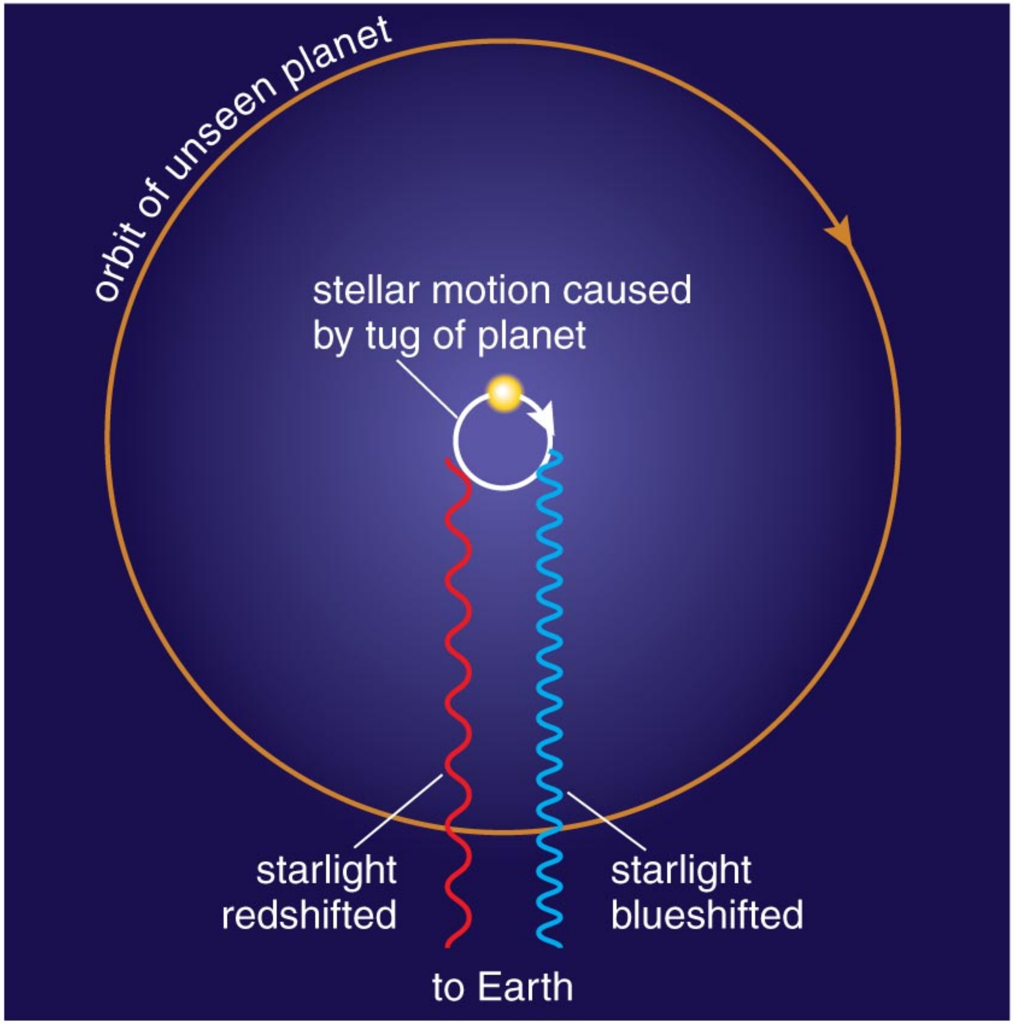
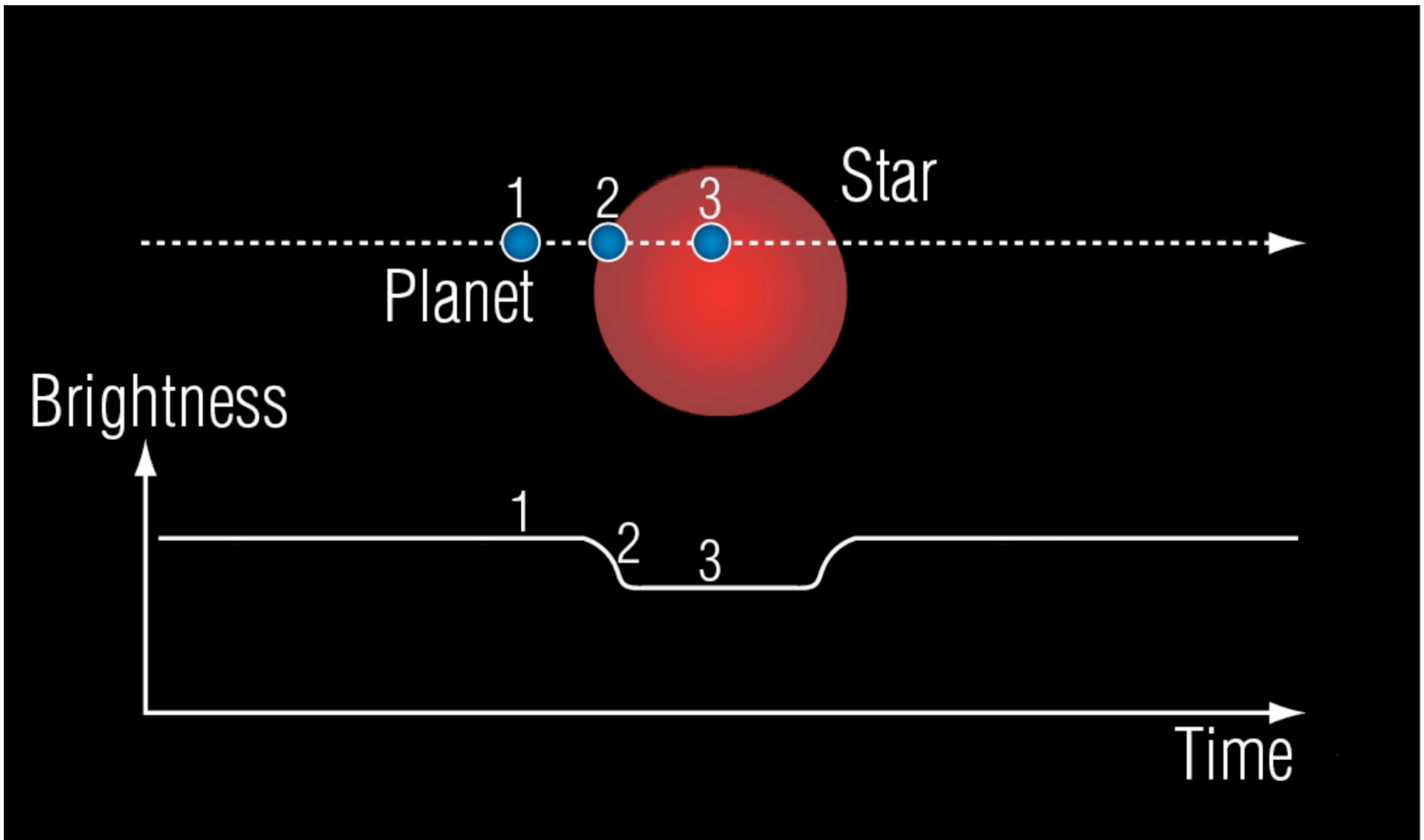
Last Time: Planet Finding

- **Radial velocity method**
- Parent star's Doppler shift
- Planet minimum mass, orbital period, semi-major axis, orbital eccentricity
- Until *Kepler Mission*, was the method with the most planets



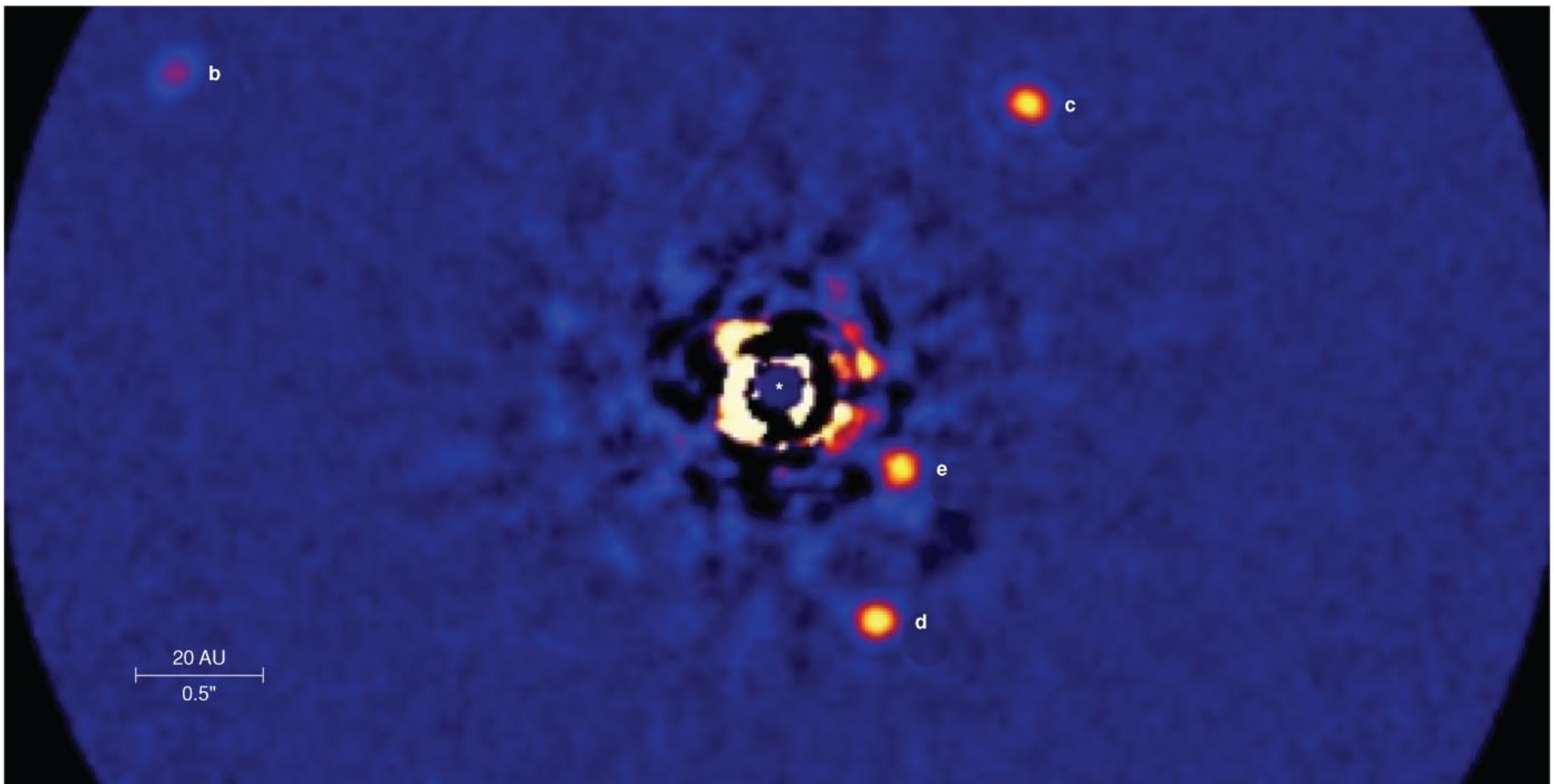
Last Time: Planet Finding

- **Transits** – eclipse of the parent star:
  - Planetary radius, orbital period, semi-major axis
  - Now the **most common way to find planets**



Last Time: Planet Finding

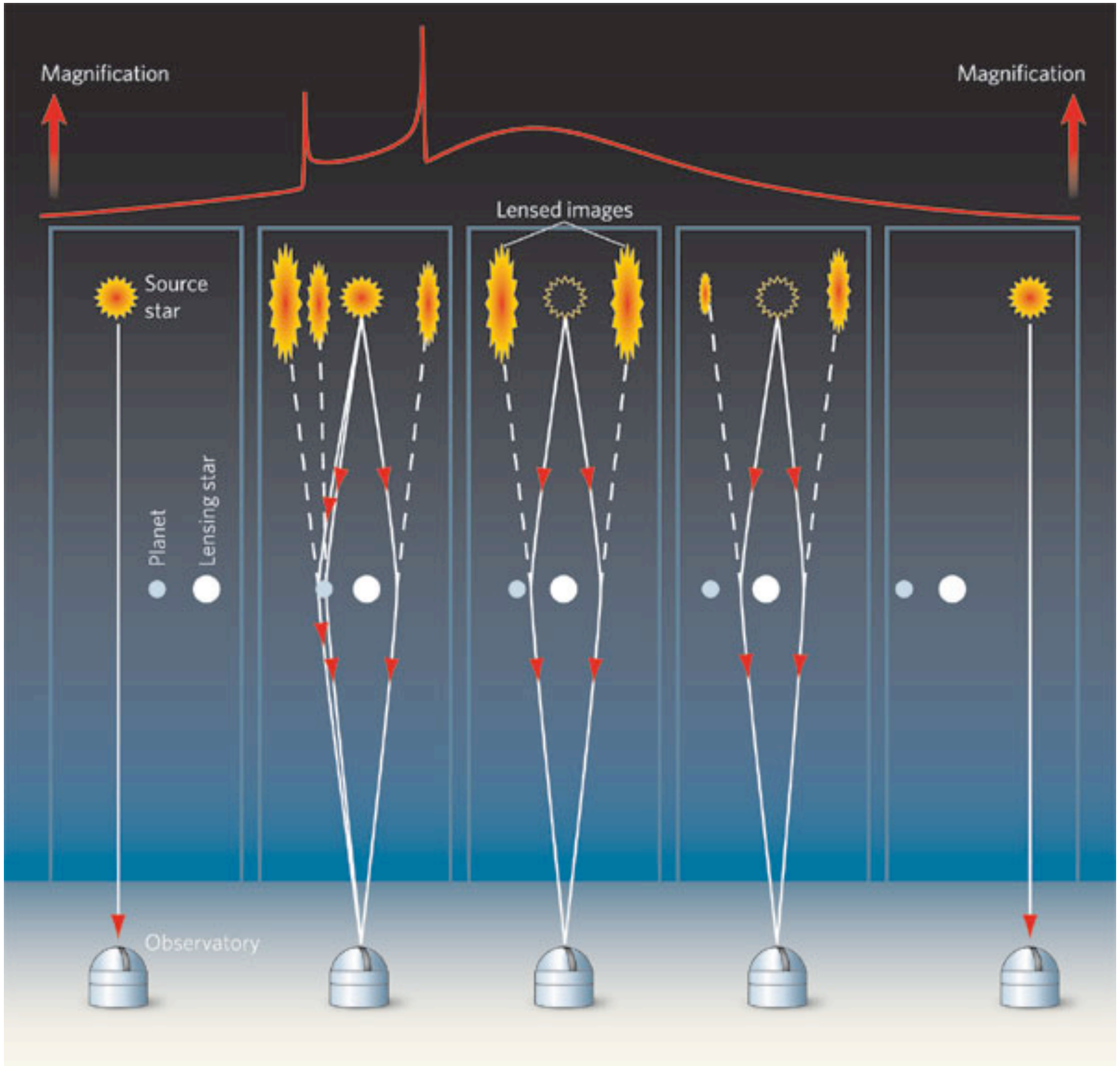
- **Direct Imaging**
  - Planetary brightness, distance from parent star at that moment
  - About 10 planets detected



Last Time: Planet Finding

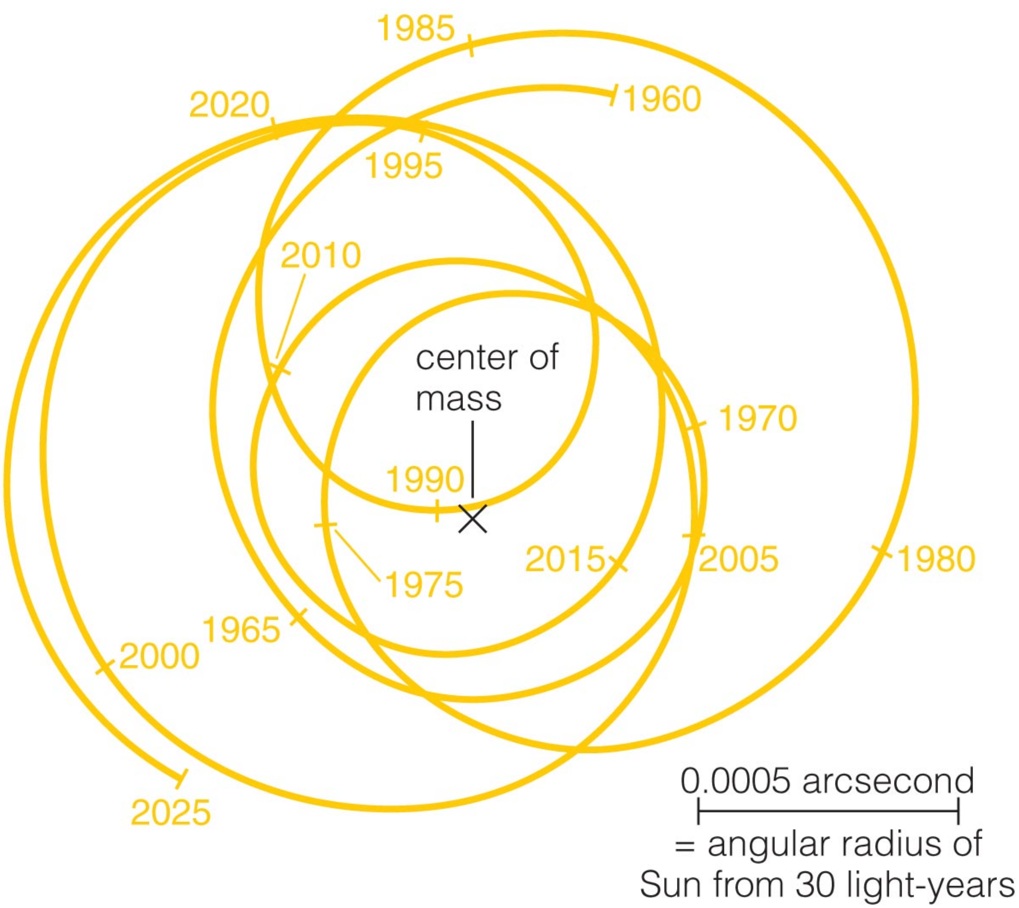
- **Lensing**
- Planetary mass and, distance from parent star at that moment

- You want to look towards the center of the galaxy where there is a high density of stars

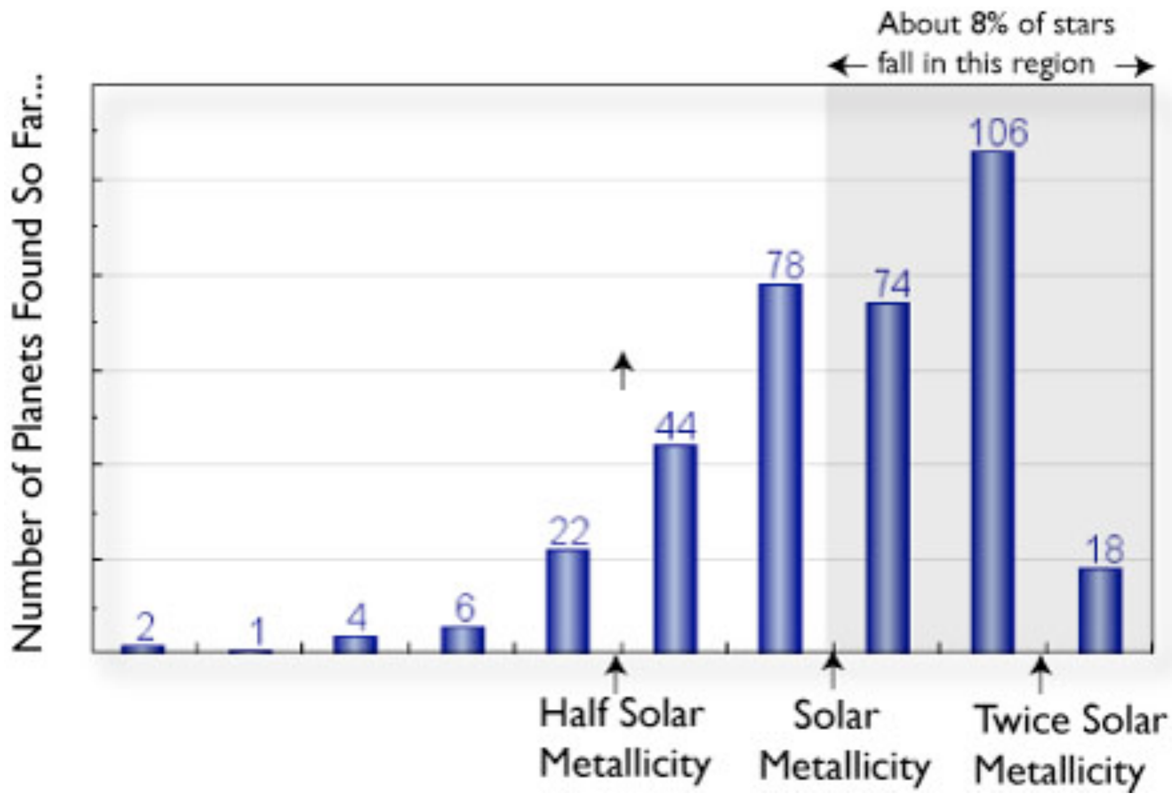


Last Time: Planet Finding

- **Astrometry**
- Tiny changes in star's position are not yet measurable
- Would give you planet's mass, orbit, and eccentricity



One more important thing to add:

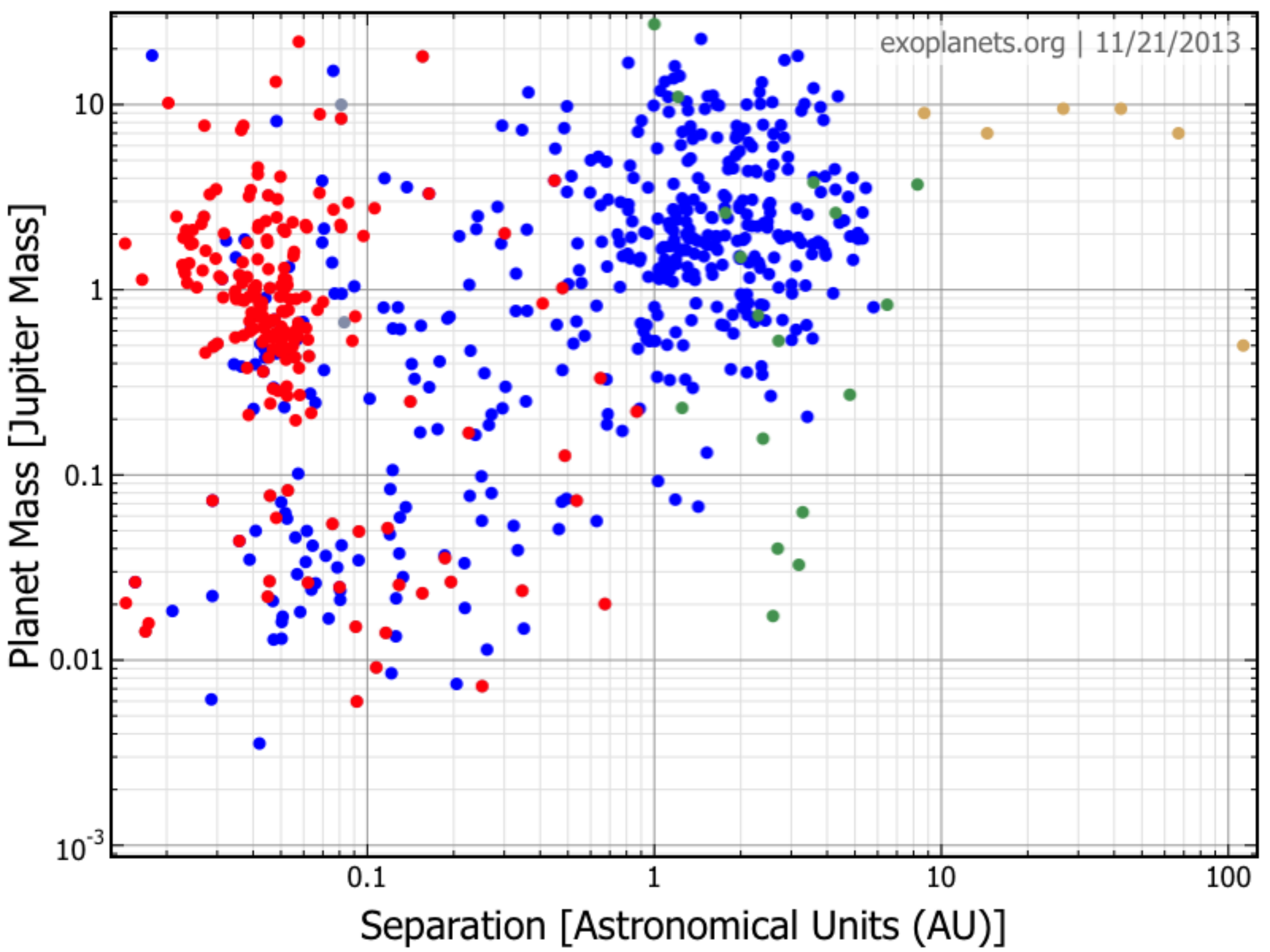


- Giant planets (which are easiest to detect) are preferentially found around stars that are abundant in iron – “metallicity”
    - Iron is the easiest heavy element to measure in a star
    - Heavy-element rich planetary systems make planets more easily

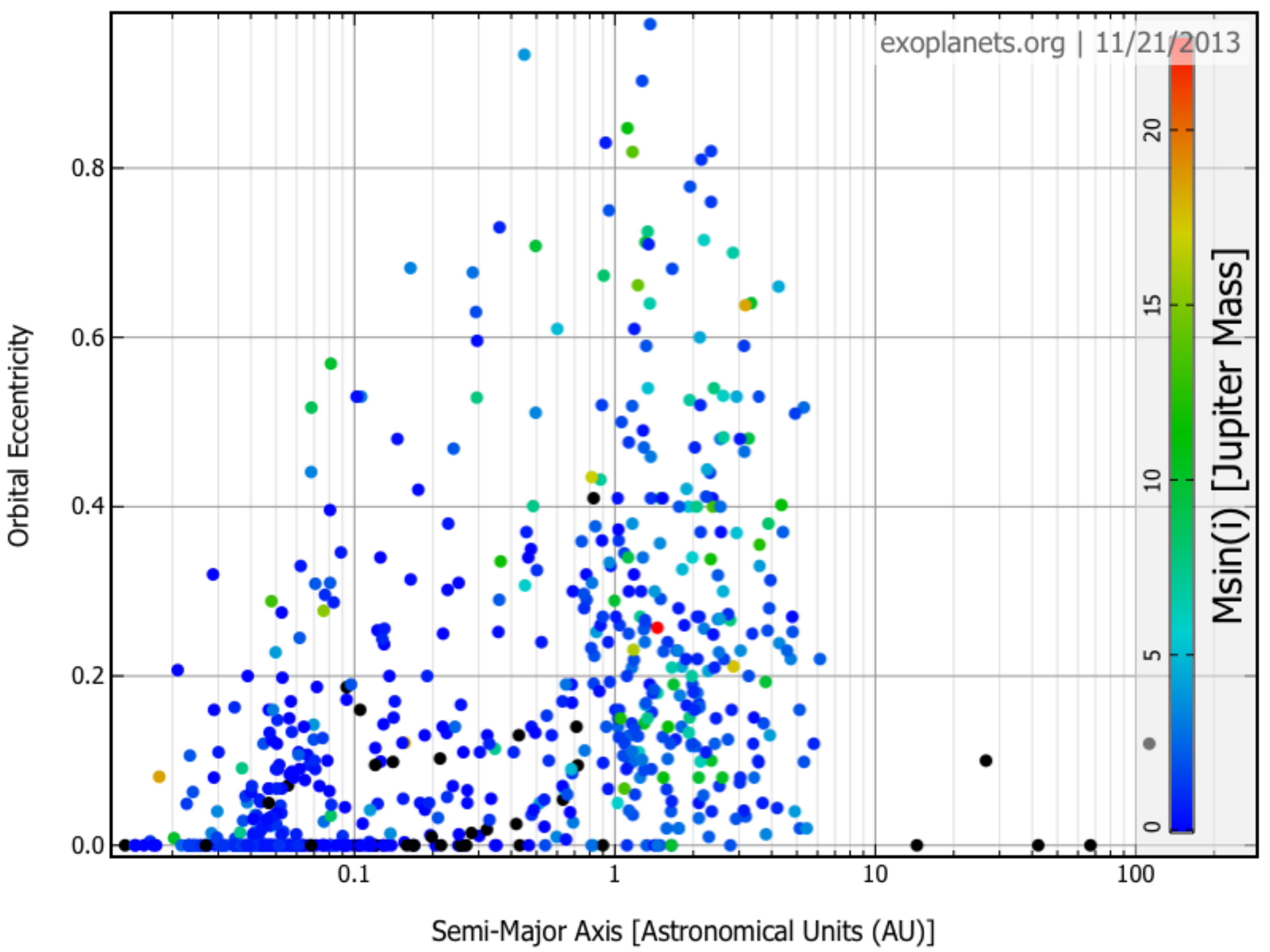
13.2 The Nature of Extrasolar Planets

Our goals for learning:

- What have we learned about extrasolar planets?
- How do extrasolar planets compare with planets in our solar system?



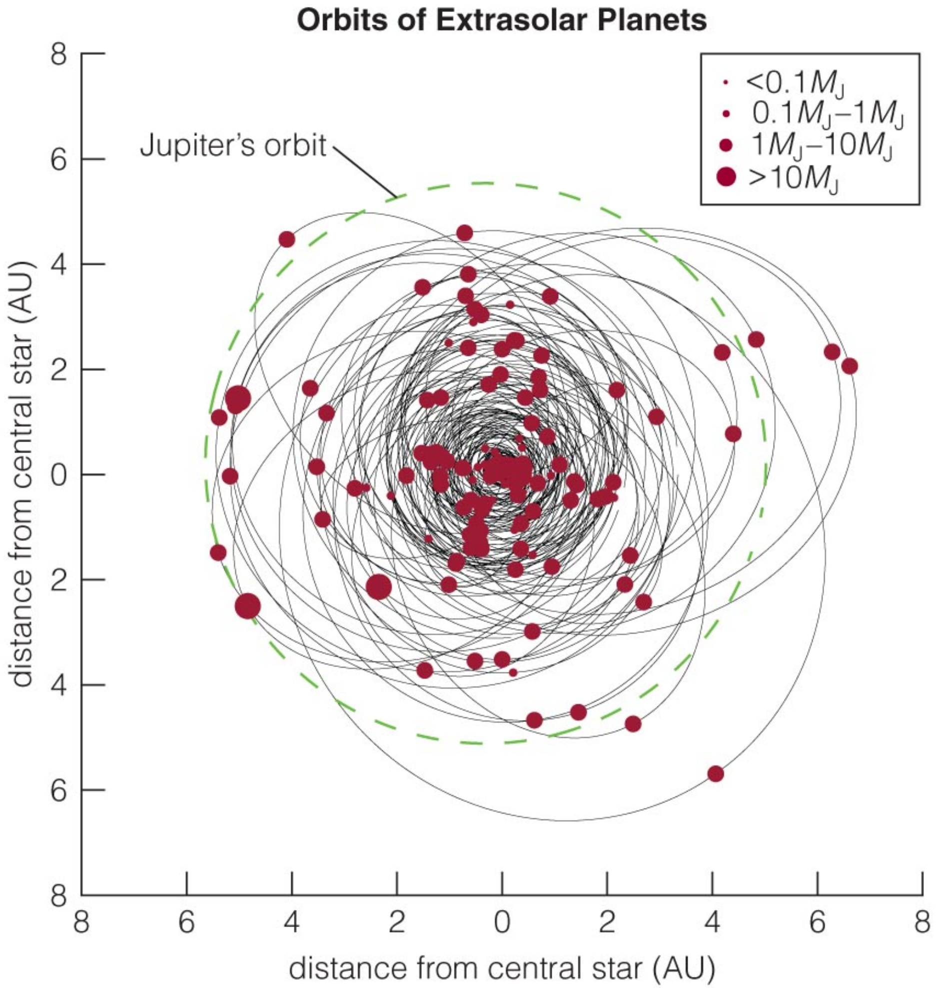
exoplanets.org | 11/21/2013
Planet Mass [Jupiter Mass]
10
1
0.1
0.01
10^{-3}
0.1
1
10
100
Separation [Astronomical Units (AU)]


exoplanets.org | 11/21/2013
Orbital Eccentricity
0.0
0.2
0.4
0.6
0.8
0.1
1
10
100
Semi-Major Axis [Astronomical Units (AU)]
Msin(i) [Jupiter Mass]
0
5
10
15
20

Measurable Properties

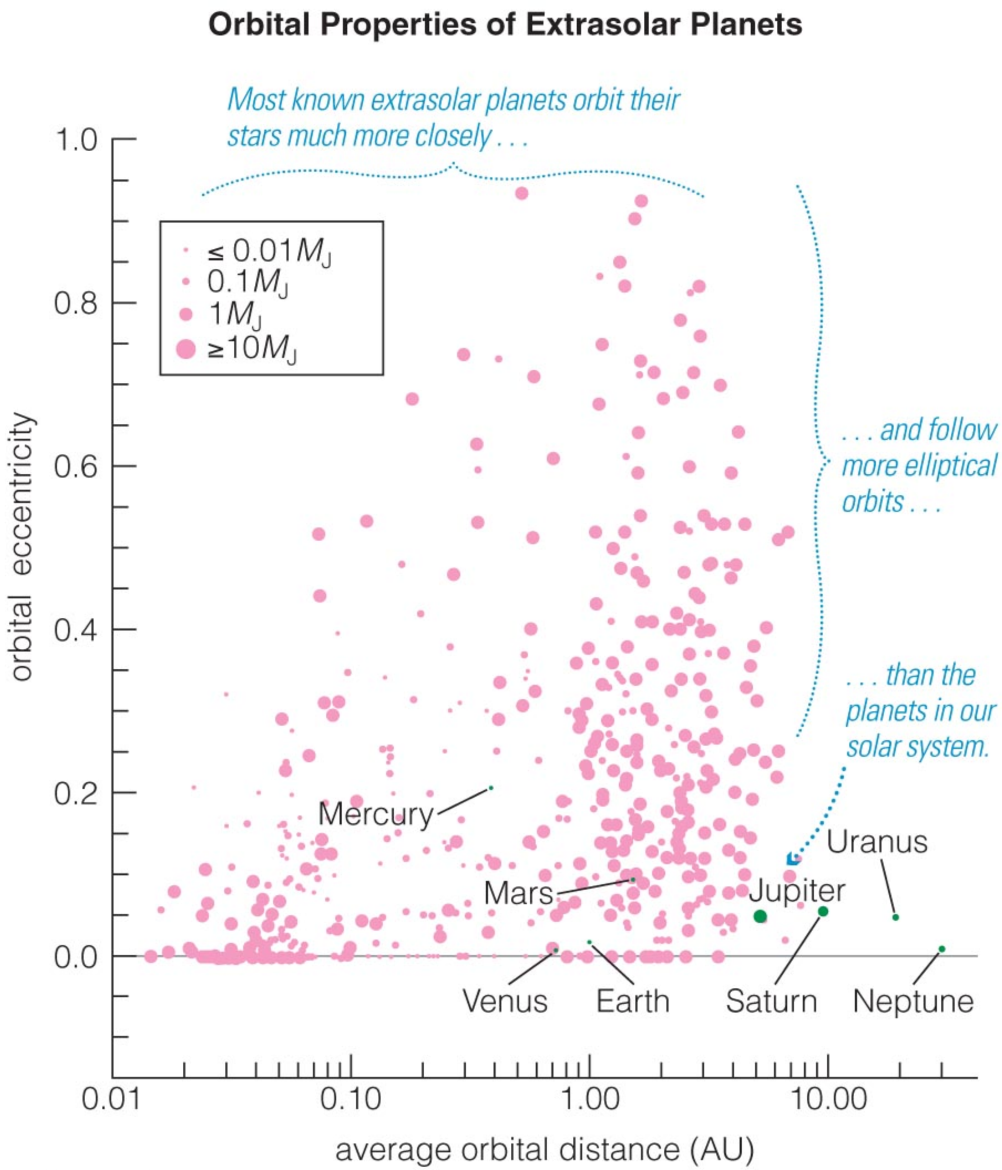
- Orbital period, distance, and orbital shape
- Planet mass, size, and density
- Planetary temperature
- Composition

Orbits of Extrasolar Planets

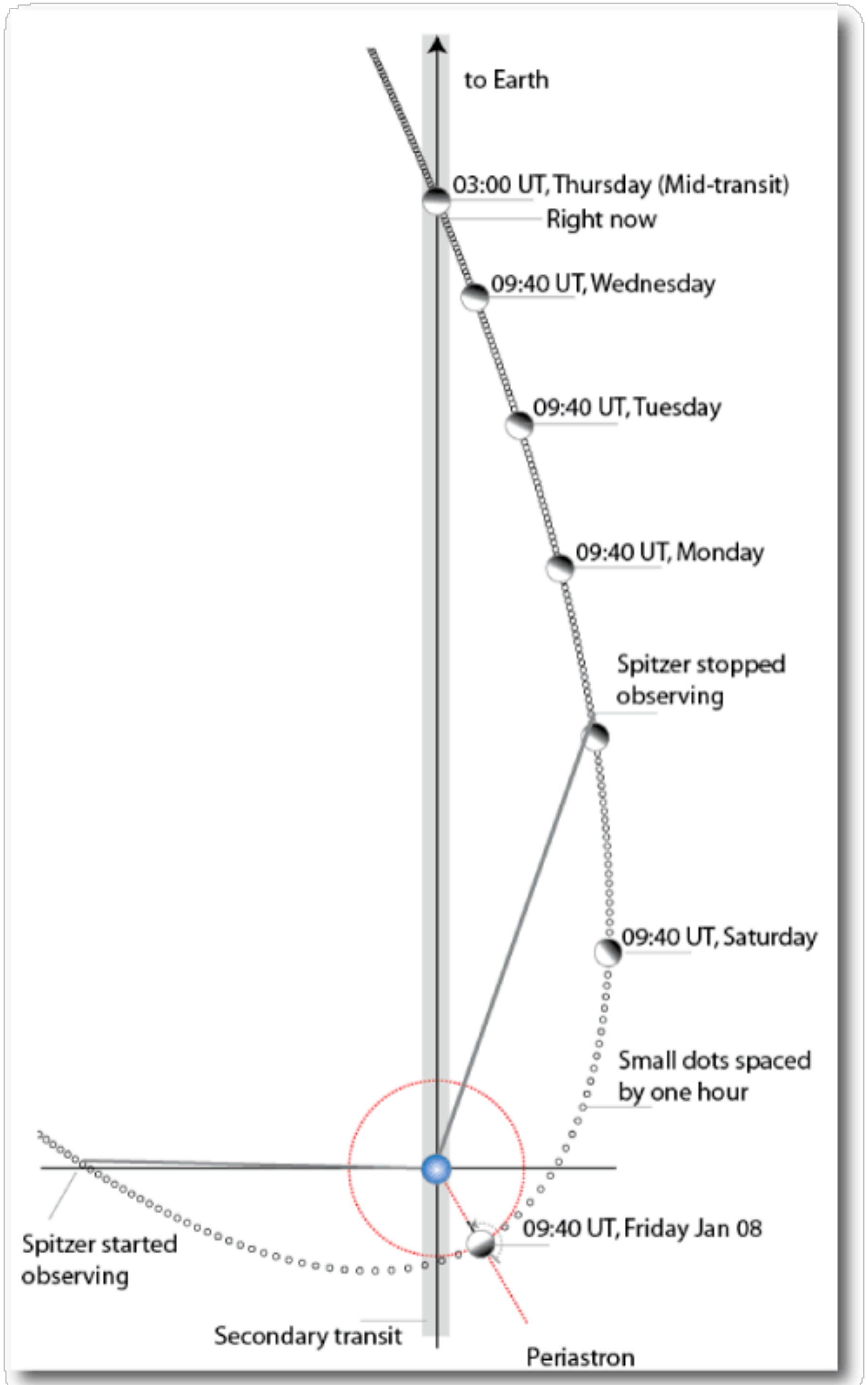


- Nearly all of the detected planets have orbits smaller than Jupiter's.
- This is a *selection effect*: Planets at greater distances are harder to detect with the Doppler technique.

Orbits of Extrasolar Planets

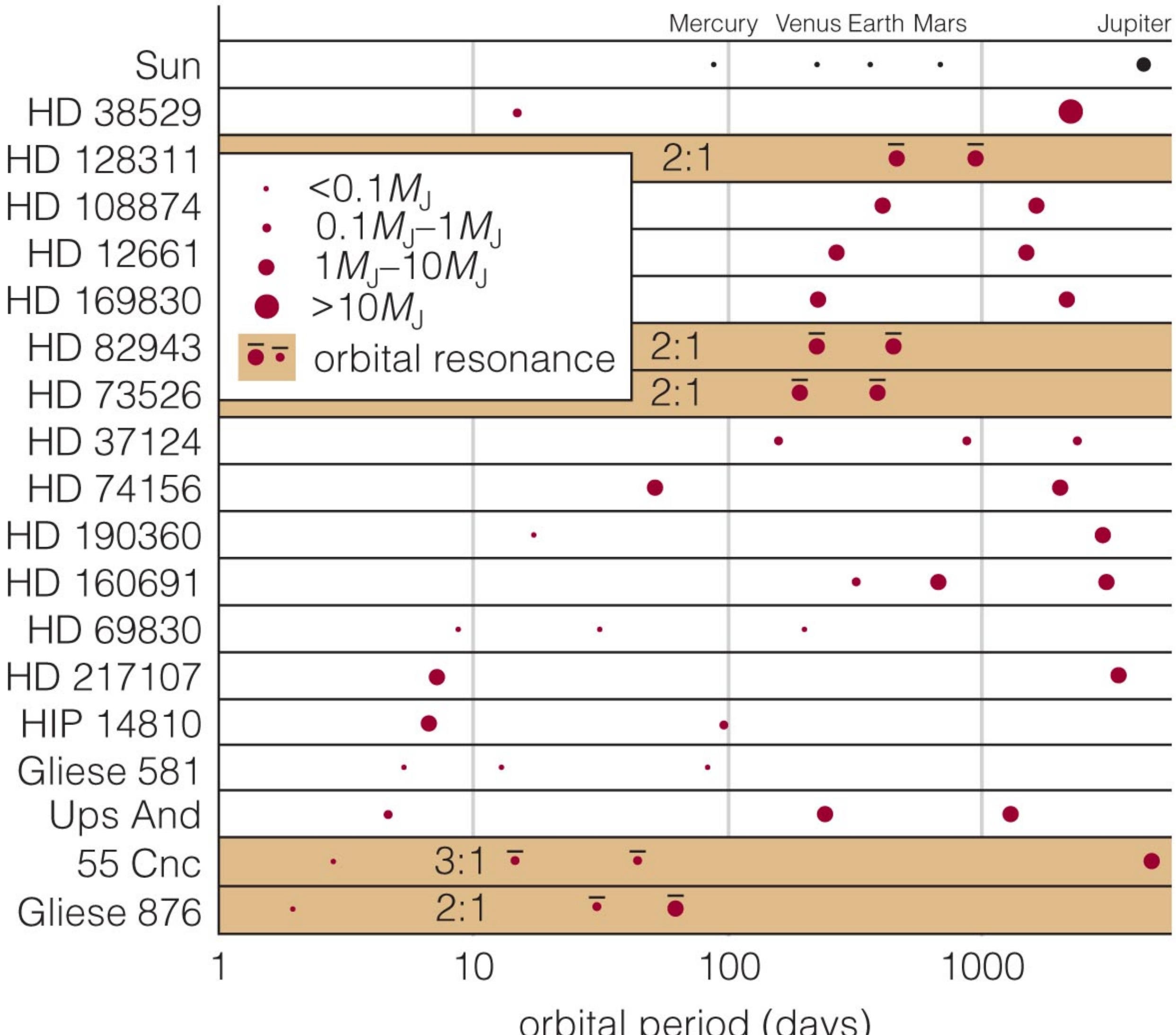


- Orbits of some extrasolar planets are much more elongated (have a greater eccentricity) than those in our solar system.
- Highest is e=0.93
- Our solar system seems to be exceptional, with small eccentricities



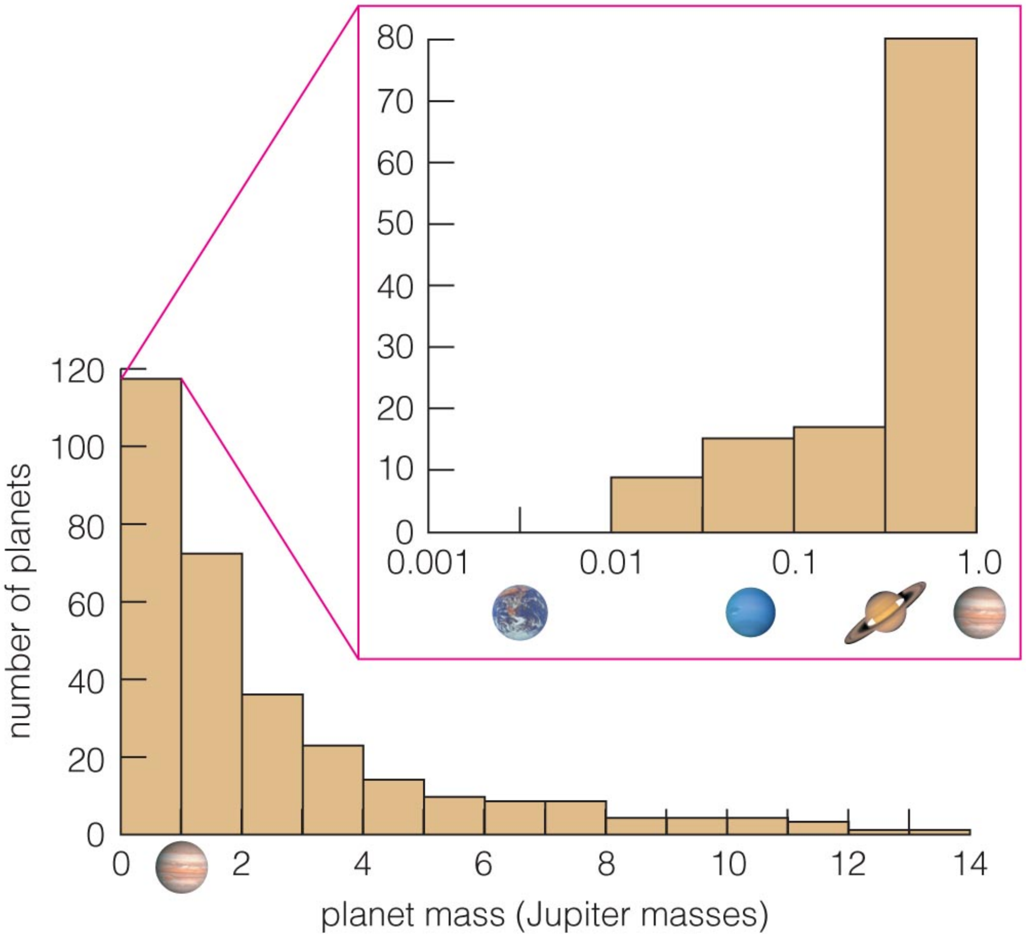
HD80606b:
The "cometary" hot Jupiter
e=0.93
P = 111 days

Multiple-Planet Systems



- Planets like to be with other planets
- Best place to find a planet is around a star where you already have detected a planet.

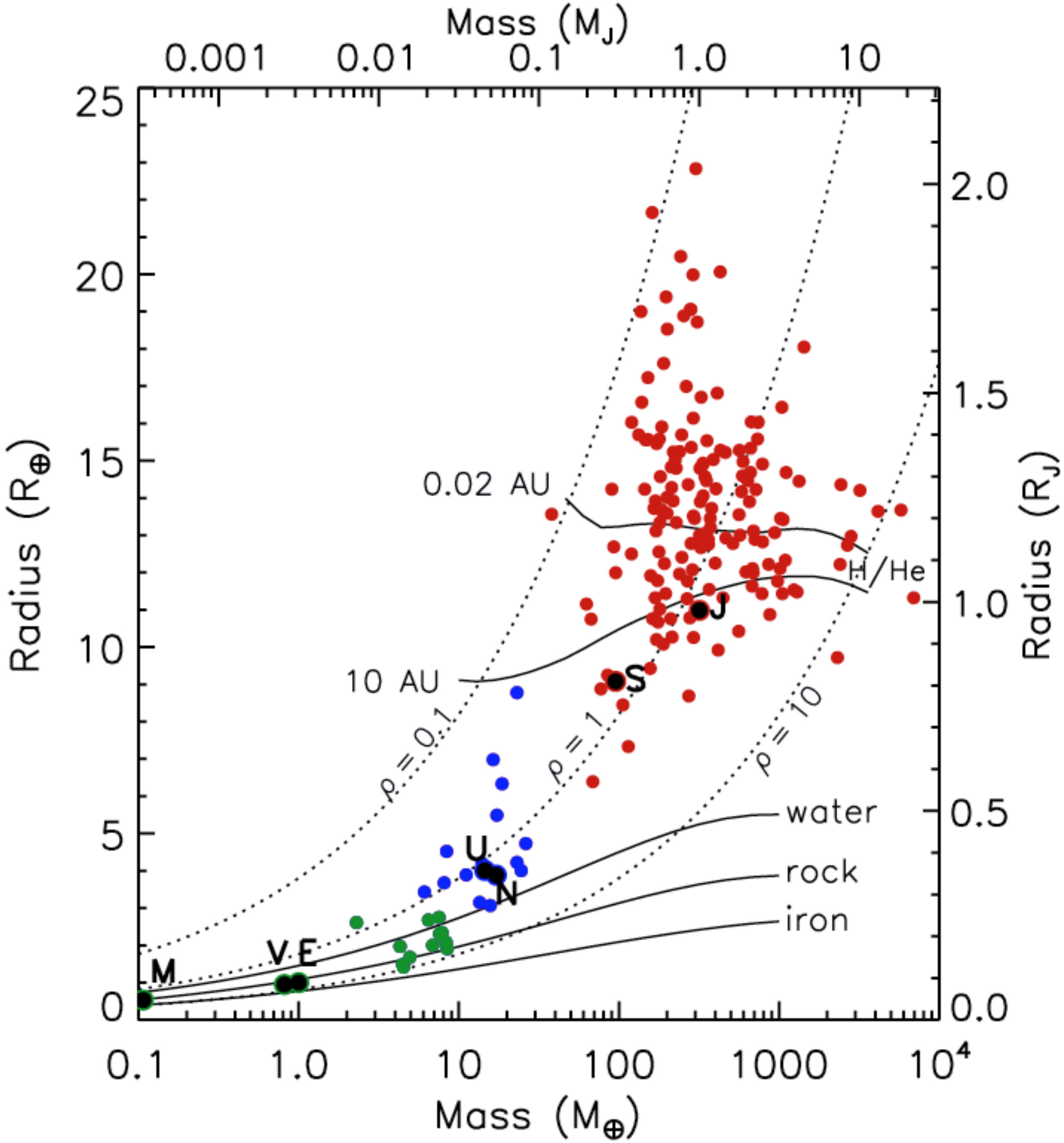
Orbits of Extrasolar Planets from Radial Velocity



- Most of the detected planets have greater mass than Jupiter.
- Planets with smaller masses are harder to detect with Doppler technique.

How do extrasolar planets compare with planets in our solar system?

There is an incredibly diversity of worlds



Surprising Characteristics

- Some extrasolar planets have highly elliptical orbits.
- Some massive planets, called *hot Jupiters*, orbit very close to their stars.
- There are classes of planets that do not exist in the solar system: 1-15 Earth Masses
- "Super Earths" or "Mini Neptunes"?

Hot Jupiters

Jupiter	**Hot Jupiters orbiting other stars**
Composed primarily of hydrogen and helium	Composed primarily of hydrogen and helium
5 AU from the Sun	As close as 0.03 AU to their stars
Orbit takes 12 Earth years	Orbit as short as 1.2 Earth days
Cloudtop temperatures ≈130 K	Cloudtop temperatures up to 1300 K
Clouds of various hydrogen compounds	Clouds of “rock dust”
Radius = 1 Jupiter radius	Radius up to 1.3 Jupiter radii
Mass = 1 Jupiter mass	Mass from 0.2 to 2 Jupiter masses
Average density = 1.33 g/cm^3	Average density as low as 0.2 g/cm^3
Moons, rings, magnetosphere	Moons, rings, magnetospheres: unknown

How do astronomers look for planets whose orbits might cause them to pass in front of a star outside our solar system?

A. They look for a small black dot passing in front of the star.
B. The look to see if the star's position shifts or "wobbles" slightly in the sky.
C. The measure the star's brightness, and look for periodic dimming (transits).

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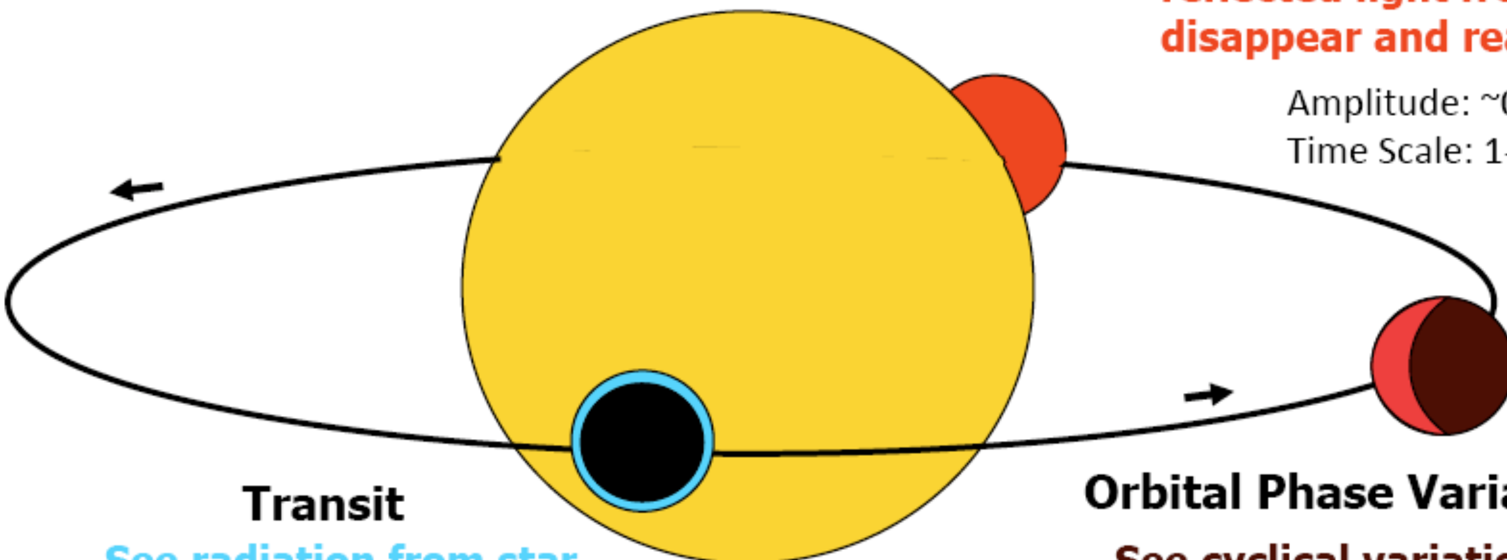
Putting It All Together: Transiting Planets as a Tool for Studying Exoplanet Atmospheres



Secondary Eclipse

See thermal radiation and reflected light from planet disappear and reappear

Amplitude: ~0.1%
Time Scale: 1-5 hours

Transit

See radiation from star transmitted through the planet's atmosphere

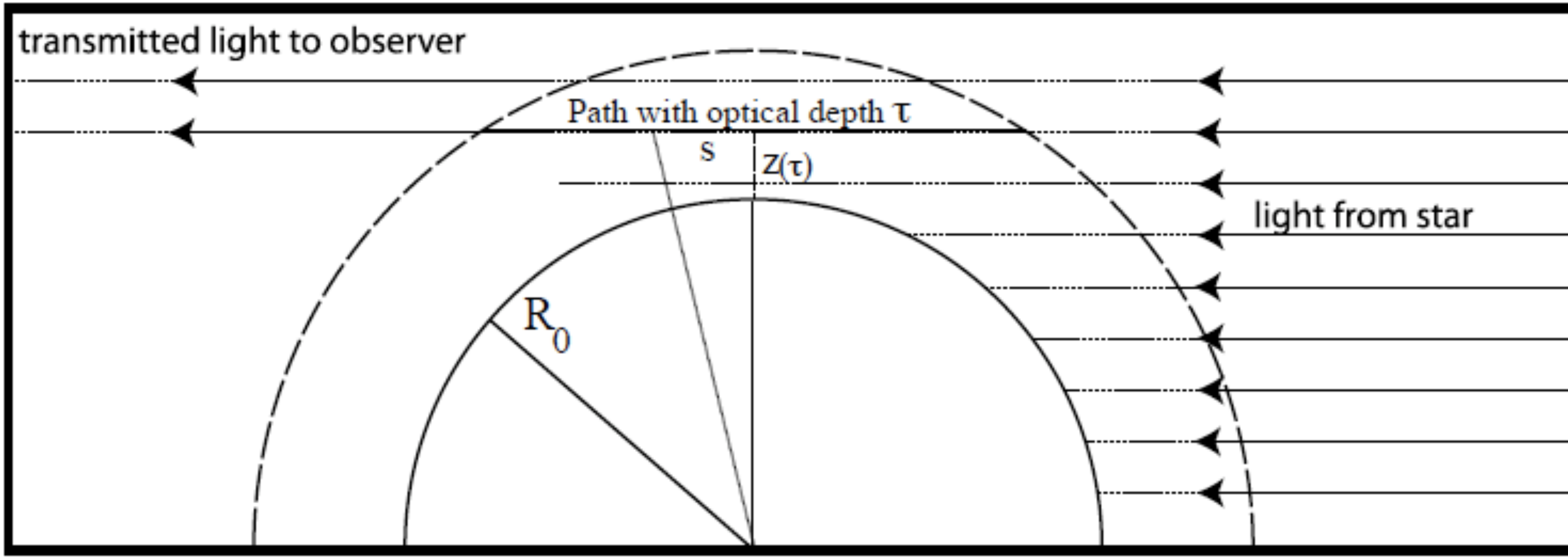
Transit depth: ~1%
Absorption feature: ~0.01%
Time Scale: 1-5 hours

Orbital Phase Variations

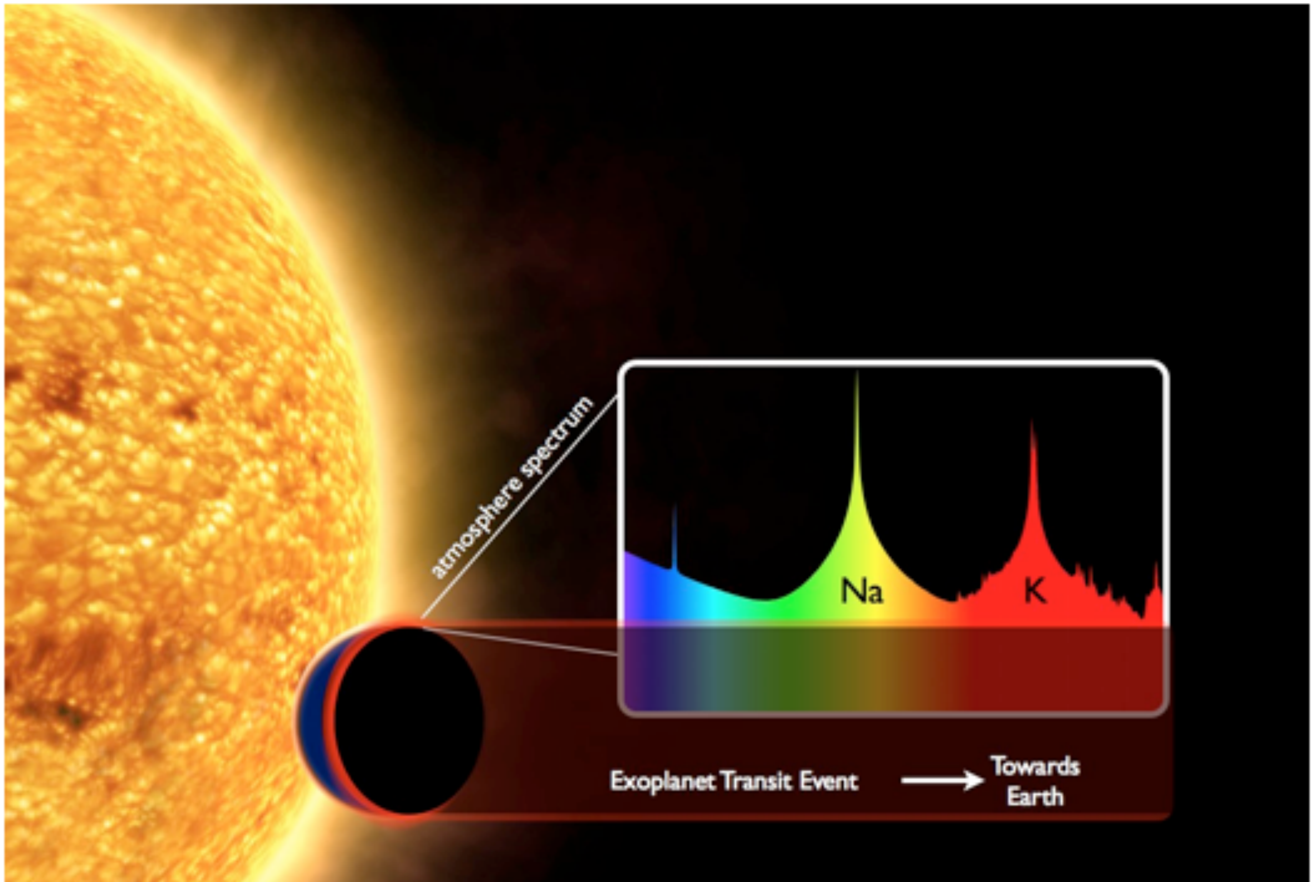
See cyclical variations in brightness of planet

Amplitude: ~0.01-0.1%
Time Scale: 30-100 hours

A "Transmission Spectrum"



A "Transmission Spectrum"



At wavelengths where the planet's atmosphere is more opaque, the planet blocks more of the parent star's light, so the planet actually looks lightly physical larger

Putting It All Together: Transiting Planets as a Tool for Studying Exoplanet Atmospheres

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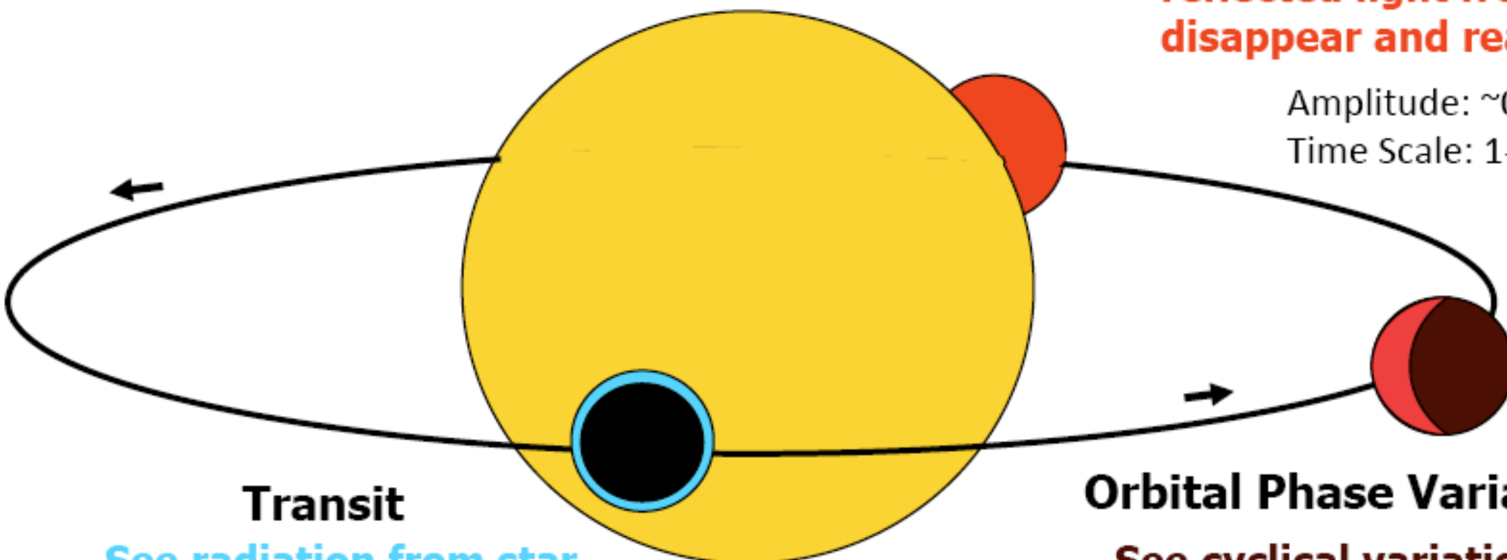

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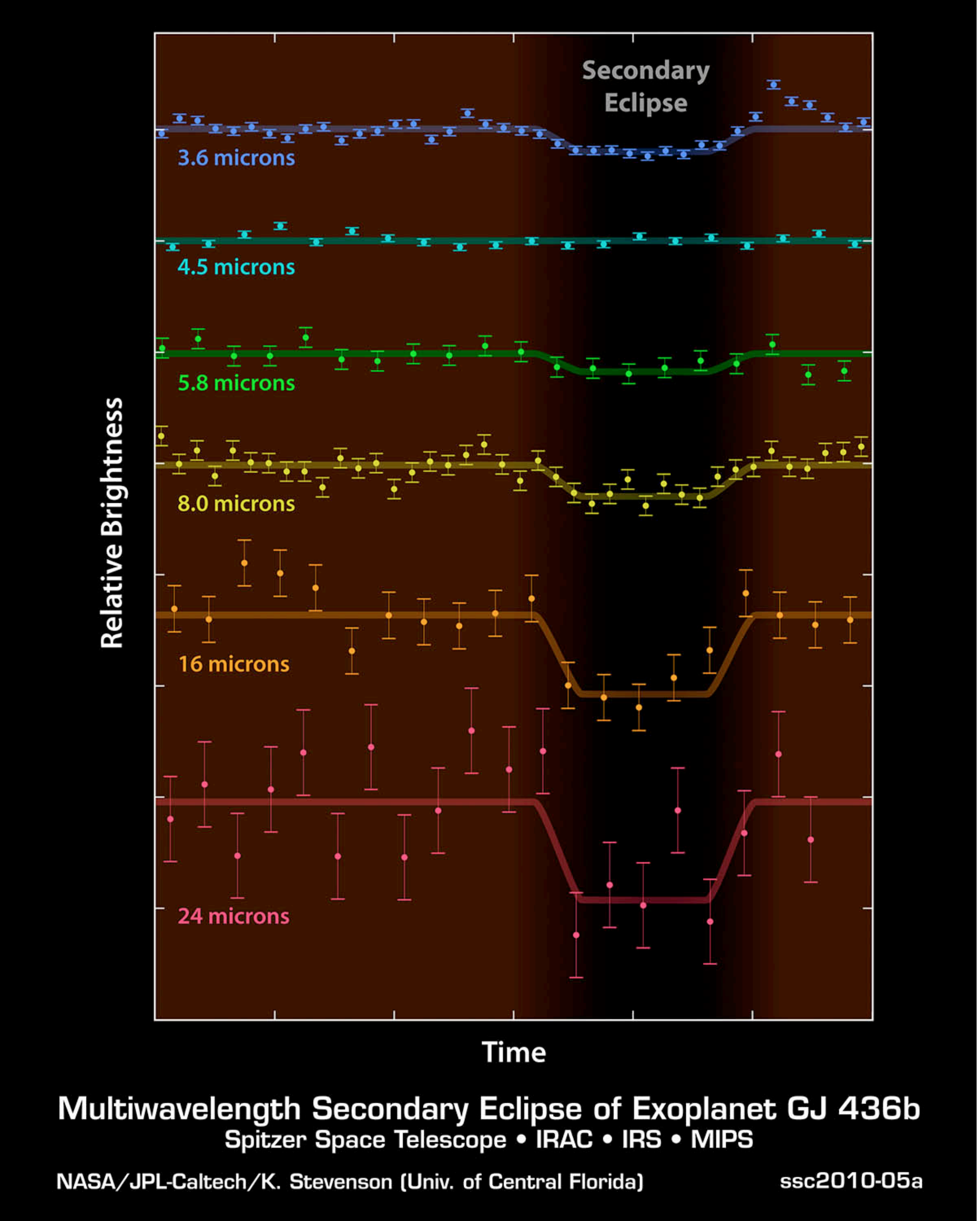
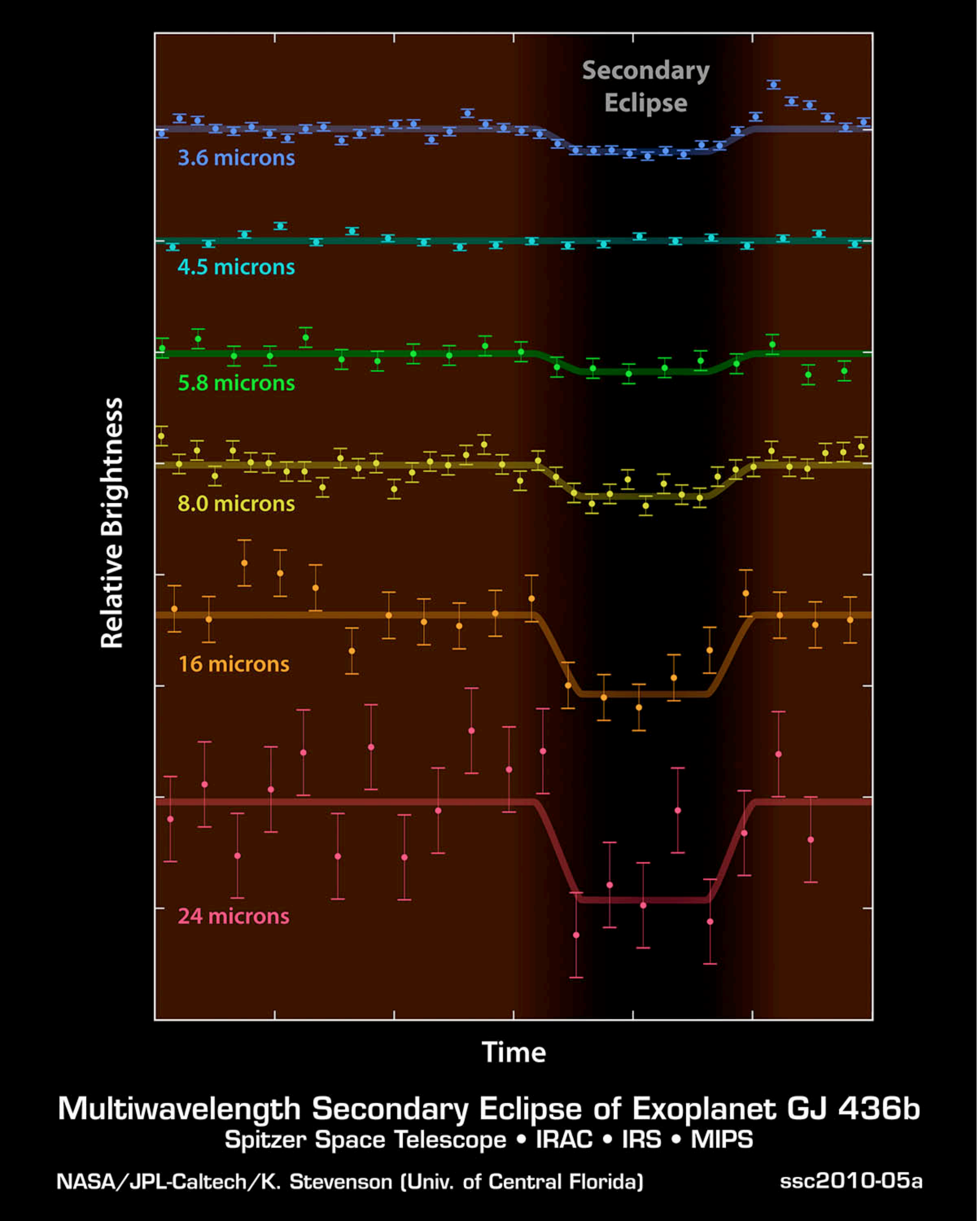
Taking the Temperature of Planets



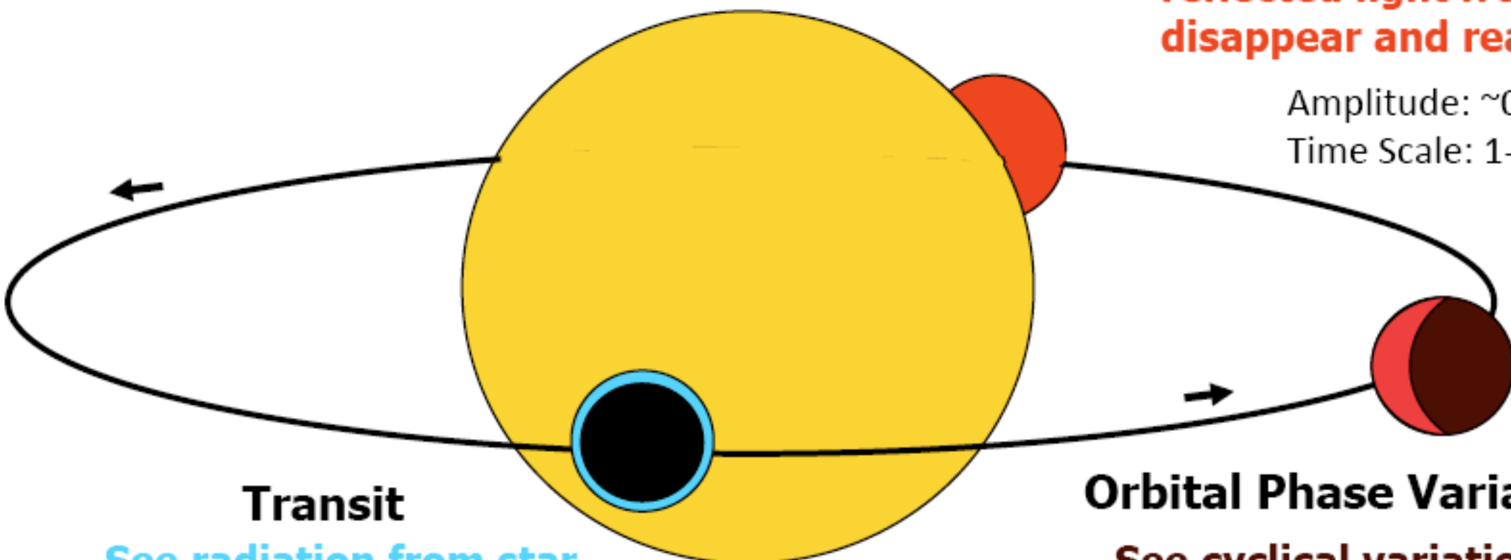
- Watch a planet disappear and reappear behind its parent stars
- What temperature would the planet be emitting at to cause that much light to be lost?
- Can measure the amount of light lost as a function of wavelength to build up an emission spectrum of the planet



Taking the Temperature of Planets

- This has been observed for about 40 planets
- Can also look for reflected light
  - Has been seen for a few planets
  - Very little reflected light as there is very little cloud material
- Tres-2b: visible albedo = 0.025

Putting It All Together: Transiting Planets as a Tool for Studying Exoplanet Atmospheres



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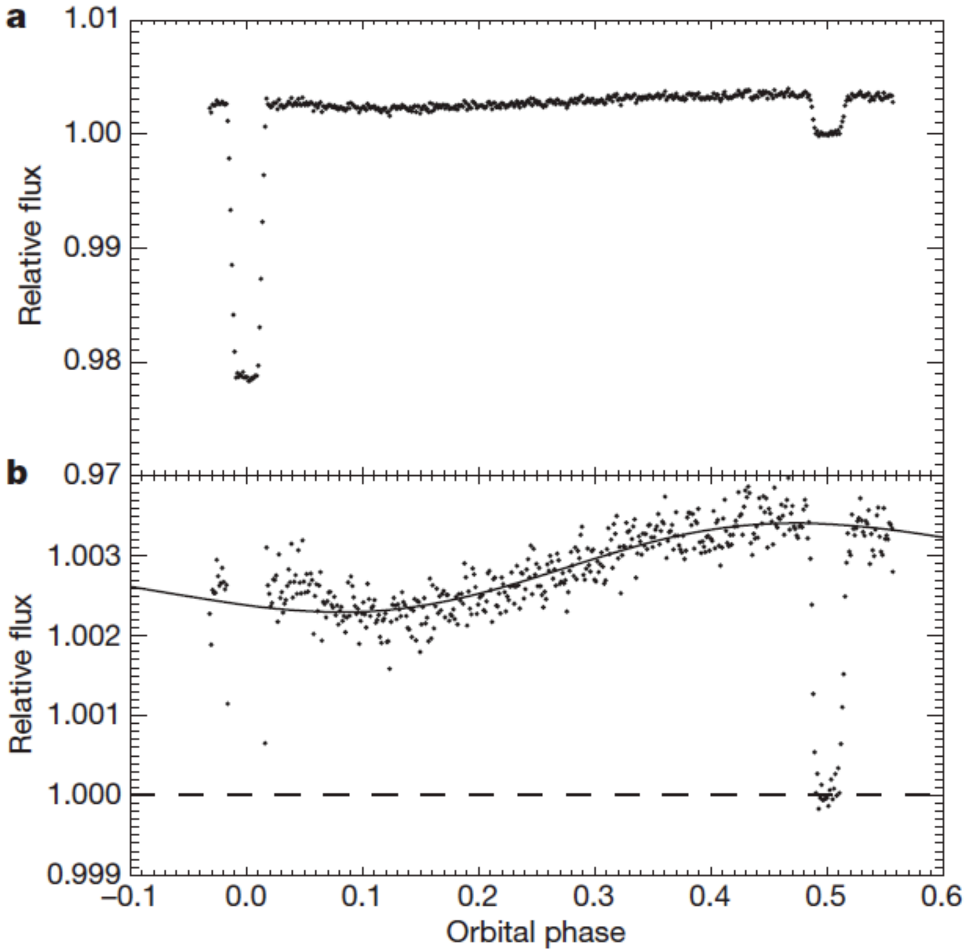
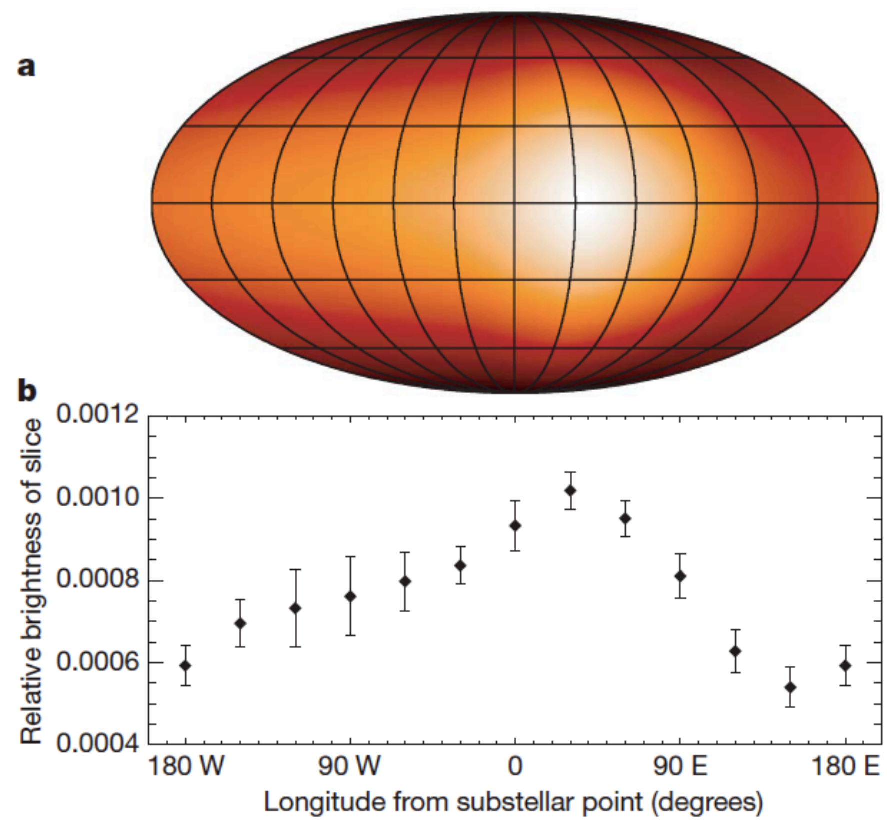
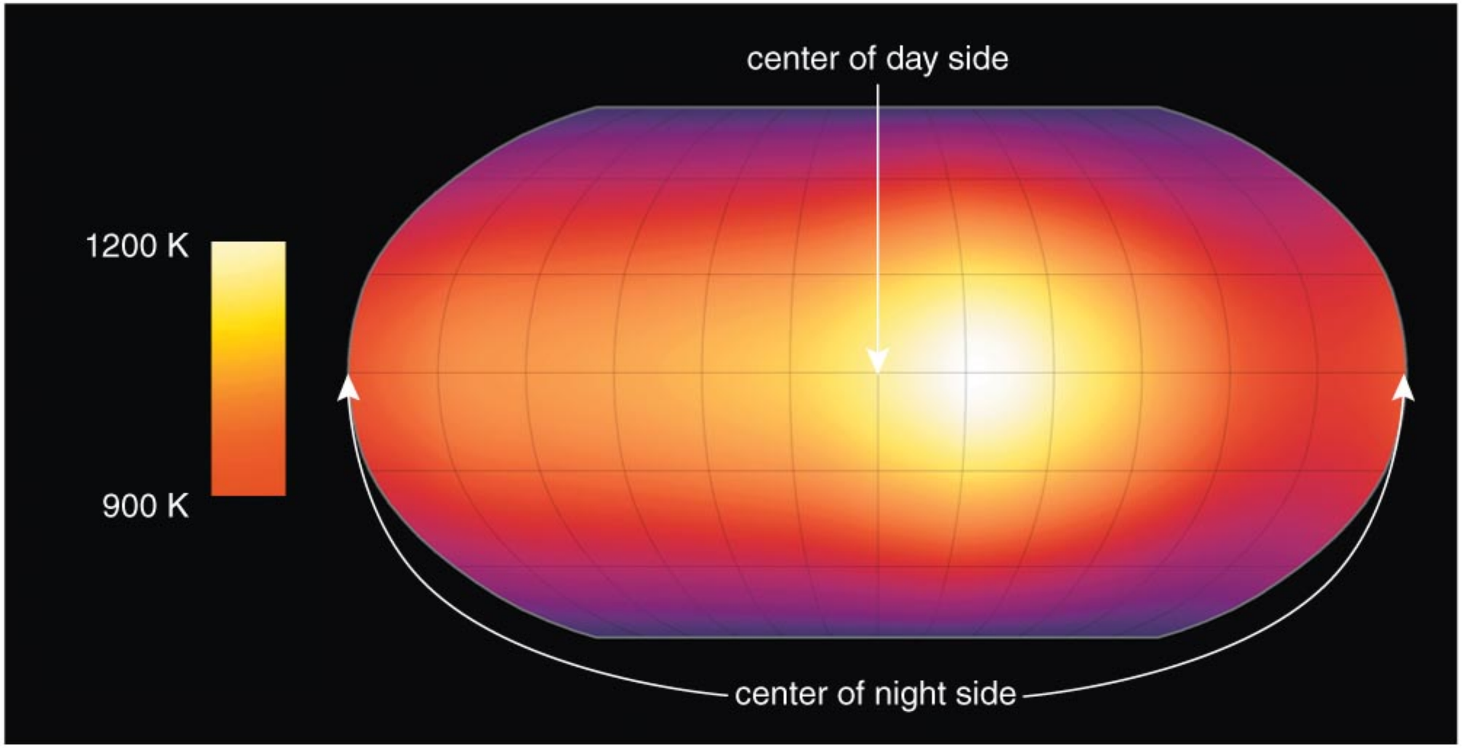
Learning Even More from Transiting Planets





- Stare at the planet + star for half of an orbit
- Build up a temperature "map" as a function of longitude
- No latitude information

Surface Temperature Map



- Measuring the change in infrared brightness during an orbit enables us to map a planet's surface temperature.
- Similar maps for about 10 planets
- Strong evidence for fast west-to-east winds

Even Better: Eclipse Mapping

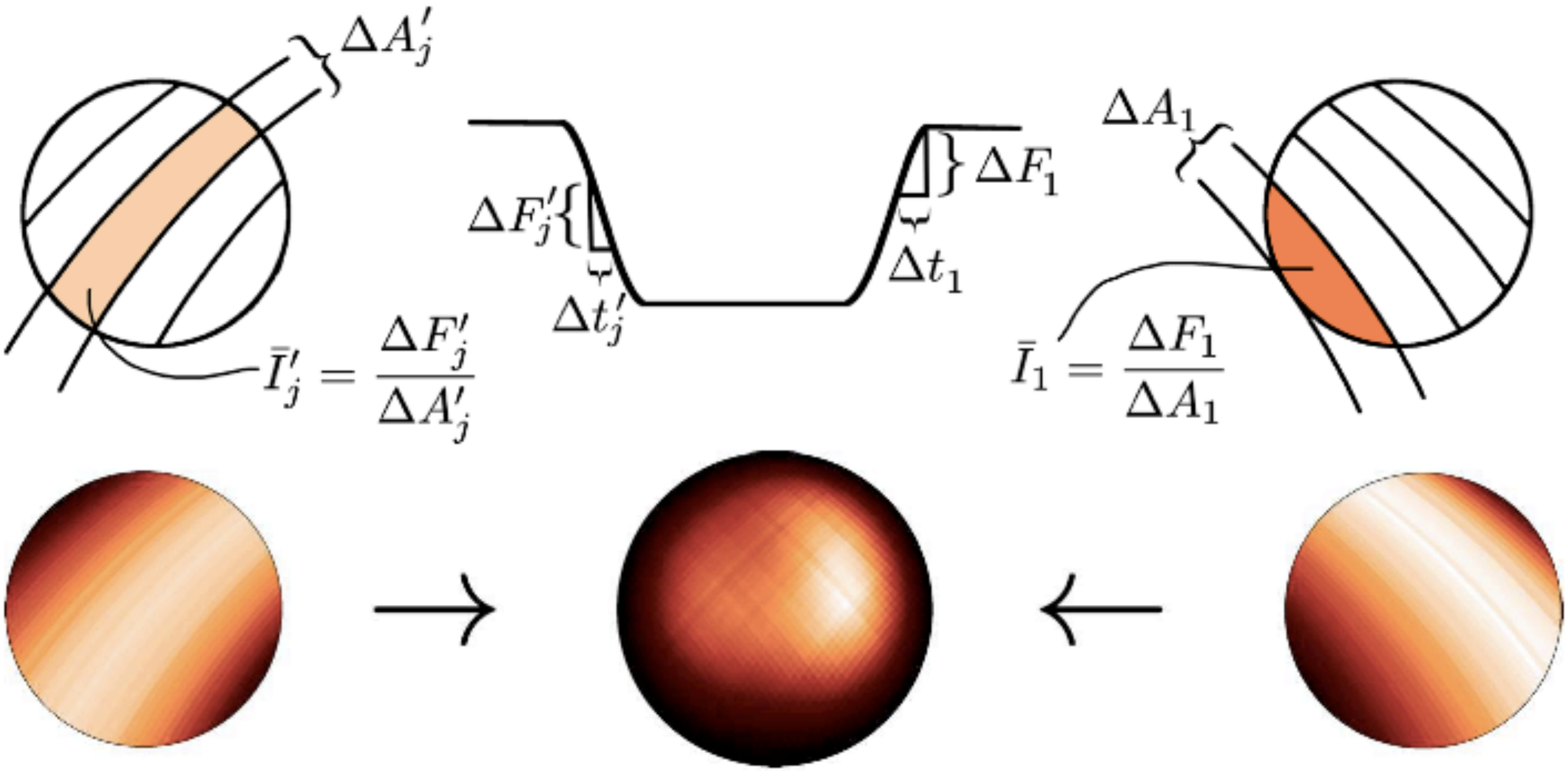
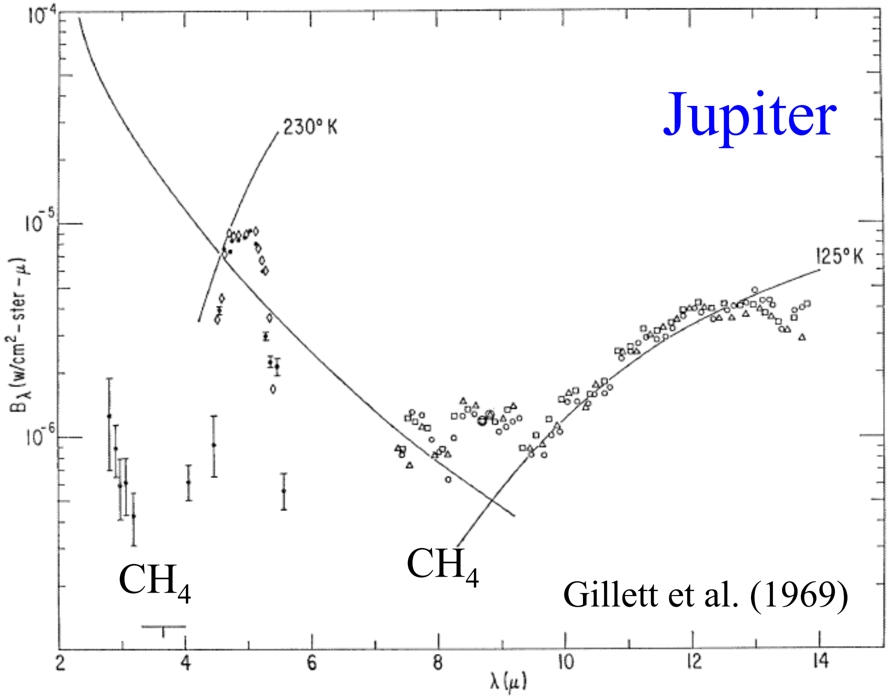


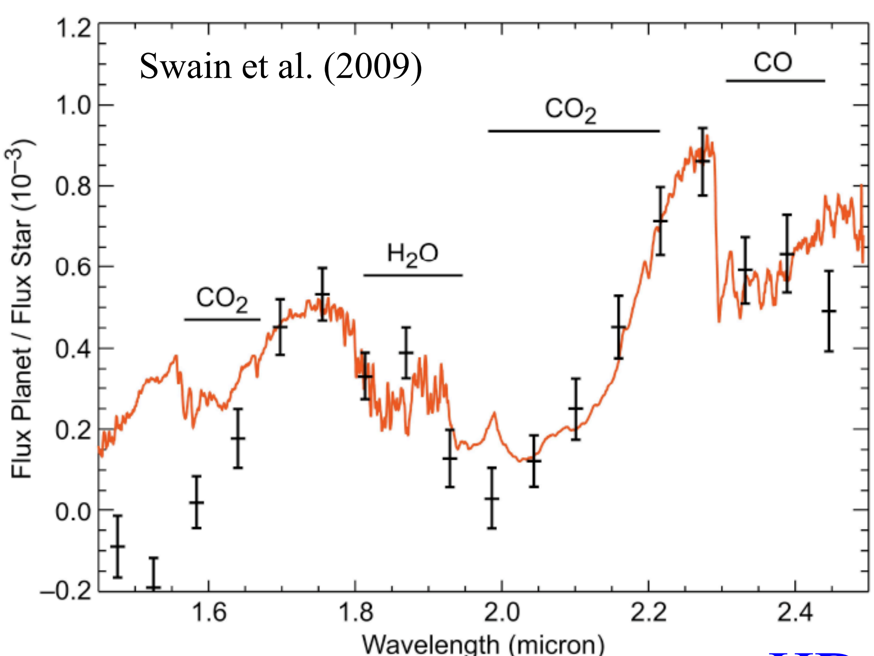
FIG. 1.— Top: Diagram demonstrating the slice mapping technique. Bottom: Ingress and egress maps (left and right), as well as combined map (center) of HD 189733b at 8 micron. The image is centered on the sub-observer point and the black regions are 50% as bright as the white.

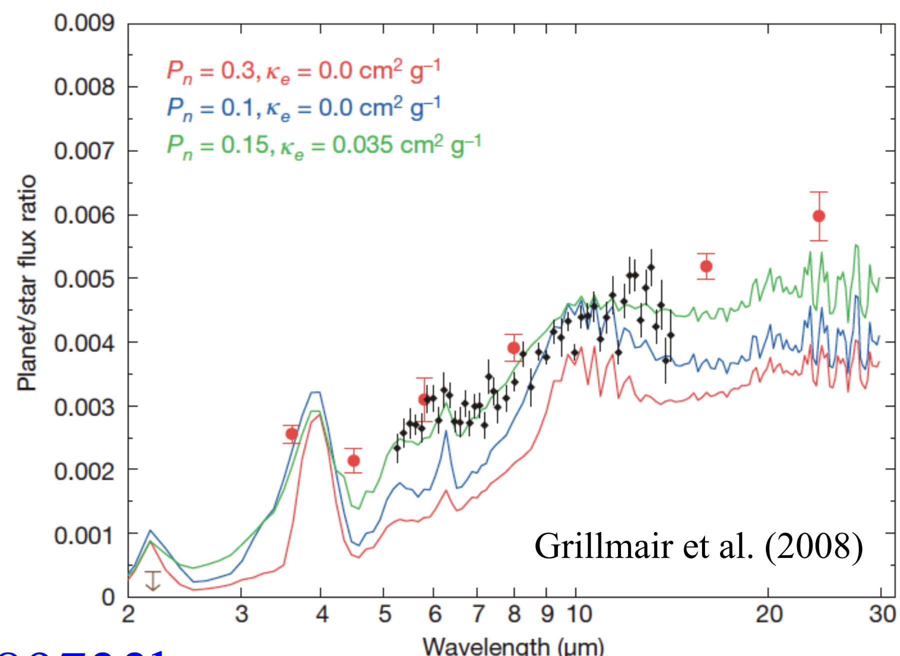


40 years behind...

- Jupiter, 1969
- HD 189733b, 2008

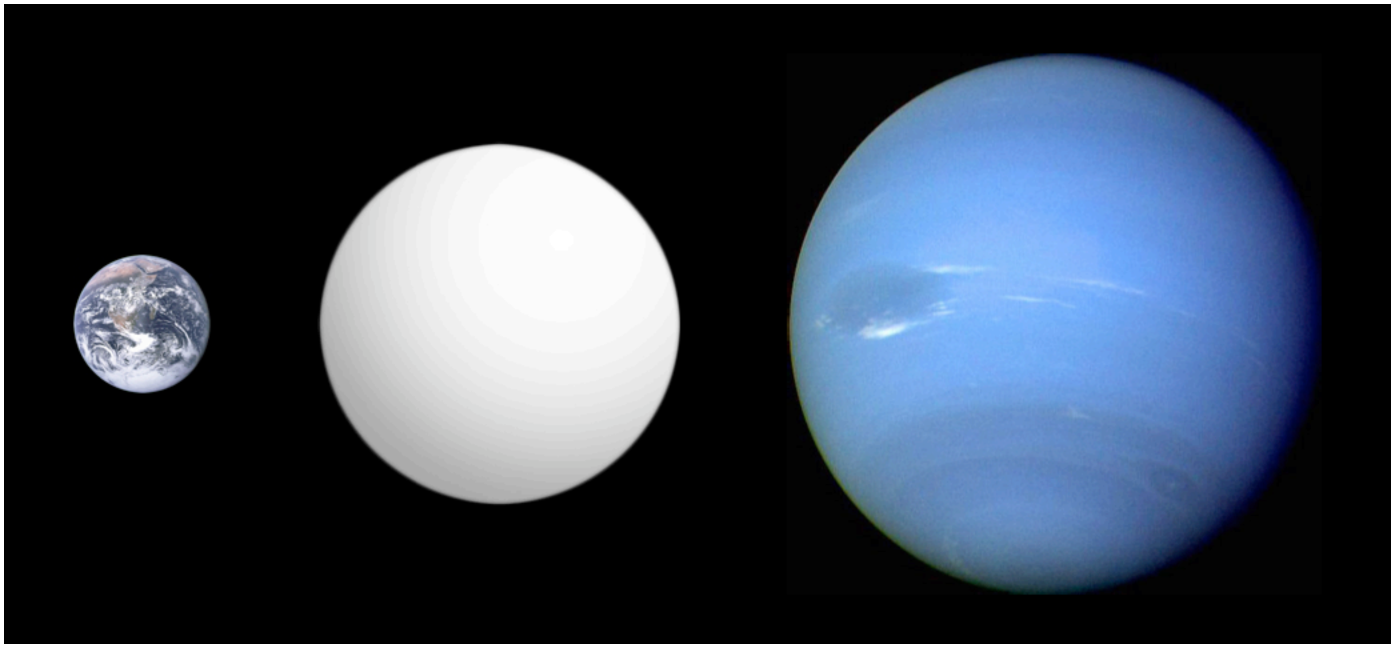
- We are able to again do the initial reconnaissance of worlds, like was done in the 1960s-1970s, but now with a MUCH larger sample size





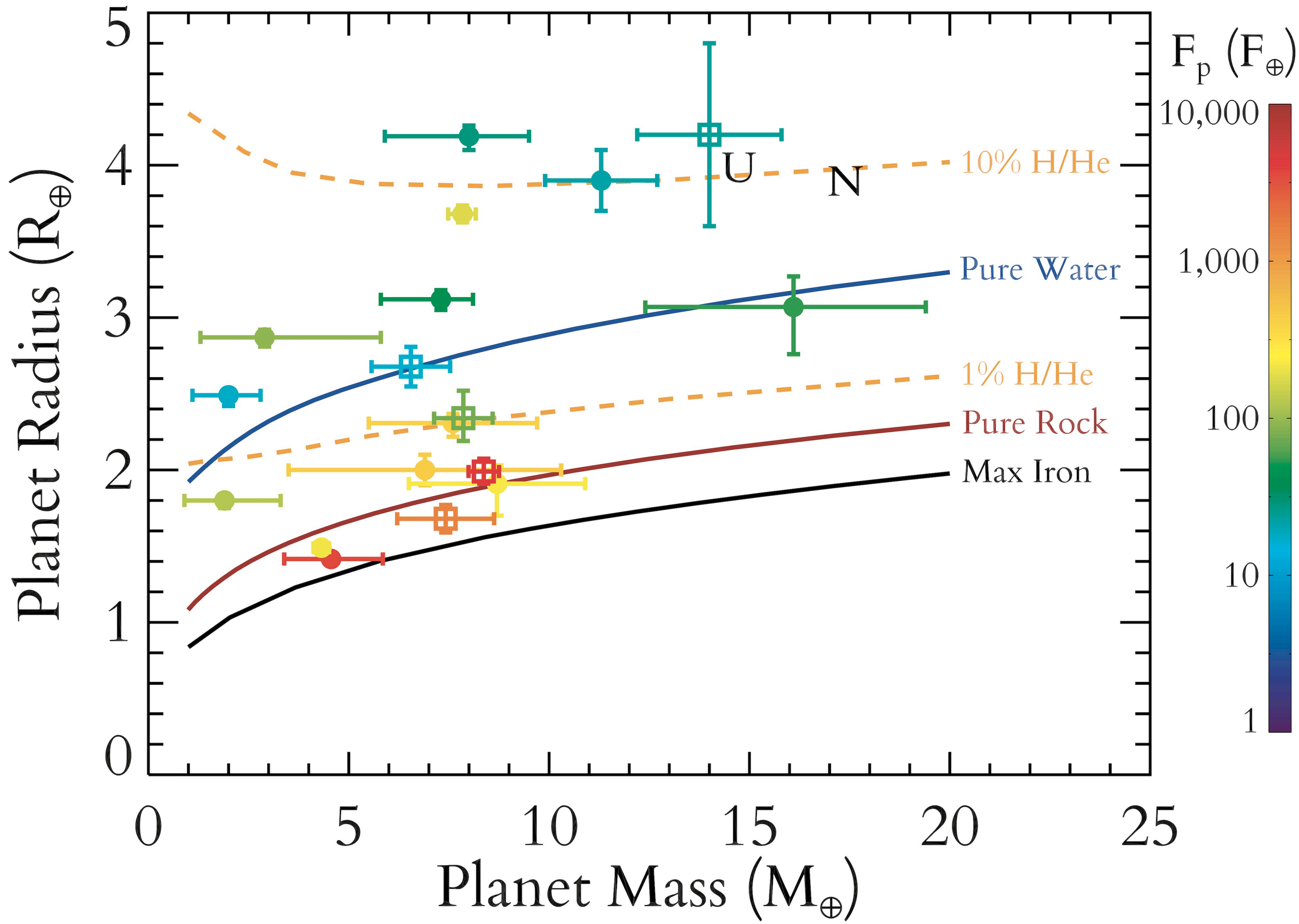
HD 189733b

Super Earth or Mini Neptune?

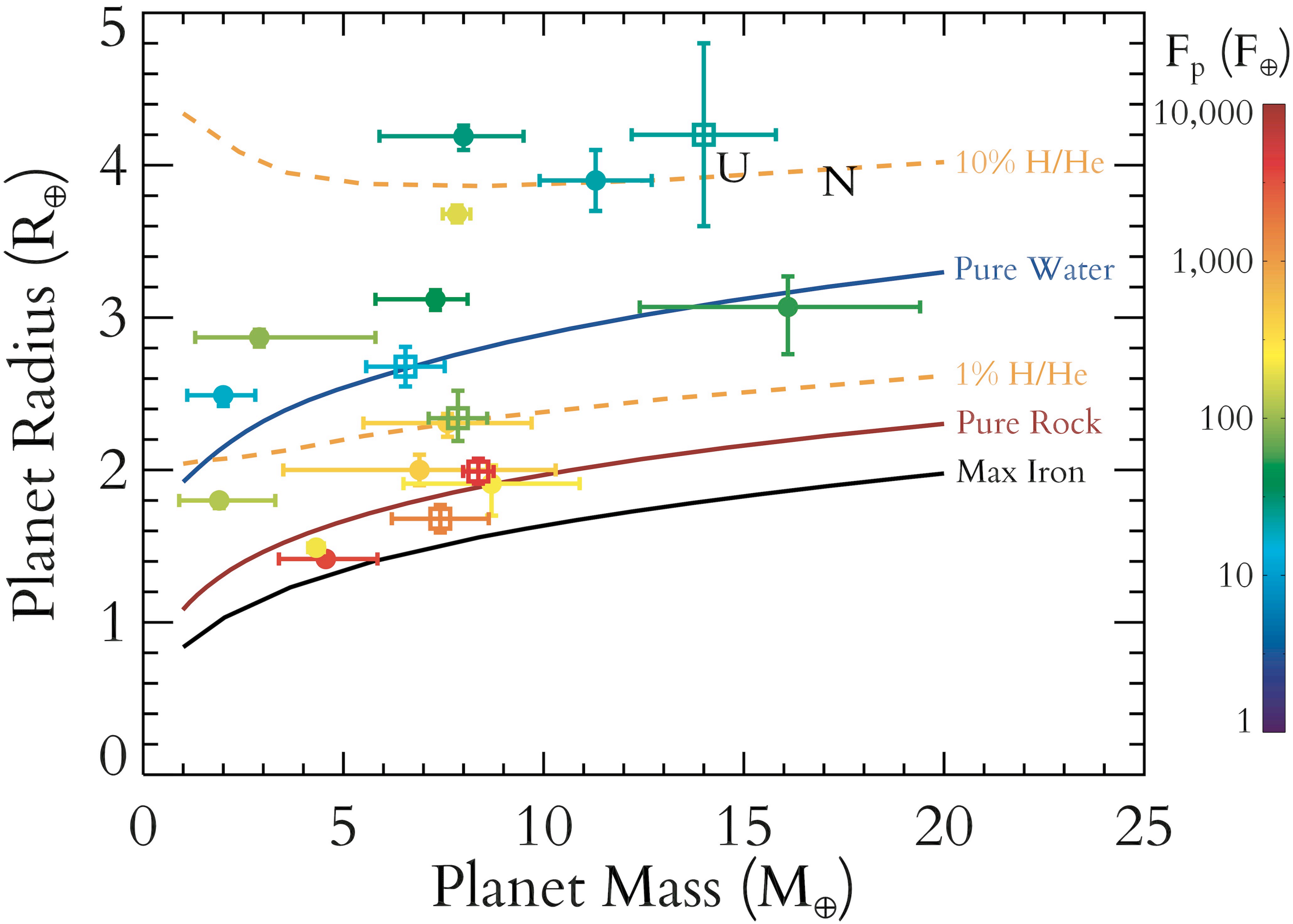


The unknown 1-15 M_{earth} Planets

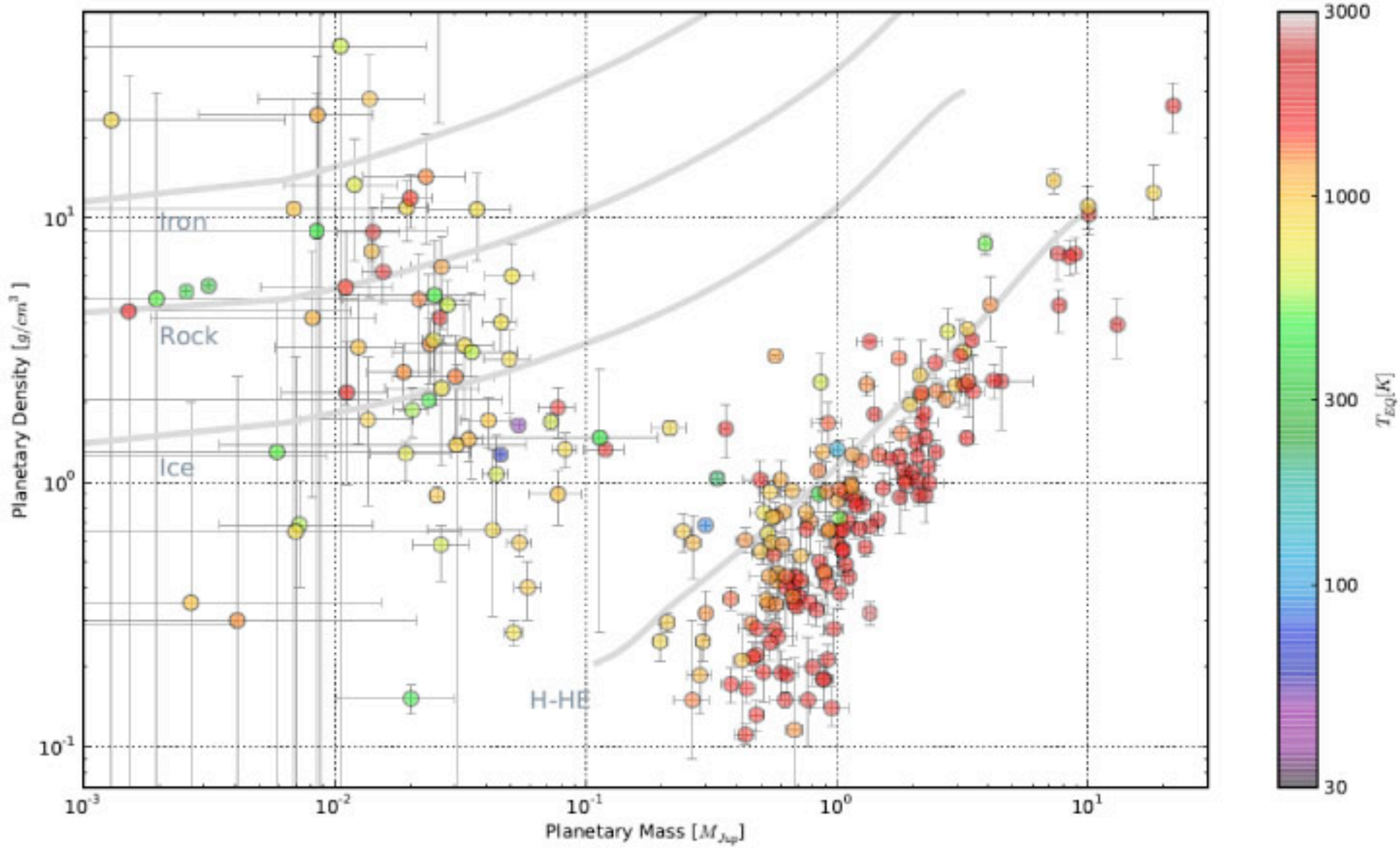
A lot of low-mass planets are not made of rock and iron



There is a problem of "degeneracy" in composition: mass and radius is not enough



The trends in planetary density



What have we learned?

- What have we learned about extrasolar planets?
  - ***Detected*** extrasolar planets are generally much more massive than Earth.
  - They tend to have orbital distances smaller than Jupiter’s.
  - Some have highly elliptical orbits.
  - We can use the star’s light to enable studies of atmospheric composition
  - Planetary bulk density can tell us much about composition

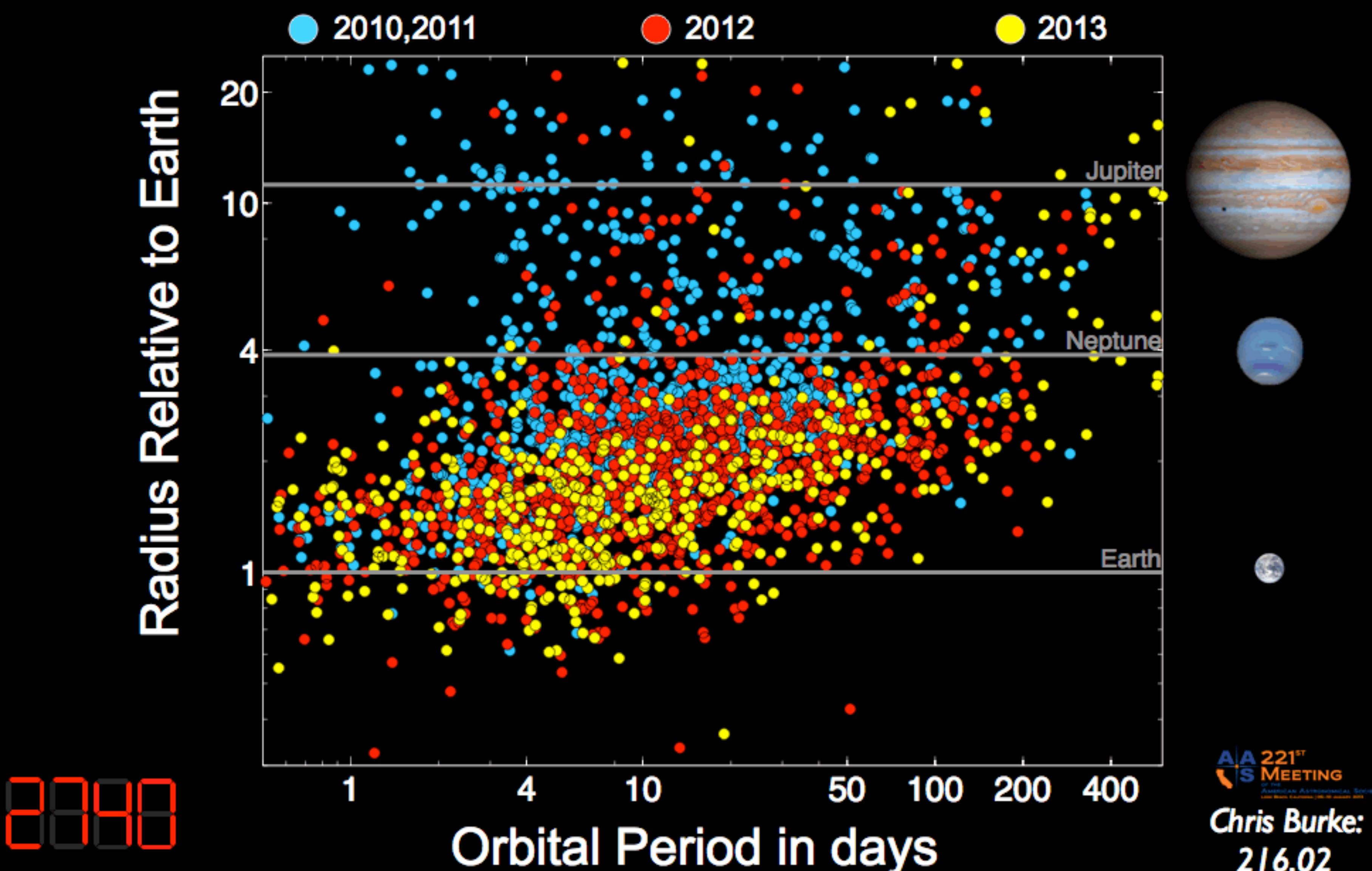
13.3 The Formation of Other Solar Systems

Our goals for learning:

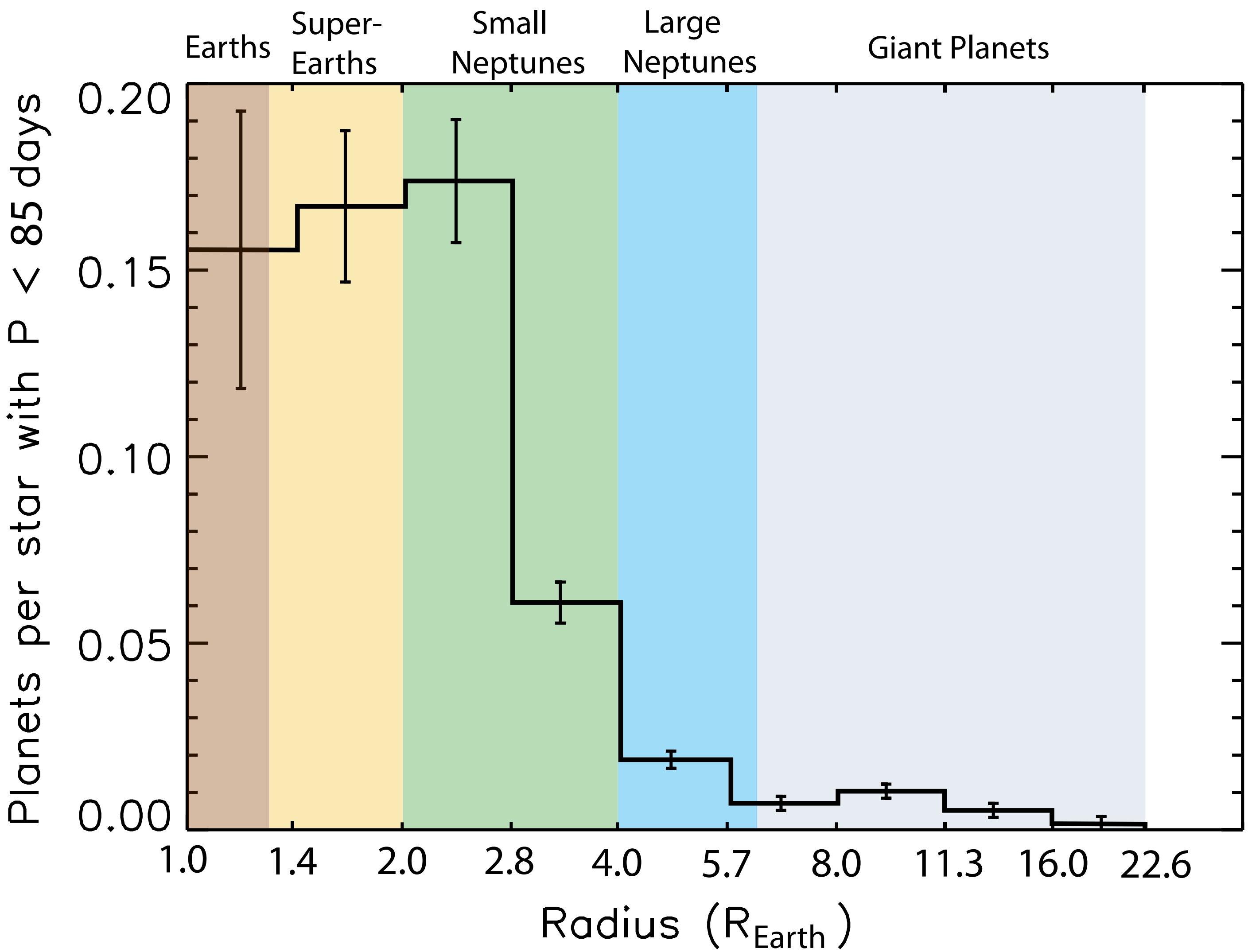
- Can we explain the surprising orbits of many extrasolar planets?
- Do we need to modify our theory of solar system formation?

Kepler's Planet Candidates

22 Months: May 2009 - Mar 2011



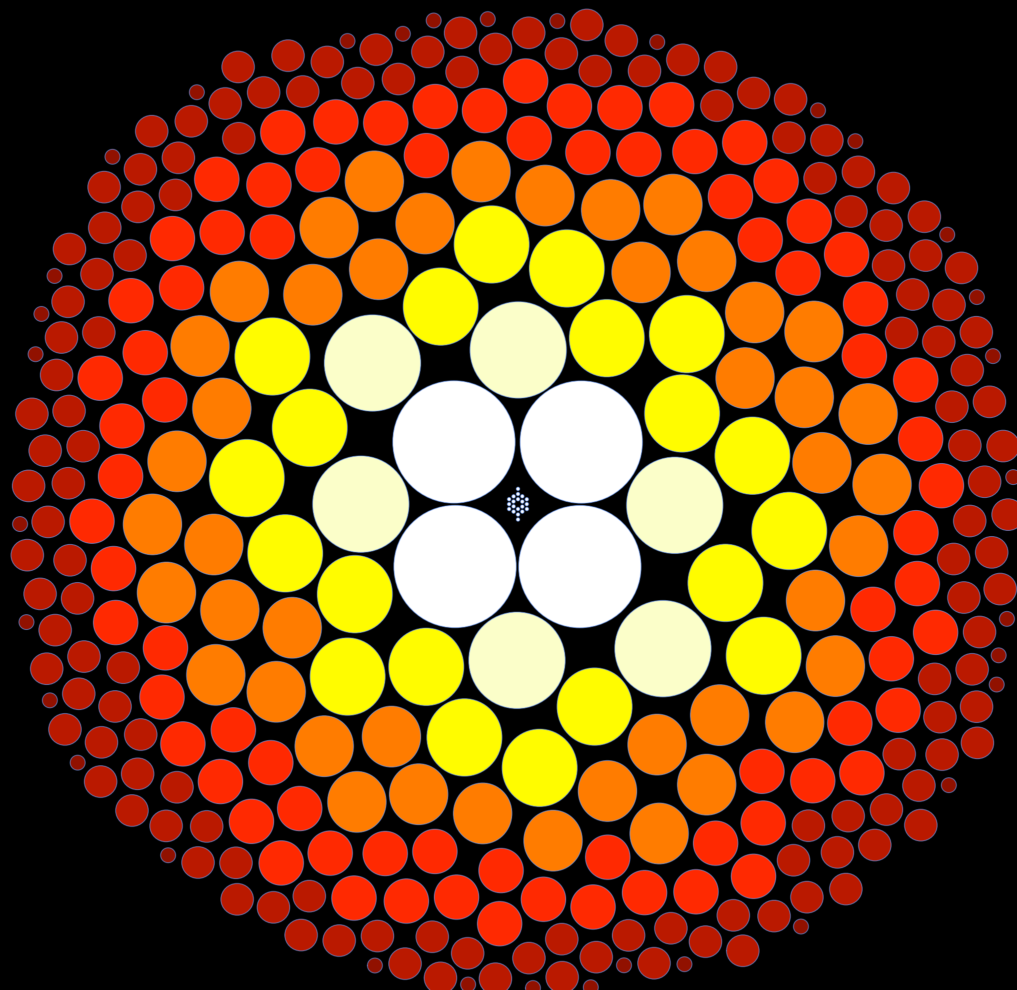
The frequency of planets within 85 days of Sun-like stars



Based on ~2300 planet candidates

Fressin et al. (2013)

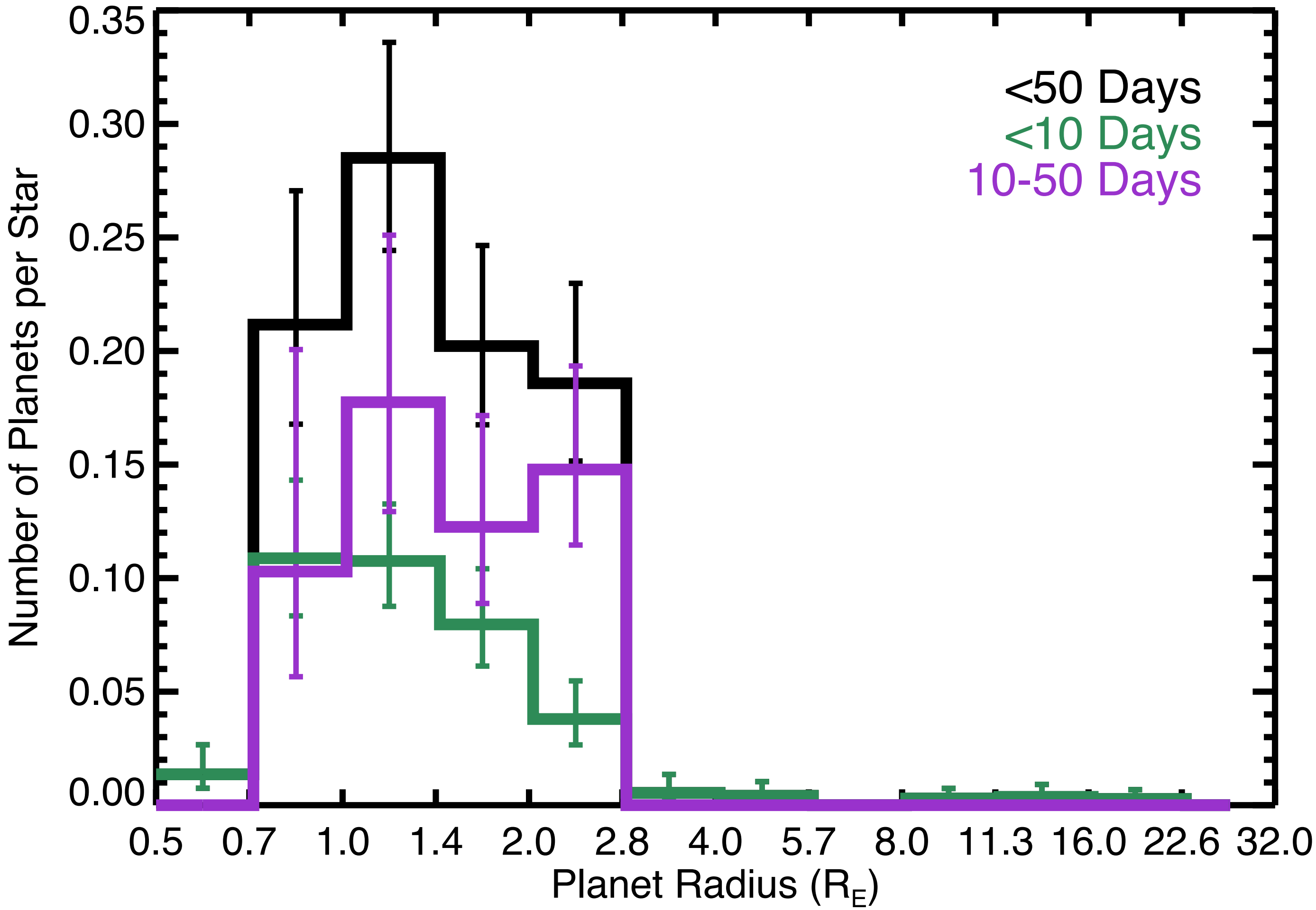
Stars within 30 lightyears of the Sun



O	0
B	0
A	4
F	6
G	20
K	44
M	246

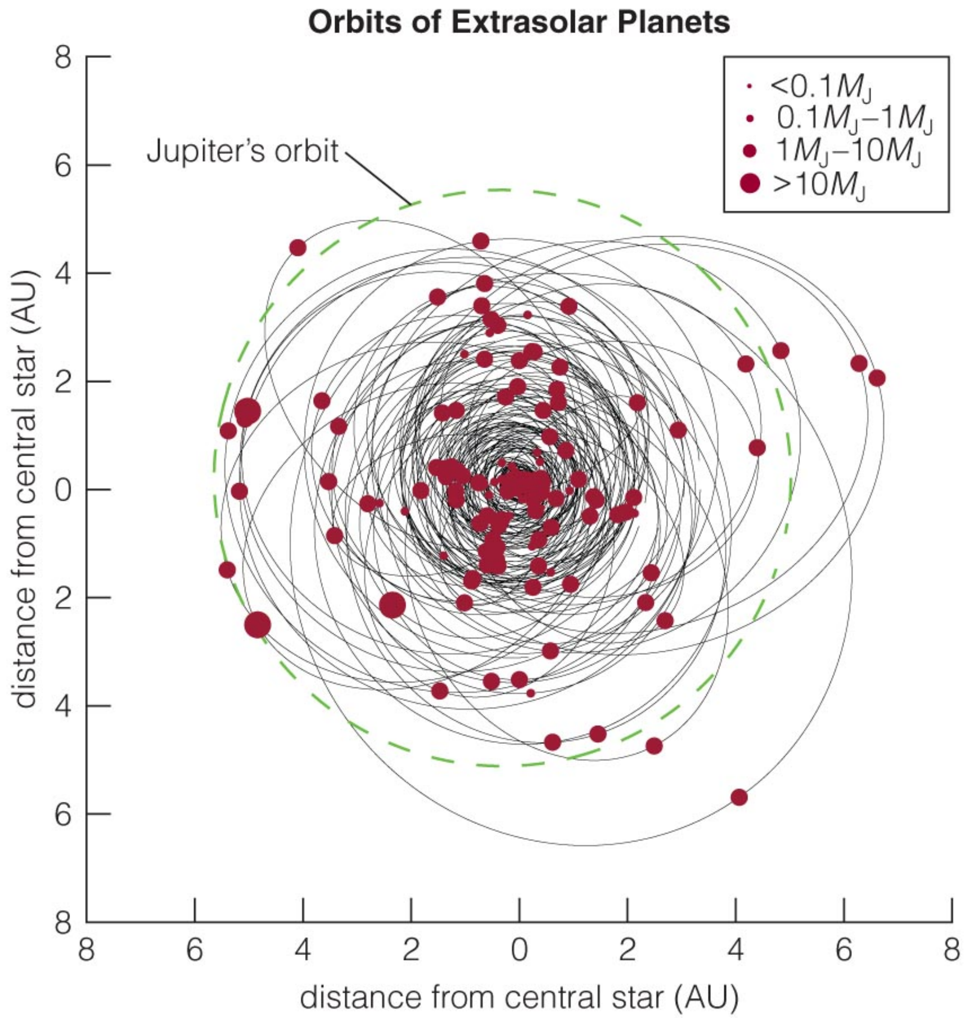
Todd Henry, Georgia State University

The frequency of planets within 50 days of M stars



1.5 planets per M star within ~80 days

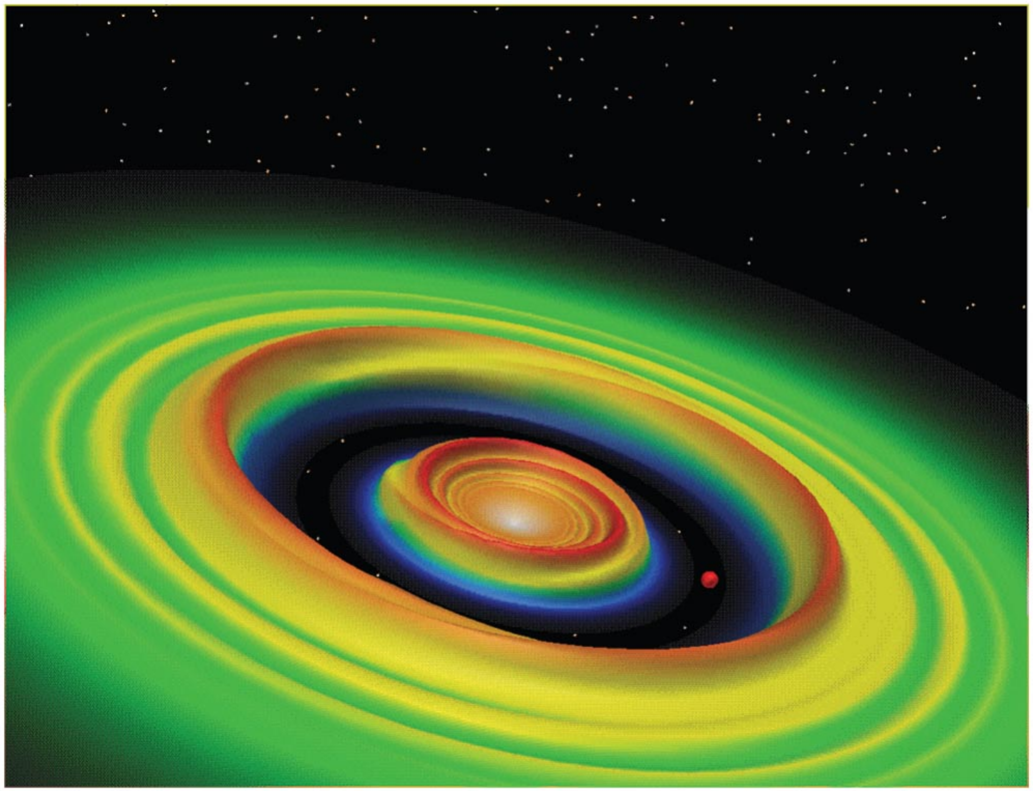
Can we explain the surprising orbits of many extrasolar planets?



Revisiting the Nebular Theory

- The nebular theory predicts that massive Jupiter-like planets should not form inside the frost line (at << 5 AU).
- The discovery of hot Jupiters has forced reexamination of nebular theory.
- *Planetary migration* or gravitational encounters may explain hot Jupiters.
- Even relatively small planets may be able to accrete H/He envelopes from the nebula

Planetary Migration

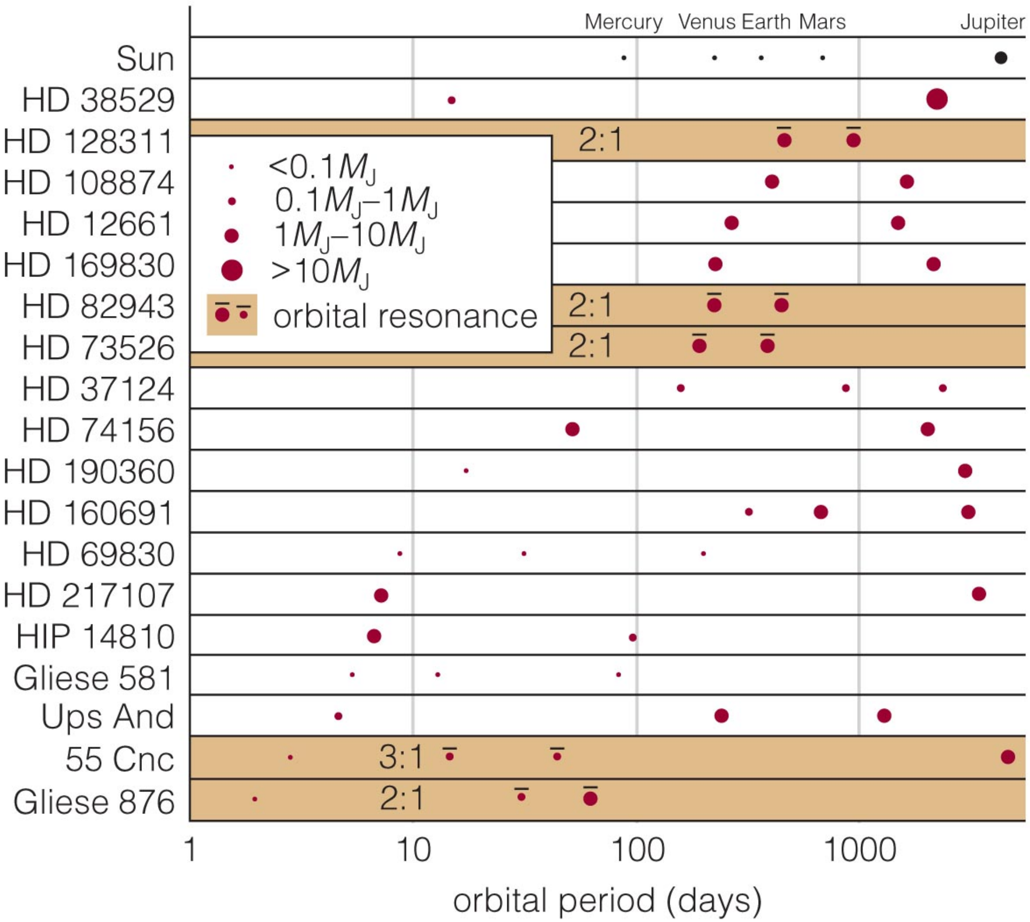


- A young planet's motion can create waves in a planet-forming disk.
- Models show that matter in these waves can tug on a planet, causing its orbit to migrate inward.

Gravitational Encounters

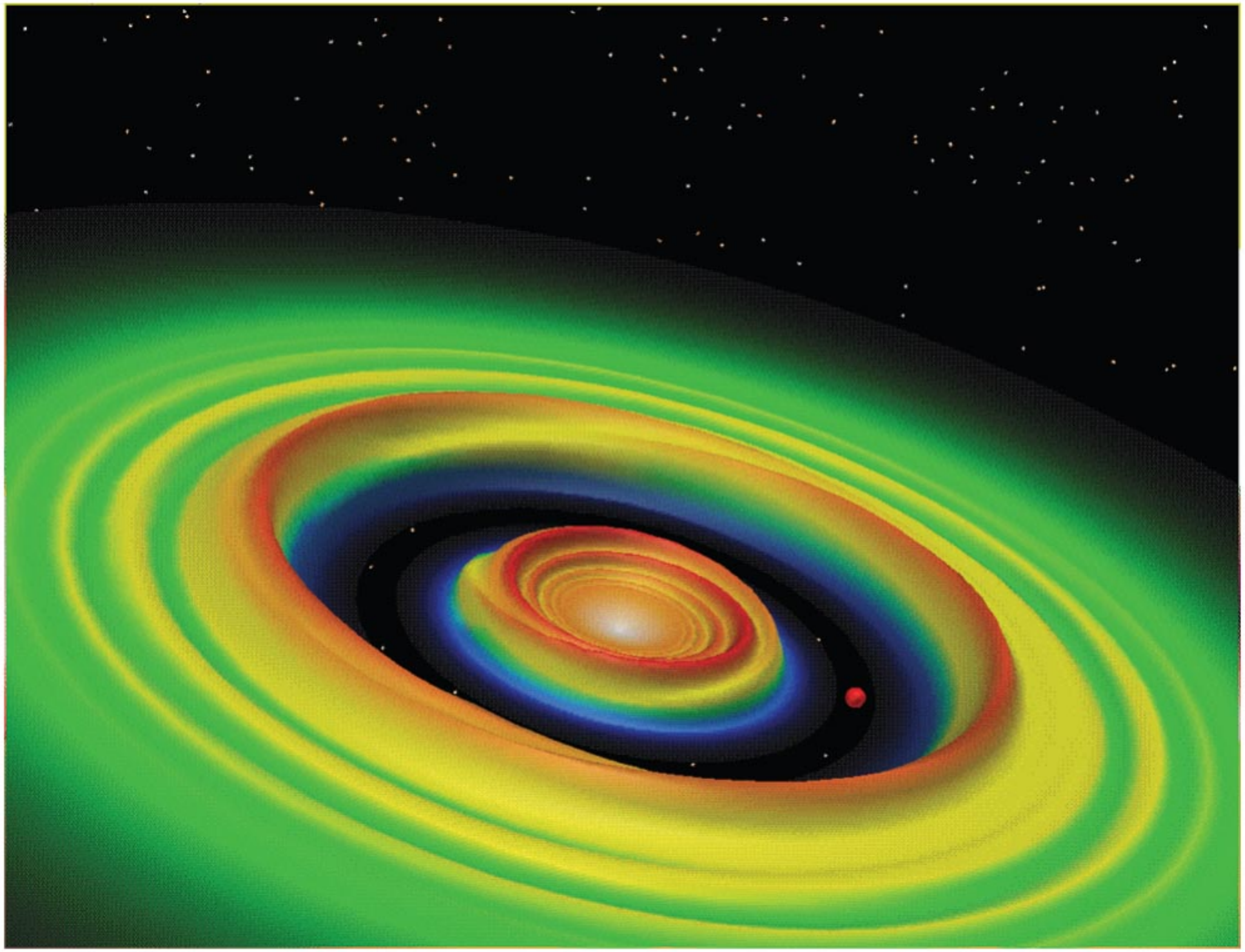
- Close gravitational encounters between two massive planets can eject one planet while flinging the other into a highly elliptical orbit.
  - One gets tossed in and is circularized by tides
  - One gets tossed out
- Multiple close encounters with smaller planetesimals can also cause inward migration.

Orbital Resonances



- Resonances between planets can also cause their orbits to become more elliptical.

Do we need to modify our theory of solar system formation?



Modifying the Nebular Theory

- Observations of extrasolar planets have shown that the nebular theory was incomplete.
- Effects like planetary migration and gravitational encounters might be more important than previously thought.