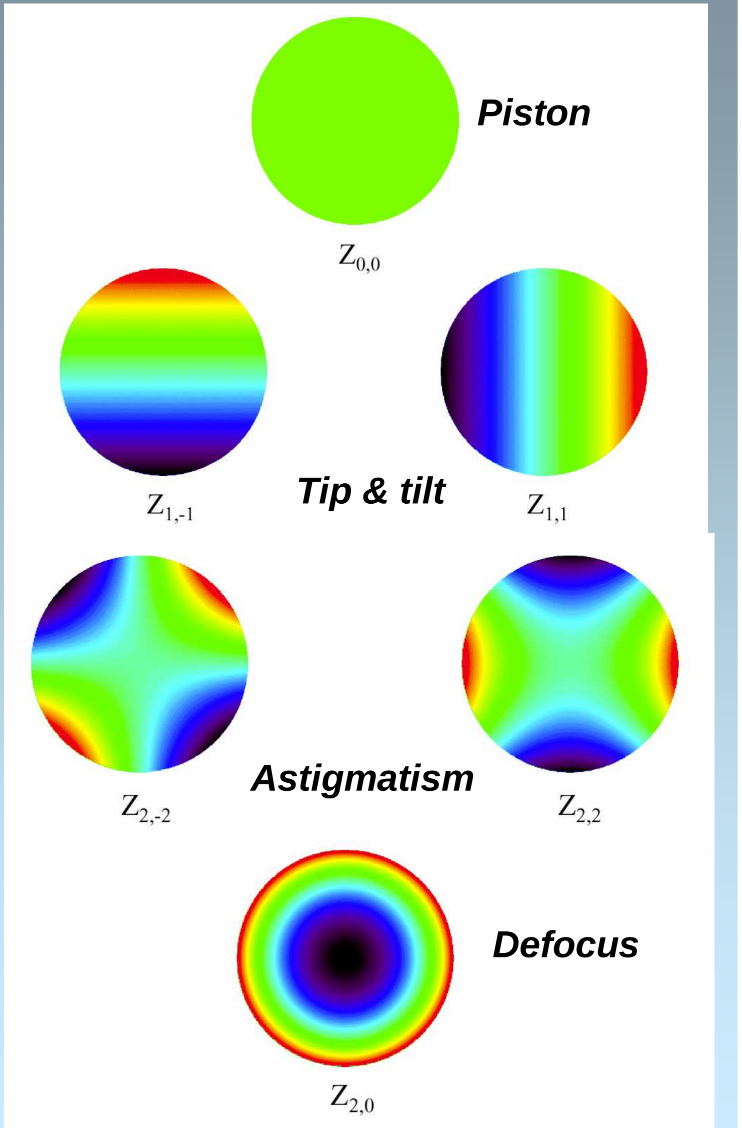




Pupil variations

- **Wavefront perturbations result in phase changes over the pupil**
- **These can be characterized by Zernike polynomials in the circular pupil plane**





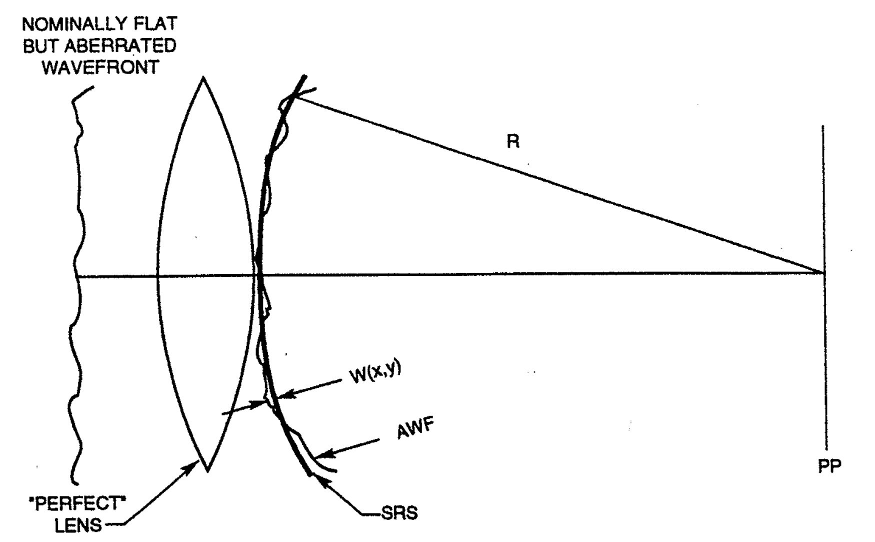
More on wavefront aberrations and Zernike terms

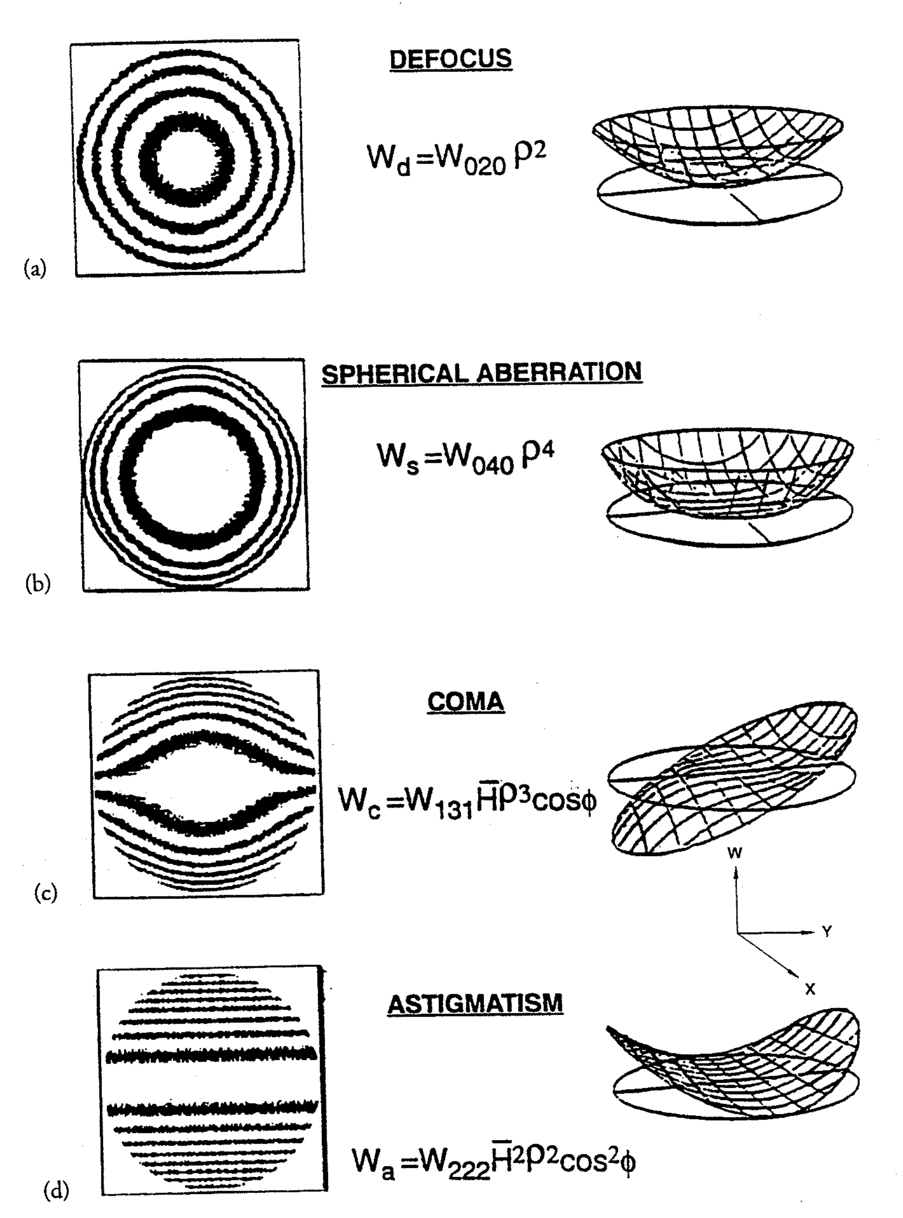
- **Check out simulation of wavefront perturbations on James Wyant's (U of A College of Optical Sciences) website**

http://wyant.optics.arizona.edu/zernikes/zernikes.htm

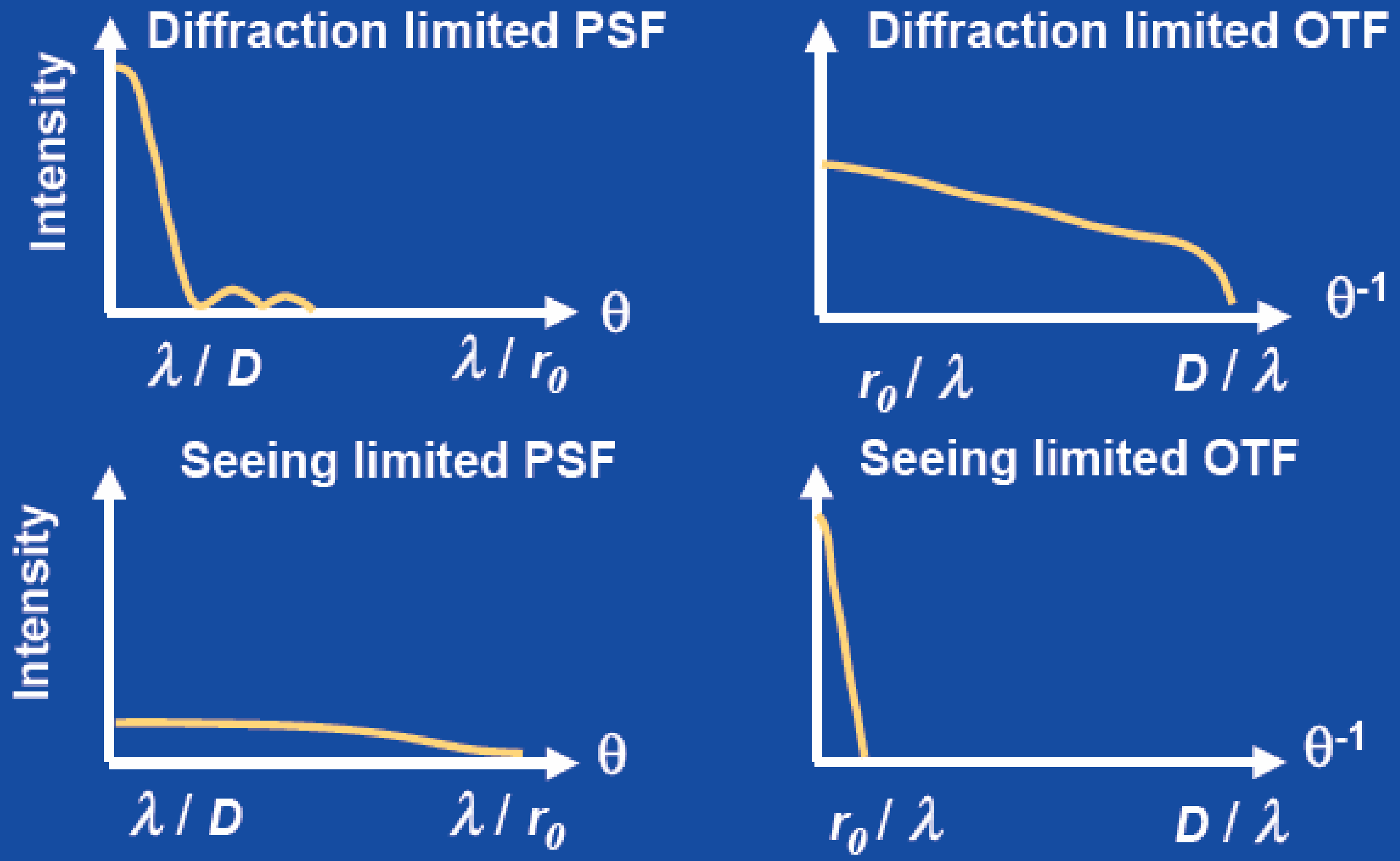
PSF variations

- **Wavefront perturbations result in PSF changes at the focus**
- **These can be characterized by Seidel polynomials**
  - **These will be convolved with the PSF to form an aberrated image**





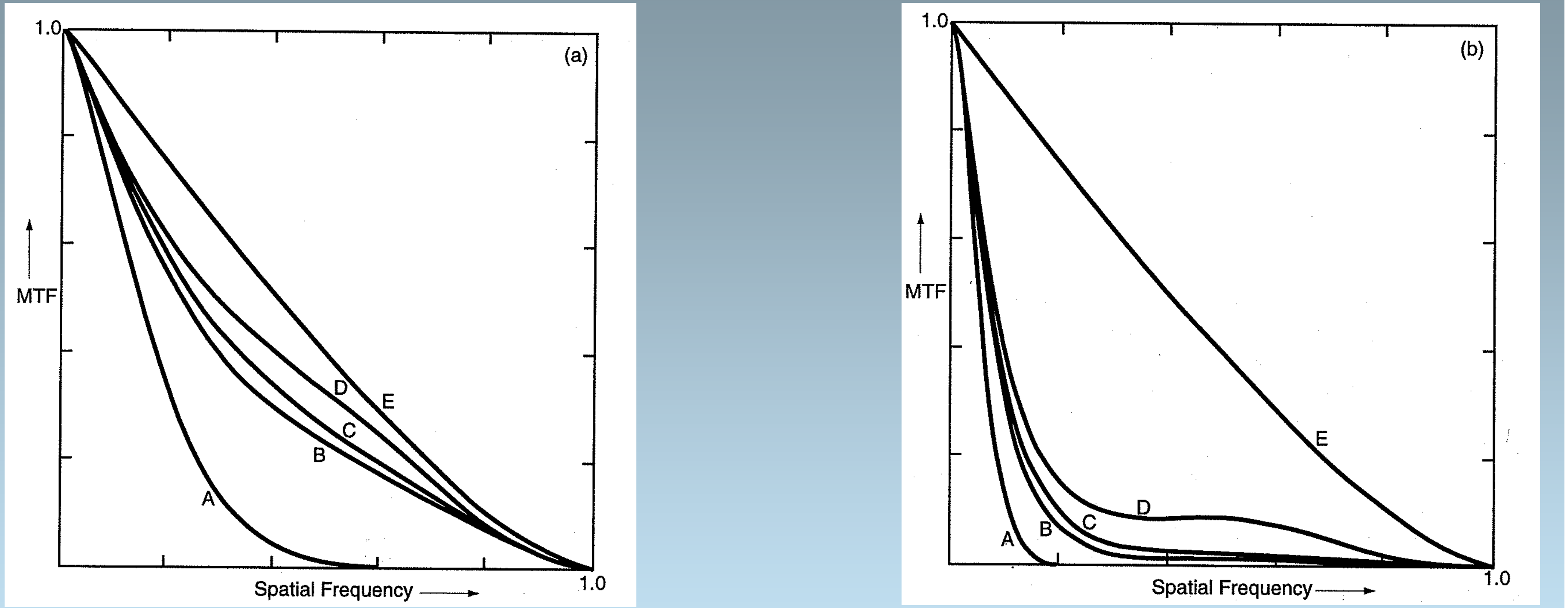
Point Spread Functions (PSFs) and Optical Transfer Functions (OTFs)



Modulation Transfer Function (MTF)

- MTF = modulus of the OTF
  - Like Power vs Amplitude in a Fourier transform or power spectrum
  - Magnitude of the OTF = MTF
- Degree to which detail is preserved from an Object to an Image
- The degree to which details of contrast, or *modulation*, in an image is preserved in the image is governed by the MTF
- If MTF = 1 ⇒ perfect transfer with no loss of detail
- Linear Fourier optics theory says:
  - Total MTF of an optical system (e.g. a telescope + eye) is the product of the individual MTFs for *all* of the optics in the total sytem
    - » i.e. all the telescope optics & the lens in the eye
  - Cannot improve things since MTF ≤ 1
  - But A-O can remove the source of poor MTF in the atmosphere

Modulation Transfer Function (MTF)



MTFs for telescopes of D/r_0 = 2 (left) and D/r_0 = 7 (right) with the following corrections:

A = no correction (fully blurred image)

B = tip/tilt correction

C = tip/tilt + focus correction

D = tip/tilt, focus & astigmatism correction

E = perfect correction to diffraction limit

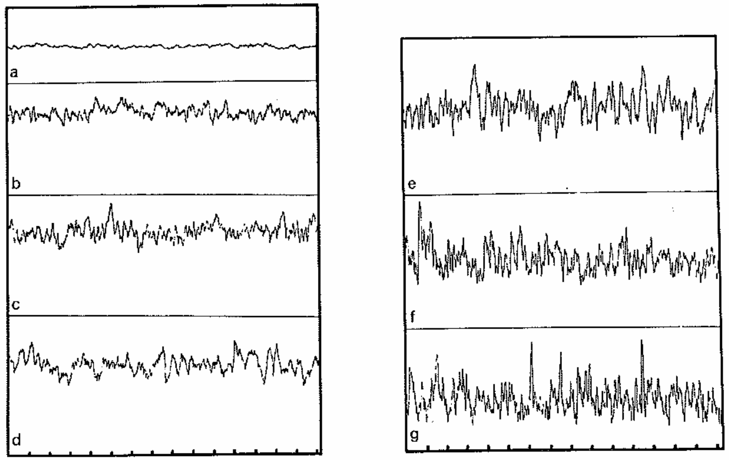
Applying high order Zernike corrections

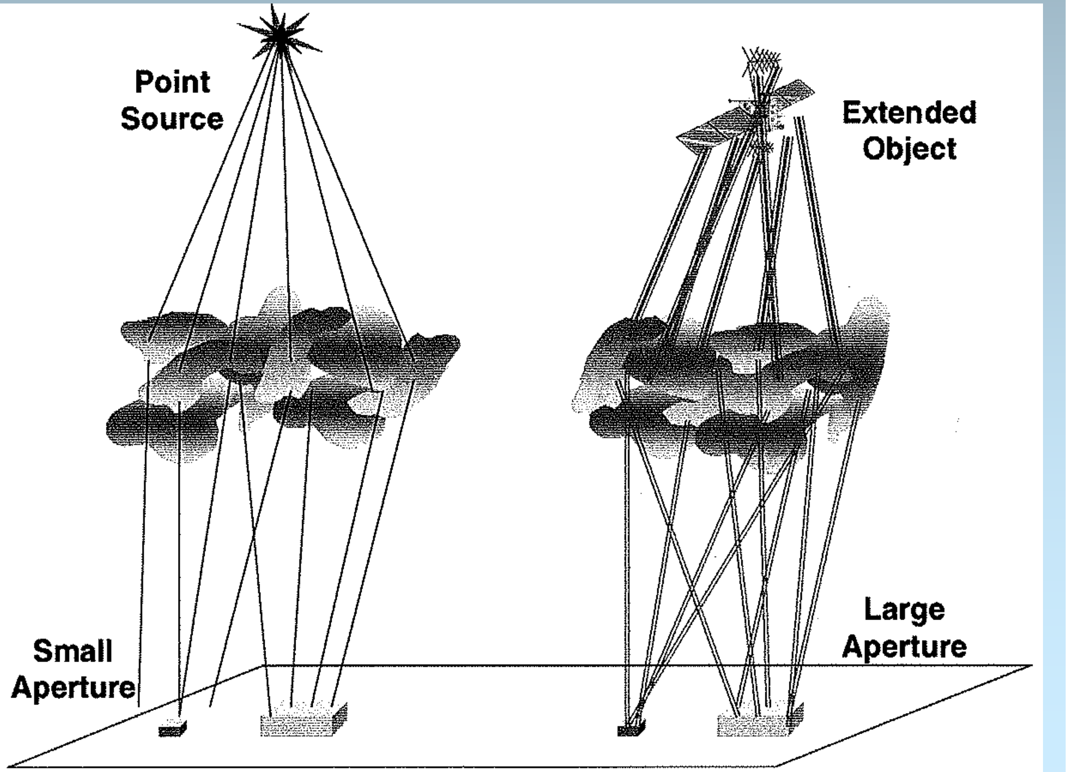
Atmospheric Scintillation

Scintillation is the intensity fluctuations arising from seeing

- ***most apparent for points sources (unresolved objects, like stars)***
- ***what produces "twinkling" of stars***
- ***not so apparent for extended objects (e.g. planets)***
- ***most obvious with small pupils (= telescope apertures)***
  (i.e. the human eye D = 6 mm, compared to binoculars D = 50 mm)

Figure 1.4. Scintillation traces for various apertures: (a) 24-in, (b) 18-in, (c) 15-in, (d) 12-in, (e) 9-in, (f) 6-in, (g) 3-in. From Warner (1962).





Atmospheric Scintillation

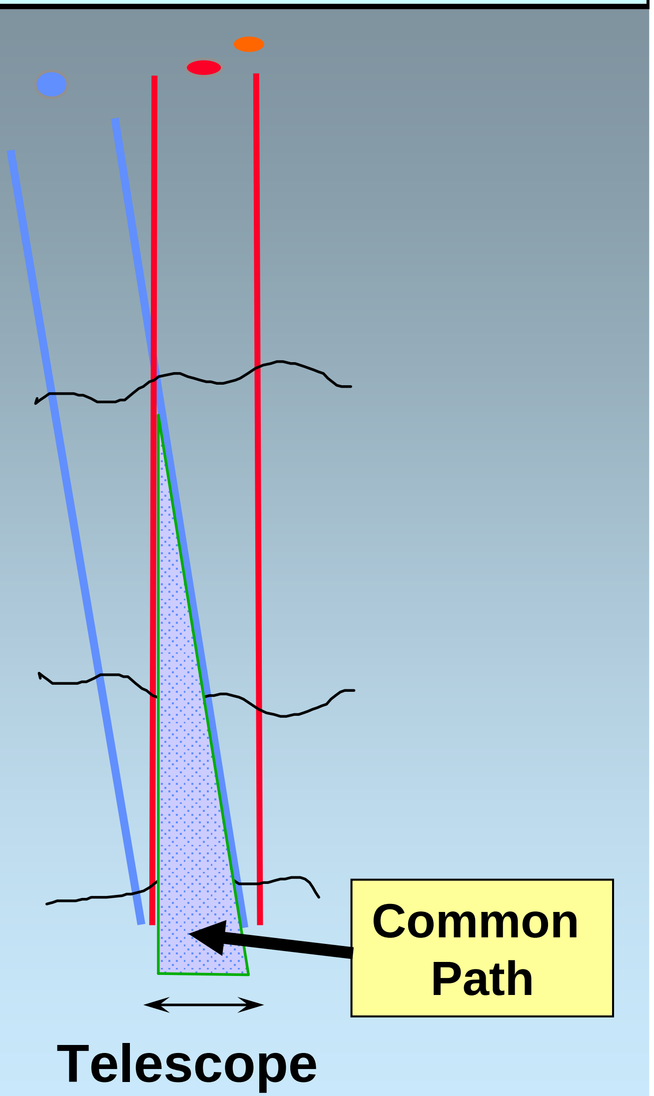
The Isoplanatic Angle

Defined as the angular region on the sky for which phase changes are correlated for all objects within that region

- *perturbations are the same for all objects in the isoplanatic "patch"*
- *for objects outside of this angle, the wavefront perturbations are uncorrelated*

So, if a reference star is used to *determine* the nature of the atmospheric wavefront perturbations, these will apply to *<u>all objects</u>* within the isoplanatic angle of the reference star.

Adaptive Optics is a technique which uses a reference star (real or artificial) to determine wavefront corrections



Effects of the Atmosphere

How do the three fundamental atmospheric parameters depend on wavelength of light?

$$r_0 = [\ 0.423\ k^2 \sec\beta \int C_n{}^2(z)\ dz\ ]^{-3/5}$$

$$\theta_0 = \left[2.91\ \ k^2\ \ \sec^{8/3}\beta \int_{\text{Path}} C_n^2(z)\ \ z^{5/3}(z)\ \ dz \right]^{-3/5}$$

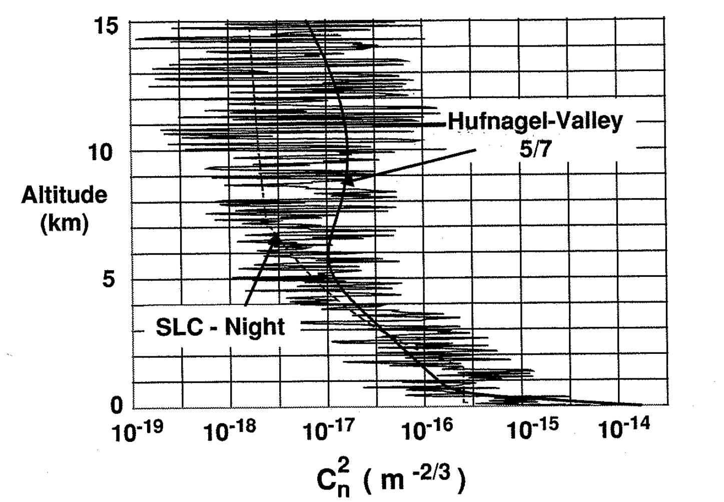
$$f_G = 2.31\ \ \lambda^{-6/5} \left[\sec\beta \int_{\text{Path}} C_n^2(z)\ \ V_{\text{Wind}}^{5/3}(z)\ \ dz \right]^{3/5}$$

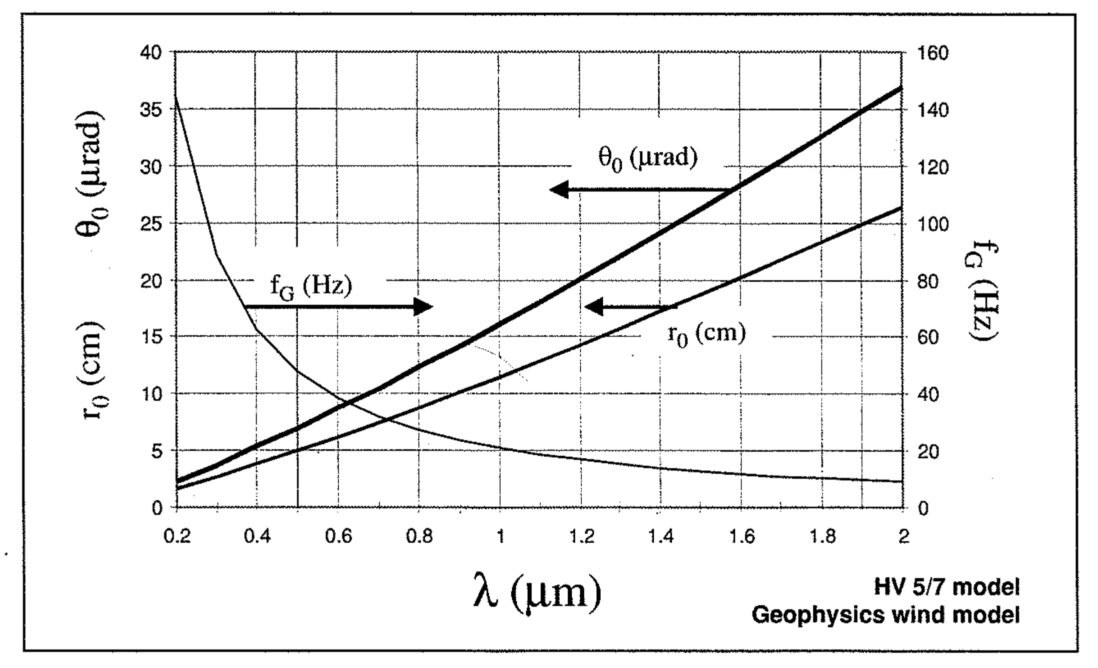
r_0: coherence length (Fried parameter)

θ_0: isoplanatic angle

f_G: Greenwood frequency ($=1/\tau_0$)

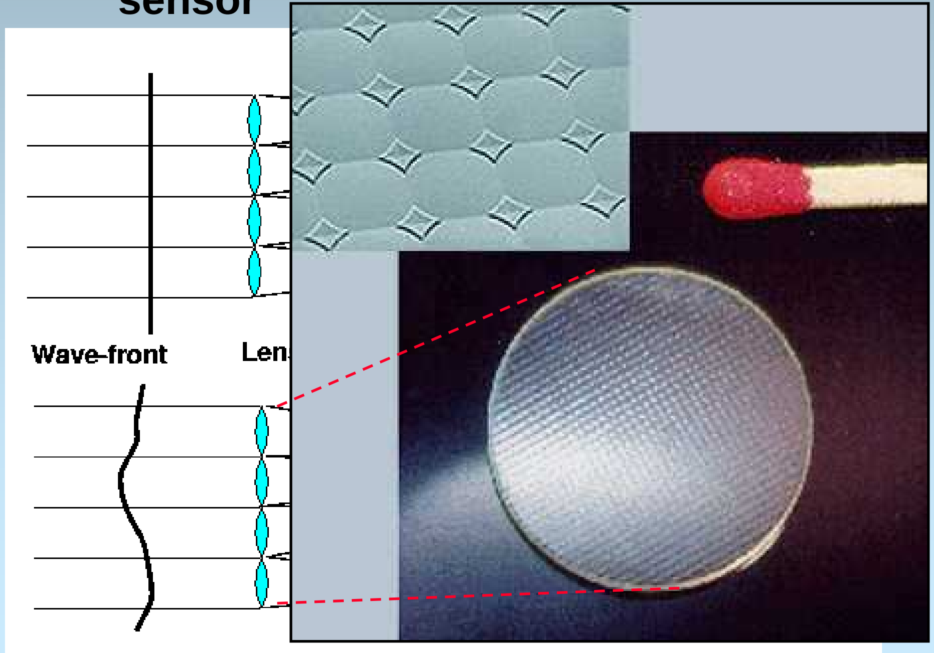
(τ_0: coherence timescale)

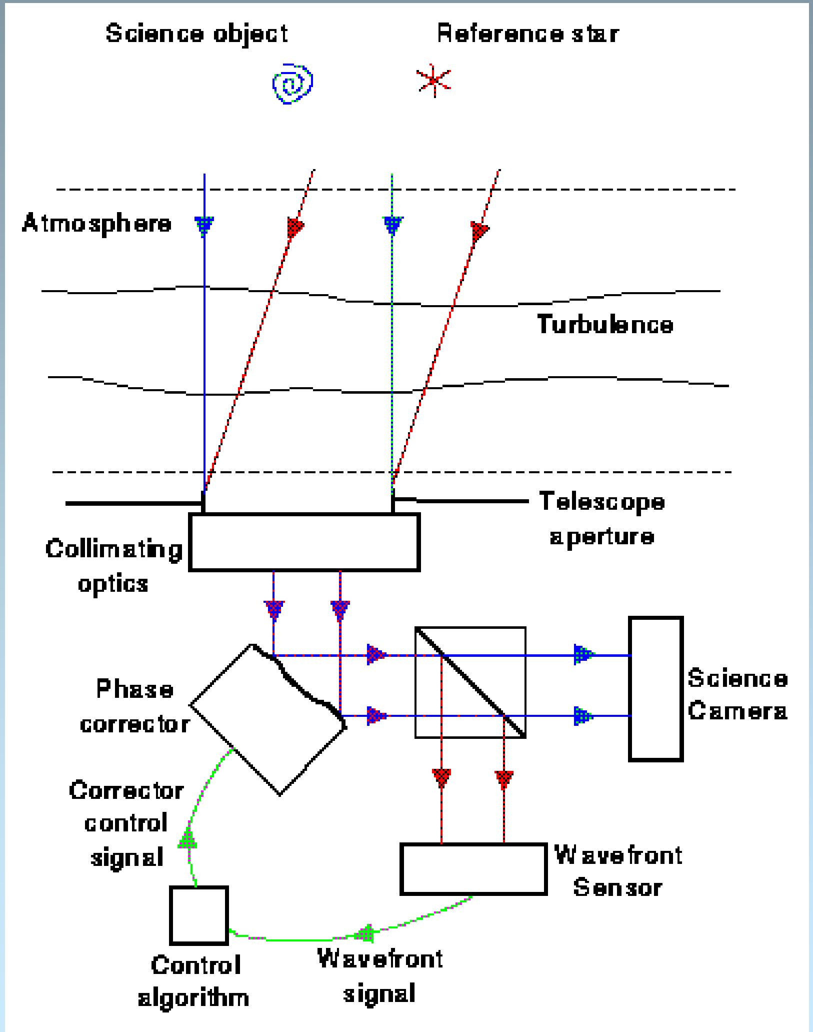




How Adaptive Optics (A-O) works

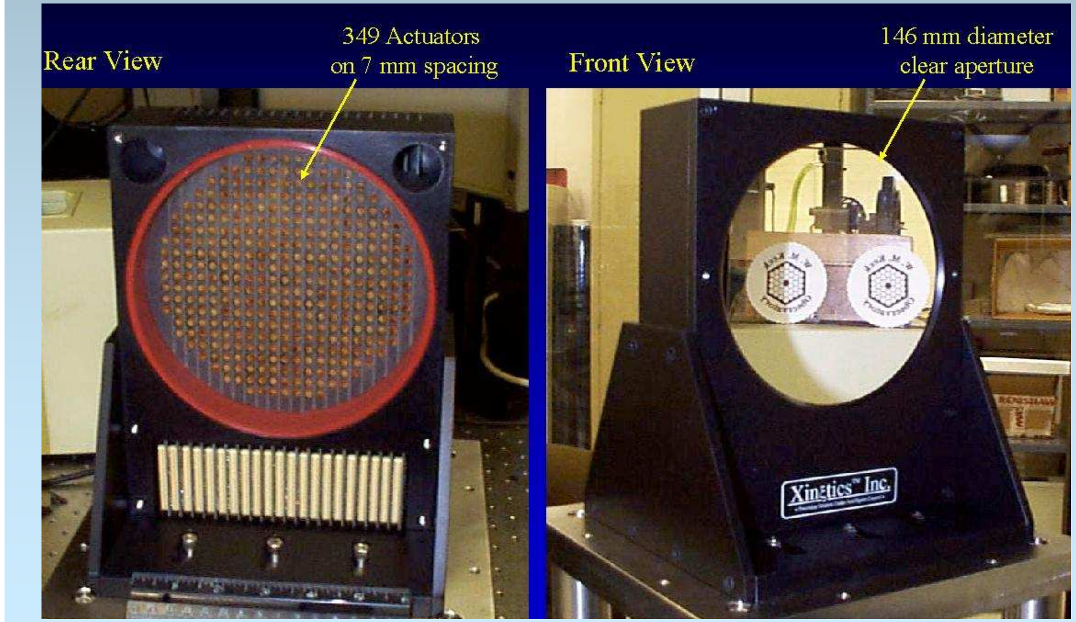
- Use bright reference star
  - Lots of photons because need to have short exposures (> Greenwood freq.)
- Analyses the wavefront from the reference star
  - e.g. Using a shack-Hartmann “wavefront sensor”

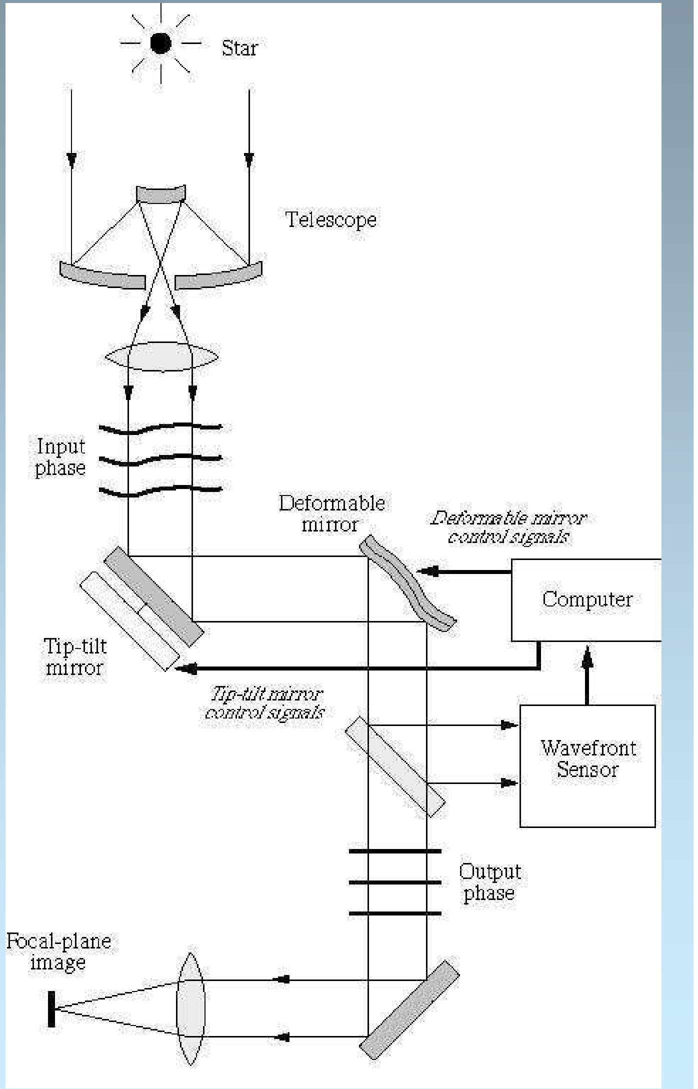




How Adaptive Optics (A-O) works

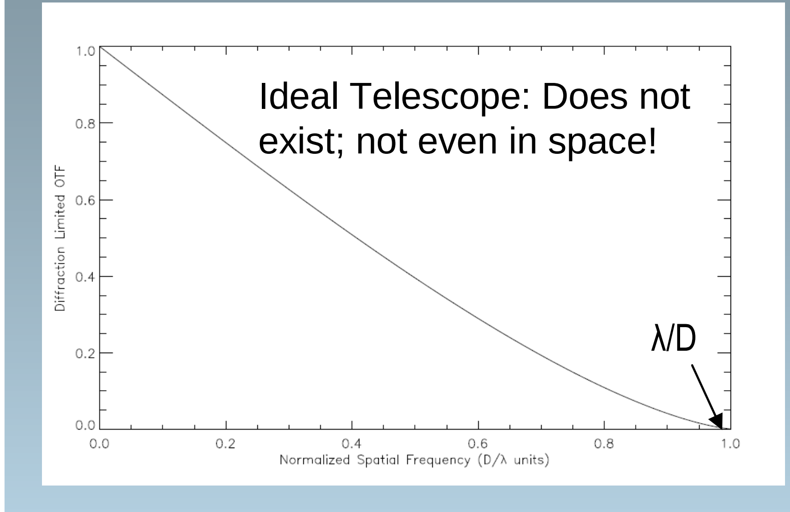
- **Determine the Zernike terms of the wavefront perturbations**
  - **Fast exposures & fast analysis**
- **Use these terms to perturb a deformable mirror in the opposite sense**
- **Remove the phase variations**
  - **Fully corrected image**



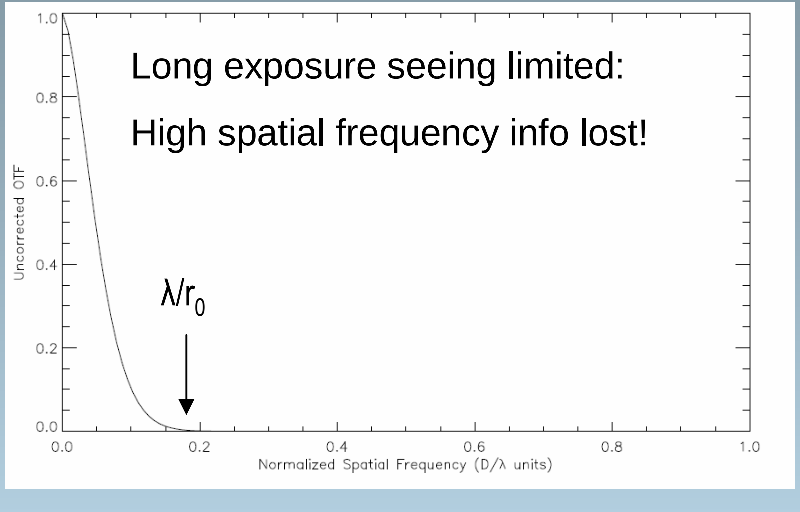


A-O Corrected OTFs

- **A-O correction reinstates some lost high ν component of the OTF**



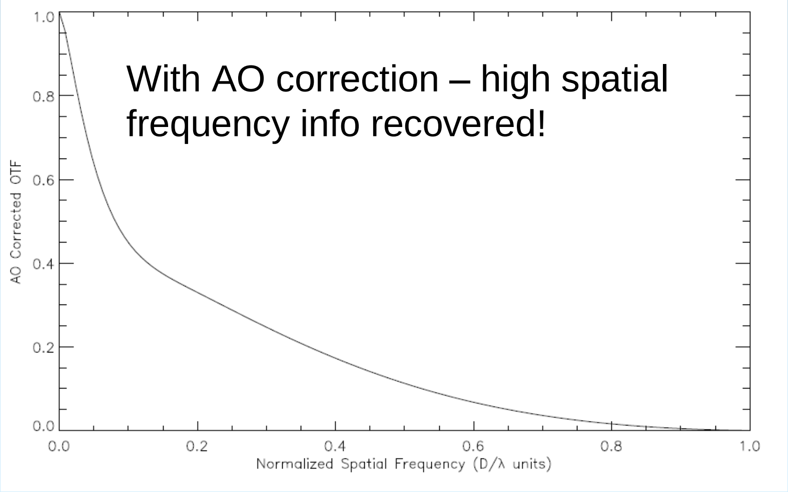
Ideal Telescope: Does not exist; not even in space!



Long exposure seeing limited:

High spatial frequency info lost!

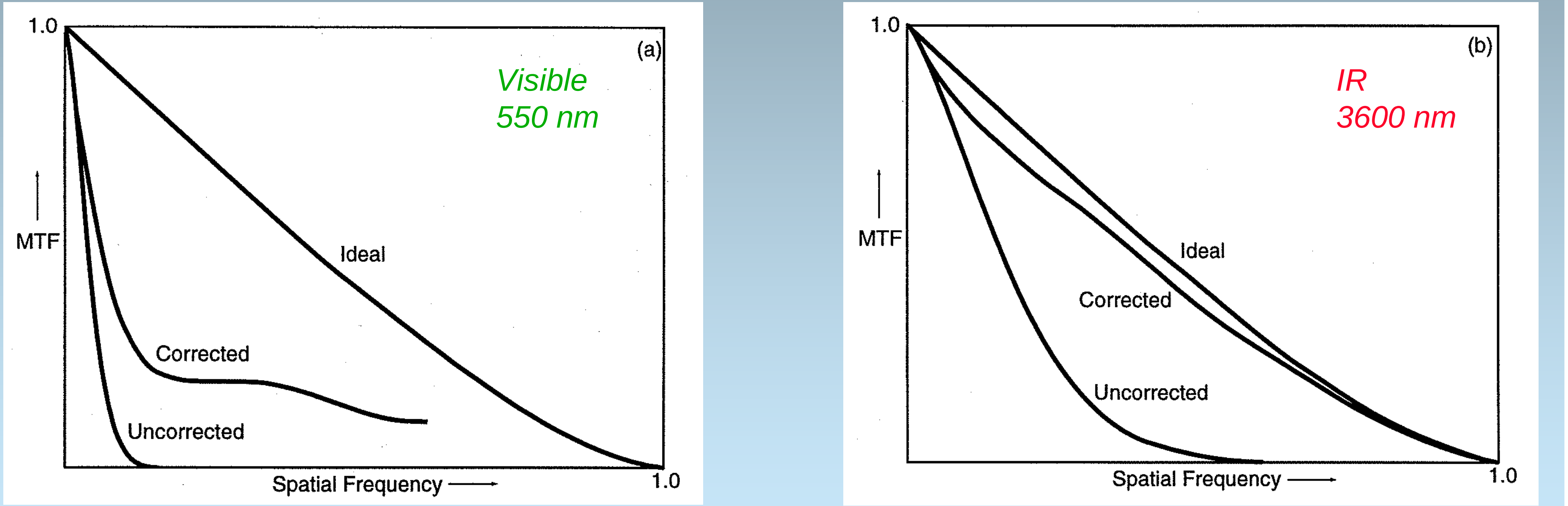
- **This produces a narrower PSF**
- **More energy moved in the “core” of the PSF from the “wings”**



With AO correction – high spatial frequency info recovered!

How Adaptive Optics (A-O) works

- Recovers the original structure in the OTF/MTF ⇒ PSF
- Equivalent to reinstating the "lost" high frequency information in the MTF

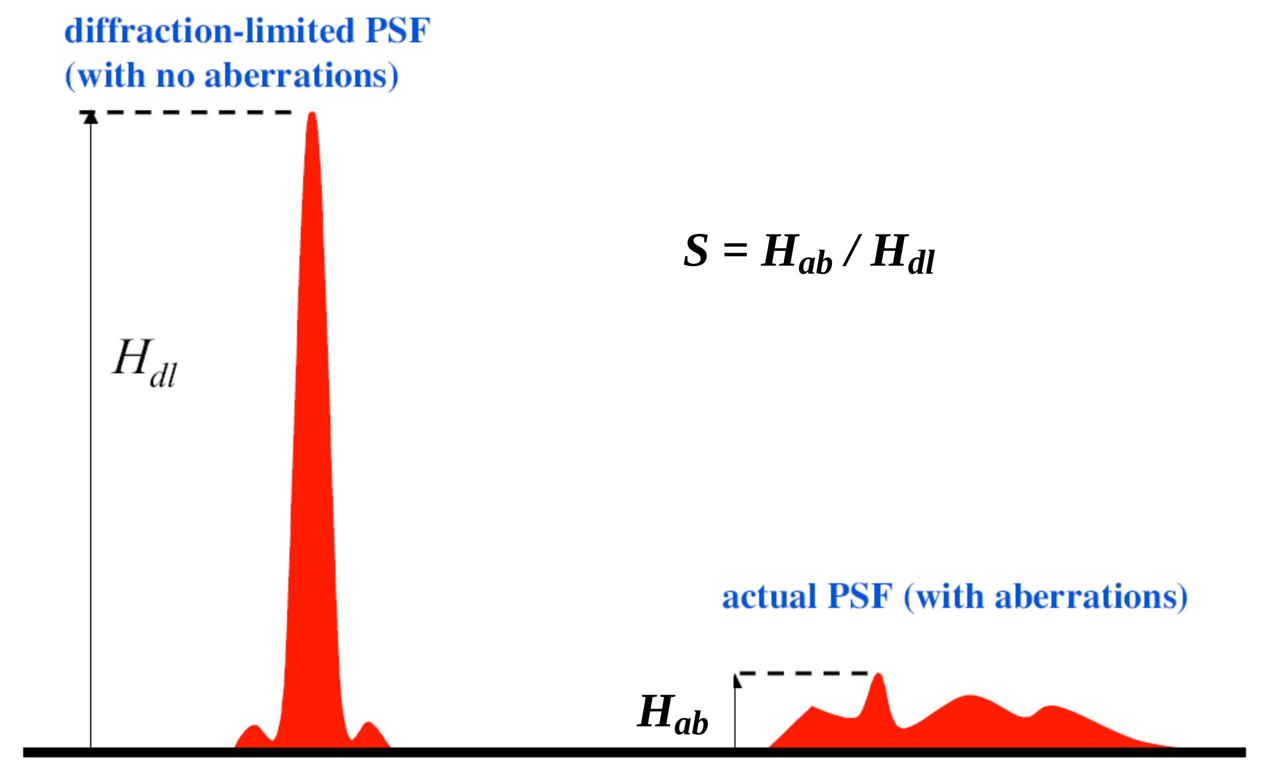


Predicted A-O correction for 2.2-m telescope with 19 actuator deformable mirror:

(a) r_0 = 10 cm @ λ = 550nm (b) r_0 = 95 cm @ λ = 3.6µm

Strehl Ratio

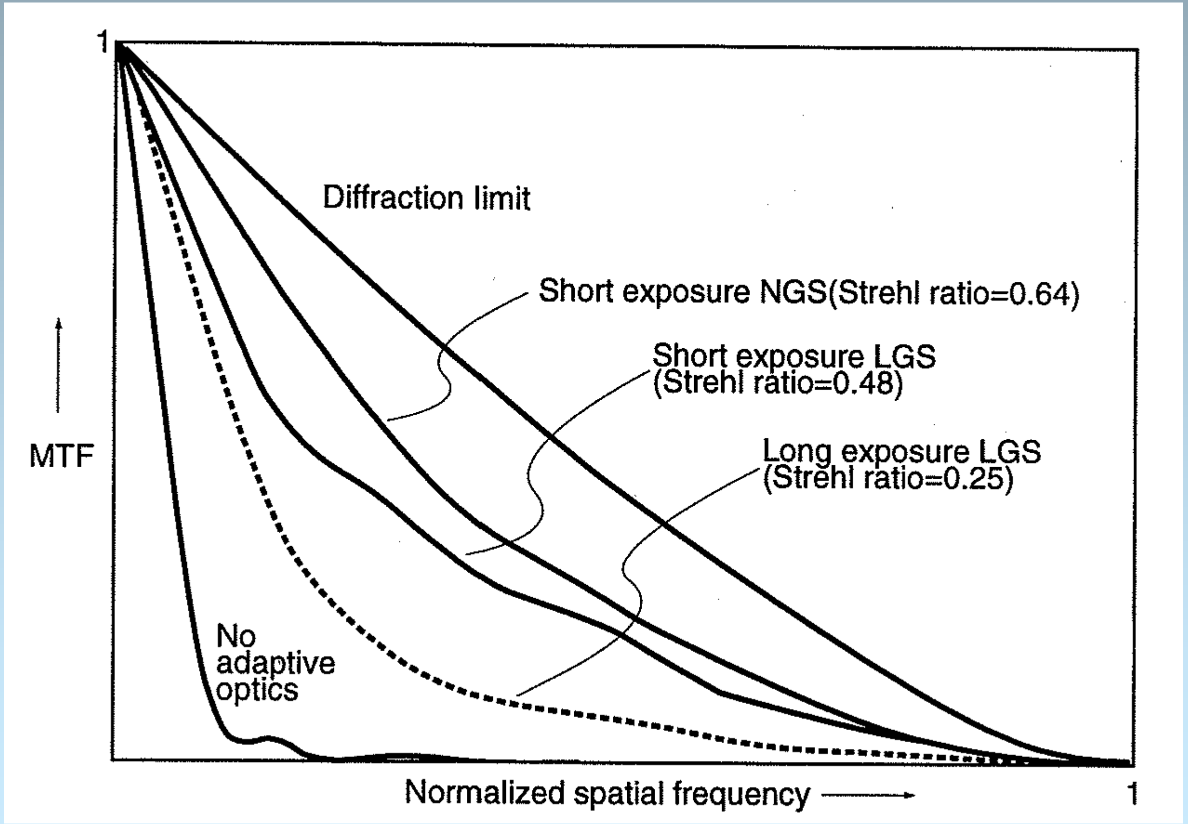
- **The ratio of the peak intensity in the *corrected* PSF to that of the diffraction limited PSF is called the *Strehl ratio***



$$S = H_{ab} / H_{dl}$$

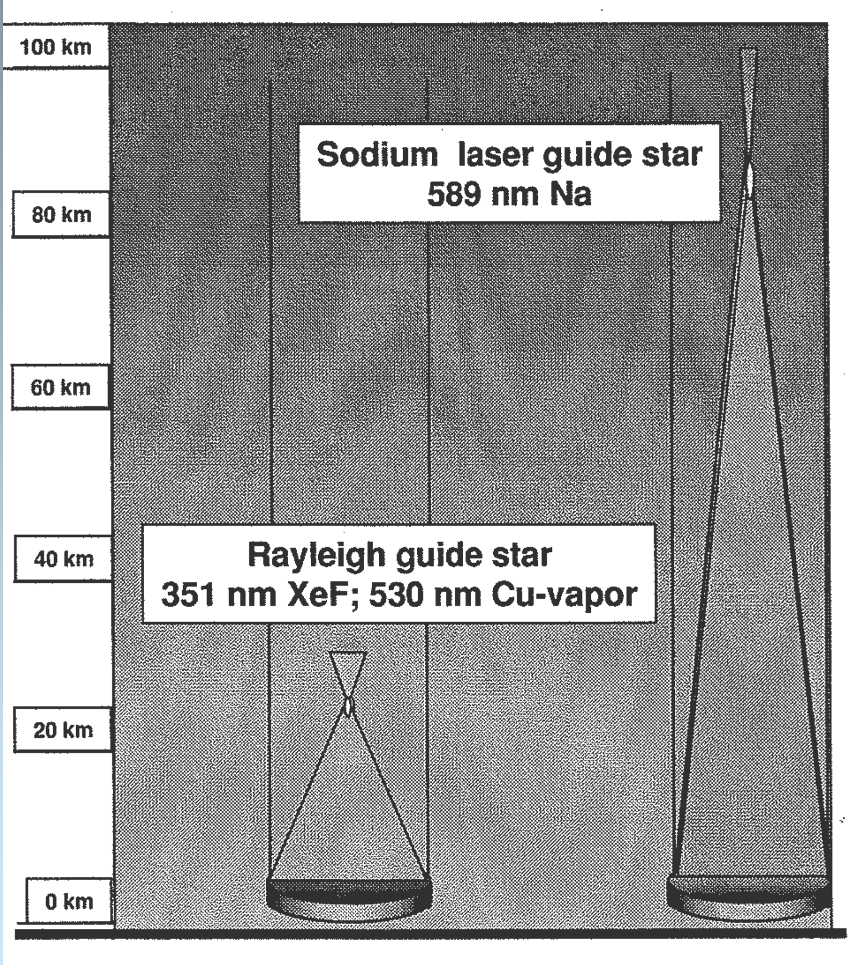
Strehl Ratio

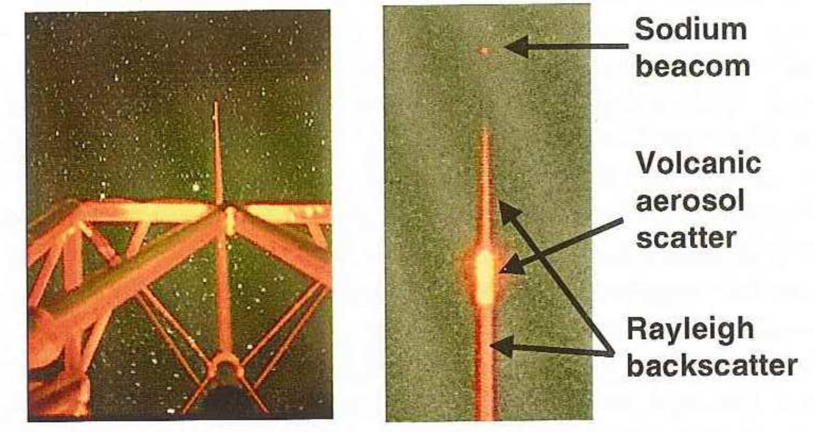
- **The ratio of the peak intensity in the *corrected* PSF to that of the diffraction limited PSF is called the *Strehl ratio***
- **Completely corrected image has a Strehl = 1 (impossible)**



Problems with Adaptive Optics

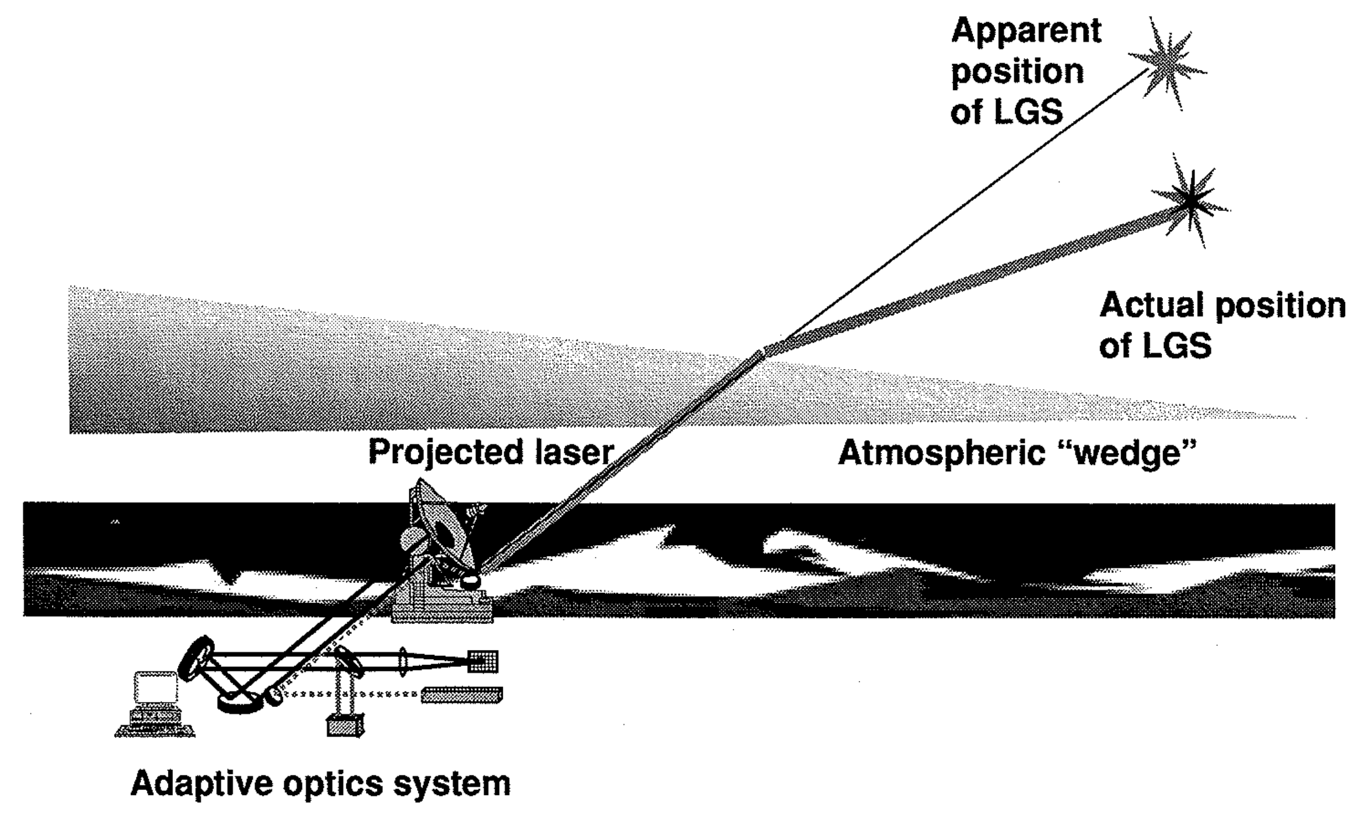
- Need to have a *bright* reference star for wavefront sensing within the isoplanatic patch
  - Only ~5” @ 550nm; ~24” @ 2.2µm
- Area density of bright enough stars too low
  - Need to create artificial guide stars
  - Excite atmosphere with Na laser (~90 km)
- r_0 decreases with wavelength
  - $r_0 \propto \lambda^{1.2}$
- # of actuators for deformable mirror $\propto D^2/r_0^2$
  - For D = 10-m (SALT) and r0 = 15 cm $\Rightarrow$ 4,400 actuators!





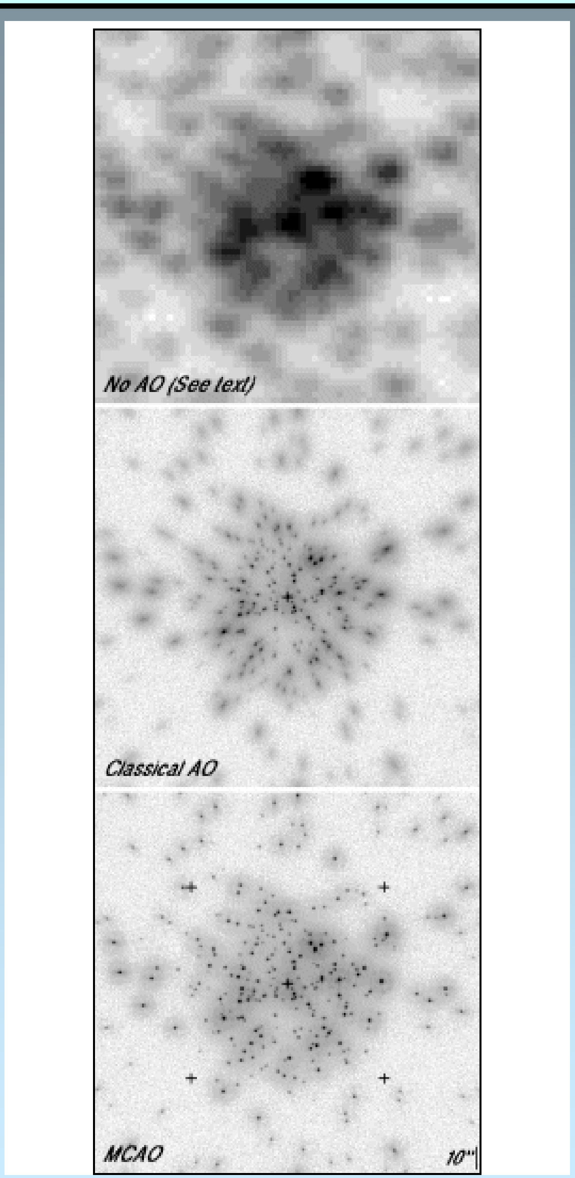
Problems with Adaptive Optics

- Can’t determine lowest order correction (tip/tilt) with a Laser Guide Star (LGS), since two-path system is impervious to atmospheric wedge effect

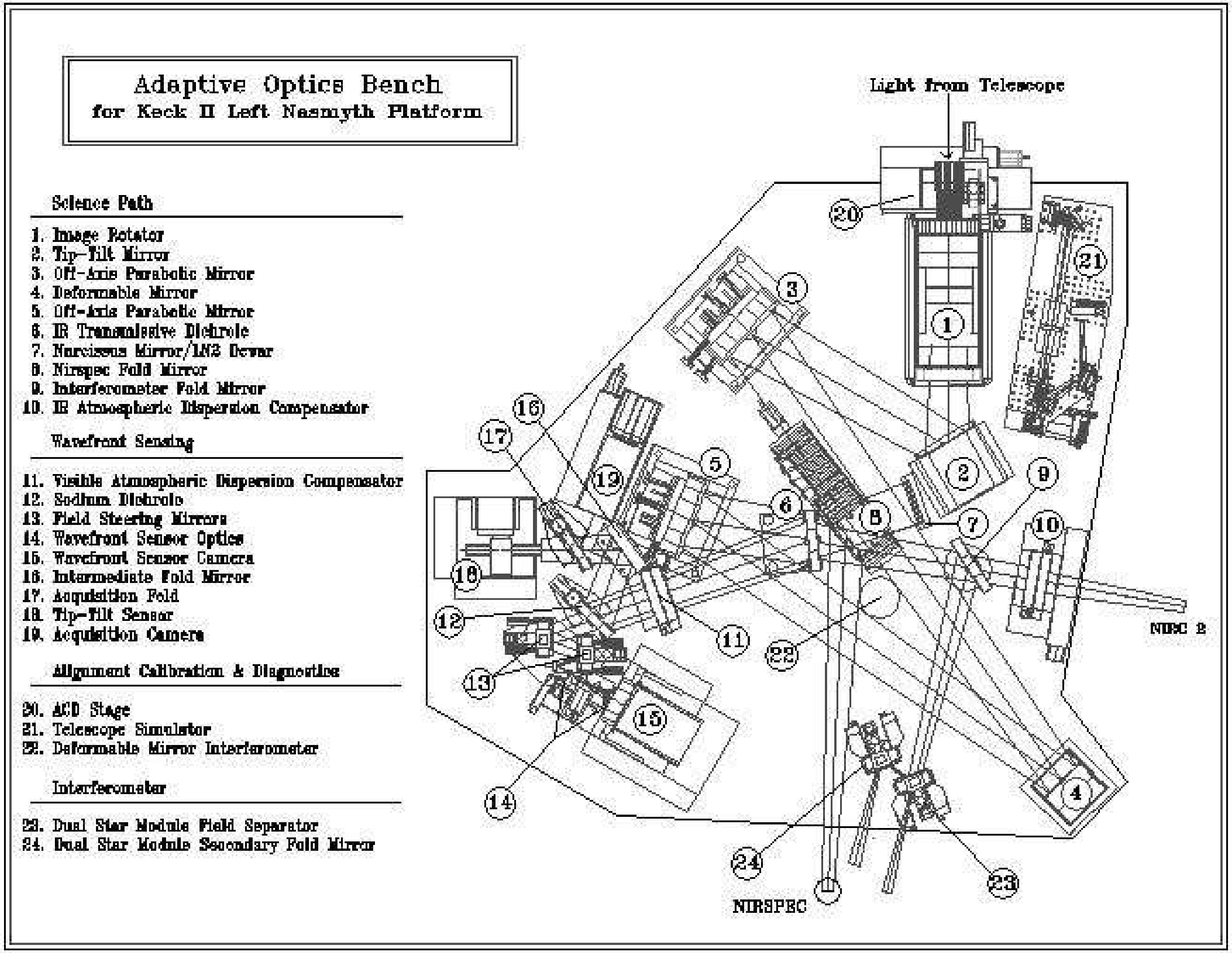


New Adaptive Optics Approaches

- Need combination of Laser Guide Stars (LGS) and Natural Guide Stars (NGS)
- Multiple LGS over wider field
  - “stitch together” adjoining isoplanatic patches
  - Multi-conjugate adaptive optics (MCAO)
- A-O systems used to correct dominant boundary layer
  - ground layer A-O (GLAO)
  - Wider field of correction



Adaptive Optics Instruments



Adaptive Optics Bench
for Keck II Left Nasmyth Platform

Science Path

1. Image Rotator
2. Tip-Tilt Mirror
3. Off-Axis Parabolic Mirror
4. Deformable Mirror
5. Off-Axis Parabolic Mirror
6. IR Transmissive Dichroic
7. Narcissus Mirror/LN2 Dewar
8. Nirspec Fold Mirror
9. Interferometer Fold Mirror
10. IR Atmospheric Dispersion Compensator

Wavefront Sensing

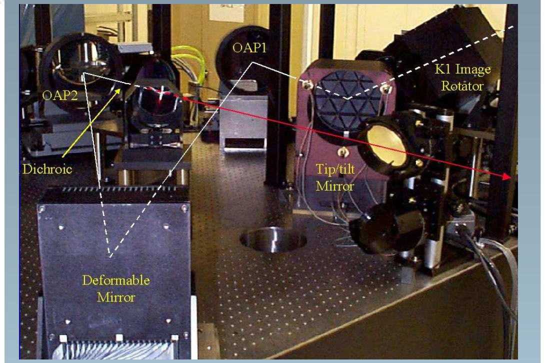
11. Visible Atmospheric Dispersion Compensator
12. Sodium Dichroic
13. Field Steering Mirrors
14. Wavefront Sensor Optics
15. Wavefront Sensor Camera
16. Intermediate Fold Mirror
17. Acquisition Fold
18. Tip-Tilt Sensor
19. Acquisition Camera

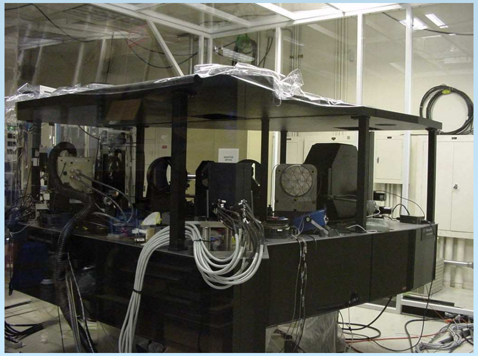
Alignment Calibration & Diagnostics

20. ACD Stage
21. Telescope Simulator
22. Deformable Mirror Interferometer

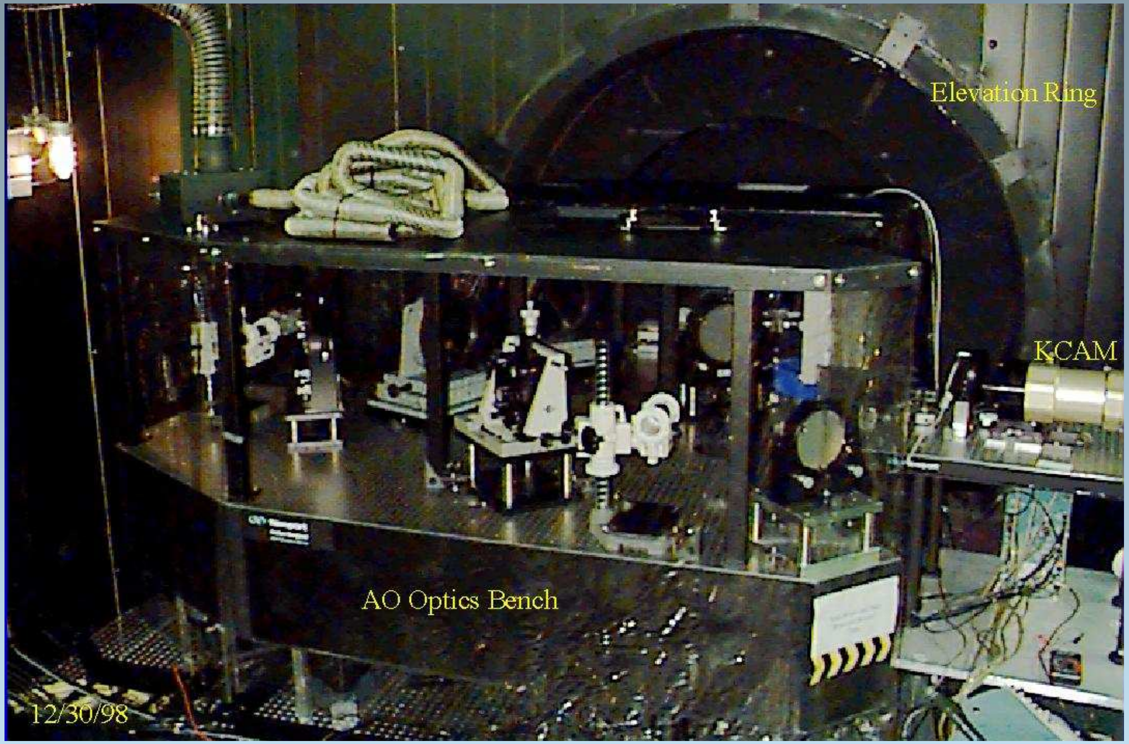
Interferometer

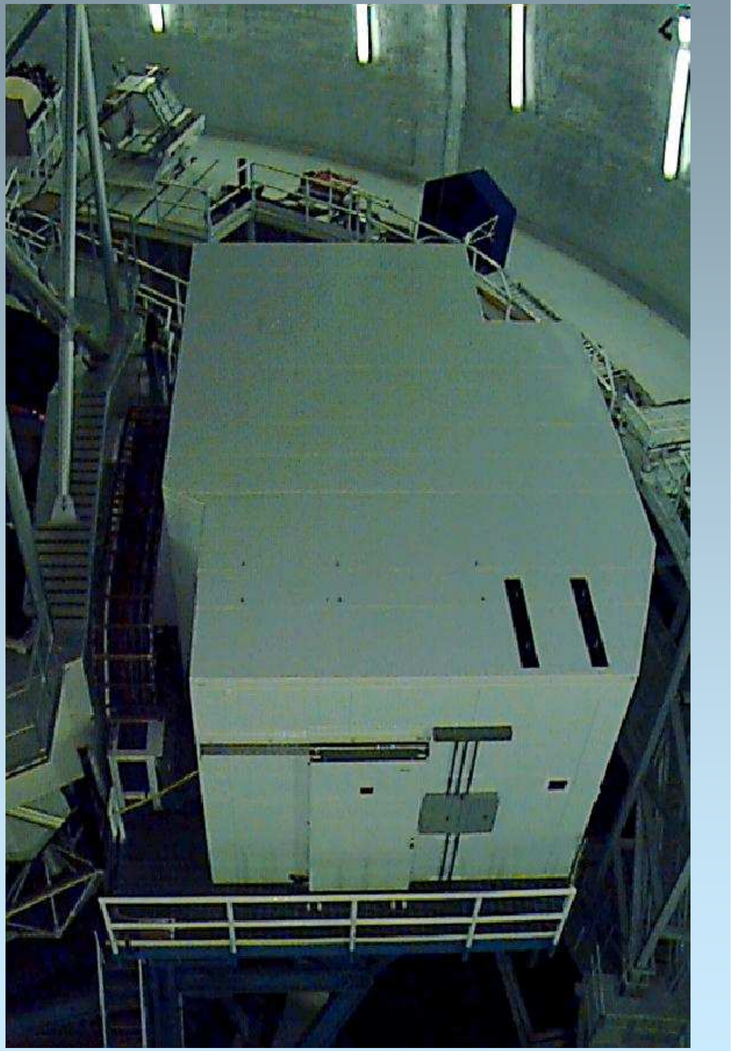
23. Dual Star Module Field Separator
24. Dual Star Module Secondary Fold Mirror



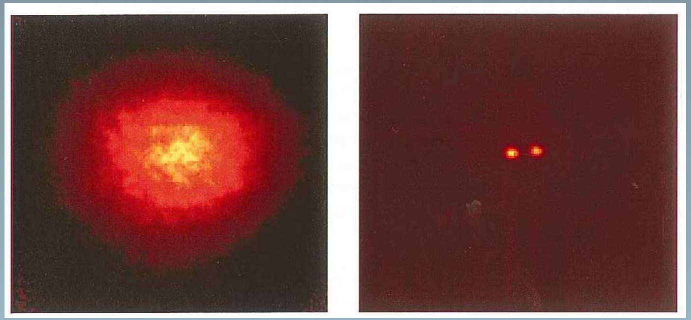


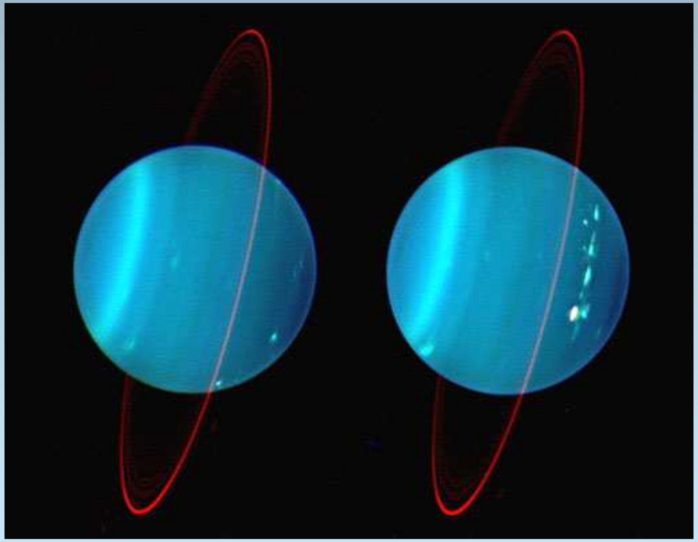
Adaptive Optics Instruments

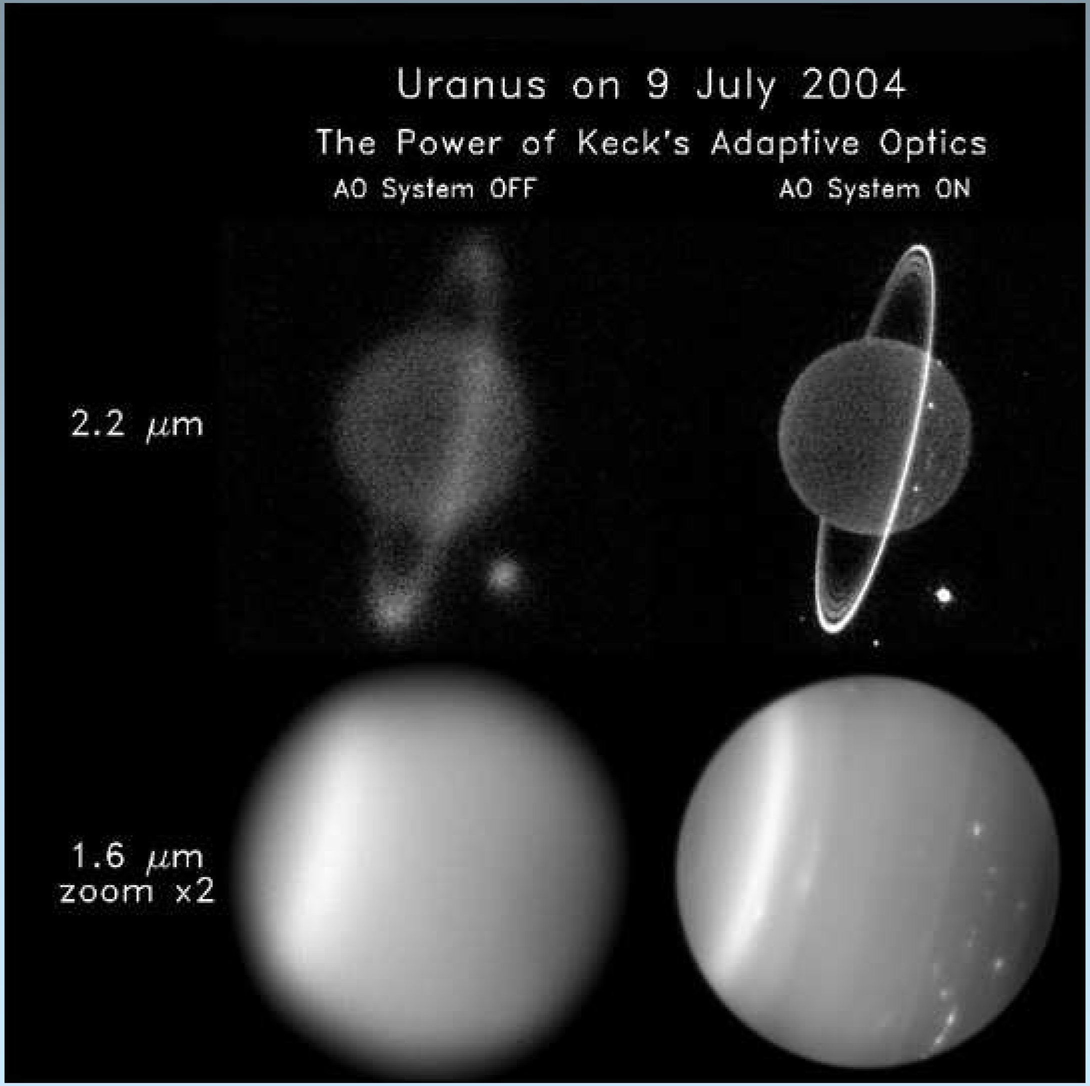




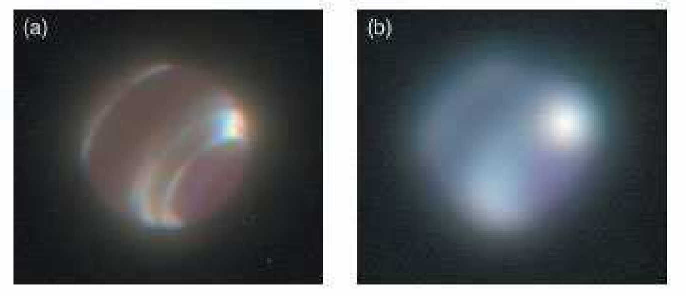
Adaptive Optics Results

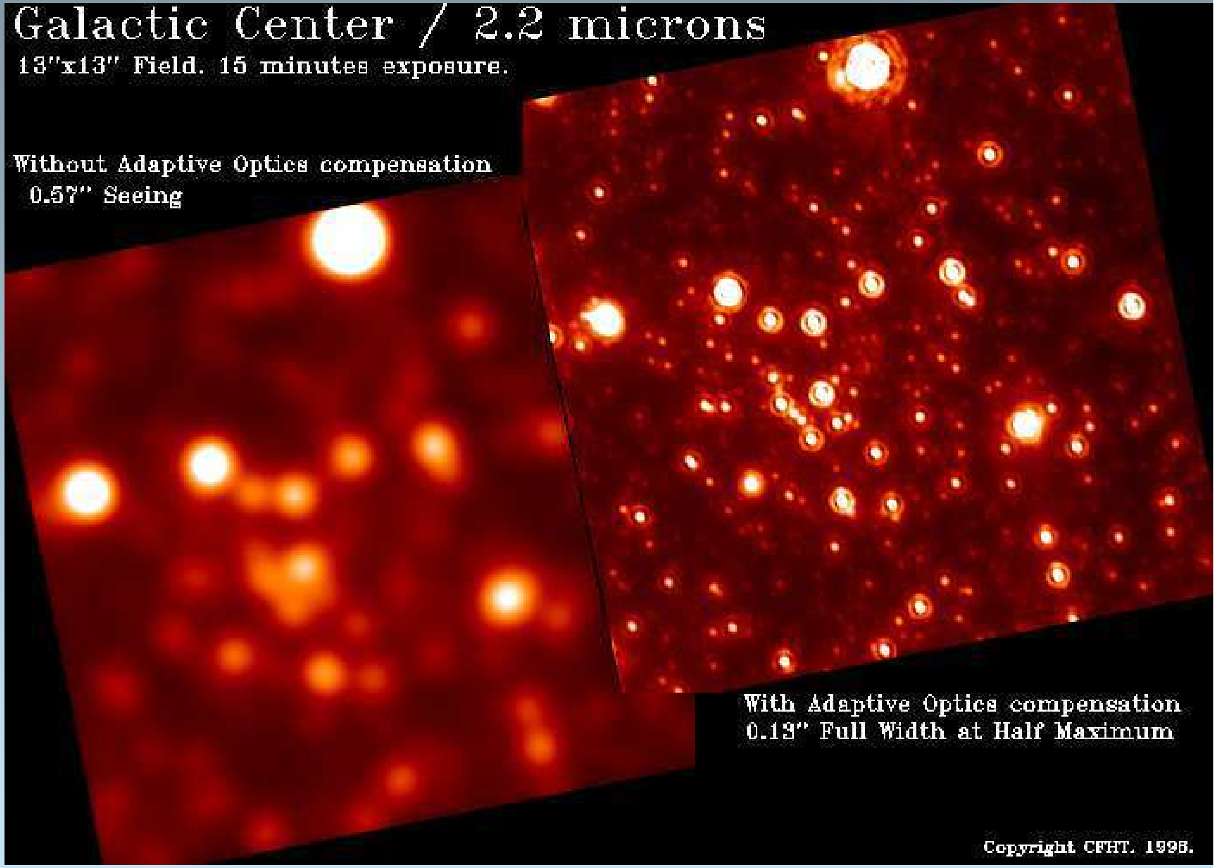






Adaptive Optics Results





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- *The Design and construction of Large Optical Telescopes:* P. Y. Bely (ed.), [Springer; SAAO library)
- *An Introduction to Adaptive Optics*, Robert K. Tyson [SPIE: SAAO library]
- *Telescopes I & II*, Dave Kilkenny (NASSP lecture notes)

Other material from:

M. Sarazin (ESO)

CfAO Summer School 2004 notes

Fourier Optics, J. Goodman

C.O. Font Jimenez

Nick Strobel (*www.astronomynotes.com*)

G. Yoon (www.imagine-optic.com/downloads/imagine-optic_yoon_article_optical-wavefront-aberrations-theory.pdf)

J. Wyant (http://wyant.optics.arizona.edu/zernikes/zernikes.htm)