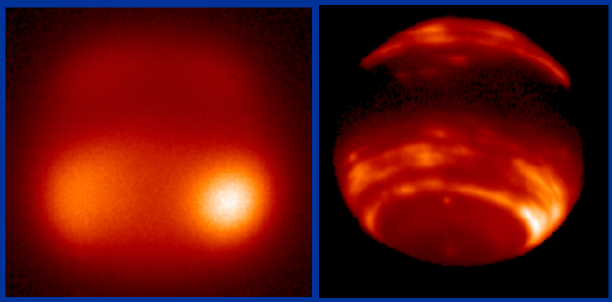
Adaptive Optics and its Applications Lecture 1



Neptune with and without AO

Claire Max
UC Santa Cruz

January 9, 2020

Outline of lecture

- Introductions, goals of this course
- How the course will work
- Overview of adaptive optics and its applications

Please remind me to stop for a break at 10:35 am !

Zoom techniques

- Please identify yourself when you speak
  - "This is Mary Smith from Santa Cruz"
- Report technical problems to Graseilah Coolidge at 831-459-2991. If that doesn't work, please text me at 510-717-1930 (my cell)
- Microphones are quite sensitive, even on laptops
  - Do not to rustle papers in front of them
  - Mute your microphone if you are making side-comments, sneezes, eating lunch, whatever
  - In fact, it's probably best if you keep microphone muted until you want to ask a question or make a comment

Who are we? continued

- In the CfAO conference room at UCSC:

Bowens-Rubin	Rachel	ucsc
Demartino	Matthew	ucsc
Luo	Yifei	ucsc
Morris	Evan	ucsc
Sanchez	Dominic	ucsc
Simha	Sunil	ucsc
Roy	Namrata	ucsc

Introductions: who are we?

- Via Zoom:

- If I haven't listed you on this slide or the previous one, please say who you are (and send me an email)

Last Name	First Name	From:
McEwen	Eden	berkeley
Lam	Casey	berkeley
Casey	Kelleen	keck
Gomez	Percy	keck
Dankel	Nick	keck
Yeh	Sherry	keck
Gautam	Abhimat	ucla
Lam	Rex	ucsd
Wilcomb	Kielan	ucsd
Theissen	Chris	ucsd
Rundquist	Nils	ucsd
Michelsen	Eric	ucsd
Steiger	Sarah	ucsb
Swimmer	Noah	ucsb
Bradshaw	Andrew	Stanford
Madurowicz	Alex	Stanford
Radzyminski	Rochelle	Stanford
Bault	Abby	uci
Abolfothi	Bela	uci
Lubin	Jack	uci
Hedglen	Alex	Univ. of Arizona

Goals of this course

- To understand the main concepts and components behind adaptive optics systems
- To understand how to do astronomical observations with AO (what is AO good for, what is it not good for?)
- To get acquainted with AO components in the Lab
- Brief introduction to non-astronomical applications
- I hope to interest a few of you in learning more AO, and doing research in the field

Course websites

- Main: http://www.ucolick.org/~max/289
  - Lectures will be on web before each class
  - Homework assignments (and, later, solutions)
  - Reading assignments
- Auxiliary: Canvas at UCSC
  - https://canvas.ucsc.edu/courses/29723
  - Will be used for some of the reading material
    - UCSC students: use your Gold login
    - Others: I'll email readings to you; they will be password protected

Required Textbook

- Field Guide to Astronomical Instrumentation by Keller, Navarro, and Brandl
  - Available from SPIE
  - I found this small spiral book very useful for lots of things
- Readings from the academic literature available from Canvas or via email from me, password protected

Outline of lecture

- Introductions, goals of this course
- How the course will work
- Overview of adaptive optics

Course components

- Lectures
- Reading assignments
- Homework problems
- Project
- Laboratory exercises
- Final exam (take-home)

How People Learn

- Research shows that the traditional passive lecture is far from the most effective teaching tool.
- It is not possible for an instructor to pour knowledge into the minds of students.
- It is the *students* who must actively *engage* in the subject matter in a manner that is meaningful to *them*.
- Hence this course will use several departures from the traditional lecture format, to encourage *active learning* and understanding of *concepts*.

I will post lectures prior to each class; you can download them

- http://www.ucolick.org/~max/289/

- I strongly suggest that those of you who are attending via video download the lectures prior to class, and project them locally

- I'll also project them via Zoom

Concept Questions

- ***Lectures*** will discuss the *underlying concepts and key points*, elaborate on reading, and address difficulties.
  - I will assume you have already done a first pass through the reading
- As feedback to me, lectures will include ***Concept Questions***
- You will be asked to first formulate your own answer, then to discuss your answer with each other, and finally to report each group's answers to the class as a whole.

Reading Assignments

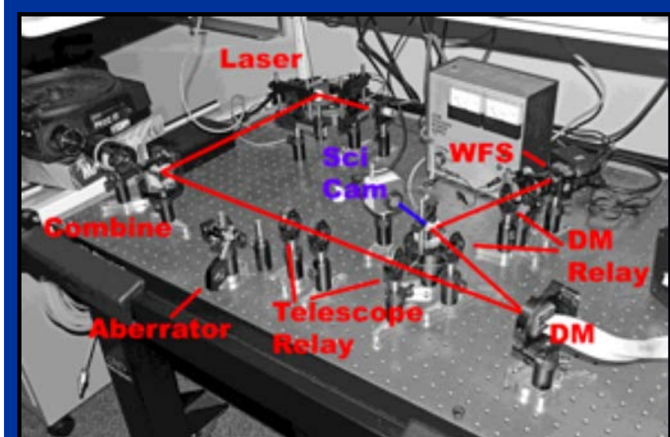
- I will expect you to do the reading BEFORE class
- Then if you want, go back and read more deeply after the lecture, to resolve areas which seem confusing
- From time to time I will give quick “Reading Quizzes” at the start of a class, where I ask few questions that you’ll be able to answer easily if you’ve spent even 20 minutes looking at the reading assignment

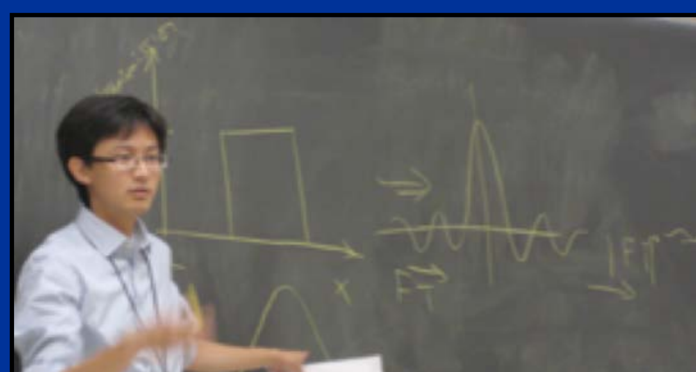
Inquiry Labs: Designed by grad students in the ISEE Professional Development Program

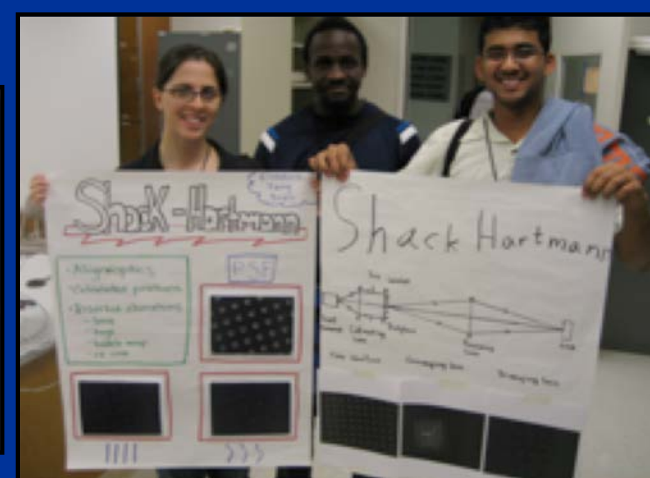
- **AO Demonstrator**
- Learning goals:
  - 3 main components of AO system
  - Ray-trace diagram
  - Optical conjugation
  - Focus and magnification
  - Alignment techniques
  - Performance of AO system

- **Fourier Optics**
- Learning goals:
  - Pupil plane and focal plane
  - Relationship between aperture and PSF
  - Phase errors and effects, including speckles
  - Wavefront error and Shack-Hartmann spots

Would be great if out-of-town students could travel to UCSC for these, but not required unless you are enrolled







Class Project: Design an AO system to meet your chosen scientific goals

- Group activity
- Learning goals:
  - Systems thinking
  - Requirements-driven design
  - Optimization and tradeoffs
  - Wavefront error terms and error budget
- Activity outline:
  - Choose a science goal
  - Sketch out the design of an AO system that best meets your science goal
  - Justify design decisions with an error budget
  - Present your design to the class

A "textbook in the process of being written"

- I've been asked to write an AO textbook by Princeton University Press
- I'll be asking for your help with homework problems
  - For problems that I assign to you, tell me what works, what doesn't
  - From time to time, I'll ask YOU to develop a homework problem, and then answer it
  - Sometimes I'll ask you to trade problems, so each person does a problem that someone else came up with

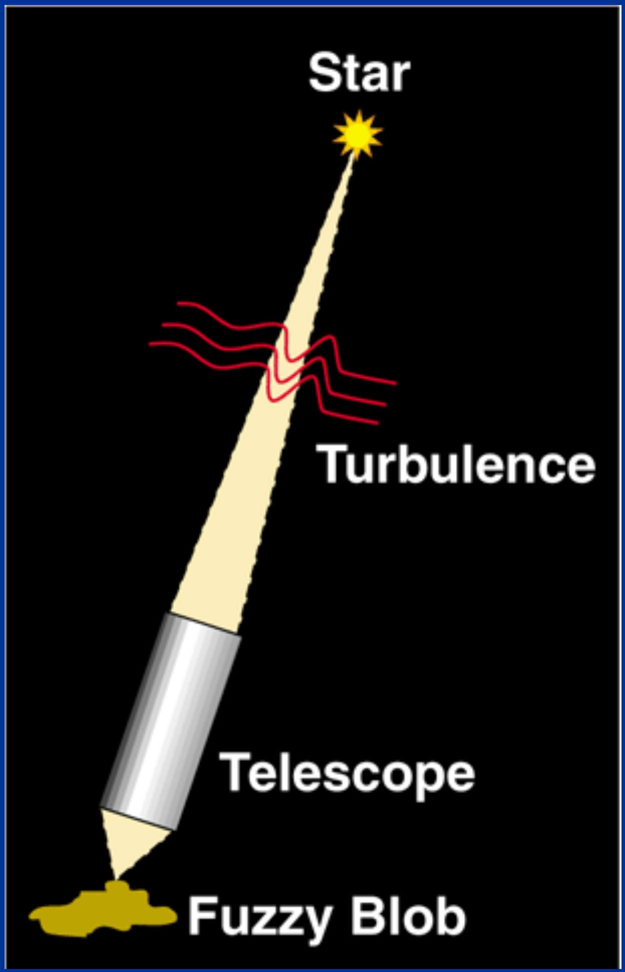
Homework for Tuesday Jan 14th (see website for details)

- Read Syllabus carefully (download from class website)
- Do Homework # 1: "Tell me about yourself"
  - Specific questions on web, won't take long
  - Email your responses to me from your favorite email address, so I'll know how to reach you
  - Always make the subject line "289" so I won't lose your email
- Reading assignment: Imaging through turbulence
  - Intro to imaging through turbulence by myself
  - More rigorous derivation by Quirrenbach
  - See class website for details and to download (public domain)

Outline of lecture

- Introductions, goals of this course
- How the course will work
- Overview of adaptive optics

Why is adaptive optics needed?



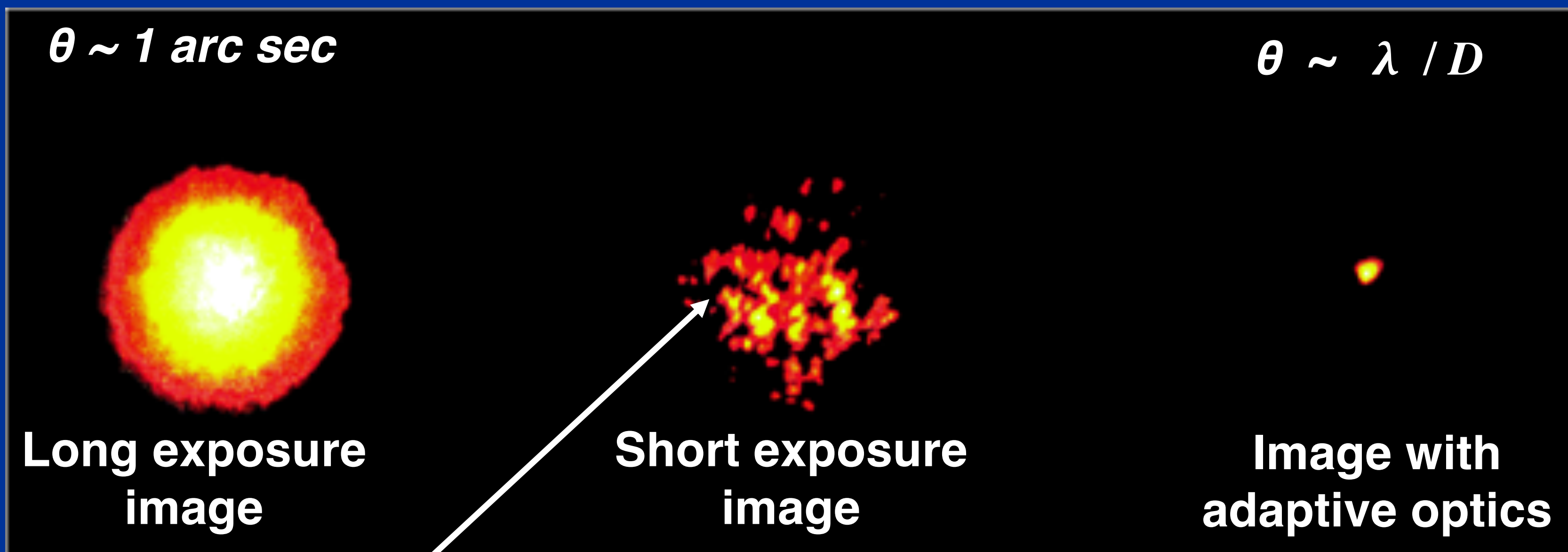
Turbulence in earth's atmosphere makes stars twinkle

More importantly, turbulence spreads out light; makes it a blob rather than a point

Even the largest ground-based astronomical telescopes have no better resolution than an 8" telescope!

Images of a bright star, Arcturus

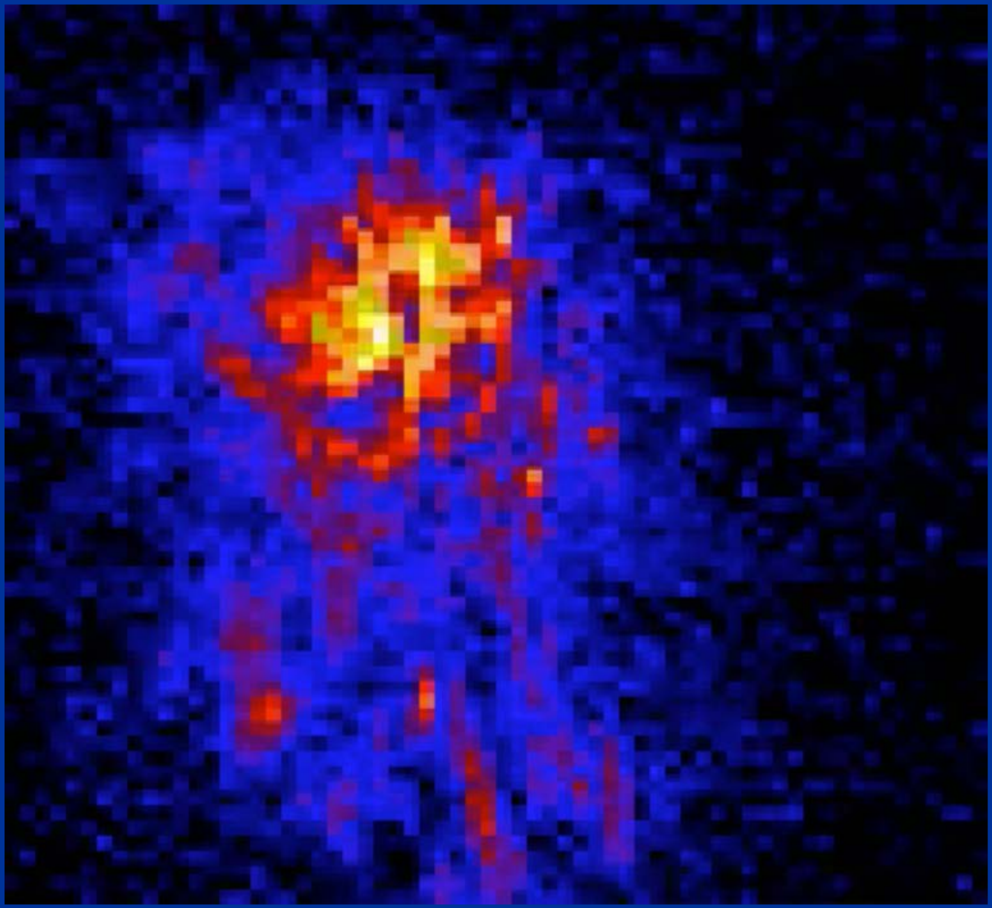
Lick Observatory, 1 m telescope



Speckles (each is at diffraction limit of telescope)

Turbulence changes rapidly with time

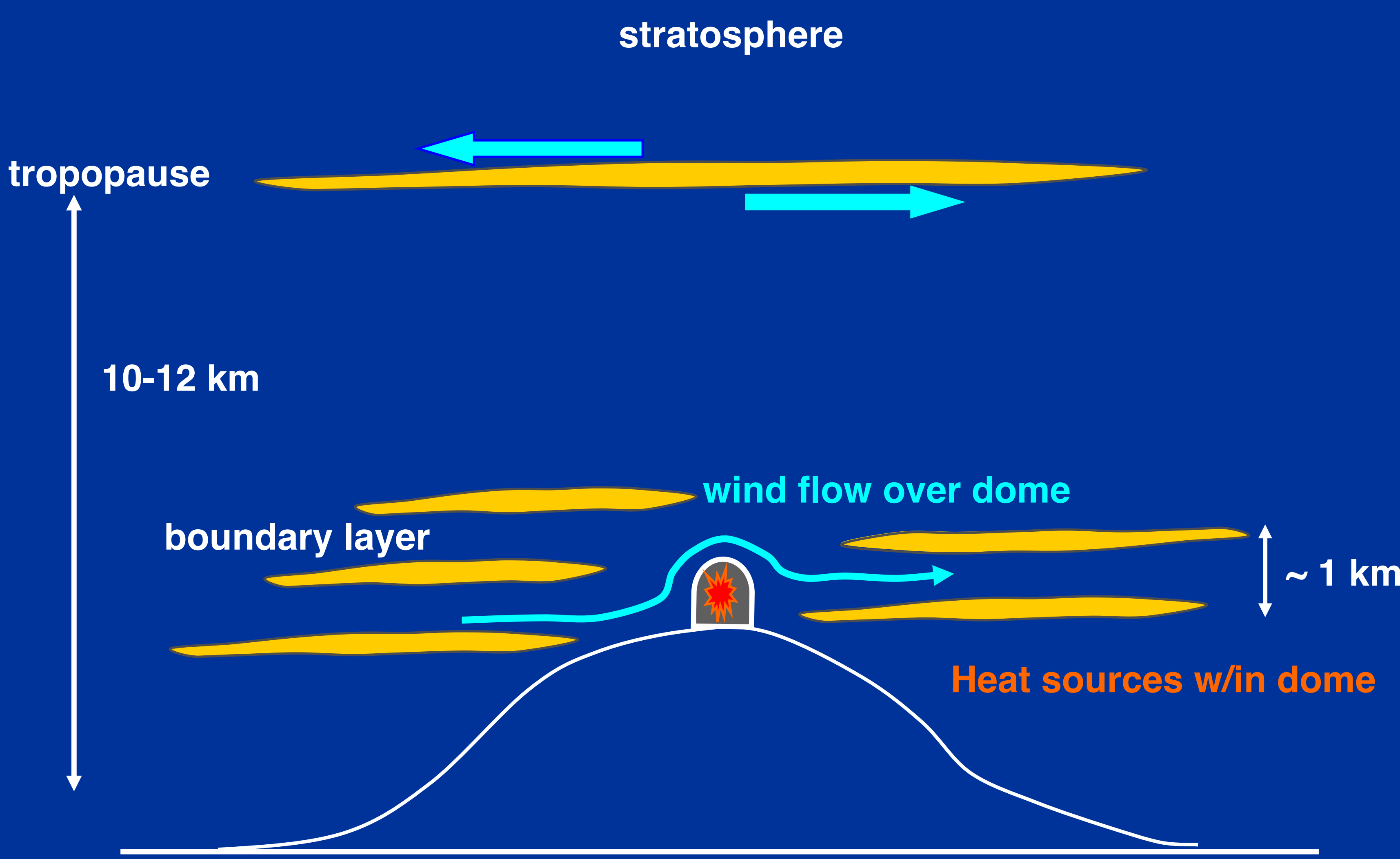
Image is spread out into speckles



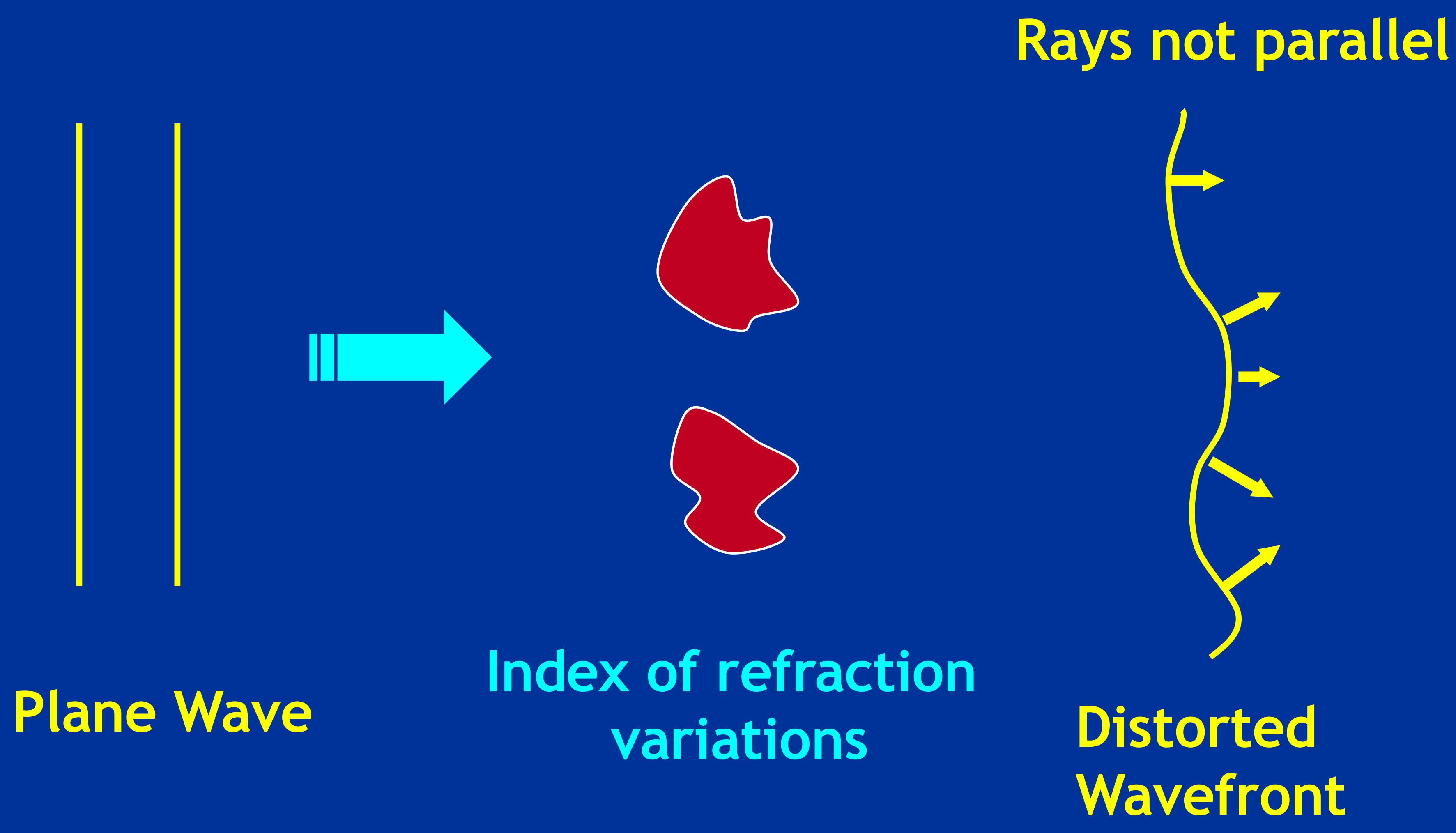
Centroid jumps around (image motion)

"Speckle images": sequence of short snapshots of a star, taken at Lick Observatory using the IRCAL infra-red camera

Turbulence arises in many places

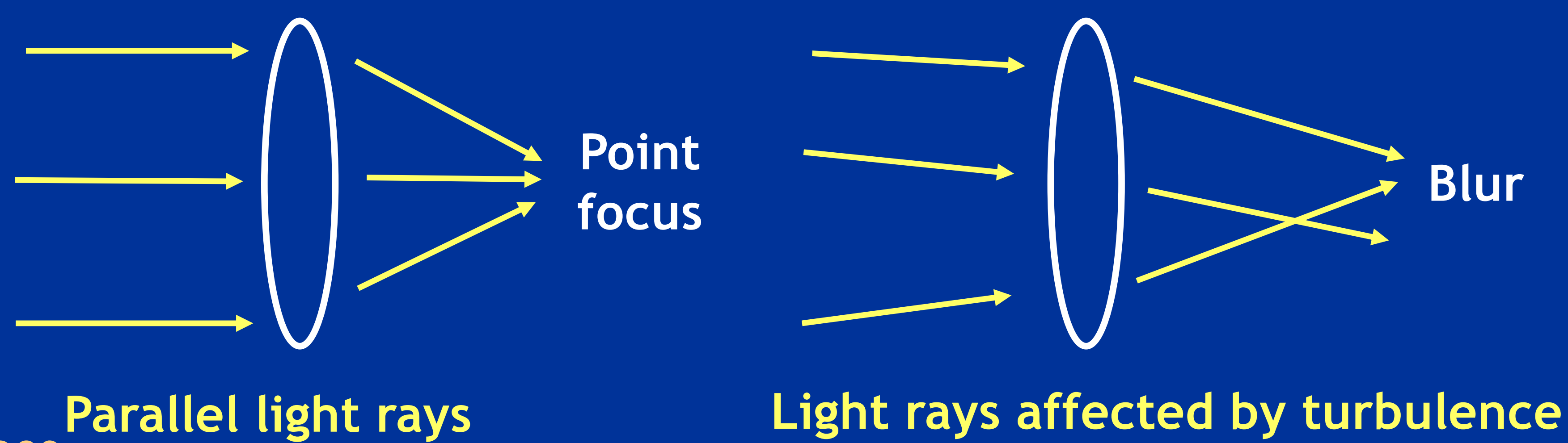


Atmospheric perturbations cause distorted wavefronts

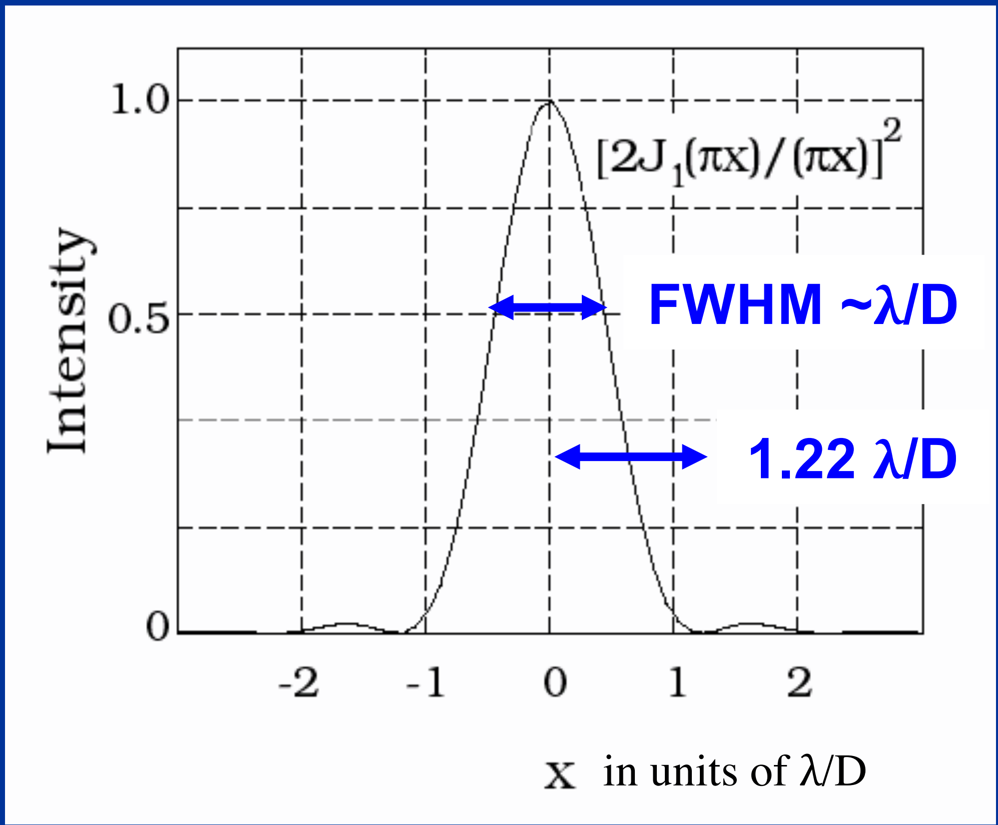


Optical consequences of turbulence

- 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:



Imaging through a perfect telescope



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

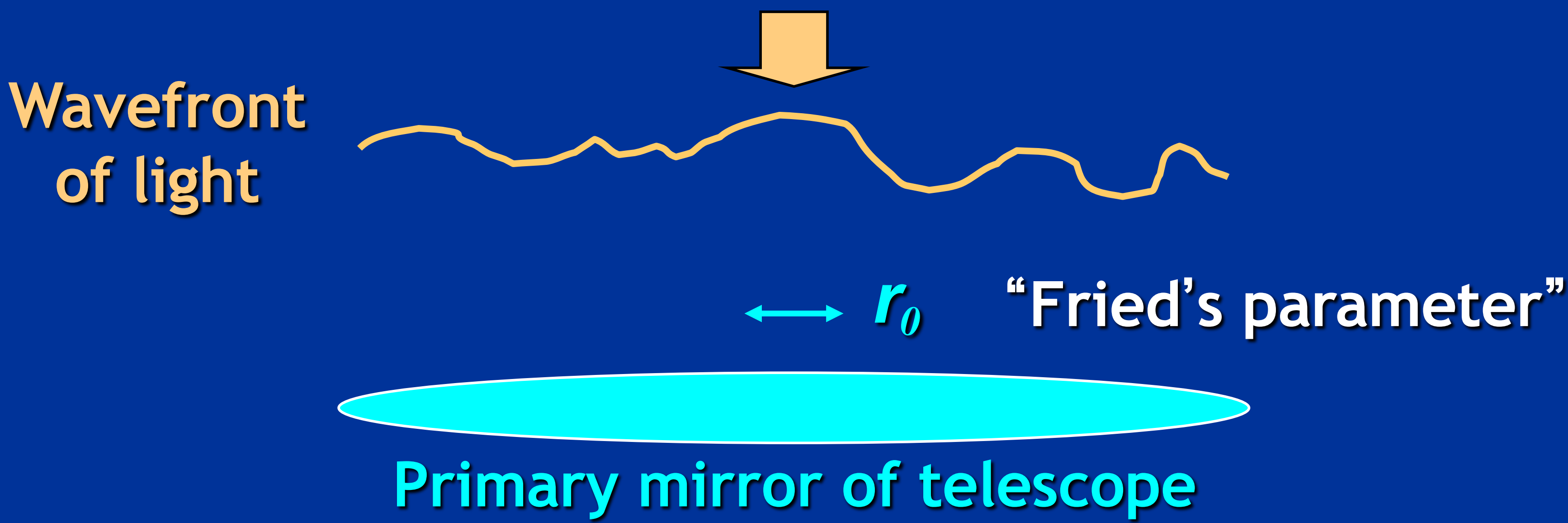
With no turbulence, FWHM is diffraction limit of telescope, $\theta \sim \lambda / D$

Example:

λ / D = 0.02 arc sec for λ = 1 μm, D = 10 m

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

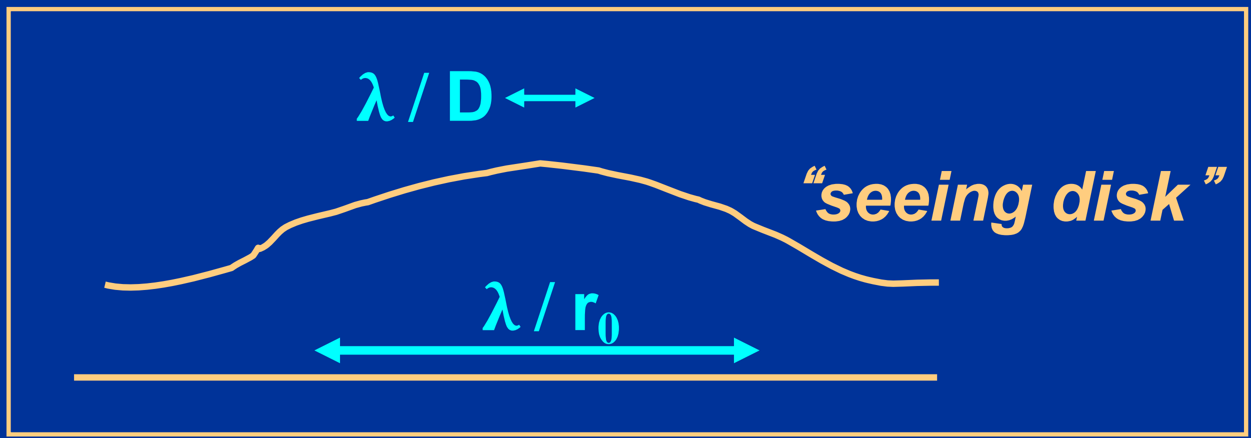
Characterize turbulence strength by quantity r_0



- "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)
- r_0 = 10 cm for seeing of 1 arc sec at λ = 0.5 μm

Effect of turbulence on image size

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



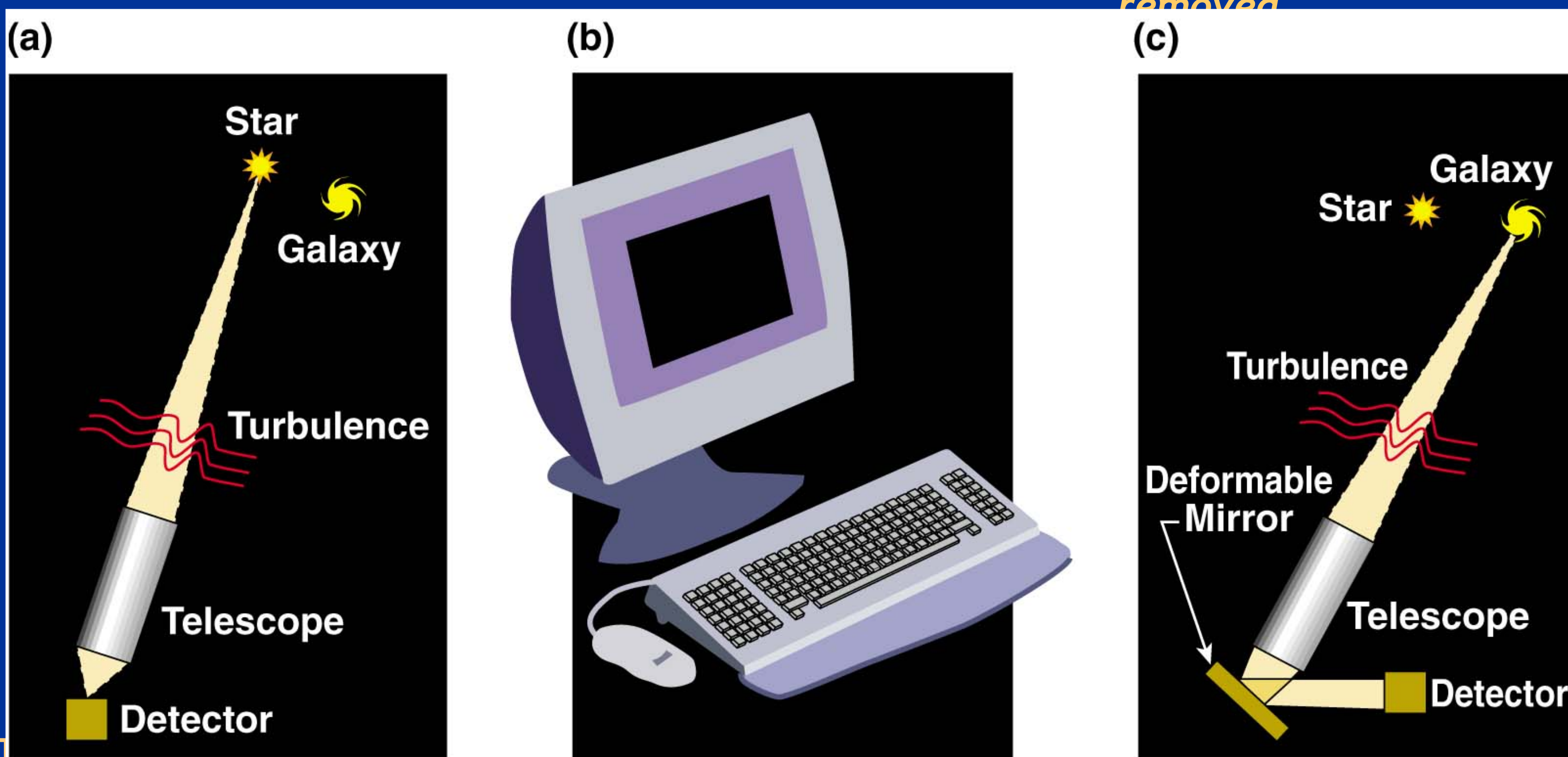
- r_0 is diameter of the circular pupil for which the diffraction limited image and the seeing limited image have the same angular resolution.
- Any telescope with diameter D > r_0 has no better spatial resolution than a telescope for which D = r_0 (!)

How does adaptive optics help? (cartoon approximation)

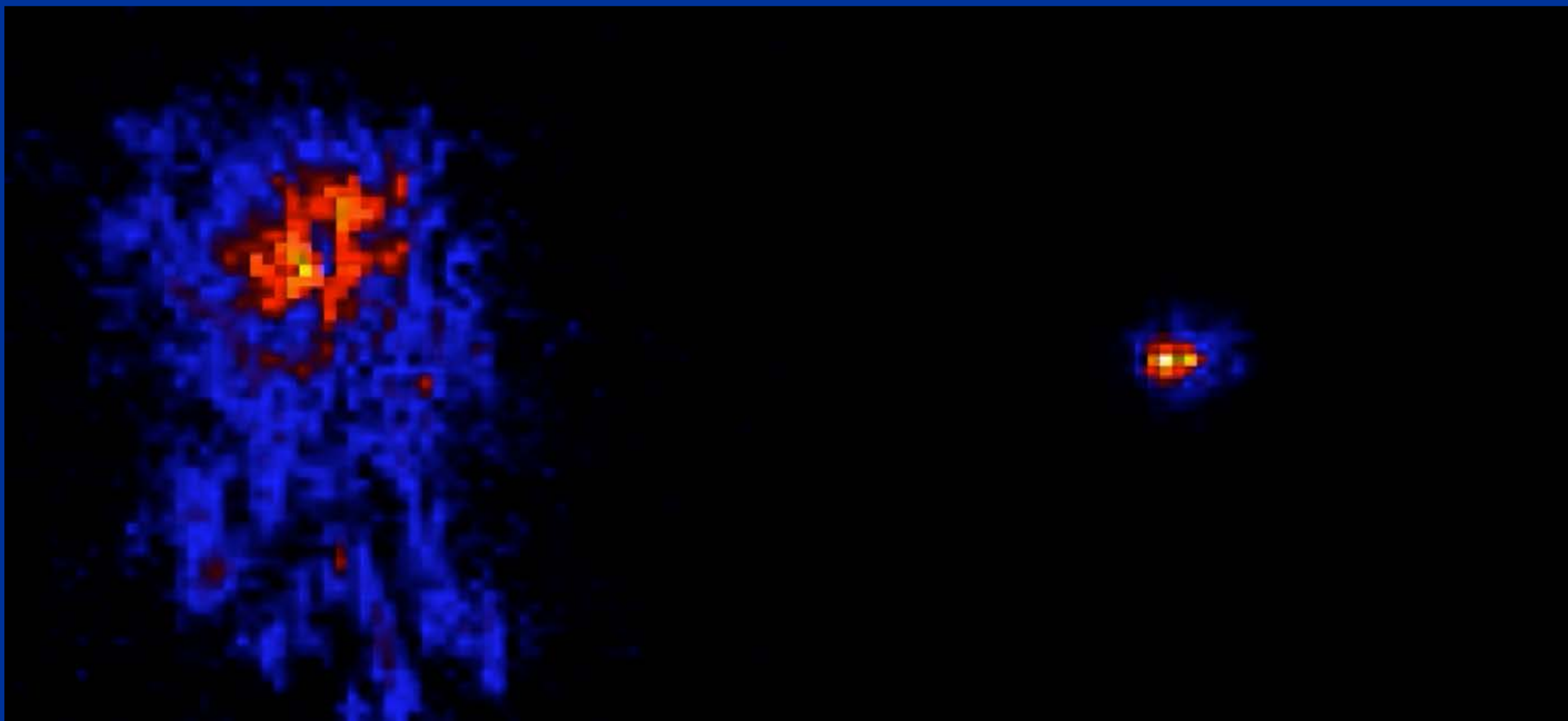
Measure details of blurring from "guide star" near the object you want to observe

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



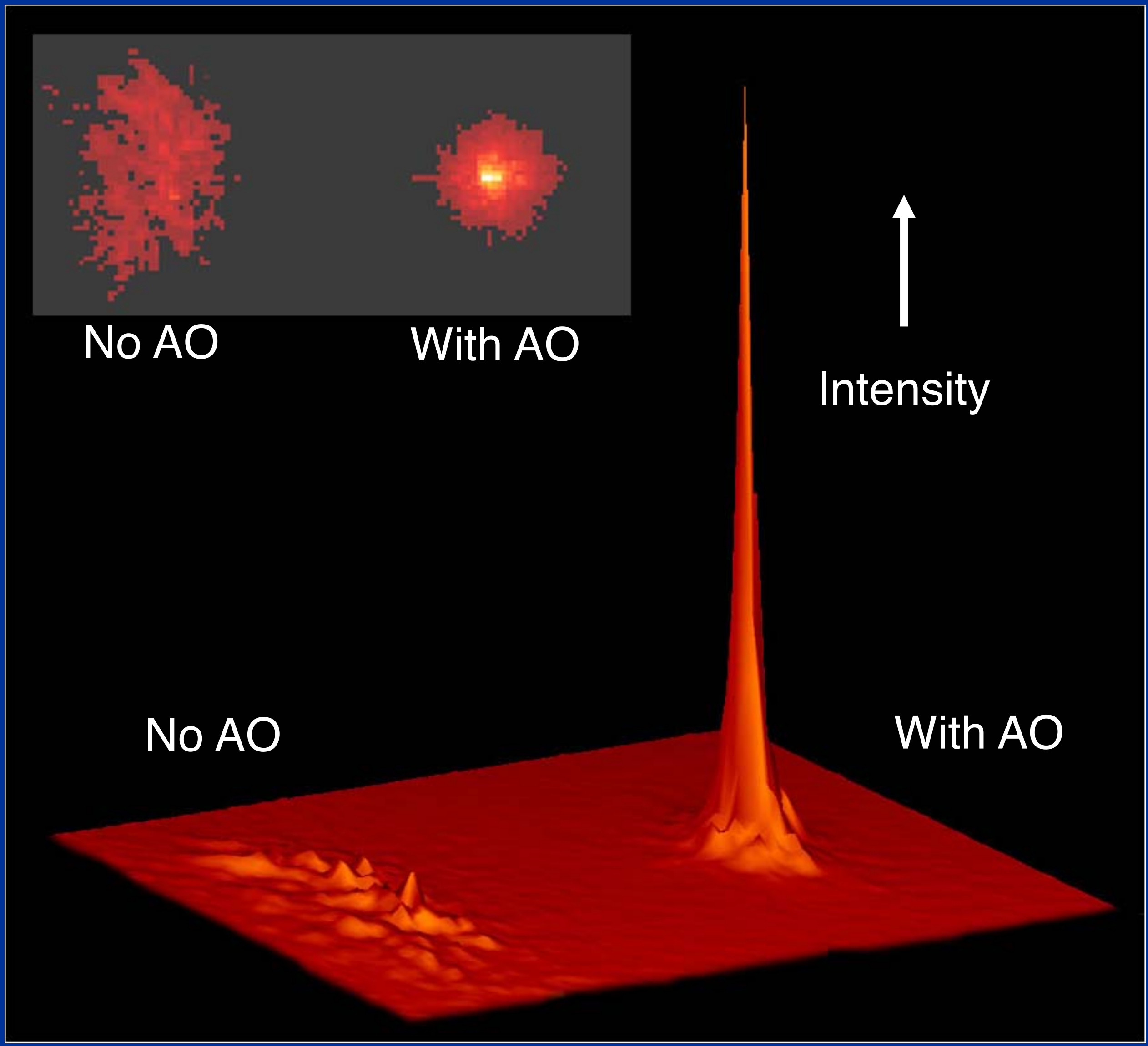
Infra-red images of a star, from Lick Observatory adaptive optics system



No adaptive optics With adaptive optics

Note: "colors" (blue, red, yellow, white) indicate increasing intensity

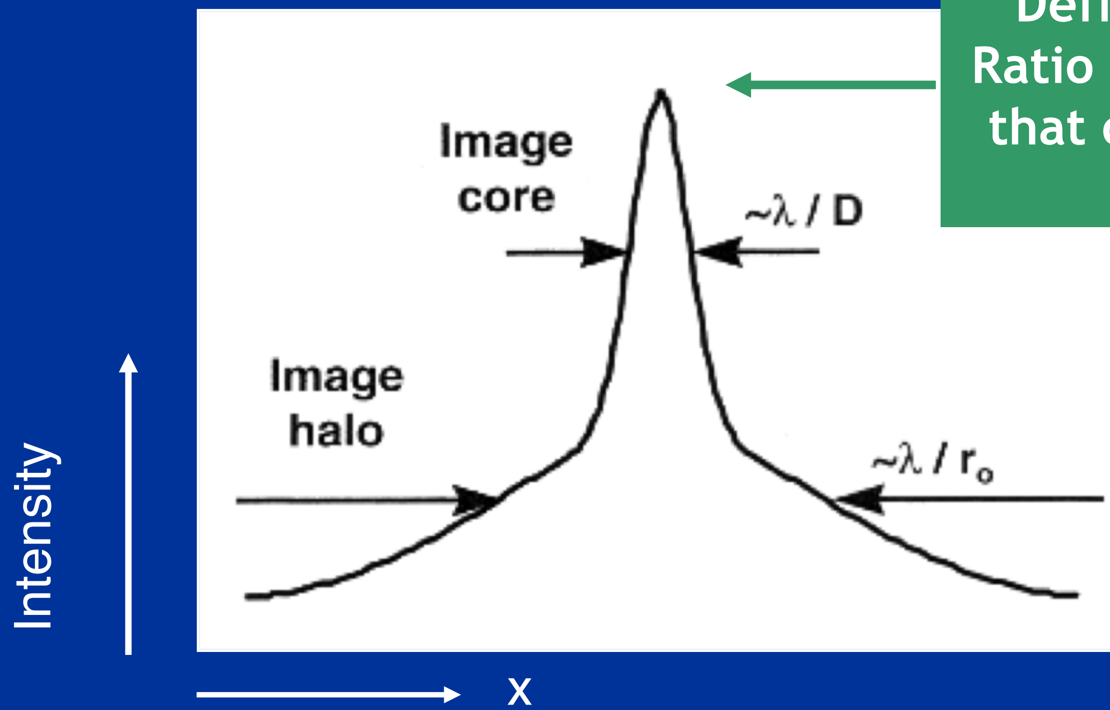
Adaptive optics increases peak intensity of a point source



Lick Observatory

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

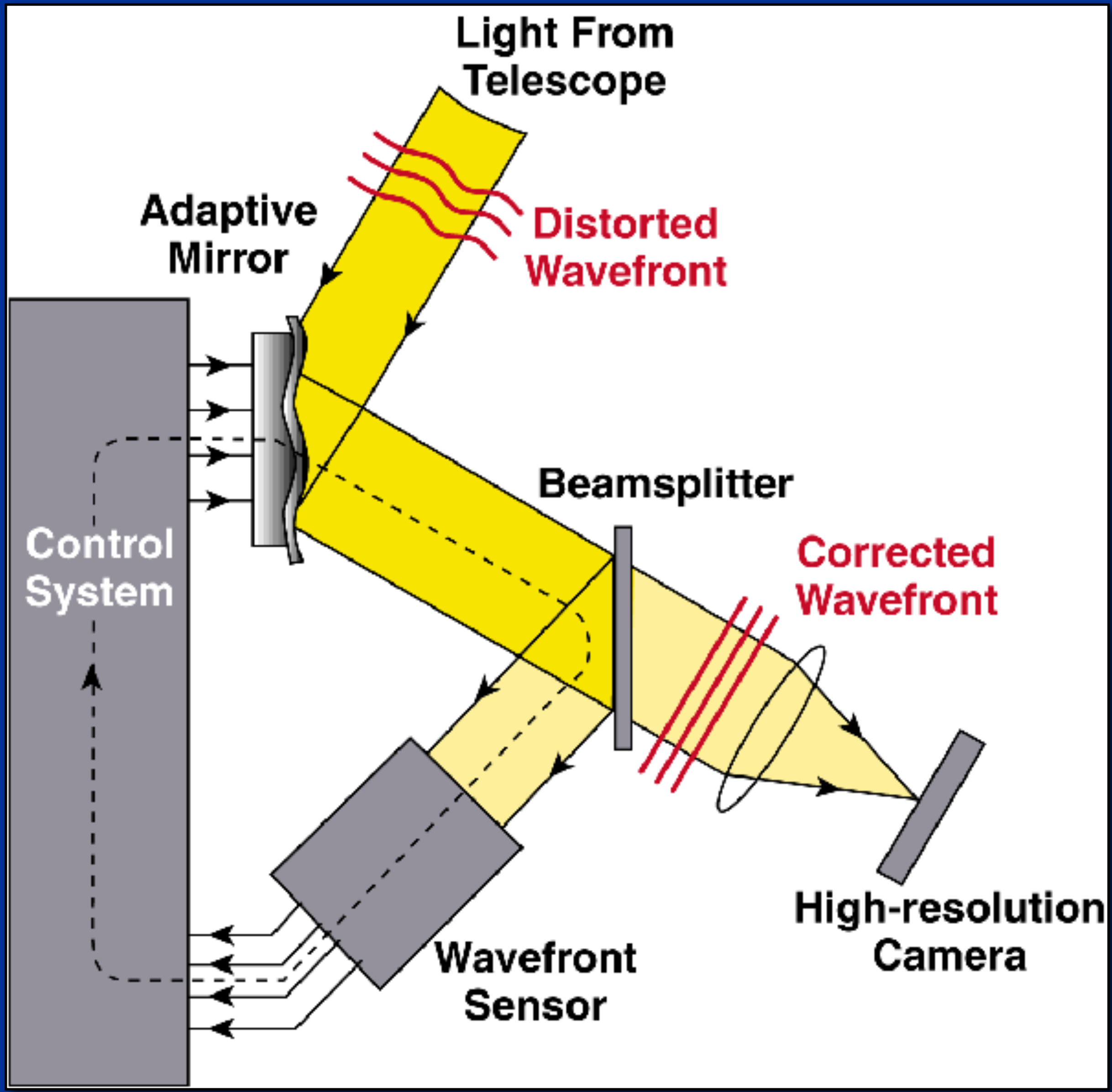
Definition of "Strehl": Ratio of peak intensity to that of "perfect" optical system



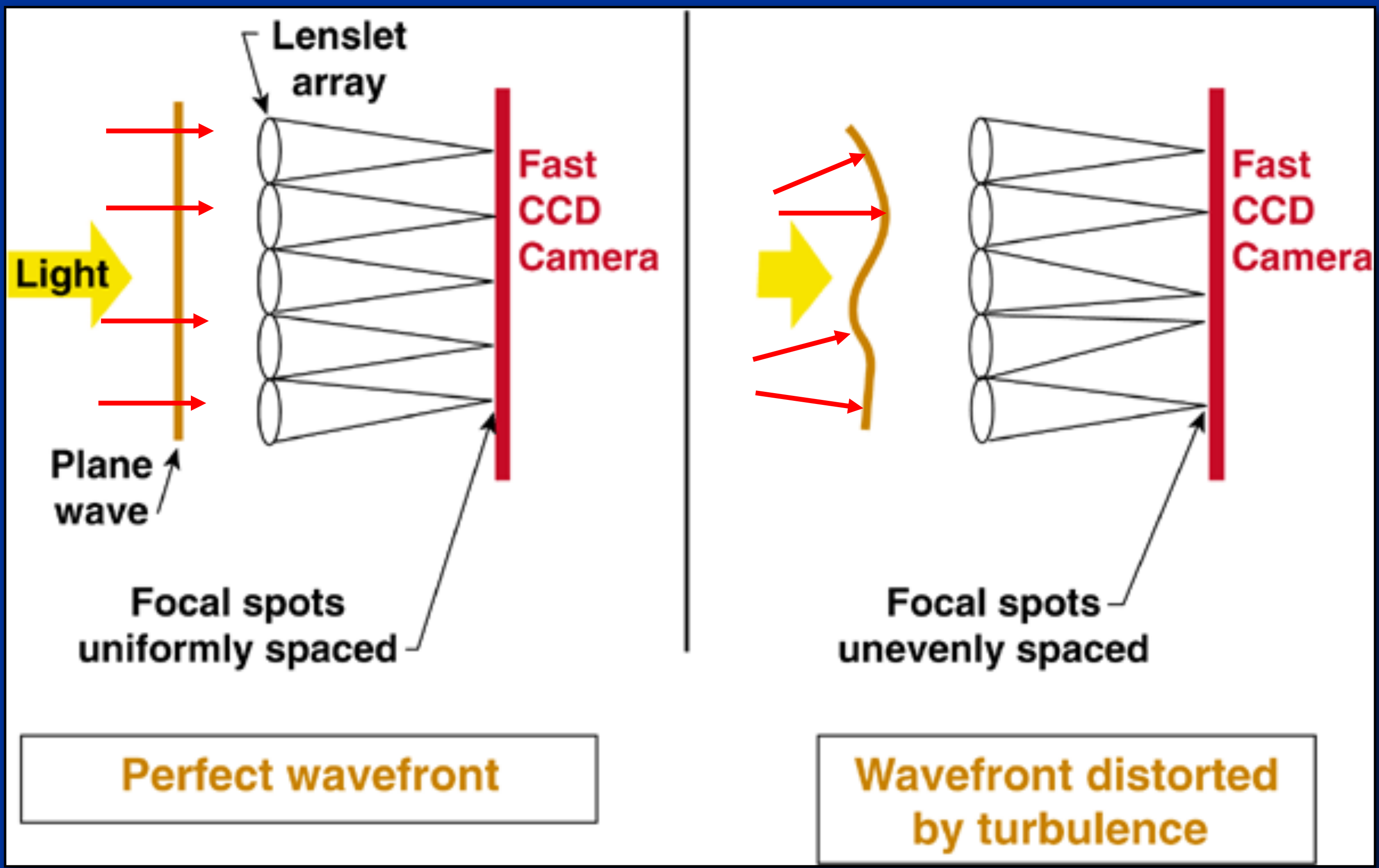
- When AO system performs well, more energy in core
- When AO system is stressed (poor seeing), halo contains larger fraction of energy (diameter ~ r_0)
- Ratio between core and halo varies during night

Schematic of adaptive optics system

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



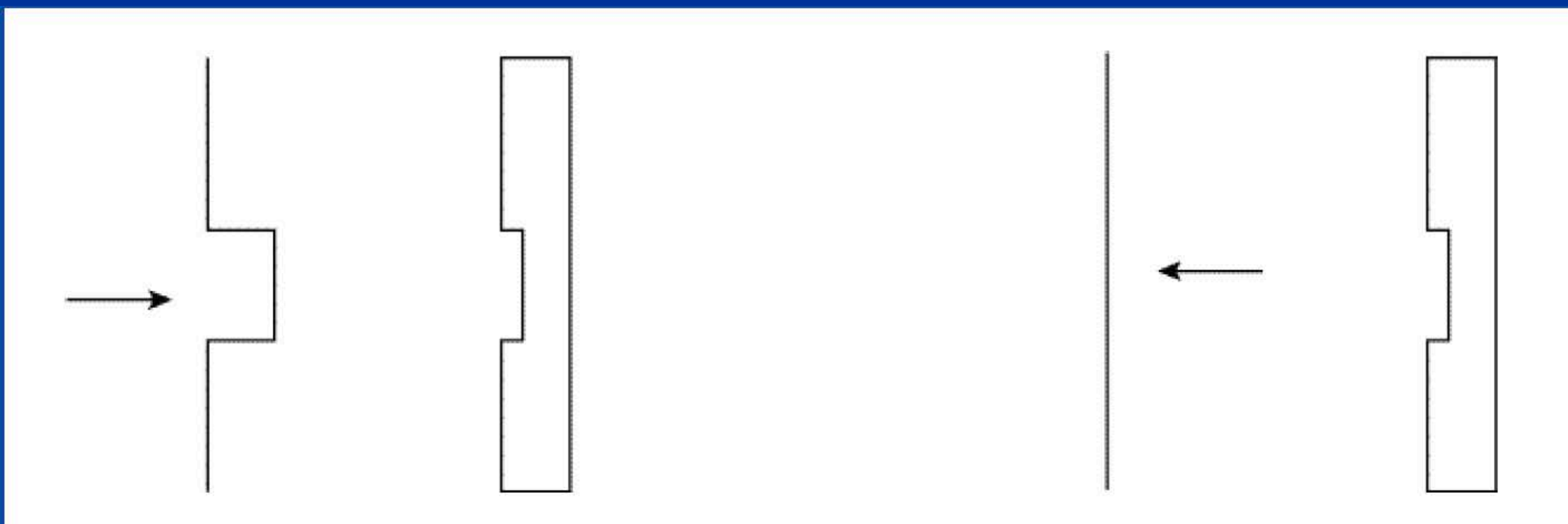
How to measure turbulent distortions (one method among many)



Shack-Hartmann wavefront sensor

How a deformable mirror works (idealization)

BEFORE **AFTER**

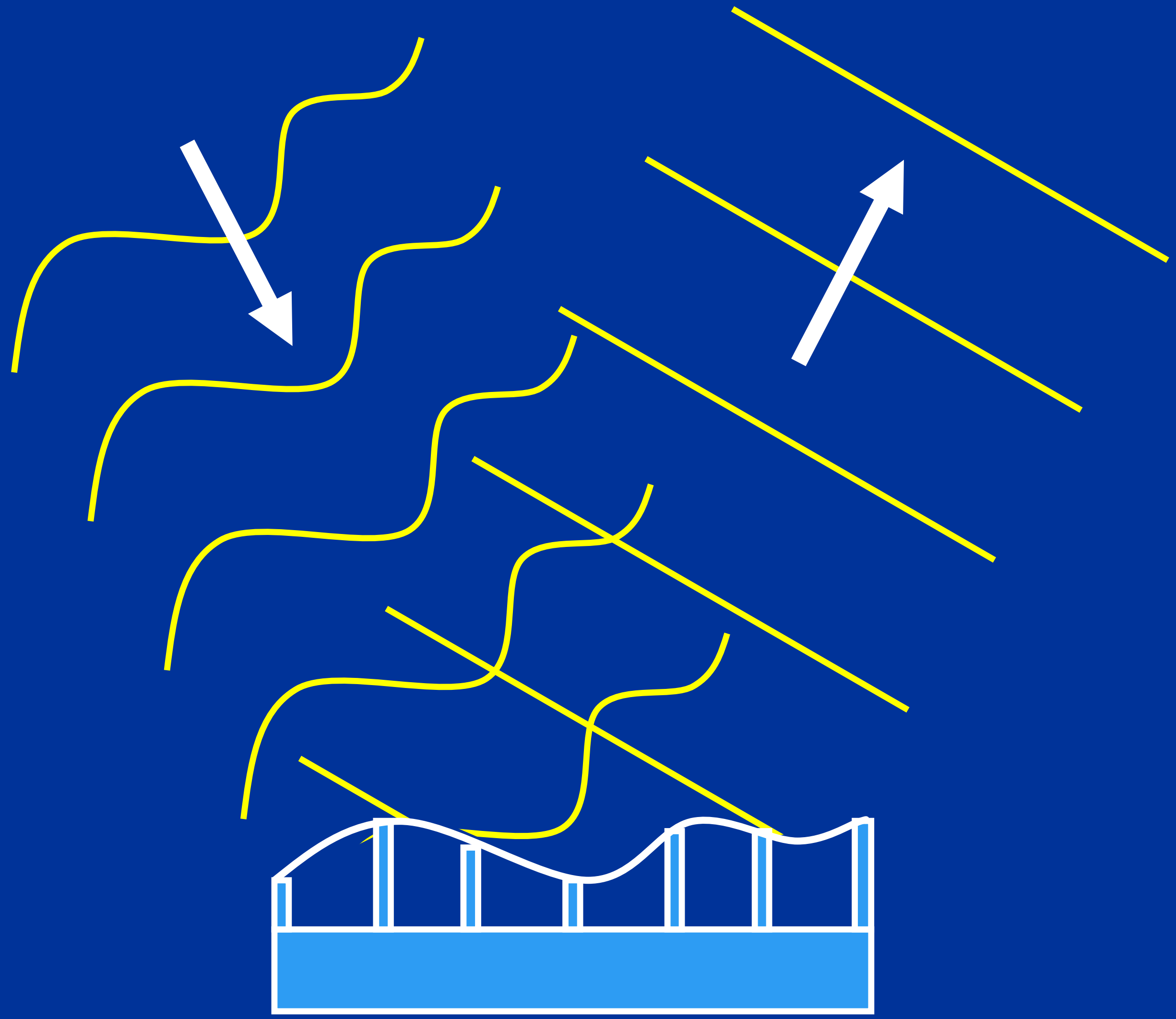


Incoming Wave with Aberration

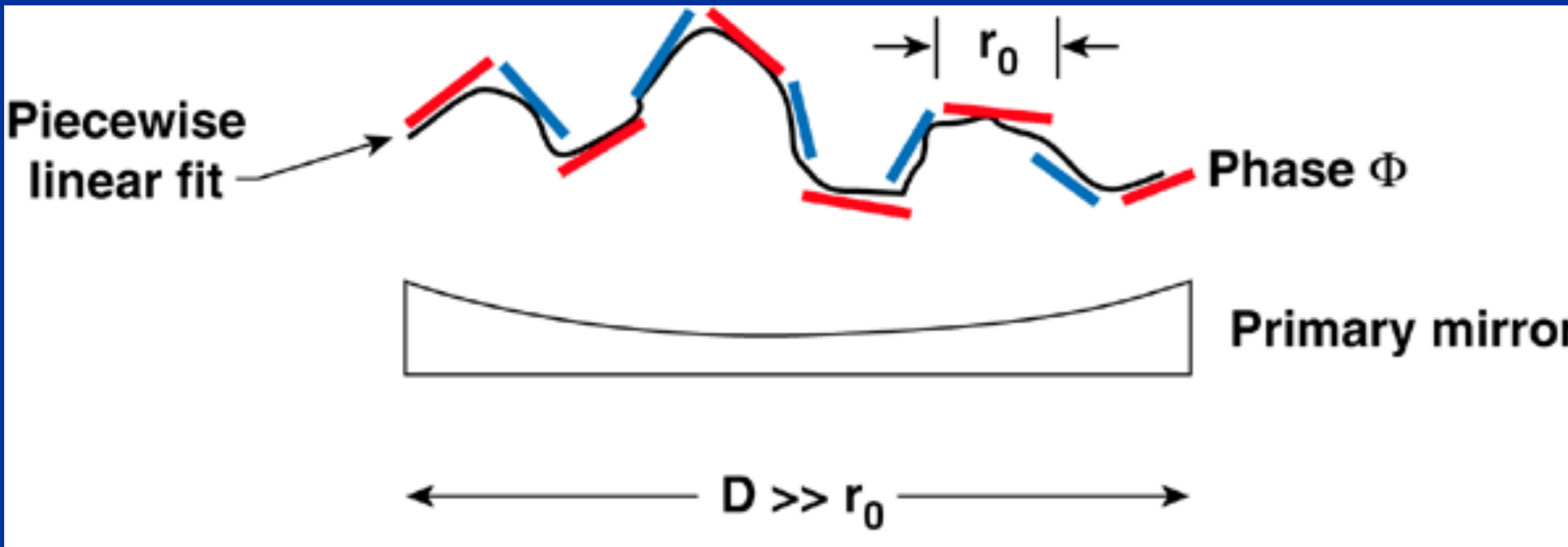
Deformable Mirror

Corrected Wavefront

Deformable Mirror for Real Wavefronts



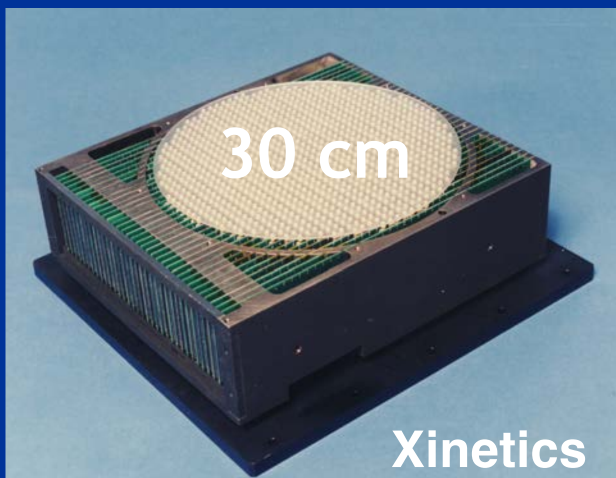
Real deformable mirrors have smooth surfaces



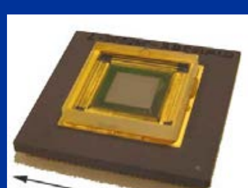
- In practice, a smaller deformable mirror with a thin bendable face sheet is used
- Frequently placed <u>after</u> main telescope mirror

Deformable mirrors come in many sizes

Glass facesheet
1000 actuators



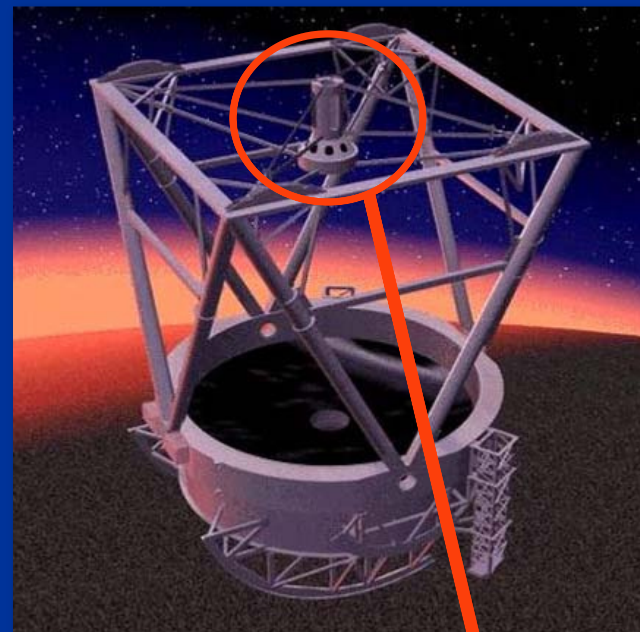
MEMS
1000 actuators

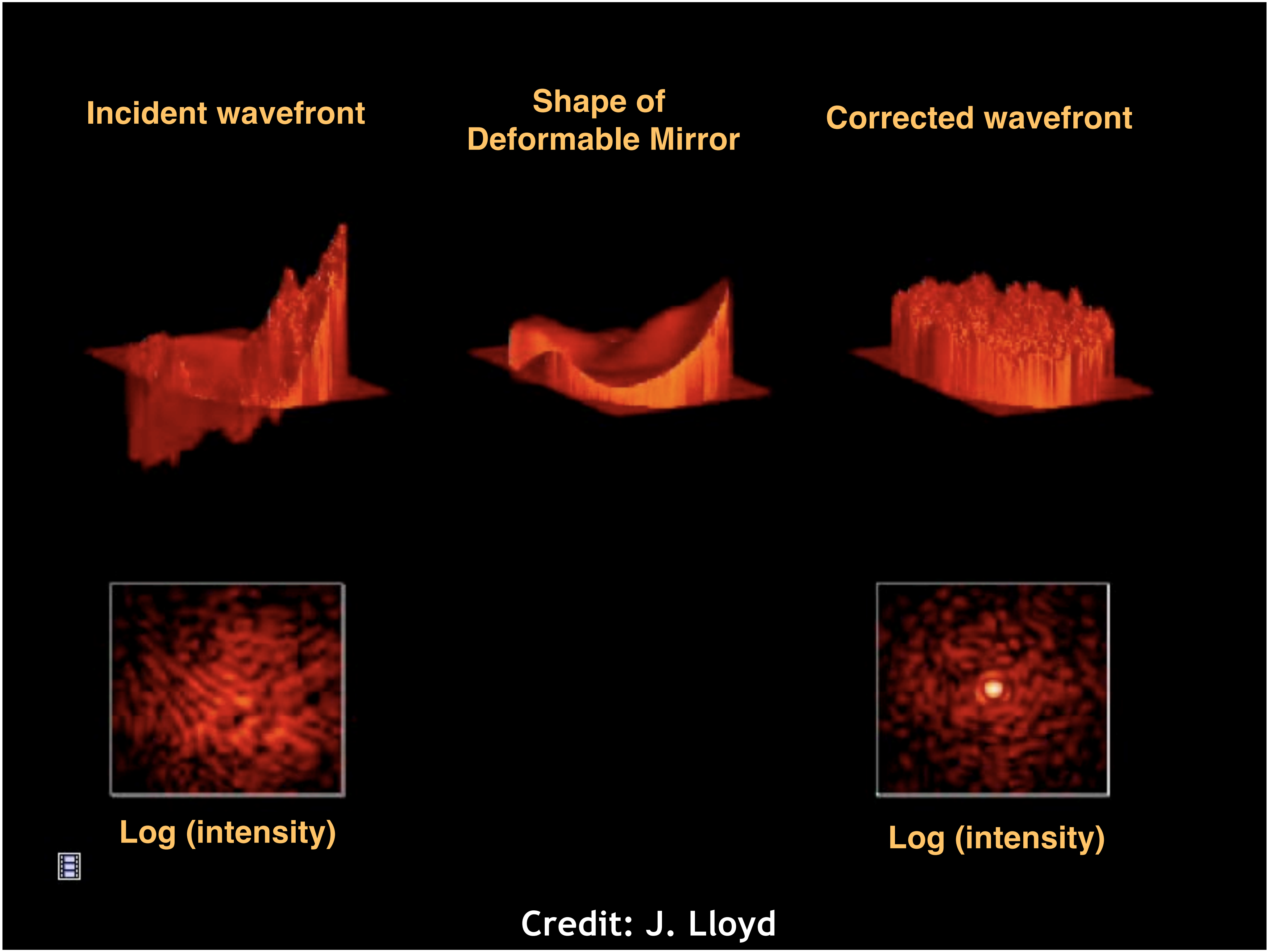


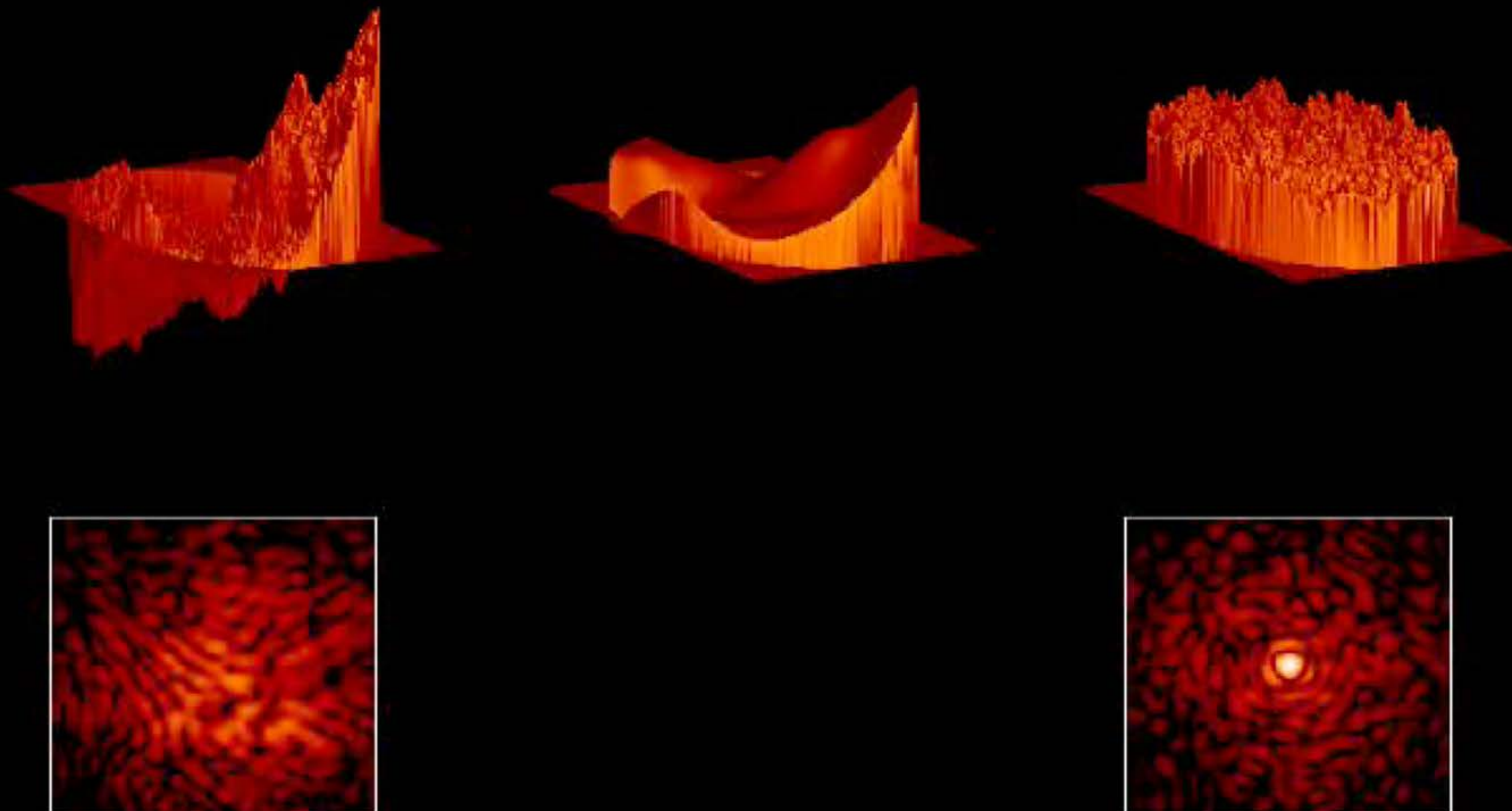
1 cm

Boston
Micro-
Machines

Adaptive
Secondary
Mirrors

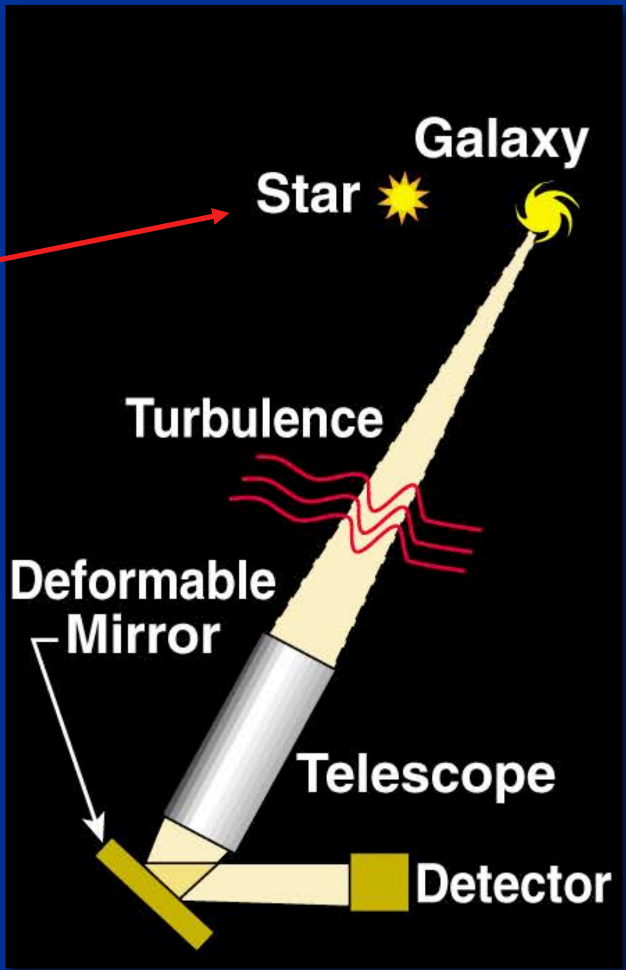



Incident wavefront
Shape of
Deformable Mirror
Corrected wavefront
Log (intensity)
Log (intensity)
Credit: J. Lloyd



If there's no close-by "real" star, create one with a laser

- Use a laser beam to create artificial "star" at altitude of 100 km in atmosphere

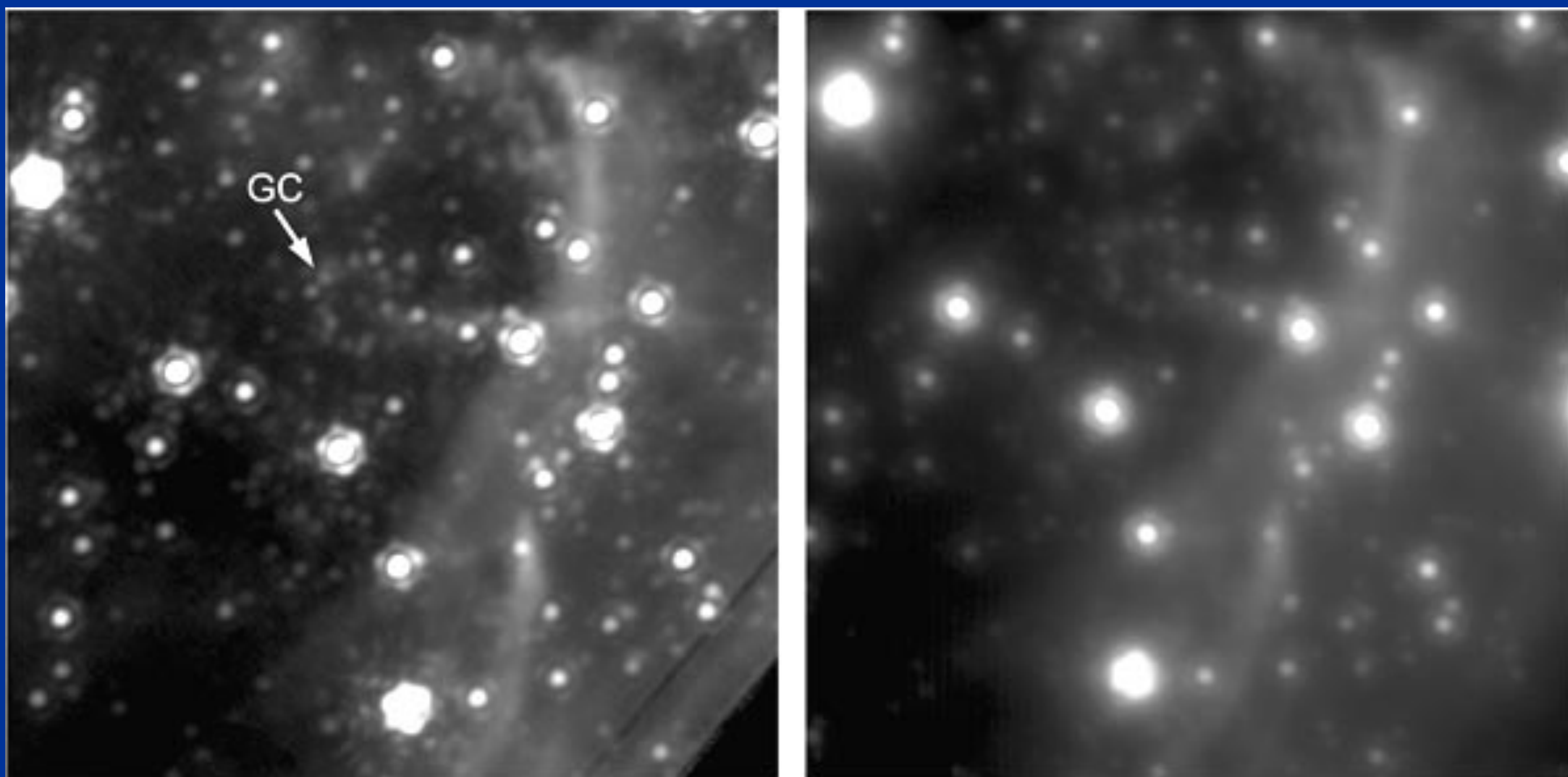


Laser guide stars are operating at Lick, Keck, Gemini N & S, VLT, Subaru, …

Four lasers on Mauna Kea: Keck 1 and 2, Gemini, Subaru telescopes

Galactic Center with Keck laser guide star (GC is location of supermassive black hole)

Keck laser guide star AO | **Best natural guide star AO**

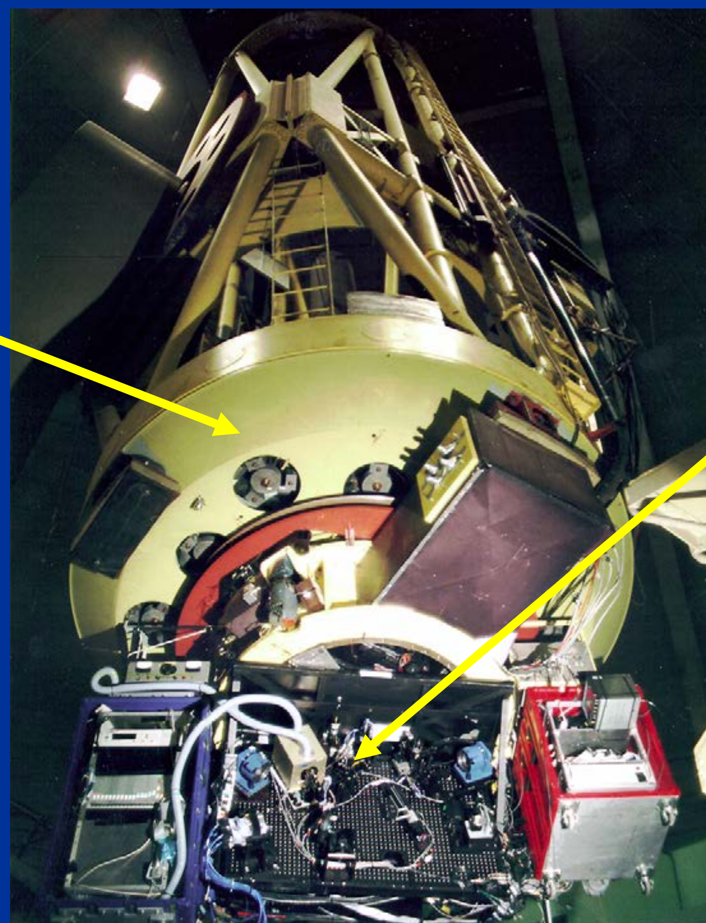


Source: UCLA Galactic Center group

Adaptive optics system is frequently <u>behind</u> the main telescope mirror

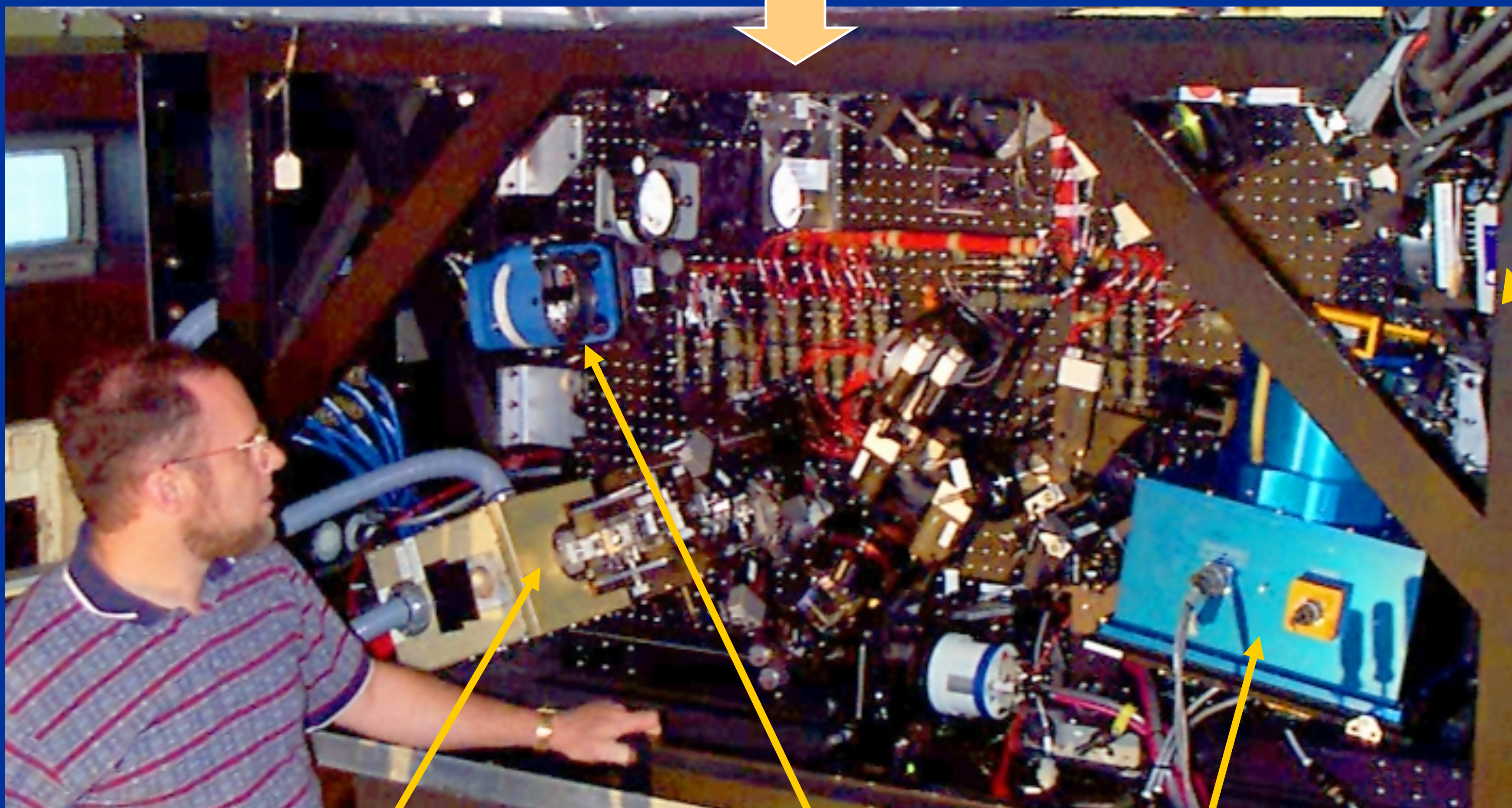
- Example: AO system at Lick Observatory's 3 m telescope

Support for main telescope mirror



Adaptive optics package below main mirror

Original Lick adaptive optics system at 3m Shane Telescope



DM

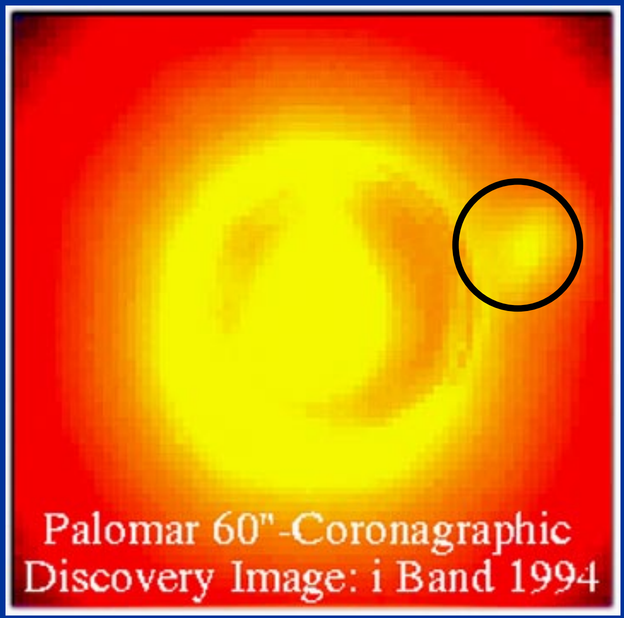
Wavefront sensor

Off-axis parabola mirror

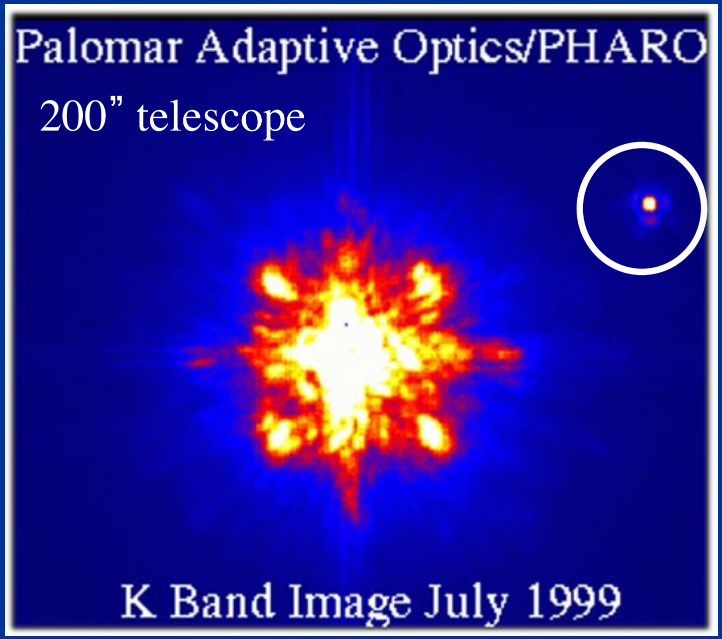
IRCAL infra-red camera

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

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



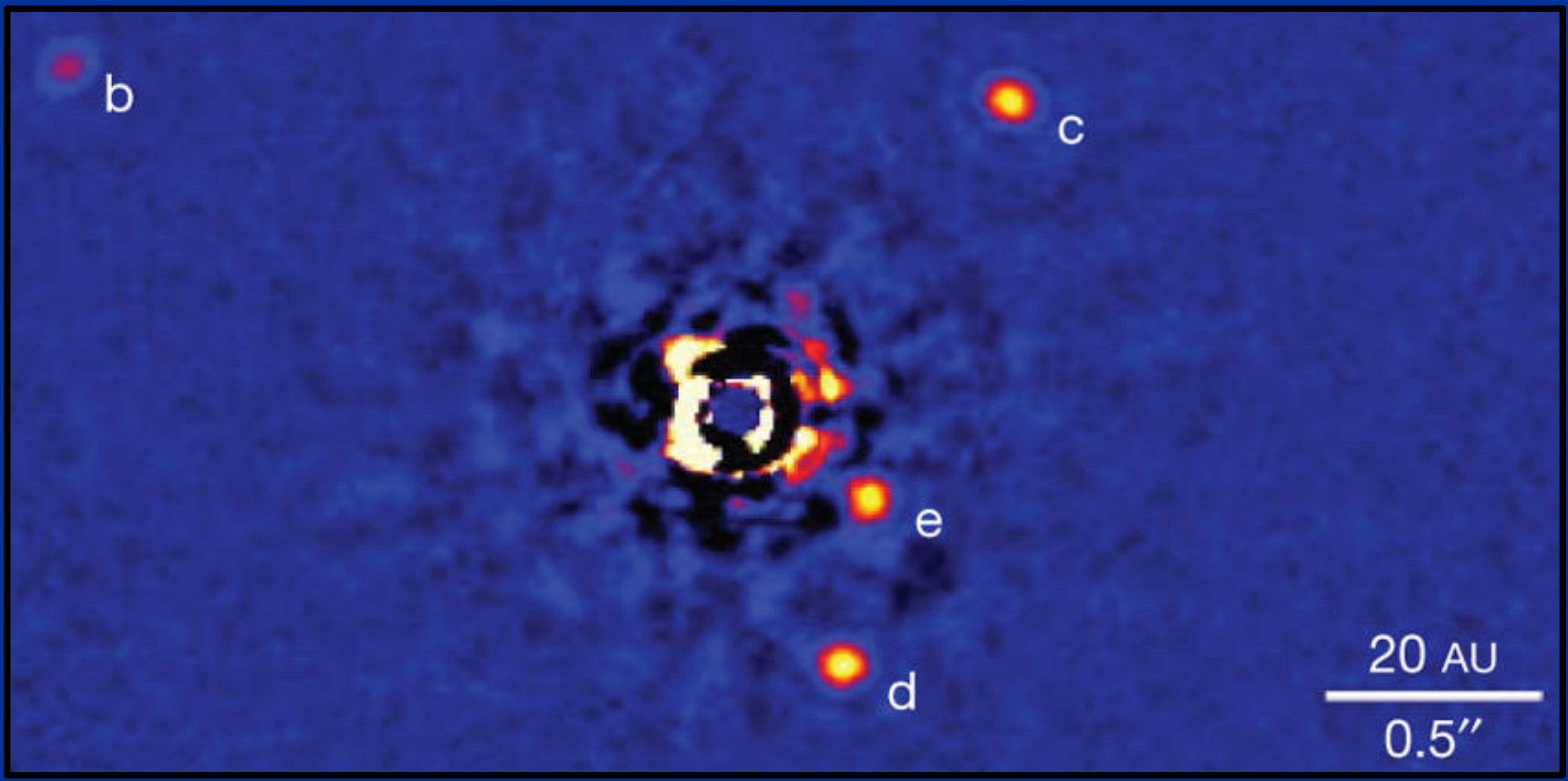
No AO



With AO

Credit: David Golimowski

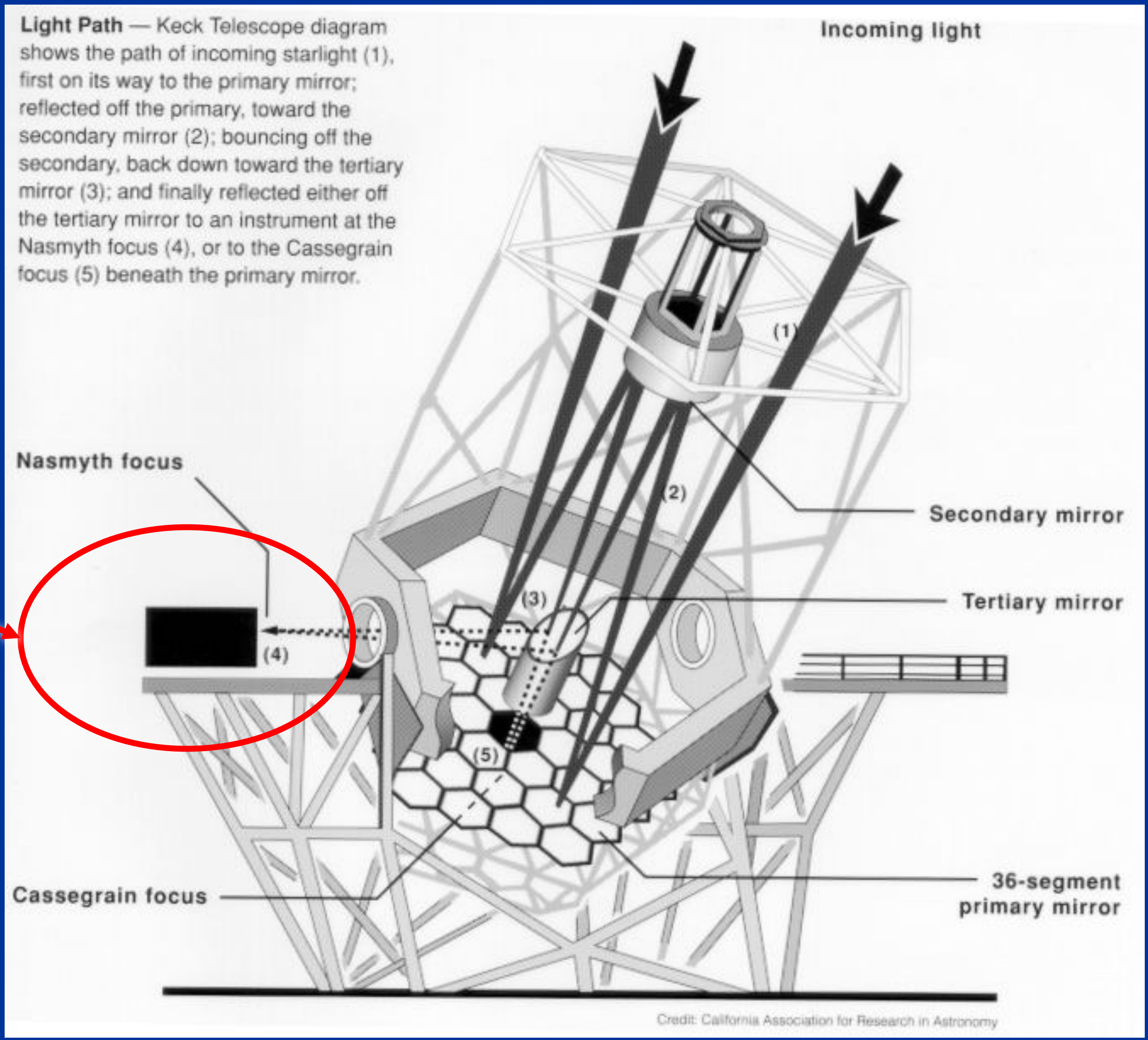
Four-planet system HR 8799



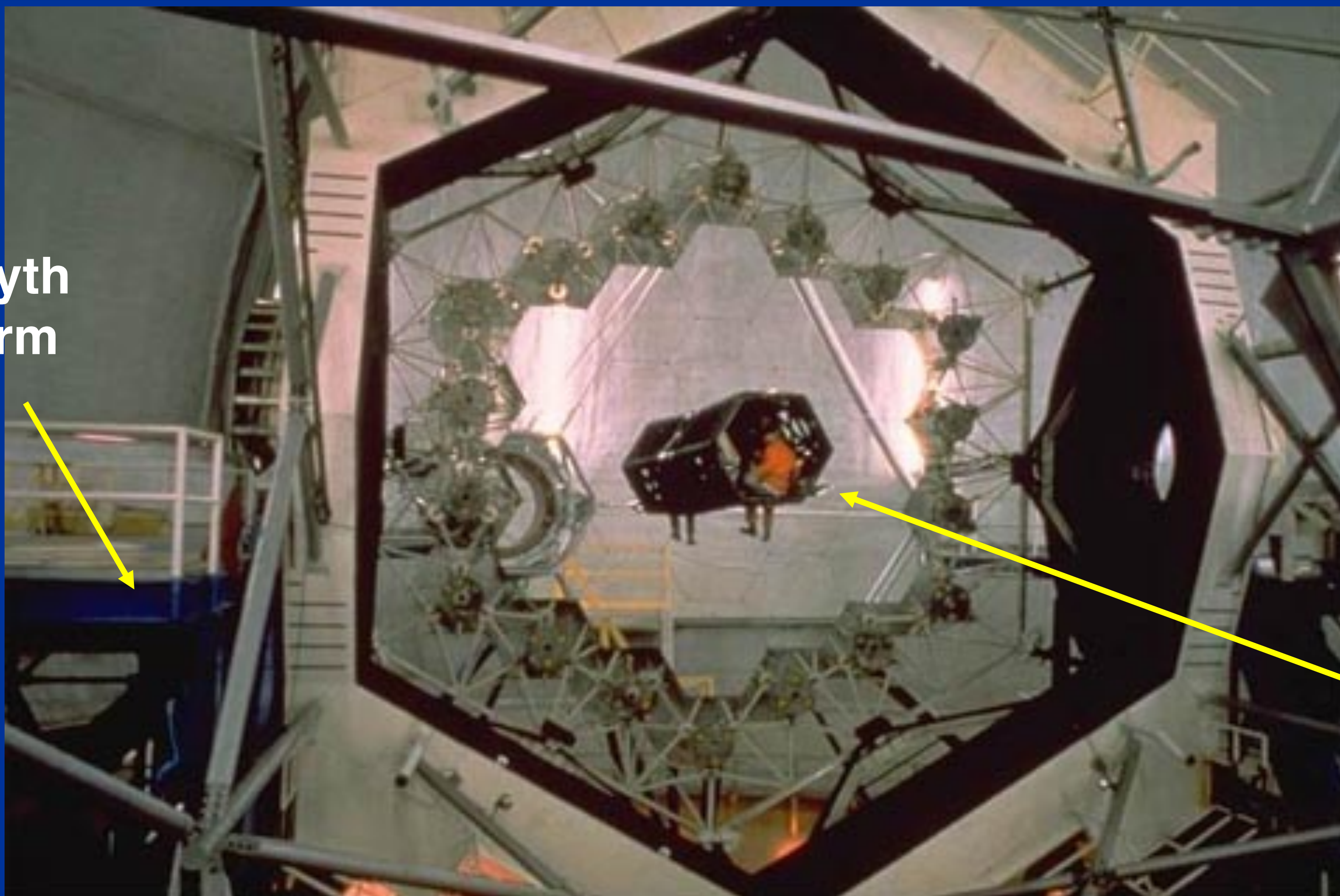
Marois et al. 2007

The Keck Telescopes

Adaptive optics lives here



Keck Telescope's primary mirror consists of 36 hexagonal segments

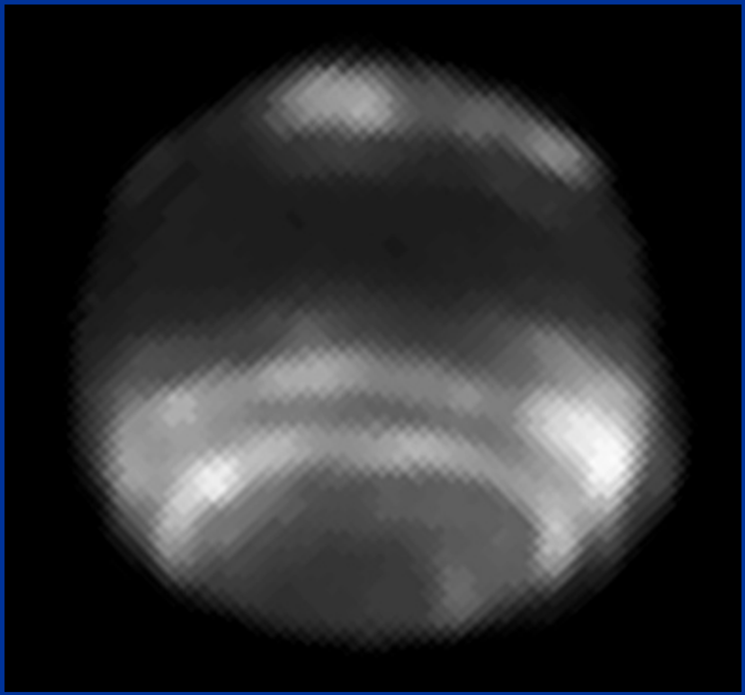


Nasmyth platform

Person!

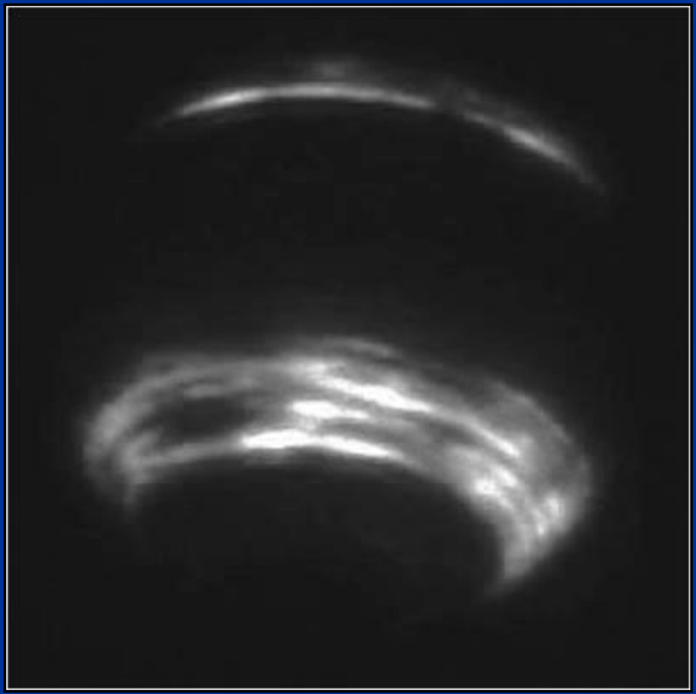
Neptune at 1.6 µm: Keck AO exceeds resolution of Hubble Space Telescope

HST - NICMOS



2.4 meter telescope

Keck AO

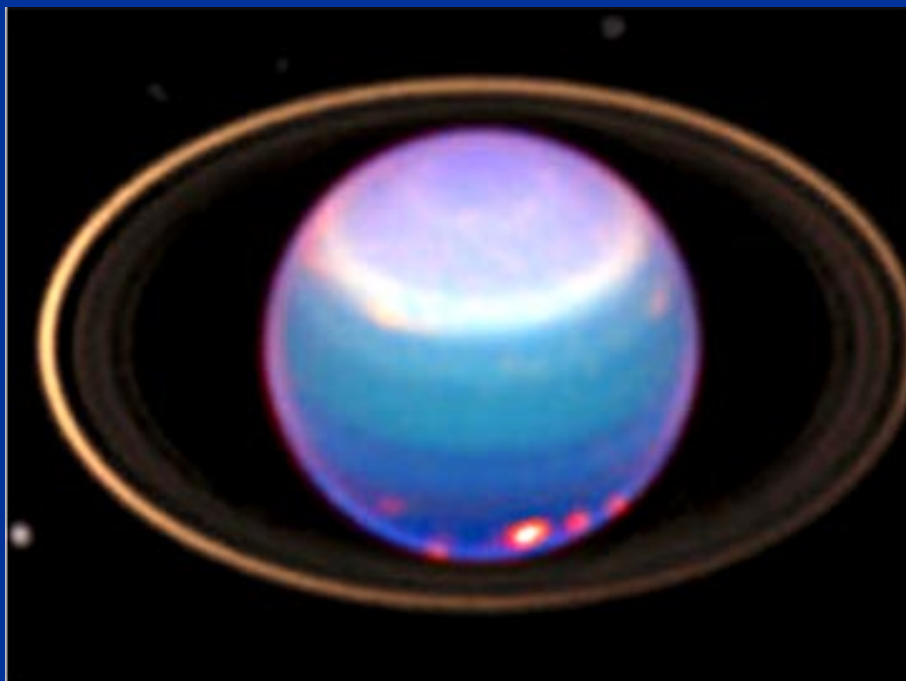


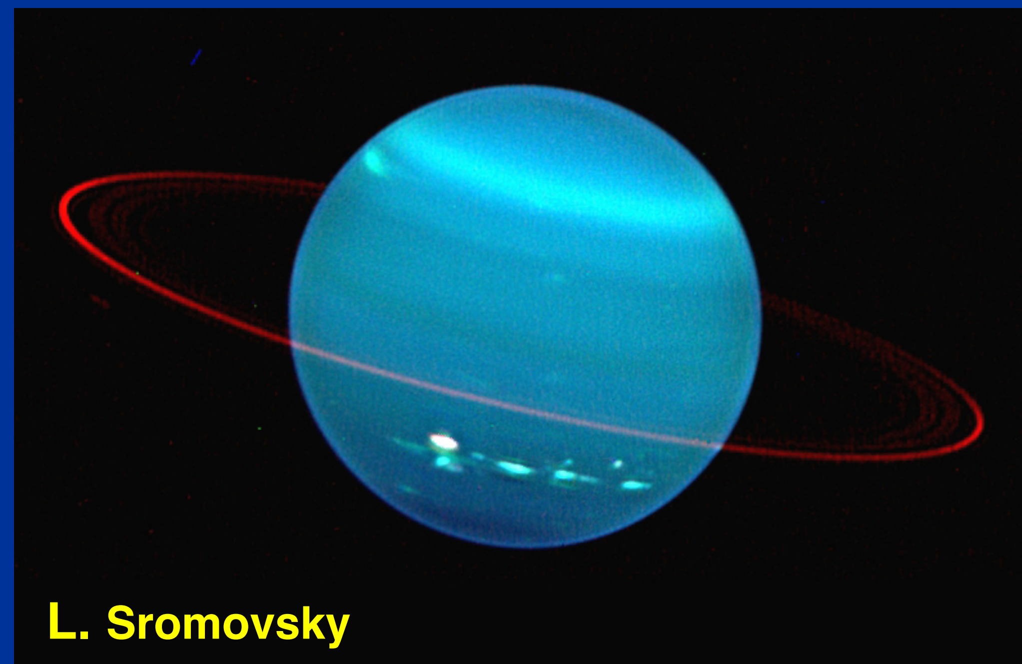
10 meter telescope

~ 2 arc sec

(Two different dates and times)

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?

- **Future systems:**
  - How far can we push new AO systems to achieve very high contrast ratios, to detect planets around nearby stars?
  - How can we best 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

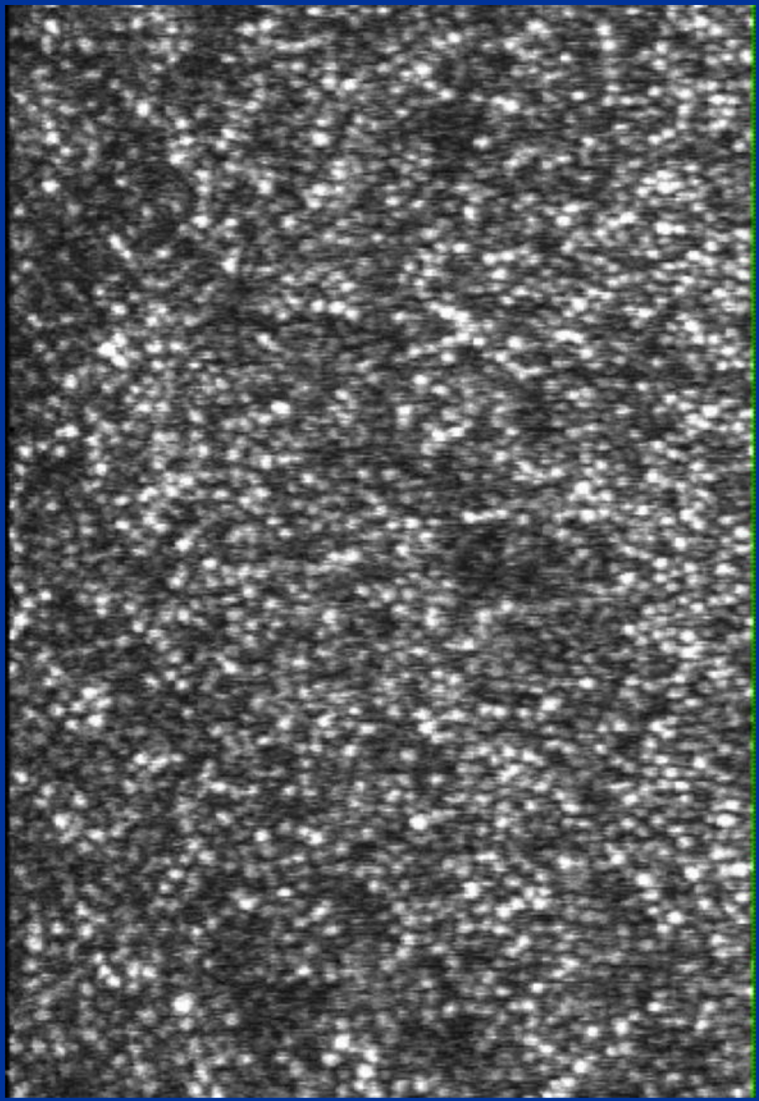
- New kinds of deformable mirrors with > 5000 degrees of freedom
- Wavefront sensors that can deal with this many degrees of freedom
- Innovative control algorithms
- "Tomographic wavefront reconstuction" using multiple laser guide stars
- New approaches to doing visible-light AO

Other AO applications

- Biology
  - Imaging the living human retina
  - Improving performance of microscopy (e.g. of cells)
- Free-space laser communications (thru air)
- Imaging and remote sensing (thru air)
- Correcting beam quality of high power lasers

Sneak preview of AO retinal imaging

Individual cones - color receptors



Watch white blood cells flow through capillaries (!)

- Enjoy!