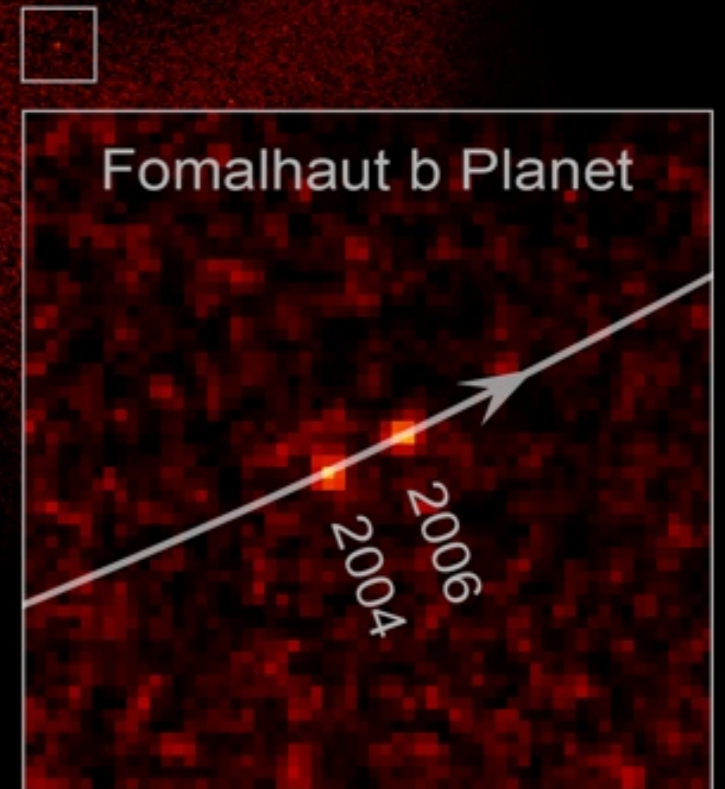
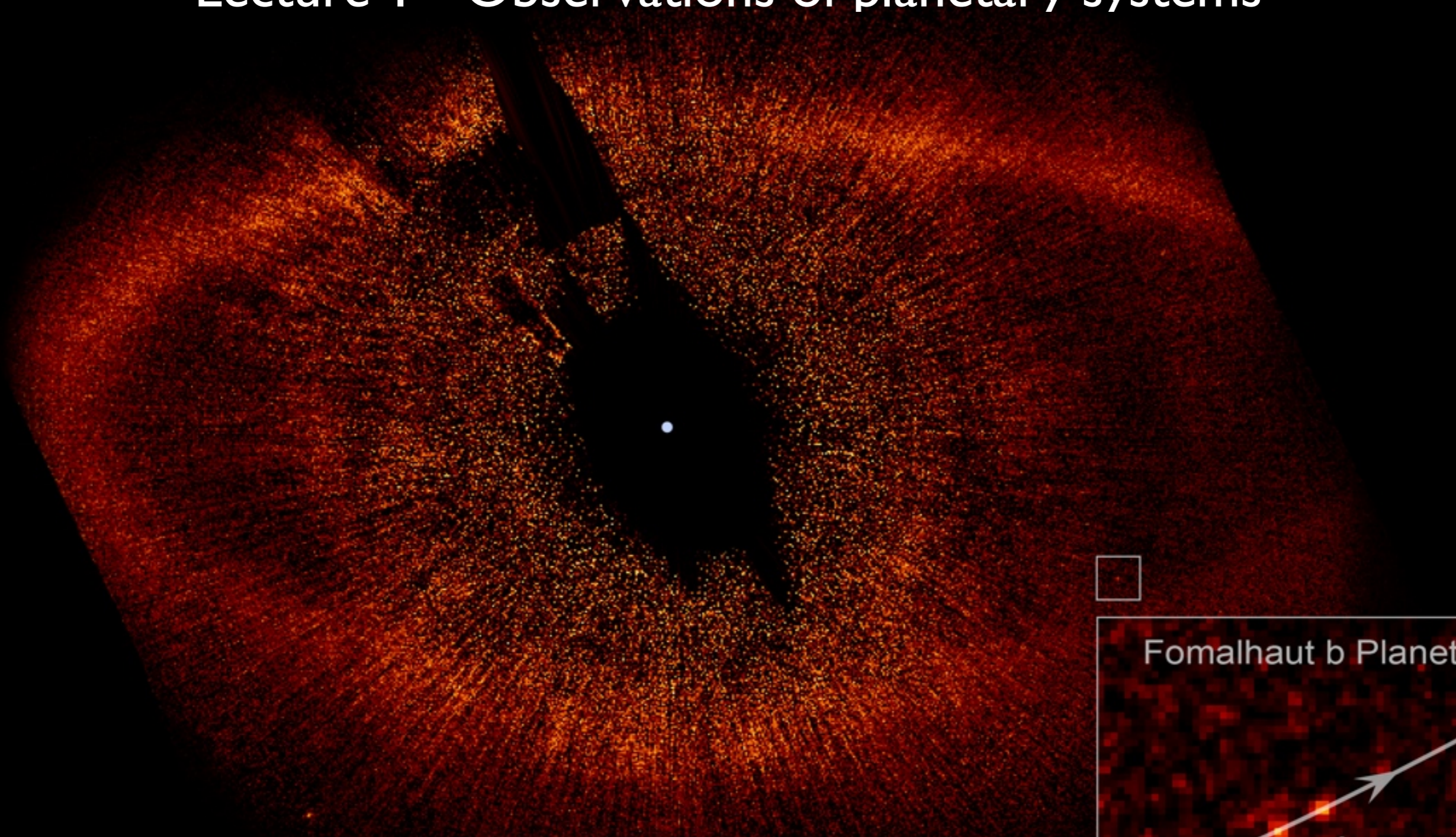


# Formation of Planetary Systems

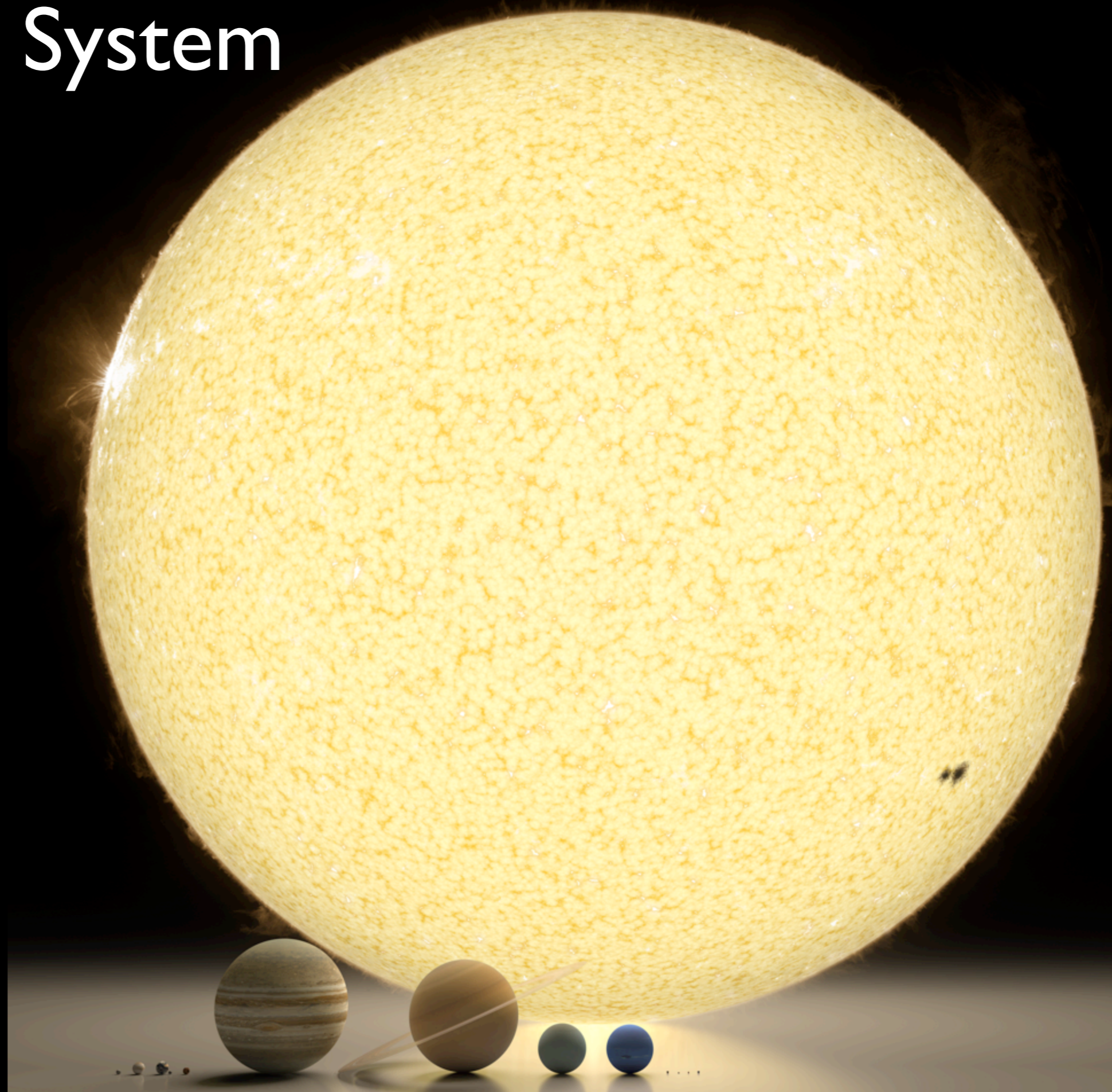
## Lecture 1 - Observations of planetary systems



# Course Outline

- 5 Lectures, 2 hours each (with a break in the middle!).
  - 1) Observations of planetary systems
  - 2) Protoplanetary discs
  - 3) Dust dynamics & planetesimal formation
  - 4) Planet formation
  - 5) Planetary dynamics
- Notes for each lecture will be placed on the course home page *in advance* - you may find it useful to annotate these as we go.
- These slides will also be posted online.
- Textbooks: Armitage - *Astrophysics of planet formation* (CUP).  
*Protostars & Planets* series (V - 2007; VI - 2014)

# The Solar System



Uranus

Saturn

Jupiter

Mars

Earth

Venus

Mercury

Sun

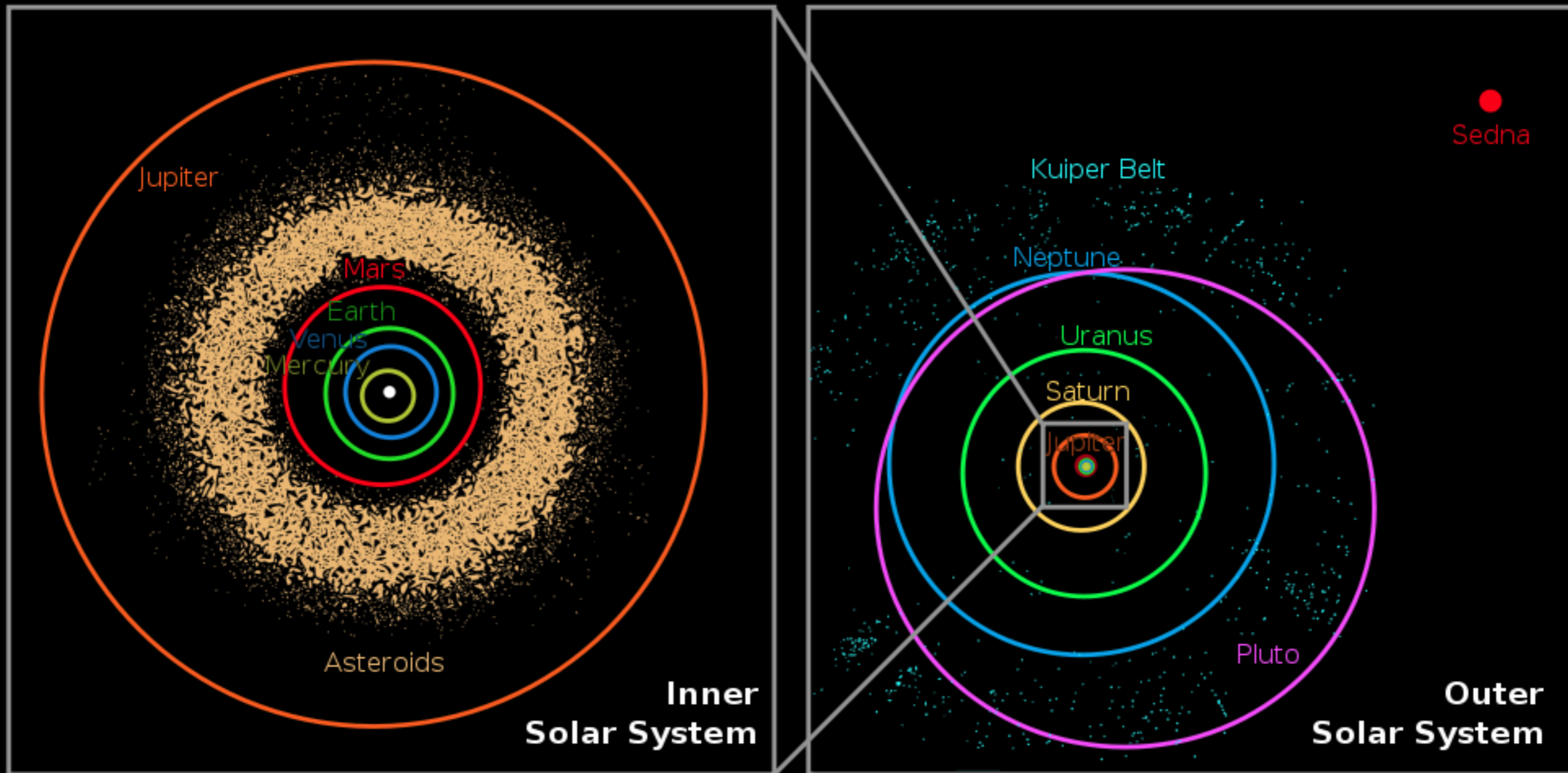
**Roberto Ziche**

**Our Solar System**

Background: The Sun    Foreground: The planets Mercury, Venus, Earth (and Moon), Mars, Jupiter, Saturn, Uranus, Neptune, and the dwarf planets Pluto, Haumea, Makemake, and Eris.

Planetary Orbits

# The Solar System



# The Solar System

	a AU	e	$M_p$ $M_{Jup}$
Mercury	0.387	0.206	$1.74 \times 10^{-4}$
Venus	0.723	0.007	$2.56 \times 10^{-3}$
Earth	1.000	0.017	$3.15 \times 10^{-3}$
Mars	1.524	0.093	$3.38 \times 10^{-4}$
Jupiter	5.203	0.048	1.00
Saturn	9.537	0.054	0.299
Uranus	19.19	0.047	0.046
Neptune	30.07	0.009	0.054

# The Solar System

- Gas giants (Jupiter & Saturn):
  - massive: >90% of total planetary mass.
  - primarily H/He, but metal-rich w.r.t. Sun.
  - $\sim 10M_{\text{Earth}}$  solid cores (probably!).
- Ice giants (Uranus & Neptune):
  - $\text{H}_2\text{O}$ ,  $\text{NH}_3$ ,  $\text{CH}_4$ , etc.
  - $\sim 1M_{\text{Earth}}$  solid cores.
- Terrestrial planets (Mercury, Venus, Earth, Mars).
- Minor bodies: “dwarf planets”, moons, asteroids, comets, Kuiper belt, Oort cloud.
- All 8 planets are nearly co-planar, with near-circular orbits.

# The Solar System

- >99% of total mass resides in the Sun.
- >99% of total angular momentum resides in the planets (mostly in Jupiter).
- Planets very metal-rich w.r.t. Sun (though majority of heavy elements are in the Sun).
- Radioactive dating (e.g.  $^{87}\text{Rb} \rightarrow ^{87}\text{Sr}$ ) finds age of 4.57Gyr.
- **Planet formation processes must:**
  - **grow solid bodies from ISM grains to  $>M_{\text{Earth}}$ .**
  - **separate mass from angular momentum.**
  - **separate metals from H/He.**

# Methods of detecting extra-solar planets

- **Directly:**
  - Light emitted/reflected by planet  
**direct imaging**
- **Indirectly:**
  - Motion of star due to planet  
**astrometry**  
**radial velocity**  
**timing methods**
  - Obscuration of stellar light by planet  
**transits**
  - Obscuration/amplification of background star by planet  
**gravitational microlensing**



# Methods of detecting extra-solar planets

- **Directly:**

- Light emitted/reflected by planet

**direct imaging**

**14**

- **Indirectly:**

- Motion of star due to planet

**astrometry**

**0**

**radial velocity**

**586**

**timing methods (inc TTVs)**

**10**

- Obscuration of stellar light by planet

**transits**

**2636 (2485)**

- Obscuration/amplification of background star by planet

**gravitational microlensing**

**16**

# Methods of detecting extra-solar planets

- **Directly:**

- Light emitted/reflected by planet

**direct imaging**

**14**

- **Indirectly:**

- Motion of star due to planet

**astrometry**

**0**

**radial velocity**

**586**

**timing methods (inc TTVs)**

**10**

- Obscuration of stellar light by planet

**transits**

**2636 (2485)**

- Obscuration/amplification of background star by planet

**gravitational microlensing**

**16**

**Total: 3262 (5747)**

# Direct Imaging

- Planets are very faint. How faint?



- Fraction of star-light reflected by planet is\*:

$$f = A \left( \frac{\text{Cross-sect. area of planet}}{\text{Area of sphere radius } a} \right) = A \left( \frac{\pi R_p^2}{4\pi a^2} \right)$$

$$\Rightarrow f_{\oplus} \simeq 2 \times 10^{-10} \quad f_{Jup} \simeq 1 \times 10^{-9}$$

- Two problems for detecting in exo-planetary systems: **brightness** and **contrast**. Contrast is usually dominant.

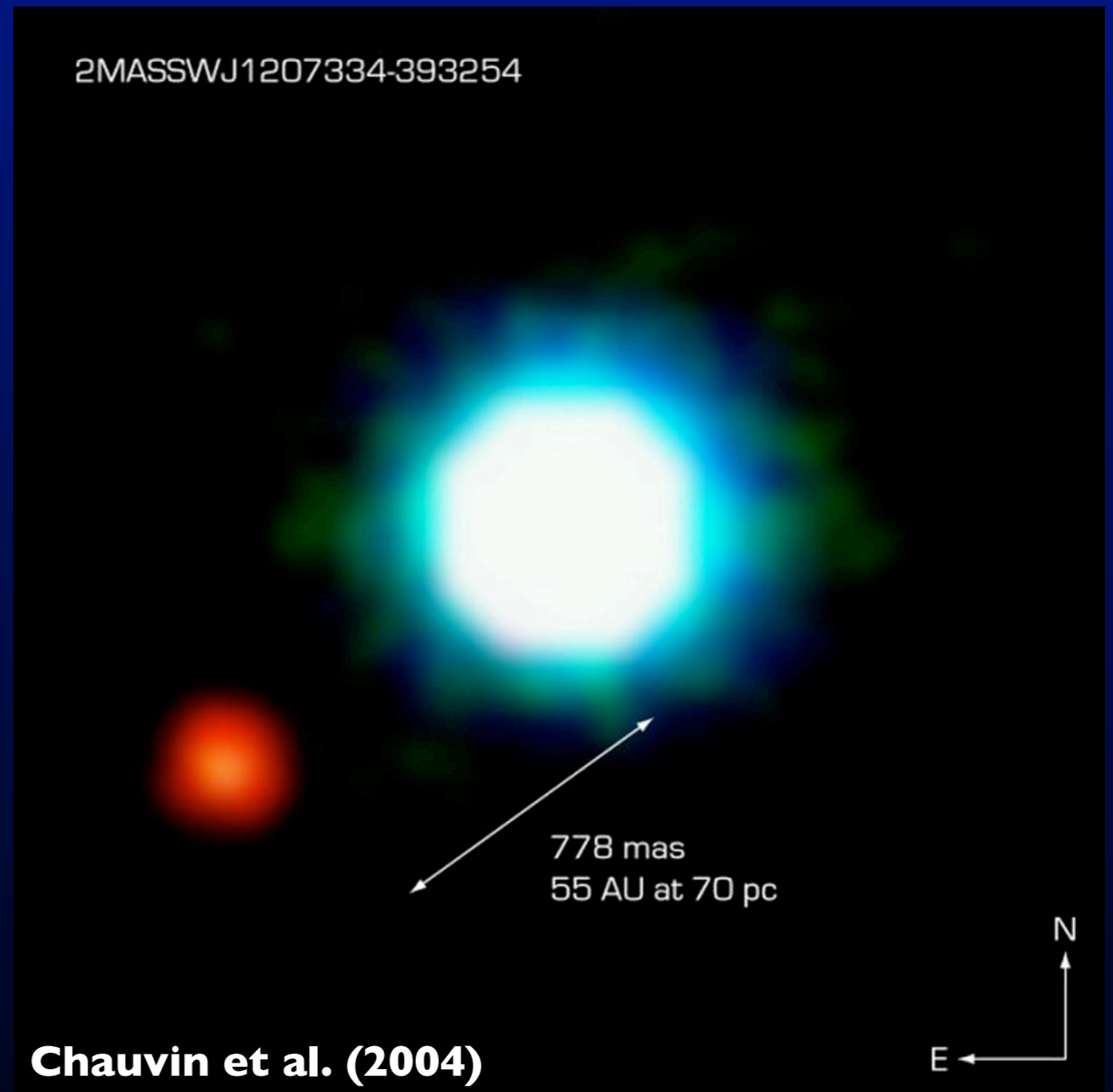
\*A is the *albedo*.

# Direct Imaging

- Two ways around the contrast problem:
  - a) Look for planets around faint stars
  - b) Try to mask out star-light

# Direct Imaging

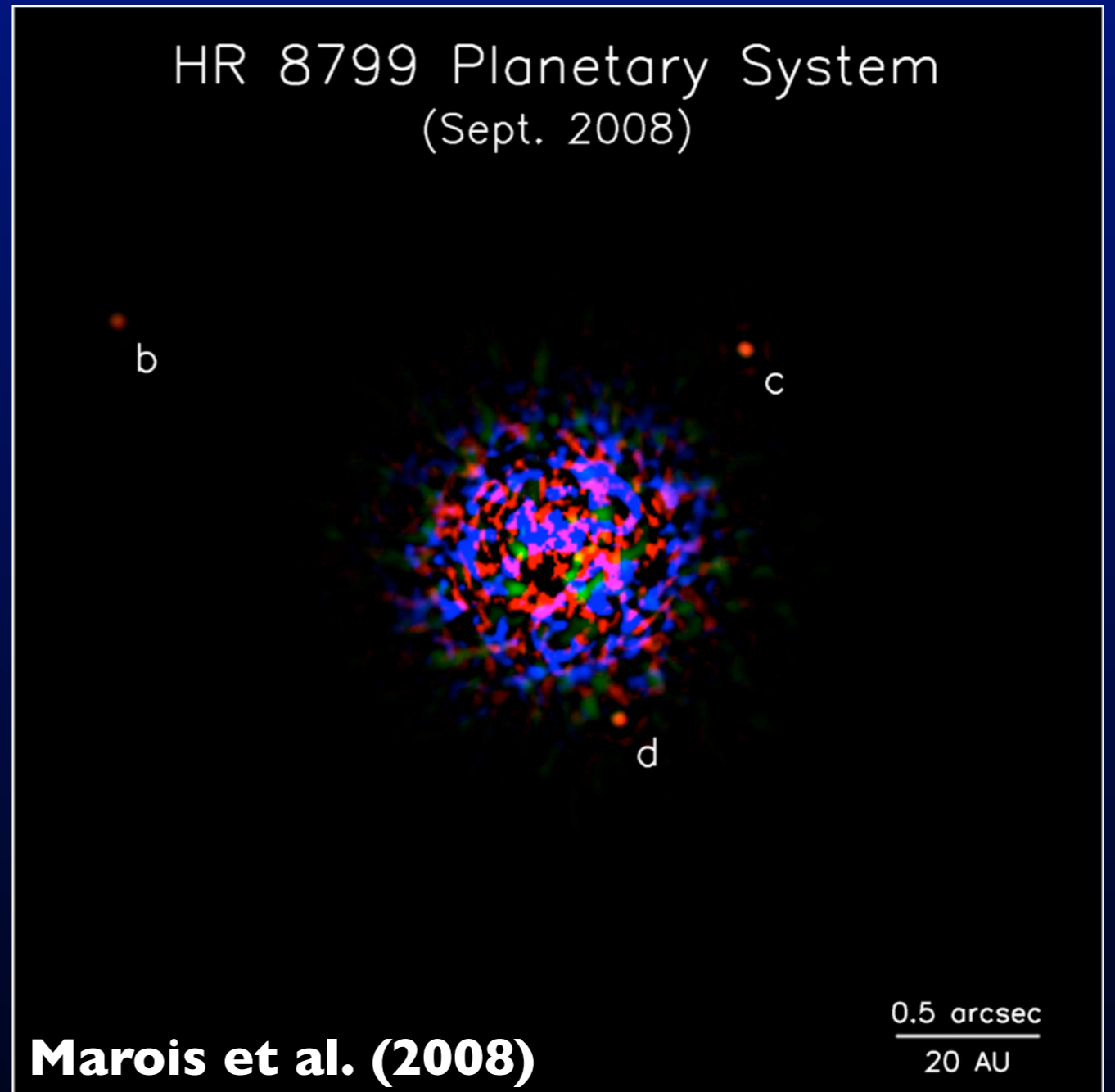
- Two ways around the contrast problem:
  - a) Look for planets around faint stars
  - b) Try to mask out star-light



“Planet” around brown dwarf 2MI 207 discovered in 2004. Primary is  $\sim 25M_{\text{Jup}}$ ; secondary is  $\sim 5M_{\text{Jup}}$ . Wide separation. More akin to a low-mass binary than a true planetary system.

# Direct Imaging

- Two ways around the contrast problem:
  - a) Look for planets around faint stars
  - b) Try to mask out star-light



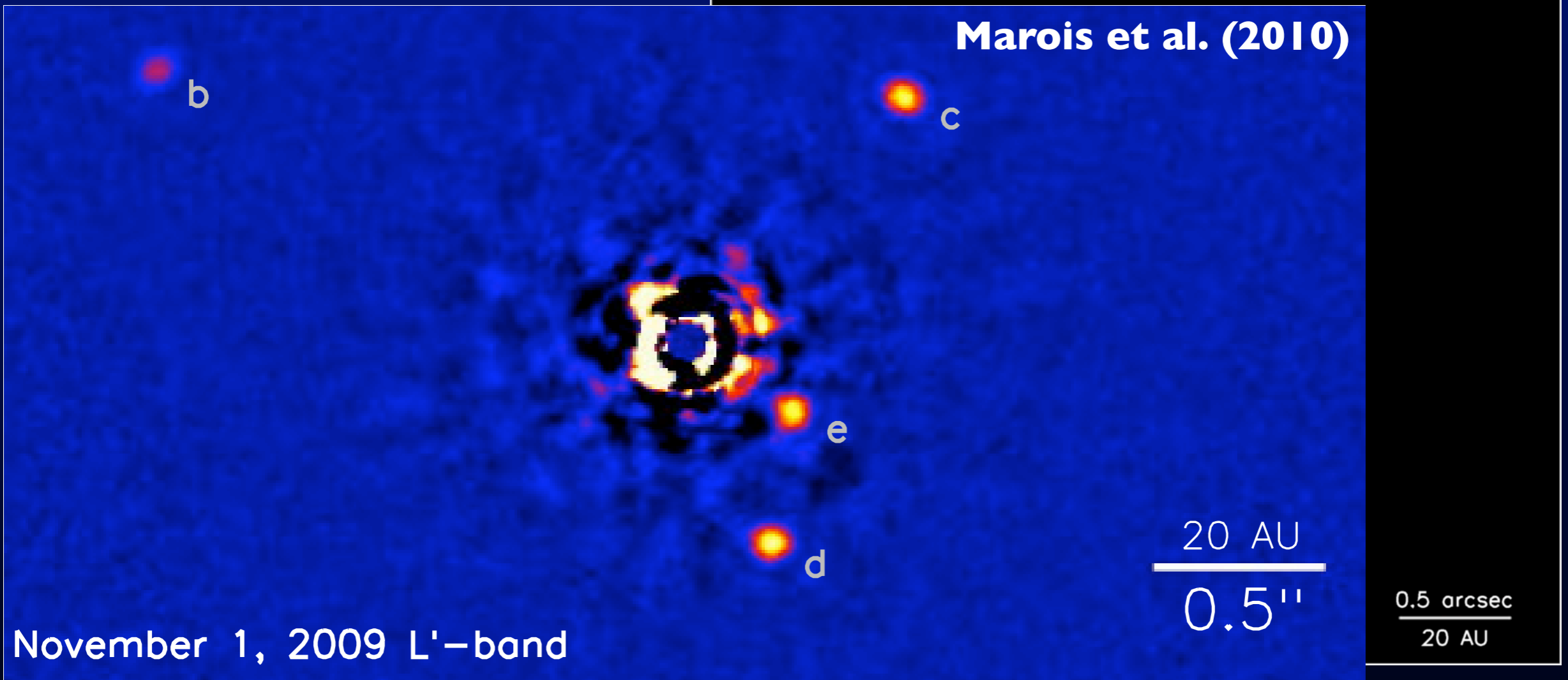
Planets around HR8799 discovered in 2008.  
Star is  $\sim 1.5M_{\odot}$ . Planet masses all estimated to be  $\sim 10M_{\text{Jup}}$ .  
Wide orbits - “d” is beyond orbit of Uranus.

# Direct Imaging

- Two ways around the contrast problem:

HR 8799 Planetary System  
(Sept. 2008)

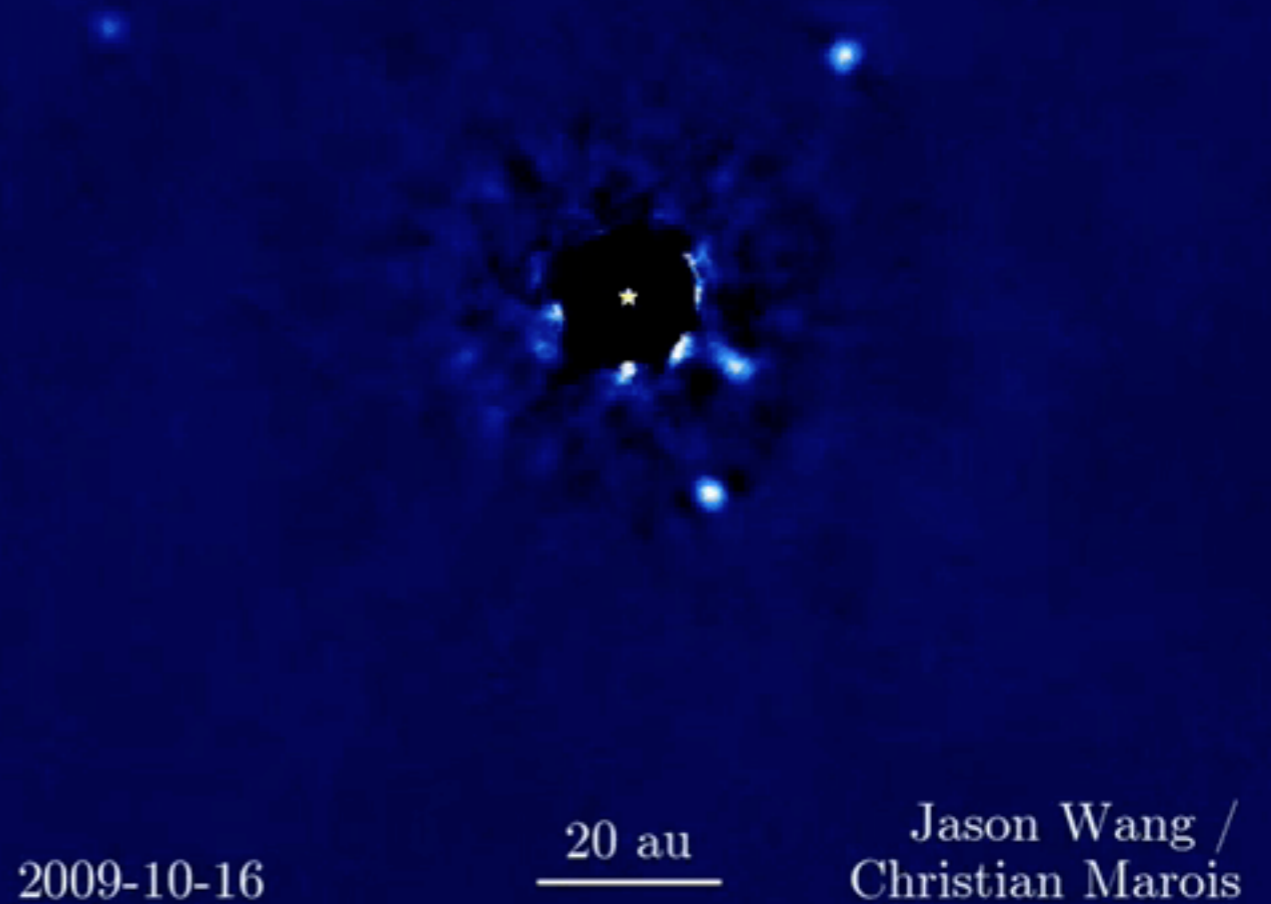
Marois et al. (2010)



# Direct Imaging

- Two ways around the contrast problem:
  - a) Look for planets around faint stars
  - b) Try to mask out star-light

**HR8799: Wang, Marois+ (2017)**





# New facilities...

Macintosh et al. (2015)

Gemini/GPI

Size of Saturn's orbit  
around the Sun

51 Eri

+

b

Type F0 pre-MS star (5-30Myr).  
Planet mass  $\sim 2M_{\text{Jup}}$ .  
Proj. separation 449mas (13.2AU).

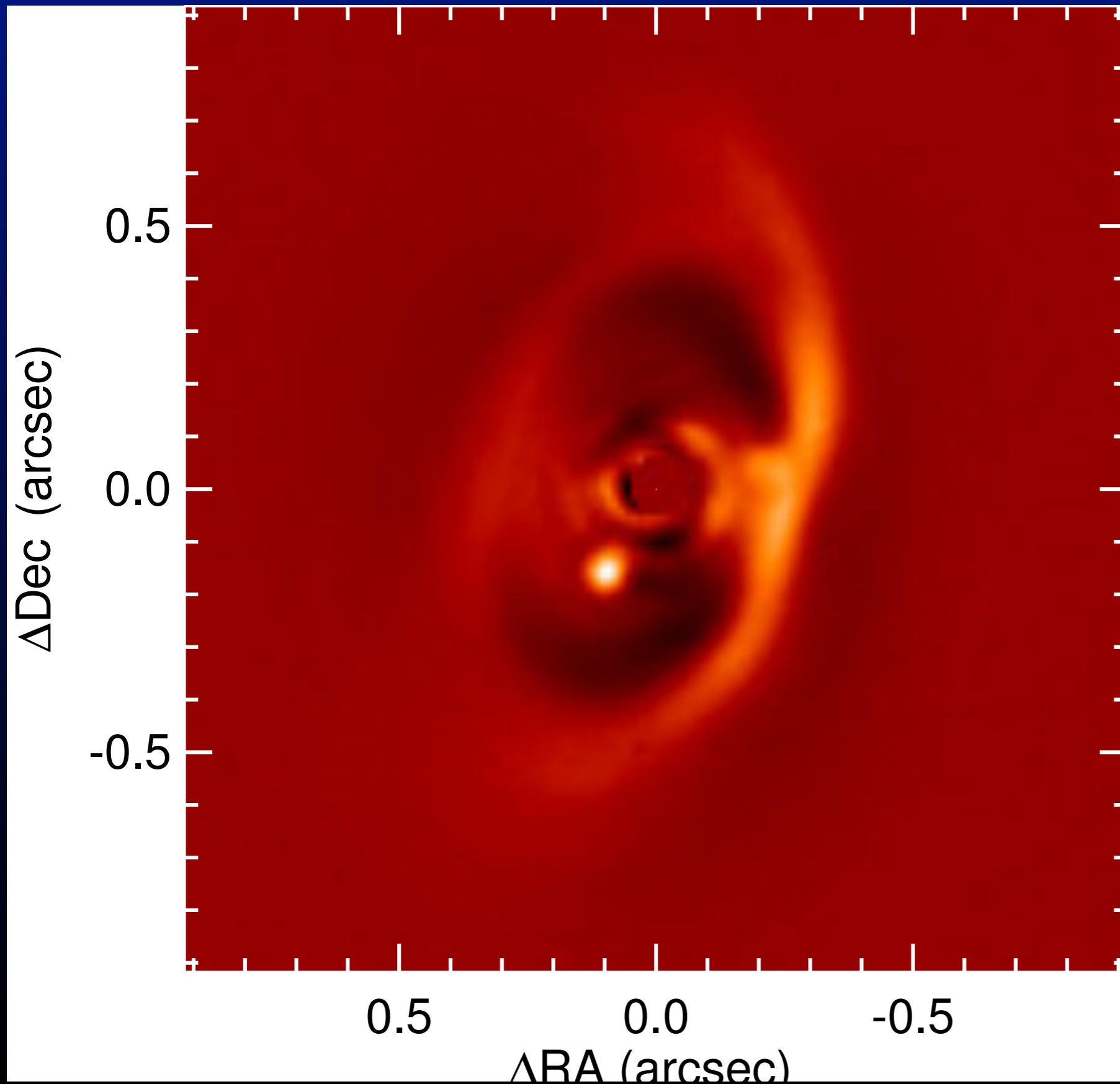
10 AU



# Young planets

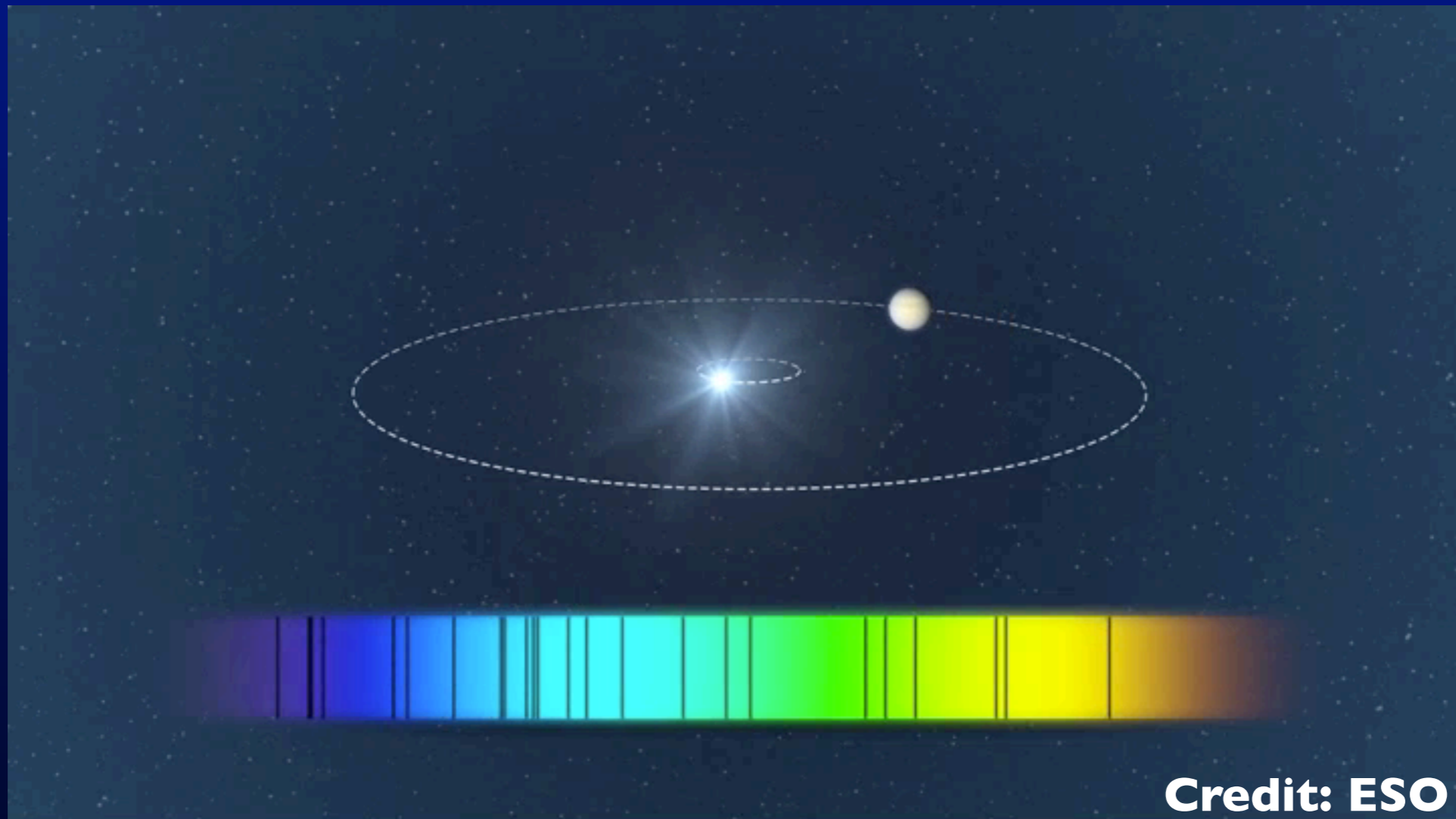
**PDS 70**

**Keppler et al. (2018)**



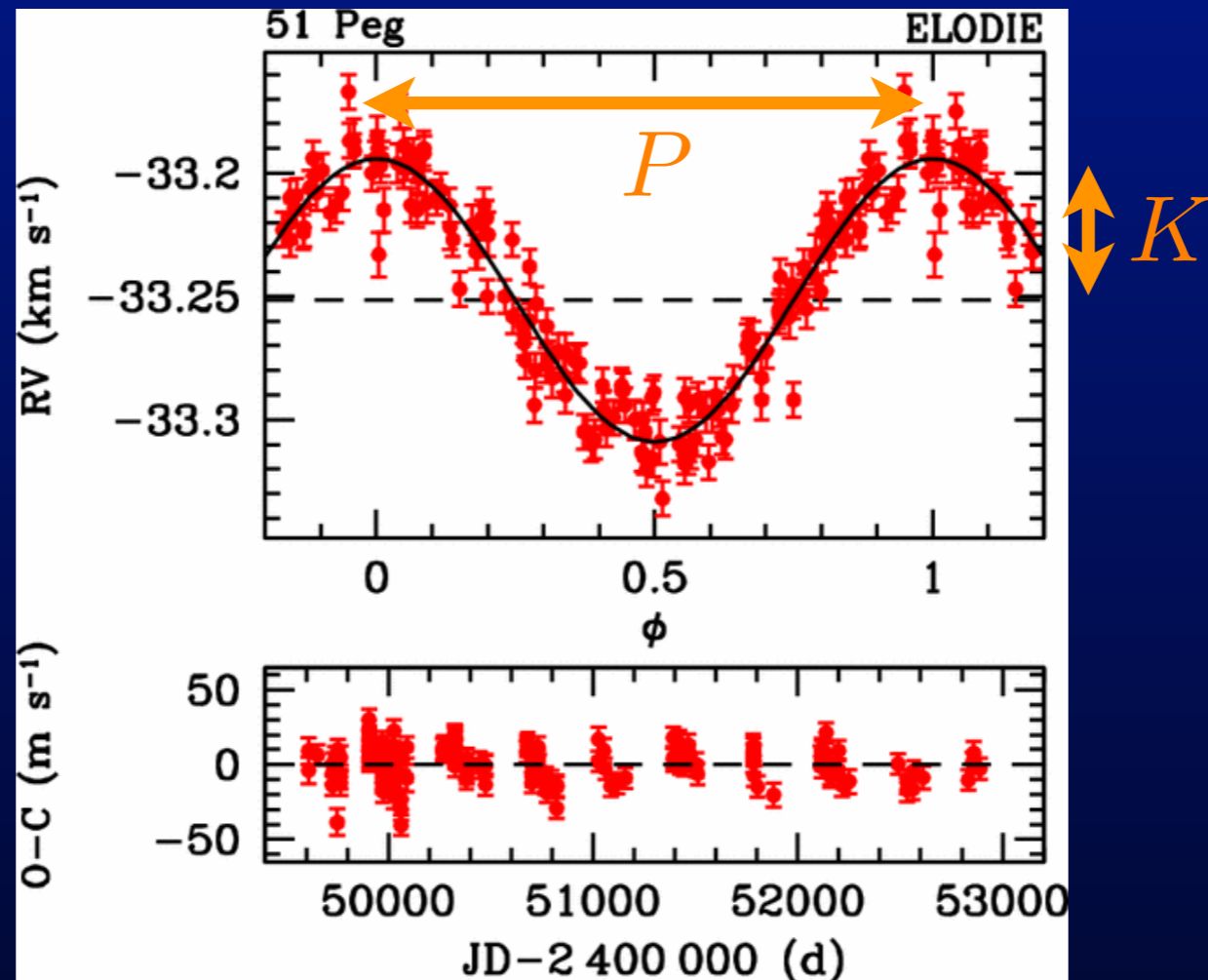
T Tauri star (5.4Myr).  
Planet mass  $\sim 5M_{\text{Jup}}$ .  
Proj. separation of  
195mas (22AU).

# Radial velocity methods



- Look for Doppler shifts caused by stellar reflex motion.
- RV surveys on-going since first detection in 1995. Now ~500 detections: until *Kepler*, was most successful detection method.
- Originally pioneered by Latham, Mayor, Griffin and others. Most discoveries have come from two groups: Geneva & Lick/California.

# Radial velocity methods



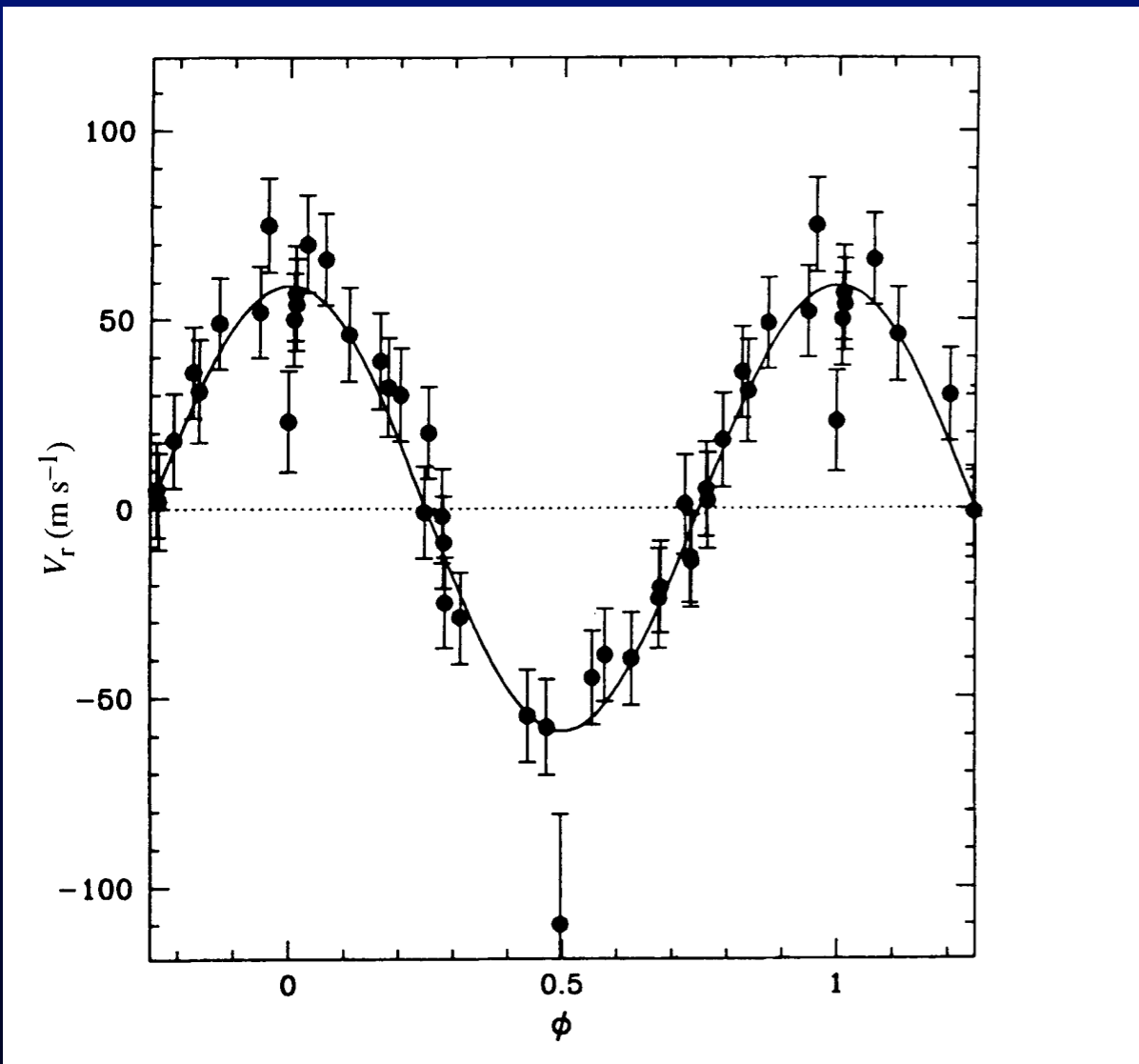
Mayor & Queloz (1995)

- Fit semi-major axis  $a$ , eccentricity  $e$ , and stellar mass  $M_p \sin i$ :

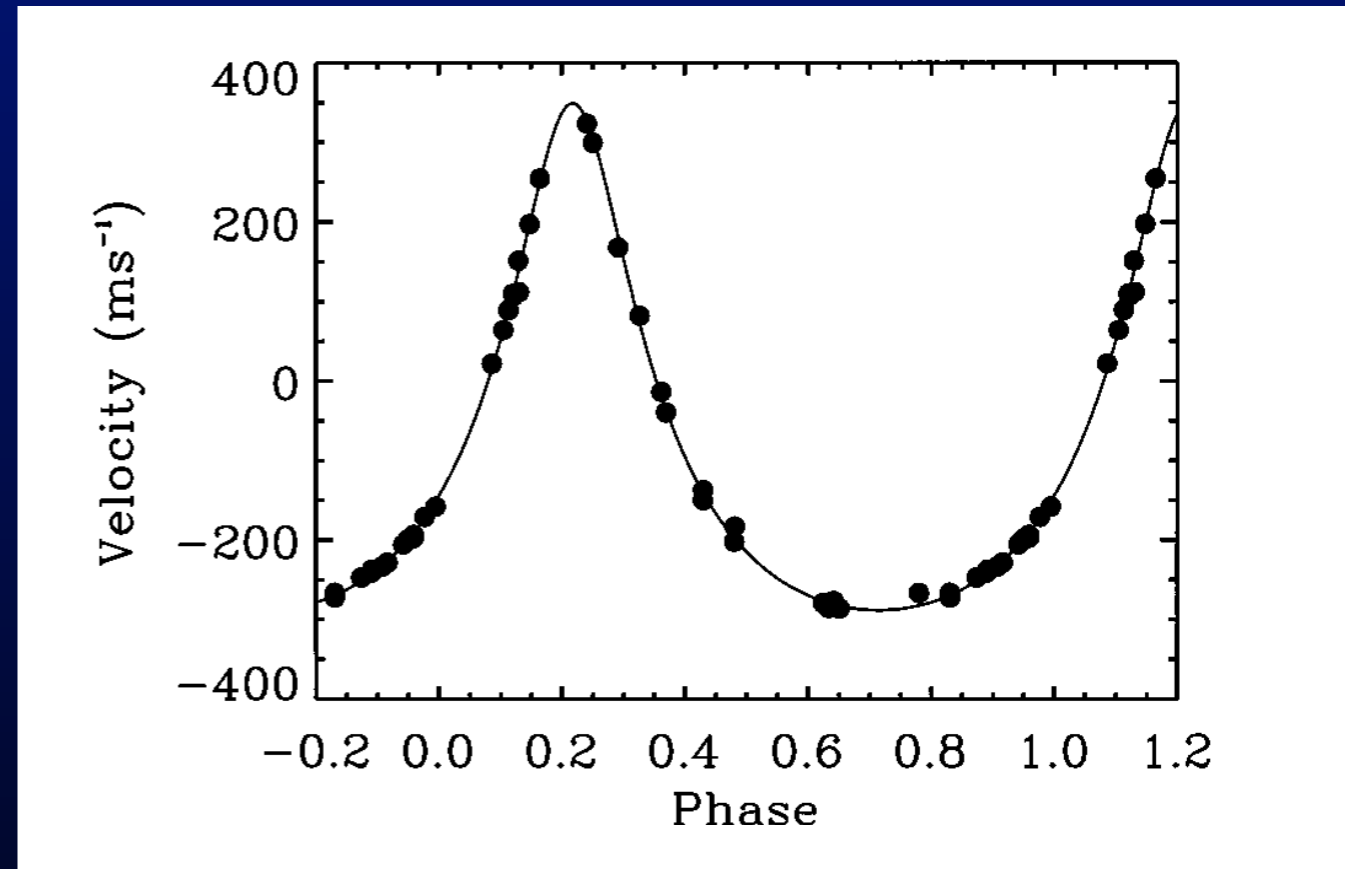
$$K = v_* \sin i = \frac{1}{\sqrt{1 - e^2}} \frac{M_p \sin i}{M_*} \sqrt{\frac{GM_*}{a}}$$

- $K_{\text{Jup}} \sim 12\text{m/s}$ ;  $K_{\text{Earth}} \sim 10\text{cm/s}$ .

# First detections...

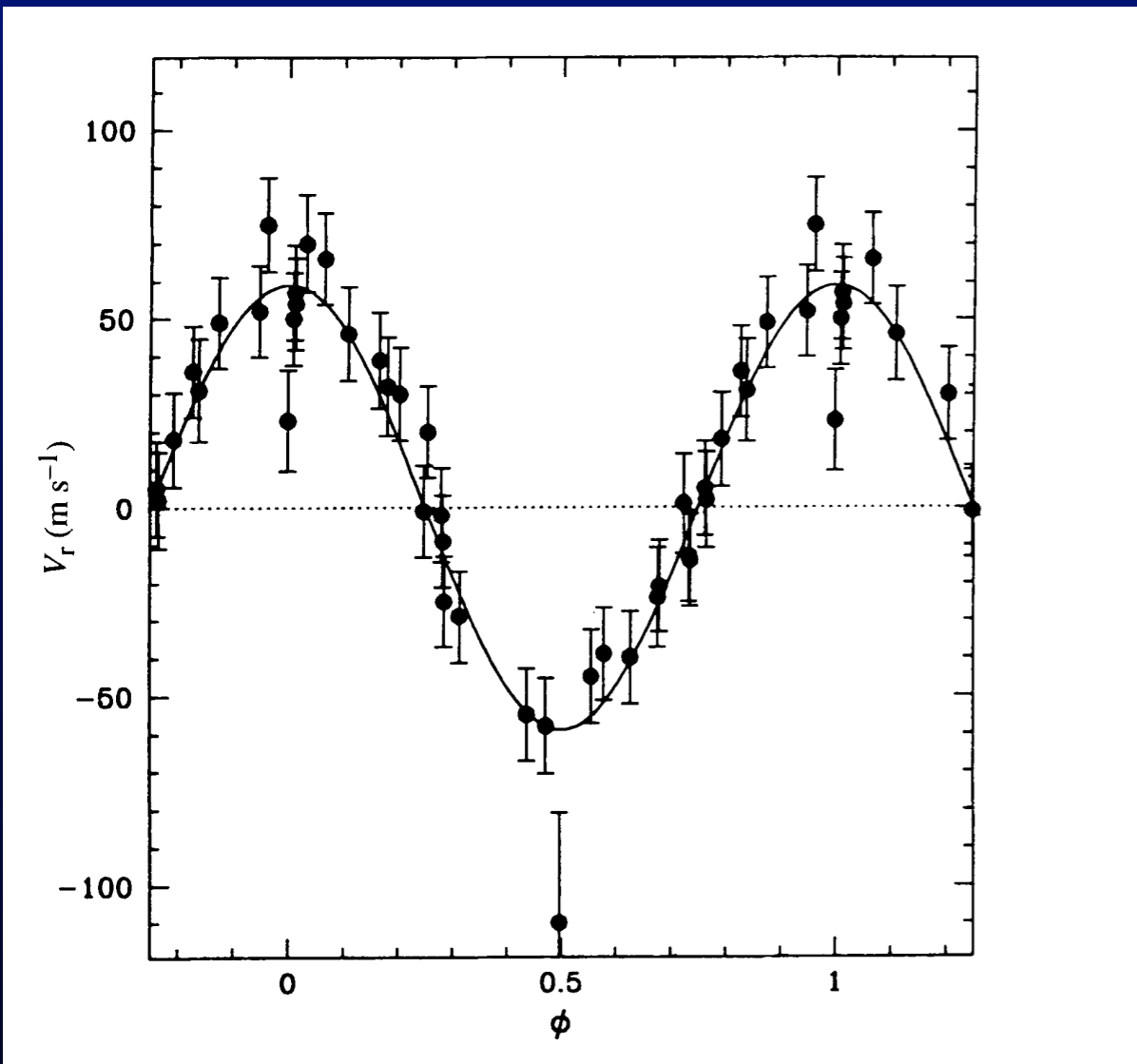


51 Peg b: Mayor & Queloz (1995)  
Planet mass  $0.47M_{\text{Jup}}$ , Period 4.23d

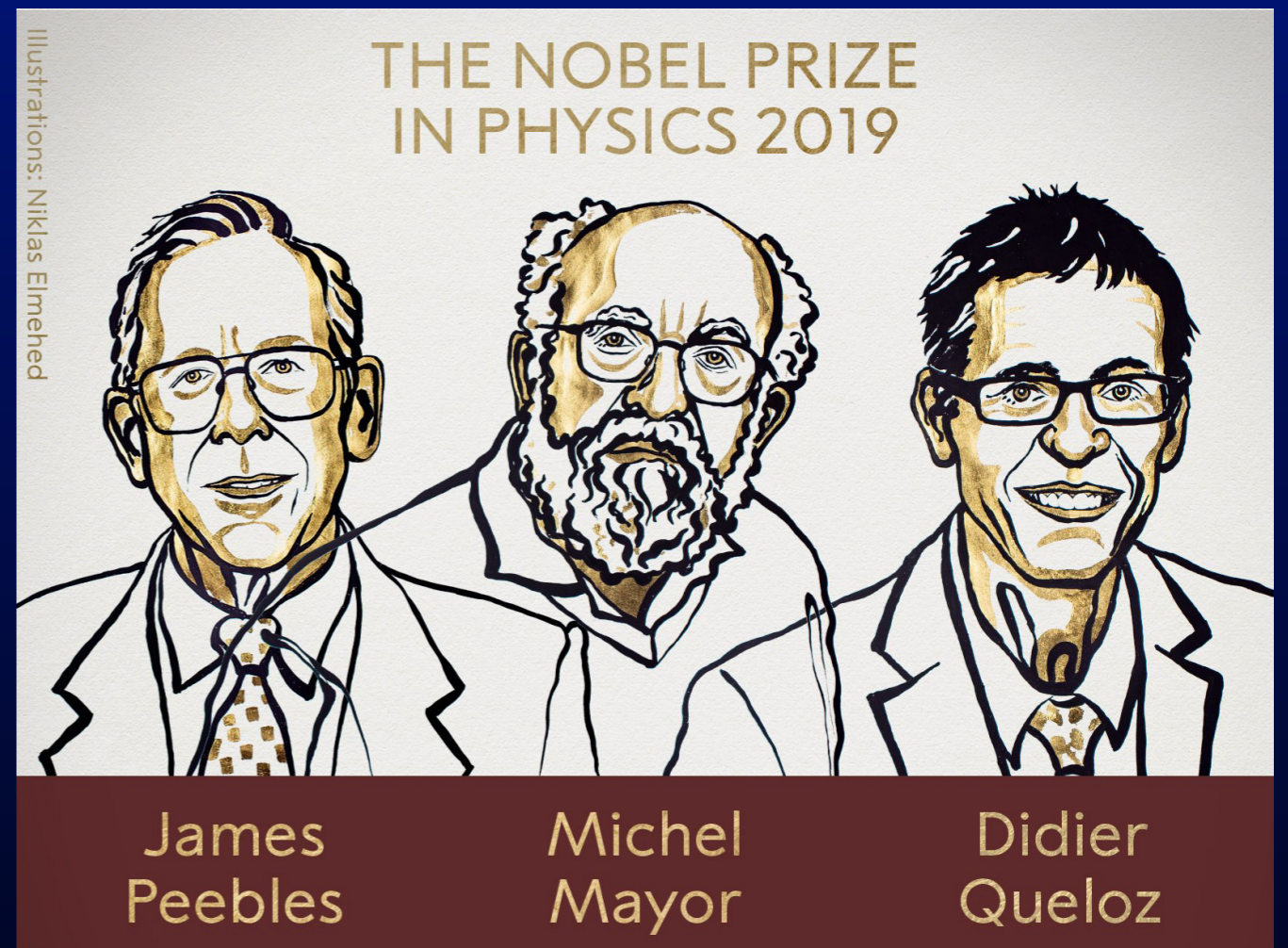


70 Vir b: Marcy & Butler (1996)  
Planet mass  $7.5M_{\text{Jup}}$ , Period 117d

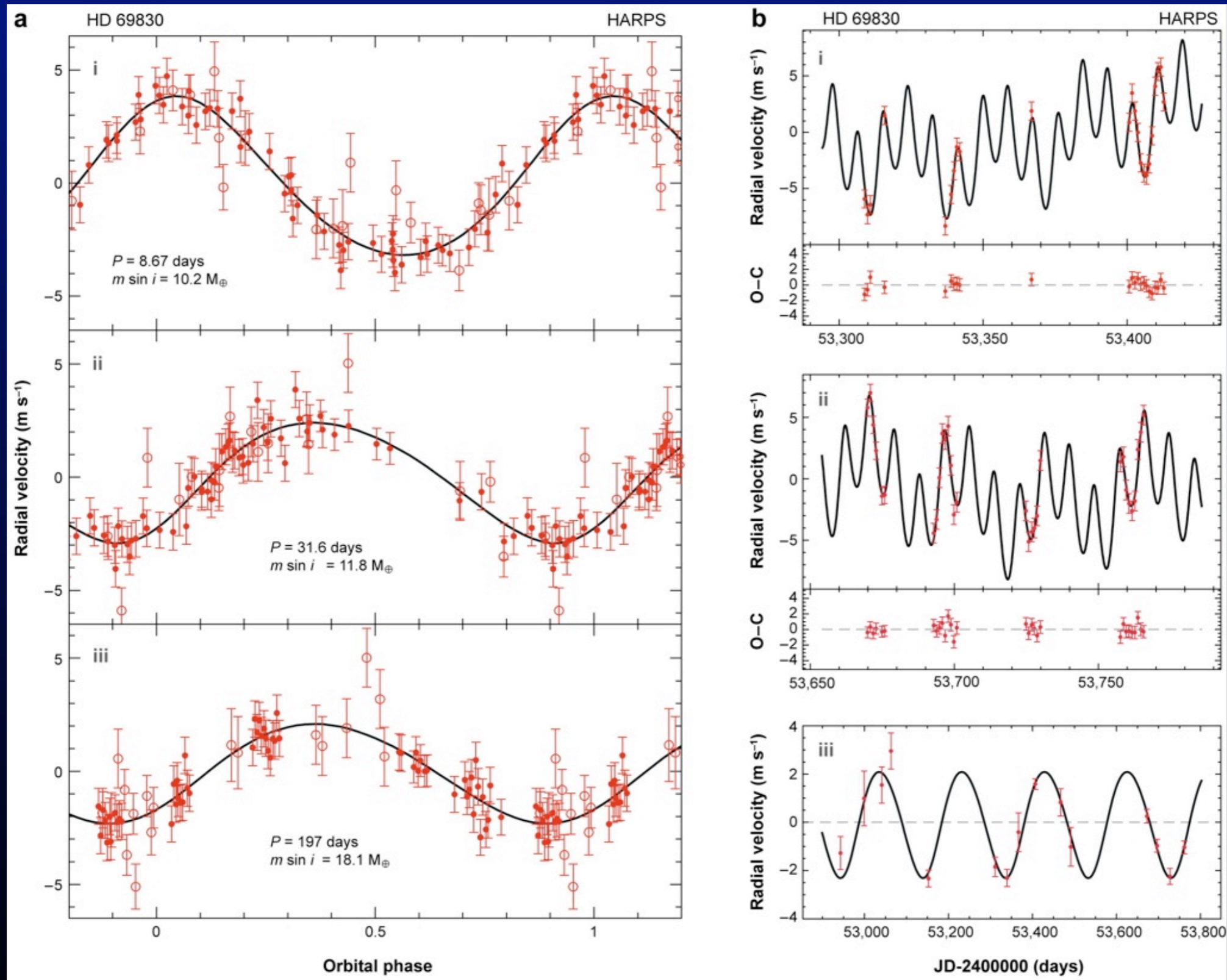
# First detections...



51 Peg b: Mayor & Queloz (1995)  
Planet mass  $0.47M_{\text{Jup}}$ , Period 4.23d

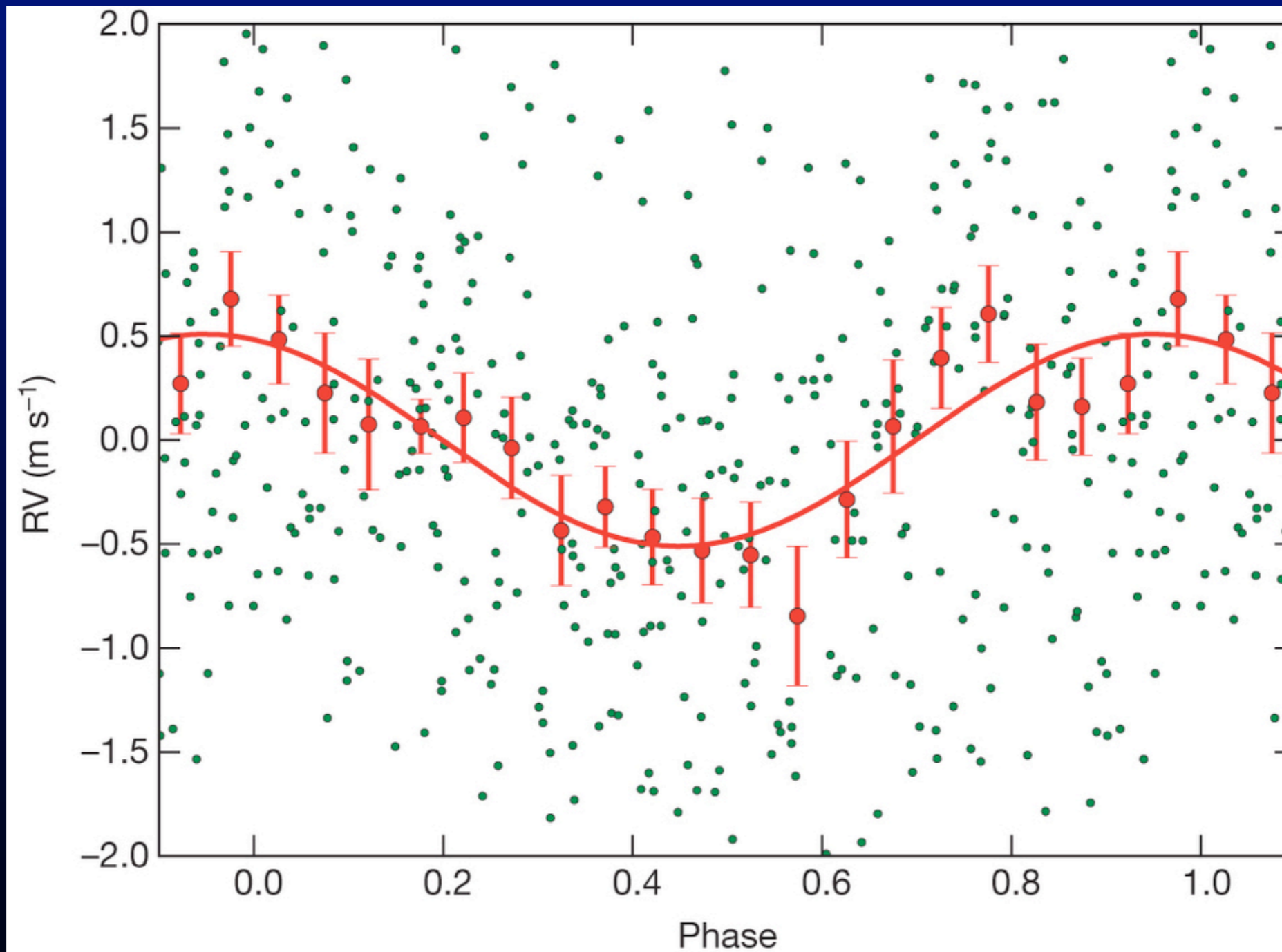


# Typical RV data



Data from Lovis et al. (2006); figure from Udry & Santos (2007)

# The cutting edge??



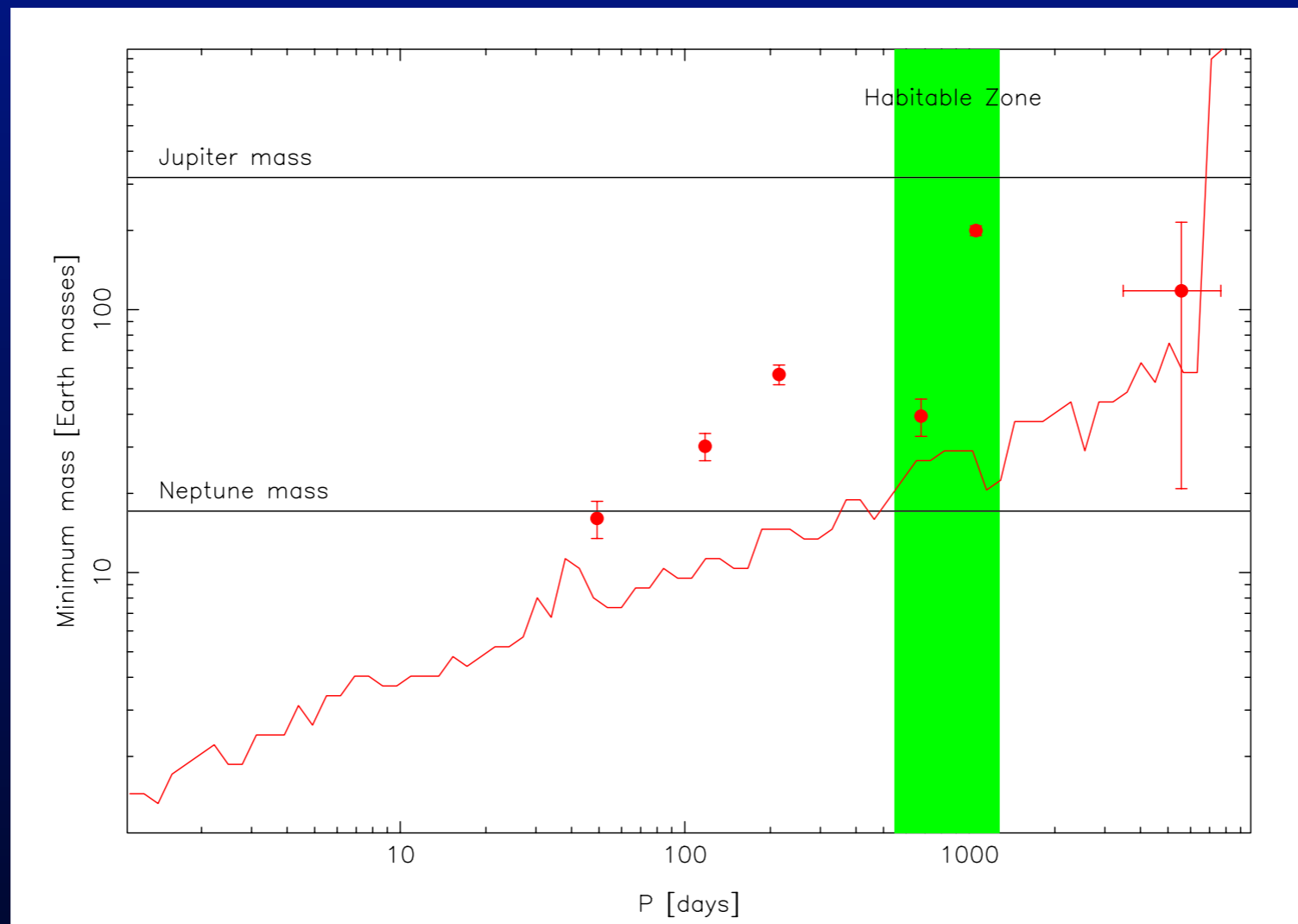
$\alpha$  Cen Bb: Dumusque et al. (2012)

Claimed planet mass  $1.1 M_{\text{Earth}}$ ,  $P=3.24\text{d}$ ,  $K=5.1\text{ cm/s}$

But actually an artefact! (see Rajpaul et al. 2016)



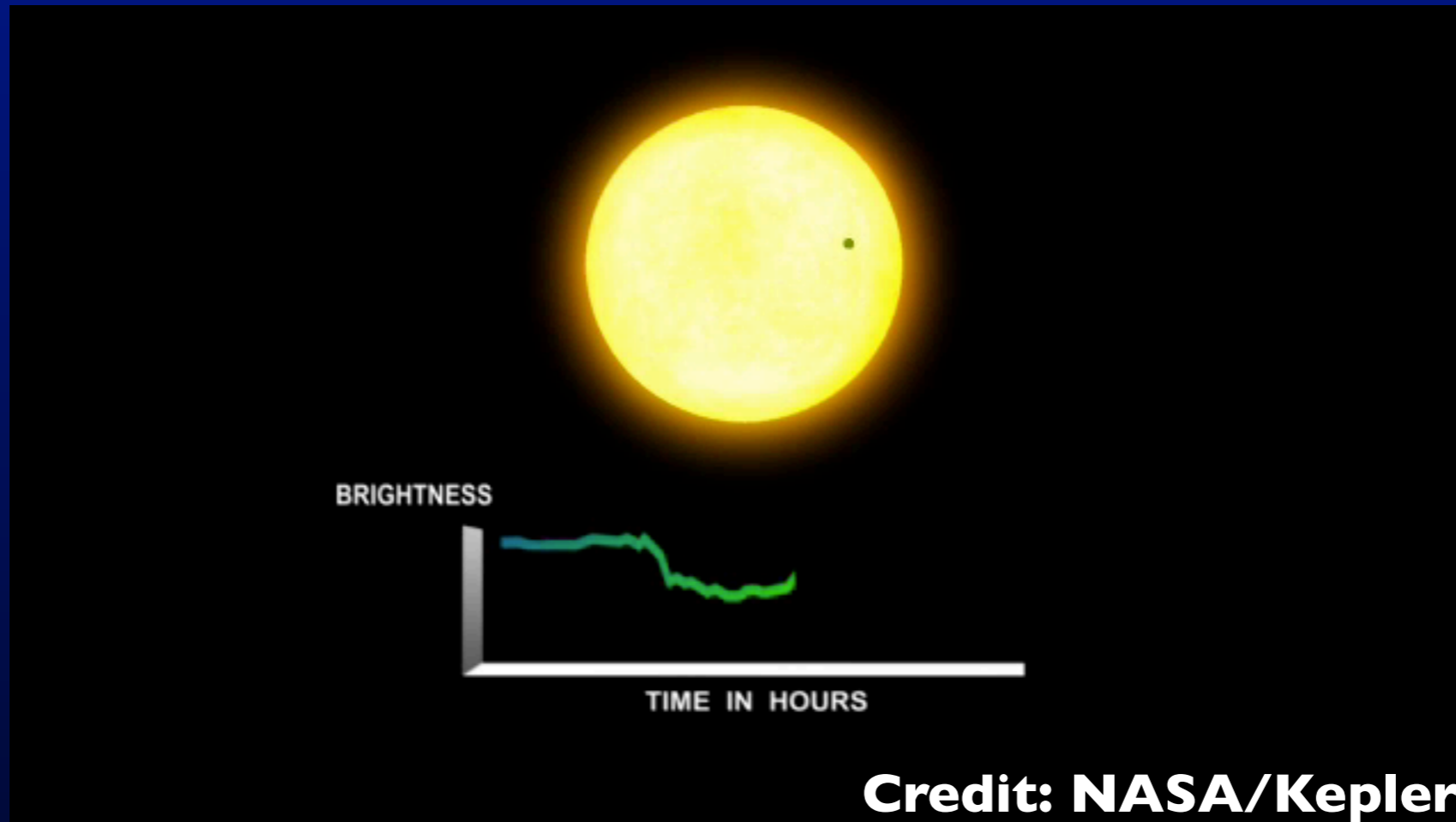
# Long surveys, long periods...



**Vogt+ (2017)**

- 6-planet RV system around HD34445.
- 18 years of RV data; 333 Keck/HIRES spectra;  $\sim 1\text{--}2\text{m/s}$  precision.
- Periods range from 50-5700d; masses from  $0.1\text{--}0.1 M_{\text{Jup}}$ ; semi-major axes from 0.26–6.4AU.

# Transit method



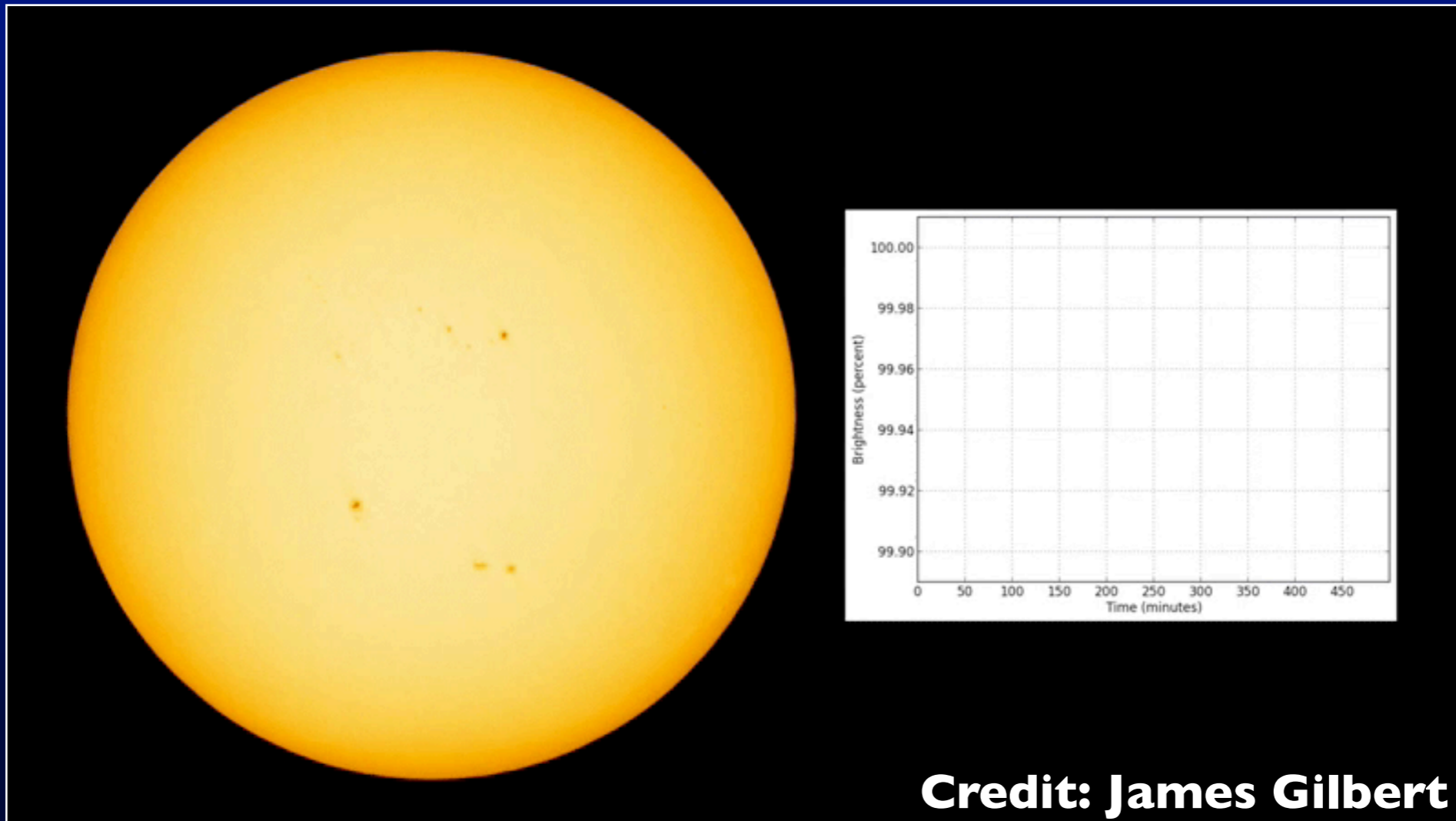
- Detect dimming of light as planet passes in front of star.
- Dimming fraction  $f$  depends on planet size:

$$f = \frac{\pi R_p^2}{\pi R_*^2}$$

$$f_{Jup} \simeq 0.01$$

$$f_{\oplus} \simeq 1 \times 10^{-4}$$

# Transit method



- Detect dimming of light as planet passes in front of star.
- Dimming fraction  $f$  depends on planet size:

$$f = \frac{\pi R_p^2}{\pi R_*^2}$$

$$f_{Jup} \simeq 0.01$$

$$f_{\oplus} \simeq 1 \times 10^{-4}$$

# Transit method

- Detecting transits requires high precision:
  - <1% precision ( $\sim$ Jupiters) attainable from the ground.
  - 0.01% precision ( $\sim$ Earths) requires us to go to space.
- Detecting transits is very unlikely: requires edge-on orbits:
  - If every star had an Earth-like planet, we would observe transits in approximately 1 in 2000 stars.
- Searching for planets using transits requires us to observe *lots* of stars simultaneously.
- Transit depth tells us the planet's radius. Require follow-up RV measurements to determine mass and eccentricity.

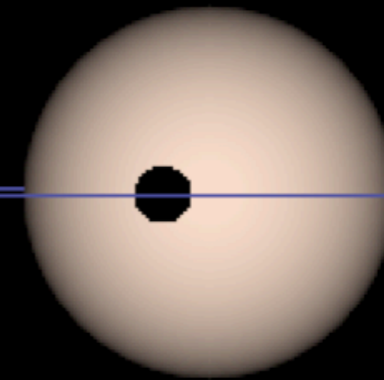
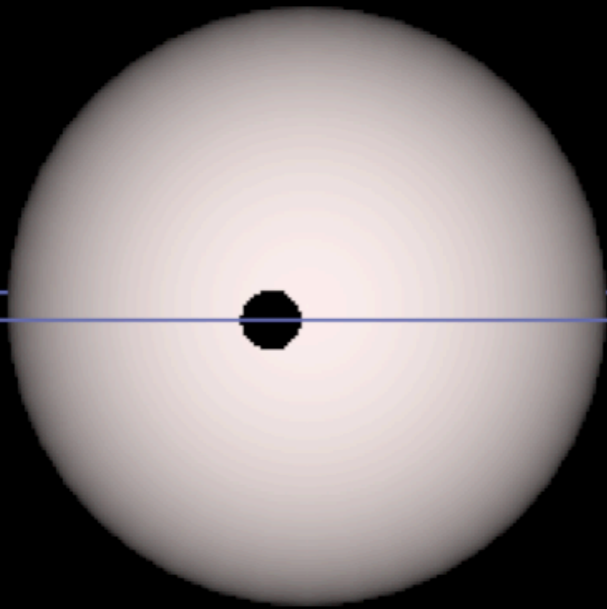
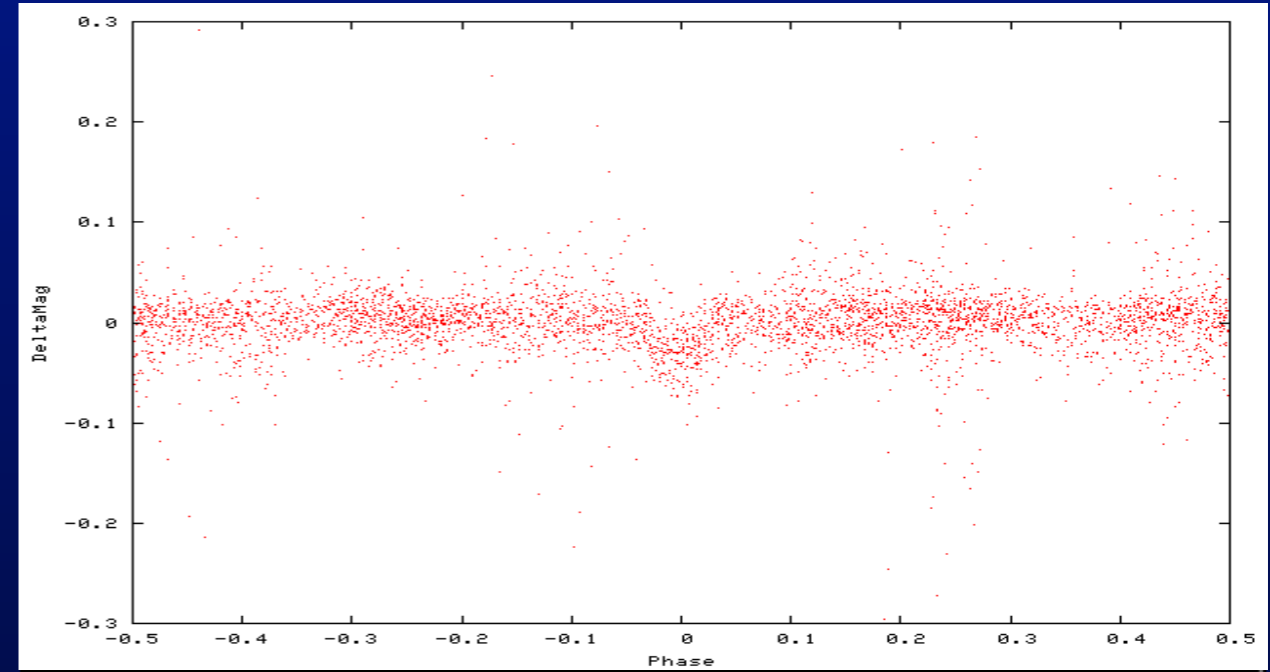
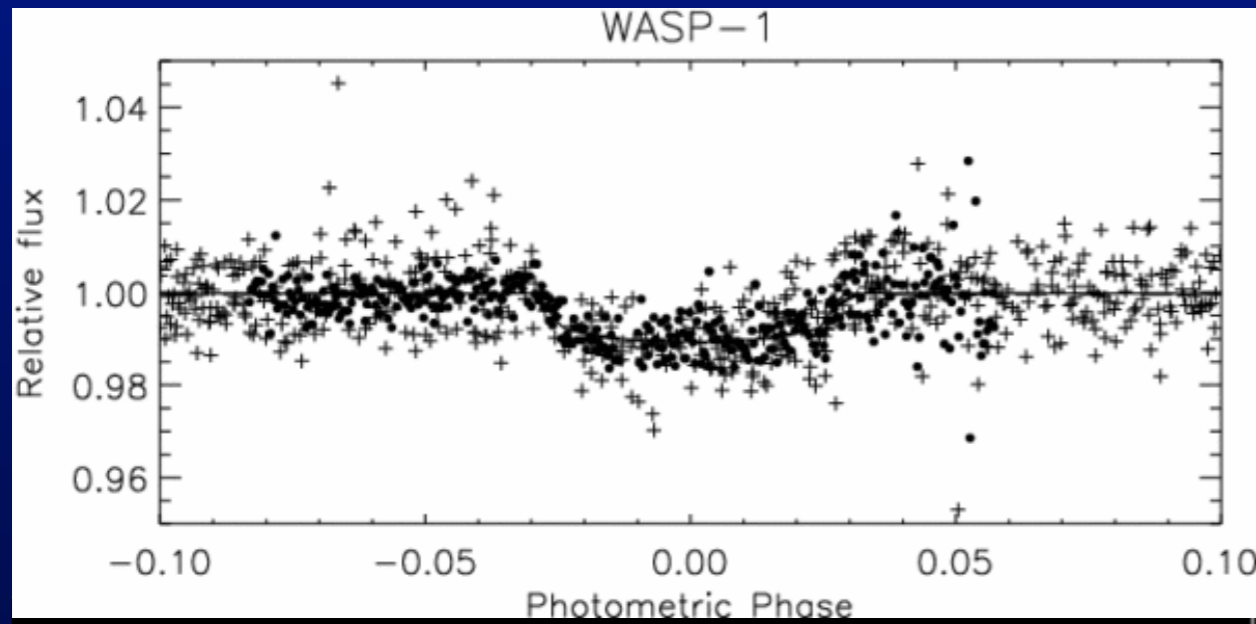
# Transit method

- Many current searches using transit methods.
- Most successful ground-based programme is SuperWASP (**W**ide-**A**ngle **S**earch for **P**lanets).
- SuperWASP surveys 1/4 of the sky every night. Monitors several million stars every few minutes.
- Generates 50-100Gb of data per night.



**Credit: Richard West**

# Ground-based transit lightcurves



# Next Generation...

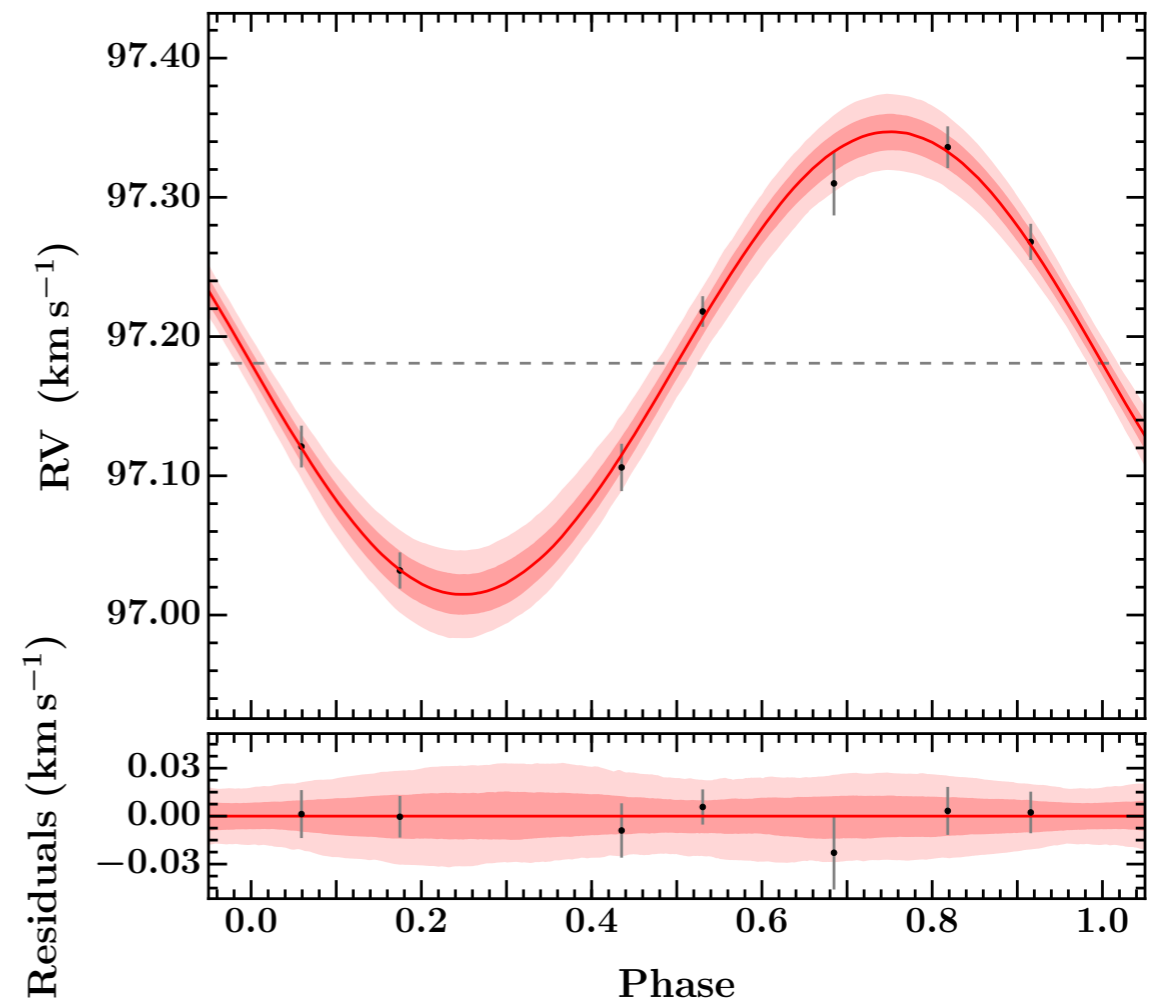
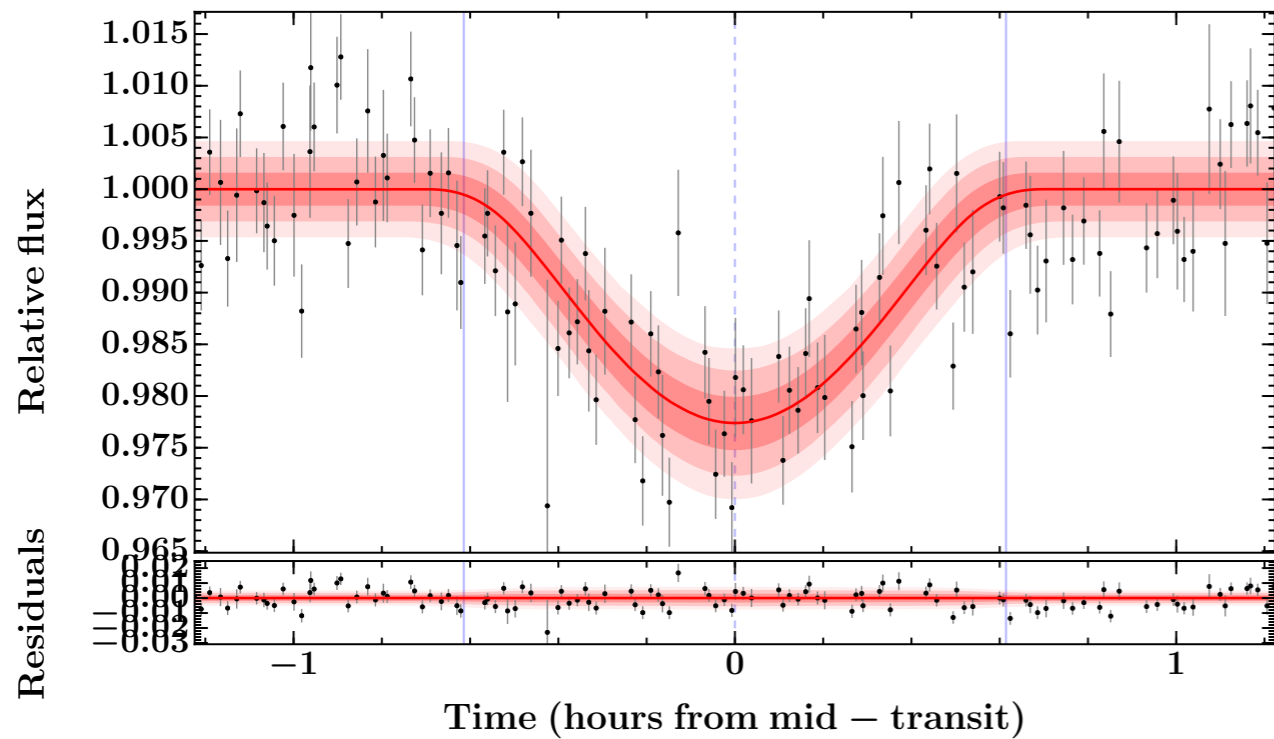


**Credit: ESO/Richard West**

- Next Generation Transit Survey (NGTS) now operating at Paranal (first light Jan 2015).
- mmag precision; should yield large sample of super-Earths suitable for follow-up from the ground.



# Ground-based cutting edge

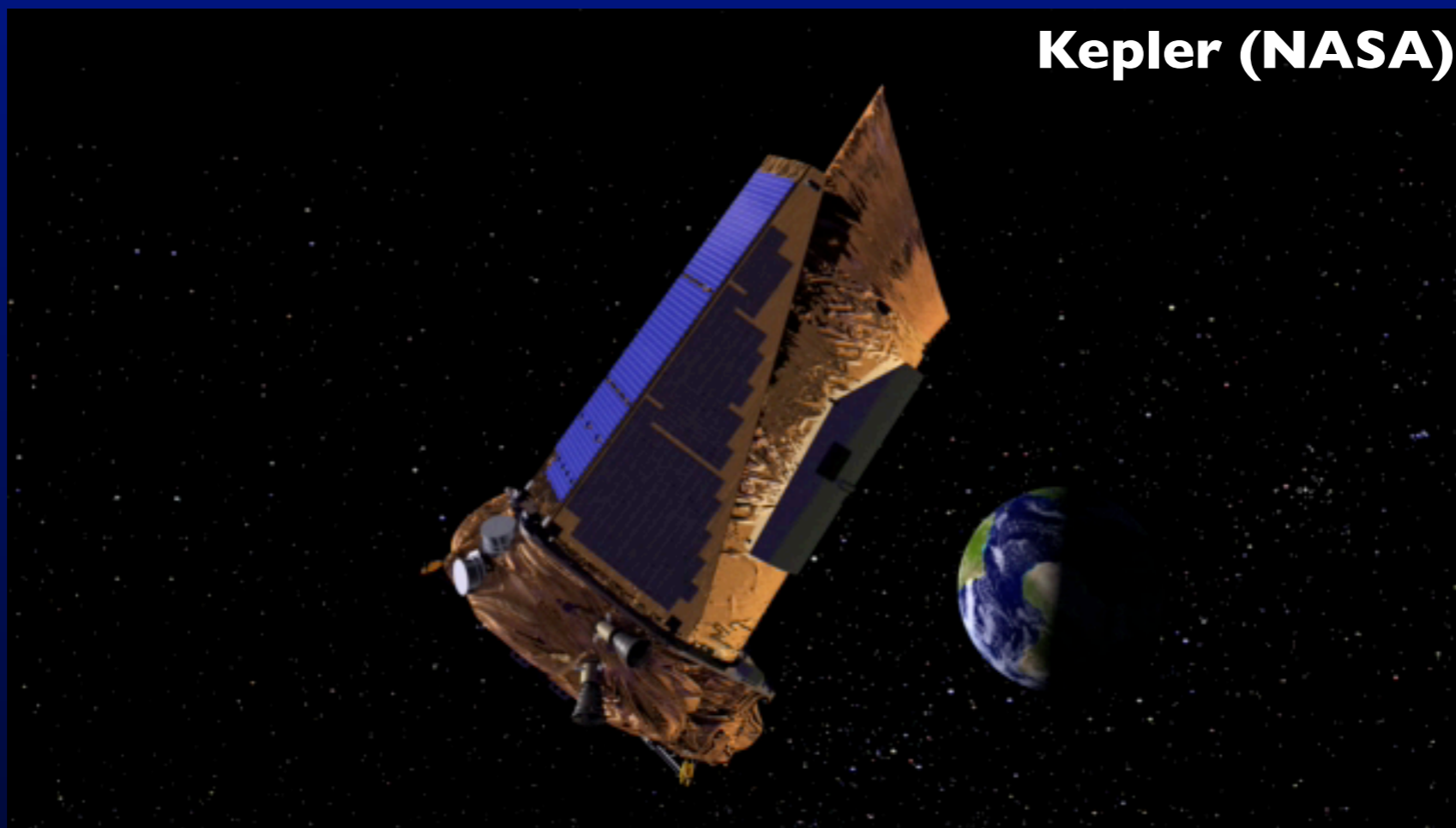


**Bayliss+ (2017)**

- First exoplanet discovery from NGTS.
- $0.8M_{\text{Jup}}$  planet in 2.65d orbit around a M0/M1-type host star.
- Most massive planet known around an M-dwarf. NGTS will give first large census of planets around low-mass stars.

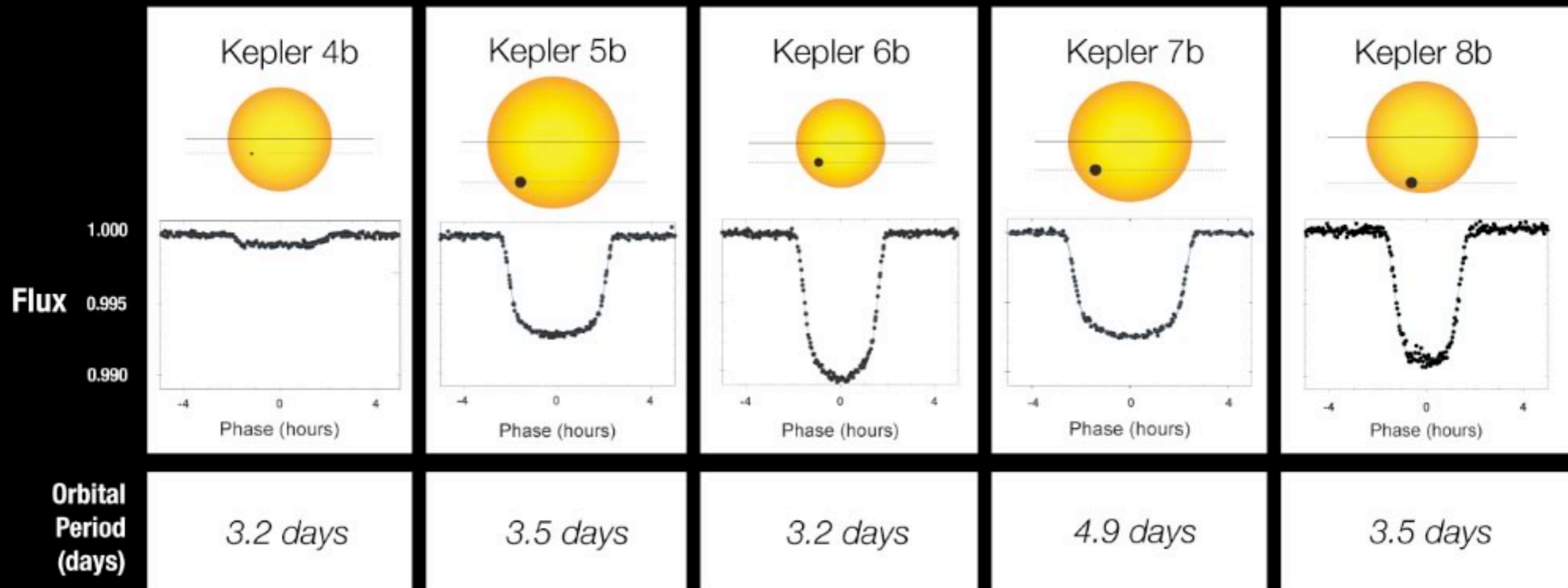


# Kepler



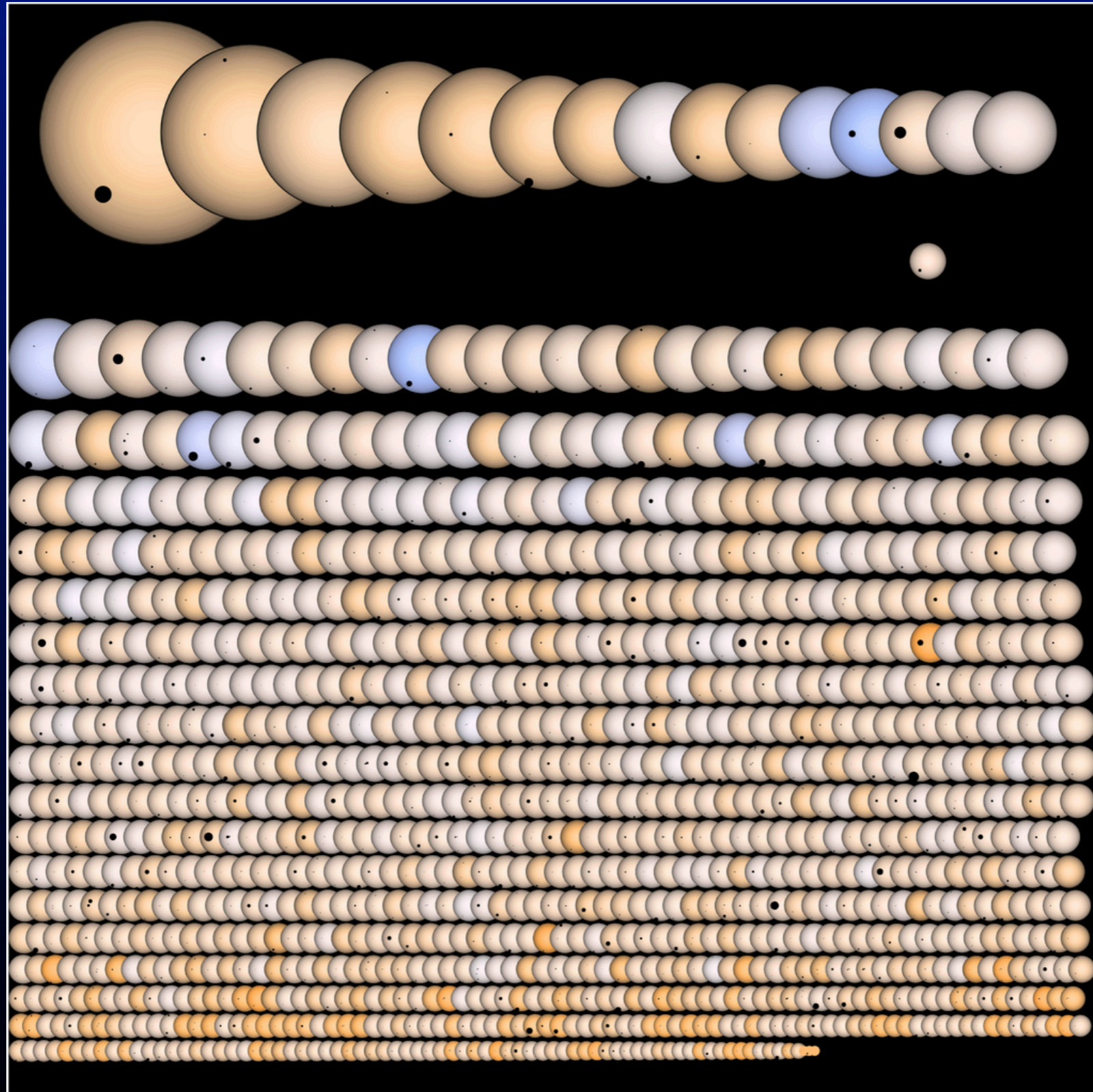
- Launched March 2009, 0.95m primary; “died” May 2013. Lived on as K2 until late 2018.
- 12° FOV, 42 CCD camera. “Stared” at fixed patch of (blank) sky to obtain light-curves for >150,000 stars.
- Photometric precision as good as ~10ppm (in some cases). Sensitive to sub-Earth-size planets.

# Kepler light-curves

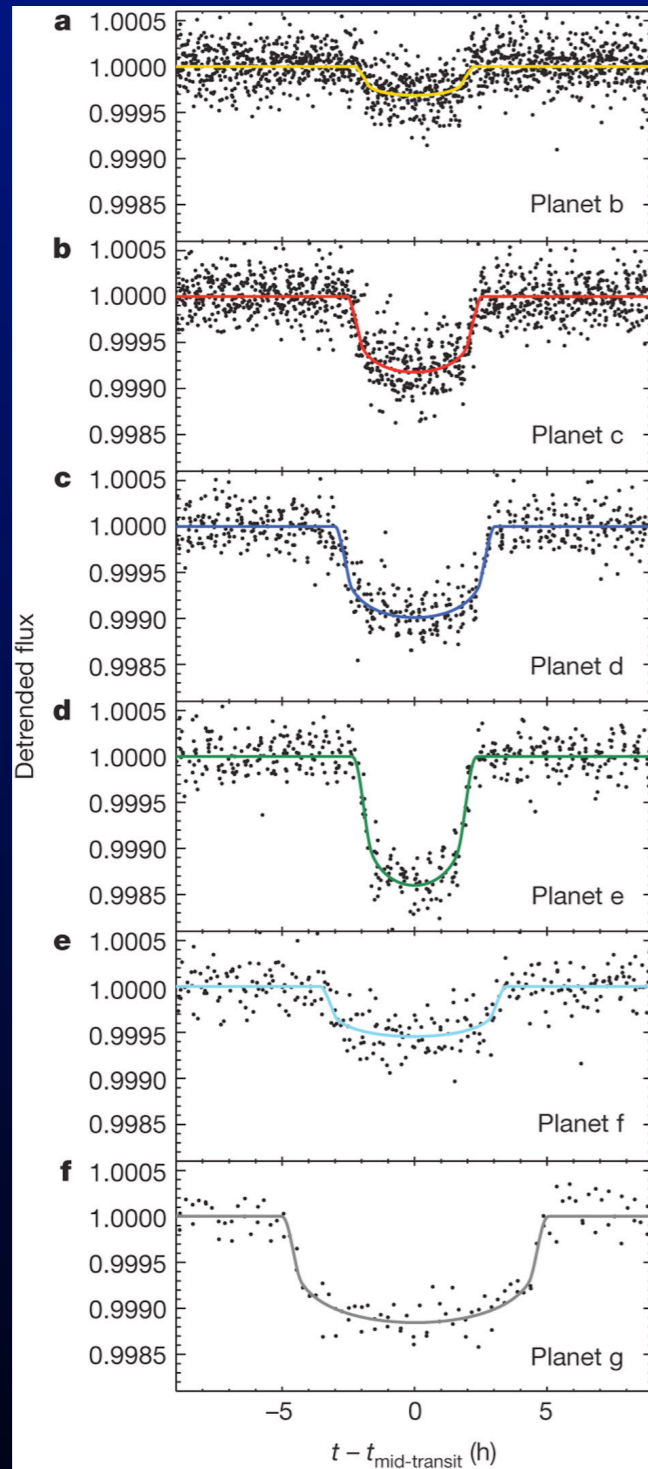


- Early data release (June 2010) focused on a few “hot Jupiters”, to demonstrate precision.
- Fourth (& final) major data release in January 2014. Total of ~4500 planet candidates, with >2000 now confirmed.

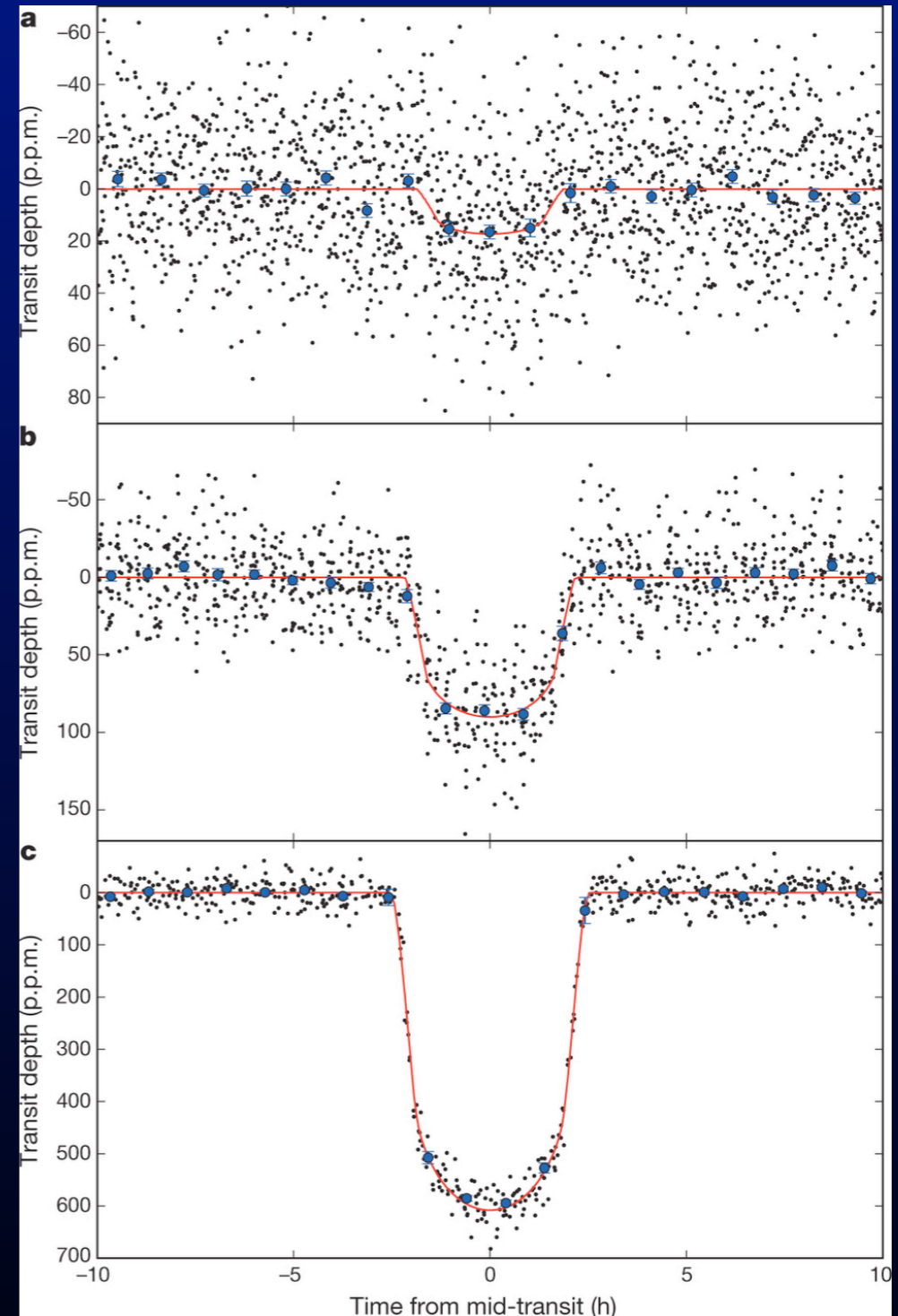
# Kepler: first results



# Kepler examples



Kepler-11: Lissauer et al. (2011)  
6-planet system, periods 10–120d.  
Masses range from 2–20 $M_{\text{Earth}}$ .



Kepler-37: Barclay et al. (2013)  
3-planet system, periods 13.4, 21.3, 39.8d.  
“b” is roughly the size of the Moon.

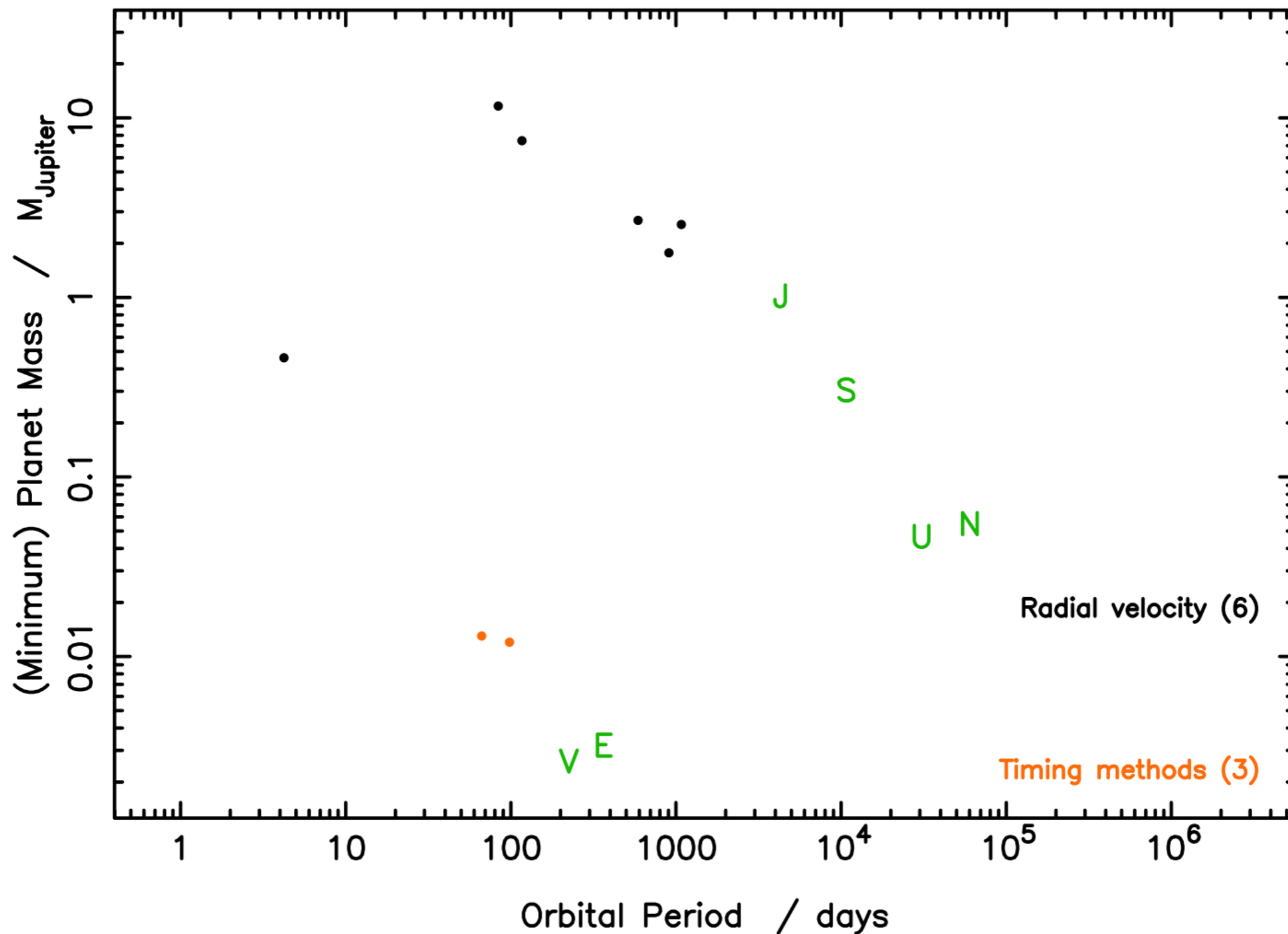
# Summary of methods and biases

- First discoveries: 1995 (RV), 2005\* (transit), 2008 (imaging).
- Now >3000 known exoplanets (+ ~2500 *Kepler* candidates):
- Direct Imaging
  - Easiest to detect bright (large  $R_p$  and/or massive) planets far from star (large  $a$ ).
- Radial velocity
  - Easiest to detect massive planets close to star (short periods, small  $a$ ).
- Transits
  - Easiest to detect large (large  $R_p$ ) planets close to star (short periods, small  $a$ ).

\*The first transiting planet was found in 1999, but it was a known RV planet.

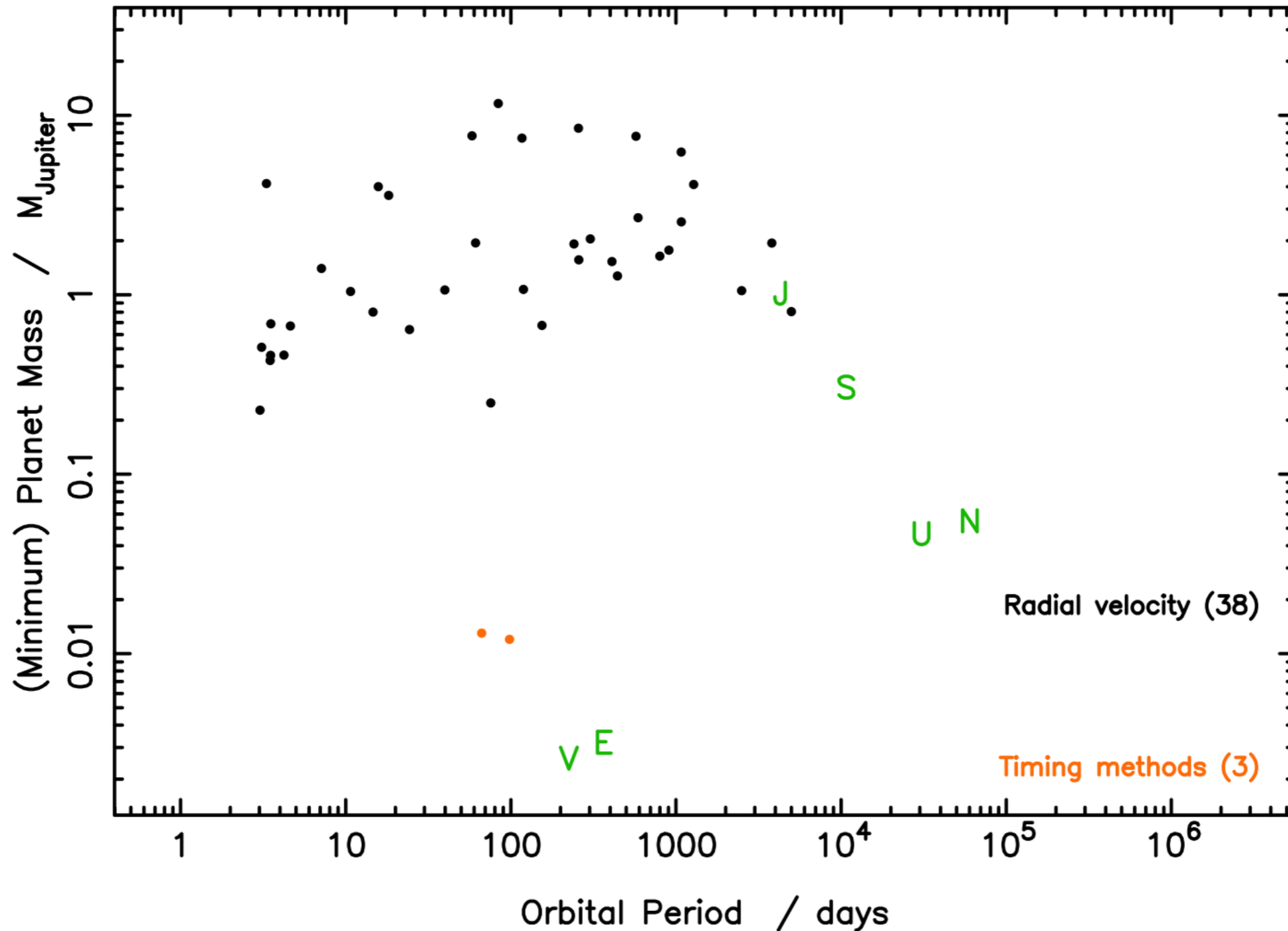


# Known planets as of 1996



Data from [exoplanet.eu](http://exoplanet.eu)

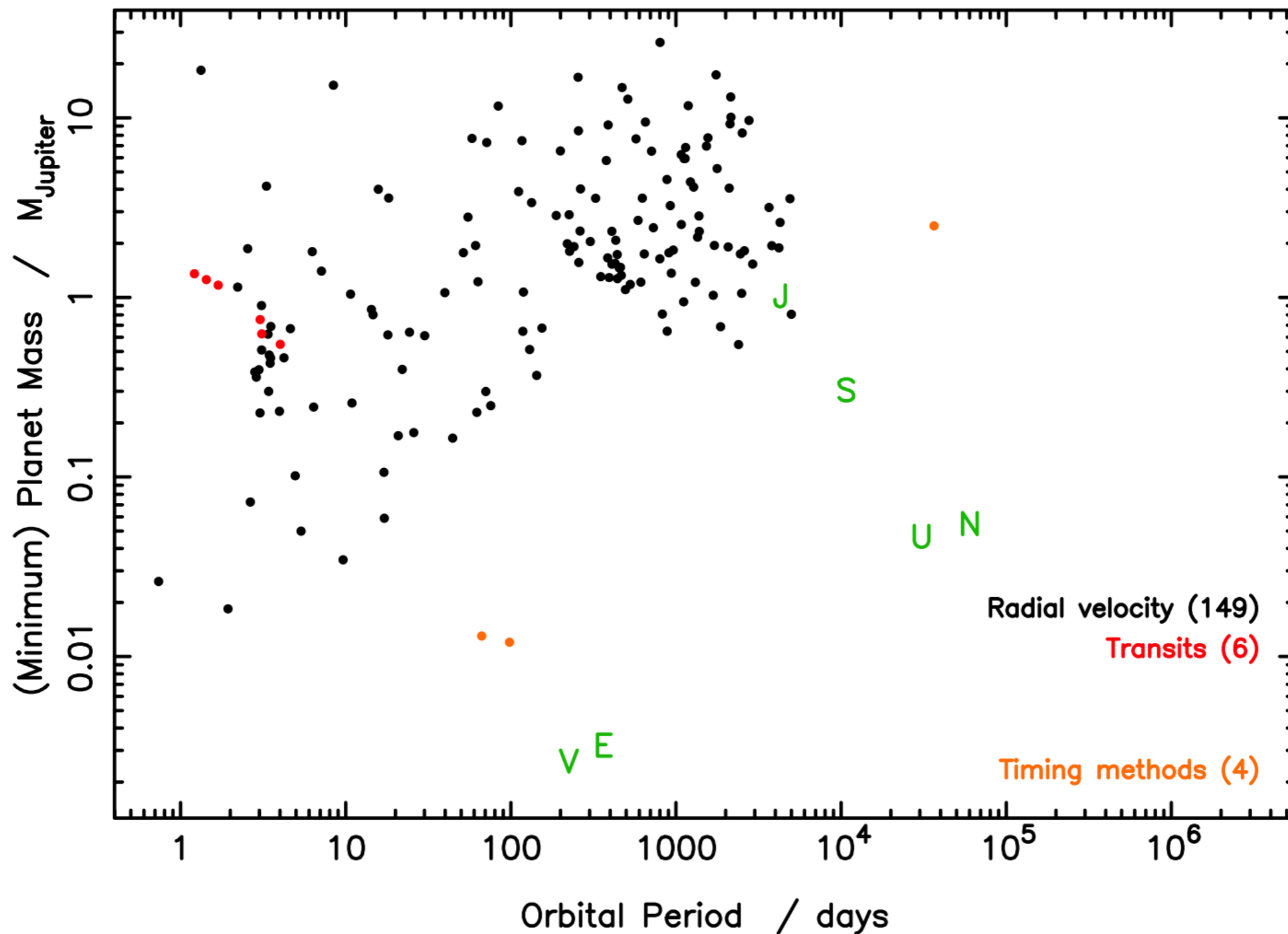
# Known planets as of 2000



Data from [exoplanet.eu](http://exoplanet.eu)

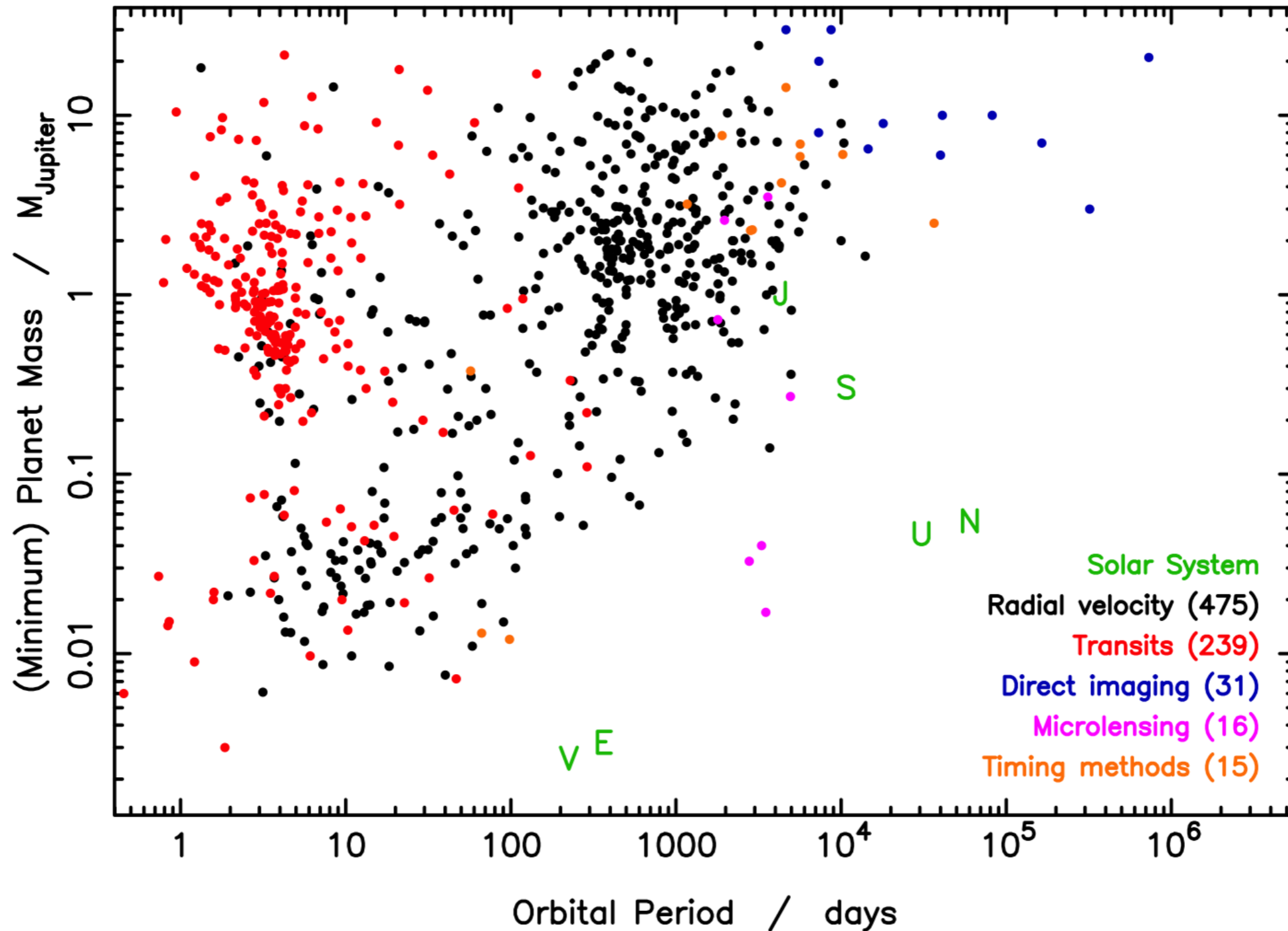


# Known planets as of 2005



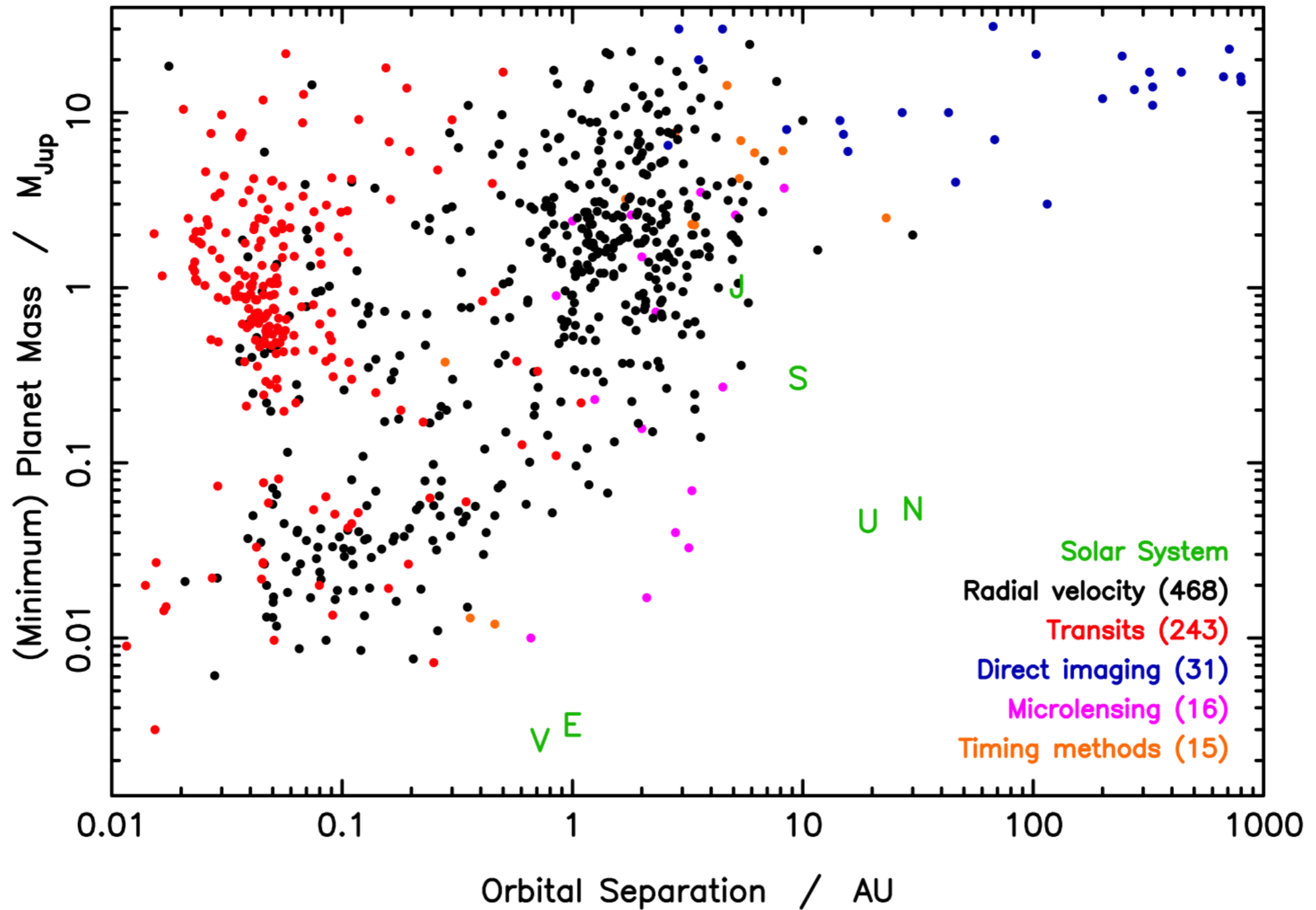
Data from [exoplanet.eu](http://exoplanet.eu)

Known planets (as of 1 Oct 2012)



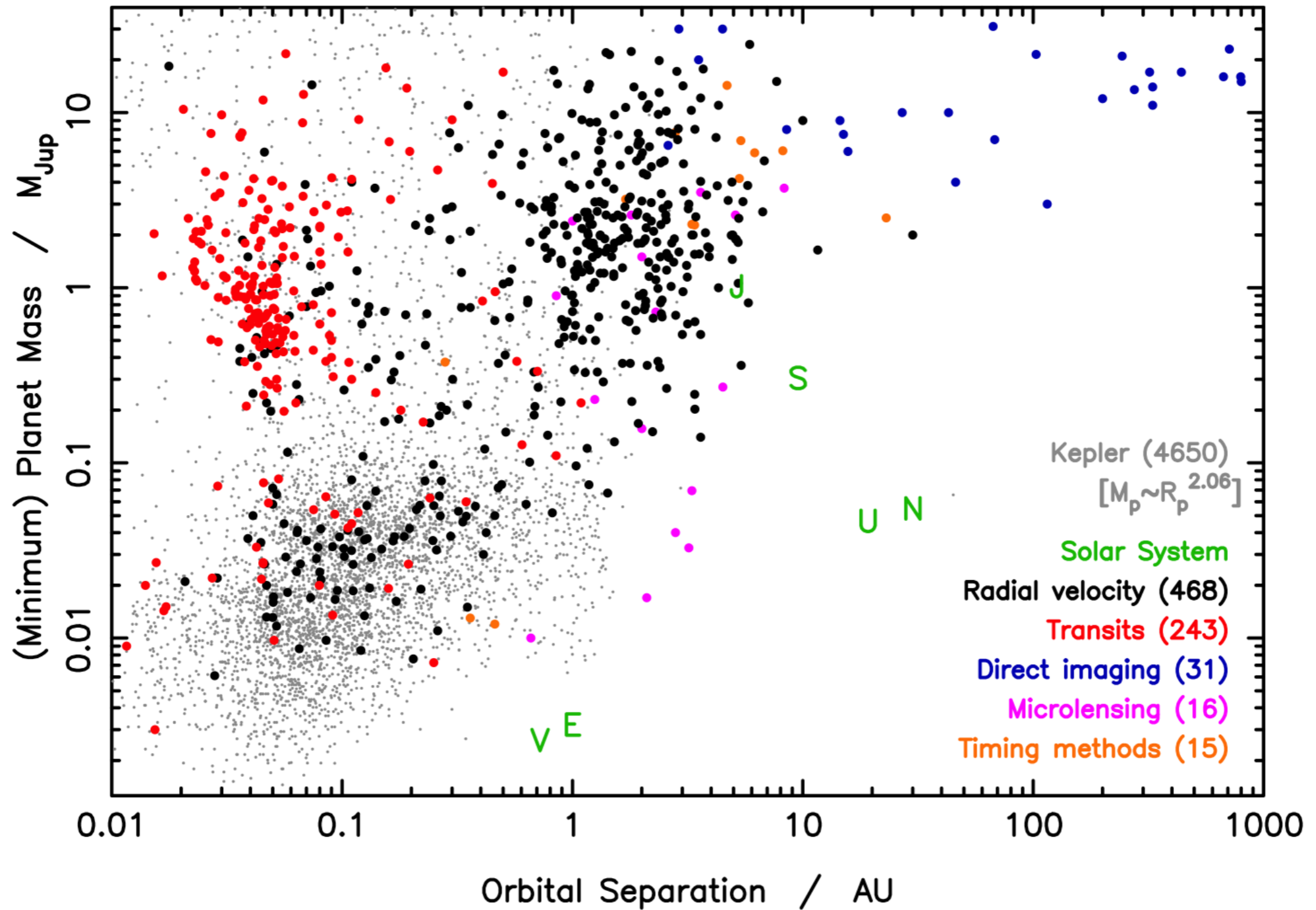
Data from [exoplanet.eu](http://exoplanet.eu)

Known planets (as of 7 Oct 2015)



Data from [exoplanets.org](http://exoplanets.org)

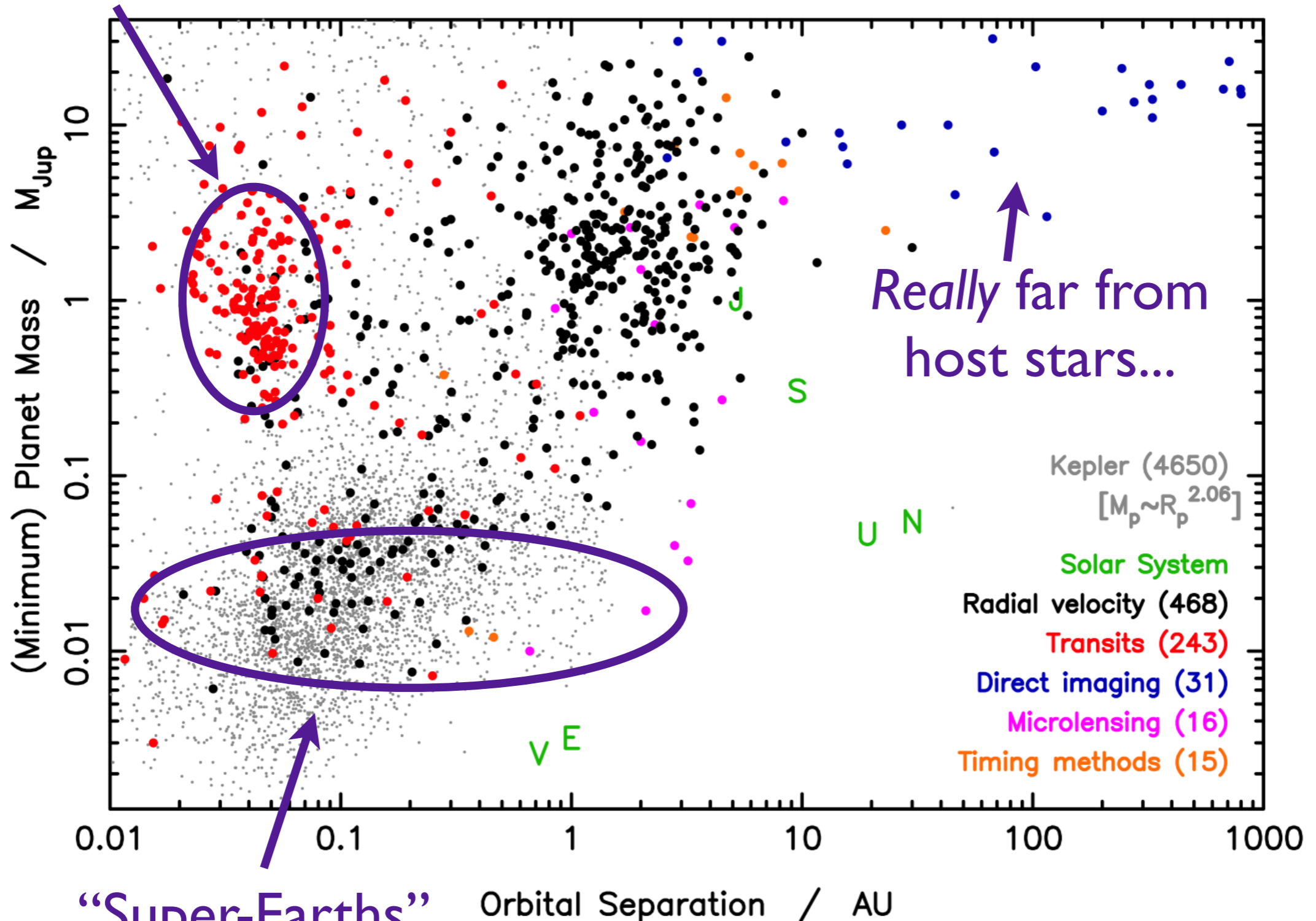
Known planets (as of 7 Oct 2015)



Data from [exoplanets.org](http://exoplanets.org)

“Hot Jupiters”

Known planets (as of 7 Oct 2015)



Really far from host stars...

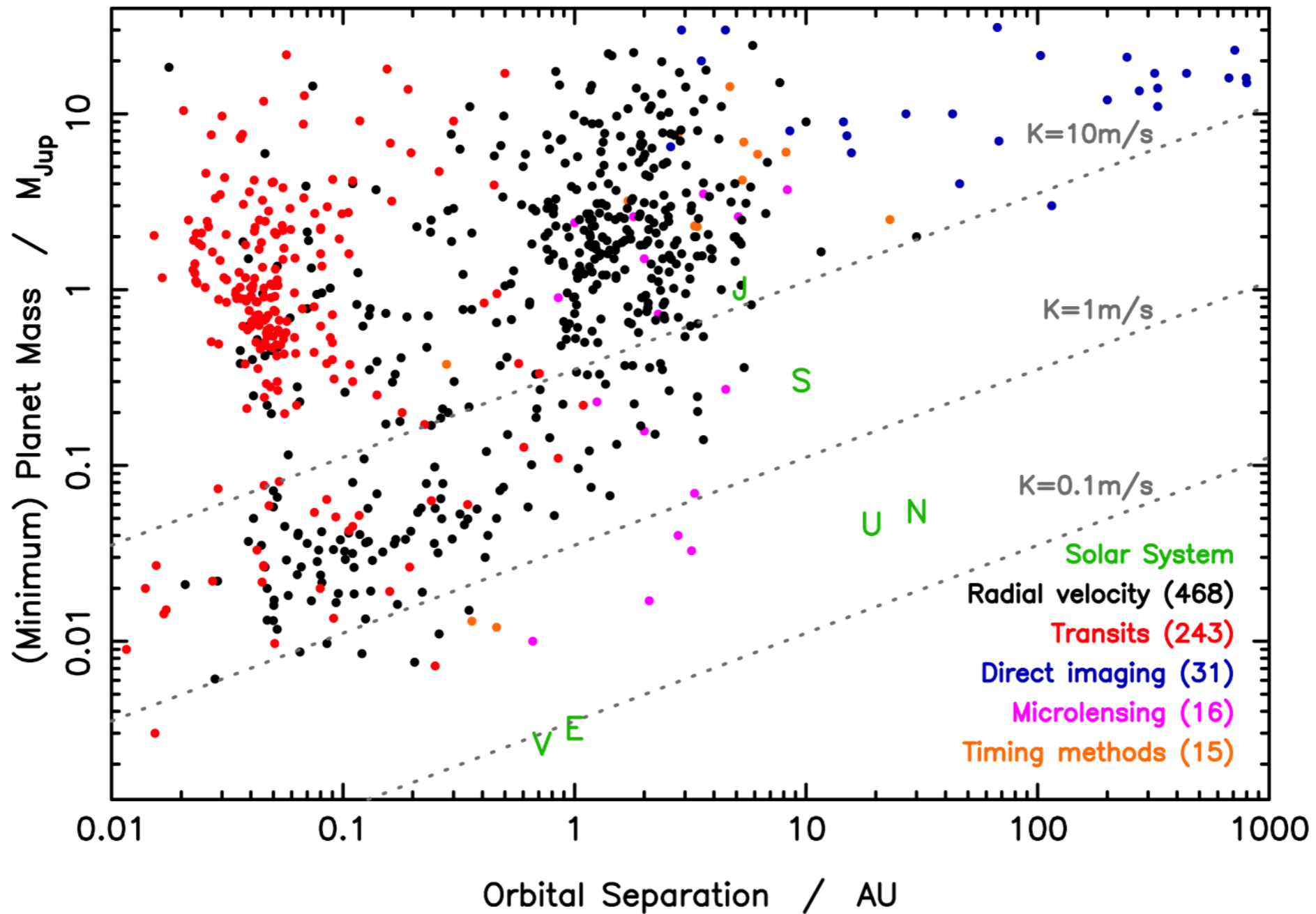
- Kepler (4650)  
[ $M_p \sim R_p^{2.06}$ ]
- Solar System
- Radial velocity (468)
- Transits (243)
- Direct imaging (31)
- Microlensing (16)
- Timing methods (15)

“Super-Earths”

Data from exoplanets.org

# Selection biases

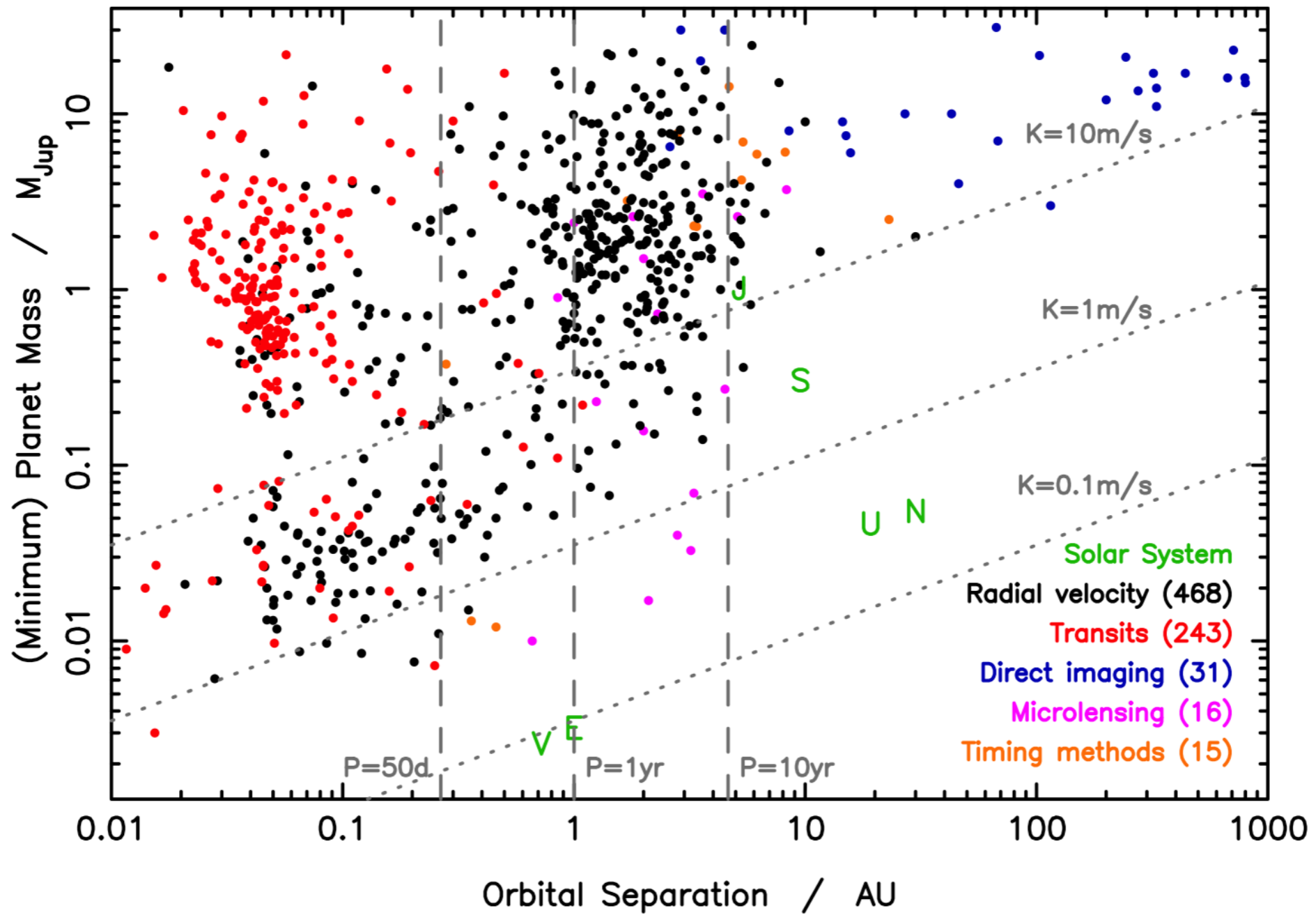
Known planets (as of 7 Oct 2015)



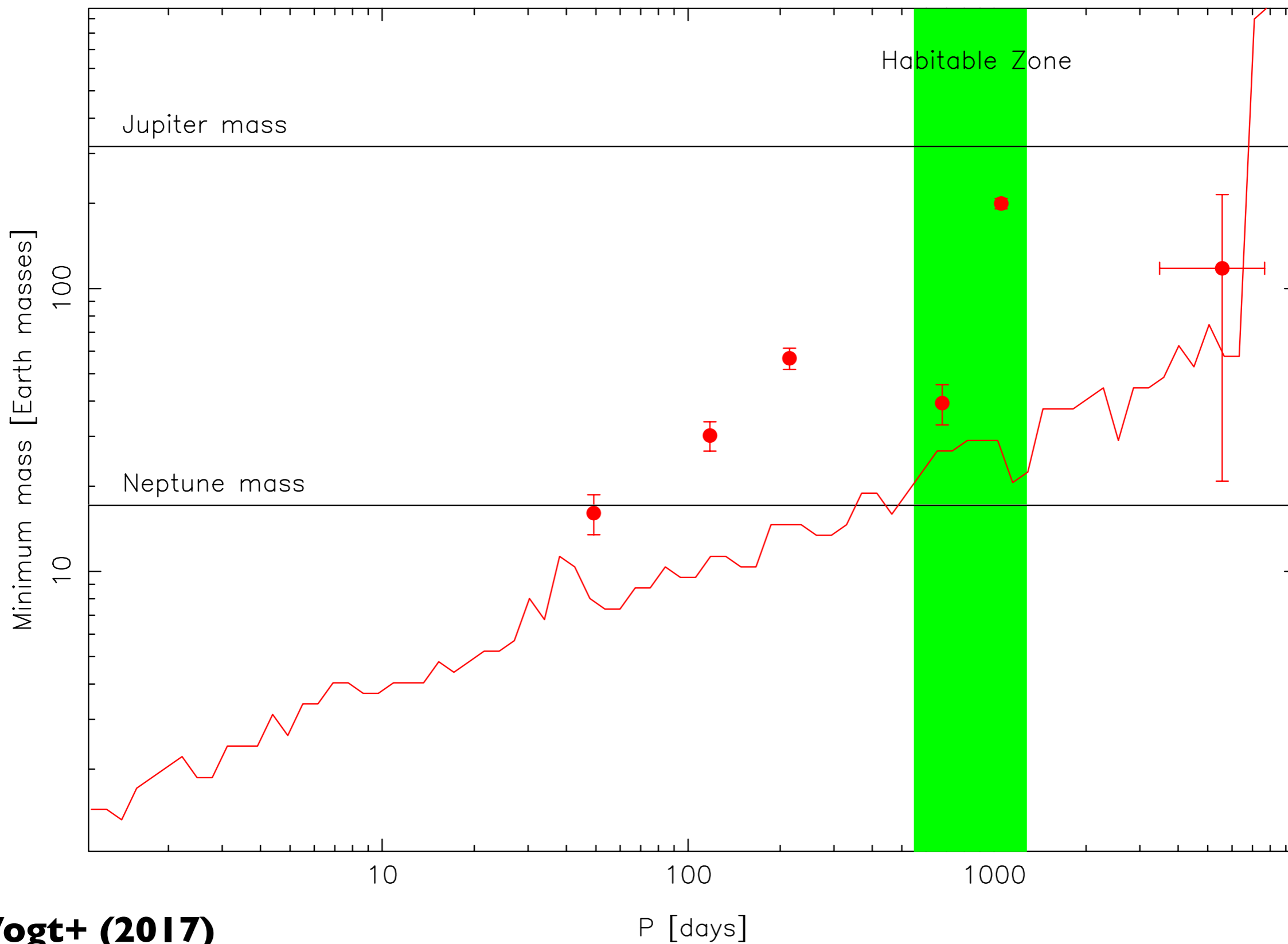
$$K \propto M_p \sin i a^{-1/2} \quad \Rightarrow \quad M_p \sin i \propto K a^{1/2}$$

# Selection biases

Known planets (as of 7 Oct 2015)

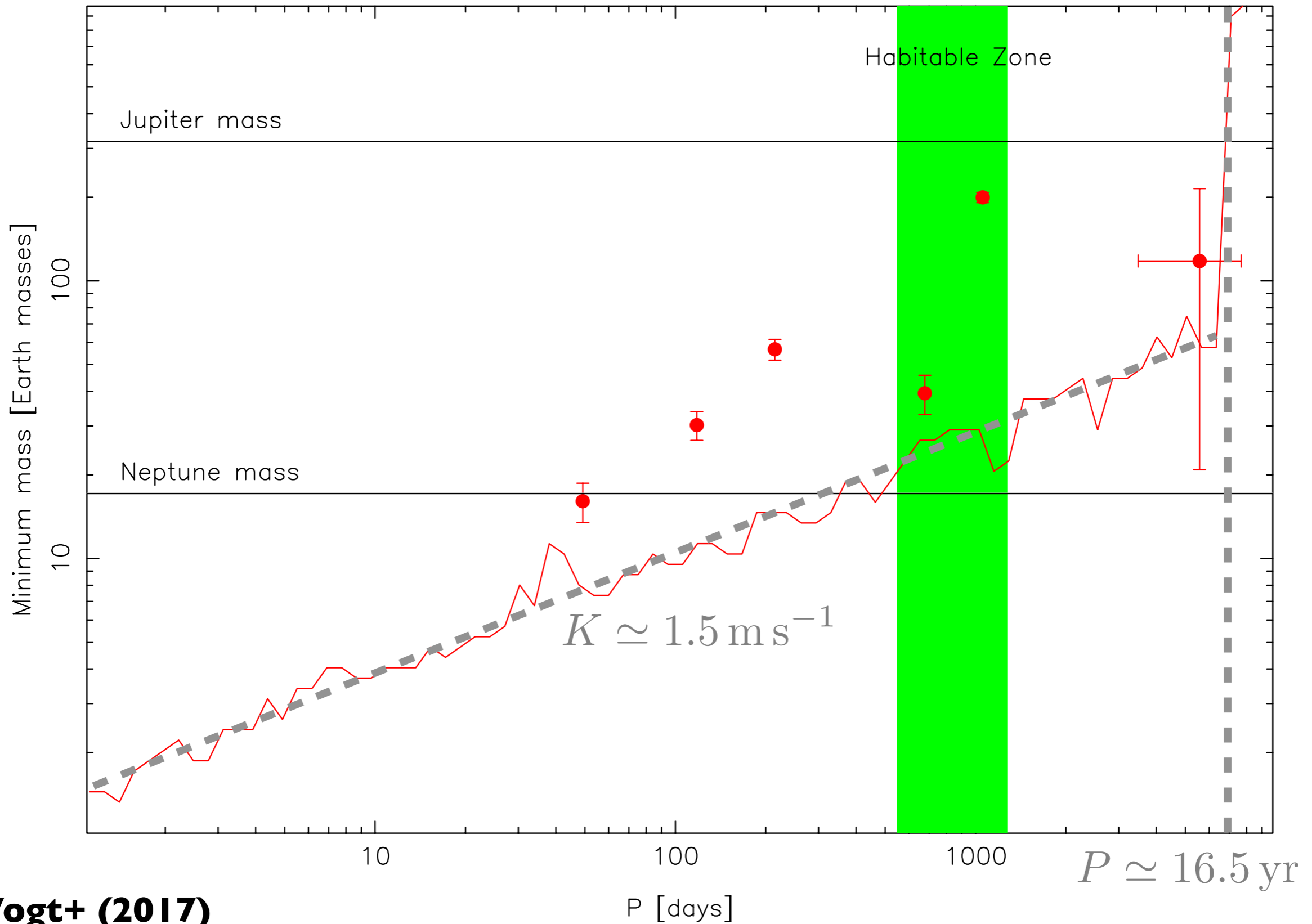


# Selection biases





# Selection biases



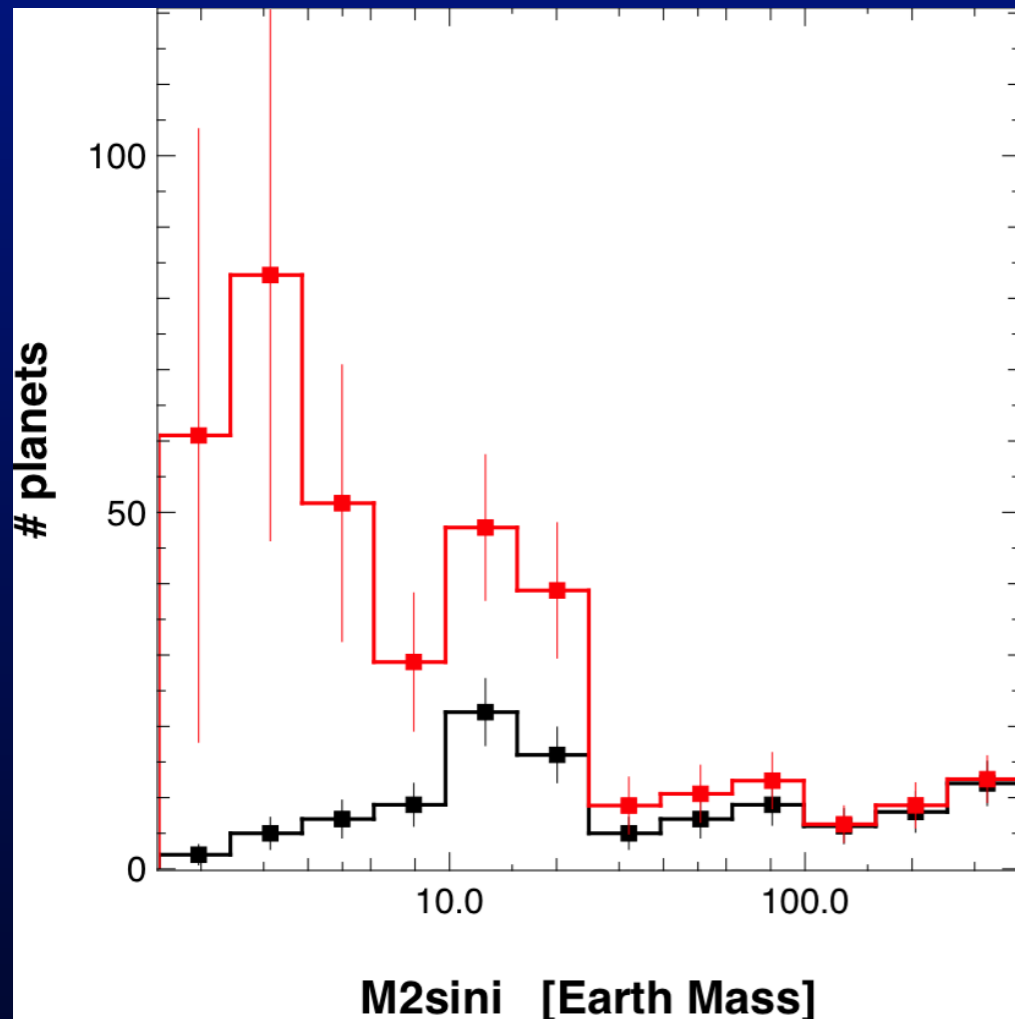
What fraction of stars host planets?

# What fraction of stars host planets?

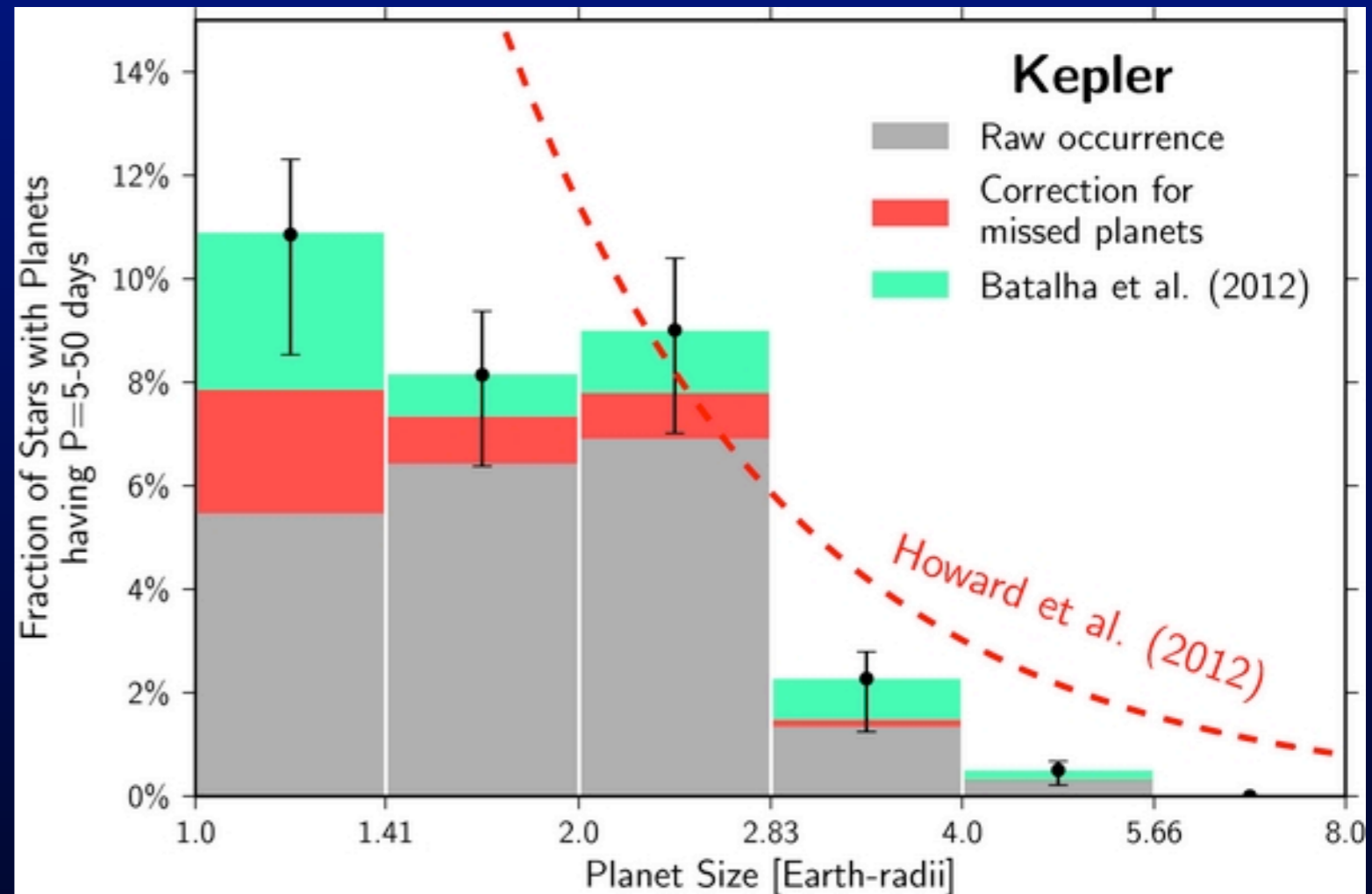
- Selection biases mean that measurements of  $f_p$  must be qualified (but detection methods are complementary).
- Current results:
  - 5-10% of FGK stars host a planet with  $M_p \geq M_{Jup}$  at  $a \leq 3AU$ .
  - >50% of FGK stars host a planet with  $M_p \geq 1M_{\oplus}$  and  $P \leq 100d$ .
  - ~90% of M stars host a planet with  $R_p \geq 0.5R_{\oplus}$  and  $P \leq 50d$ .
- Extension of these results to larger radii will take time. Future missions will probe lower masses, but orbital periods at large (>AU) radii are long.
- Can currently say that  $f_p \geq 0.5$  for sun-like stars. Seems likely that the true value is very close to 1.

# Statistical properties of exoplanets

# Planet mass function



RV: Mayor et al. (2011)



Kepler: Petigura et al. (2013)

- Distribution of planet masses increases to low  $M_p$ .
- Apparent “plateau” in mass (size) function below a few times the size of Earth.

# Mass-radius relation

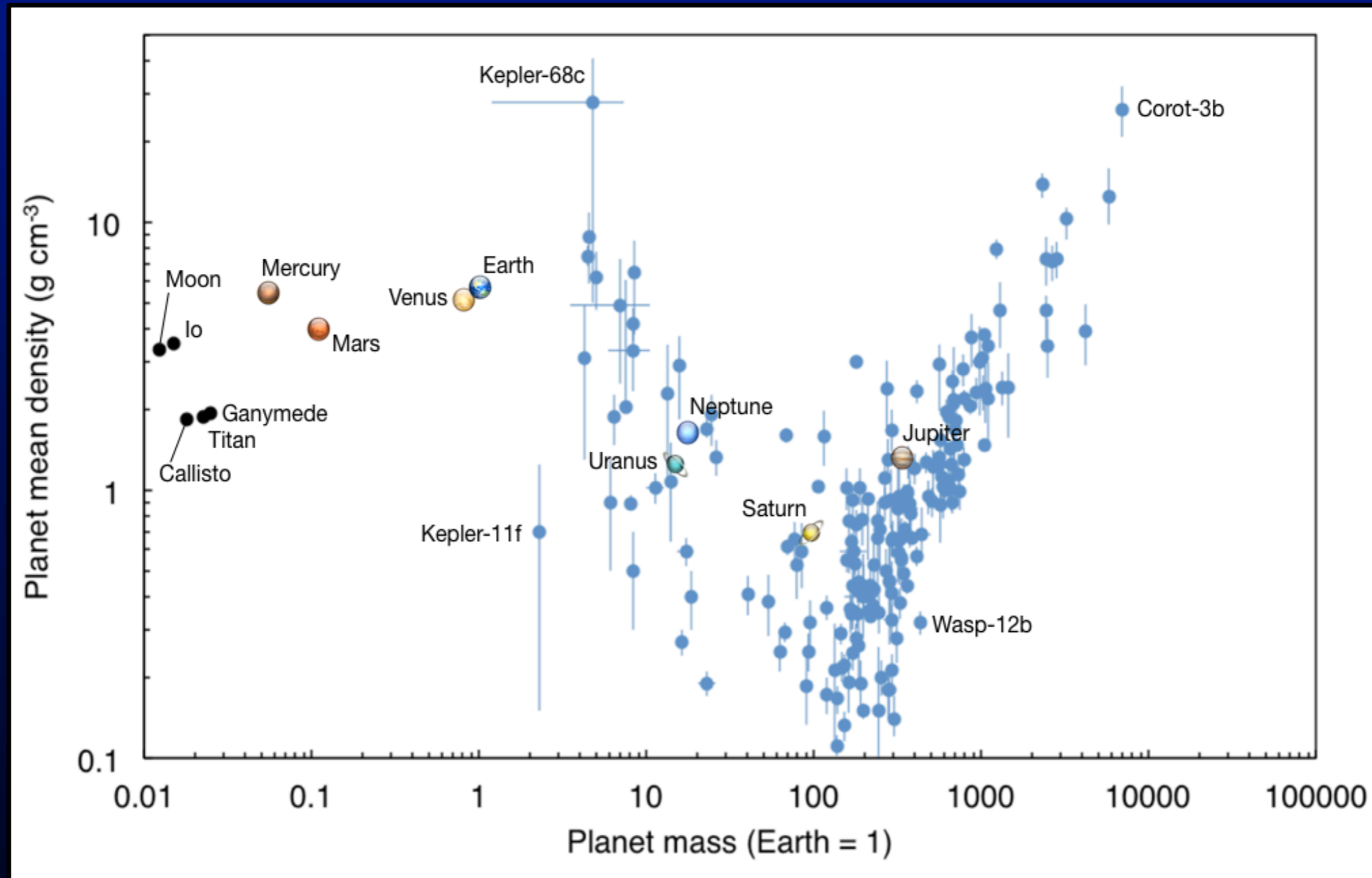
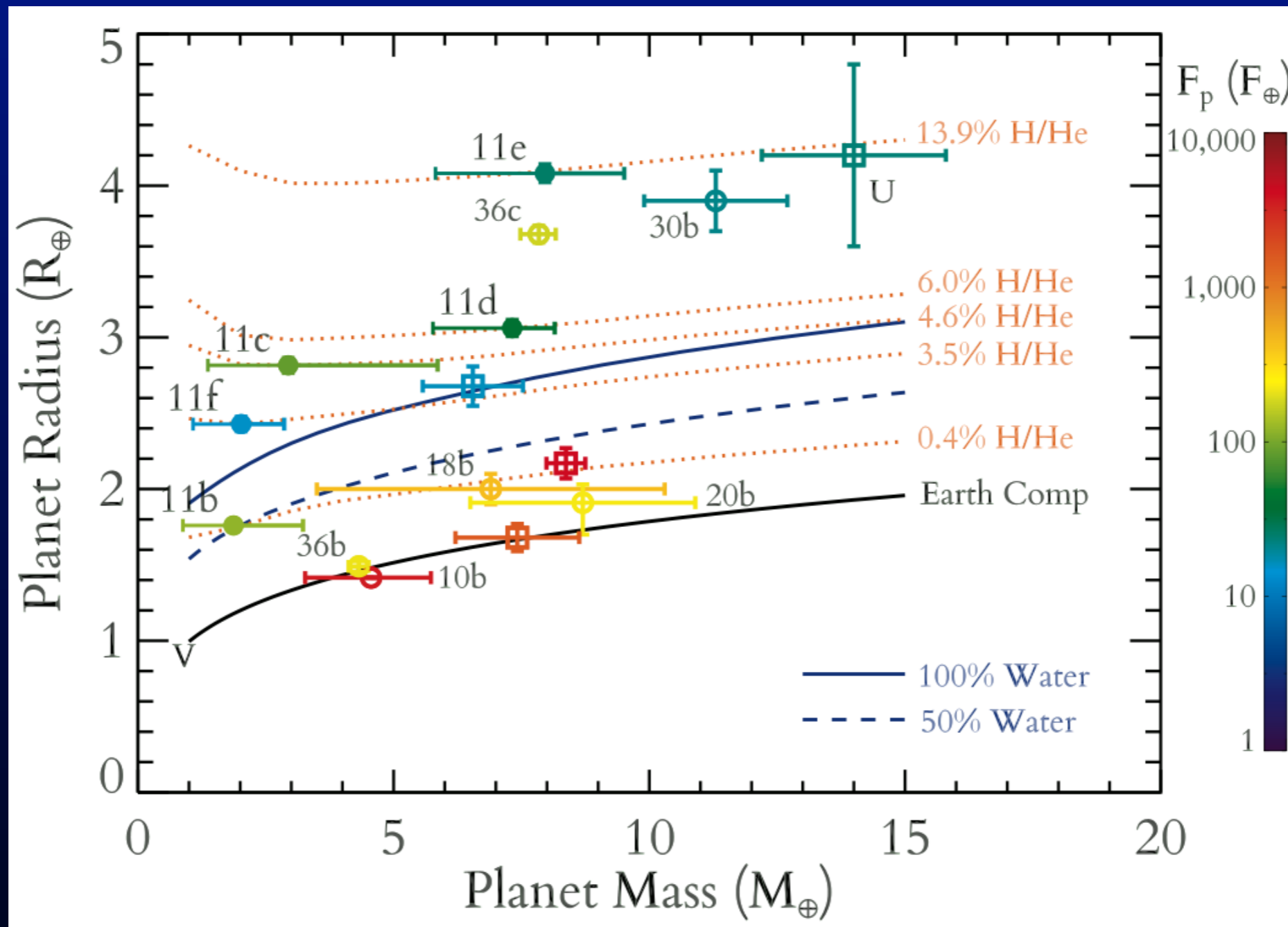


Figure courtesy of Didier Queloz

- Tight correlation for rocky & giant planets; large scatter in intermediate region.
- Dominant source of error is often stellar properties.

# Mass-radius relation

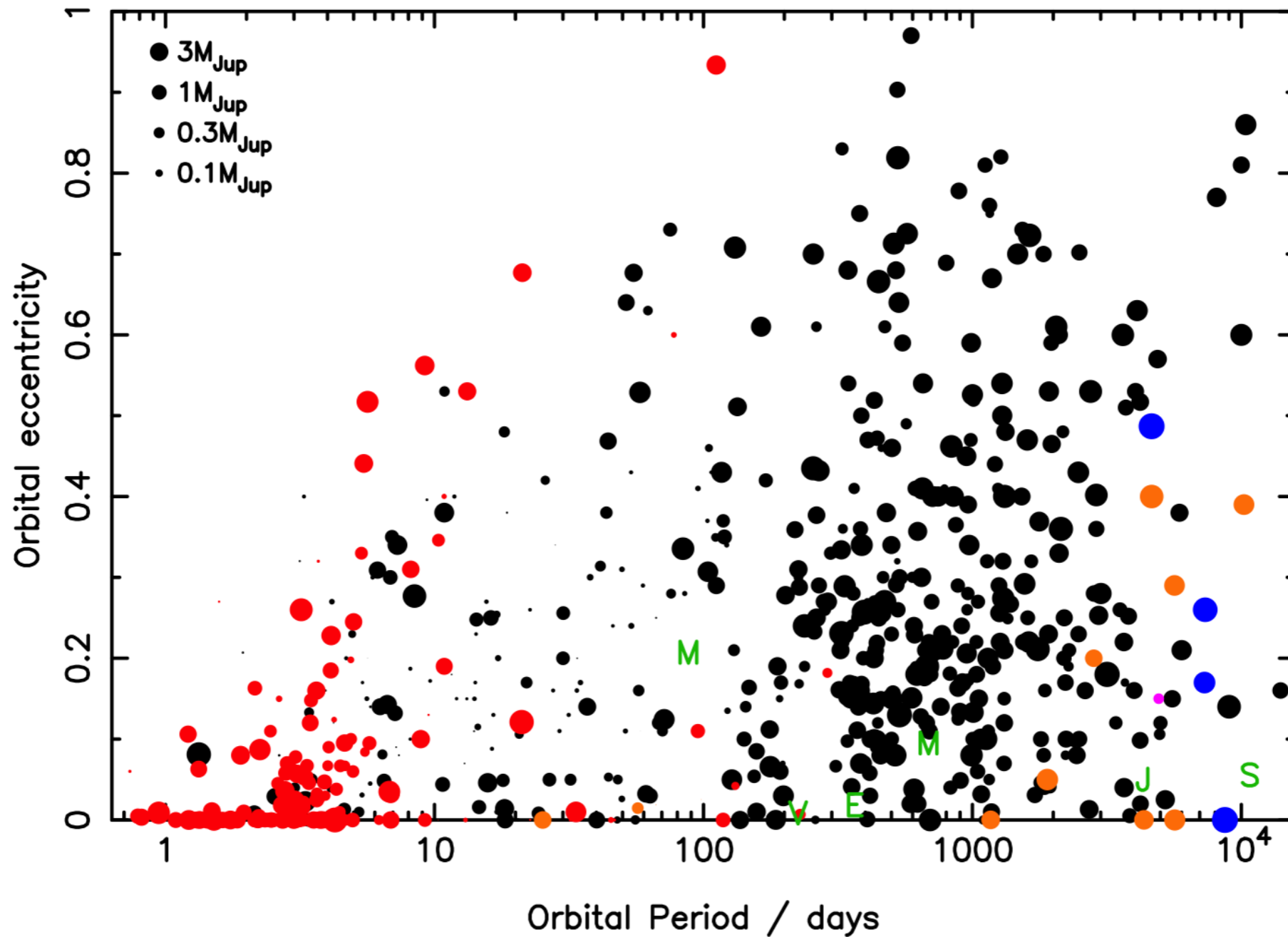


Lissauer et al. (2013)

- Comparison to models possible, but in many cases mean density not strongly constraining.
- However, some exoplanets are unambiguously rocky!

# Eccentricities

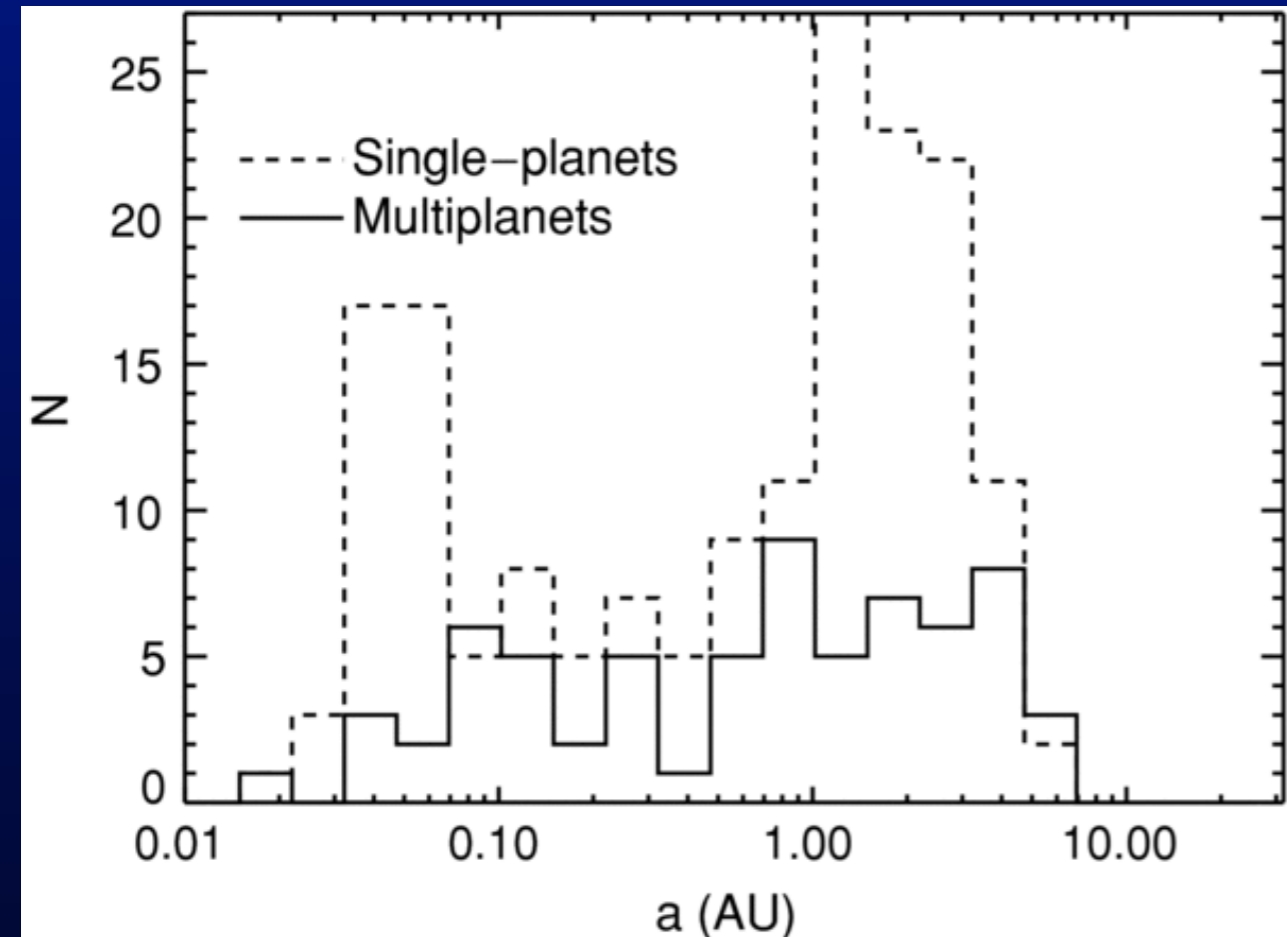
All known planets (as of 1 Oct 2012) with  $M_p \sin i > 3.2M_\oplus$



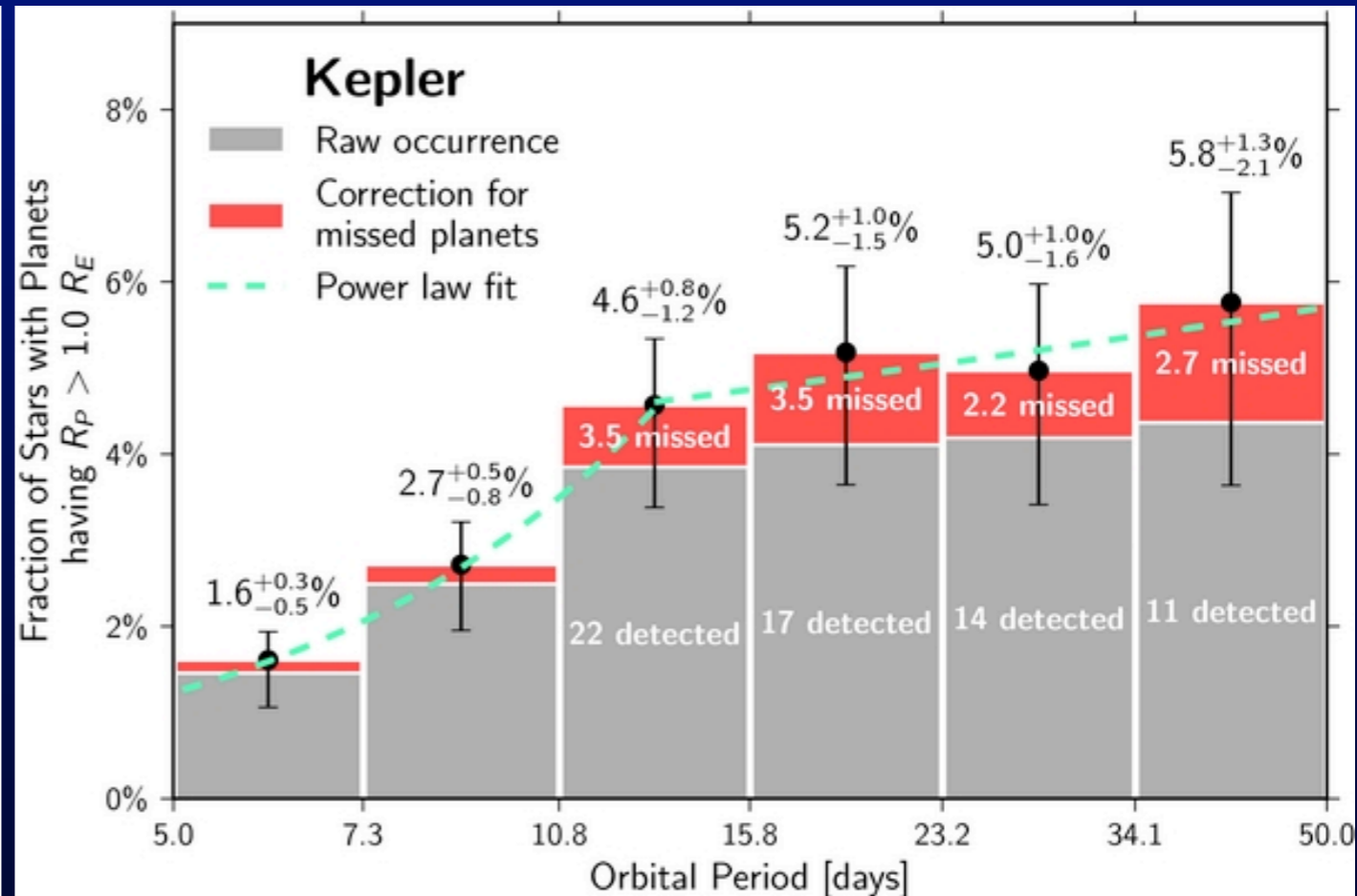
Data from [exoplanets.org](http://exoplanets.org)



# Radial distribution



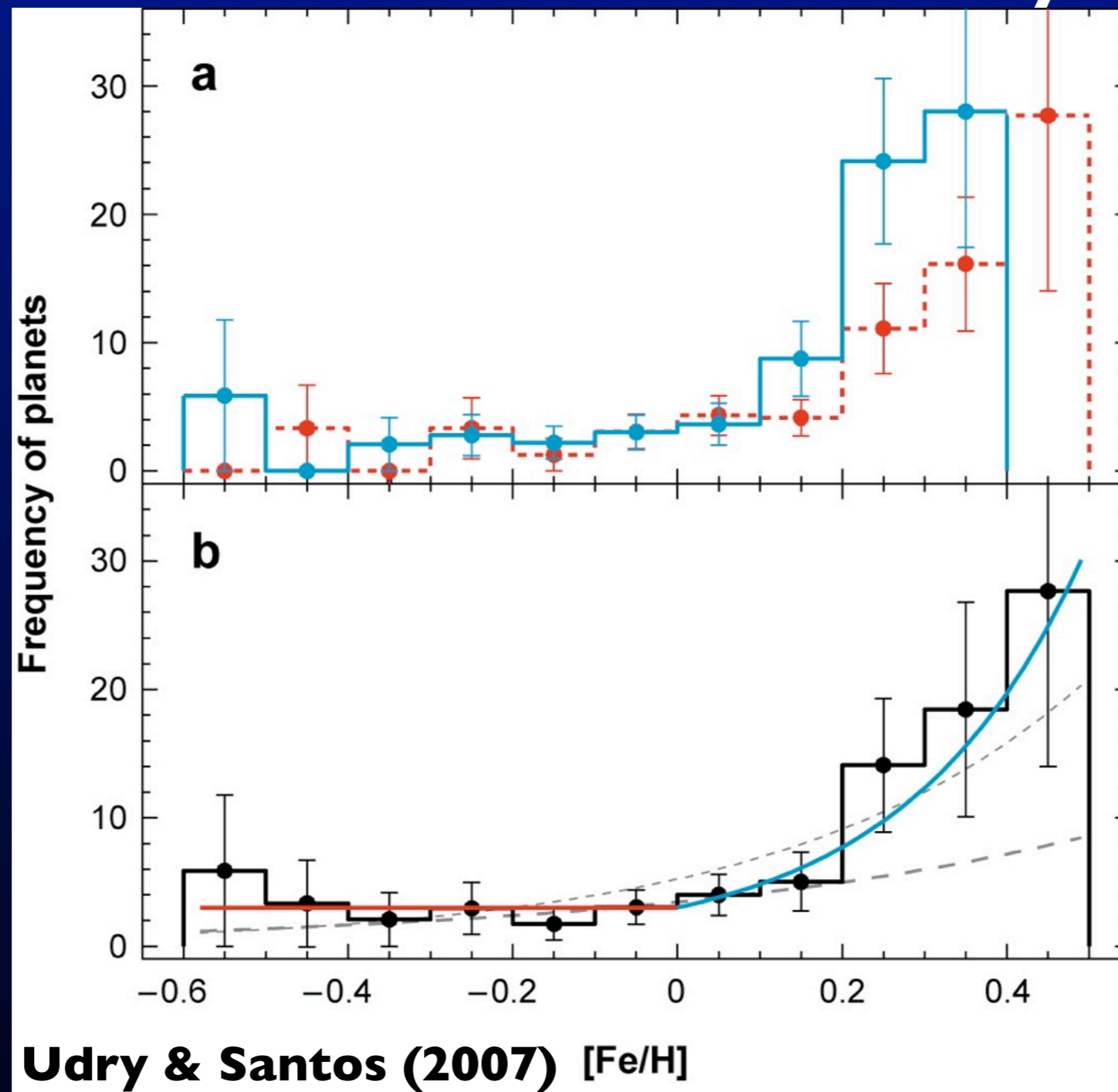
RV: Wright et al. (2009)



Kepler: Petigura et al. (2013)

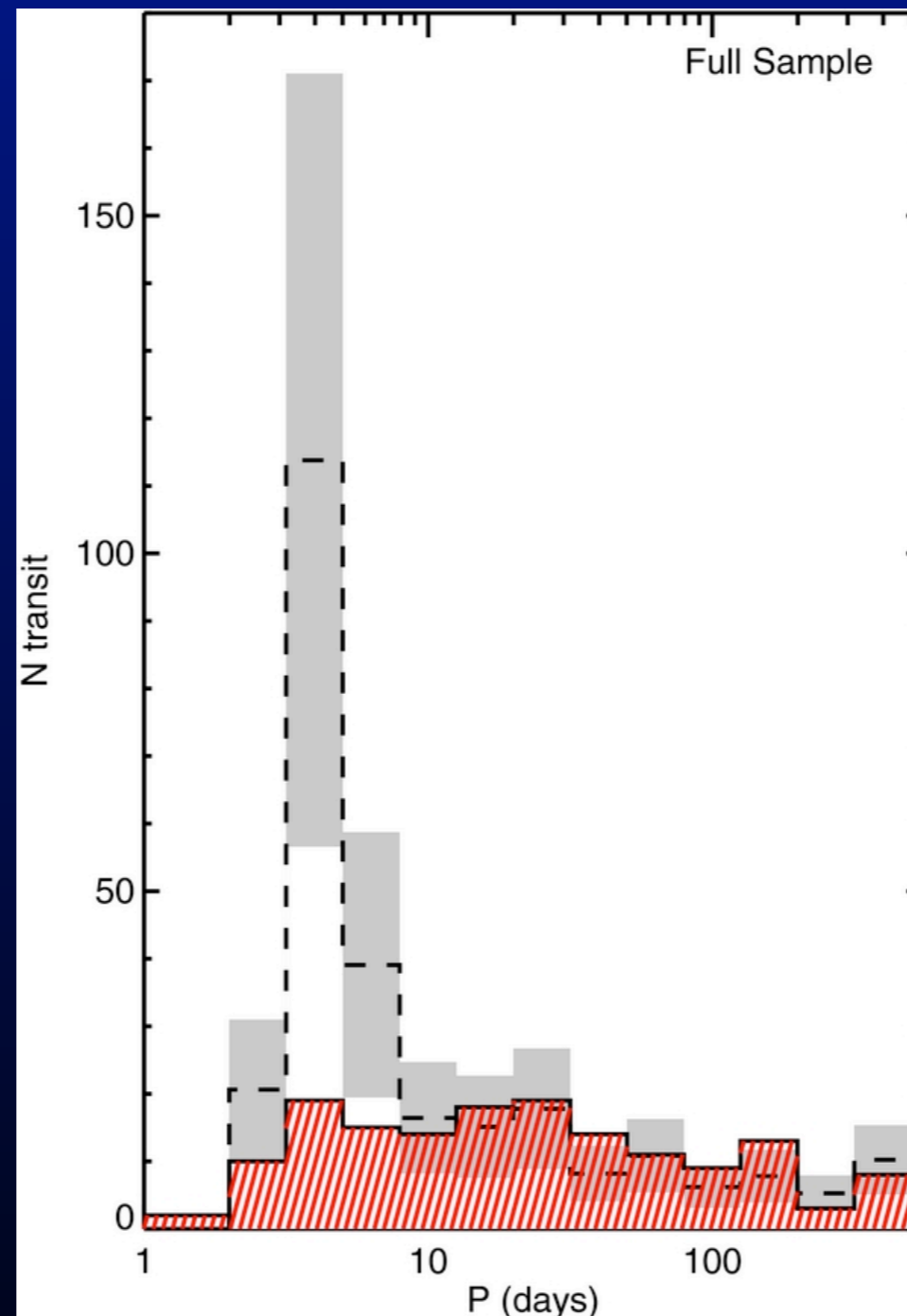
- Radial distribution is “smooth”, though data are limited.
- Evidence of excesses of  $\sim$ Jupiters at  $\sim 0.05$  AU and  $\sim 1$ -2 AU in RV data.
- “Pile-up” of hot Jupiters only seen in metal-rich stars.

# Host star metallicity



- Probability of hosting giant planets increases very sharply with host star metallicity.
- Appears not to hold for Neptune-mass planets.

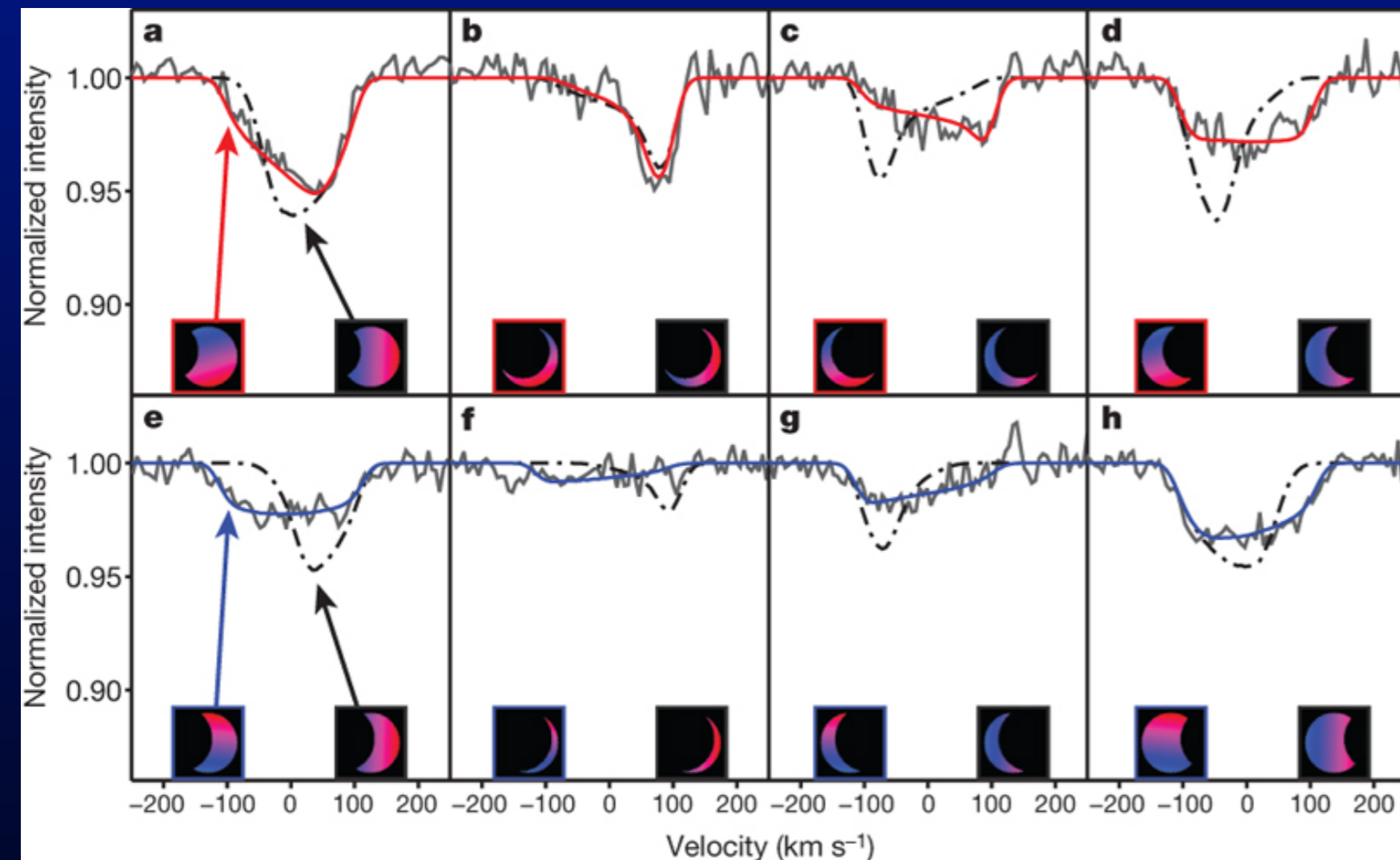
# Host star metallicity



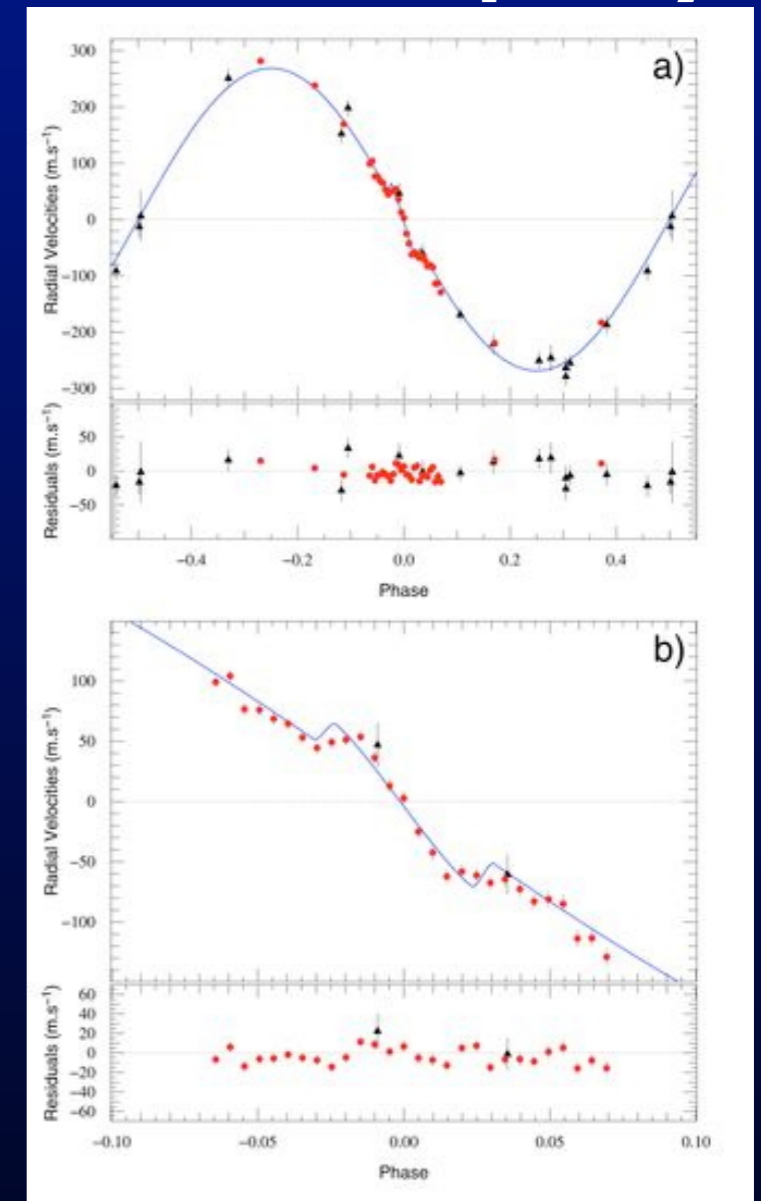
**Dawson & Murray-Clay (2013)**

- Systematic differences between RV & Kepler samples.
- Most likely explanation is metallicity: Kepler stars are more distant than RV sample, with lower  $\langle Z \rangle$ .

# Rossiter-McLaughlin effect & obliquity



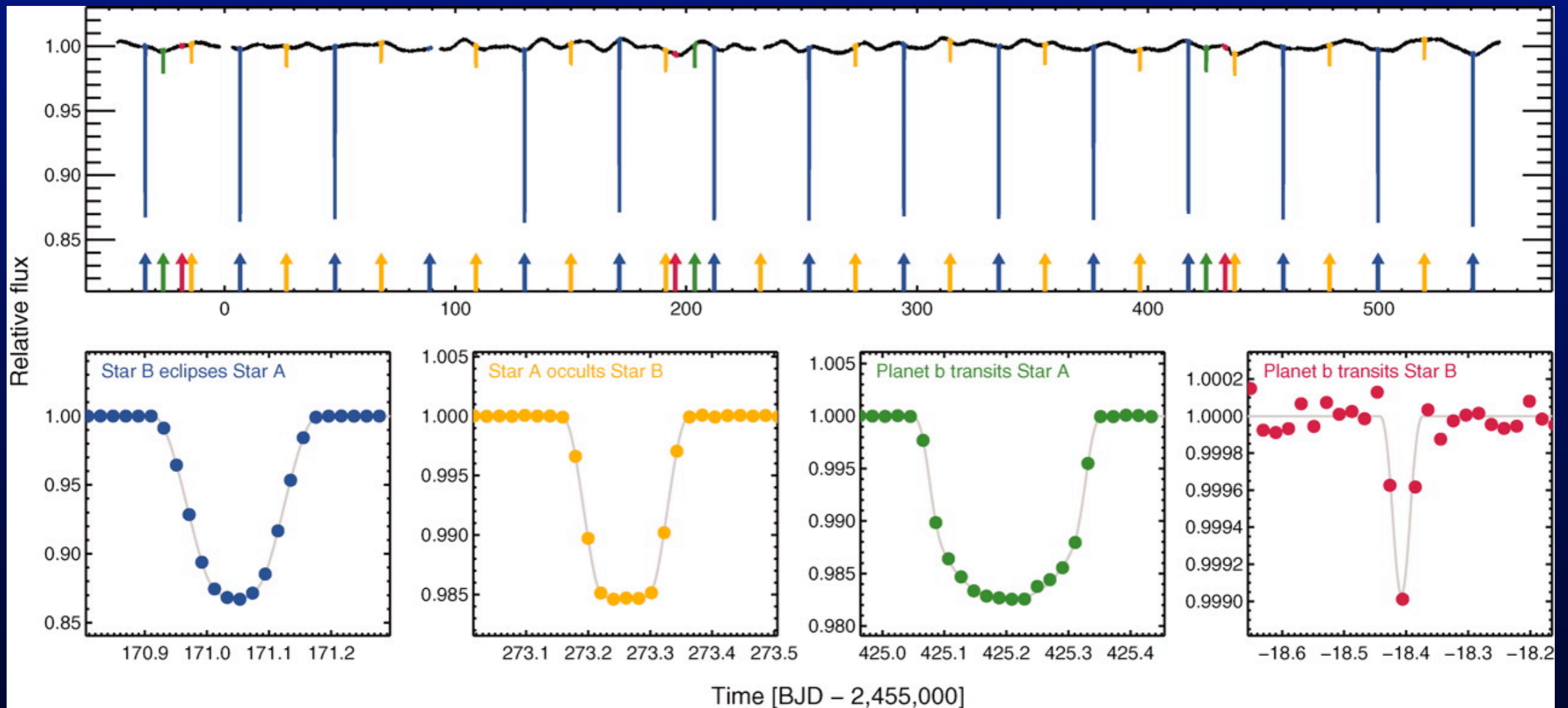
Albrecht et al. (2009)



Triaud et al. (2010)

- Line shifts during transit (R-M) allow us to measure relative inclination of orbit and stellar rotation axis.
- Significant fraction (~10-50%) of short-period gas giants show high (projected) obliquities.

# Kepler-16b: the first “Tatooine”



**Kepler-16b: Doyle et al. (2011)**



# Exoplanet Resources

The screenshot shows the website **exoplanets.org** with the following navigation tabs: Exoplanets Data Explorer, Methodology and FAQ, Exoplanets Links, and California Planet Survey. A large image of Earth is on the left. In the center, there are two buttons: **Table** (with a grid icon) and **Plots** (with a scatter plot icon). To the right, a summary table lists planet counts:

<b>707</b>	<b>EOD Planets</b> Planets with good orbits listed in the Exoplanet Orbit Database
<b>25</b>	<b>Other Planets</b> Including microlensing and imaged planets
<b>732</b>	<b>Total Confirmed Planets</b>
<b>3469</b>	<b>Unconfirmed Kepler Candidates</b>
<b>4201</b>	<b>Total Planets</b> Confirmed planets + Kepler Candidates

The Exoplanet Data Explorer is an interactive table and plotter for exploring and displaying data from the Exoplanet Orbit Database. The Exoplanet Orbit Database is a carefully constructed compilation of quality, spectroscopic orbital parameters of exoplanets orbiting normal stars from the peer-reviewed literature, and updates the Catalog of nearby exoplanets.

A detailed description of the Exoplanet Orbit Database and Explorers is published [here](#) and is available on [astro-ph](#).

In addition to the Exoplanet Data Explorer, we have also provided the entire Exoplanet Orbit Database in CSV format for a quick and convenient download [here](#). A list of all archived CSVs is available [here](#).

[exoplanets.org/plots](http://exoplanets.org/plots) and documentation for the Exoplanet Data Explorer is available [here](#). A FAQ and overview of our methodology is

# Exoplanet Resources

The screenshot shows a web browser window displaying the Exoplanet.eu website. The browser's address bar shows 'exoplanet.eu'. The website's title is 'The Extrasolar Planets Encyclopaedia'. The navigation menu includes 'Home', 'Catalog', 'Diagrams', 'Bibliography', 'Searches', 'Meetings', 'Other Sites', and 'VO'. The main content area features a large title 'The Extrasolar Planets Encyclopaedia' and a brief history: 'Established in February 1995', 'Jean Schneider, CNRS/LUTH - Paris Observatory', and 'Last update: Sept. 14, 2013 (973 planets)'. Below this, there are two main sections: 'Catalog' (with a calendar icon) and 'Diagrams' (with a 3D pie chart icon). The 'Catalog' section describes filtering and sorting capabilities, while 'Diagrams' describes an online plotting tool. A 'News' section on the left lists recent updates, including the Exoplanet catalogue in binaries, Kepler-62 e and f, TESS selection, and the discovery of five planets around tau Cet. On the right, there are links to 'Tutorials', 'Meetings', 'Bibliography', 'Theory Work', 'Searches', and 'Other sites', each with its last update date.

The Extrasolar Planets Encyclopaedia

Home Catalog Diagrams Bibliography Searches Meetings Other Sites VO

## The Extrasolar Planets Encyclopaedia

Established in February 1995  
Jean Schneider, CNRS/LUTH - Paris Observatory  
Last update: Sept. 14, 2013 (973 planets)  
Please report any problems to [vo.exoplanet@obspm.fr](mailto:vo.exoplanet@obspm.fr)

### Catalog

Filter, sort, export — arbitrary data manipulations with the Extrasolar Planets Encyclopaedia

### Diagrams

Analyze the Extrasolar Planets Encyclopaedia data online. Simple plotting tool right in the browser

### News

May 28, 2013 Exoplanet catalogue in binaries and multiple systems (Richard Schwarz ) in [exoplanet.eu/sites/](http://exoplanet.eu/sites/)

April 18, 2013 Kepler-62 e and Kepler 62 f, two potentially habitable planets in a [five planet system](#) (Borucki et al).

April 8, 2013 [TESS selected for launch in 2017](#)

Dec. 19, 2012 Five planets around tau Cet ? [tau Cet b](#) [tau Cet c](#) [tau Cet d](#) [tau Cet e](#) [tau Cet f](#) (Tuomi et al. 2012)

### Tutorials

Last update: May 17, 2012

### Meetings

Last update: May 17, 2011

### Bibliography

Last update: May 17, 2012

### Theory Work

Last update: April 3, 2012

### Searches

Last update: April 18, 2012

### Other sites

Last update: April 16, 2012

exoplanet.eu

# Exoplanet Resources



Exoplanet for iPhone and iPad

exoplanetapp.com

Google Apple Common Use Accounts Astronomy Stuff Mac Stuff Nottingham Blogs Camera Open in Papers

The Extrasolar Planets Encyclo... exovis - Exoplanet catalogue vi... Exoplanet for iPhone and iPad Exoplanet Orbit Database | Exo...



## Exoplanet

Tweet 40

*889 planets and counting.*

The free Exoplanet App for iPhone, iPad and iPod touch is a daily updated database of all discovered extrasolar planets with fancy and interactive visualisations.

**FREE** Available on the App Store

### Features

Extensive database

The exoplanet database used in this app is based on an open

