Introduction to Adaptive Optics

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Center for Adaptive Optics
UC Santa Cruz
June 11th, 2009

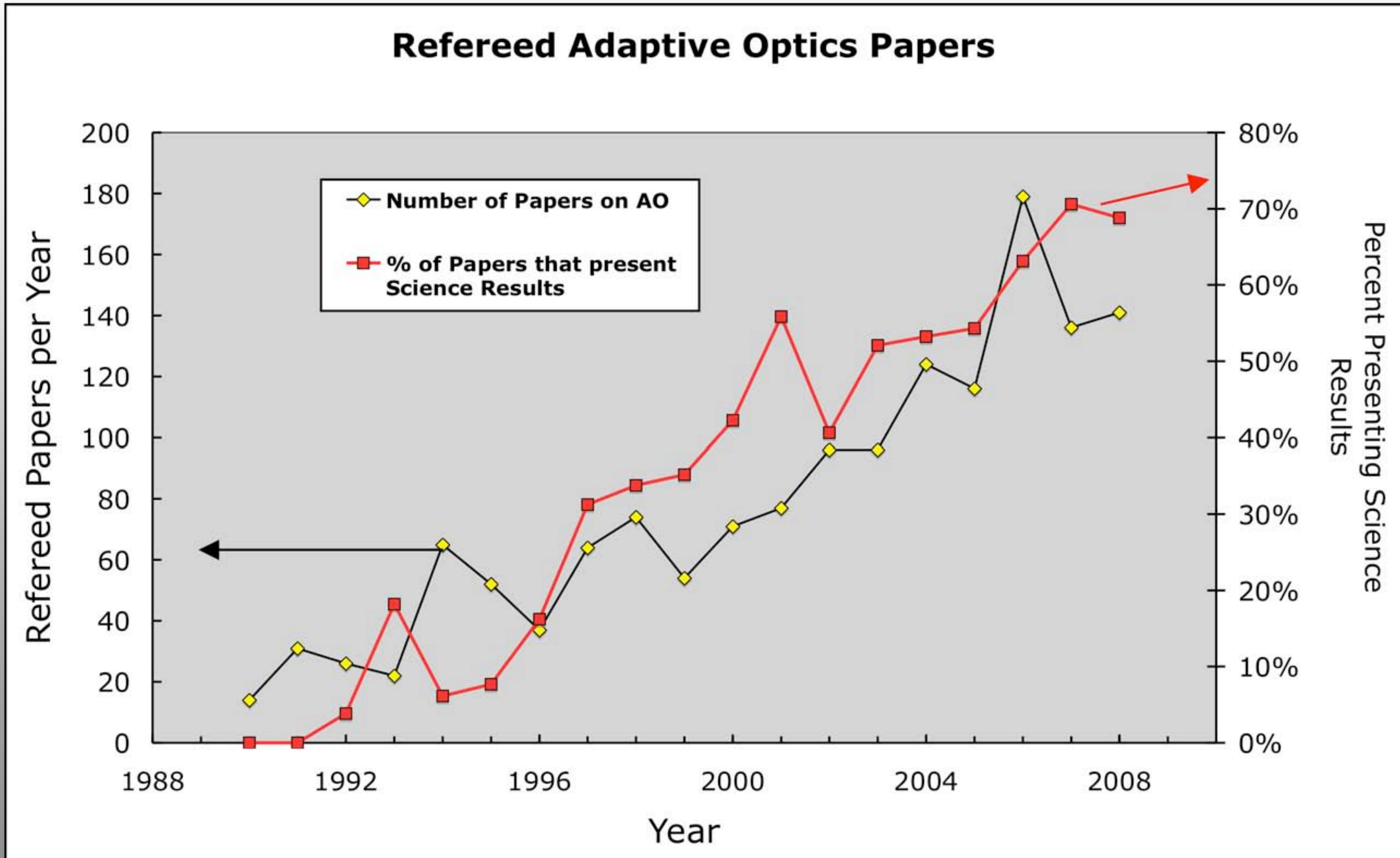
Outline

- Motivations for this "Meeting within a Meeting"
- What is AO and how does it work?
- Science with AO: Current Examples
- How should somebody decide whether to use AO?
- Future directions
- Summary

Motivation for this AO Meeting within a Meeting

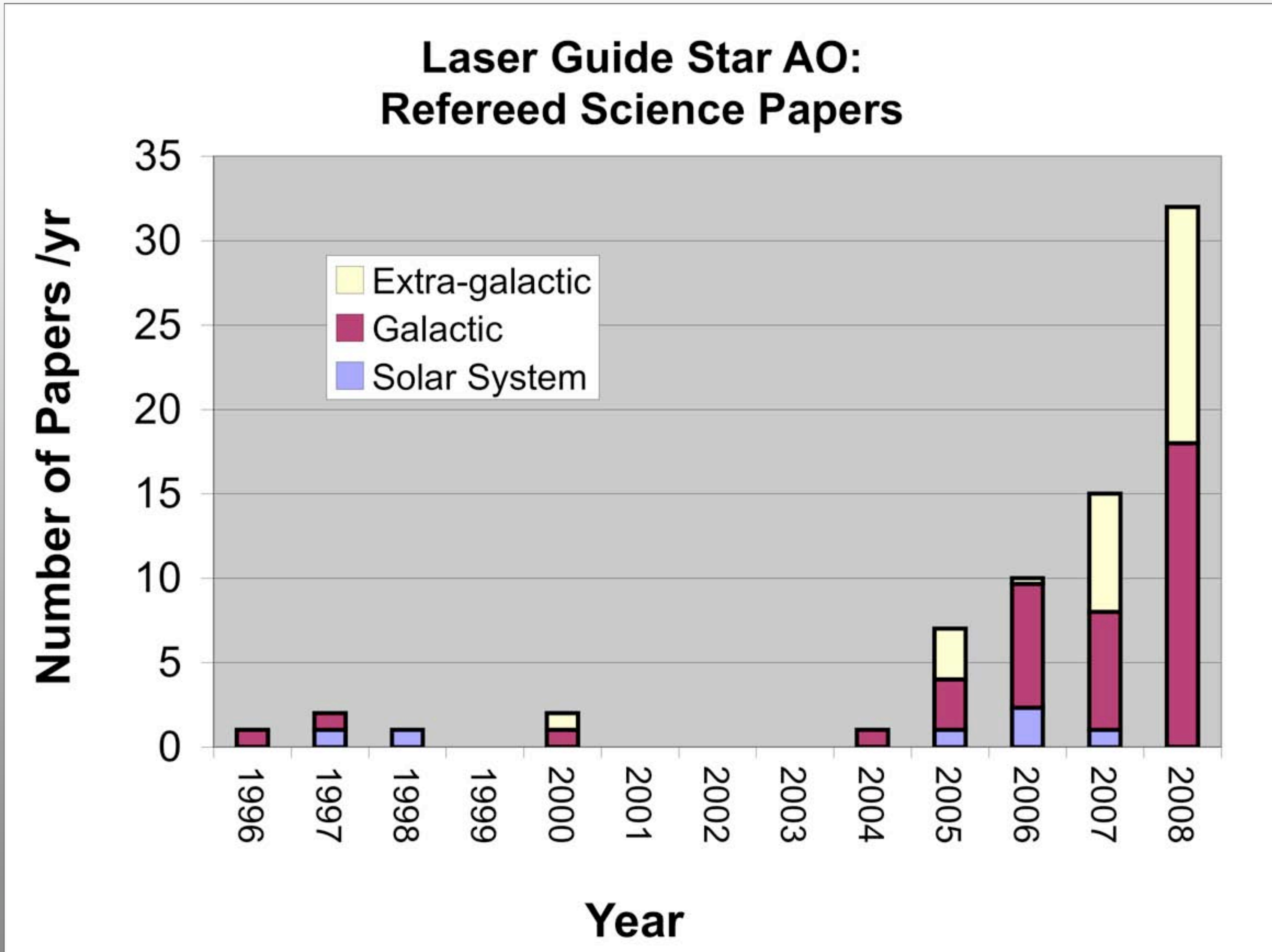
- Last 2 Decadal Surveys in Astronomy and Astrophysics strongly endorsed development of adaptive optics (AO) technology and instrumentation for large telescopes.
- Only over the last few years have facility AO systems on 6-10m telescopes become generally available.
- Laser guide stars: Keck since 2005, Gemini & VLT since 2007
- Today: very significant science results
  - 1993-1995 avg 5 science papers/yr
  - 2006-2008 avg 152 science papers/yr
- This Meeting within a Meeting:
  - Highlight science results that have already been obtained using AO
  - Discuss the opportunities that AO now offers to the general astronomical community

Dramatic growth in science with AO

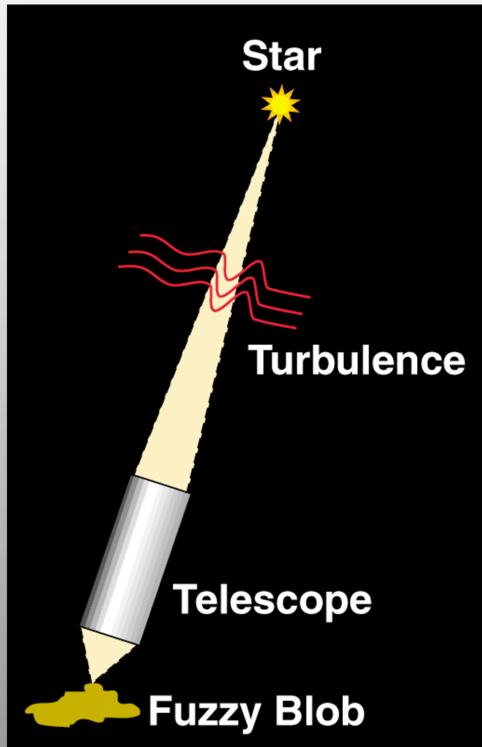


Credit: Jay Frogel, AURA

Science papers using laser guide star AO: still growing rapidly



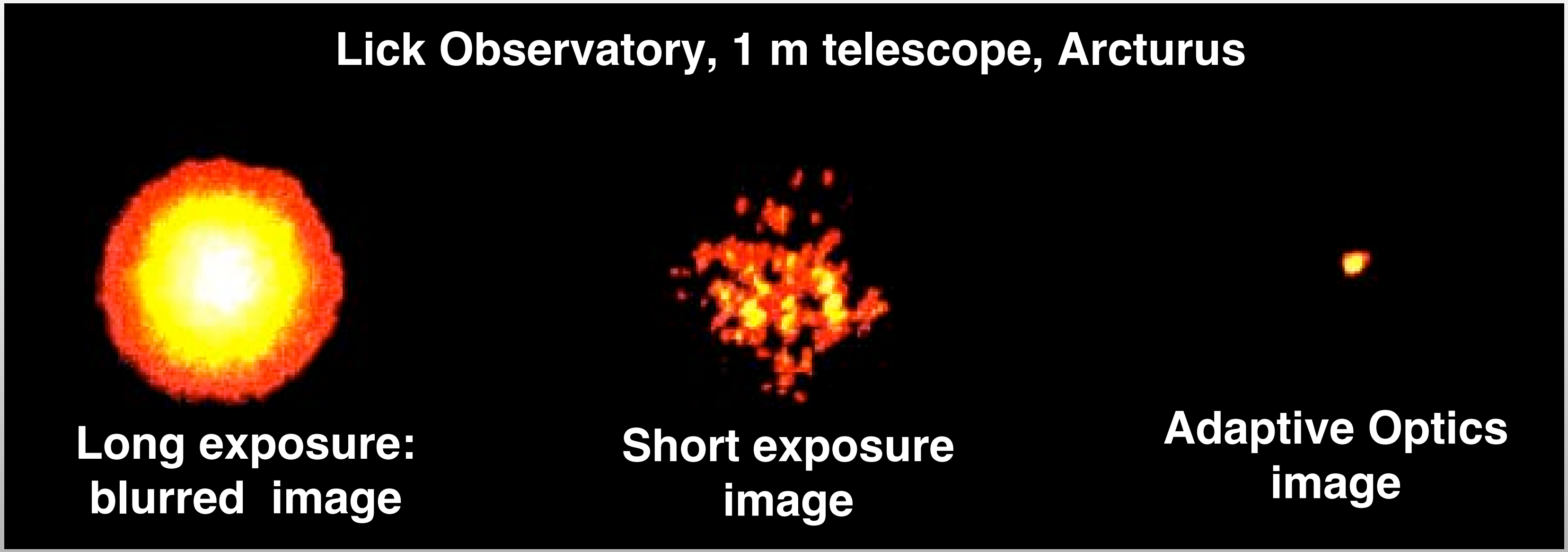
Introduction to adaptive optics



- 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

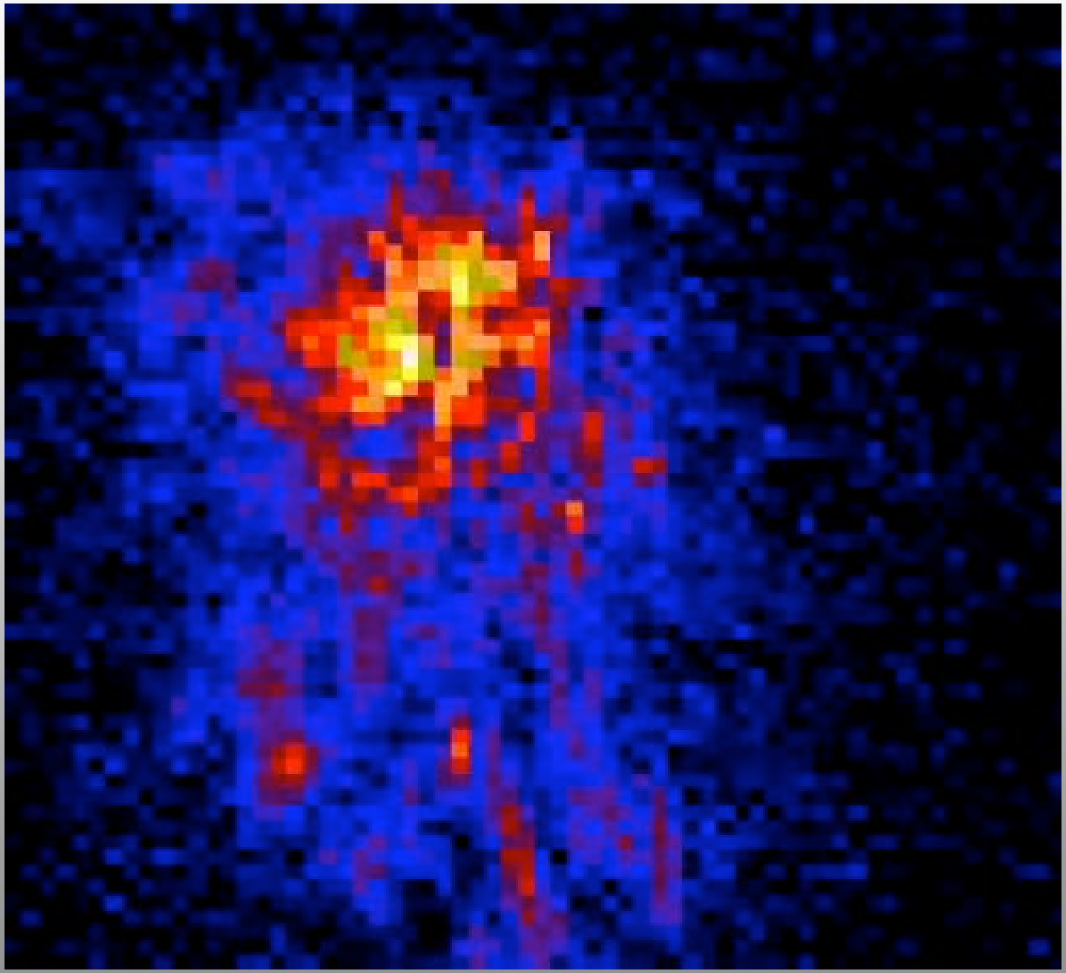


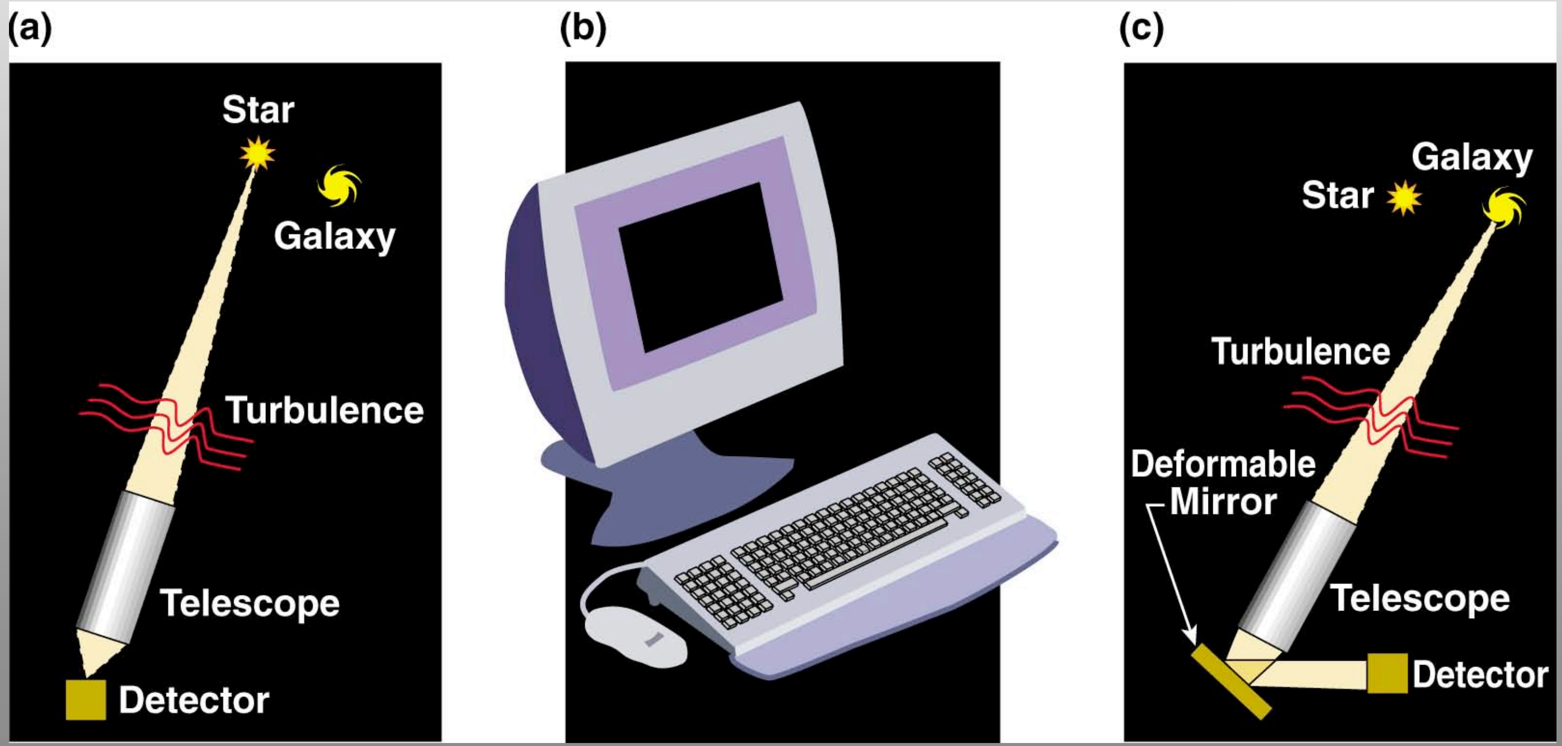
Image is greatly magnified and slowed down

Adaptive optics corrects for atmospheric blurring

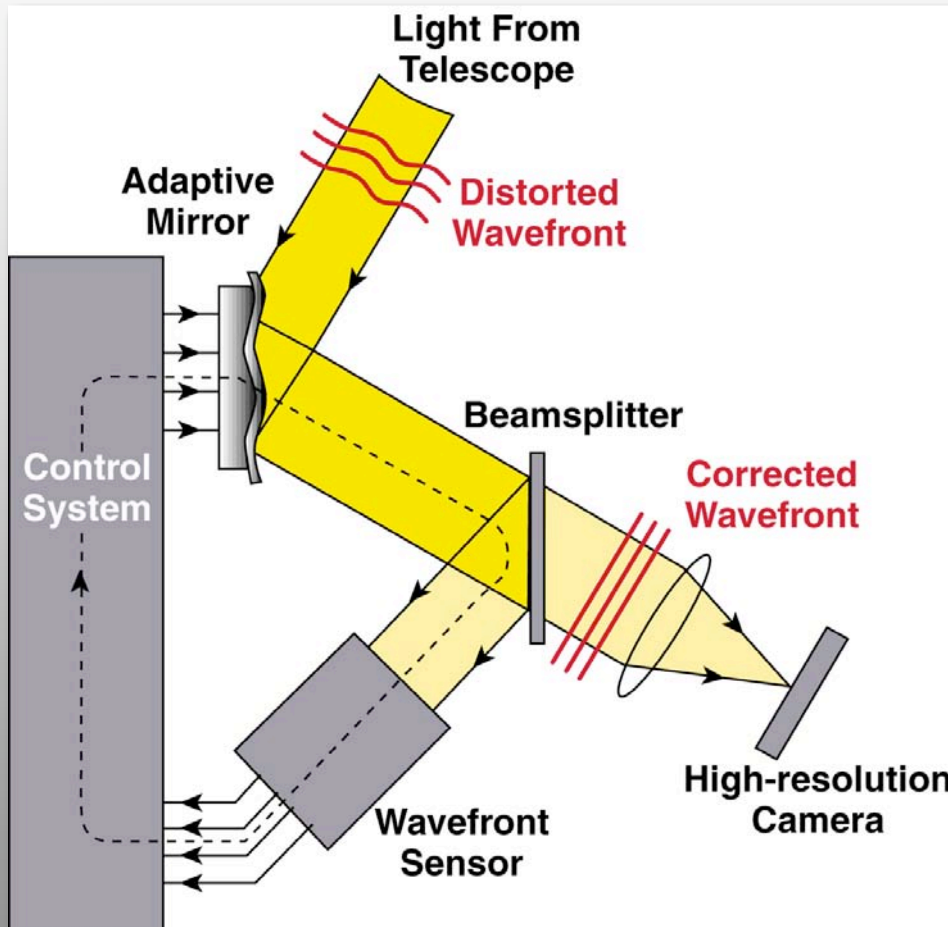
Measure details of blurring from "guide star" near the object you want to observe

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

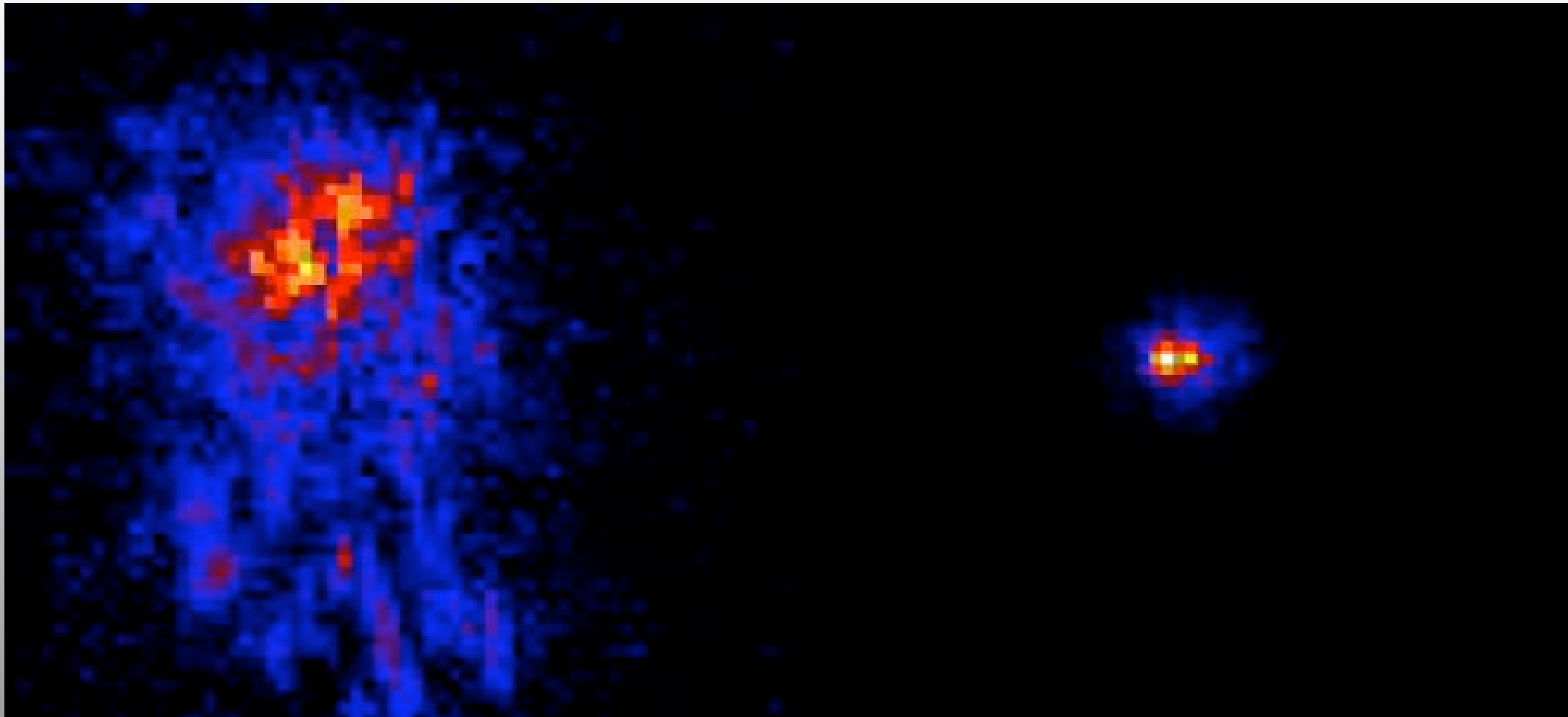


Schematic of adaptive optics system



Closed-loop feedback control system

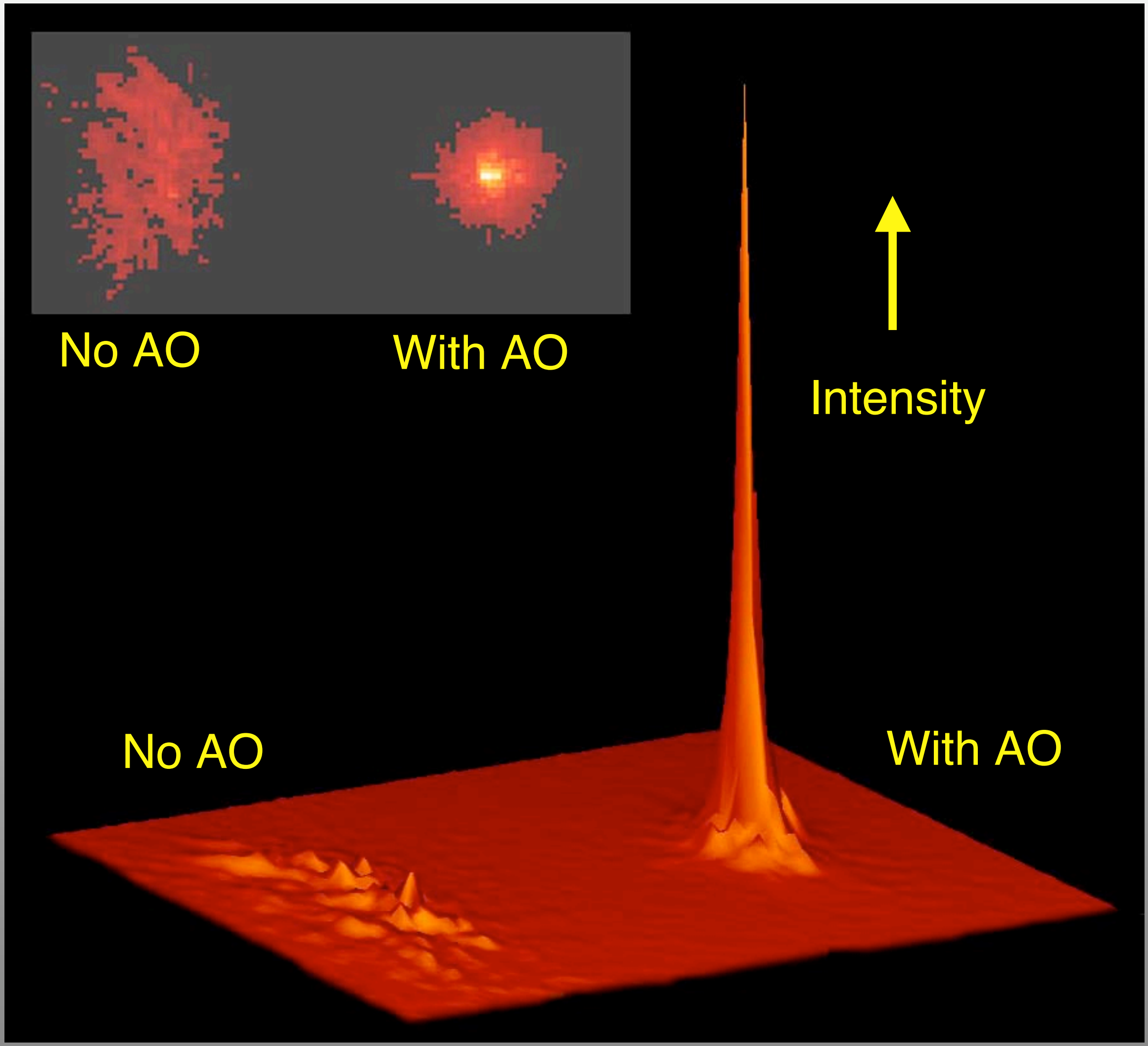
Infra-red images of a star showing improvement using adaptive optics



No adaptive optics

With adaptive optics

Adaptive optics increases peak intensity of a point source

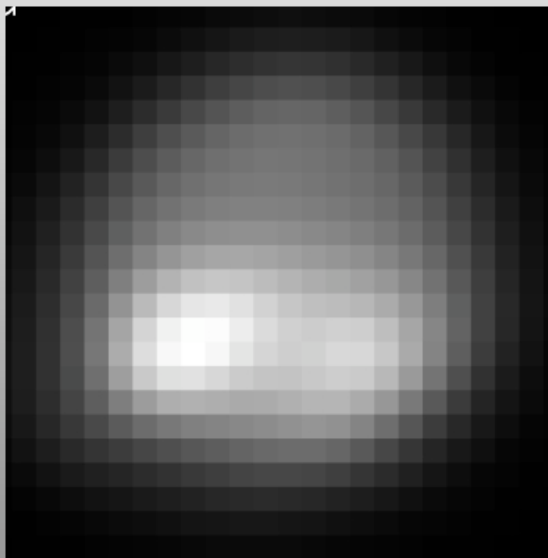


Lick Observatory

Compare AO with seeing-limited observations and Hubble Space Telescope

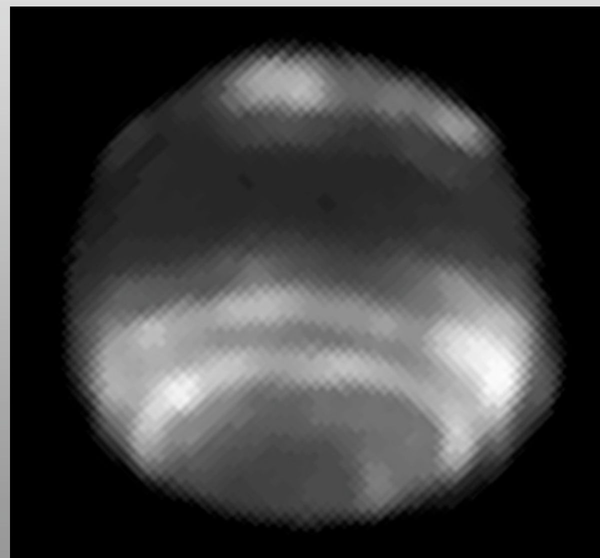
Neptune at H band: λ = 1.6 μm

Keck Telescope
no AO



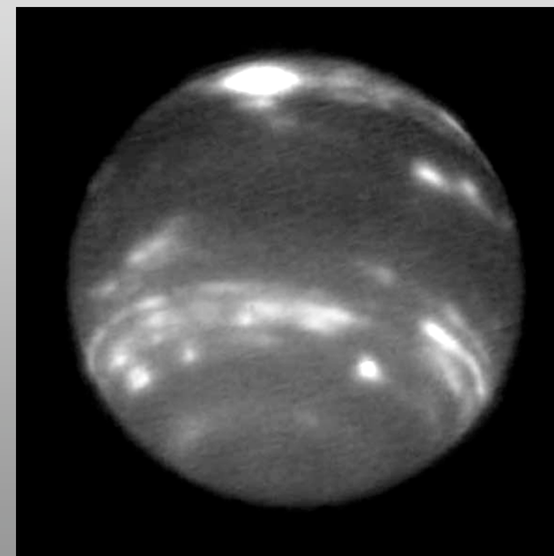
10 meter telescope

Hubble Space Telescope
NICMOS camera



2.4 meter telescope

Keck Telescope
with AO



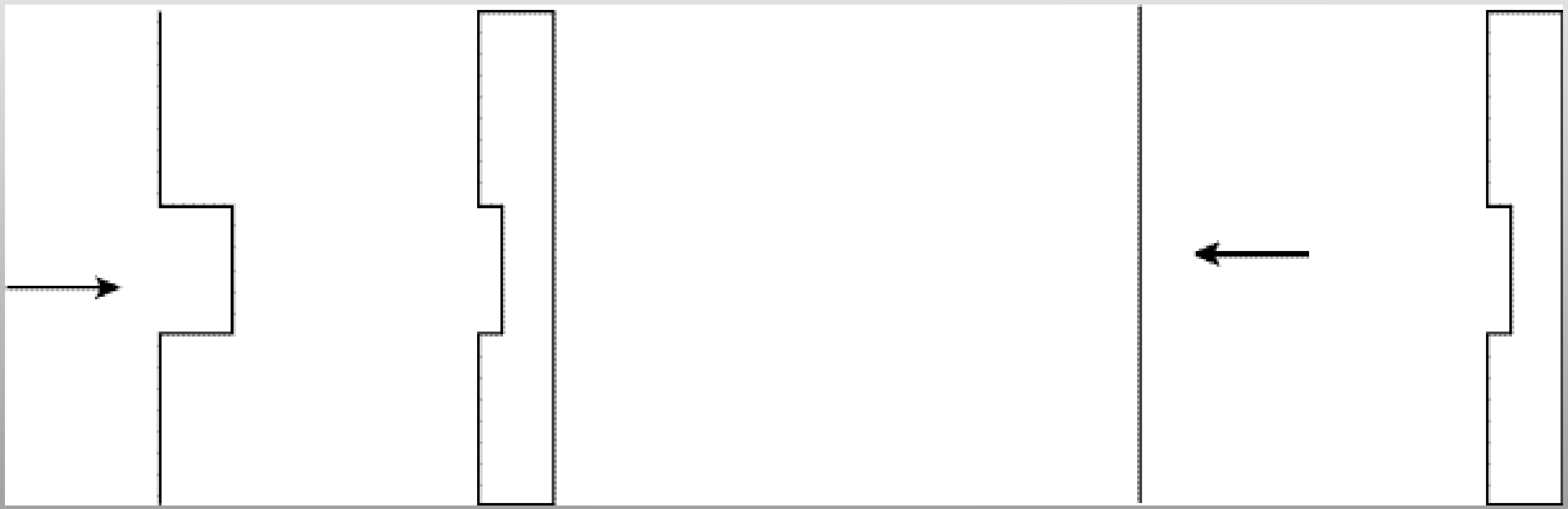
~2 arc sec

10 meter telescope

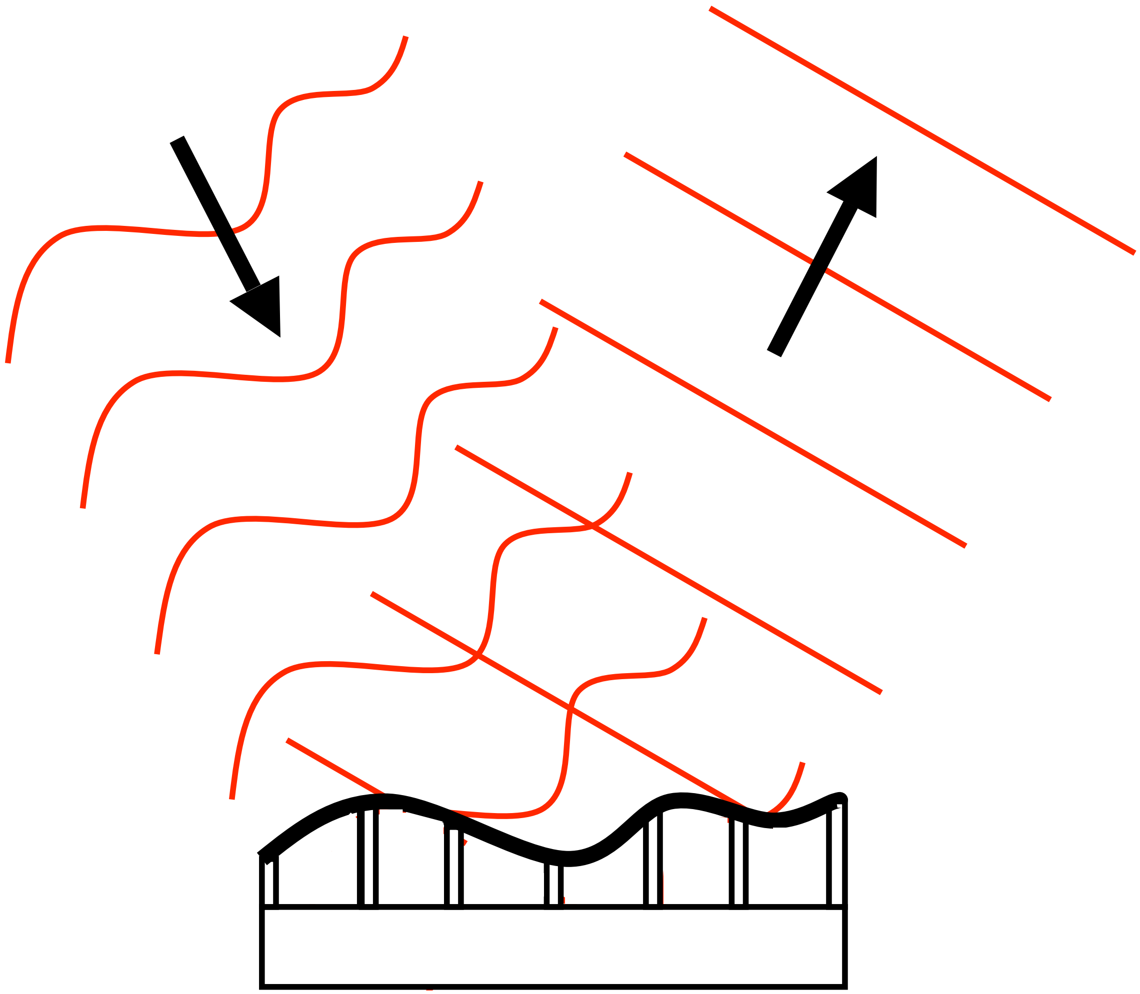
(Three different dates and times)

How a deformable mirror works: zero'th order approximation

BEFORE **AFTER**

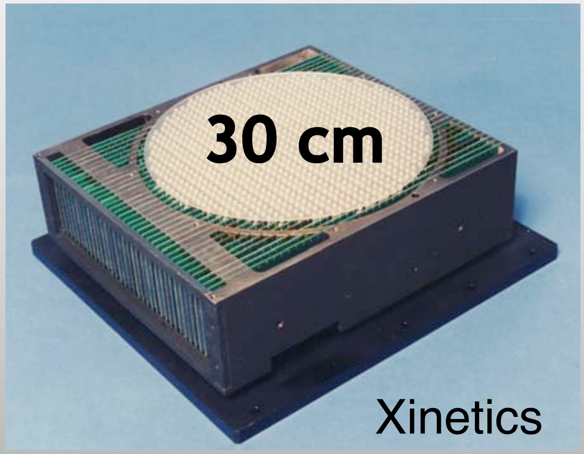


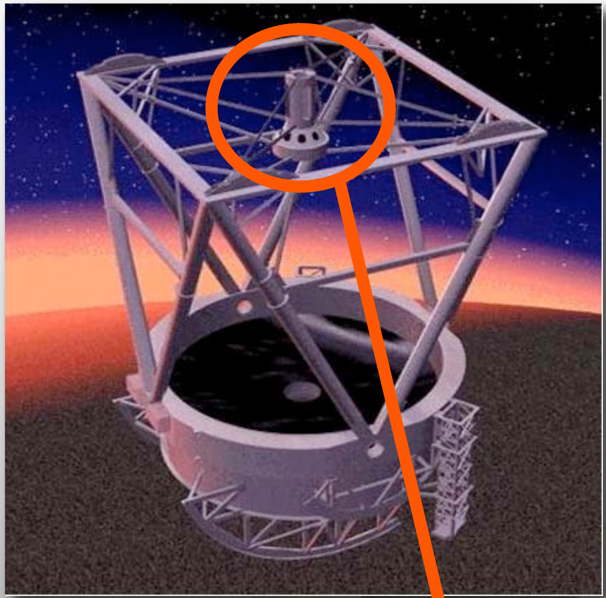
How a deformable mirror works: first order approximation



Deformable mirrors come in many sizes & shapes

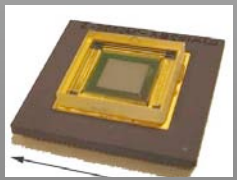
Glass facesheet
1000 actuators





Adaptive Secondary Mirrors

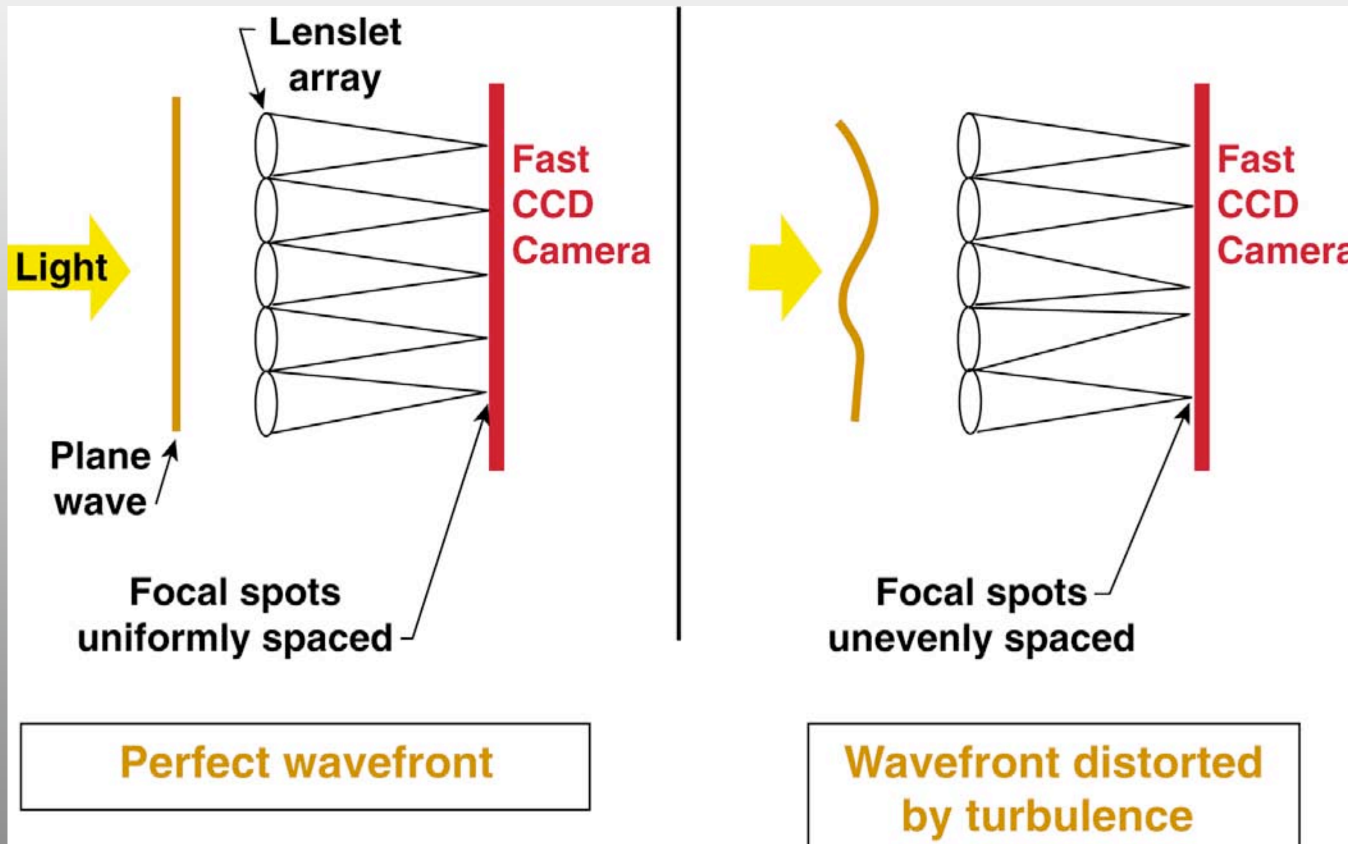
MEMS
1000 actuators



1 cm

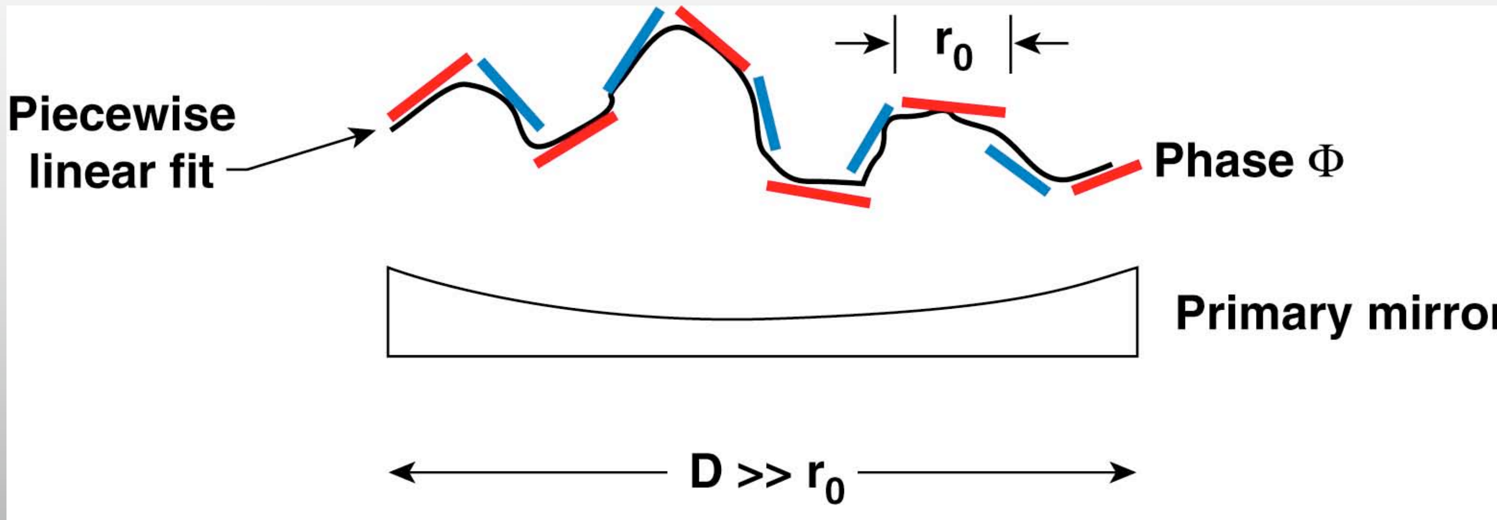
Boston Micro-Machines

How to measure optical distortions (one method among many)



Shack-Hartmann Wavefront Sensor

Deformable mirror makes a piece-wise fit to the shape of the incoming wavefront



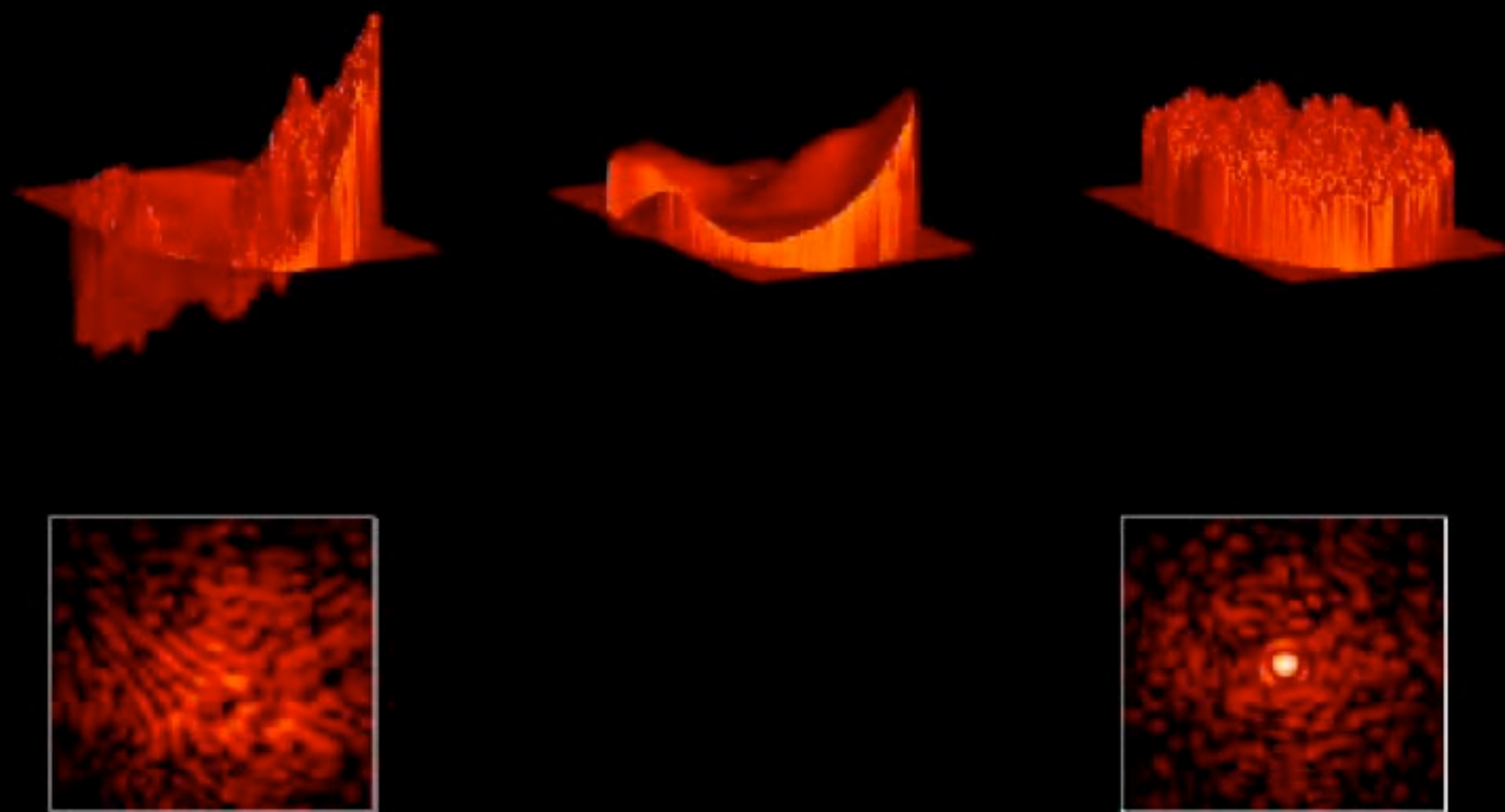
r_0 is defined as largest distance (on telescope mirror) over which phase of incoming wave is well-correlated

Typical values: at good site, r_0 ~ 10 - 15 cm, $\lambda = 0.5\ \mu m$

Incident wavefront

Shape of Deformable Mirror

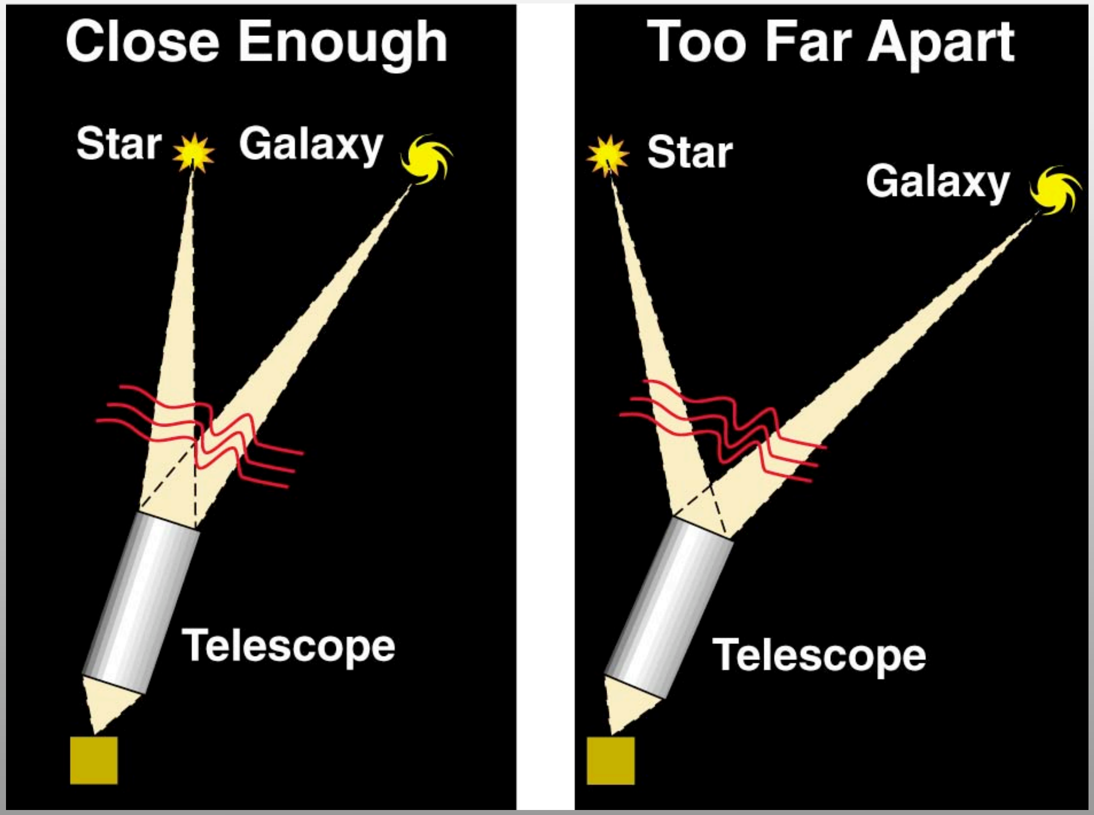
Corrected wavefront



Credit: James Lloyd, Cornell Univ.

Adaptive optics needs a bright "star" nearby

"Same turbulence"



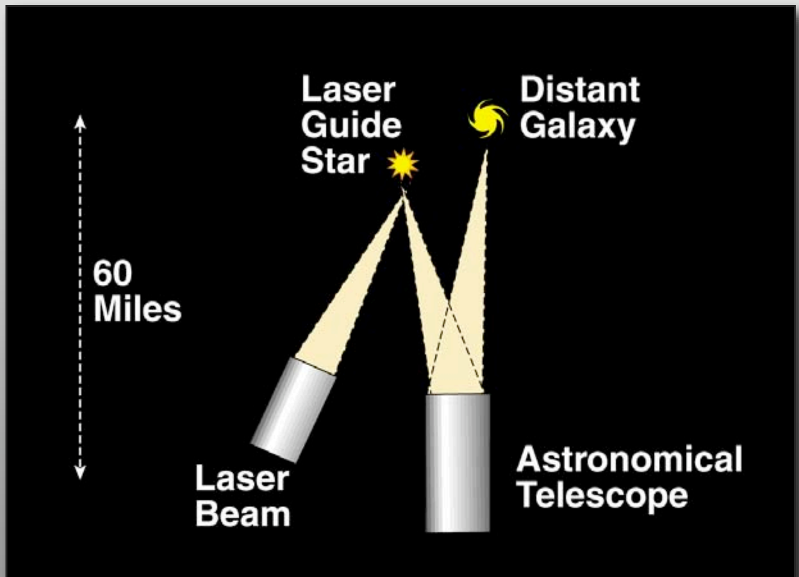
"Different turbulence"

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

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

Happer, MacDonald, Max, Dyson

Concept

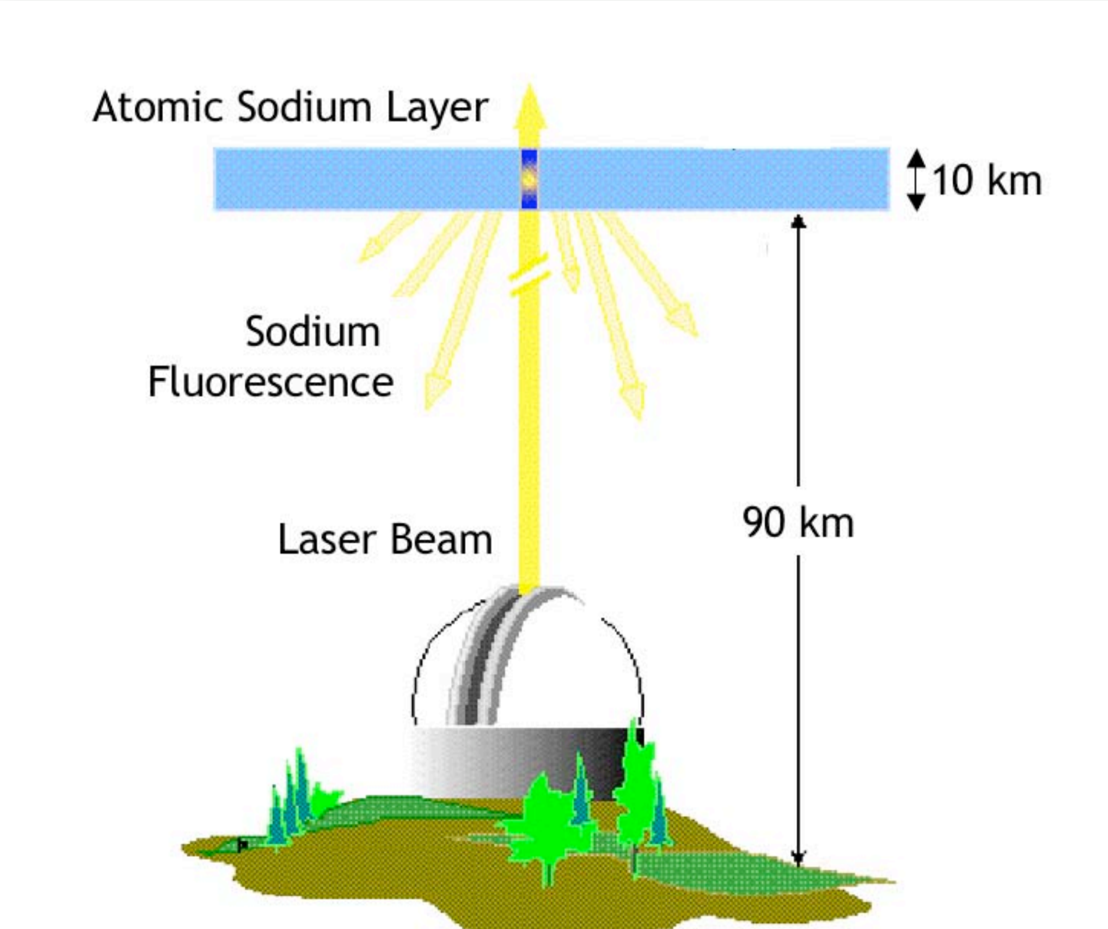


Crucial for extragalactic astrophysics

Implementation

Keck Observatory

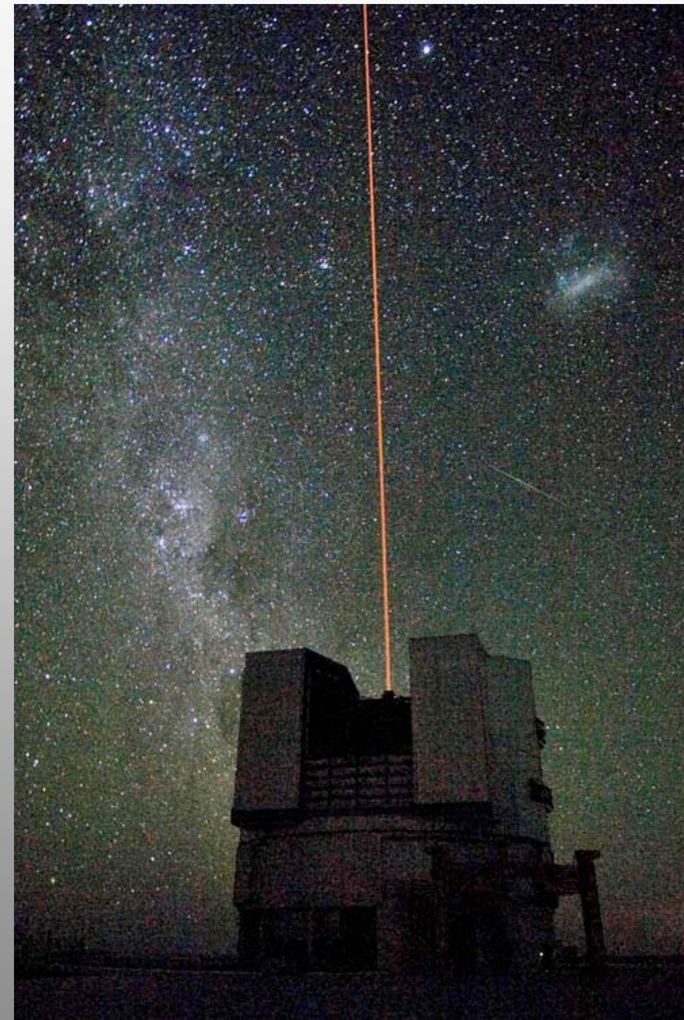
Physics of “sodium-layer” laser guide stars



Credit: Peter Milone

- Sodium layer: region of increased density of atomic sodium (95-105 km)
- Excite sodium atoms by shining 589 nm light onto sodium layer (Na D_2 line)
- Keck, Gemini N, VLT
- Coming soon: Keck 1, Gemini S, Subaru

“Sodium-layer” laser guide stars on 8-10m telescopes



Left: Keck 2

Middle: Gemini N

Right: VLT

Physics of "Rayleigh" laser guide stars

- Rayleigh scattering in atmosphere ~ λ^{-4}
- Green laser light scatters well
- Most of scattering is in bottom ~10 km of atm
  - Within a scale height
- Not as high as sodium-layer guide stars (95km)
  - Hence not quite as good a wavefront measurement
- MMT, Wm. Herschel Tel.

Rayleigh guide star at MMT

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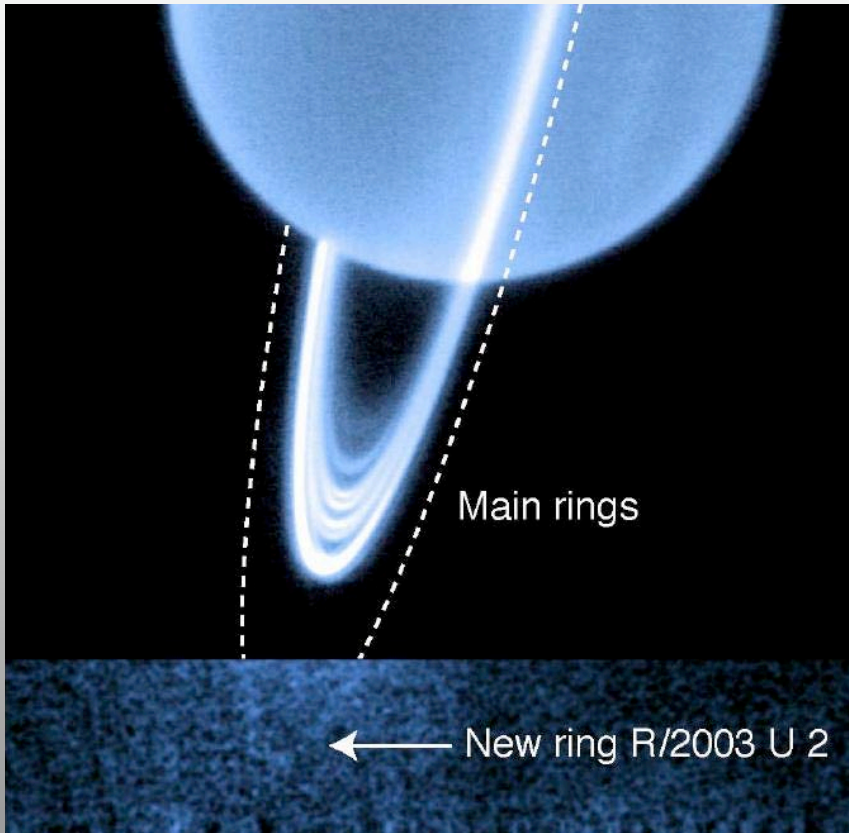
Solar System AO is thriving

A new ring of Uranus



Credit: Imke de Pater & Keck Observatory

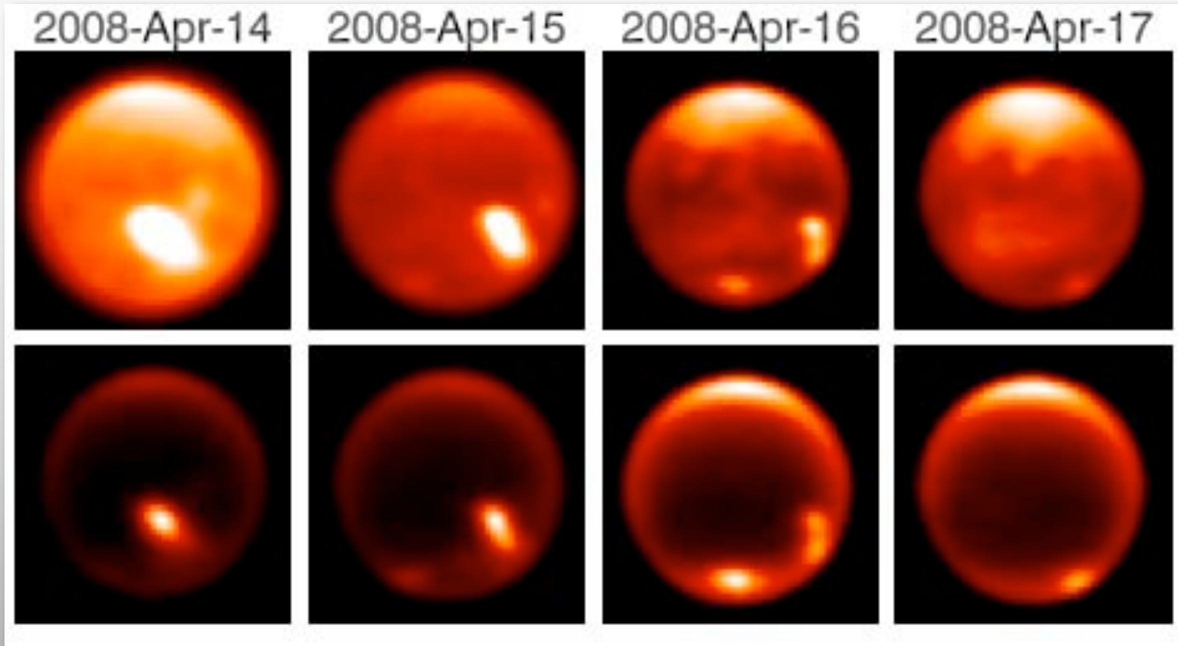
Nix and Hydra

Pluto/Charon

Credit: D. Tholen & Keck Observatory

Talk by Mike Brown Tuesday AM

Active meteorology on Titan

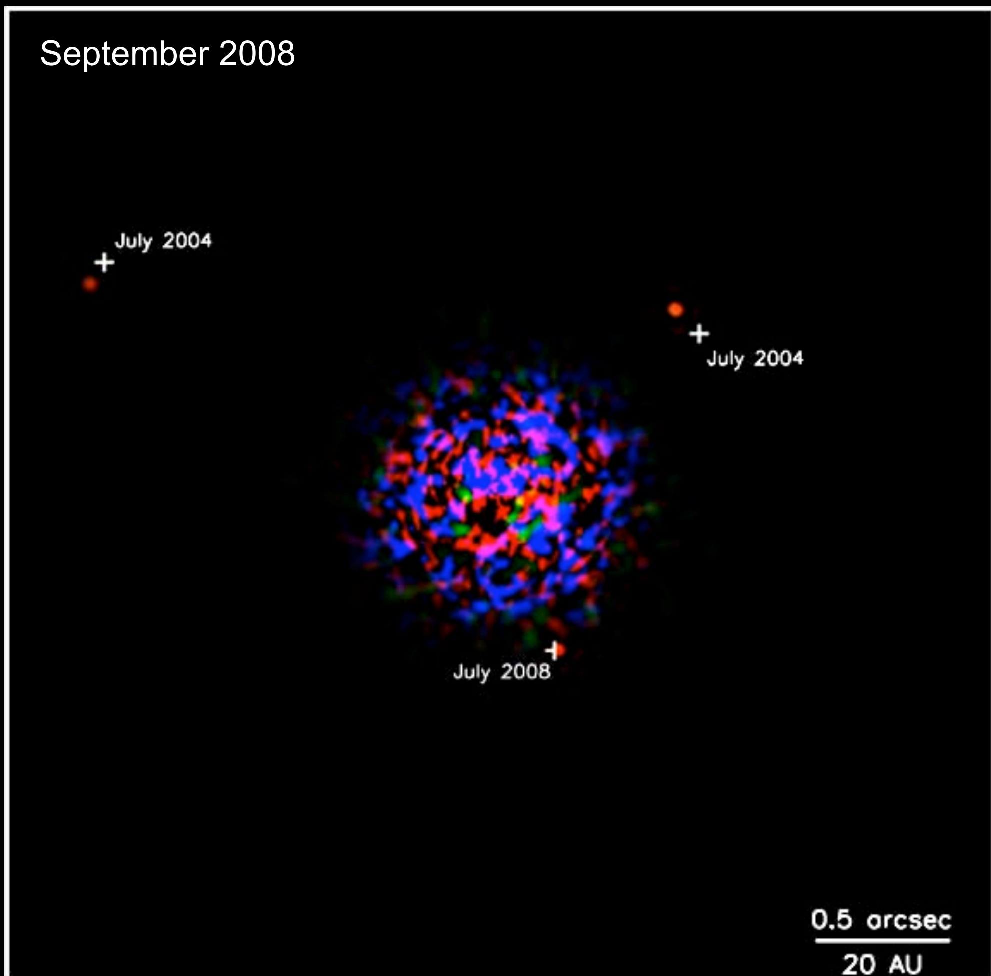


K': low altitude features and surface

H_2 1-0 (2.12 μm): tropospheric clouds

- Figure from Henry Roe. Talks by Roe, Adamkovics Tues AM.
- Strong seasonal variations.
- What is connection between active meteorology and the active surface methane/ethane "hydrology" seen by Cassini/Huygens?

The HR 8799 planetary system



Detected at Gemini with Altair/NIRI, followed by Keck AO (JHK bands)

A5V star, 60 Myr @ 39 pc

Three planets 7-10 M_{Jup} and ~800-1100K at 24, 38 and 68 AU

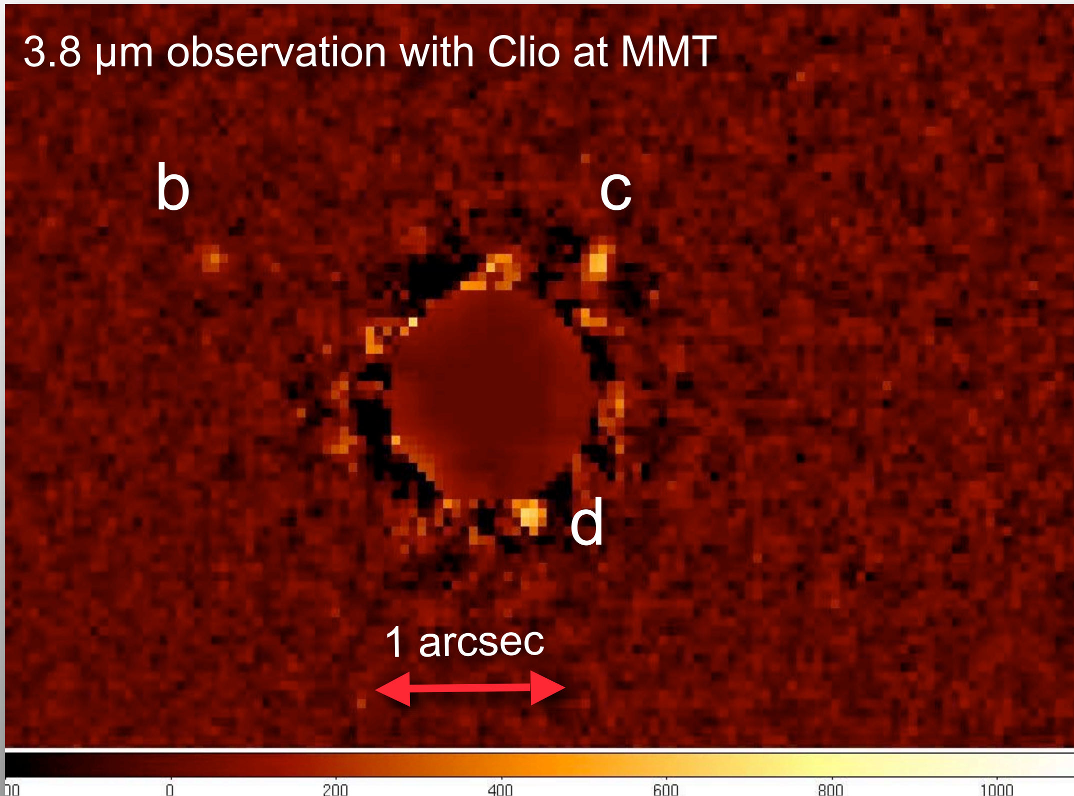
~ circular orbits
~ face on

Formed in a disk?

Marois et al., Science, Nov. 13 2008

See Marois's talk Tuesday 2-3:30pm

HR 8799 Planetary System in Thermal IR: MMT observations at 3-5 μm

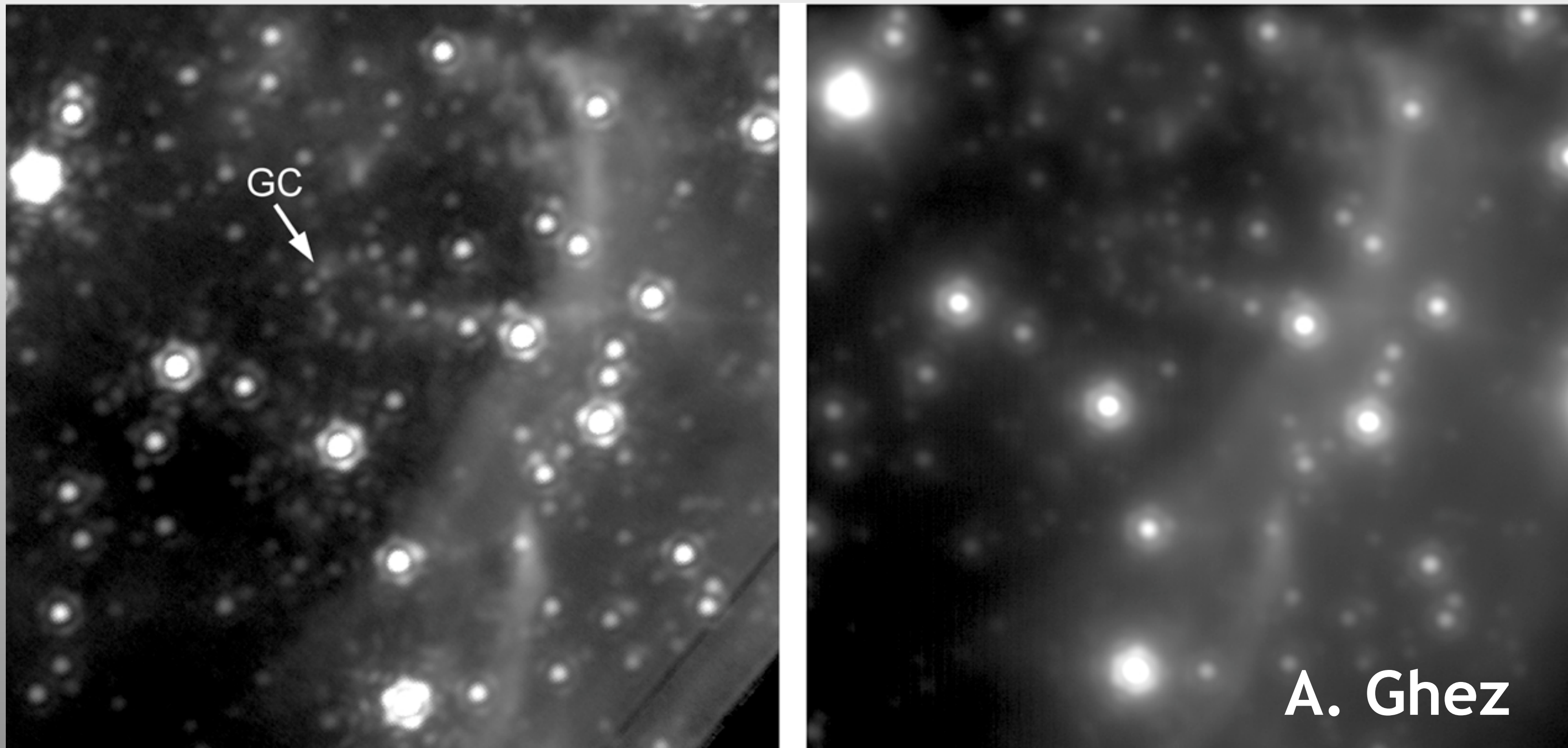


- Observed at 3.3, 3.8 and 4.8 μm.
- Observations enabled by the low background adaptive secondary mirror on the 6.5 m MMT.
- Planets are surprisingly blue in L'-M, indicating nonequilibrium chemistry and perhaps enhanced metallicity.

See talk by Phil Hinz, Tuesday 2:00 - 3:30 pm

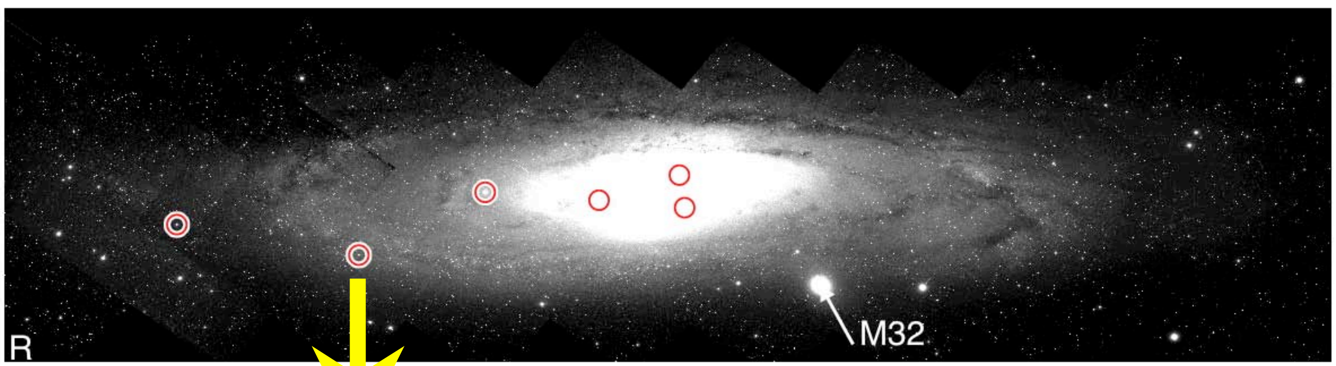
Galactic Center with Keck laser guide star AO

Keck laser guide star AO | Best natural guide star AO

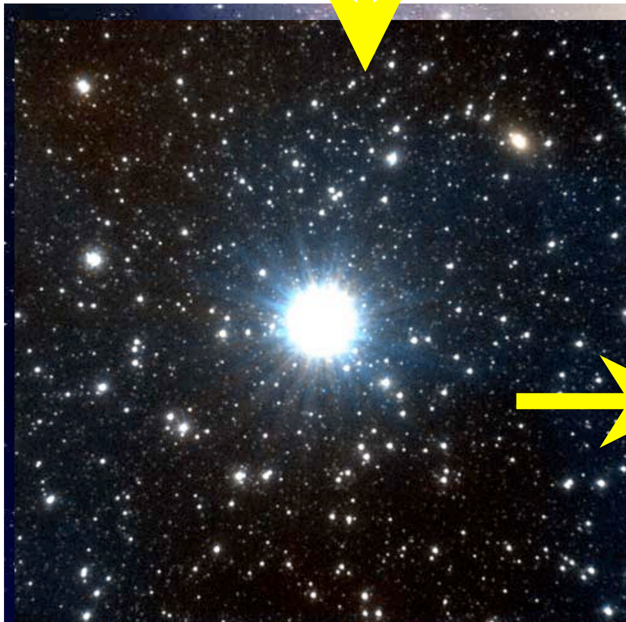


See talks by Ghez and Lu, Wed AM

The Star Formation History of M31

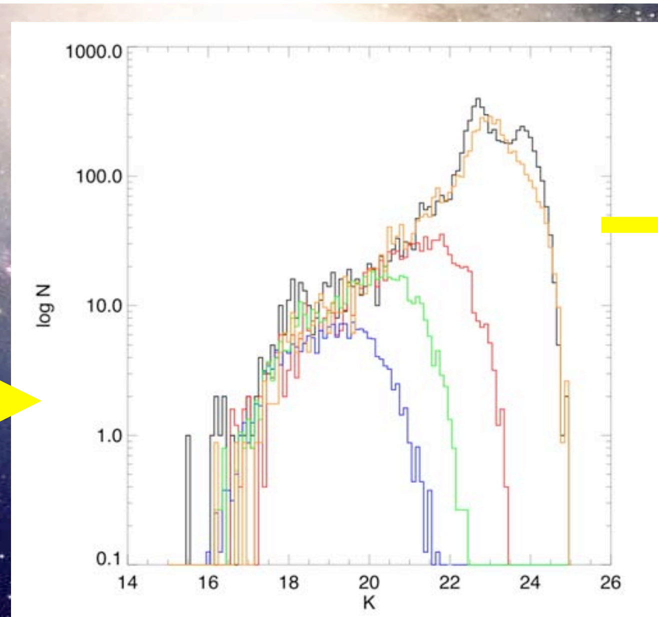


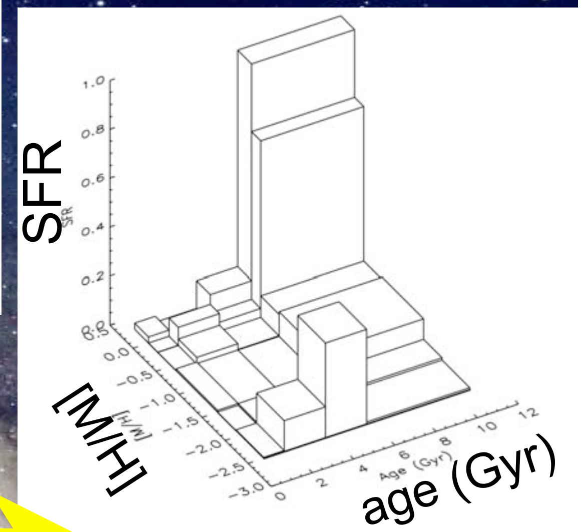
Bulge and inner disk

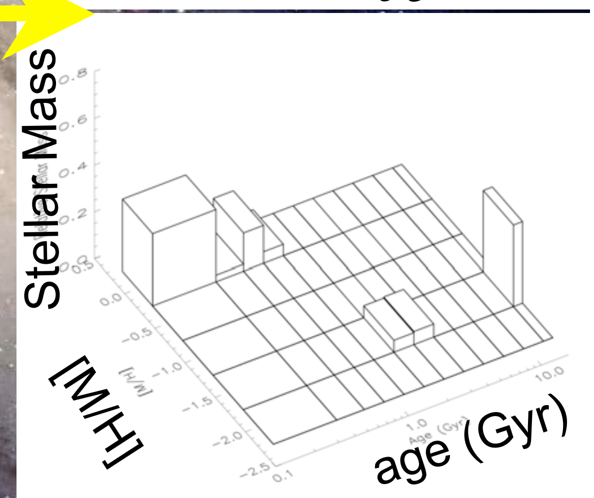


540s H, 3420s K

0.”059 H (~30% Strehl), 0.”066 K (~40% Strehl)







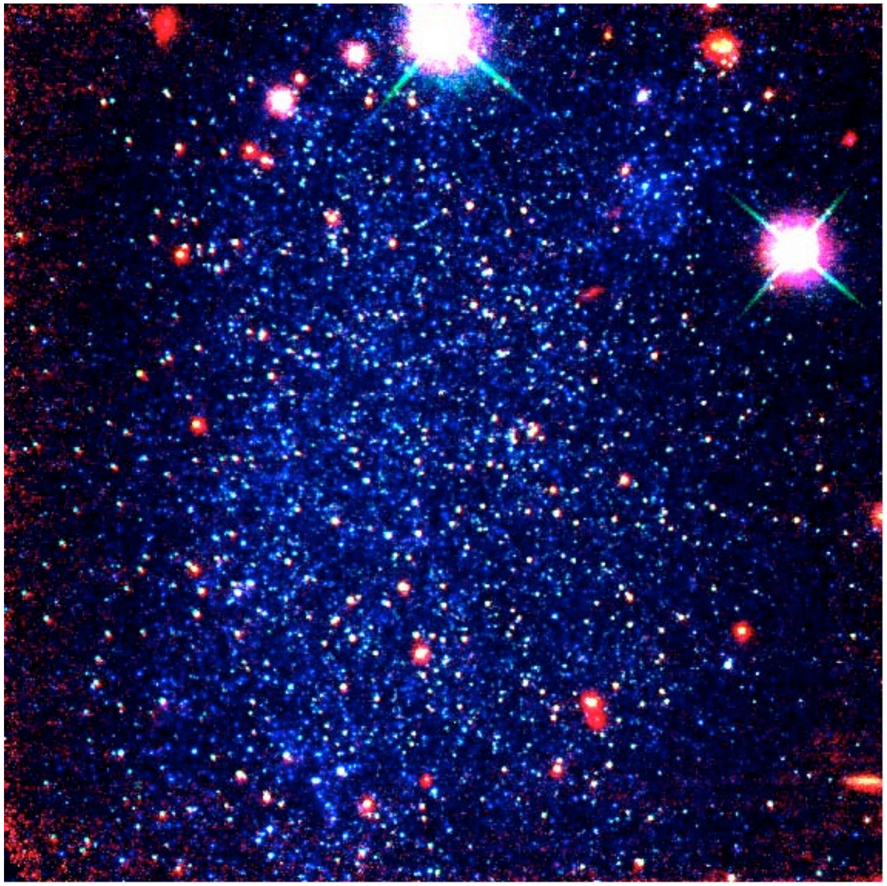
Olsen, Blum, & Stephens (240.05)

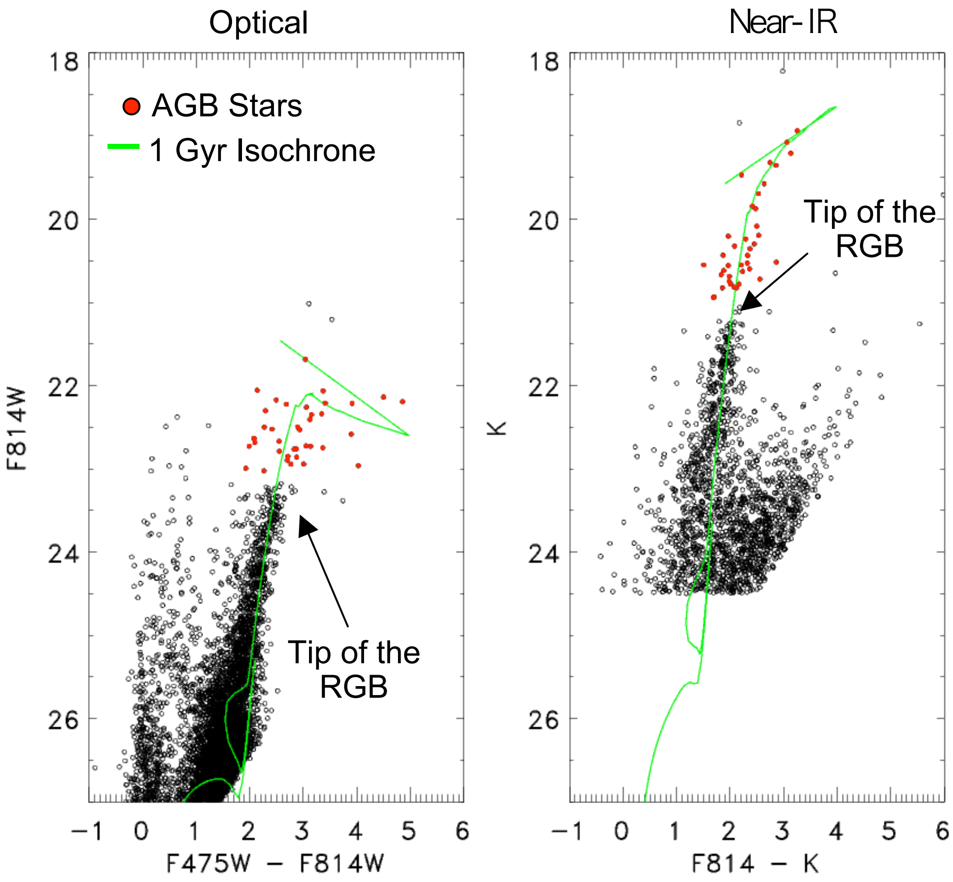
10 kpc ring

Mining Nearby Galaxies to Constrain the Numbers, Luminosities, and Colors of Evolved Stars Within Different Stellar Populations

Talk Thursday: Jason Melbourne (Caltech)

Nearby (2.5 Mpc) Dwarf Irregular Galaxy KKH 98
HST F475W (Blue), HST F814W (Green), Keck AO K-band (red)



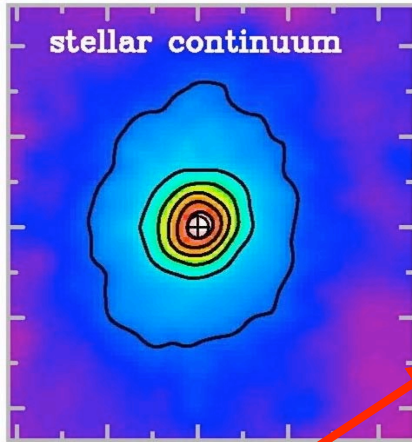


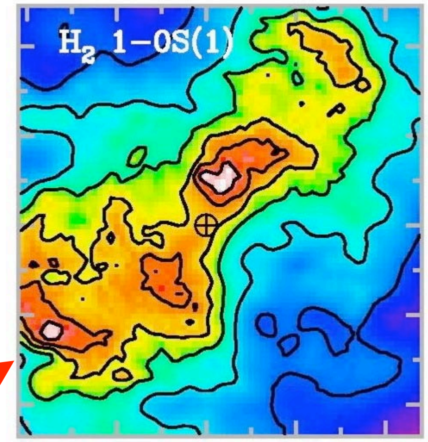
Melbourne et al. in Preparation

Black Hole Mass from Stellar Kinematics in a Seyfert 1: NGC 3227

Goal:
- Measure M_{BH} using stellar kinematics
- Spatial resolution 7 pc (0.085 arc sec)

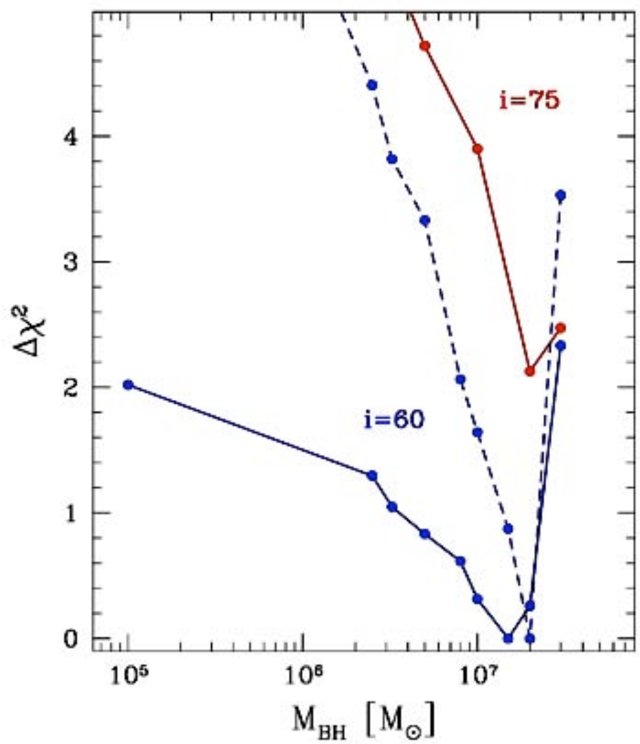
Important considerations:
- 2 distinct stellar populations: young starburst + older stars
- Molecular gas mass is significant (torus)





Have good constraints:
- H_2 & CO observations provide gas mass
- Starburst models give distributions & M/L ratios of stellar populations

Schwarzschild orbit superposition models:
- Resulting M/L ratios consistent with starburst models
- $M_{BH} \sim 1.5\times10^7 M_{sun}$
- Mass less than, but consistent within uncertainties, reverb. mapping, M_{BH}-σ, X-ray variability

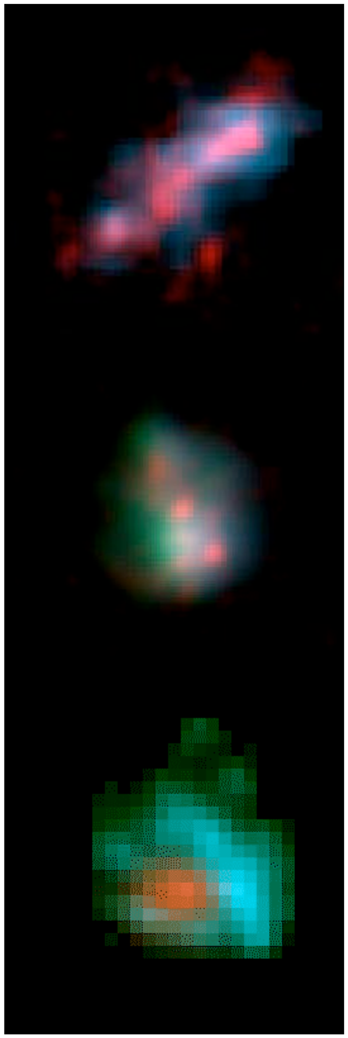


Davies et al. ApJ 646, 754 (2006). VLT SINFONI.

See poster 603.11 by Erin Hicks

High-z Galaxy Kinematics and Star Formation

Erin K. S. Hicks & SINS team
Max Planck Institut für extraterrestrische Physik
MAX – PLANCK – GESELLSCHAFT



Kinematics of massive star-forming galaxies at z~2

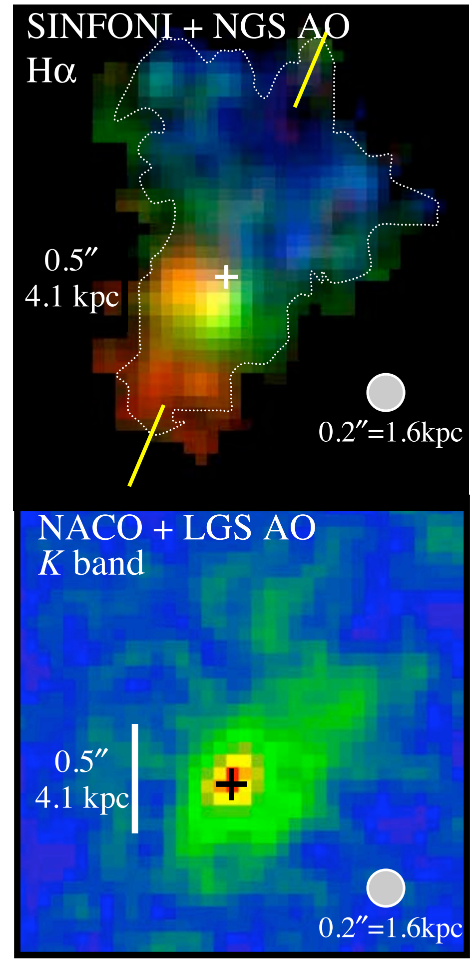
- ~1kpc spatial resolution with LGS & NGS AO
- 3D spectroscopy with SINFONI on VLT
- ~1/3 rotation-dominated, ~1/3 compact dispersion-dominated, ~1/3 mergers
- Fraction of rotation-dominated systems increases at higher masses

Properties of massive z ~ 2 star-forming disks

- Significantly more turbulent and gas-rich than local disks
- Higher SFRs, large luminous/massive clumps

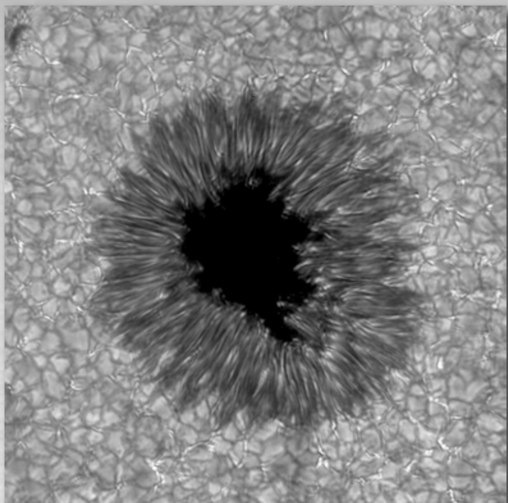
Mass assembly, early evolution, and star formation activity

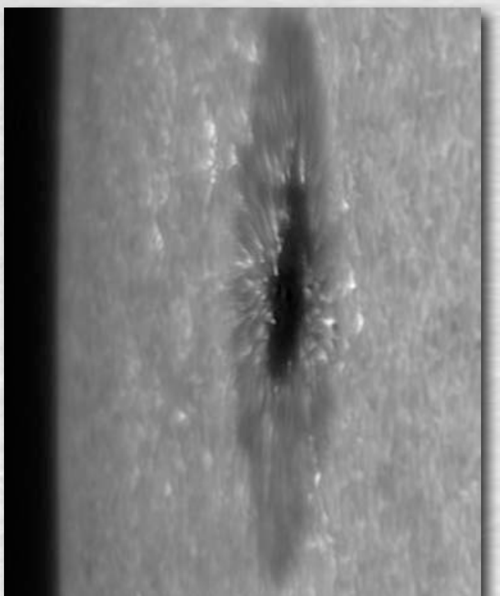
- Evidence for smooth+rapid mass accretion via cold flows/minor mergers
- Evidence for internal/secular processes in gas-rich disks & rapid bulge formation

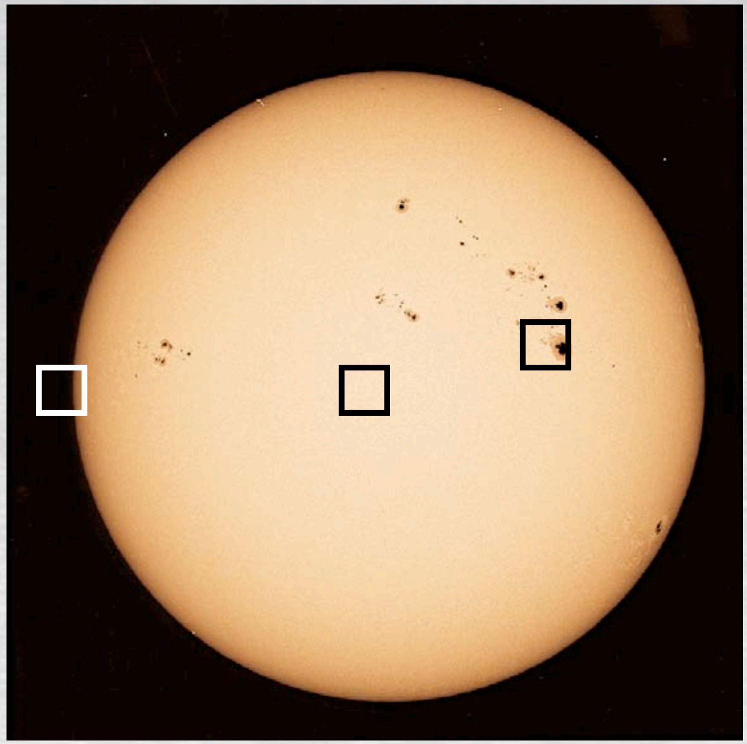


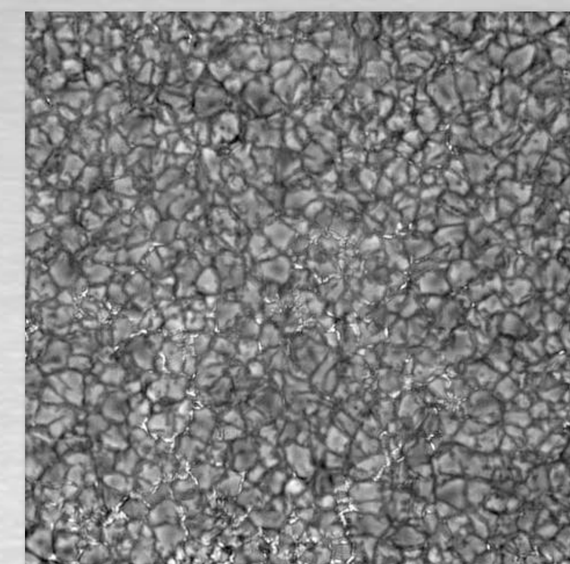
Thursday Morning Session 10-11:30 am Oral 257

Solar Adaptive Optics



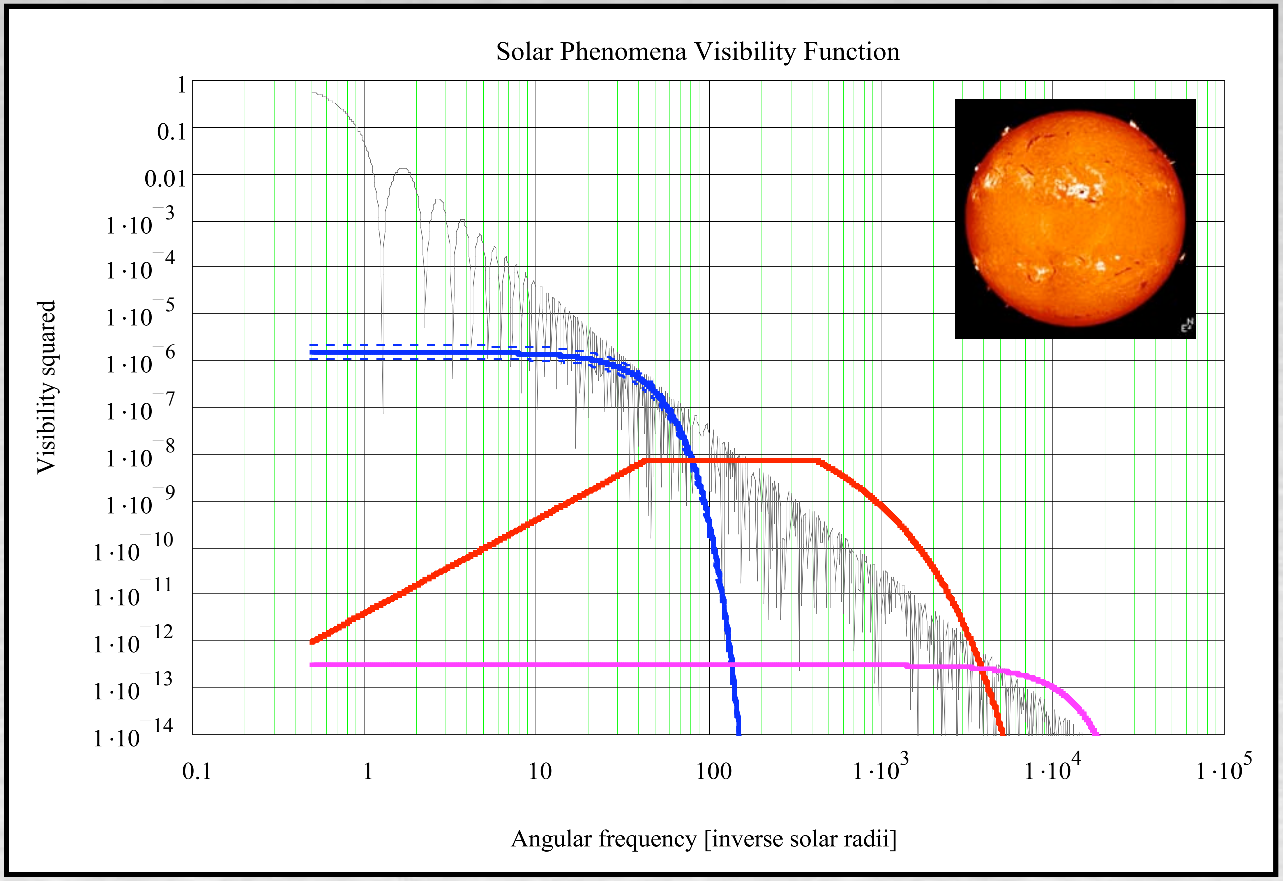


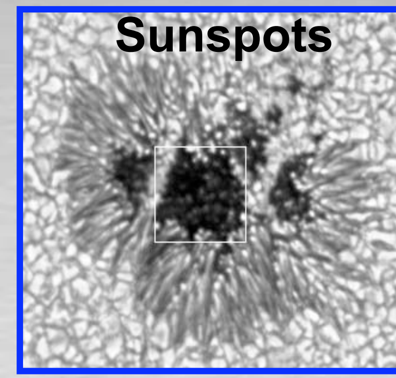


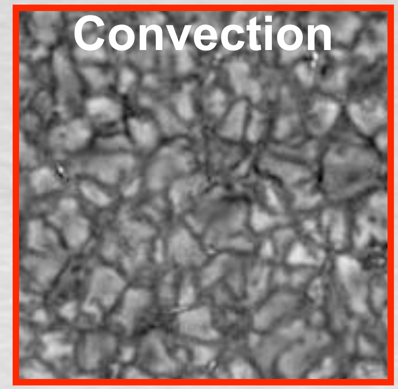


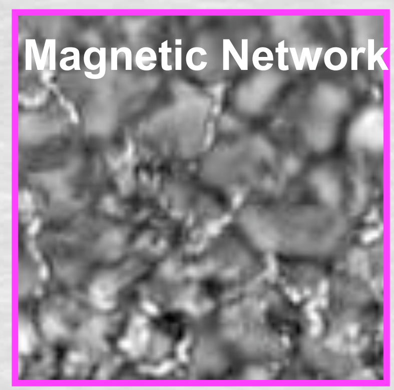
Based on slides by O. von der Lühe

Why high angular resolution on the Sun?

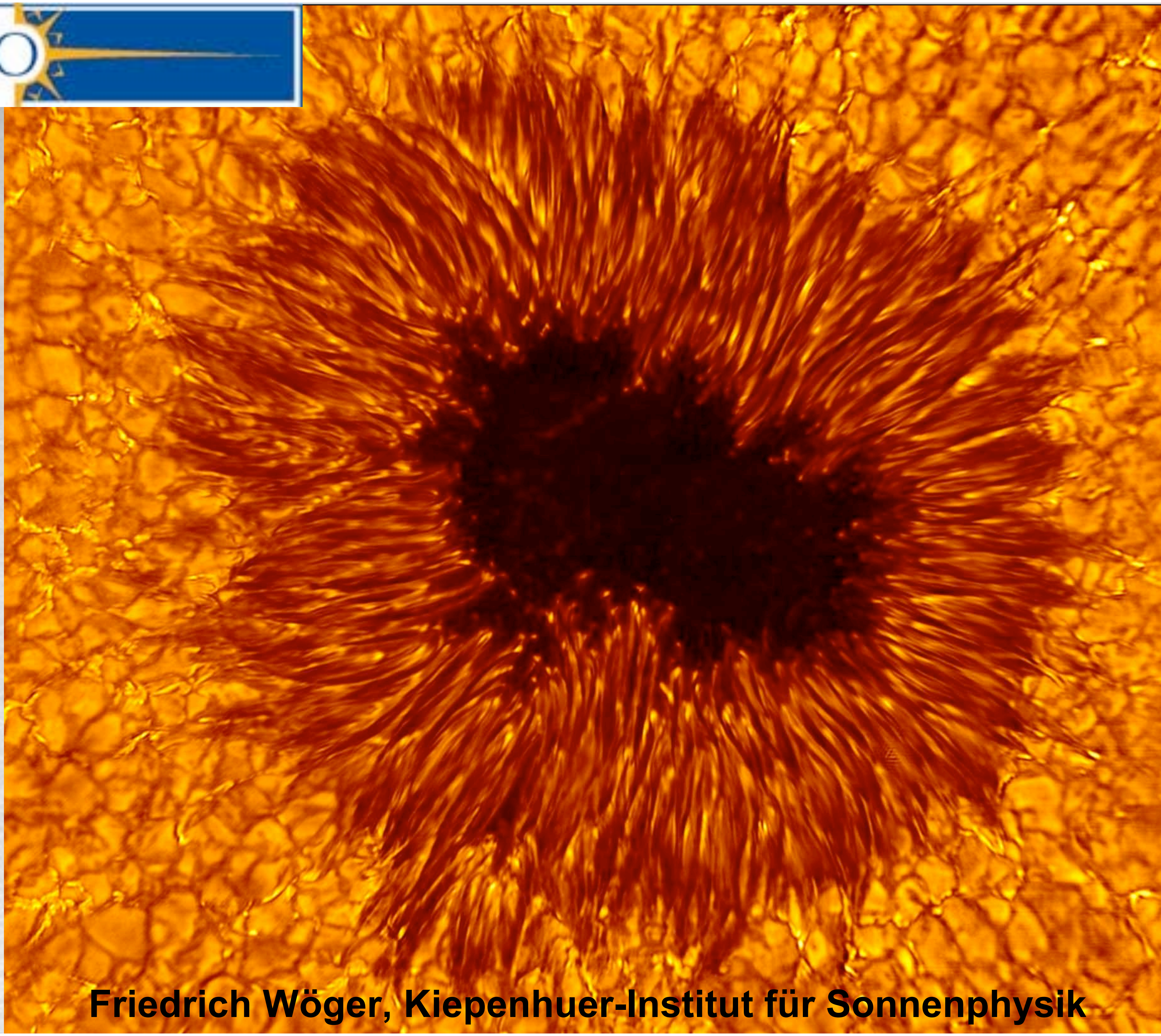




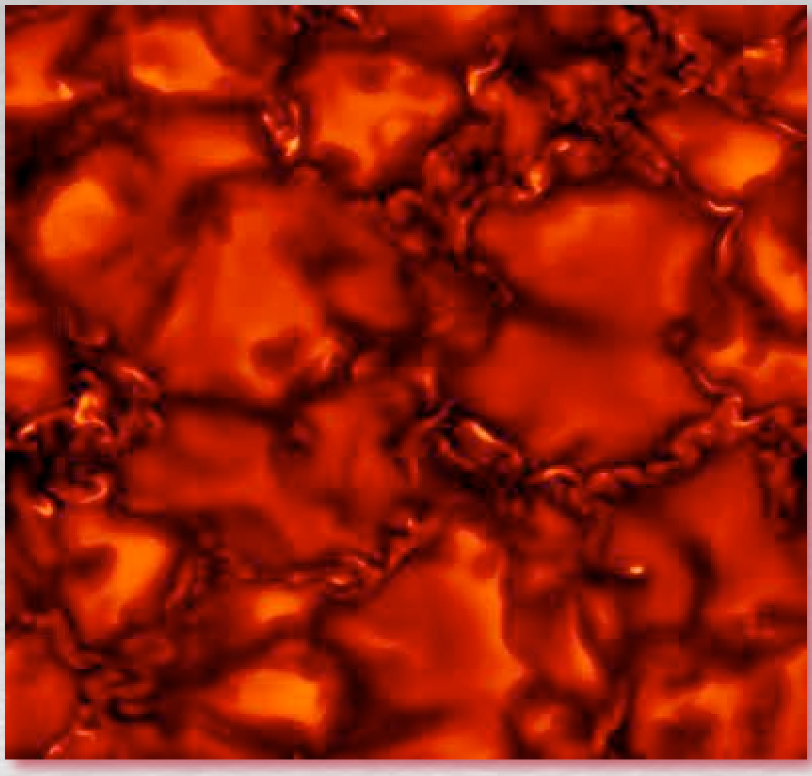




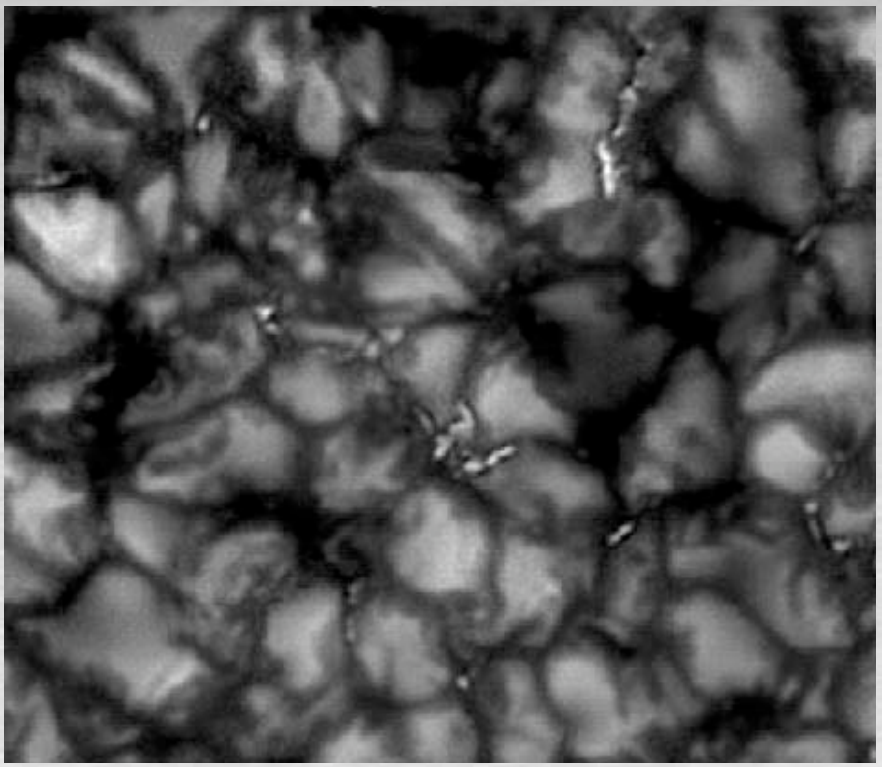
Credit: O. von der Lühe


Friedrich Wöger, Kiepenhuer-Institut für Sonnenphysik

AO observations can now confront simulations



Simulations at Max-Planck-
Institut für Sonnensystemforschung



AO observations:
O. von der Luhe

AO is used the great majority of the time, at telescopes where it is installed

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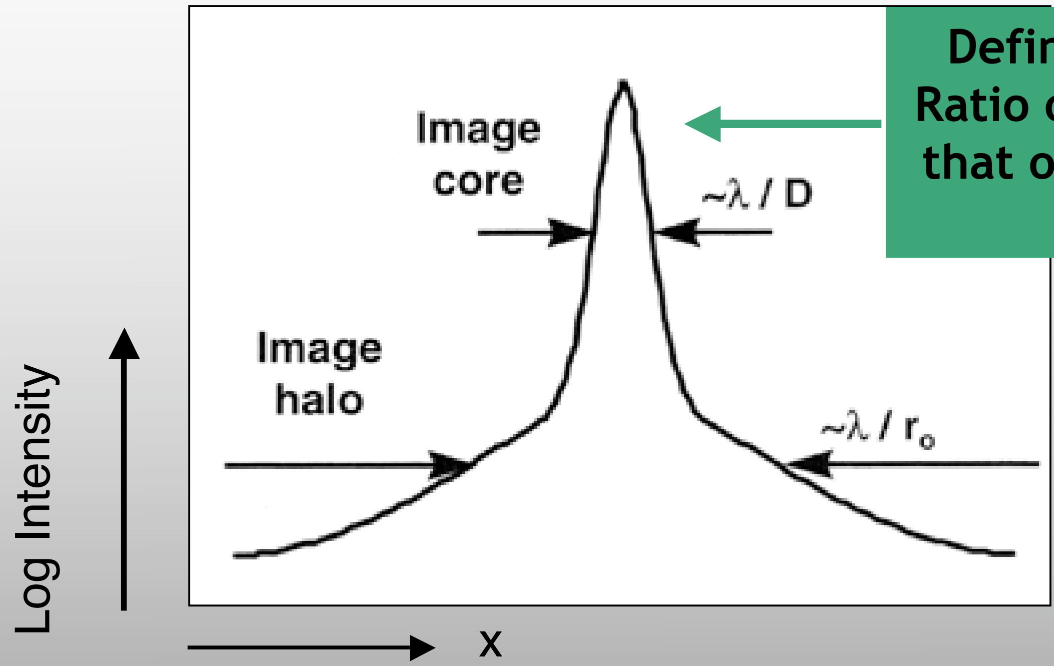
- Motivations for this "Meeting within a Meeting"
- What is AO and how does it work?
- Science with AO: Current Examples
- How should somebody decide whether to use AO?
  - Basic Features
  - Strengths and weaknesses compared with space, and with seeing-limited ground observations
- Future directions
- Summary

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



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

- Point spread function: what the image of a perfect point source should look like
- 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

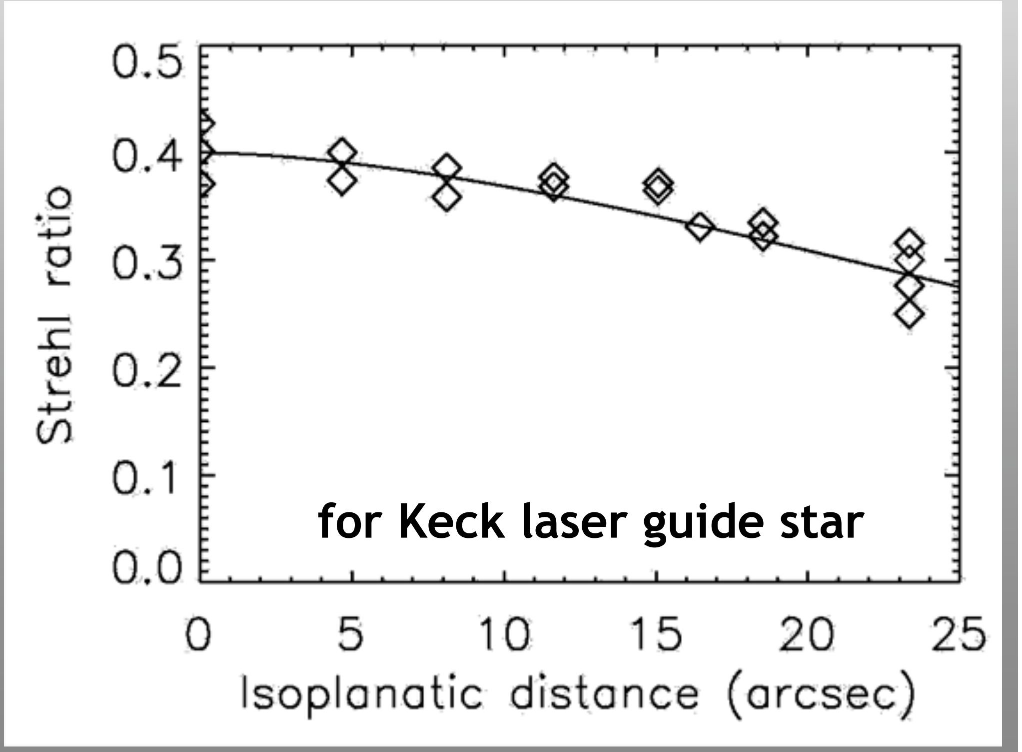
Today's AO systems on 6-10m telescopes operate in the near-IR

- Basic scaling:
  - Atmospheric coherence length $r_0 \propto \lambda^{6/5}$
- So for shorter λ, need
  - More degrees of freedom
  - Faster wavefront control
  - Brighter guide stars (laser or natural)
- Today's AO systems on largest telescopes all operate in the near-infrared
- But note that Air Force has two 6-m class telescopes with visible light AO, and future astronomical systems will work at shorter wavelengths as well

Characteristics of today's AO systems

- The need for guide stars close to your target
  - Natural Guide Star AO: m_V < 12 - 14 w/in ~ 30". Need to measure high-order wavefront distortions.
  - Laser Guide Star AO: m_V < 18 - 19 within ~ 60". Tip-tilt star needed to stabilize image.

- Narrow field of view
  - Quality of AO correction decays when you get too far from guide star or laser. "Anisoplanatism"



Photometry and astrometry

- Time varying PSF is an issue
- Several specific methods have been developed to cope
- Current state of the art: Relative Astrometry
  - Galactic Center: astrometry to 170 μas using many stars
  - For more isolated systems, relative astrometry to a few mas
  - See talk by Brandner Wed afternoon
- Current state of the art: Photometry
  - Accuracy 14% for H=24 supernova at z ~1.3 (Melbourne et al. 2007)
  - Better for brighter objects

Strengths and weaknesses compared with seeing-limited

- **AO Strengths:**
  - Much higher spatial resolution than seeing-limited (10-50X)
  - Enables higher spectral resolution if spectrograph is designed for AO
  - Higher contrast for faint objects near bright objects
  - Can have higher sensitivity if AO system is designed for low background (e.g. adaptive secondary mirrors @ MMT, LBT)
- **AO Weaknesses:**
  - Lower sky coverage fraction (LGS still needs m_V=18-19 star)
  - Time-varying PSF $\Rightarrow$ harder to do highly accurate astrometry and photometry (but much progress has been made)
  - Can't (yet) work at visible wavelengths
  - Much smaller field of view
  - AO systems without adaptive secondaries usually have higher backgrounds, $\Rightarrow$ lower sensitivity esp. for faint diffuse objects

Strengths and weaknesses of AO compared with Hubble Space Telescope

- AO Strengths: 8-10 meter ground-based telescopes
  - Spatial resolution of 8-10m telescope, compared with 2.4m
  - In near-IR, AO has ~4X the spatial resolution of HST at same λ
  - Means that AO in the near-IR has same spatial resolution as Hubble in the visible (e.g. λ = 2 μm compared with 0.5 μm)
  - Extremely fruitful paradigm: papers use HST data in visible plus AO in near-IR to obtain a long wavelength reach at high spatial resolution
  - Today's 8-10m ground-based telescopes have very powerful spectroscopic capabilities, especially for IR 3D spectroscopy
- AO Weaknesses: 8-10 meter ground-based telescopes
  - Lower Strehl ratio
  - Much smaller field of view
  - Time-varying PSF
  - Lower sky coverage fraction
  - AO can't (yet) work in the visible
  - AO imaging has lower near-IR sensitivity due to IR sky background

Future directions: a quick overview

- Larger fields of view
  - Multi-Conjugate AO (Gemini S) of order 1 - 2 arc min
  - Ground-Layer AO (MMT, VLT) of order several arc min or more
- Higher contrast
  - Dedicated planet-finding instruments (e.g. GPI, SPHERE)
- Higher sky coverage fraction
  - Multi-Conjugate AO or Multi-Object AO, with AO-corrected IR tip-tilt stars (Keck Next Generation AO)
- Continued progress in accurate photometry and astrometry
  - Use independent information about atmospheric turbulence to give better PSF knowledge

Summary

- Dramatic growth in science with adaptive optics over past 5 years
  - Current pace >150 refereed science papers/yr
  - AO now scheduled for half of all Keck 2 time
- Laser guide stars: in routine use at Keck, Gemini N
  - Soon at VLT, Subaru, Gemini S
  - Key enabler for extragalactic science
- Solar AO used the majority of the time at those observatories where it's a facility instrument
- Consider strengths and weaknesses of AO on 8-10m telescopes, compared with seeing-limited instruments and HST

We are excited about AO's strong science contributions!