Astro 7 Chap 13: Other Solar Systems Around Other Stars

- ***Exoplanets*** = planets around other stars
- How do we discover them?
- How do selection effects bias our results?
- What are these exoplanets like?
- What are their orbits and how influence climate?
- Can we detect their atmospheres, climate?
- Stars form around other stars in Open Star Clusters, leading to angular momentum in infalling material. Disks and solar systems expected therefore to be common

Discovering Other Solar Systems

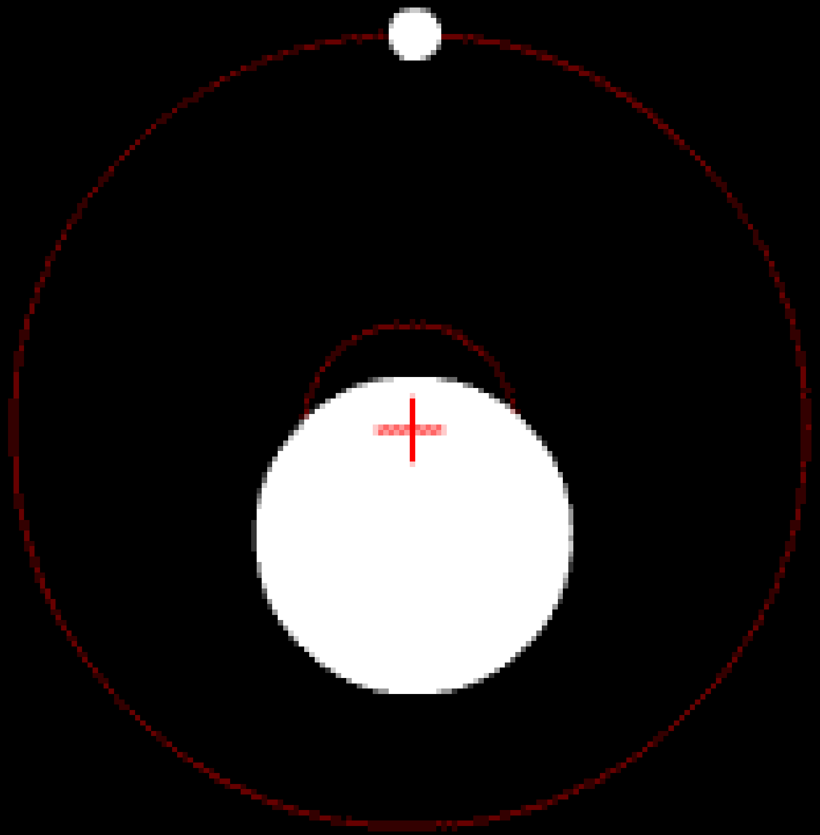
- It's hard finding planets around other stars?
- Planets are **too faint**, too close to parent star to actually "see", except in a tiny handful of cases. Must be clever (as always! Astronomers are good at that)
- There are **3 main methods of finding exoplanets** today…

- **1. Periodic Doppler shifts in parent star's spectral lines show Newton's 3rd Law (action/reaction) reflex motion of the star as the planet orbits**
- **2. Transits of planet in front of star result in tiny drop in star's brightness.**
- **3. Direct Imaging: By far the hardest!**

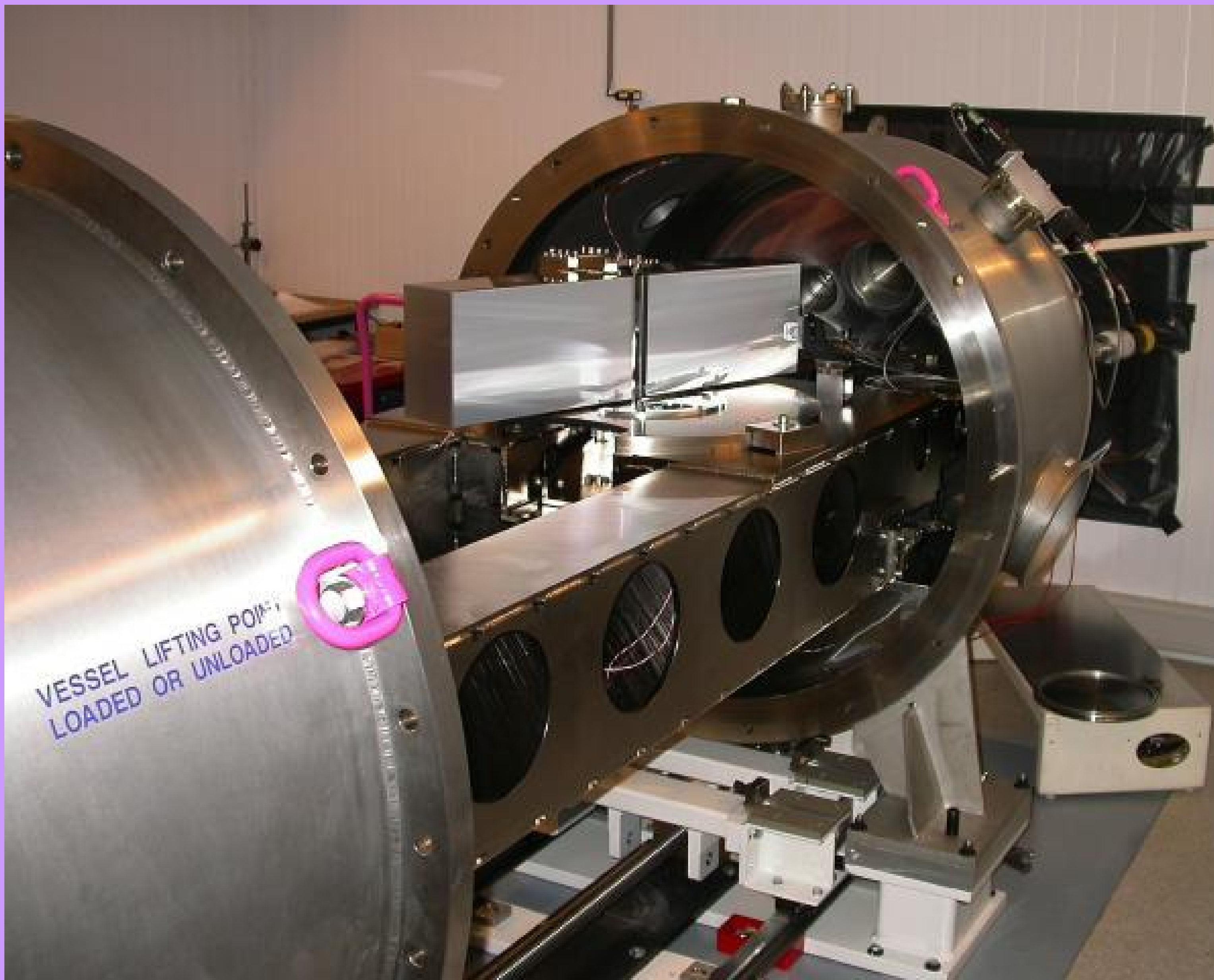
<u>Doppler Method</u>: From the Ground, this is the least-hardest Way to Find Solar Systems - Observing Periodic Doppler Shifts in the Parent Star

- Stars are massive, planets are not…
- So, the Doppler Shifts of the parent star would be tiny.
- Even mighty Jupiter is only 1/1000 the mass of the sun.
- It moves at a speed of 12.7 km/sec in its orbit, so the reflex motion of the sun is only 1/1000 of that, or 13 m/sec
- So v/c is $4x10^{-8}$ or 40 billionths or 1 part in 25 million!!
- Wavelength shifts of only 1 part in 25 million, even assuming the orbital plane allows all of that to be line-of-sight and so detectable by the Doppler shift. Very hard!
- It means we're going to bias the kinds of solar systems we can find; preferentially massive planets very close to low mass stars
- Yet still, need high precision, expensive **<u>spectrographs…</u>**

Orbiting planet makes the star orbit too: Doppler Effect makes that detectable in the spectrum of the parent star



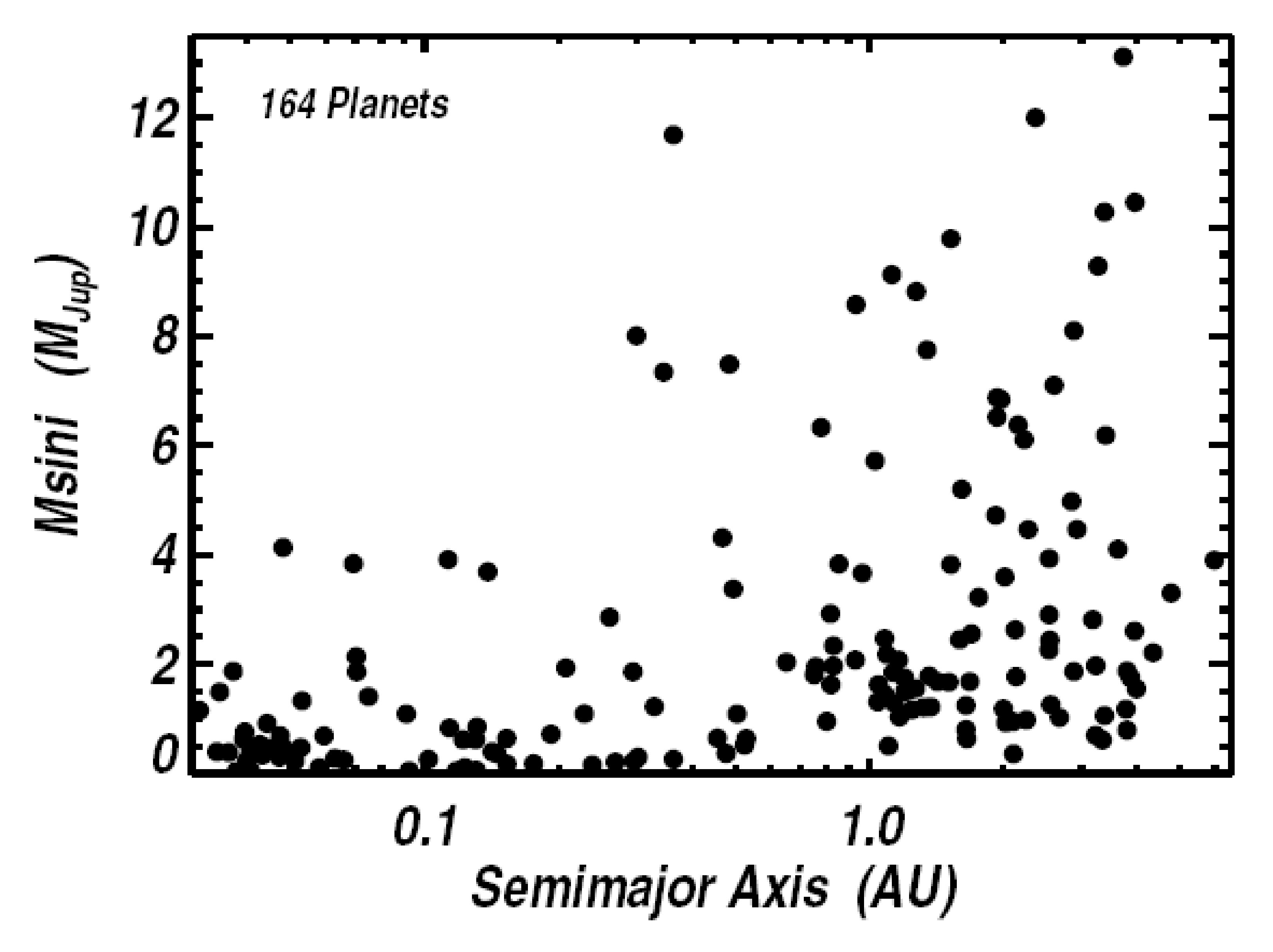
The HARPS Spectrograph at Keck Observatories



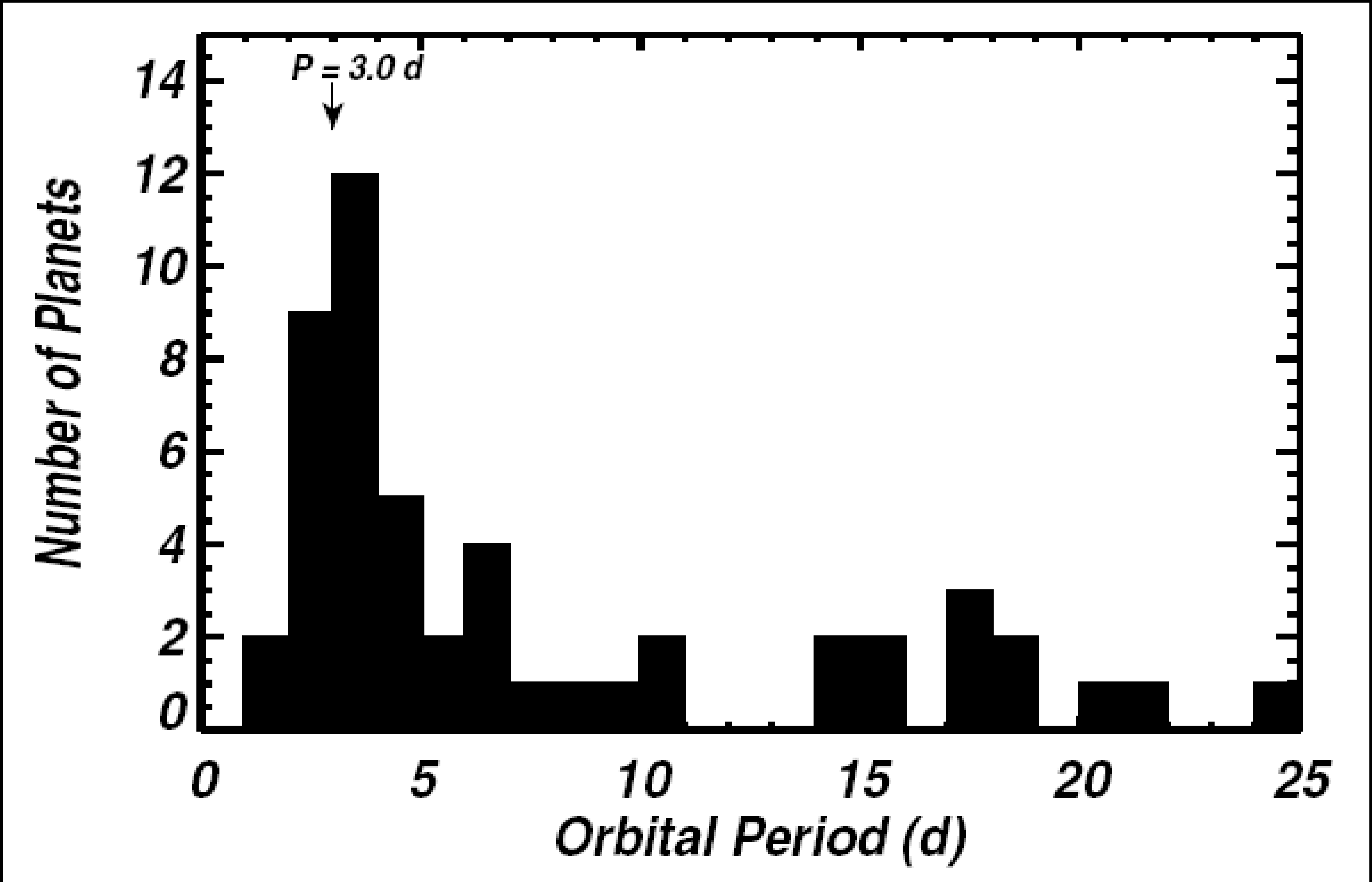
But Perseverance Pays!

- Marcy and Butler, and Queloz and Mayor in Europe had success.
- As of Sept 2013, about 800 nearby stars had planetary systems discovered around them, 150 by Kepler Mission via transit method, the rest by Doppler method.
- Today, 4200 Kepler Mission likely solar systems discovered by transit method, 1000 confirmed. More than by the Doppler Method.
- Calculated implications: **<u>over 90% of sun-like stars are have planetary systems around them!</u>**

The large majority of early discoveries by Doppler Method: Lots of “Hot Jupiters” found



Strong Doppler shift requires strong gravity, close-in orbits, and so planet orbital periods of a month or less were first to be discovered



We Don’t Think Such “Jupiters” Can Form So Close to Stars

- It’s too hot for hydrogen and helium to collect onto rocky cores this hot. The amount of rocky material is always just a few percent of the total mass – which is mostly Hydrogen and Helium and could not be ices here
- We know they’re not rocky planets because we can measure their mass by the Doppler method, and their size by the depth of the transit (in transit cases), and combining those measurements tells us the density; it’s too low to be rock.

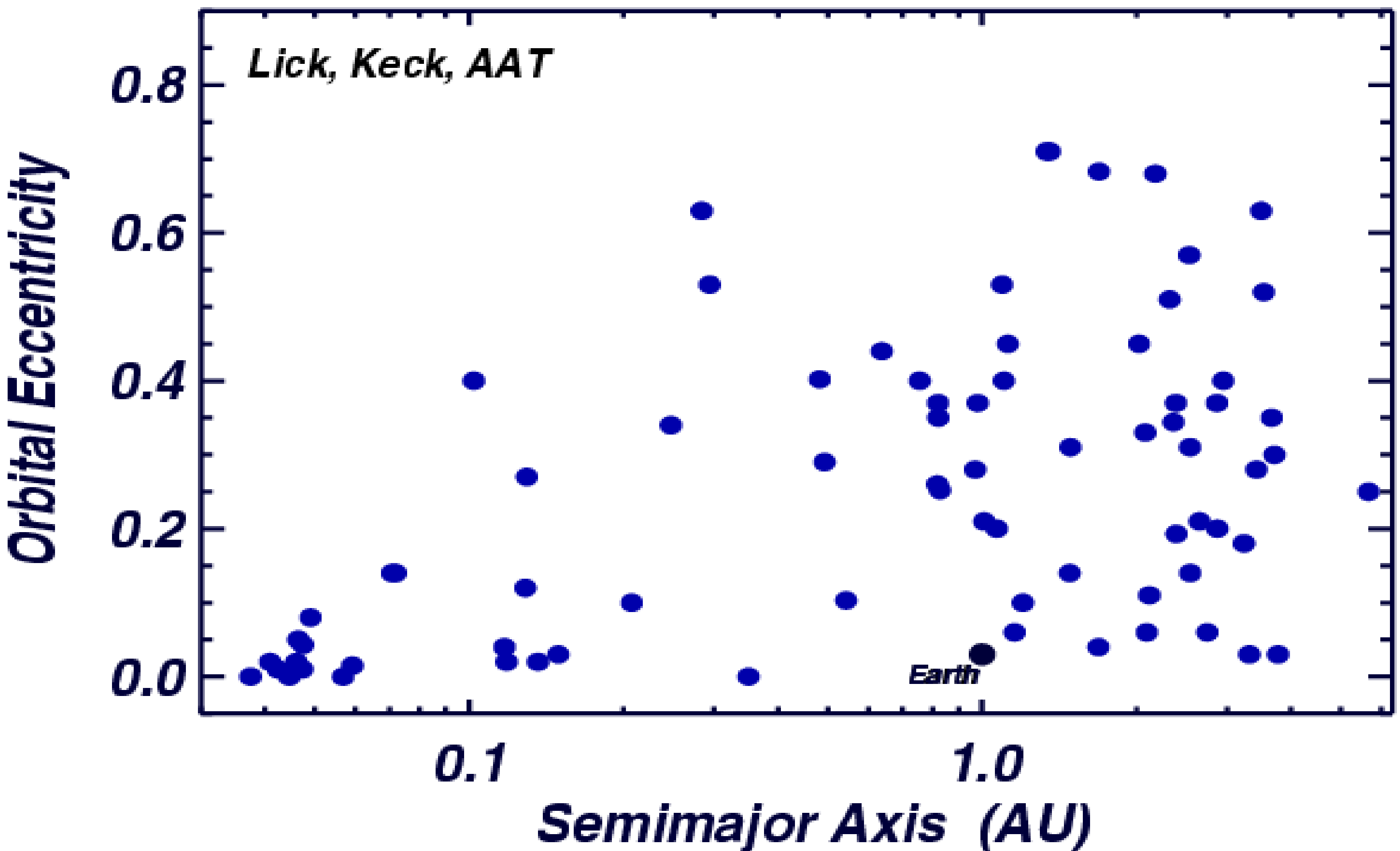
But then how can there be so many “hot Jupiter” systems?

- **<u>Planetary Orbit Migration!</u>**
- What if these “Jupiters” can MIGRATE inward from their cold distant birth place, and find themselves in close to their star for a reasonable amount of time before they evaporate?

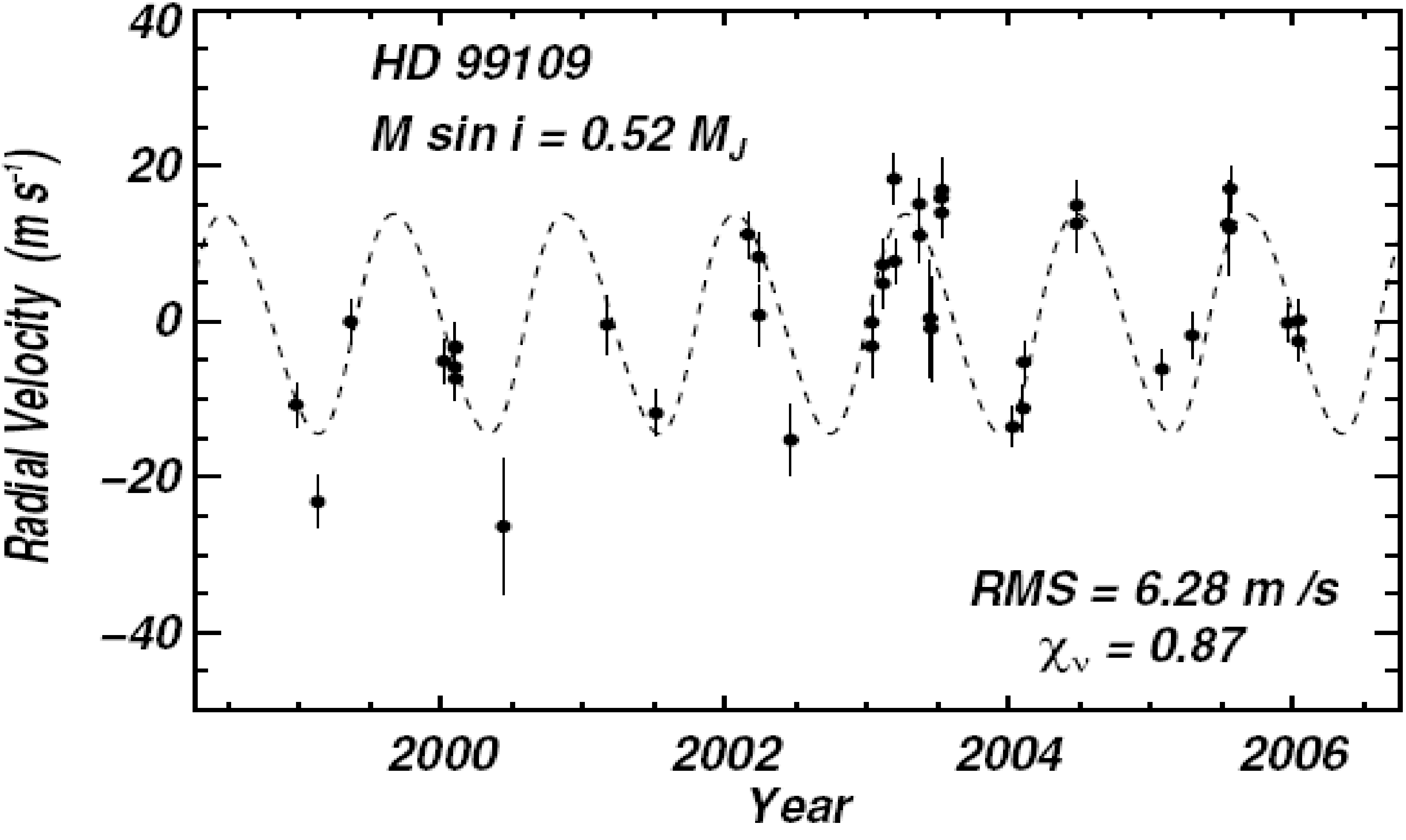
Resonance-induced close encounters w/ other planets

- Planets should, by physics, form in fairly circular orbits since the disk gas/dust will be in circular motion, with plenty of space between planets by the time formation is about done.
- But resonances can amplify eccentricity of an orbit, to the point of orbit-crossing (close encounter possible!), and then the two planets could end up almost ANYwhere, and very likely on fairly eccentric orbits.
- The older a solar system is, the more time for even weak resonances to build up to this point.
- Computer simulations show **eccentric orbits should be the rule**, which would argue that our own solar system is very unusual (our system has most planets in pretty circular orbits, and no evidence of significant migration for any planets except Neptune and Uranus.

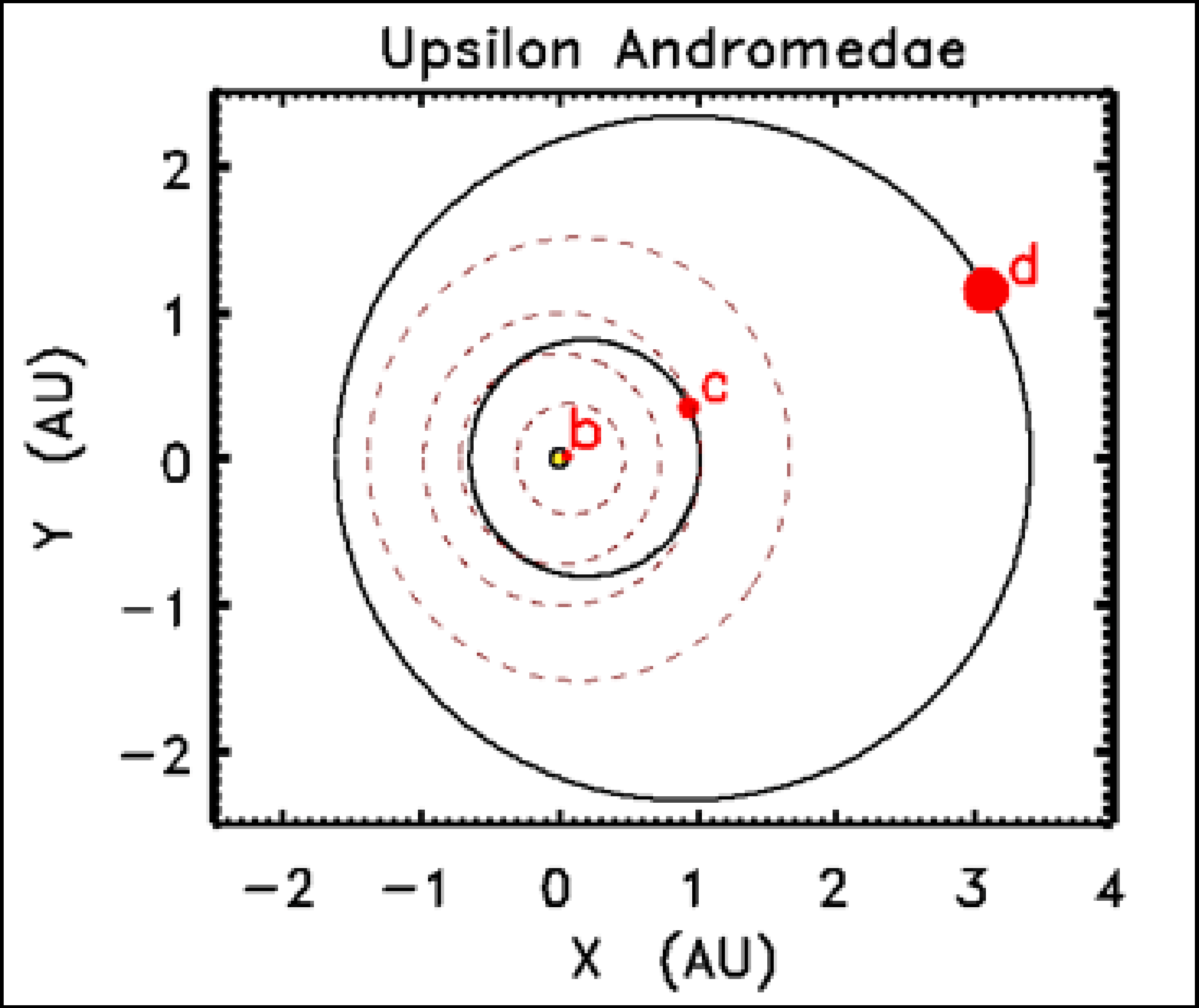
Indeed we see… lots of planets have very eccentric orbits, unlike the circular orbits of our own Solar System. Dynamics studies indicate this is caused by migration. How to measure Eccentricity of Orbits?



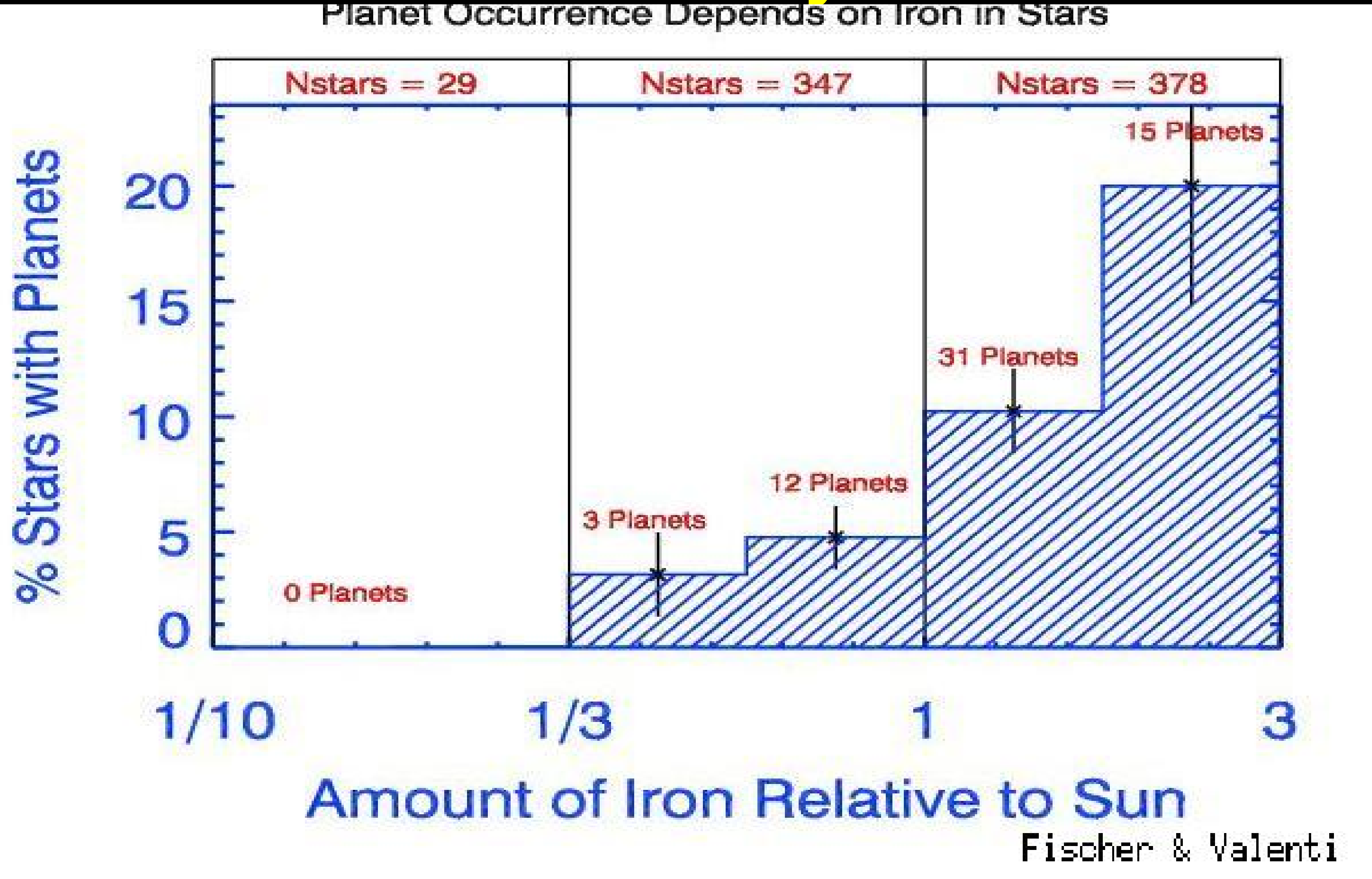
A Fairly Circular Orbit Fits For This One (sinusoidal Doppler velocity)



Upsilon Andromedae has 3 planets in fairly eccentric orbits



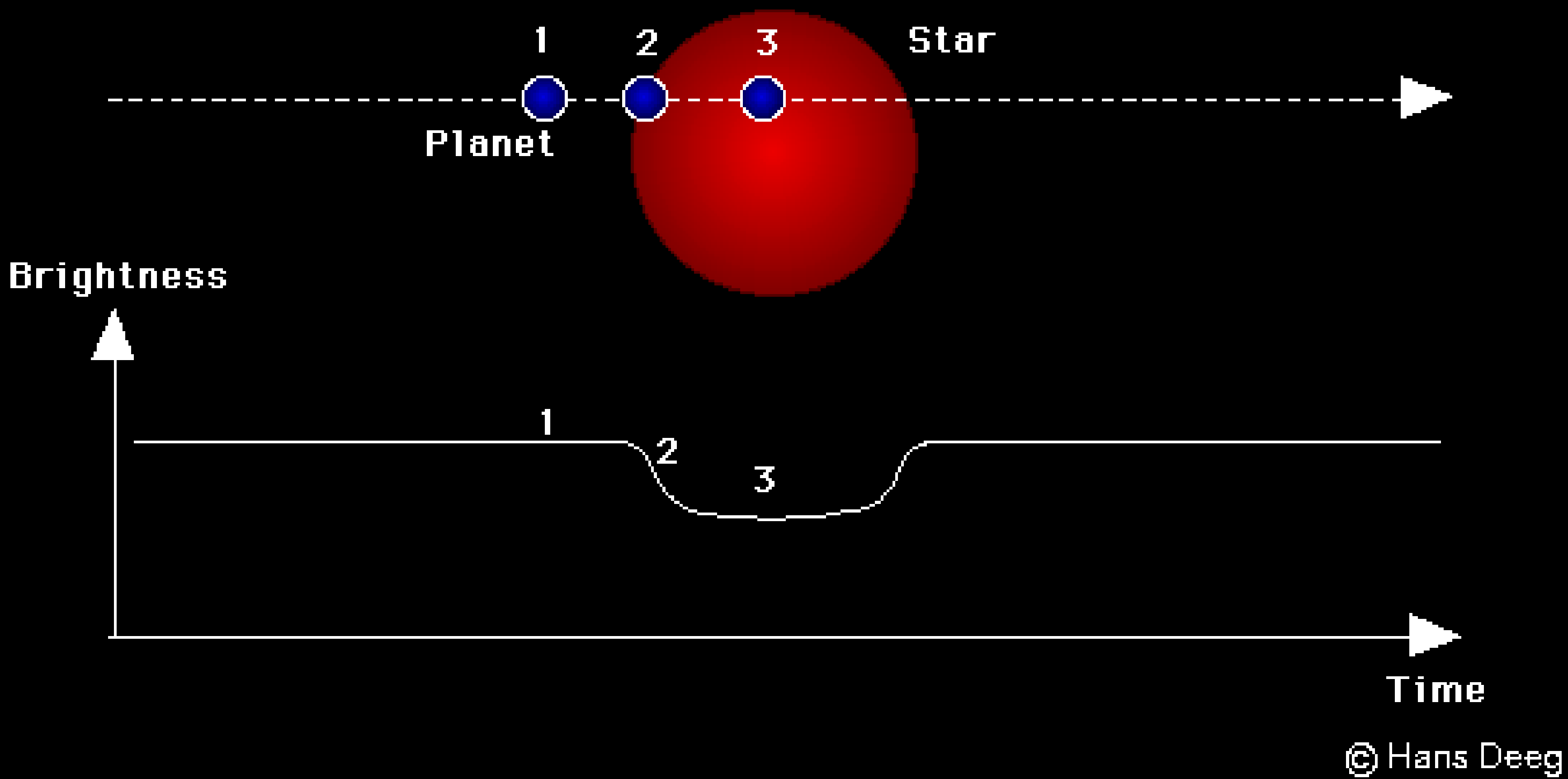
Stars richer in heavy elements are more likely to have planets – which are of course rich in heavy elements



Finding Earth-like Rocky Planets

- To find Earth-like planets, which are much less massive and so give very tiny Doppler signals, best to try to discover by the **Transit Method**.
- Transiting planets also allow measuring their size (by the amount of light lost), and combined with mass from Doppler signal, gives DENSITY!
- Knowing Density is key to know what it’s made of. Rock? Ice? Liquid? Hydrogen?

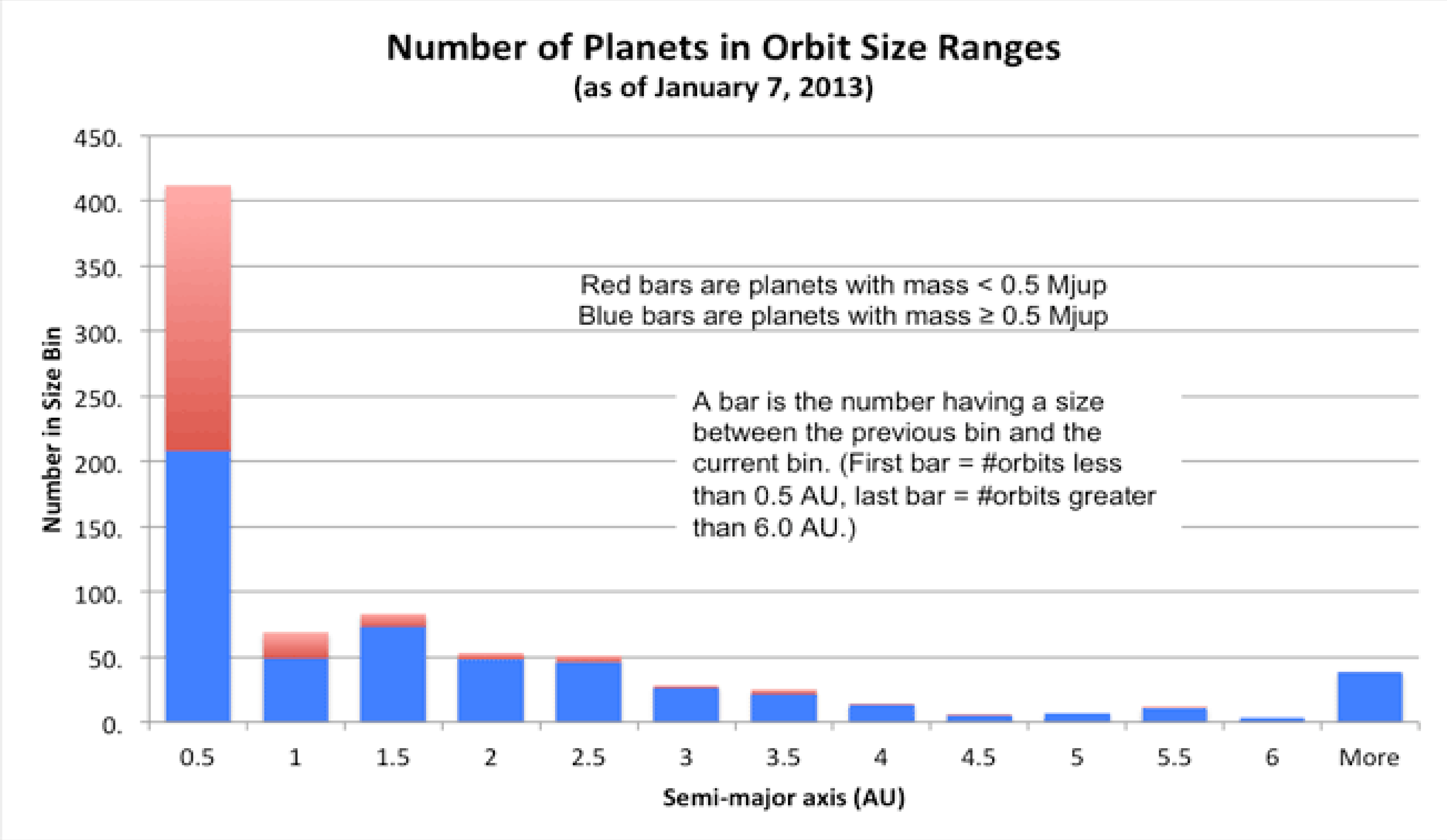
The Transit Method: Transiting Planets Discovered by Precision Monitoring of Star's Brightness



Transits are HARD to Detect!

- Planets are tiny and stars are large.
- Must be able to do accurate photometry (the science of measuring the brightness of an object) down to the level of a few thousandths of a magnitude, or a few hundredths of 1 percent of the total light.

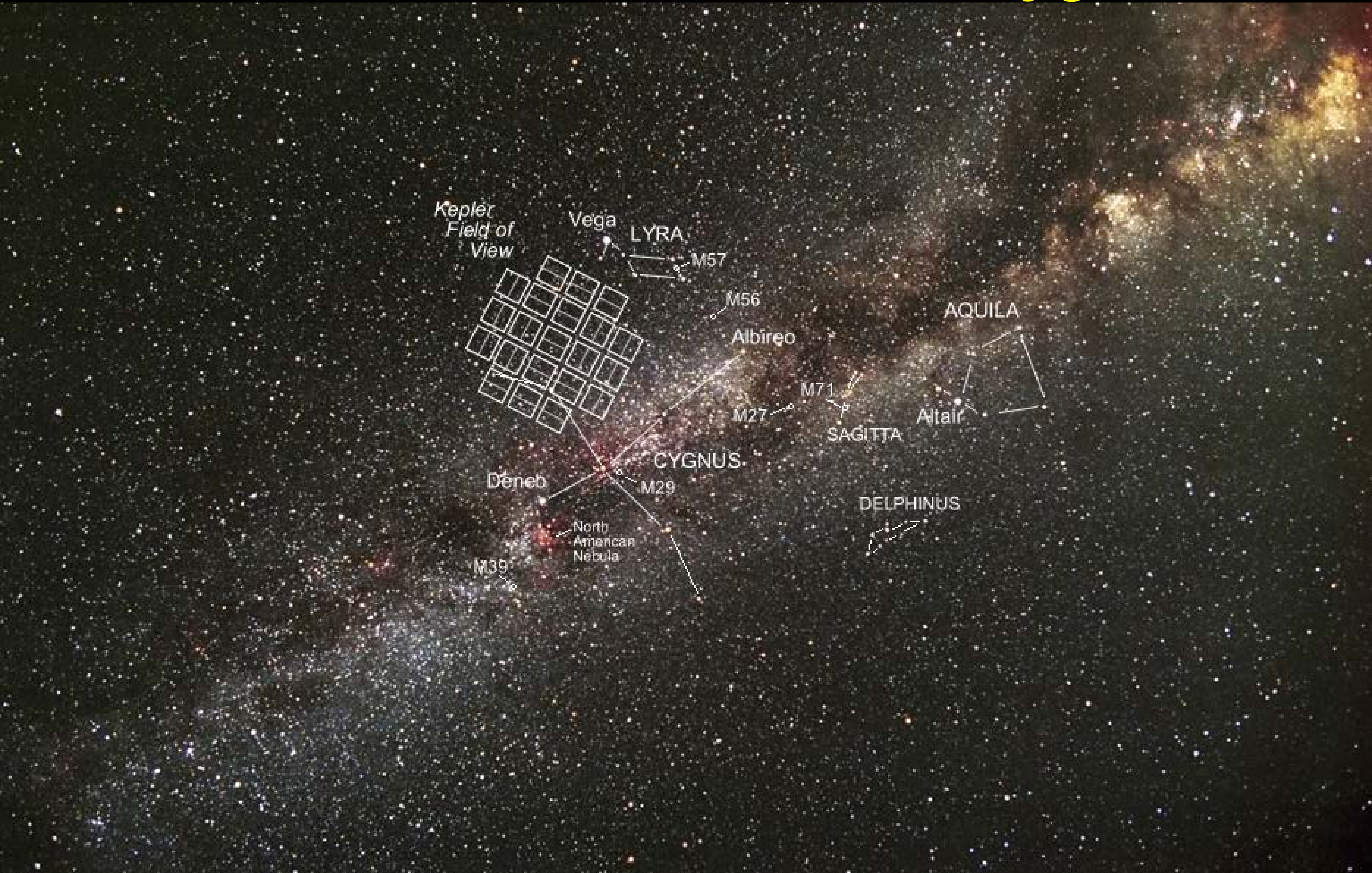
Even the transit method is biased towards discovering close-in planets, since close-in orbits needn't be so perfectly edge-on in order to transit



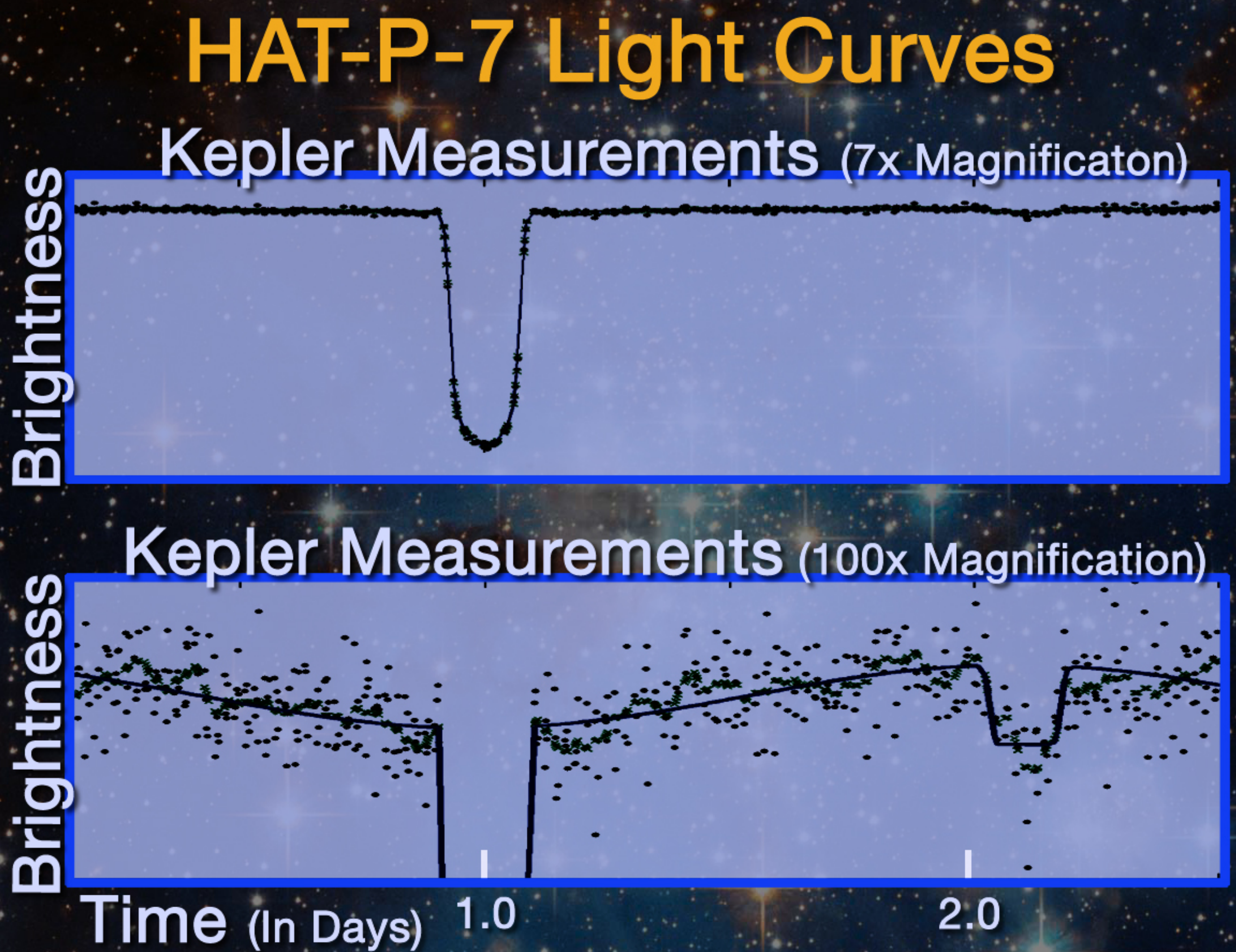
A Specialized Transit-Finding Satellite Launched in 2009 – The <u>Kepler Mission</u>

- Kepler monitored many tens of thousands of stars in the constellation Cygnus for transits, down to 14^{th} magnitude
- Discovered over 3,000 exoplanets, most of them “Super-Earths” between 1-2 Earth diameters.
- But, Kepler only studies stars in a small square in the constellation of Cygnus, not the entire sky
- And alas, In summer 2013 – **<u>Kepler died</u>**, victim of failed gyros.
- (Limited other observations still planned and possible, however, but not in Cygnus)

The Kepler Mission – Targeted on a corner of the constellation Cygnus



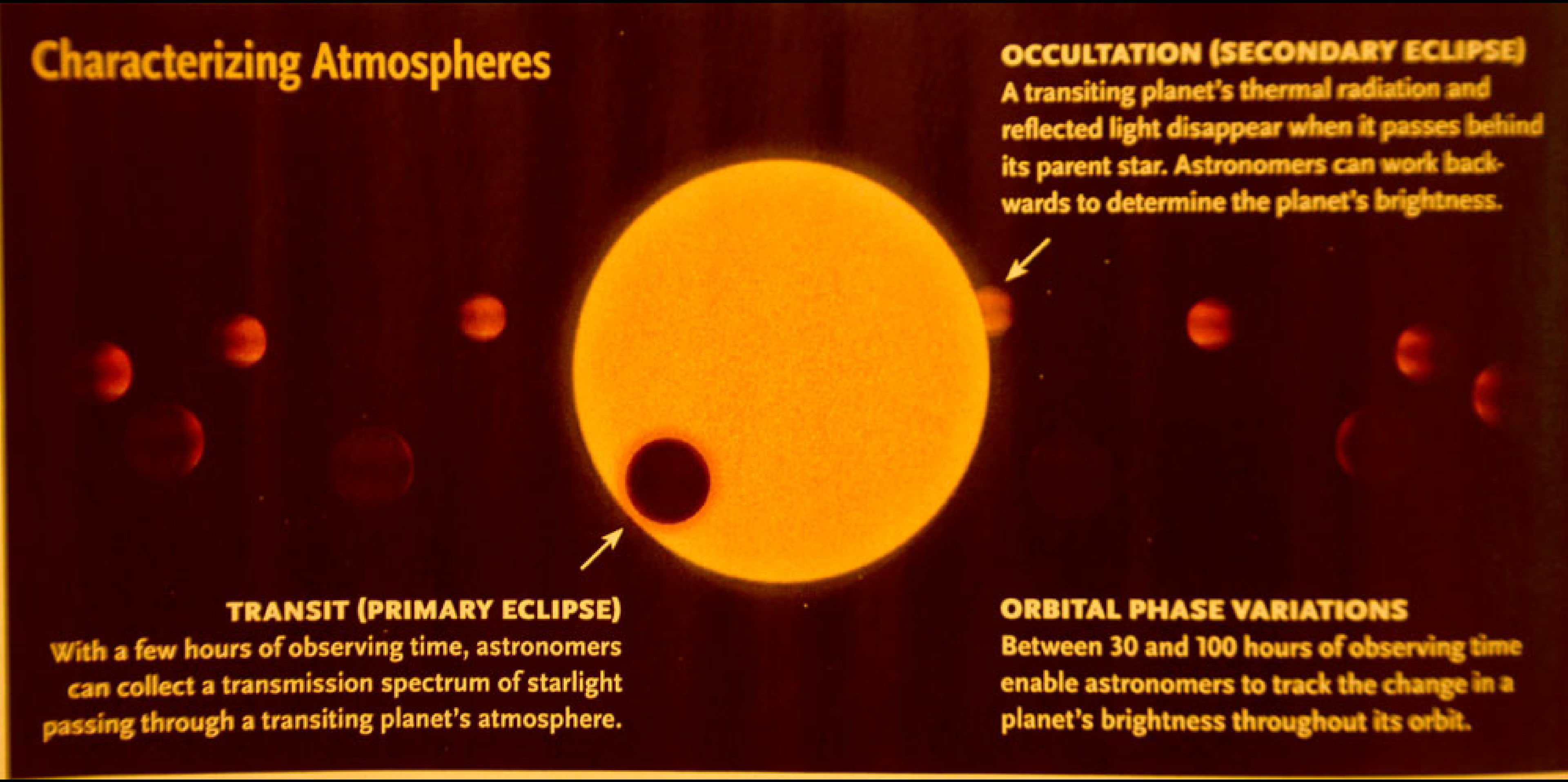
Compared to Ground Observations, Kepler Produces Beautifully Noise-free Light Curves



The Transit method provides crucial data not possible from Doppler

- The method is being pushed hard at this time – because it has one key advantage which other methods do not:
- **We get the *size of the planet*, since that's what determines the observed transit light loss**
- The **mass** of the planet then comes from Doppler Method measurements on parent star
- Combining these gives the **density** and, together with distance from the star and star luminosity, the approximate **chemical composition can be guessed**
- And, if we're lucky and careful, we can see absorption in the star's spectrum due to the planetary atmosphere's varying opacity at different wavelengths during the transit. This tells us directly what the planet's atmosphere is made of, via this "**transmission spectrum**" (more later on this)
- Over 4,200 possible transiting planets have now been found in Kepler data. 3,000 have been confirmed as of 2015

Transit Light Curve – What's Happening to Cause the Light Variations

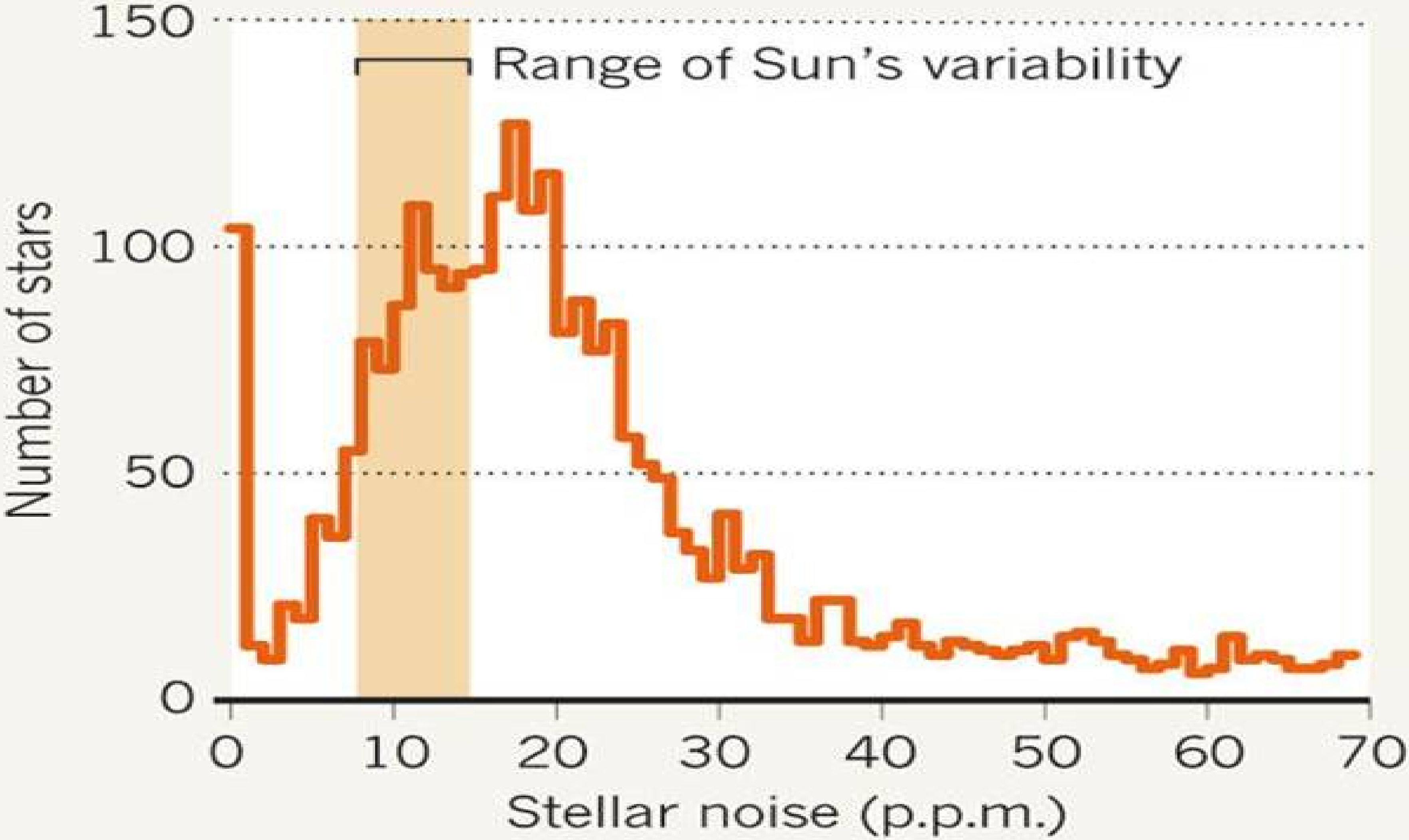


Some Kepler Findings…

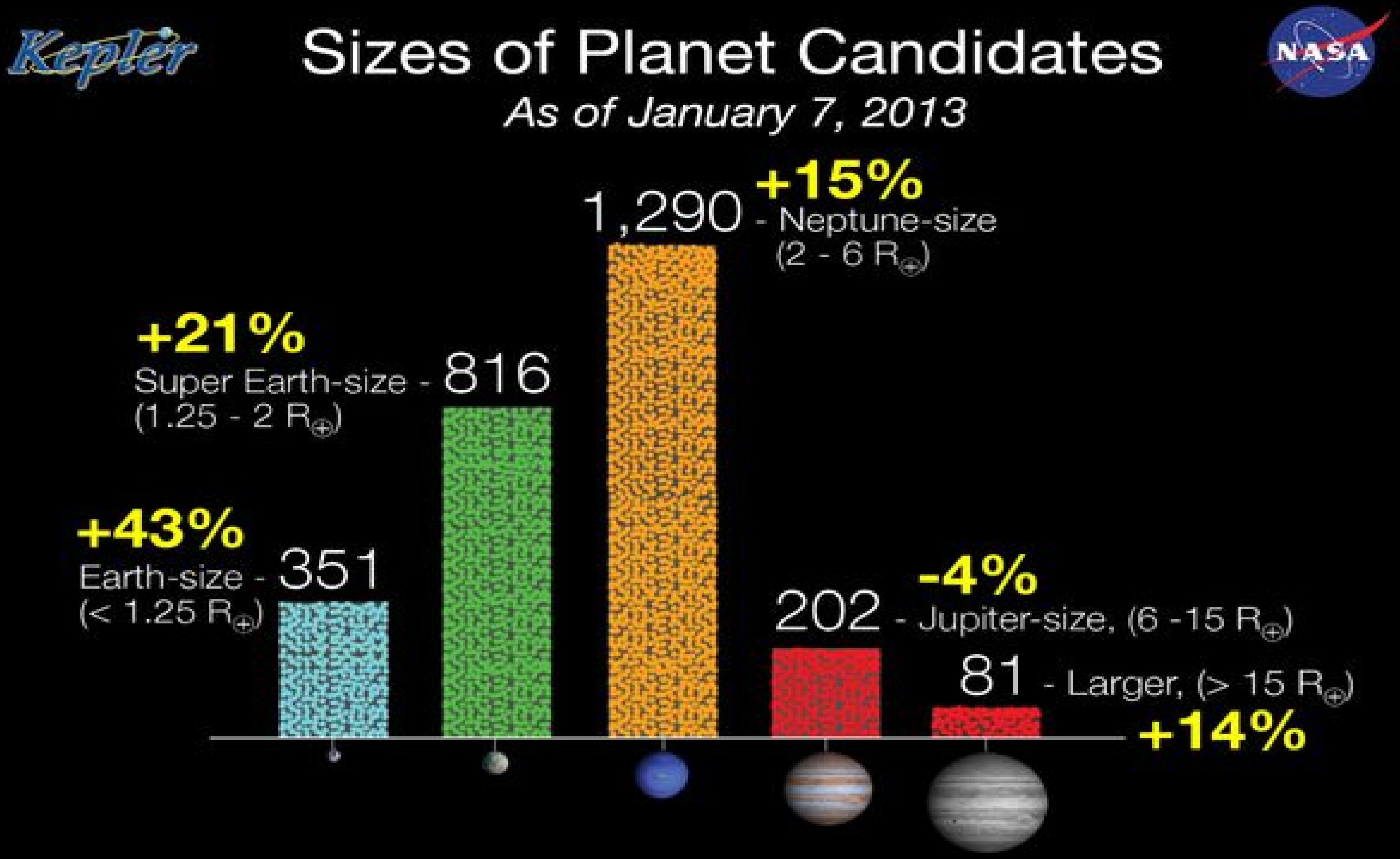
- First, that there is micro-level variations in stellar luminosities more commonly than we had guessed.
- This makes transits harder to detect, but good software, and humans (see "Citizen Science" Zooniverse website), have mostly overcome this.
- **Planets are common! Well over 90% of solar-type stars calculated to have planetary systems**
- Small planets are the most common, but very tough to pull out of the data because transit light loss is so tiny and the "twinkle" of other causes of light variation (pulsations, star spots, etc.) are possible.

TOO MUCH TWINKLE

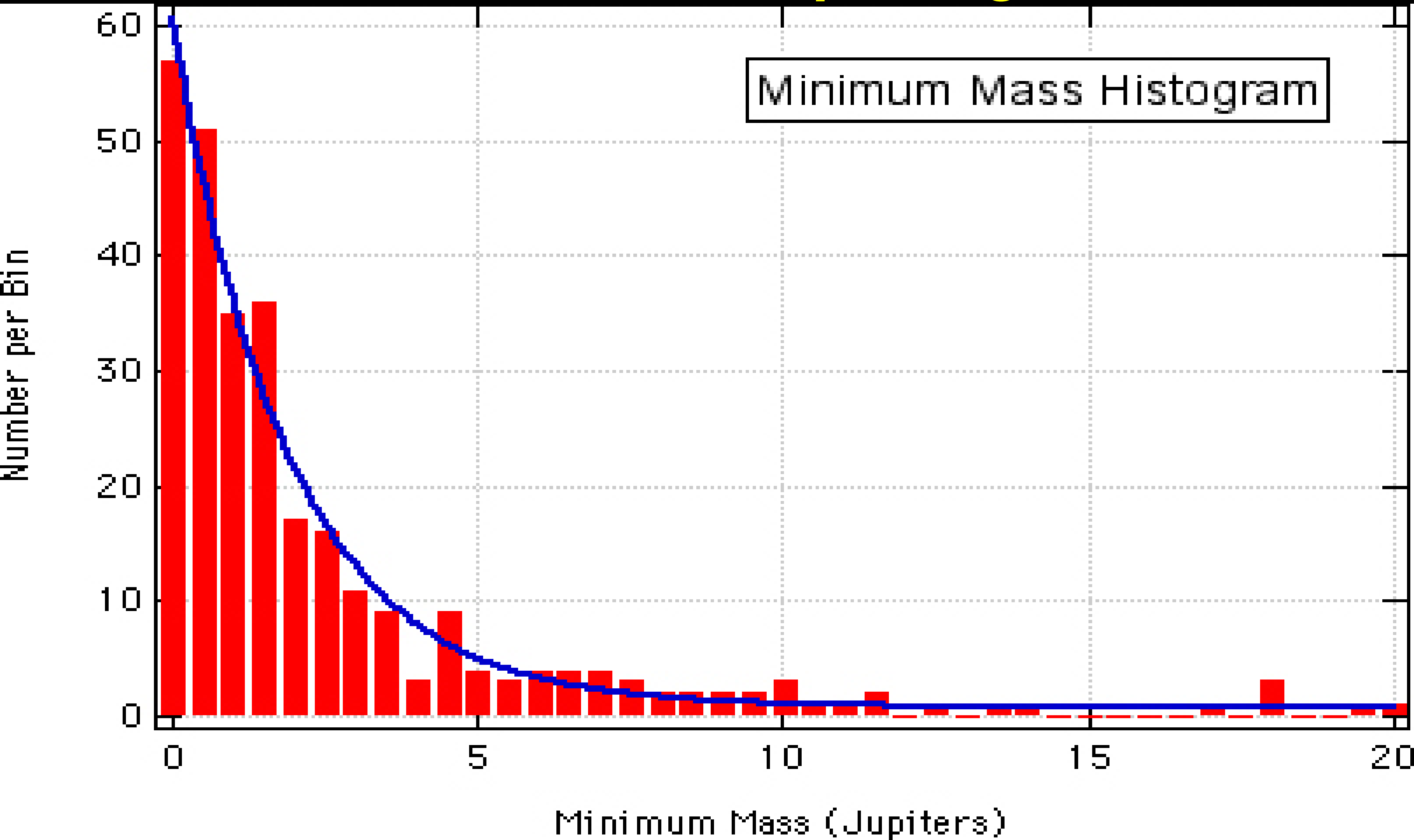
In a sample of 2,500 Sun-like stars monitored by the Kepler probe, most vary in brightness more than the Sun does, which makes planets harder to see.



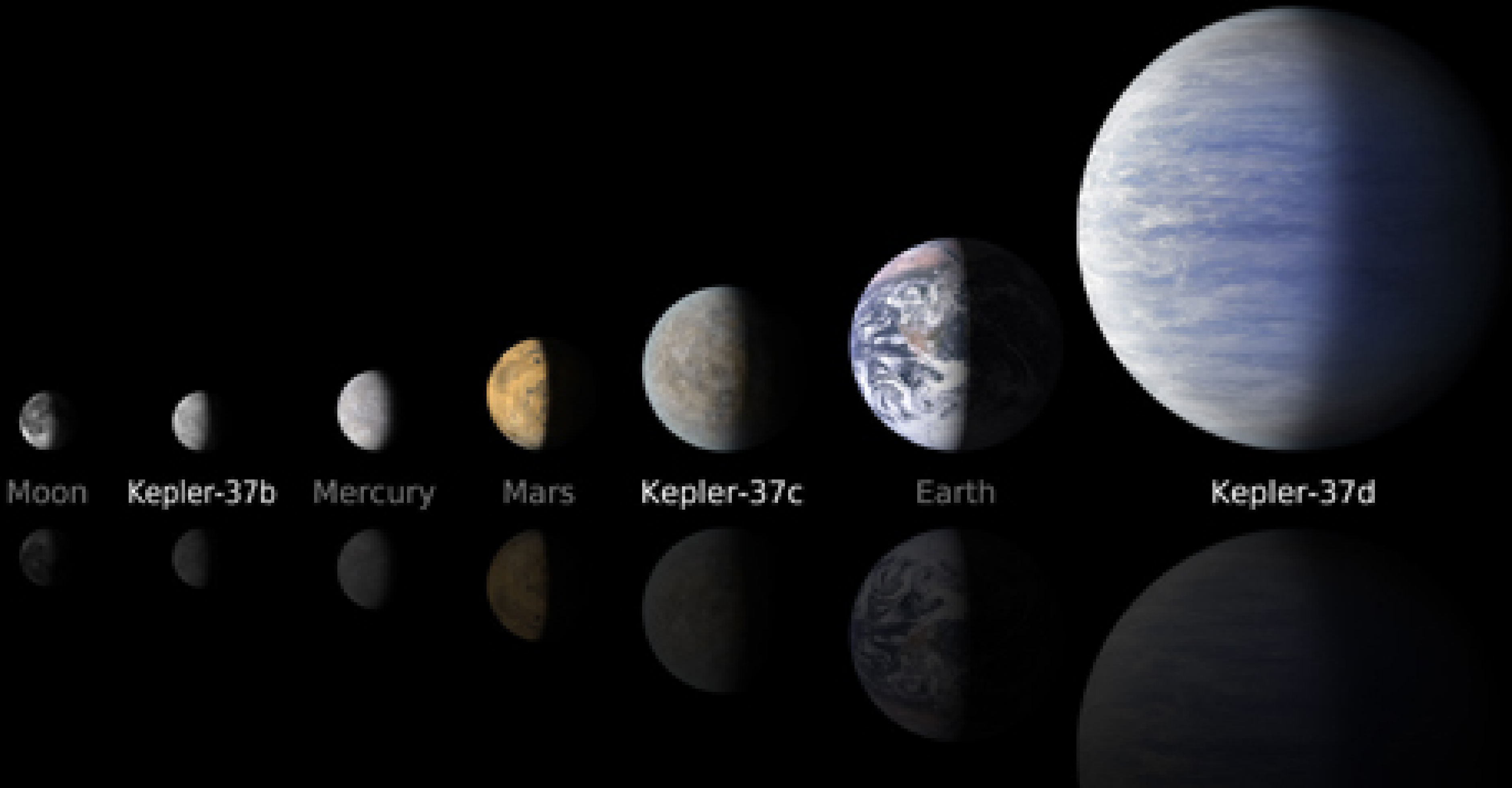
The Kepler Planets Discovered as of Jan '13 (but Biased by Selection Effects; Earth's are Hard to Detect)



Correcting for Observational Bias Shows Small Planets More Common Than Big Ones, Not Surprising



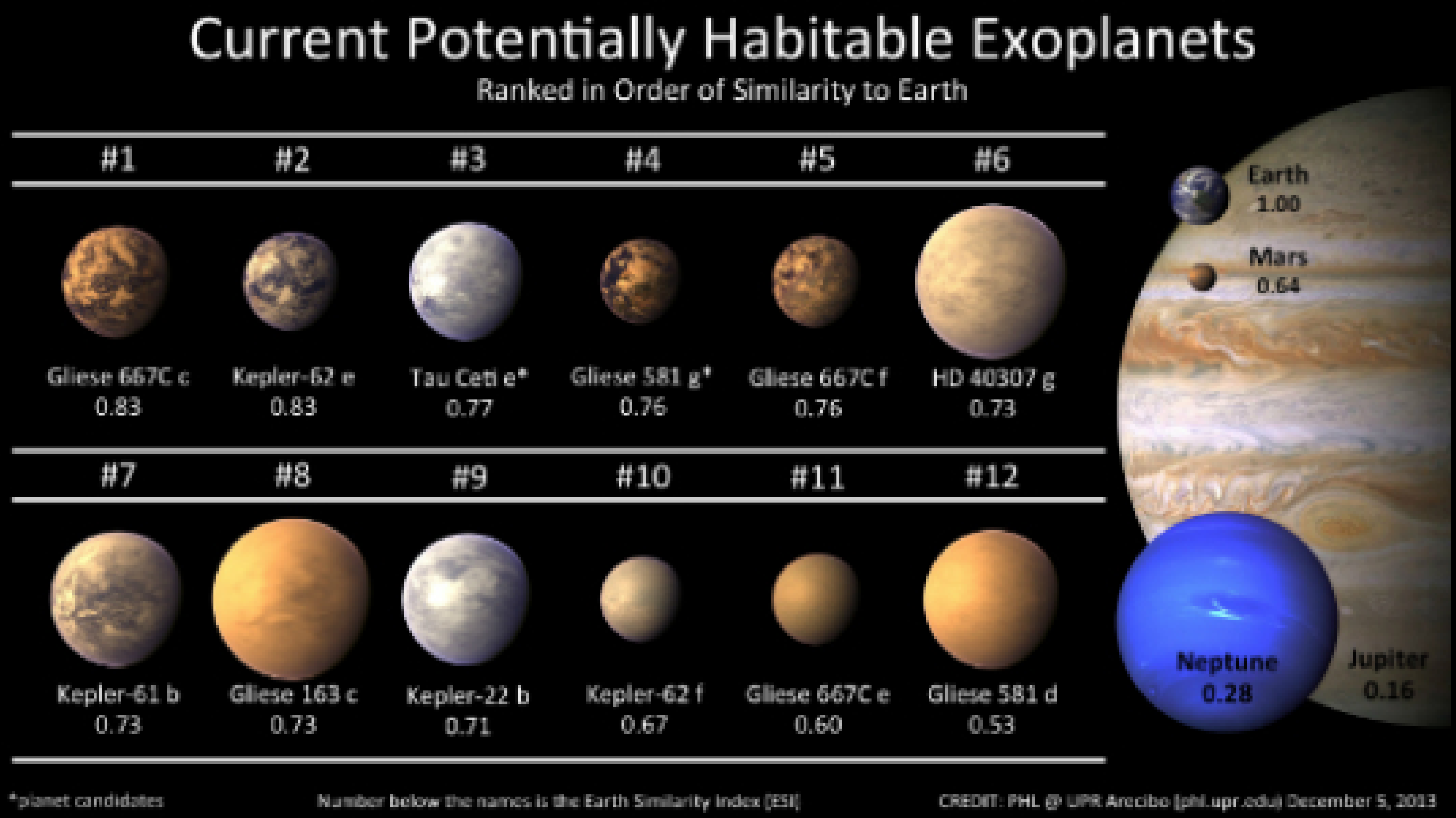
System= Kepler-37 Planets *vs.* Our Own Solar System’s Small Planets



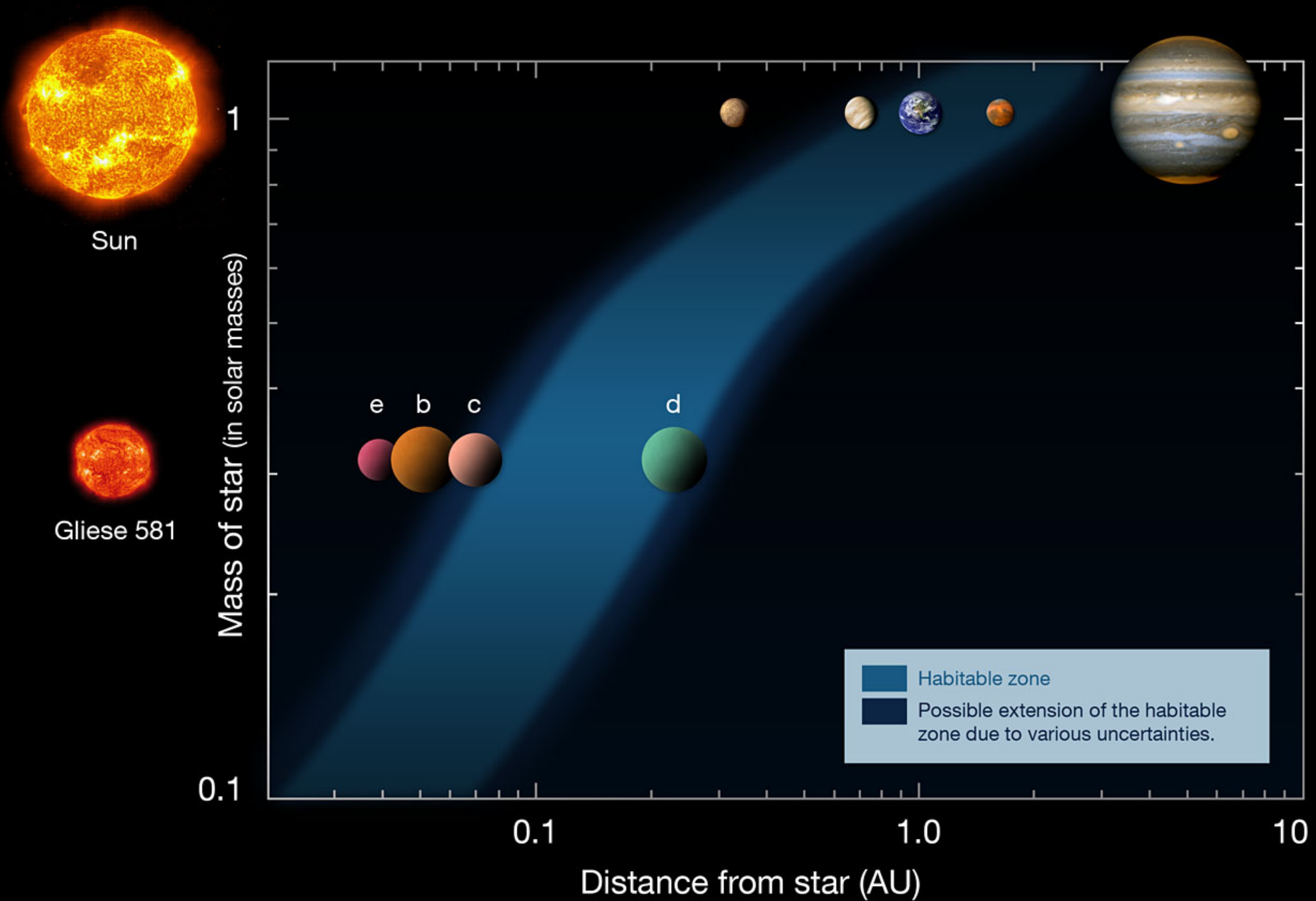
The Definition of the "Habitable Zone"

- **No, it doesn't mean there are probably civilizations here**
- And it doesn't even mean life is likely here
- The Habitable Zone is a distance range from the parent star such that the calculated equilibrium temperature here, for a planet**, can permit liquid water to exist <u>if other conditions are met.</u>**
- The existence of liquid water requires the right atmospheric composition and density and mild orbit parameters. If liquid water exists in enough abundance and permanence, some sort of life may well be possible. Intelligent life requires far more special conditions than just liquid water (see Ch 24)

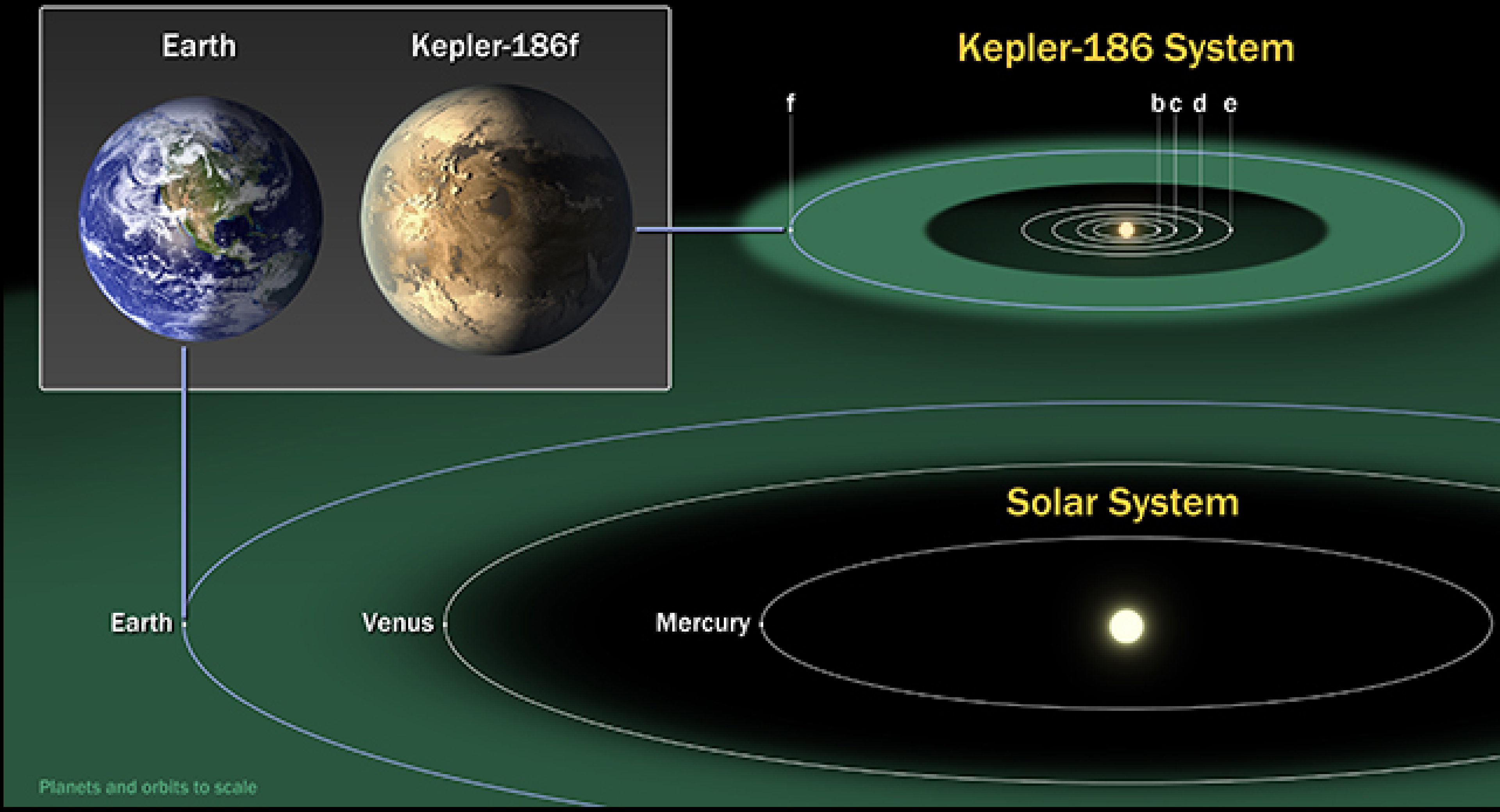
No True Earth's, but Some SuperEarth's in Roughly Habitable Zone



The Habitable Zone: Solar System *vs.* Gliese 581 System



Kepler 186f: Closest Earth Analog So Far?



Kepler 186f: What Do We Know?

- First Earth-sized planet in habitable zone, but…
- Orbits a red dwarf (often have strong UV flares)
- Orbit has ~50% odds of being tidally locked (day=year). Even if not, daytime likely is months long – not good for good climate, or life
- Mass unknown and unmeasurable (~0.3-3.8$M_{\mathbf{earth}}$)?,
- Atmosphere unknown and unmeasurable. If 0.5 to 5 bars of CO_2, Greenhouse could warm it enough for liquid water
- Orbit circular, that's good – but SETI has listened since Apr. '14 – no intelligent signals

The Kepler Solar Systems

- In animation…
- The Kepler Orrery III
- The Kepler Orrery for compact solar systems
- UCSC PhD Natalie Batahla's 90 min lecture with visuals "Finding the Next Earth". (Oct '12)

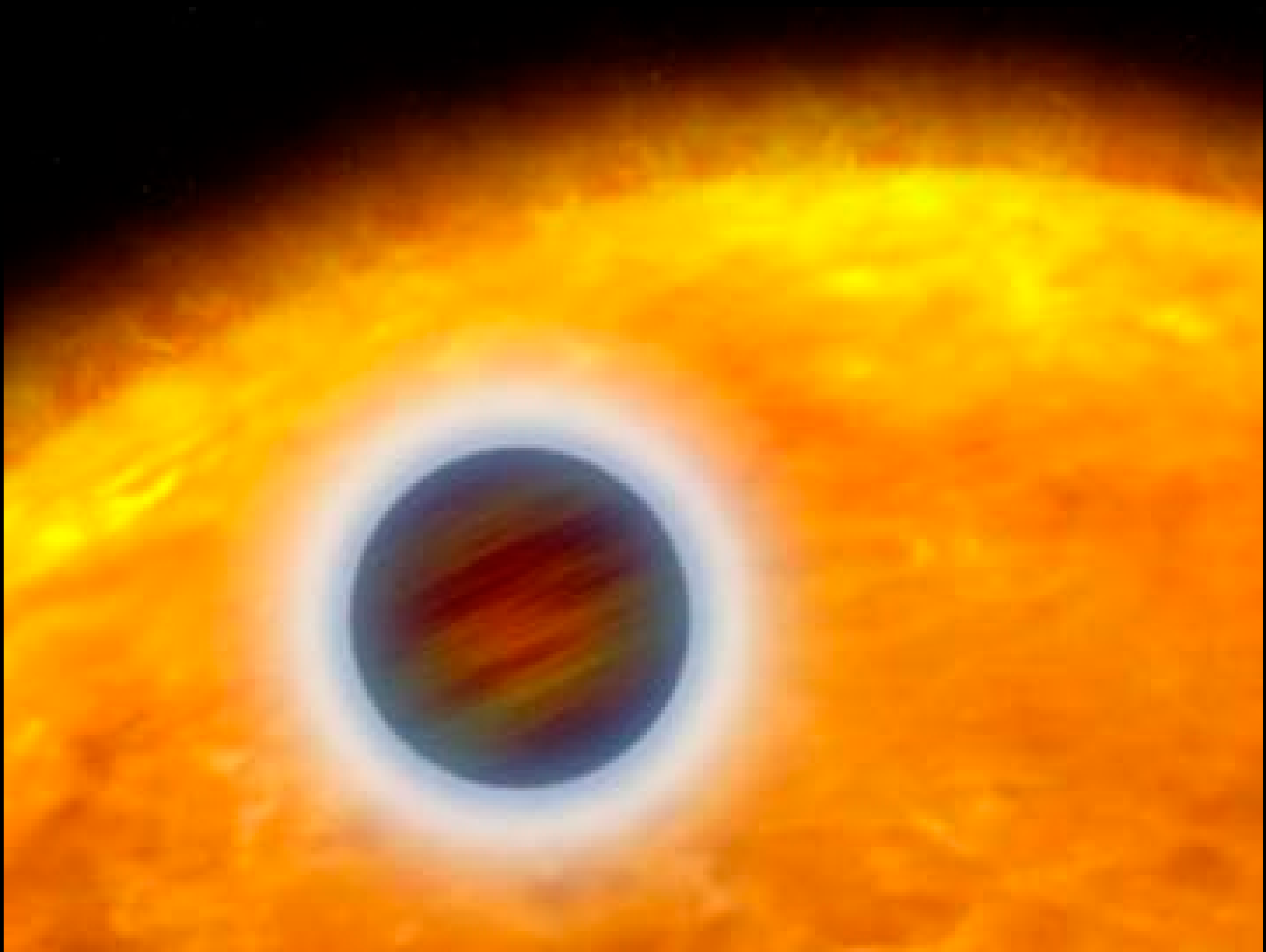
Key Kepler Findings as of 2013

- ~20% of all stars have Earth-sized planets
- Small planets (rocky?) are equally common around both small dim and large luminous stars
- **Almost all stars (at least ~90%) have planets!**
- 43% of Kepler planets have other planet(s) in the same system (which is NOT saying that 43% of all stars have multiple planets)

How to Discover and Characterize the Atmospheres and Climate of Exoplanets?

- During a transit, some of the light of the parent star is filtering through the atmosphere of the planet before making it into our telescopes.
- Measuring the depth of the transit light loss in narrow molecular absorption wavelength bands results in a low-resolution spectrum of the outer atmosphere of the exoplanet…
- …this is a "**<u>transmission spectrum</u>**"
- But this amount of filtered light is TINY!
- We have a few detections now – like Carbon monoxide and water detected in HR 8799's planet's atmosphere

Transmission spectra - tough, but can tell us the atmospheric composition if lucky



Transmission spectra via Transit Depth - Explained

- NASA – "**Alien Atmospheres**" (3:22)
- How the transit's diameter is larger when observing at wavelengths where the atmosphere is more opaque – visualization (0:11)
- Example; if the atmosphere has a lot of CO2, then if you observe the transit in the absorption band wavelength of CO2, the planet will look bigger (as big as the planet+CO2 atmosphere) and the transit light depth will therefore be deeper

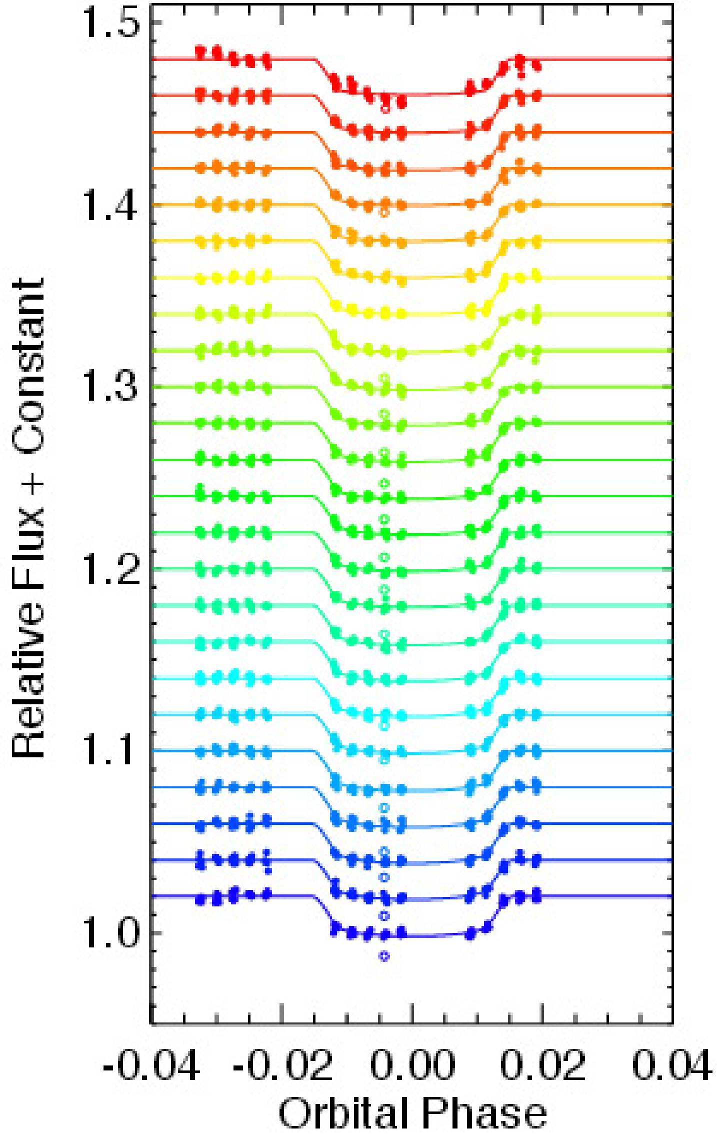
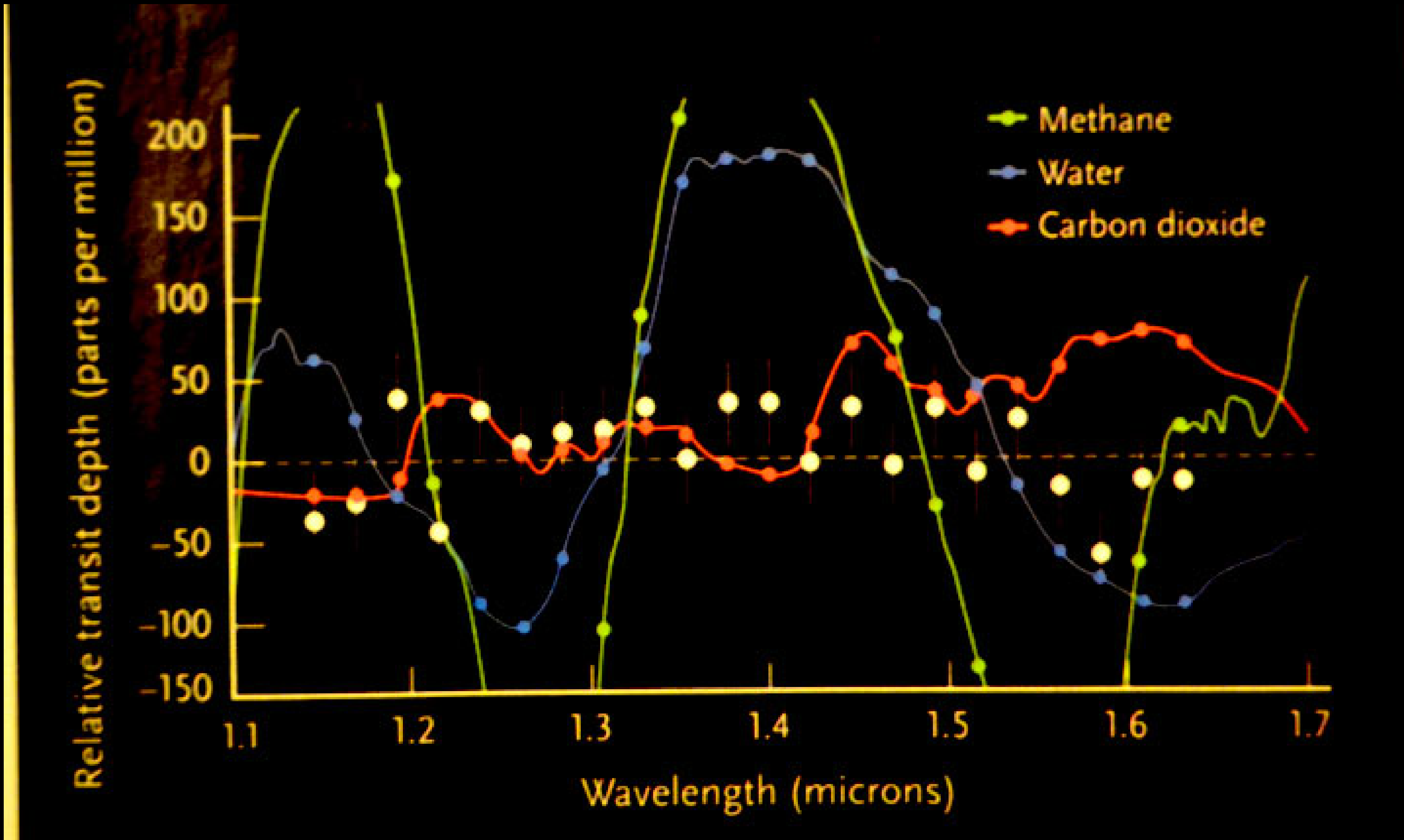


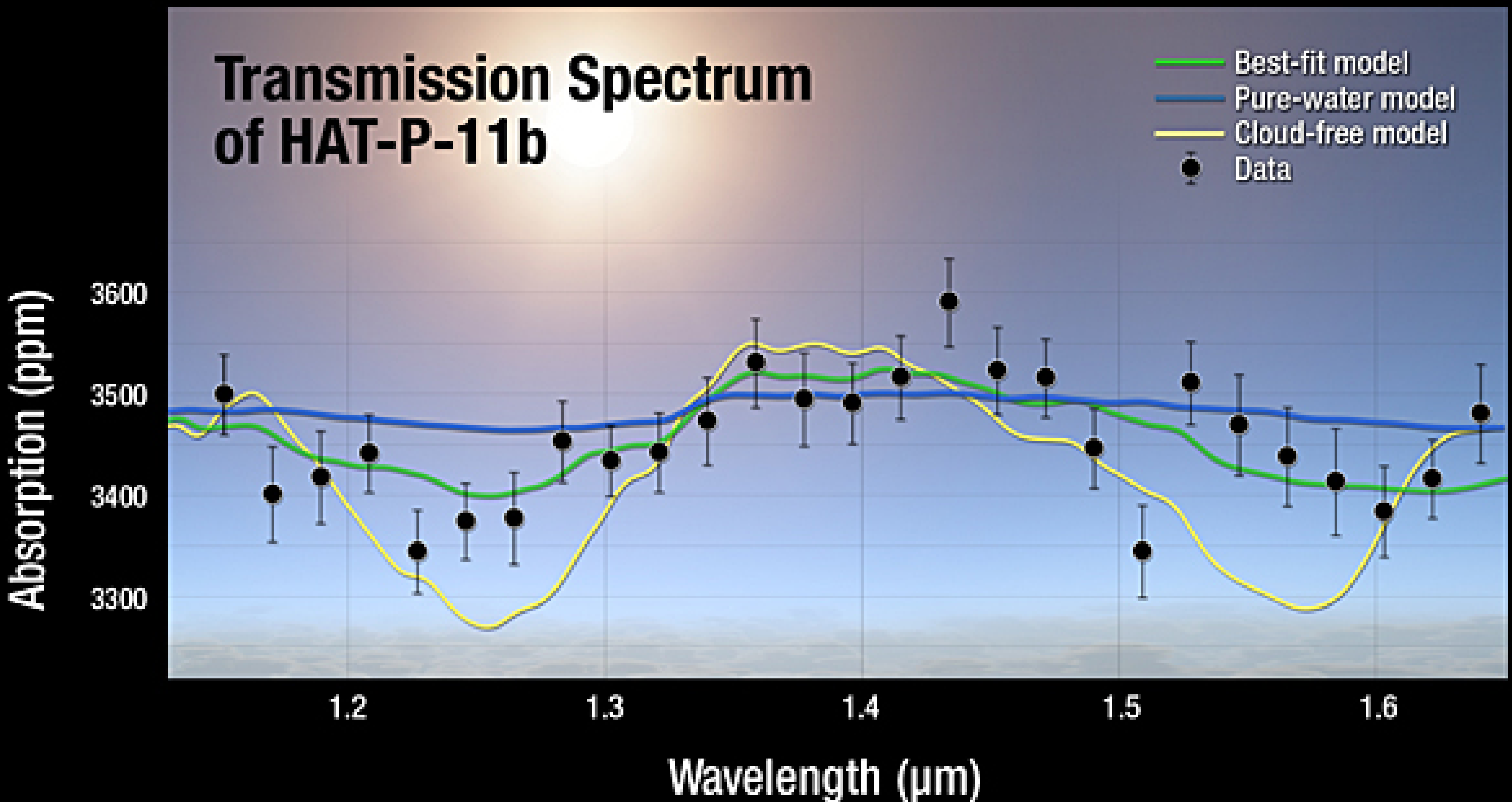
FIG. 3.— Transit model fit to each spectral bin. The systematics are removed from the data (round points with error bars). The solid curves are the best fit light curve models for each bin. Transit eclipse depths for the shorter wavelengths are denoted by blue near the bottom and the longer wavelengths are shown in red near the top. The hollow circles are the outlier point that we exclude from the fits.

- Different transit depth at different wavelengths (colors) allows making a “transmission spectrum”;
- This tells us what is the atmosphere’s opacity at those wavelengths, and comparing to molecular absorption bands, what the atmosphere’s chemical mix is.

Even better, with a bright enough star…by taking the known spectral signatures of common molecules, and fitting them to an observed transmission spectrum, you can find roughly how much of each there is in the atmosphere



Water vapor discovered in exo-planet HAT-P-11b atmosphere



High Clouds are Apparently Common on Hot Jupiters

- A recent example – exoplanet HAT-P-12b has had a **transmission spectrum** taken by the Hubble Space Telescope (**Line *et al.* 2013**)
- Shows that this is planet does not have a hydrogen-dominated outer atmosphere, but instead likely dominated by high clouds.
- This and other data suggest high clouds may be common in “Hot Jupiters”.
- On Earth, high clouds enhance the greenhouse effect. Is this true on exoplanets heated already by proximity to the sun? Not enough known about the clouds to say much as yet.

Exoplanet Atmospheres - Observations

- 79] Water vapor, sodium vapor, methane, and carbon dioxide have been detected in the atmospheres of various exoplanets in this way.[80][81] The technique might conceivably discover atmospheric characteristics that suggest the presence of life on an exoplanet, but no such discovery has yet been made.
- **Seeing both free oxygen and methane in an atmosphere is a sure-fire giveaway for the existence of plant life!**
- Another line of information about exoplanetary atmospheres comes from observations of orbital phase functions. Extrasolar planets have phases similar to the phases of the Moon. By observing the exact variation of brightness with phase, astronomers can calculate particle sizes in the atmospheres of planets because this affects their reflectivity.
- Stellar light is polarized by atmospheric molecules; this could be detected with a polarimeter. So far, only one planet has been detected and studied by polarimetry.
- **This research is very much in its infancy! We've barely begun. But here's a couple of papers….**

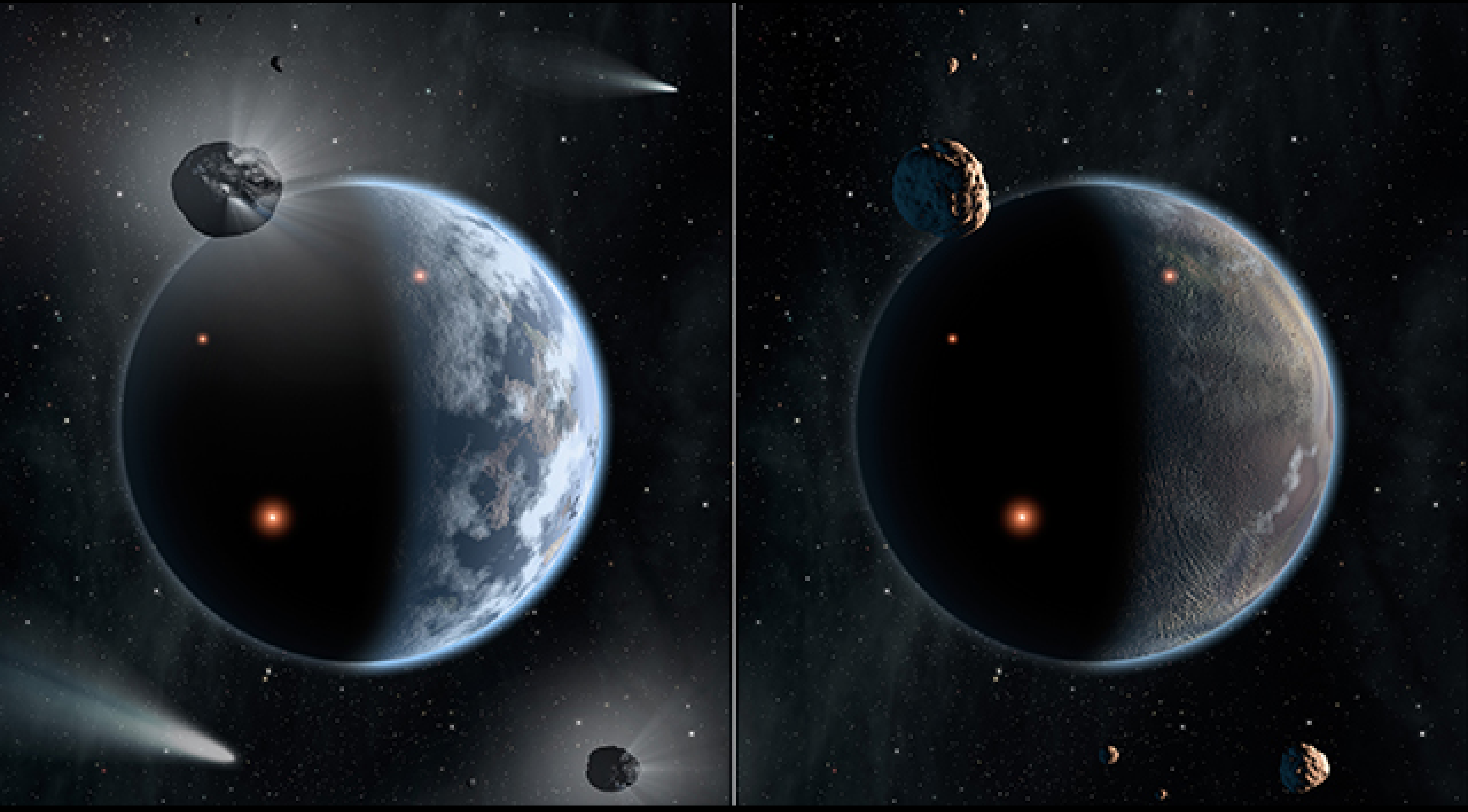
Infrared Light from Hot Jupiters Directly Detected in Favorable Cases

- Detecting the IR tells you the temperature of the planet directly, and as the planet spins…
- …This allows a crude estimate of how the day / night temperature differs on such a planet, as “Hot Jupiters” are expected by elementary physics to be tidally locked with their parent star
- http://arxiv.org/abs/0705.0993

Carbon Monoxide Discovered in Tau Bootis b

- High resolution spectroscopy of the planet orbiting the bright star Tau Bootis has detected CO.
- Carbon Monoxide happens to have a very easily measured spectral signature, among molecules.
- http://arxiv.org/abs/1206.6109

Solar Systems Too Rich in Carbon Won't have Oceans, Says New Study in '13



We on Earth were lucky!

- Oxygen would rather bind to carbon (CO_2) than to hydrogen (H_2O), if possible.
- Excess carbon will grab the oxygen and lock it into CO and CO_2, or in crystalline form as diamond if mass is high enough. That leaves no oxygen left to bind with hydrogen and make **water**
- Bummer. But, our own solar nebula happened to be low (but not too low) in carbon, hence we have an ocean-dominated and so climate stable planet, and life. We were lucky!
- You want carbon for life, but just some, not a lot. Too much and it'll tie up all the oxygen and you'll have no water for oceans.
- This is yet another argument that planets which are favorable for 4 billion years of life are rare – you need just the right amount of carbon: too little or too much, and you cannot have a living planet

Here are orbital configurations which are more likely to lead to long-term stable climates favorable to Life

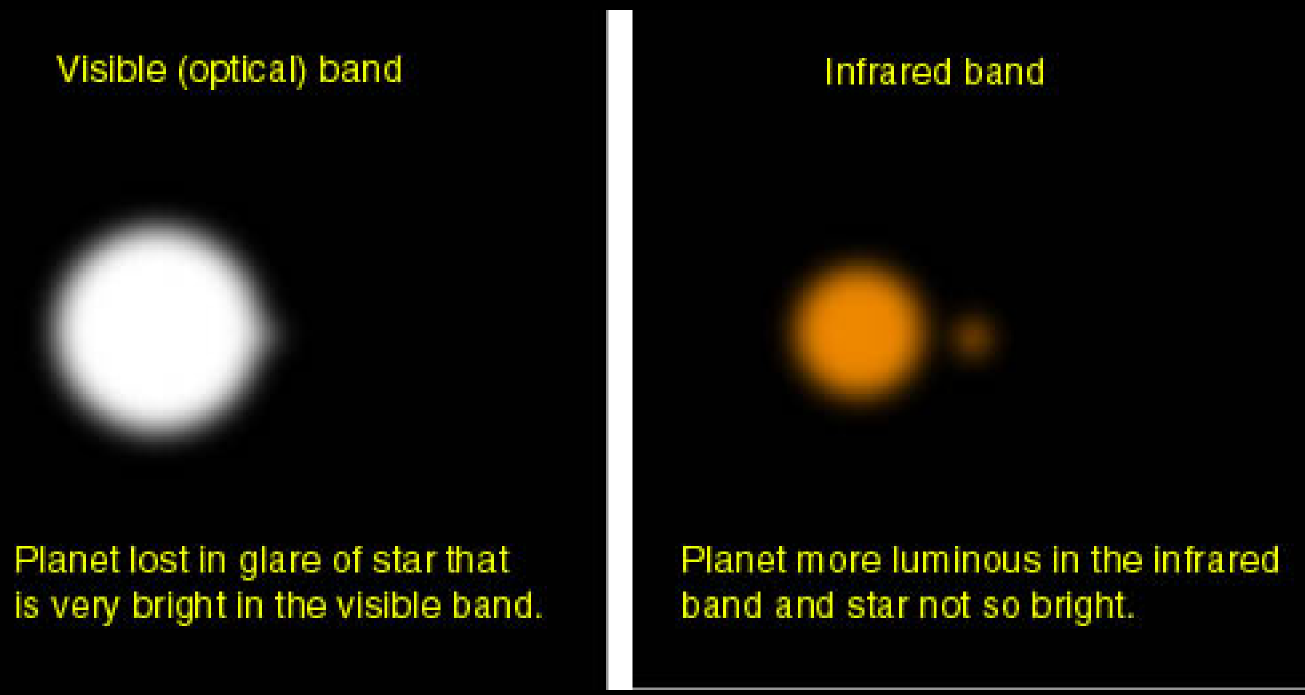
- Near circular orbits, so heat from star stays about the same during their "year"
- No "hot Jupiters"; They'd have migrated from far to near, wrecking orbits along the way and therefore wrecking their climates
- That means need to have ~no planet migrations for most of mid/late history of the system.
- A rapid spin rate would help too – leveling out the day/night temperature range and leading to milder winds

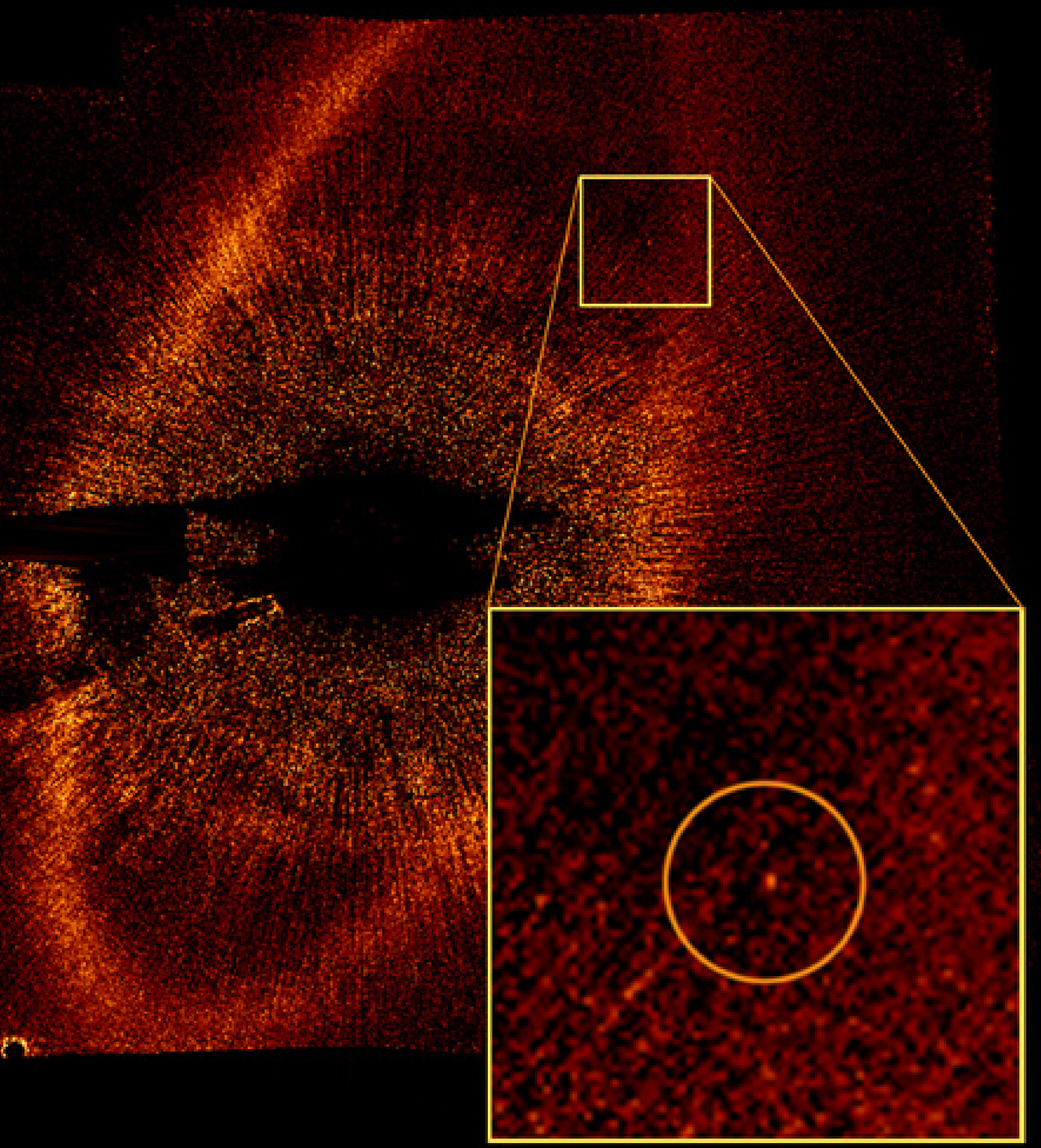
In the year – 2008…

- ***The first image of planets around another star…. !***

- ***But this is by far the least likely way to find planets.***
- ***Stars are BRIGHT and planets are DIM and too CLOSE, for the most part***

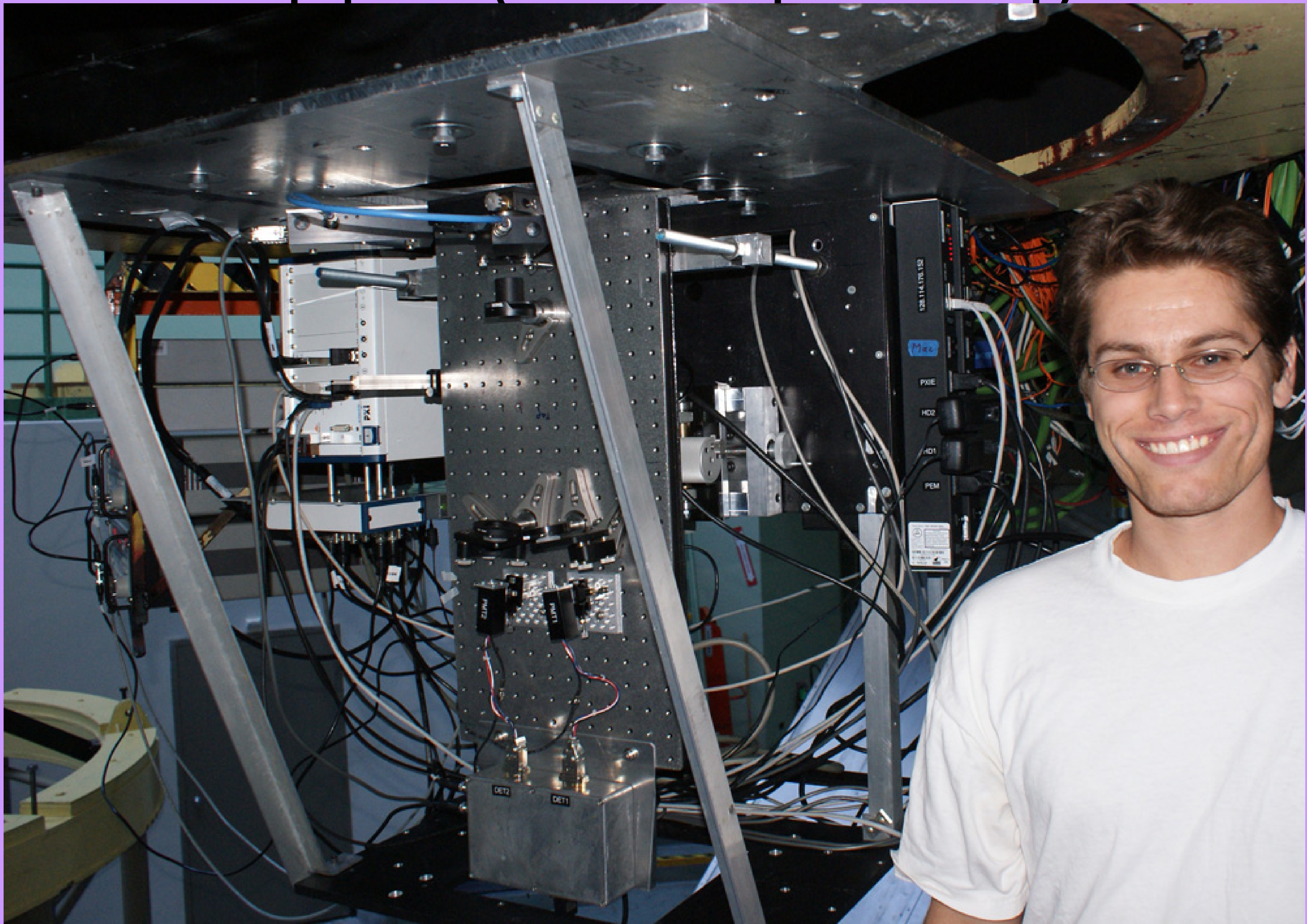
Much easier to see planets (but still very tough) in the infrared, where planet puts out ~all of its light



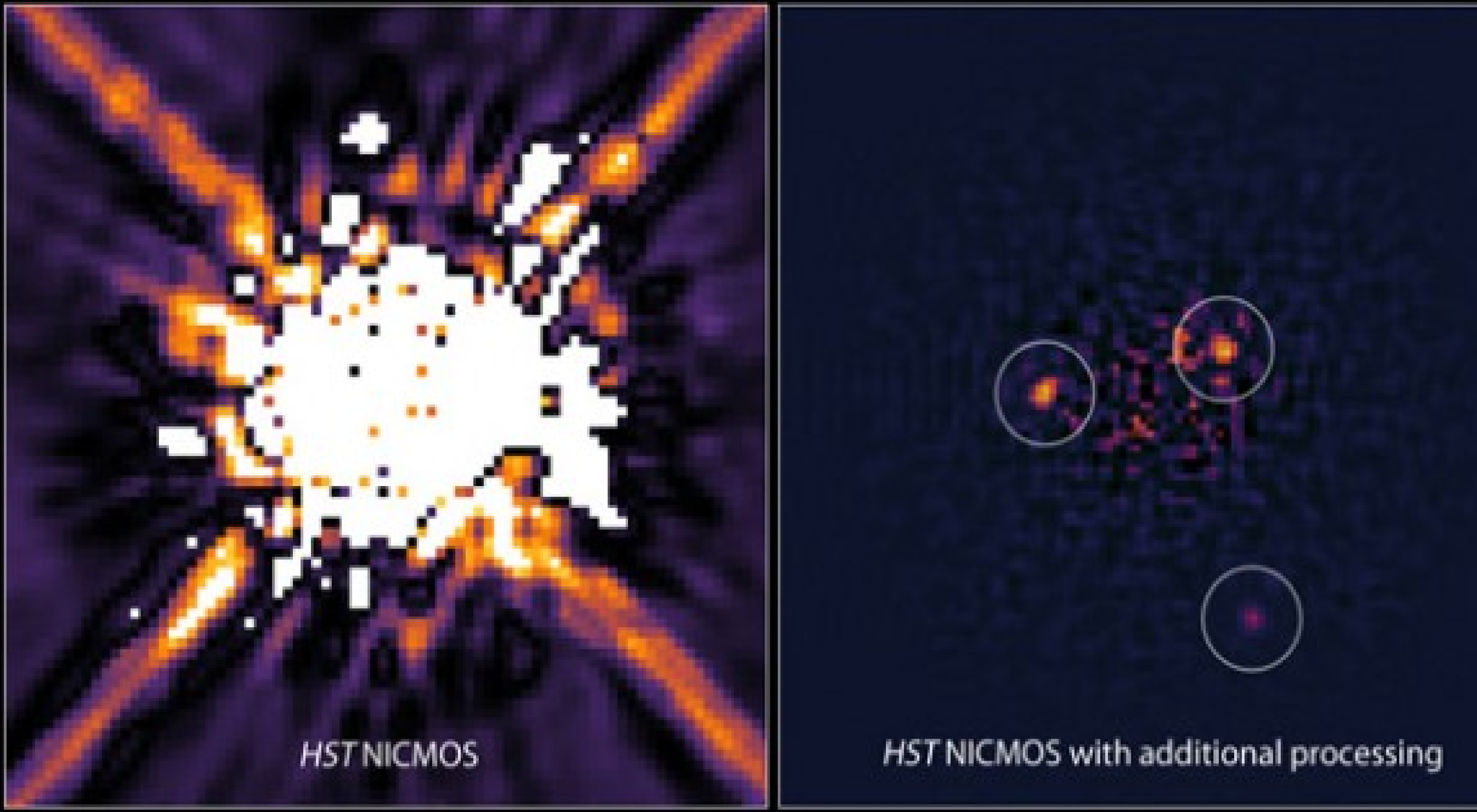


- This particular speck was NOT digital noise; it followed the laws of gravity, and so must be a planet!

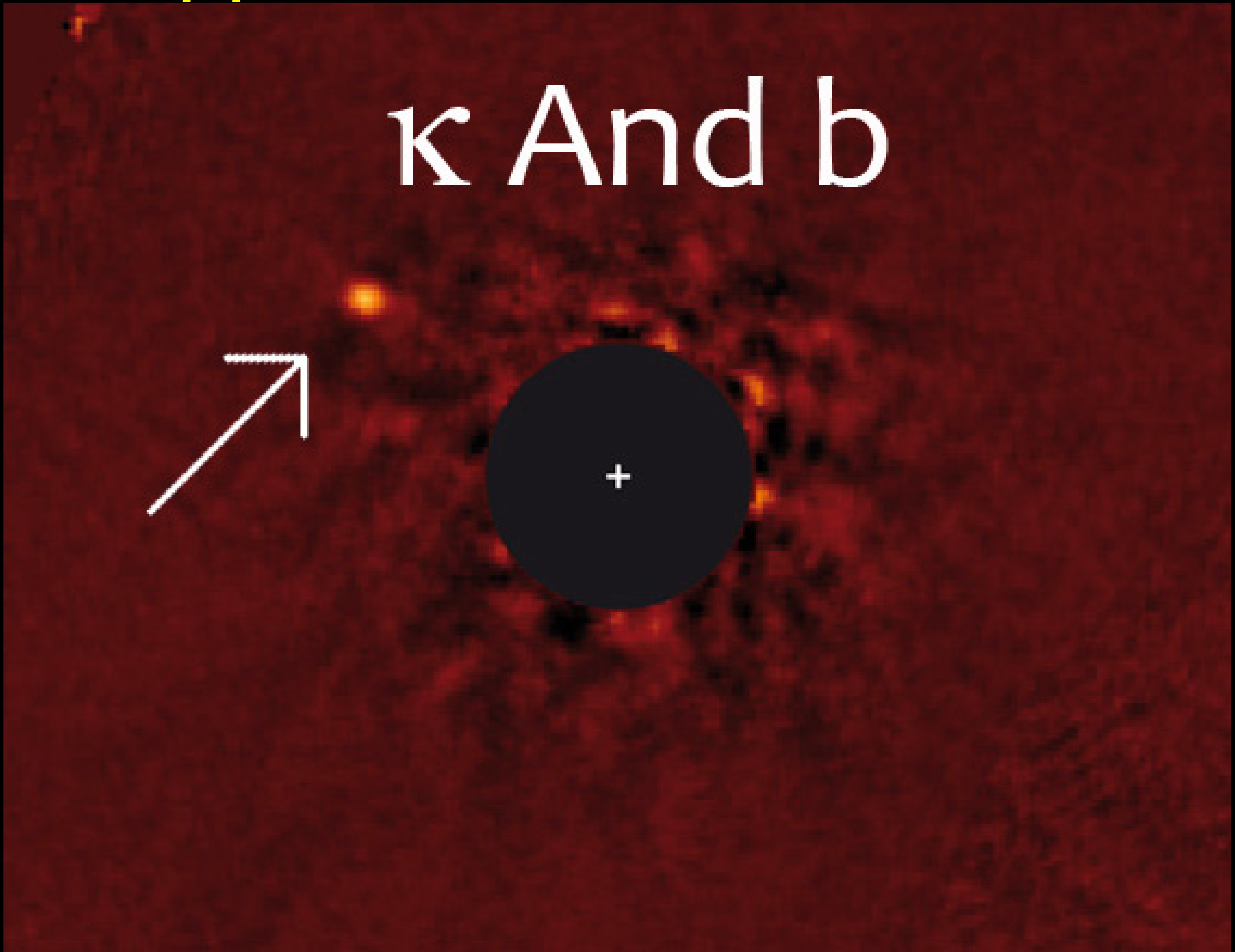
Young CalTech Astronomer and spectrograph equipment (Caltech Exoplanet Group)



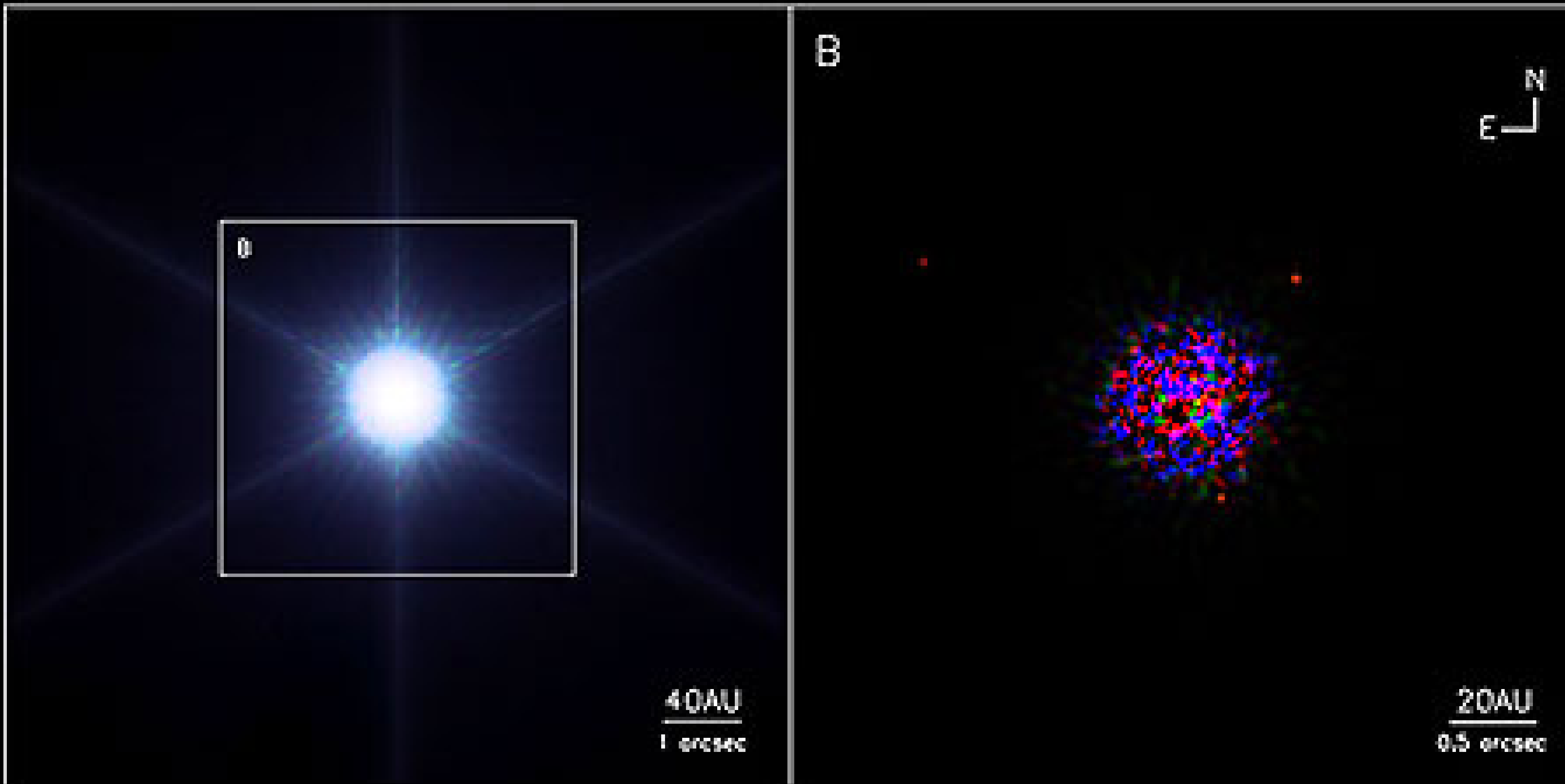
Lots of image processing needed to pull out the Planet from the image moise



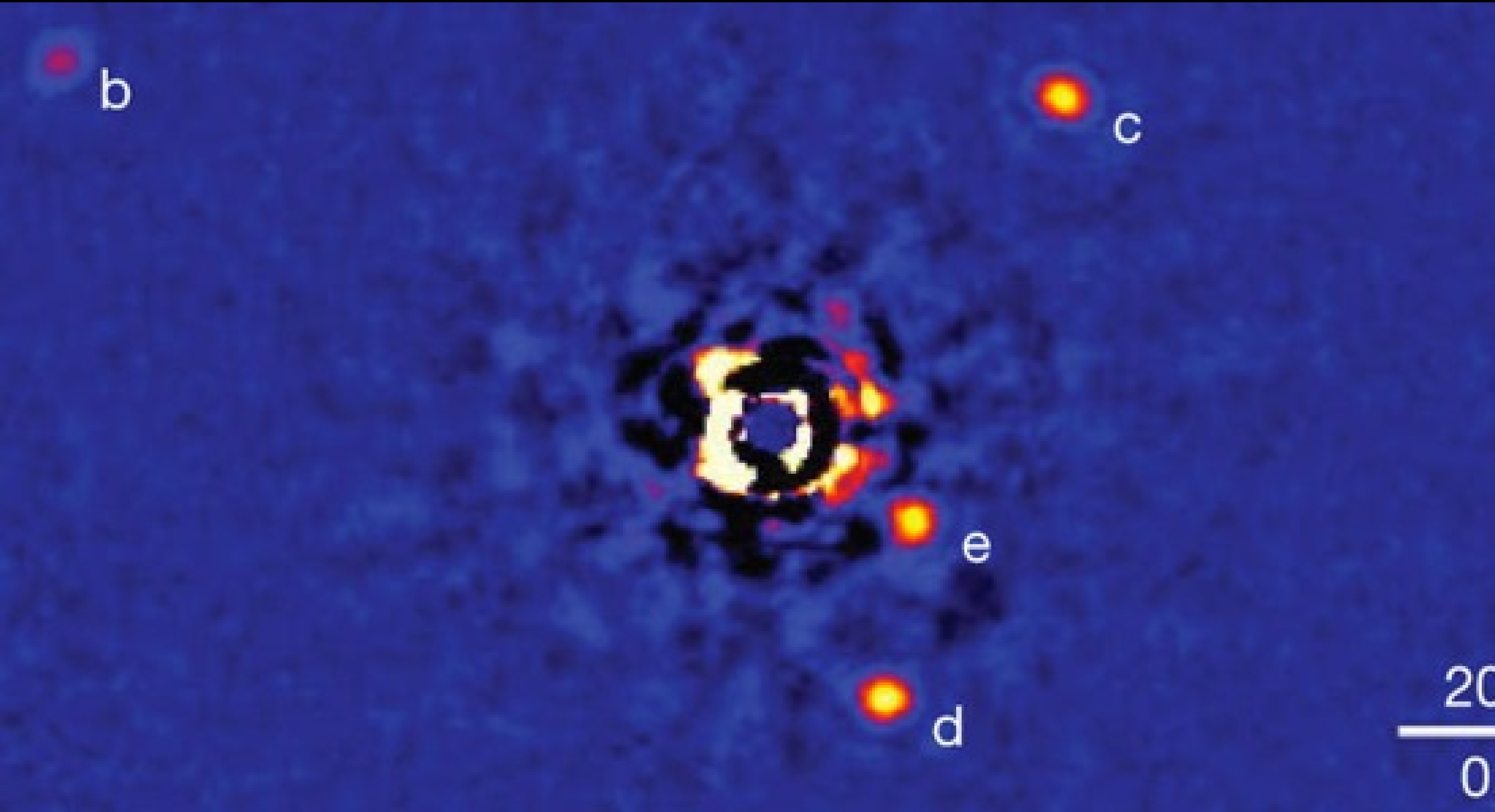
Kappa Andromedae's Planet



HR 8799 Planetary System



20 AU Is About the Size of Neptune's Orbit, So These are Distant, Cold Exoplanets



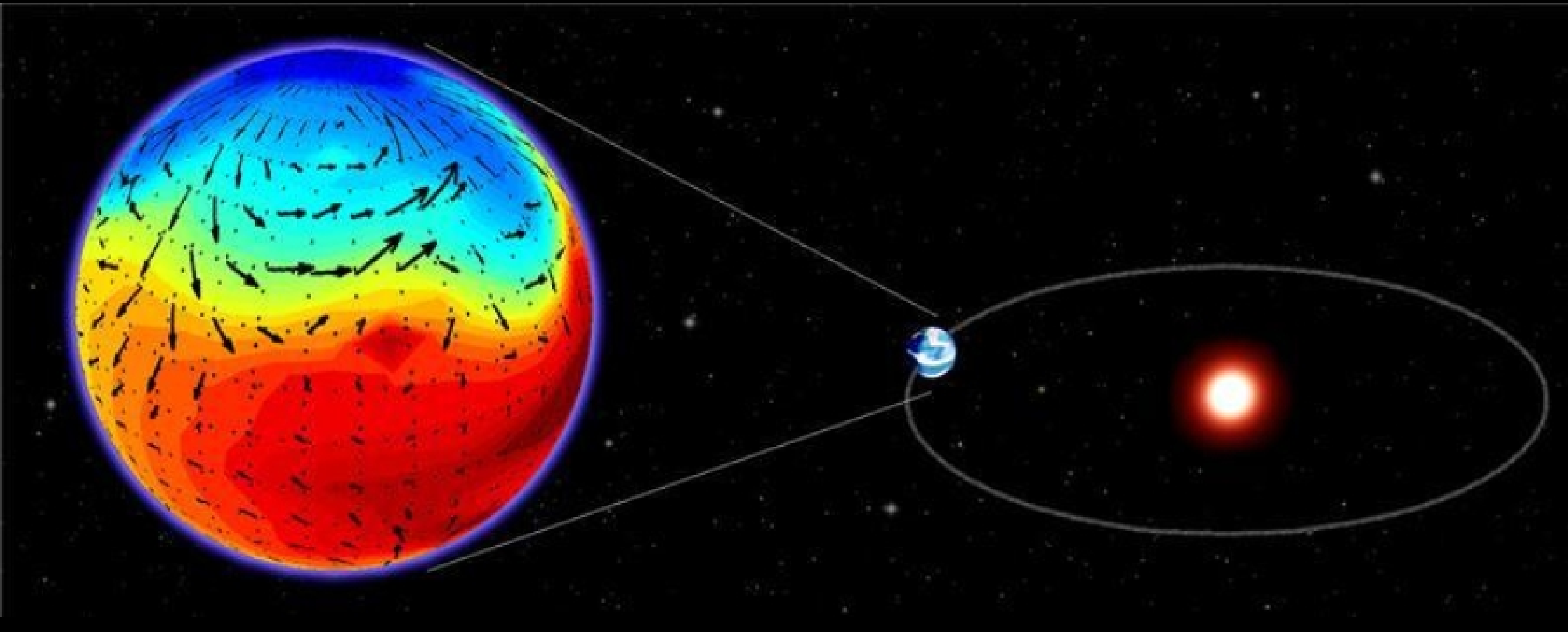
Other Niche Methods of Discovering Exo-Planets

- **Astrometry**: See the wobble on the sky plane of a star as it is tugged by the planet. Easiest for BIG orbits, complements the transit and Doppler methods which favor discovery of SMALL orbits. GAIA Mission should discover thousands, beginning soon!
- **Polarimetry:** Light reflected off planetary atmospheres will be polarized. Sensitive polarimetery might detect this. So far, only a couple of post-detections of already-known exoplanets, no discoveries.
- **Gravitational Micro-Lensing:** Seeing distant background star momentarily brighten as planet focuses that light. Hundreds(?) of detections, but occurances are random and so no constraints or follow-up possible, so doesn't teach us much.

Kepler discovers: Red dwarfs have planets too

- They're the most common of all stars, so planets common too.
- But Red Dwarfs are so cool and so dim, planets in the "habitable zone" need to be so close to stay warm, that tidal stretching would grab hold of the planet's rotation and halt it – i.e "**Tidally Locked**"
- Sunny side would be permanently hot and sunny, night side cold and permanently night
- Tough on climate!!

Tidally locked planets close to star, will show HIGH WINDS driven by strong day/night temperature gradient



Could They Support Life?

- A narrow zone permanently at sunset or sunrise <u>might</u> be the right temperature…
- But high winds would transfer heat from the hot to cold side by rising heated air on the sunny side moving to cold side, and cooling would make it denser, falling, and moving back to the sunny side
- Maybe some life could happen, but it would have to survive in **hurricane speed winds, likely hundreds of km/hr**

Key Points – A7 Chap 13: Exo-Planets

- Doppler method tells you the MASS of the planet and DISTANCE from star
- Only **transits can give you the size, and density of exoplanets**
- Direct imaging – very tough; only a handful of discoveries
- **Depth of transit in different absorption line wavelengths ("transmission spectra") tells us roughly the composition of the atmosphere**
- **Infrared light variations during orbit can tell us the temperature of the planet, by thermal radiation laws**
- Data implies **90% or more of all solar-type stars have solar systems**
- Most planets in **fairly elliptical orbits**, most likely caused by orbital **migration.**
- **Stars with solar systems are very preferentially those with higher metallicity (i.e. made from proto-stellar clouds with enhanced dust)**
- Most easily detected planets are "hot Jupiters" which have migrated in from their formation point, and ruined habitable planets in doing so, but most common are small planets, after correcting for observational bias.
- **The Habitable Zone: where it is possible for liquid water, if the atmosphere chemistry is right.**
- **Planetary migration appears very common**. Our solar system unusual in not having much migration
- **Red Dwarf "hab zone" planets would be tidally locked, likely have very strong winds driven by the temperature difference**
- No observable detailed climate around exoplanets yet, only rough estimates of temps and a few molecules (water, CO) detected.
- No TRULY Earth-like planets yet discovered out of the ~3000 detections.