ASTRONOMY STATE OF THE ART

3. Exoplanets

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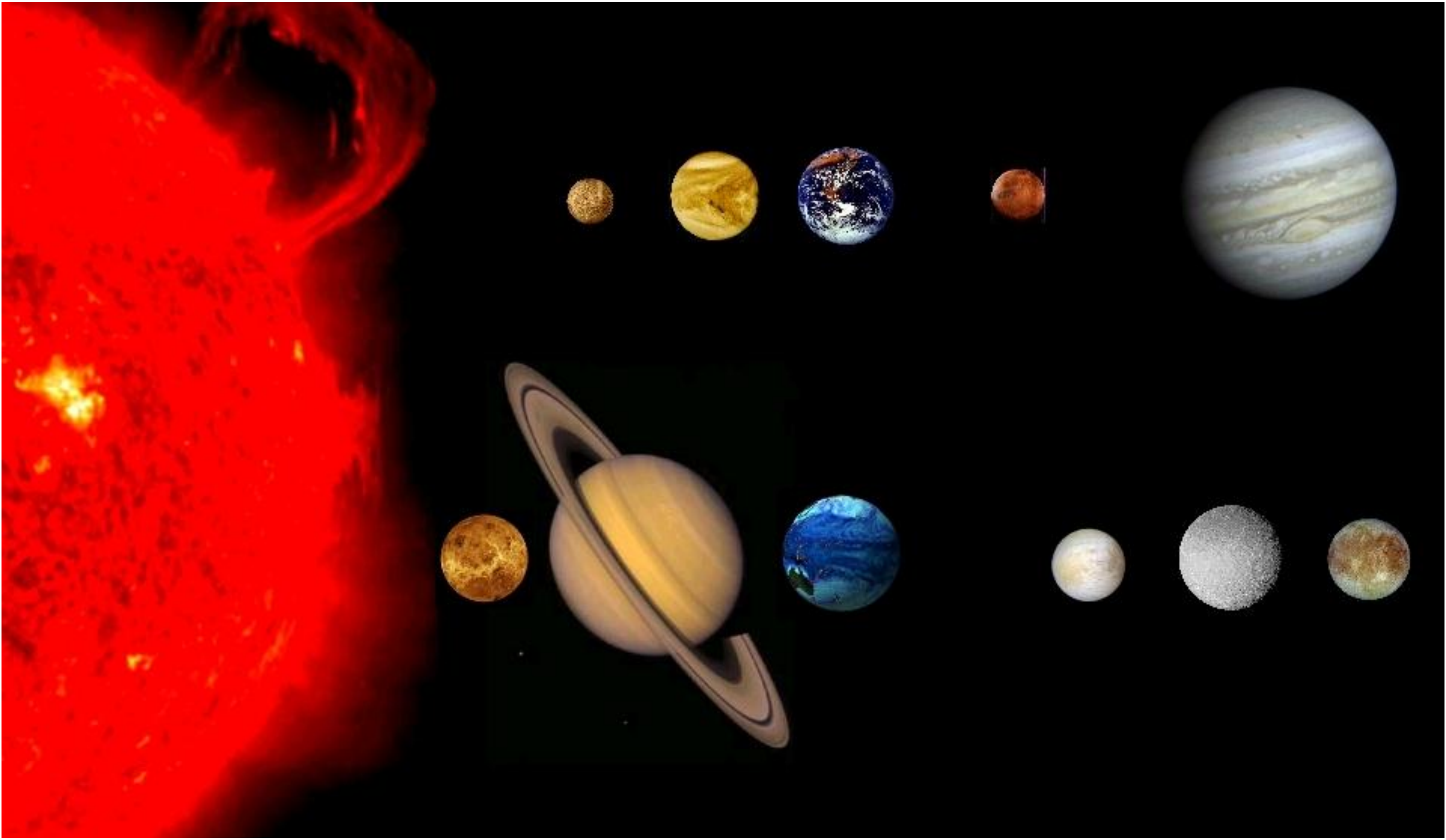
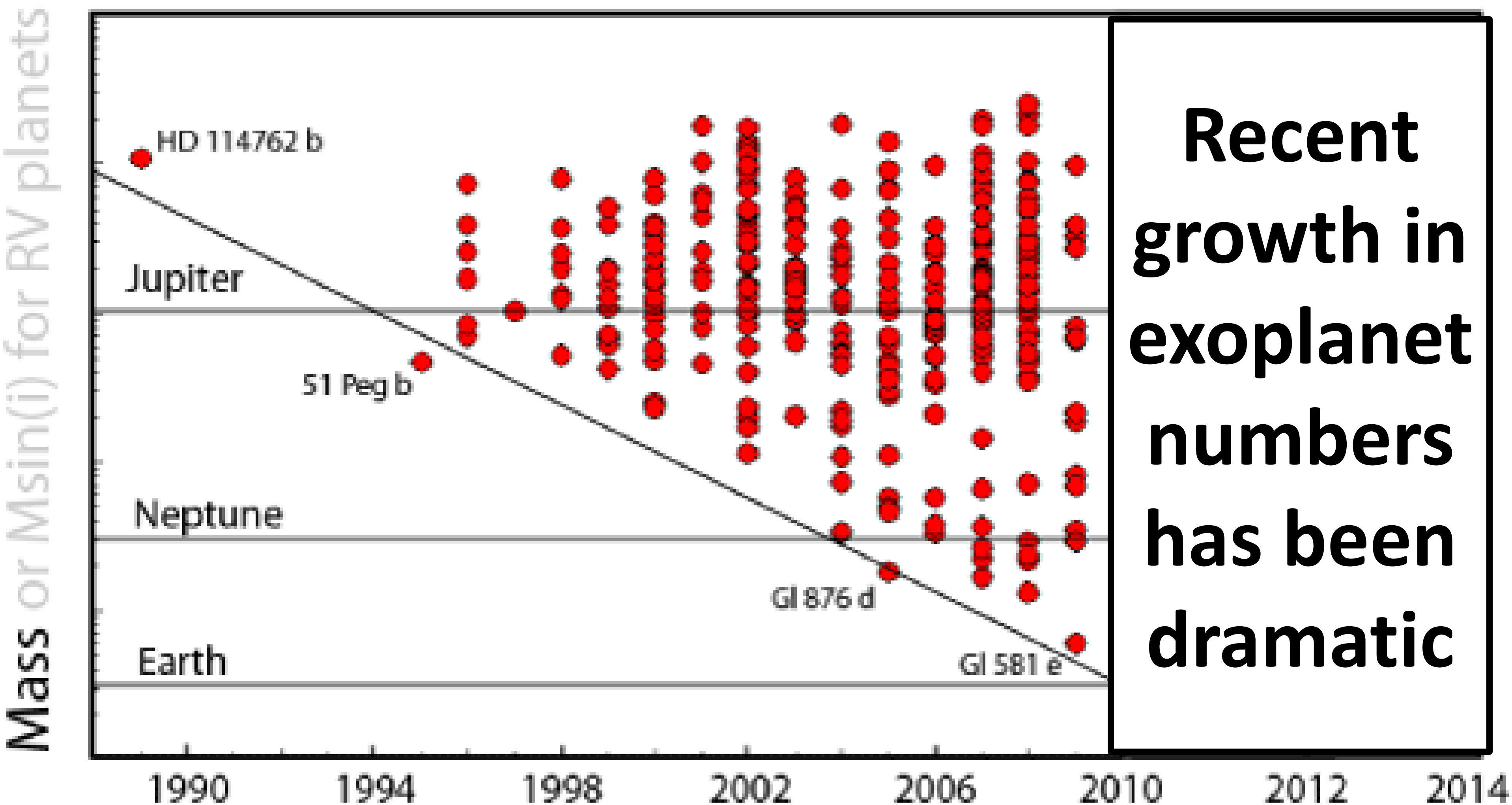
Exoplanets

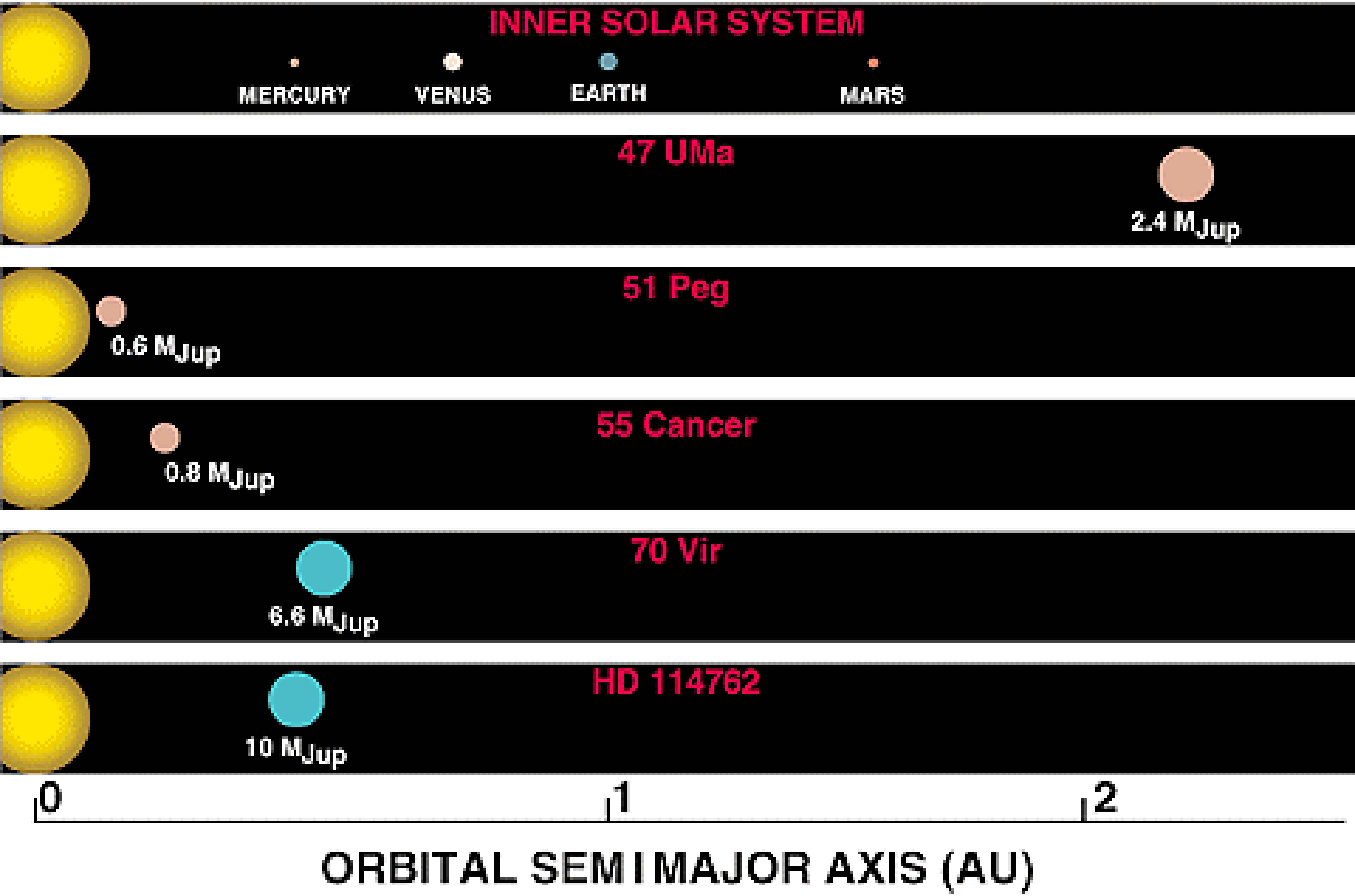


Homing in on Home

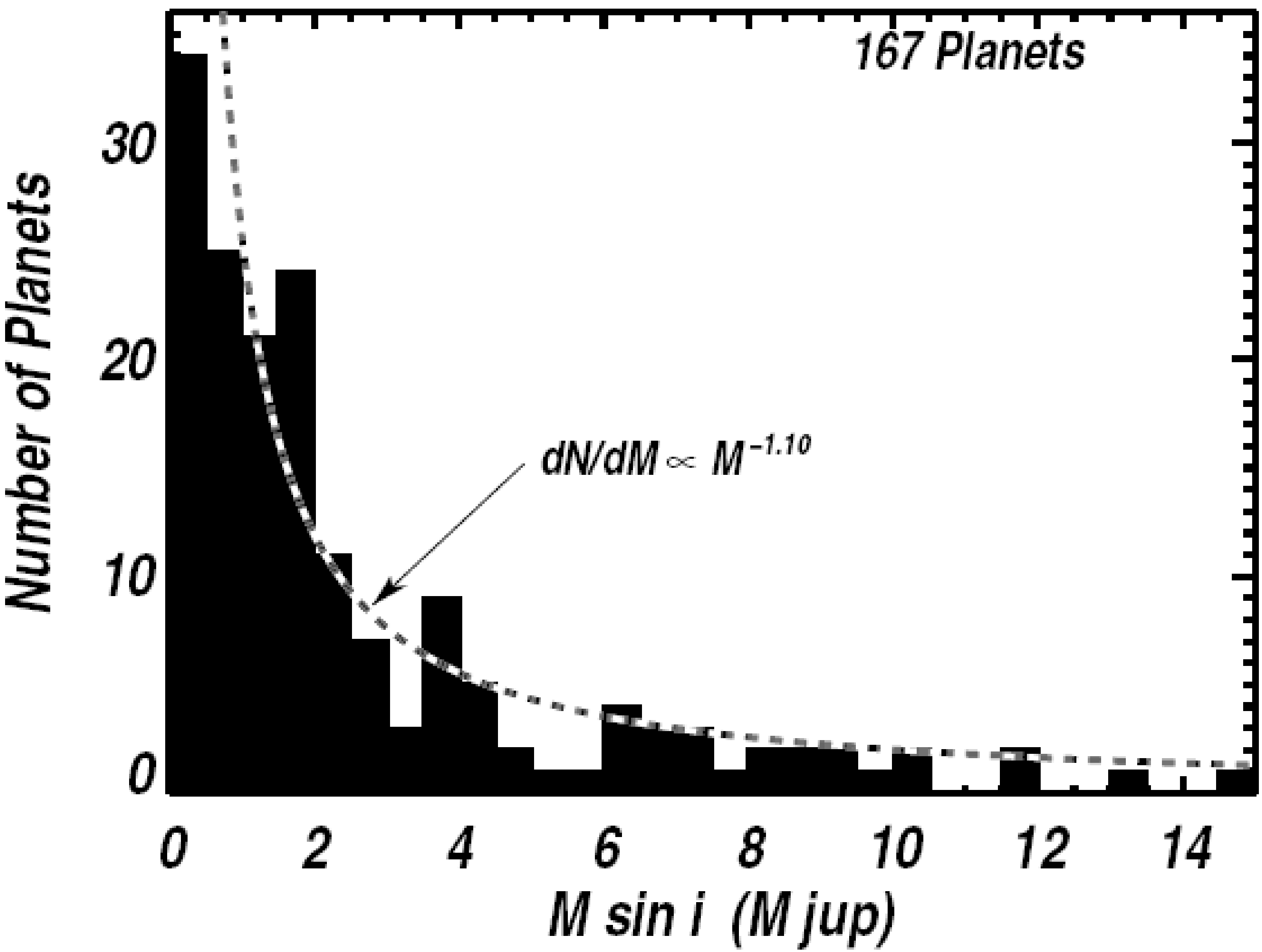


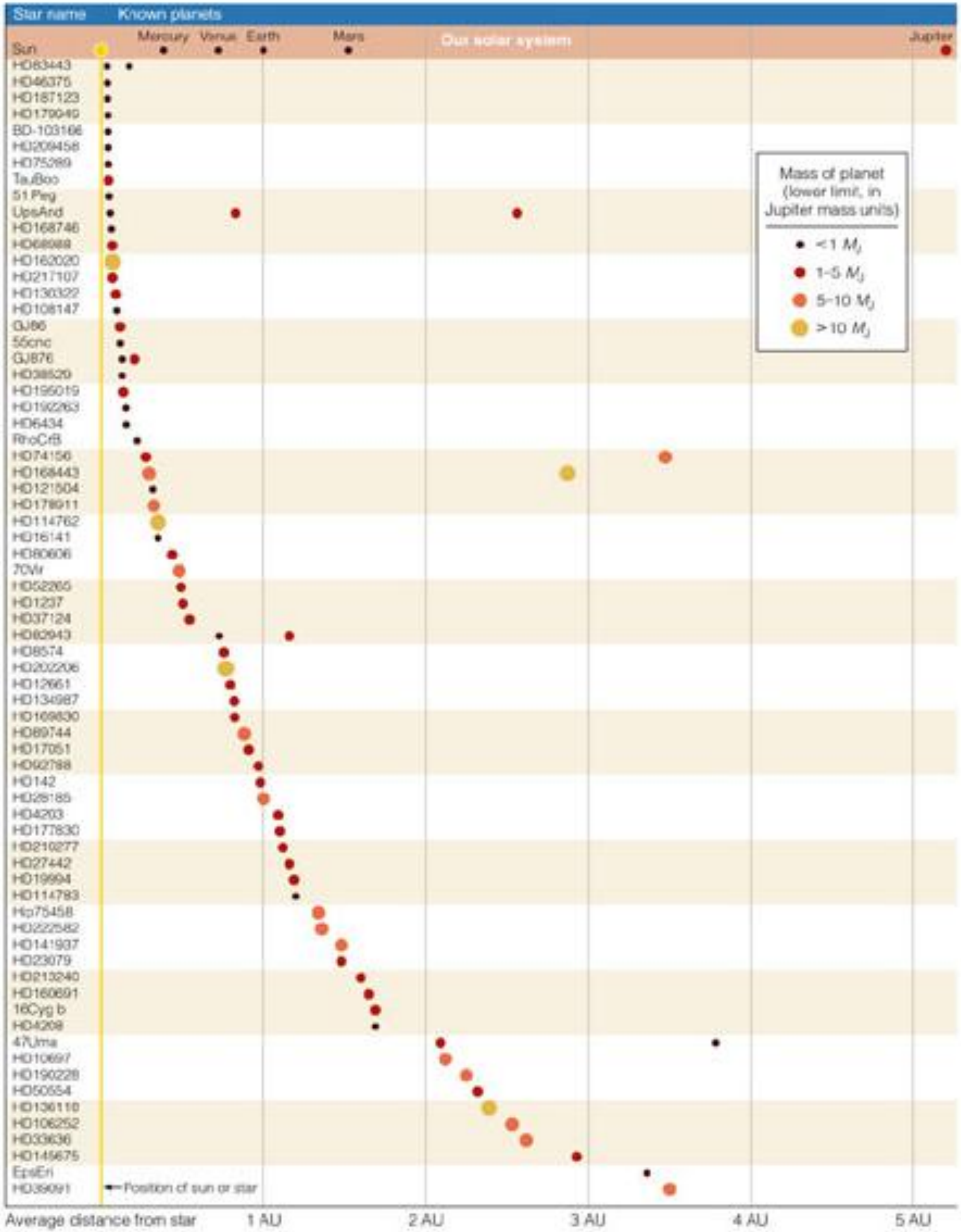
Recent growth in exoplanet numbers has been dramatic

Early Discovery of Hot Jupiters



Indication of More Low Mass Than High Mass Planets

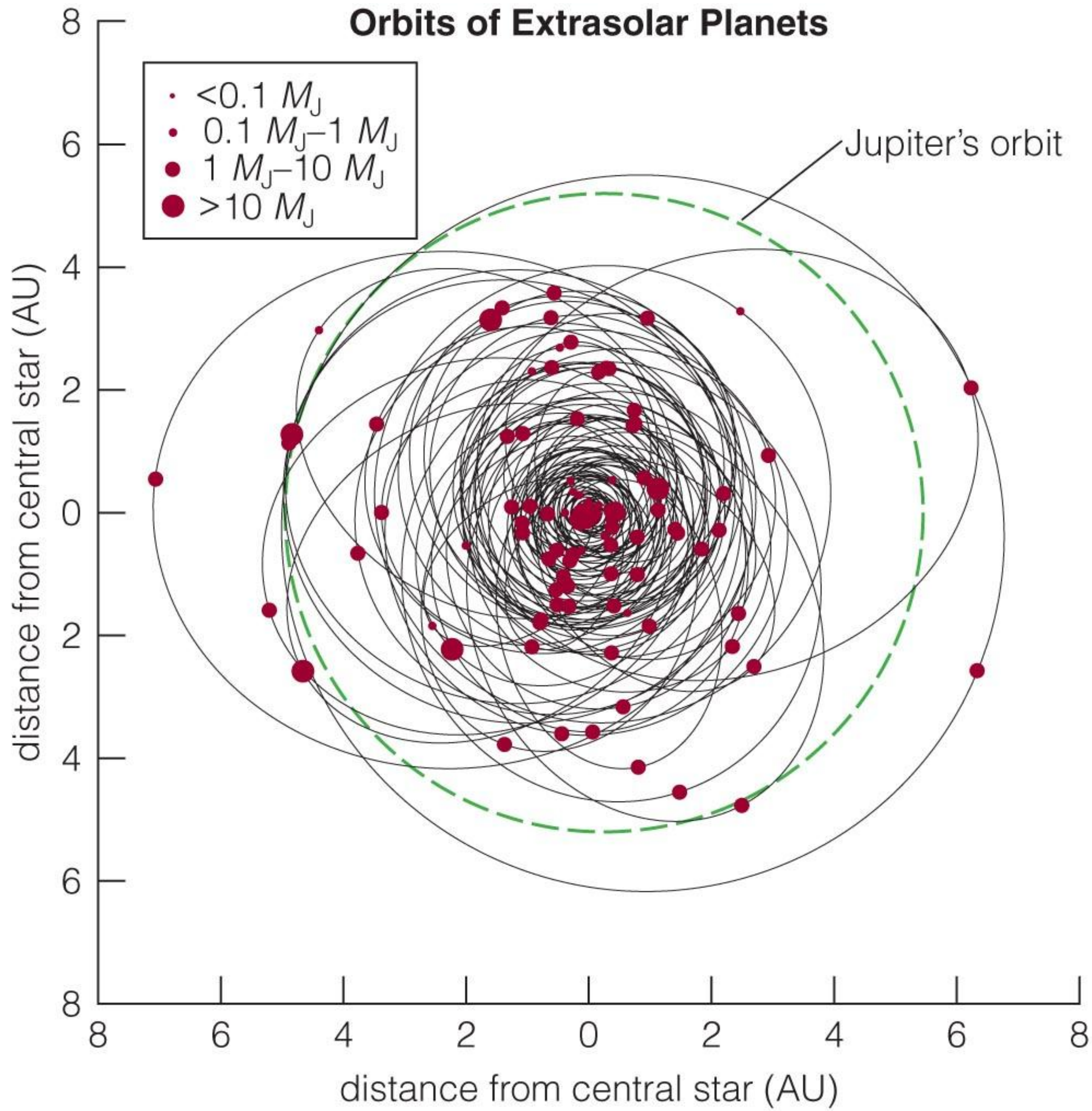




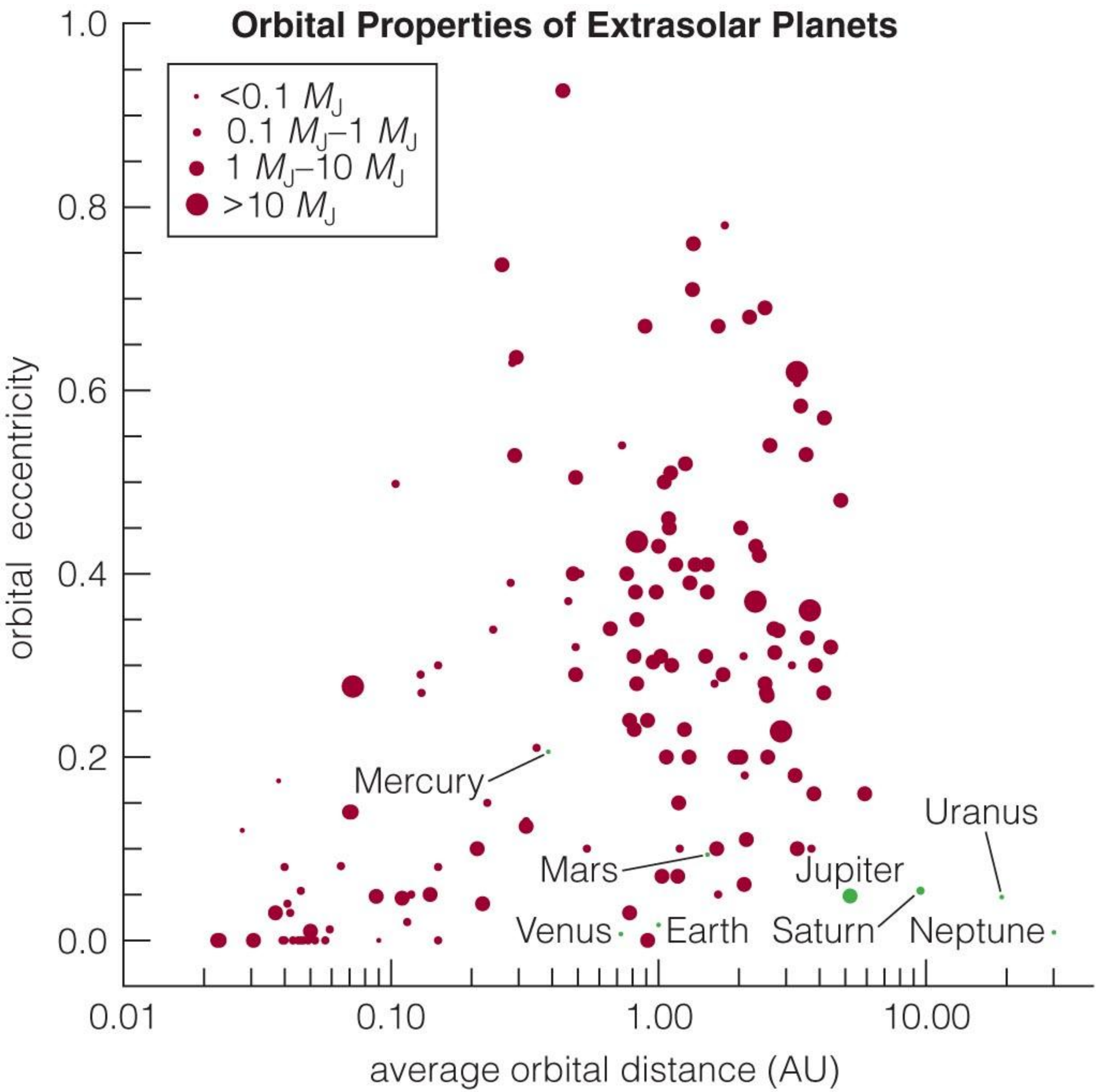
There are 3000+ known ***extrasolar planets*** as of Jan 2013, all discovered within the past 18 years, half within the last 2 yrs.

Many are more massive than Jupiter and closer to their star than Earth is to Sun, but many terrestrial planets are being found.

Revisions to the nebular theory are necessary! Planets can apparently migrate in from their birthplaces farther out.



Orbits of Extrasolar Planets
<0.1 M_J
0.1 M_J–1 M_J
1 M_J–10 M_J
>10 M_J
Jupiter's orbit
distance from central star (AU)
distance from central star (AU)
8
6
4
2
0
2
4
6
8



Orbital Properties of Extrasolar Planets
<0.1 M_J
0.1 M_J–1 M_J
1 M_J–10 M_J
>10 M_J
orbital eccentricity
1.0
0.8
0.6
0.4
0.2
0.0
Mercury
Mars
Venus
Earth
Jupiter
Saturn
Uranus
Neptune
0.01
0.10
1.00
10.00
average orbital distance (AU)

Chaotic Solar Systems

- The discovery of “hot Jupiters” with eccentric orbits was a total surprise. Few systems found so far look like our Solar System.
- Computer models challenge the earlier views that planets formed in an orderly way at their current locations.
- The models suggest that Jovian planets have changed orbits substantially, and Uranus and Neptune maybe swapped places.
- These chaotic motions could also explain a ‘spike’ in the number of impacts in the inner solar system about 3.8 billion years ago.

The Moon and terrestrial planets were bombarded by planetesimals early in solar system history.

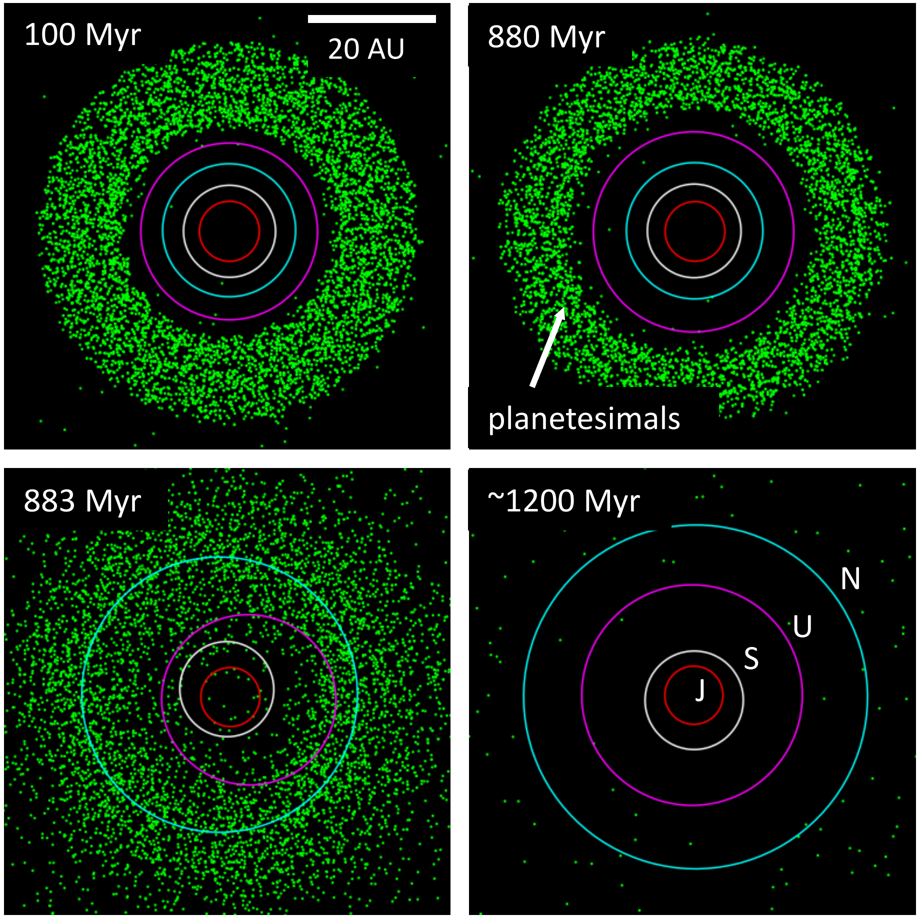
Cosmic Billiards

- **The model predicts:**

1. Giant planets were affected by early gravitational 'nudges' from the surrounding planetesimals.

2. Jupiter and Saturn crossed a *1:2 orbital resonance* (the ratio of orbital periods), making their more elliptical. This impetus suddenly enlarged and tilted the orbits of Uranus and Neptune.

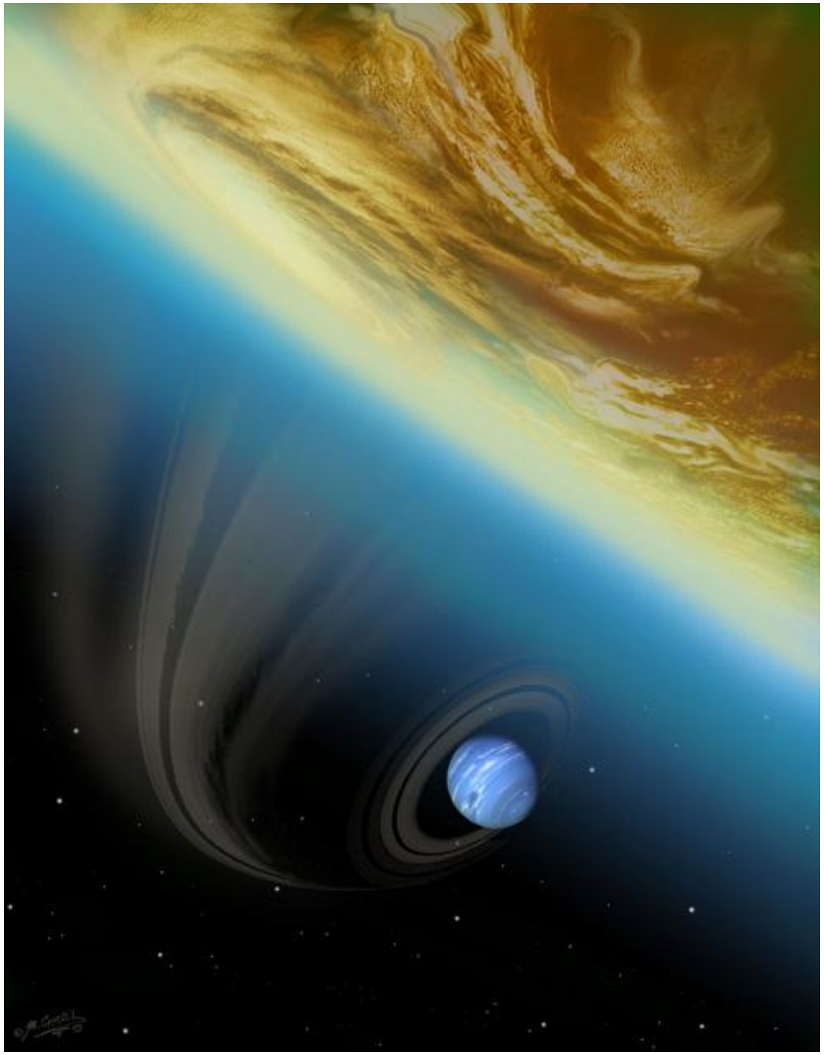
3. Uranus/Neptune cleared away the planetesimals, sending some to the inner solar system causing impacts (Heavy Bombardment).



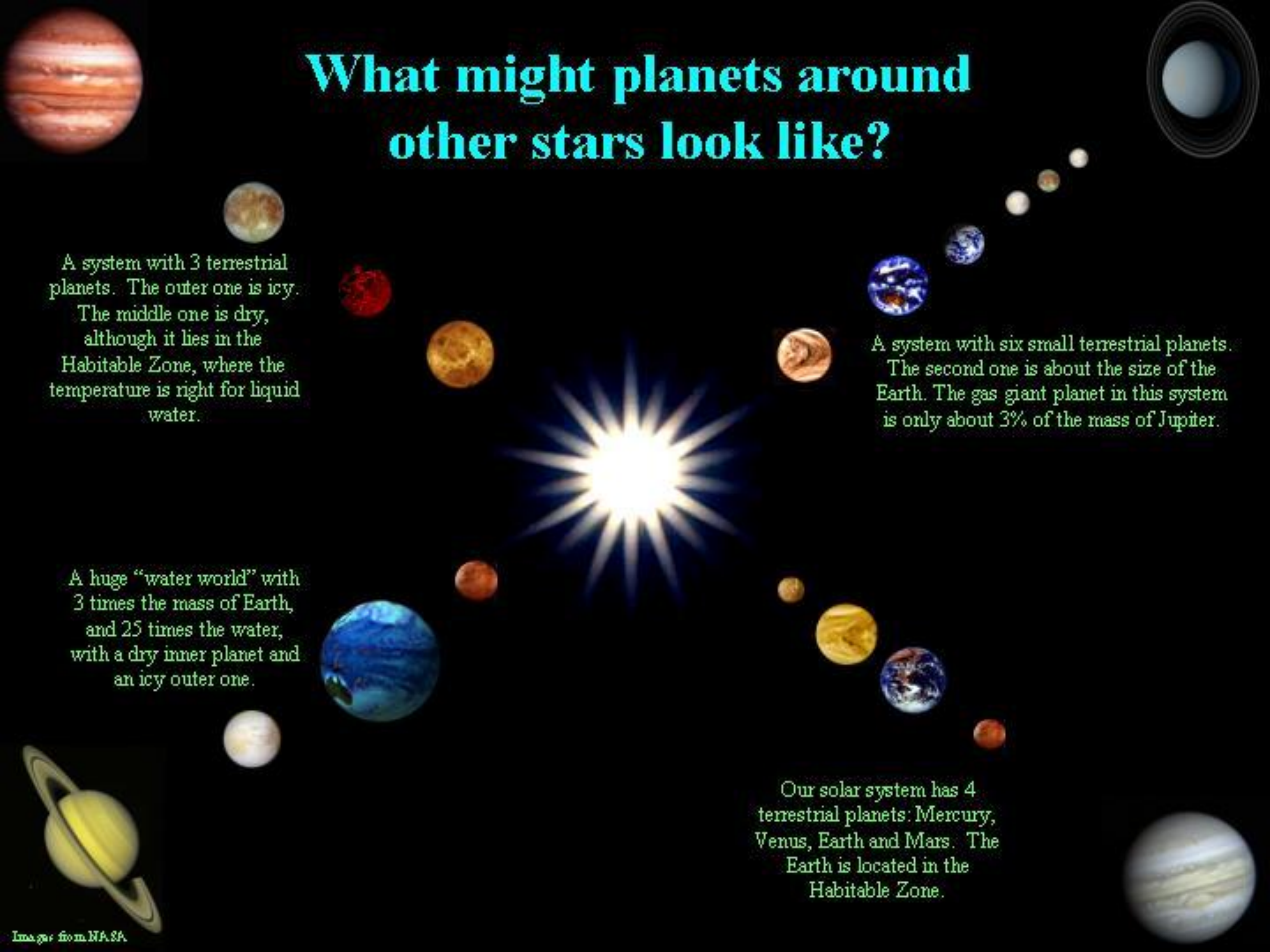
The early layout of the solar system may have changed dramatically due to gravitational interactions between the giant planets. Note how the orbits of Uranus and Neptune moved outwards, switched places, and then scattered the planetesimal population.

Planetary Migration

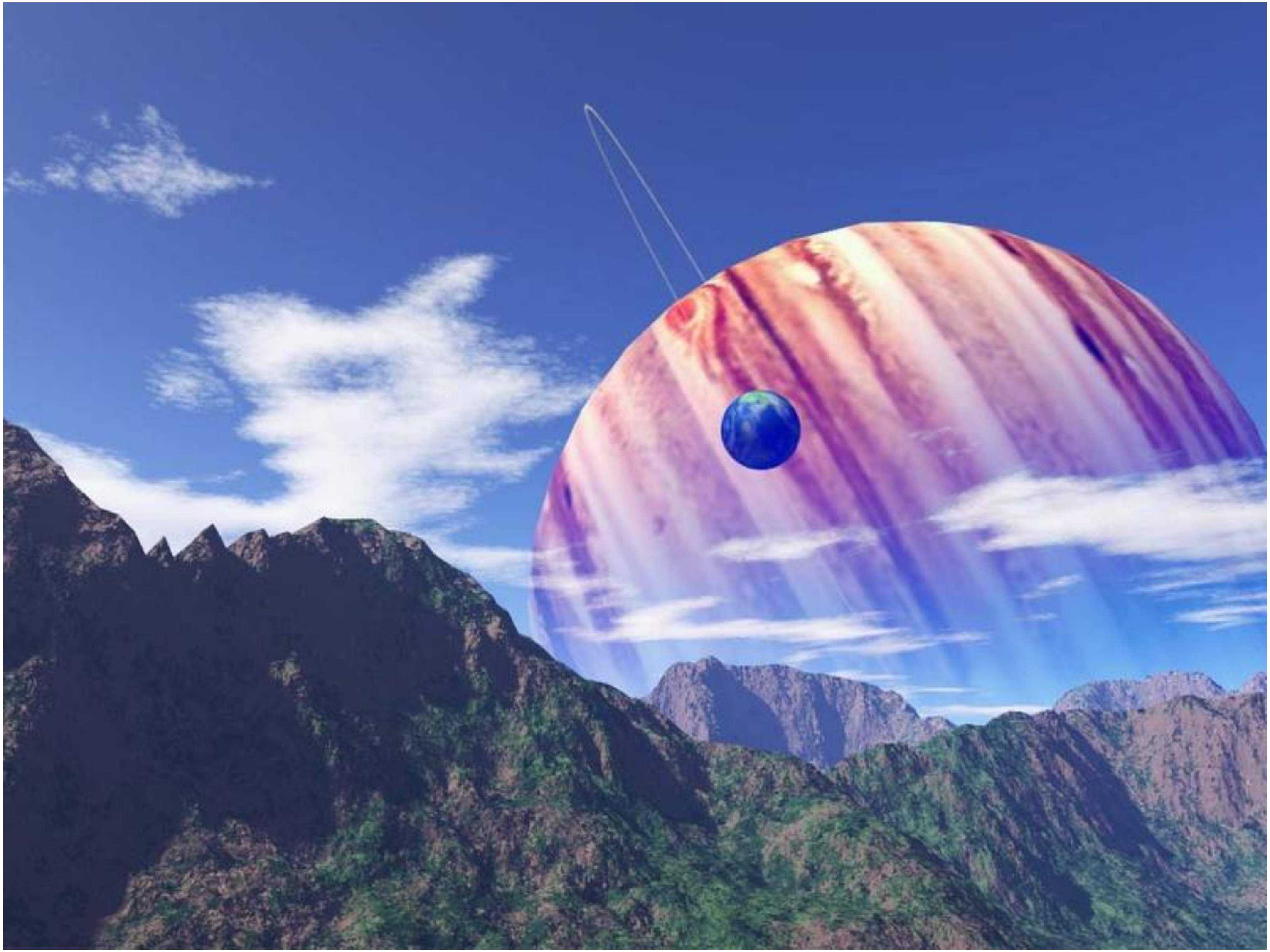
- The current layout of our solar system may bear very little resemblance to its original form.
- This view is in line with the type of “planetary migration” thought to occur even more dramatically in many extrasolar planet systems.
- It’s hard to verify these models of our early solar system. The physical nature & orbits of planets, comets and asteroids provide clues.
- Despite all the empty space, the Solar System is “full”: add another planet and it would be unstable.



Artist’s depiction of Neptune orbiting close to Jupiter (courtesy Michael Carroll)


What might planets around other stars look like?
A system with 3 terrestrial planets. The outer one is icy. The middle one is dry, although it lies in the Habitable Zone, where the temperature is right for liquid water.
A system with six small terrestrial planets. The second one is about the size of the Earth. The gas giant planet in this system is only about 3% of the mass of Jupiter.
A huge "water world" with 3 times the mass of Earth, and 25 times the water, with a dry inner planet and an icy outer one.
Our solar system has 4 terrestrial planets: Mercury, Venus, Earth and Mars. The Earth is located in the Habitable Zone.
Images from NASA

Detection



Selection Effects

Doppler

Spectra measure the radial component of the 3D motion, so mass is really $M \sin i$, where i is the inclination, a lower limit.

Eclipse

The orientation has to be edge on or "just right" to see a transit/eclipse; only a small fraction of exoplanets eclipse their stars.

Direct

Imaging an exoplanet requires suppression of 10^8-10^9 times brighter star, favoring cold planets and observations in the infrared.

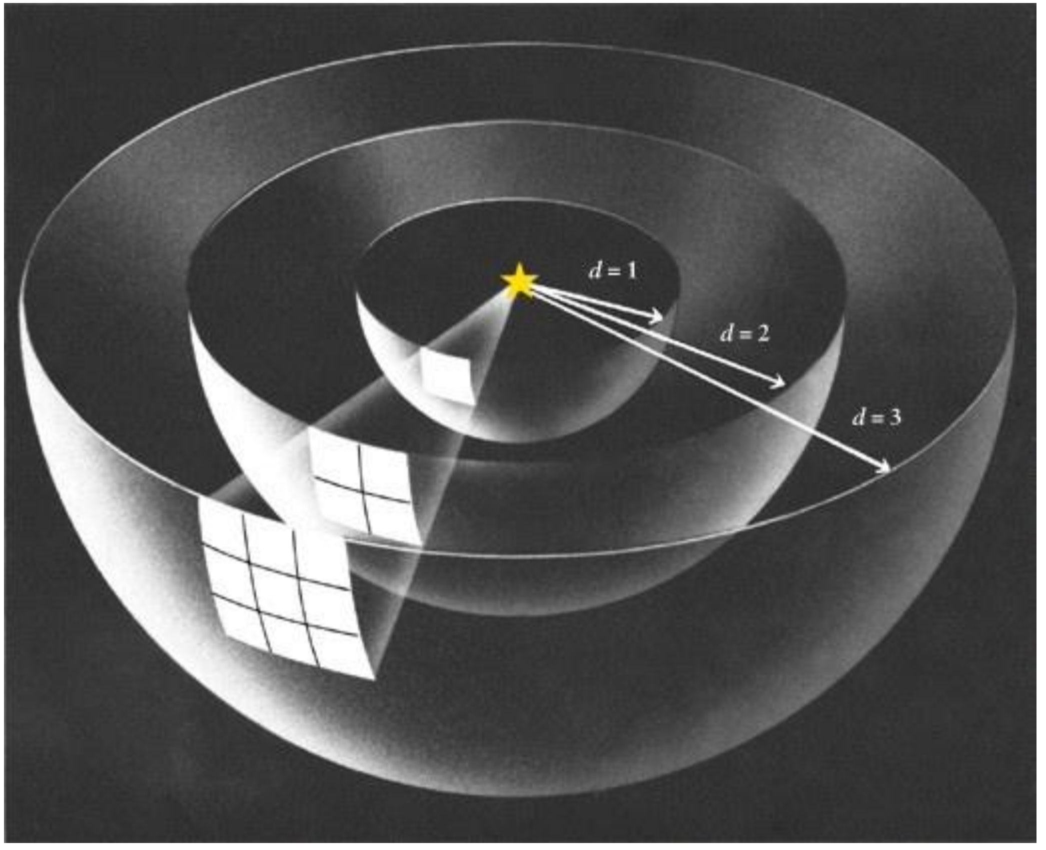
How to Detect Planets

1. Doppler effect (planet motion caused by the star)
2. Eclipses (planet passes in front of and dims star)
3. Imaging (see planet by reflected light from star)

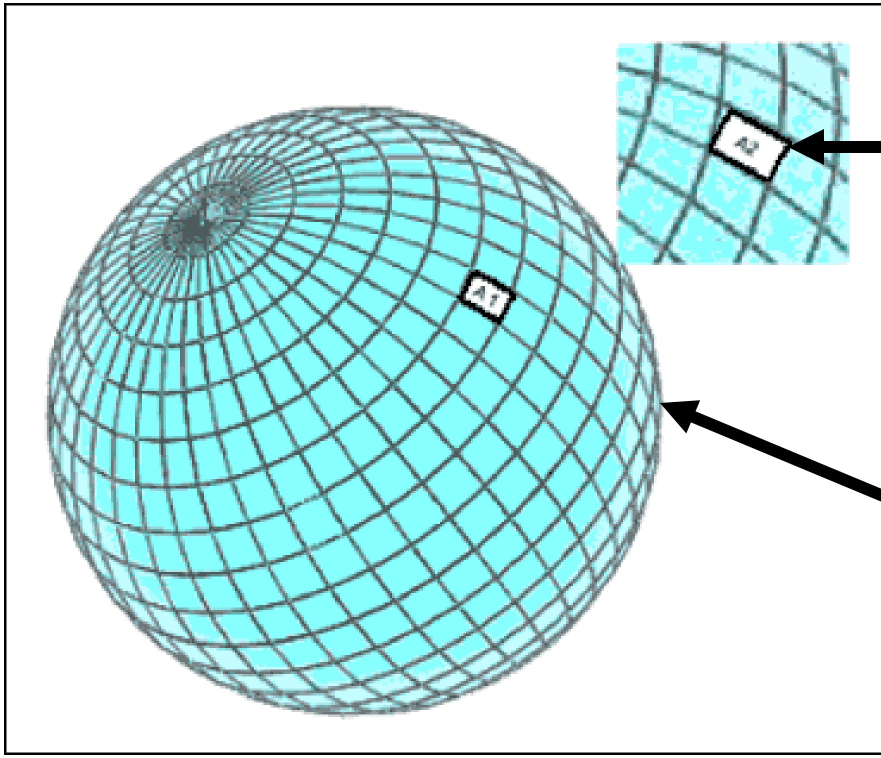
All you need to know:

1. The Sun is 10^6 km across and Jupiter is 10^5 km across
2. The Sun is 1000 times more massive than Jupiter
3. Distance of Jupiter from Sun: 10^9 km, or a billion km

Direct Detection



Light from the star goes down as the square of the distance. Alternatively, the light intercepted (and reflected) from any patch goes down as the square of the distance of the patch.



Area intercepted = $2\pi r^2$

r is radius of Jupiter

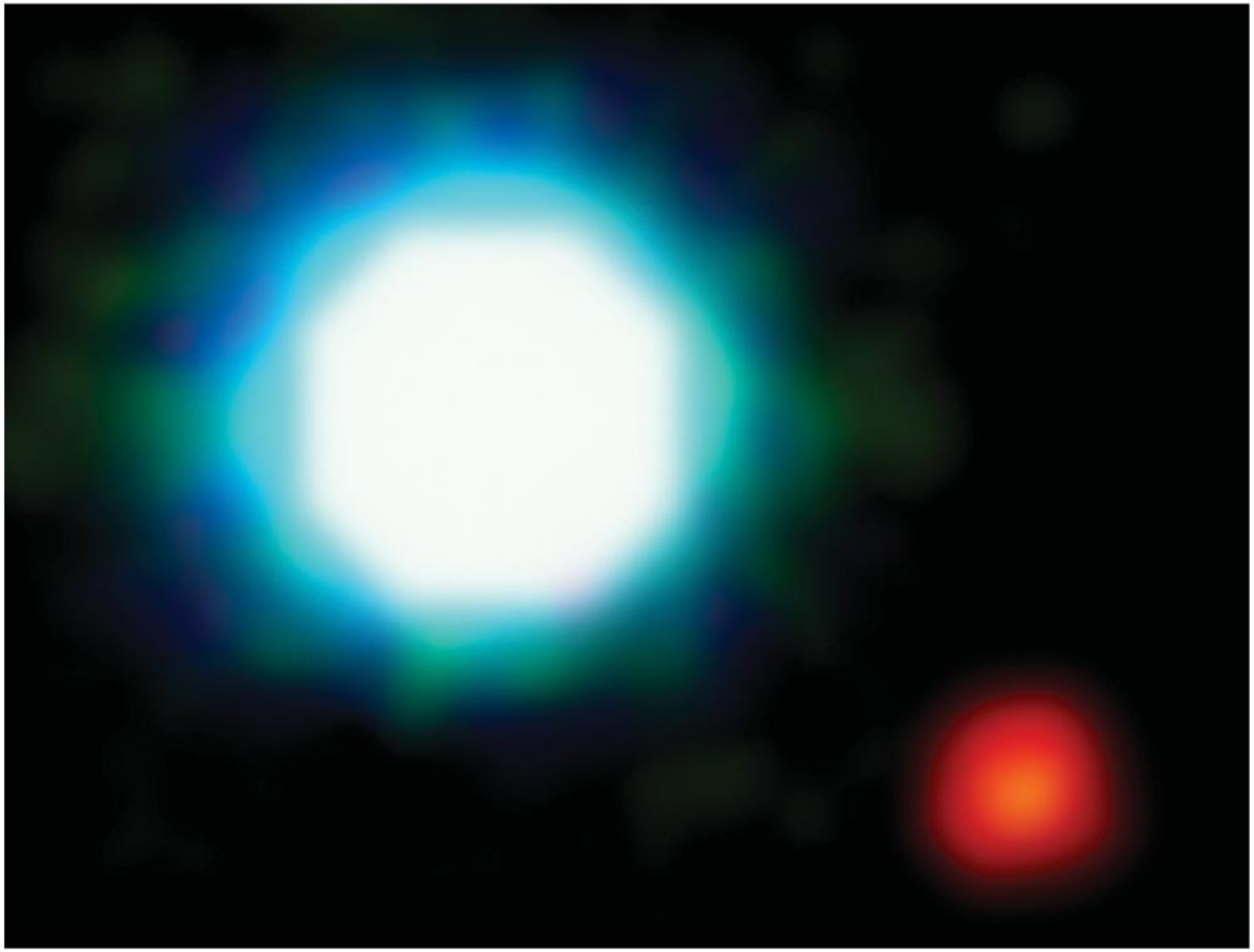
Area filled by star = $4\pi d^2$

d is distance of Jupiter

Light from the star spreads out over the an area $4\pi d^2$ at the distance of Jupiter. The fraction of it we see by reflection is roughly the ratio of the area intercepted by Jupiter divided by the total area receiving light at the distance of Jupiter.

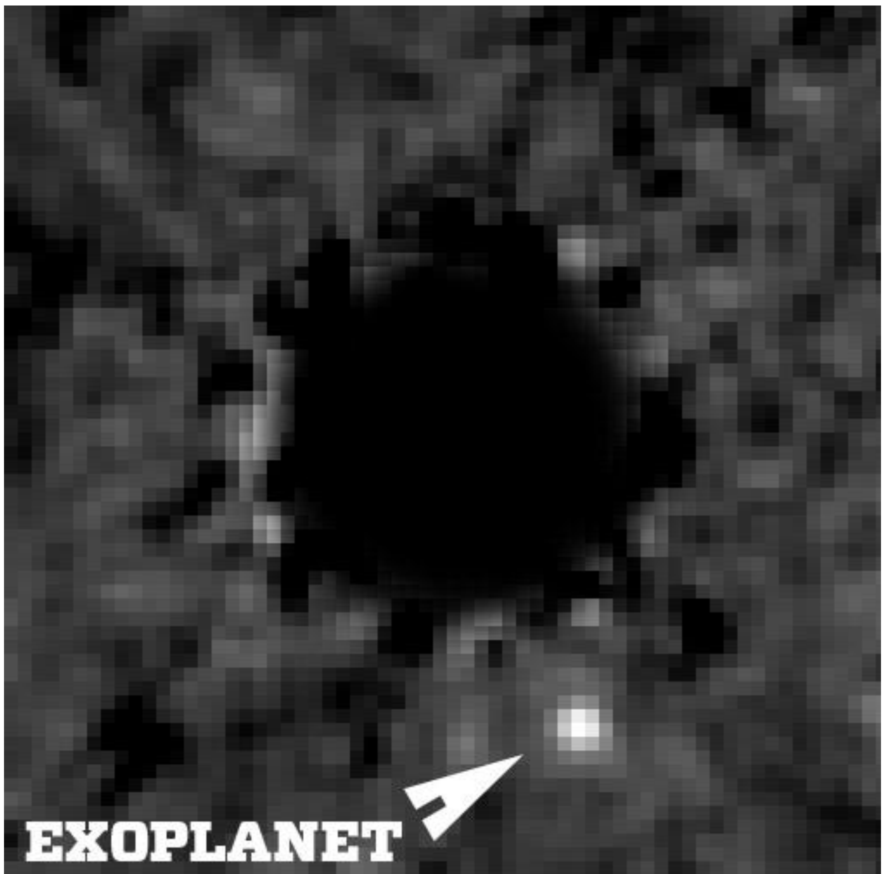
What fraction of the Sun's light does Jupiter reflect?

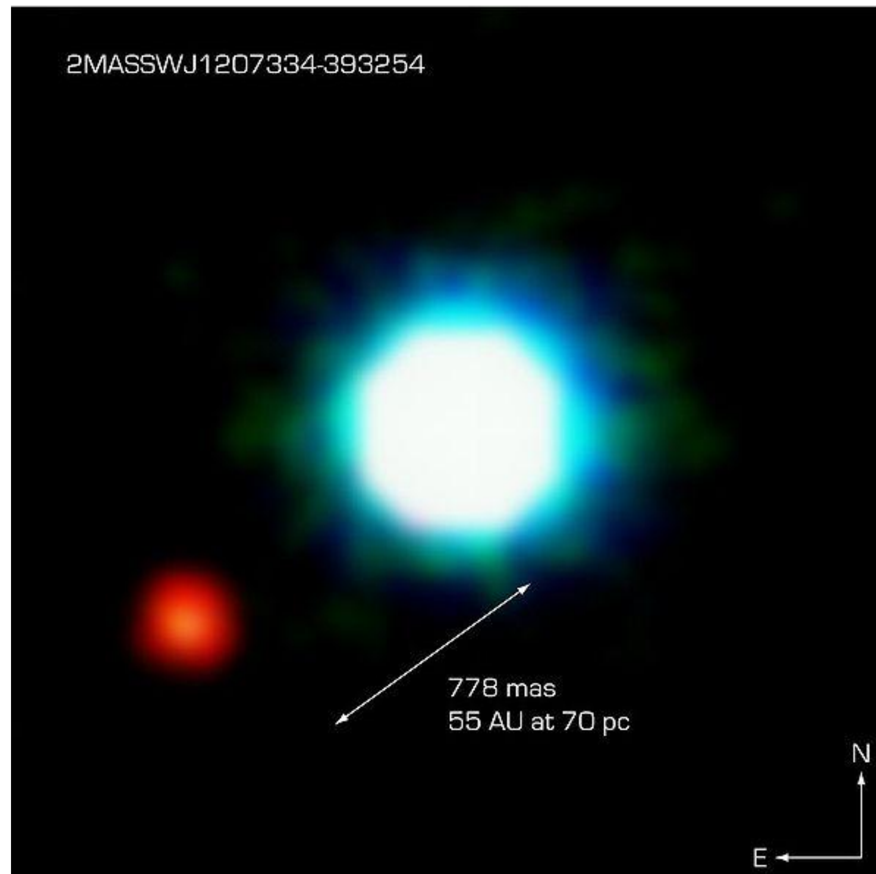
Why not just make an image to detect exoplanets?



They are billions of times fainter than the stars they orbit; think of trying to see a firefly next to a stadium floodlight!

Planets were finally imaged in 2008! The method requires digging out the signal from near a star >100 million times brighter, easier done in the IR.





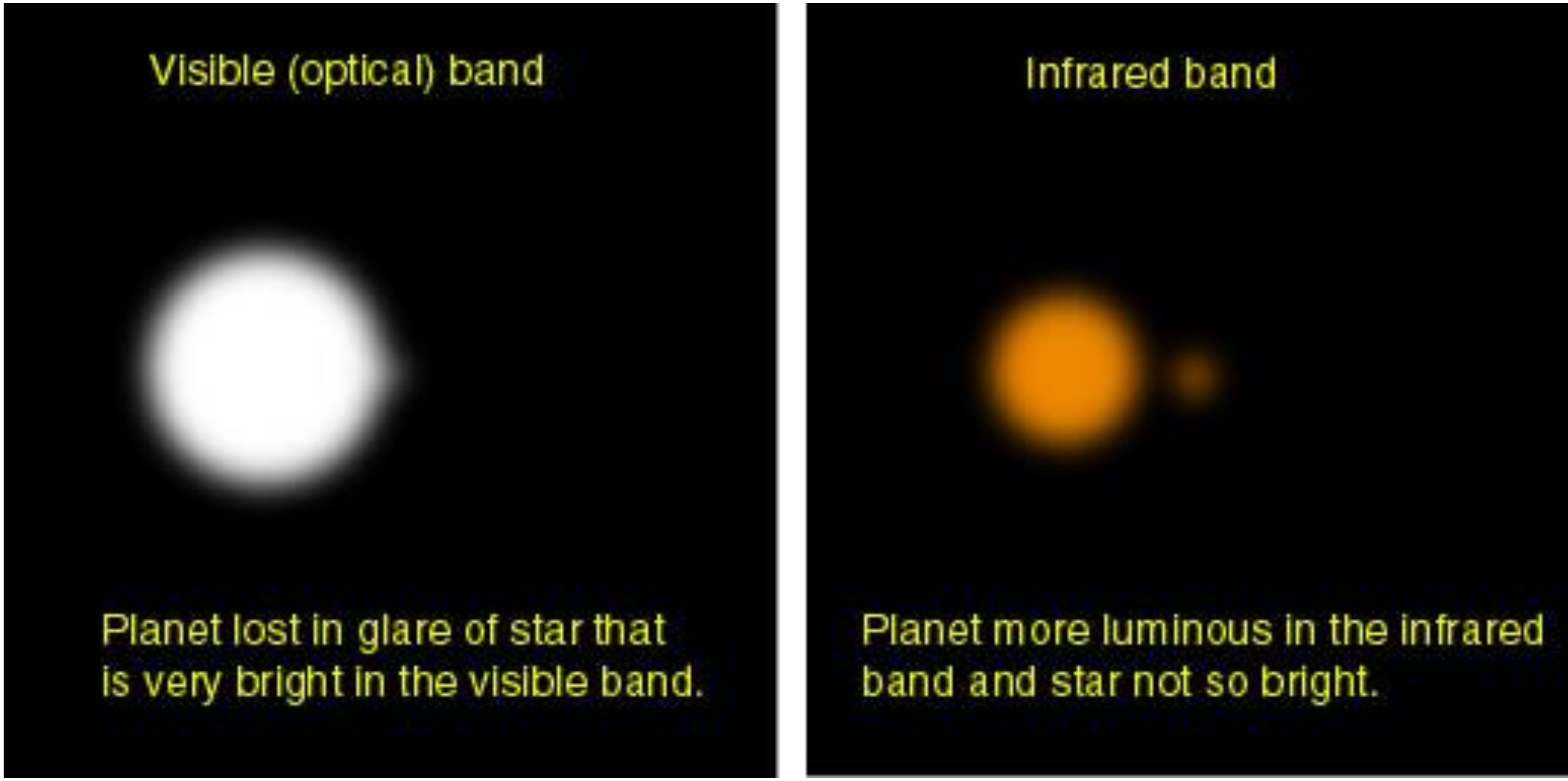
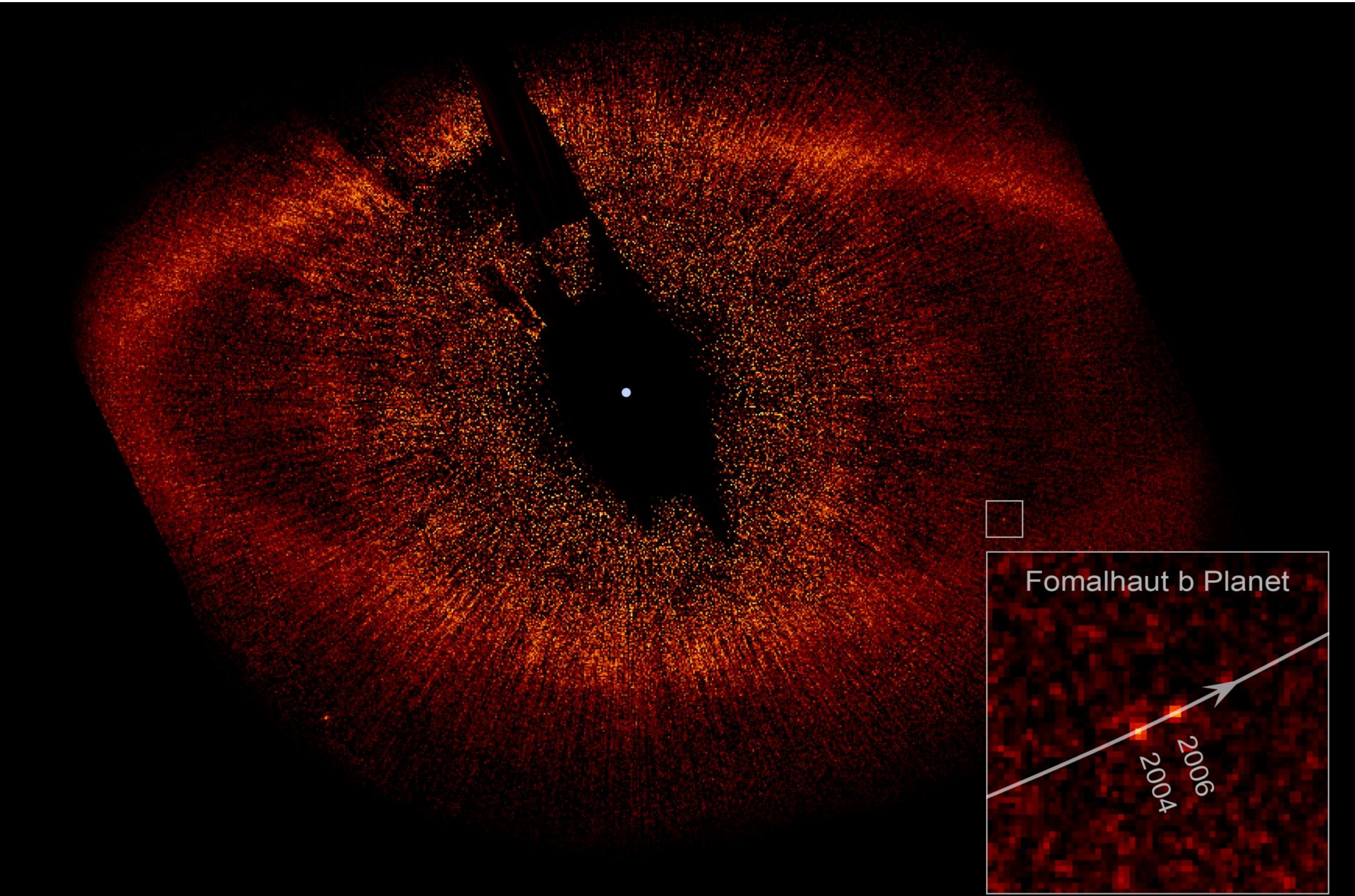


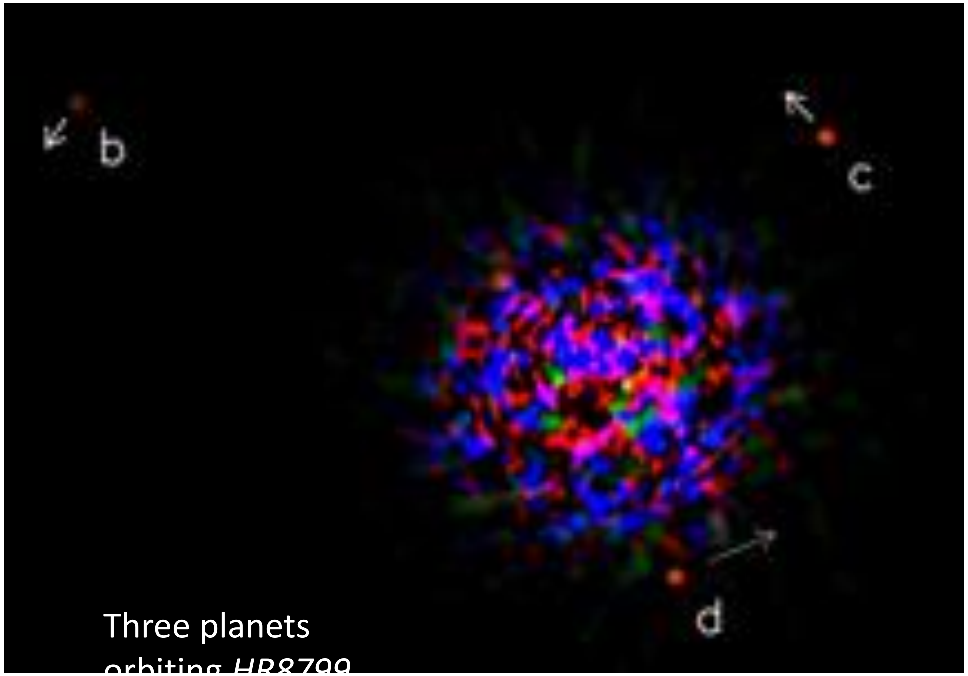
Image contrast (the ratio of the reflected exoplanet brightness to the star brightness) can be >10 times better at near infrared than at optical wavelengths.

One was found serendipitously in the HST archive.



Imaging Exoplanets

- This star has three planets - the first imaged *planetary system*!
- Planets are much fainter than their parent star, challenging to image.
- Why are *these* pictures possible?
  - Special observing techniques used to ***block the star's light***.
  - Observations were ***repeated over years***, confirming the planetary motion and orbit.
  - The planets are ***young and hot***, and glow more brightly than by reflected starlight alone.



Keck Observatory infrared image of star HR8799 and three orbiting planets with orbital directions indicated by arrows. The light from the star was subtracted, but an imperfectly modeled PSF means that a lot of 'noise' remains.

Detecting Unseen Exoplanets

The gravity pull of a planet on a star equals that of the star on the planet (Newton's third law)

Unseen planets causes a reflex motion or "wobble" on the visible stars they orbit

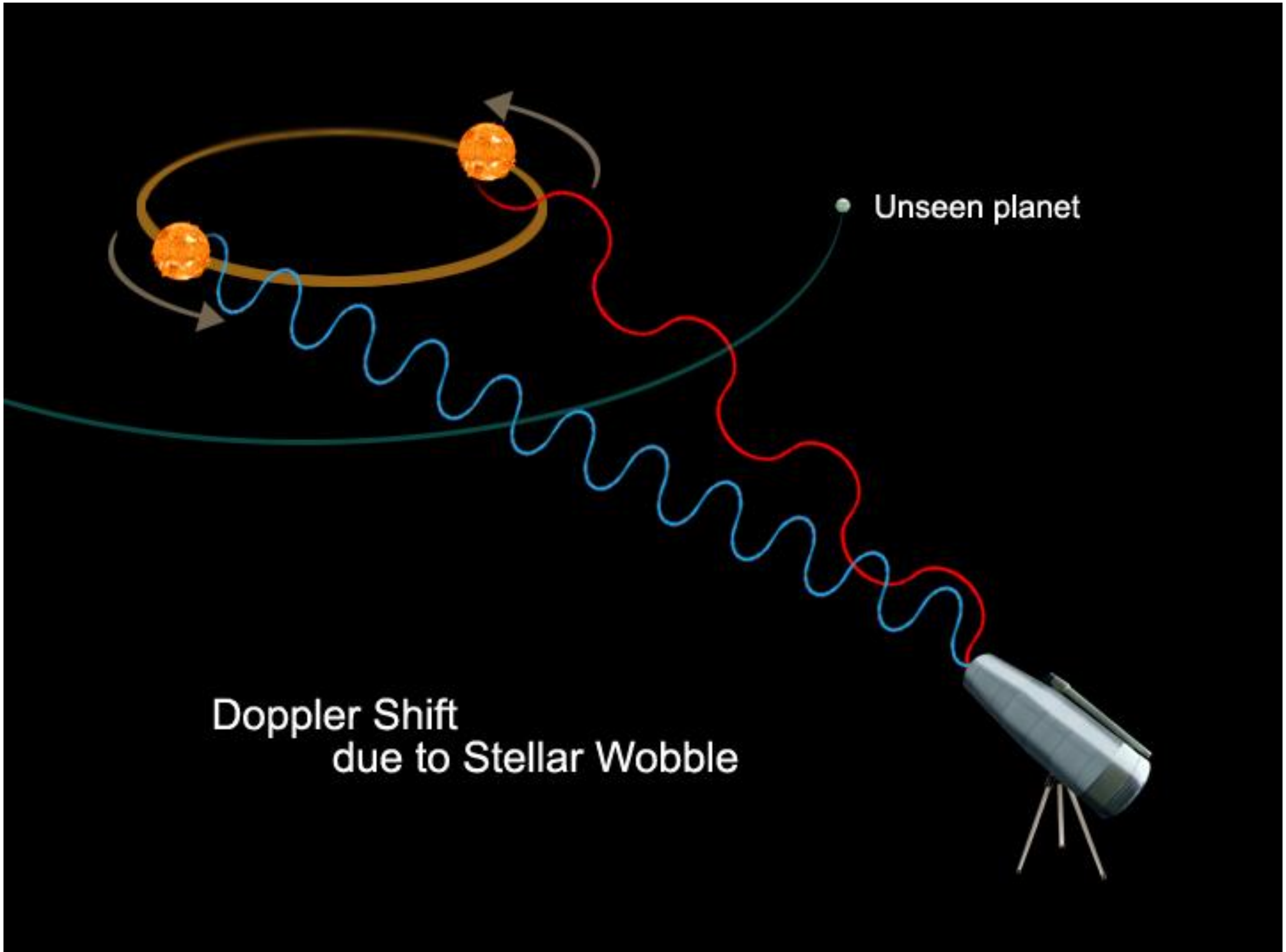
The more massive the planet, the bigger the wobble, but it's a very subtle effect

The wobble is too hard to see by imaging so spectra of the star are used to detect it

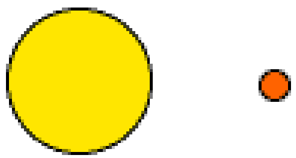
Most of the 500 extrasolar planets discovered before 2010 were found in this way

With the launch of Kepler, transit detection took over, yielding most of the 3000+ exoplanets

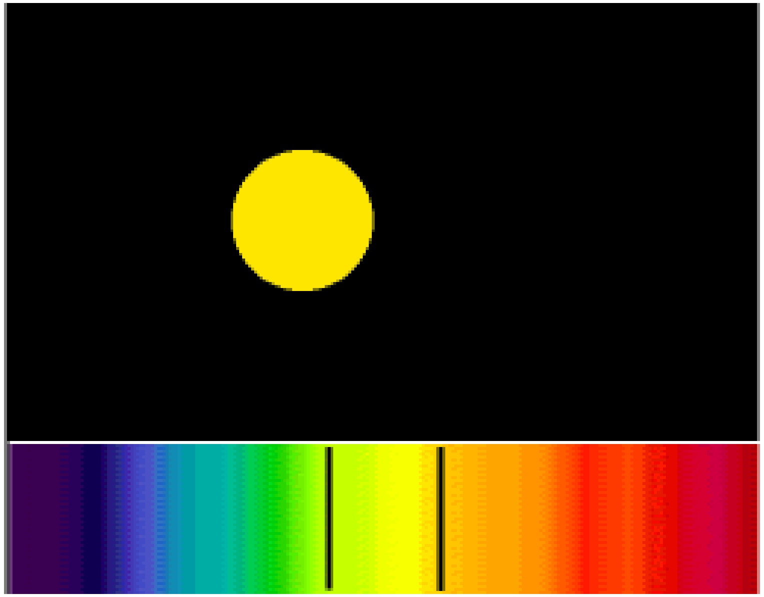
Doppler



Doppler Detection



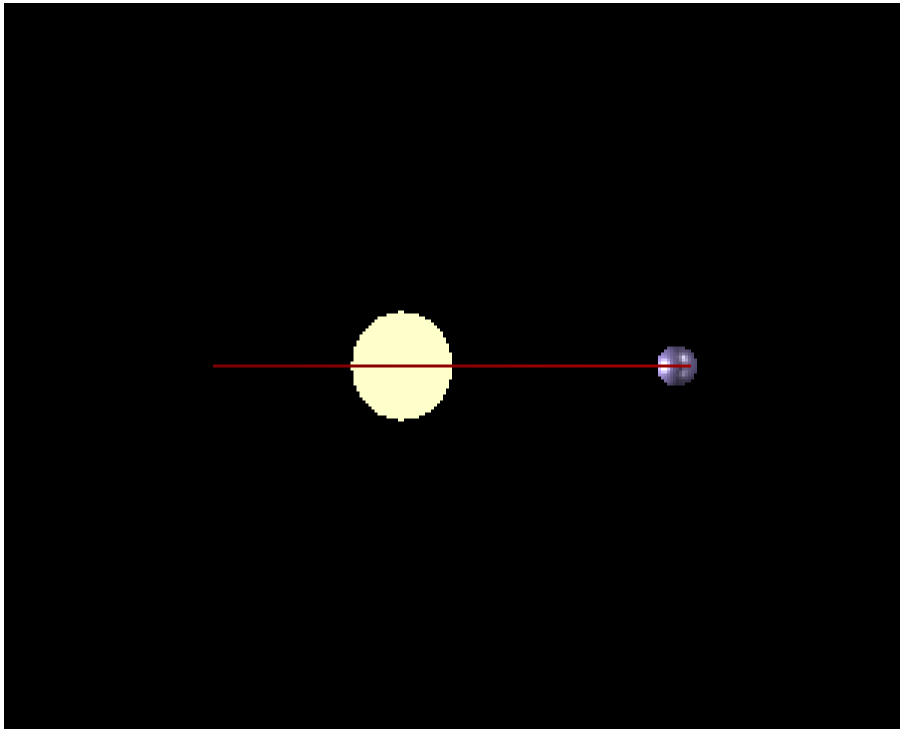
What is happening



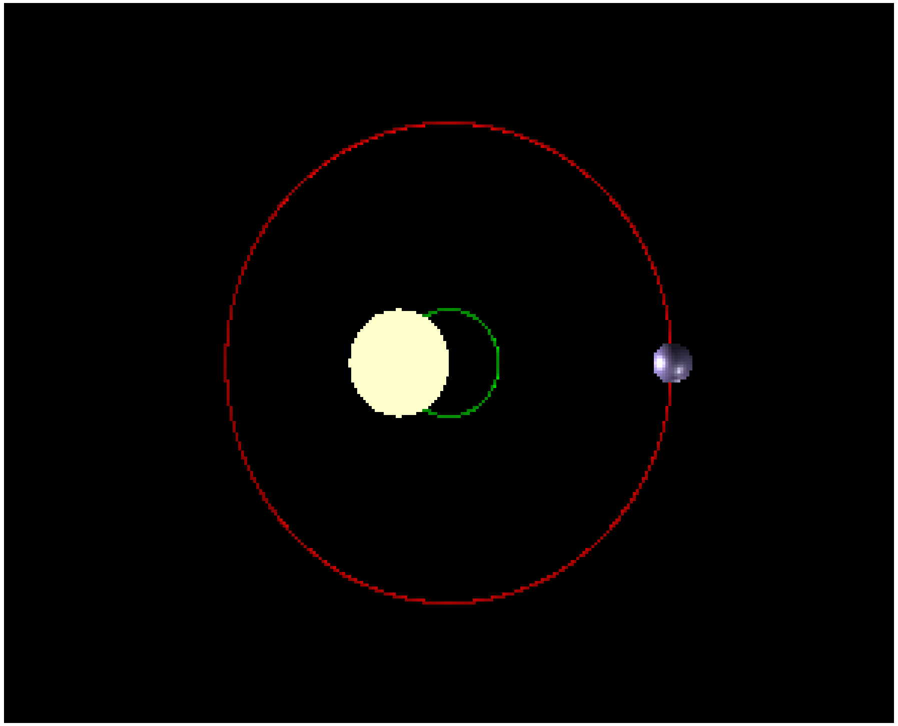
What we see

The star spectrum is imprinted with narrow absorption lines, which serve as markers of wavelength, permitting periodic reflex motion of the star to be monitored.

Range of Inclinations



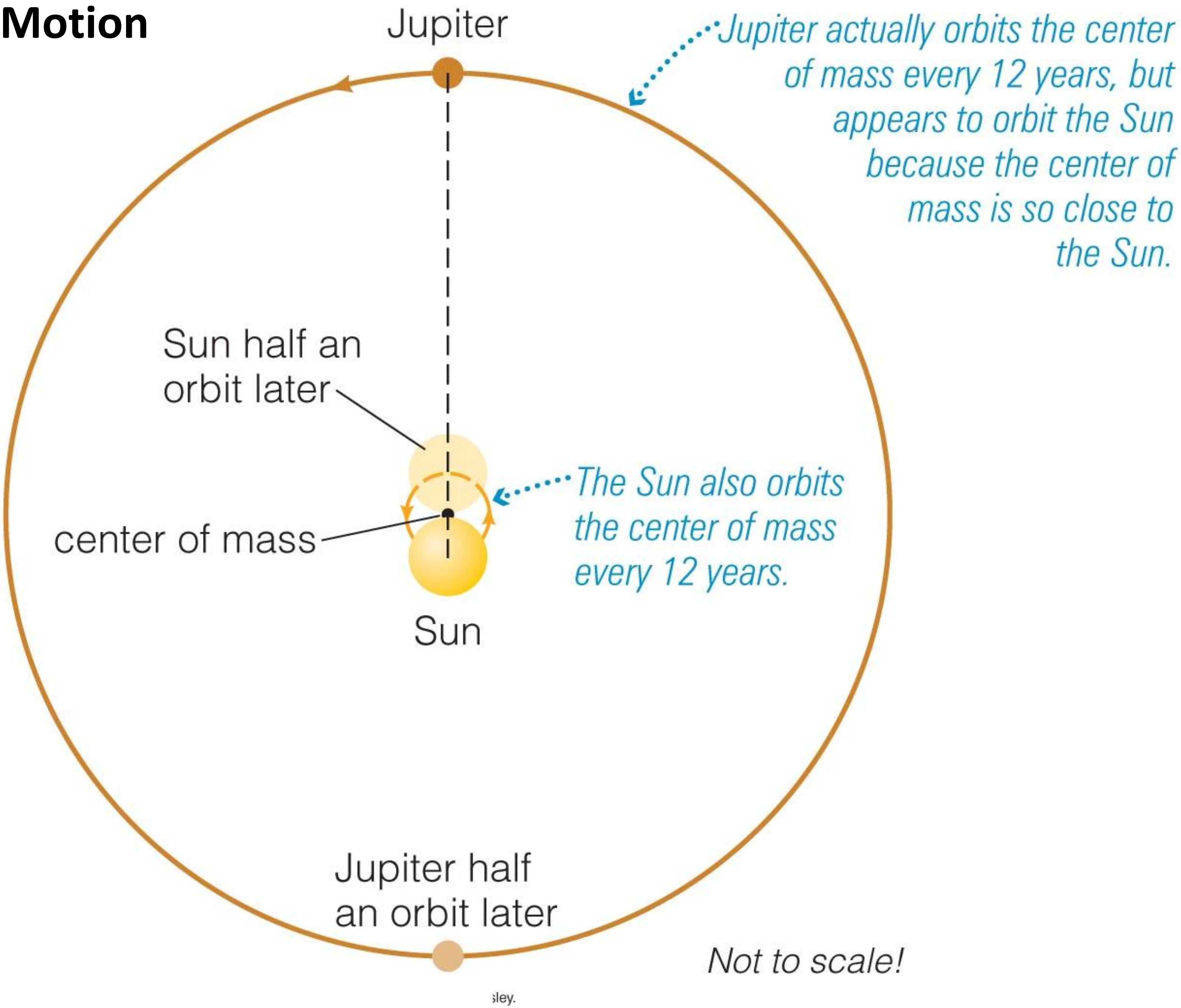
Inclination, *i*, is 90 degrees, so the full amplitude Doppler signal is observed.



Inclination, *i*, is 0 degrees, so there is zero Doppler signal and no detection.

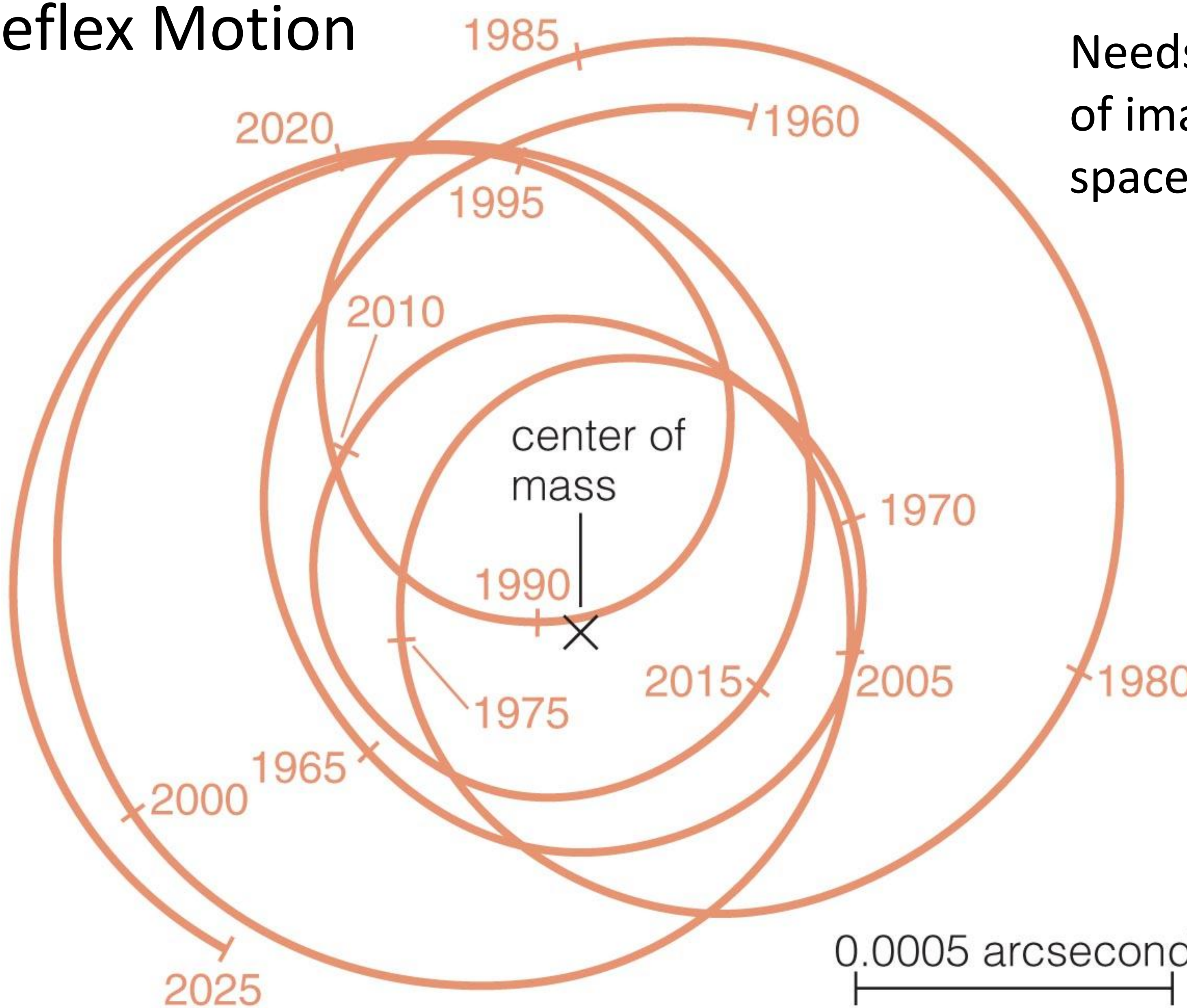
Exoplanet orbits are randomly distributed. The mass of a particular exoplanet is indeterminate and on average all the masses are underestimated by a factor of two.

Reflex Motion

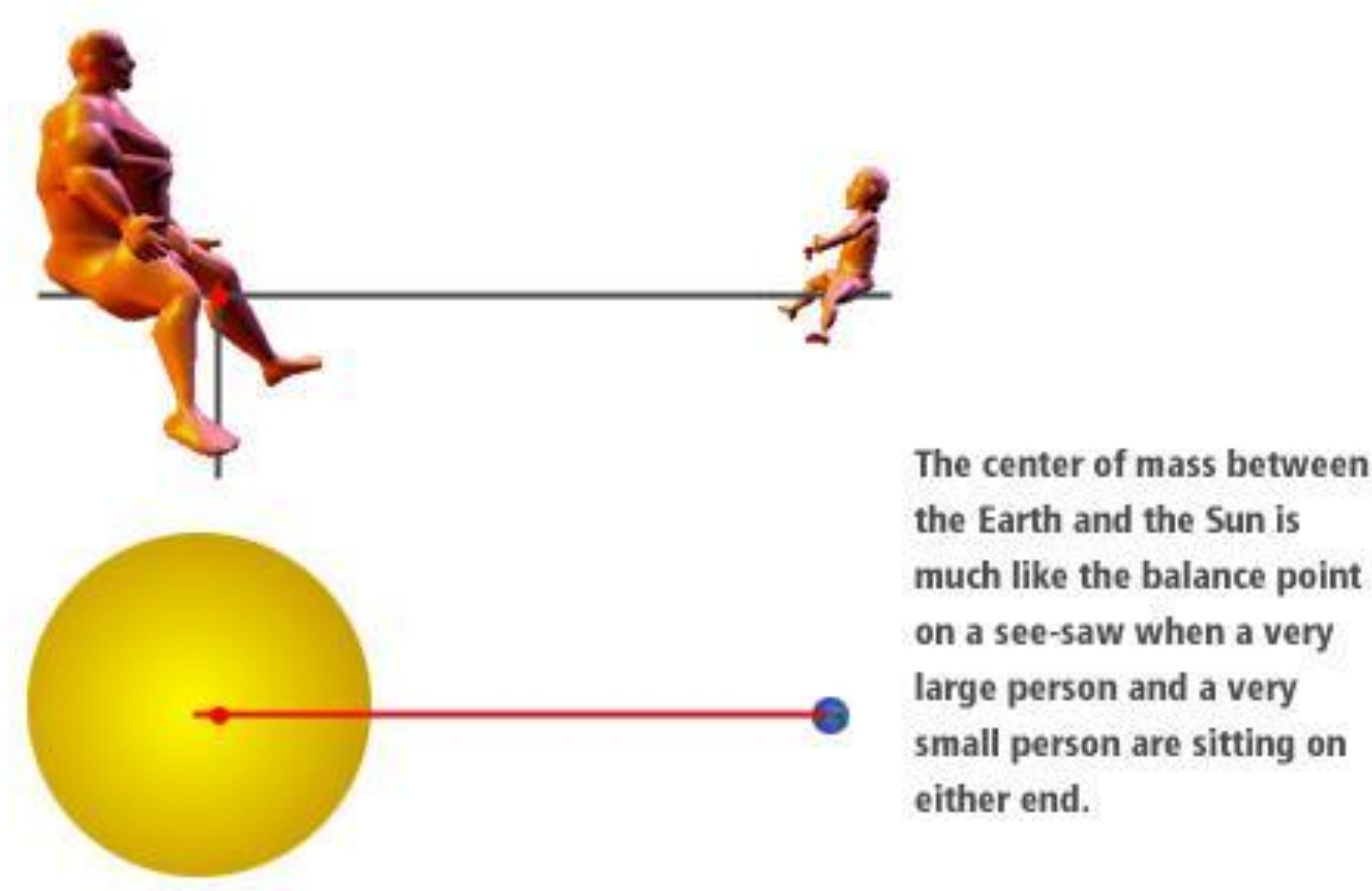


Reflex Motion

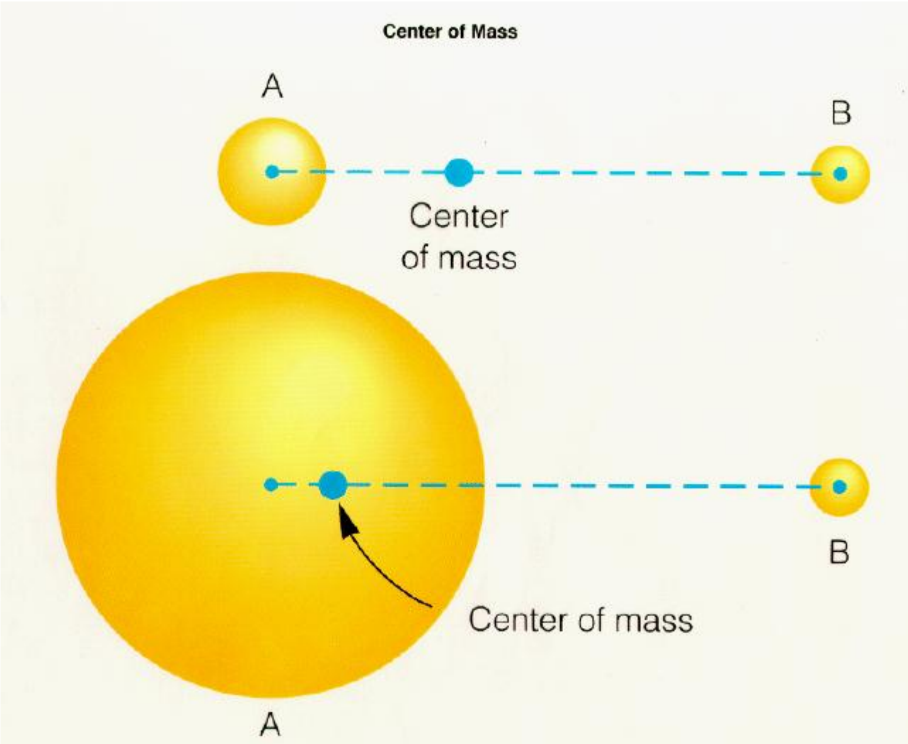
Needs stability of imaging from space to detect.

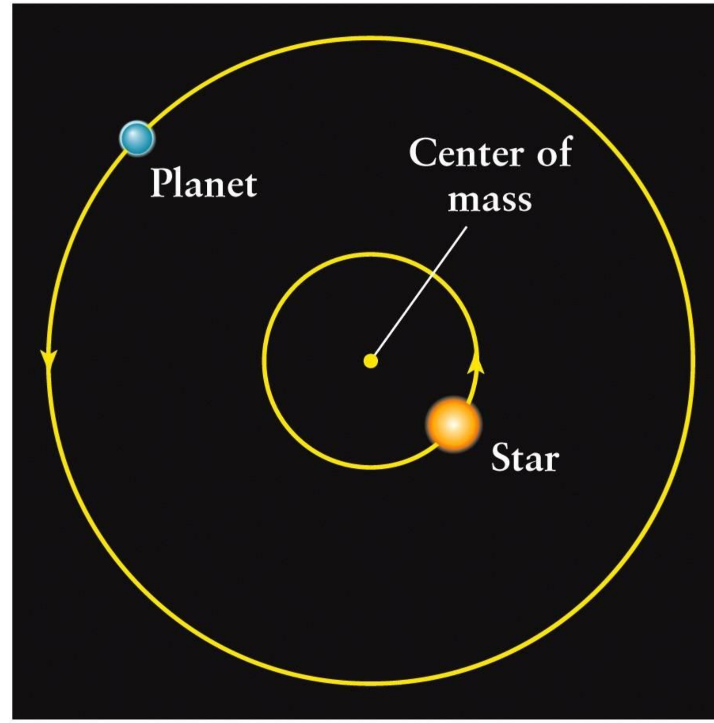


Doppler Detection



The balance point divides the distance according to mass. Equal masses balance at the midpoint, if one mass is 10x the other, the balance point is 10x closer to the large mass.





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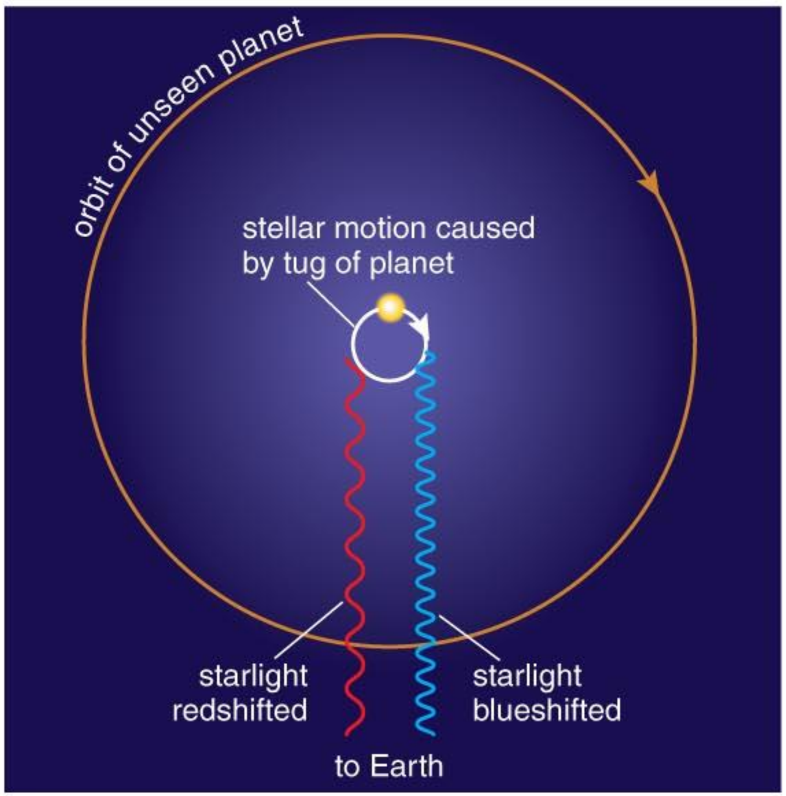
Now it's the same situation, except the two objects orbit about the balance point, or center of mass. Equal masses orbit at equal speeds. If one mass is 10x larger than the other it moves in an orbit 10x slower than the larger mass.

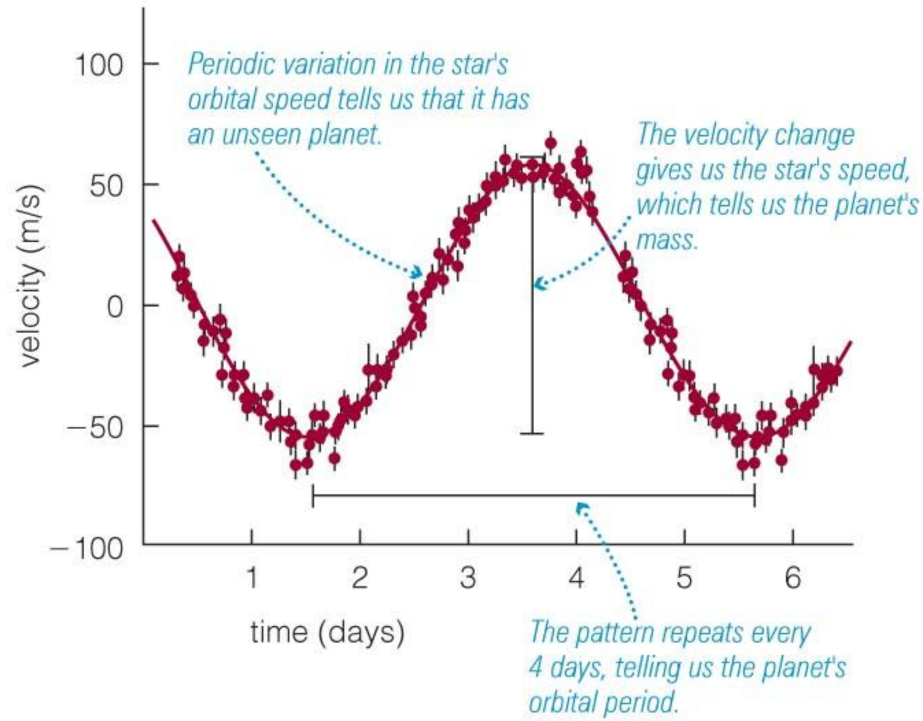
How much slower does the Sun go than Jupiter?

The first exoplanet discovered in this way was 51 Pegasi in 1995.

It was a surprise because it was a Jupiter-mass planet on a fast 4-day orbit, much closer to its star than Mercury is to the Sun! Mayor and Quleoz were studying binary stars with rapid orbits.

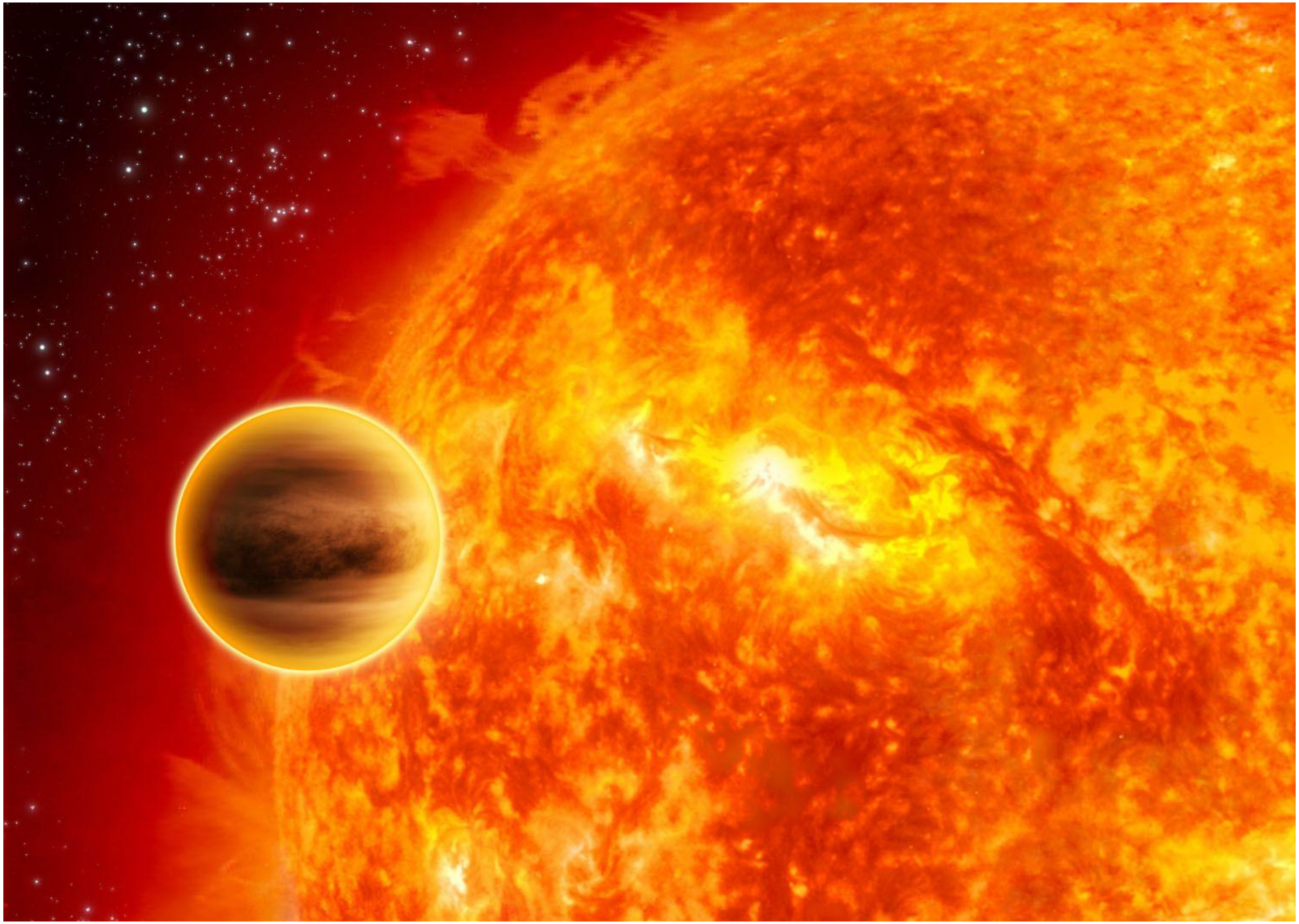


a Doppler shifts allow us to detect the slight motion of a star caused by an orbiting planet.

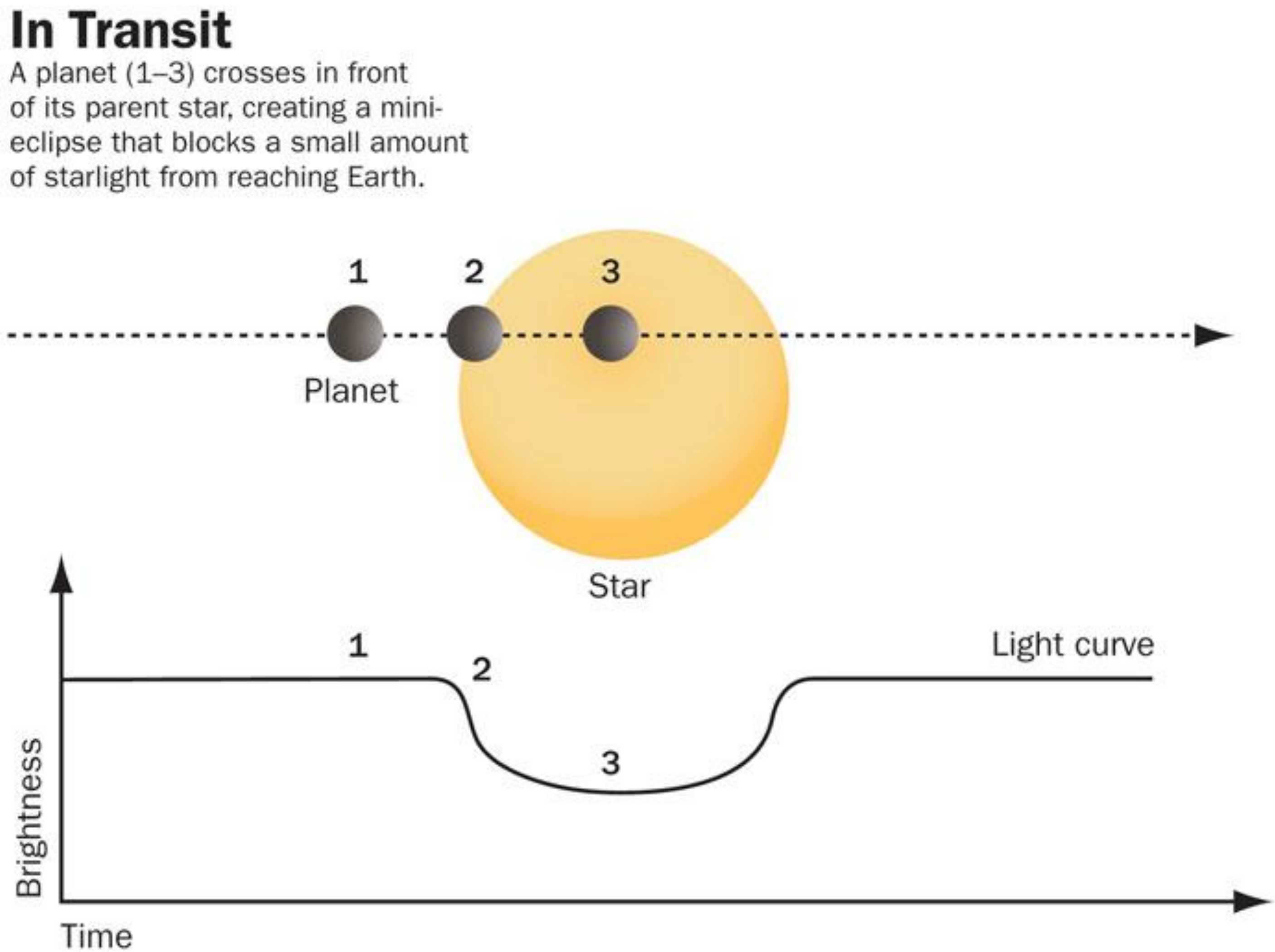


b A periodic Doppler shift in the spectrum of the star 51 Pegasi shows the presence of a large planet with an orbital period of about 4 days. Dots are actual data points; bars through dots represent measurement uncertainty.

Transits

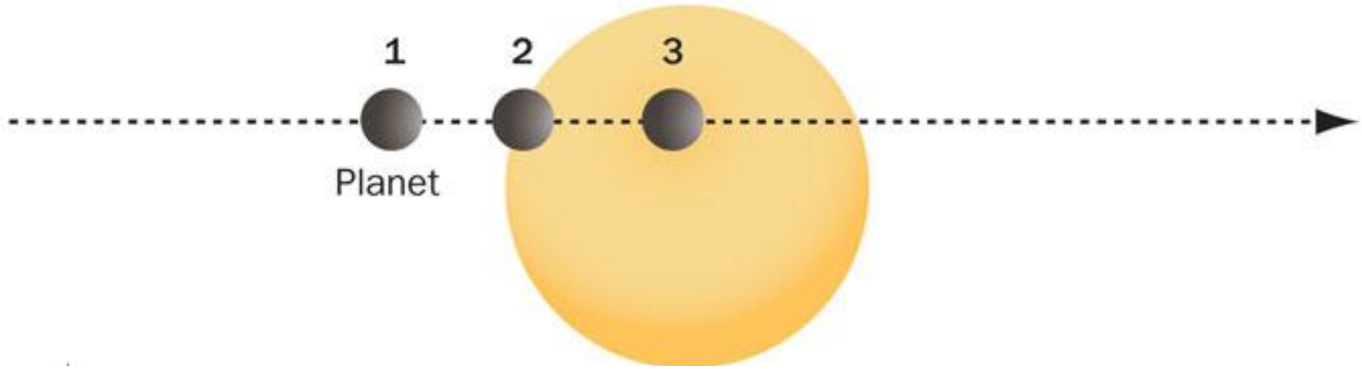


Eclipse Detection



What fraction of the Sun's area does Jupiter cover?

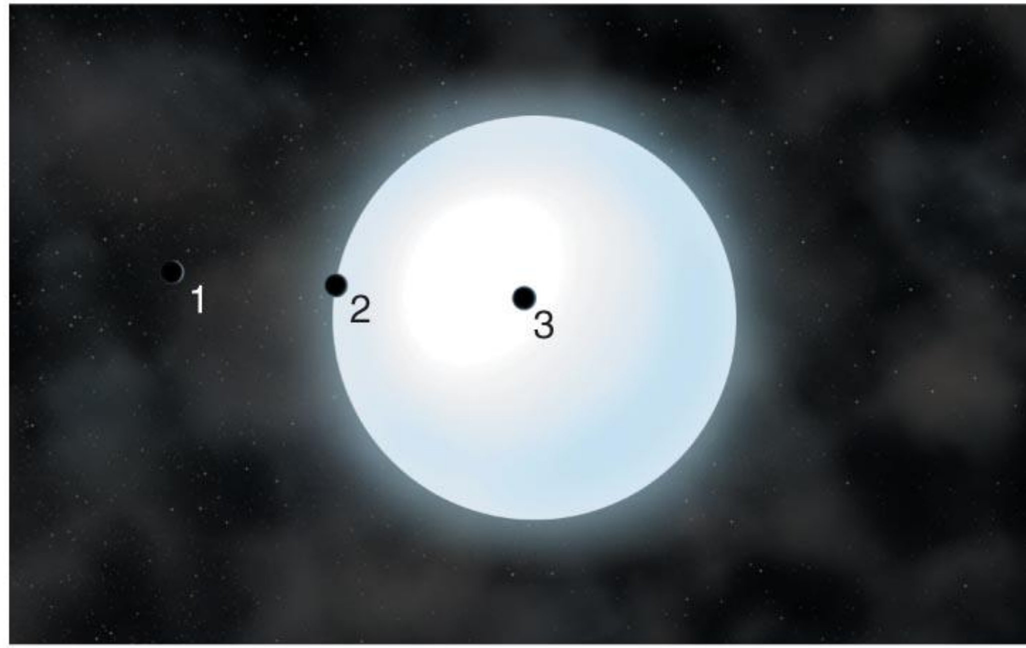
But a problem…



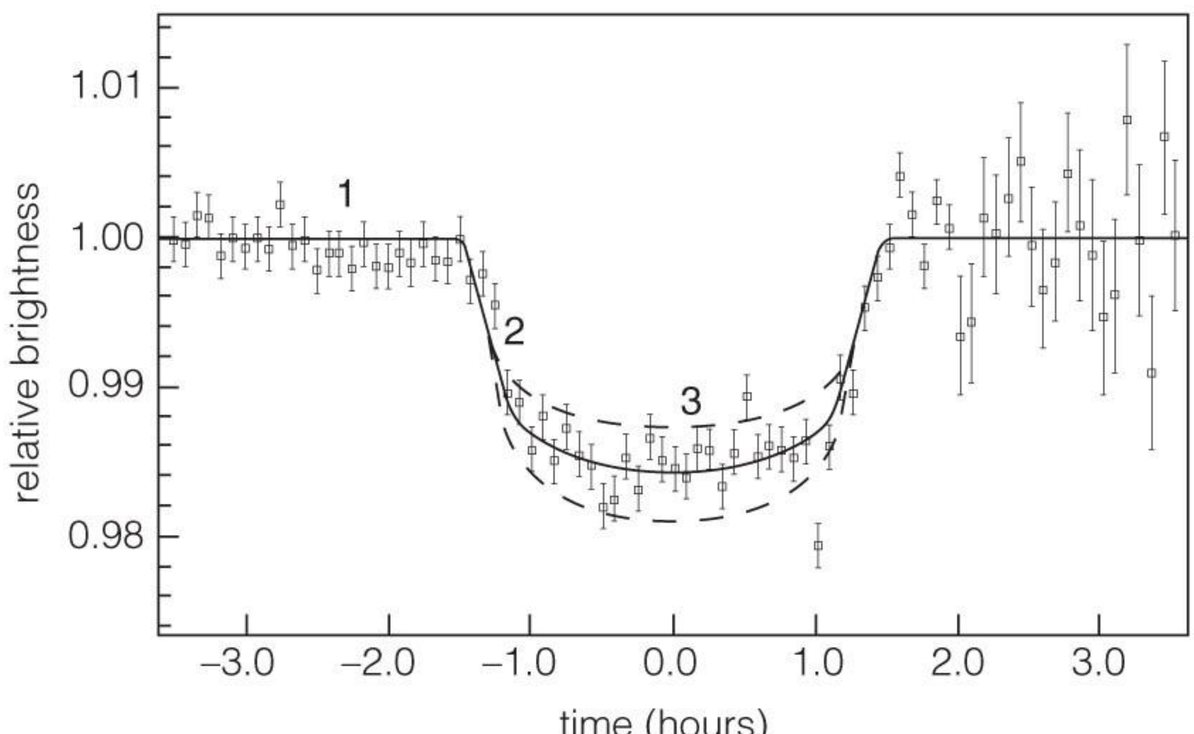
Jupiter moves at 13 km/s so it takes 1,000,000/13 seconds or less than a day to cross the Sun's surface. In a 12 year orbit that's 1/500 of the time, you have to watch closely!

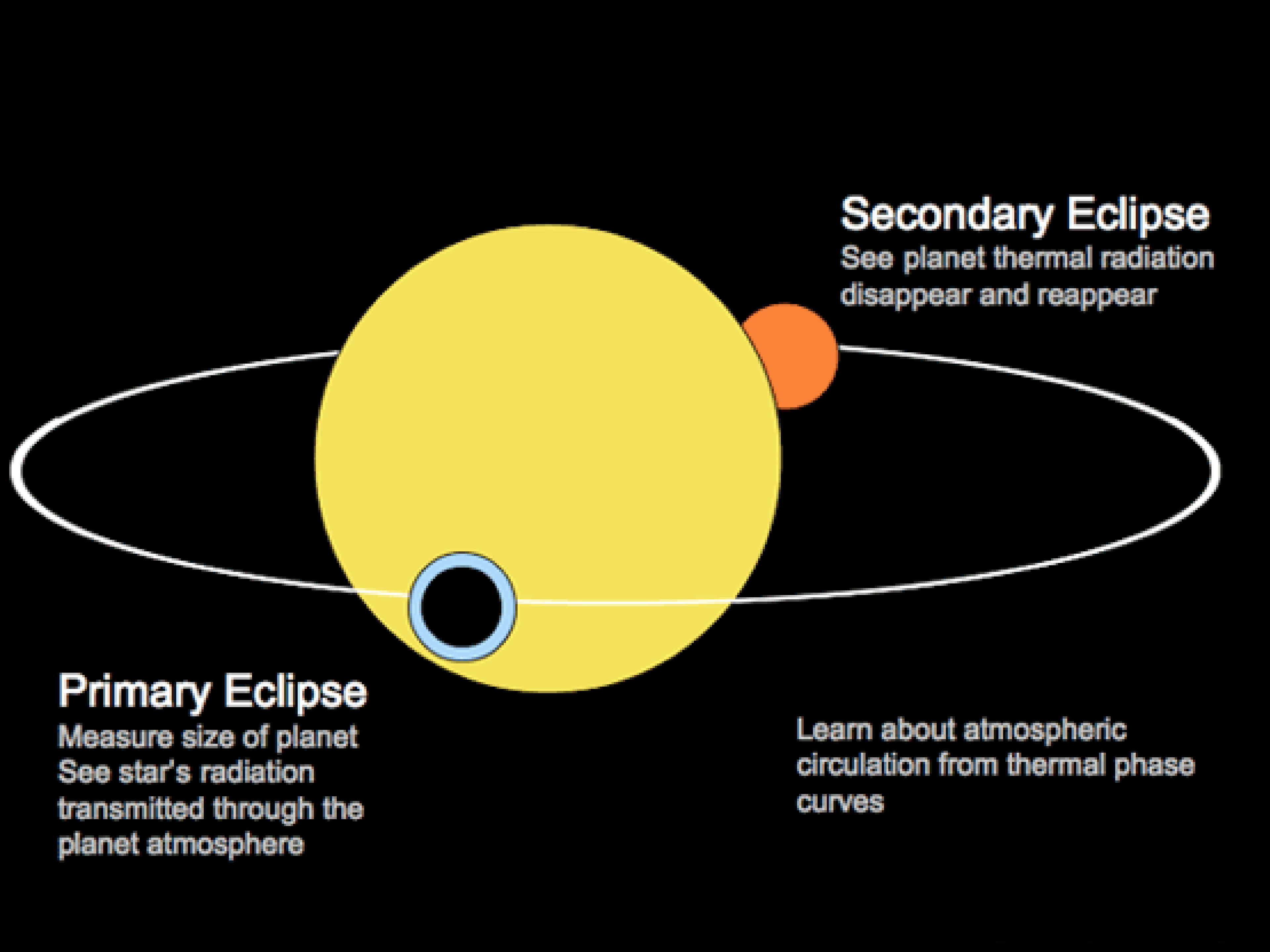
The solution is to observe a large number of stars at a time so that the rare eclipses are detected with good statistics.

More than 150 of the planets first discovered by the Doppler method have been followed up in this way.



The shape of the eclipse rise and fall can be used to calculate the thickness of the atmosphere.




Secondary Eclipse
See planet thermal radiation disappear and reappear
Primary Eclipse
Measure size of planet
See star's radiation transmitted through the planet atmosphere
Learn about atmospheric circulation from thermal phase curves

Astrometric Method

$$\theta'' = \left(\frac{M_p}{M_*}\right)\left(\frac{a}{r}\right) \approx \frac{10^{-3}}{r(pc)}\left[\frac{P(yr)}{M_*(\odot)}\right]^{2/3} M_p(J)$$

$$V_r(m/s) \approx \frac{30}{[P(yr)]^{1/3}}\frac{M_p(J)\sin i}{[M_*(\odot)]^{2/3}}$$

Microlensing Method

$$R_E^2 = \frac{4GMD}{c^2}, \quad D = \frac{D_{ds}D_d}{D_s}, \quad t_0 = \frac{R_E}{V_e}$$

$$t_0 = \frac{2D_L\theta_E}{V_L} = \frac{2D_L}{V_L}\sqrt{\frac{4GM(1-D_d/D_s)}{c^2 D_d}}$$

$$A = \frac{u^2+2}{u(u^2+4)^{1/2}}, \quad u = impact\ parameter$$

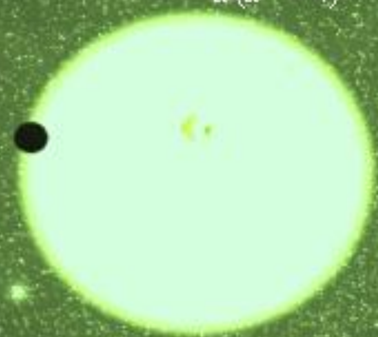
Radial Velocity Method

$$K = \left(\frac{2\pi G}{P}\right)^{1/3}\frac{M_p \sin i}{(M_* + M_p)^{2/3}}\frac{1}{\sqrt{1-e^2}}$$

$$M_p \sin i = \left(\frac{P}{2\pi G}\right)^{1/3} K M_*^{2/3}(1-e^2)^{1/2}$$

Direct Detection

$$B \geq \frac{\lambda D}{r} \approx \left(\frac{\lambda}{10\,\mu m}\right)\left(\frac{D}{10\,pc}\right)\left(\frac{r}{1AU}\right)^{-1} m$$



Effective Temperature

$$T_p = \frac{(1-A)^{1/4}}{\sqrt{2}}\left(\frac{R_*}{r}\right)^{1/2} T_*$$

$$A_\oplus \sim 0.39, \; T_* \sim 5770K, \; r_\oplus \sim 1AU$$

$$\Rightarrow T_p \sim 280K \Rightarrow Greenhouse\ Effect!$$

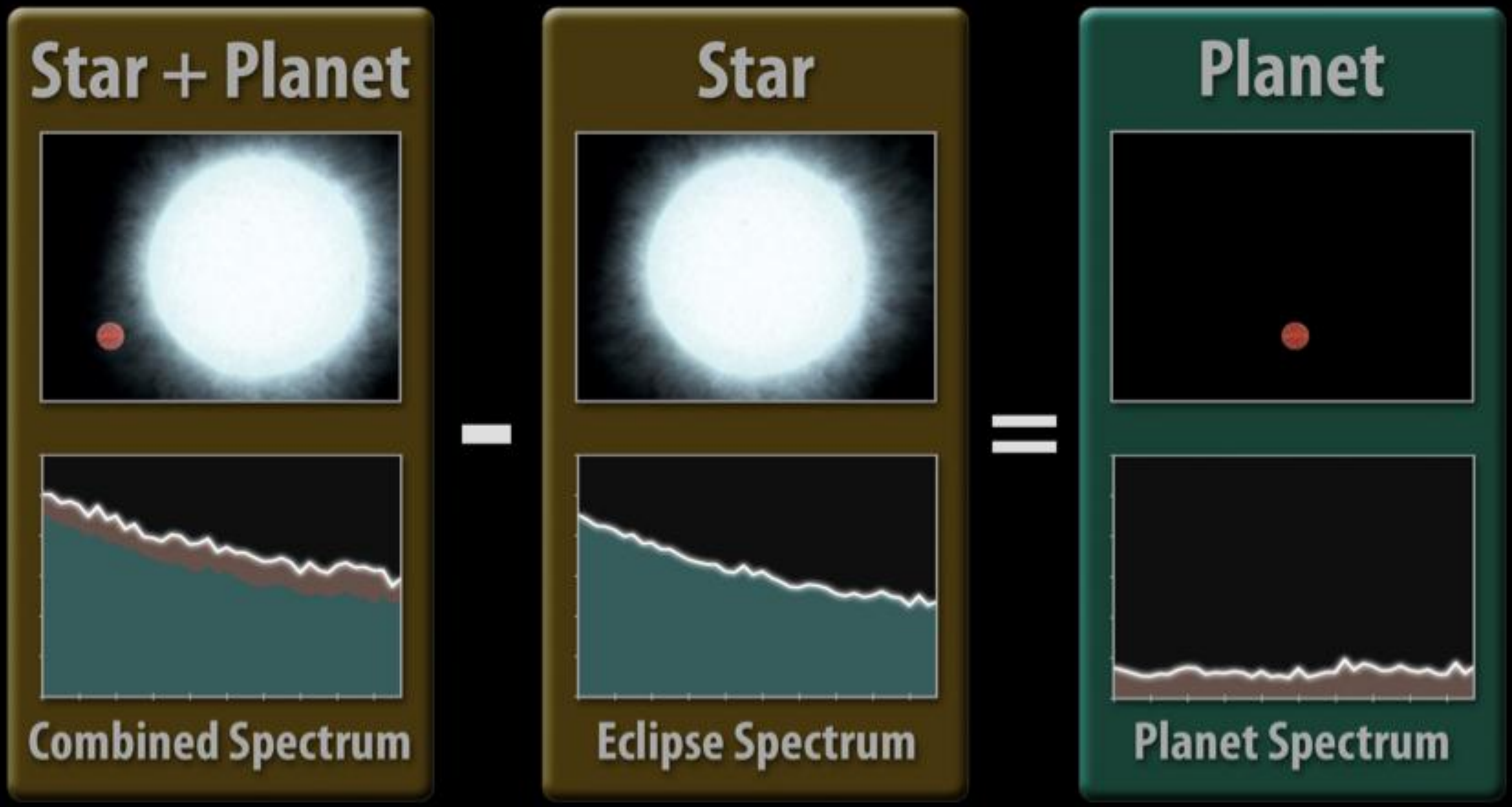
Transit Method

$$\frac{\Delta F}{F} = \left(\frac{R_p}{R_*}\right)^2, \quad t = \frac{P_p}{\pi}\left(\frac{R_*\cos\delta + R_p}{a_p}\right)$$

$$i_{min} = \cos^{-1}\left(\frac{R_*}{a_p}\right), \quad \cos i = \frac{R_*\sin\delta}{a_p}$$

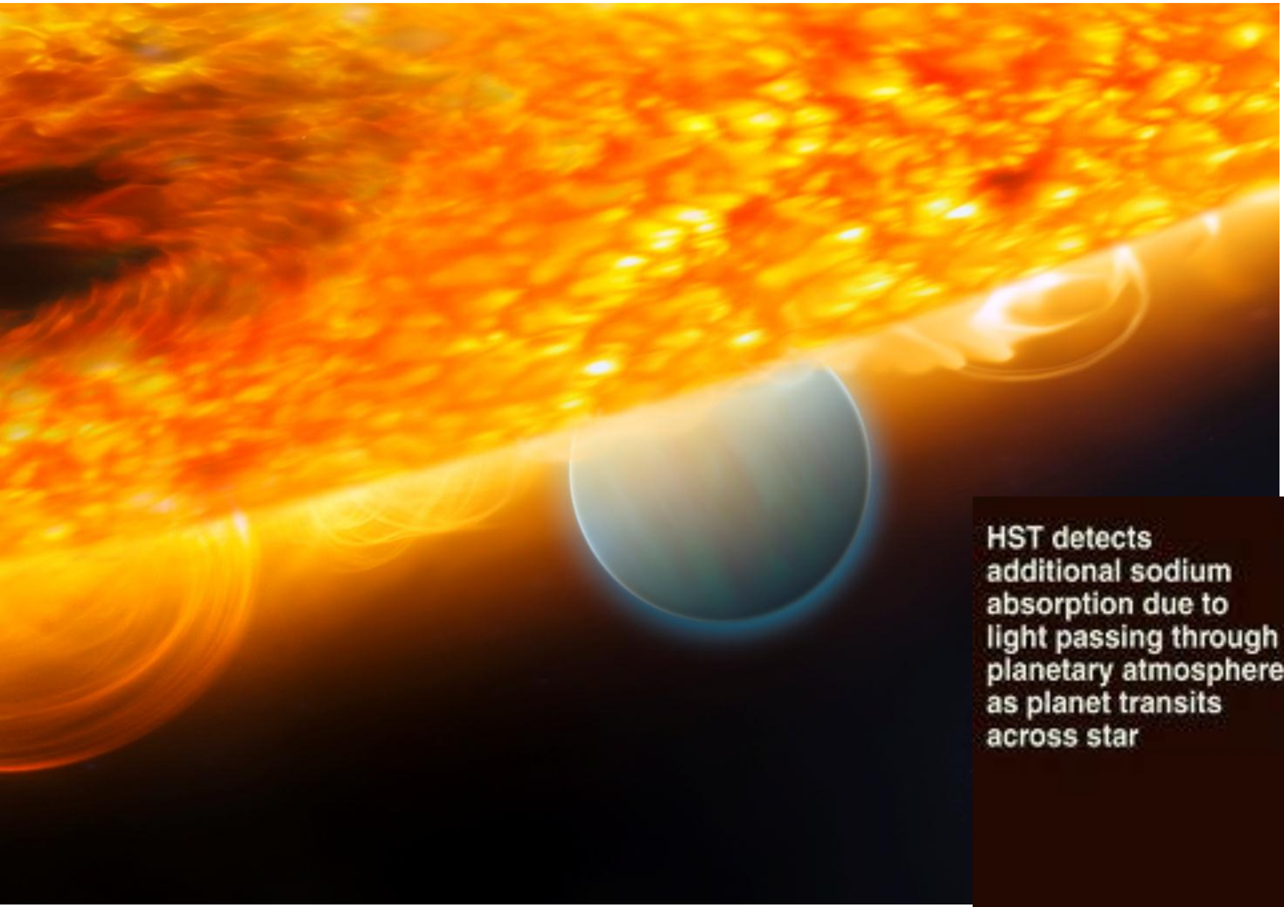
Characterization

Eight 16” telescopes monitor a few thousand stars nearby cooler than the Sun, searching for transiting planets as small as the Earth, in the MEarth project.

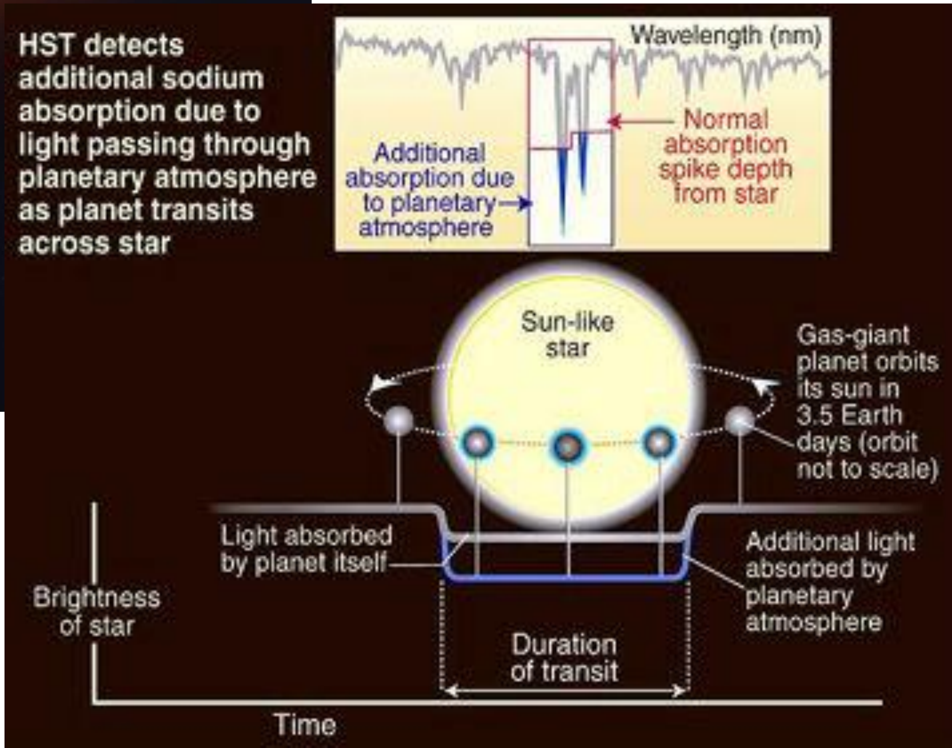


Isolating a Planet's Spectrum

Probing Atmospheres



An atmosphere backlit by a star can reveal the composition by absorption in the star's spectrum.



Sodium , carbon dioxide and steam have been found; but no strong biomarkers yet…

Exoplanet Density

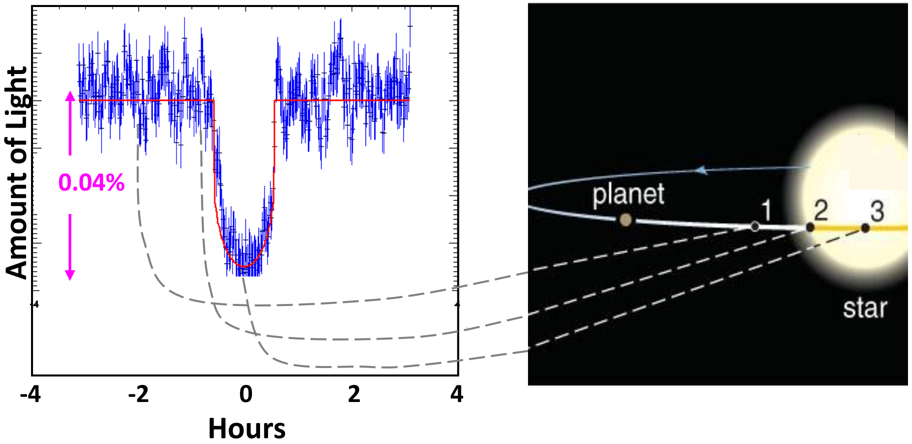
- **Density = Mass / Volume**

- The planet's mass was measured using the ***radial velocity method:***
  The planet gravitationally 'tugs' the star, shifting the wavelength and the amount of shift gives the planet's mass.

Changes in the measured wavelengths of star light are caused by a planet with mass ~5 times Earth's.

- **Volume = 4/3 π R^3**

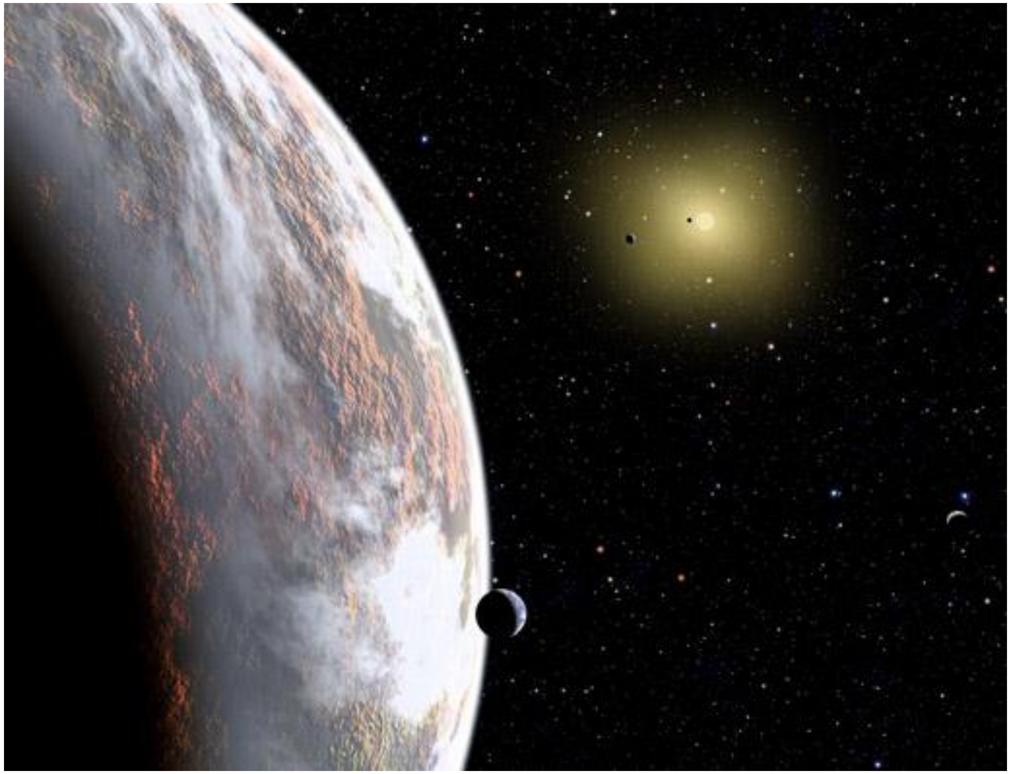
- The planet's size was determined using the ***transit method:***
  The light from a star decreases when a planet passes in front of it. The amount of dimming indicates the planet's size.



Periodic decreases in light from the star are caused by a planet with diameter 1.7 times Earth's passing in front.

Rocky Exoplanets

- After discovering hundreds of exoplanets resembling Jupiter, astronomers have found the most Earth-like planets so far.
- Although Corot-7b's density is close to the Earth's, differences abound: it orbits its star in ~20 hours (faster than any known exoplanet). That is so close its rocky surface may be molten.
- With the existence of Earth-like planets now demonstrated, astronomers are confident that Kepler will discover hundred more, some smaller than Earth.



Detection of more rocky exoplanets (super-Earths) like those in this artist's depiction should come rapidly, thanks to dedicated space telescopes and improving ground-based detection capabilities (Image from D. Aguilar, Harvard Smithsonian CfA).

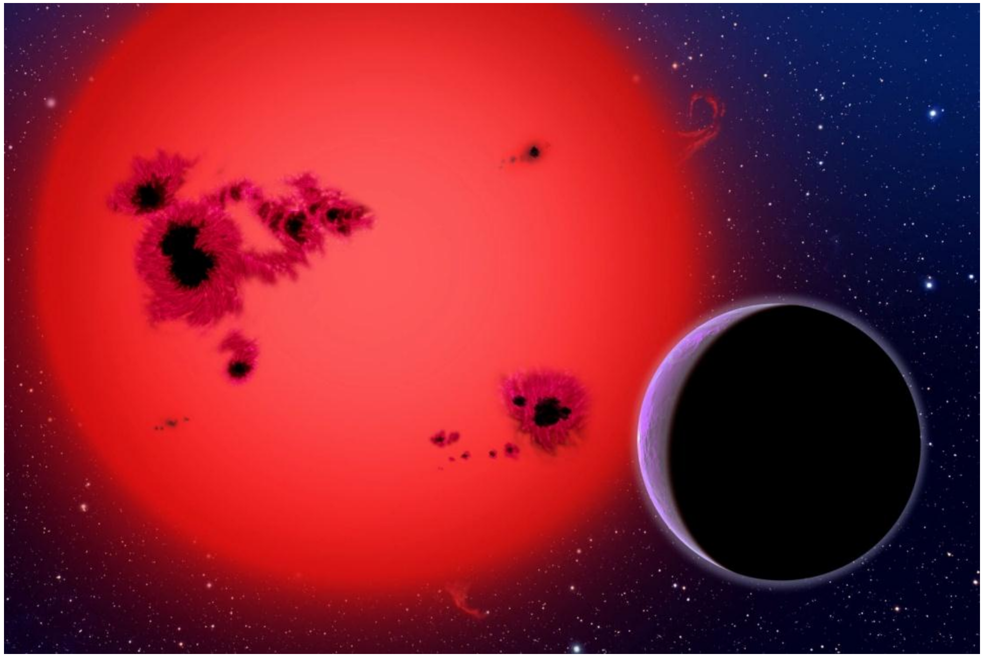
Water World

- A set of eight small telescopes detected an exoplanet passing in front of a nearby red dwarf star.

- Observations provide estimates of the planet's size (~2.7x Earth) and mass (~6x Earth).

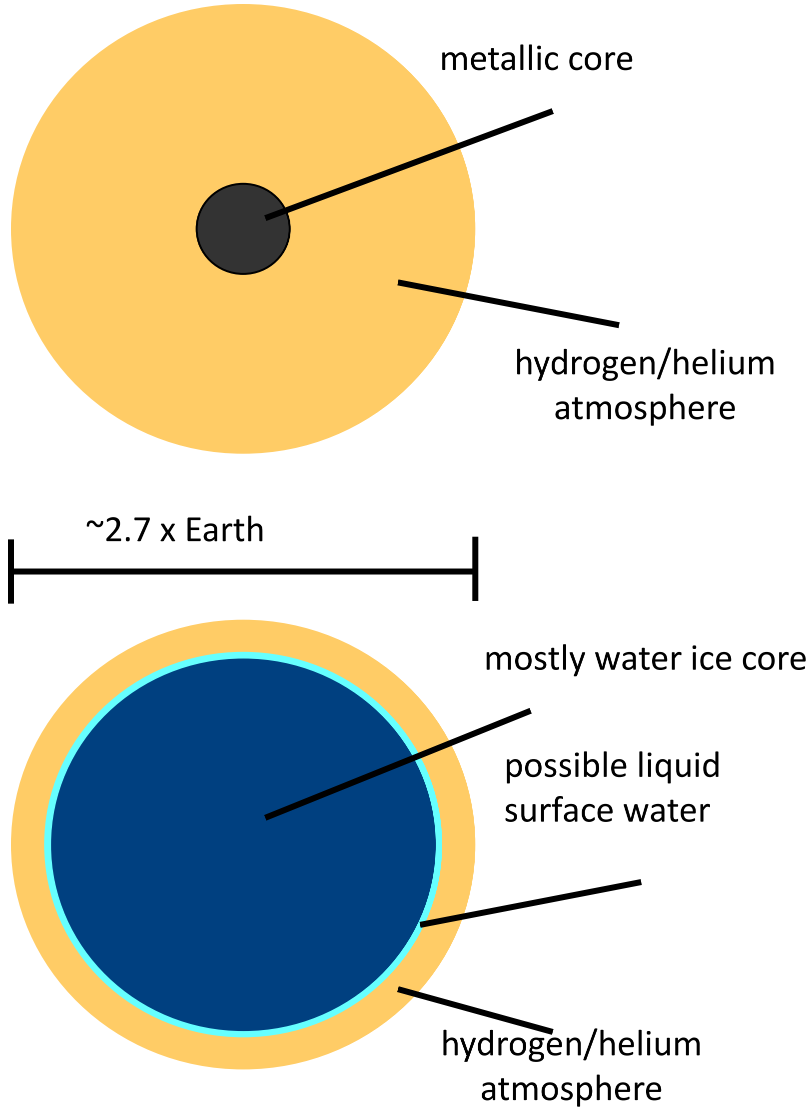
- The density of 1.8 g/cm^3 implies the planet may be composed primarily of water, which has the density of 1 g/cm^3.

- The planet is only 40 light years away, so our radio and our TV transmissions have swept over it

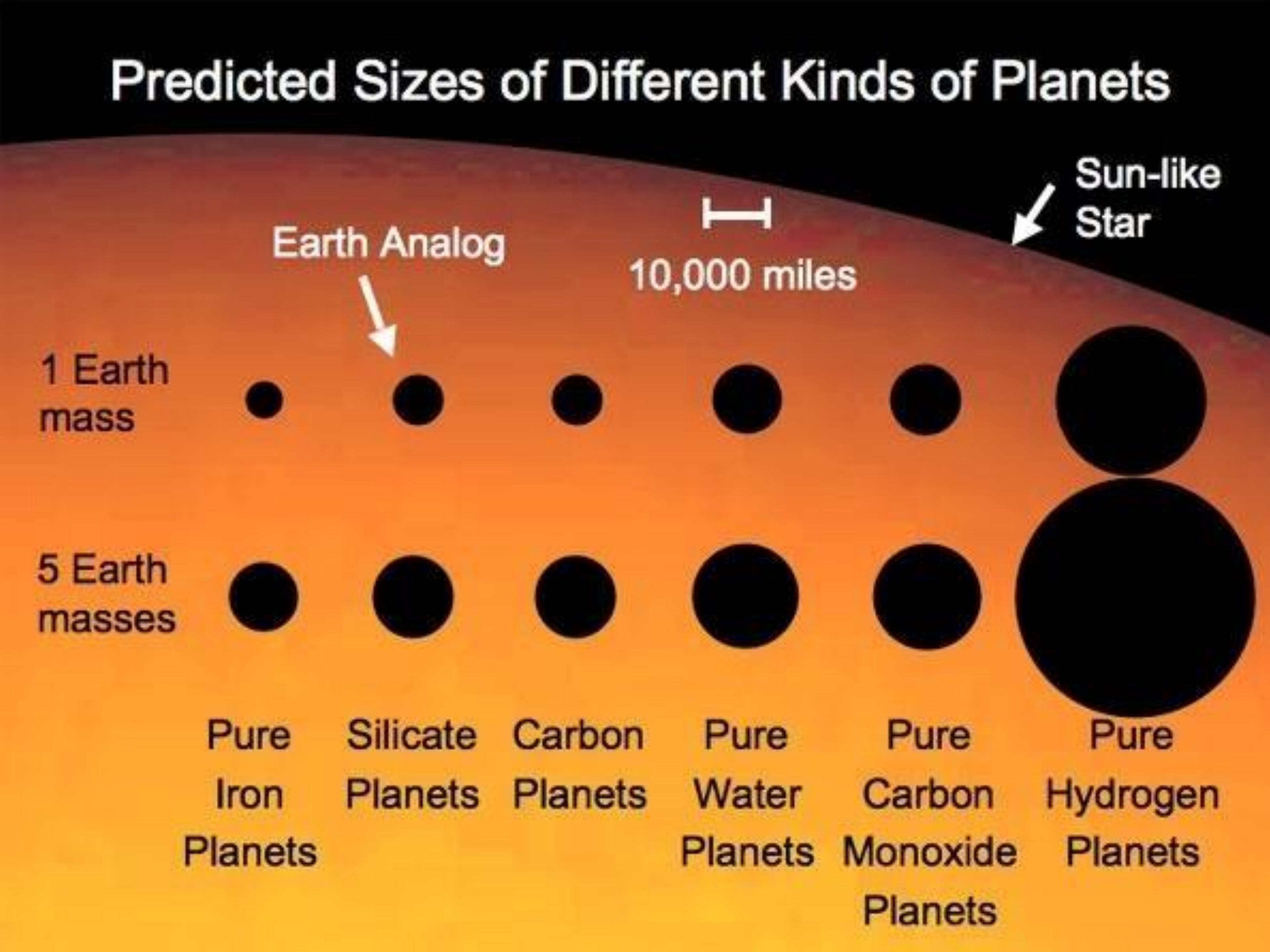


Artist's conception of GJ 1214b - a 'Super Earth' orbiting a star 40 light-years away. The planet orbits at a distance of only 15 stellar radii (Image from David Aguilar).

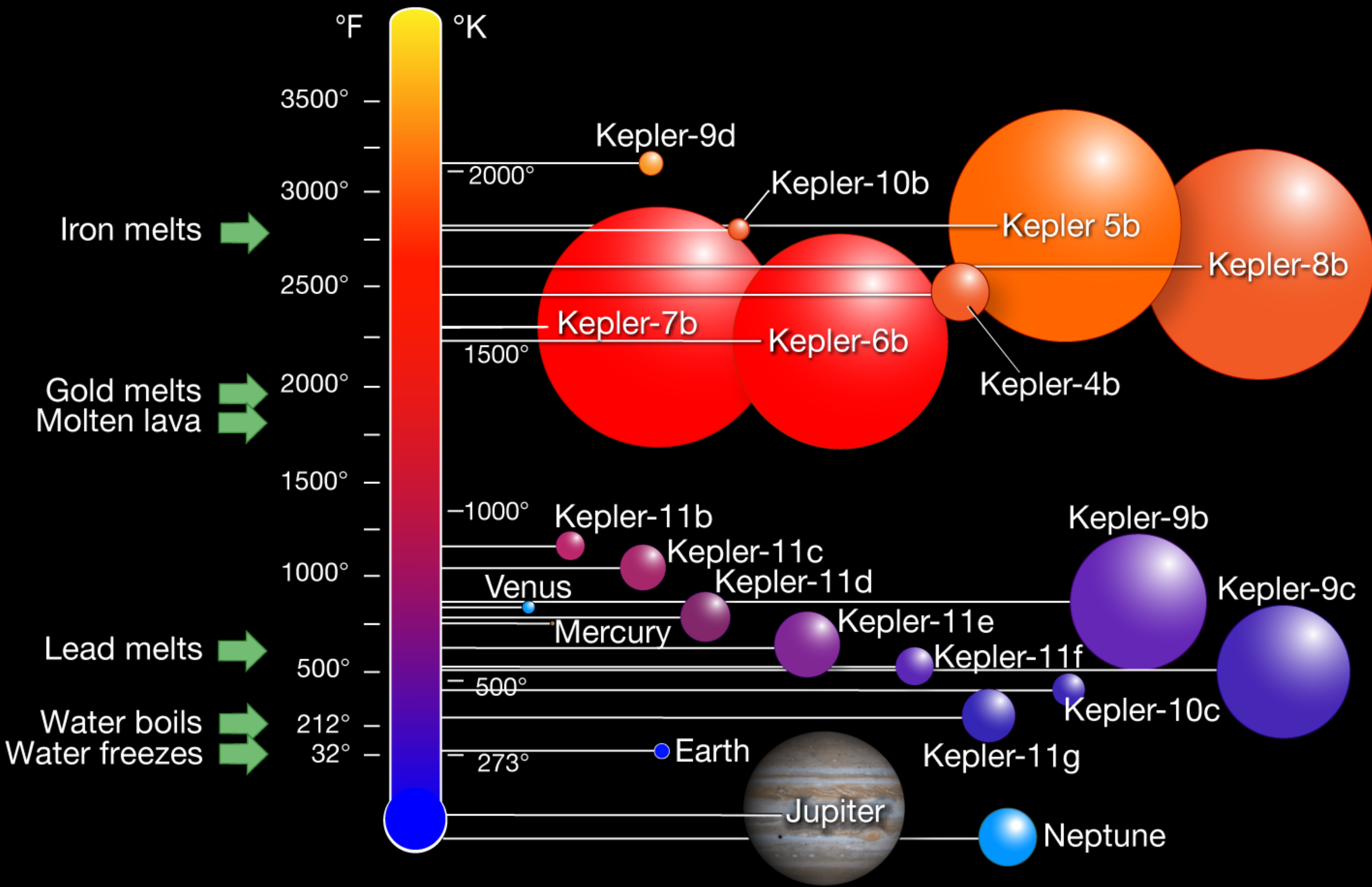
- Knowing the mean density of the planet does not uniquely tell us its composition. There are many models that can match the single mean density measured.
- The planet *might* have a small, dense metallic core surrounded by large hydrogen atmosphere - but the star should rapidly boil the atmosphere away.
- *More likely* the planet has a core made mostly of solid water (ice) and small hydrogen atmosphere (expected for a planet orbiting so close to its star).



Two possible interior structures of GJ 1214b.

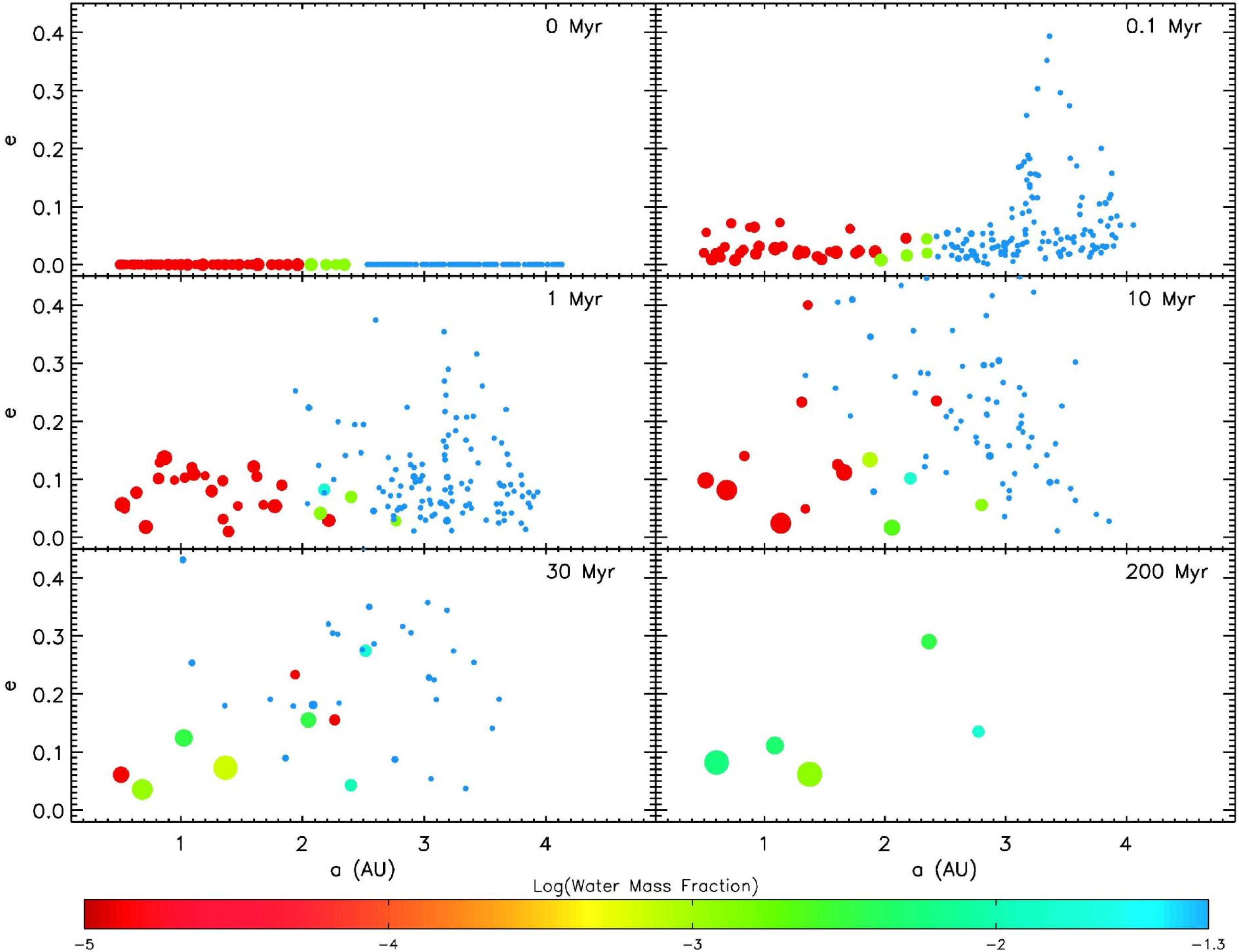

Predicted Sizes of Different Kinds of Planets
Sun-like Star
Earth Analog
10,000 miles
1 Earth mass
5 Earth masses
Pure Iron Planets
Silicate Planets
Carbon Planets
Pure Water Planets
Pure Carbon Monoxide Planets
Pure Hydrogen Planets

Planet Temperature & Size

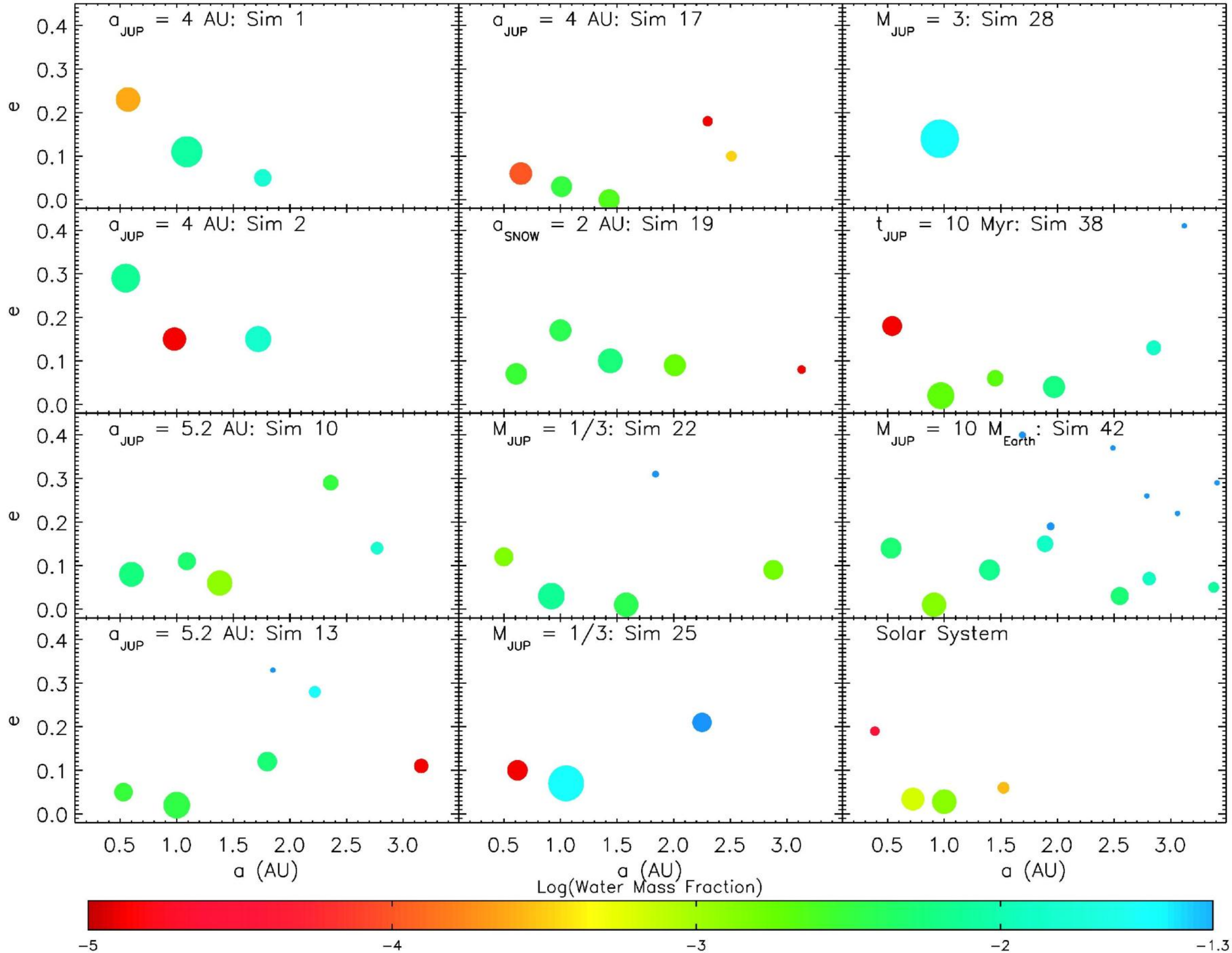


Earths

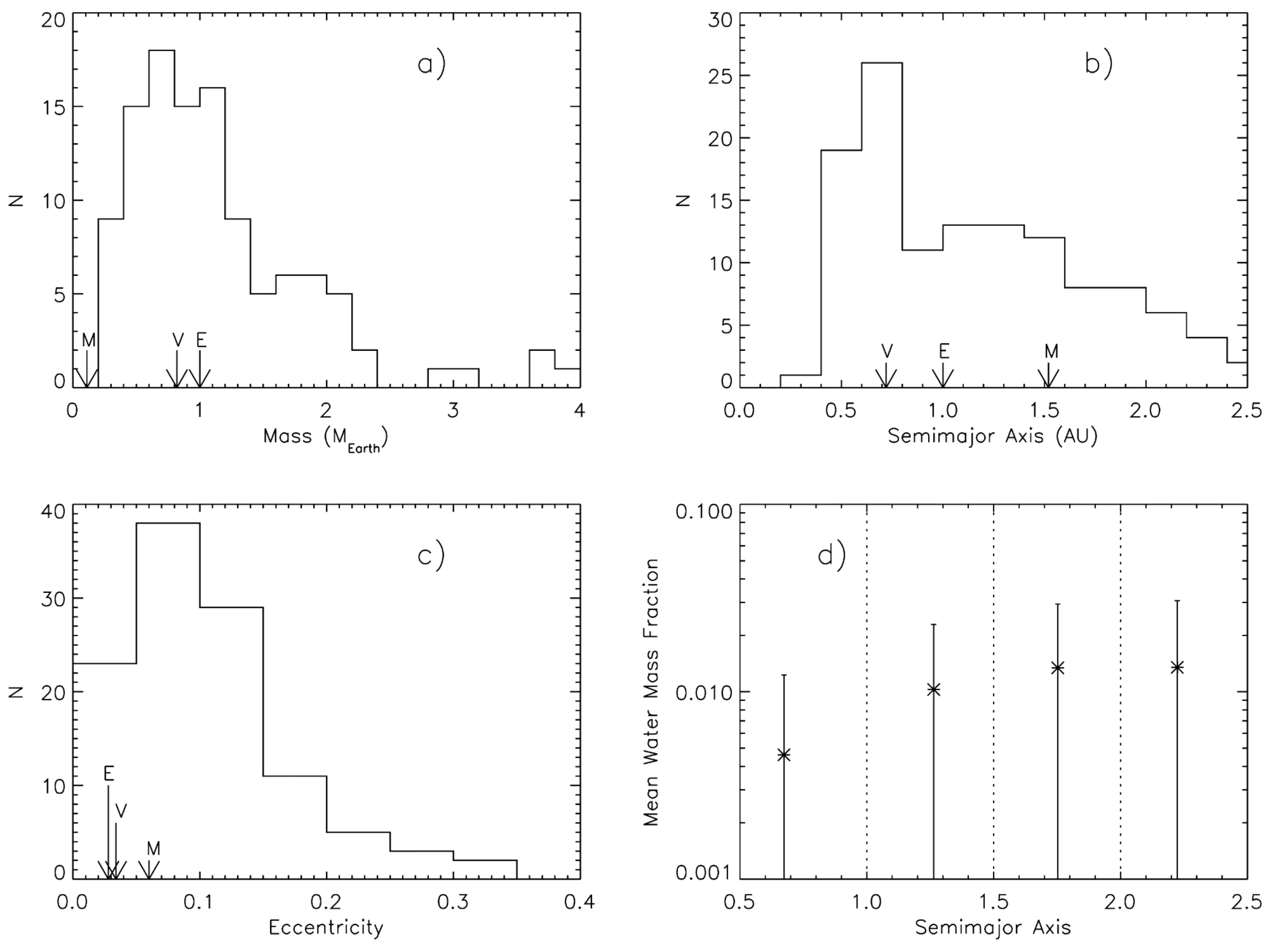
- No planets exactly like the Earth have been discovered. But close…
- Not enough data yet to tell if they are common or rare, but theory says they will be abundant.
- The record-holder from Doppler method is 1.9x Earth mass, but Kepler transits are now turning up dozens of Earth-size and smaller exoplanets.



0 Myr
0.1 Myr
1 Myr
10 Myr
30 Myr
200 Myr
e
0.0
0.1
0.2
0.3
0.4
1
2
3
4
a (AU)
Log(Water Mass Fraction)
−5
−4
−3
−2
−1.3

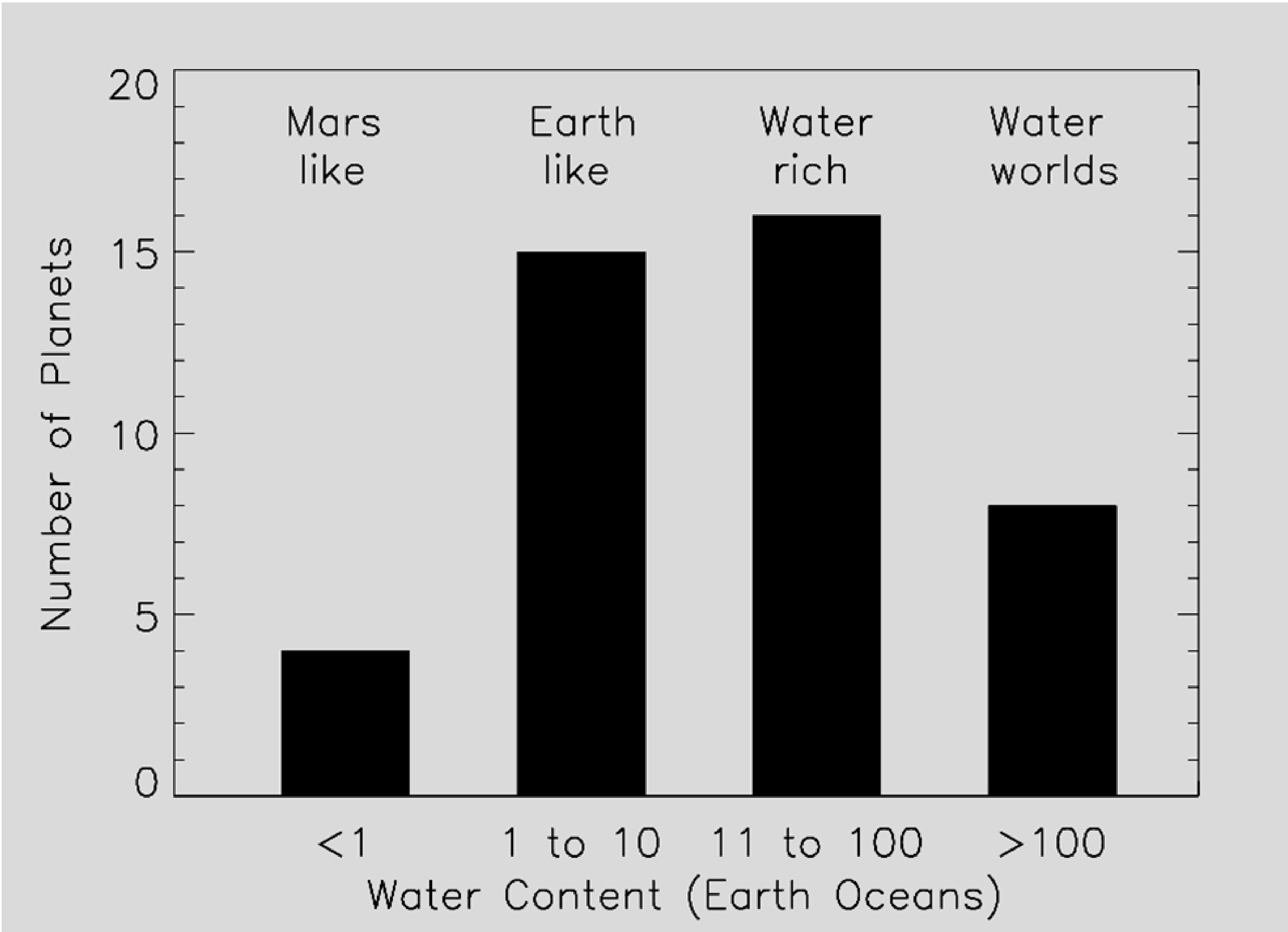


a_JUP = 4 AU: Sim 1
a_JUP = 4 AU: Sim 17
M_JUP = 3: Sim 28
a_JUP = 4 AU: Sim 2
a_SNOW = 2 AU: Sim 19
t_JUP = 10 Myr: Sim 38
a_JUP = 5.2 AU: Sim 10
M_JUP = 1/3: Sim 22
M_JUP = 10 M_Earth: Sim 42
a_JUP = 5.2 AU: Sim 13
M_JUP = 1/3: Sim 25
Solar System
e
a (AU)
Log(Water Mass Fraction)
−5
−4
−3
−2
−1.3



a)
N
Mass (M_{Earth})
M
V
E
b)
Semimajor Axis (AU)
c)
Eccentricity
d)
Mean Water Mass Fraction
Semimajor Axis

Computer simulations of planet formation "create" 1-6 terrestrial planets per Sun-like star, many with more water than the Earth.



Detecting Earths

Compared to Jupiter, the Earth is 5x further away, 10x smaller and 1000x less massive. How does this affect the detectability.

Doppler

Earth is 5x closer but 1000x less massive, so a 5/1000 = 200x worse lever arm. The Sun speed caused by Earth is only 9 cm/s!

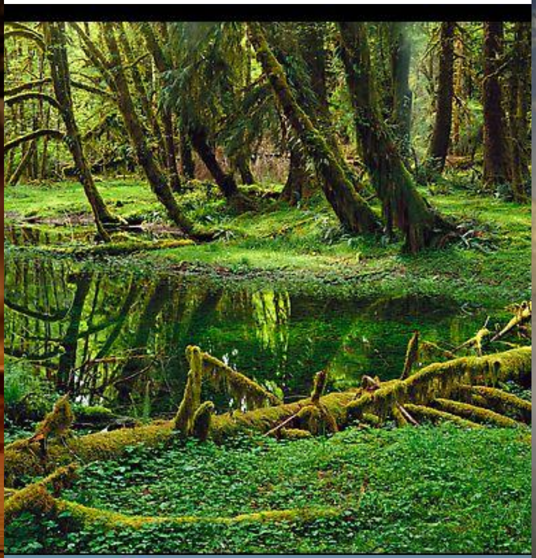
Eclipse

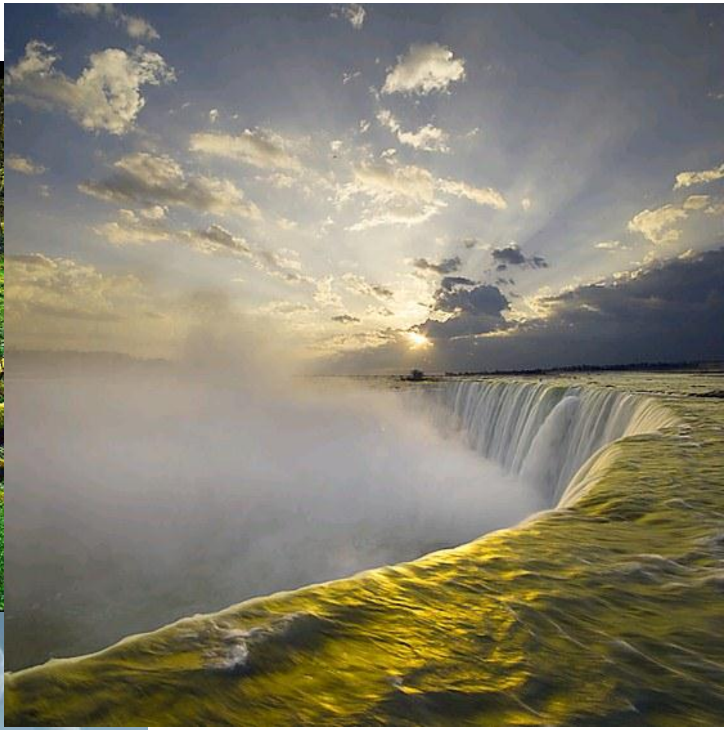
Earth is 10x smaller so 100 times less area so the 1% dimming of a Jupiter drops to a 0.01% dip for the Earth. Tough but doable!

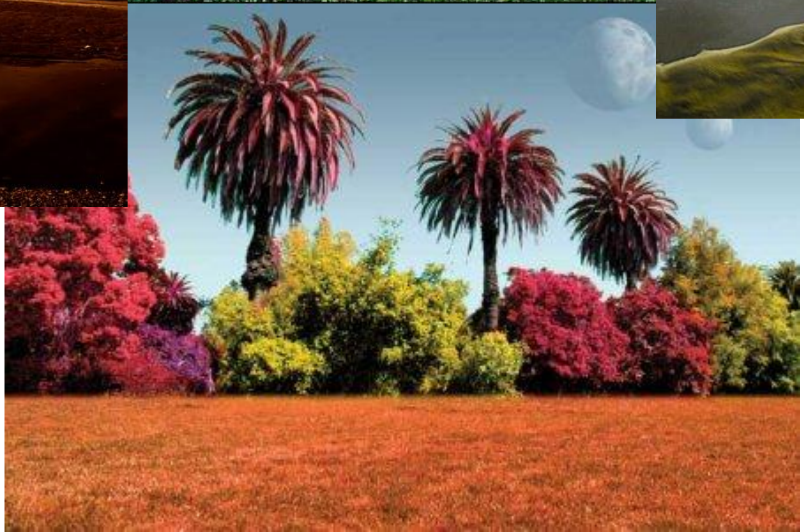
Direct

Earth is 100x less area but 5x times closer which gains back a factor of 25, so only 4x less reflected light than a Jupiter. Difficult!

Earth 2.0



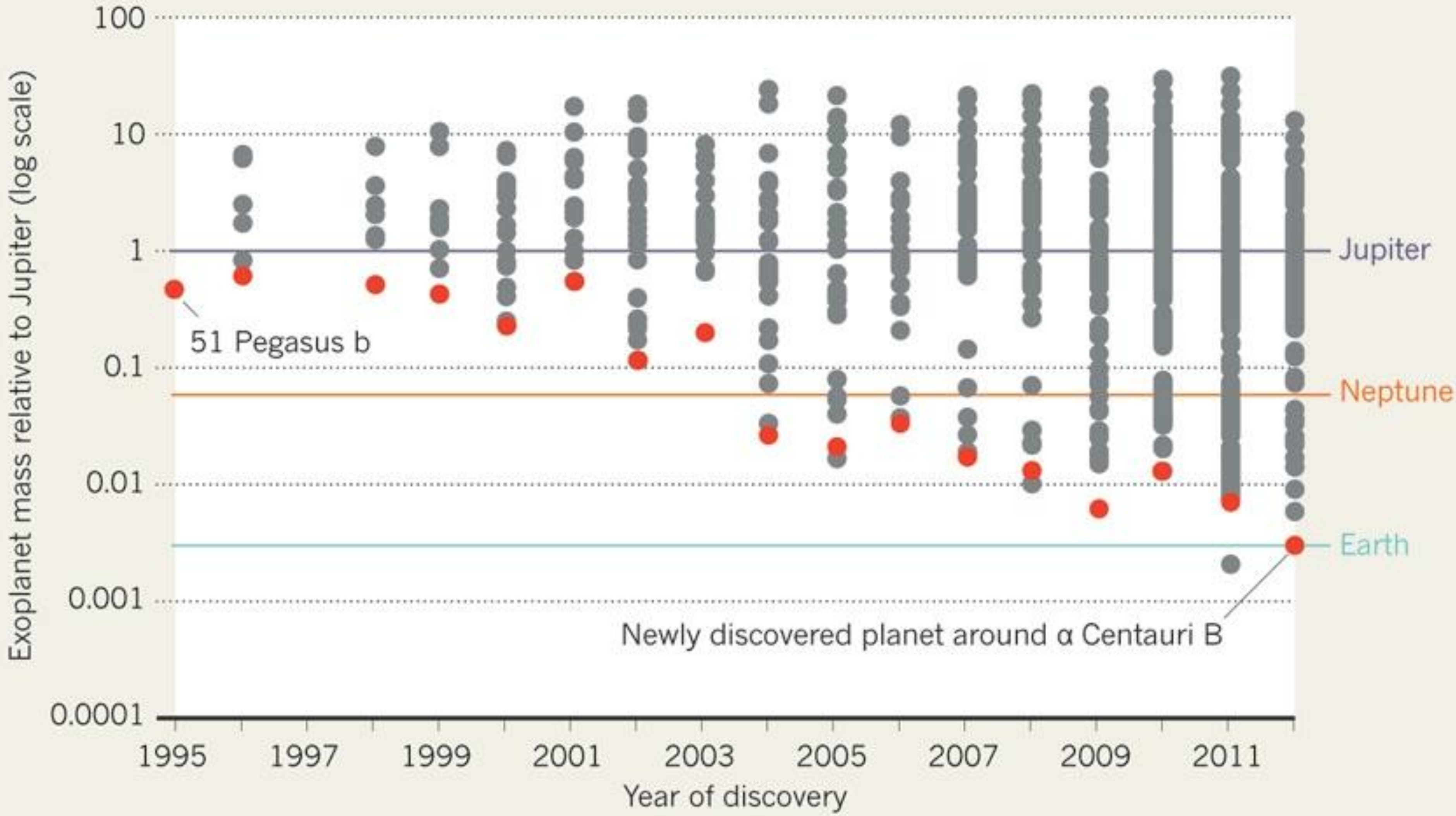




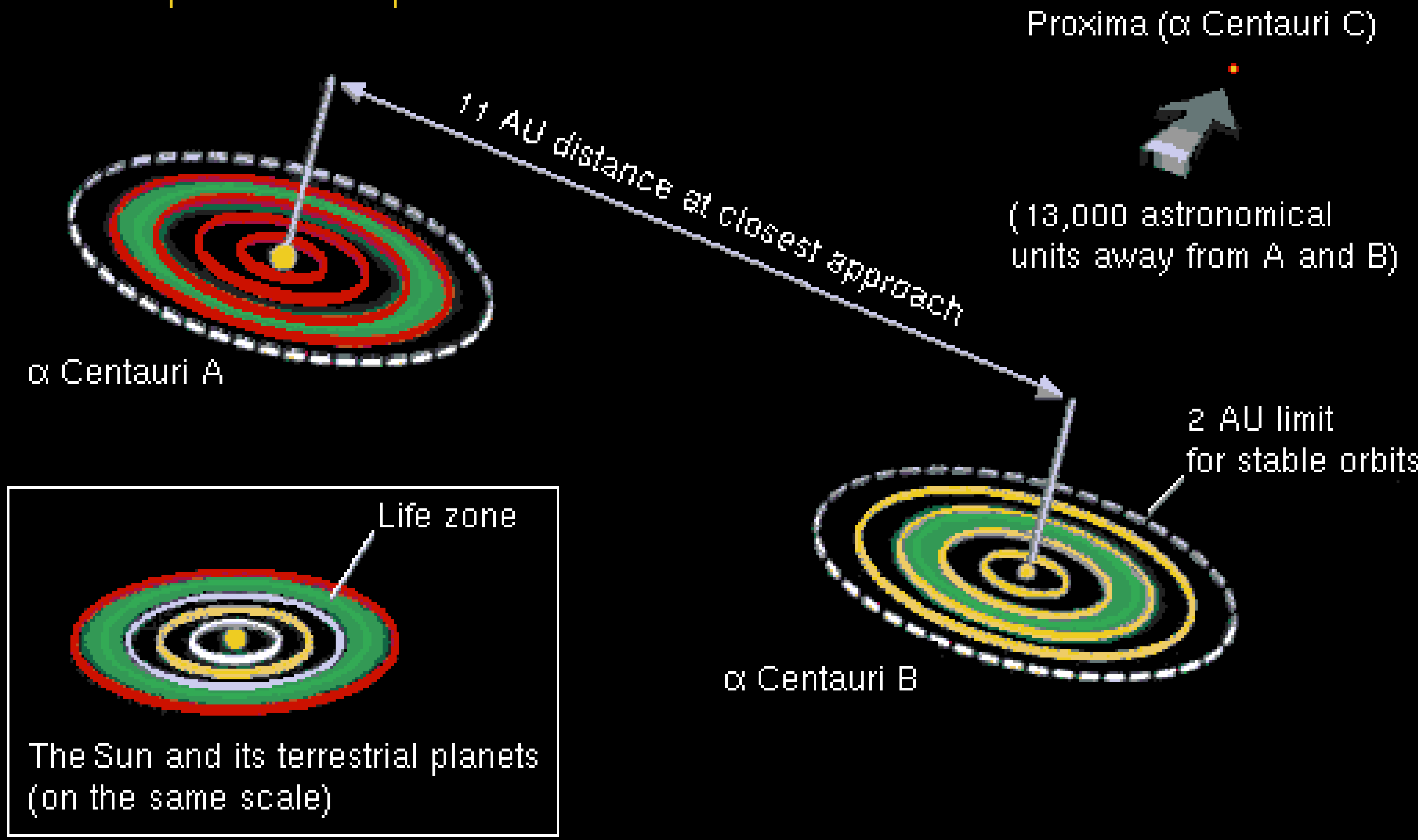
Earth 1.0

LOWEST OF THE LOW

With improving techniques for measuring exoplanets' mass through their gravitational influence on stars, the lightest exoplanets detected each year (red dots) have reached the range of Earth-mass planets.

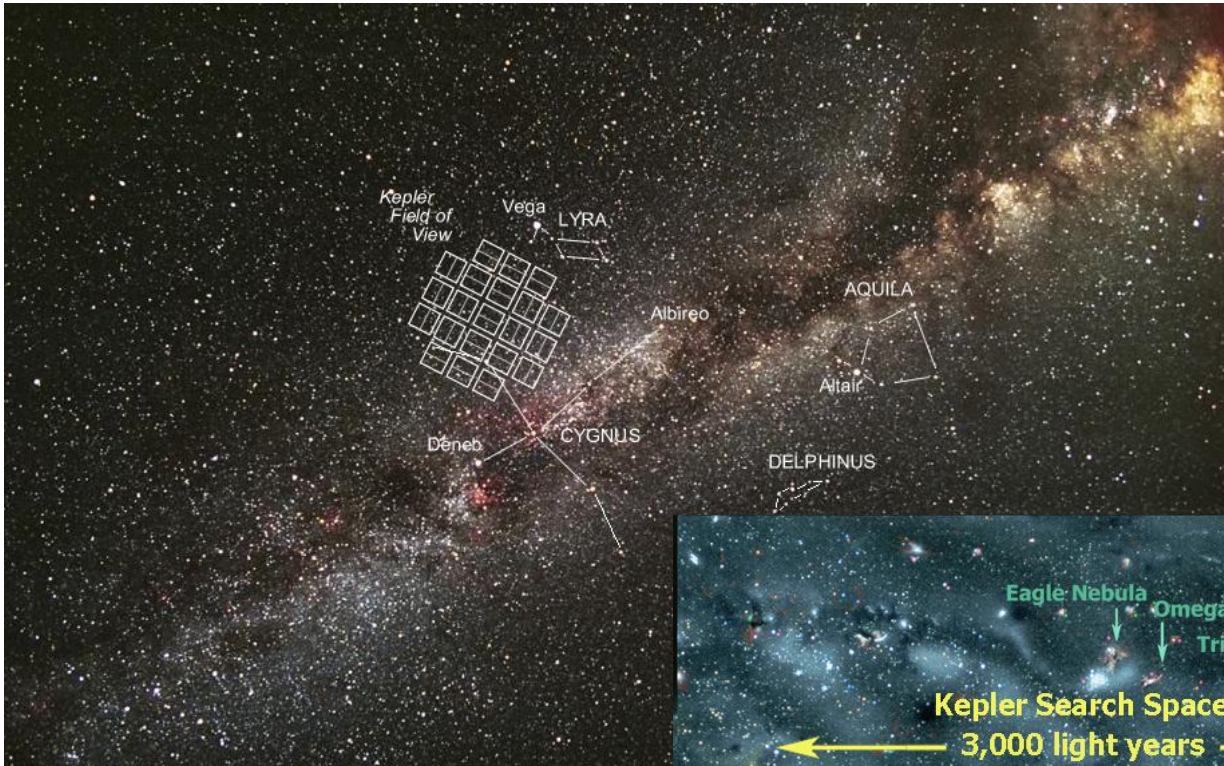


Possible planets at Alpha Centauri

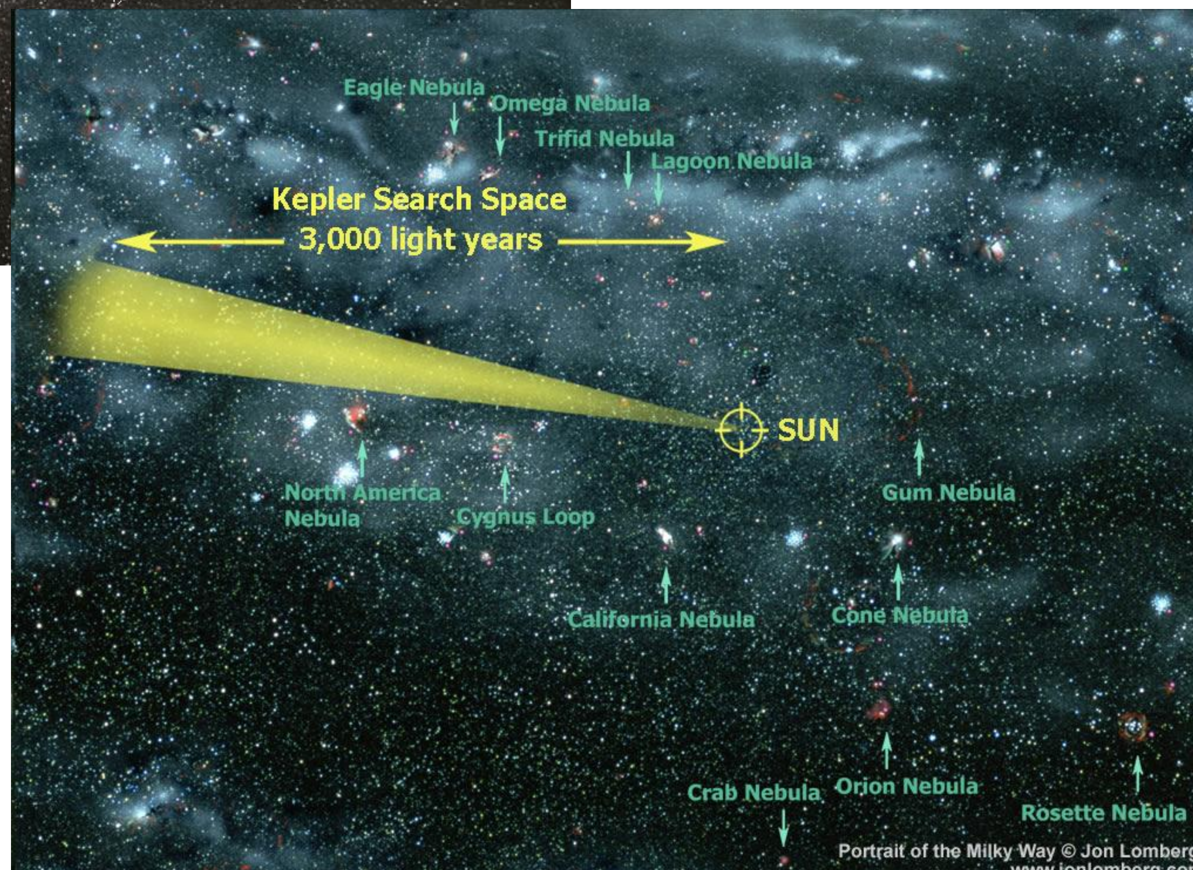


With the nearest Earth perhaps only 4.3 light years away, we could explore it with fleets of remote sensing nanobots in 40 to 50 years.

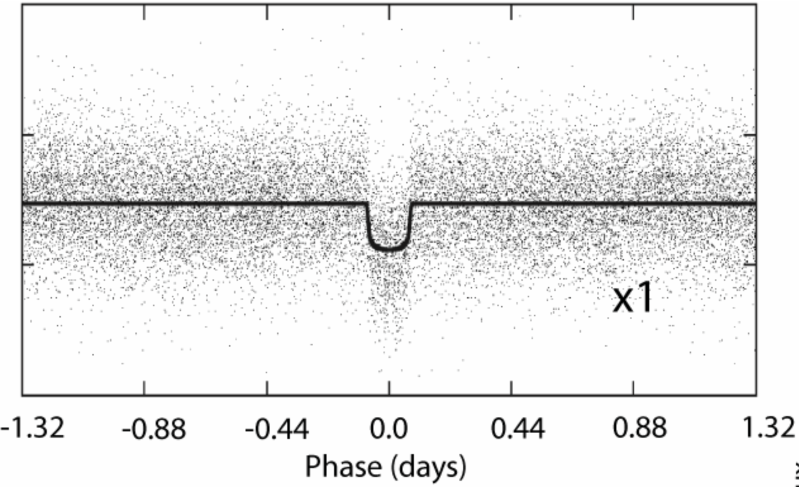
Kepler



Kepler is a 1-meter telescope that is staring at 100 sq. degrees of the sky for 3.5 (+3) years.

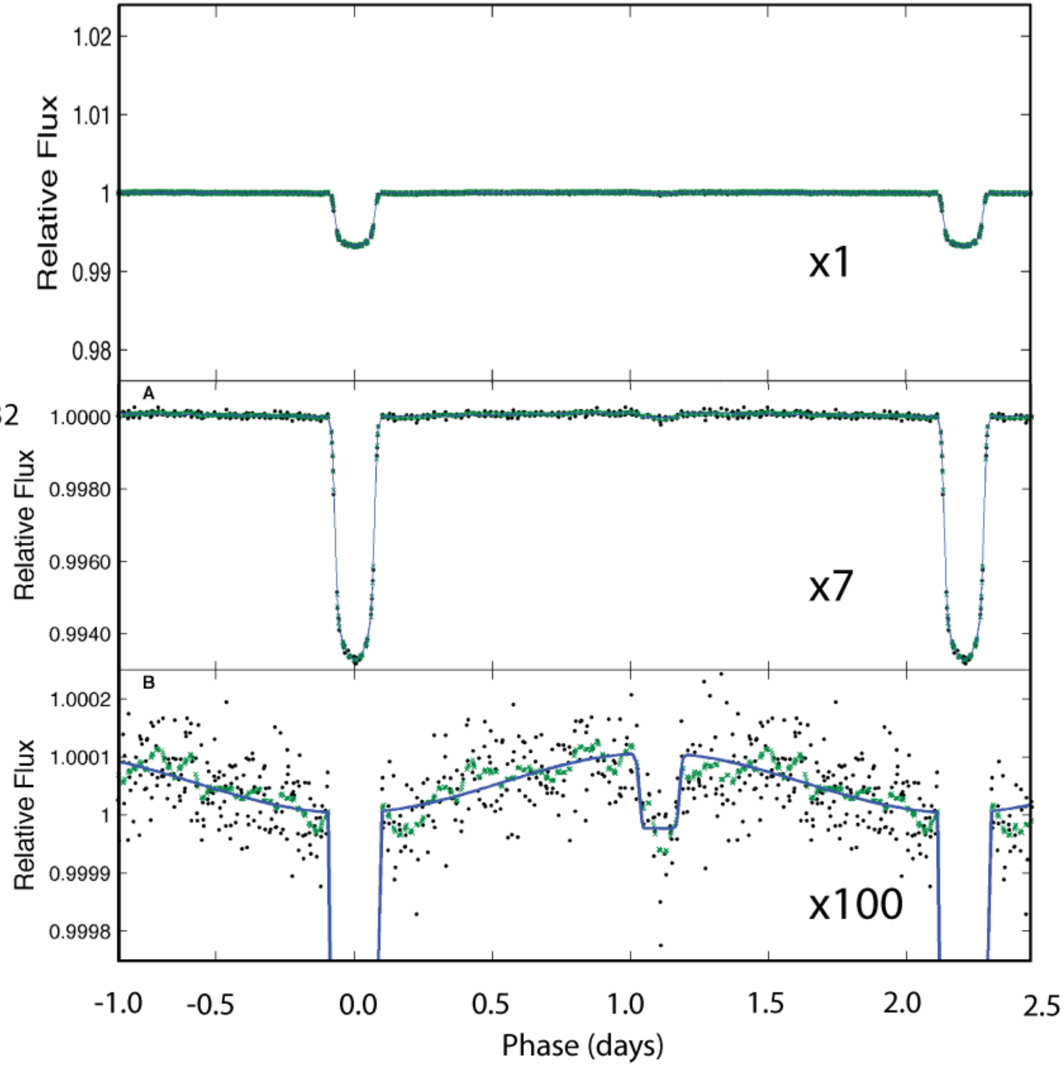


It's monitoring about 150,000 stars for the signs of eclipses by a planet. It can detect 0.001% variation and could find 10^3 Earths



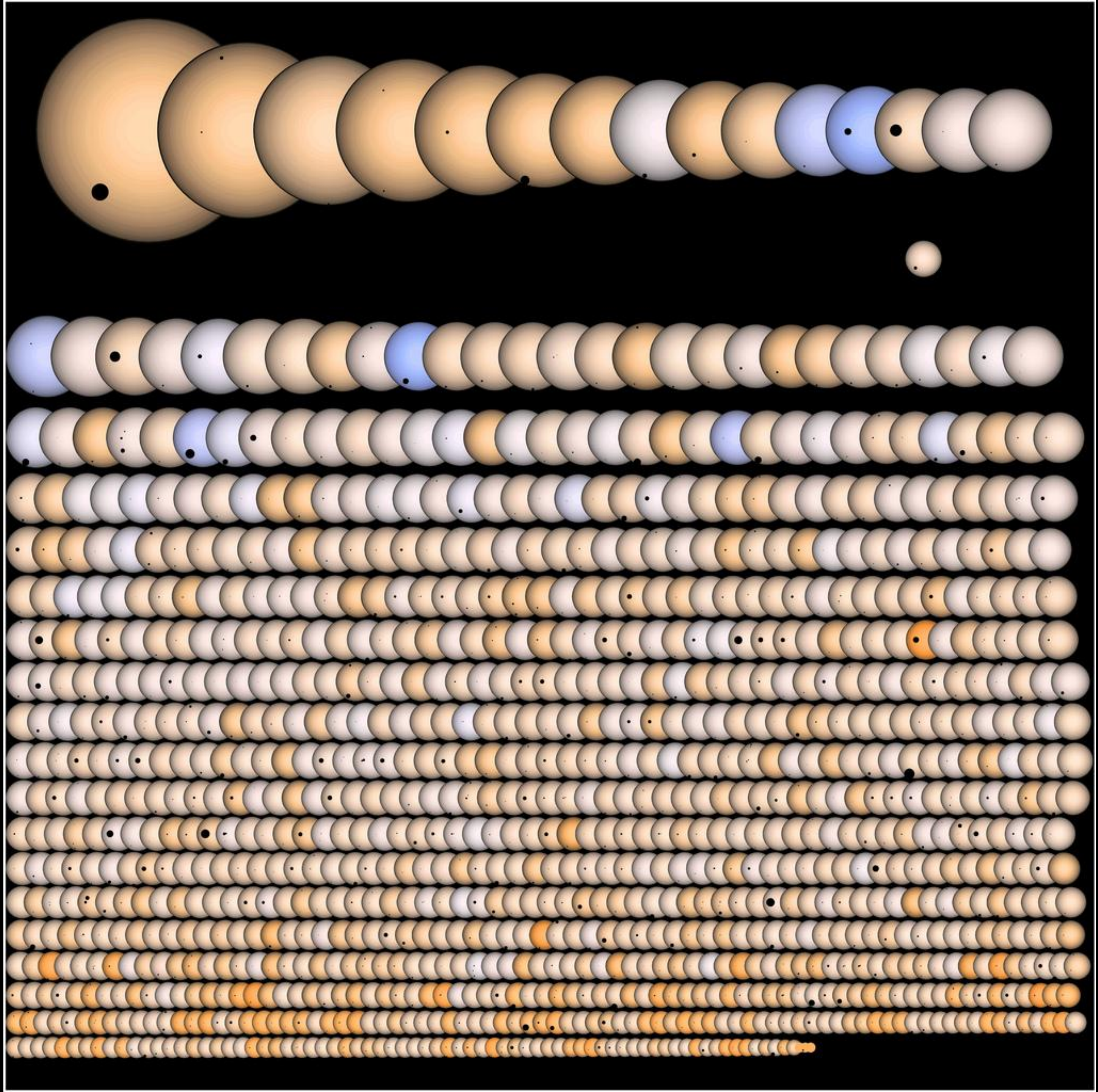
16,620 HATNet data points (57.7 days of data)

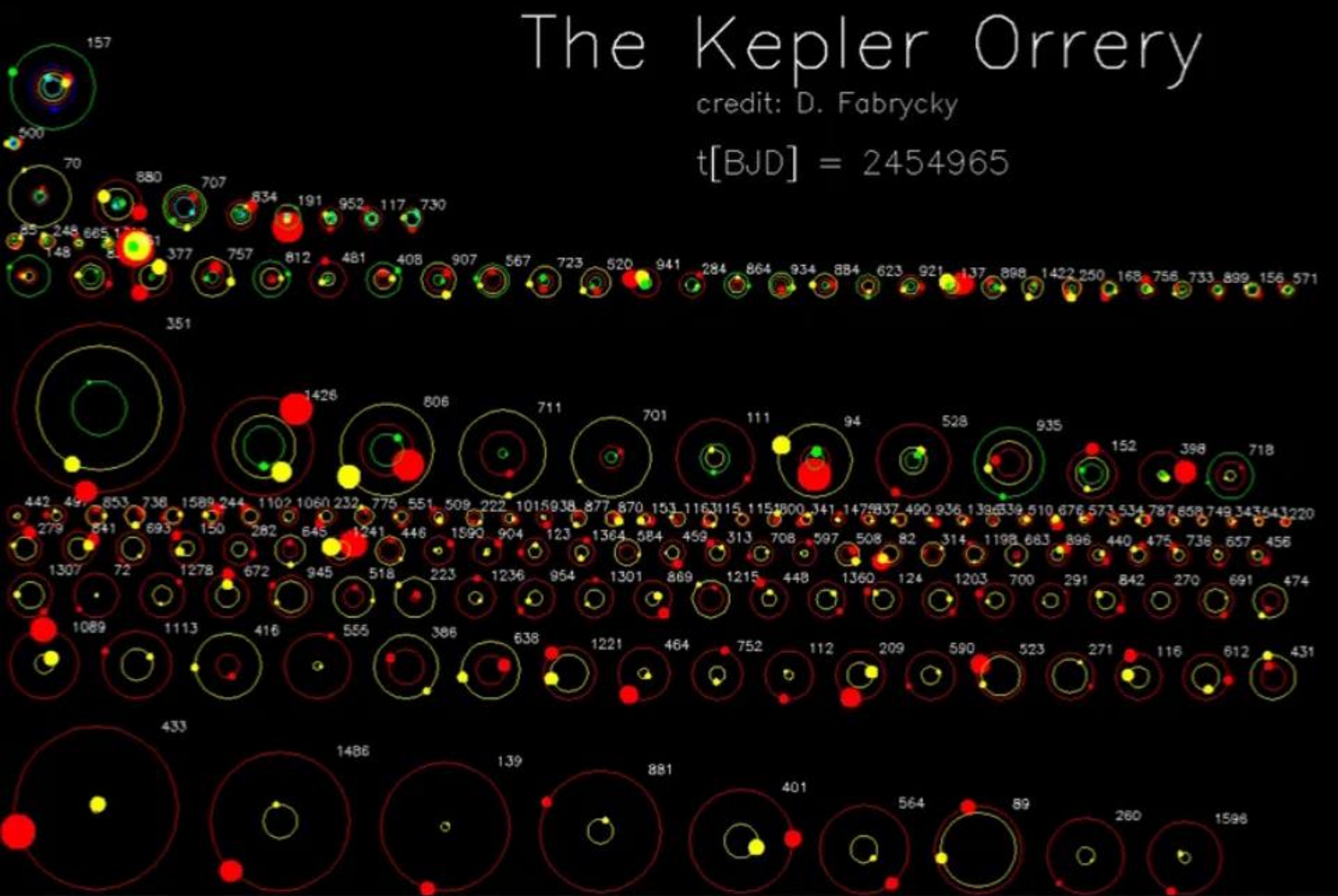
HAT-P-7b data from the ground
A. Pal et al., 2008

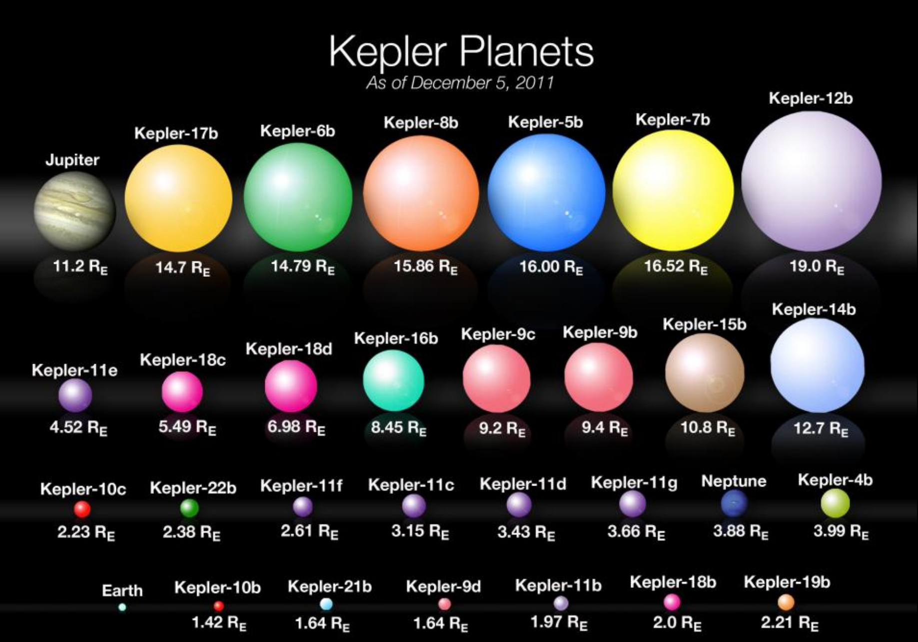


Kepler Commissioning data (10 days)
W. Borucki et al., 2009

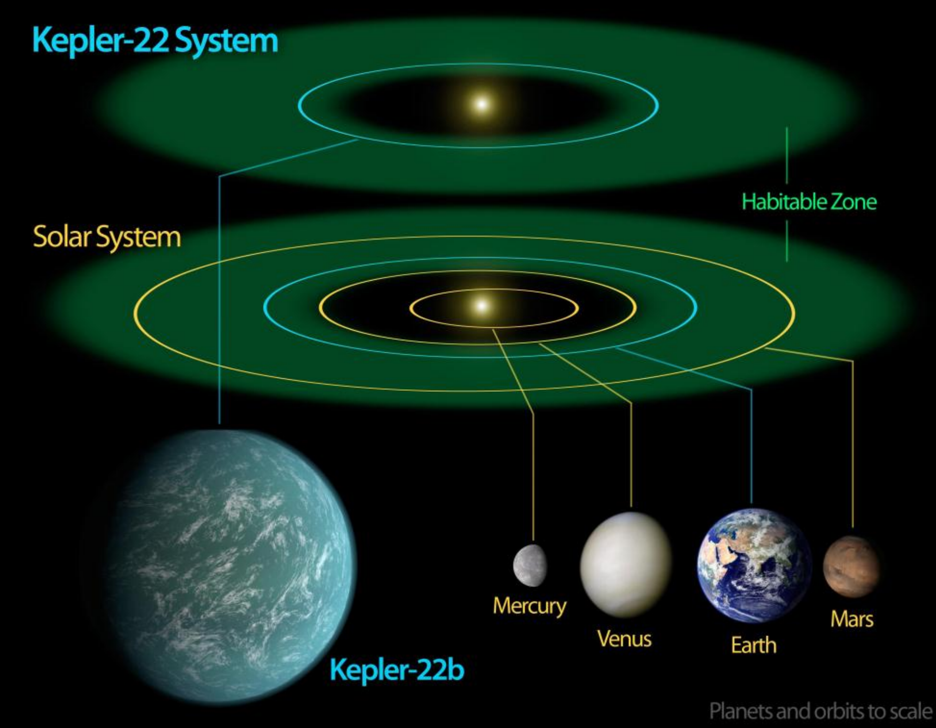
Early data showed that Kepler easily meets all its design goals, but it will take years for it to see Earth-like planets at Earth-like distances.



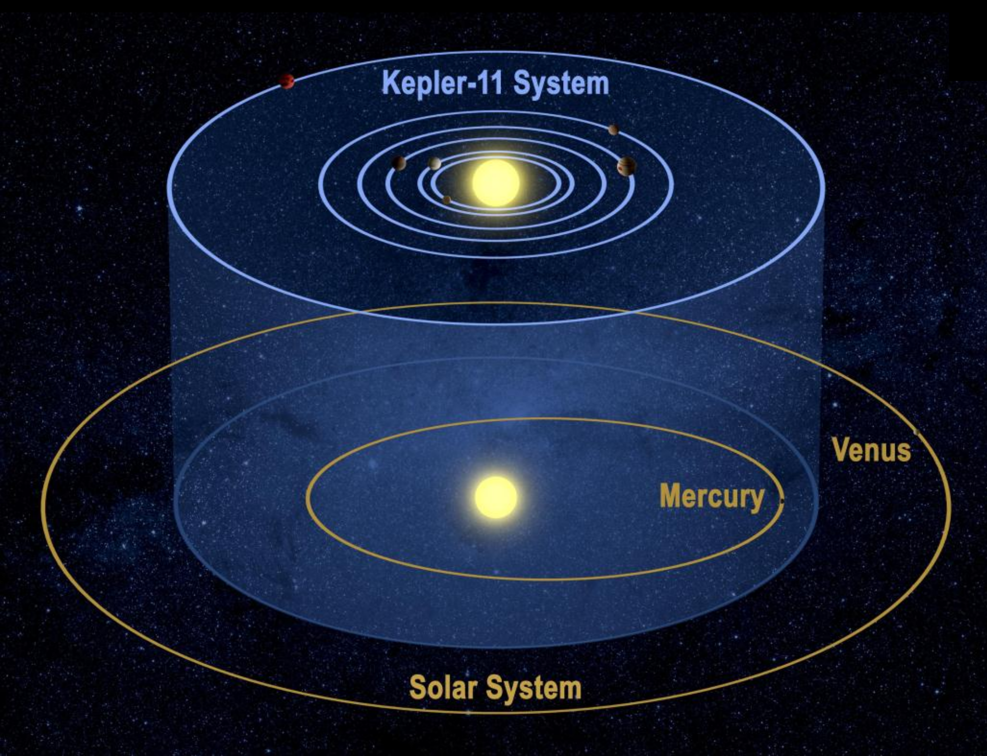

The Kepler Orrery
credit: D. Fabrycky
t[BJD] = 2454965



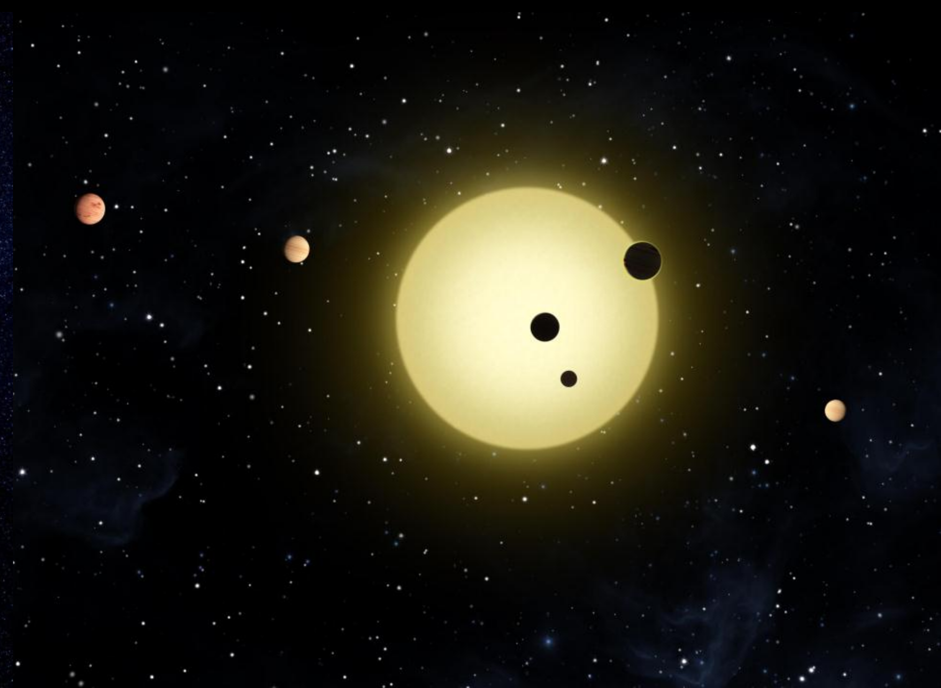
Kepler Planets
As of December 5, 2011
Jupiter
11.2 R_E
Kepler-17b
14.7 R_E
Kepler-6b
14.79 R_E
Kepler-8b
15.86 R_E
Kepler-5b
16.00 R_E
Kepler-7b
16.52 R_E
Kepler-12b
19.0 R_E
Kepler-11e
4.52 R_E
Kepler-18c
5.49 R_E
Kepler-18d
6.98 R_E
Kepler-16b
8.45 R_E
Kepler-9c
9.2 R_E
Kepler-9b
9.4 R_E
Kepler-15b
10.8 R_E
Kepler-14b
12.7 R_E
Kepler-10c
2.23 R_E
Kepler-22b
2.38 R_E
Kepler-11f
2.61 R_E
Kepler-11c
3.15 R_E
Kepler-11d
3.43 R_E
Kepler-11g
3.66 R_E
Neptune
3.88 R_E
Kepler-4b
3.99 R_E
Earth
Kepler-10b
1.42 R_E
Kepler-21b
1.64 R_E
Kepler-9d
1.64 R_E
Kepler-11b
1.97 R_E
Kepler-18b
2.0 R_E
Kepler-19b
2.21 R_E



Kepler-22 System
Habitable Zone
Solar System
Kepler-22b
Mercury
Venus
Earth
Mars
Planets and orbits to scale

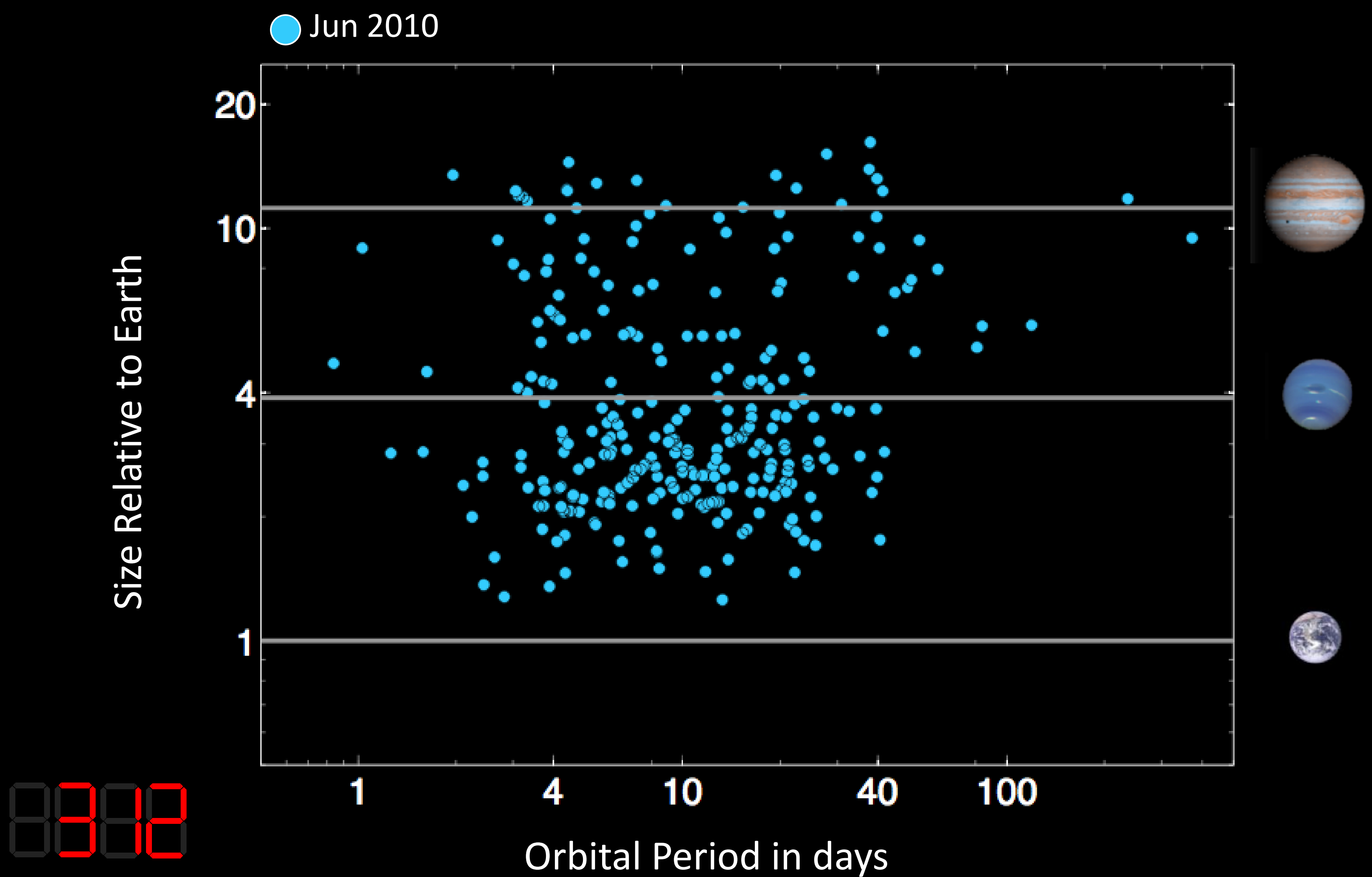


Kepler-11 System
Venus
Mercury
Solar System



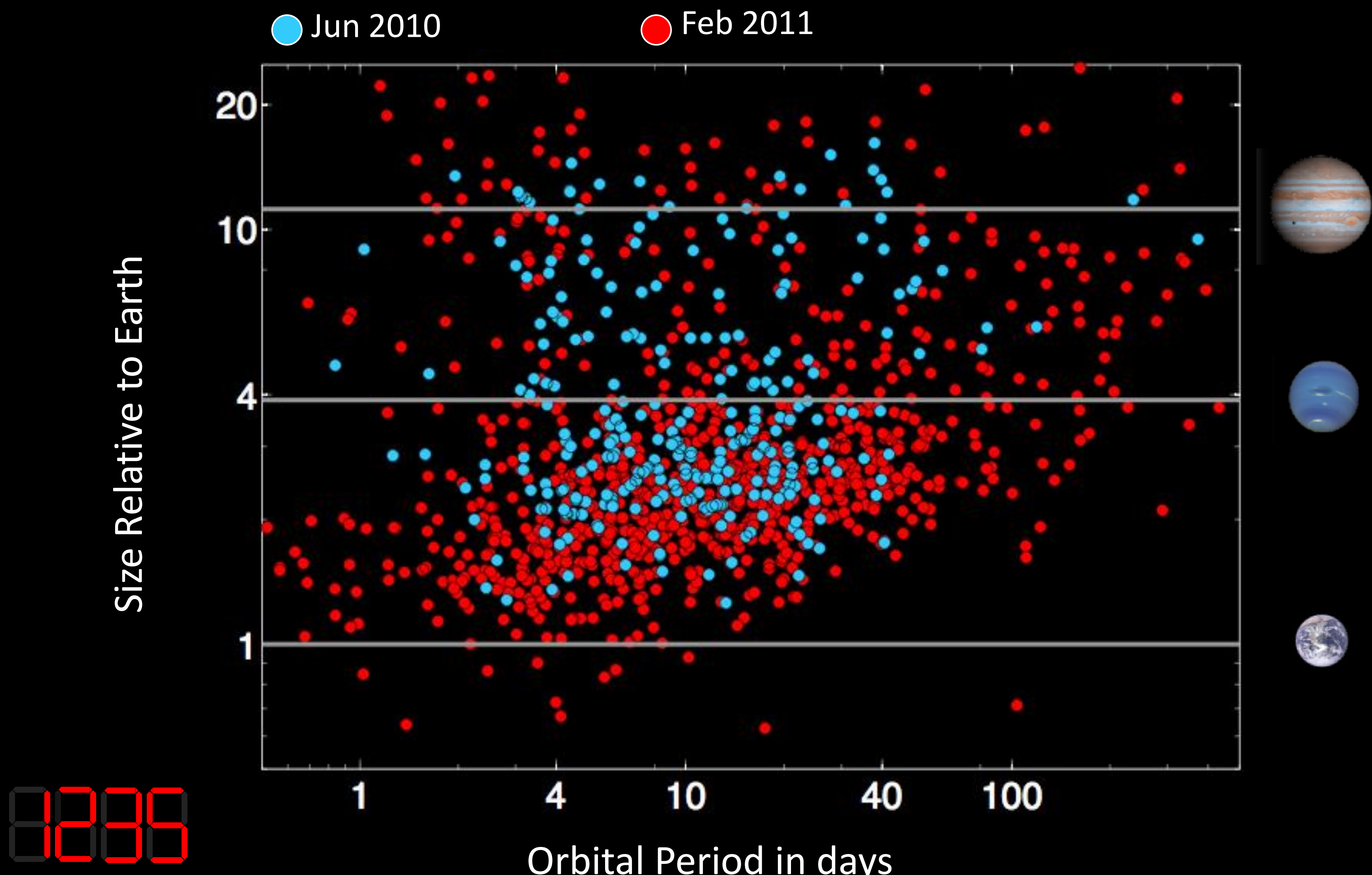
Candidates as of June 2010

Q0-Q1: May 2009 - June 2009



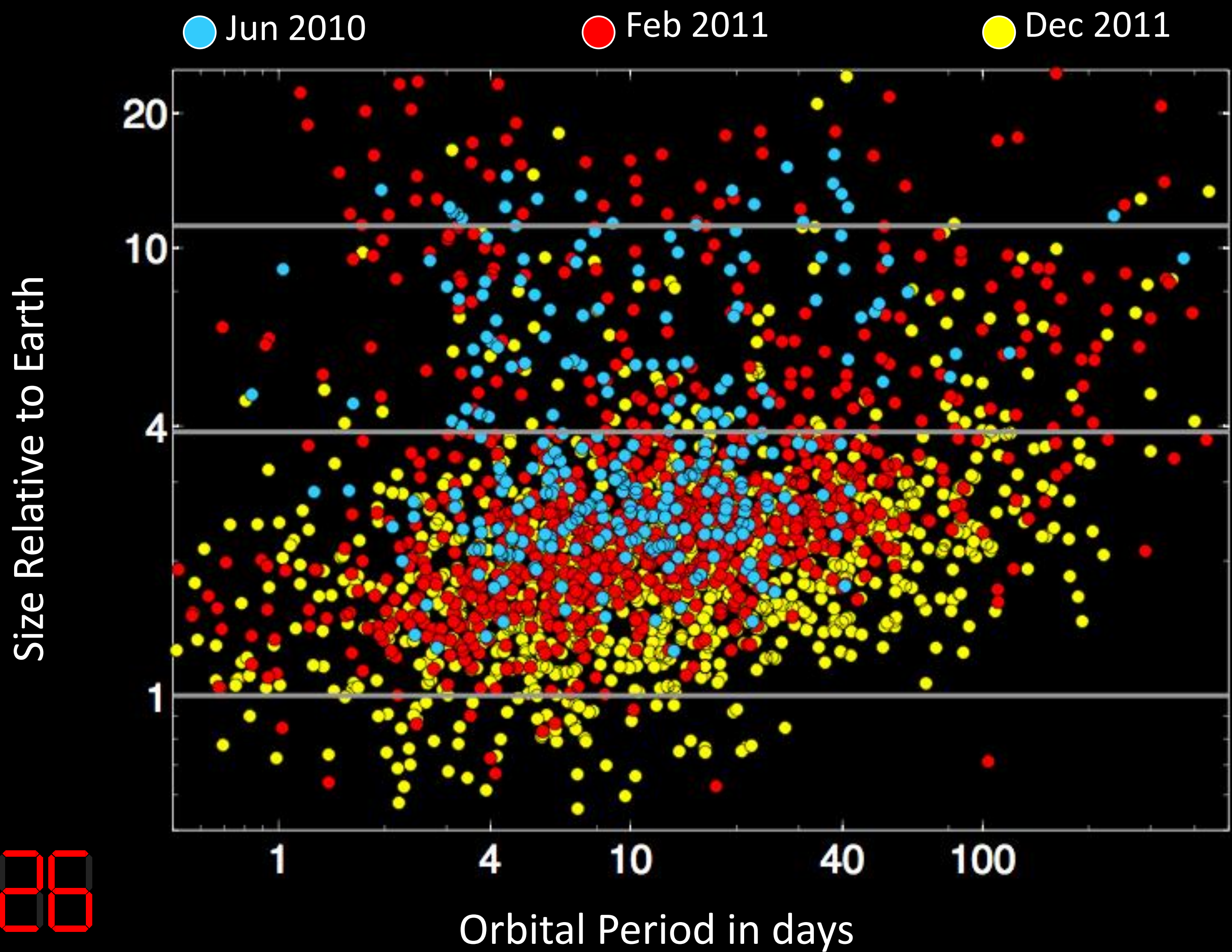
Candidates as of Feb 2011

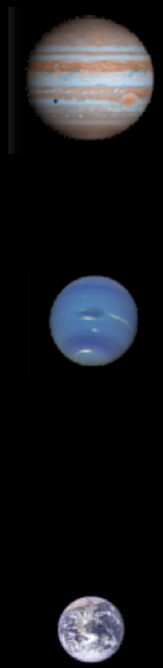
Q0-Q5: May 2009 - Jun 2010



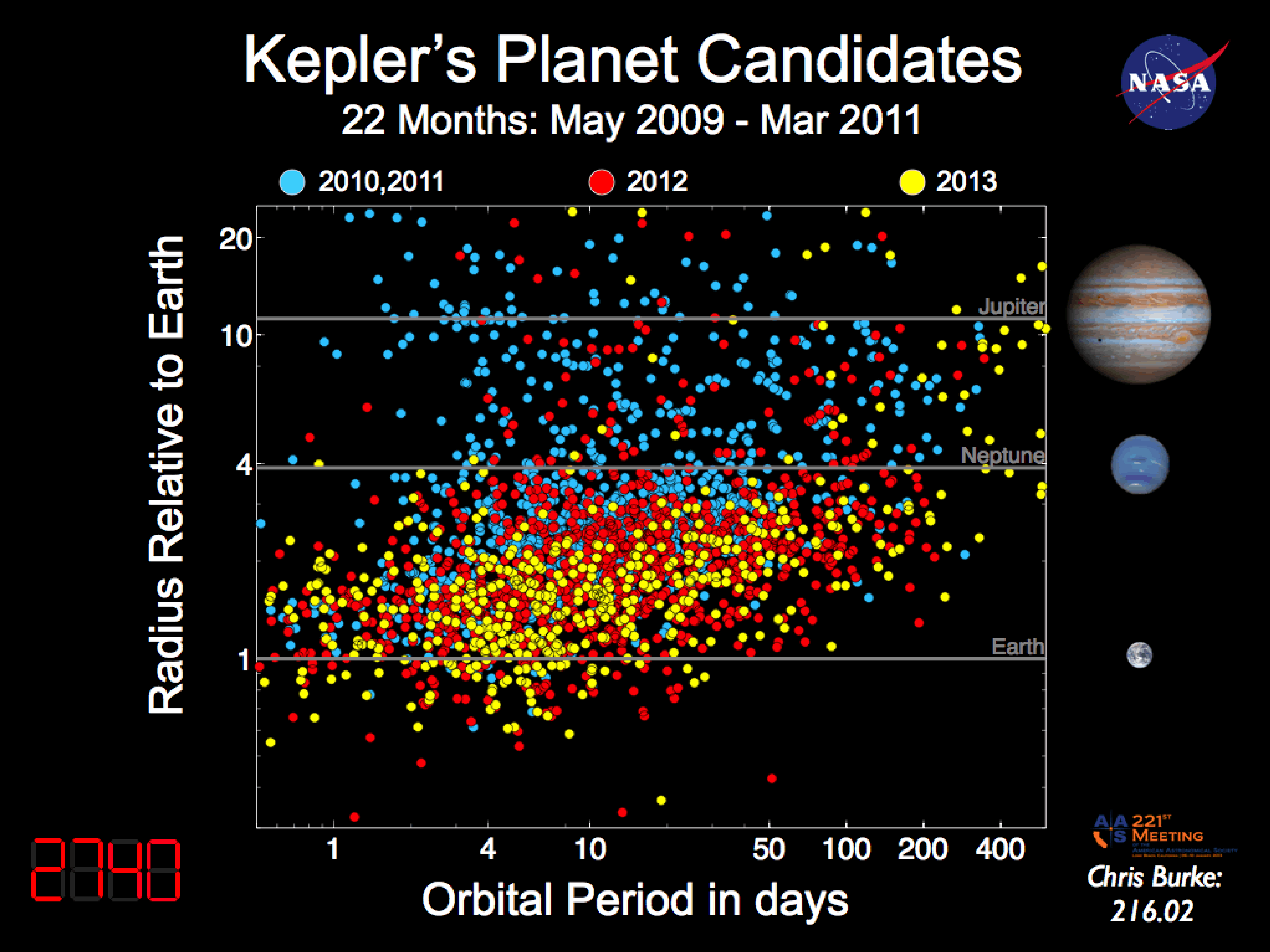
Candidates as of Dec 2011

Q0-Q6: May 2009 - Sep 2010





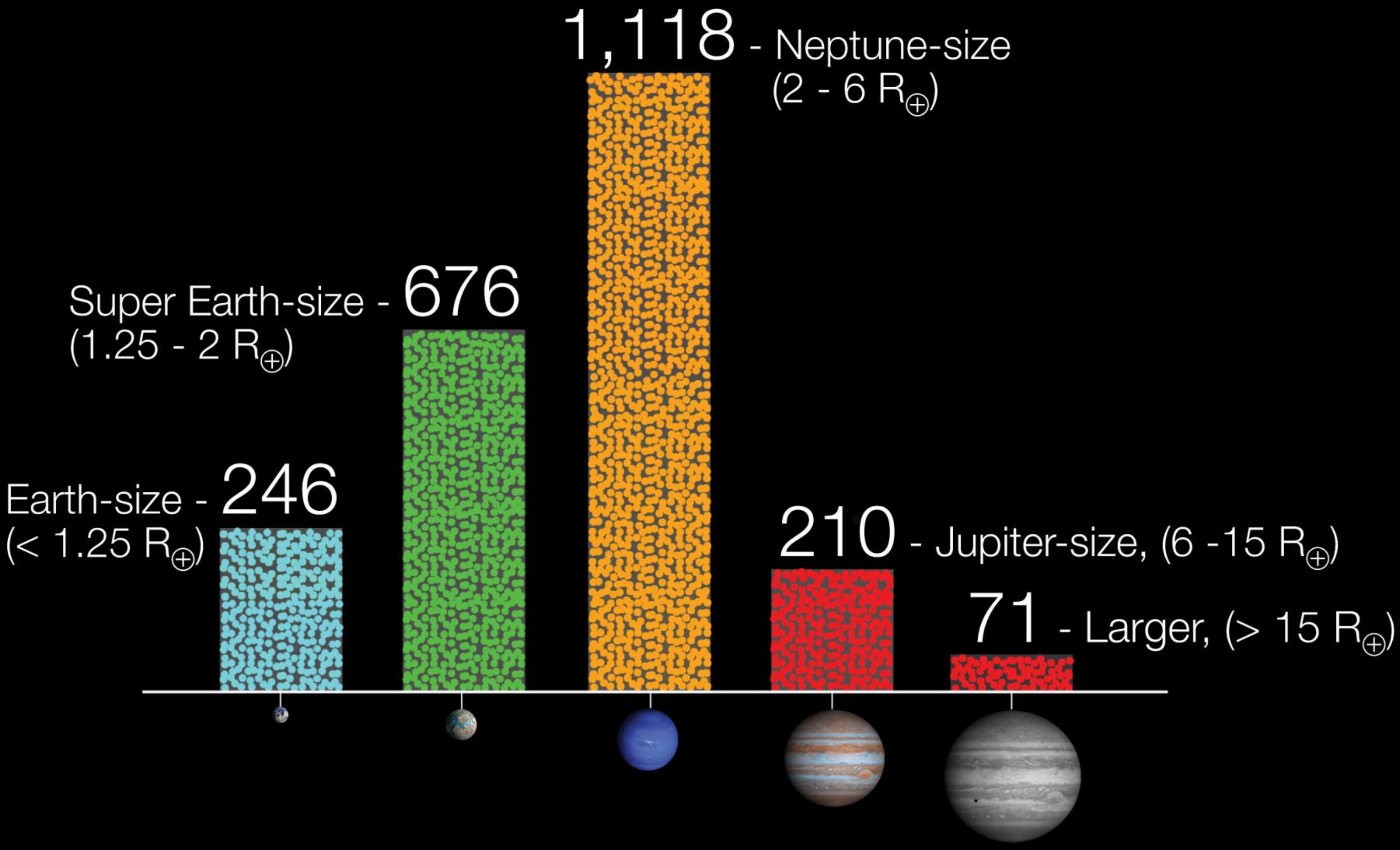
2326



Kepler's Planet Candidates
22 Months: May 2009 - Mar 2011
2010,2011
2012
2013
Radius Relative to Earth
20
10
4
1
Jupiter
Neptune
Earth
1
4
10
50
100
200
400
Orbital Period in days
2740
NASA
AAS 221st MEETING
Chris Burke:
216.02

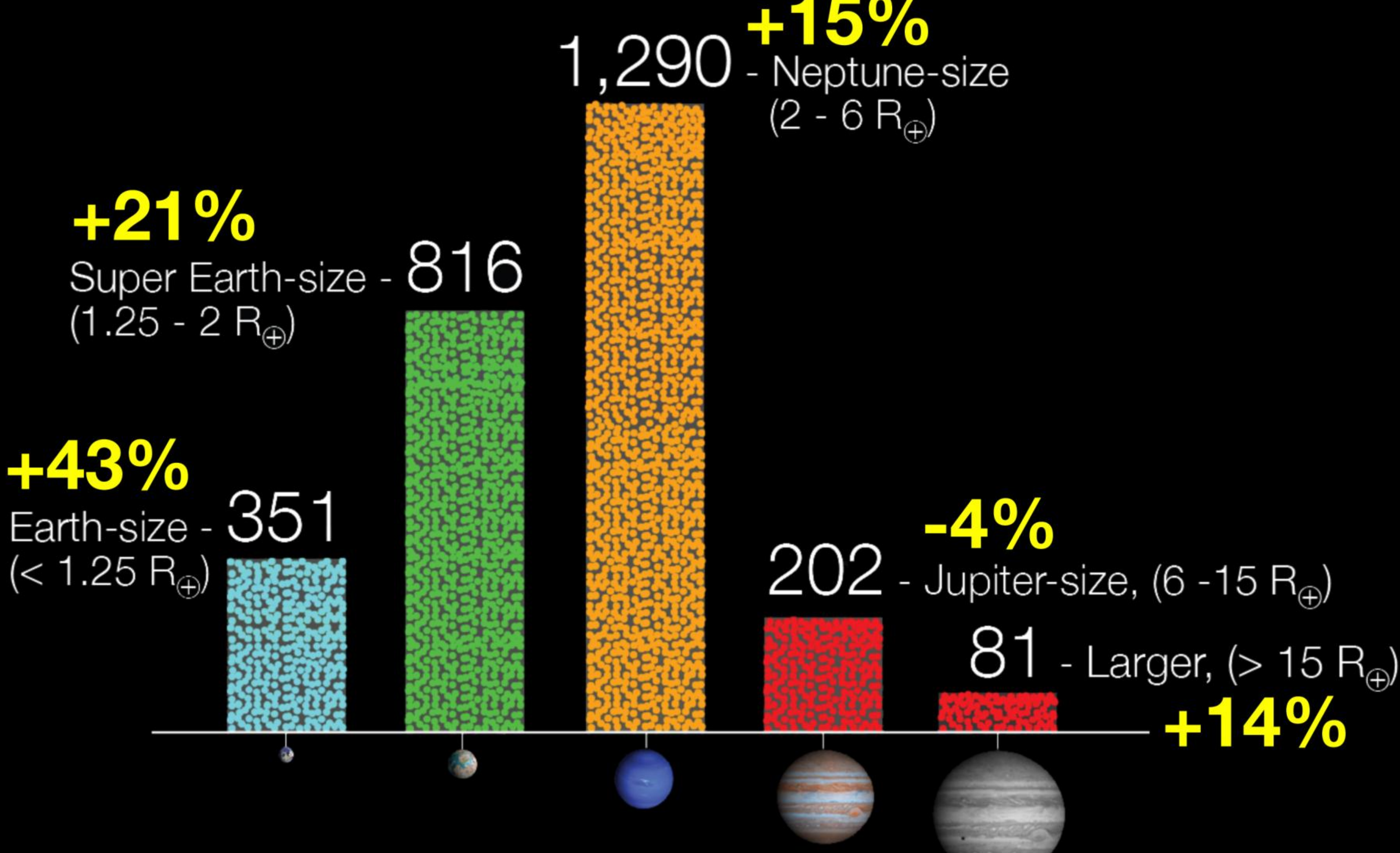
Sizes of Planet Candidates

As of February 27, 2012

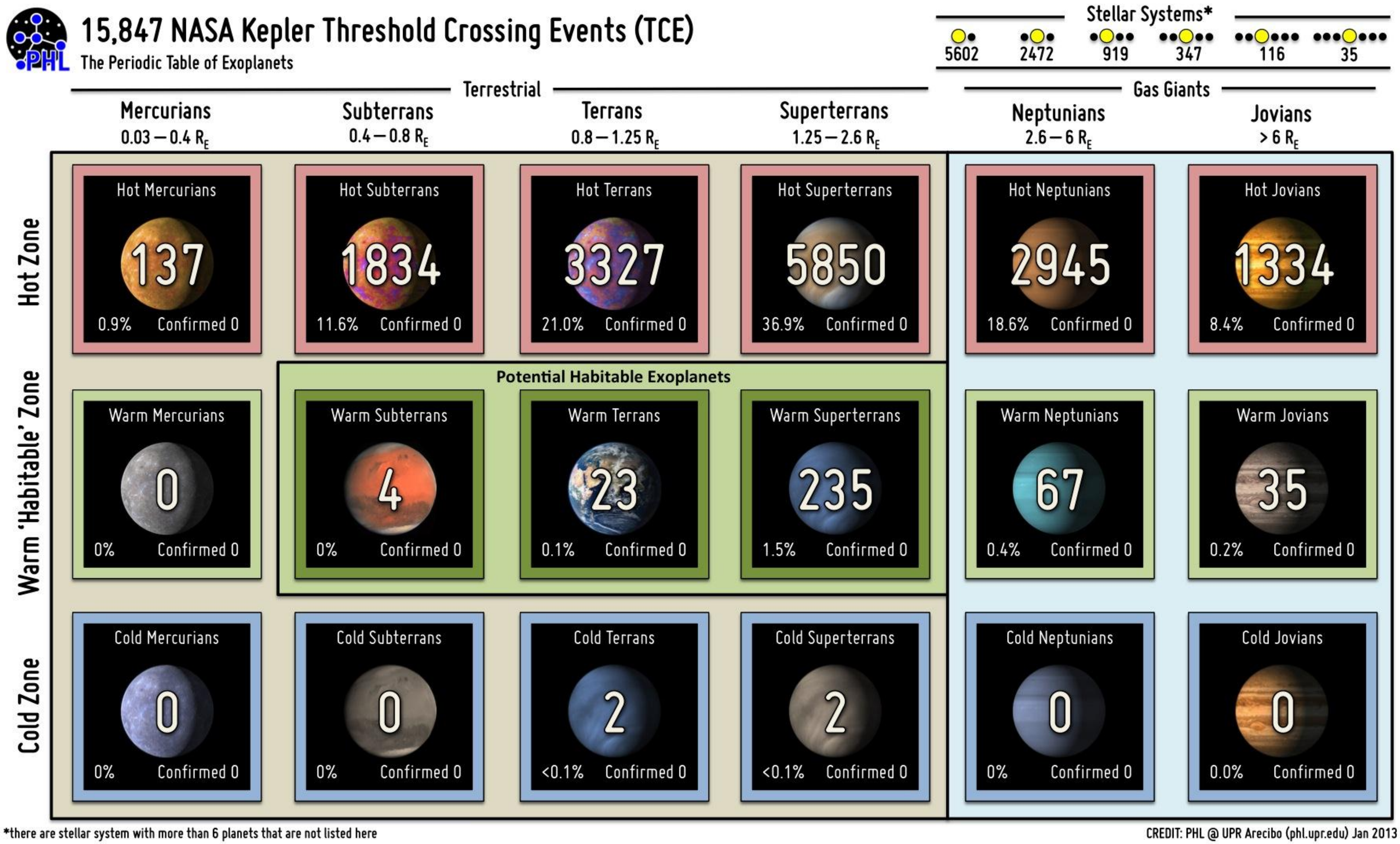


Sizes of Planet Candidates

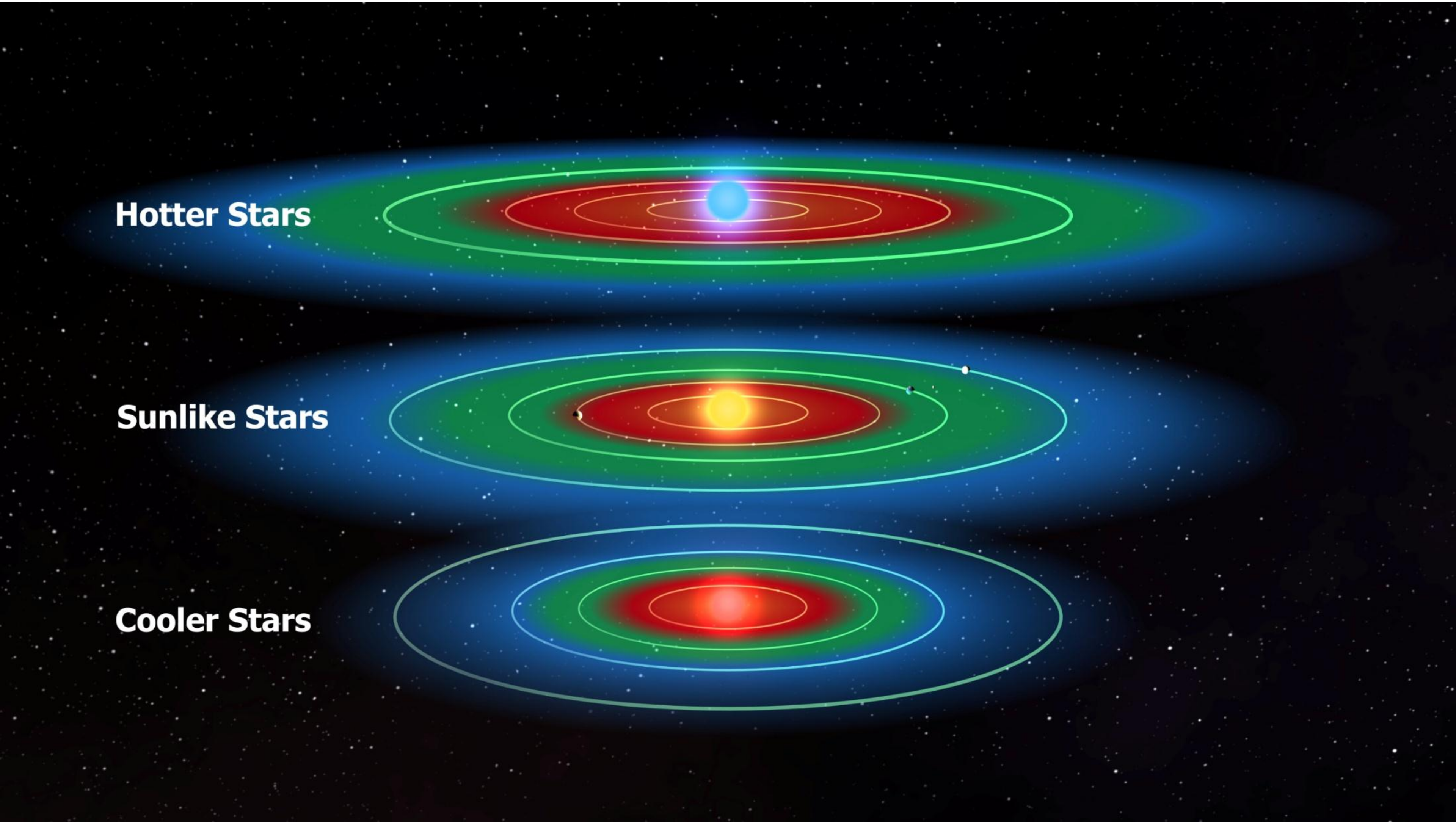
As of January 7, 2013



Exoplanet "Zoo"



Habitability

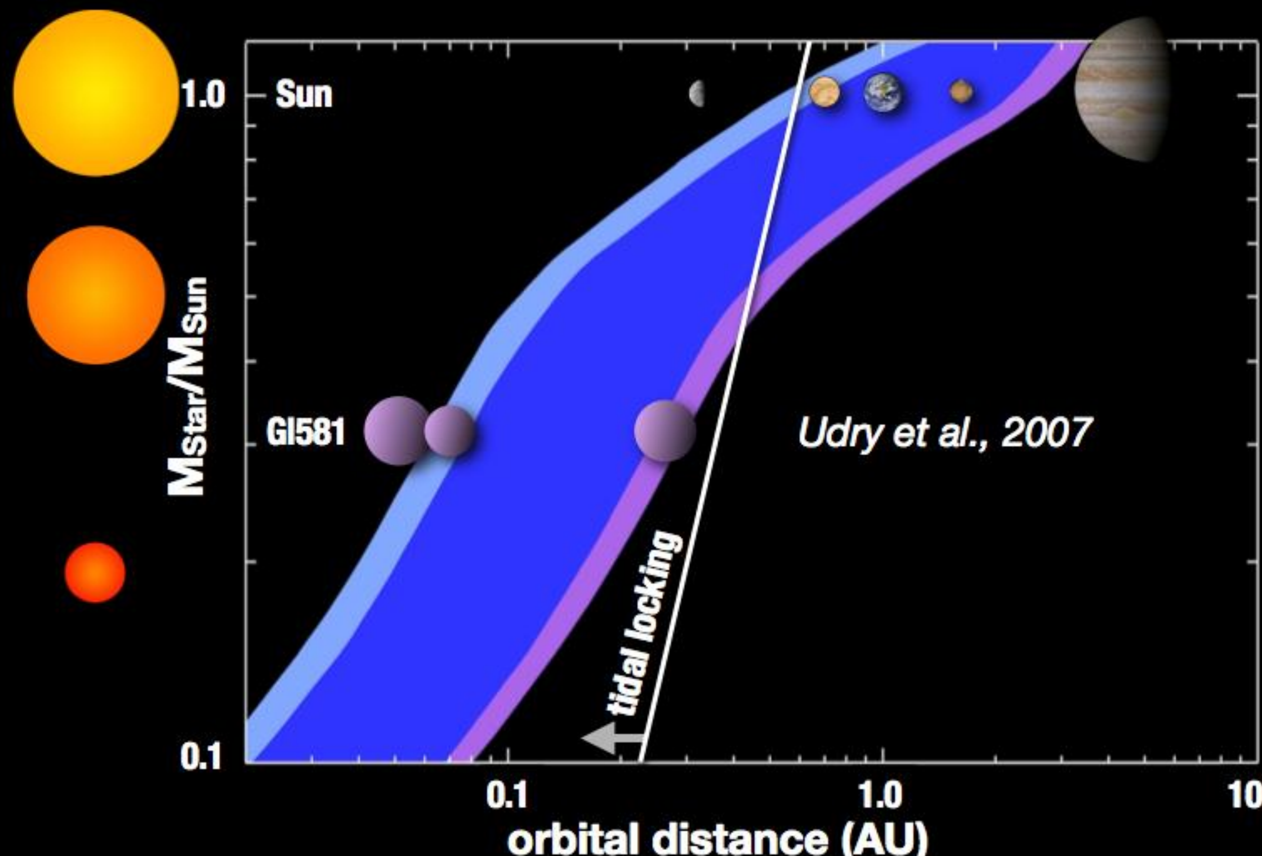


Unresolved Issues Regarding the Habitability of the Earth

Our Moon maintains the Earth's moderate axial tilt.
We have plate tectonics to maintain a carbon-silicate cycle.
Is the high water content of the mantle needed for plate tectonics?
If the Earth formed "dry" then how was water delivered?
Do we need a large ocean to maintain thermal inertia?
Do we need the right amount of water to not cover *all* landforms?
Is dry land necessary?
Does Jupiter hoover up comets or toss asteroids in?
Why do we have a hydrogen-poor atmosphere?
Is water the only suitable solvent for life?
Is it important that we lack a close stellar binary companion?
Do we need an especially "calm" sun?
Do we need a low eccentricity?
Earth is not too large as to have ended up as a mini-Neptune.
Earth is not too small to end up like Mars with little atmosphere.
Do we need our nickel-iron core for magnetic field generation?

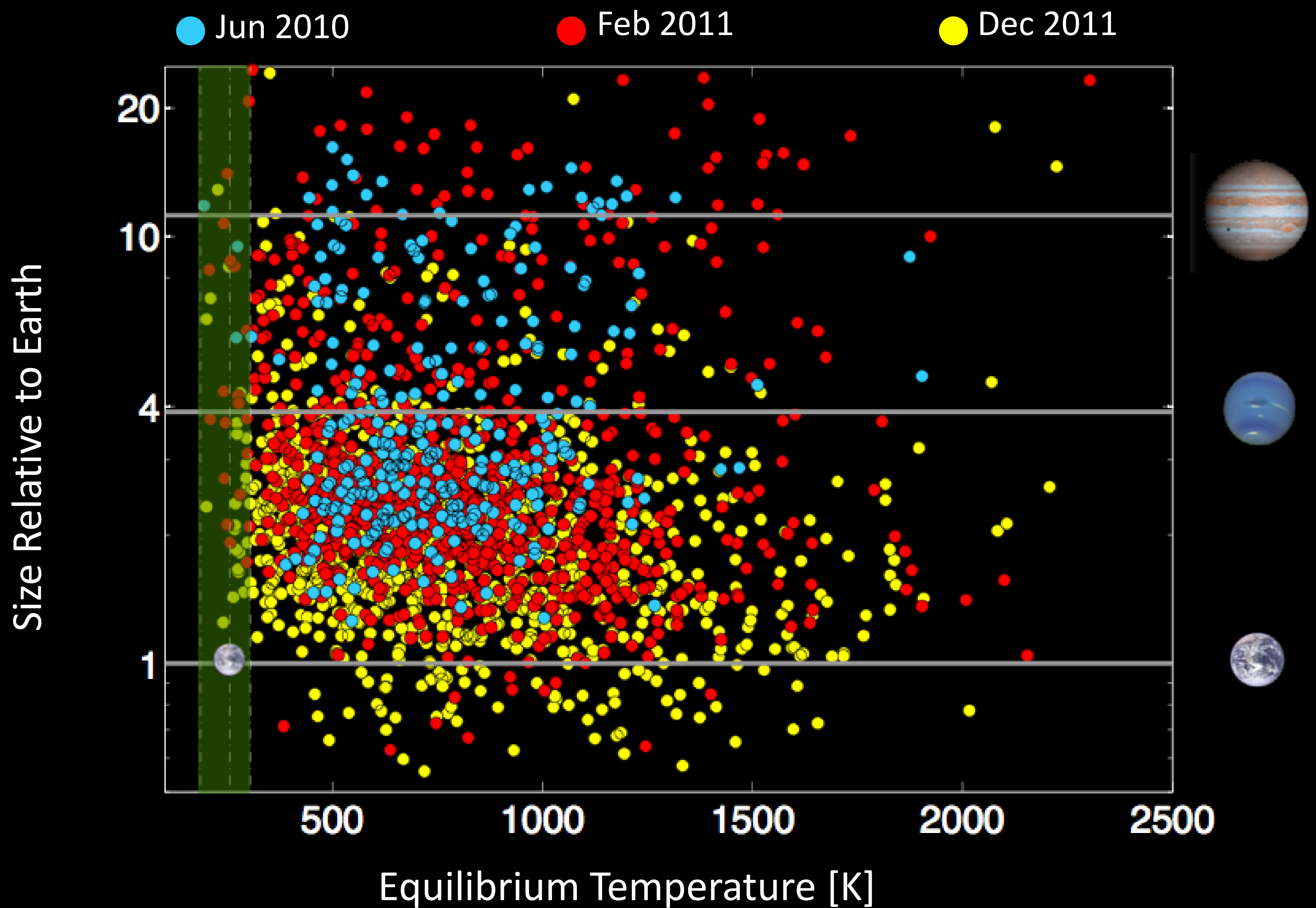
Habitable Zone

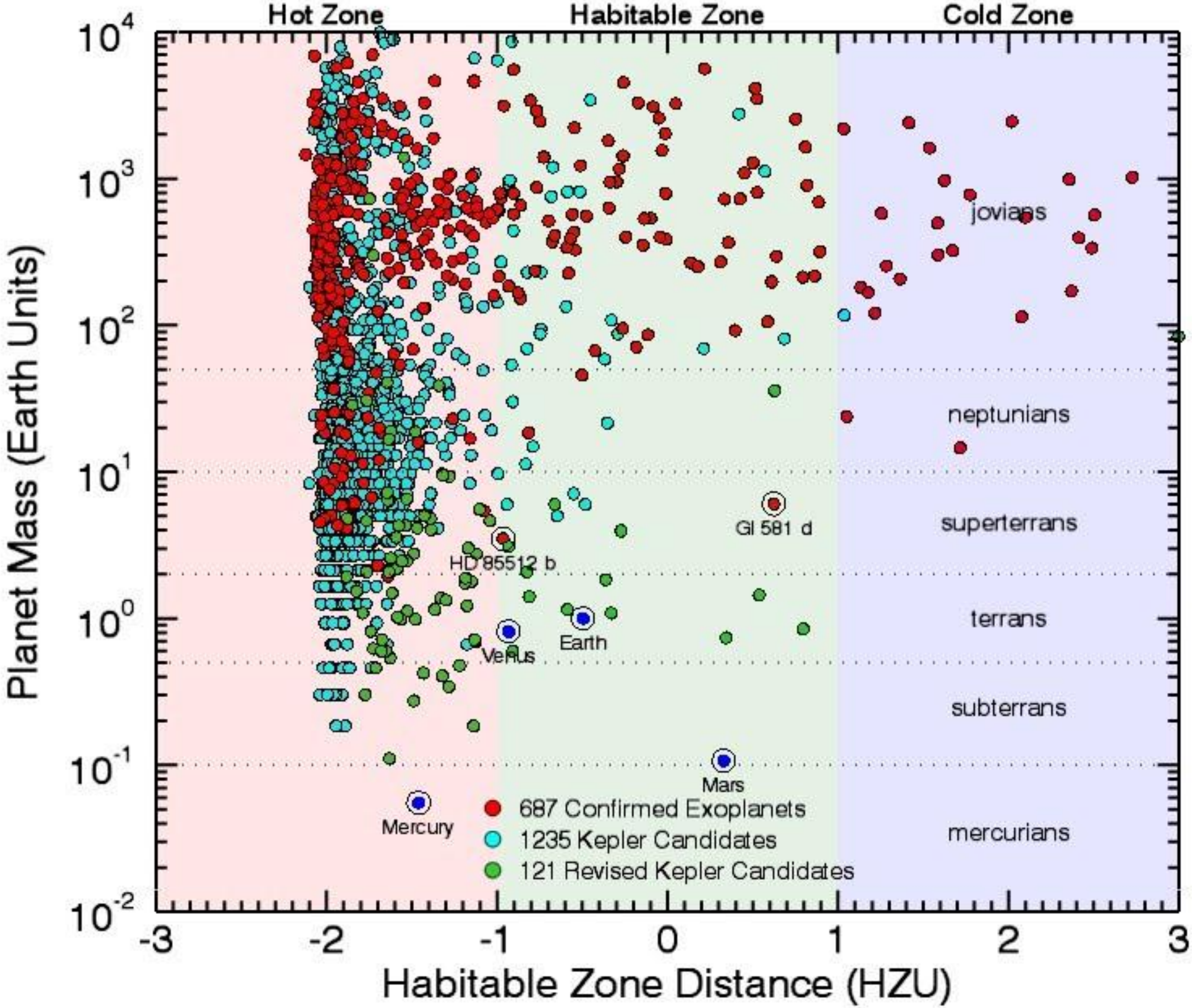
The traditional definition of a habitable zone is the range of distances from a star where water can be liquid on the surface of a planet or moon



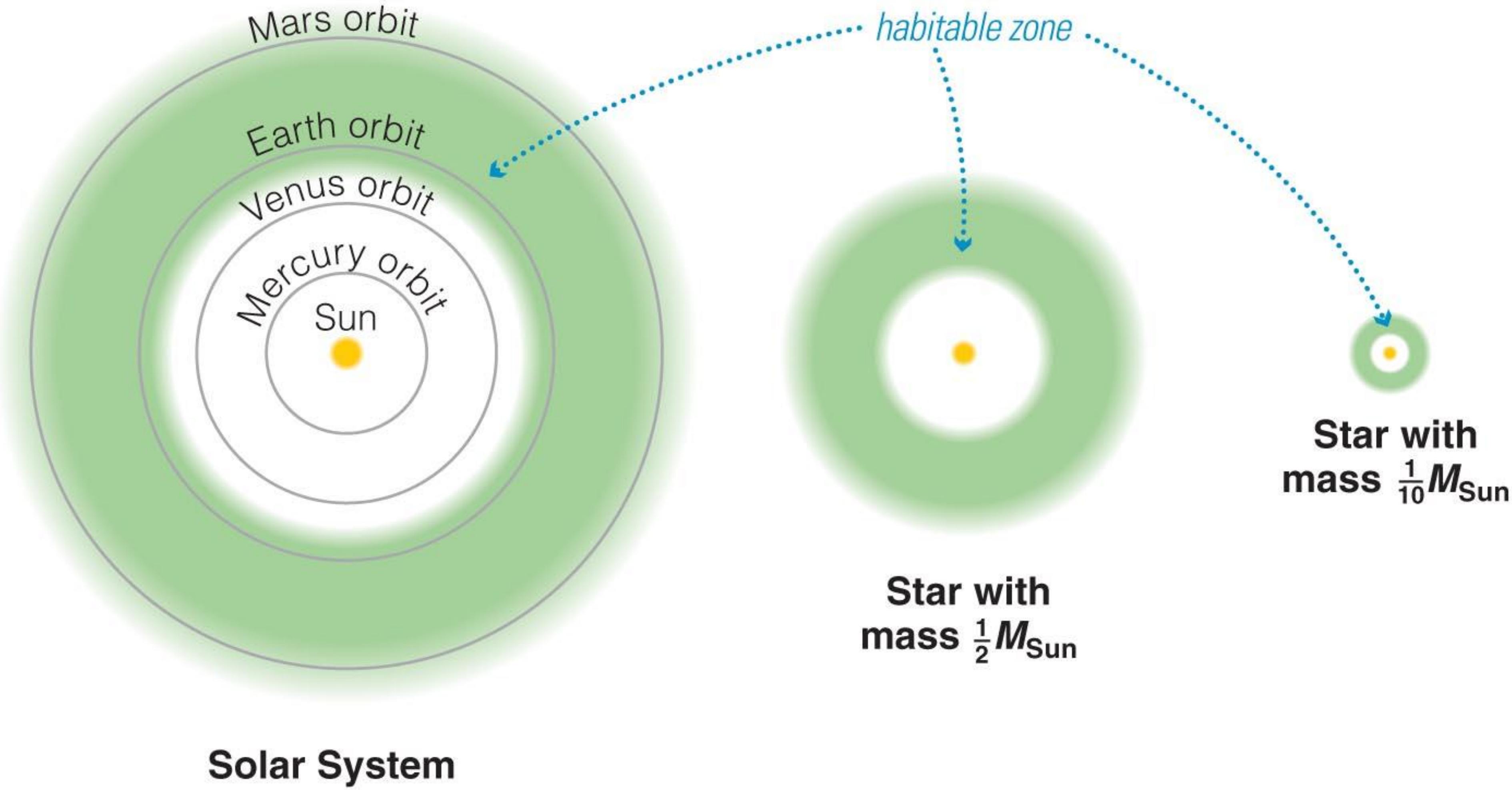
Habitable Zone Candidates

48 with T_{eq} between 185 and 303 K

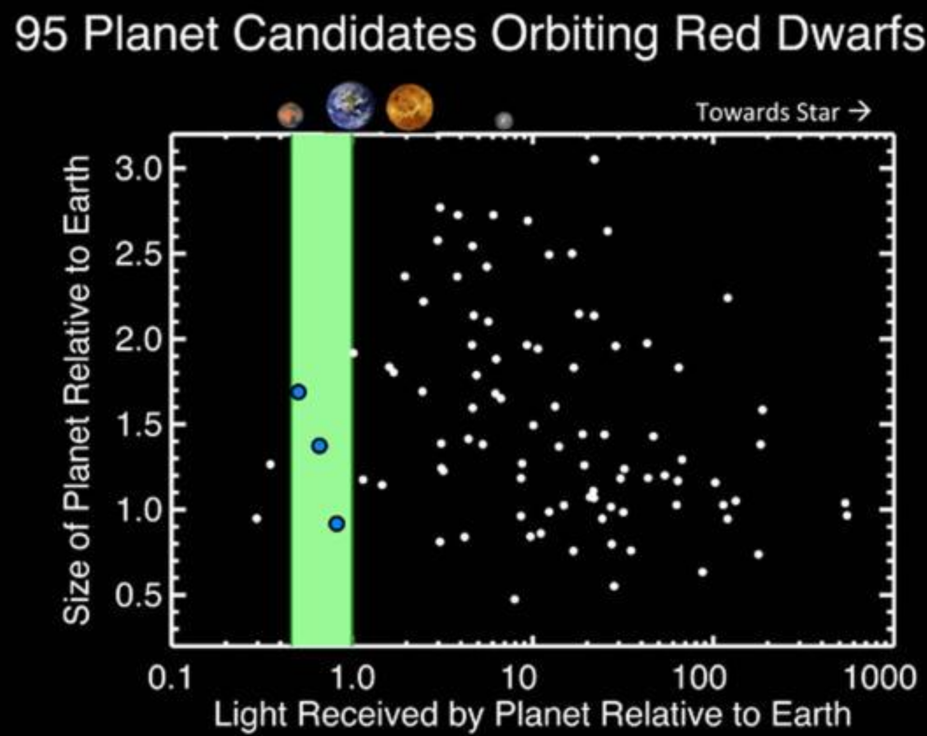



Hot Zone
Habitable Zone
Cold Zone
Planet Mass (Earth Units)
Habitable Zone Distance (HZU)
jovians
neptunians
superterrans
terrans
subterrans
mercurians
Gl 581 d
HD 85512 b
Venus
Earth
Mars
Mercury
687 Confirmed Exoplanets
1235 Kepler Candidates
121 Revised Kepler Candidates

Dwarf star habitable zones are small, but the much larger number of dwarfs means they dominate the total habitable "real estate."

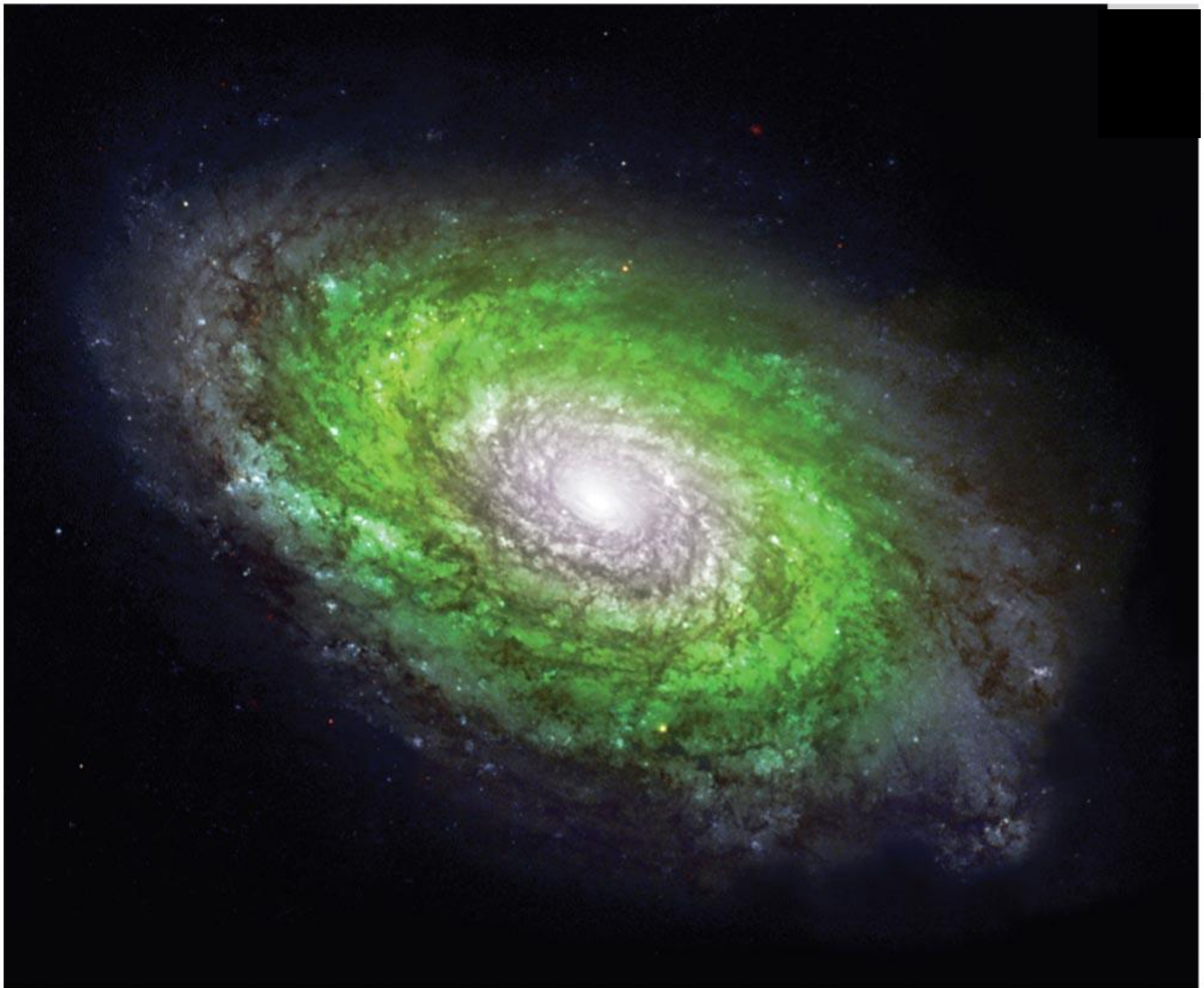


Plus, the cryogenic biosphere is the largest of all.

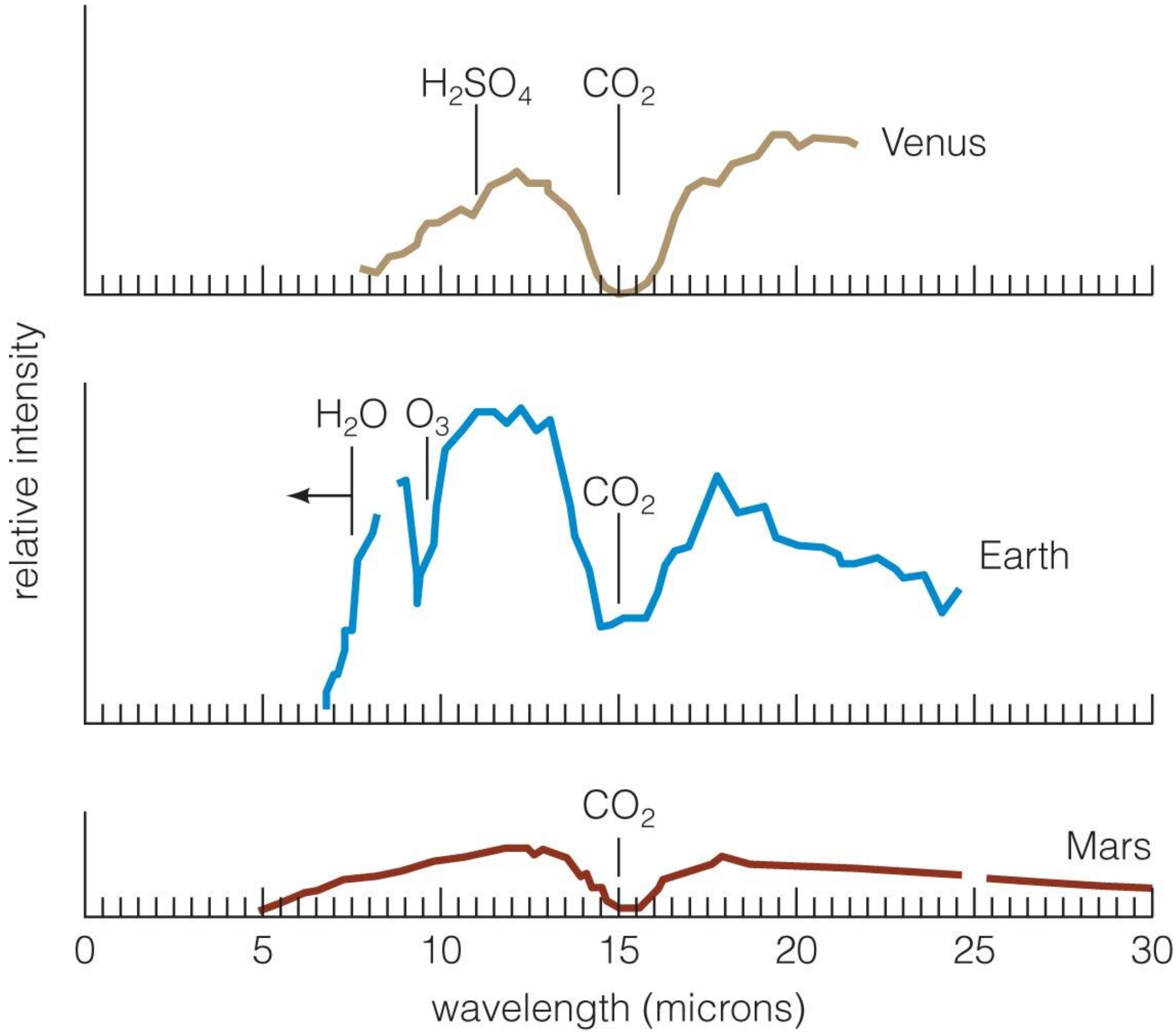


The census projects to about 5 billion Earth-like planets around 75 billion red dwarfs in the Milky Way, with the closest about 15 light years away.

The Galactic habitable zone: near the center too many encounters and supernovae, far from the center not enough heavy elements.

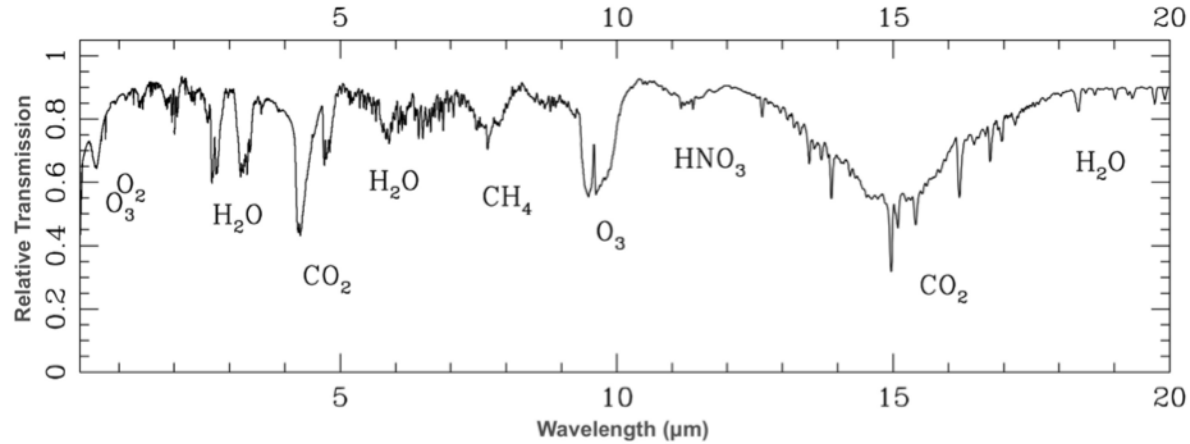


Biomarkers

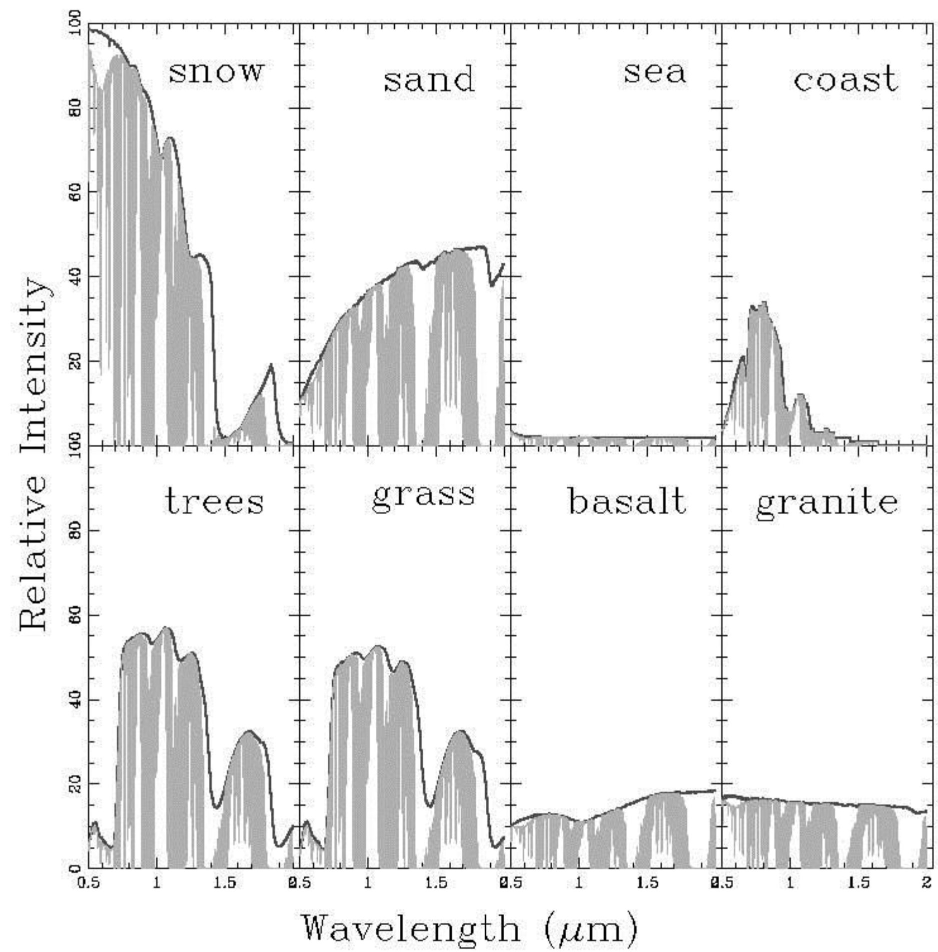


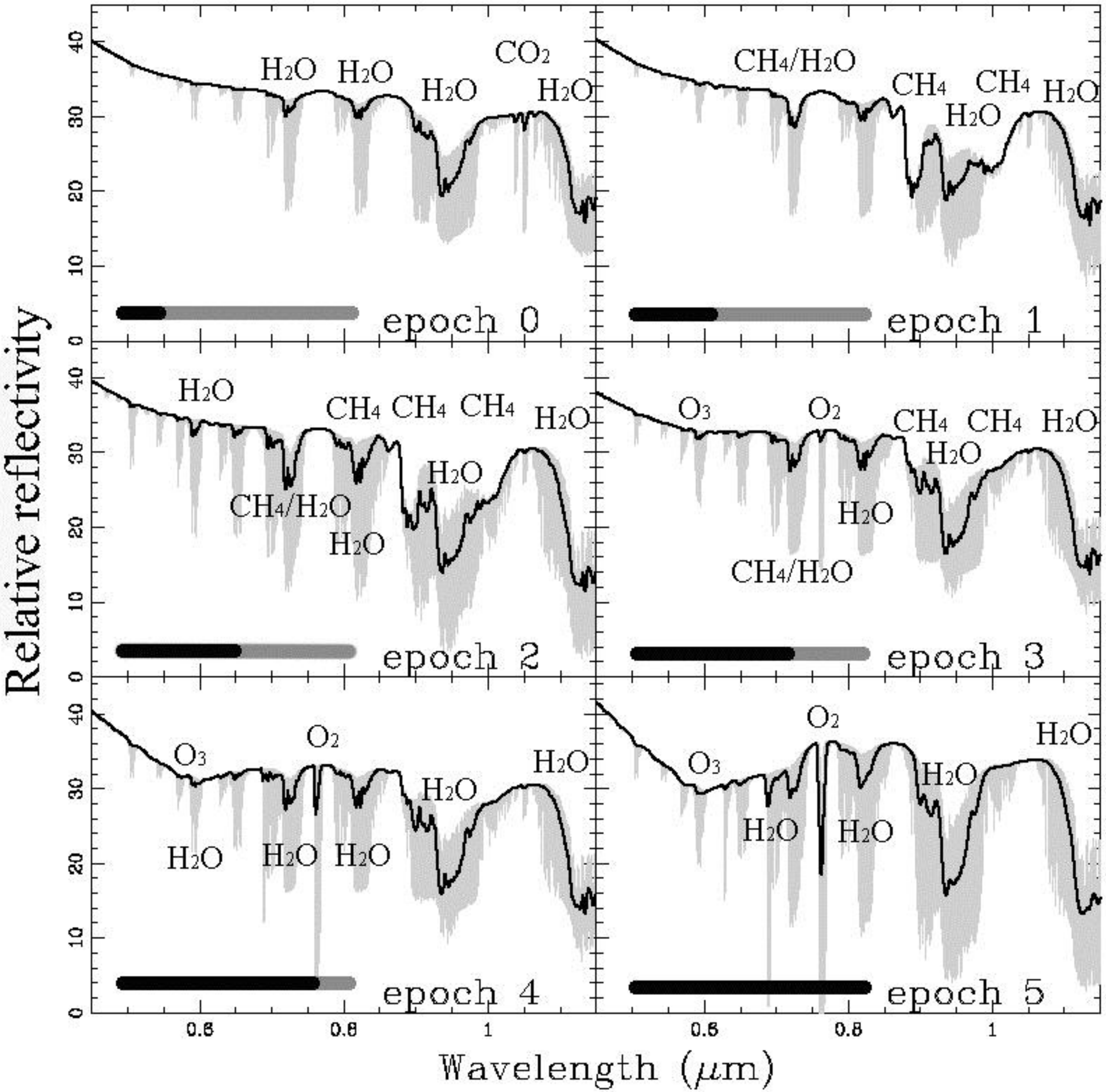
H_2SO_4
CO_2
Venus
H_2O
O_3
CO_2
Earth
CO_2
Mars
relative intensity
0
5
10
15
20
25
30
wavelength (microns)

Global Infrared Earth Spectrum:



Reflected Spectra of various surface Components:





Earth Spectra

0: 3.9 Gyr ago

1: 3.5 Gyr ago

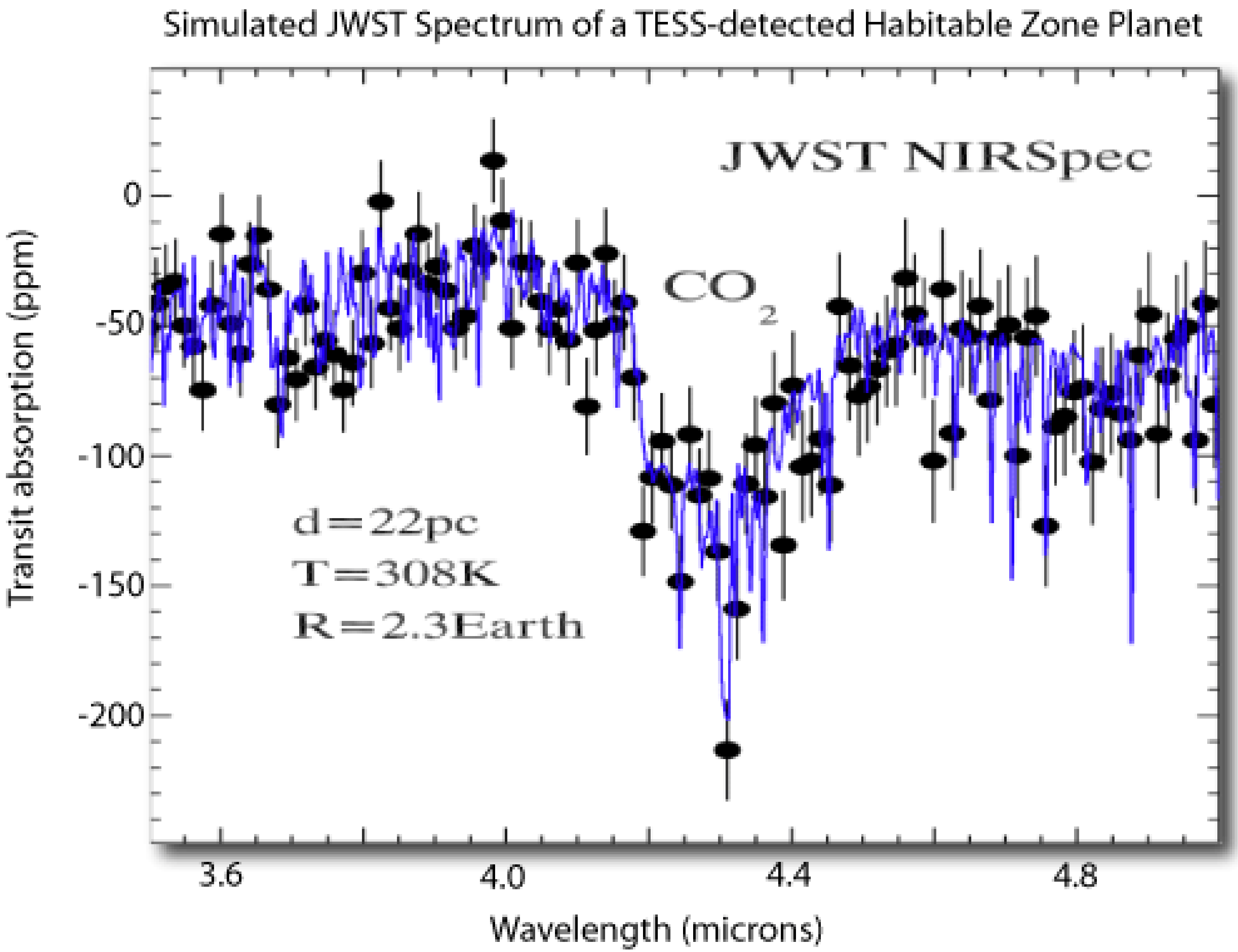
2: 2.4 Gyr ago

3: 2.0 Gyr ago

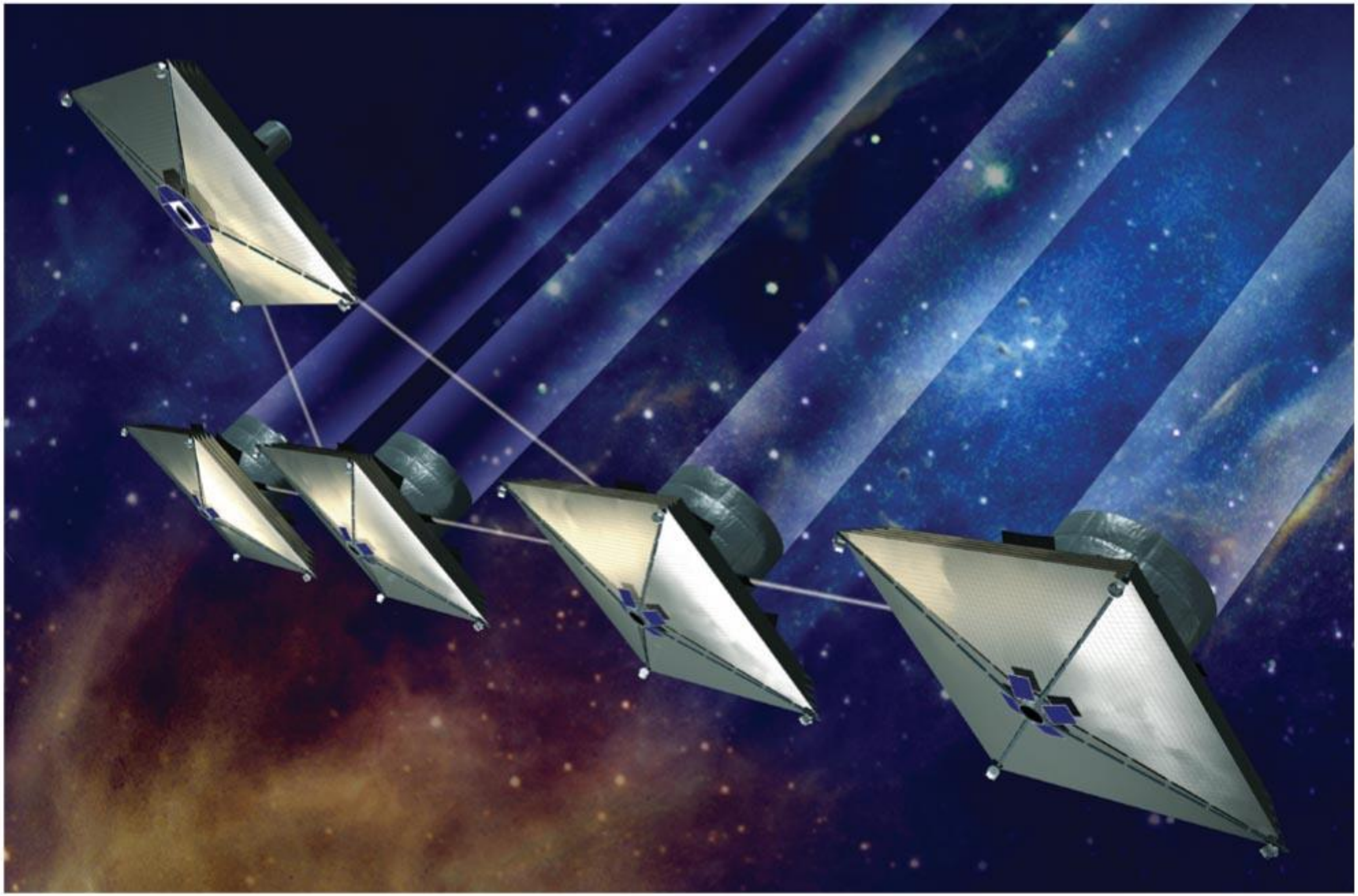
4: 0.8 Gyr ago

5: 0.3 Gyr ago

The light grasp of ground-based telescopes will be used to look for biomarkers. Space observatories like JWST will play a big role.



Harvesting terrestrial planets and characterizing “Earths” will requires expensive space missions; TPF is currently unfunded.



The Bottom Line

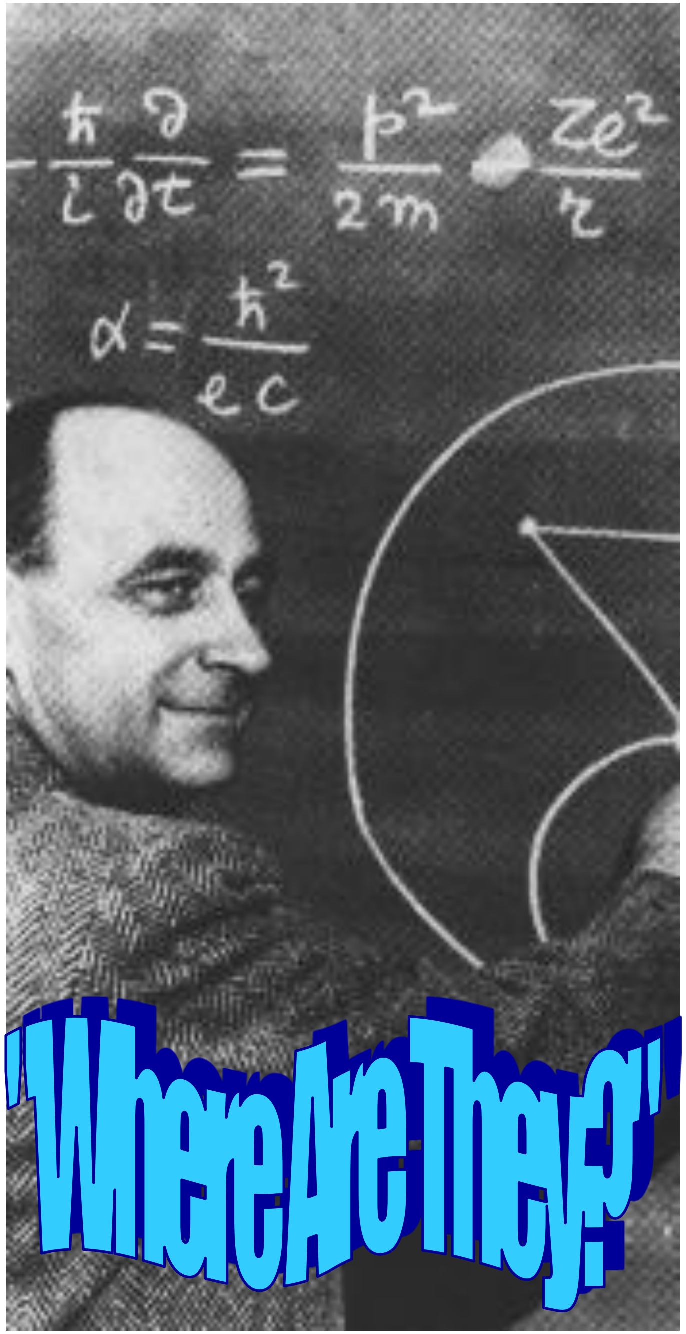
Over 3000 exoplanets are known, most like gas giants but detections are now at or below Earth mass

All Sun-like stars may have giant planets and there are even larger numbers of lower mass planets

Models indicate that many terrestrial planets should be "water worlds" with all life's ingredients

More than one billion terrestrial planets in the Milky Way, and about ten billion habitable "worlds"

The next frontier is the study of Earth-like planets for atmospheric chemistry altered by biology



The Fermi Question

As originally phrased by Erico Fermi in 1950, it seems a reasonable proposition that:

- Our civilization and technology are **very young**, so the life forms with much more advanced technology could have remarkable capabilities, perhaps unimaginable to us.

- A **modest extrapolation** of our current technology would allow us mine asteroids and moons, and create probes that could create replicas of themselves and propagate through the galaxy in a few million years.

- There are **many likely sites** for complex life, and time for technology to develop, even billions of years before Earth formed.

Chandra
Deep Space Network Radio Transceiver
DLR
Astronomy
State of the Art
With Chris Impey
of the University
of Arizona