Secrets of Adaptive Optics

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June 25, 2012

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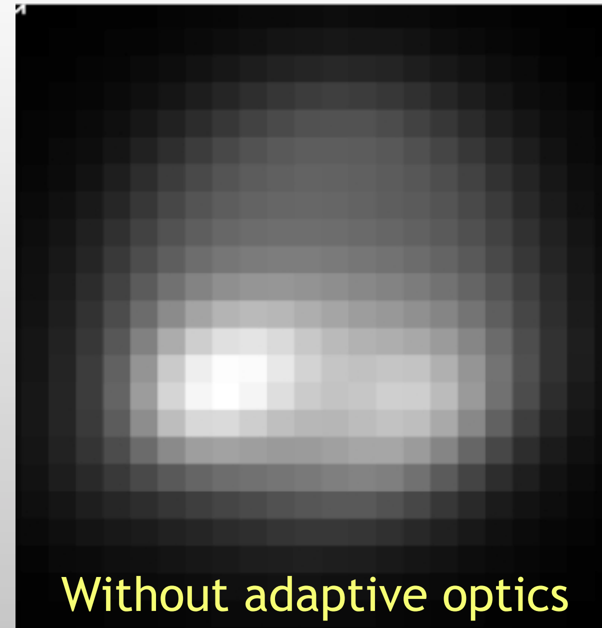
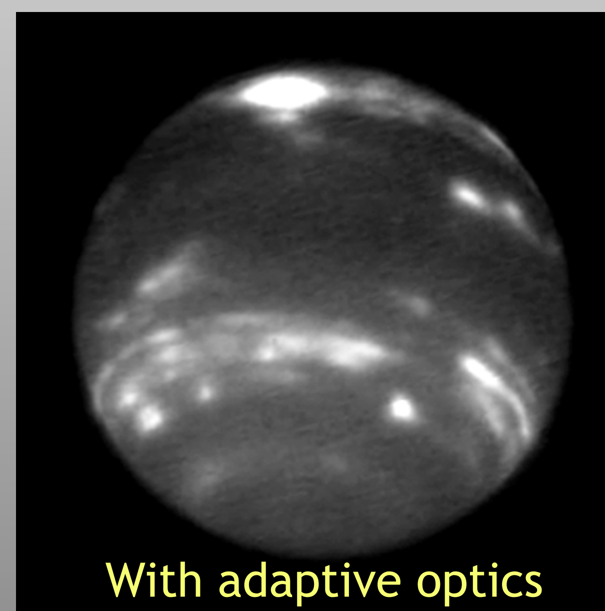
The Planet Neptune

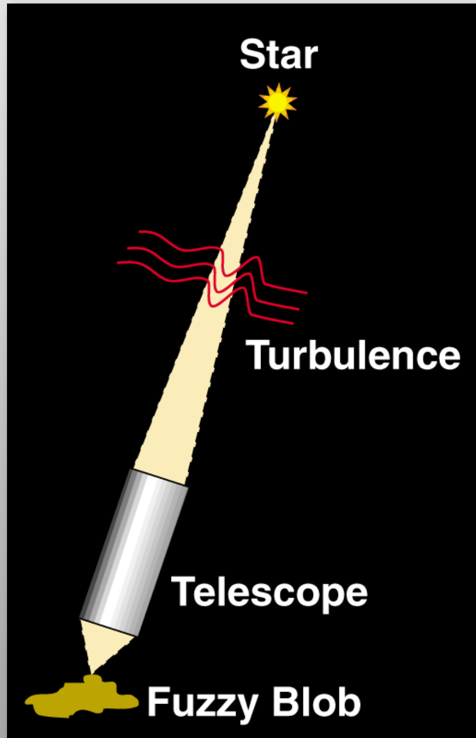




Outline

- What is adaptive optics and how does it work?
- Examples of astrophysics enabled by AO
- Computational challenges (present, future)
- AO for imaging the living human retina
- Summary

Introduction to adaptive optics



- Turbulence in the Earth's atmosphere is what limits the spatial resolution of ground-based telescopes
- Turbulence is why stars twinkle
- More important for astronomy, turbulence spreads out the light from a star; makes it a blob rather than a point

Even ground-based 8 - 10 meter telescopes have no better spatial resolution than a 20 cm backyard telescope!

Why Adaptive Optics?

- AO is a technique for correcting optical distortions to dramatically improve image quality.
- Useful in astronomy, vision science, laser eye surgery, communications, high-powered lasers, …

Short exposure images, bright star (should be a point of light)

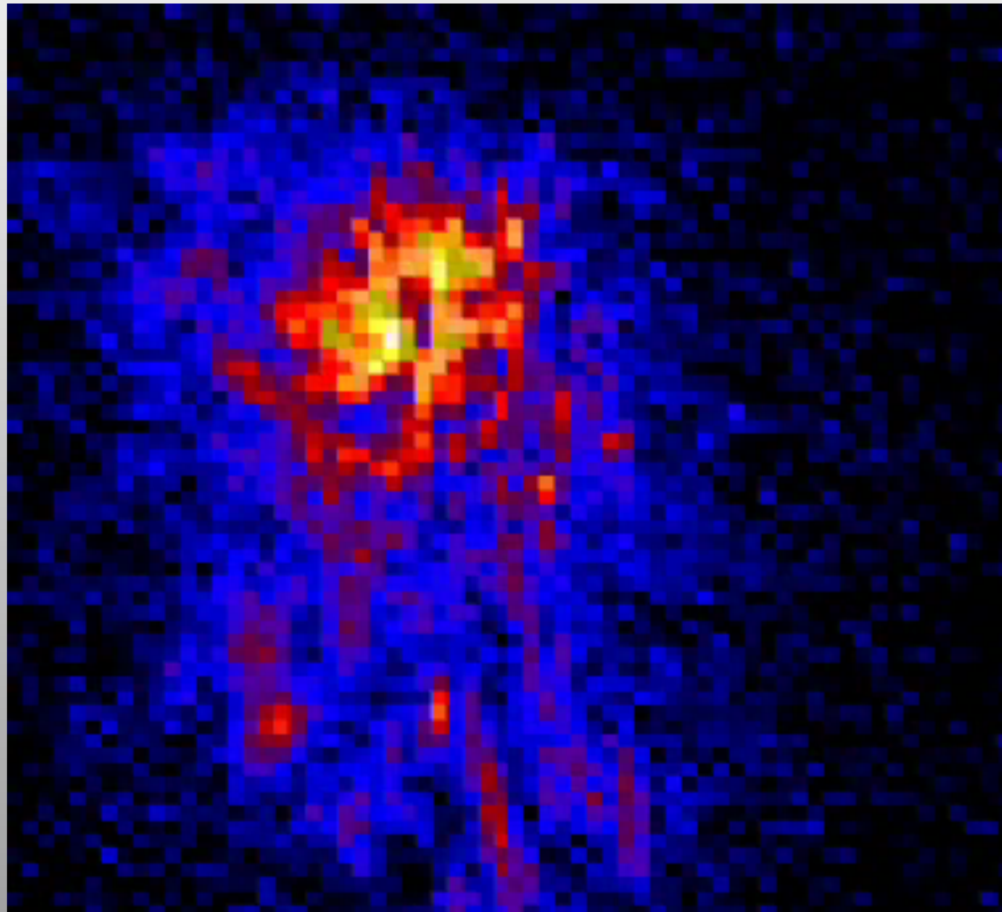


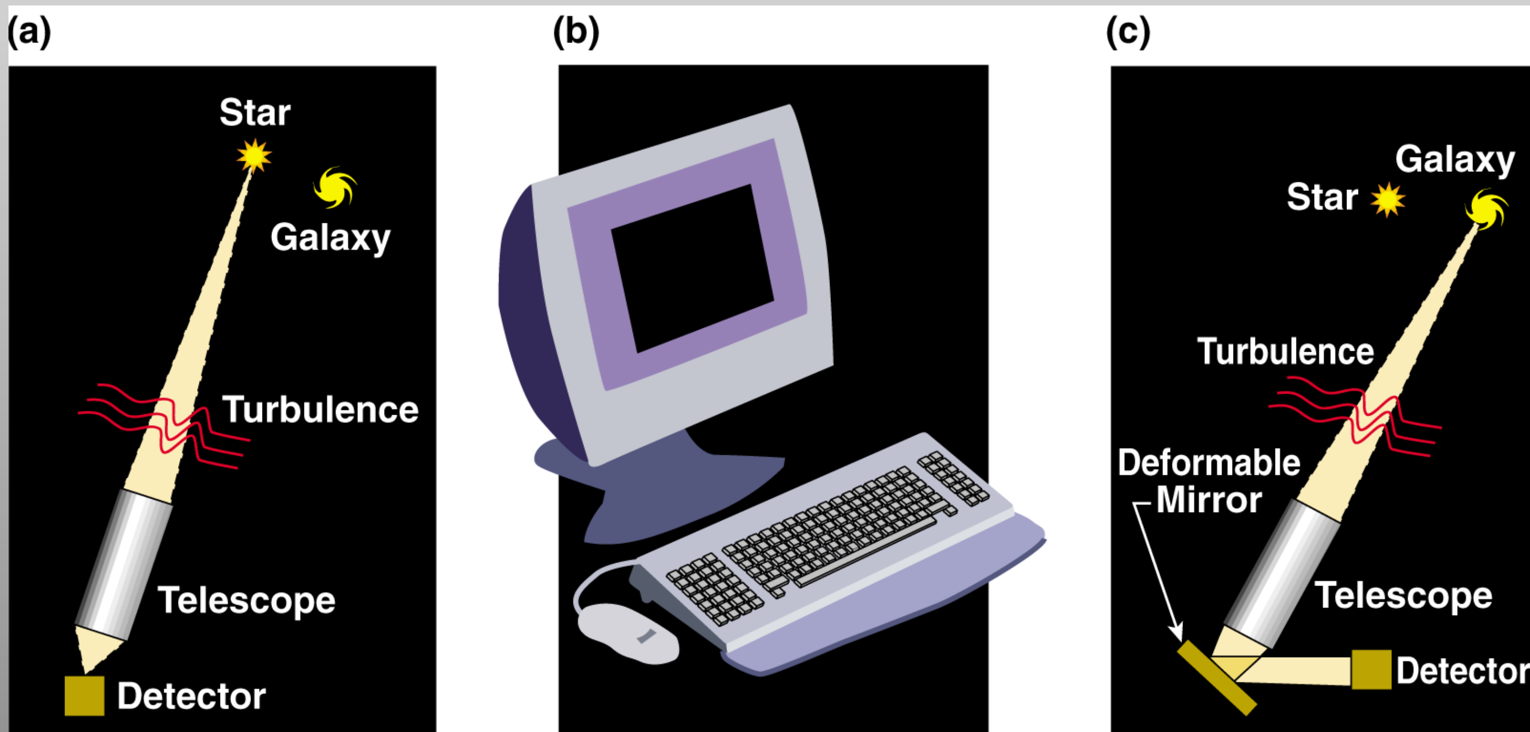
Image is greatly magnified and slowed down

Adaptive optics corrects for atmospheric blurring

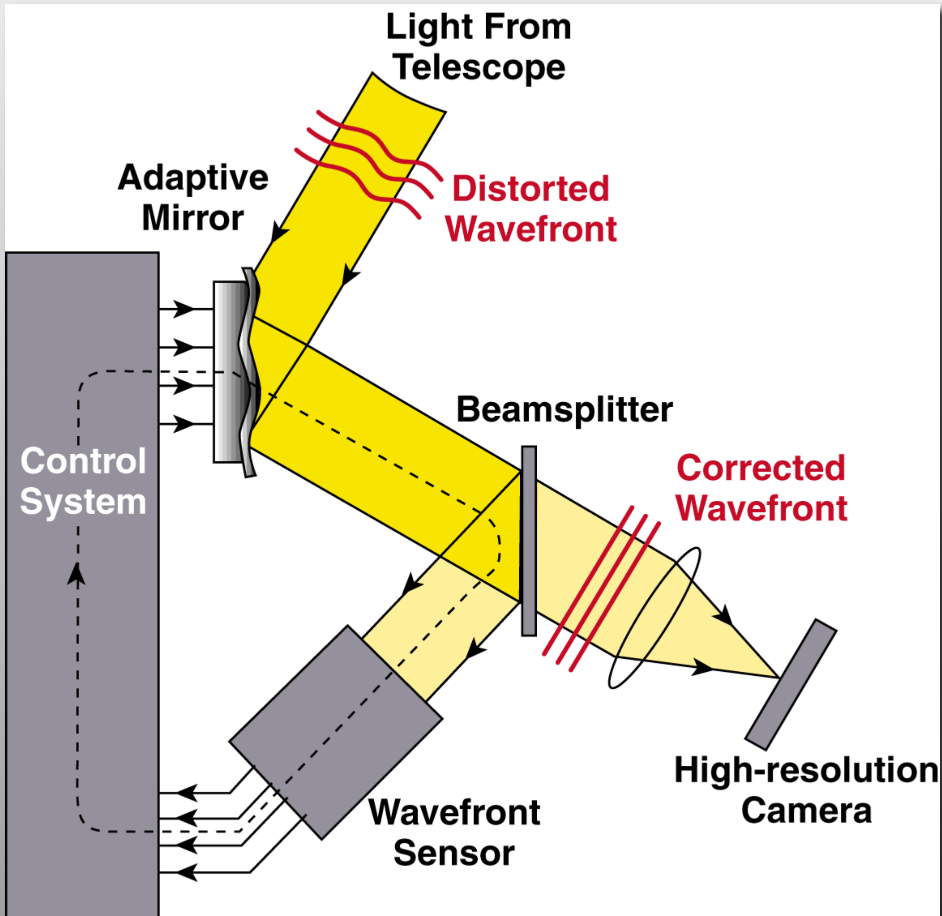
Measure details of blurring from "guide star" near the object you want to observe

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

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



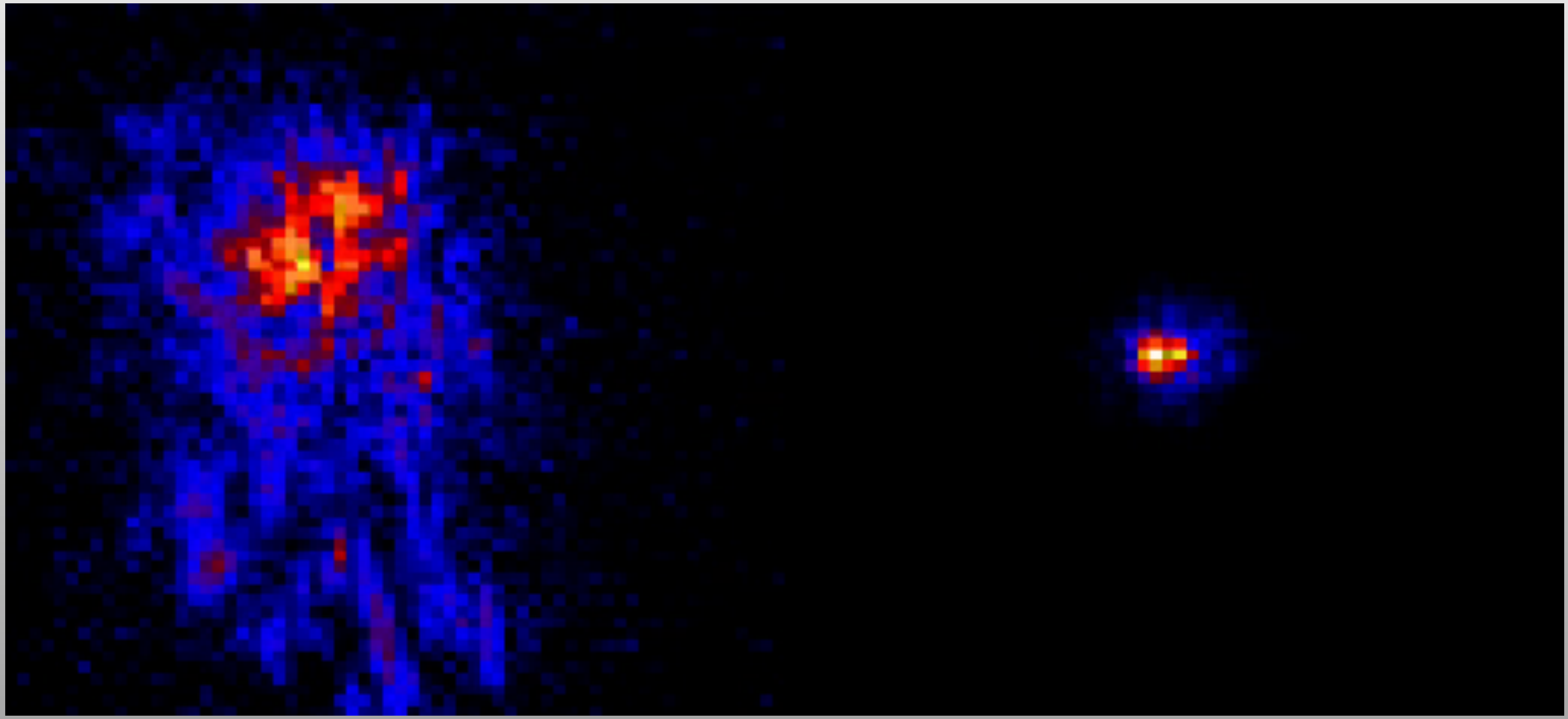
Adaptive optics system runs a "closed-loop control system"



- Measure optical distortions 100's of times a second with a "wavefront sensor"
- Computer calculates, in a few milliseconds, signals that need to be sent to the deformable mirror to correct these distortions
- Reshape the deformable mirror according to the instruction signals
- Do this over and over again

I will discuss computational challenges later in this talk

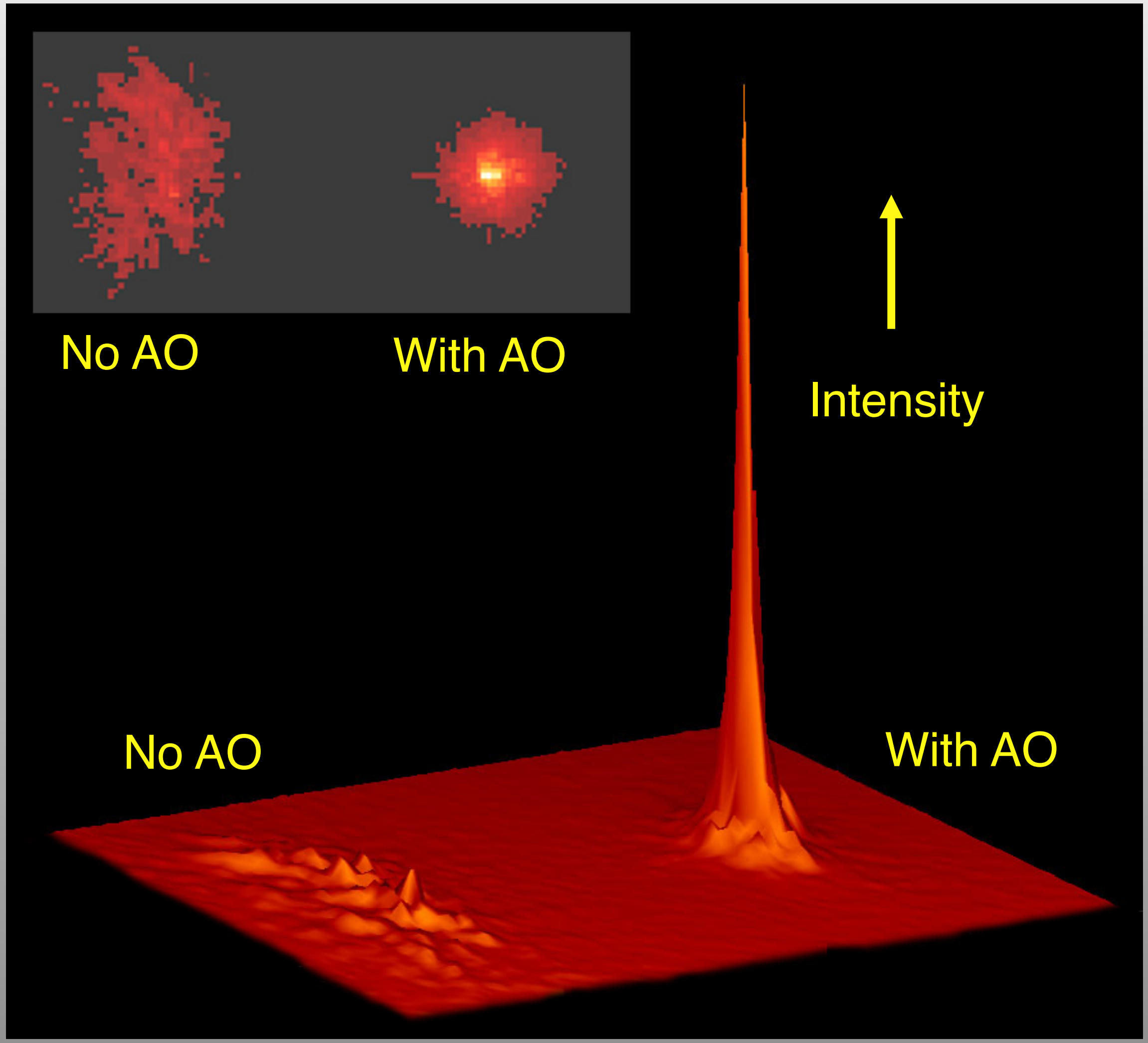
Infra-red images of a star showing improvement using adaptive optics



No adaptive optics

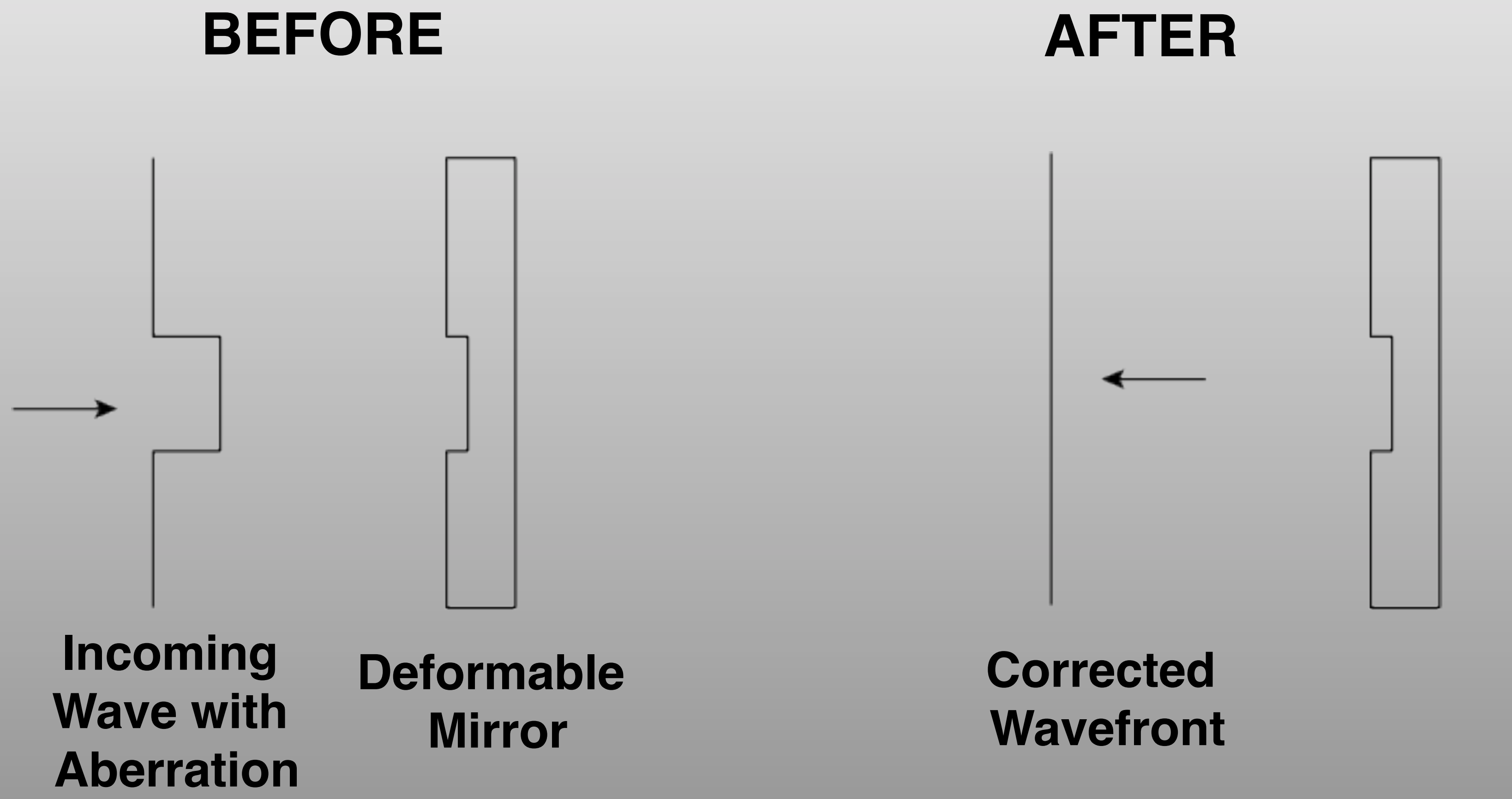
With adaptive optics

Adaptive optics increases peak intensity of a point source

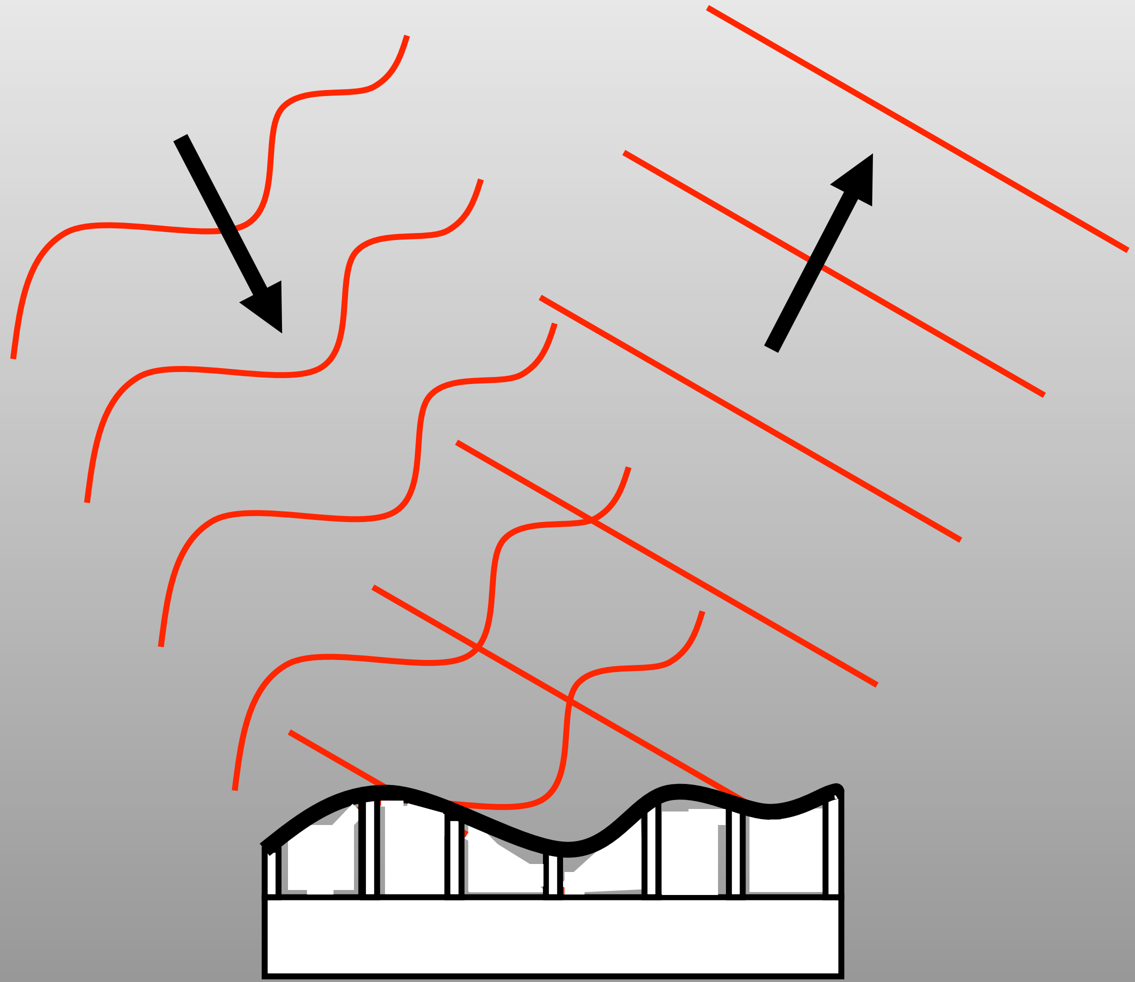


Credit: Lick Observatory

How a deformable mirror works: zero'th order approximation

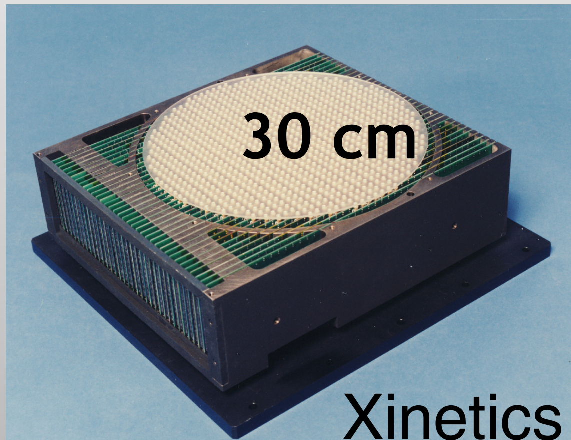


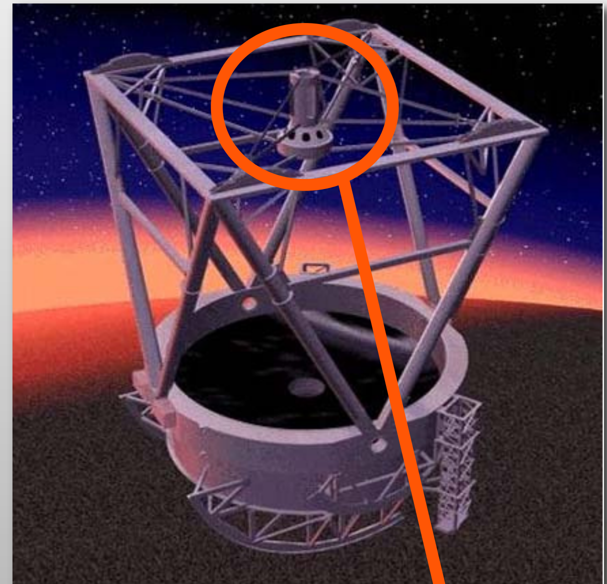
How a deformable mirror works: more realistic approximation



Deformable mirrors come in many sizes

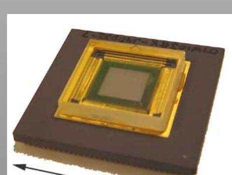
Glass facesheet
1000 actuators





Adaptive
Secondary
Mirrors

MEMS
1000 actuators

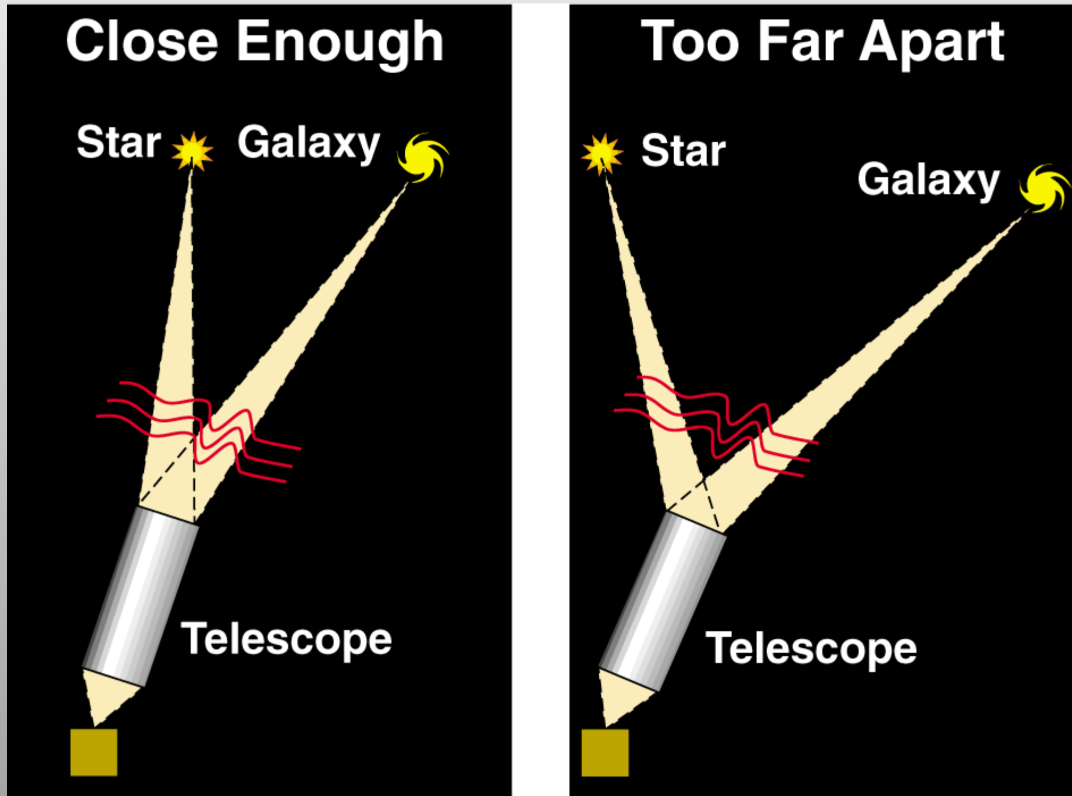


1 cm

Boston
Micro-
Machines

Adaptive optics needs a bright "star" nearby

“Same turbulence”

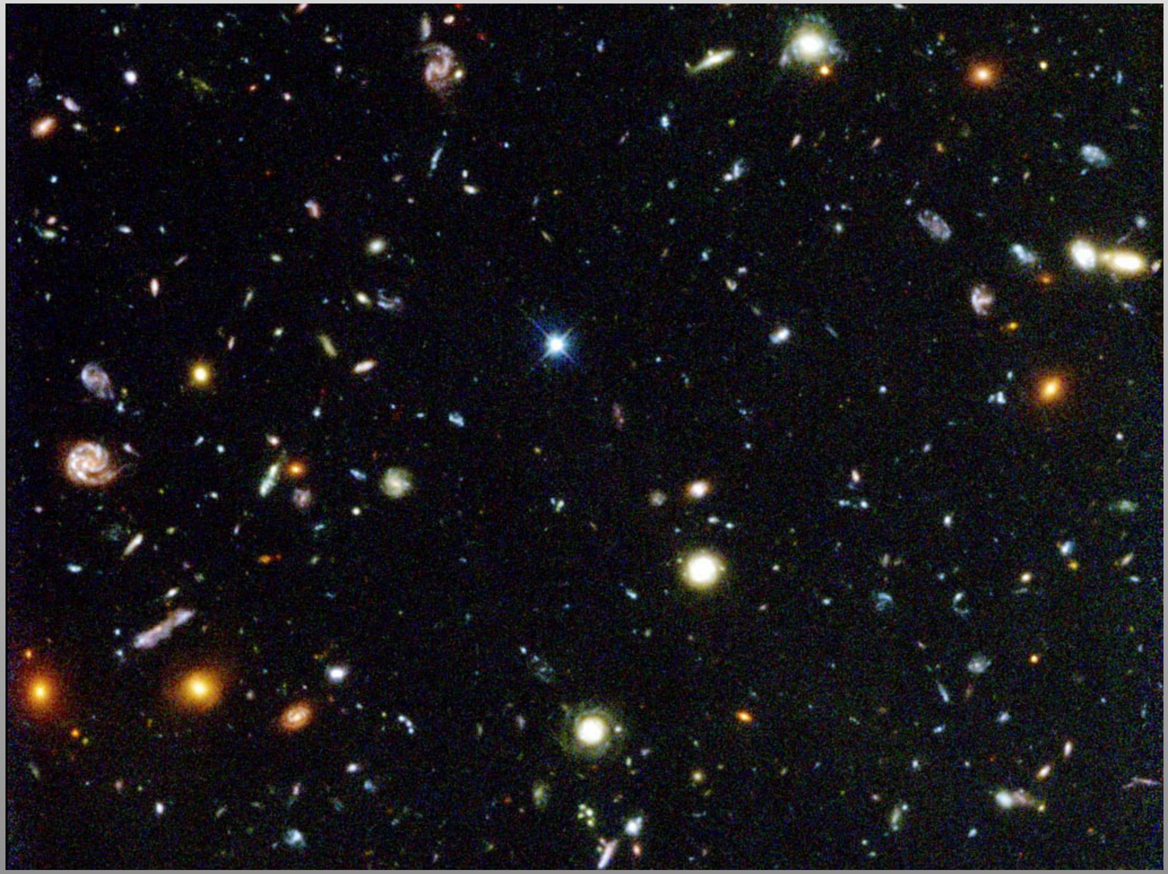


“Different turbulence”

Less than 10% of objects in the sky have a bright enough star nearby!

Example: Hubble Deep Field

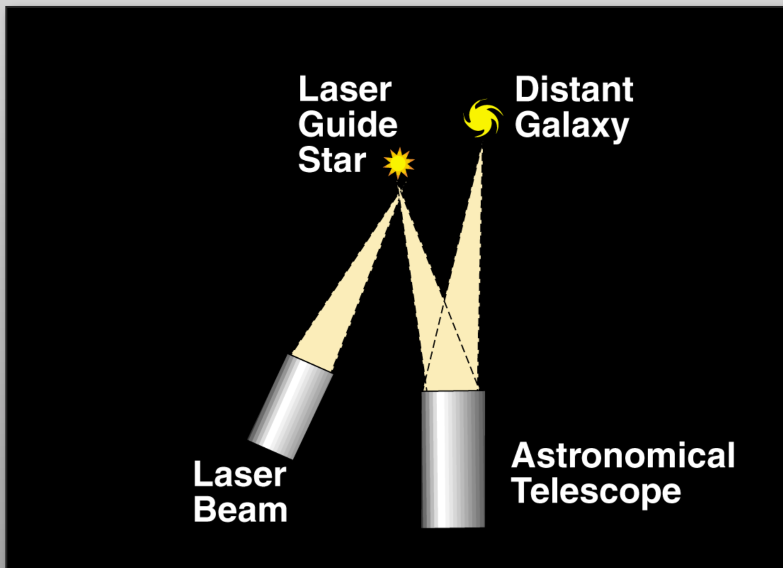
- Almost every object is a distant galaxy
- Only one star in this image (and it's dim!)



If there is no nearby star, make your own “star” using a laser

Happer, MacDonald, Max, Dyson

Concept

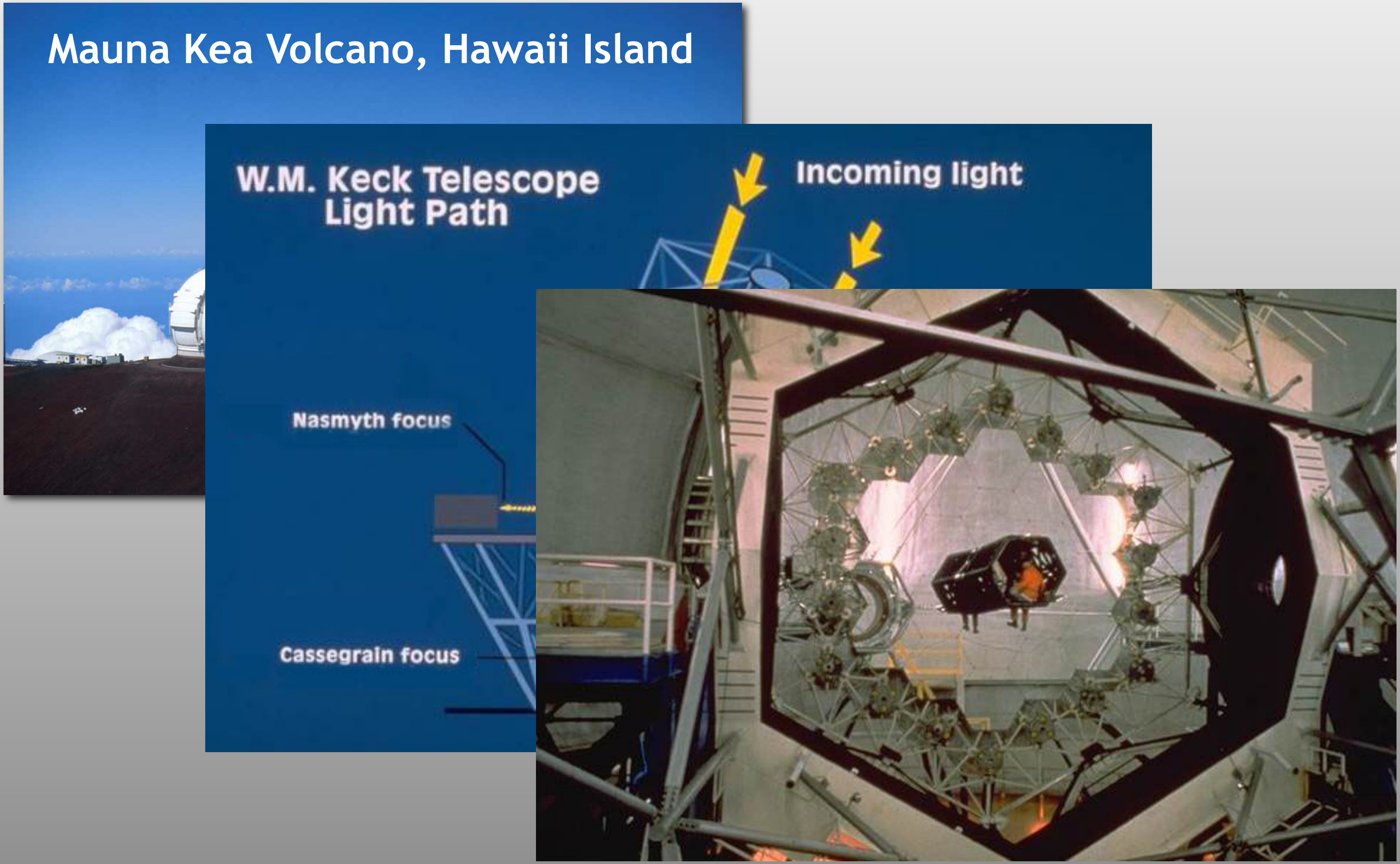


Crucial for extragalactic astrophysics

Implementation

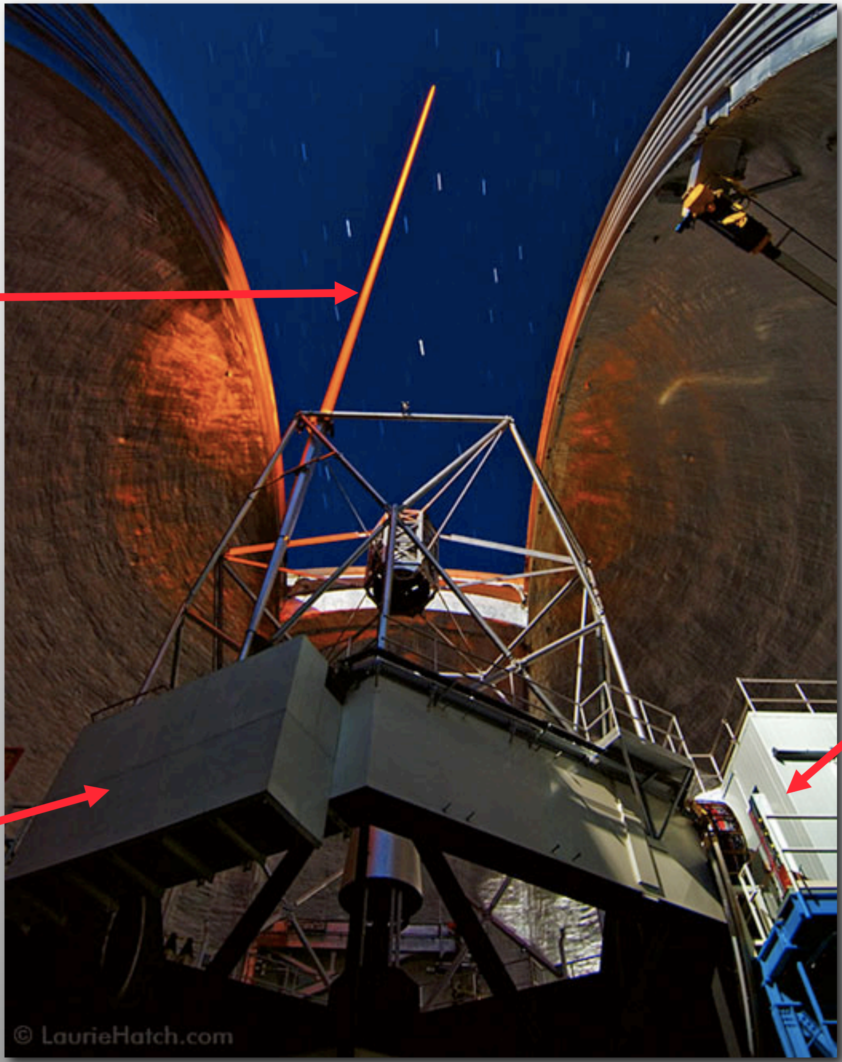
Facility lasers at Lick & Keck Observatories, Gemini, Subaru, Palomar, MMT, VLT, ...

AO systems at Both Keck Telescopes



Laser at Keck II Telescope atop Mauna Kea, HI

Yellow laser beam



Adaptive optics inside this enclosed room

Dye laser amplifier

Keck 2 laser was joint project of Keck Observatory & LLNL

Took most of a decade to complete and optimize

Today most major observatories have laser guide star AO

- Allows you to observe almost anywhere in the sky
  - Not exactly everywhere, because you still need a dim star for image stabilization
- A major benefit for extragalactic astronomy
  - Galaxies are distributed randomly on the sky, not just near bright stars!
- Hence strong interest in installing laser guide star AO on the largest telescopes
- Existing systems at Keck, Gemini N + S, Subaru, VLT observatories
- Planned at LBT, GTC

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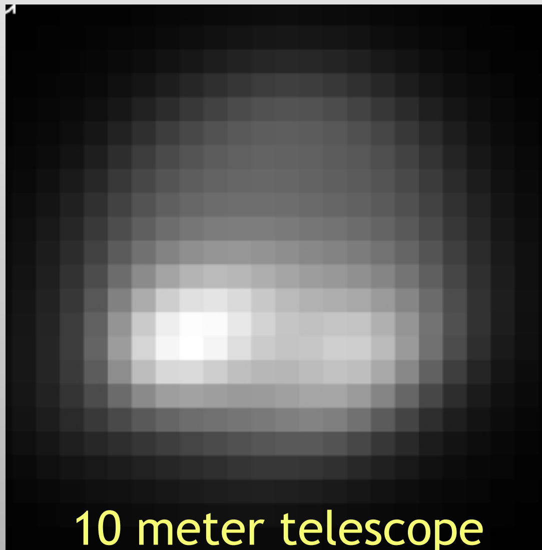
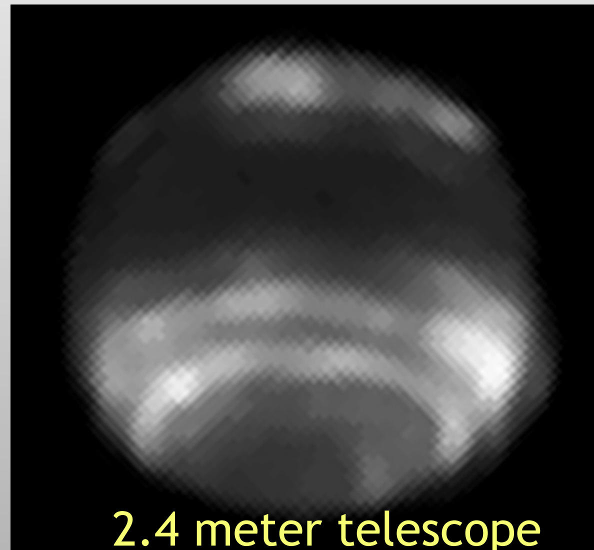
The planet Neptune in infrared light: The benefits of adaptive optics (AO)

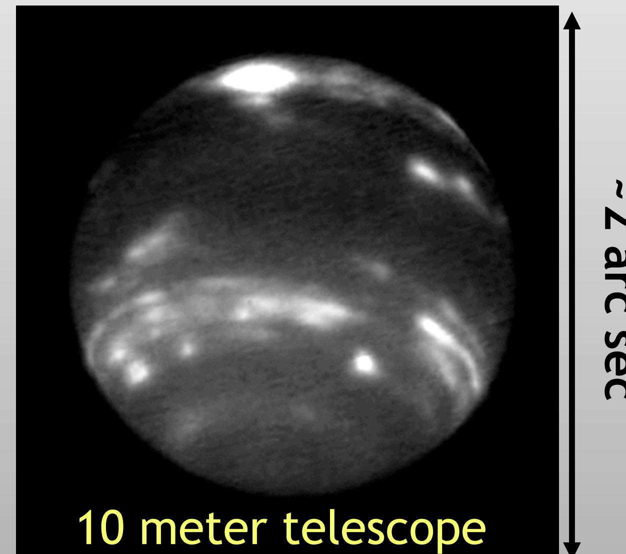
Keck Telescope no AO



Hubble Space Telescope NICMOS camera

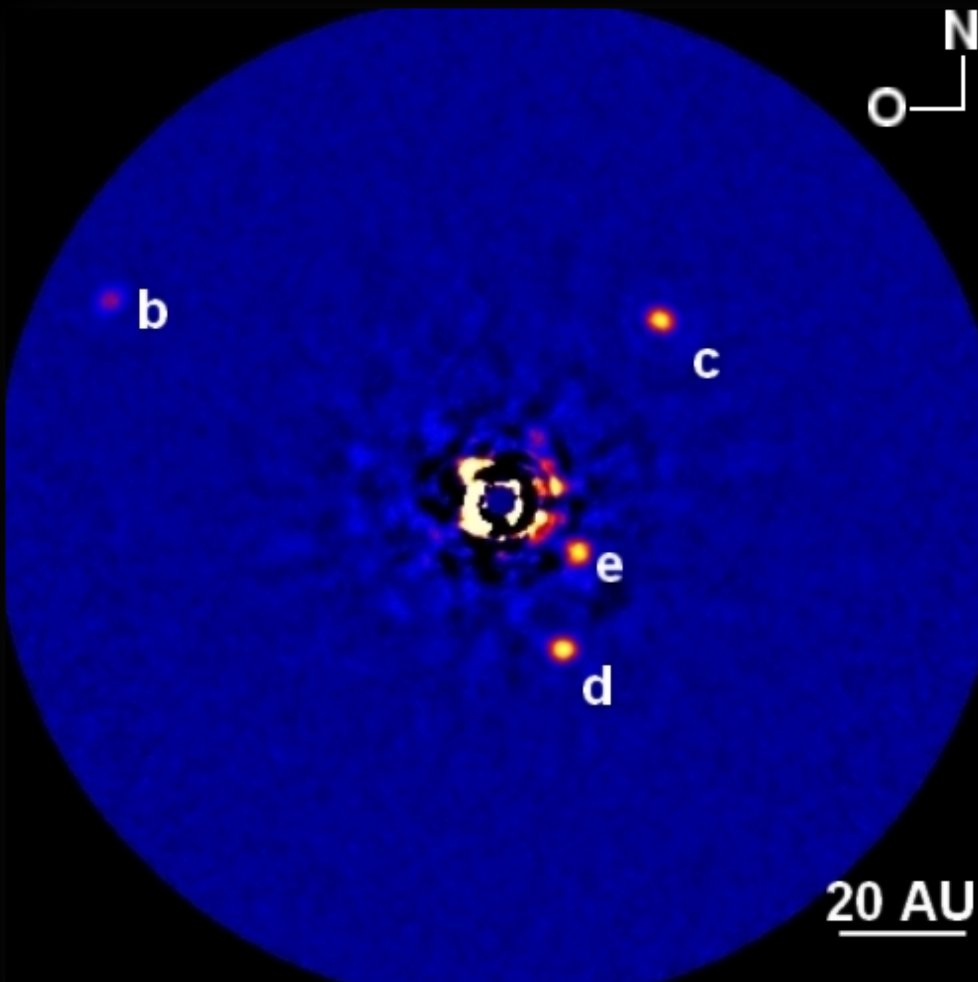


Keck Telescope with AO



- In absence of turbulent distortions, spatial resolution should scale as λ / D (observing wavelength ÷ telescope diameter).
- So with AO, 10-meter Keck telescope should have 4 times better resolution than HST, at the same observing wavelength. ✔

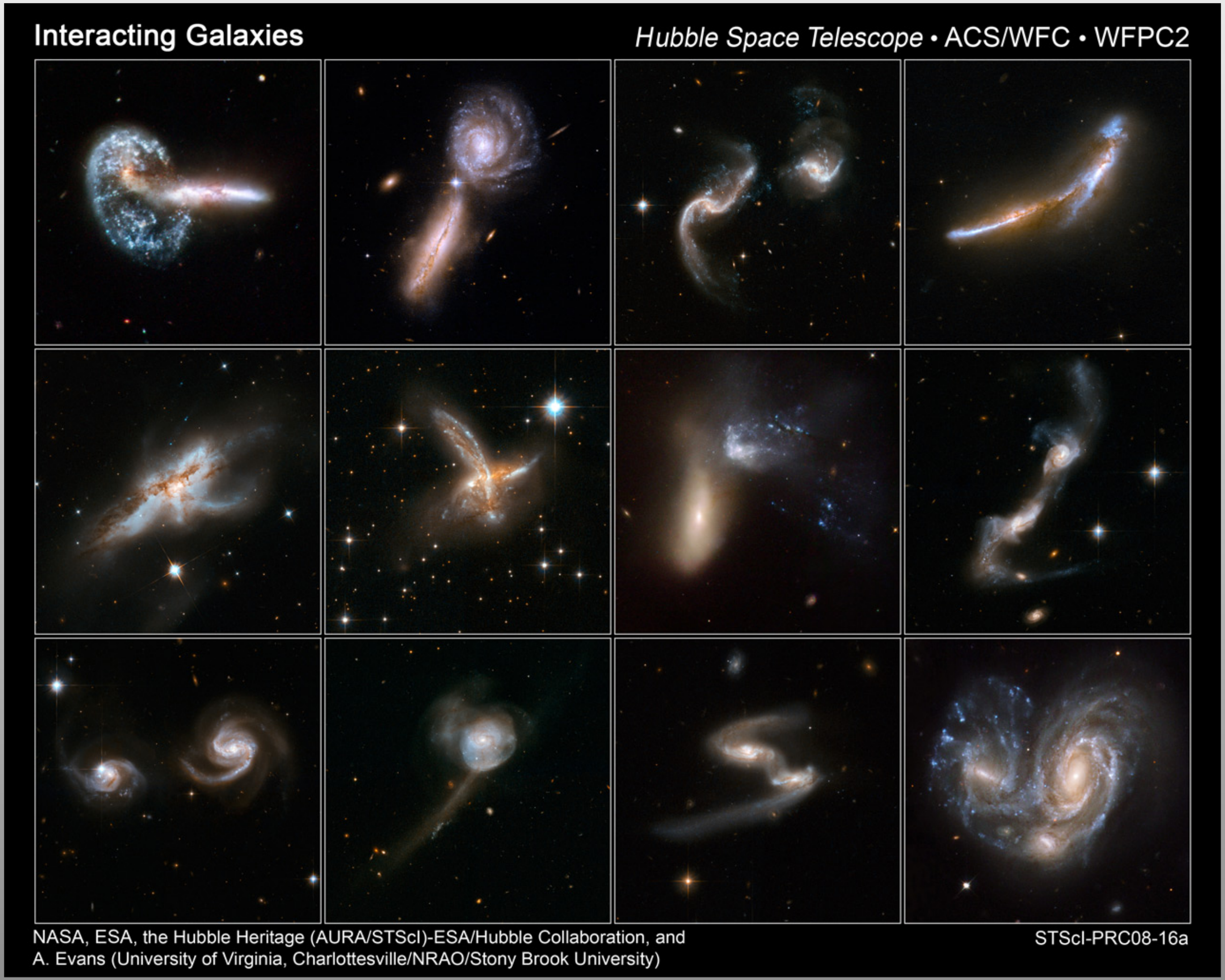
HR 8799 EXO-PLANETARY SYSTEM



- Detected at Gemini, Keck, and MMT Observatories with AO
- 60 Myr old parent star
- 130 light-years away
- 4 planets: 7-10 $M_{Jupiter}$
- ~ circular orbits
- ~ face on
- Formed in a disk?

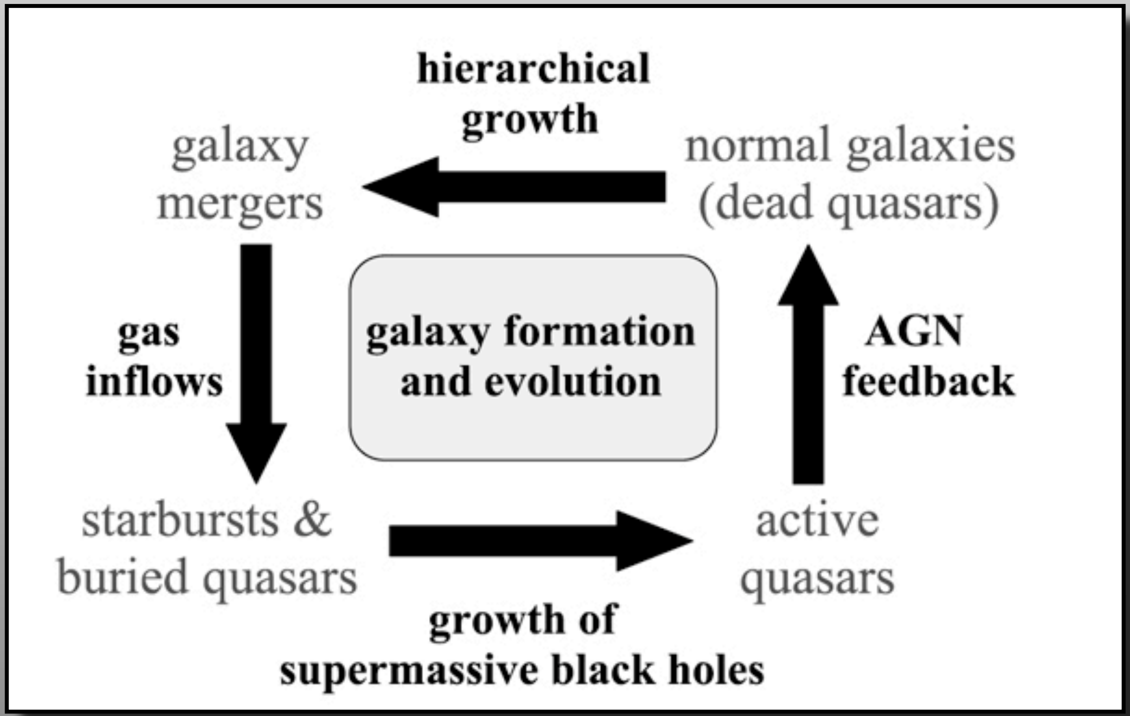
Marois et al., Science, Nov. 13 2008

Hubble Space Telescope images of some nearby galaxy mergers



Galaxy Evolution: Potential role of galaxy mergers and active galactic nuclei

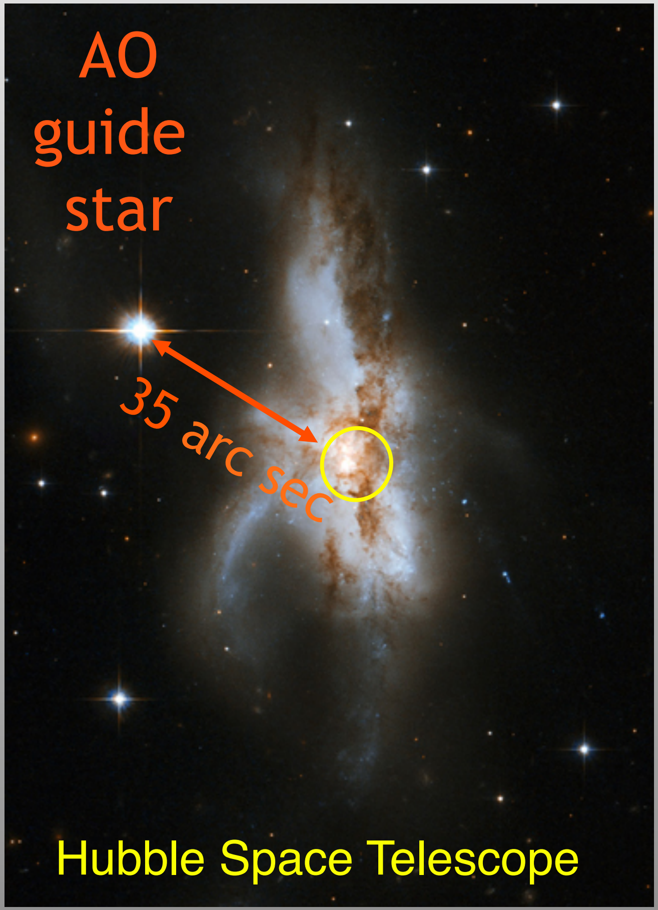
- Active galactic nuclei: galaxies that have actively accreting black holes in their cores
- All galaxies with bulges have black holes; most not active
- Mass of black hole is correlated with bulge properties. Why?
- One explanation: They both grow together during galaxy mergers



Hopkins, Hernquist et al.

Example: NGC 6240, a nearby merger of two gas-rich galaxies

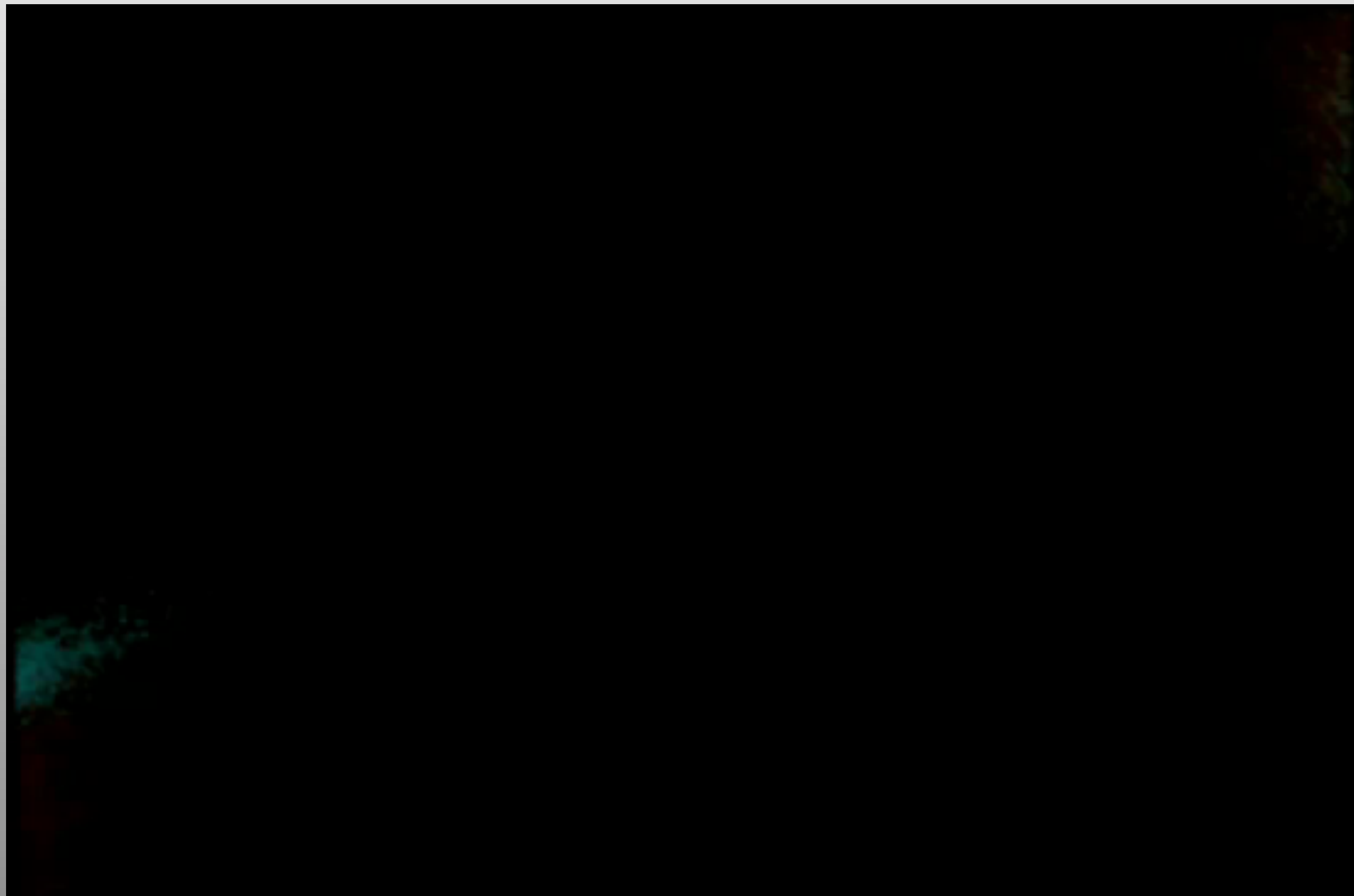
- A starburst galaxy (very intense star formation)
  - Hosts 2 actively accreting black holes



- Relatively nearby: ~300M light-years
- Double nucleus
- Tidal tails due to merger ("bow-tie")

Computer simulation of how merging disk galaxies form bow-tie shapes and tidal tails

Josh Barnes (Univ. Hawaii) :
2 disk galaxies plus their dark-matter halos (red)



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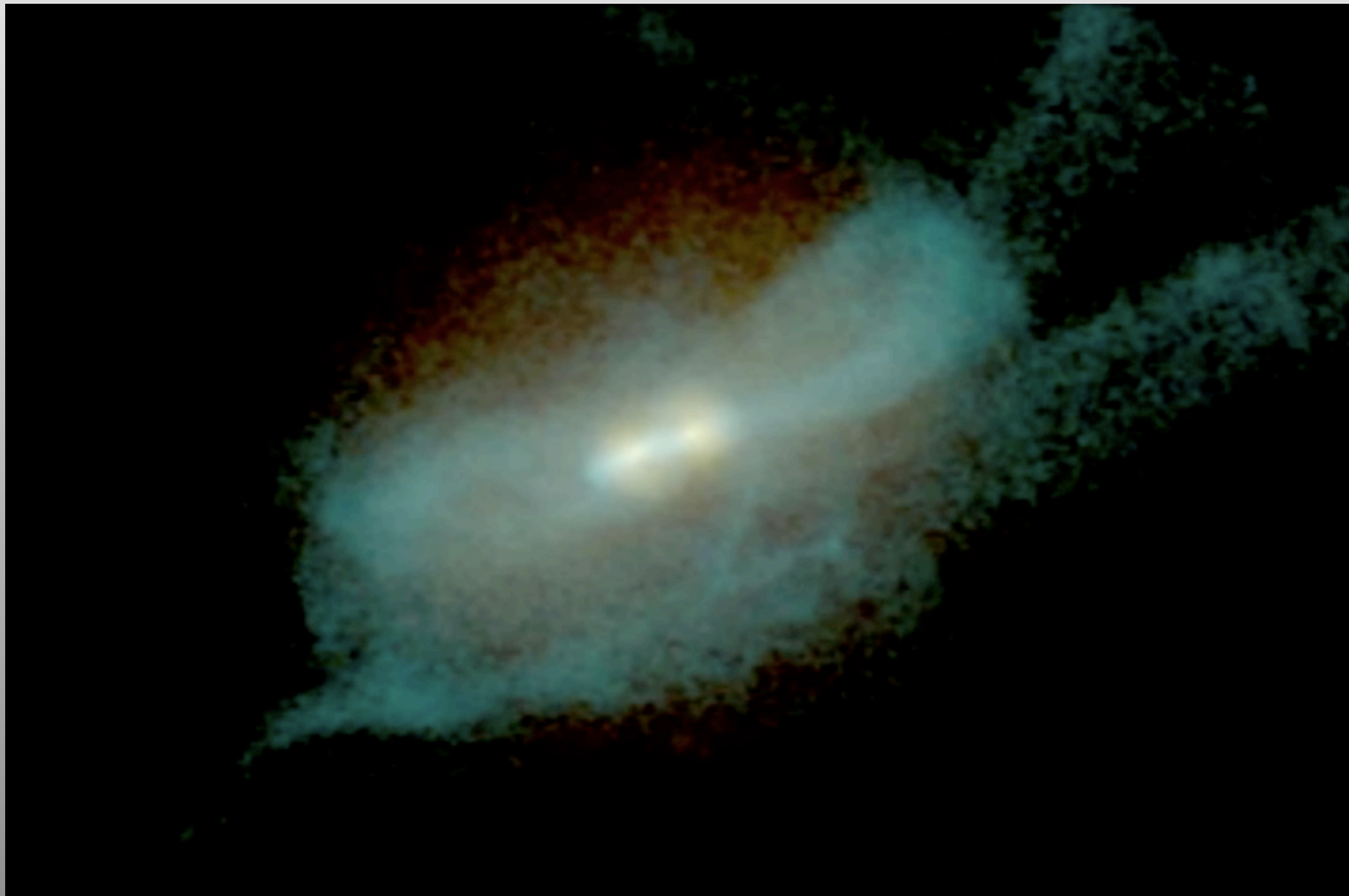
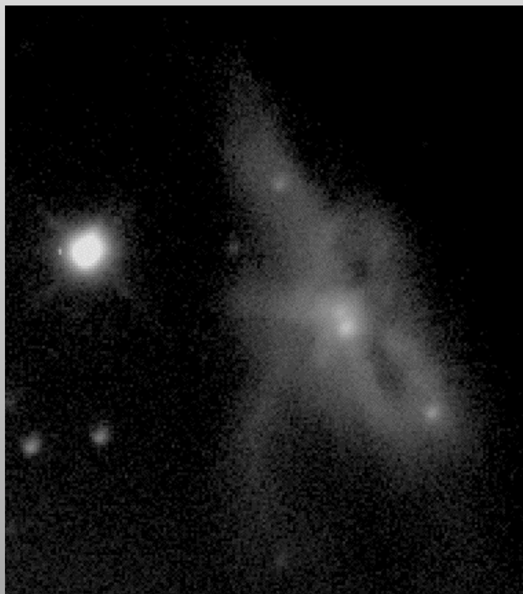


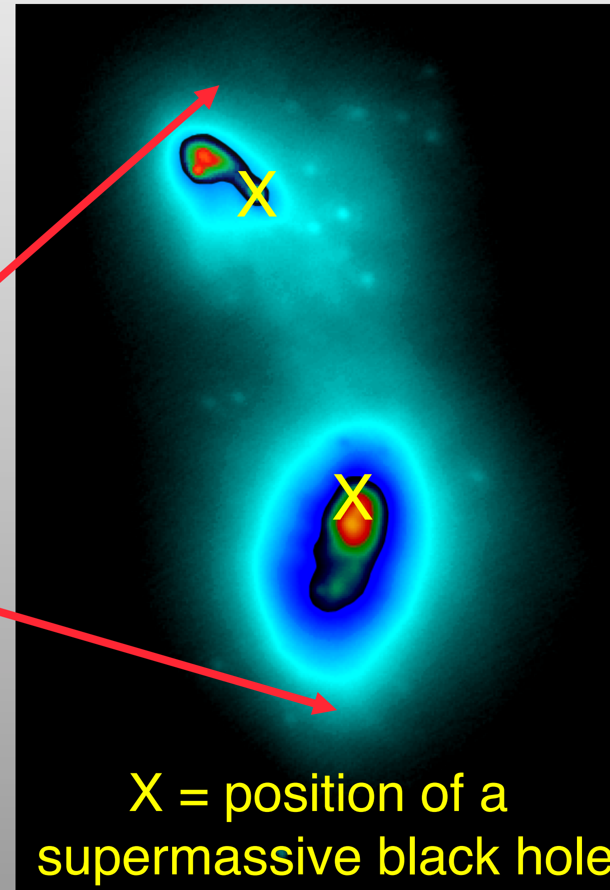
A closer look at the NGC 6240 galaxy merger, using AO

Ongoing merger between two massive disk galaxies



Conventional image,
Lick Observatory

Hubble Space Telescope,
Visible light



Near-infrared image,
Keck laser guide star
adaptive optics

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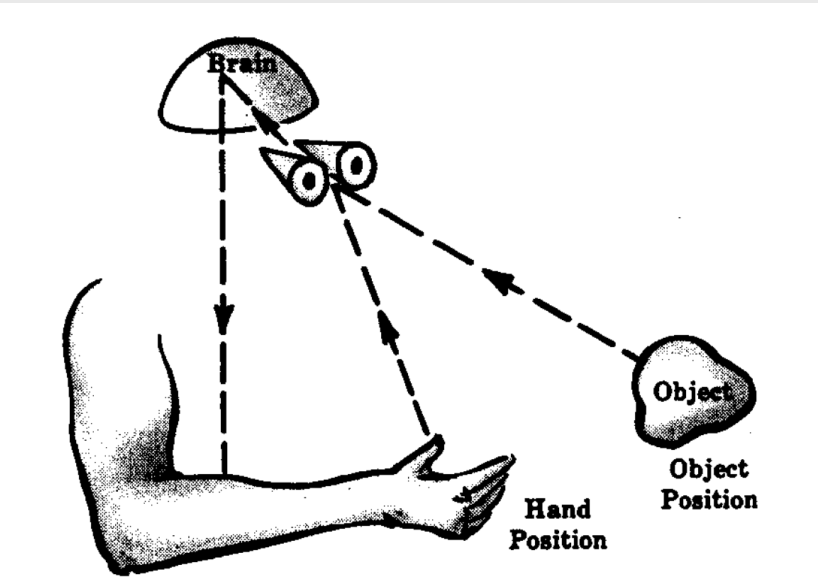
Computational challenges for AO involve "Real-Time Control"

- Fundamentally different kind of computing than used on super-computers for astrophysical modeling.

- "Real-Time Control"
  - Sensing and responding to external events almost simultaneous with their occurrence.
  - Results of the computation are used to influence a process while it is taking place.

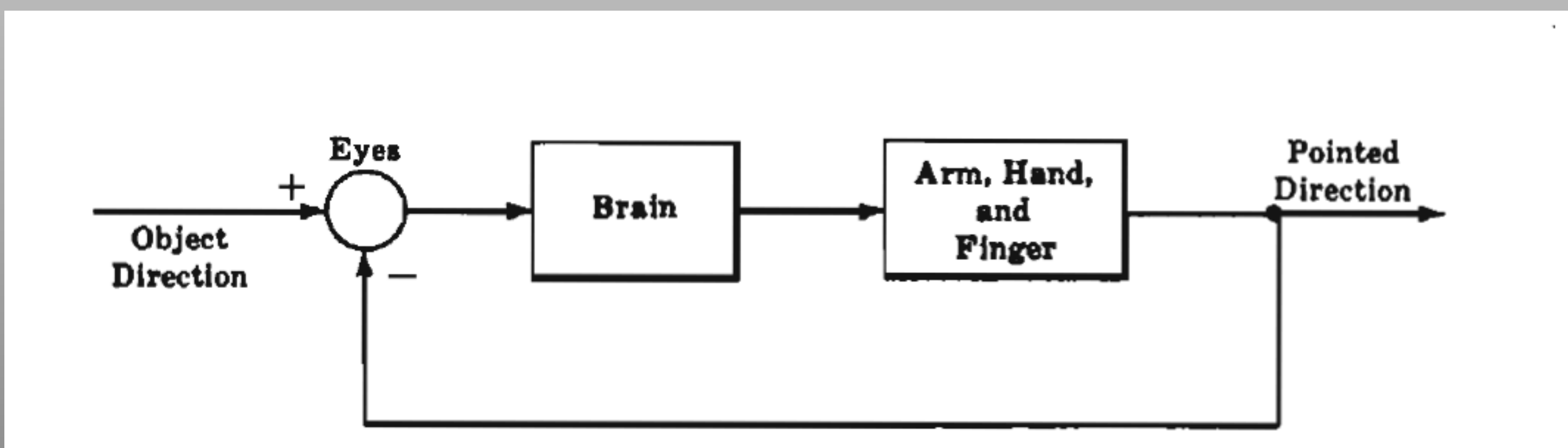
- Other examples of real-time control systems:
  - Home: thermostat, toilet tank, automatic toaster
  - Autopilot for boat or plane, car cruise control
  - SCADA control for industrial processes (electricity generation and distribution, factories, water treatment plants, …)

A close-to-home real-time control system: you, grasping an object



Control System Components

- Sensor (eyes)
- Computer (brain)
- Actuators (arm, hand, fingers)



What determines how big a computer is needed for adaptive optics?

- Depends on how ambitious the AO system is, and how large the telescope
- Number of actuators behind the deformable mirror grows like telescope diameter D^2 (area of mirror)
- Also need more actuators if you are observing at shorter wavelengths (e.g., visible light)
  - Today most AO systems observe in infrared light
- Fundamental timescale: time it takes wind to blow a turbulent element across telescope mirror (a few msec)

Some examples of real-time computer systems used in AO

Observatory / Telescope Diam.	Observing wavelength	# mirror actuators	Computer
Lick / 3 meters	infrared	60	PC
Keck / 10 meters	infrared	249	8 DSP's
LBT / 8 meters	infrared	672	336 DSP's
Thirty Meter Telescope (proposed)	infrared	~ 6700	thousands of DSP's or FPGAs or GPUs

DSP: digital signal processor FPGA: floating point gate arrays GPU: graphical processing unit

- **Challenge: design and build a real-time computer that can calculate instructions for 5000 - 10,000 mirror actuators in a millisecond!**

A few words about SCADA control systems

- SCADA = Supervisory Control and Data Acquisition
- A type of control system
- Widely used in industry, electric utilities, water treatment plants, …

- SCADA system controlling Iran’s gas centrifuges to enrich Uranium was hacked by STUXNET
- SCADA systems are not inherently susceptible to hacking, but at present they have many vulnerabilities. Lack of attention to security.
- Genuine worry for critical infrastructure such as electric grid

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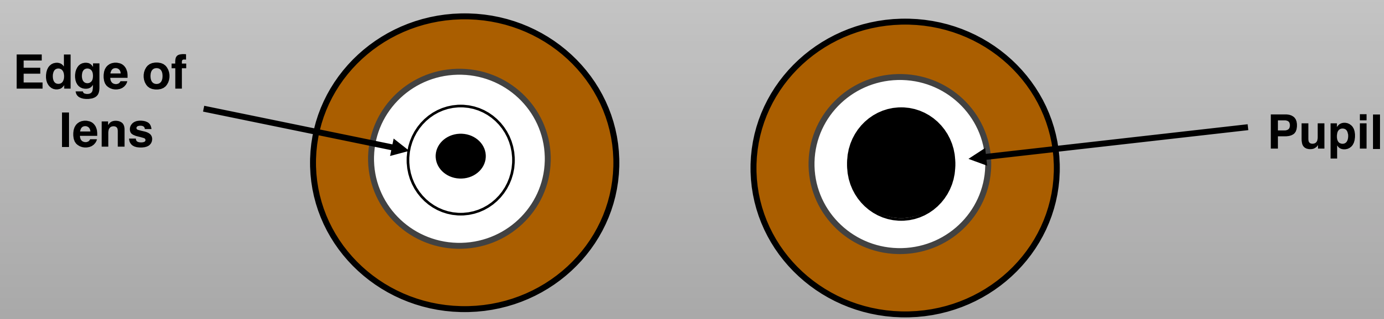
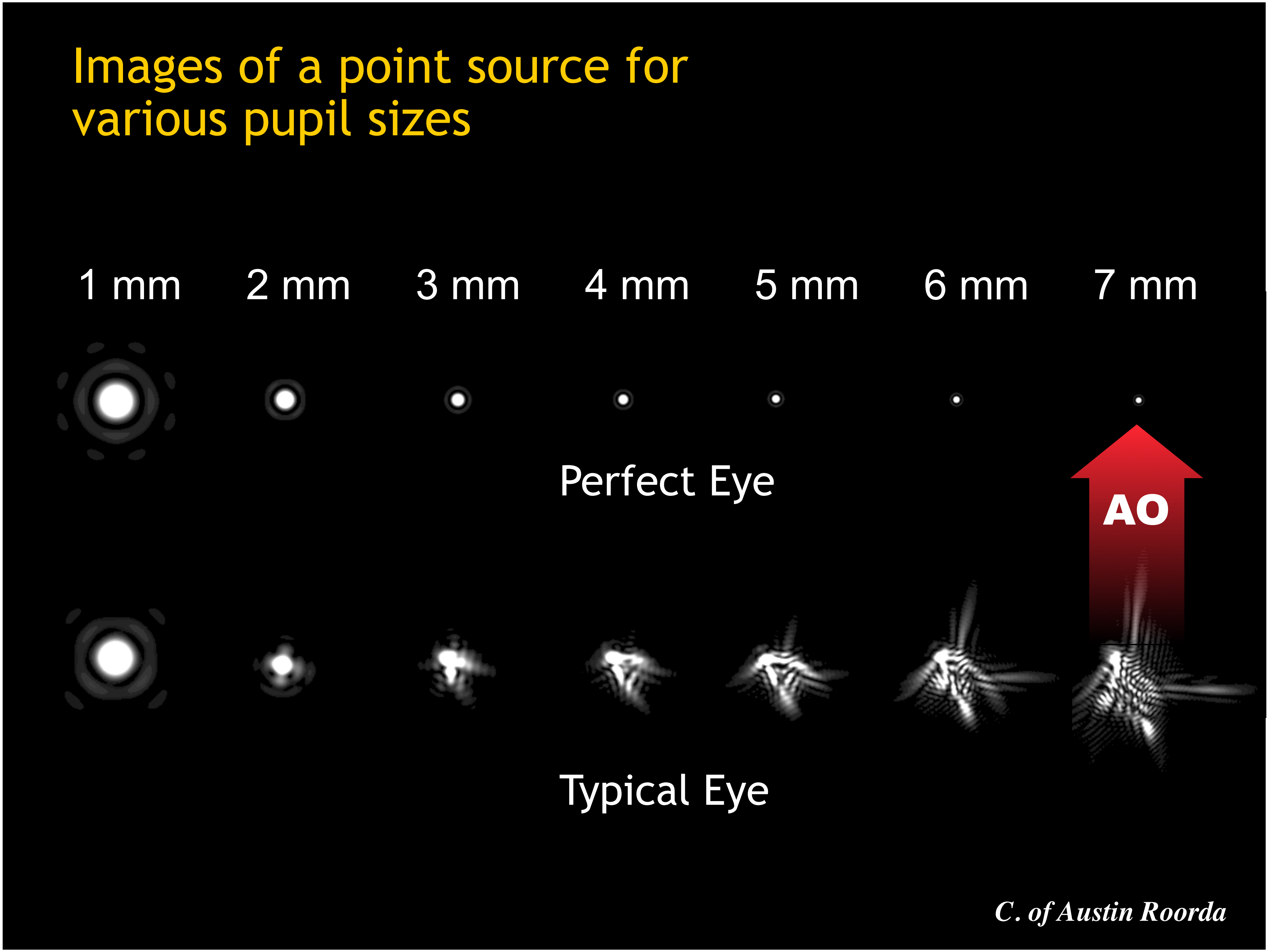
Why is adaptive optics needed for the human eye?

- Around edges of lens and cornea, imperfections cause distortion
- In bright light, pupil is much smaller than size of lens, so distortions don't matter much
- But when pupil is large, incoming light passes through the distorted regions

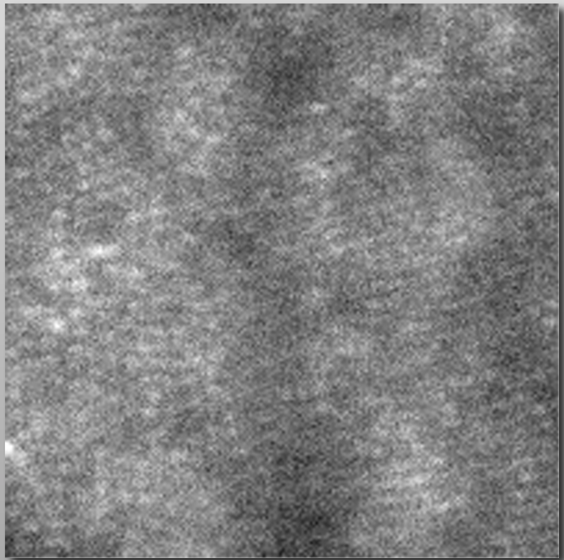


- Results: Poorer night vision (flares, halos around streetlights). Can't image the retina very clearly (for medical applications)

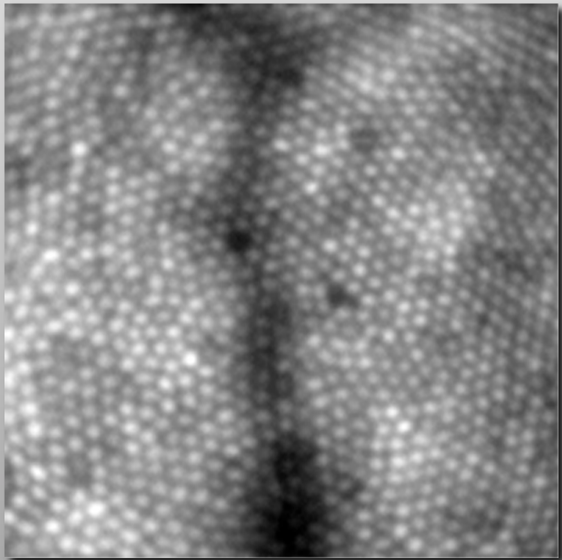

Images of a point source for various pupil sizes
1 mm
2 mm
3 mm
4 mm
5 mm
6 mm
7 mm
Perfect Eye
AO
Typical Eye
C. of Austin Roorda

Adaptive optics allows imaging of individual cone photoreceptors (color vision detectors)

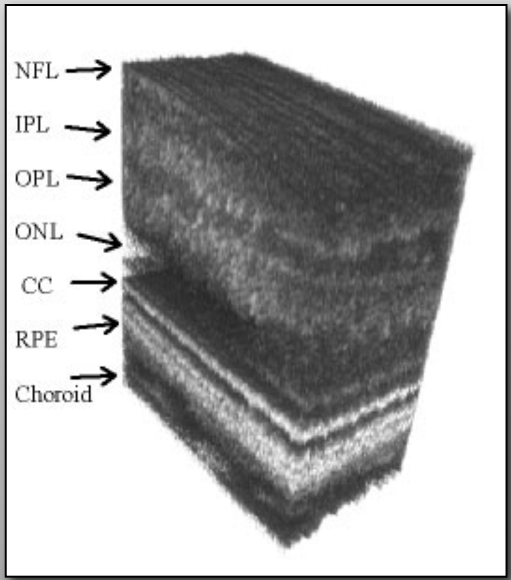
Without AO



With AO: individual cone photoreceptors

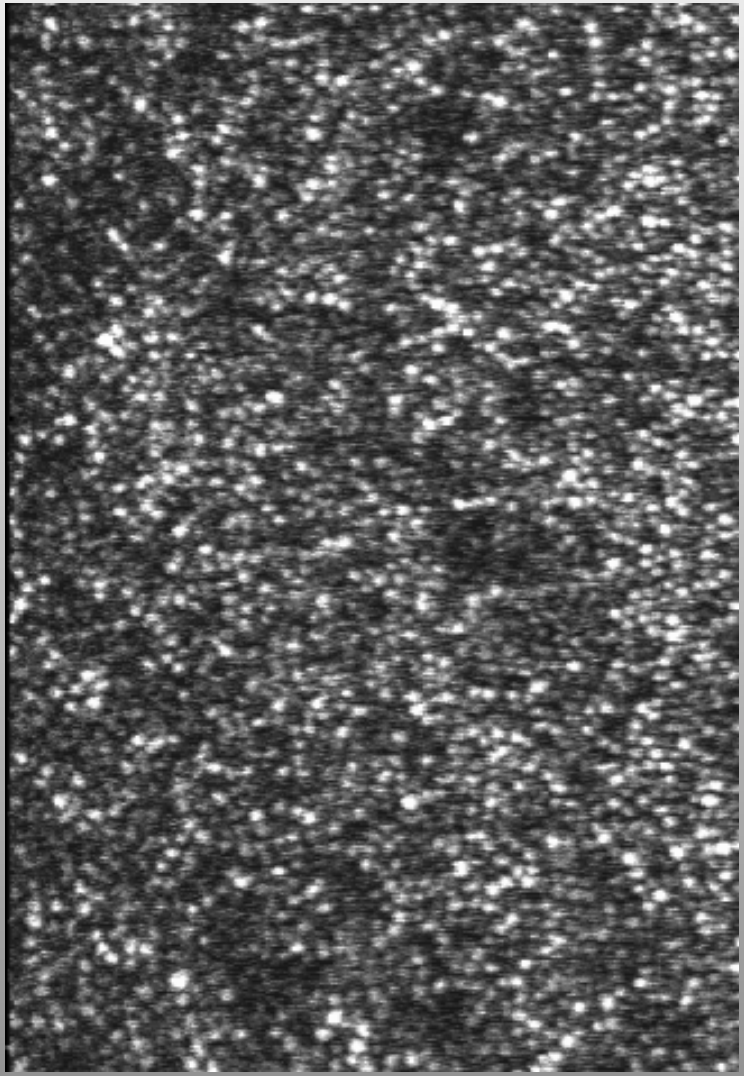


AO + dedicated instruments: 3D structure



Credit: Austin Roorda, UC Berkeley

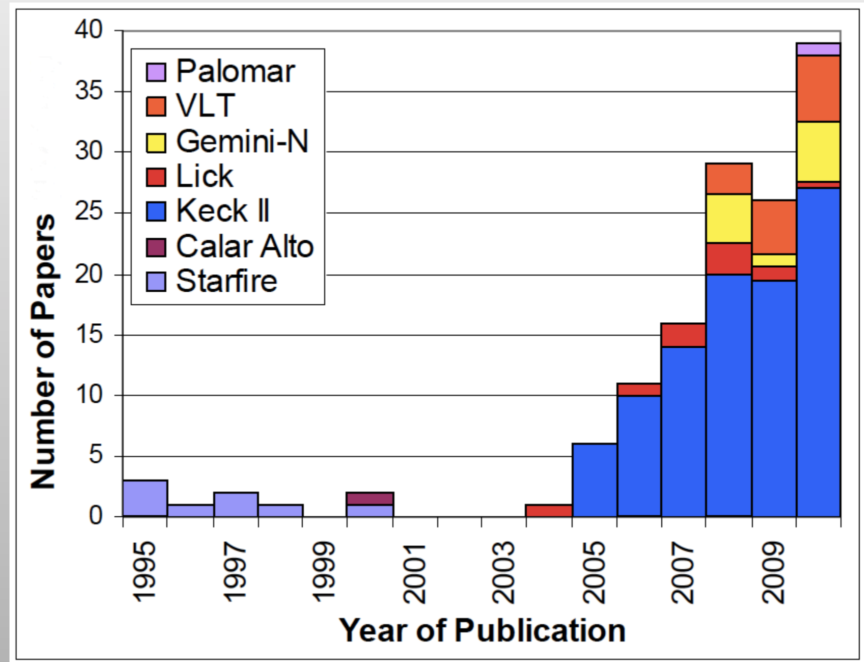
Watch individual blood cells flow through capillaries in the eye



- Courtesy of Austin Roorda, UC Berkeley
- 3D sectioning of the retina with confocal microscopy
- Resolve capillaries, individual white blood cells
- Measure velocity of blood flow, …

Main points

- Adaptive optics and laser guide stars have become key instruments at largest (8 - 10m) telescopes
- Number of scientific publications growing very fast
- Real-time computing requirements OK for current systems, a challenge for next generation giant telescopes
- Exciting applications to vision science, and now AO microscopy for biology



Science papers/yr using laser guide stars

Three lasers over Mauna Kea

Movie of 3 laser guide stars over Mauna Kea