Today in Astronomy 106: exoplanets

- Exoplanets and their diversity
- How many stars have planets
  - Spoiler alert: essentially all of them
- How to find exoplanets
  - Direct imaging: taking pictures and watching them orbit the star
  - Radial velocity (RV) planet detection

Robert Hurt, SSC/JPL/Caltech/NASA.

The bad news

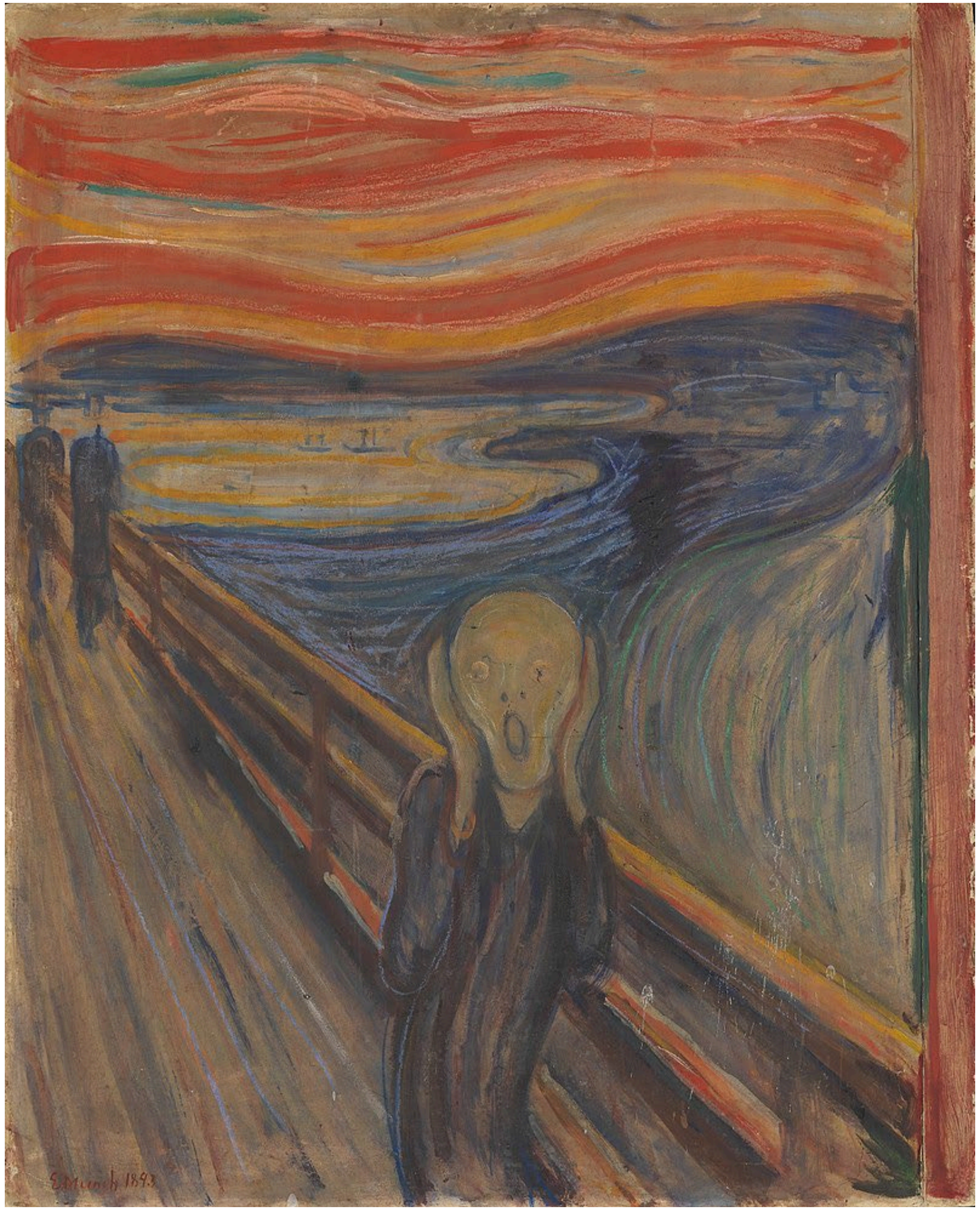
Exam #2 takes place here a week from Thursday. You are hereby reminded:

- To the test bring only a writing instrument, a calculator, and one 8.5”×11” sheet on which you have written all the formulas and constants that you want to have at hand.

- No computers, no access to internet or to electronic notes.

- The best way to study is to work problems like those in homework and workshop, understand the solutions we distributed, refer to the lecture notes when you get stuck, and make up your cheat sheet as you go along.

- Try the Practice Exam on the web site. Under realistic conditions, of course.



Exoplanets

The first exoplanet known to humans and belonging to a normal star, 51 Pegasi b, was discovered in 1995, by Michel Mayor and Didier Queloz.

- Mayor & Queloz shared half of the 2019 Nobel Prize in Physics for their discovery.

This discovery spawned intensive searches for more, which have revealed, as of today, **5787 confirmed** exoplanets and **7341** additional good candidates. (No exomoons yet.)

- The number of confirmed exoplanets doubles about every 28 months…

- … growing almost as fast as the number of transistors on the most advanced integrated circuits, which doubles about every 24 months.

Michel Mayor and
Didier Queloz

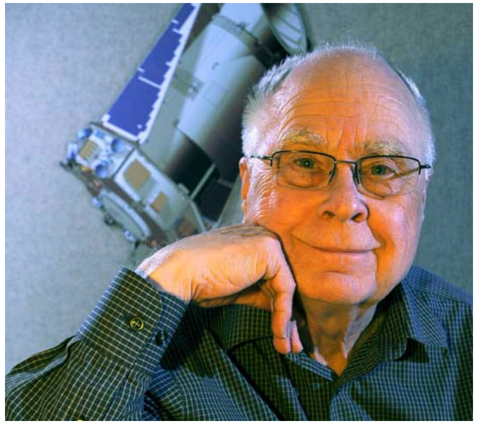
Exoplanets (continued)

The [NASA Kepler satellite] has made the lion's share of the discoveries.

- To date, 2778 confirmed and 1982 awaiting confirmation from the main mission; 548 and 975, from the extended mission ("K2").

Once Kepler had extended the exoplanet list to the thousands, their demographic statistics began to reveal

- that essentially all stars have planets, just as essentially all young stars have protoplanetary disks.
- wide and unexpected diversity among the planets and their host stars.
- both Earthlike planets lying in the **habitable zone** around their host star, and how frequently such situations are found.



Bill Borucki, leader of the Kepler team

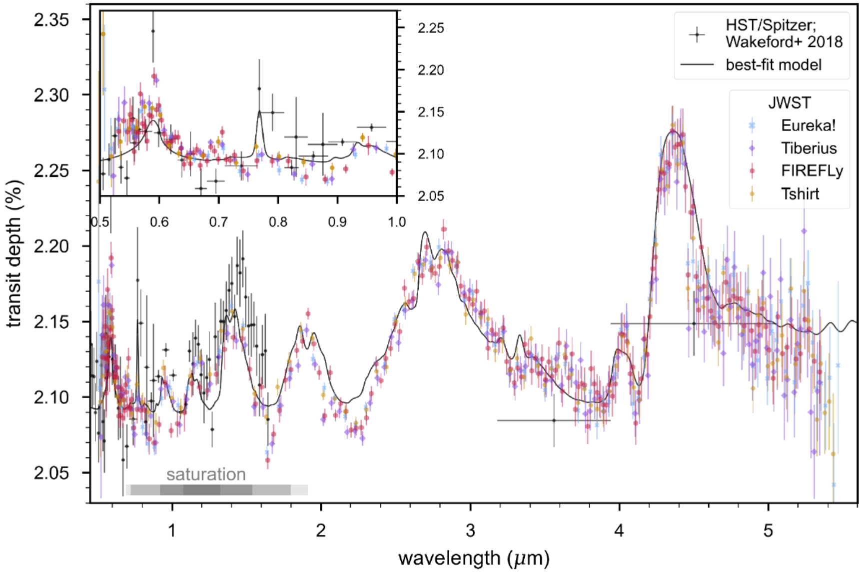
Exoplanets (continued)

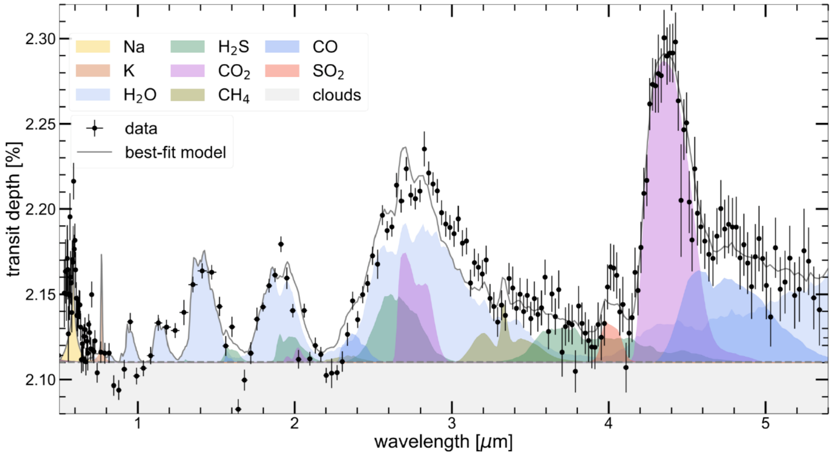
State-of-the-art exoplanet observations now include studies of their atmospheres, both

- in transmission, as backlit by the host star,
- and in the planet's own emitted light.

Most of the exoplanet-atmosphere detections so far have been by HST, but …

- … ground-based observatories are becoming capable, and adding many abilities not possessed by HST, and …
- … JWST, as expected, has begun to produce high-quality exoplanet-atmospheric spectra in large numbers.
  - 25% of JWST's observing time is going toward exoplanets, their atmospheres, and protoplanetary disks.





Rustamkulov et al. 2022

Exoplanetary diversity

The five main types of exoplanets found in big surveys like Kepler:

- **Jupiters**: giant gaseous planets like our own Jupiter and Saturn. Large; mostly made of H_2 and He. Some would identify the largest examples of these as “super-Jupiters.”

- **Neptunes**: medium-size planets with rocky cores and thick atmospheres mostly made of H_2 and He. Like our own Uranus and Neptune. Some would segregate the smaller ones into “mini-Neptunes.”

- **Super-earths**: medium-size, rocky planets with little to no atmosphere. Our solar system has no super-earths. (But see below …)

- **Earths**: small rocky planets like ours. No exo-Earth has yet yielded an atmospheric detection; Earth wouldn’t have, either, at our current sensitivity.

- **Sub-earths**: Mars, Mercury, and such.

Exoplanetary diversity (continued)

Other dimensions of exoplanetary diversity:

- **Tidally-locked planets**: those whose day is precisely the same duration as their year, or, like Mercury, an integer-ratio multiple of their year. Most have permanent day- and night-sides; they are very common.
- **Hot Jupiters** and **hot Neptunes**: giant planets in orbits closer to their host stars than Mercury is to the Sun. They couldn't have formed in the orbits in which they are seen, for lack of enough mass there in the protoplanetary disk.
- **Tatooines**: planets in orbit around binary stars.
- **Superpuffs**: hot giant planets with especially extended atmospheres. For the atmospheres to last long enough for us to see them in this condition, is a theoretical challenge.
- **Waterworlds**: apparently covered with water. The few we know about are hot and have atmospheres mostly made of steam.
- **Doomed worlds**: planets in orbit around brown dwarfs, white dwarfs, or giant/supergiant stars.

Exoplanetary demographics

How do we know there are all these different kinds? Because we can **measure** the orbits, masses, and radii of the exoplanets.

- The following pages contain graphs of the observed properties of exoplanets, and comparison to physical models, which demonstrate the distinctions between the planet types we currently distinguish.

- They come from data, updated in real time, and contained in the **NASA Exoplanet Archive**, at

  https://exoplanetarchive.ipac.caltech.edu

  On the archive's plotting page, you can easily make your own graphs at any time, and easily download the data.

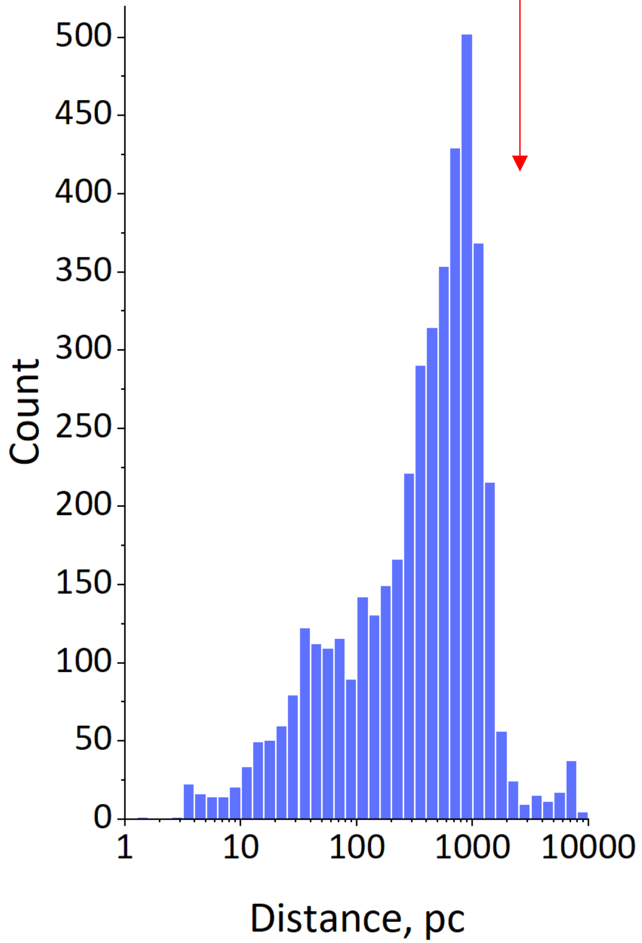
- For the following graphs I used the data as posted on 11 November 2024, on that day's total of 5787 **confirmed planets**.

  - By confirmed, we mean observations which are shown to have a very small probability to be a false-positive signal, and which have been published in peer-reviewed journals.

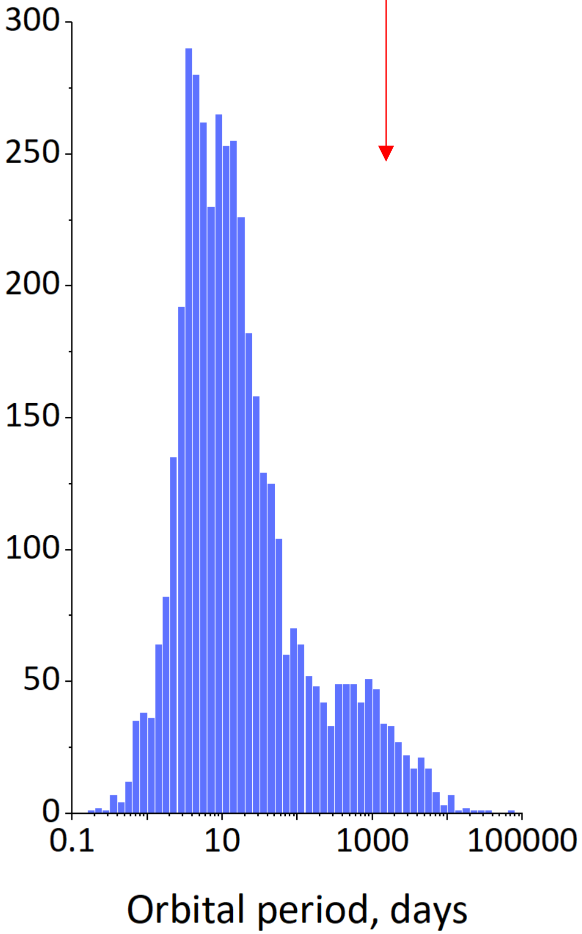
Exoplanet distances from Earth, orbital periods, and number of multiplanet systems

We do not yet have compre-hensive statistics for exoplanets of all distances, orbital periods, and masses.

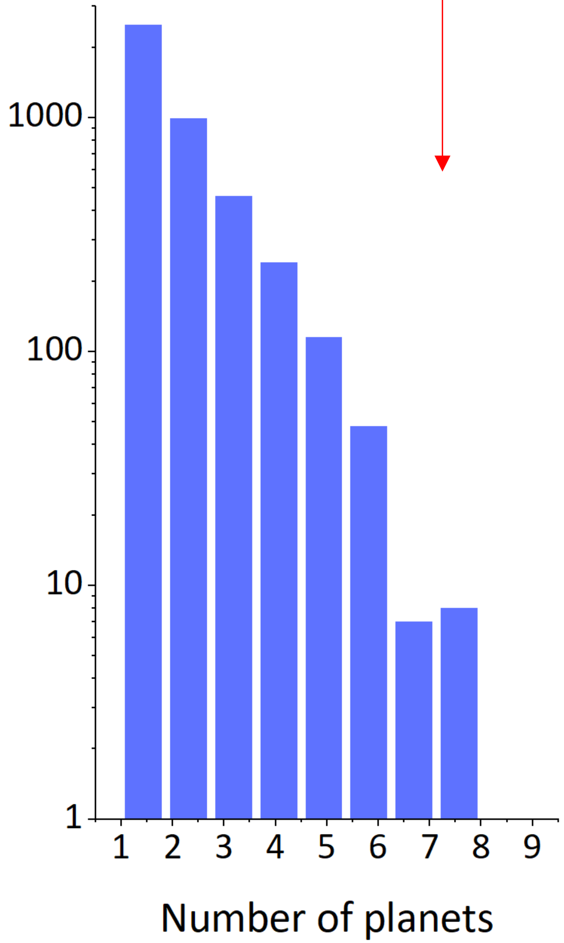
Bias: more distant objects are too faint for high-precision spectroscopy.



Bias: haven't been at this long enough to measure long orbital periods.



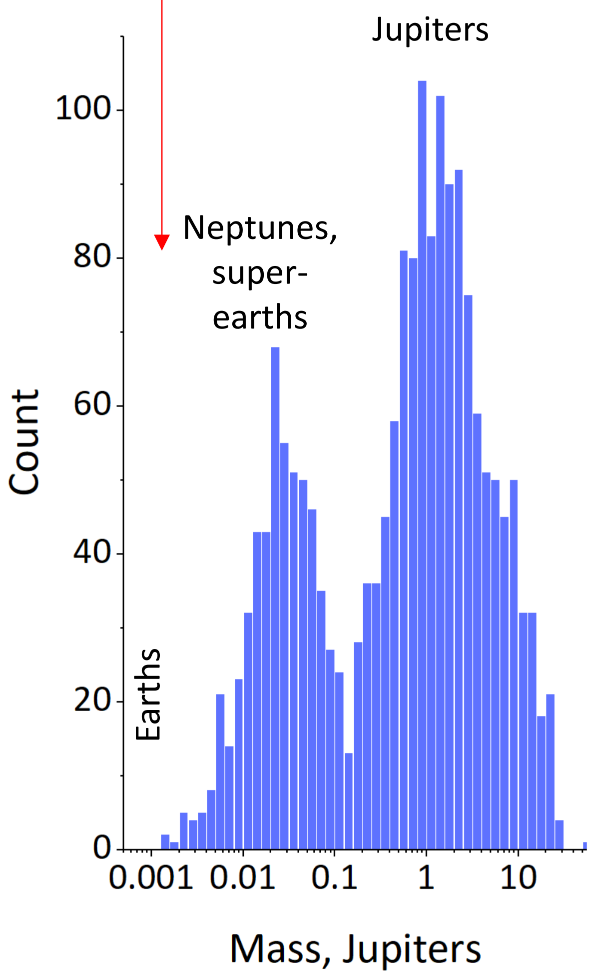
Bias: not yet finding all the low-mass planets in most planetary systems.

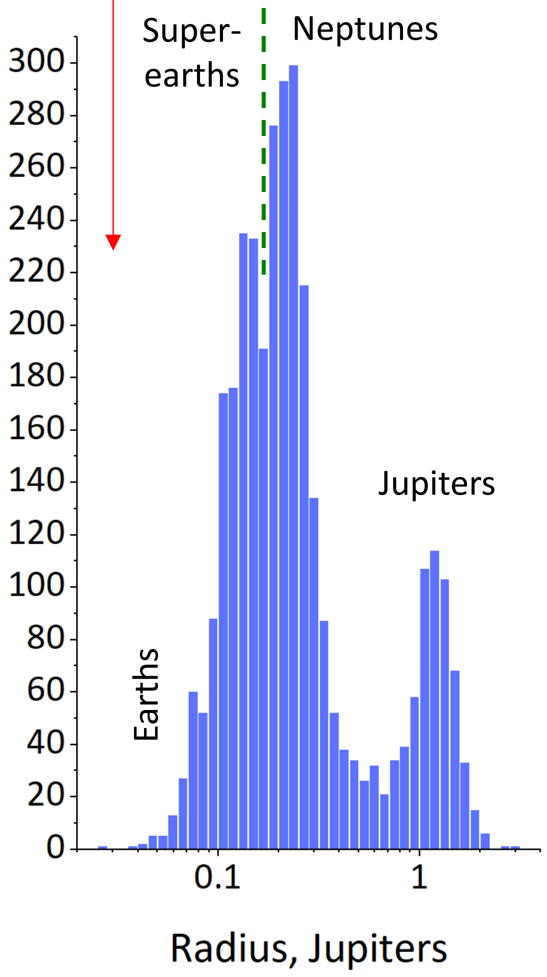


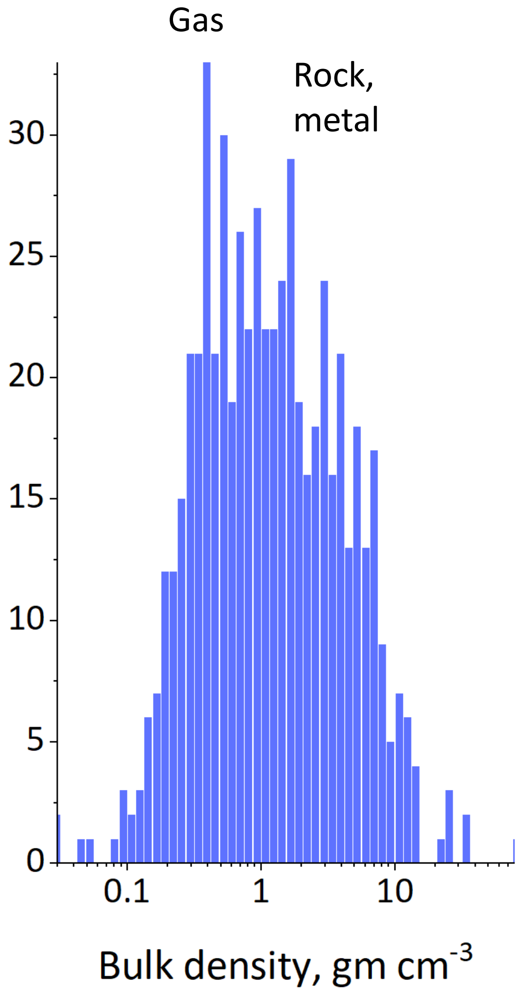
[NASA Exoplanet Archive, 11 November 2024]

Exoplanet masses, radii, and bulk densities

Bias: it is still hard to detect Earths and sub-Earths.





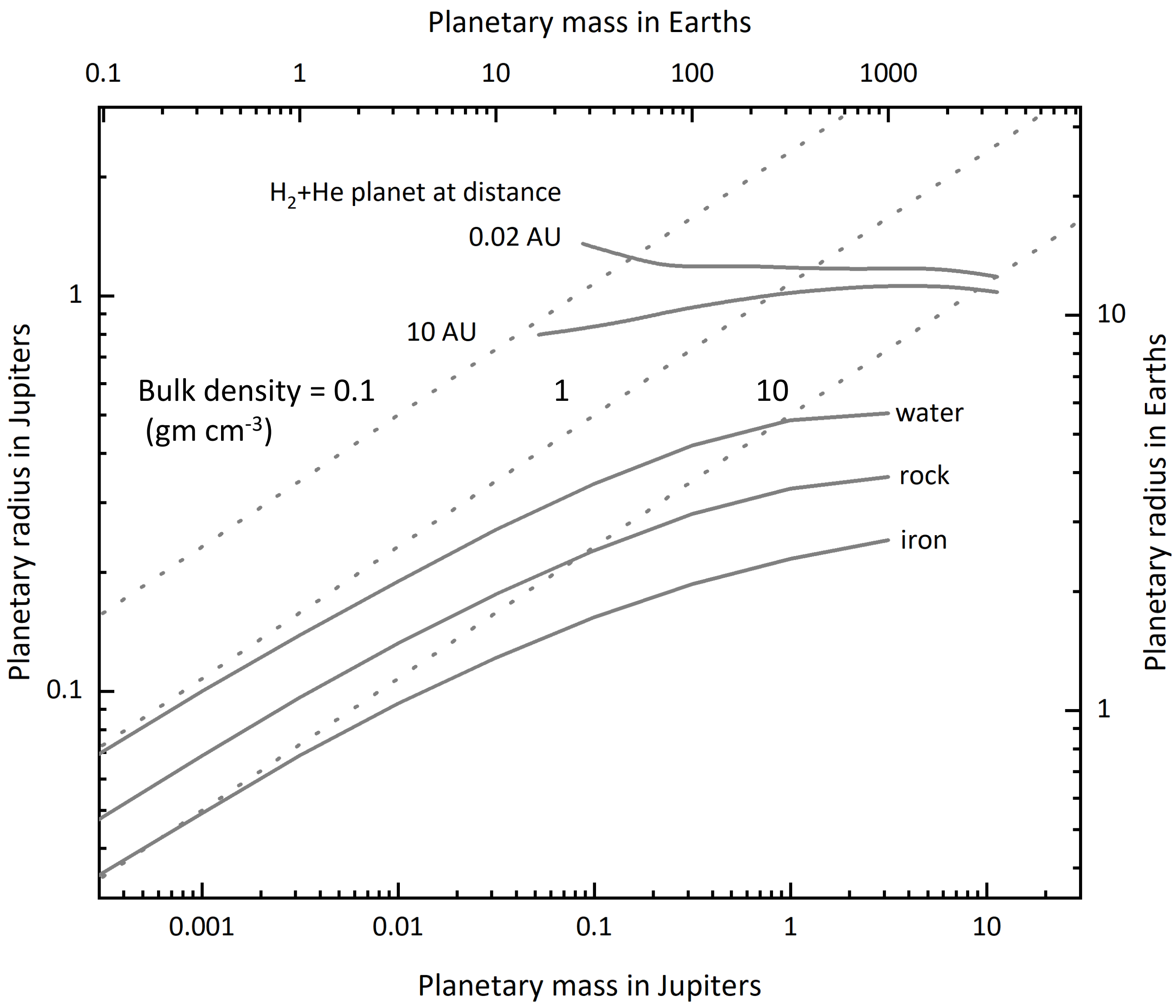


But the high-mass cutoff to the Jupiters, and the dips defining Neptunes and superearths, are not due to bias.

Exoplanet statistics are complete in certain important senses.

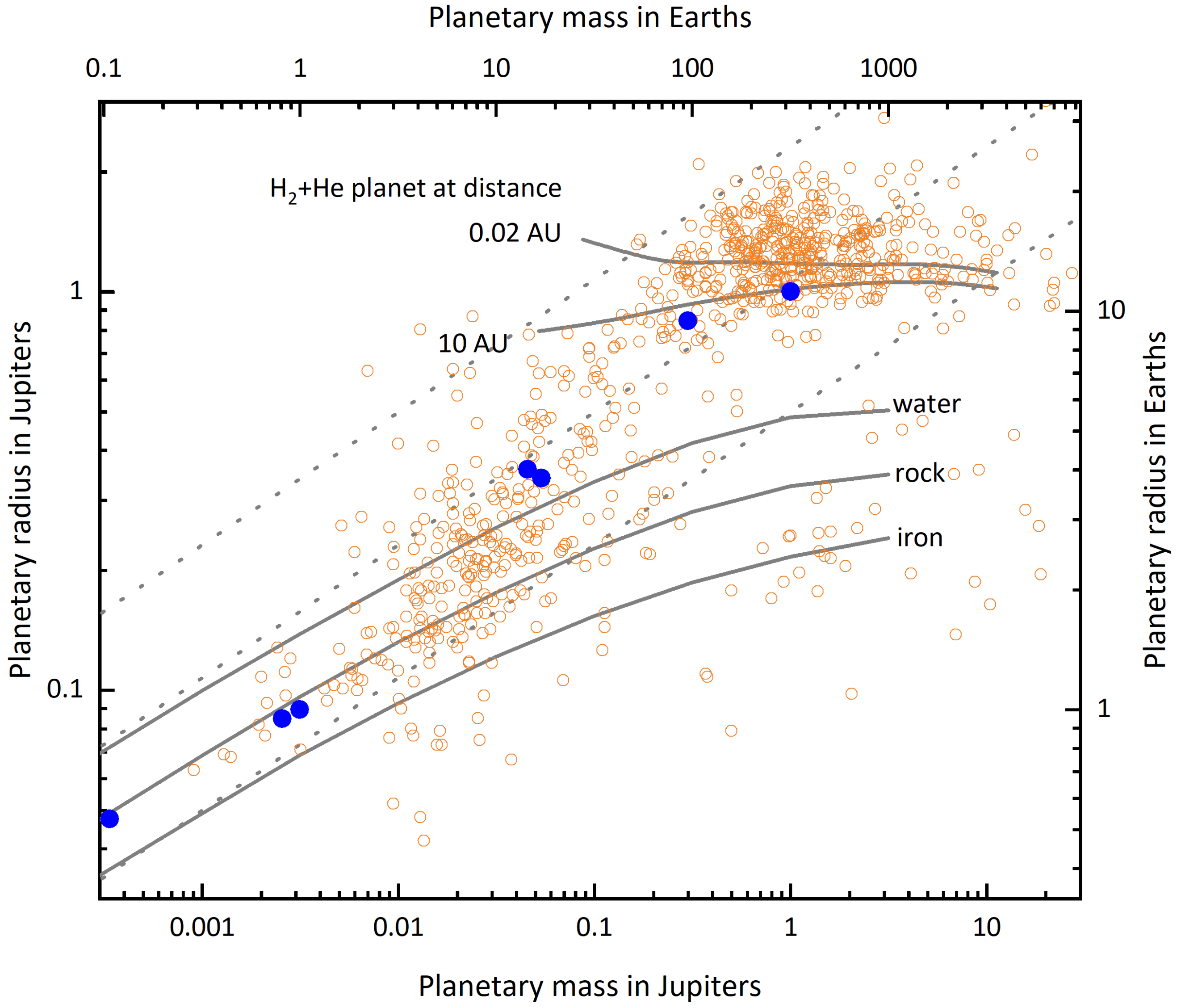
[NASA Exoplanet Archive, 11 November 2024]

Exoplanet internal structure



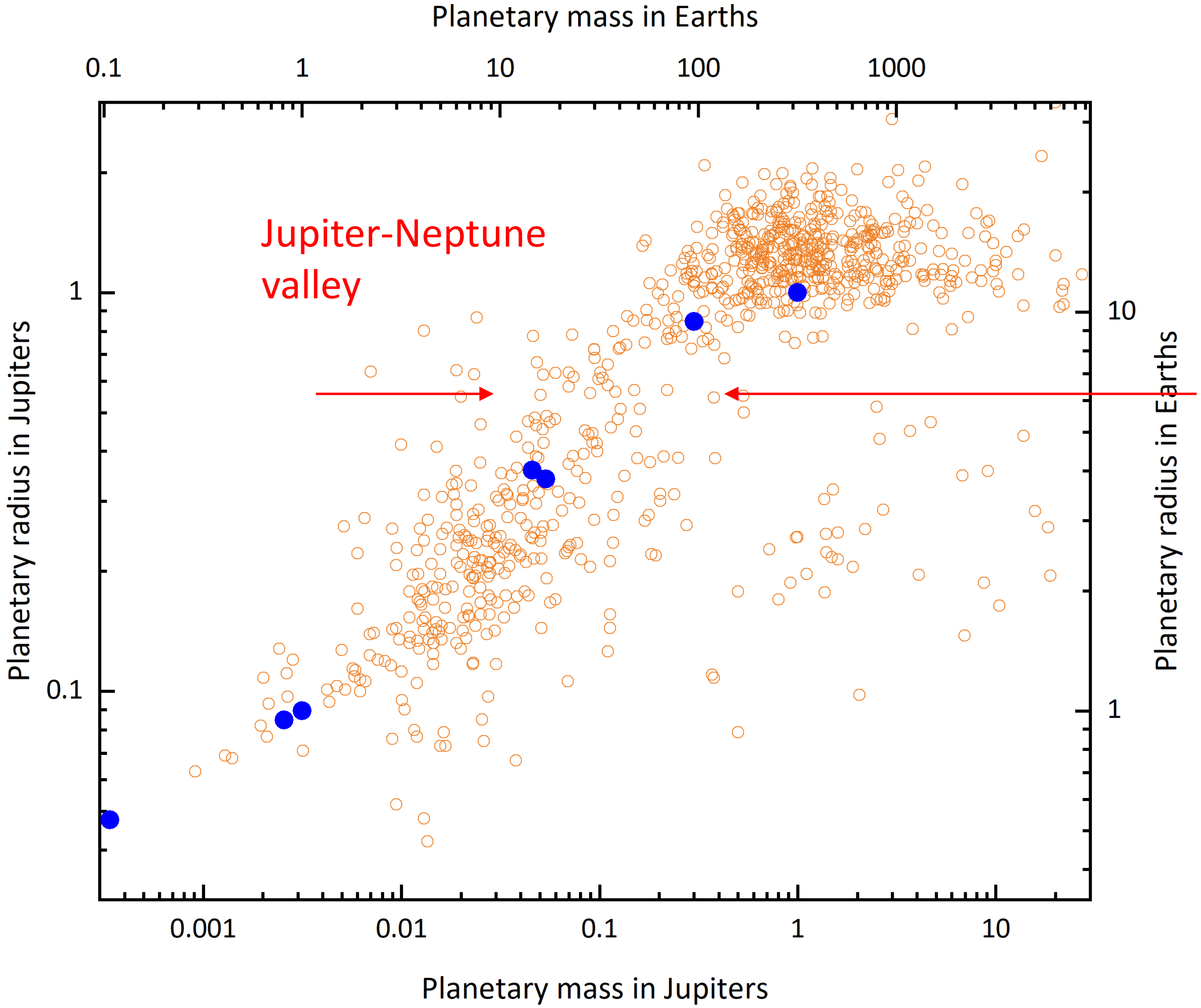
From planetary models by [Fortney et al (2007)]

Exoplanet internal structure (continued)

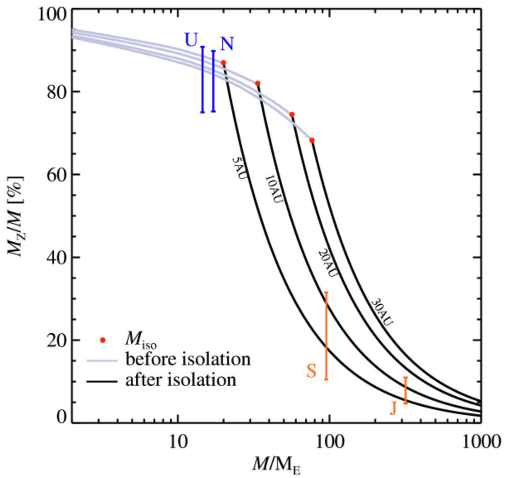


Data from the [NASA Exoplanet Archive, 11 November 2024]

Exoplanet internal structure (continued)



Neptunes = core mass < isolation mass in pebble disk?

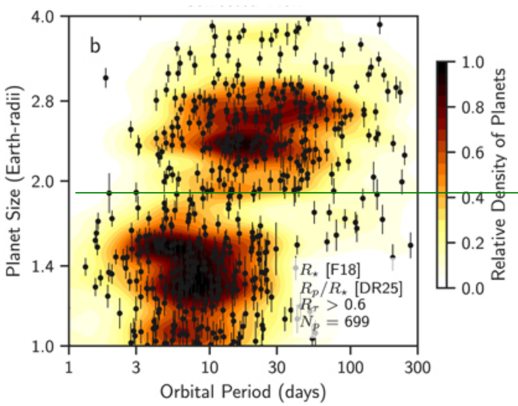


[Lambrechts et al. 2014]

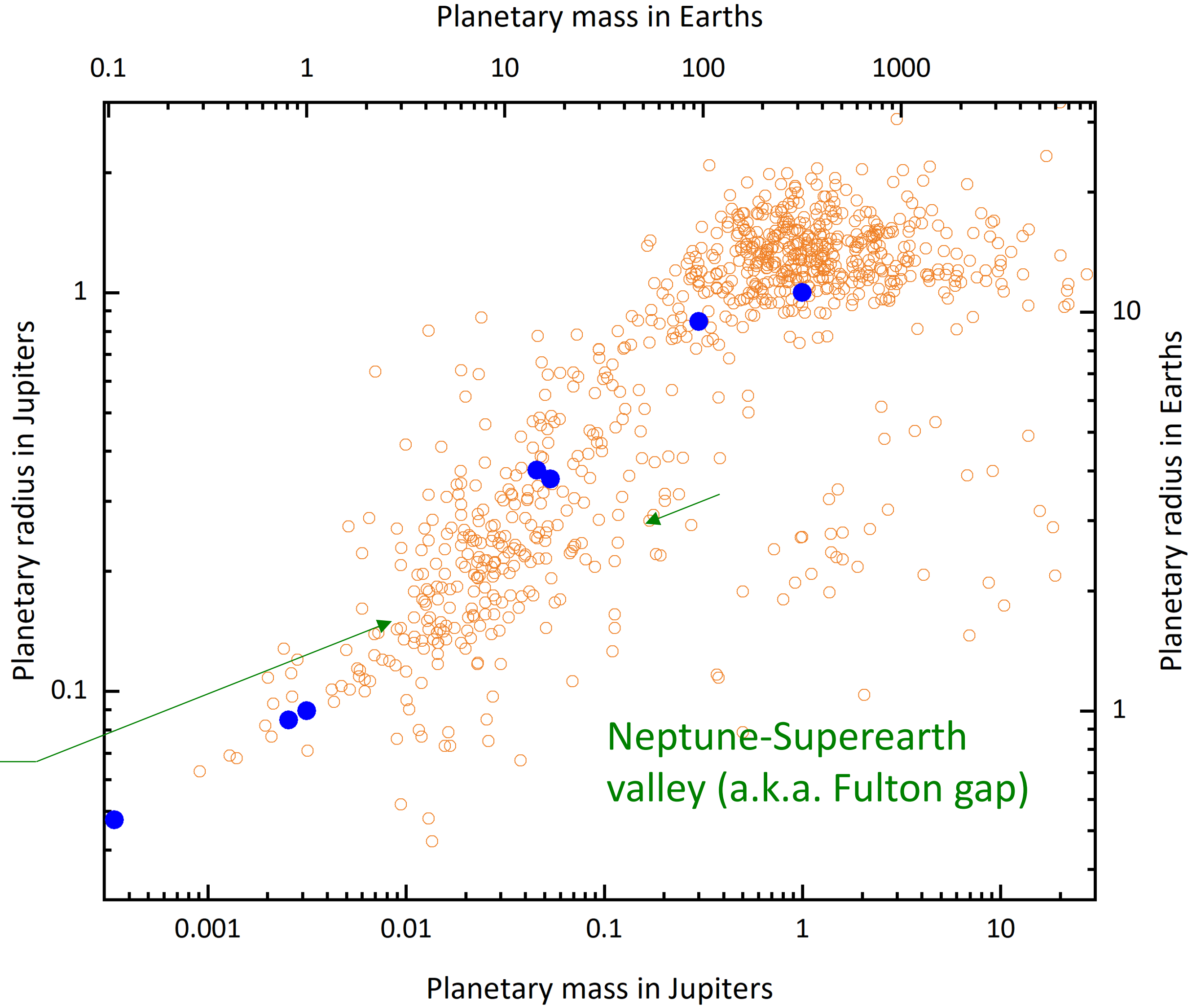
Data from the [NASA Exoplanet Archive, 11 November 2024]

Exoplanet internal structure (continued)

Superearths = Neptune cores with atmospheres driven off by stellar winds and radiation?

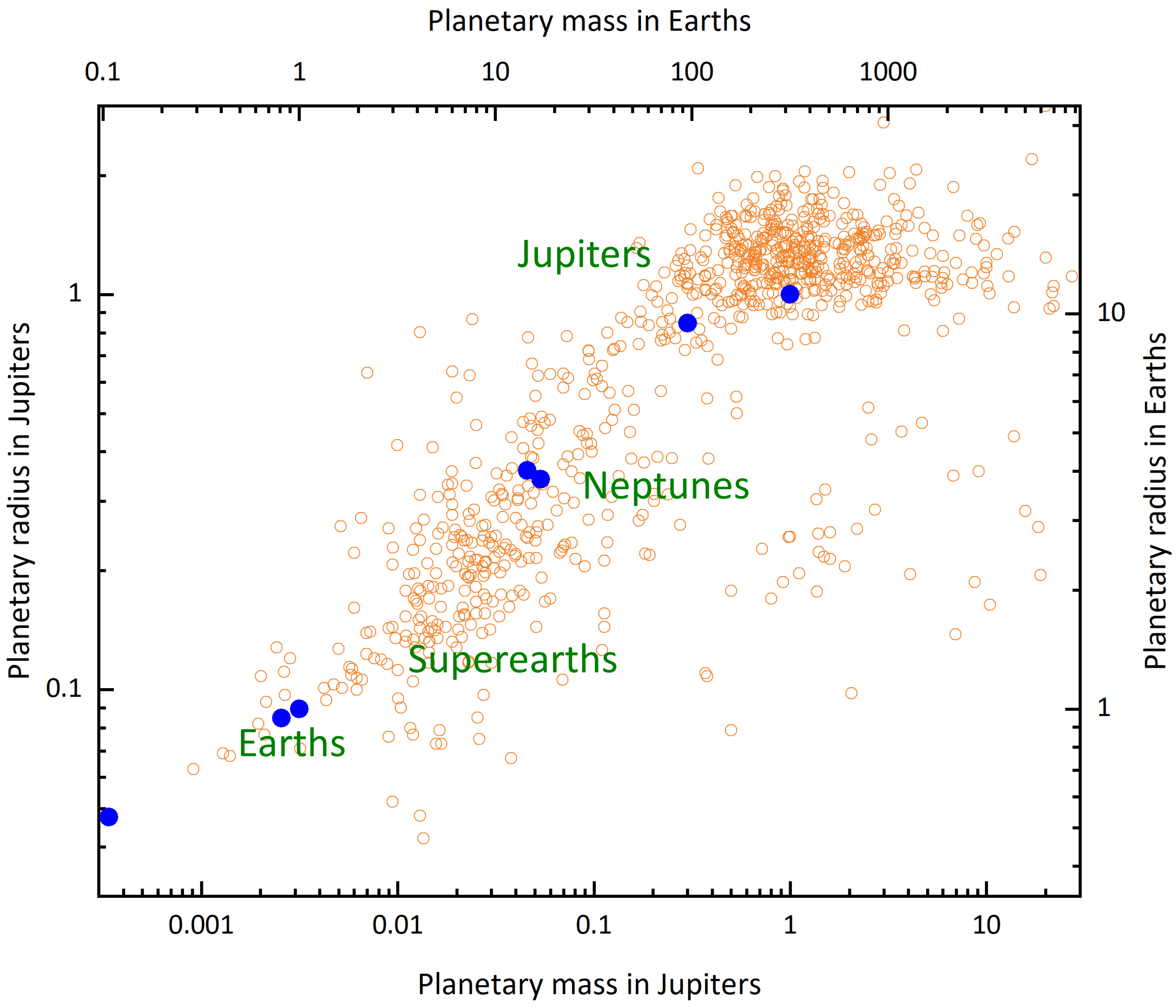


Petigura 2020



Data from the NASA Exoplanet Archive, 11 November 2024

Exoplanet internal structure (continued)



Data from the [NASA Exoplanet Archive, 11 November 2024]()

The fraction of stars with planets

As we have seen, essentially 100% of stars are born with enough disk material to make multiple planets of all sorts.

- Despite the biases labelled above, we have made surveys, of nearby stars for planets, that are unbiased or bias-correctable over well-defined ranges of masses and orbital periods.
- The resulting score (e.g. Mayor et al. 2012), for stars with mass $M_* = 0.6\text{-}1.5 M_\odot$:
  - 14%$\pm$2% host a gas-giant planet with $P \leq 10$ years.
  - **75%** $\pm$2% host a planet of any currently-detectable mass with $P \leq 10$ years.
- Stars with mass $M_* = 0.6\text{-}1.5 M_\odot$, have small planets ($R = 0.5\text{-}1.5 R_E$) orbiting **in their habitable zone** in **40%-90%** of all cases (Bryson et al. 2020).
- And we aren't even very good yet at detecting Earths and sub-Earths, or planets with long orbital periods, so **the fraction of stars with planets is very close to 100%.**

Detecting exoplanets

Stars are vastly brighter and more massive than planets, and most stars are far enough away that the planets are lost in the glare.

So astronomers have had to be clever, and employ the **motion** of the orbiting planet. They **mostly** use:

- **Transits**: periodic eclipsing of star by planet, or *vice versa*.
- **Radial velocity (RV)**: measure tiny, periodic wobble in star's motion along the line of sight by Doppler shift.

And whenever they can, they use

- **Imaging**: take pictures over a period of time, watch the planet orbit the star.

Discovery Method	Number of Planets
Astrometry	3
Imaging	82
Radial Velocity	1094
Transit	4309
Transit timing variations	32
Eclipse timing variations	17
Microlensing	230
Pulsar timing variations	8
Pulsation timing variations	2
Orbital brightness modulations	9
Disk Kinematics	1

Statistics of confirmed exoplanets, 11 November 2024 (NASA Exoplanet Archive). Click each link to get the technique's list of planets.

Measuring the properties of exoplanets

Here are the planetary properties that the three popular techniques can measure, **in principle**:

	Measure planetary mass?	Measure stellar mass?	Measure tilt of orbit from line of sight?	Measure planetary size?	Measure stellar size?	Detect planet close to star?	Detect planet far from star?	Detect planet orbiting very distant star?	Detect emission by planetary atmosphere?	Detect absorption by planetary atmosphere?
Images	No	Yes	Yes	No	No	No	Yes	No	Yes	Yes*
Radial velocity	Yes	Yes	No	No	No	Yes	Yes, if monitored	With largest existing telescopes	No	No
Transits	Not easily	Not easily	Yes	Yes	Yes	Yes	Yes, if monitored	Yes	Yes	Yes*

* Different continuum sources

- None of the three can do everything on the list all by itself, but combining results in pairs does.
- So let’s discuss these three techniques.

Taking images of exoplanets

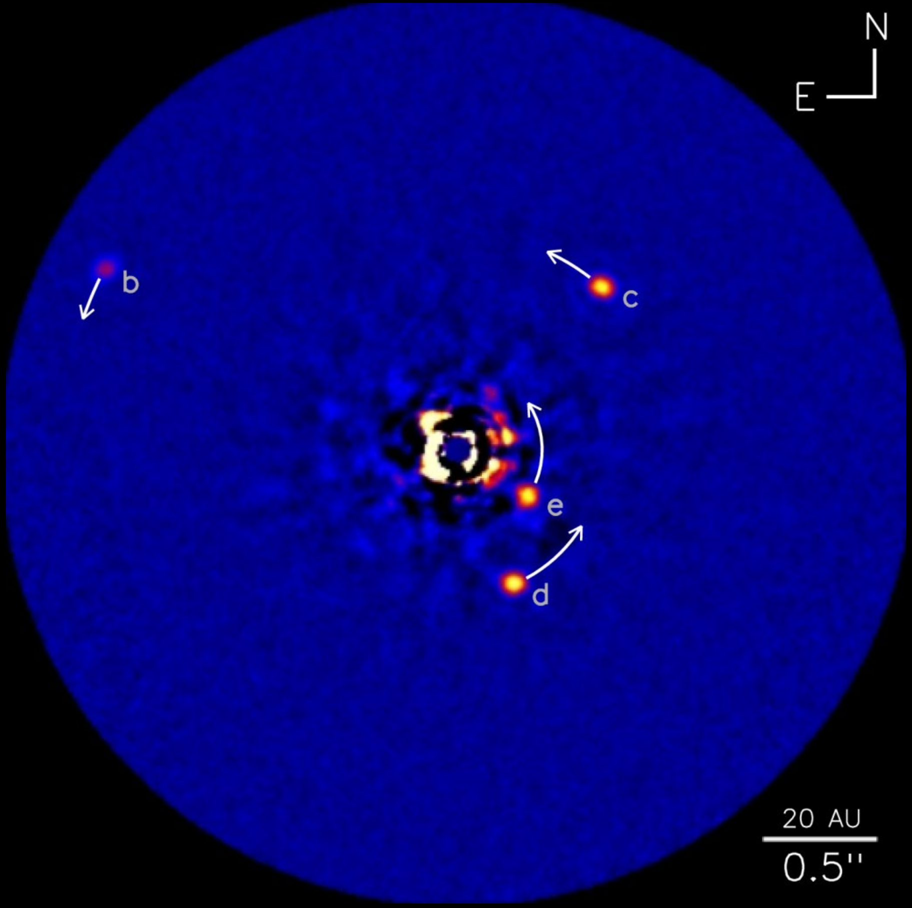
For most planets, in orbits with $r < 100$ AU, this is a lot harder than it sounds. Consider:

- Seen from a great distance, the Sun would appear to be two **billion** times brighter than Jupiter.
- Seen from a distance of 100 light years, Jupiter and the Sun would be separated by an angle no more than 0.17 arcseconds (4.5×10^{-5} degrees). Compare to blur:
  - 0.06 arcsec on HST at visible wavelengths, or JWST in the near-infrared;
  - 0.04 arcseconds on 10 m ground-based telescopes at near-infrared wavelengths with adaptive-optical (AO) atmospheric-blur correction;
  - > 0.5 arcseconds on telescopes on Earth without AO.
- The blur would have to be <<<<< 0.17 arcsec to see the faint planet in the glare of the bright star.
- Currently ultra-high-contrast imagers on ground-based telescopes (e.g. GPI) are capable of rejecting starlight at the 99.999% level starting about 40 milliarcsec from the star.

Taking images of exoplanets (continued)

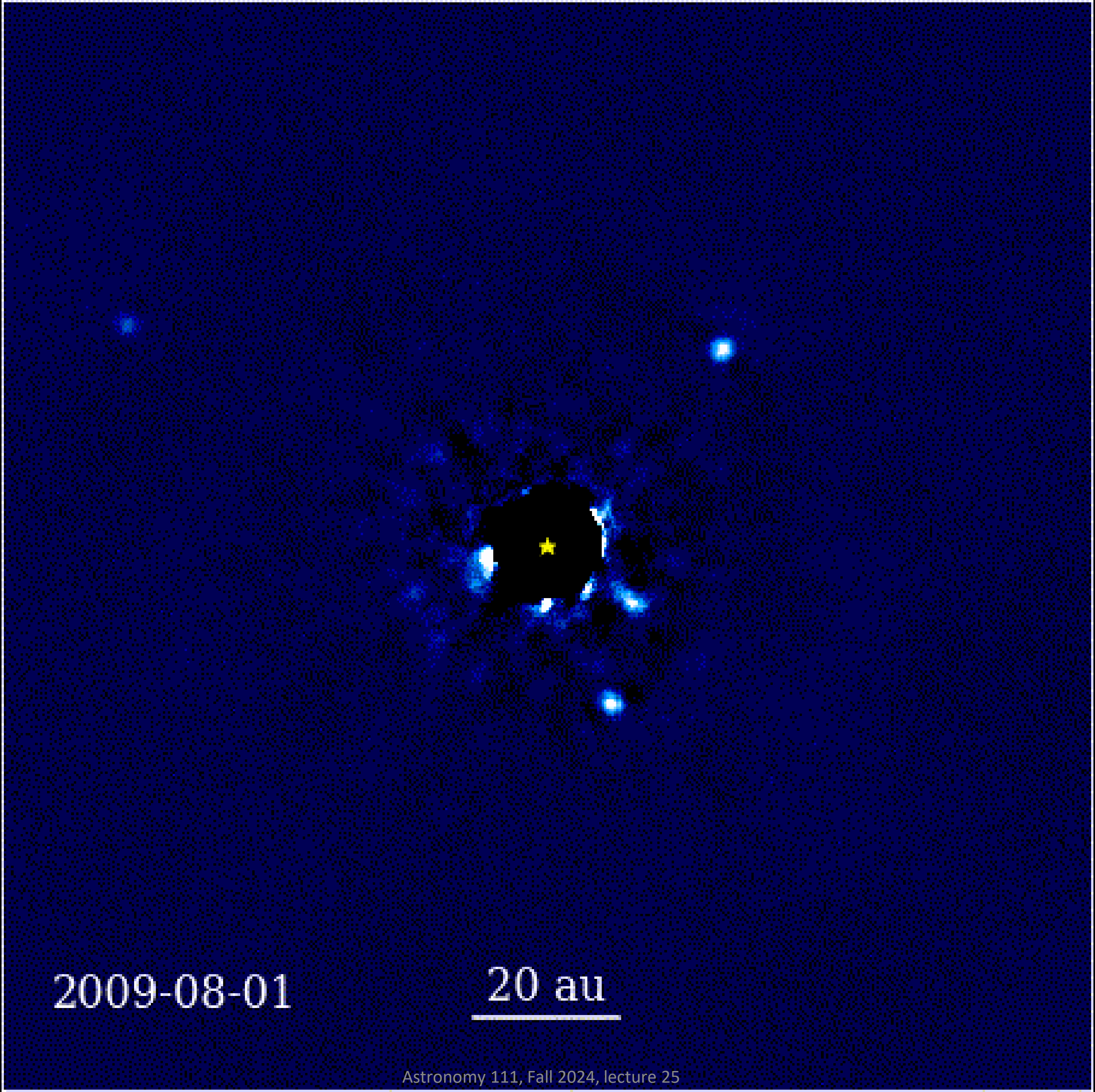
This has enabled the imaging on solar-system scales for some exoplanetary systems. Good examples:

- The nearby star HR 8799, 40 parsecs away, has at least four giant planets in orbit, in the gap between two asteroid belts.
- All 5-10 times Jupiter's size.
- Apart from size, a striking resemblance to our four giant planets lying between two asteroid belts.
- Ironically, the two asteroid belts were detected by the Spitzer Space Telescope before the planets were found ([Chen et al. 2009](#)).



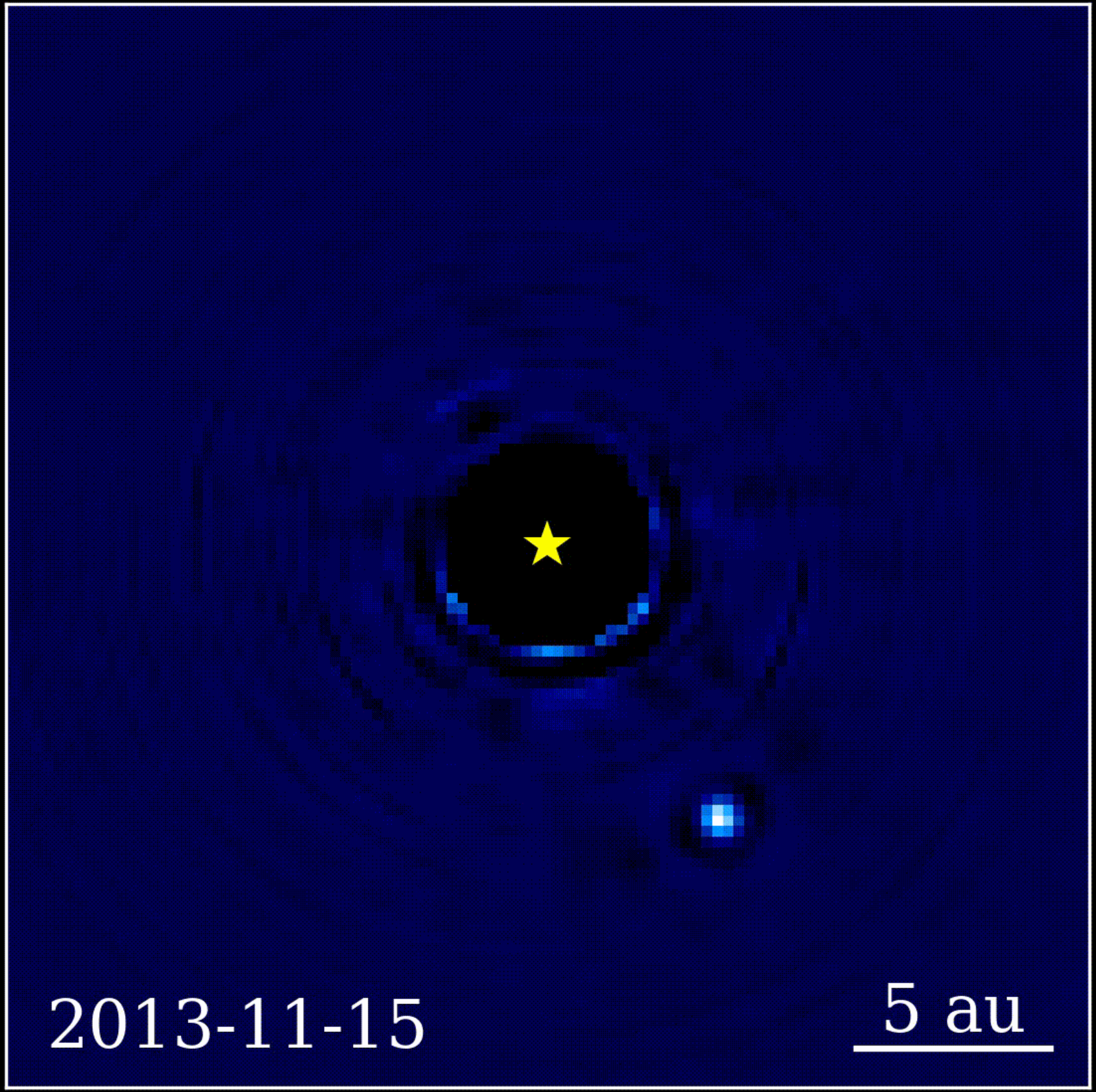
Infrared image of the HR8799 system, using adaptive optics, coronagraphy, and angular differential imaging on the Keck II 10.4 m telescope ([Marois et al. 2010](#)).

HR 8799 and its planets HR 8799 b-e, in motion.



Credit: Keck Observatory; Jason Wang

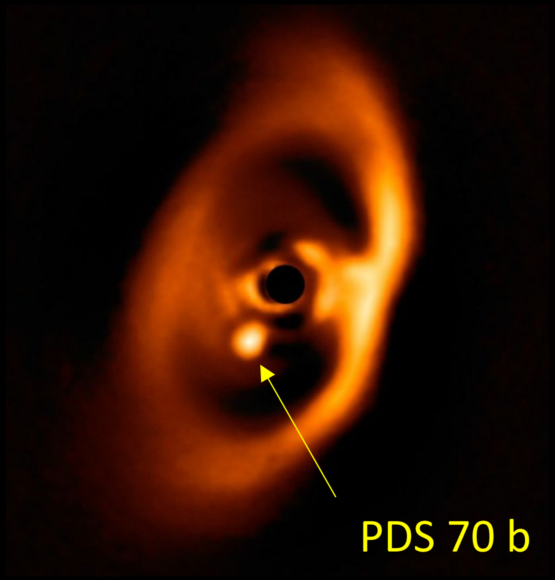
β Pictoris and β Pic b.



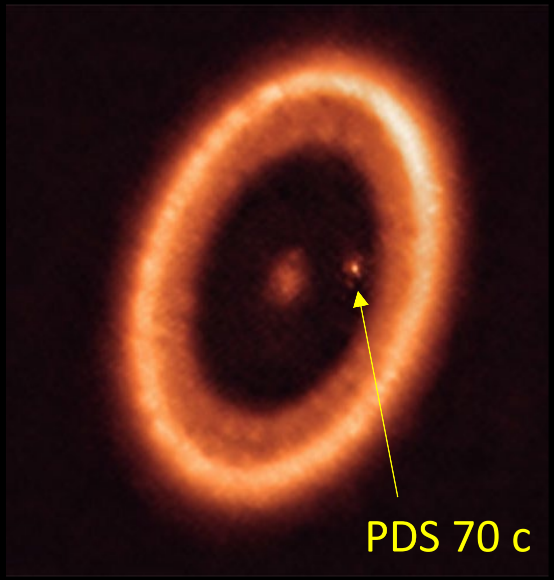
Credit: Gemini Observatory South; [Jason Wang]

Taking images of exoplanets (continued)

- The transitional disk around the young star PDS 70 – 370 light years away – has two Jupiter-like planets orbiting in the gap. One, PDS 70 c, looks to be surrounded by a proto-lunar disk.



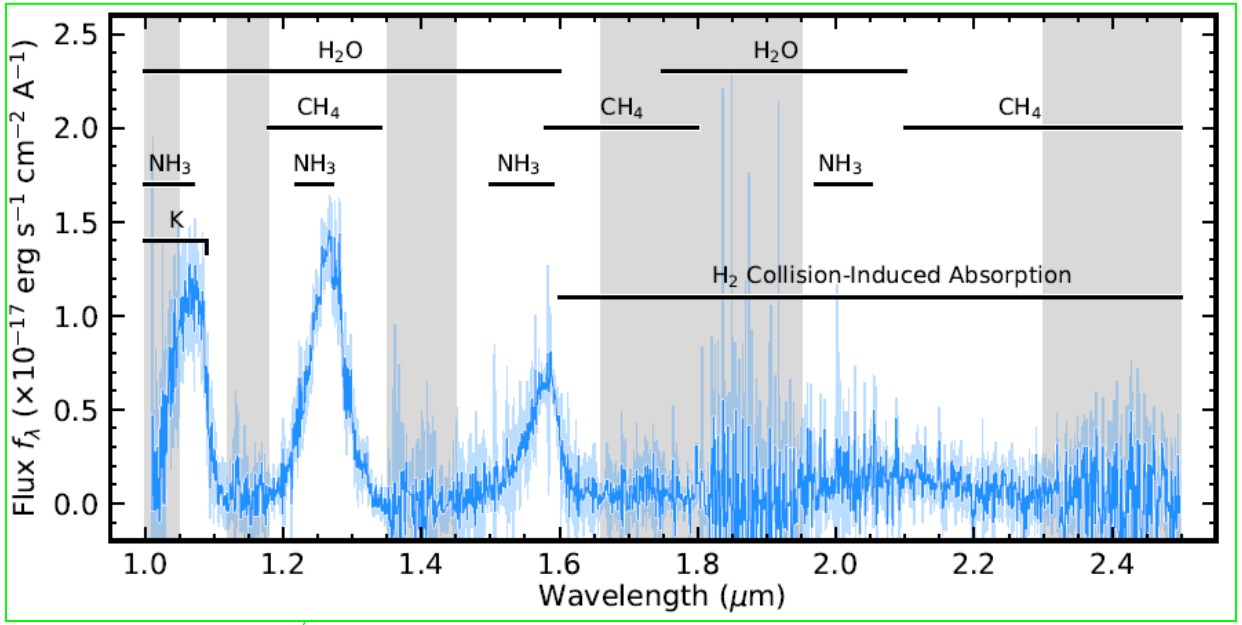
VLT/SPHERE: Keppler et al 2018

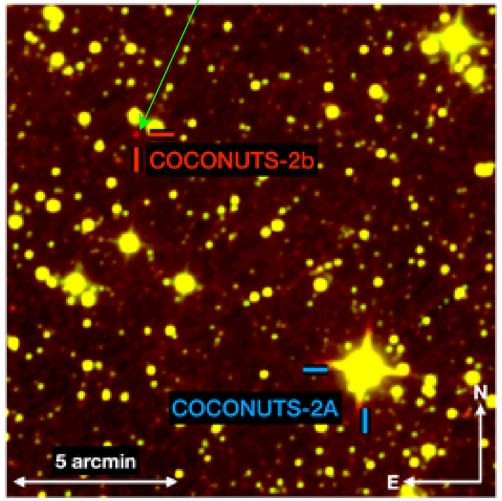


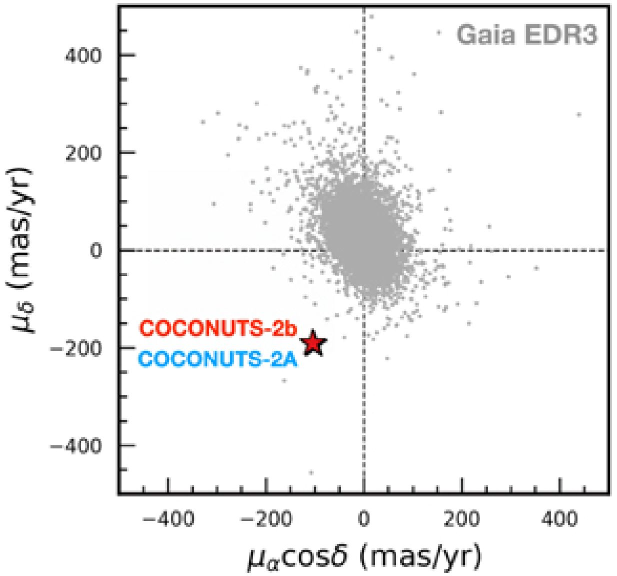
ALMA: Benisty et al 2021

Taking images of exoplanets (continued)

- Planetary systems with larger orbits can be also be revealed astrometrically, using ESA Gaia survey results.
- This leads to identification of nearby systems unidentifiable by other techniques…
- … which can be imaged, and have their spectra measured, by conventional ground-based means.
    - Like COCONUTS-2 b, here (Zhang et al. 2021, 2024).







Radial velocity (RV) detection of planets

The method used by Mayor & Queloz for the 51 Peg b discovery, and for hundreds of other exoplanets.

Also not easy, but easier than imaging. Here's how it works.

- Stars and their planets orbit their common center of mass (see the notes for [24 September 2024]). For example, the Sun and Jupiter:

Reduced mass: $\mu = \dfrac{M_\odot M_J}{M_\odot + M_J} = 1.897 \times 10^{30}$ gm $\left(\cong M_J\right)$

Orbital speeds, dictated by momentum conservation:

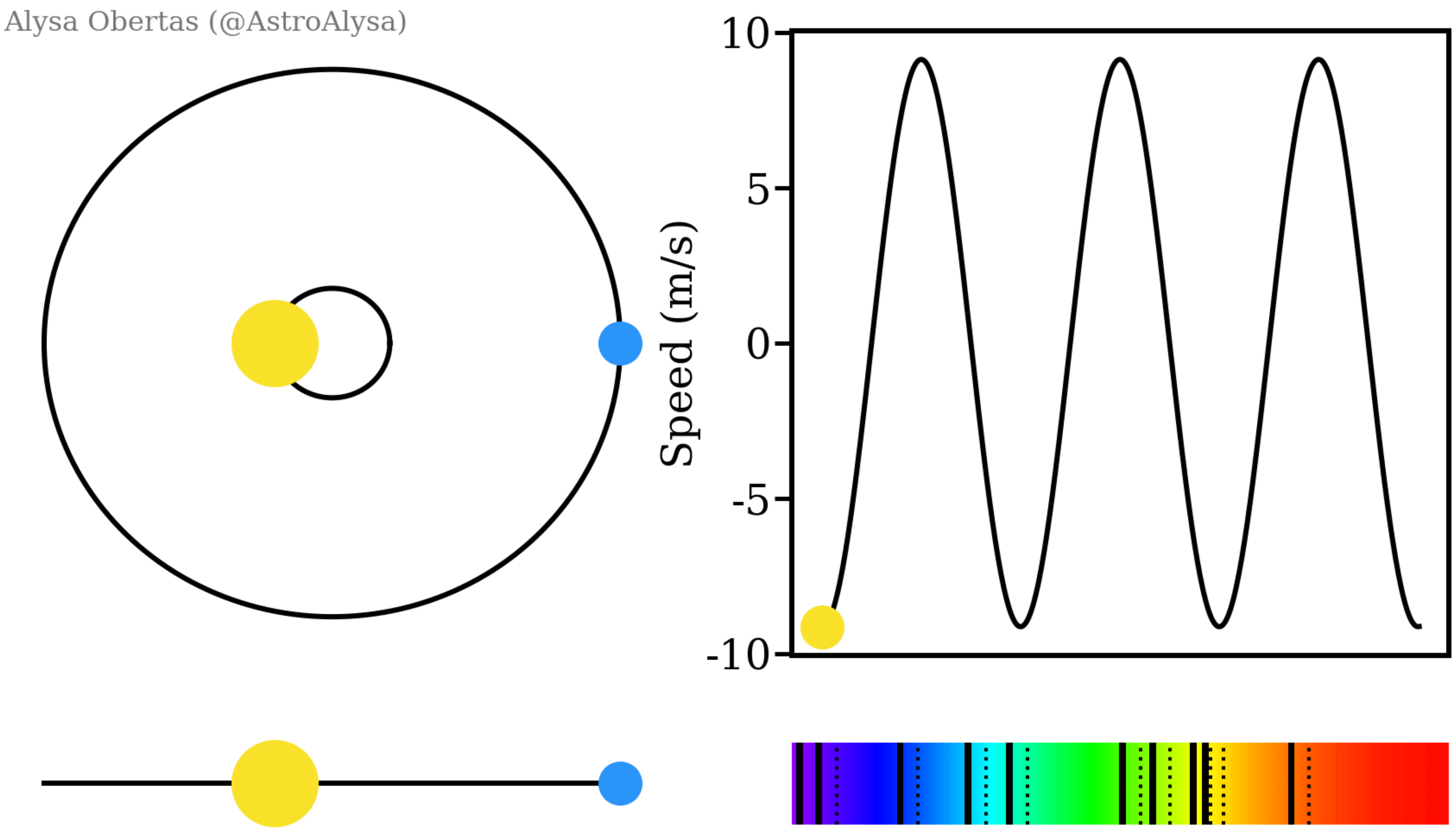
$$v_J = \frac{\mu}{M_J}\sqrt{\frac{GM_\odot}{r}} = 13.044 \text{ km sec}^{-1}$$

$$v_\odot = \frac{\mu}{M_\odot}\sqrt{\frac{GM_\odot}{r}} = v_J \frac{M_J}{M_\odot} = 0.012 \text{ km sec}^{-1}$$

RV detection of planets (continued)

- With an unusually mechanically- and optically-stable spectrometer, one can measure **radial velocities** – i.e. along the line of sight – by **Doppler shifts** (lecture, 27 August 2024) of spectral lines.
    - Nowadays the best RV systems can measure Doppler velocities as small as 20 cm sec^{-1}, which approaches the ultimate limit set by turbulent velocities in the star's atmosphere.
- Originally, high Doppler-shift precision and accuracy was achieved by
    - building a diffraction-grating spectrometer to cover the whole visible wavelength range simultaneously,
    - planning to concentrate on Sun-like stars, which have thousands of absorption lines at visible wavelengths, and
    - interposing a thermally-stabilized gas absorption cell in the beam of starlight on its way to the spectrograph, and filling the cell with a gas that has lots of absorption lines at wavelengths different from those in the star.
        - Iodine was the original gas-cell absorber. There isn't much iodine in stars.
- Then whatever wavelength drifts occur are the **same** in the stellar and gas-cell lines, and the **differences** in wavelength – averaged over the thousands of lines in the spectrum – can be very small.

RV detection of planets (continued)



[Wikimedia Commons/Alysa Obertas](#)

RV detection of planets (continued)

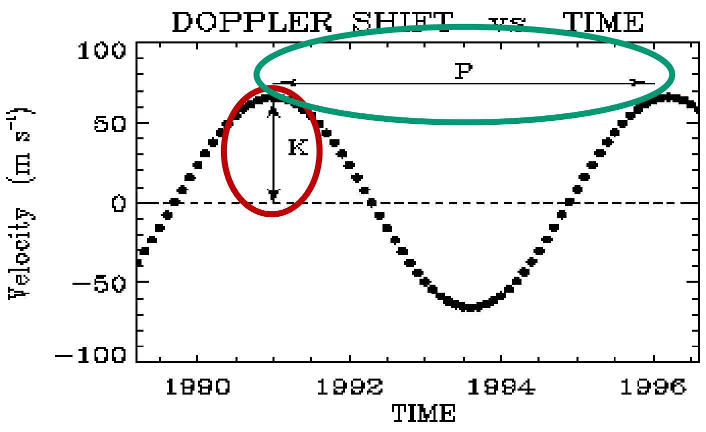
- So after building such a spectrometer and gas cell – or, nowadays, a spectrometer and laser comb – on a telescope, point the telescope at a star and focus its light into the spectrometer.

- And proceed to make many accurate measurements its Doppler shift, over the course of the orbital period range of the planets for which one is hunting.

- One needs to make enough Doppler-shift measurements to determine both orbital period ***P*** and Doppler velocity amplitude ***K***.

  - *P* determines the length of the semimajor axis of the planet-star separation *via* Kepler's third law. With *M* the mass of the star and *m* that of the planet,

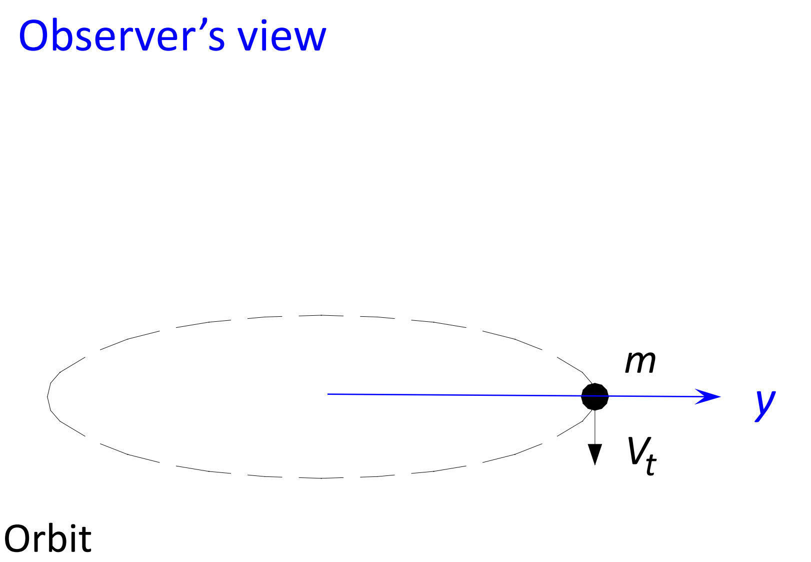
$$a^3 = \frac{G(M+m)}{4\pi^2}P^2 \cong \frac{GM}{4\pi^2}P^2$$

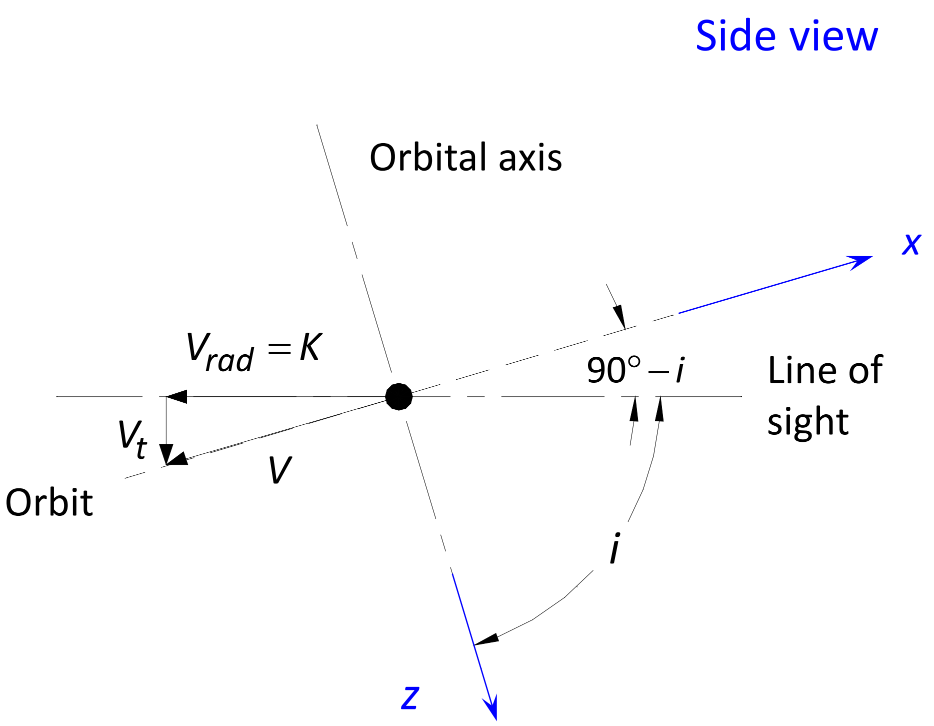


exoplanets.org

RV detection of planets (continued)

- K is the maximum Doppler shift (with respect to the average) of the star's radial velocity, which is related directly to the planet's orbital speed V: $K = V \sin i$, where i is the angle between the orbital axis and the line of sight.
- Here's the geometry. Note that the diagrams are tiny relative to the blurred image of the star; it is only the periodically-variable Doppler shift that signals the presence of the orbiting body.

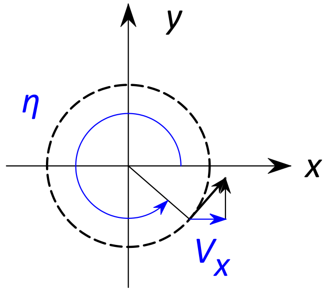




RV detection of planets (continued)

- If the orbital eccentricity is close to zero, the **radial velocity varies sinusoidally with time:**

$$\eta = \omega t = \frac{Vt}{a} \quad \Rightarrow \quad V_x(t) = V\cos\left(\frac{Vt}{a}\right)$$



- If the orbital eccentricity is *not* close to zero, the radial- velocity curve looks lopsided or sawtooth-like, compared to a sine wave.

- In this case, fitting the velocities of an elliptical orbit to the radial-velocity curve allows one to determine the eccentricity and the position of periastron, as well as $V\sin i$ as a function of time.

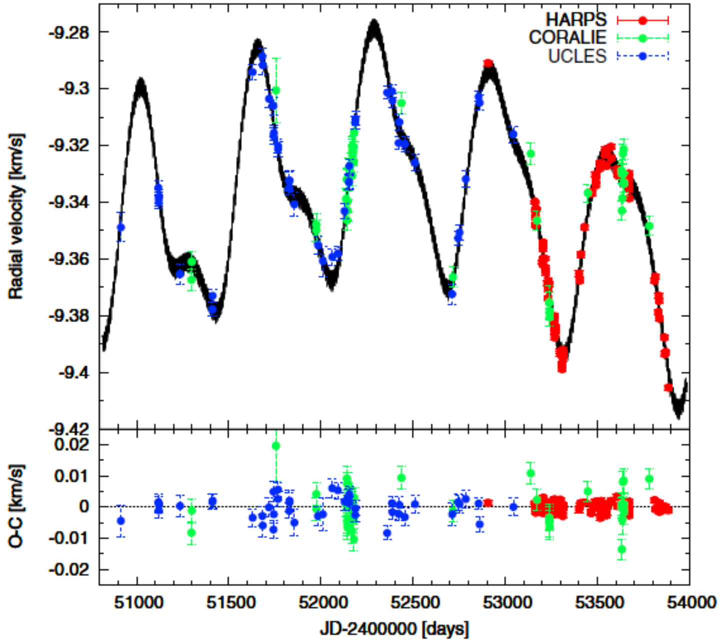
- Either way, this allows a determination of the planet mass m, times $\sin i$. For low eccentricity,

$$m = M\frac{V}{v} = MV\sqrt{\frac{a}{GM}} = V\sqrt{\frac{aM}{G}} \quad \Rightarrow \quad m\sin i = K\sqrt{\frac{aM}{G}}$$

RV detection of planets (continued)

- The mass M of the star is usually known, from its age and spectral type.
- So measurement of P and K yields $m\sin i$ semimajor axis length a. If m is of planetary mass, then one has detected a planet. (The alternative would be a stellar mass: the target is a binary star.)

- Upsides of exoplanet detection with radial velocity:
  - From radial velocity observed over an orbital period, get planet mass, plus shape and radius of orbit.
  - No need for high image contrast or high-resolution images.
  - Can detect many thousands with existing instruments and telescopes.



RV measurements on μ Arae, over some eight years, showing the presence of four planets. (Pepe et al. 2007)

RV detection of planets (continued)

- Unfortunately, the inclination angle *i* usually is not known, unless:
  - the star and planet are both seen in images, and the transverse component of motion is seen too; or
  - the star has a debris disk that is resolved in images: the planet will usually be in the same plane; or
  - the star and planet eclipse or transit one another other, in which case *i* would be very close to 90º.
- This makes less difference than you might think …
  - … as the average value of sin *i* for a large population of randomly-oriented exoplanet orbits is 0.785, and the probability that sin *i* $\leq$ 0.1 is only 0.5%.
- However, there is one serious shortcoming of RV detection: Since it doesn't involve detecting light from the planet, one can't learn about the planet's surface, atmosphere, density, *etc*. thereby.
- Which leads us to exoplanet transit observations, which in turn helps alleviate these shortcomings.