



Adaptive Optics Overview

Presentation to Summer School

2003, August 10

Jerry Nelson



Outline

- **The Center for Adaptive Optics**
 - CfAO Organization and Mission
 - Thematic structure
- **Main thrust of summer school: pragmatic**
 - Design, construction, evaluation, use of AO systems
 - Astronomy and vision science
- **Principles of Adaptive Optics**
 - Basic ideas
 - Astronomy
 - Vision science
- **Mathematical imaging improvement**
- **Design and evaluation of AO systems**
- **Existing systems**



Background

- **NSF periodically supports Science and Technology Centers (program started in 1989)**
 - Supports innovative, cross disciplinary programs
 - Support for up to 10 years
 - Support up to \$4M/yr
- **CfAO is NSF funded STC, start November 1999**
 - One of five selected that year by NSF for funding out of ~ 400
- **Center headquartered at the University of California at Santa Cruz**



Mission and Strategies

- **CfAO Mission : Advance and Disseminate Adaptive Optics knowledge in service to science, health care, industry, and education**
- **CfAO will pursue its purpose and achieve its goal by:**
 - 1) Demonstrating the power of AO by doing forefront science
 - 2) Increasing the accessibility of AO to the scientific community
 - 3) Developing and deploying highly capable AO systems and laser beacons
 - 4) Coordinating and combining research efforts to take advantage of the synergies afforded by the Center mode of operations

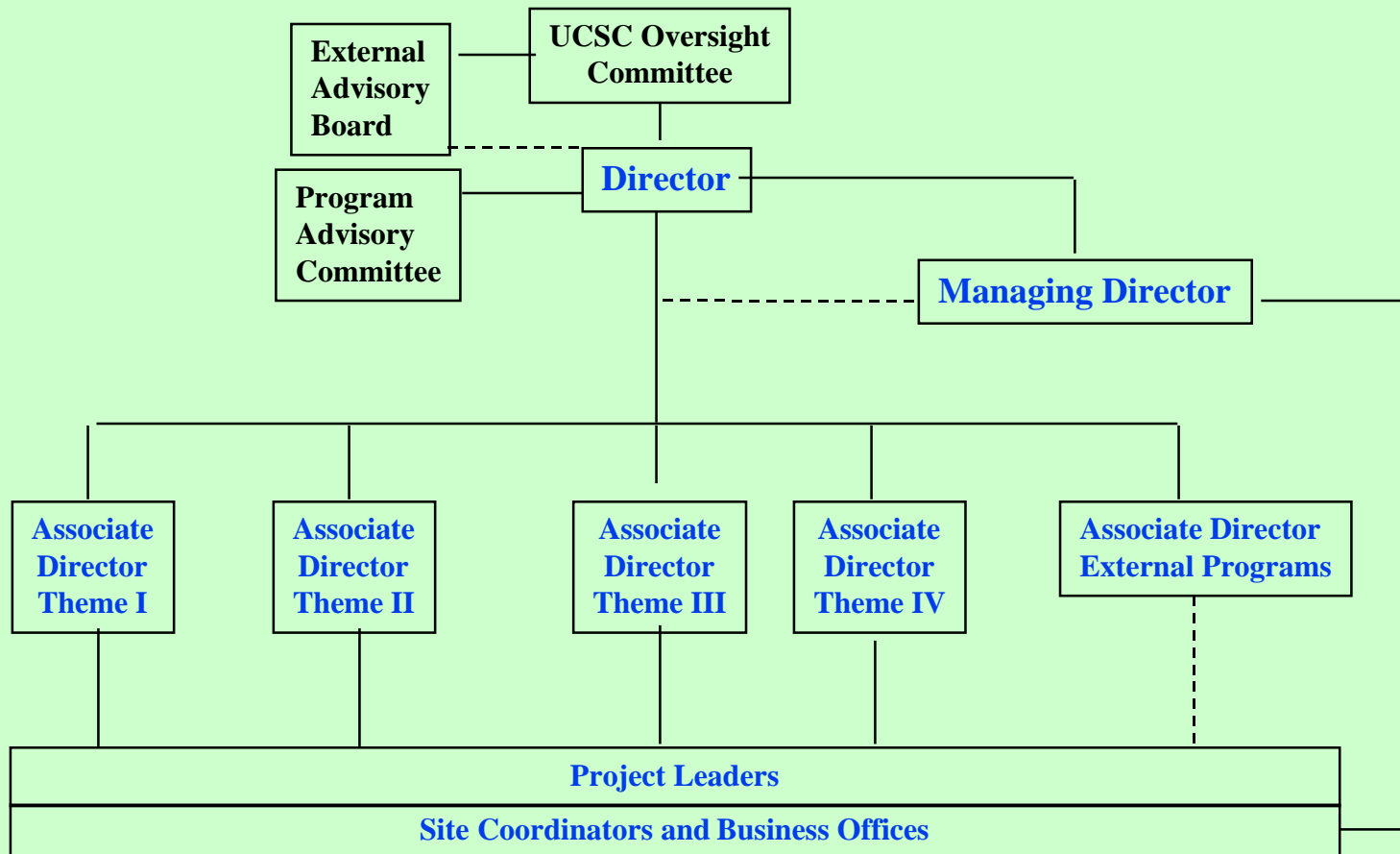


Strategies (cont)

- 5) Integrating education with our research
 - 6) Building a Center community that is supportive of diversity through vigorous recruiting, retention, and training activities
 - 7) Encouraging the interaction of vision scientists and astronomers to promote the emergence of new science and technology
 - 8) Leveraging our efforts through industry partnerships and cross-disciplinary collaborations
- We will enable all of these strategies by achieving, nurturing, and maintaining NSF funding as a Science and Technology Center.



Organizational Chart



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Theme Organization

- **Designed to focus our efforts, to foster Center-wide collaborations toward common goals (Themes), and to leave valued “monuments” as our legacy**

- **Themes**

Theme 1: Education and Human Resources

Theme 2: AO for Extremely Large Telescopes

Theme 3: “Extreme AO” (ultra high contrast)

Theme 4: Compact Vision Science Instrumentation for Clinical and Scientific Use



How CfAO works

- **Composed of ~ 12 academic institutions**
 - Strong astronomy (UCB, UCSC, UCLA, UCI, Caltech, Chicago)
 - Astronomical observatories (Keck, Lick, Gemini, Palomar)
 - Strong Vision science (Rochester, Houston, Indiana)
 - Strong technology (LLNL, Montana, Michigan tech, NOAO)
 - Industrial partners
 - Education partners (Exploratorium, UCSC education, Cosmos, Maui, etc)
- **Funding Process**
 - Proposals submitted annually and reviewed by PRC for quality, previous effectiveness, relation to themes, and synergy with other members- cooperative research strongly encouraged
 - Multi year projects encouraged



CfAO

- CfAO Brochures are in your packets
- CfAO building will be the host location for the reception tomorrow
- **Lisa Hunter will present a description of the summer intern program and student presentations after this talk**
- A Laboratory for Adaptive Optics was recently funded with a \$9M grant by the Moore Foundation, and is based at UCSC. **Claire Max will give a talk at the summer school** that describes the objectives of LAO and the opportunities for research scientists to use or take advantage of these facilities



CfAO Summer School 2003

- **CfAO sponsors a summer school in adaptive optics each year**
 - Even years are introductory
 - Odd years are more pragmatic and deal with advanced aspects
 - Introductory text available for this years students
 - Participants include
 - Astronomers
 - Vision scientists
 - Technologists
 - Engineers
 - Students



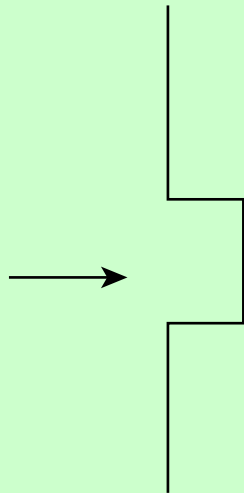
What is Adaptive Optics

- **AO is an optical system that senses wavefront error (optical aberrations) and cancels them with an equal and opposite wavefront error**
 - Slopes of wavefront errors determine image blur
 - Wavefront error measurements are processed to produce an estimate of the wavefront error
 - Estimate of the wavefront errors must be good enough (temporal and spatial resolution, accuracy) to allow adequate estimate and removal of the wavefront error
 - This error estimate is applied to a wavefront compensator or deformable mirror
 - This process is repeated in real time as frequently as needed to keep up with the temporal variations
- **This allows the optical system to deliver improved images ultimately limited only by diffraction**
- **AO is designed to change the correction as a function of time as the disturbance varies in time**



How a Deformable Mirror Works

BEFORE

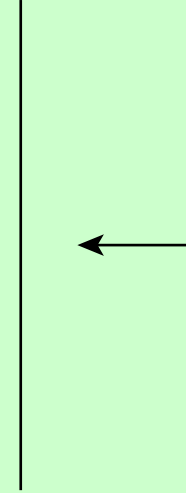


**Incoming
Wave with
Aberration**



**Deformable
Mirror**

AFTER

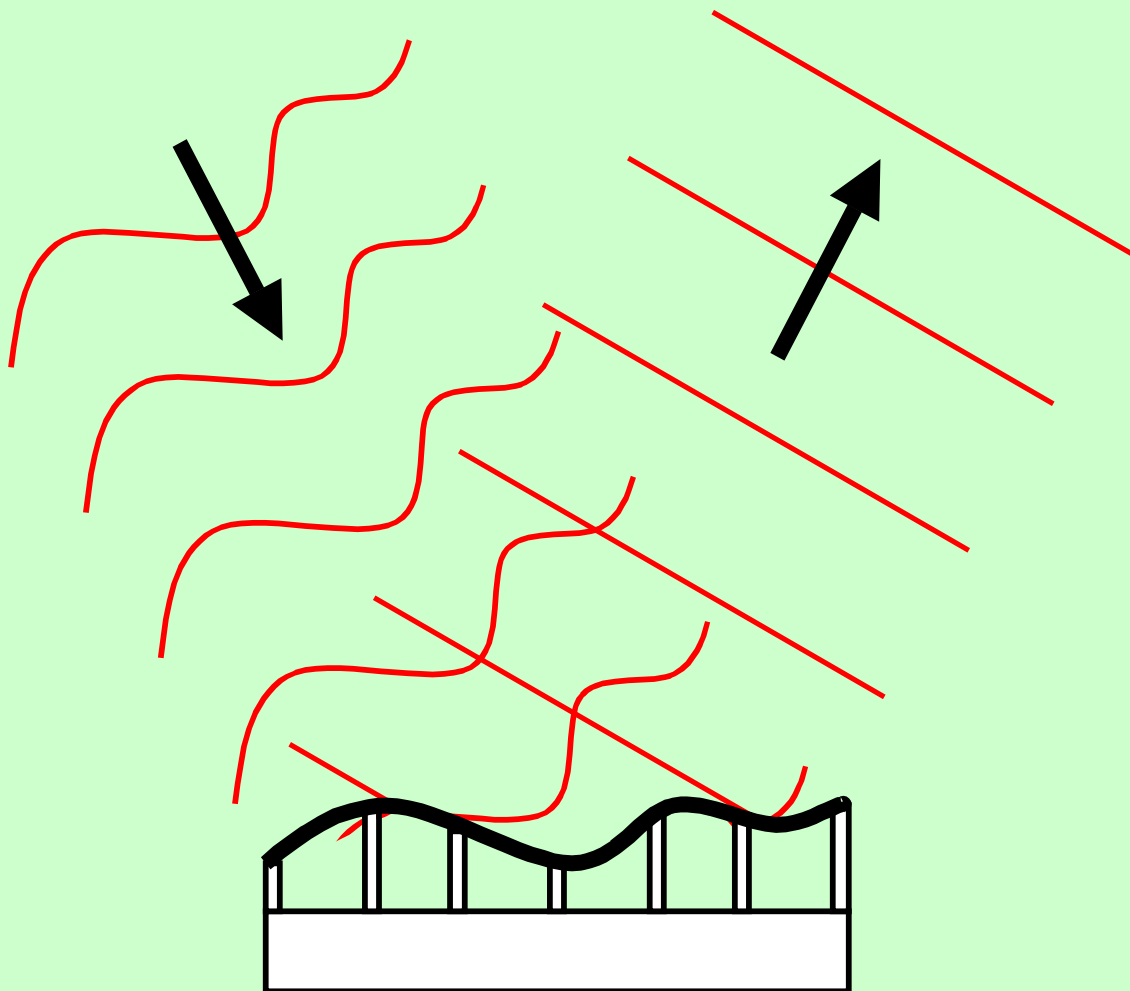


**Corrected
Wavefront**



**Deformable
Mirror**

The Deformable Mirror





Deformable Mirrors

- **Scot Olivier will give a talk on the principles of deformable mirrors at the summer school**
- **Buzz Graves will give a talk on AO for Laser communications which includes a discussion of bimorph DM's**



DM requirements

- **Dynamic range:**
 - Typical stroke for astronomy \pm a few microns, for vision science up to 10 microns
- **Temporal frequency response:**
 - DM must respond faster than coherence time τ_0
- **Spatial density of actuators**
 - Need enough actuators to remove the expected wavefront errors
- **Influence function of actuators:**
 - Shape of mirror surface when you push just one actuator (like Greens' function)
 - Can optimize your AO system with a particular influence function, but pretty forgiving



Types of deformable mirrors: large

- **Segmented**

- Made of separate segments with small gaps
- Each segment has 1 - 3 actuators and can correct:
 - Piston only (in and out), or
 - Piston plus tip-tilt (three degrees of freedom)

- **“Continuous face-sheet”**

- Thin glass sheet with actuators glued to the back
- Zonal (square actuator pattern)
- Modal (sections of annuli, as in curvature sensing)

- **Bimorph**

- 2 piezoelectric wafers bonded together with array of electrodes between them. Front surface acts as mirror.

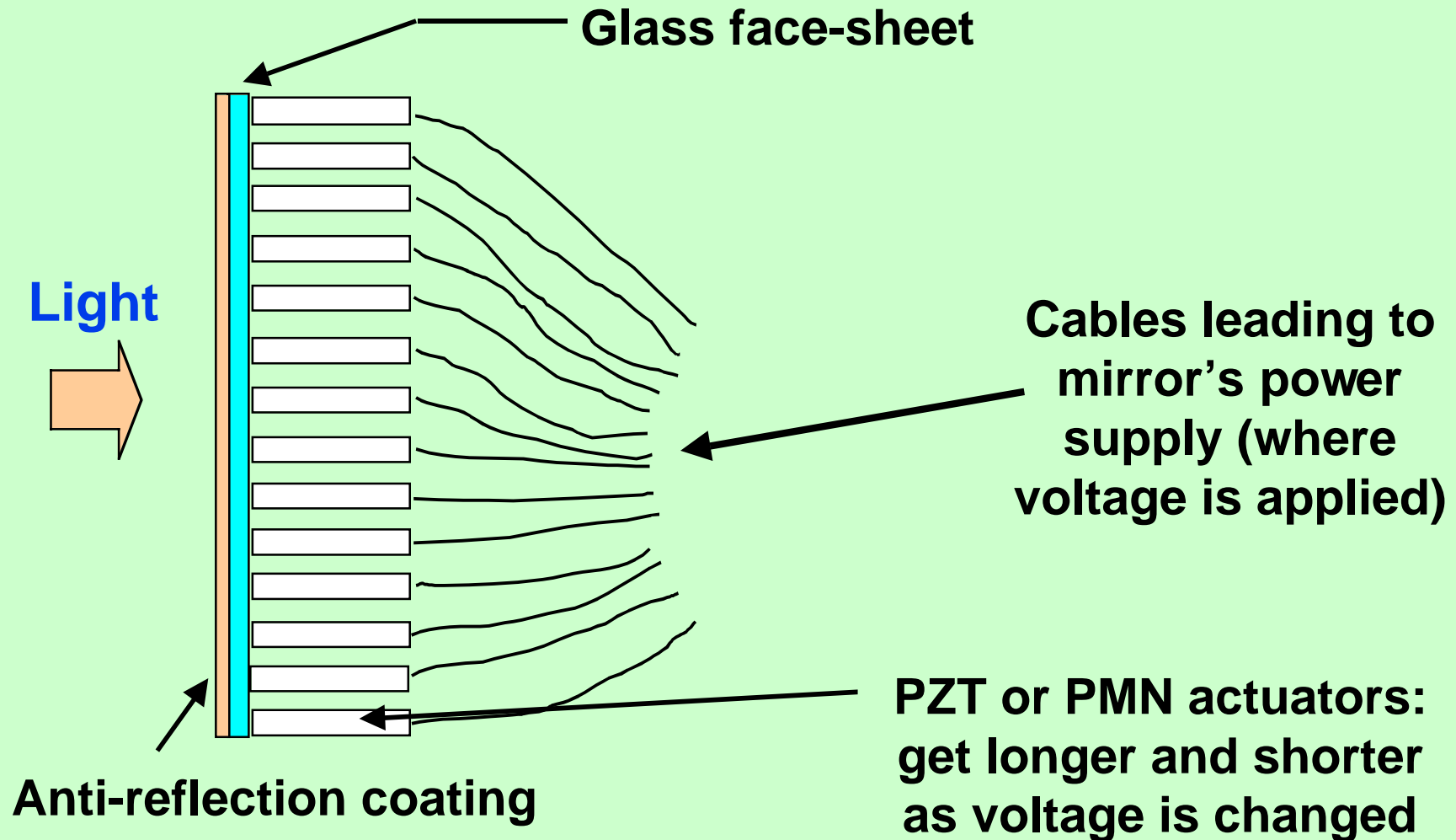


Types of deformable mirrors: small

- **Liquid crystal spatial light modulators**
 - Applied voltage orients long thin molecules, changes index of refraction
 - Response time too slow for astronomy?
- **MEMS (micro-electro-mechanical systems)**
 - Fabricated using microfabrication methods of the integrated circuit industry (photoresist, etch, etc)
 - Many different mirror configurations possible
 - Potential to be very inexpensive



Most deformable mirrors today have thin glass face-sheets

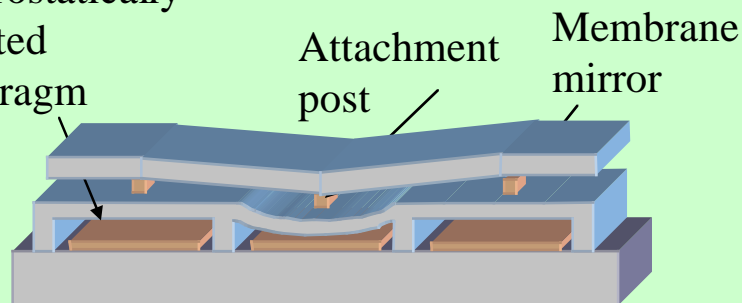




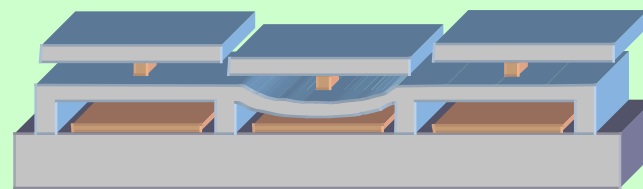
New developments: MEMS devices (micro-electro-mechanical systems)

- Potential for lower cost per degree of freedom
- Suitable for small systems such as vision science AO
- Liquid crystal devices
 - Voltage applied to back of each pixel changes index of refraction locally

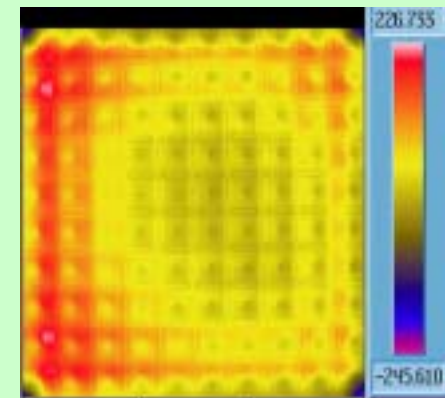
Electrostatically actuated diaphragm



Continuous mirror



Segmented mirrors (piston)



Mirror surface map



Deformable mirrors come in many sizes

- Range from 13 to > 900 actuators (degrees of freedom)



About 12"

A couple
of inches

Xinetics

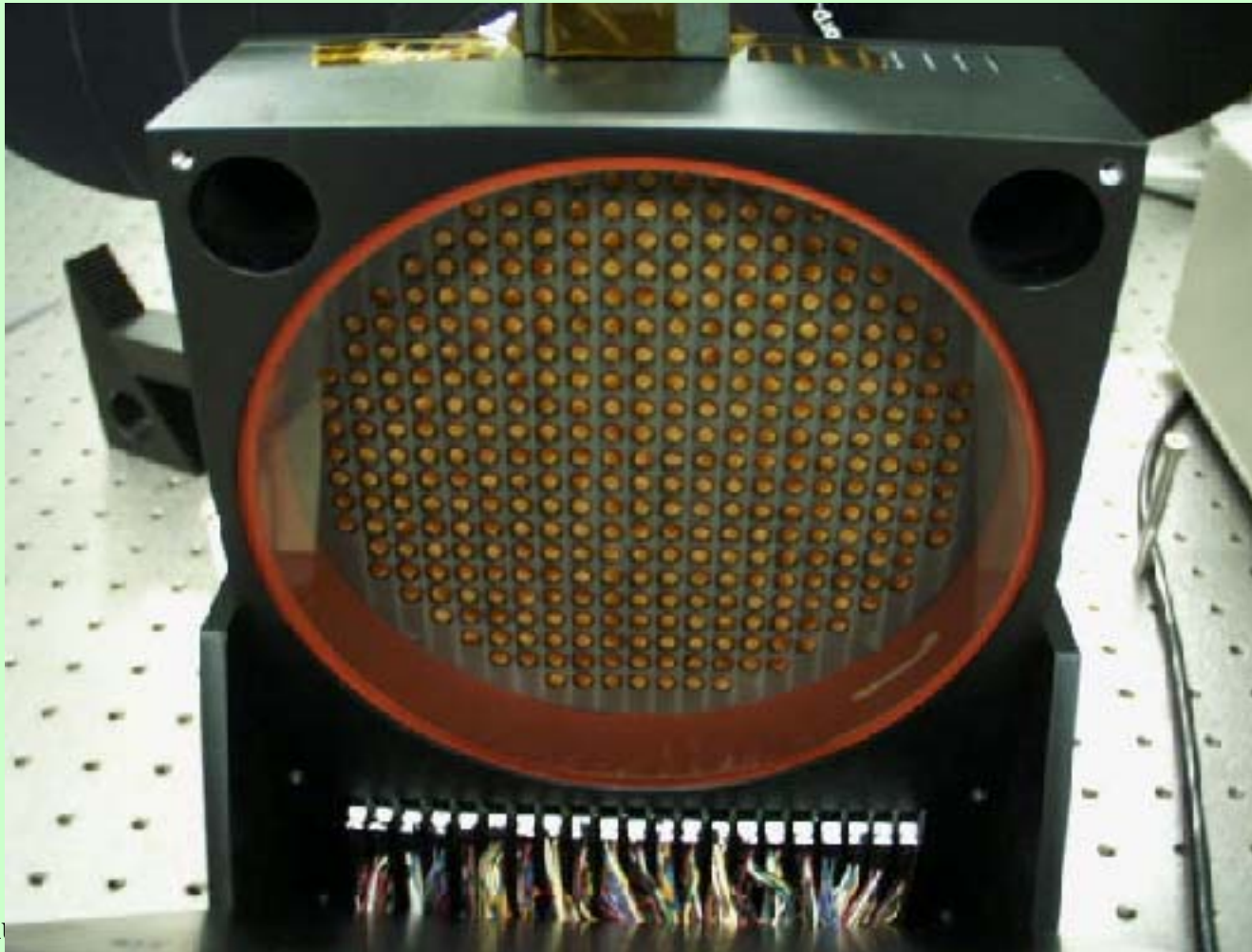
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Rear view of Xinetics 349 actuator DM used in Keck Telescope AO system





Front view of Xinetics DM (Keck)



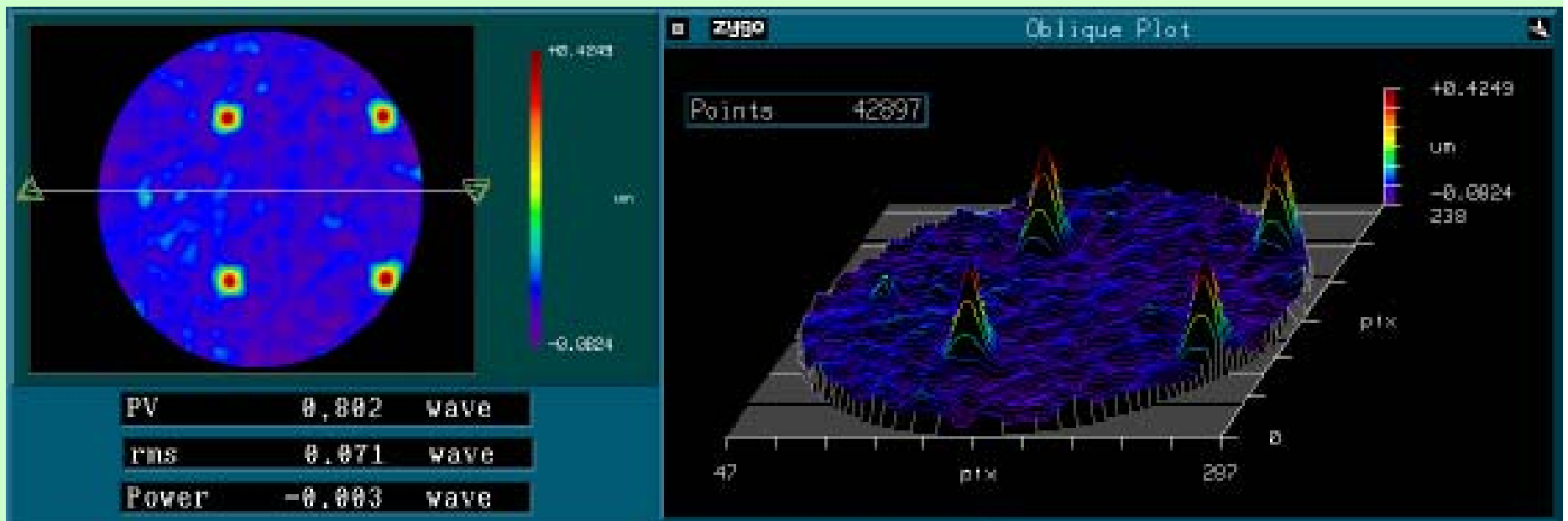
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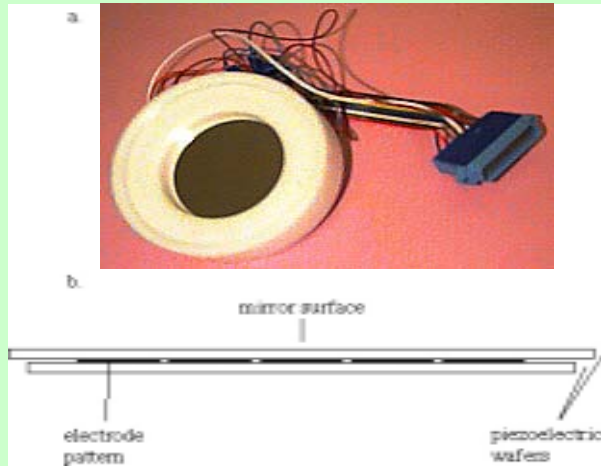
Influence functions for Xinetics DM

- Push on four actuators, measure deflection with an optical interferometer





Bimorph mirrors



Bimorph mirror made from 2 piezoelectric wafers with an electrode pattern between the two wafers to control deformation

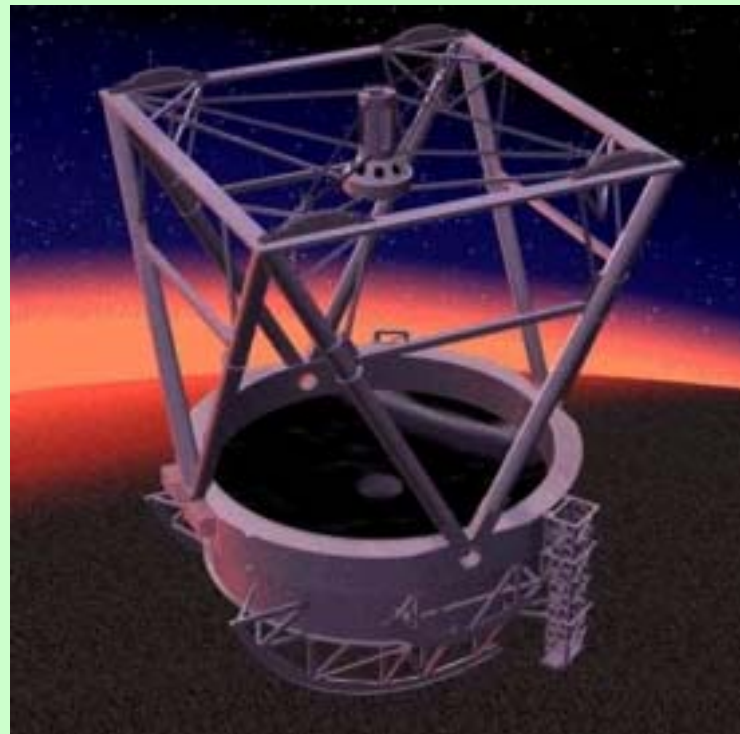
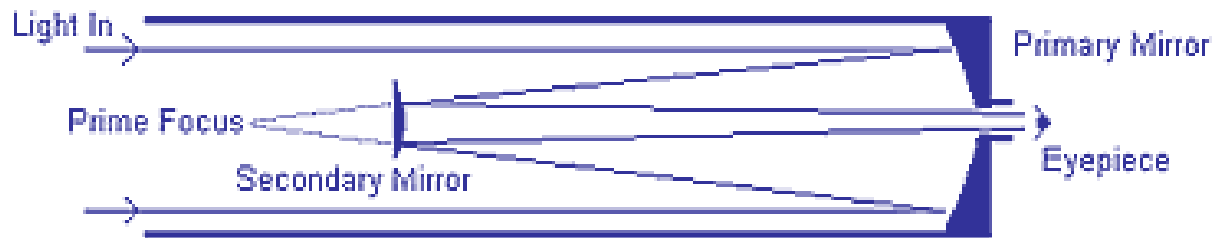
Front and back surfaces are electrically grounded.

When V is applied, one wafer contracts as the other expands, inducing curvature

Naturally handles curvature signals



Cassegrain telescope concept



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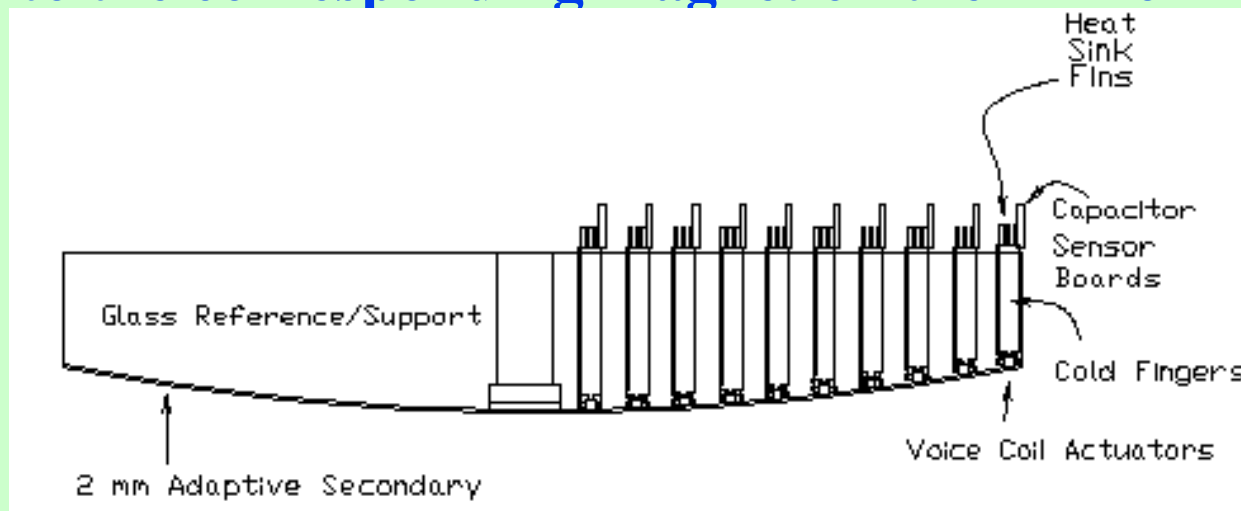
Adaptive secondary mirrors

-
- **Make the secondary mirror into the “deformable mirror”**
 - **Curved surface (~ hyperboloid) \Rightarrow tricky**
 - **Advantages:**
 - No additional mirror surfaces \Rightarrow lower emissivity, higher reflectivity. Ideal for thermal infrared
 - Common to all imaging paths except prime focus
 - **Disadvantages:**
 - Harder to build: heavier, larger actuators
 - Difficult to control mirror’s edges (no outer “ring” of actuators outside the pupil)



MMT-Upgrade: adaptive secondary

- Magnets glued to back of mirror under each actuator. On end of each actuator finger is coil through which current is driven to provide bending force.
- Copper fingers conduct heat away: to minimize mirror seeing, secondary must be $< 0.2^\circ \text{C}$ above ambient.
- Within each copper finger is small bias magnet, which couples to the corresponding magnet on the mirror



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Testing of adaptive secondary for the MMT Upgrade telescope

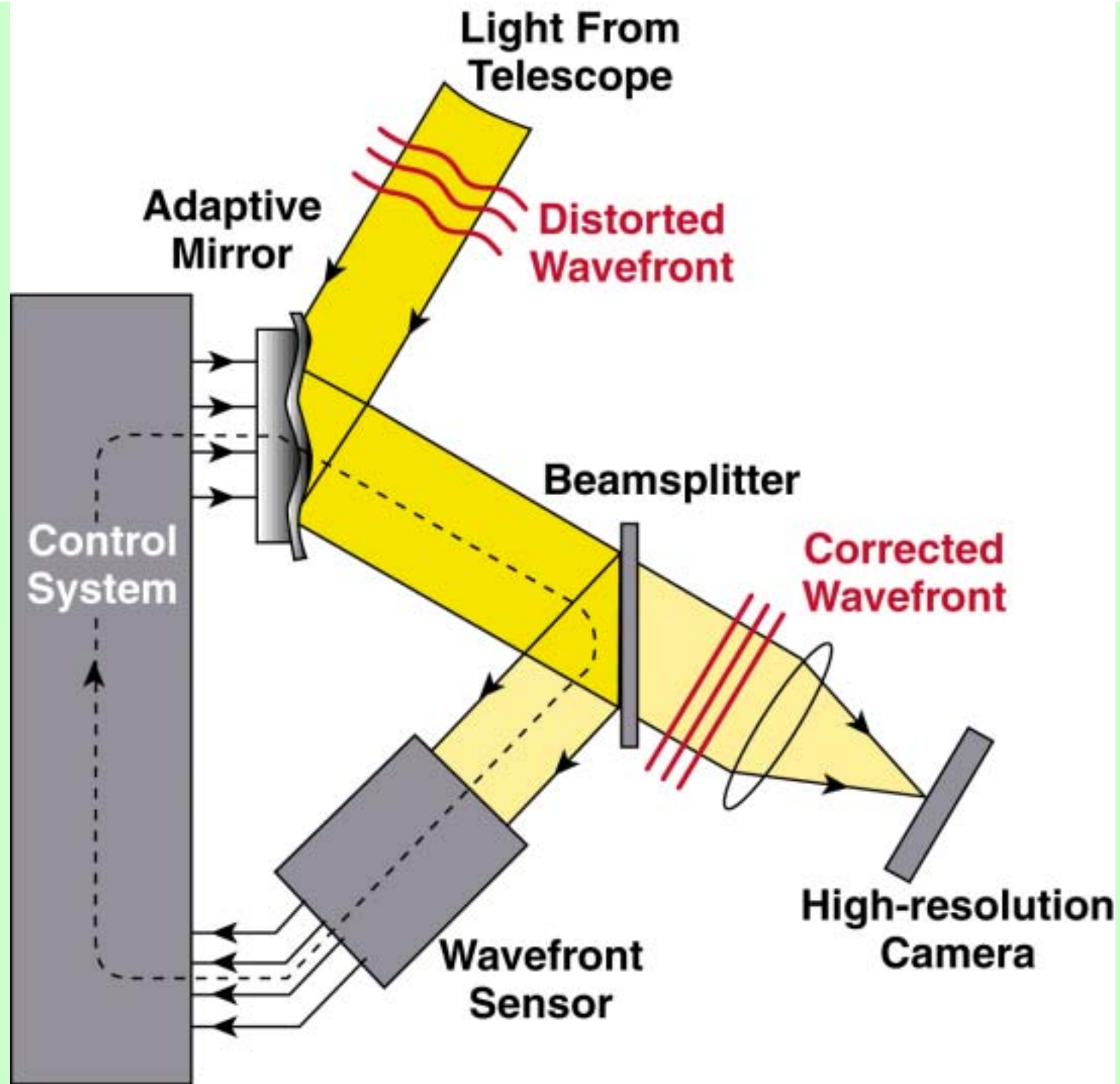
- U. Arizona + Arcetri Observatory (Italy)
- 336 actuators, 642 mm diameter, 2mm facesheet



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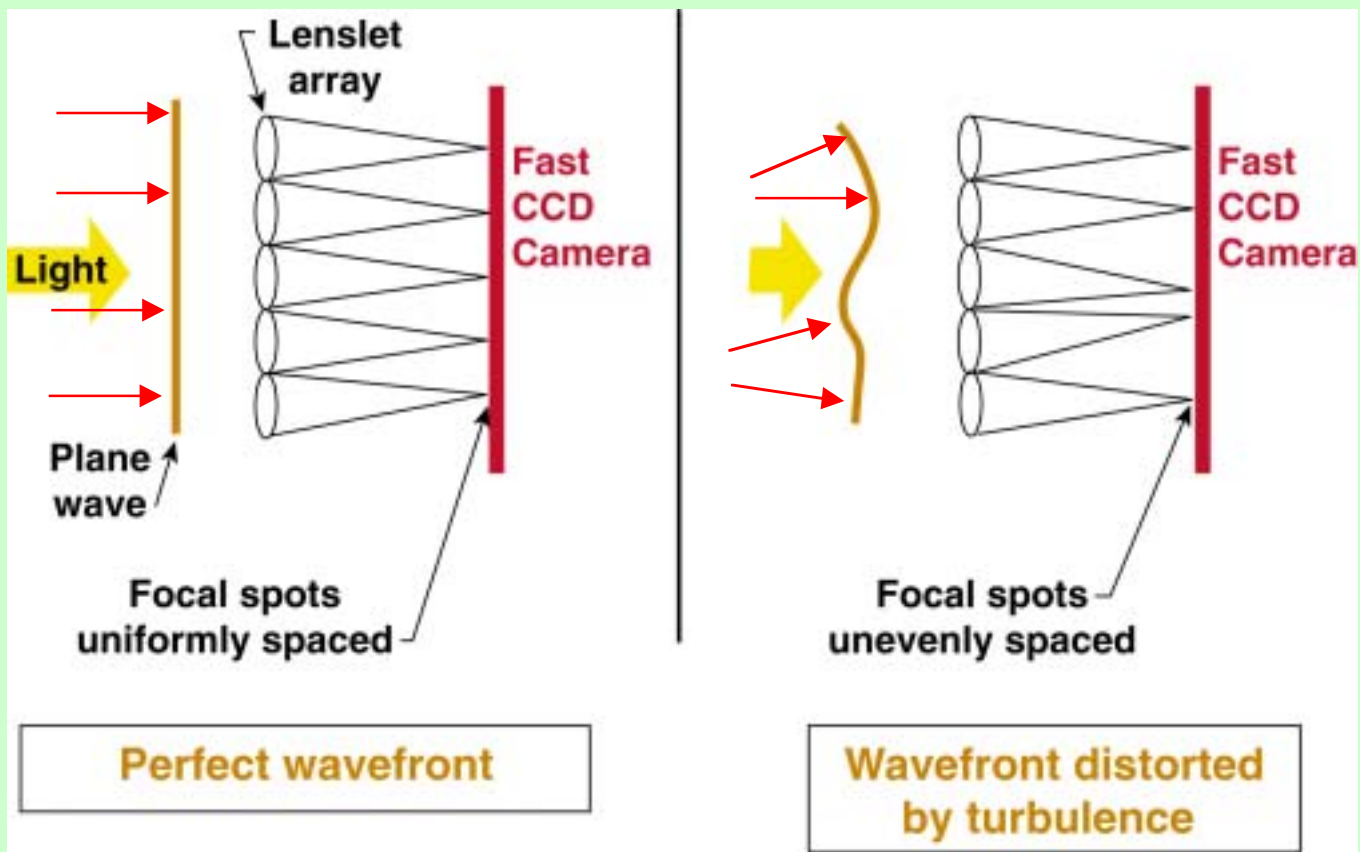
Wavefront Sensing

- **Lisa Poyneer will give a talk on wavefront sensing at this summer school**
- **Various methods have been developed with different strengths and weaknesses**
 - Slope estimation with Shack-Hartmann methods
 - Slope estimation with pyramid sensing
 - Slope estimation with shear methods
 - Curvature methods
 - Direct interference with reference beam
 - Phase diversity



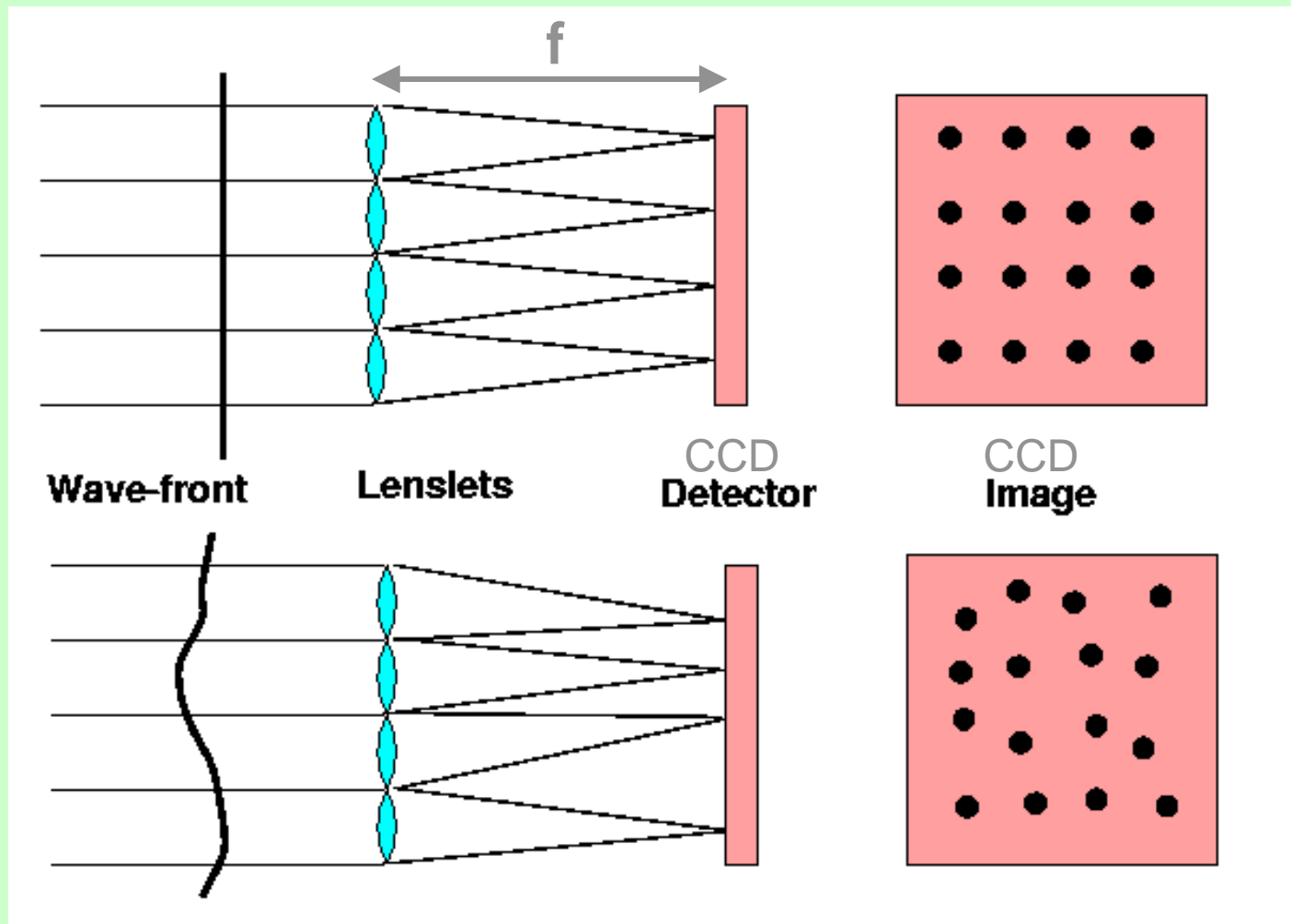
How to measure turbulent distortions (one method among many)

Shack-Hartmann wavefront sensor



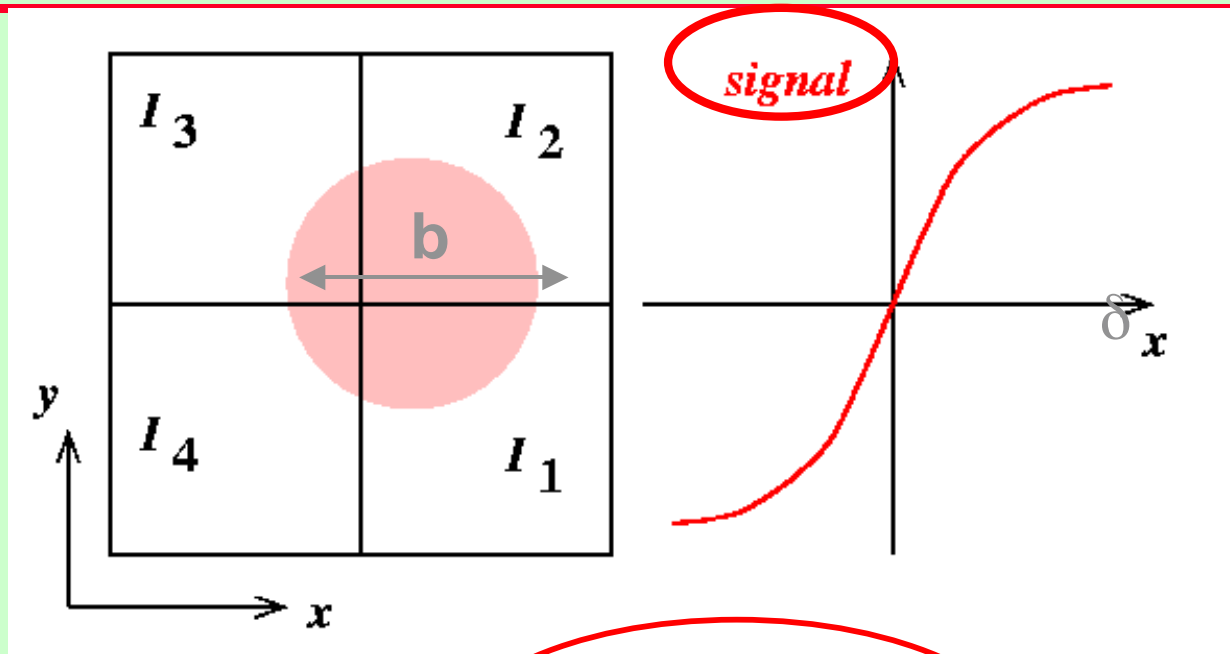


Shack-Hartmann wavefront sensor concept - measure subaperture tilts





How to measure distance a spot has moved on CCD? “Quad cell formula”

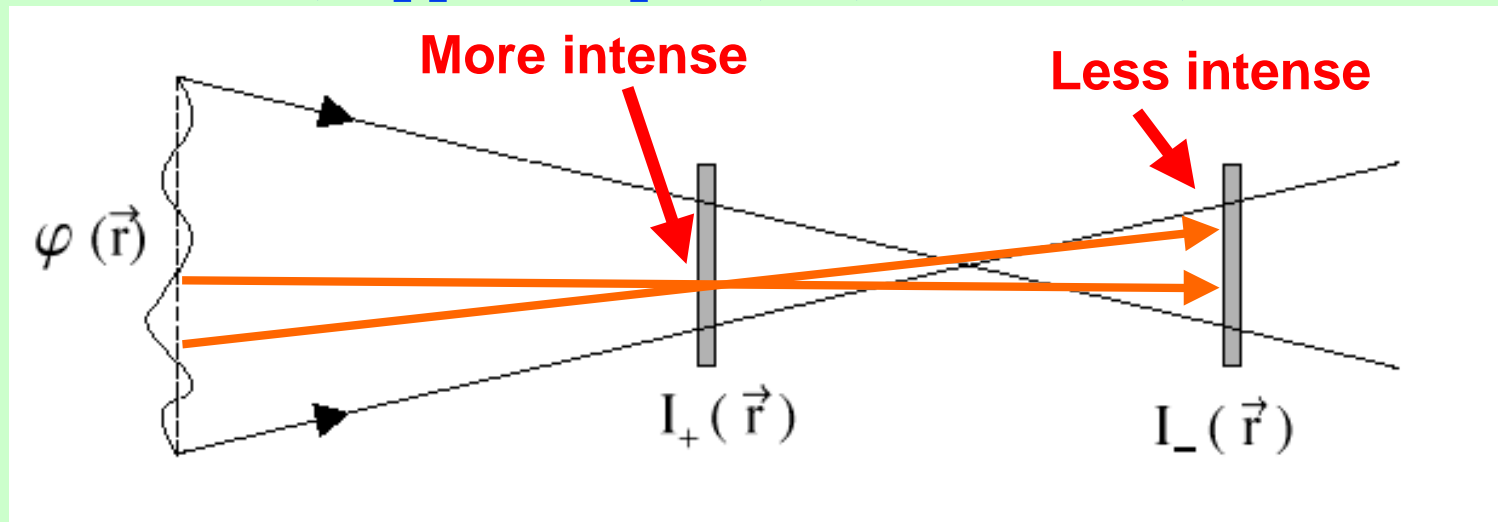


$$\delta_x \approx \frac{b}{2} \left[\frac{(I_2 + I_1) - (I_3 + I_4)}{(I_1 + I_2 + I_3 + I_4)} \right]$$
$$\delta_y \approx \frac{b}{2} \left[\frac{(I_3 + I_2) - (I_4 + I_1)}{(I_1 + I_2 + I_3 + I_4)} \right]$$



Curvature wavefront sensing

- F. Roddier, *Applied Optics*, 27, 1223- 1225, 1998



$$\frac{I_+ - I_-}{I_+ + I_-} \propto \nabla^2 \phi - \frac{\partial \phi}{\partial r} \frac{\mathcal{I}}{\delta_R}$$

Normal derivative at boundary

Laplacian (curvature)

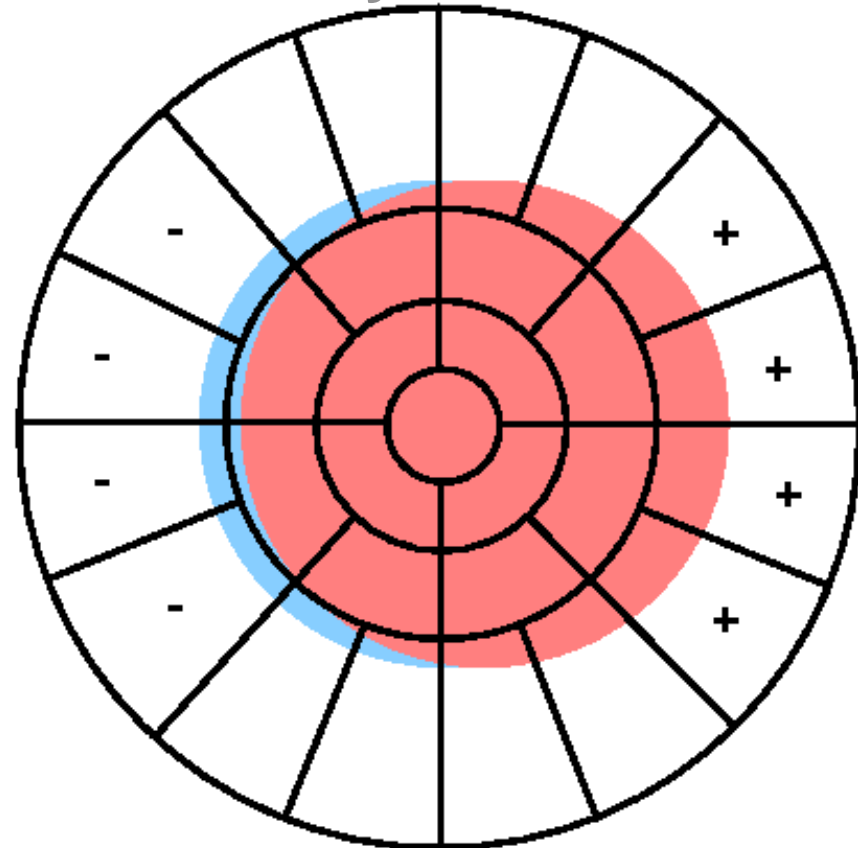


Wavefront sensor lenslet shapes are different for edge, middle of pupil

- **Example: This is what wavefront tilt (which produces image motion) looks like on a curvature wavefront sensor**

- Constant I on inside
- Excess I on right edge
- Deficit on left edge

Lenslet array



Gradient sensing



Status of AO systems today

- **Curvature systems: modest no. of degrees of freedom (dof)**
 - Canada France Hawaii Telescope: 13 dof, 14th mag
 - Univ. of Hawaii: 19 dof, 12th mag
 - San Pedro Martir (Baja CA): 19 dof
 - Subaru: 19 dof
 - Hokupaa on Gemini Telescope: 36 dof, 13-17th mag
 - Hokupaa 85 (under construction): 85 dof
- **Shack-Hartmann systems: tend to have more degrees of freedom but in general need brighter guide stars**
 - Lick: 61 dof, 13.5 mag
 - Palomar: 241 dof
 - Keck: 250 dof, 13.5 mag
 - ADONIS: 50 dof (?), 13 mag
 - VLT (ESO) NAOS



Wavefront Reconstruction

- Most wavefront sensing methods give information about the wavefront errors, but do not directly measure the wavefront error
- In general the measurements need to be processed to determine the best estimate of the wavefront. In practice the DM actuator commands are what is usually sought. This is called wavefront reconstruction. **Lisa Poyneer will talk about wavefront reconstruction at the summer school**
- Often these methods are mathematically sophisticated and computationally difficult. **Curt Vogel will talk about mathematical tools; basics, estimation theory at the summer school**



Adaptive Optics in Astronomy

- **The fundamental limit to image quality of a telescope is the diffraction limit**
 - Image size = wavelength of light/diameter of telescope = λ/D
 - Bigger telescopes can deliver smaller images
 - Images are smaller with shorter wavelength light
 - Typical results (1 μm wavelength)
 - Lick 3m 0.07 arcseconds
 - Keck 10m 0.021 arcsecond
 - CELT 30m 0.007 arcseconds
- **Ground based telescopes deliver degraded images due to atmospheric turbulence**
 - Temperature variations in the atmosphere, turbulently mixed, degrade the image quality (1 arcsecond is considered excellent)
 - Largely describable as a wavefront error introduced by atm.
 - AO seeks to measure and remove this wavefront error, thereby restoring diffraction limited imaging- this is DIFFICULT

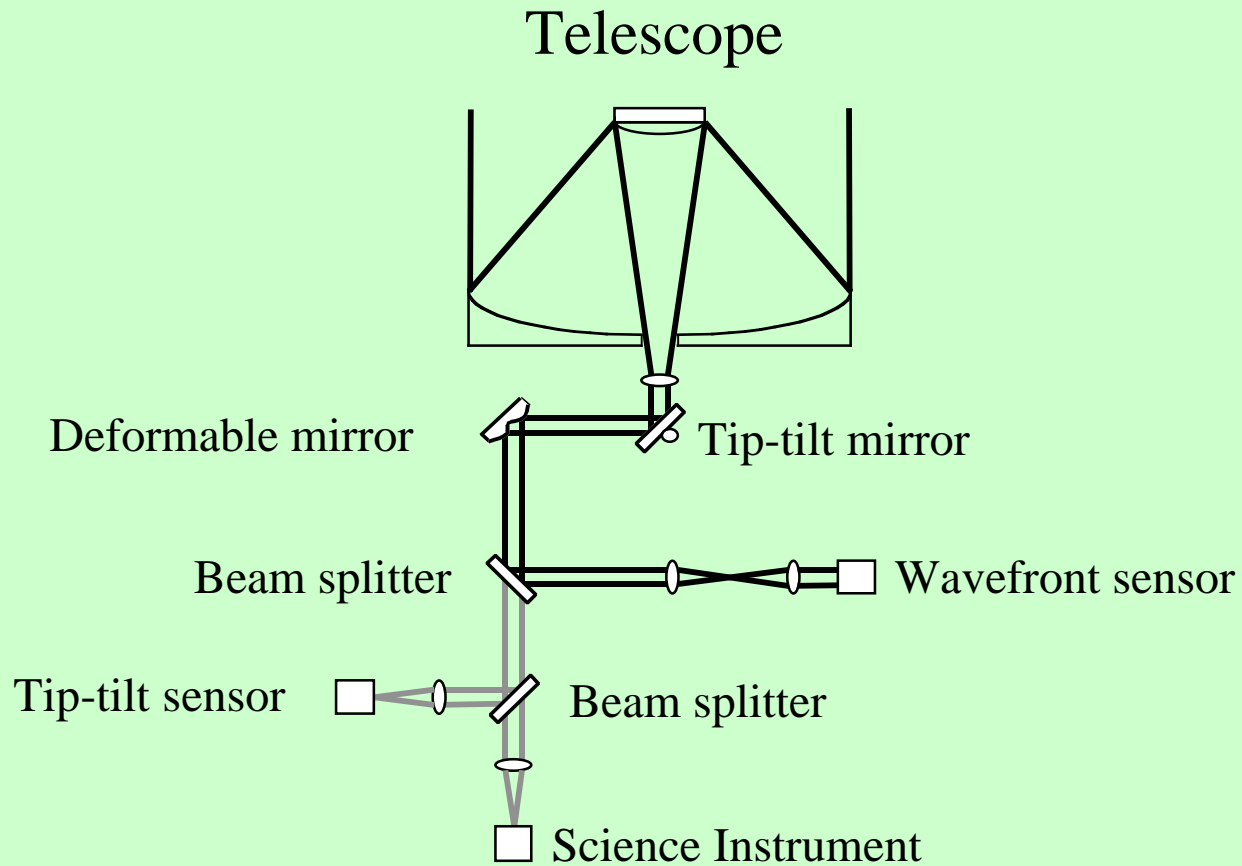


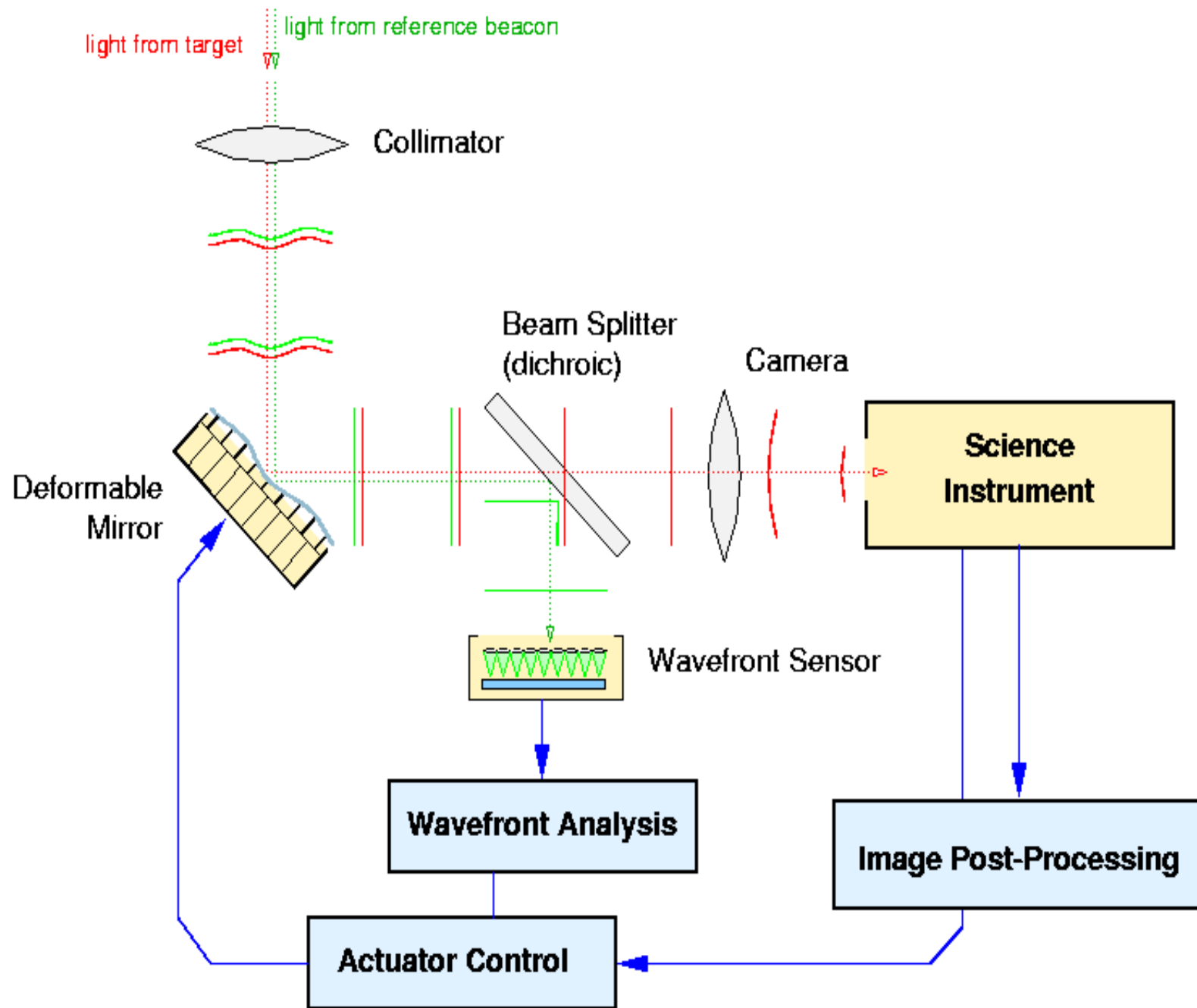
Astronomical Adaptive Optics

- **The dominant source of wavefront error is the earth's atmosphere**
 - Statistical properties of the wavefront error are generally understood (Kolmogorov model)
 - Wavefront errors are largely independent of wavelength
- **AO system complexity grows with increasing telescope size and shorter wavelengths (as do the benefits)**
- **Starlight is the best probe of the atmosphere but for most objects, the object light is insufficient to measure the wavefront errors**
 - This leads to the need for measurement beacons: either bright natural stars or laser beacons



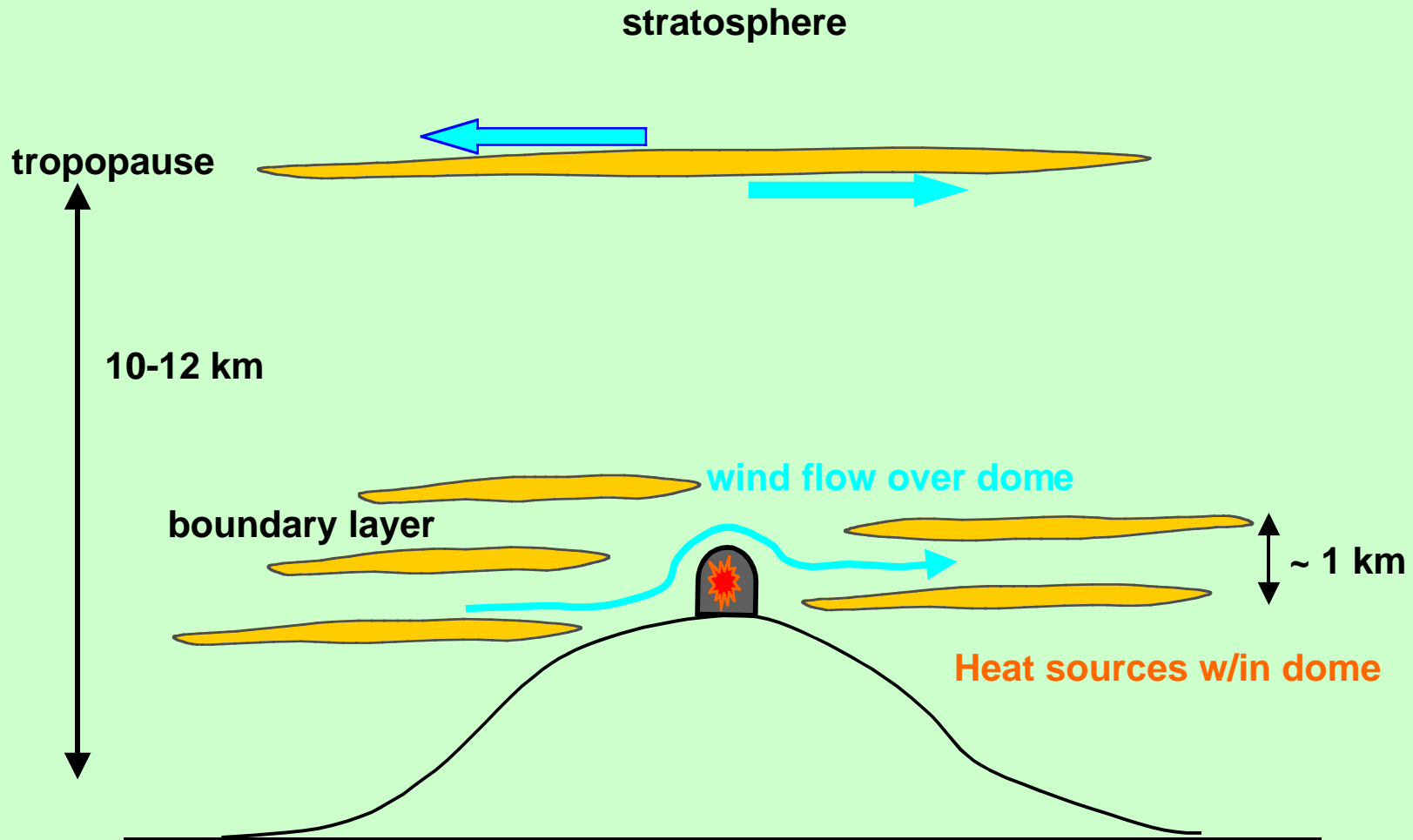
Schematic of astronomical AO system







Turbulence arises in several places

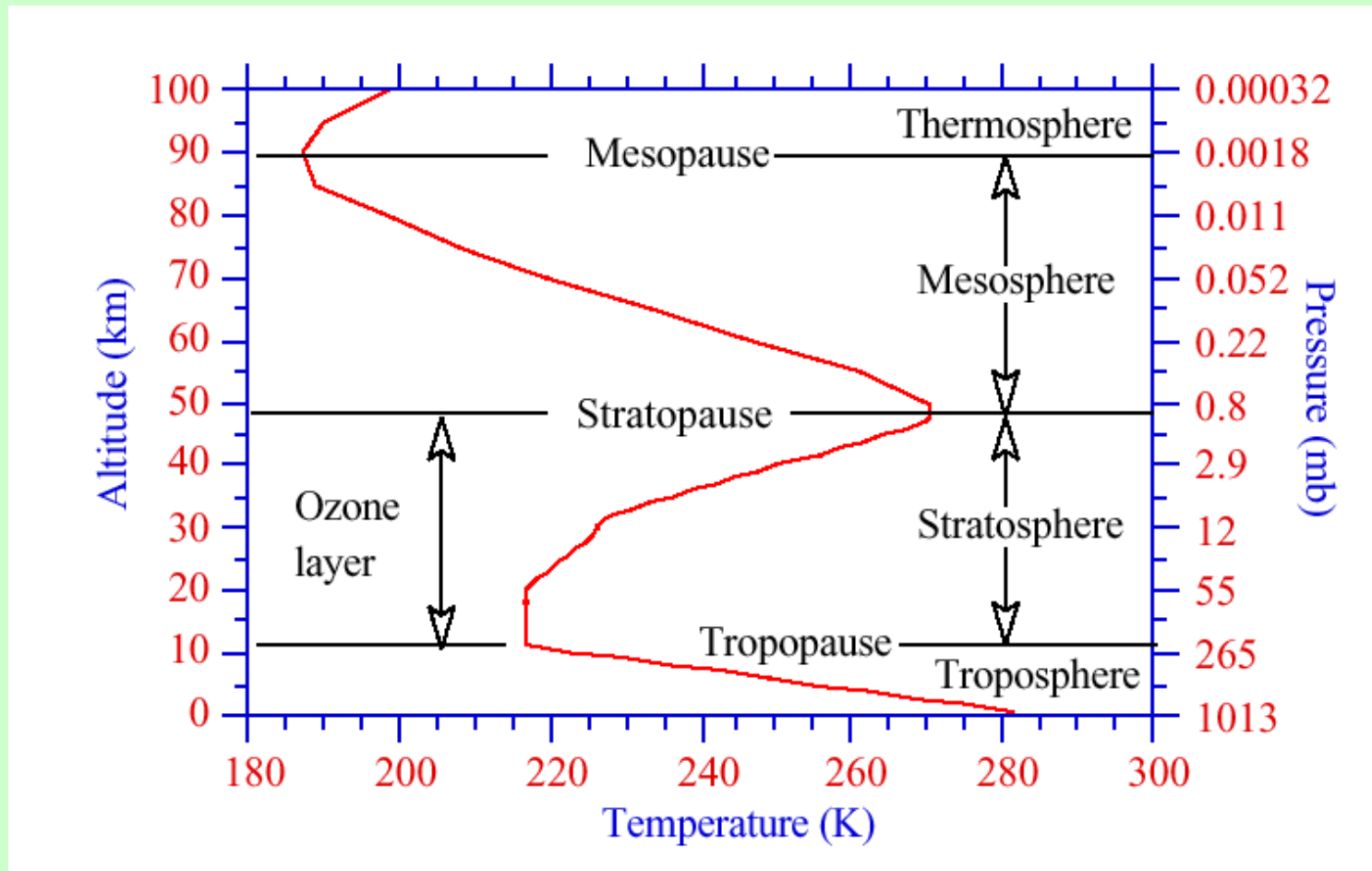


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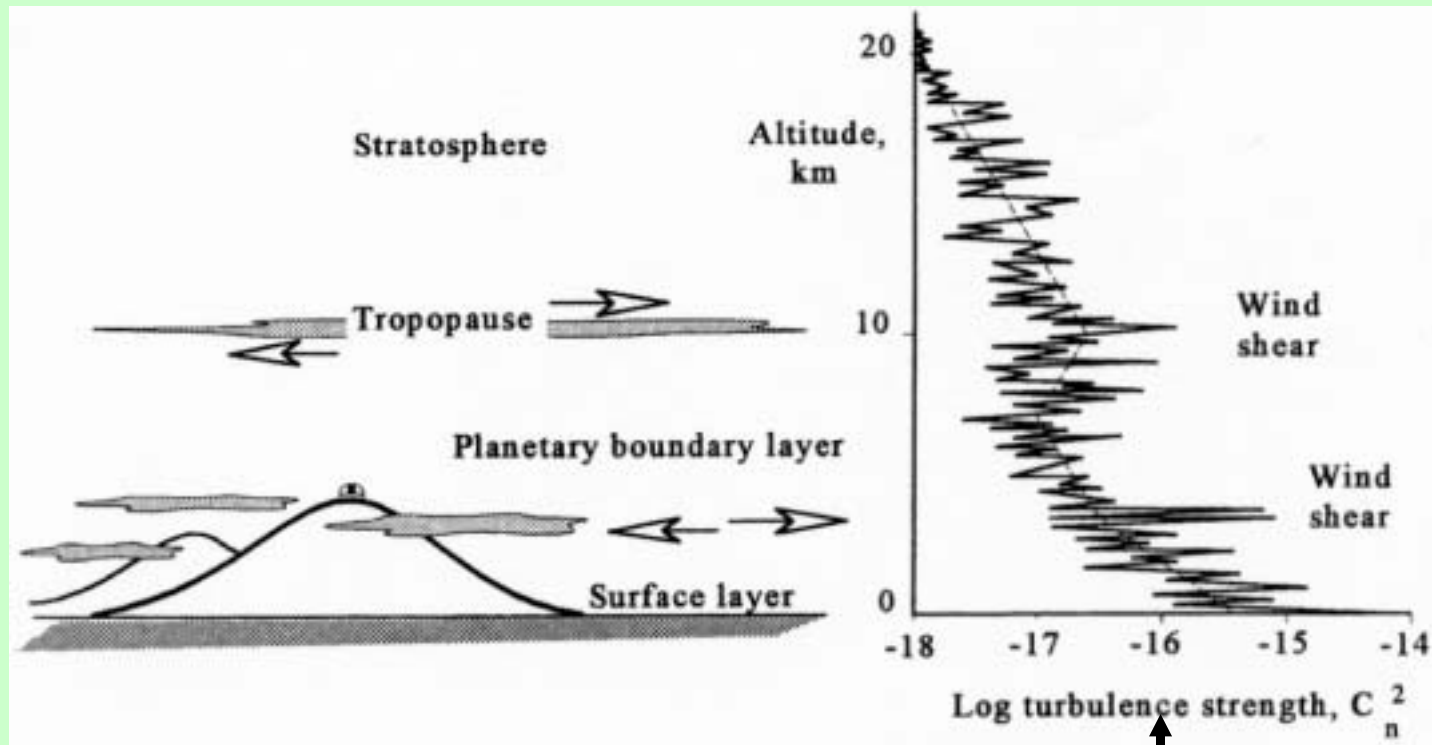
Temperature profile in atmosphere



Temperature gradient at low altitudes + wind shear will produce index of refraction fluctuations



Vertical profile of turbulence

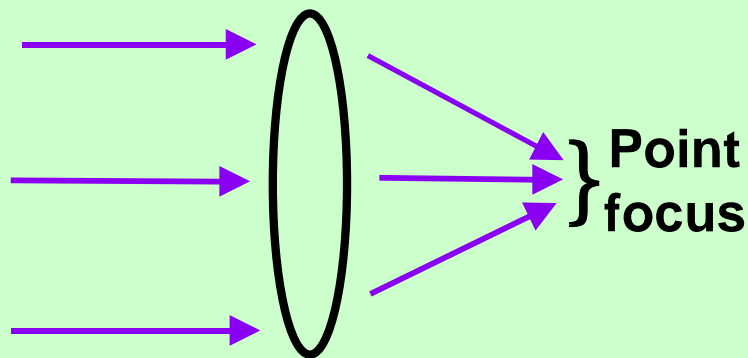


Measured from a balloon rising through various atmospheric layers

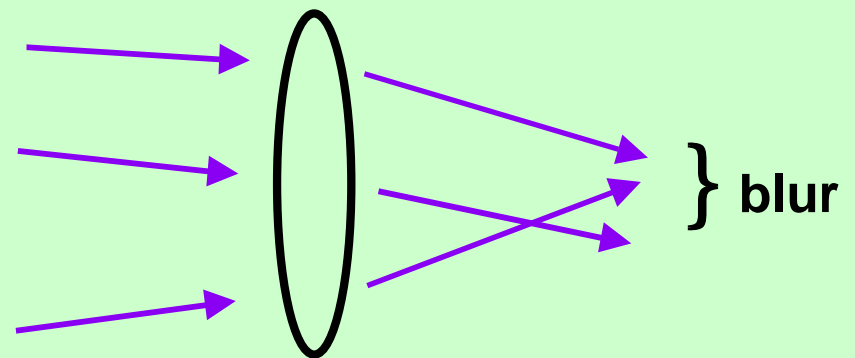


Optical consequences of turbulence

- 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



Quantitative use of C_n^2

- Atmospheric coherence length r_0

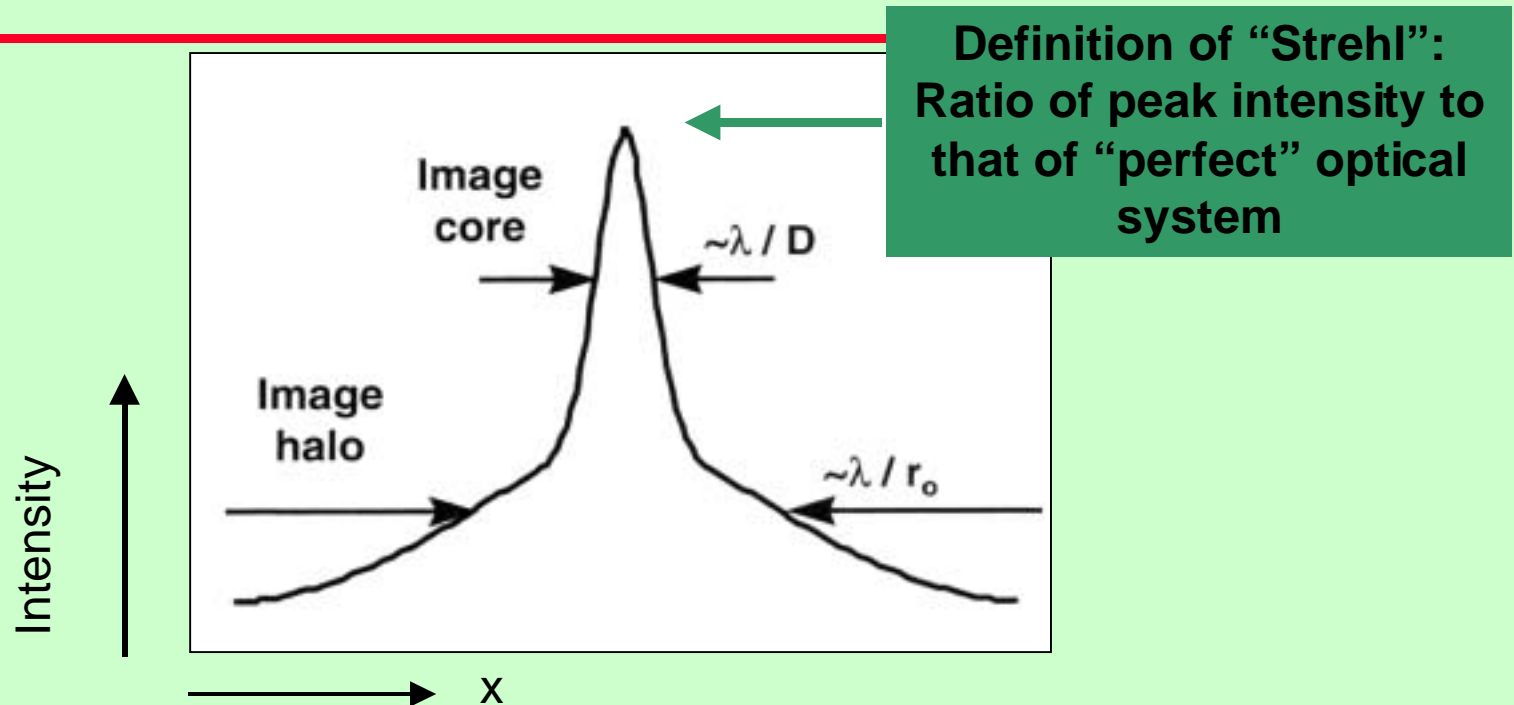
$$r_0 = \left[0.423 k^2 \sec \beta \int_0^H C_N^2(z) dz \right]^{-3/5} \propto \lambda^{6/5} (\sec \beta)^{-3/5}$$

- ~ Size of diffraction limited subaperture, sets scale of all AO correction

**Easy to remember:
 $r_0=10\text{cm} \Leftrightarrow \text{FWHM} = 1 \text{ arc sec in the visible } (\lambda = 0.5\mu\text{m})$**



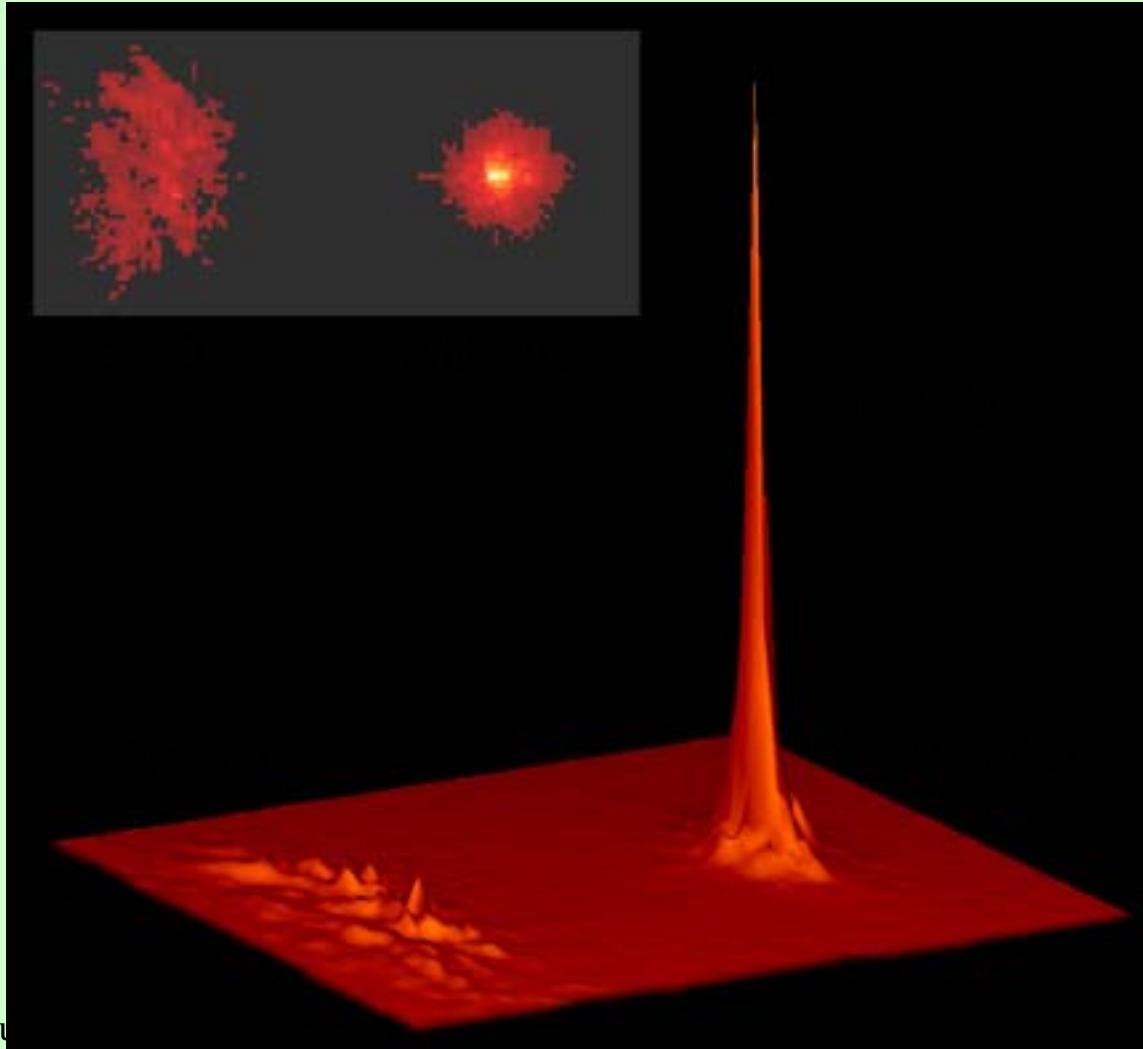
AO produces point spread functions with a “core” and “halo”



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



Adaptive optics increases peak intensity of a point source



Lick
Observatory



Field angle limitations

- Because the atmosphere varies in 3 dimensions, wavefront errors measured in one direction do not usually apply in other directions
- This limits the field of view of traditional AO systems
- This also limits the useful sky coverage
- **Miska LeLouarn will talk on Multi Conjugate AO at the summer school, a method to increase the useful field of view**

Anisoplanatism

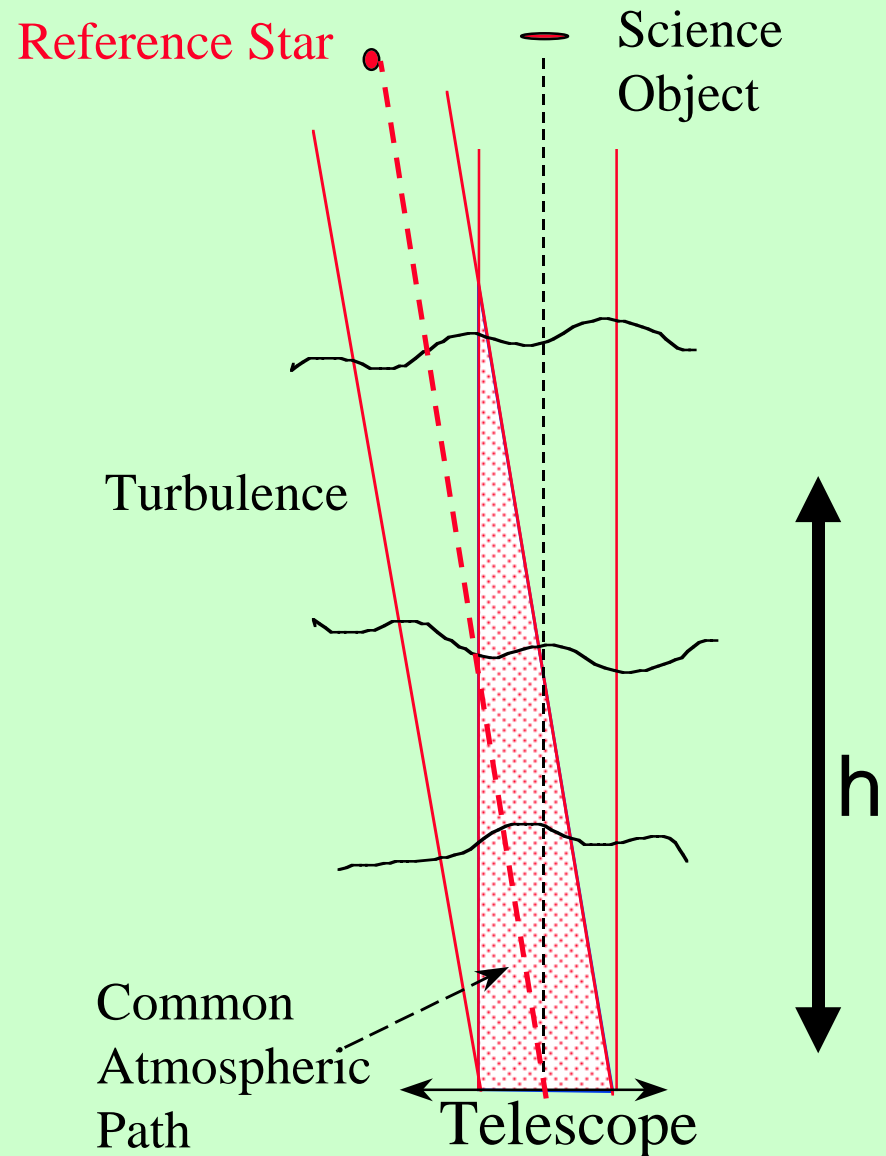
Anisoplanatism

sets a limit to the
distance of the
reference star from
the science object

Strehl = 0.38 at $\theta = \theta_0$

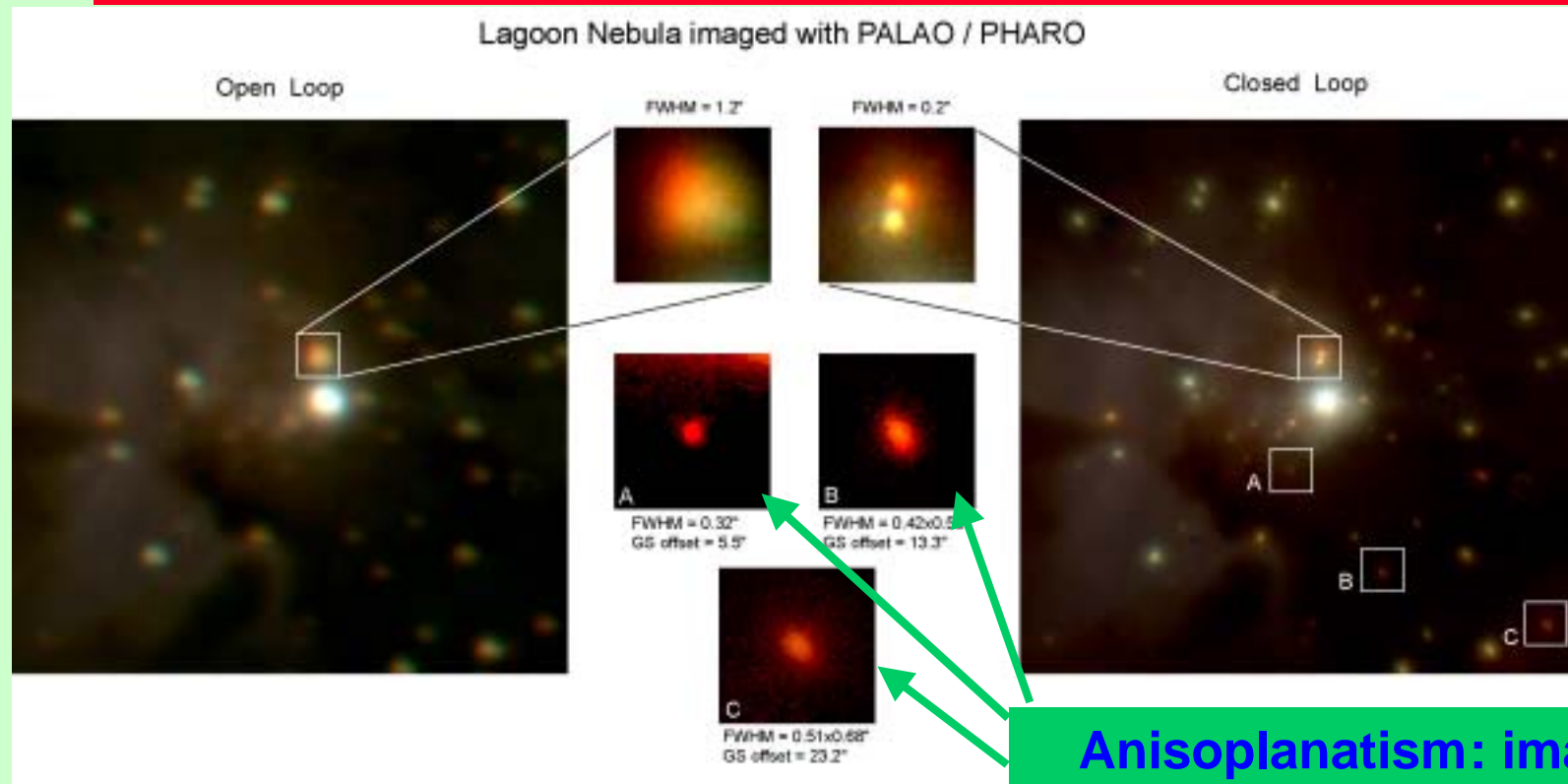
θ_0 is isoplanatic angle

$$\theta_0 \sim 0.3 \cos\beta (r_0(\beta) / h)$$





Palomar: anisoplanatism with AO



- Composite J, H, K band image
- Field of view 40''x40'' (at 0.04 arc sec / pixel)
- On-axis K-band Strehl ~ 40%, falls to 25% at corner



Sky coverage

- **Because the field of view around a single bright star is limited, generally only a small portion of the sky can be viewed with AO**
- **Astronomy needs artificial beacons to increase sky coverage**
- **Laser beacons act as artificial stars, placed near the science object of interest**
- **Na laser beacons are best (furthest away), due to fact that a layer of Na atoms exists 90 km above us**



Keck Laser is Commissioned

