

Formation of Planetary Systems

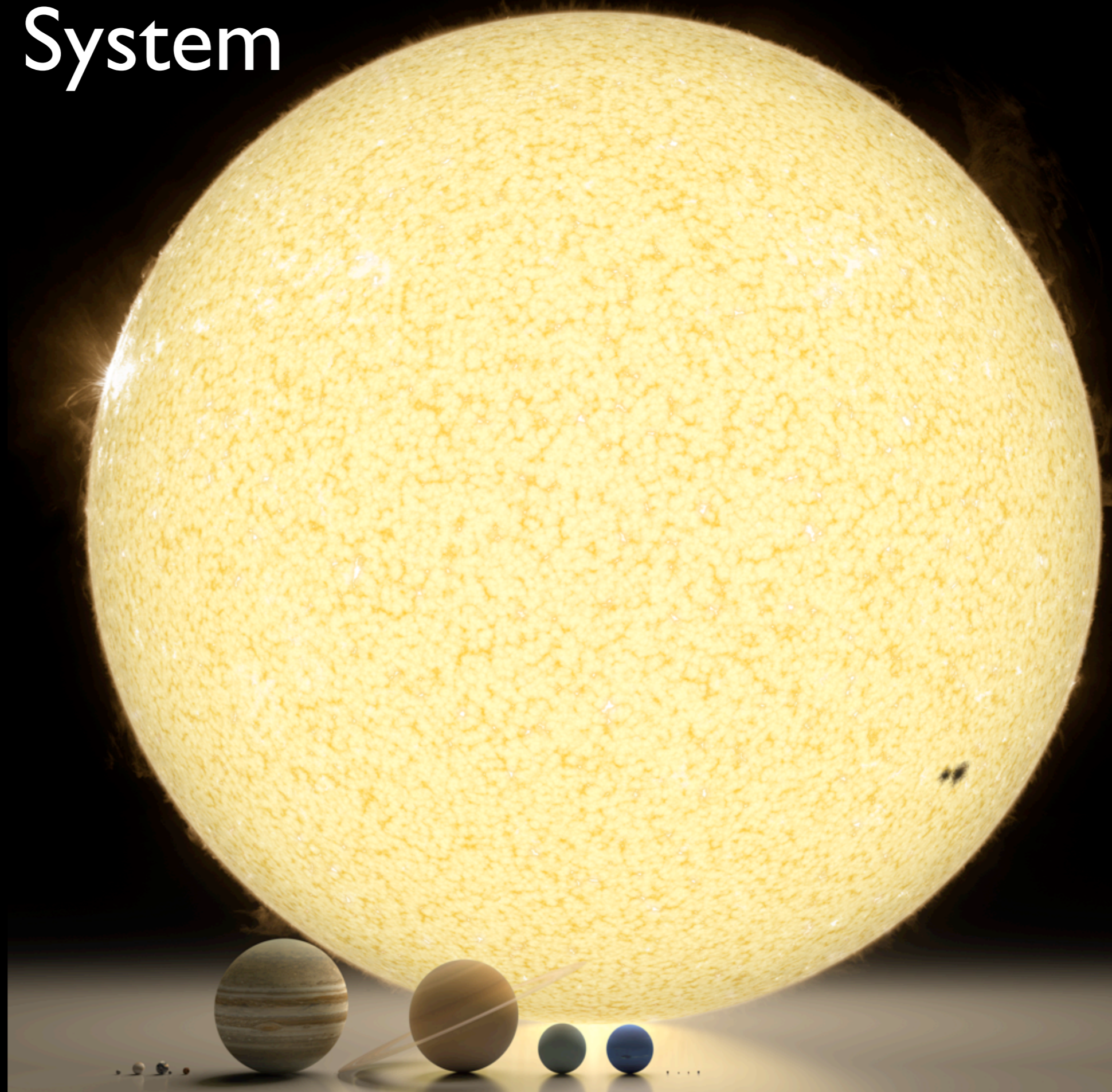
Lecture 1 - Observations of planetary systems



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 (VI - 2014; VII - 2023)

The Solar System



Uranus

Saturn

Jupiter

Mars

Earth

Venus

Mercury

Sun

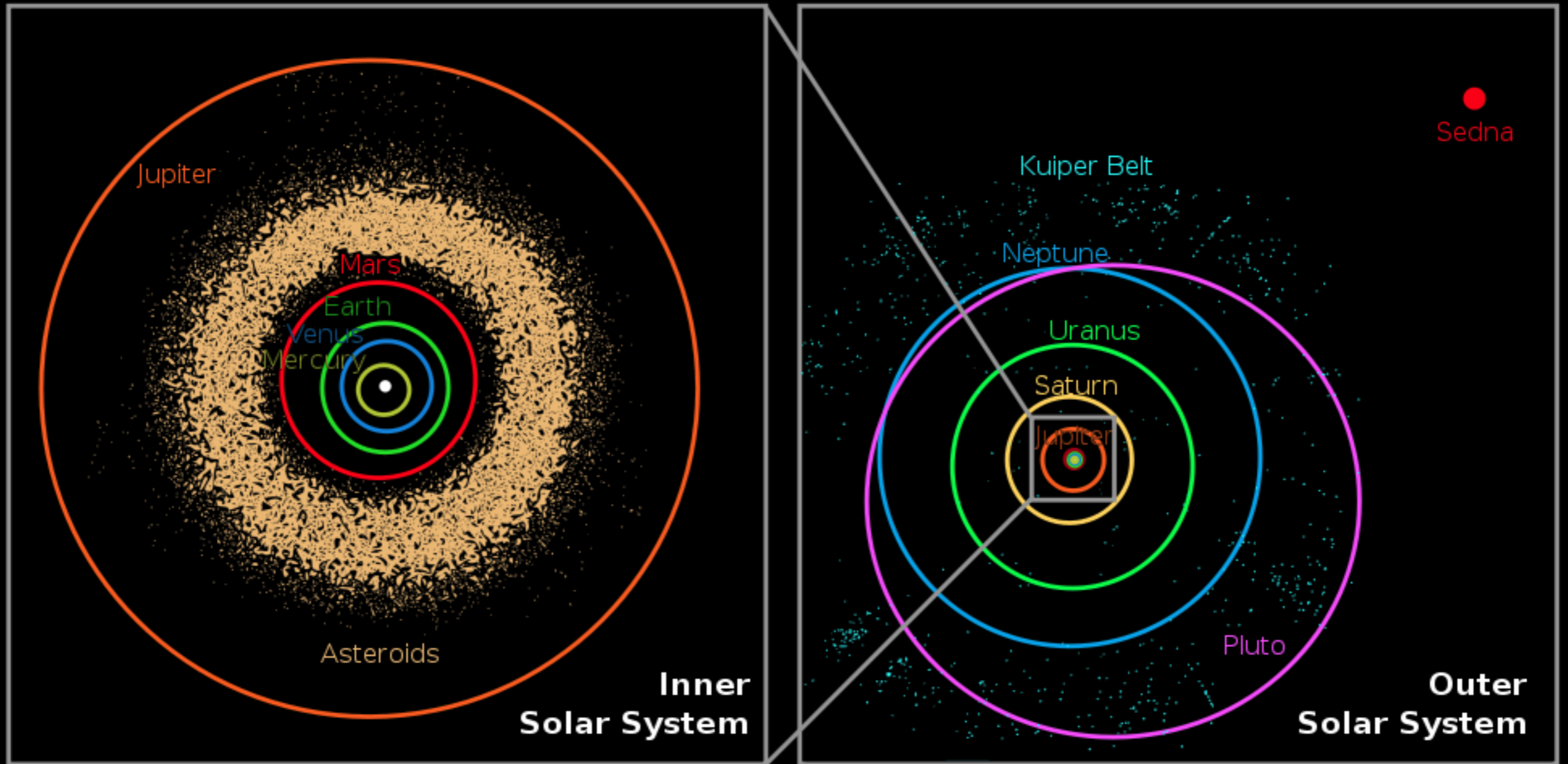
Roberto Ziche

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	1.74×10^{-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.
 - $\sim 1M_{\text{Earth}}$ 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

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direct imaging **69**
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astrometry **3**
radial velocity **1068**
timing methods (inc TTVs) **43**
 - Obscuration of stellar light by planet
transits **4128**
 - Obscuration/amplification of background star by planet
gravitational microlensing **204**

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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.

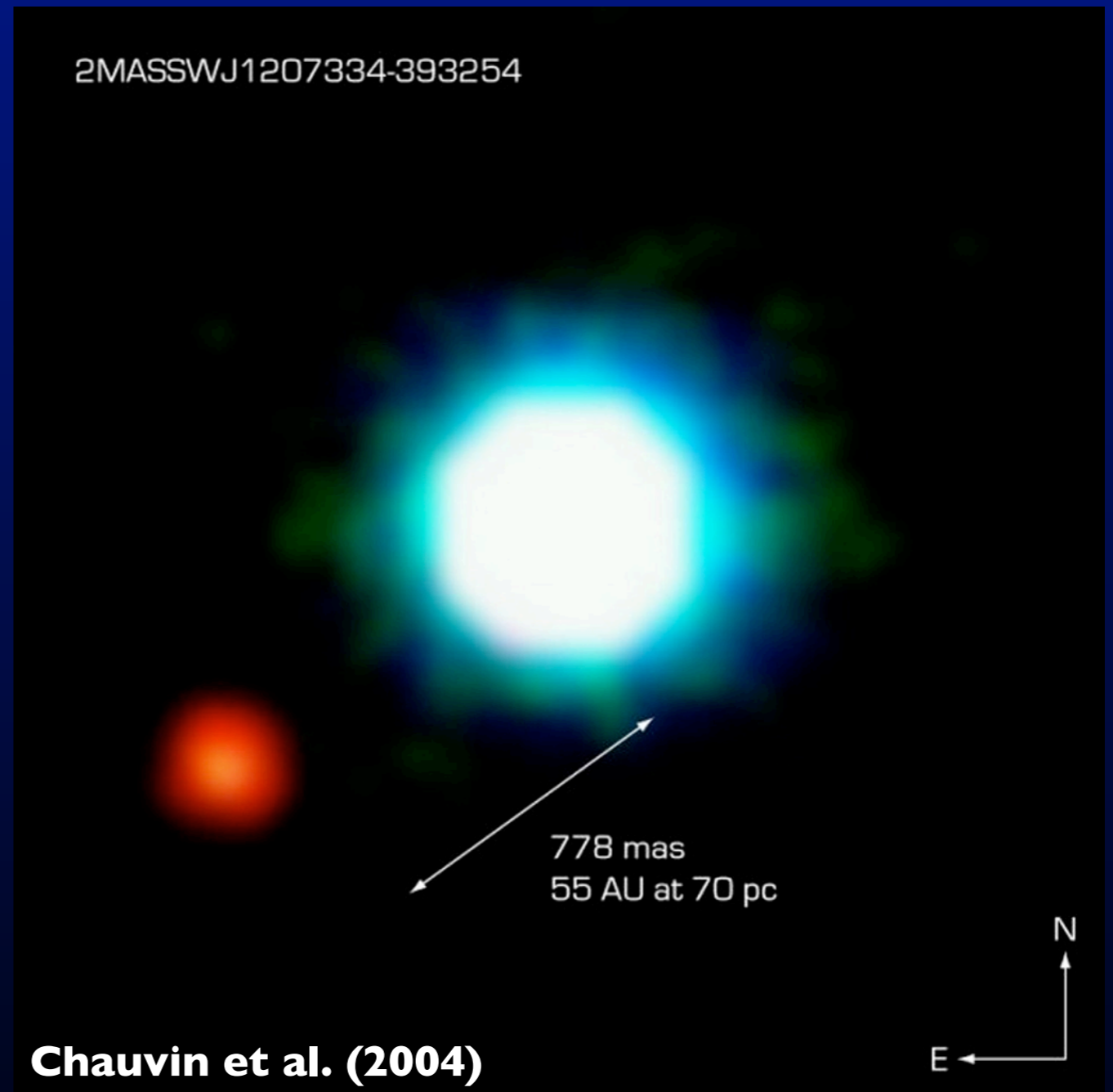
*A is the *albedo*.

Direct Imaging

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

Direct Imaging

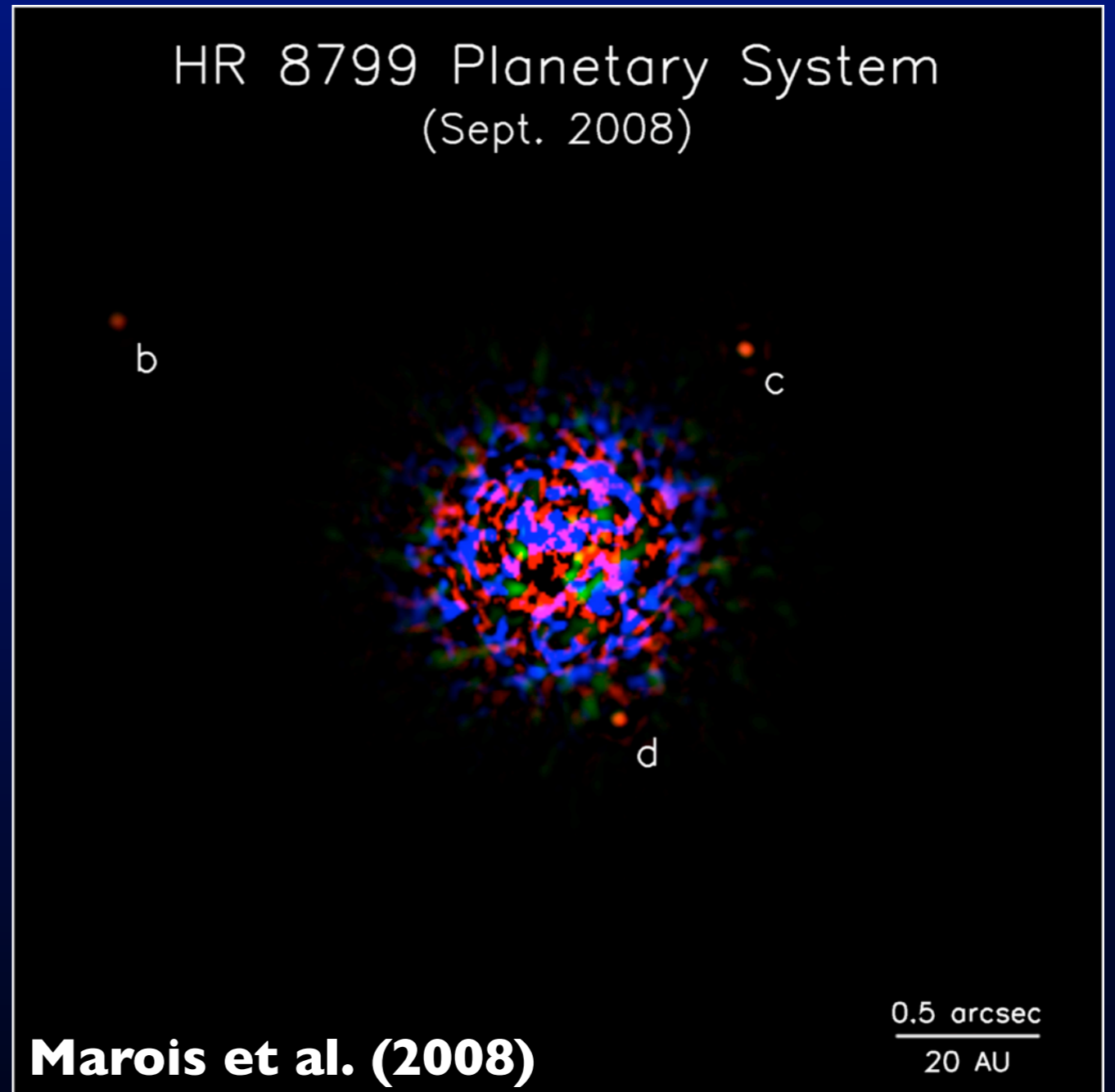
- Two ways around the contrast problem:
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“Planet” around brown dwarf 2MI 207 discovered in 2004. Primary is $\sim 25M_{\text{Jup}}$; secondary is $\sim 5M_{\text{Jup}}$. Wide separation. More akin to a low-mass binary than a true planetary system.

Direct Imaging

- Two ways around the contrast problem:
 - a) Look for planets around faint stars
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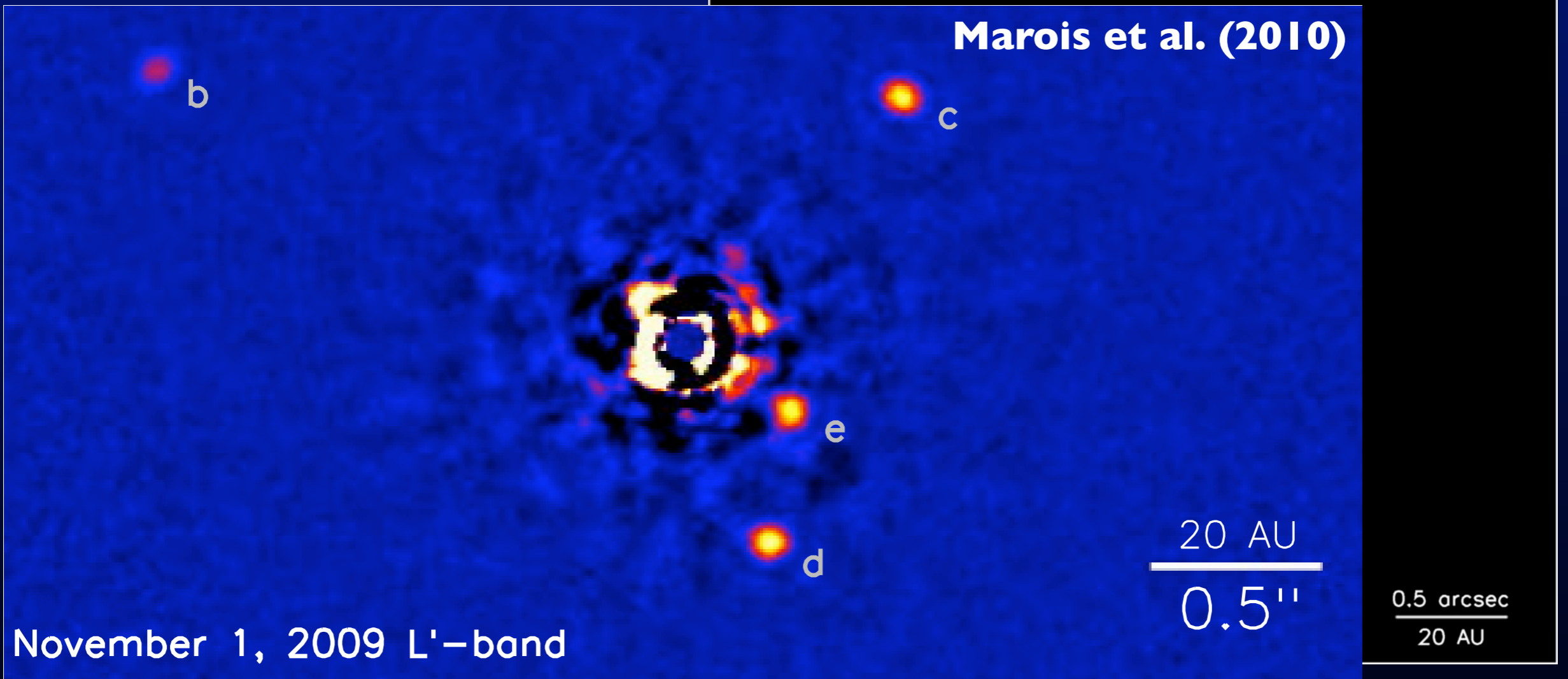
Planets around HR8799 discovered in 2008.
Star is $\sim 1.5M_{\odot}$. Planet masses all estimated to be $\sim 10M_{\text{Jup}}$.
Wide orbits - “d” is beyond orbit of Uranus.

Direct Imaging

- Two ways around the contrast problem:

HR 8799 Planetary System
(Sept. 2008)

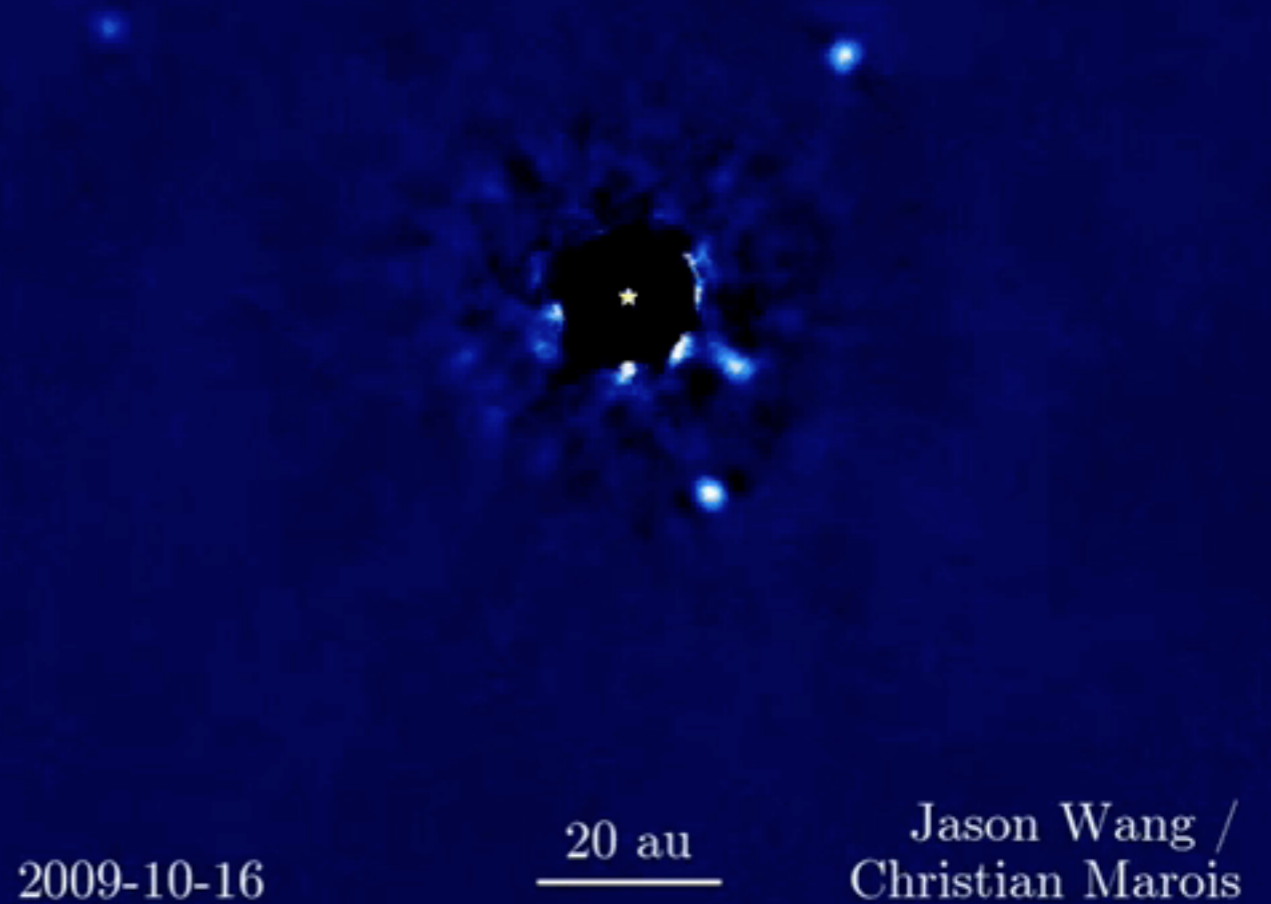
Marois et al. (2010)



Direct Imaging

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 - a) Look for planets around faint stars
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HR8799: Wang, Marois+ (2017)



New facilities...

Macintosh et al. (2015)

Gemini/GPI

Size of Saturn's orbit
around the Sun

51 Eri

+

b

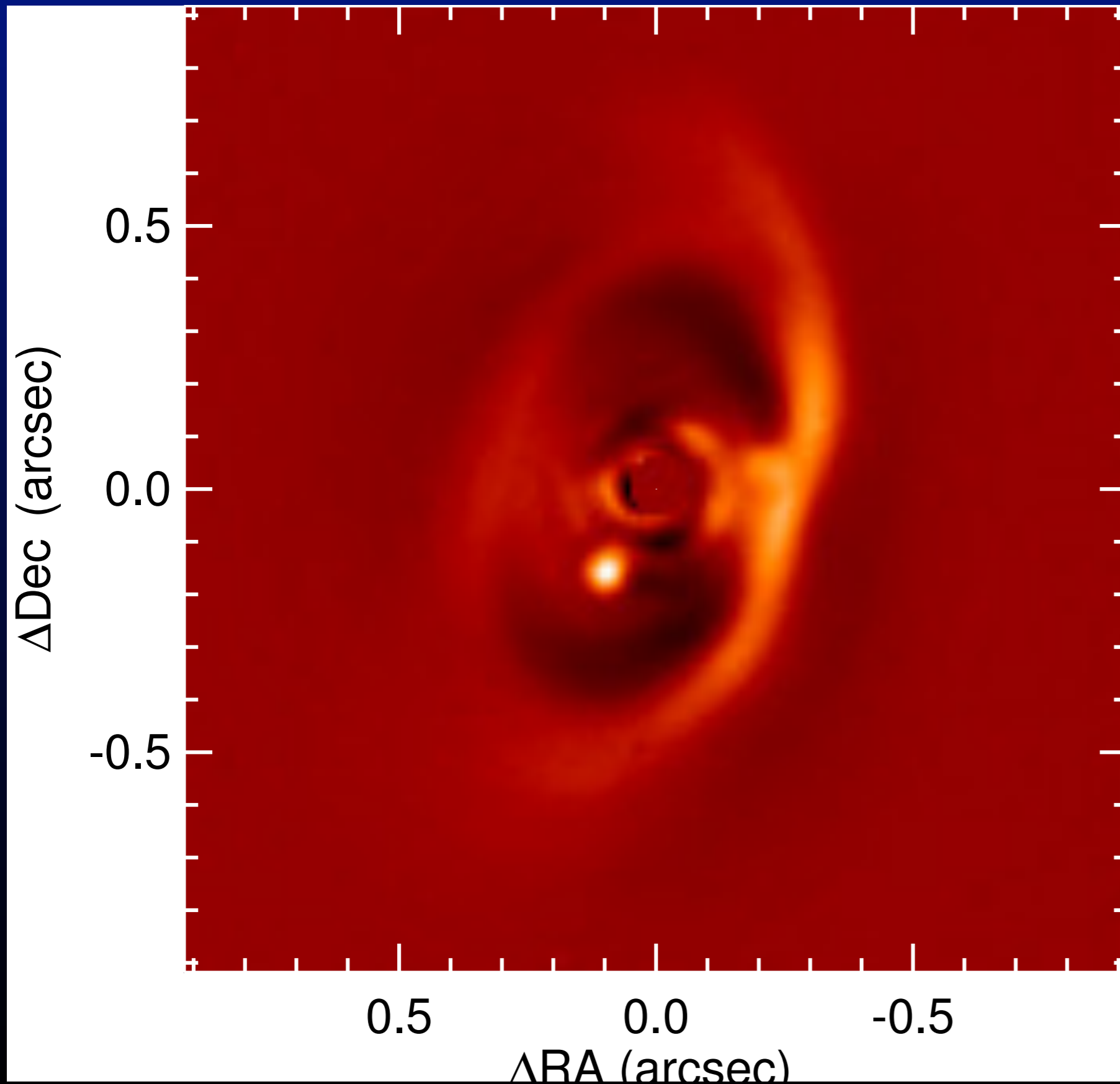
Type F0 pre-MS star (5-30Myr).
Planet mass $\sim 2M_{\text{Jup}}$.
Proj. separation 449mas (13.2AU).

10 AU



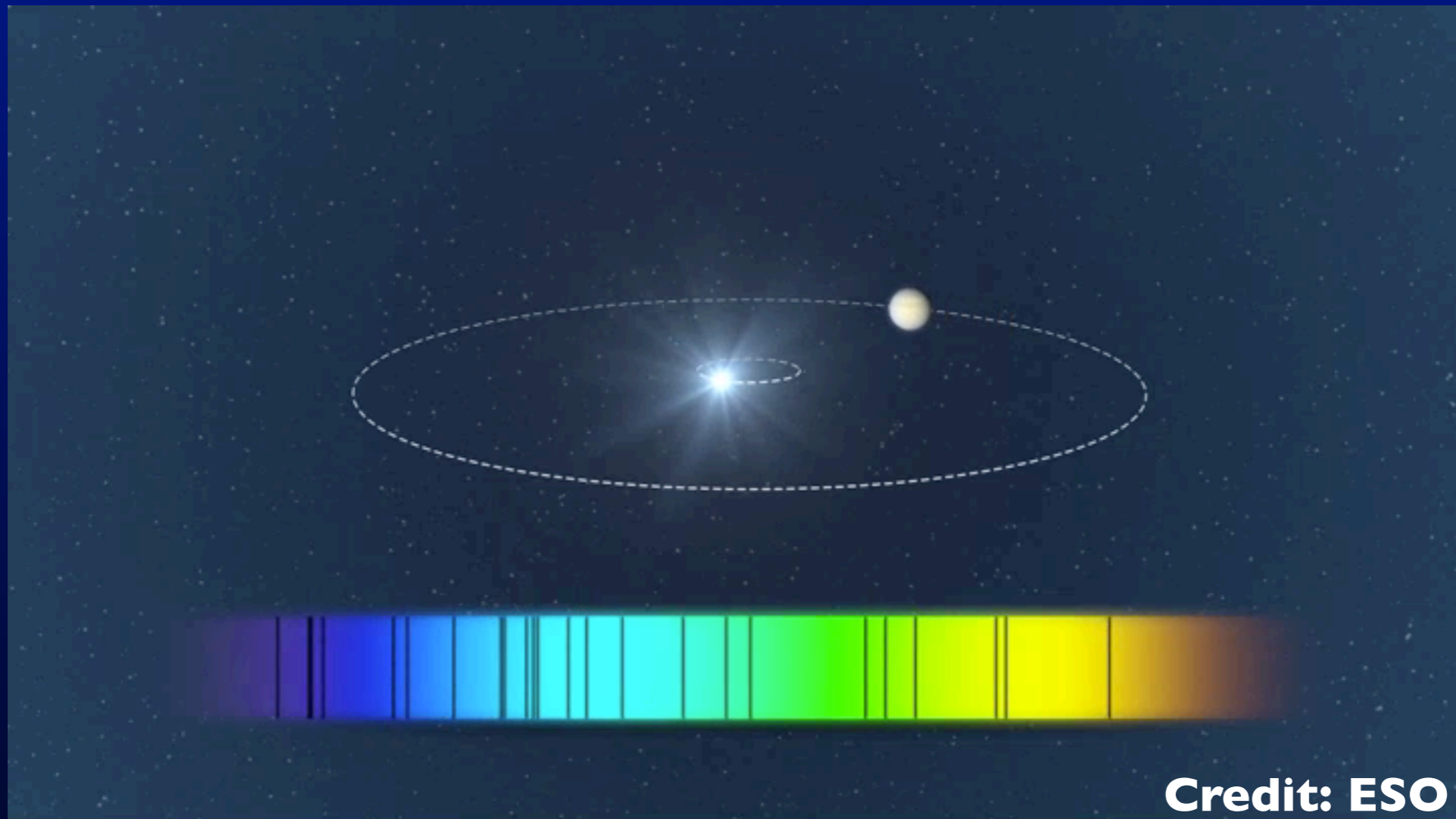
Young planets

PDS 70
Keppler et al. (2018)



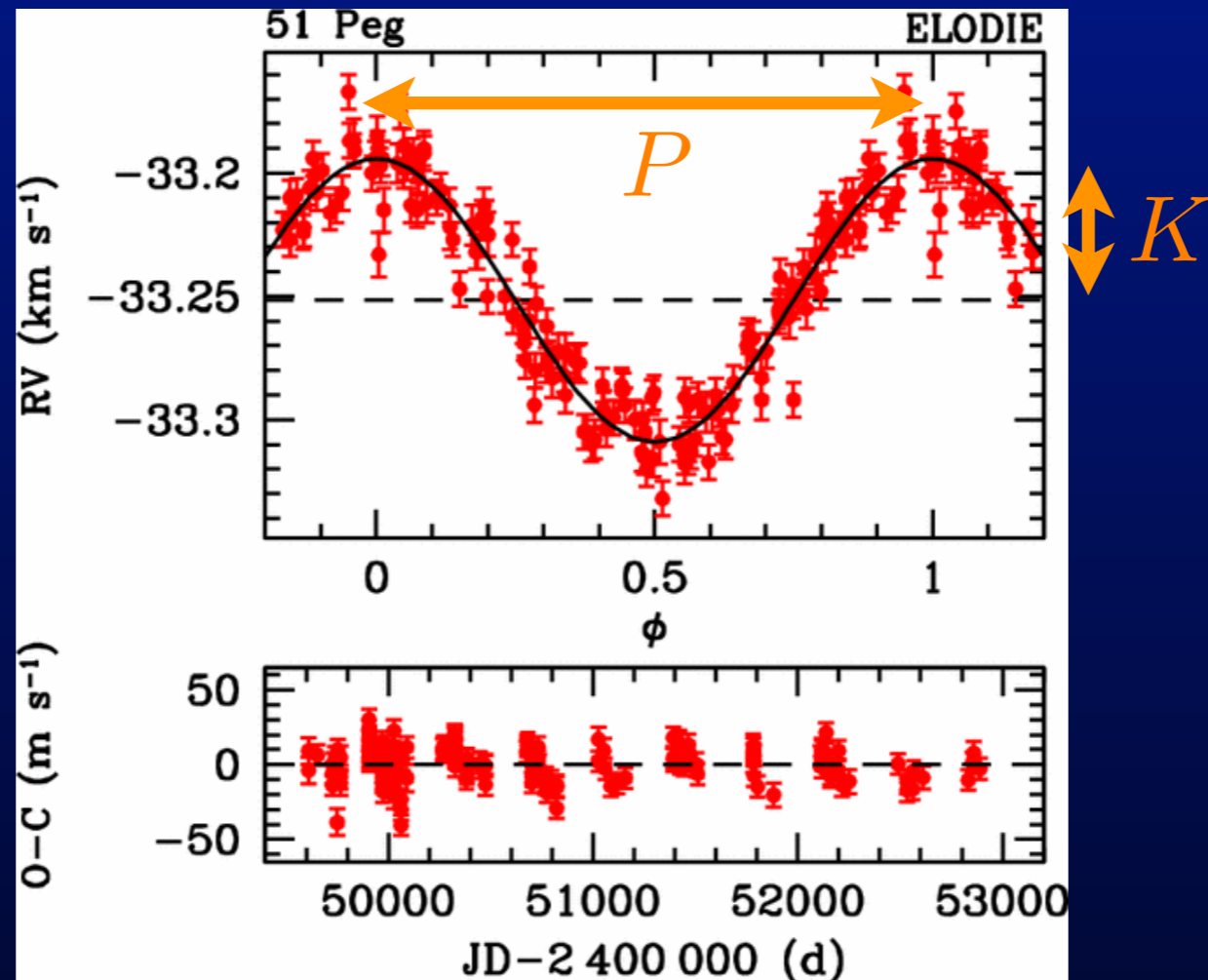
T Tauri star (5.4Myr).
Planet mass $\sim 5M_{Jup}$.
Proj. separation of
195mas (22AU).

Radial velocity methods



- Look for Doppler shifts caused by stellar reflex motion.
- RV surveys on-going since first detection in 1995. Now ~1000 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



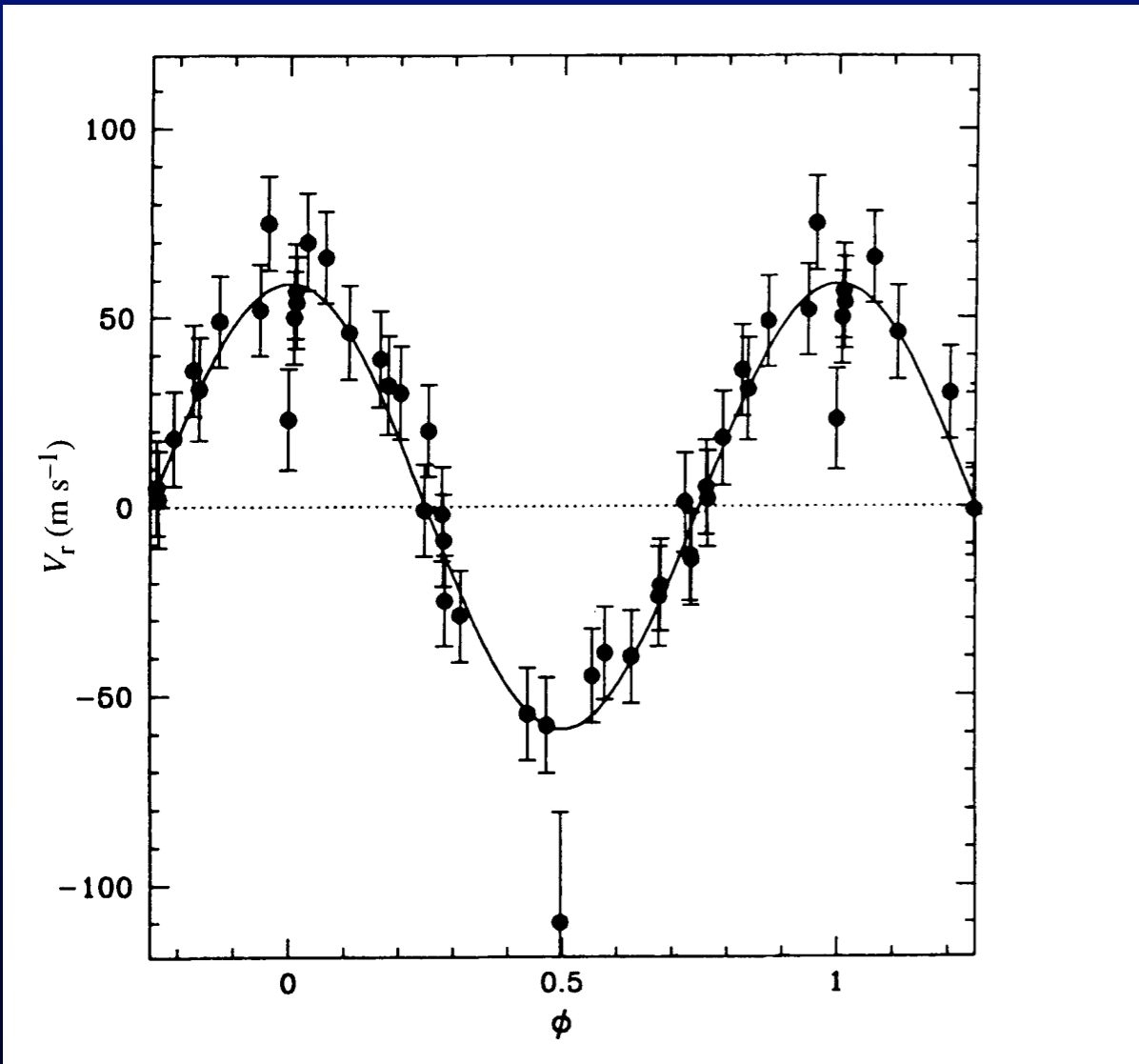
Mayor & Queloz (1995)

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

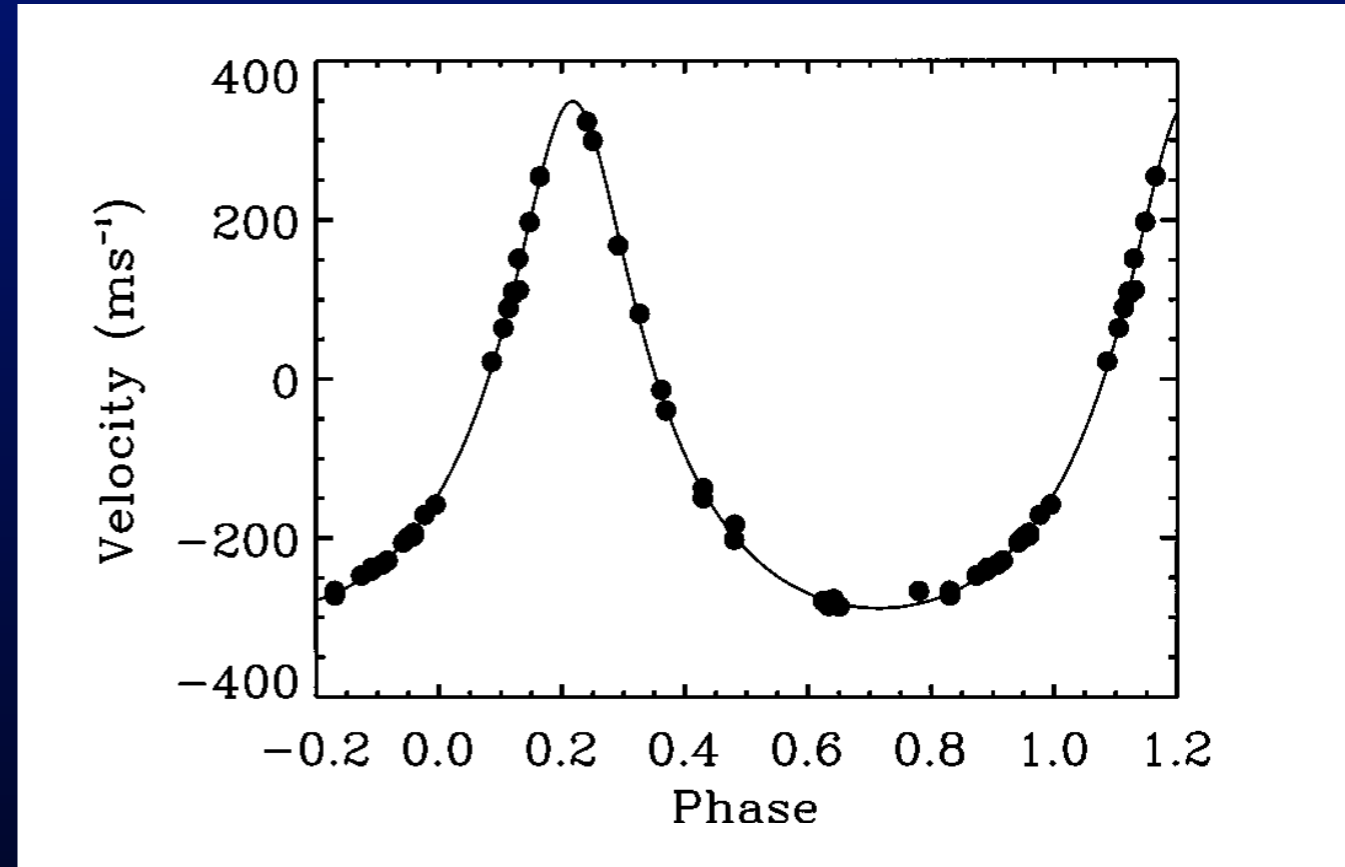
$$K = v_* \sin i = \frac{1}{\sqrt{1 - e^2}} \frac{M_p \sin i}{M_*} \sqrt{\frac{GM_*}{a}}$$

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

First detections...

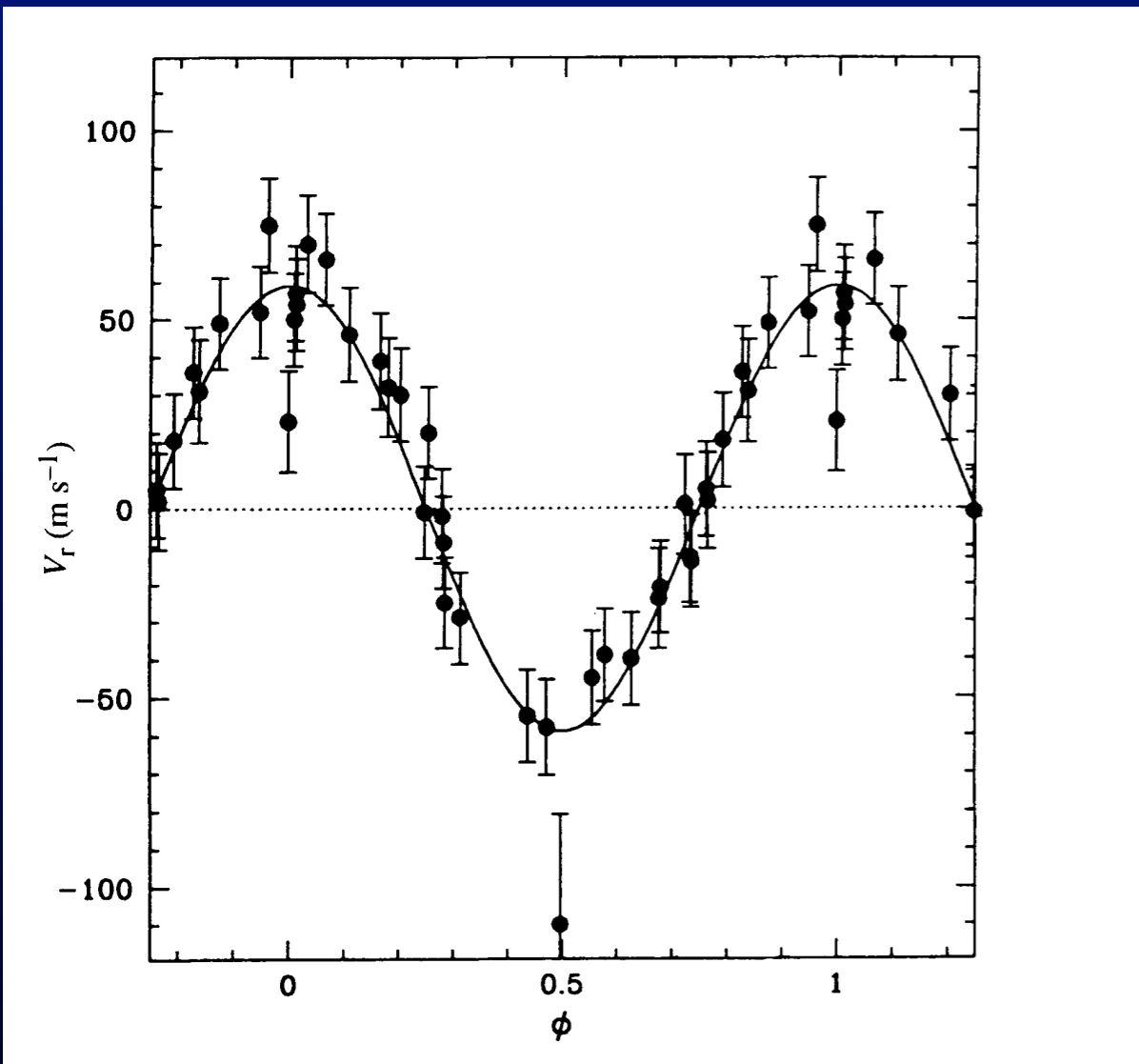


51 Peg b: Mayor & Queloz (1995)
Planet mass $0.47M_{\text{Jup}}$, Period 4.23d

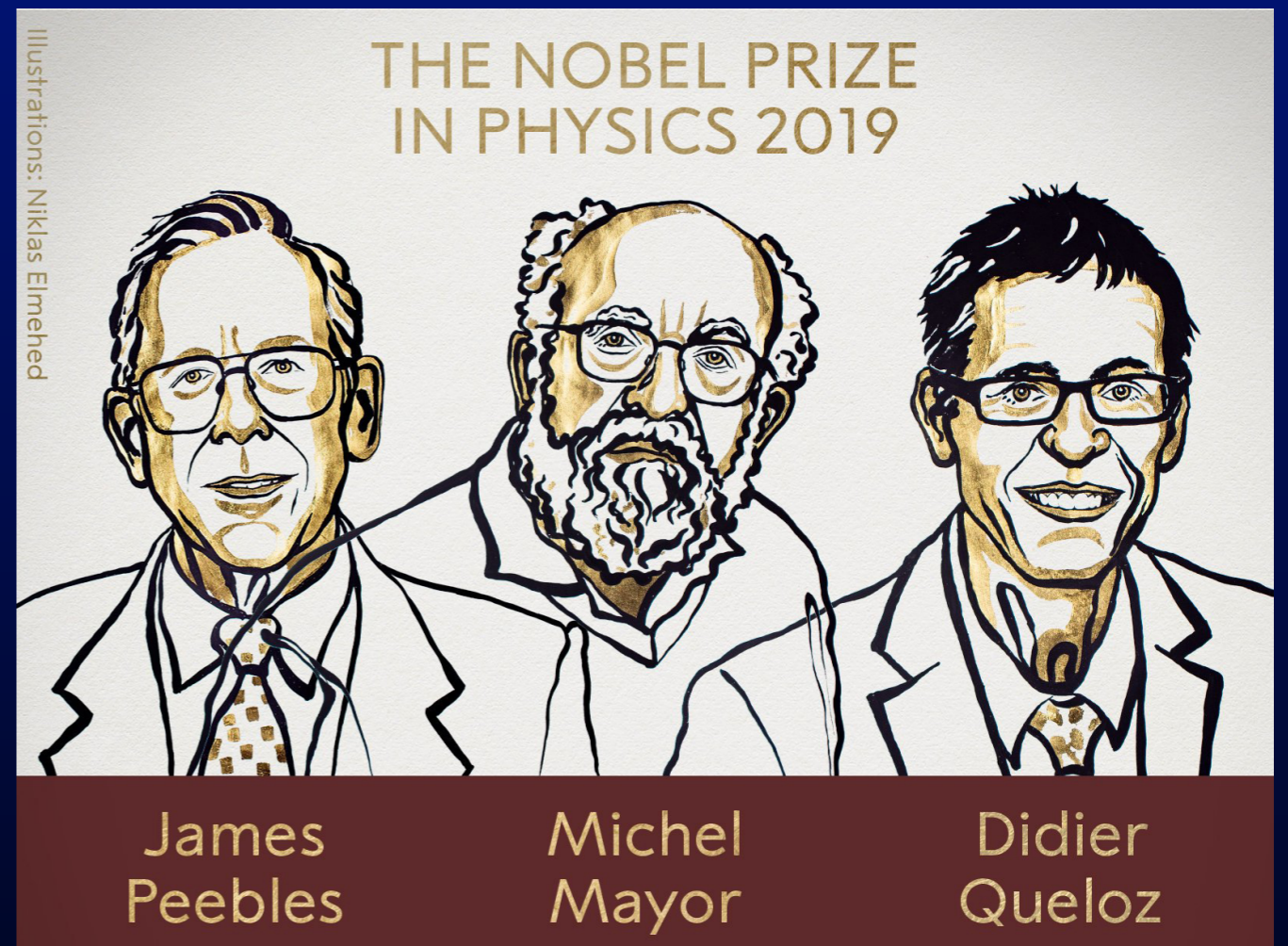


70 Vir b: Marcy & Butler (1996)
Planet mass $7.5M_{\text{Jup}}$, Period 117d

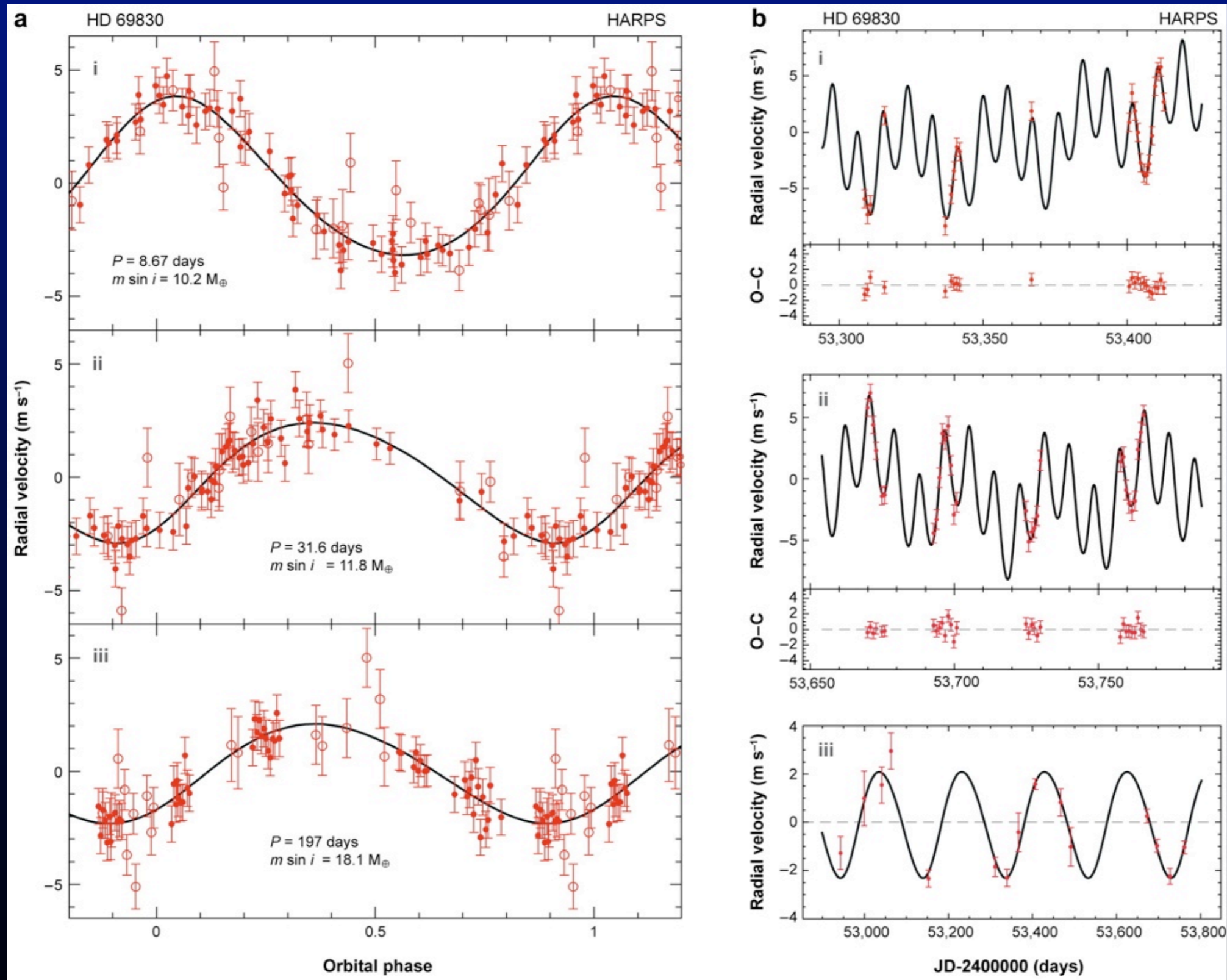
First detections...



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

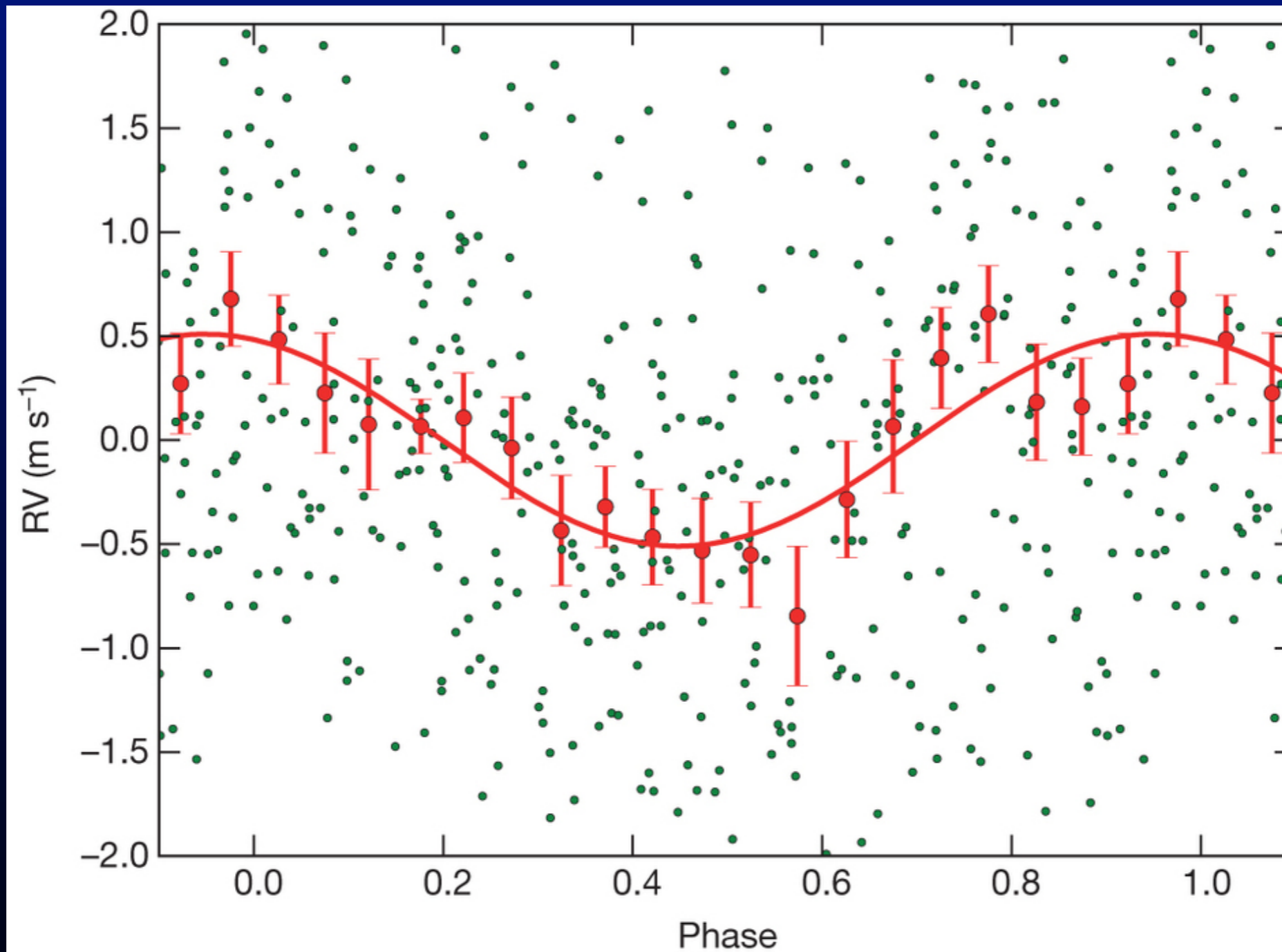


Typical RV data



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

The cutting edge??

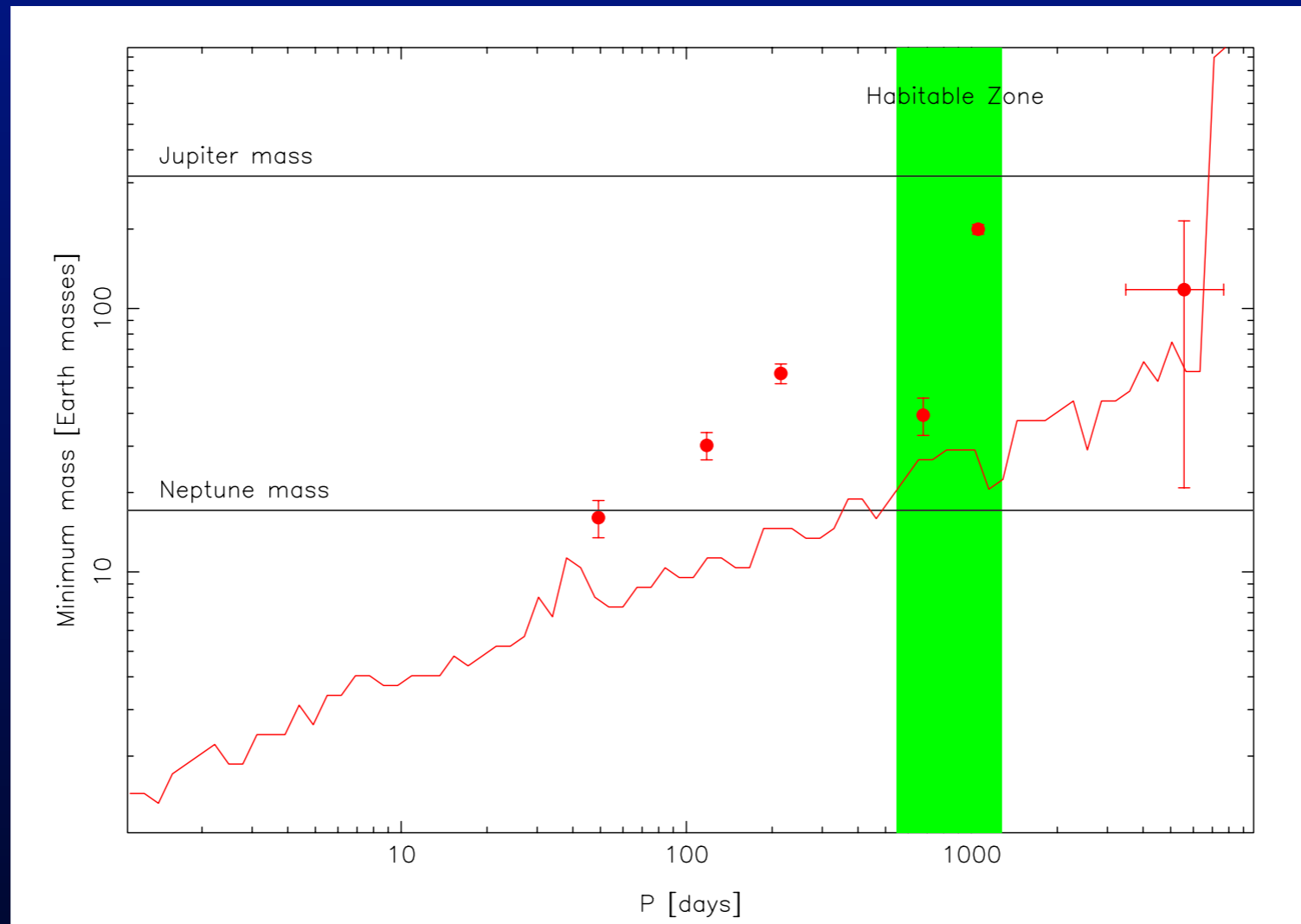


α Cen Bb: Dumusque et al. (2012)

Claimed planet mass $1.1 M_{\text{Earth}}$, $P=3.24\text{d}$, $K=51 \text{ cm/s}$

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

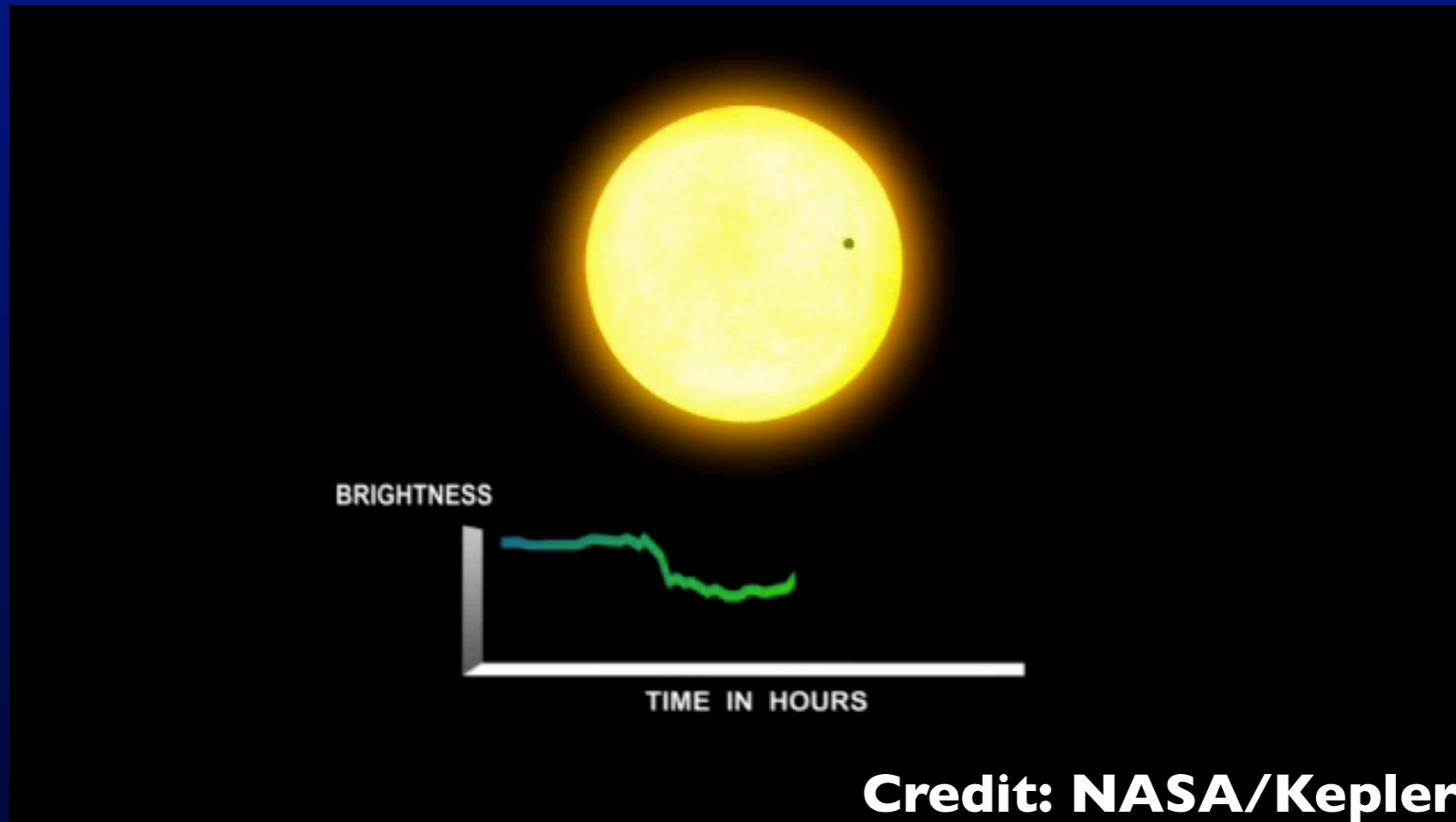
Long surveys, long periods...



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 $0.05\text{--}0.65M_{\text{Jup}}$; semi-major axes from 0.26–6.4AU.

Transit method



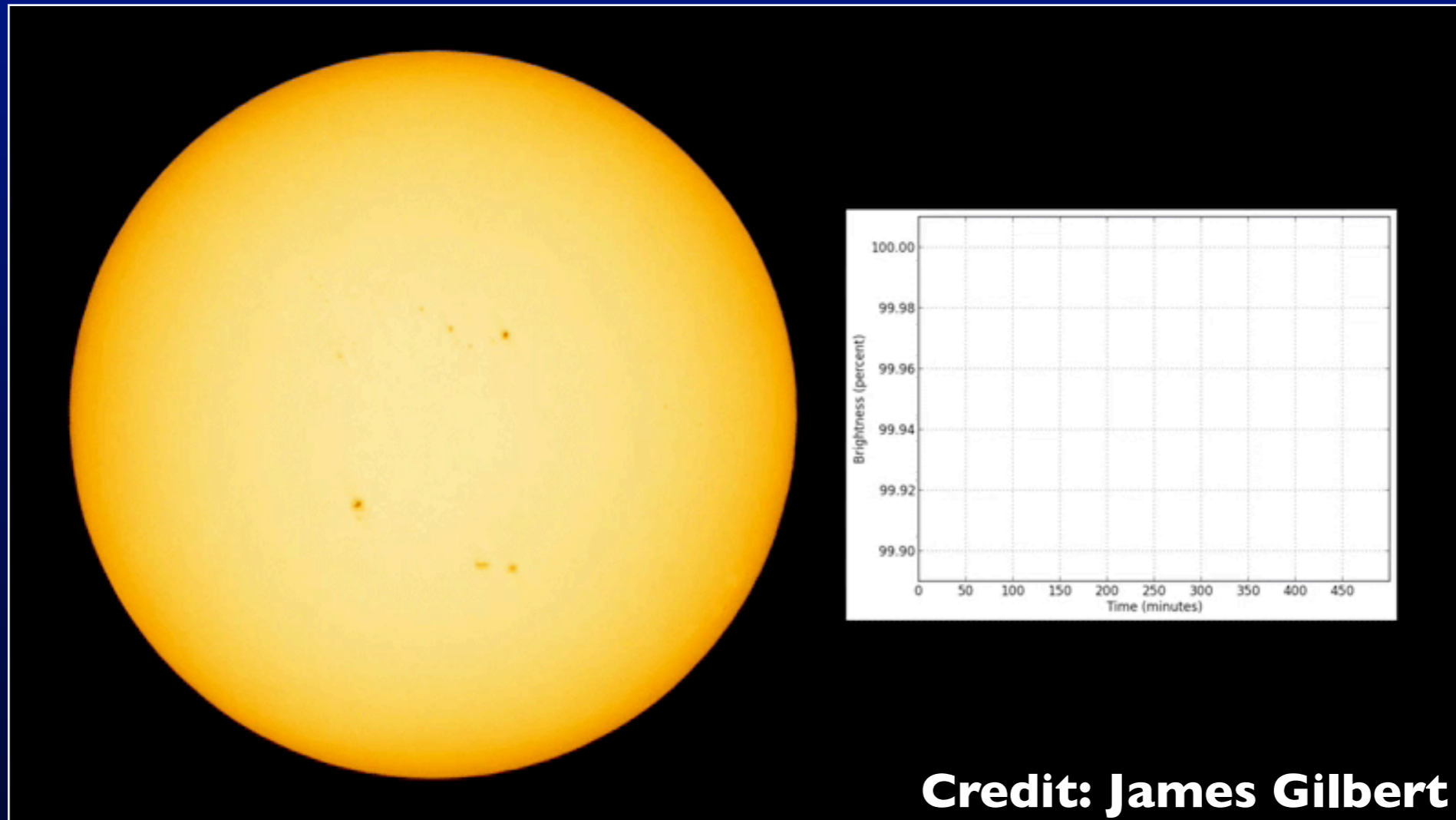
- Detect dimming of light as planet passes in front of star.
- Dimming fraction f depends on planet size:

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

$$f_{Jup} \simeq 0.01$$

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

Transit method



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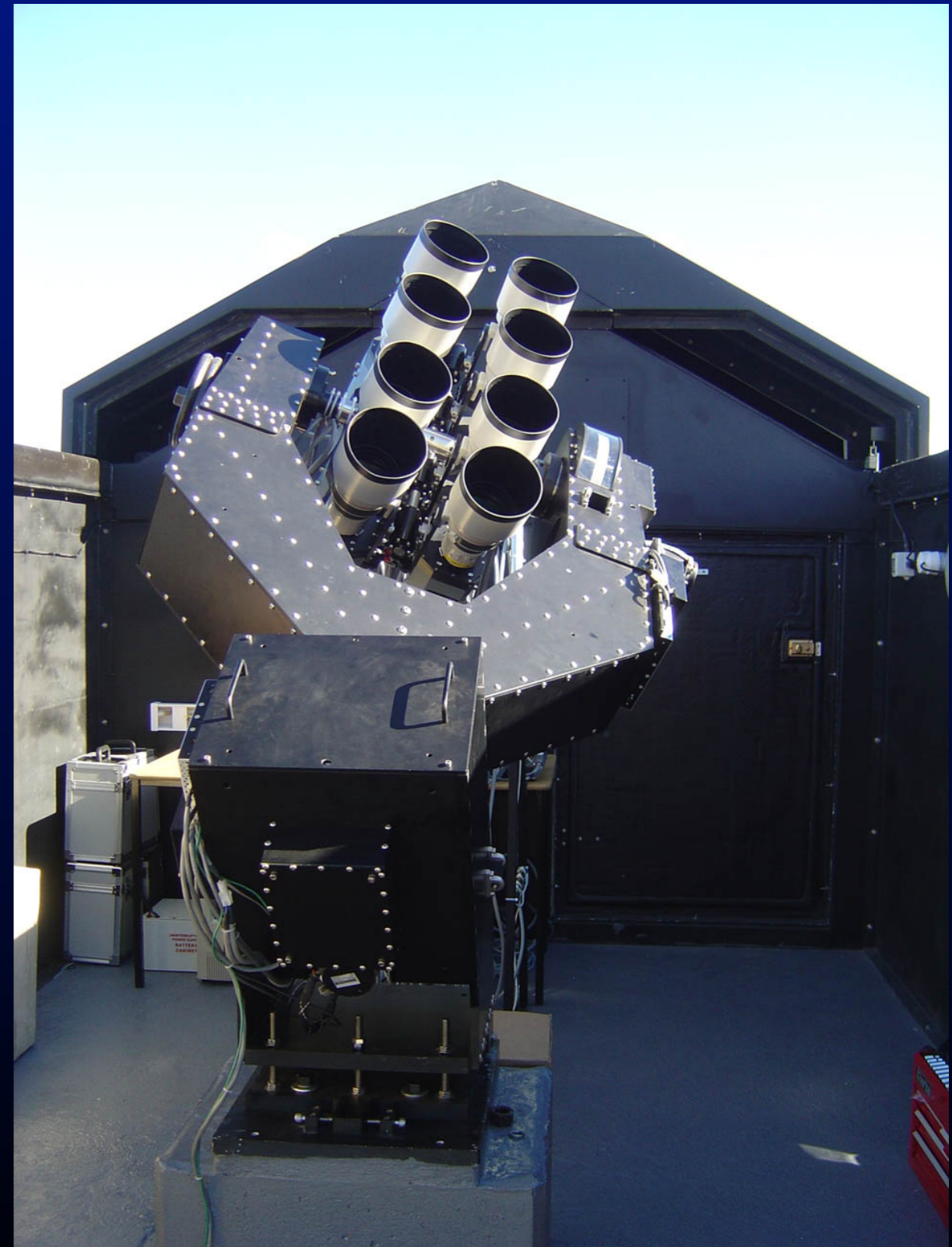
$$f_{\oplus} \simeq 1 \times 10^{-4}$$

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.

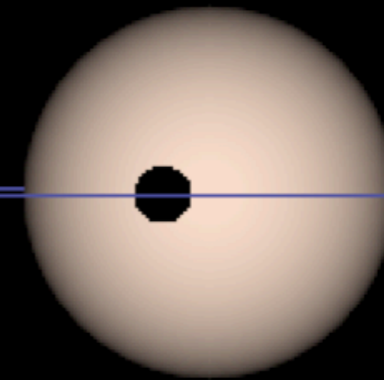
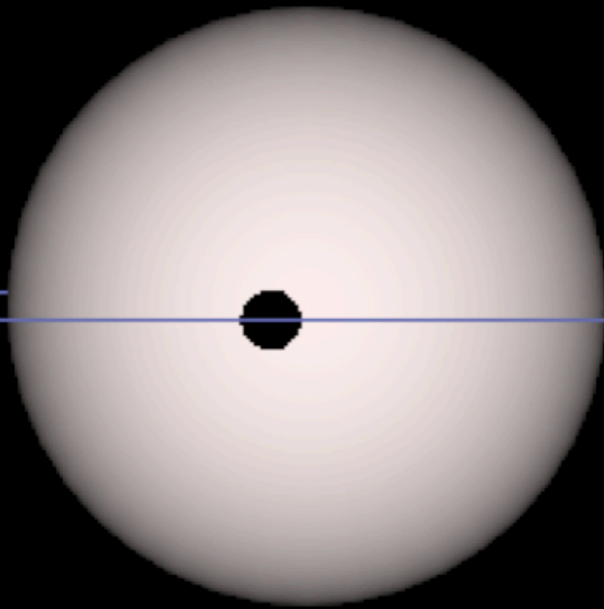
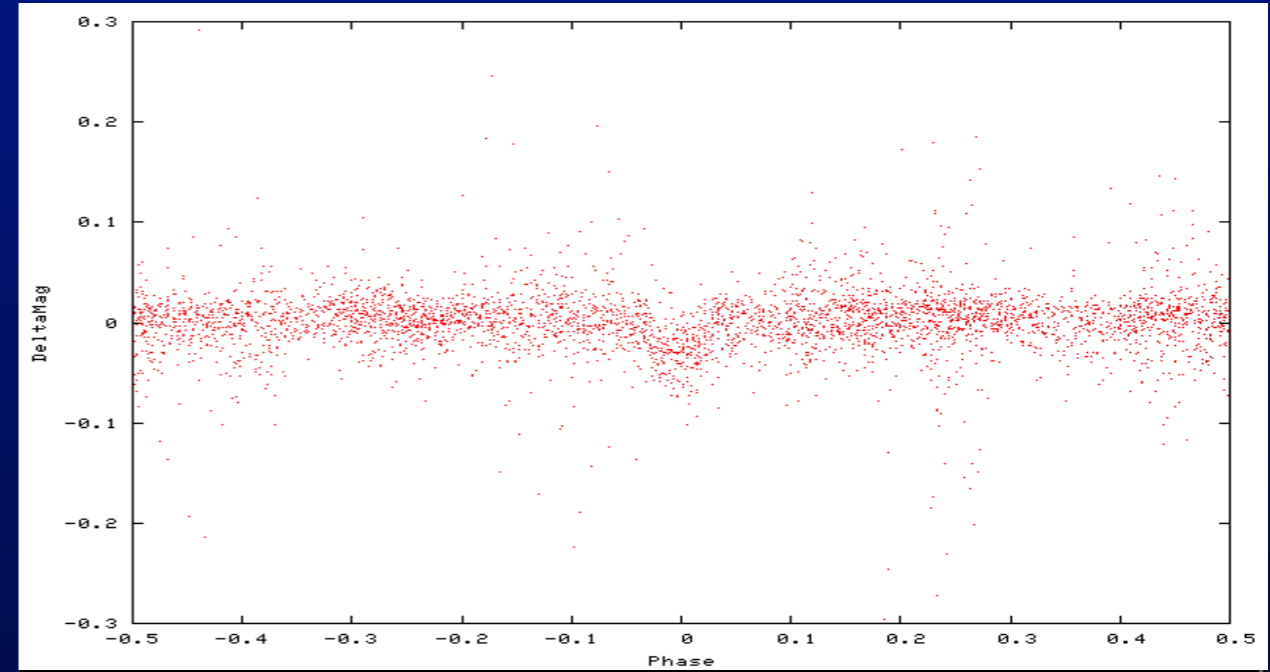
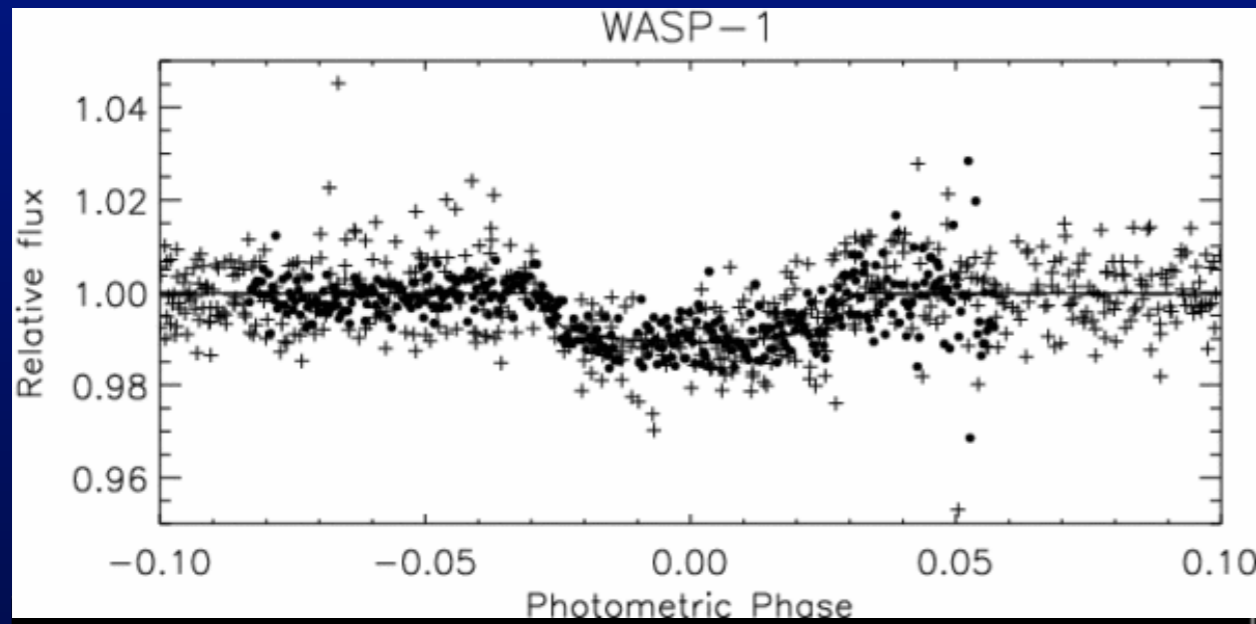
Transit method

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



Credit: Richard West

Ground-based transit lightcurves



Next Generation...

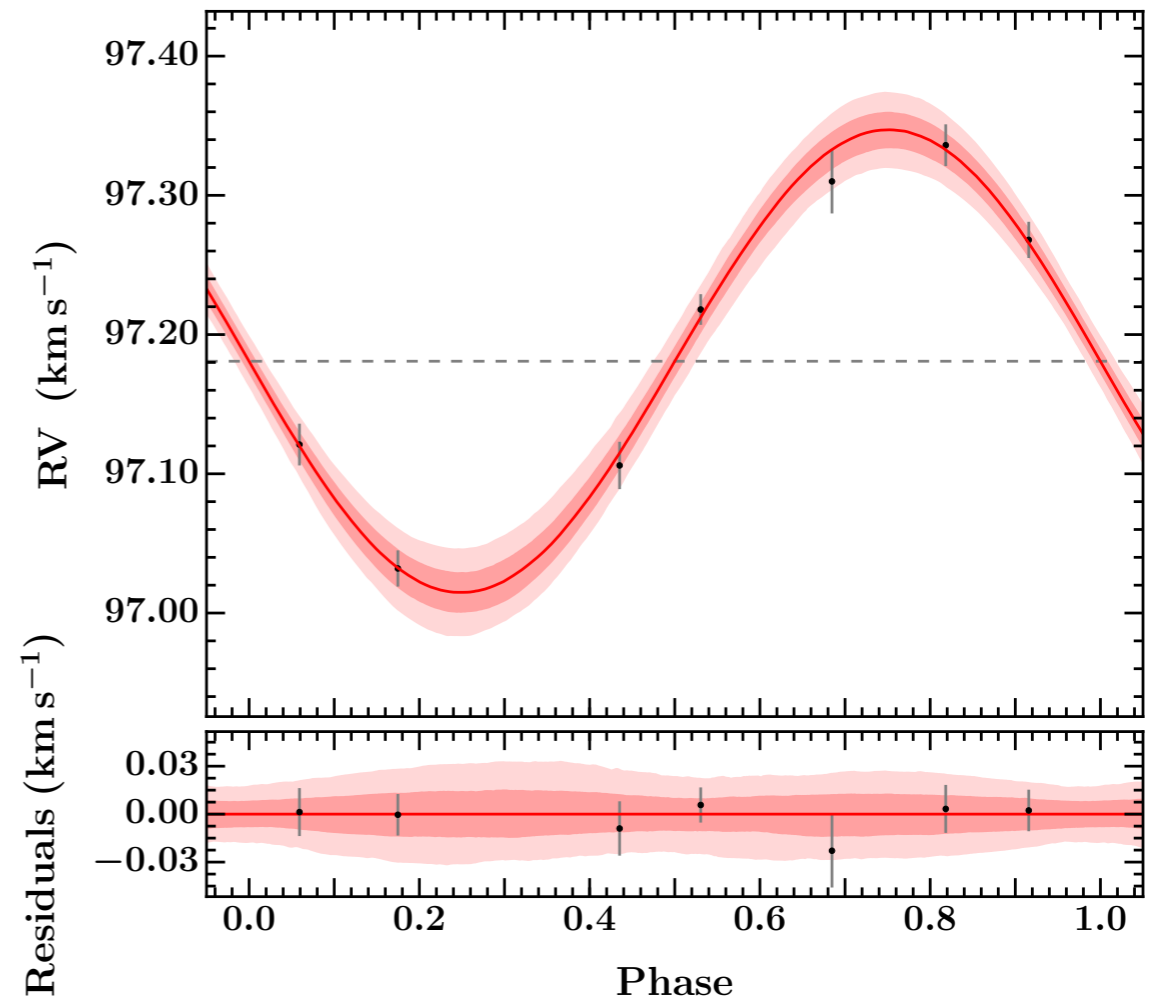
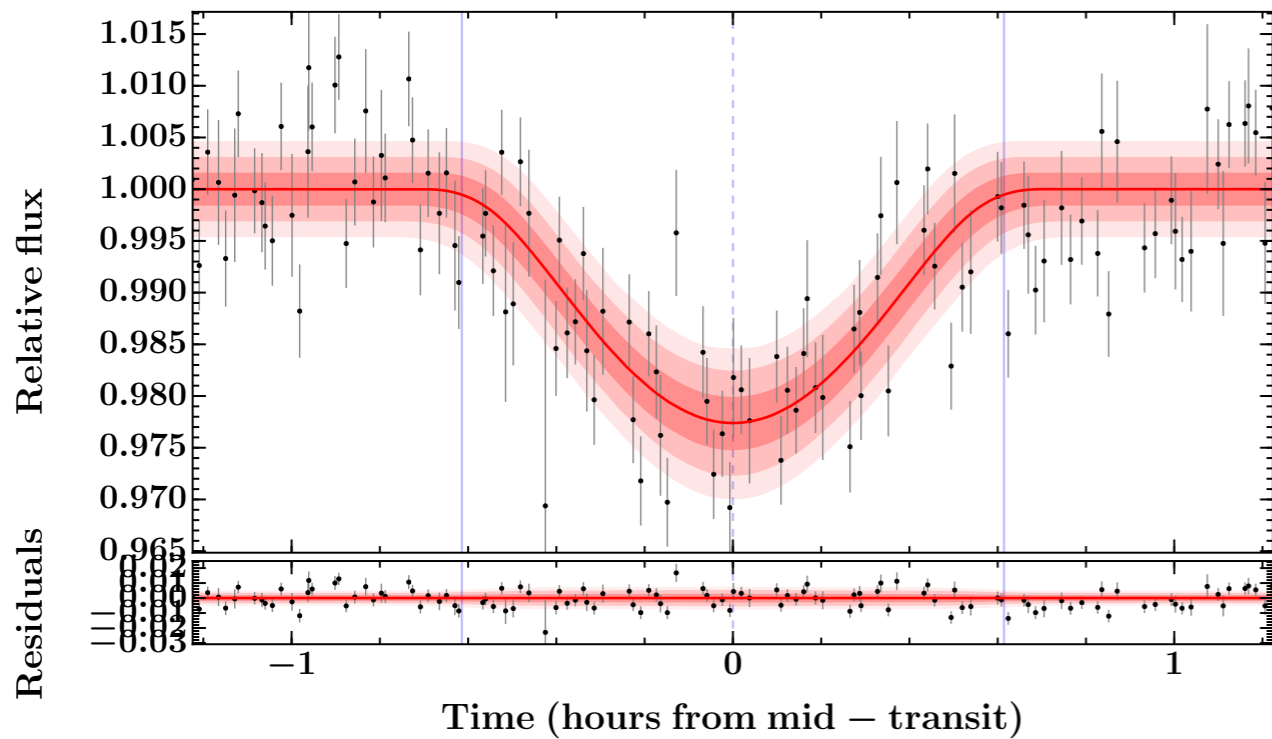


Credit: ESO/Richard West

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



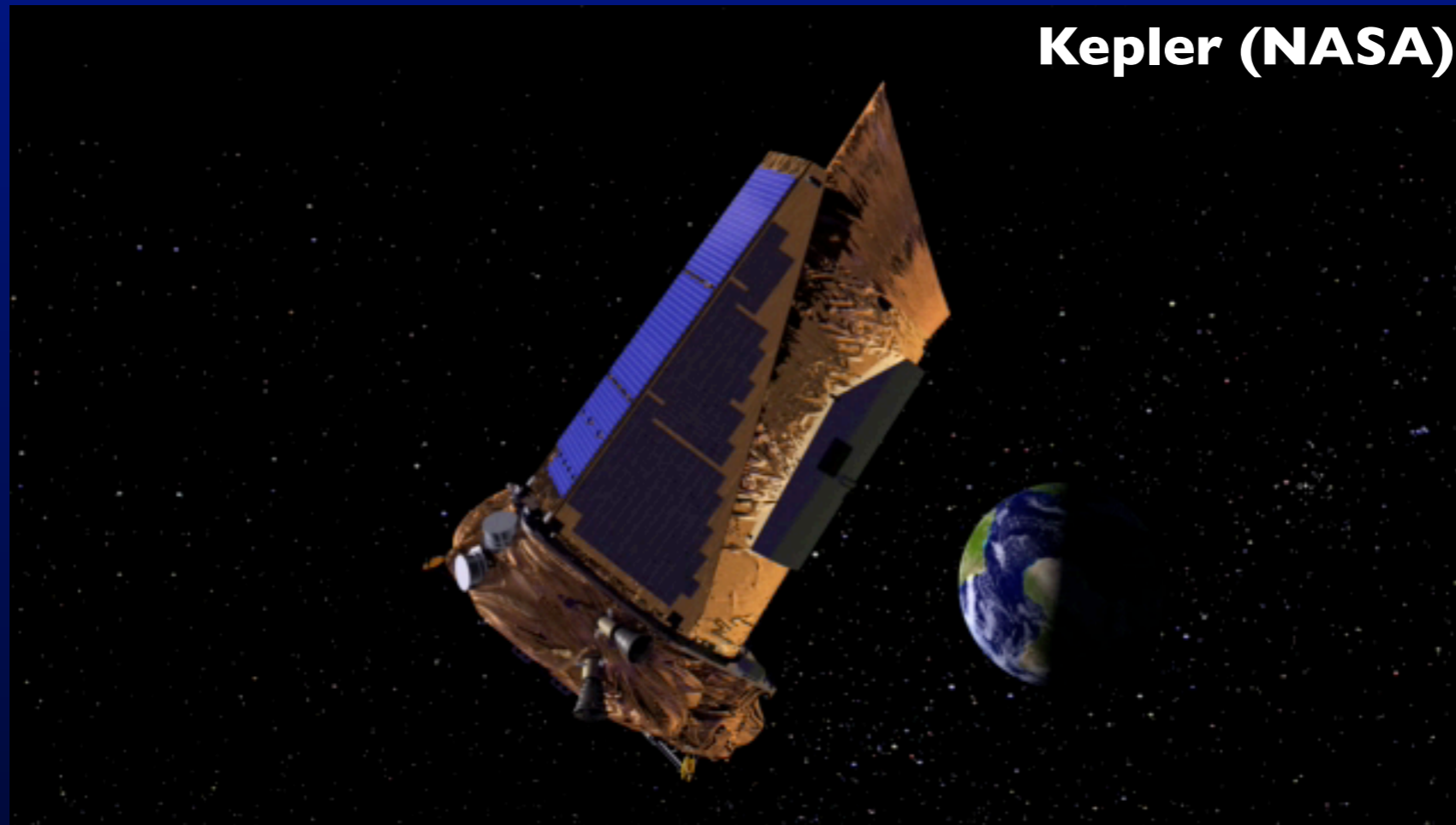
Ground-based cutting edge



Bayliss+ (2017)

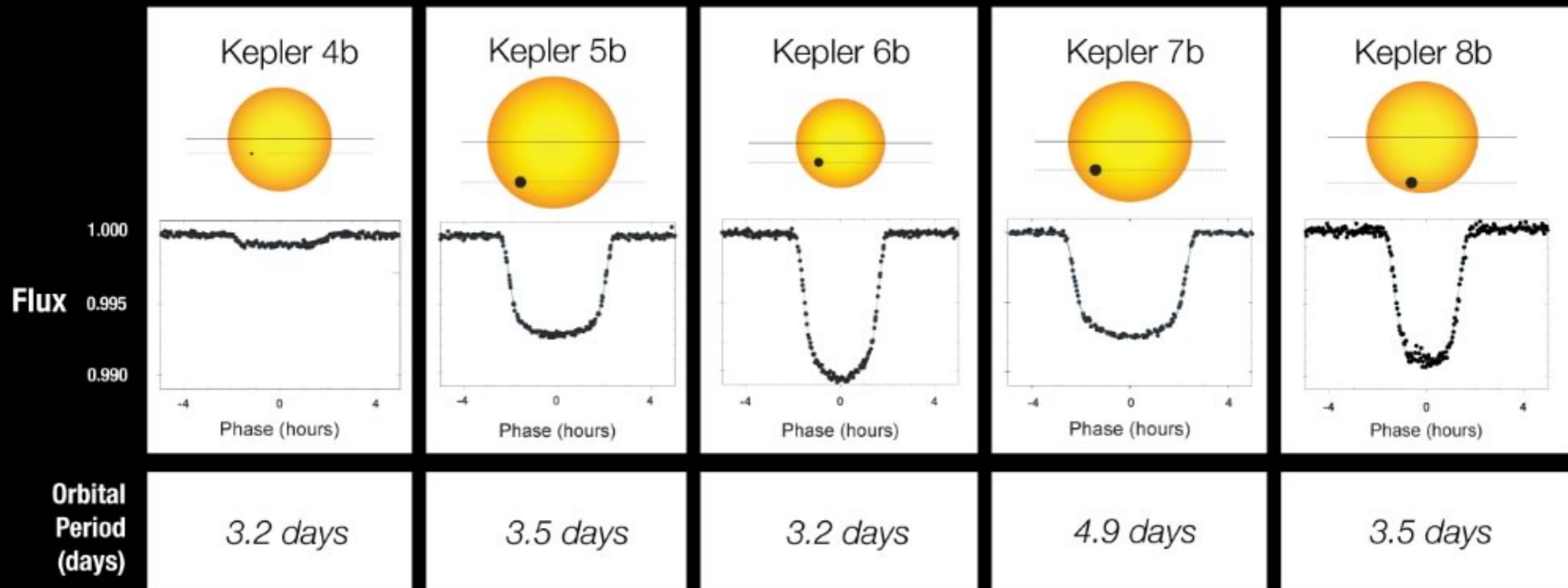
- First exoplanet discovery from NGTS.
- $0.8M_{\text{Jup}}$ planet in 2.65d orbit around a M0/M1-type host star.
- Most massive planet known around an M-dwarf. NGTS is providing first large census of planets around low-mass stars.

Kepler



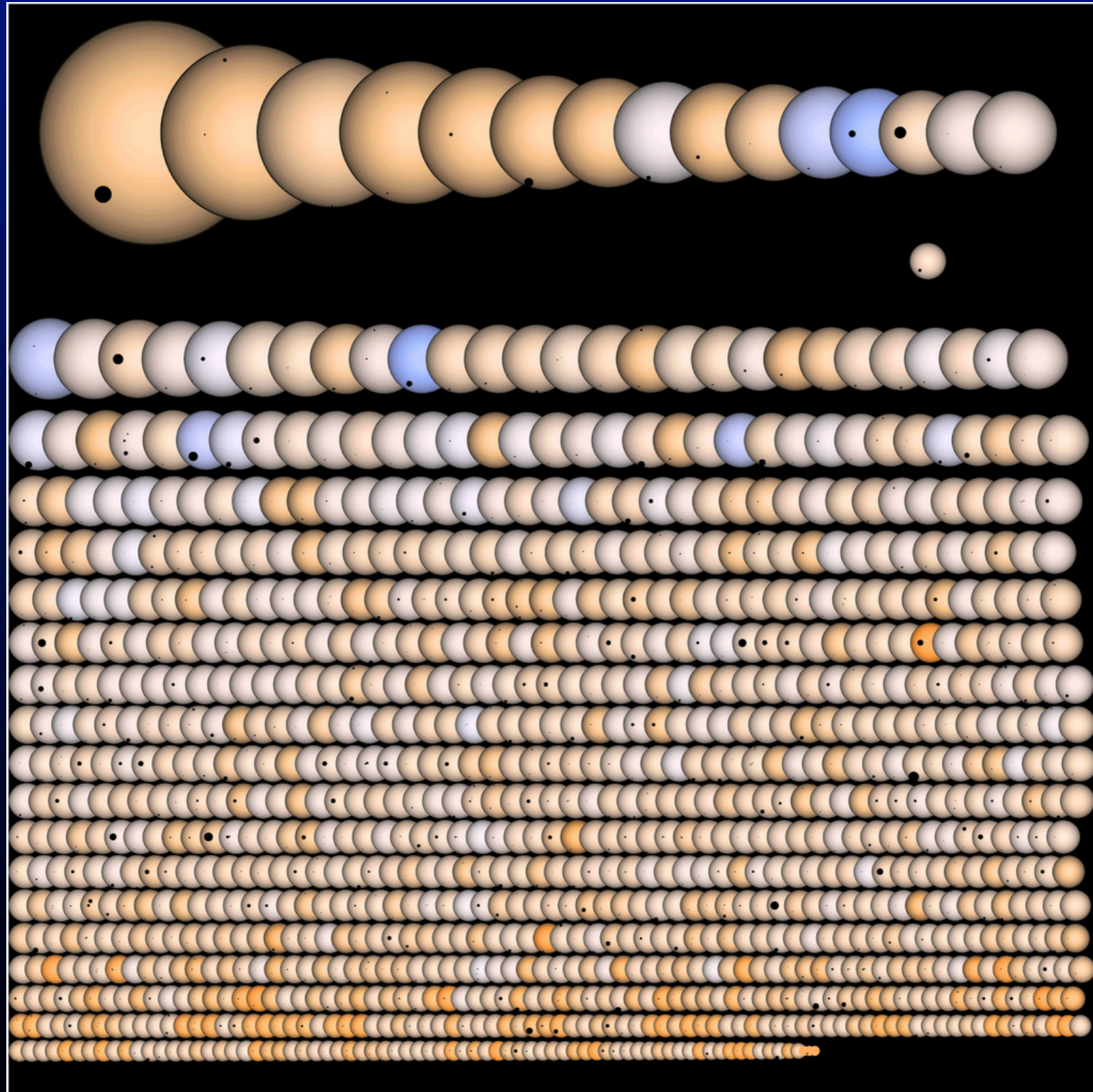
- Launched March 2009, 0.95m primary; “died” May 2013. Lived on as K2 until late 2018.
- 12° FOV, 42 CCD camera. “Stared” at fixed patch of (blank) sky to obtain light-curves for >150,000 stars.
- Photometric precision as good as ~10ppm (in some cases). Sensitive to sub-Earth-size planets.

Kepler light-curves

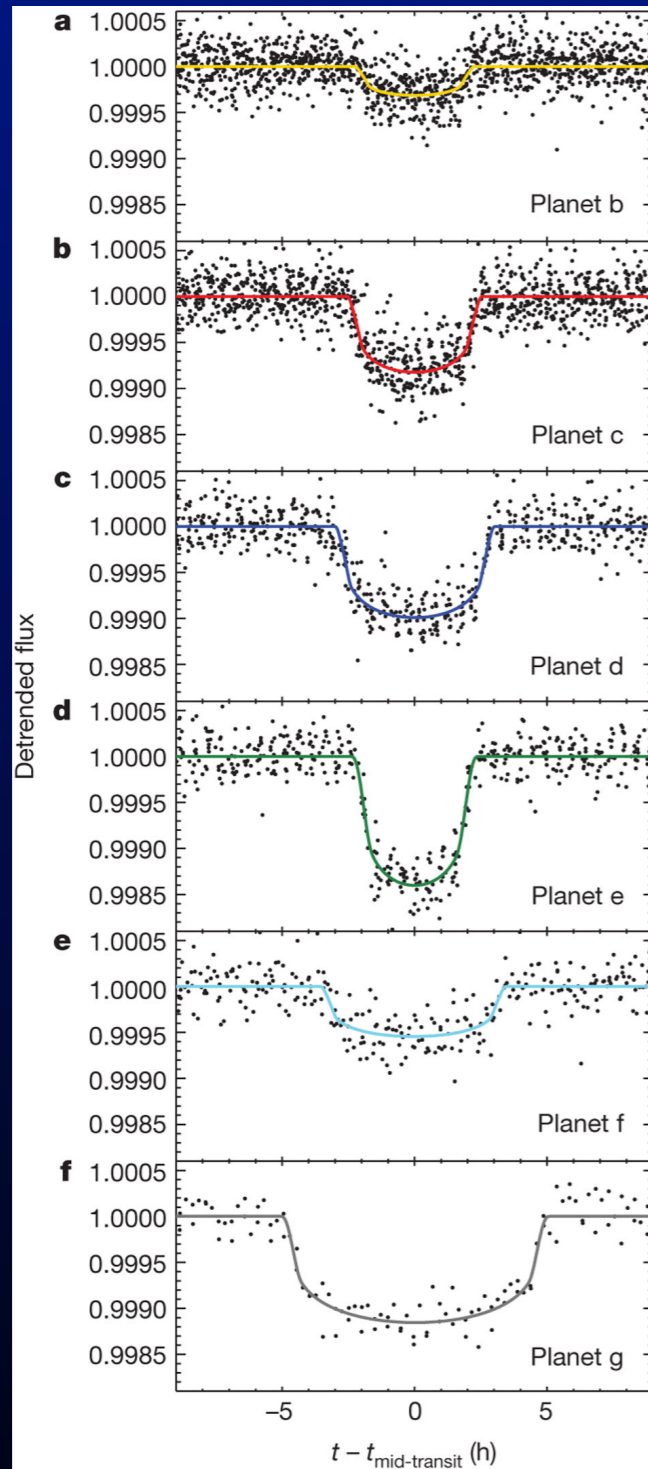


- Early data release (June 2010) focused on a few “hot Jupiters”, to demonstrate precision.
- Fourth (& final) major data release in January 2014. Total of ~4500 planet candidates, with >2000 now confirmed.

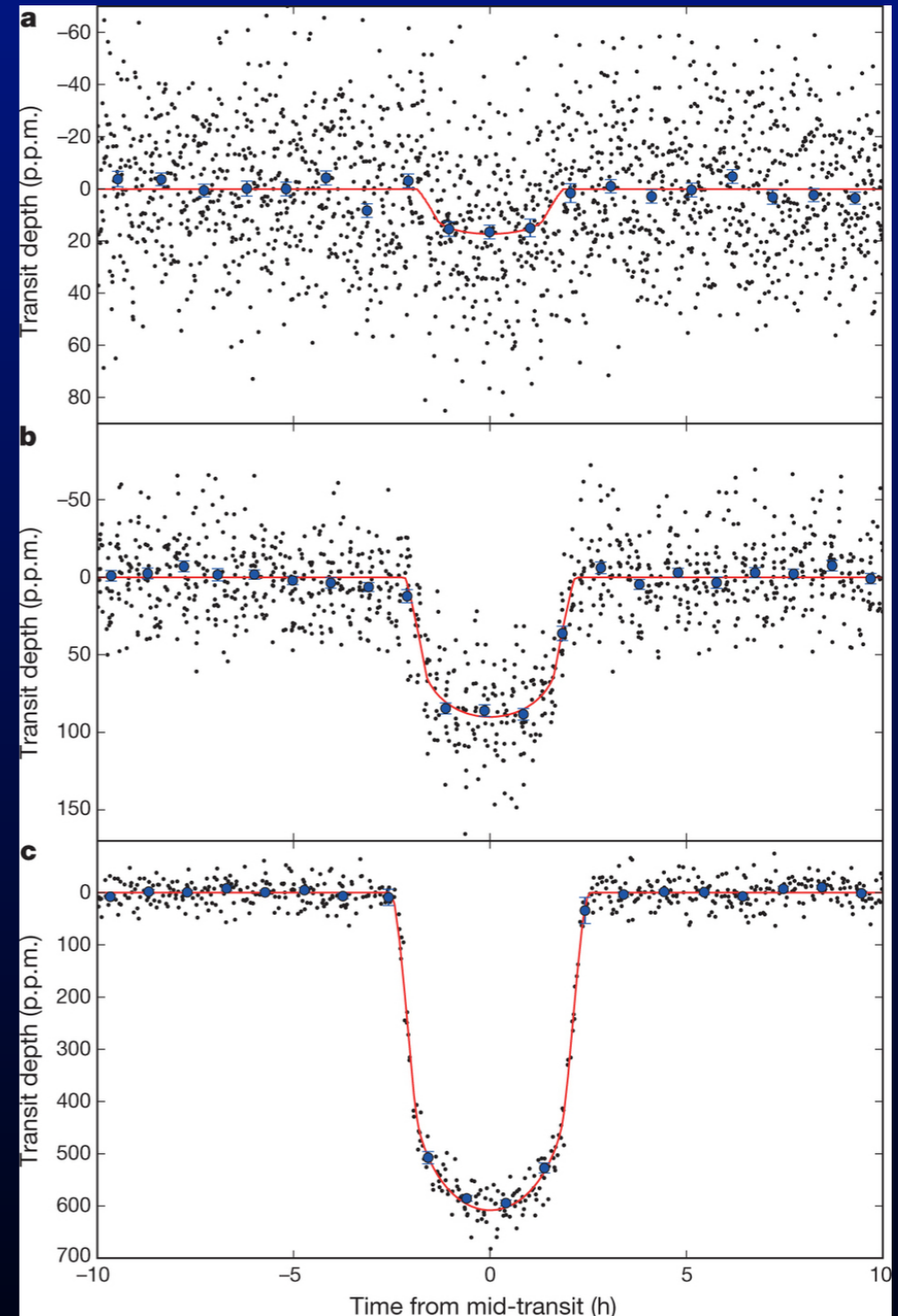
Kepler: first results



Kepler examples



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



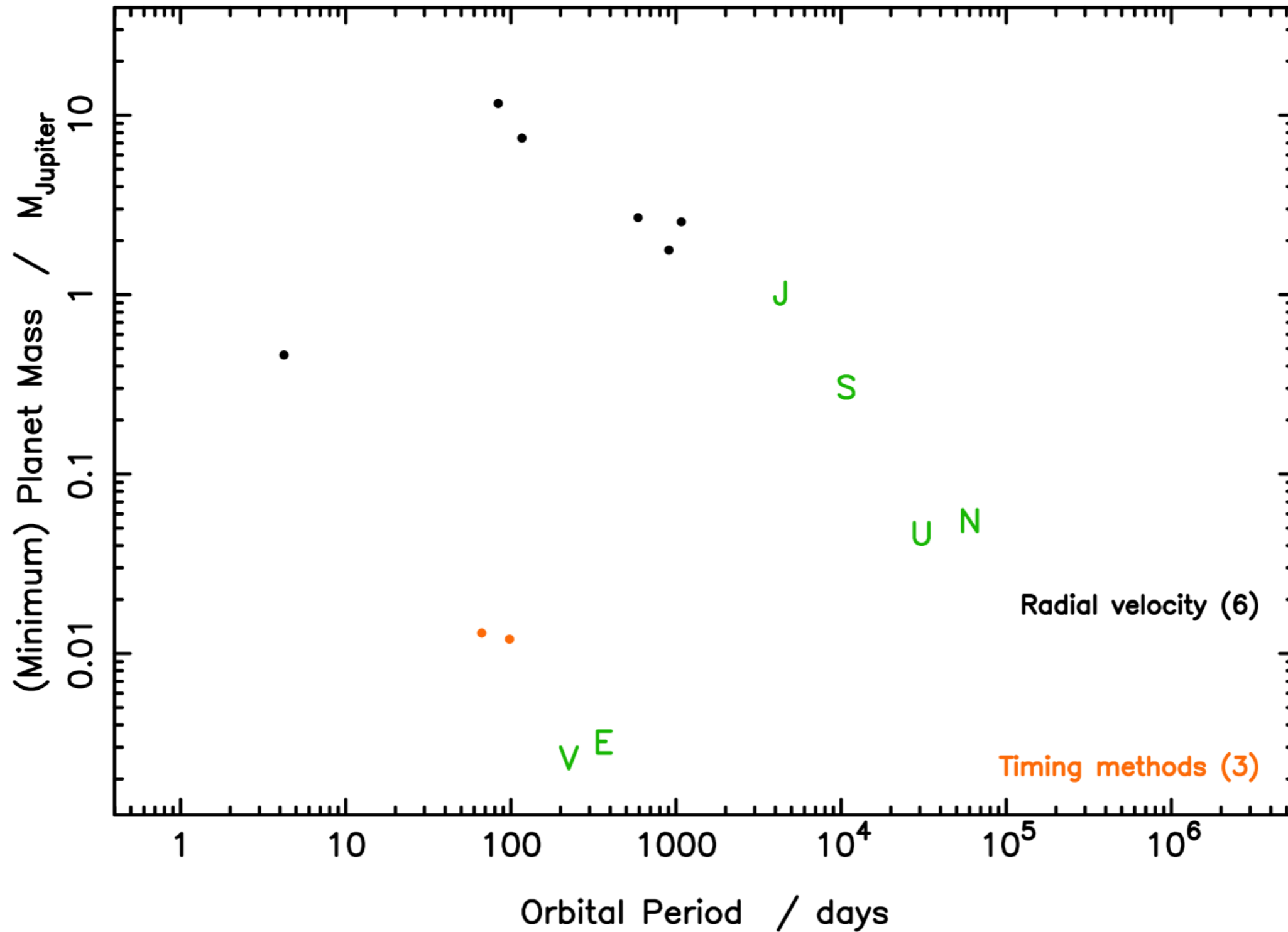
Kepler-37: Barclay et al. (2013)
3-planet system, periods 13.4, 21.3, 39.8d.
“b” is roughly the size of the Moon.

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).

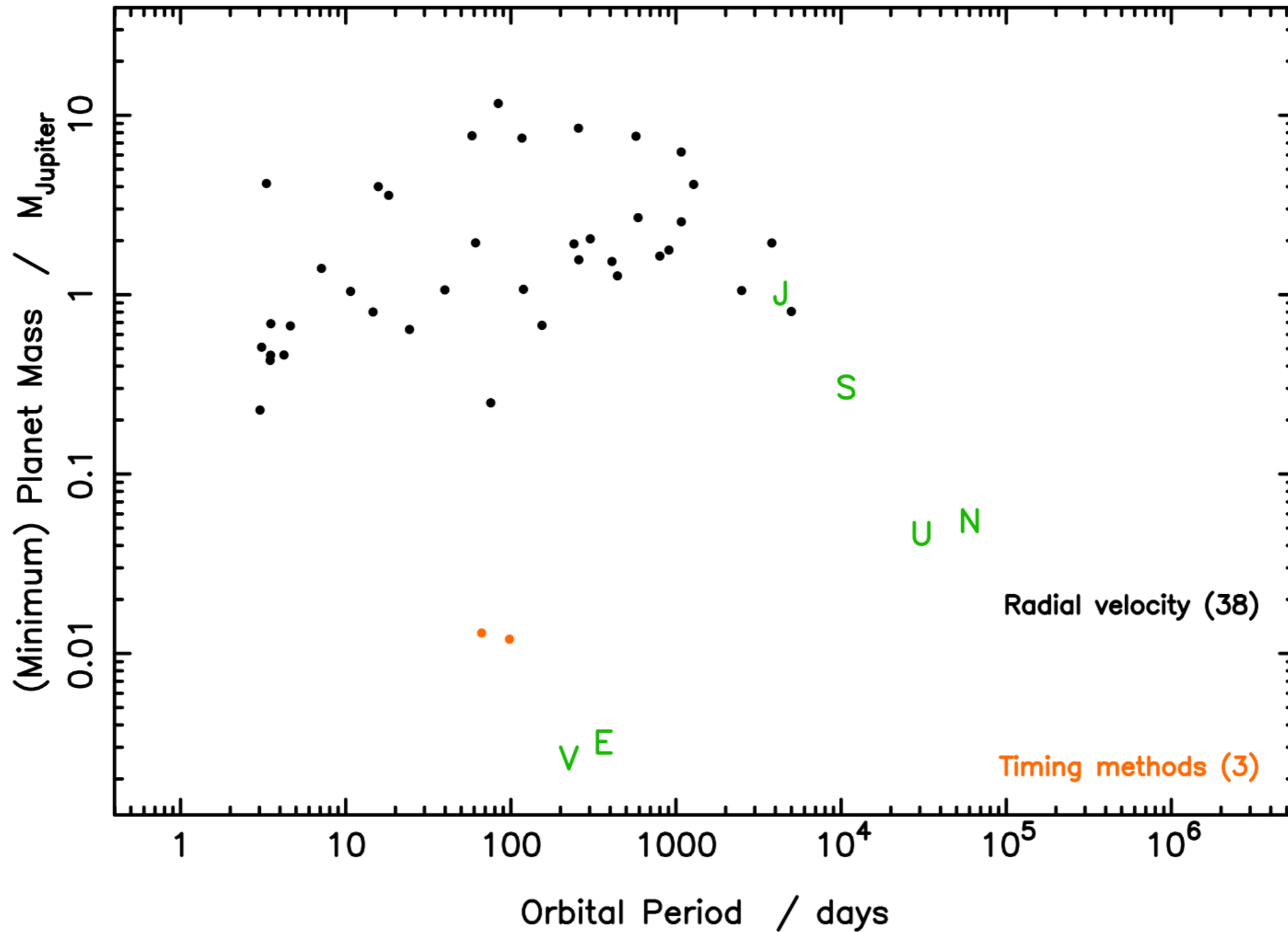
*The first transiting planet was found in 1999, but it was a known RV planet.

Known planets as of 1996



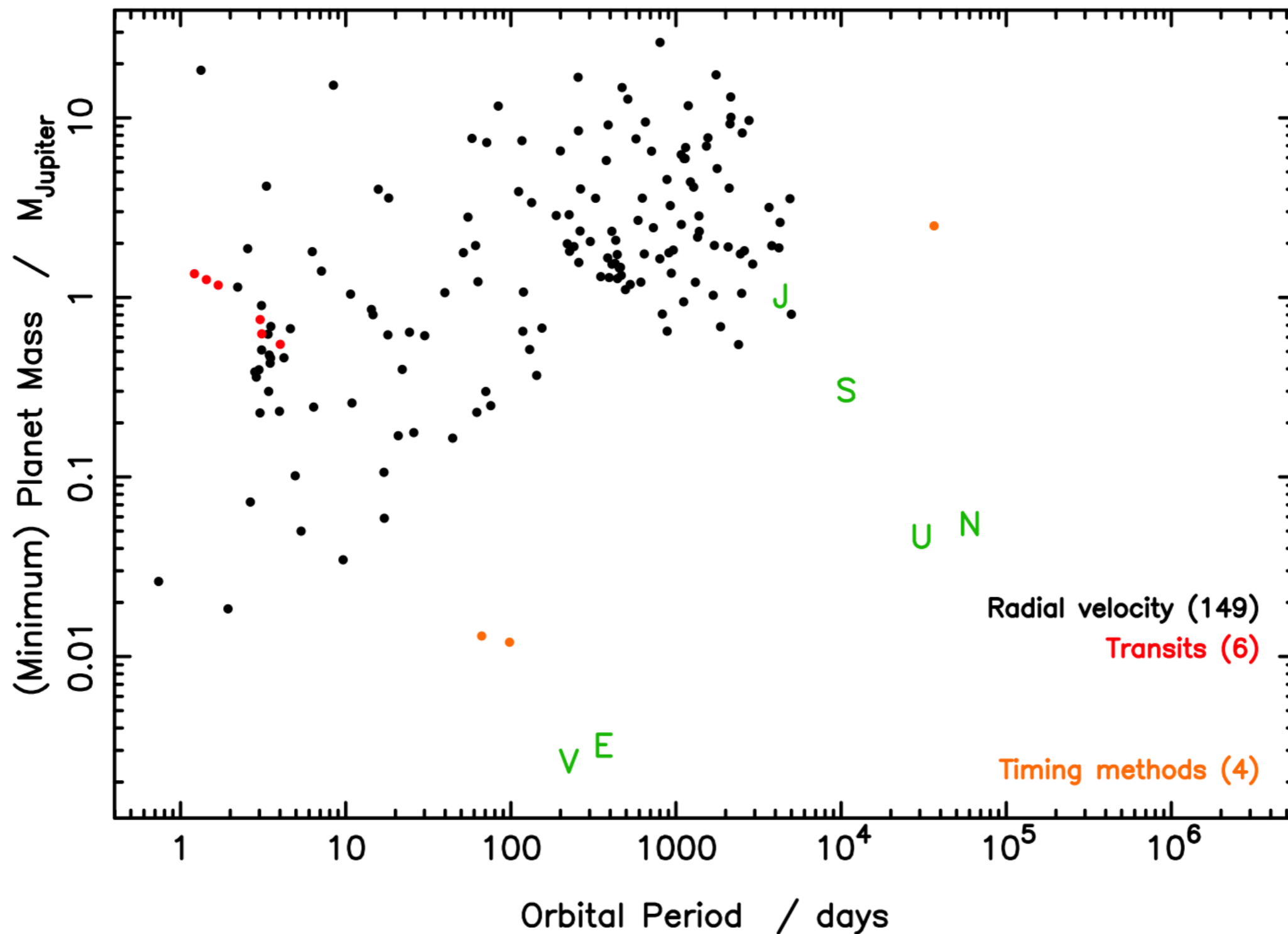
Data from exoplanet.eu

Known planets as of 2000



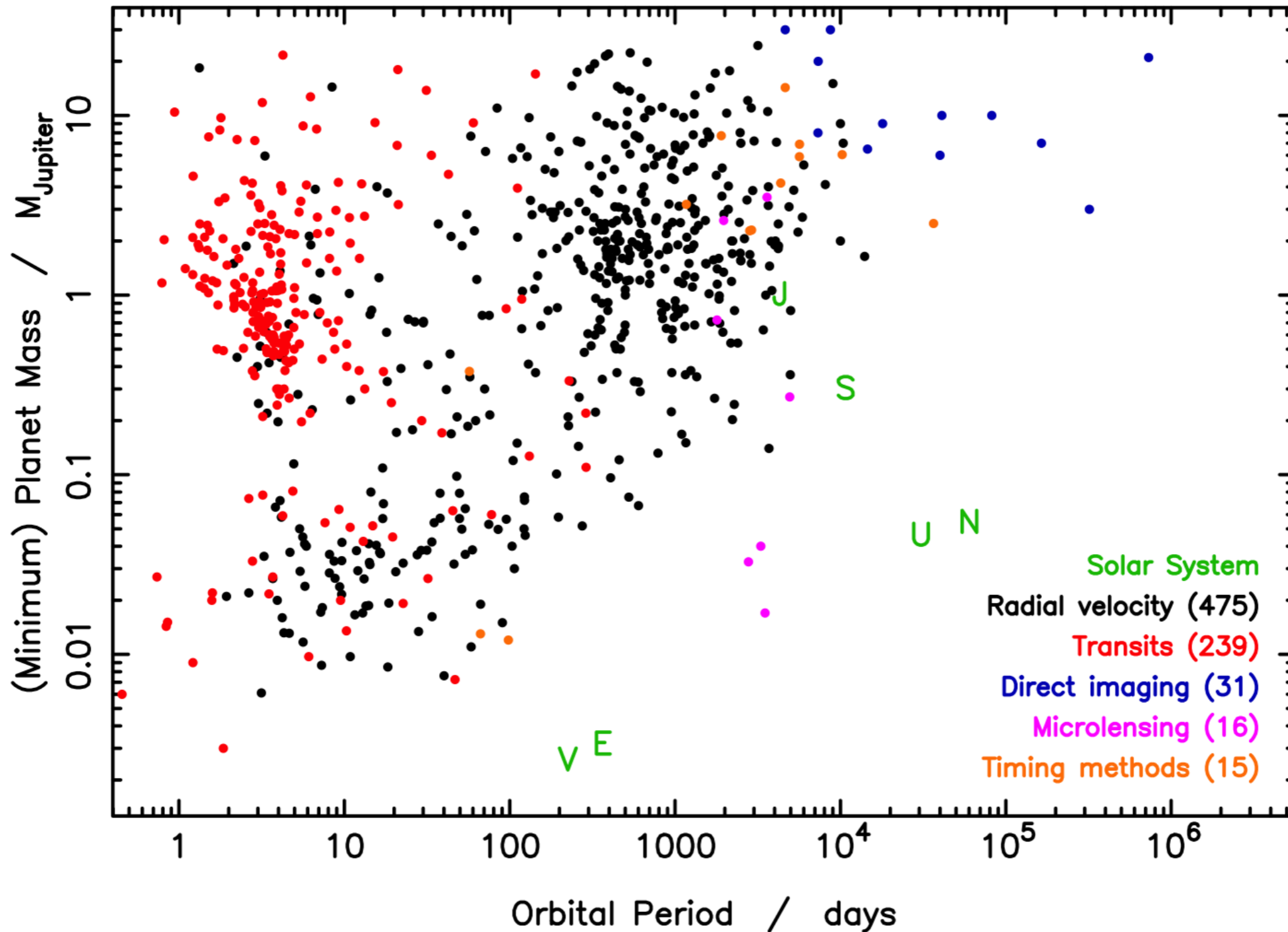
Data from exoplanet.eu

Known planets as of 2005



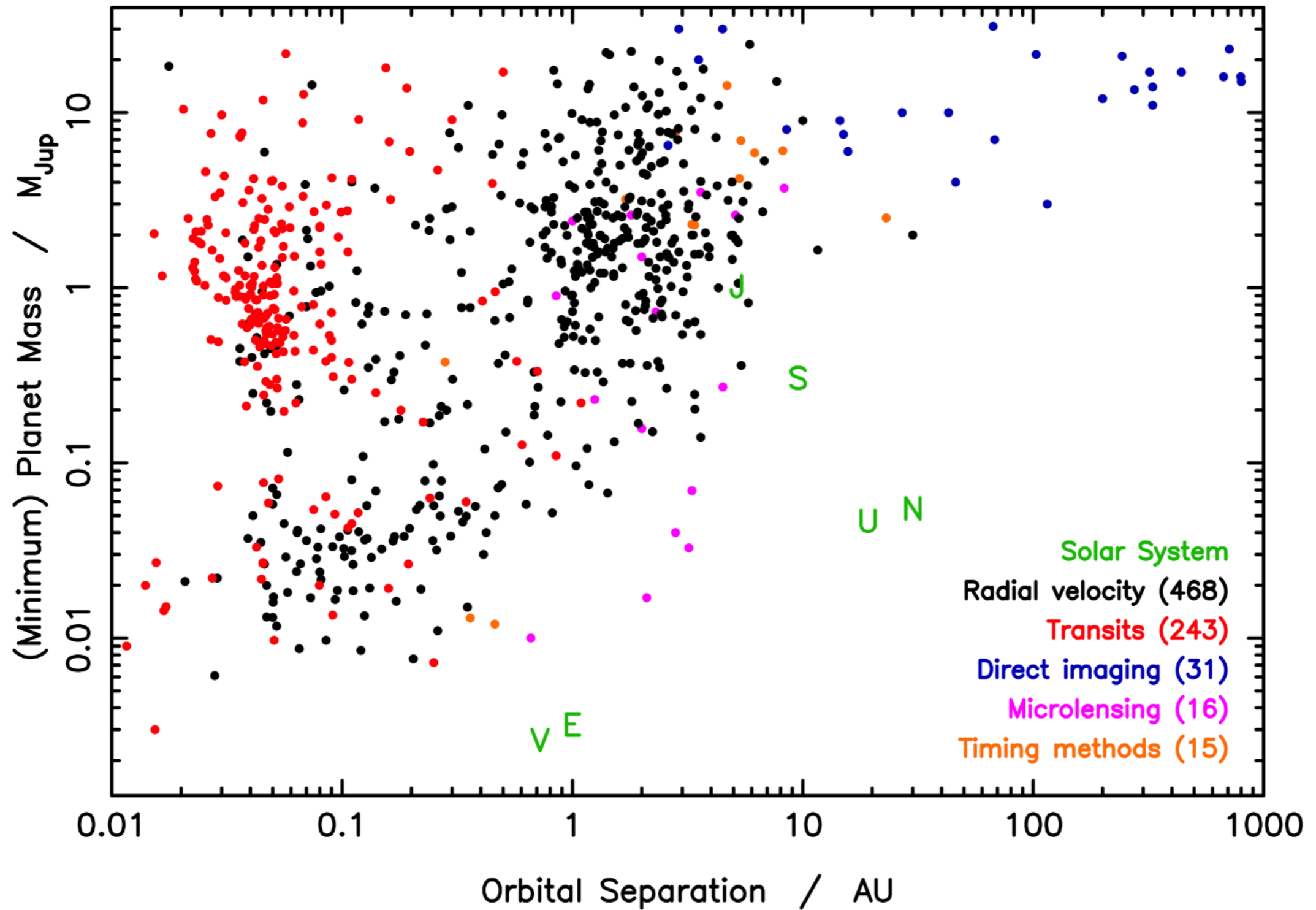
Data from exoplanet.eu

Known planets (as of 1 Oct 2012)



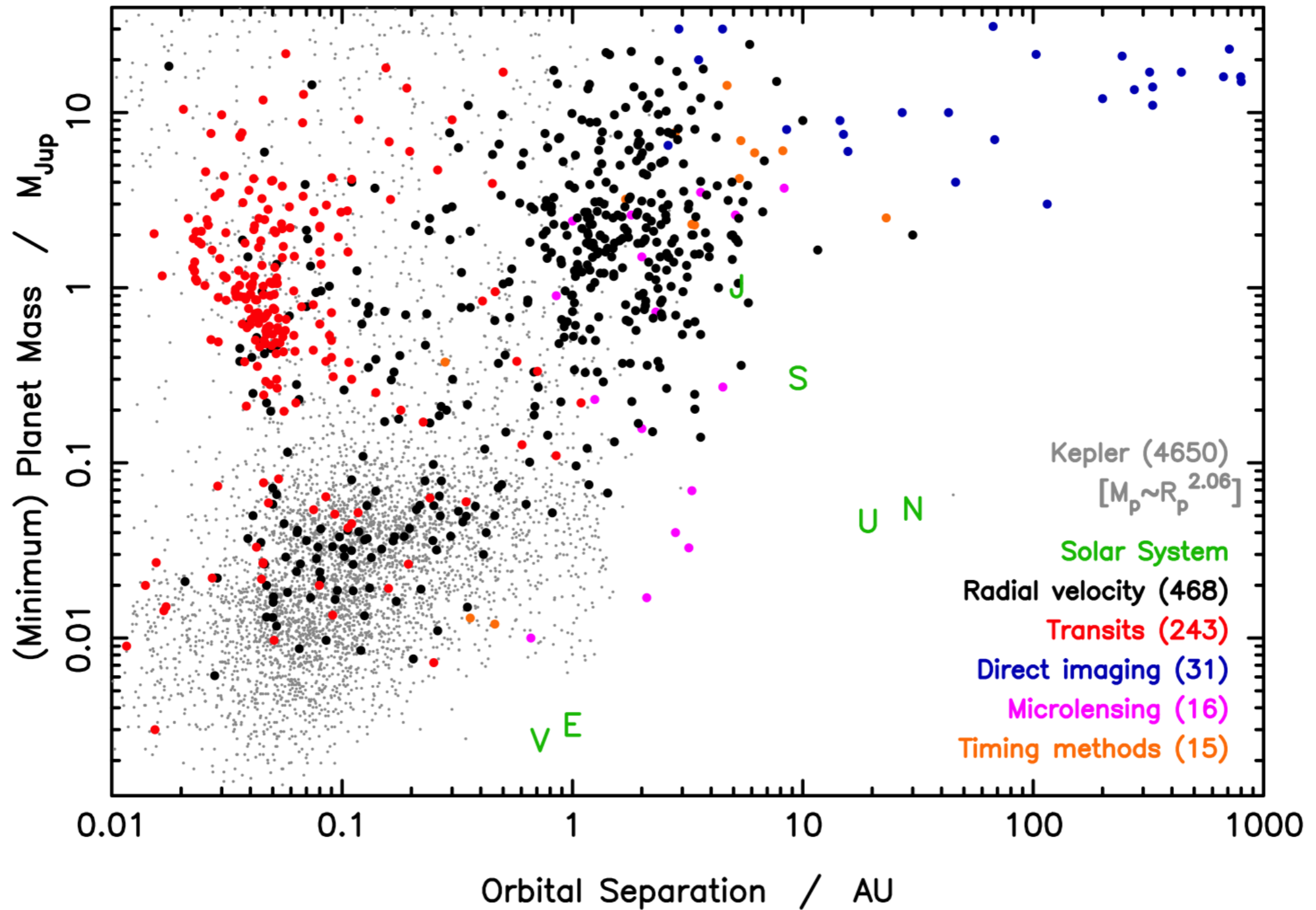
Data from exoplanet.eu

Known planets (as of 7 Oct 2015)



Solar System
Radial velocity (468)
Transits (243)
Direct imaging (31)
Microlensing (16)
Timing methods (15)

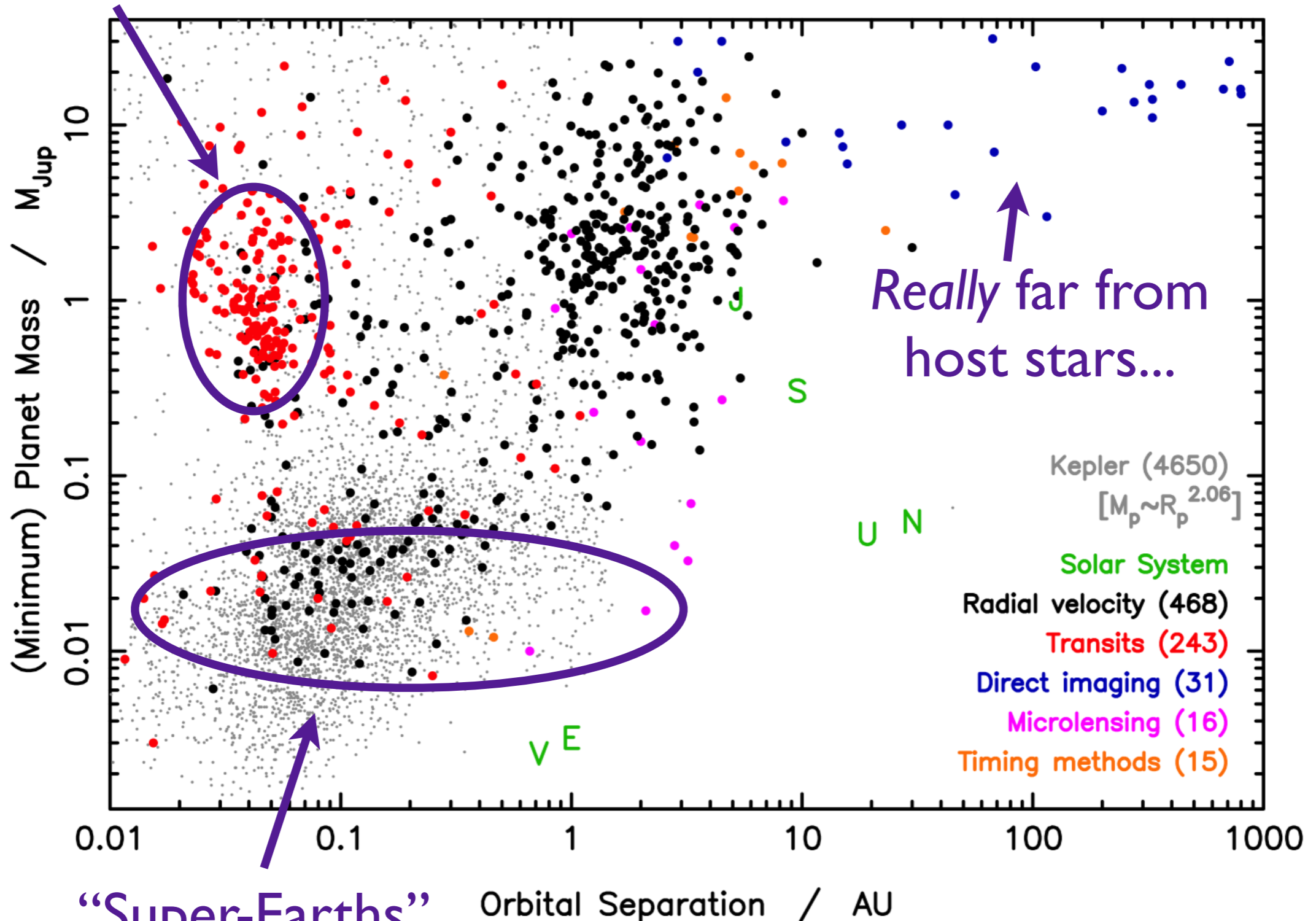
Known planets (as of 7 Oct 2015)



Data from exoplanets.org

“Hot Jupiters”

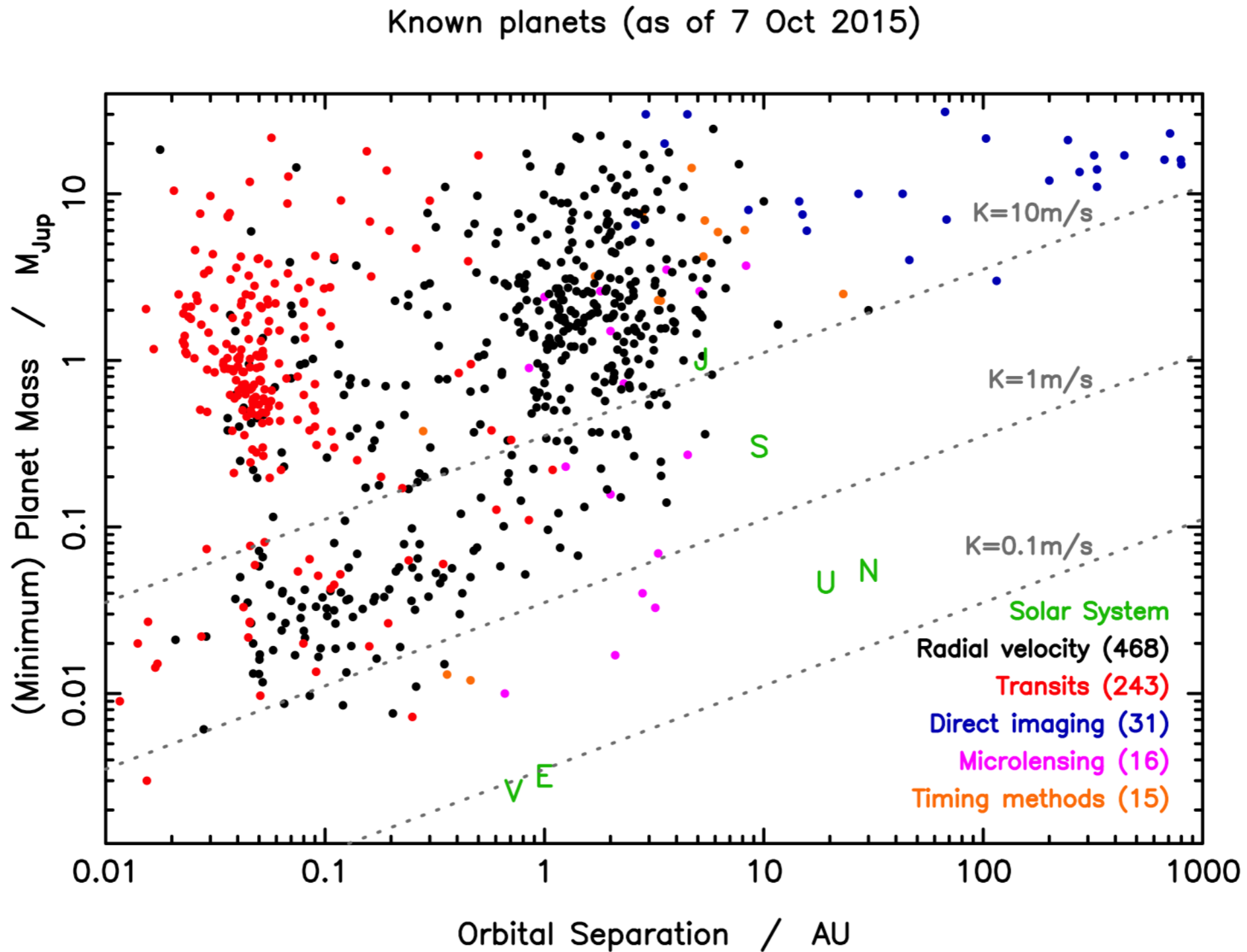
Known planets (as of 7 Oct 2015)



“Super-Earths”

Data from exoplanets.org

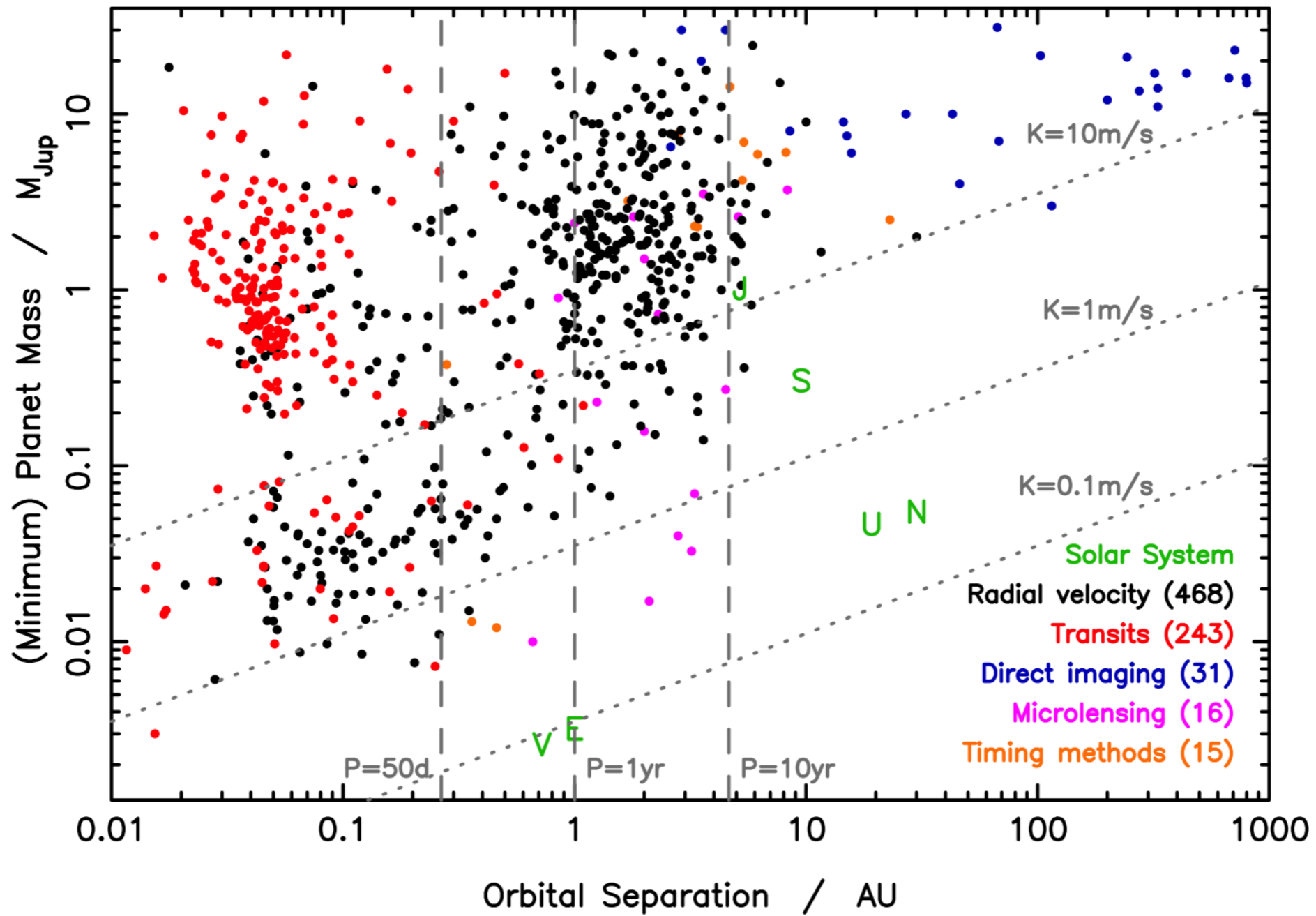
Selection biases



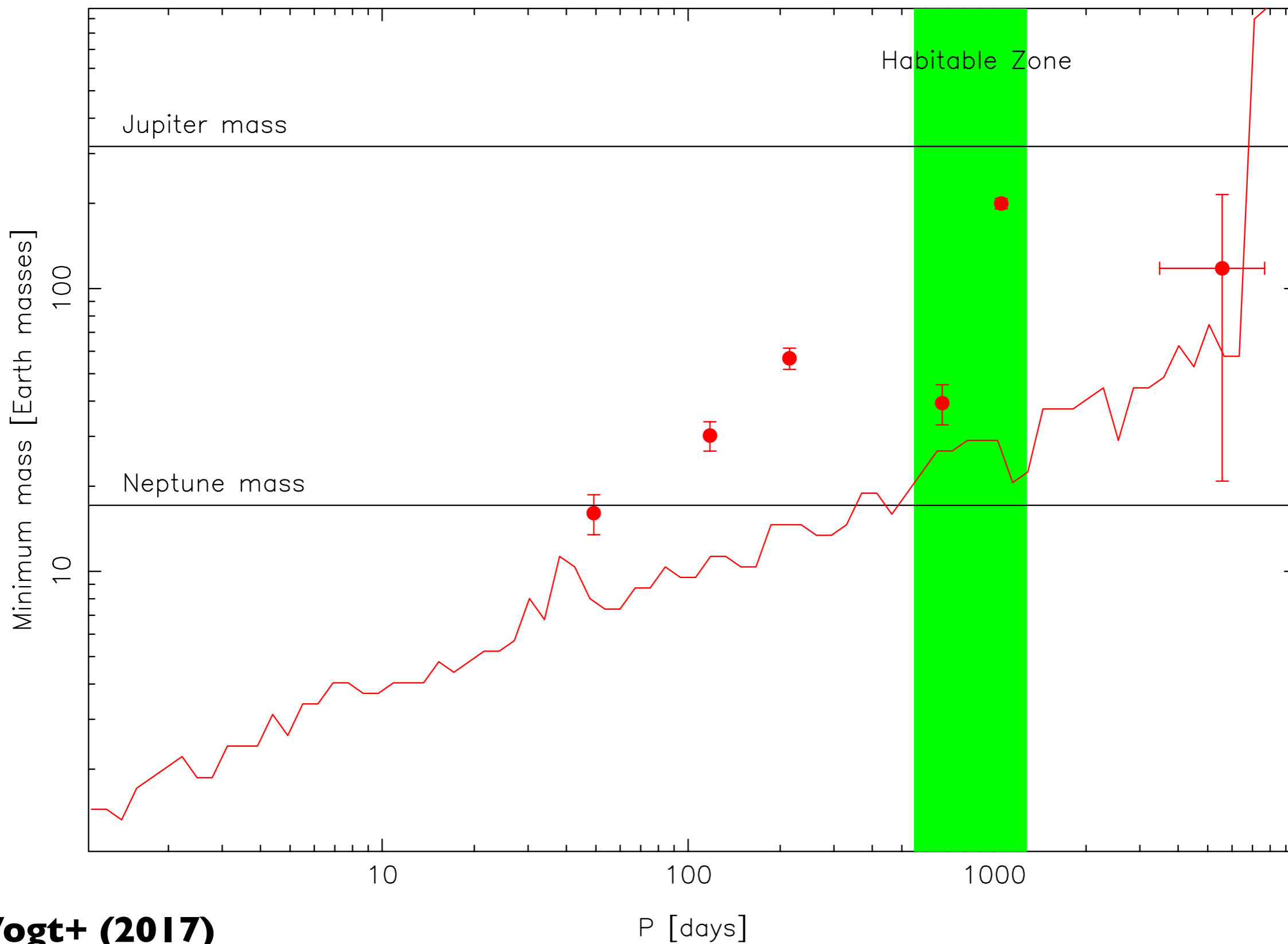
$$K \propto M_p \sin i a^{-1/2} \quad \Rightarrow \quad M_p \sin i \propto K a^{1/2}$$

Selection biases

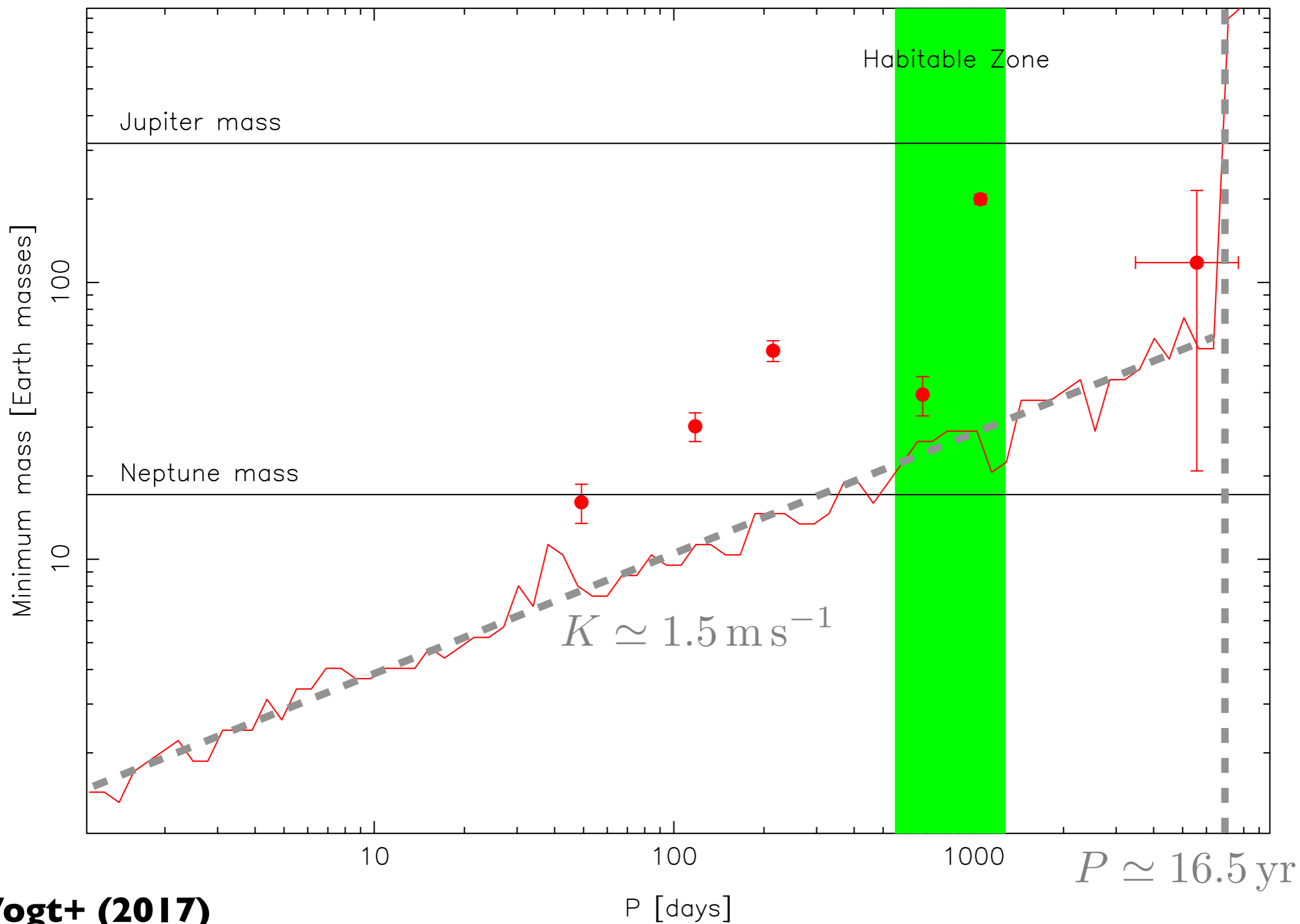
Known planets (as of 7 Oct 2015)



Selection biases



Selection biases



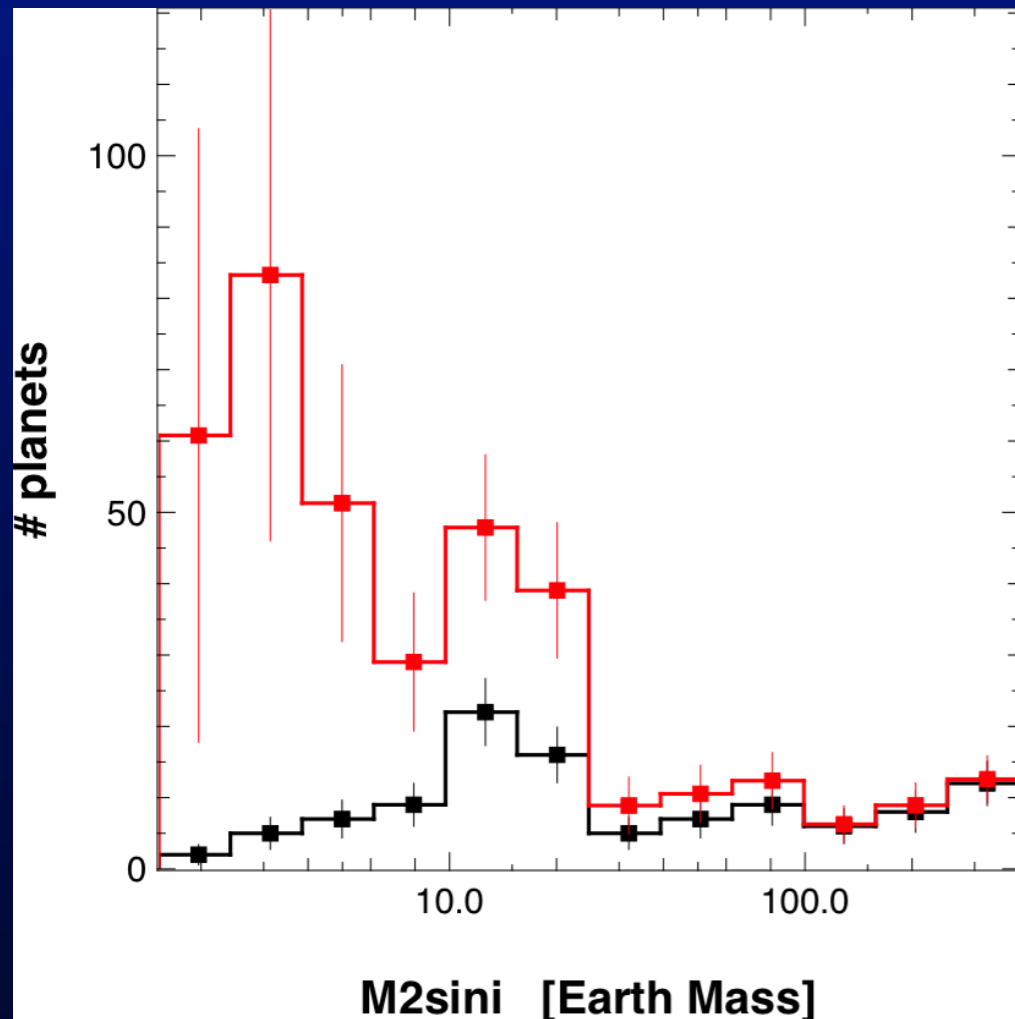
What fraction of stars host planets?

What fraction of stars host planets?

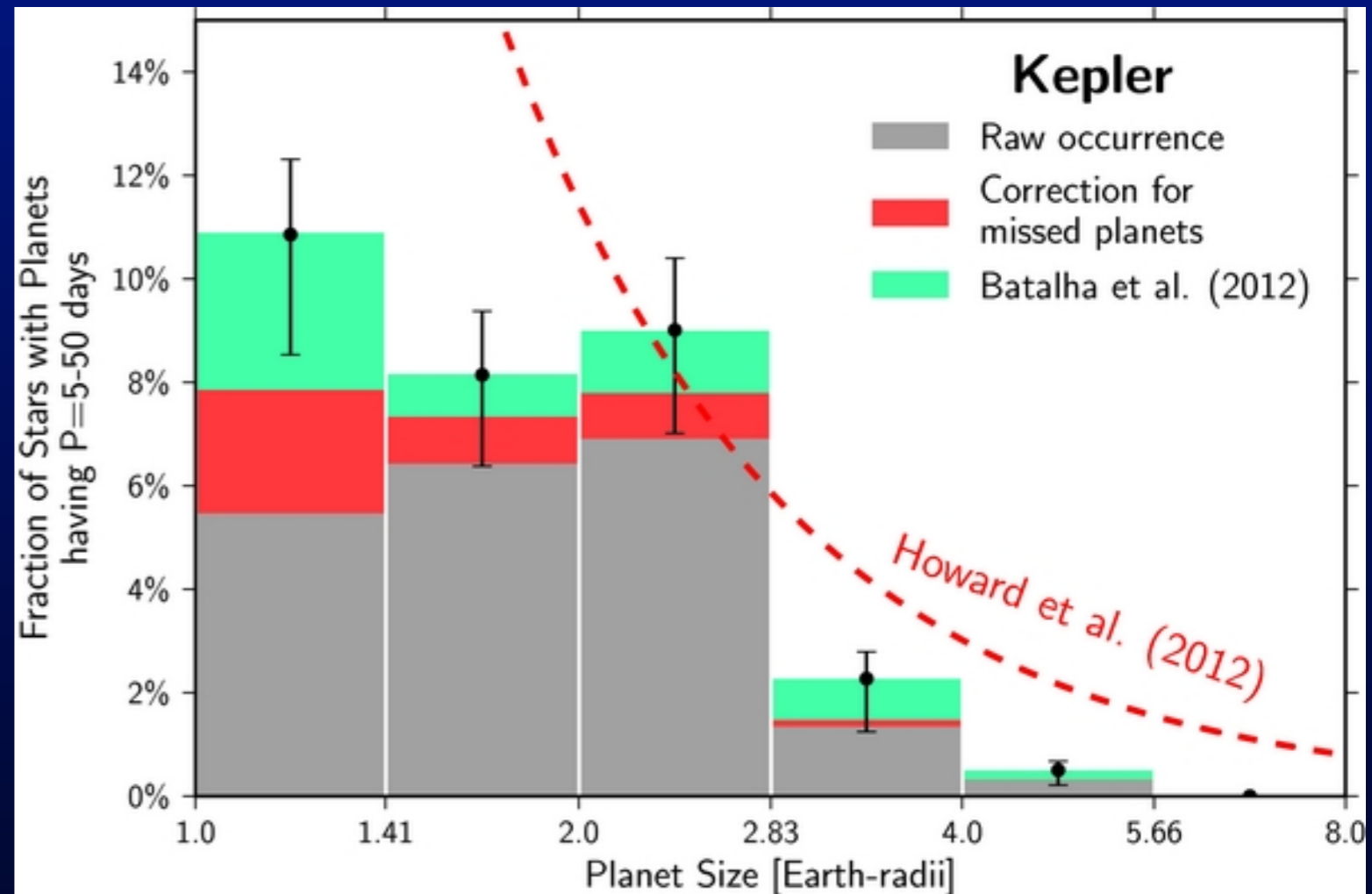
- Selection biases mean that measurements of f_p must be qualified (but detection methods are complementary).
- Current results:
 - 5-10% of FGK stars host a planet with $M_p \geq M_{Jup}$ at $a \leq 3AU$.
 - >50% of FGK stars host a planet with $M_p \geq 1M_{\oplus}$ and $P \leq 100d$.
 - ~90% of M 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

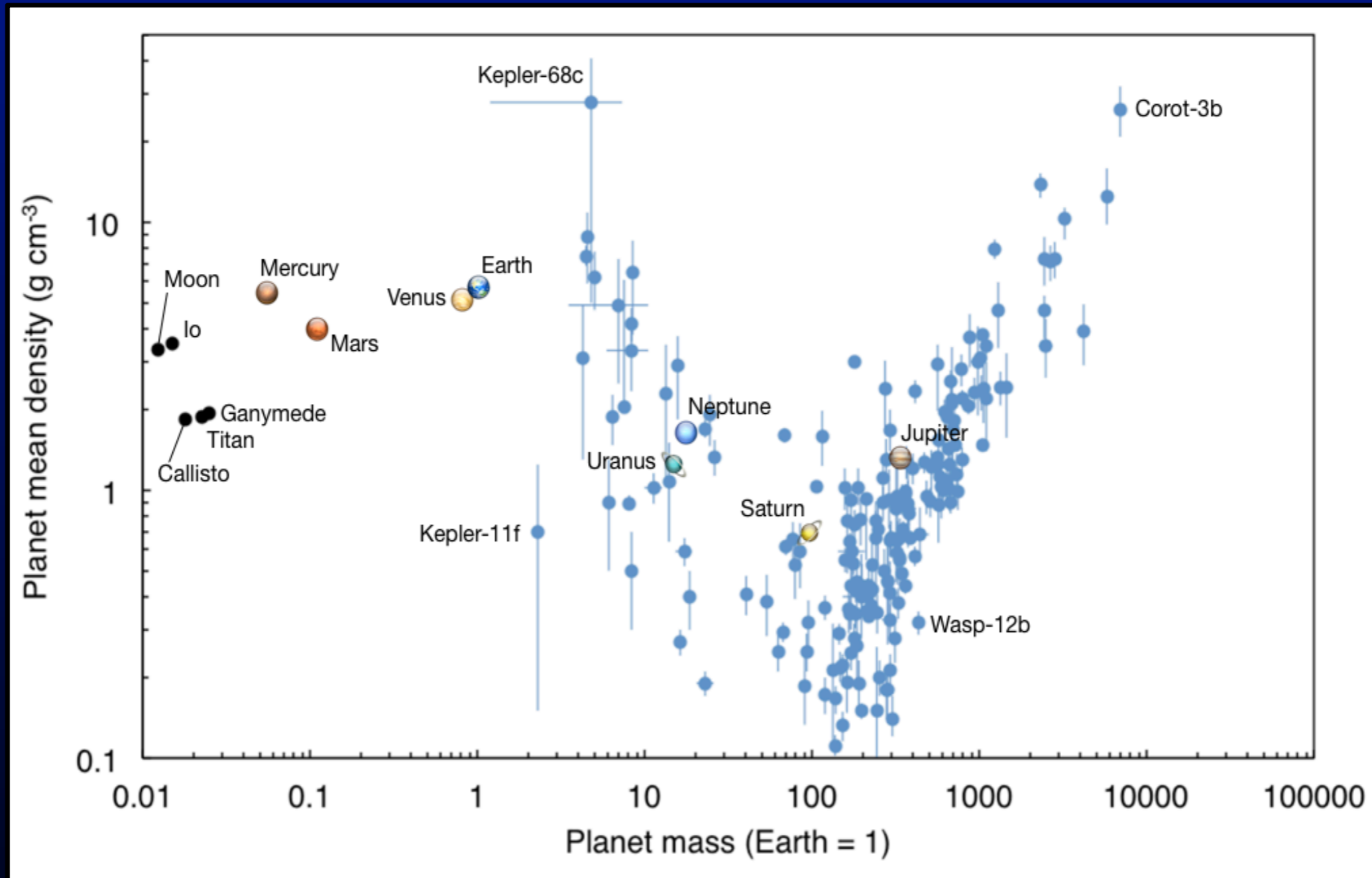
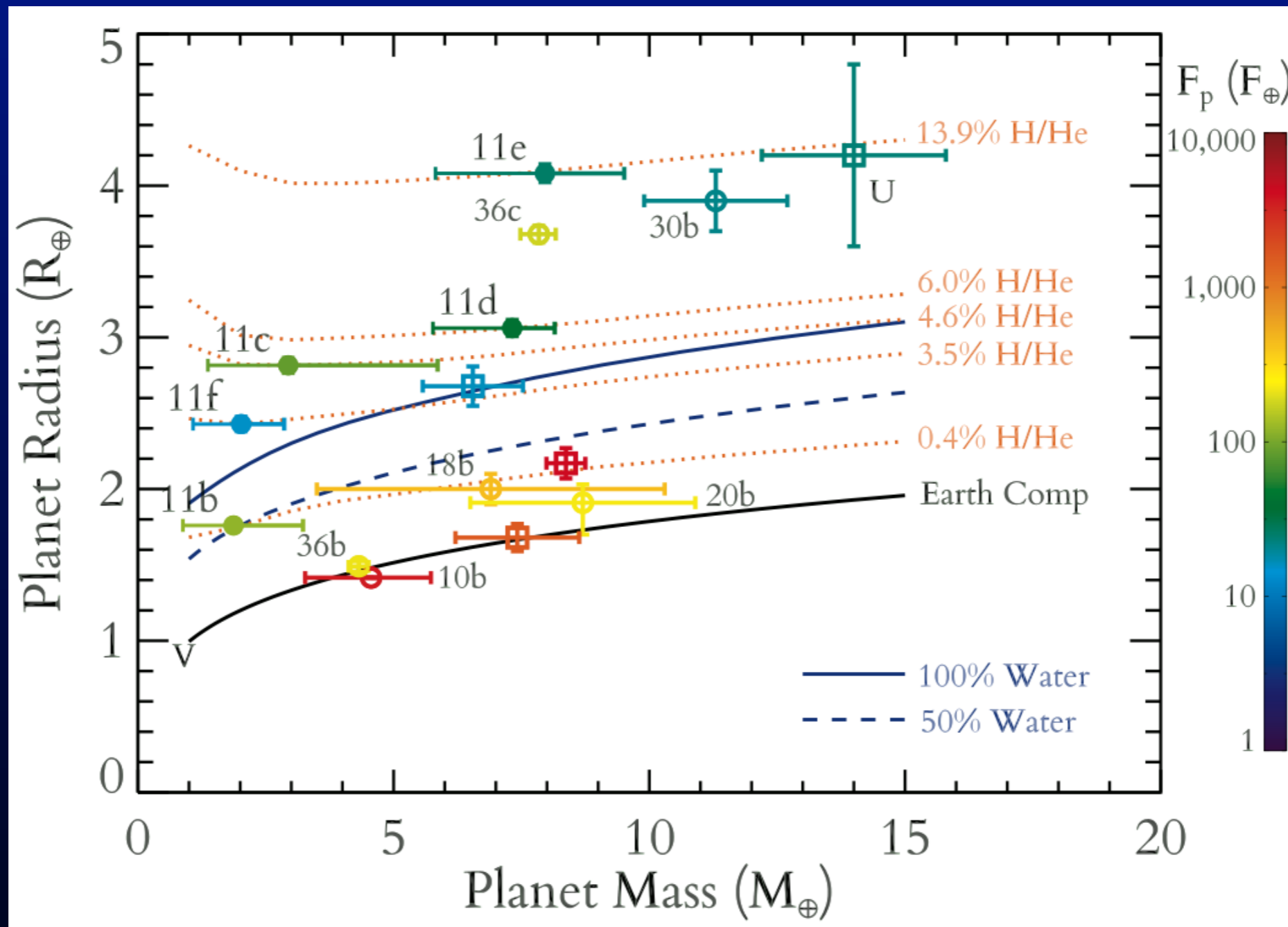


Figure courtesy of Didier Queloz

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

Mass-radius relation

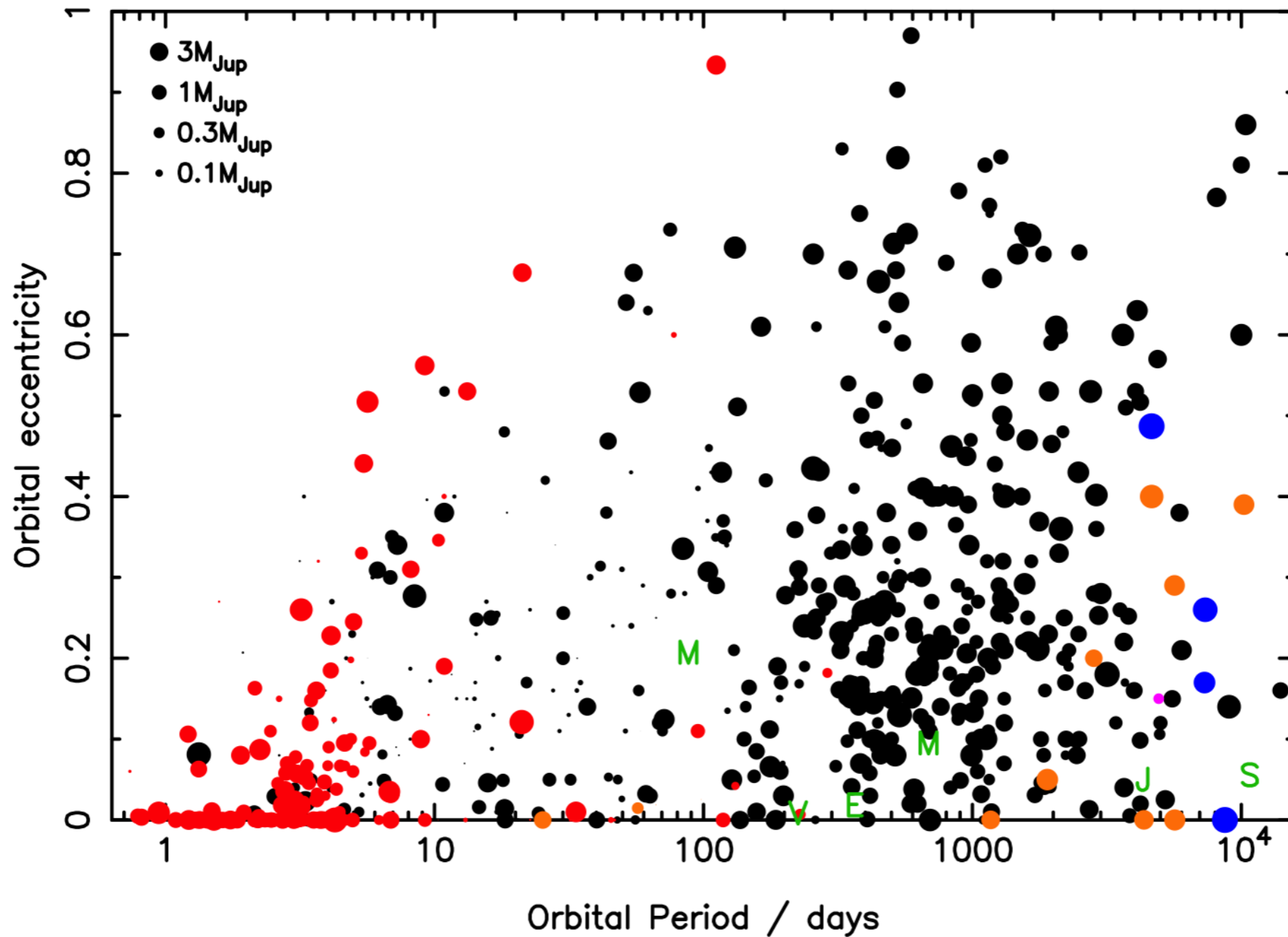


Lissauer et al. (2013)

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

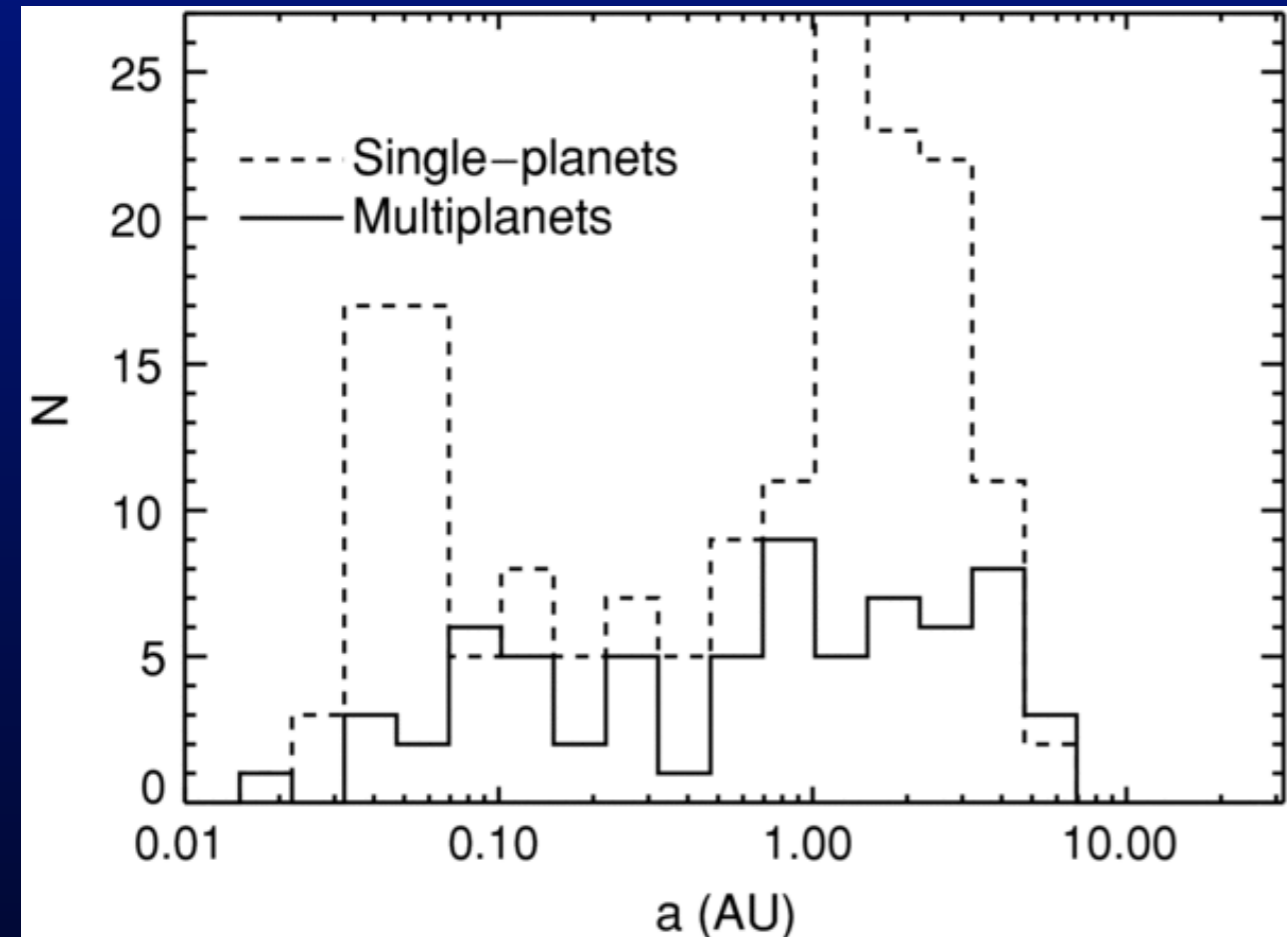
Eccentricities

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

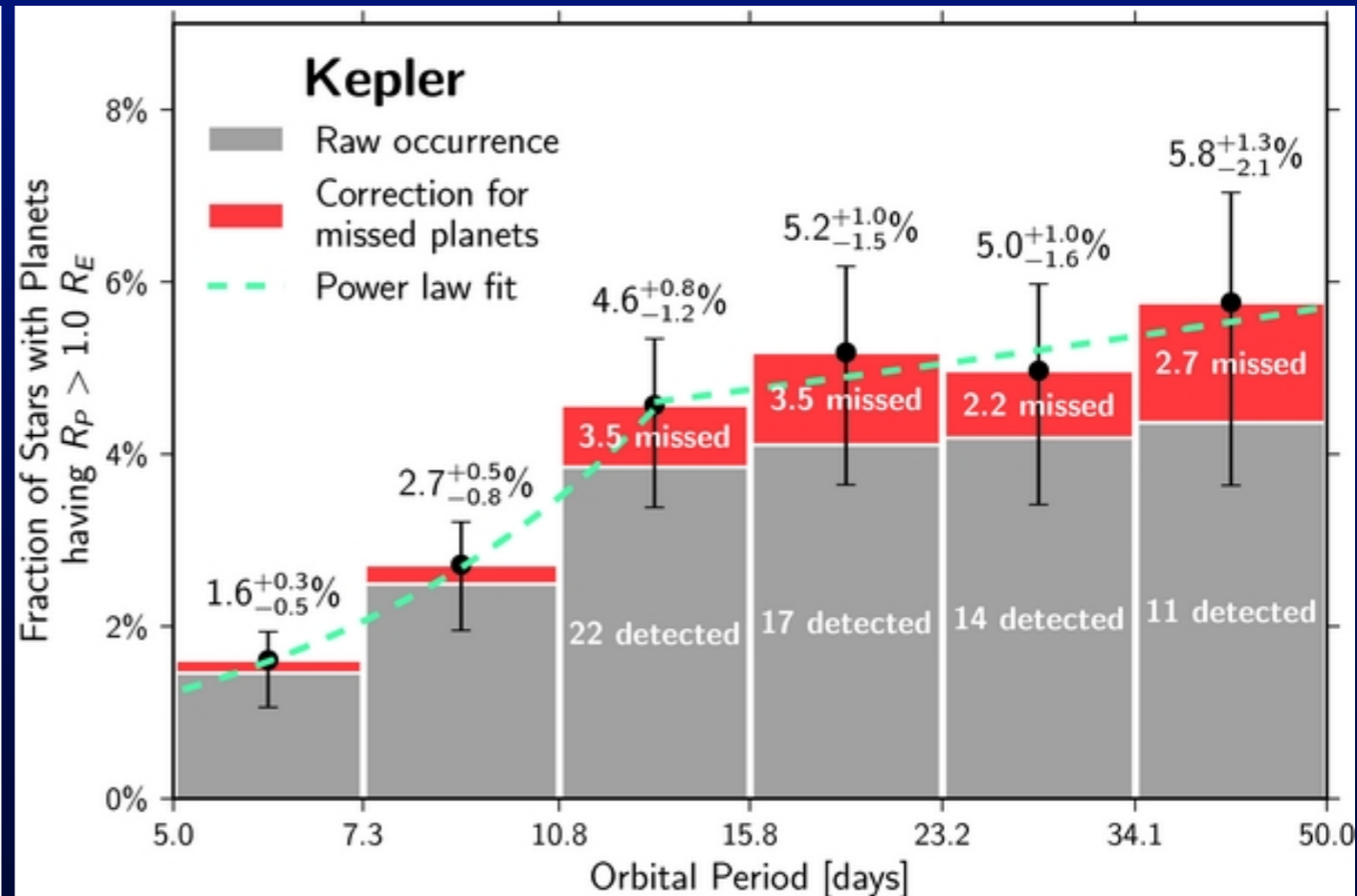


Data from exoplanets.org

Radial distribution



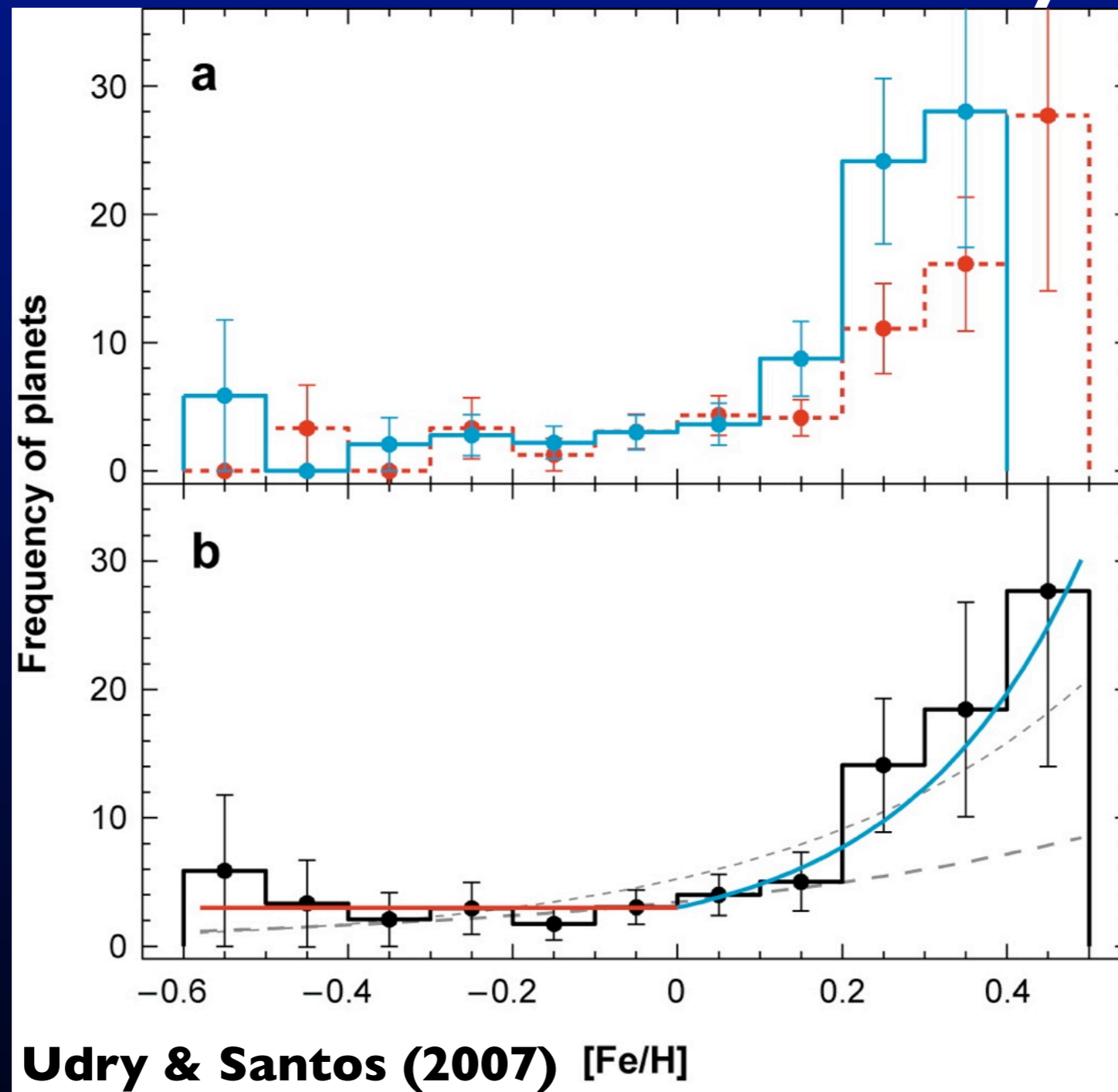
RV: Wright et al. (2009)



Kepler: Petigura et al. (2013)

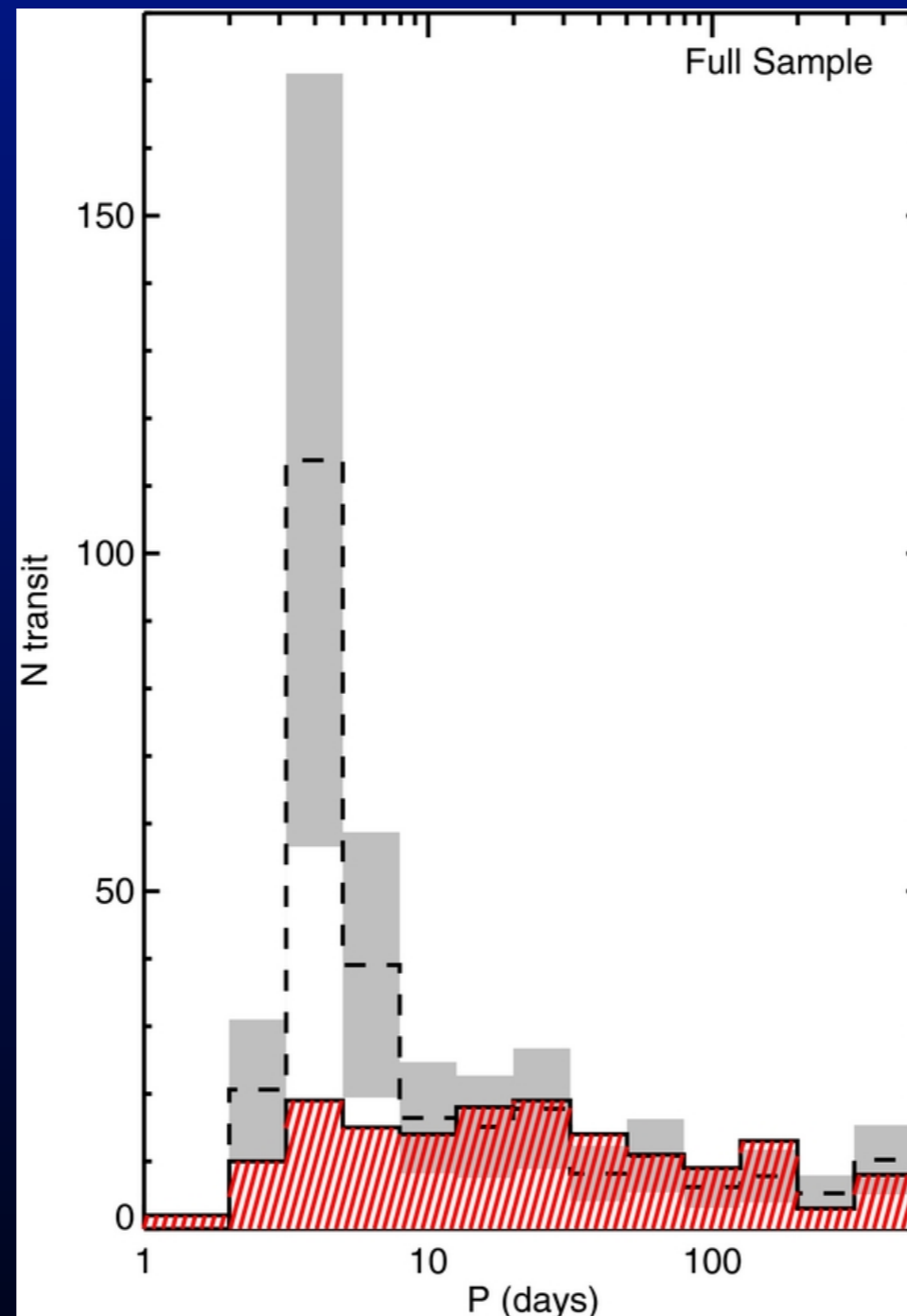
- Radial distribution is “smooth”, though data are limited.
- Evidence of excesses of ~Jupiters at ~0.05AU and ~1-2AU in RV data.
- “Pile-up” of hot Jupiters only seen in metal-rich stars.

Host star metallicity



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

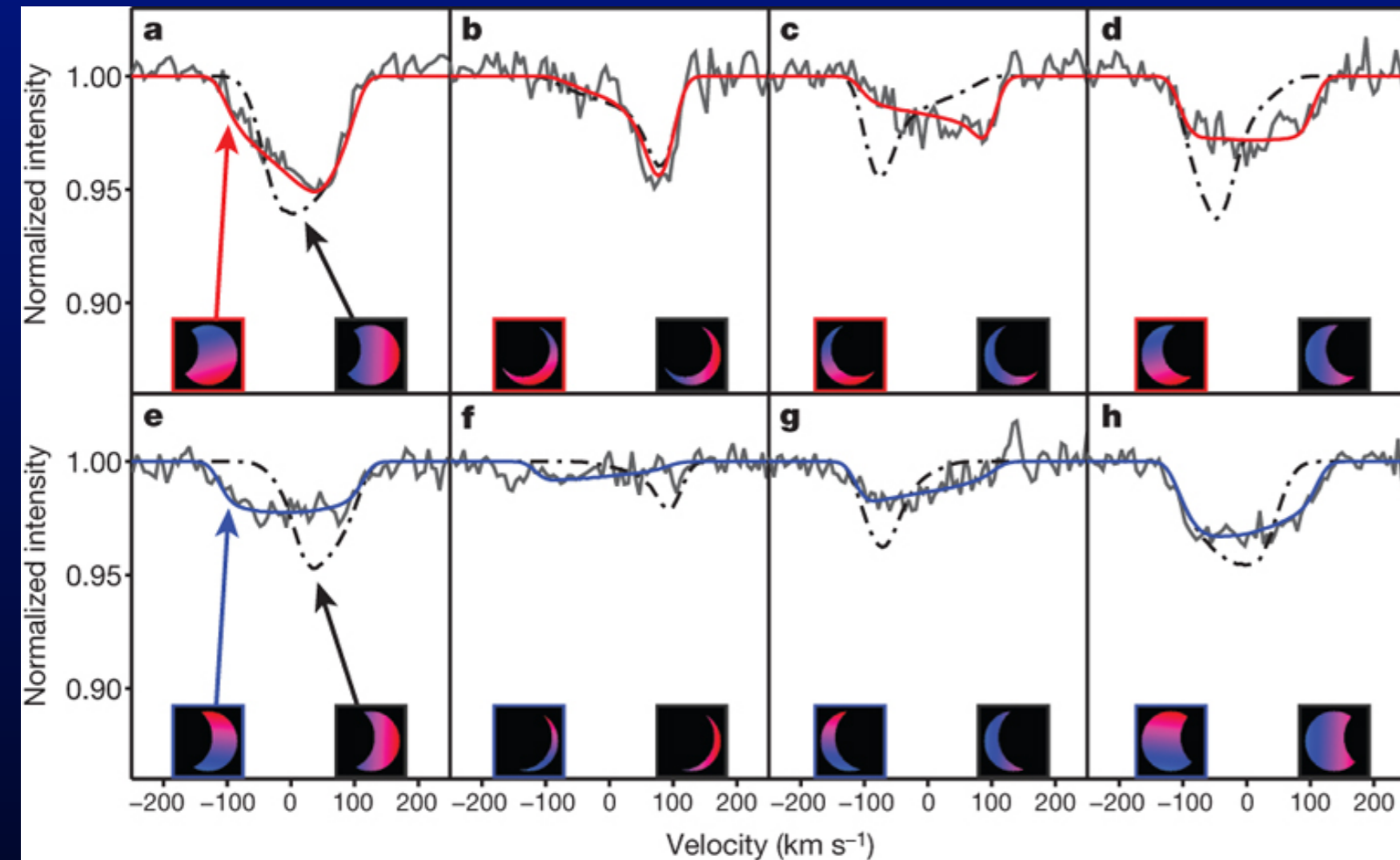
Host star metallicity



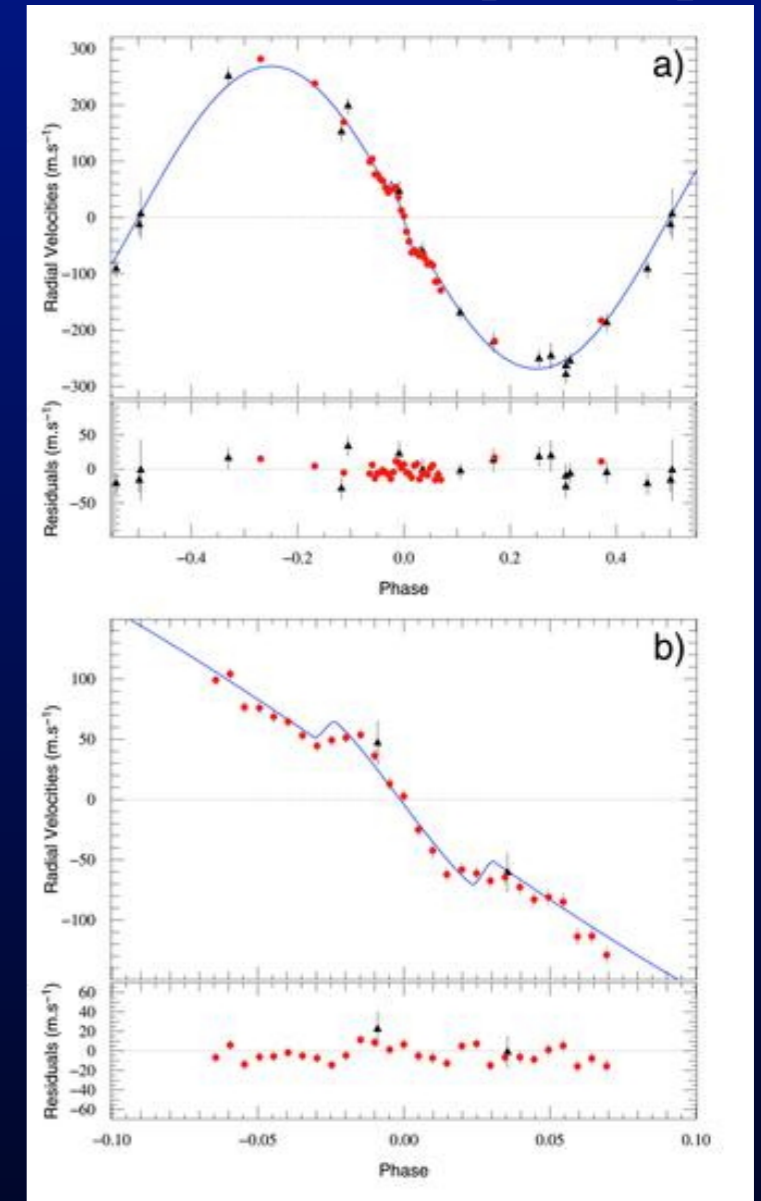
Dawson & Murray-Clay (2013)

- 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



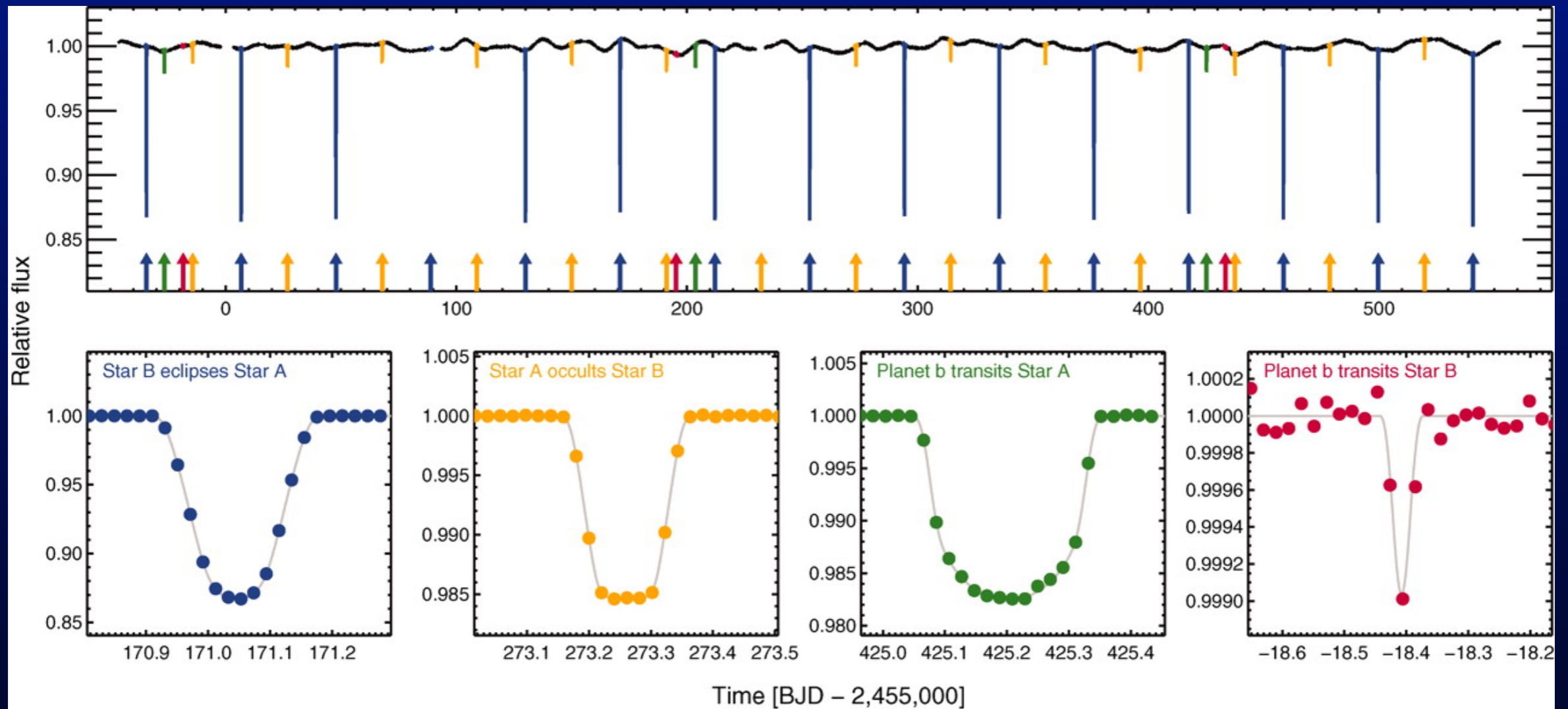
Albrecht et al. (2009)



Triaud et al. (2010)

- Line shifts during transit (R-M) allow us to measure relative inclination of orbit and stellar rotation axis.
- Significant fraction (~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 image shows a browser window displaying the homepage of the Exoplanet.eu website. The browser's address bar shows the URL <https://exoplanet.eu/home/>. The website's navigation menu includes links for Home, Catalogue, Plots, Tools, News, Bibliography, Meetings, and Links, along with a language selector (UK flag). The main heading reads "ENCYCLOPAEDIA OF EXOPLANETARY SYSTEMS". Below this, a paragraph describes the site's content: "This encyclopaedia provides latest detections and data announced by professional astronomers about exoplanetary systems. It is about objects lighter than 60 Jupiter masses, which are orbiting stars/brown dwarf or are free floating. It provides also a database about planets in binary systems, and a database about circumstellar disks." Further down, it states "Established in February 1995 Developed and maintained by the exoplanet TEAM" and "Last update: Nov. 6, 2023 currently 5529 planets." At the bottom, there are three buttons: "The catalog: Filter, sort, export", "The plots: Online plotting tool", "BIBLIOGRAPHY", "PLANETS IN BINARIES", and "OTHER SITES".

Encyclopaedia of exoplanetary s X

https://exoplanet.eu/home/

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ENCYCLOPAEDIA OF EXOPLANETARY SYSTEMS

This encyclopaedia provides latest detections and data announced by professional astronomers about exoplanetary systems. It is about objects lighter than 60 Jupiter masses, which are orbiting stars/brown dwarf or are free floating. It provides also a database about planets in binary systems, and a database about circumstellar disks.

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The catalog: Filter, sort, export

The plots: Online plotting tool

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Exoplanet Resources

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5,535
Confirmed Planets
10/24/2023

398
TESS Confirmed Planets
10/21/2023

6,875
TESS Project Candidates
10/20/2023

View more Planet and Candidate statistics


Explore the Archive

Name or Coordinates

Optional Radius (arcsec)

Transit Surveys

130,041,578 Light Curves

 Launched in April 2018, TESS is surveying the sky for two years to find transiting exoplanets around the brightest stars near Earth.

TESS Kepler K2 KELT UKIRT

Exoplanet Mass vs. Period

Mass – Period Distribution

02 Nov 2023
exoplanetarchive.ipac.caltech.edu

Legend:

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- Timing Variations
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