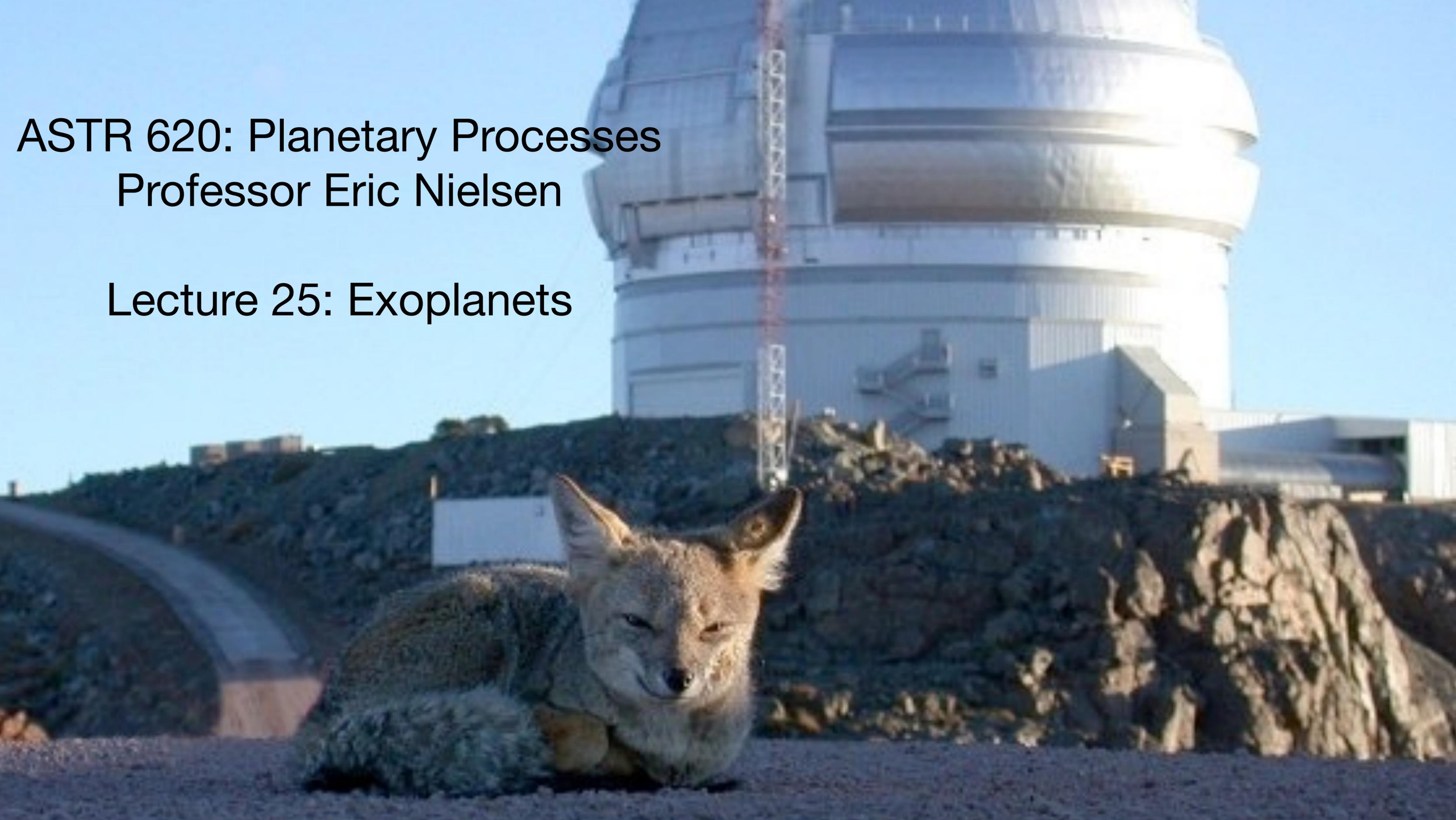


ASTR 620: Planetary Processes
Professor Eric Nielsen

Lecture 25: 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 tonight, 11:59pm
- Final Exam: Monday, December 5, 10:30-12:30 (this room)

Review of the last class

- Which planet-finding techniques let me take the spectrum of an exoplanet?
 - (A) — Direct imaging only
 - (B) — Transit only
 - (C) — RV only
 - (D) — Direct imaging and transit
 - (E) — Direct imaging, transit, and RV

Review of the last class

- An exoplanet orbits a star 40 pc from us, and has a projected physical separation from its star of 10 AU. What is the angular separation between star and exoplanet?
 - (A) — 400"
 - (B) — 4"
 - (C) — 1"
 - (D) — 0.25"
 - (E) — 0.0025"

Review of the last class

- Without adaptive optics, the resolution of most ground-based telescopes is about:
 - (A) — 100"
 - (B) — 10"
 - (C) — 1"
 - (D) — 0.1"
 - (E) — 0.01"

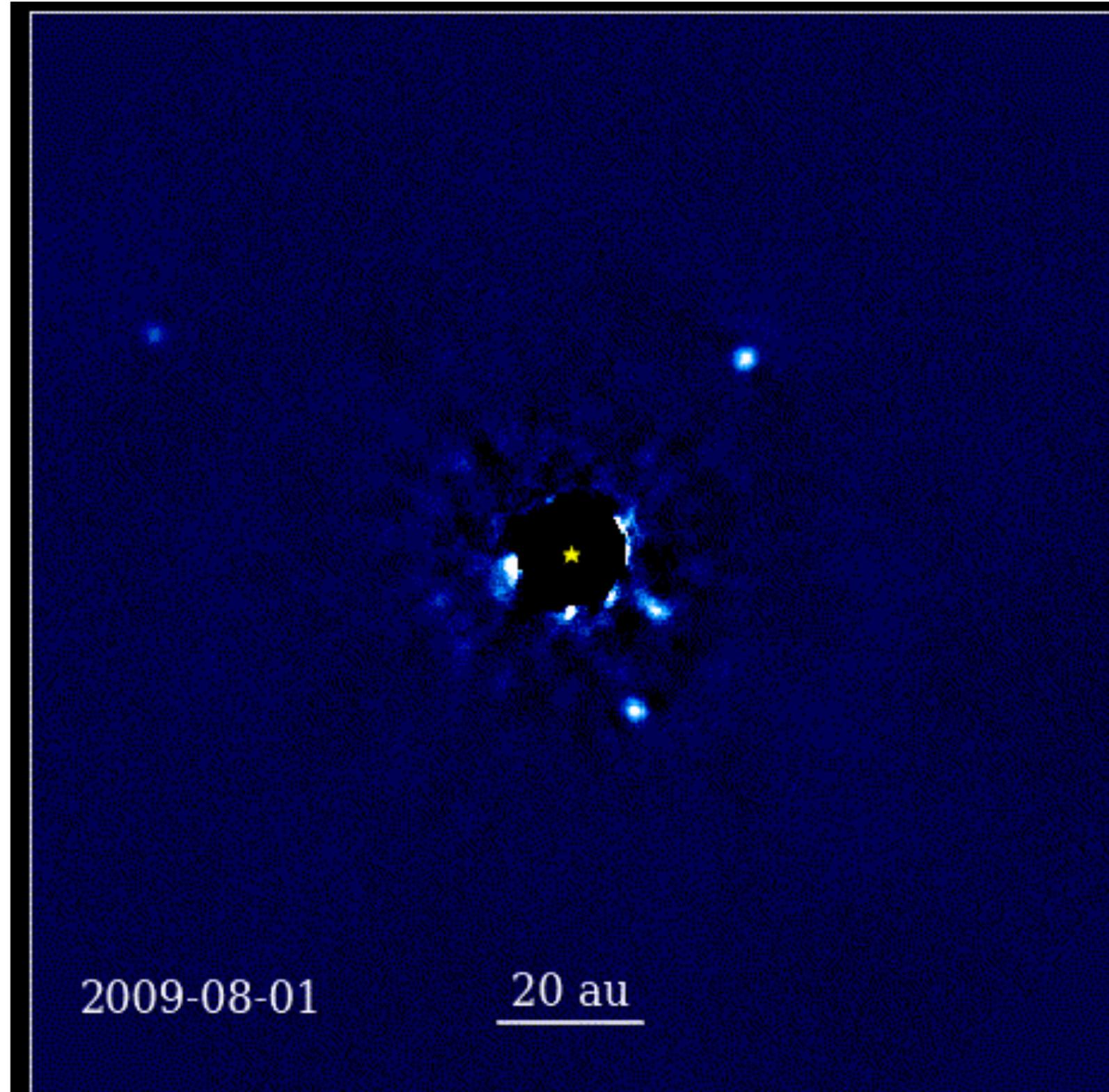
Review of the last class

- Modern, ground-based direct imaging surveys detect exoplanets in:
 - (A) — Visible reflected light
 - (B) — Visible thermal emission
 - (C) — Infrared reflected light
 - (D) — Infrared thermal emission
 - (E) — Ultraviolet reflected light

Review of the last class

- In visible, reflected light, for an observer outside our Solar System, how bright is the Earth compared to the Sun?
 - (A) — 10^{-4}
 - (B) — 10^{-6}
 - (C) — 10^{-8}
 - (D) — 10^{-10}
 - (E) — 10^{-12}

Direct Imaging



Movie from Jason Wang and Christian Marois

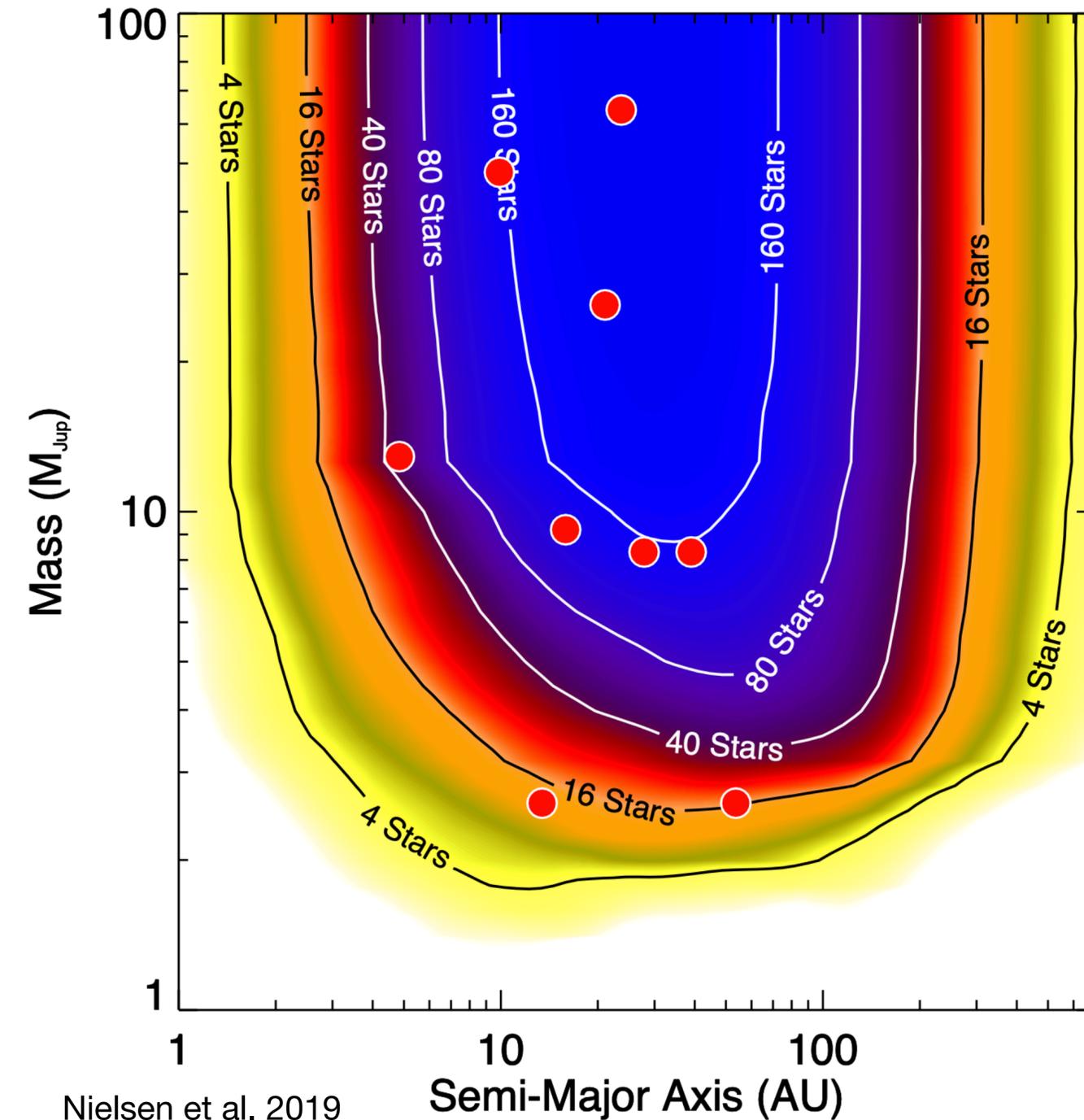
The Gemini Planet Imager Exoplanet Survey

- 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



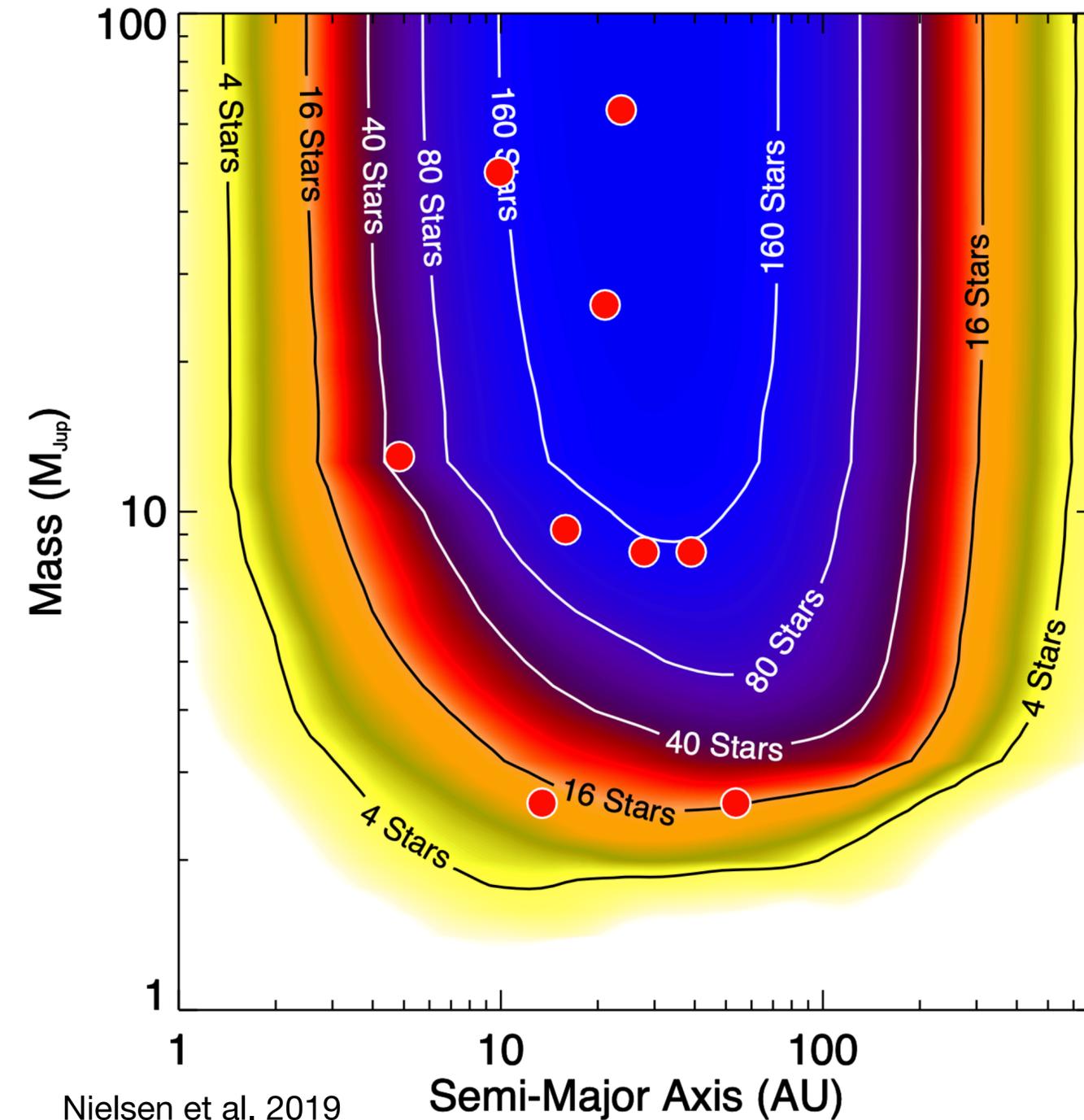
Direct imaging is currently sensitive to wide-separation, giant planets

- This tongue plot shows detections (red dots) from the first 300 stars surveyed by GPIES
 - 75 Jupiter masses and above are stars (will fuse hydrogen in their cores)
 - 13 - 75 Jupiter masses are “brown dwarfs” (won’t fuse hydrogen, but will fuse deuterium in their cores)
 - Below 13 Jupiter masses are giant planets (won’t fuse deuterium)



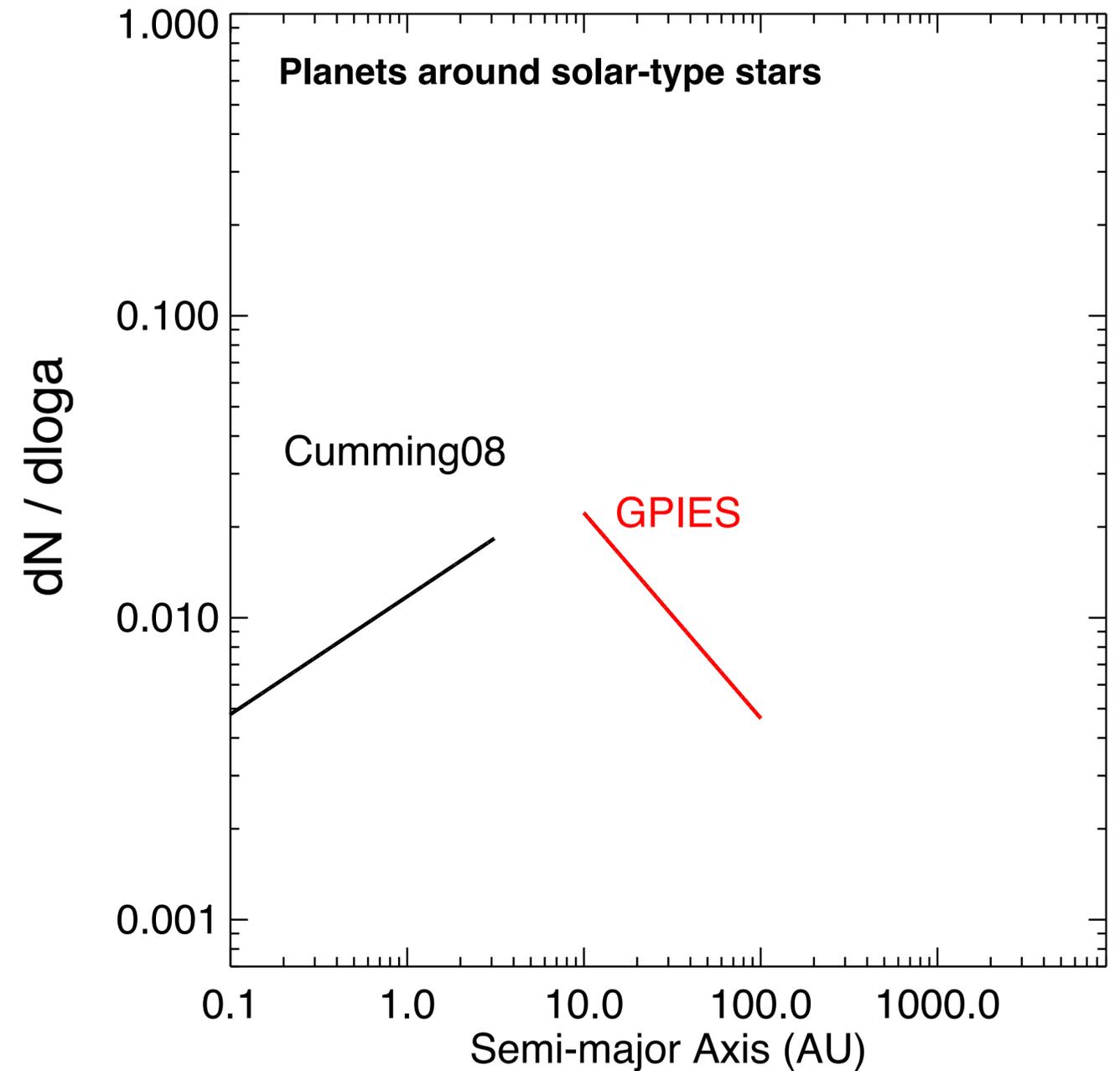
Direct imaging is currently sensitive to wide-separation, giant planets

- Colors and contours show how sensitive we were to objects of different masses and semi-major axis
- Wide-separation giant planets (above 2 Jupiter masses, from 5-100 AU) are more common around stars more massive than the Sun:
 - About 10% of more massive stars have a wide-separation giant planet
 - About 3% of Sun-like stars have such a planet



Direct Imaging

- Cumming et al. 2008 (radial velocity): giant planets are more common the further you move from the host star ($\sim 0-3$ AU)
- GPIES (direct imaging): giant planets are more common the closer you move to the host star (10-100 AU)
- Taken together: a peak in the distribution around $\sim 3-5$ AU (the snow line)



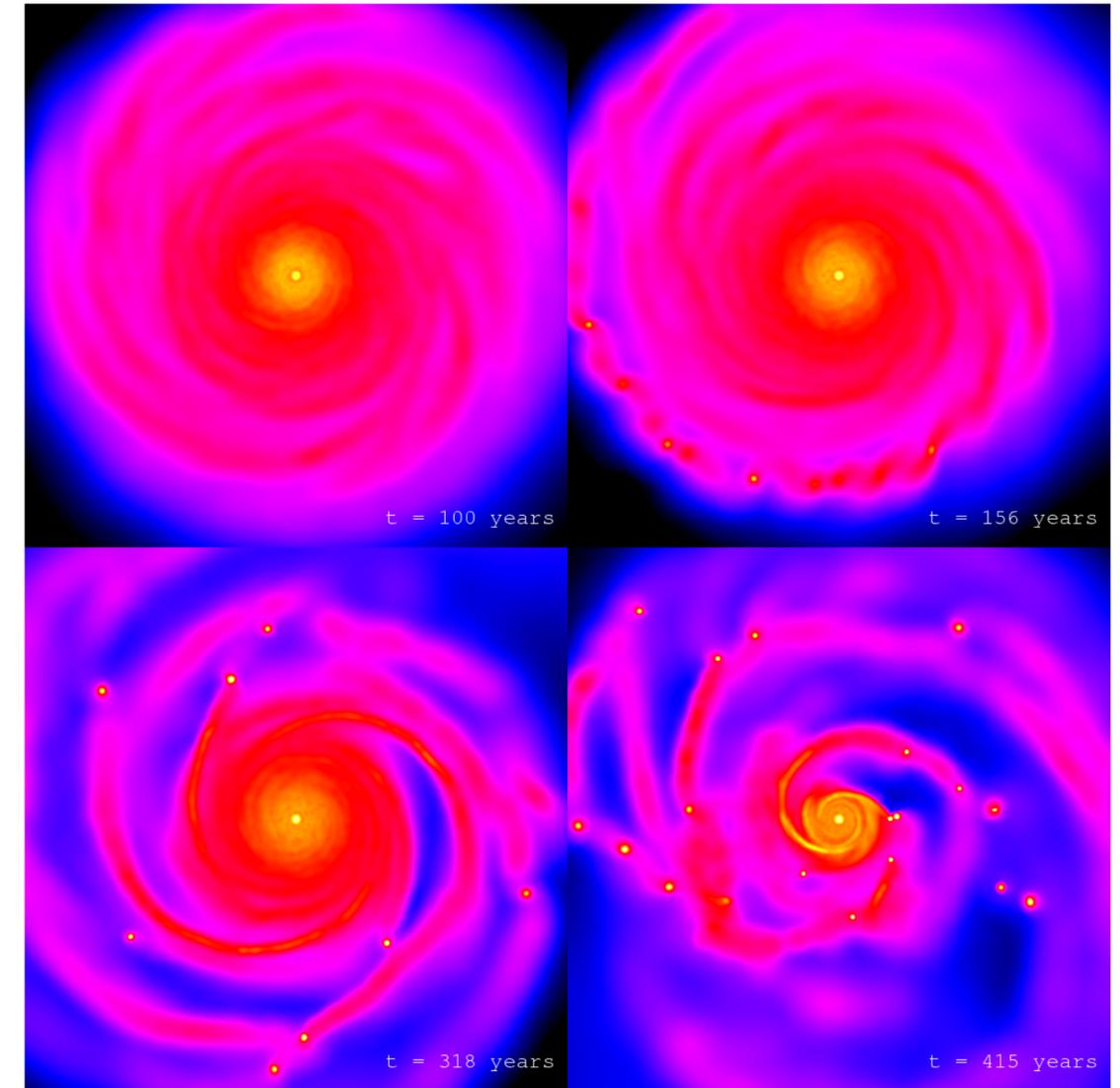
Direct Imaging



Core accretion

- More companions around higher-mass stars
- More low-mass companions than high-mass
- More close-in companions than farther-out

GPIES Giant Planets



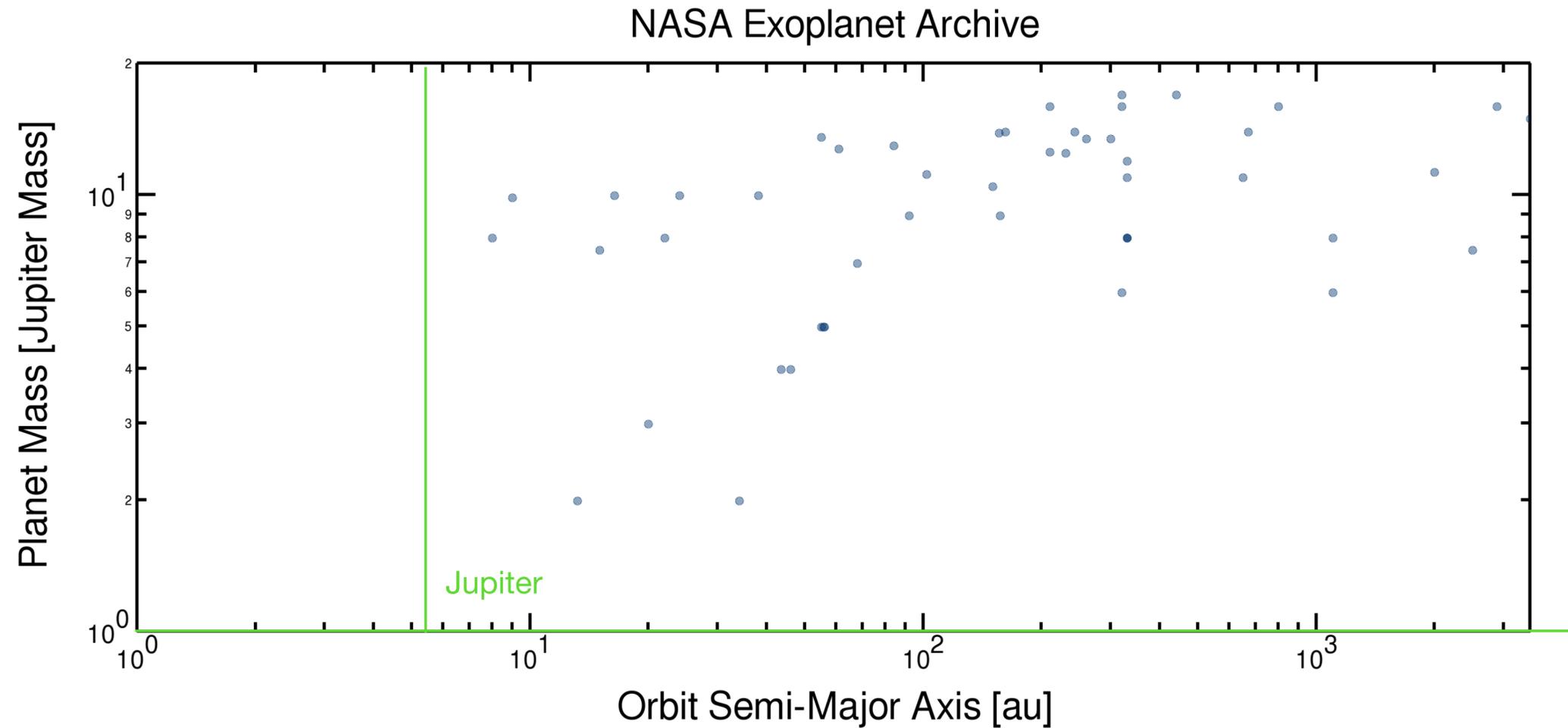
Gravitational Instability

- Weak dependence on mass of host star
- More high-mass companions than low-mass
- Should be at much larger orbital separations

GPIES Brown dwarfs

Direct Imaging

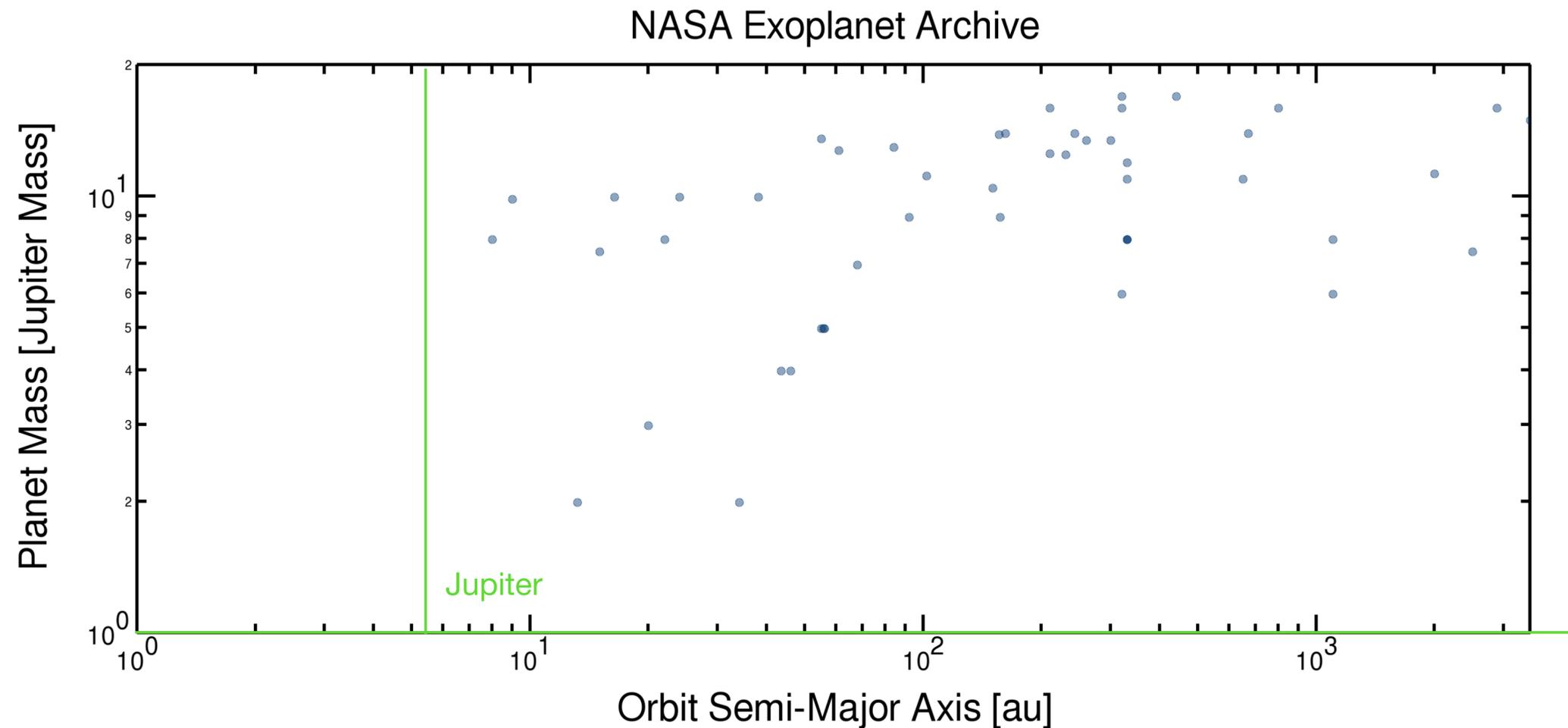
- Can measure:
 - orbital period, semi-major axis, eccentricity, inclination angle
 - temperature and luminosity
 - spectra of atmosphere



Direct Imaging

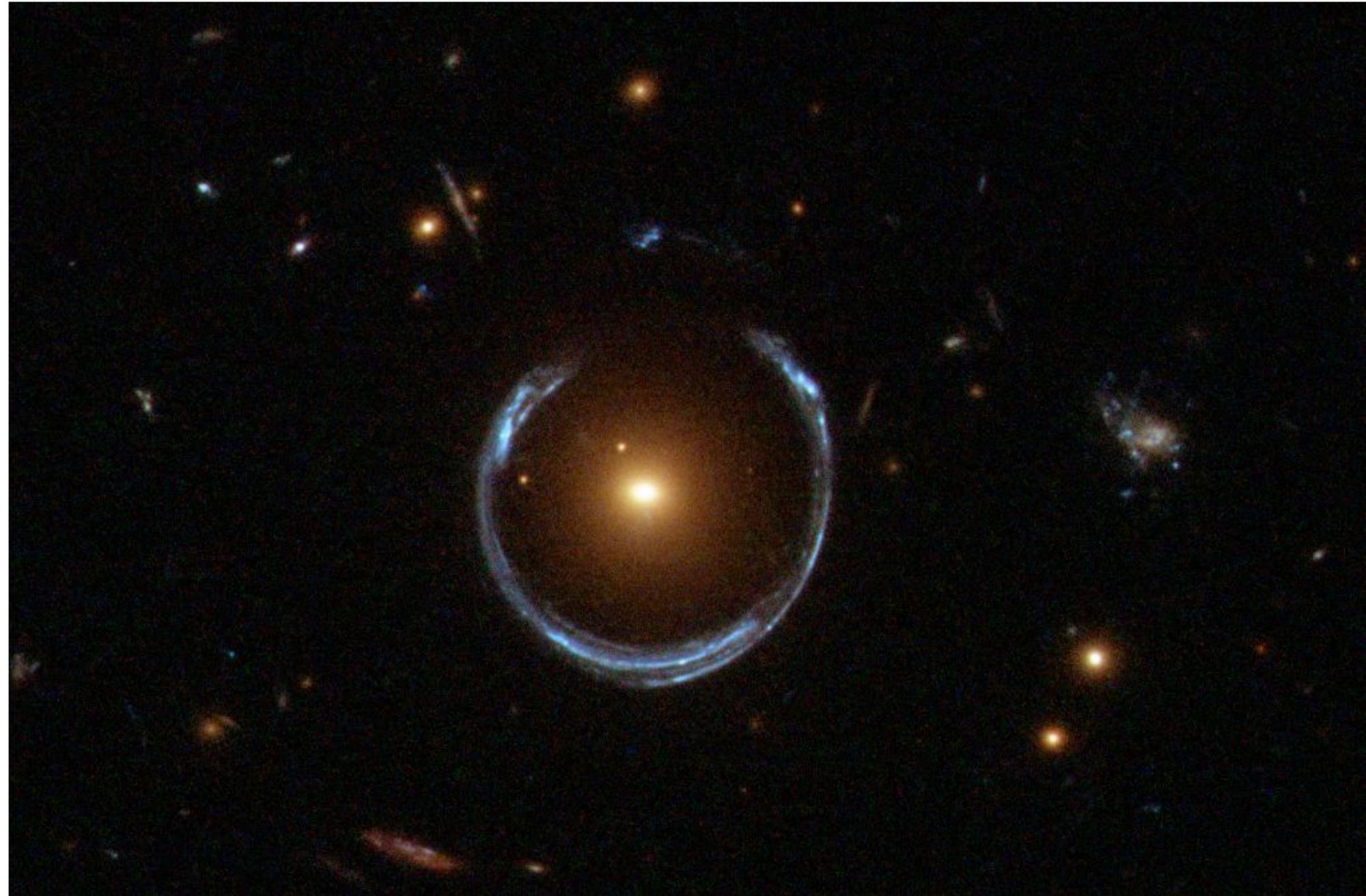
- Biases:

- Larger, wider separation planets are easier to detect
- Currently only possible with young (<100 million years) planets
- Works best for very nearby stars (within about 100 parsecs)
- Can't measure the mass of the planet without using an evolutionary model or combining with another method



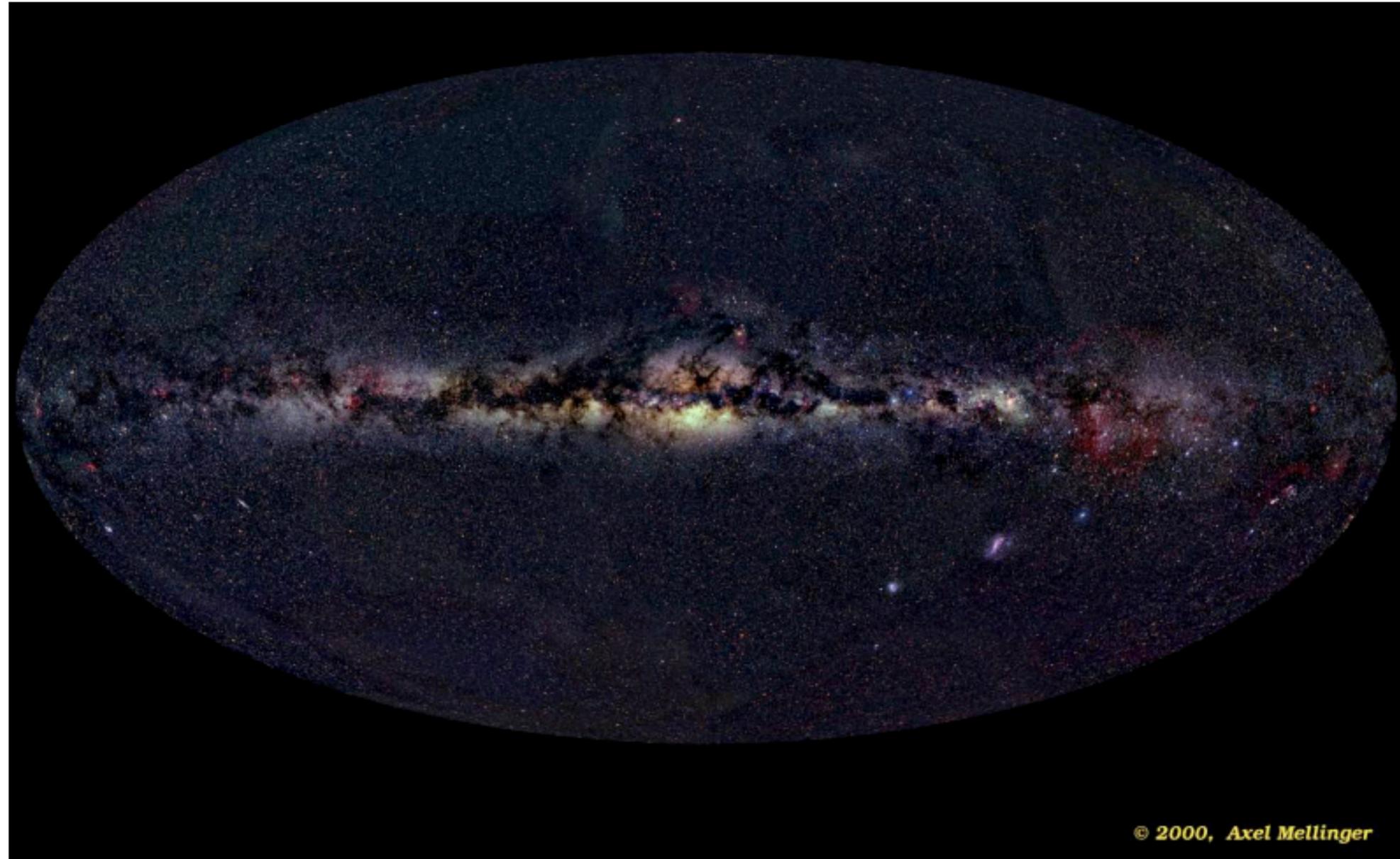
Gravitational Microlensing

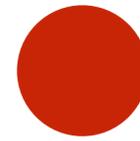
- Einstein's General Relativity tells us how massive objects bend light: **Gravitational Lensing**
- **Gravitational Microlensing:** (increases in brightness of a background star as its light is magnified by a foreground star)
- Microlensing allows us to detect planets



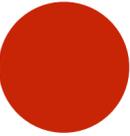
Microlensing Surveys

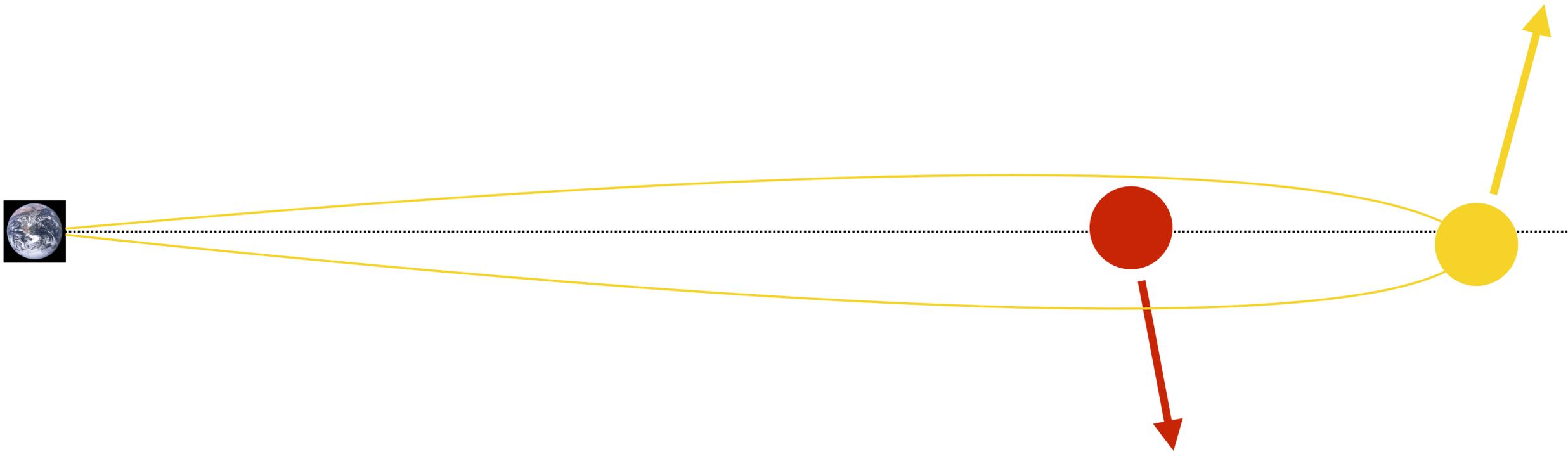
- Two stars need to be very precisely aligned for detectable microlensing to happen
- Stars are always moving, orbiting the center of the galaxy
- Microlensing surveys target the bulge of our galaxy, continually observing hundreds of thousands of stars, looking for one star that starts to get brighter

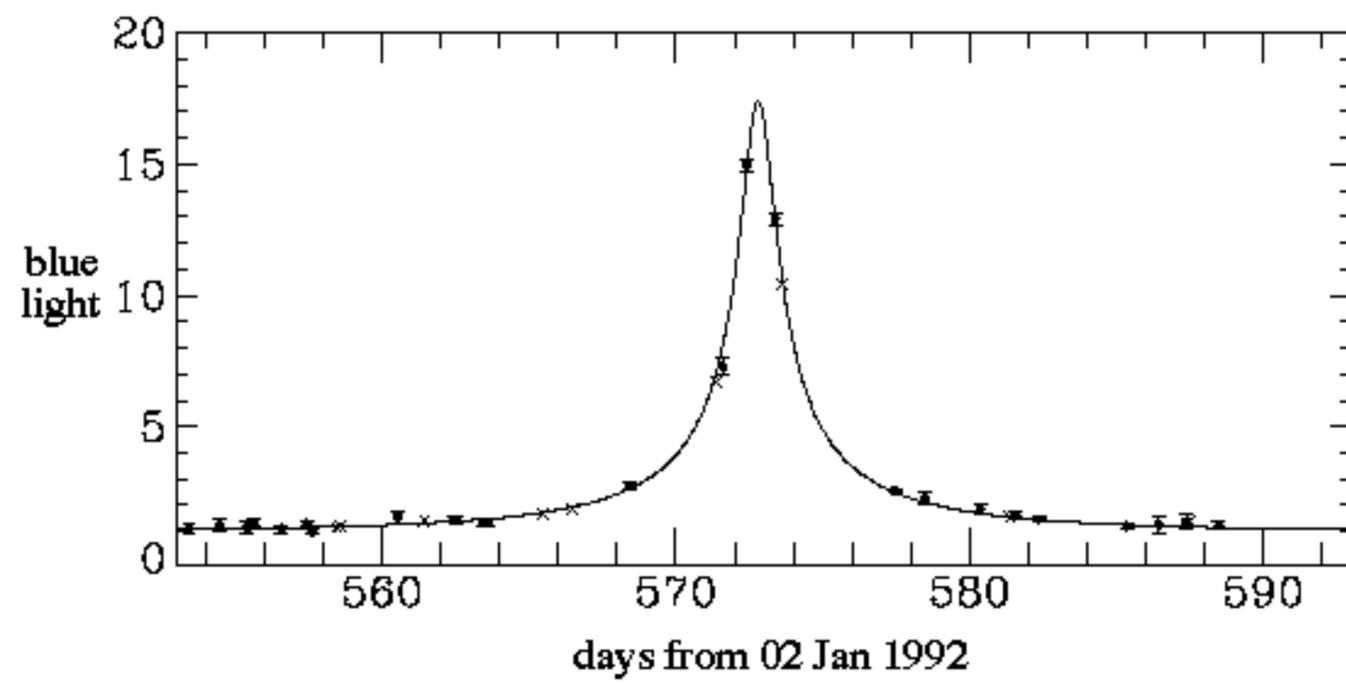
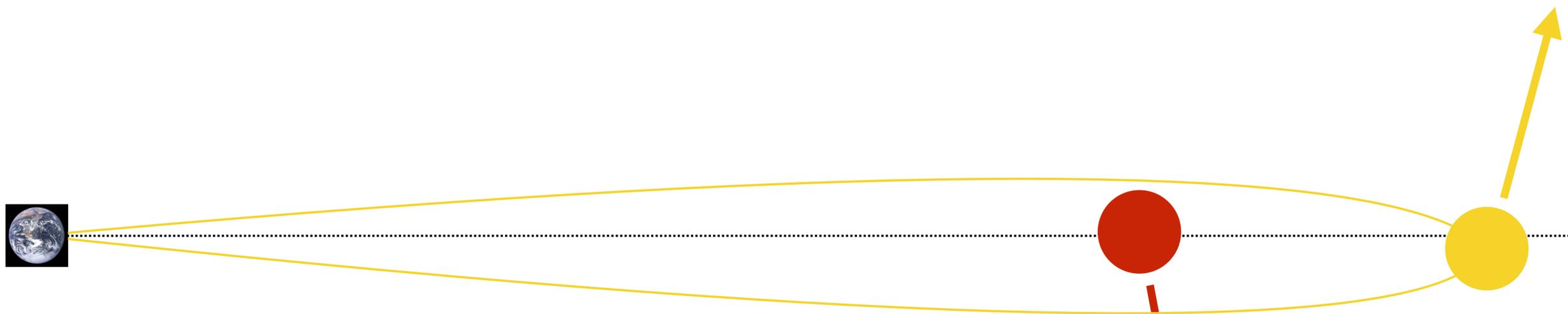




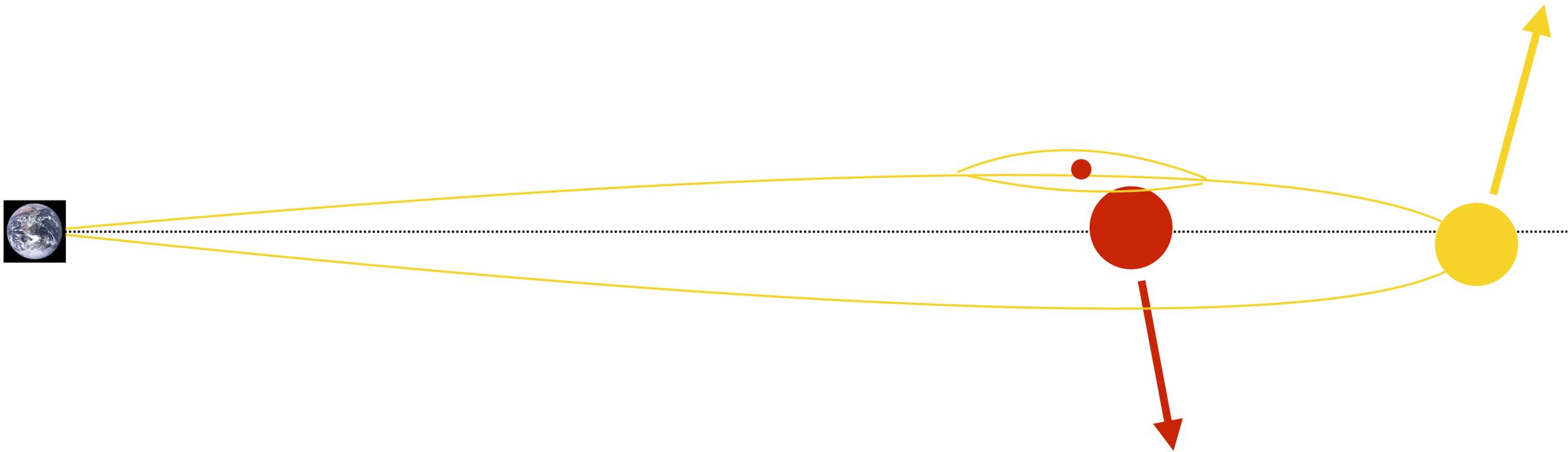






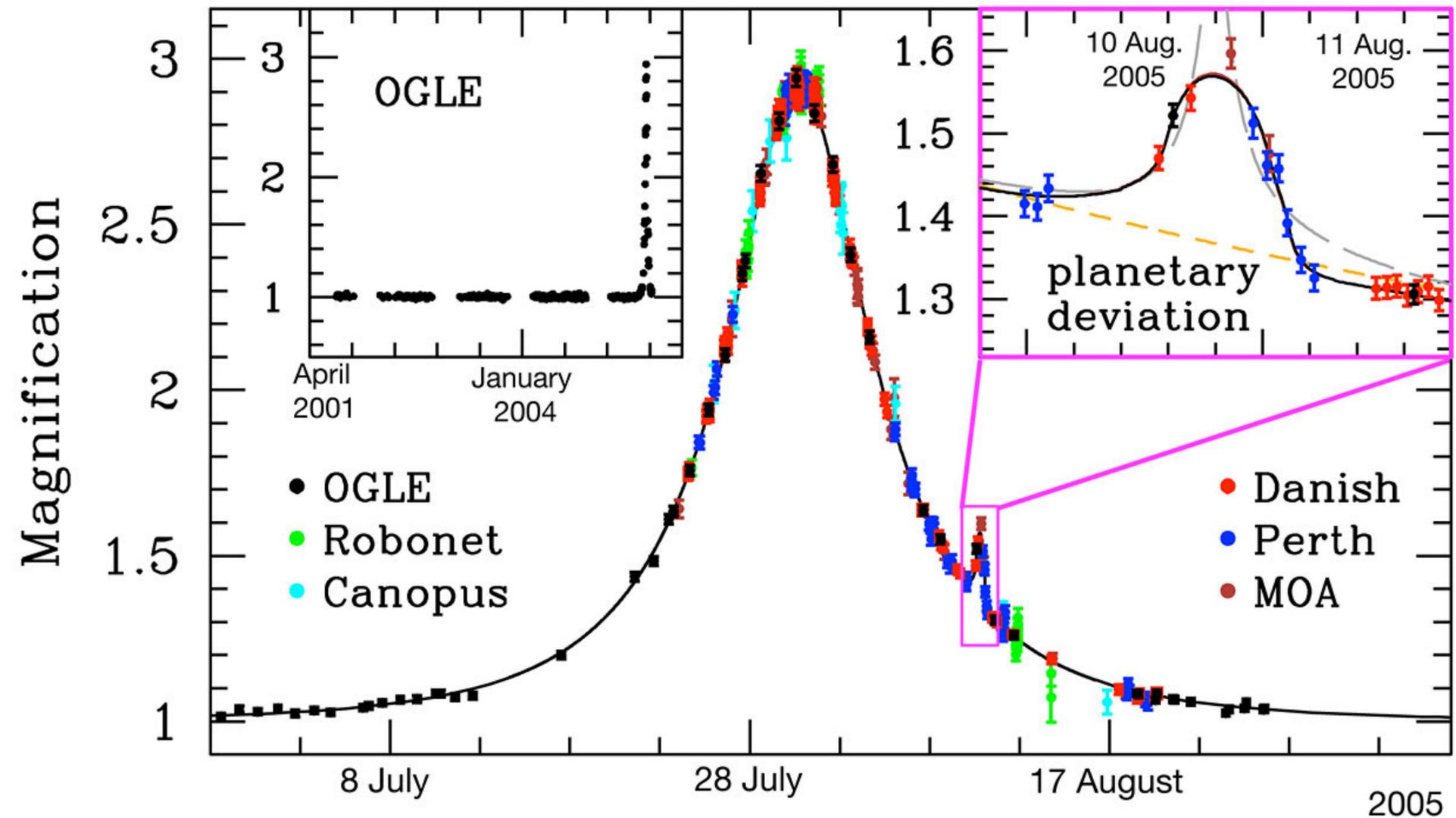


Sutherland 1992



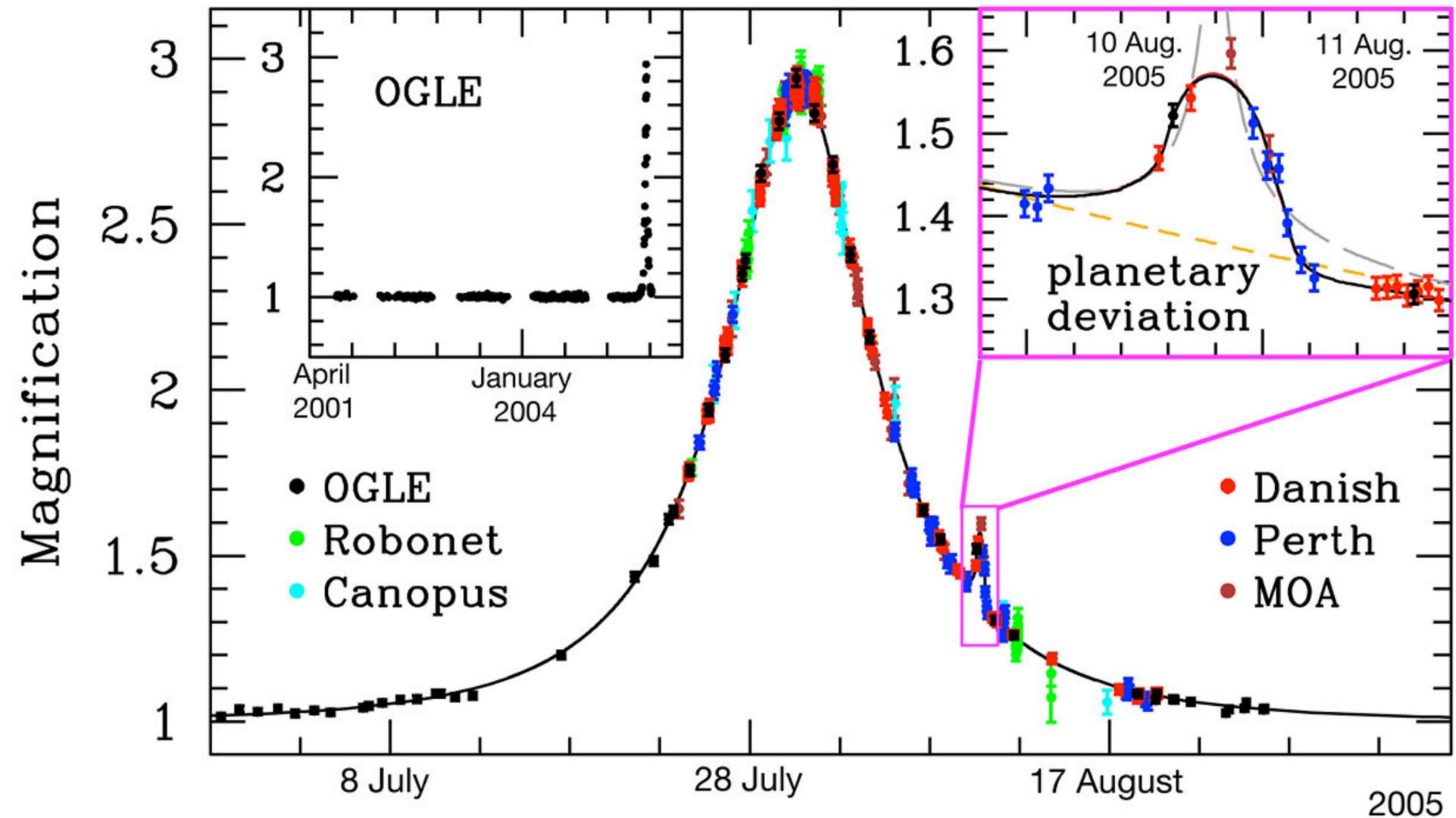
Exoplanets with Microlensing

- As the two stars move with respect to each other, the magnification changes, and the star gets brighter or fainter
- Planets cause a small deviation in the shape of the “microlensing light curve”



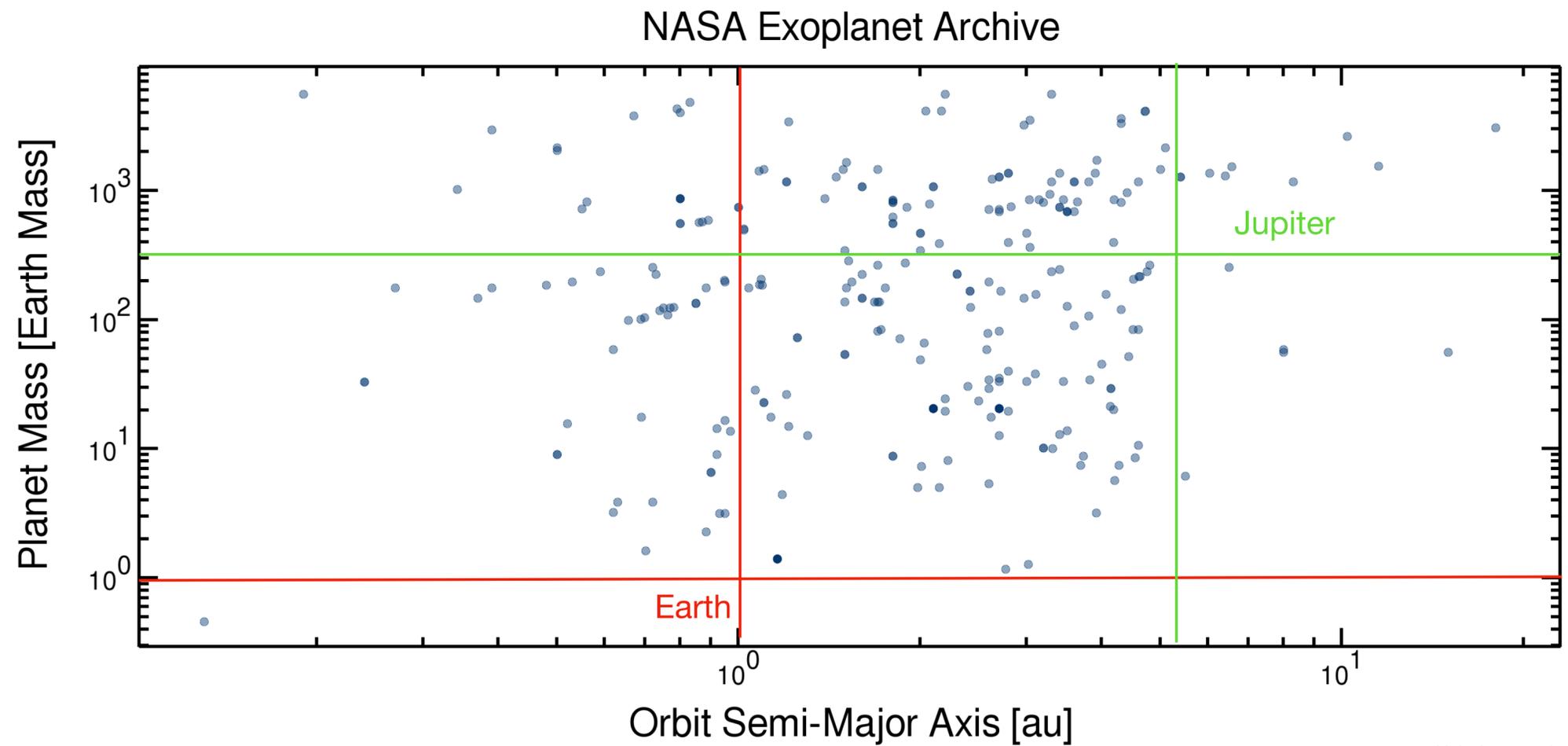
Exoplanets with Microlensing

- Microlensing lets us measure the mass ratio between the host star and planet very precisely, but in many cases it's difficult to measure the host star mass (and so the planet mass)
- After a microlensing event is over, we can never go back and study the planet



Microlensing

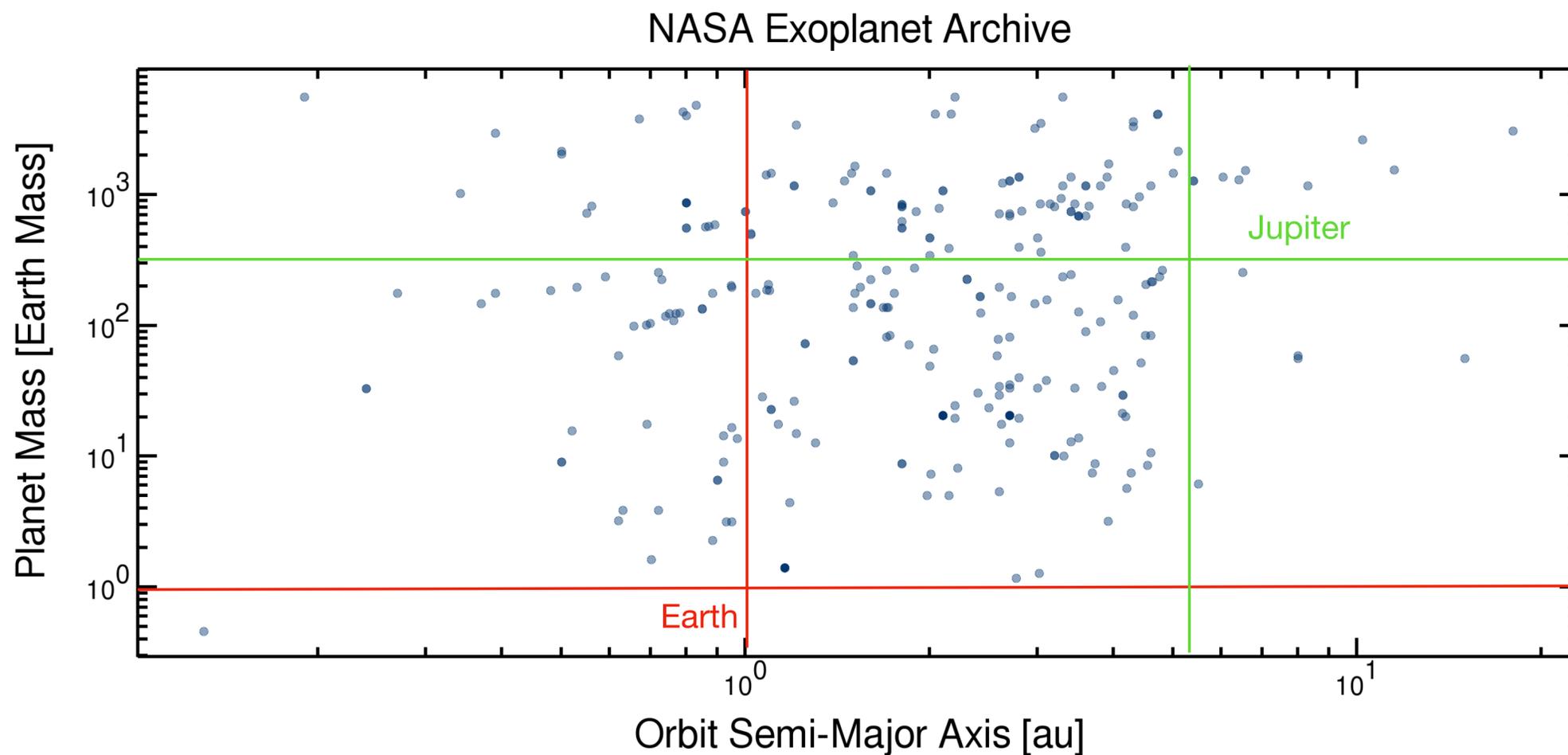
- Can measure:
 - Mass ratio between star and planet
 - Projected separation in units of the “Einstein radius”



Microlensing

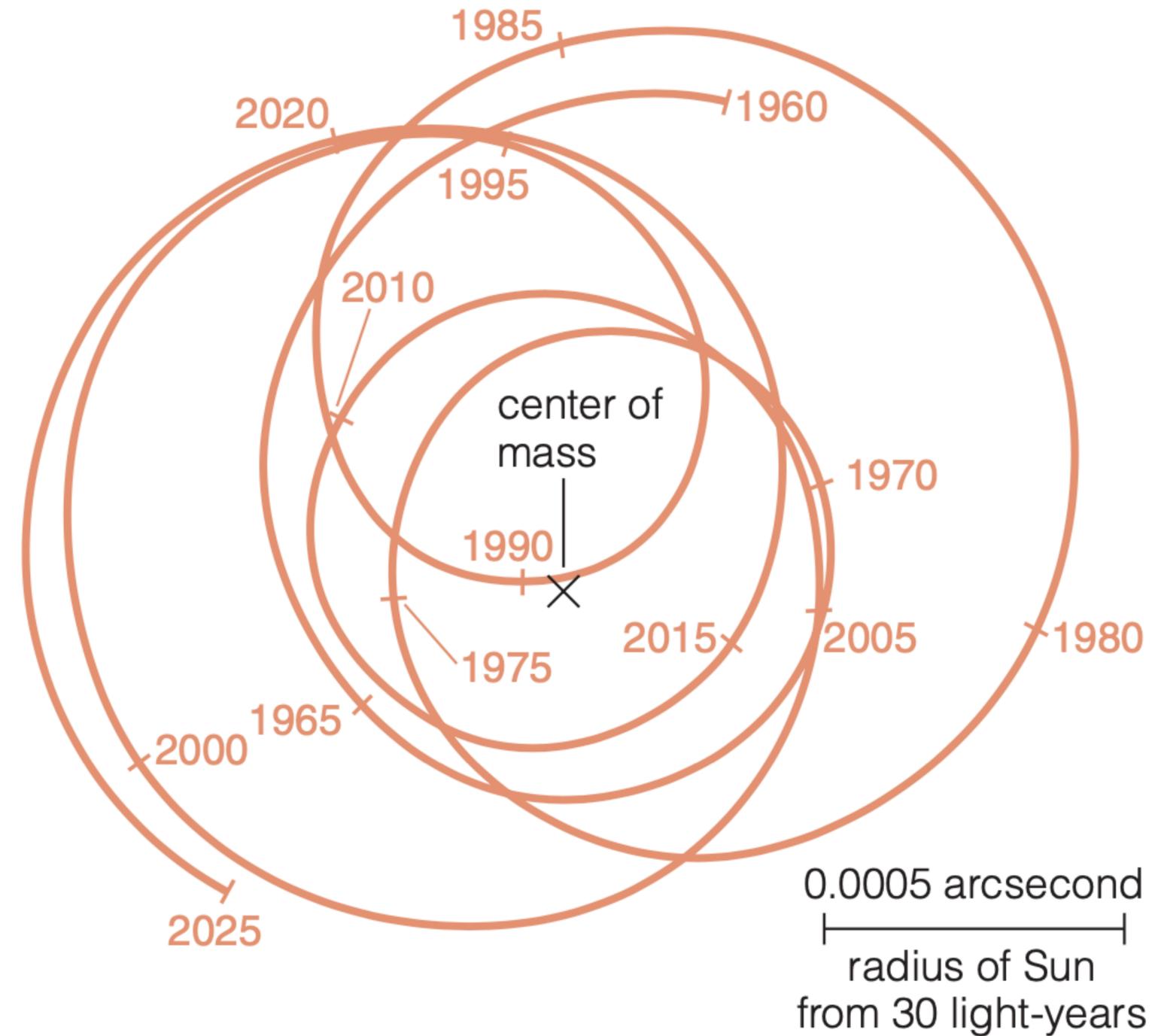
- Biases:

- Very good for finding planets about 1-10 AU from their host star
- Very difficult to convert from mass ratio to planet mass (points on this plot are from a probabilistic model)
- Most sensitive to planets around stars about 6 kpc away
- Planets can never be followed up, we can never get spectra



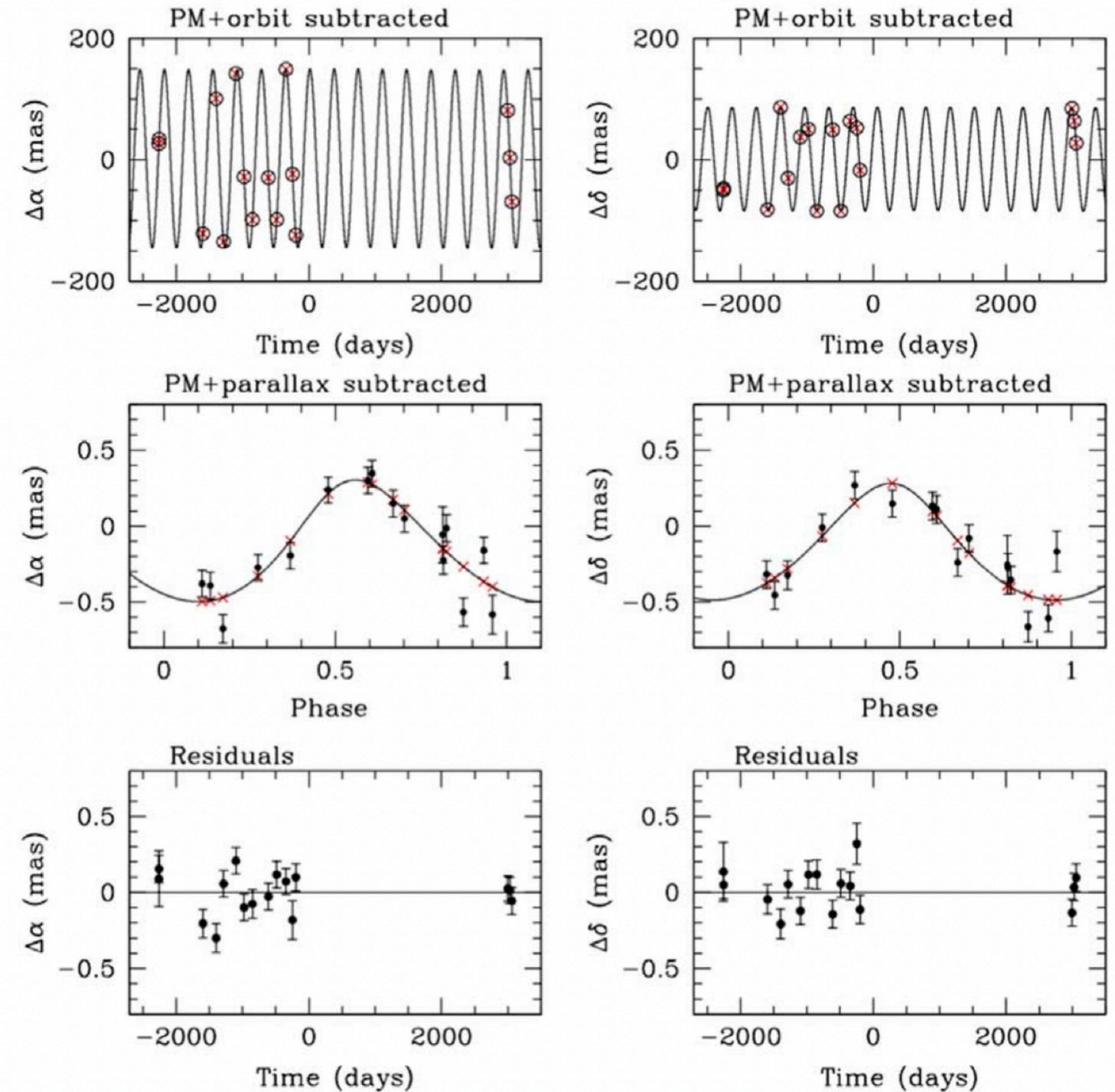
Astrometry

- Stars move around the center of mass of their stellar system, due to the orbits of planets
- We can detect that motion along the line-of-sight using radial velocity
- It's also possible to detect that motion on the sky by making precise measurements of the position of stars over time
- ~~As of now, no exoplanets have been detected by this technique, but that will likely change in a few years (Gaia)~~



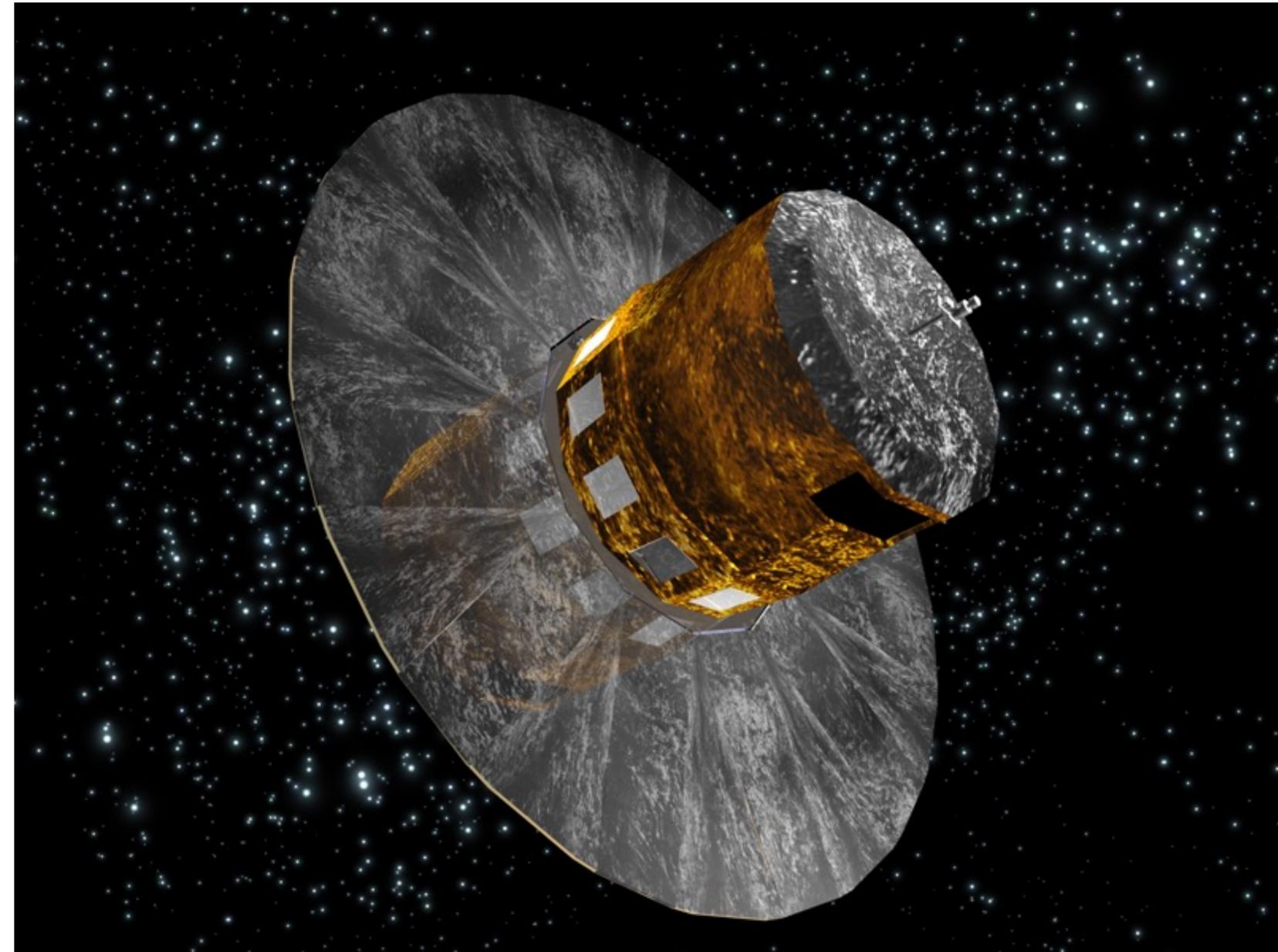
Astrometry

- VLBI observations of the binary system GJ 896 AB
- GJ 896 A has a 2 Jupiter mass companion in a 280 day orbit



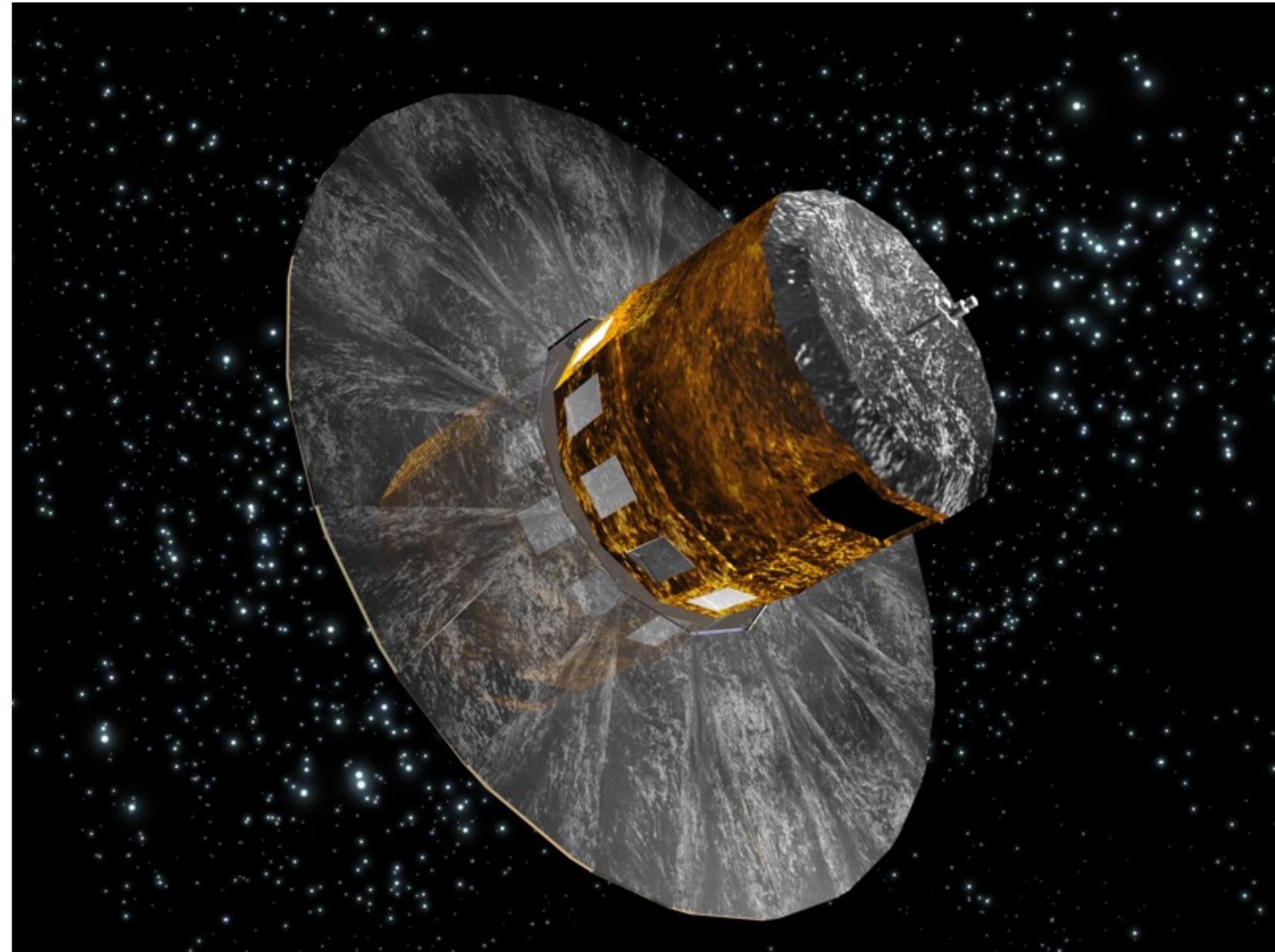
Gaia

- Gaia is a space telescope, launched in 2013, that is continually measuring the position of stars in the sky multiple times a year
- The precision of Gaia: 10 micro-arcseconds (the diameter of a coin held 100,000 miles away)



Order of Magnitude: Gaia Exoplanets

- The precision of Gaia: 10 micro-arcseconds
- Gaia observes a Sun-like star 10 pc away, and detects a planet on a 1-year orbit.
- (1) What is the smallest mass planet (in Jupiter masses) Gaia can detect?



Order of Magnitude: Gaia Exoplanets

- (1) What is the smallest mass planet (in Jupiter masses) Gaia can detect?

- First, convert an angular size to a physical size:

$$\theta_{\text{arcseconds}} = \frac{S_{AU}}{d_{pc}} \quad S_{AU} = \theta_{\text{arcseconds}} d_{pc} = 10^{-5} \times 10 = 10^{-4} AU$$

- This is the orbit of the star around the center of mass. Luckily, we know that 1 year = 1 AU for the planet, so we just need a ratio:

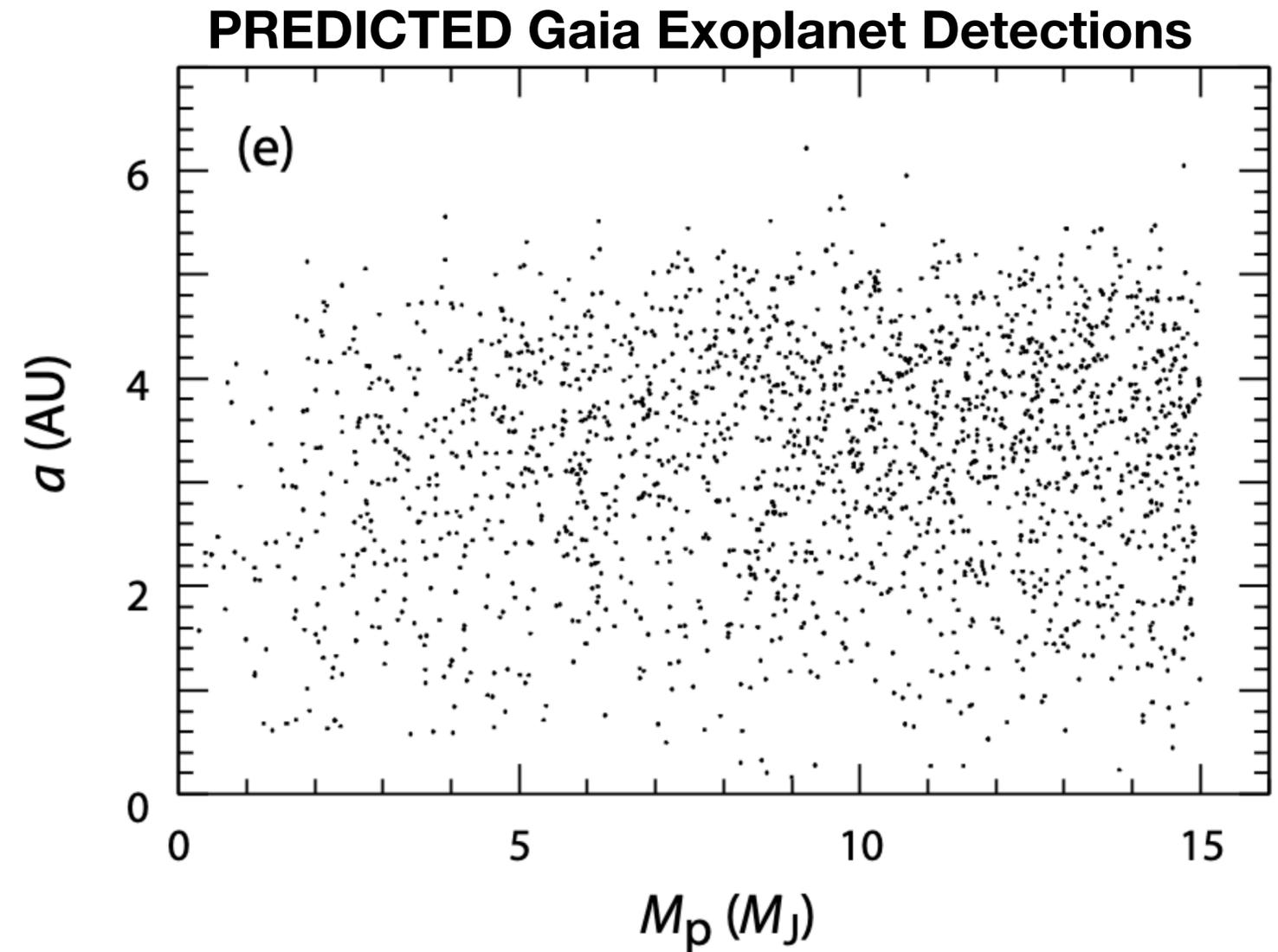
$$a_p M_p = a_s M_s \quad M_p = M_s \frac{a_s}{a_p}$$

- The semi-major axis of the planet is 1 AU, the mass is 1000 Jupiter masses, and the smallest semi-major axis of the star we can detect is $10^{-4} AU$. Putting it all together:

$$M_p = M_s \frac{a_s}{a_p} = 1000 M_{Jup} \frac{10^{-4} AU}{1 AU} = 0.1 M_{Jup} \quad \text{So about one third the mass of Saturn. Nice!}$$

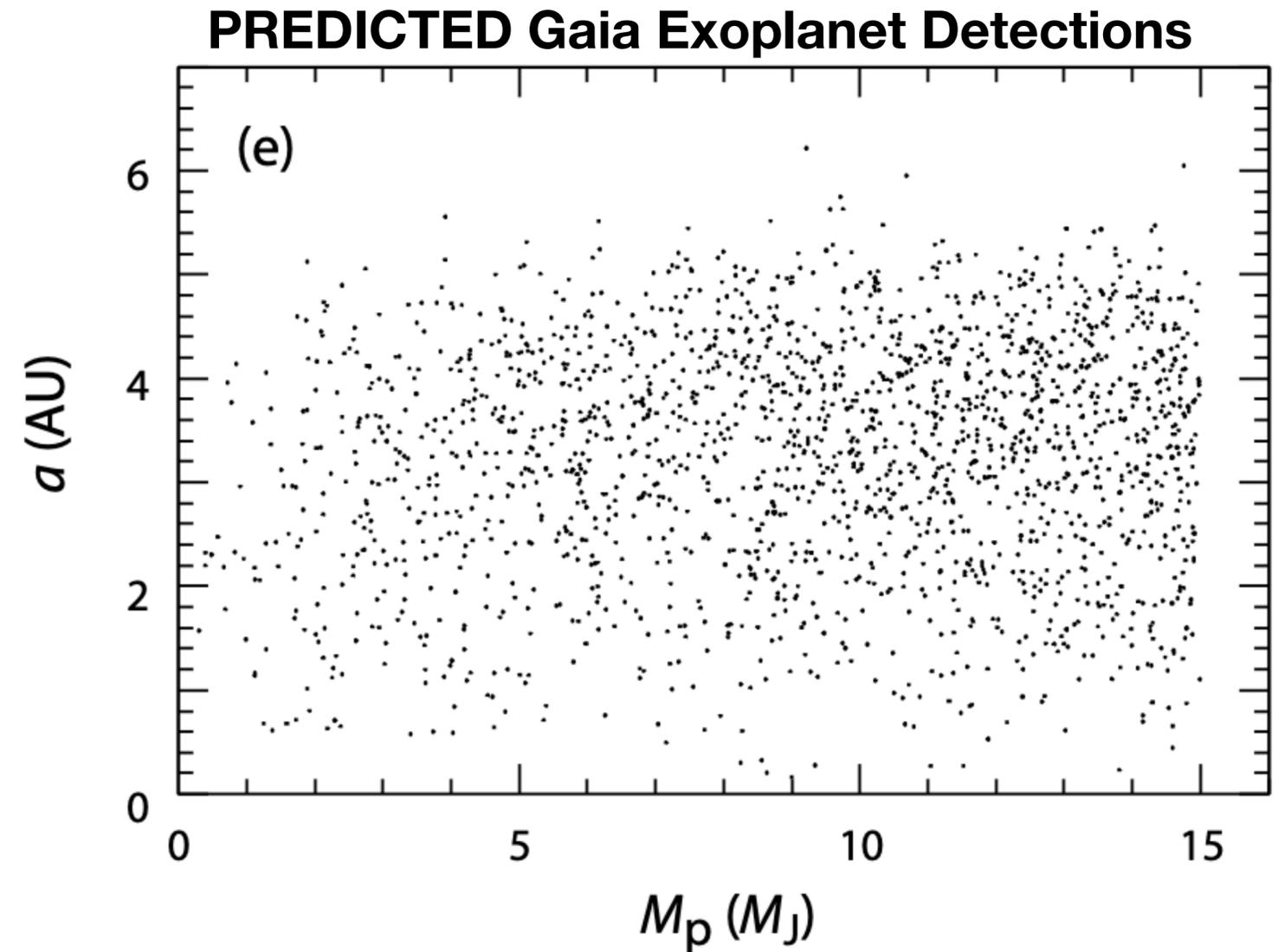
Astrometry and Exoplanets

- Currently, ~~no exoplanets have~~ one exoplanet has been discovered by astrometry
- Can measure:
 - Semi-major axis, orbital period, eccentricity, inclination angle
 - Mass of the planet (no $\sin(i)$ uncertainty)



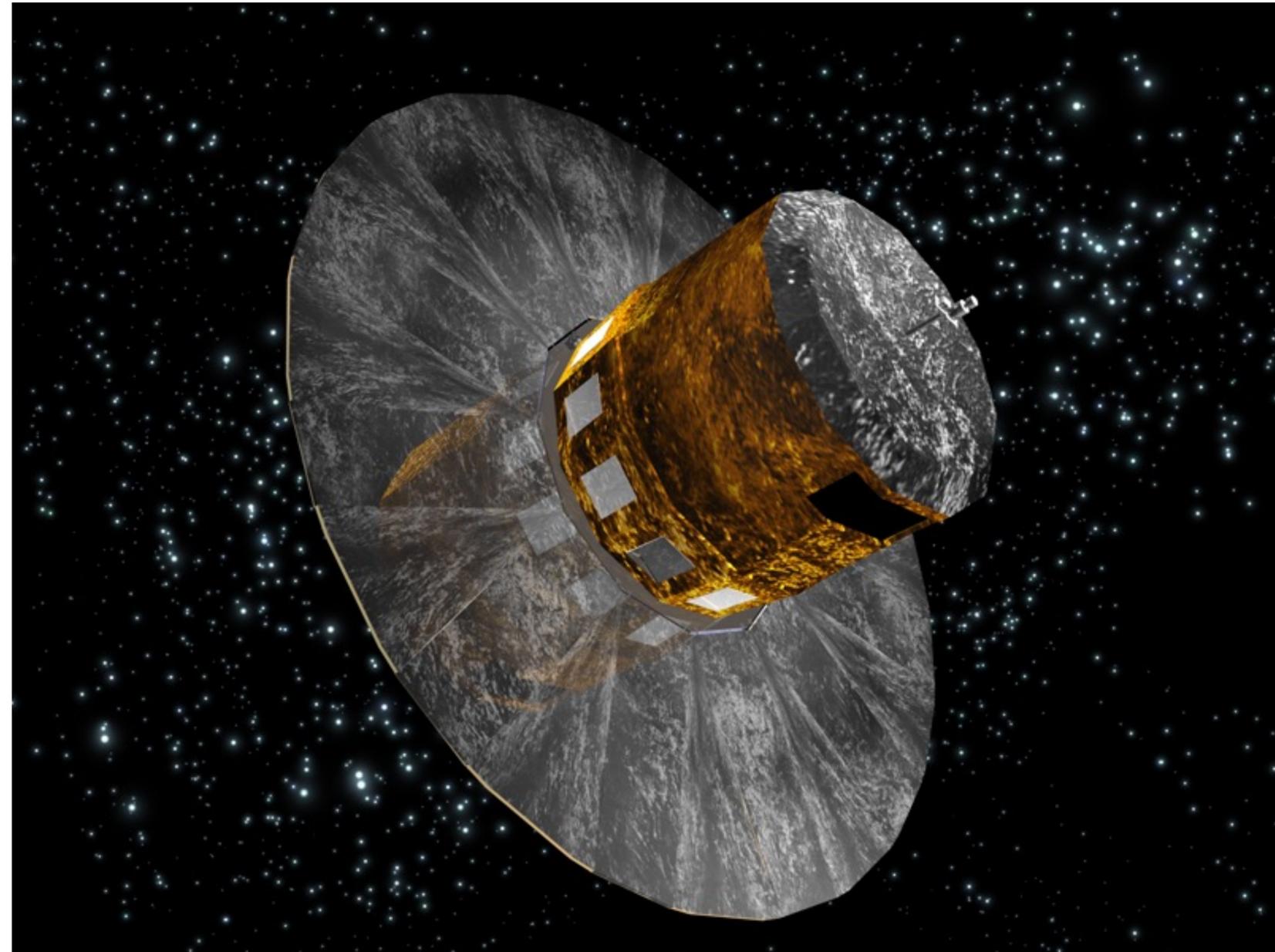
Astrometry and Exoplanets

- Biases:
 - Works best for planets about the mass of Jupiter and larger, and most sensitive to nearby stars (within about 100 pc)
 - Planets within about 1 AU are too close to move the star enough, and planets further than 5 AU are too far for enough orbital motion over the lifetime of the Gaia mission
- Gaia-detected exoplanets will be very good targets for future direct imaging missions to measure spectra



Gaia

- Gaia is a space telescope, launched in 2013, that is continually measuring the position of stars in the sky multiple times a year
- The precision of Gaia: 10 micro-arcseconds (the diameter of a coin held 100,000 miles away)
- At the end of its mission, Gaia will likely detect hundreds (or maybe thousands) of giant planets (Jupiter mass and above) around nearby stars

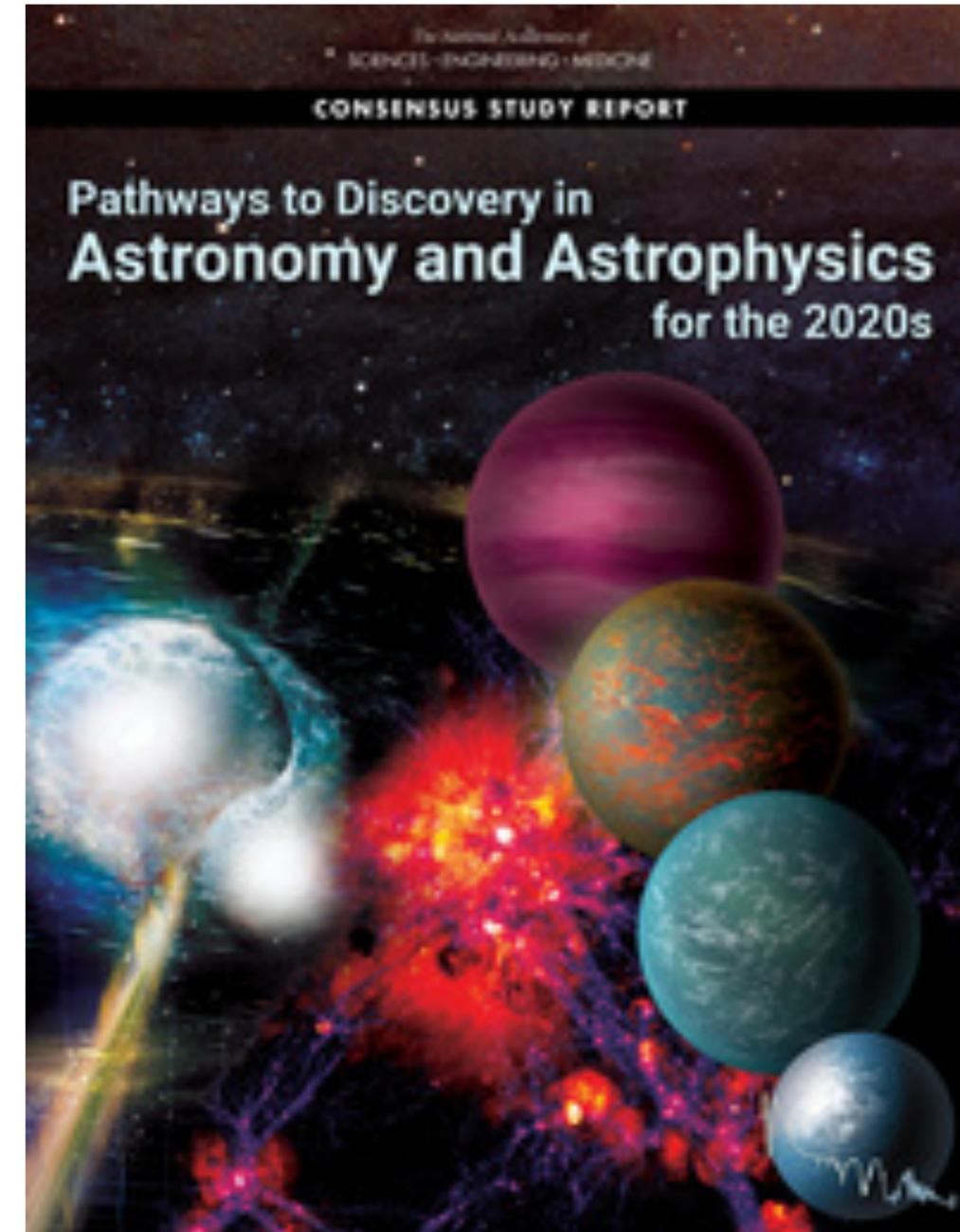


Break

05:00

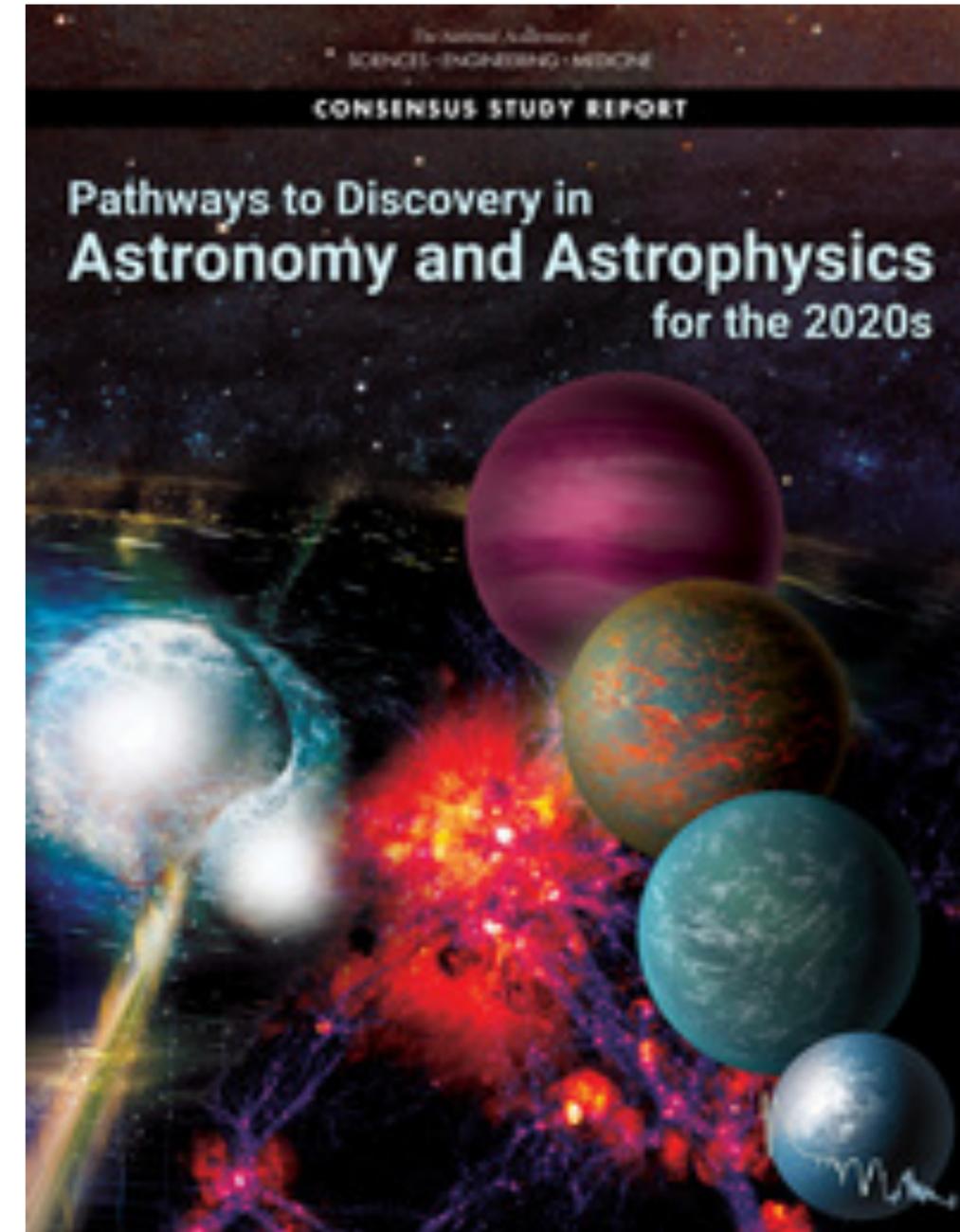
Astronomy 2020 Decadal Survey

- “After a successful mission and technology maturation program, NASA should embark on a program to realize a mission to search for biosignatures from a robust number of about ~25 habitable zone planets and to be a transformative facility for general astrophysics. If mission and technology maturation are successful, as determined by an independent review, implementation should start in the latter part of the decade, with a target launch in the first half of the 2040’s”



Astronomy 2020 Decadal Survey

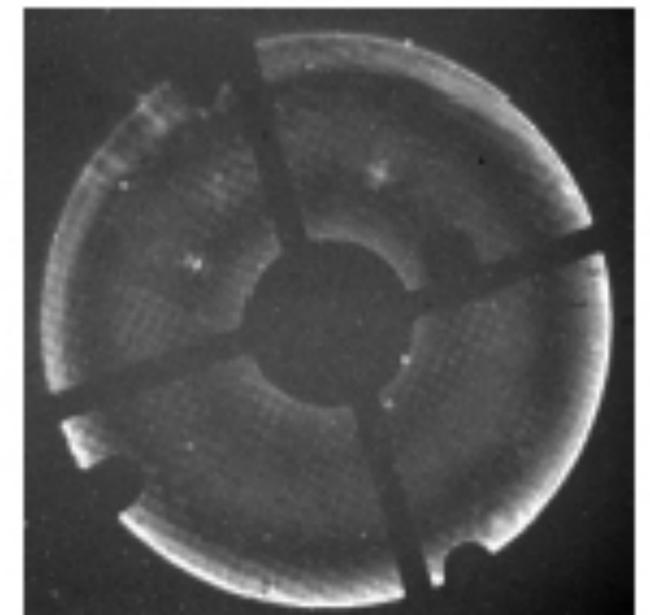
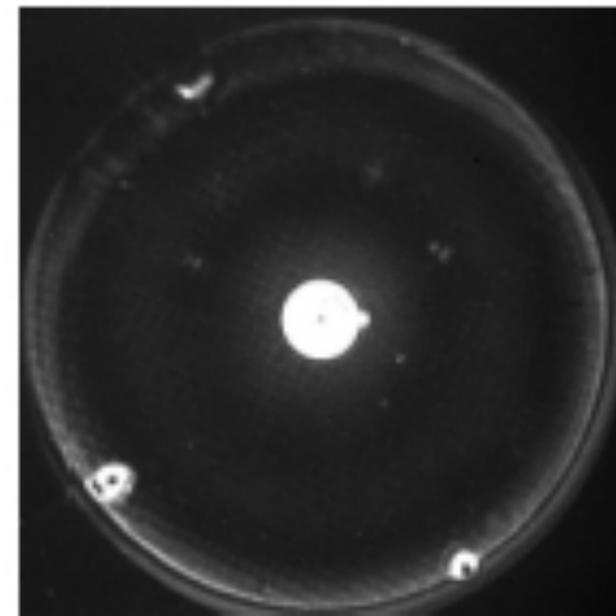
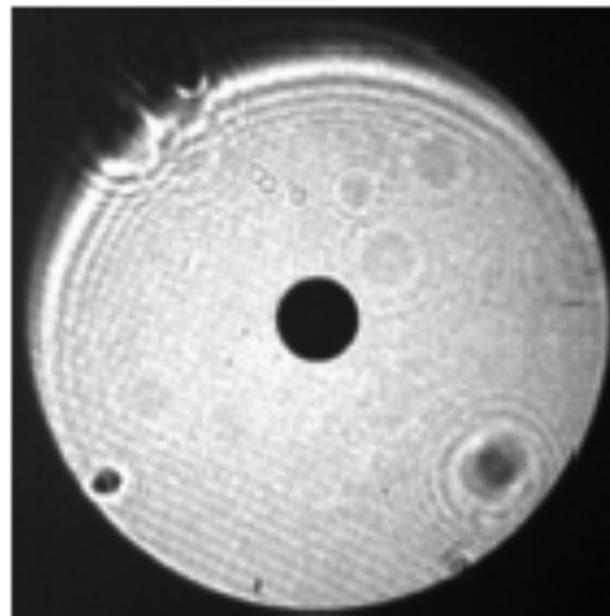
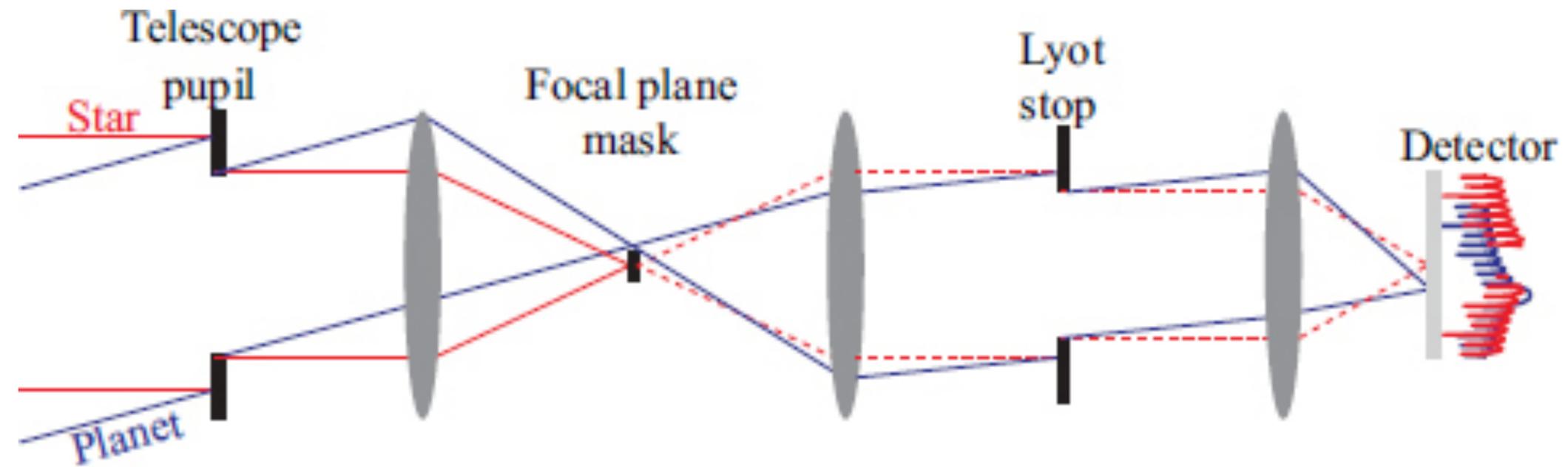
- Likely a 6m space telescope specifically designed to detect and take spectra of Earth-like exoplanets
 - UV, Optical, NIR
- Will also do general astrophysics
- A melding of the “HabEx” and “LUVOIR” mission concepts



Blocking Starlight: Coronagraph

- With ground-based 8-10 meter telescopes, working in the infrared, using state-of-the-art adaptive optics, and coronagraphs:

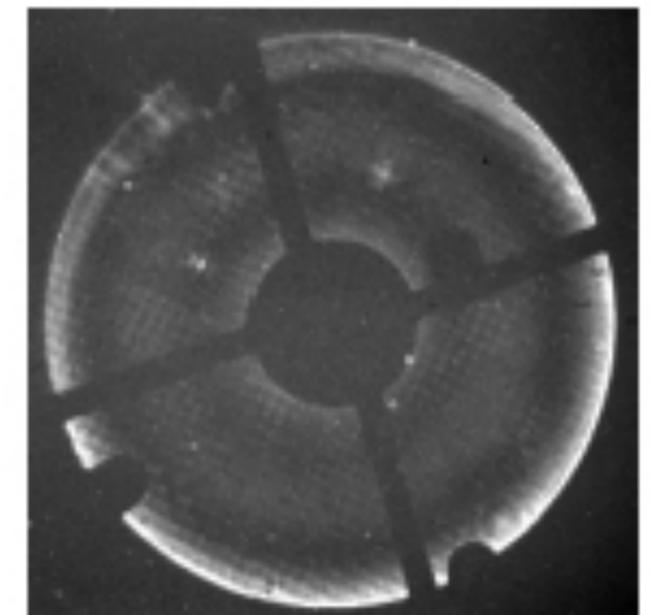
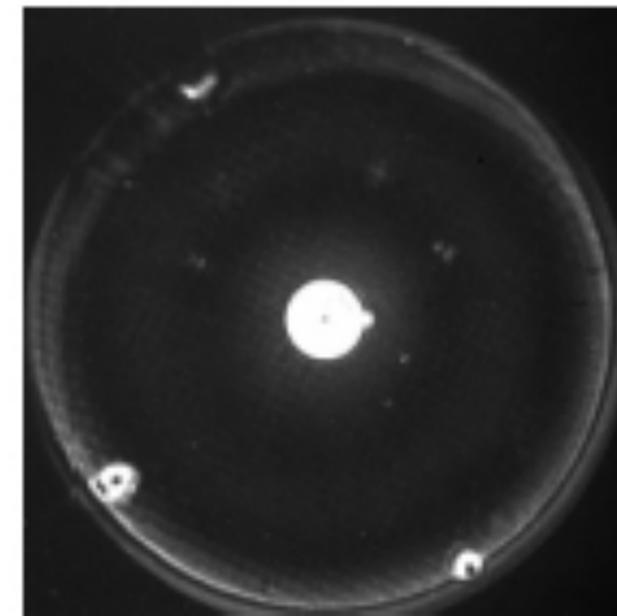
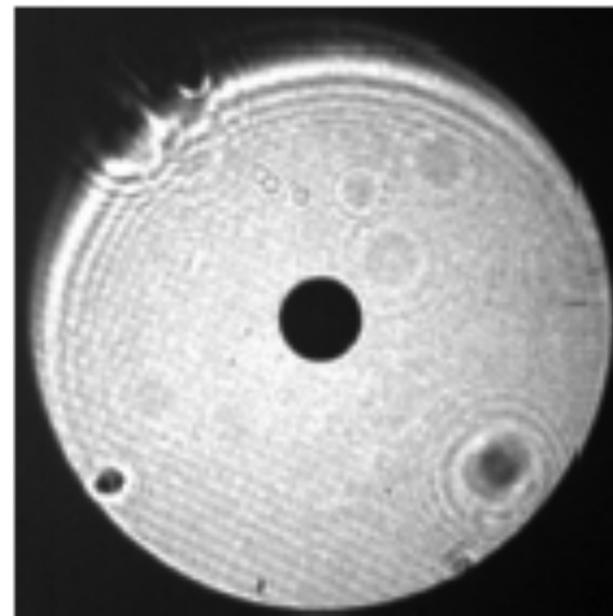
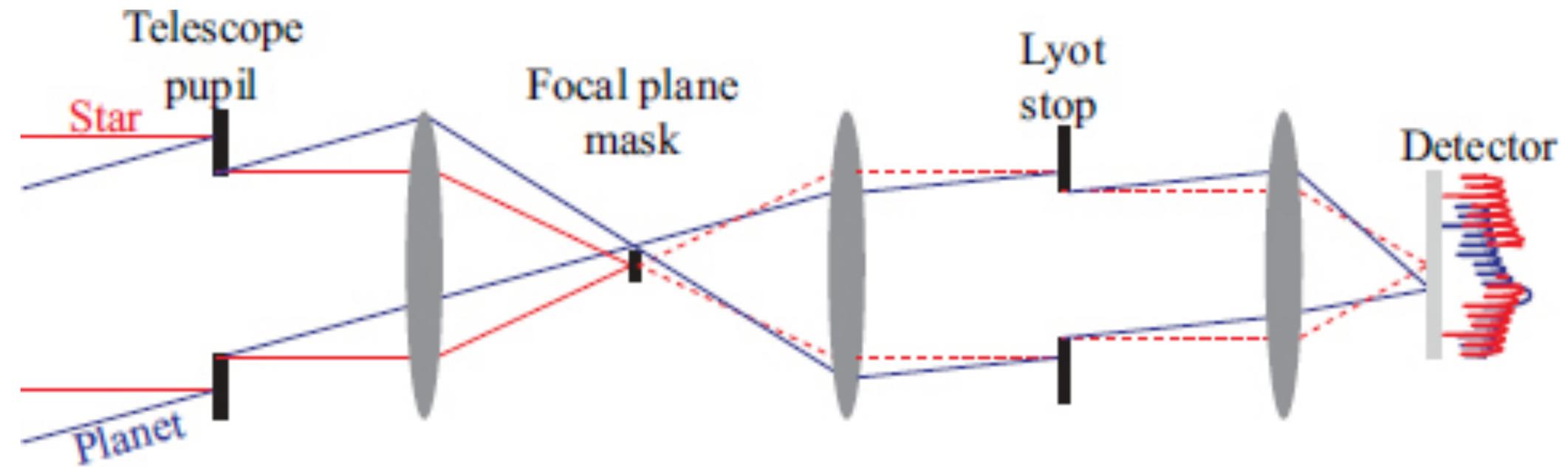
- We can image planets 1 million times fainter than their star, 0.5 arcseconds from the star



Blocking Starlight: Coronagraph

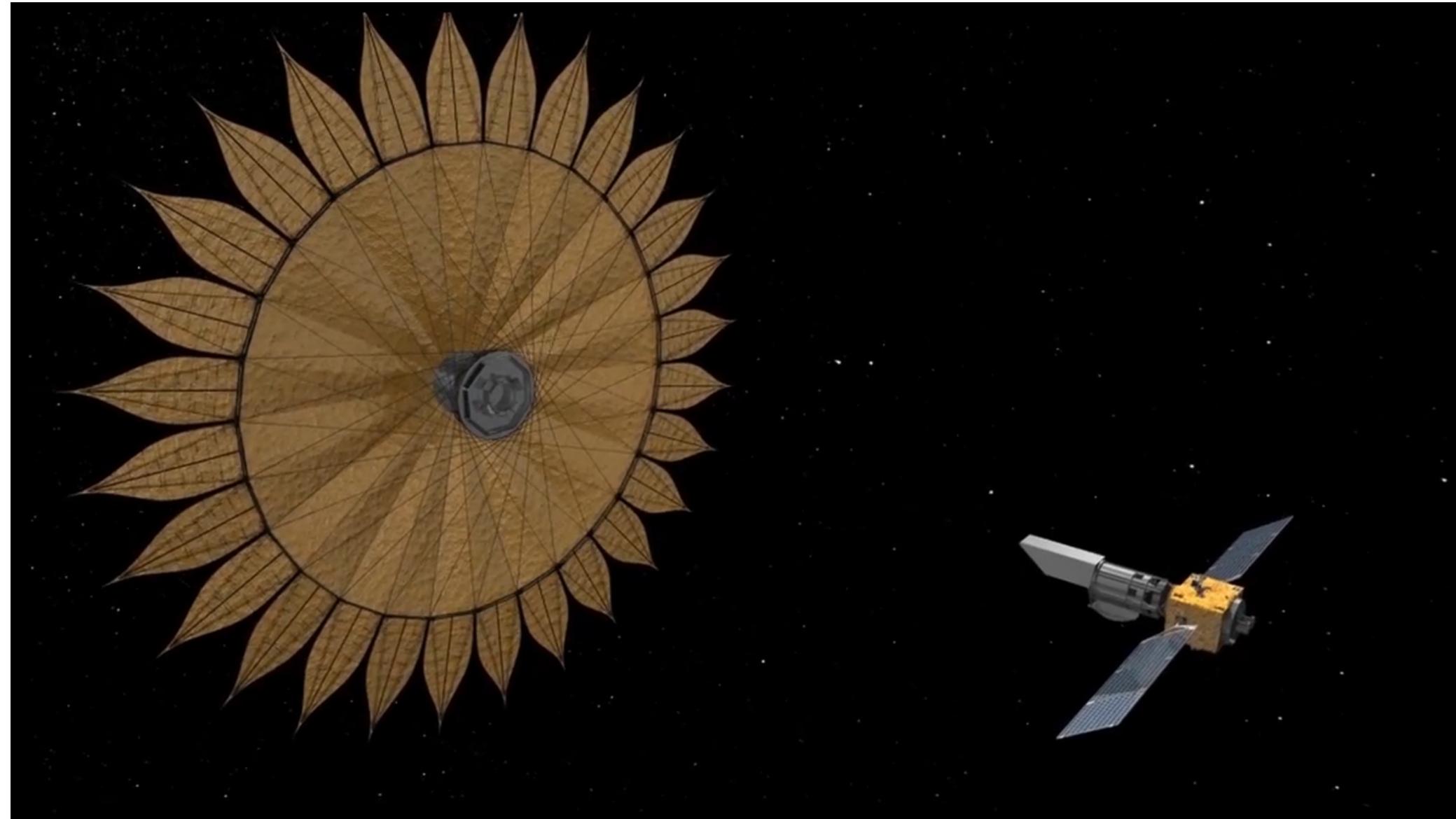
- Advanced coronagraph designs on future space telescopes can reach 10 billion-to-1 contrasts

- These coronagraphs will also block much of the planet's light too: it will take days or weeks to take a single spectrum



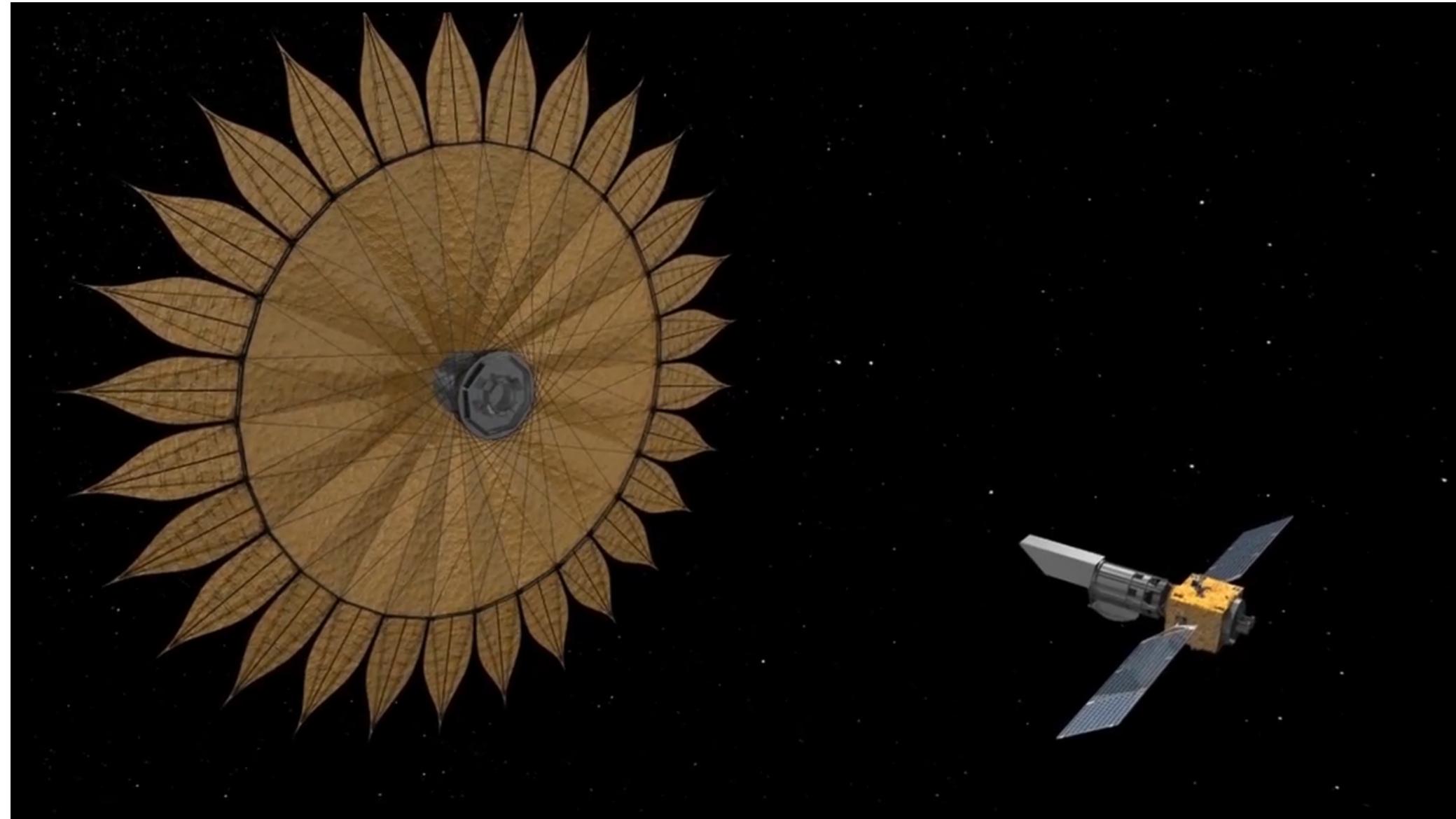
Blocking Starlight: Starshade

- A coronagraph is built inside a space telescope
- A starshade is a separate spacecraft, 10s of meters across, flying 10s of thousands of miles away from the telescope



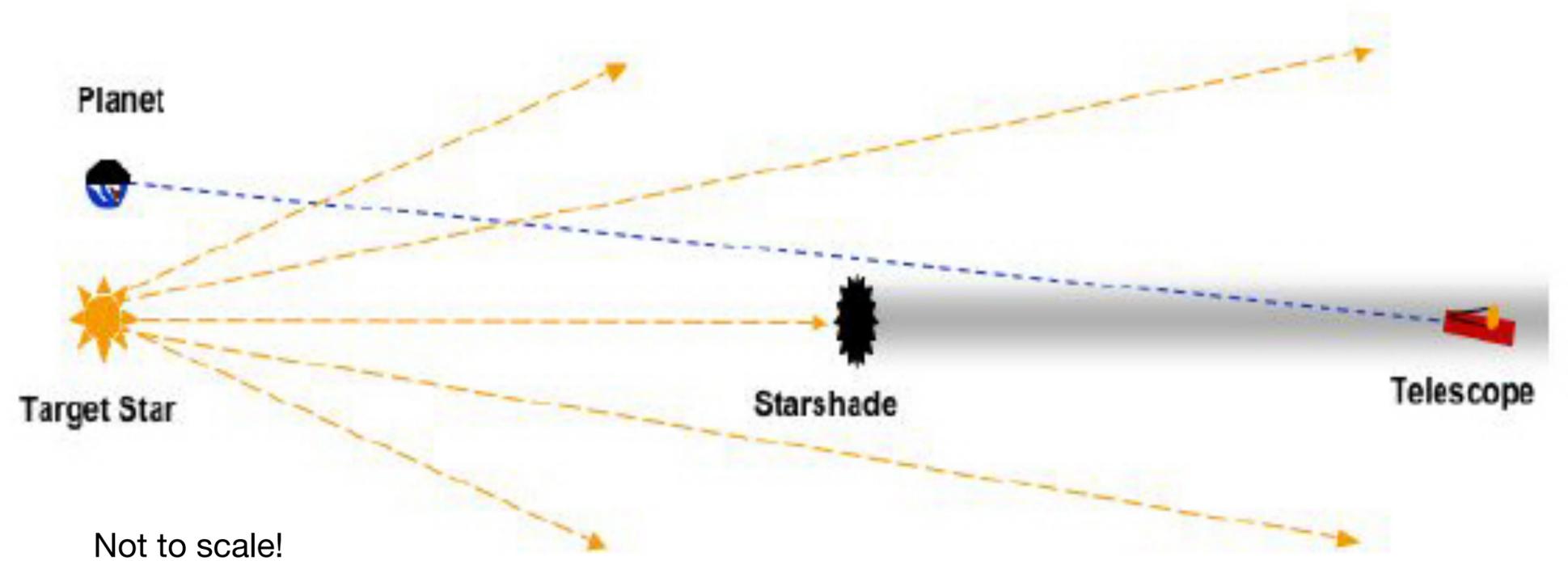
Blocking Starlight: Starshade

- The starshade maneuvers to be directly between the space telescope and the star that (hopefully!) hosts an exoplanet, casting a shadow
- The telescope, inside the starshade's shadow, can then observe the exoplanet without the glare of the host star's light



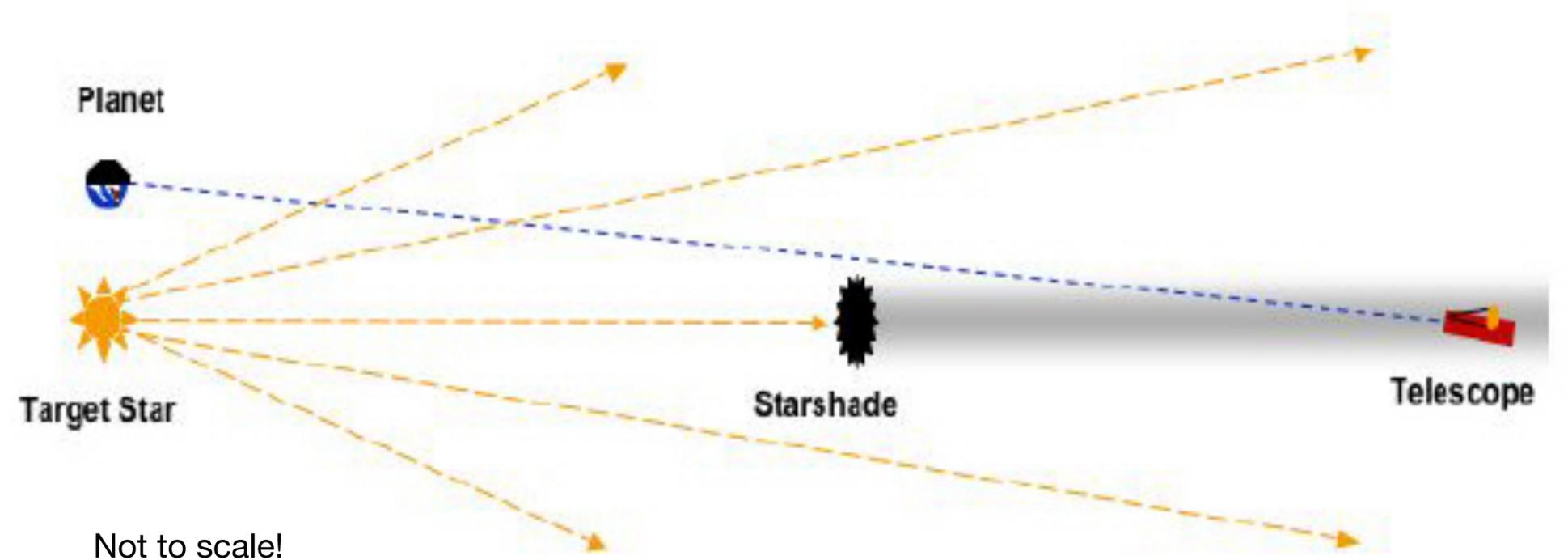
Starshades

- Starshades are much more efficient than coronagraphs: they only block out the star's light, not the planet's
- Spectra of exoplanets can be collected much more quickly using a starshade



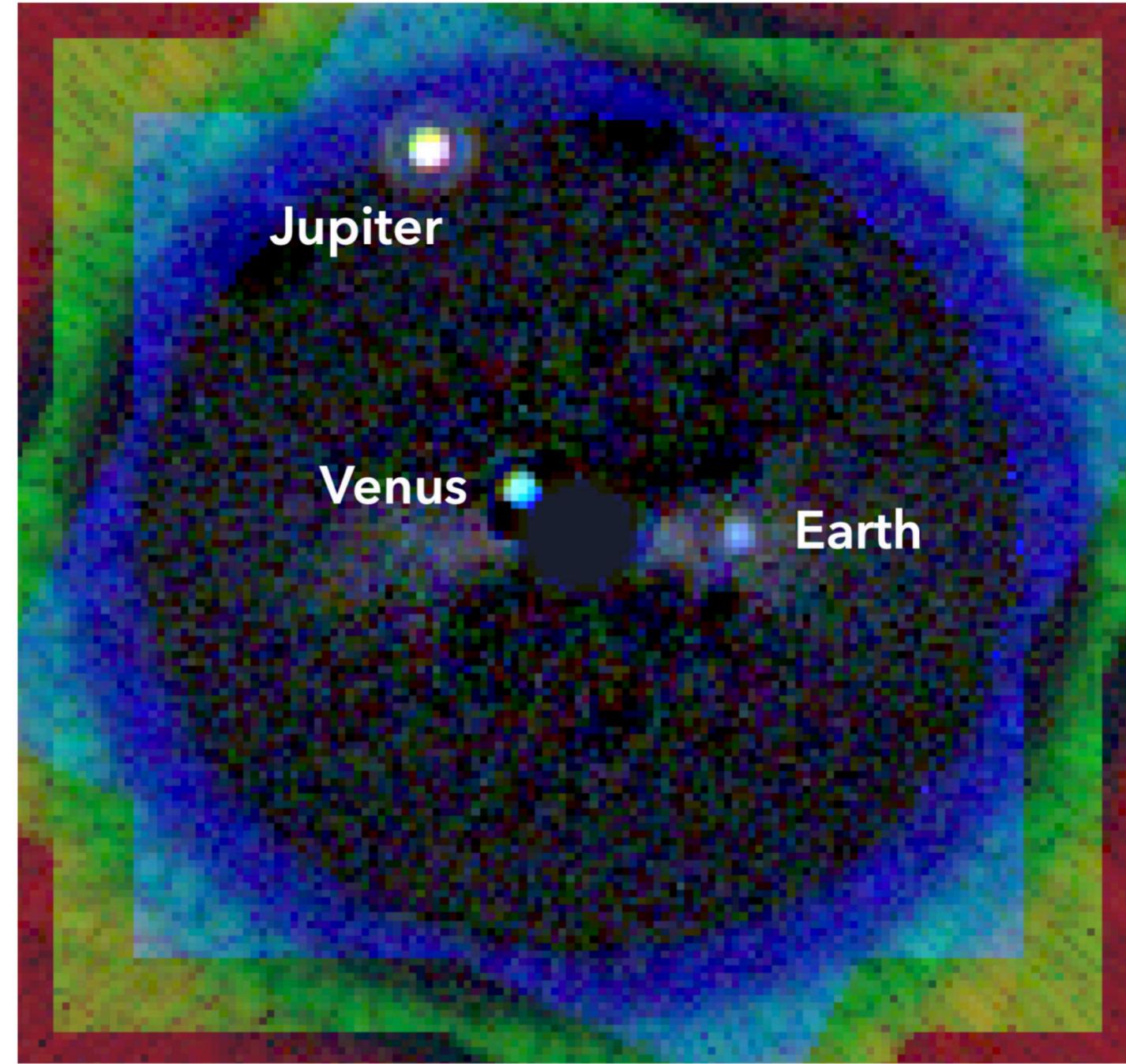
Starshades

- Starshades are much more expensive: two spacecraft are required that must align precisely
- Each time you want to observe a new star, there's a large fuel cost to move the starshade
- But, the space telescope can do other science while the starshade is moving



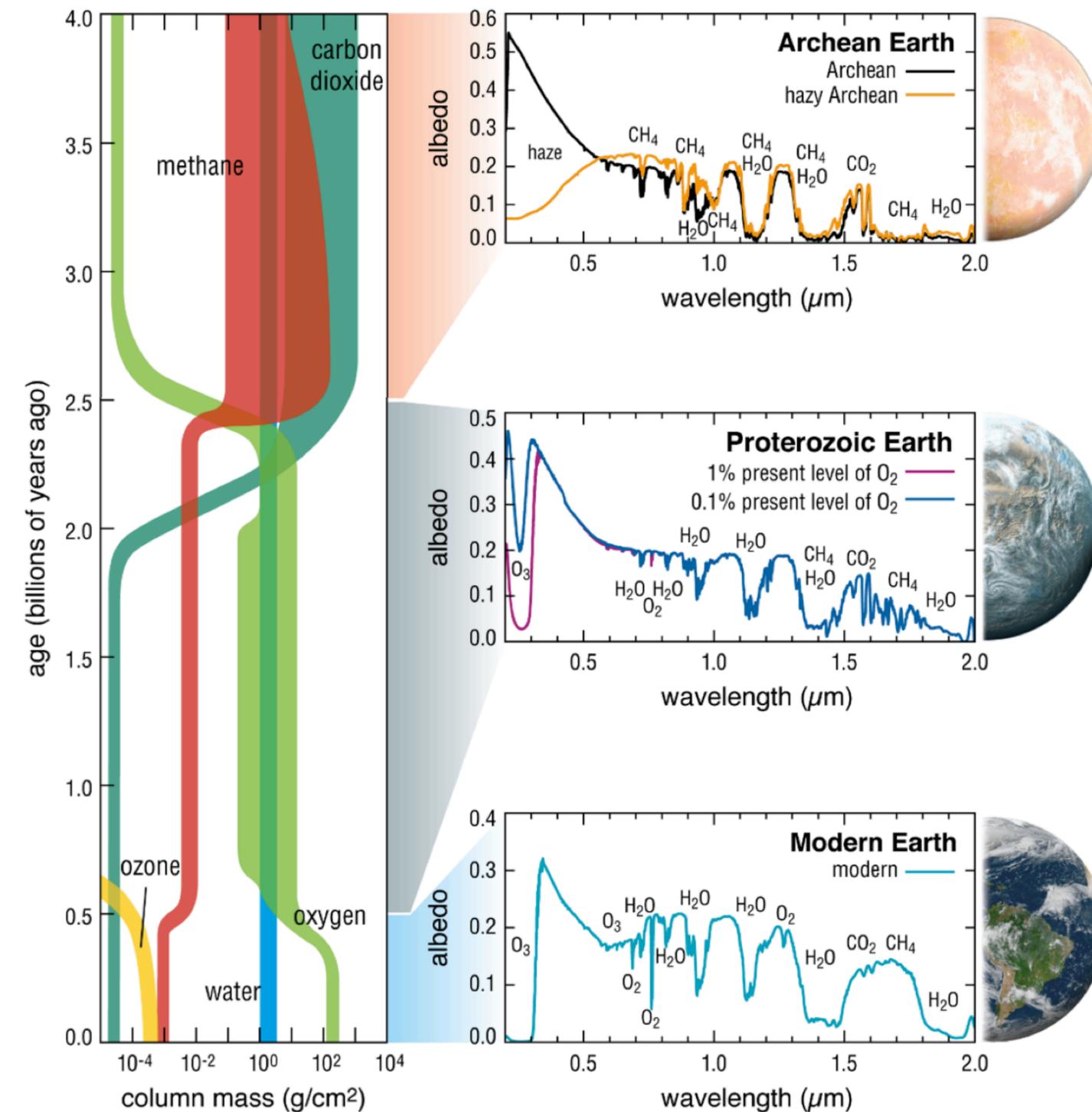
Imaging Exoplanets with a Coronagraph

- Use a coronagraph to take images and spectra of planets (terrestrial and giant) around nearby stars, in reflected light



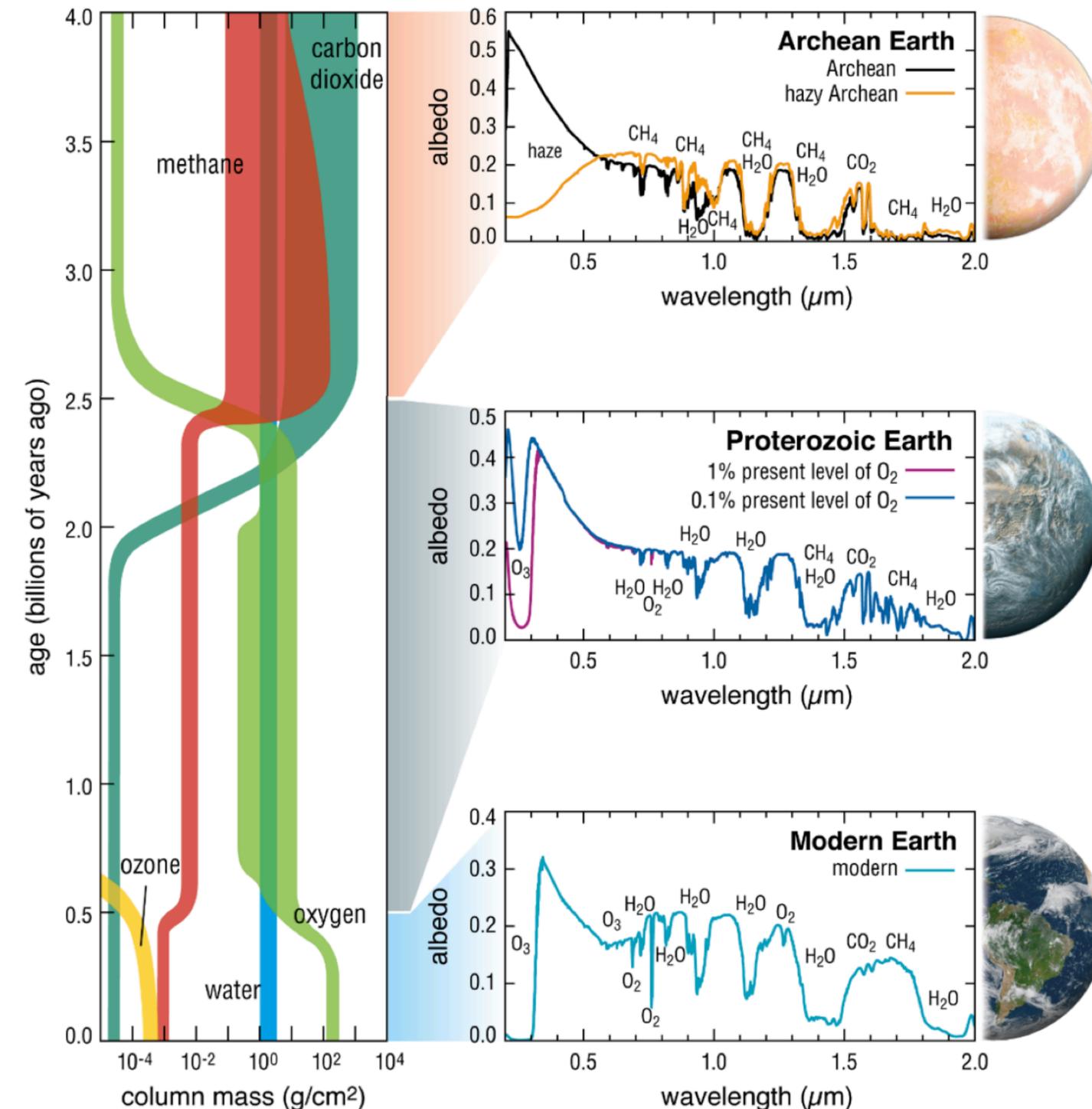
Spectra and habitability

- Absorption features, in the visible and near-infrared, tell us what an atmosphere is made out of
- The composition of Earth's atmosphere has changed over billions of years



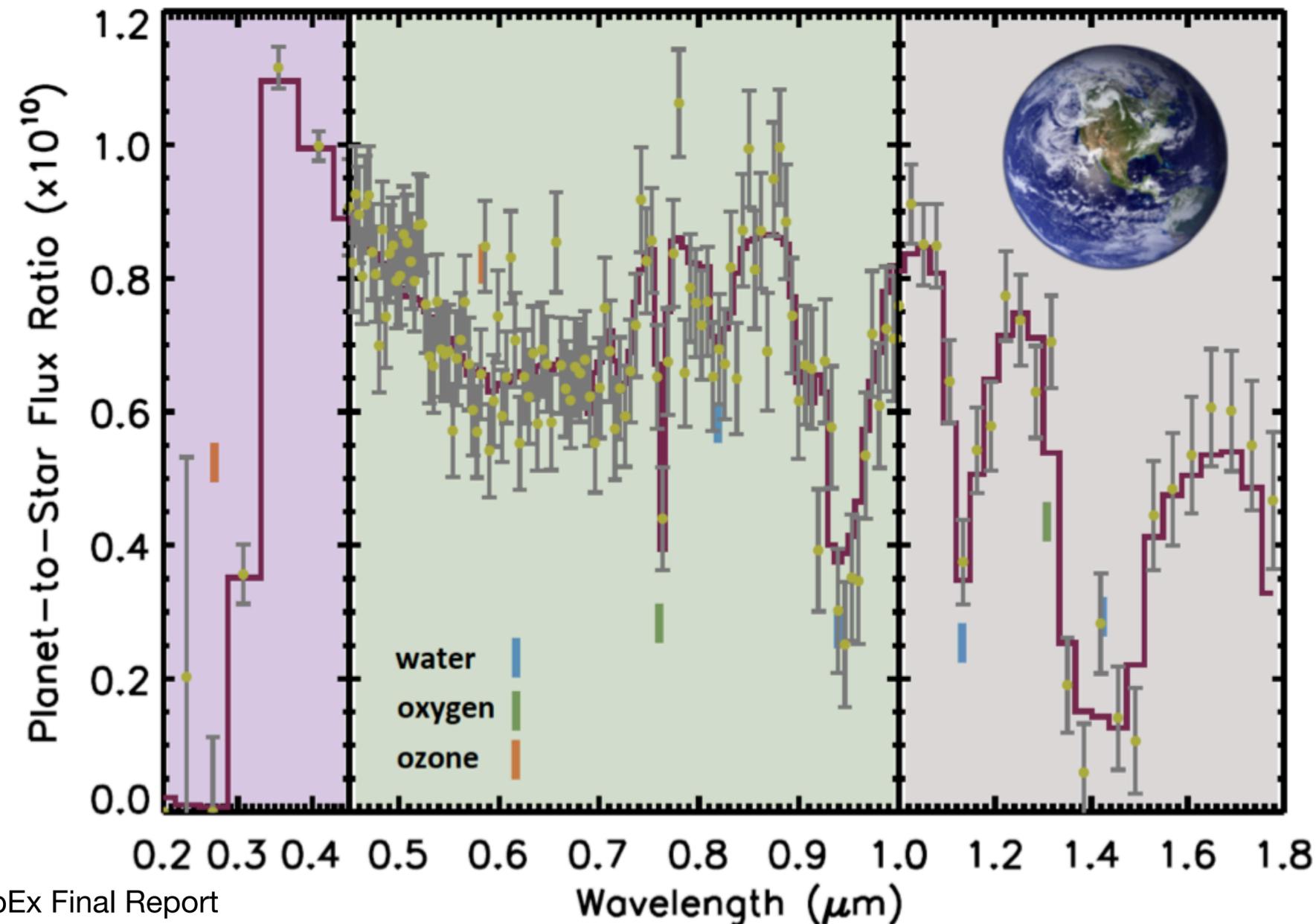
HabEx spectra and habitability

- In the Archean, molecules in our atmosphere were mainly carbon dioxide, methane, and water vapor
- Over time, photosynthesis increased the amount of oxygen, decreased the amount of carbon dioxide, and methane reacted with oxygen
- Spectra taken of Earth during these different stages would show large changes
- Spectra can determine if they have atmospheres similar to Earth now, or Earth in the past (or something else!)



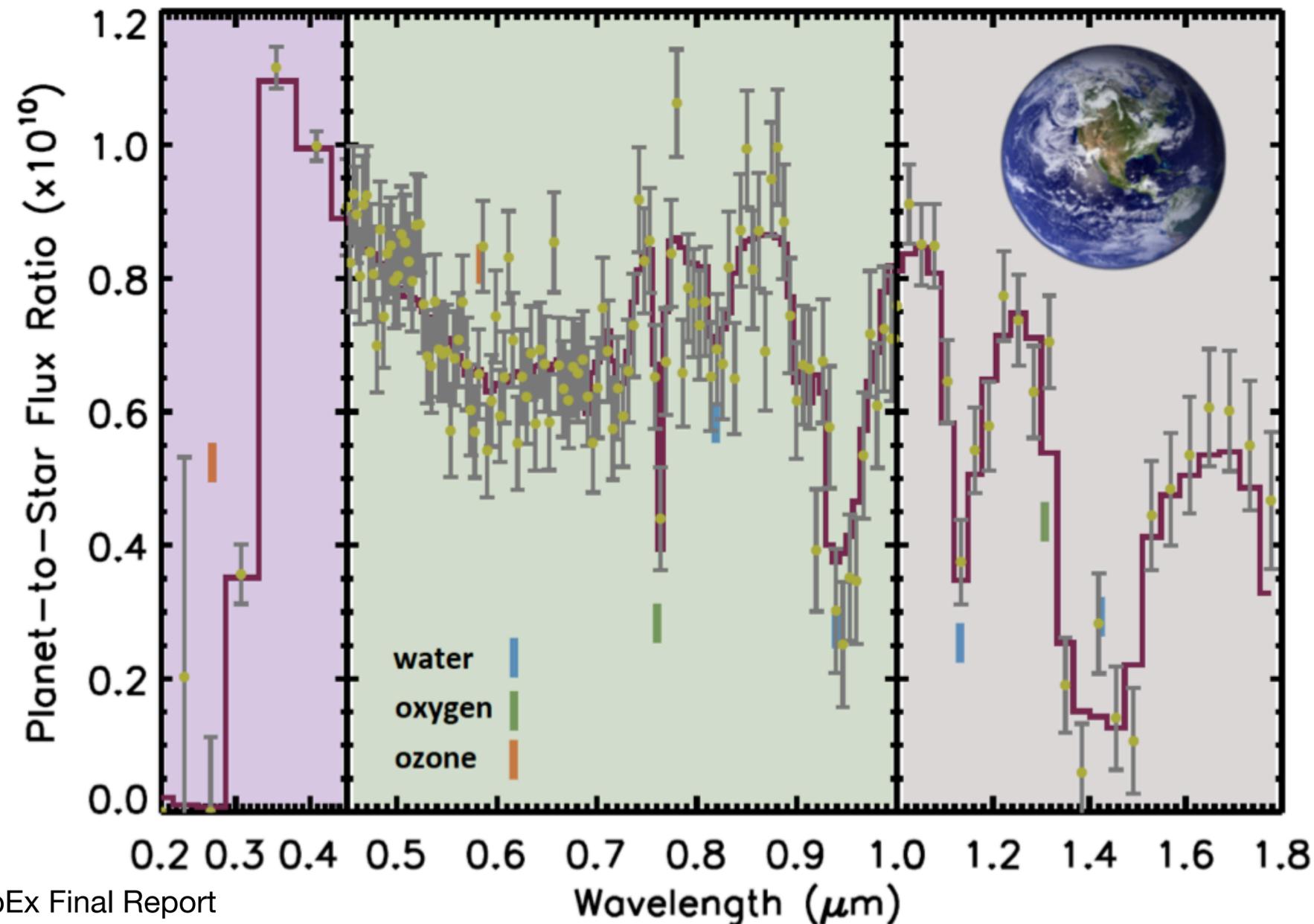
HabEx spectra and biosignatures

- Certain molecules are biosignatures, that are known to be produced by life, but aren't thought to occur naturally (without life)
- For example, methane and oxygen is a strange combination:
 - By themselves, both methane and oxygen form through natural processes
 - But together, methane reacts with oxygen to produce water and other molecules



HabEx spectra and biosignatures

- On Earth, we have methane in our atmosphere because life is producing methane just as fast as it's being destroyed
- If we see these combinations of molecules out of chemical equilibrium, it would be evidence there is life on the planet
- A key goal of the 2040s planet-finding space telescope will be to search for biosignatures in the atmospheres of Earth-like planets around nearby stars



~~For next time~~

- Homework 6 due tonight at 11:59pm
- Final Exam Monday, December 5 10:30-12:30 (this room)
 - Don't need a calculator or paper, just something to write with