ASTR 620: Planetary Processes

Professor Eric Nielsen

Lecture 24: Exoplanets

Logistics

- Masks are encouraged
- No laptops, phones, or other electronic devices during class (I'll let you know in advance if we'll need laptops for an activity) **You may use a tablet to take notes if prefer, but please only use it for note-taking.**
- Remember to bring you response card to class
- Homework 6 due Wednesday, November 30, 11:59pm
- Final Exam: Monday, December 5, 10:30-12:30 (this room)

Review of the last class

- Observing exoplanet transits:
  - (A) — can’t give us the mass of exoplanets
  - (B) — can give us the mass of exoplanets, if we observe a secondary eclipse
  - (C) — can give us the mass of exoplanets, if there is more than one planet in the system and the time of transits change
  - (D) — can give us the mass of exoplanets, if there is more than one planet in the system and there is a secondary eclipse for each planet
  - (E) — We’ve never observed exoplanet transits

Review of the last class

- The most common size of planet found by the transit method (so far) is:
  - (A) — about the size of Jupiter
  - (B) — between the size of Jupiter and the size of Neptune
  - (C) — about the size of Neptune
  - (D) — between the size of Neptune and the size of Earth
  - (E) — about the size of Earth

Review of the last class

- A newly discovered exoplanet is found to be in its star’s habitable zone. Therefore:
  - (A) — The planet is an Earth twin
  - (B) — The planet contains water
  - (C) — The planet contains an atmosphere
  - (D) — The planet contains water and an atmosphere
  - (E) — The surface temperature of the planet, if it has an Earth-like atmosphere, is between 0-100 Celsius

Review of the last class

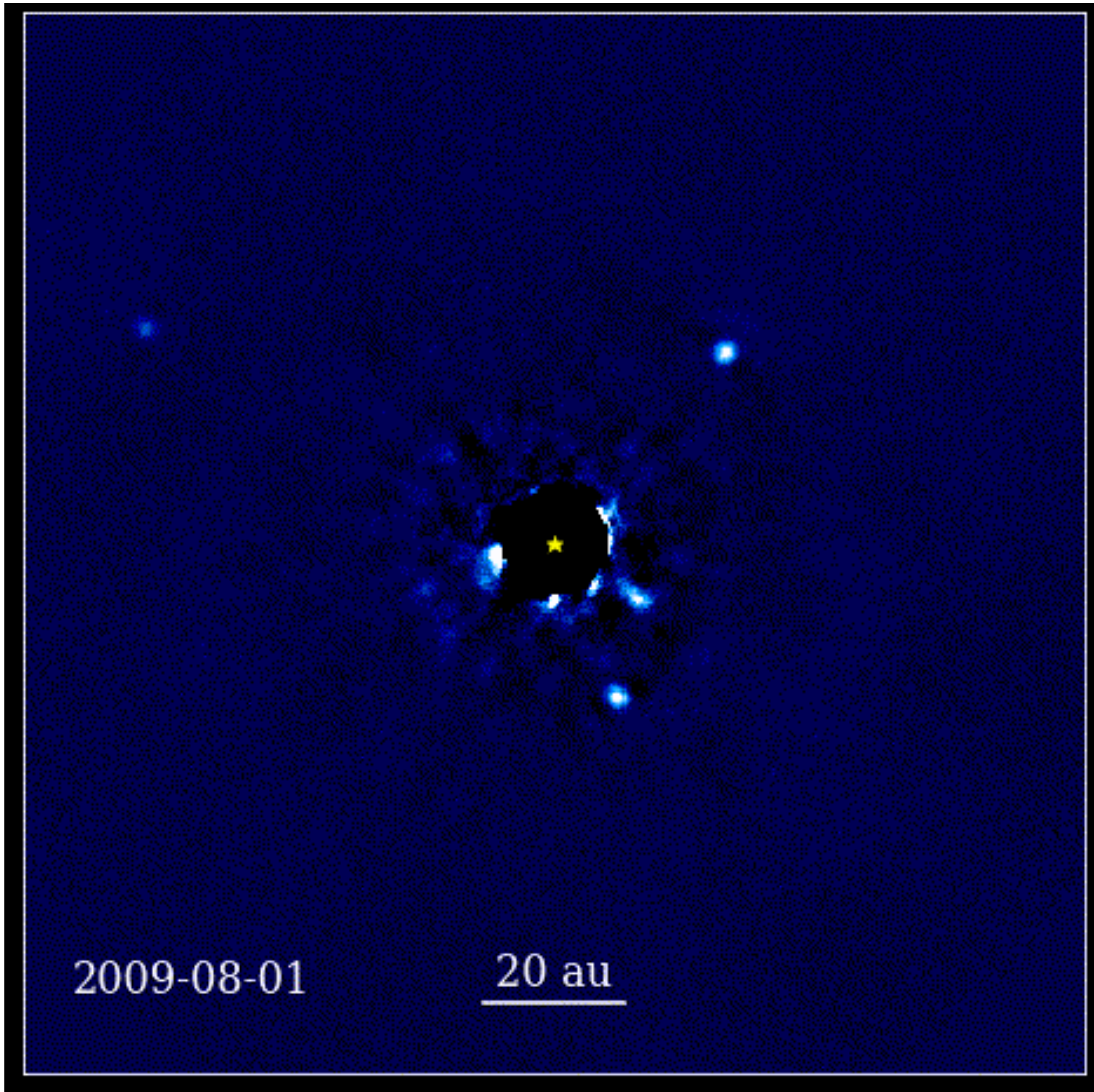
- An exoplanet with a 7-day orbital period:
  - (A) — Cannot be in its star’s habitable zone
  - (B) — Is definitely in its star’s habitable zone
  - (C) — Could be in its star’s habitable zone, if the star is an M star
  - (D) — Could be in its star’s habitable zone, if the star is a G star
  - (E) — Could be in its star’s habitable zone, if the star is a B star

Review of the last class

- An exoplanet orbits a star 10 pc from us, and the angular separation between star and planet is 0.5”. What is the projected physical separation between star and planet?

  - (A) — 20 AU
  - (B) — 5 AU
  - (C) — 1 AU
  - (D) — 0.2 AU
  - (E) — 0.05 AU

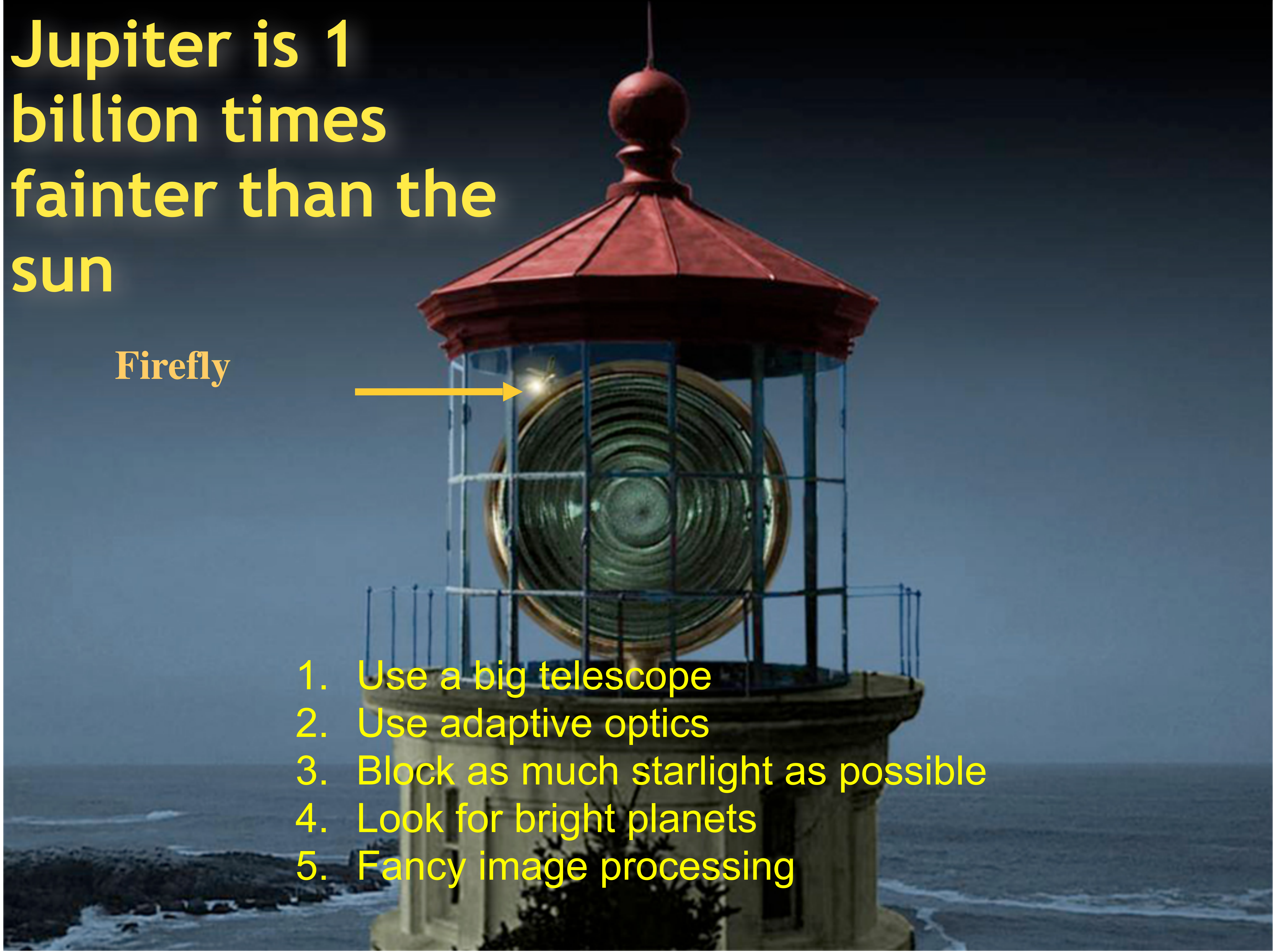
Direct Imaging



Movie from Jason Wang and Christian Marois


Directly
imaging
exoplanets

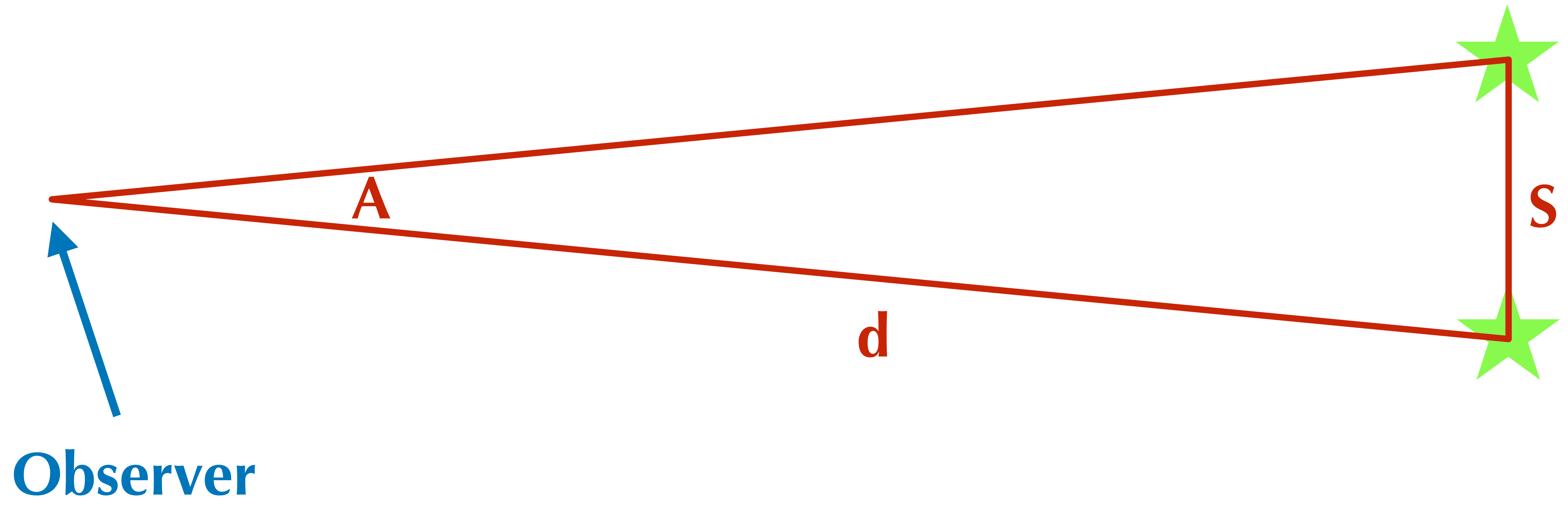
Jupiter is 1 billion times fainter than the sun



1. Use a big telescope
2. Use adaptive optics
3. Block as much starlight as possible
4. Look for bright planets
5. Fancy image processing

Angular Size

- When taking an image of something, a telescope measures separations in angular distance: the angle between two point source
  - For example, two stars in a binary system
- $A_{arcseconds} \approx \dfrac{S_{AU}}{d_{pc}}$



Telescope Resolution

- The resolution of a telescope is given by:

$$\theta_{min} \approx \frac{\lambda}{D}$$

- θ_{min}: minimum angular size that can be resolved, in radians

- λ: wavelength of light

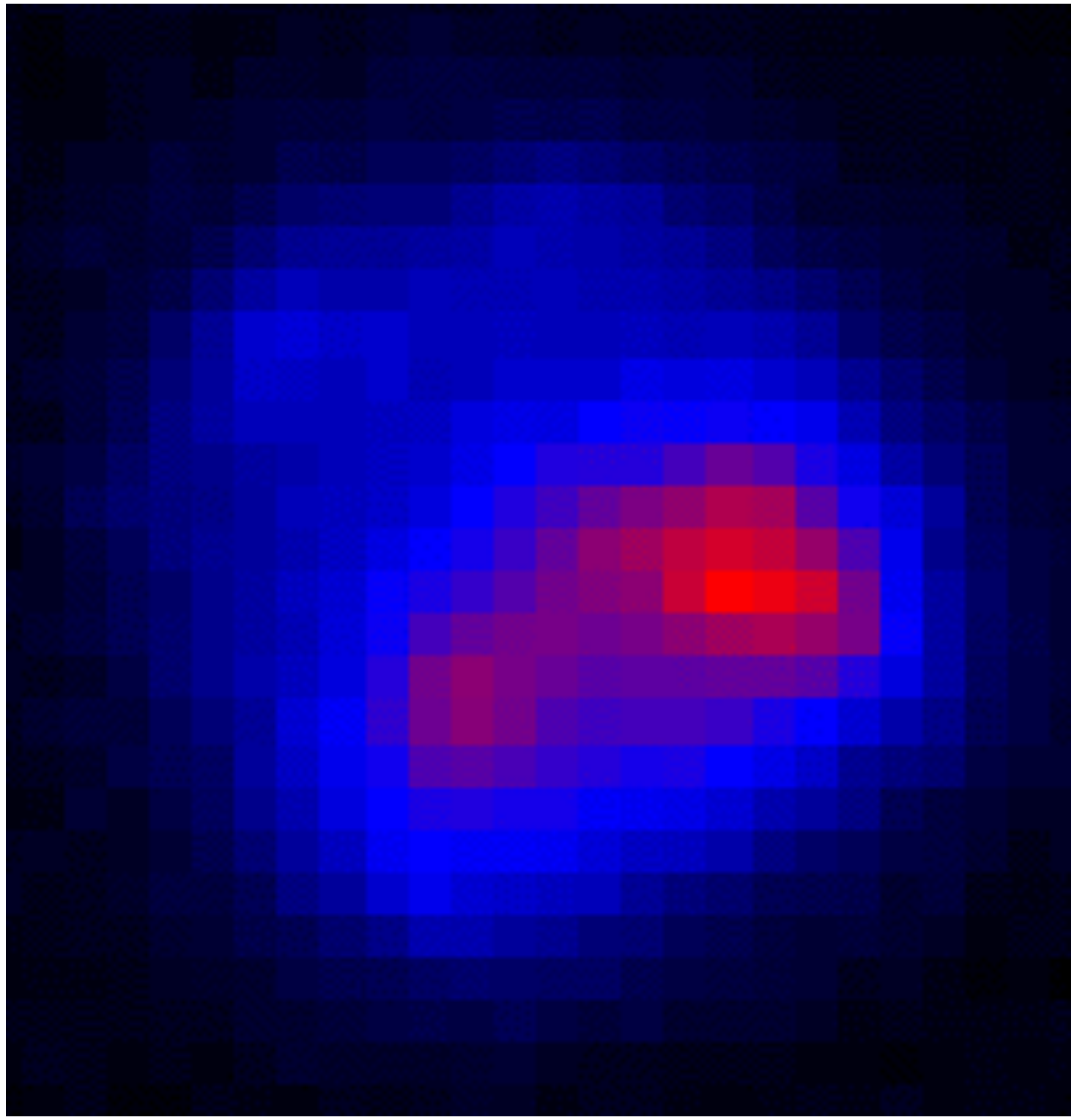
- D: diameter of the telescope's primary mirror

Telescope Resolution

- $\theta_{min} \approx \frac{\lambda}{D}$
- For the 10m Keck telescope in the near-infrared (1 micron):
- $\theta_{min} \approx \frac{10^{-6}m}{10m}\frac{206265''}{1radian} = 0.02'' = 20mas$

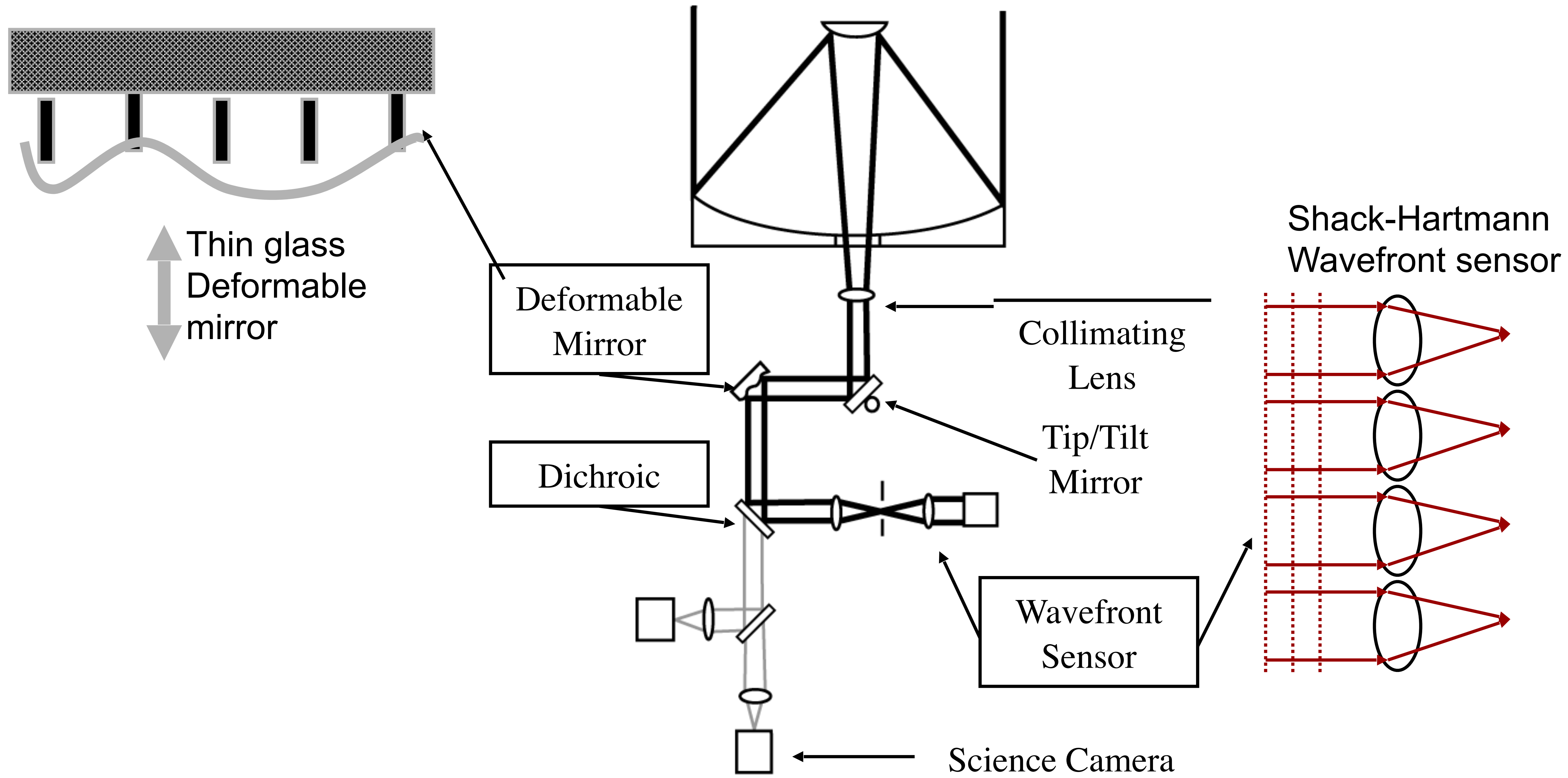
Telescope Resolution

- Turbulence in Earth's atmosphere limits resolution
- Typical "seeing" at a good site is 0.5"-1"
- A 10 meter telescope still has the collecting area of its large mirror, but the effective resolution of a much smaller telescope
- Can use "adaptive optics" to correct for distortion in the atmosphere

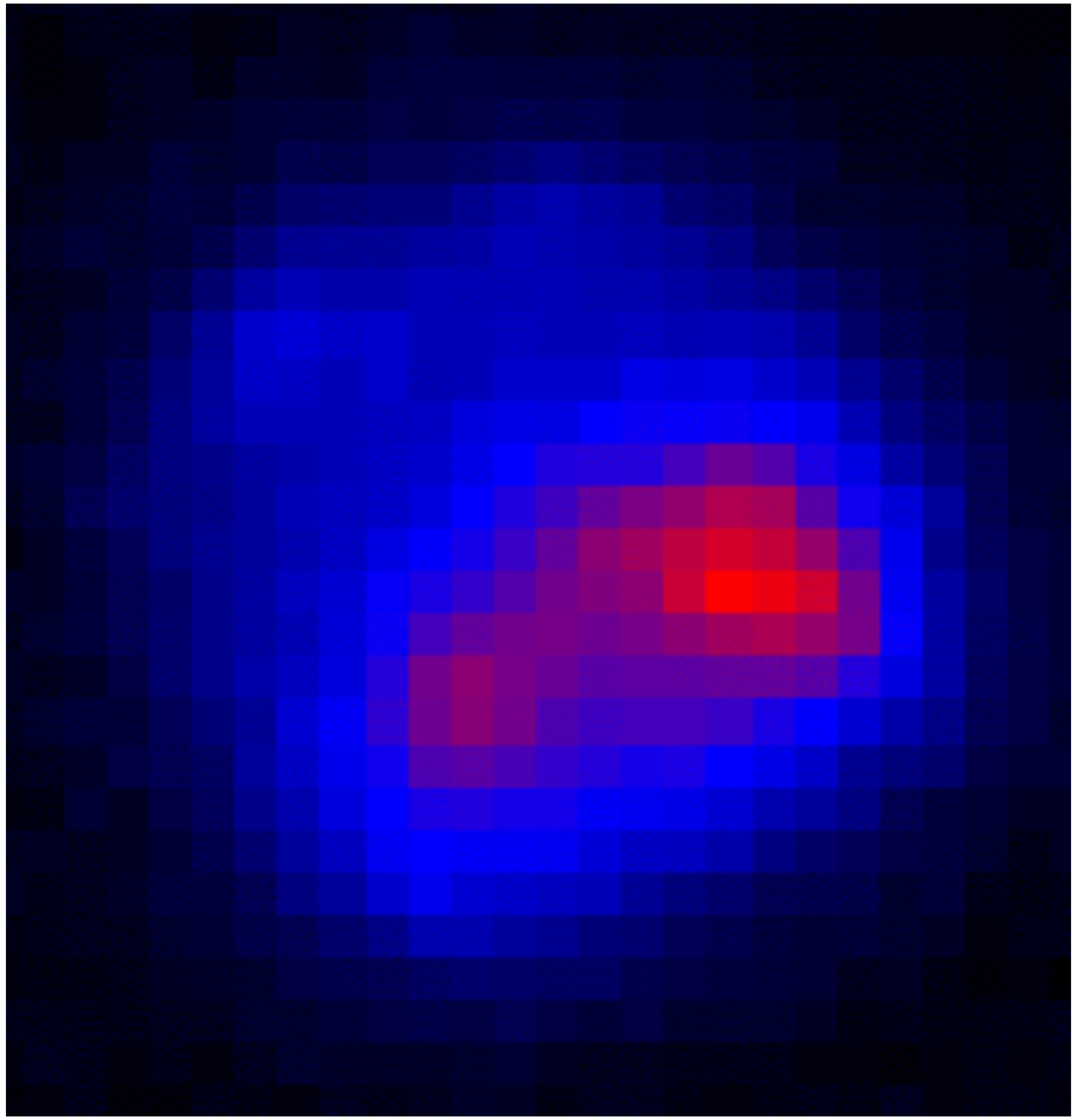


Adaptive Optics

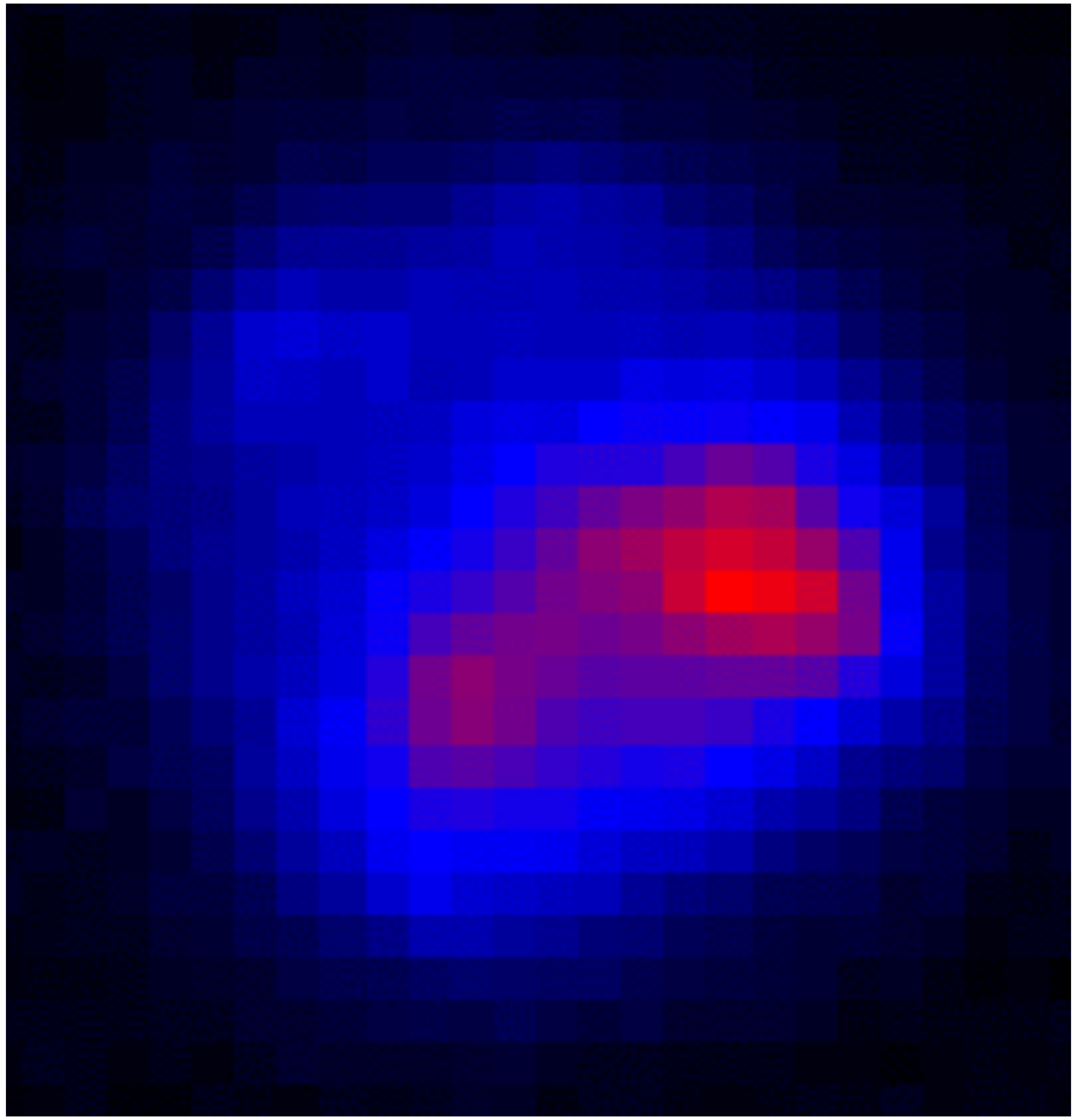
- Use a wavefront sensor to measure distortion in the atmosphere above telescope
- A deformable mirror changes shapes to correct distortion
    - Typically need to change shapes hundreds to thousands of times per second
- In the best cases, can restore resolution back to the diffraction limit



Adaptive Optics

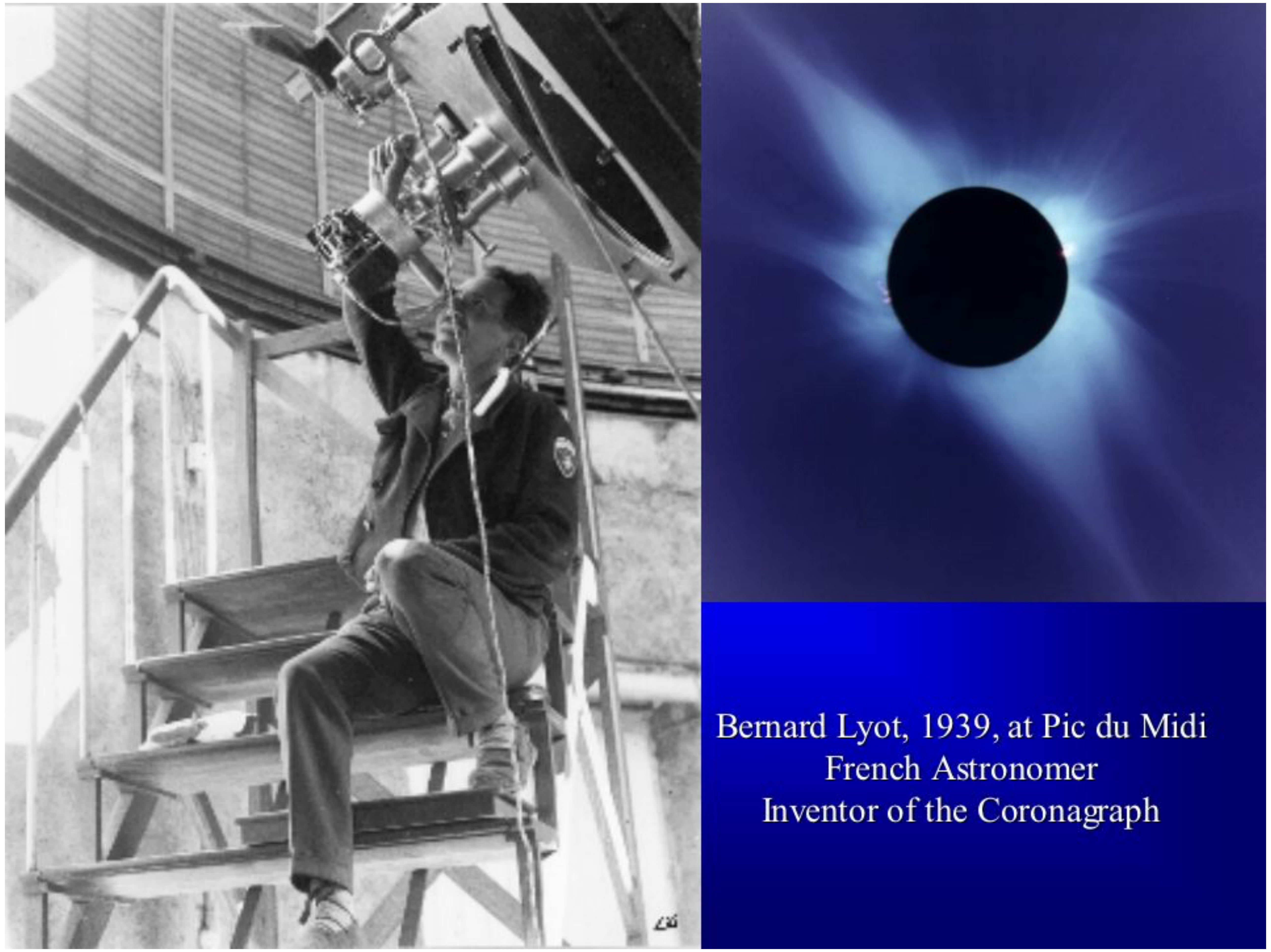


Adaptive Optics



Coronagraphs

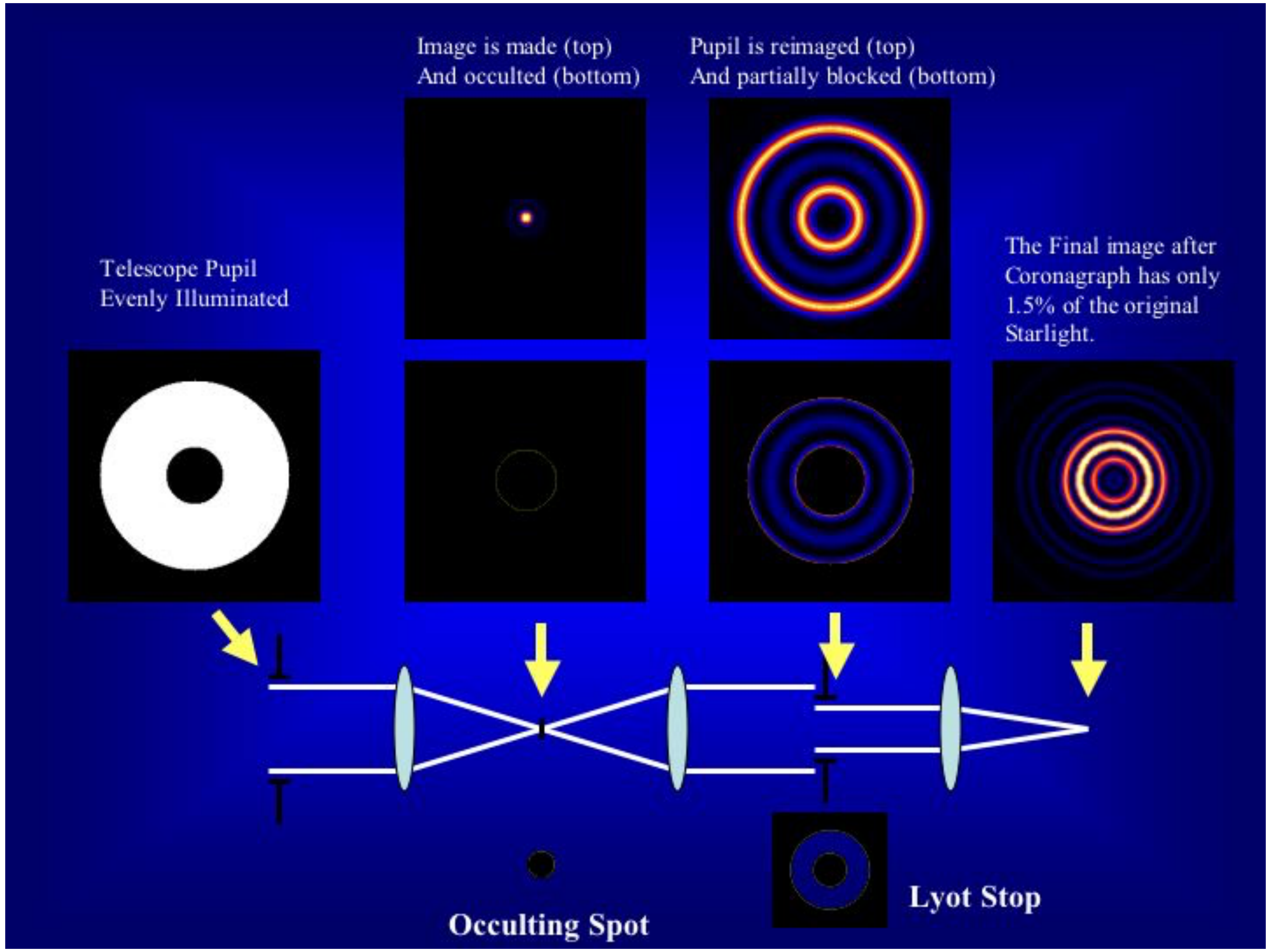
- Originally designed to block out the disk of the Sun to study the corona
    - Otherwise you have to wait for the next solar eclipse



Lyot Project

Coronagraphs

- Coronagraphs are built into high-contrast imagers to block out the bright star
    - Have to carefully design coronagraph to minimize diffraction of starlight around coronagraph



Lyot Project

Order of Magnitude: Planets in reflected light

- ~30% of the light that leaves Earth is reflected sunlight (mainly in the visible)

- Can estimate brightness ratio ("contrast ratio") between the Sun and the Earth

  - Compare surface area of a sphere at 1AU (total amount of solar output) to surface area of the Earth in cross section (amount of solar photons intercepted)

- Considering only reflected sunlight:

- (1) What is the brightness ratio between the Sun and the Earth in visible light?

- (2) What is the brightness ratio between the Sun and Jupiter in visible light?

Order of Magnitude: Planets in reflected light

- Considering only reflected sunlight:
- (1) What is the brightness ratio between the Sun and the Earth in visible light?
- $$C = 0.3\frac{\pi R_E^2}{4\pi d^2} \approx 0.3\left(\frac{6000km}{2x1.5x10^8km}\right)^2 = 0.3\left(\frac{6x10^3km}{3x10^8km}\right)^2 = 0.3(2x10^{-5})^2 = 0.3x4x10^{-10} = 1x10^{-10}$$
- One part in 10 billion!
- (2) What is the brightness ratio between the Sun and Jupiter in visible light?
- Same problem, but swap in the radius of Jupiter (10x that of Earth) and the larger semi-major axis of Jupiter (5x that of Earth), and assume the albedo stays about the same:
- $$\frac{C_J}{C_E} = \left(\frac{R_J}{R_E}\frac{d_E}{d_J}\right)^2 = \left(\frac{10}{1}\frac{1}{5}\right)^2 = 2^2 = 4$$
- Jupiter is 4 times brighter than Earth, or $4x10^{-10}$ 4 parts in 10 billion!

Break

Planets in reflected light

- Earth is ~10 billion times fainter than the Sun in reflected light

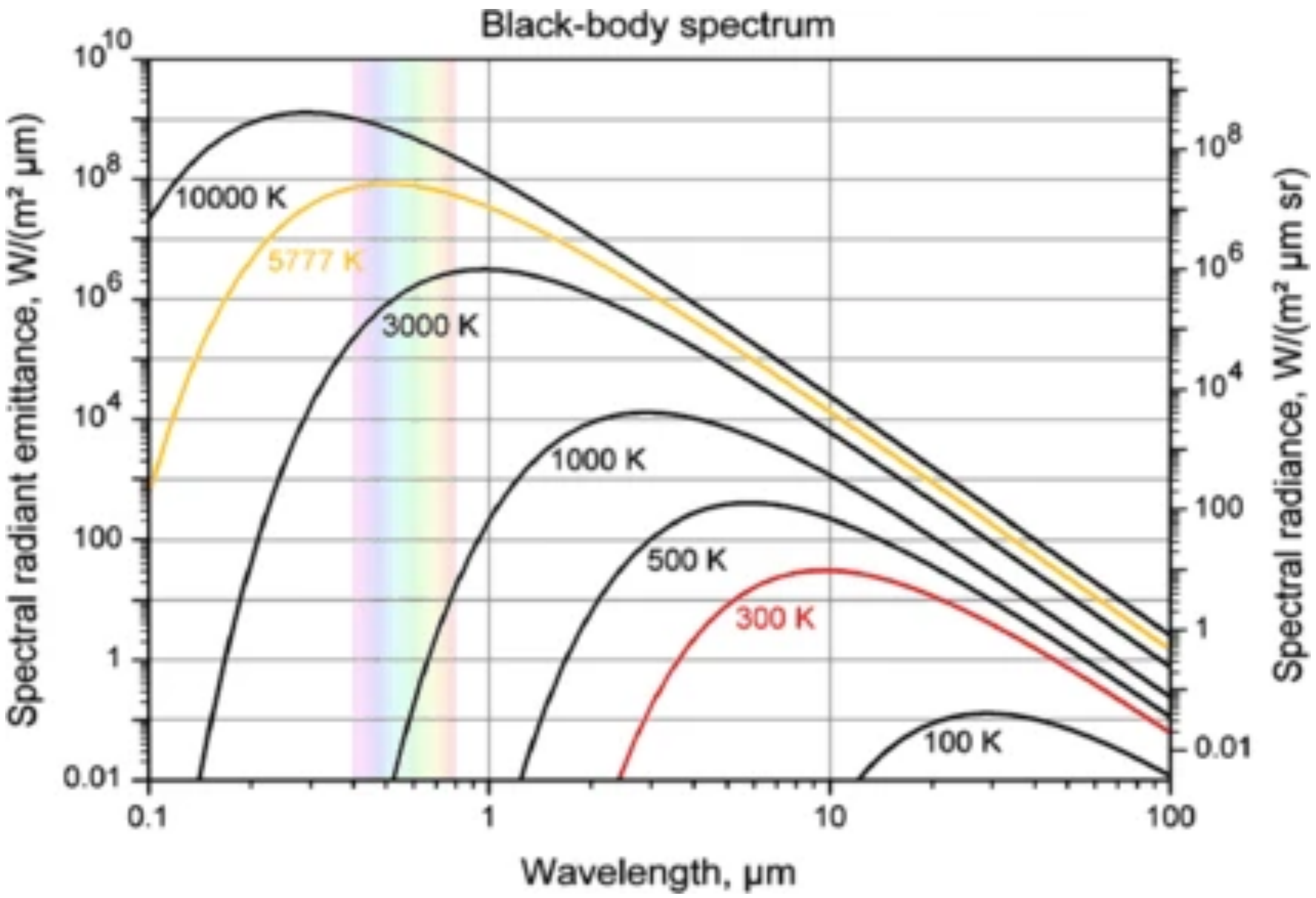
- At 10 pc, an Earth-like planet is only 0.1” from its star

- That contrast at that separation can only be done with a custom-built space telescope with an aperture of at least a few meters

- What if we found brighter planets?

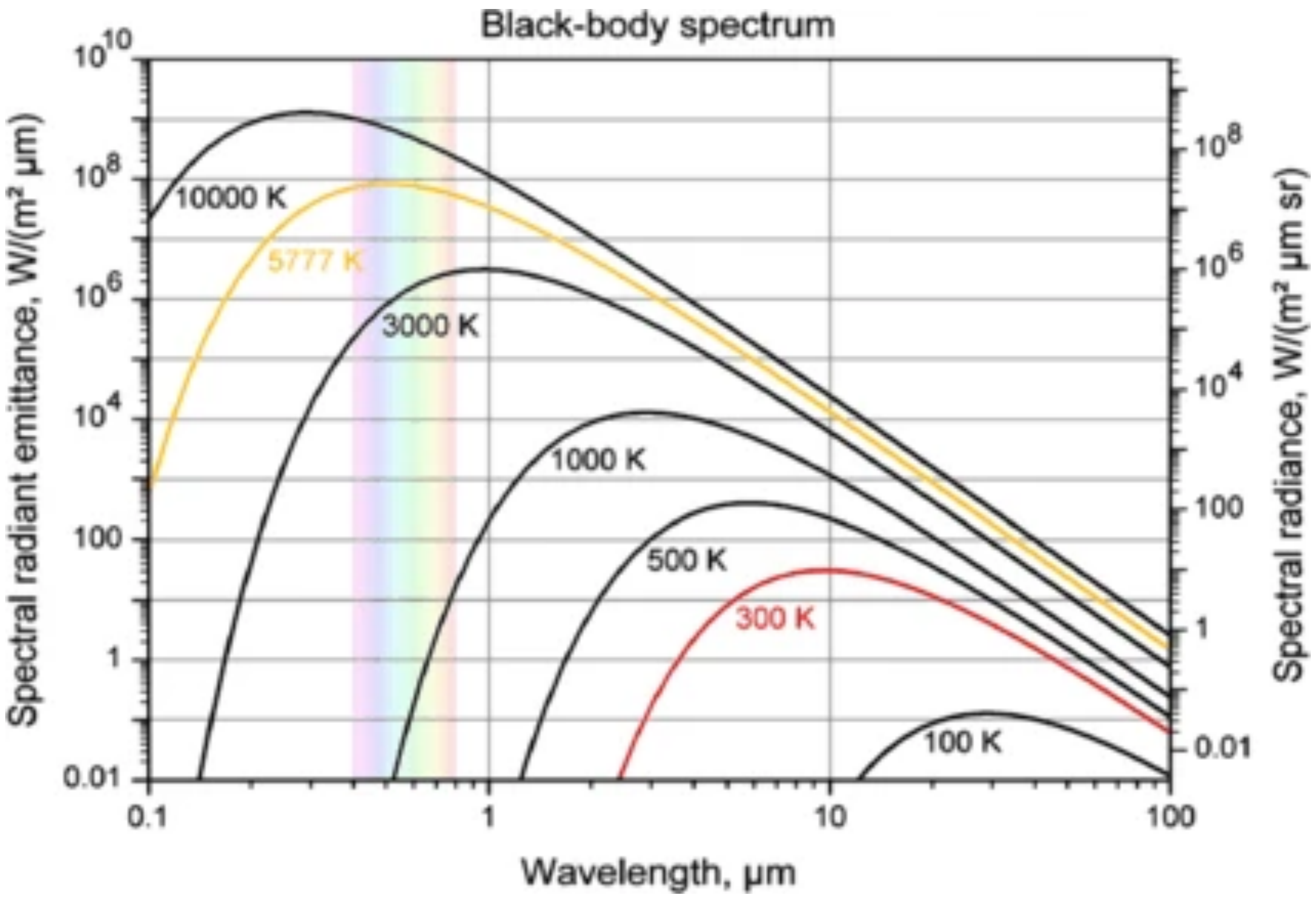
Planets in emitted light

- Blackbodies:
  - Hotter planets emit more light
  - The peak of the emission moves blueward with increasing temperature
- (Planets aren't blackbodies due to molecular absorption, but the overall trend is correct)



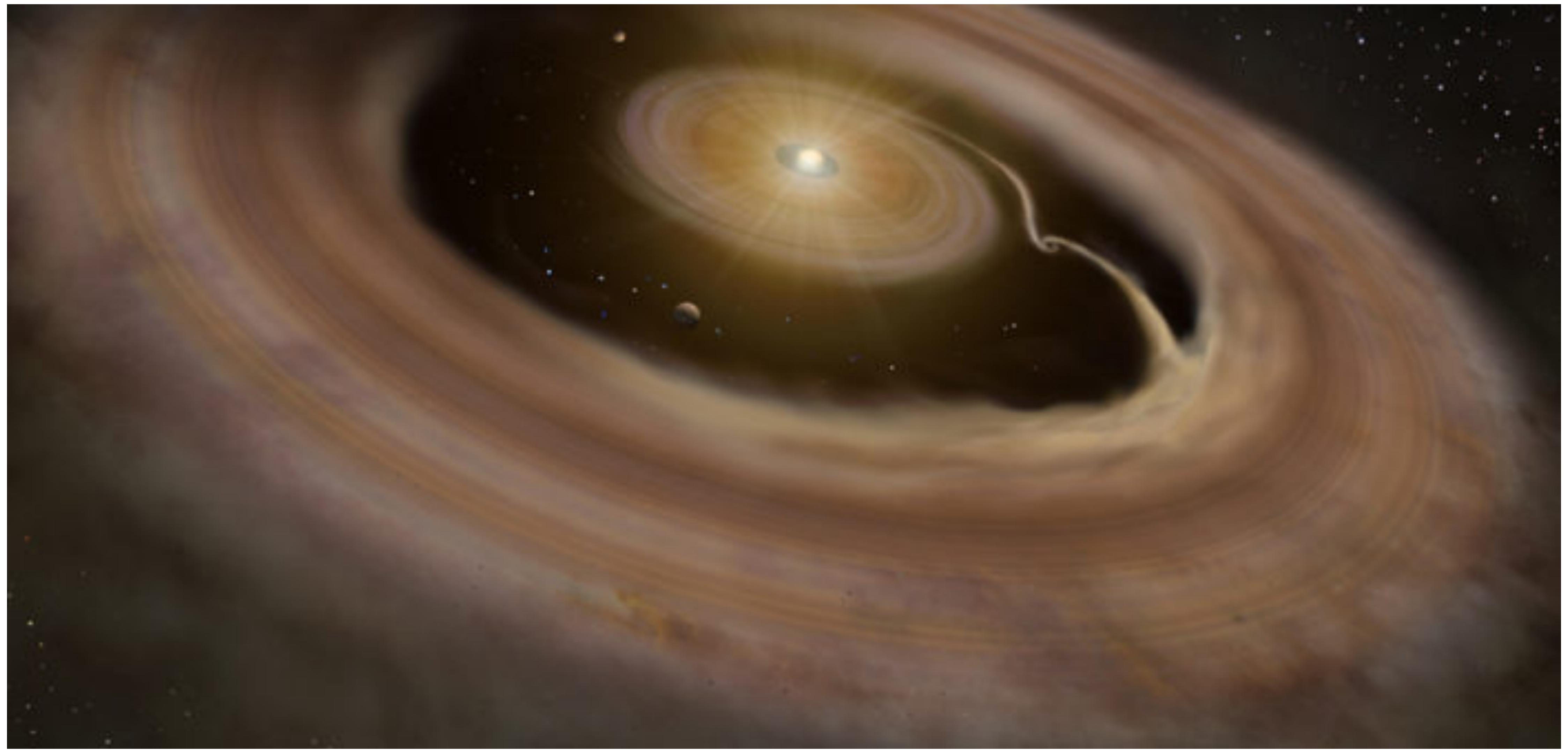
Planets in emitted light

- Emitted luminosity depends on both temperature and size of the planet:
    - $L = \sigma T_{eff}^4 x 4\pi R^2$
- Contrast ratio between star and a hot planet is more favorable in the infrared than in the optical



Young Planets are Hot (and bright)

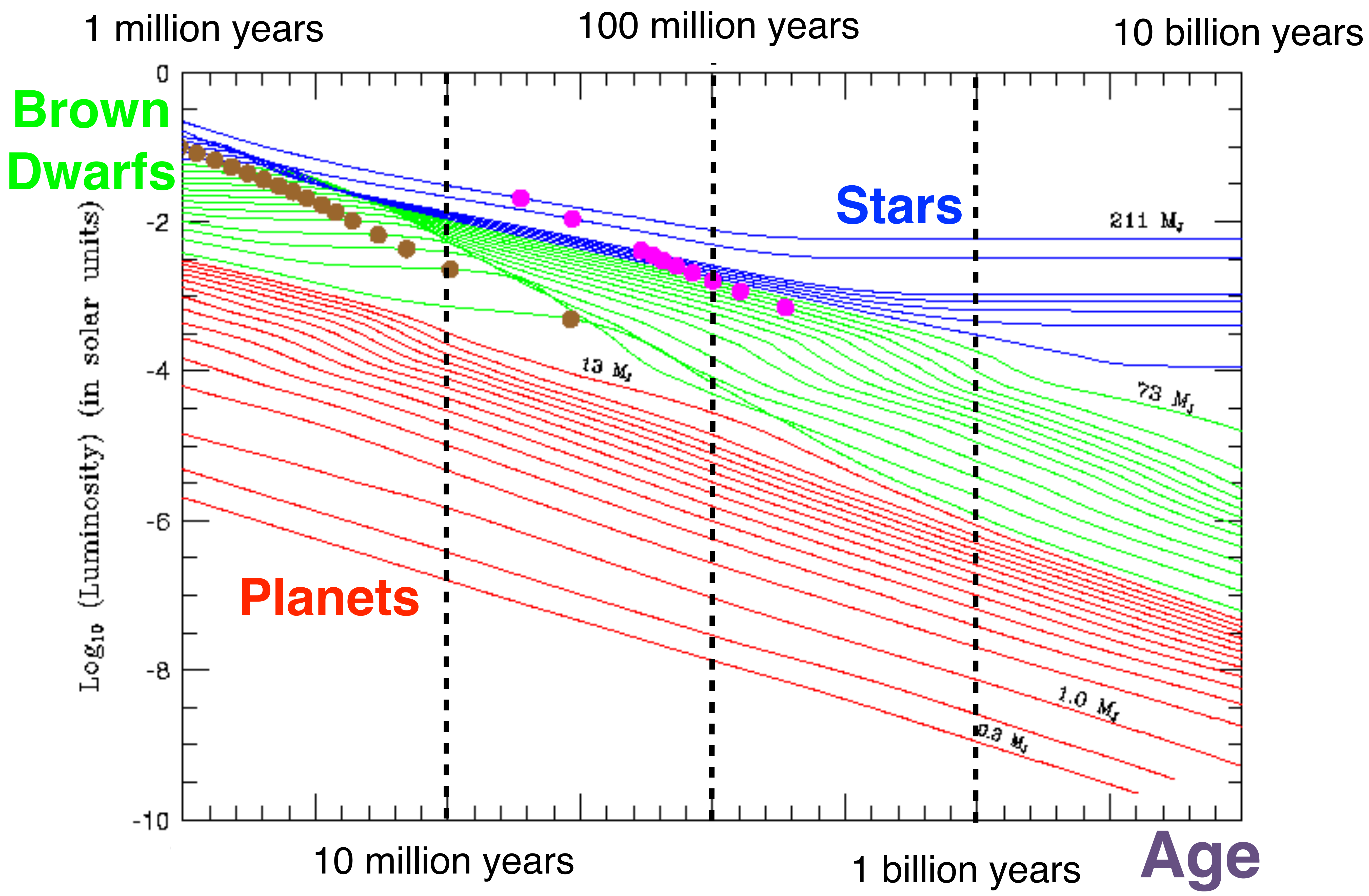
- Planets form in a disk
- Material is spread out to large distances, then brought together into a small volume
- Gravitational potential energy is lost
- To conserve energy, the newly-formed planet is very hot
    - And hot things are bright



The Graduate Institute for Advanced Studies/NOAJ

Young Planets are Hot (and bright)

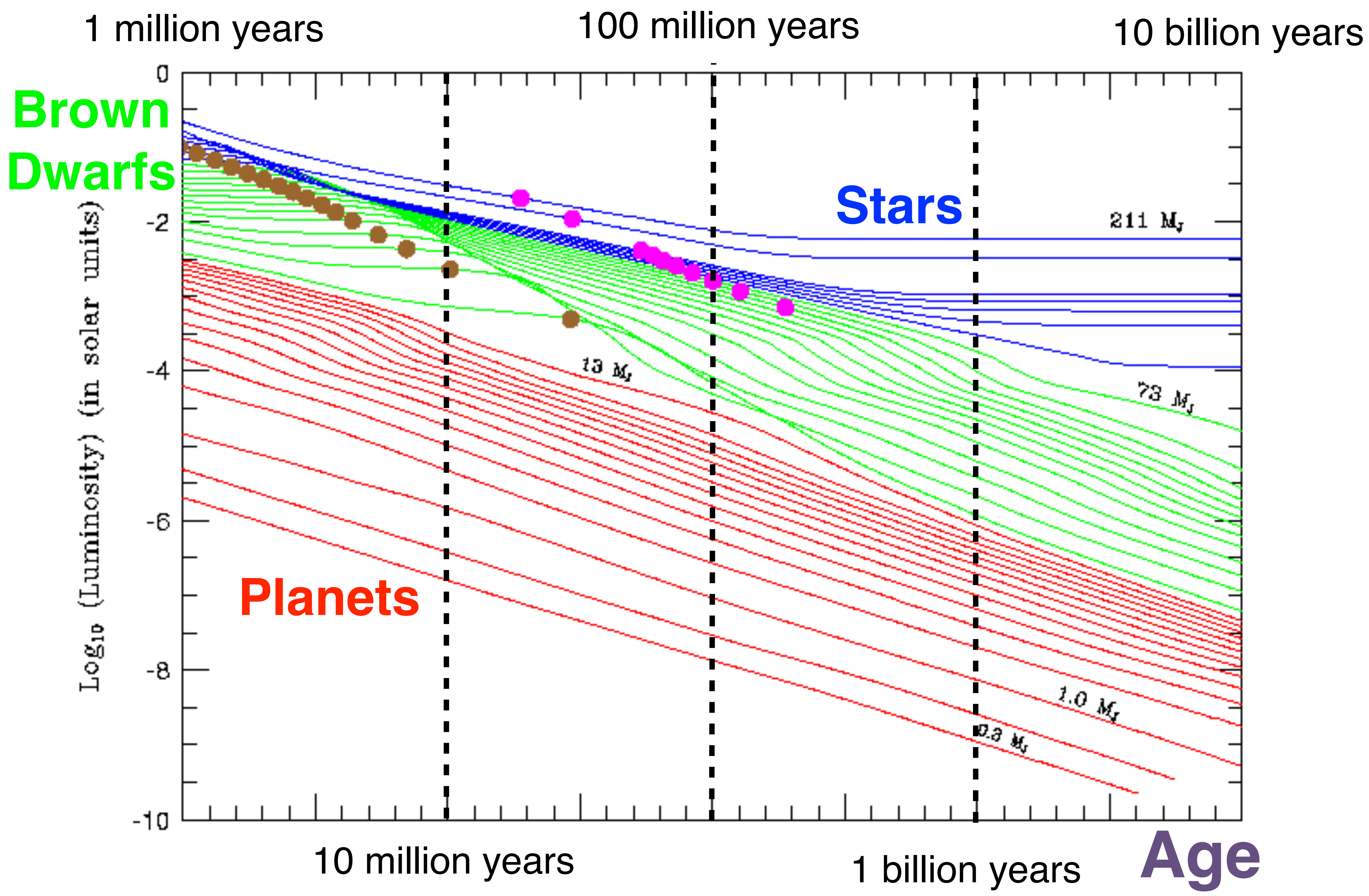
- Low mass stars, brown dwarfs, and giant planets form hot, then contract and cool (getting fainter)
- The cores of stars get hot enough to fuse hydrogen into helium, and stop contracting



Adam Burrows

Young Planets are Hot (and bright)

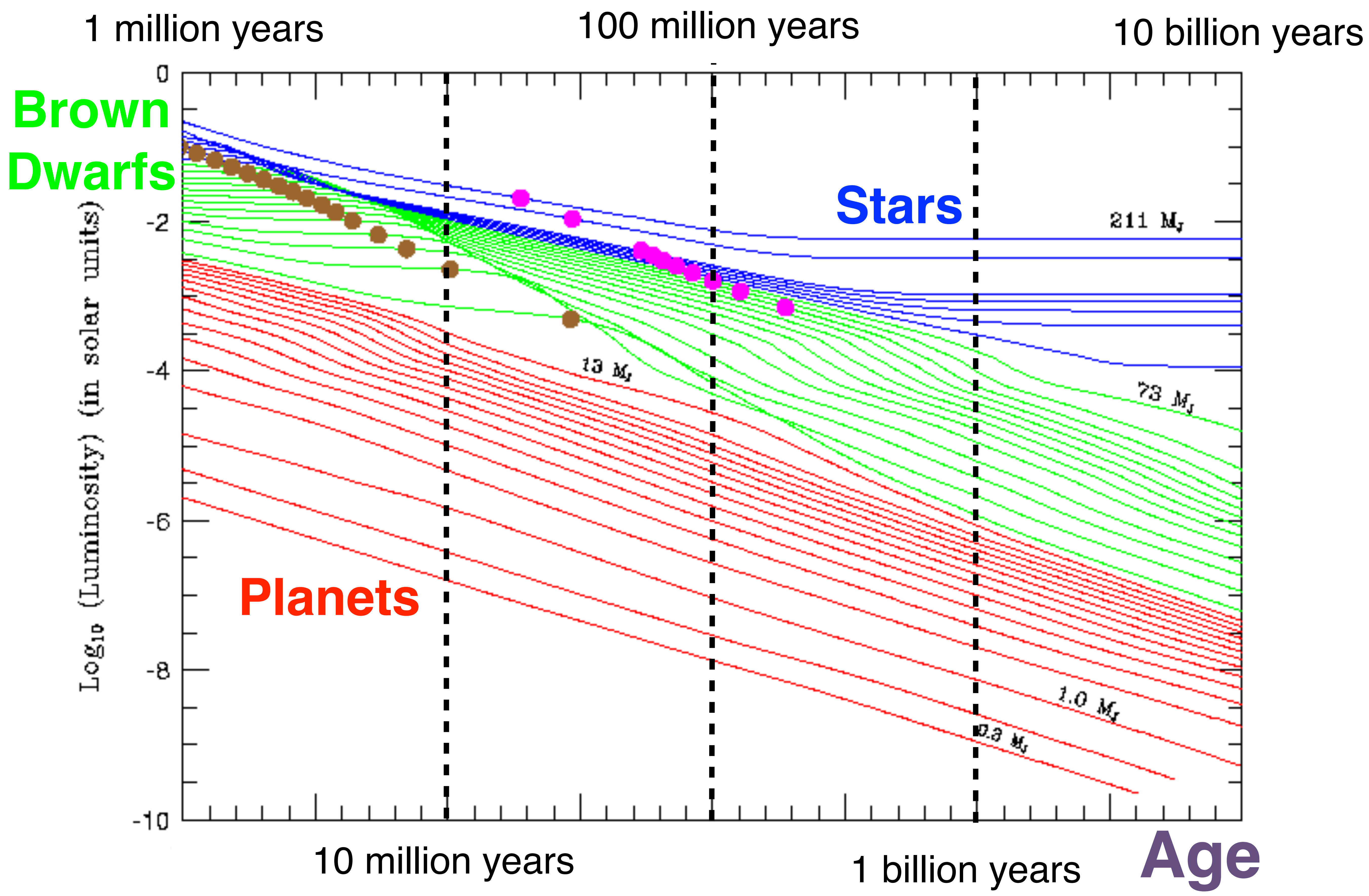
- The cores of brown dwarfs (13 M_{Jup}-75 M_{Jup}) will get hot enough to fuse deuterium
  - they don't have much deuterium, so they go back to collapsing and cooling
- Giant planets (below 13 M_{Jup}) never even fuse deuterium, just collapse and cool over time



Adam Burrows

Young Planets are Hot (and bright)

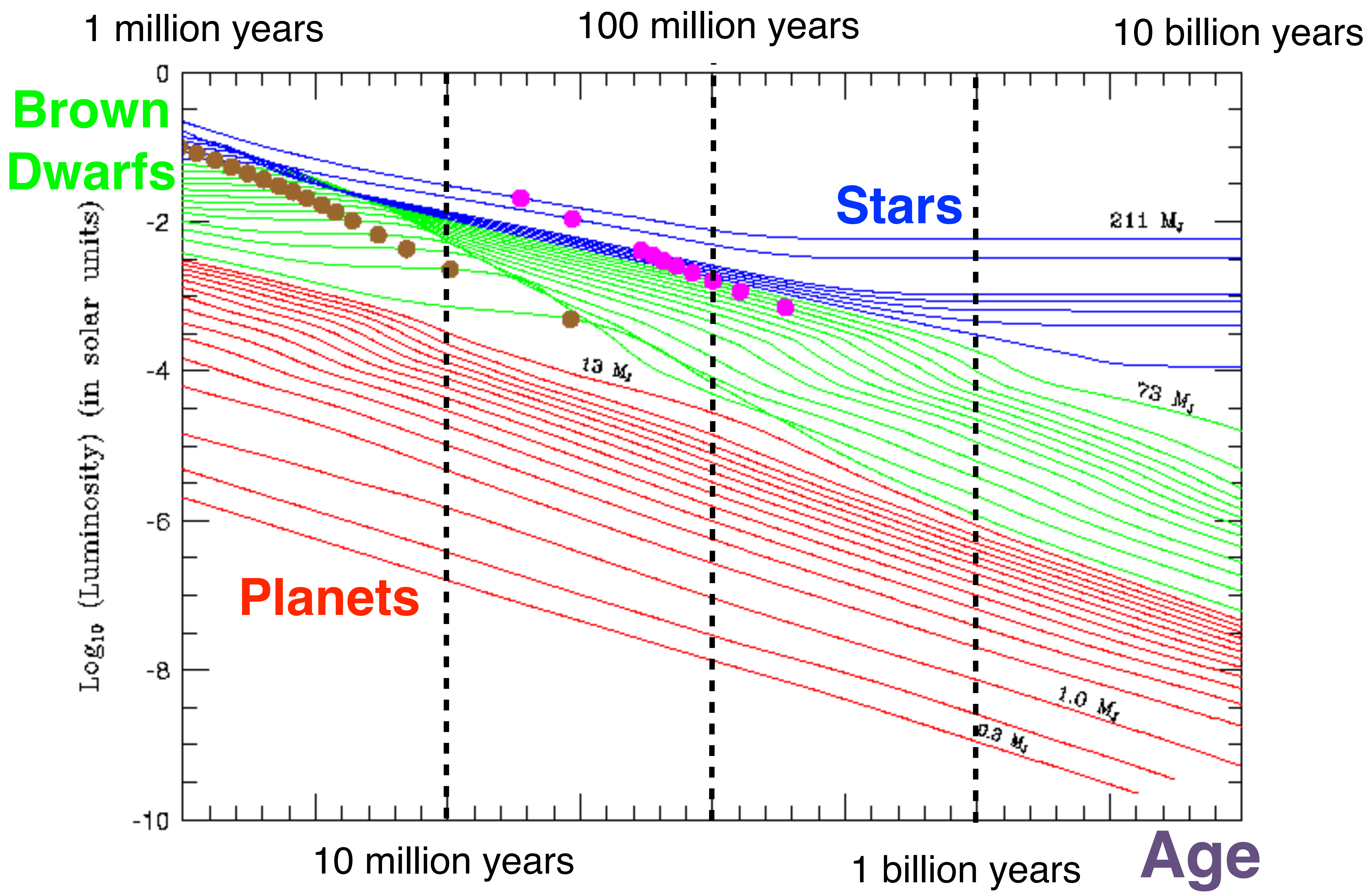
- Collapse of brown dwarfs and giant planets eventually halted by electron degeneracy pressure
    - Will stop contracting, but will keep cooling
- Objects between 1 and 100 M_{Jup} (very low-mass stars, brown dwarfs, giant planets) are all about the same size: ~1 R_{Jup}
    - So mainly temperature that sets luminosity



Adam Burrows

Young Planets are Hot (and bright)

- Younger planets are brighter (haven't cooled off yet)
- More massive planets are brighter (started with higher temperatures)
- Can find brighter (easier-to-detect) planets by looking around young stars
    - Less than ~100 Myr

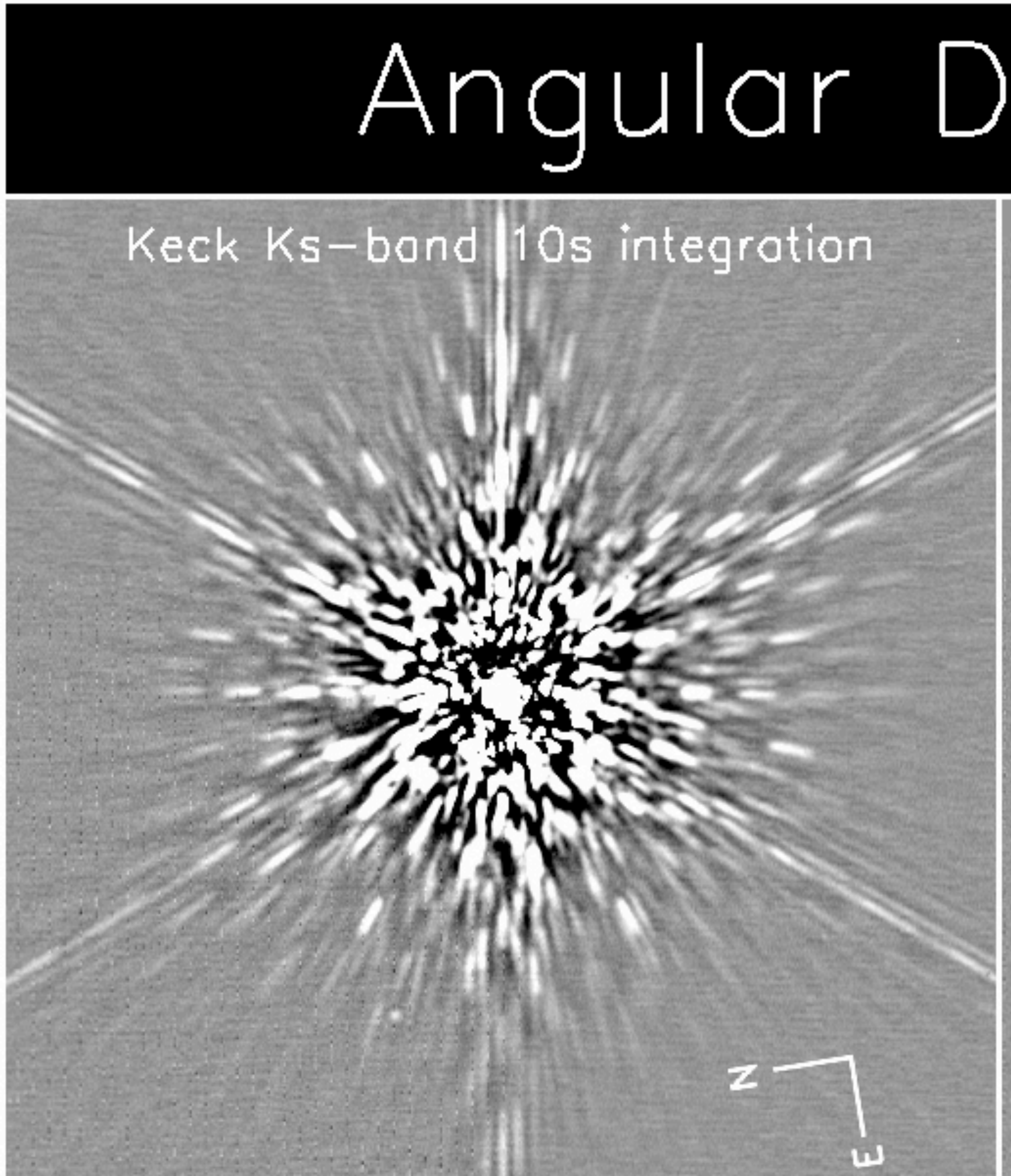


Adam Burrows

Image Processing

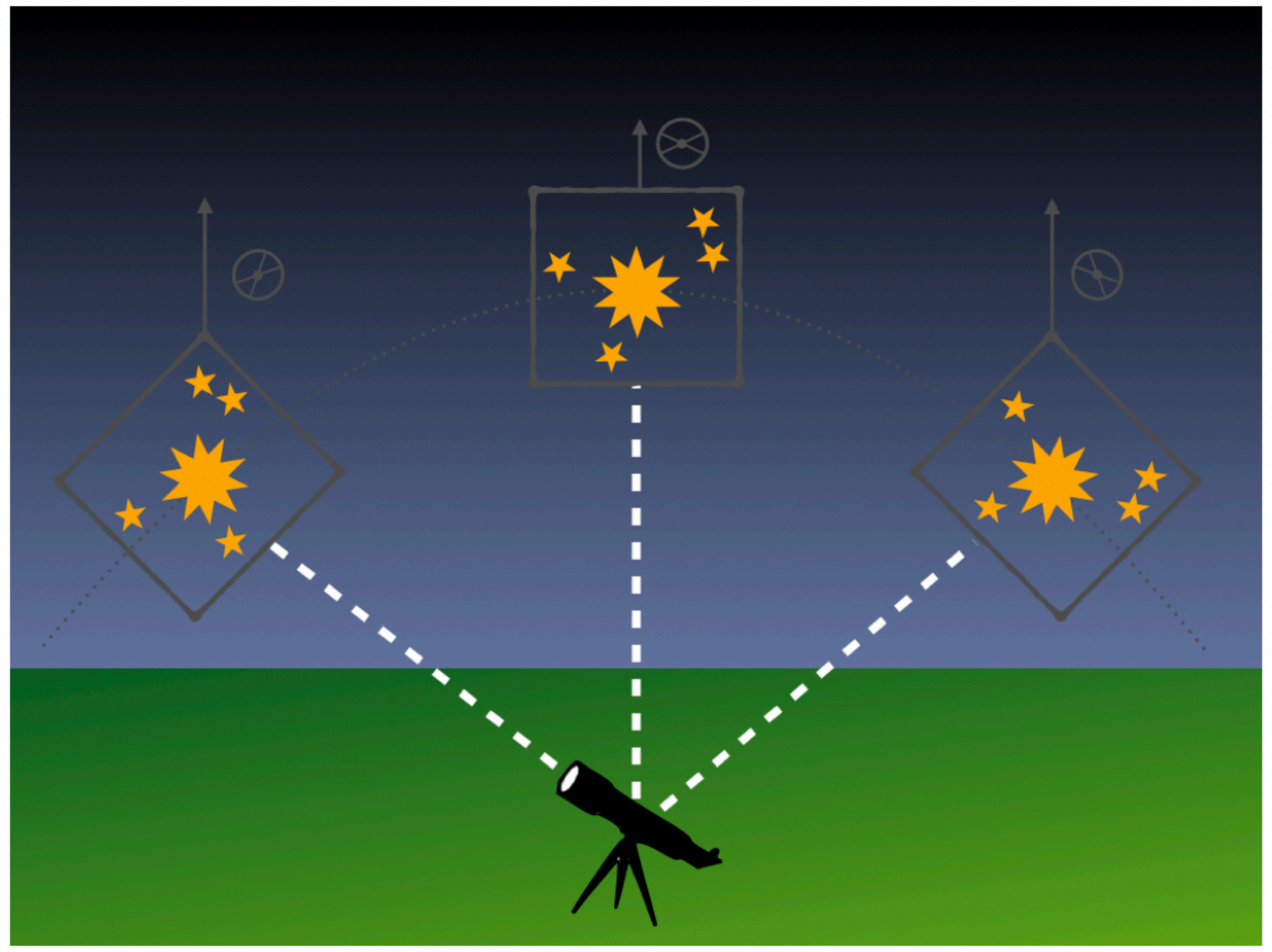
- Optics aren't perfect, and some residual starlight makes it into the image
  - PSF: Point spread function
- "Speckles" are diffraction-limited blobs made out of starlight that complicate searches for planets
  - Have timescales of ~hours
  - Change and move as instrument changes temperature, telescope moves
- Solution is "Differential Imaging"
  - Have almost-identical images of the PSF, one with the planet one without, and subtract

Christian Marois

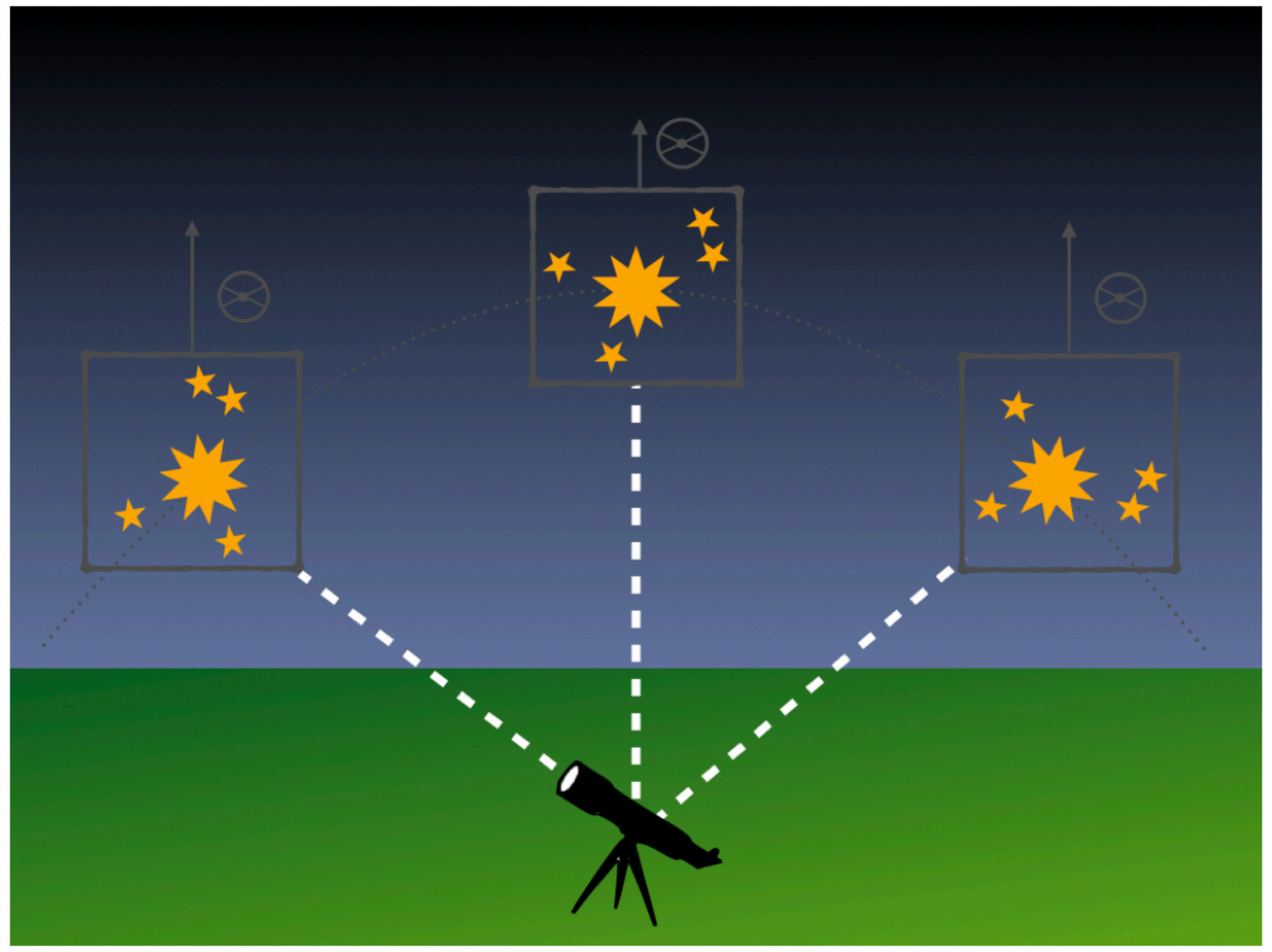


Angular Differential Imaging

- As a telescope tracks an object across the sky, the field of view rotates
- Most imaging instruments have a derotator, so the image stays fixed on the detector
- Turning the derotator off means the planet is in a slightly different part of your image in each subsequent exposure
- Speckles, residual starlight, are created by your instrument, so they don't move as the sky rotates



(a) Normal Telescope Rotation



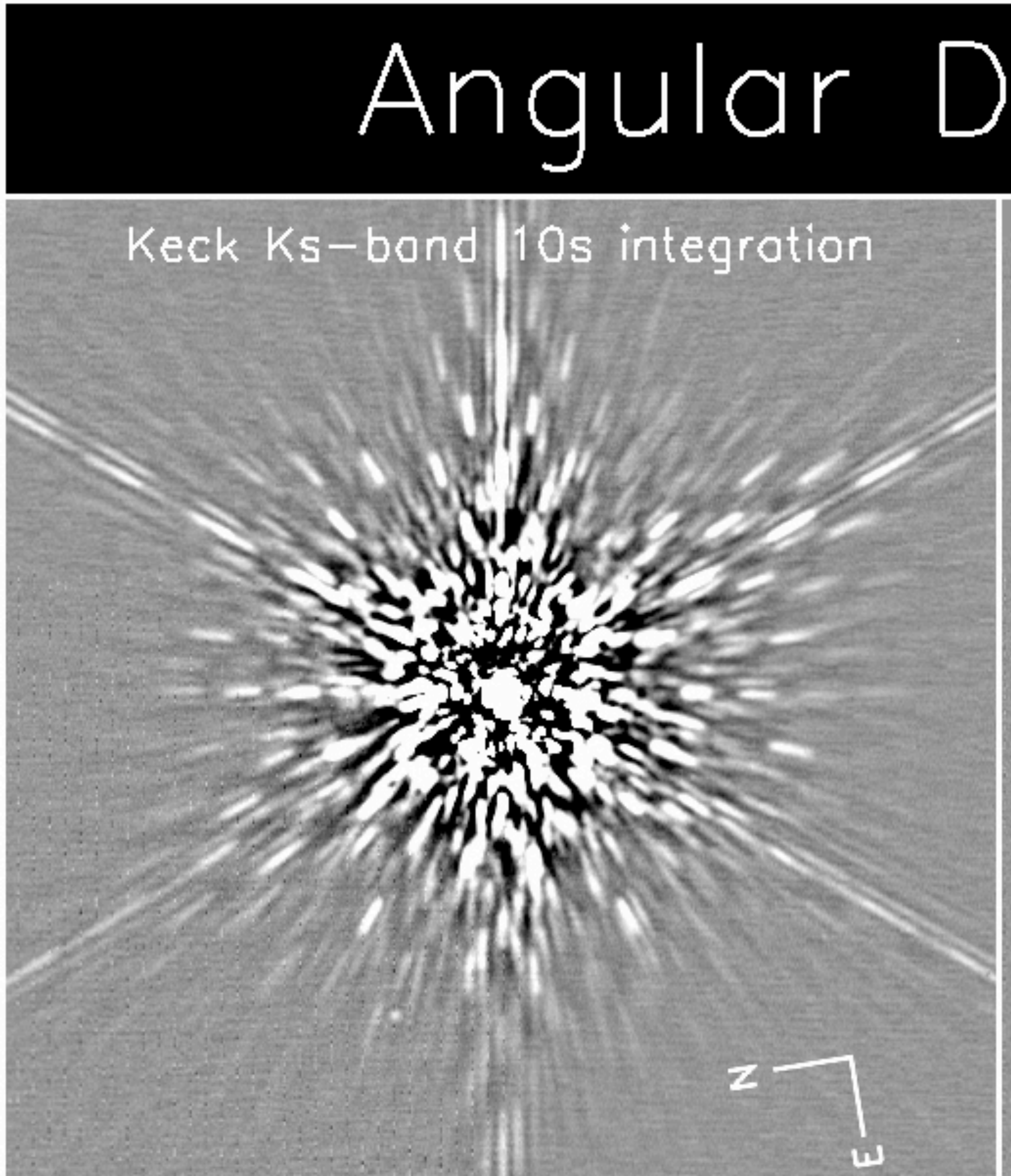
(b) ADI without Telescope Rotation

Johnson-Groh 2017

Christian Marois

Image Processing

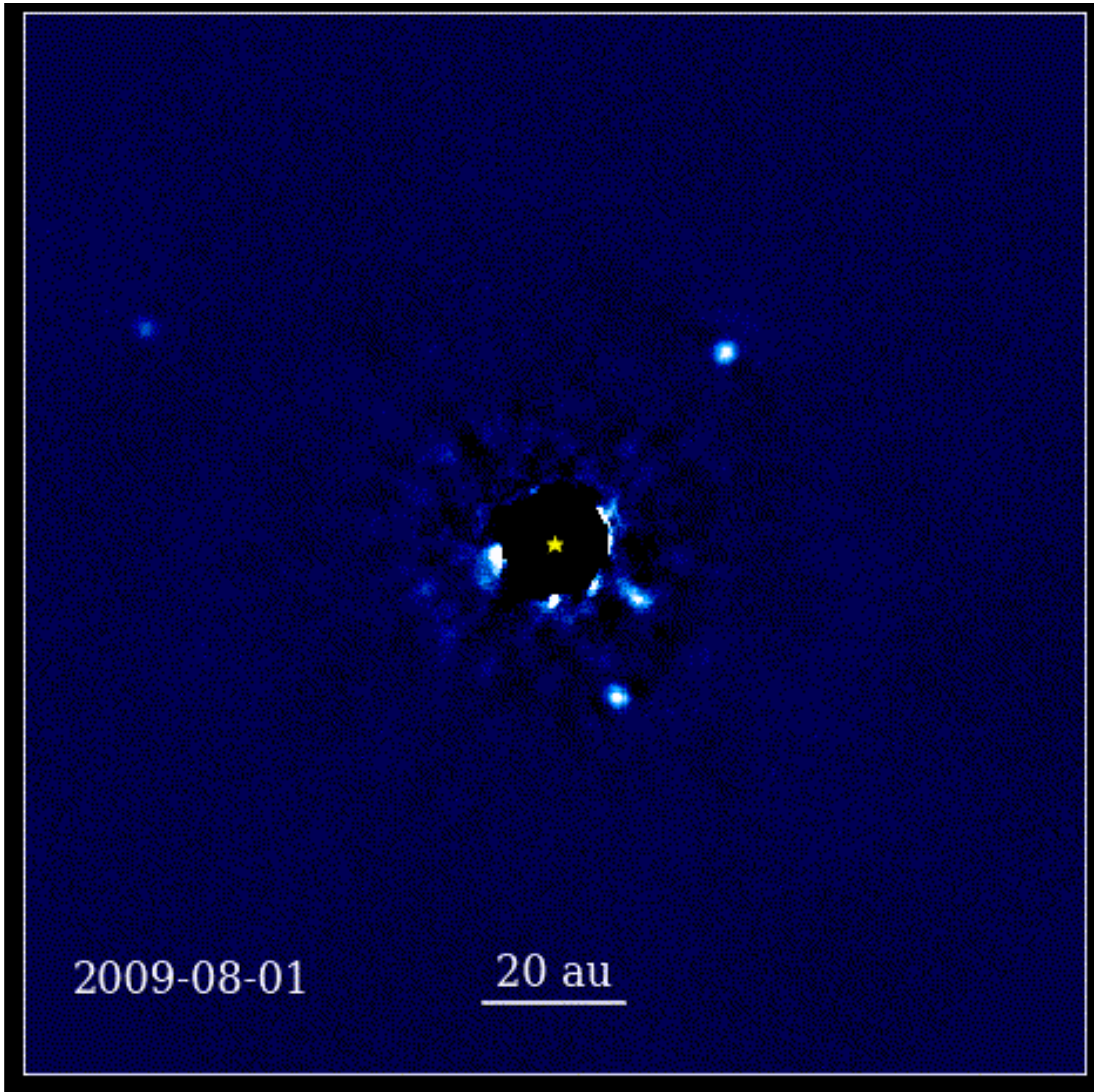
- Other types of differential imaging:
  - Spectral Differential Imaging (SDI): two narrow filters that observe inside and outside a molecular absorption band
  - Reference Differential Imaging (RDI): Observe another star quickly after observing your star
  - Polarmetric Differential Imaging (PDI): If the planet is seen in reflected light, you'd expect the light from the planet to be polarized



Christian Marois

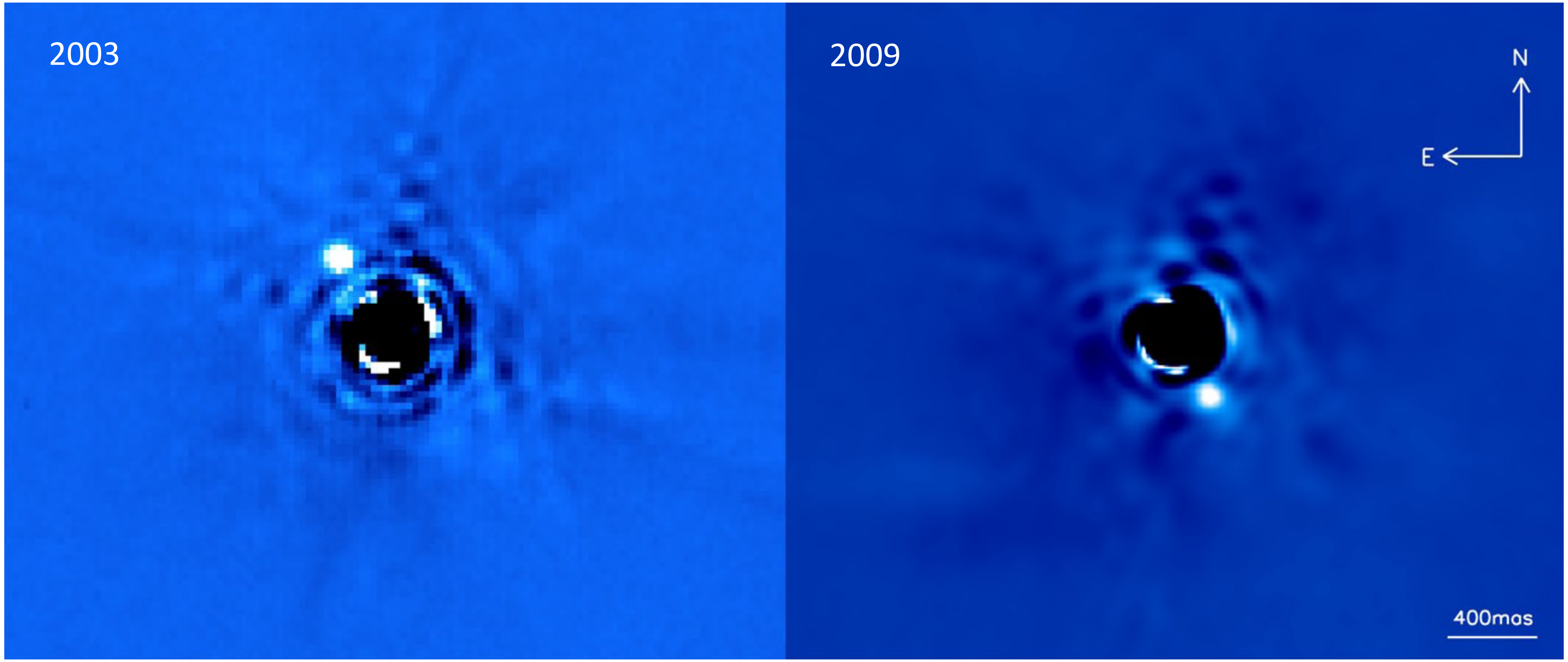
HR 8799 bcde

- Young star: 40 Myr
- Higher-mass host star: ~1.5 solar masses
- 4 planets detected (Marois et al. 2008, Marois et al. 2010)
- 5-7 Jupiter masses
    - Contrast ratio of 10^{-4}
- Semi-major axis of ~15, 25, 40, 70 AU

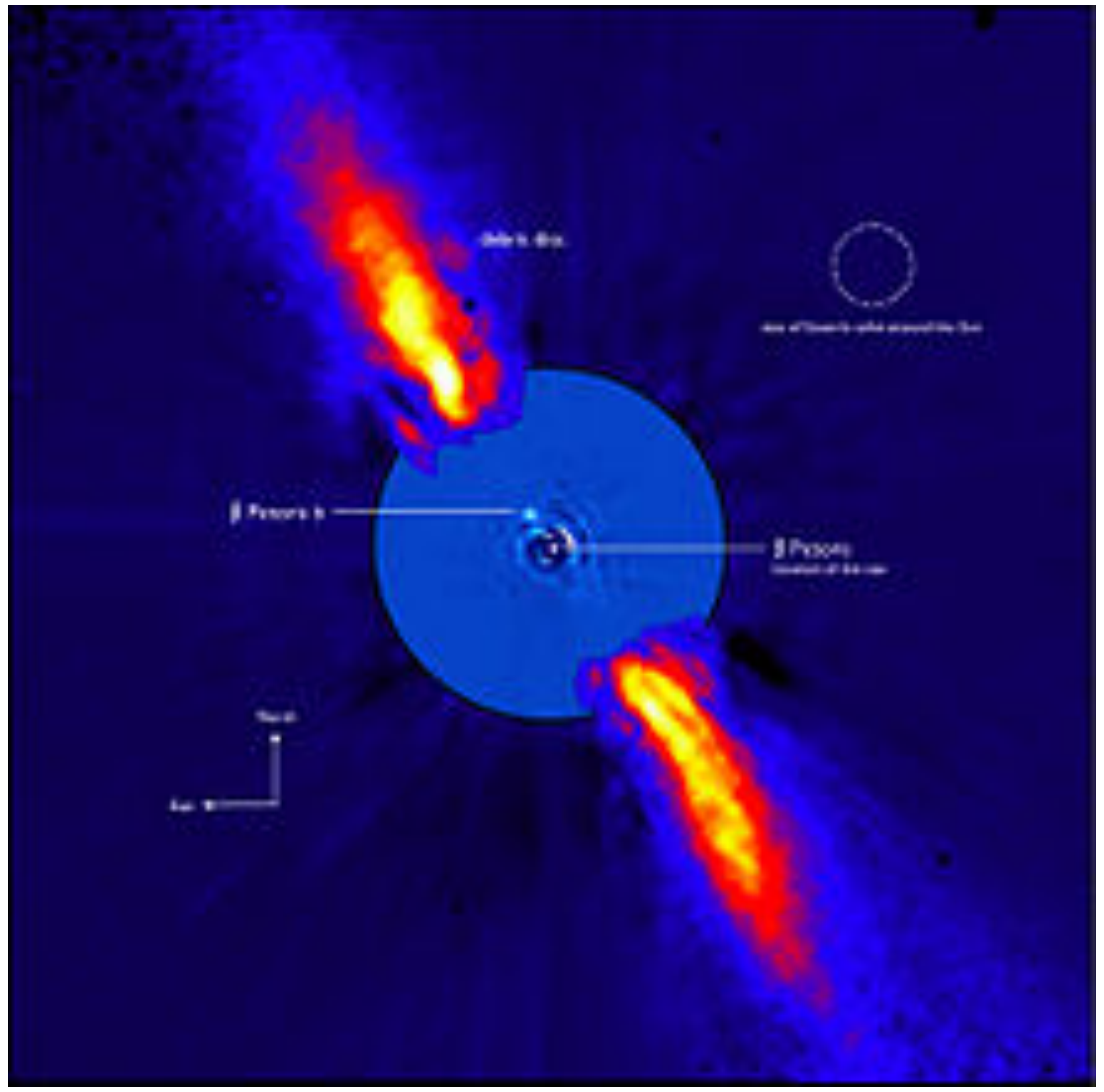


Movie from Jason Wang and Christian Marois

beta Pictoris b

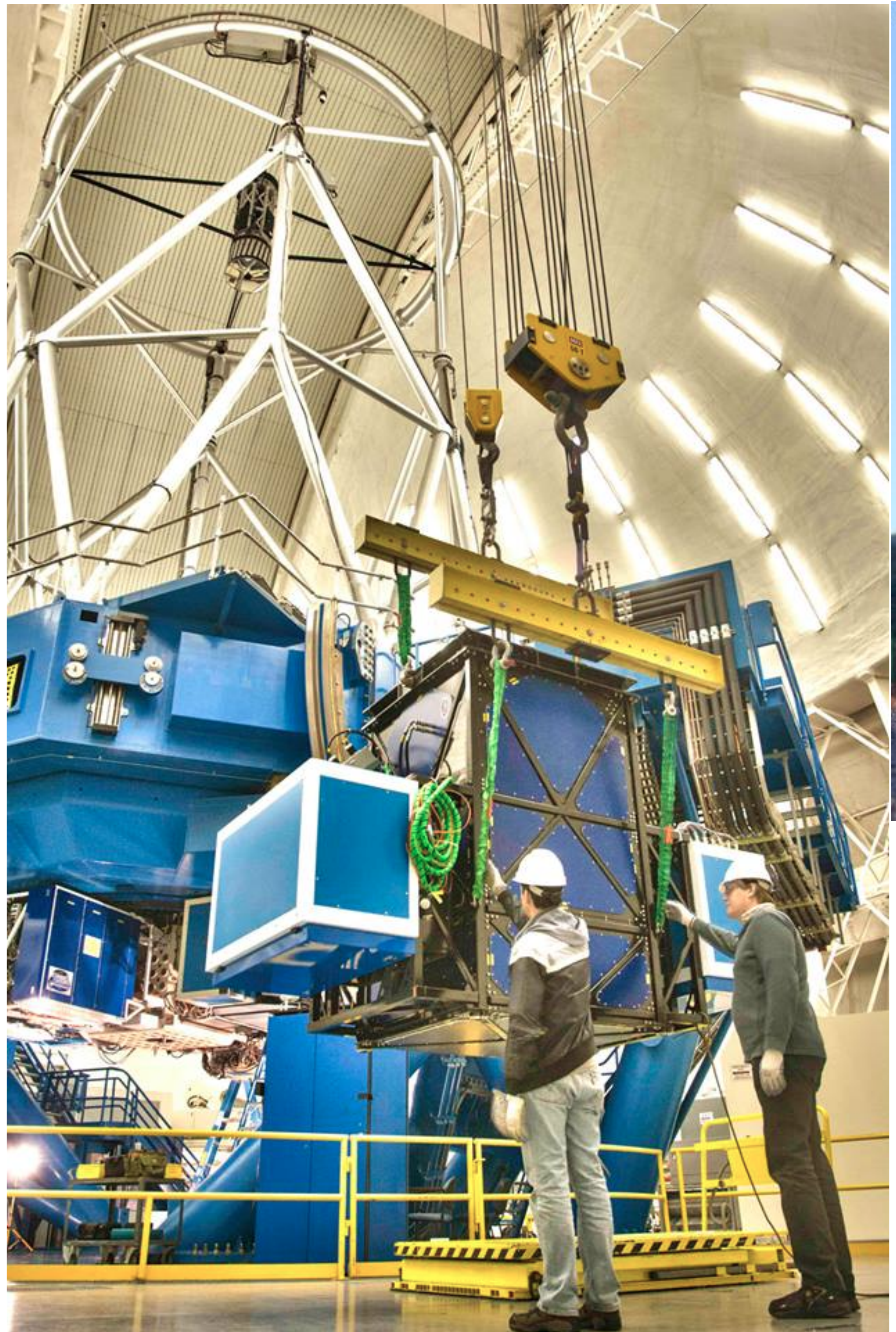


LaGrange et al 2010

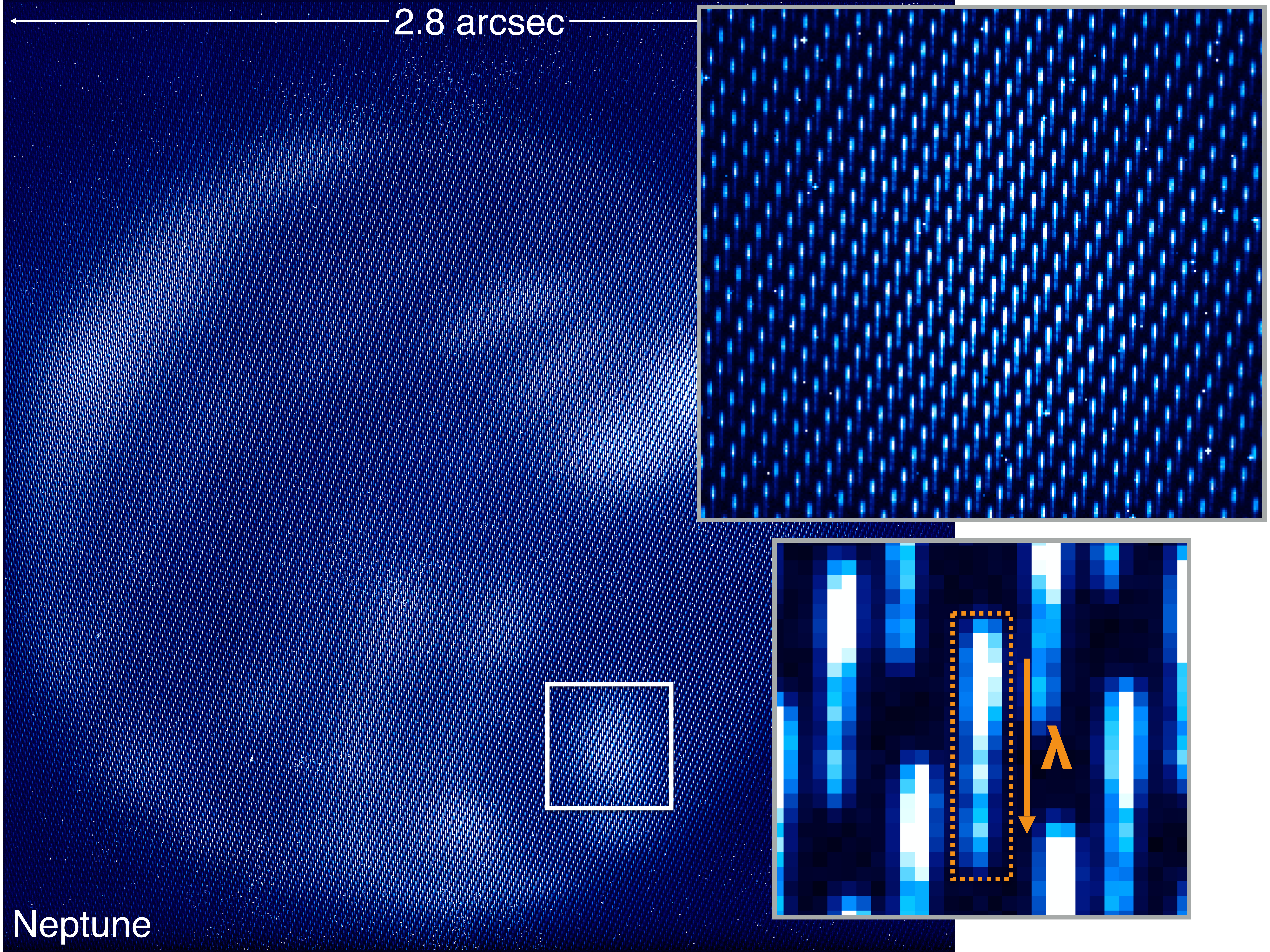


The Gemini Planet Imager

- Built specifically to find and characterize planets using direct imaging
- Uses an advanced adaptive optics system and a specialized chronograph to block starlight
- Installed at the 8.2 meter Gemini-South Telescope in Chile in 2013



Dmitry Savransky



2.8 arcsec
Neptune
λ

The Gemini Planet Imager Exoplanet Survey

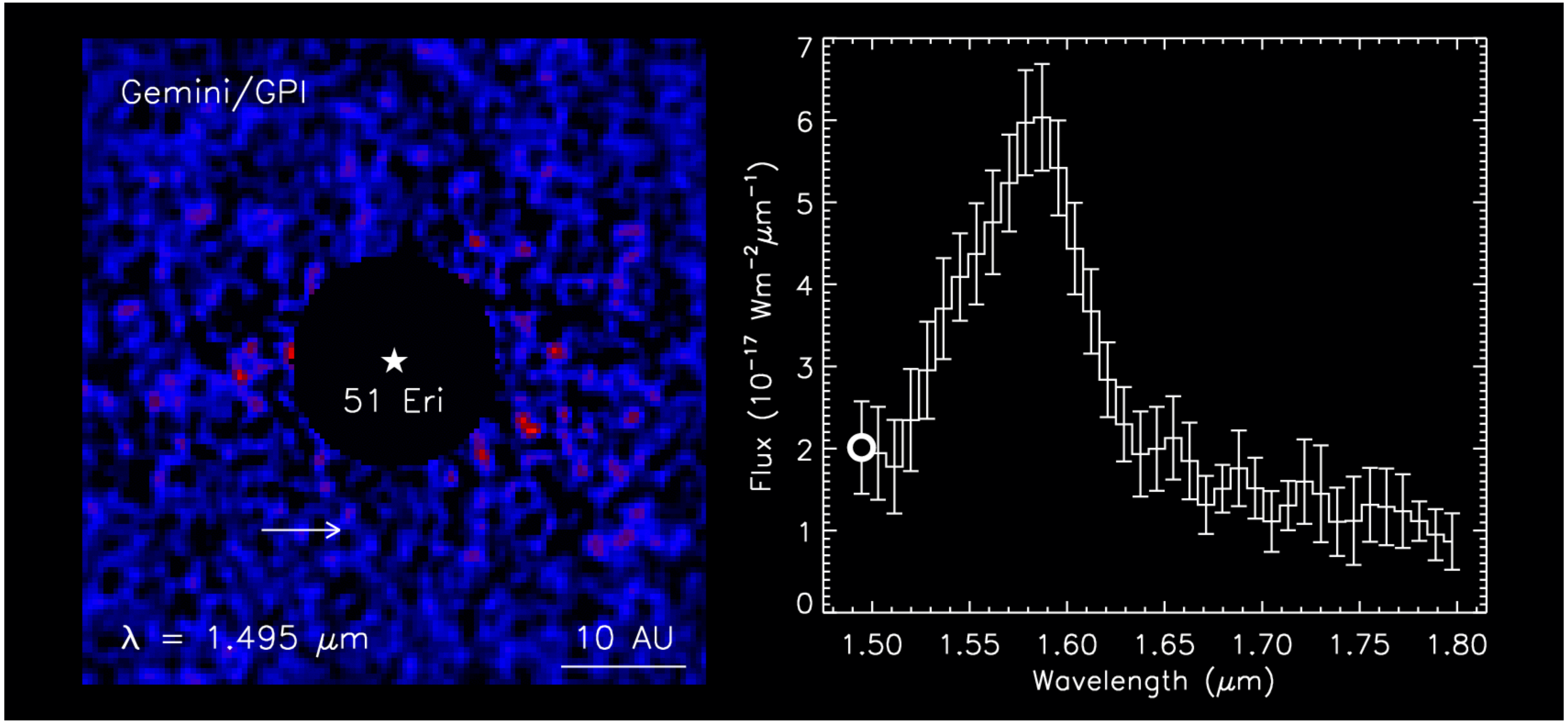
- With GPI, we conducted a survey (GPIES) to search for exoplanets around 500 of the youngest, closest stars in the sky

- GPI is more sensitive to giant planets than previous generations of planet-imaging instruments

- The Gemini-South survey is complete, and we are currently upgrading the instrument before beginning a new survey from Gemini-North on Mauna Kea

51 Eridani b

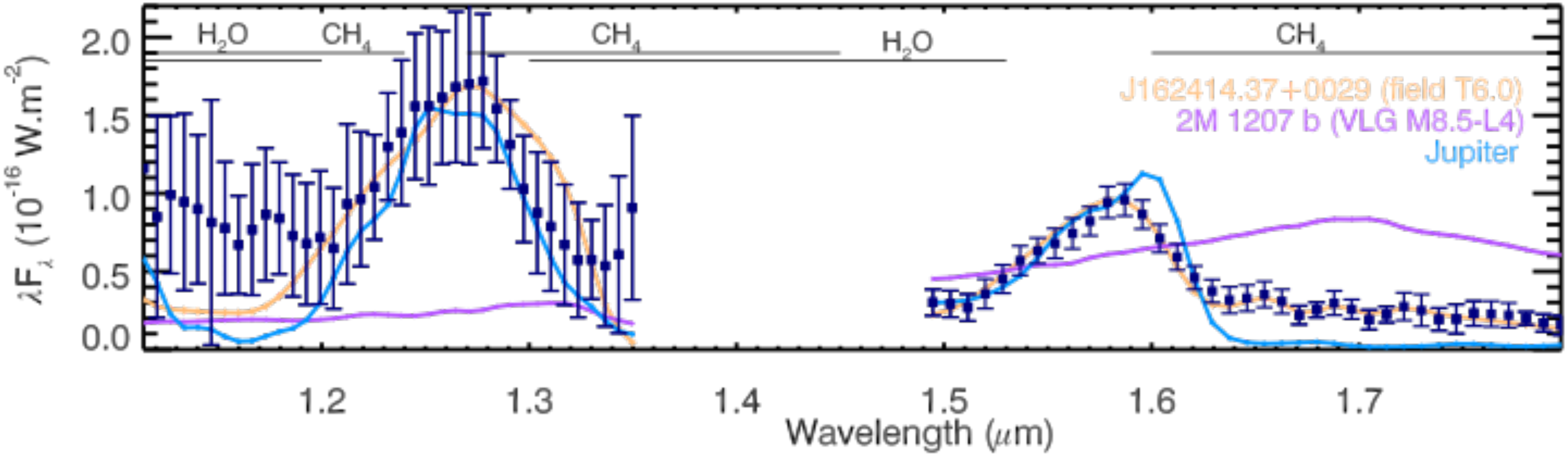
- The first new planet discovered with GPI
- Orbiting a 26 million year old F star at 13 AU, the planet is about 2.5 times the mass of Jupiter



Jason Wang/Rob De Rosa

Direct Imaging allows us to take spectra of the planets we find

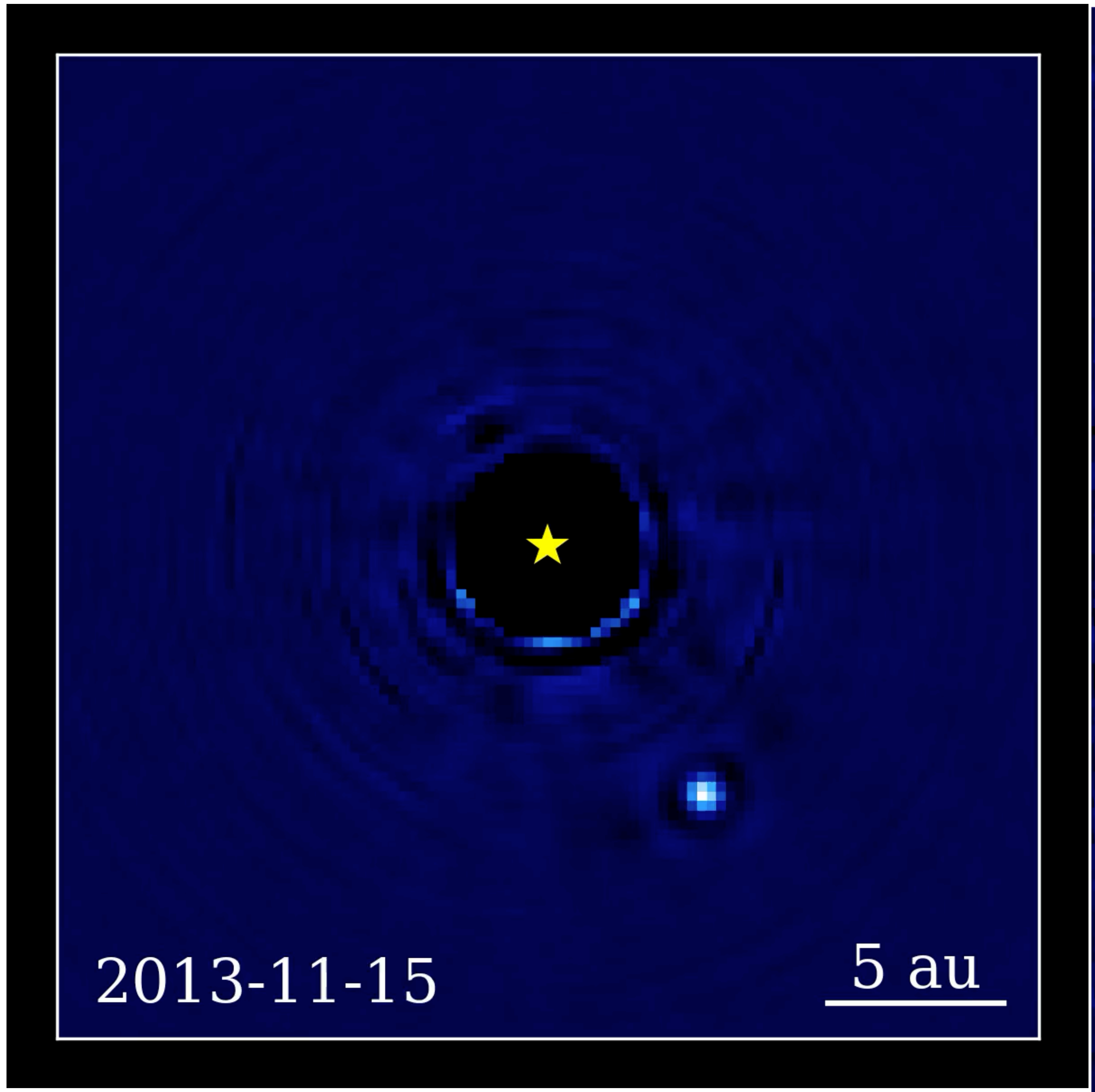
- With spectra we learn the structure of the atmosphere (these young planets are very cloudy), and what molecules make up the atmosphere



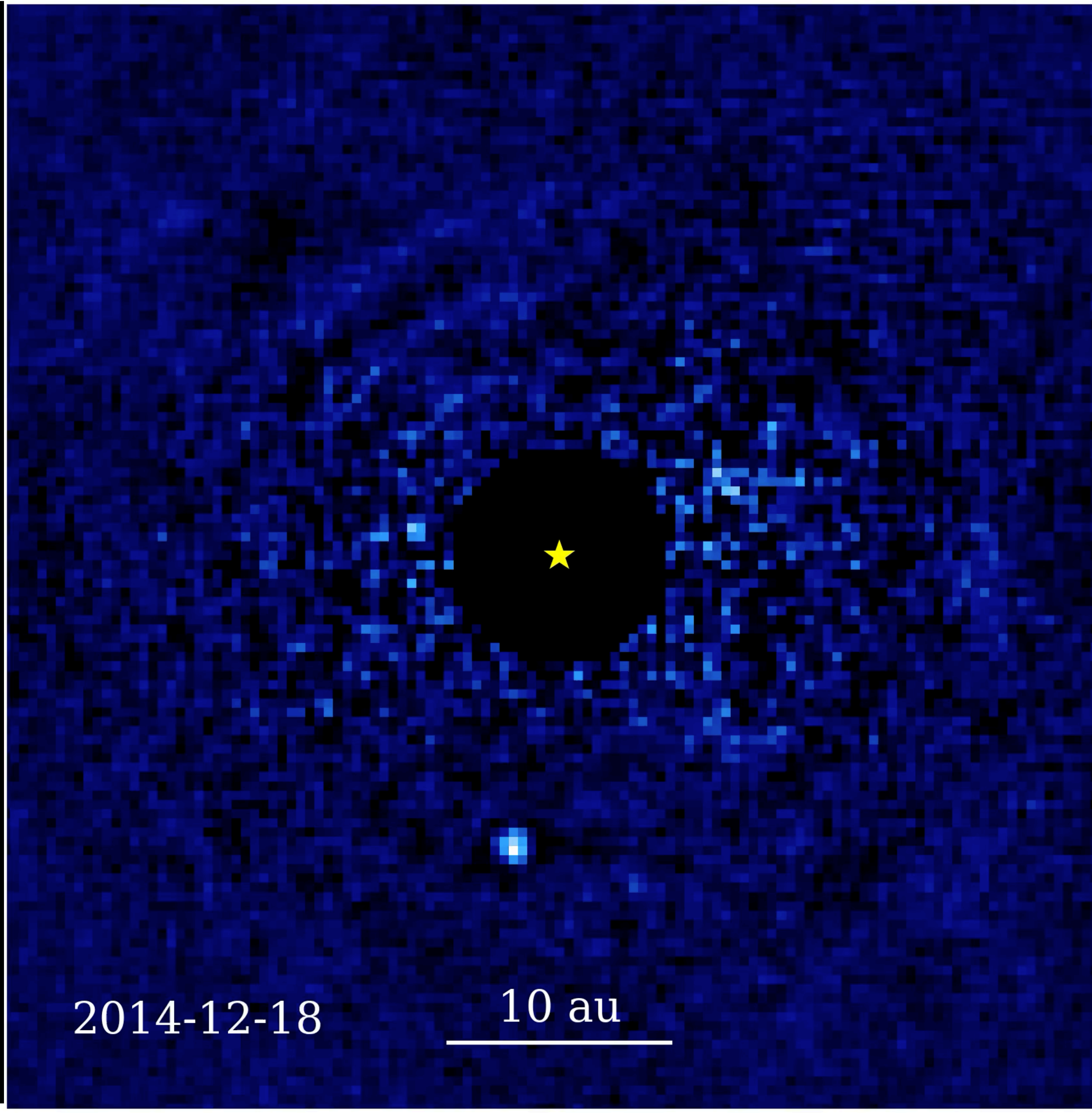
Macintosh et al. 2014

Tracking Orbits

- With GPI we can see giant planets that are closer to their star than previous instruments, so there's significant orbital motion over just a few years
- With even a little motion, we can measure the eccentricity, semi-major axis, and orbital period of these planets



beta Pictoris b

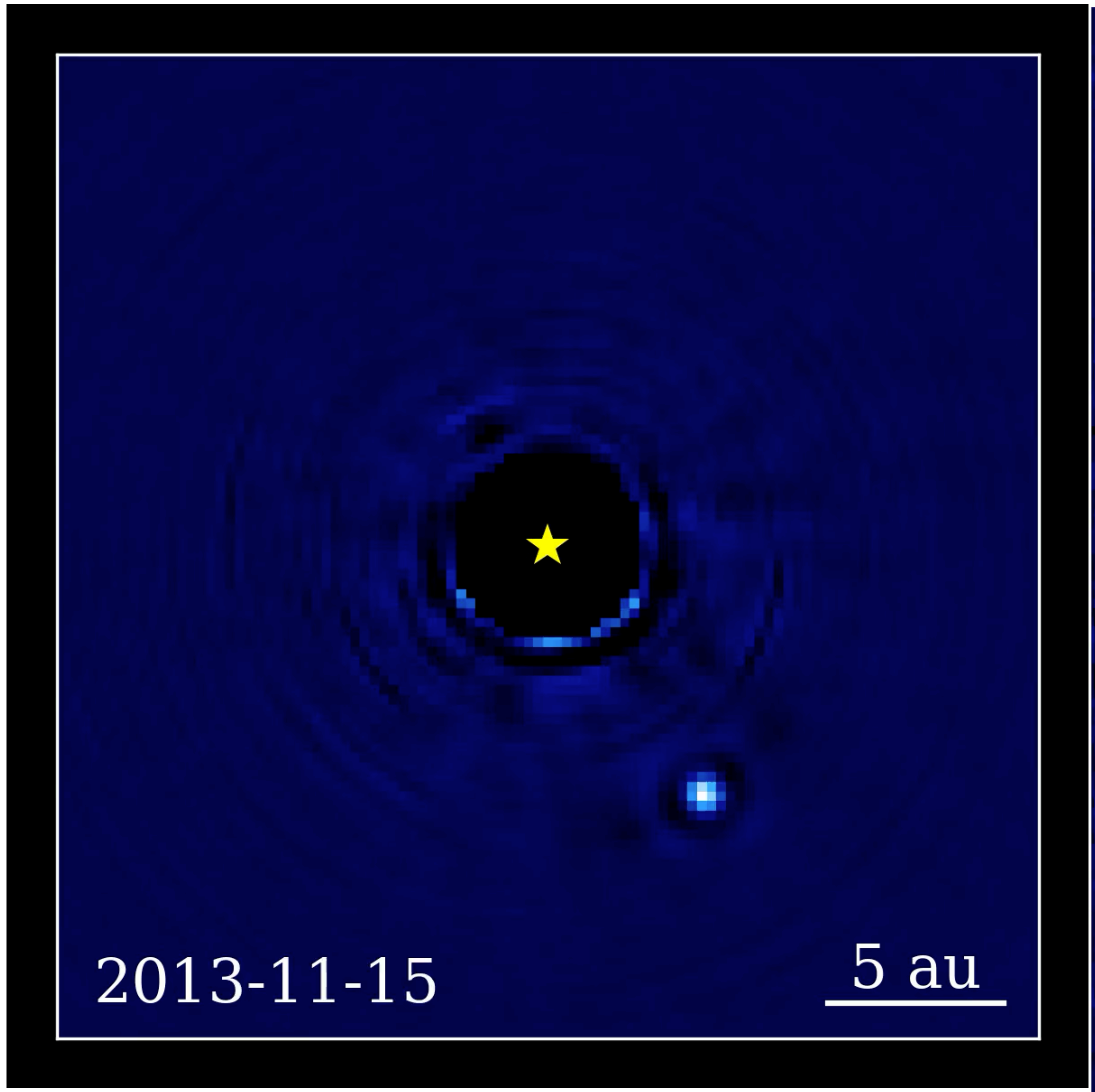


51 Eridani b

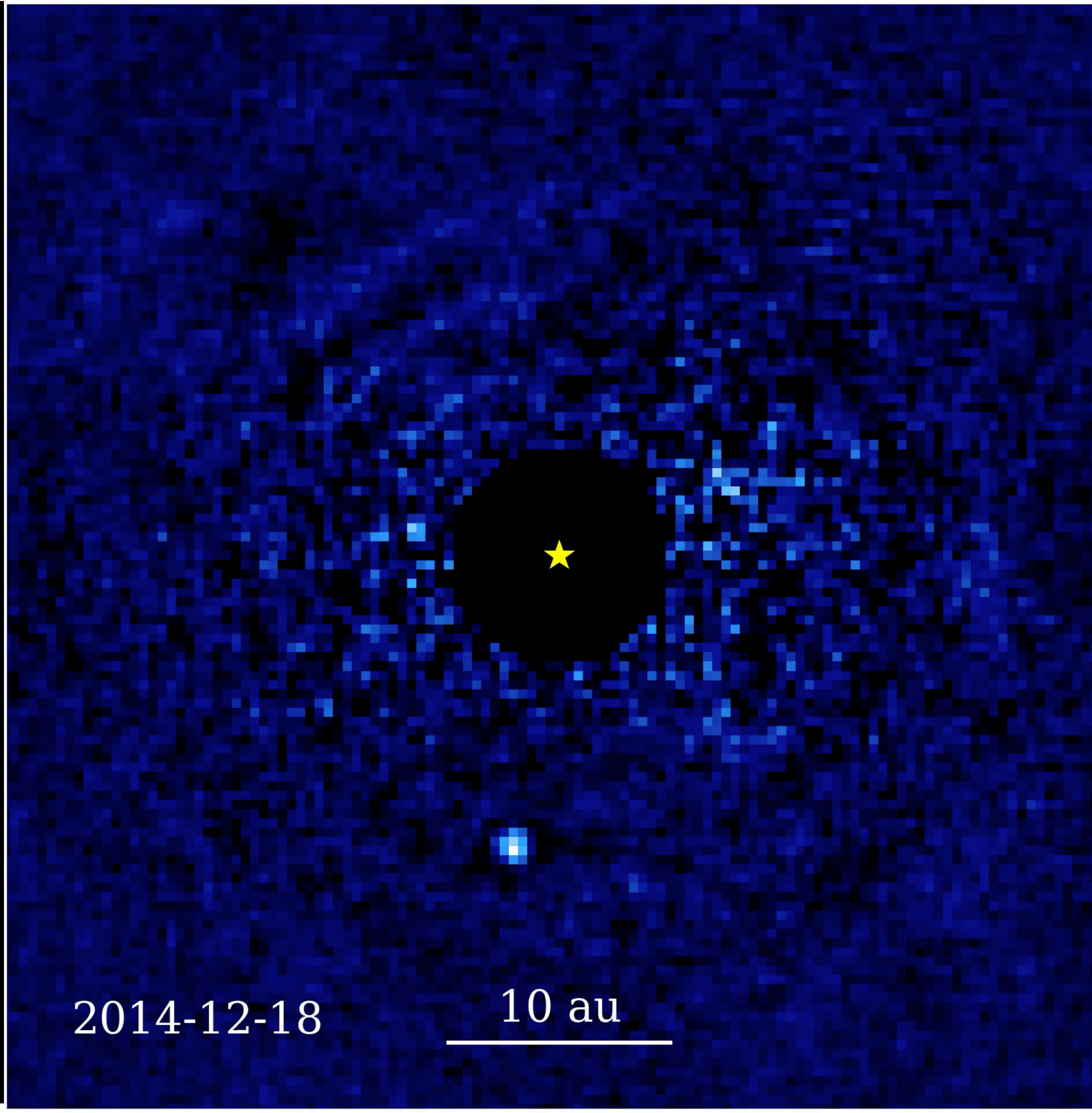
Jason Wang

Response Card Question

- What are the inclination angles of these planets?
  - (A) — beta Pictoris b: i=180, 51 Eridani b: i=90
  - (B) — beta Pictoris b: i=90, 51 Eridani b: i=90
  - (C) — beta Pictoris b: i=180, 51 Eridani b: i=180
  - (D) — beta Pictoris b: i=90, 51 Eridani b: i=180
  - (D) — beta Pictoris b: i=90, 51 Eridani b: i=0



beta Pictoris b



51 Eridani b

For next time

- Homework 6 due Wednesday at 11:59pm
- Final Exam Monday, December 5 10:30-12:30 (this room)