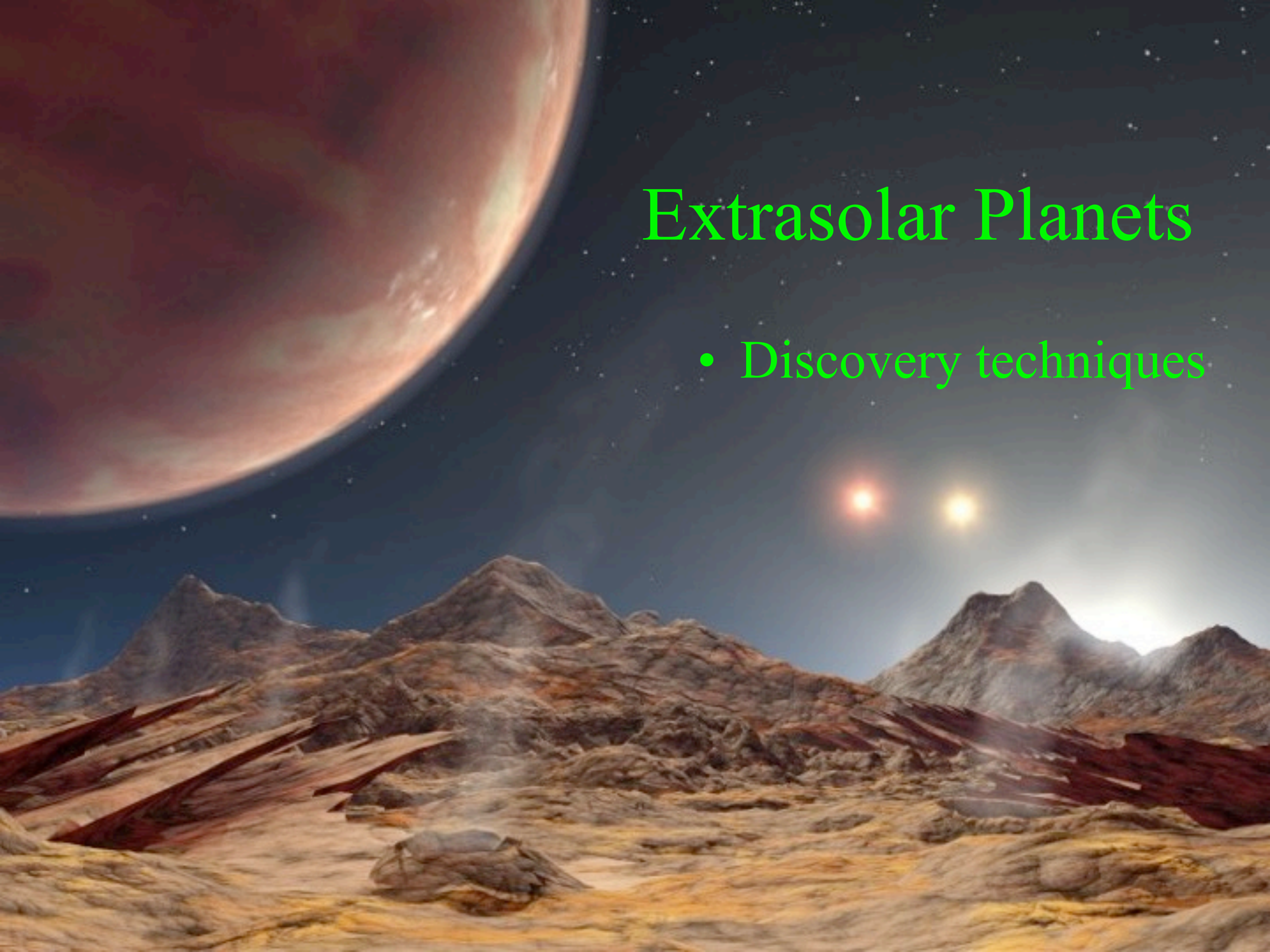
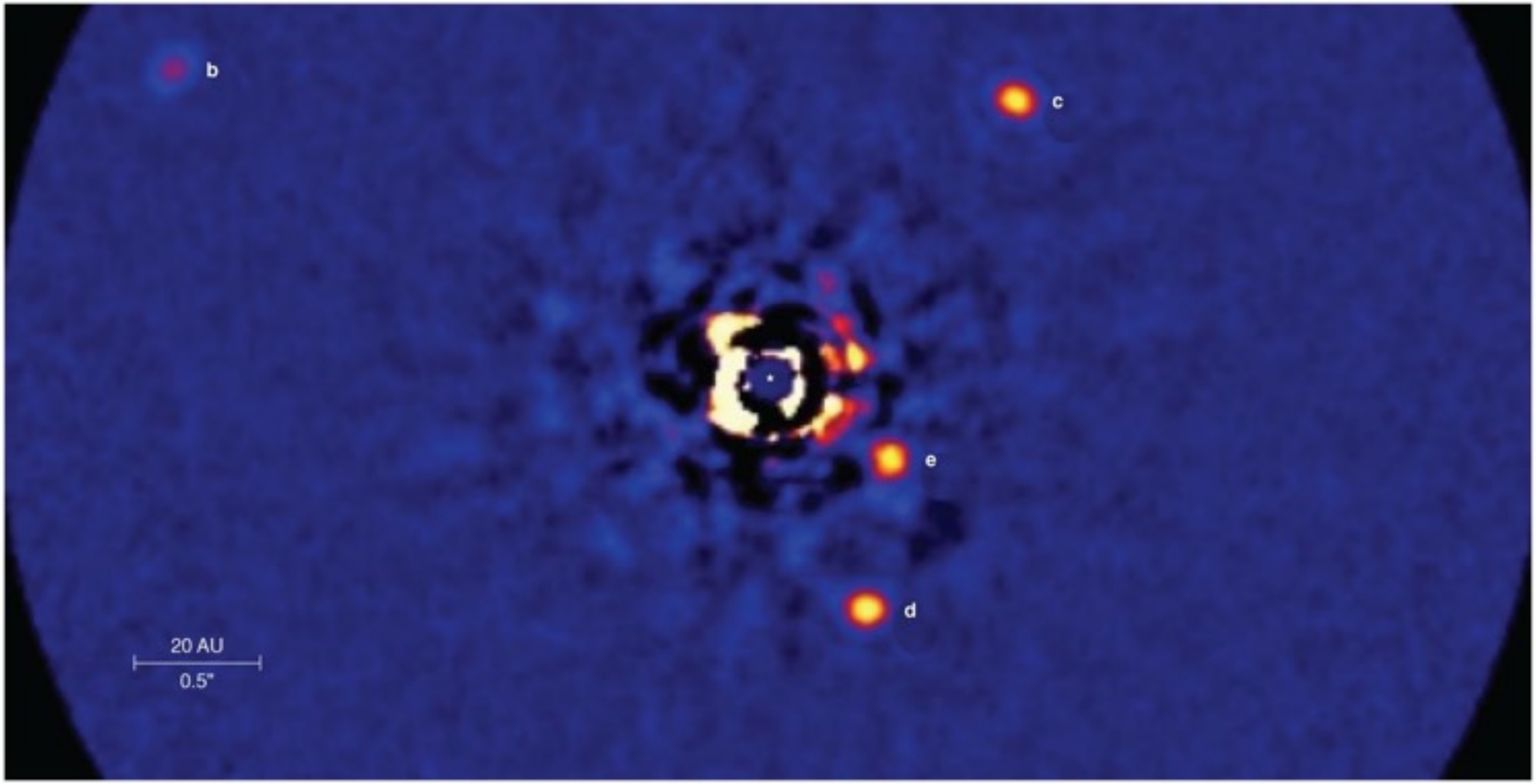


Extrasolar Planets

- Discovery techniques

Finding extrasolar planets is hard

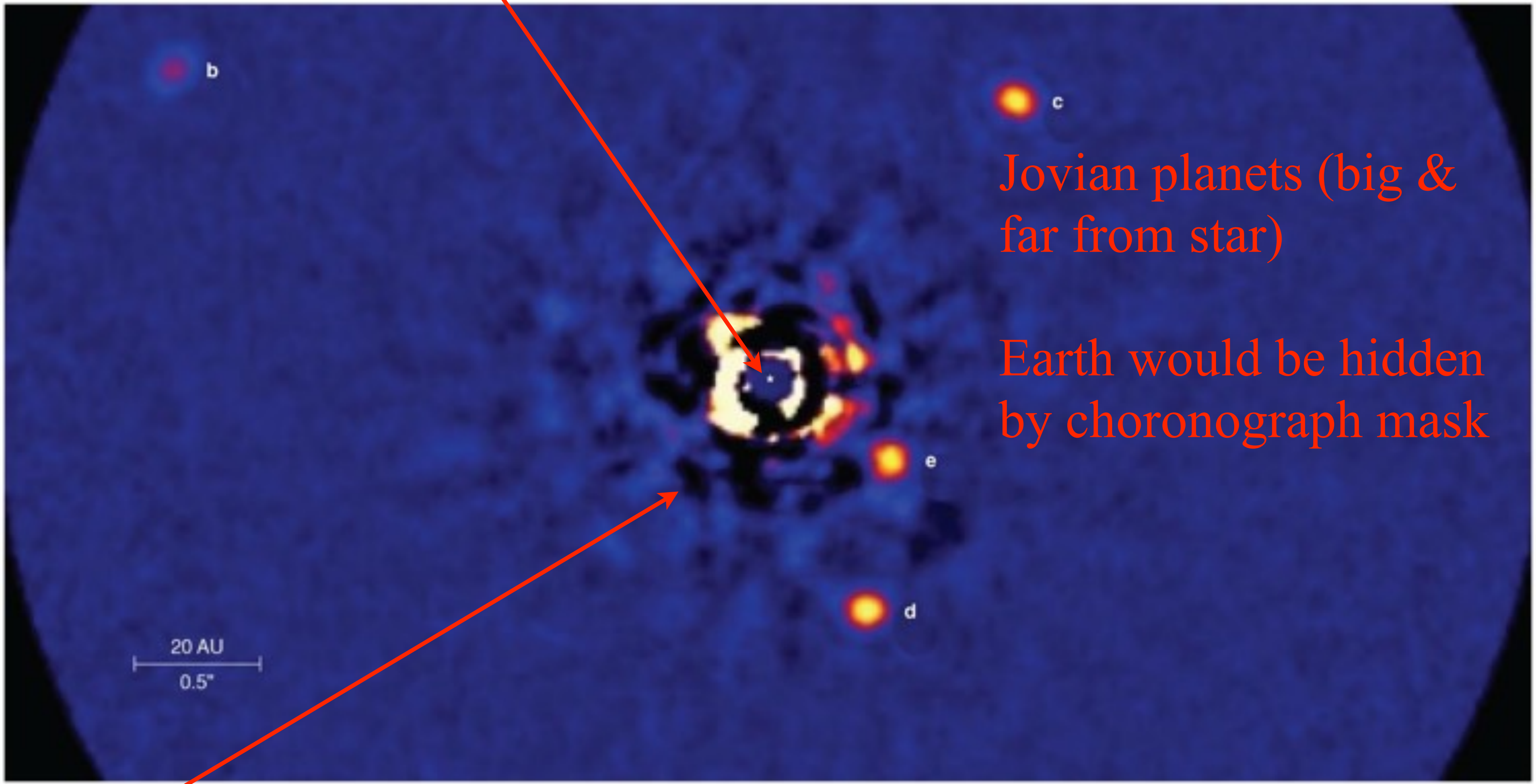


Brightness and Distance

- A Sun-like star is about a billion times brighter than the light reflected from its planets.
- Planets are close to their stars, relative to the distance from us to the star.
  - This is like being in San Francisco and trying to see a pinhead 15 meters from a grapefruit in Washington, D.C.
  - Only the grapefruit is ridiculously bright, while the pinhead is just a pinhead, and reflects a tiny bit of the grapefruit's light.

Finding extrasolar planets is hard

Choronographic mask to block direct light from star



Jovian planets (big & far from star)

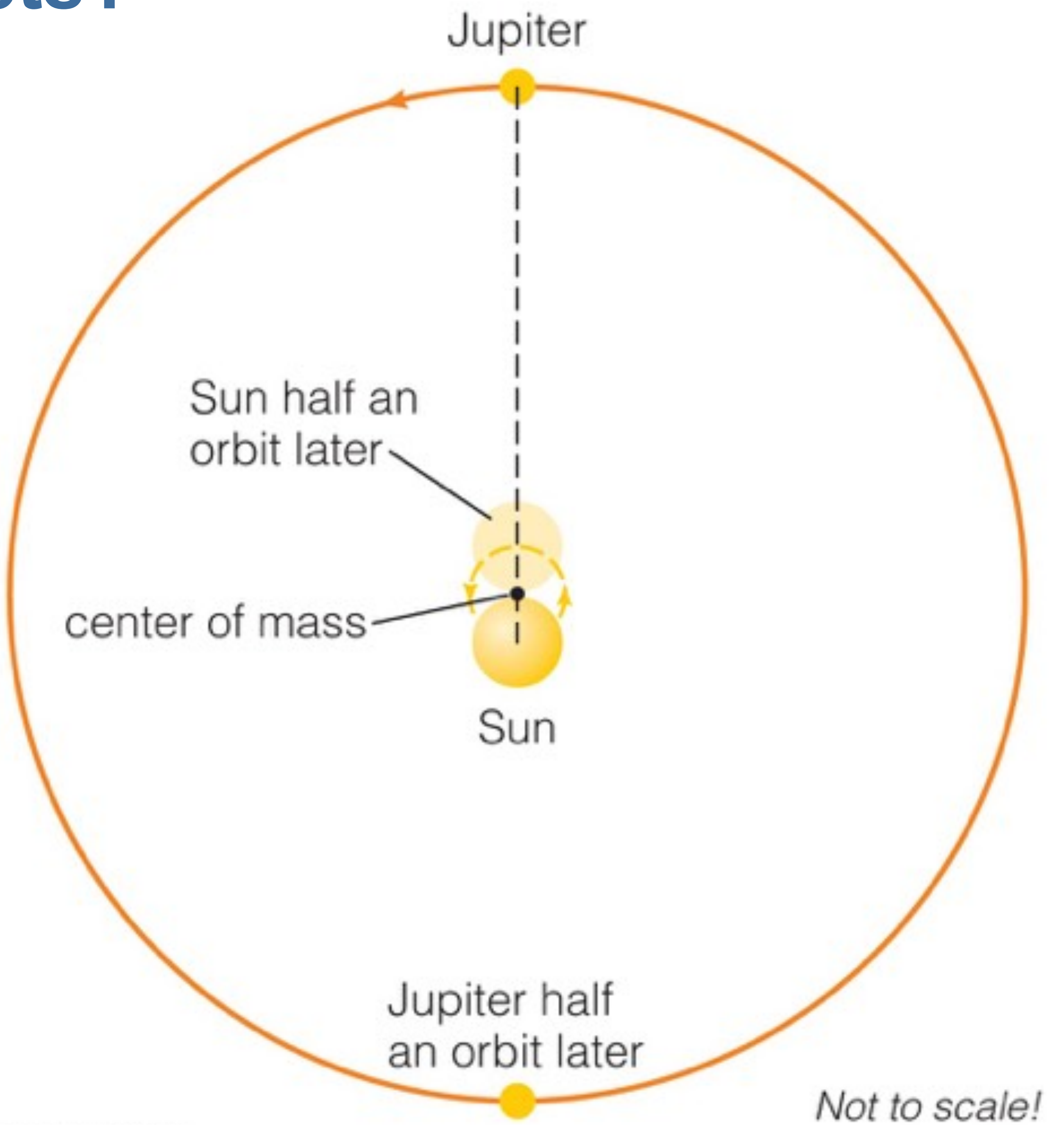
Earth would be hidden by choronograph mask

Noise from scattered light (internal reflections within telescope)

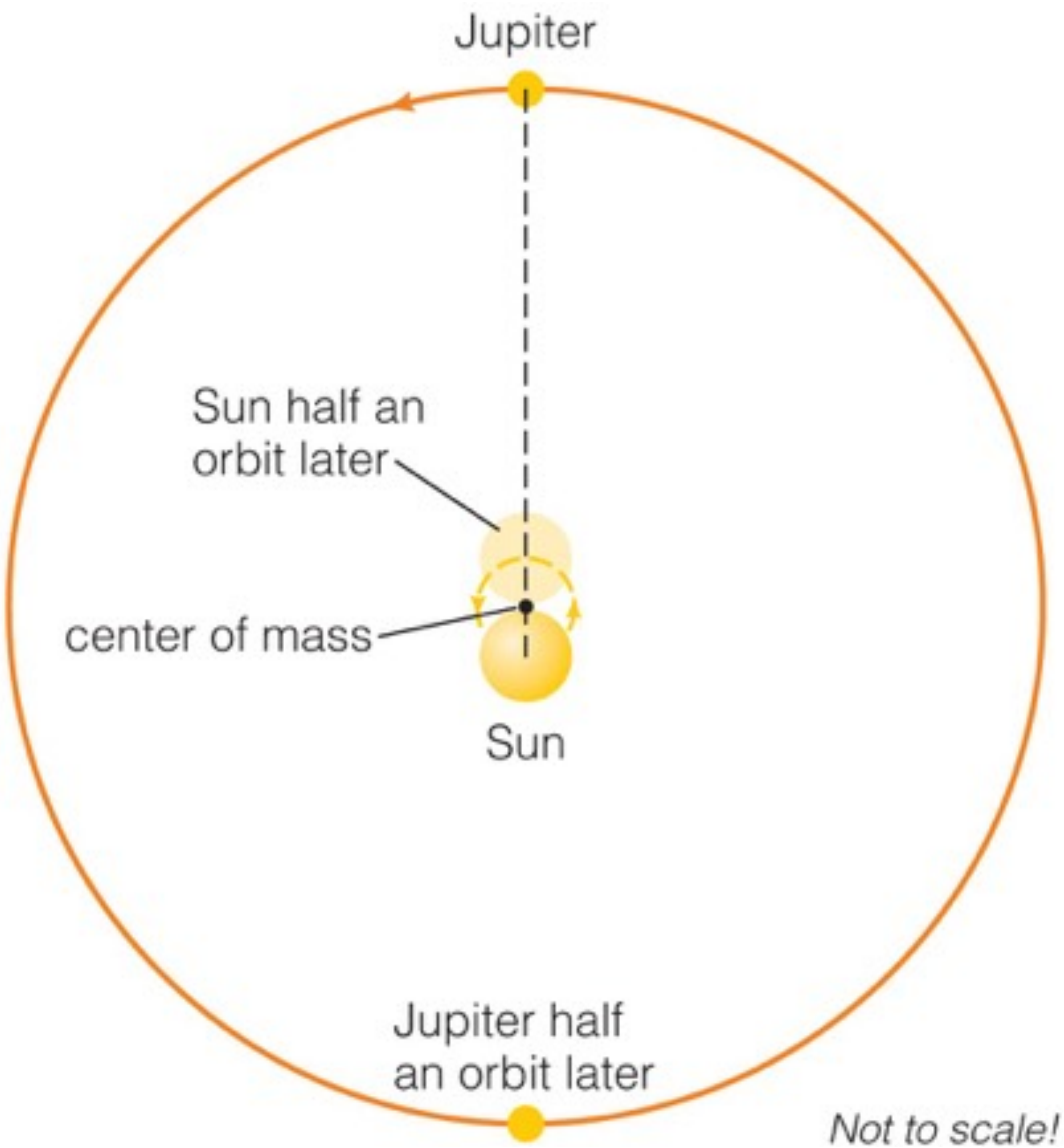
Planet Detection

- **Direct:** pictures or spectra of the planets themselves
- **Indirect:** measurements of stellar properties revealing the effects of orbiting planets

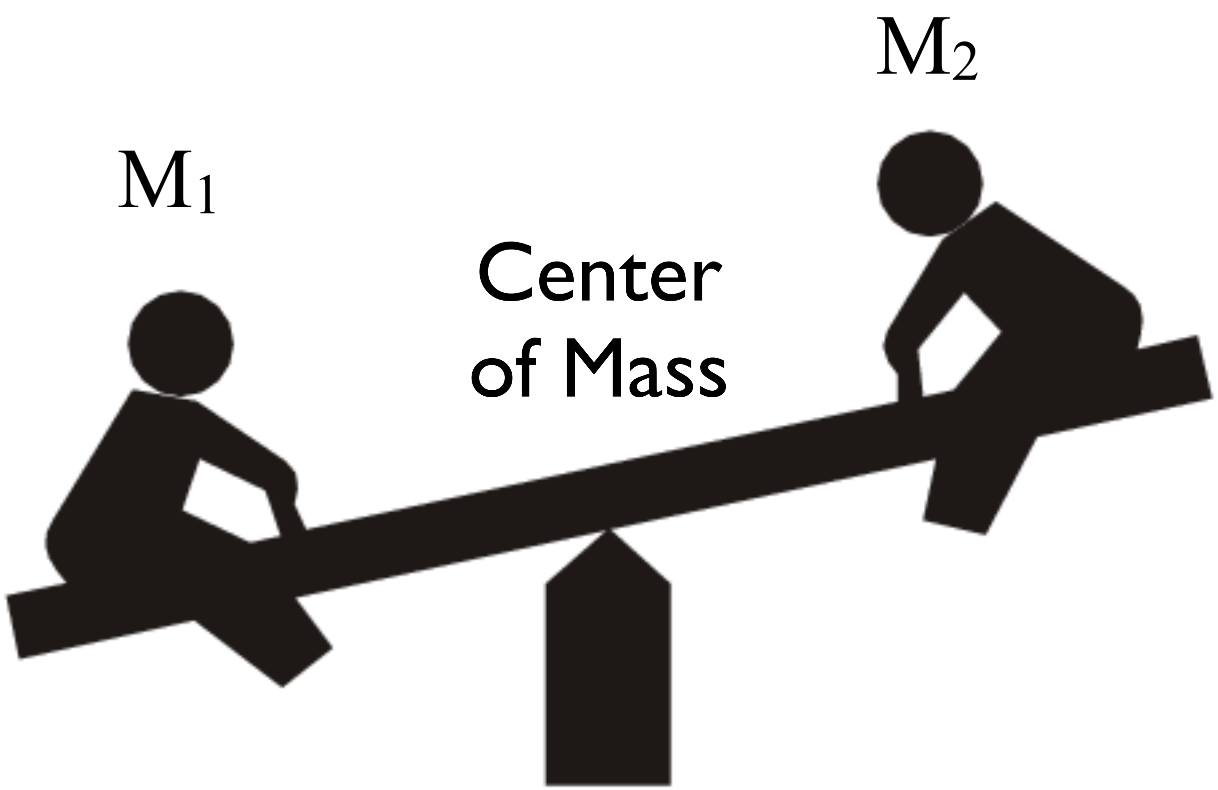
How can a star's motion reveal the presence of planets?



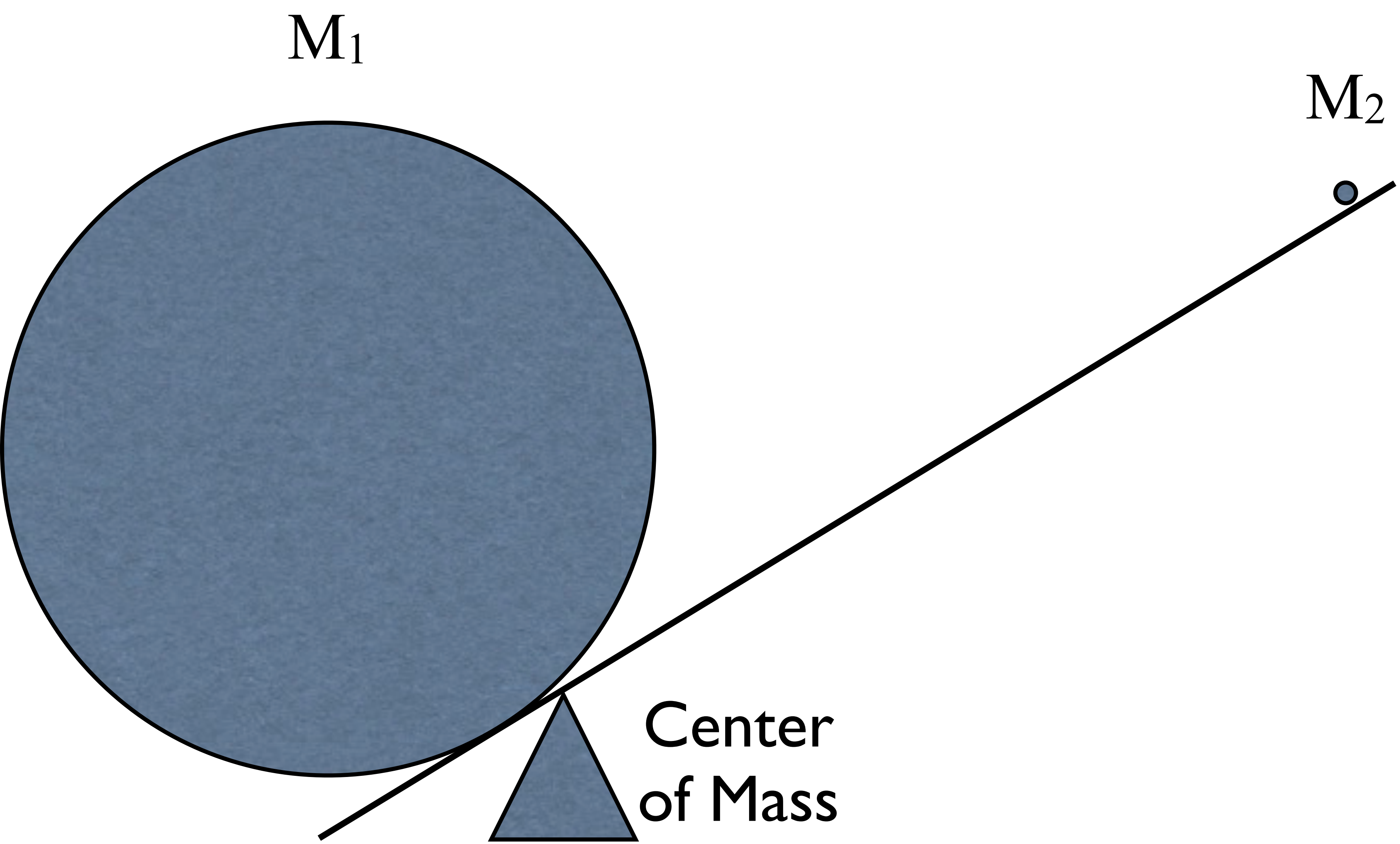
Gravitational Tugs



- The Sun and Jupiter orbit around their common center of mass.
- The Sun therefore wobbles around that center of mass with same period as Jupiter.



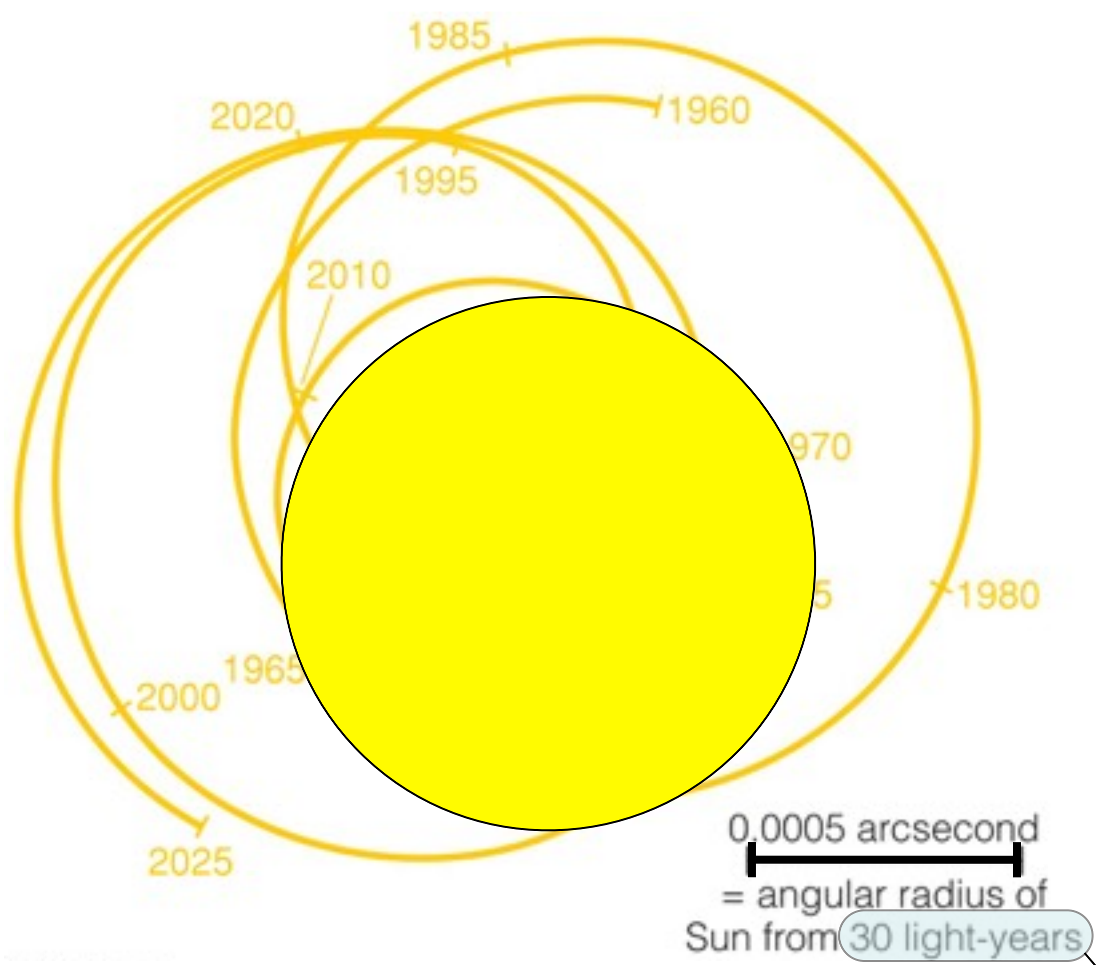
Center of Mass in the middle when $M_1 = M_2$



Center of Mass close to M_1 when $M_1 >> M_2$

Recall: the sun is about 1,000 times more massive than Jupiter

Gravitational Tugs

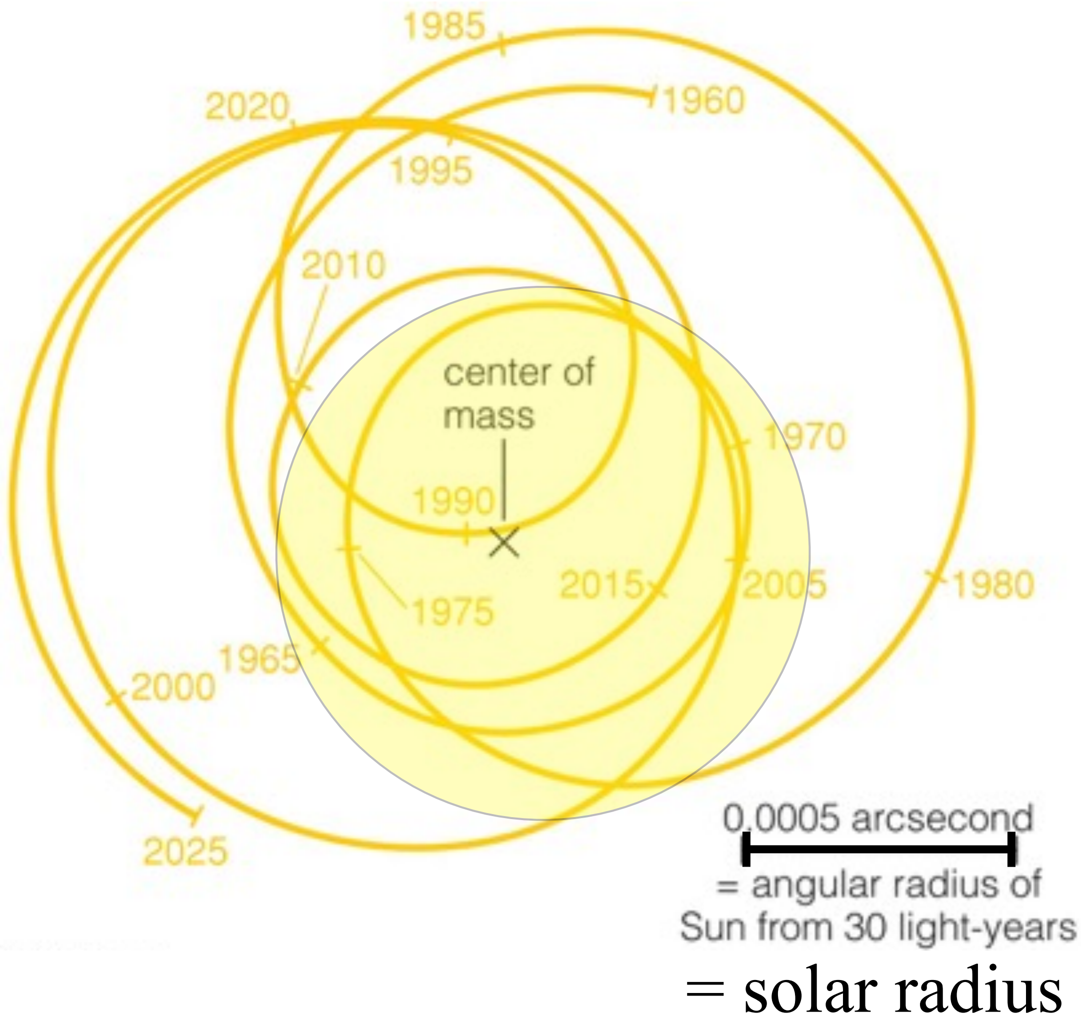


= solar radius

- The Sun's motion around the solar system's center of mass depends on tugs from all the planets.
- Astronomers around other stars that measured this motion could determine the masses and orbits of all the planets.

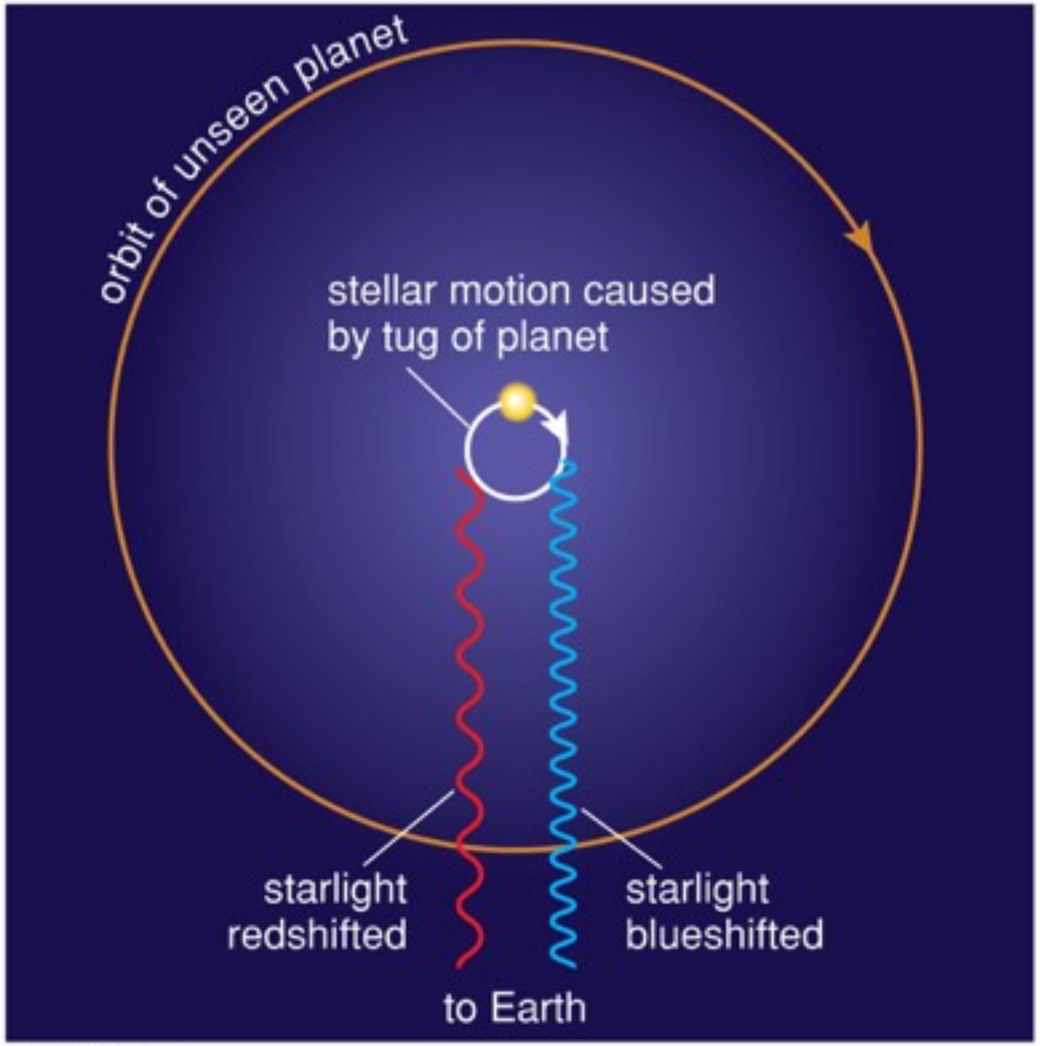
30 light-years is pretty nearby by astronomical standards

Astrometric Technique



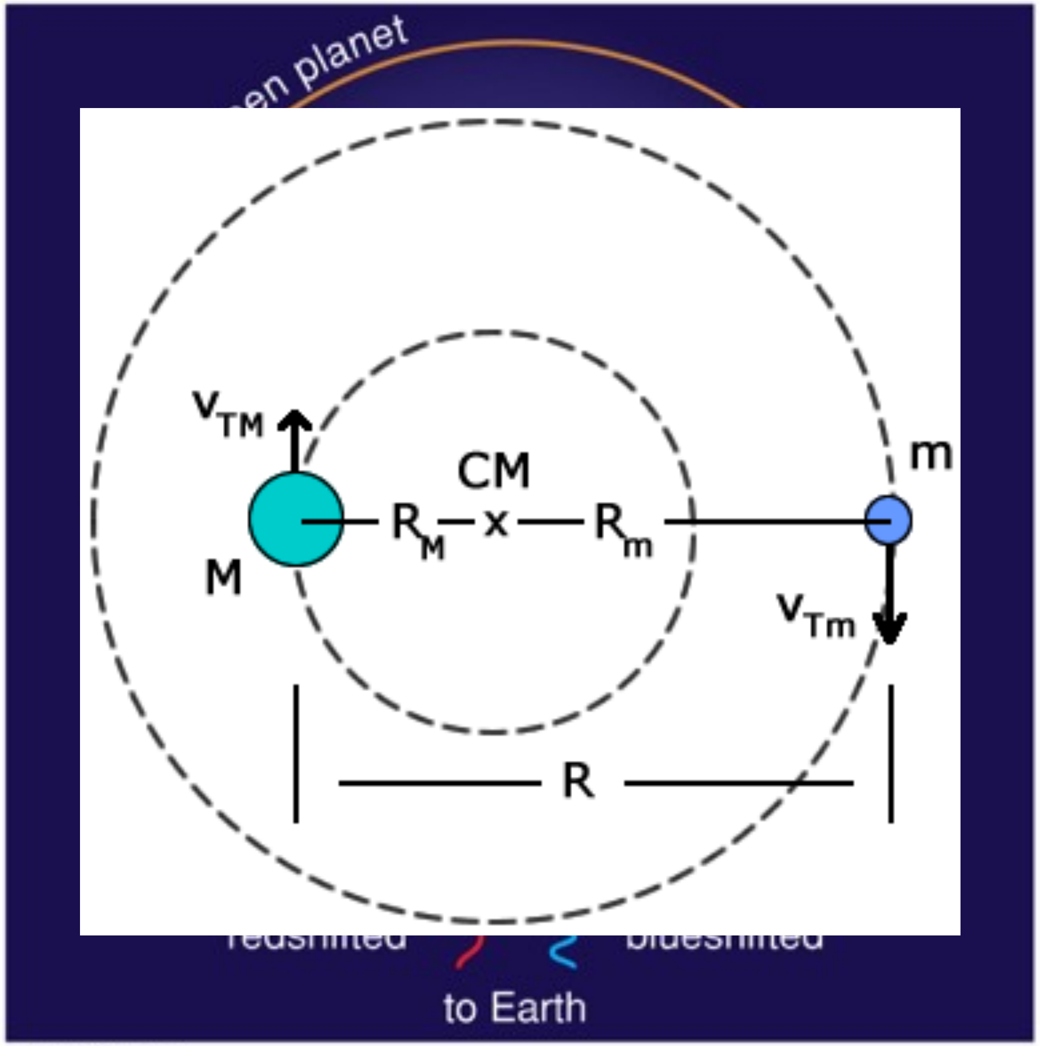
- We can detect planets by measuring the change in a star's position on sky.
- However, these tiny motions are very difficult to measure (~ 0.001 arcsecond).
- Best seen face-on

Doppler Technique



- Measuring a star's Doppler shift can tell us its motion toward and away from us.
- Current techniques can measure motions as small as 1 m/s (walking speed!).

Doppler Technique

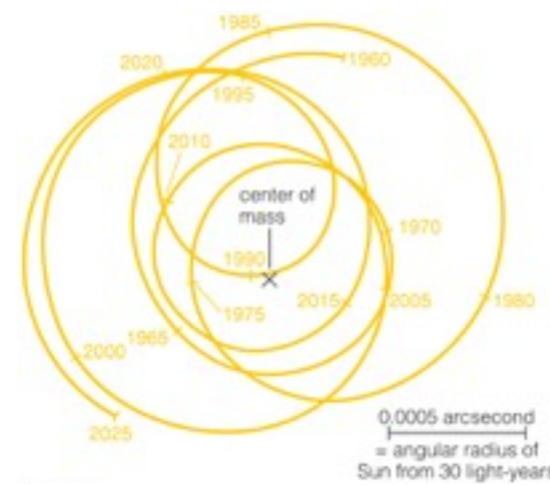


- Measuring a star's Doppler shift can tell us its motion toward and away from us.
- Current techniques can measure motions as small as 1 m/s (walking speed!).
- Best seen edge-on

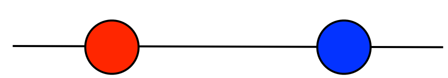
Same thing seen different ways

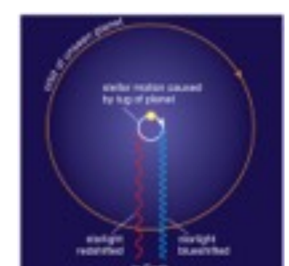
- The Astrometric technique and the
- Doppler technique
  - are both looking for center of mass motion

  - Astrometric: space motion seen face-on

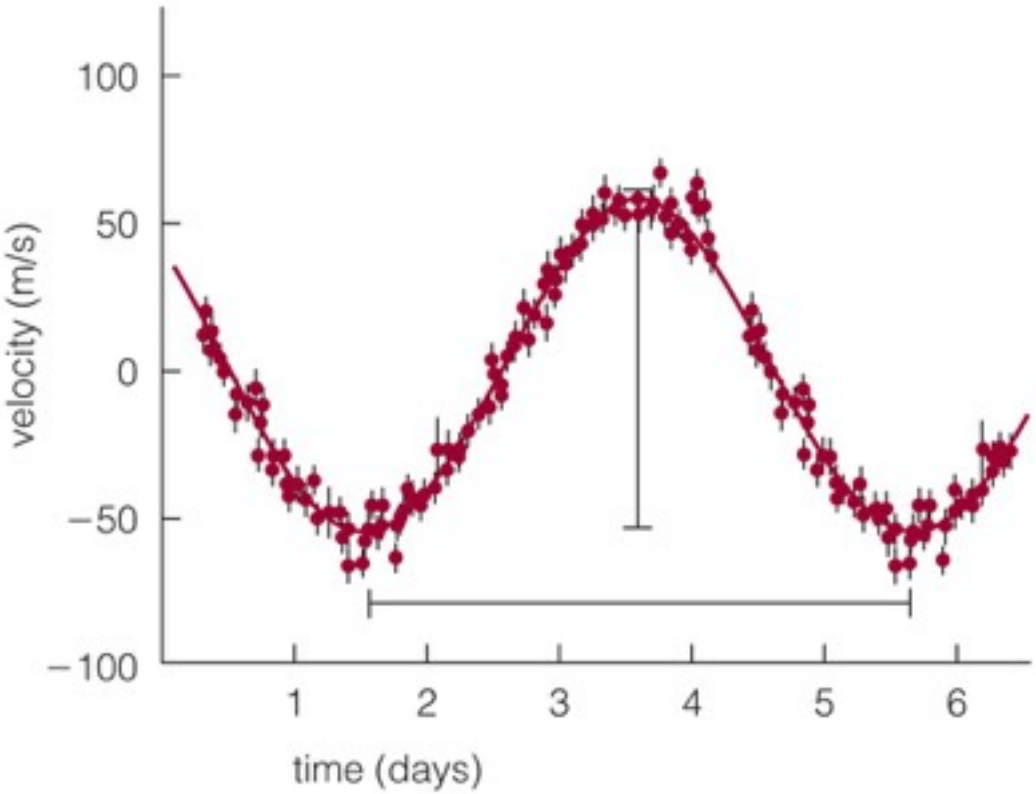


  - Doppler: velocity seen edge-on



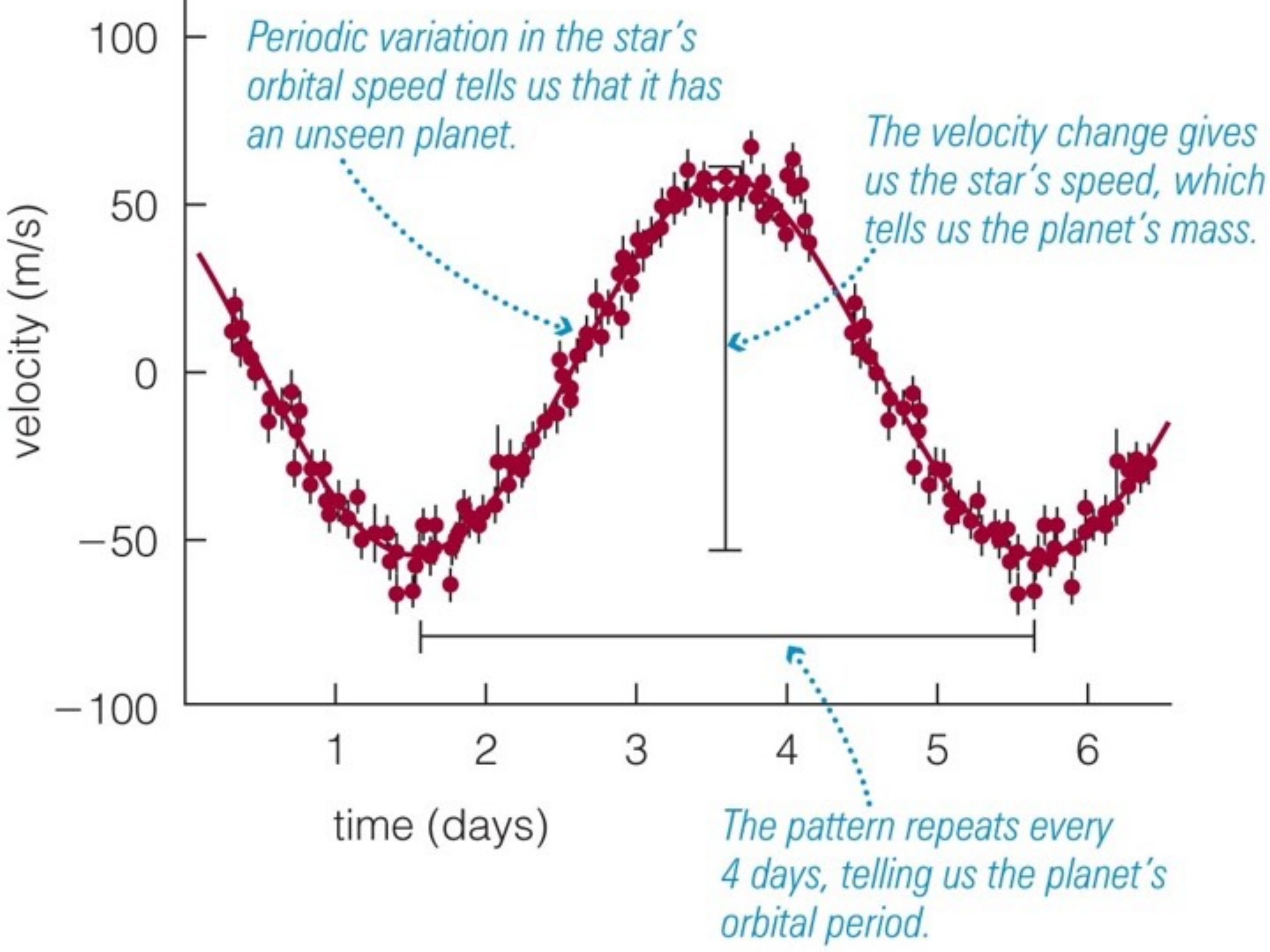


First [proper] Extrasolar Planet



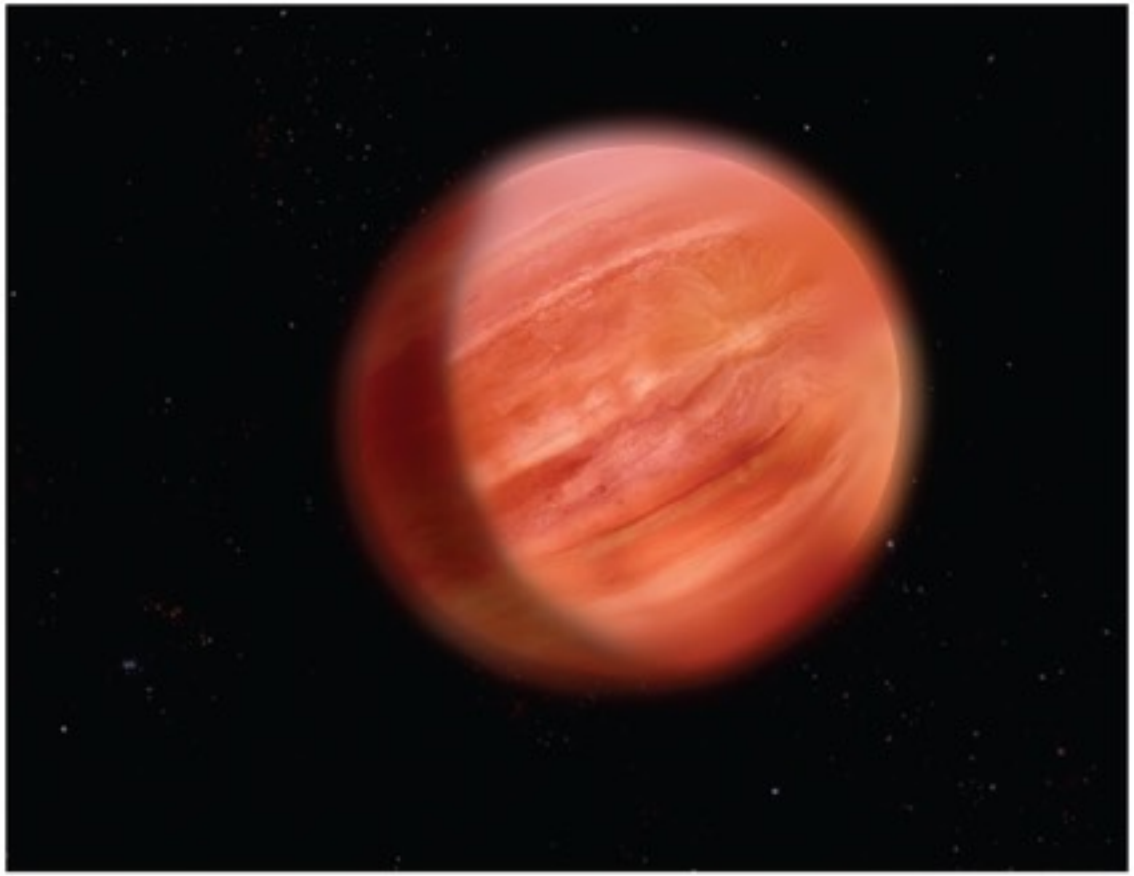
a A periodic Doppler shift in the spectrum of the star 51 Pegasi shows the presence of a large planet with an orbital period of about 4 days. Dots are actual data points; bars through dots represent measurement uncertainty.

- Doppler shifts of the star 51 Pegasi indirectly revealed a planet with 4-day orbital period.
- This short period means that the planet has a small orbital distance.
- This was the first extrasolar planet to be discovered around a Sun-like star (1995).



Periodic variation in the star's orbital speed tells us that it has an unseen planet.
The velocity change gives us the star's speed, which tells us the planet's mass.
The pattern repeats every 4 days, telling us the planet's orbital period.
velocity (m/s)
100
50
0
−50
−100
1
2
3
4
5
6
time (days)

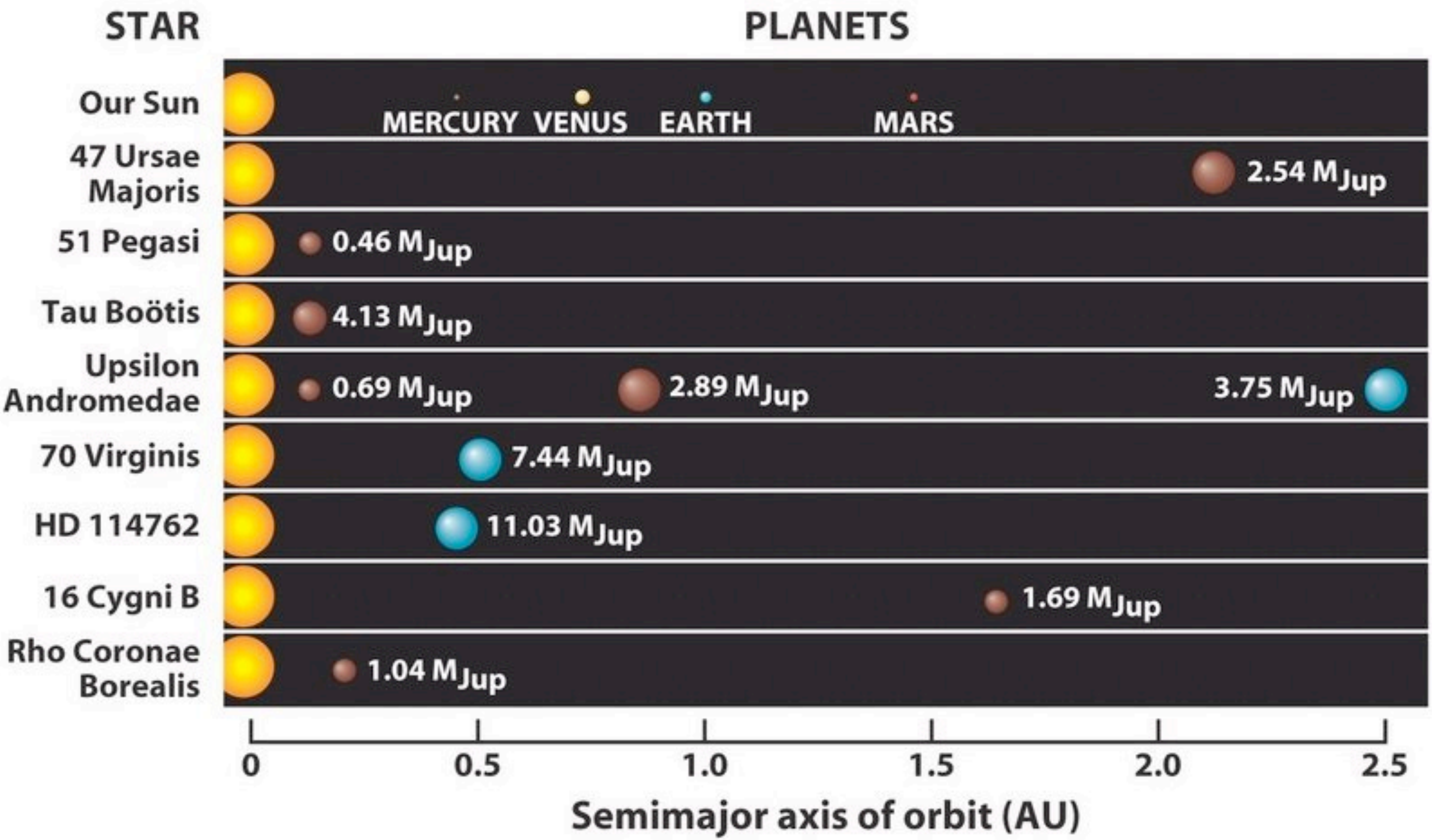
First Extrasolar Planet



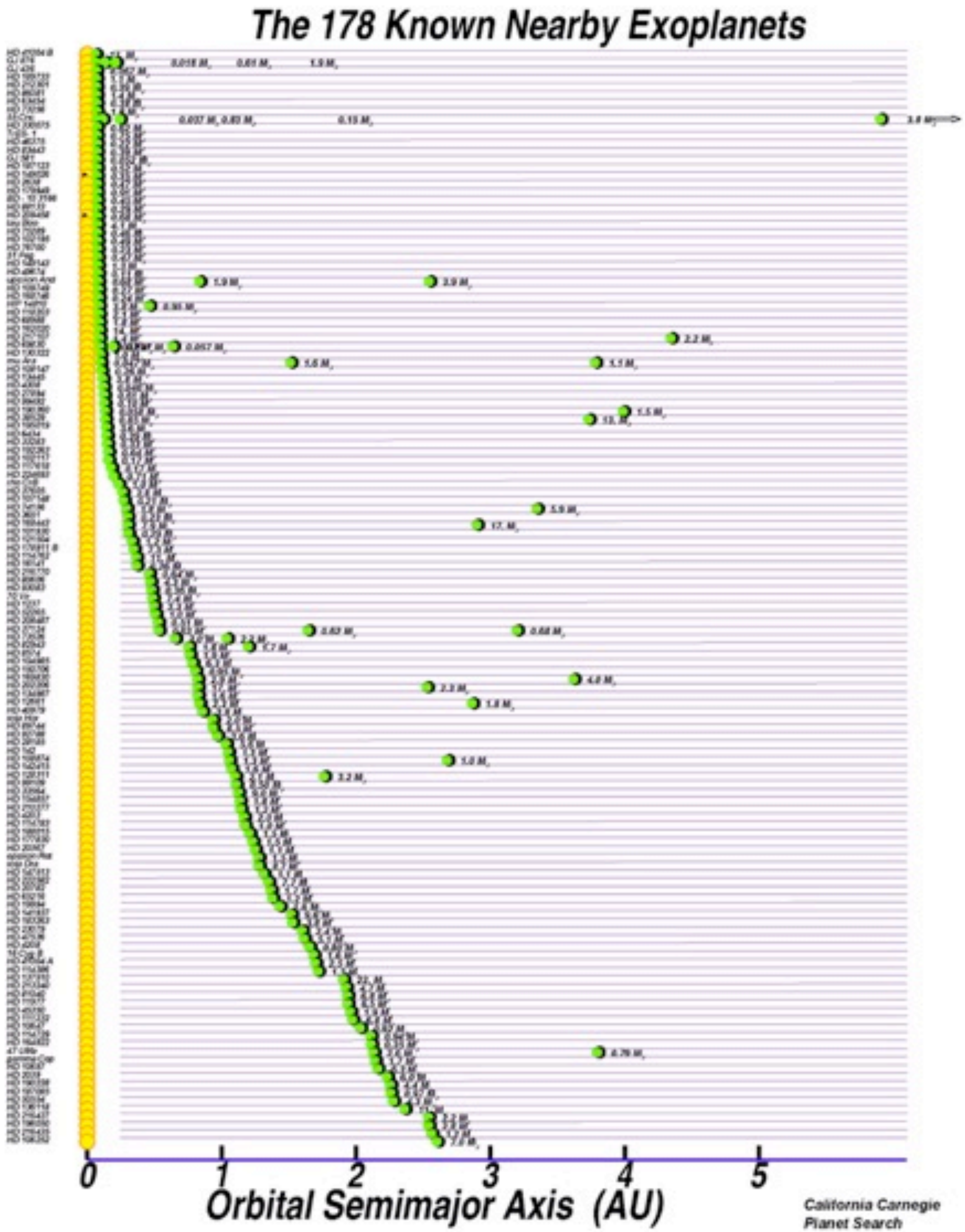
b Artist's conception of the planet orbiting 51 Pegasi, which probably has a mass similar to that of Jupiter but orbits its star at only about one-eighth of Mercury's orbital distance from the Sun. It probably has a surface temperature above 1000 K, making it an example of what we call a hot Jupiter.

- The planet around 51 Pegasi has a mass similar to Jupiter's, despite its small orbital distance.

A few of the early discoveries of planets around solar tpye stars



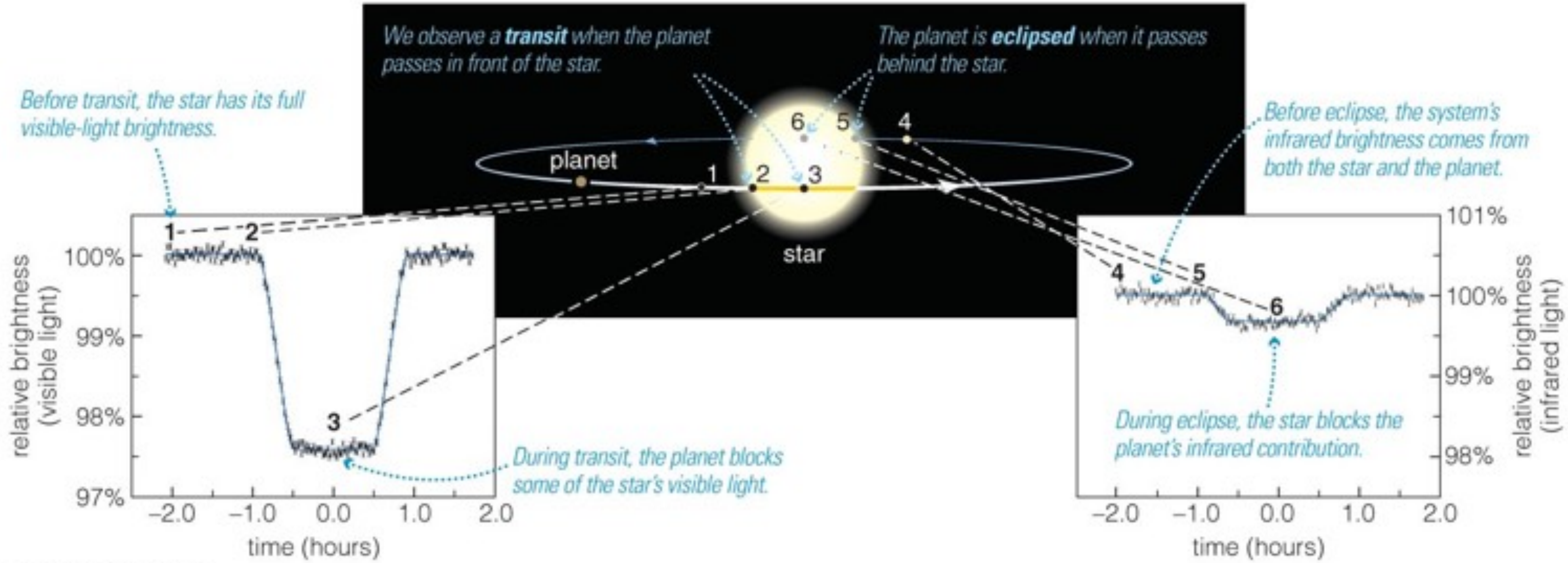
Note diversity; frequency of large planets close to host star (*selection effect*)



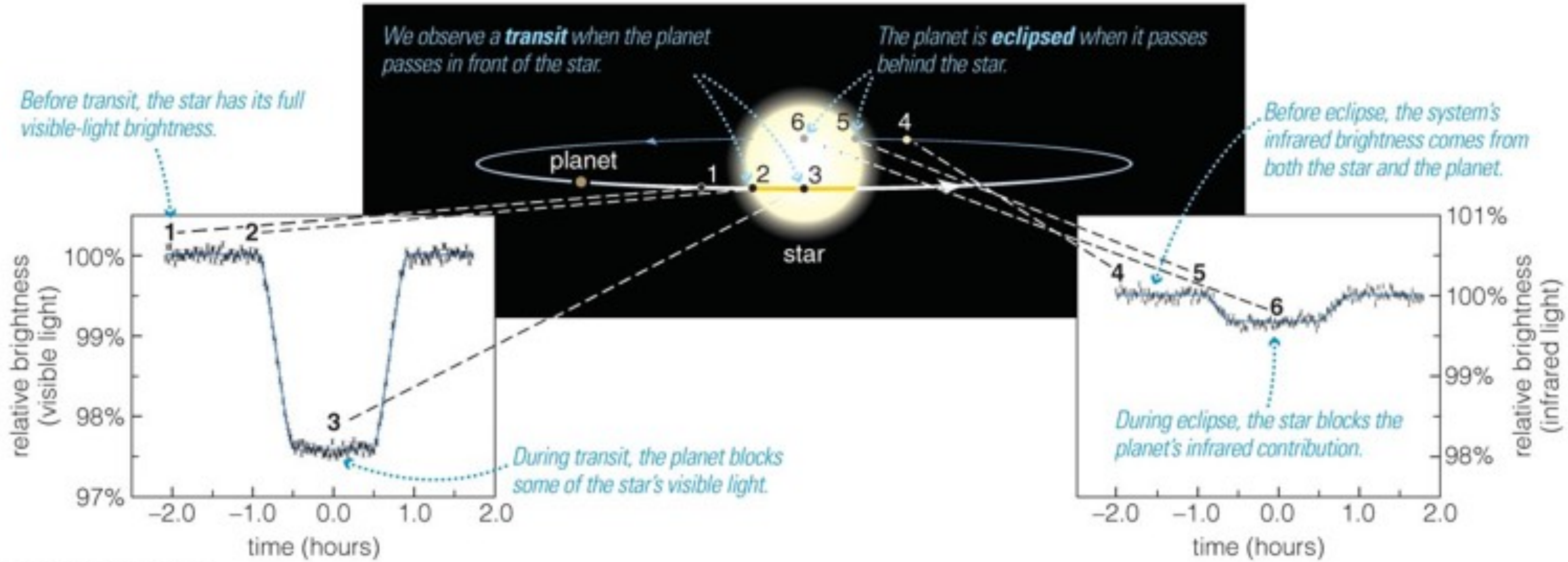
178 planets known by 2005, a decade after the discovery of 51 Peg.

178 seemed like a lot before the Kepler mission (launched 2009).

How can changes in a star's brightness reveal the presence of planets ?

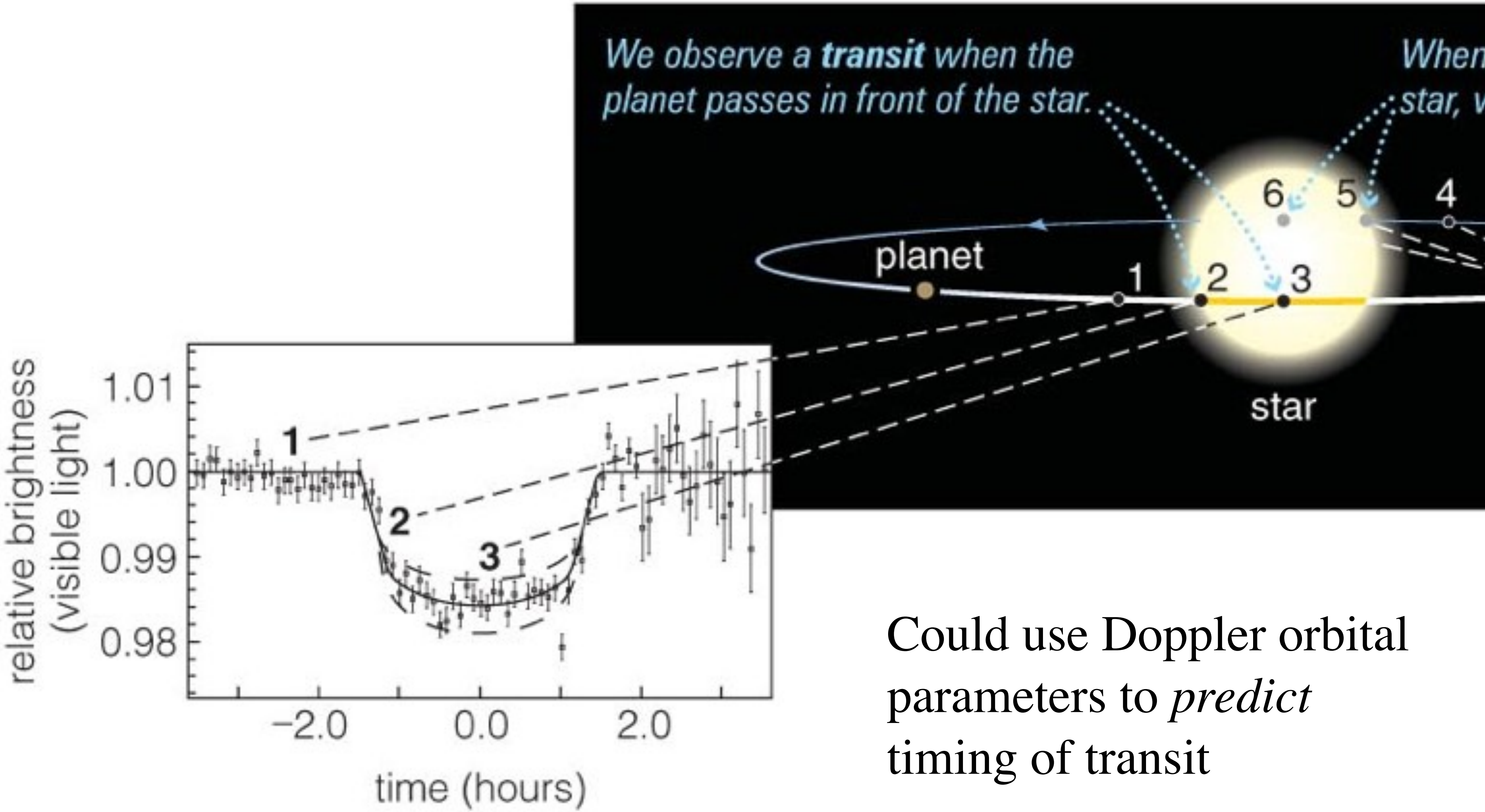


Transits and Eclipses

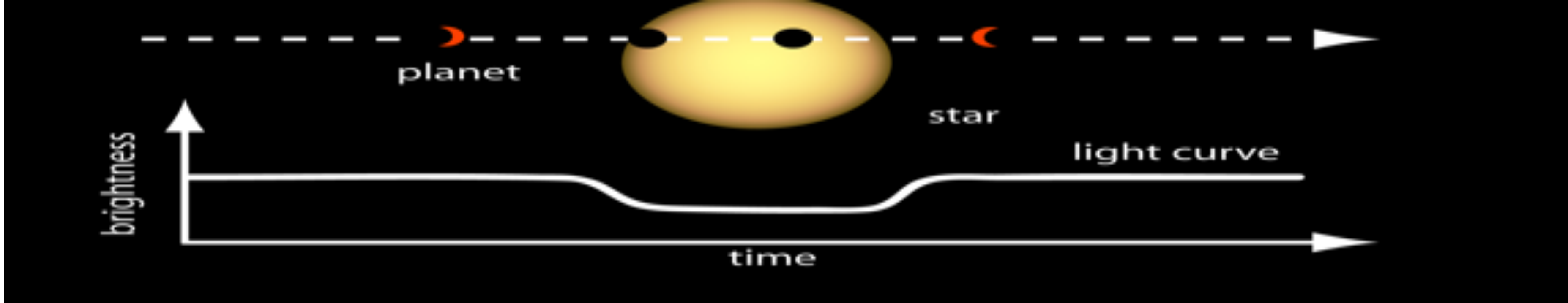


- A **transit** is when a planet crosses in front of a star.
- The resulting eclipse reduces the star's apparent brightness and tells us planet's radius.
- No orbital tilt: accurate measurement of planet mass
  – best seen edge-on

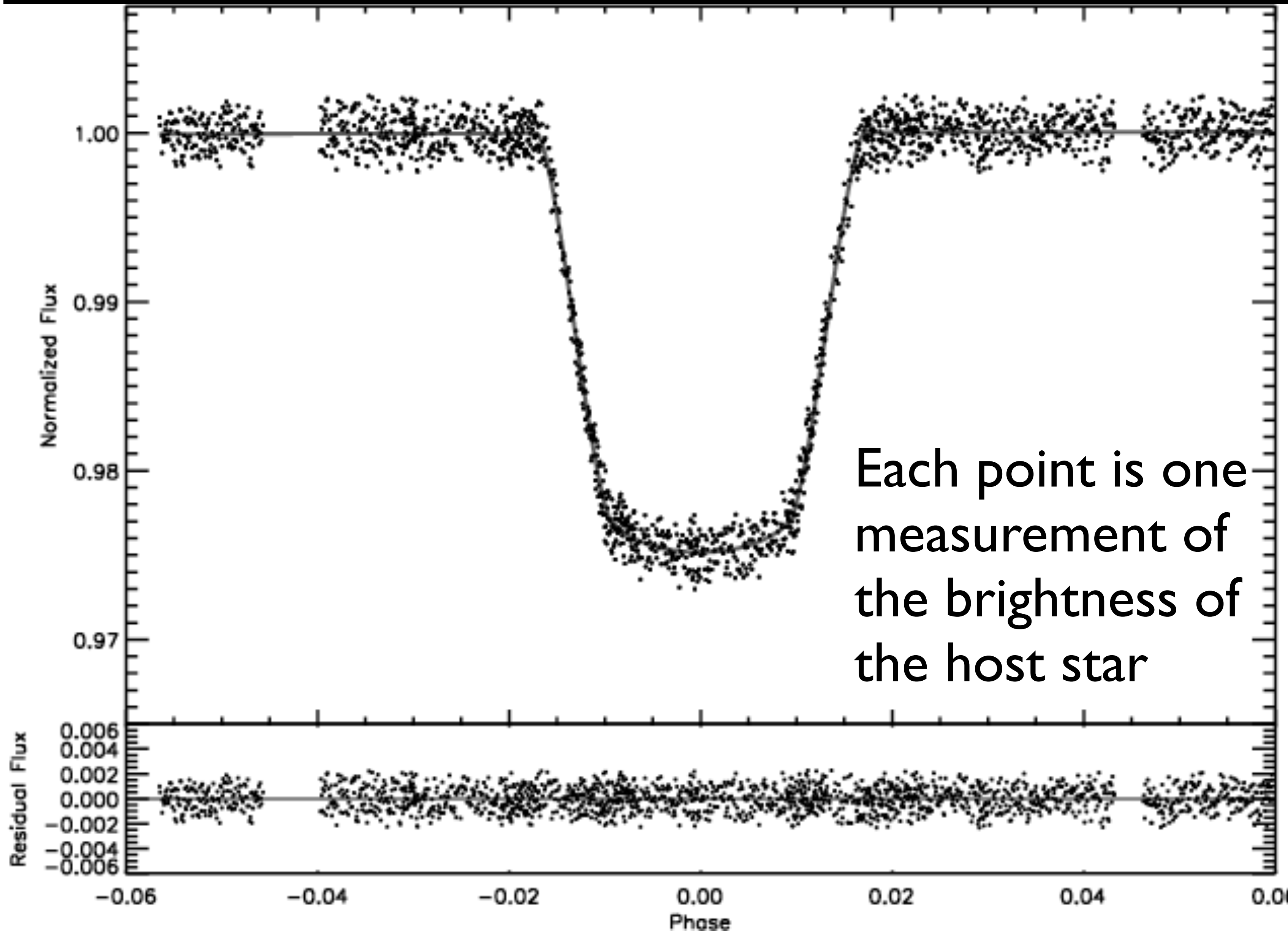
Some planets detected via the Doppler effect have been confirmed by transit observations:



Could use Doppler orbital parameters to *predict* timing of transit

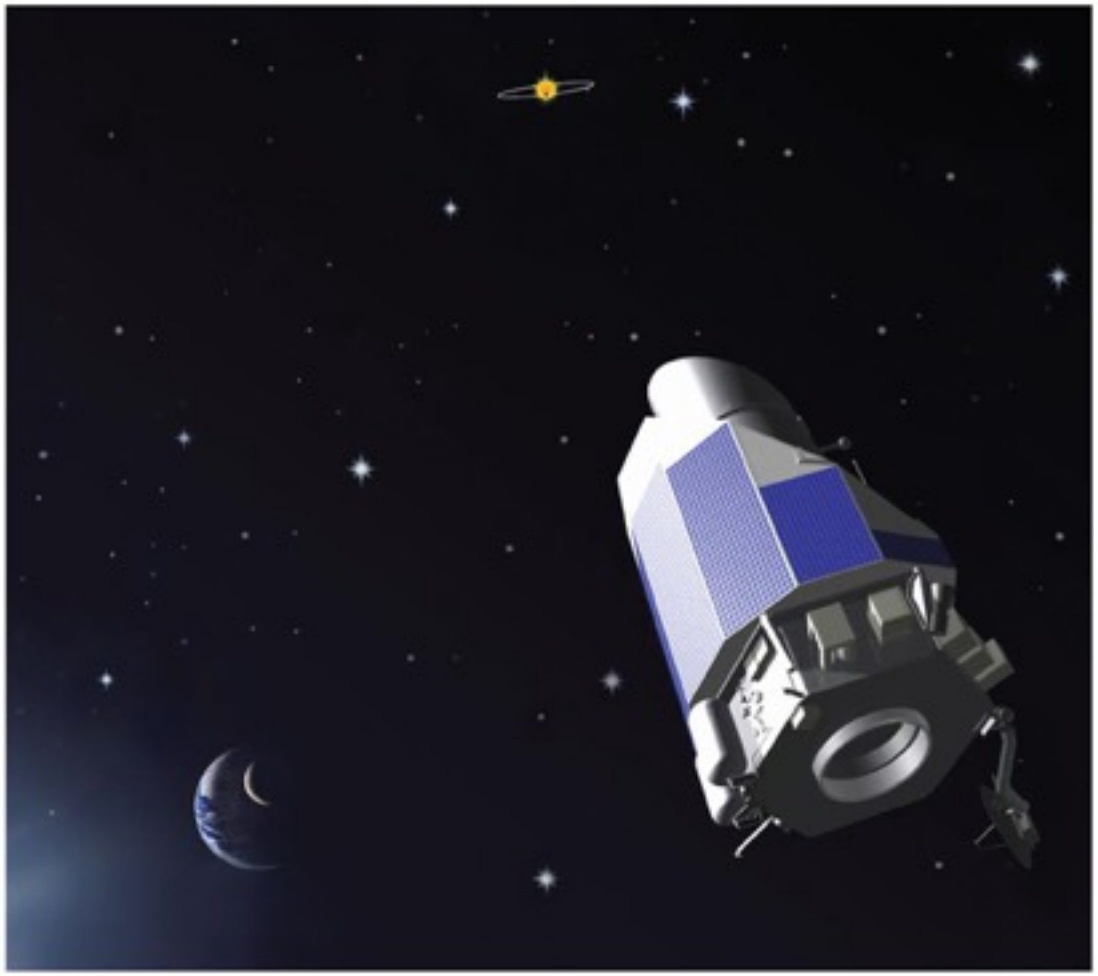


NOTE SCALE



Each point is one measurement of the brightness of the host star

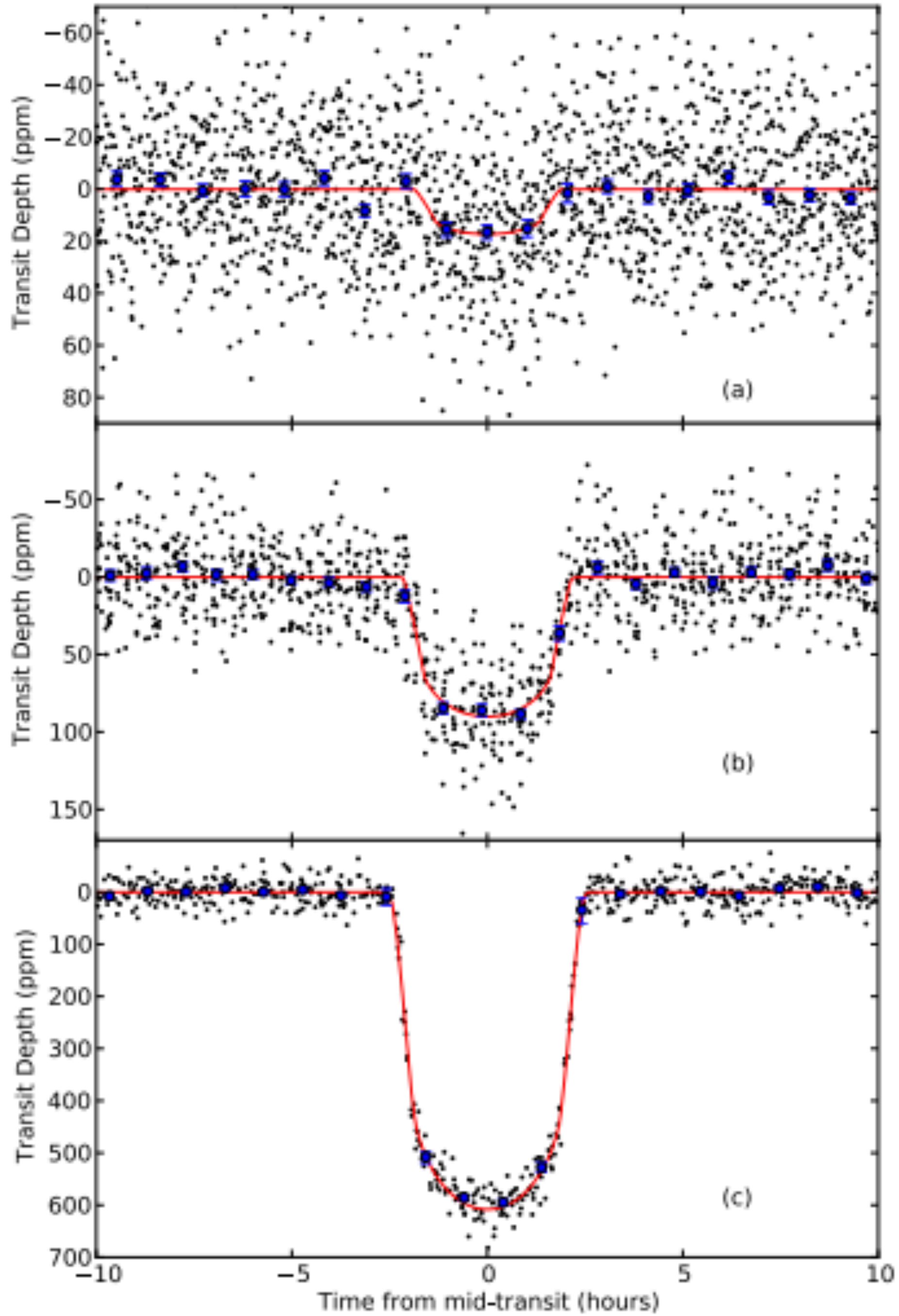
Kepler mission



- NASA's *Kepler* mission searched for transiting planets 2009-2013.
- Second reaction wheel failure ended primary mission
- Still very successful -
- Detected thousands of transiting planets down to 0.008% decline in brightness of the host star.

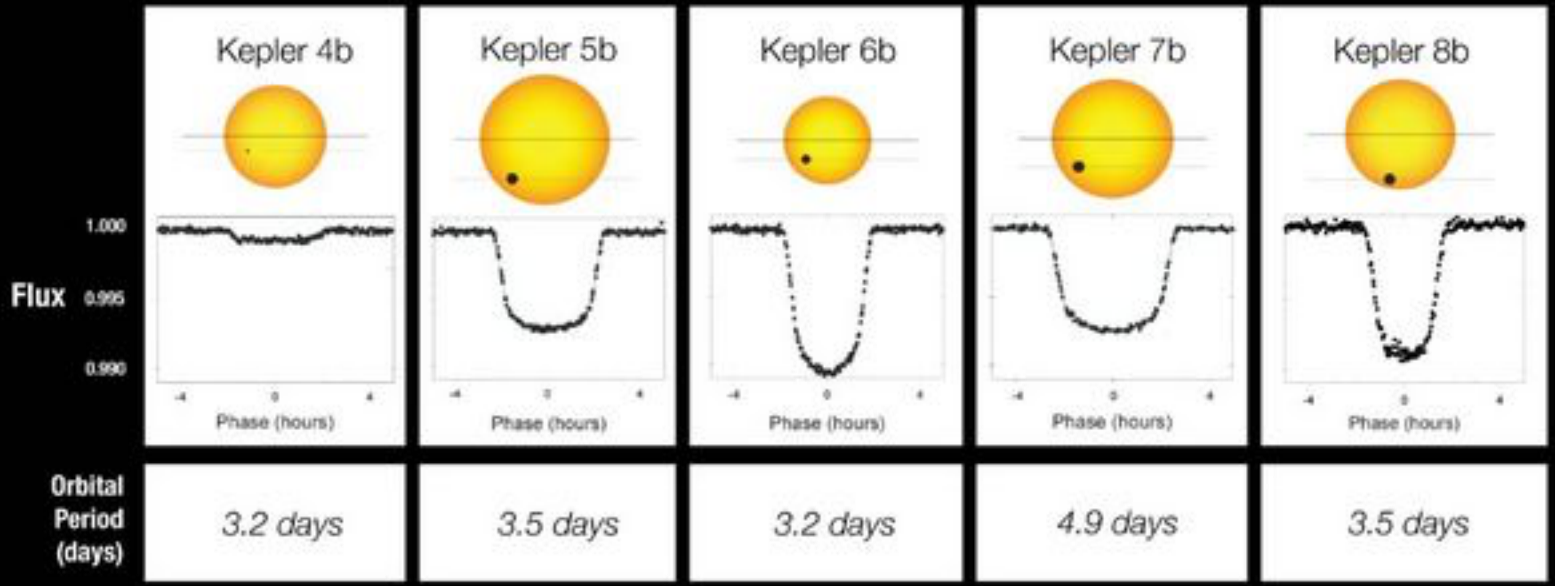
Kepler transit data

transit depths measured in parts per million

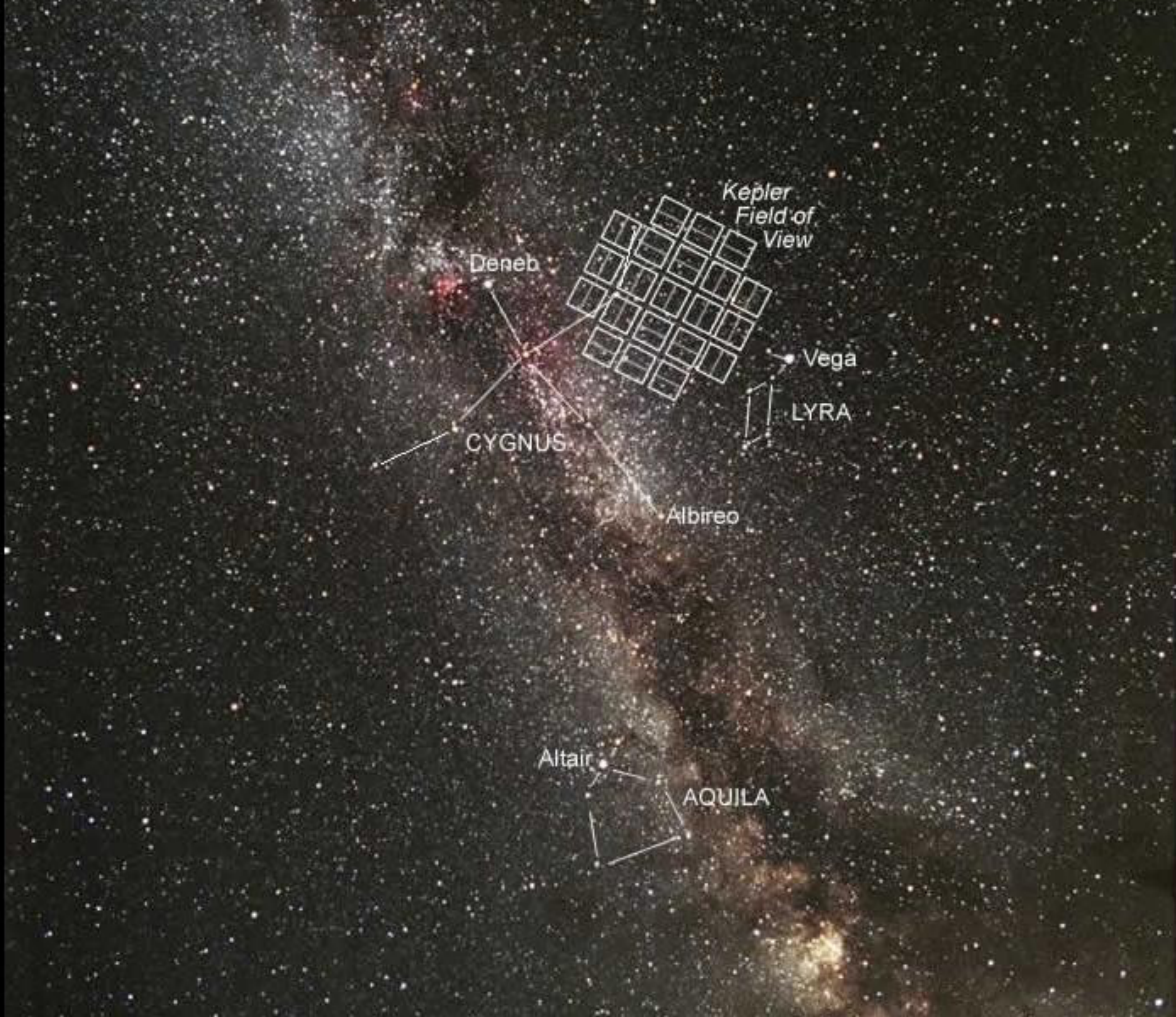


transit depths depend on the radius of the planet relative to the host star

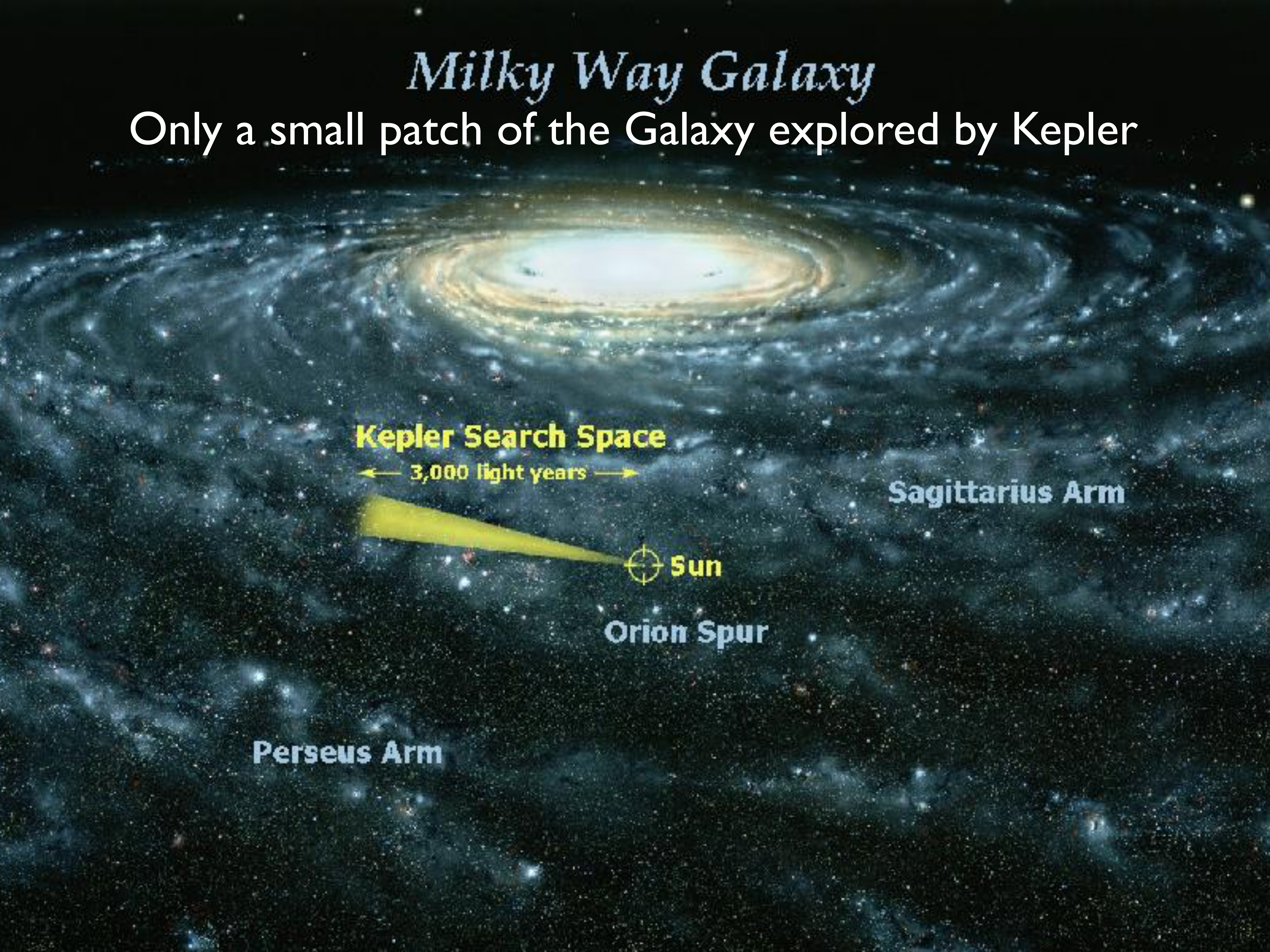
Transit Light Curves



Kepler stared continuously at the same field looking for transits

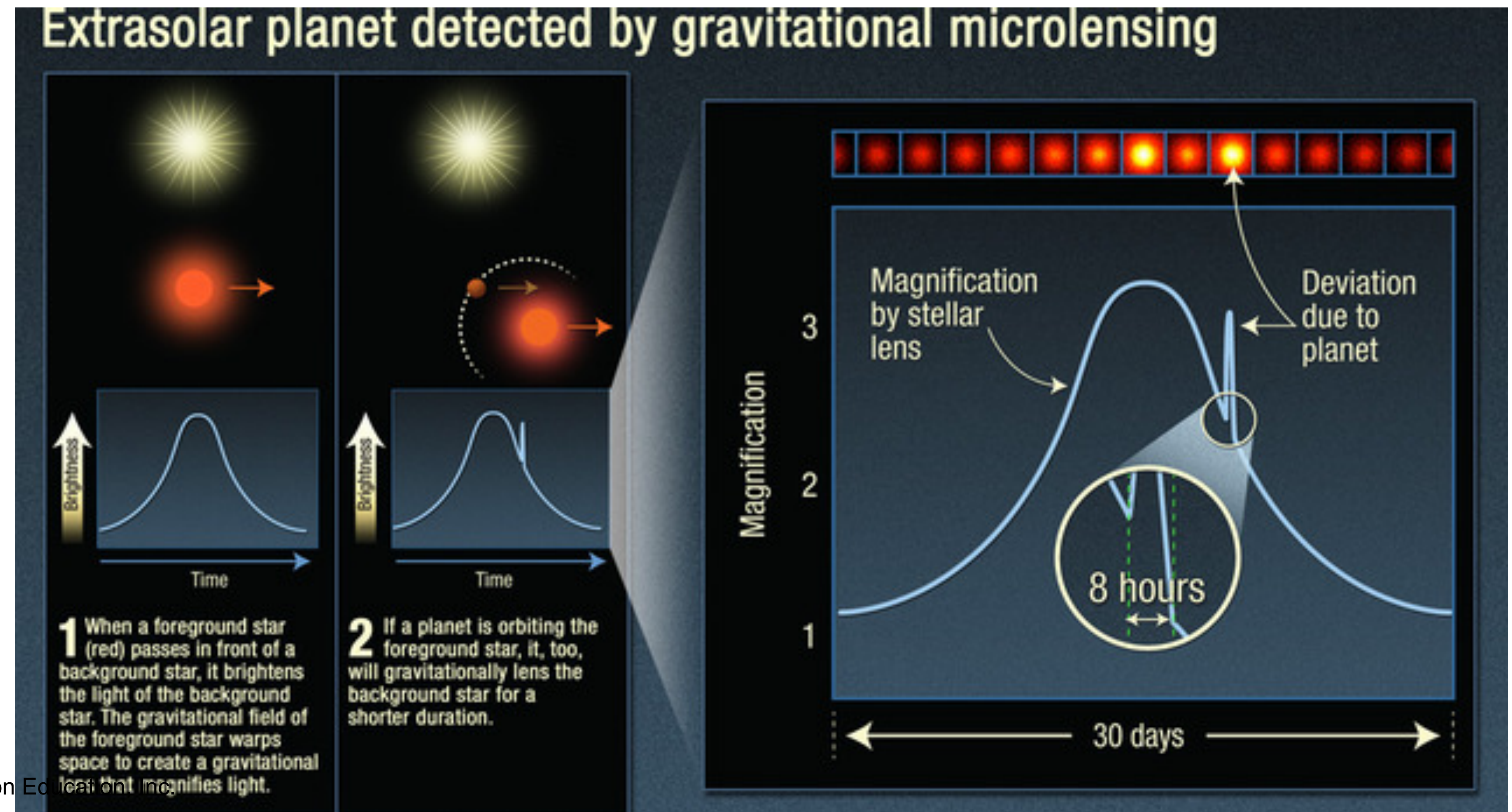


Only a small patch of the Galaxy explored by Kepler

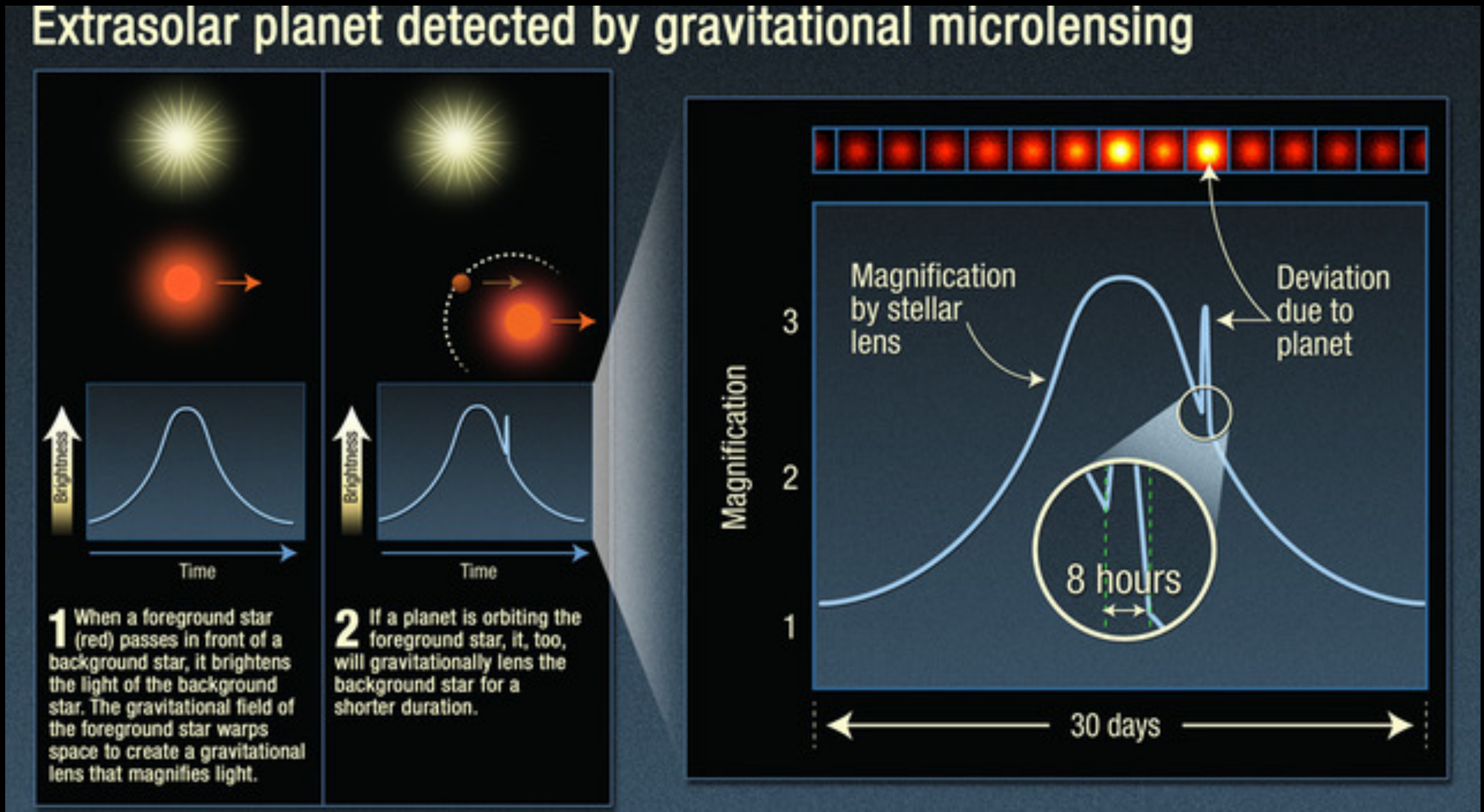


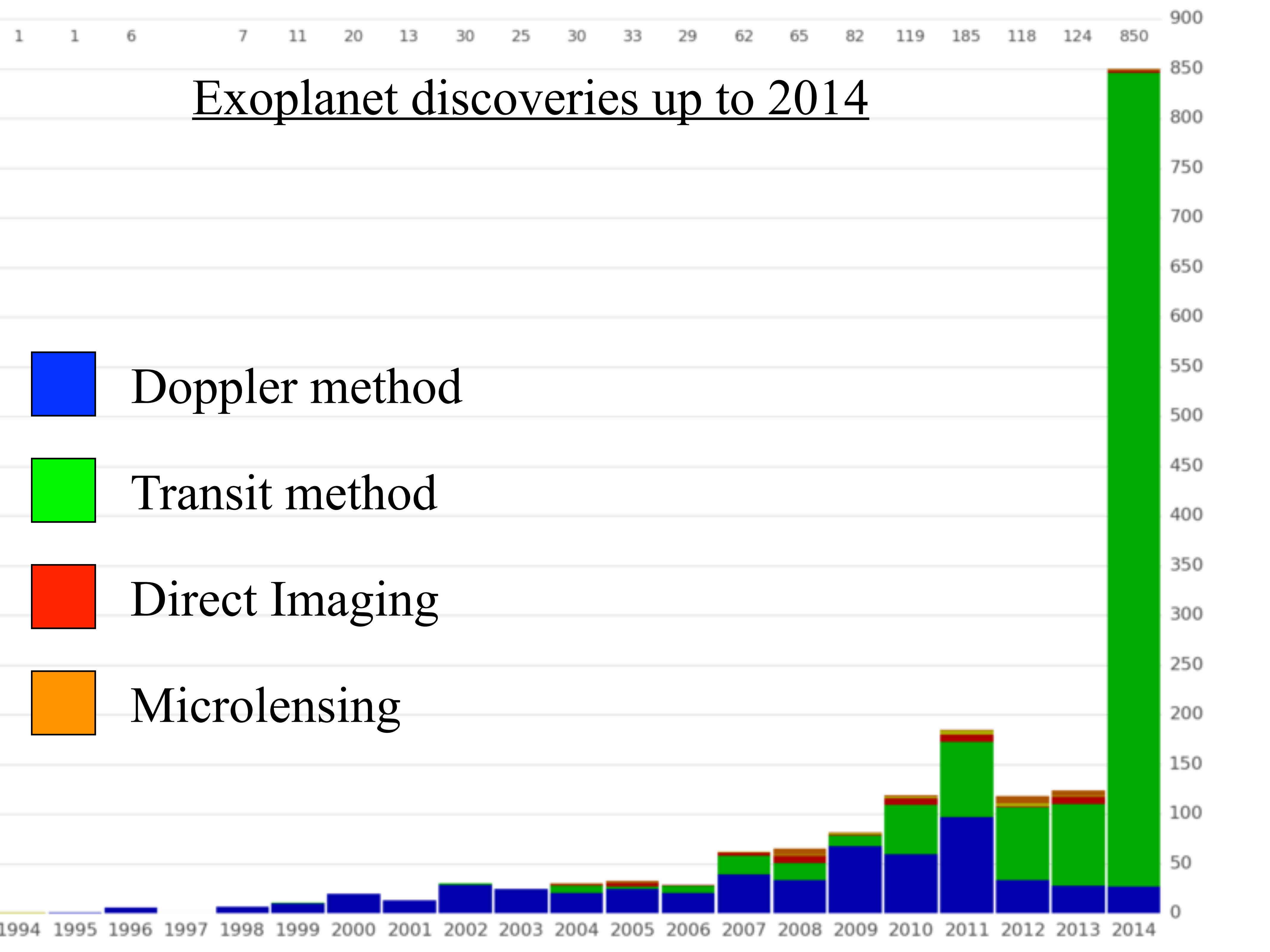
Yet Another Planet-Hunting Strategy

- **Gravitational Lensing:** Mass bends light in a special way when a star with planets passes in front of another star.
  - "microlensing"



Gravitation Microlensing




Exoplanet discoveries up to 2014
Doppler method
Transit method
Direct Imaging
Microlensing
1 1 6 7 11 20 13 30 25 30 33 29 62 65 82 119 185 118 124 850
900
850
800
750
700
650
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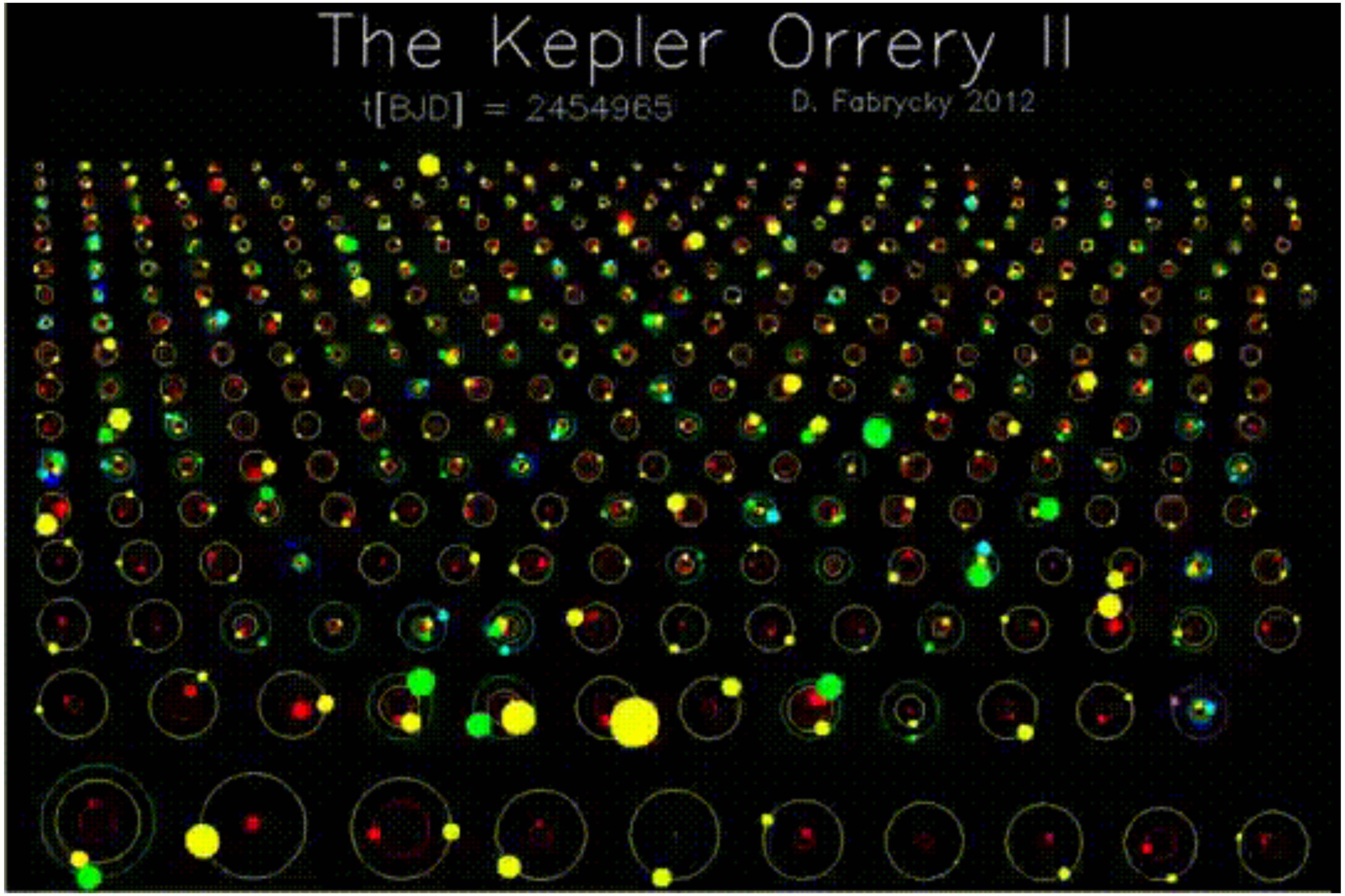
1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014



http://www.nytimes.com/interactive/science/space/keplers-tally-of-planets.html?_r=0

What have we learned?

- **Why is it so challenging to learn about extrasolar planets?**
  - Direct starlight is billions of times brighter than the starlight reflected from planets.
- **How can a star's motion reveal the presence of planets?**
  - A star's periodic motion (detected through Doppler shifts or by measuring its motion across the sky) tells us about its planets.
  - Transiting planets periodically reduce a star's brightness.

What have we learned?

- **How can changes in a star's brightness reveal the presence of planets?**
  - Transiting planets periodically reduce a star's brightness.
  - The *Kepler* mission has found thousands of candidates using this method.