Modern Astronomy: Voyage to the Planets

Lecture 10

Extra-solar planets

University of Sydney
Centre for Continuing Education
Spring 2014

"One theorist admitted to me he cannot think of a single prediction that he and his colleagues made about extrasolar planets that has been supported by observations."

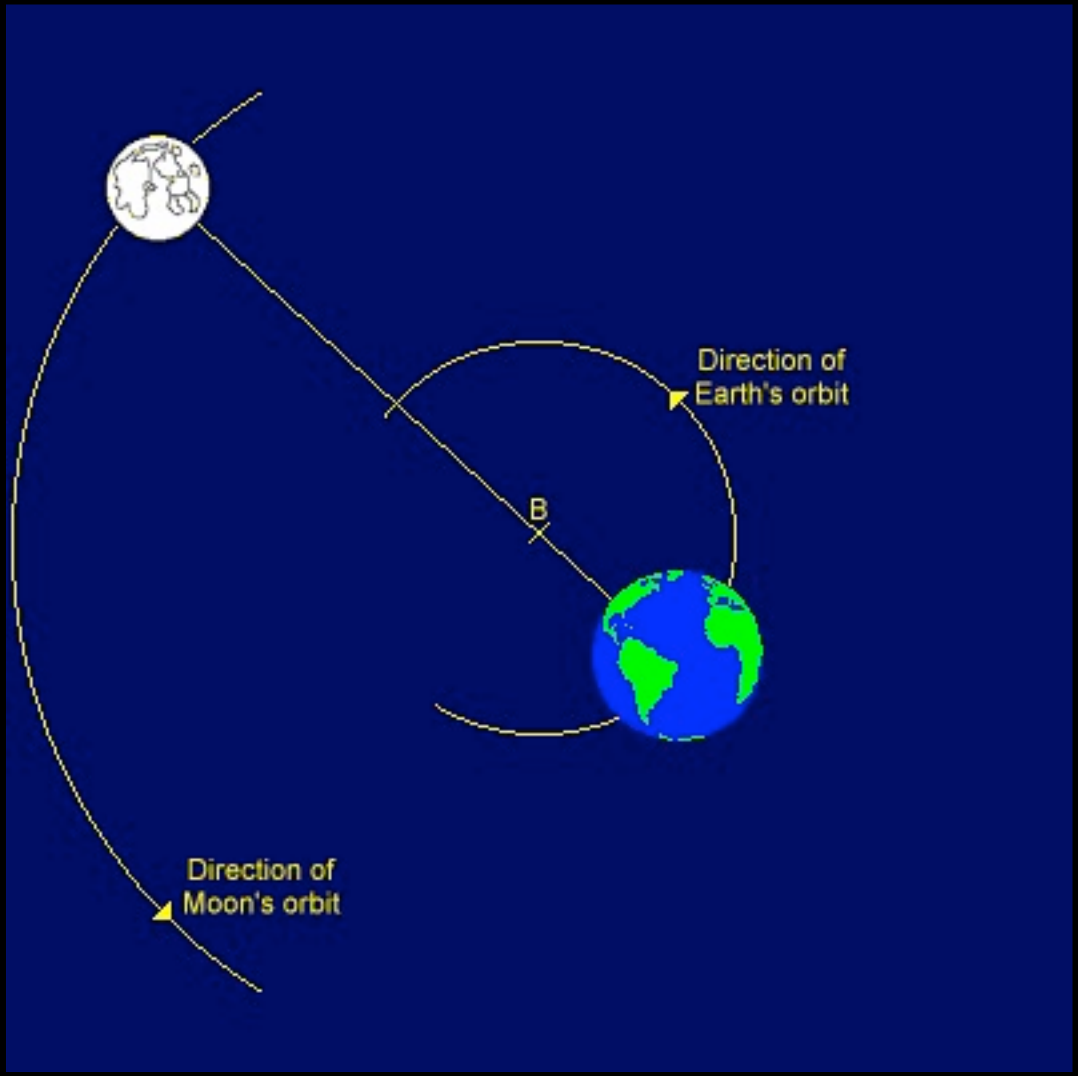
– Geoffrey Marcy, quoted in "Planetary Harmony"
by Robert Naeye, Aust S&T Jan 2005

Tonight:

- How to find a planet
- What we found
- The *Kepler* mission
- What does it mean?

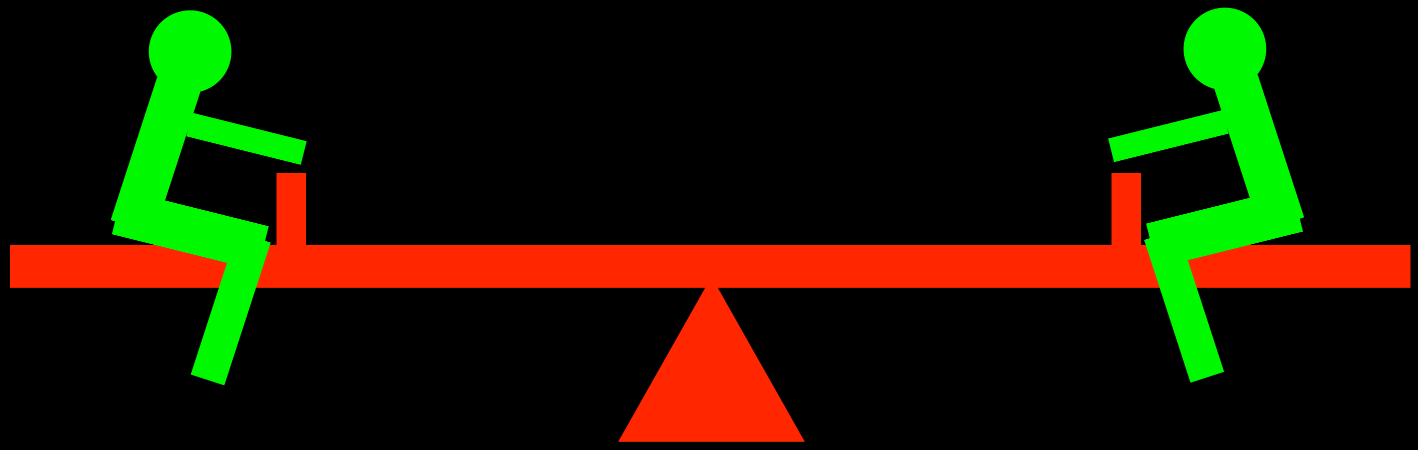
Orbits

We talk about planets orbiting the Sun, but in fact both planet and Sun move. Two bodies in orbit each move about the *centre of mass* (or *barycentre*).



The centre of mass is always directly between the two objects, and where it is depends on their masses.

Just like a see-saw, where the fulcrum has to be placed closer to the heavier child.



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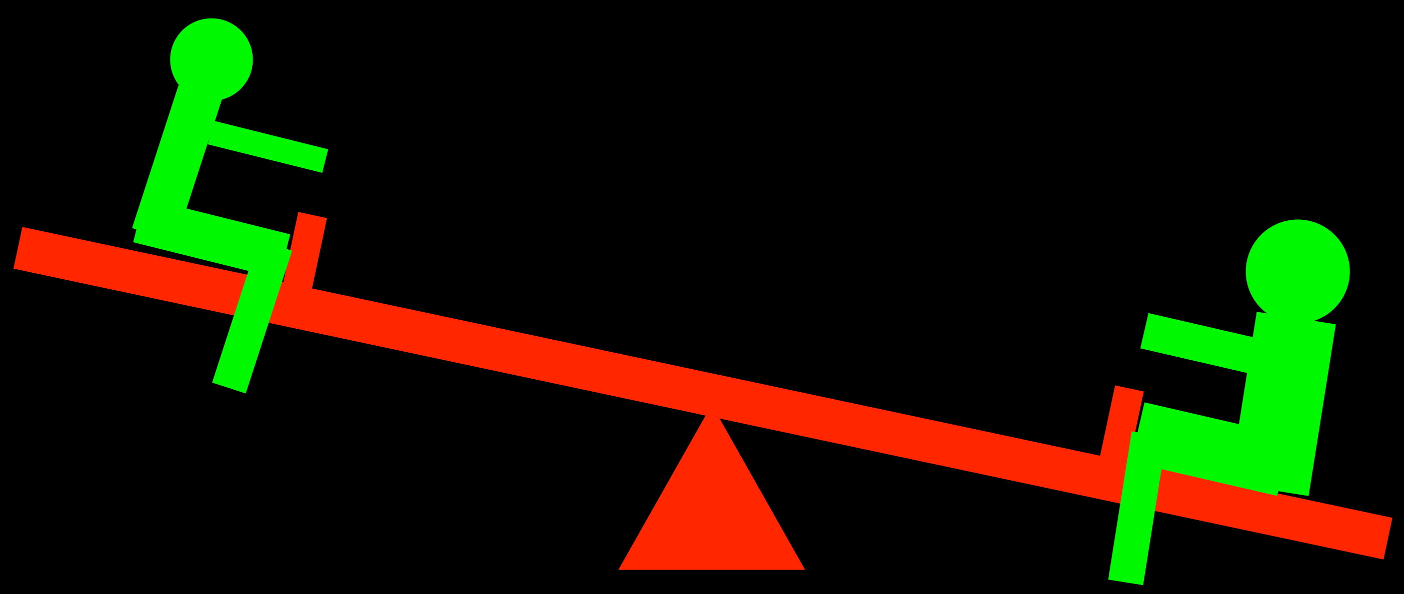

The centre of mass is always directly between the two objects, and where it is depends on their masses.

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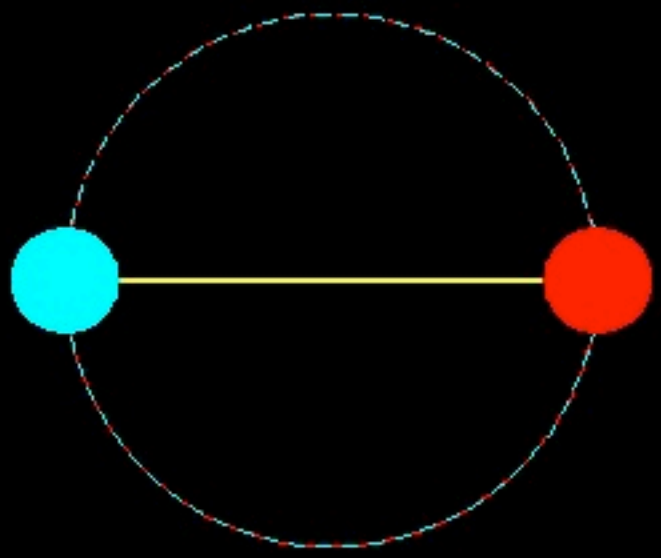
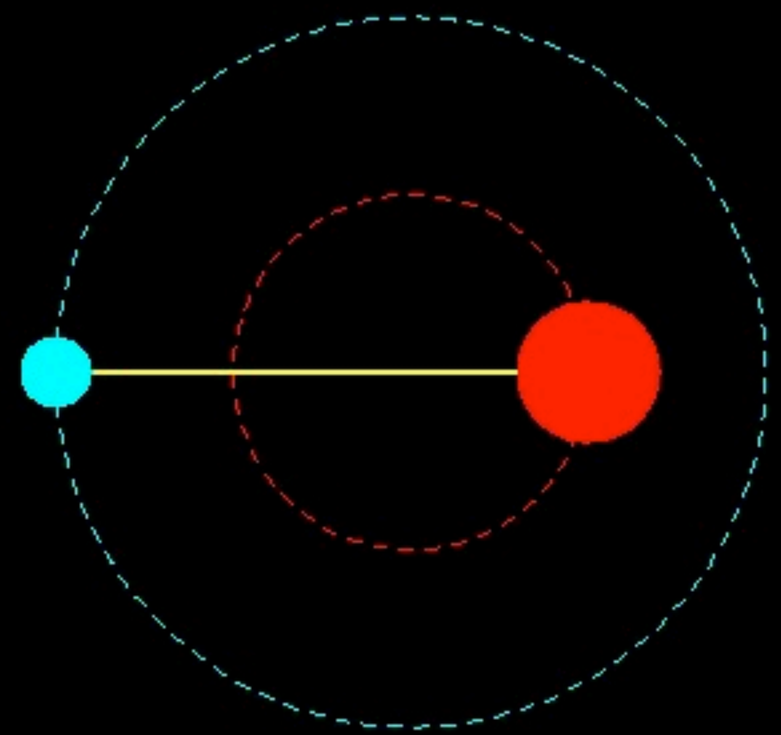
Two objects of equal mass will orbit with the centre of mass exactly halfway between them.



Two objects of equal mass will orbit with the centre of mass exactly halfway between them.

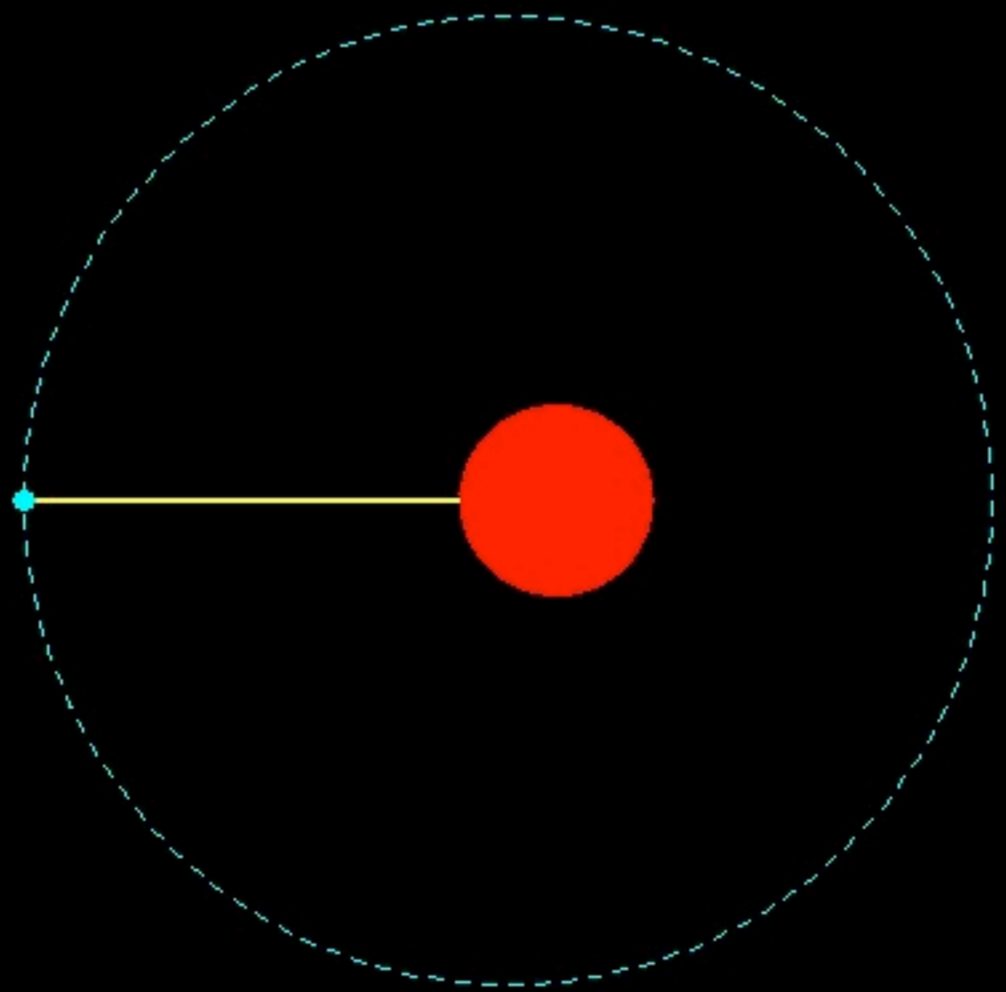
If one object is twice as massive as the other, the centre of mass will be twice as close to it.



Two objects of equal mass will orbit with the centre of mass exactly halfway between them.

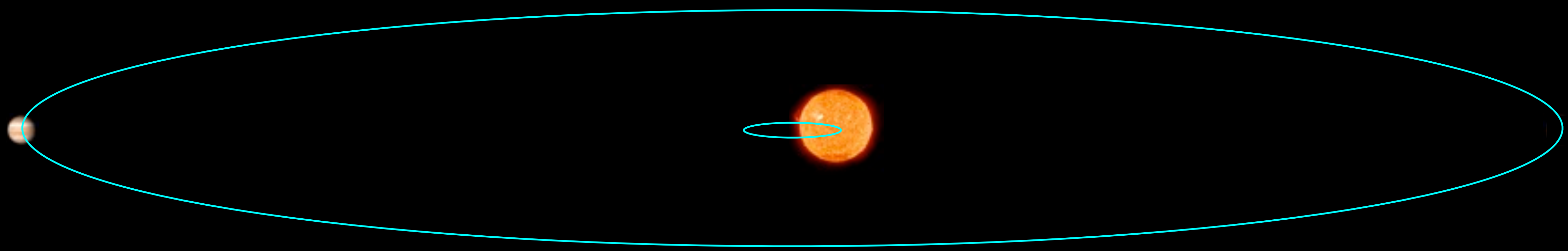
If one object is twice as massive as the other, the centre of mass will be twice as close to it.

If one object is one hundred times as massive as the other, the centre of mass will be one hundred times as close to it.

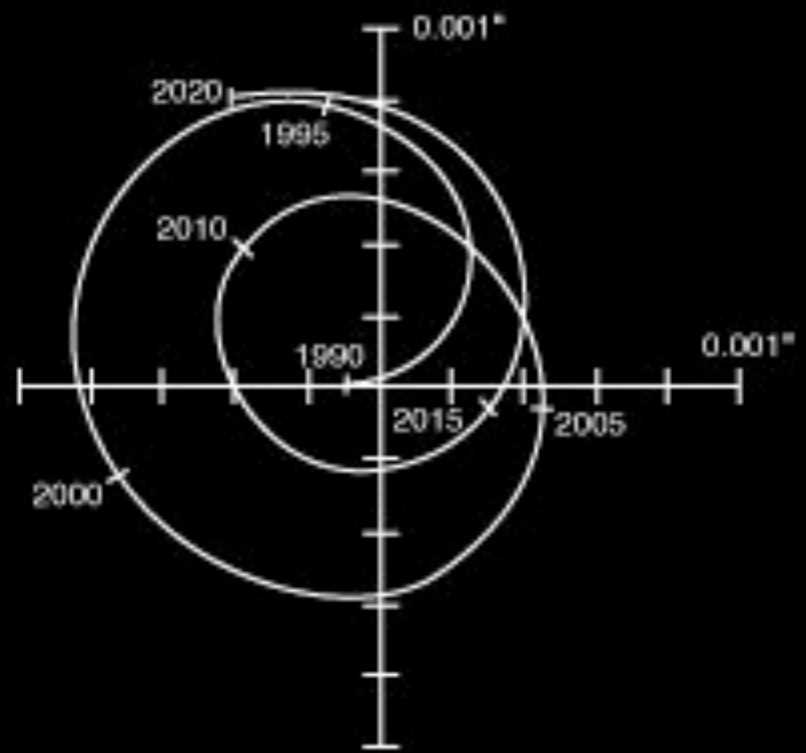


The ratio of the mass of the Sun to the mass of Jupiter is 1000, so the centre of mass is 1000 times closer to the Sun than it is to Jupiter.

The radius of the Jupiter's orbit is just over 1100 times the radius of the Sun, so its barycentre with the Sun lies just above the Sun's surface. Thus as Jupiter executes its 12 year orbit, the Sun executes a much smaller ellipse, wobbling just over one solar diameter.



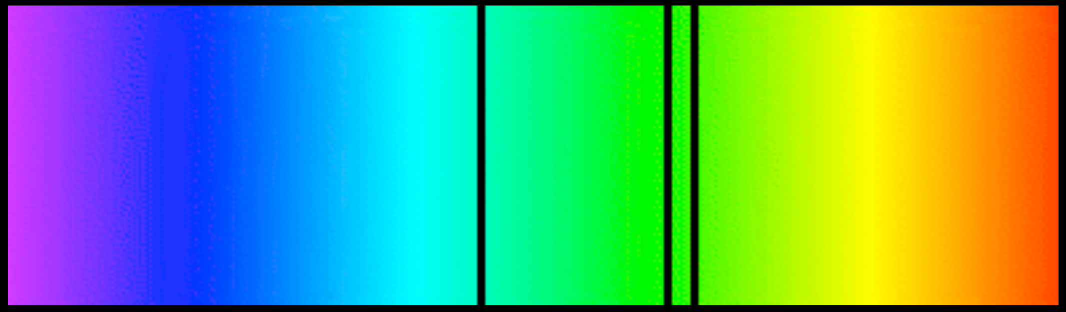
The motion of a star due to a planet is tiny in the extreme: no planets have yet been detected this way, though the next generation of space missions will change that.



Astrometric displacement of the Sun due to Jupiter as at it would be observed from 10 parsecs, or about 33 light-years.

However, we can detect *velocities* very easily, because of the Doppler shift.

As the star wobbles to and fro, we see lines in its spectrum moving first to the red, and then to the blue. Measuring the size of this shift allows us to determine the velocity of the star, and hence (from Kepler's law) the mass of the companion.



The Sun moves about the Sun–Jupiter barycentre at about 12 metres per second, so if we can measure a regular change in a star's velocity of 12 m/s over 12 years, then we can detect a Jupiter-sized planet in a Jupiter-sized orbit.

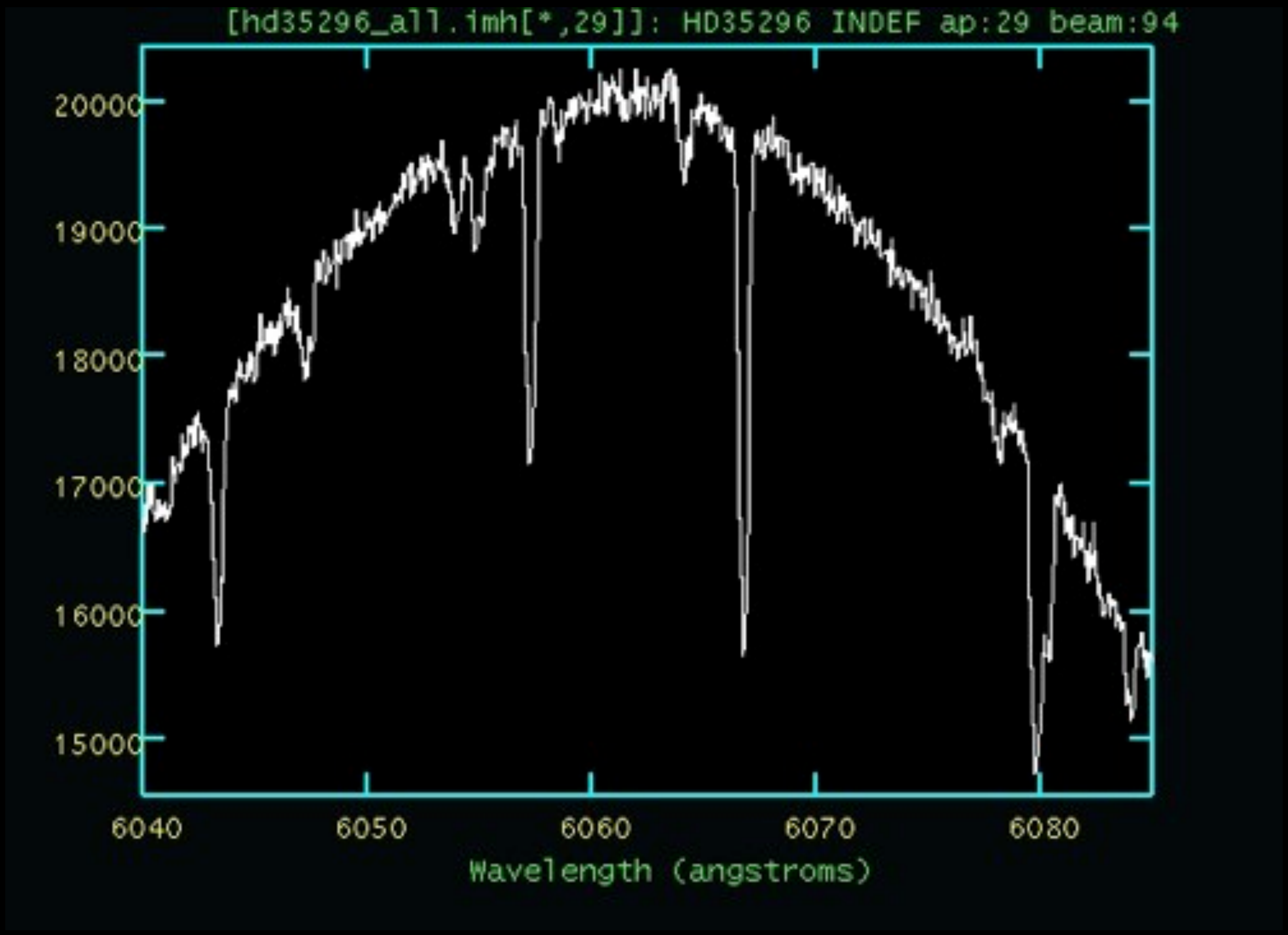
However, this means we have to be able to measure shifts in velocity to 12/300,000,000, or a precision of 4 in a *billion*.

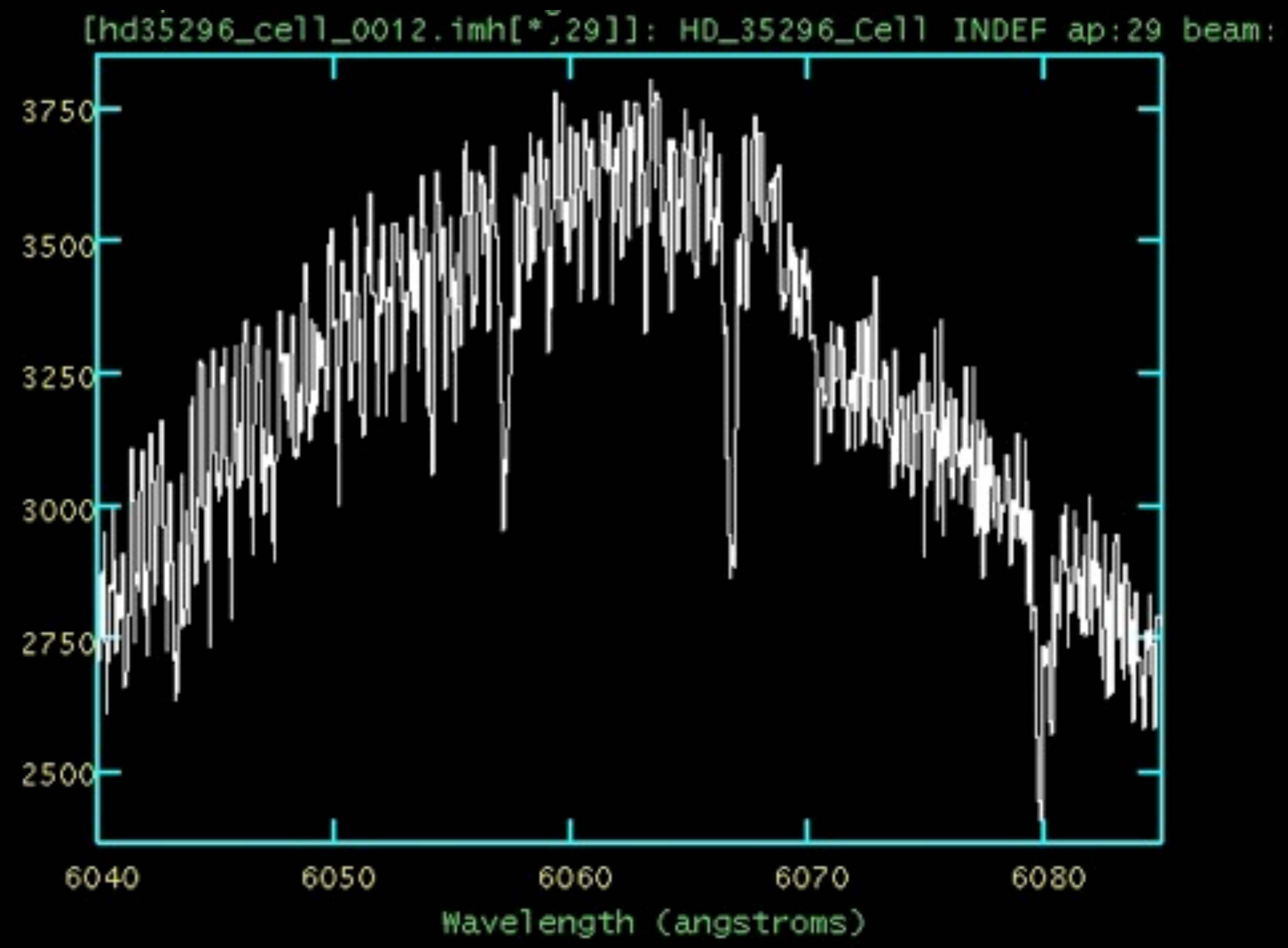
This places extraordinary demands on the stability of the instrument used to make the measurement. We need to spread the light out a long way to measure the tiny shifts, but also have a very stable reference system.

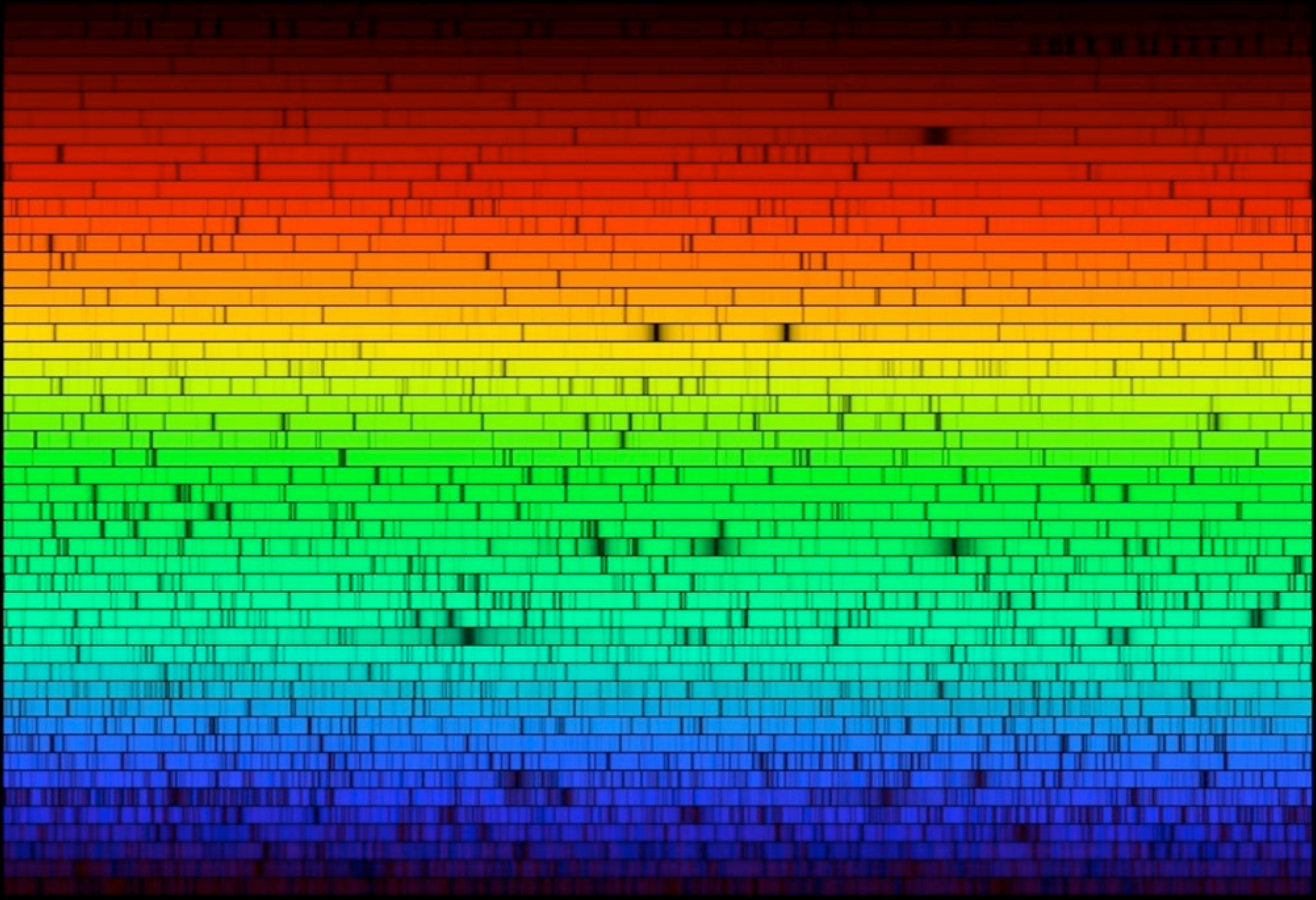
Solution: pass the light from the star through an iodine cell, which superimposes a large number of reference absorption lines on the star's spectrum.

The iodine cell used in the Anglo-Australian planet search.

Here is the spectrum of a nearby F dwarf, by itself, and with the light sent through an iodine cell. Each of the wiggles is a sodium line, which allows very precise wavelengths to be measured.



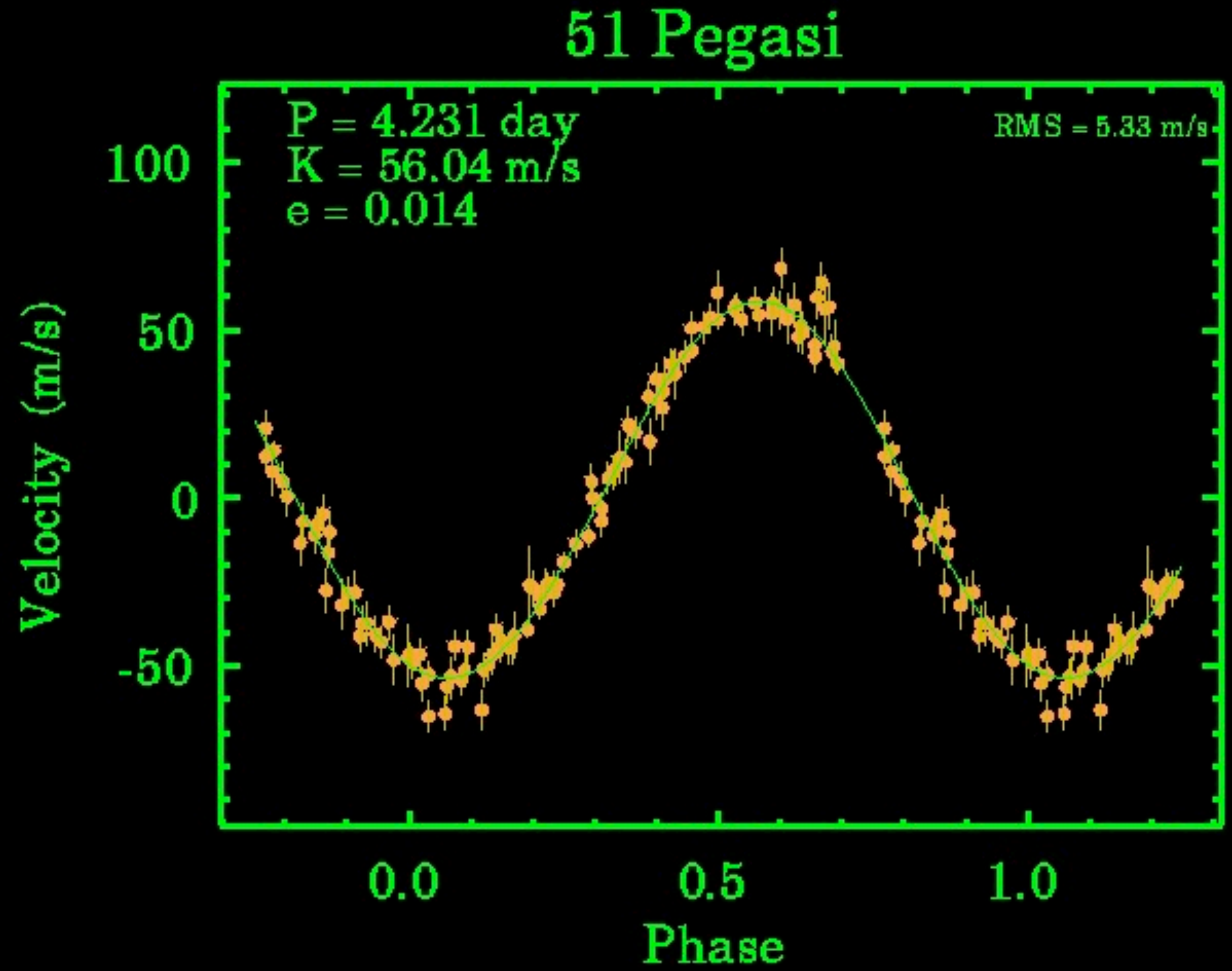




Example echelle spectrum from the Keck HIRES instrument

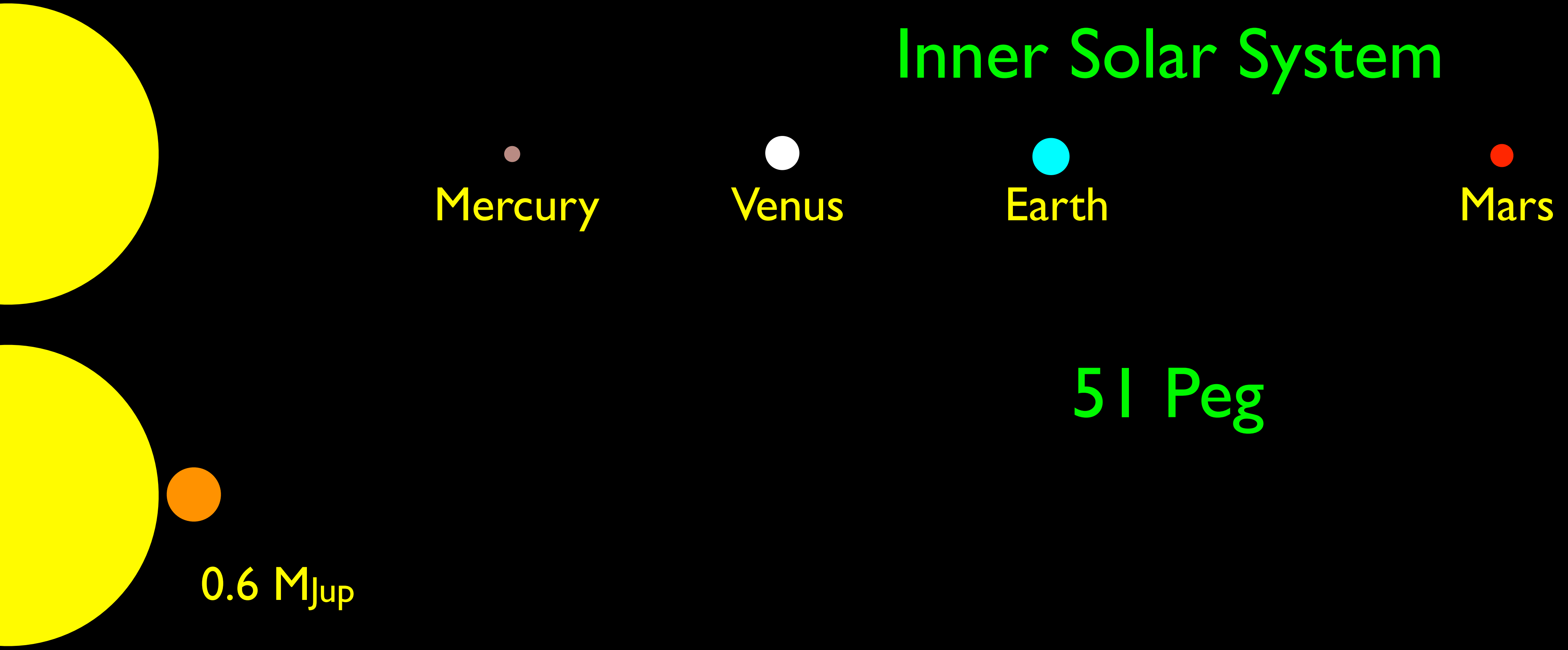
In 1995, Michel Mayor and Didier Queloz, from the Geneva Observatory, announced the discovery of the first extra-solar planet. They had found a regular oscillation of the star 51 Pegasi, a G5 dwarf, very similar to our own Sun, at a distance of 42 lightyears.

Most astonishingly, the period was only *4.2 days*.



They had found a planet which was 60% as massive as Jupiter, in an orbit much smaller than Mercury's (0.05 AU): a Jovian-mass planet in a sub-Mercurian orbit.

What is such a planet (a gas giant? a giant rocky planet?) doing so close to its star?

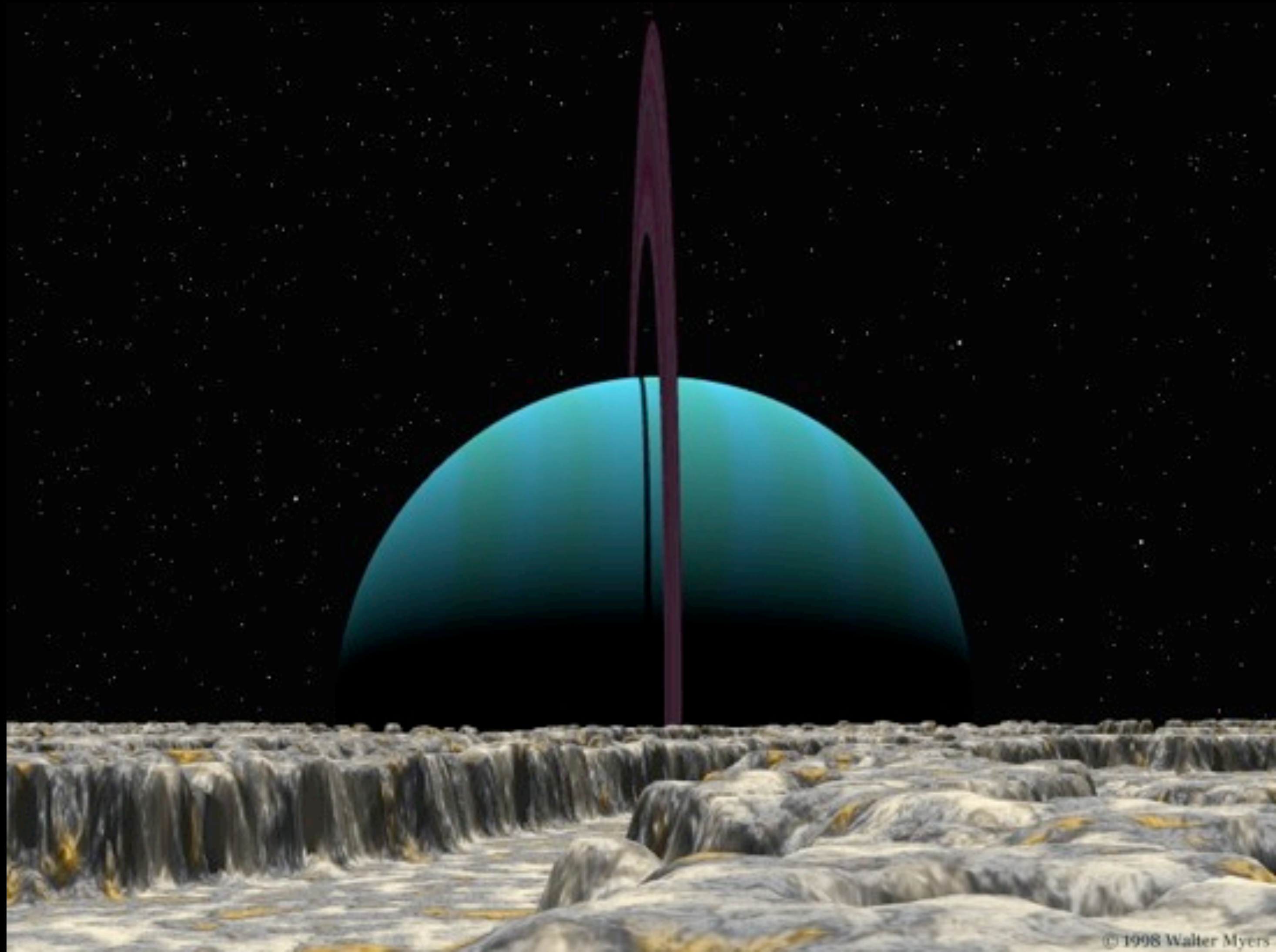


The unlikelihood of forming a massive planet so close to a star could only mean one thing: several people immediately suggested that planets *might not stay put where they were made*.

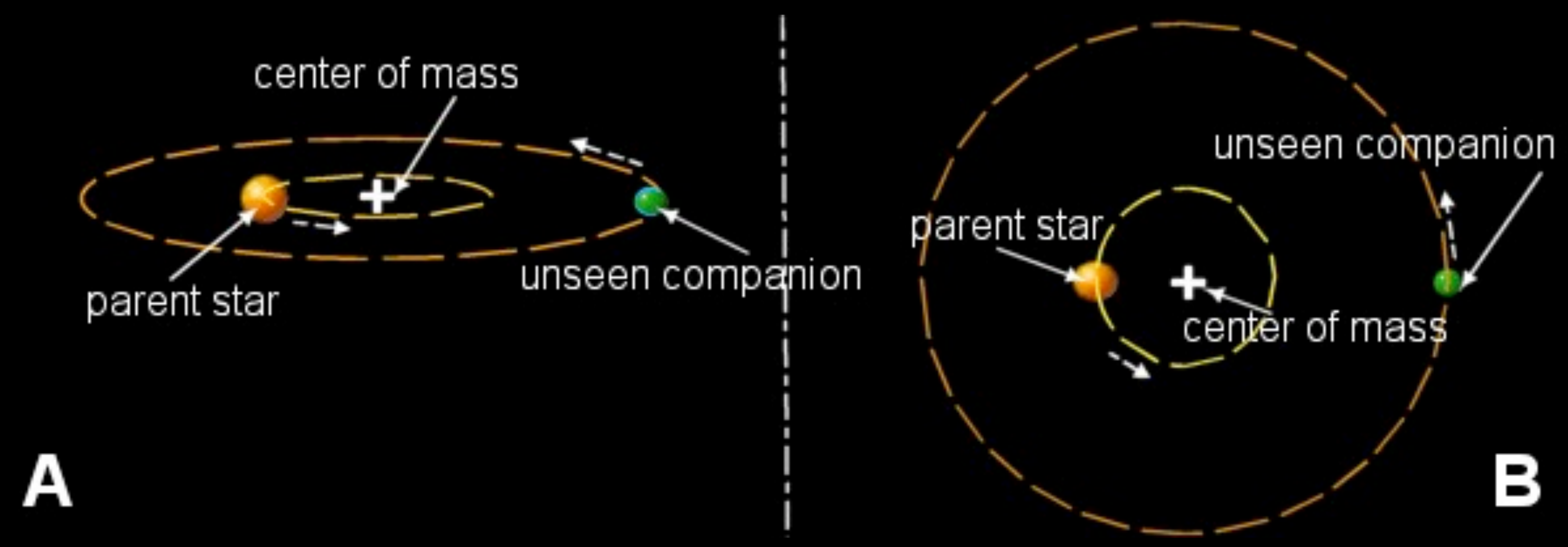
Artist's impression of the planet around 51 Pegasi.

Almost immediately, two new planets were announced, one around 47 Ursa Majoris and one around 70 Virginis, which, at 7.4 M_{Jup}, is still one of the most massive planets found.

After that, they started arriving at an enormous rate.

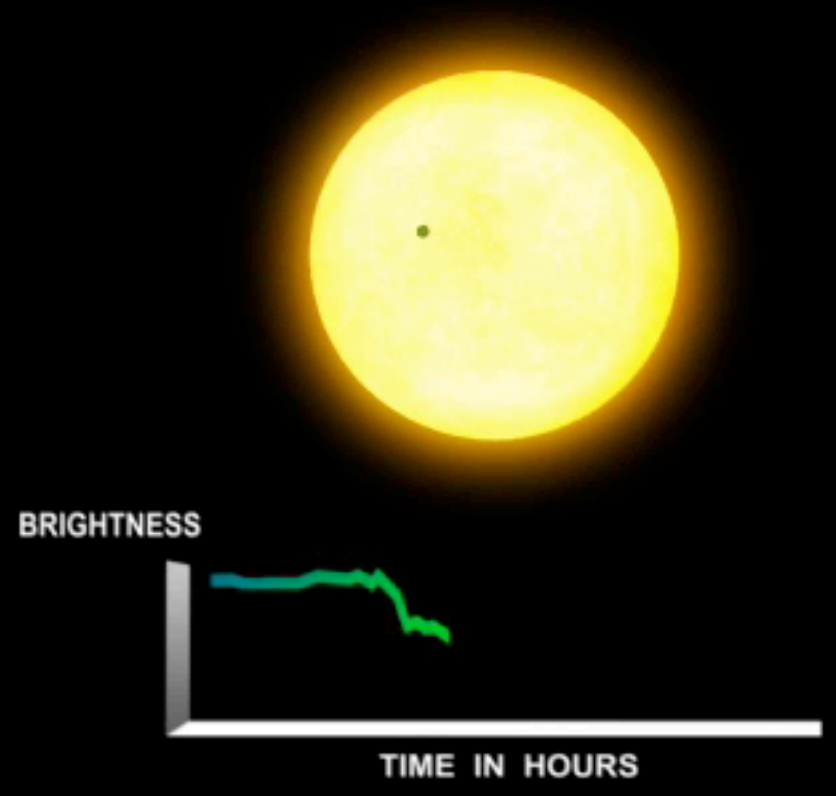


Radial velocity searches are biased towards finding *massive* planets in *small* orbits (maximises velocity variation). We can only measure the velocity along our line of sight, so if the orbit is tilted, the velocity we measure is less than the true velocity, so our mass estimate is only a lower limit.



Large orbits also have long orbital periods, which means you have to observe for much longer to see a whole orbit.

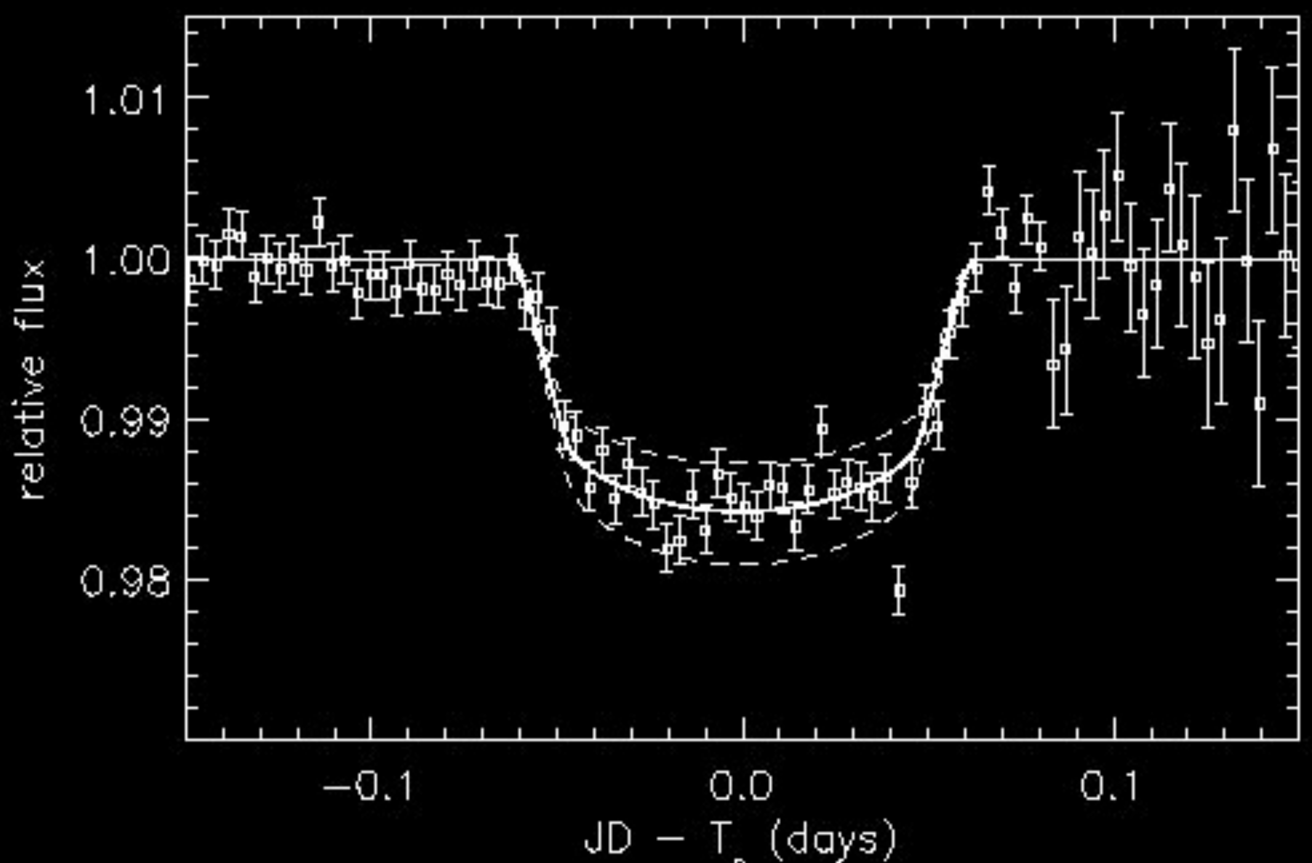
If the orbit of a planet around a star happens to be edge-on, then once during every revolution, the planet will pass in front of its star in a *transit*. This can be detected by recording the star's brightness very accurately and looking for dips.



This can only work if the viewing geometry is favourable, and is biased towards finding *large* planets in *small* orbits. The 2004 transit of Venus showed that terrestrial planets don't cause much of a decrease in the light from the star!

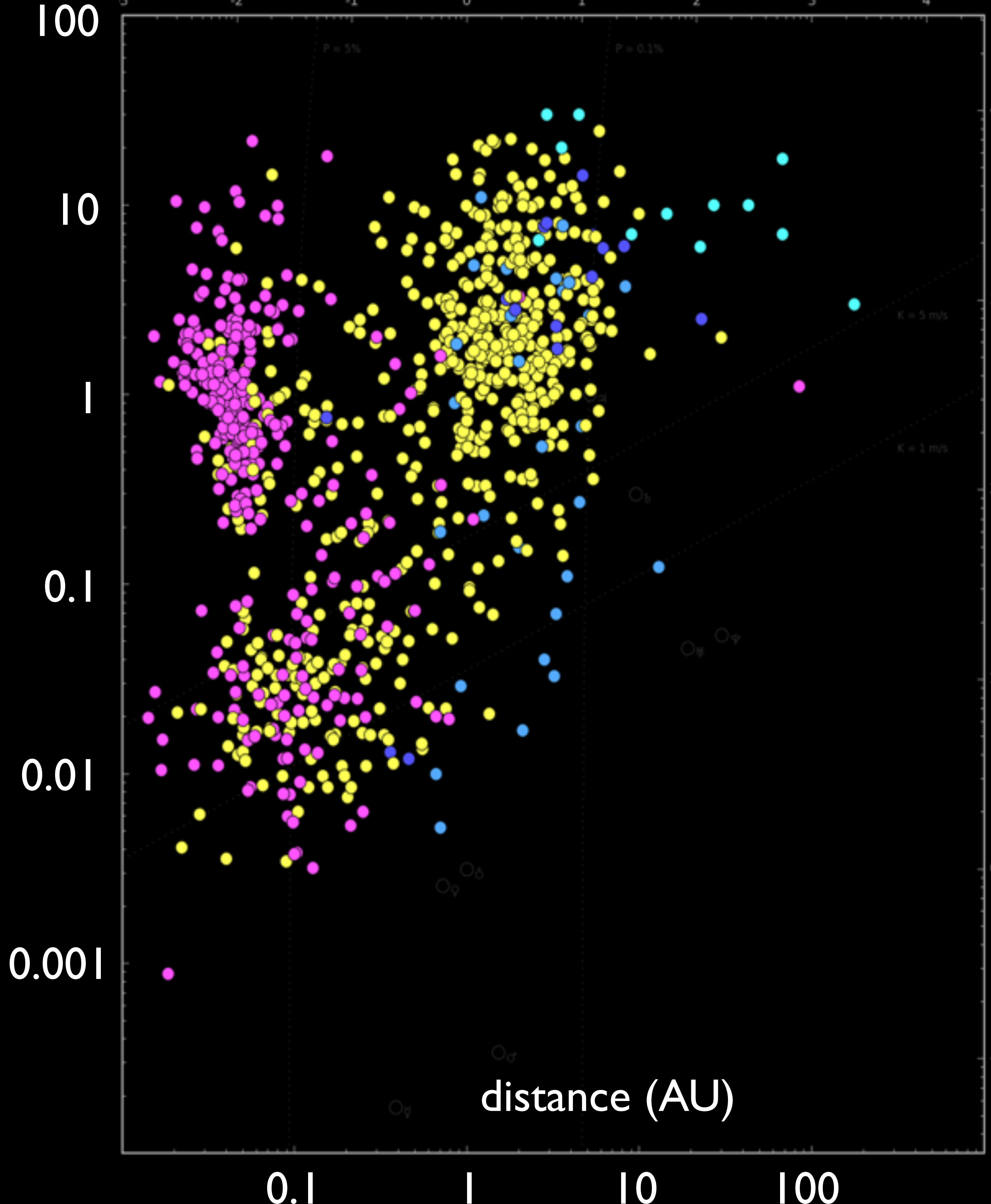
Hubble image of Titan transiting across Saturn, taken in February 2009

Before the launch of *Kepler*, 185 planets were found through transits. Measuring transits of planets which have been detected via velocity variations is particularly valuable because this enable both the mass and the radius to be determined exactly (not just lower limits).



As of October 2014, we know of 1763 confirmed planets around 1145 stars.

None of them look anything like what we were expecting.

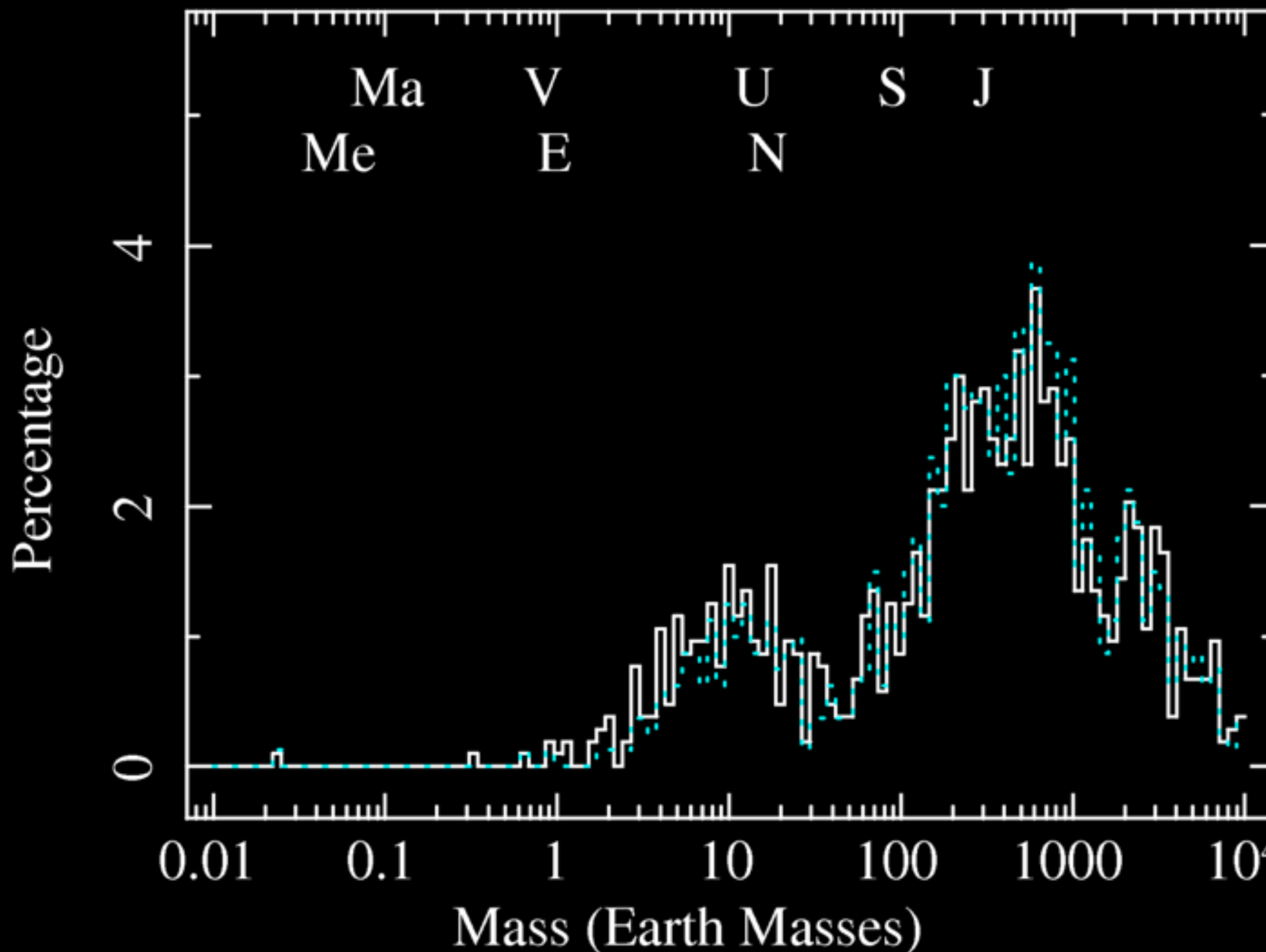


100
10
1
0.1
0.01
0.001
mass (MJ)
distance (AU)
0.1
1
10
100

Amongst these 1763 planets are:

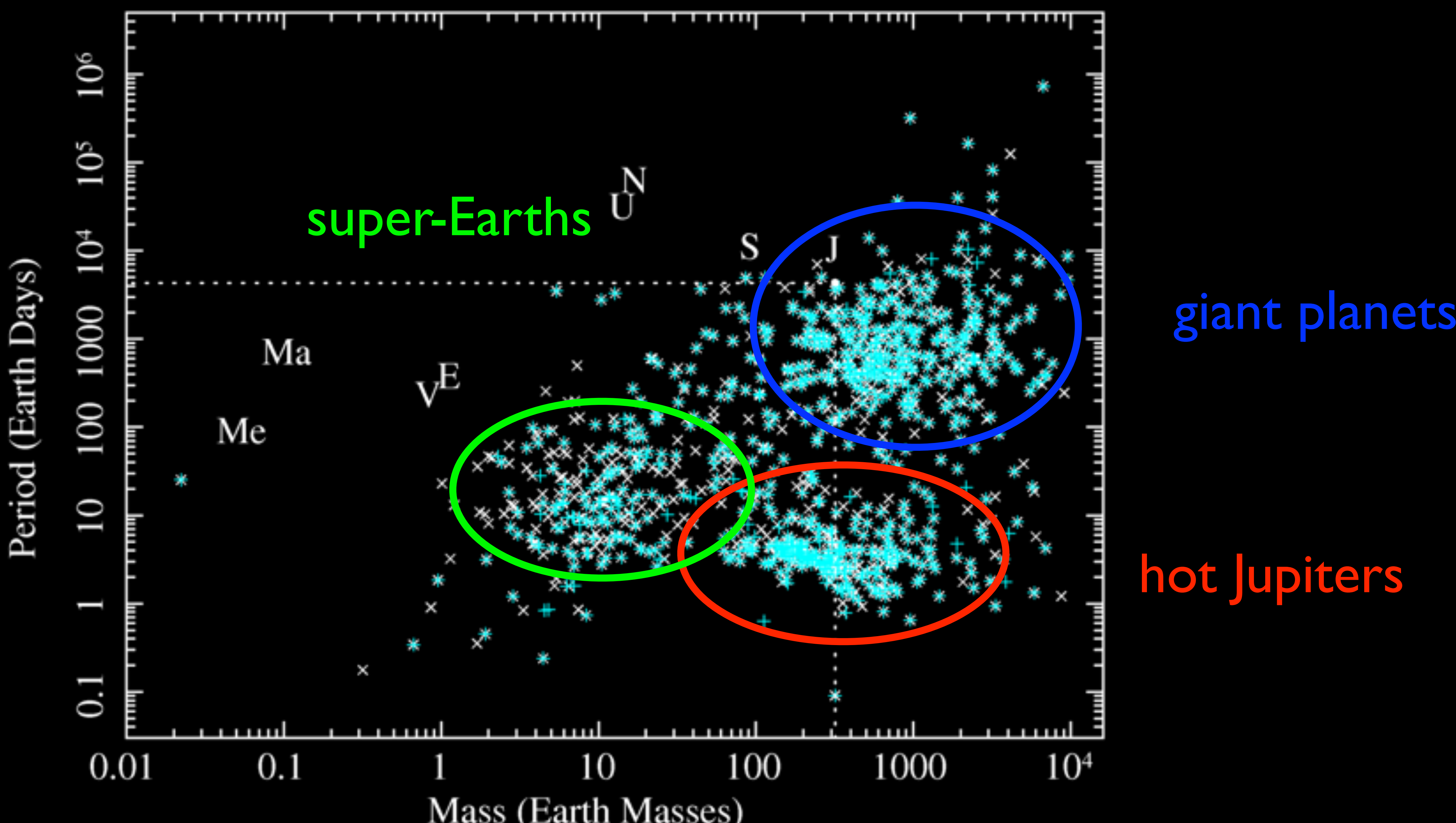
- 469 multiple planet systems
- As many as half of exoplanet host stars have a companion star; most planets orbit just one star, but some orbit both (*circumbinary* planets)

- The masses range between ~1 M_{Earth} and about 25 M_{Jup}. The distribution has two broad peaks, one near a Jupiter mass and one near a Uranus/Neptune mass.

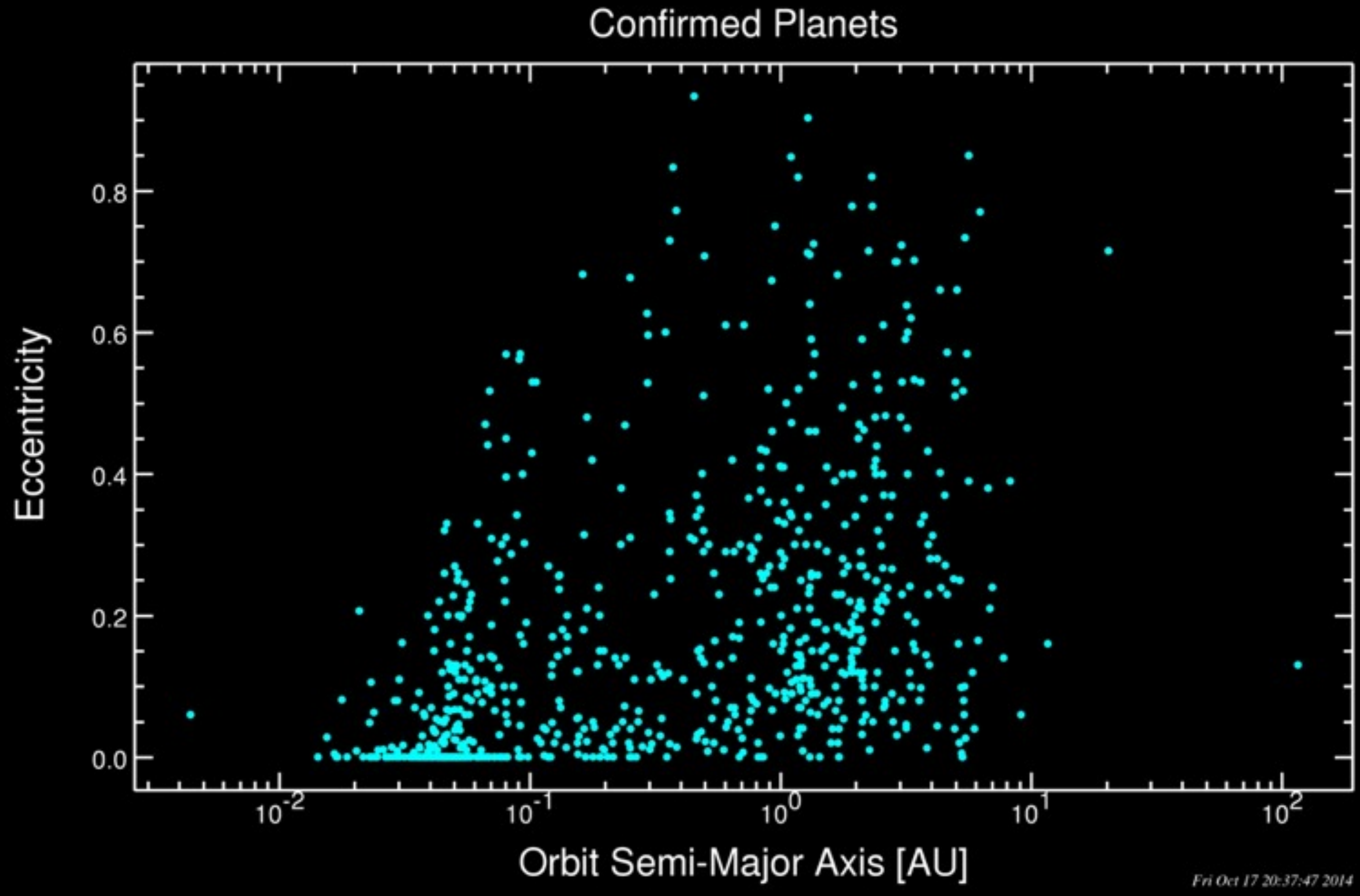


Data as of July 2014

- The planets tend to fall into three categories: *hot Jupiters* like 51 Peg-b, *giant planets* with idiosyncratic orbits, and *super-Earths*, with masses between the mass of Earth and Neptune.

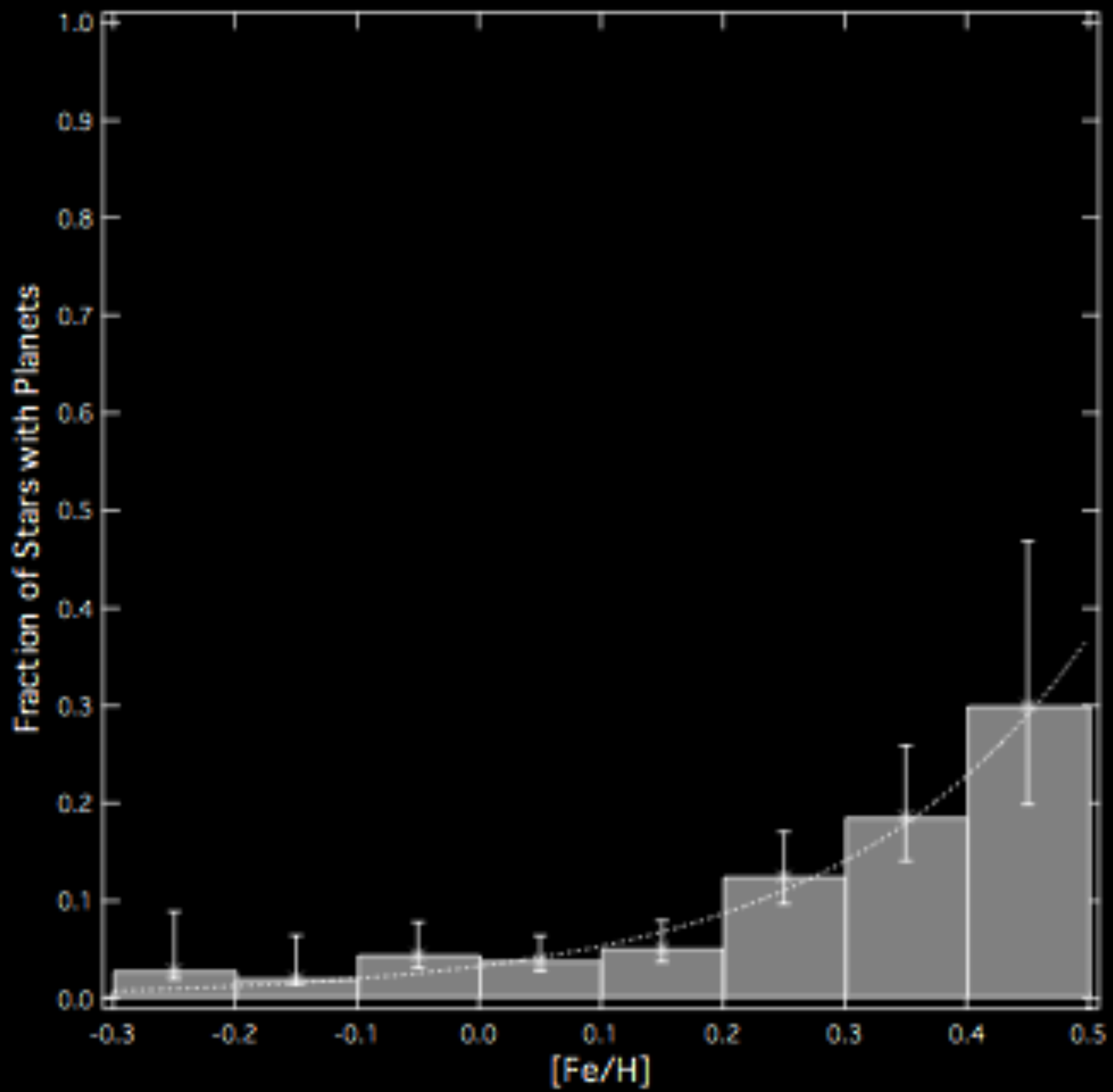


- Most of the planets have eccentric orbits: the mean eccentricity is about 0.20 (compared with Jupiter's orbital eccentricity of 0.094, or Earth's of 0.017). Planets very close to their sun have almost circular orbits, while planets further away can have any eccentricity.



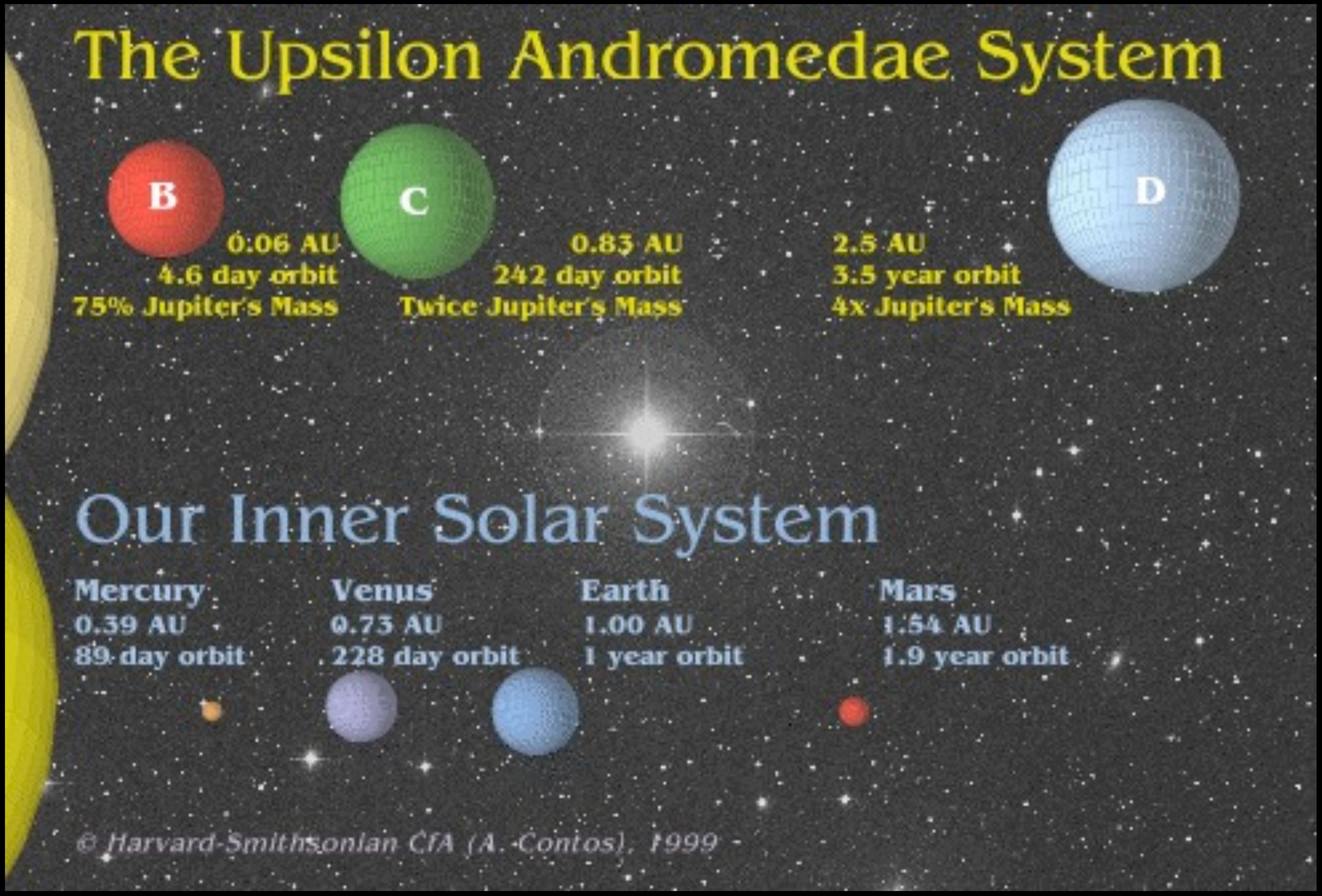
- About 7% of nearby G, F and K stars have at least one giant planet within 5 AU.

The *chance* of having a planetary companion depends on the metallicity of the star:
stars with higher metal content have significantly more planets.

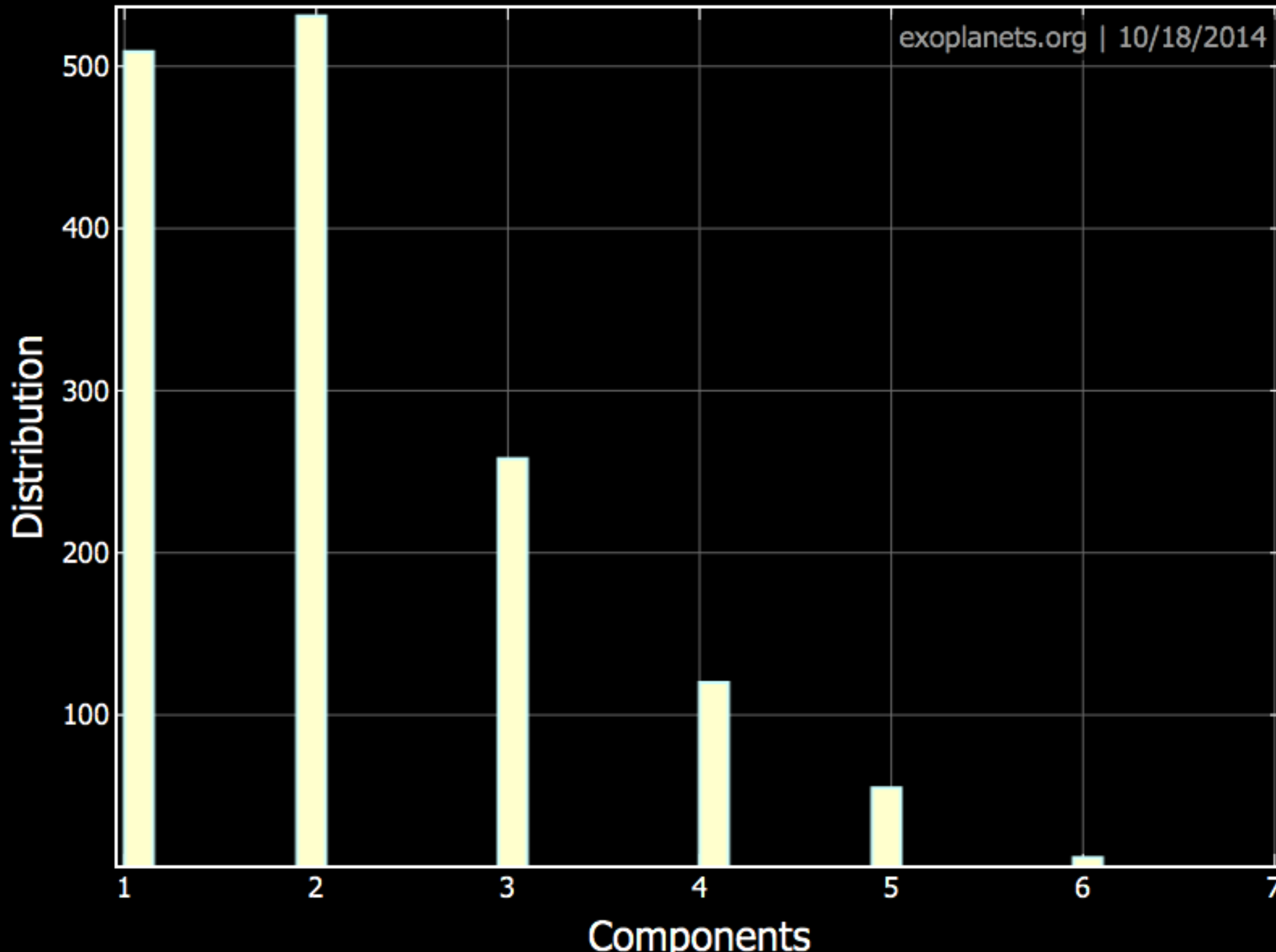


from Gonzalez 2013

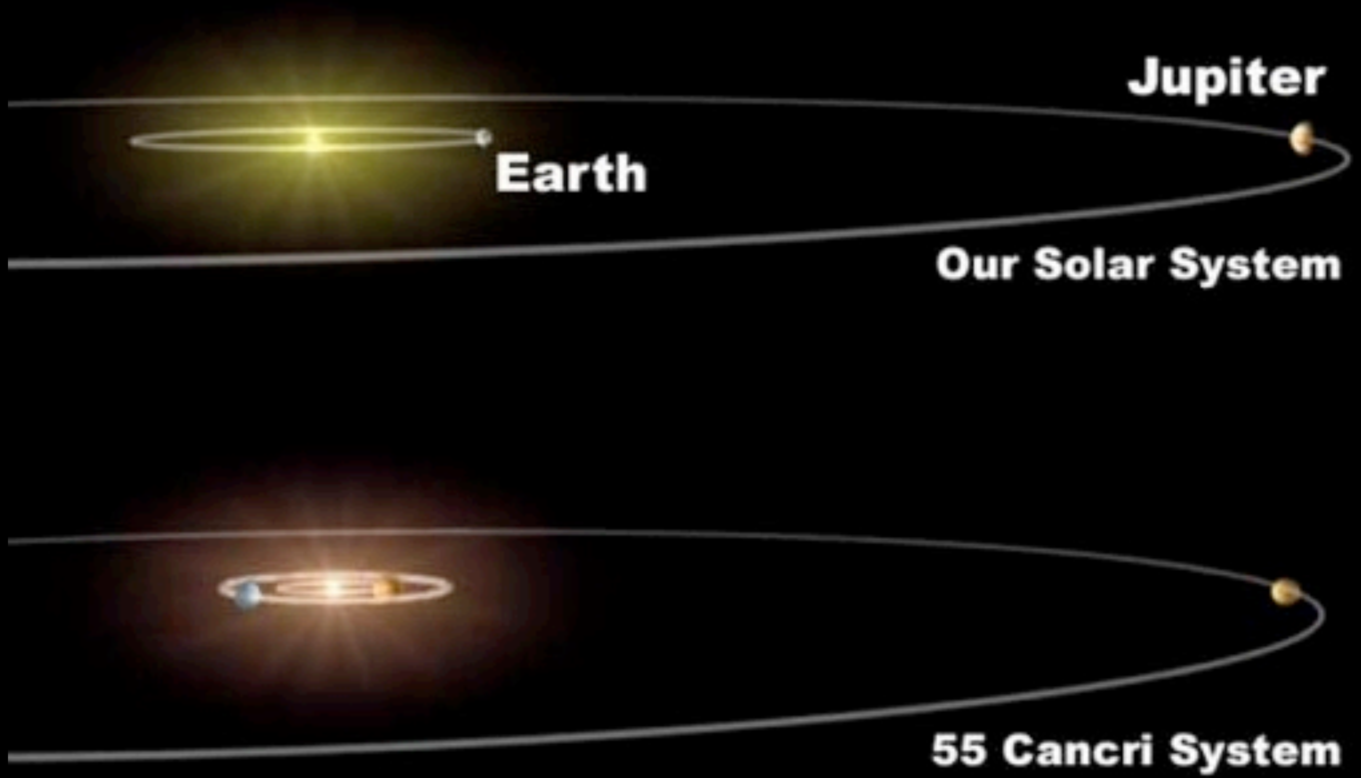
In 1999, the first multiple-planet system was found, around Upsilon Andromedae. All three planets are massive, with the innermost orbiting extremely close to the star.



We now know of 469 systems with more than one planet.



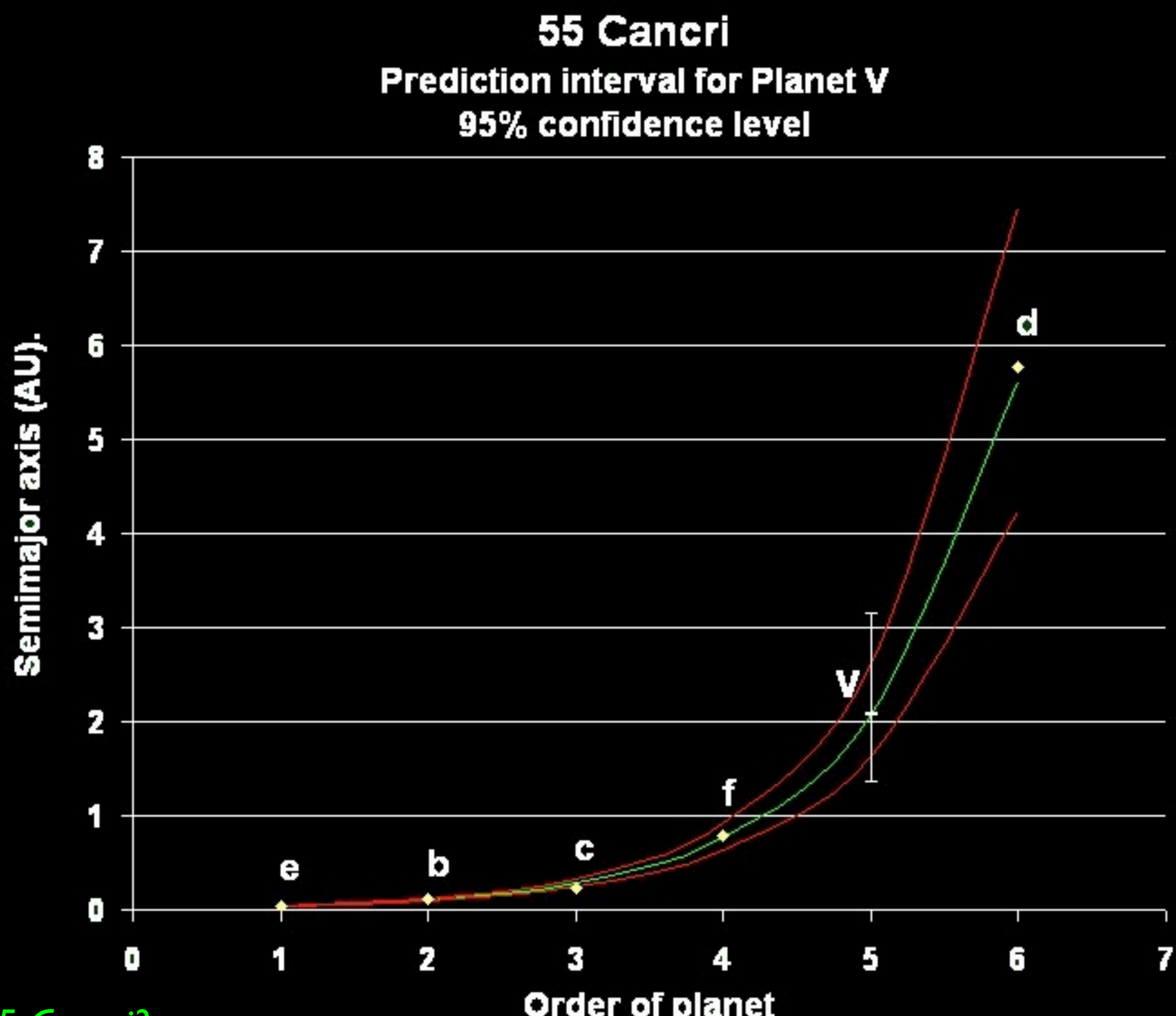
The system around 55 Cancri has five planets. The outermost planet, 55 Cancri d, has an orbit very similar in size to Jupiter's.



It is possible there are smaller (terrestrial?) planets in the gap between f and d.

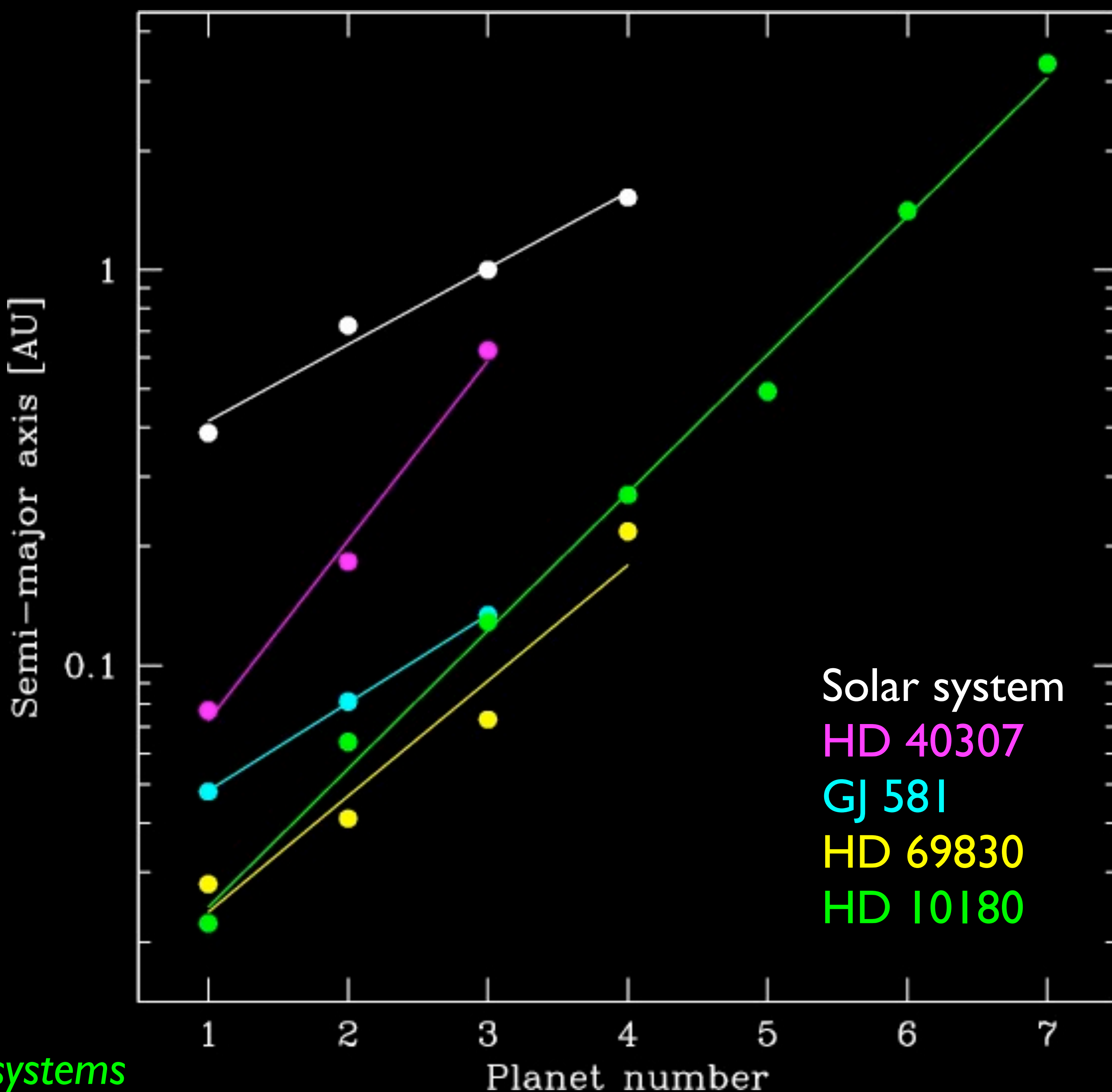
Planet	Mass (M_J)	Distance (AU)	Period (d)
e	0.03	0.04	2.8
b	0.82	0.12	15
c	0.17	0.24	44
f	0.14	0.78	260
d	3.8	5.8	5218

In 2007, an amateur astronomer suggested the 55 Cancri system has a "Bode's Law"-like relationship, which would predict the existence of two more planets.



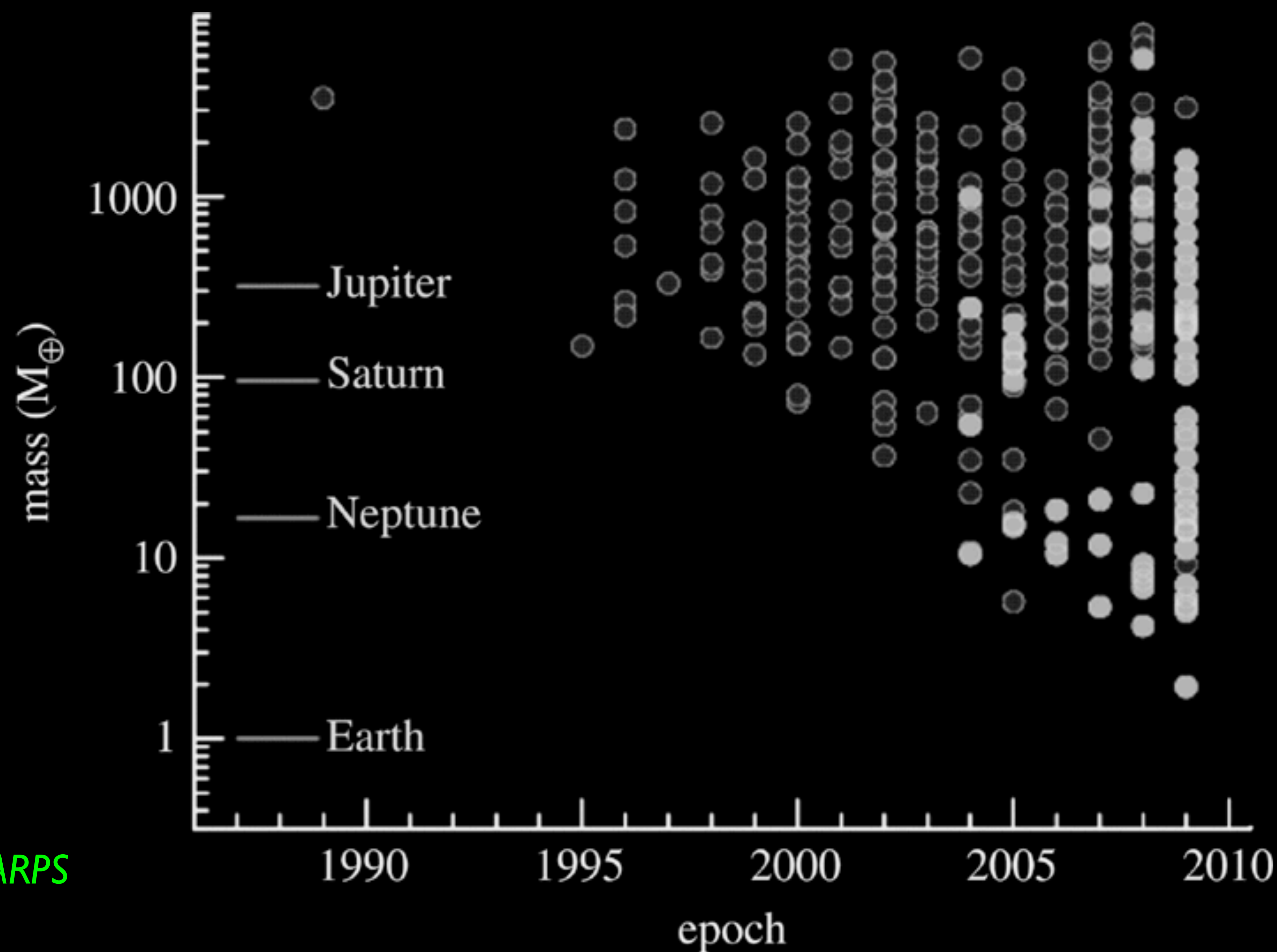
Bode's law with missing planets in 55 Cancri?

However, analysis of more systems suggests that most systems have somewhat regular spacings, but all different.



Fits to planet distances for five systems

As the timespan of data on each star increases, we can find smaller and smaller planets on longer and longer orbits.

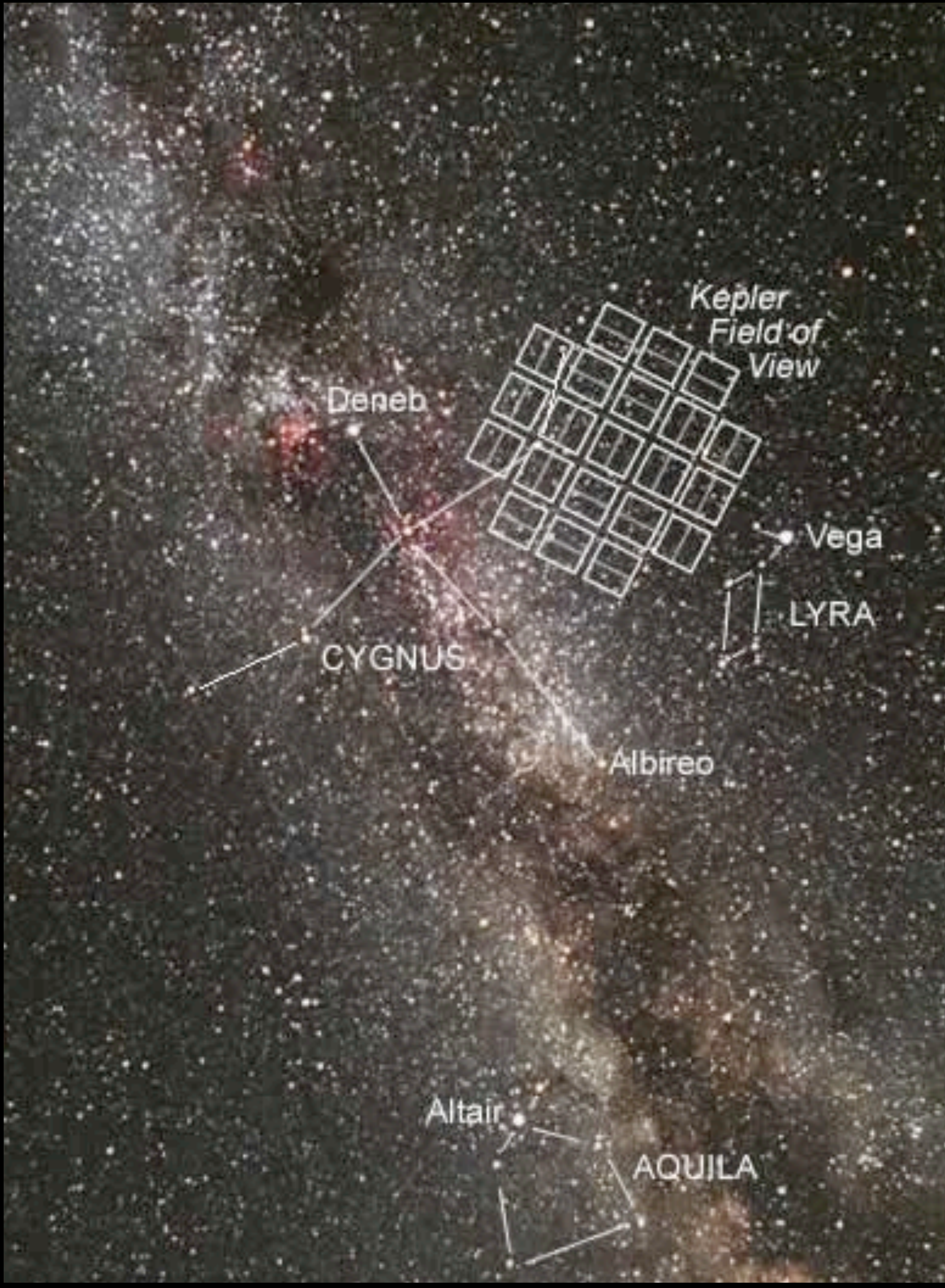


Planets detected by the HARPS radial velocity survey

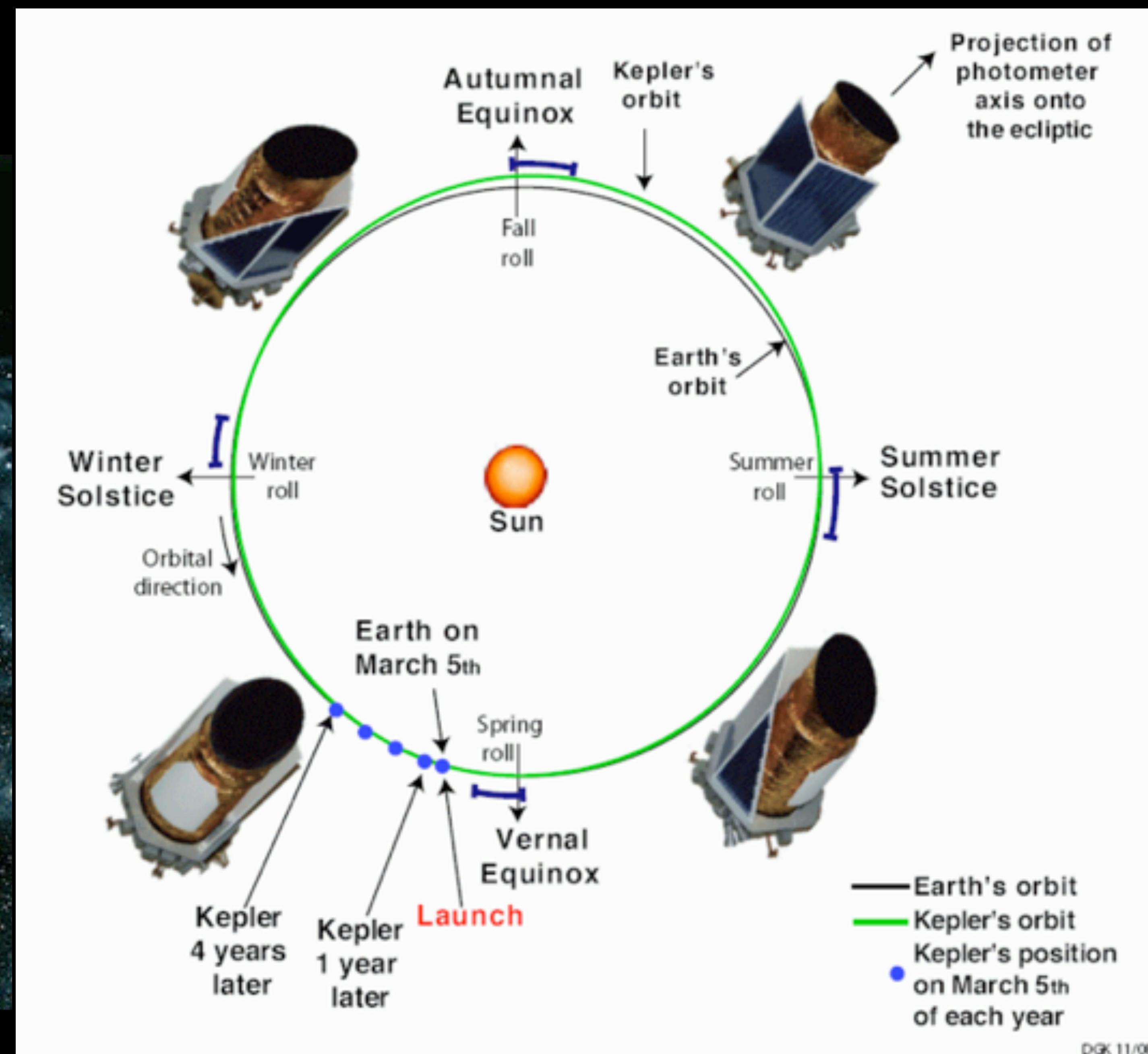
The *Kepler* mission

The *Kepler* mission to find transiting planets was launched in March 2009. It is designed to observe 155,000 stars in a single field in Cygnus, observing continuously (every 30 min) for 3.5 years.

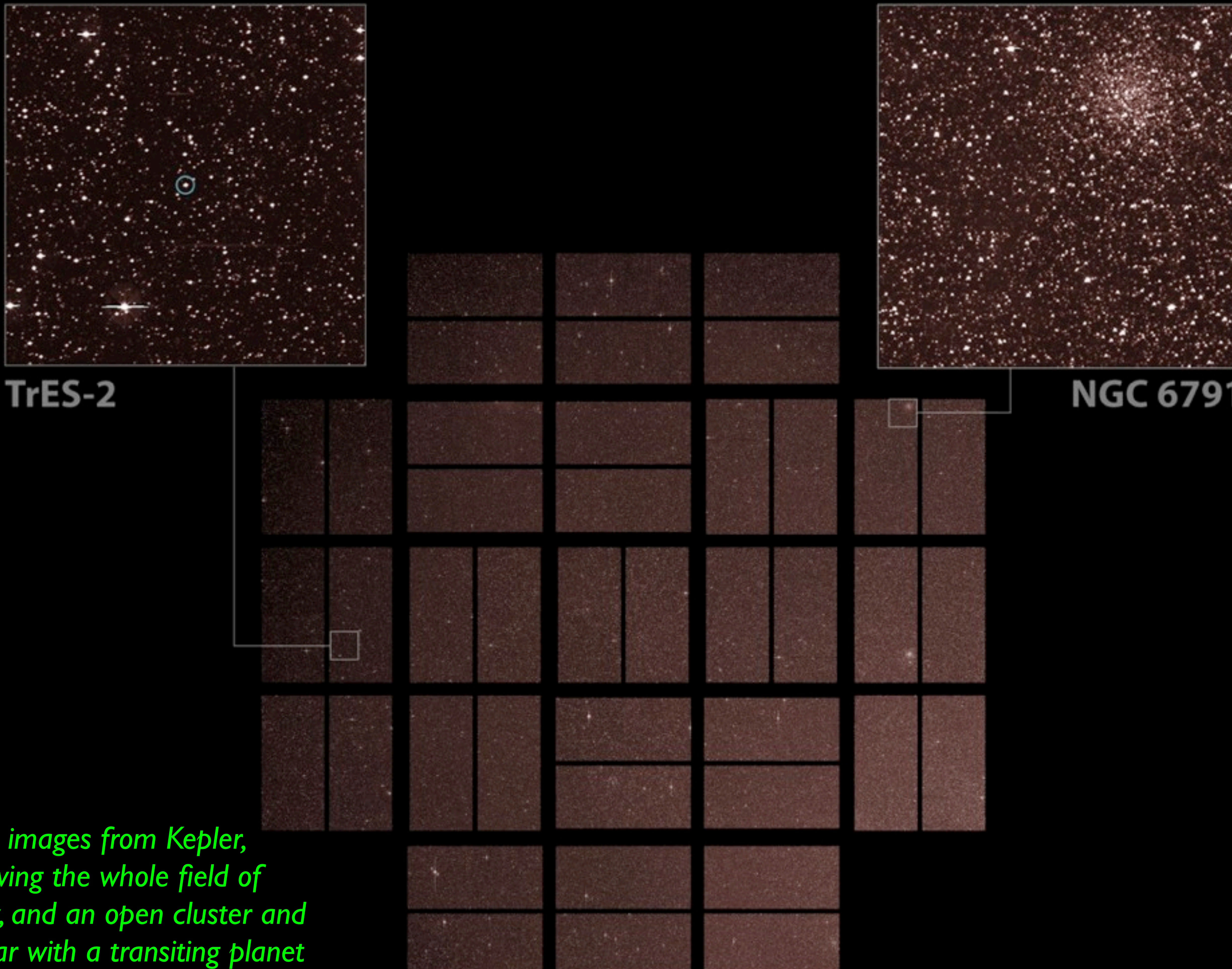
To detect the transit of an Earth-like planet, it needs to detect brightness changes of 1/10,000 when an Earth-sized planet on an Earth-like orbit makes a ~12-hour passage in front of a Sun-sized star.



Kepler is in a heliocentric, Earth-trailing orbit, falling gradually further behind the Earth. It is pointing to a region in the Orion arm, in the direction of the Sun's motion around the Galaxy.

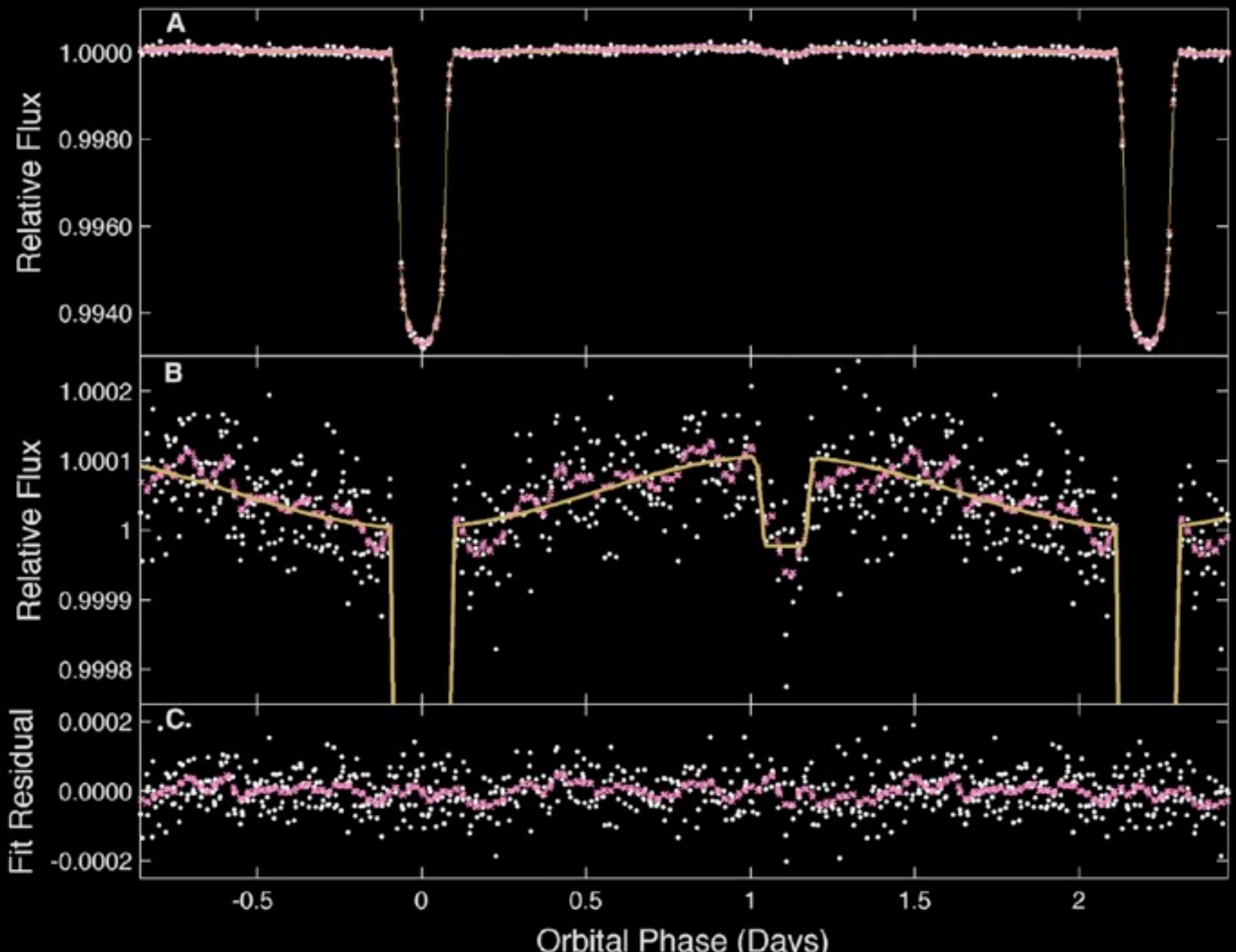


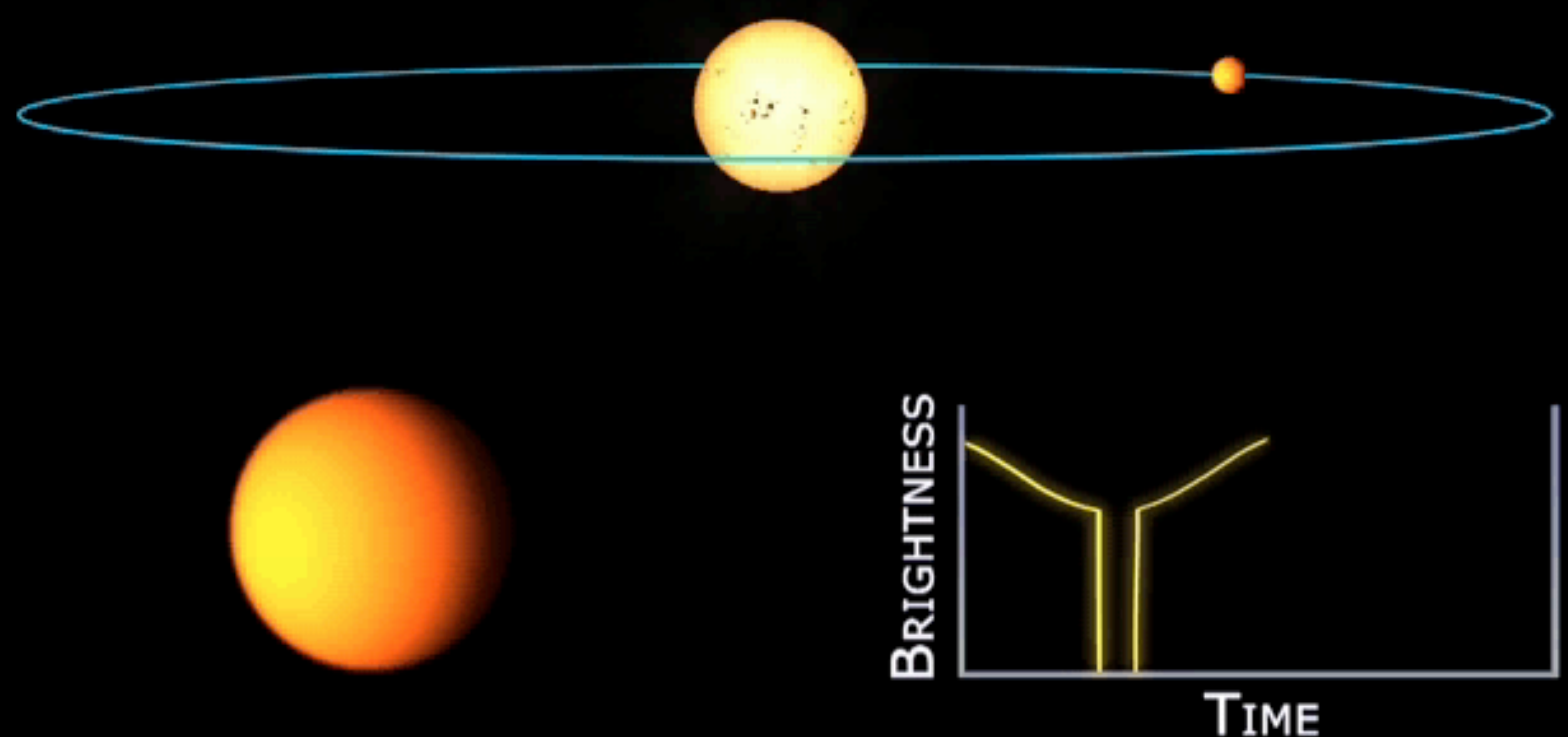
The portion of the Galaxy being observed by Kepler



First images from Kepler, showing the whole field of view, and an open cluster and a star with a transiting planet

From its first 10 days of commissioning data, *Kepler* detected a previously known giant transiting exoplanet, HAT-P-7b




Brightness
Time

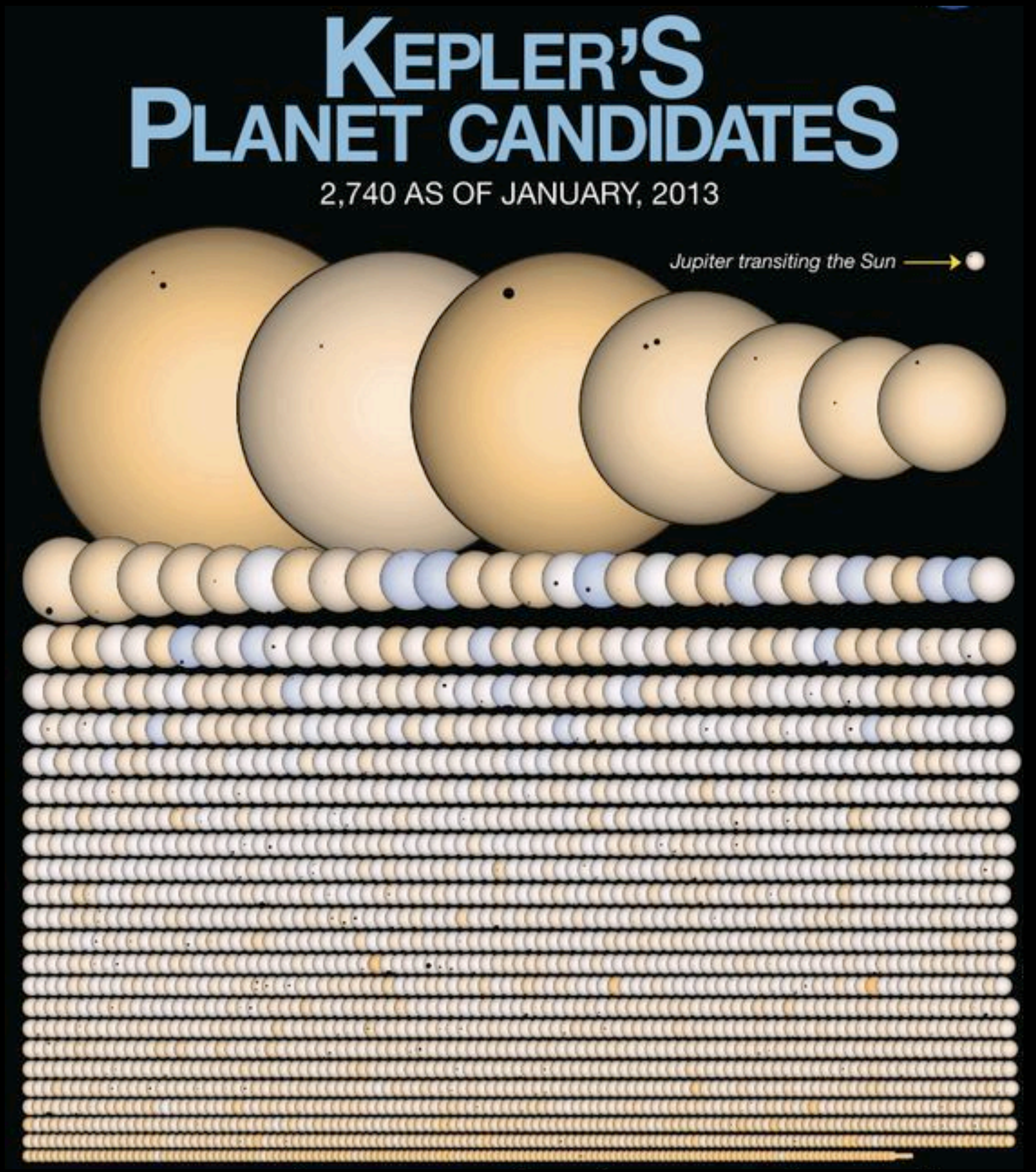
Since then, *Kepler* has been finding planets continuously. Planetary candidates are only confirmed when large ground-based telescopes have detected the radial velocity variations due to the planet. There are so many candidate planets that these confirming observations are now the limiting step.

So far, *Kepler* has discovered 992 confirmed planets.

Because the data become public after 1–2 years, the team periodically releases lists of "*Kepler* objects of interest" (KOIs).

In February 2014 the *Kepler* team released the latest list of 715 new planetary candidates circling 305 host stars. These candidates are yet to be confirmed, but more than 90% are turning out to be real planets.

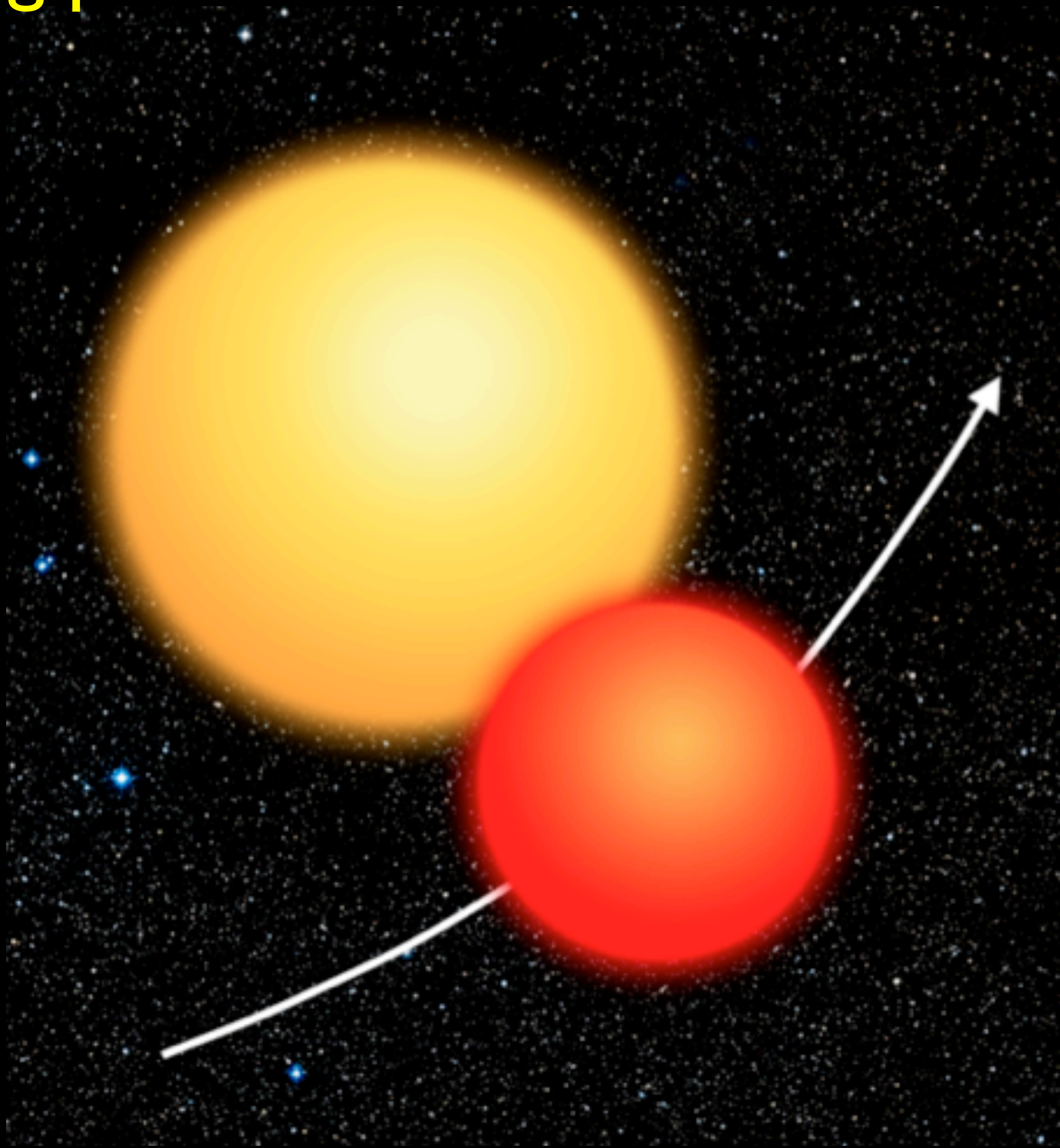
The number of (potential) Earth-sized planets is now 738.



Why so many new planets all at once?

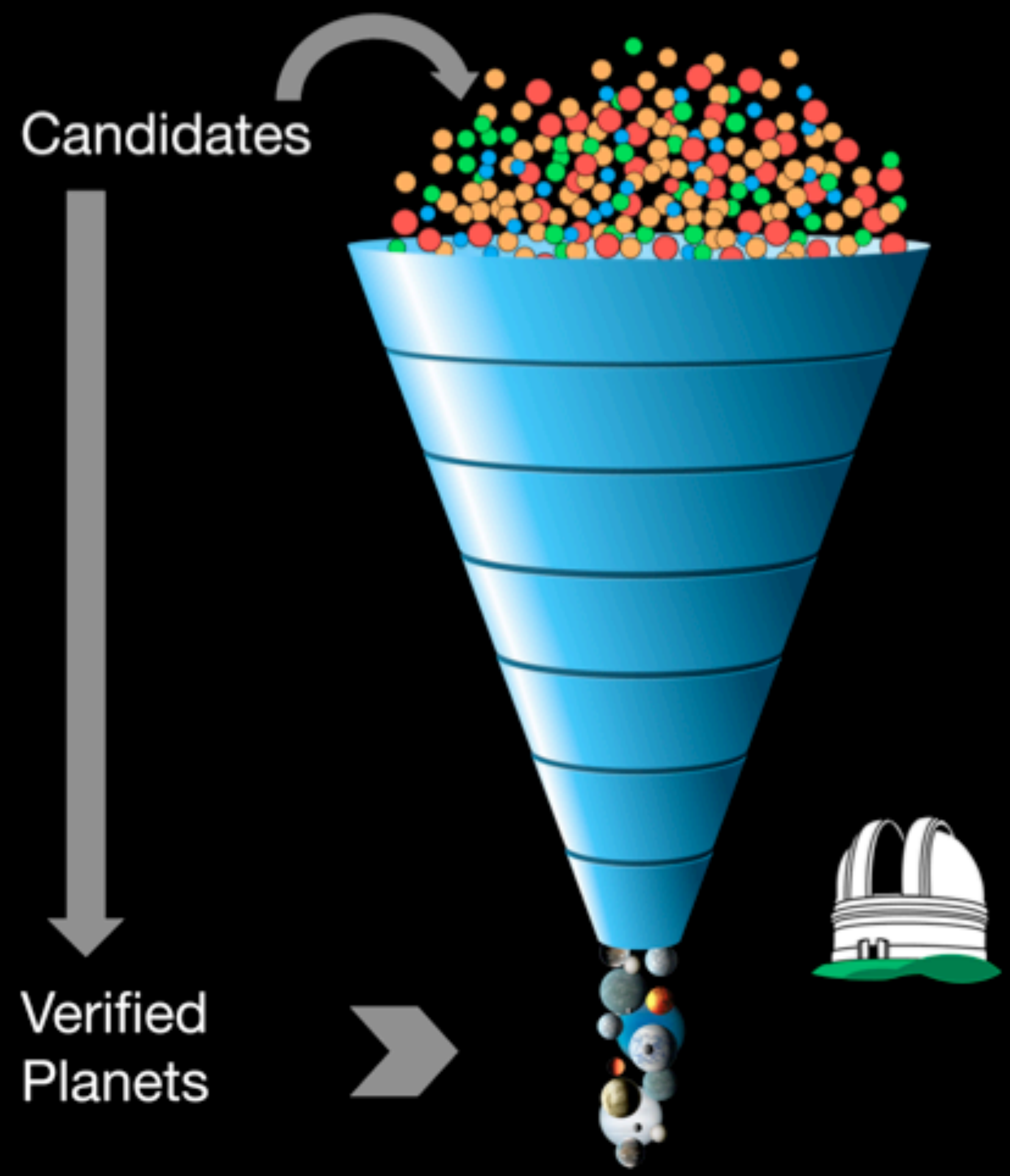
Most common false positives are eclipsing binaries with grazing eclipses mimicking planets.

Confirming observations with ground-based telescopes are required to rule these out.

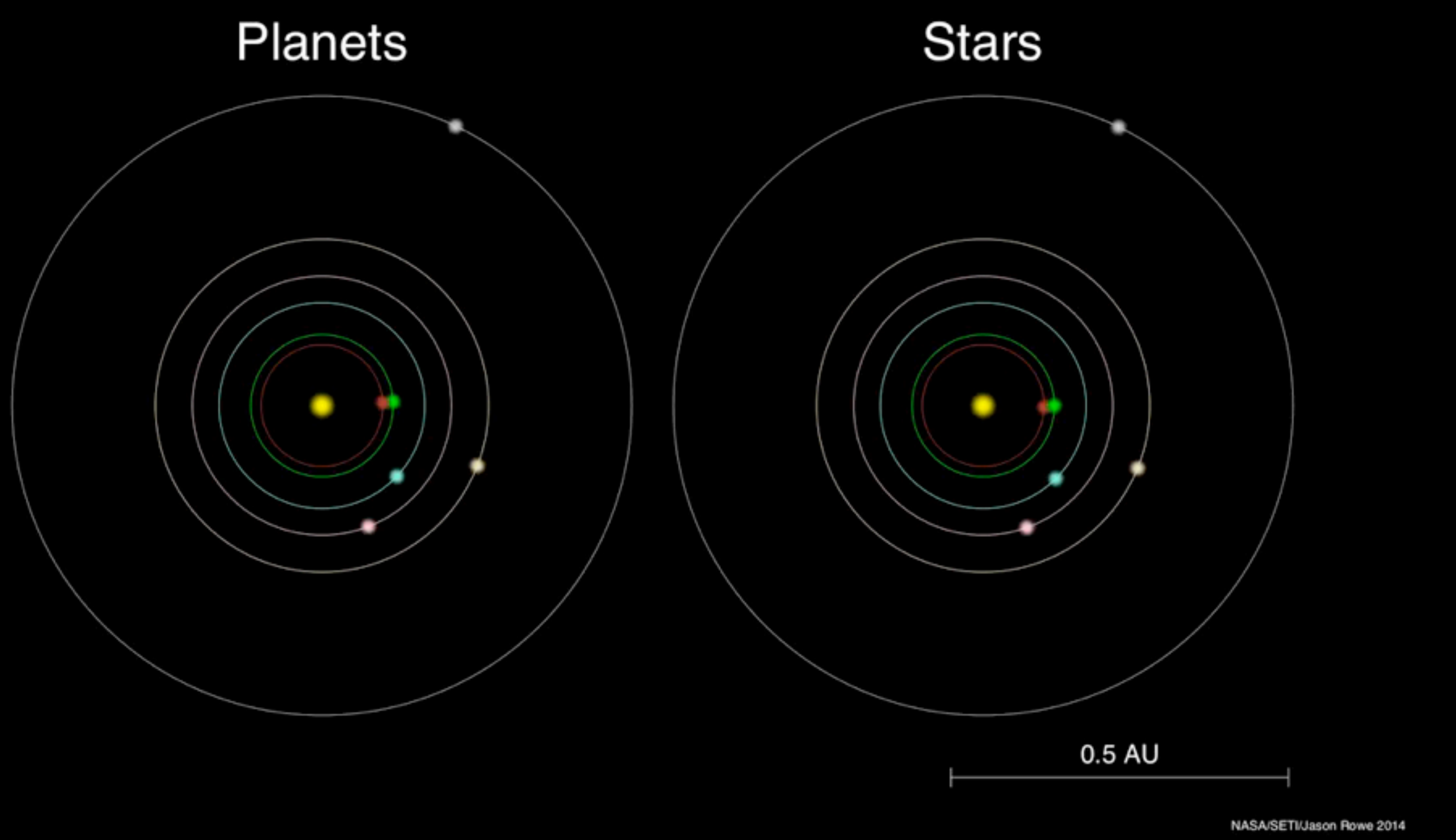


images from "Kepler Planet Bonanza" press kit

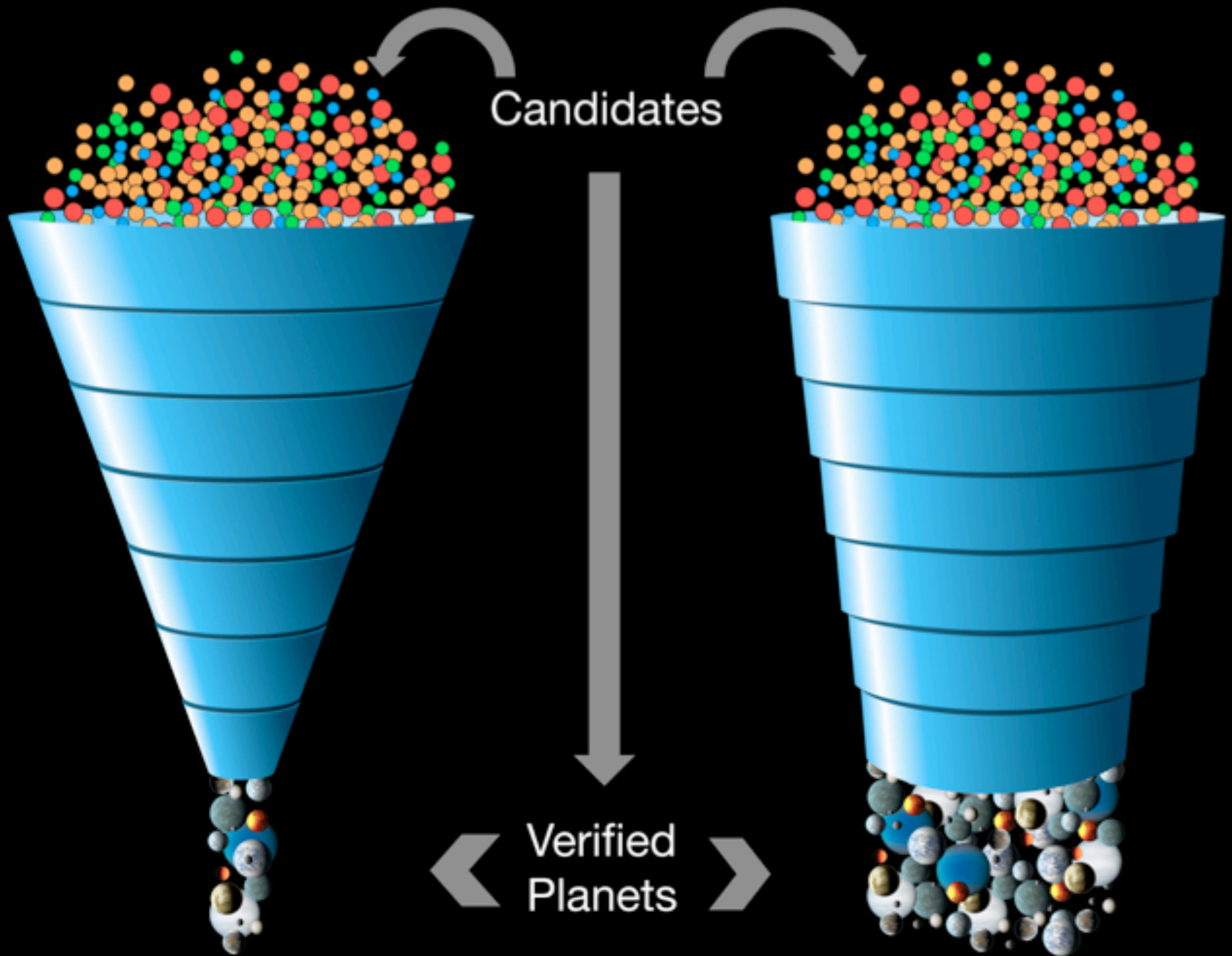
Planet Verification Bottleneck



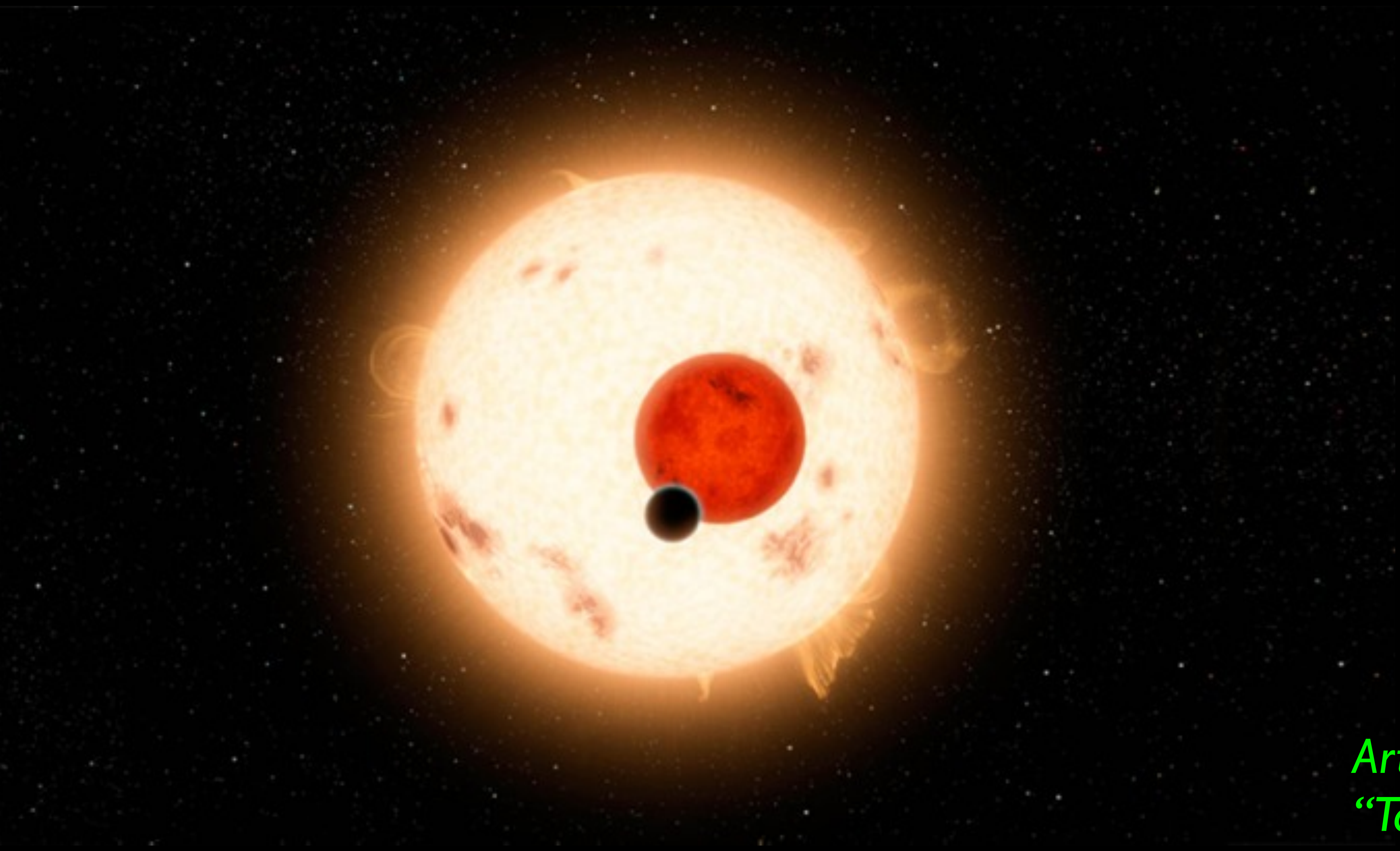
But where a star shows *more than one* transiting planet candidate, it is very unlikely to be multiple stars.



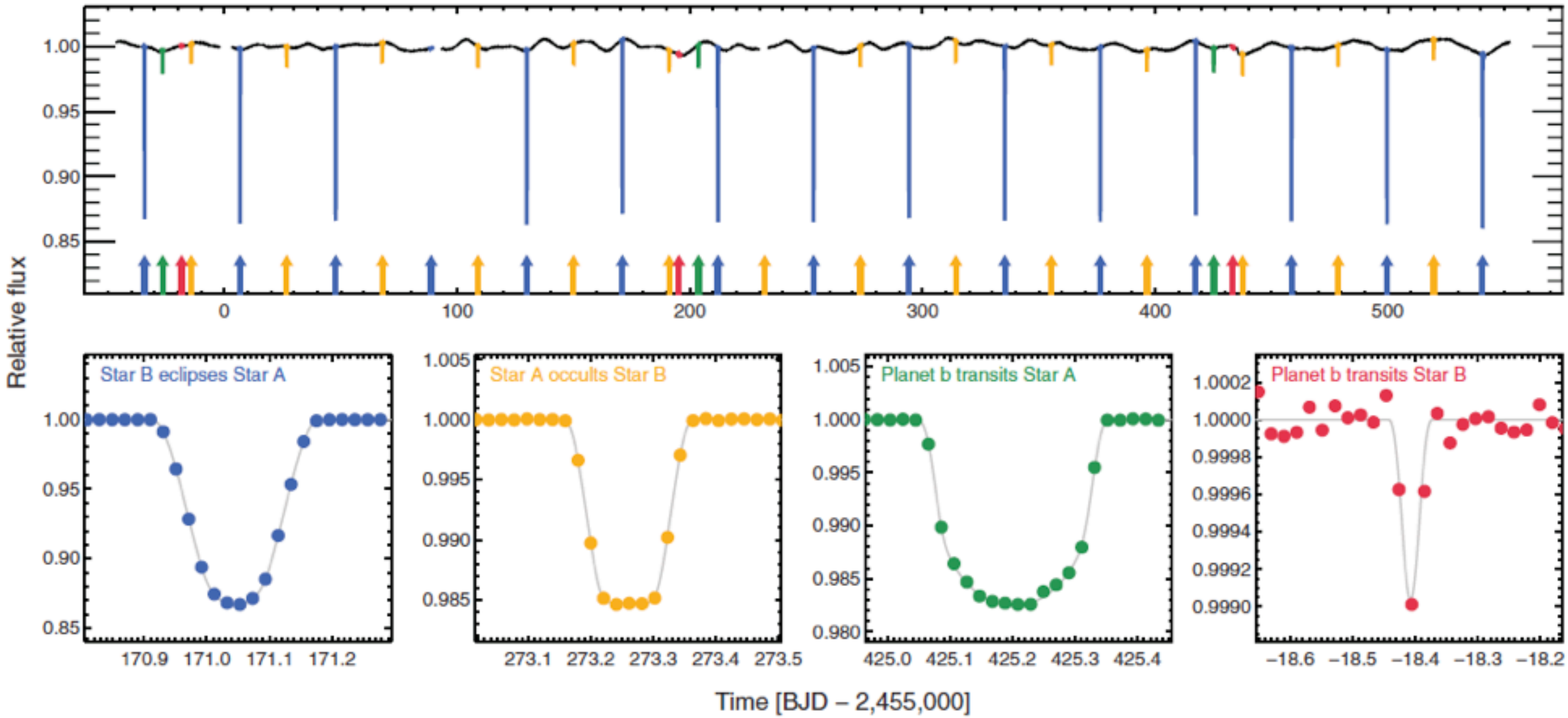
Opening the Planet Verification Bottleneck

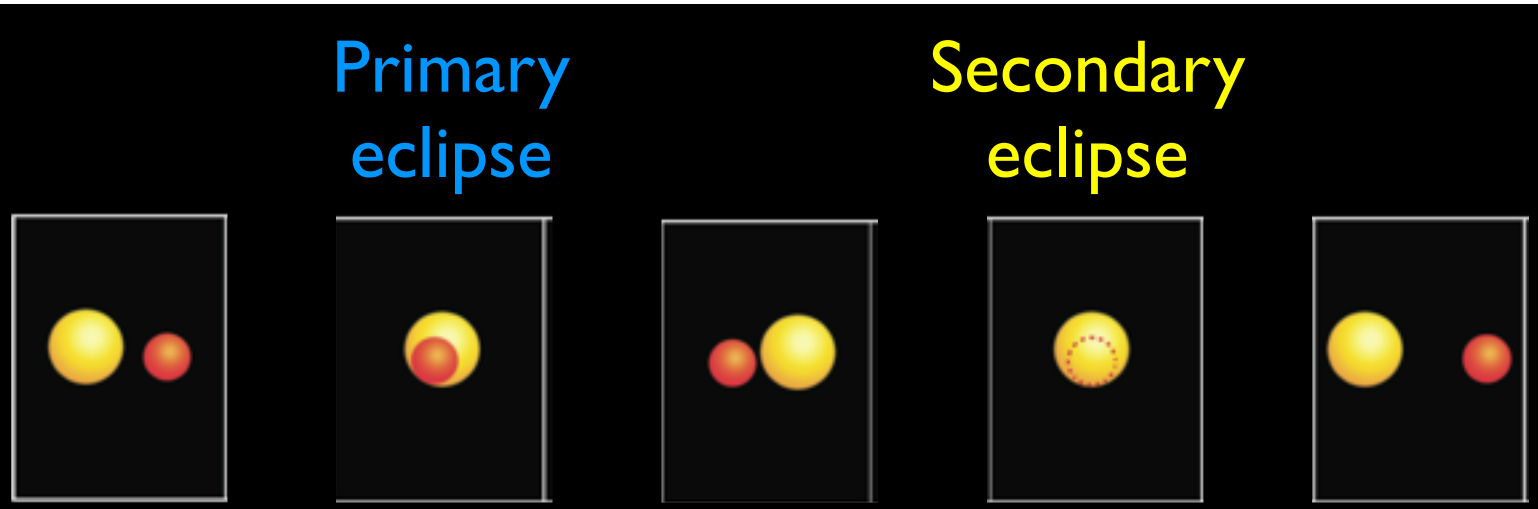


In 2011, the Kepler team announced the first discovery of a *circumbinary* planet – a planet orbiting two stars. The two orbiting stars regularly eclipse each other; the planet also transits, each star, and Kepler data from these planetary transits allowed the size, density and mass of the planet to be extremely well determined.

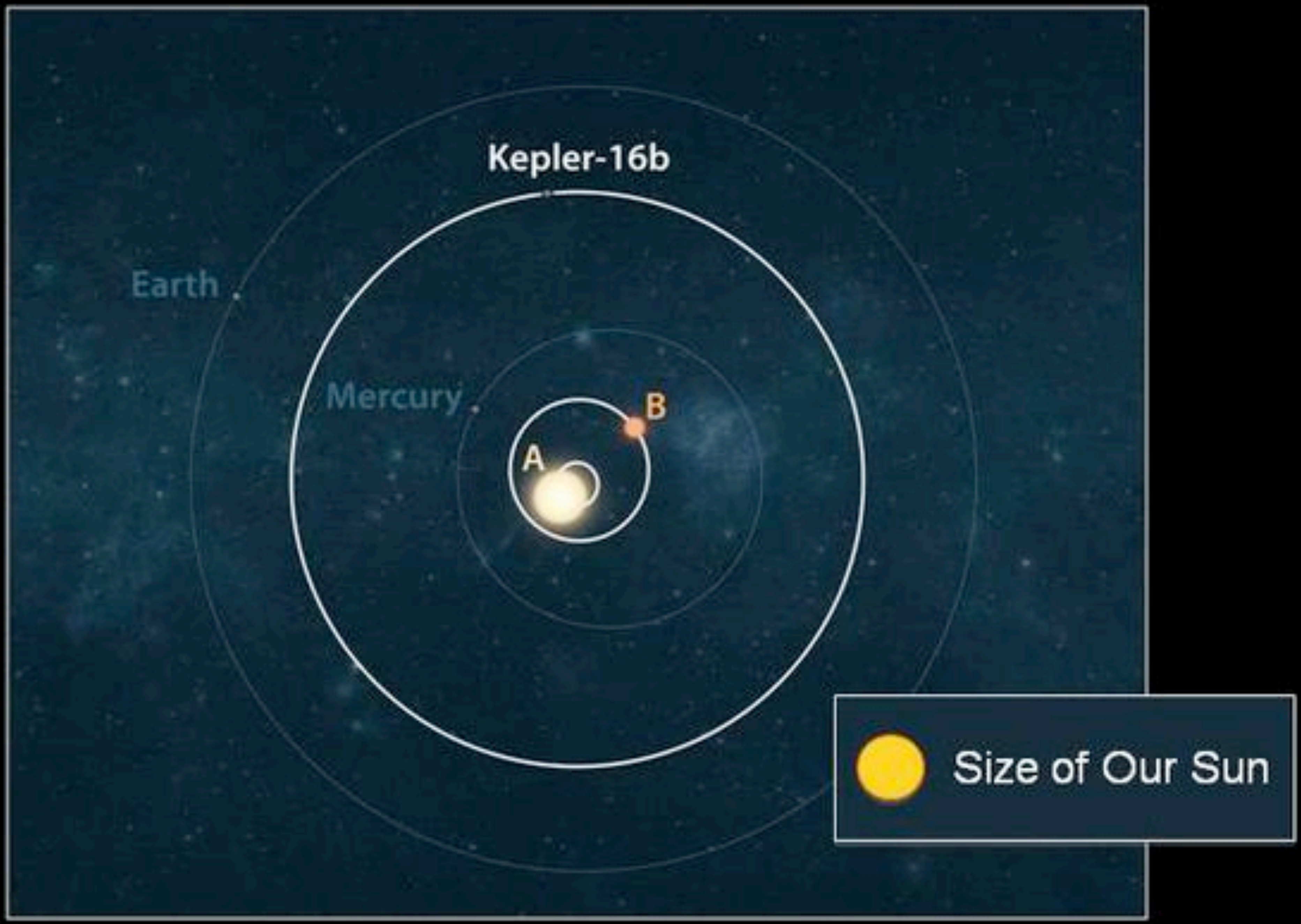


Artist's impression of Kepler-16b , the "Tatooine planet"



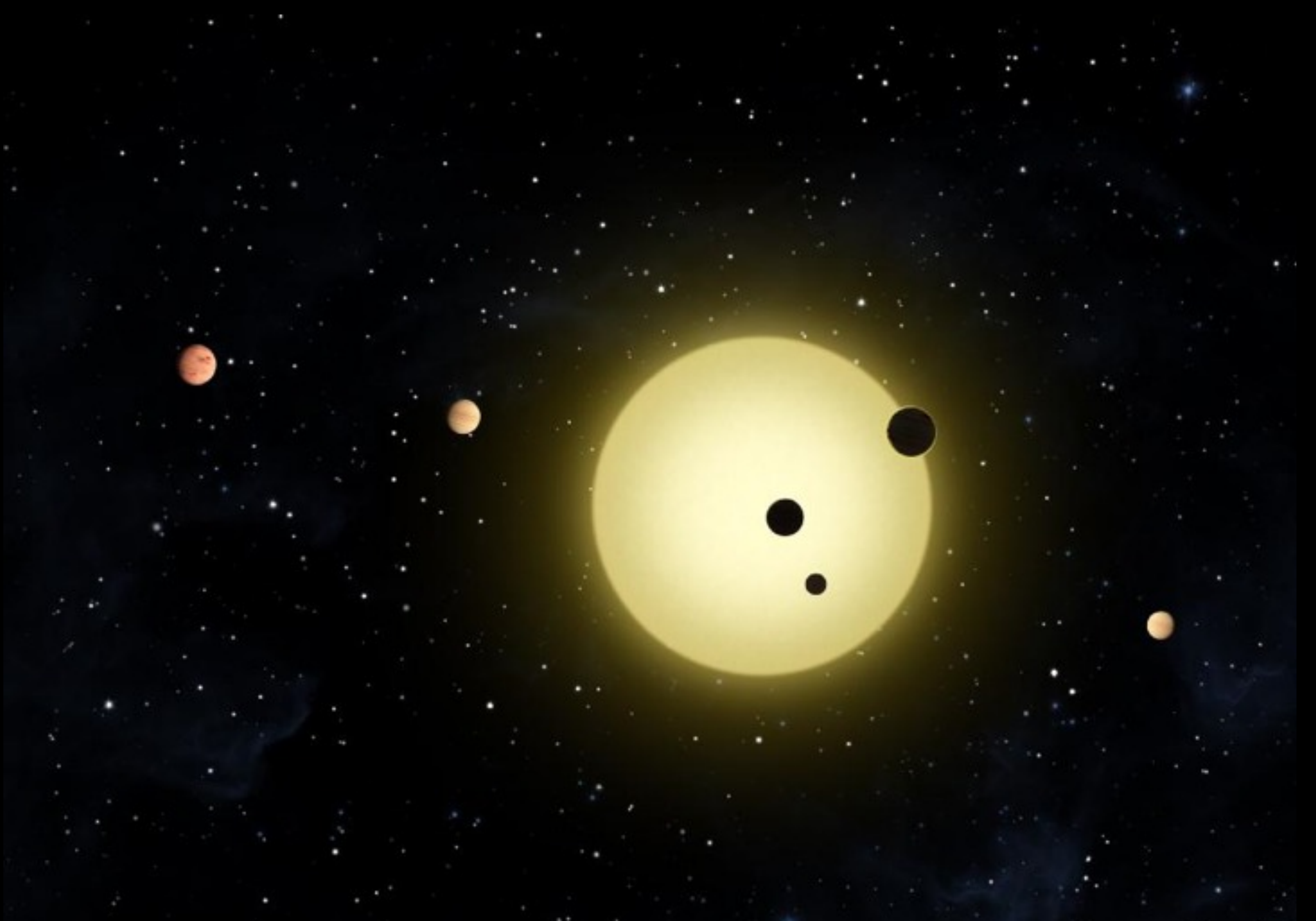


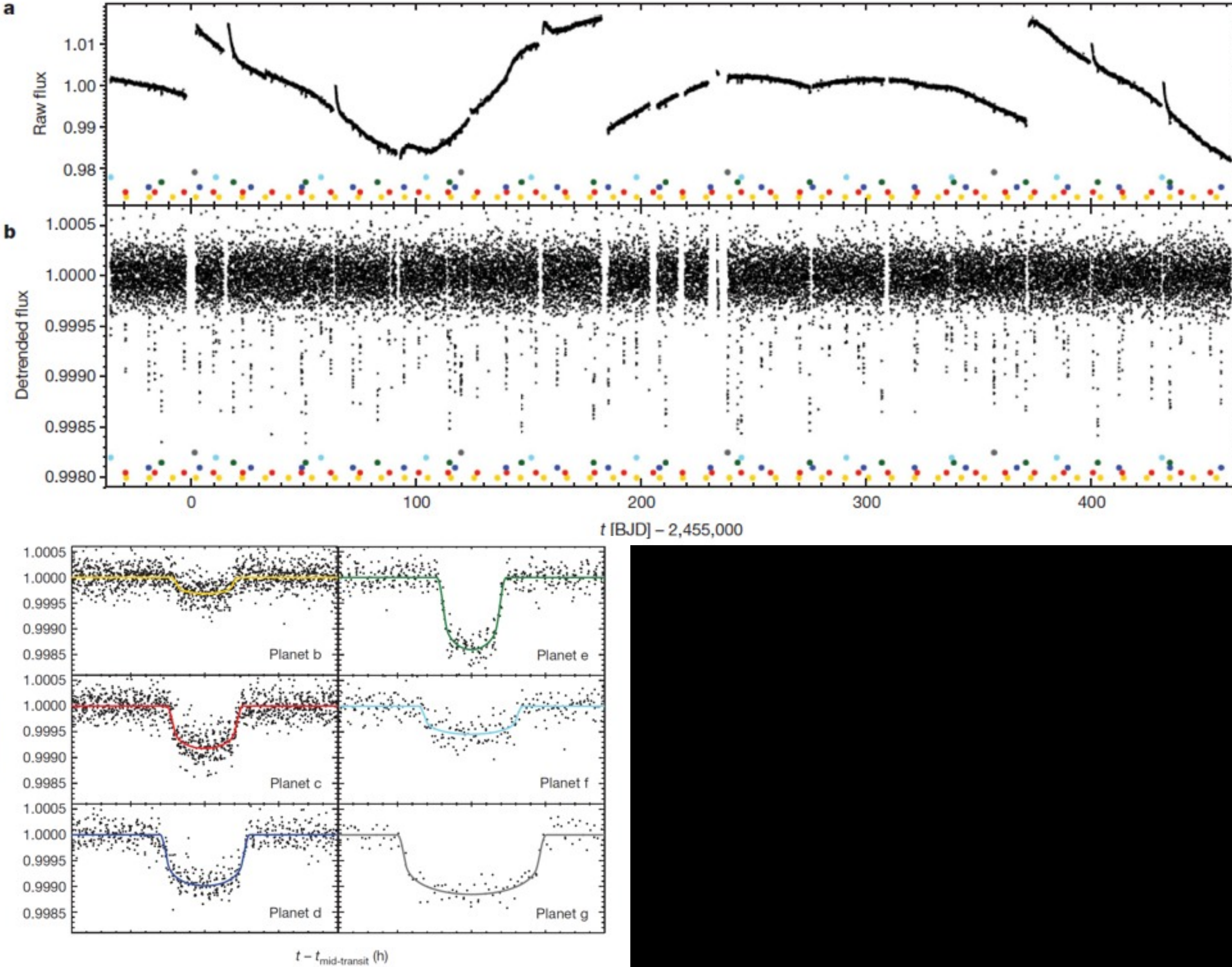
Light-curve of Kepler-16b , showing primary and secondary eclipses, as well as the transits of the planet across each star.



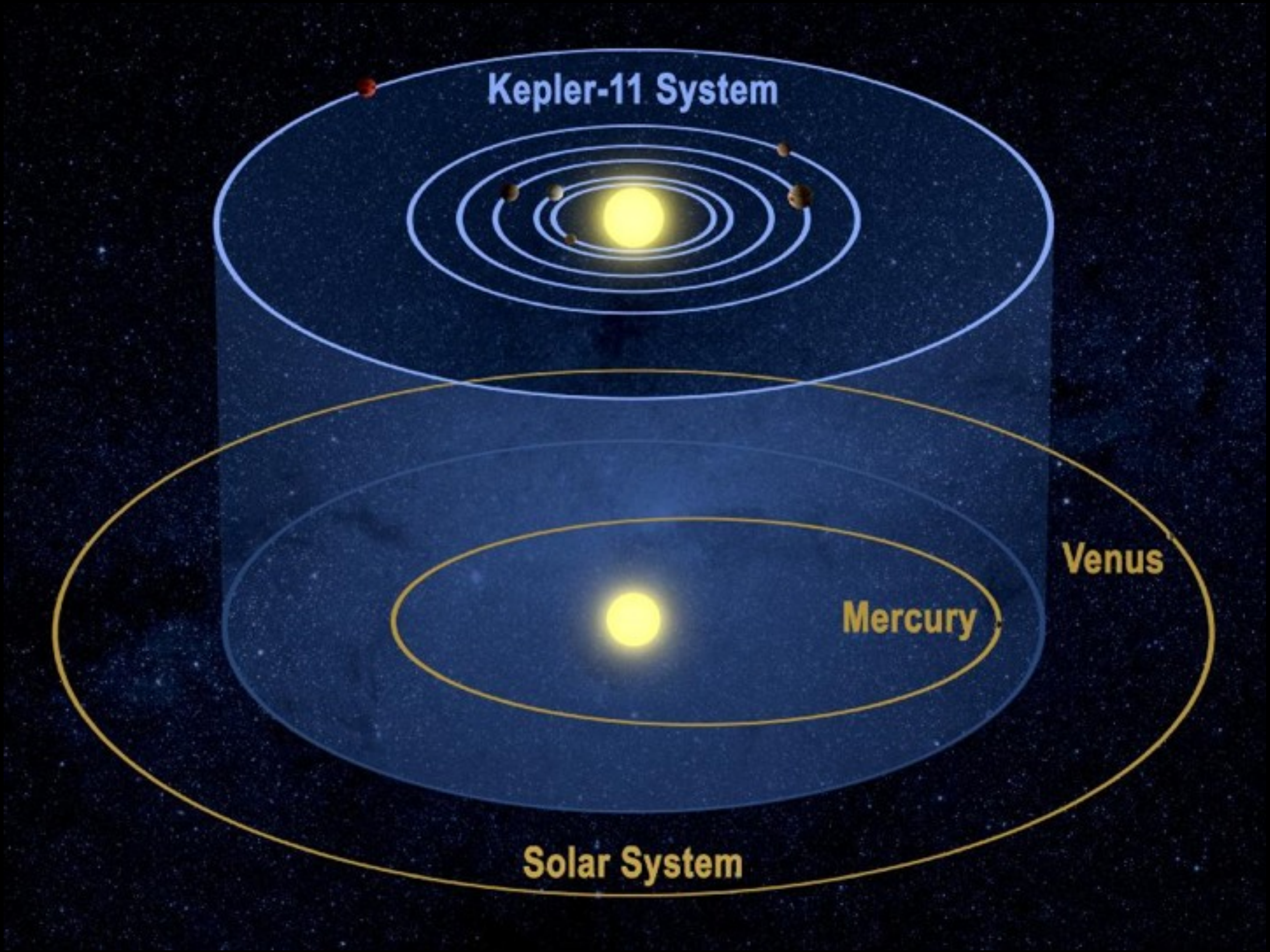
Bird's eye view of the Kepler-16b system. The planet, which is 1/3 the mass of Jupiter, orbits its star at a distance comparable to that of Venus in our own solar system, but is actually cold, as both stars are cooler than our Sun.

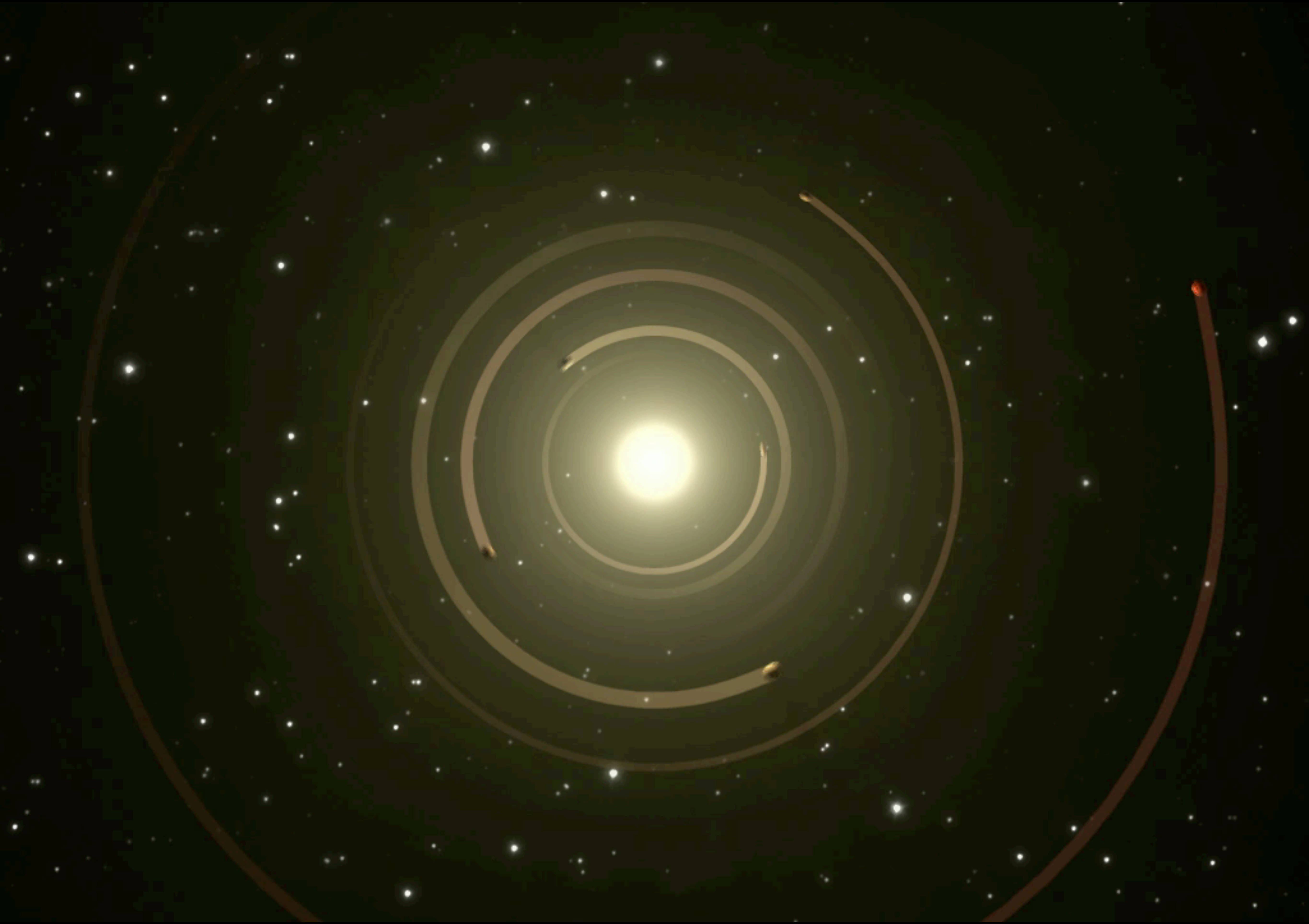
The same year, the Kepler team announced the discovery of a system of *six* low-mass planets transiting Kepler-11.



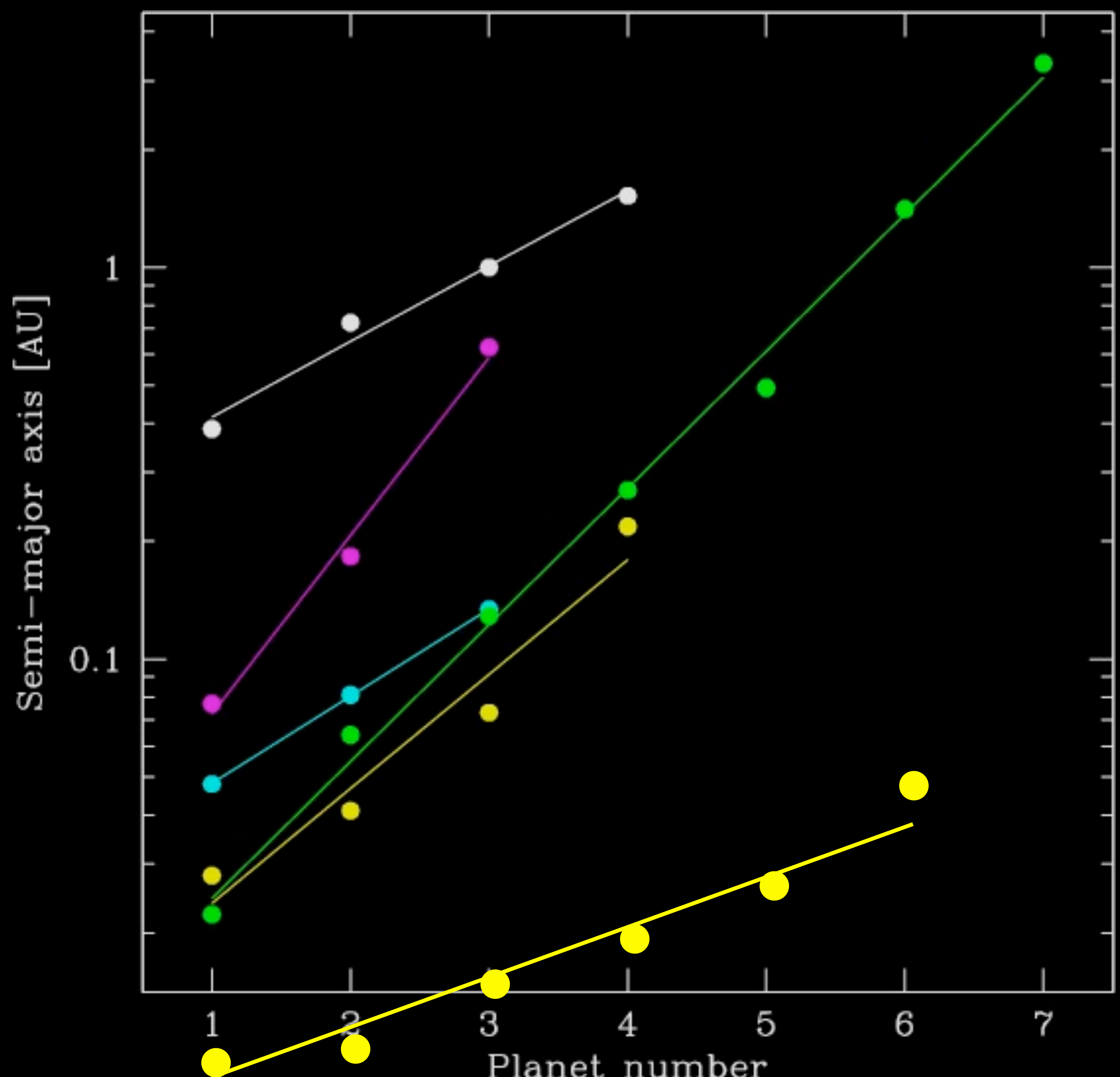

a
Raw flux
1.01
1.00
0.99
0.98
b
Detrended flux
1.0005
1.0000
0.9995
0.9990
0.9985
0.9980
0
100
200
300
400
t [BJD] – 2,455,000
Planet b
Planet e
Planet c
Planet f
Planet d
Planet g
Detrended flux
t – t_mid-transit (h)

All six planets have orbits smaller than Venus, and five of the six have orbits smaller than Mercury's. The sizes are between 2 and 5 Earth radii.

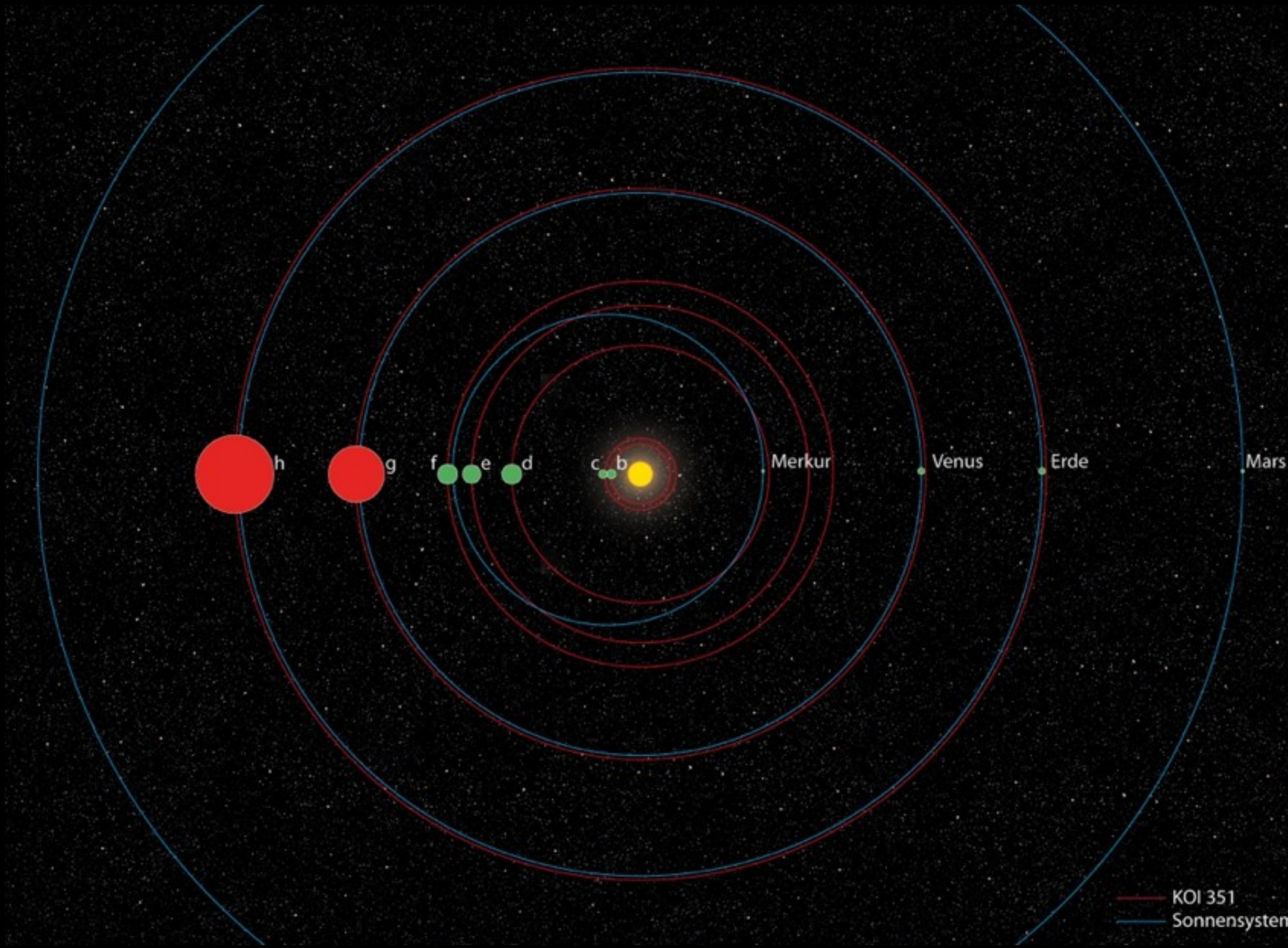


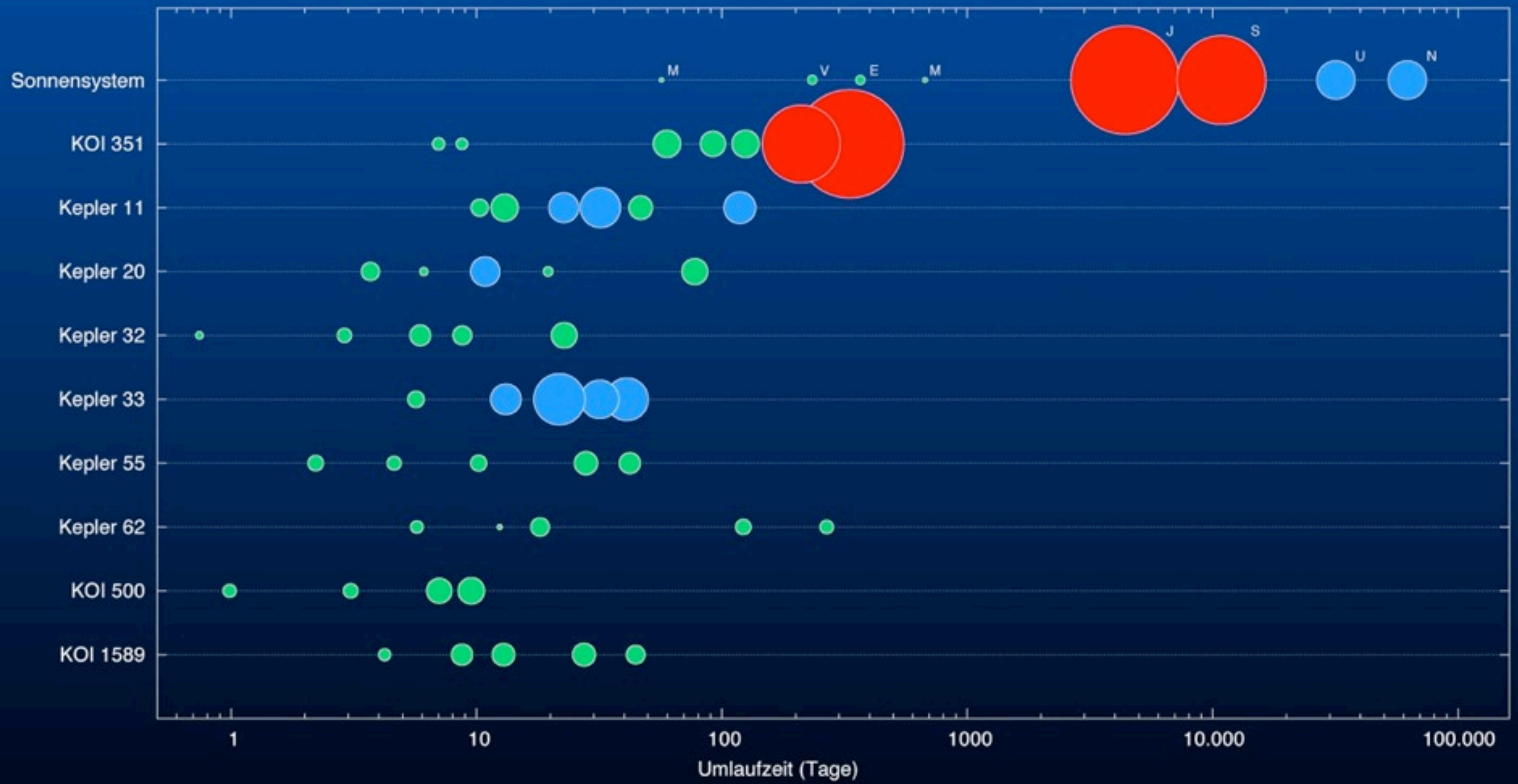


Here's the Bode's law fit for that system:



Last year, a *seven* planet system was discovered around Kepler-90 (KOI 351) – the current record holder.





Comparison of Kepler's multiple-planet systems with the Solar System (top)

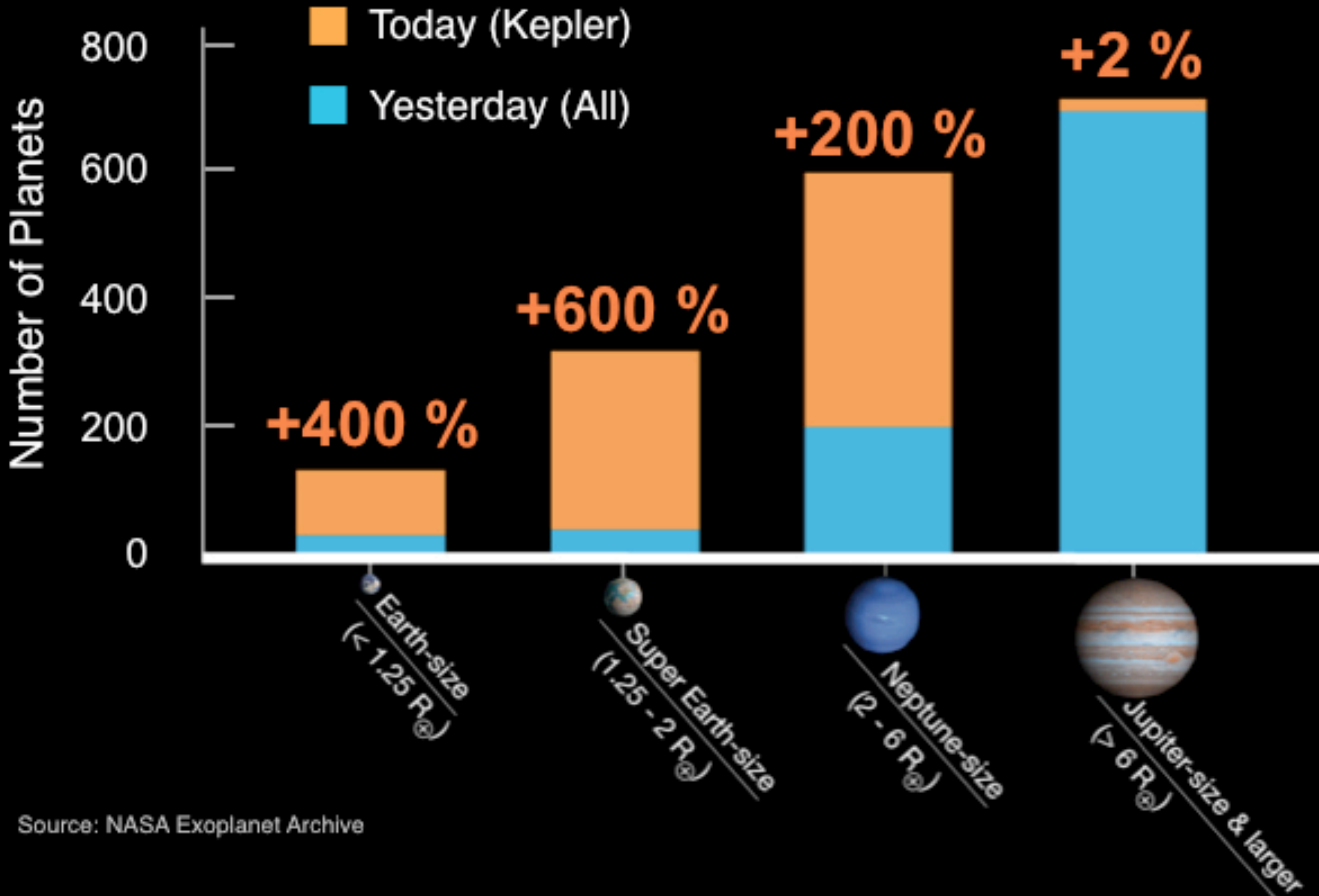
Kepler’s findings

Kepler’s planets are pouring in thick and fast. Here are some (preliminary) statistics on what has been found so far.

- about half of Sun-like stars have at least one planet with an orbital period of 100 days or fewer
- systems with multiple transiting planets are common (*17% of host stars, 34% of planets*)
- such systems are less likely to include a transiting giant planet
- either systems are likely to be highly co-planar, or typical systems have *many* planets

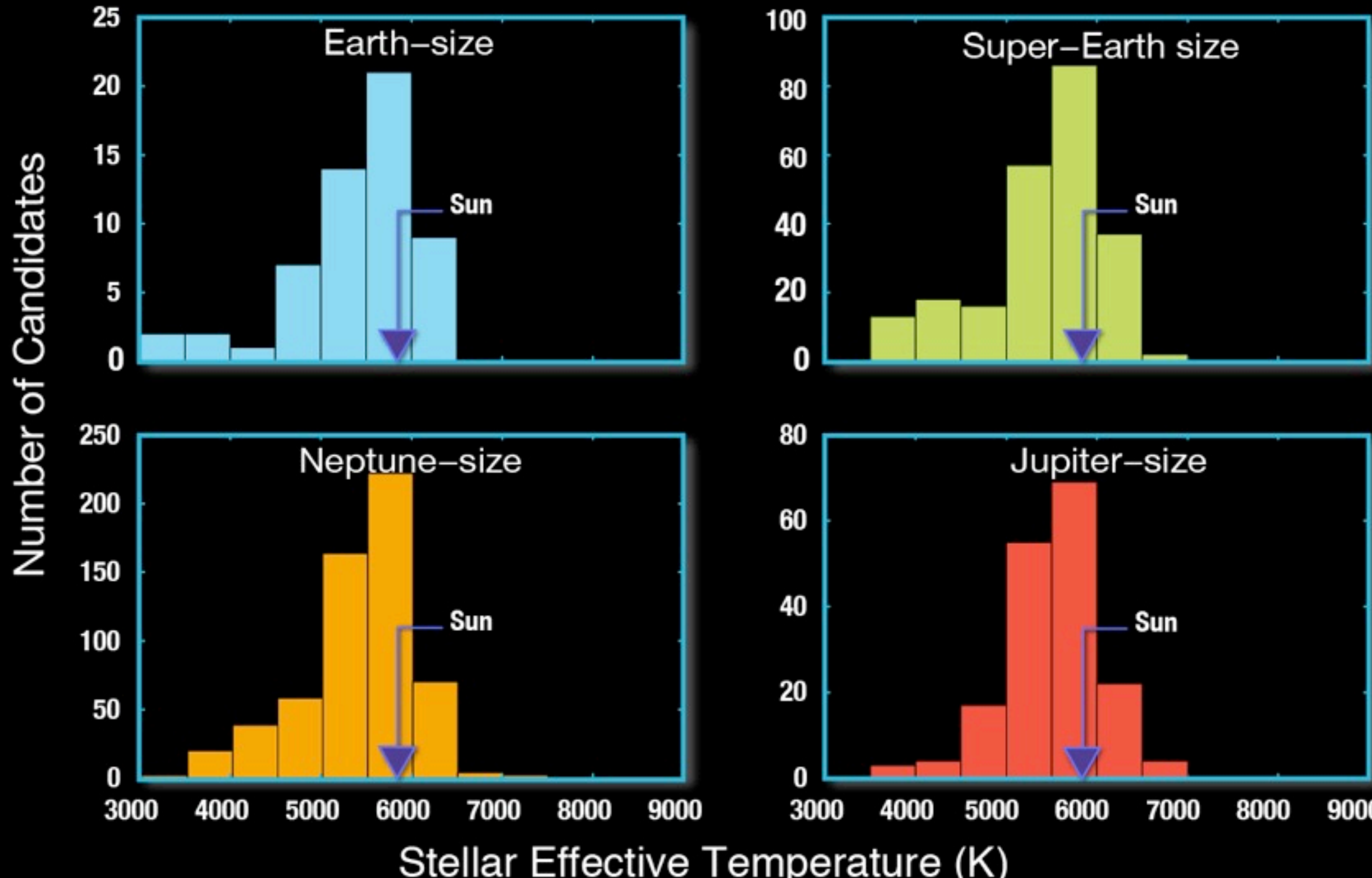
Sizes of Known Exoplanets

As of February 26, 2014

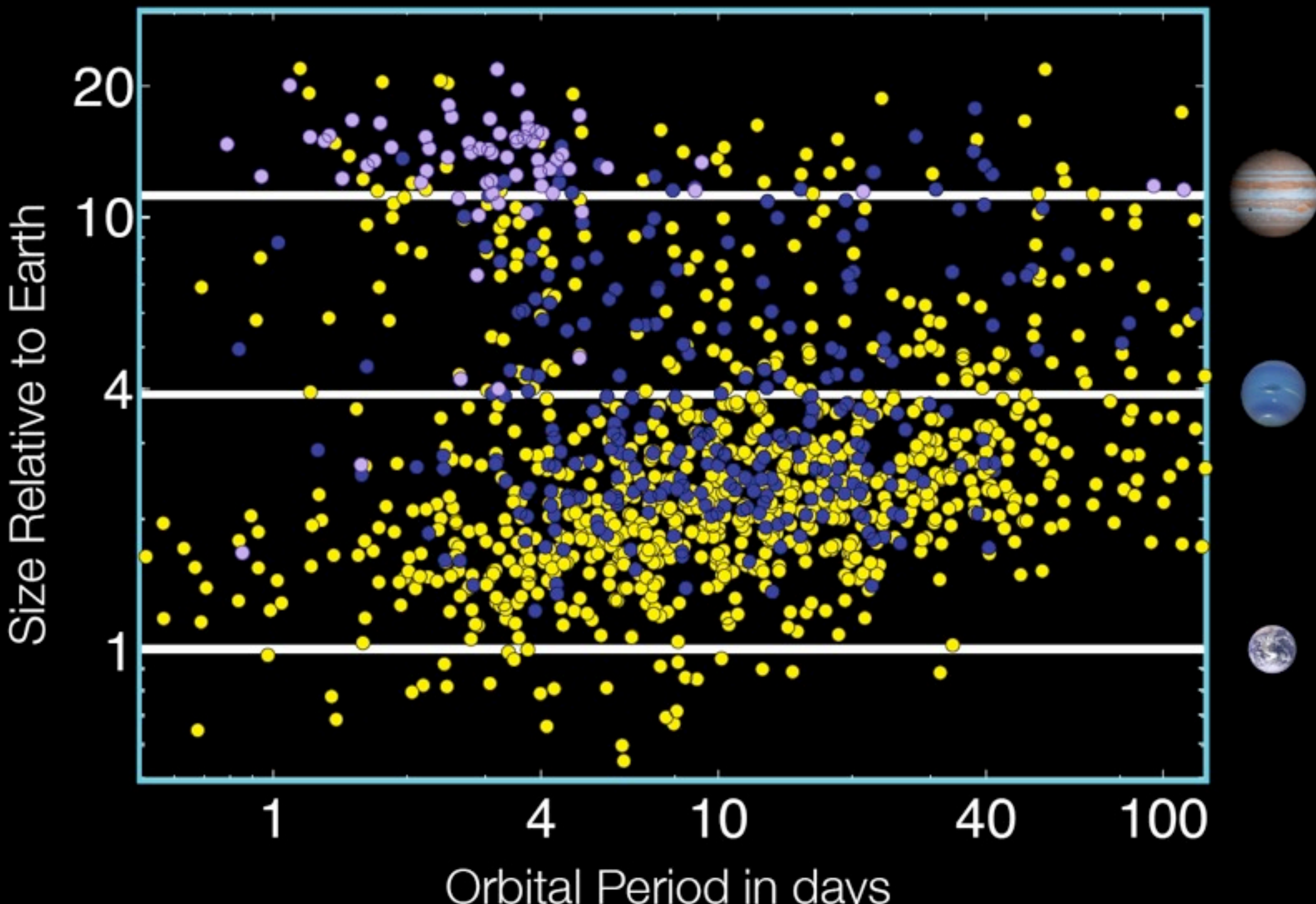


Source: NASA Exoplanet Archive

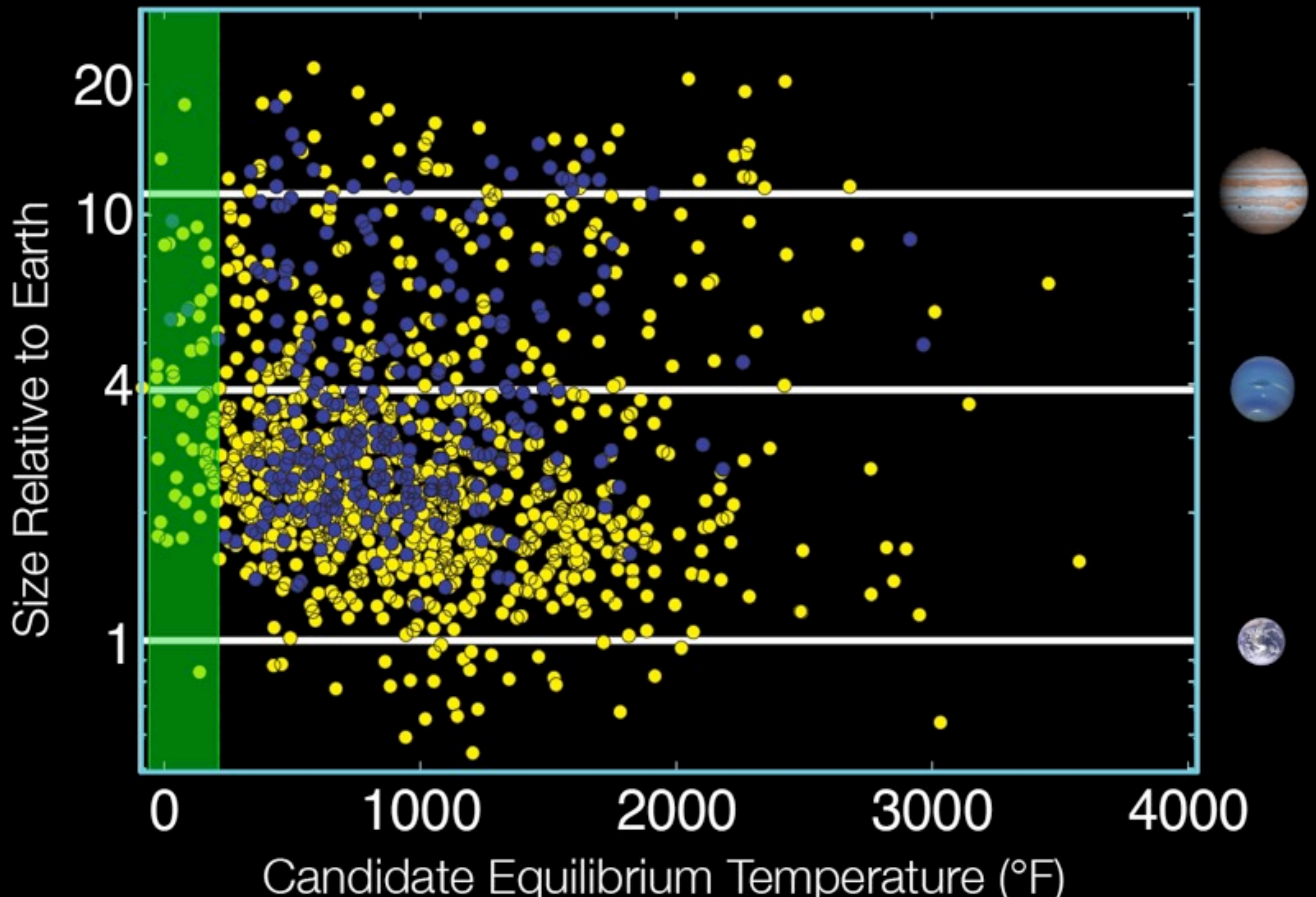
Most of the Candidates Orbit Stars Like our Sun



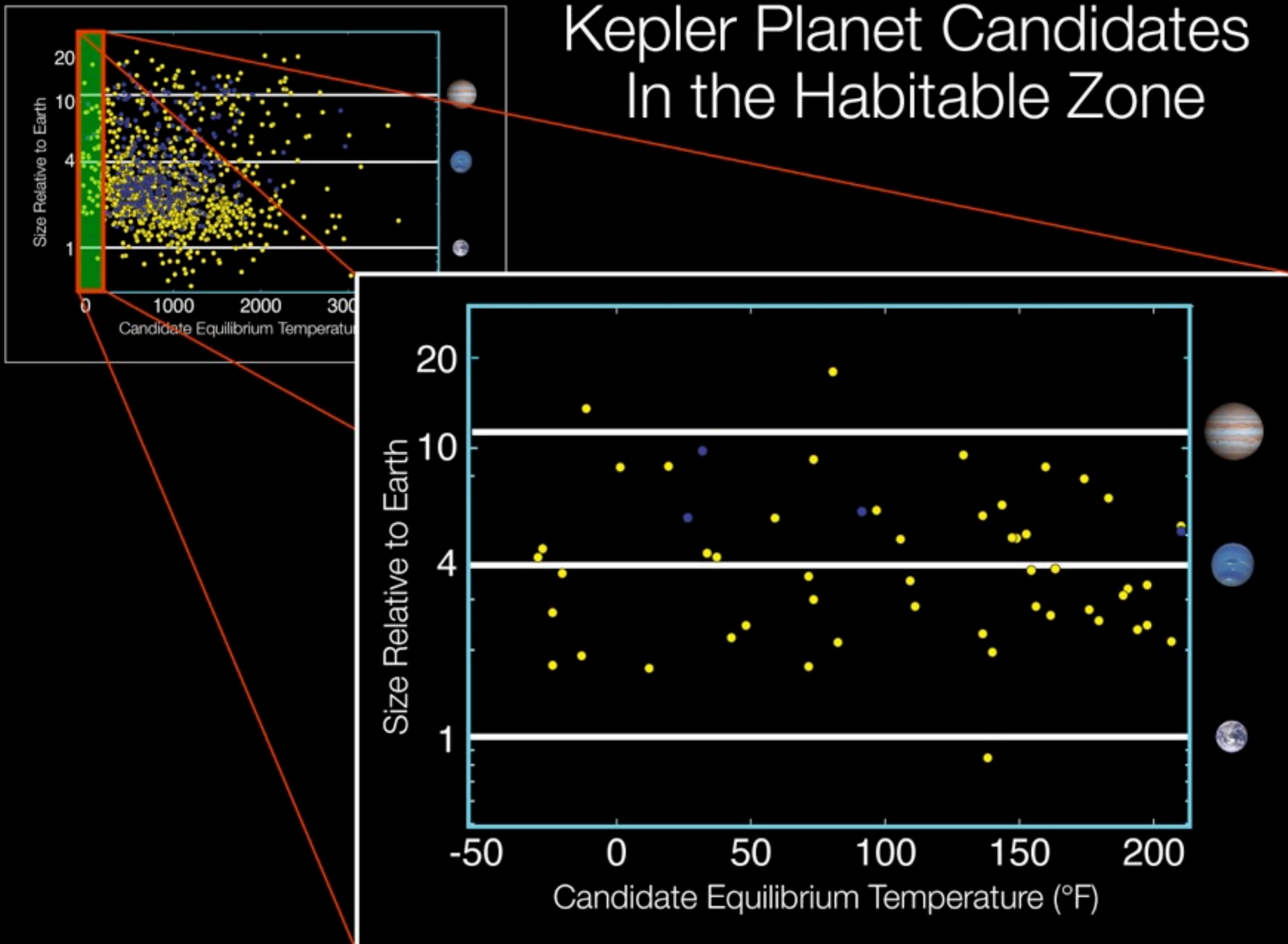
Kepler Candidates as of February 1, 2011



Kepler Candidates as of February 1, 2011



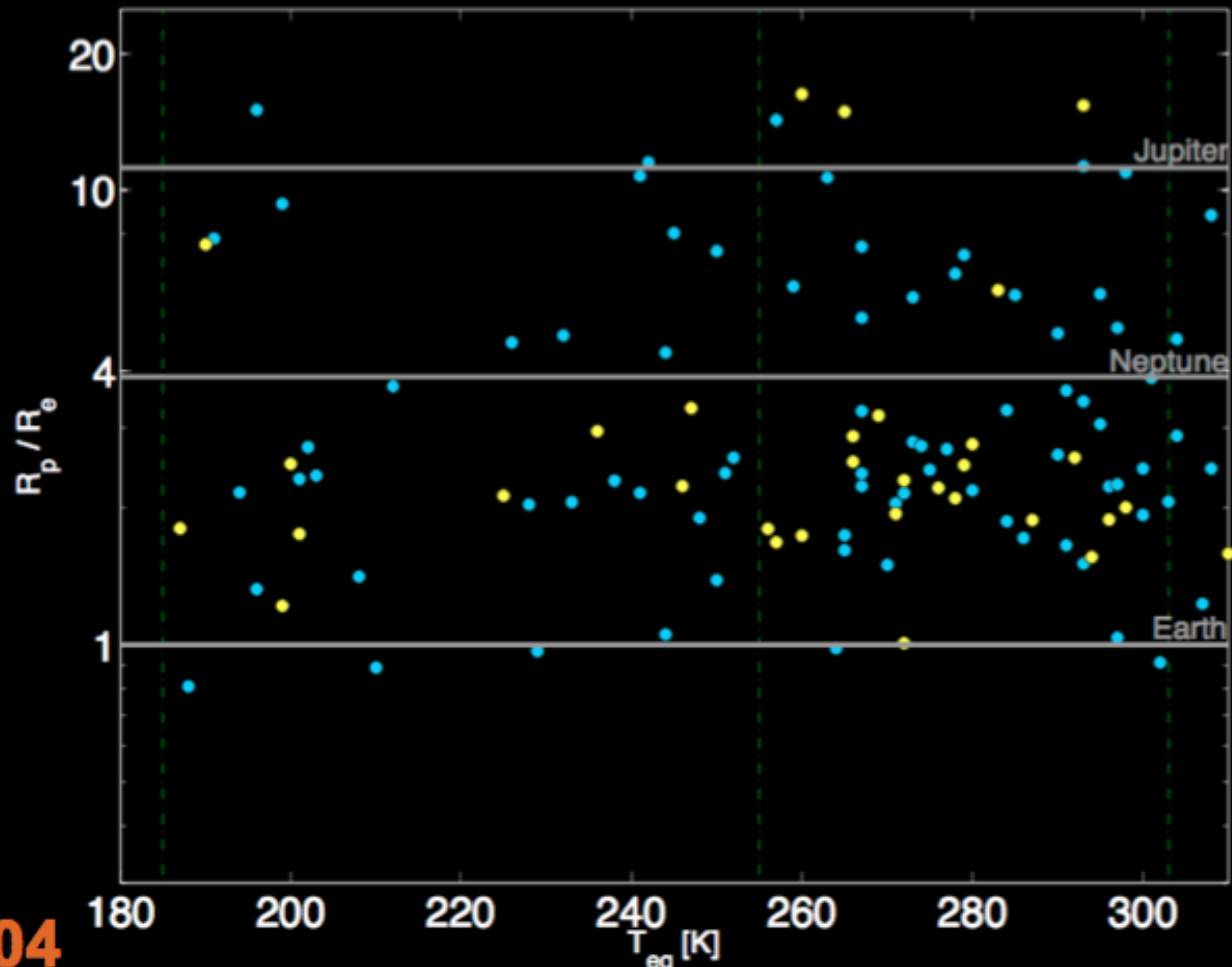
Kepler Planet Candidates In the Habitable Zone



54 candidates in the habitable zone of their host star.

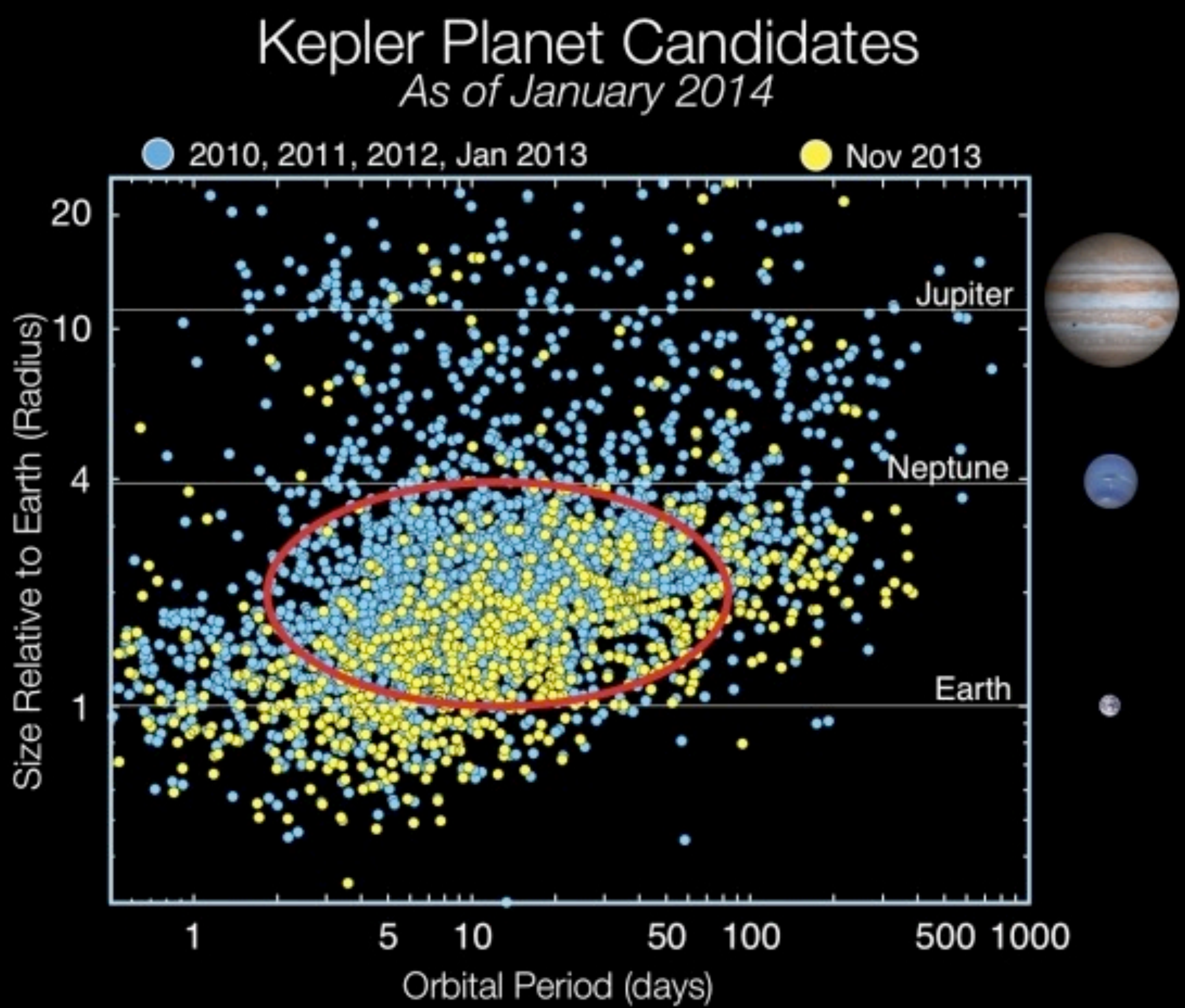
Candidates in Habitable Zone

As of November 4, 2013



Total = 104

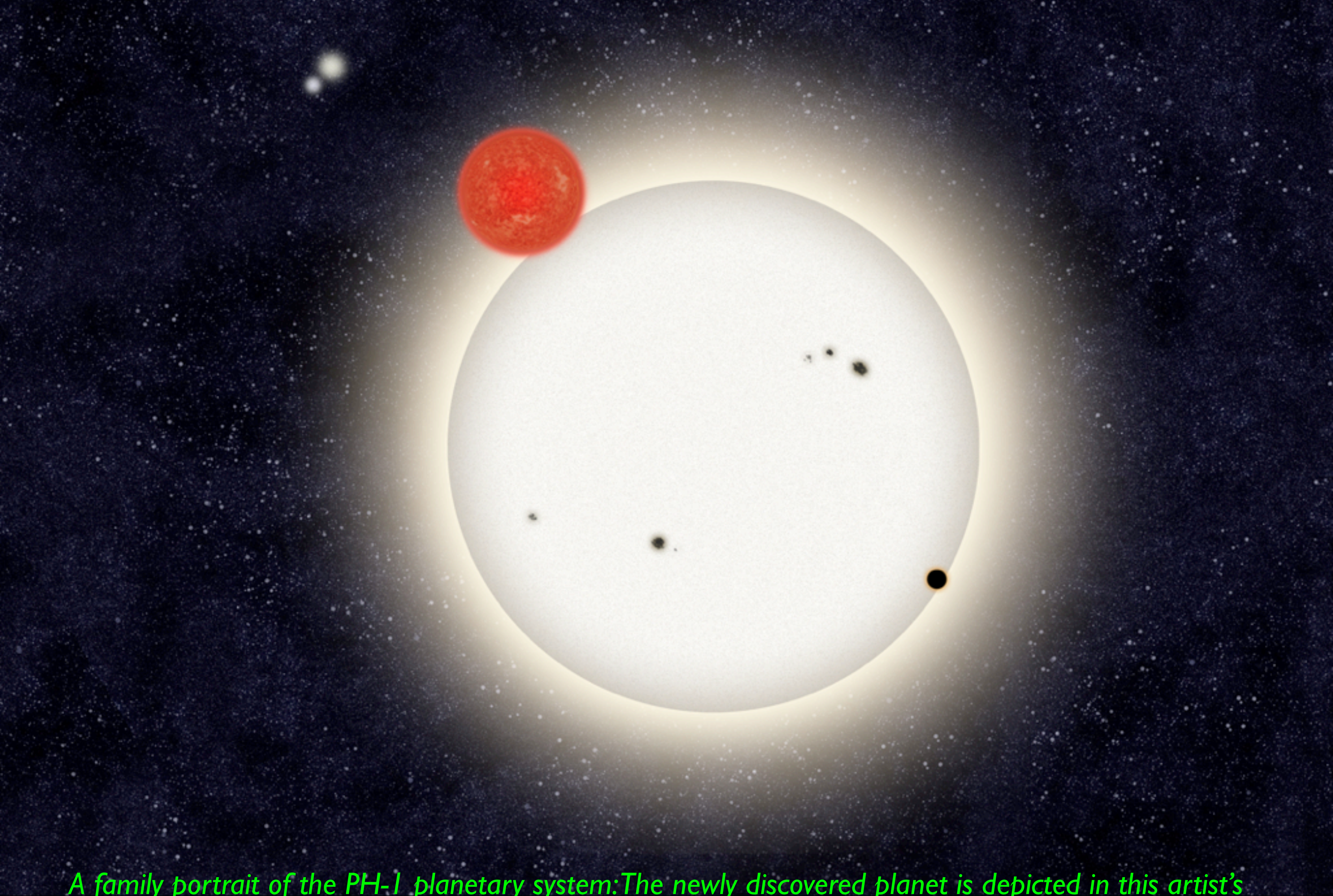
More than three-quarters of the planet candidates discovered by *Kepler* have sizes ranging from that of Earth to that of Neptune, which is nearly four times as big as Earth. Such planets dominate the galactic census but are not represented in our own solar system.



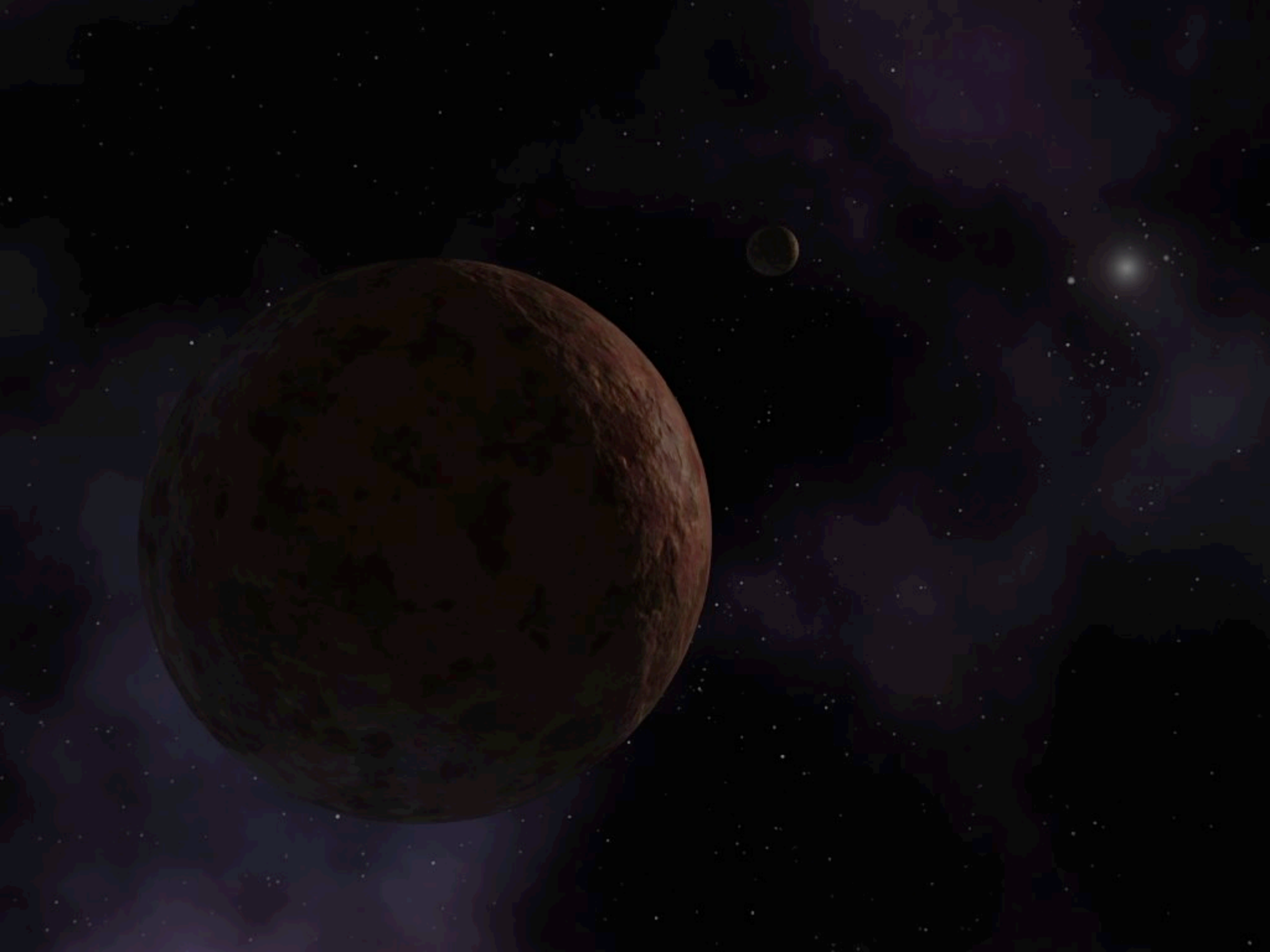
There is a "**Citizen Science**" project associated with *Kepler*, where members of the public identify transit events in the light curves to identify planets that the computer algorithms might miss. The first person to flag a potential transit gets credit for the discovery, and is offered authorship on the paper.

At least 60 new candidates have been identified and two confirmed planets, including the first known planet in a *quadruple* star sytstem.

* see https://www.zooniverse.org/publications?project=planethunters for a list of publications

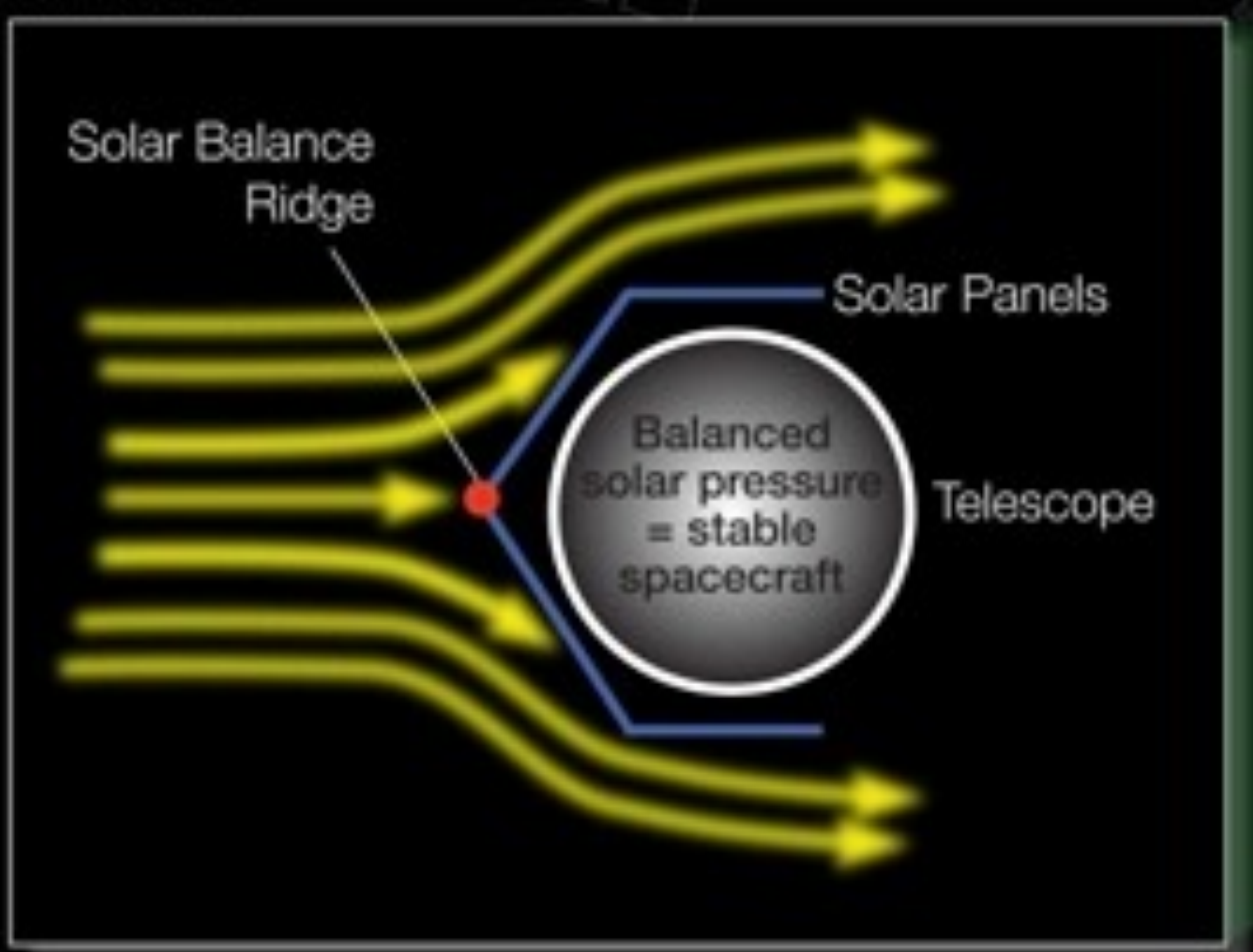


A family portrait of the PH-1 planetary system: The newly discovered planet is depicted in this artist's rendition transiting the larger of the two eclipsing stars it orbits. Off in the distance, well beyond the planet orbit, resides a second pair of stars bound to the planetary system.



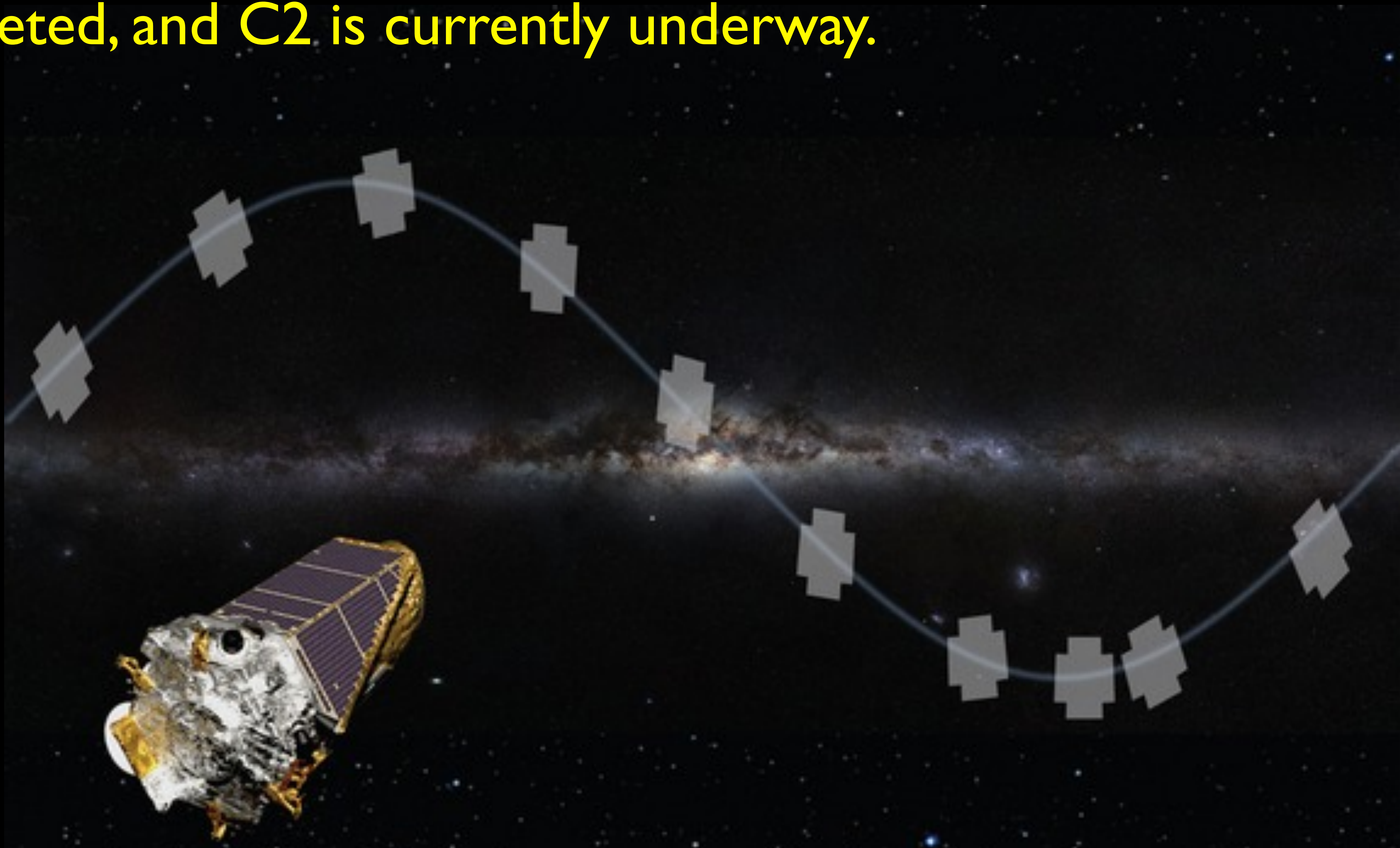
In May 2013, the second of *Kepler's* four reaction wheels failed. Without the ability to maintain its orientation, the spacecraft was no longer able to point precisely enough, thus terminating the main mission.

In May this year, an extension mission called K2 was approved. This uses the solar wind to help stabilise the spacecraft, recovering
pointing stabiity.

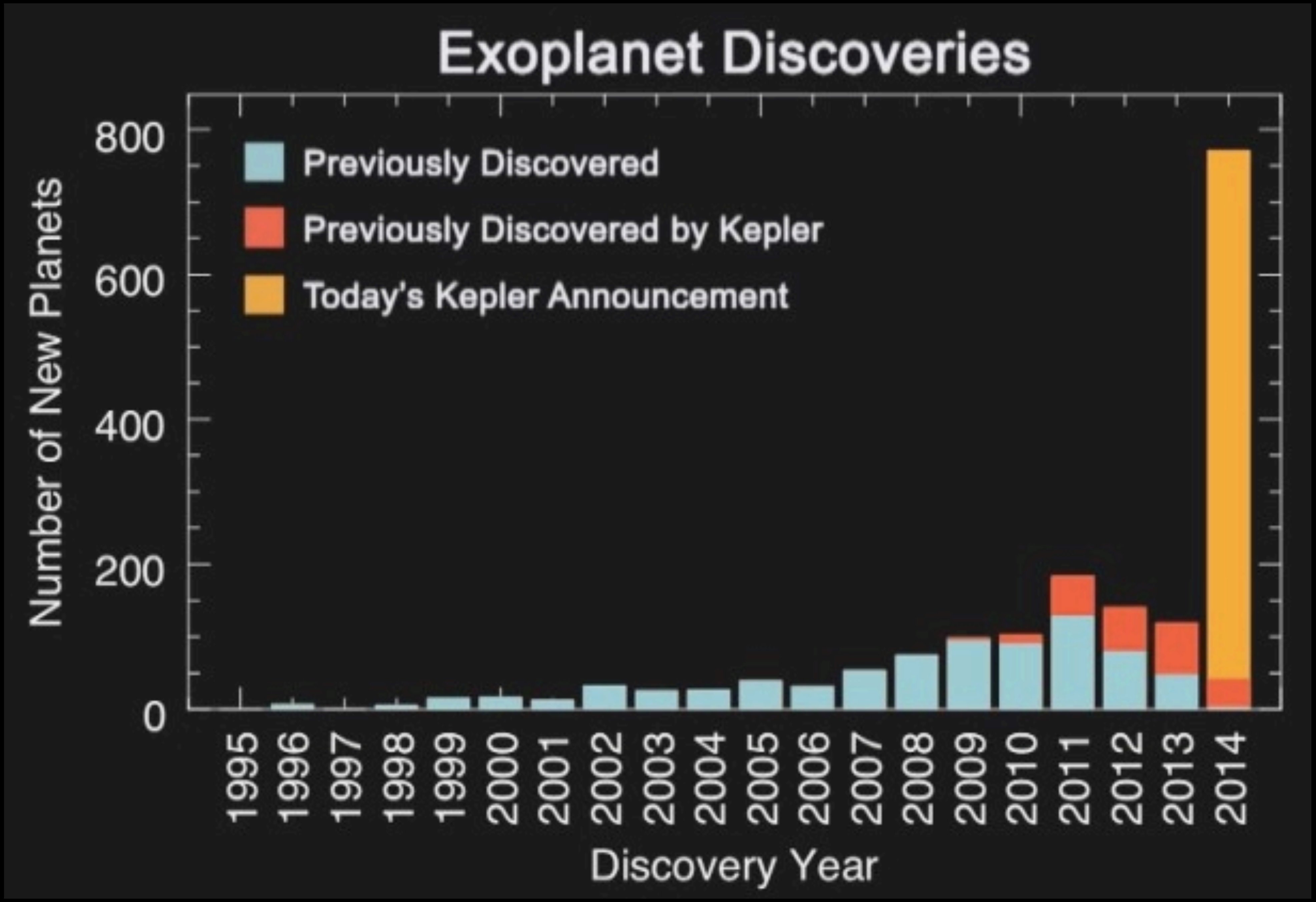


Kepler will stare at target fields in the ecliptic for about 75 days, before the spacecraft has to be rotated again.

This means completely different fields will be observed. Observations of the first field, C1, have been completed, and C2 is currently underway.



Planetary candidates in the *Kepler* data will continue to be confirmed for a while yet, but the rate of new planet discoveries is going to drop. Now we can concentrate on understanding the distribution we've got.



What does it mean?

The core-accretion theory for the formation of our Solar System explained all the major features: why the planets orbit the Sun in nearly circular orbit in the same direction and in the same plane, why the inner planets are small and rocky and the outer planets huge and gaseous.

Since the theory was so beautiful, we expected that any system of planets would look pretty much the same.

Instead, as we have seen, we found planets the size of Jupiter in tiny orbits, planets in highly elliptical orbits or in orbits that don't go around their star's equator. And the most common type of planet is a "super-Earth", a type of planet that doesn't even exist in our Solar System.

Basically, *none* of the systems we've discovered look much like the Solar System at all.

Here are some of the major problems in explaining exoplanet systems, with possible solutions.

See Ann Finkbeiner, "Astronomy: Planets in chaos", Nature 511, 22 (2014)

How do you form “hot Jupiters”?

In the model of planet formation we discussed last week, it’s very difficult:

– too hot

– too little material

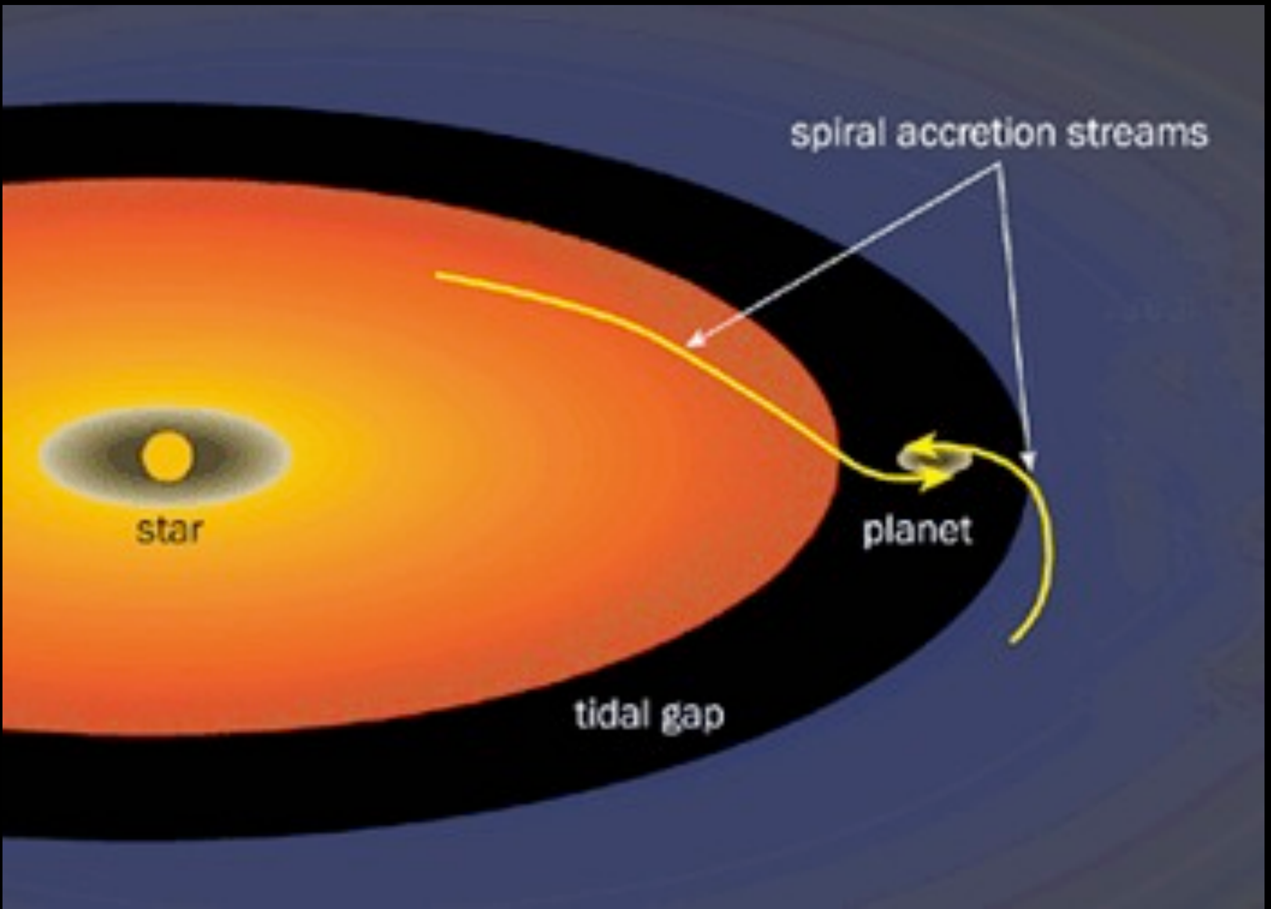
– too little gas to form envelope

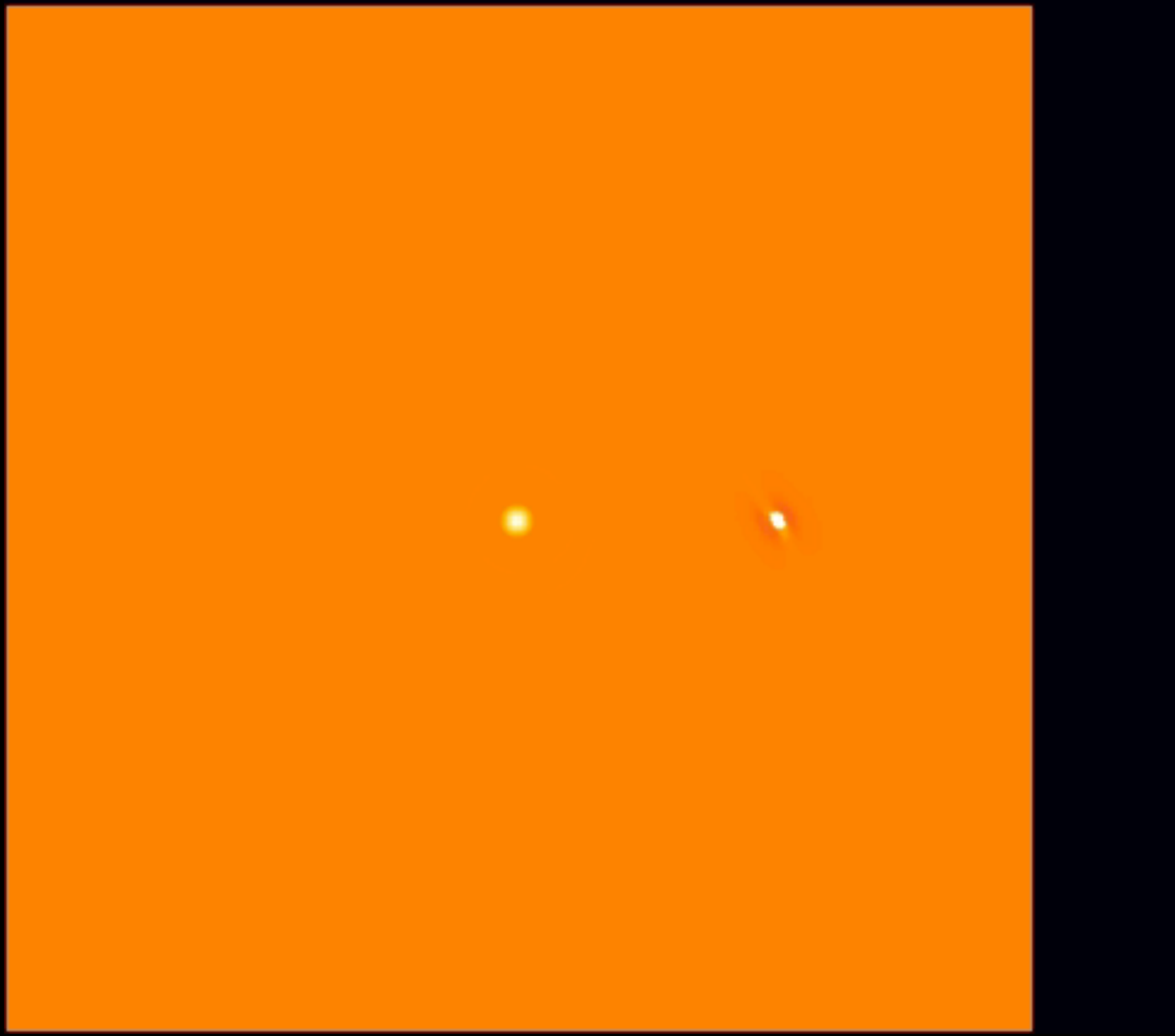
To explain this, we require *planetary migration*.

You remember that the giant planets accreted gas directly from the disk. We discussed how they had to complete their accretion before the proto-Sun blew the gas away. What we didn't stress was that there must have been a period when the giant proto-planets were embedded in the disk.

What effect does this have?

Simulations have shown that tidal interactions with the disk force the planet to migrate inwards.

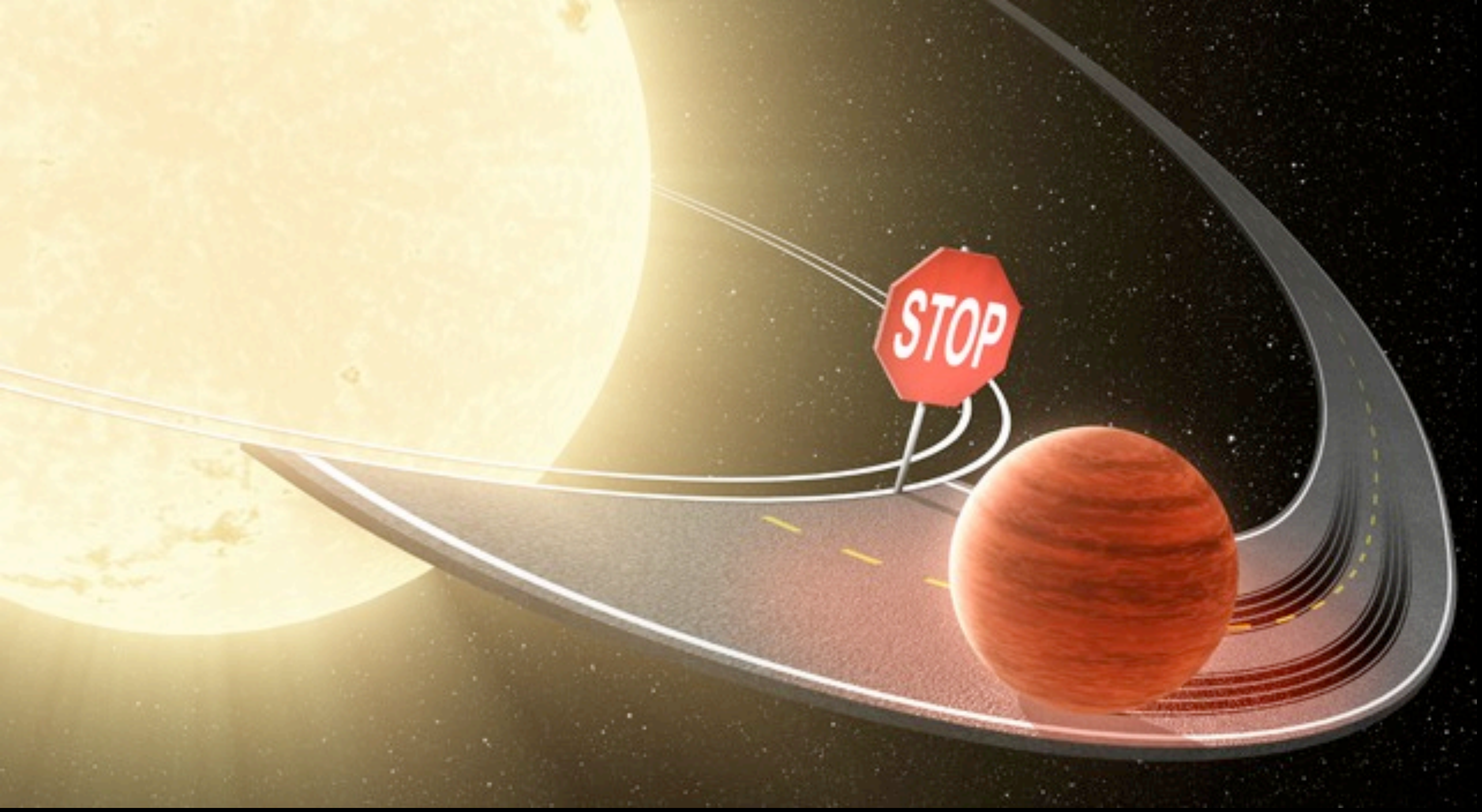




Simulation of a proto-planet growing from 10 Earth masses to 1.5 Jupiter masses

So why does it stop? Why doesn’t it plunge into the star?

— It reaches the inner edge of the disk? (cleared by the star’s magnetic field, perhaps?)
— Tidal interactions with the star?
— Planet fills its Roche lobe and recedes from the star?
— Orbit stabilised by resonant interactions with other planets?
— Perhaps they didn’t stop: the visible planets are merely the survivors from a long chain of planets which spiralled into the star...

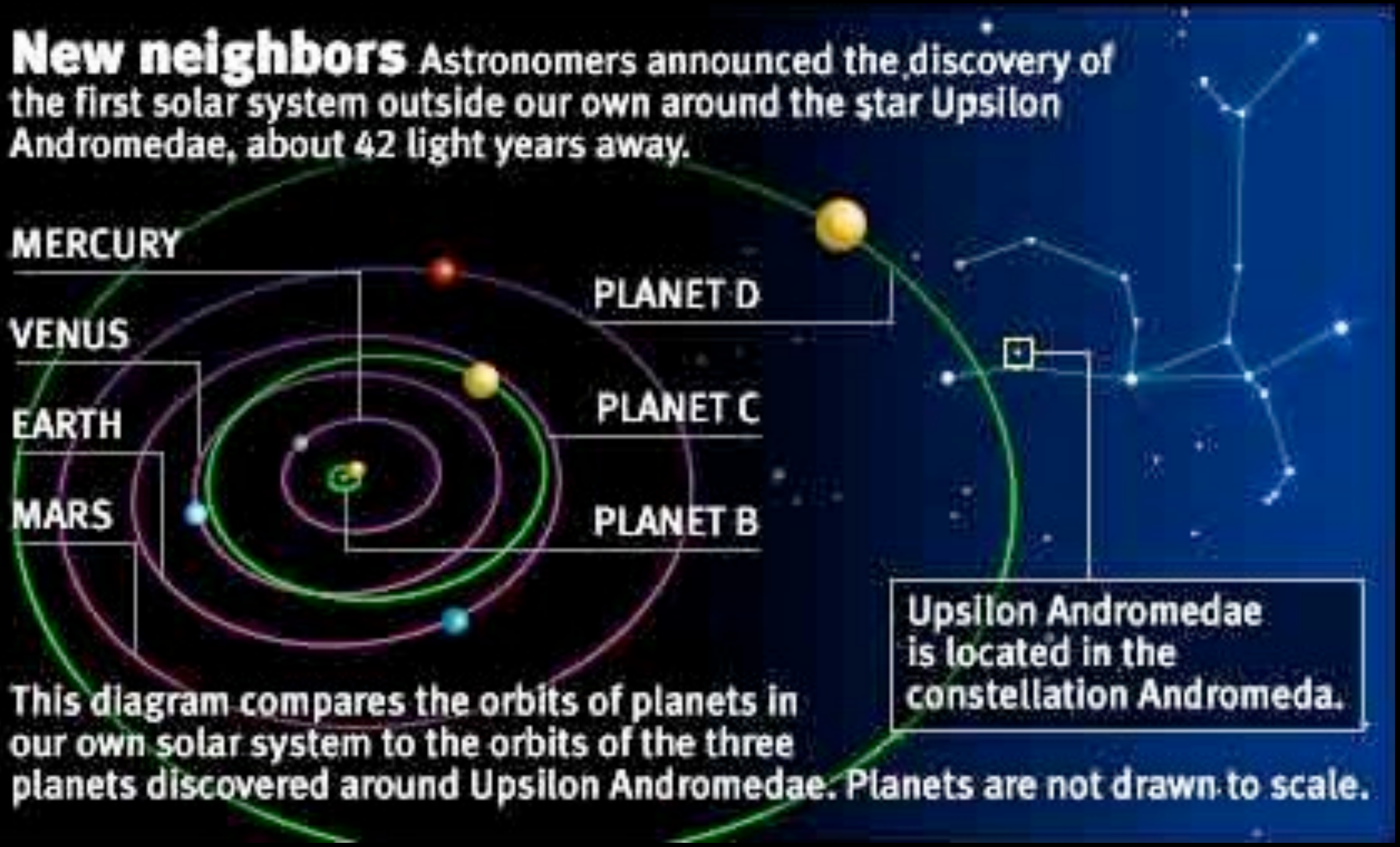


A paper last year claimed that stars do not in fact consume planets very often, and that tidal forces halt the migration before the planet plunges into the star. The theory predicts that the hot Jupiters of more massive stars would orbit farther out, on average, which is in fact what is observed.

Resonances between planet orbits may be important in many systems. At least seven of the multiple-planet systems show resonances. Kepler's planets, on the other hand, are typically *not* in resonance.

System	*N*	Resonance type
Gliese 876	2	Planets in a tight 2:1 mean-motion resonance and a secular resonance
Upsilon Andromedae	3	Planets c and d in a secular resonance
55 Cancri	4	Planets b and c probably in a 3:1 mean-motion resonance
HD 82943	2	Planets in a 2:1 mean-motion resonance
HD 12661	2	Planets in a secular resonance, but anti-aligned
HD 37124	2	Planets probably in a 5:1 mean-motion resonance
HD 128311	2	Planets in a 2:1 mean-motion resonance and a secular resonance

Resonance is important in the peculiar system around Upsilon Andromedae. The two outer planets have highly elliptical orbits ($e \sim 0.3$) which interact on timescales of 10,000 years, and whose combined effect circularises the inner planet's orbit every 7000 years.



The Upsilon Andromedae orbits compared to the inner Solar System.

Recent work suggests this may be the result of interactions with another giant planet. This planet had a close encounter with the outermost planet, and was then ejected from the system, leaving the middle two planets in eccentric orbits.

A Simulation of
Planet-Planet Scattering in the
Upsilon Andromedae
Planetary System

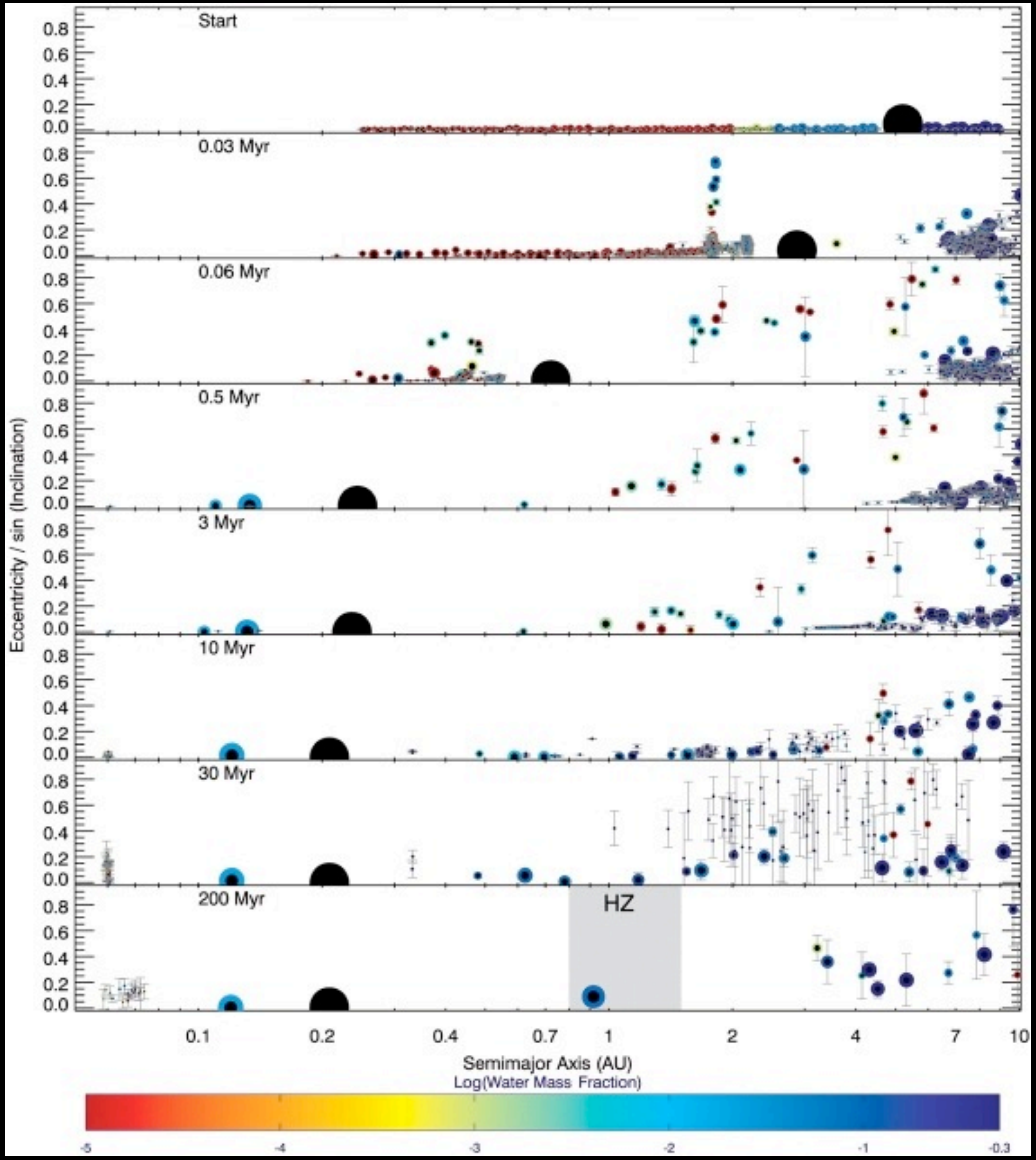
Diameters of planets have been
greatly exaggerated for visibility

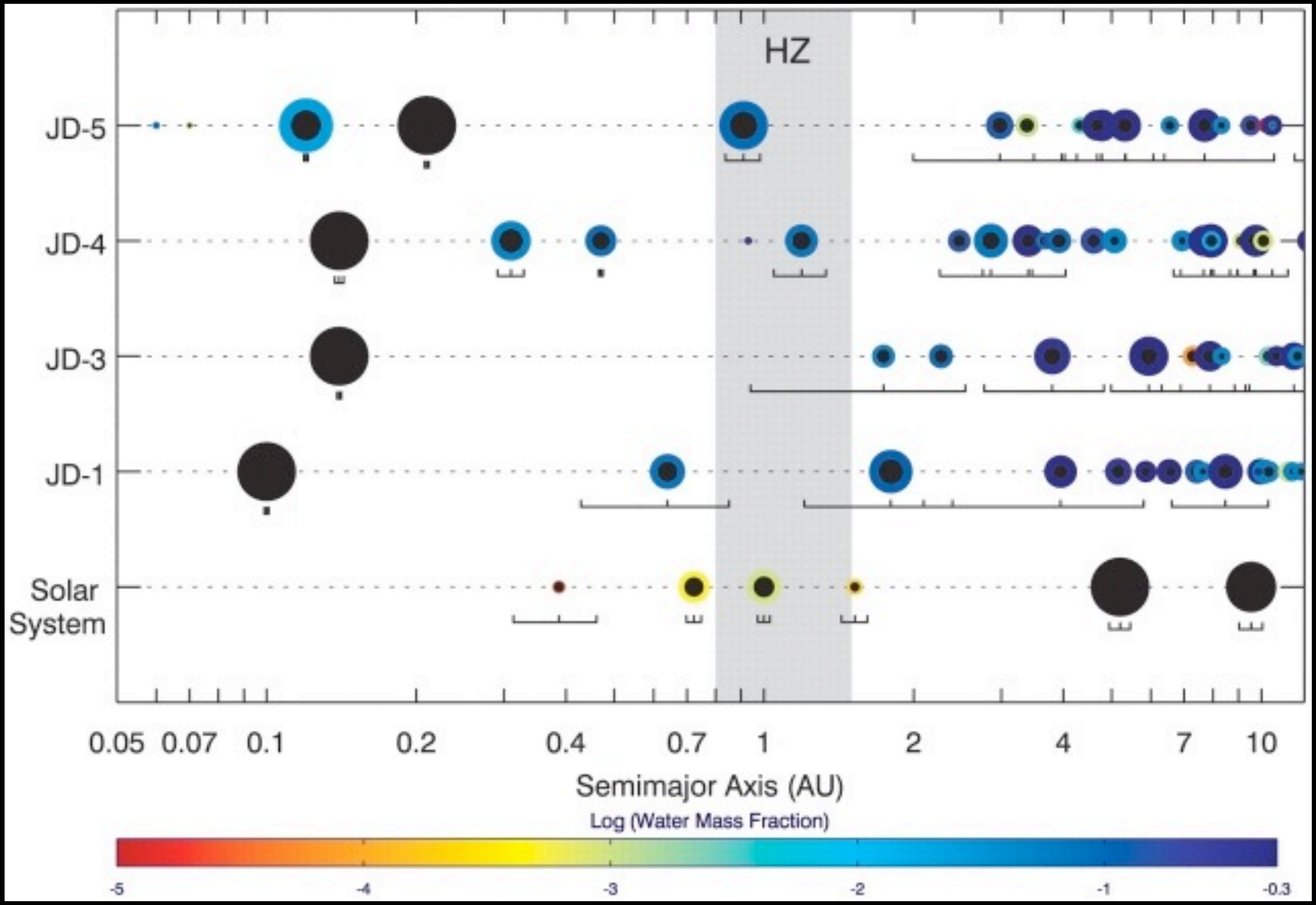
If giant planets migrate to very small orbits, does that destroy any terrestrial planets in the habitable zone?

Recent research suggests: not necessarily. Assembly of the terrestrial planets continues after the migration: the planetesimals are stirred up by the migrating giant, not necessarily destroyed.

Whether small planets survive depends mostly on *how fast* the giant planet migrates, as well as how massive they are. Simulations using “reasonable guesses” for these result in ~⅓ of systems with a hot Jupiter having an Earth-like planet of at least $0.3M_\oplus$ in the habitable zone.

Snapshots in time of one simulation of a forming solar system with a migrating giant planet. The colour of each dot corresponds to its water content (Earth = 10^{-3}). If the gas giant has formed by the time Moon- to Mars-sized planetesimals have formed, and the giant planet migrates reasonably fast, then terrestrial planets can form outside the giant planet, even after the disk is stirred up by the migration. (From Raymond et al. 2006)





Final configurations of four different simulations, with the Solar System shown for scale. (From Raymond et al. 2006)

How do you form “super-Earths”?

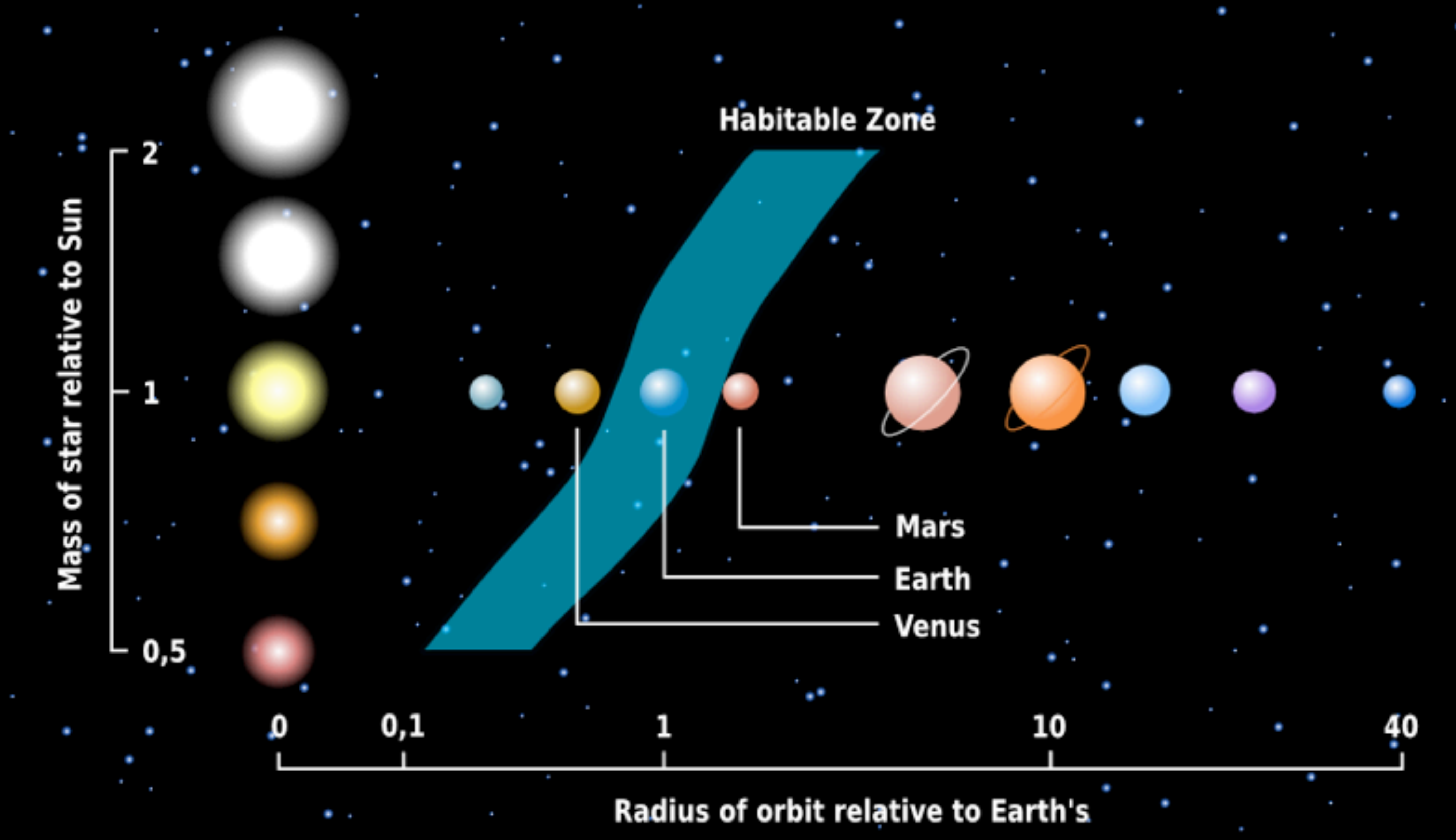
These are much harder to account for. Not only do you have to grow rocky planets larger than any in our Solar system, but you have to grow *lots* of them.

Did they form in more massive disks? or form further out and migrate in?

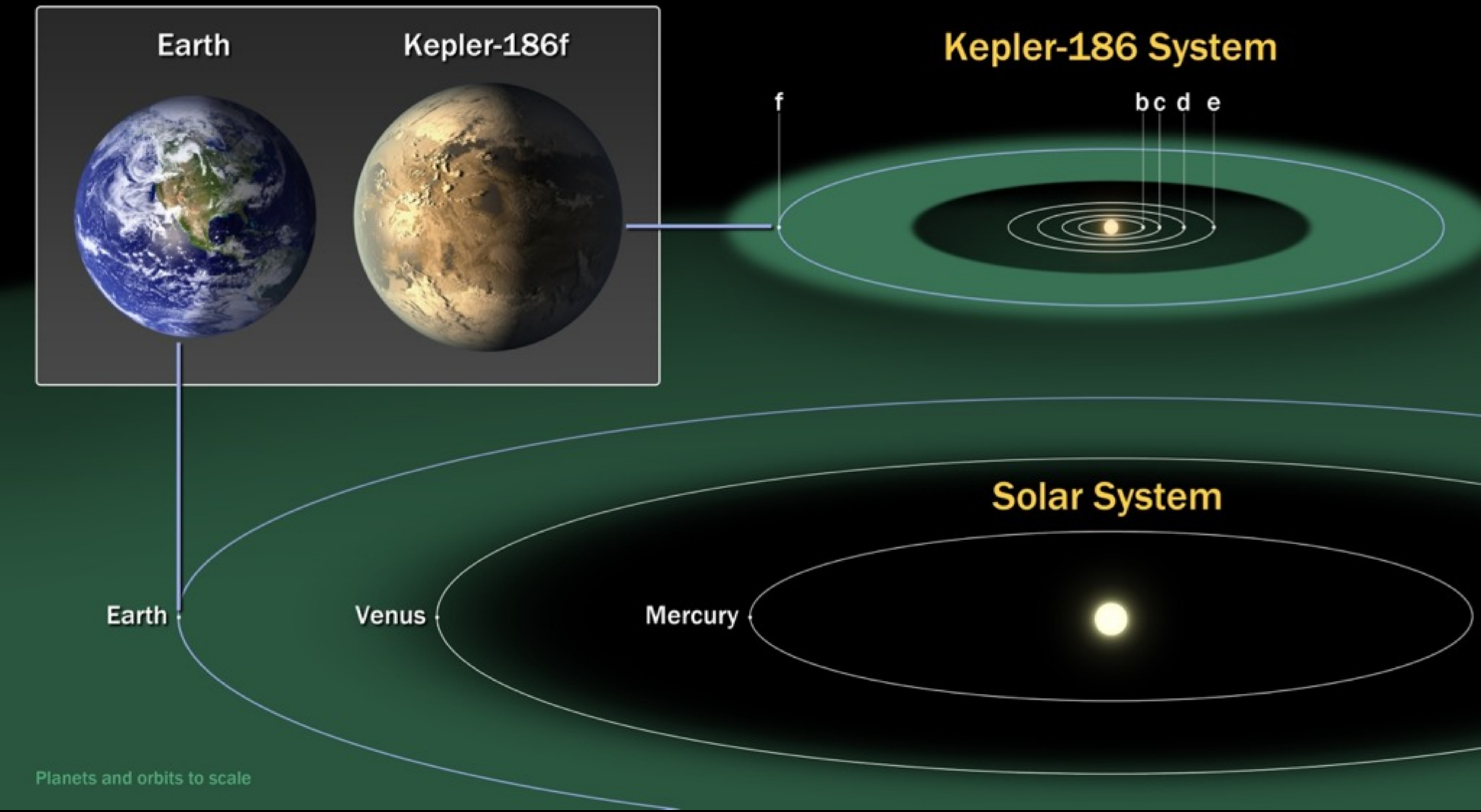
Of course, perhaps there is more than one sort of super-Earth: the very closest in might be the stripped cores of migrating planets that got too close and lost their gas.

Where next?

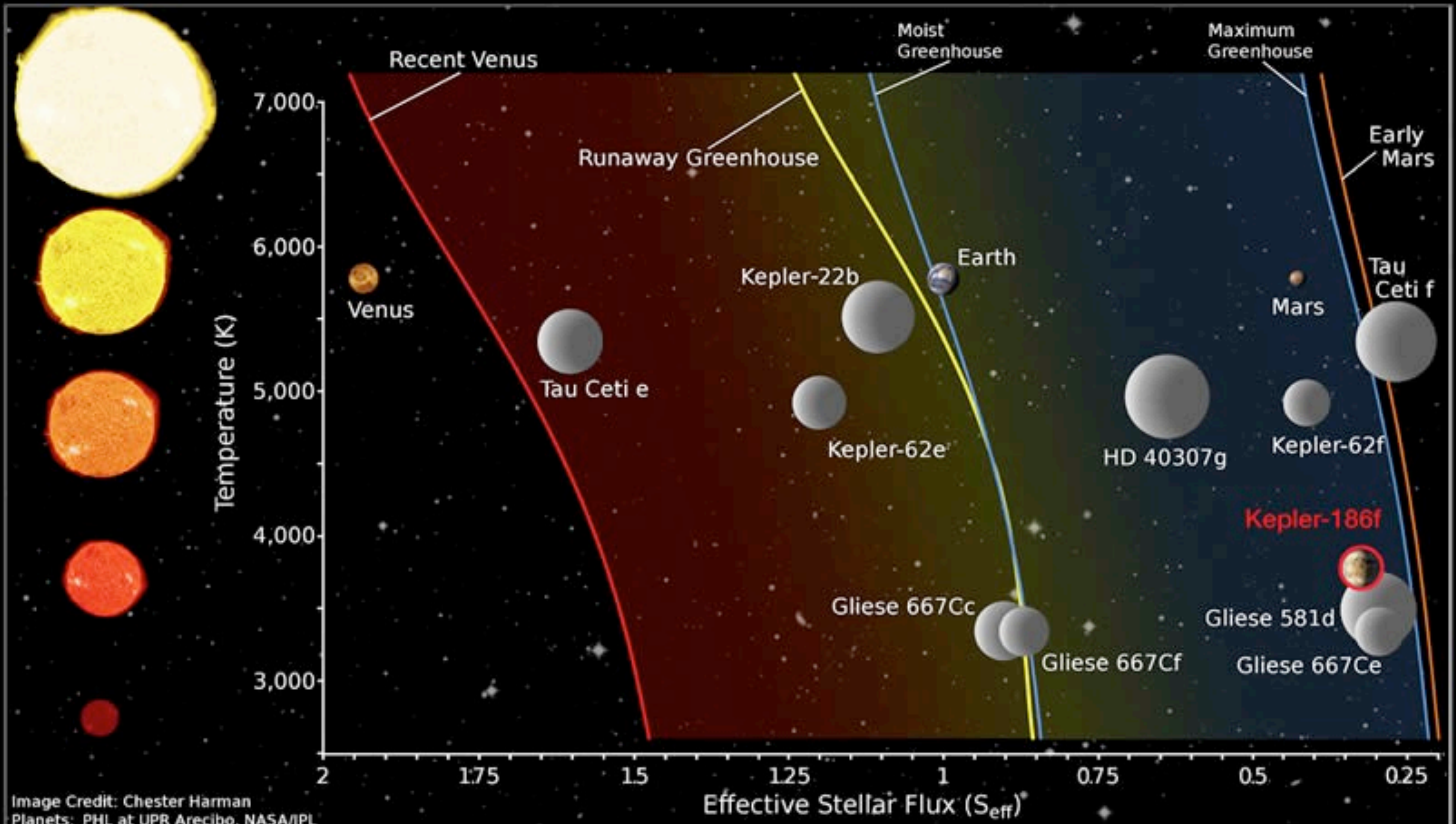
The Holy Grail has been to find a planet located in the *habitable zone*, where it should be possible for Earth-like conditions (particularly liquid water) to prevail.



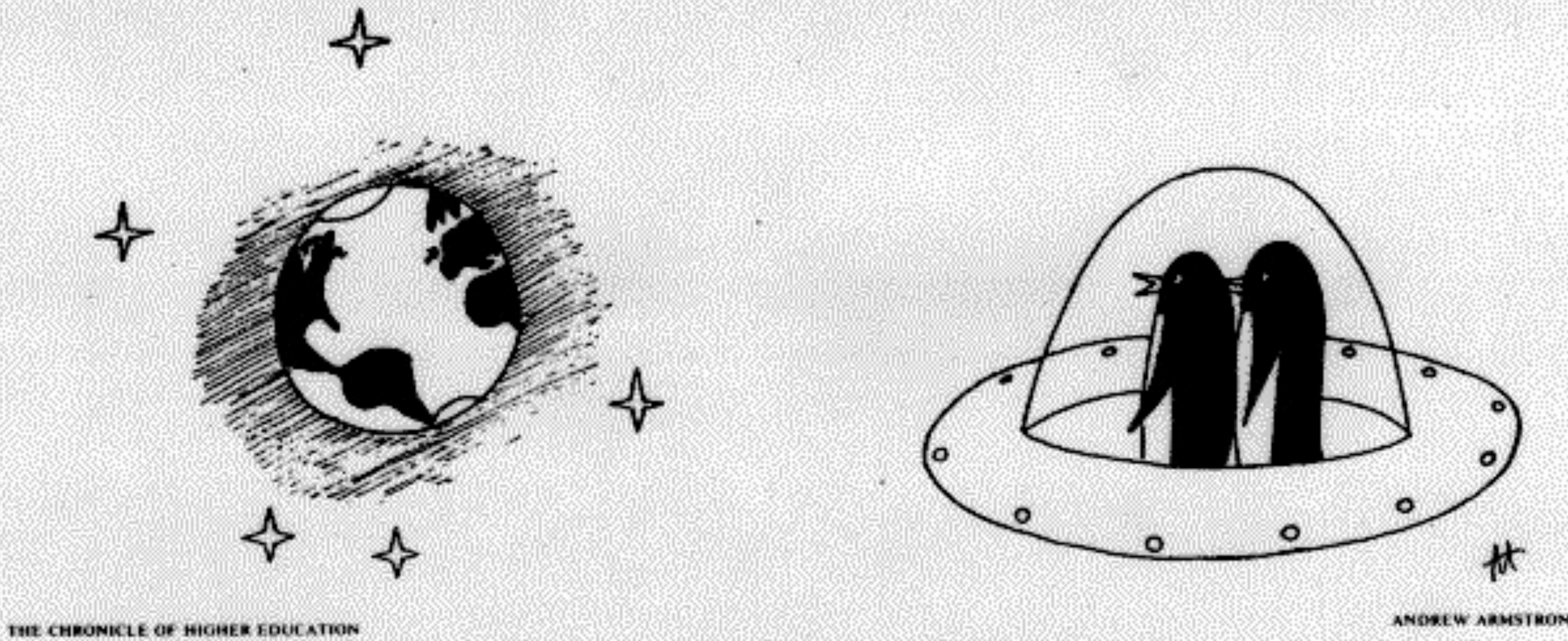
Earlier this year, the discovery of the first Earth-sized planet in the habitable zone of another star was announced. Kepler-186f is less than 10% larger than Earth, in a 130-day orbit around an M star with four other planets already known.


Earth
Kepler-186f
Kepler-186 System
f
b c d e
Solar System
Earth
Venus
Mercury
Planets and orbits to scale

The Habitable Zone

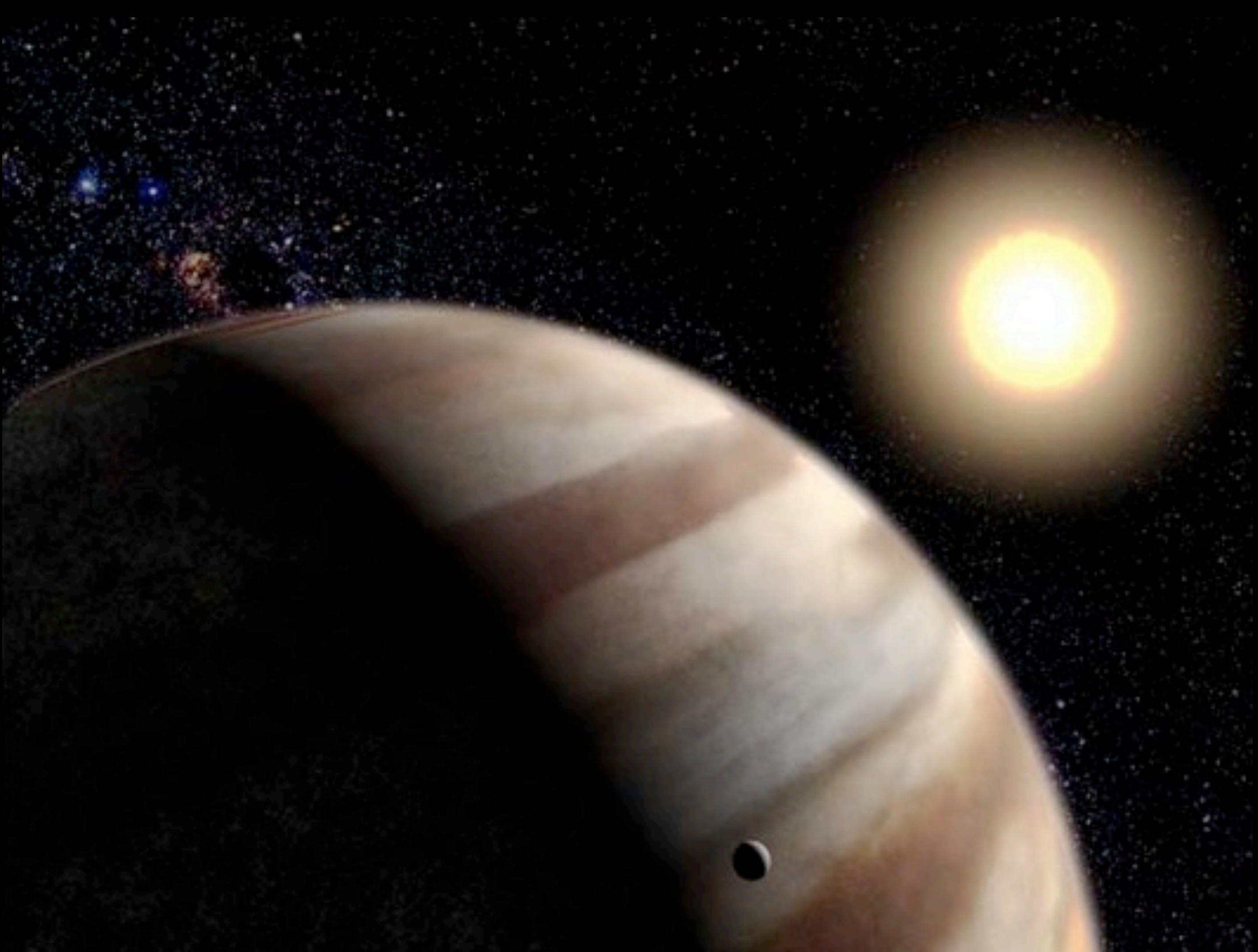


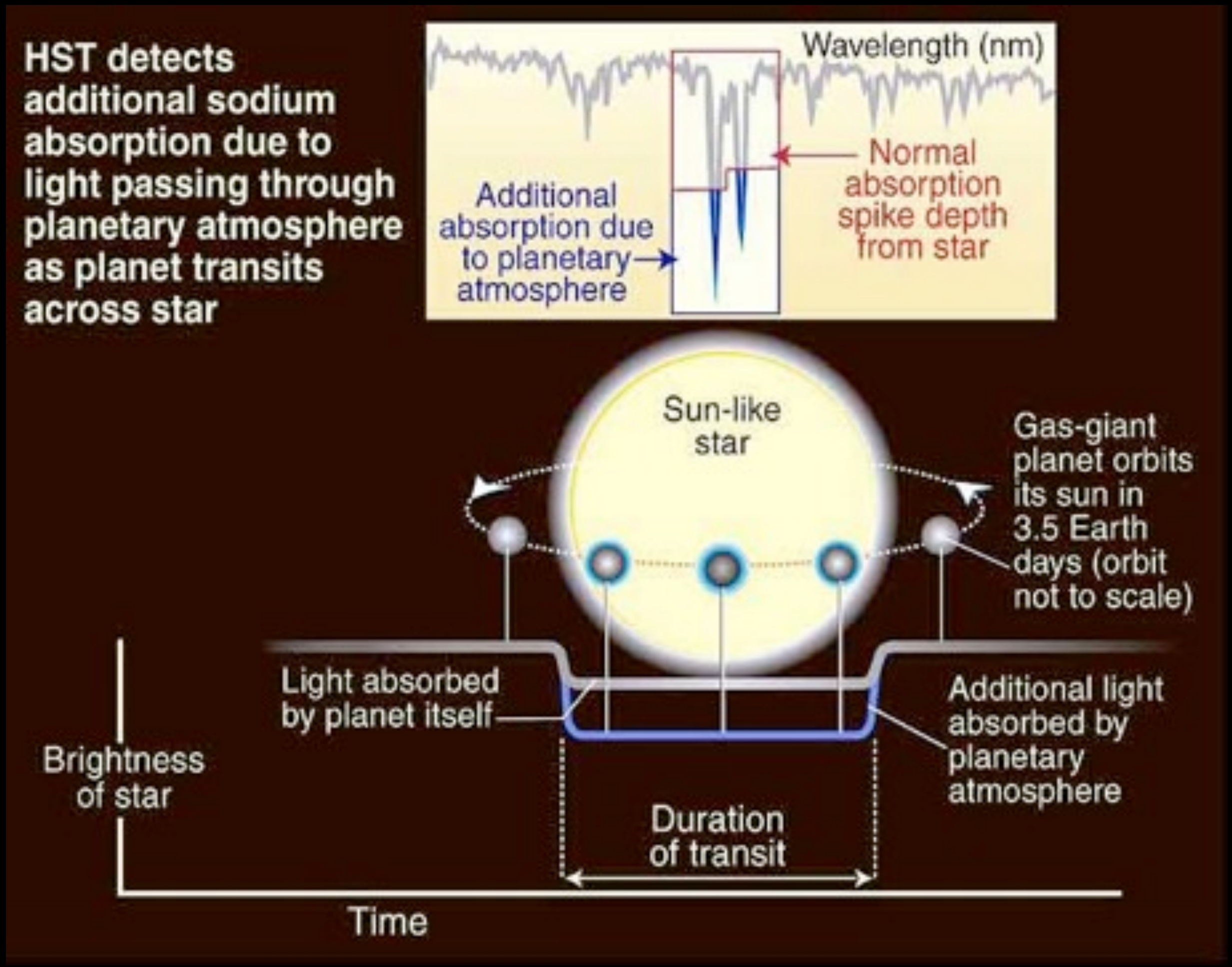
Habitable zone exoplanets as of April 2014. "Stellar flux" on the x-axis is essentially how much of the star's energy the planet is receiving.



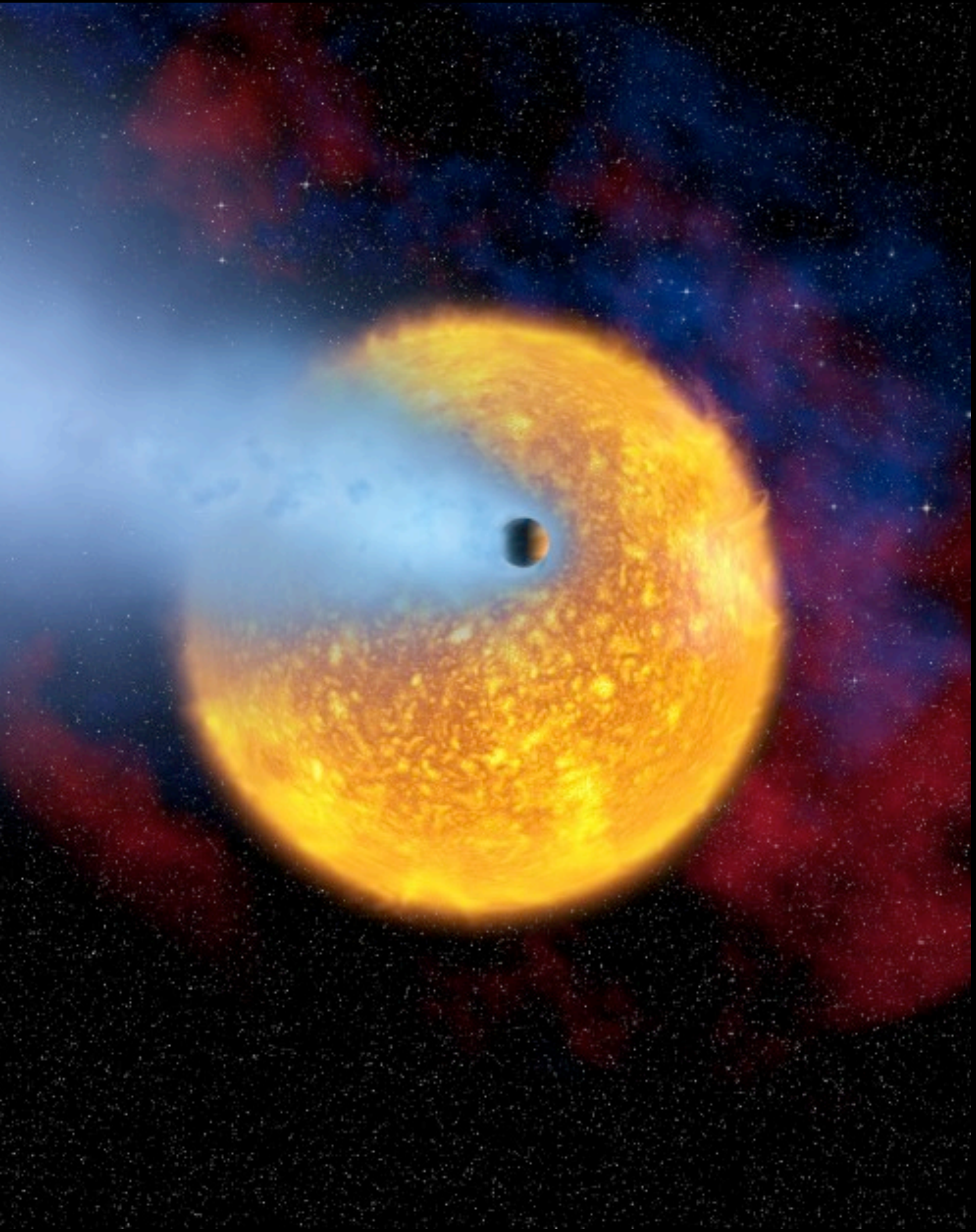
"I see only a little snow at the poles. Obviously, this planet can't support intelligent life."

In 2001, Hubble detected an atmosphere around an extrasolar planet for the first time, detecting sodium in the atmosphere of a $0.7M_{Jup}$ mass planet orbiting HD 209458 in just 3.5 days.



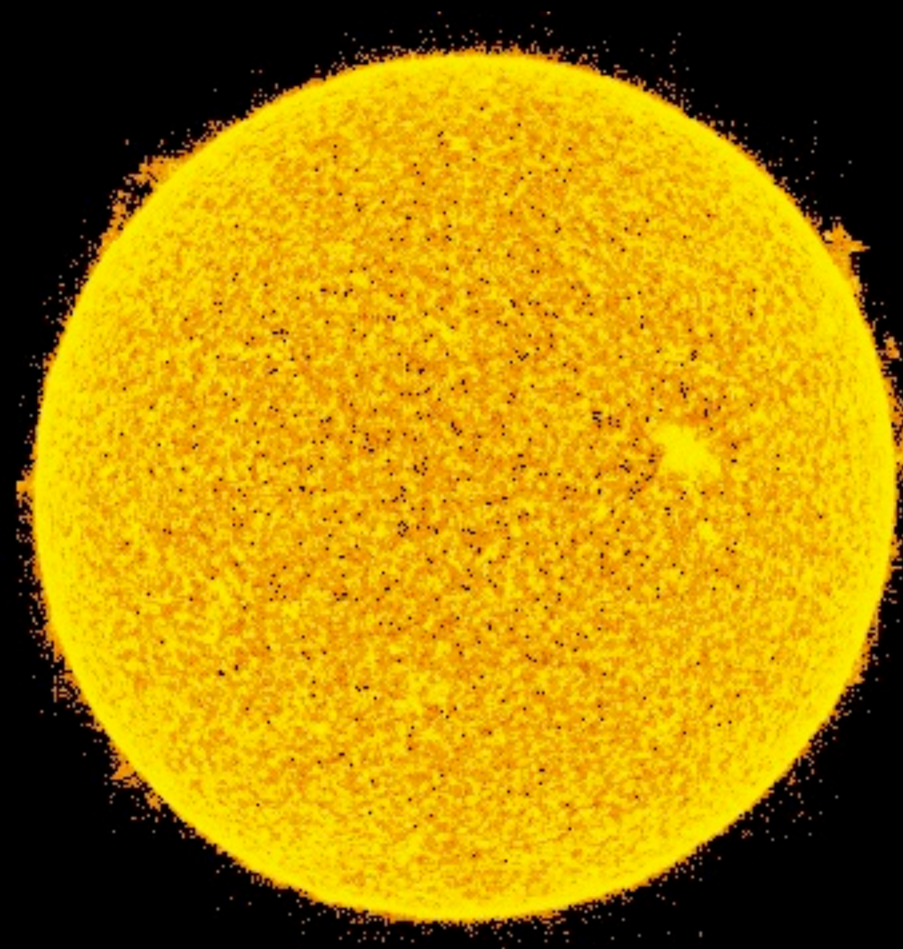


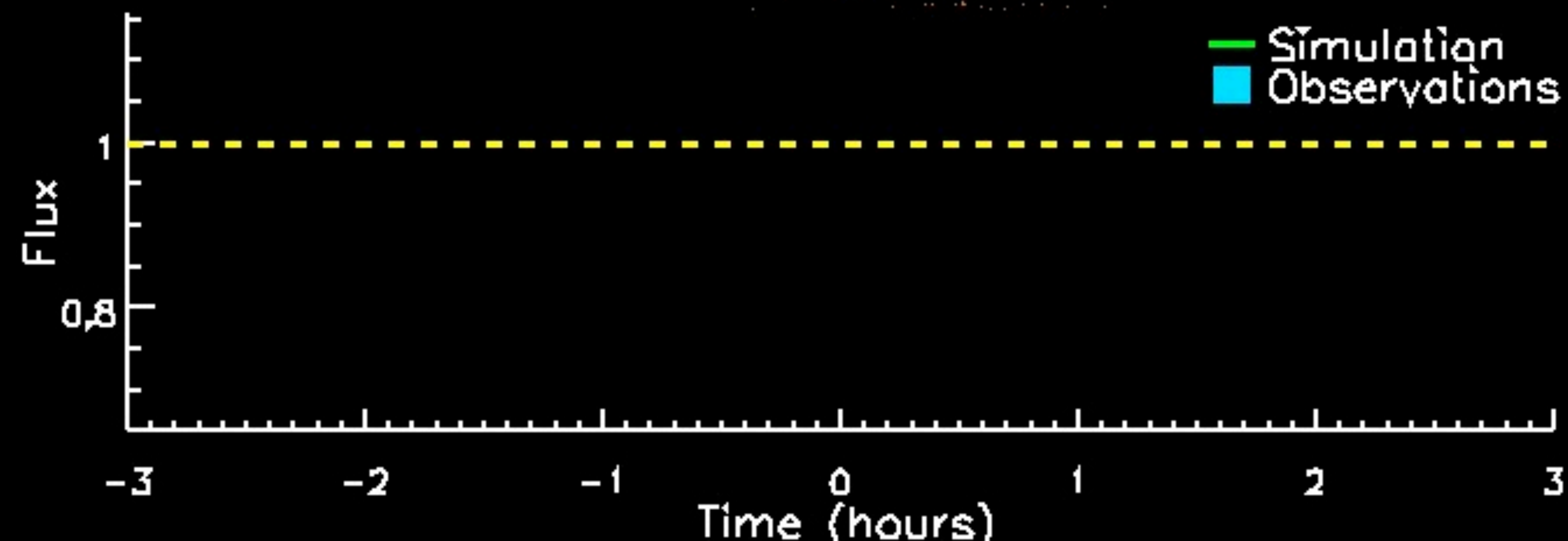
Other notable planets include:



- HD 209458 b, the evaporating planet. Nicknamed "Osiris", HD 209458b is in a 3.5 day orbit around a star somewhat hotter than the Sun, at a distance of 0.045 AU. With a mass 69% of Jupiter's but a radius 32% larger, the density of the planet is only ⅓ that of water.

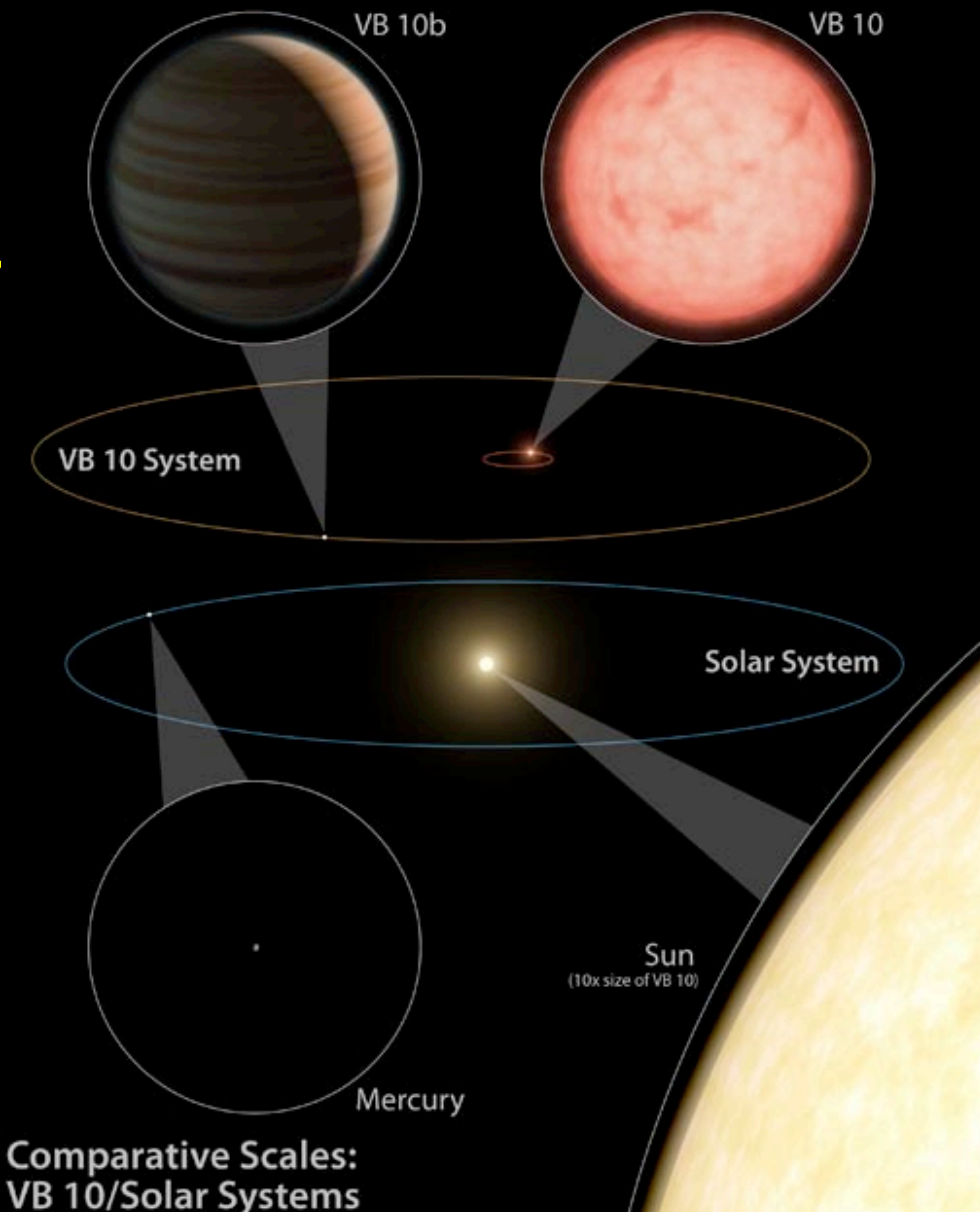
HST observed the transit of the planet across its star. These observations showed an enormous ellipsoidal envelope of hydrogen, carbon and oxygen evaporating off the planet.



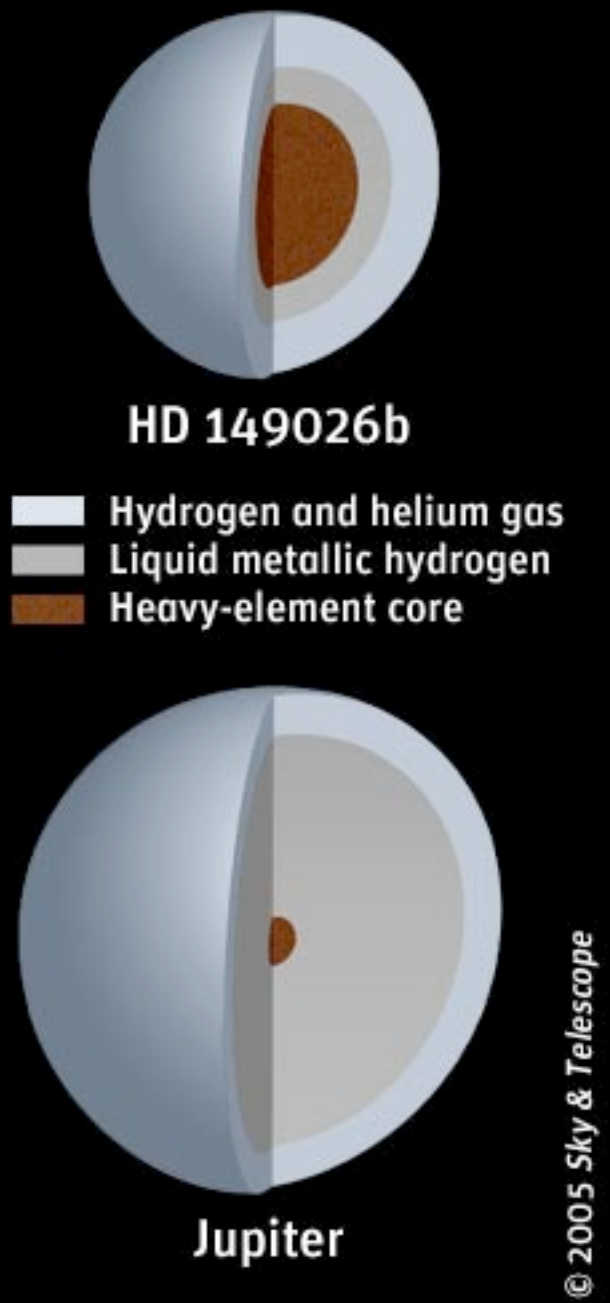


- SWEEPS-10, a star-hugging planet. This planet has the shortest orbital period yet found: it completes an orbit of its star in just 10 hours. The surface temperature must be about 2000 K.

- VB 10, a planet the same size as its star! VB 10 is the first planet to be found by observing the wobble of its parent star. The star is a dim, red M-dwarf with only one-tenth the size, and one-twelfth the mass, of our sun, while the planet is six times the mass of Jupiter. Though the planet is less massive than the star, the two orbs would be about the same size.

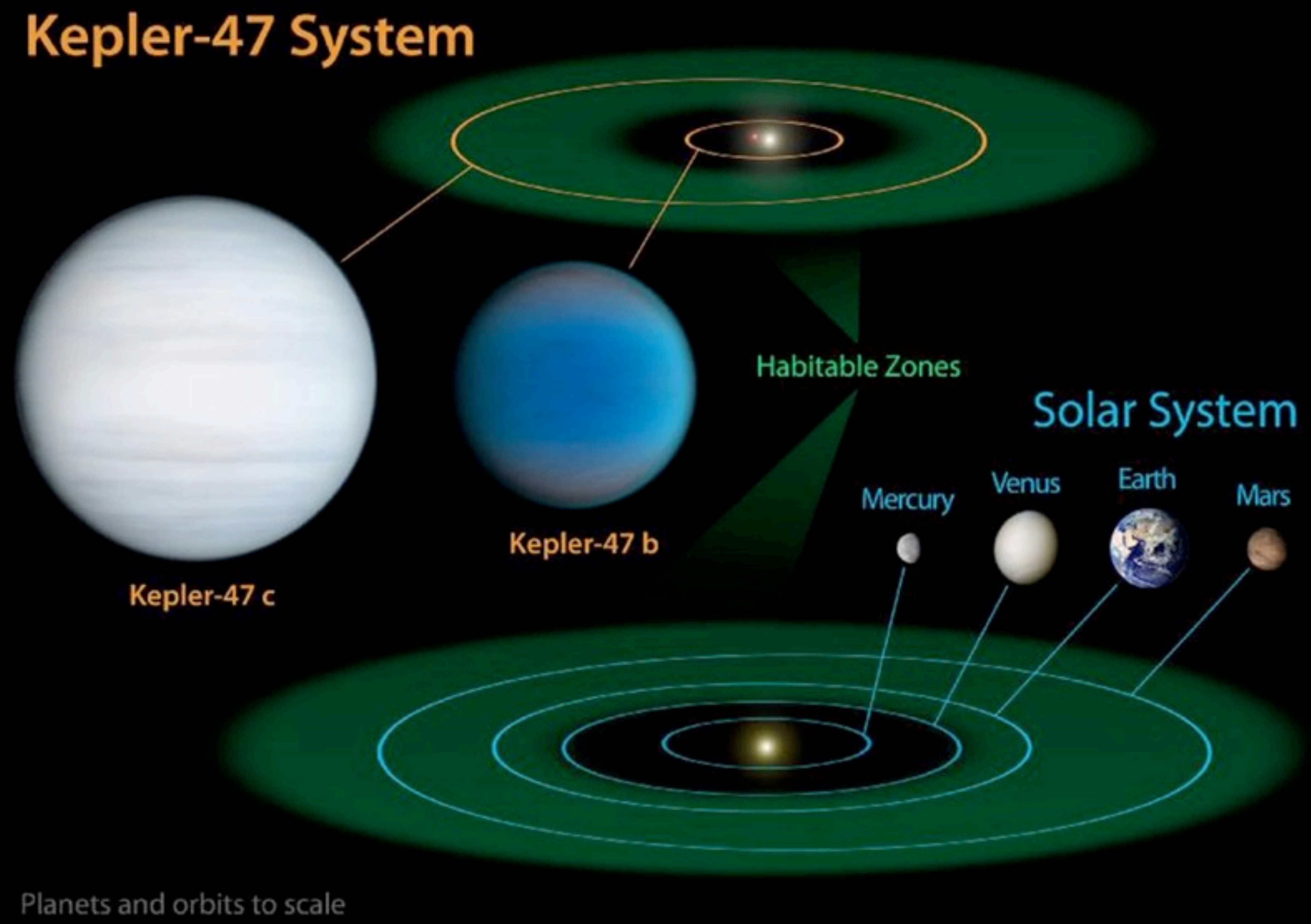


- HD 149026, a hot Jupiter with a core of heavy elements that may amount to 65 or 70 times the mass of Earth: more heavy elements than all the planets and asteroids in our solar system combined. Its mean density is about 1.7 g cc^{-3}, denser than Jupiter; its orbital period is only 2.88 days, with a surface temperature of 2300 K.

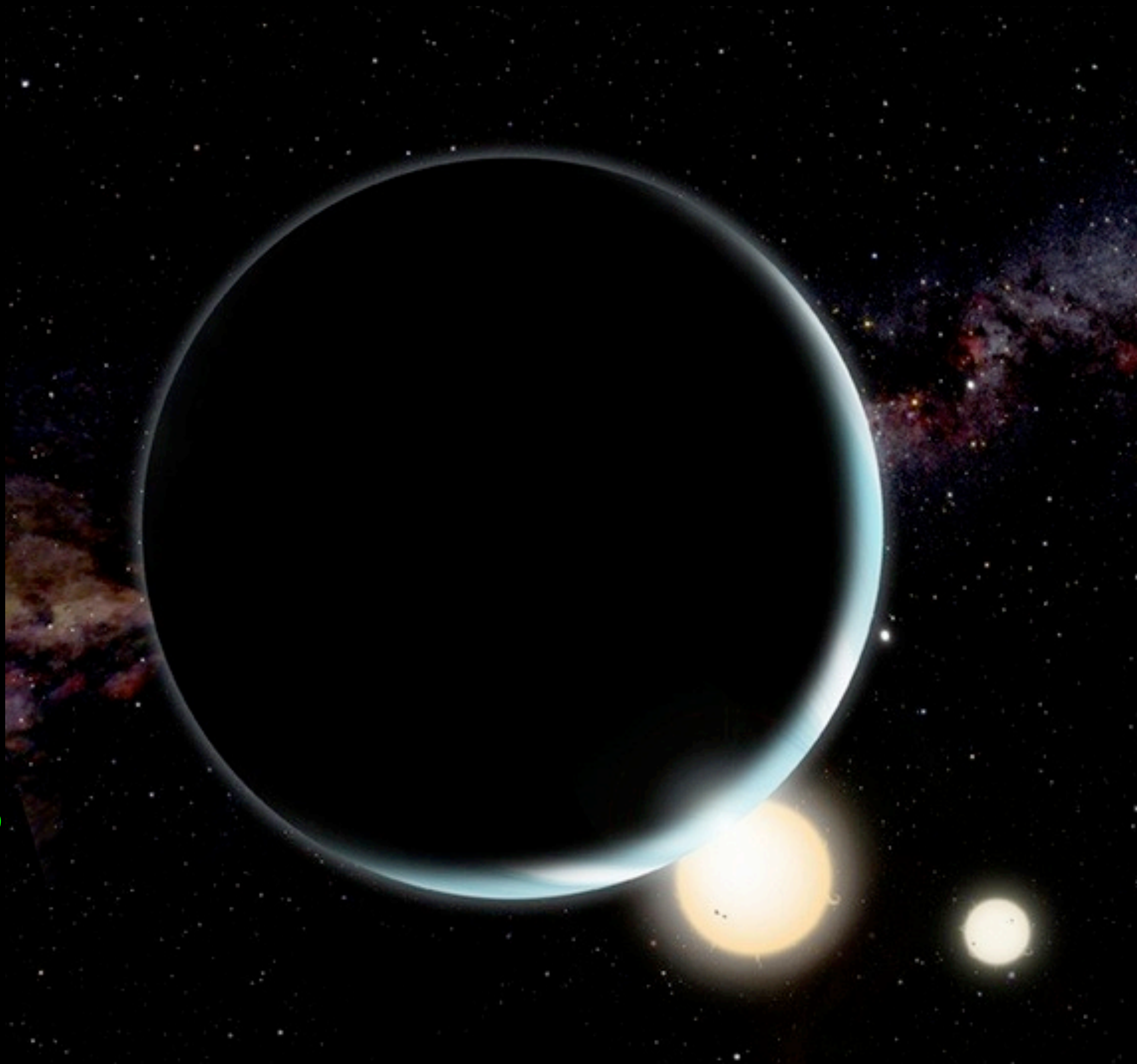


(above) Models of Jupiter's interior and the interior of HD 149026b are compared. (left) Artist's concept of HD 149026, the hottest planet yet observed in the universe – about 3 times hotter than Venus.

Binary systems: We now know of many planets in binary star systems. Most of them have the planets orbiting just one of the stars, but there are increasing numbers of *circumbinary* planets being found (*7 in 2012*).

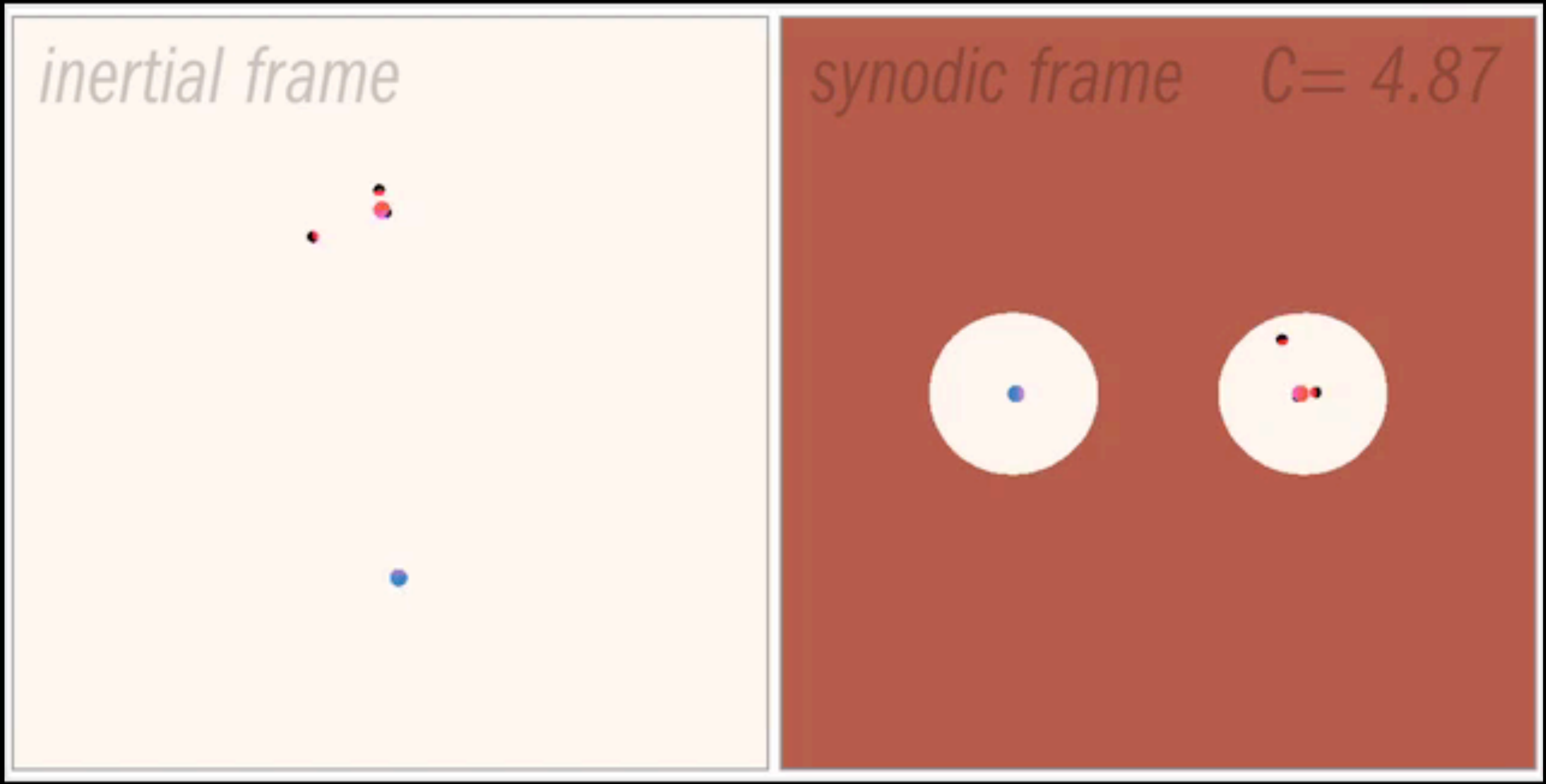


Forming circumbinary planets is very difficult to explain: the gravity perturbations from the two stars on a circumbinary disk would have led to many destructive collisions.

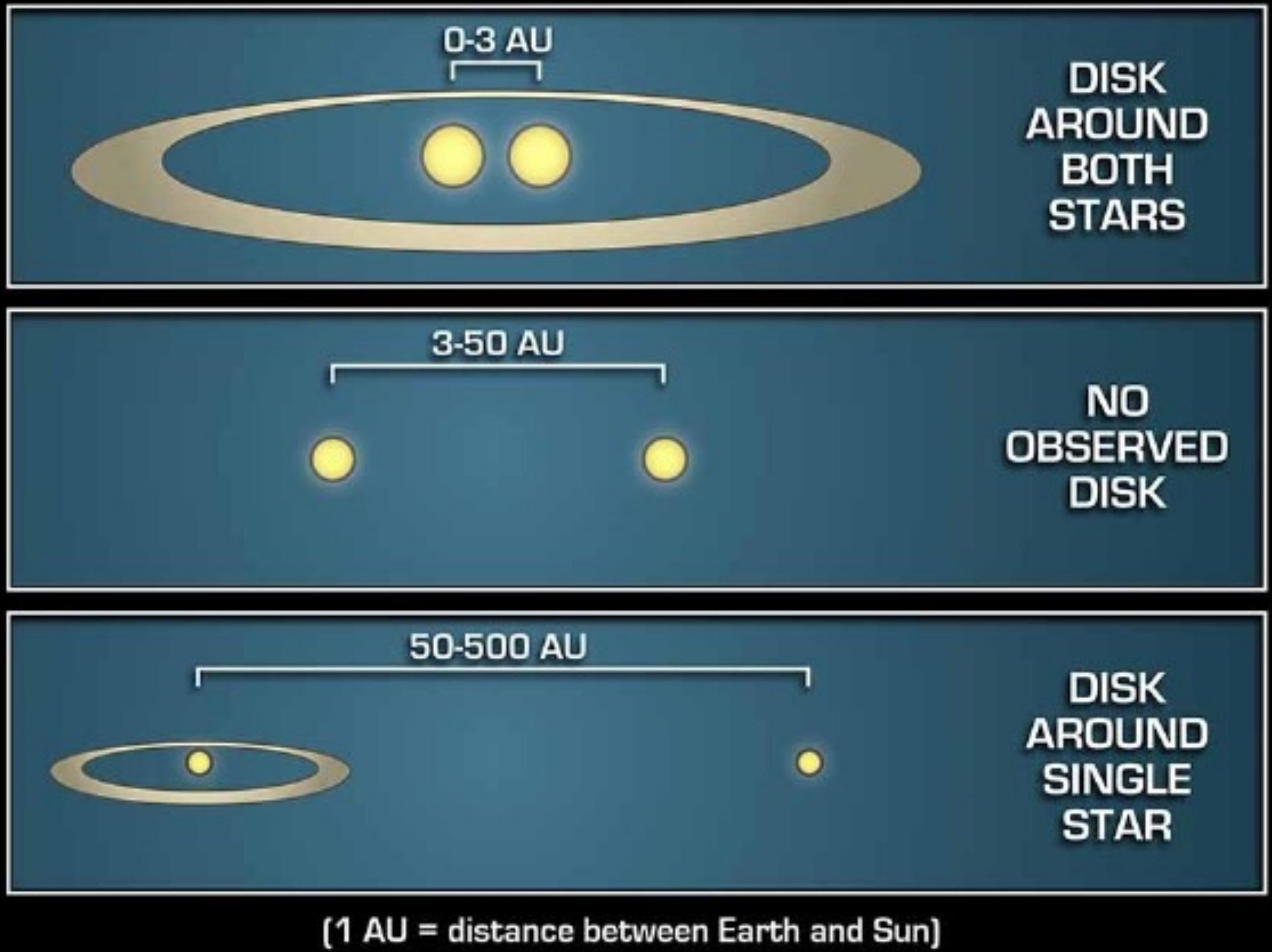


Artist's impression of Kepler-34b, a gas-giant planet that orbits a double-star system. Its two suns are both yellow G-type stars that swing around each other every 28 days. The planet circles them both in 289 days.

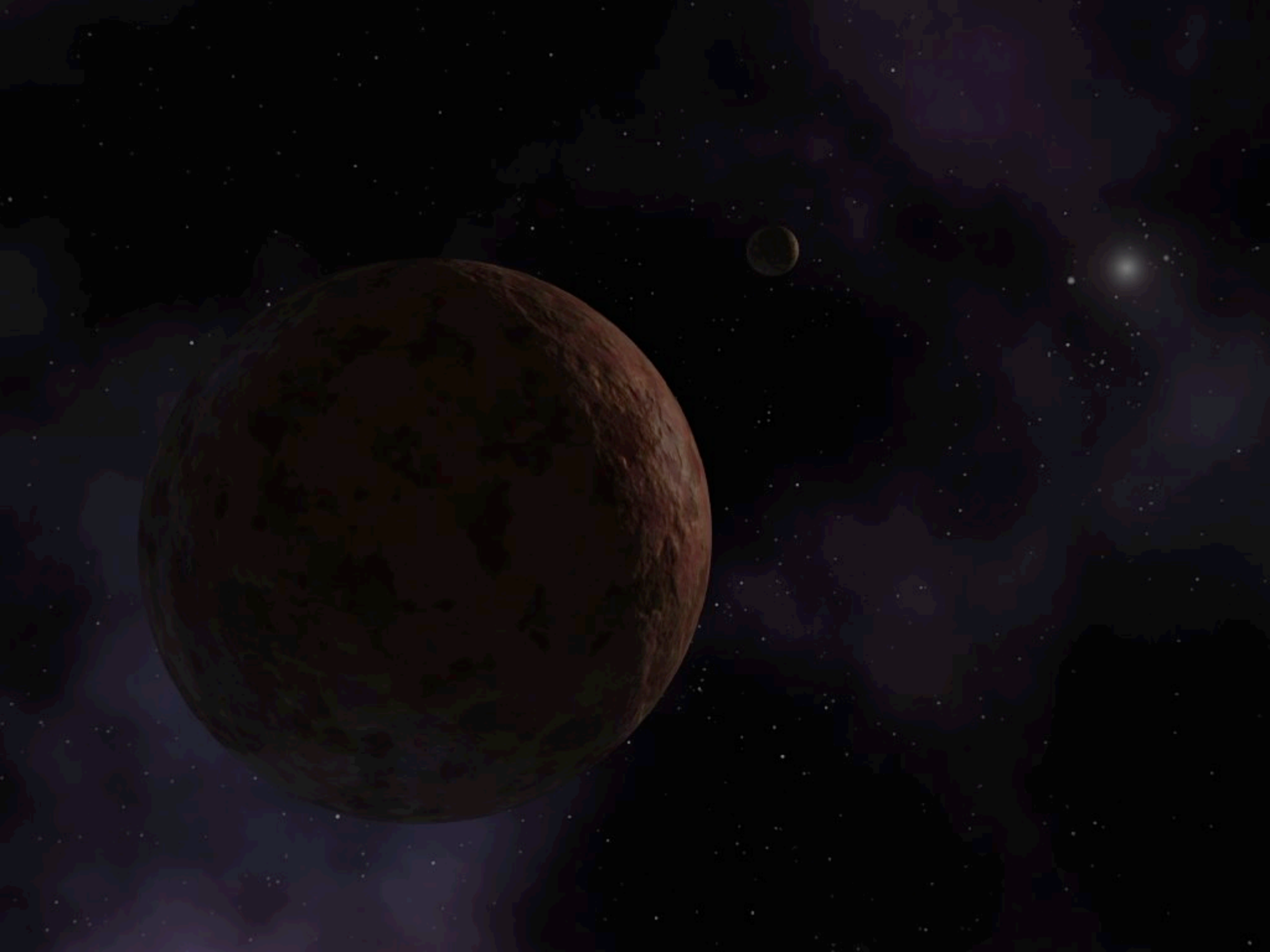
And planets orbiting one star in a binary can find themselves bouncing from star to star.



Astronomers using the *Spitzer* telescope found dust disks are just as likely to be found around stars in binary systems as around single stars. Around 40% of binaries showed dust disks, including extremely tight binaries. Only binaries with intermediate separations, between 3 and 50 AU, showed fewer disks.



Where planets take up residence. If two stars are as far apart from each other as the sun is from Jupiter (5 AU) or Pluto (40 AU), they would be unlikely to host a family of planetary bodies.



Our understanding of what this all means is still very much at an early stage. One of the biggest questions which needs to be answered is: why is the Solar System so different from exoplanet systems? Why doesn't it contain any super-Earths? Why are there no planets inside Mercury's orbit? Why do we have a balance of large and small planets, when most other systems seem to choose one or the other but not both?

One thing is clear: *diversity* seems to be the rule. There are lots more surprises ahead of us...

"There are infinite worlds both like and unlike this world of ours."

– Epicurus (341–270 B.C.)

"There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy."

– Hamlet, Act 1, Scene V

Upcoming dates

- 2014 November 12: *Philae* probe from *Rosetta* lands on Comet 67P/Churyumov-Gerasimenko
- 2015 February 1: *Dawn* goes into orbit around Ceres
- 2015 July 14: *New Horizons* reaches Pluto and Charon
- 2015 August 15: Launch of ESA's *Bepi-Colombo* orbiter/lander to Mercury
- 4,000,000: *Pioneer 11* – flyby of star Lambda Aquila

see *http://nssdc.gsfc.nasa.gov/planetary/upcoming.html*

That’s all, folks!

Future astronomy courses

Introduction to Astronomy

A general introduction to the most important concepts in astronomy

Lives of the Stars

A more detailed look at how stars live and die

Further reading

Quite a few books have been written in recent years about the discovery of planets outside our solar system, but unfortunately most of them seem to have been written immediately after the first few were found in 1996, so are now seriously out of date, barely a decade and a half later! What we really need is good book including all the *Kepler* results.

- One of the ones I read was **"Looking for Earths: The race to find new solar systems"** by Alan Boss (John Wiley, 1998). He has a good description of the early years, and the many failures and retractions of planets before eventual success. The last part of the book spends far too long on NASA acronyms of projects that don't exist yet, and the tentative suggestions about distinguishing between planets and brown dwarfs are now very out of date. He's got a newer book out, called **"The Crowded Universe: The search for living planets"** (Basic Books, 2009), but it's all too much about Alan Boss and not enough about exoplanets, for my taste.
- Michel Mayor, co-discoverer of the first planet, has a book called **"New Worlds in the Cosmos: The discovery of exoplanets"** by Michel Mayor and Pierre-Yves Frei, transl. Boud Roukema (Cambridge UP, 2003). It's slightly more up-to-date, and has a good description of what people are now thinking about how to make these planets. It's starting to look out of date too, after *Kepler*.
- The article by Ann Finkbeiner, **"Planets in chaos"** is an excellent summary of the current state of affairs in our (lack of) understanding of planet formation: http://www.nature.com/news/astronomy-planets-in-chaos-1.15480

- Web-sites can at least stay up-to-date, even if they're less readable. A couple of good ones:
  - exoplanets.org has a complete up-to-date list of all exoplanets, plus some terrific tools for plotting the data.
  - The **Nasa Exoplanet Archive** at http://exoplanetarchive.ipac.caltech.edu has lots of similar features
  - NASA now has a site called "**PlanetQuest: Exoplanet exploration**" at http://planetquest.jpl.nasa.gov/, which has a host of useful information, including a page to search the catalogue of exoplanets in various ways
  - space.com has a list of **"The Strangest Alien Planets"** at http://www.space.com/159-strangest-alien-planets.html
- The *Kepler* website is at kepler.nasa.gov: they have loads of good pictures and animations, as well as a live counter telling you how many planets they've found!
- The Citizen Science project **Planet Hunters** is at http://www.planethunters.org; you can help identify transits and find new planet candidates. The site is part of the **zooniverse** project, which has many participatory projects, from identifying galaxies, to exploring features on the Moon, and identifying potential Kuiper Belt targets for New Horizons.
- Check out http://www.nytimes.com/interactive/science/space/keplers-tally-of-planets.html
- NASA maintains an "**Upcoming Planetary Launches and Events**" page at http://nssdc.gsfc.nasa.gov/planetary/upcoming.html

Sources for images used:

- Background image: Artist's conception of Sedna, from Spitzer Press Release 15 March 2004, http://www.spitzer.caltech.edu/Media/releases/ssc2004-05/index.shtml
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