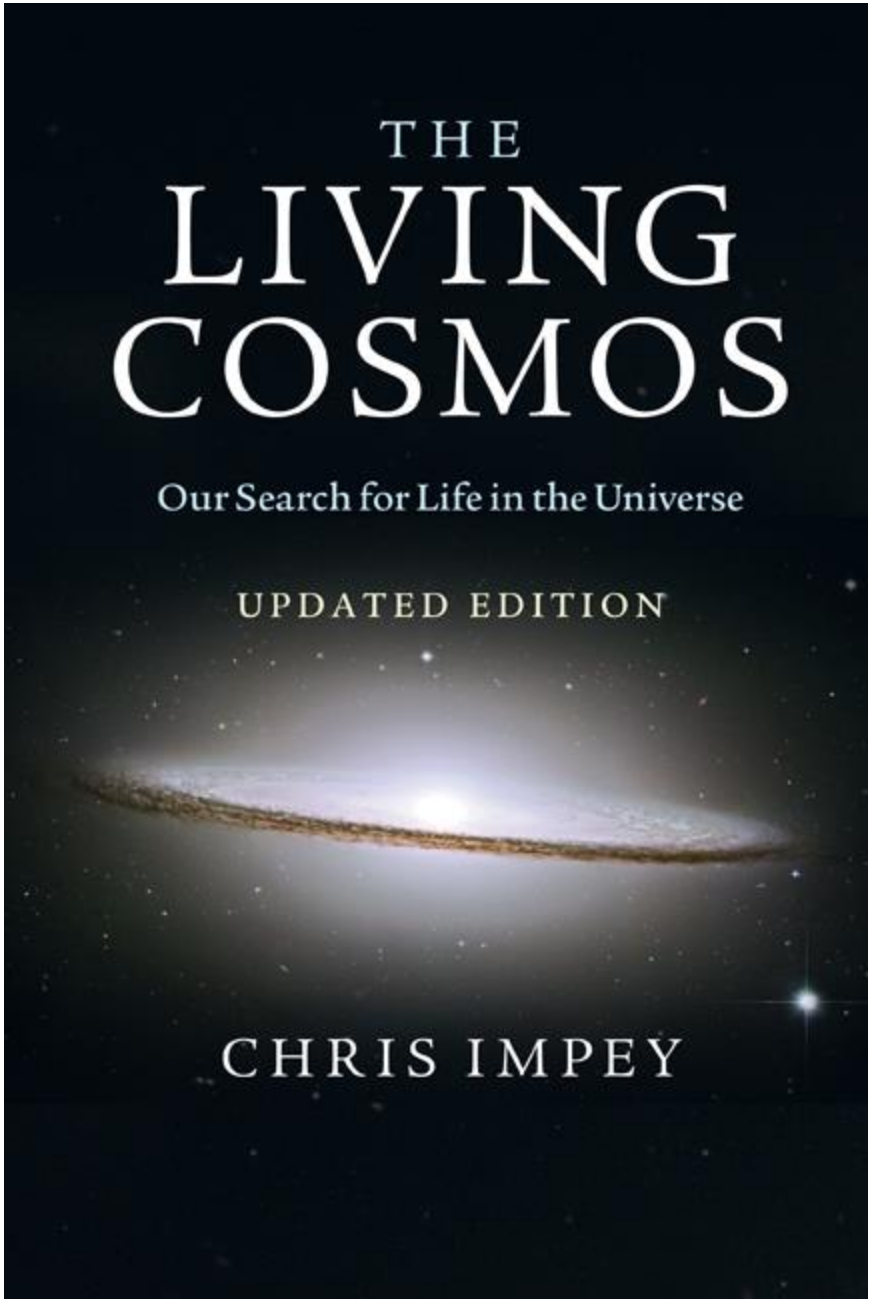
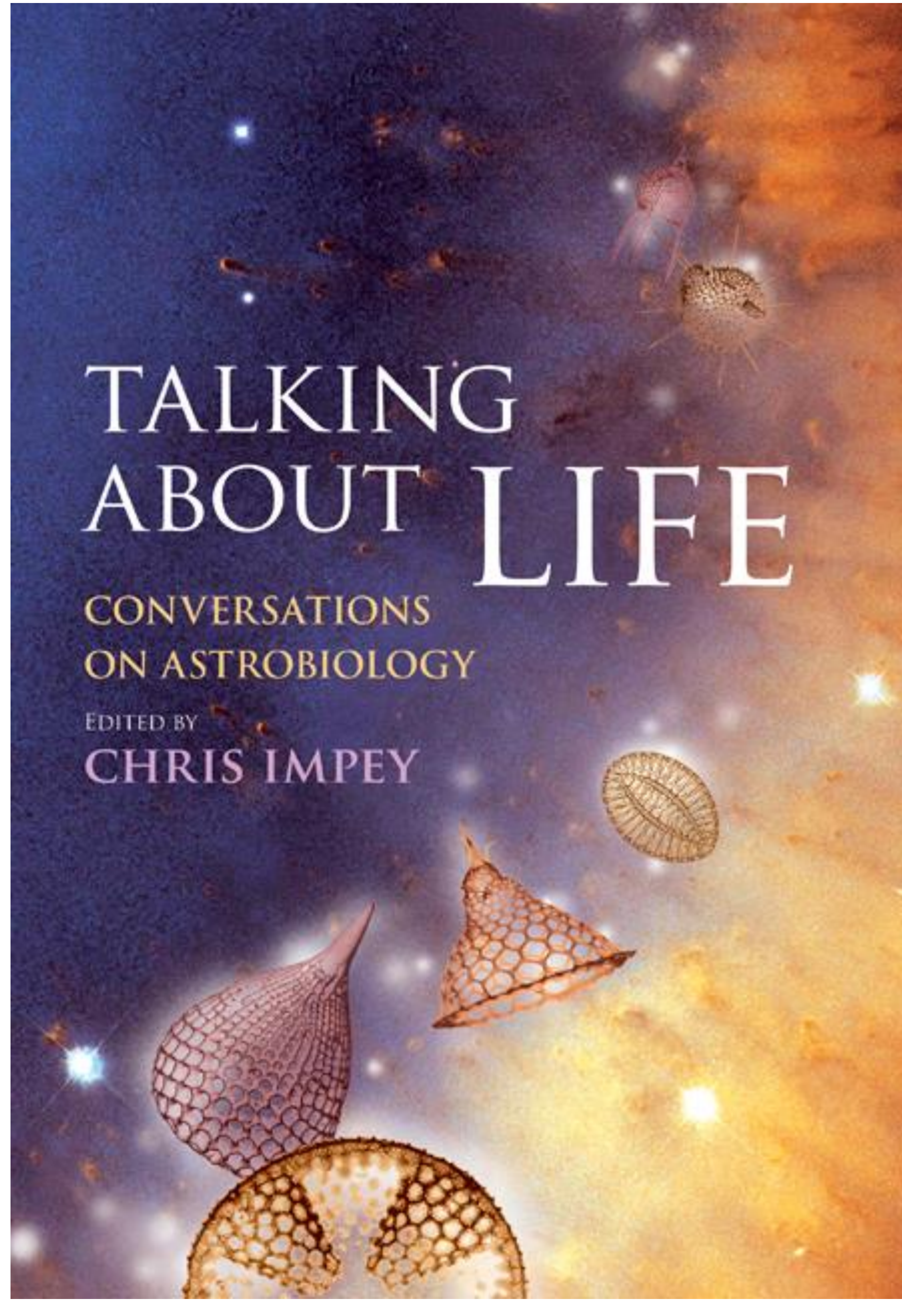
# The Search for Earths


THE
LIVING
COSMOS
Our Search for Life in the Universe
UPDATED EDITION
CHRIS IMPEY


TALKING
ABOUT LIFE
CONVERSATIONS
ON ASTROBIOLOGY
EDITED BY
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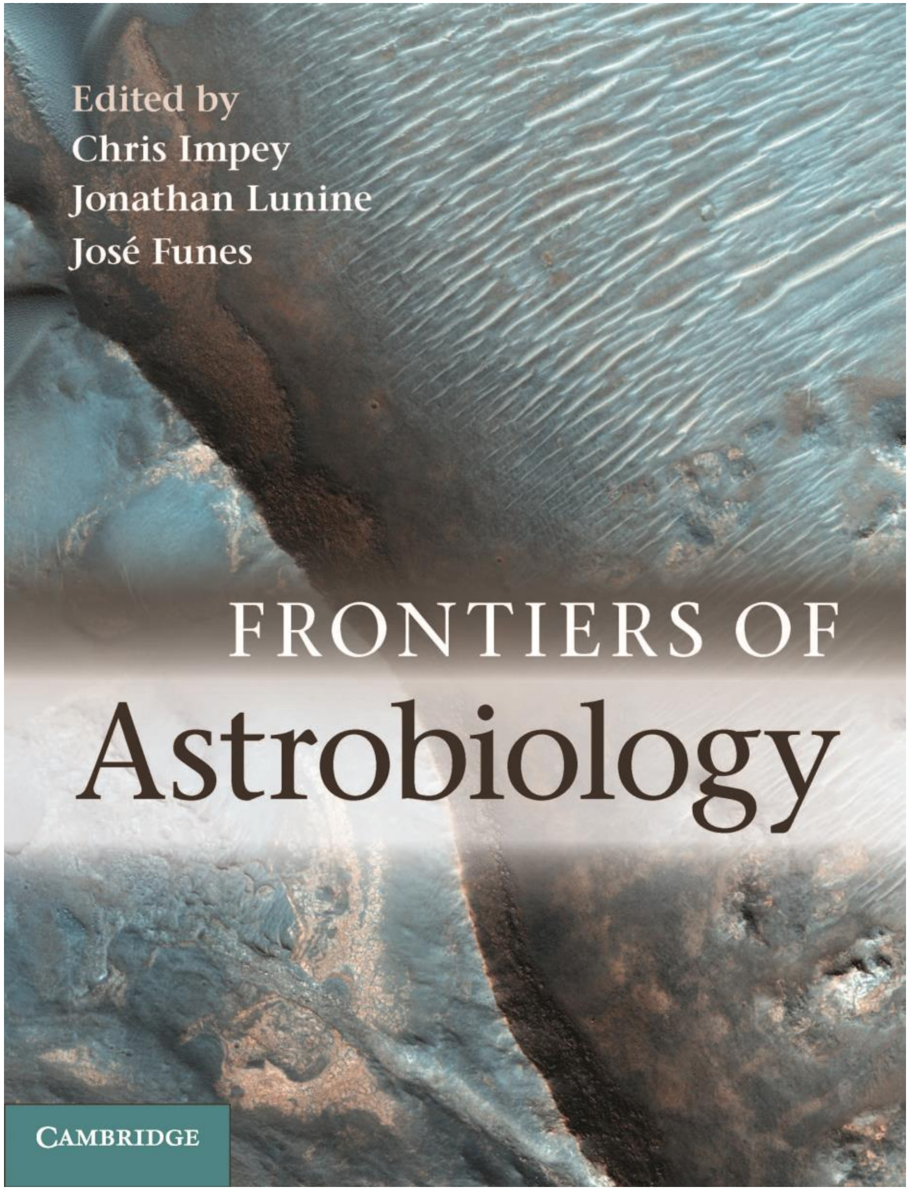
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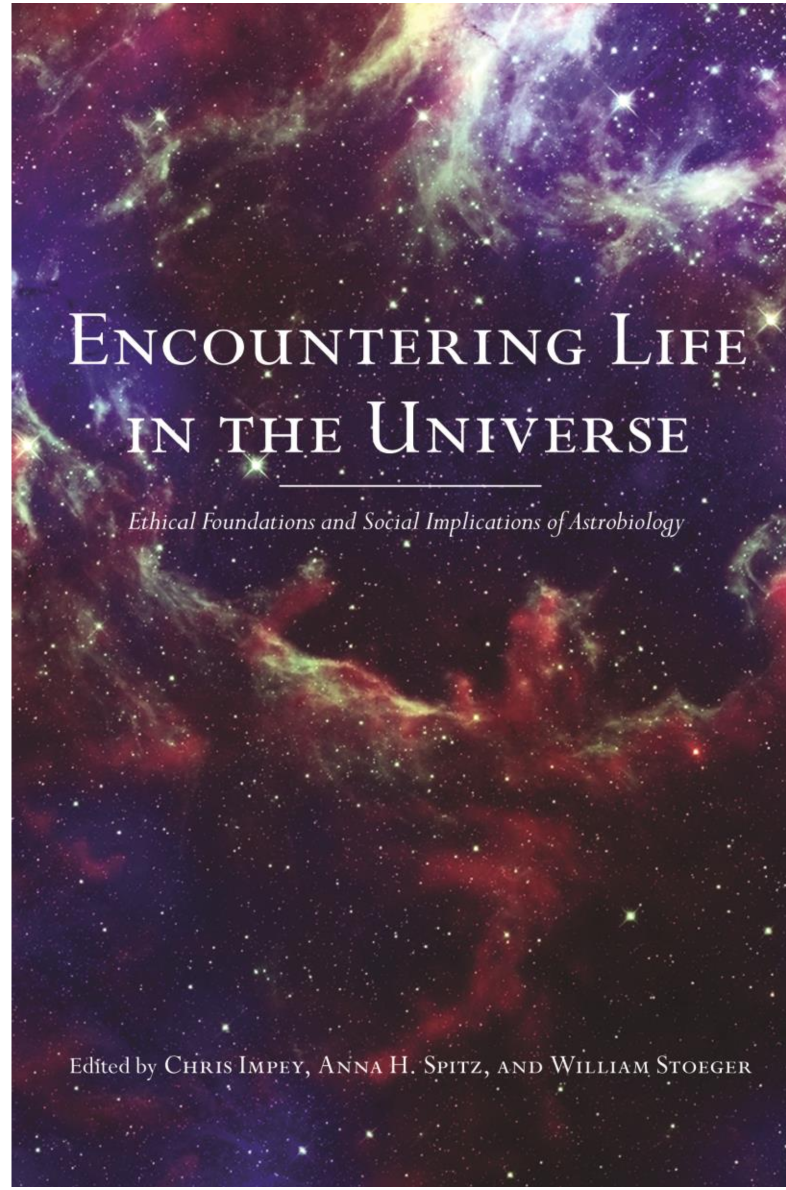
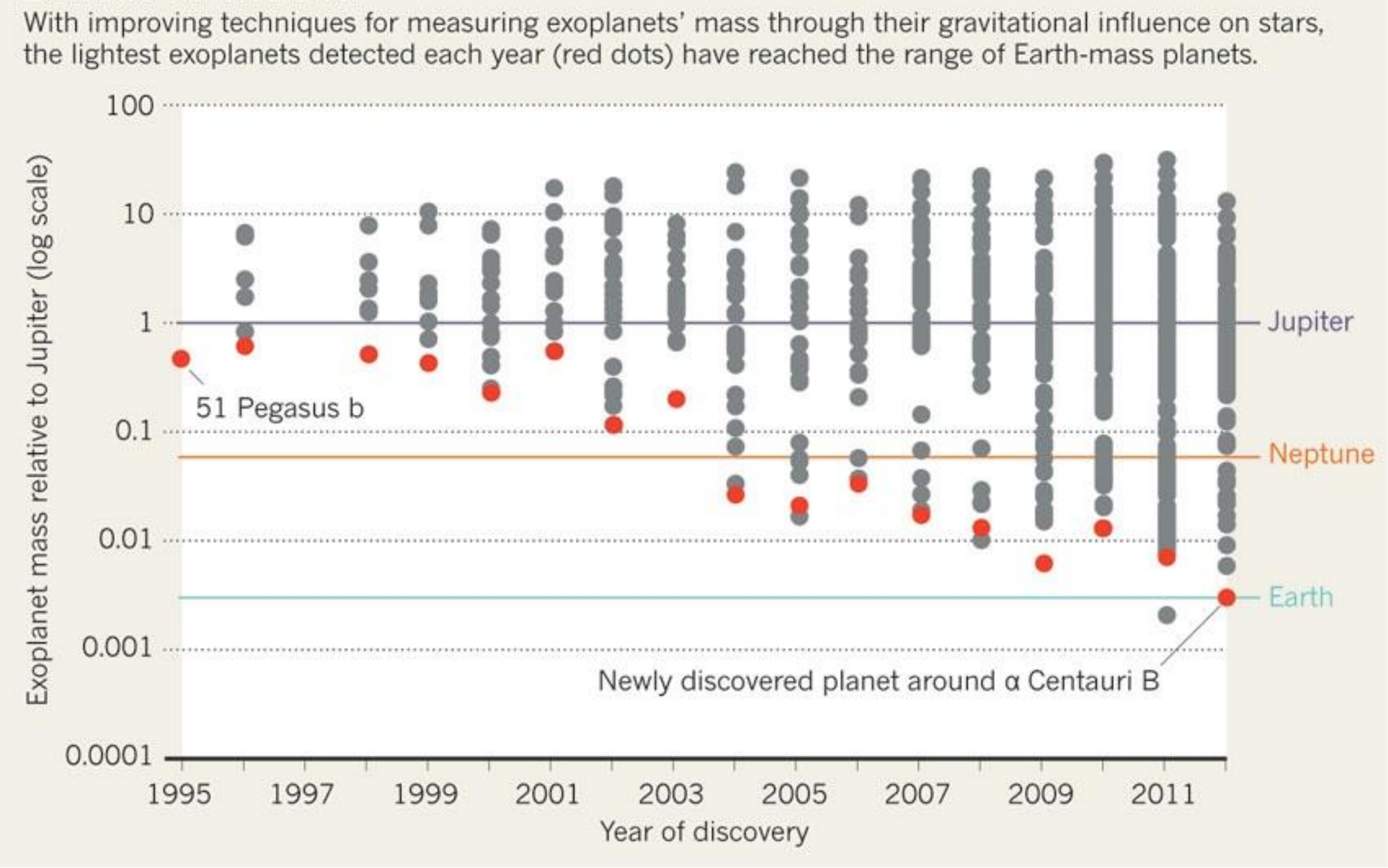
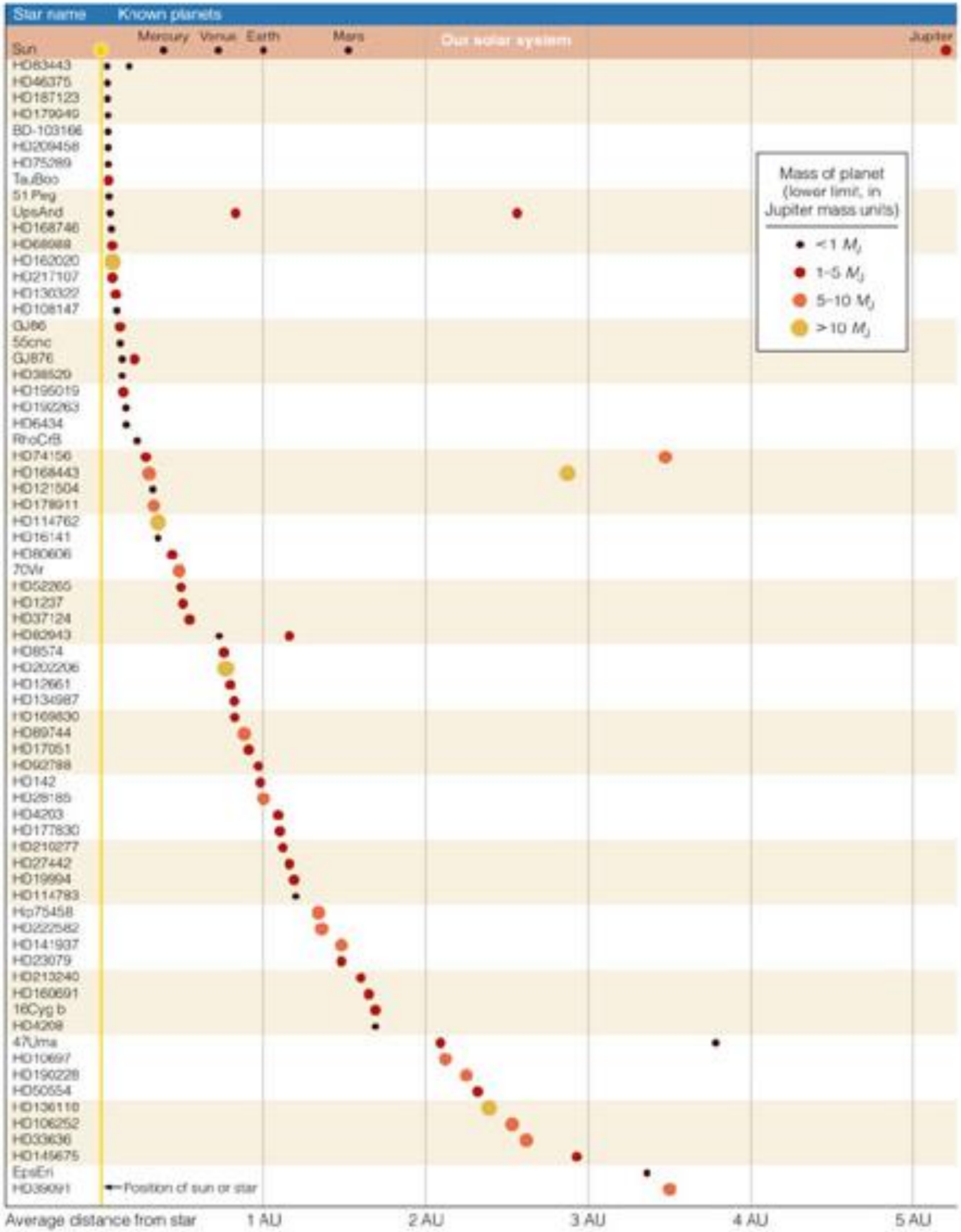

ENCOUNTERING LIFE
IN THE UNIVERSE
Ethical Foundations and Social Implications of Astrobiology
Edited by CHRIS IMPEY, ANNA H. SPITZ, AND WILLIAM STOEGER

# Homing in on Home

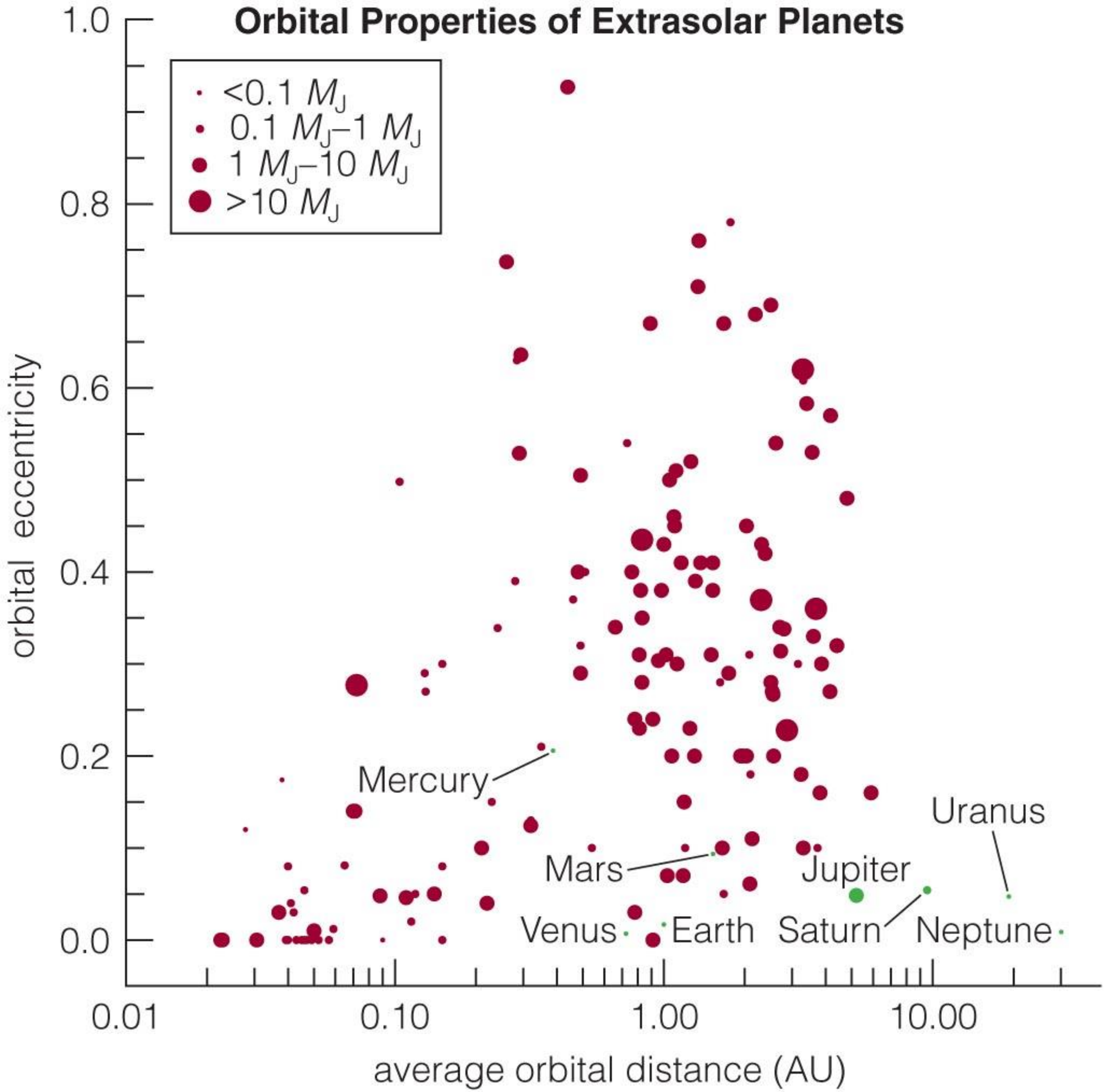





There are 3000+ known ***extrasolar planets*** as of mid 2013, all discovered within the past 18 years, half in the last 2 years!

Most are more massive than Neptune and closer to their star than Earth is to the Sun but terrestrial planets are being found.

Revisions to the nebular theory are necessary. Planets can apparently migrate in from places of birth much farther out.


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)

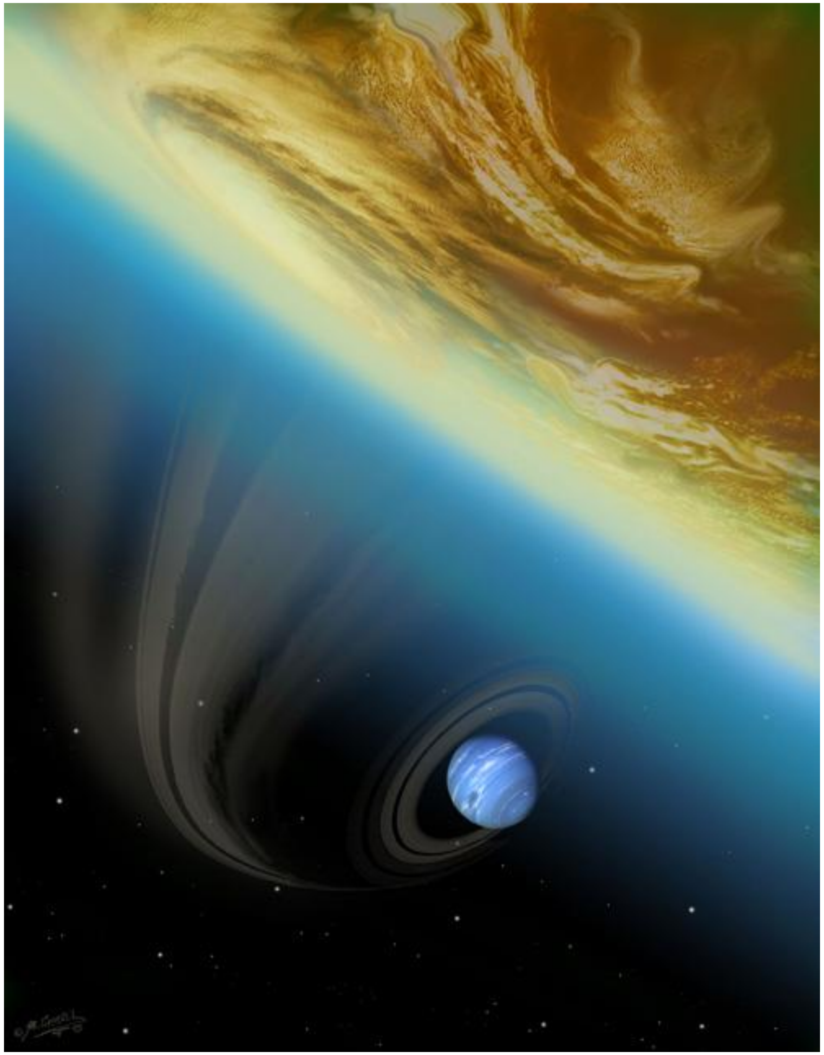
# Chaotic Solar Systems

- Computer models challenge earlier views that the planets formed in an orderly way at their current locations.
- Models suggest that the Jovian planets changed their orbits a lot; Uranus and Neptune could have changed places.
- These chaotic motions could explain a ‘spike’ in the number of impacts in the inner solar system ~3.8 billion years ago.

The Moon and terrestrial planets were bombarded by planetessimals early in the Solar System history.

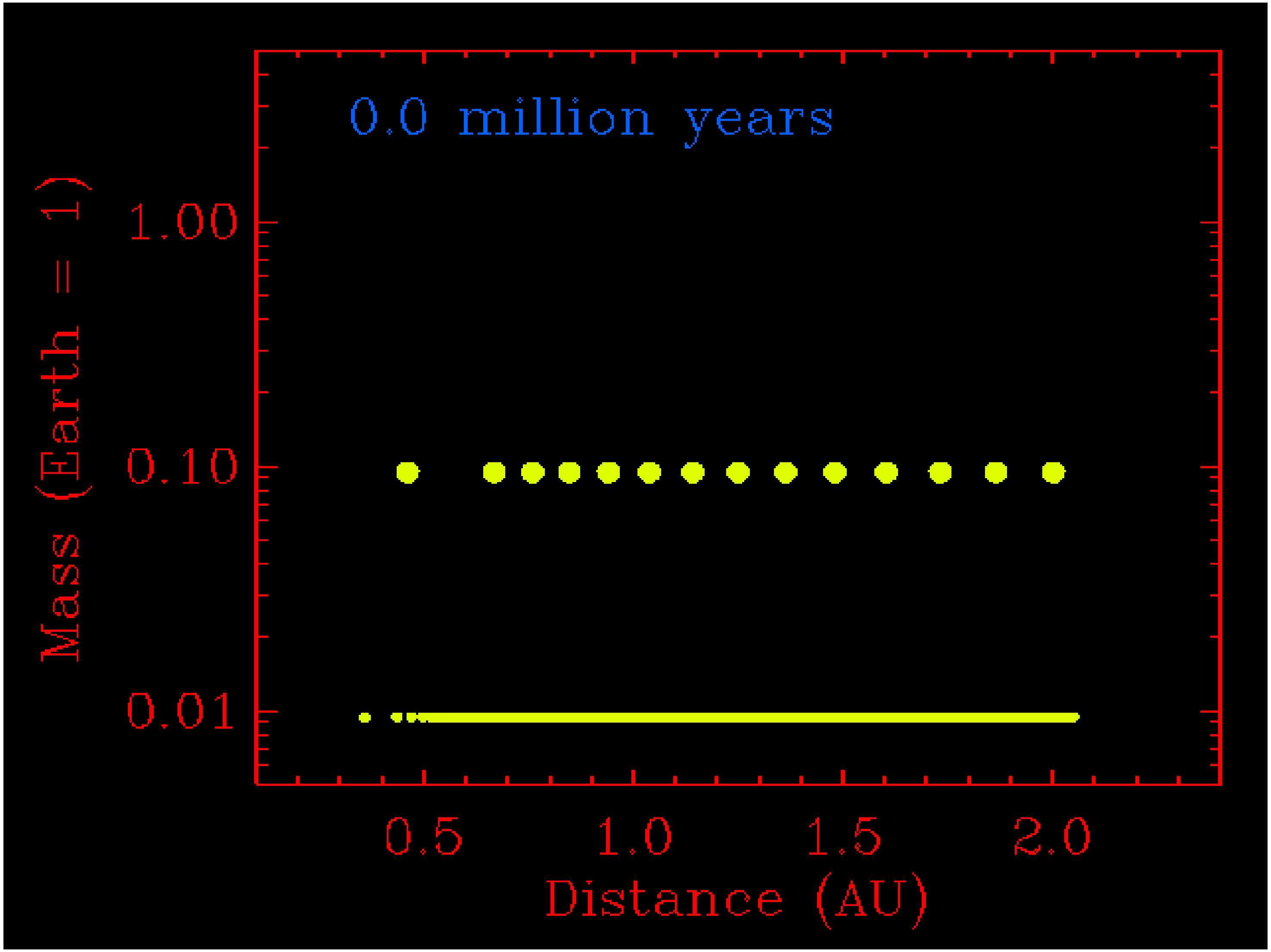
# Planetary Migration

- The current layout of our Solar System might bear very little resemblance to its original form.
- Planetary migration is thought to occur even more dramatically in extrasolar planet systems.
- It may be difficult to prove or disprove models of the early Solar System, although comets and asteroids provide clues.
- Despite all the empty space our solar system is full: adding a planet would make it unstable.



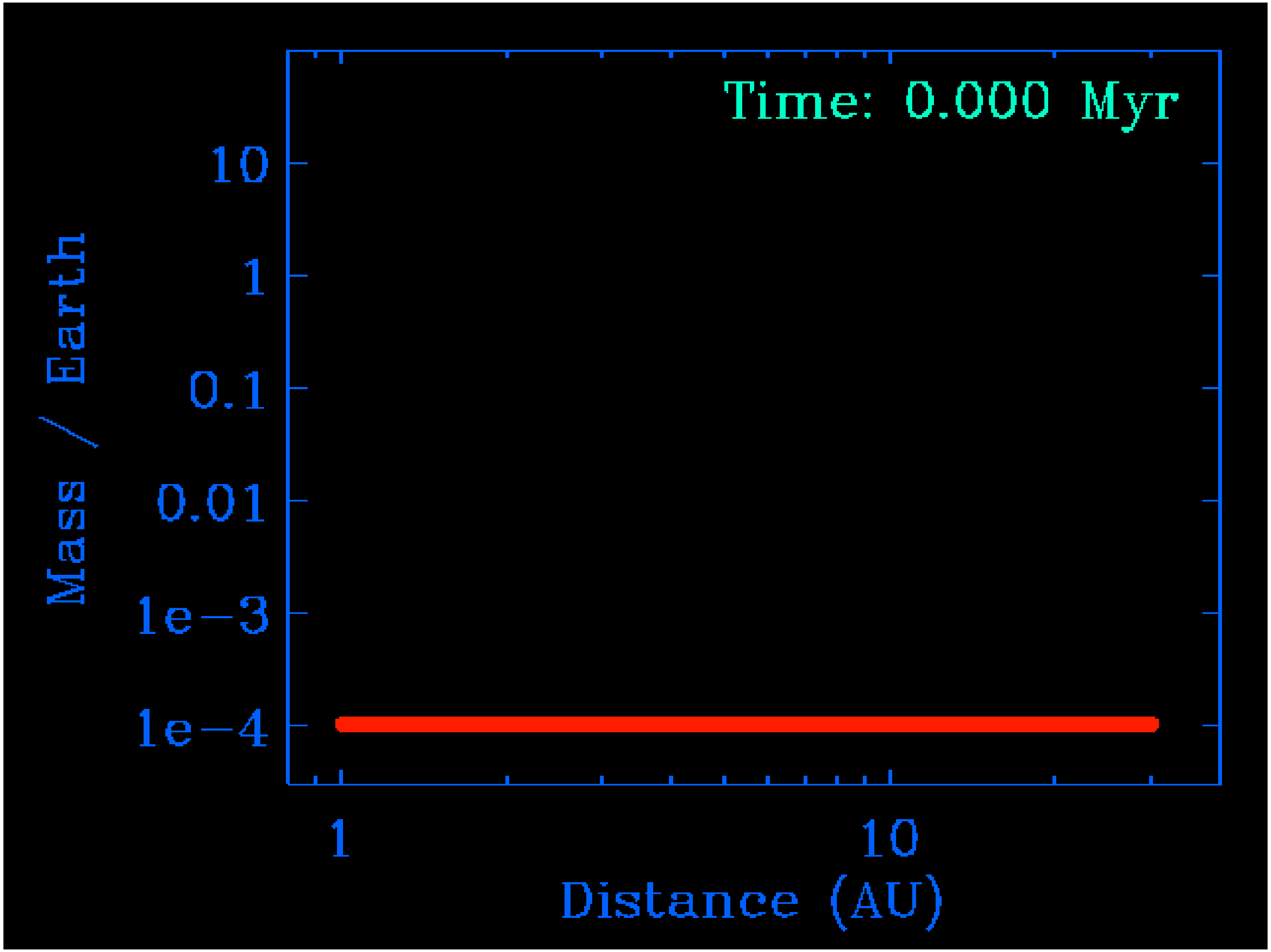
Artist's depiction of Neptune orbiting close to Jupiter (courtesy Michael Carroll)

# Terrestrial Planets



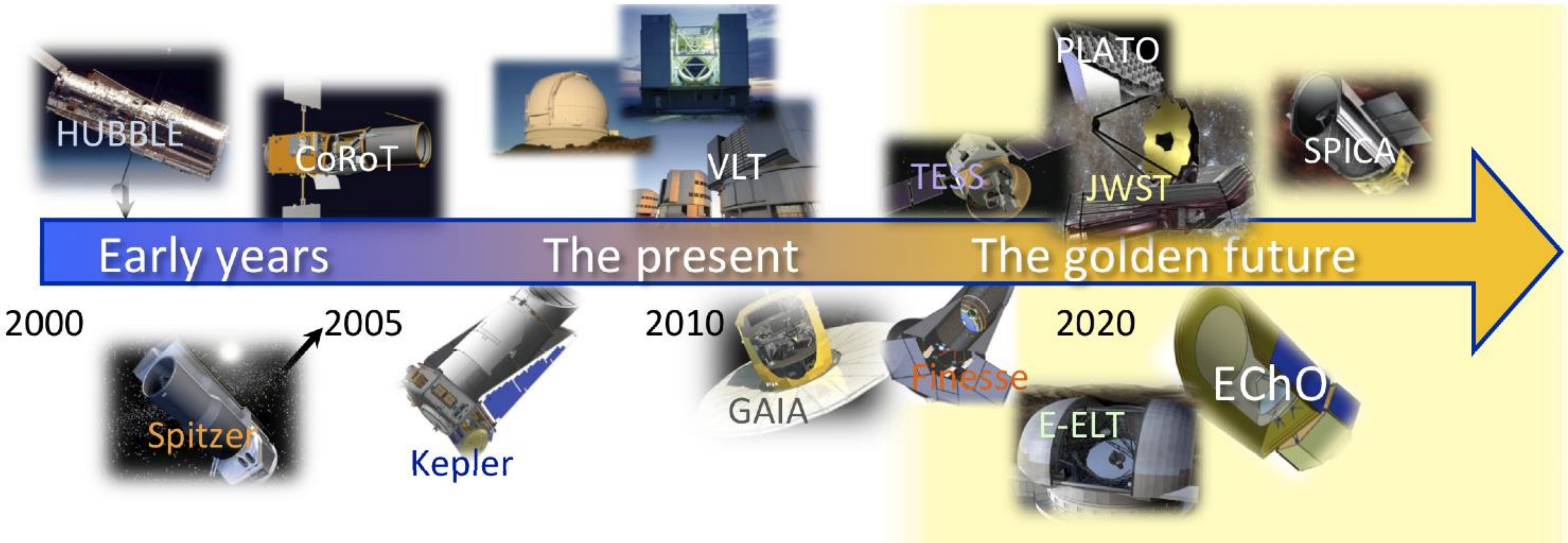

In simulations, hundreds of Moon mass planetesimals accrete to form a handful of terrestrial planets. Some of the collisions are destructive.

# Gas Giant Planets

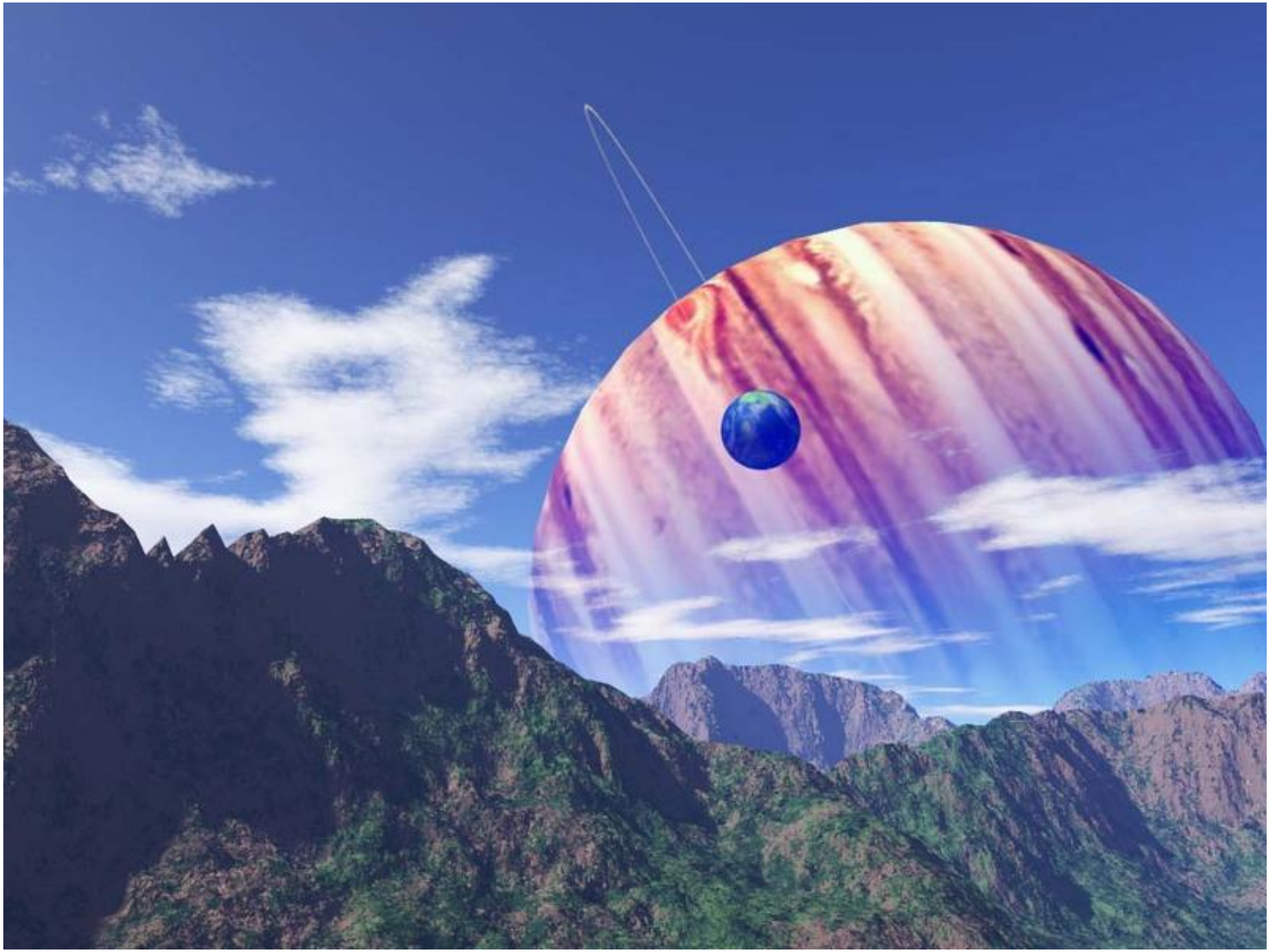



The gas giants are formed further out and many are swept in by interactions with the gas disk. The late formers stabilize and park.

# A Golden Age for Exoplanets



# Detection Methods



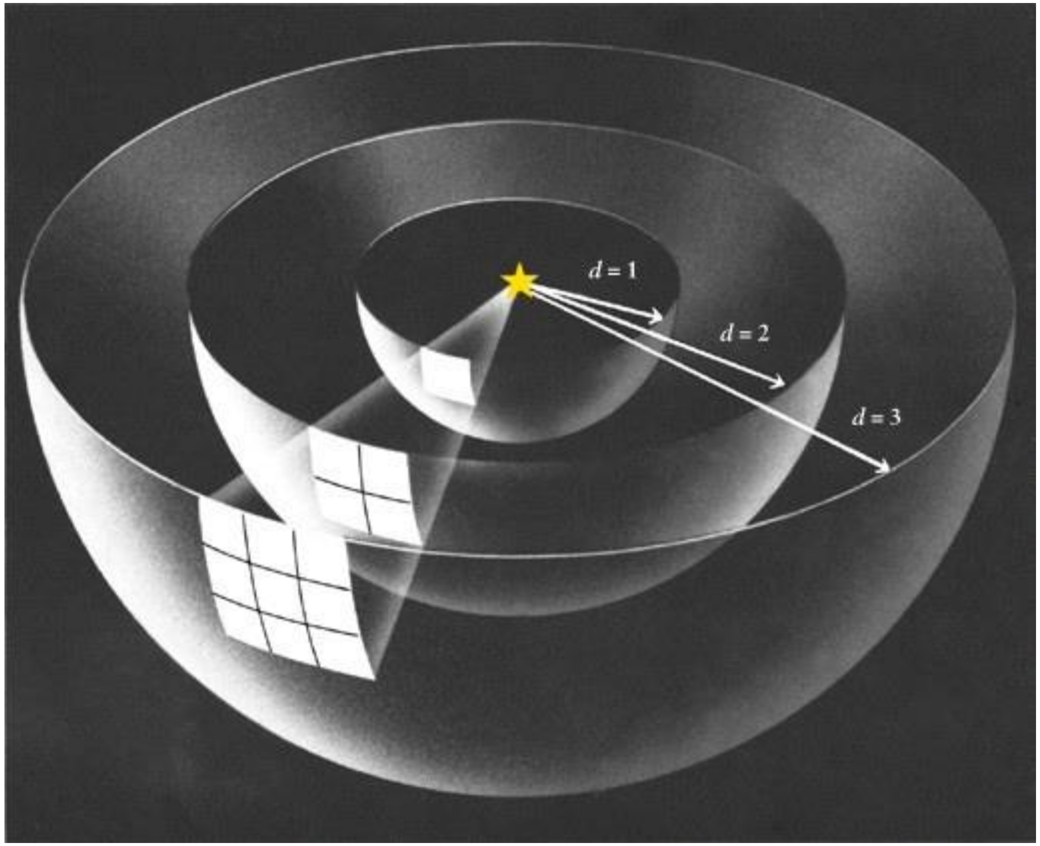
# How to Detect Planets

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:*

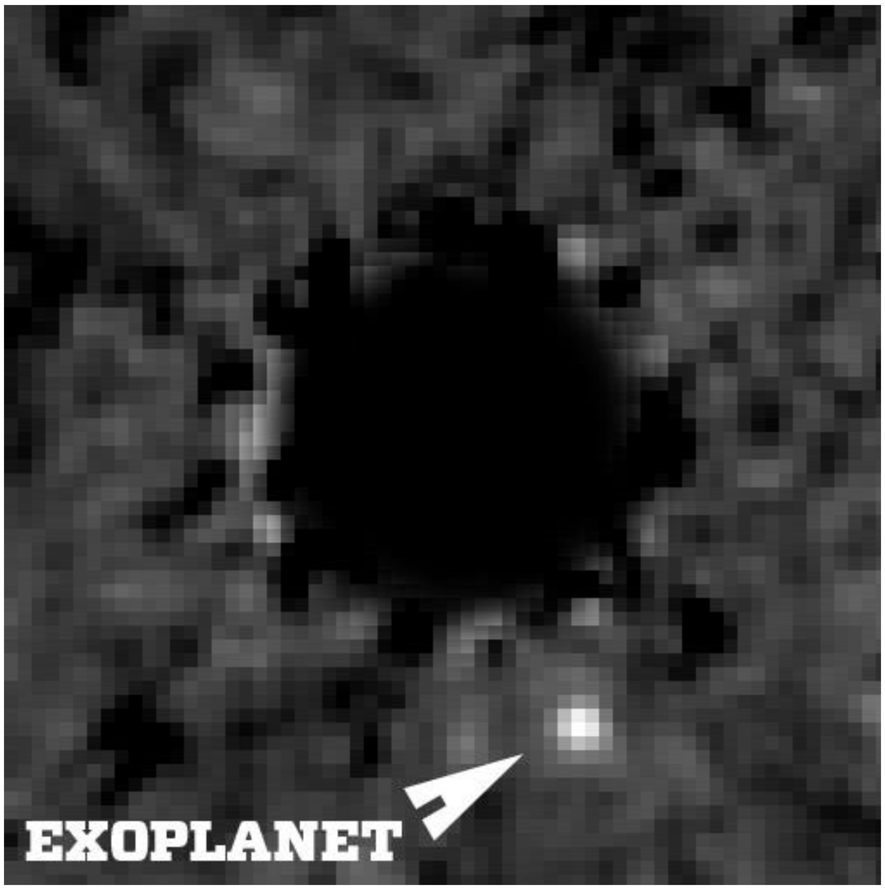
1. The Sun is $10^6$ km across and Jupiter is $10^5$ km across
2. The Sun is 1000 times more massive than Jupiter
3. Distance of Jupiter from Sun: $10^9$ km, or a billion km

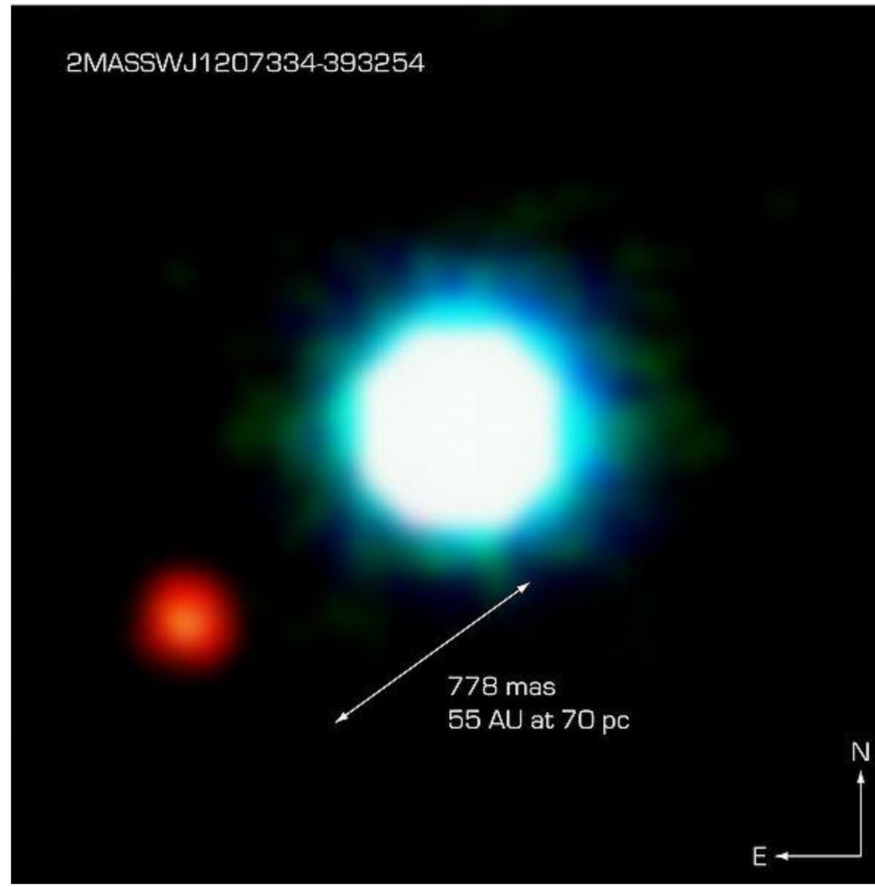
# Direct Detection



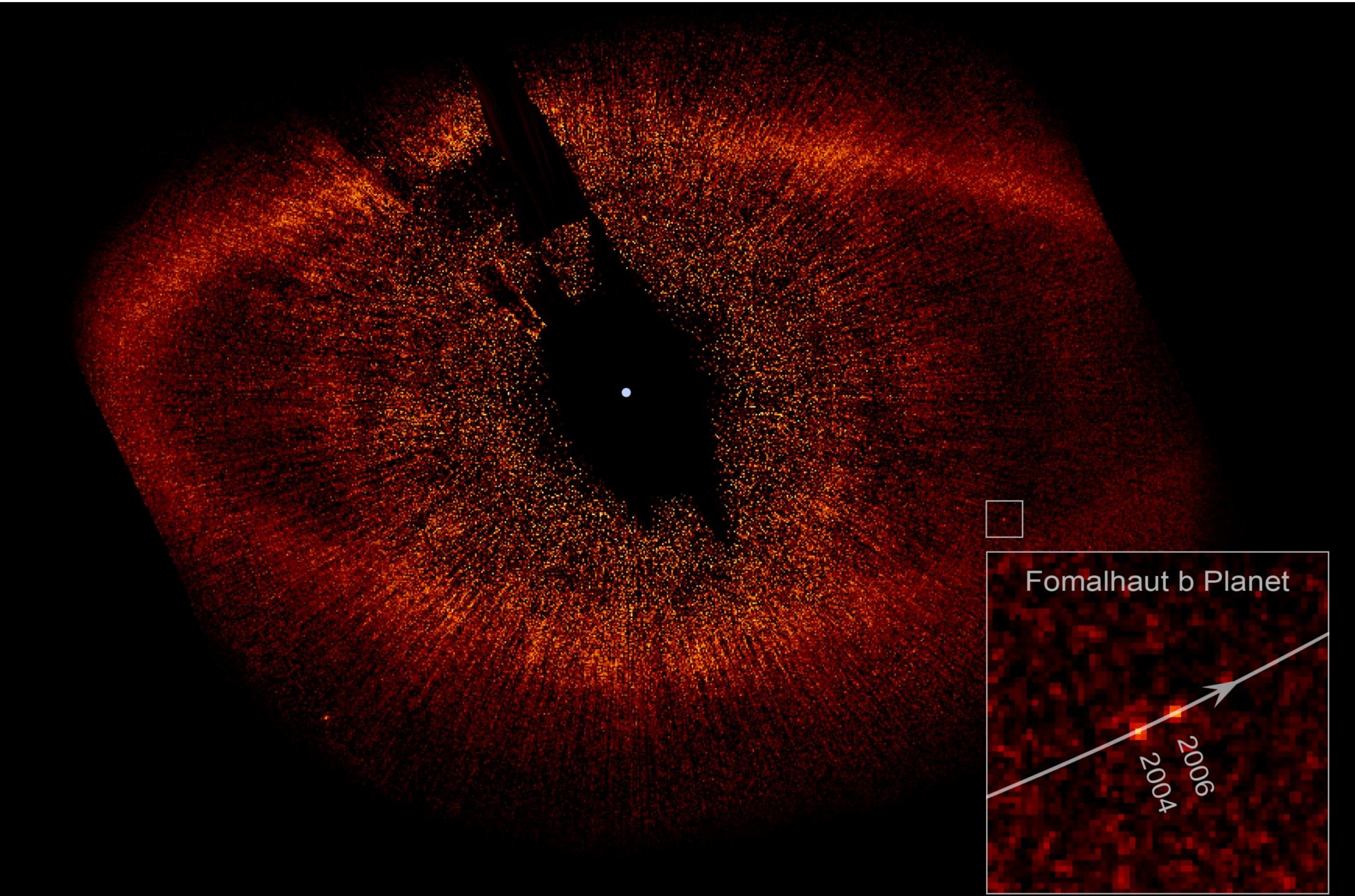

Light from the star goes down as the square of the distance. Alternatively, the light intercepted (and reflected) from any patch goes down as the square of the distance of the patch.

# Exoplanets were finally imaged in 2008!



# Found by chance in the HST archive (~50 more to dig out).



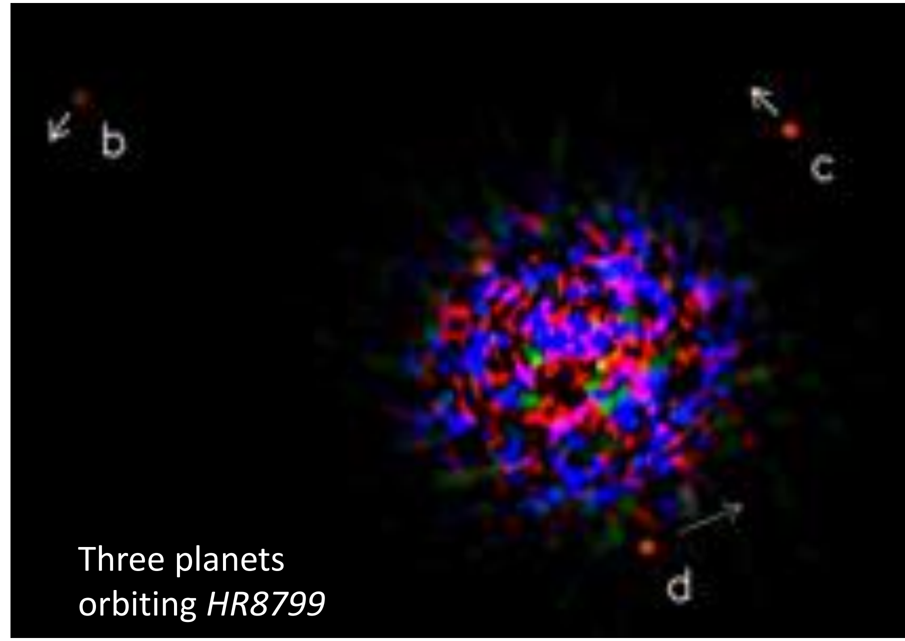
# Imaging Exoplanets

- This star has the first imaged (3-planet) *exolanetary system*!

- Planets are much fainter ($10^{-8}$ or $10^{-9}$) than their parent star.

- Getting these images requires:

    - Adaptive optics methods to *block the star's light*.
    - Observations *repeated over years*, confirming motion.
    - The planets are *young and hot*, and glow more brightly than by reflected starlight.



Three planets orbiting *HR8799*

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 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)**

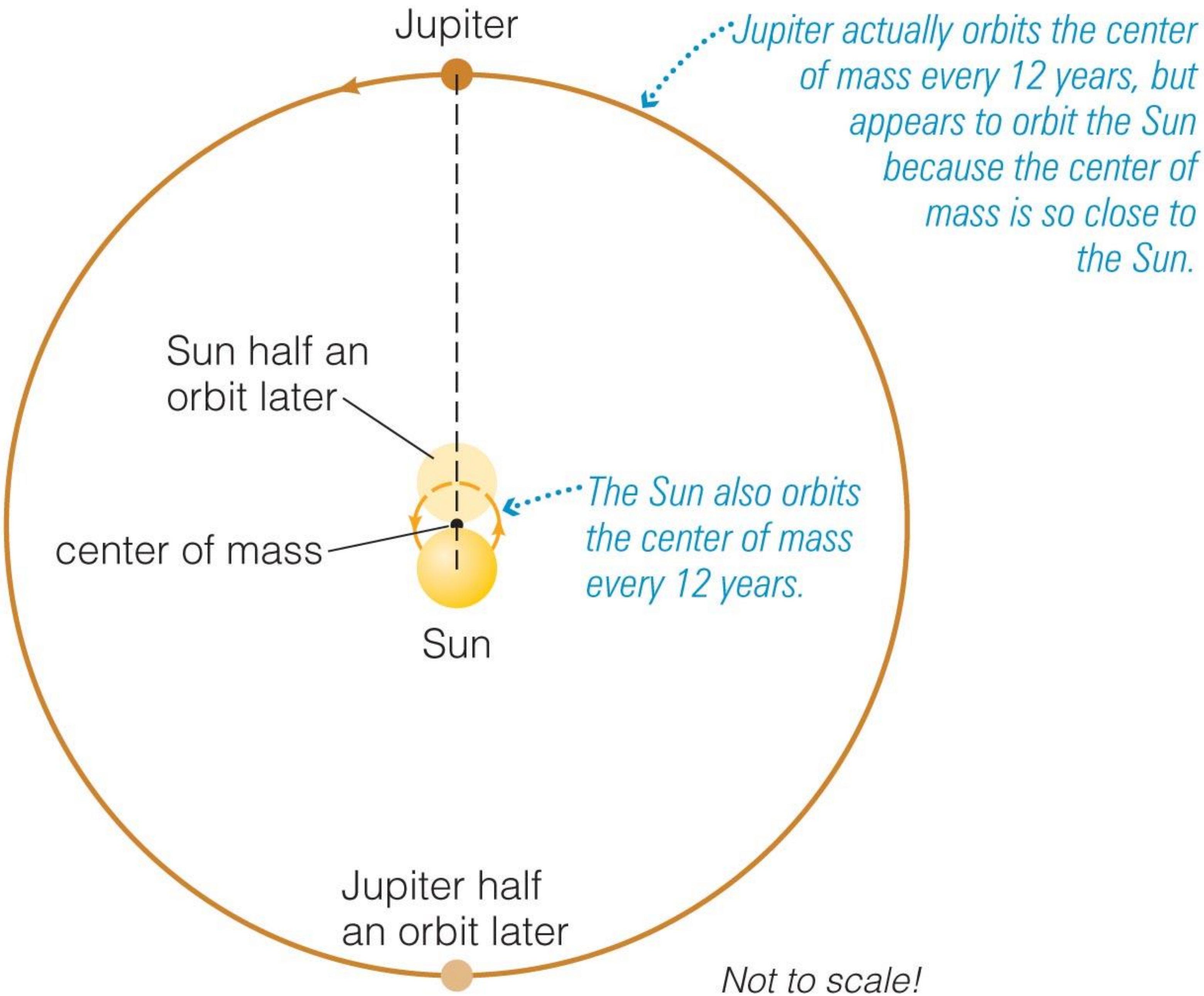
**Unseen planets causes a reflex motion or "wobble" on the visible stars they orbit**

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

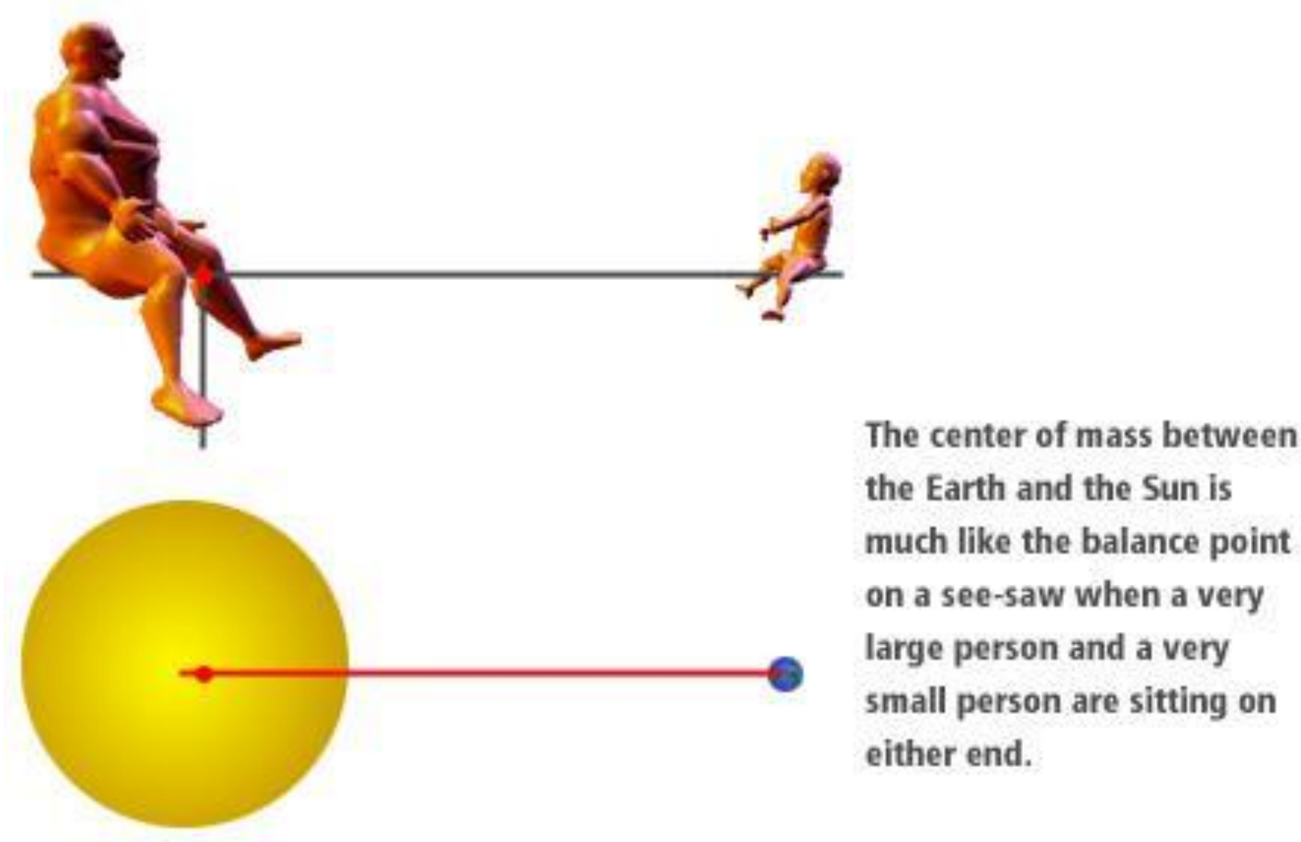
**The wobble is too hard to see by imaging so spectra of the star are used to detect it**

**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**


Jupiter
Jupiter actually orbits the center of mass every 12 years, but appears to orbit the Sun because the center of mass is so close to the Sun.
Sun half an orbit later
center of mass
The Sun also orbits the center of mass every 12 years.
Sun
Jupiter half an orbit later
Not to scale!

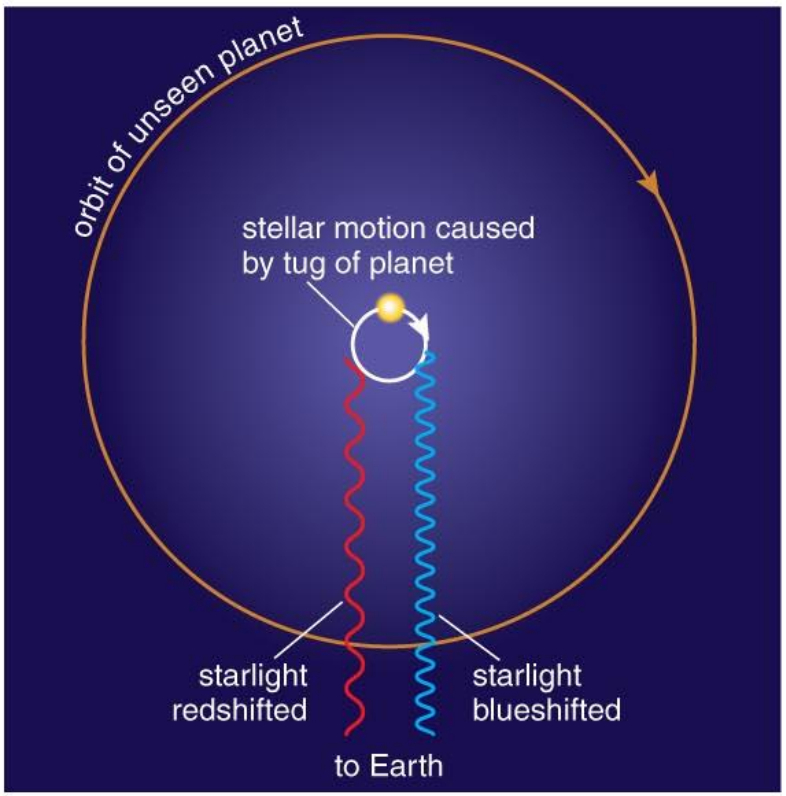
# Doppler Detection



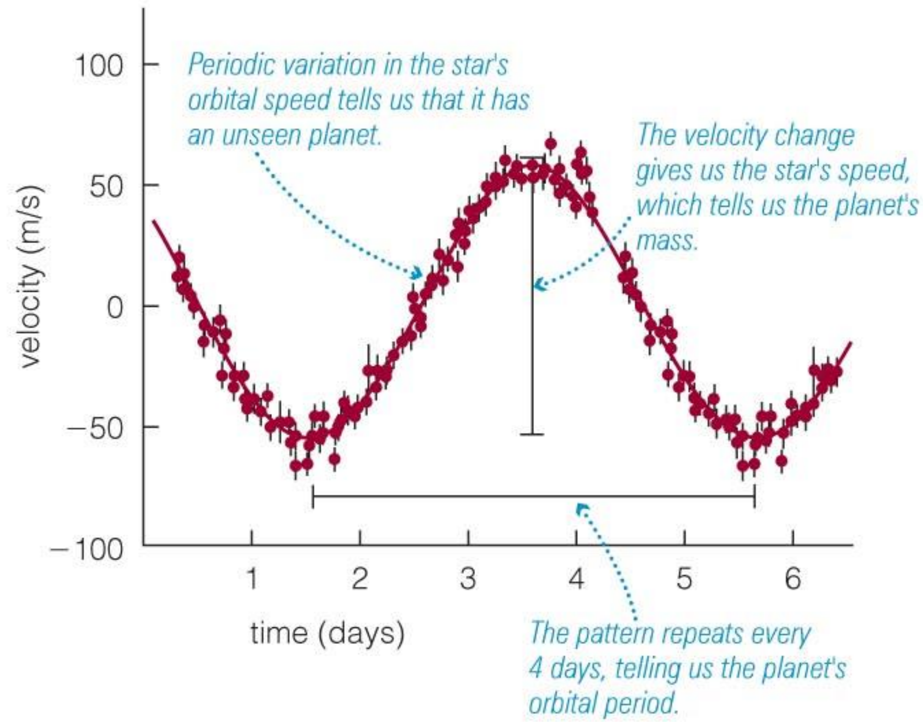

The balance point divides the distance according to mass. Equal masses balance at the midpoint, if one mass is 10x the other, the balance point is 10x closer to the large mass.

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 very rapid 4-day orbit, far closer to its star than Mercury is to the Sun!

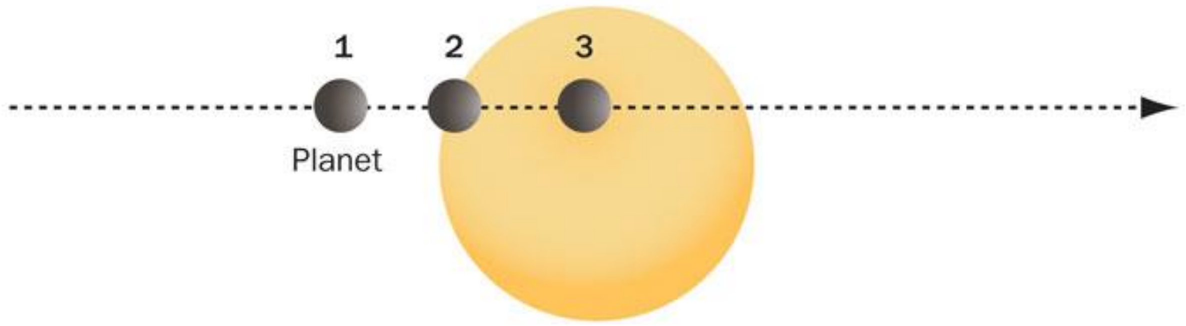



**a** Doppler shifts allow us to detect the slight motion of a star caused by an orbiting planet.



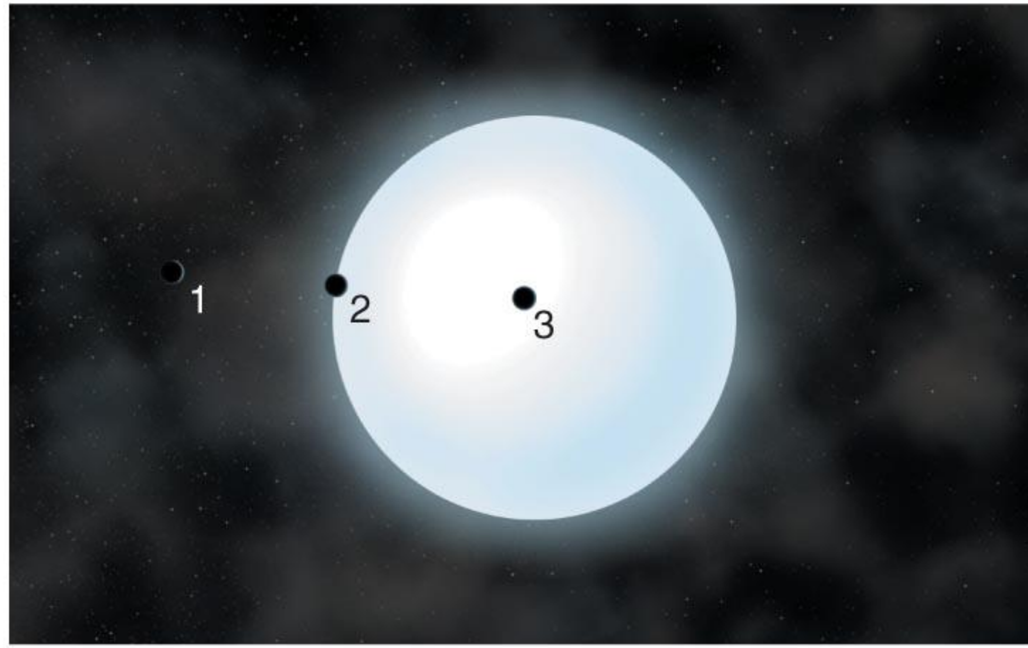

**b** A periodic Doppler shift in the spectrum of the star 51 Pegasi shows the presence of a large planet with an orbital period of about 4 days. Dots are actual data points; bars through dots represent measurement uncertainty.

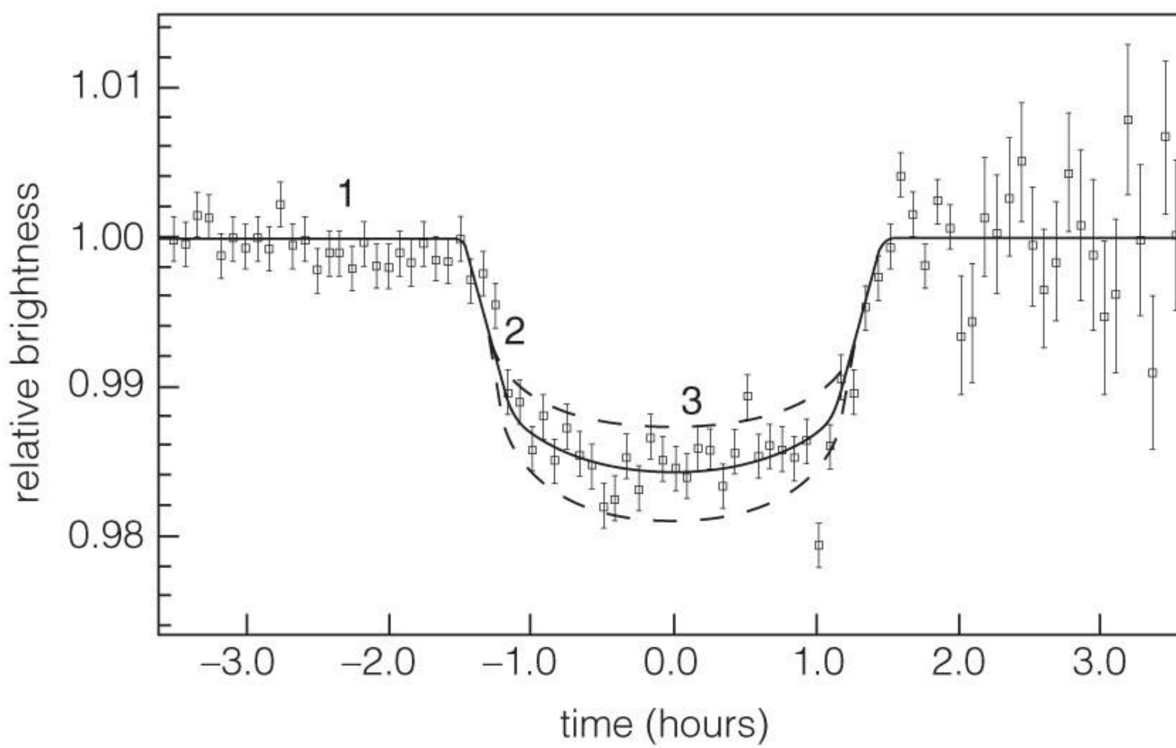
# *But a problem…*




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! Or watch a large number of stars to catch the rare eclipses.

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.

# Characterization

Eight 16” telescopes monitor a few thousand stars cooler than the Sun, searching for transiting planets. Similar ground-based setups may soon be able to detect Earths.

# Exopanet Density

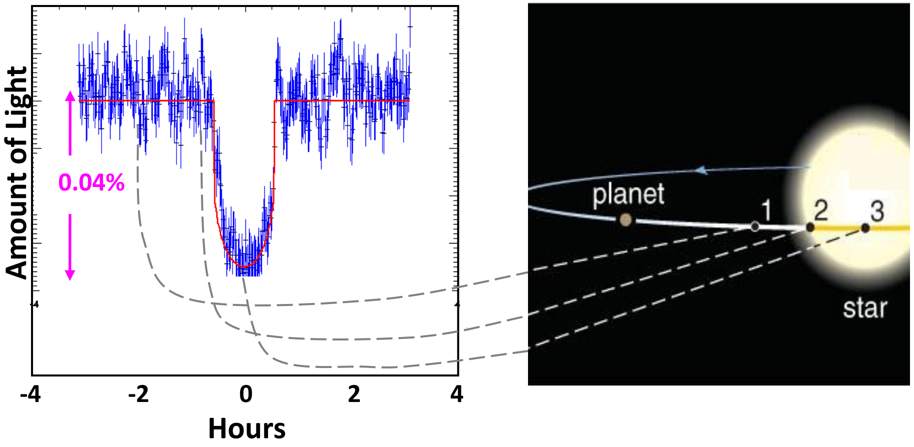
- **Density = Mass / Volume**

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

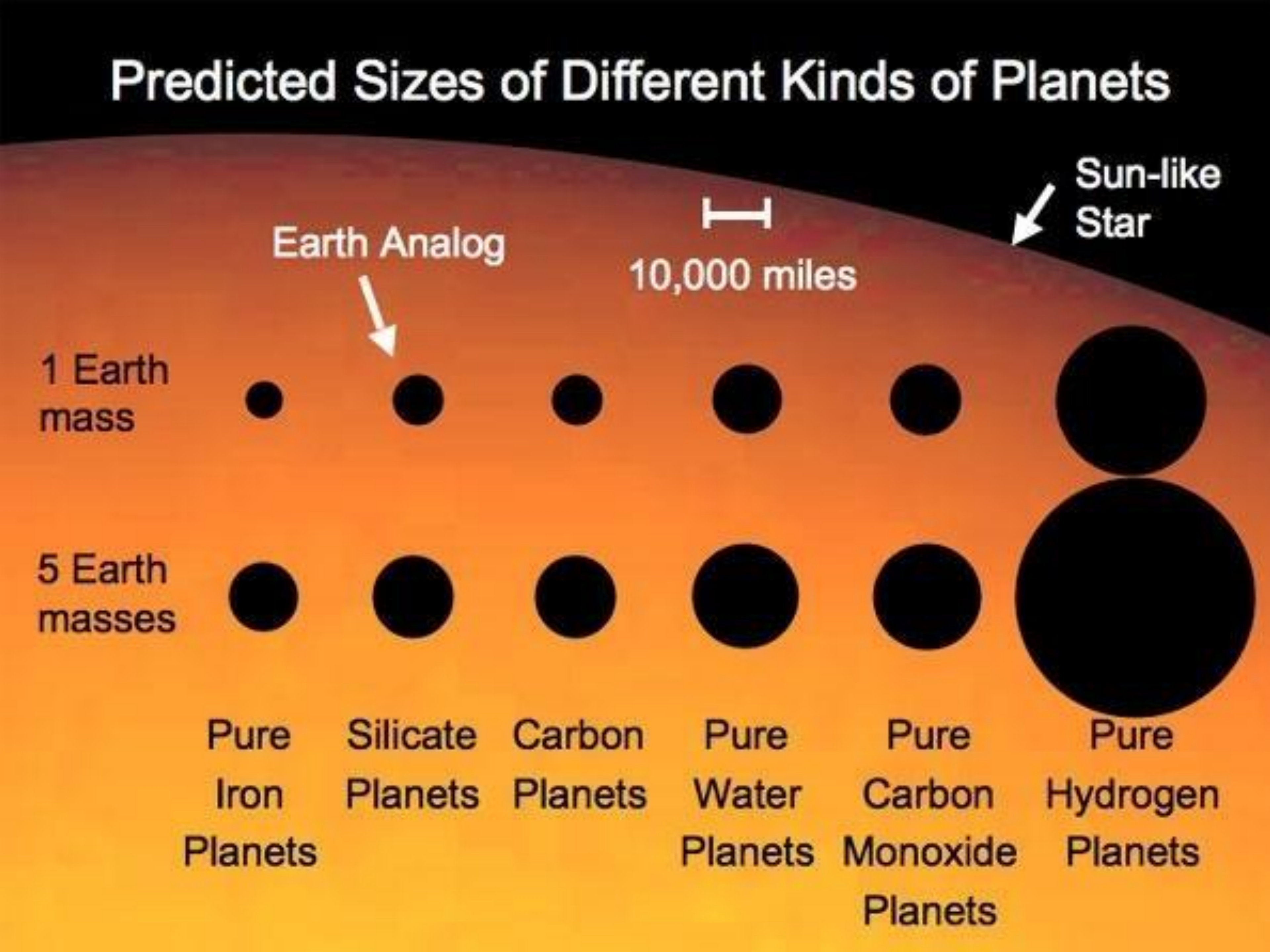
Changes in the measured wavelengths of star light are caused by a planet with mass ~5 times Earth's.

- **Volume = 4/3 $\pi$ $R^3$**

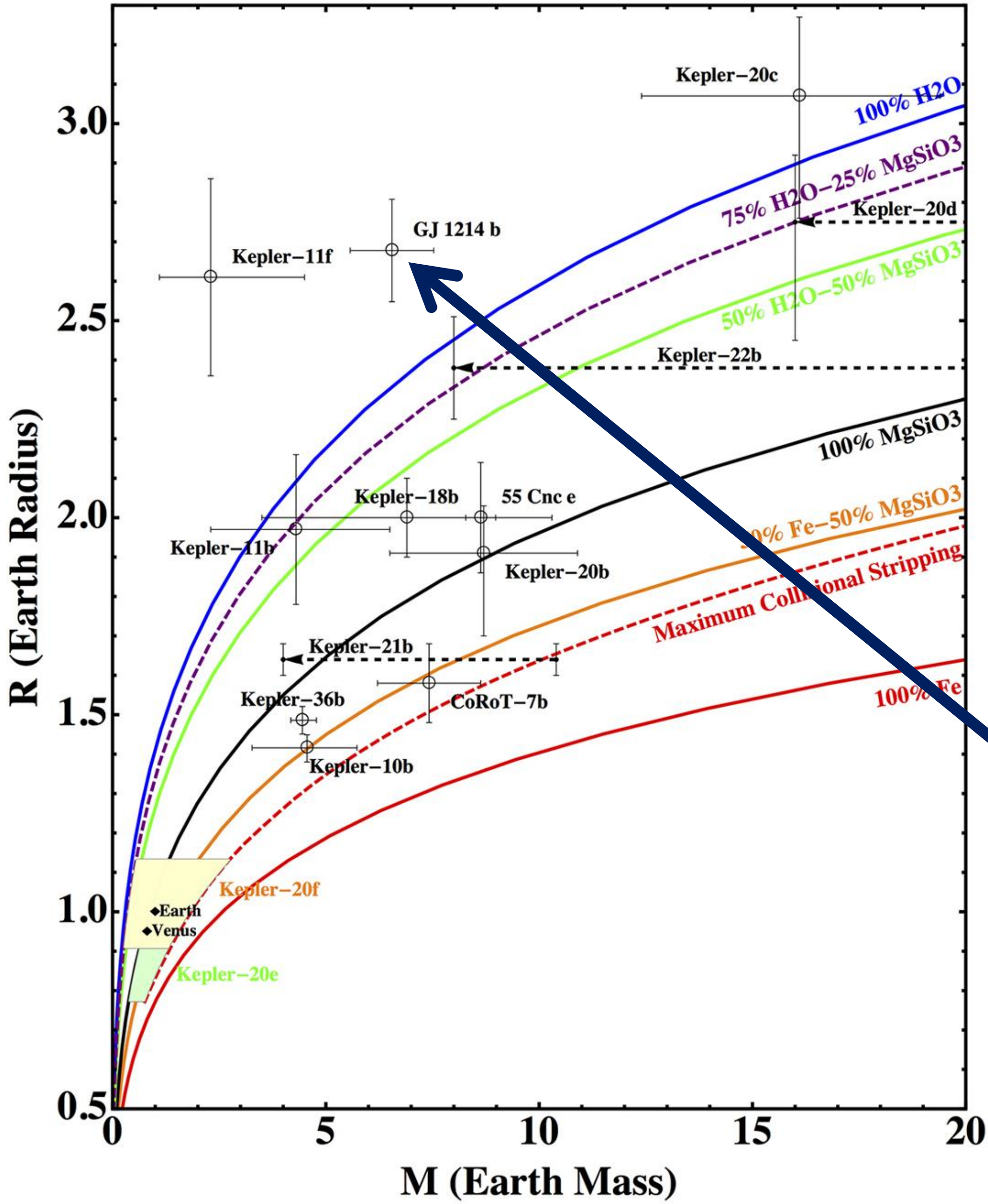
- The planet's size was determined using the *transit method*:
  The light measured from a star decreases each time the planet passes in front of it. The amount of the decrease indicates the planet's area or size.

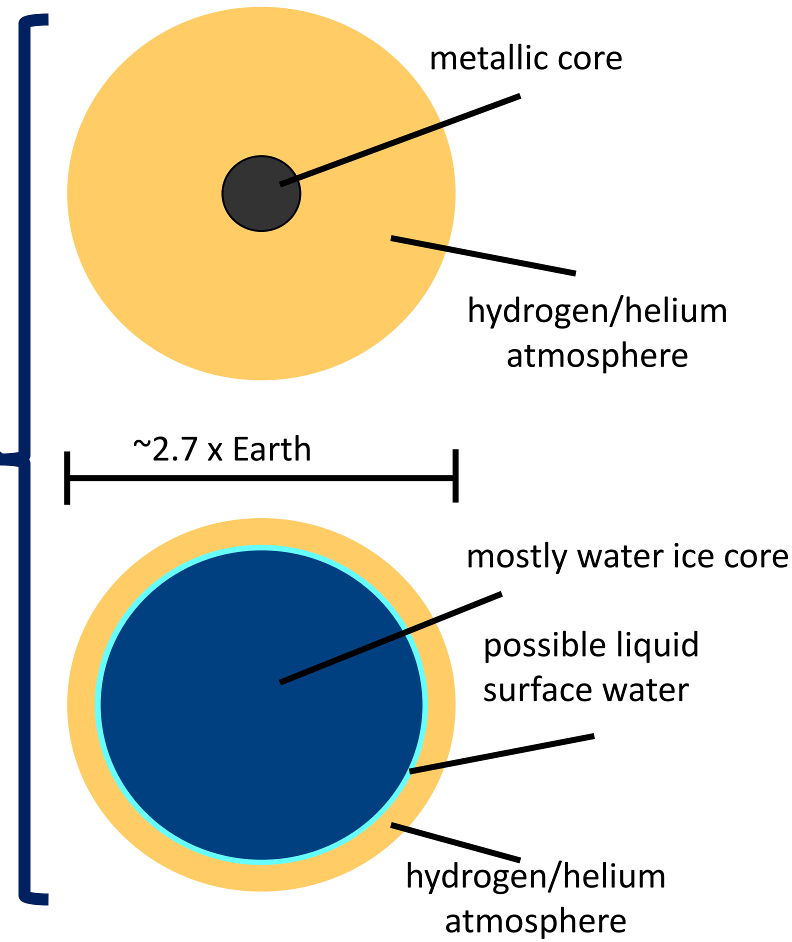



Periodic decreases in light from the star are caused by a planet with diameter 1.7 times Earth's passing in front.

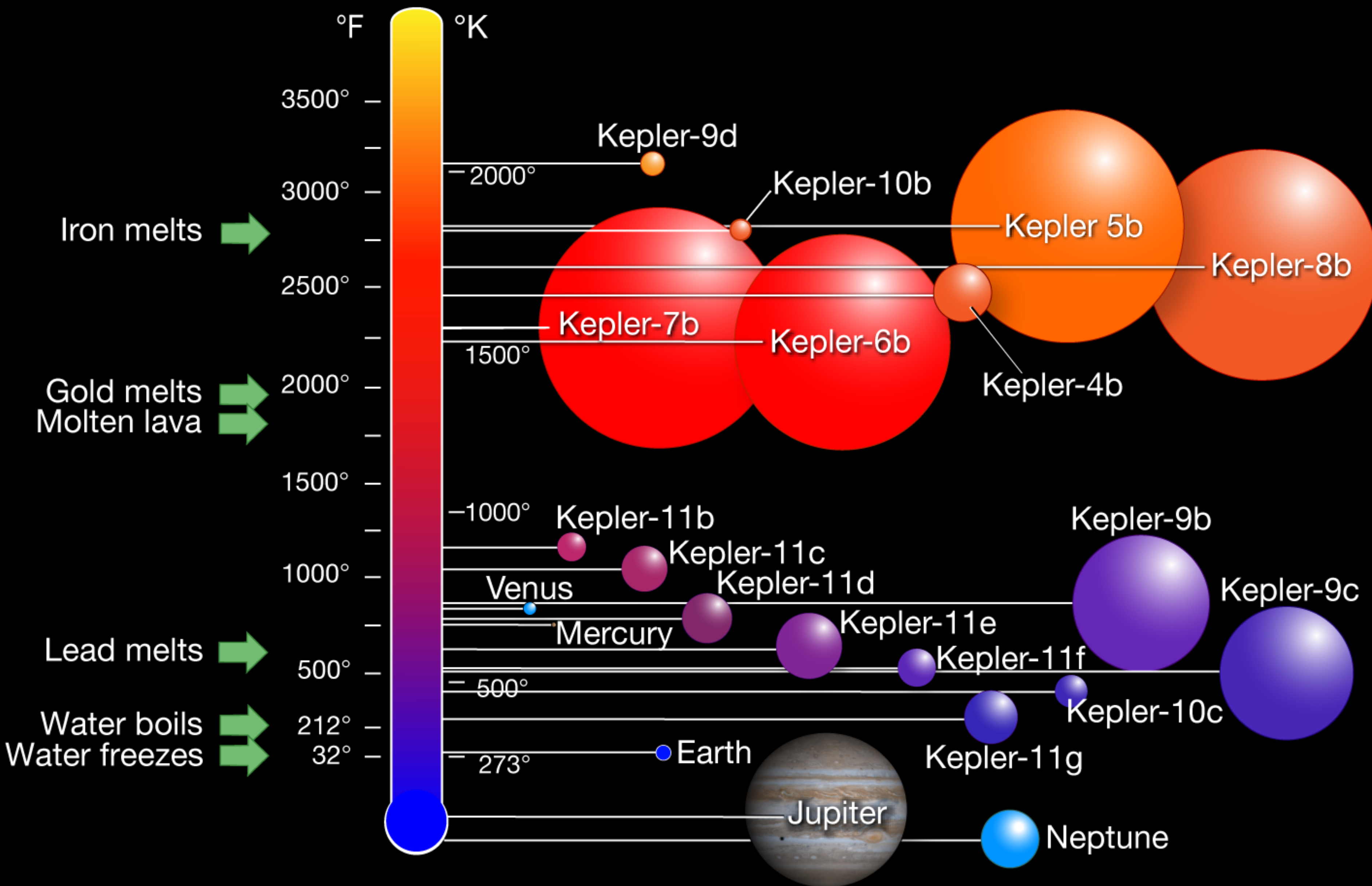

Predicted Sizes of Different Kinds of Planets
Sun-like Star
10,000 miles
Earth Analog
1 Earth mass
5 Earth masses
Pure Iron Planets
Silicate Planets
Carbon Planets
Pure Water Planets
Pure Carbon Monoxide Planets
Pure Hydrogen Planets

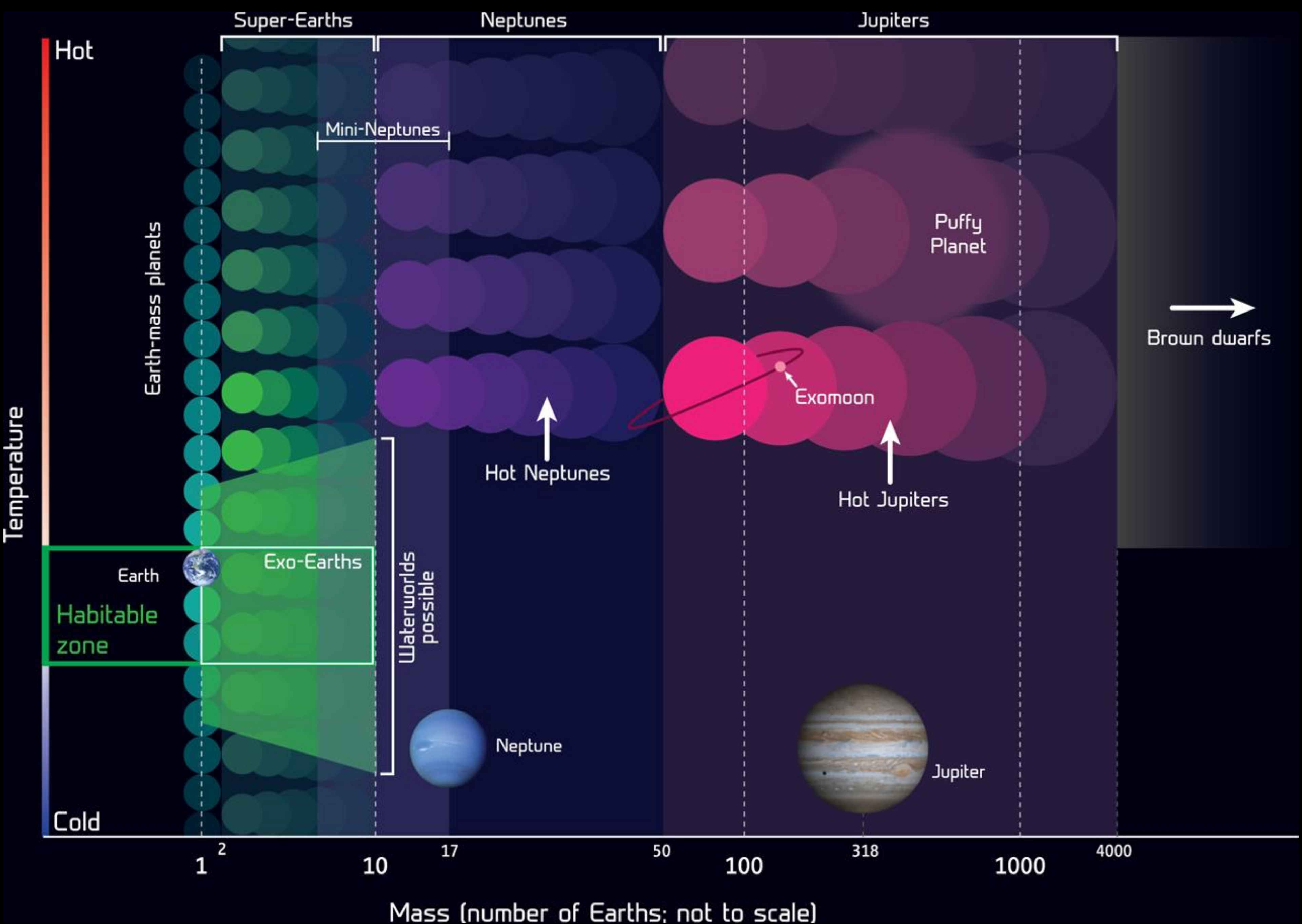
As this example shows, a single mean density can correspond to very different structures.



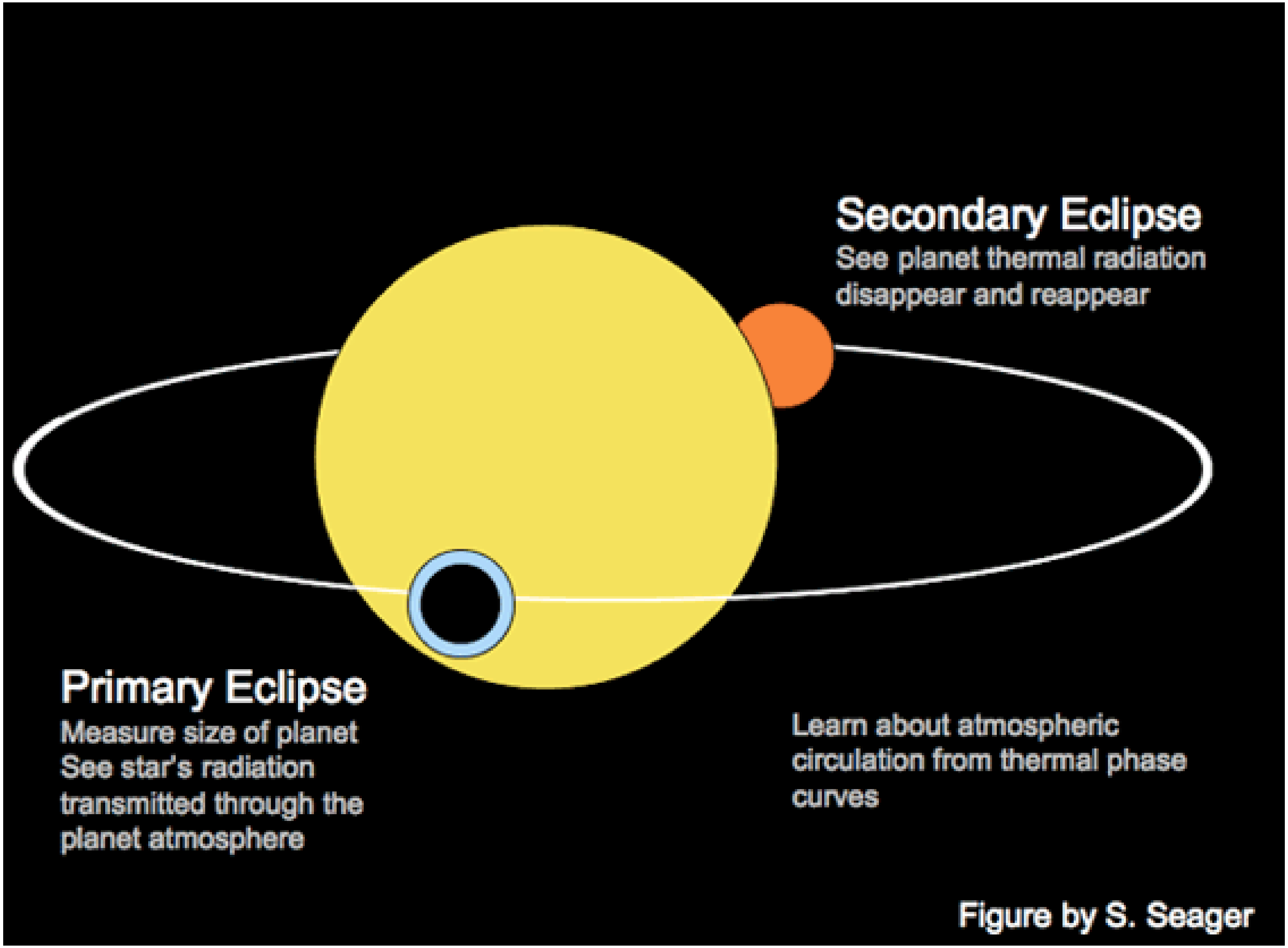
# Planet Temperature & Size

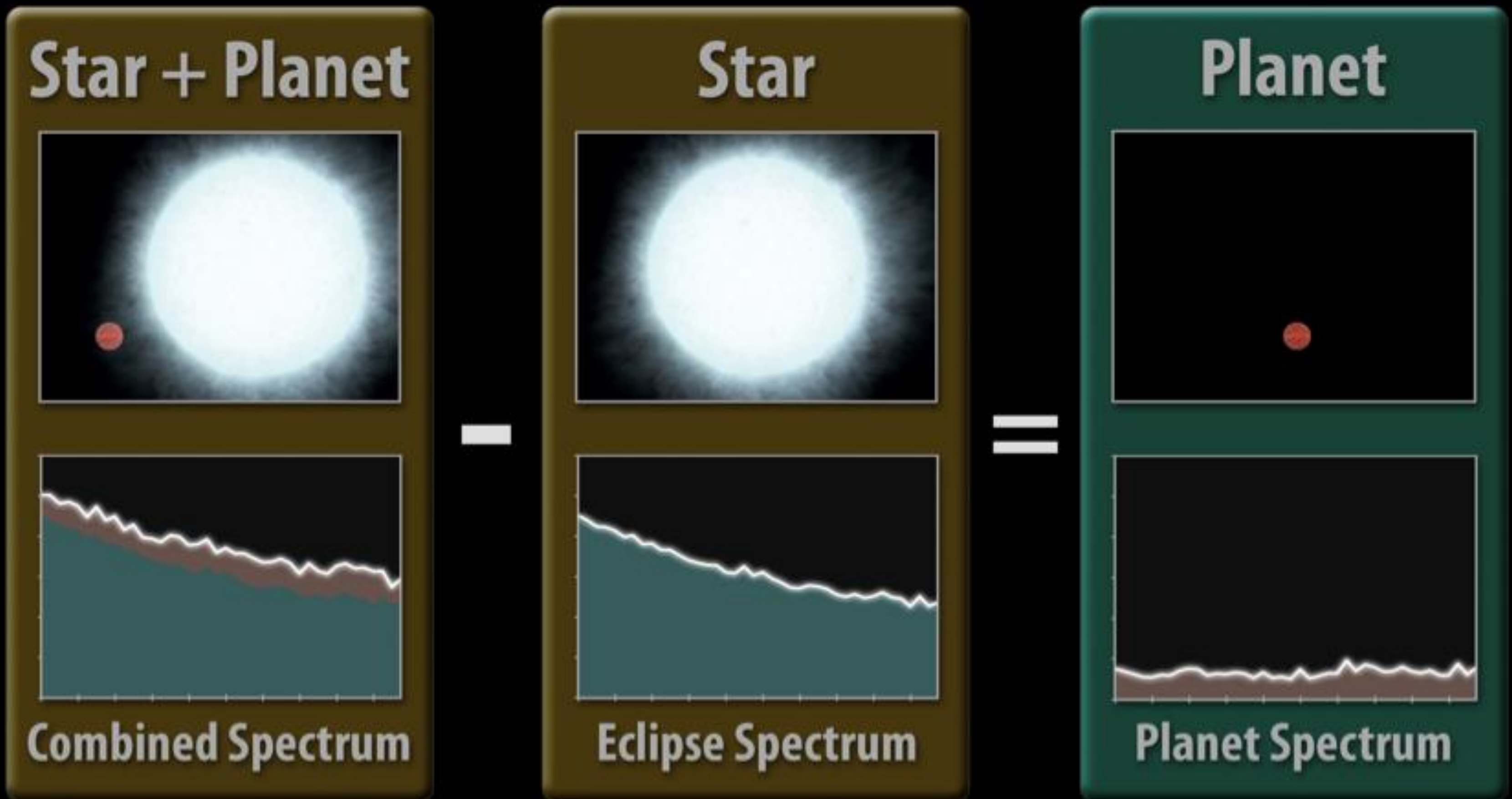




Super-Earths
Neptunes
Jupiters
Hot
Cold
Temperature
Earth-mass planets
Mini-Neptunes
Puffy Planet
Brown dwarfs
Exomoon
Hot Neptunes
Hot Jupiters
Earth
Habitable zone
Exo-Earths
Waterworlds possible
Neptune
Jupiter
1
2
10
17
50
100
318
1000
4000
Mass (number of Earths; not to scale)

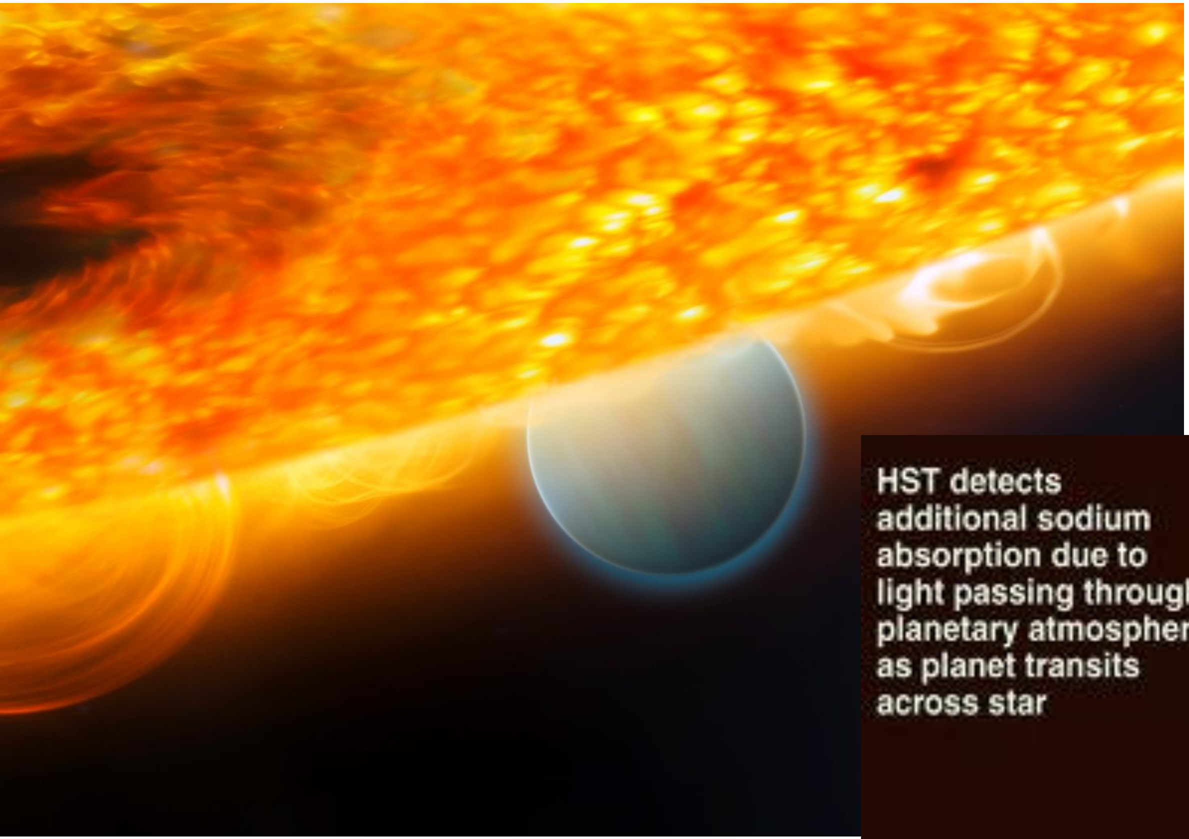
# Learning from Transits



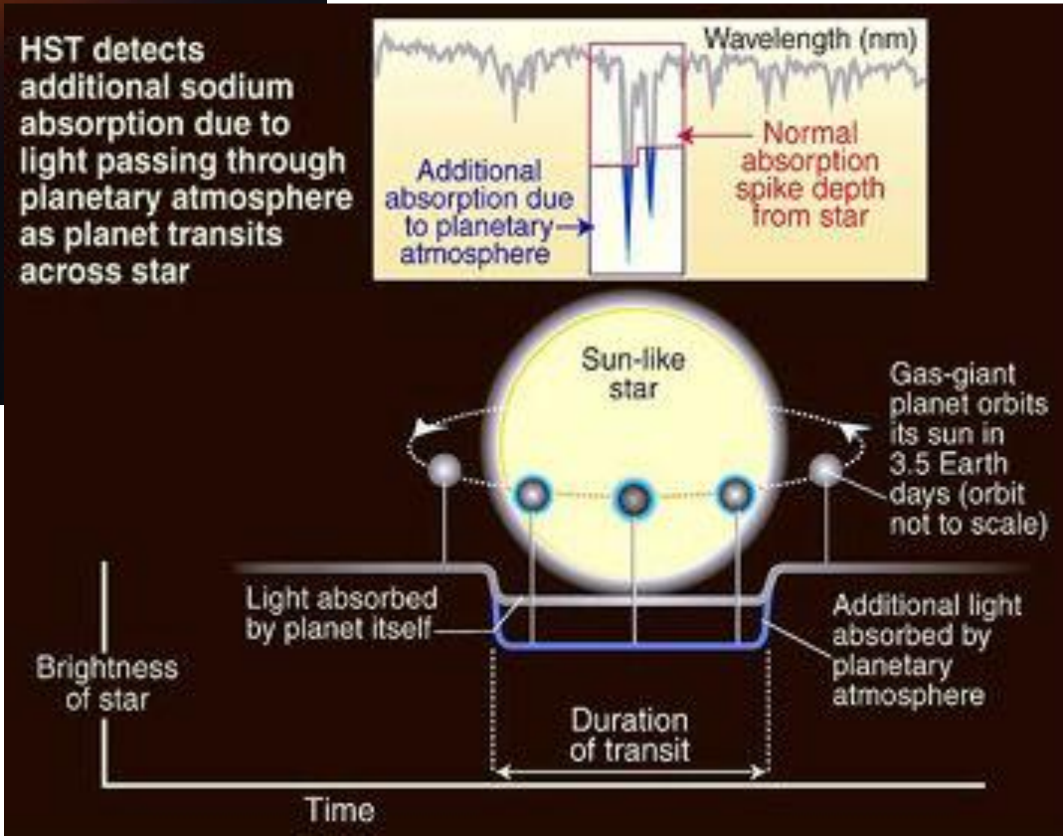



# Isolating a Planet's Spectrum

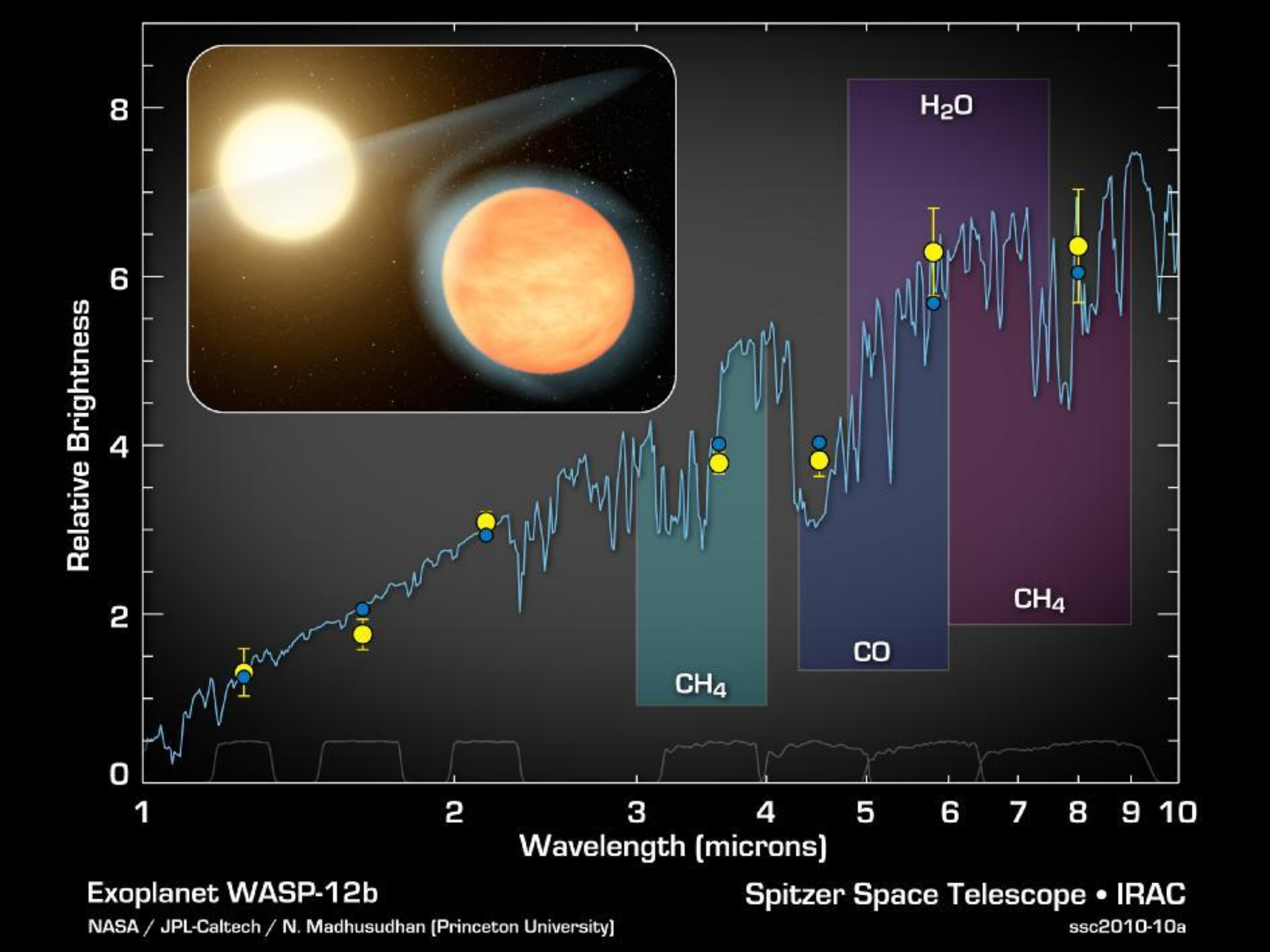
# Probing Atmospheres



An atmosphere backlit by a star can reveal the composition by absorption.




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

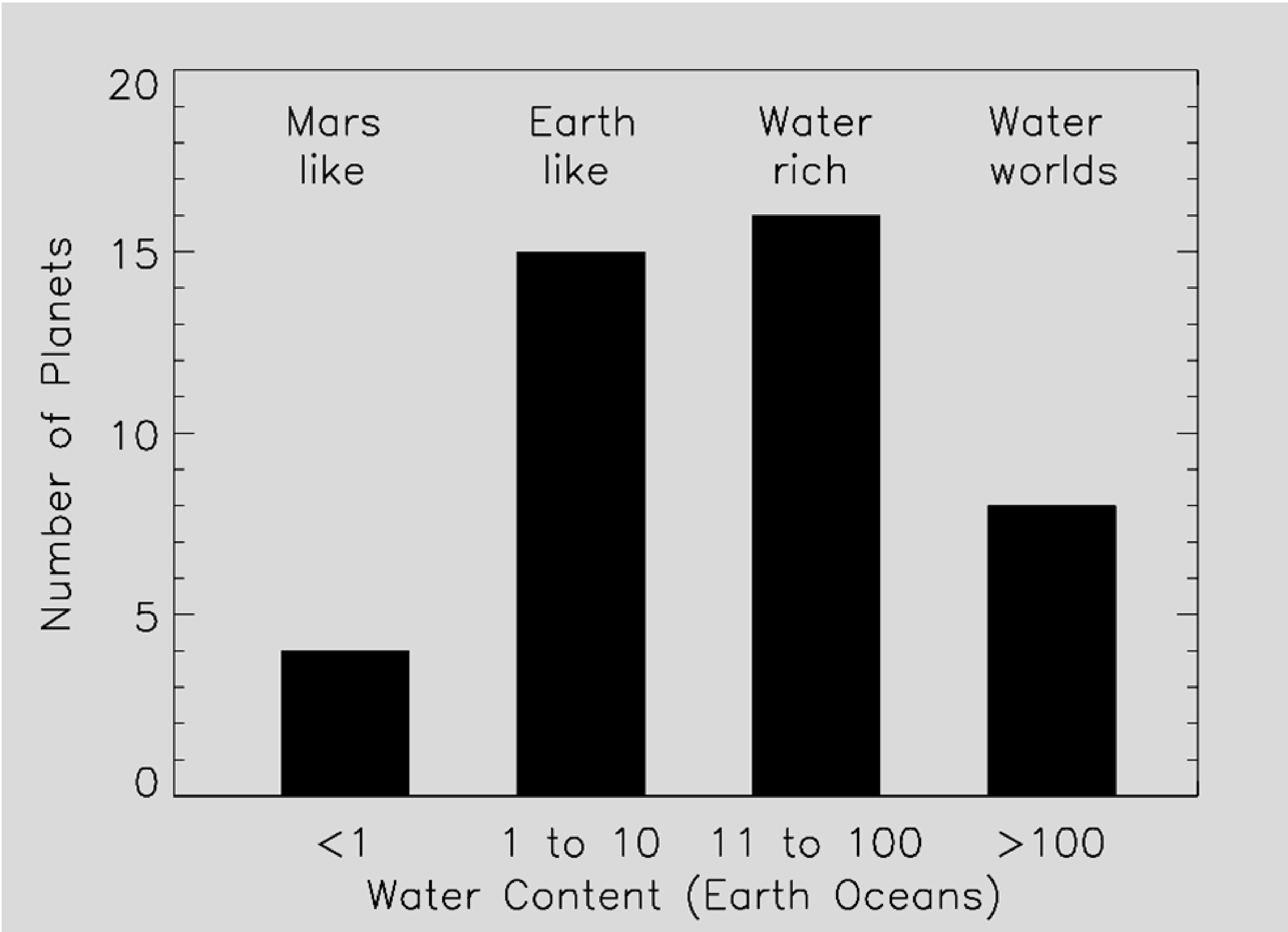


H$_2$O
CH$_4$
CO
CH$_4$
Relative Brightness
0
2
4
6
8
1
2
3
4
5
6
7
8
9
10
Wavelength (microns)
Exoplanet WASP-12b
NASA / JPL-Caltech / N. Madhusudhan (Princeton University)
Spitzer Space Telescope • IRAC
ssc2010-10a

# Earth Clones

- No planets exactly like the Earth have been discovered. But close…
- The data aren't good enough to tell if they are common or rare, but theory says they should be abundant.
- The Doppler record-holder is 1.9 x Earth mass, but by transits Kepler have already found Earth-size or smaller exoplanets.

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!

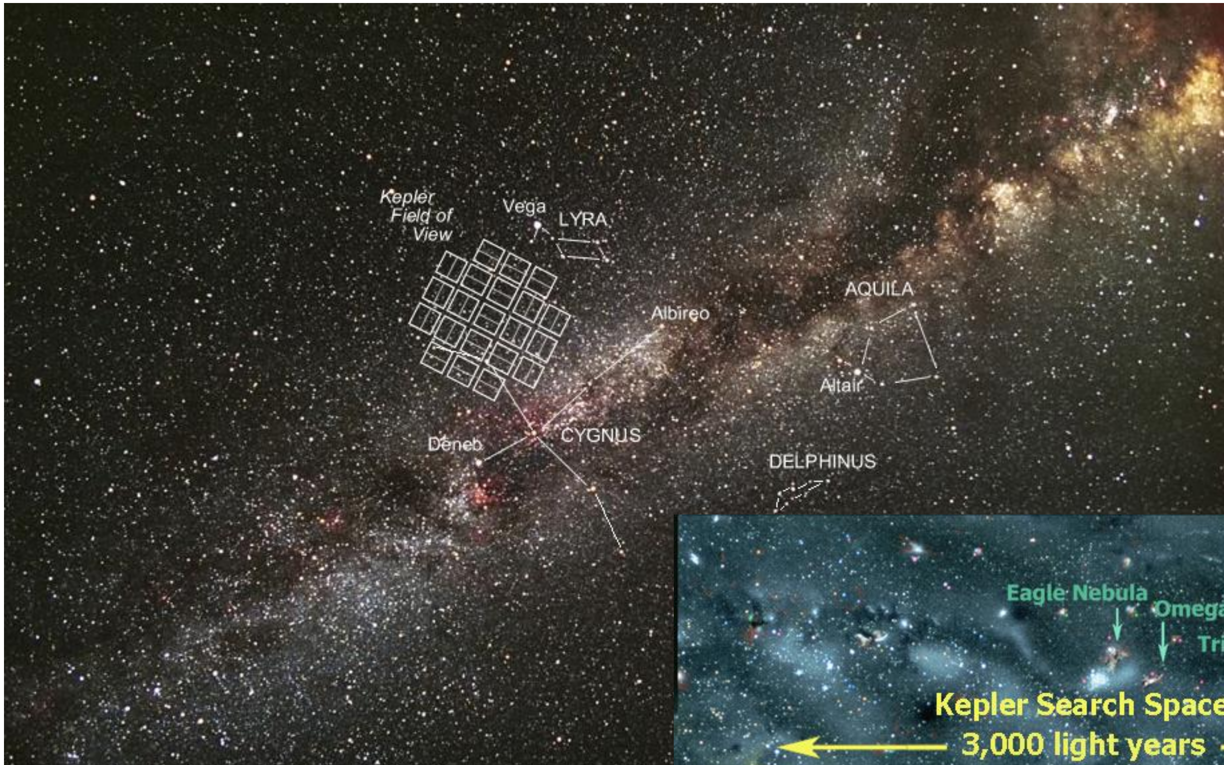
## Eclipse

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!

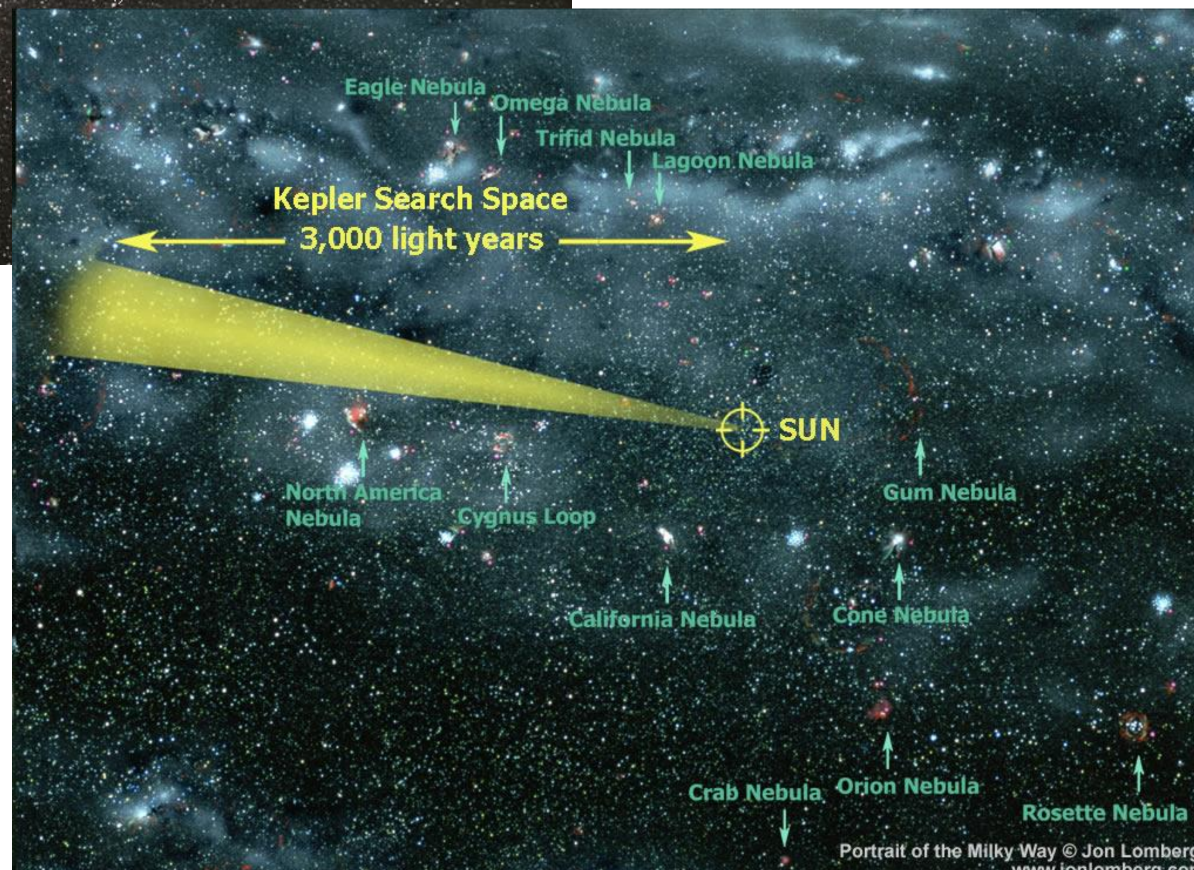
## Direct

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!

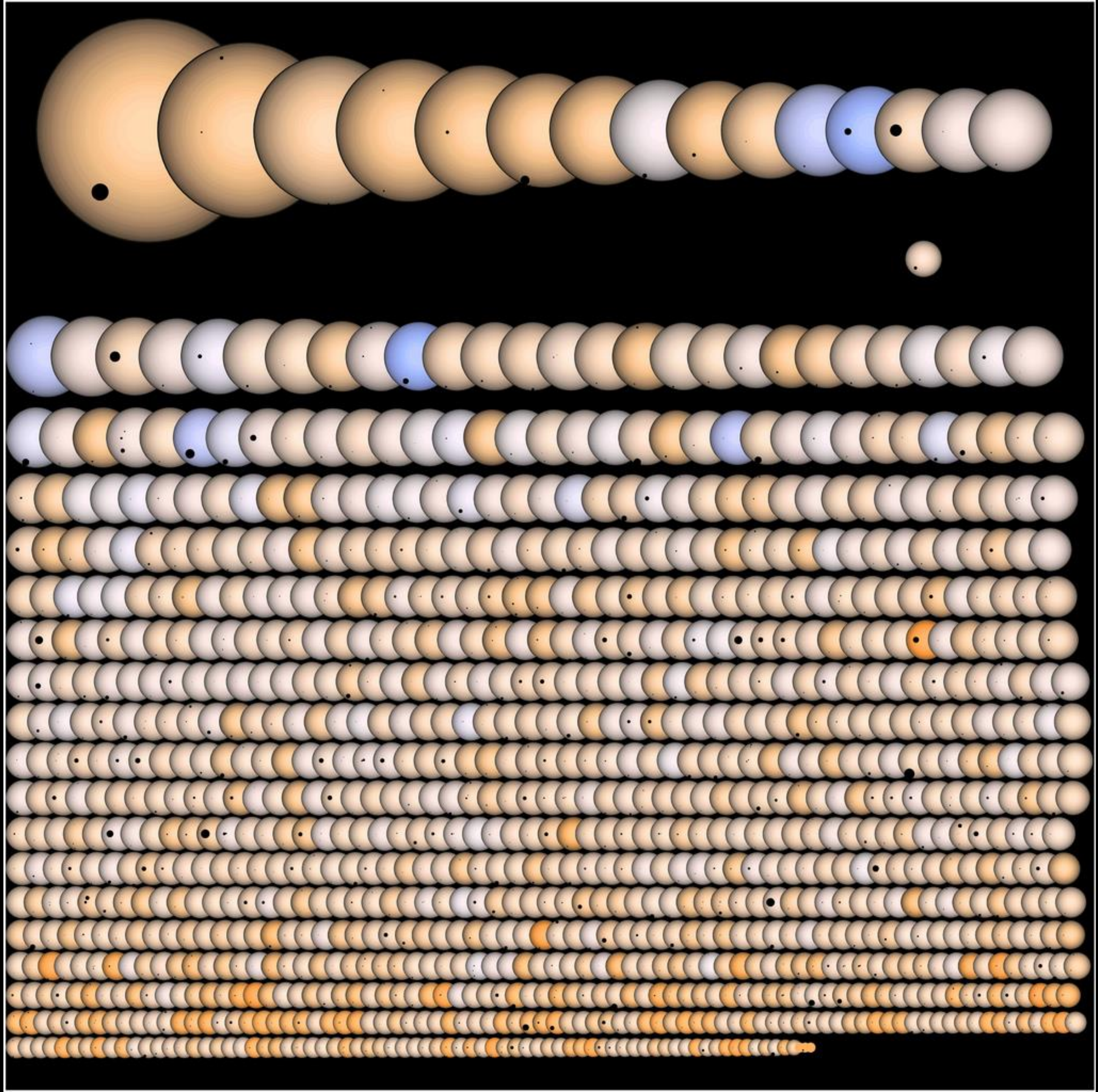
# Kepler




Kepler is a 1-meter telescope that has stared at 100 square degrees of the sky for about five years.

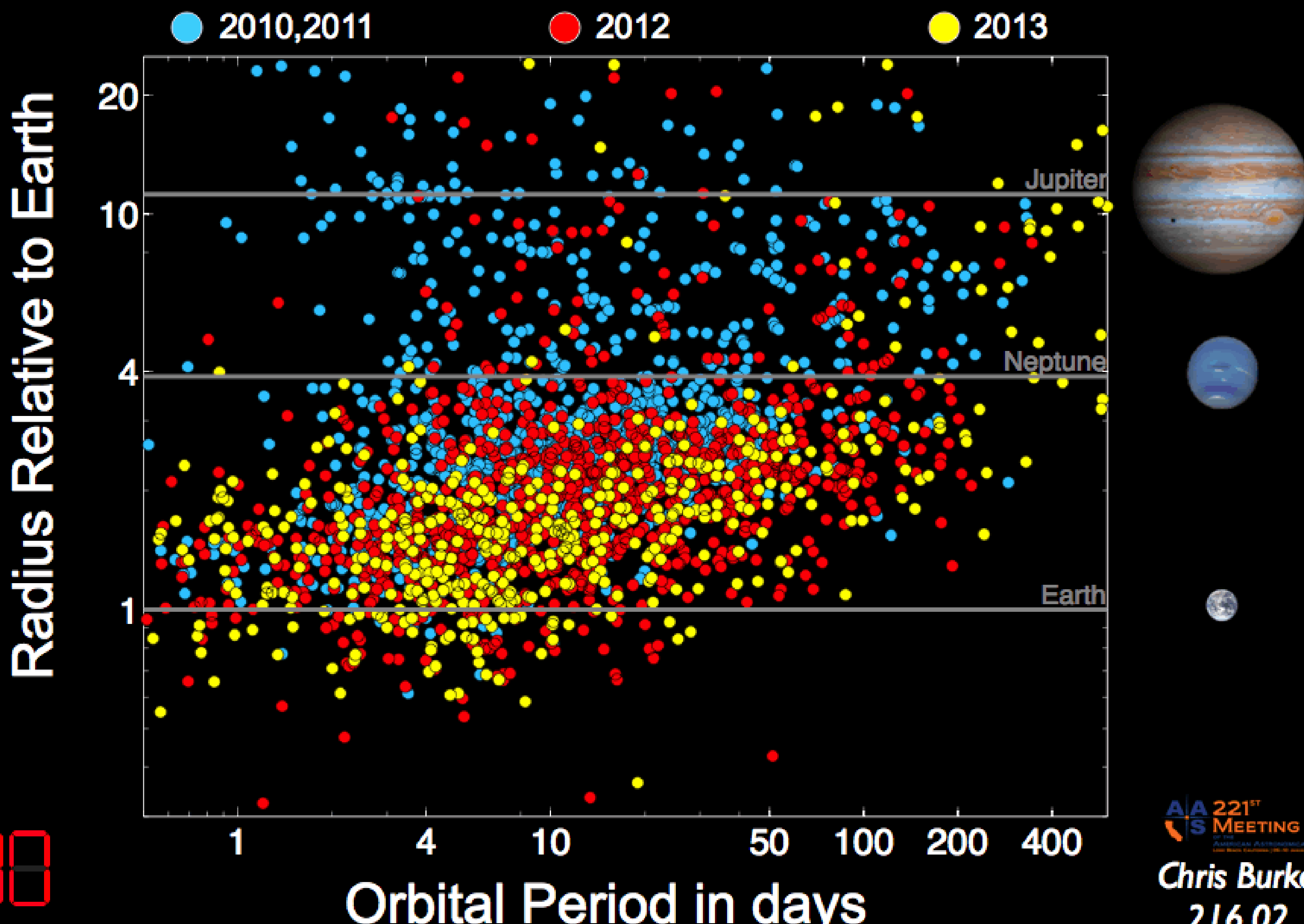



It's monitored about 150,000 stars for the signs of eclipses by a planet. It can detect 0.001% variation and could find $10^2$ Earths.



# Kepler's Planet Candidates

## 22 Months: May 2009 - Mar 2011



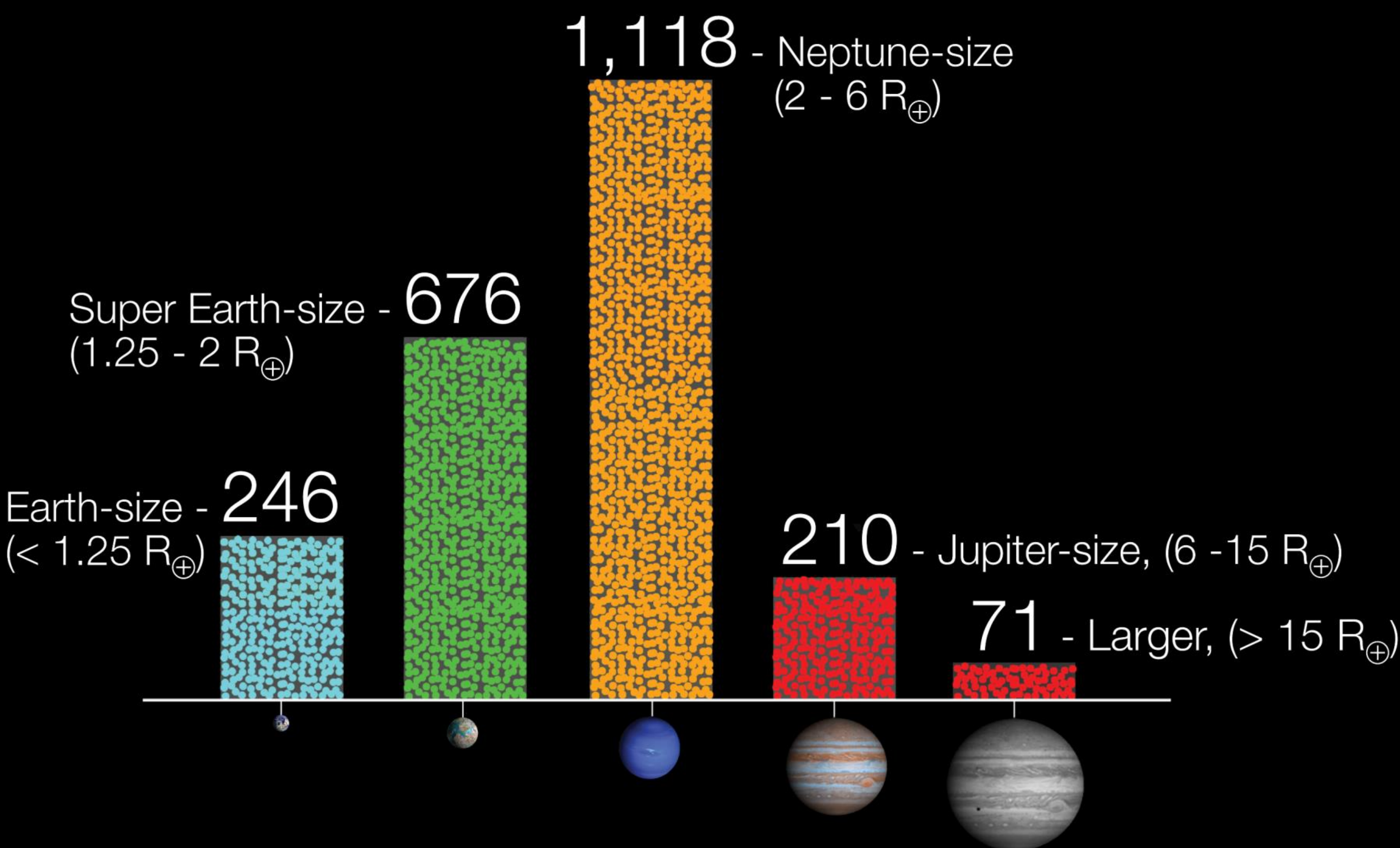

2740

221st Meeting of the American Astronomical Society

Chris Burke: 216.02

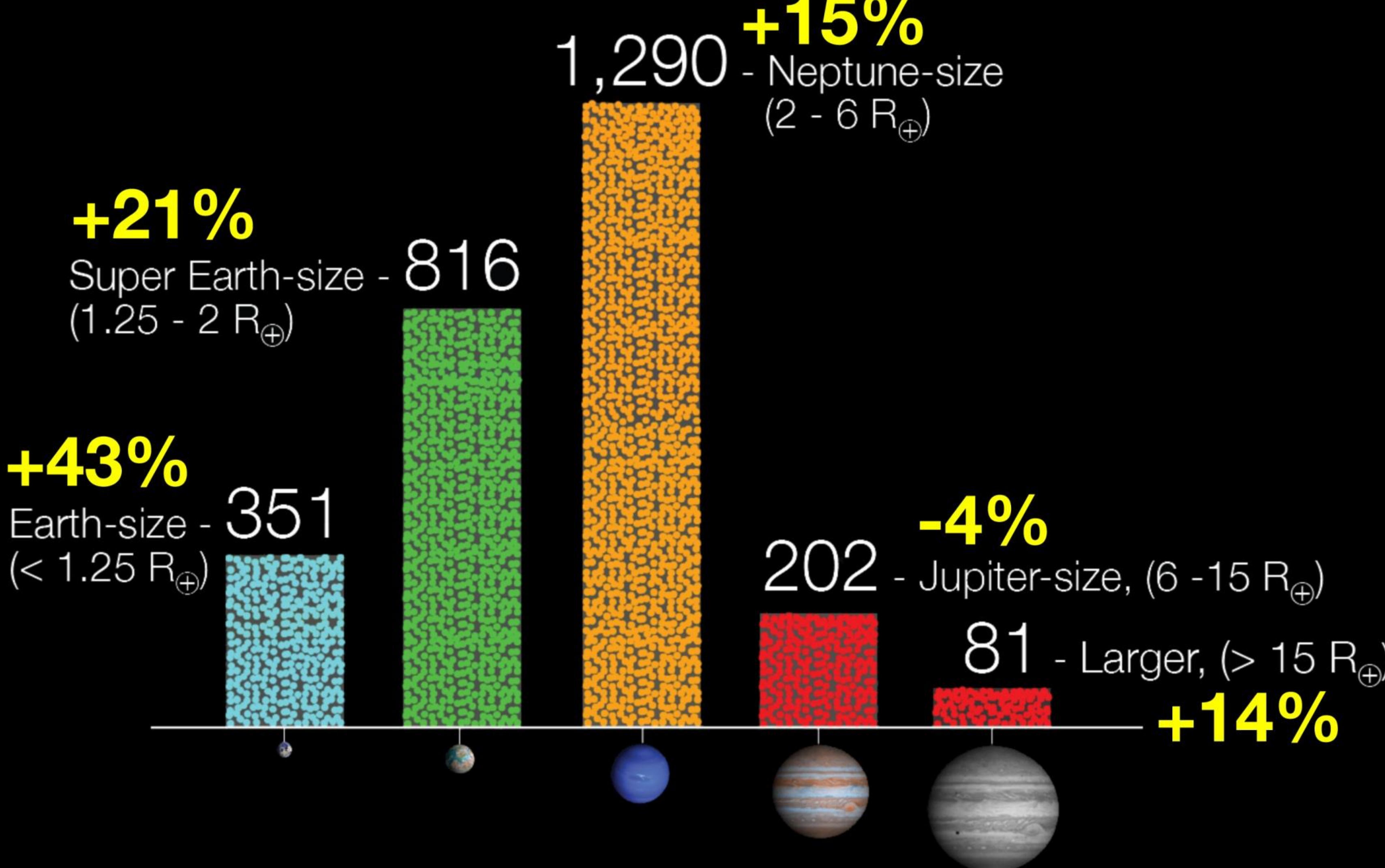
# Sizes of Planet Candidates

*As of February 27, 2012*



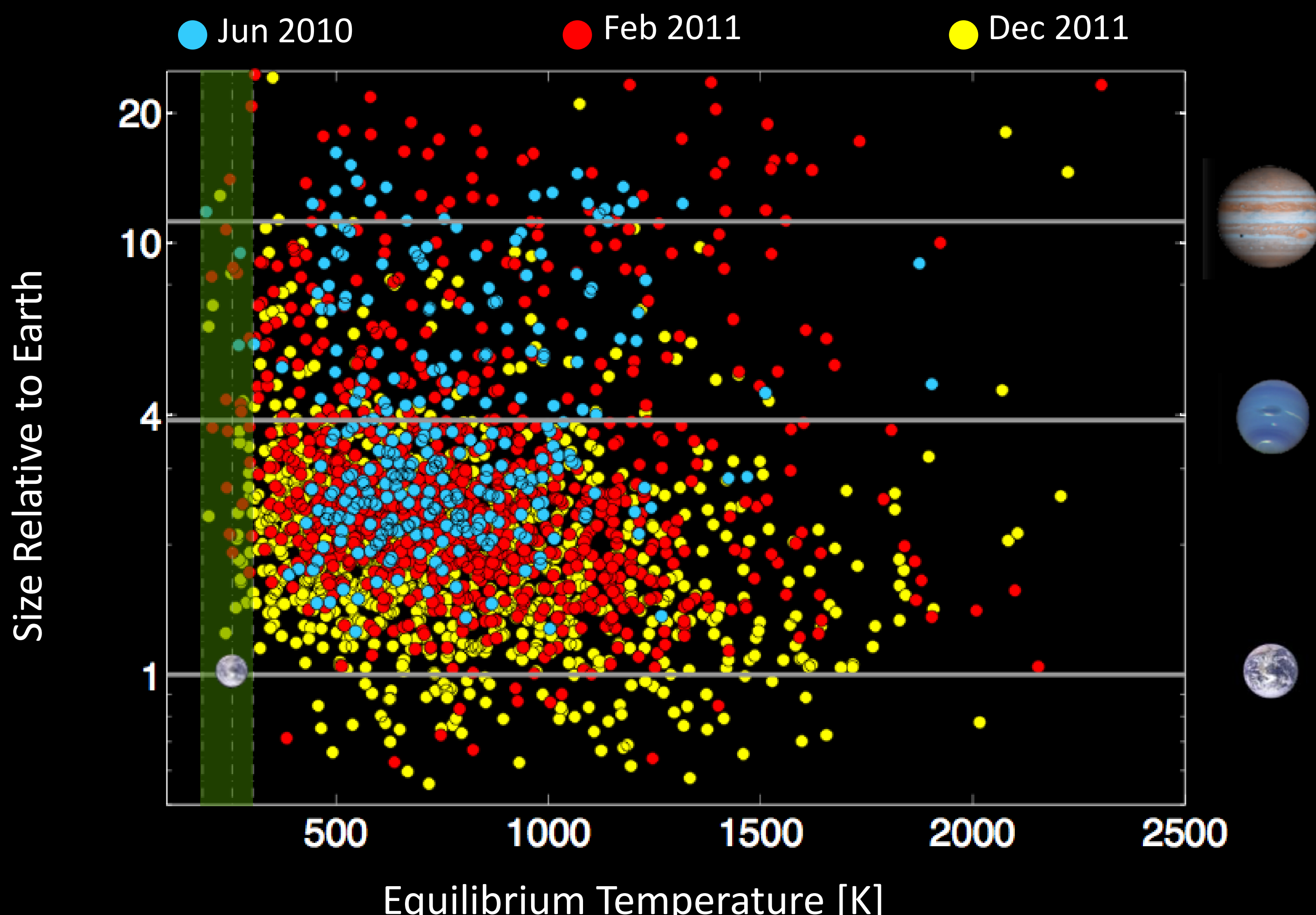
# Sizes of Planet Candidates

*As of January 7, 2013*



# Habitable Zone Candidates

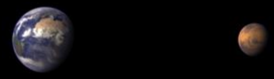
## 48 with $T_{eq}$ between 185 and 303 K



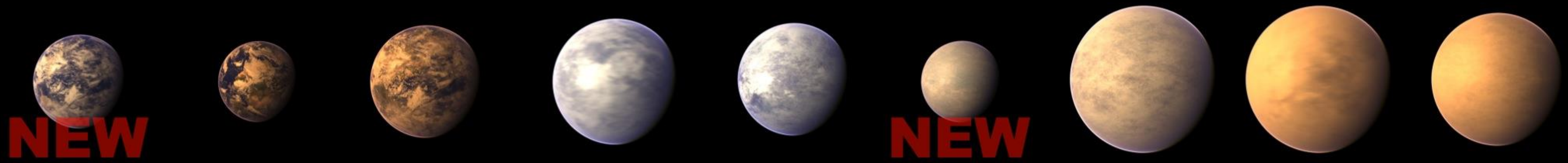
# Current Potential Habitable Exoplanets

Compared with Earth and Mars and Ranked in Order of Similarity to Earth

| ESI | 1.00 | 0.64 |
|---|---|---|
| | Earth | Mars |



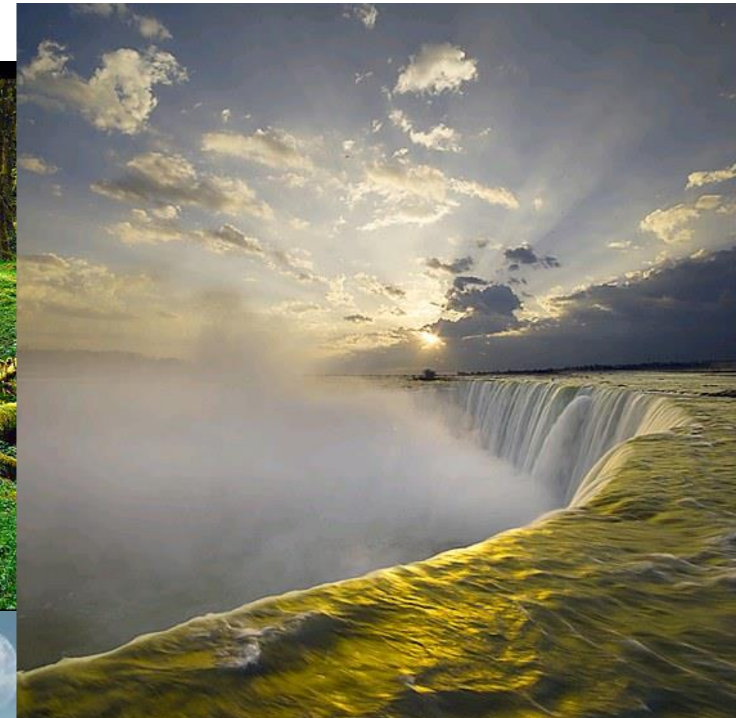
| | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8 | #9 |
|---|---|---|---|---|---|---|---|---|---|
| Earth Similarity Index (ESI) | 0.82 | 0.82 | 0.79 | 0.75 | 0.74 | 0.69 | 0.68 | 0.67 | 0.50 |
| | Kepler-62 e | Gliese 581 g* | Gliese 667C c | Kepler-22 b | Tau Ceti e* | Kepler-62 f | Gliese 163 c | HD 40307 g* | Gliese 581 d |
| Discovery Date | Apr 2013 | Sep 2010 | Nov 2011 | Dec 2011 | Dec 2012 | Apr 2013 | Sep 2012 | Nov 2012 | Apr 2007 |

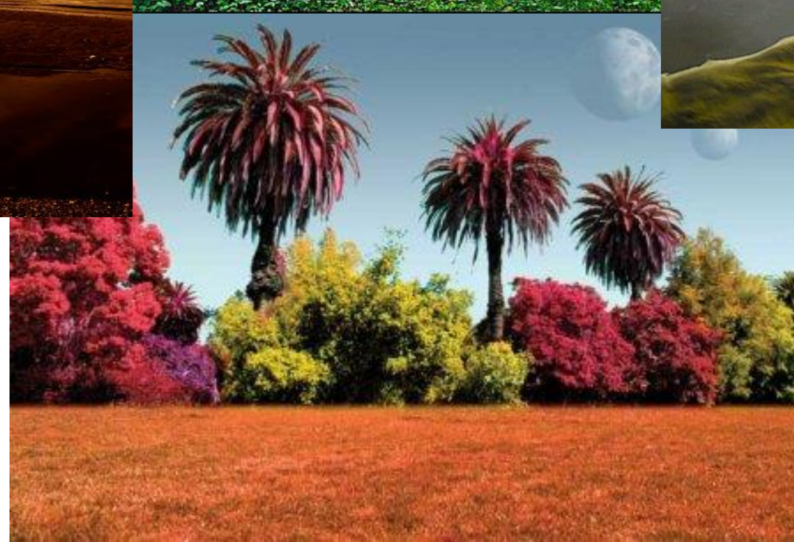



*planet candidates

CREDIT: PHL @ UPR Arecibo (phl.upr.edu) April 18, 2013

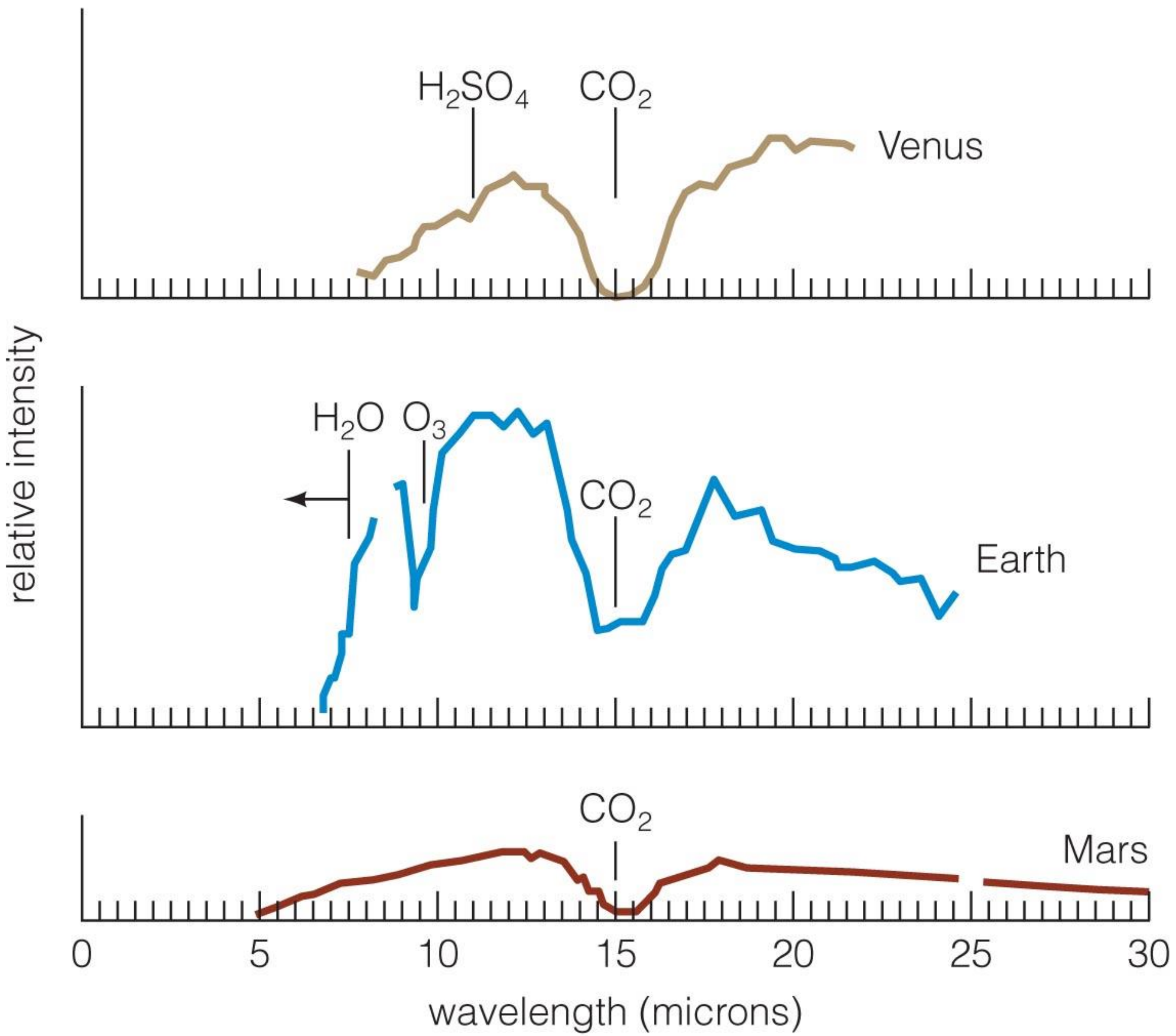
# Earth 2.0





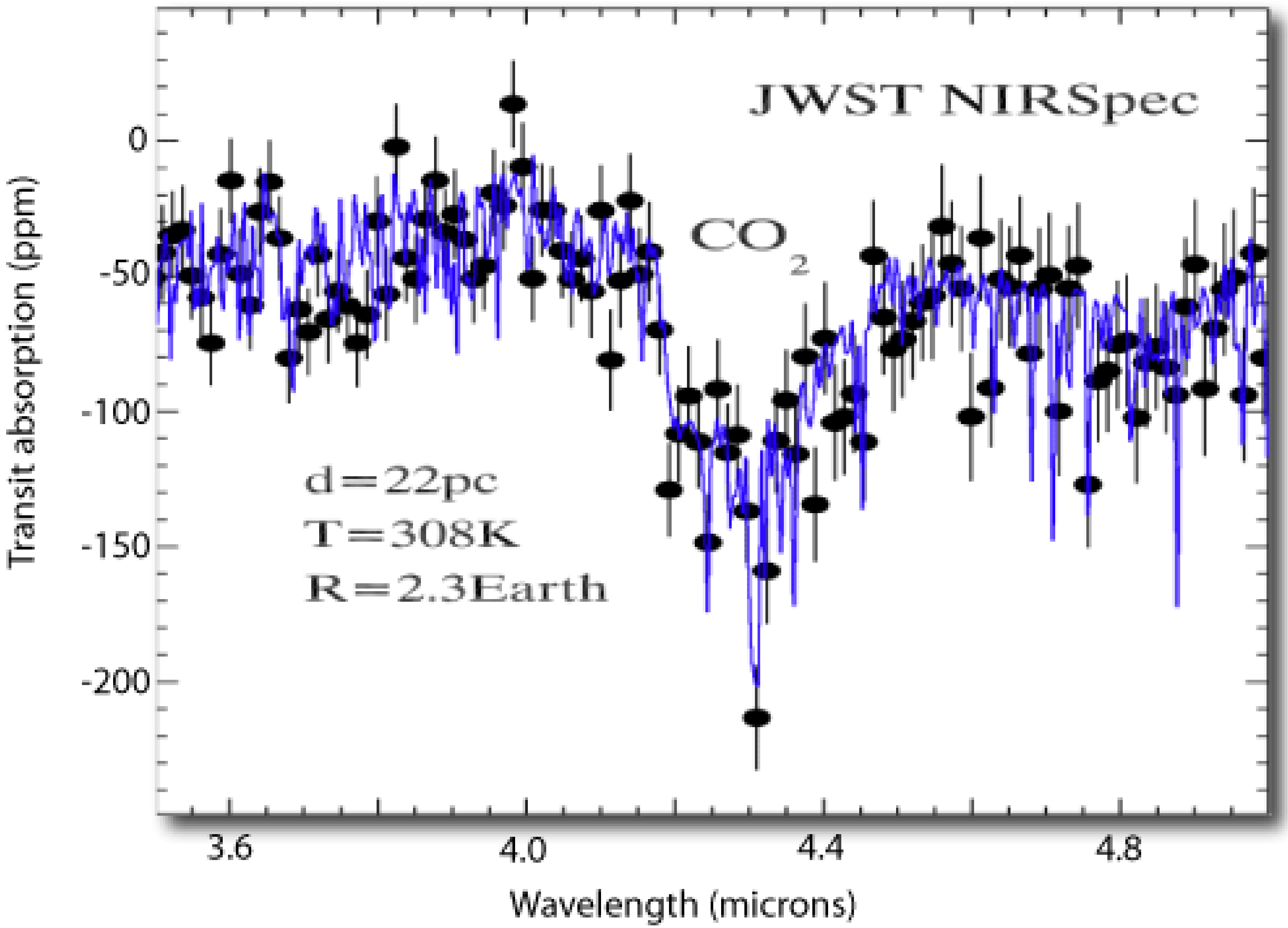
# Earth 1.0

# Biomarkers

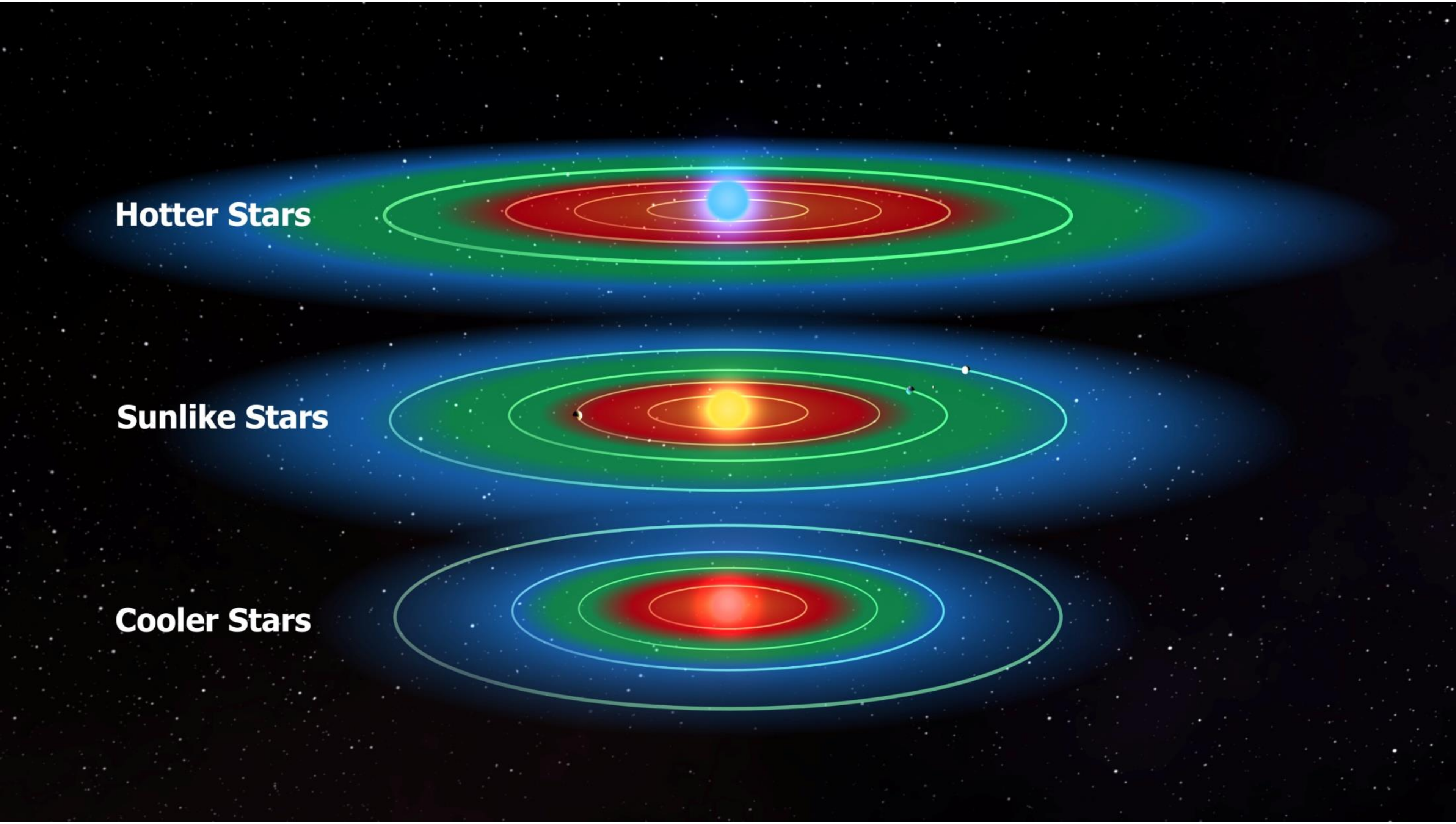


$H_2SO_4$
$CO_2$
Venus
$H_2O$
$O_3$
$CO_2$
Earth
$CO_2$
Mars
relative intensity
0
5
10
15
20
25
30
wavelength (microns)

The light grasp of ground-based telescopes will be used to look for biomarkers. Space observatories like JWST will play a big role. Kepler is disabled and its planets are faint so difficult to follow up.

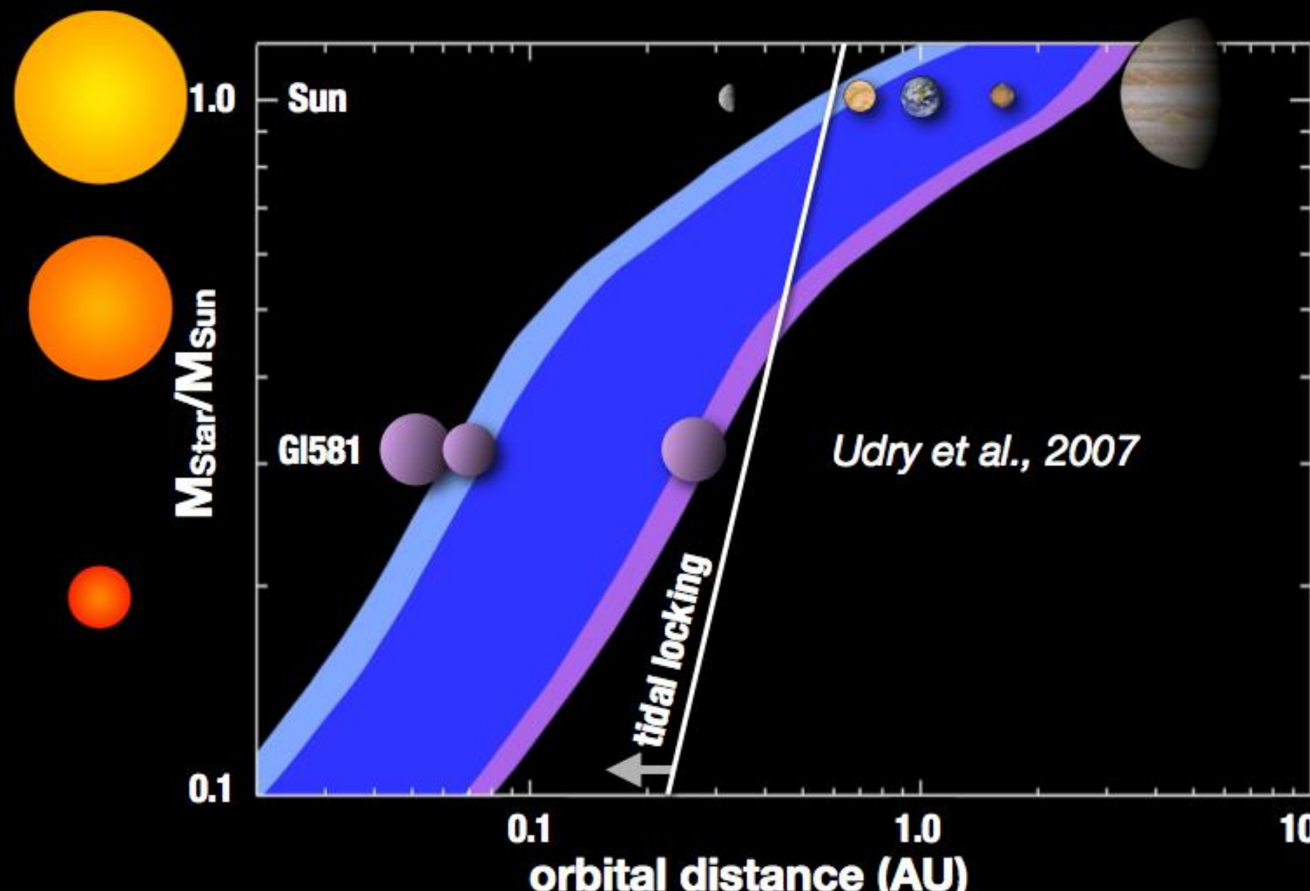


# Habitability

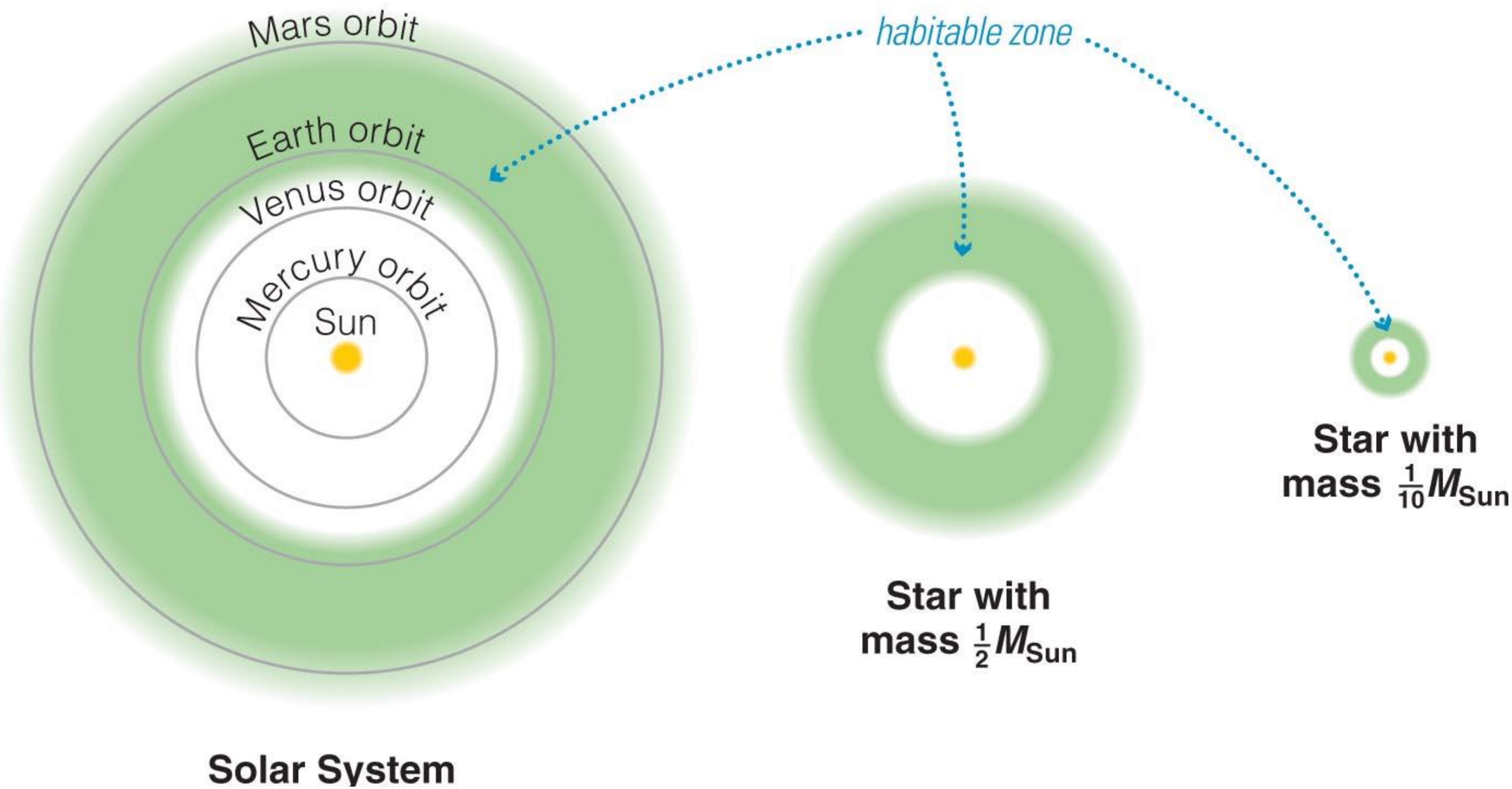


# Habitable Zone

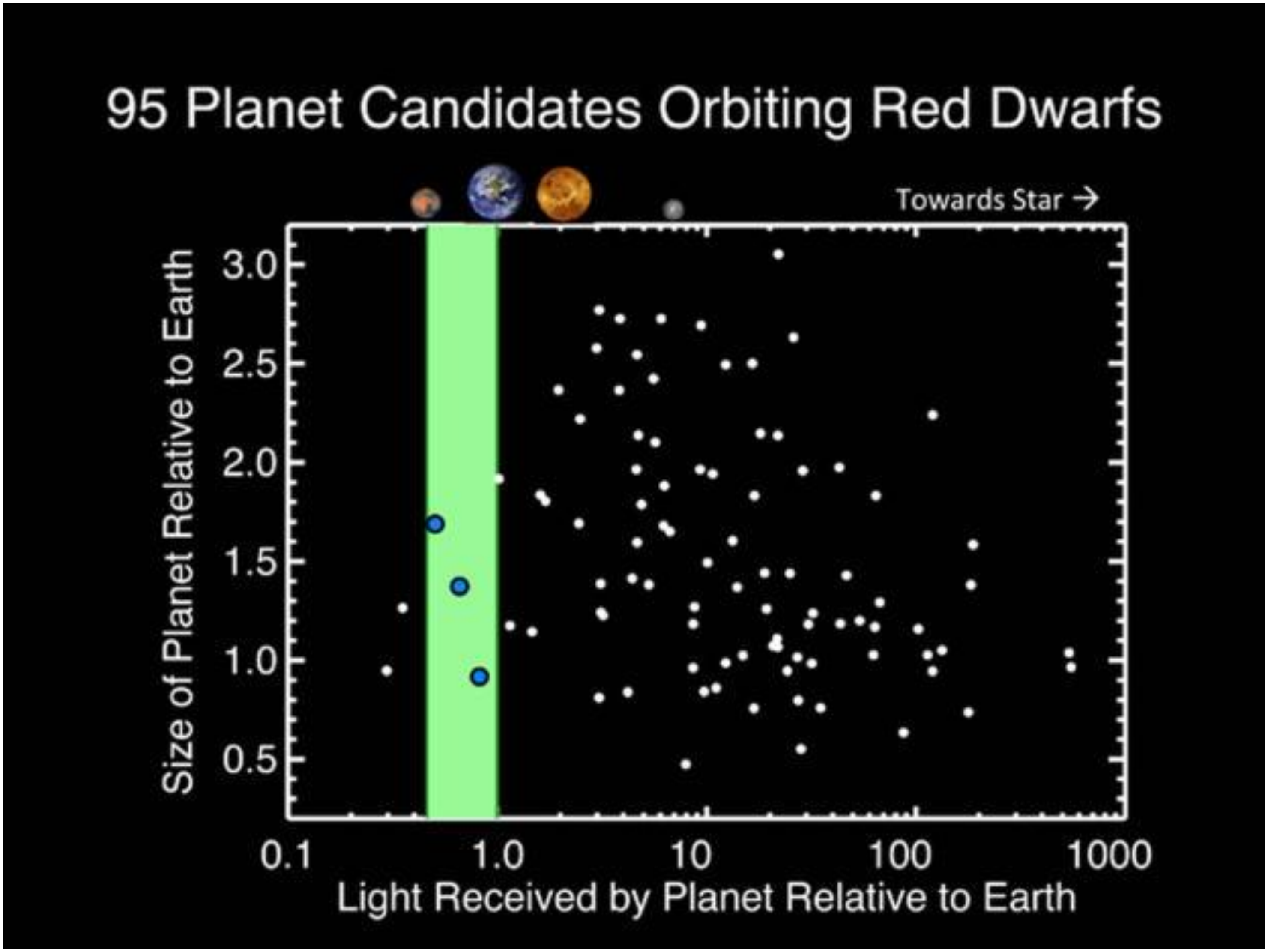
The traditional definition of a habitable zone is the range of distances from a star where water could be liquid on the surface of a planet or moon. But based on terrestrial extremophiles, this is very restrictive.



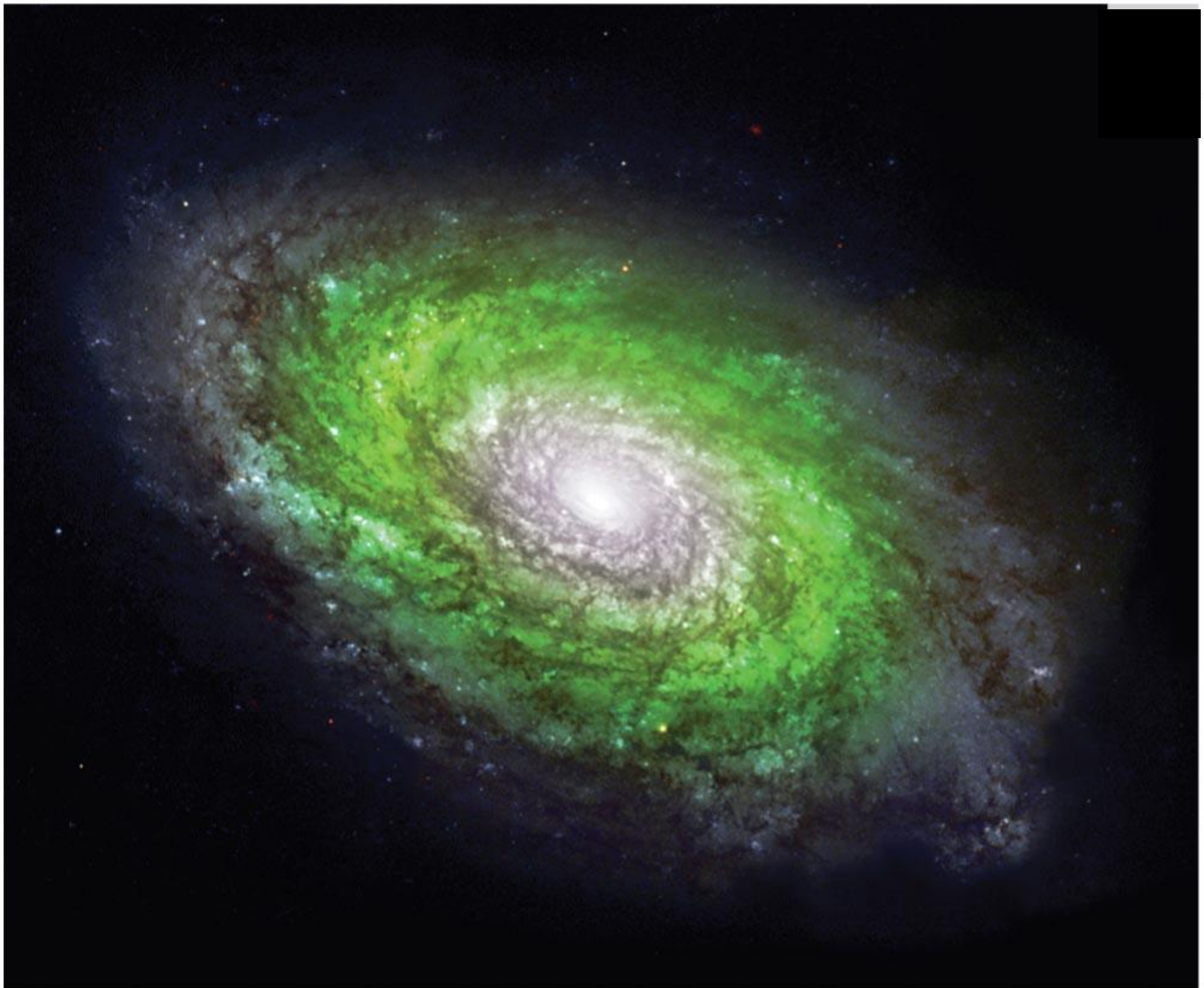
Dwarf star habitable zones are small, but the much larger number of dwarfs means they dominate the total habitable "real estate."



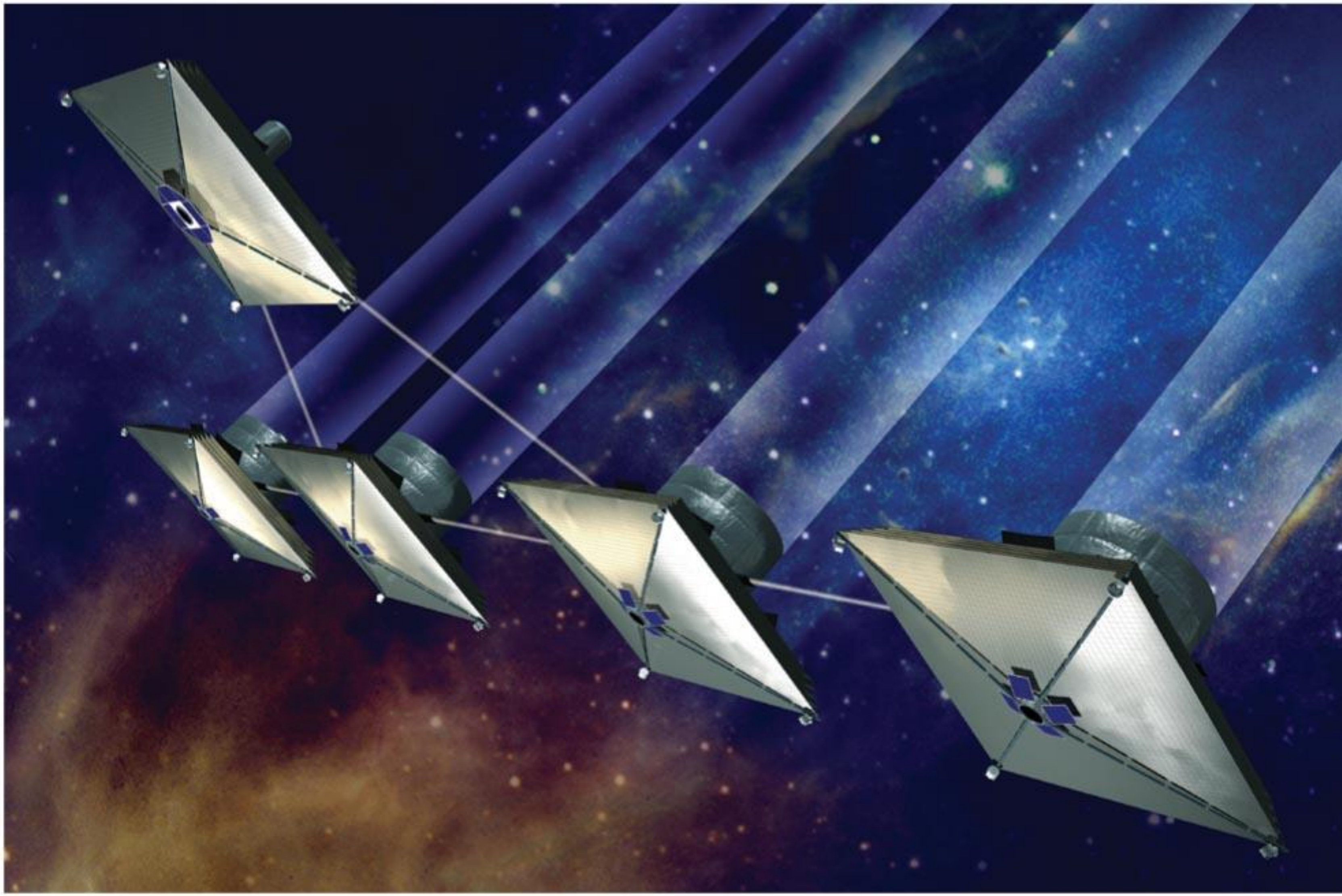
The red dwarf “opportunity” is important because the stars are dim and small so eclipses are deeper;  better characterization.



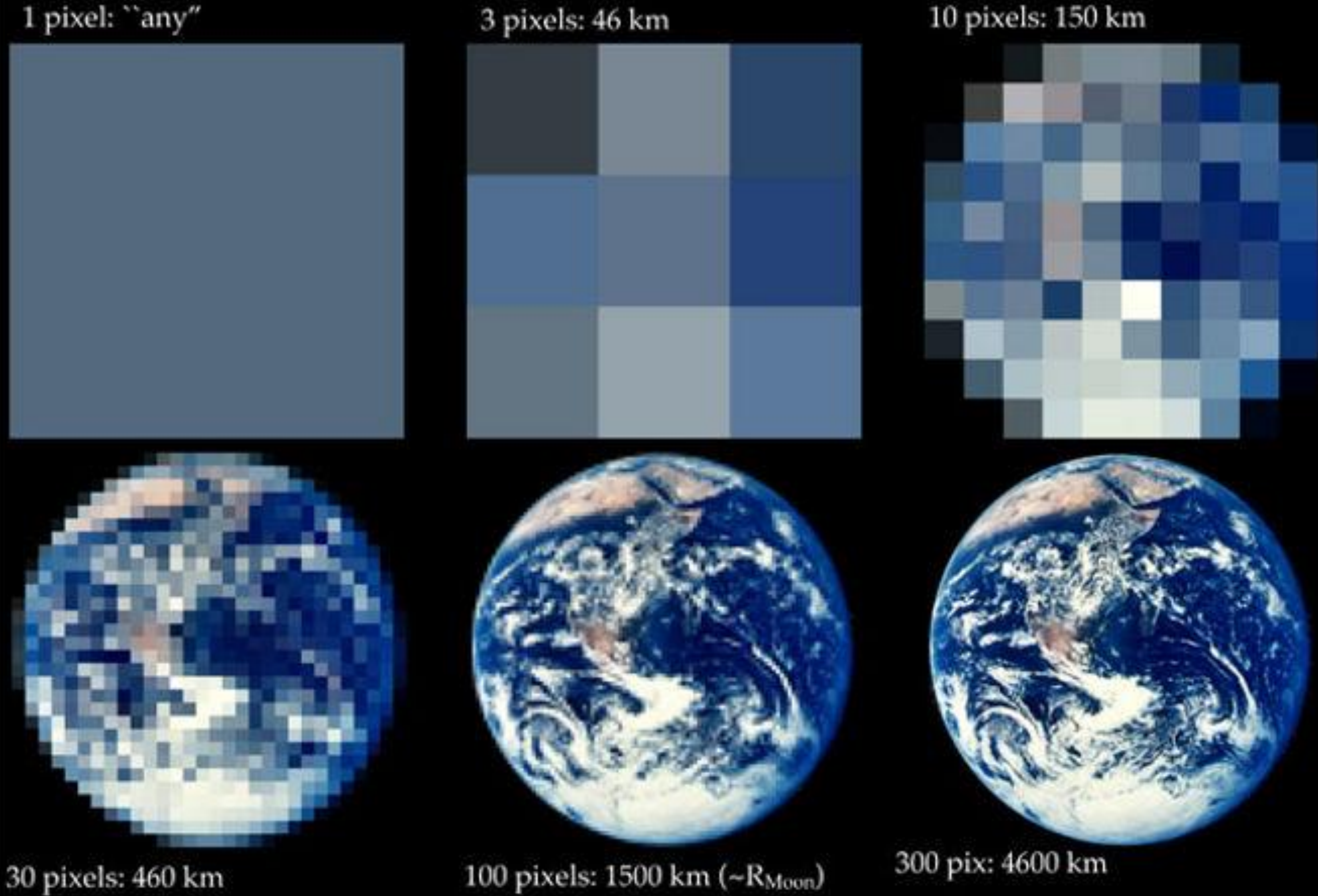
The Galactic habitable zone: near the center too many encounters and supernovae, far from the center not enough heavy elements.



Harvesting and characterizing Earth clones will be expensive and difficult; Kepler is unable to point and TPF is currently unfunded.



# Telescope Diameter needed to achieve different resolutions for Earth at 10 pc



# The Bottom Line

**Over 3000 exoplanets are known, most are Jupiter to Neptune mass but detection has reached Earths**

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

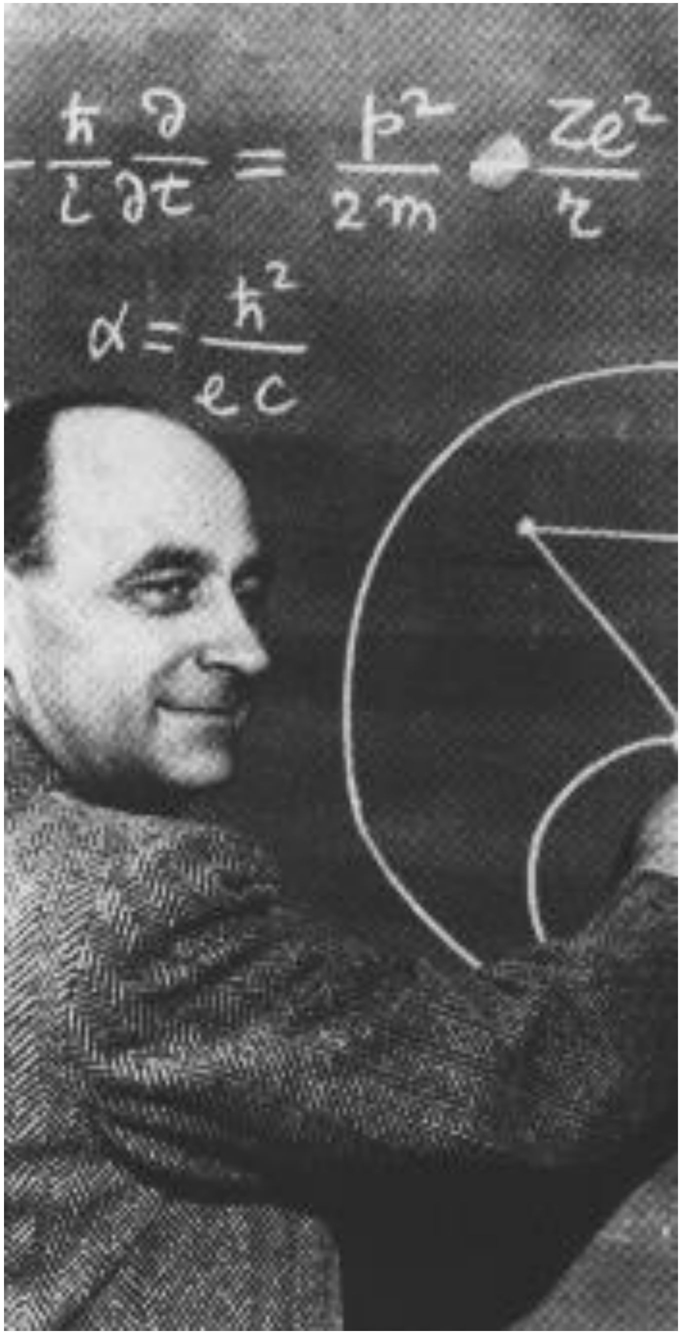
**Models indicate that many terrestrial planets should be “water worlds” with all of life’s ingredients**

**More than 100 million terrestrial planets in the Milky Way, and several billion habitable “worlds”**

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

**A billion habitable worlds in the Milky Way galaxy, and 100 billion galaxies in the observable universe**

**Conservatively there are about a billion billion ($10^{18}$) terrestrial planets in traditionally-defined, habitable zones in the universe**



# The Fermi Question

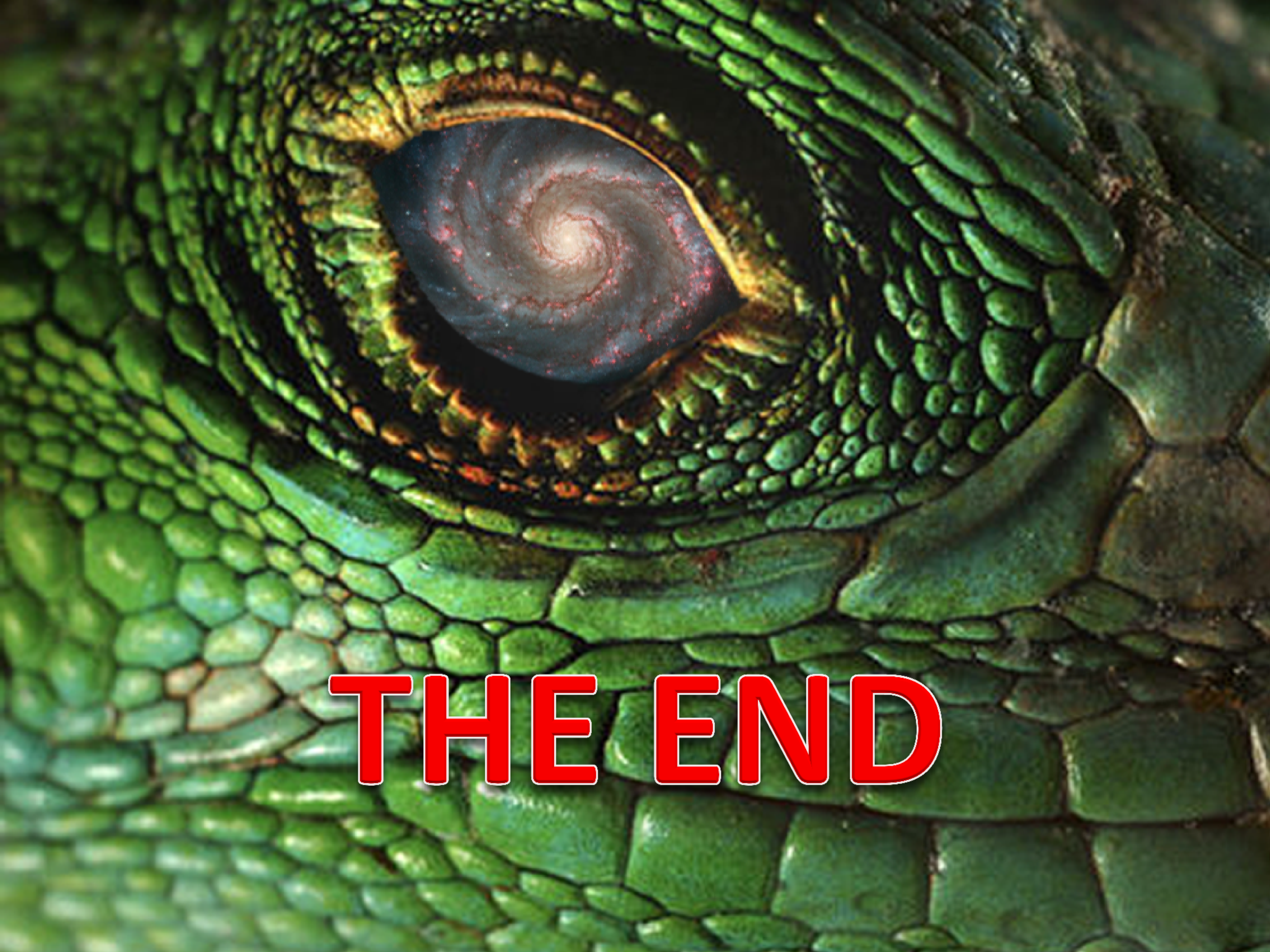
As originally phrased by Erico Fermi, it seems a reasonable proposition that:

• Our civilization & technology is **very young**, so the life forms with much more advanced technology could have remarkable capabilities.

• A very **modest extrapolation** of our current technology allows us mine asteroids or moons, and create probes that could create replicas of themselves and propagate through the galaxy.

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

**"Where Are They?"**


THE END