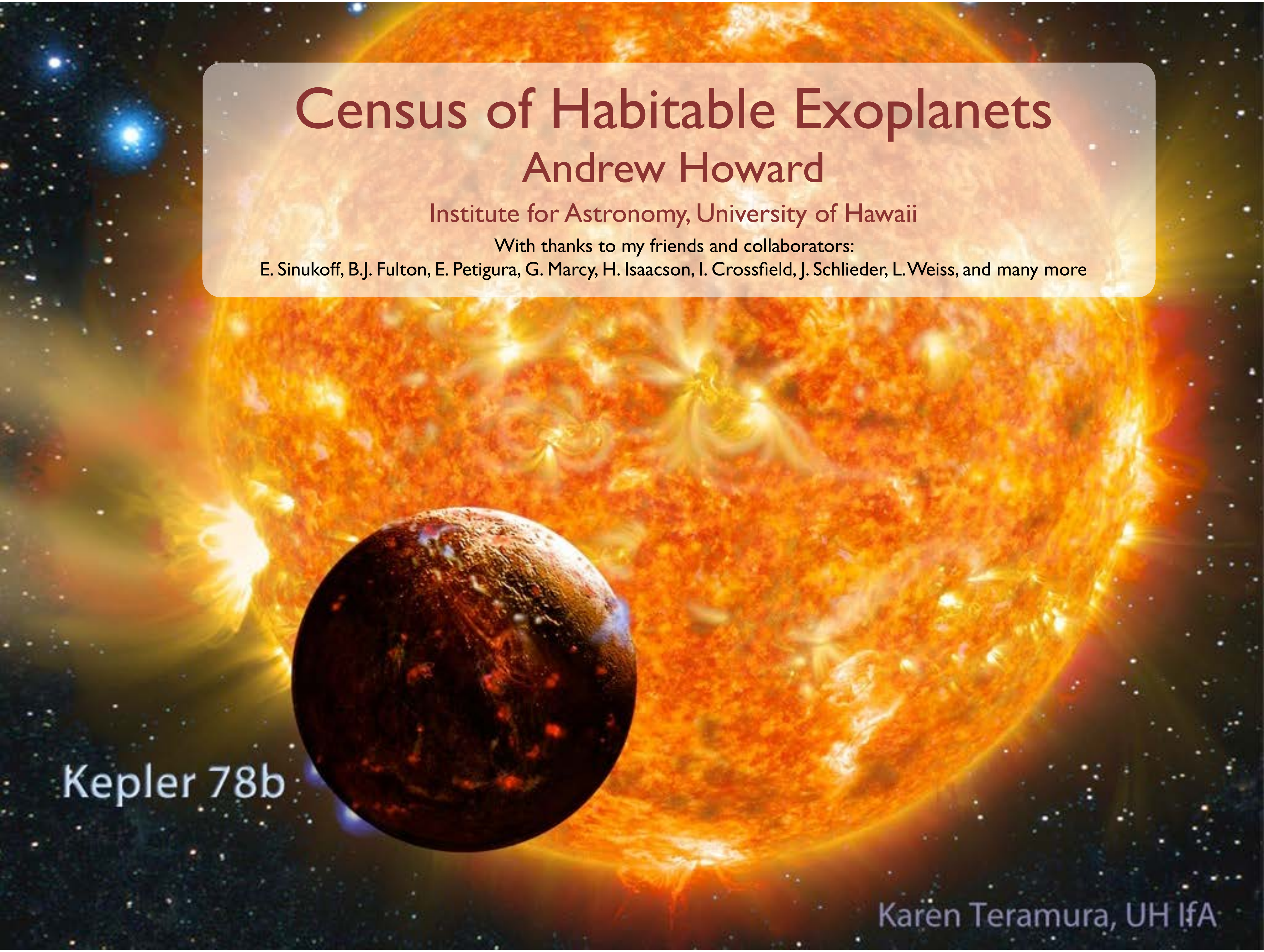
Census of Habitable Exoplanets

Andrew Howard

Institute for Astronomy, University of Hawaii

With thanks to my friends and collaborators:
E. Sinukoff, B.J. Fulton, E. Petigura, G. Marcy, H. Isaacson, I. Crossfield, J. Schlieder, L. Weiss, and many more



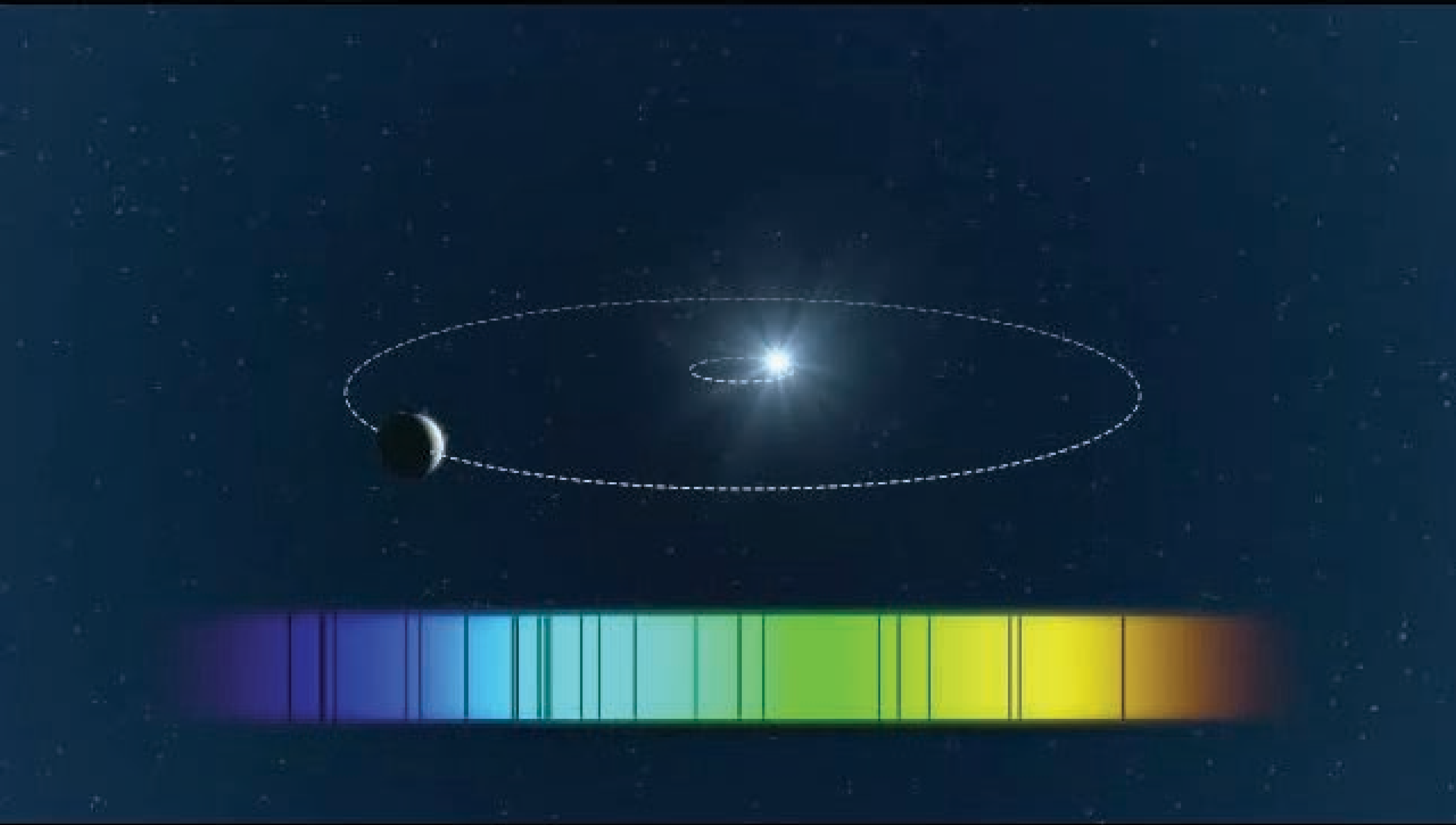
How common are Earth-like planets?

Image: NASA

What do we mean by "Earth-like"?

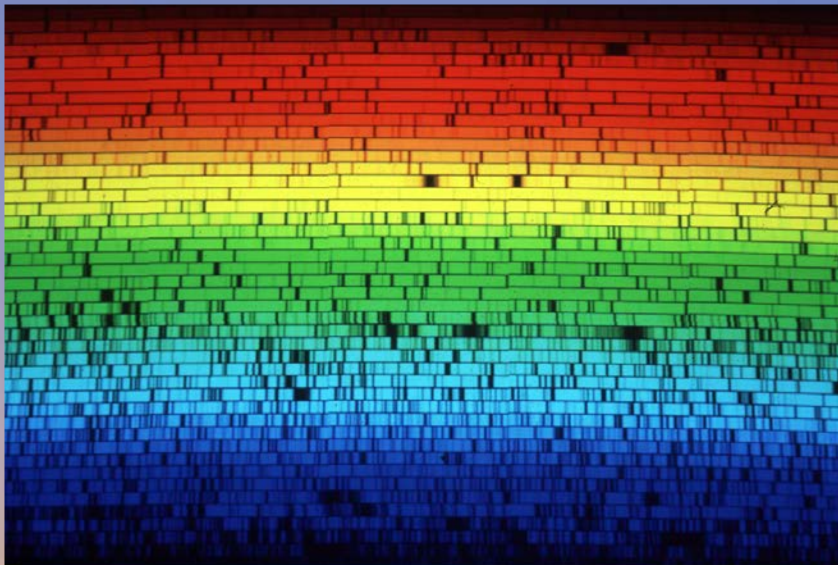
Mass, radius, temperature, atmosphere, water content?

How Do We Detect Exoplanets?



Doppler Method

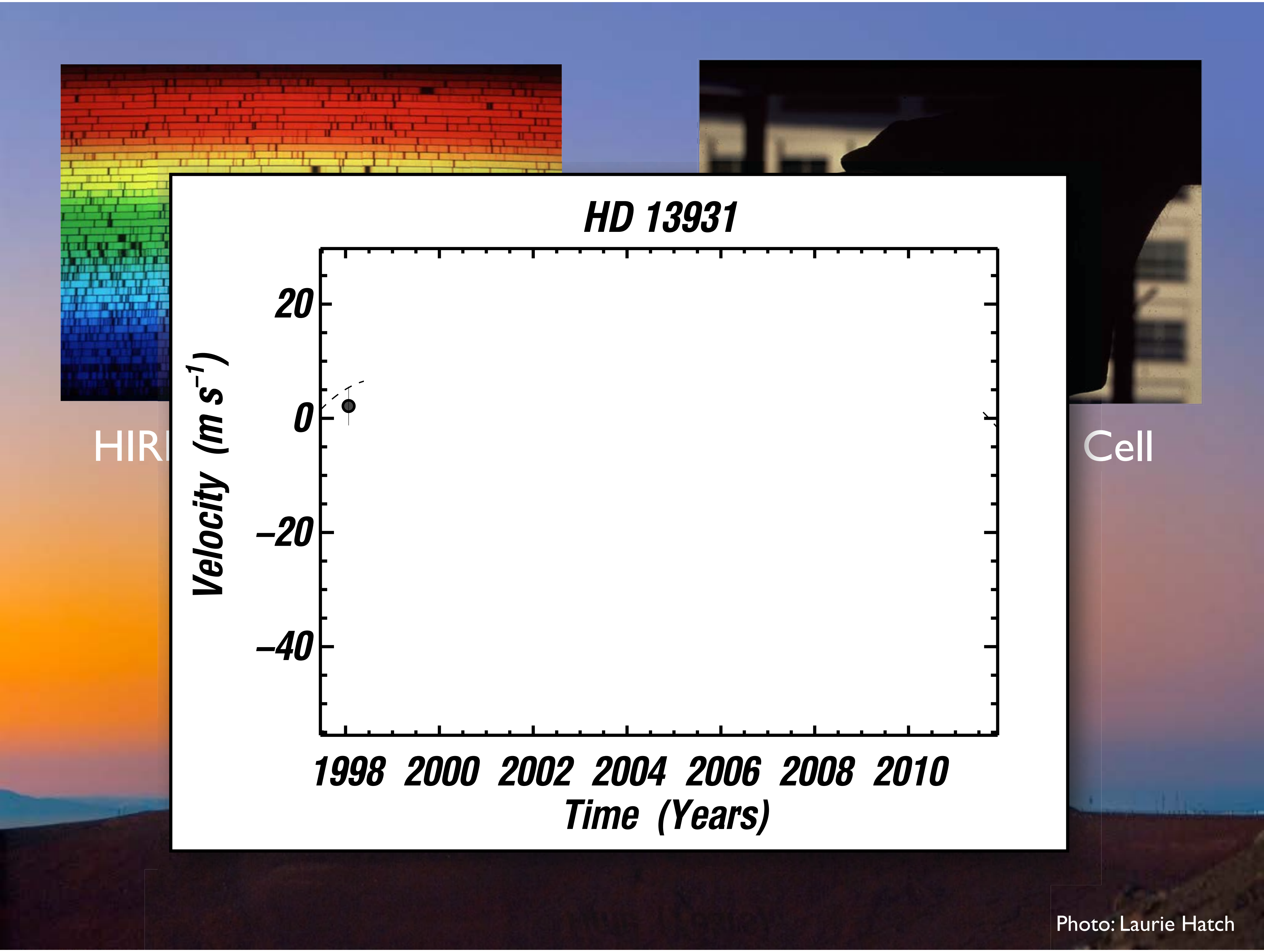
Movie credit: ESO



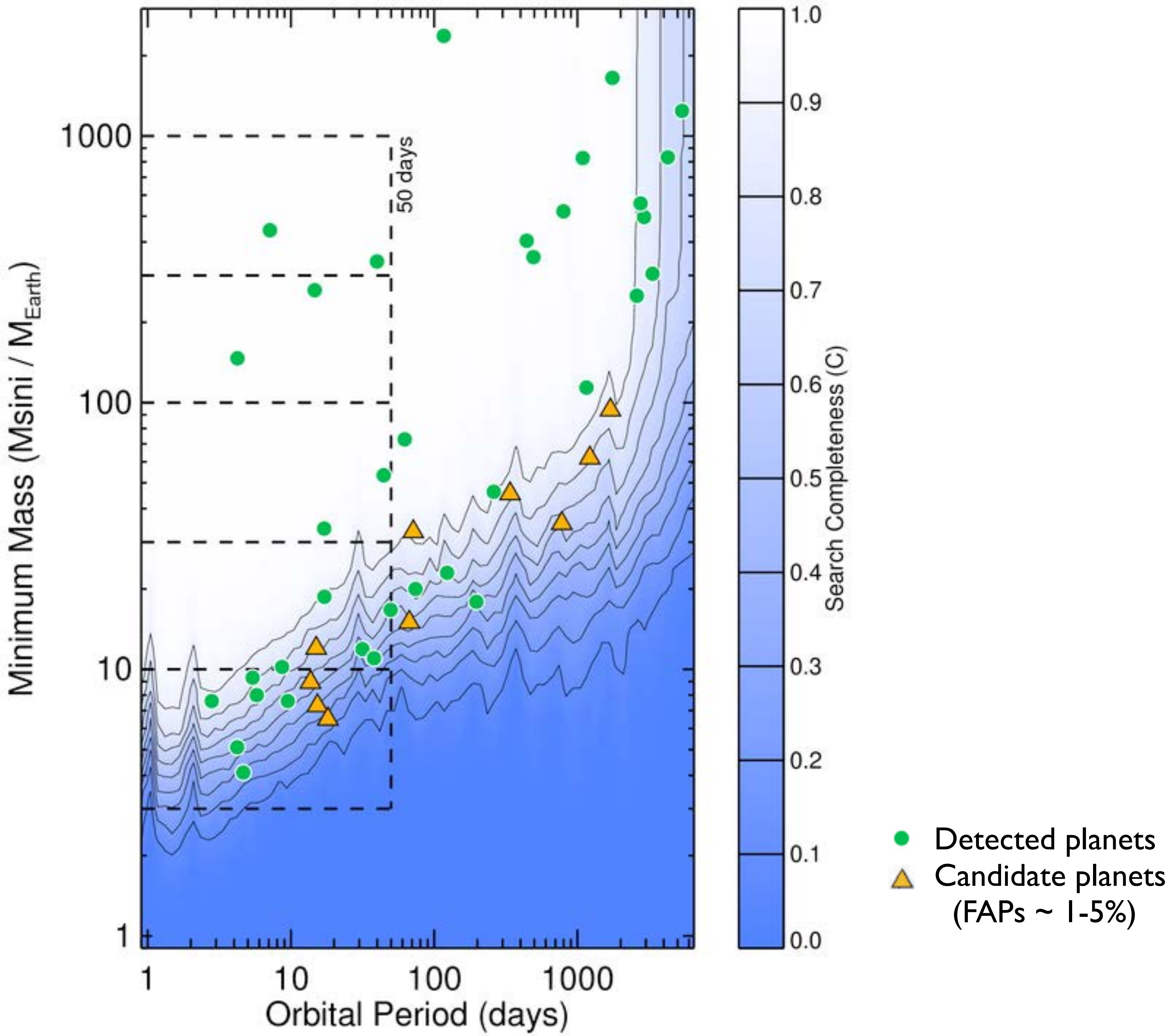
HIRES Echelle Spectrum

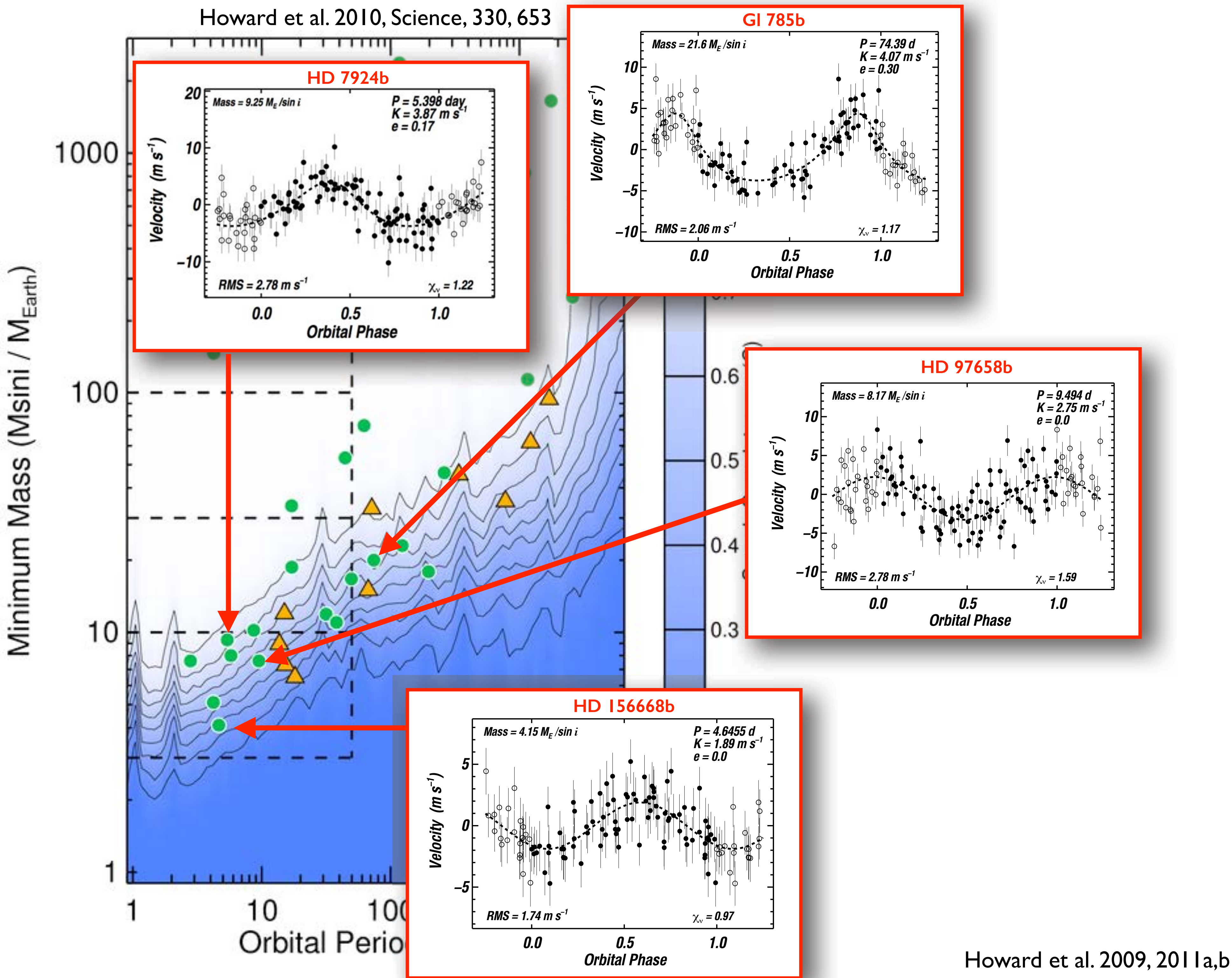
Iodine Absorption Cell

Photo: Laurie Hatch


HIRI
Cell
HD 13931
Velocity (m s^{-1})
20
0
−20
−40
1998
2000
2002
2004
2006
2008
2010
Time (Years)
Photo: Laurie Hatch

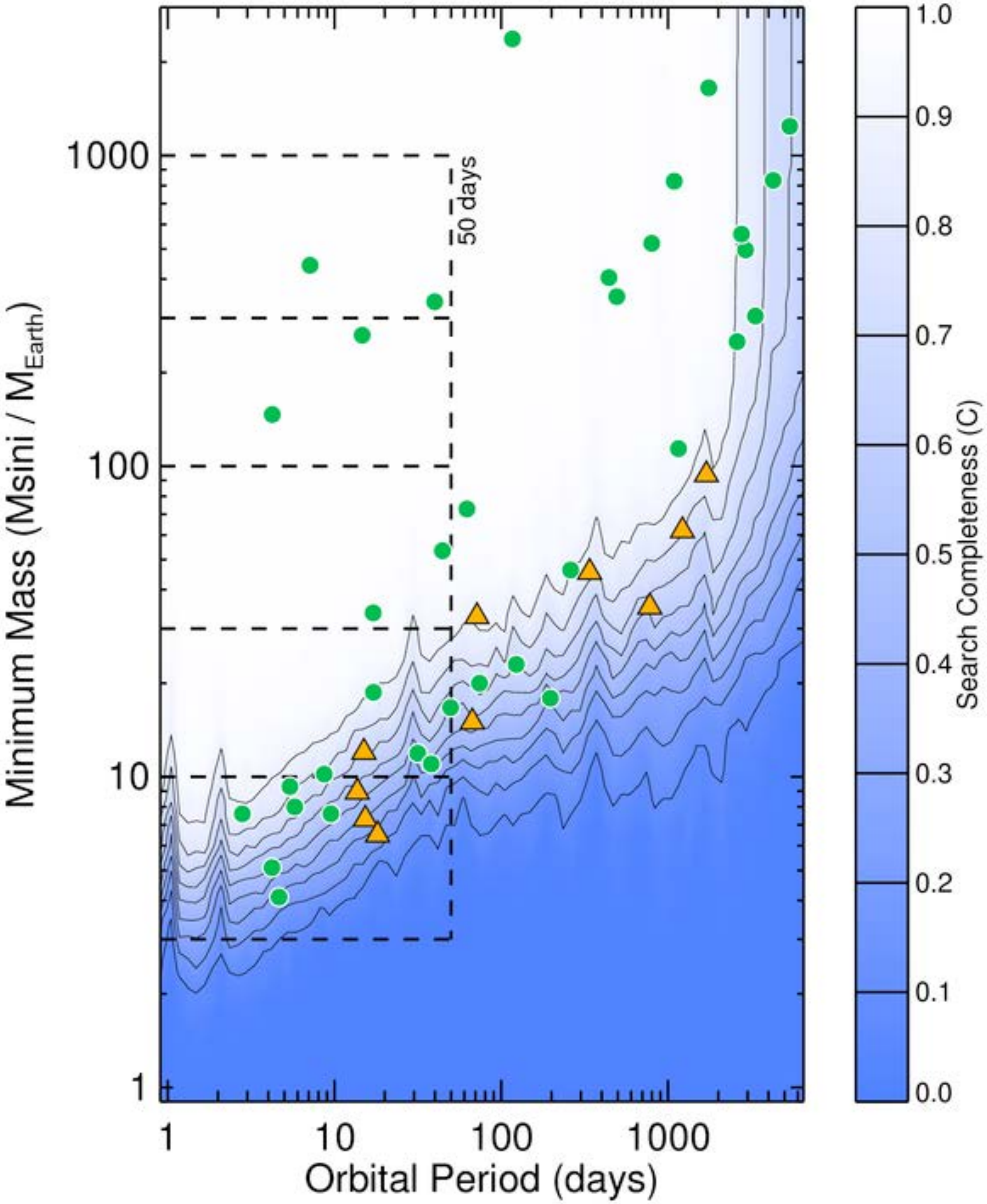
Howard et al. 2010, Science, 330, 653





Howard et al. 2010, Science, 330, 653
Minimum Mass (Msini / M_Earth)
Orbital Period
1000
100
10
1
1
10
100
0.6
0.5
0.4
0.3
HD 7924b
Mass = 9.25 M_E /sin i
P = 5.398 day
K = 3.87 m s^-1
e = 0.17
RMS = 2.78 m s^-1
χ_ν = 1.22
Velocity (m s^-1)
Orbital Phase
Gl 785b
Mass = 21.6 M_E /sin i
P = 74.39 d
K = 4.07 m s^-1
e = 0.30
RMS = 2.06 m s^-1
χ_ν = 1.17
HD 97658b
Mass = 8.17 M_E /sin i
P = 9.494 d
K = 2.75 m s^-1
e = 0.0
RMS = 2.78 m s^-1
χ_ν = 1.59
HD 156668b
Mass = 4.15 M_E /sin i
P = 4.6455 d
K = 1.89 m s^-1
e = 0.0
RMS = 1.74 m s^-1
χ_ν = 0.97
Howard et al. 2009, 2011a,b

Howard et al. 2010, Science, 330, 653



1. Low-mass planets are common

2. A diagonal "ridge" in high planet occurrence:
   - Msini=10-30 M_E, P > ~20 days
   - Msini=3-10 M_E, P > ~5 days

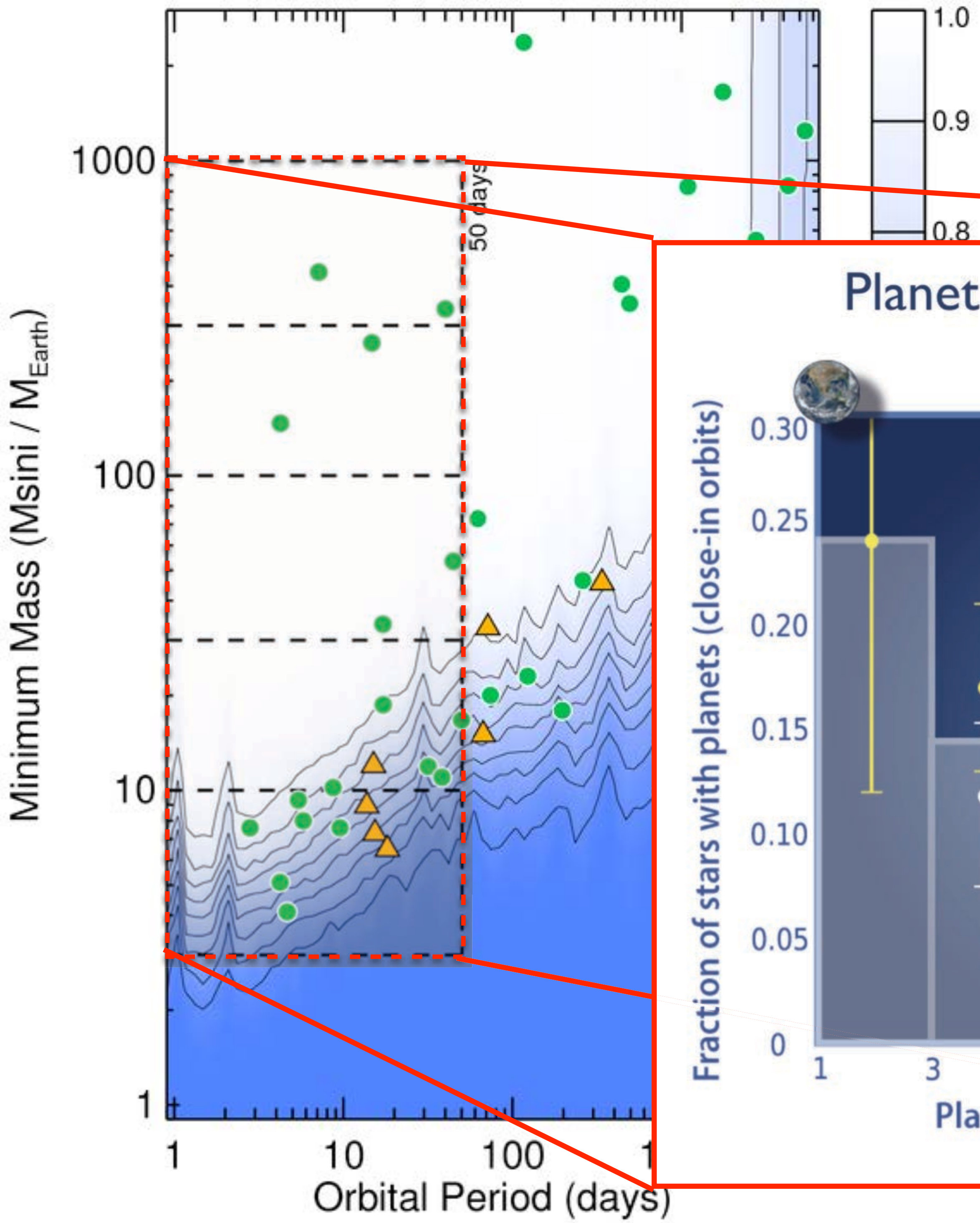
3. Low-mass planets: No short-period pileup

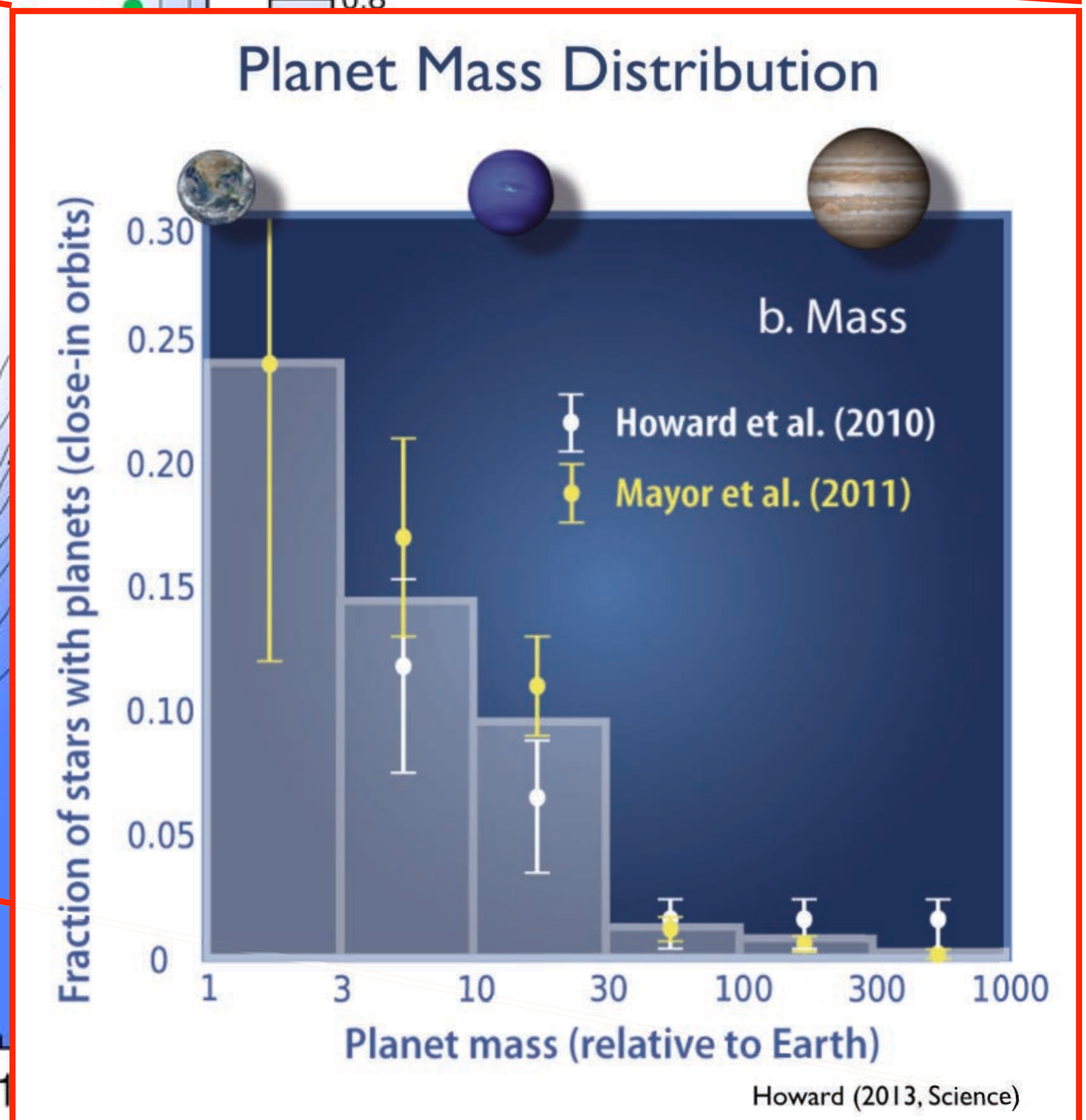
4. Absence of hot Neptunes

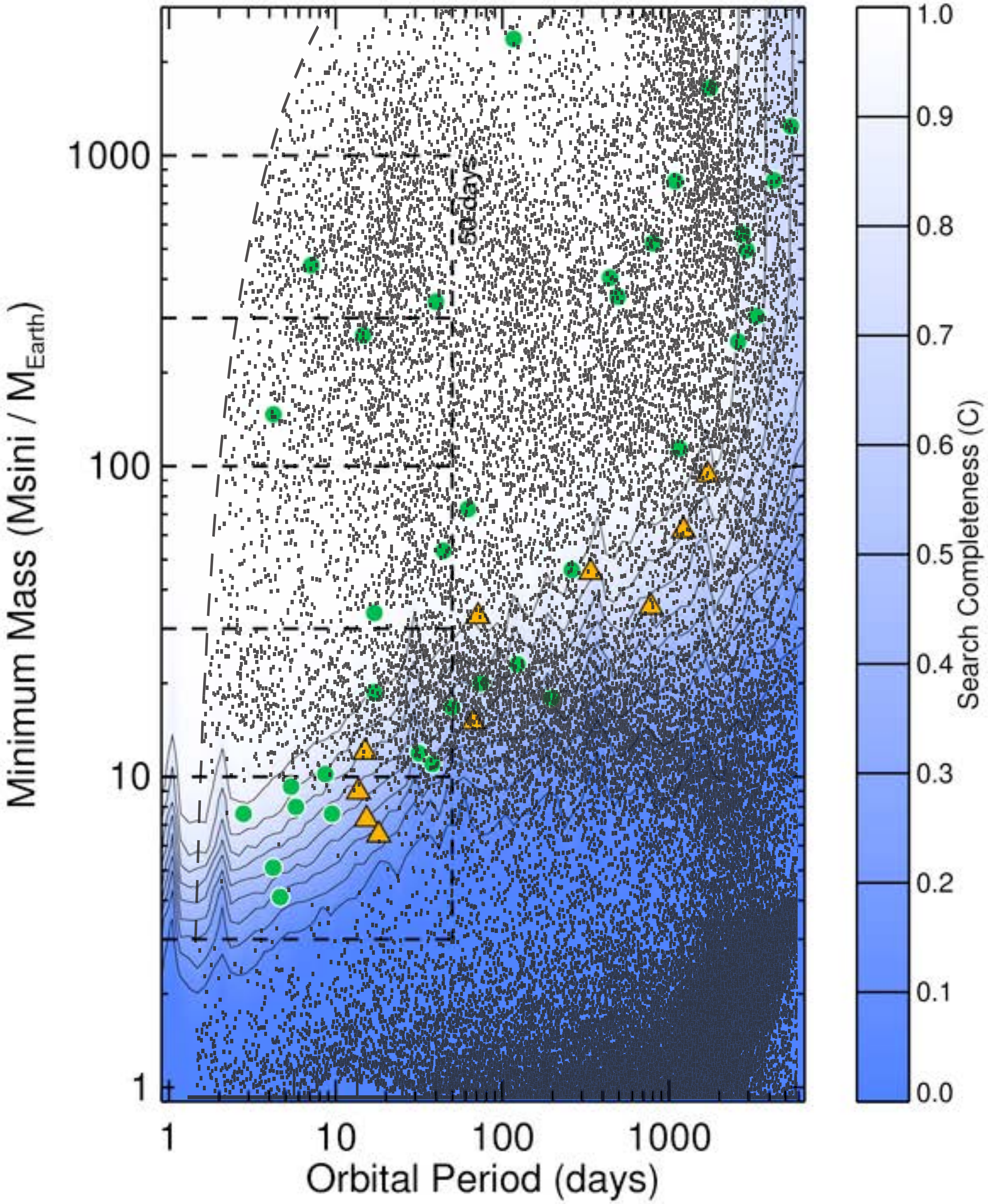
● Detected planets

△ Candidate planets (FAPs ~ 1-5%)

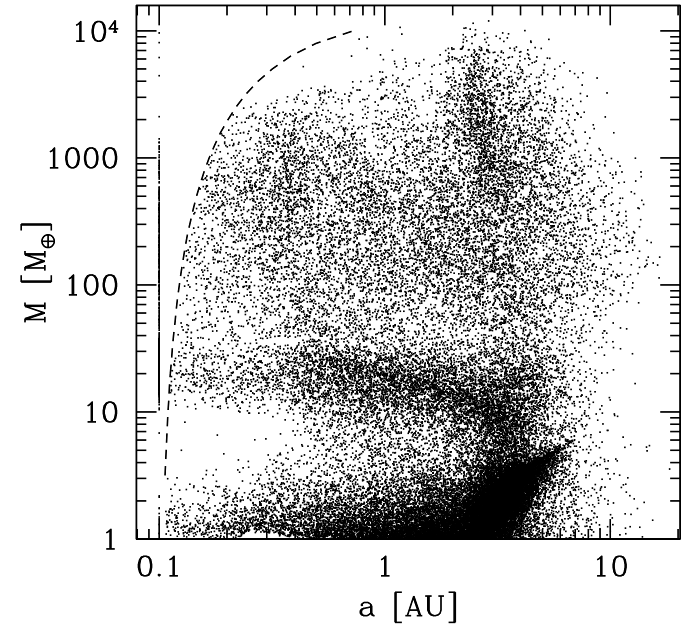
Howard et al. 2010, Science, 330, 653







Population Synthesis Model
Mordasini et al. 2009



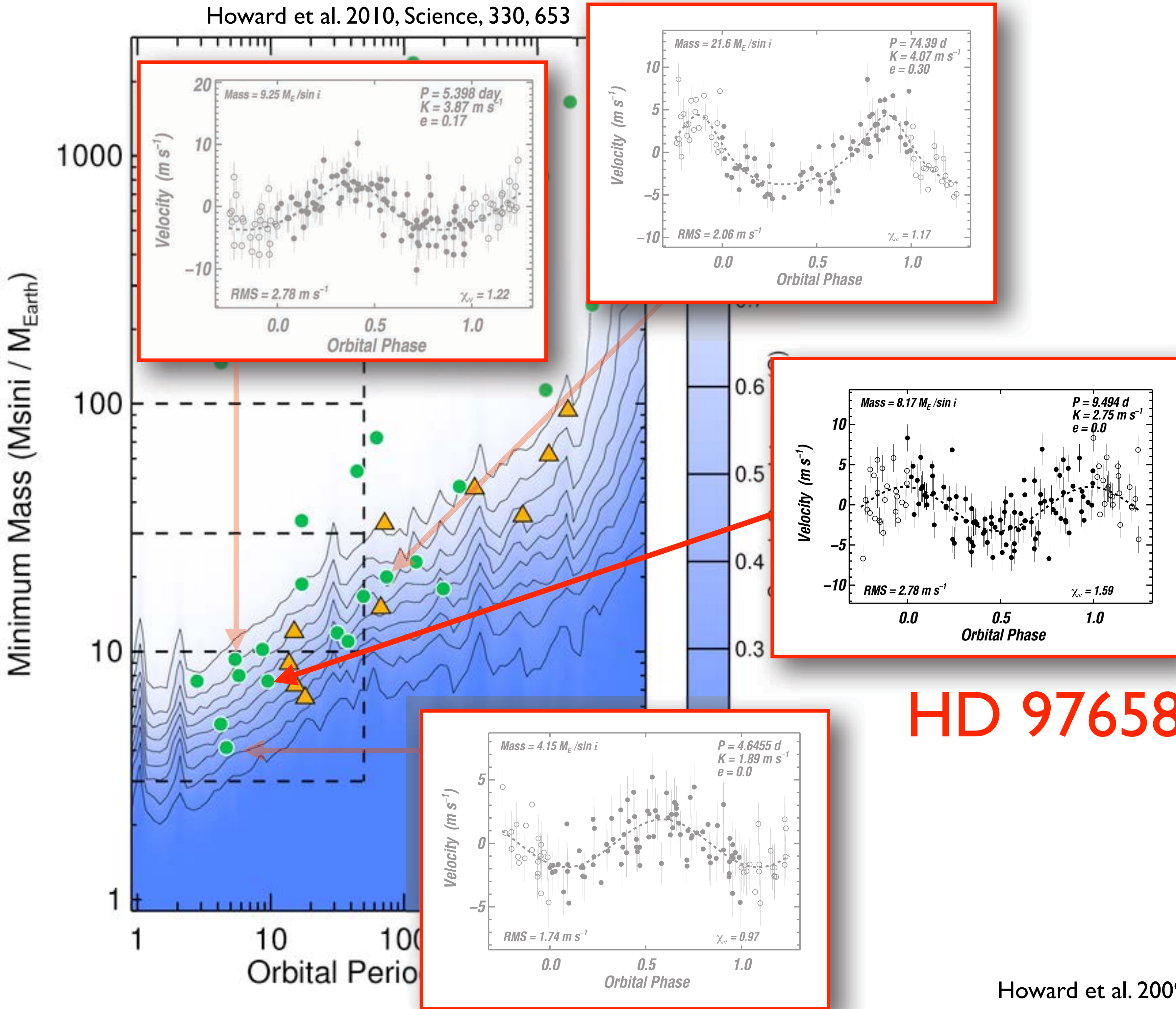
Fixes for Population Synthesis models:

- Ida & Lin (2010, 2013)
- Mordasini et al. (2012, 2014)
- Paardekooper et al. (2011, 2013)
- …

In Situ Formation:

- Hansen & Murray (2012)
- Chiang & Laughlin (2013)
- Lee et al. (2014)
- Chatterjee & Tan (2015)
- …

Howard et al. 2010, Science, 330, 653

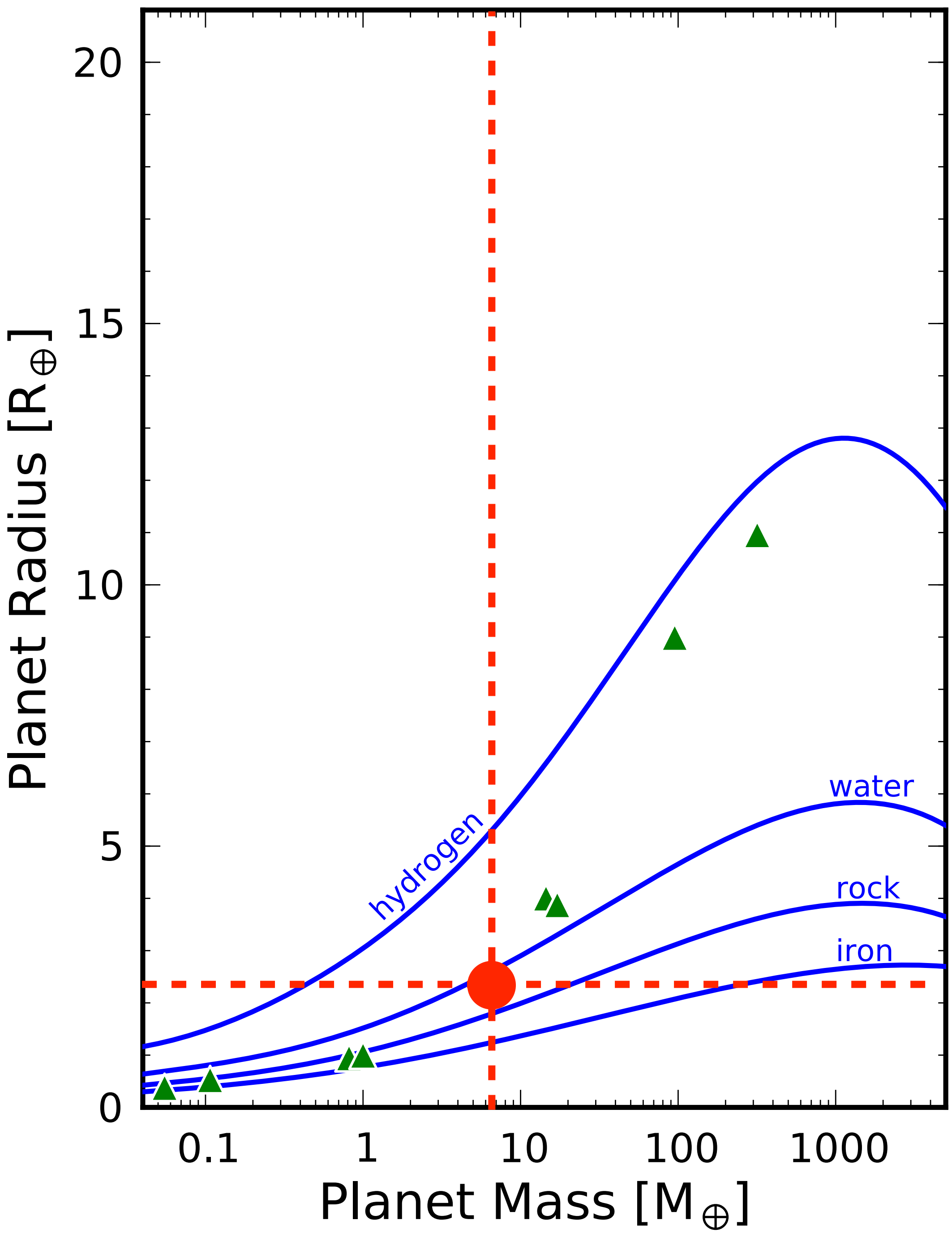


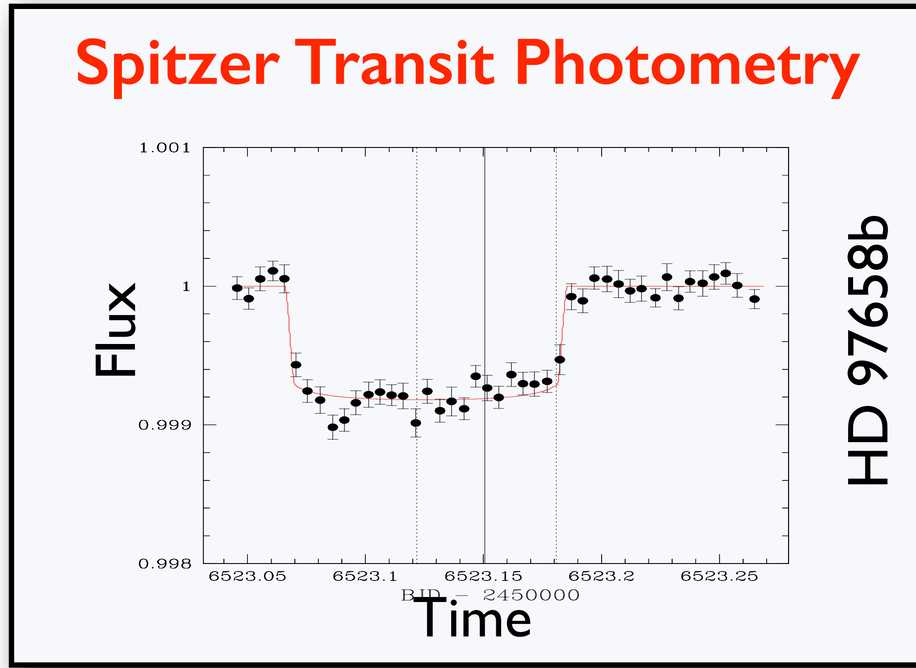
HD 97658

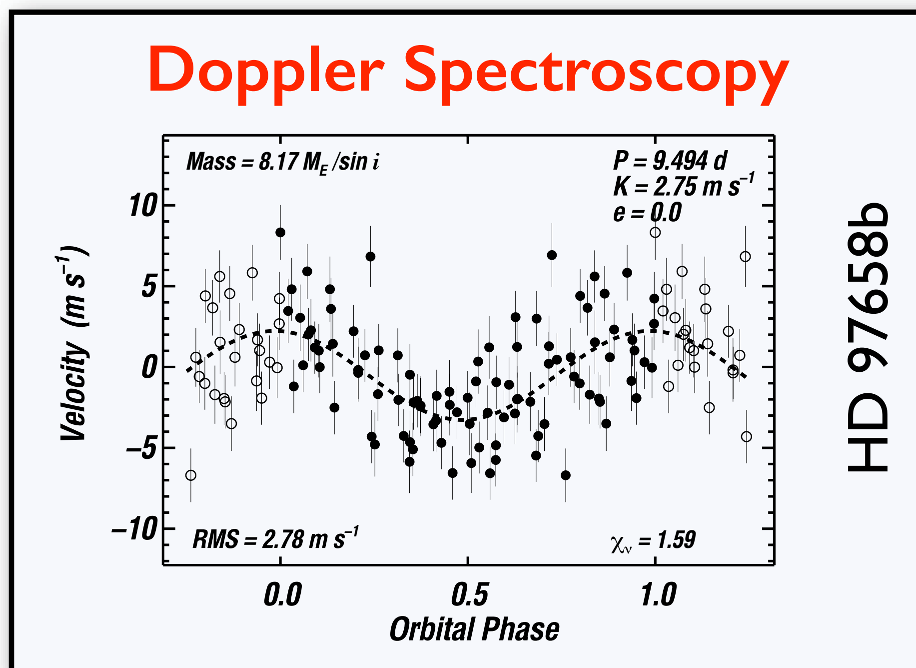
Howard et al. 2009, 2011a,b

HD 97658b

van Grootel et al. 2014
see also Dragomir et al. 2013

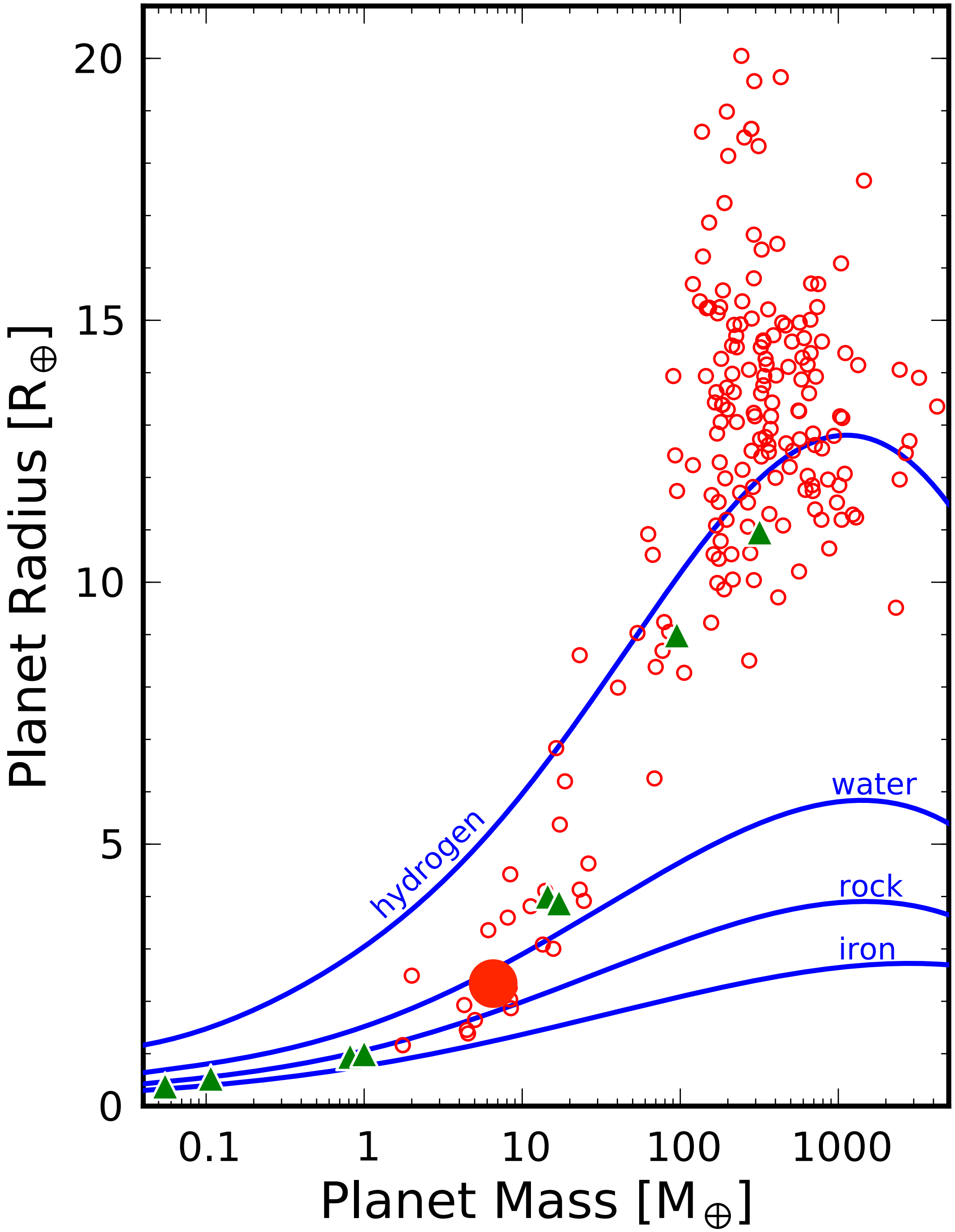


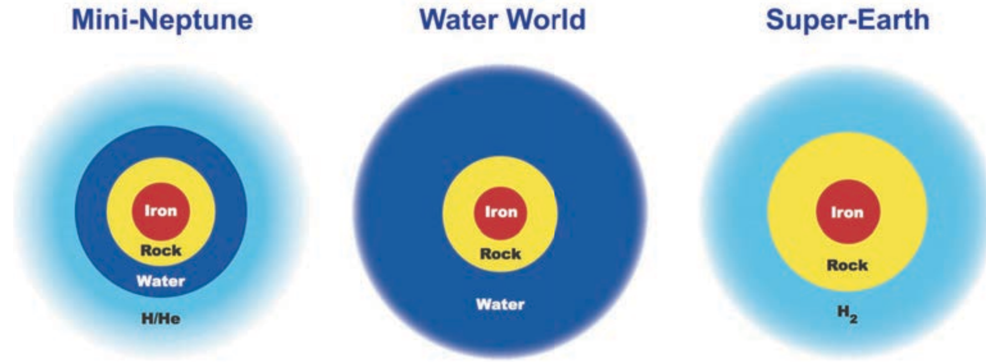




Howard et al. 2011b

HD 97658b





H/He mass fraction = 10^{-4} to 6.8%

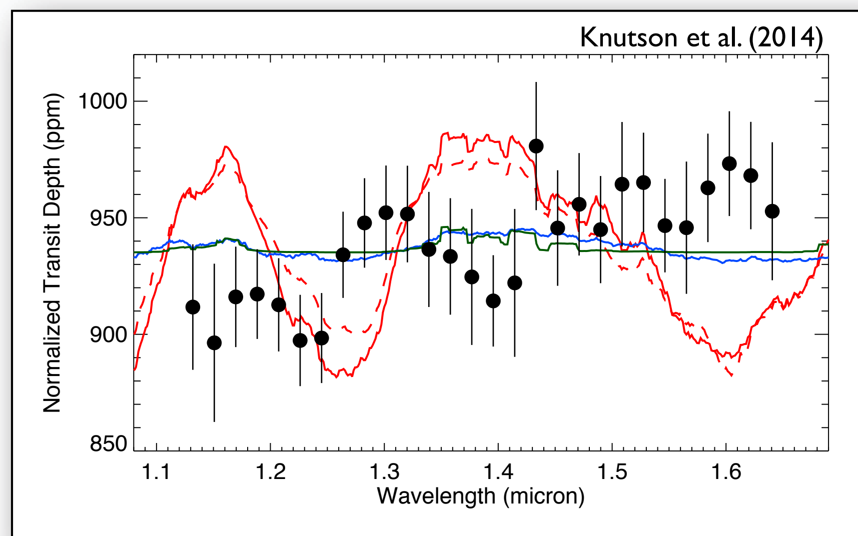
H_2O mass fraction ≥ 47%

H_2 mass fraction = 5×10^{-4} to 3%

Formed > ~2 AU
Migrated to 0.1 AU
No violent heating

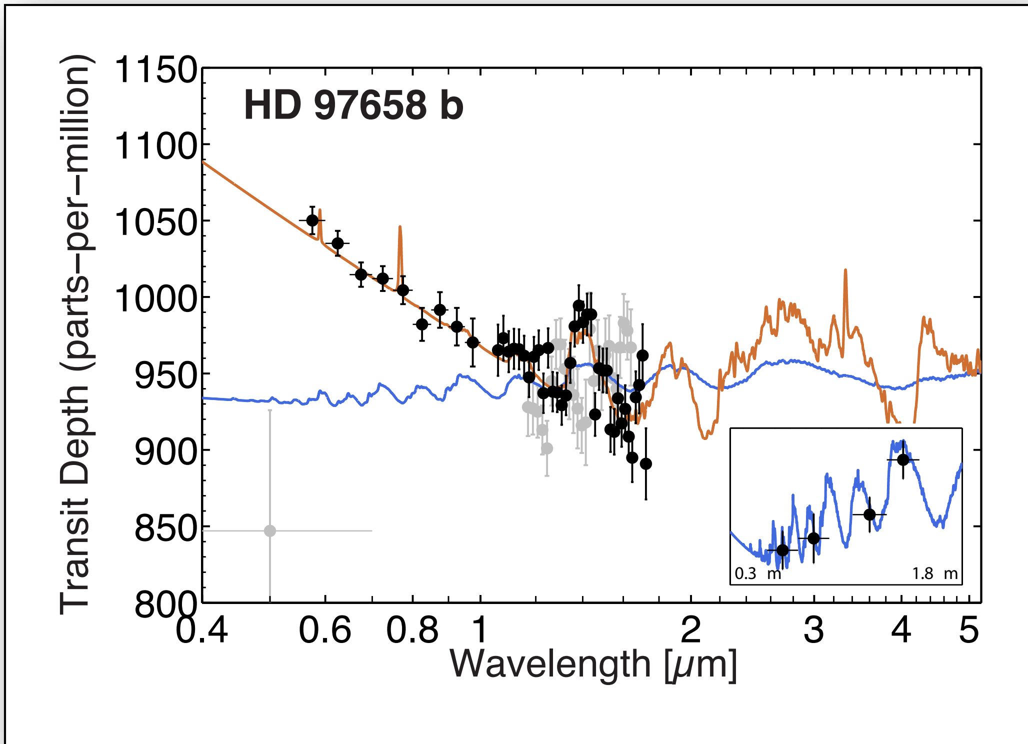
Formed > ~2 AU
Migrated to 0.1 AU
Lost H/He gas
or formed late

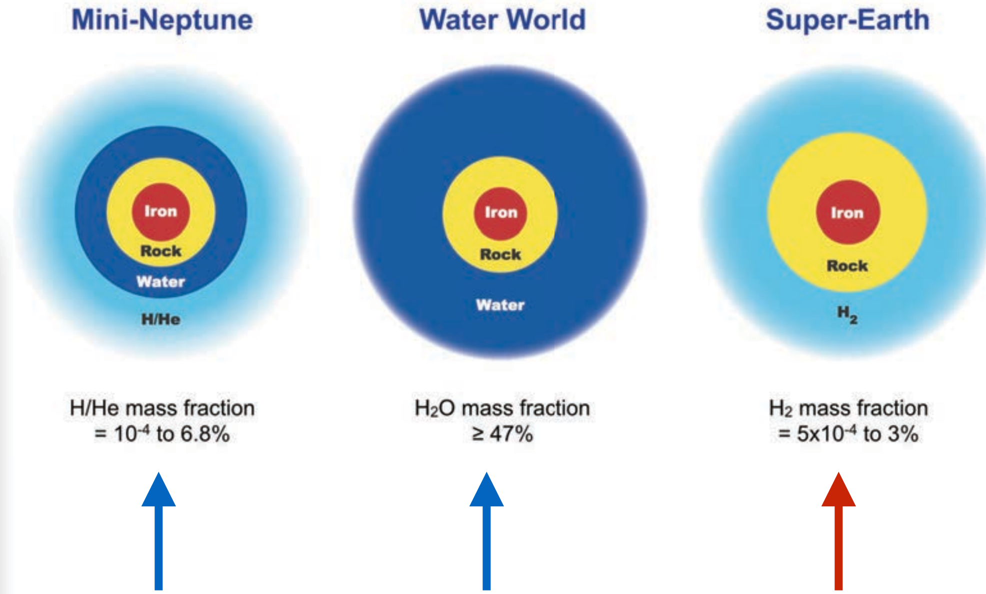
Formed in situ
quickly



HD 97658b

Simulated Data - Hubble Space Telescope



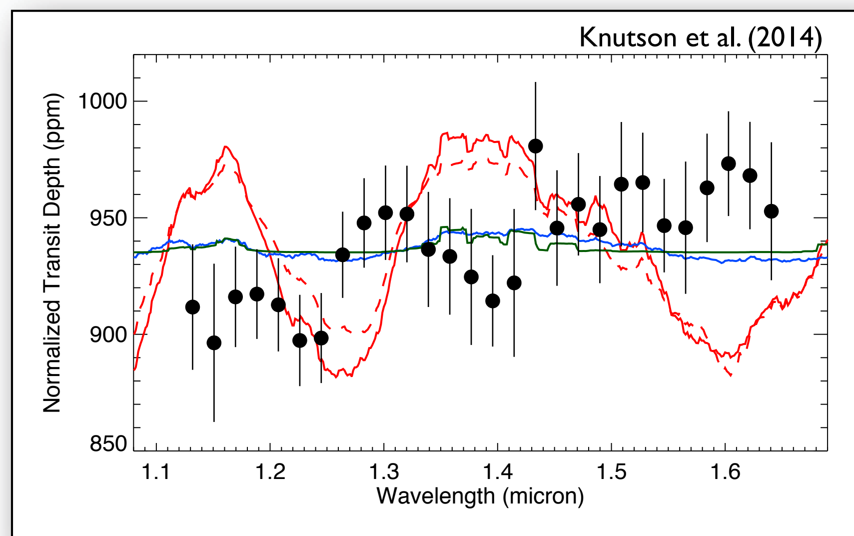


Formed > ~2 AU
Migrated to 0.1 AU
No violent heating

Formed > ~2 AU
Migrated to 0.1 AU
Lost H/He gas

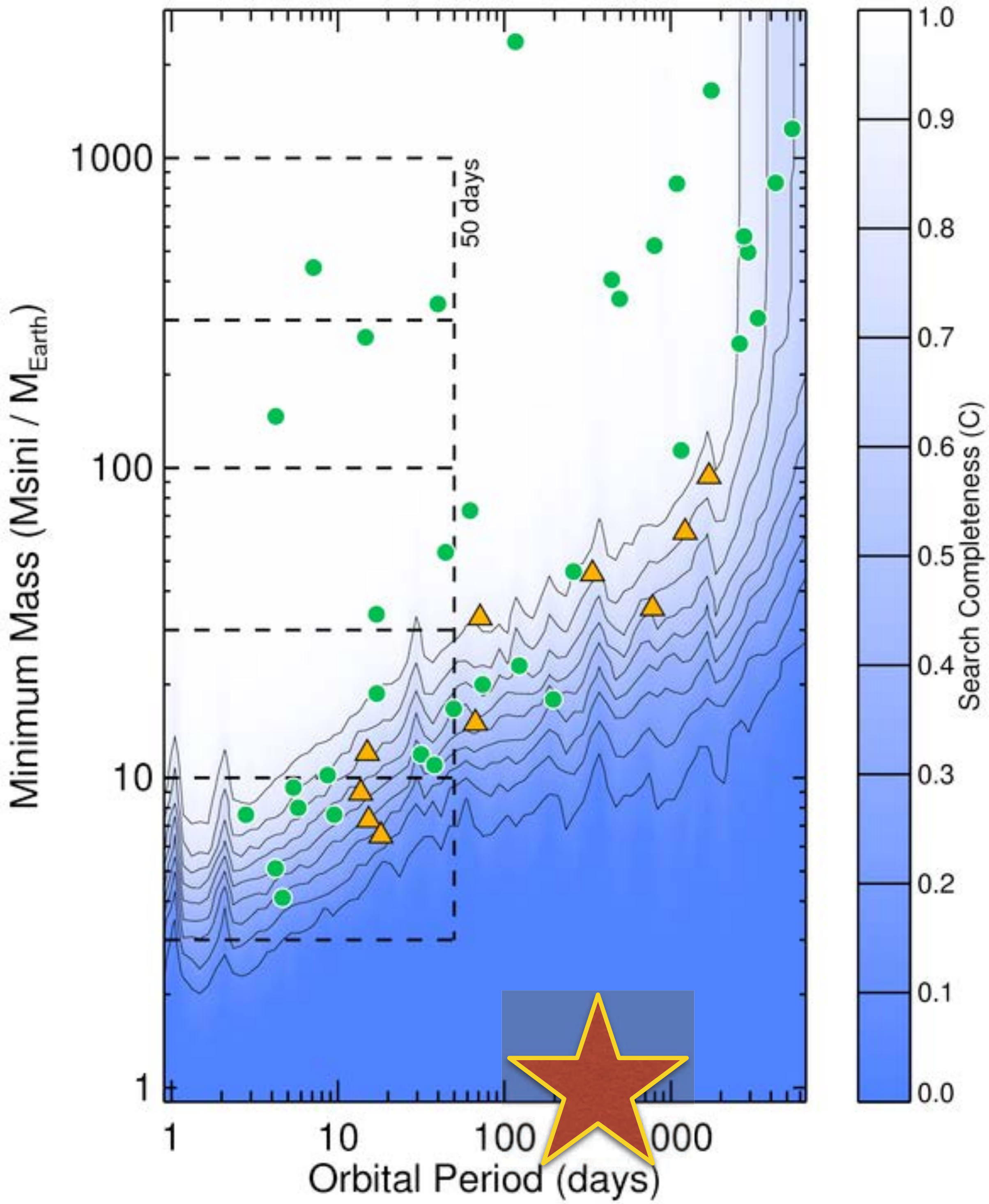
Formed in situ

Approved HST Large Program
B. Benneke, H. Knutson, I. Crossfield, A. Howard, et al.



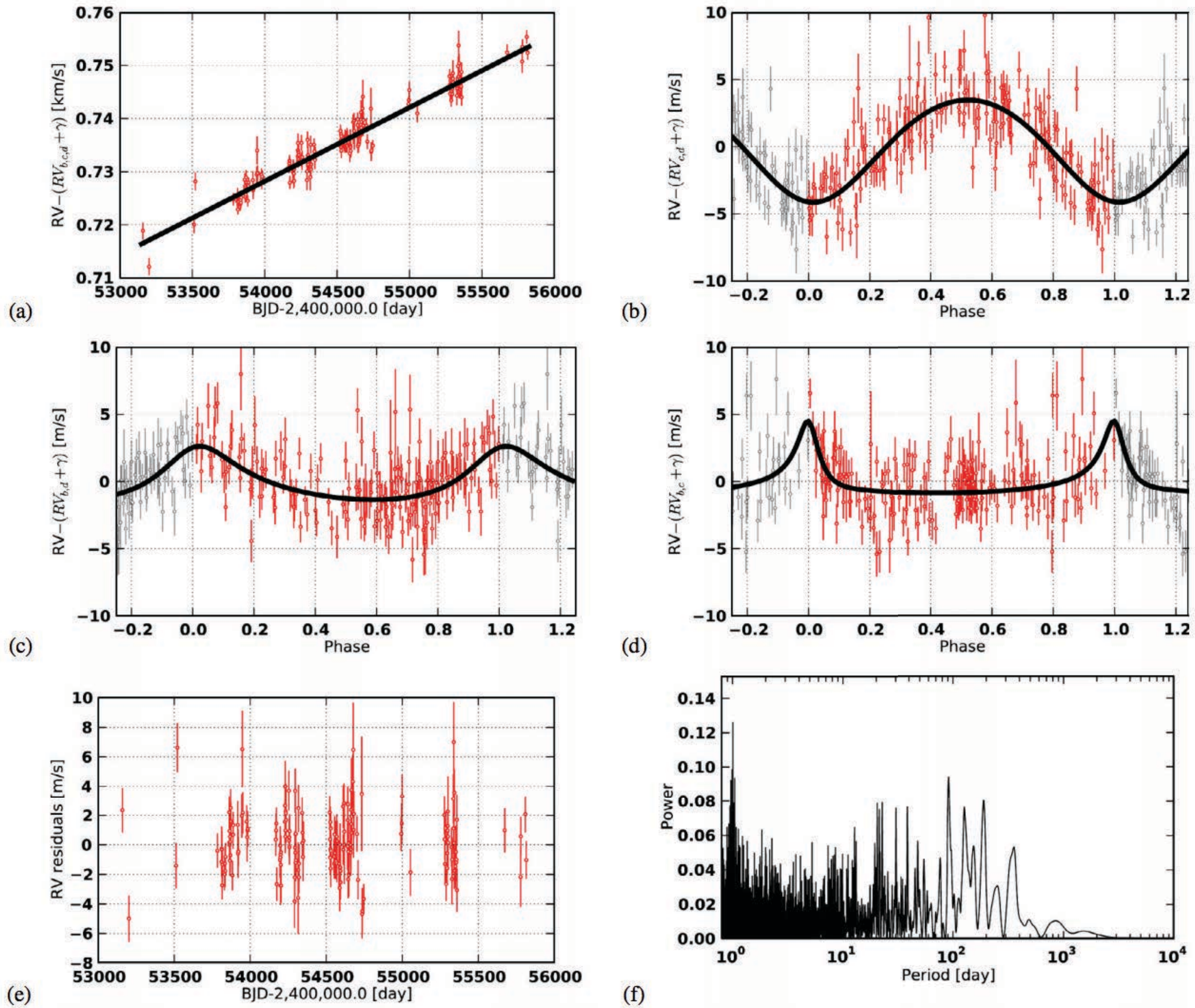
Howard et al. 2010, Science, 330, 653

Earth 2.0 = Difficult to Find



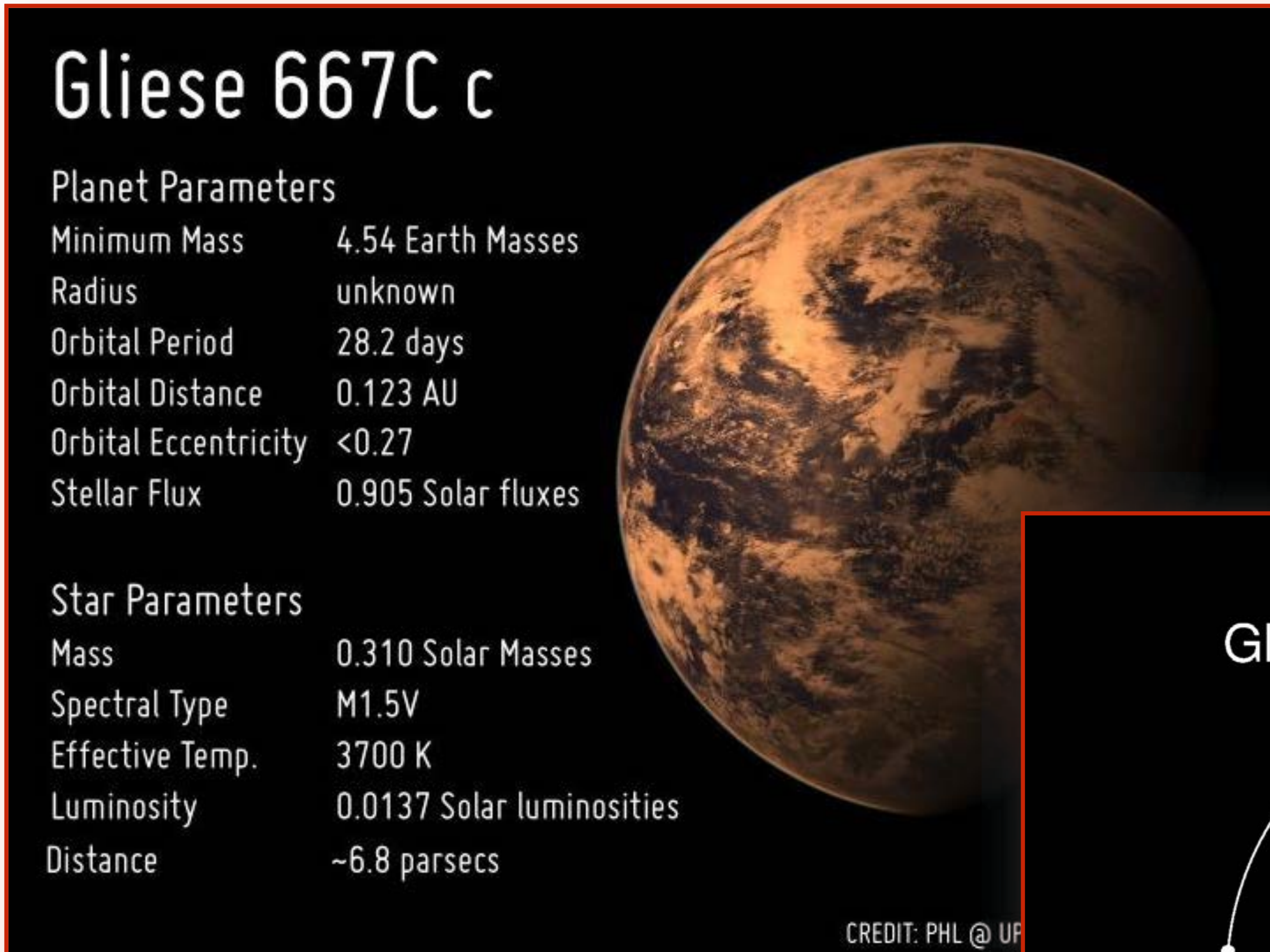
- Detected planets
- Candidate planets (FAPs ~ 1-5%)

Gl 667C — Two clear planets + more?

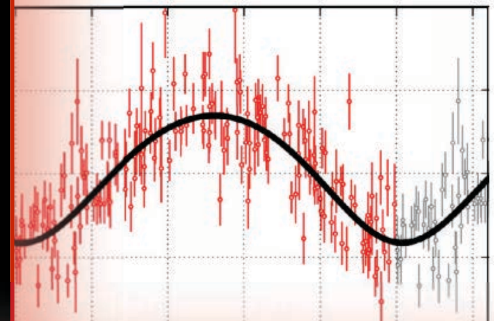


Data from HARPS, Delfosse et al. (2013)

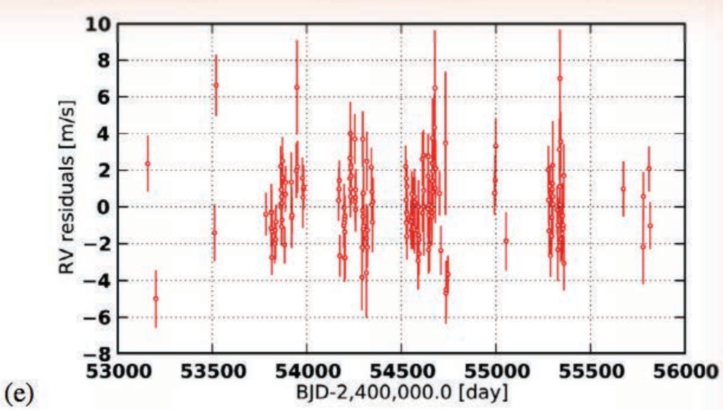
…ets + more?



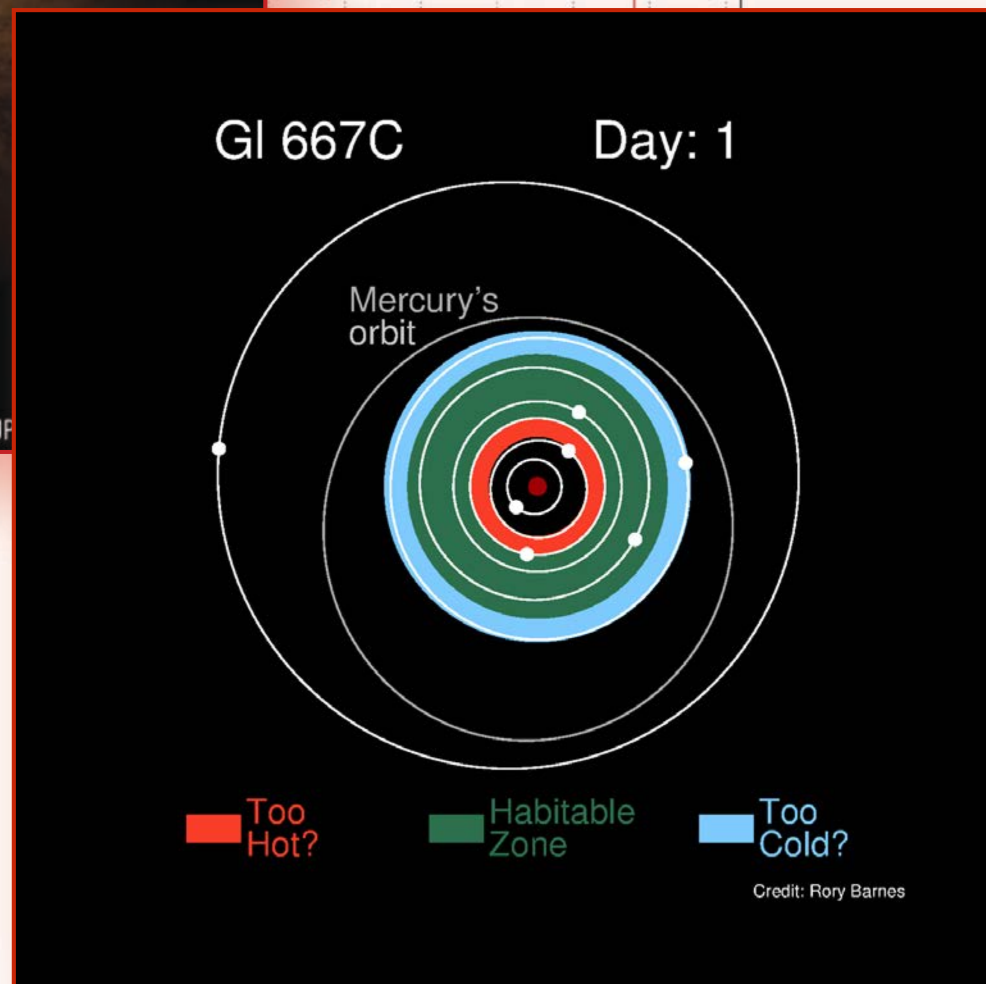
Gliese 667C c
Planet Parameters
Minimum Mass 4.54 Earth Masses
Radius unknown
Orbital Period 28.2 days
Orbital Distance 0.123 AU
Orbital Eccentricity <0.27
Stellar Flux 0.905 Solar fluxes
Star Parameters
Mass 0.310 Solar Masses
Spectral Type M1.5V
Effective Temp. 3700 K
Luminosity 0.0137 Solar luminosities
Distance ~6.8 parsecs
CREDIT: PHL @ UP



(c)
−0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2
Phase

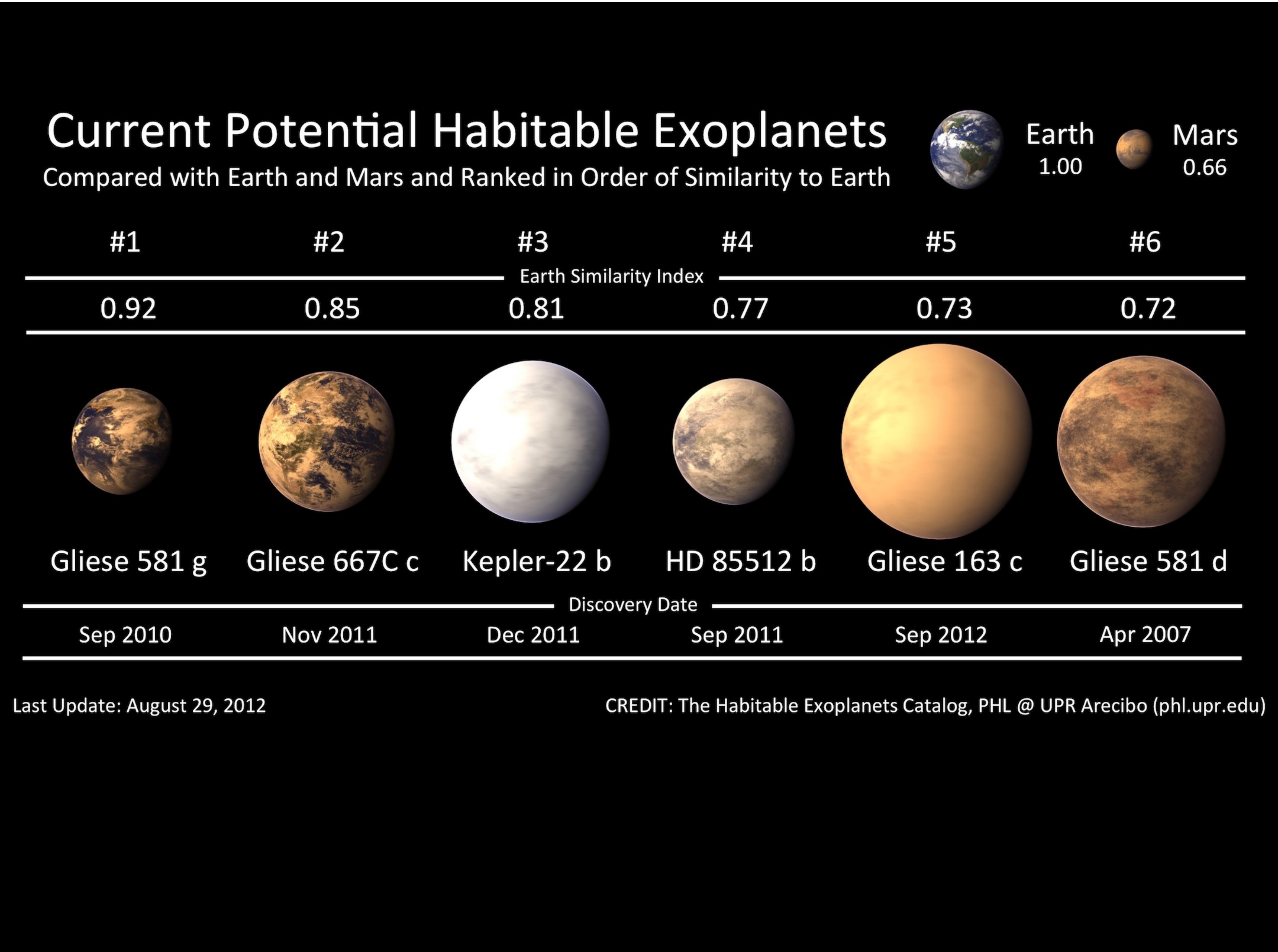


(e)
RV residuals [m/s]
10 8 6 4 2 0 −2 −4 −6 −8
53000 53500 54000 54500 55000 55500 56000
BJD-2,400,000.0 [day]

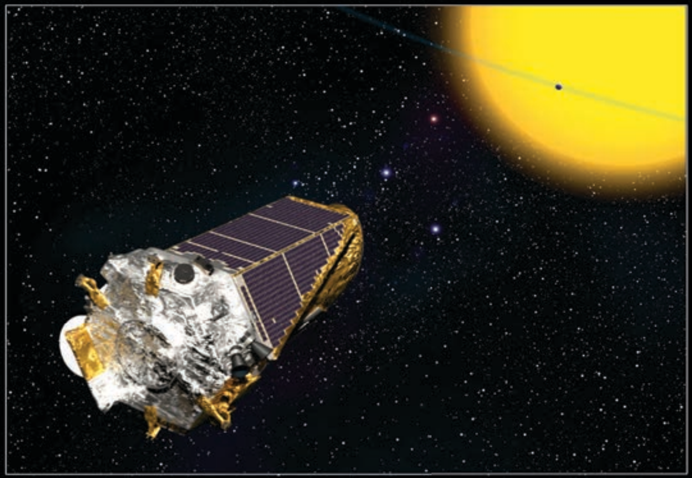


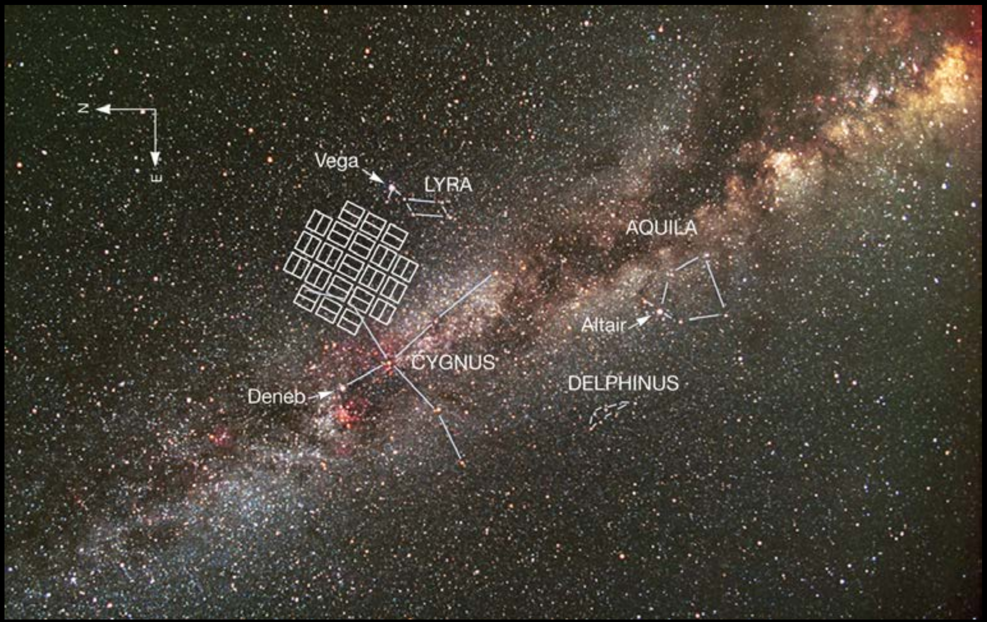
Gl 667C
Day: 1
Mercury's orbit
Too Hot?
Habitable Zone
Too Cold?
Credit: Rory Barnes

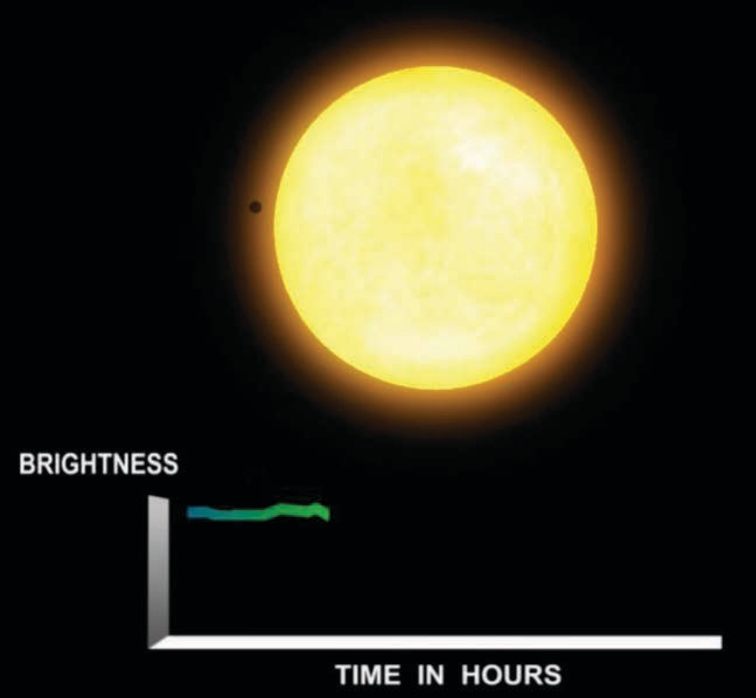
3)

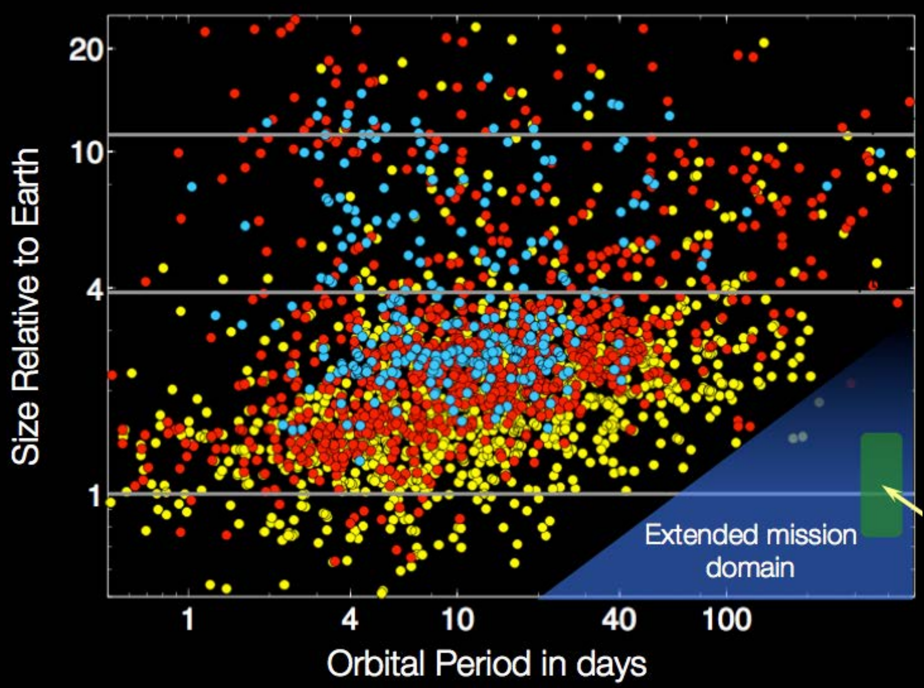

Current Potential Habitable Exoplanets
Compared with Earth and Mars and Ranked in Order of Similarity to Earth
Earth
1.00
Mars
0.66
#1
#2
#3
#4
#5
#6
Earth Similarity Index
0.92
0.85
0.81
0.77
0.73
0.72
Gliese 581 g
Gliese 667C c
Kepler-22 b
HD 85512 b
Gliese 163 c
Gliese 581 d
Discovery Date
Sep 2010
Nov 2011
Dec 2011
Sep 2011
Sep 2012
Apr 2007
Last Update: August 29, 2012
CREDIT: The Habitable Exoplanets Catalog, PHL @ UPR Arecibo (phl.upr.edu)

Kepler Space Telescope

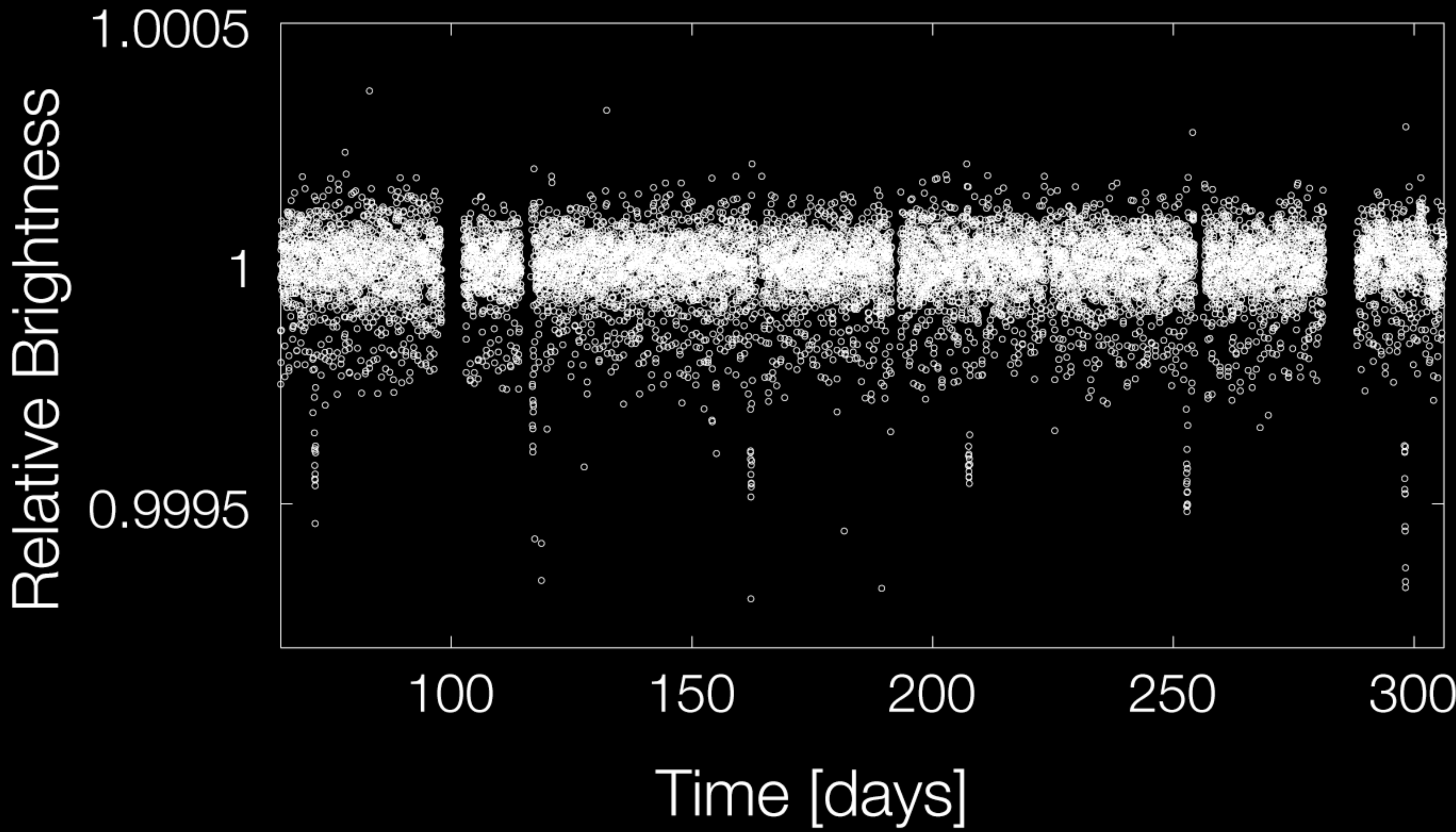






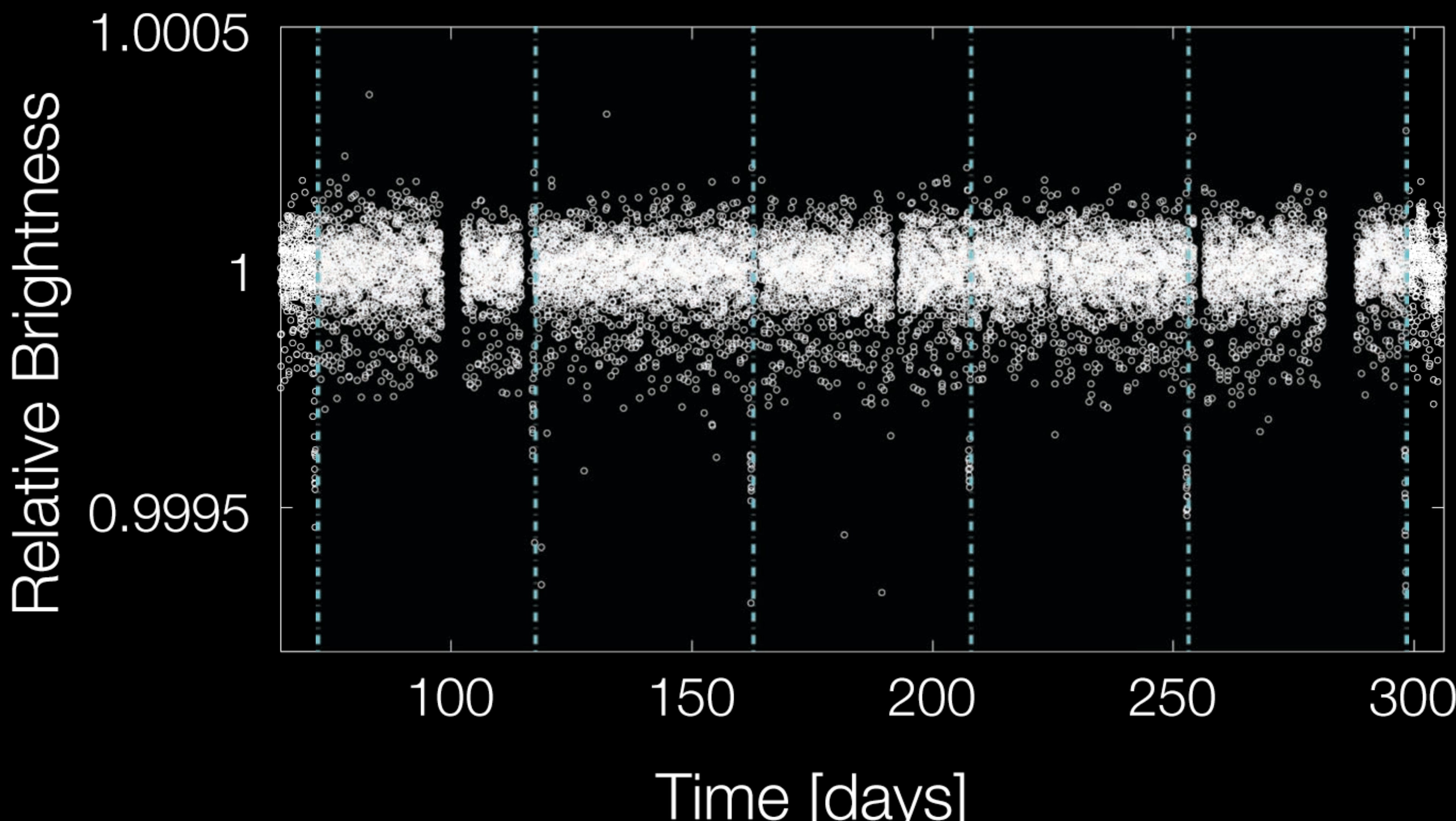


Kepler-10 Light Curve



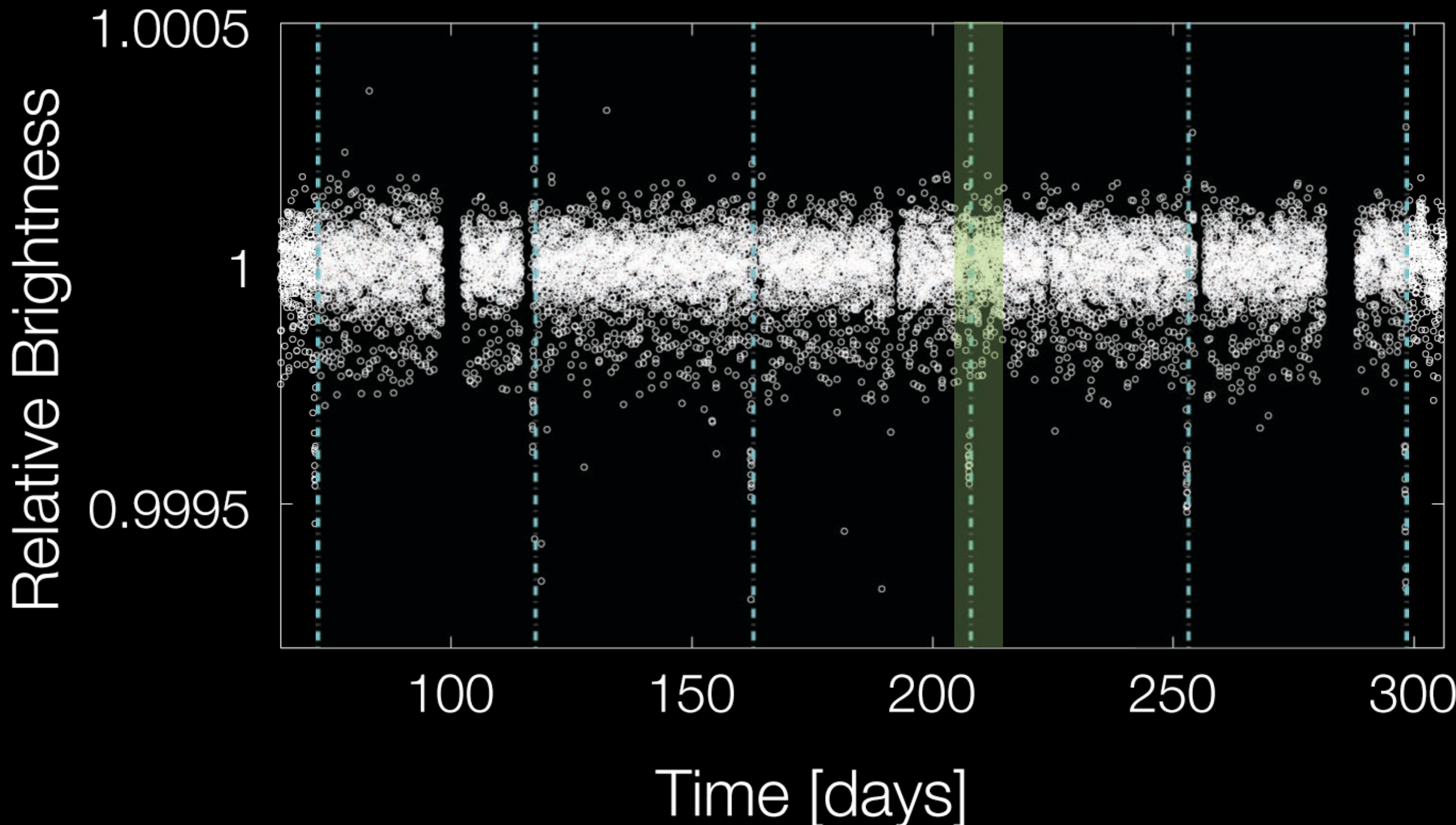
Kepler-10 Light Curve

Period = 45.29 days

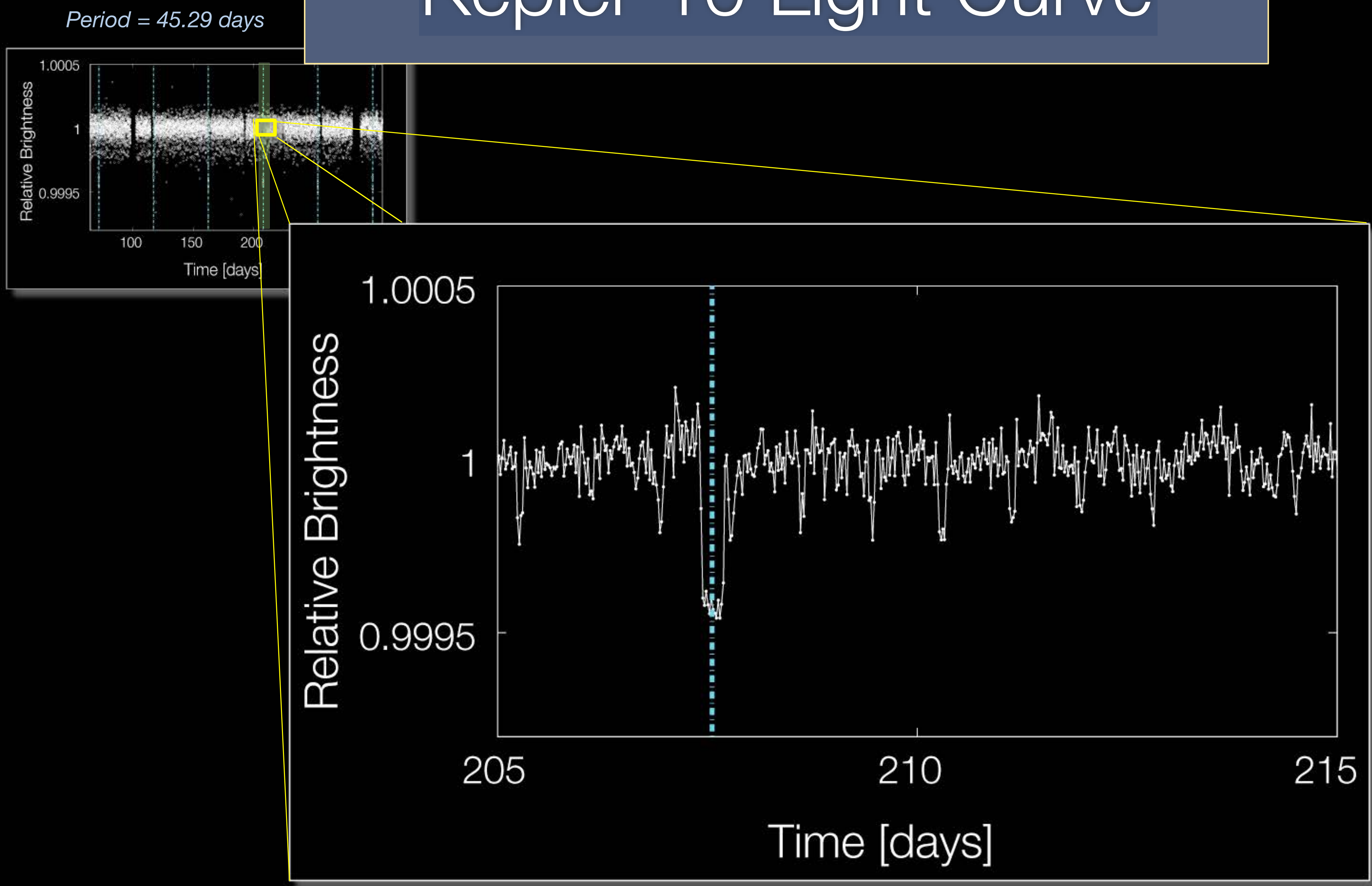


Kepler-10 Light Curve

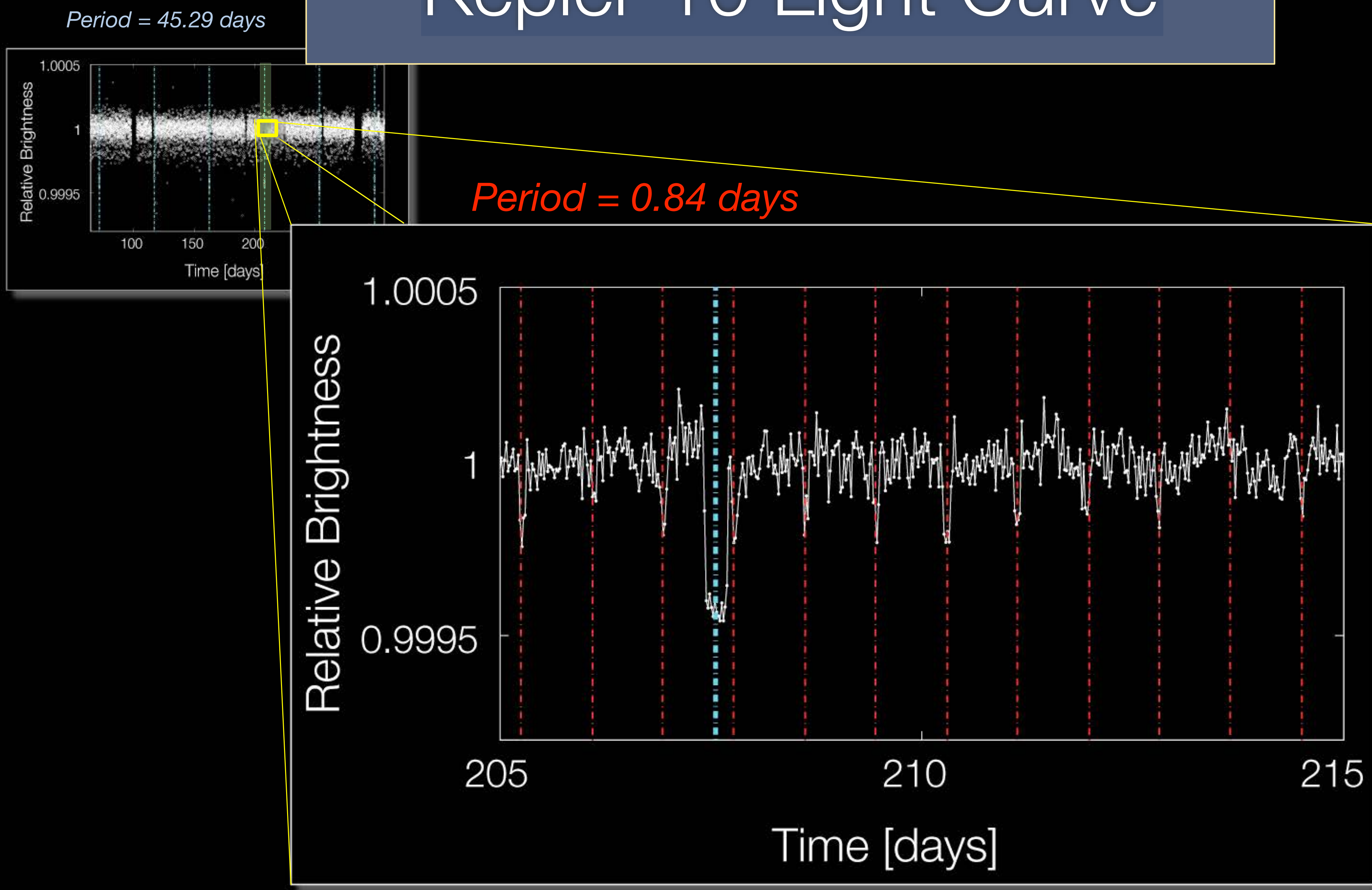
Period = 45.29 days



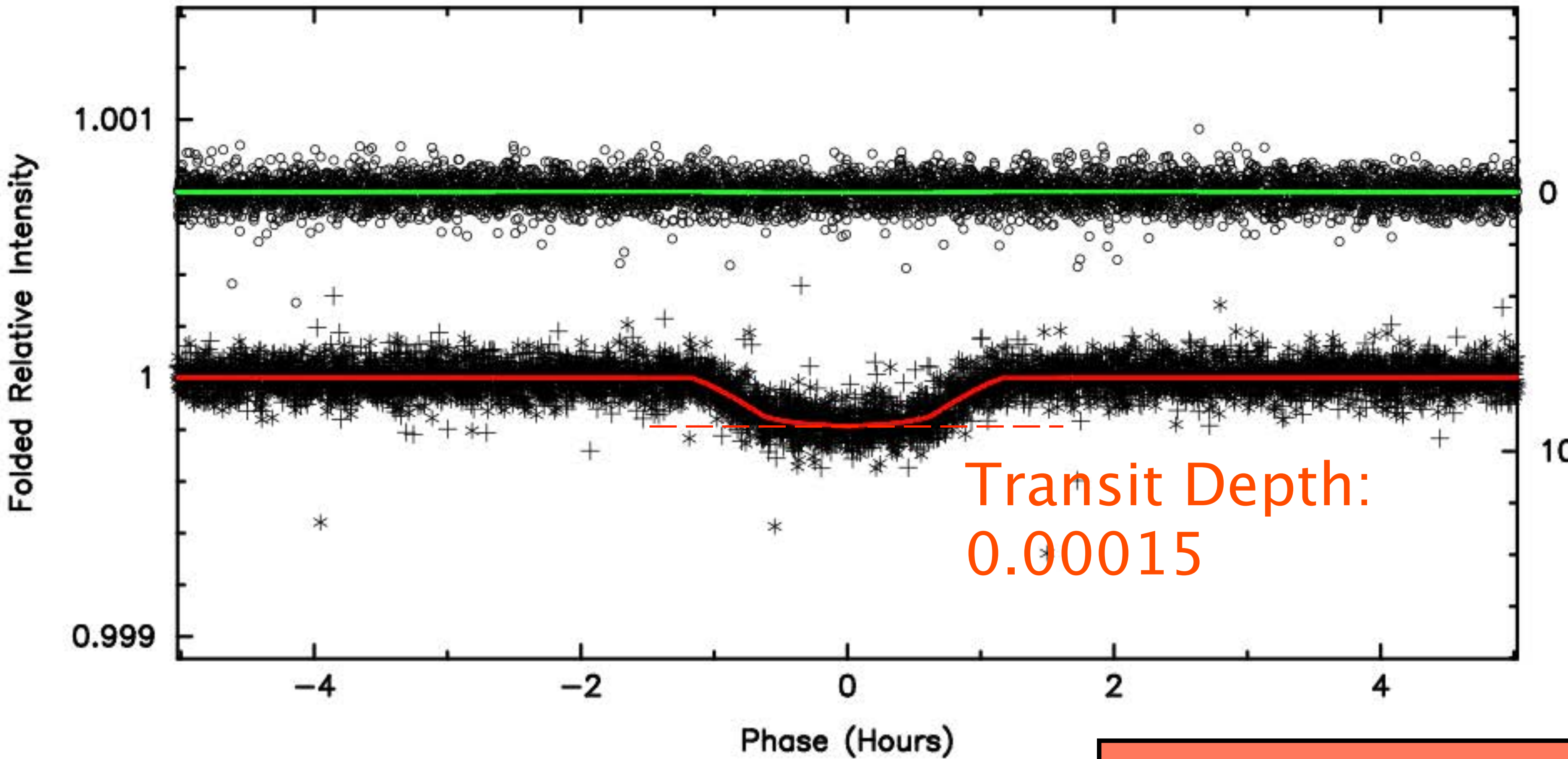
Kepler-10 Light Curve



Kepler-10 Light Curve



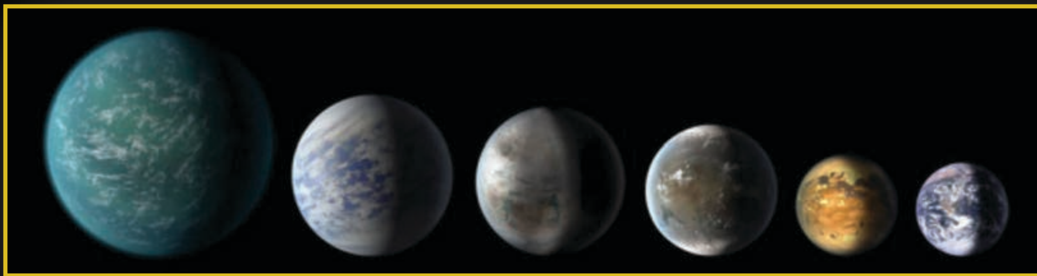
Kepler-10 Light Curve



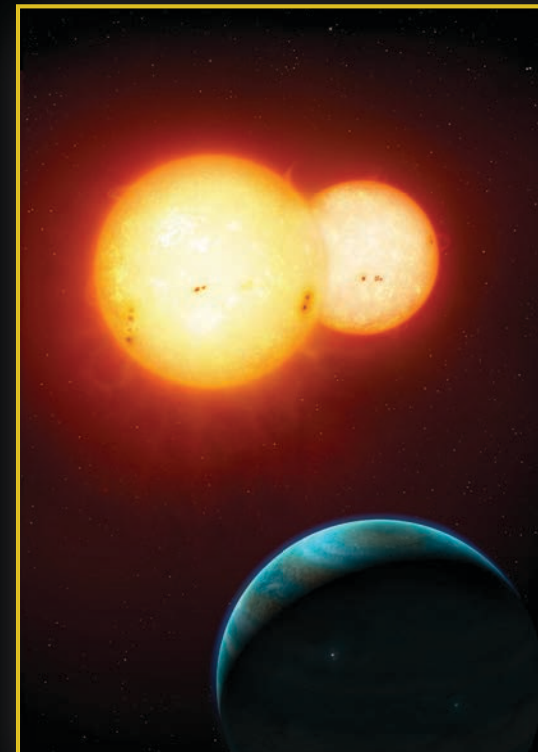
Batalha et al. (2011)

Kepler–10b
Radius = 1.4 R_{earth}
Period = 0.83 days

Super-Earths ↔ Earths



Circumbinary Planets



Multi-planet Systems

Planets in the Habitable Zone

Lava Planets

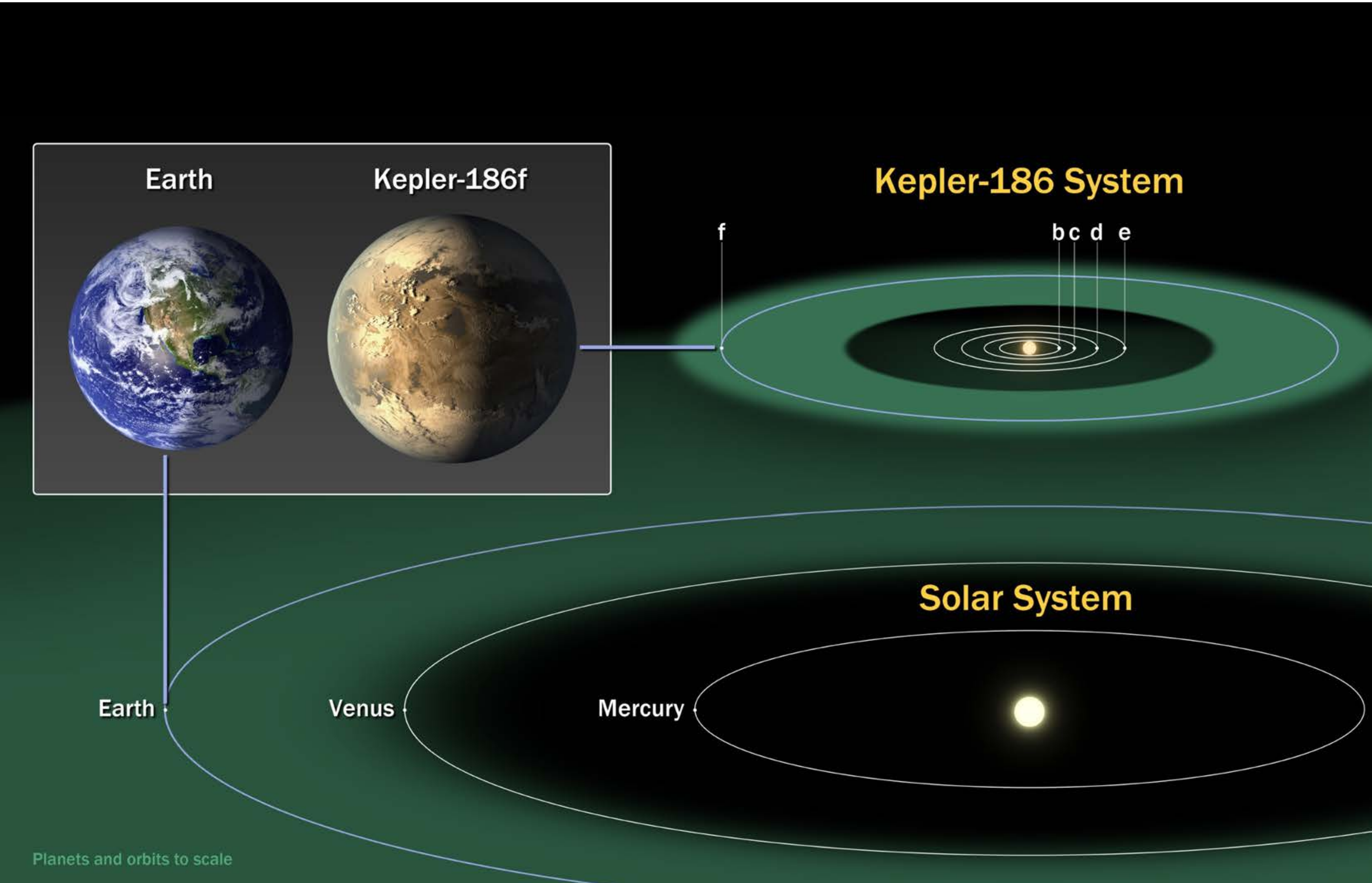

Earth
Kepler-186f
Kepler-186 System
f
b c d e
Solar System
Earth
Venus
Mercury
Planets and orbits to scale

Image: NASA

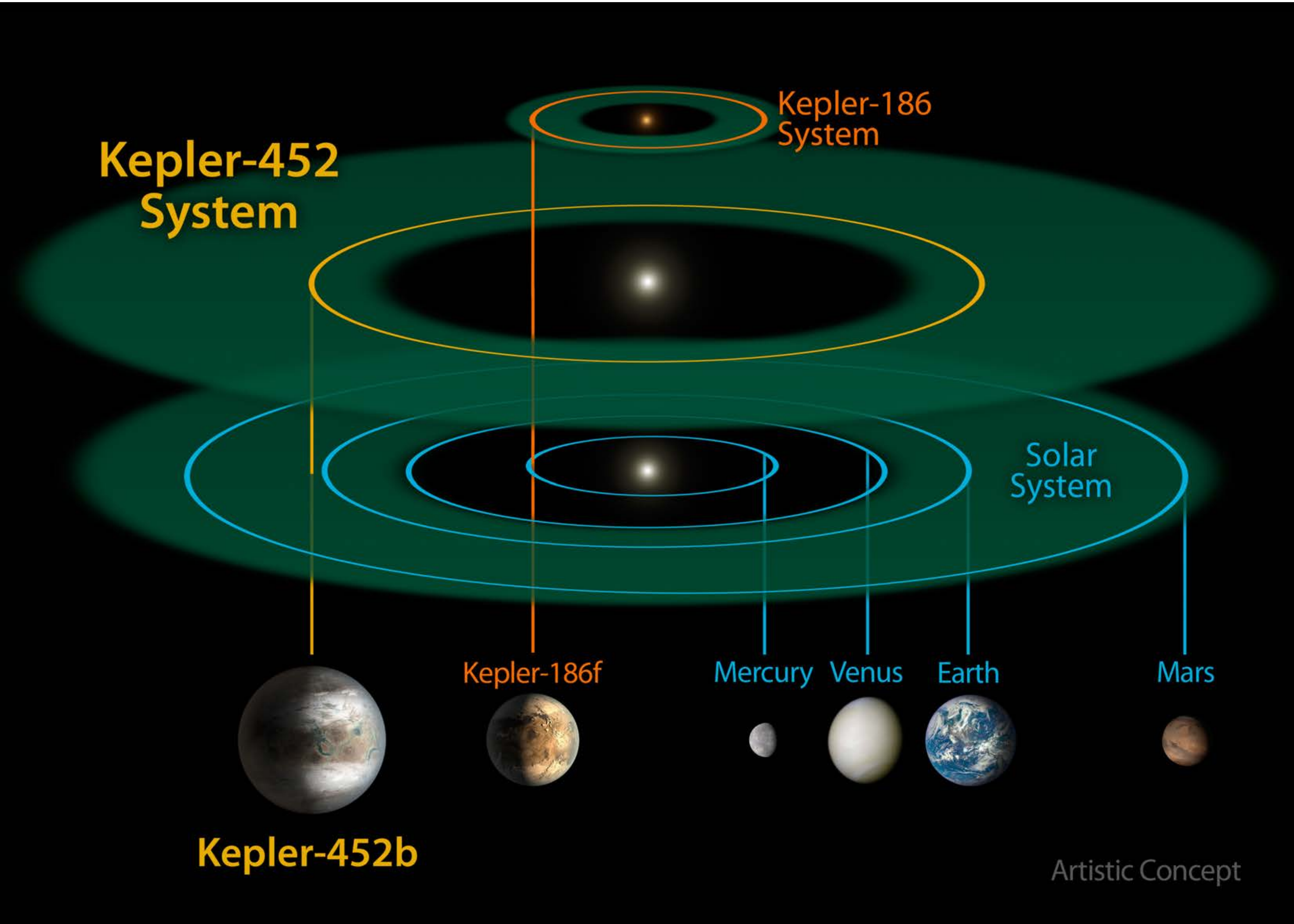
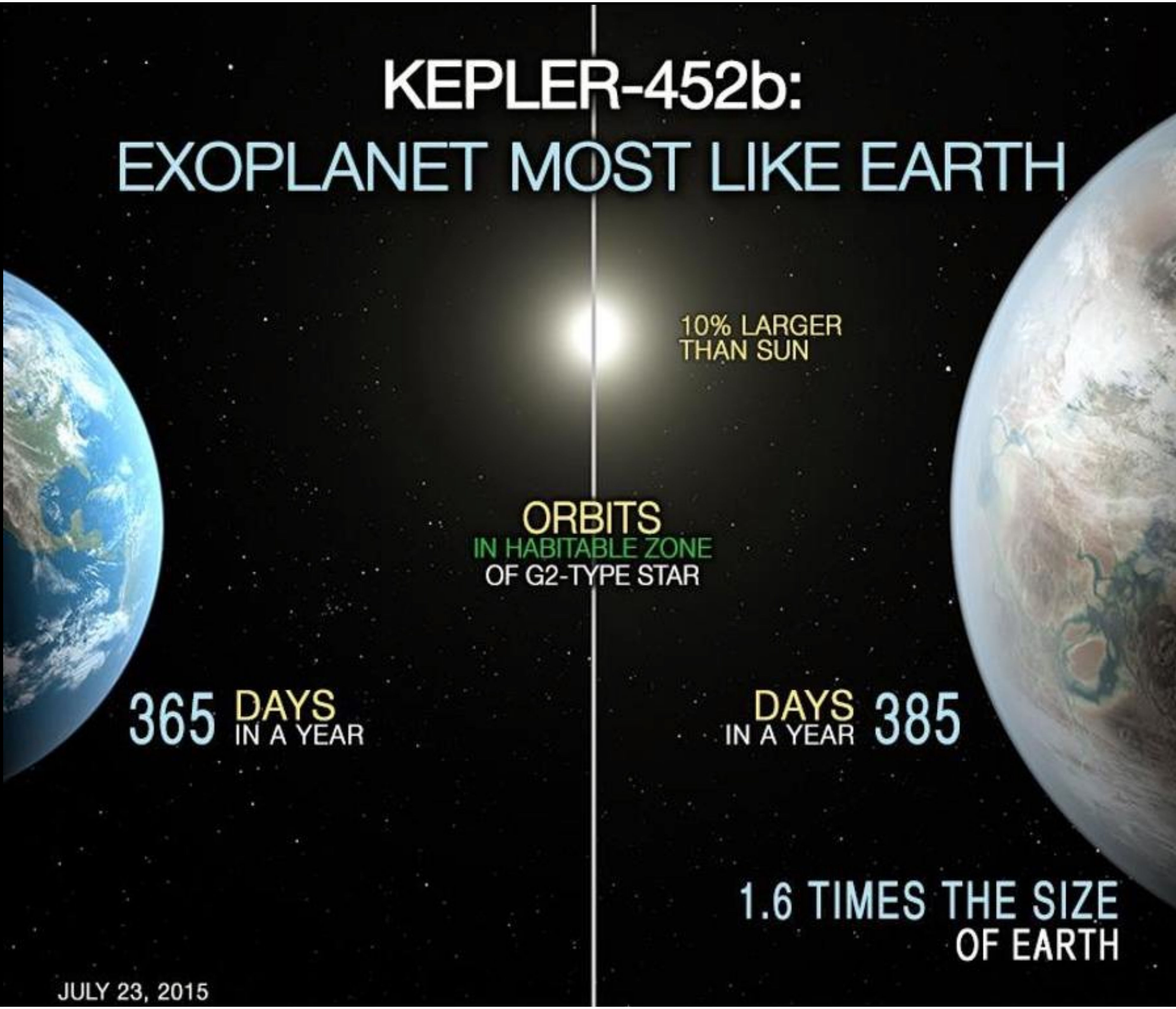

Kepler-186
System
Kepler-452
System
Solar
System
Kepler-186f
Mercury
Venus
Earth
Mars
Kepler-452b
Artistic Concept

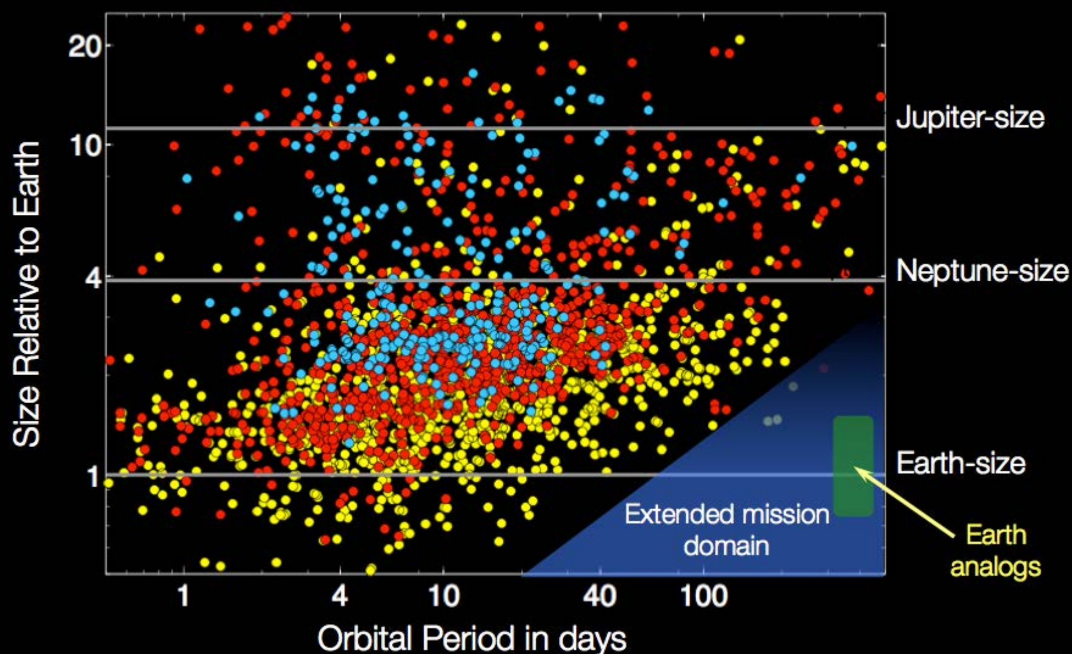
Image: NASA


KEPLER-452b:
EXOPLANET MOST LIKE EARTH
10% LARGER
THAN SUN
ORBITS
IN HABITABLE ZONE
OF G2-TYPE STAR
365 DAYS
IN A YEAR
DAYS
IN A YEAR 385
1.6 TIMES THE SIZE
OF EARTH
JULY 23, 2015

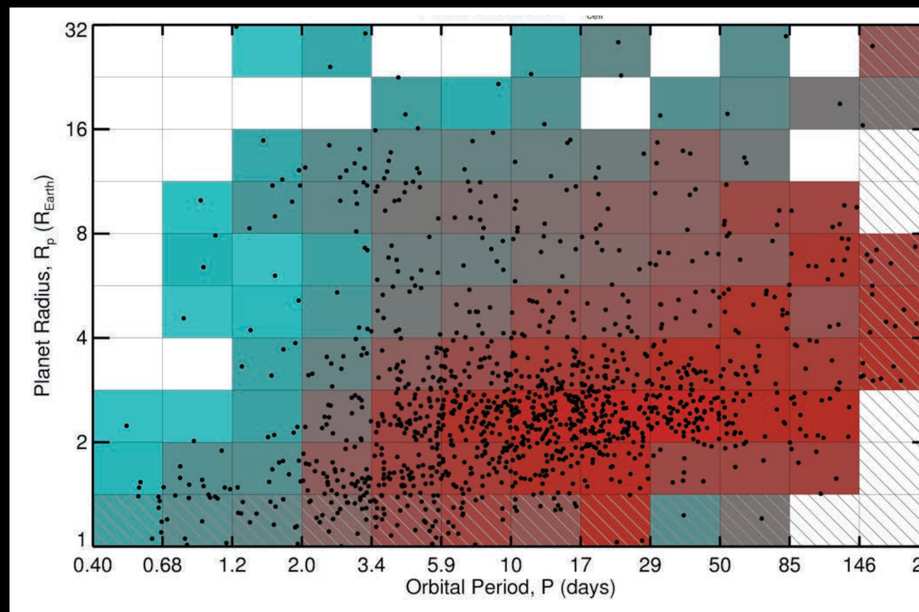
ıge: NASA

Planet Occurrence from Kepler

Observed Planets

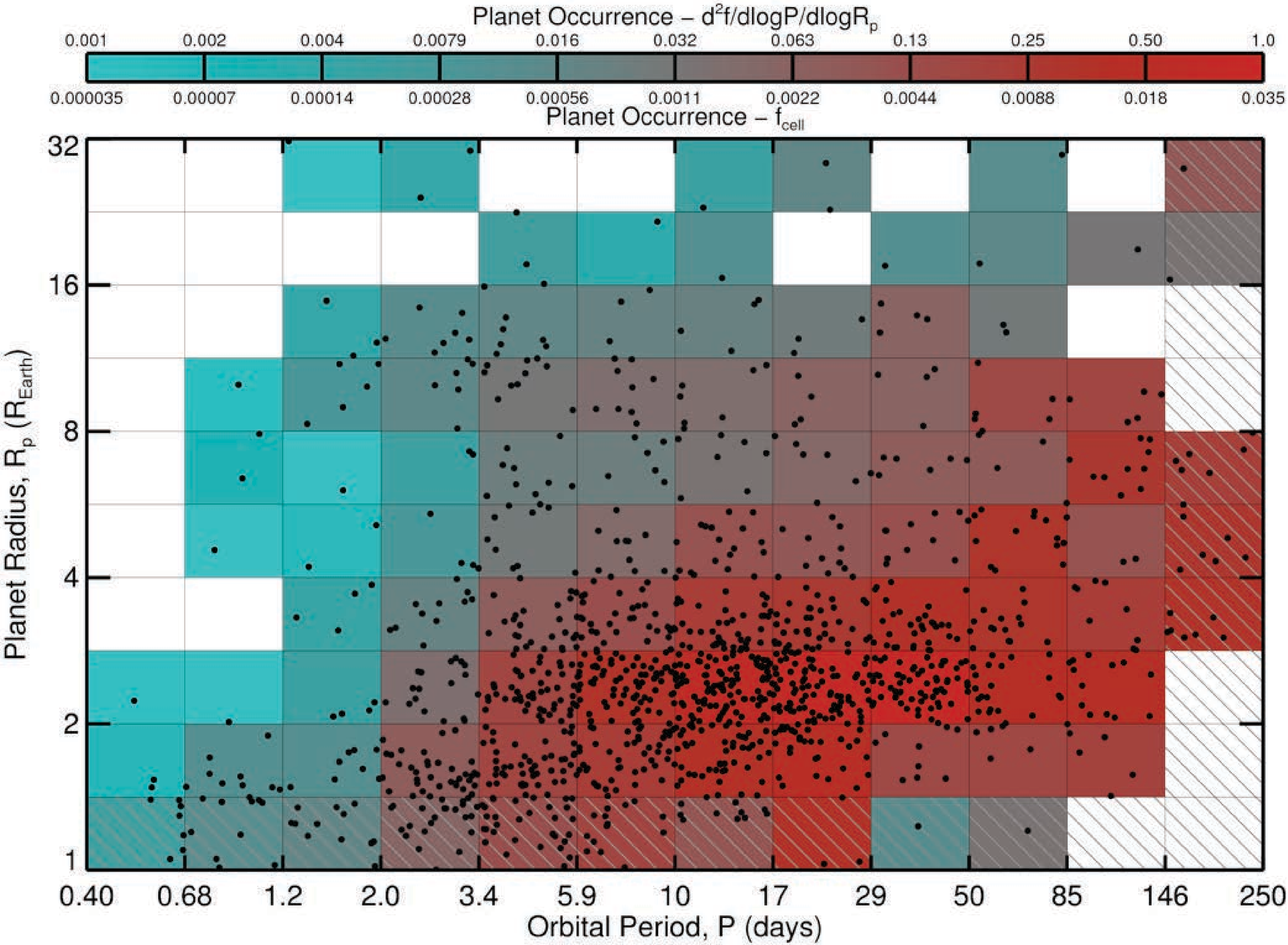


Intrinsic Planet Distribution



Howard et al. (2012)

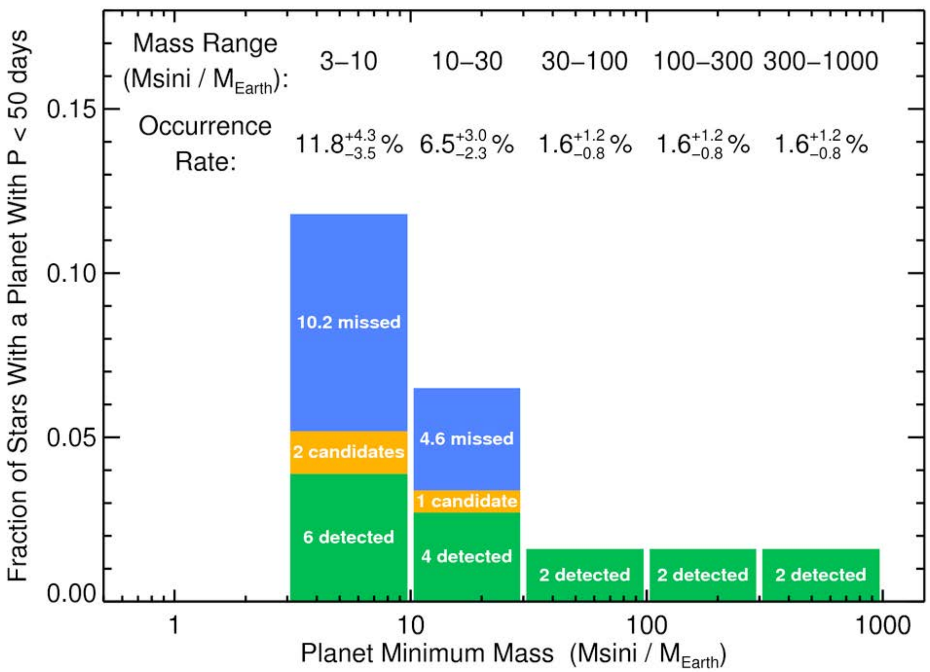
Correct for: • Inclined orbital planes
• Photometric noise
Assume: • 100% complete planet search to SNR threshold



Howard et al. (2012; updated)

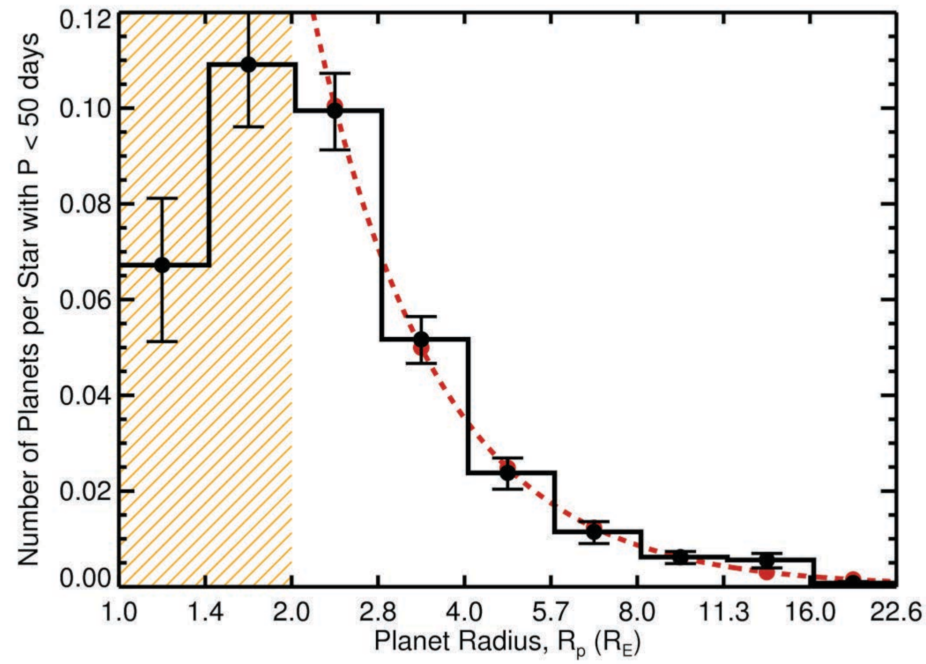
Planet Mass Distribution
Eta-Earth Survey (*Doppler*)

Howard et al. 2010, Science, 33, 653



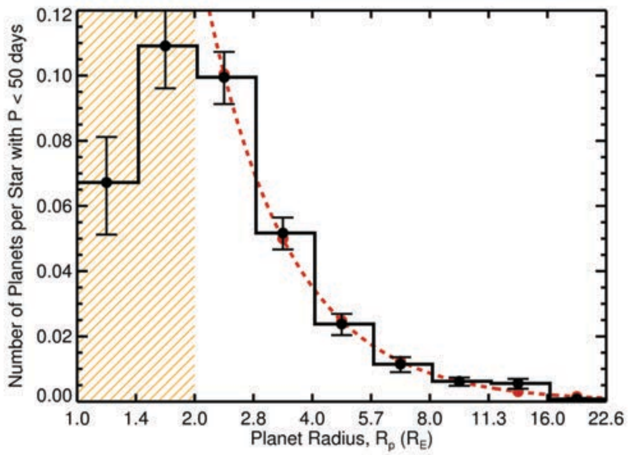
Planet Radius Distribution
Kepler

Howard et al. 2012, ApJ, 330, 653

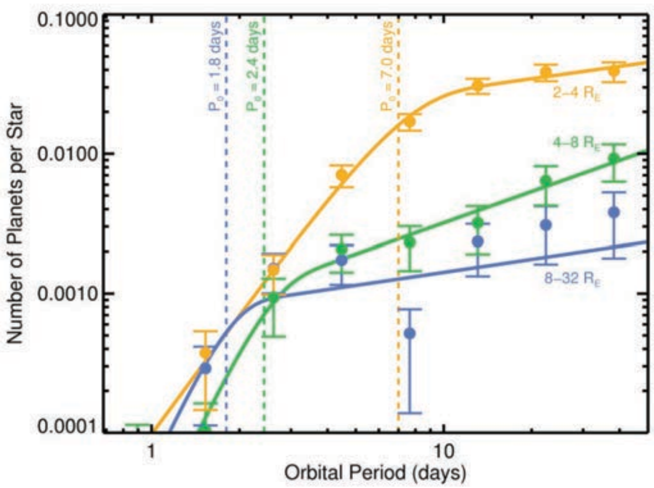


Key Planet Occurrence Trends for GK dwarfs stars from Kepler

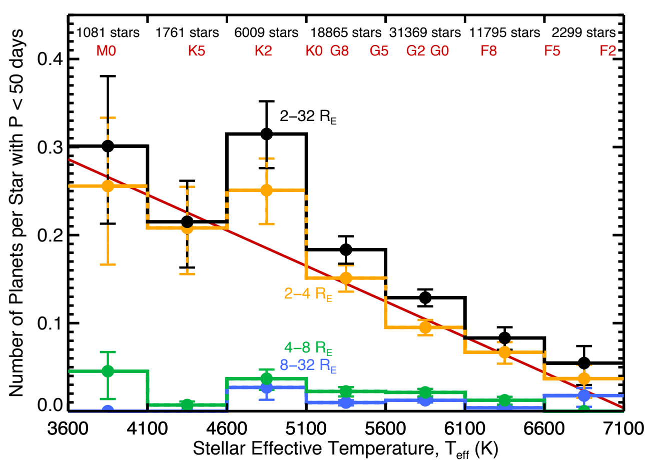
Howard et al. 2012, ApJ, 330, 653



Small planets are common

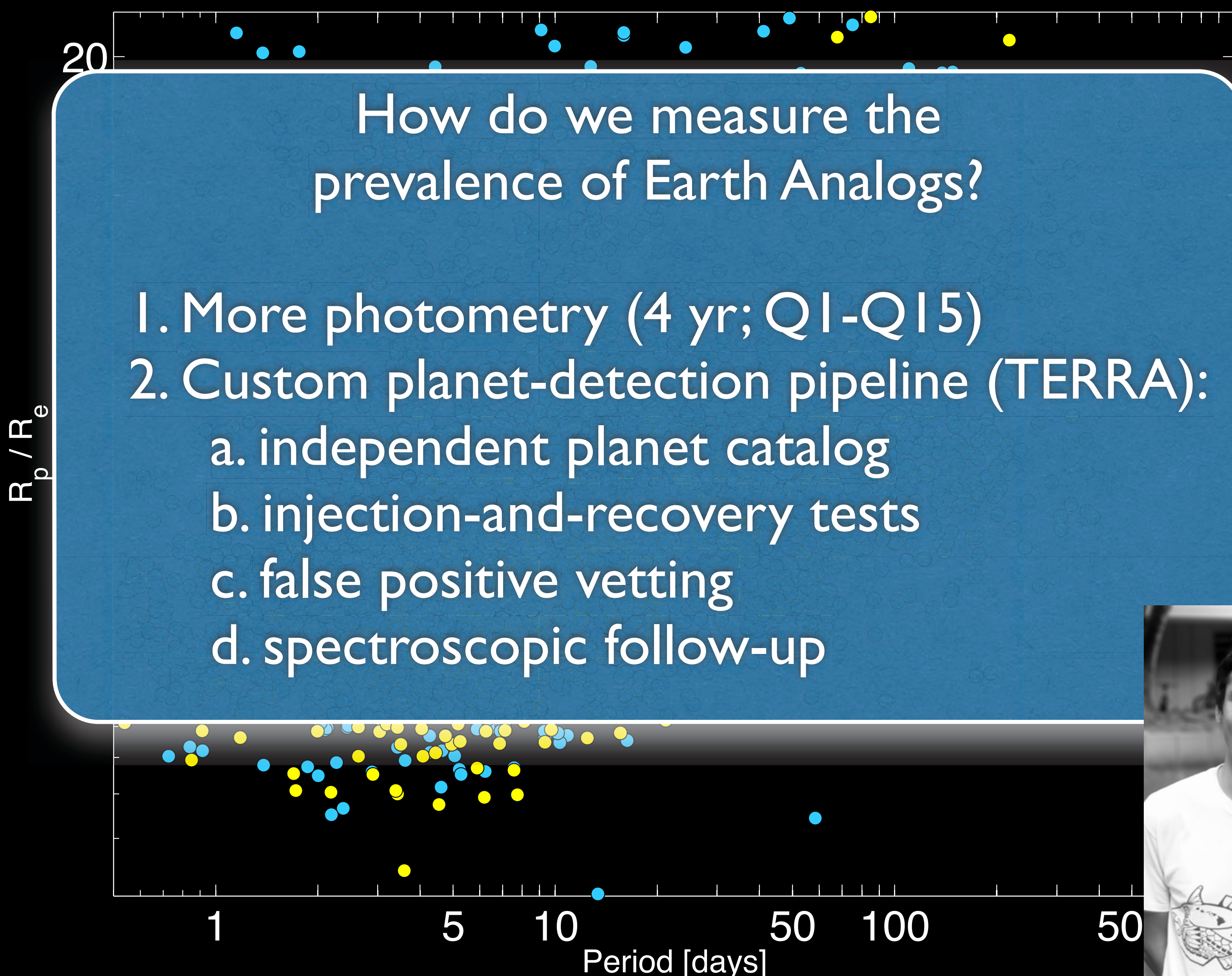


Occurrence vs. period: cut-off power law



Small planets prefer small stars

Kepler Planets



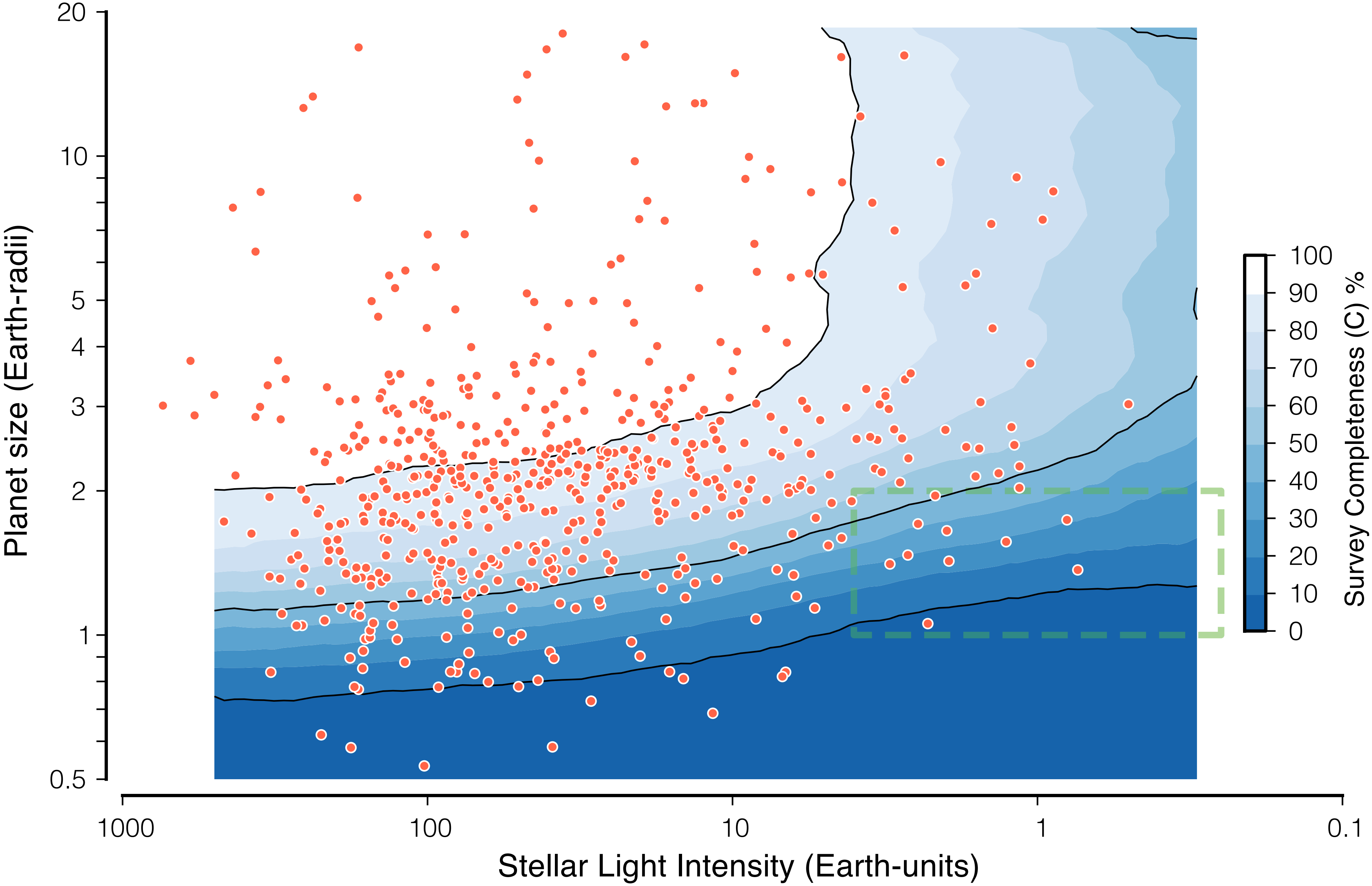
How do we measure the prevalence of Earth Analogs?

1. More photometry (4 yr; Q1-Q15)
2. Custom planet-detection pipeline (TERRA):
   a. independent planet catalog
   b. injection-and-recovery tests
   c. false positive vetting
   d. spectroscopic follow-up

Rowe et al. (2013)

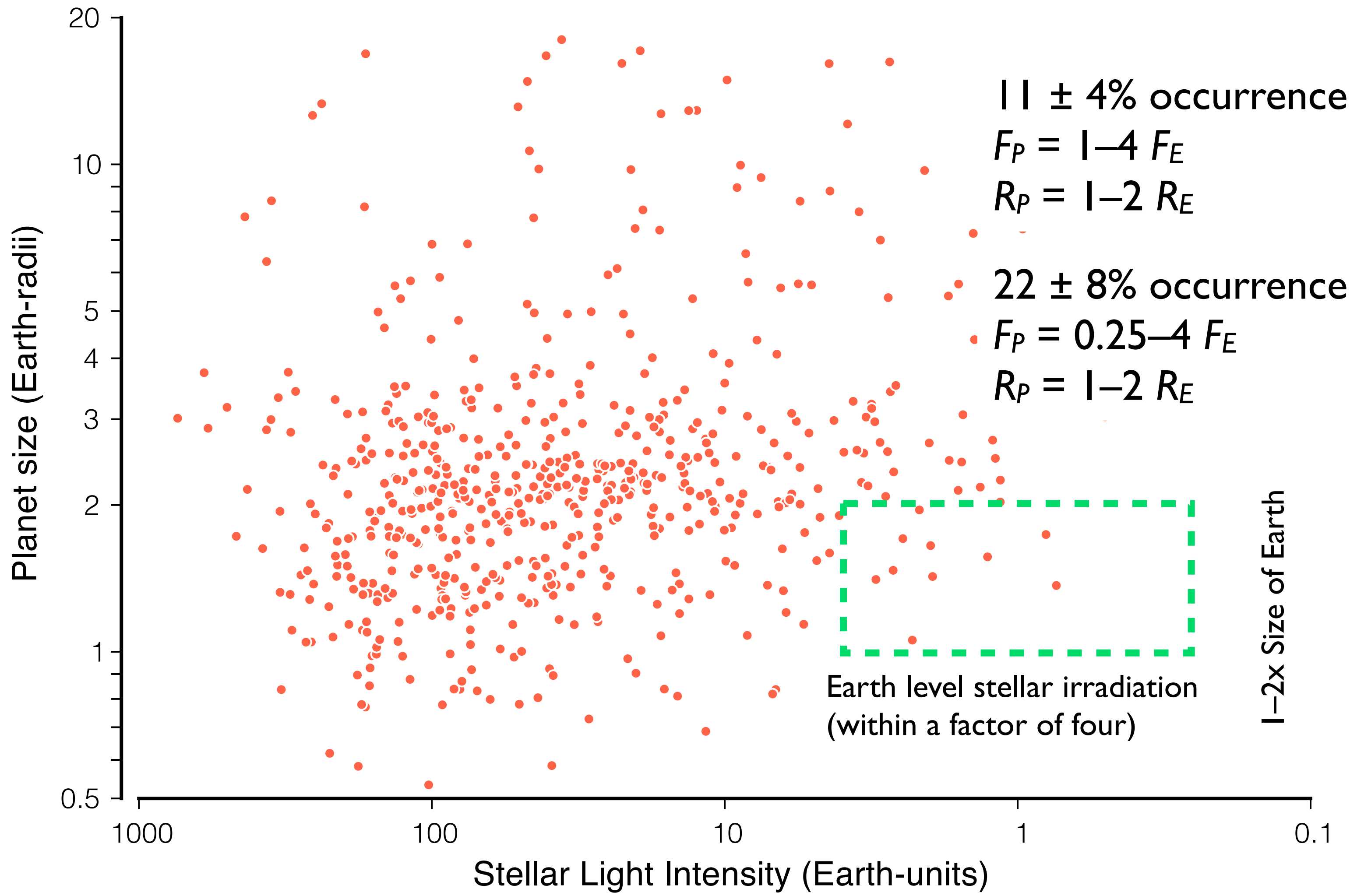
Erik Petigura & Andrew Howard

Planet Size and Incident Flux



Petigura, Howard, & Marcy (2013)

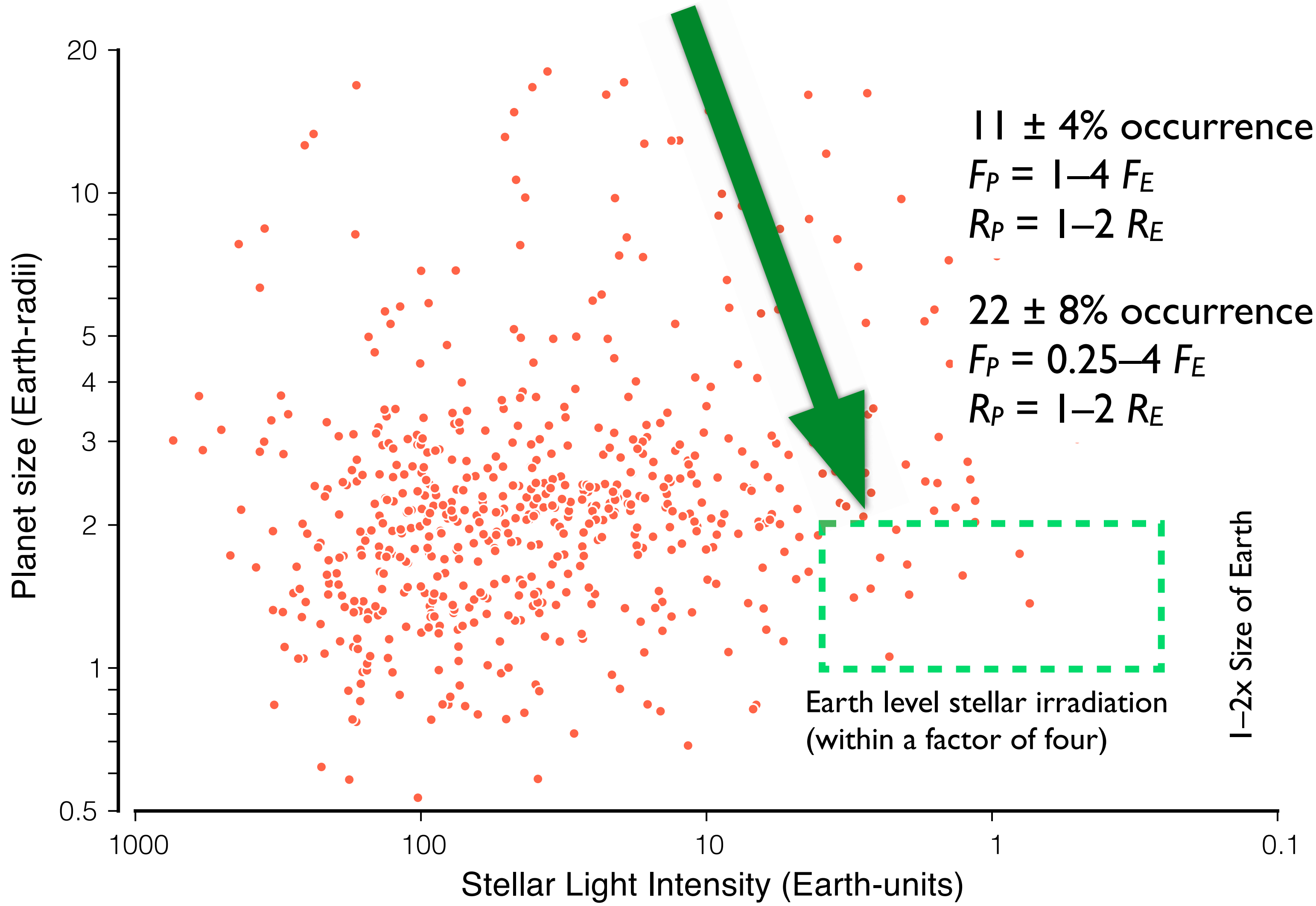
The Occurrence of Warm, Earth-size Planets



Petigura, Howard, & Marcy (2013)

Uncertainties

How big is the $\eta_\oplus$ Box?



Petigura, Howard, & Marcy (2013)

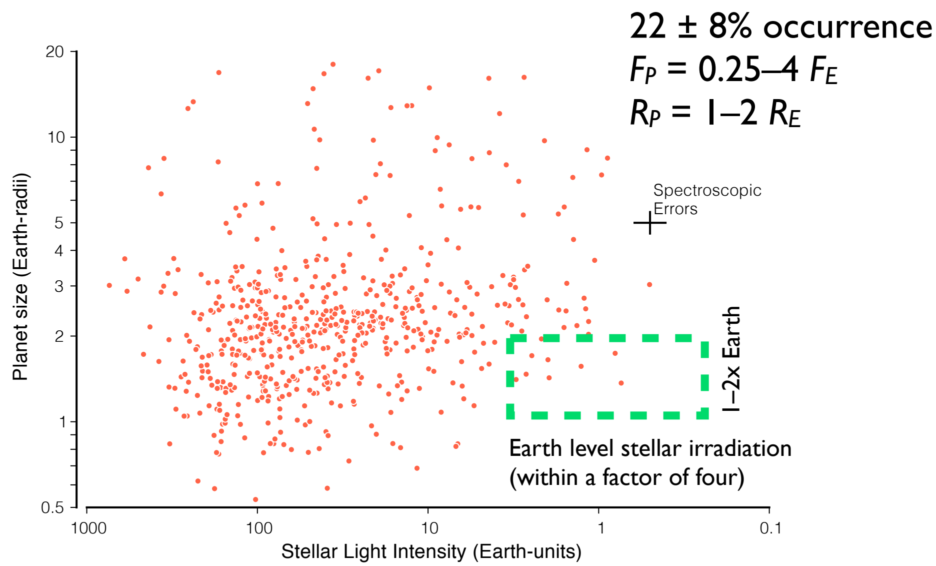


Table 1. Occurrence of small planets in the habitable zone

HZ definition	a_{inner}	a_{outer}	$F_{P,inner}$	$F_{P,outer}$	f_{HZ} (%)
Simple	0.5	2	4	0.25	22
Kasting (1993)	0.95	1.37	1.11	0.53	5.8
Kopparapu et al. (2013)	0.99	1.70	1.02	0.35	8.6
Zsom et al. (2013)	0.38		6.92		26*
Pierrehumbert and Gaidos (2011)		10		0.01	~50†

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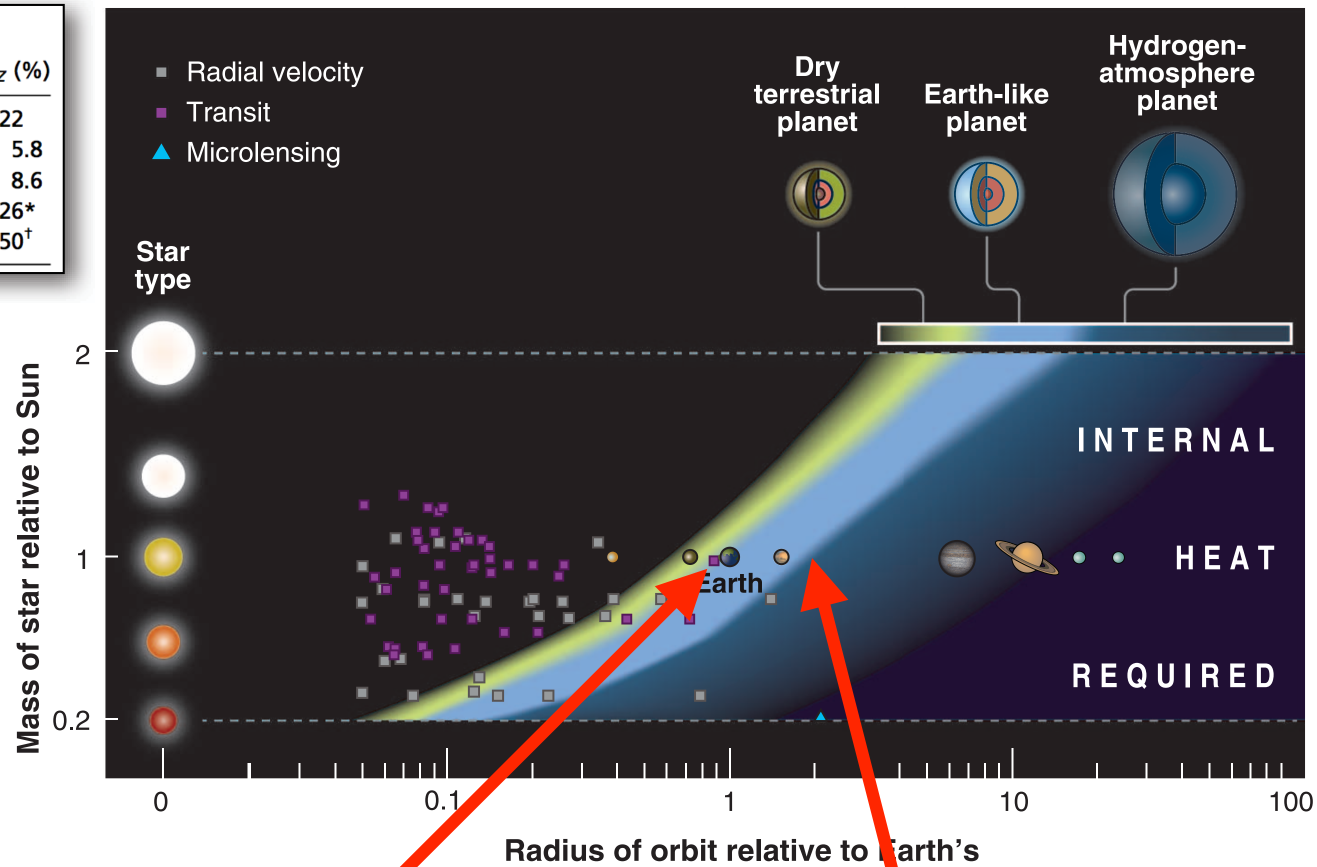

Inner Edge: water loss by photolysis

Outer Edge: maximum CO_2 greenhouse

Kasting et al. (1993)	**0.95-1.37 AU**
Kopparapu et al. (2013)	**0.99-1.70 AU**

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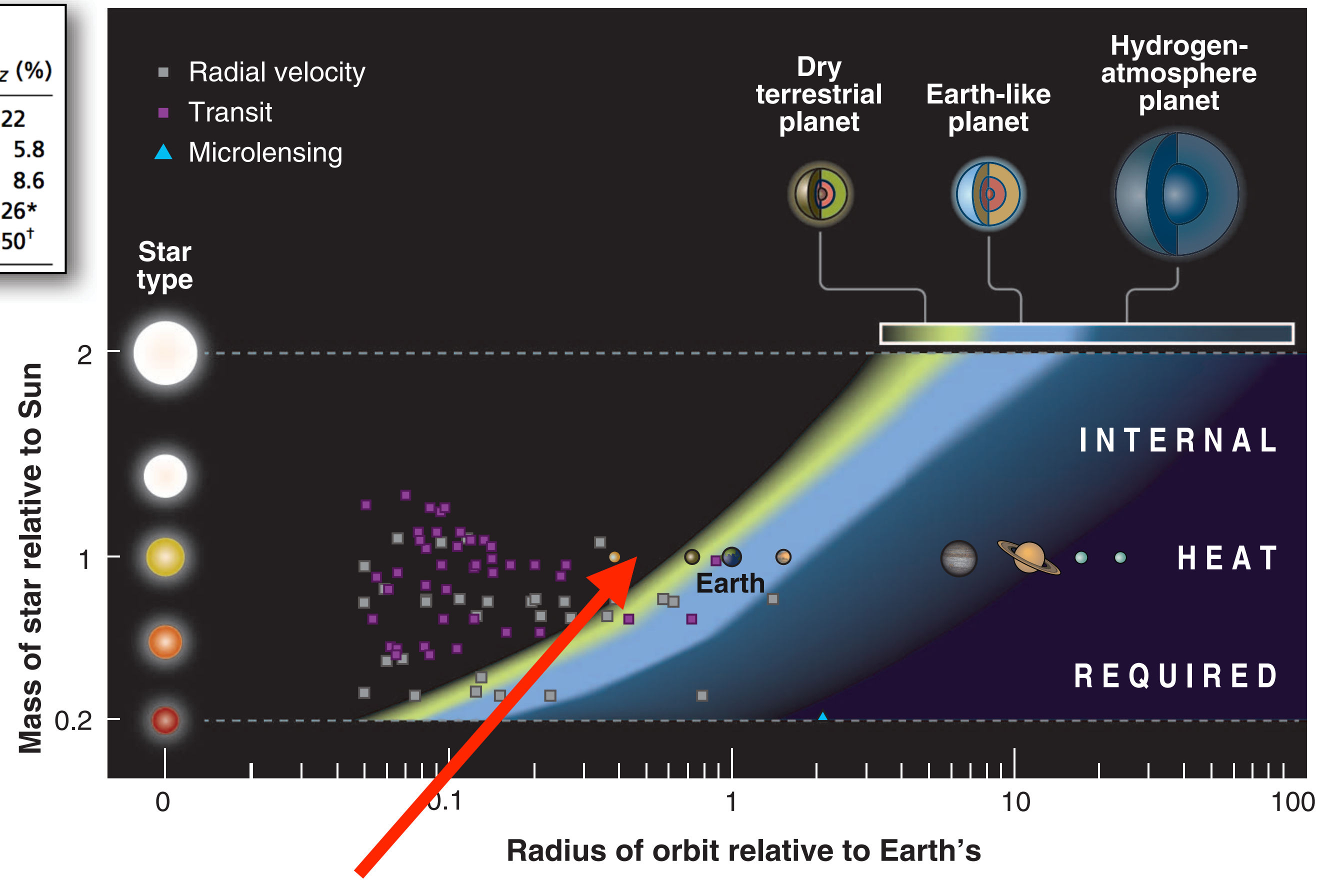

Inner Edge (0.38 AU):
reduced greenhouse (1% humidity)
increased albedo (reflectivity)

Zsom et al. (2013) 0.38 AU (inner edge)

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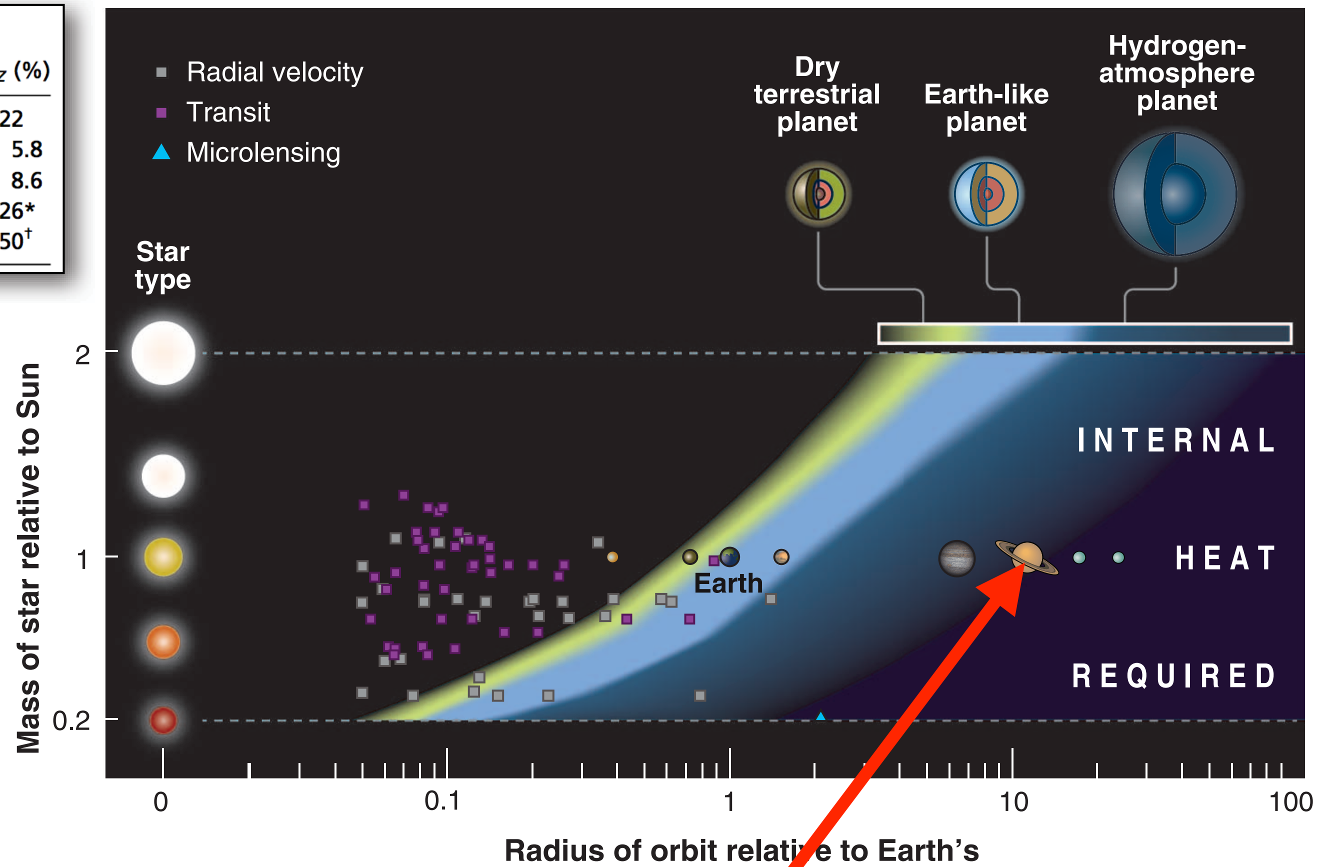


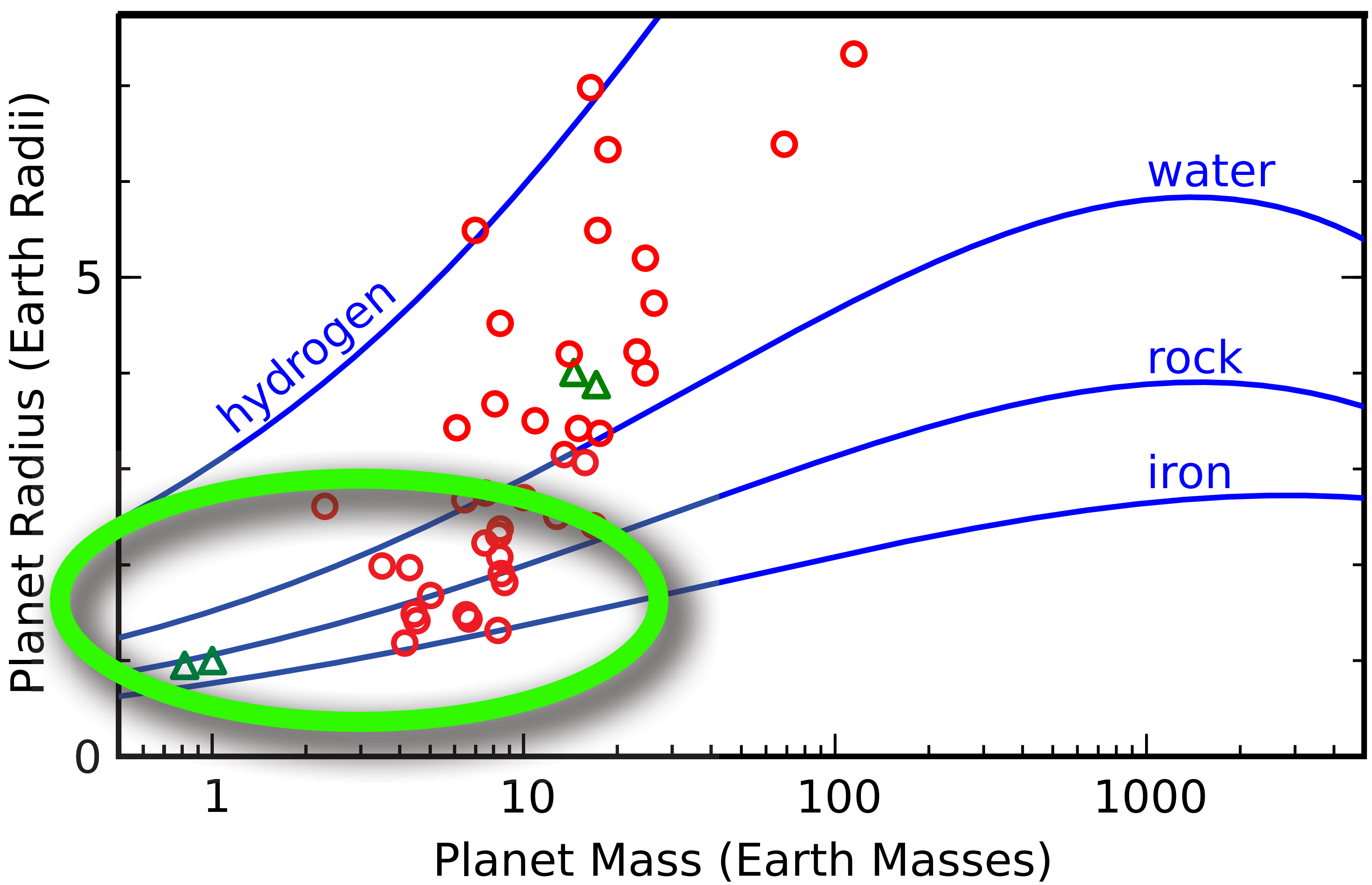
Outer Edge (0.38 AU):
heavy greenhouse from H_2
(collisionally-induced absorption)

Pierrehumbert & Gaidos (2011) ~10 AU (outer edge)

Uncertainties

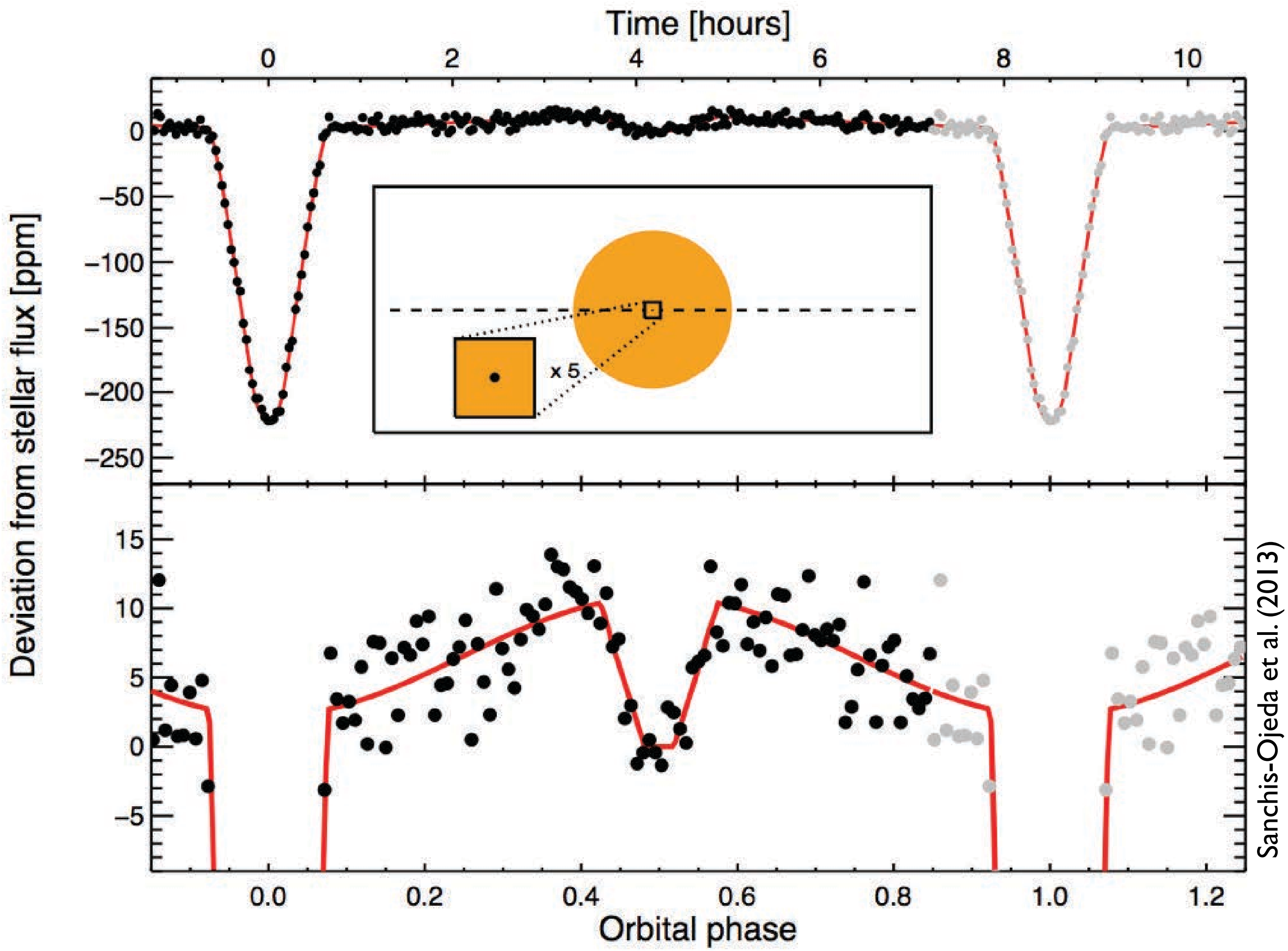
Mass-Radius Relationship

What is an Earth?
Where is the rocky/gas-rich transition?



Kepler-78b Transit Discovery

Sanchis-Ojeda et al. (2013)



Planet Radius:

$1.16^{+0.19}_{-0.14}\ R_{\oplus}$

Orbital Period:

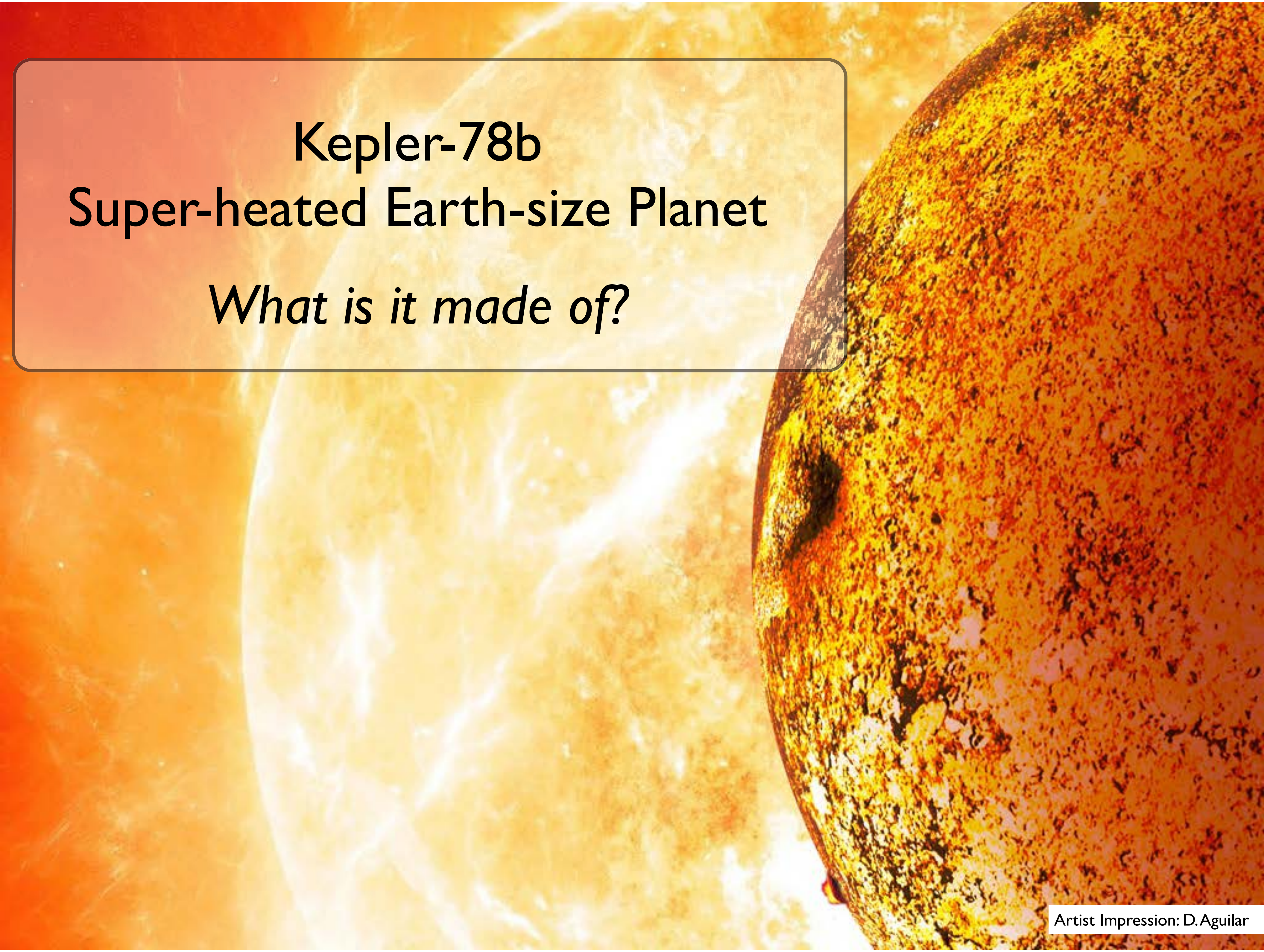
8.5 hours!

Roberto Sanchis-Ojeda

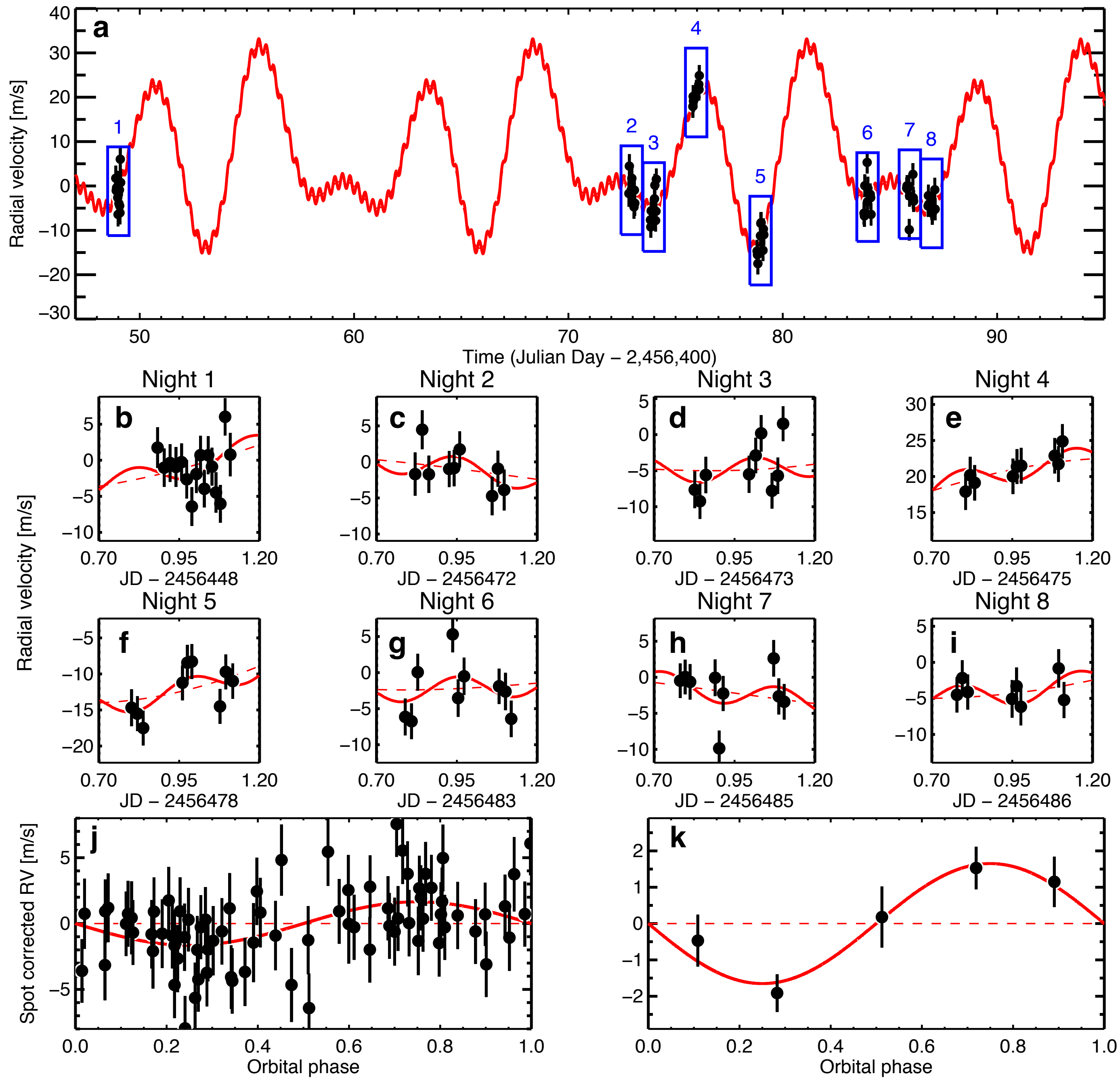
Kepler Photometry

Kepler-78b
Super-heated Earth-size Planet

What is it made of?



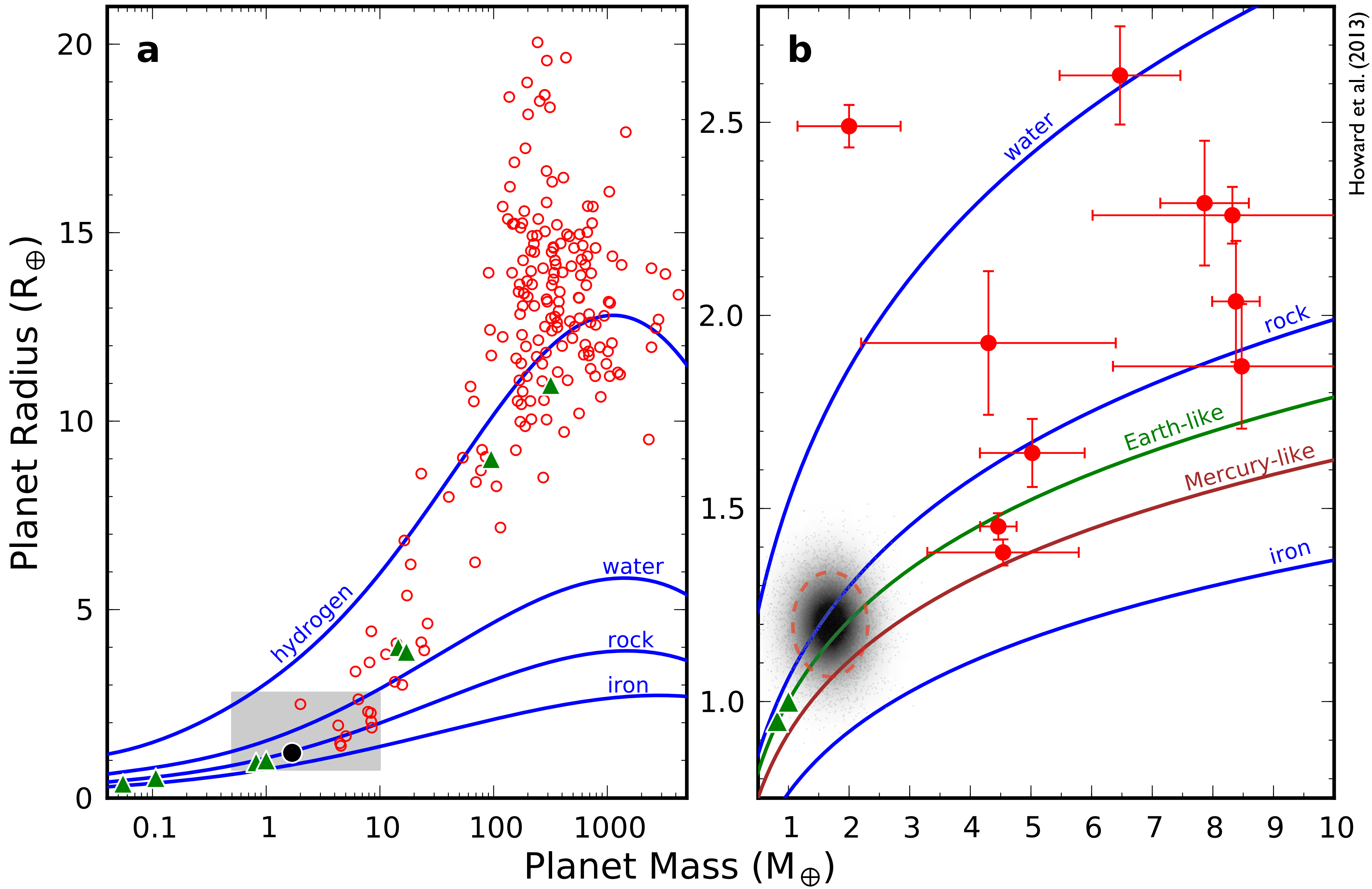
Kepler-78b - Keck-HIRES Doppler Measurements



1.66 ± 0.40 m/s
1.69 ± 0.41 $M_\oplus$

Howard et al. (2013)

Known Planets - Masses and Radii



LETTER

doi:10.1038/nature12767

A rocky composition for an Earth-sized exoplanet

Andrew W. Howard[1], Roberto Sanchis-Ojeda[2], Geoffrey W. Marcy[3], John Asher Johnson[4], Joshua N. Winn[2], Howard Isaacson[3], Debra A. Fischer[5], Benjamin J. Fulton[1], Evan Sinukoff[1] & Jonathan J. Fortney[6]

Planets with sizes between that of Earth (with radius $R_\oplus$) and Neptune (about $4R_\oplus$) are now known to be common around Sun-like stars[1–3]. Most such planets have been discovered through the transit technique, by which the planet's size can be determined from the fraction of starlight blocked by the planet as it passes in front of its star. Measuring the planet's mass—and hence its density, which is a clue to its composition—is more difficult. Planets of size $2–4R_\oplus$ have proved to have a wide range of densities, implying a diversity of compositions[4,5], but these measurements did not extend to planets as small as Earth. Here we report Doppler spectroscopic measurements of the mass of the Earth-sized planet Kepler-78b, which orbits its host star every 8.5 hours (ref. 6). Given a radius of $1.20 \pm 0.09R_\oplus$ and a mass of $1.69 \pm 0.41M_\oplus$, the planet's mean density of $5.3 \pm 1.8\,\mathrm{g\,cm^{-3}}$ is similar to Earth's, suggesting a composition of rock and iron.

$8M_\oplus$ could be ruled out because the planet's gravity would have deformed the star and produced brightness variations that were not detected.

We measured the mass of Kepler-78b by tracking the line-of-sight component of the host star's motion (the radial velocity) that is due to the gravitational force of the planet. The radial-velocity analysis is challenging not only because the signal is expected to be small (about $1–3\,\mathrm{m\,s^{-1}}$) but also because the apparent Doppler shifts due to rotating star spots are much larger (about $50\,\mathrm{m\,s^{-1}}$ peak-to-peak). Nevertheless the detection proved to be possible, thanks to the precisely known orbital period and phase of Kepler-78b that cleanly separated the timescale of spot variations ($P_{rot} \approx 12.5$ days) from the much shorter timescale of the planetary orbit ($P \approx 8.5$ hours). We adopted a strategy of intensive Doppler measurements spanning 6–8 hours per night, long enough to cover nearly the entire

Keck/HIRES (10-m)

LETTER

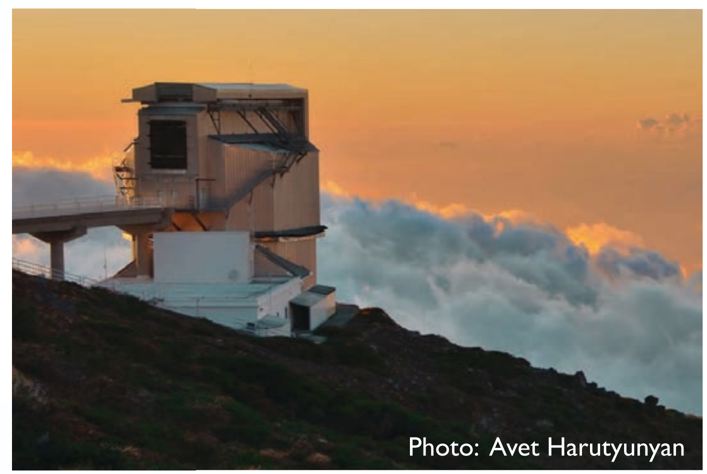
doi:10.1038/nature12768

An Earth-sized planet with an Earth-like density

Francesco Pepe[1], Andrew Collier Cameron[2], David W. Latham[3], Emilio Molinari[4,5], Stéphane Udry[1], Aldo S. Bonomo[6], Lars A. Buchhave[3,7], David Charbonneau[3], Rosario Cosentino[4,8], Courtney D. Dressing[3], Xavier Dumusque[3], Pedro Figueira[9], Aldo F. M. Fiorenzano[4], Sara Gettel[3], Avet Harutyunyan[4], Raphaëlle D. Haywood[2], Keith Horne[2], Mercedes Lopez-Morales[3], Christophe Lovis[1], Luca Malavolta[10,11], Michel Mayor[1], Giusi Micela[12], Fatemeh Motalebi[1], Valerio Nascimbeni[11], David Phillips[3], Giampaolo Piotto[10,11], Don Pollacco[13], Didier Queloz[1,14], Ken Rice[15], Dimitar Sasselov[3], Damien Ségransan[1], Alessandro Sozzetti[6], Andrew Szentgyorgyi[3] & Christopher A. Watson[16]

Recent analyses[1–4] of data from the NASA Kepler spacecraft[5] have established that planets with radii within 25 per cent of the Earth's ($R_\oplus$) are commonplace throughout the Galaxy, orbiting at least 16.5 per cent of Sun-like stars[1]. Because these studies were sensitive to the sizes of the planets but not their masses, the question remains whether these Earth-sized planets are indeed similar to the Earth in

observing campaign (Methods) of Kepler-78 ($m_v = 11.72$) in May 2013, acquiring HARPS-N spectra of 30-min exposure time and an average signal-to-noise ratio of 45 per extracted pixel at 550 nm (wavelength bin of 0.00145 nm). From these high-quality spectra, we estimated[12,13] the stellar parameters of Kepler-78 (Methods and Extended Data Table 1). Our estimate of the stellar radius, $R_* = 0.737^{+0.034}_{-0.042}R_\odot$, is



TNG/HARPS-N (3.6-m)

Known Planets - Masses and Radii

HIRES (Howard et al. 2013)

Radius: 1.20 ± 0.09 $R_\oplus$

Mass: 1.69 ± 0.41 $M_\oplus$

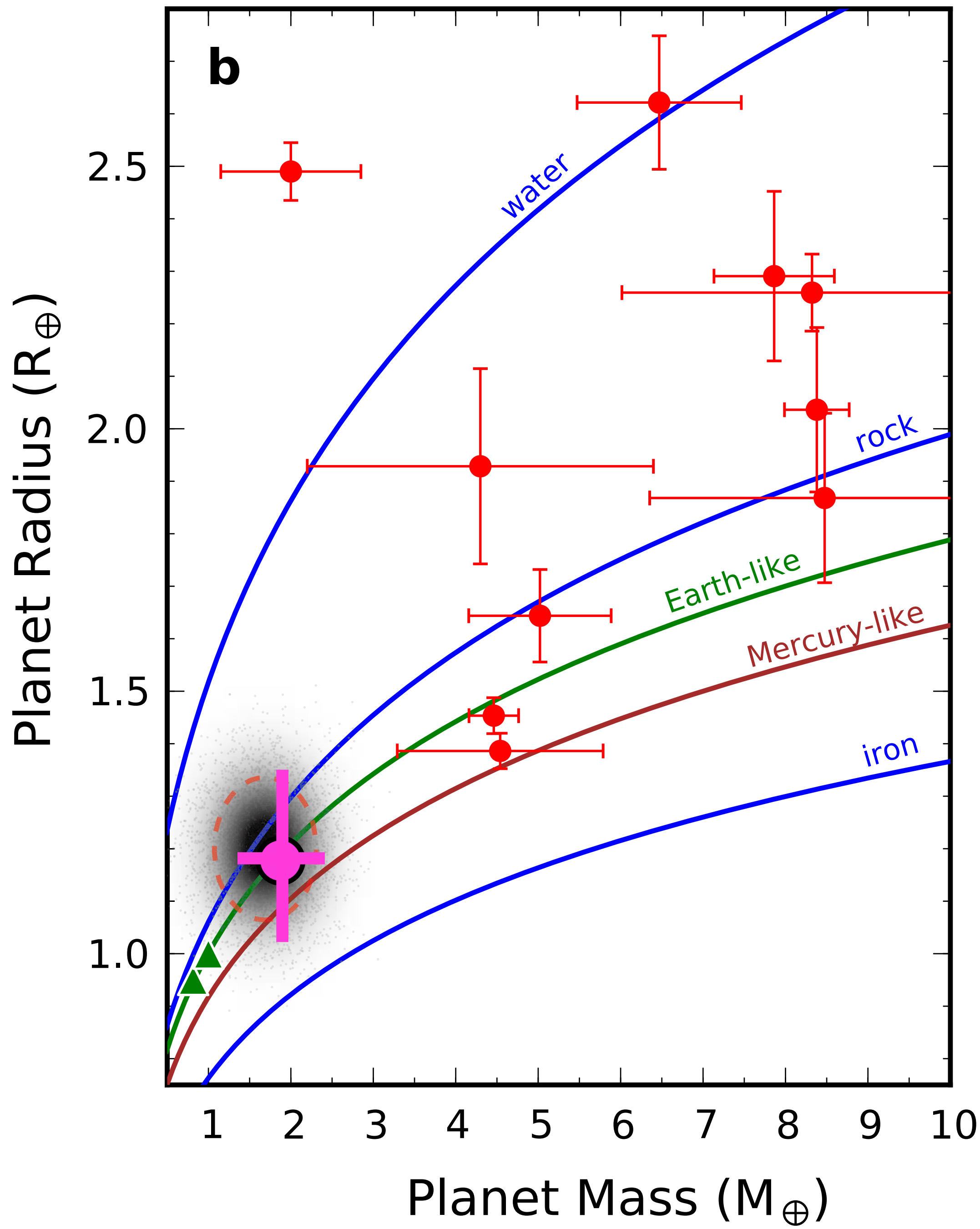
Density: $5.3^{+2.0}_{-1.6}\ \mathrm{g\,cm^{-3}}$

Iron fraction: 0.20 ± 0.33

HARPS-N (Pepe et al. 2013)

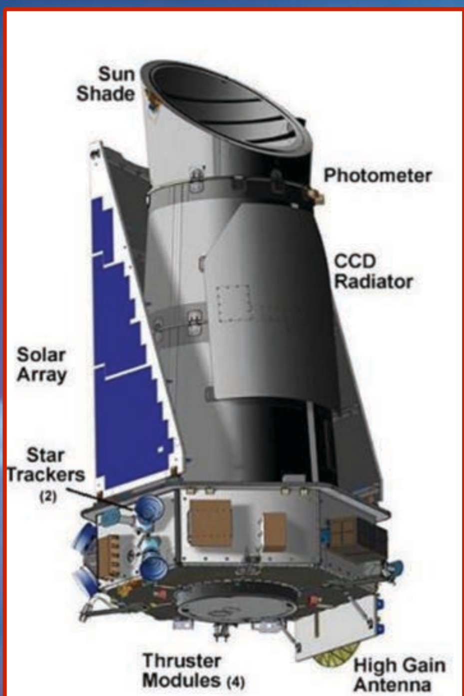
Mass: $1.86^{+0.38}_{-0.25}\ M_\oplus$

Density: $5.6^{+3.0}_{-1.3}\ \mathrm{g\,cm^{-3}}$

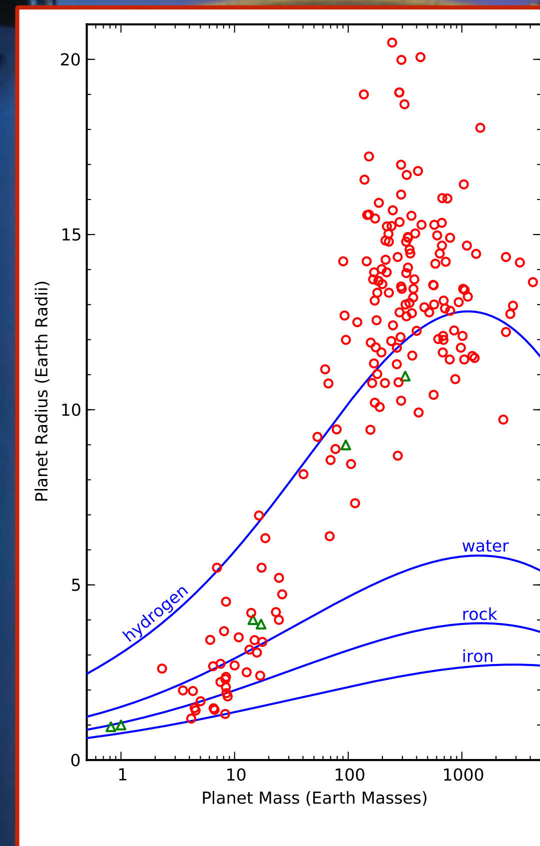


Masses and Radii of 52 Small Planets
Kepler + Keck Observatory

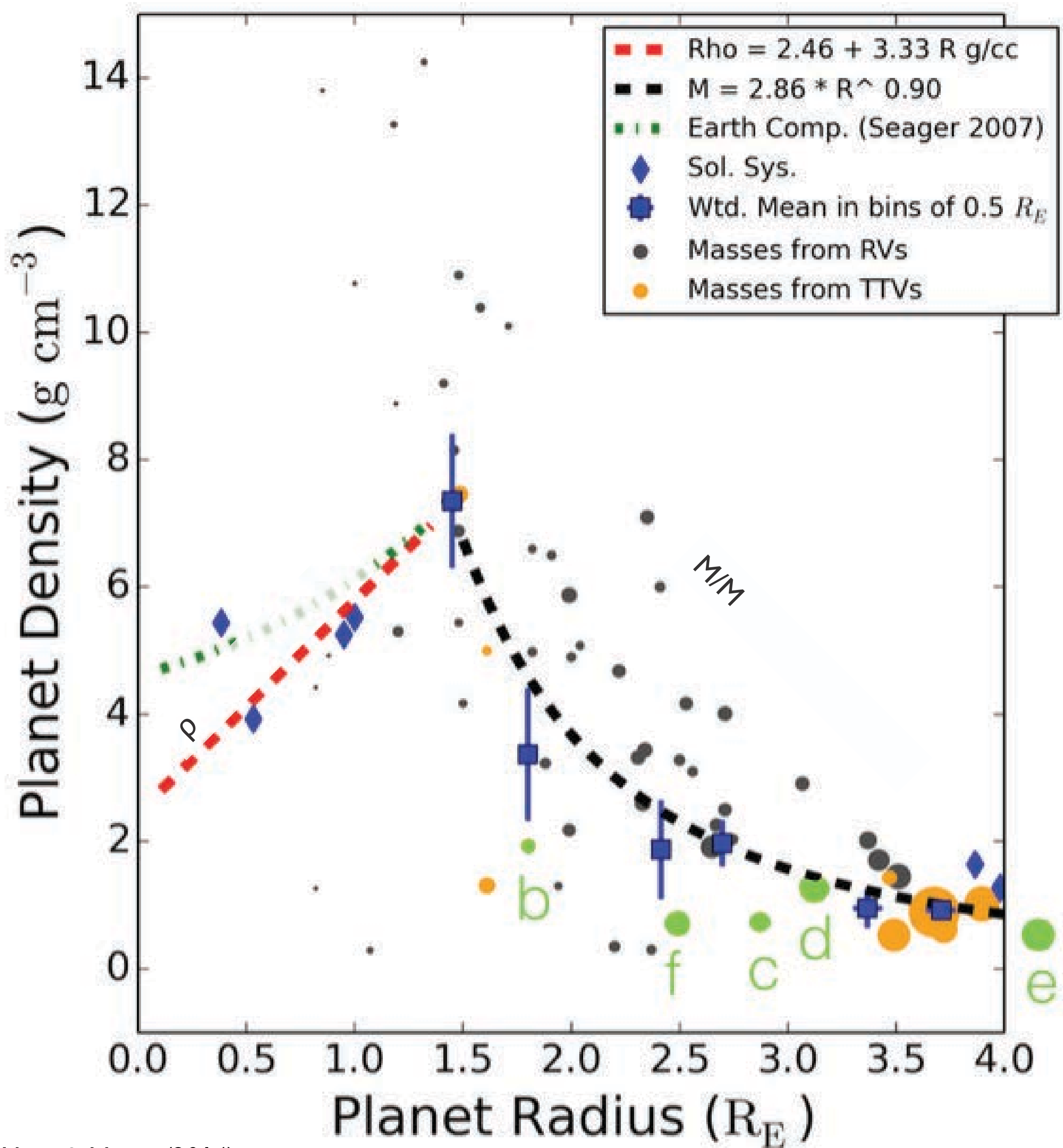
Marcy, Isaacson, Howard et al. (2014)



+



Rock → Gas Transition

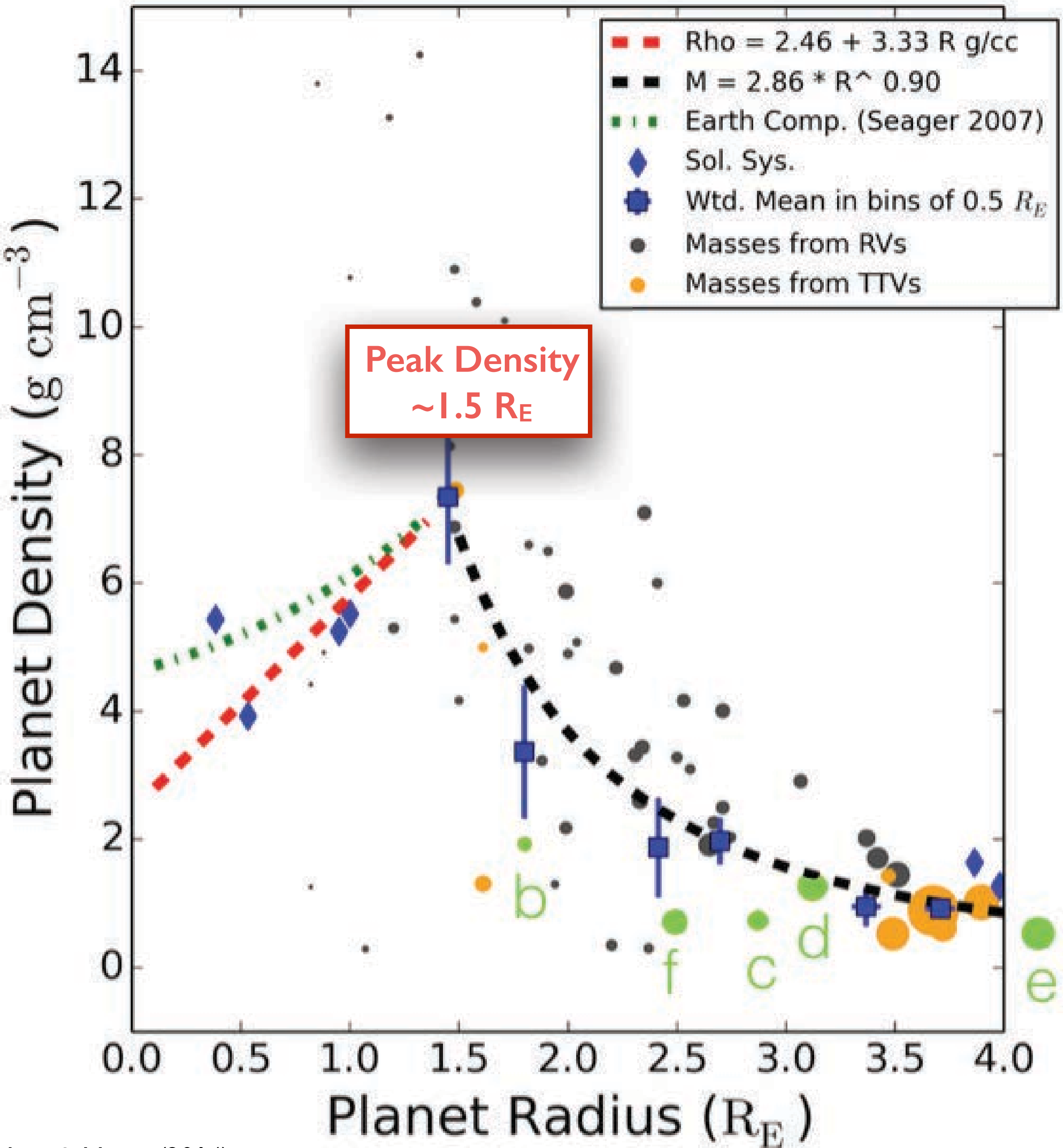


Weiss & Marcy (2014)
see also: Rogers (2015)
Dressing et al. (2015)

Lauren Weiss (Berkeley)

Weiss & Marcy (2014)

Rock → Gas Transition

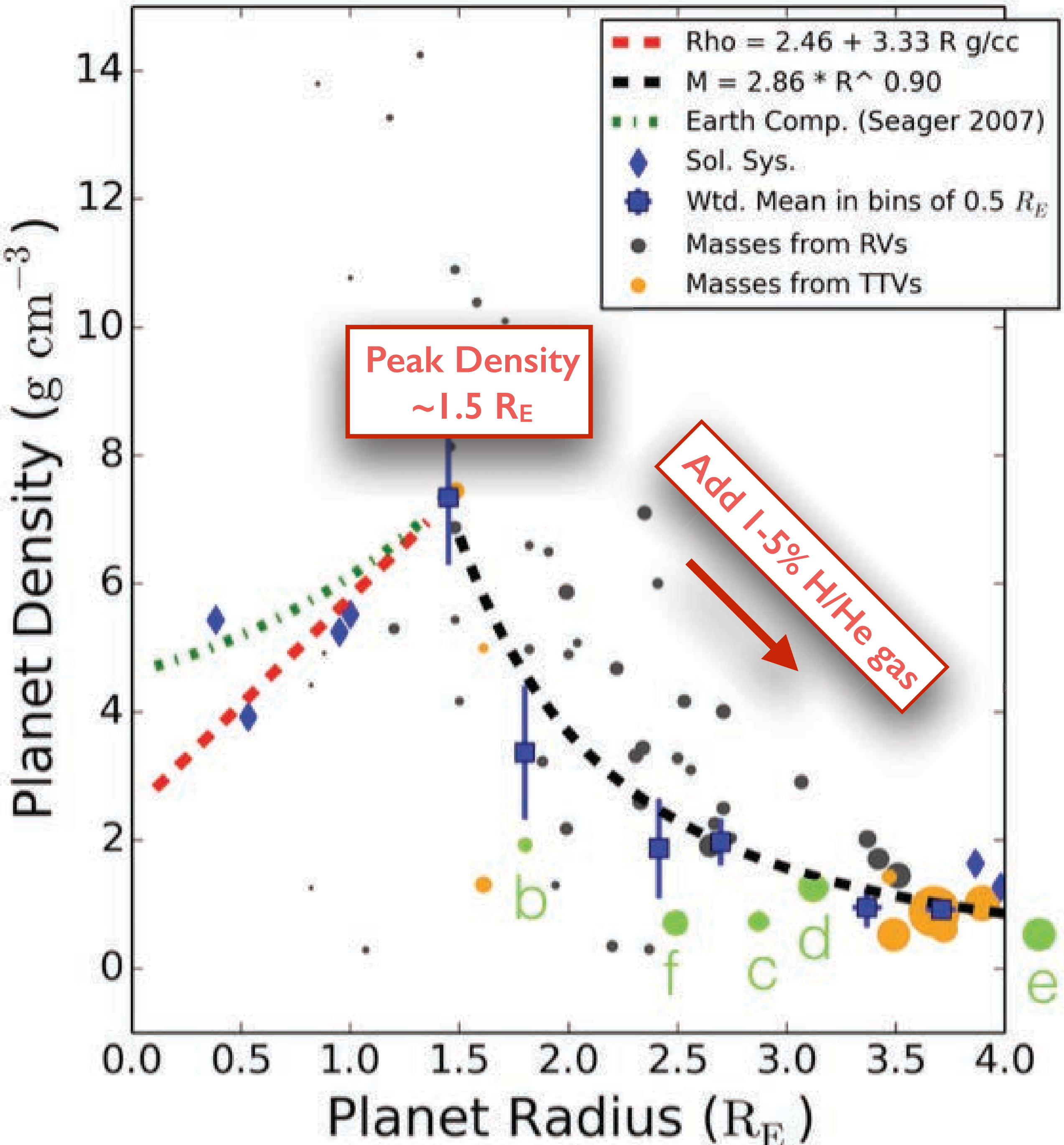


Weiss & Marcy (2014)

1. Peak Density ~1.5 R_E

Lauren Weiss (Berkeley)

Rock → Gas Transition

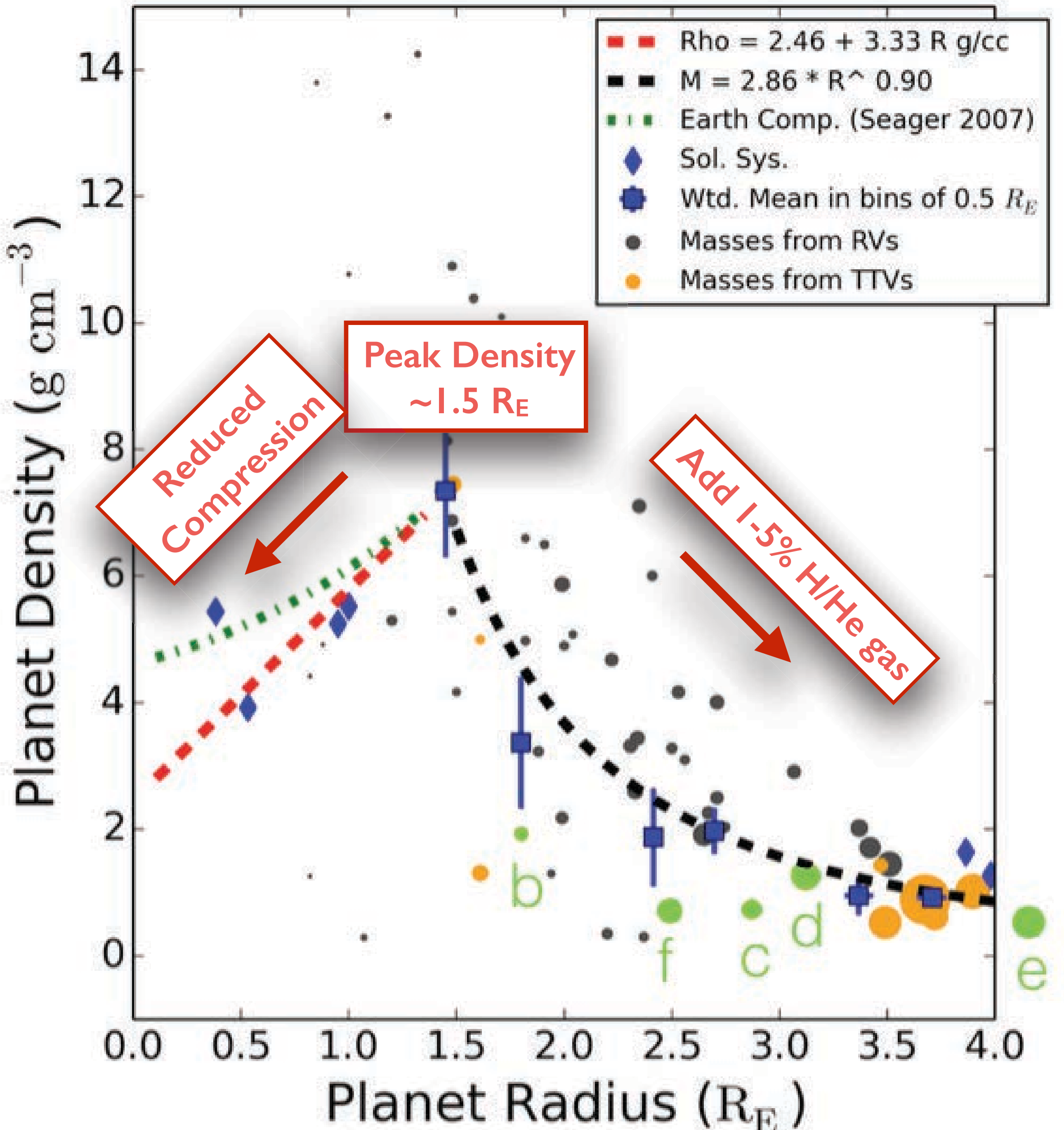


Weiss & Marcy (2014)

1. Peak density ~1.5 R_E
2. ≳1.5 R_E → smaller density
   add 1-5% H/He gas
   density → 1 g cm^{-3}

Lauren Weiss (Berkeley)

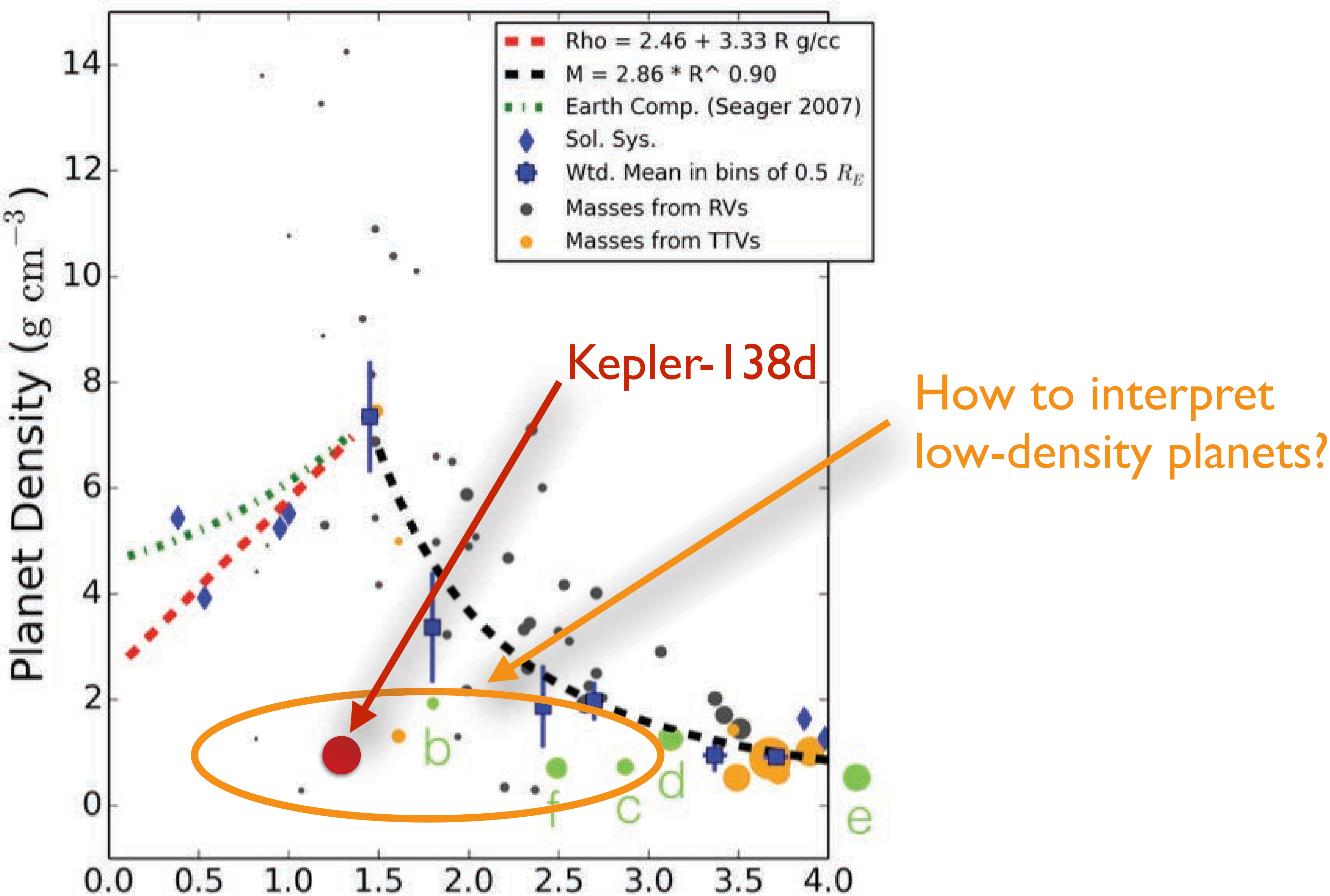
Rock → Gas Transition



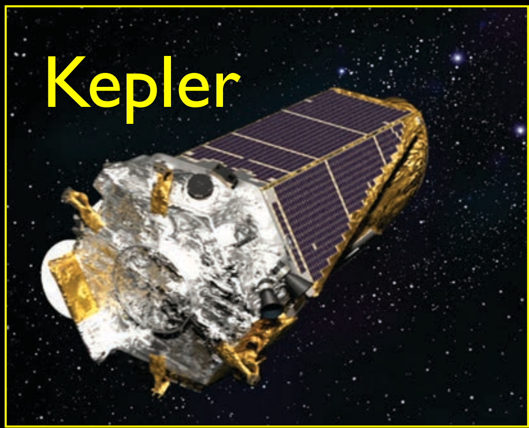
Weiss & Marcy (2014)

1. Peak density ~1.5 R_E
2. $\gtrsim$1.5 R_E → smaller density
   add 1-5% H/He gas
   density → 1 g cm^{-3}
3. $\lesssim$1.5 R_E → smaller density
   same rocky composition
   with reduced compression?

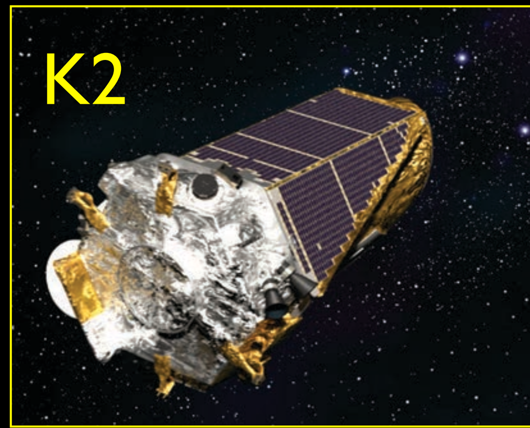
Lauren Weiss (Berkeley)



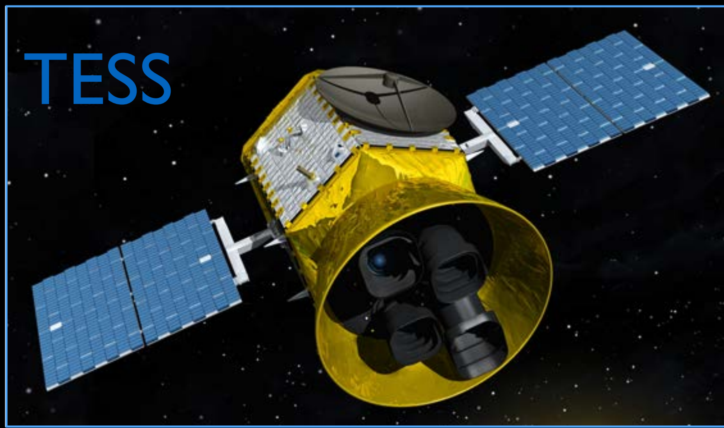
Weiss & Marcy (2014)



2009-2013

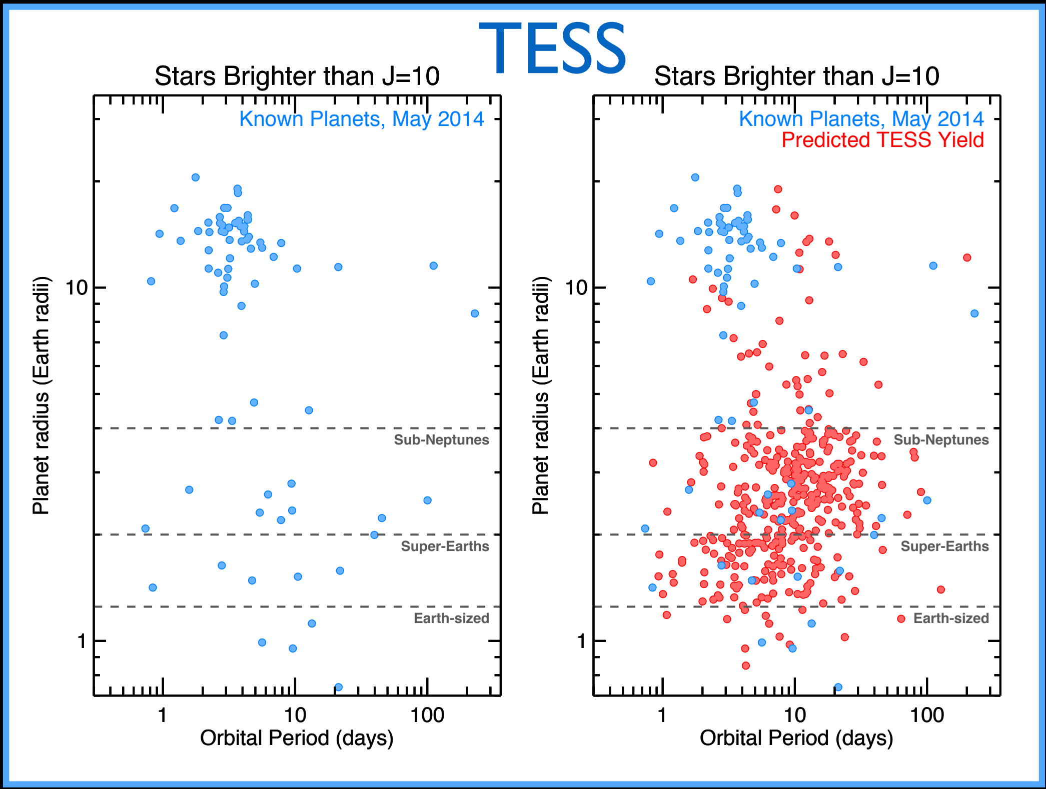


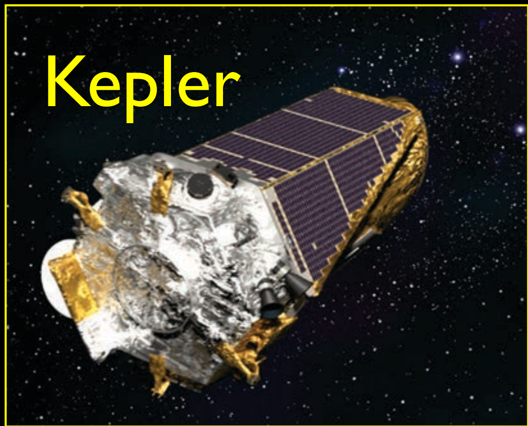
2014-2017?



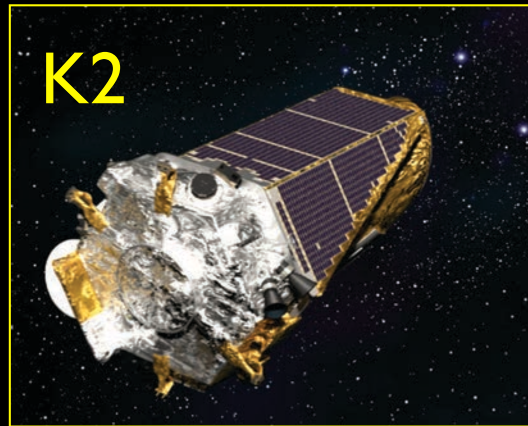
2017+

Photo: Ethan Tweedie

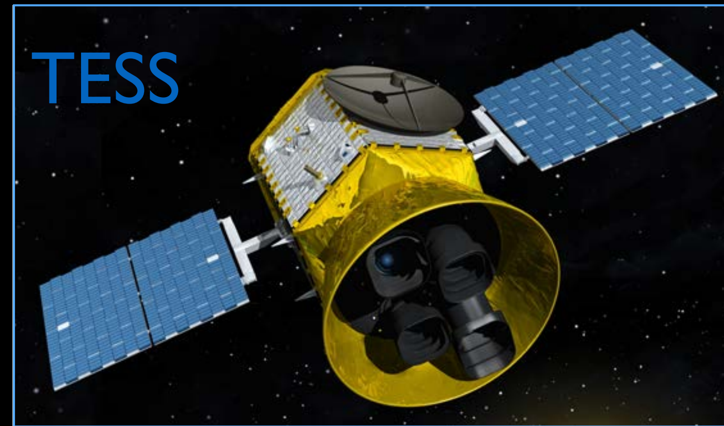




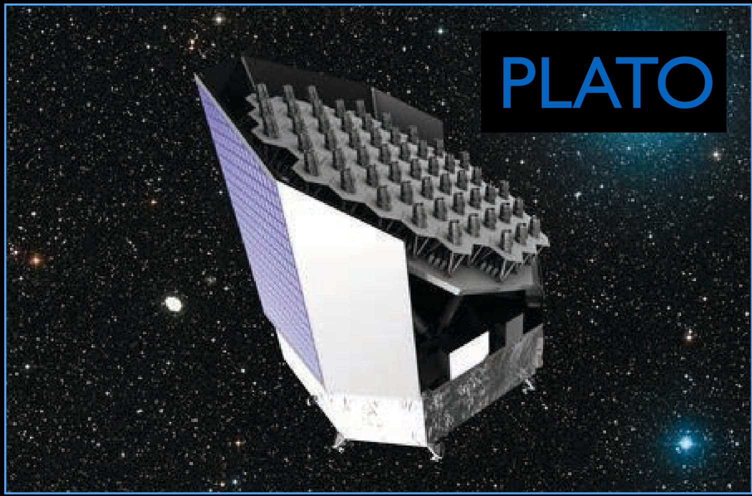
2009-2013



2014-2017?

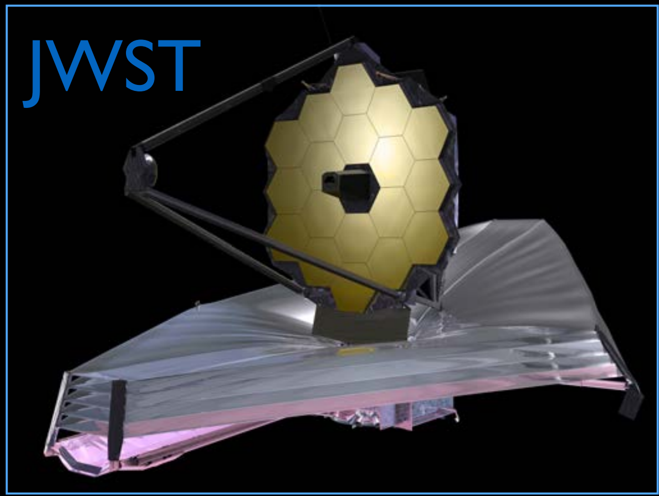


2017+



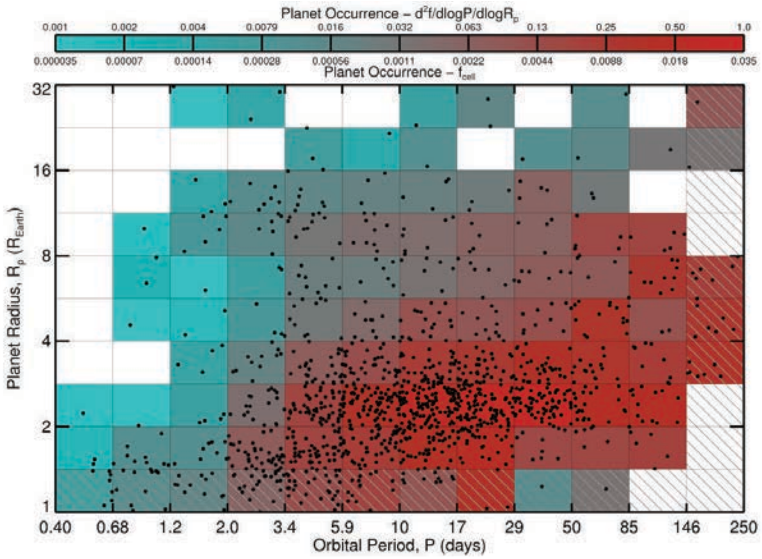
2024+

2017-2020

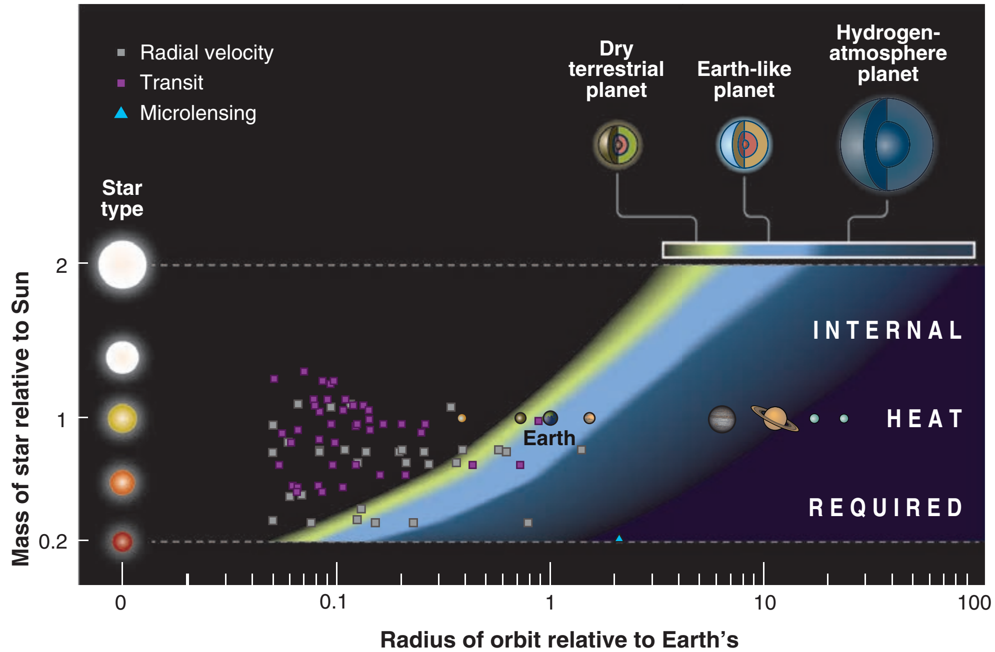


2018+

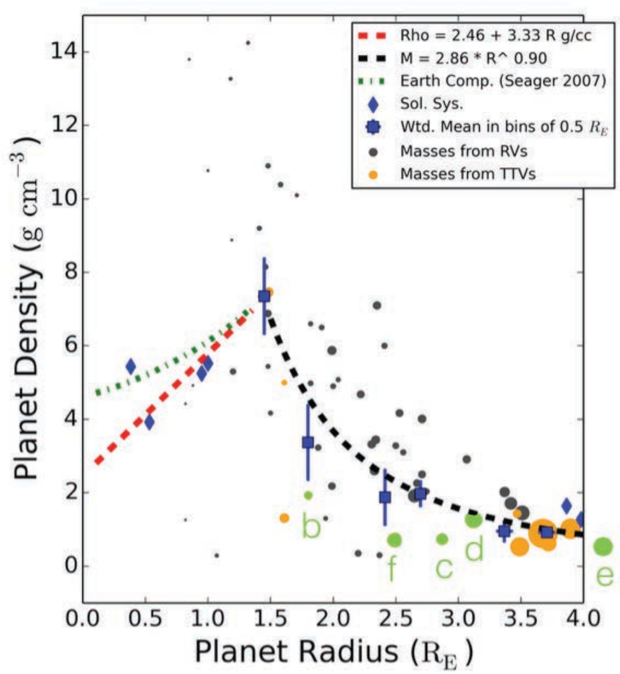
Questions?



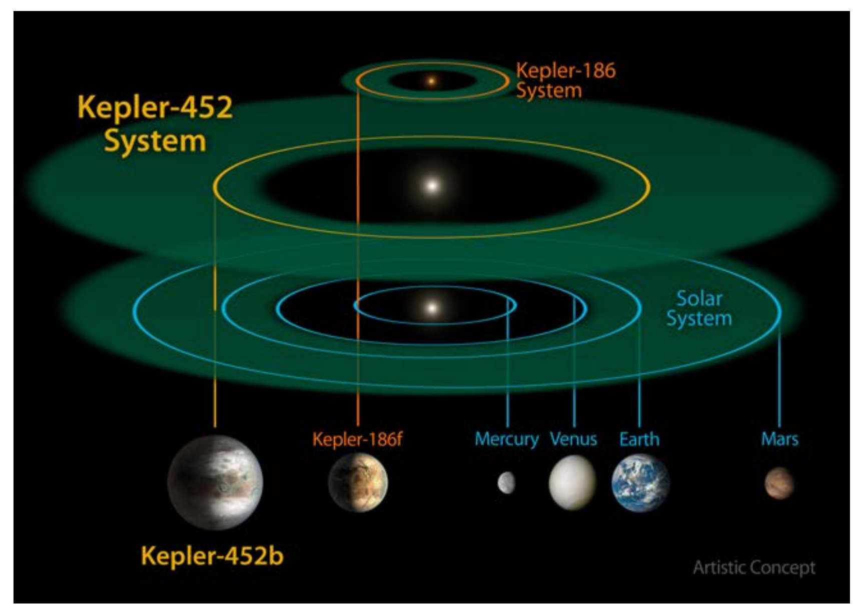
Planet Occurrence – d²f/dlogP/dlogR_p
Planet Occurrence – f_cell
Planet Radius, R_p (R_Earth)
Orbital Period, P (days)
0.40 0.68 1.2 2.0 3.4 5.9 10 17 29 50 85 146 250
1 2 4 8 16 32



Radial velocity
Transit
Microlensing
Dry terrestrial planet
Earth-like planet
Hydrogen-atmosphere planet
Star type
Mass of star relative to Sun
2
1
0.2
Earth
INTERNAL
HEAT
REQUIRED
0 0.1 1 10 100
Radius of orbit relative to Earth's



Rho = 2.46 + 3.33 R g/cc
M = 2.86 * R^ 0.90
Earth Comp. (Seager 2007)
Sol. Sys.
Wtd. Mean in bins of 0.5 R_E
Masses from RVs
Masses from TTVs
Planet Density (g cm⁻³)
0 2 4 6 8 10 12 14
Planet Radius (R_E)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
b
f
c
d
e



Kepler-186 System
Kepler-452 System
Solar System
Kepler-186f
Mercury
Venus
Earth
Mars
Kepler-452b
Artistic Concept