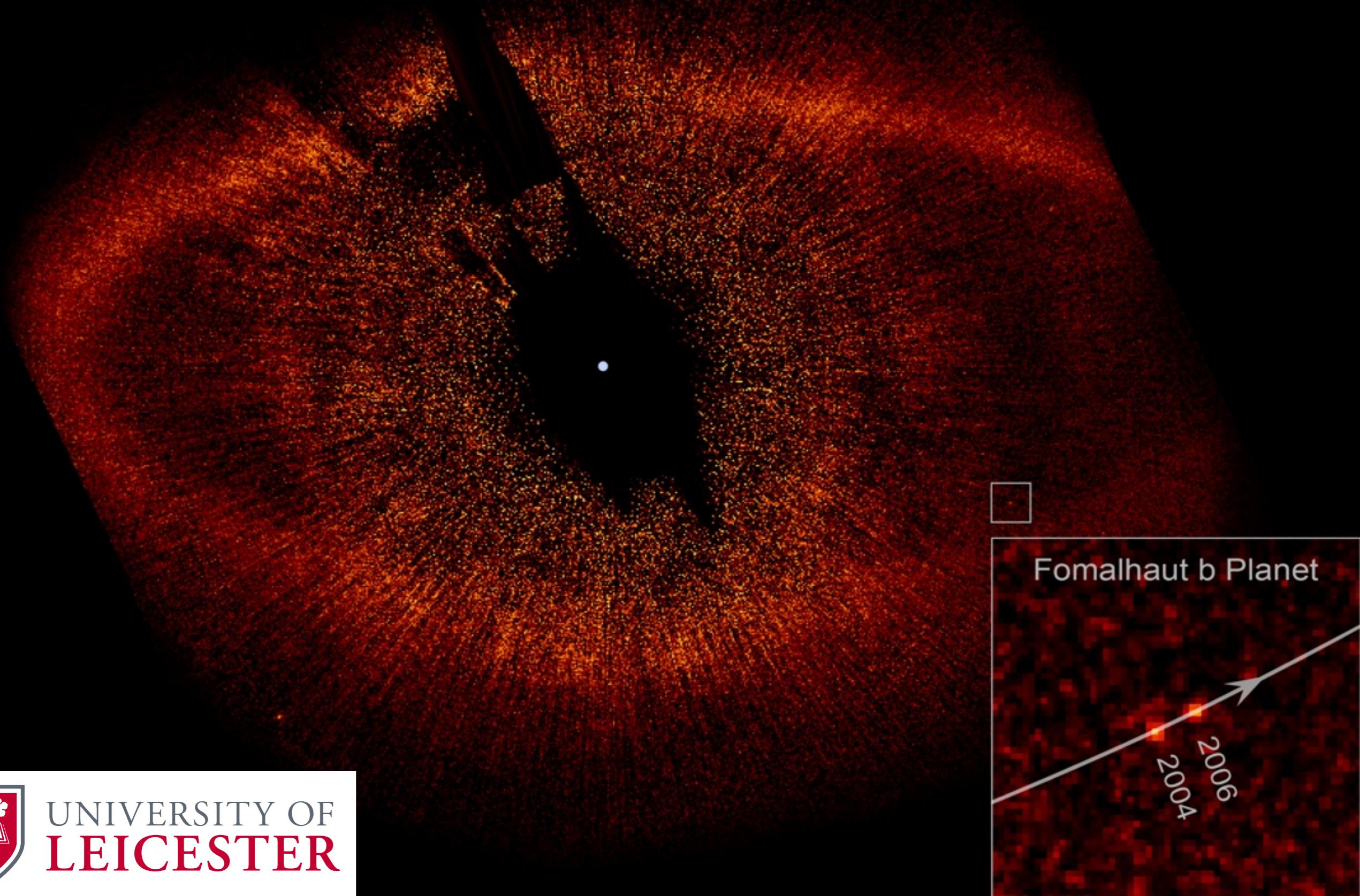


Formation of Planetary Systems

Lecture 1 - Observations of planetary systems

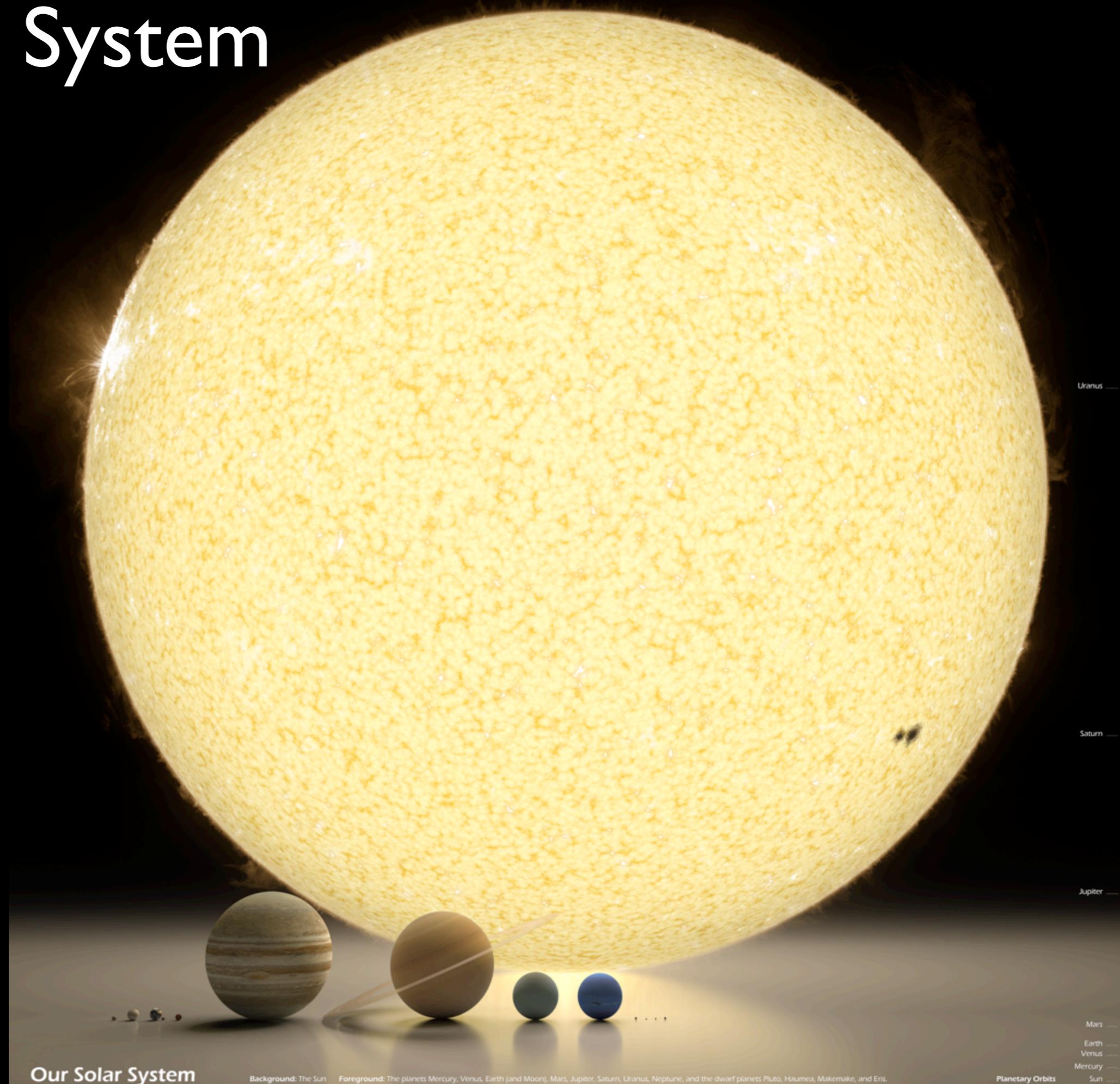


UNIVERSITY OF
LEICESTER

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

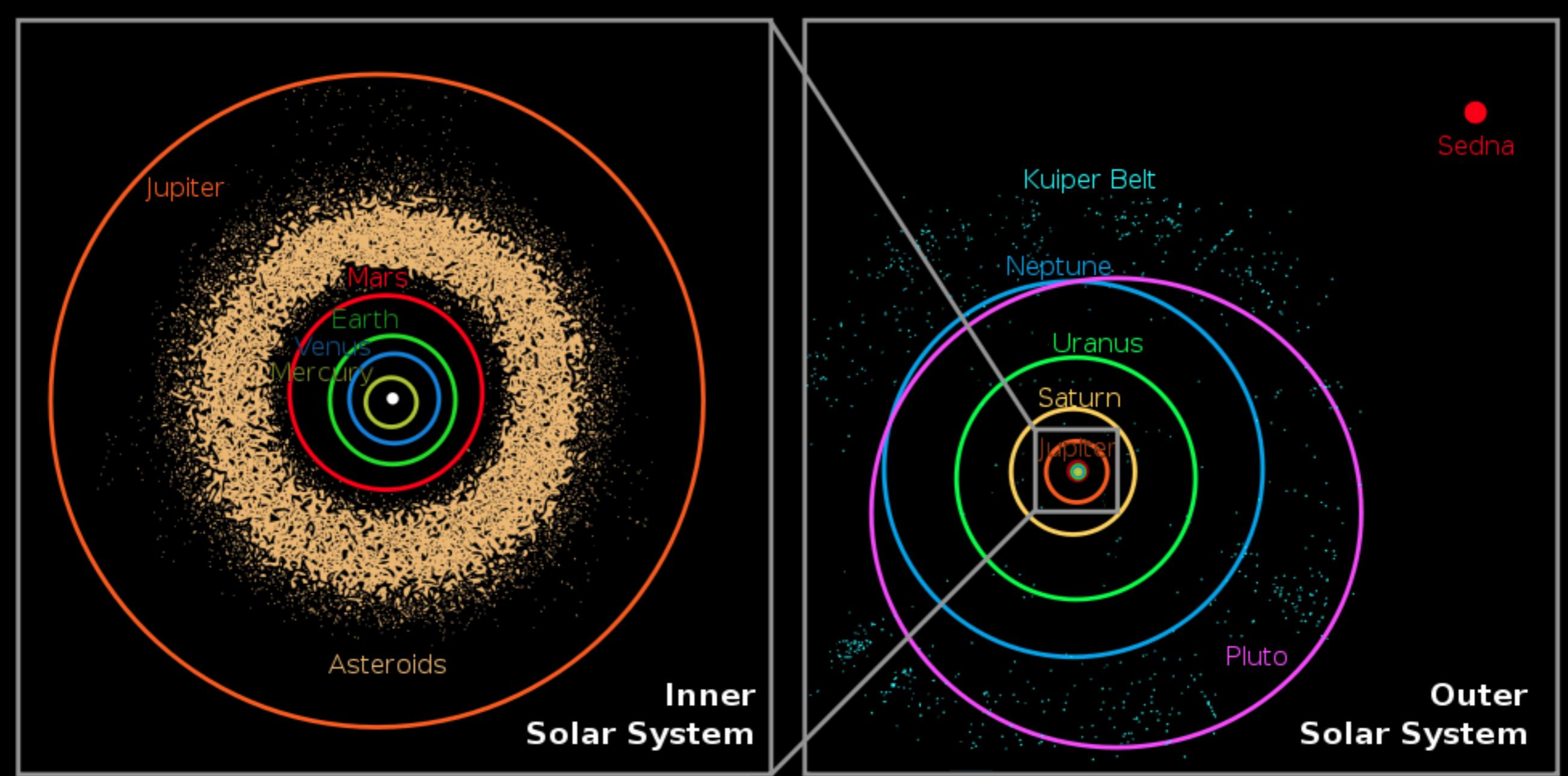
Venus

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. Illustration by Roberto Ziche. Photography courtesy of NASA, JPL, and PlanetaryScapes.com.**Planetary Orbits**

The Solar System



The Solar System

	a AU	e	M_p M_{Jup}
Mercury	0.387	0.206	1.74×10^{-4}
Venus	0.723	0.007	2.56×10^{-3}
Earth	1.000	0.017	3.15×10^{-3}
Mars	1.524	0.093	3.38×10^{-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):
 - H_2O , NH_3 , CH_4 , etc.
 - $\sim 1 M_{\text{Earth}}$ 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 $>\text{M}_{\text{Earth}}$.**
 - **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

Total: 3262 (5747)

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

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.

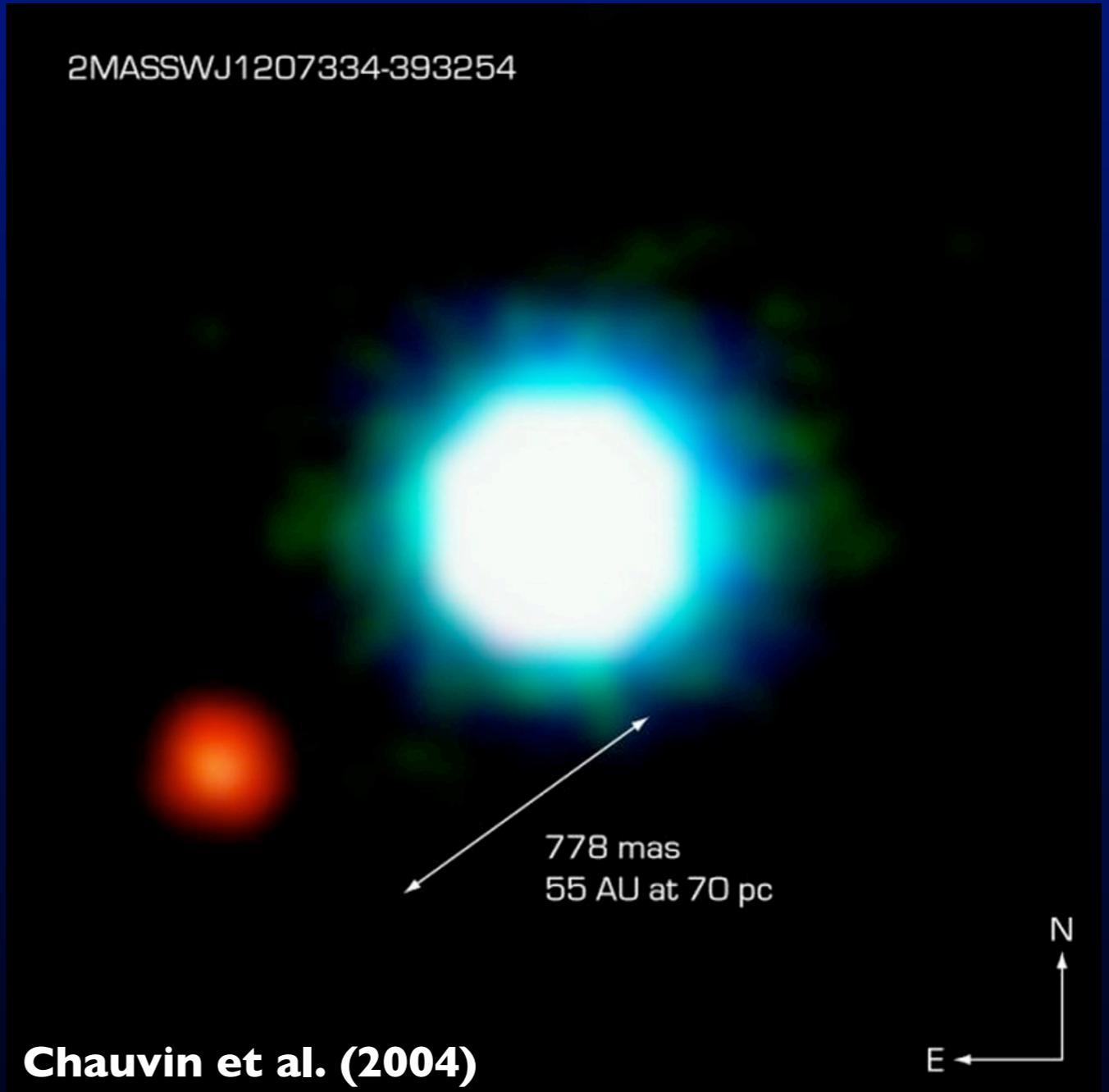
* A is the albedo.

Direct Imaging

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

Direct Imaging

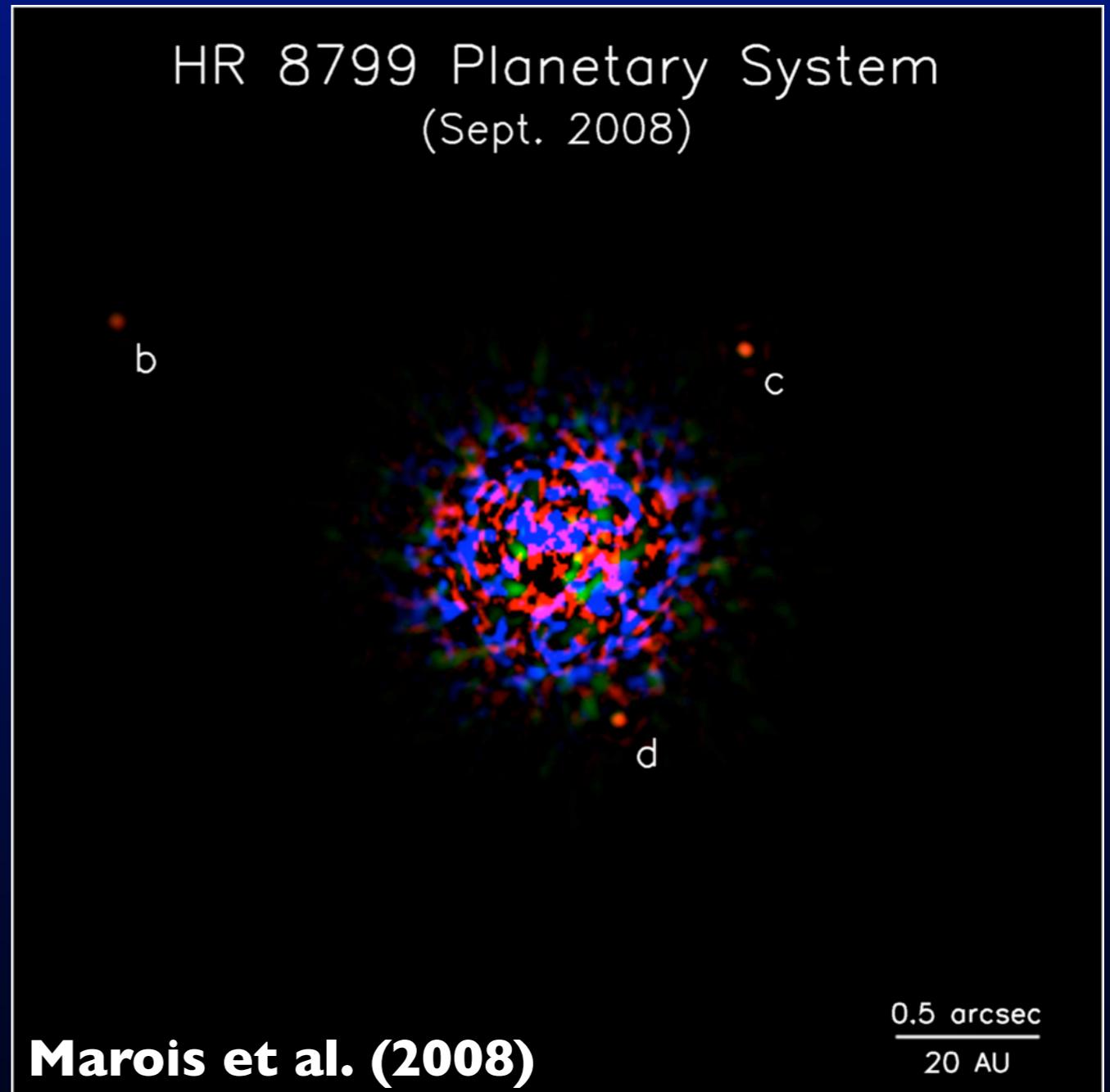
- Two ways around the contrast problem:
 - a) Look for planets around faint stars
 - b) Try to mask out star-light



“Planet” around brown dwarf 2M1207 discovered in 2004.
Primary is $\sim 25 M_{Jup}$; secondary is $\sim 5 M_{Jup}$. Wide separation.
More akin to a low-mass binary than a true planetary system.

Direct Imaging

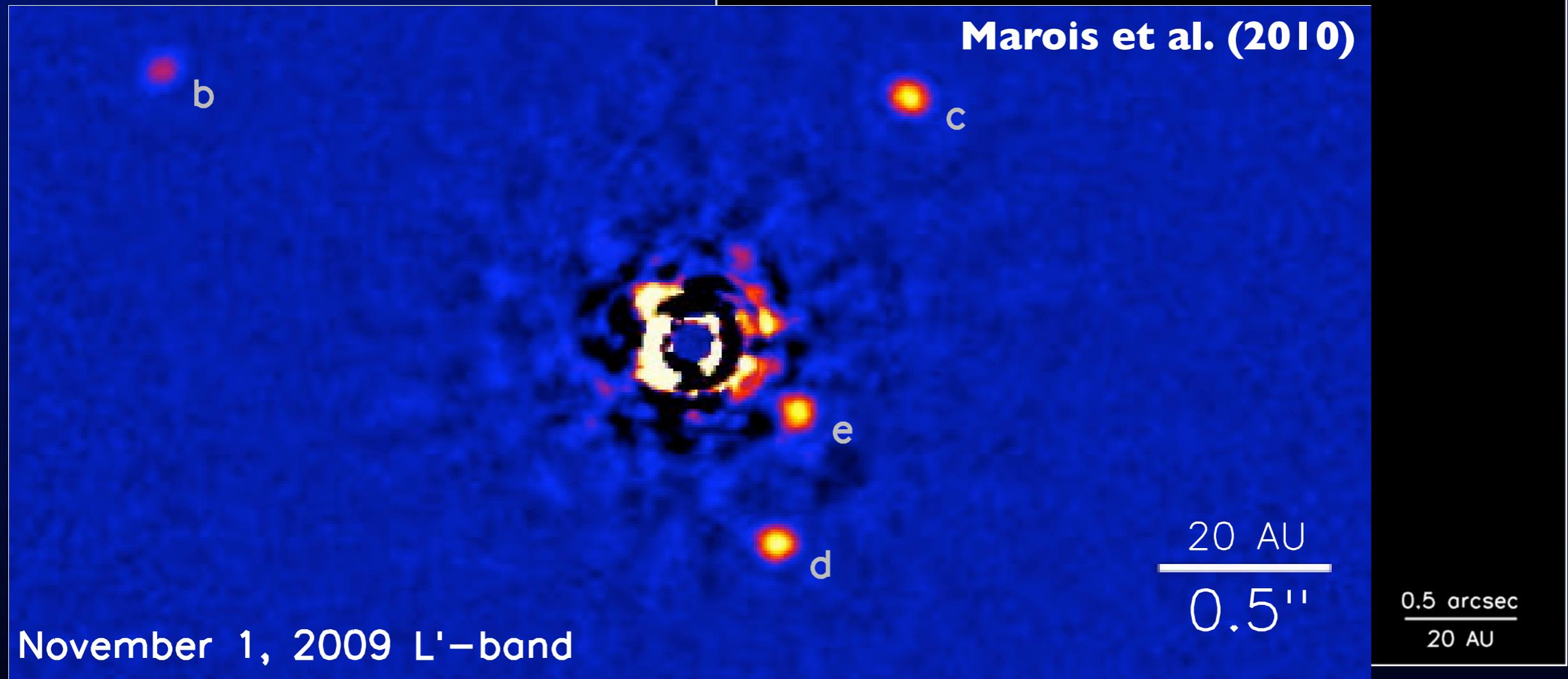
- Two ways around the contrast problem:
 - a) Look for planets around faint stars
 - b) Try to mask out star-light



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

Direct Imaging

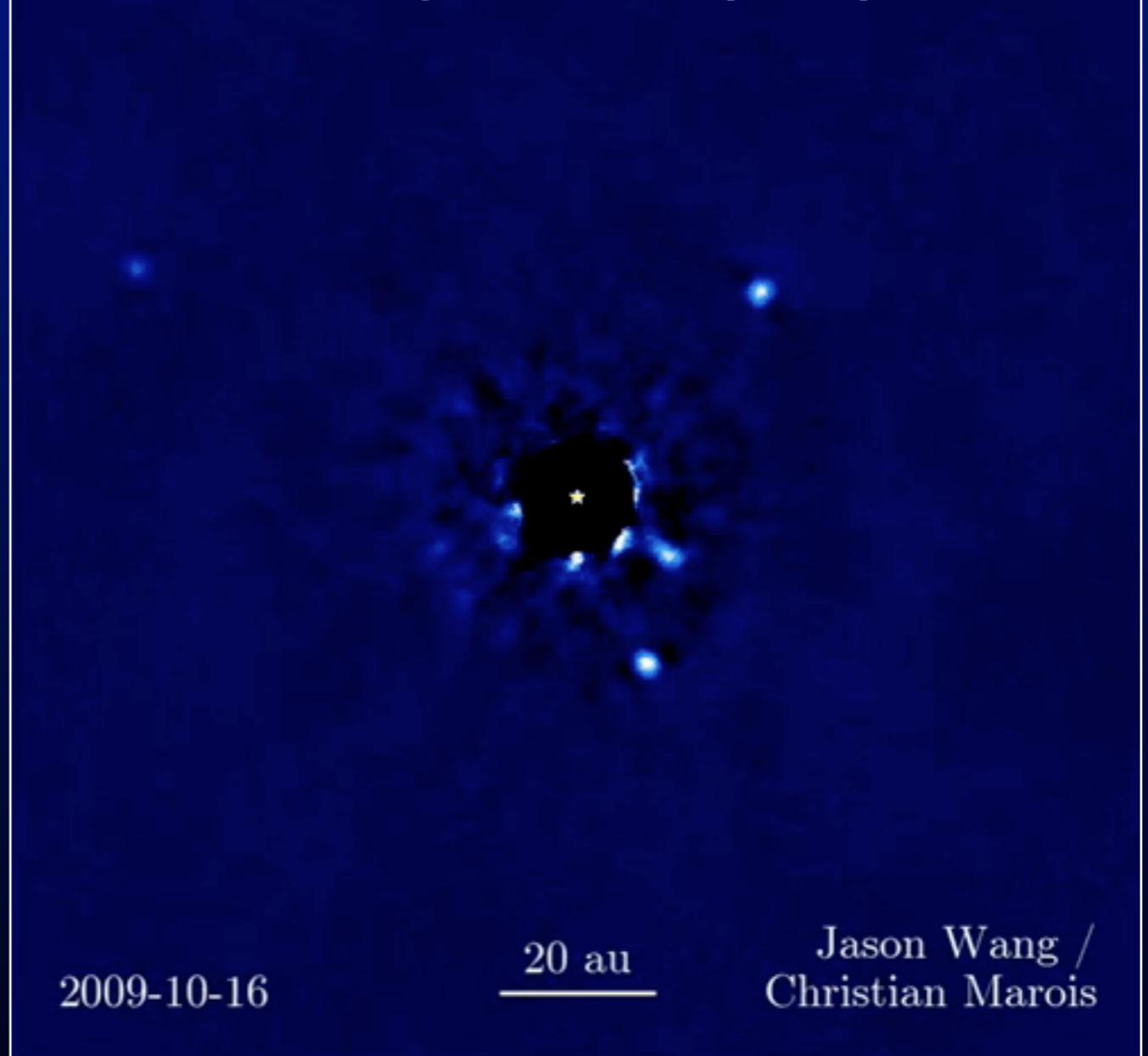
- Two ways around the contrast problem:



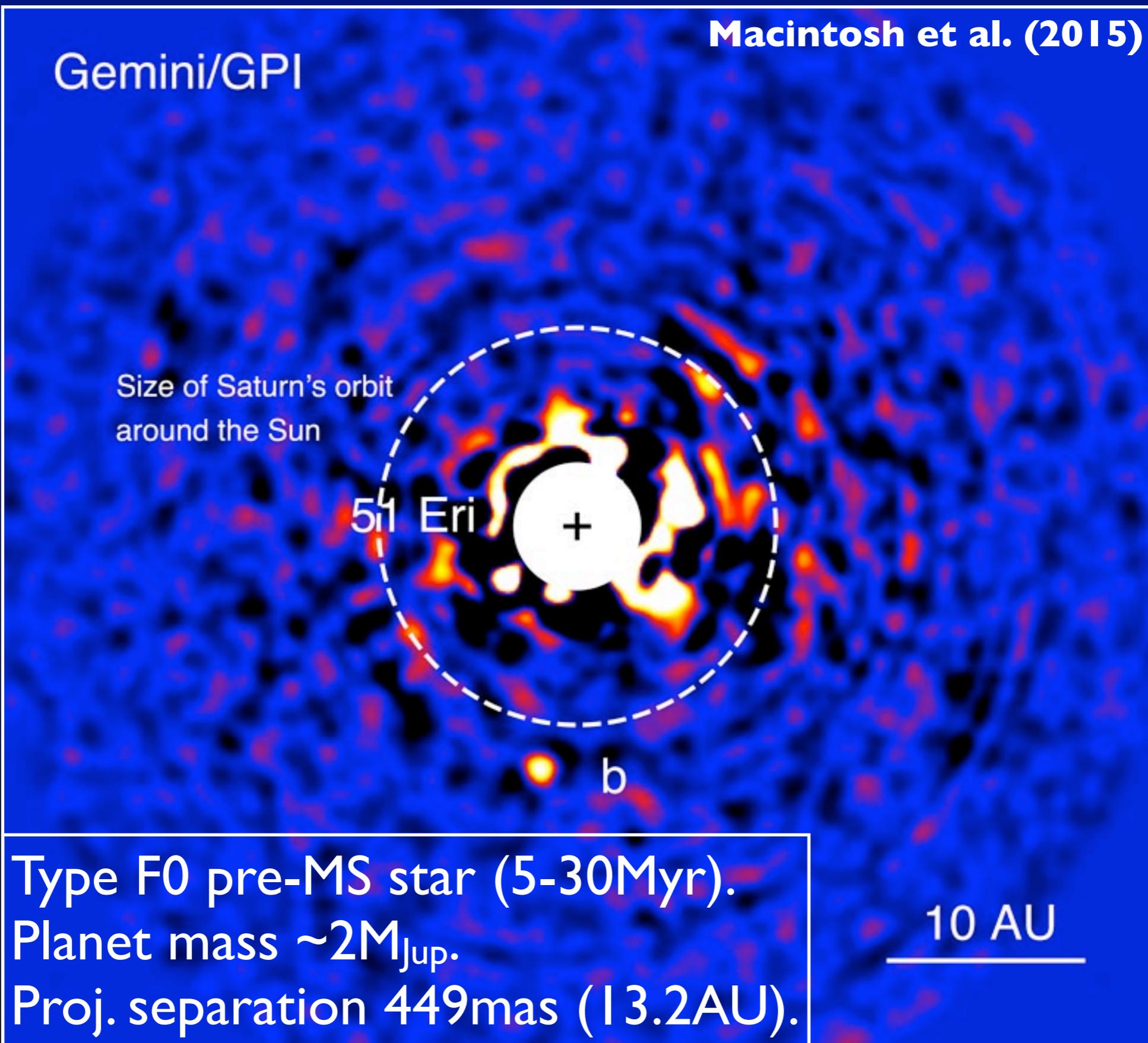
Direct Imaging

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

HR8799: Wang, Marois+ (2017)

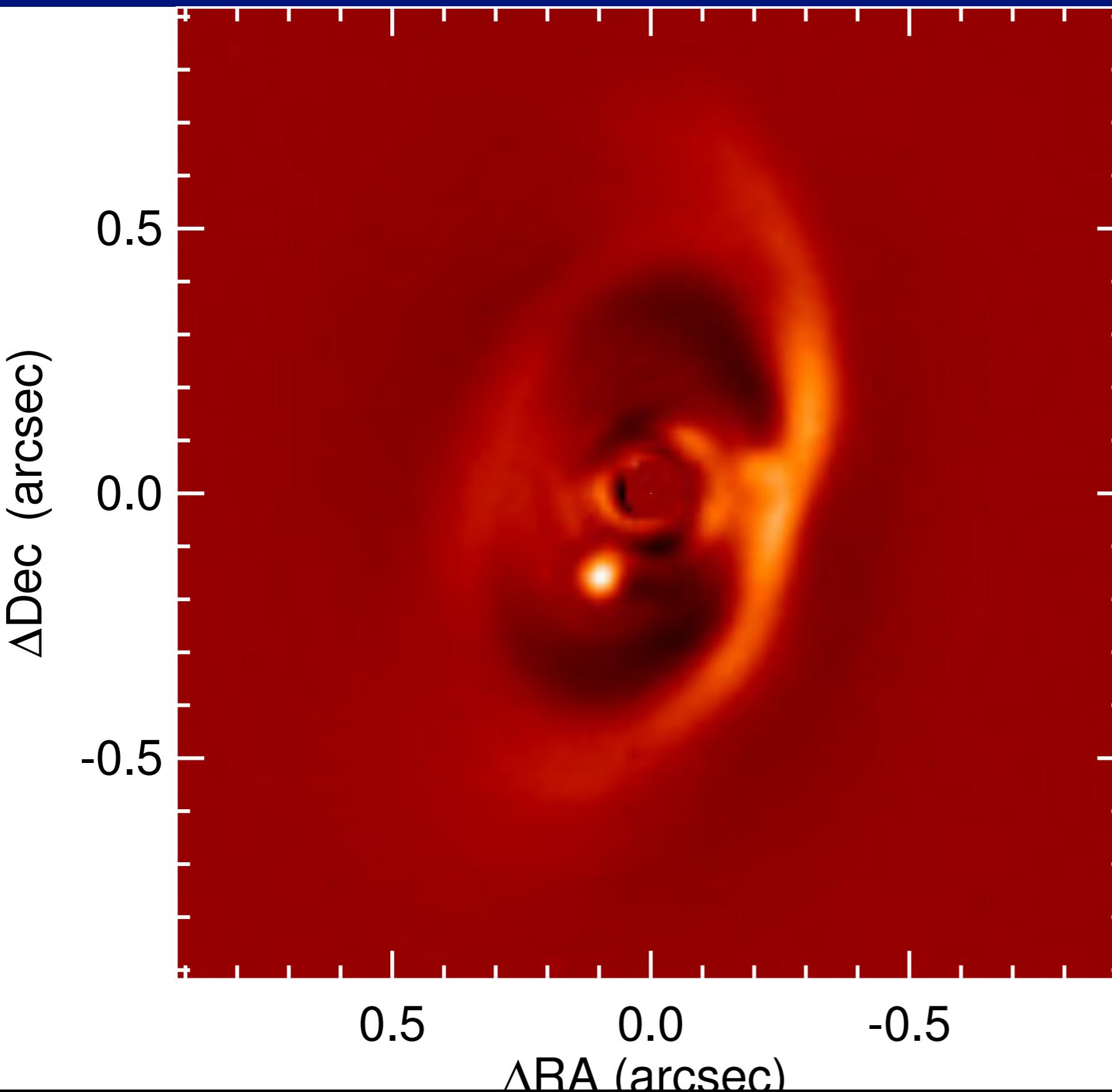


New facilities...



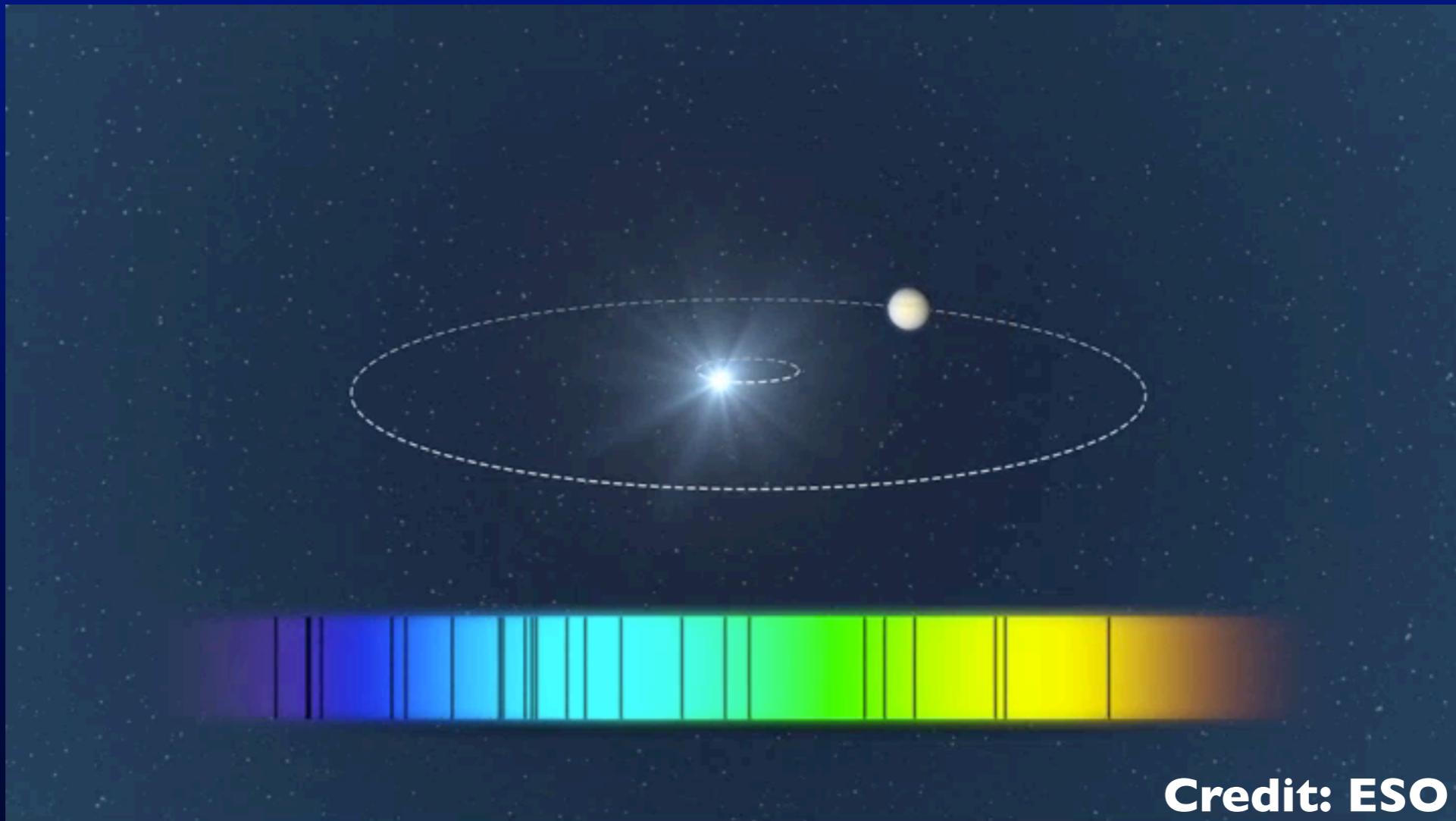
Young planets

PDS 70
Keppler et al. (2018)



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

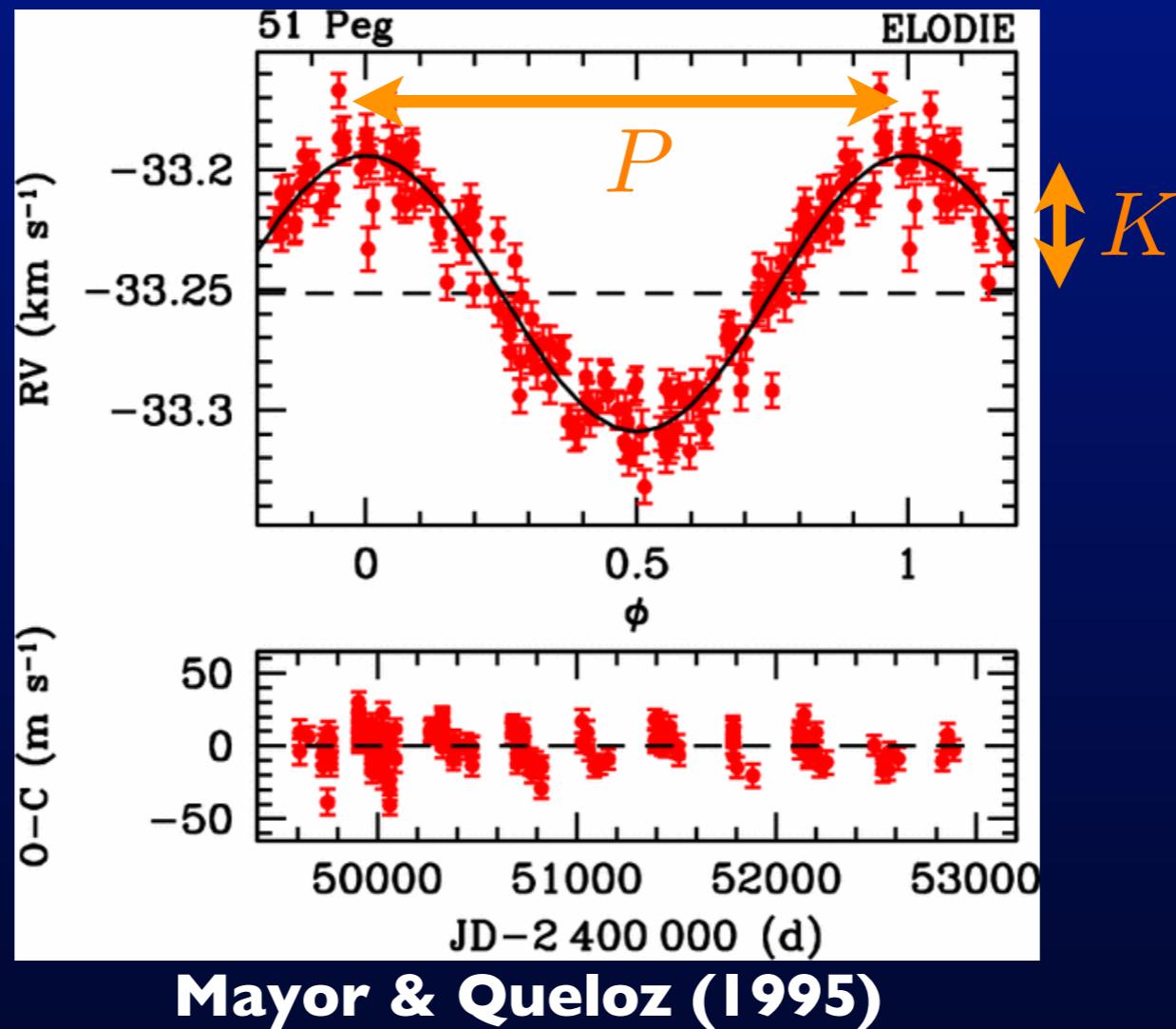
Radial velocity methods



Credit: ESO

- 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

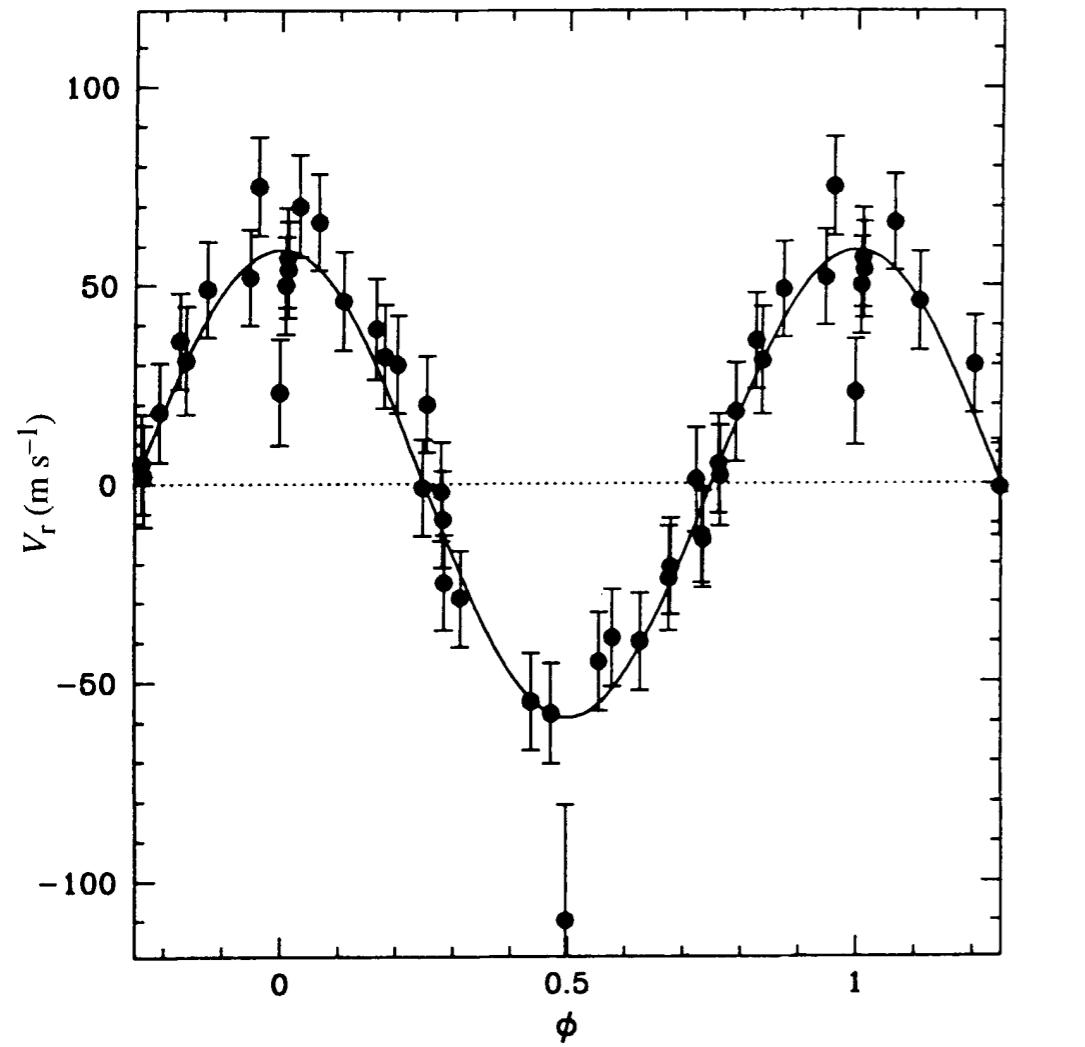


- Fit semi-major axis a , eccentricity e , and stellar mass $M_p \sin i$:

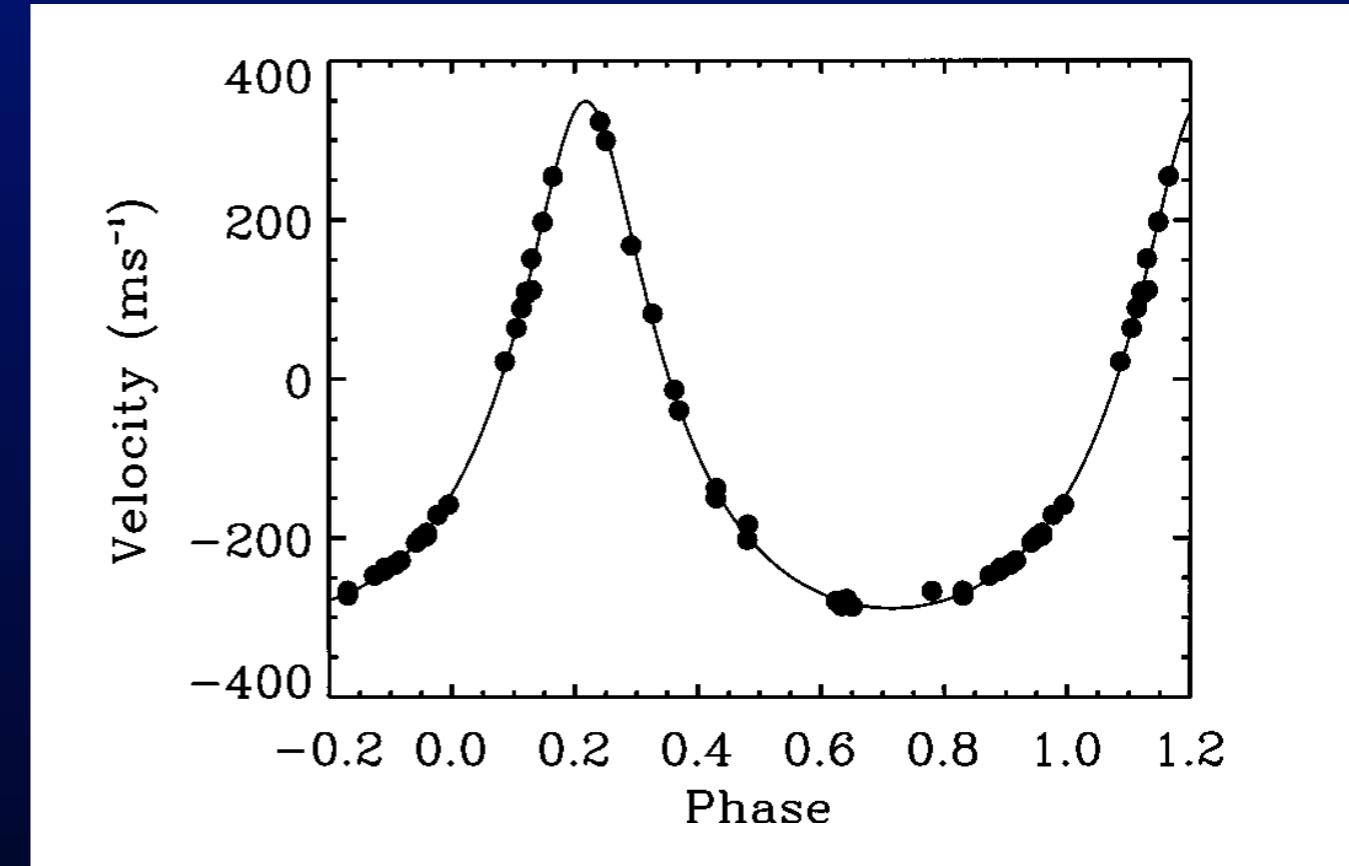
$$K = v_* \sin i = \frac{1}{\sqrt{1 - e^2}} \frac{M_p \sin i}{M_*} \sqrt{\frac{GM_*}{a}}$$

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

First detections...

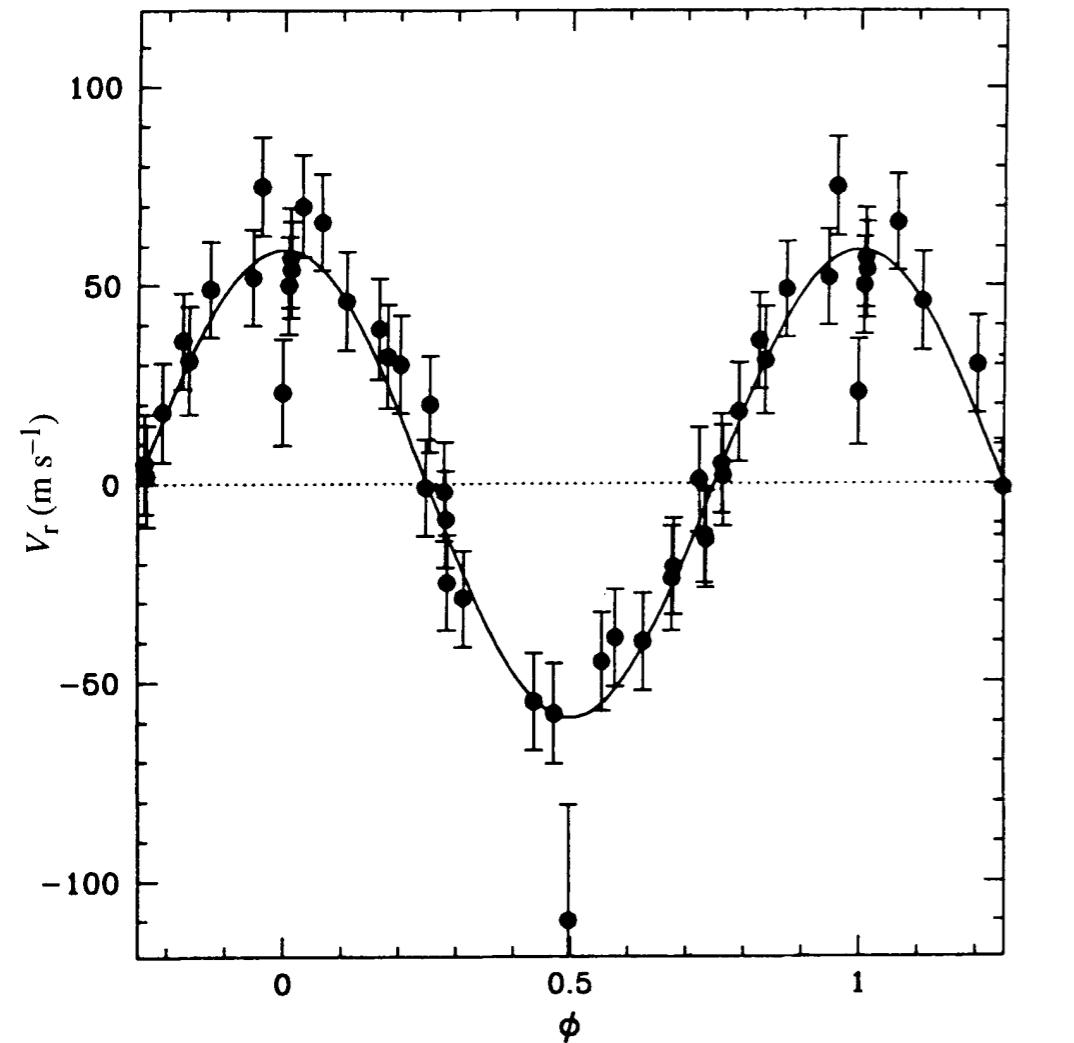


51 Peg b: Mayor & Queloz (1995)
Planet mass $0.47\text{M}_{\text{Jup}}$, Period 4.23d

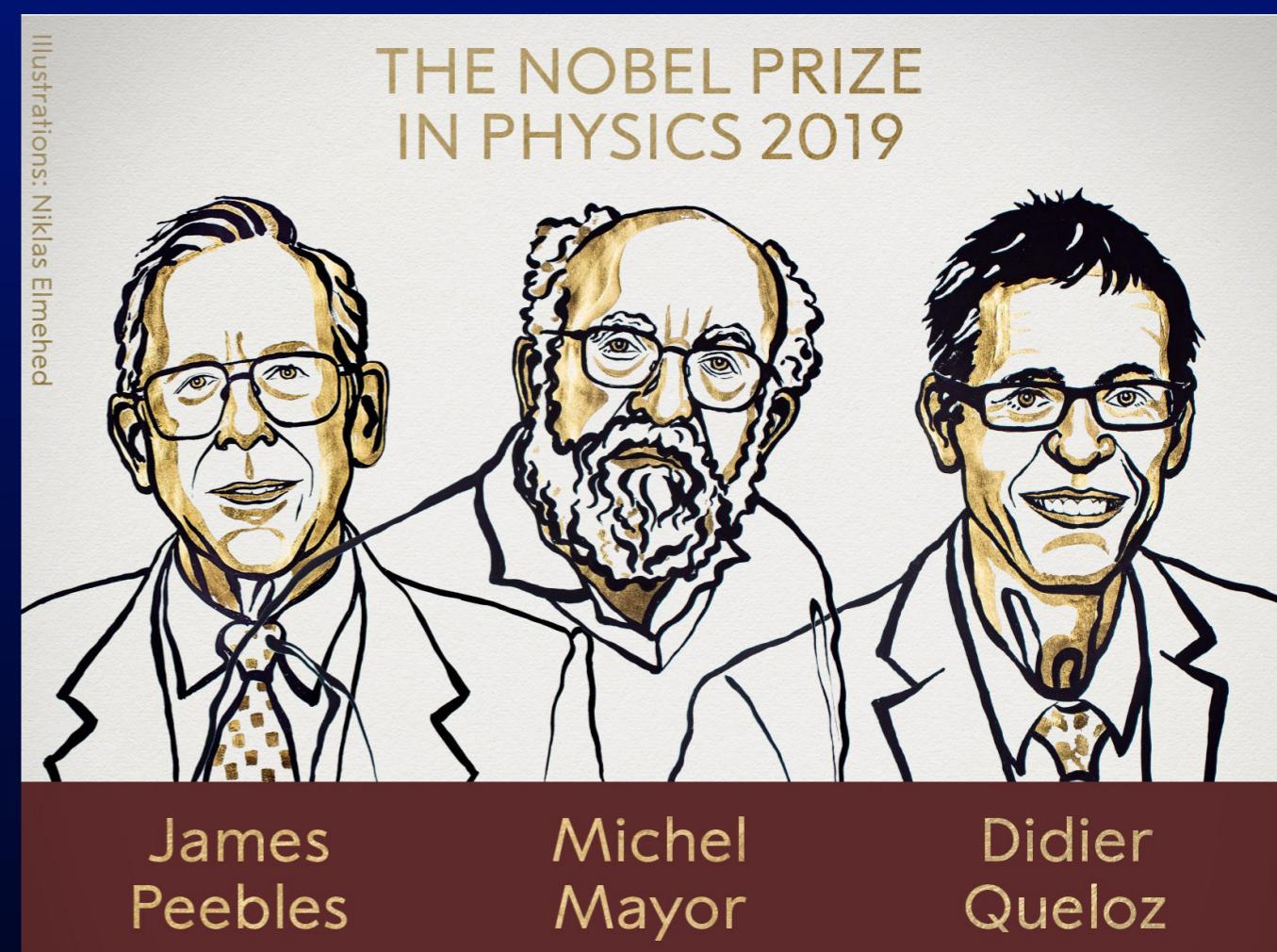


70 Vir b: Marcy & Butler (1996)
Planet mass 7.5M_{Jup} , Period 117d

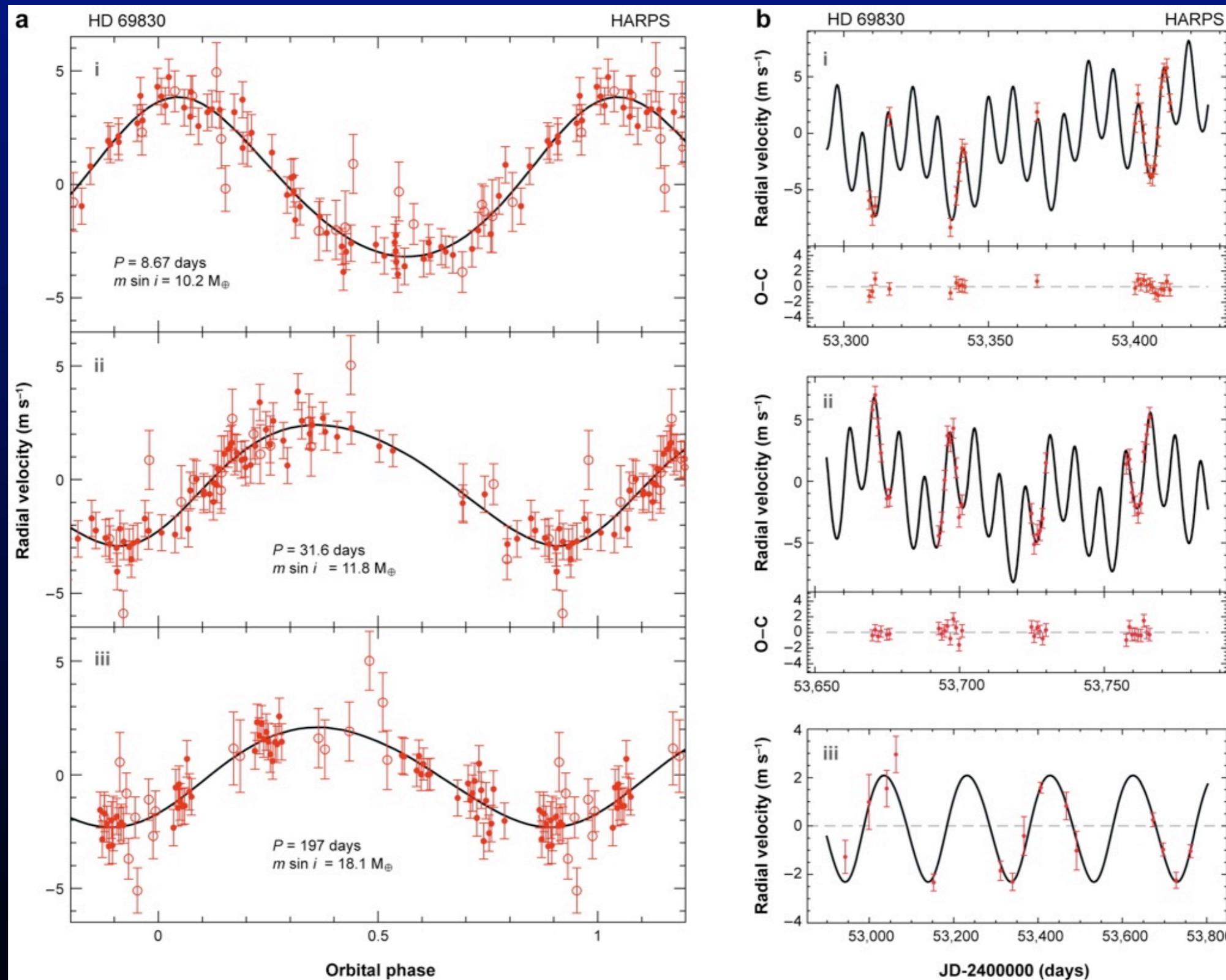
First detections...



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

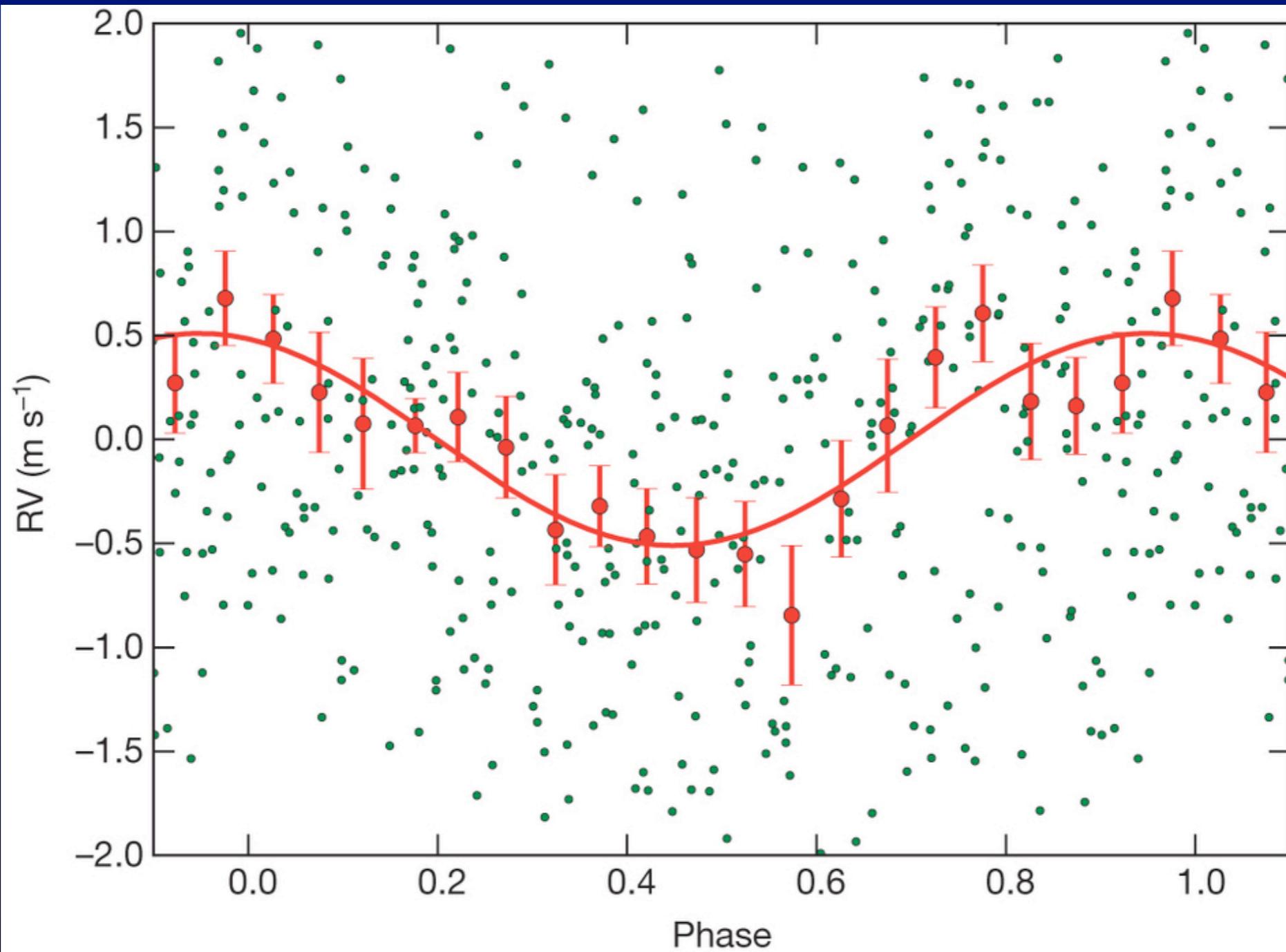


Typical RV data



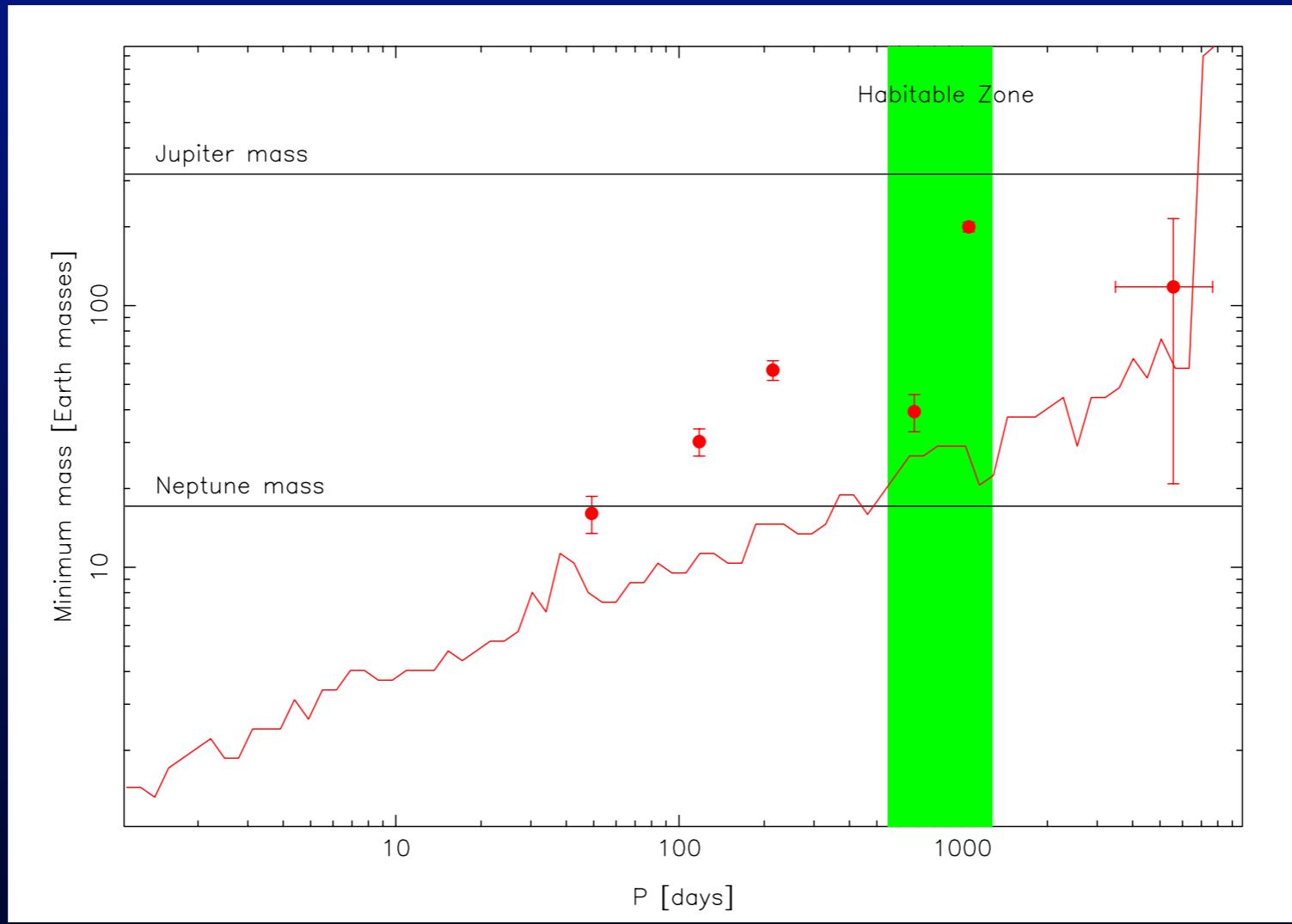
Data from Lovis et al. (2006); figure from Udry & Santos (2007)

The cutting edge??



a Cen Bb: Dumusque et al. (2012)
Claimed planet mass $1.1M_{\text{Earth}}$, $P=3.24\text{d}$, $K=51\text{cm/s}$
But actually an artefact! (see Rajpaul et al. 2016)

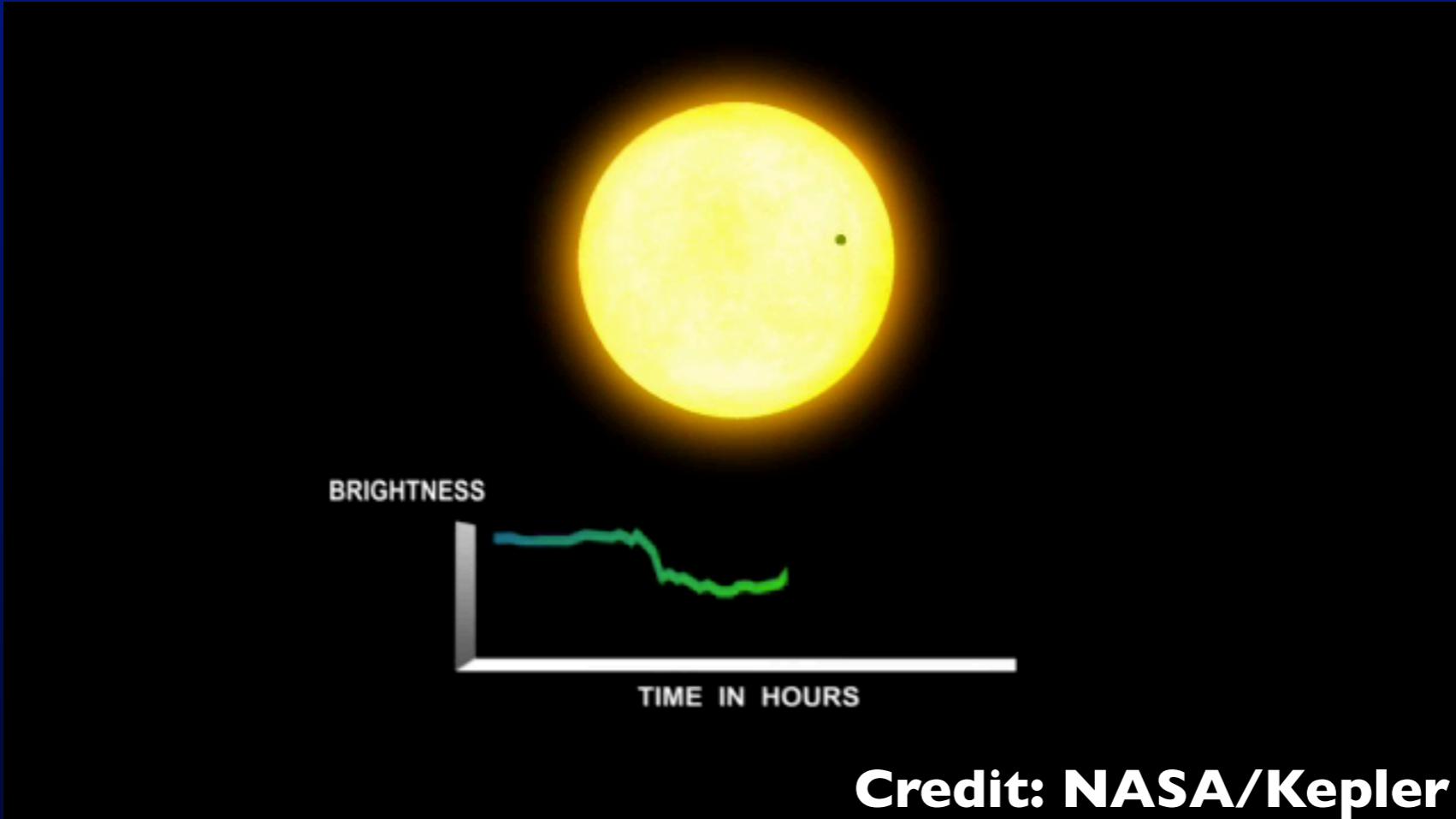
Long surveys, long periods...



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 0.1–0.1 M_{Jup} ; semi-major axes from 0.26–6.4AU.

Transit method

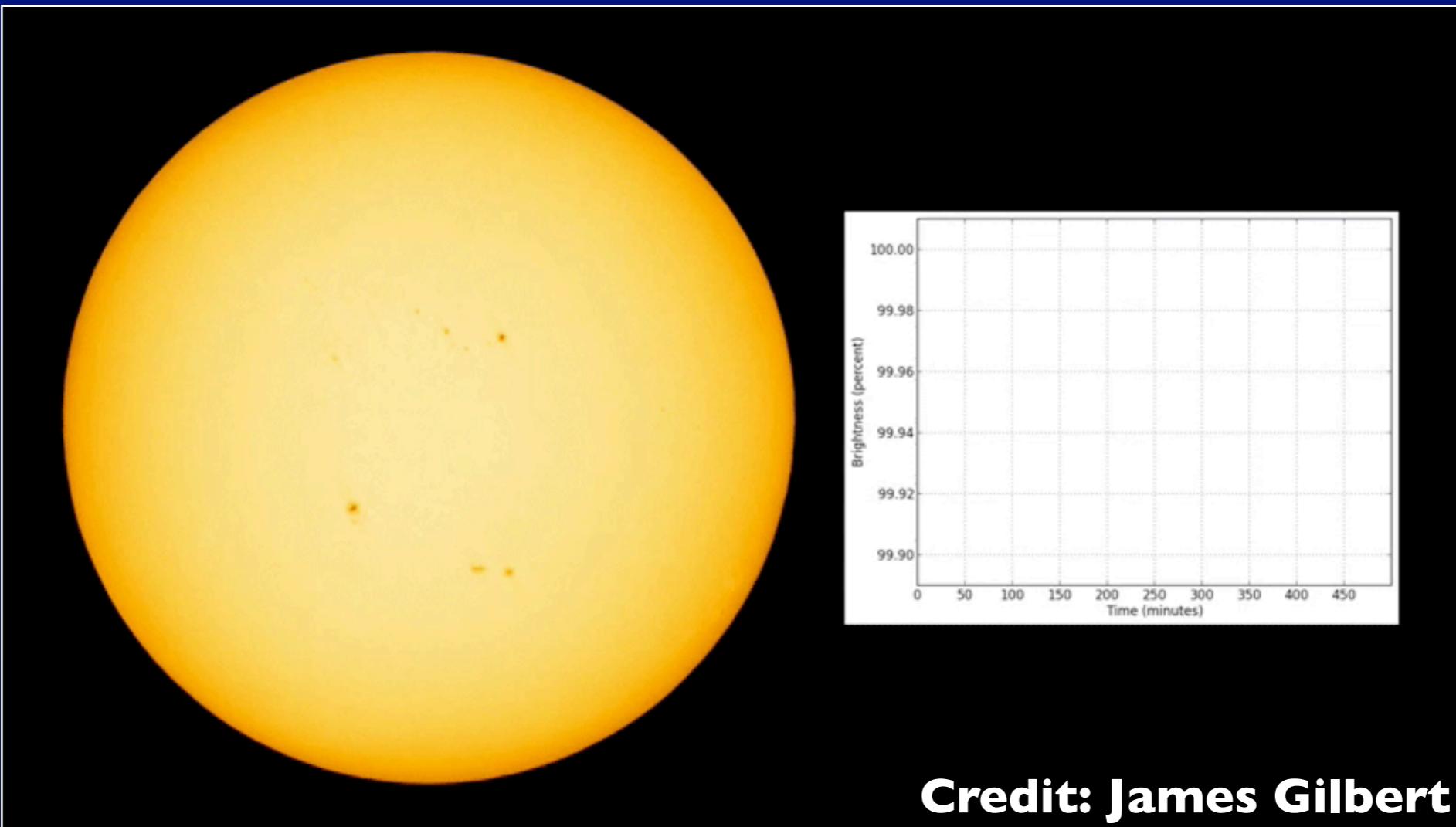


- Detect dimming of light as planet passes in front of star.
- Dimming fraction f depends on planet size:

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

$$f_{Jup} \simeq 0.01$$
$$f_{\oplus} \simeq 1 \times 10^{-4}$$

Transit method



- Detect dimming of light as planet passes in front of star.
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$$f = \frac{\pi R_p^2}{\pi R_*^2}$$

$$f_{Jup} \simeq 0.01$$
$$f_{\oplus} \simeq 1 \times 10^{-4}$$

Transit method

- Detecting transits requires high precision:
 - <1% precision (~Jupiters) attainable from the ground.
 - 0.01% precision (~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.

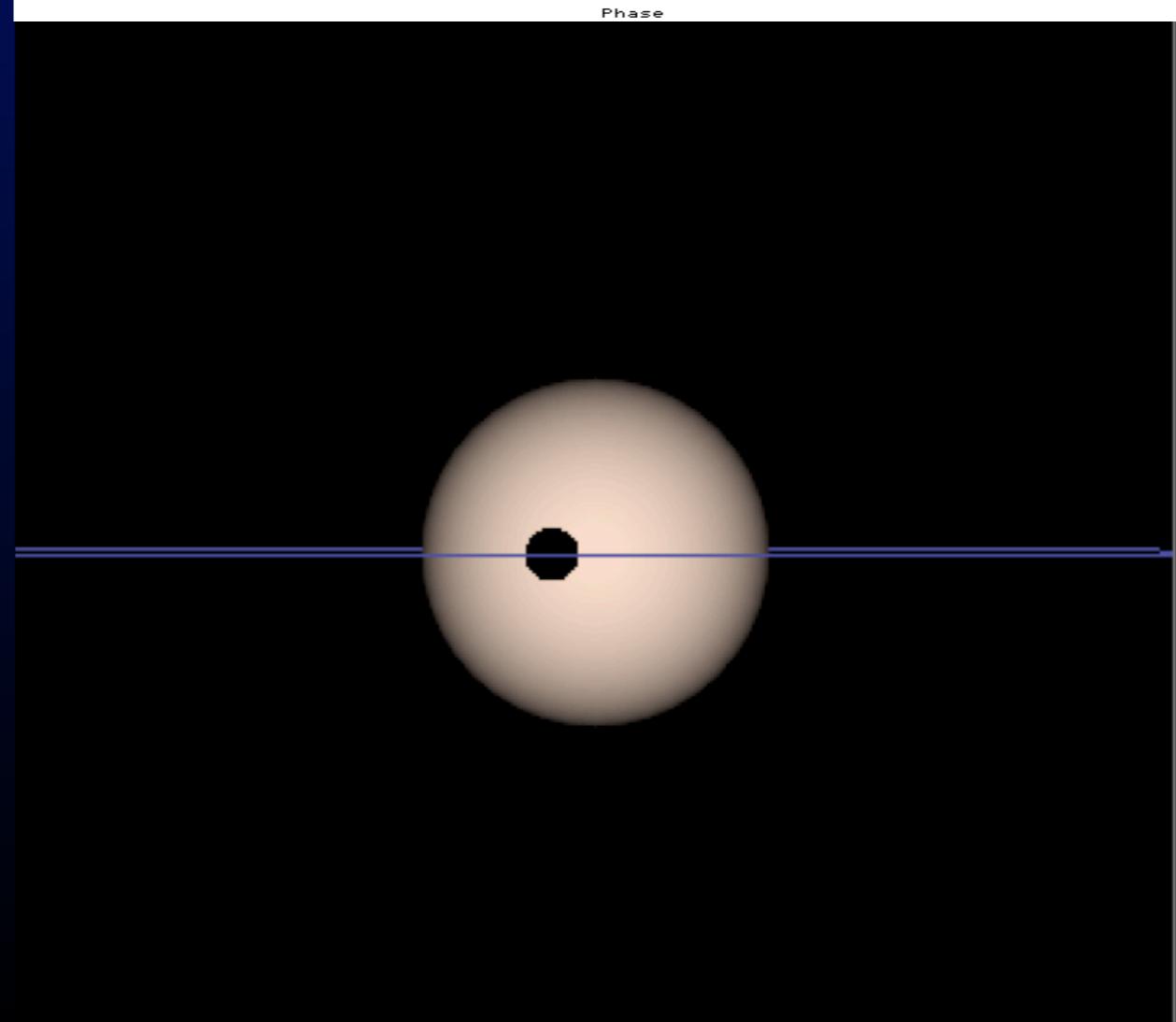
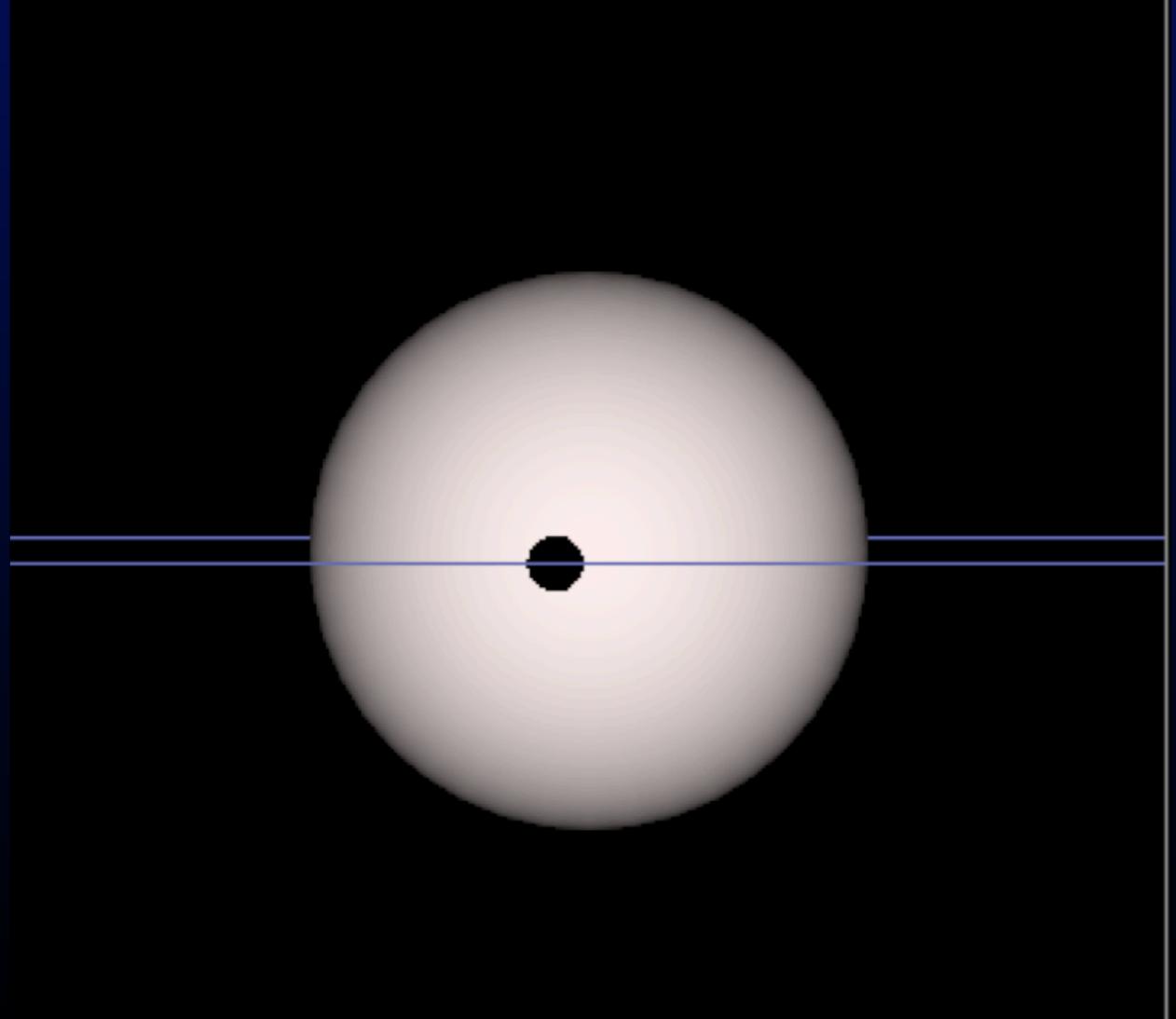
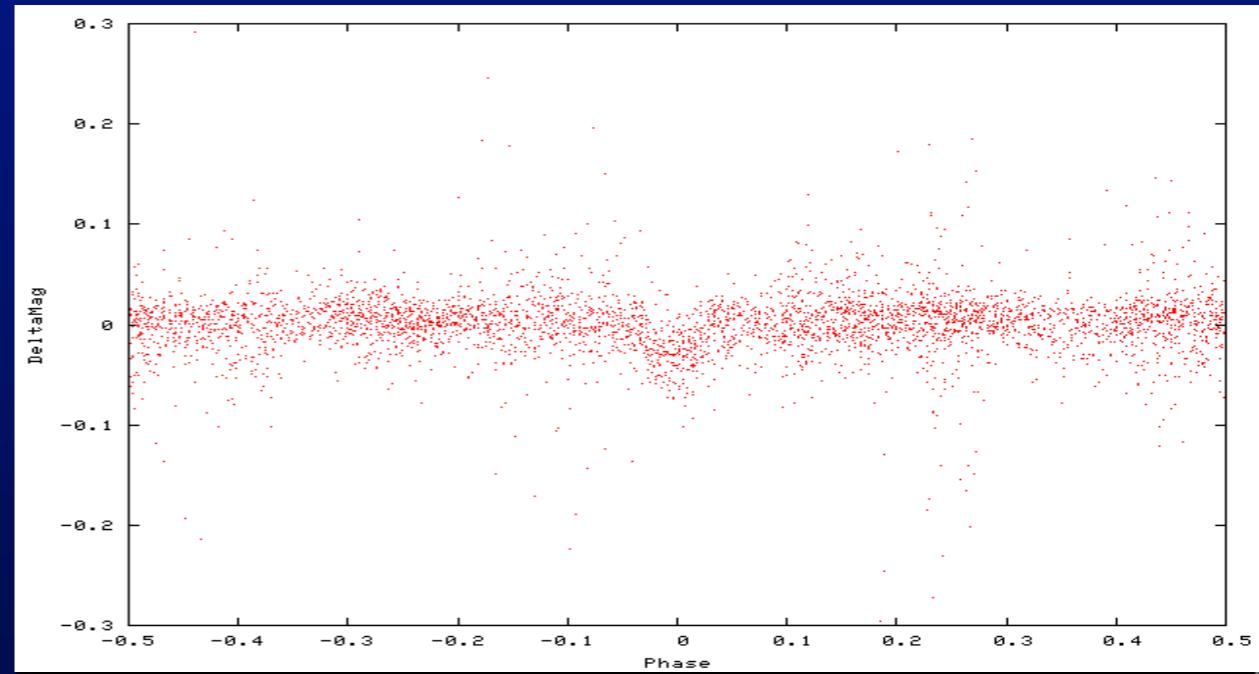
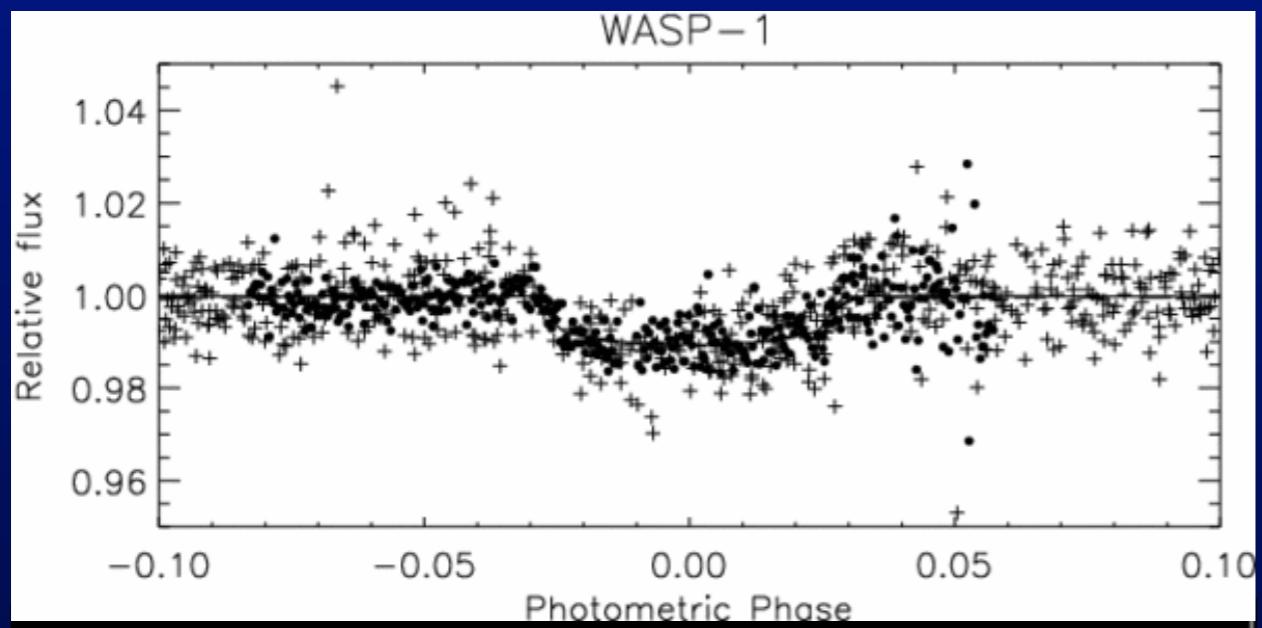
Transit method

- Many current searches using transit methods.
- Most successful ground-based programme is SuperWASP (**Wide-Angle Search for Planets**).
- 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...

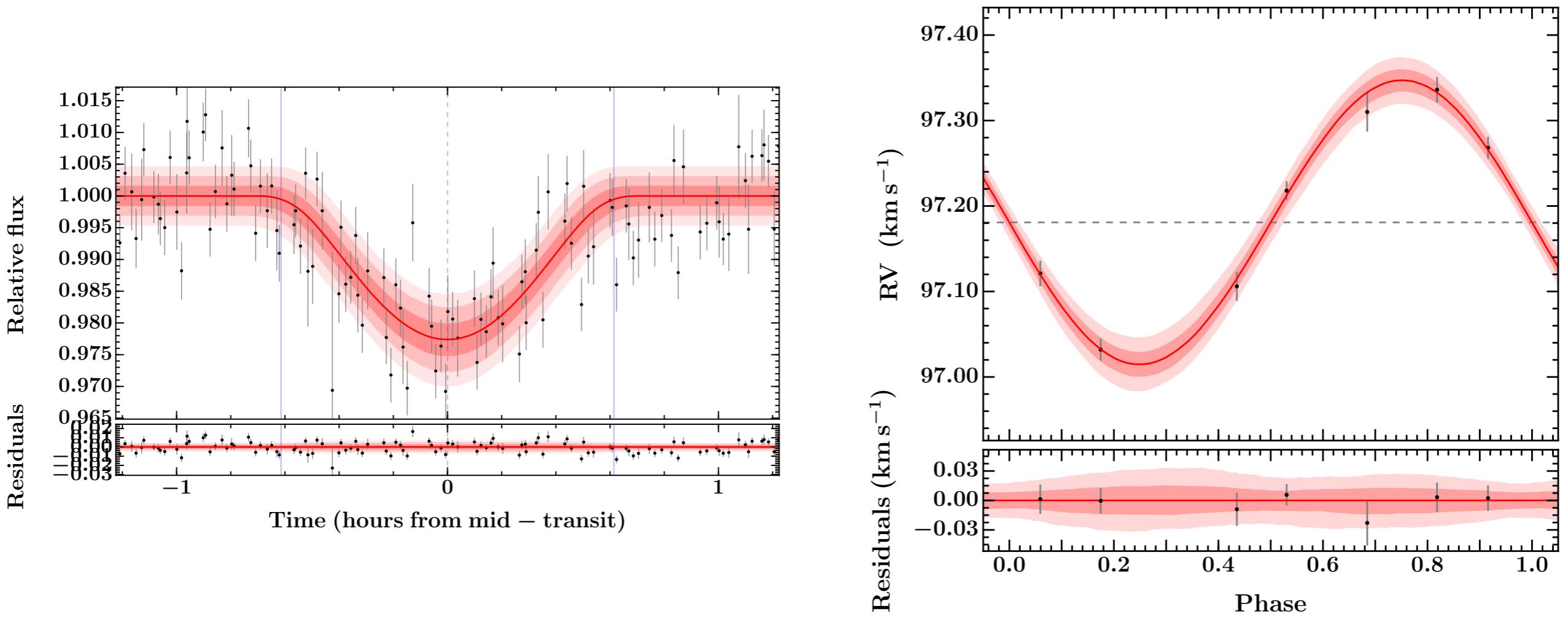


Credit: ESO/Richard West

- 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.



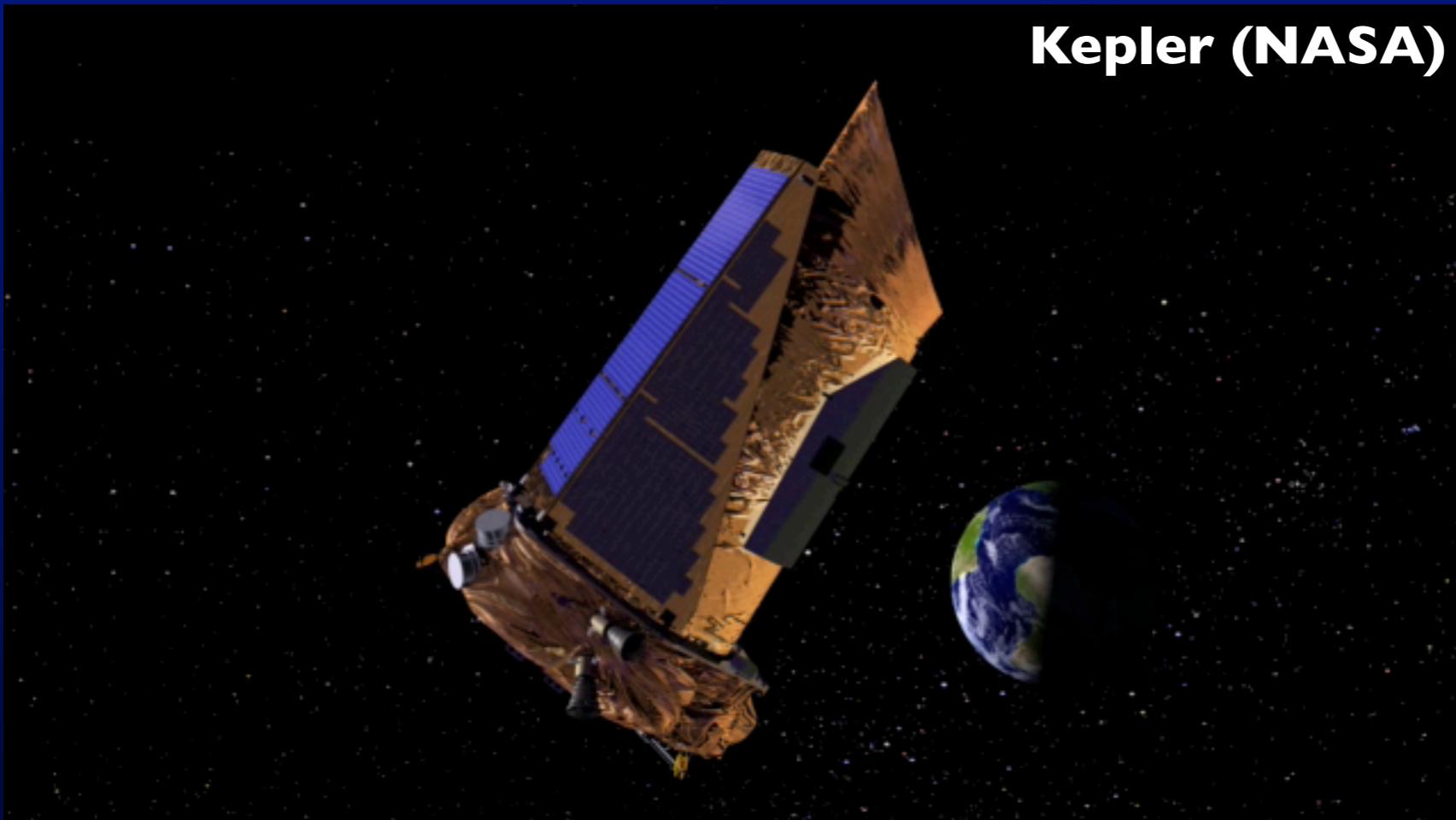
Ground-based cutting edge



Bayliss+ (2017)

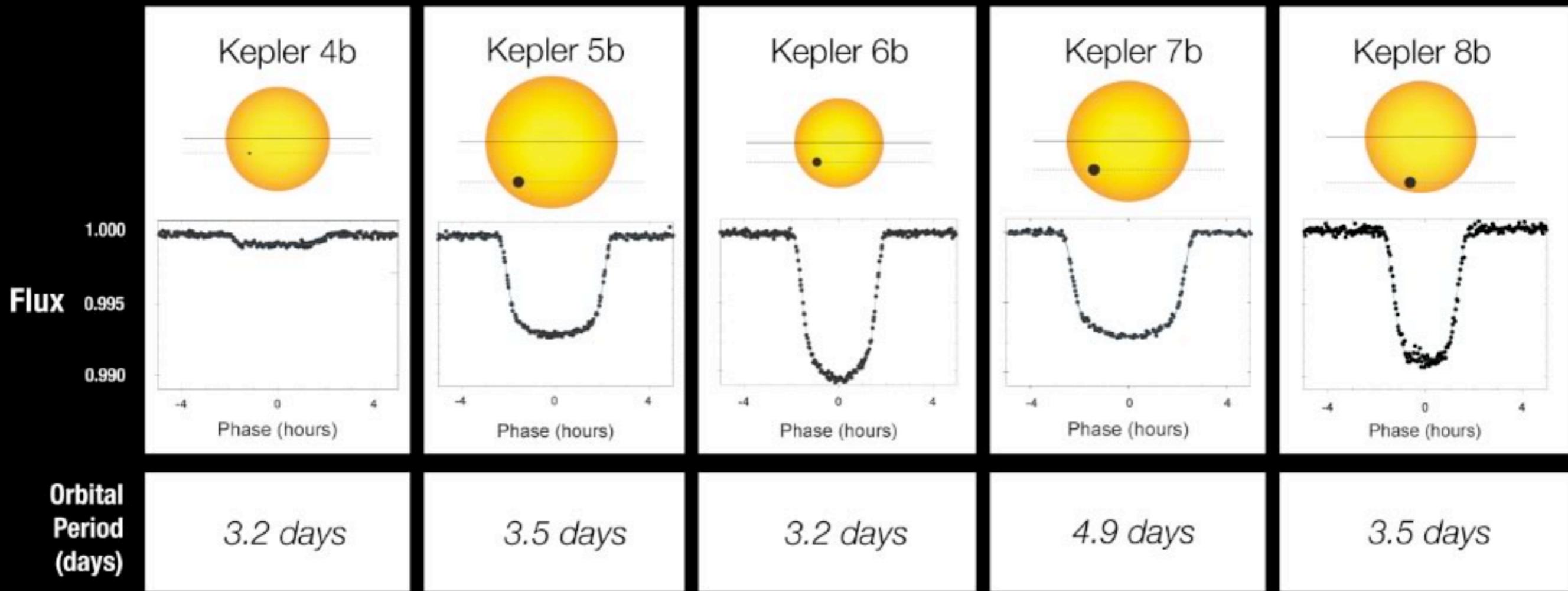
- First exoplanet discovery from NGTS.
- $0.8M_{Jup}$ planet in 2.65d orbit around a M0/M1-type host star.
- Most massive planet known around an M-dwarf. NGTS will give first large census of planets around low-mass stars.

Kepler



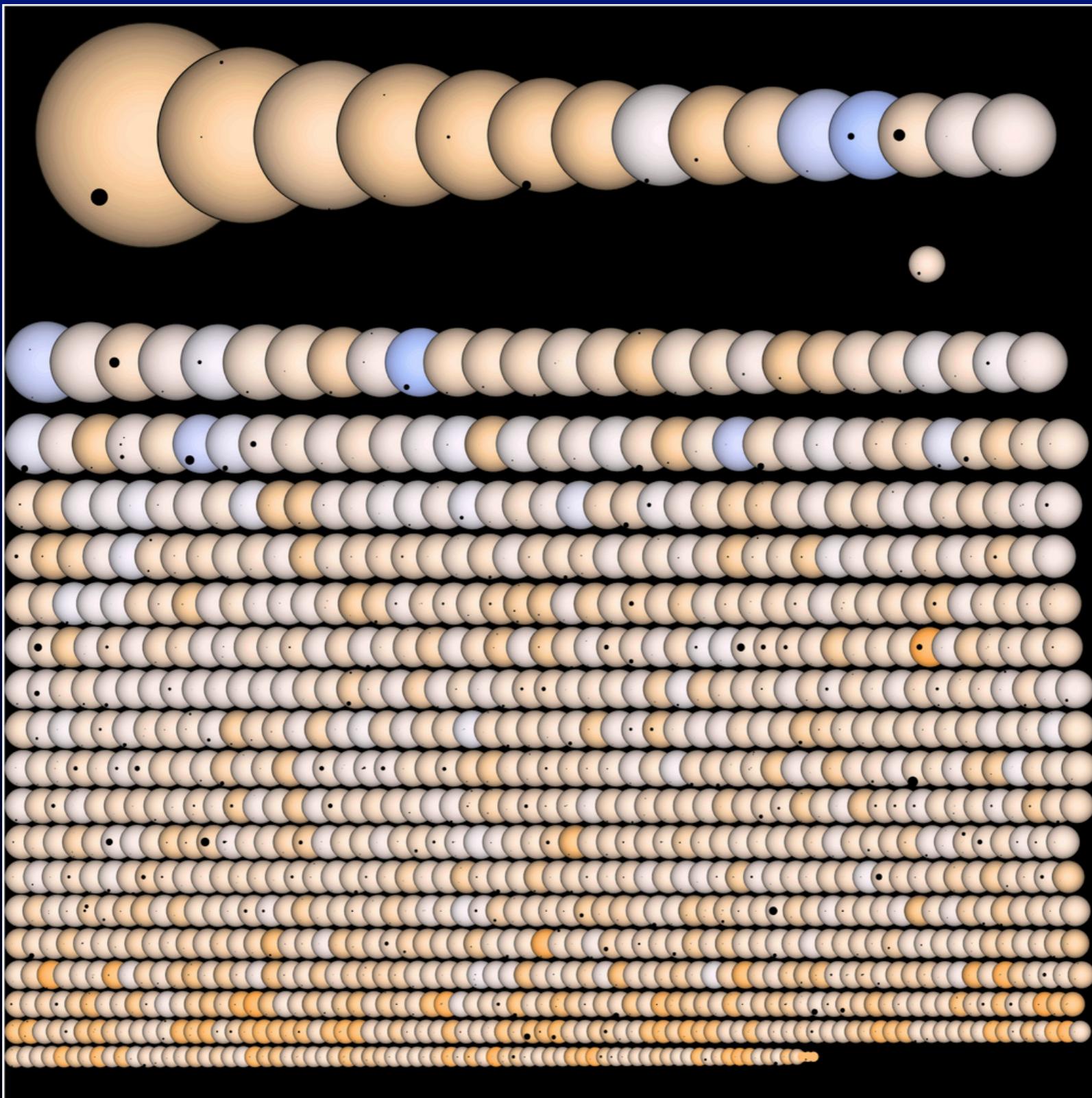
- Launched March 2009, 0.95m primary; “died” May 2013. Lived on as K2 until late 2018.
- 12° FOV, 42 CCD camera. “Stared” at fixed patch of (blank) sky to obtain light-curves for >150,000 stars.
- Photometric precision as good as ~10ppm (in some cases). Sensitive to sub-Earth-size planets.

Kepler light-curves

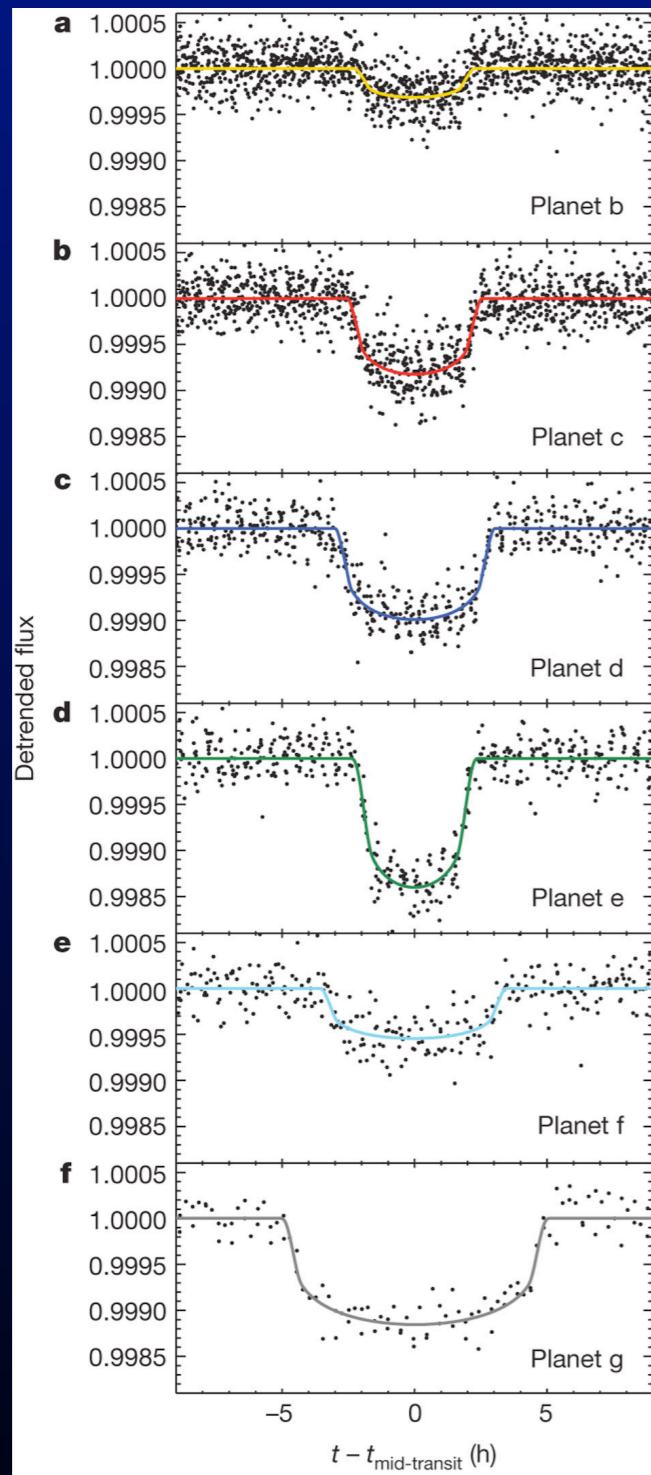


- Early data release (June 2010) focused on a few “hot Jupiters”, to demonstrate precision.
- Fourth (& final) major data release in January 2014. Total of ~4500 planet candidates, with >2000 now confirmed.

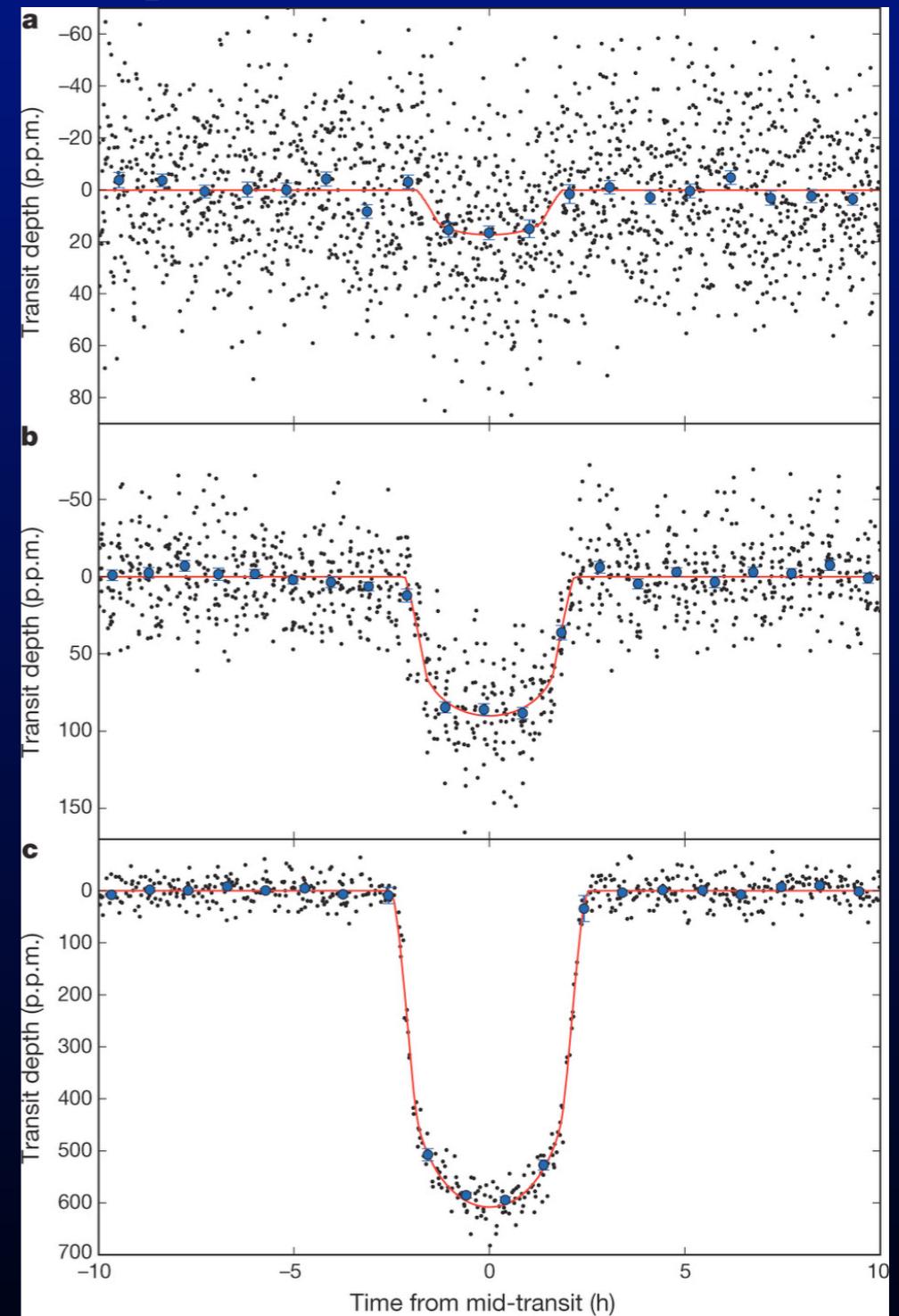
Kepler: first results



Kepler examples



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



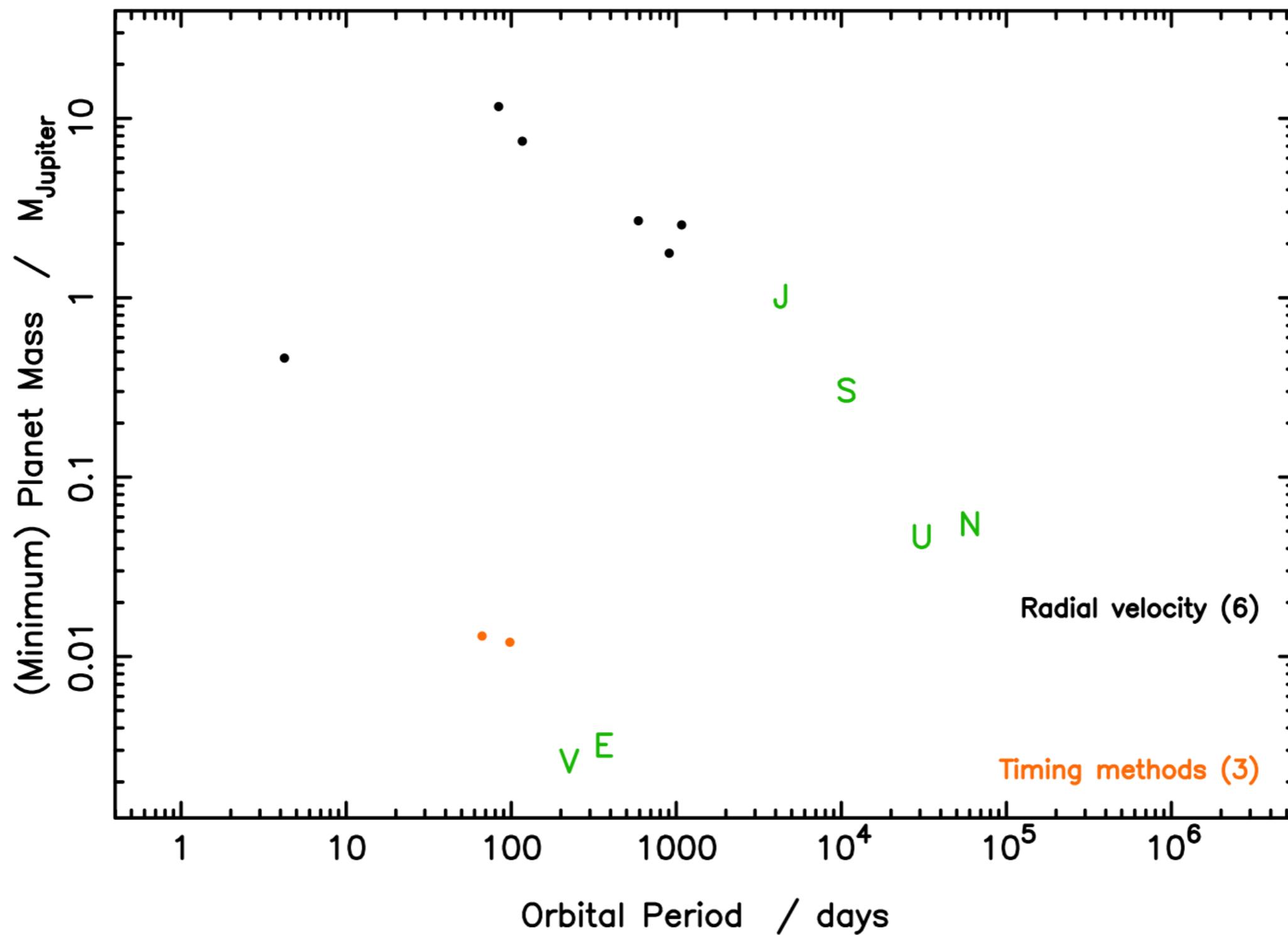
Kepler-37: Barclay et al. (2013)
3-planet system, periods 13.4, 21.3, 39.8d.
“b” is roughly the size of the Moon.

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).

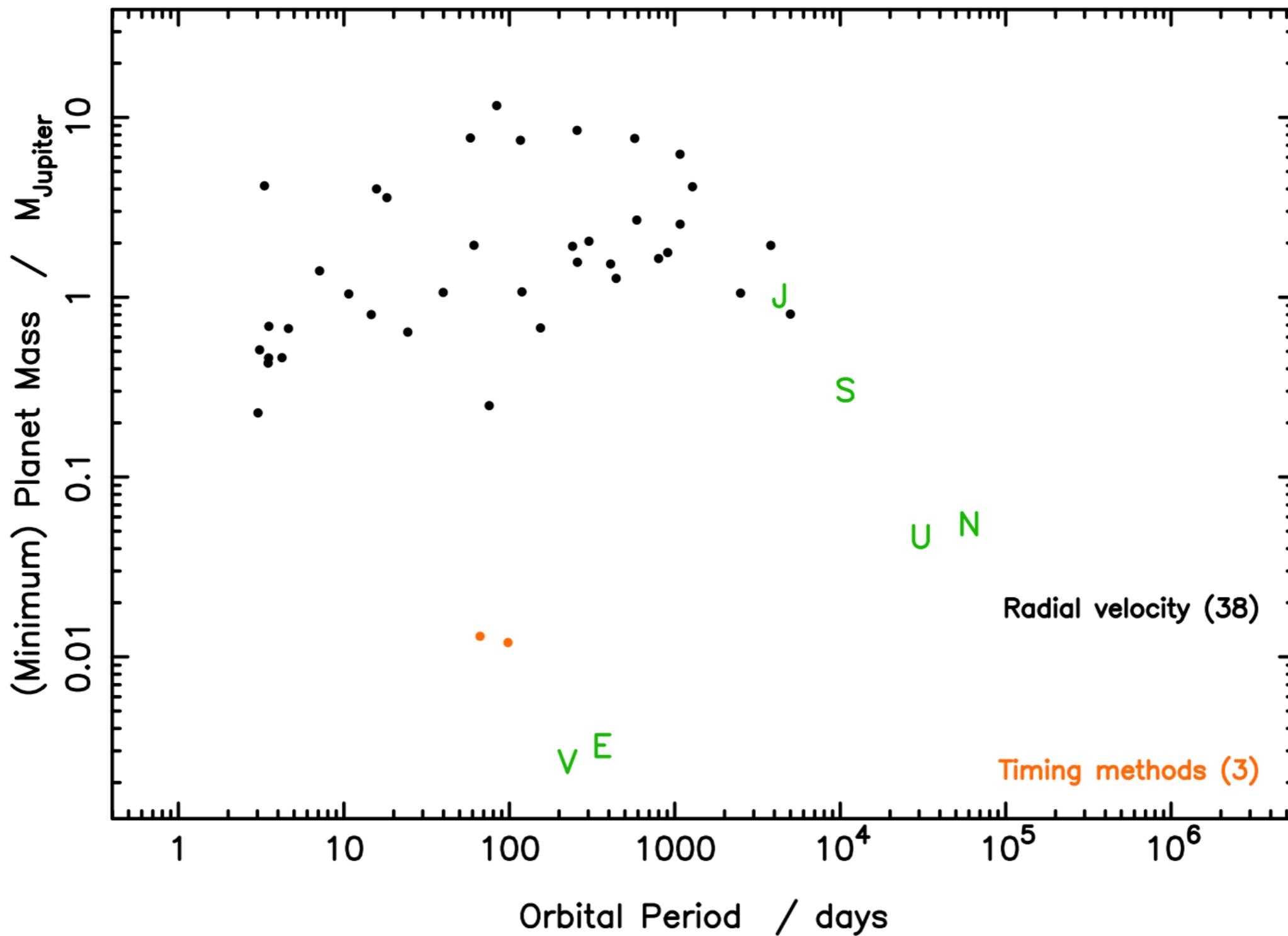
*The first transiting planet was found in 1999, but it was a known RV planet.

Known planets as of 1996



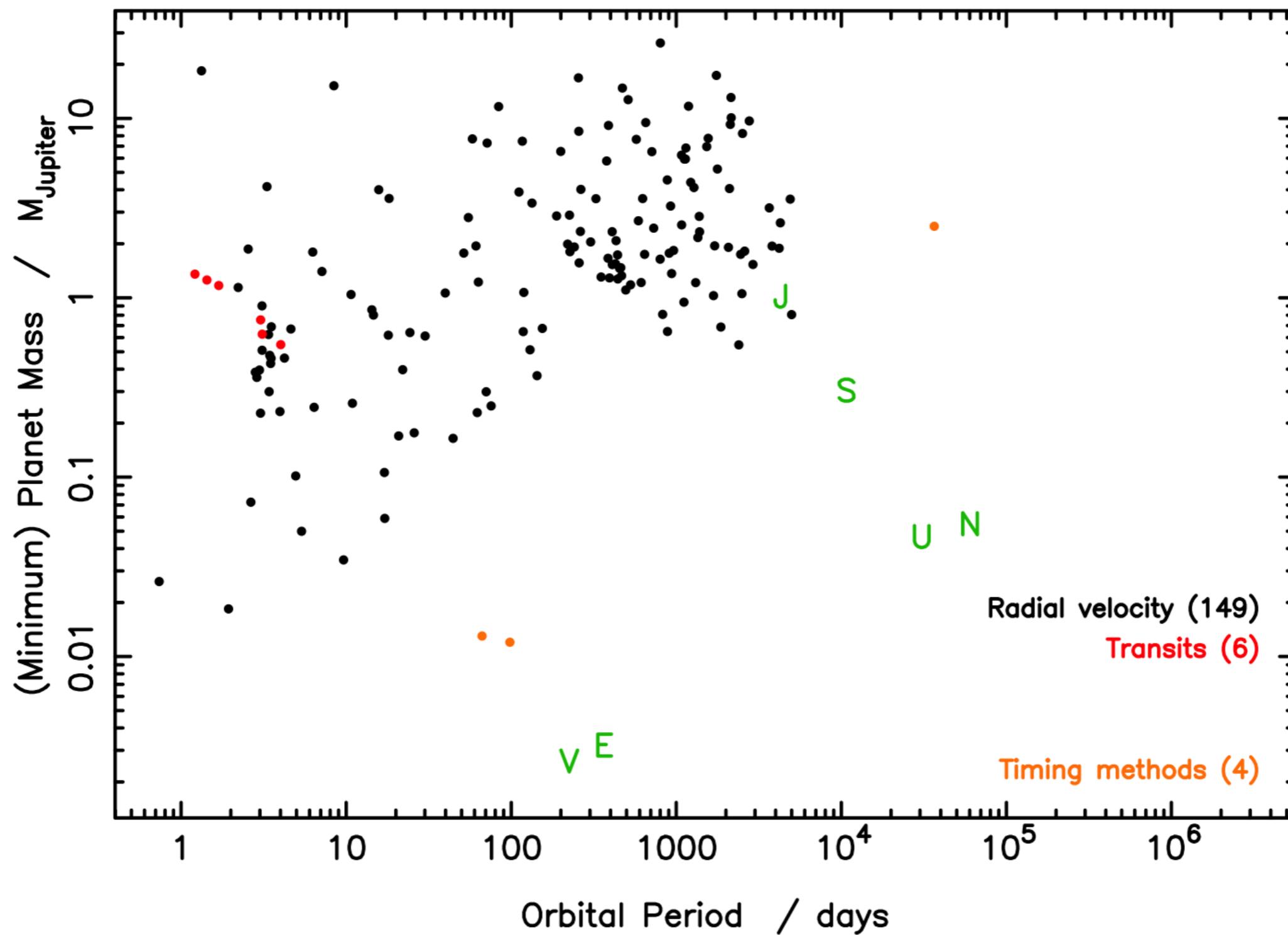
Data from exoplanet.eu

Known planets as of 2000



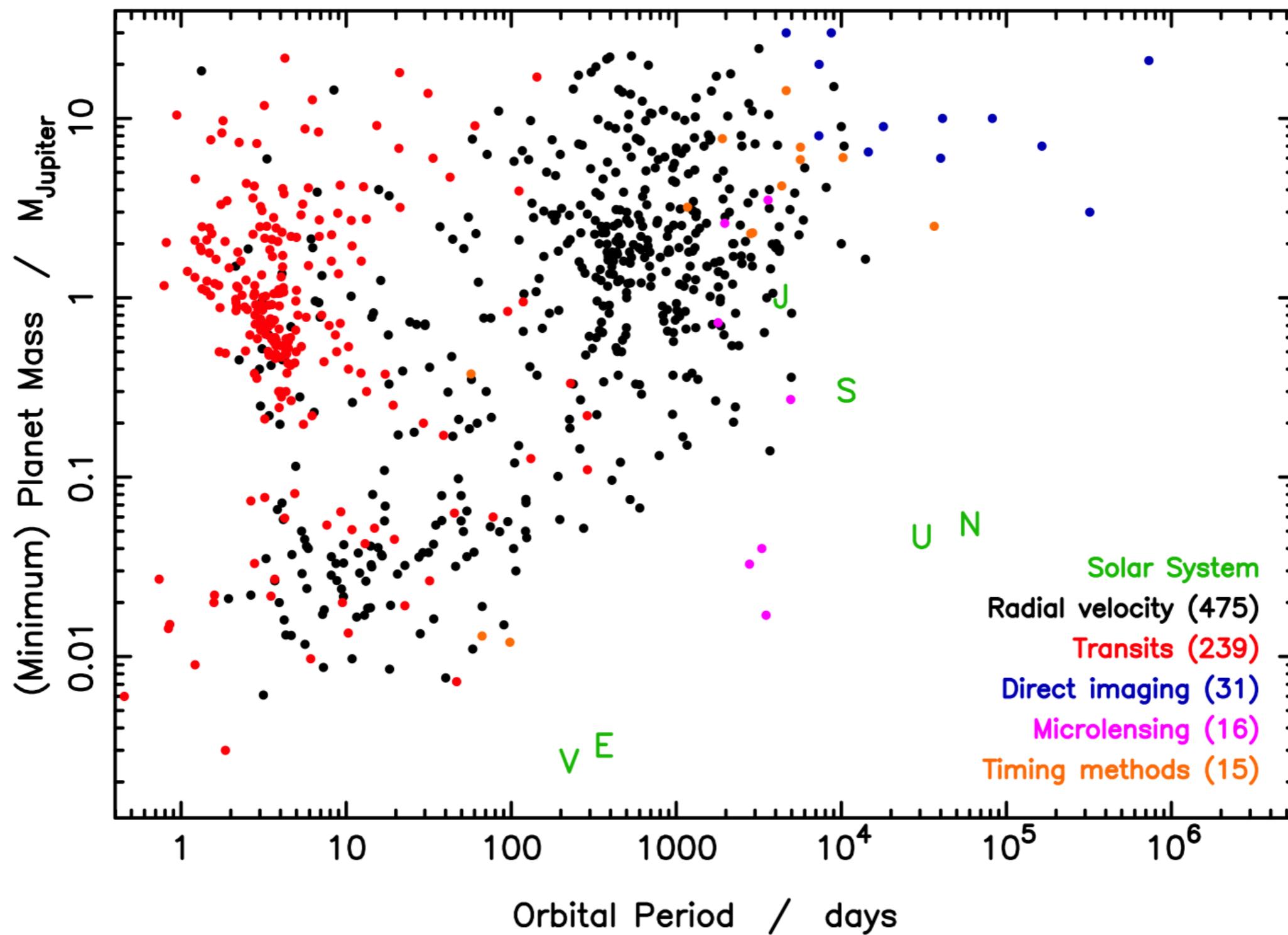
Data from exoplanet.eu

Known planets as of 2005



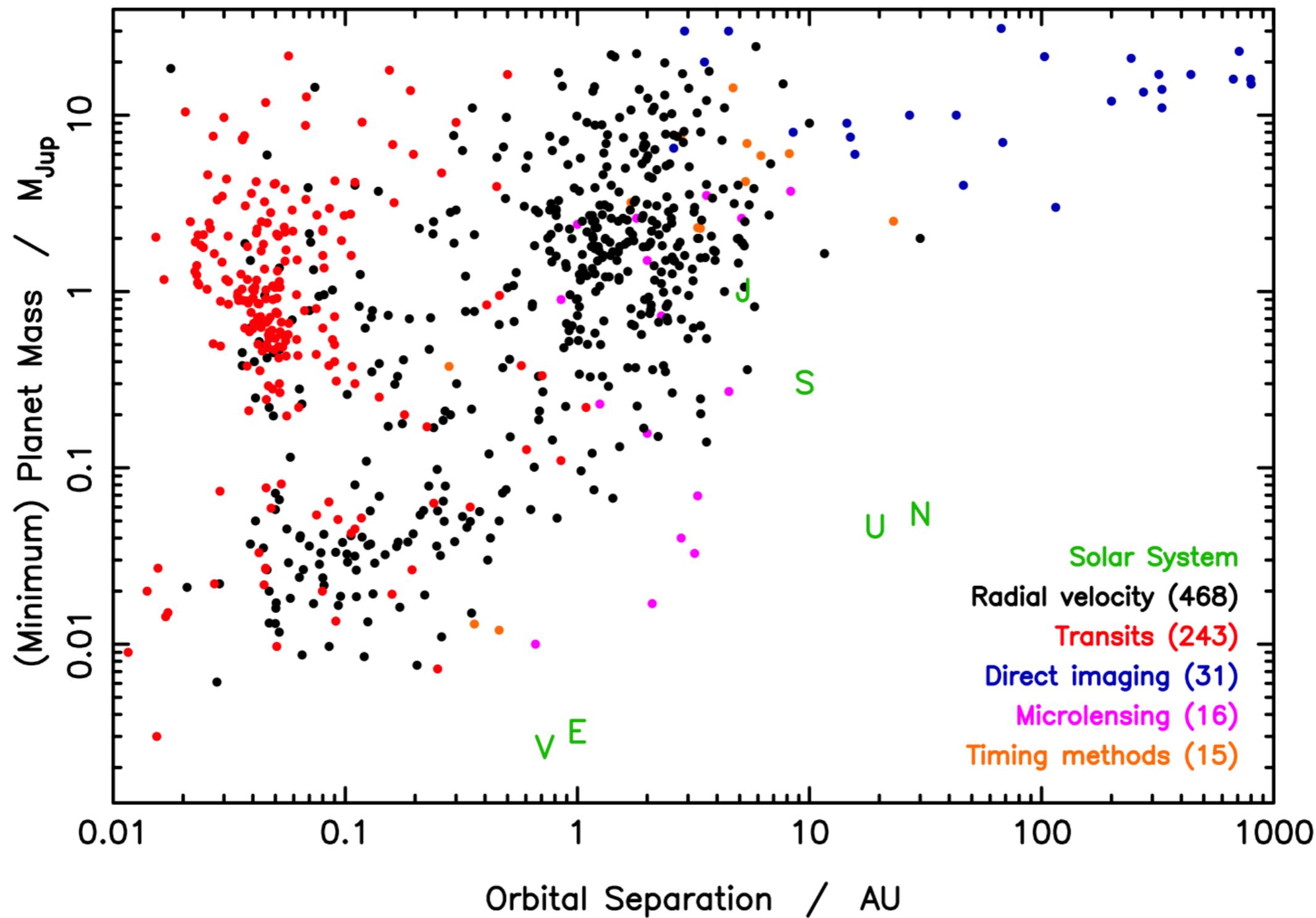
Data from exoplanet.eu

Known planets (as of 1 Oct 2012)



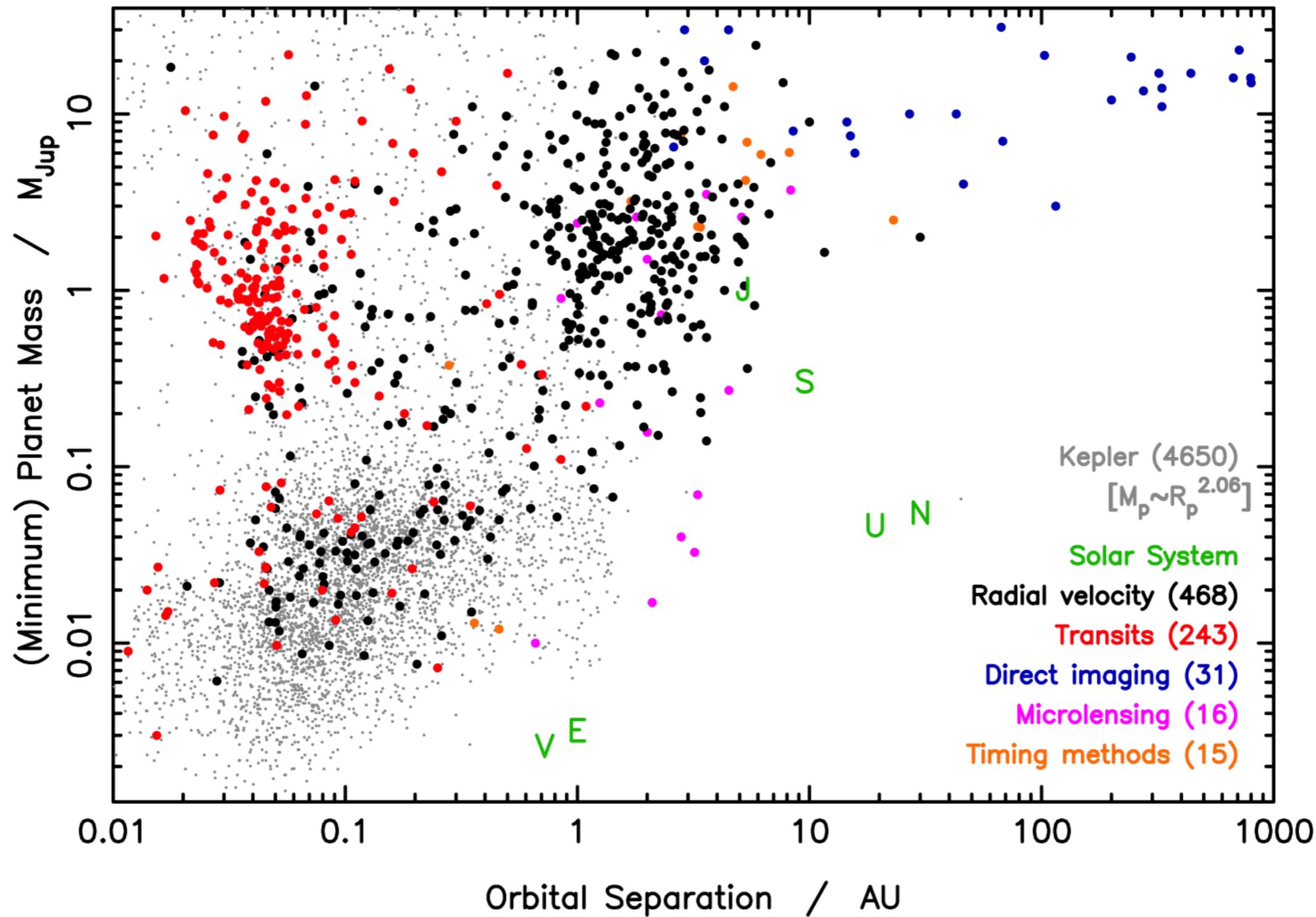
Data from exoplanet.eu

Known planets (as of 7 Oct 2015)



Data from exoplanets.org

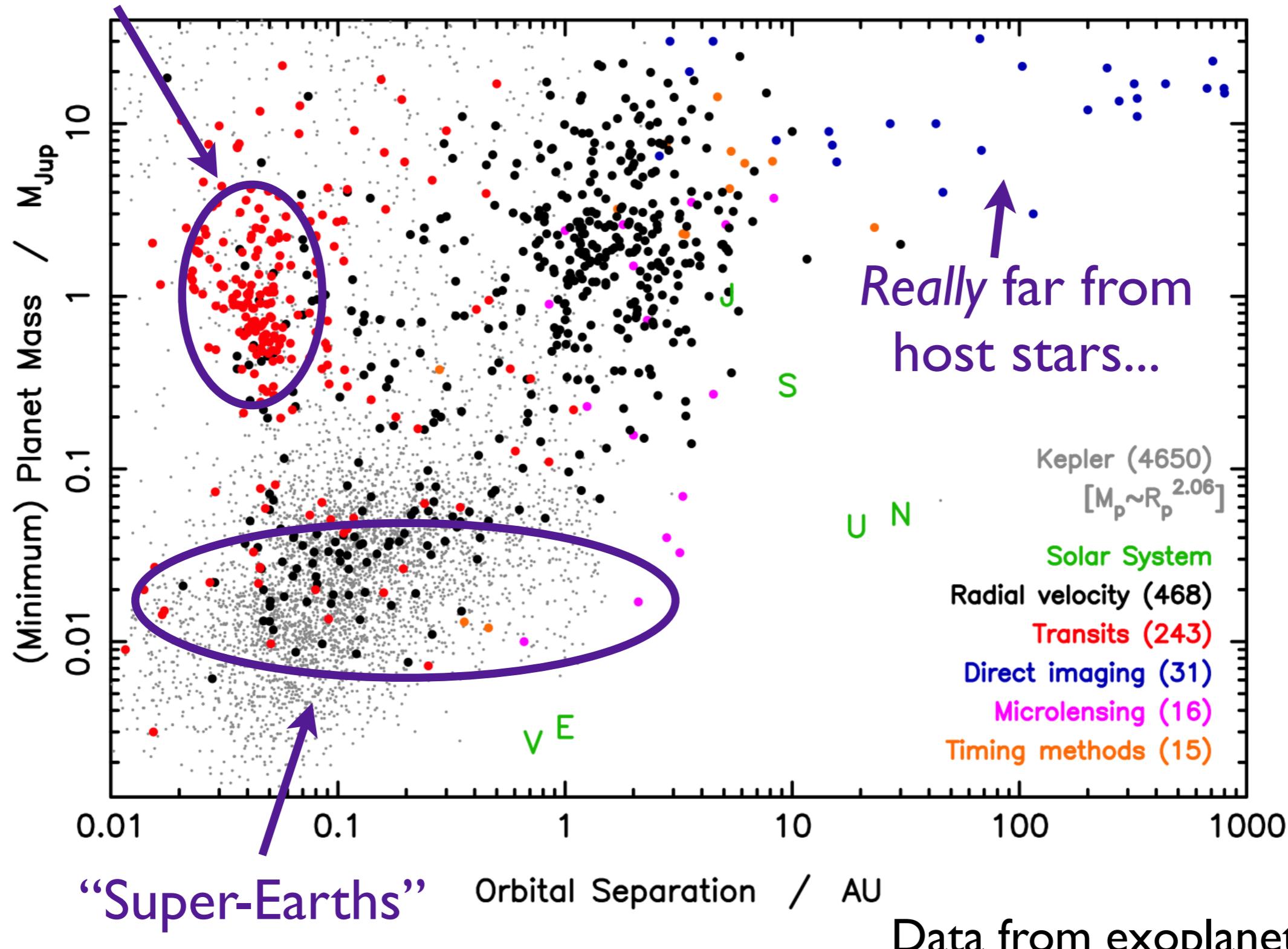
Known planets (as of 7 Oct 2015)



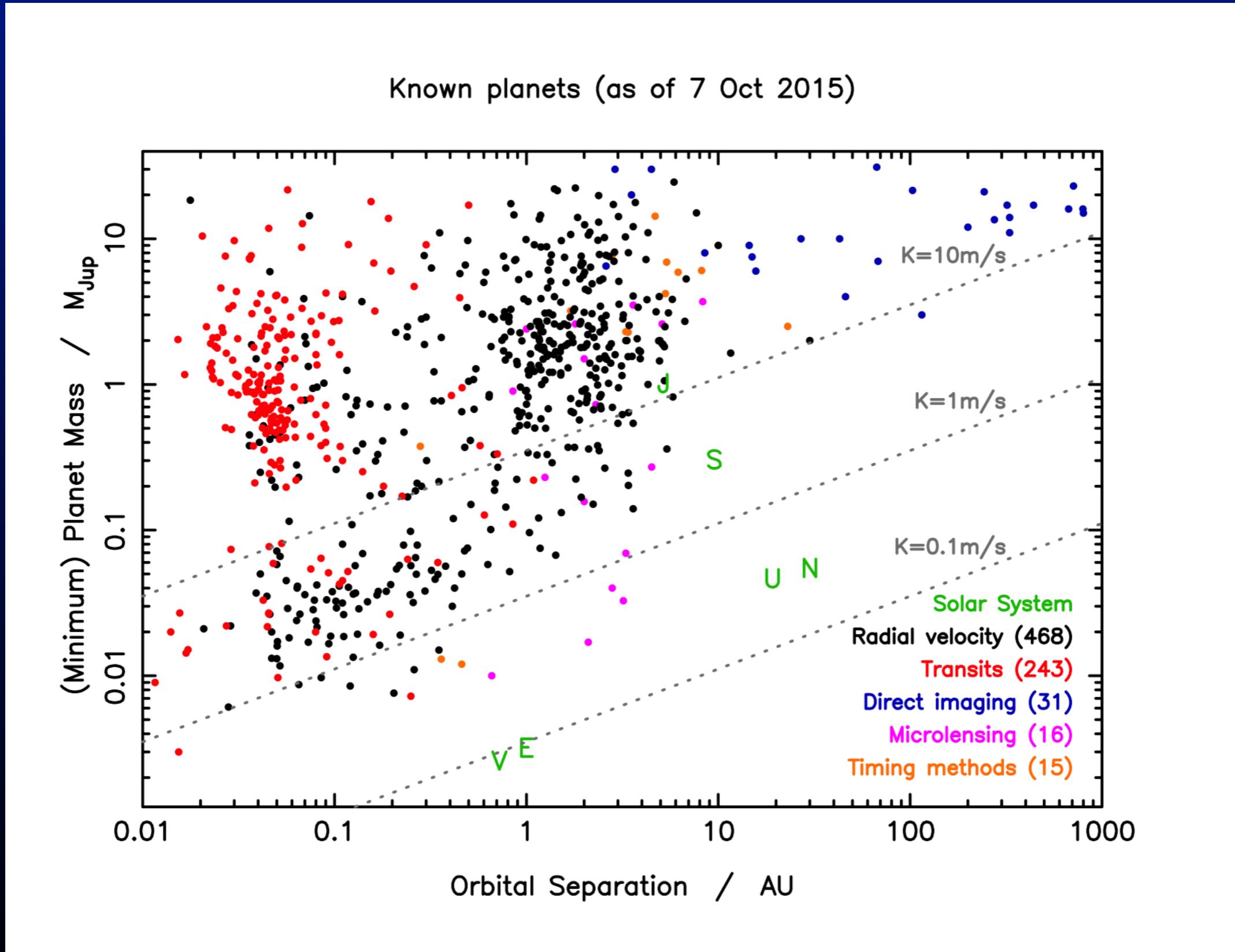
Data from exoplanets.org

“Hot Jupiters”

Known planets (as of 7 Oct 2015)

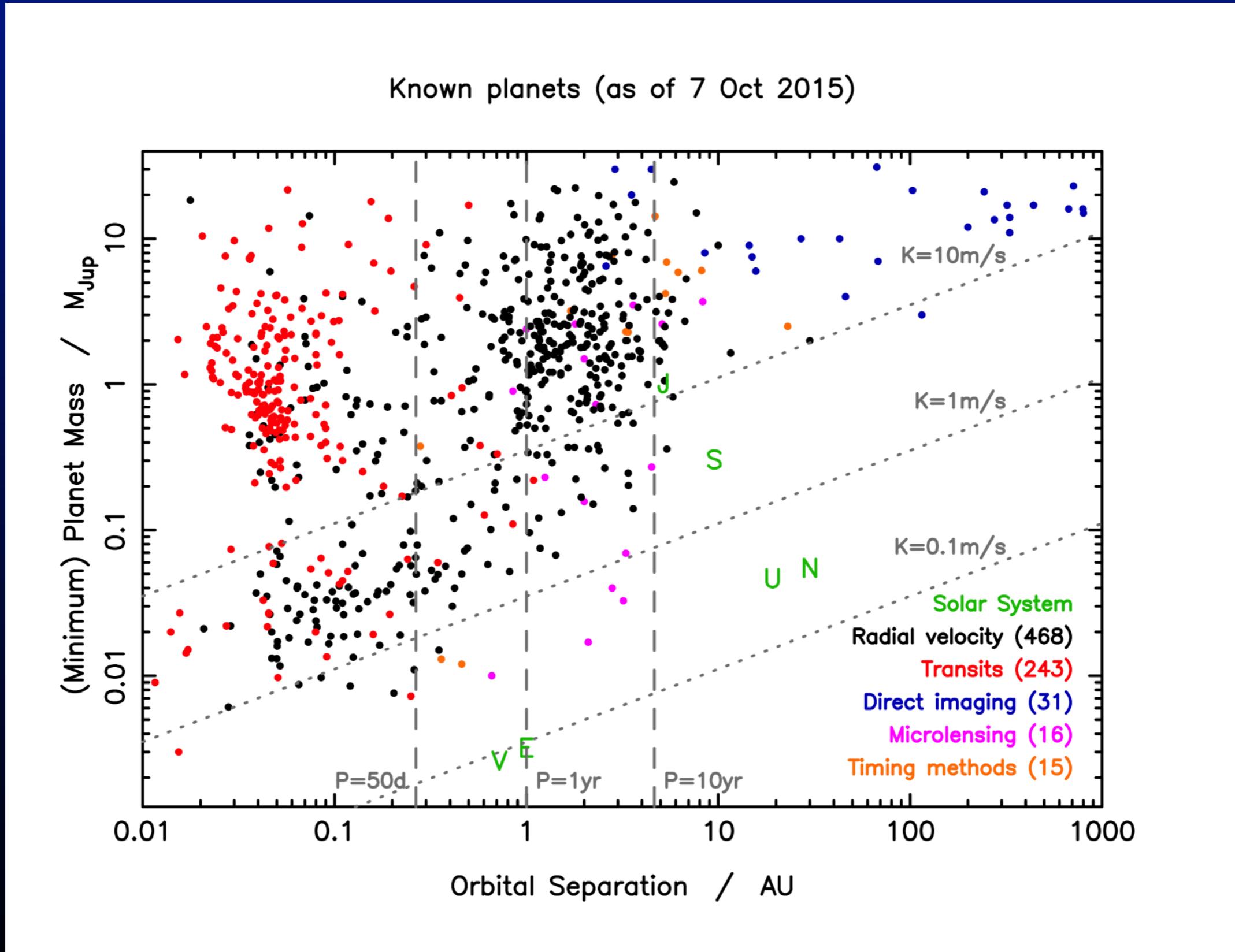


Selection biases

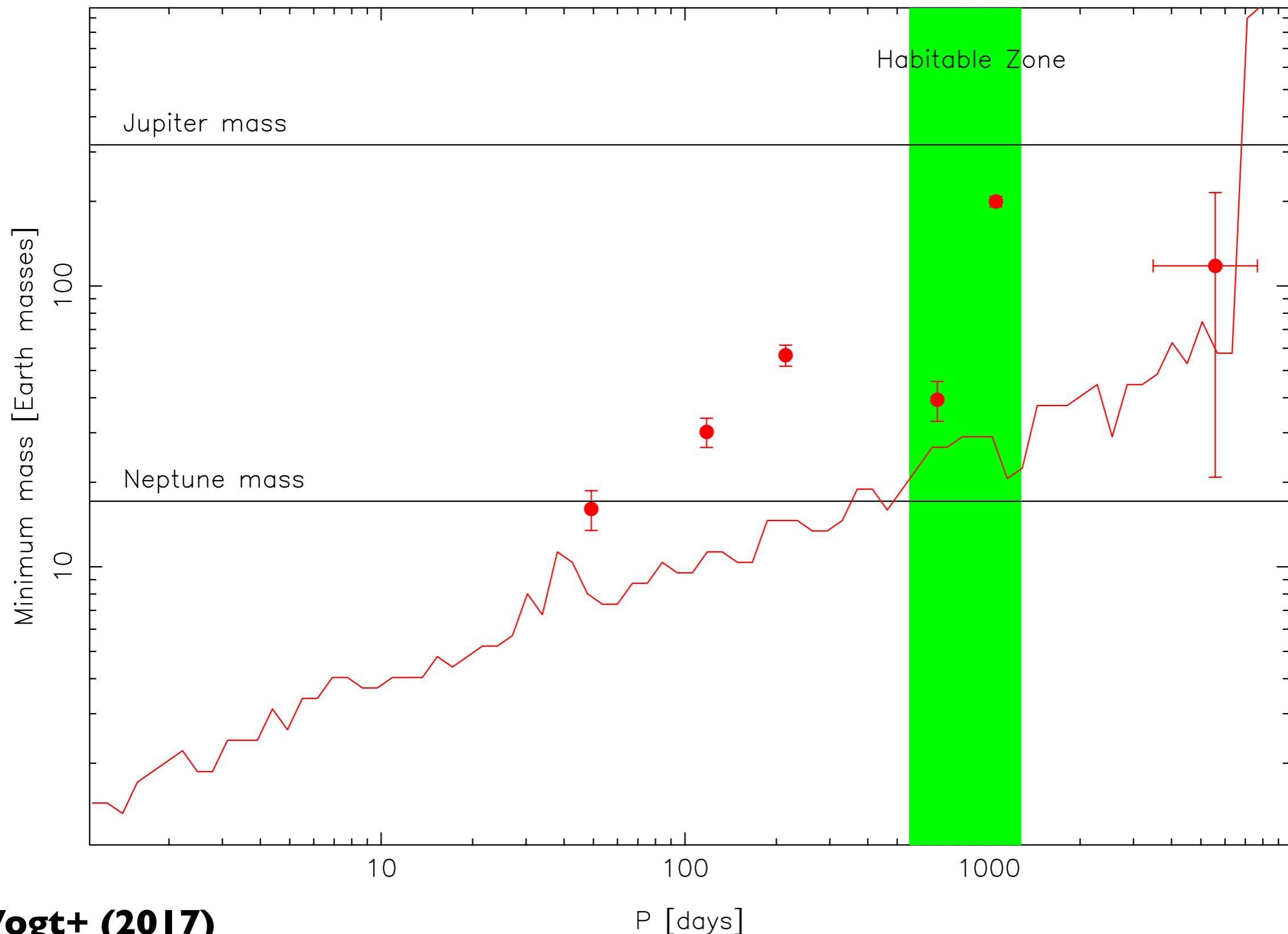


$$K \propto M_p \sin i a^{-1/2} \Rightarrow M_p \sin i \propto K a^{1/2}$$

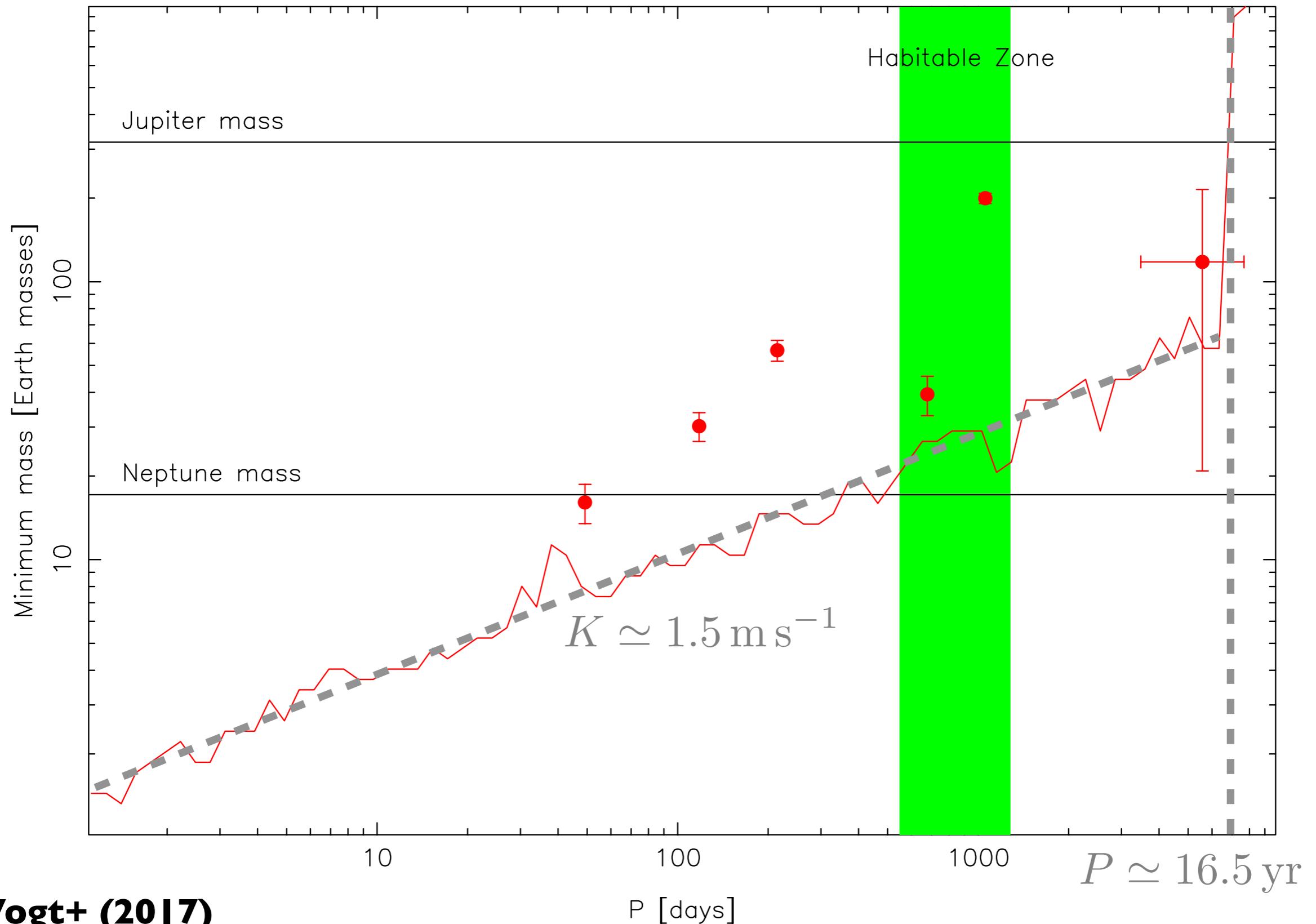
Selection biases



Selection biases



Selection biases



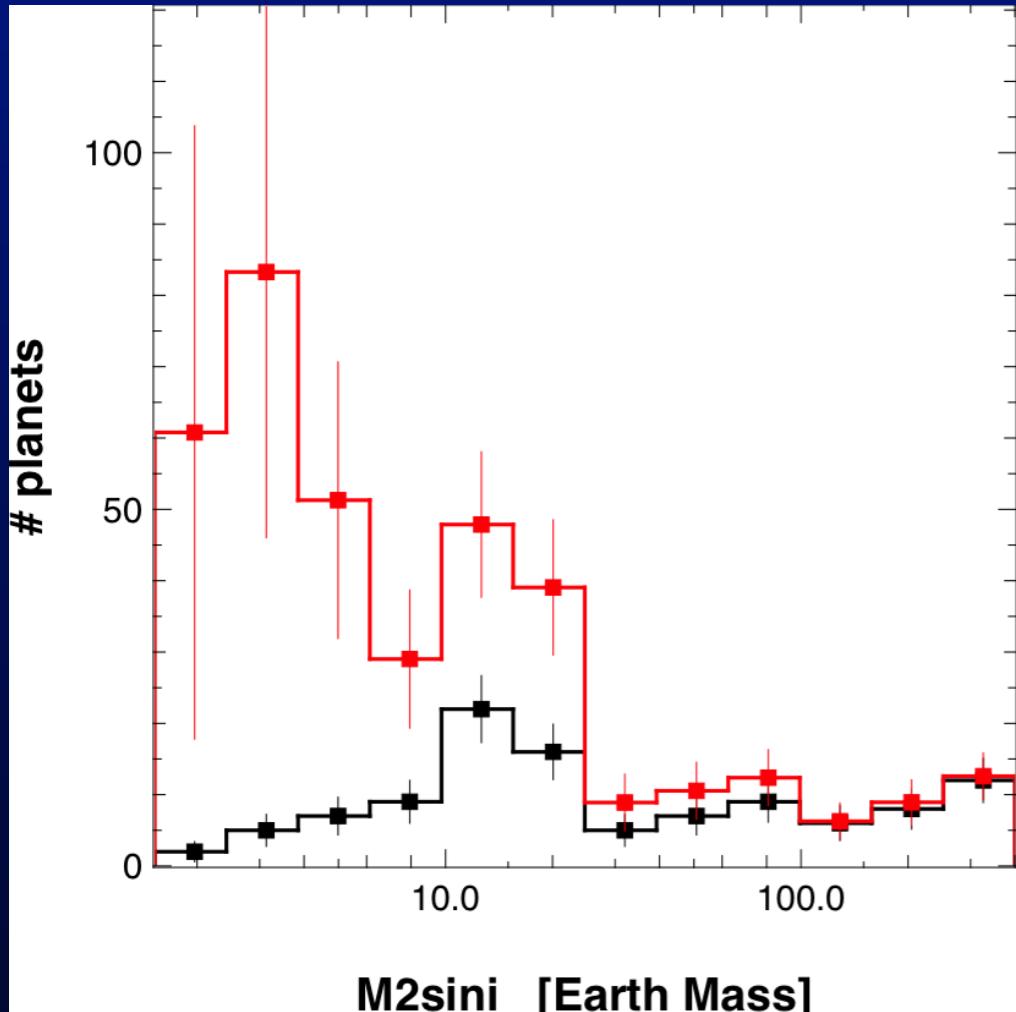
What fraction of stars host planets?

What fraction of stars host planets?

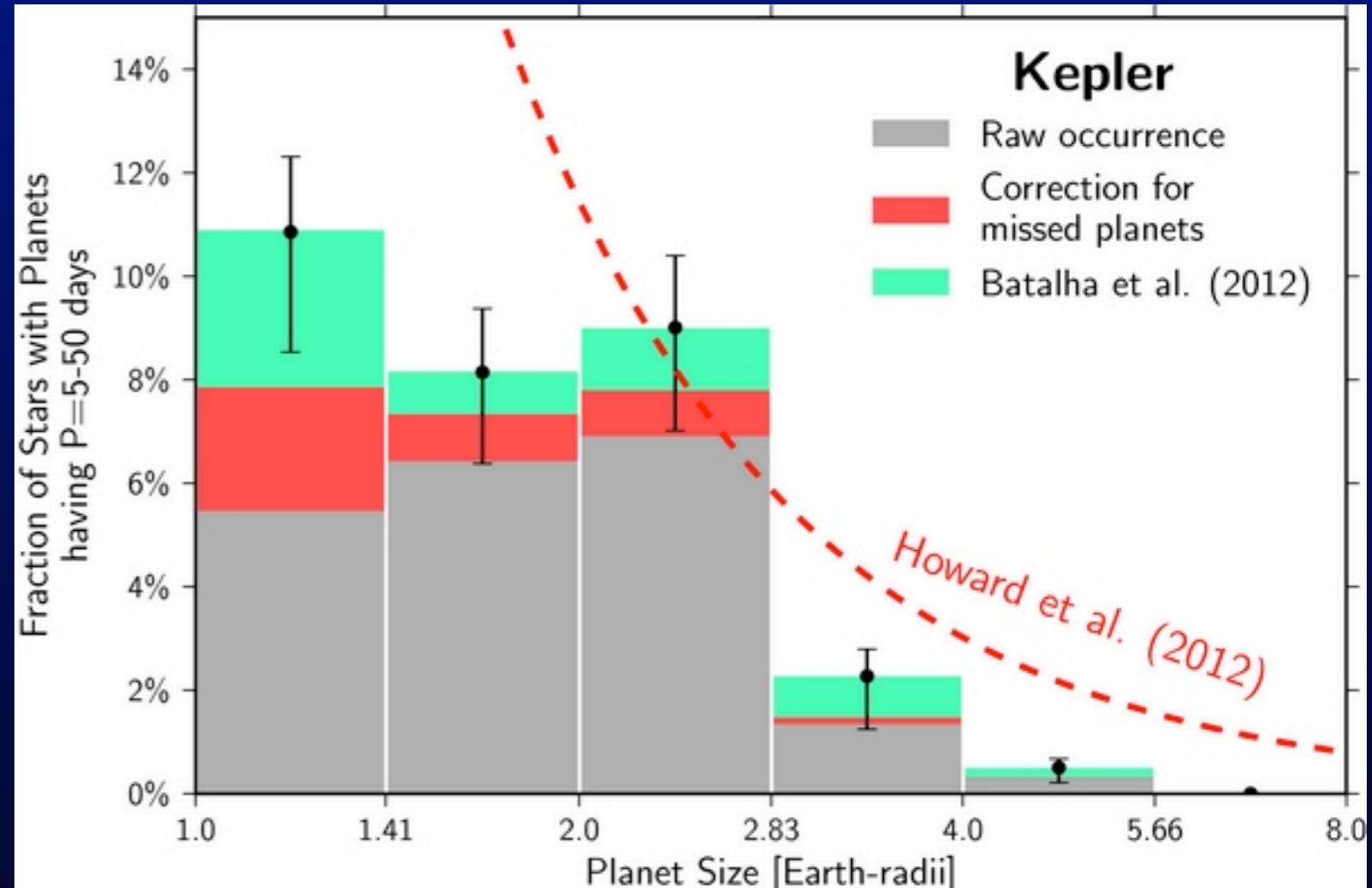
- Selection biases mean that measurements of f_p must be qualified (but detection methods are complementary).
- Current results:
 - 5-10% of FGK stars host a planet with $M_p \geq M_{Jup}$ at $a \leq 3\text{AU}$.
 - $>50\%$ of FGK stars host a planet with $M_p \geq 1M_\oplus$ and $P \leq 100\text{d}$.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

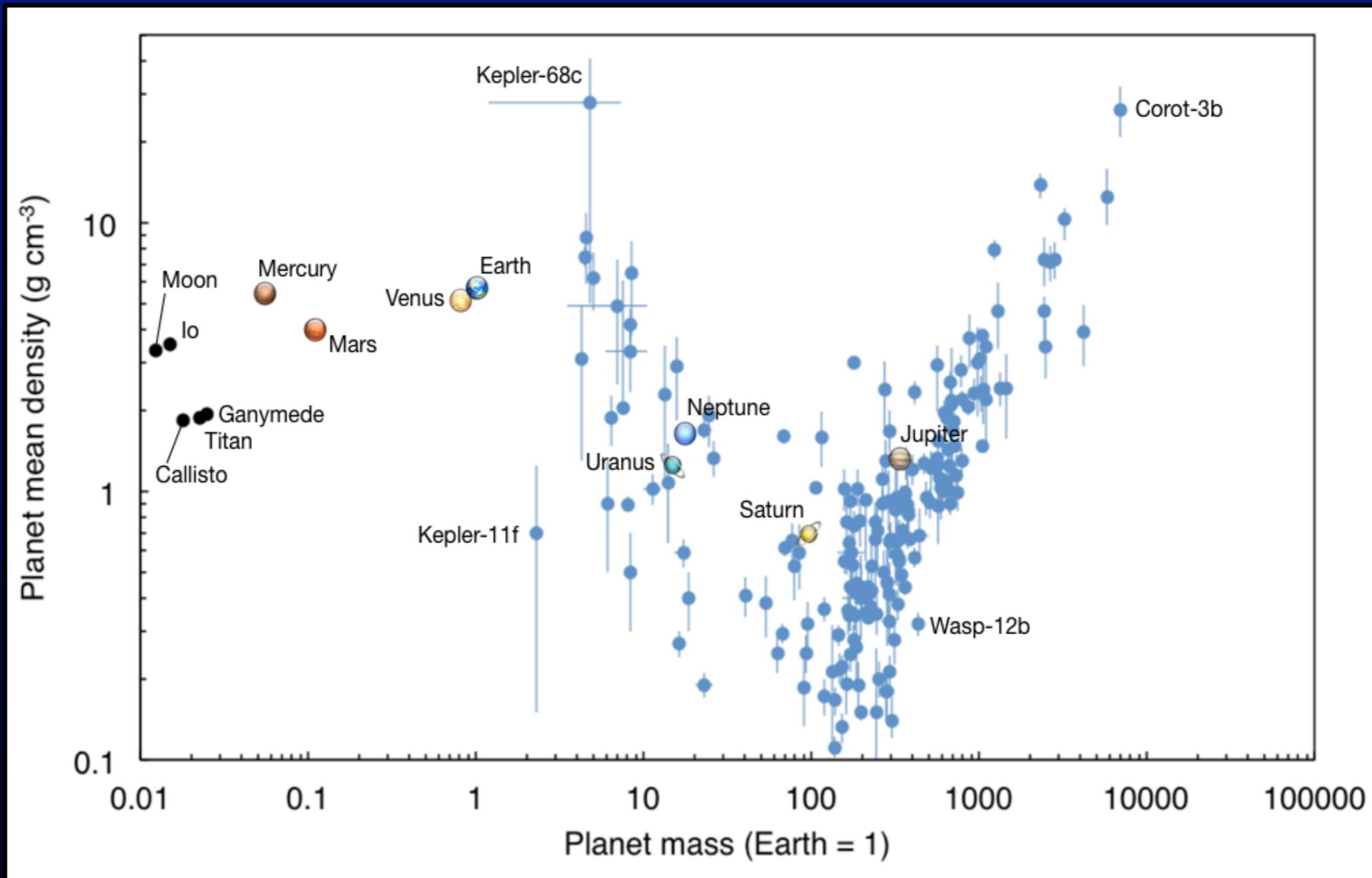
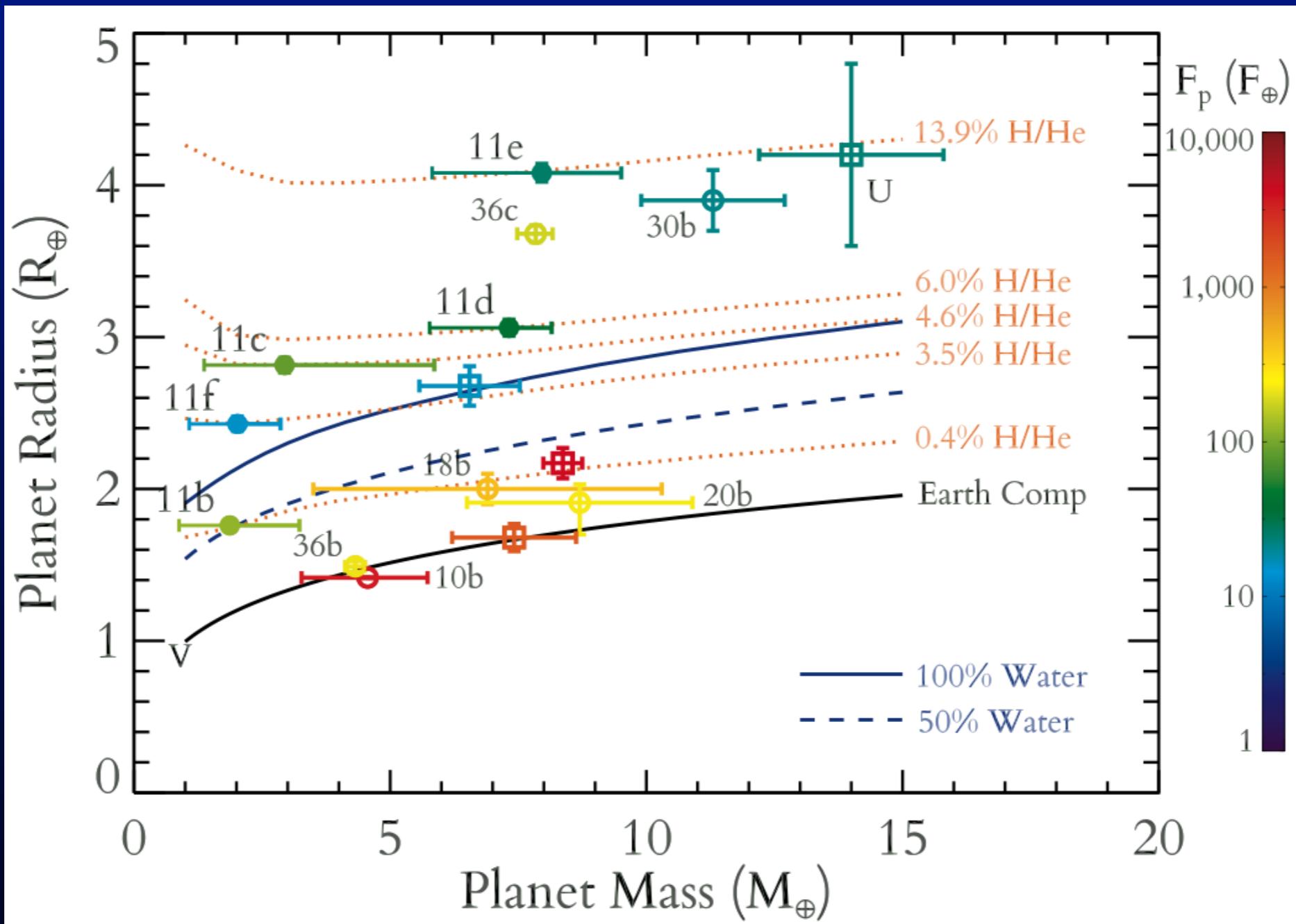


Figure courtesy of Didier Queloz

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

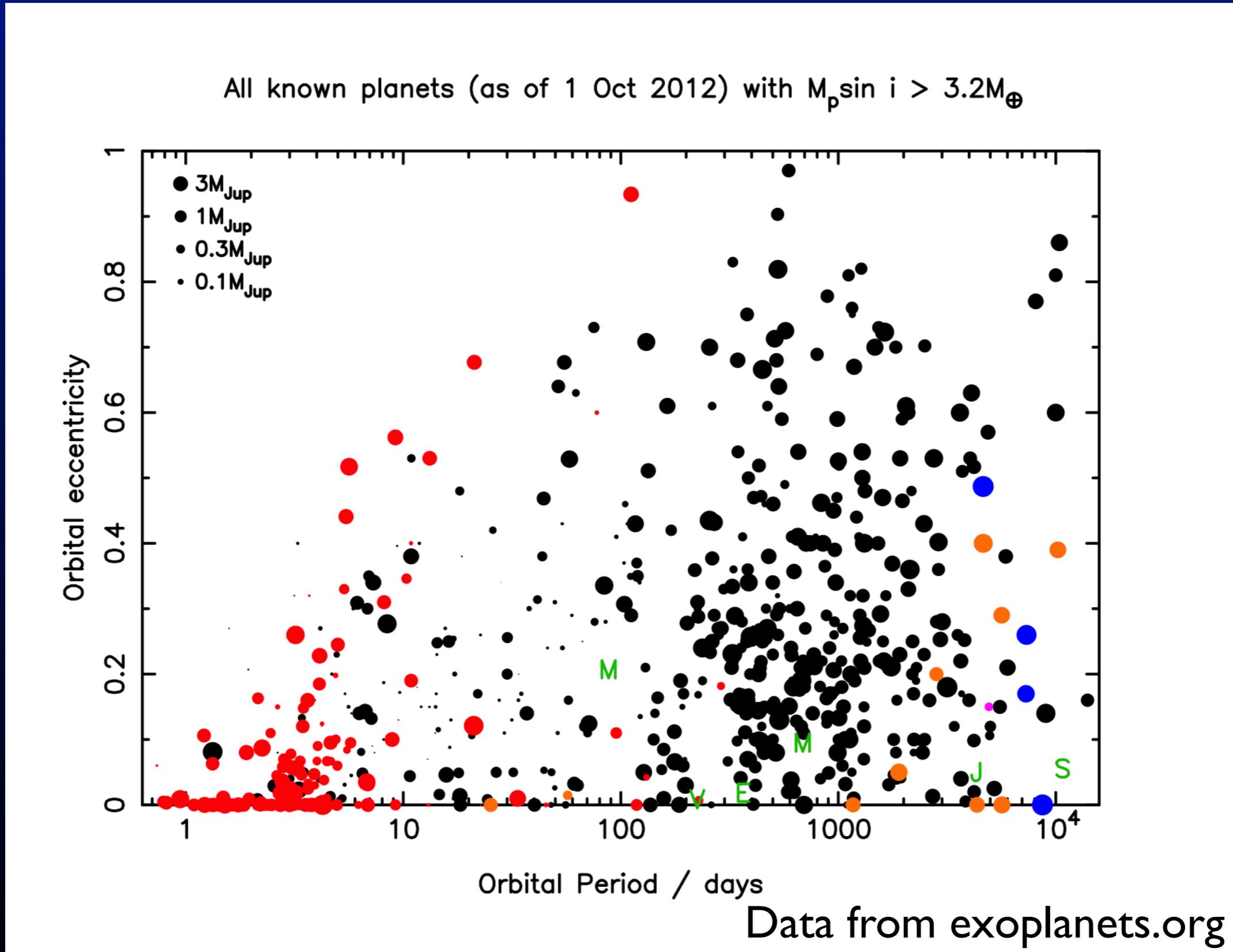
Mass-radius relation



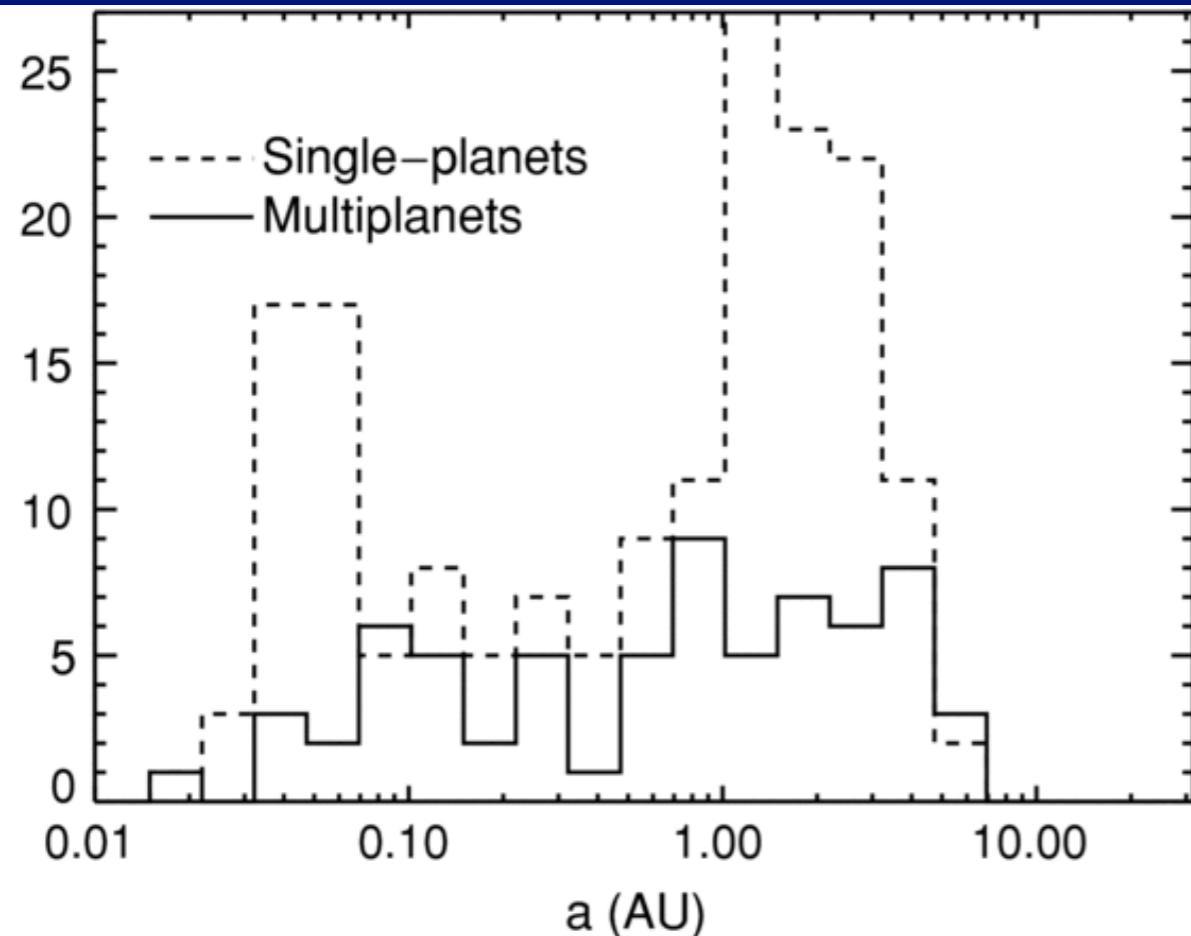
Lissauer et al. (2013)

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

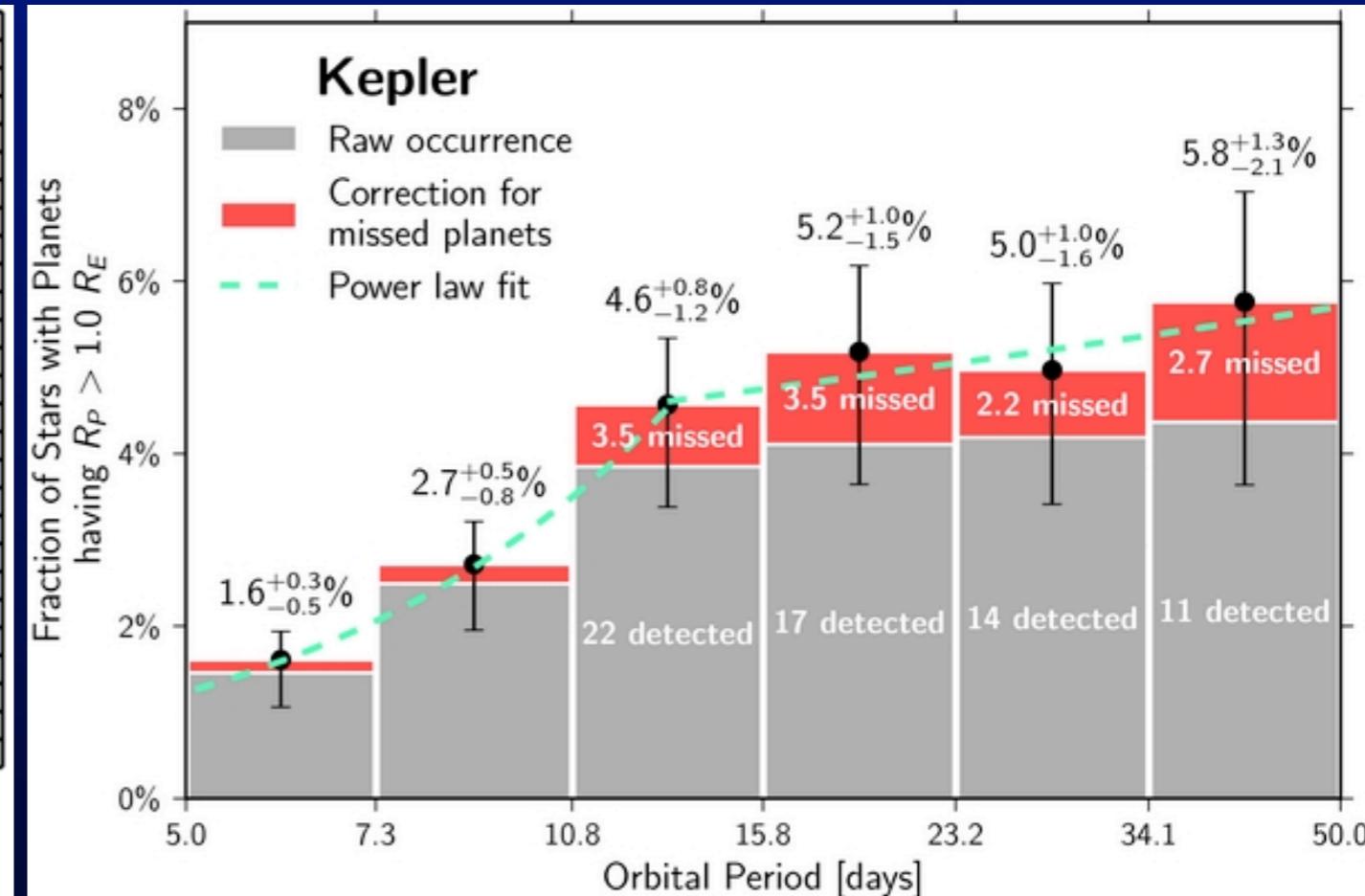
Eccentricities



Radial distribution



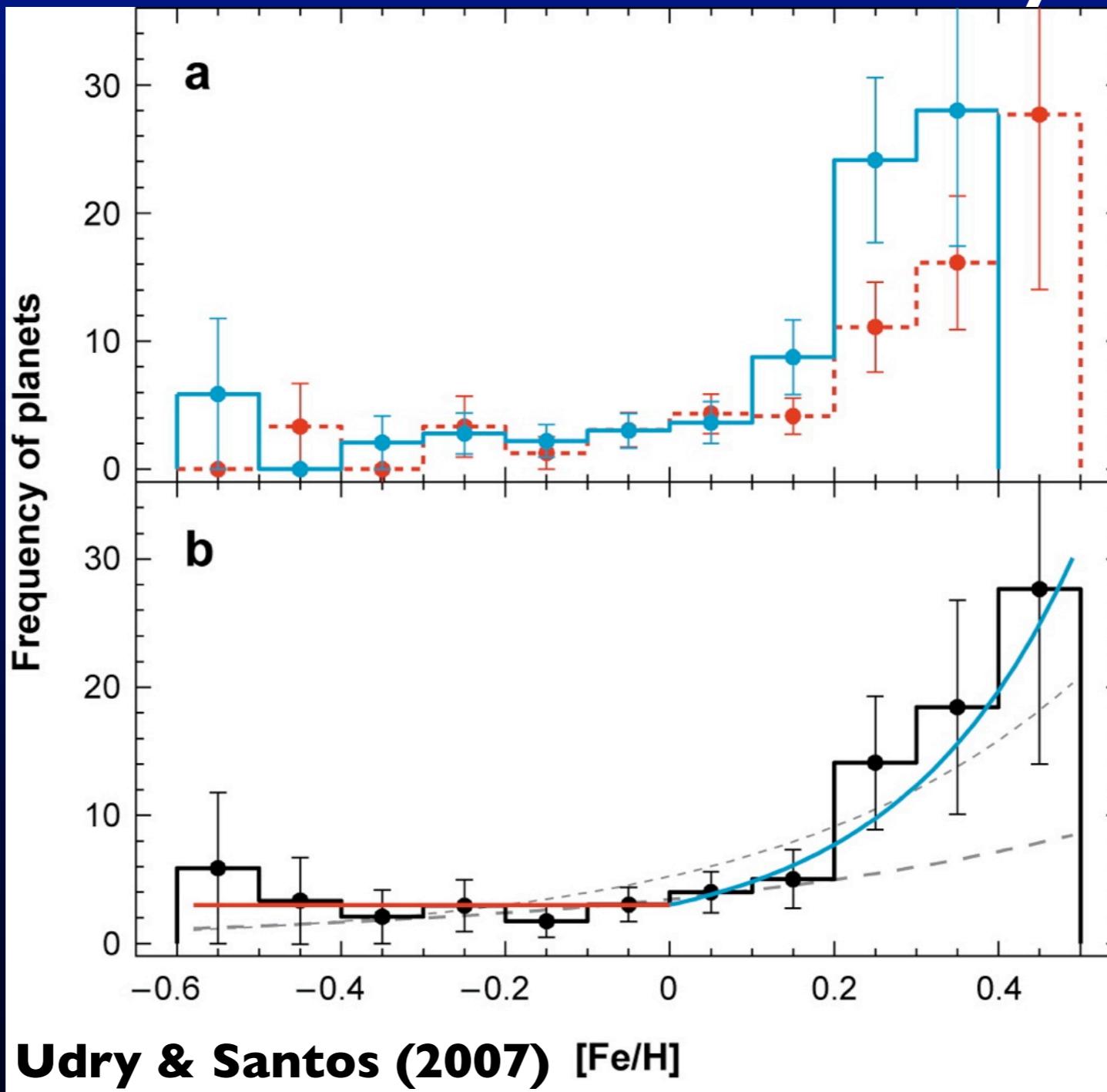
RV: Wright et al. (2009)



Kepler: Petigura et al. (2013)

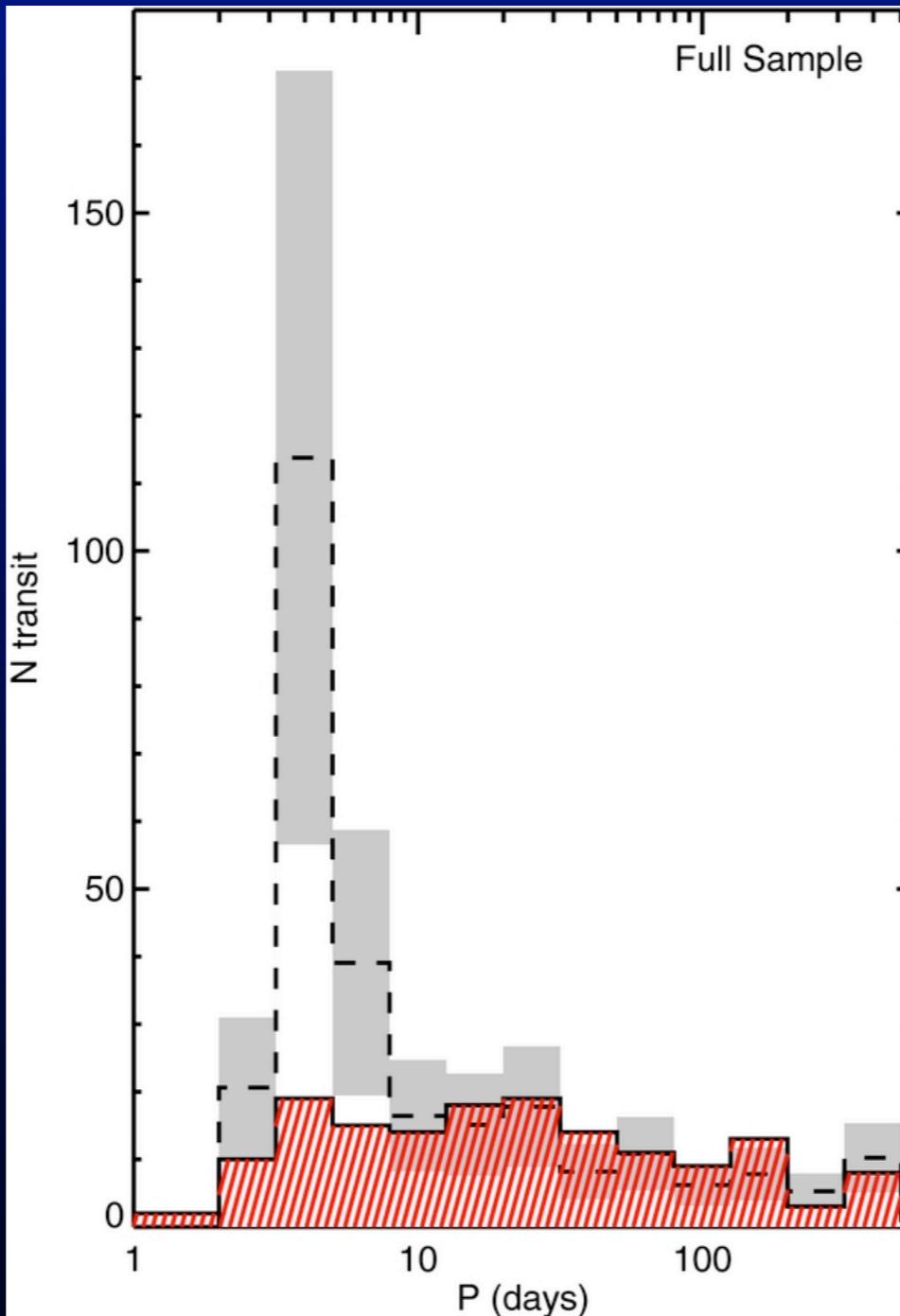
- Radial distribution is “smooth”, though data are limited.
- Evidence of excesses of \sim Jupiters at \sim 0.05AU and \sim 1-2AU in RV data.
- “Pile-up” of hot Jupiters only seen in metal-rich stars.

Host star metallicity



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

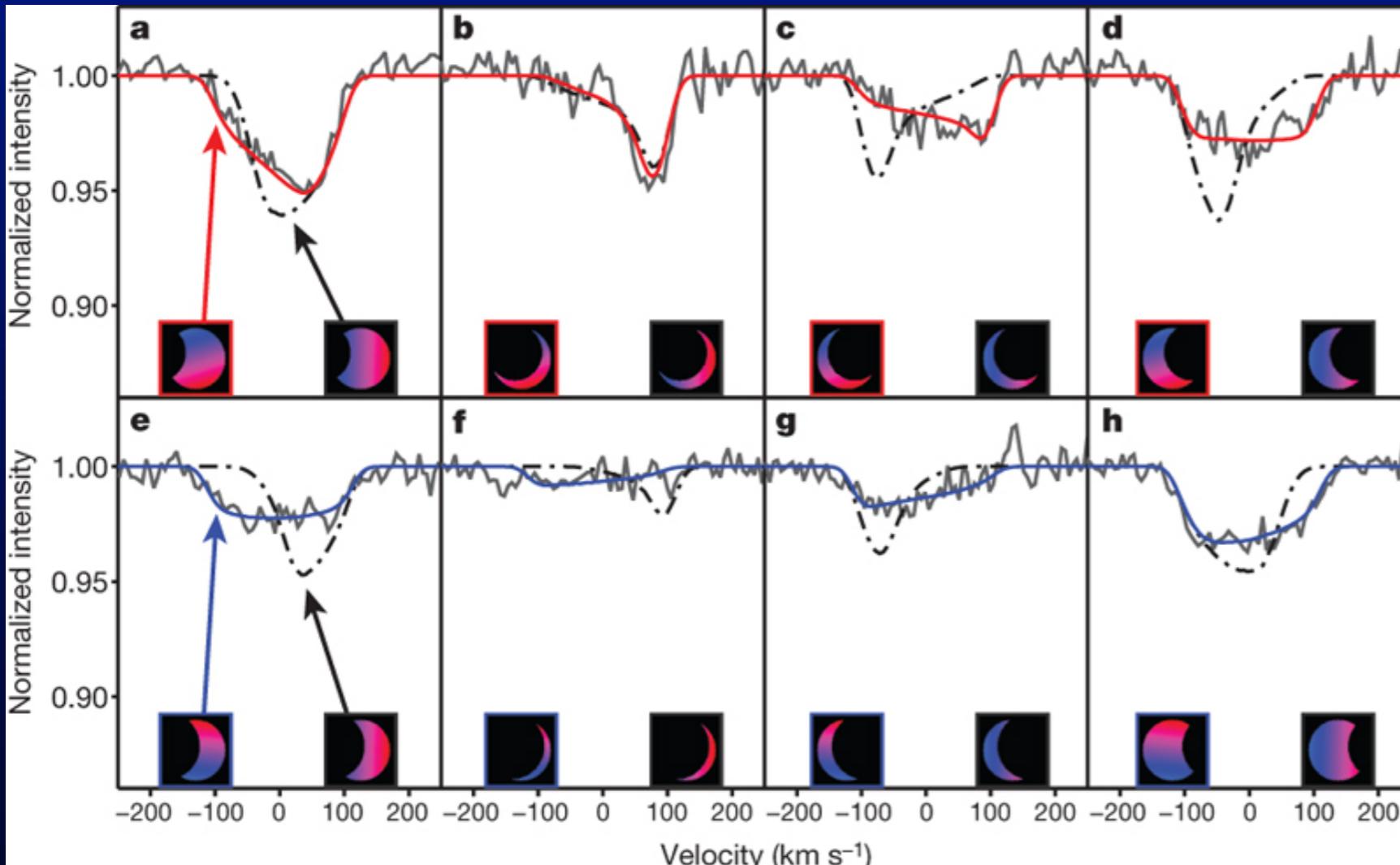
Host star metallicity



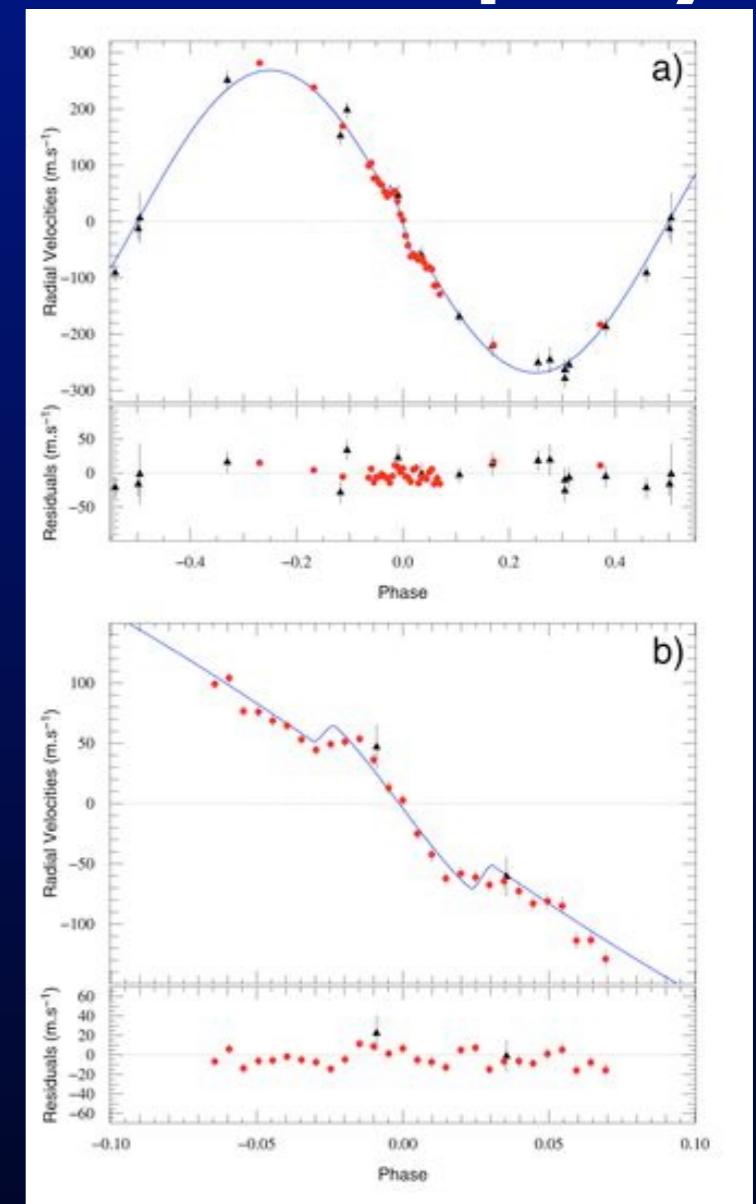
**Dawson & Murray-
Clay (2013)**

- 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



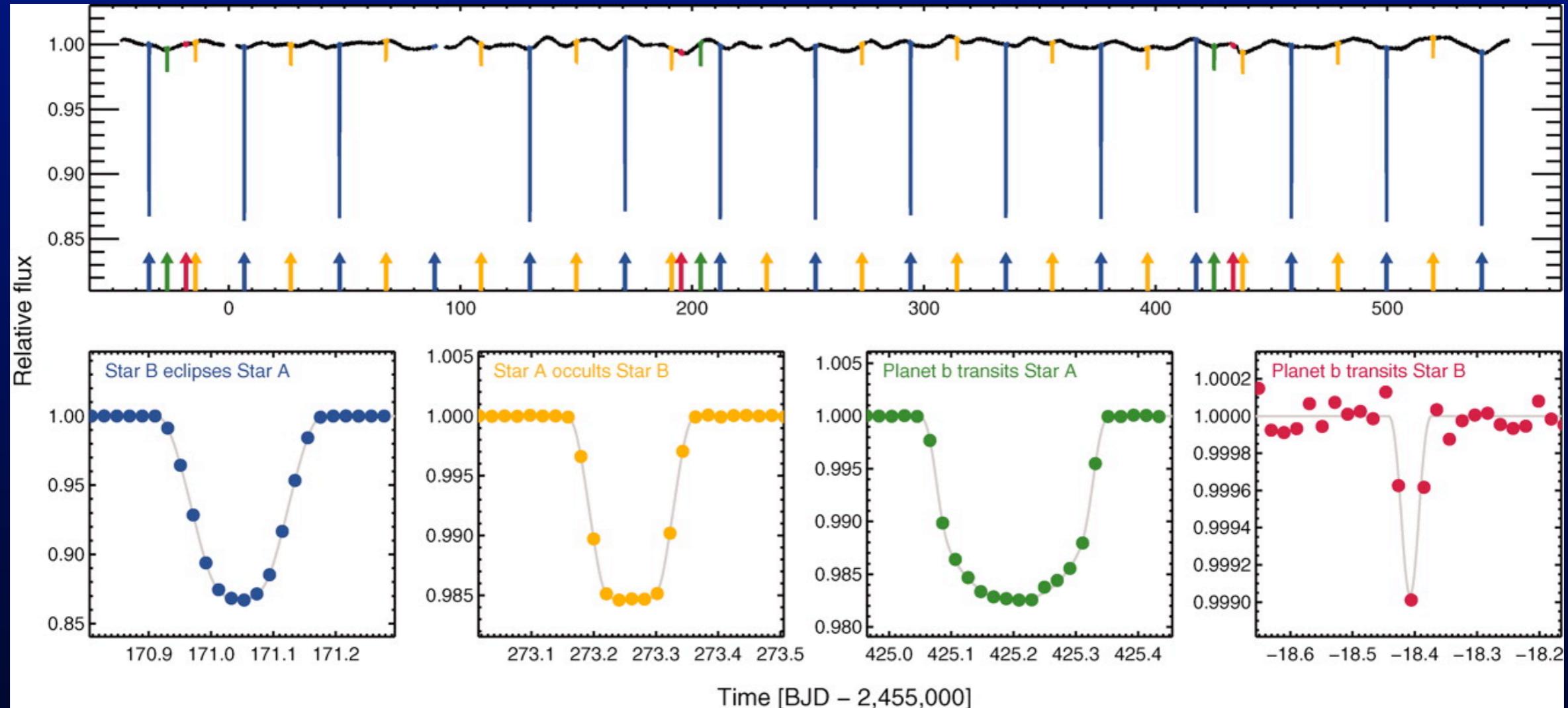
Albrecht et al. (2009)



Triaud et al. (2010)

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

Kepler-16b: the first “Tatooine”



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



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Table

Plots

EOD Planets
707 Planets with good orbits listed in the Exoplanet Orbit Database

Other Planets
25 Including microlensing and imaged planets

Total Confirmed Planets
732

Unconfirmed Kepler Candidates
3469

Total Planets
4201 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 and documentation for the Exoplanet Data Explorer is available [here](#). A FAQ and overview of our methodology is

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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

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/](#)

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

Bibliography

Last update: May 17, 2012

Searches

Last update: April 18, 2012

Meetings

Last update: May 17, 2011

Theory Work

Last update: April 3, 2012

Other sites

Last update: April 16, 2012

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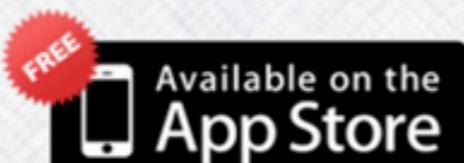
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The screenshot shows the Exoplanet app interface. At the top, it displays "Carrier" and "8:43 PM". Below this is a navigation bar with tabs for "Database" and "KOI-13 b". The main screen features a large, bright blue star with radiating light rays. In the foreground, there are several planetary bodies of different sizes and colors, including a prominent yellowish-orange planet labeled "KOI-13 b". The background is a dark space scene with numerous small stars. At the bottom of the screen, there is a grid-like pattern with some red and blue markings.

Exoplanet

 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 dataset called the [Open Exoplanet Catalogue](#).