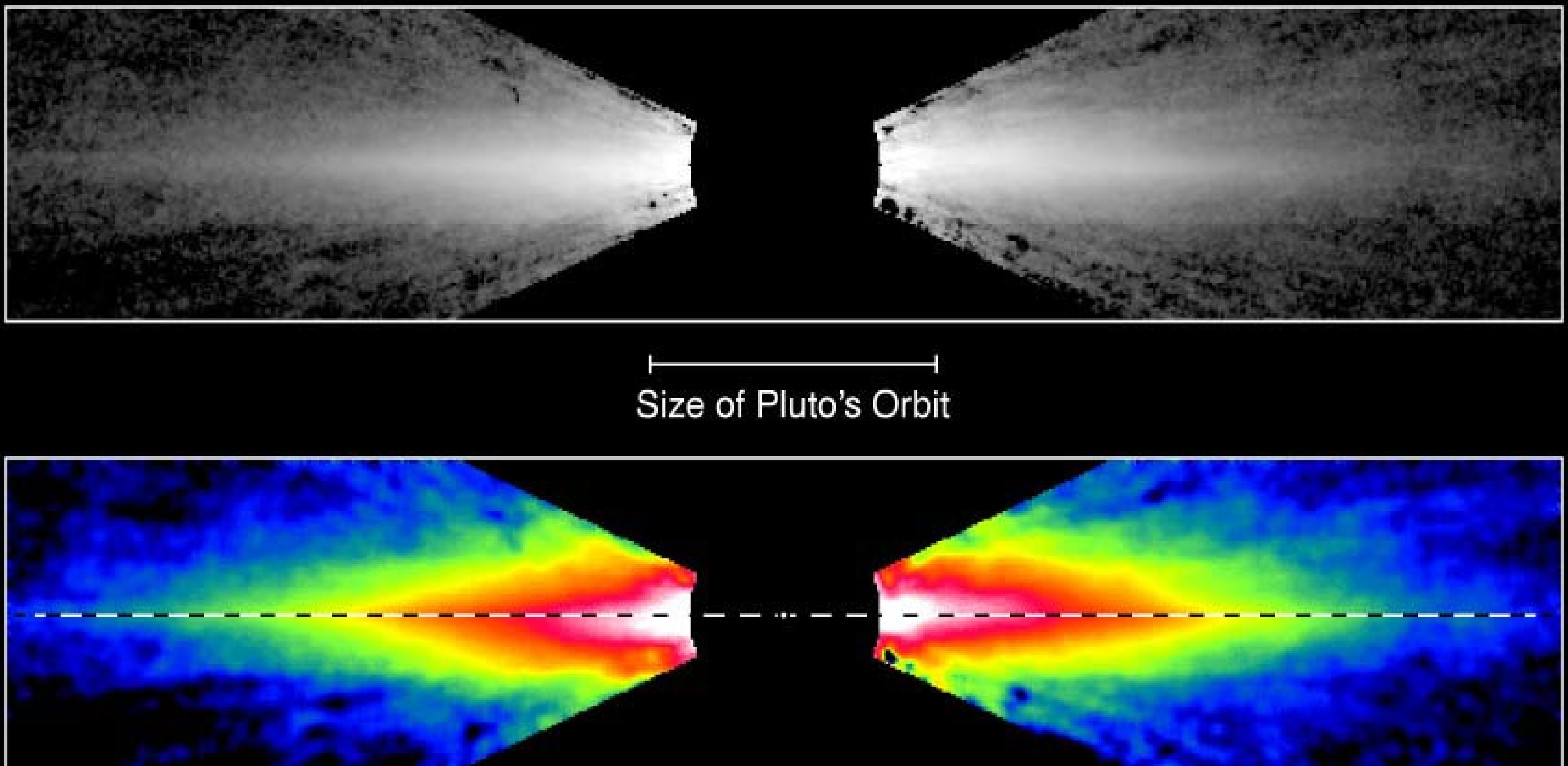
Bennett *et al.* Chap 13: Other Solar Systems Around Other Stars

- 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
- Exoplanets = planets around other stars
- How do we discover them?
- How do selection effects bias our results?
- What are these exoplanets like?
- Can we detect their atmospheres, climate?

First, Let's Review Evidence for Formation of Other Solar Systems



Warped Disk • Beta Pictoris HST • WFPC2

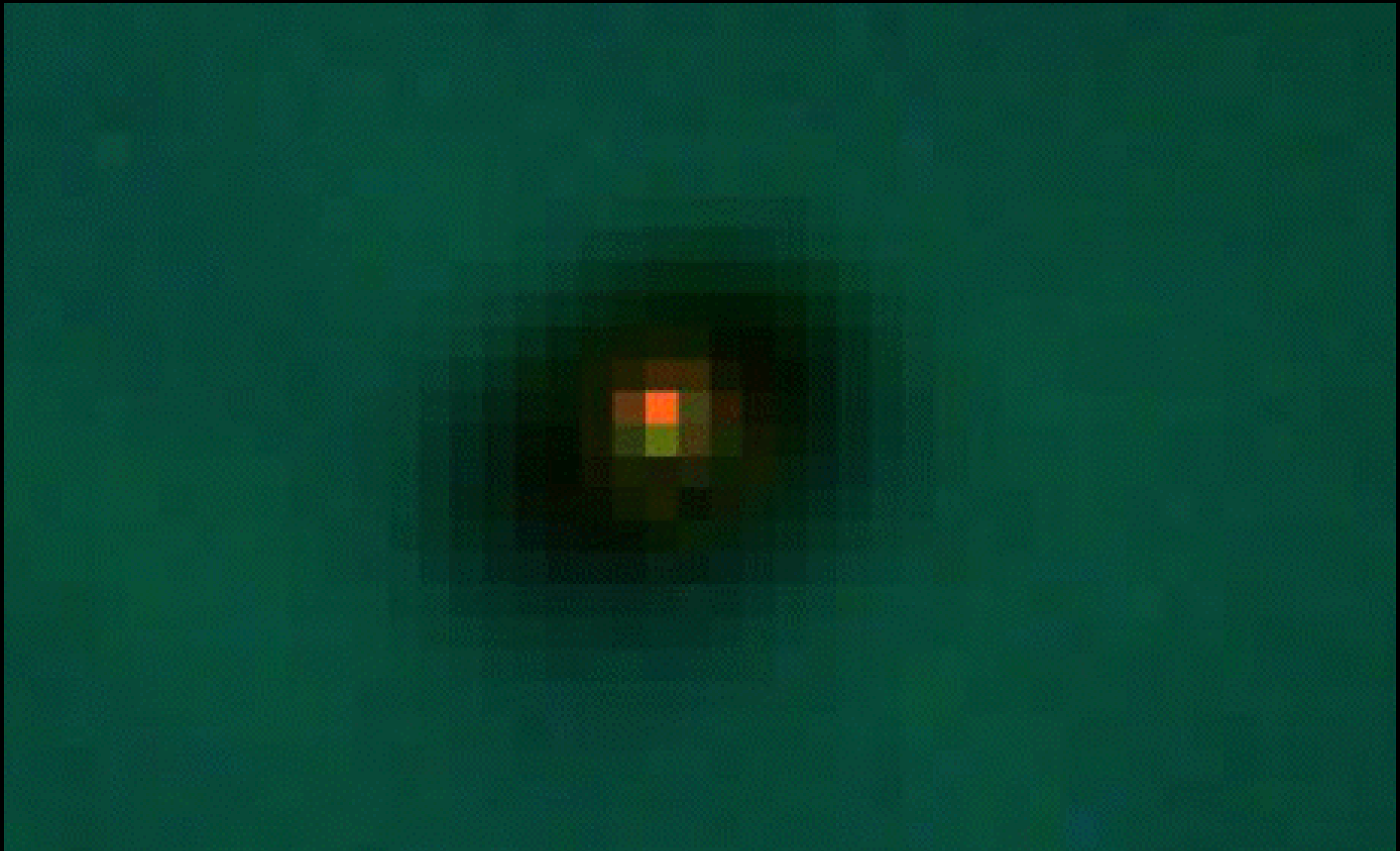
PRC96-02 • ST ScI OPO • January 17, 1995 • C. Burrows and J. Krist (ST ScI), WFPC2 IDT, NASA

Dark Dusty Inner Disks

- The warp in the disk of Beta Pictoris is believed to be indirect evidence for a planet
- Additional indirect evidence – The Orion star forming region has many prostars with protoplanetary disks…. These disks often are dark in the inner region – condensing dust would have a smaller surface/volume ratio, and therefore reflect light more poorly – appearing dark.
- Condensing dust grains = dark disk interior = initiation of planet formation, is the idea

ProtoPlanetary Disk System

- As condensation of dust proceeds, the light of the star inside begins to emerge



Discovering Other Solar Systems

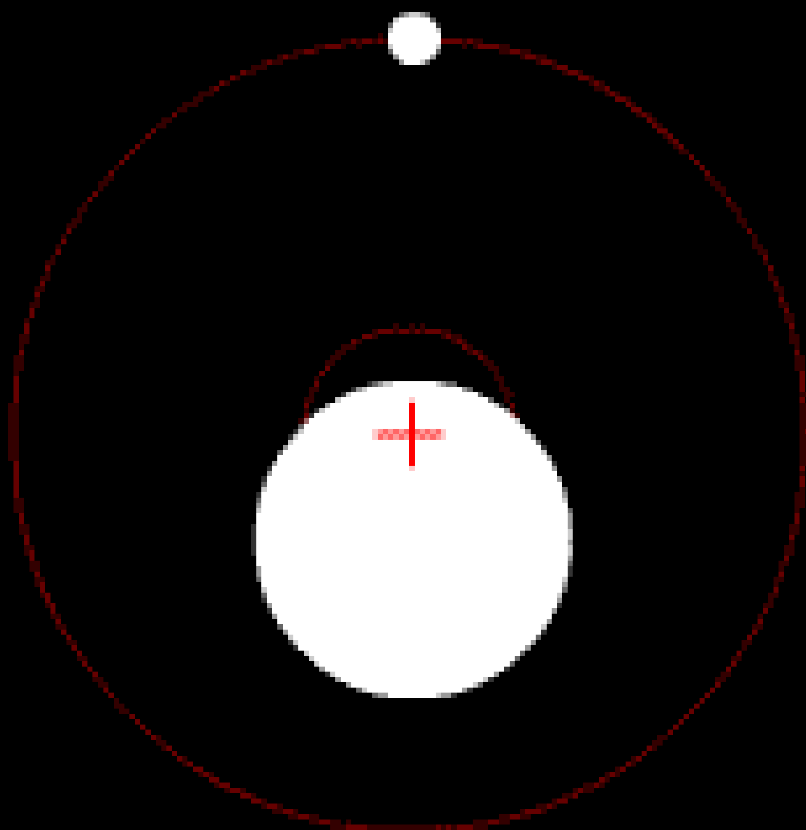
- How do we find planets around other stars? It's hard!!
- Planets are too faint, too close to parent star to actually "see", except in a tiny handful of cases. Must be clever (as always! Astronomers are good at that)
- There are **3 methods of finding exoplanets** today…

- **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!**

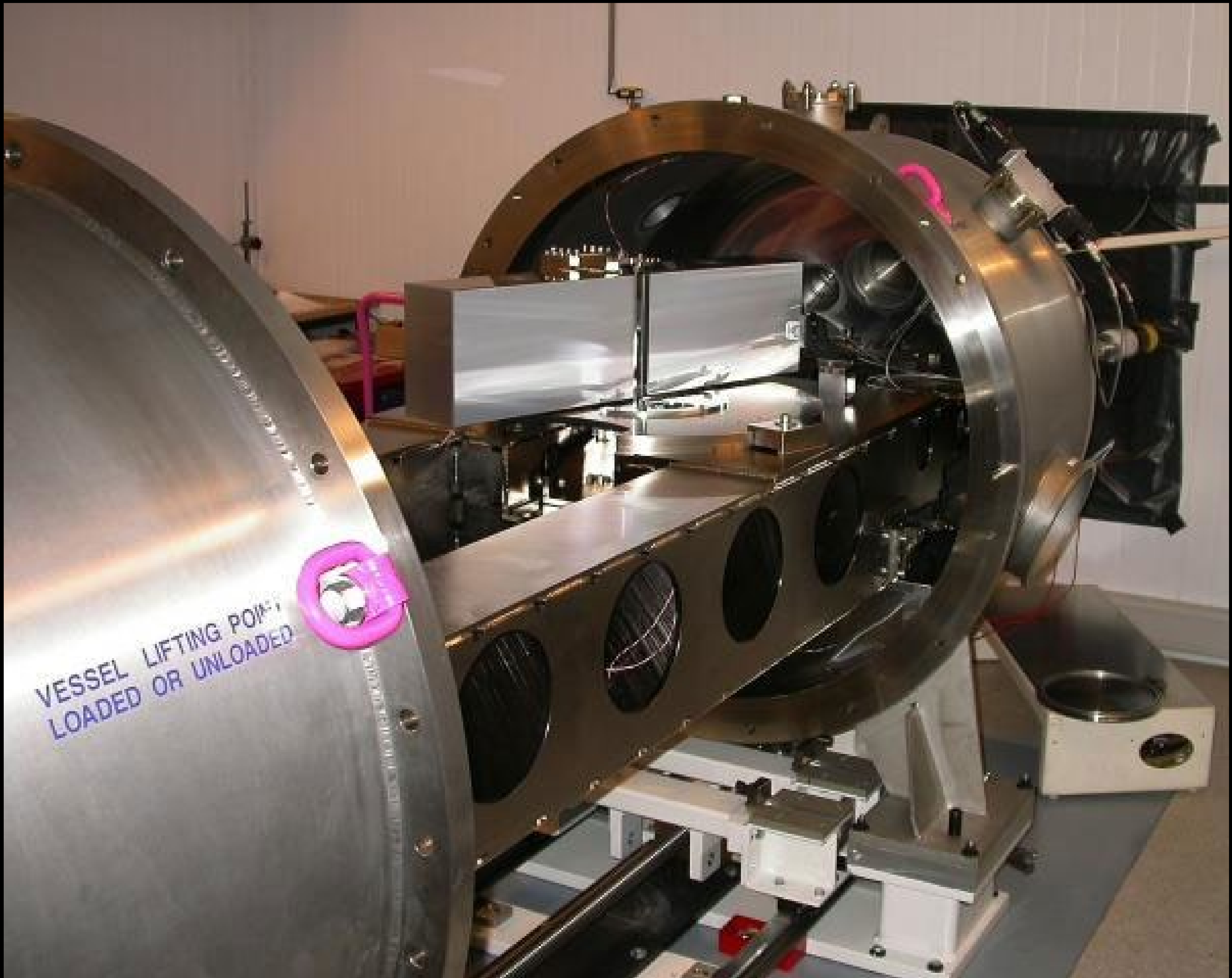
<u>Doppler Method</u>: From the Ground, this is the least-hardest Way to Find Solar Systems - Observing Periodic Doppler Shifts in the Parent Star

- 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 sun moves only 1/1000 of that, or 13 meters/sec
- So v/c is 4×10^{-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
- Need high precision, expensive **<u>spectrographs…</u>**

Orbiting Planet Makes Star Orbit too: Doppler Effect Makes That Detectable



The HARPS Spectrograph

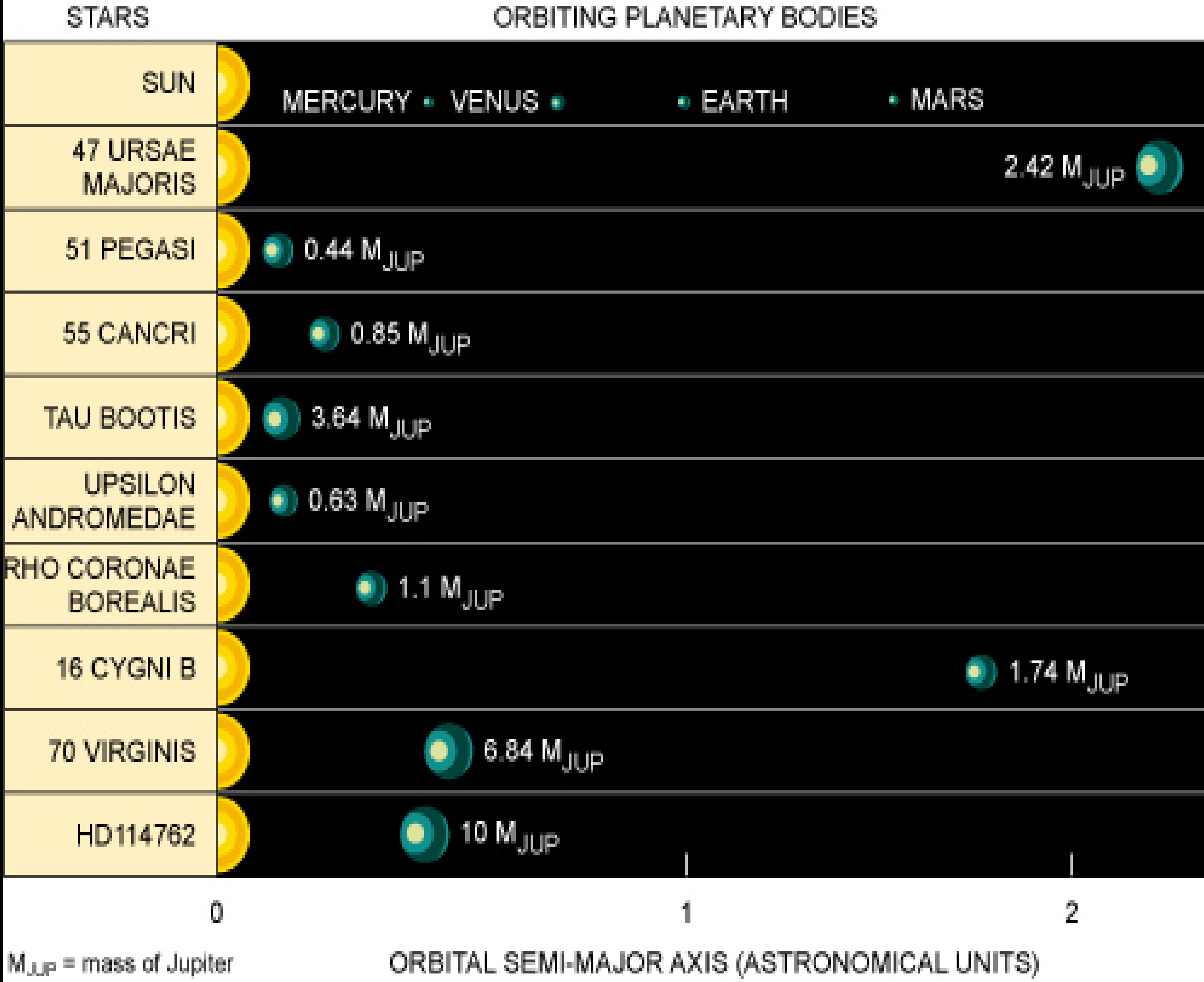


Strong Selection Effect from the Doppler Method

- The signal-to-noise ratio will be too small to detect unless the planet is MASSIVE and the planet is CLOSE to the parent star, so that the parent star is reaction'ing as FAST AS POSSIBLE
- That means the method is highly biased to find BIG Jupiter-like planets in orbits well inside the equivalent of Mercury's orbit.
- **"Hot Jupiters" is what we call such exoplanets**
- From what we've learned in class, this sounds like a pretty unlikely situation! Heavy elements are rare, massive planets must be made mostly of the dominant chemical elements – hydrogen and helium. These would evaporate away on a time scale which is likely short compared to the age of the system.

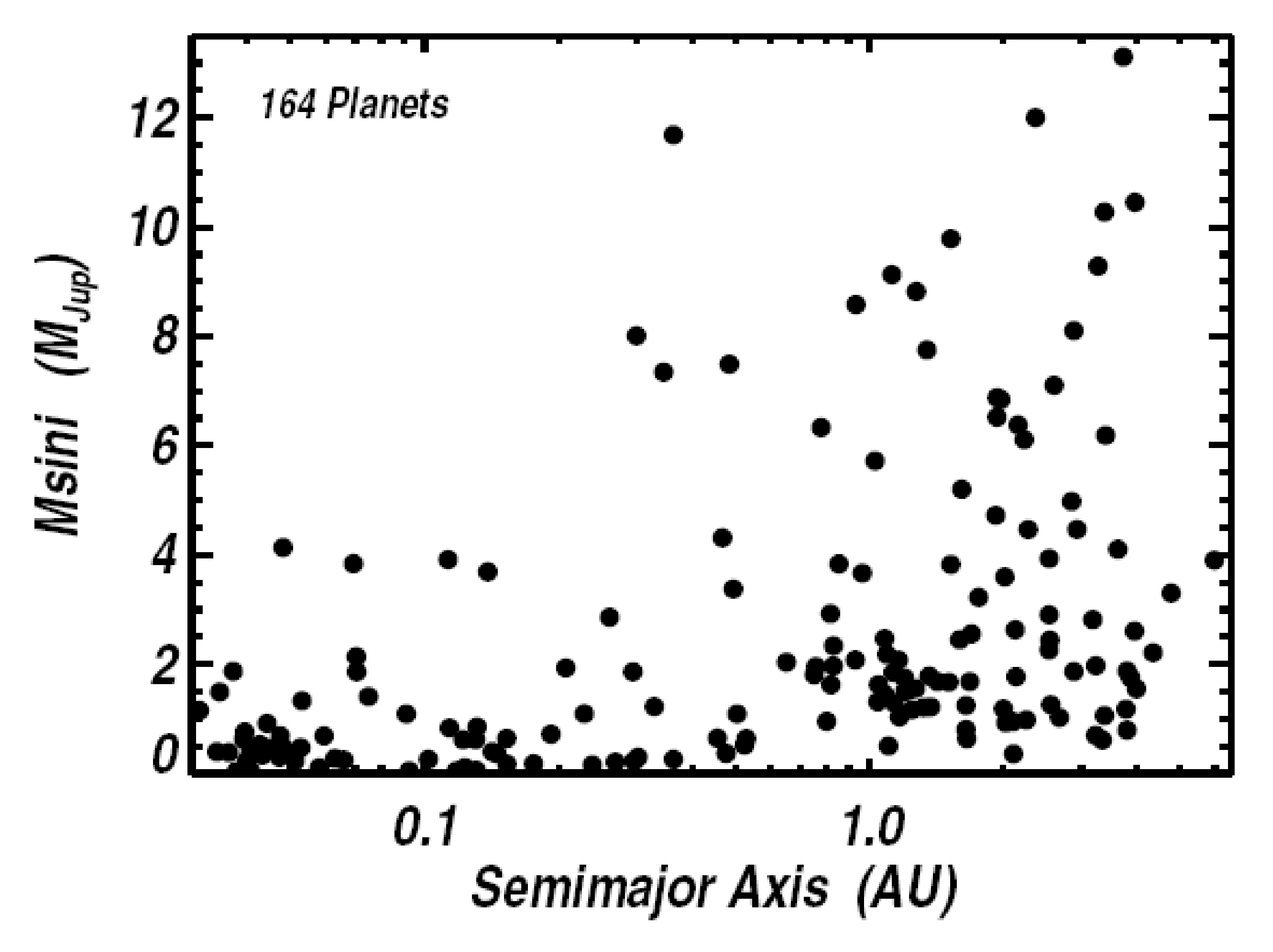
But Perseverance Pays!

- So, we were not optimistic about finding ANY planets with 1990’s technology. But Queloz and Mayor in Europe, and Marcy and Butler in the U.S., initiated searches
- They carefully monitored the position of spectral lines for a large number of bright stars, taking frequent observations over years, and….. **found tiny Doppler shifts... Planets!**
- As of Sept 2013, about 800 nearby stars have had planetary systems discovered around them, 150 by Kepler Mission via transit method, the rest by Doppler method.
- Today, ~4200+ likely solar systems discovered by transit Kepler Mission transits. Far more than by Doppler Method.
- Calculated implications: <u>**over 90% of sun-like stars are have planetary systems around them!**</u>

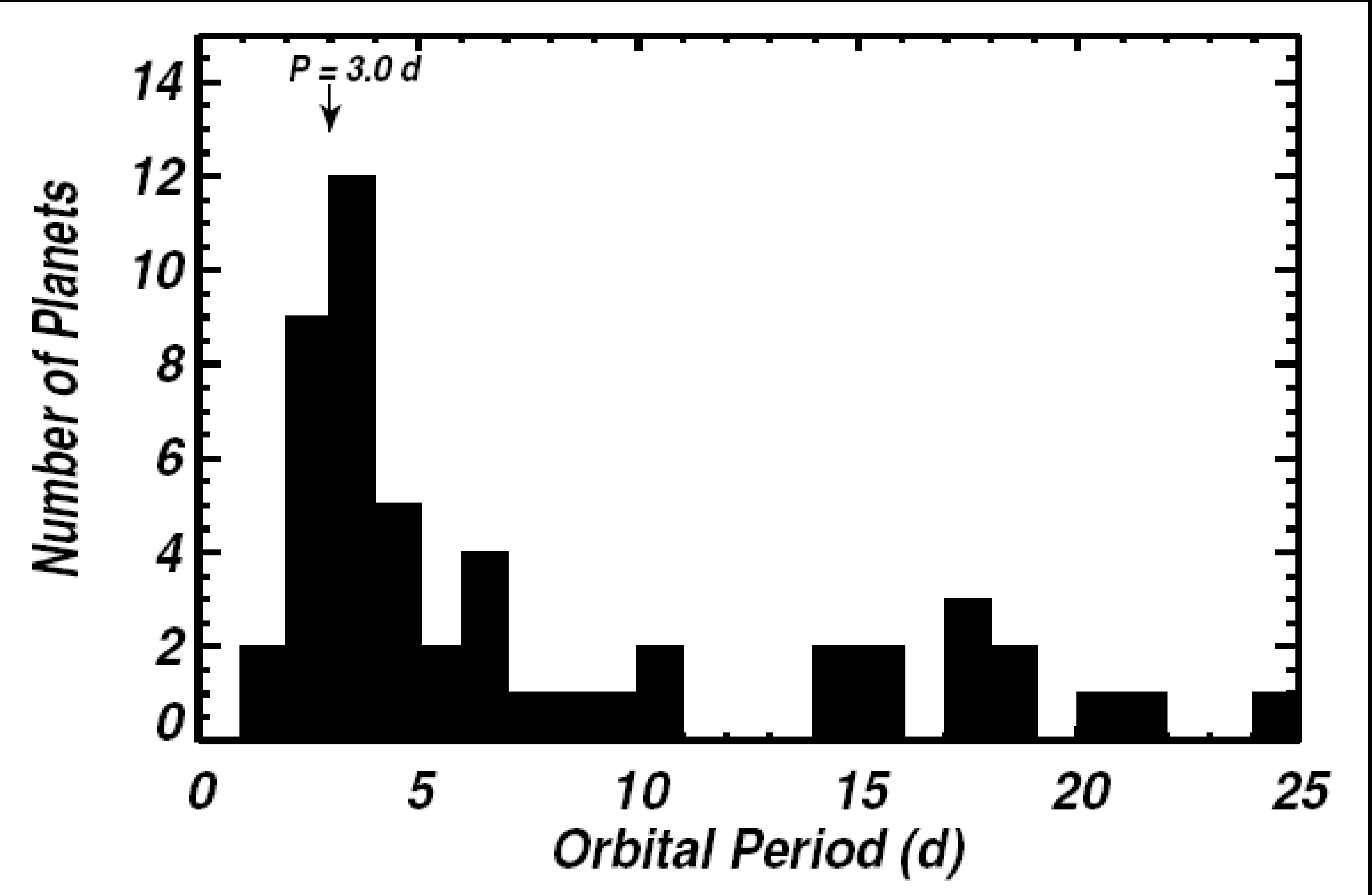


STARS
ORBITING PLANETARY BODIES
SUN
MERCURY
VENUS
EARTH
MARS
47 URSAE MAJORIS
2.42 M JUP
51 PEGASI
0.44 M JUP
55 CANCRI
0.85 M JUP
TAU BOOTIS
3.64 M JUP
UPSILON ANDROMEDAE
0.63 M JUP
RHO CORONAE BOREALIS
1.1 M JUP
16 CYGNI B
1.74 M JUP
70 VIRGINIS
6.84 M JUP
HD114762
10 M JUP
0
1
2
M JUP = mass of Jupiter
ORBITAL SEMI-MAJOR AXIS (ASTRONOMICAL UNITS)

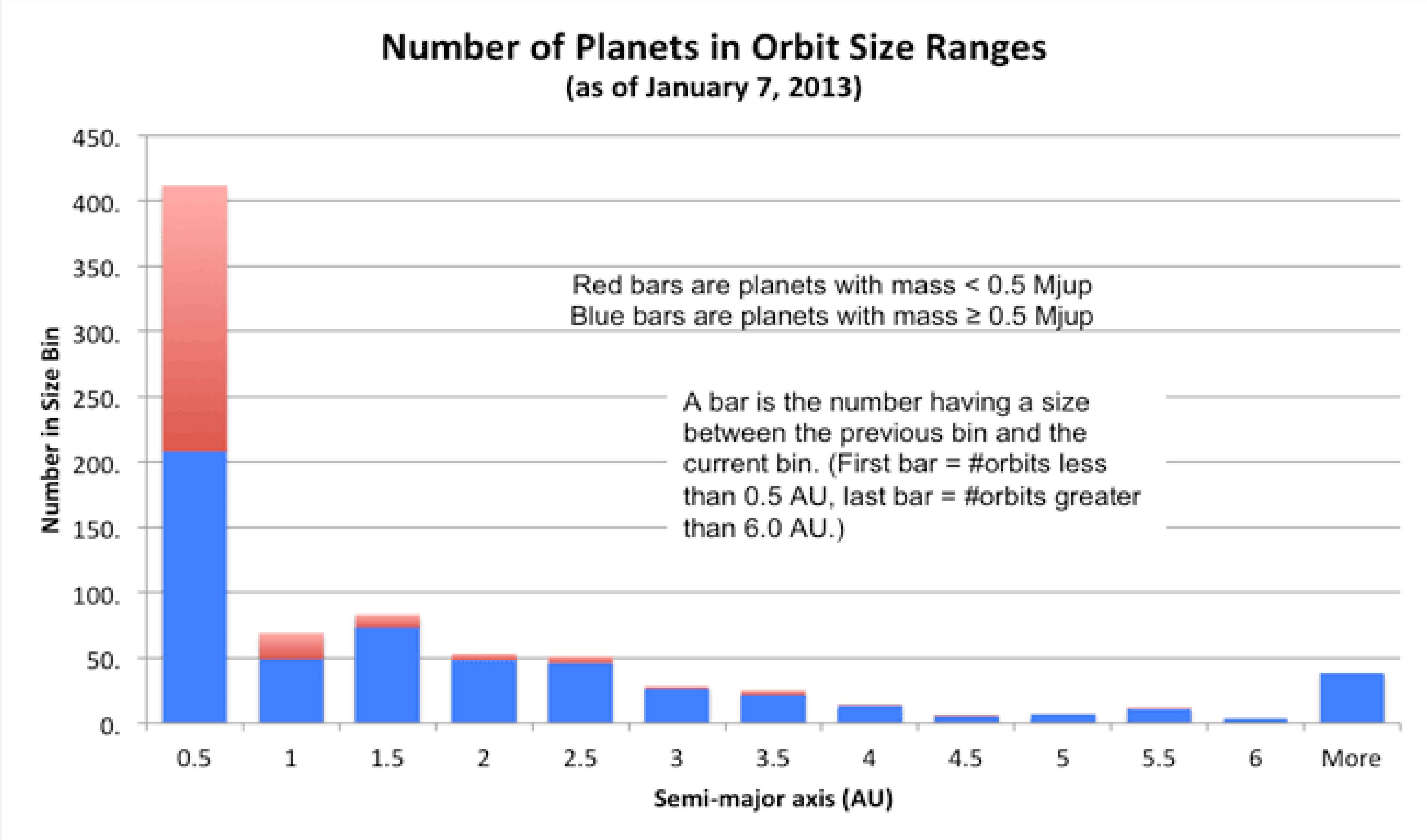
The large majority of early discoveries by Doppler Method: Lots of "Hot Jupiters" found



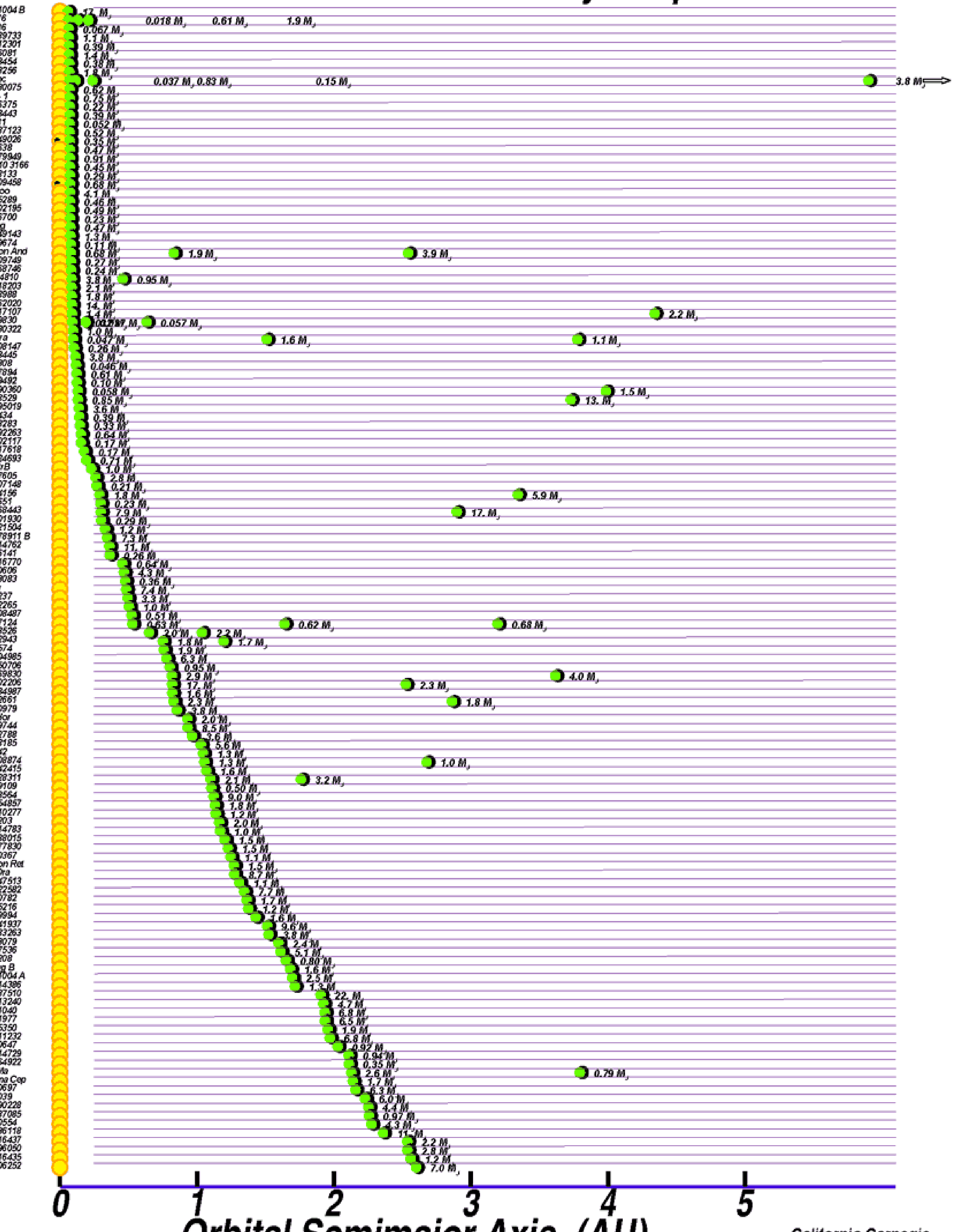
Orbital Periods of a Month or Less Give the Strongest, Easiest Signal; First to be Found



Even Transit method is biased Towards Close-in Discoveries. Most Discoveries Correspond to Inside Venus' Orbit



The 178 Known Nearby Exoplanets



Clearly, We Don't Think Such "Jupiters" Can Form So Close to Stars

- It's too hot, and the amount of rocky material is always a tiny fraction of the total mass – which is mostly Hydrogen and Helium and would not collect onto such a massive small rocky core to make a "hot Jupiter".

But Then How Can There be So Many Hot Jupiter Systems?

- **<u>Planetary Orbit Migration!</u>**
- What if Jupiter's 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?
- Two Prime Mechanisms can cause planetary migration…

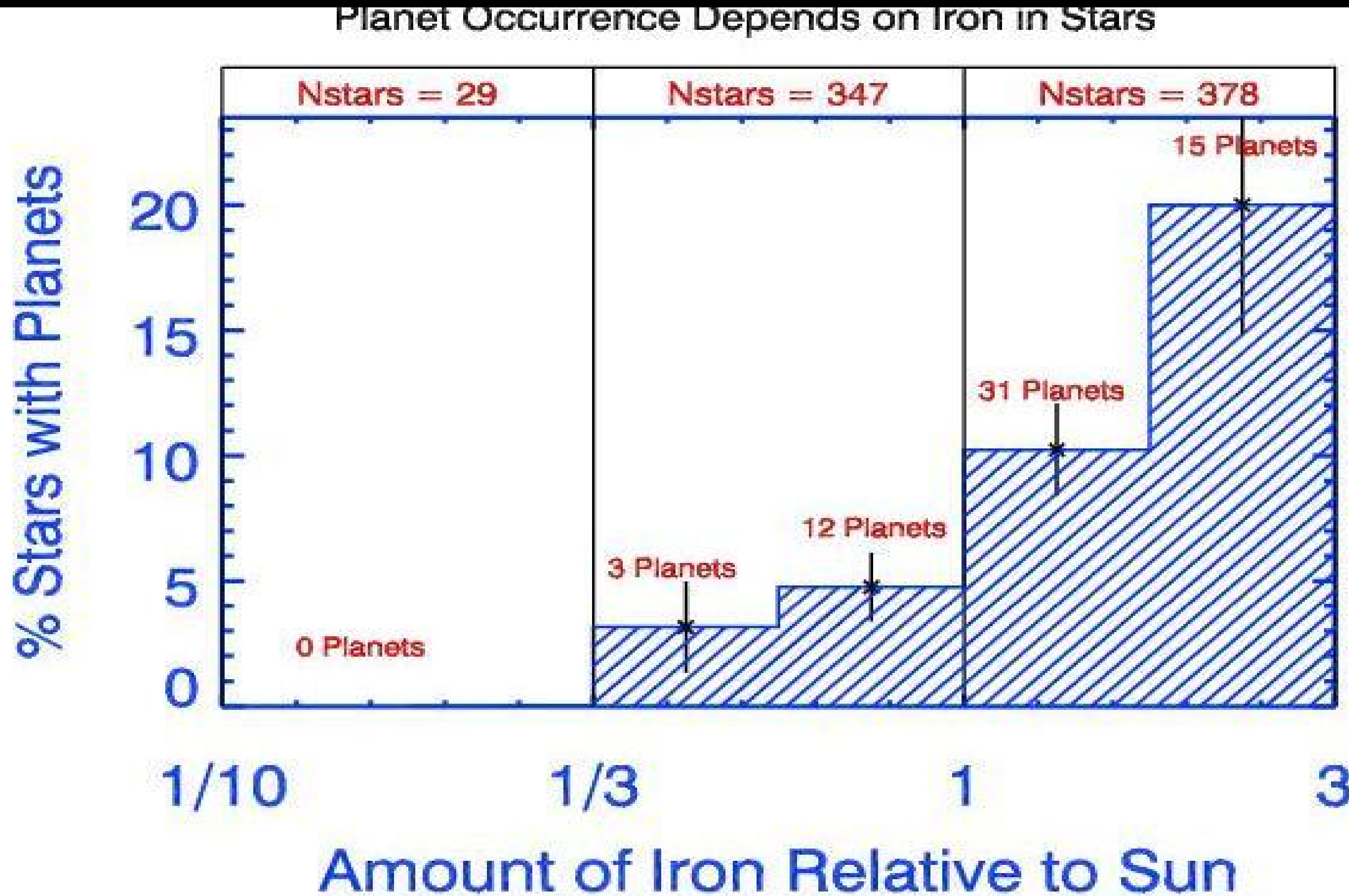
1. Disk Friction Drags Planet Inward

- A disk of dust will feel much internal friction due to the differing rotation speeds at neighboring radii.
- Friction turns to heat, radiated away, and the energy loss is subtracted from the orbital motion energy of the disk particles.
- Gas is lightweight enough that it'll more tend to be blown away by the stellar winds and radiation pressure.
- But dust will not feel nearly so much, and a thick dust disk will instead tend to fall towards the star as this frictional energy dissipation of orbital energy proceeds
- So this mechanism requires dust, and dust is made of "metals" (elements heavier than helium).
- ***Do high-metallicity stars have planets? <u>Yes!</u>***

Giant planets take shape far from their star, where raw material is abundant. But astronomers have found scores of giants that apparently migrated inward after forming. In one theory, the process begins as a newborn giant carves a gap in the disk of gas and dust swirling around a young star (below left). The gap doesn't stay put: Friction between particles and gas molecules gradually slows down the disk. The material spirals inward, carrying the gap—and the planet—with it (below).

ART BY MOONRUNNER DESIGN. CONSULTANT: DEREK C. RICHARDSON, UNIVERSITY OF MARYLAND

Stars with High Metallicity Are More Likely to Have Planets…

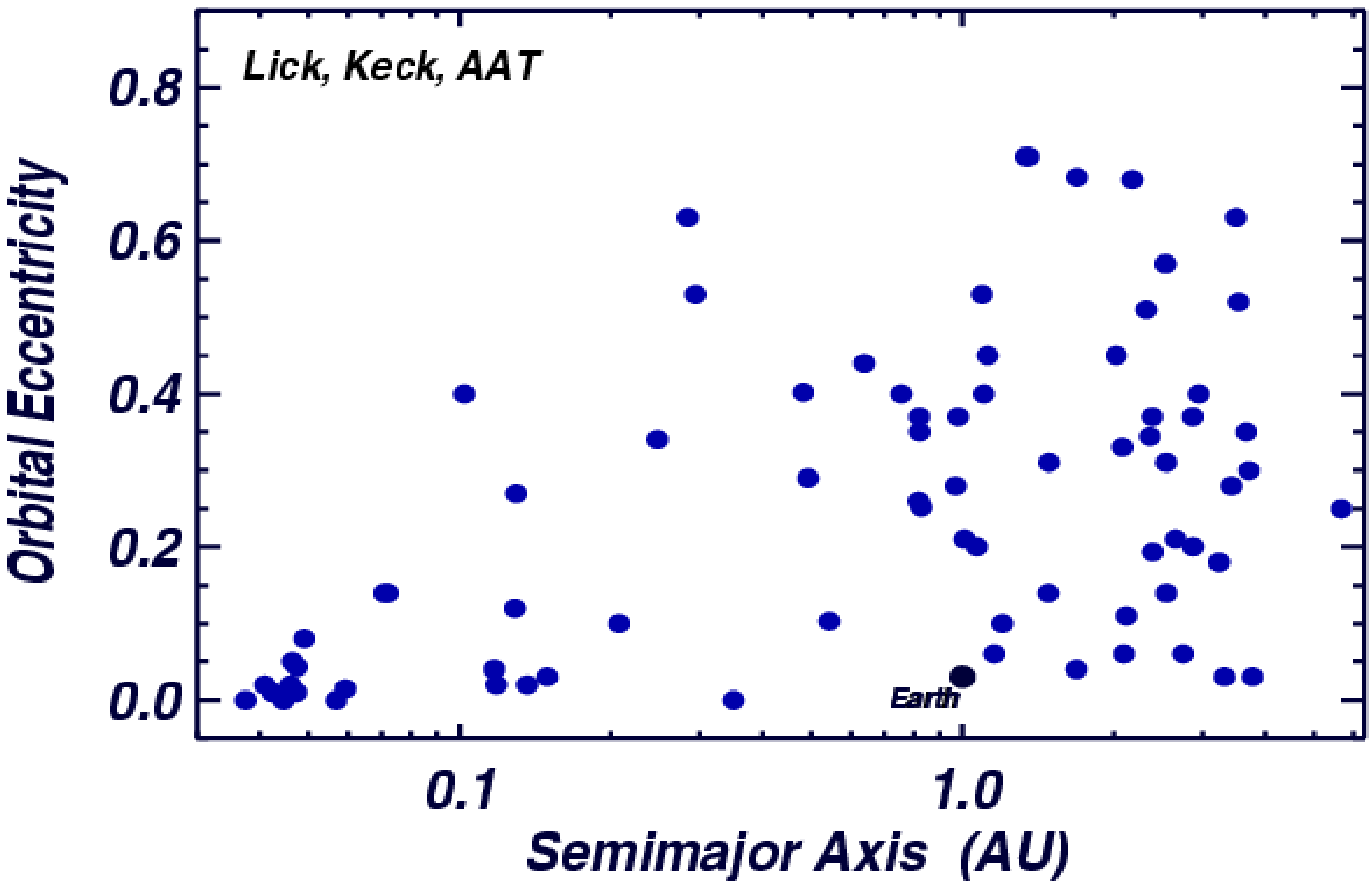


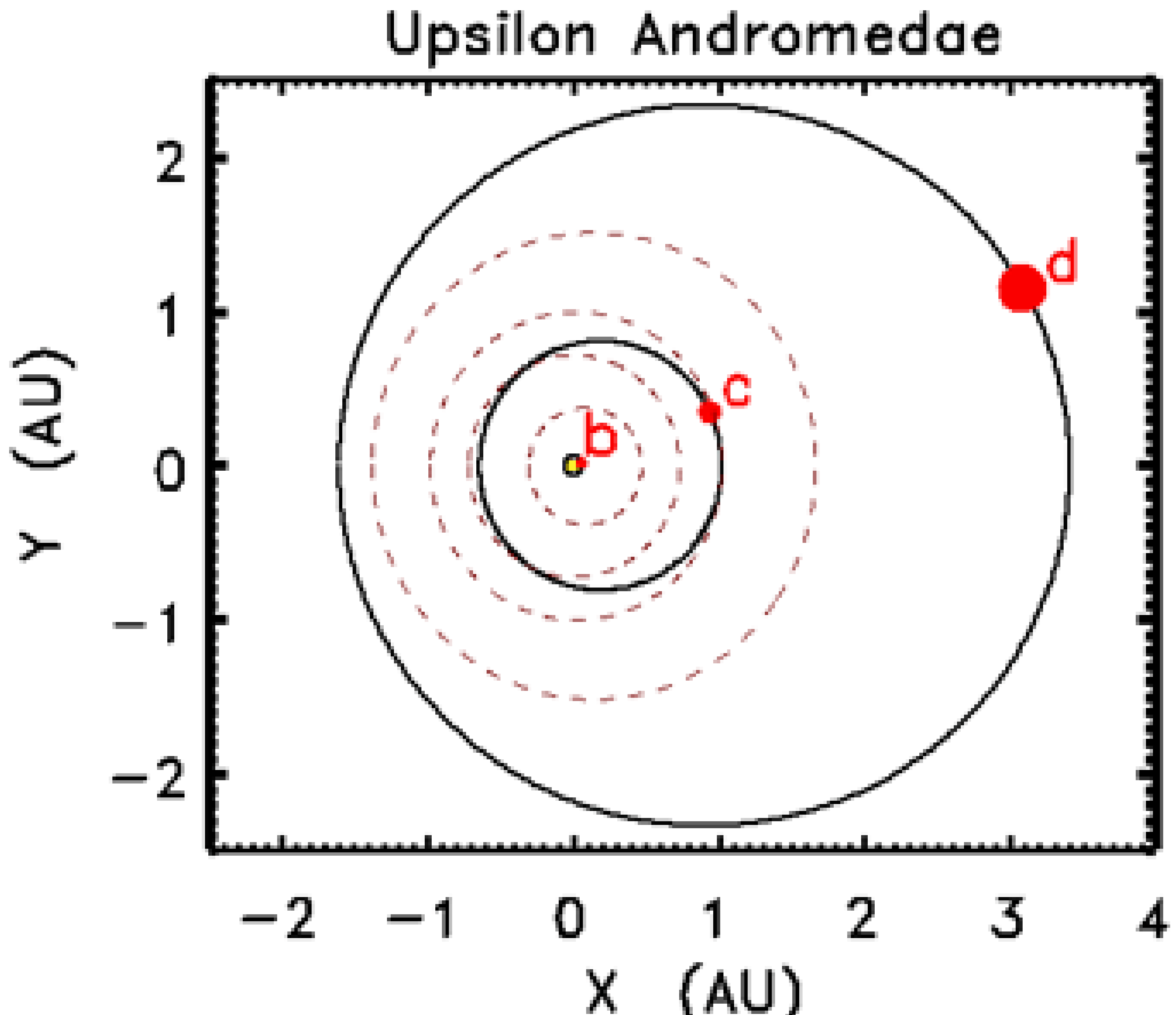
Fischer & Valenti

2. Resonance-induced Close Encounters w/ Other Planets

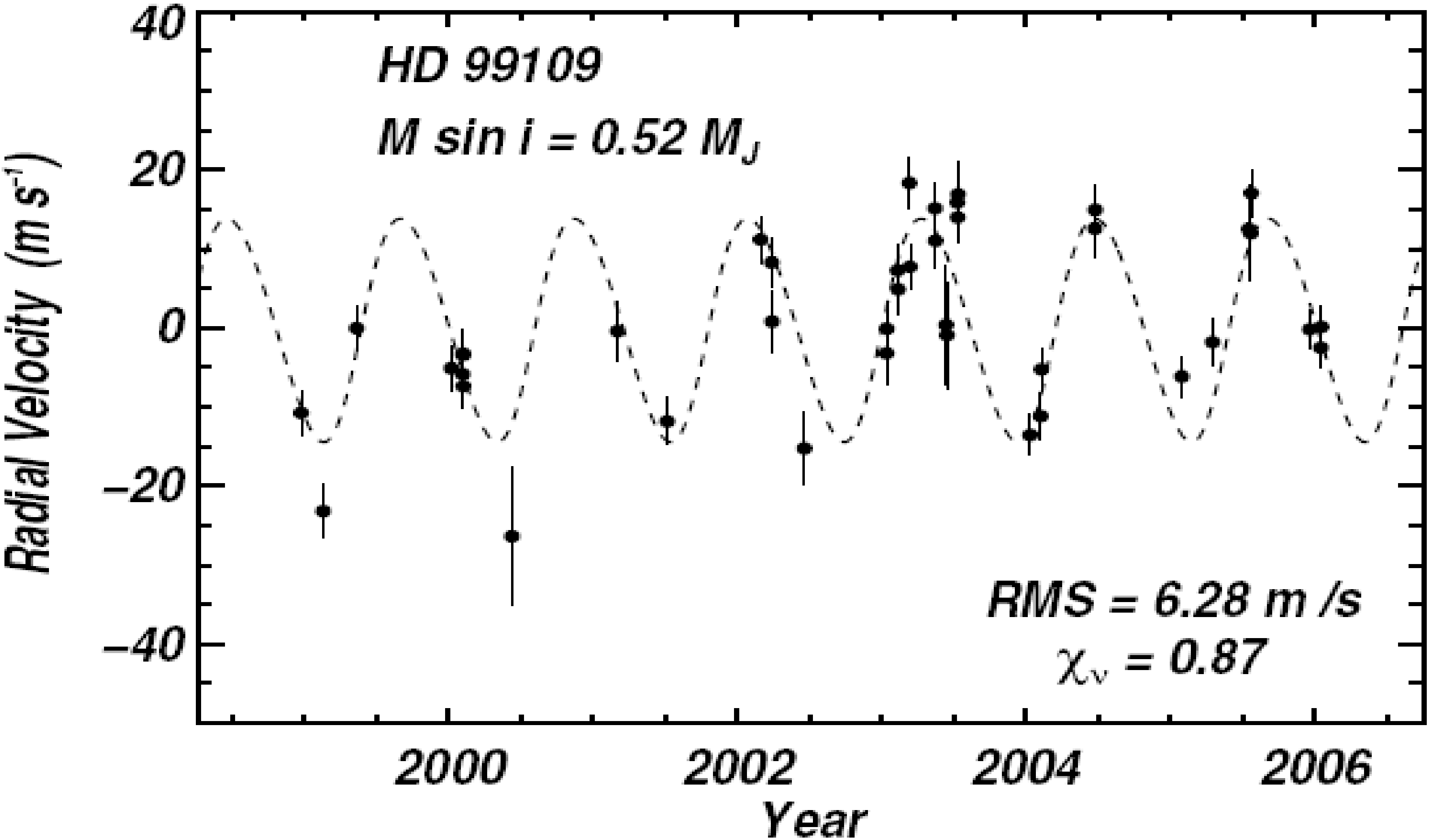
- Planets should, by physics, form in fairly circular orbits since the disk gas/dust will be in circular motion, with plenty of space between planets by the time formation is about done.
- But resonances can amplify eccentricity of an orbit, to the point of orbit-crossing (close encounter possible!), 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 migration for any planets except Neptune and Uranus.

We see… lots of planets have very eccentric orbits, unlike the circular orbits of our own Solar System. Dynamics indicates this is caused by migration

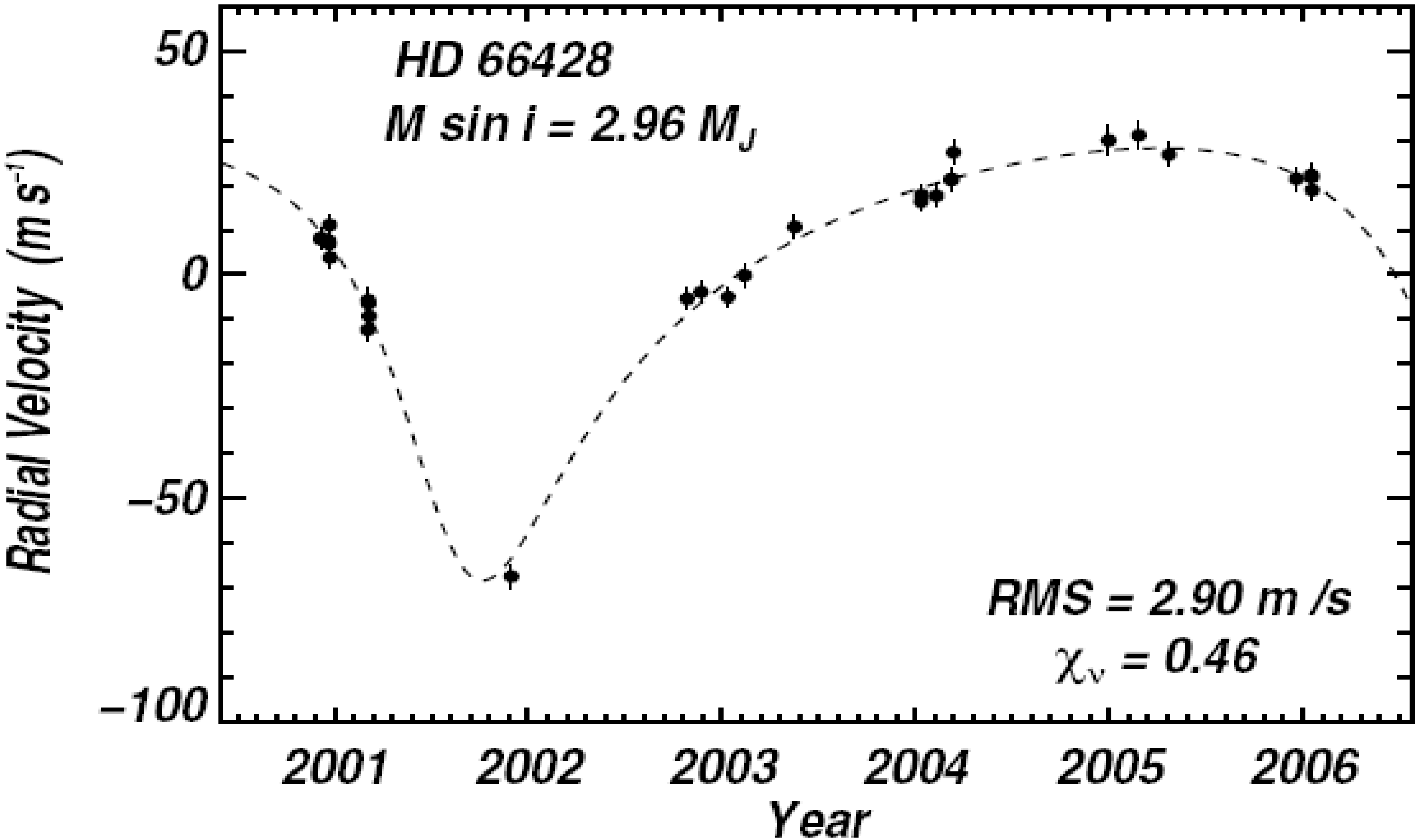



Upsilon Andromedae
Y (AU)
X (AU)
2
1
0
−1
−2
−2
−1
0
1
2
3
4
b
c
d

A Fairly Circular Orbit Fits For This One



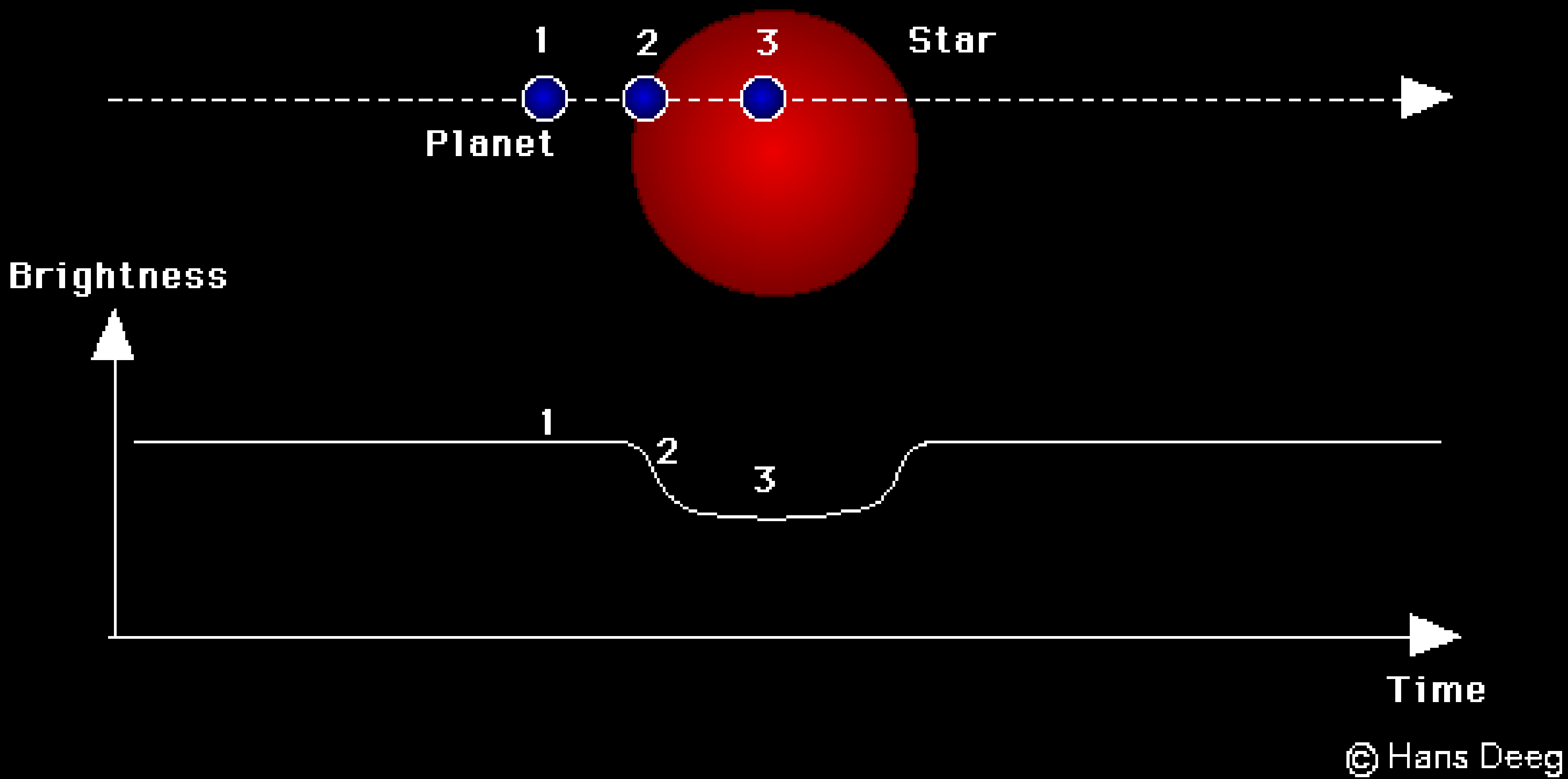
But A Very Elliptical Orbit Needed for a Good Fit Here



We'd Love to Find Earth-like Planets…

- In part that's because Earth is so tiny even Kepler has a hard time detecting such small planets.
- In part, we do think Earth-like planets (vs. just Earth-*sized* planets) are rare.
- But interest is high – we want to find planets which may have life. We want to know we're not alone out here!
- Discovery of Earth-like planets requires **transit** data to measure their size and therefore get their density (rock? Ice? Gas?).

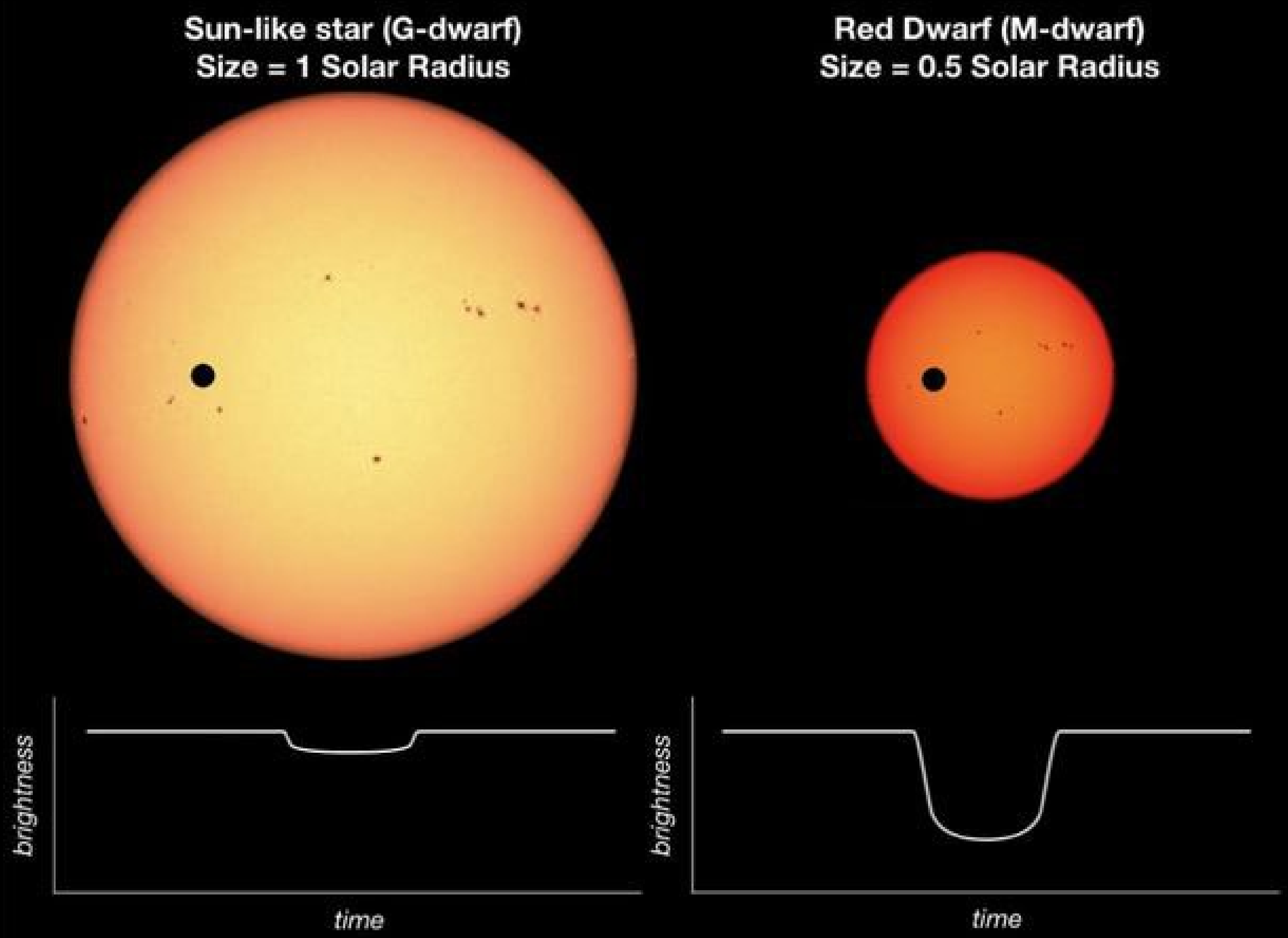
The Transit Method: Transiting Planets Discovered by Precision Monitoring of Star's Brightness



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.
- Red dwarfs are more common stars, and also more easily show transits…

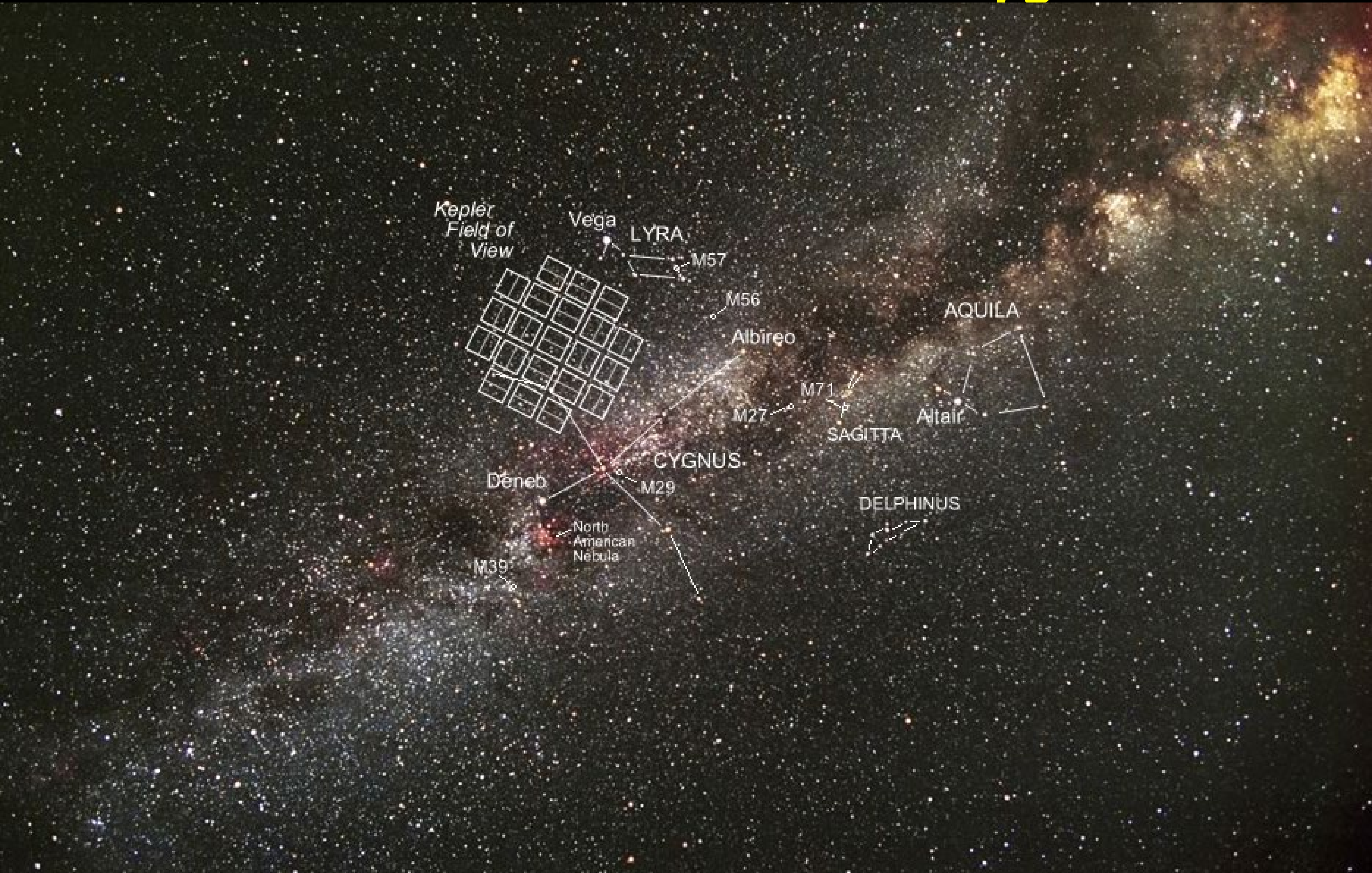
The bigger the star, the harder to see transits.



A Specialized Satellite Launched in 2009 – The Kepler Mission

- Kepler monitored many tens of thousands of stars in the constellation Cygnus for transits, down to 14^{th} magnitude
- Has discovered 1000 confirmed and over 4,000 unconfirmed planets around other stars, most of them "Super-Earths" between 1-2 Earth diameters.
- (**confirmed** means have been seen over enough transits to determine orbital nature. Unconfirmed are likely/possible transits but might yet turn out to be starspots, etc. Need more transits to confirm. But Kepler team estimates ~80% are real)
- But, Kepler only studies stars in a small square in the constellation of Cygnus, not the entire sky
- And alas, In summer 2013 – **Kepler died**, victim of failed gyros. By being clever using natural pressure from sunlight with still-working gyro's, Kepler has been **Kepler reborn;** reprogrammed and is now looking in other directions

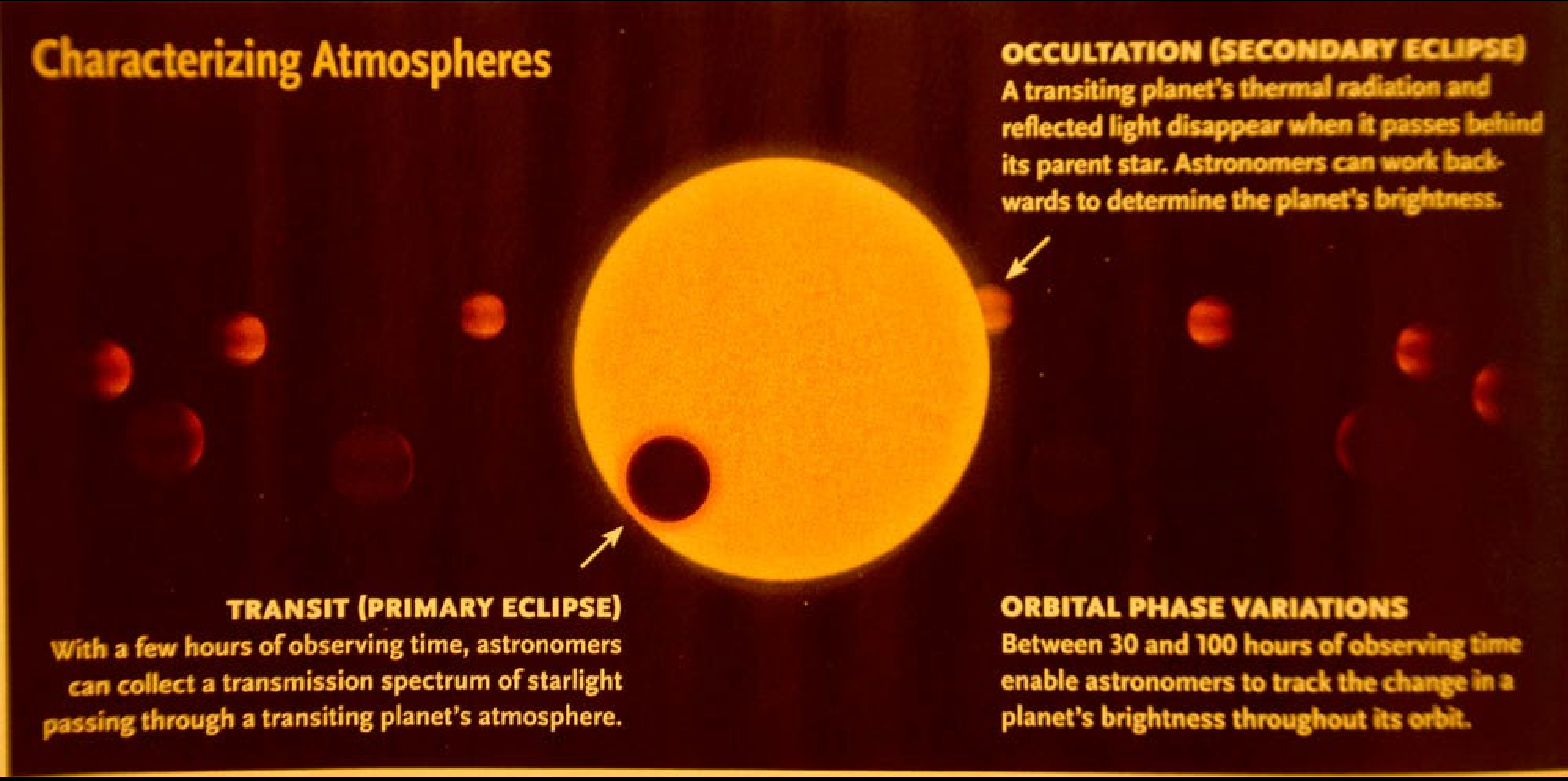
The Kepler Mission – Targeted on A Corner of Constellation Cygnus



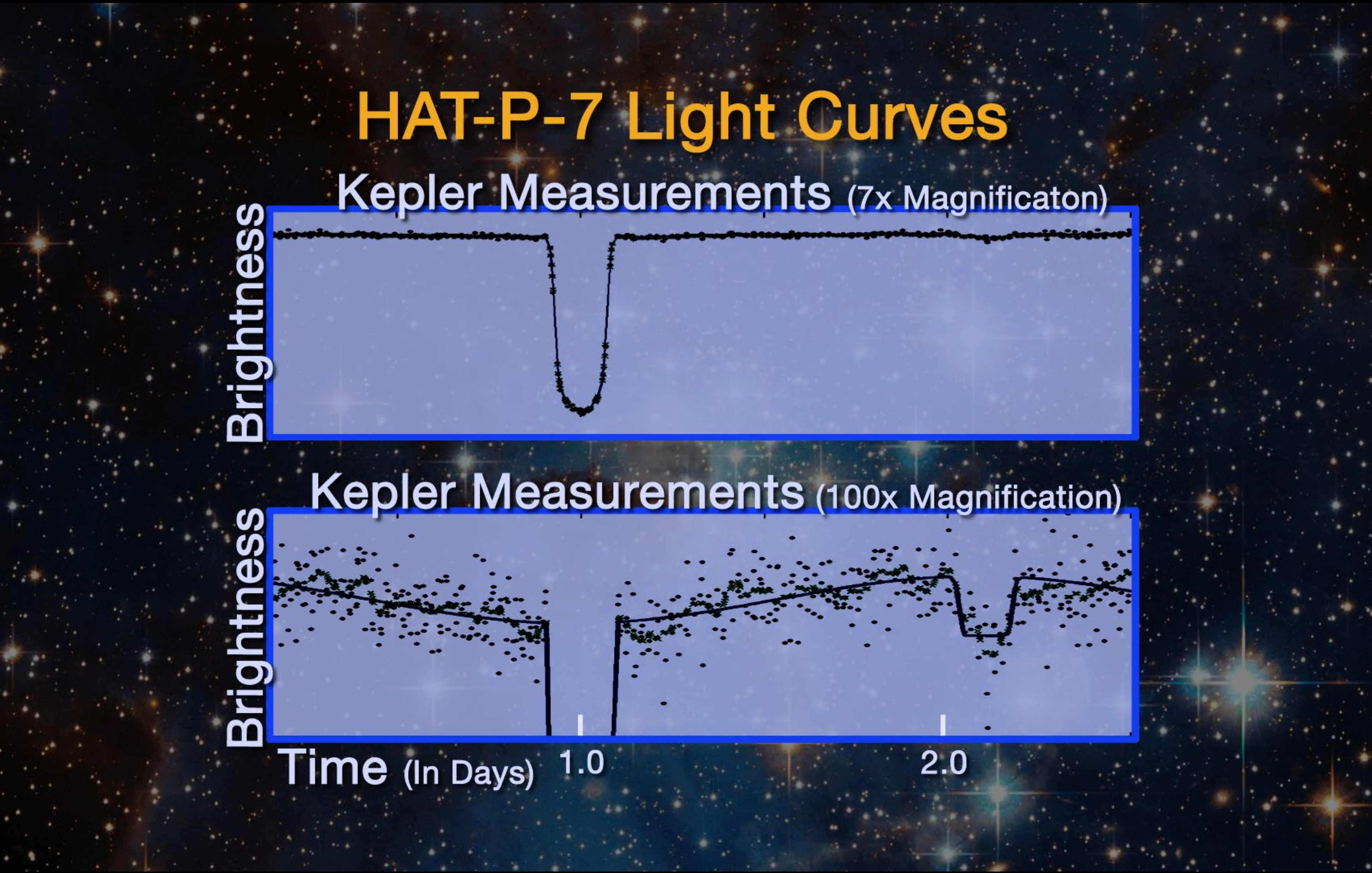
Transit Method Provides Crucial Data Not Possible from Doppler

- 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 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**"
- Over 4200 possible transiting planets have now been found in Kepler data. 1000 have been confirmed as of December 2014.

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



That's a Beautifully Noise-free Light Curve!

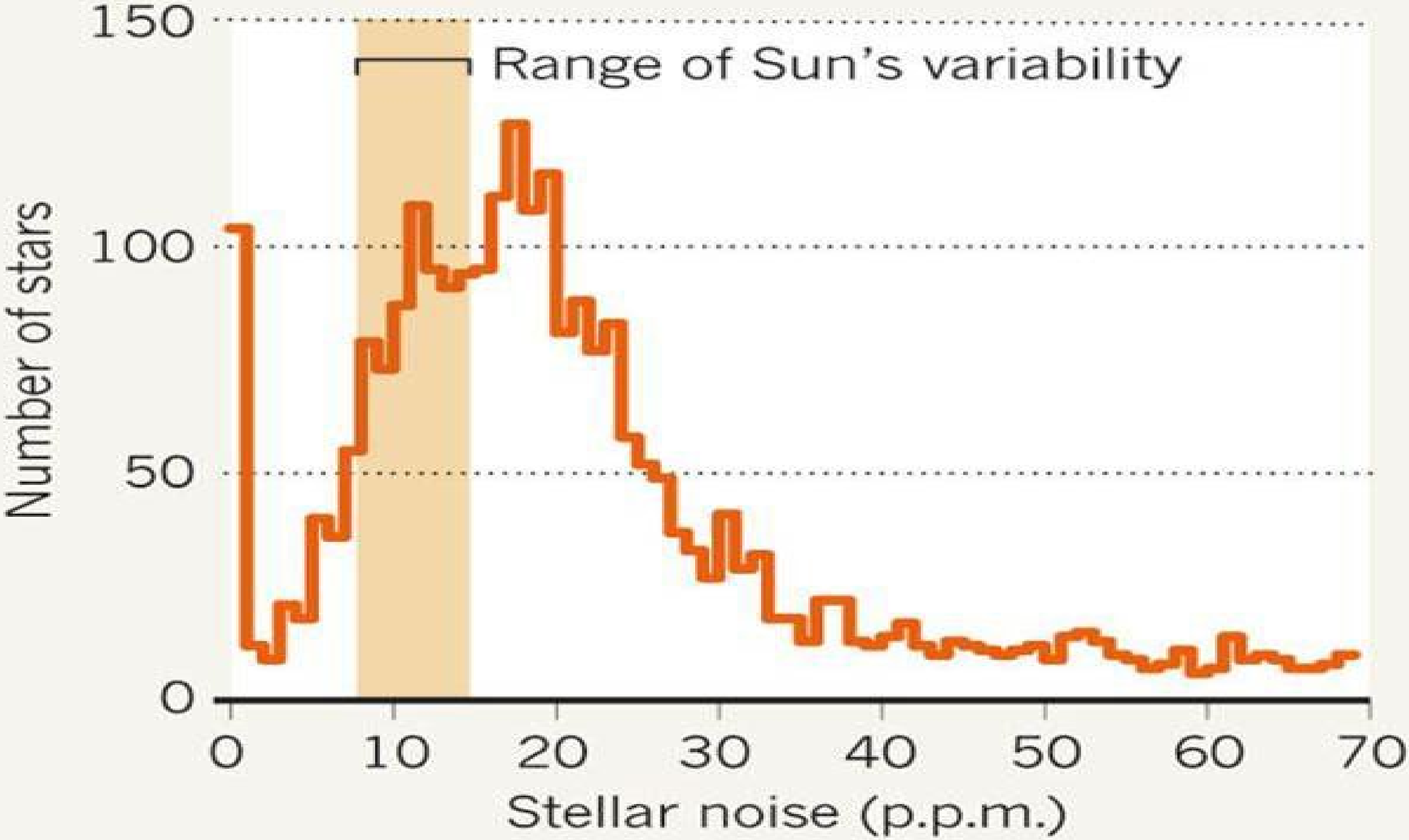


Some Kepler Findings…

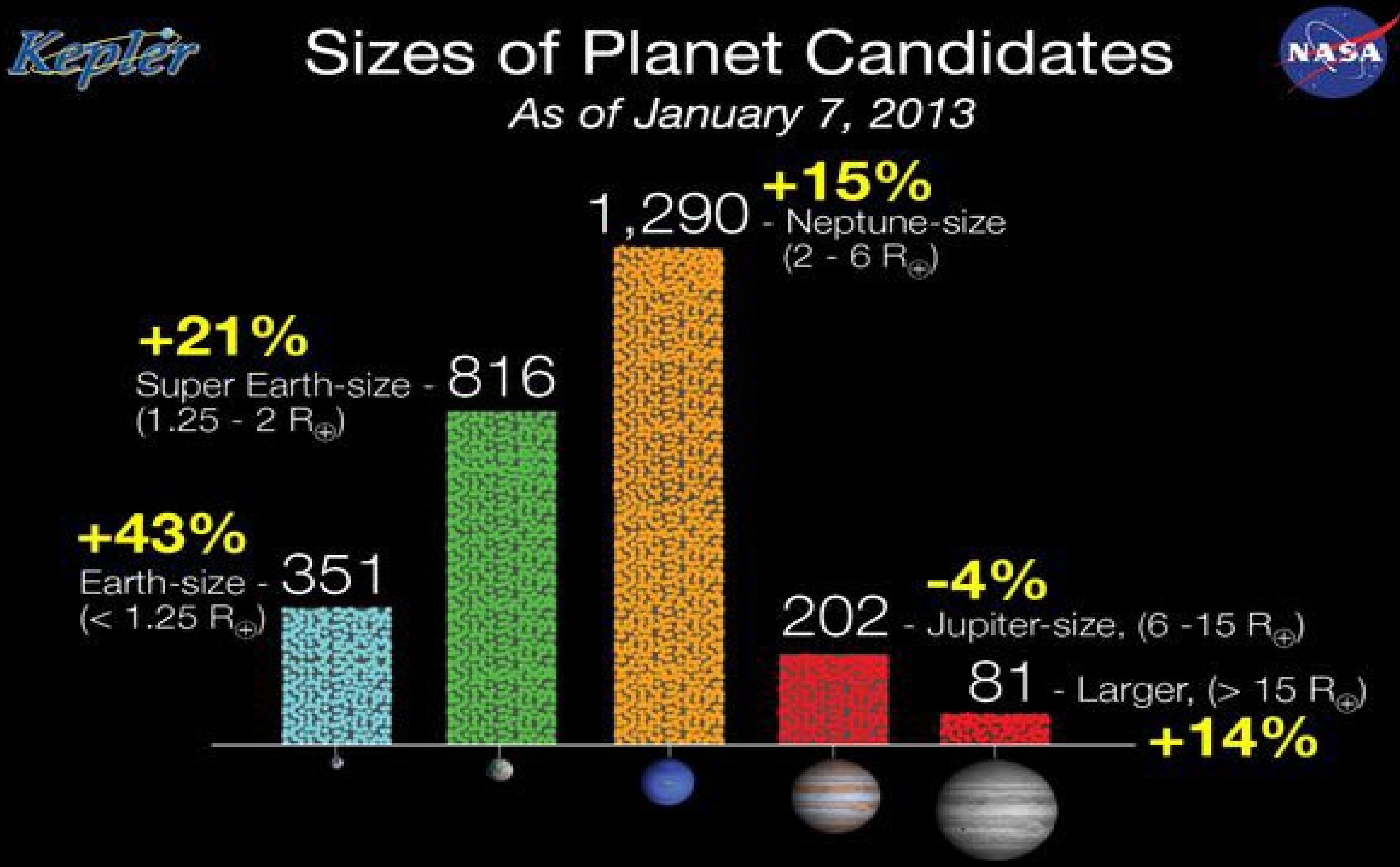
- First, that there is micro-level variations in stellar luminosities more commonly than we had guessed.
- This makes transits harder to detect, but good software and humans (see citizen science Zooniverse website) have mostly overcome this.
- **Planets are common! Well over 90% of solar-type stars calculated 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

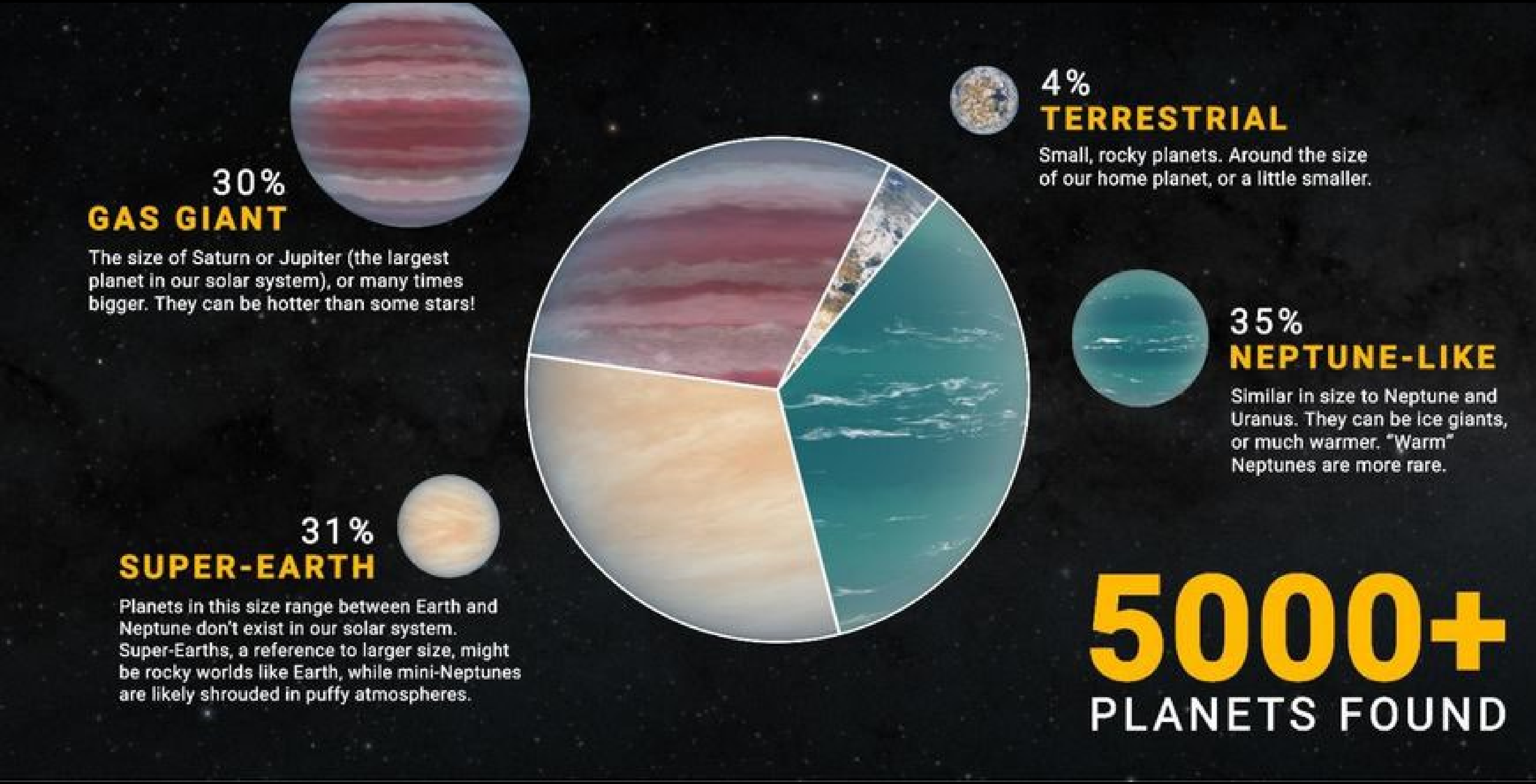
In a sample of 2,500 Sun-like stars monitored by the Kepler probe, most vary in brightness more than the Sun does, which makes planets harder to see.



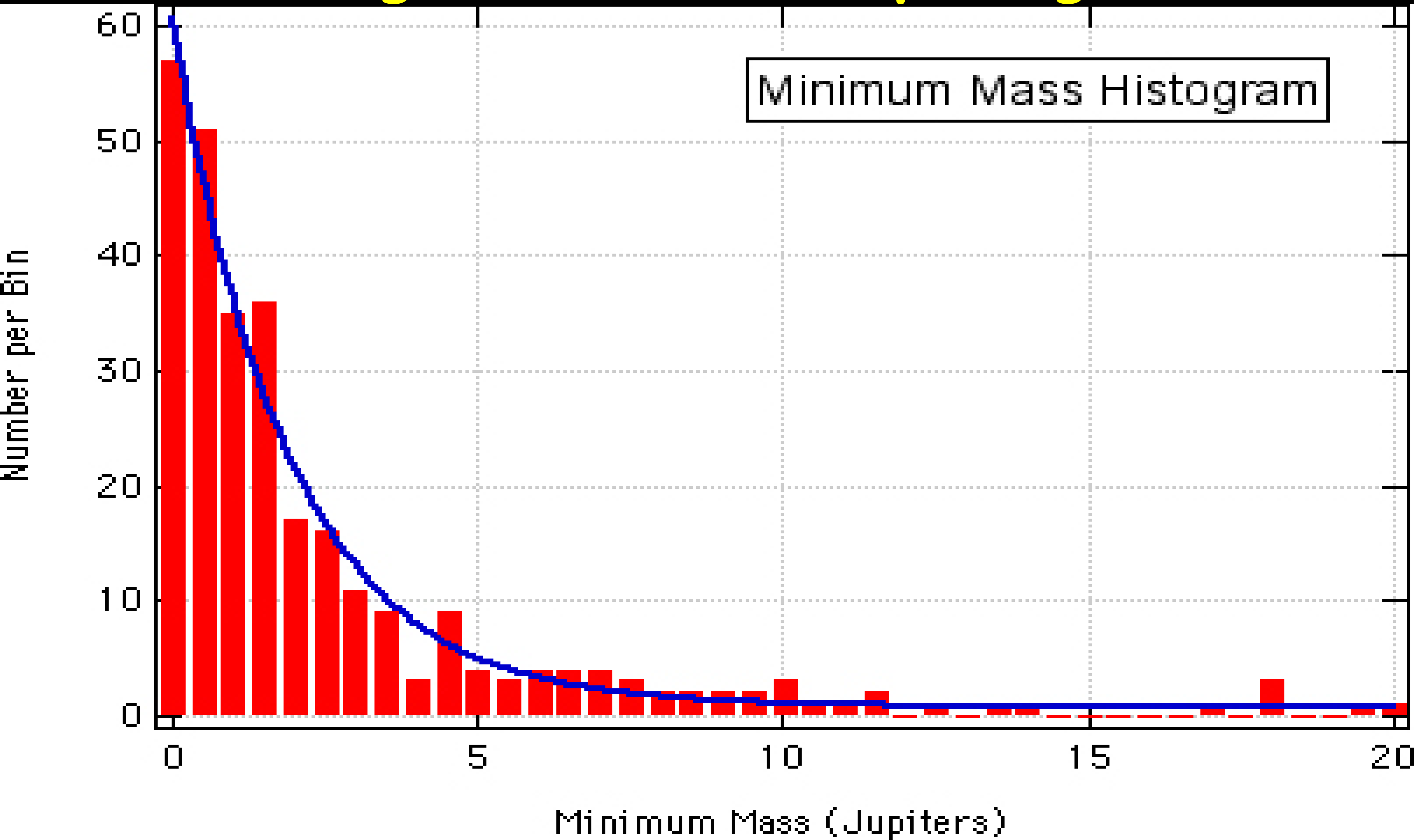
The Kepler Planets Discovered as of Jan '13 (but Biased by Selection Effects; Earth's Hard to Detect)



Selection effects make for discovery of the larger planets, but small rocky planets are believed to actually dominate. Today…



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

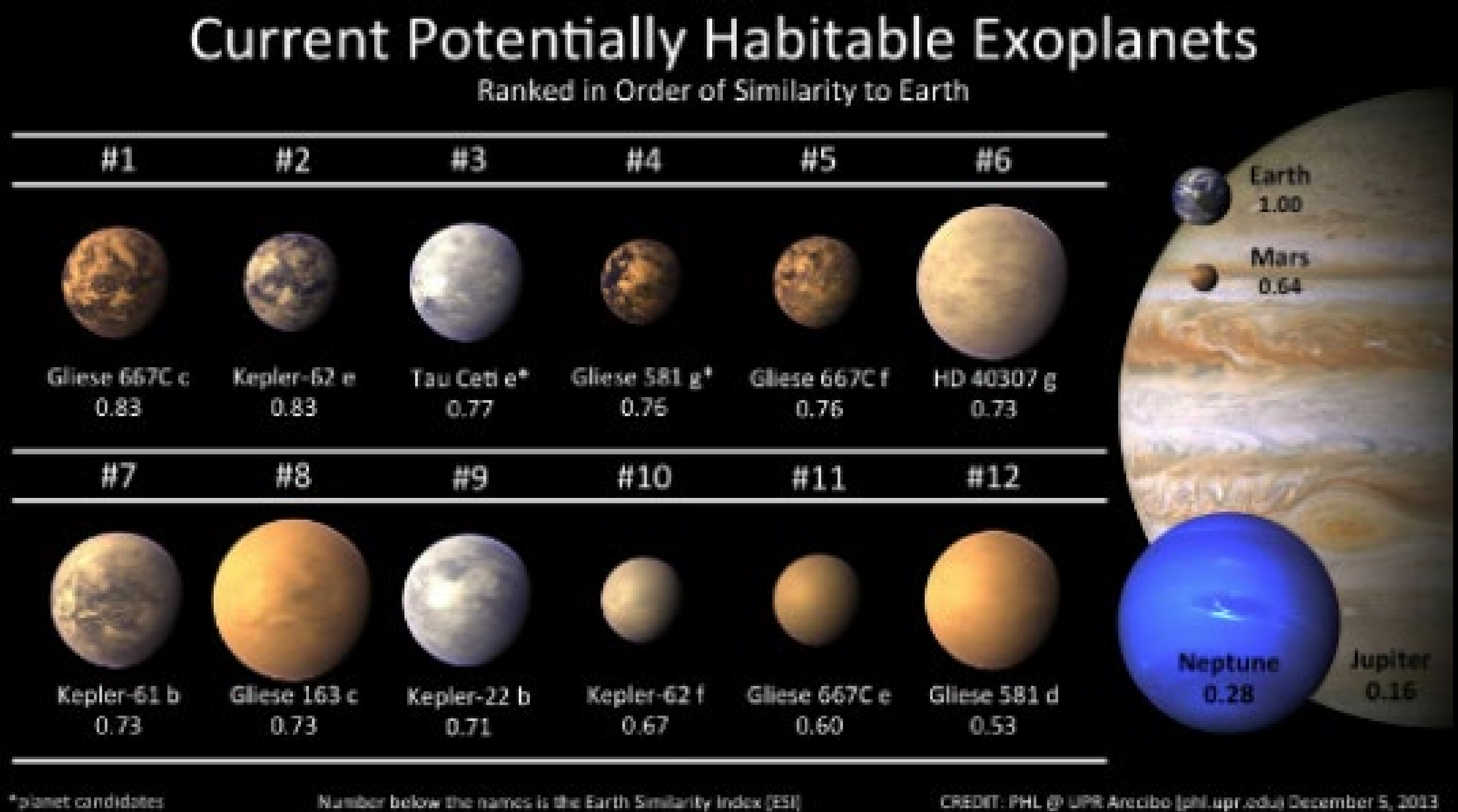


Some Small Kepler Planets vs. Our Own Solar System's Small Planets

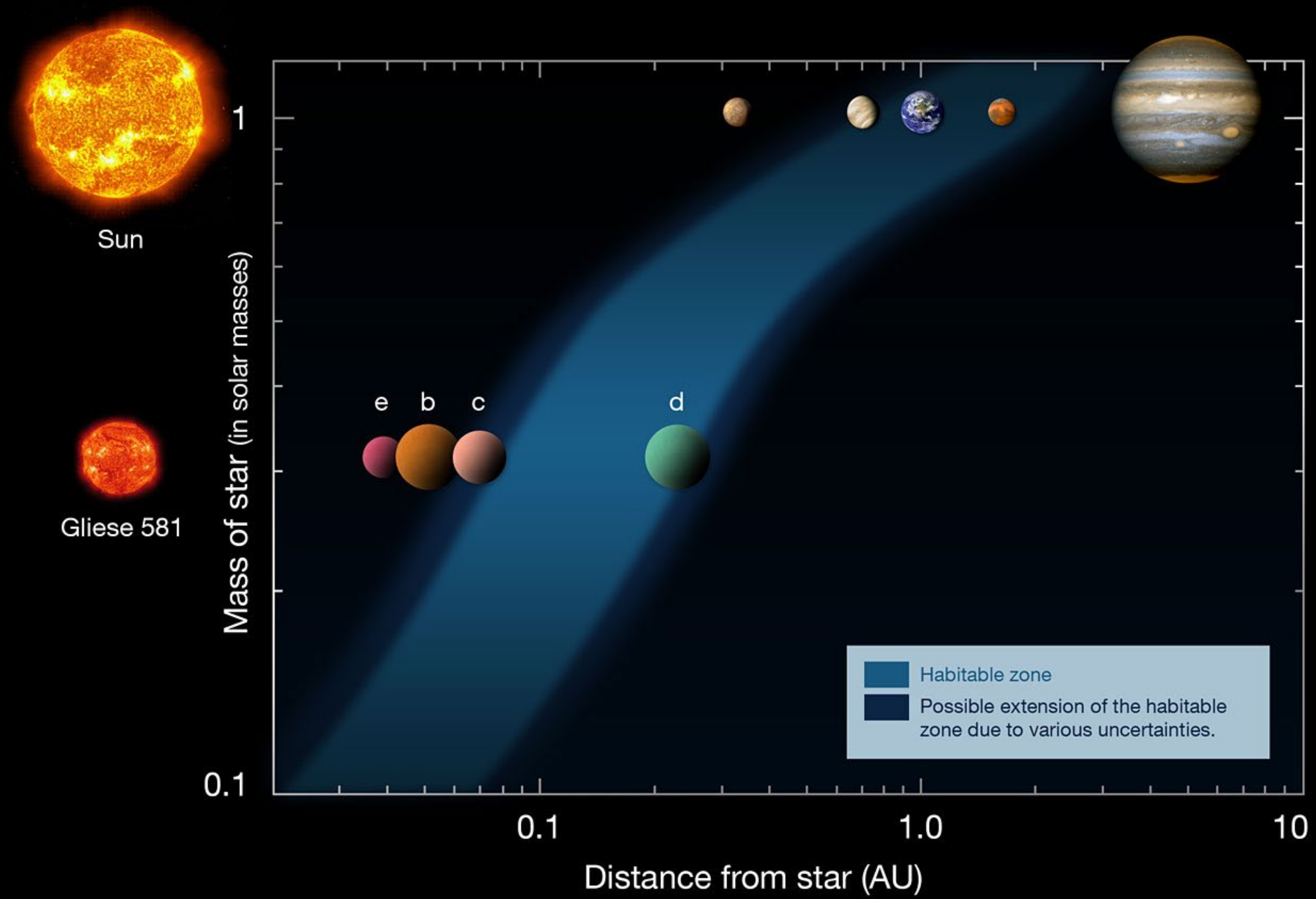
The Definition of the "Habitable Zone"

- No, it doesn't mean there are probably civilizations here
- And it doesn't even mean life is likely here
- It means only that the calculated equilibrium temperature in this region, for a planet, can permit liquid water to exist. BUT, even this requires the right atmospheric composition and density so that greenhouse heating permits liquid water. We believe life requires liquid water.

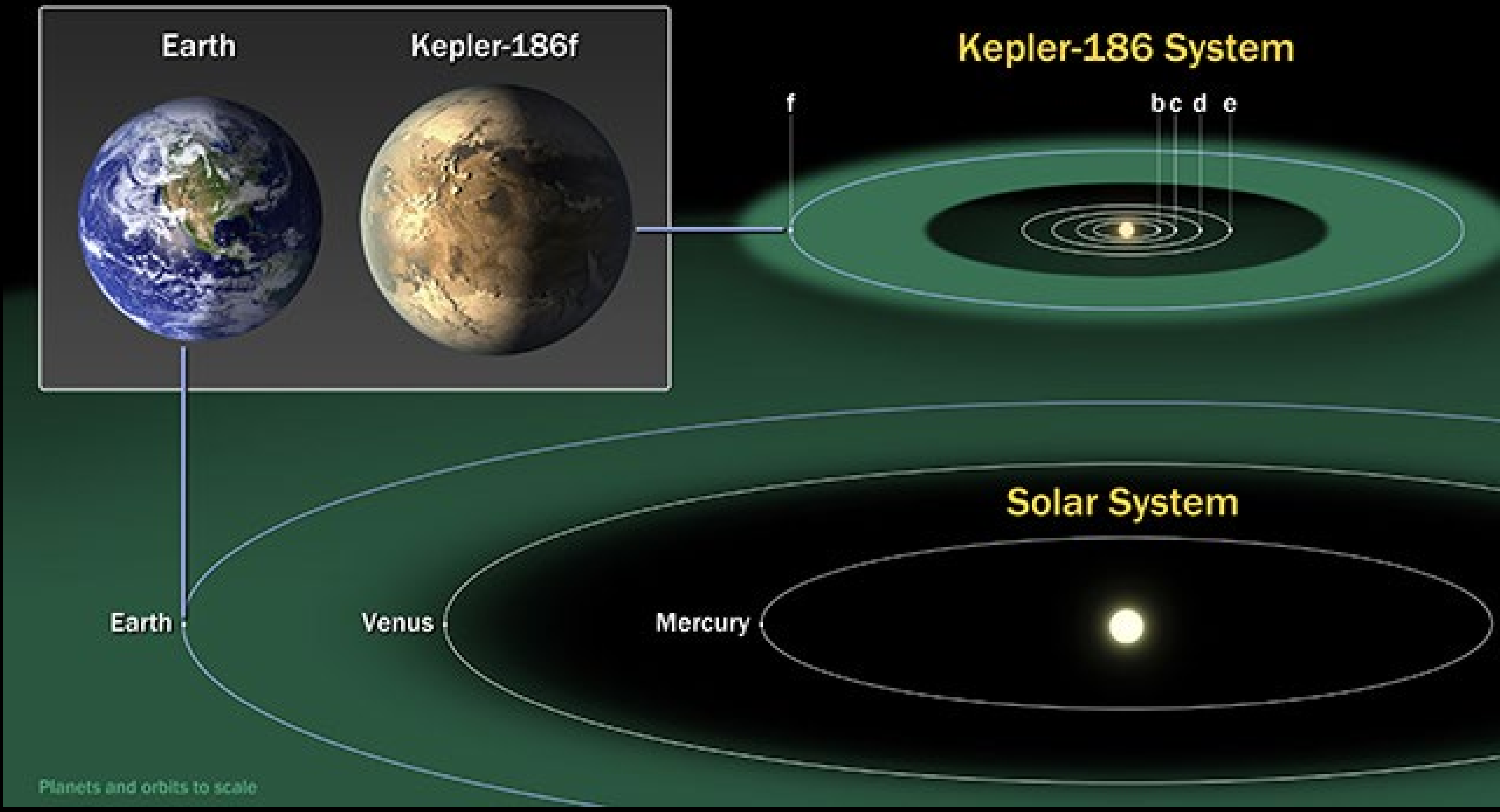
No True Earth's, but Some SuperEarth's in Roughly Habitable Zone



The Habitable Zone: Solar System vs. Gliese 581 System – a red dwarf



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, day likely months long – not good for life
- Mass unknown and unmeasurable (~$0.3\text{-}3.8M_{\mathbf{earth}}$),
- Atmosphere unknown and unmeasurable. If 0.5 to 5 bars of CO2, 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)

Kepler Mission Discovered…

- Kepler, being in space, is capable of very precise photometry and so is sensitive to transits even of plants as small as the Earth
- As expected, Kepler found that small planets are indeed common. More common than the surprising “Hot Jupiters” first discovered.
- **Most extra-solar planets are almost certainly roughly Earth-sized (plus or minus a factor of a few), *vs.* the gas giants first discovered just because they were so discoverable**.

Key Kepler Findings as of 2013

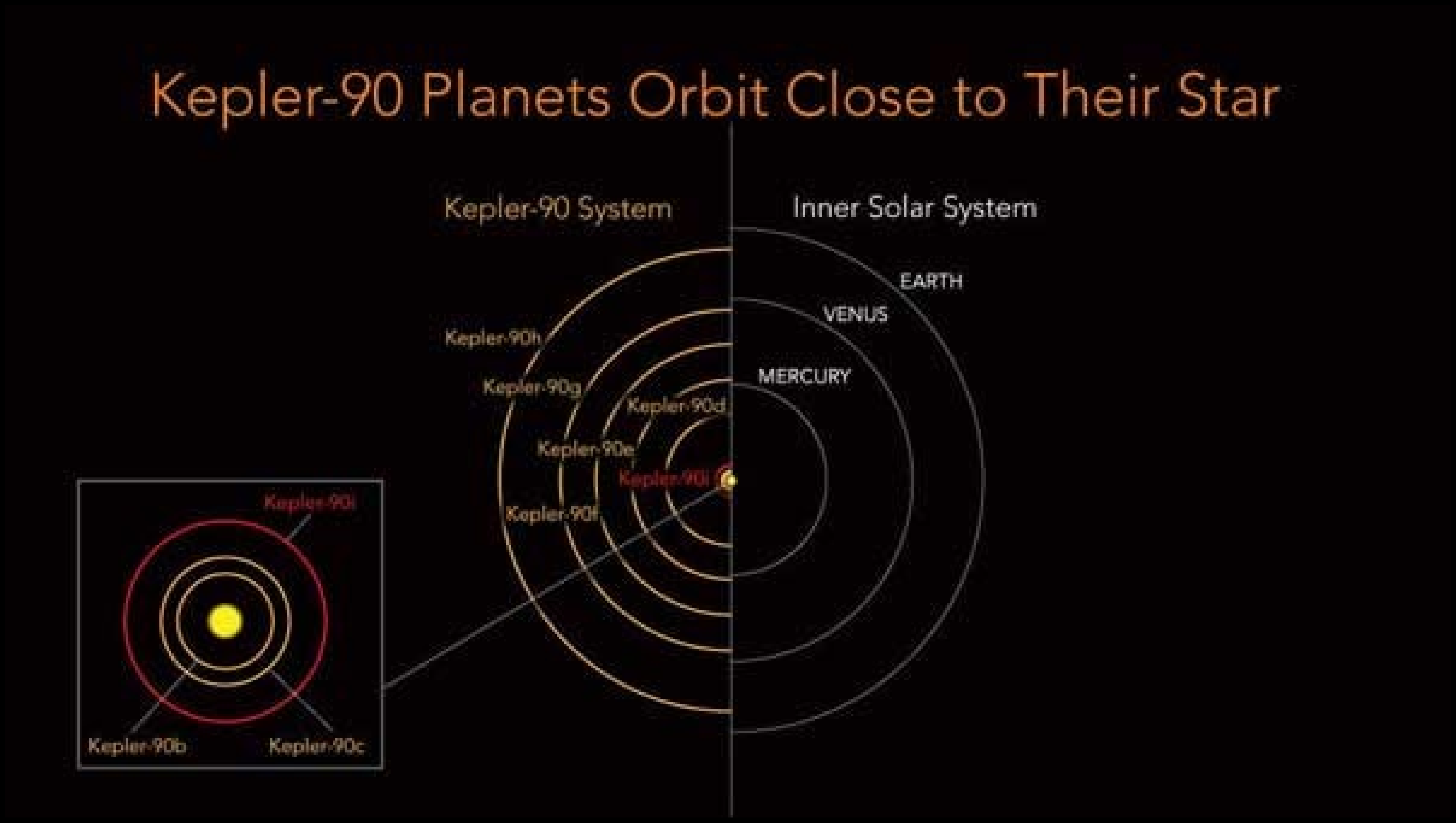
- ~20% of all stars have Earth-sized planets
- Small planets (rocky?) are equally common around both small dim and large luminous stars
- **Almost all stars (at least ~90%) have planets!**
- 43% of Kepler planets have other planet(s) in the same system (which is NOT saying that 43% of all stars have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

Any Solar Systems Out There Like Ours?

- 2,500 planets so far confirmed, but none look truly like ours or our solar system.
- The closest analogue is **Kepler 90**
- **Like: Kepler 90 has 8 planets just like ours, 2 giants, 6 small rocky planets**
- **Like: It orbits a G-type star, very similar to our G2 sun**
- **Unlike: all planets are inside "the frost line" so migration must have been strong. Planets are too hot for life**

Kepler 90: The small inner planets are all larger than any in our solar system: either "Super Earths" or "Neptunes" in structure, depending on their history

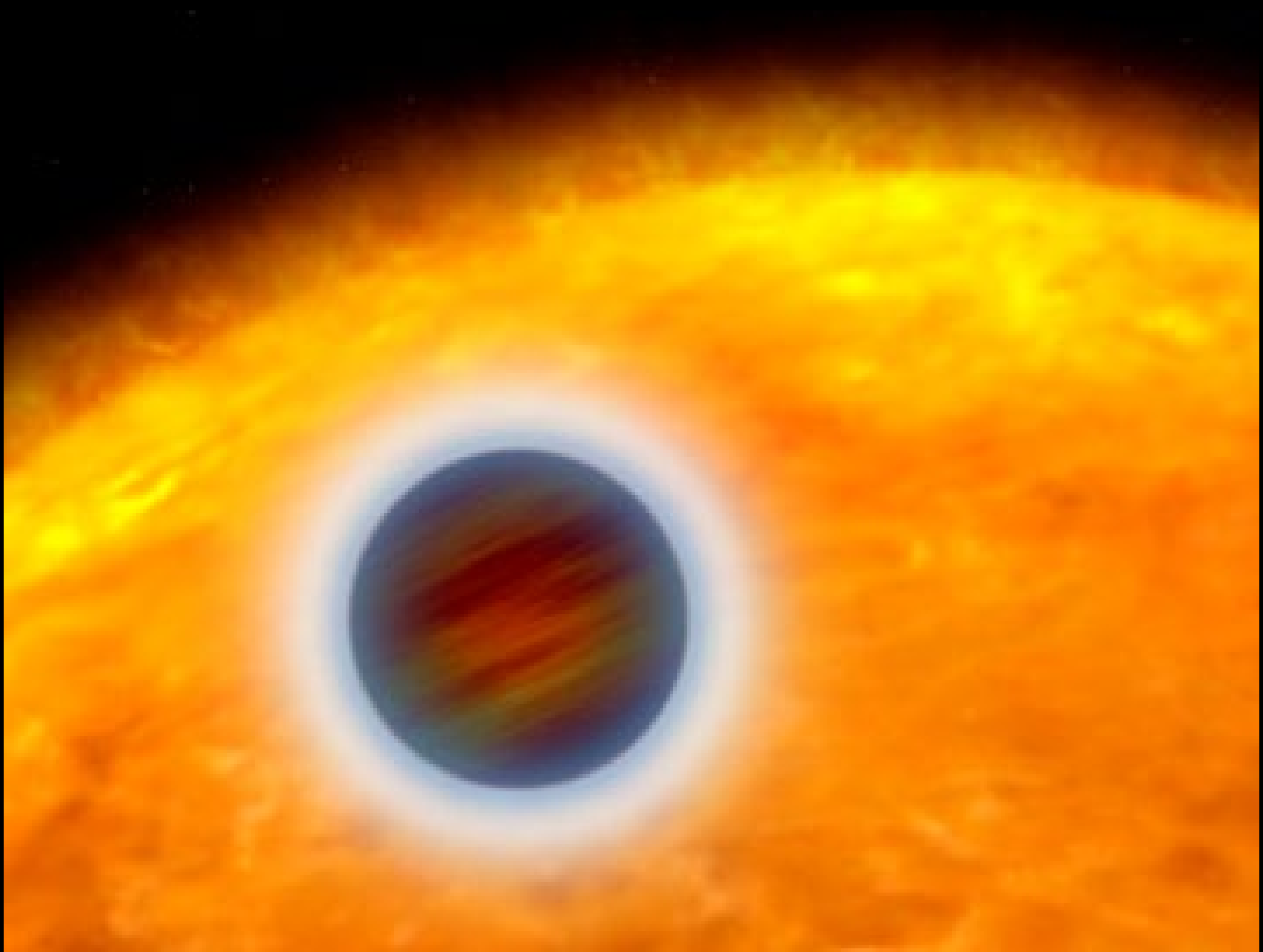
The Whole 8 planet system fits insider the Earth's Orbit: Too Hot!



How to Discover and Characterize the Atmospheres, 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 wavelength bands results in a low-resolution spectrum of the outer atmosphere of the exoplanet…
- …this is a "**transmission spectrum**"
- 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
- HAT-P-12b shows no water vapor absorption, which was surprising. Most likely explanation is the water vapor layer is beneath opaque high clouds which masked the signal

Transmission Spectra- Tough, But CanTell Us Atmospheric Composition



Transmission spectra via Transit Depth - Explained

- NASA – "Alien Atmospheres" (3:22)

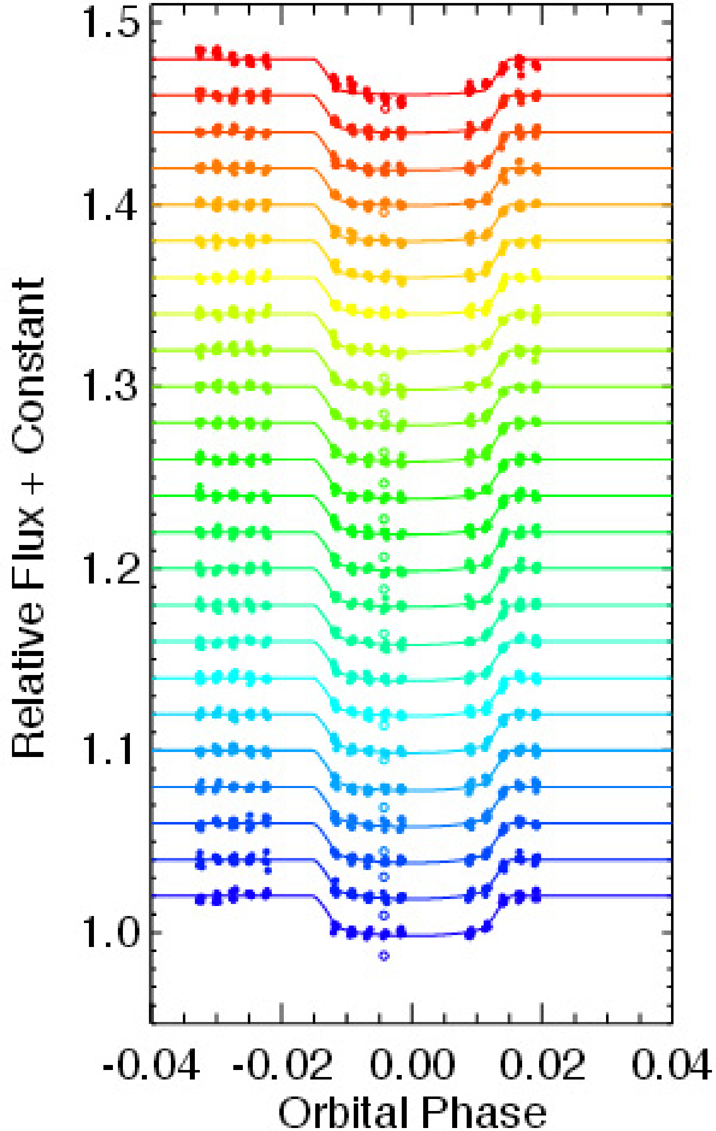
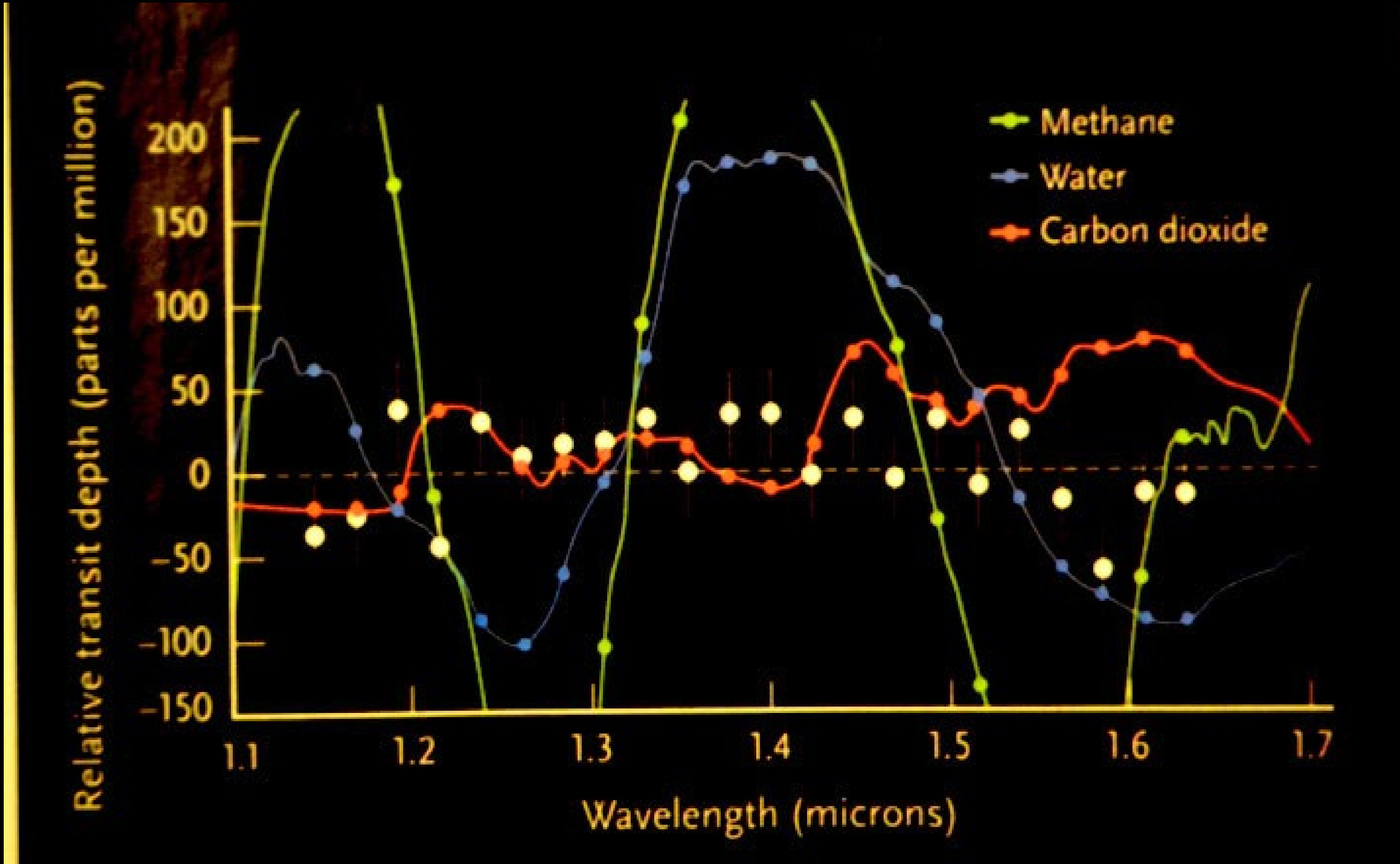


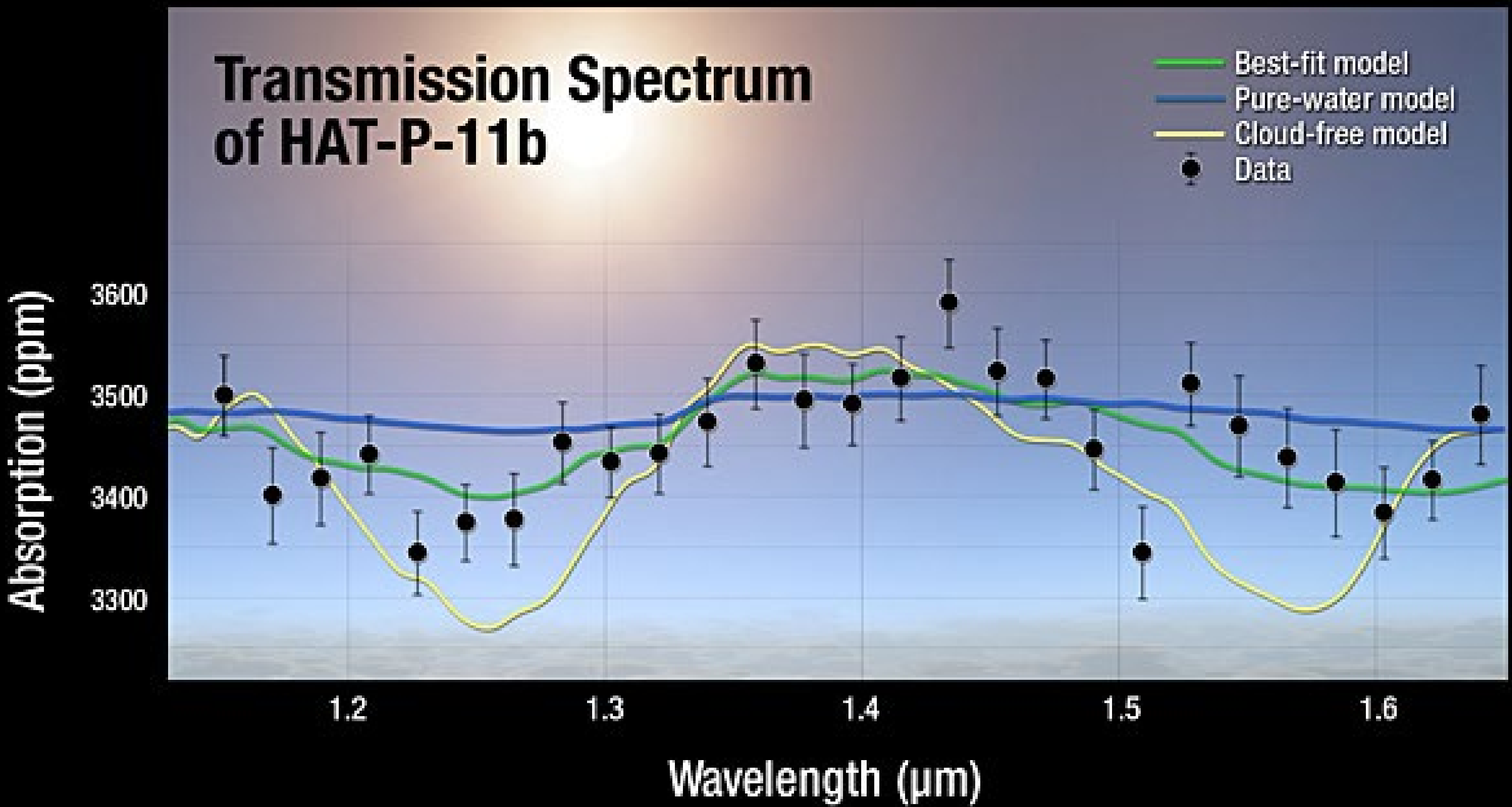
FIG. 3.— Transit model fit to each spectral bin. The systematics are removed from the data (round points with error bars). The solid curves are the best fit light curve models for each bin. Transit eclipse depths for the shorter wavelengths are denoted by blue near the bottom and the longer wavelengths 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) tell us what the atmosphere opacity is and therefore what the atmosphere's chemical composition is.

By taking the known spectral signatures of common molecules, and fitting them to an observed spectrum, you can find roughly how much of each there is in the atmosphere



Water Discovered on Planet HAT-P-11b



High Clouds are Apparently Common on Hot Jupiters

- A recent example – exoplanet HAT-P-12b has had a so-called **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.

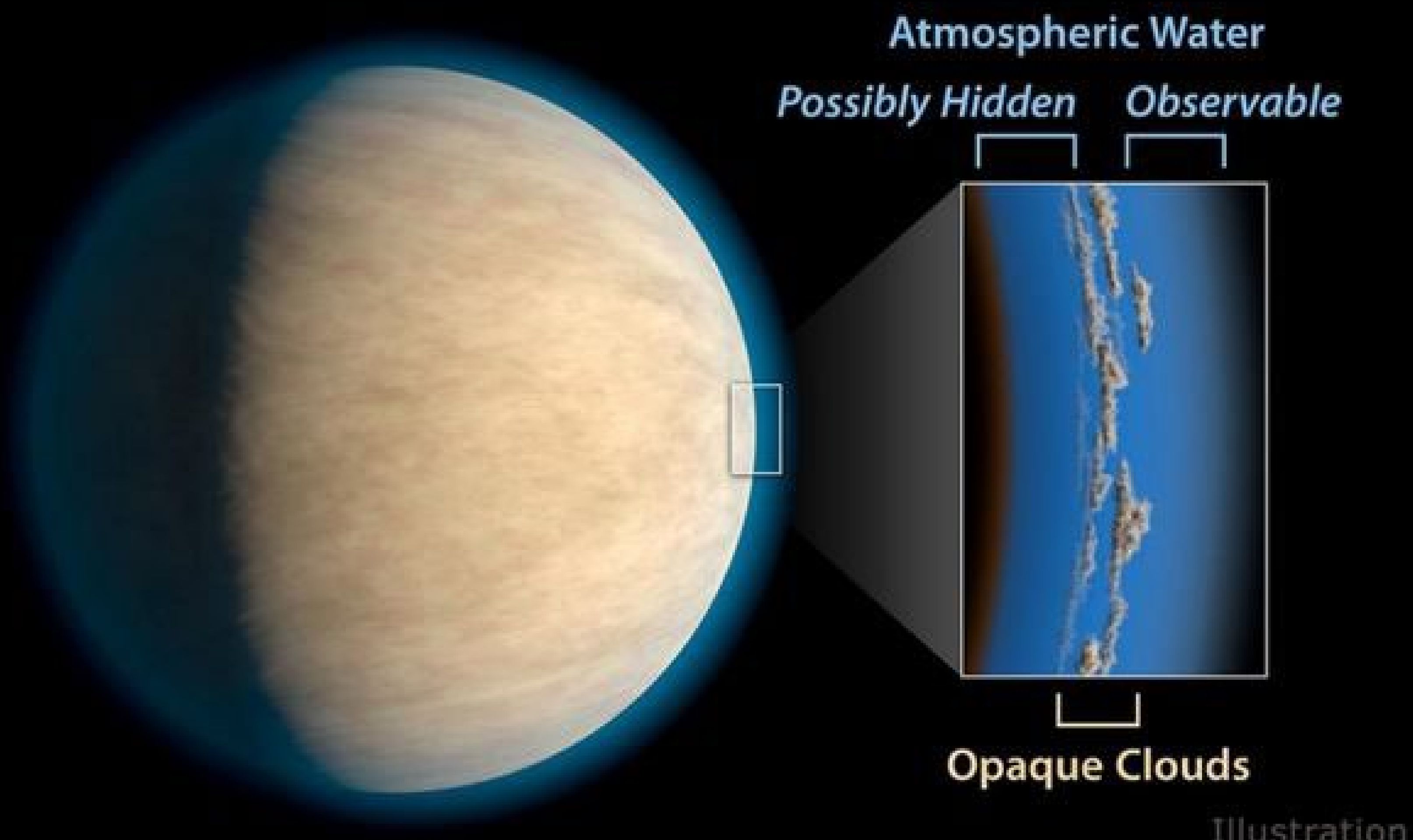
So, How Best to Find Such Candidates for doing Transmission Spectra?

- Signal-to-noise ratio will be very small, and so we must make sure the "signal" is as large as possible – in other words…
- **Bright** stars needed!
- This is where Cabrillo Astronomy may help!

Exoplanet Atmospheres - Observations

- Spectroscopic measurements can be used to study a transiting planet's atmospheric composition.[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.
- 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.
- Stellar light is polarized by atmospheric molecules; this could be detected with a polarimeter. So far, one planet has been studied by polarimetry.
- This research is very much in its infancy! We've barely begun. But here's a couple of papers….

Clouds can hide what the surface is like. Water especially, as it's rather infrared-opaque



Unlike the Doppler or Direct Imaging Methods, Amateur Astronomers Can Contribute to the Discovery and Study of Transits

- Doppler requires very high resolution very expensive spectrographs
- Direct imaging requires coronagraphs, state-of-the-art active optics (see later in this PowerPt)
- But transits only require accurate photometry, which technology is possible for thousands, not millions of dollars.
- Amateur astronomers have confirmed and refined the parameters of several transiting exoplanets

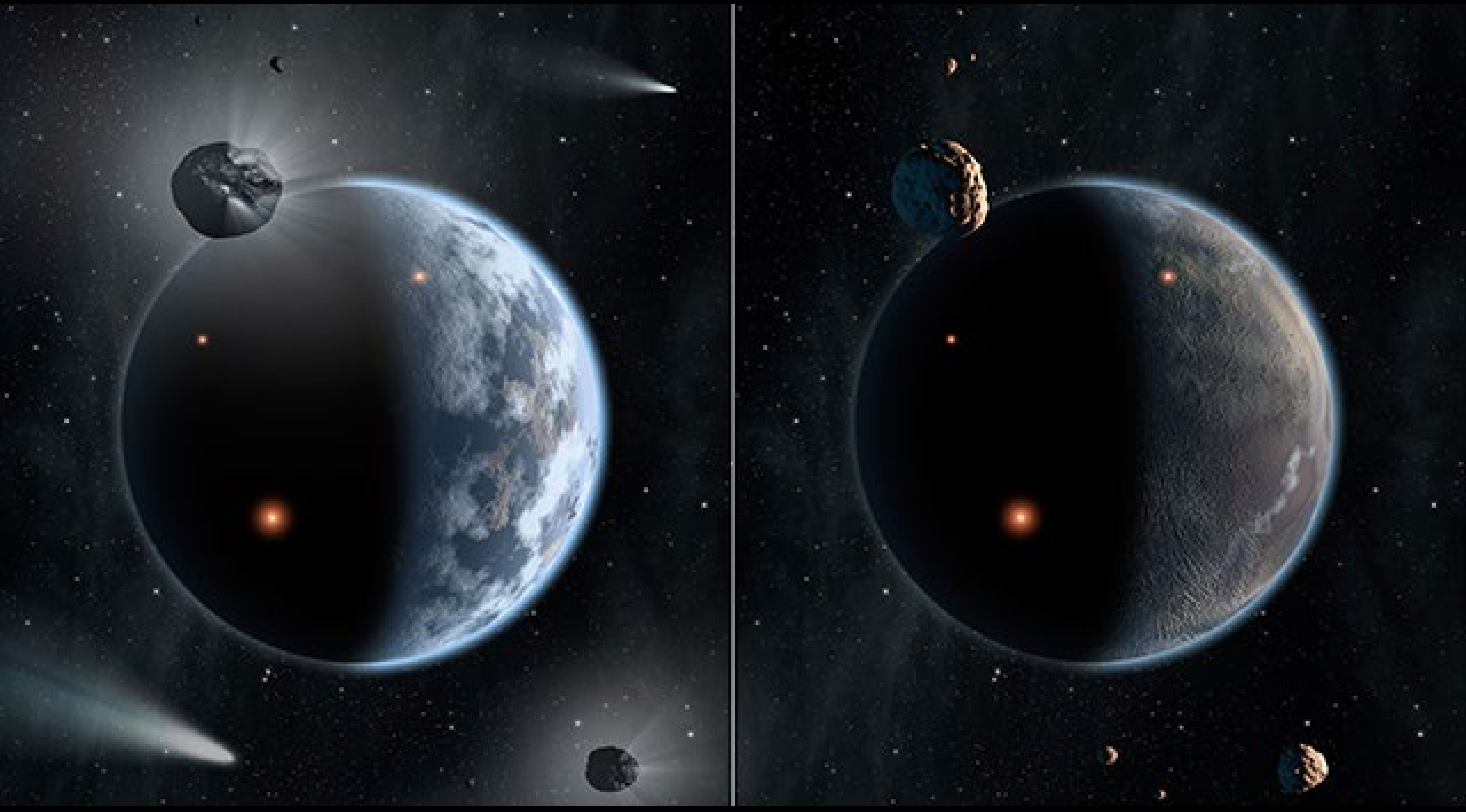
Infrared Light from Hot Jupiters Directly Detected in Favorable Cases

- 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 Rich in Carbon – Don't have Oceans, Says New Study in '13



We were Lucky!

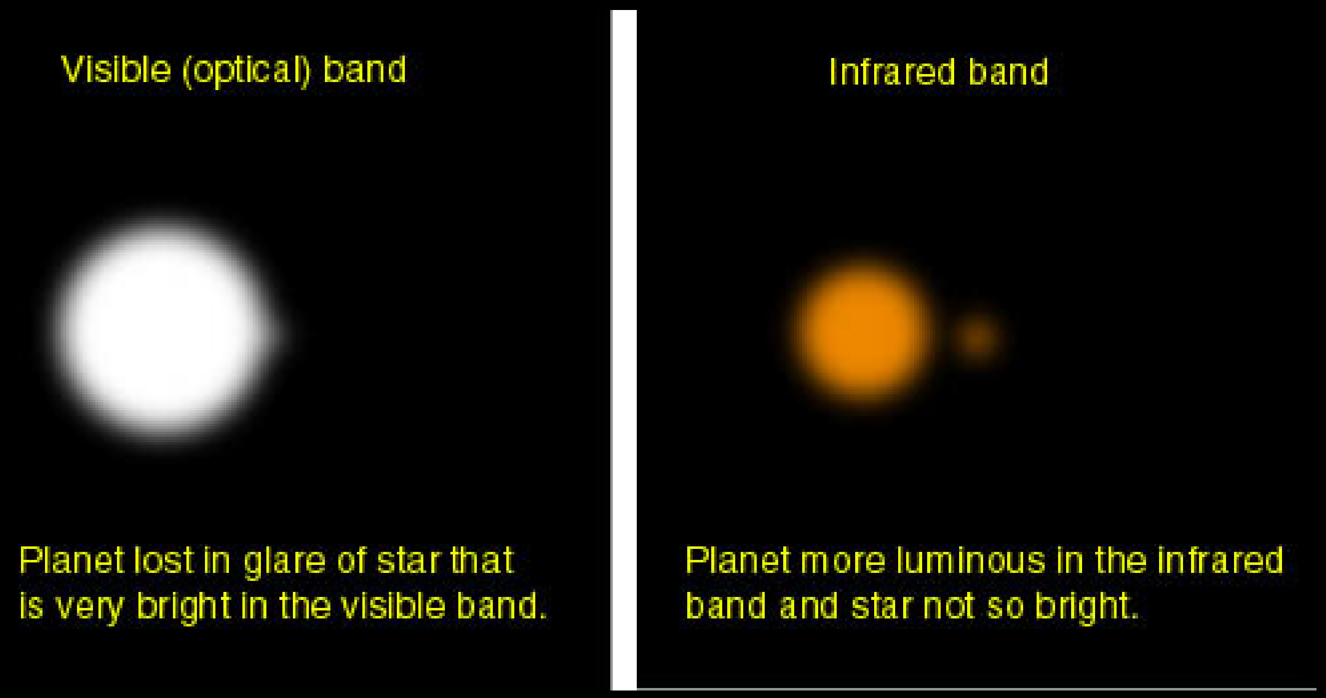
- Excess carbon will grab the oxygen and lock it into CO and CO_2, or in crystalline form as diamond if mass and pressure is high enough
- That leaves no oxygen left to bind with hydrogen and make water
- Bummer. But, our own solar nebula happened to be low in carbon, hence we have an oxygen left to bind with hydrogen and make an ocean-dominated planet and life. We were lucky!
- You want carbon for life, but just some, not a lot, or you get no water or oceans, which are also required for life.
- 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

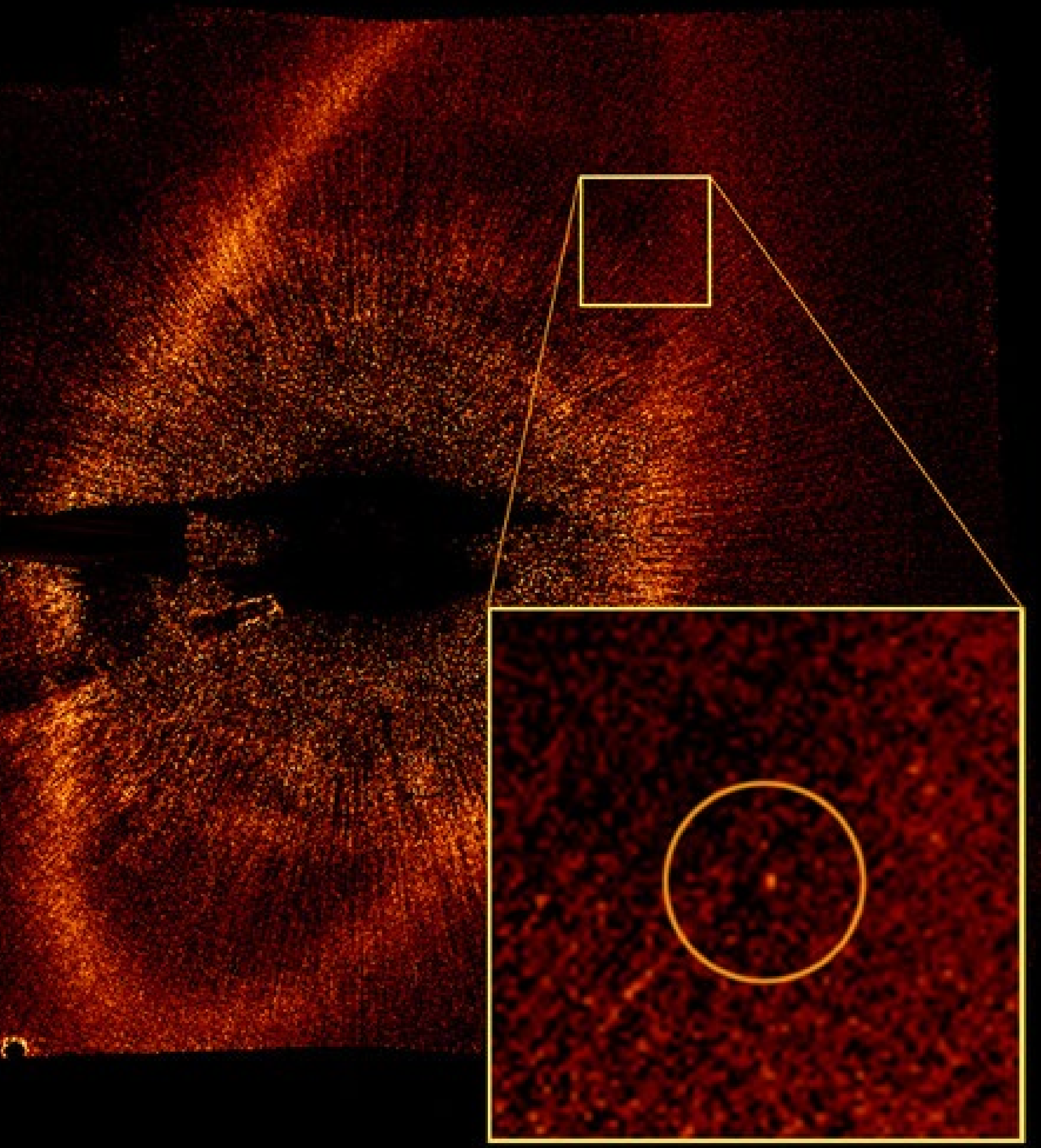
And in the year – 2008…

- ***<u>The first image of planets around another star…. !</u>***

- ***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***

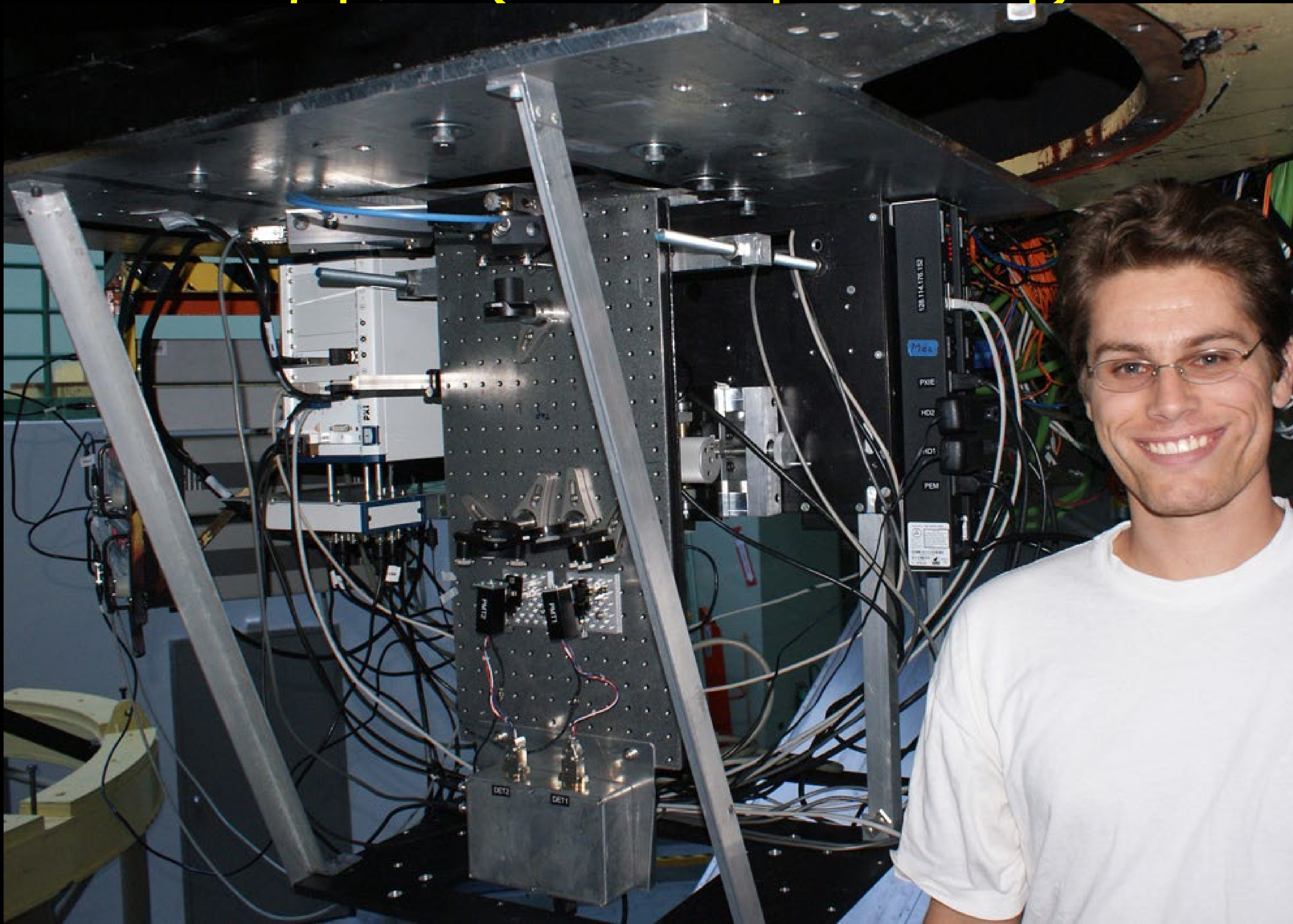
Much Easier to See Planets (but still very tough) in the Infrared, Where Planet Puts Out ~All of it's Light



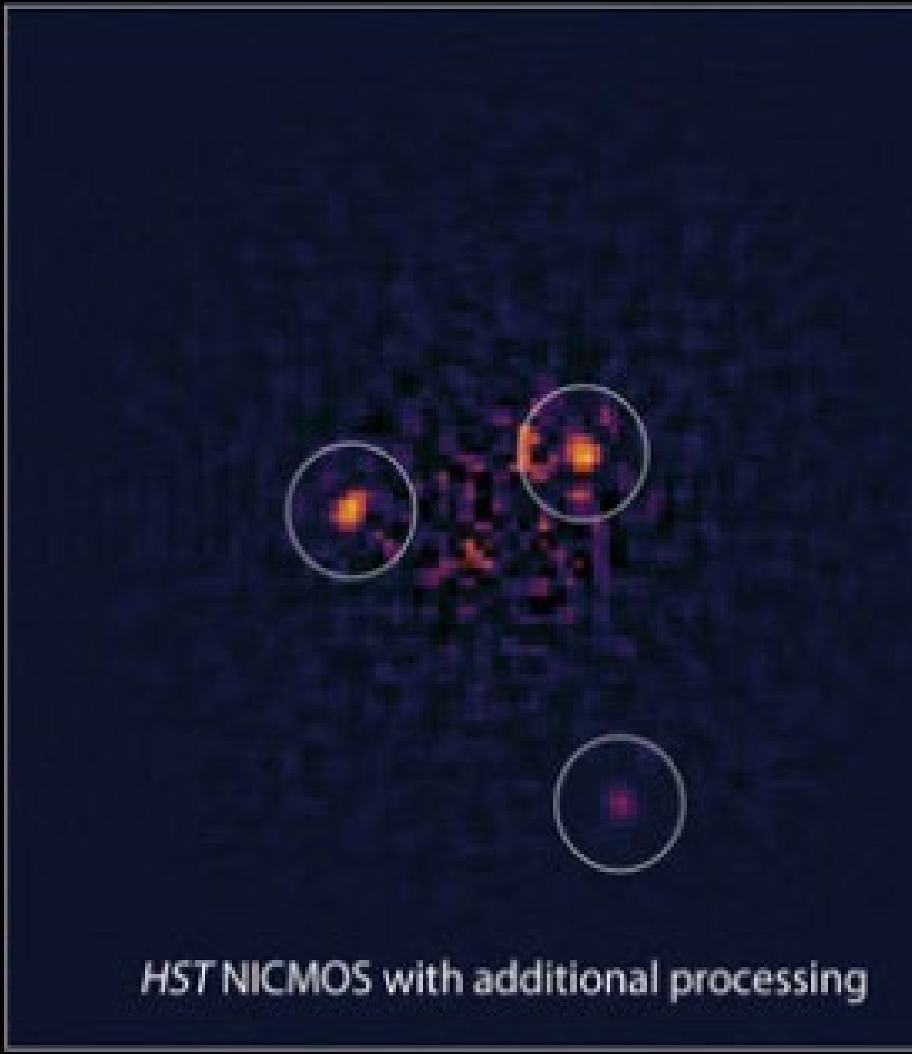


- This particular speck was NOT digital noise; it followed the laws of gravity, and must be a planet!

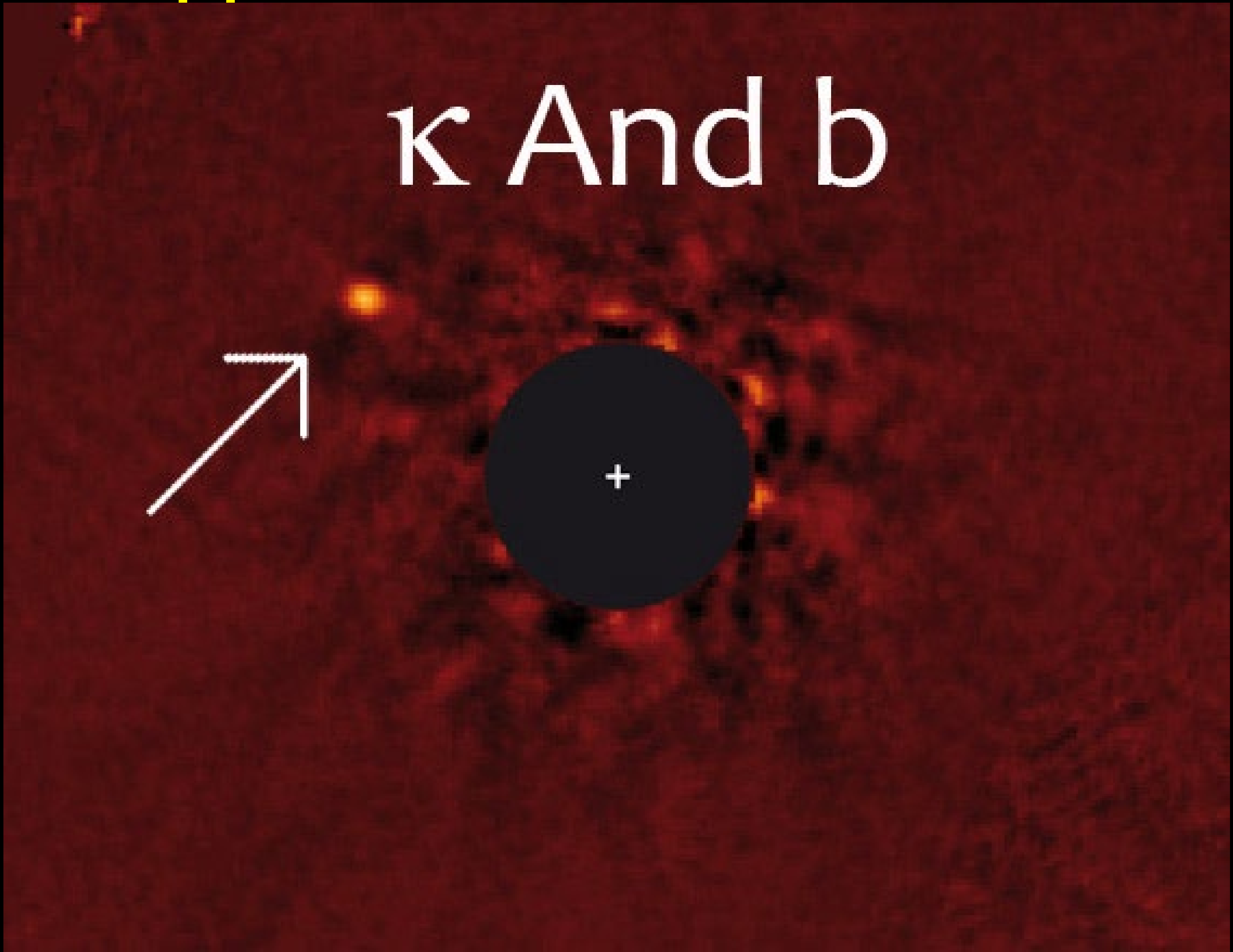
Young CalTech Astronomer and spectrograph equipment (Caltech Exoplanet Group)



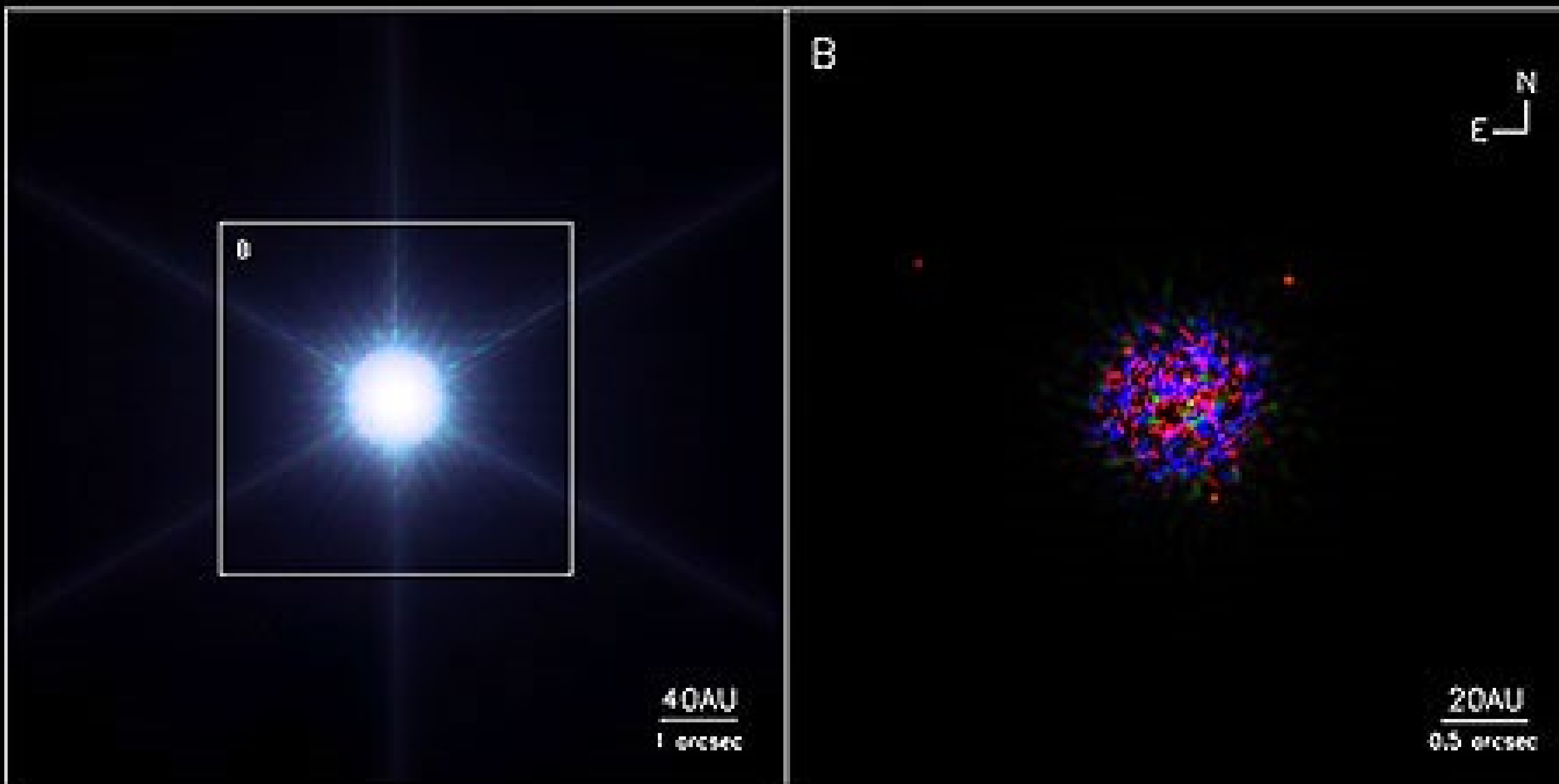
Lots of Image Processing Needed to Pull out the Planet from the Image Noise



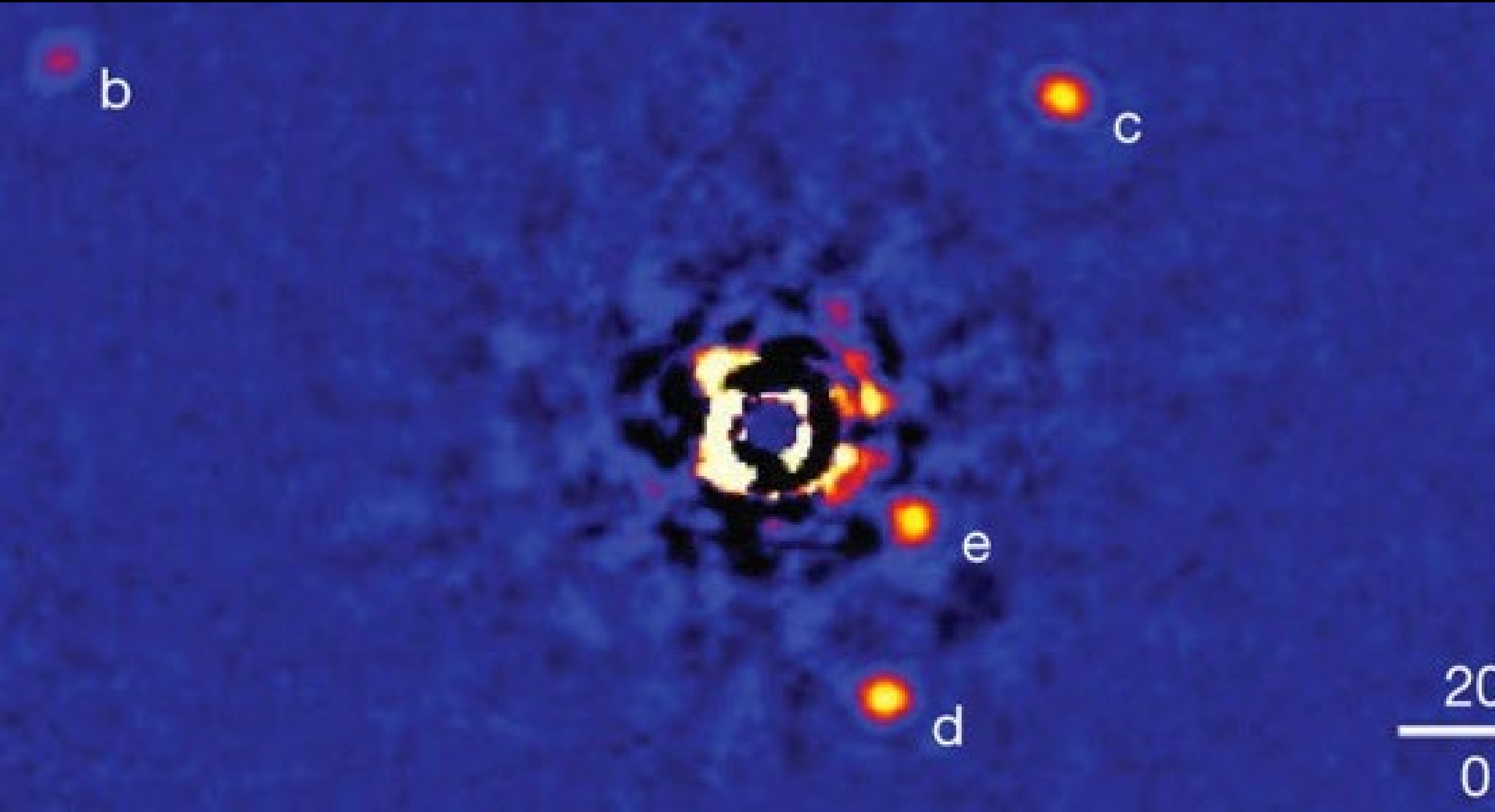
Kappa Andromedae's Planet

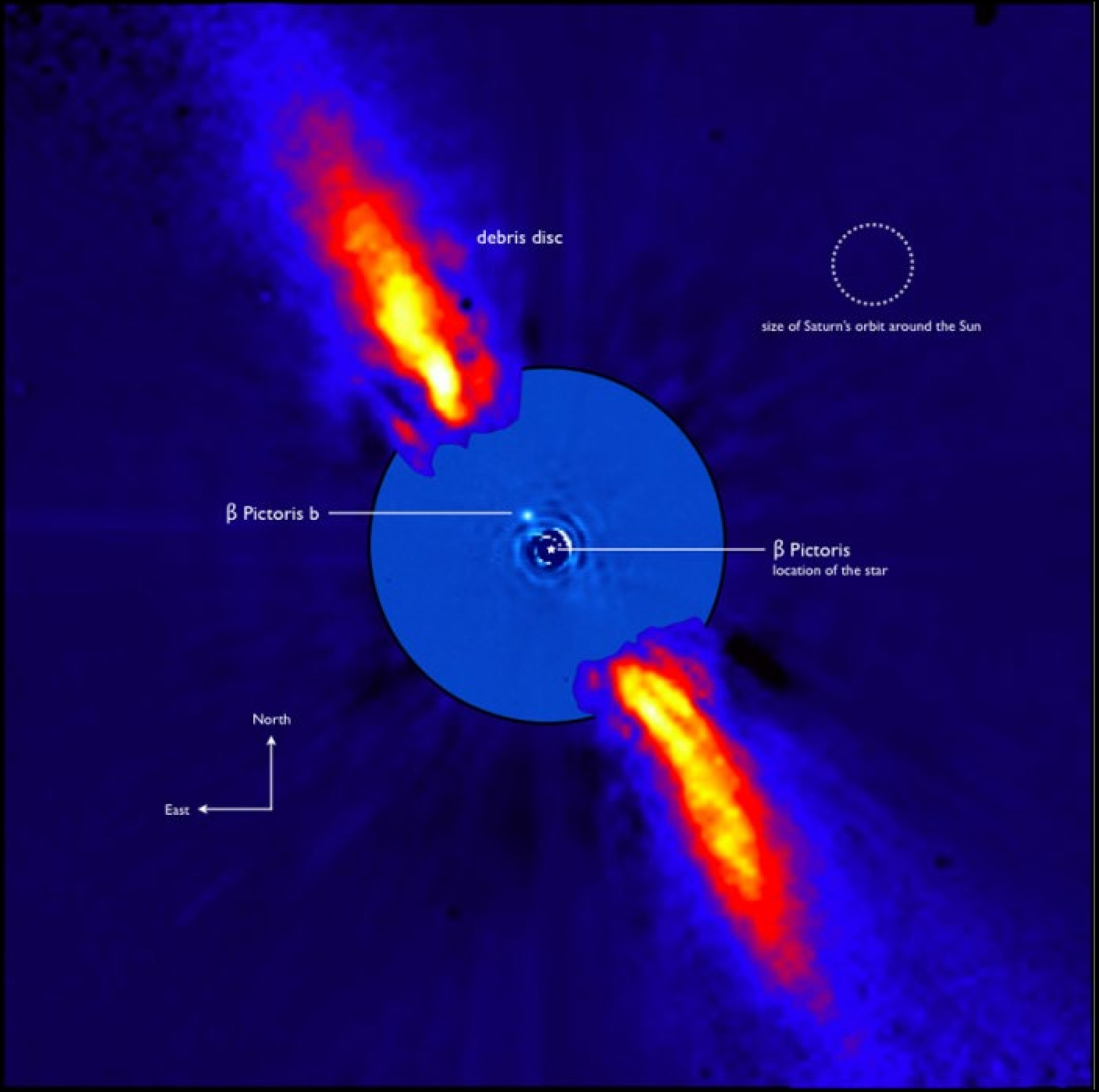


HR 8799 Planetary System



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




debris disc
size of Saturn's orbit around the Sun
β Pictoris b
β Pictoris
location of the star
North
East

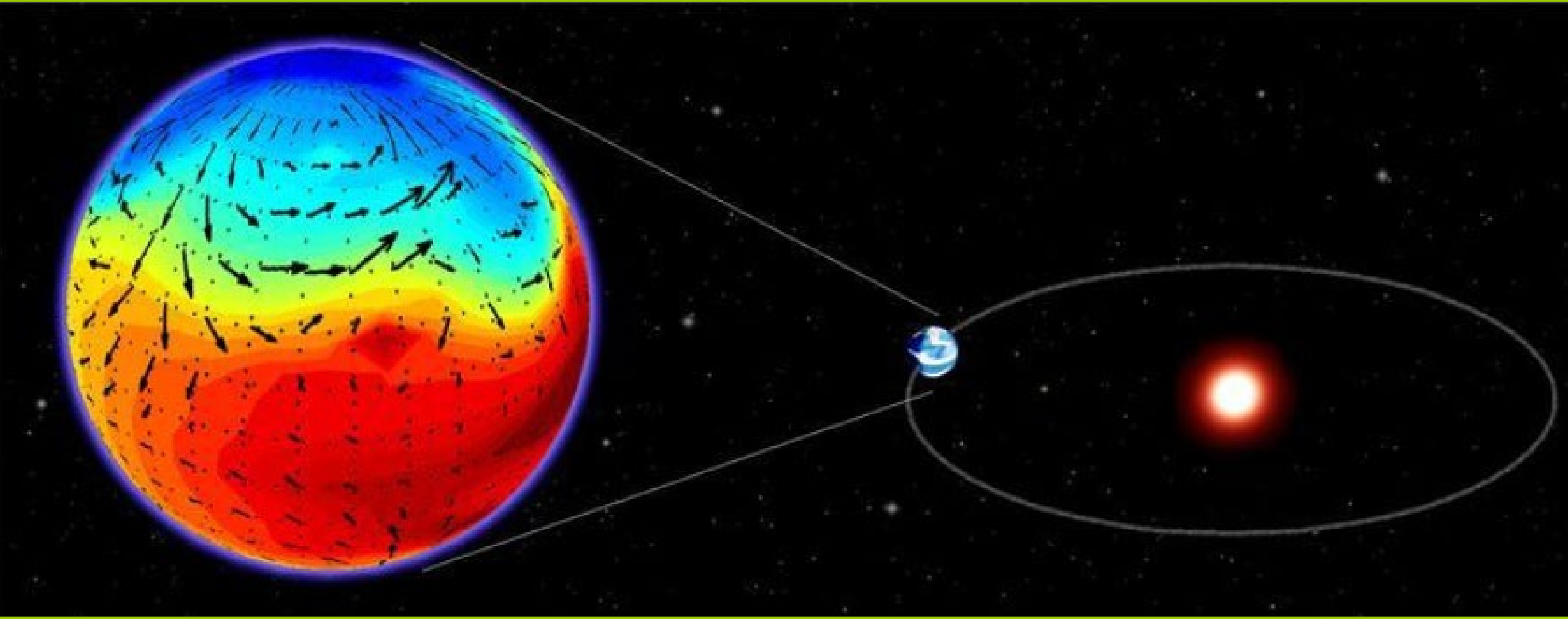
Other Niche Methods of Discovering Exo-Planets

- **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 need to be so close to be warm and in the "habitable zone", that tidal stretching would grab hold of the planet's rotation and halt it – **"Tidally Locked"**
- Sunny side would be permanently sunny, night side cold and permanently night
- Tough on climate!!

Tidally Locked Planet, with High Winds from Cold to Hot Side



Could They Support Life?

- A narrow zone permanently at sunset or sunrise might 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 high winds

Key Points – Chap 13: Exo-Planetary Systems

- Doppler method preferrentially finds CLOSE and MASSIVE 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
- Absorption lines from bright star transits may tell us atmospheric chemistry
- Infrared light variations during orbit can tell us the temperature of the planet
- Transits: Transmission spectra tell us atmosphere structure and some constraints on composition, clouds
- Amateur astronomers have contributed, via the observations of transits
- Data so far implies **90% or more of all solar-type stars have solar systems**
- Most planets in **very elliptical orbits**, most likely caused by **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 from their formation point, and ruined habitable planets in doing so, but most common are small planets closer to Earth sized, after correcting for observational bias.
- **Planetary migration appears very common**. Our solar system unusual in <u>not</u> having much migration
- Habitable Zone: Where liquid water can exist, IF the atmosphere is right.
- Red Dwarf habitable planets would be tidally locked, likely have 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 TRUELY Earth-like planets yet discovered out of the ~3000 detections.