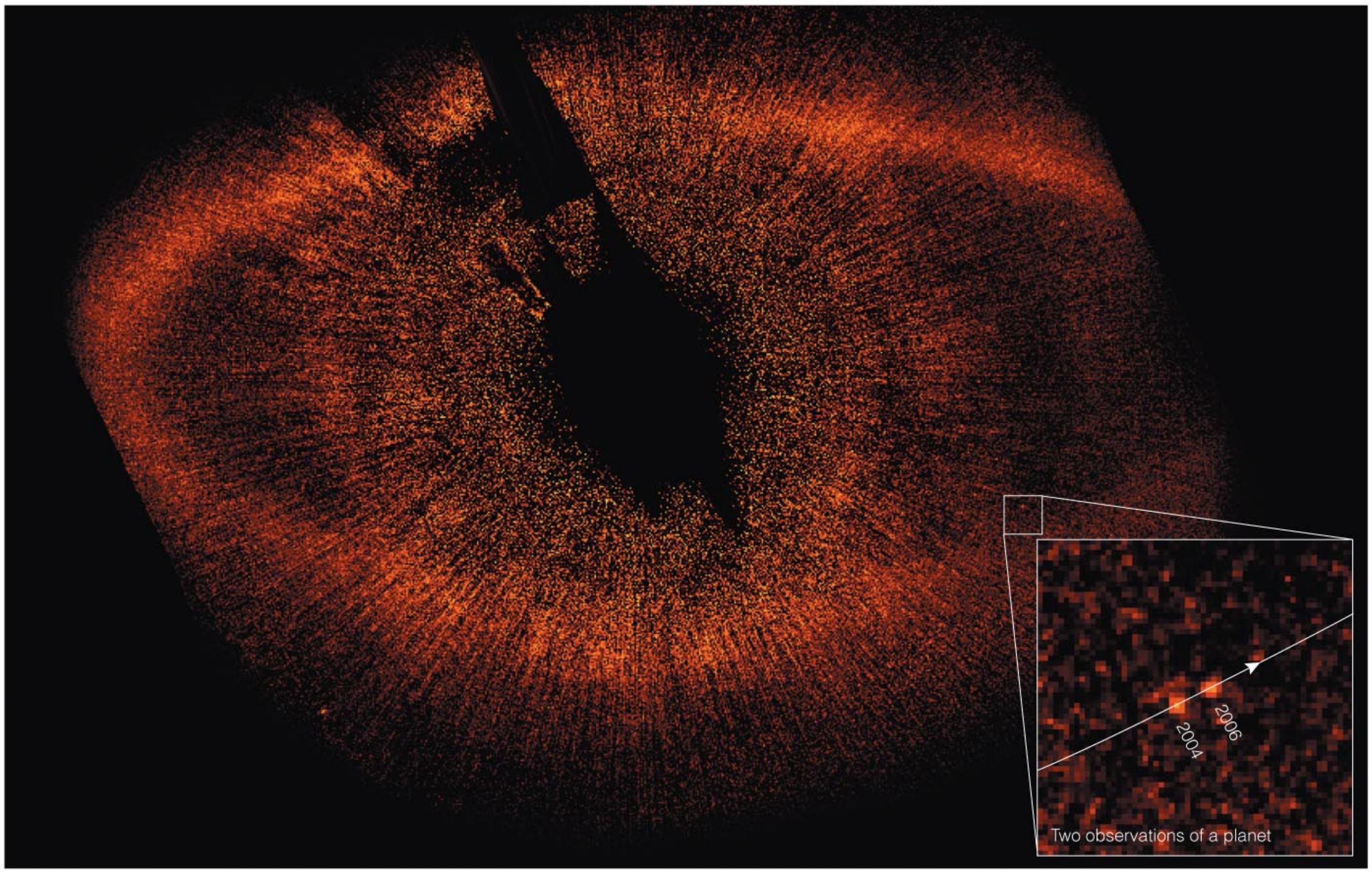
Chapter 13
Other Planetary Systems:
The New Science of Distant Worlds

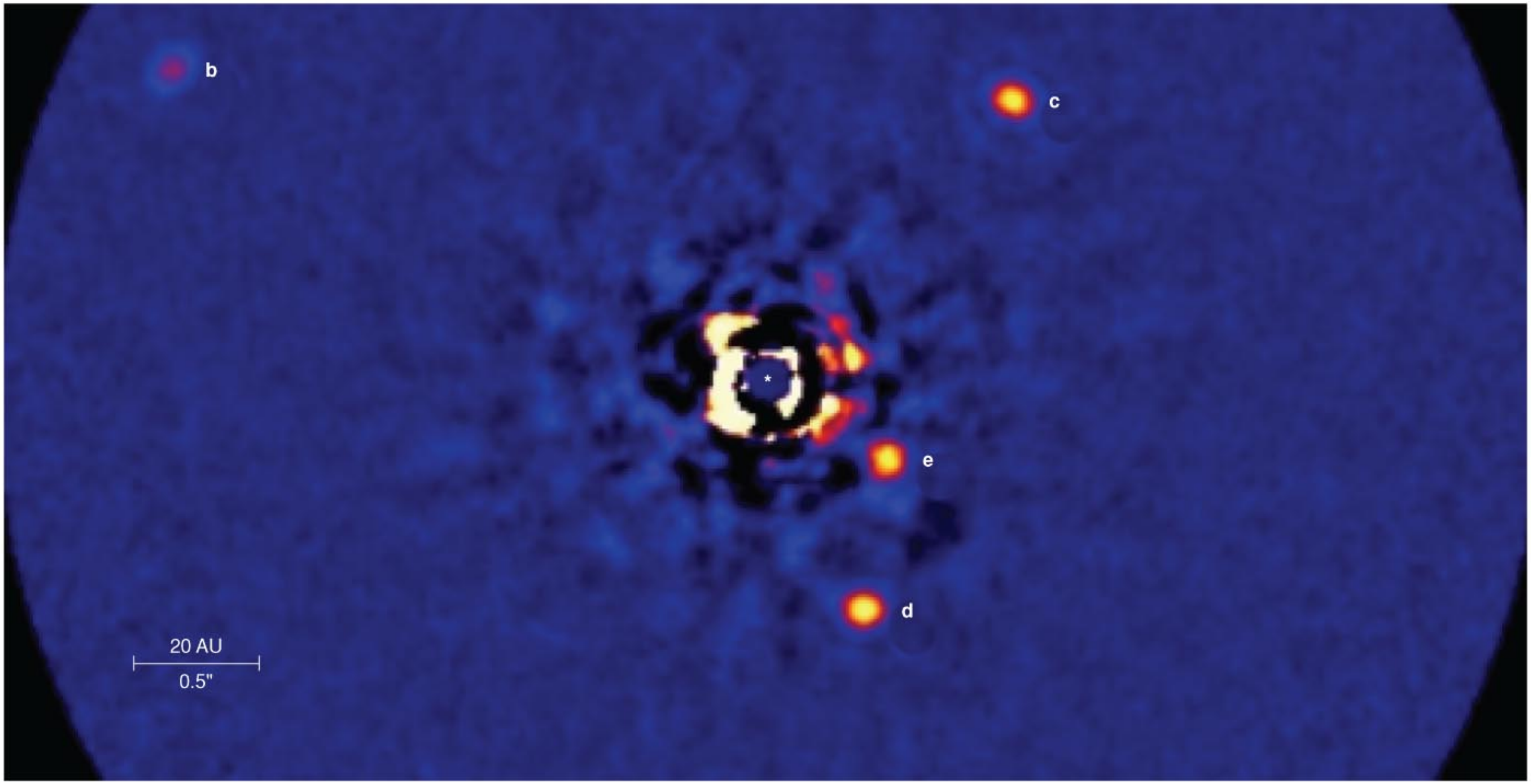


13.1 Detecting Extrasolar Planets

Our goals for learning:

- Why is it so difficult to detect planets around other stars?
- How do we detect planets around other stars?

Why is it so difficult to detect planets around other stars?



Brightness Difference

- A Sun-like star is about a billion times brighter than the light reflected from its planets.

- Also the *angular separation* is tiny—the planet and star are very close together

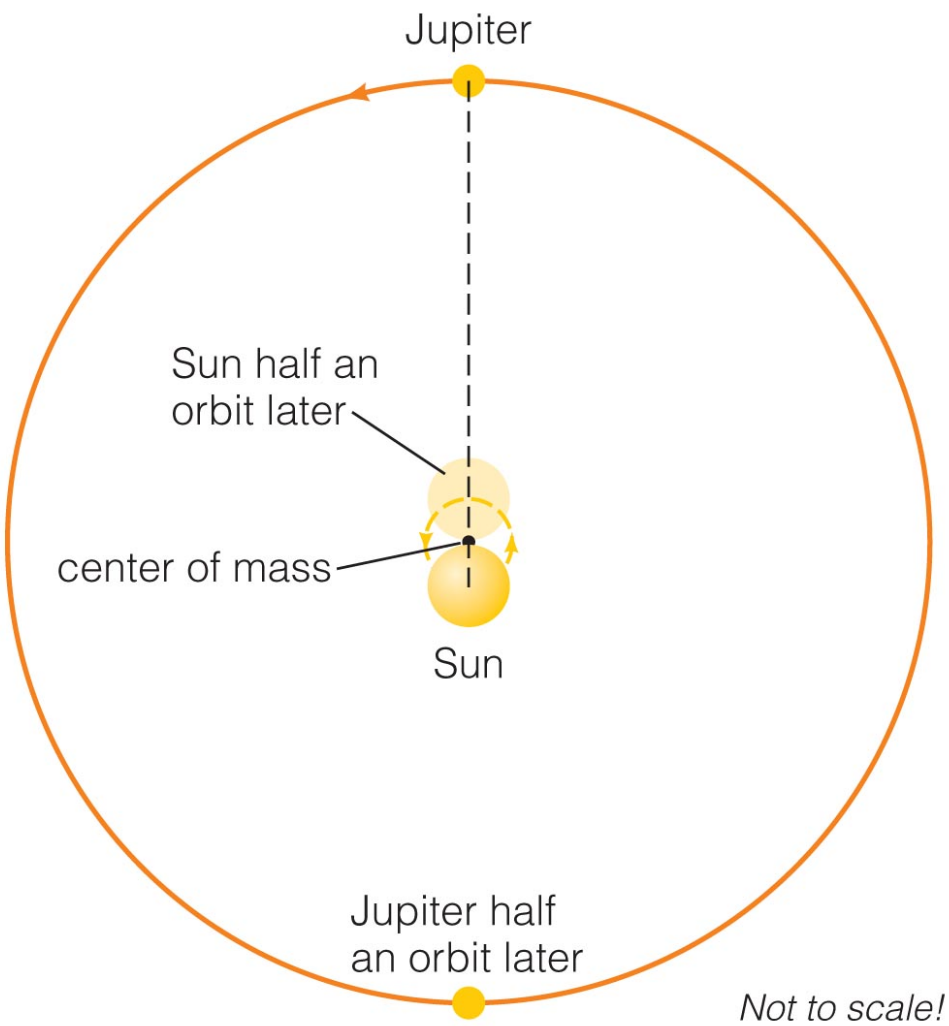
- This is like being in San Francisco and trying to see a pinhead 15 meters from a grapefruit in Washington, D.C.

- The problem of detecting extrasolar planets (or "exoplanets") isn't that they are *too faint*, it is that they are faint *and* next to really bright things---their stars

Special Topic: How Did We Learn That Other Stars Are Suns?

- Ancient observers didnt think stars were like the Sun because Sun is so much brighter.
- Christian Huygens (1629–1695) used holes drilled in a brass plate to estimate the angular sizes of stars.
  - Looked at the Sun through a tiny hole 1/30,000th the apparent size of the Sun
  - Brightness of light from the hole was about the same as the star Sirius, which must be 30,000 times further away, or around ½ light year
- His results showed that, if stars were like Sun, they must be at great distances, consistent with the lack of observed parallax.

How do we detect planets around other stars?



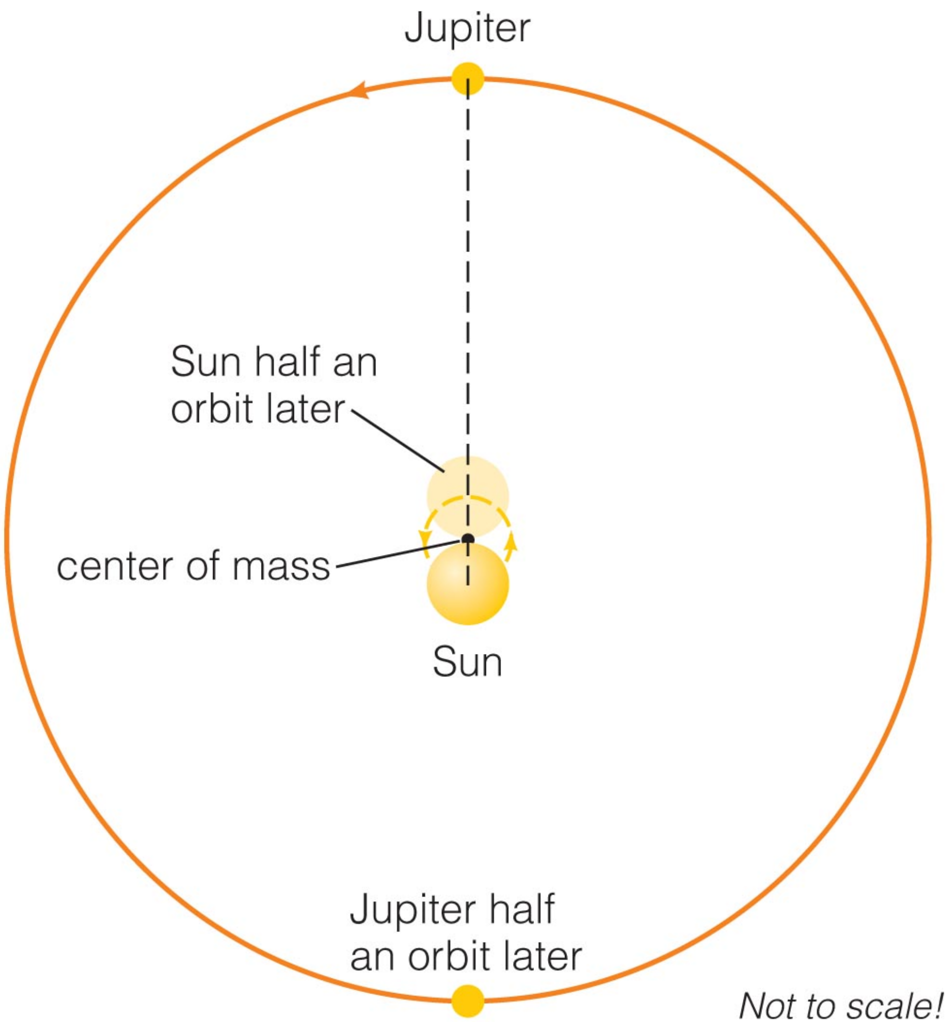
Planet Detection

- **Direct:** pictures or spectra of the planets themselves

- **Indirect:** measurements of stellar properties revealing the effects of orbiting planets
  (this method is much further along)

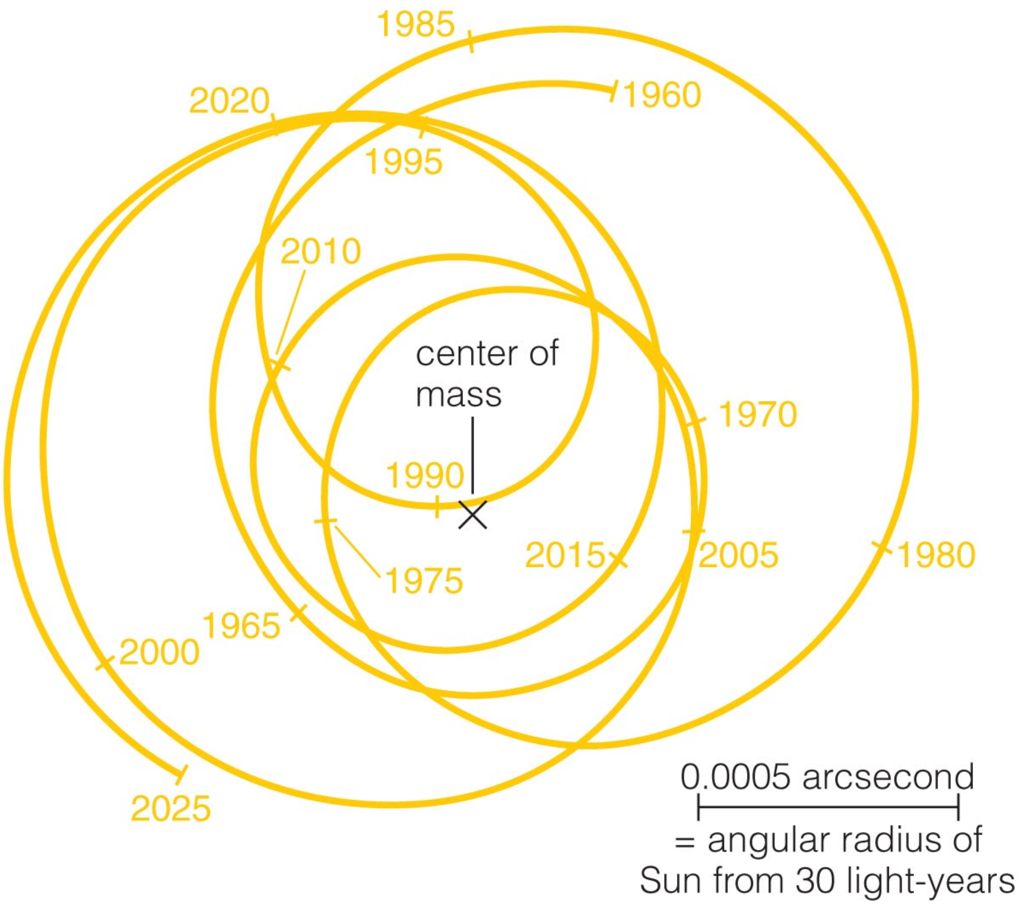
Use the star to our advantage

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.

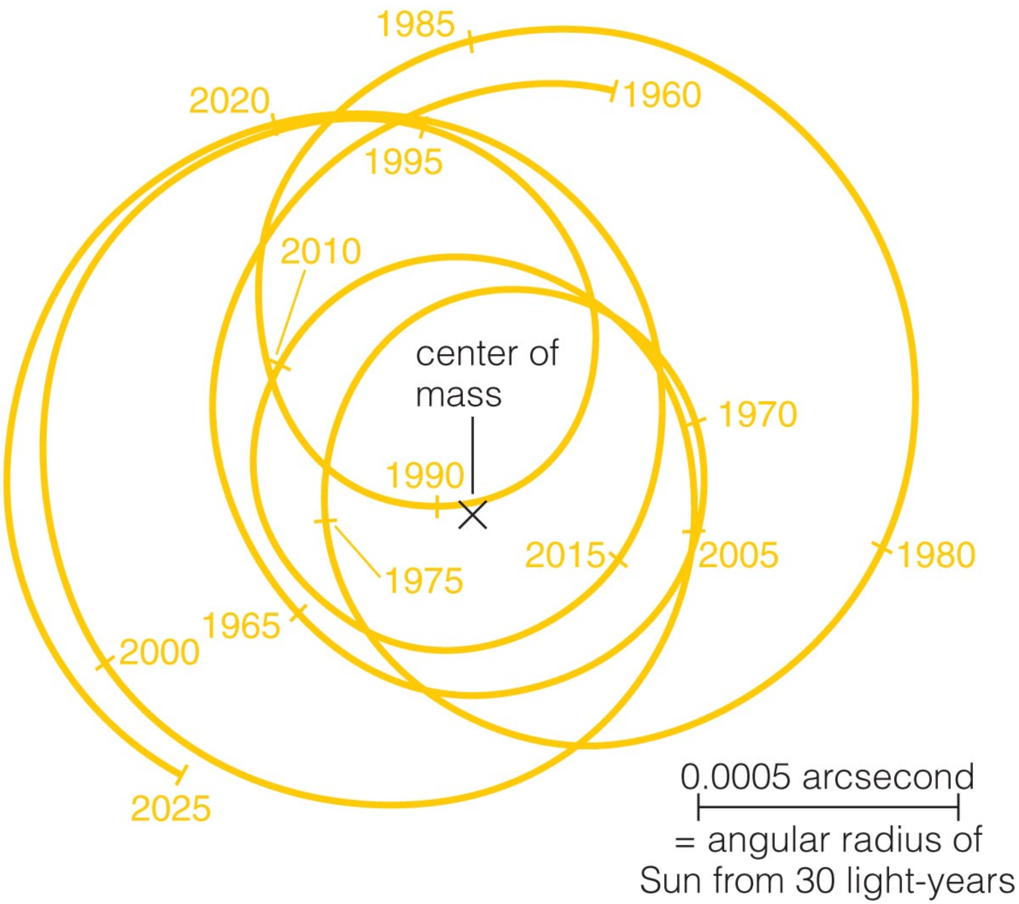
Gravitational Tugs



- The Sun's motion around the solar system's center of mass depends on tugs from all the planets.

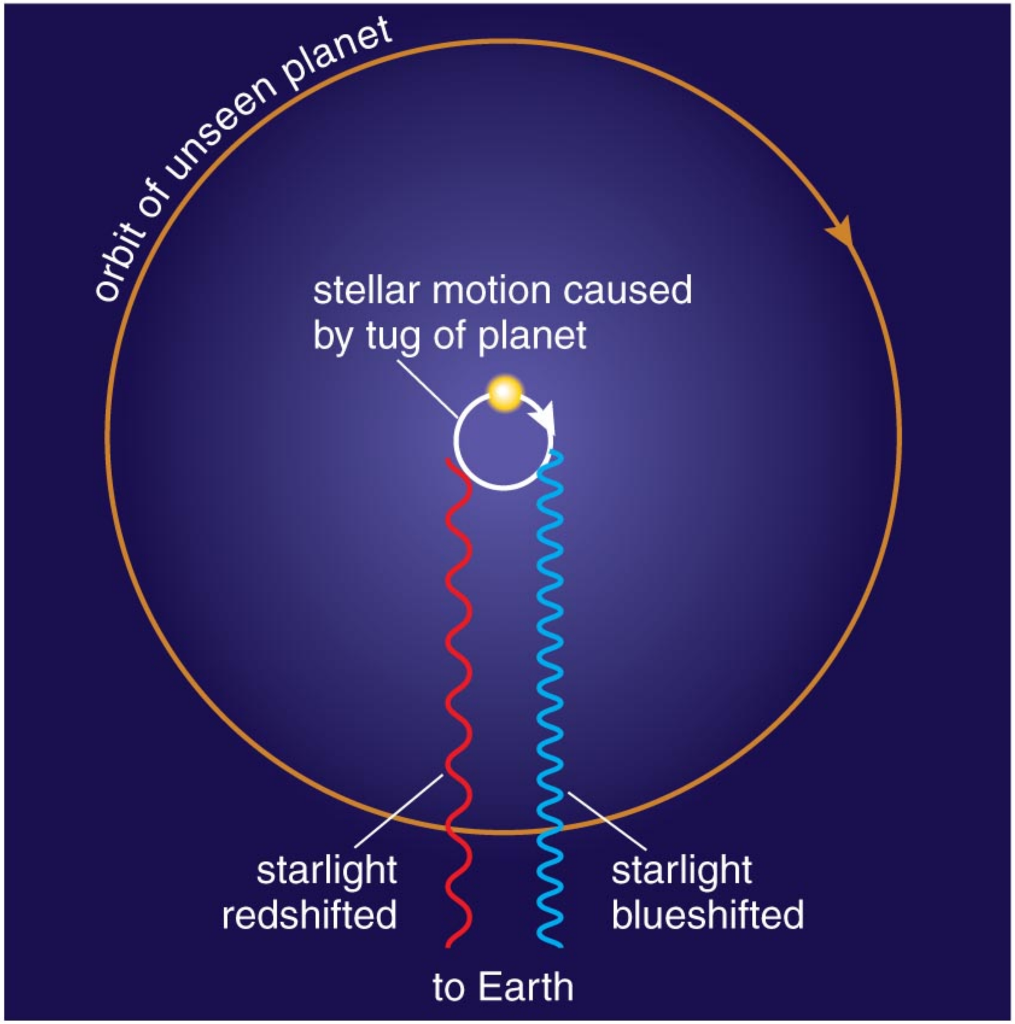
- Astronomers around other stars that measured this motion could determine the masses and orbits of all the planets.

Astrometric Technique



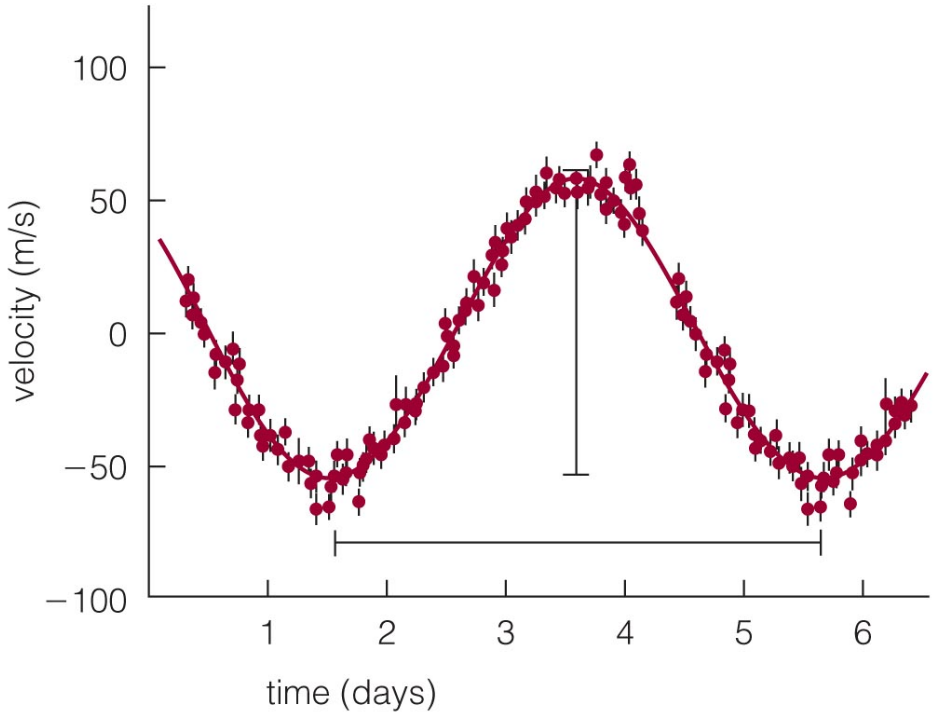
- We can detect planets by measuring the change in a star's position on sky.
- However, these tiny motions are very difficult to measure (~ 0.001 arcsecond)
- Has *never* been done successfully – motions are just too tiny

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!).

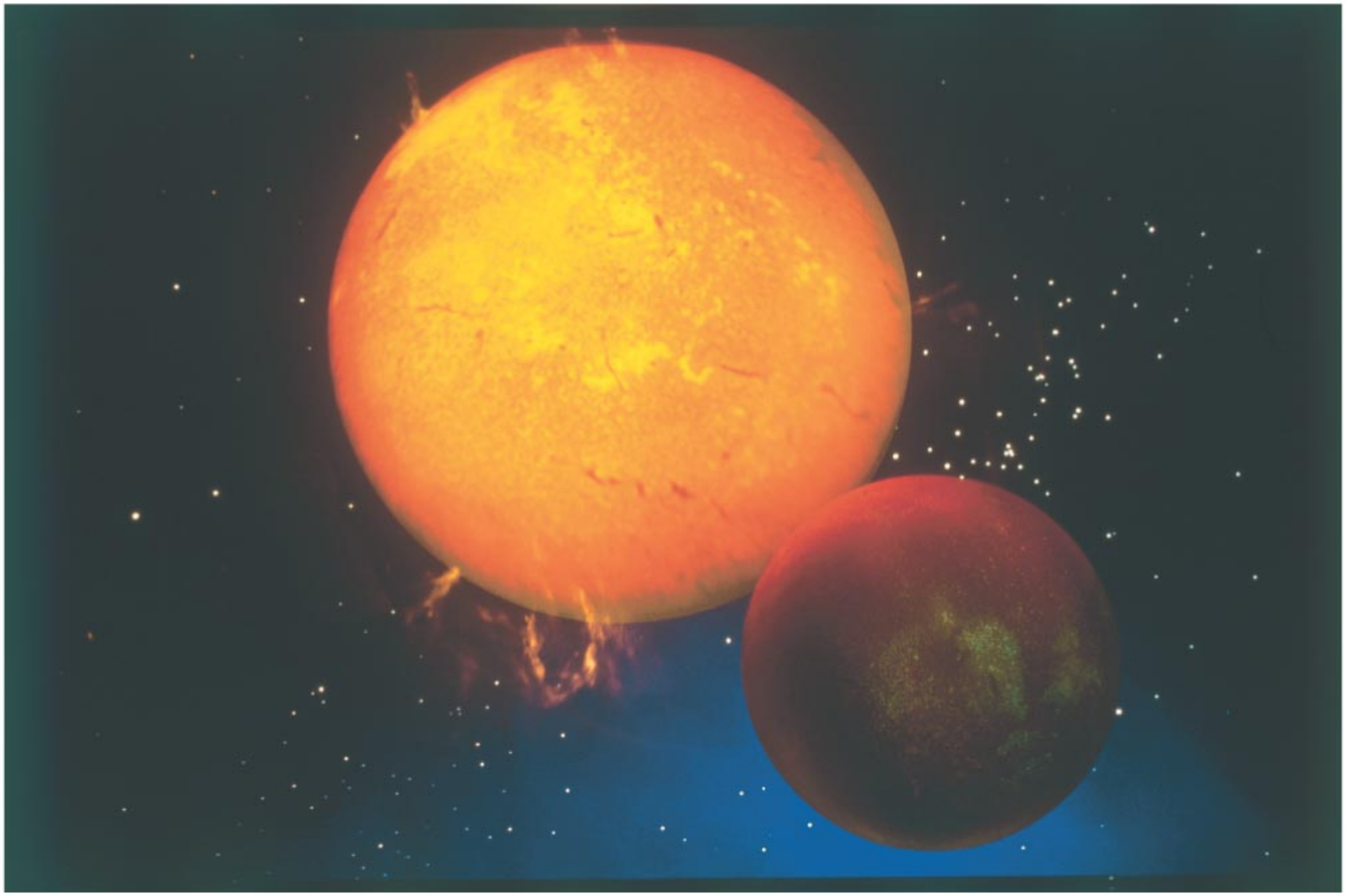
First Extrasolar Planet



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.

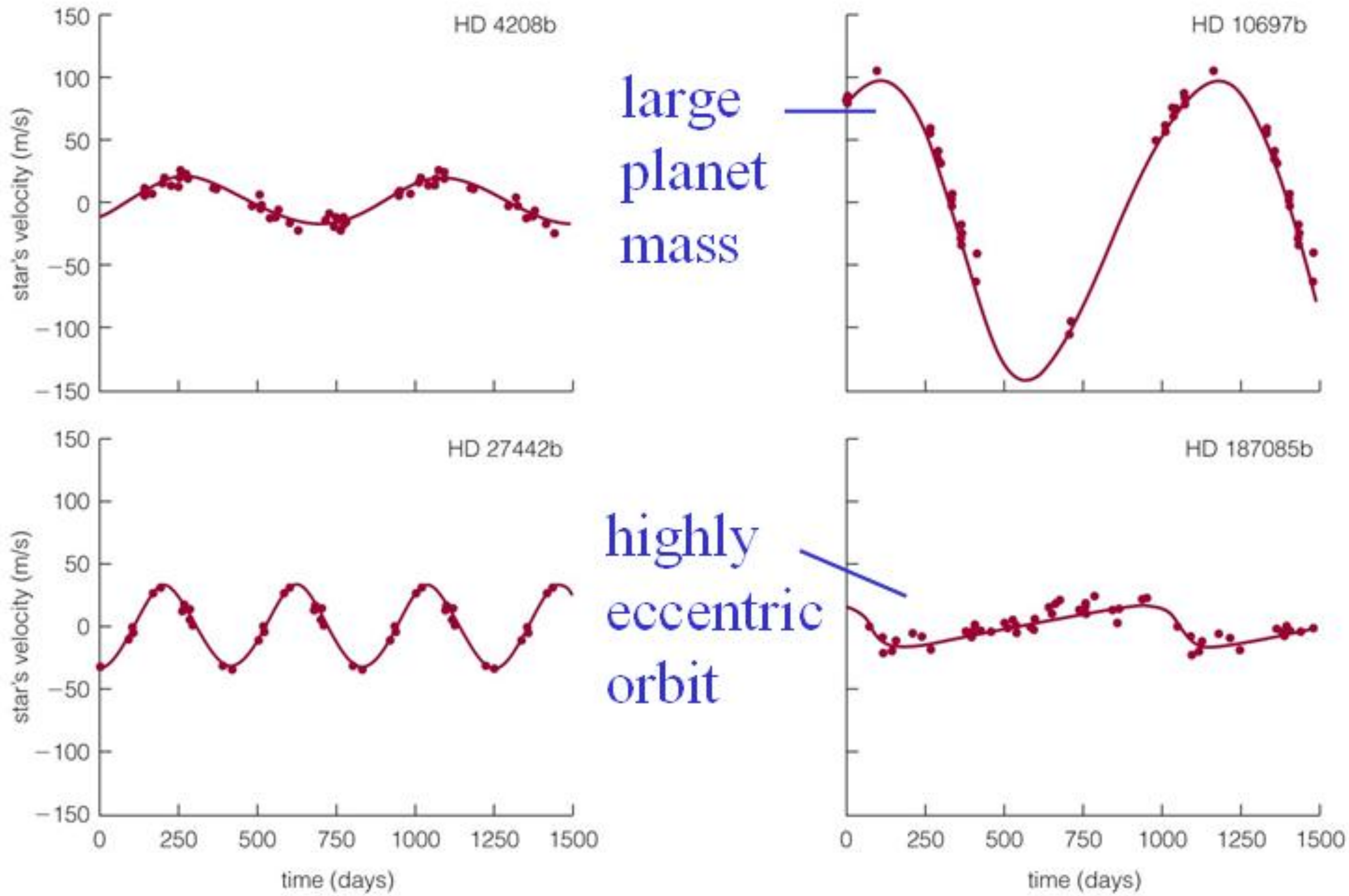
- Doppler shifts of the star 51 Pegasi indirectly revealed a planet with 4-day orbital period.
- This short period means that the planet has a small orbital distance.
- This was the first extrasolar planet to be discovered (1995).

First Extrasolar Planet



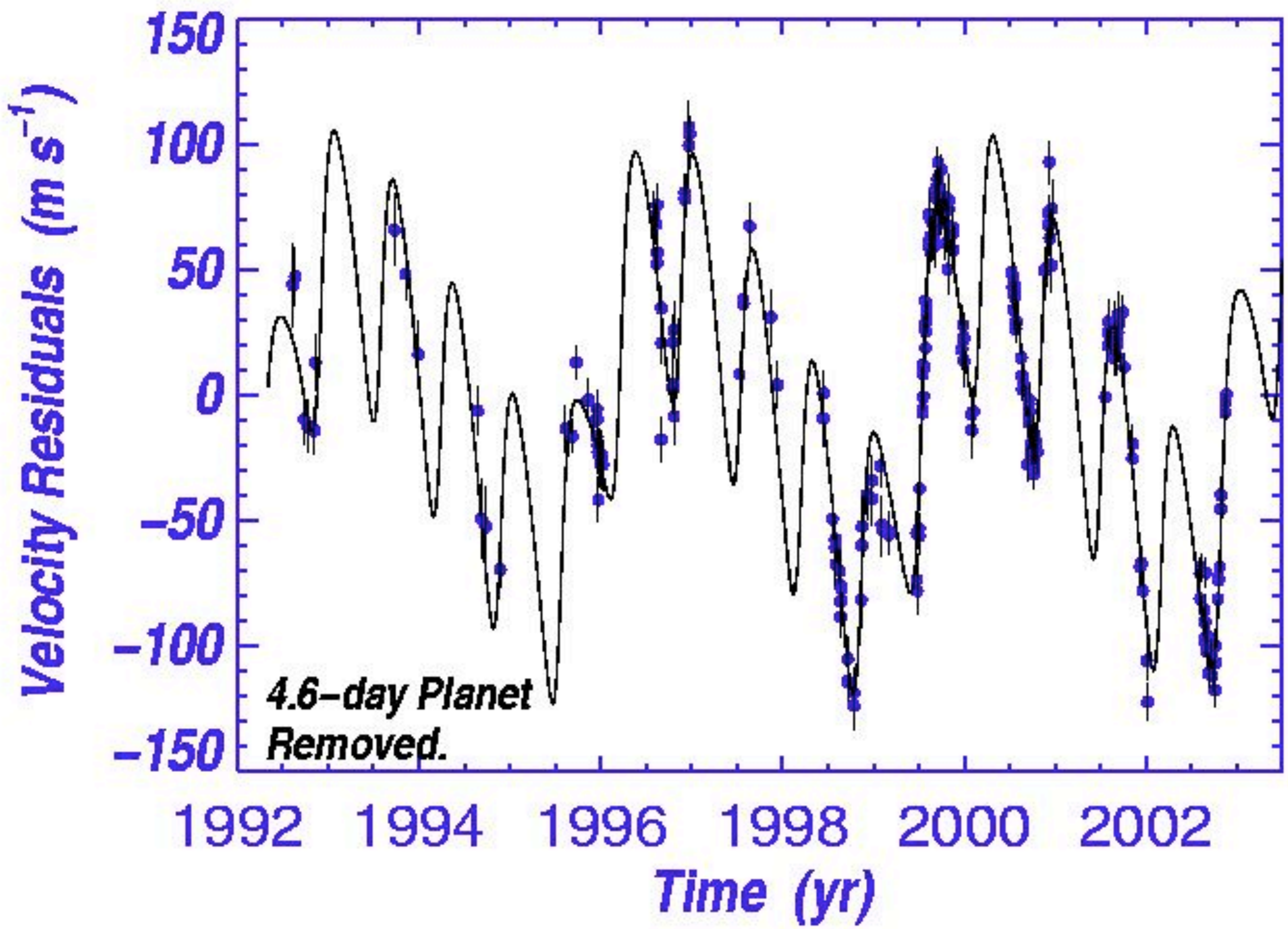
- The planet around 51 Pegasi has a mass similar to Jupiter’s (1/2 Jupiter), despite its small orbital distance.

Other Extrasolar Planets

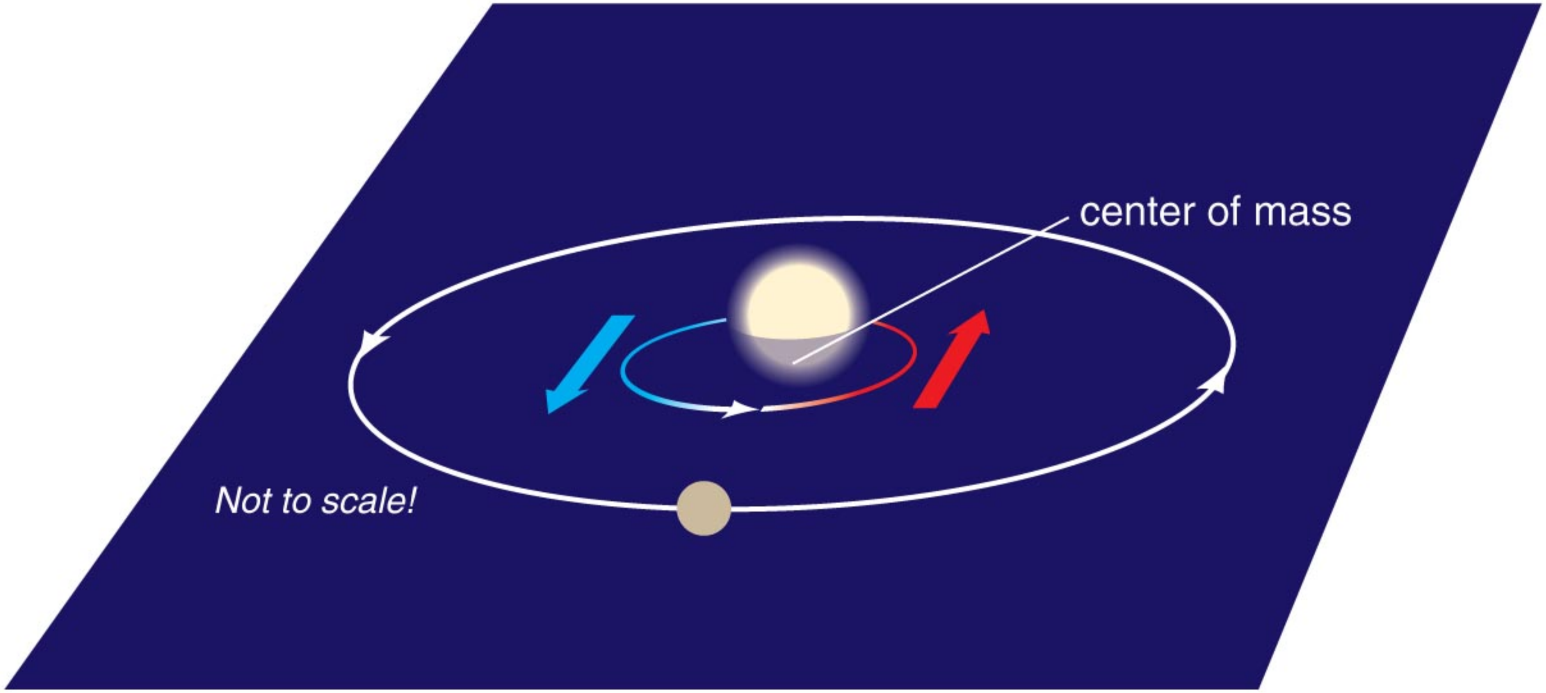


- Doppler shift data tell us about a planet's ***minimum*** mass and the shape of its orbit.

Multi-planet systems can get very complicated



Planet Mass and Orbit Tilt



- We cannot measure an exact mass for a planet without knowing the tilt of its orbit, because Doppler shift tells us only the velocity toward or away from us.
- Doppler data give us lower limits on masses.
- Seeing a system "face on," we would detect no Doppler shift

Clicker Question

Suppose you found a star with the same mass as the Sun moving back and forth with a period of 16 months. What could you conclude?

A. It has a planet orbiting at less than 1 AU.
B. It has a planet orbiting at greater than 1 AU.
C. It has a planet orbiting at exactly 1 AU.
D. It has a planet, but we do not have enough information to know its orbital distance.

Clicker Question

Suppose you found a star with the same mass as the Sun moving back and forth with a period of 16 months. What could you conclude?

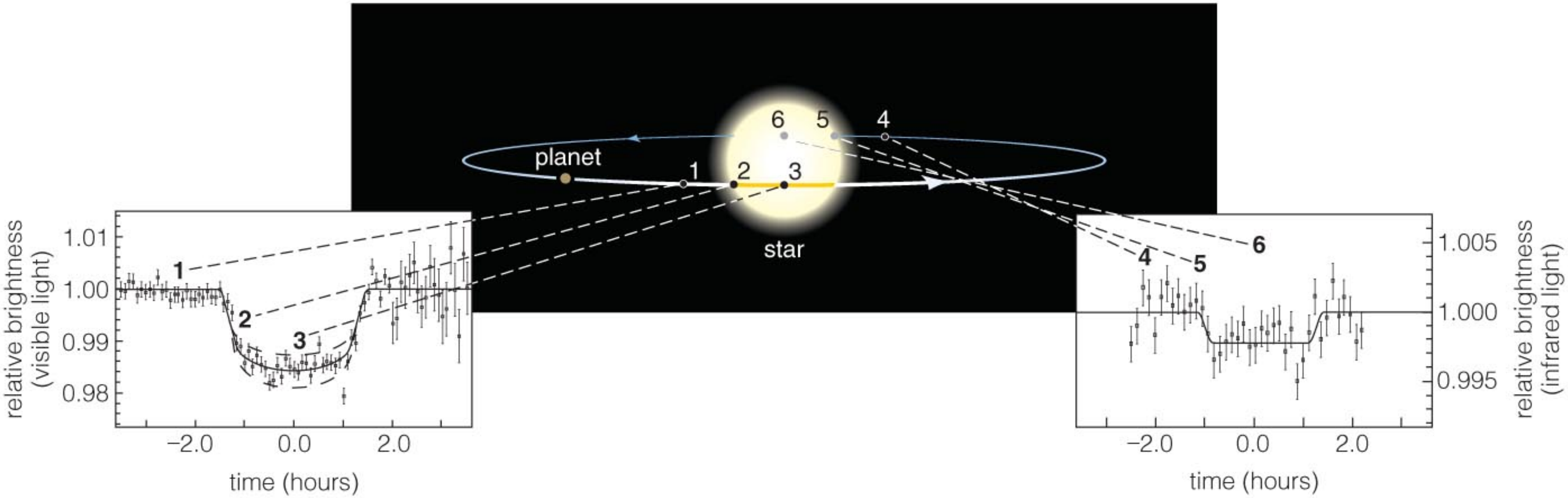
A. It has a planet orbiting at less than 1 AU.

B. It has a planet orbiting at greater than 1 AU.

C. It has a planet orbiting at exactly 1 AU.

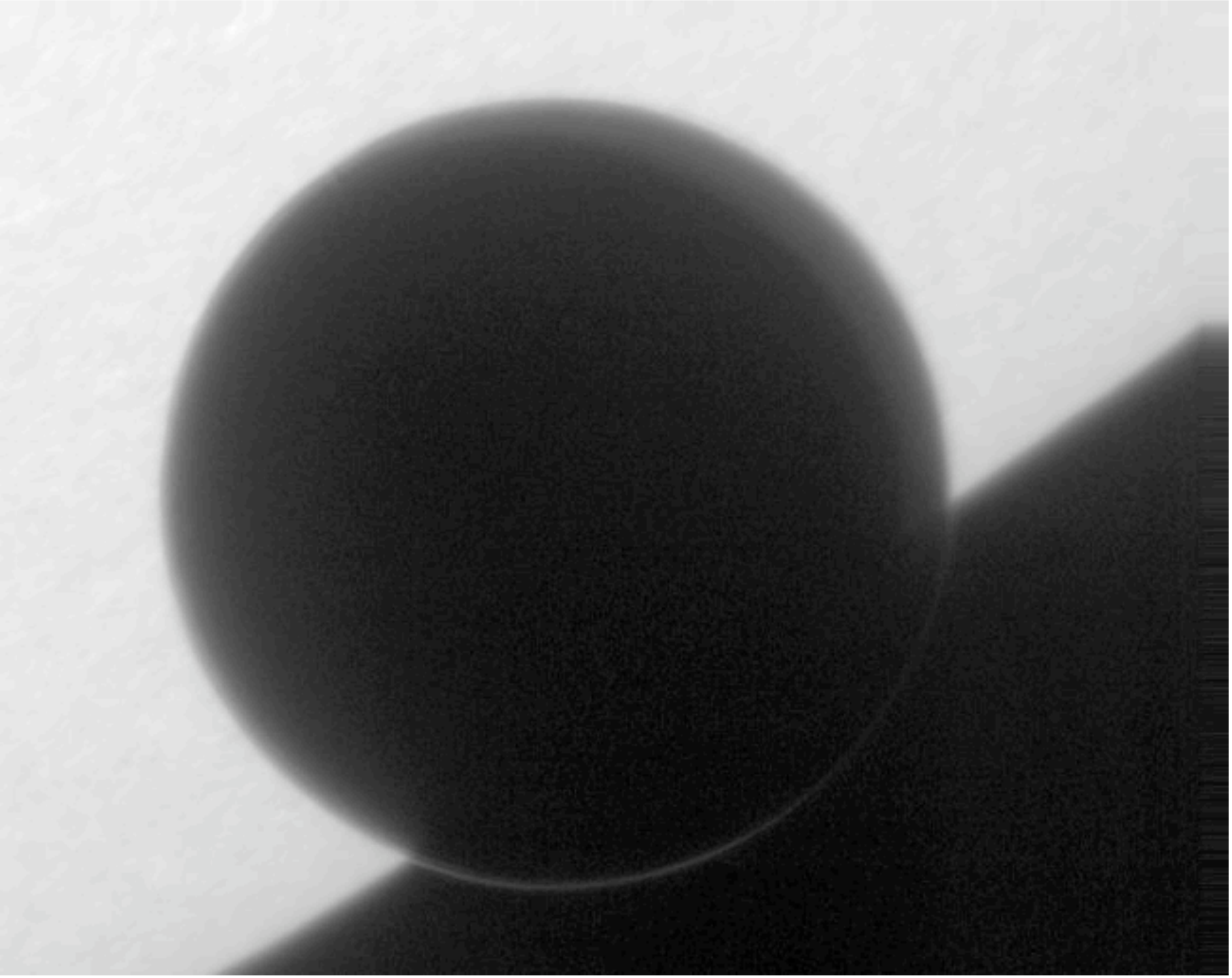
D. It has a planet, but we do not have enough information to know its orbital distance.

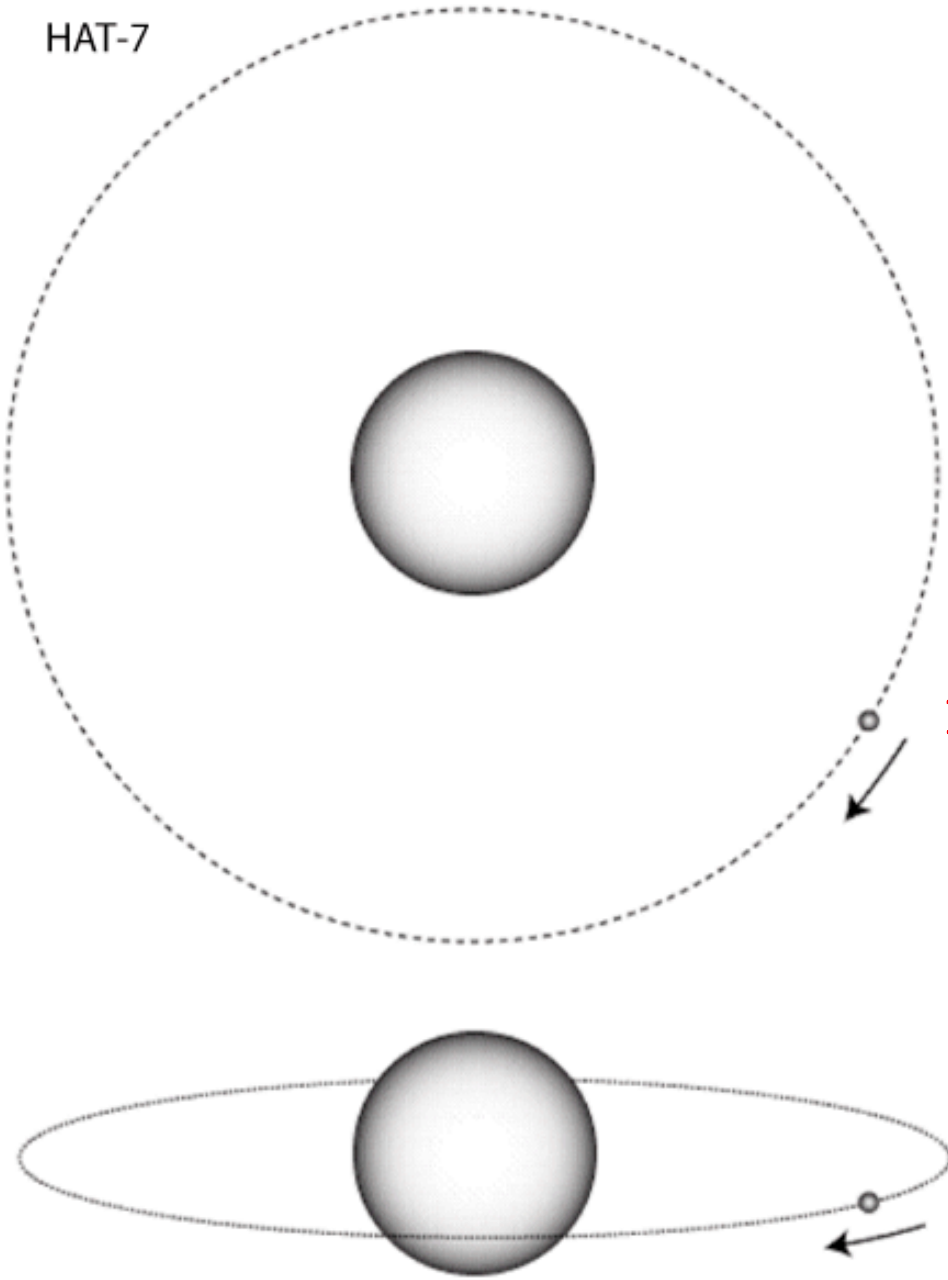
Transits and Eclipses



- 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 (if we know the star's radius!)
- No orbital tilt: accurate measurement of planet mass if you also get radial velocity
- You "miss" most of the planetary systems, though

Lomonosov, 1760: Discovery of Venus's Atmosphere





14 Earth radii

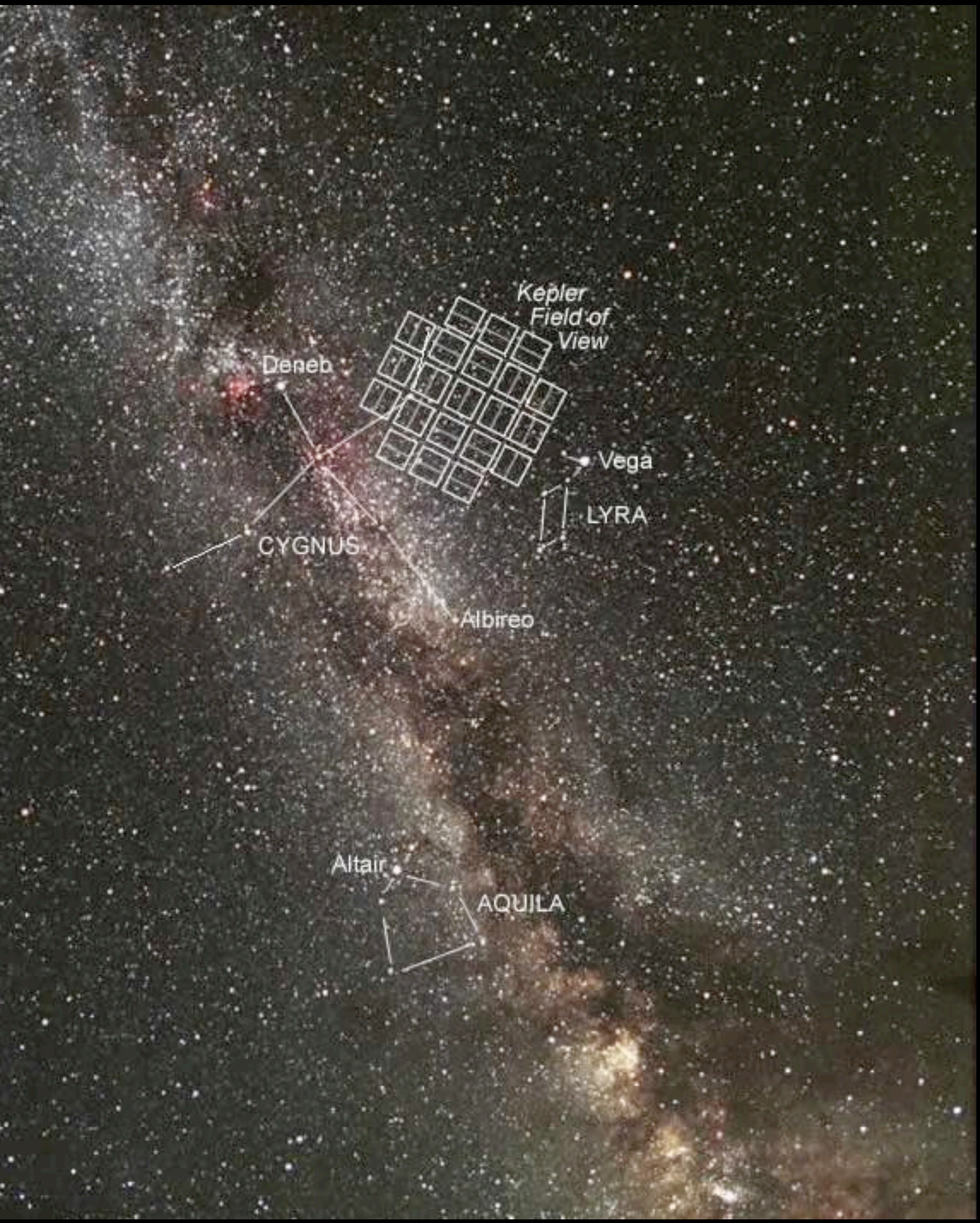
If you look at small stars,
You can find small planets!

2.7 Earth radii

Gliese 1214 (at the same scale)

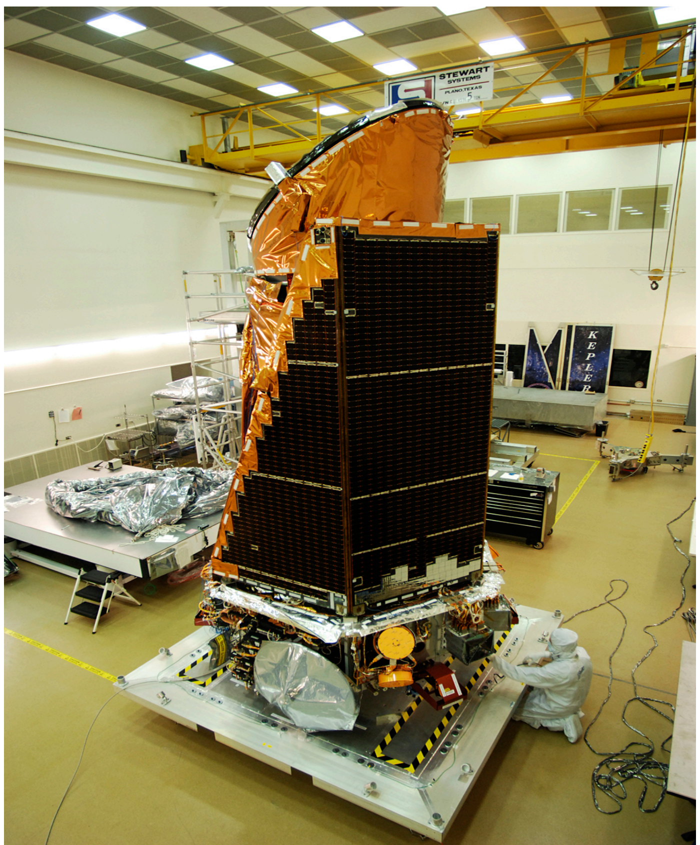
What signals are we dealing with?

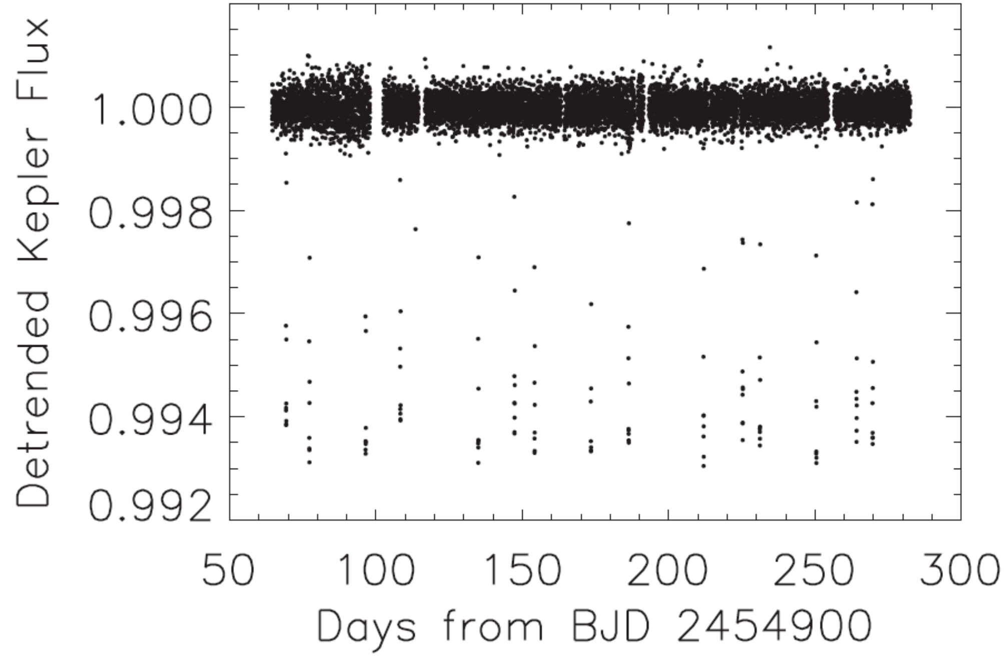
- 1 Jupiter radius is about 1/10 Sun's radius
  - Blocks out 1% of parent star's light
- 1 Earth radius is about 1/100 Sun's radius
  - Blocks out 0.01% (1 part in 10,000) of parent star's light
- Astronomers really need to build some *precision* instruments to measure these tiny signals

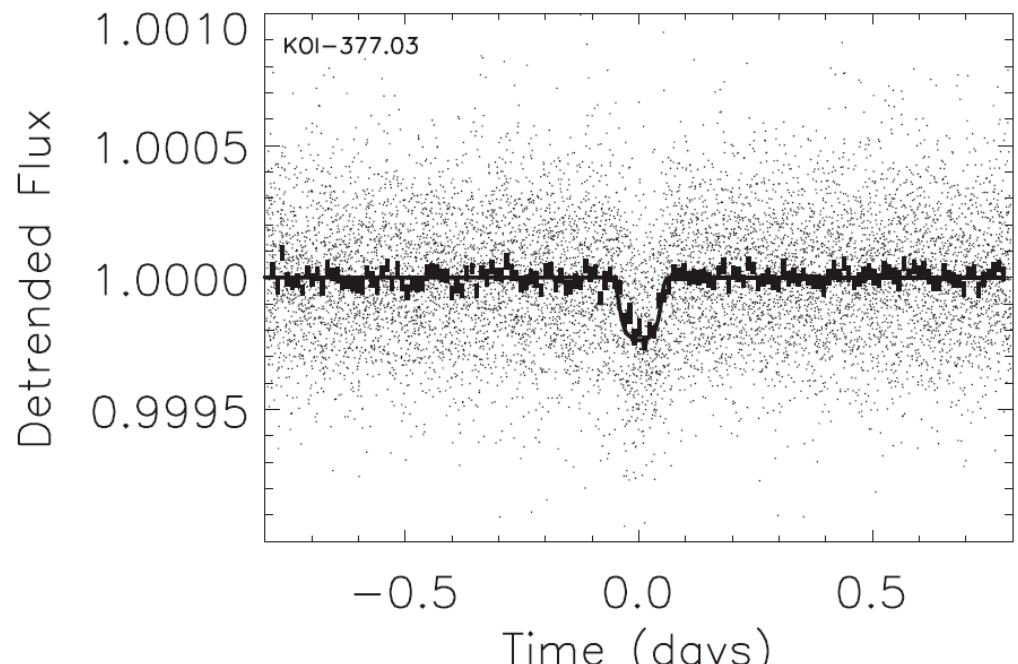


- The idea of the *Kepler* Mission was from Bill Borucki, NASA Ames, in the Mid 1980s
- If you sample a large enough number of stars (a "statistically significant sample"), you can determine the fraction of Sun-like stars that have Earth-size planets in Earth-size orbits
- Having a large sample size is essential to the entire project
- 95 megapixel space camera built to do one thing exceptionally well

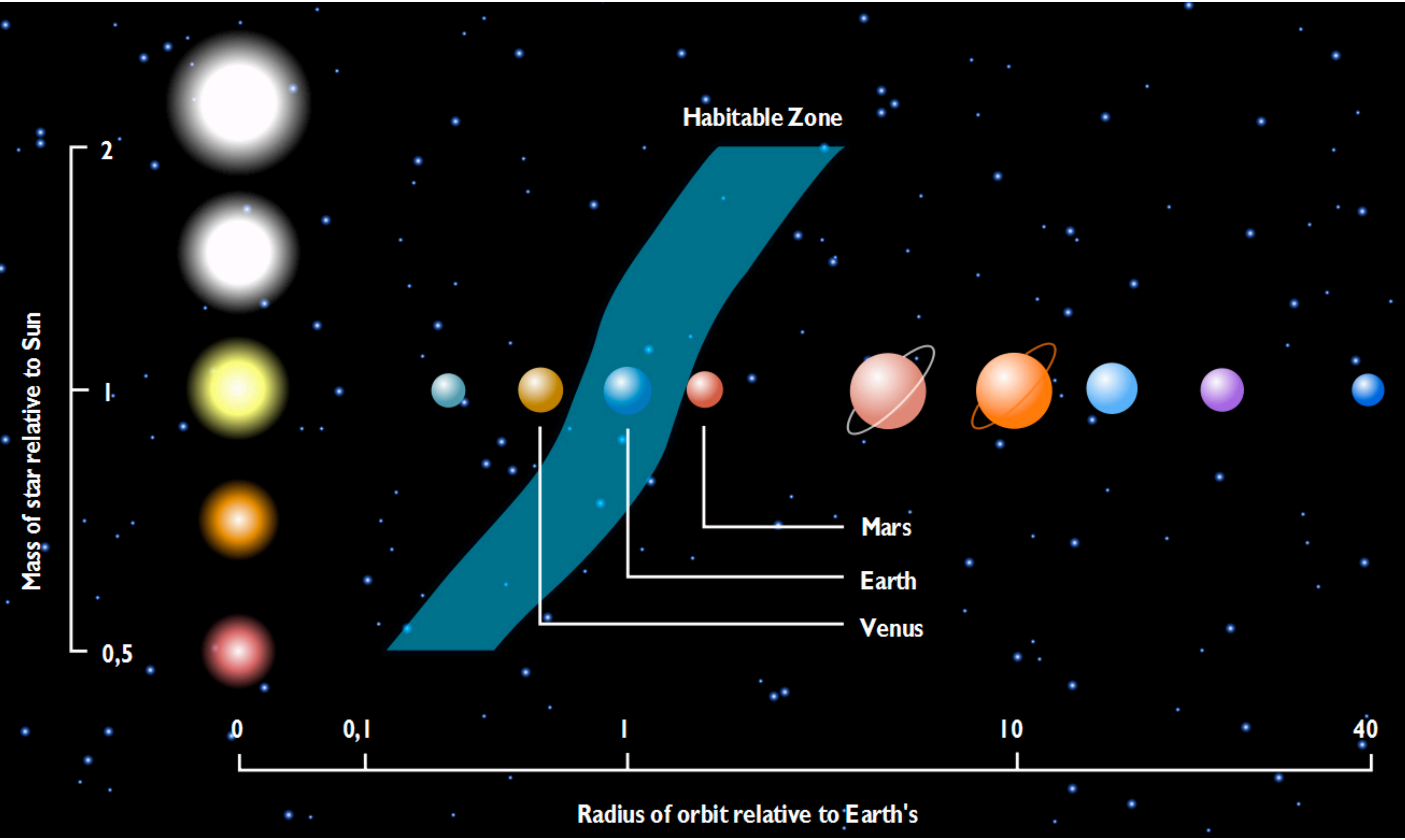
- *Kepler Mission* is optimized for finding potentially habitable planets (0.5 to 1.5 Earth radii) in the *Habitable Zone* (near 1 AU) of Sun-like stars
- Continuously monitoring 150,000 stars for 3.5 years (now 7.5 years!) using a 1 meter telescope



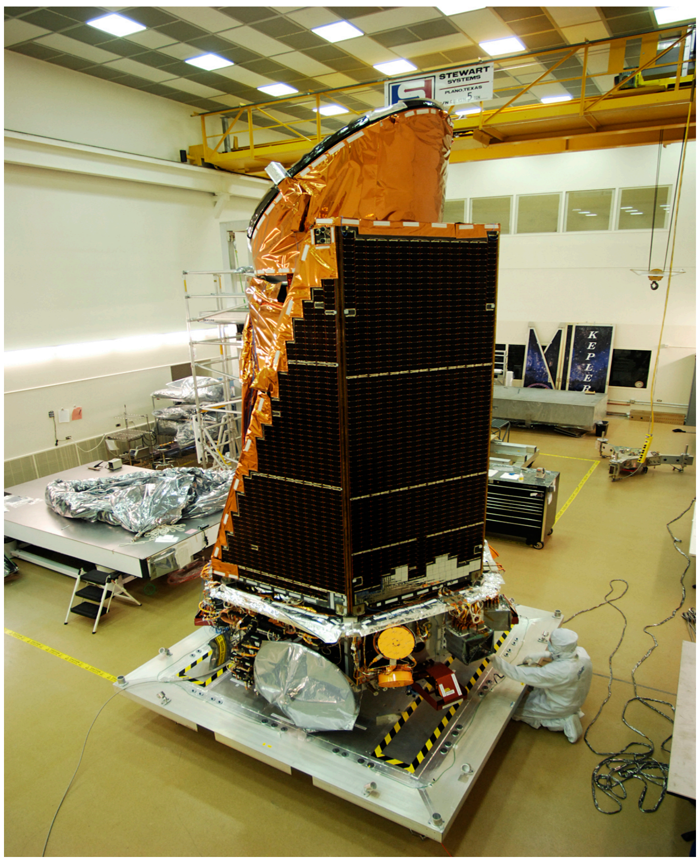


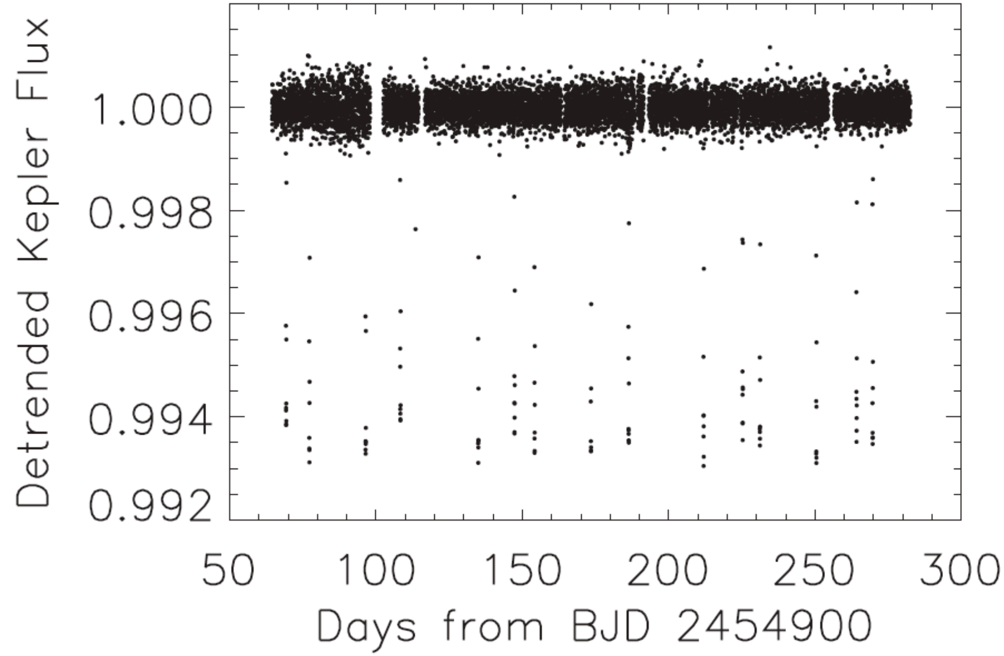


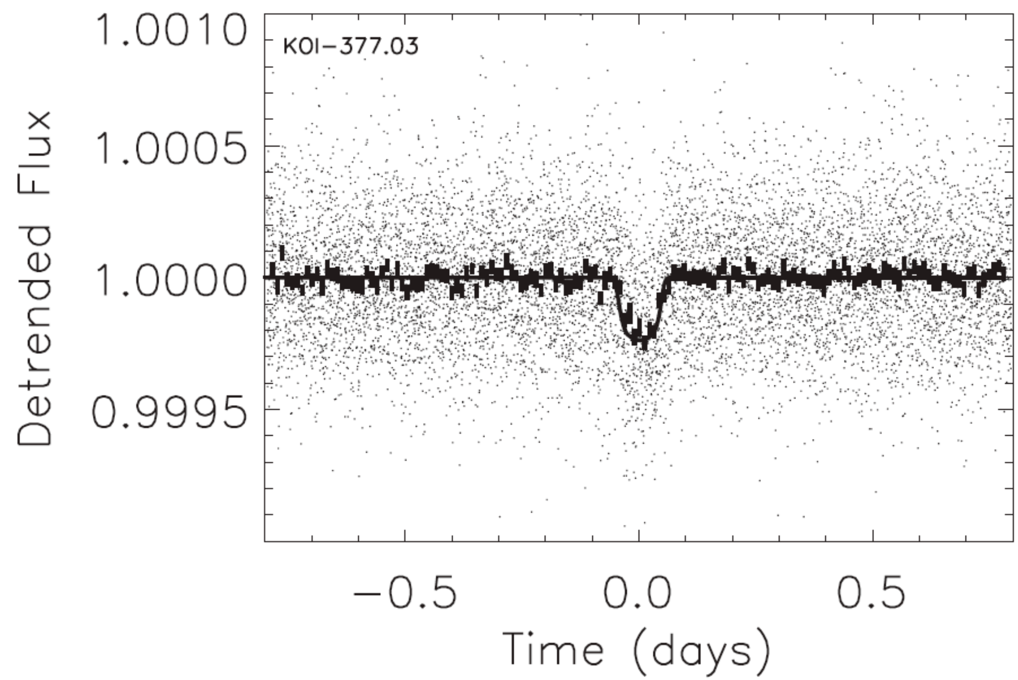
The habitable zone is defined a planetary temperature range when liquid water can exist at the planet's surface



What does Kepler data look like?







Kepler-11: Picking out the Planets

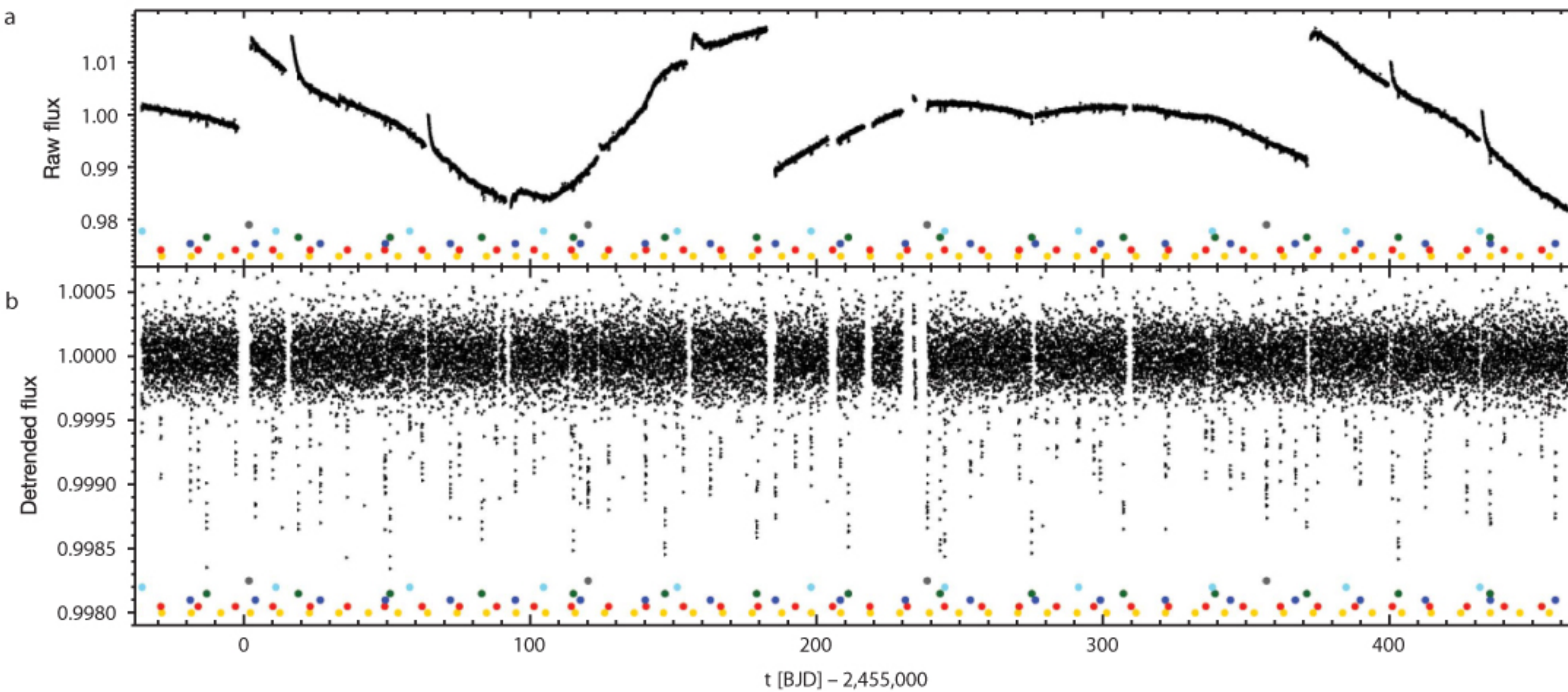
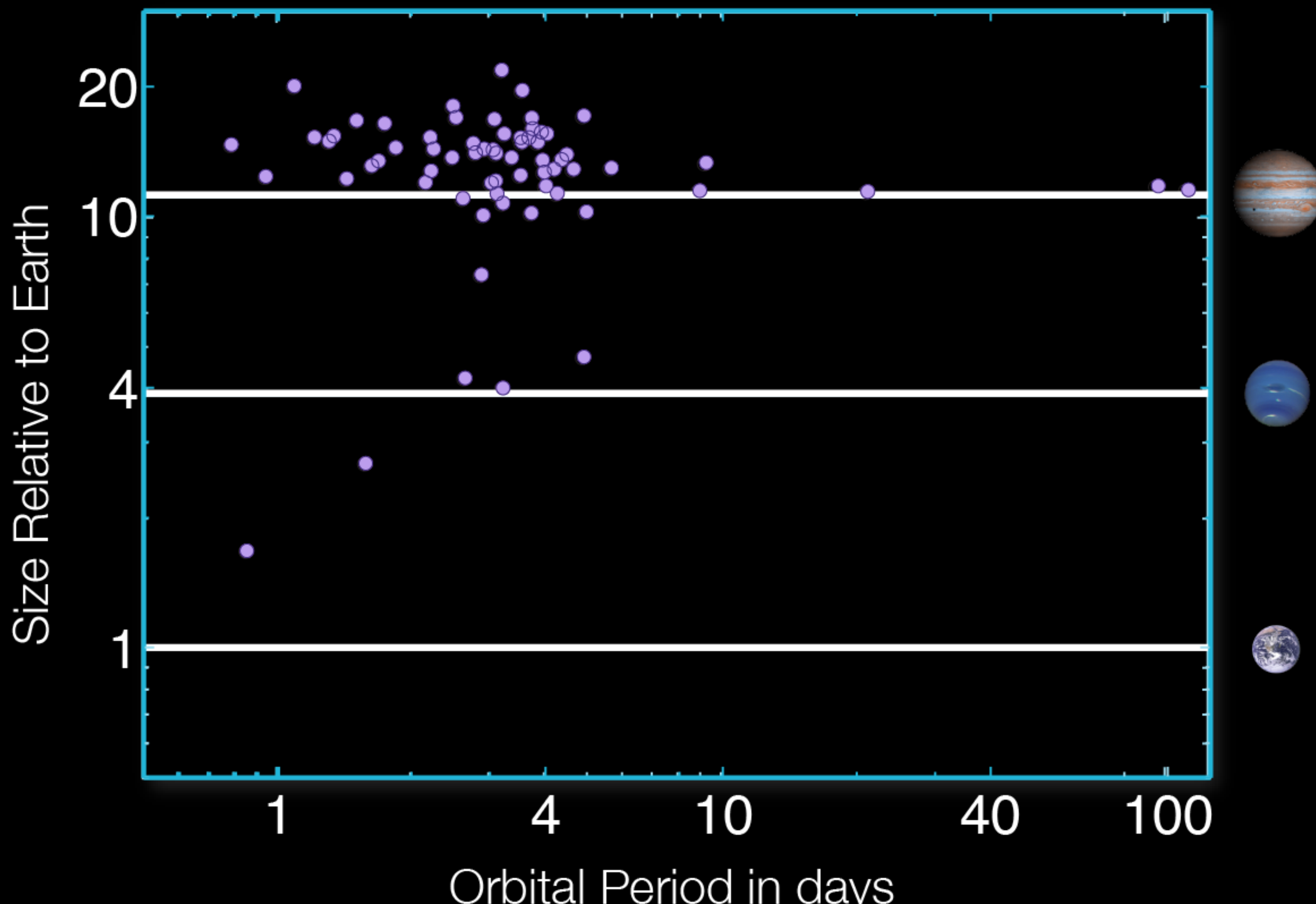


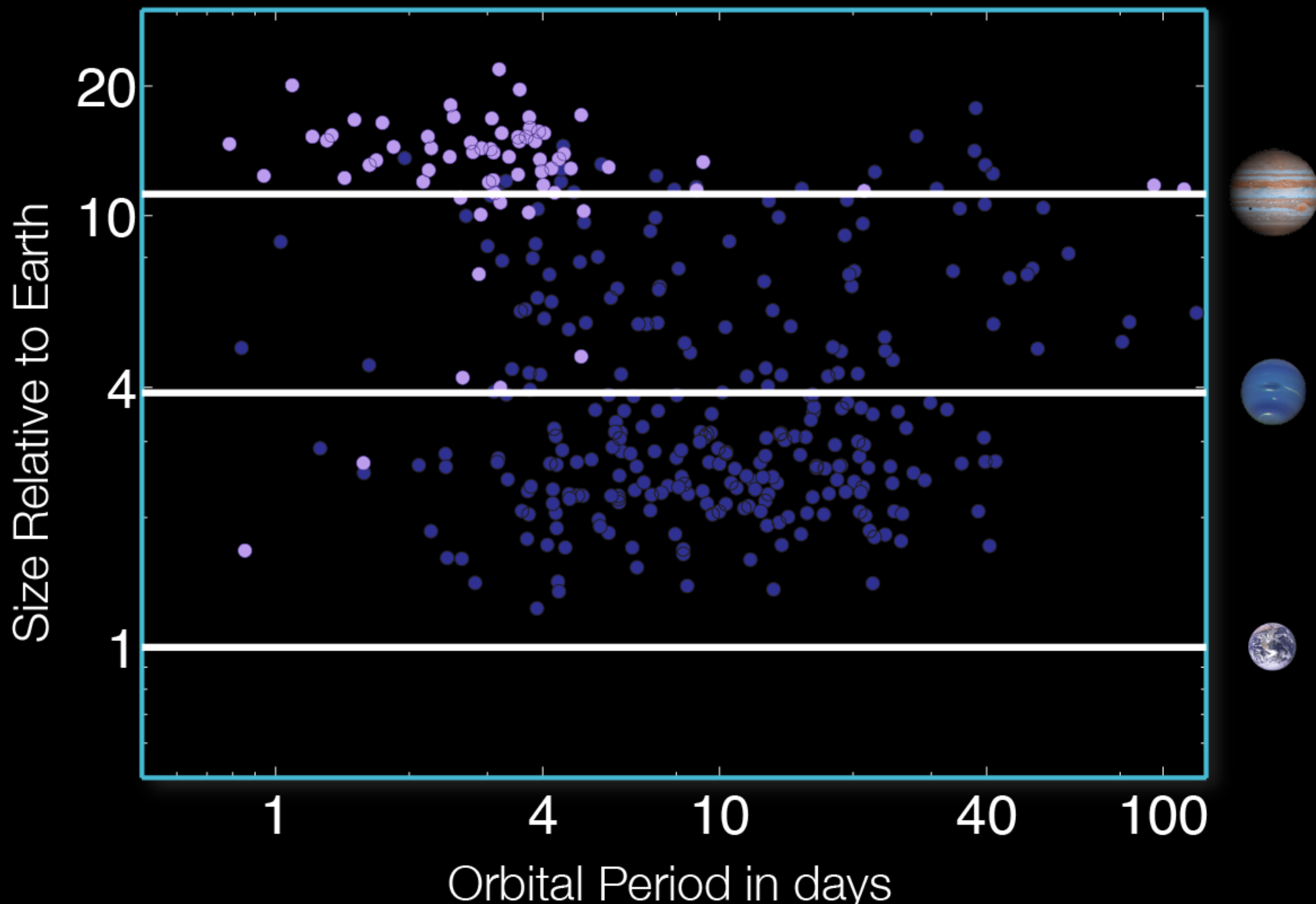
Table 1 | Planet properties

Planet	Period (days)	Epoch (BJD)	Semi-major axis (AU)	Inclination (°)	Transit duration (h)	Transit depth (millimagnitude)	Radius ($R_\oplus$)	Mass ($M_\oplus$)	Density (g cm^{-3})
b	10.30375 ± 0.00016	$2{,}454{,}971.5052 \pm 0.0077$	0.091 ± 0.003	$88.5^{+1.0}_{-0.6}$	4.02 ± 0.08	0.31 ± 0.01	1.97 ± 0.19	$4.3^{+2.2}_{-2.0}$	$3.1^{+2.1}_{-1.5}$
c	13.02502 ± 0.00008	$2{,}454{,}971.1748 \pm 0.0031$	0.106 ± 0.004	$89.0^{+1.0}_{-0.6}$	4.62 ± 0.04	0.82 ± 0.01	3.15 ± 0.30	$13.5^{+4.8}_{-6.1}$	$2.3^{+1.3}_{-1.1}$
d	22.68719 ± 0.00021	$2{,}454{,}981.4550 \pm 0.0044$	0.159 ± 0.005	$89.3^{+0.6}_{-0.4}$	5.58 ± 0.06	0.80 ± 0.02	3.43 ± 0.32	$6.1^{+3.1}_{-1.7}$	$0.9^{+0.5}_{-0.3}$
e	31.99590 ± 0.00028	$2{,}454{,}987.1590 \pm 0.0037$	0.194 ± 0.007	$88.8^{+0.2}_{-0.2}$	4.33 ± 0.07	1.40 ± 0.02	4.52 ± 0.43	$8.4^{+2.5}_{-1.9}$	$0.5^{+0.2}_{-0.2}$
f	46.68876 ± 0.00074	$2{,}454{,}964.6487 \pm 0.0059$	0.250 ± 0.009	$89.4^{+0.3}_{-0.2}$	6.54 ± 0.14	0.55 ± 0.02	2.61 ± 0.25	$2.3^{+2.2}_{-1.2}$	$0.7^{+0.7}_{-0.4}$
g	118.37774 ± 0.00112	$2{,}455{,}120.2901 \pm 0.0022$	0.462 ± 0.016	$89.8^{+0.2}_{-0.2}$	9.60 ± 0.13	1.15 ± 0.03	3.66 ± 0.35	<300	–

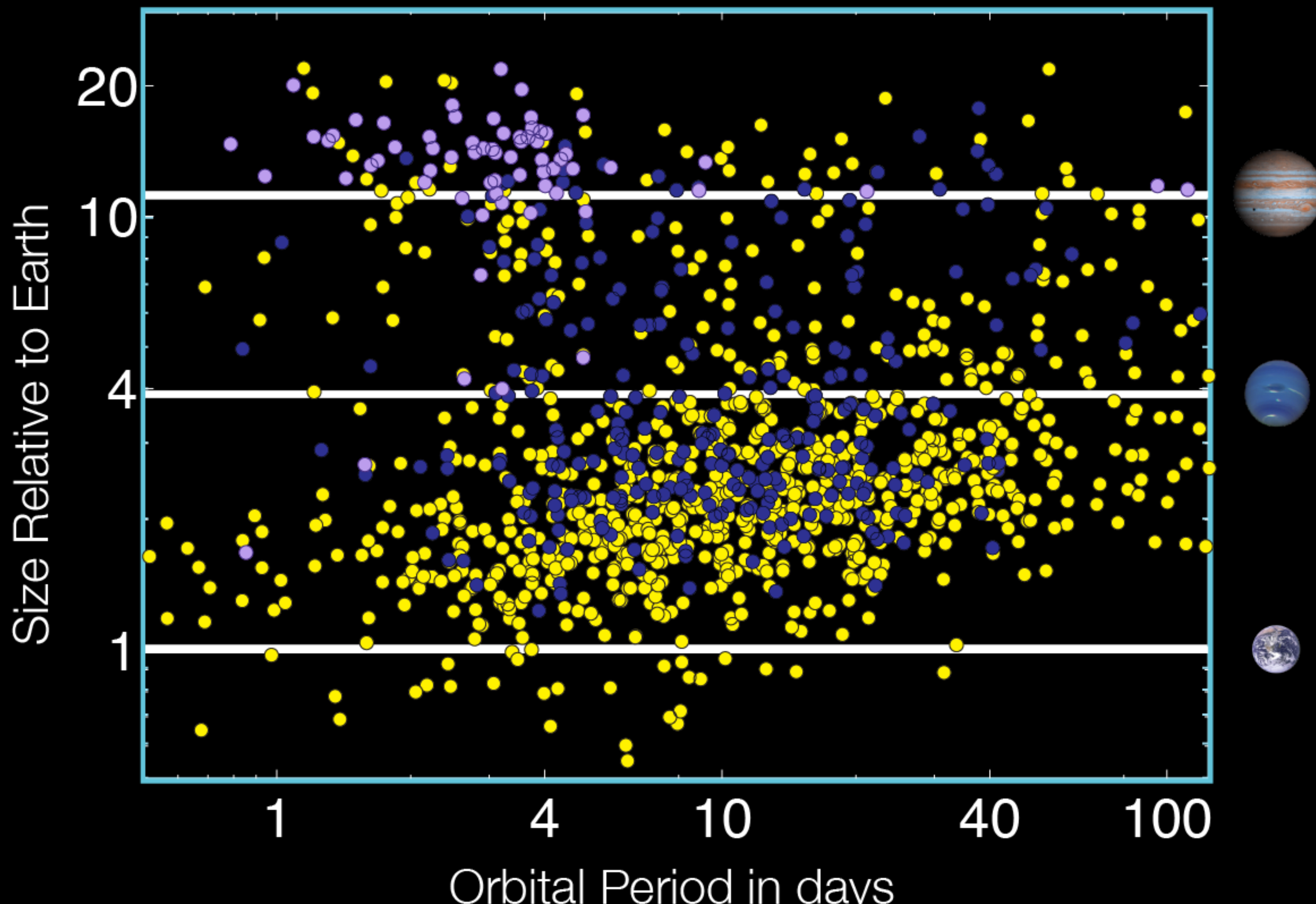
Pre-Kepler Transiting Planets - 2009



Kepler Candidates as of June 2010

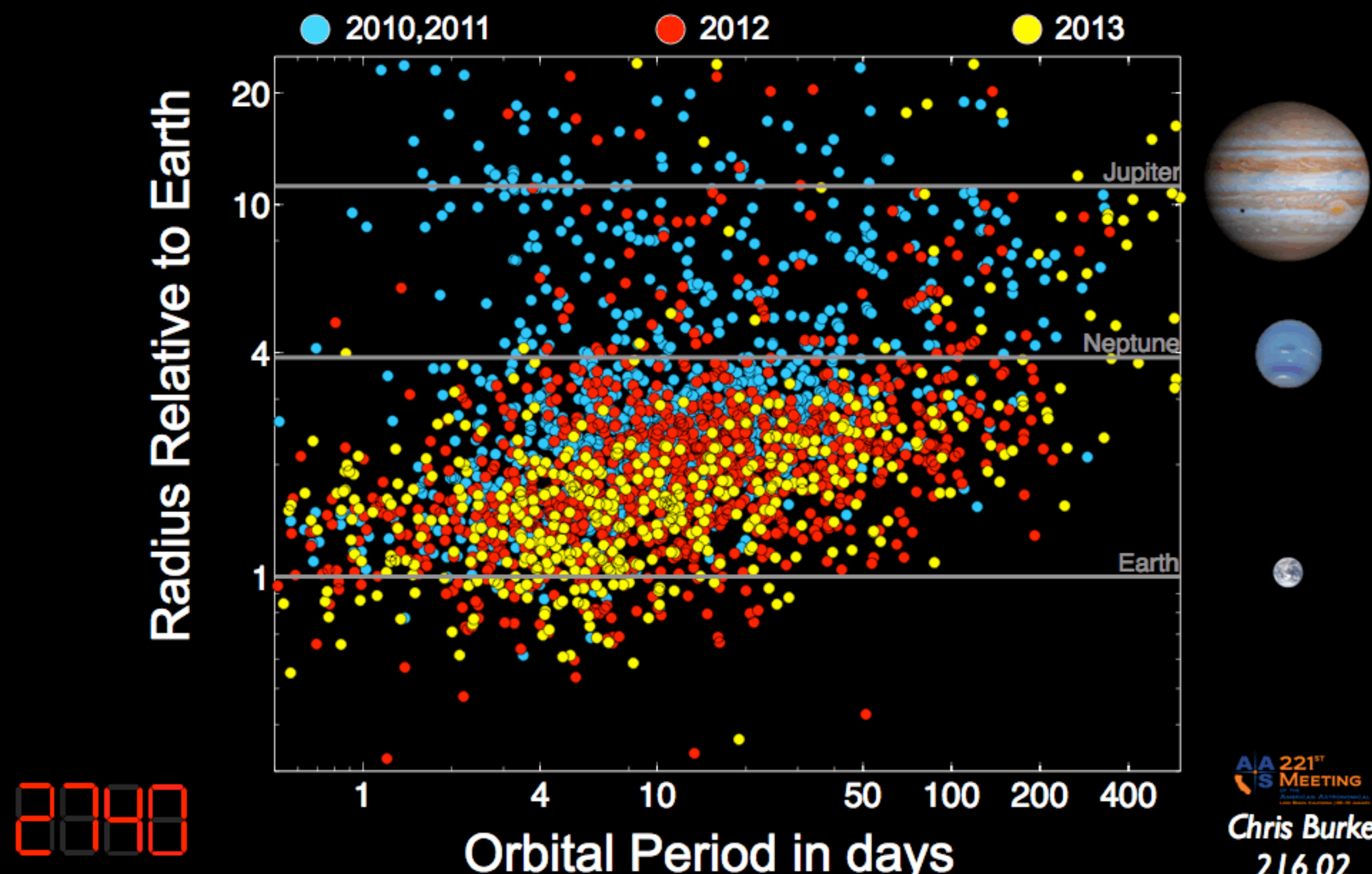


Kepler Candidates as of February 1, 2011



Kepler's Planet Candidates

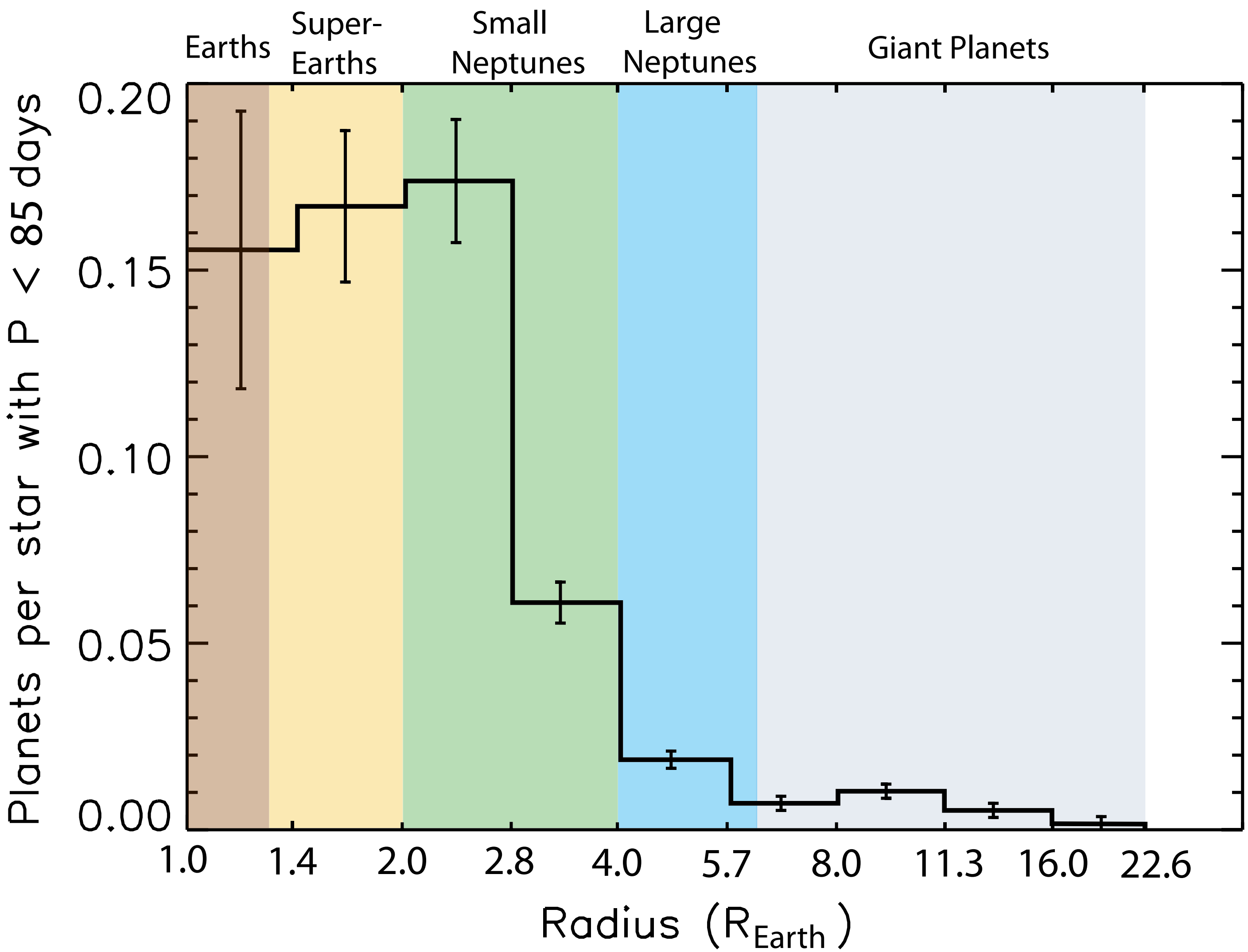
22 Months: May 2009 - Mar 2011



AAS 221st Meeting

Chris Burke: 216.02

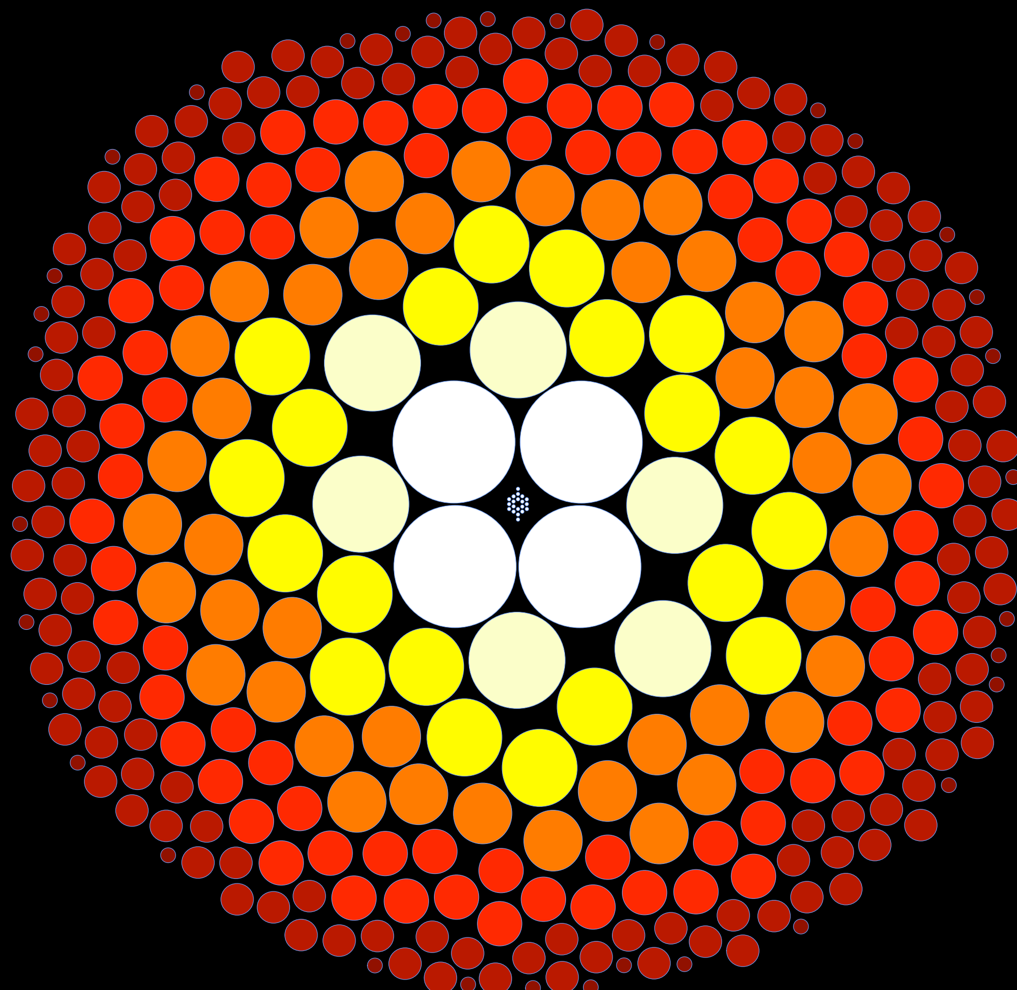
The frequency of planets within 85 days of Sun-like stars



Based on ~2300 planet candidates

Fressin et al. (2013)

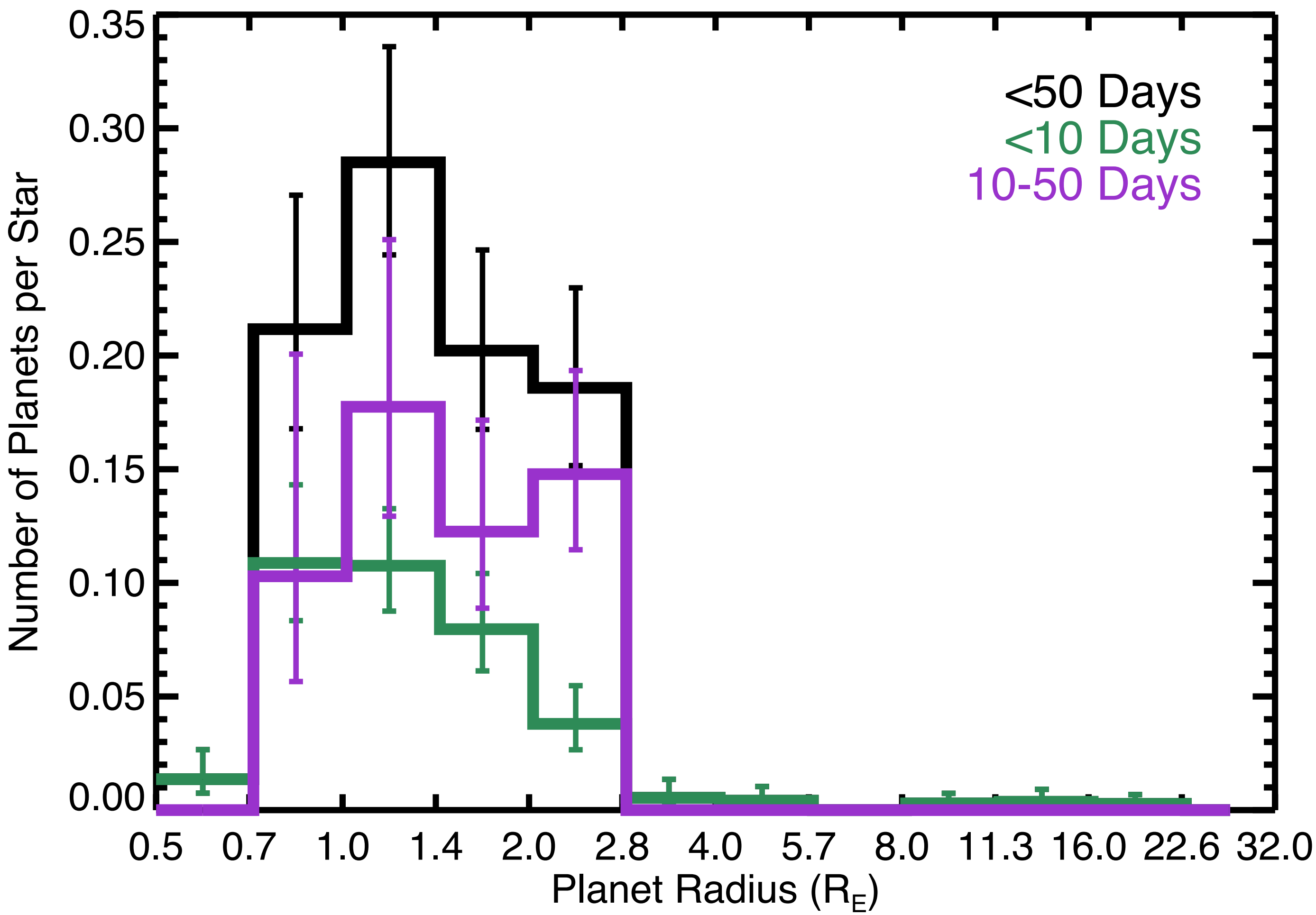
Stars within 30 lightyears of the Sun



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

Todd Henry, Georgia State University

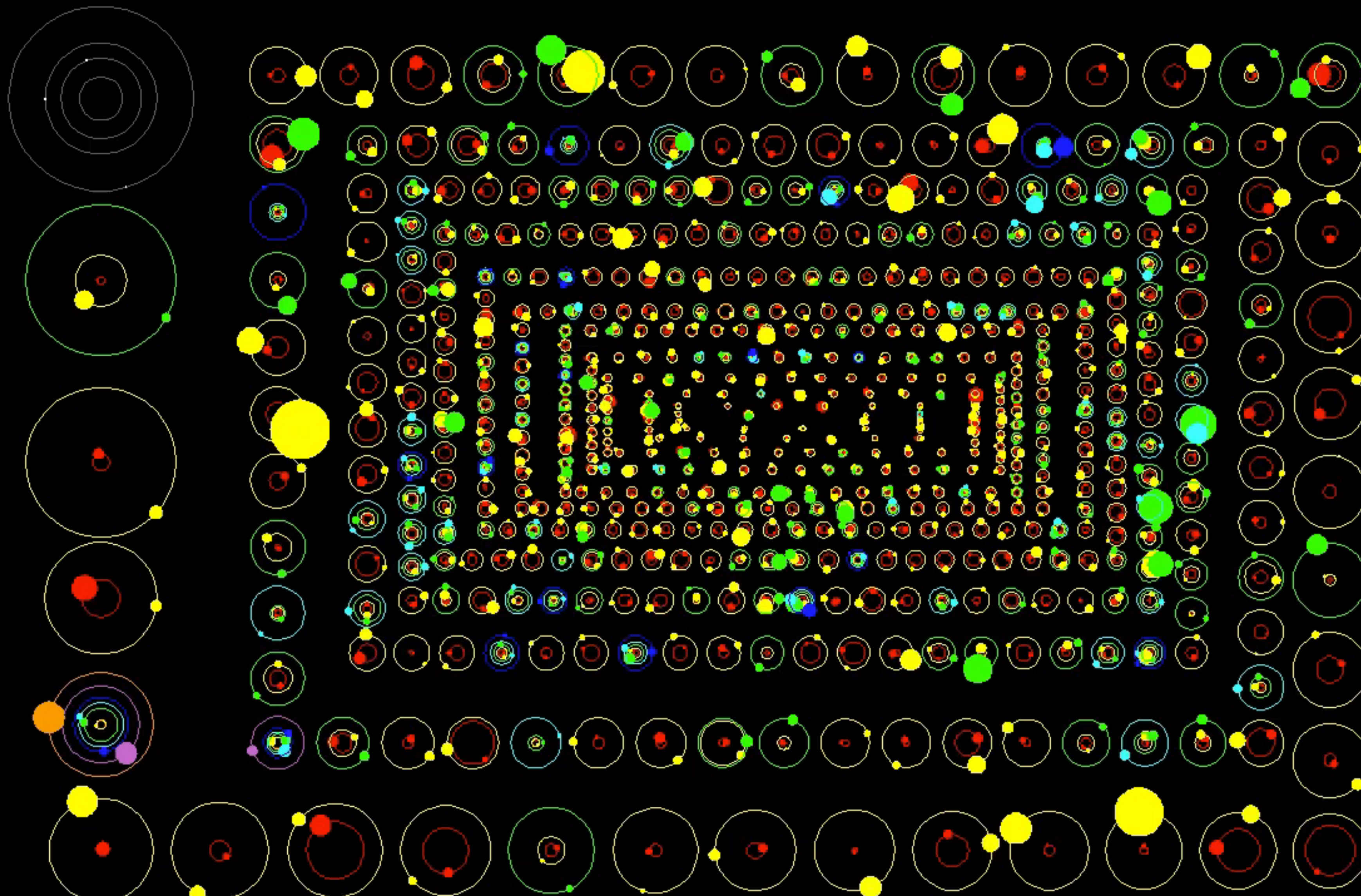
The frequency of planets within 50 days of M stars



1.5 planets per M star within ~80 days

The Kepler Orrery III

t[BJD] = 2455215



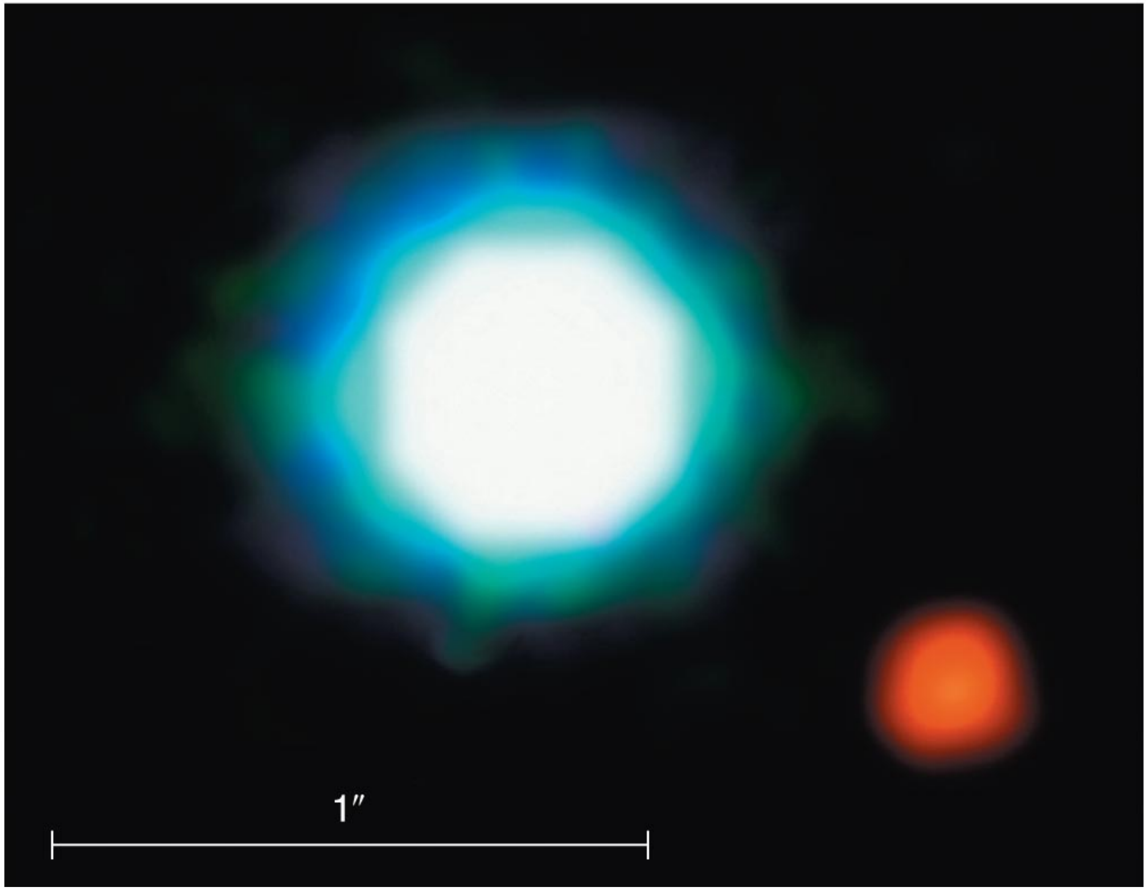
How do astronomers look for planets whose orbits might cause them to pass in front of a star outside our solar system?

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).

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

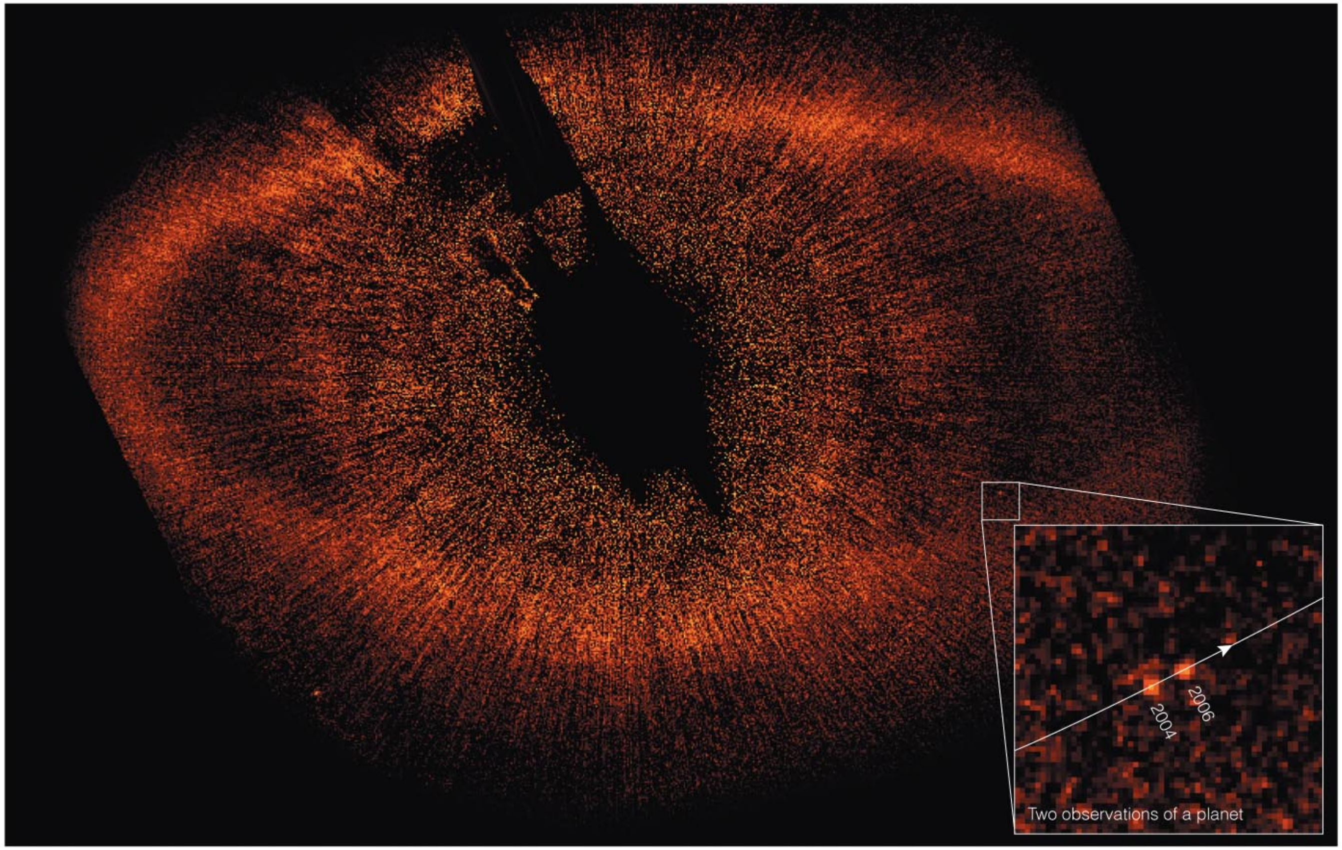
A. They look for a small black dot passing in front of the star.
B. The look to see if the star's position shifts or "wobbles" slightly in the sky.
C. The measure the star's brightness, and look for periodic dimming (transits).

Direct Detection

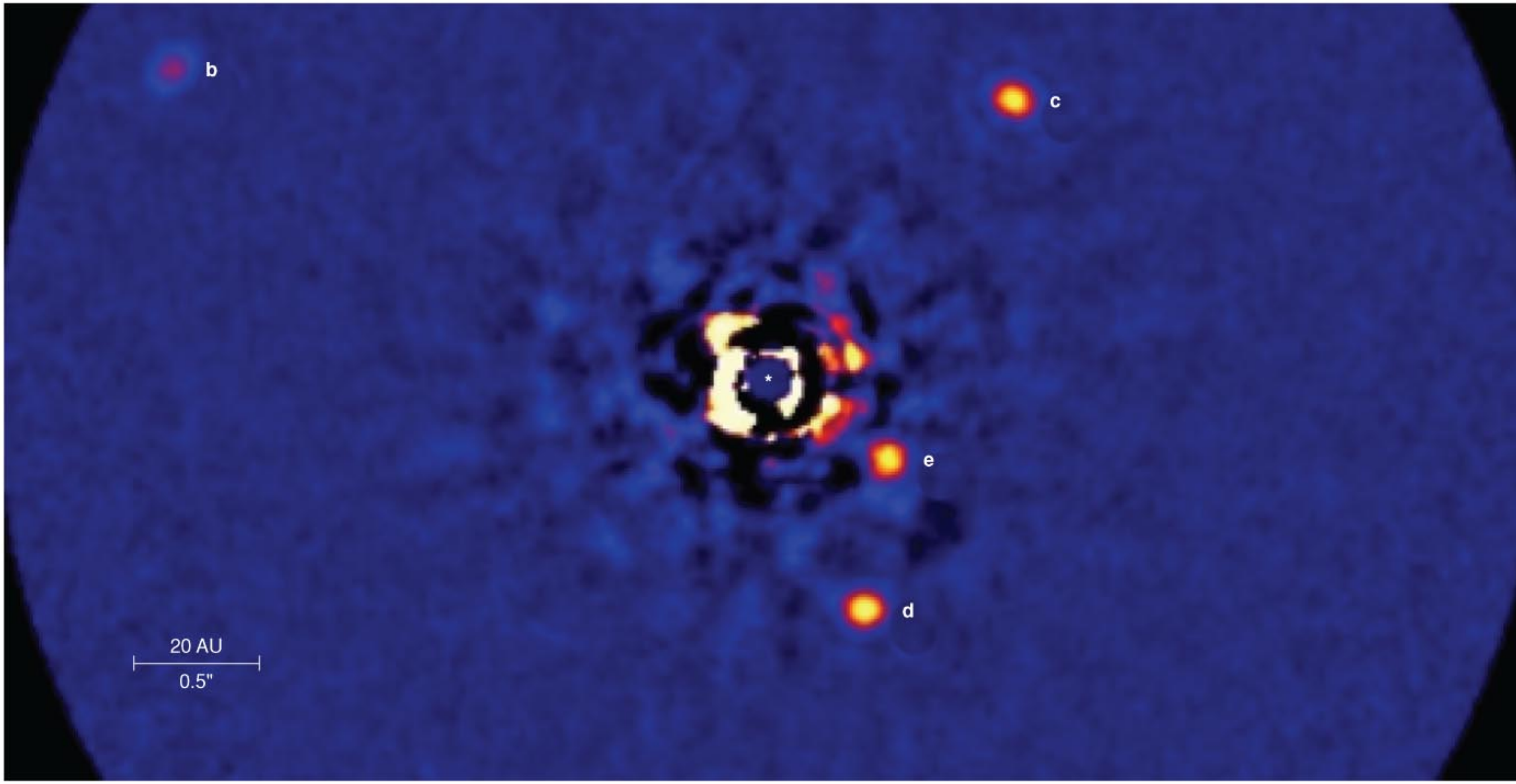


- Special techniques like adaptive optics are helping to enable direct planet detection.

Direct Detection

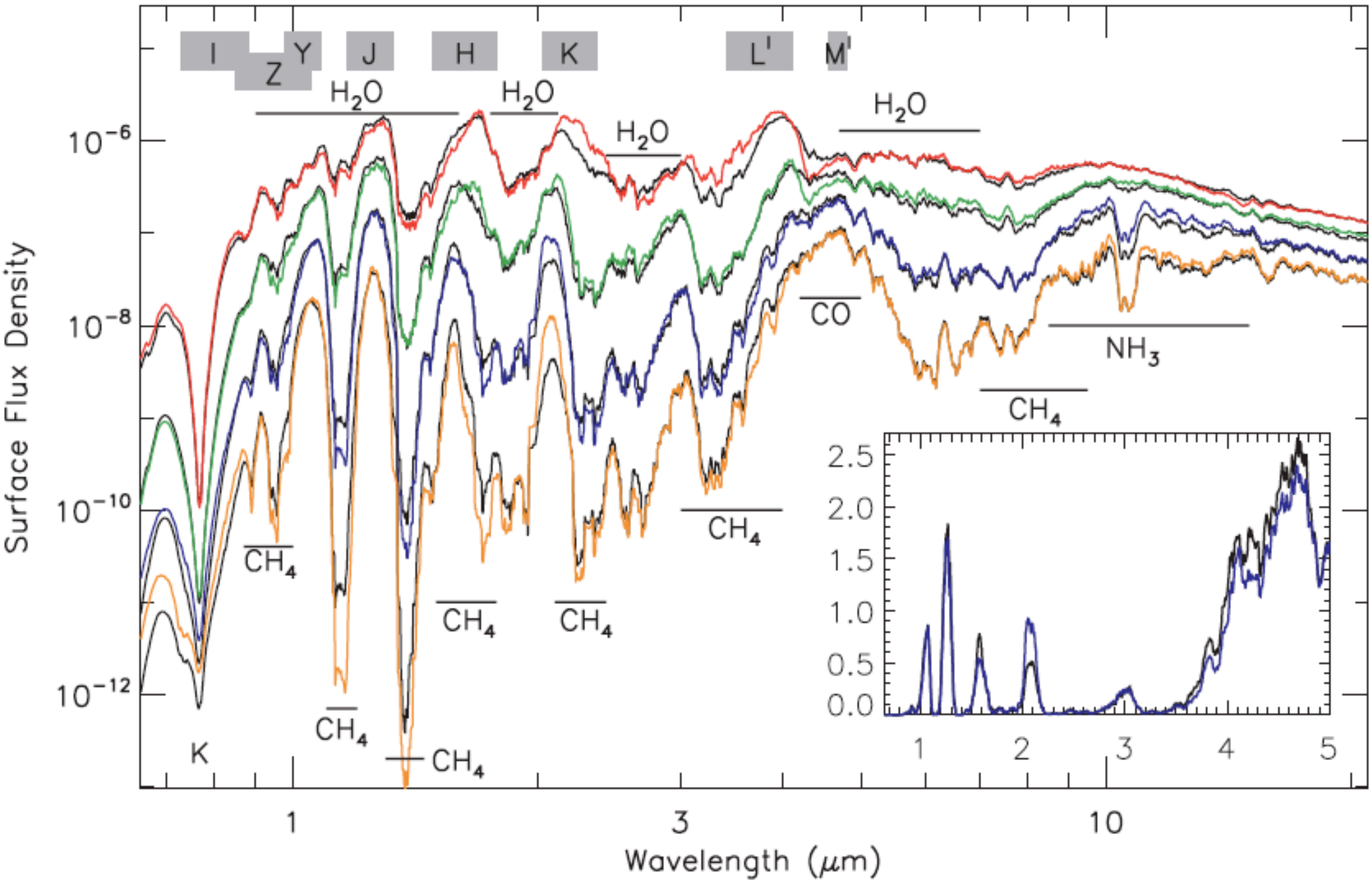


- Techniques that help block the bright light from stars are also helping us to find planets around them.

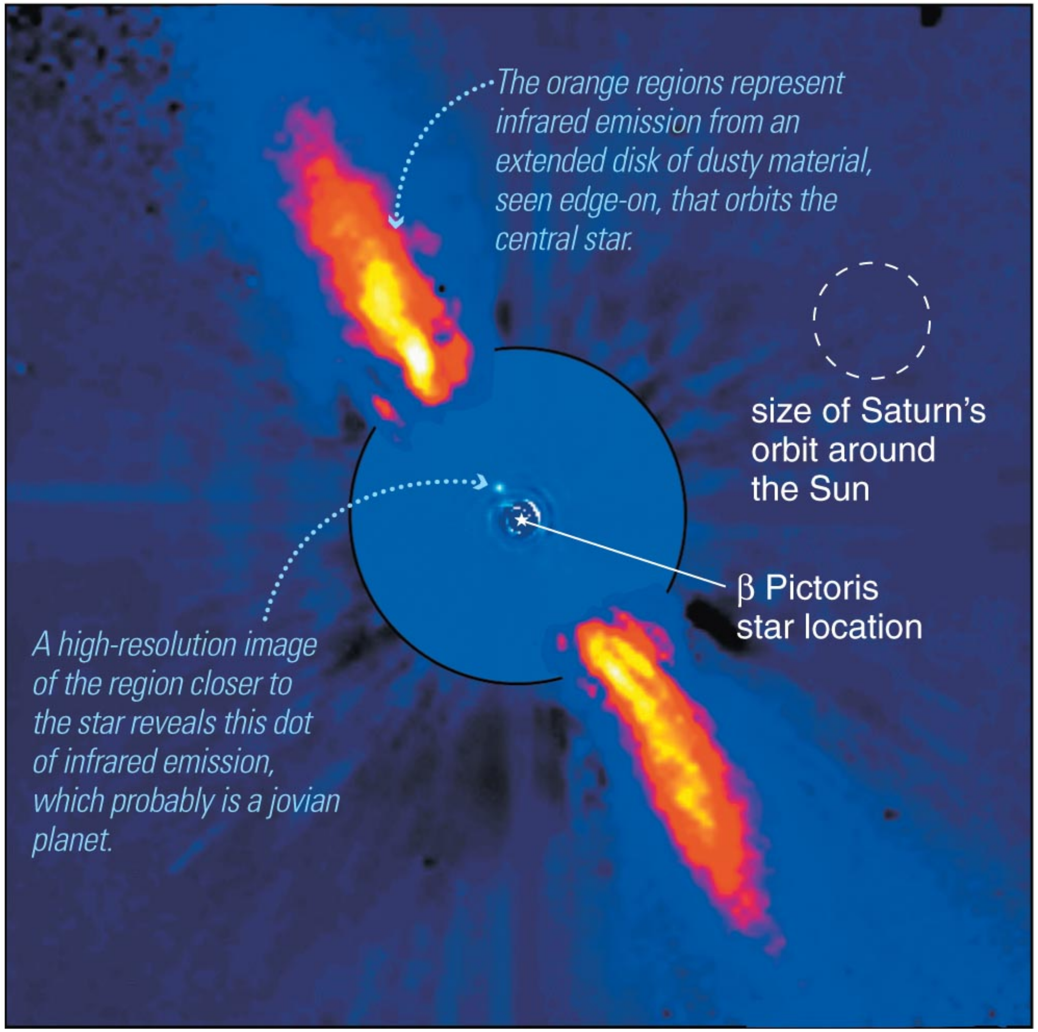


HR 8799: 4-planet system

How Bright are Young Exoplanets?



Direct Detection



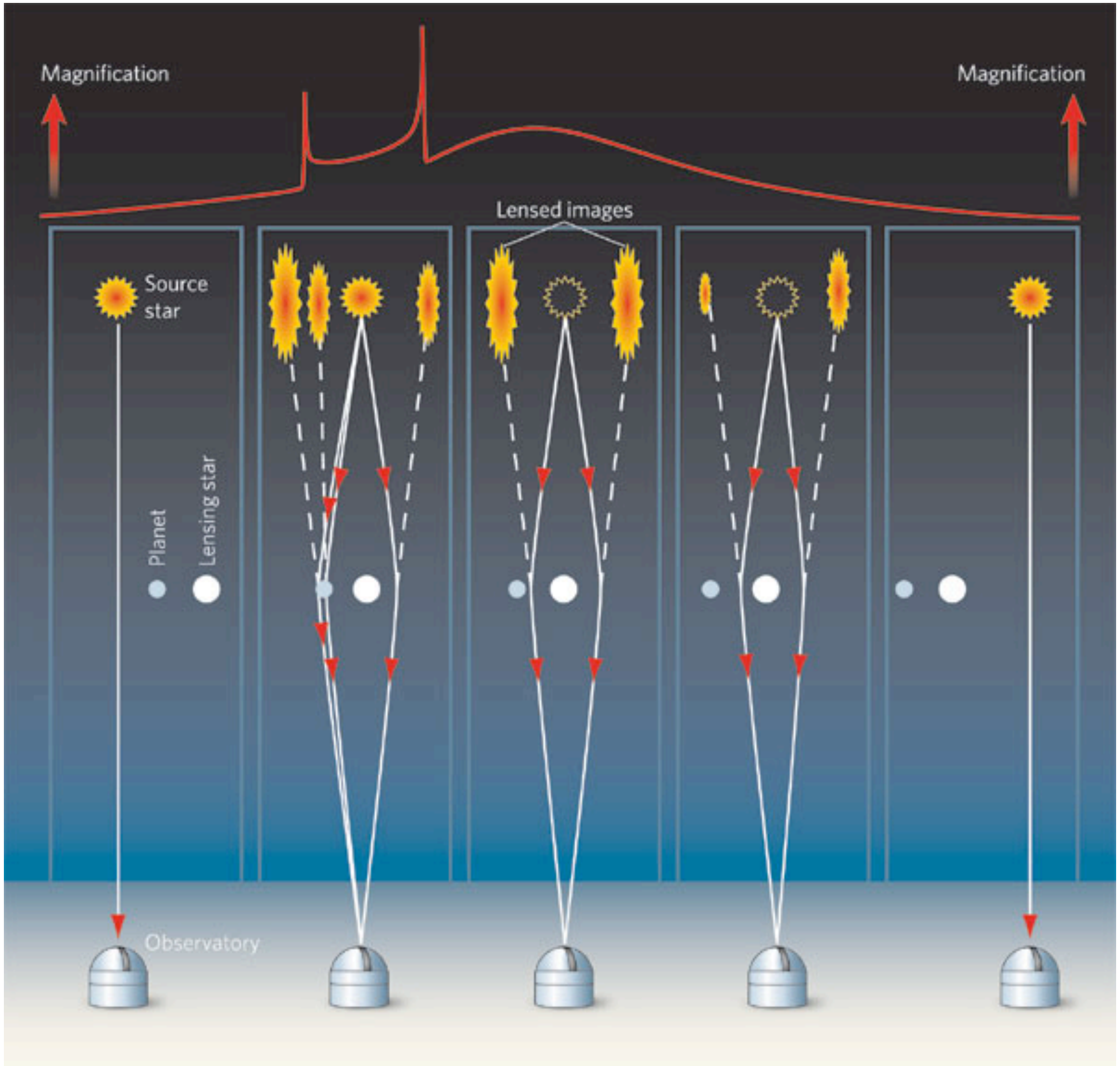
- Techniques that help block the bright light from stars are also helping us to find planets around them.

Other Planet-Hunting Strategies

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

- **Features in Dust Disks:** Gaps, waves, or ripples in disks of dusty gas around stars can indicate presence of planets.

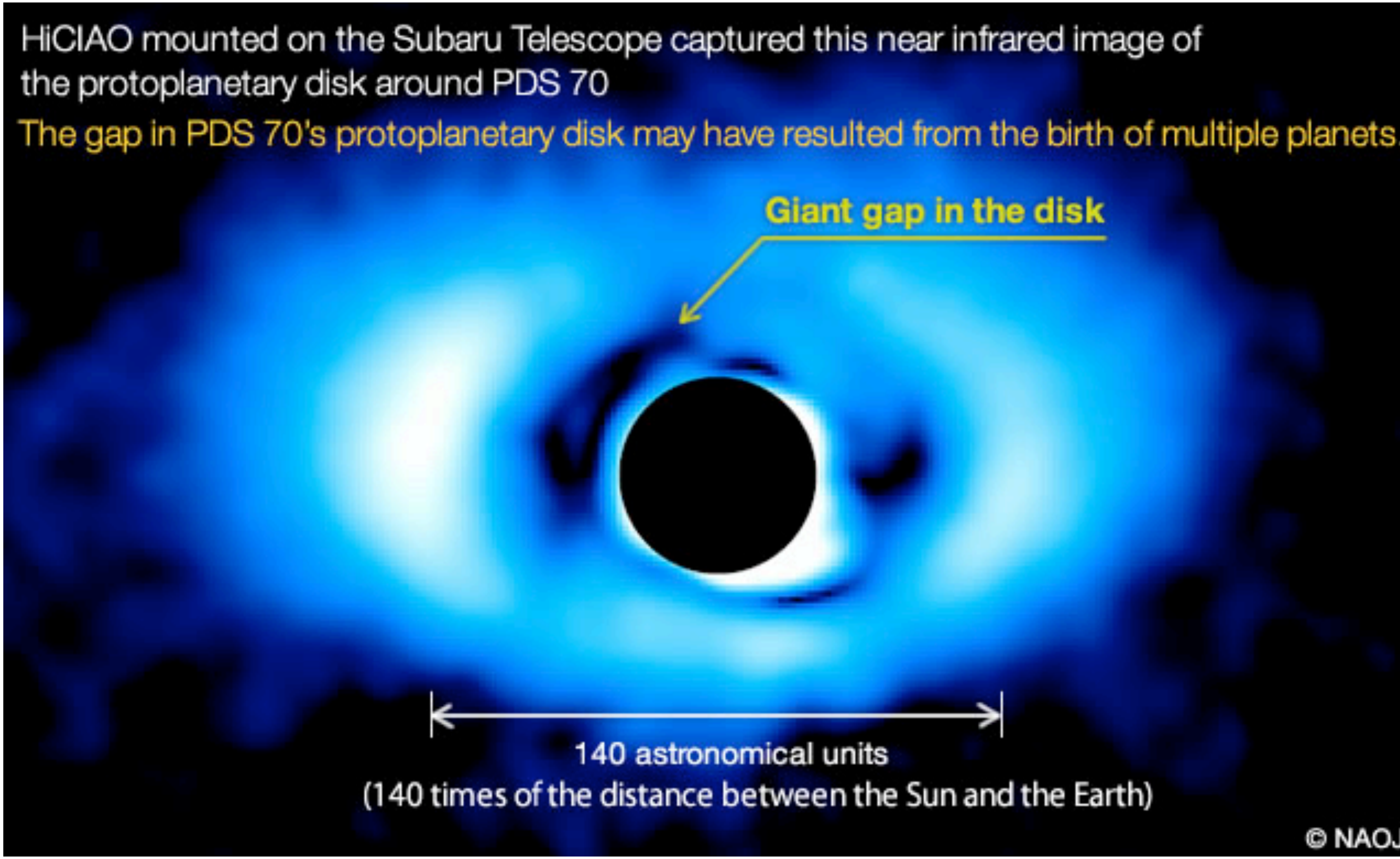
Gravitational Lensing



Other Planet-Hunting Strategies

- **Gravitational Lensing:** Mass bends light in a special way when a star with planets passes in front of another star.
  - Requires chance alignment that will never repeat
  - Can find lots of planets – good for statistics
  - Can very rarely ever follow up the systems

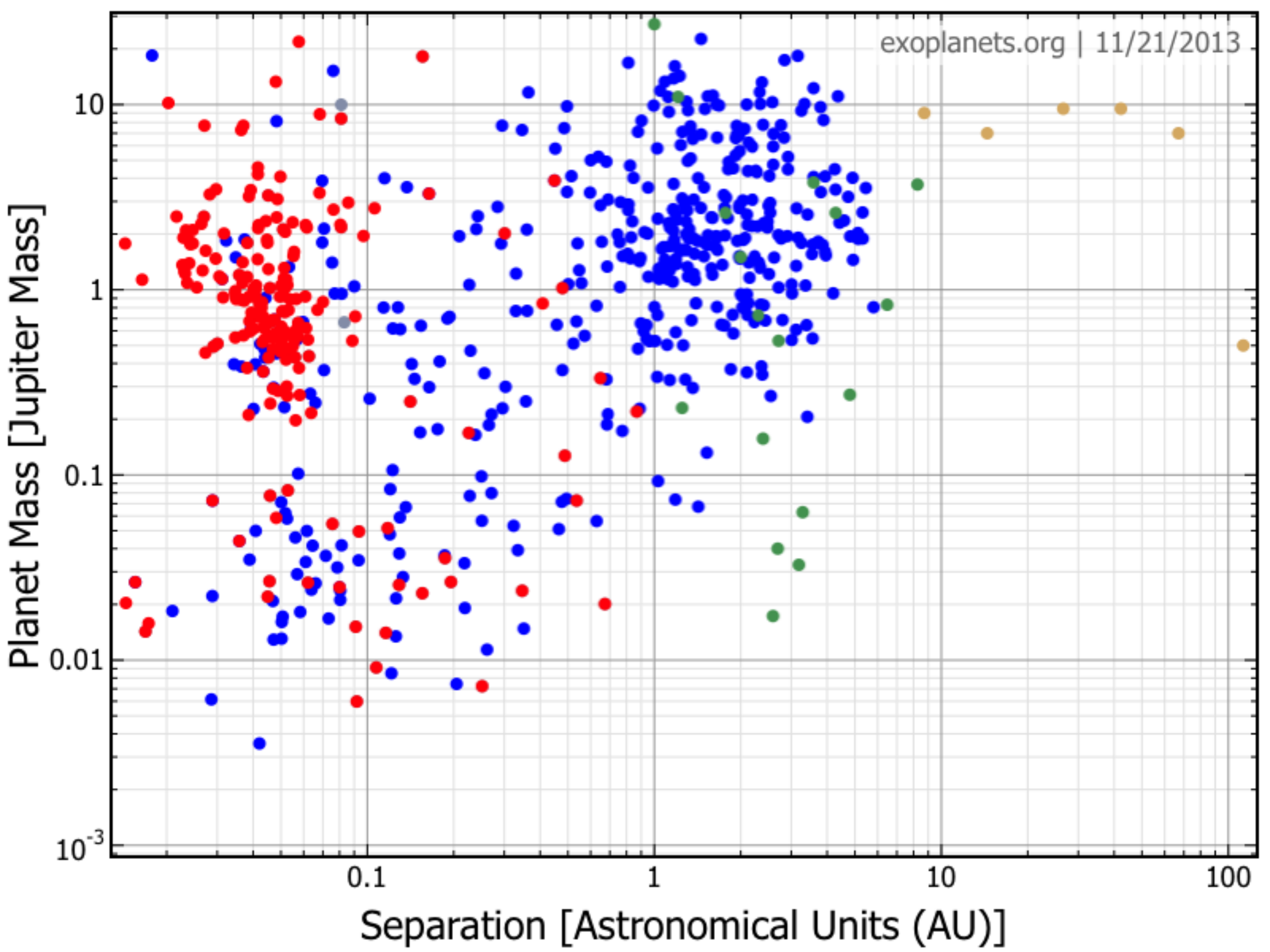
- **Features in Dust Disks:** Gaps, waves, or ripples in disks of dusty gas around stars can indicate presence of planets.

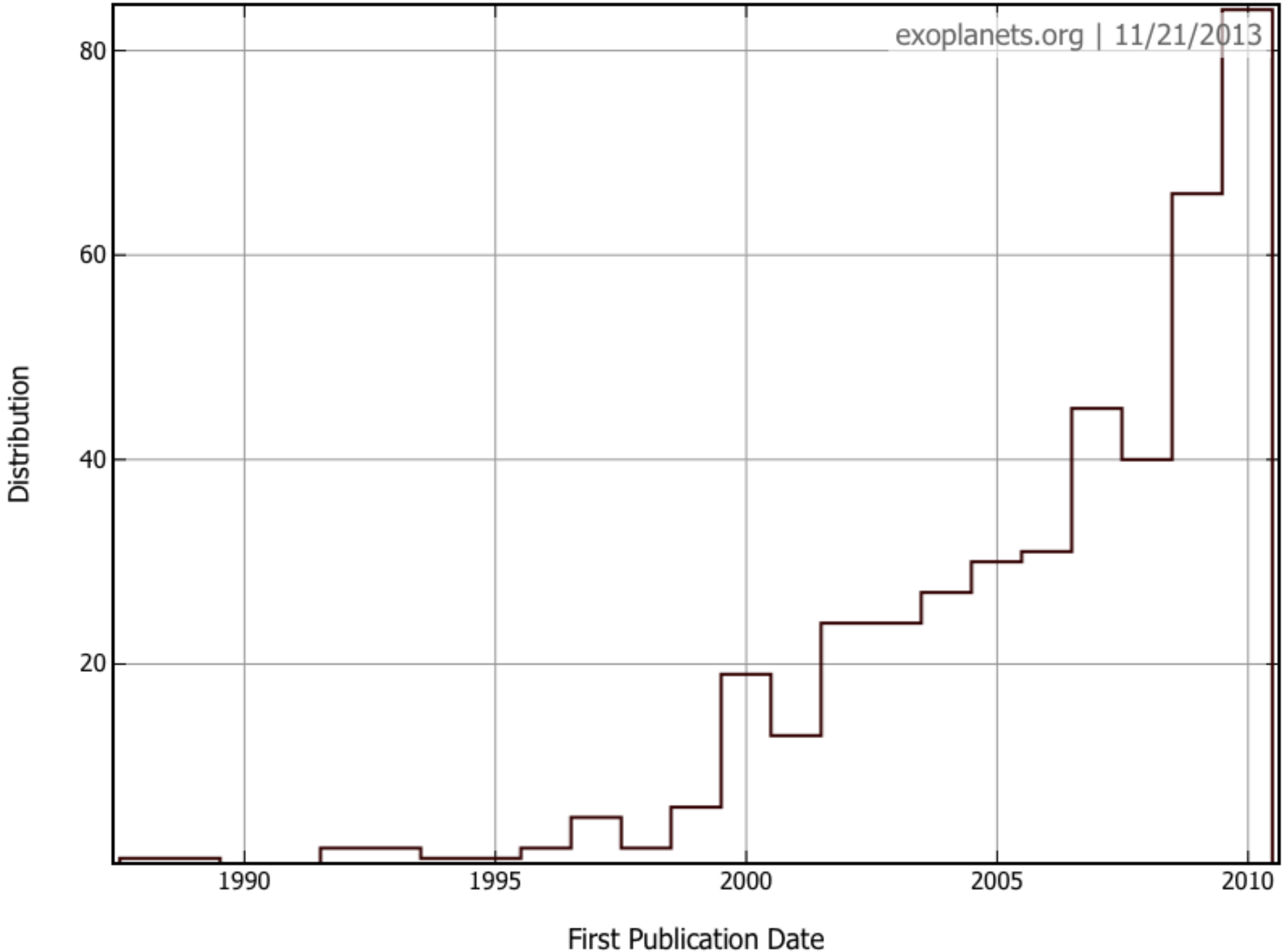

HiCIAO mounted on the Subaru Telescope captured this near infrared image of the protoplanetary disk around PDS 70
The gap in PDS 70's protoplanetary disk may have resulted from the birth of multiple planets.
Giant gap in the disk
140 astronomical units
(140 times of the distance between the Sun and the Earth)
© NAOJ

Other Planet-Hunting Strategies

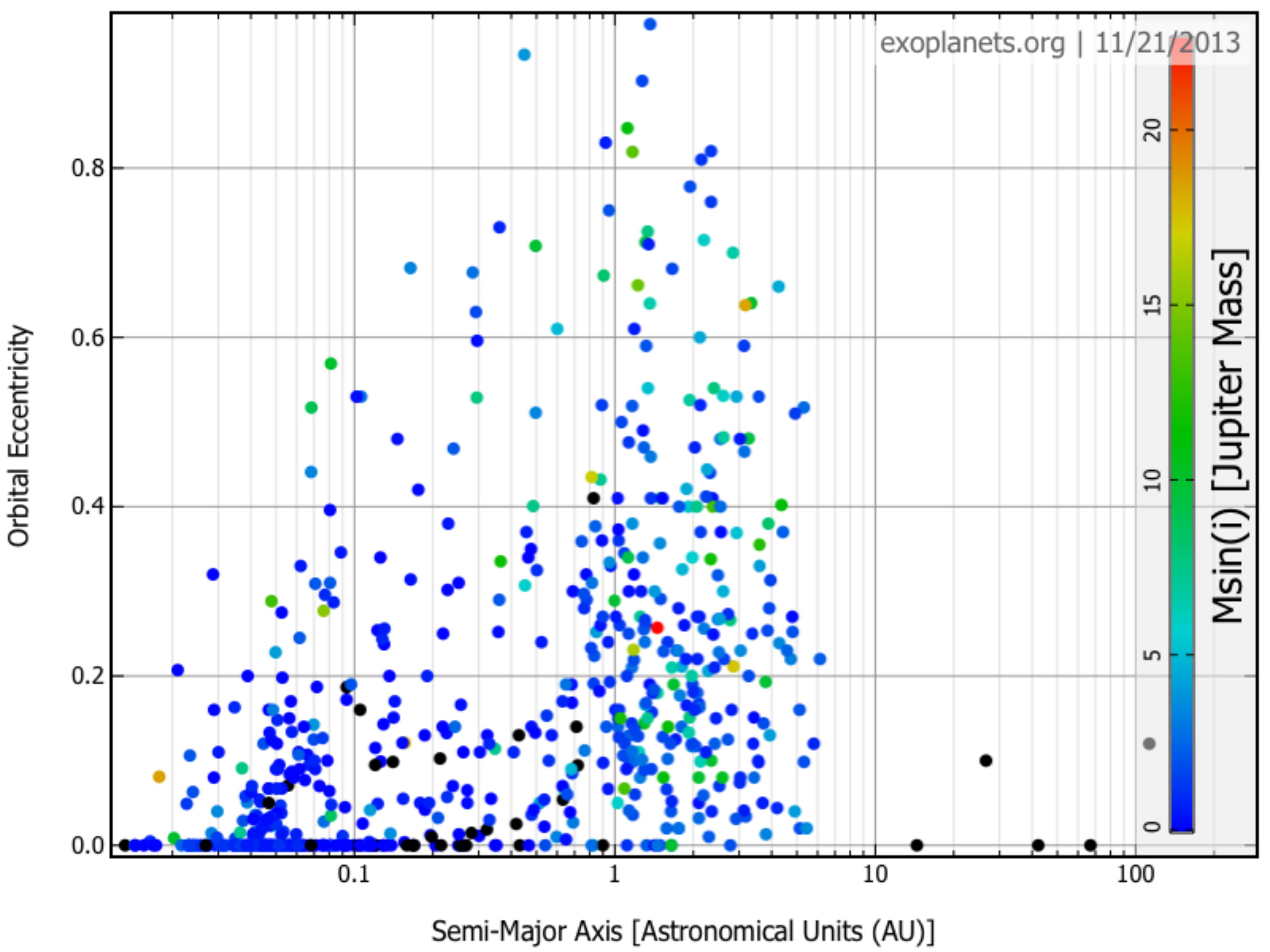
- **Gravitational Lensing:** Mass bends light in a special way when a star with planets passes in front of another star.

- **Features in Dust Disks:** Gaps, waves, or ripples in disks of dusty gas around stars can indicate presence of planets.
  - Good evidence for planets
  - Very hard to interpret what you're seeing


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
80
60
40
20
Distribution
1990
1995
2000
2005
2010
First Publication Date


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

What have we learned?

- Why is it so difficult to detect planets around other stars?
  - Direct starlight is billions of times brighter than the starlight reflected from planets.
- How do we detect planets around other stars?
  - A star's periodic motion (detected through Doppler shifts) tells us about its planets.
  - Transiting planets periodically reduce a star's brightness.
  - Direct detection is possible if we can reduce the glare of the star's bright light.