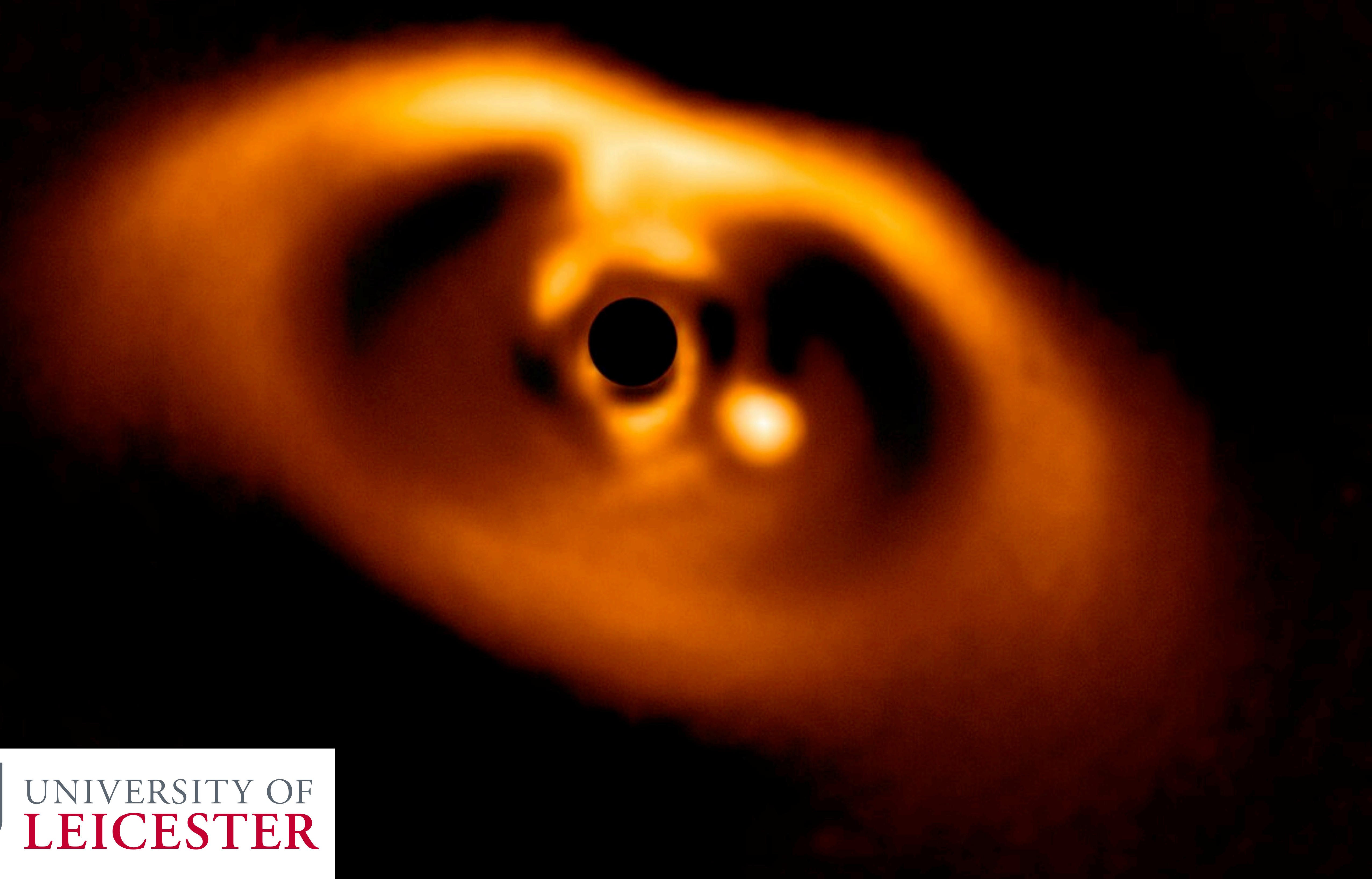
Formation of Planetary Systems

Lecture 1 - Observations of planetary systems



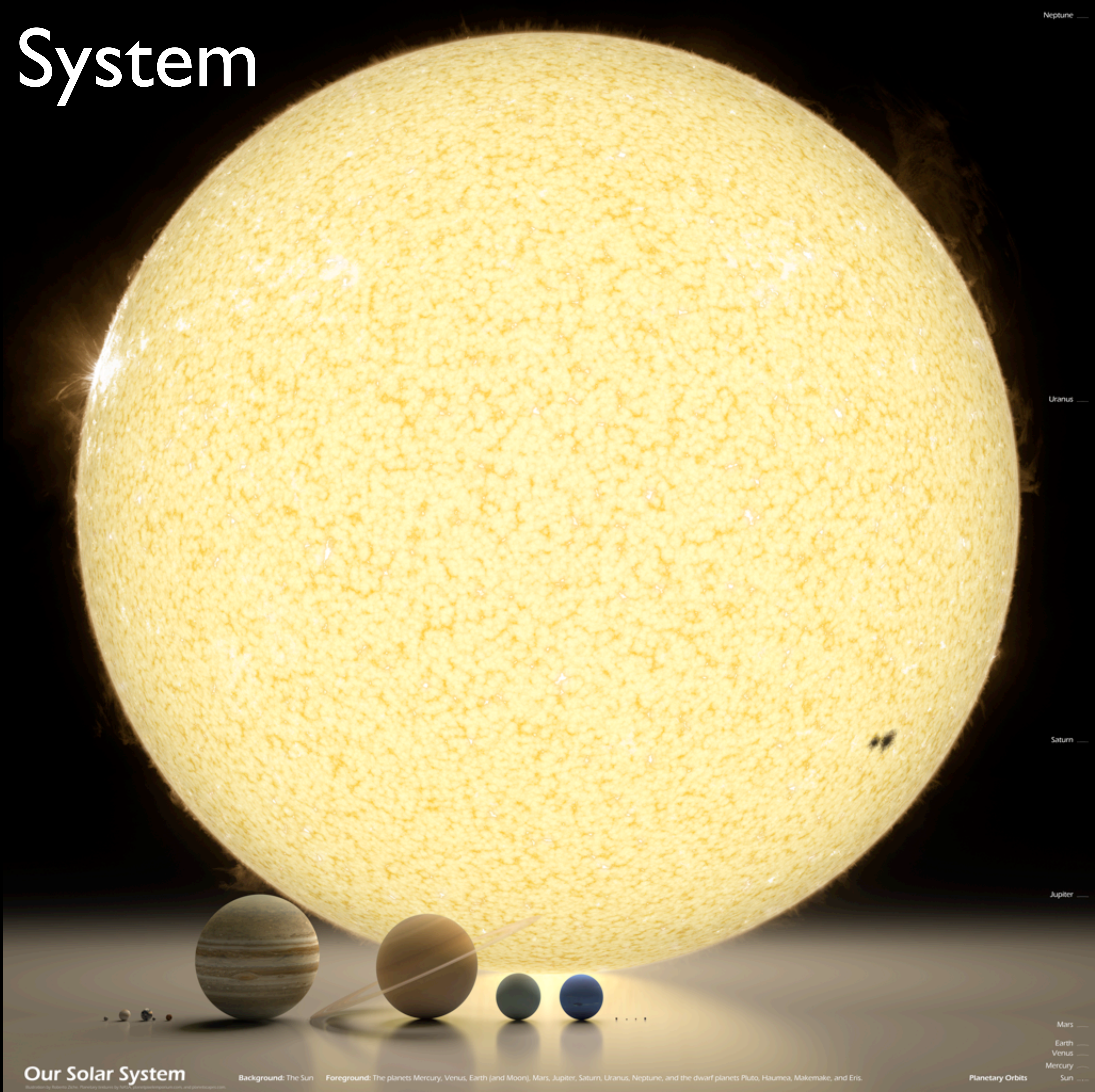
UNIVERSITY OF LEICESTER

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 (*VI* - 2014; *VII* - 2023)

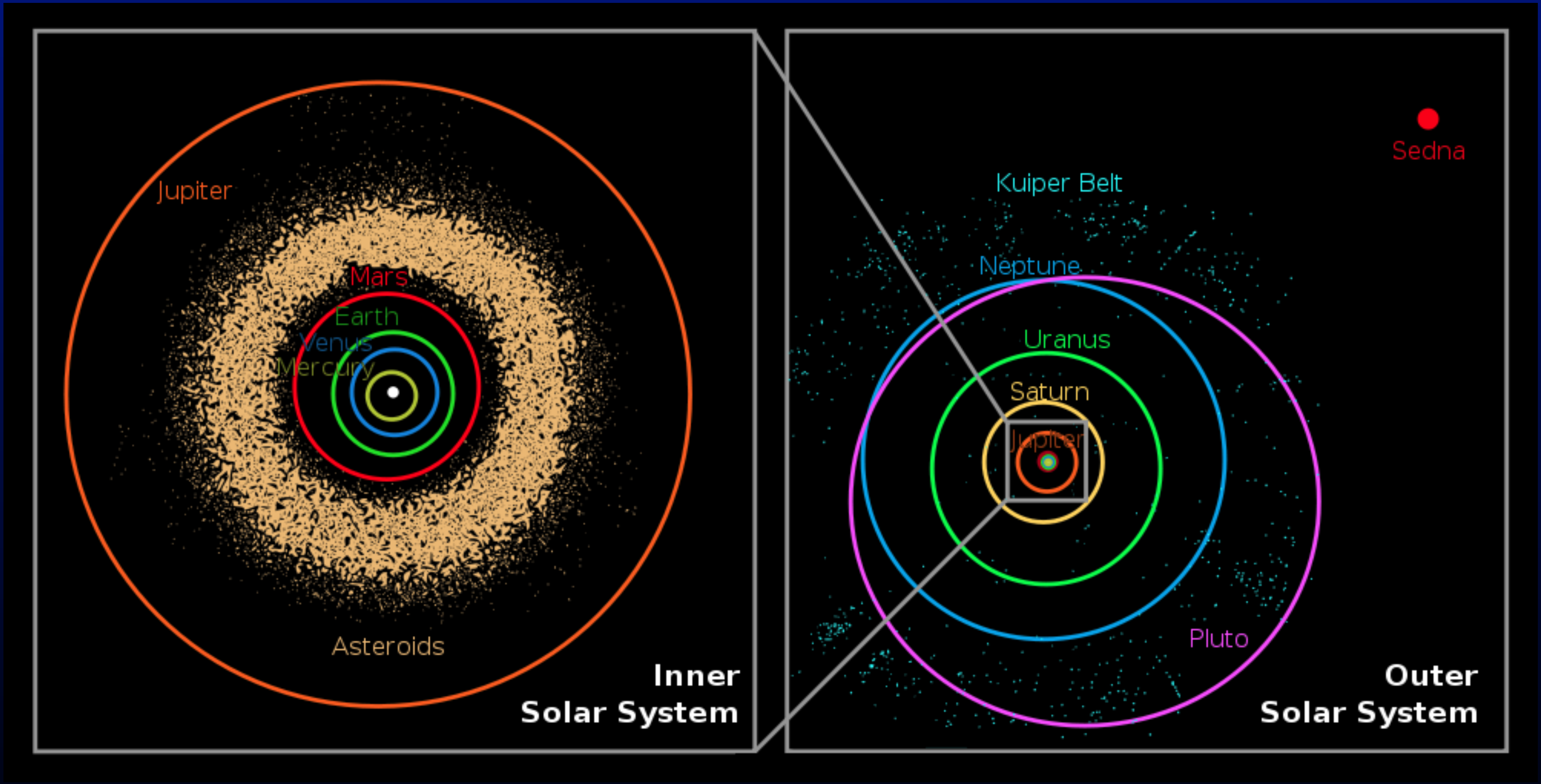
Course home-page: `rdalexander.github.io/planets_2023.html`

The Solar System



Roberto Ziche

The Solar System



Wikipedia Commons

The Solar System

	a	e	M_p
	AU		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
Nepture	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.
  - ~10M_{Earth} solid cores (probably!).
- Ice giants (Uranus & Neptune):
  - H_2O, NH_3, CH_4, etc.
  - ~1M_{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. $^{87}\mathrm{Rb} \rightarrow {}^{87}\mathrm{Sr}$) finds age of 4.57Gyr.
- **Planet formation processes must:**
  - **grow solid bodies from ISM grains to $>M_{Earth}$.**
  - **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	**69**

- **Indirectly:**
  - Motion of star due to planet

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**

(Data from NASA Exoplanet Archive.)

Total: 5535

Methods of detecting extra-solar planets

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Total: 5535

Direct Imaging

- Planets are *<u>very</u>* faint. How faint?

- Fraction of star-light reflected by planet is[*]:

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

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

- 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

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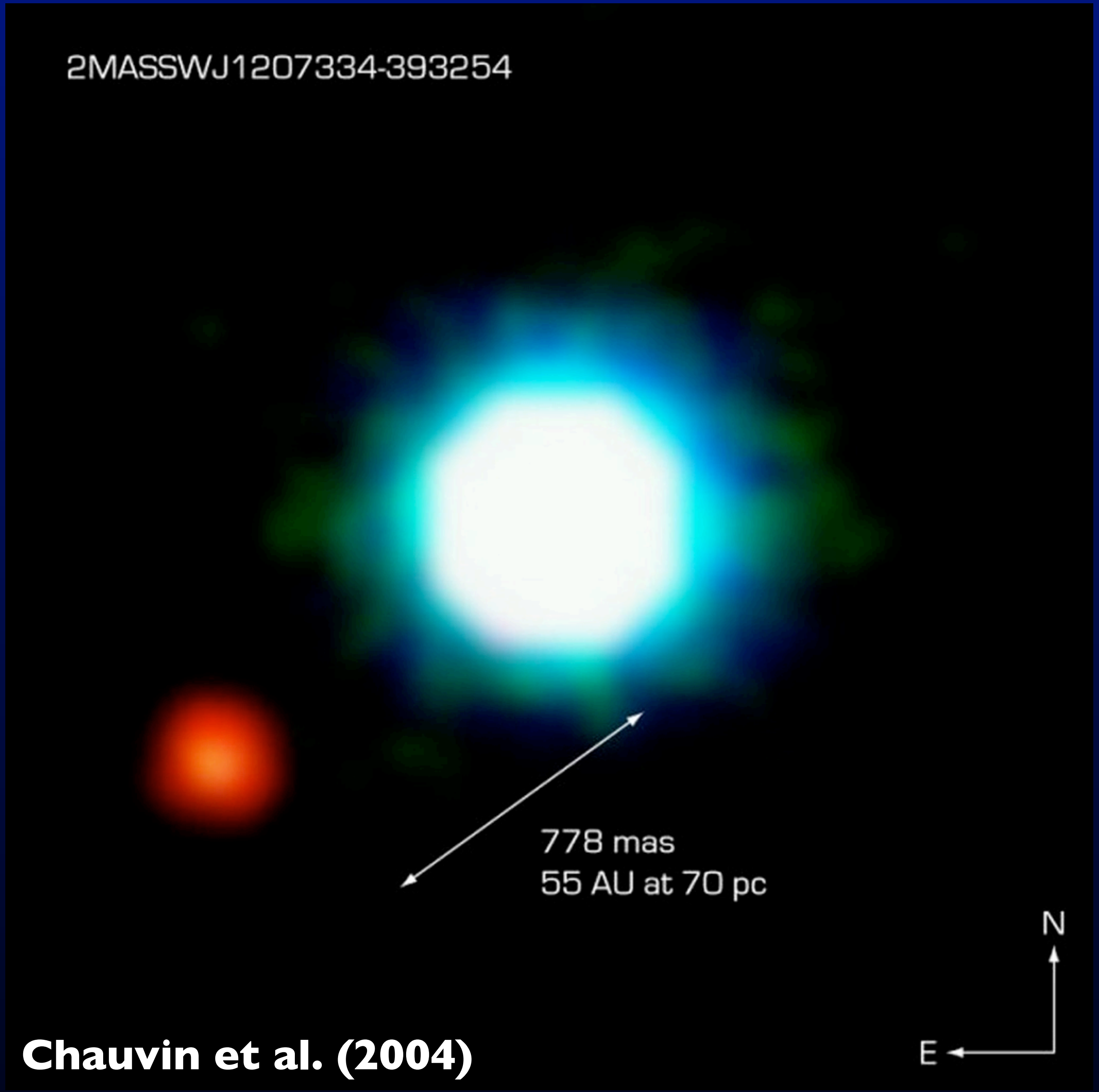

"Planet" around brown dwarf 2M1207 discovered in 2004. Primary is ~25M_{Jup}; secondary is ~5M_{Jup}. Wide separation. More akin to a low-mass binary than a true planetary system.

Direct Imaging

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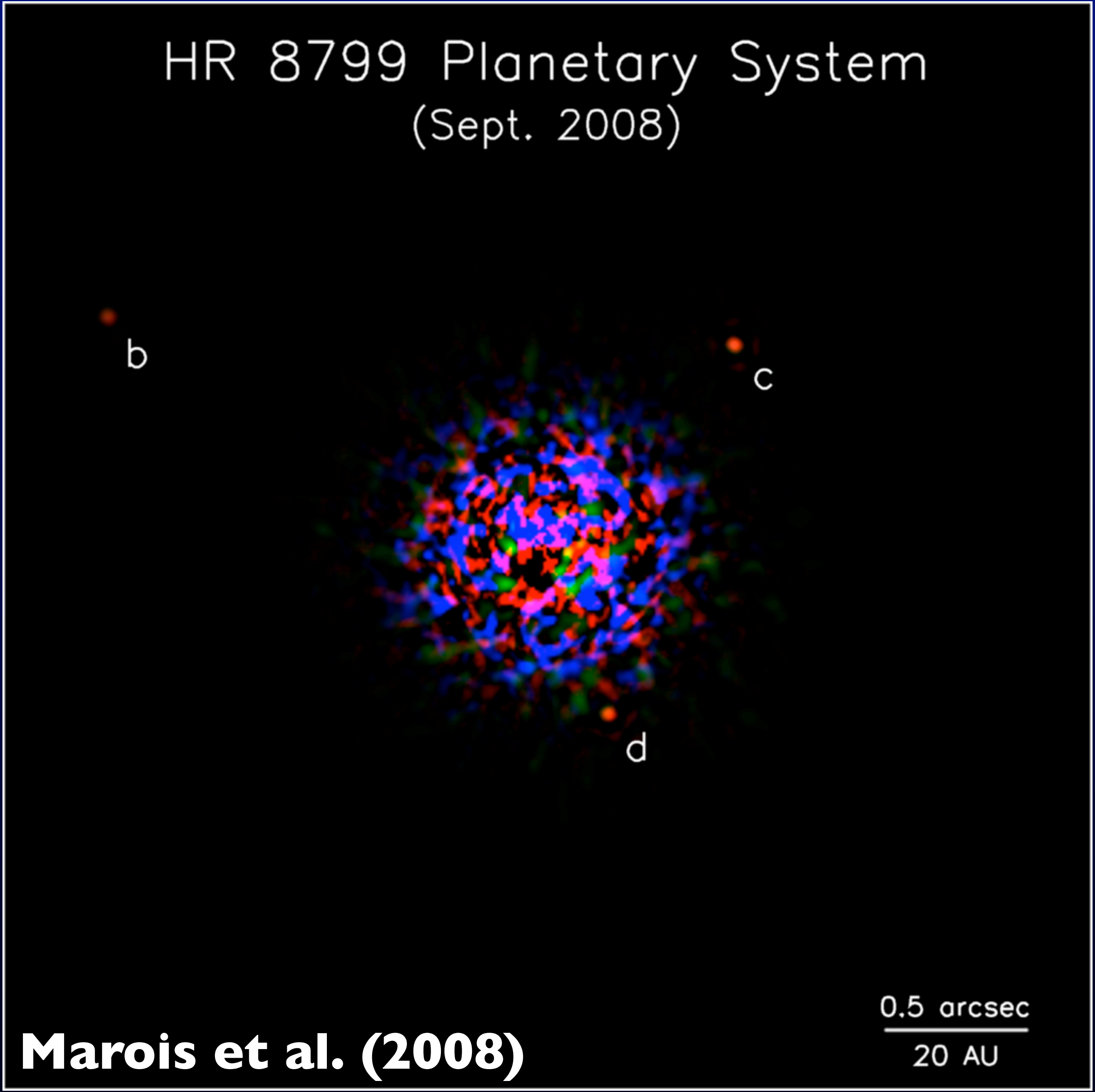
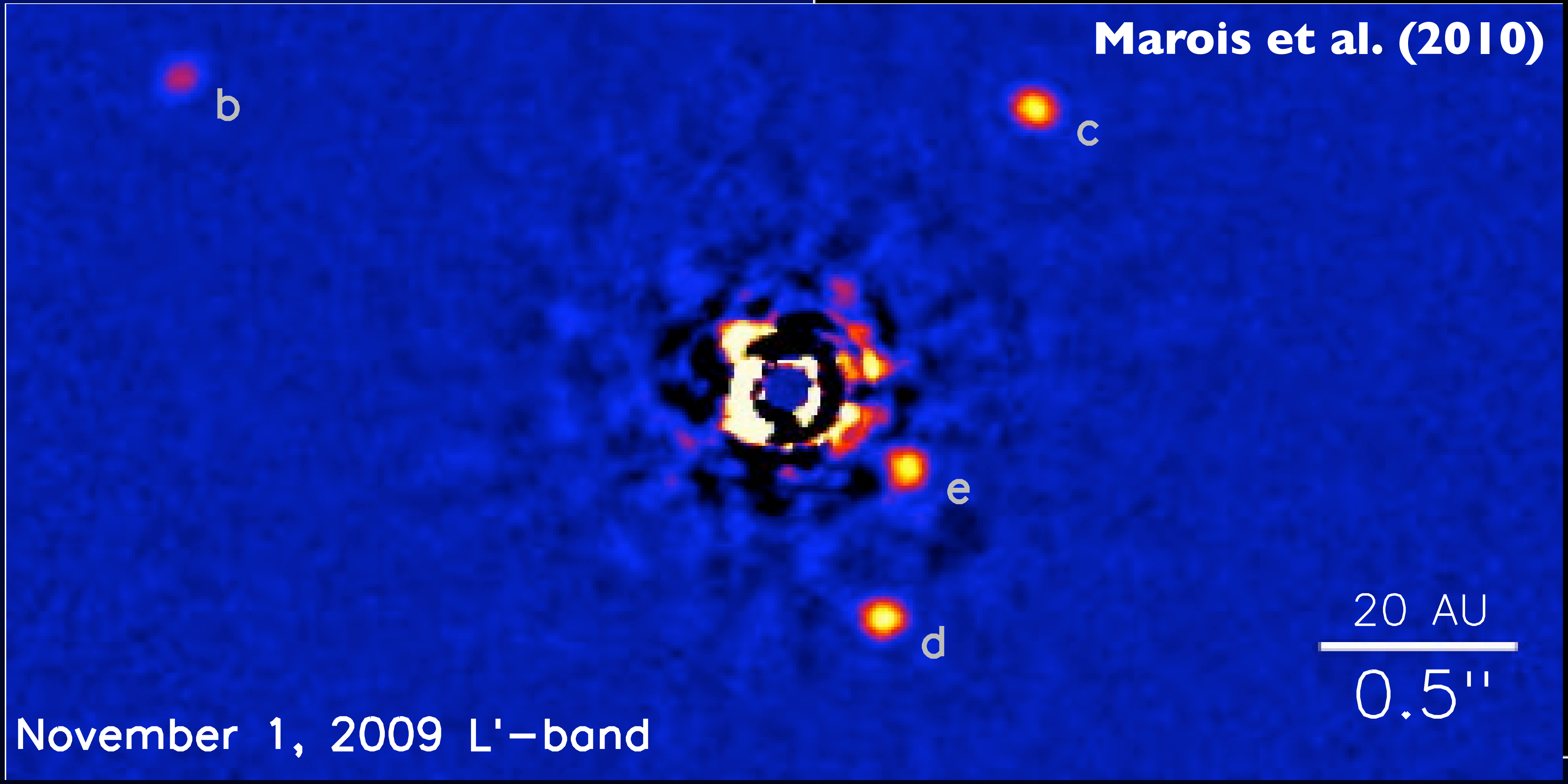


Planets around HR8799 discovered in 2008.
Star is ~1.5$M_{\odot}$. Planet masses all estimated to be ~10M_{Jup}.
Wide orbits - “d” is beyond orbit of Uranus.

Direct Imaging

- Two ways around the contrast problem:



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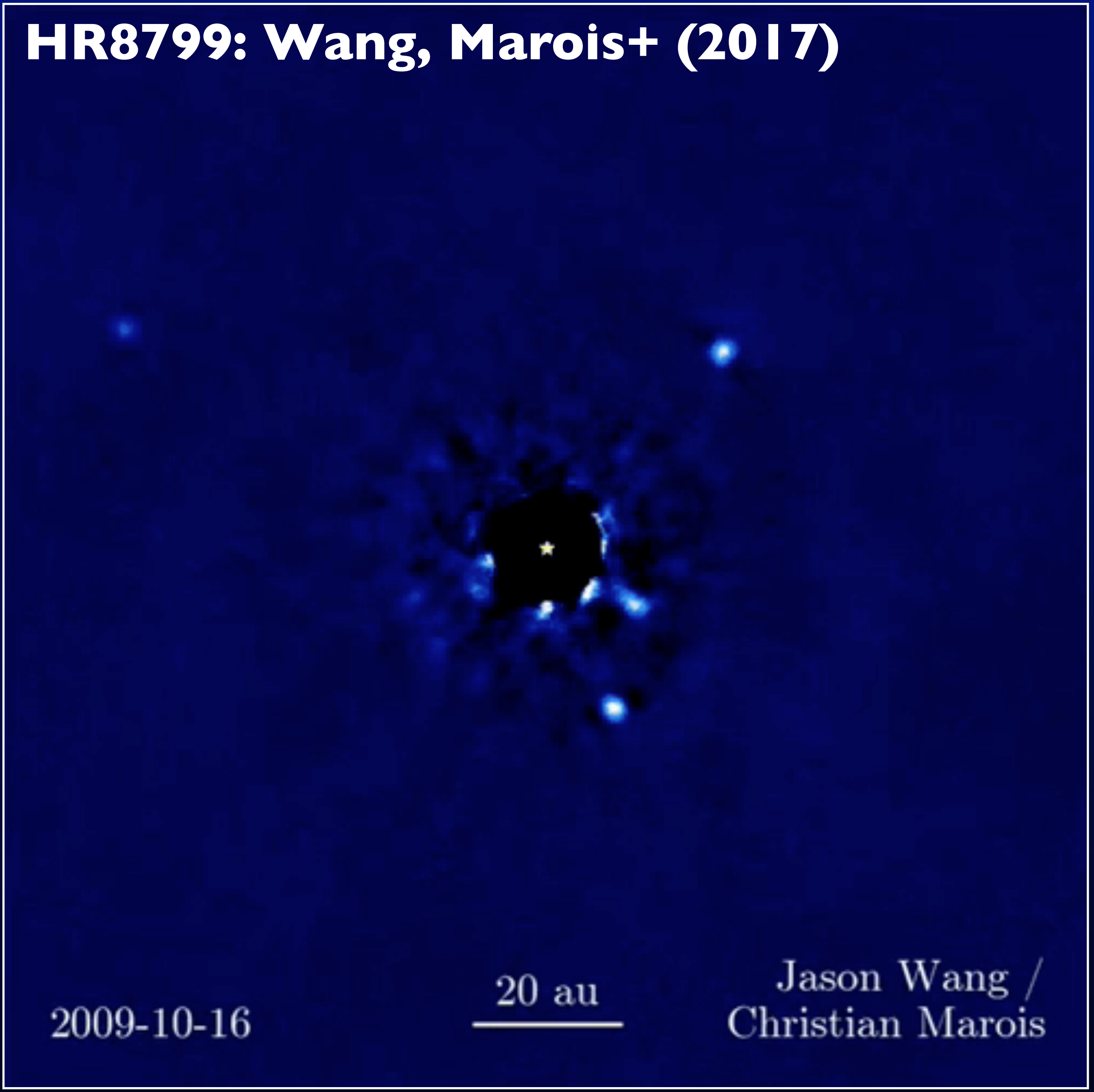
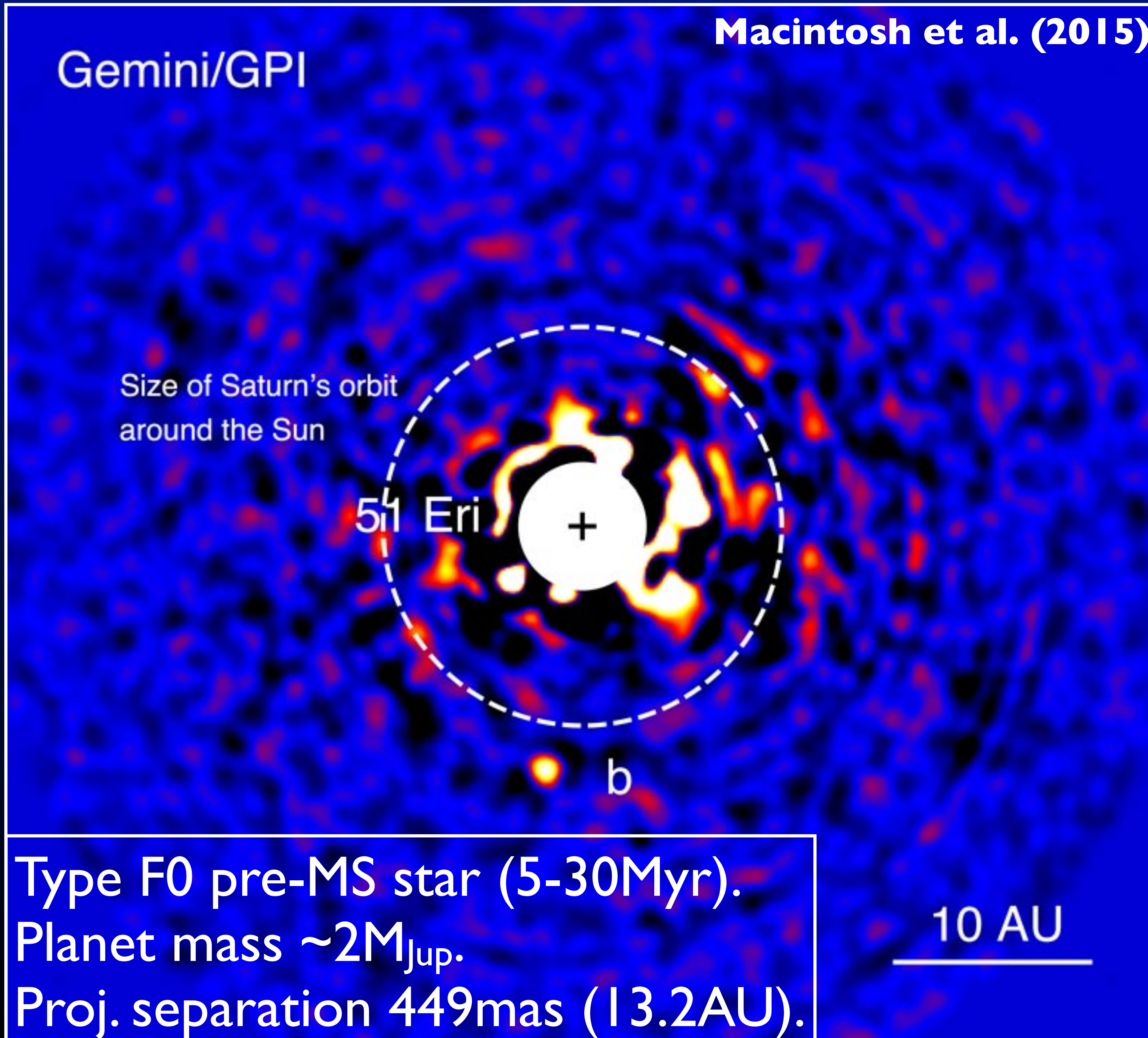
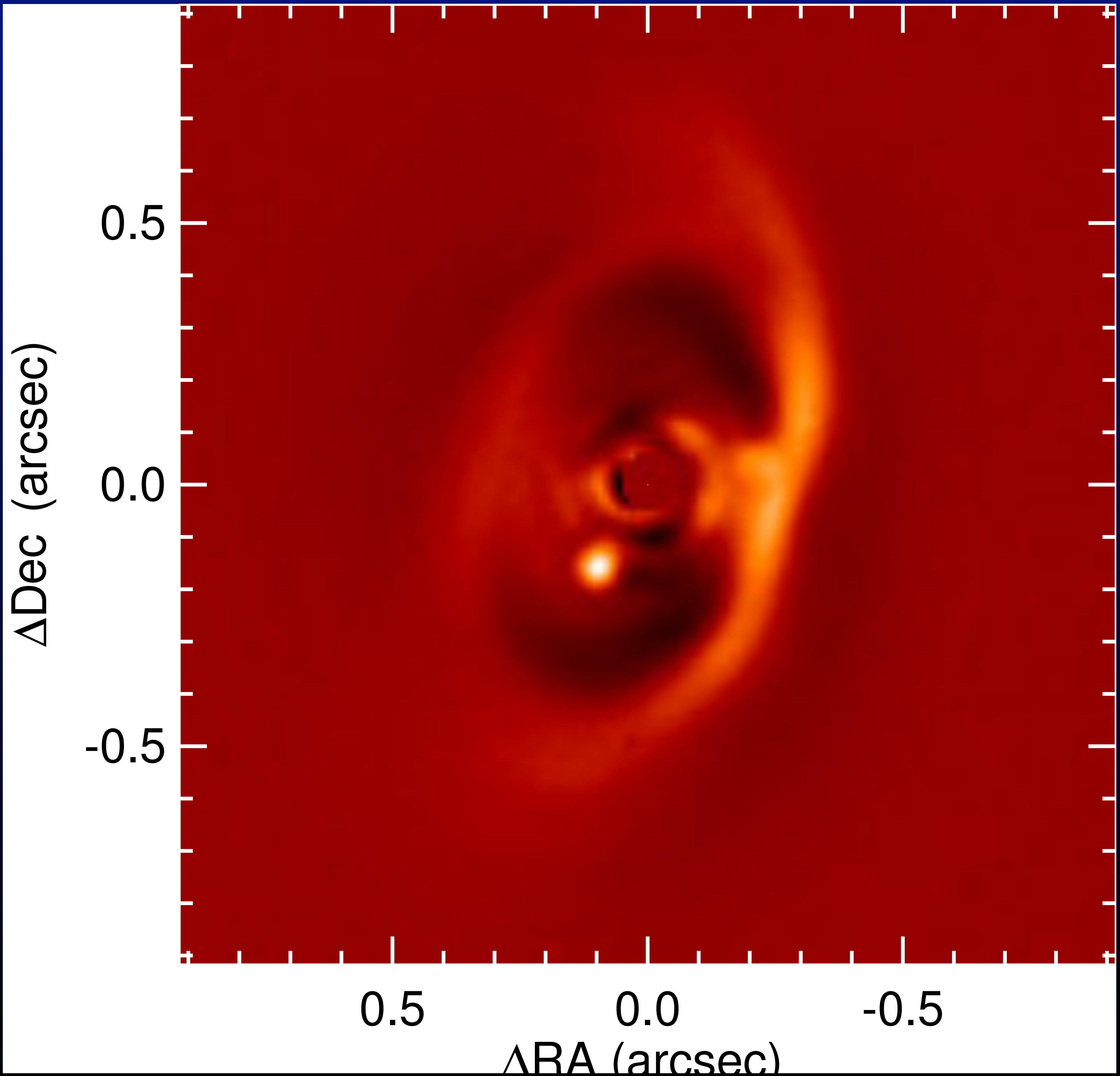


New facilities...



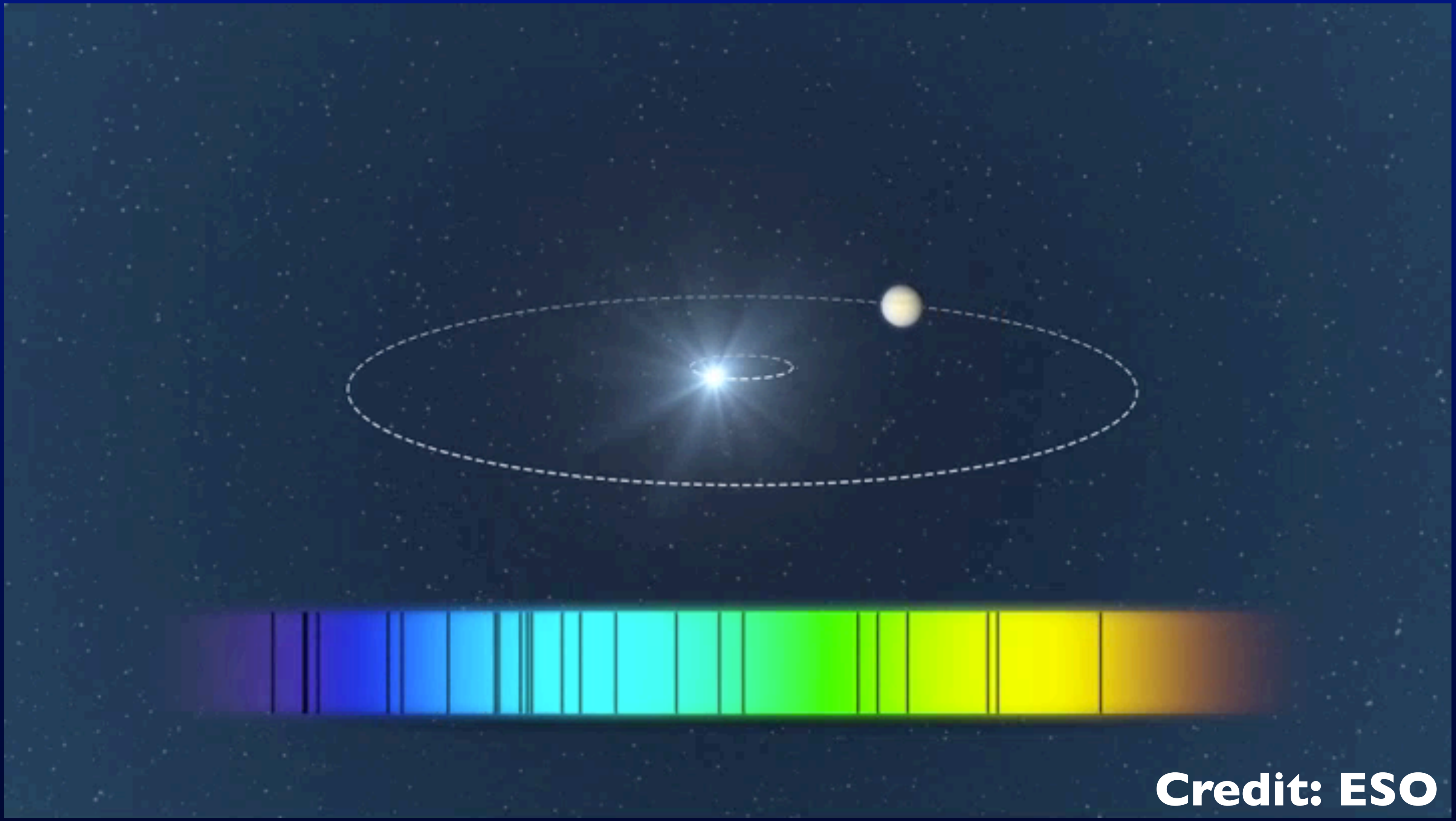
Young planets



PDS 70
Keppler et al. (2018)

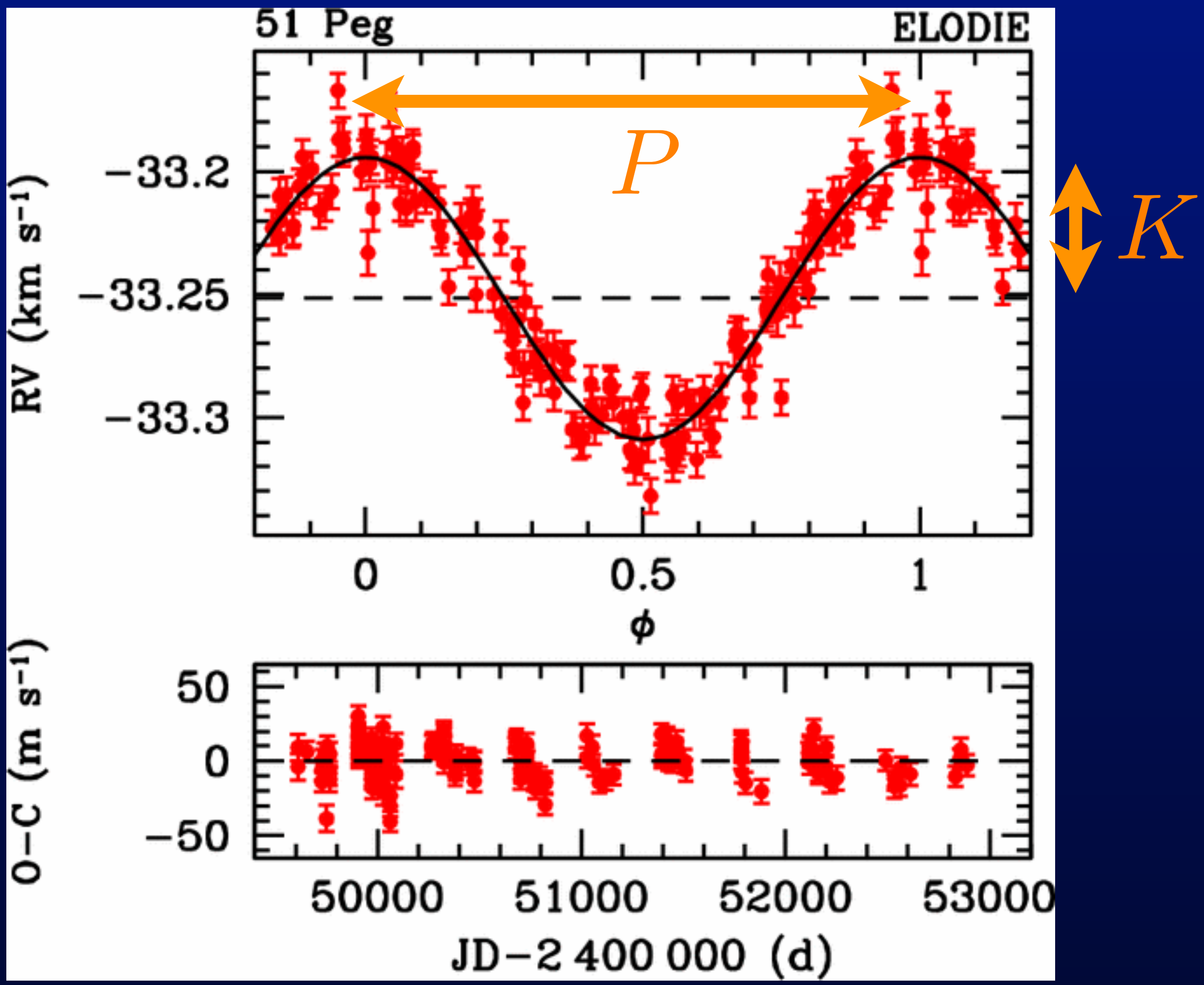
T Tauri star (5.4Myr).
Planet mass ~5M_{Jup}.
Proj. separation of 195mas (22AU).

Radial velocity methods



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



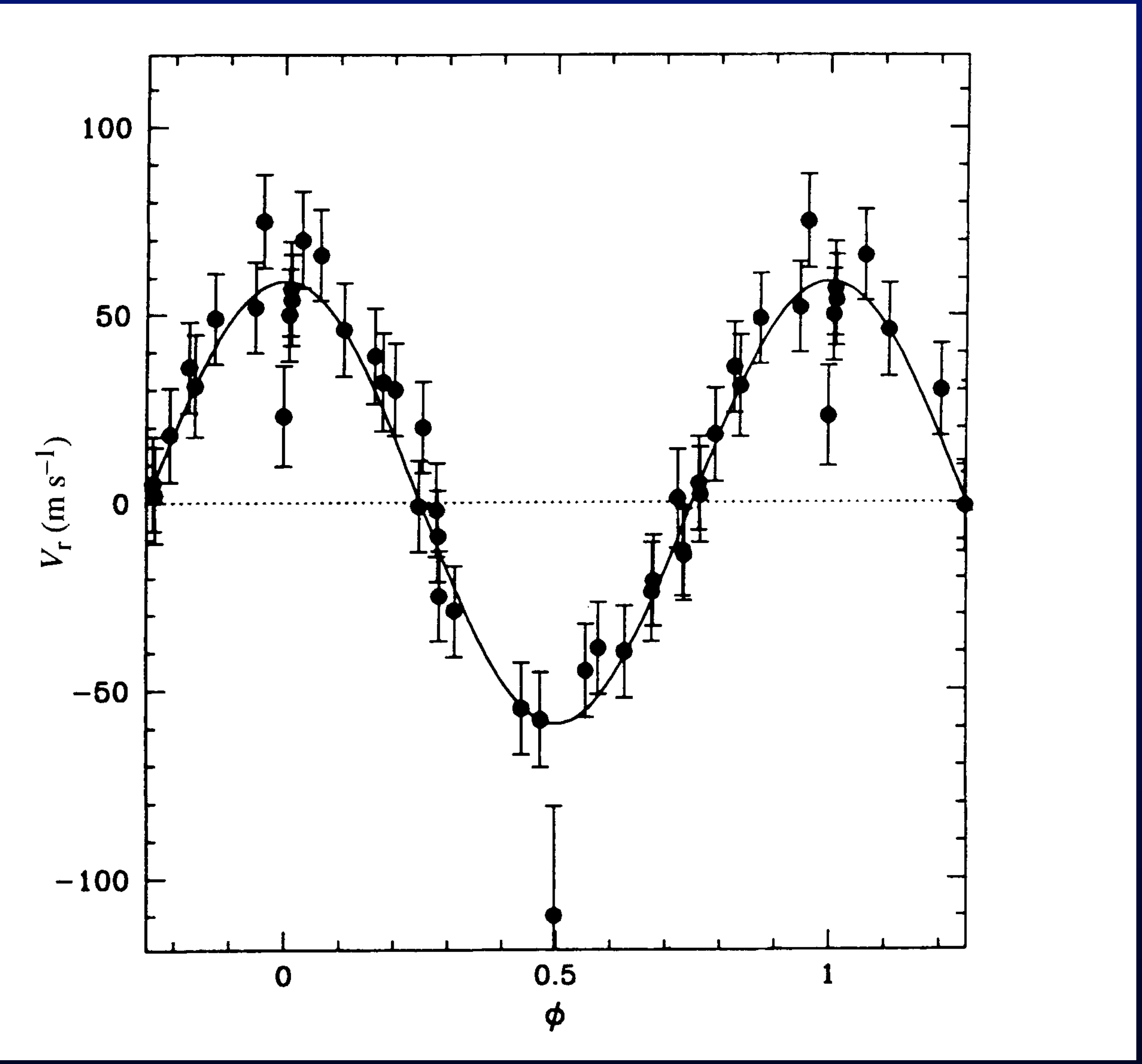
Mayor & Queloz (1995)

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

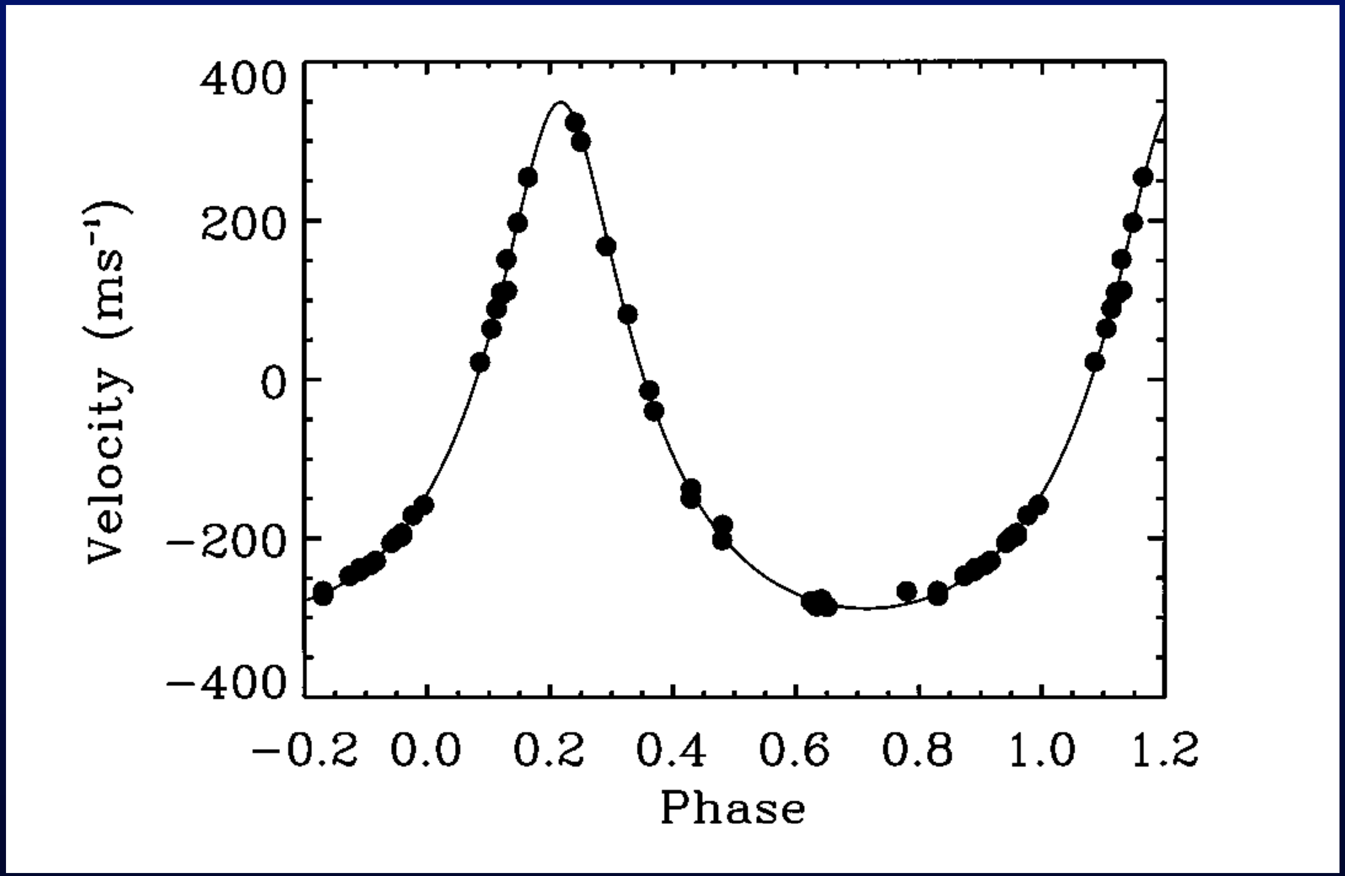
$$K = v_* \sin i = \frac{1}{\sqrt{1-e^2}} \frac{M_p \sin i}{M_*} \sqrt{\frac{GM_*}{a}}$$

- K_{Jup} ~ 12m/s; K_{Earth} ~ 10cm/s.

First detections...

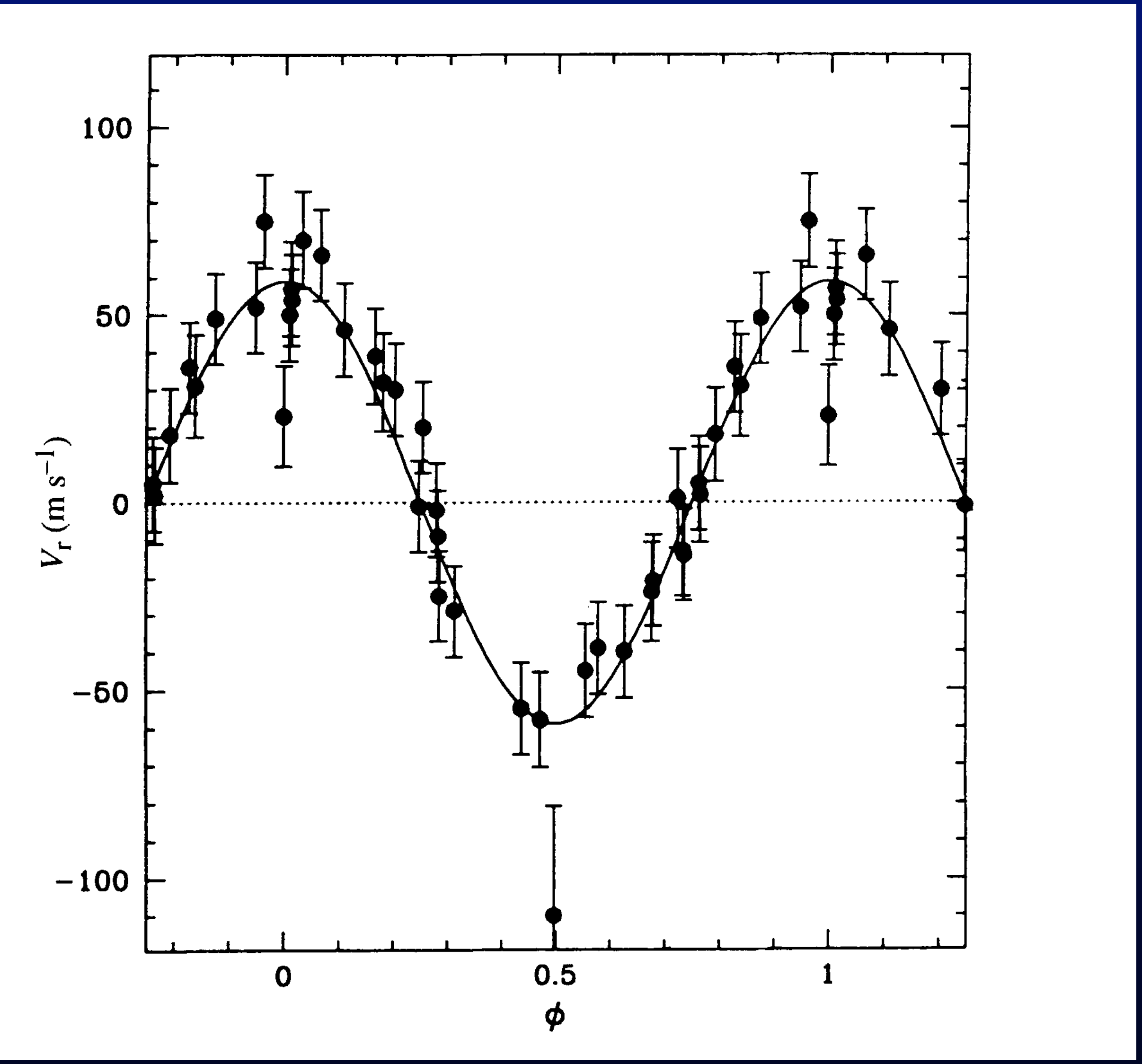


51 Peg b: Mayor & Queloz (1995)
Planet mass 0.47M$_{Jup}$, Period 4.23d



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

First detections…



51 Peg b: Mayor & Queloz (1995)
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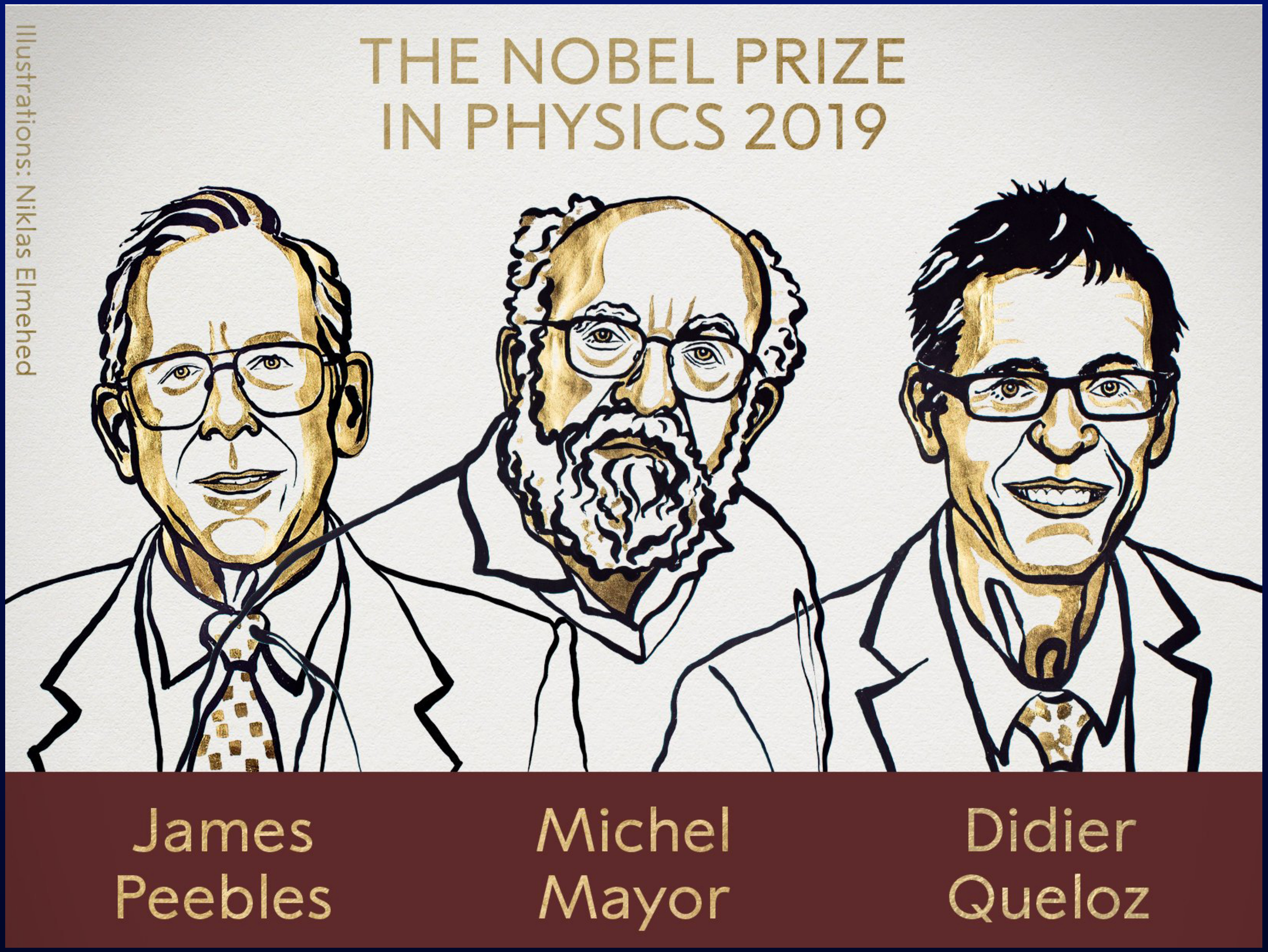
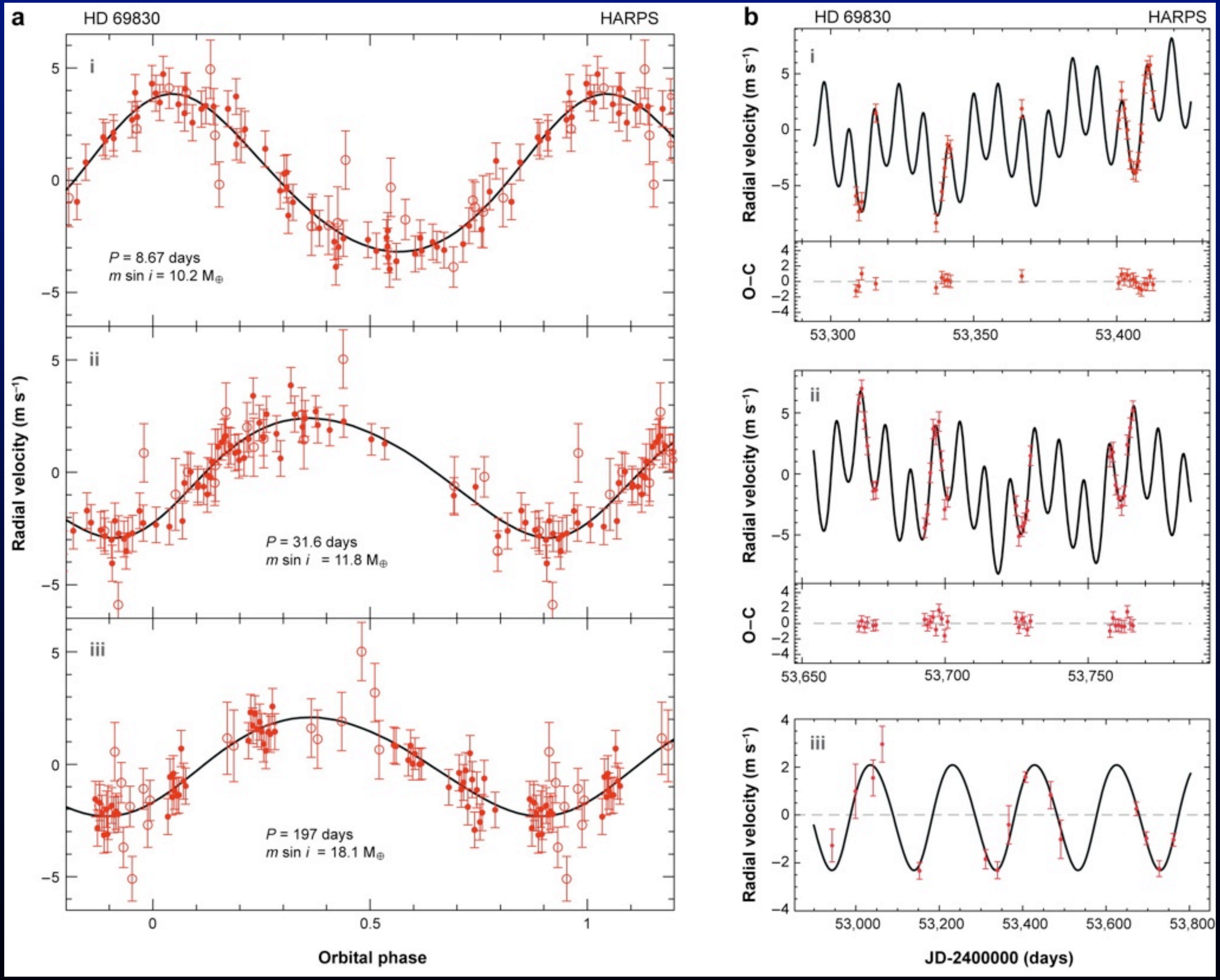
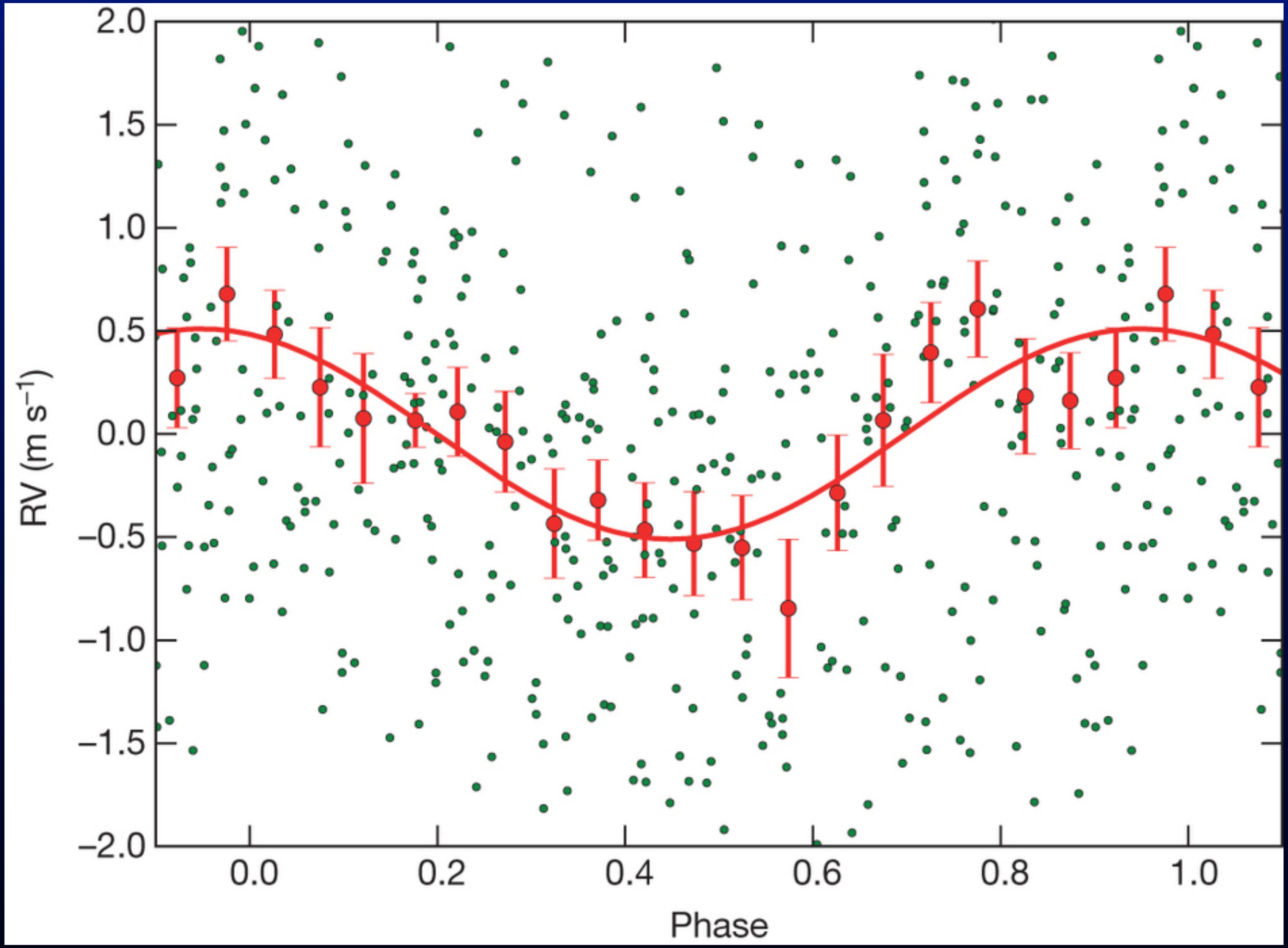


Typical RV data



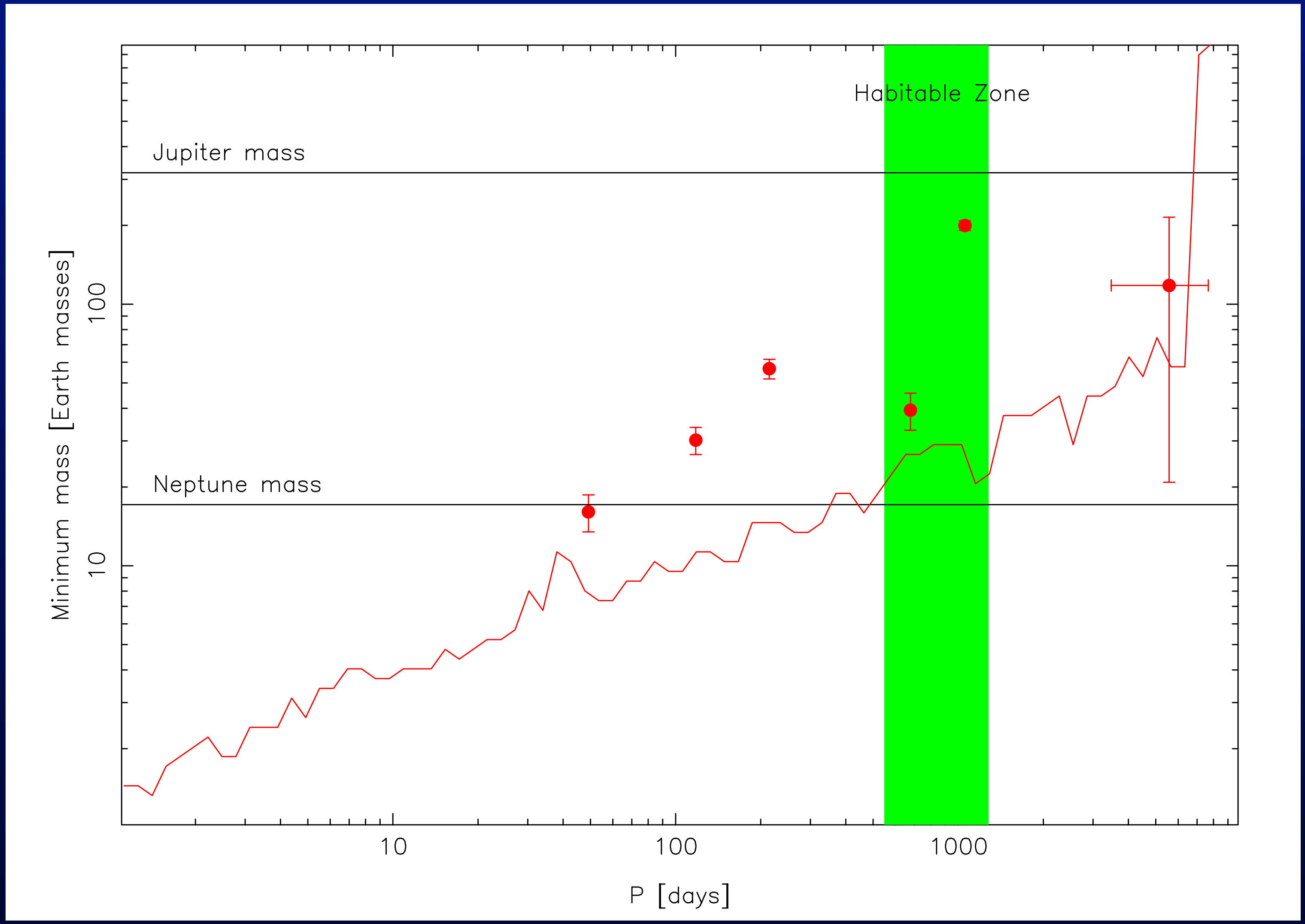
Data from Lovis et al. (2006); figure from Udry & Santos (2007)

The cutting edge??



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

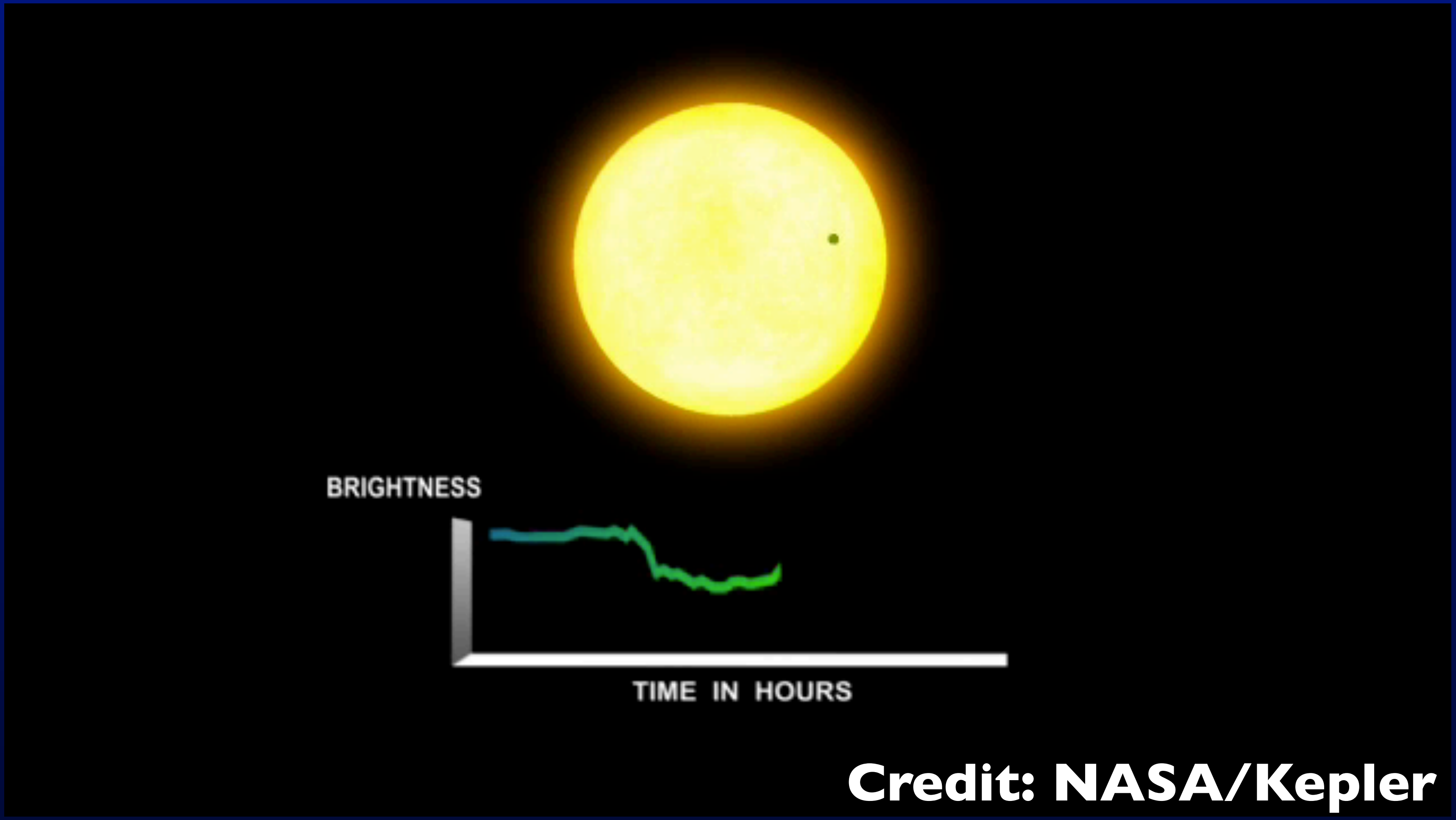
Long surveys, long periods…



Vogt+ (2017)

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

Transit method



Credit: NASA/Kepler

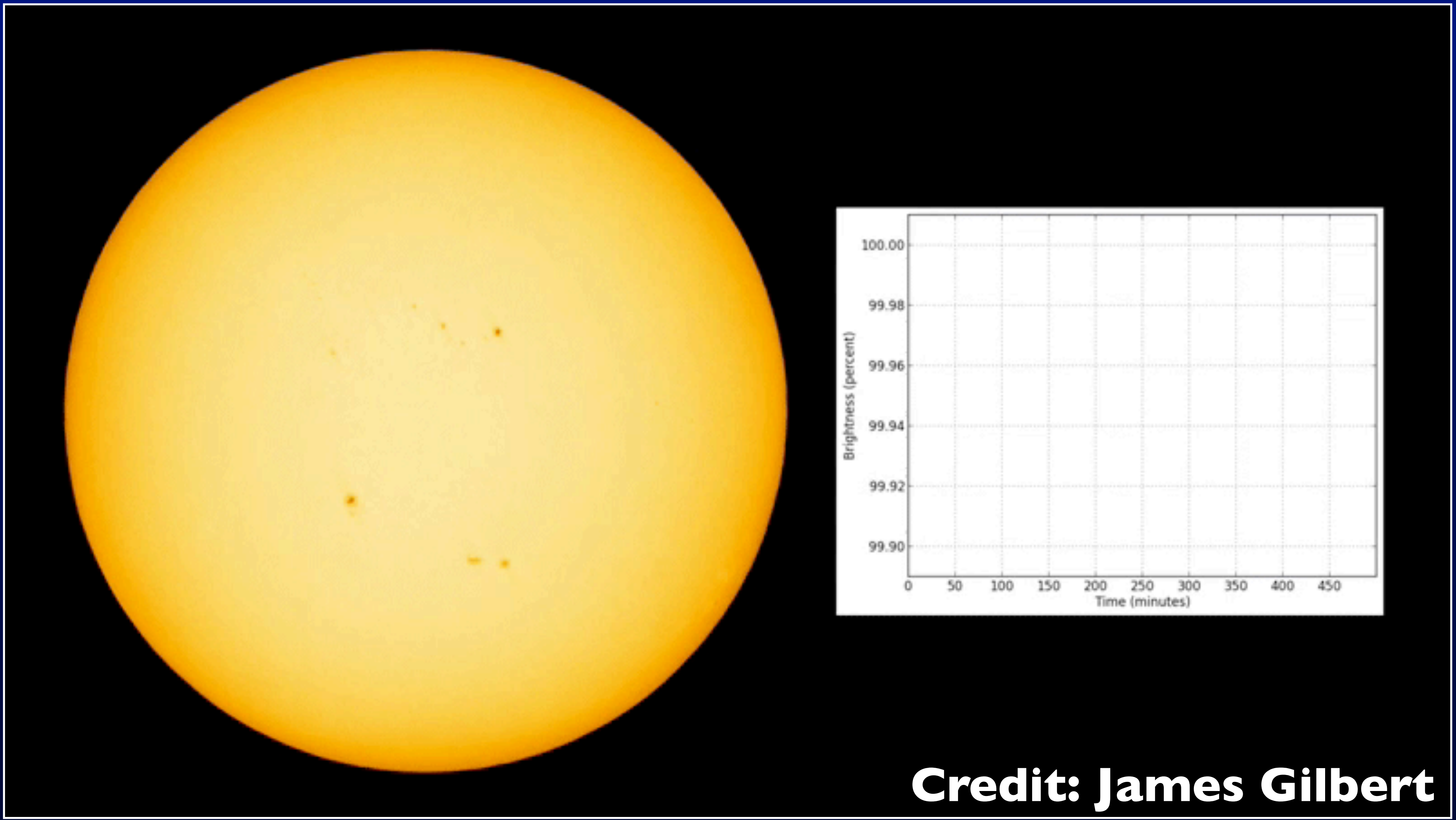
- Detect dimming of light as planet passes in front of star.
- Dimming fraction f depends on planet size:

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

$$f_{Jup} \simeq 0.01$$

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

Transit method



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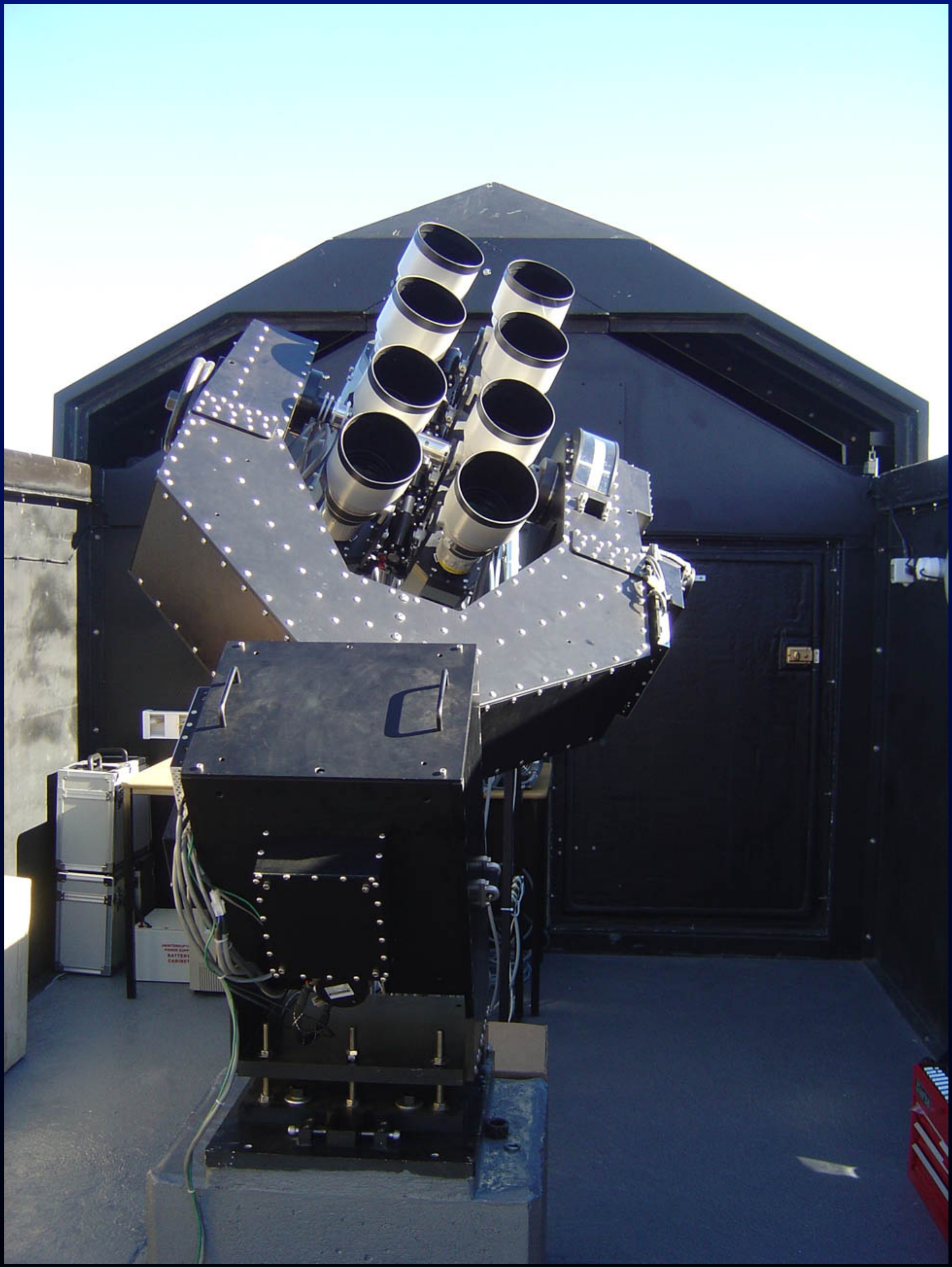
Transit method

- 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.

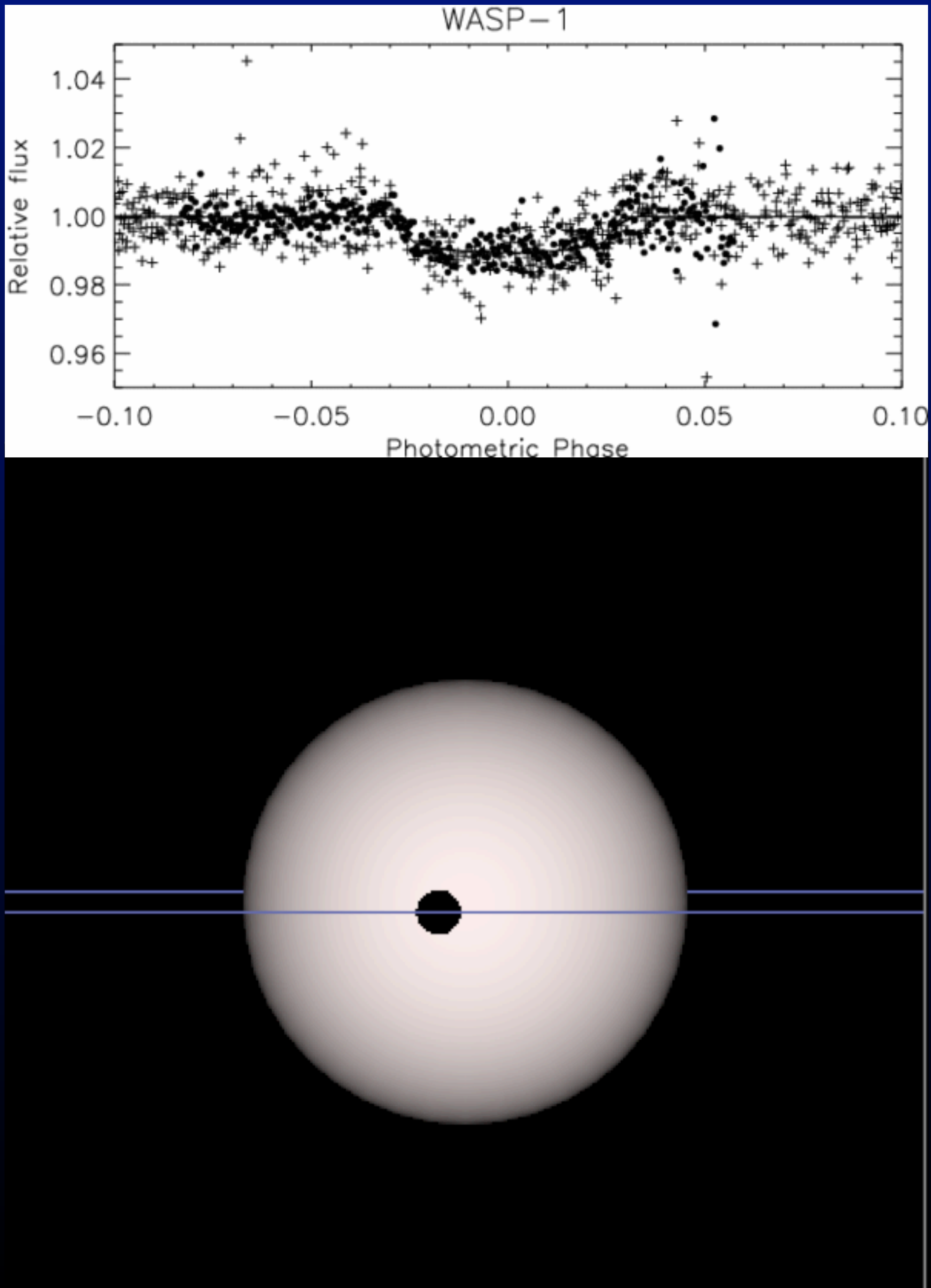
Transit method

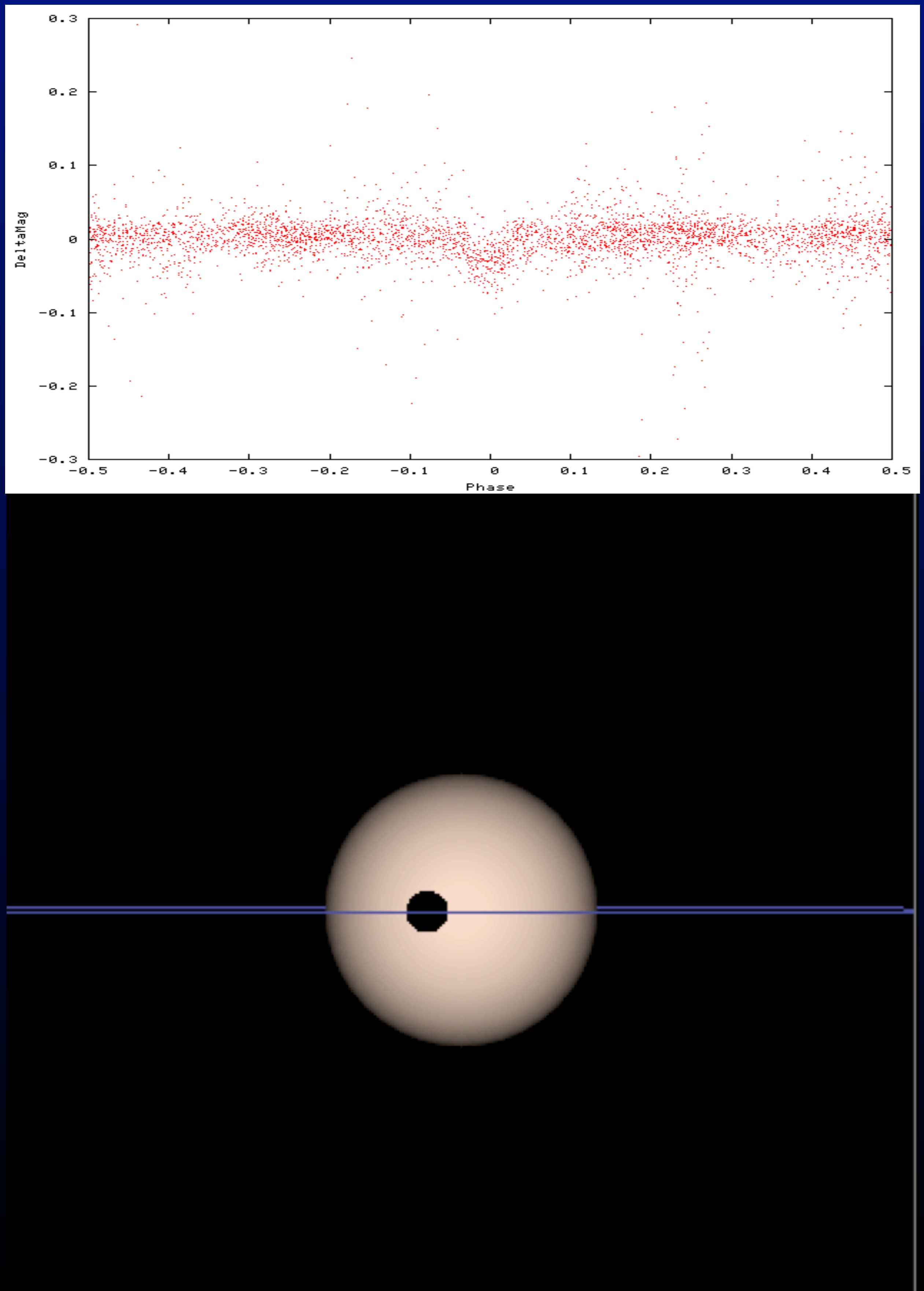
- Many current searches using transit methods.
- Most successful ground-based programme is SuperWASP (**W**ide-**A**ngle **S**earch for **P**lanets).
- SuperWASP surveyed 1/4 of the sky every night. Monitored several million stars every few minutes.
- Generates 50-100Gb of data per night.



Credit: Richard West

Ground-based transit lightcurves





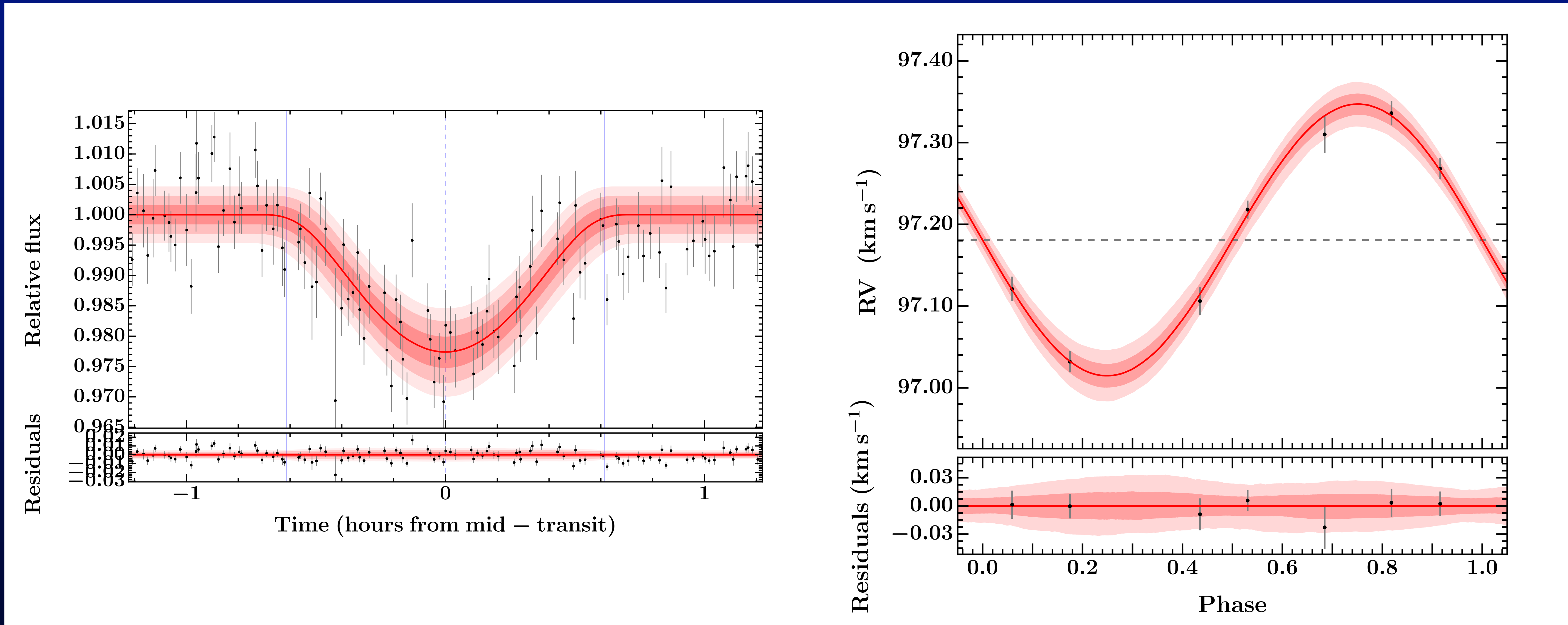
Next Generation...

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.

NGTS
NEXT-GENERATION TRANSIT SURVEY

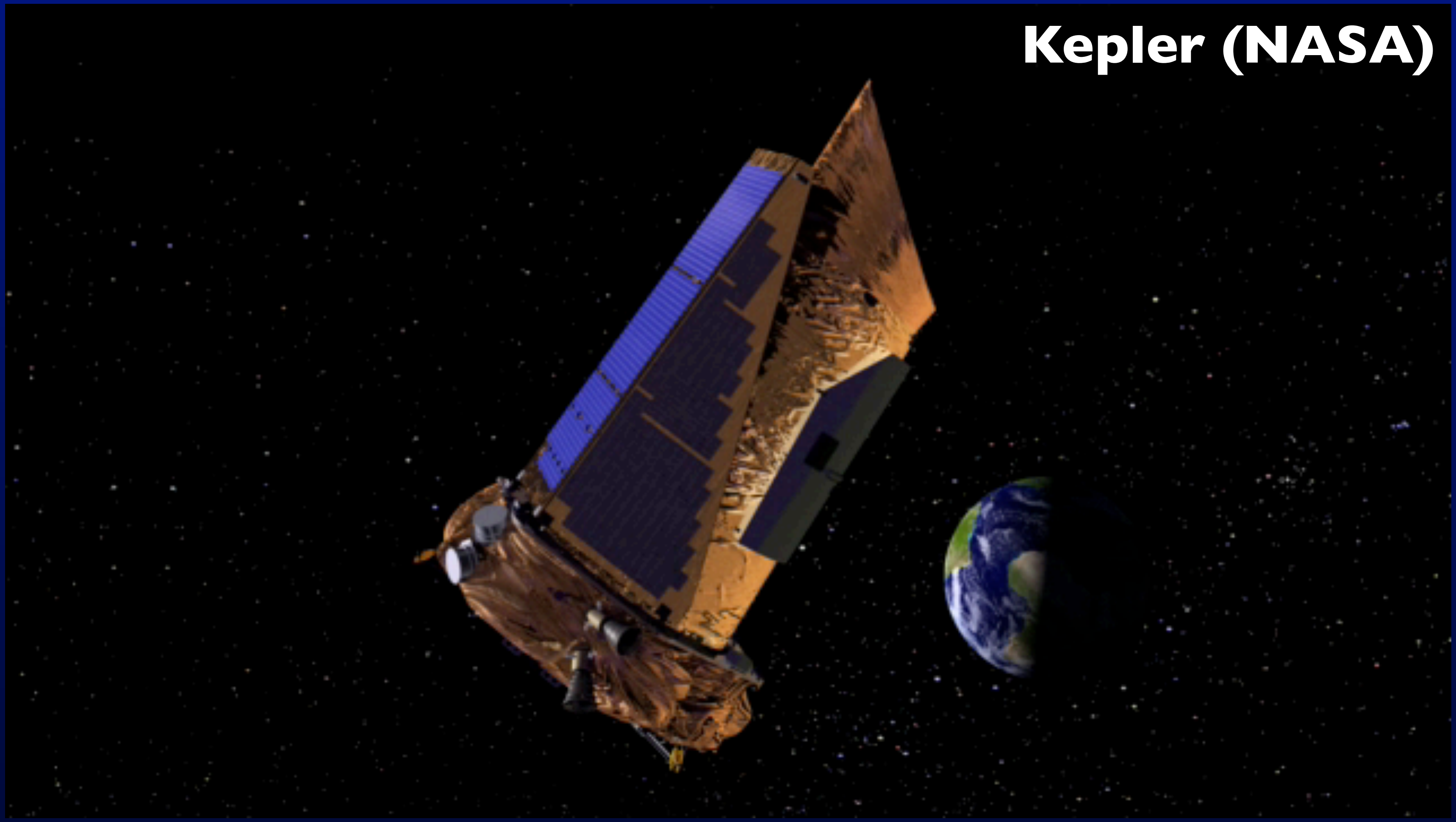
Ground-based cutting edge



Bayliss+ (2017)

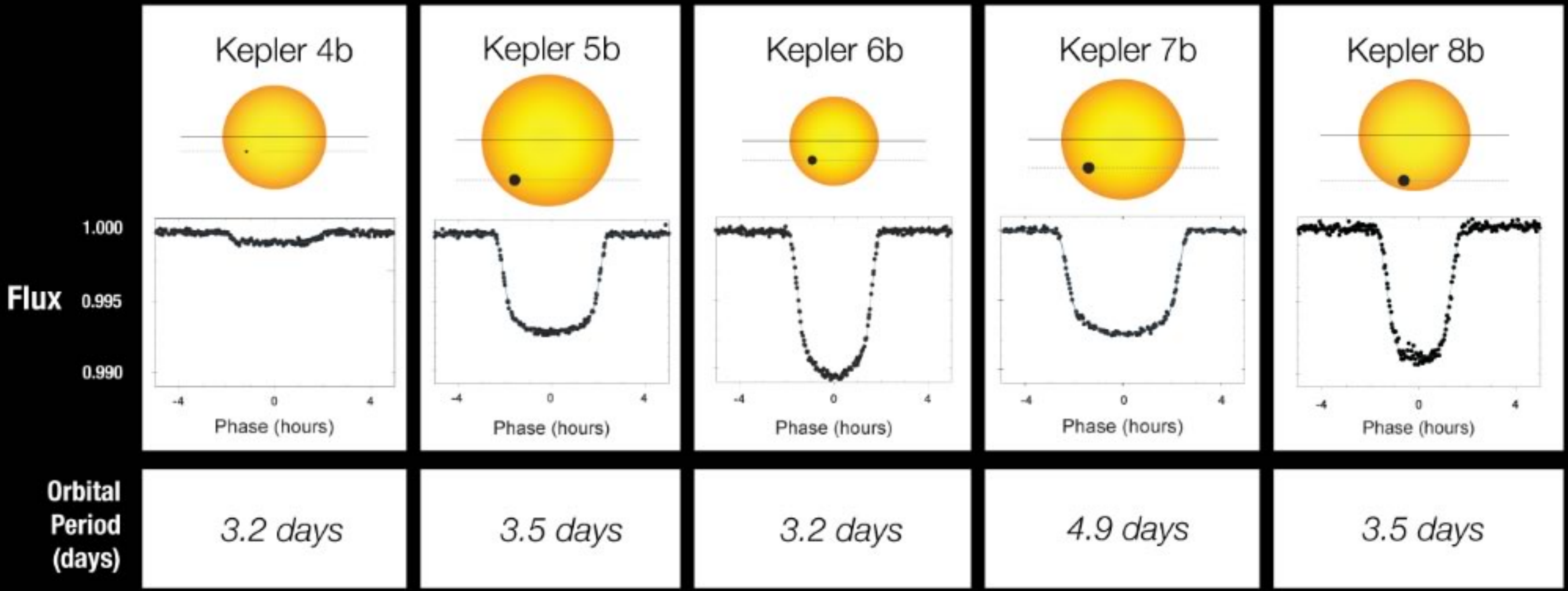
- First exoplanet discovery from NGTS.
- $0.8M_{Jup}$ planet in 2.65d orbit around a M0/M1-type host star.
- Most massive planet known around an M-dwarf. NGTS will give first large census of planets around low-mass stars.

Kepler



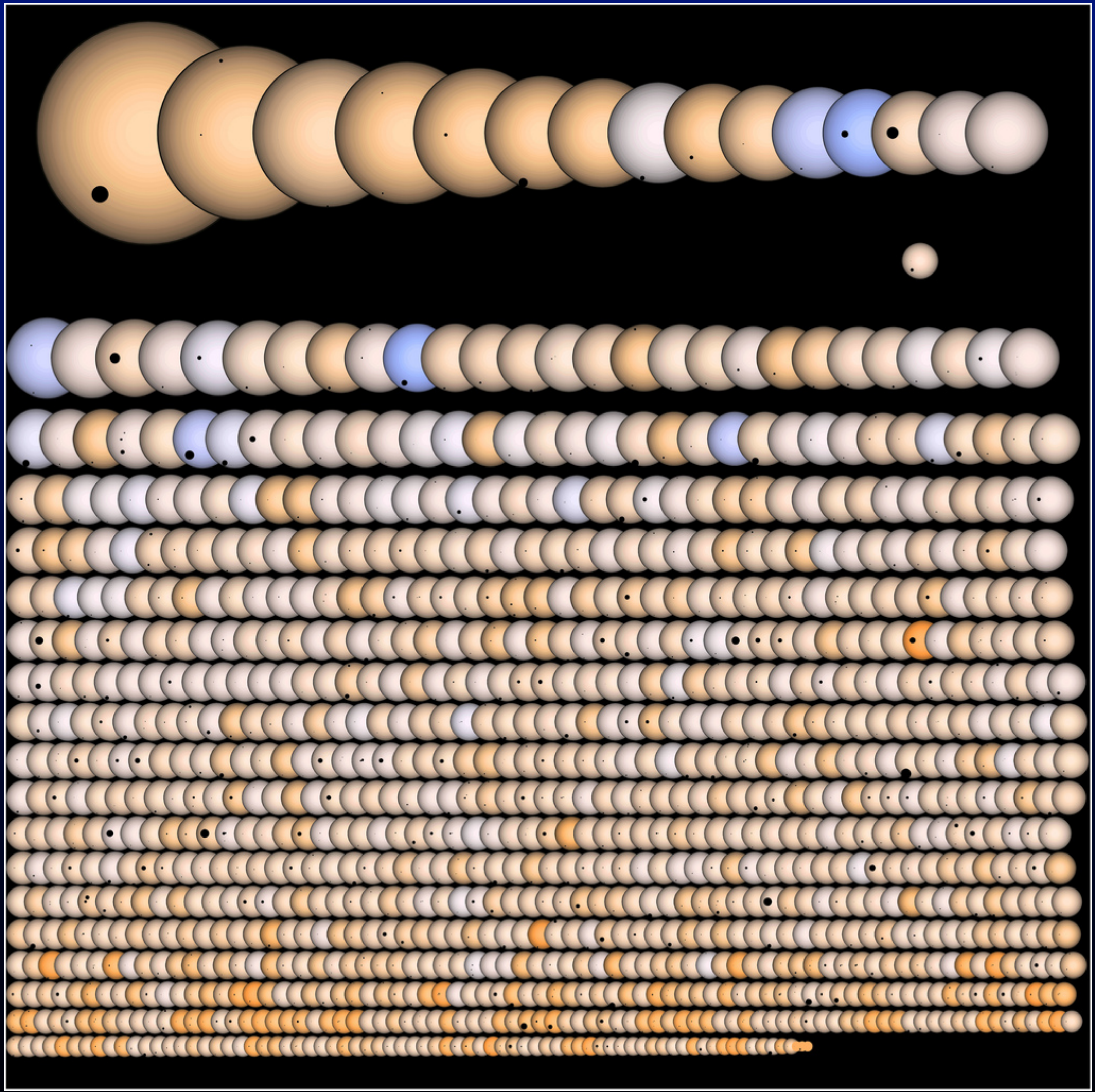
- Launched March 2009, 0.95m primary; "died" May 2013. Lived on as K2 until late 2018.
- 12° FOV, 42 CCD camera. "Stared" at fixed patch of (blank) sky to obtain light-curves for >150,000 stars.
- Photometric precision as good as ~10ppm (in some cases). Sensitive to sub-Earth-size planets.

Kepler light-curves

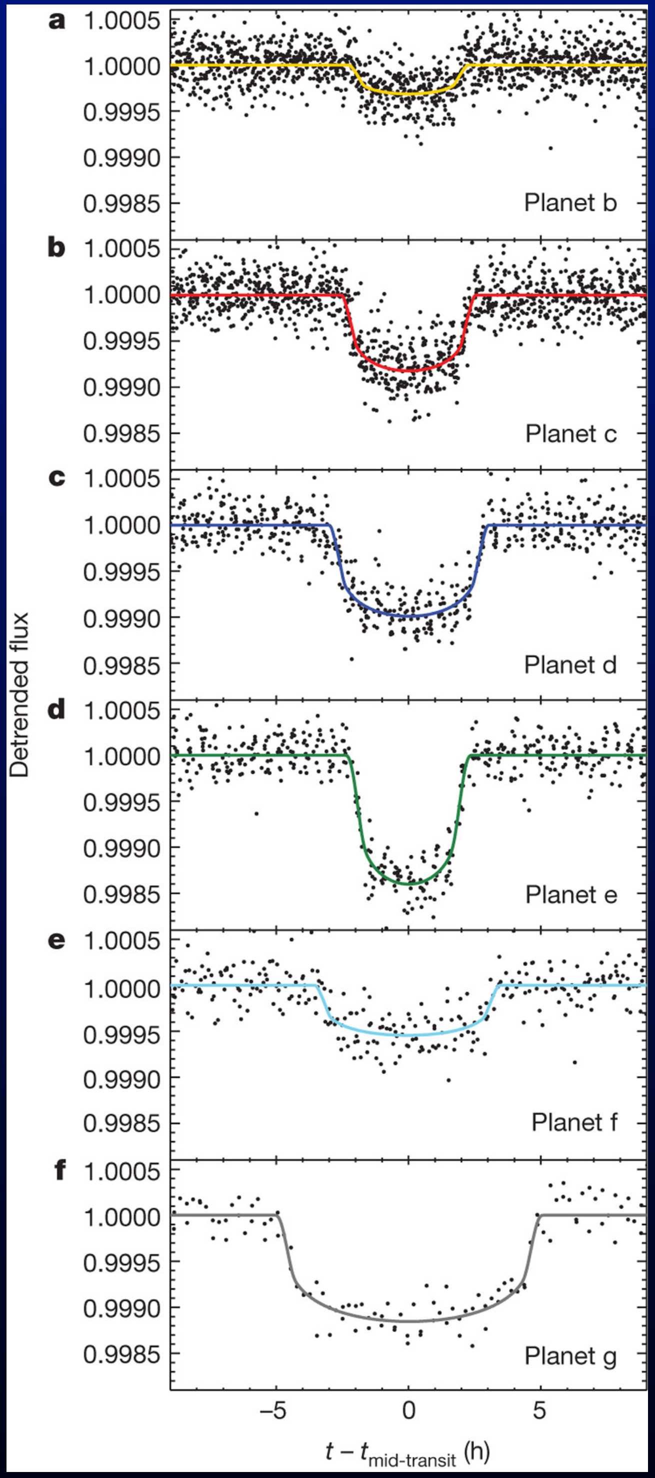


- Early data release (June 2010) focused on a few "hot Jupiters", to demonstrate precision.
- Fourth (& final) major data release in January 2014. Total of ~4500 planet candidates, with >2000 now confirmed.

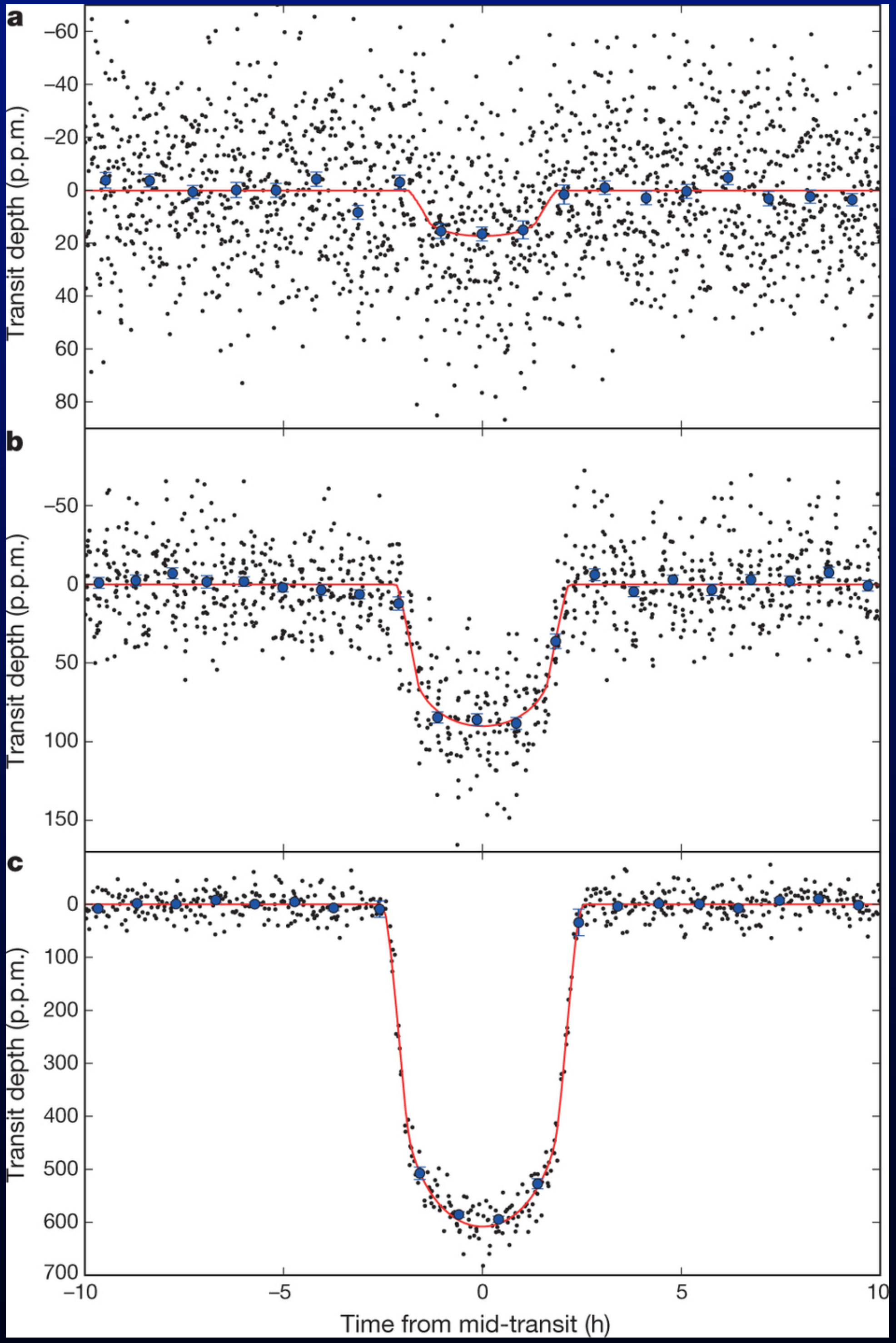
Kepler: first results



Kepler examples



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

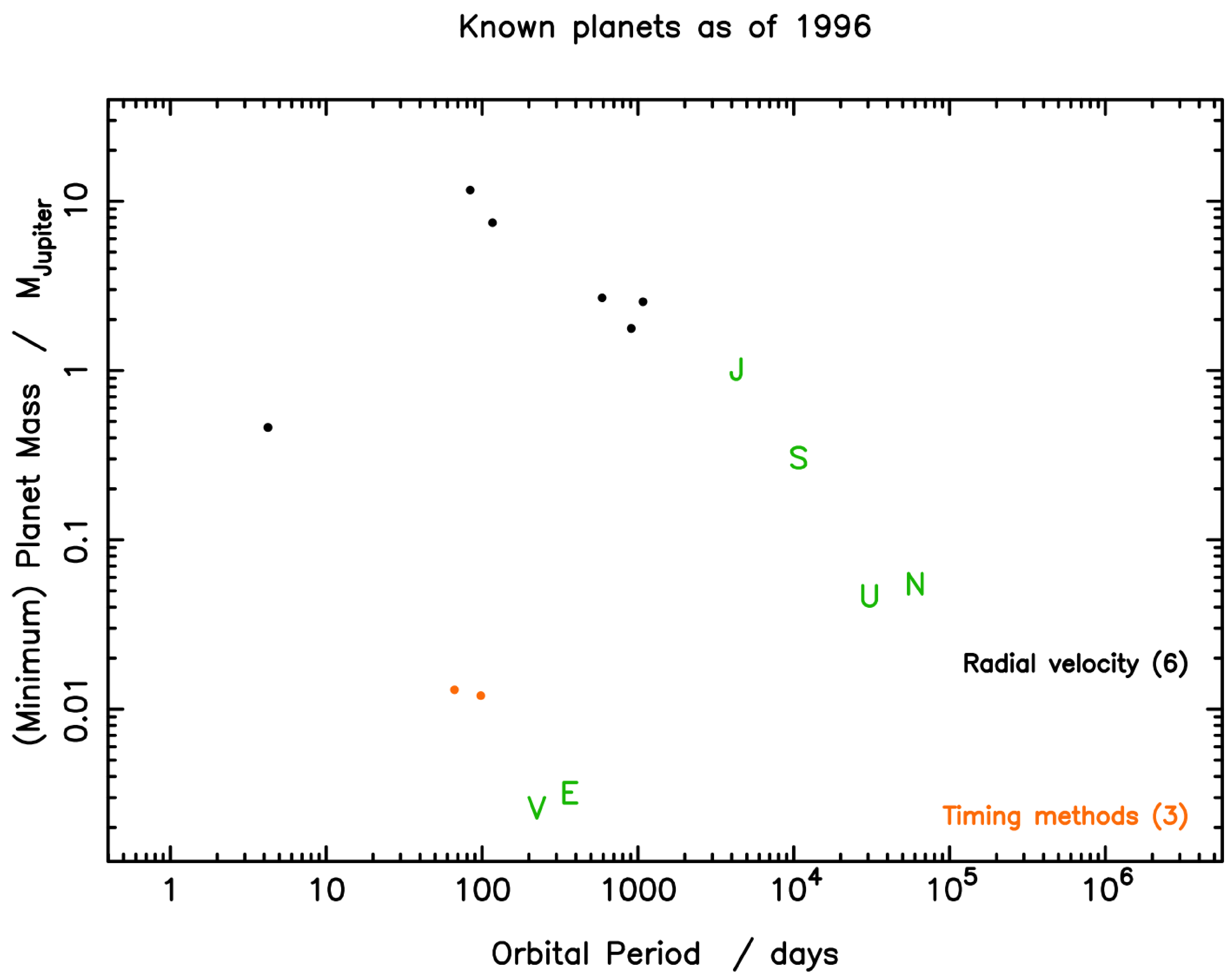


Kepler-37: Barclay et al. (2013)
3-planet system, periods 13.4, 21.3, 39.8d.
"b" is roughly the size of the Moon.

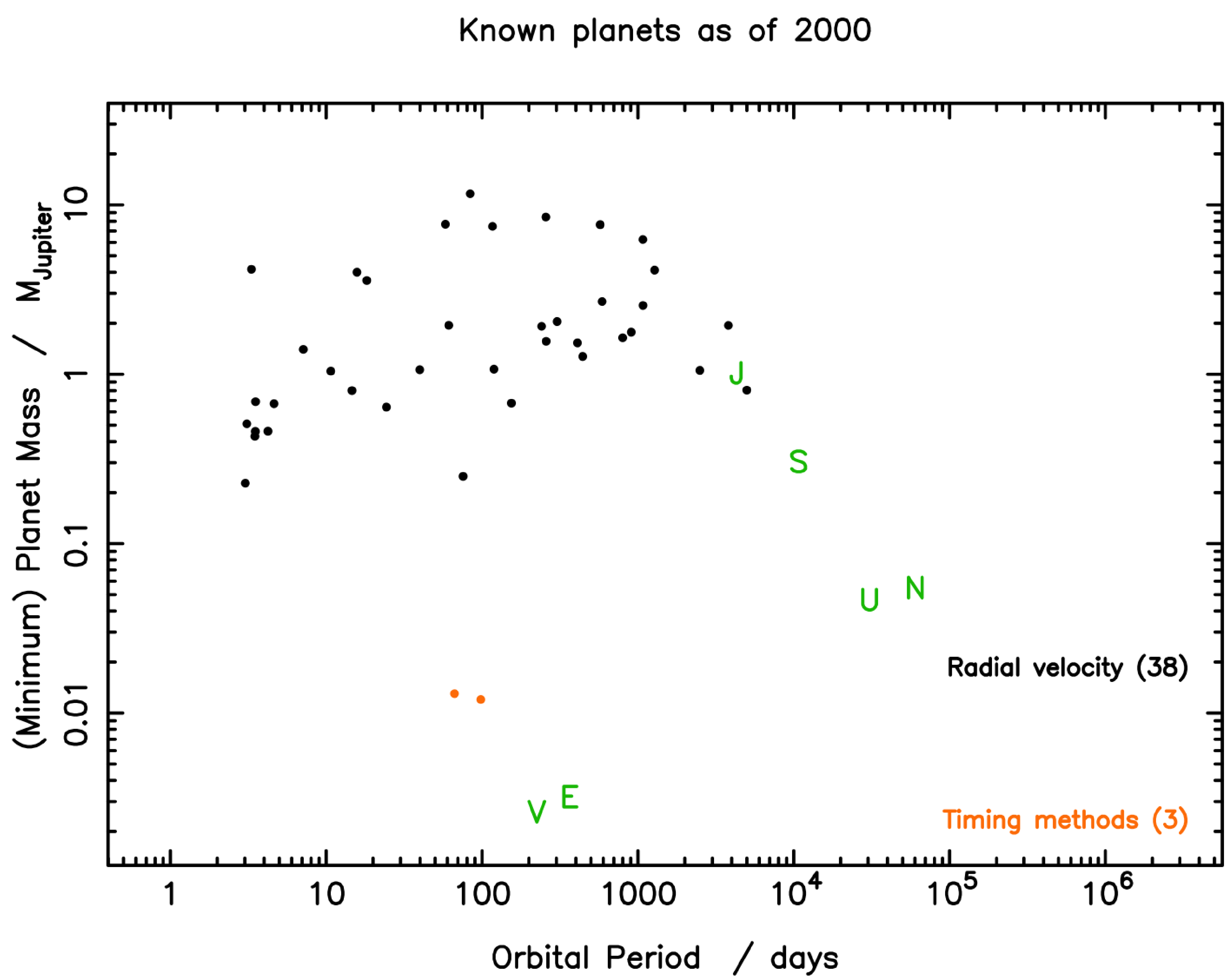
Summary of methods and biases

- 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.



Data from exoplanet.eu



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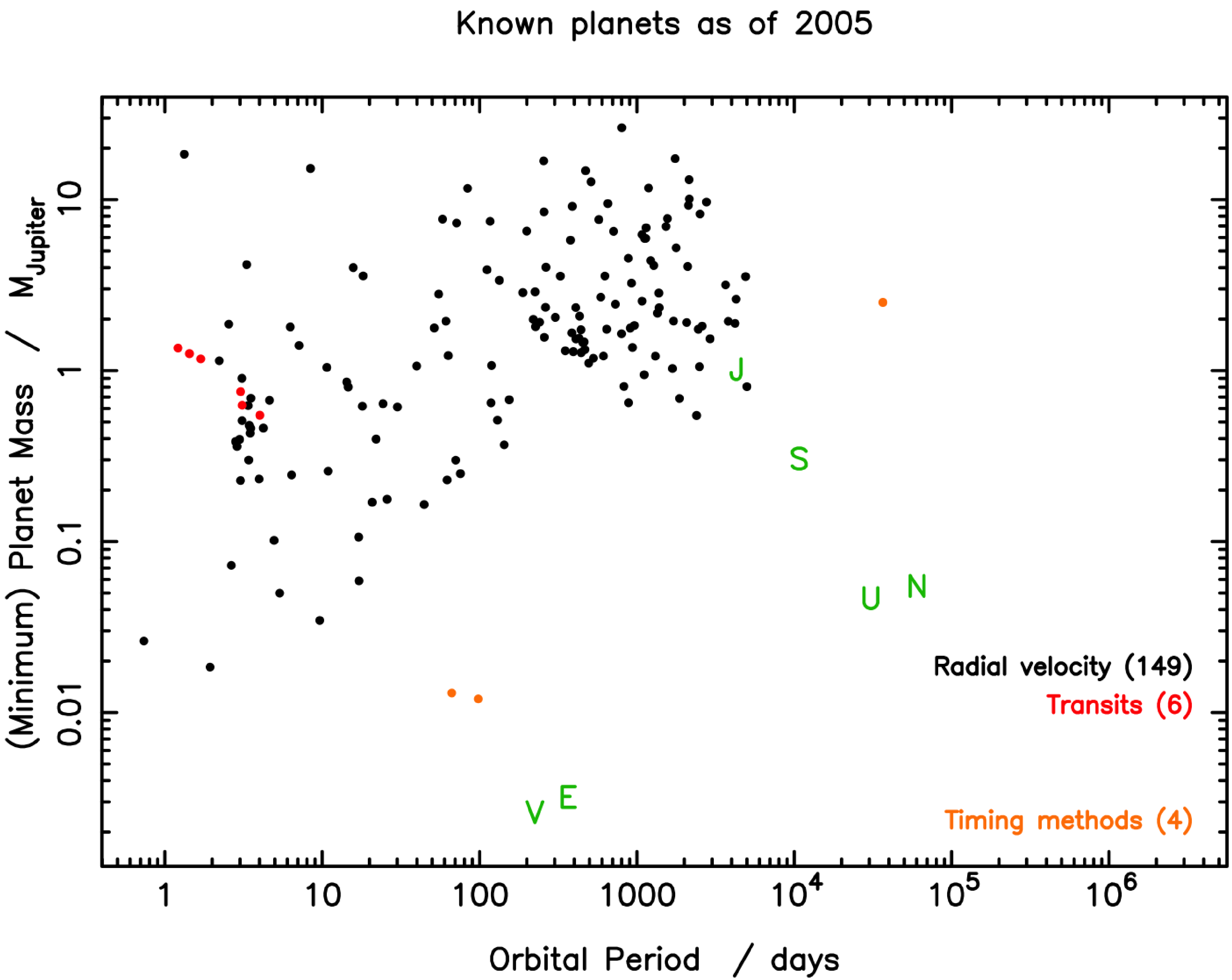

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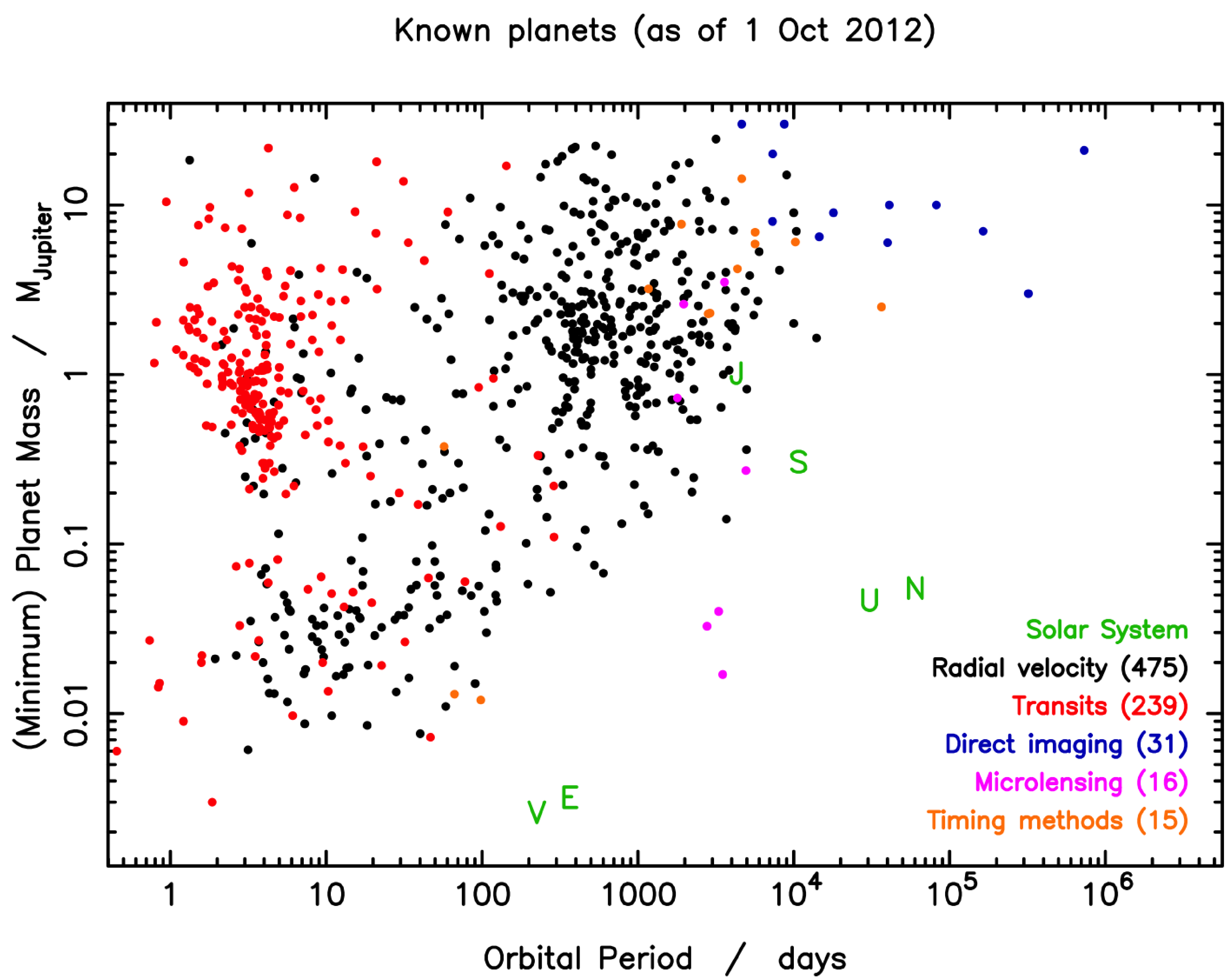

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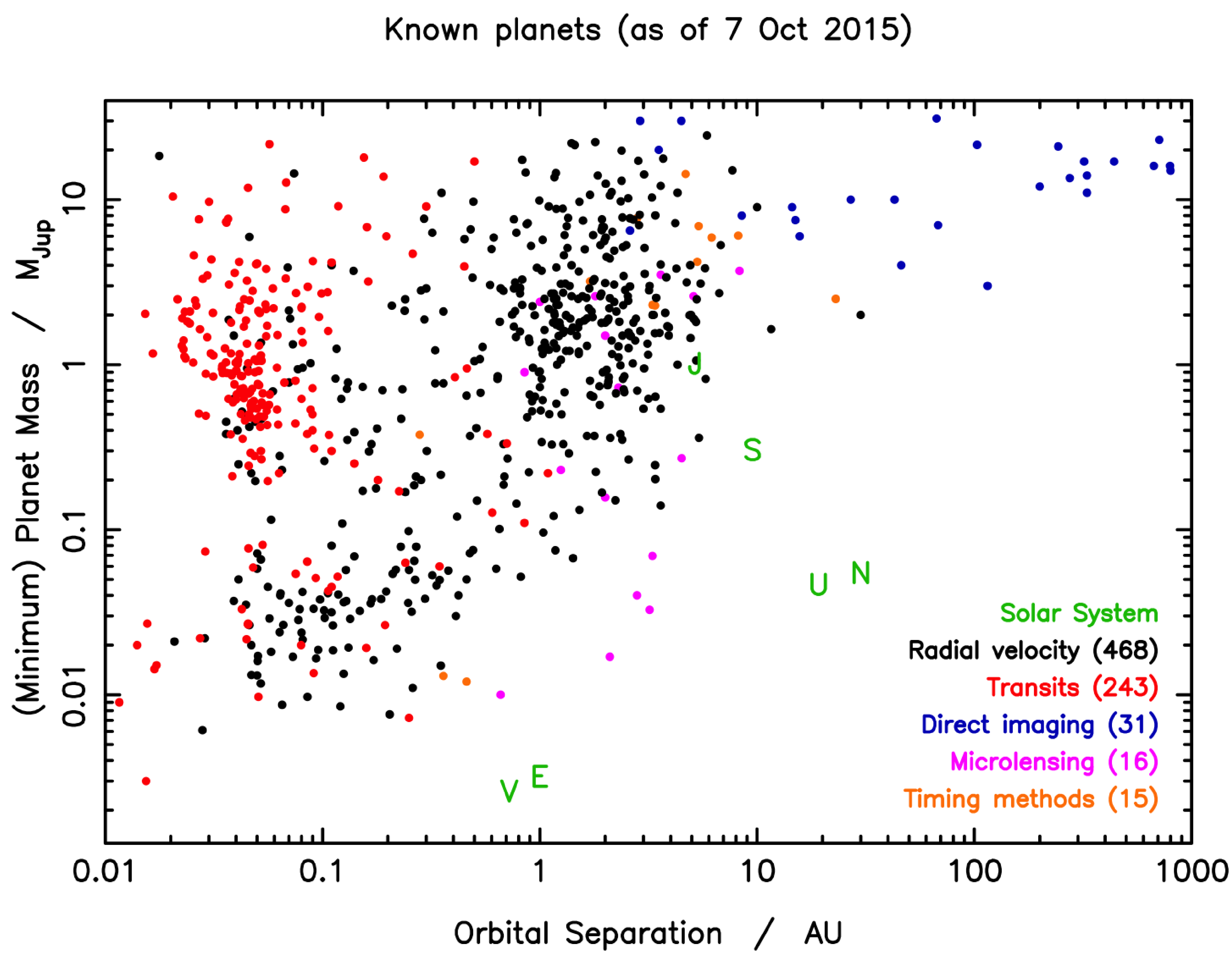
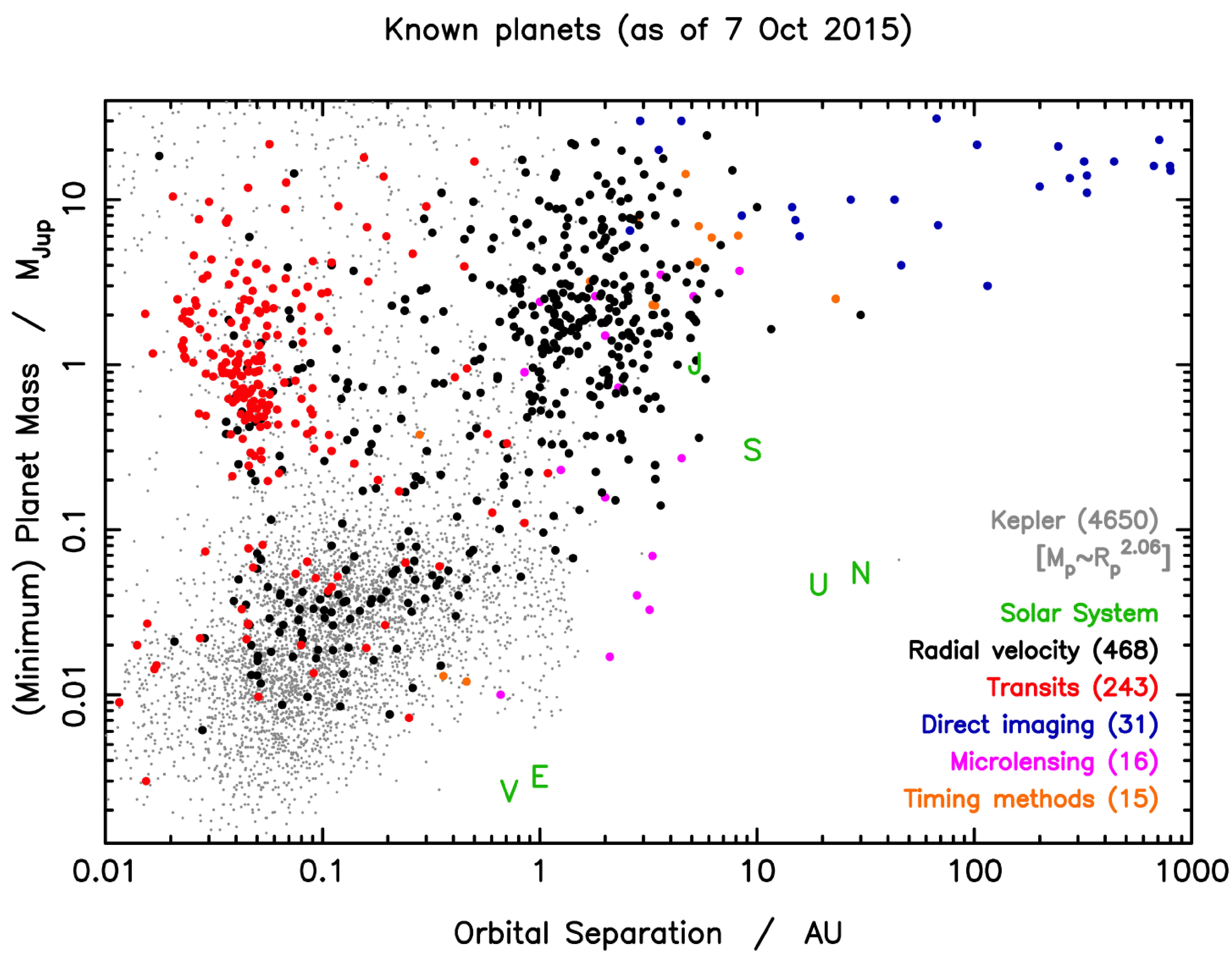


Data from exoplanets.org



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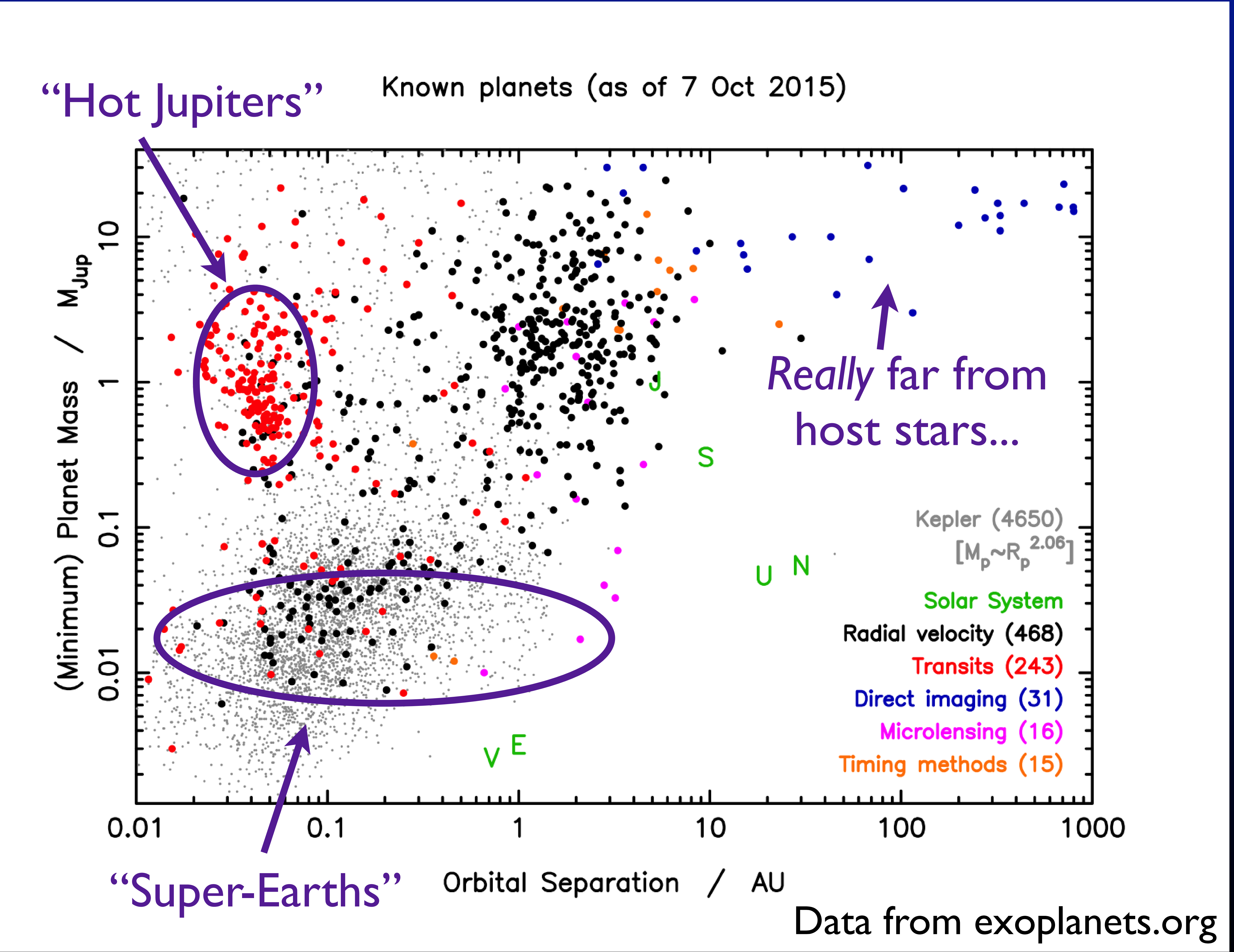
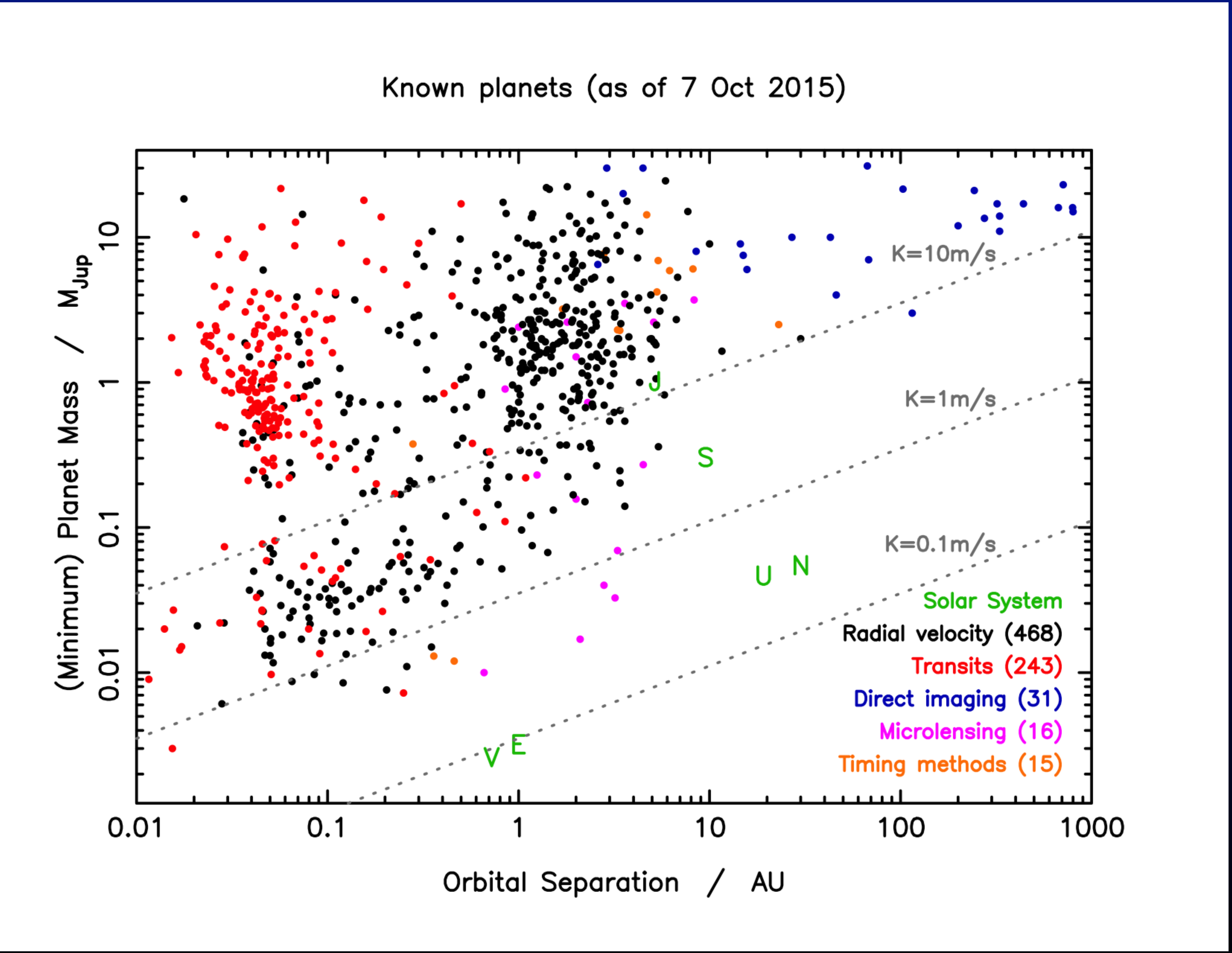
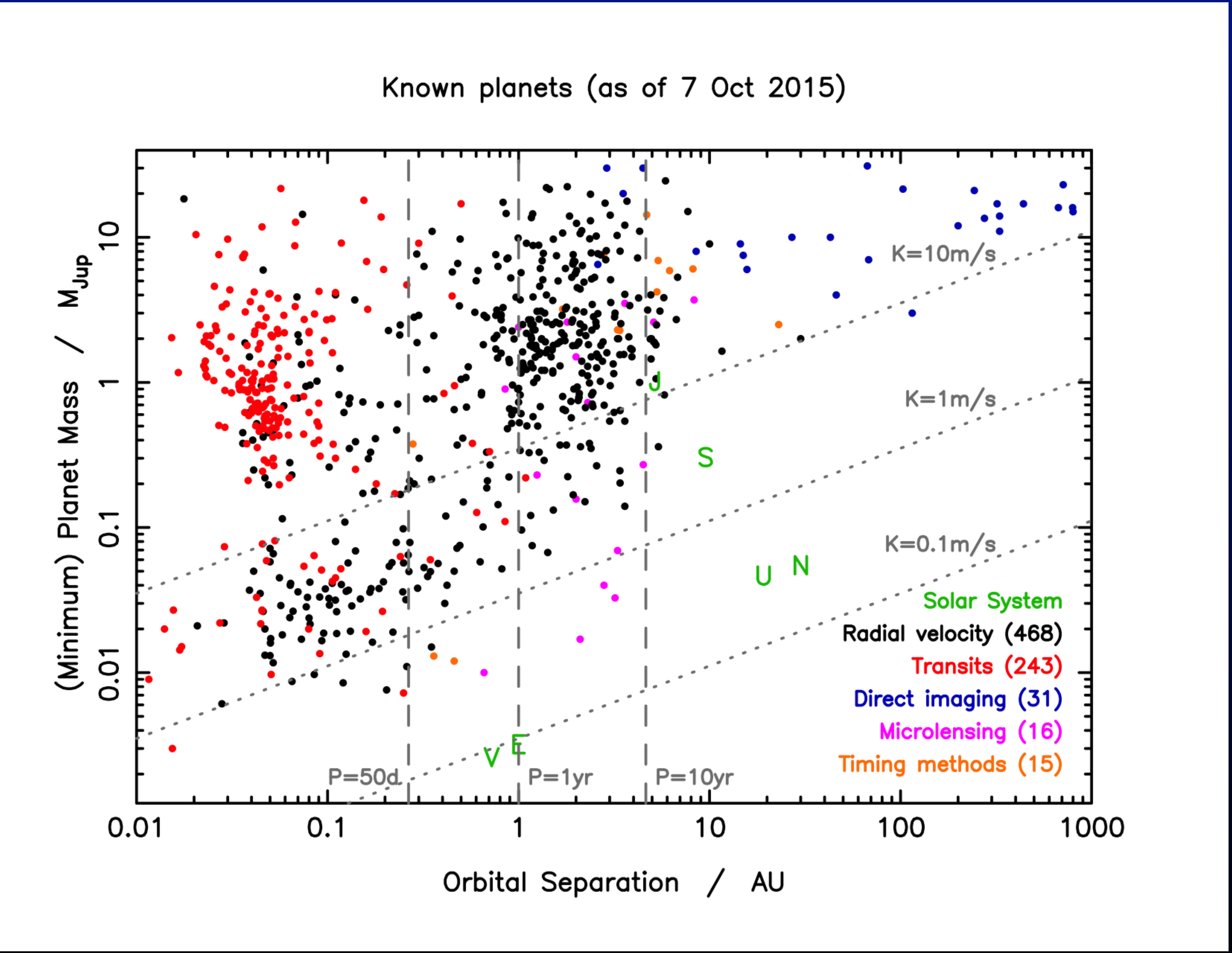

"Hot Jupiters"
Known planets (as of 7 Oct 2015)
(Minimum) Planet Mass / M_{Jup}
10
1
0.1
0.01
Really far from host stars...
J
S
U
N
V
E
Kepler (4650)
$[M_p \sim R_p^{2.06}]$
Solar System
Radial velocity (468)
Transits (243)
Direct imaging (31)
Microlensing (16)
Timing methods (15)
0.01
0.1
1
10
100
1000
"Super-Earths"
Orbital Separation / AU
Data from exoplanets.org

Selection biases

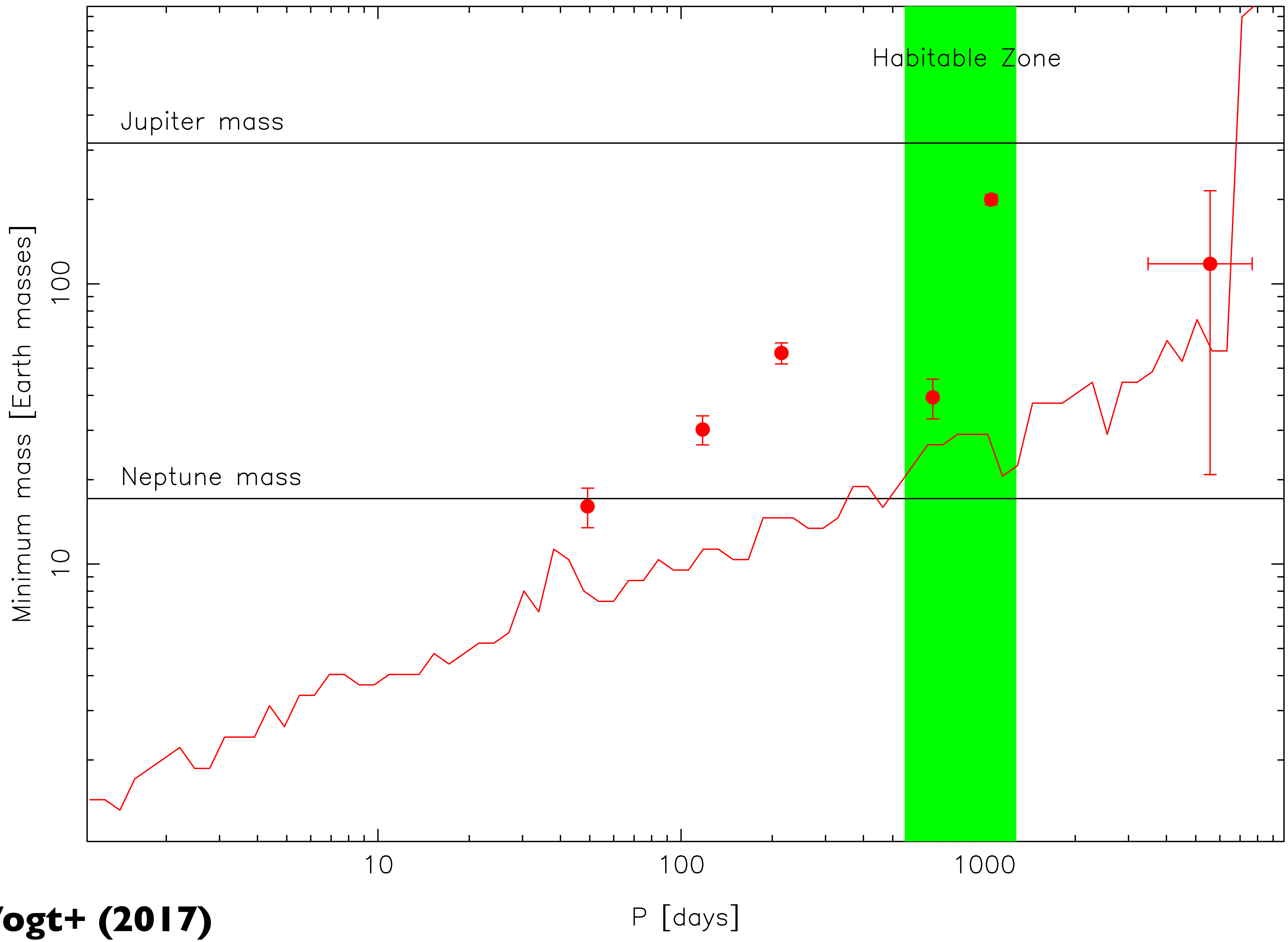


$$K \propto M_p \sin i a^{-1/2} \quad \Rightarrow \quad M_p \sin i \propto K a^{1/2}$$

Selection biases

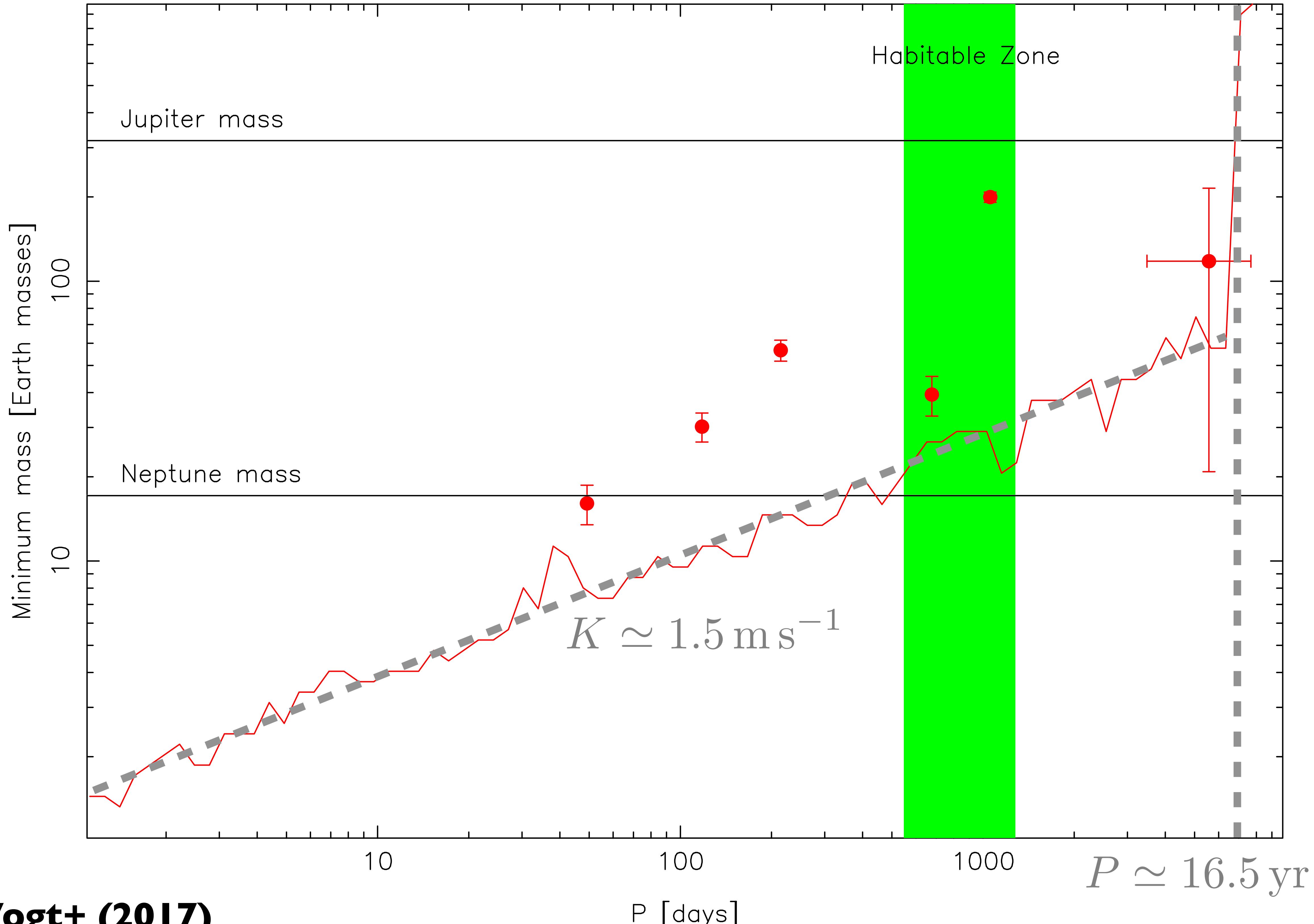


Selection biases



Vogt+ (2017)

Selection biases



Vogt+ (2017)

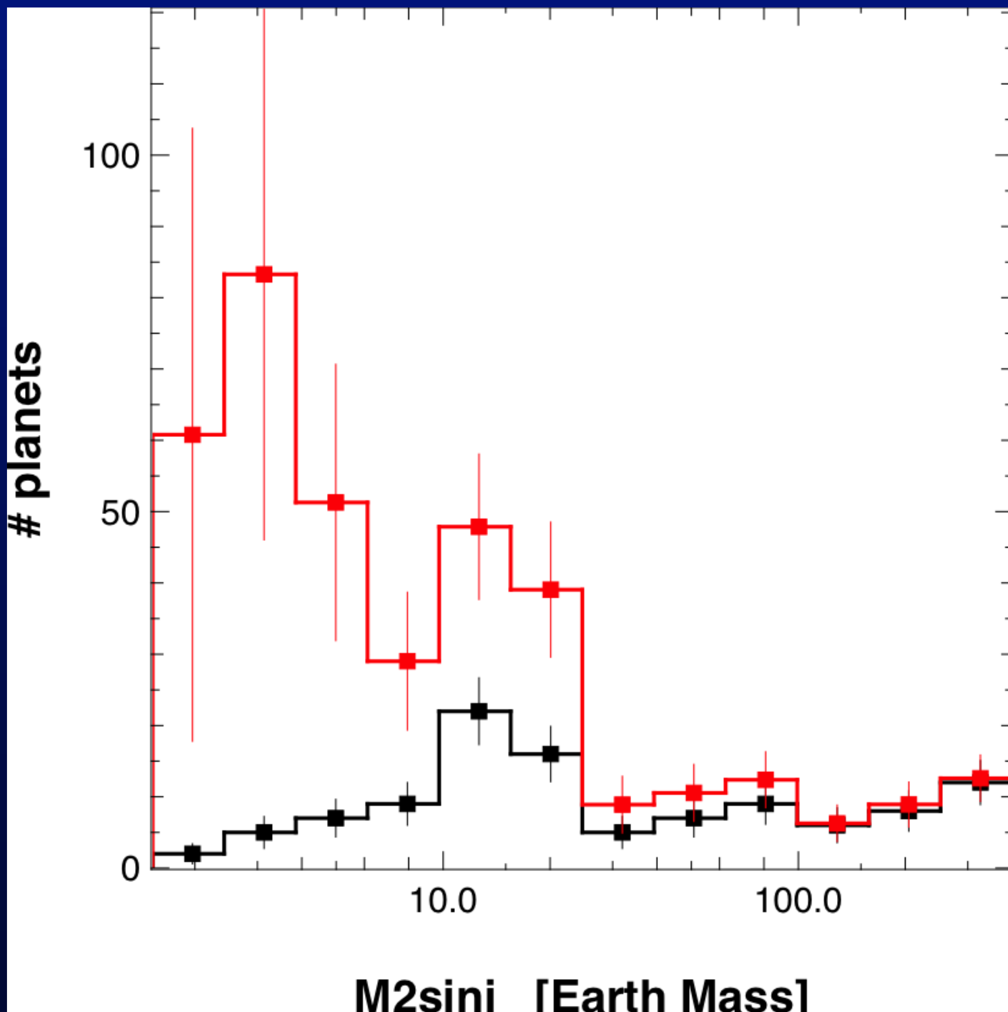
What fraction of stars host planets?

What fraction of stars host planets?

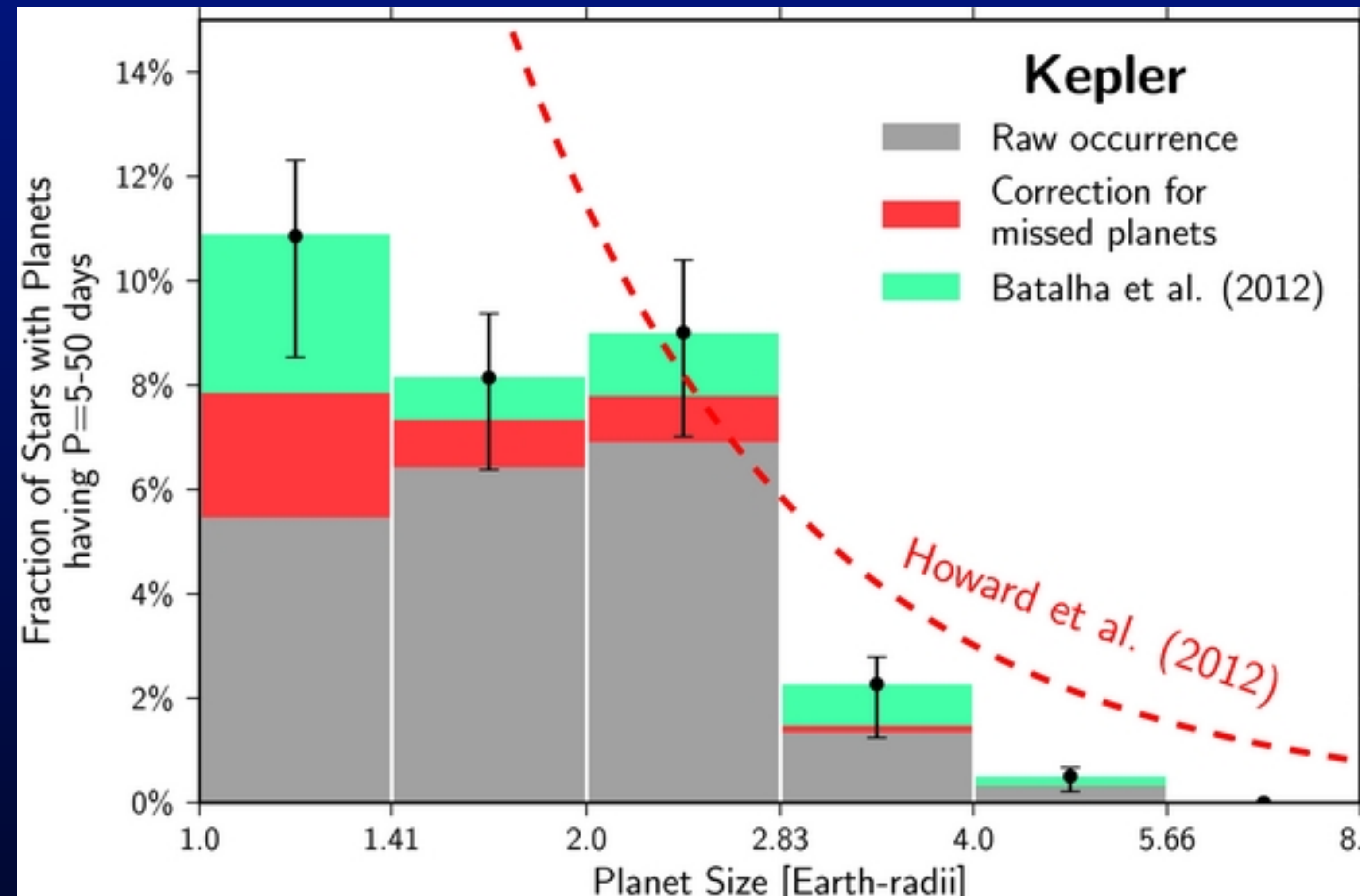
- Selection biases mean that measurements of f_p must be qualified (but detection methods are complementary).
- Current results:
  - 5-10% of FGK stars host a planet with $M_p \geq M_{Jup}$ at $a \leq 3AU$.
  - >50% of FGK stars host a planet with $M_p \geq 1M_\oplus$ and $P \leq 100d$.
  - ~90% of M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

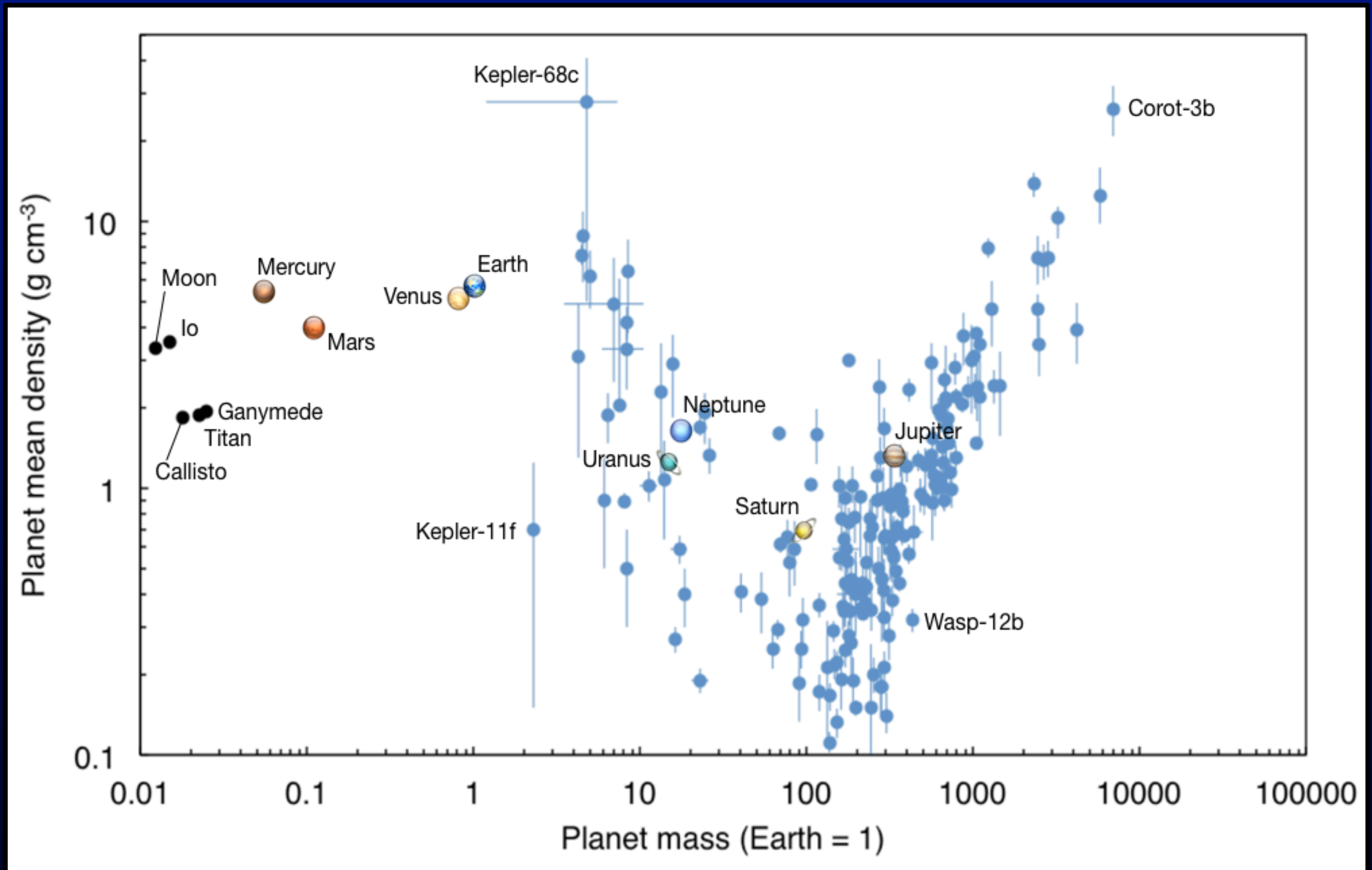
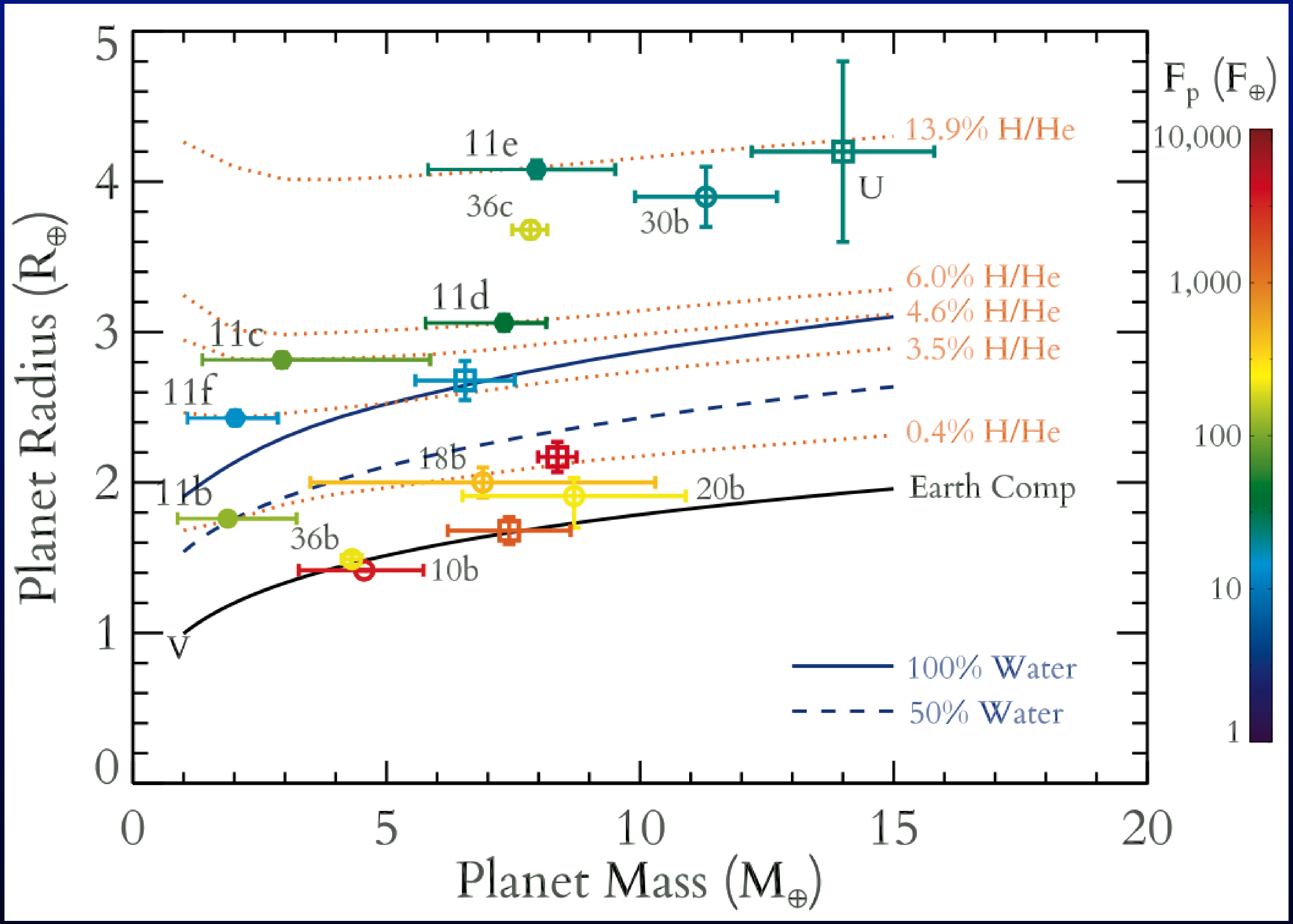


Figure courtesy of Didier Queloz

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

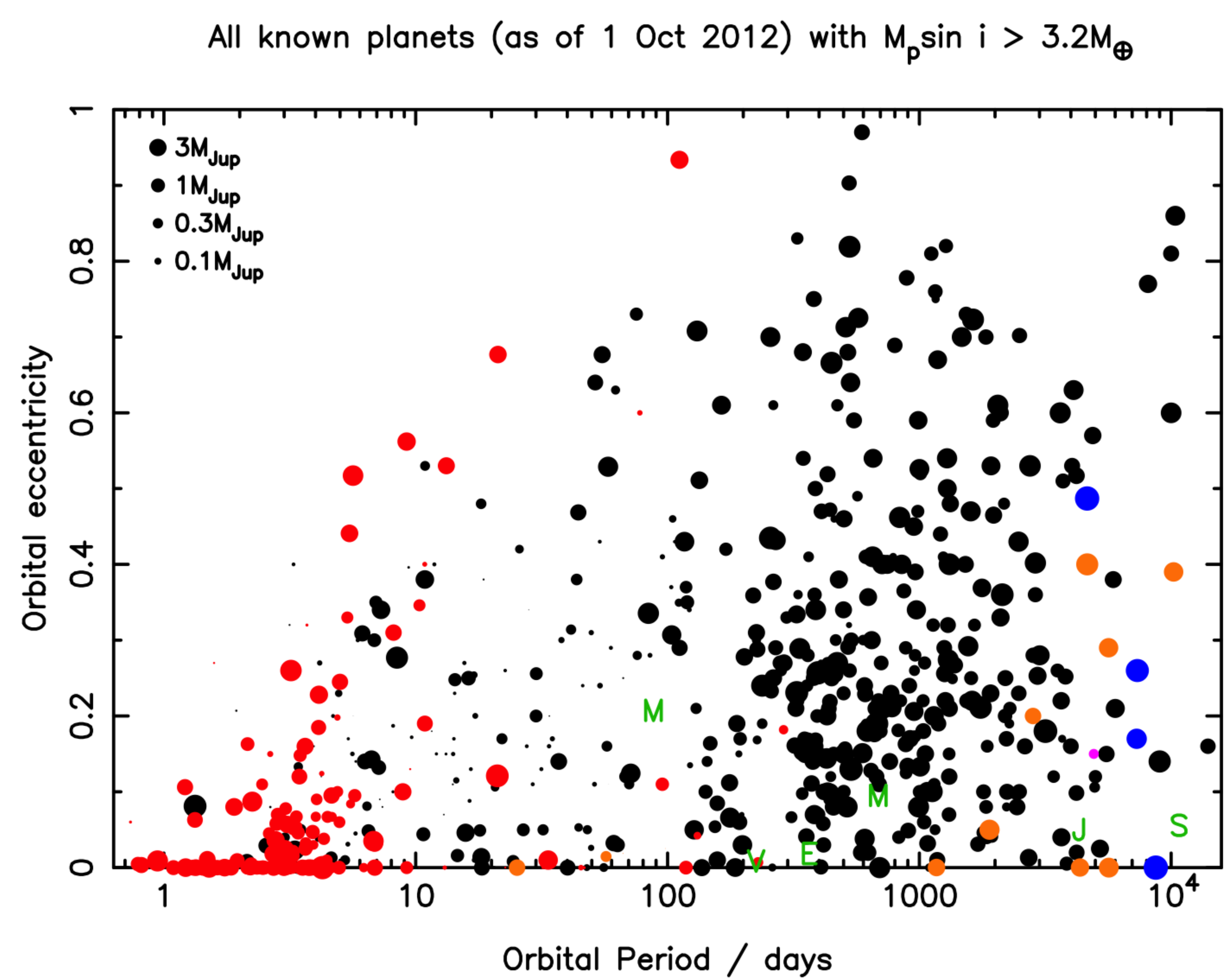
Mass-radius relation



Lissauer et al. (2013)

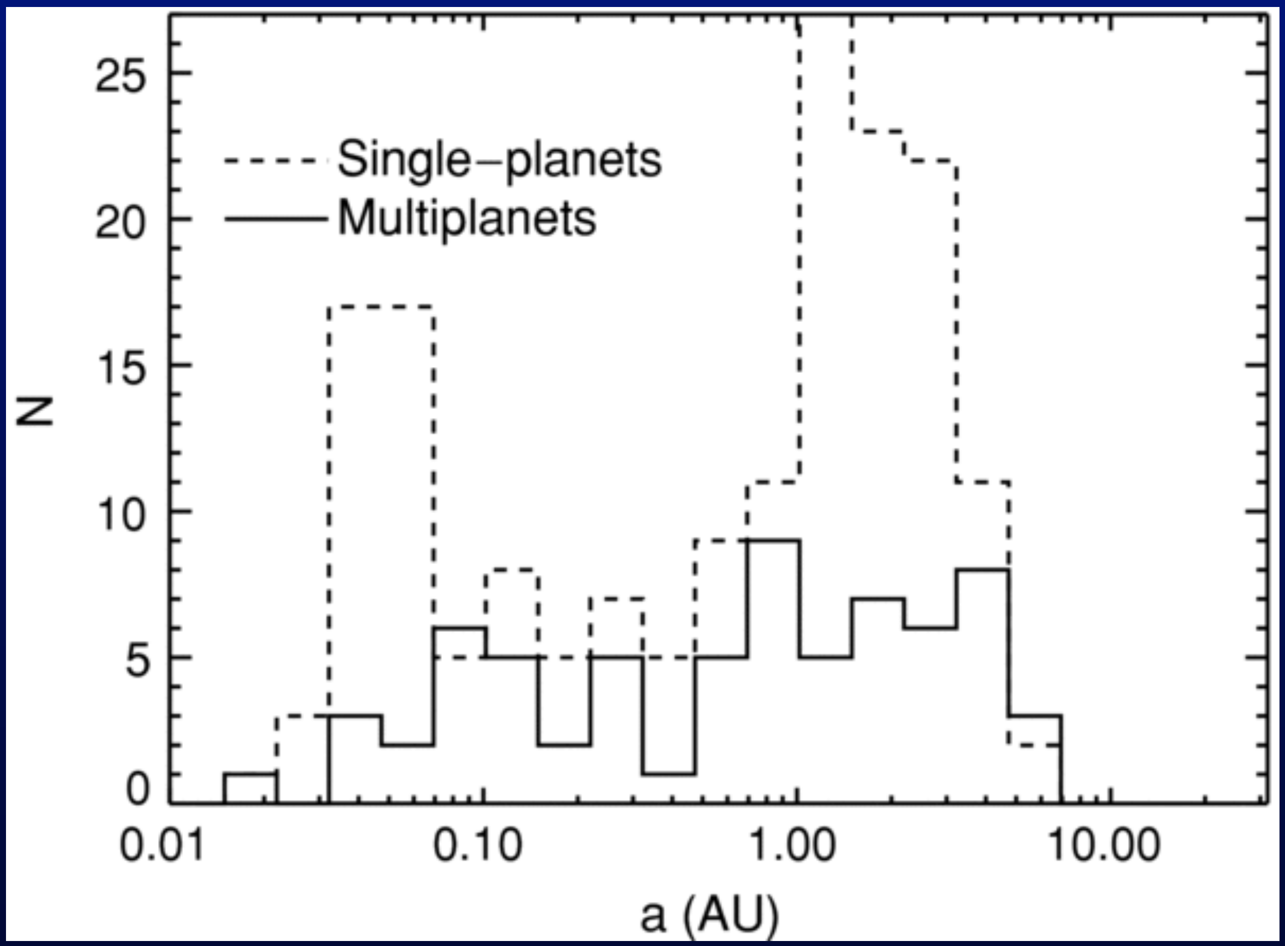
- Comparison to models possible, but in many cases mean density not strongly constraining.
- However, some exoplanets are unambiguously rocky!

Eccentricities

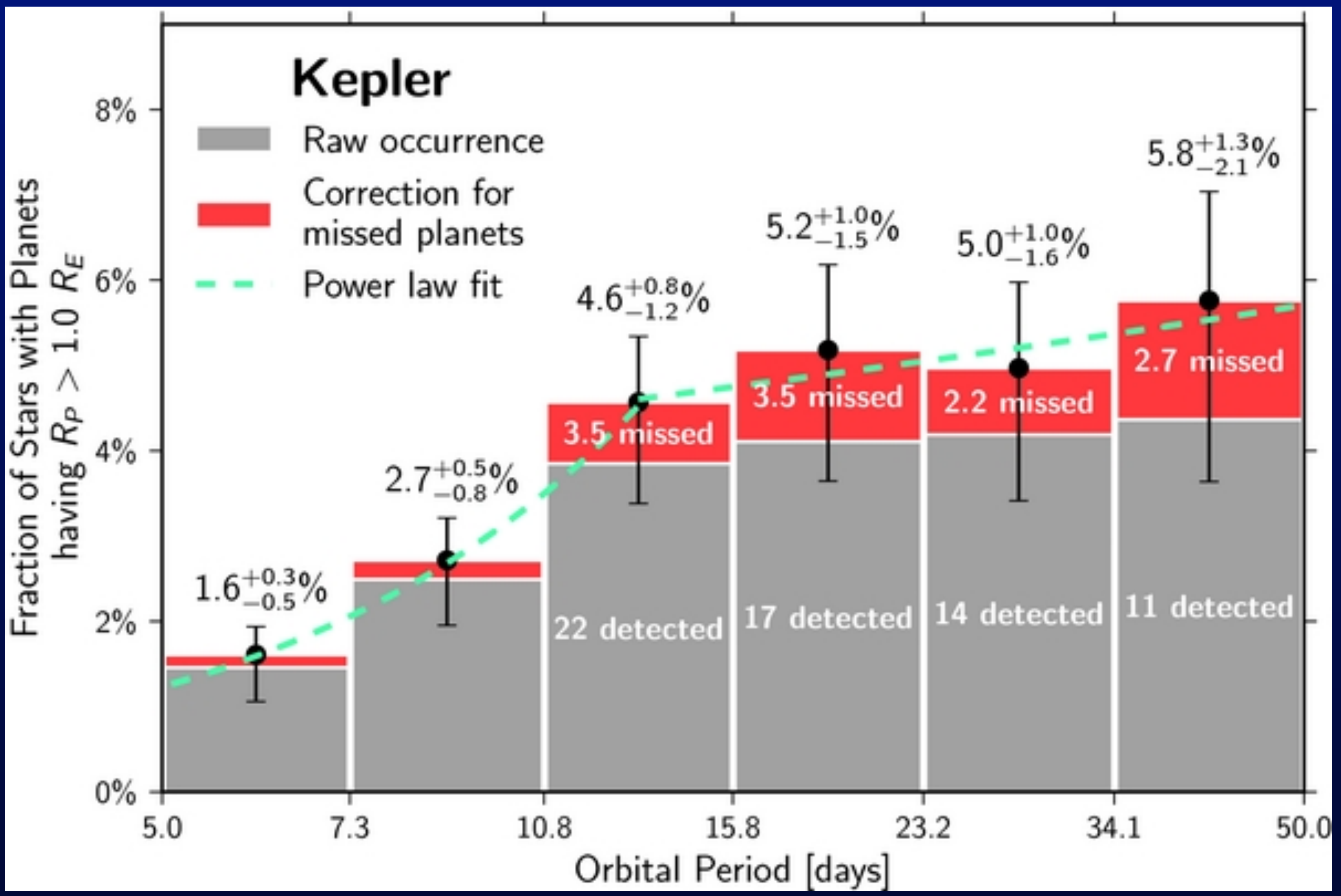


Data from exoplanets.org

Radial distribution



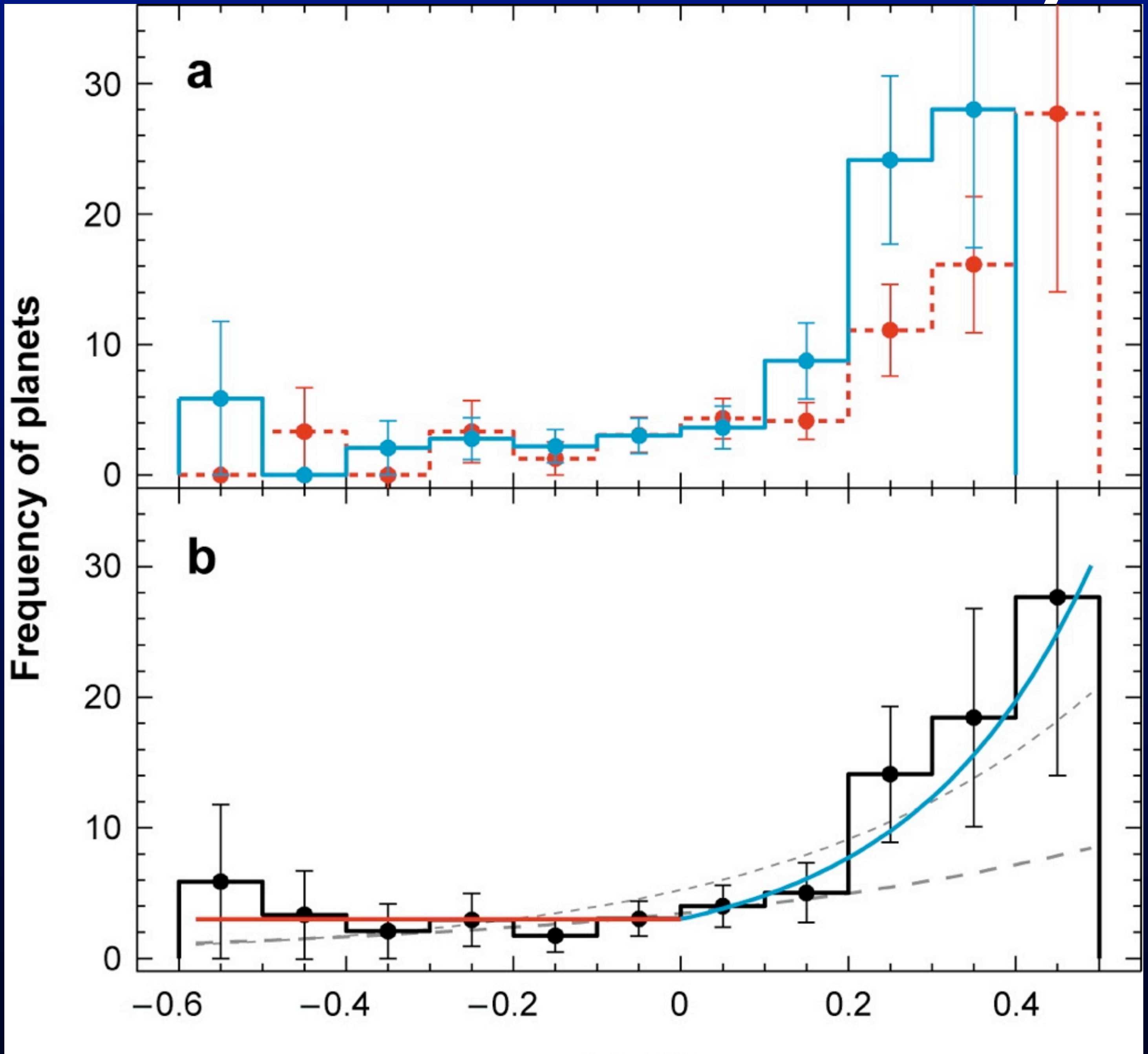
RV: Wright et al. (2009)



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.

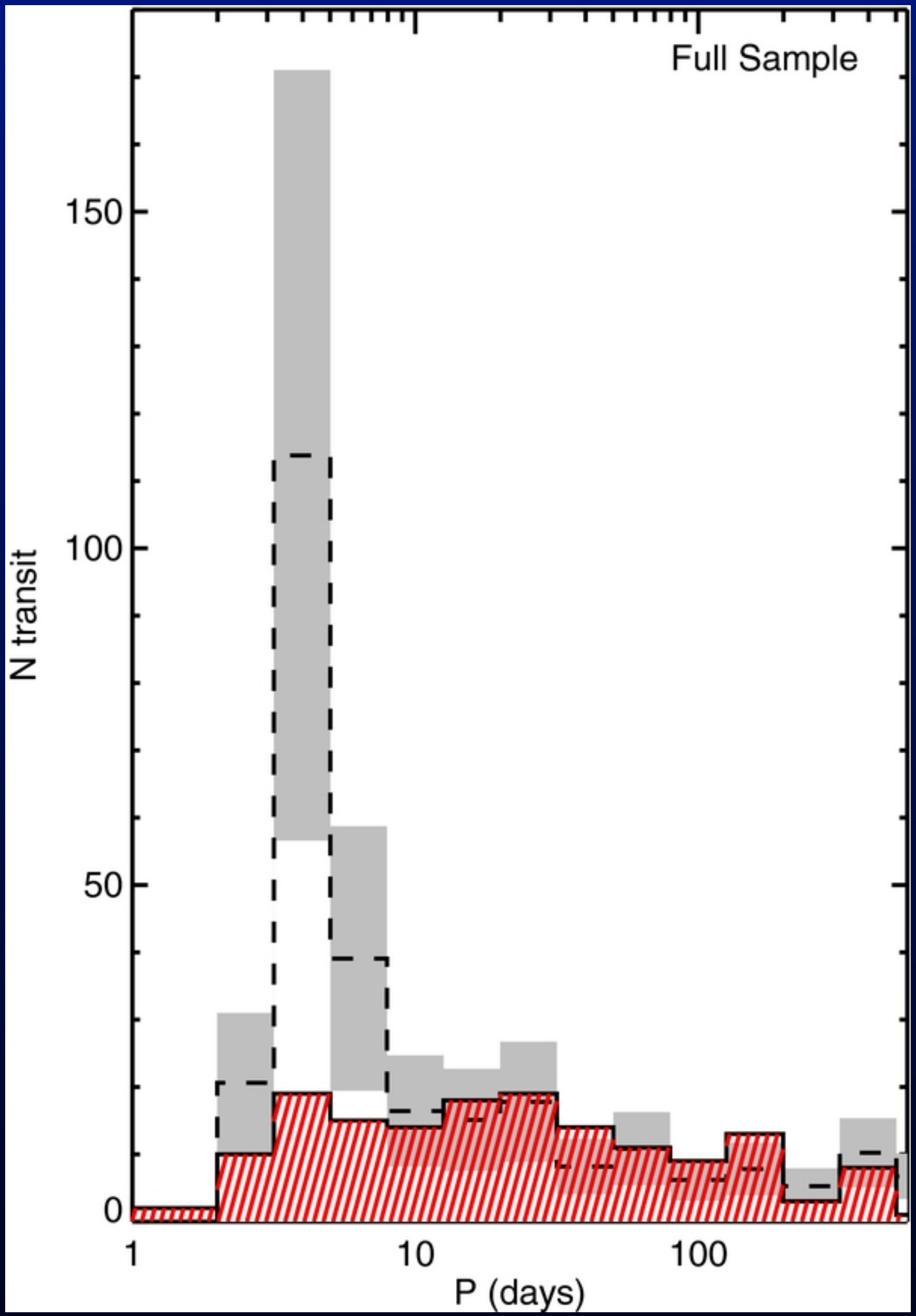
Host star metallicity



Udry & Santos (2007)

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

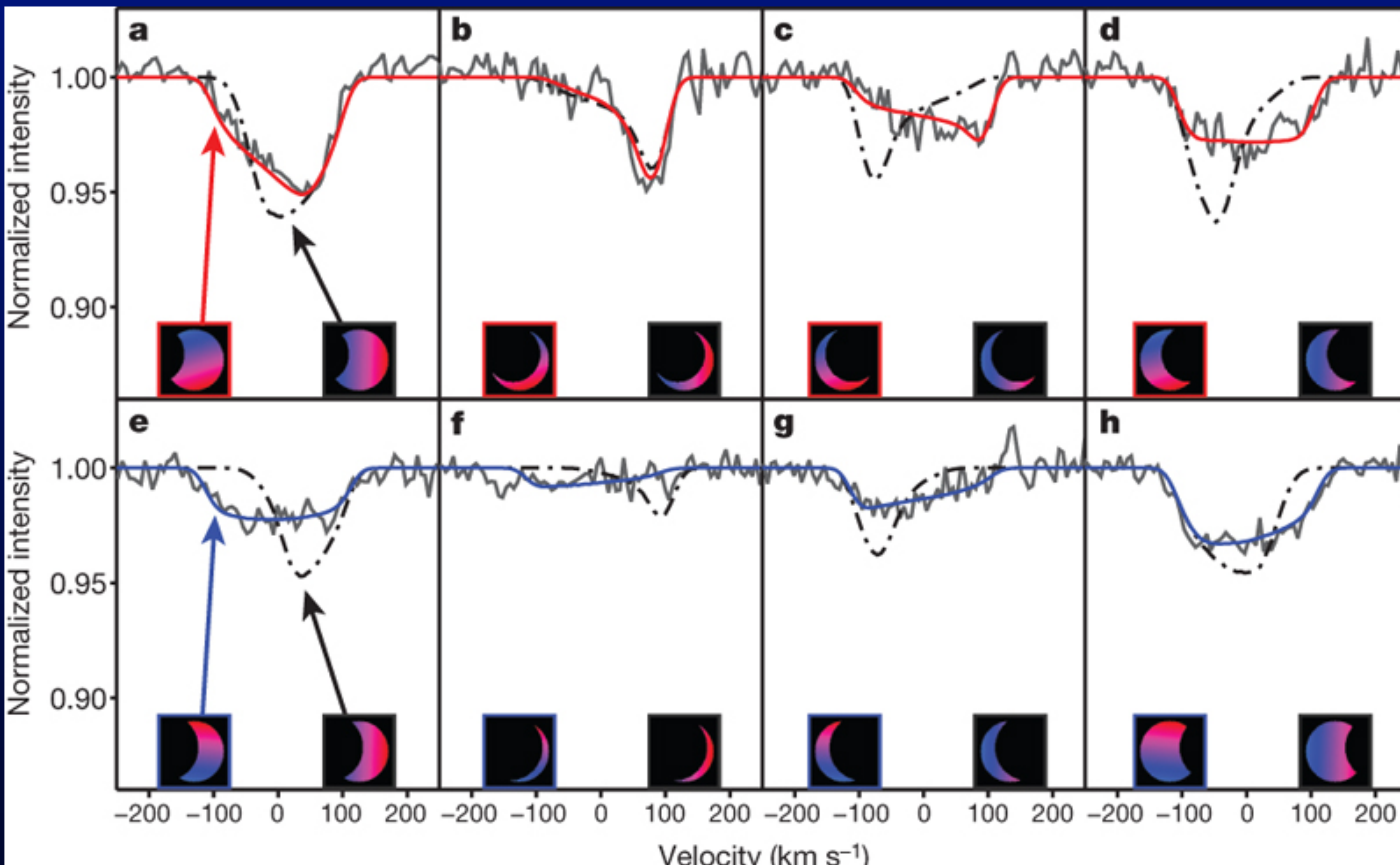
Host star metallicity



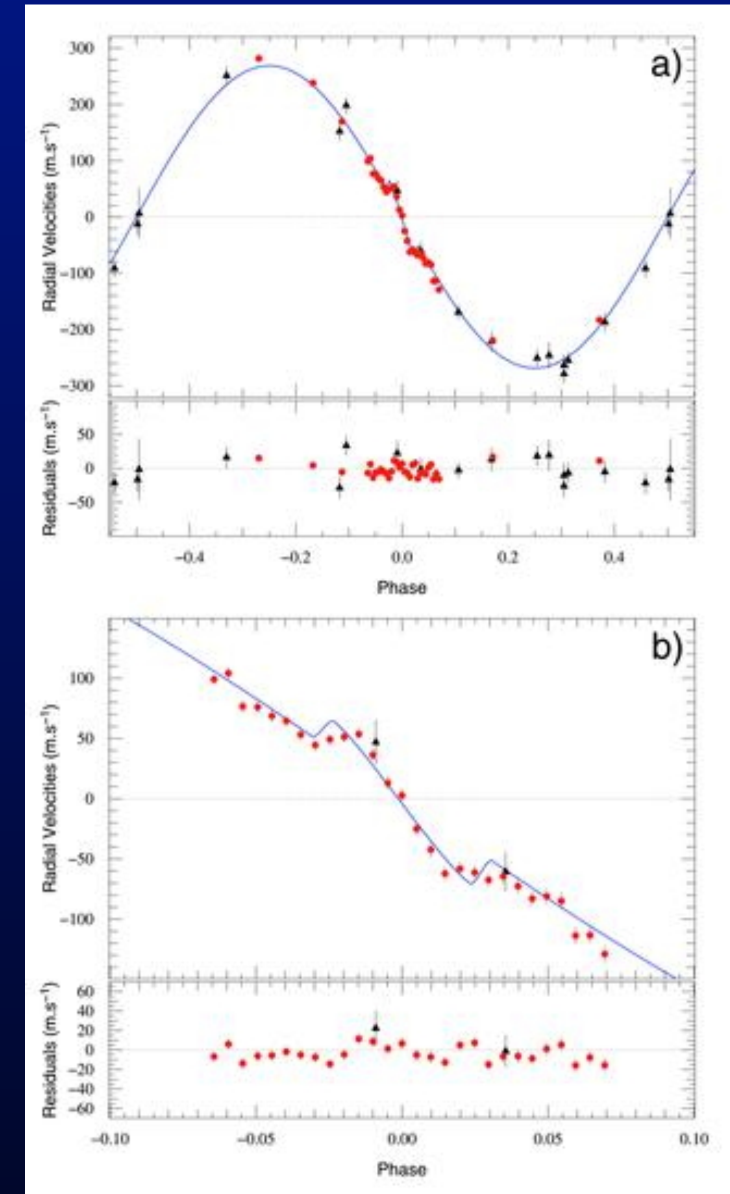
Dawson & Murray-Clay (2013)

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

Rossiter-McLaughlin effect & obliquity



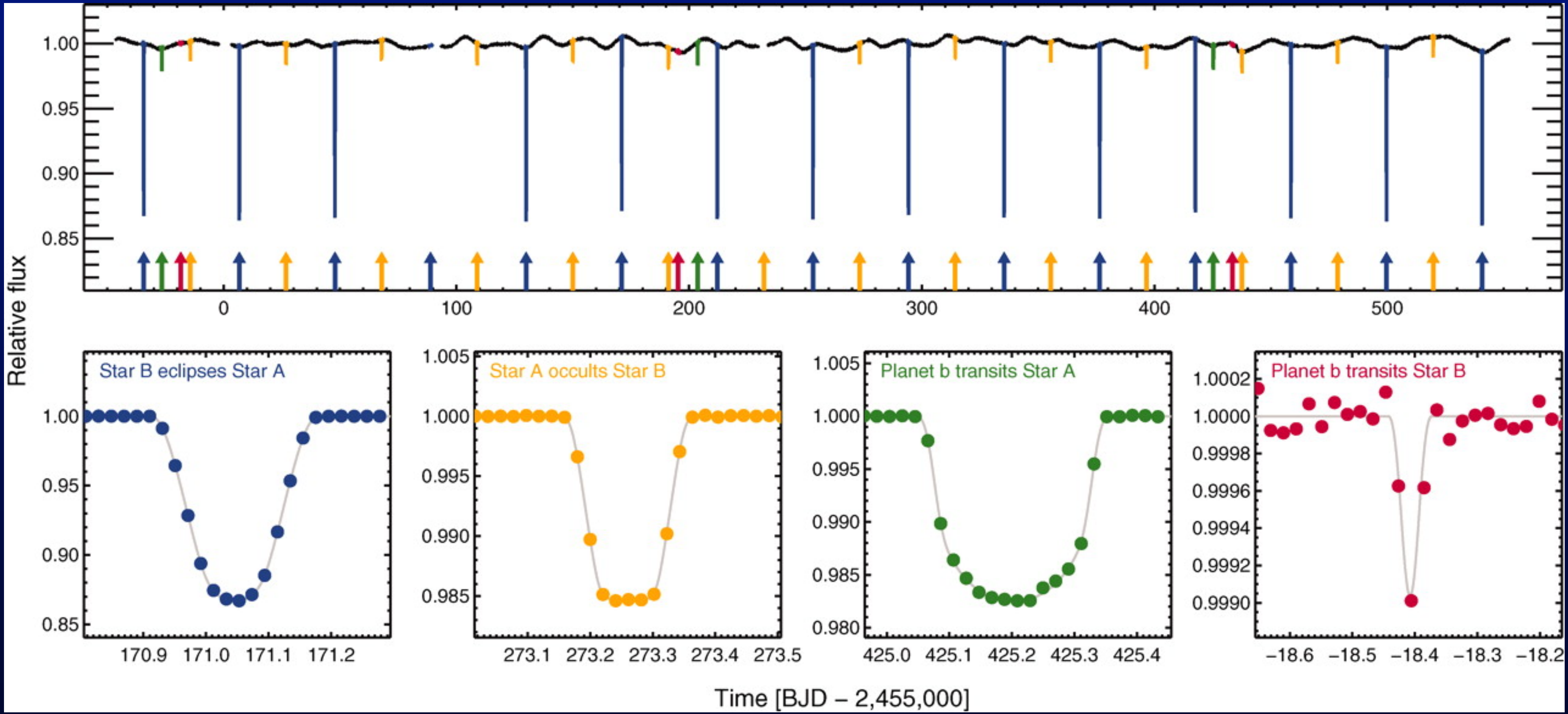
Albrecht et al. (2009)



Triaud et al. (2010)

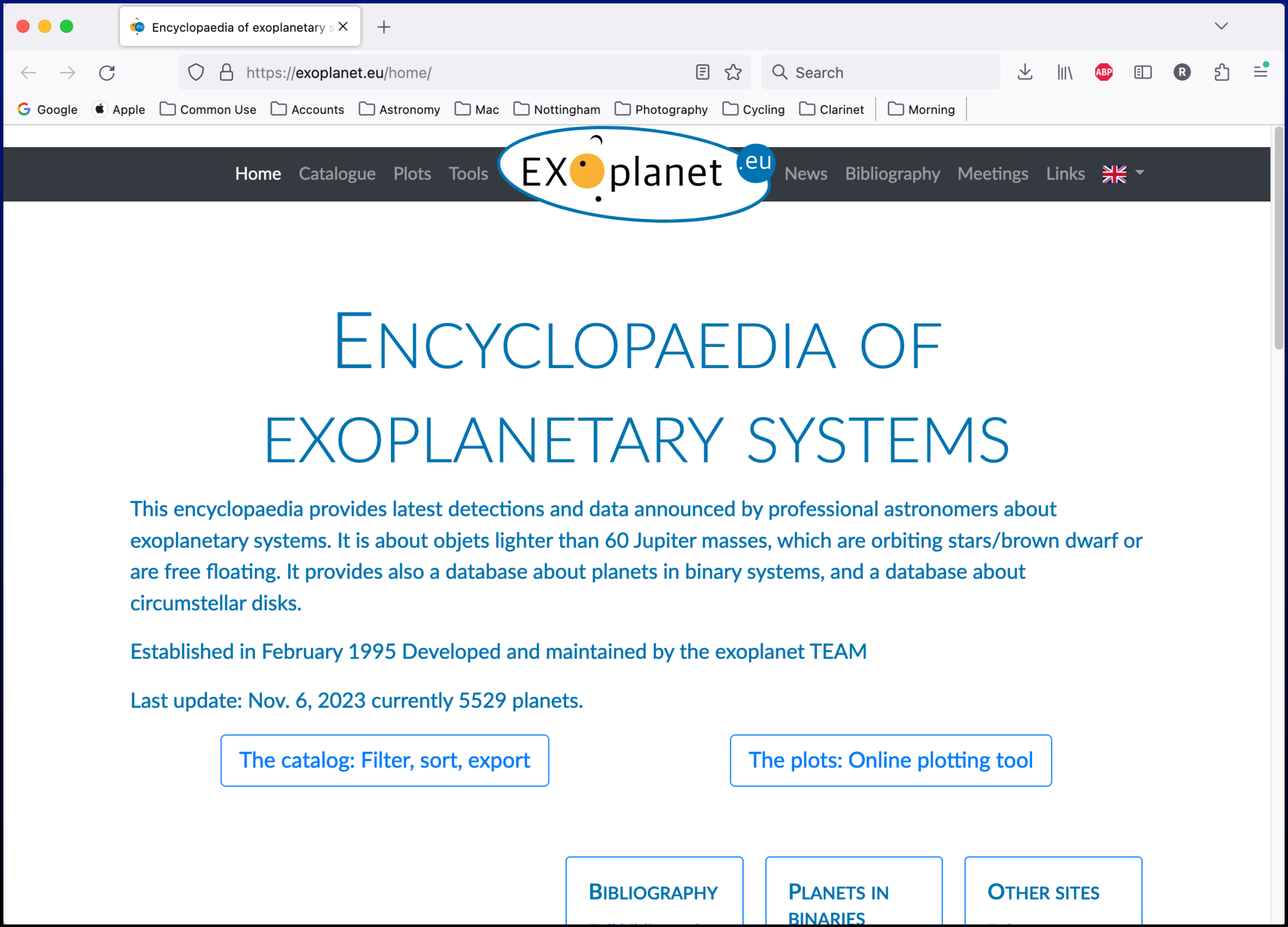
- Line shifts during transit (R-M) allow us to measure relative inclination of orbit and stellar rotation axis.
- Significant fraction (~10-50%) of short-period gas giants show high (projected) obliquities.

Kepler-16b: the first "Tatooine"



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

Exoplanet Resources



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