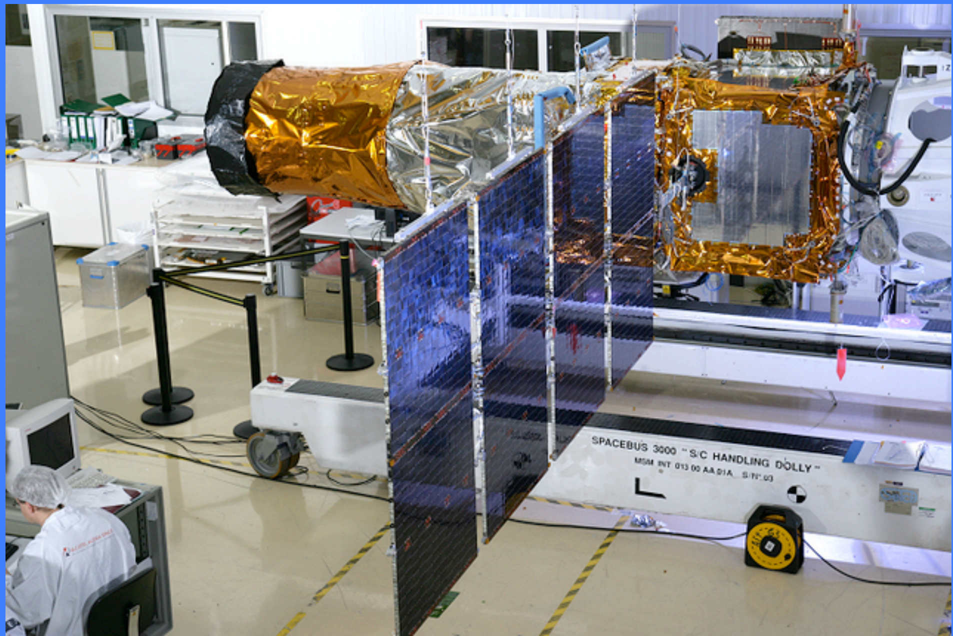
The Golden Age of Transiting Exoplanets

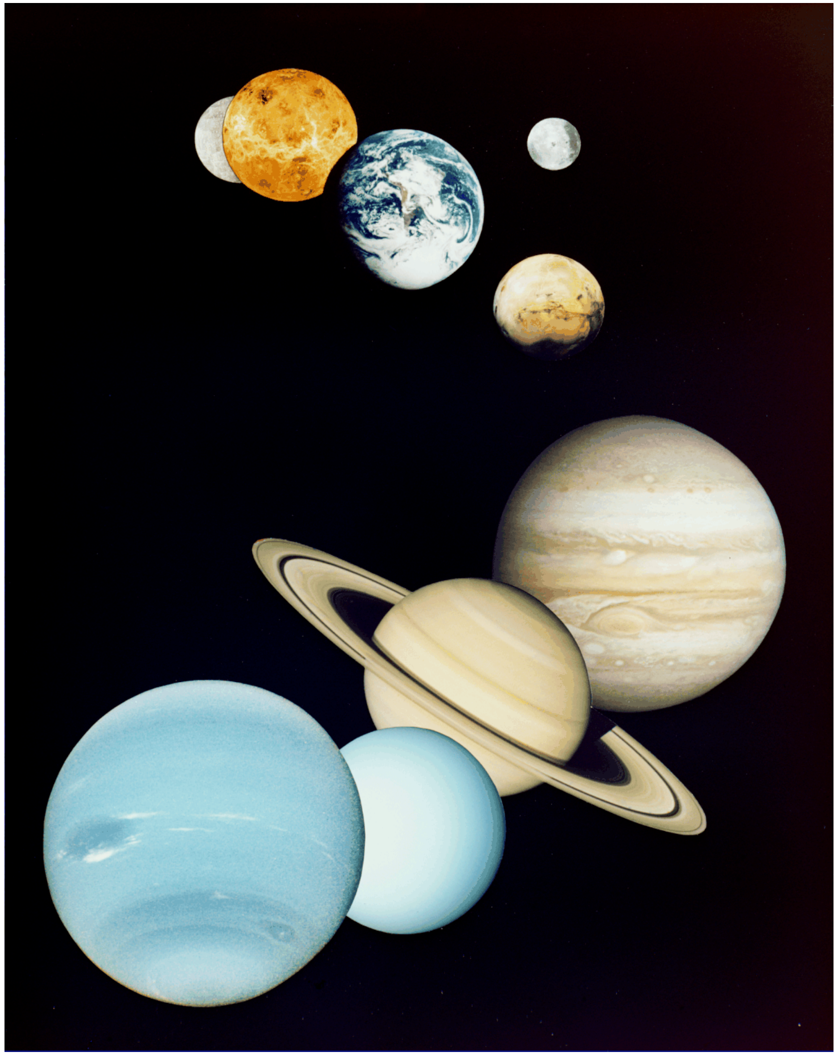


The Legacy of the CoRoT and Kepler Space Missions

Artie P. Hatzes

Thüringer Landessternwarte Tautenburg

Why search for Exoplanets?

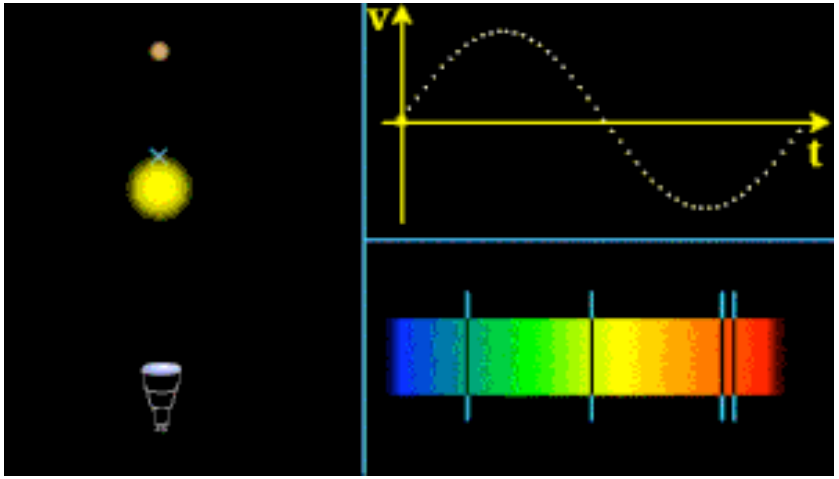


To answer these questions

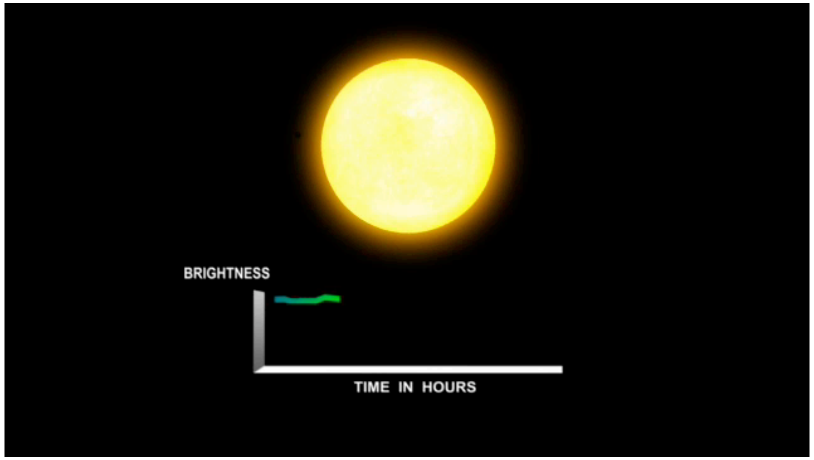
- How do planets form?
- How frequent is the process?
- How unique is our Solar System?
- What are the conditions for life?
- Is there other intelligent life in our Galaxy?

The so far most successful methods:

Radial velocity method



Transit method



→ Orbit Parameters

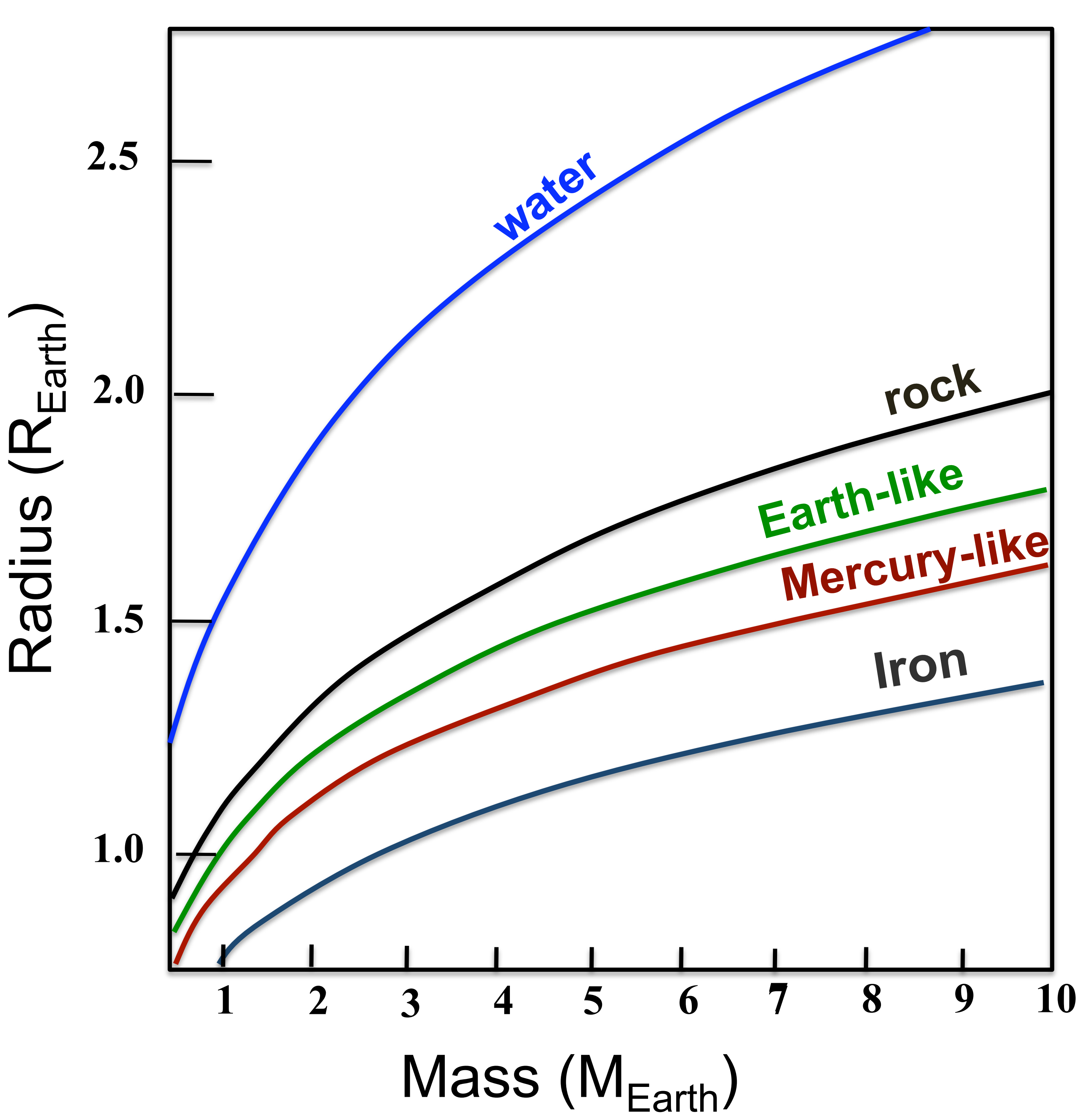
→ lower limit of planet mass (m *sin* i)

→ Orbit Parameters

→ Inclination i

→ Planet radius

True mass and mean density

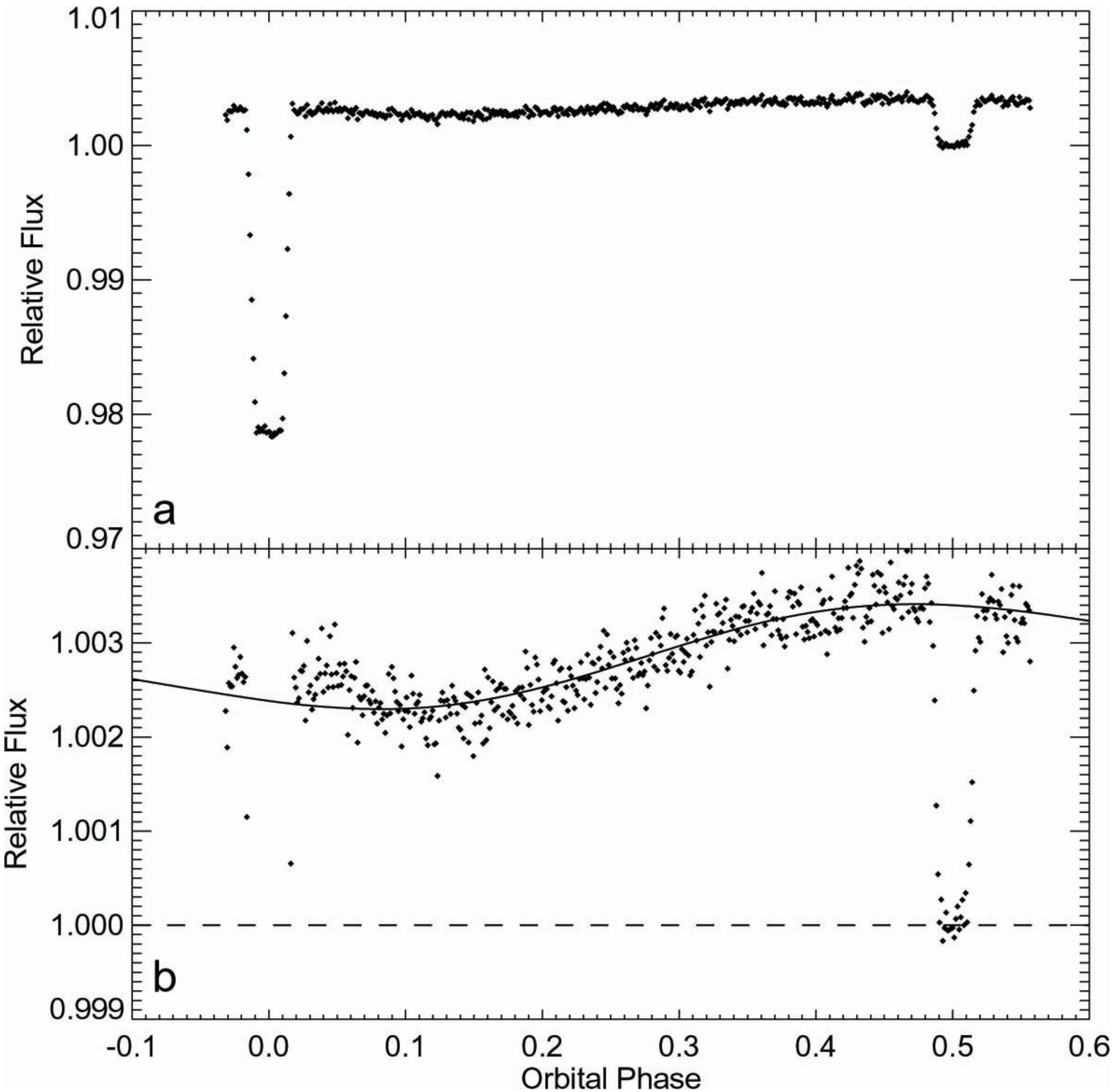


Radius (R_{Earth})
2.5
2.0
1.5
1.0
water
rock
Earth-like
Mercury-like
Iron
1
2
3
4
5
6
7
8
9
10
Mass (M_{Earth})

Planet Phases and Secondary Eclipse

Spitzer Measurements of Radiated Light at 8 μm of HD 189733

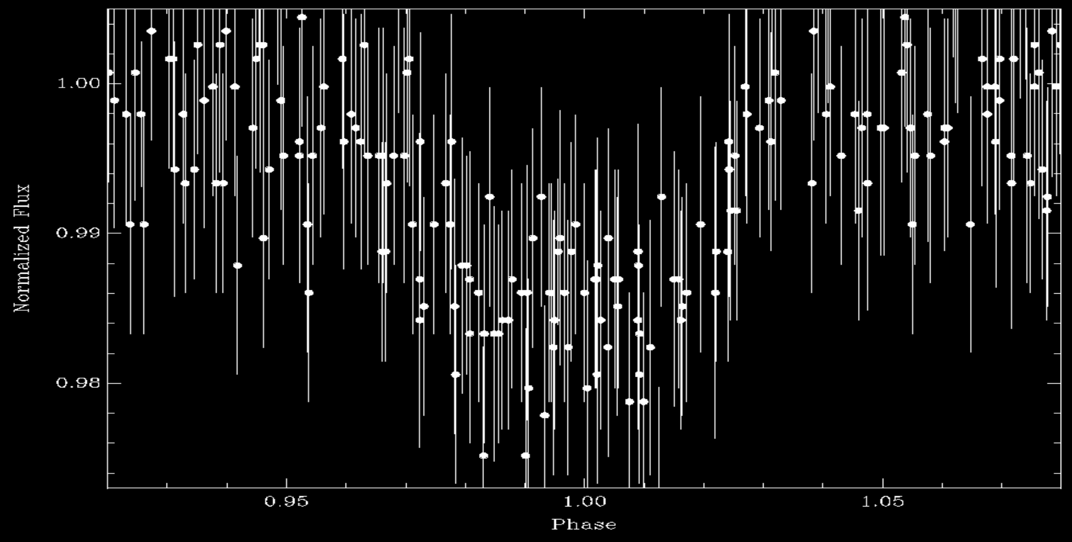
Knutson et al. 2007



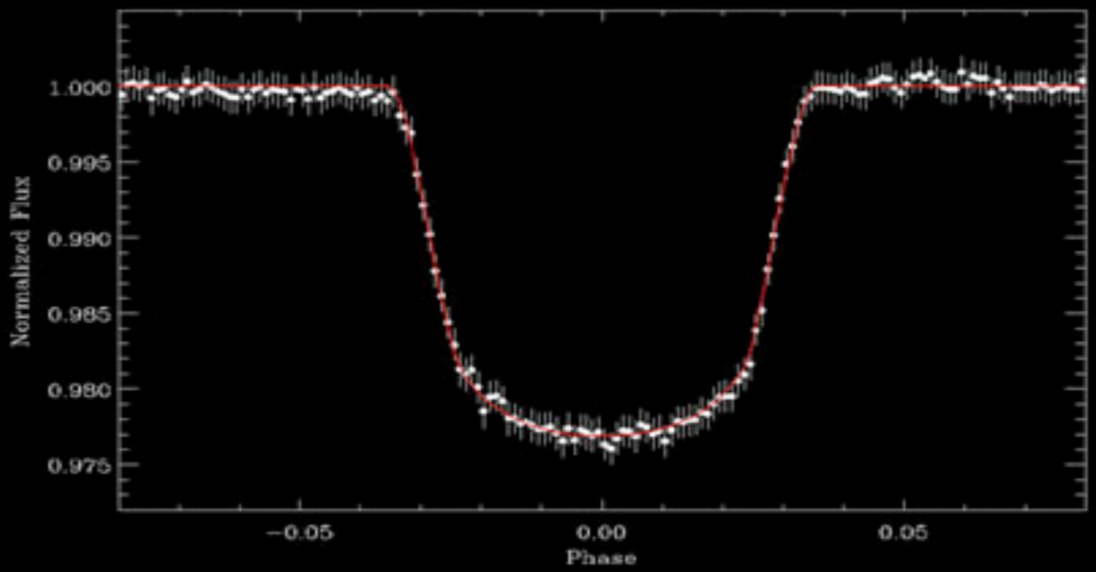
$T_{max} = 1211$ K

$T_{min} = 973$ K

Why observe from space (1)?

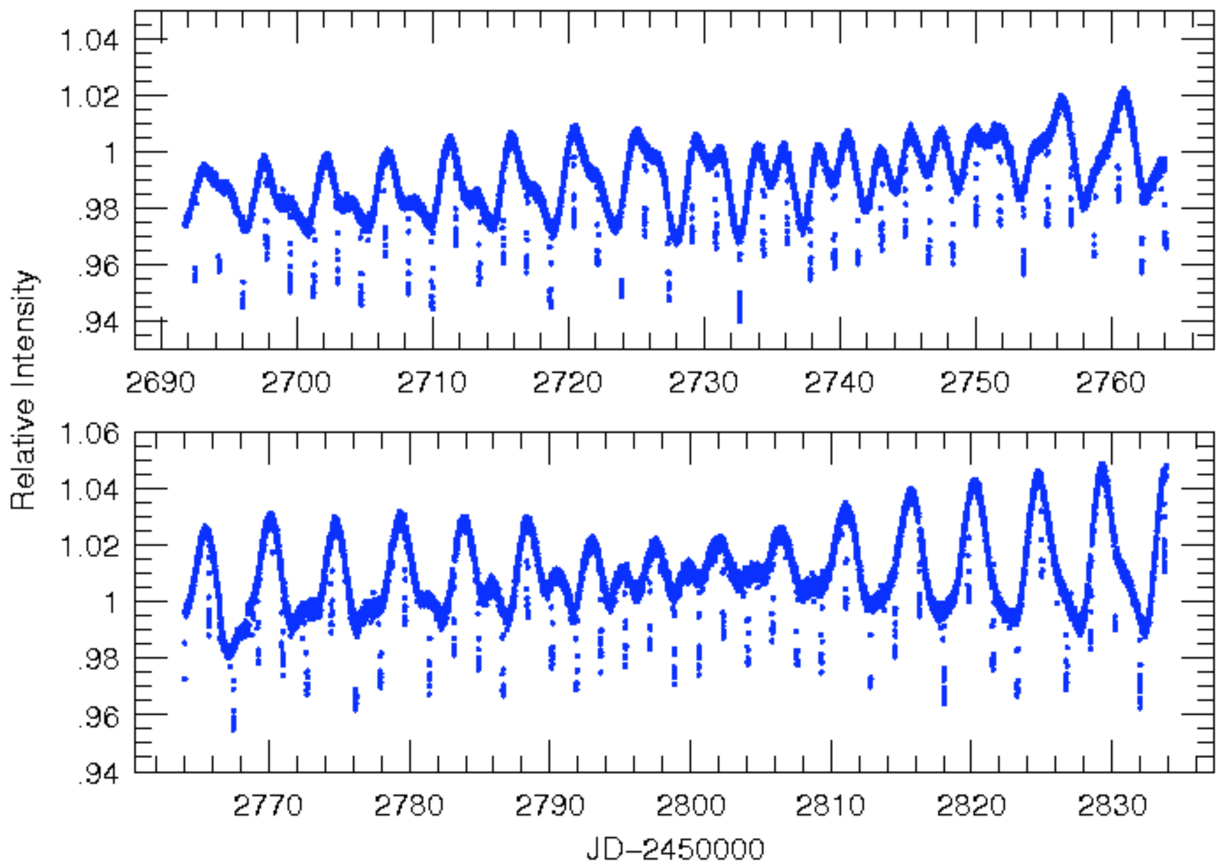


An OGLE transit discovery (ground-based)

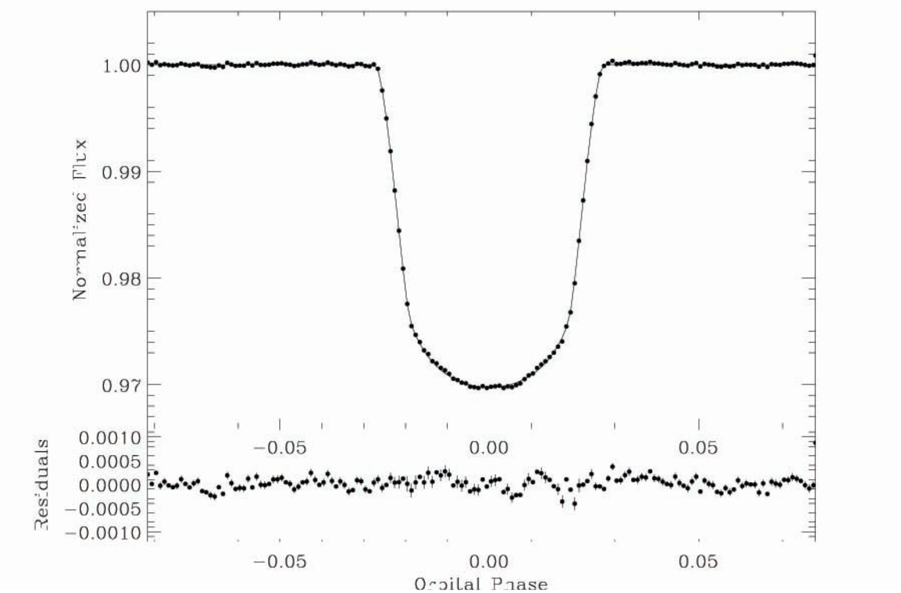


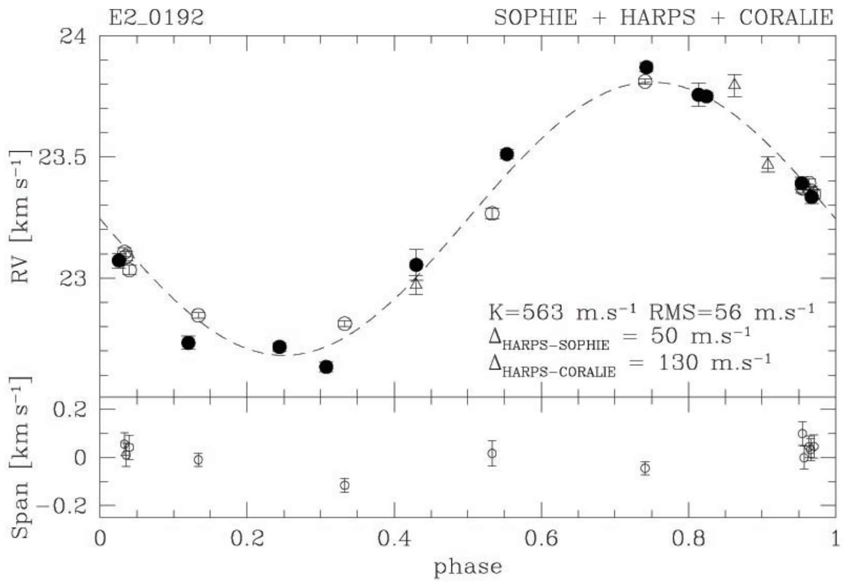
A CoRoT transit discovery

Why observe from space (2)?
CoRoT-2b



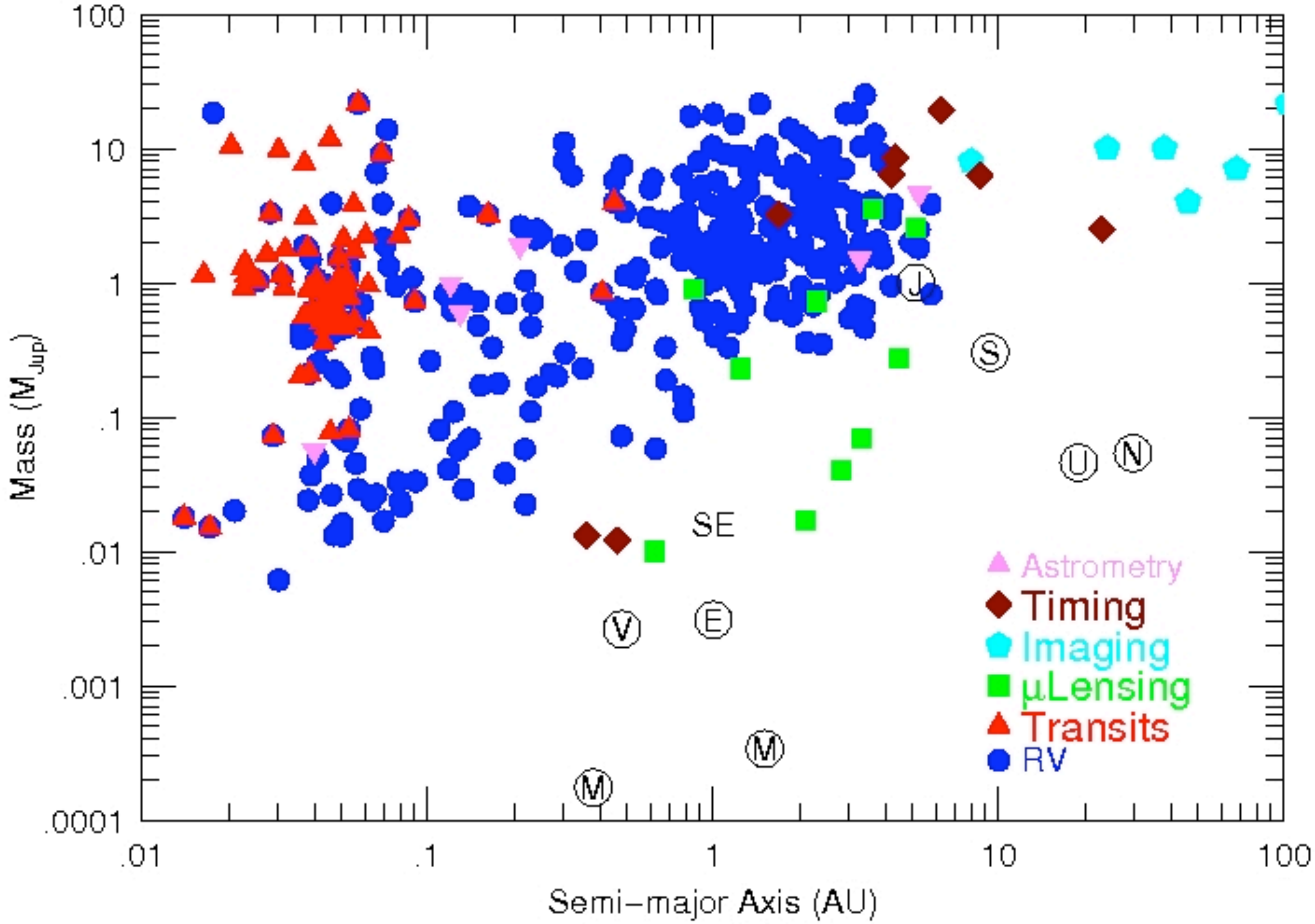
In spite of activity noise one can get a beautiful transit and RV curve:





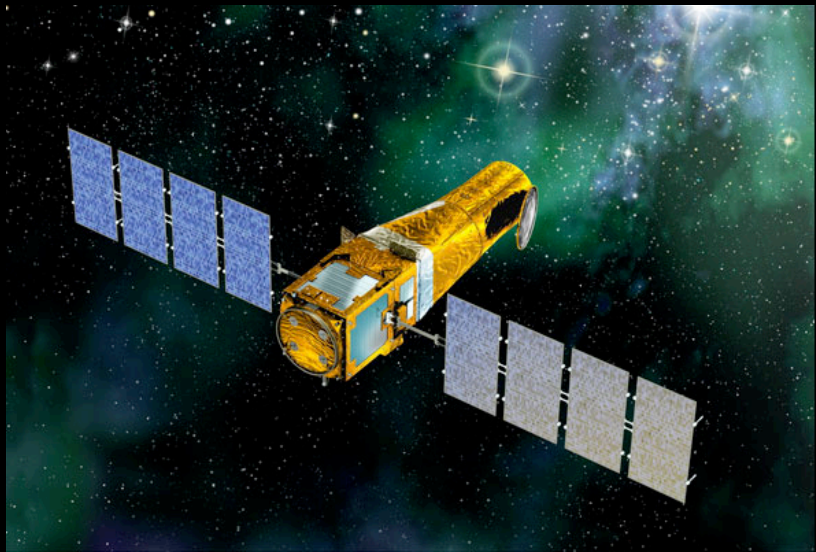
- Period = 1.7 d
- Radius = 1.46 $R_{Jupiter}$
- Mass = 3.3 $M_{Jupiter}$
- Density = 1.3 gm cm^{-3}

The Exoplanet Discovery Space



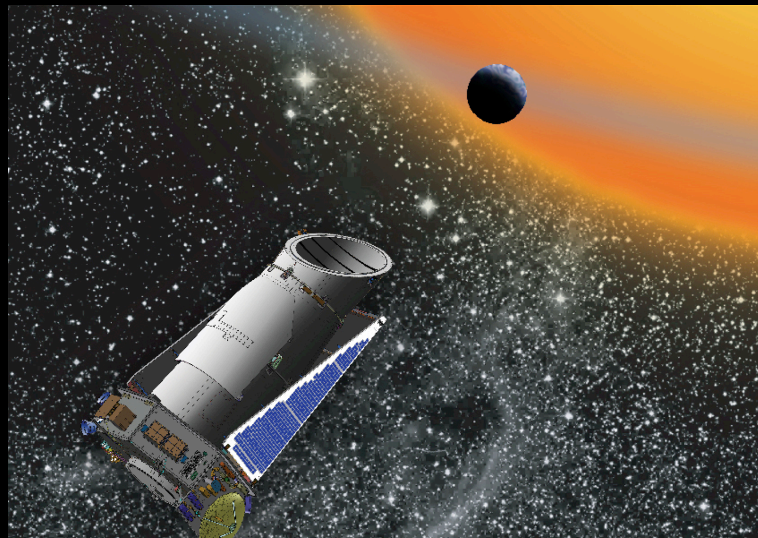
A Tale of Two Transit Space Telescopes: The Golden Era of Transit Searches

The CoRoT Mission (CNES)
Convection Rotation
and Planetary Transits



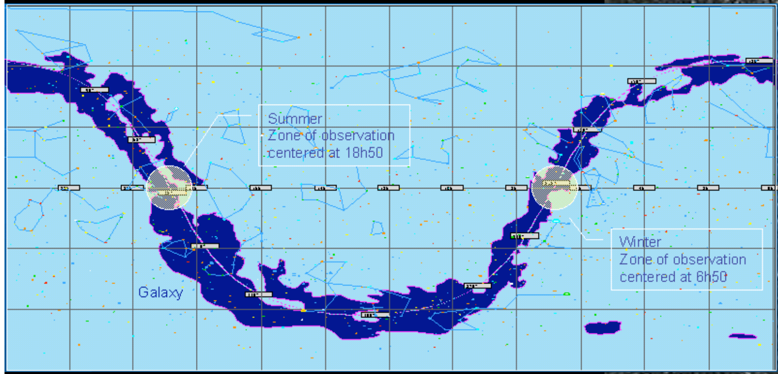
- Goals: exoplanets + astroseismology
- Polar Earth Orbit
- 27 cm Schmidt Telescope
- 4 CCD detectors
- 2.8° x 2.8° field-of-view
- Max. 150 days observing 12000 stars
- Duration 6 years
- Launched: 27th December 2006

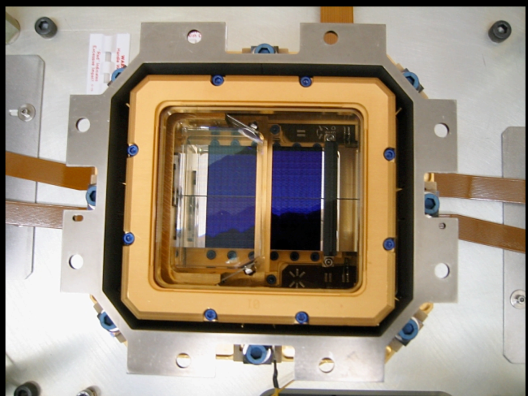
The Kepler Mission (NASA)



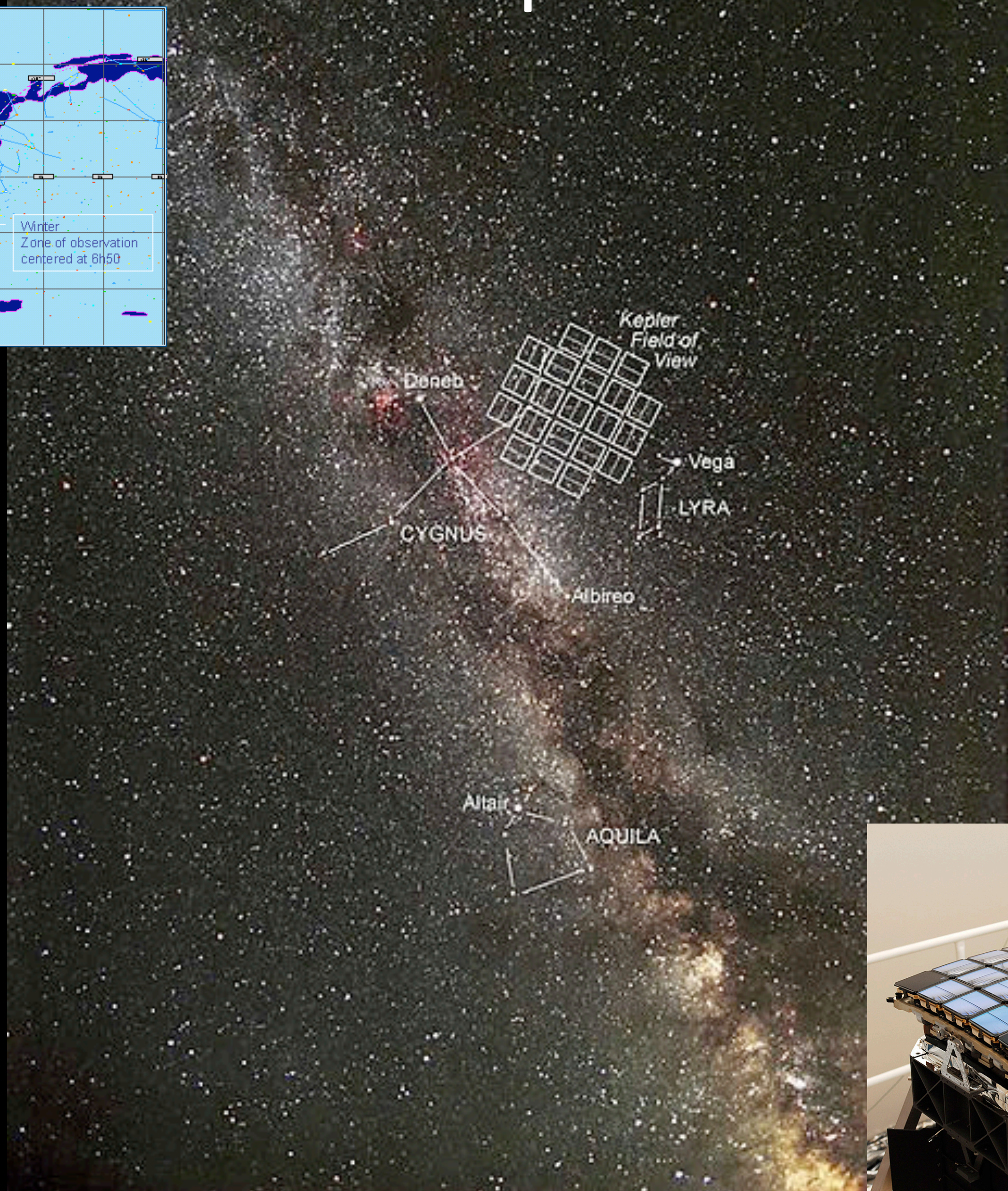
- Goal: detect Earth-sized planet in HZ
- Orbit: Earth trailing
- 0.95 m aperture Schmidt telescope
- 42 CCD detectors
- 105 square degree field of view
- Stare at one star field of 100,000 stars
- Duration: 4.5 years
- Launched: March 6, 2009

CoRoT Eyes

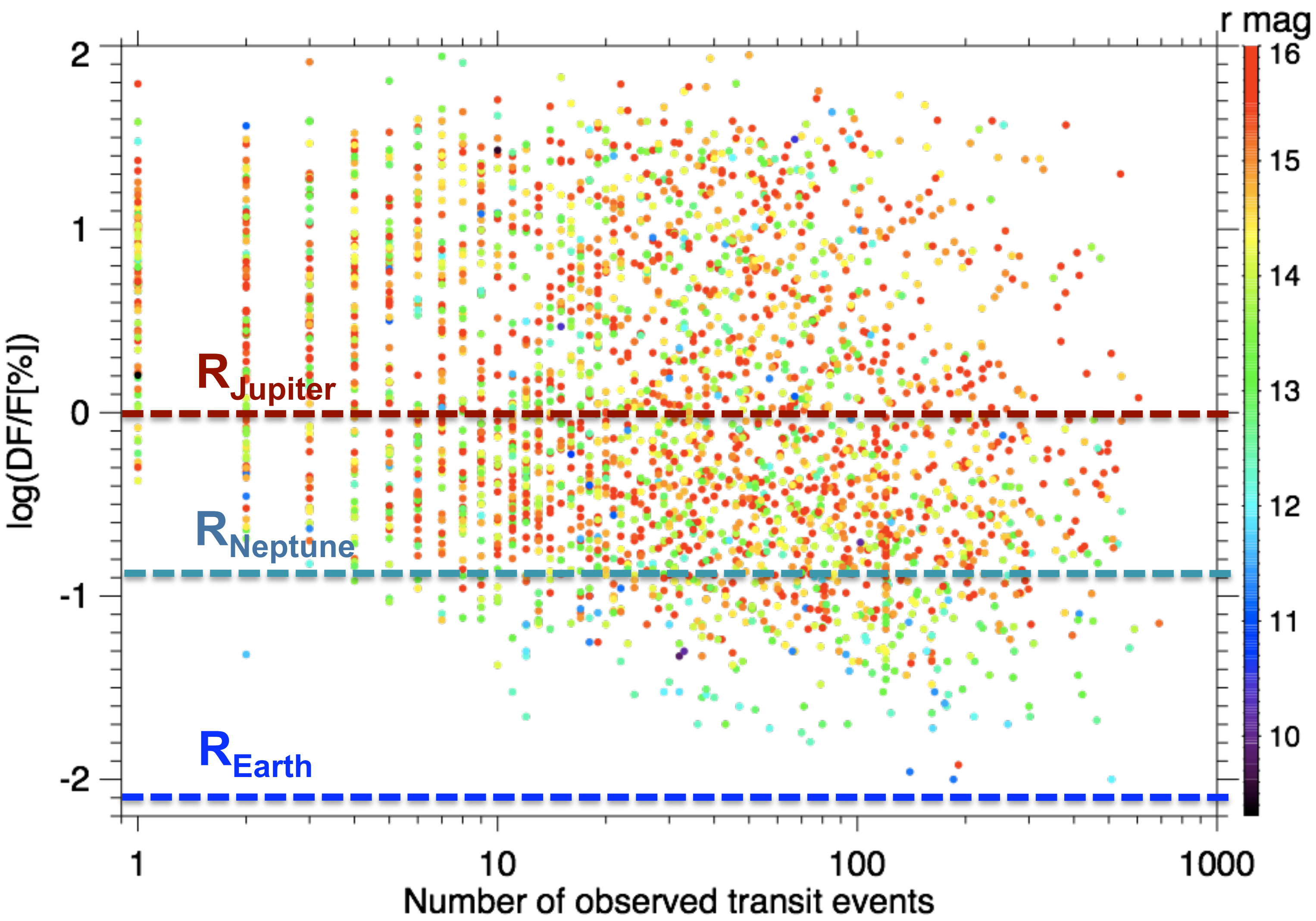




The Kepler Field

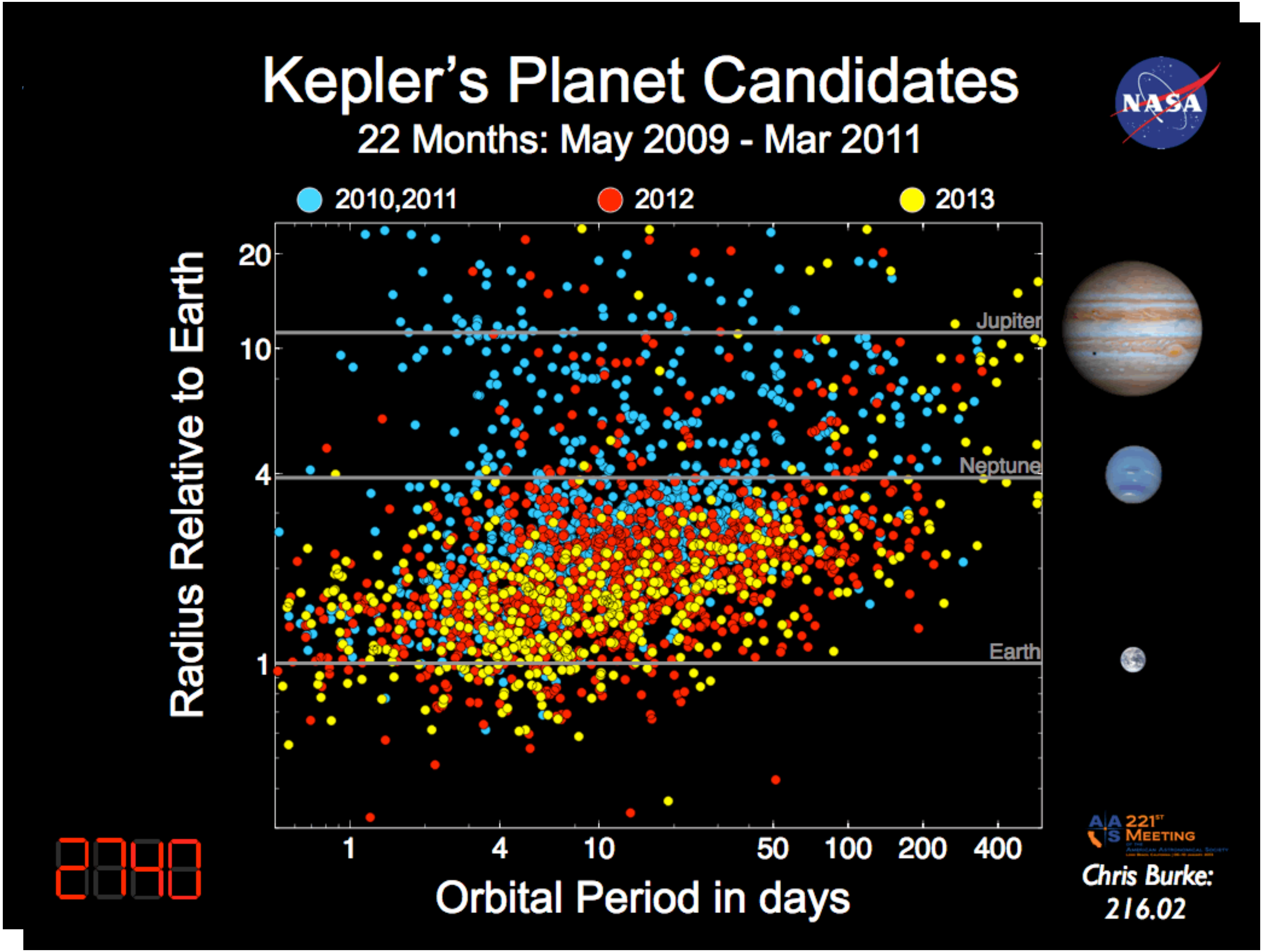


CoRoT's Exoplanet Candidates



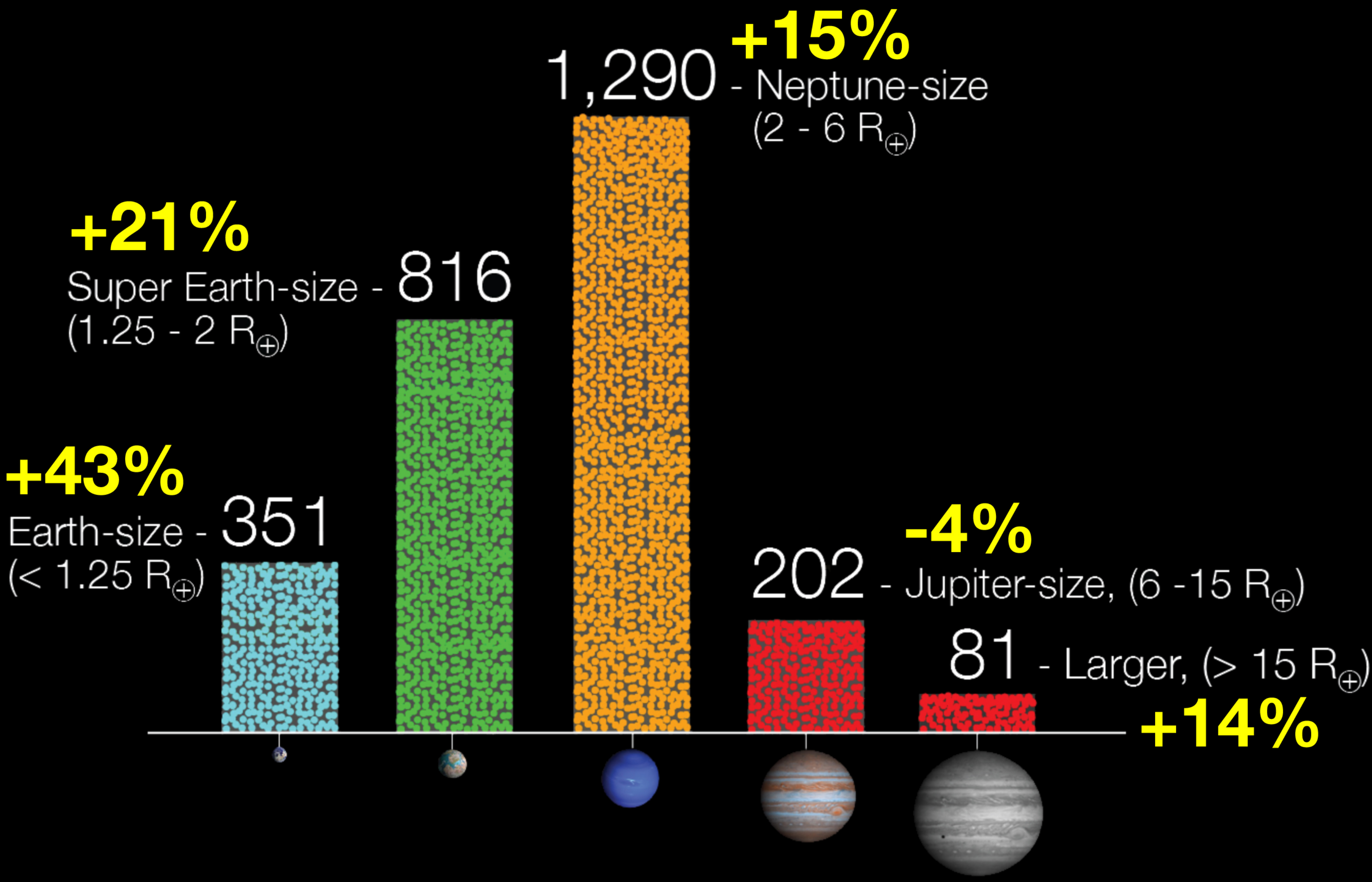
INCLUDES CLOSE TO 3000 DETECTIONS,
ALSO EBS

CREDIT: J.M. ALMENARA

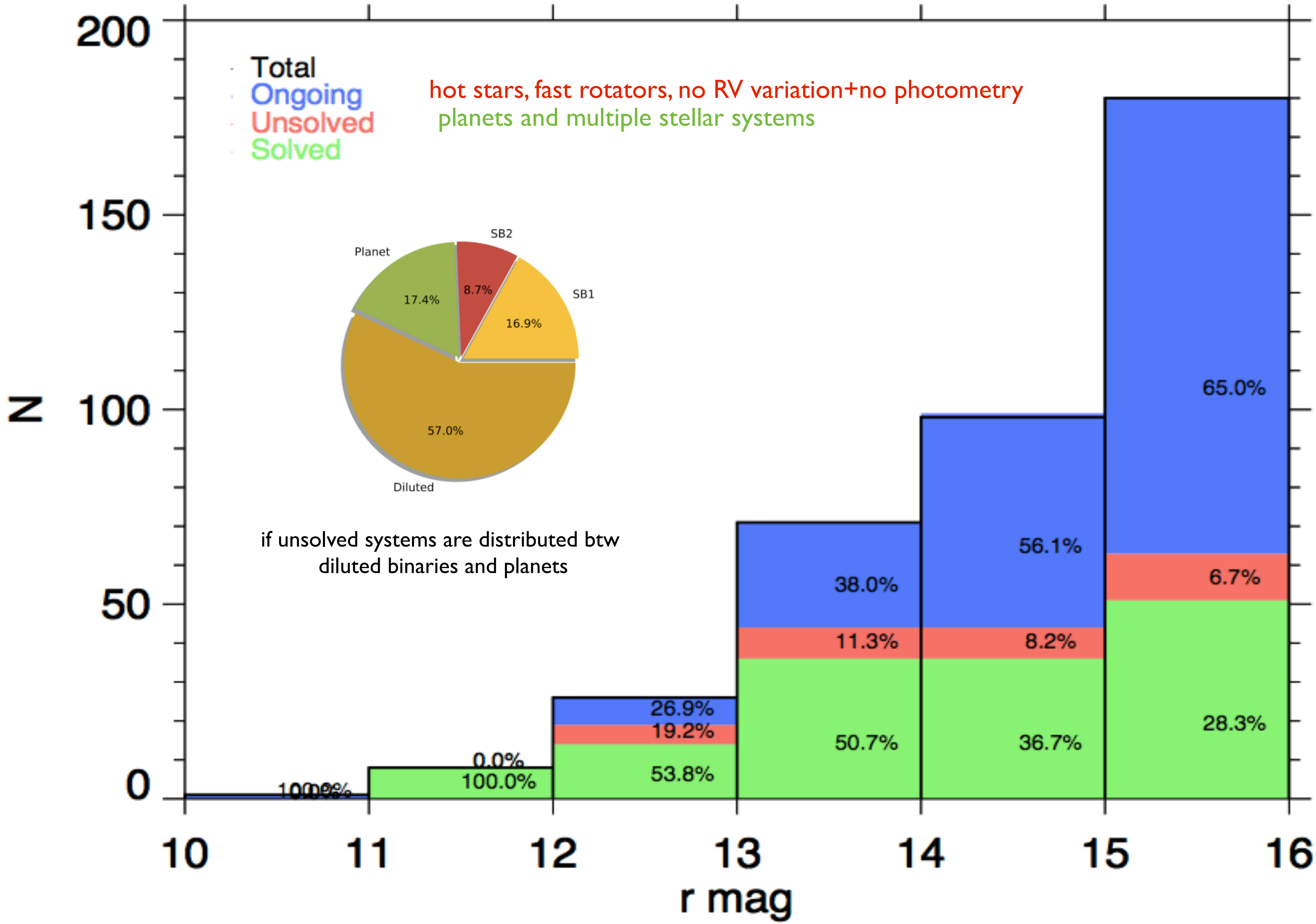

Kepler's Planet Candidates
22 Months: May 2009 - Mar 2011
NASA
2010,2011
2012
2013
Radius Relative to Earth
20
10
4
1
Jupiter
Neptune
Earth
1
4
10
50
100
200
400
Orbital Period in days
2740
AAS 221st Meeting
Chris Burke:
216.02

Sizes of Planet Candidates

As of January 7, 2013

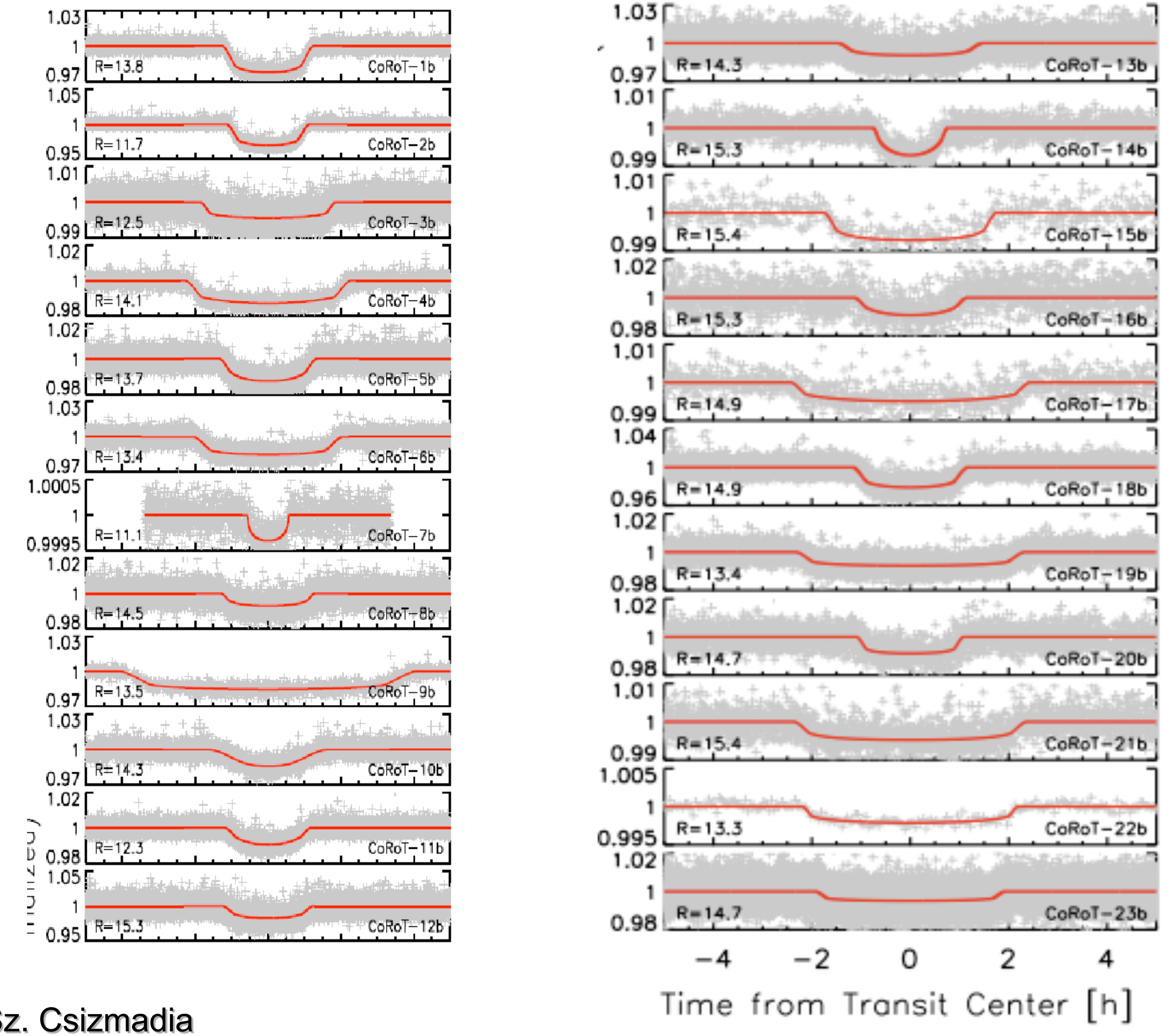


Follow-up facilities: if it collects photons, we will use it!

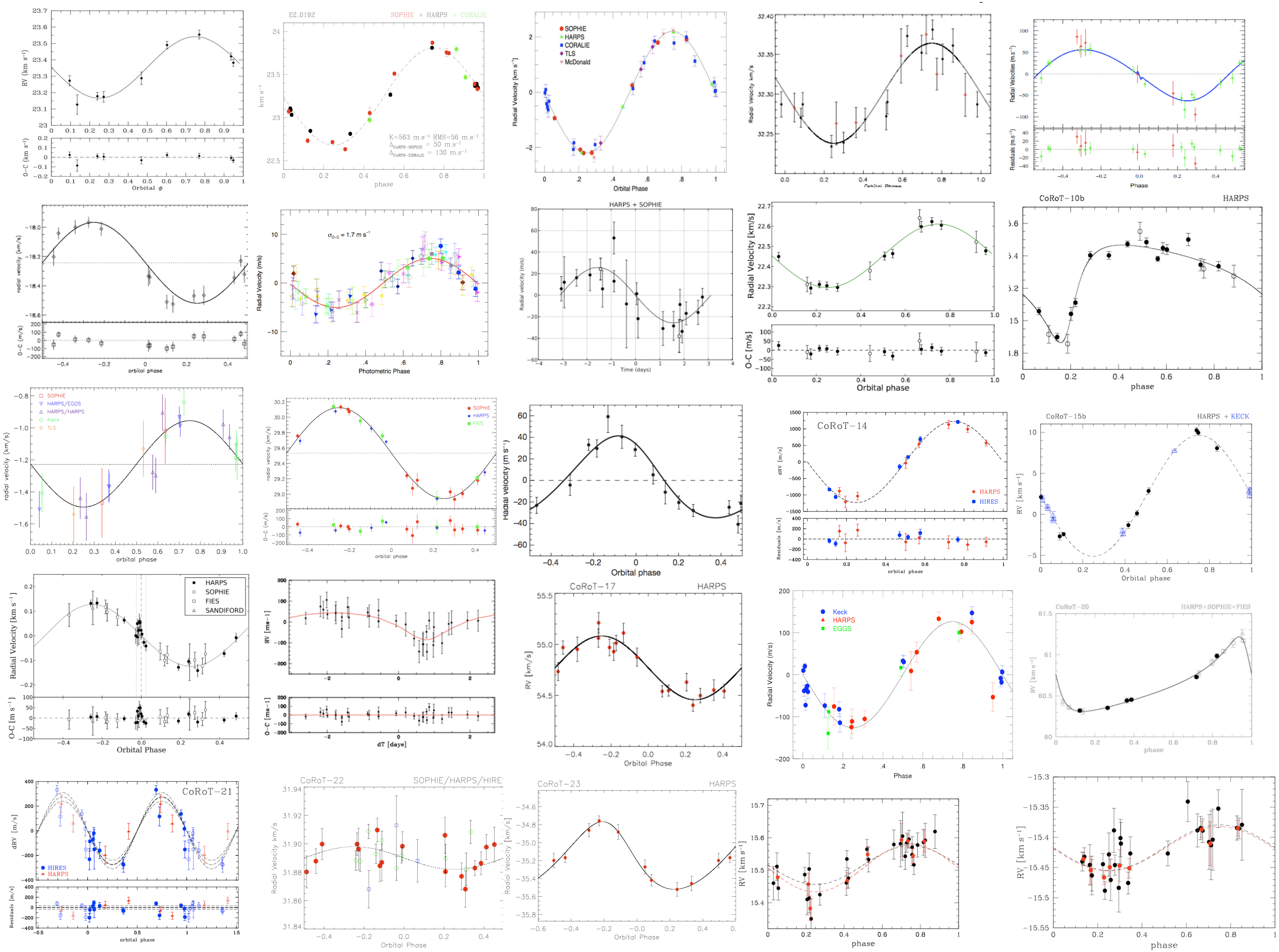


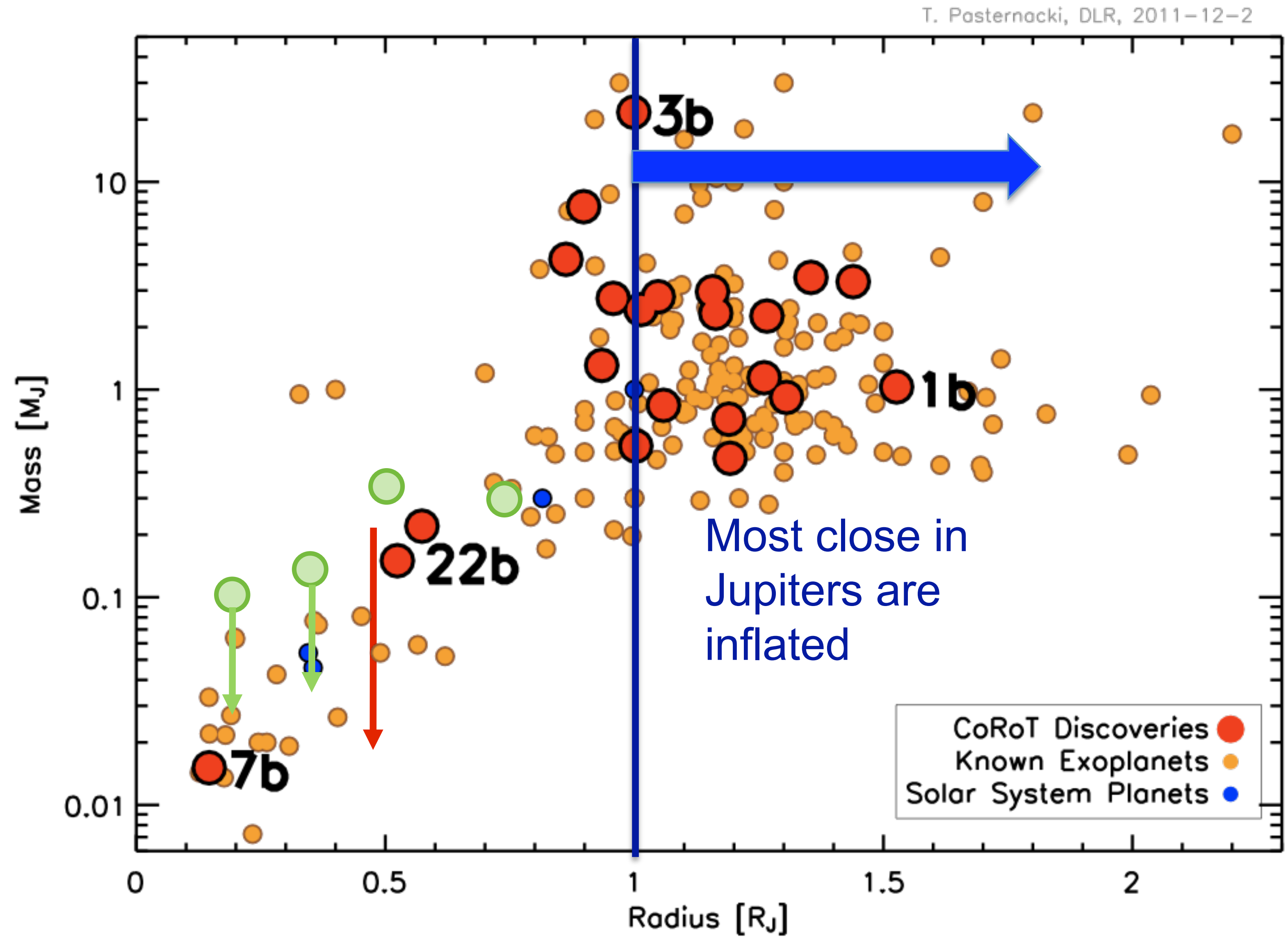
CREDITS: J.M. ALMENARA AND R. DIAZ

Confirmed CoRoT Planets



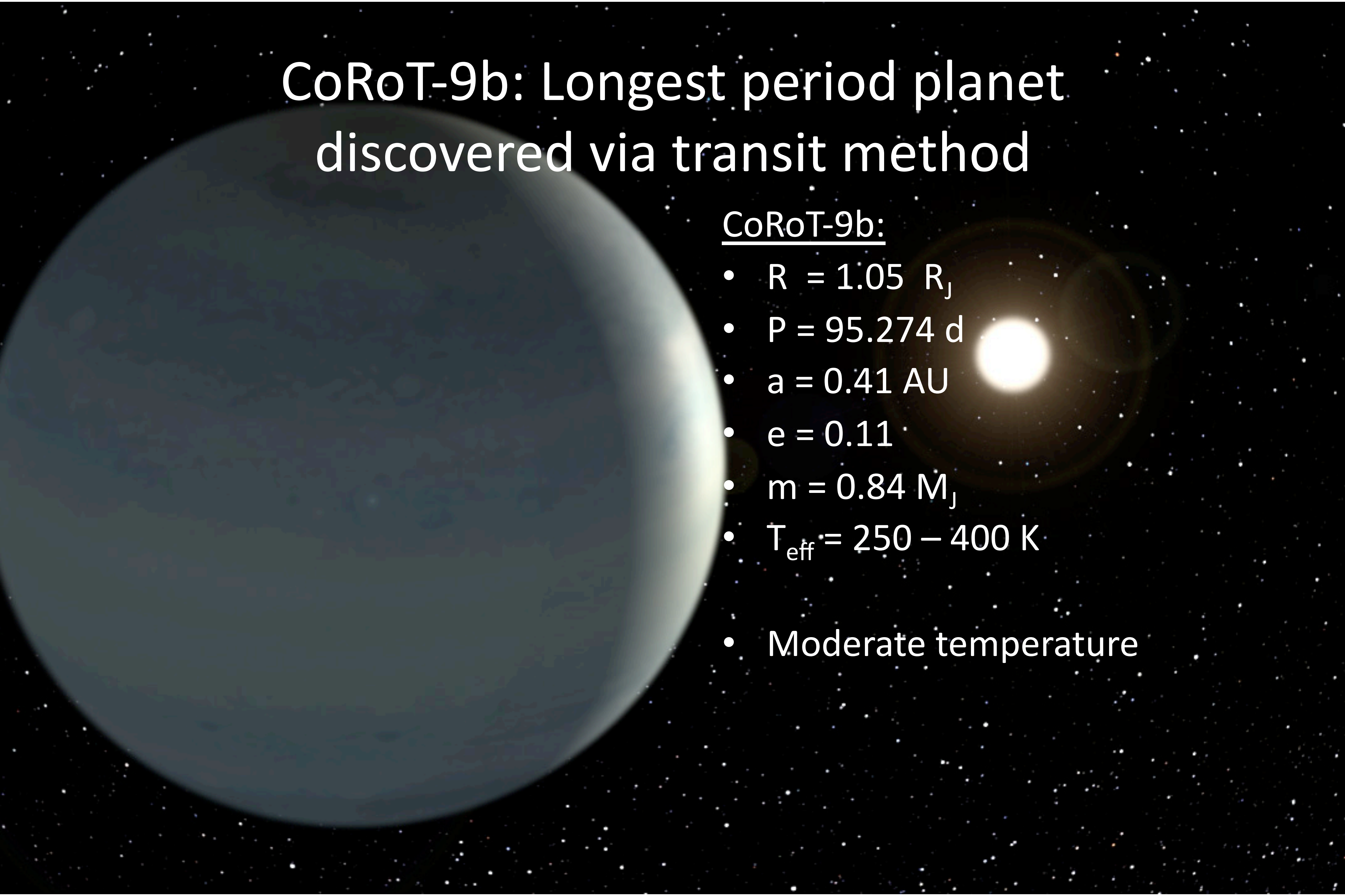
Credits: Sz. Csizmadia


E2_0192
SOPHIE + HARPS + CORALIE
SOPHIE
HARPS
CORALIE
TLS
McDonald
HARPS + SOPHIE
CoRoT-10b
HARPS
SOPHIE
HARPS/EGGS
HARPS/HARPS
Keck
TLS
FIES
CoRoT−14
HIRES
CoRoT−15b
HARPS + KECK
SANDIFORD
CoRoT−17
EGGS
CoRoT−20
HARPS+SOPHIE+FIES
CoRoT−21
CoRoT−22
SOPHIE/HARPS/HIRE
CoRoT−23
Orbital phase
Orbital Phase
Photometric Phase
Time (days)
dT [days]
phase



T. Pasternacki, DLR, 2011-12-2
Mass [MJ]
Radius [RJ]
10
1
0.1
0.01
0
0.5
1
1.5
2
3b
1b
22b
7b
Most close in Jupiters are inflated
CoRoT Discoveries
Known Exoplanets
Solar System Planets

CoRoT-9b: Longest period planet discovered via transit method

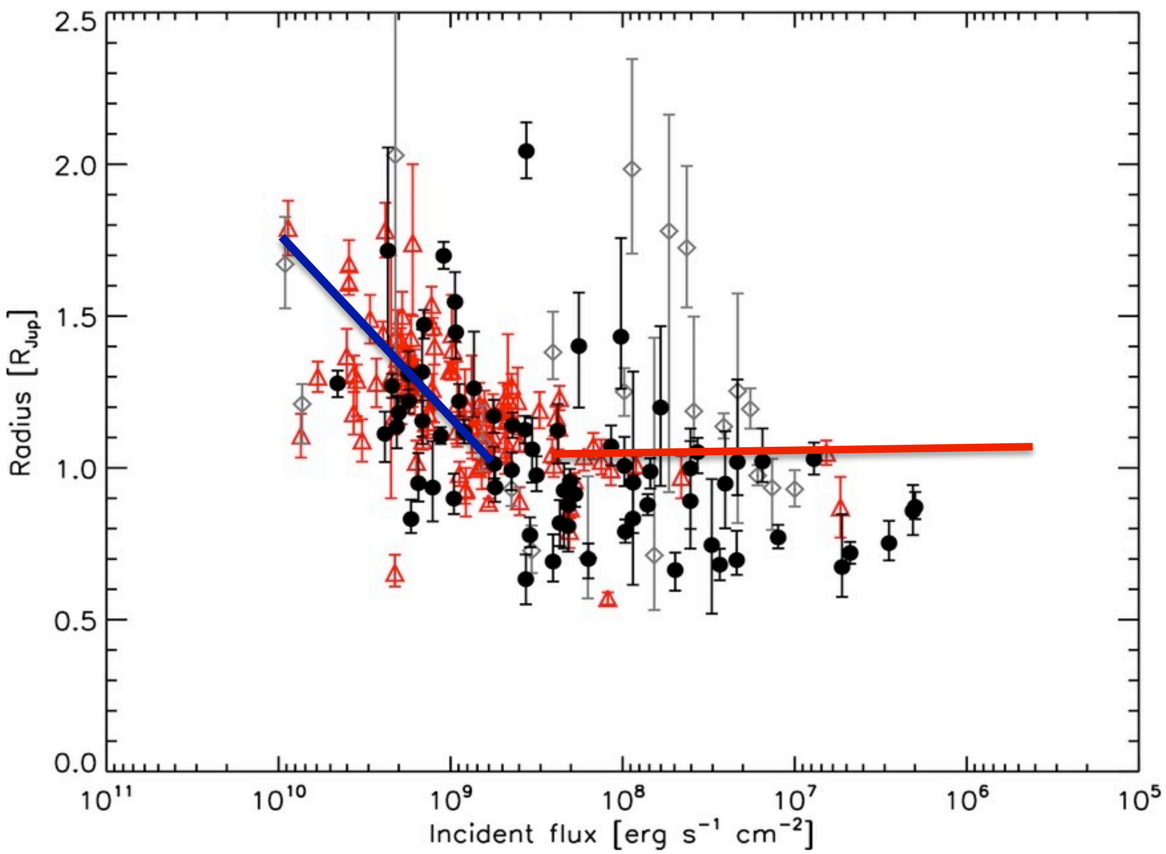


CoRoT-9b:

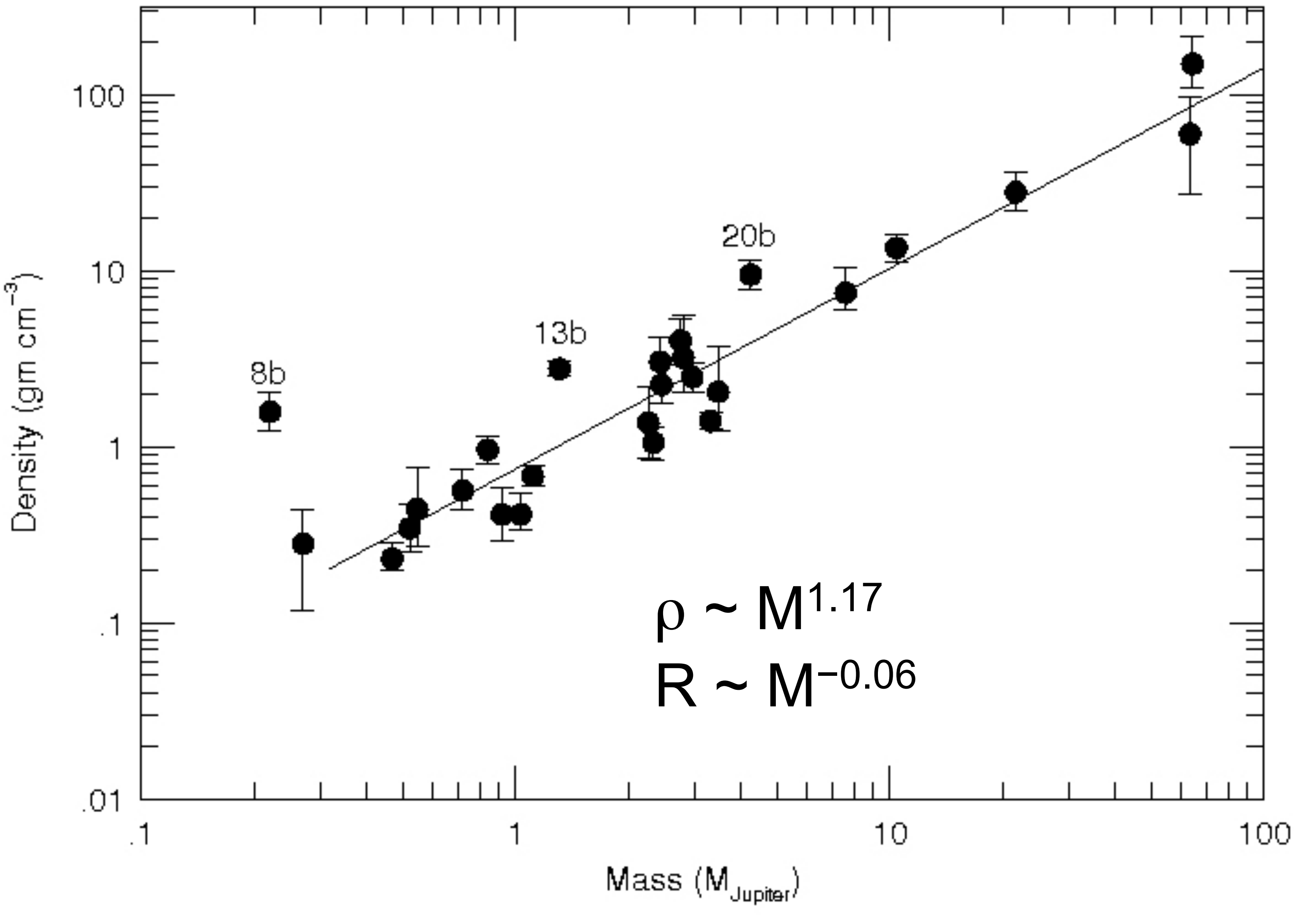
- $R = 1.05\ R_J$
- $P = 95.274$ d
- $a = 0.41$ AU
- $e = 0.11$
- $m = 0.84\ M_J$
- $T_{eff} = 250 – 400$ K

- Moderate temperature

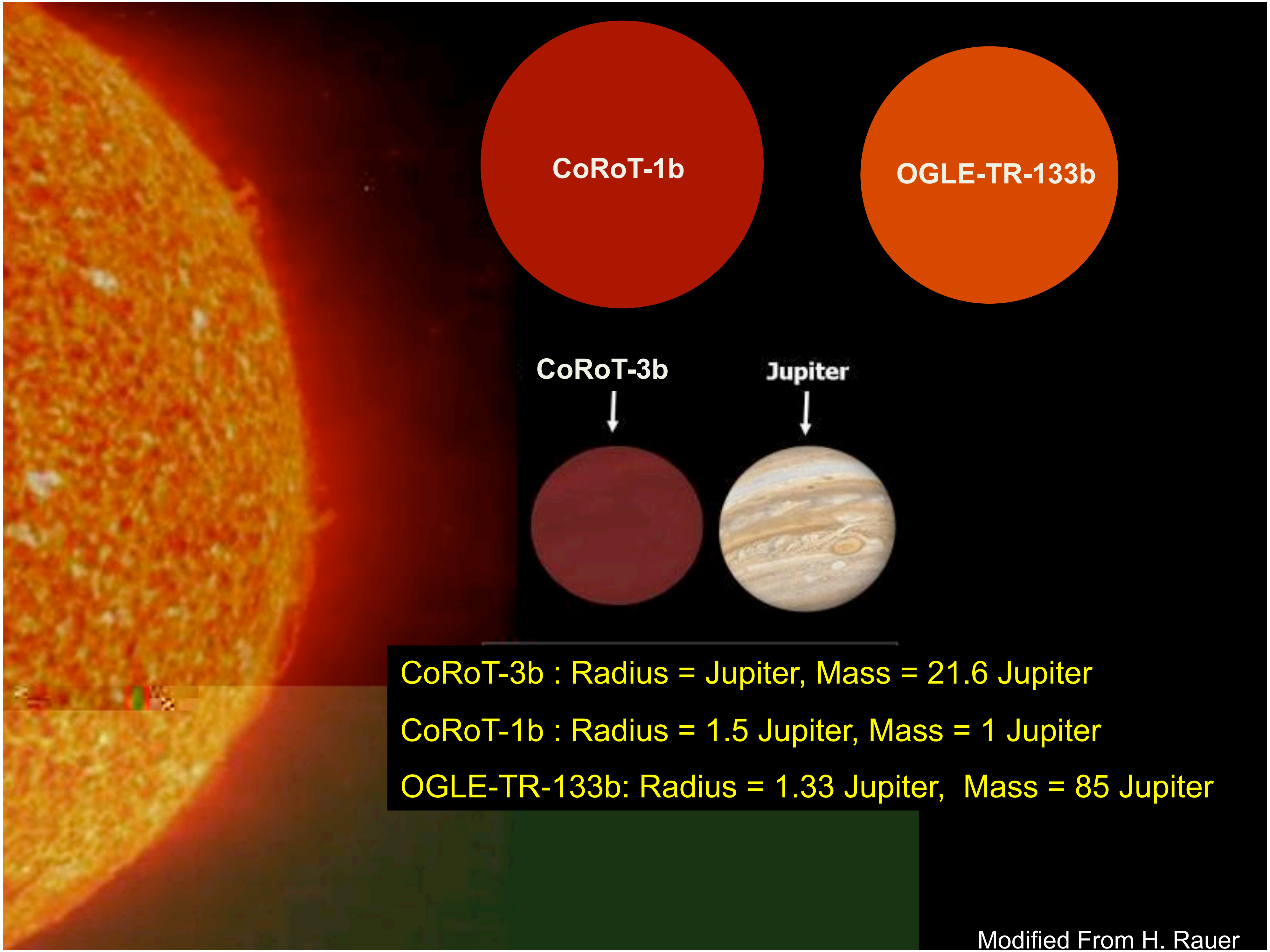
Are Close-in Jupiters inflated because they are hot?



Demory and Seager 2011



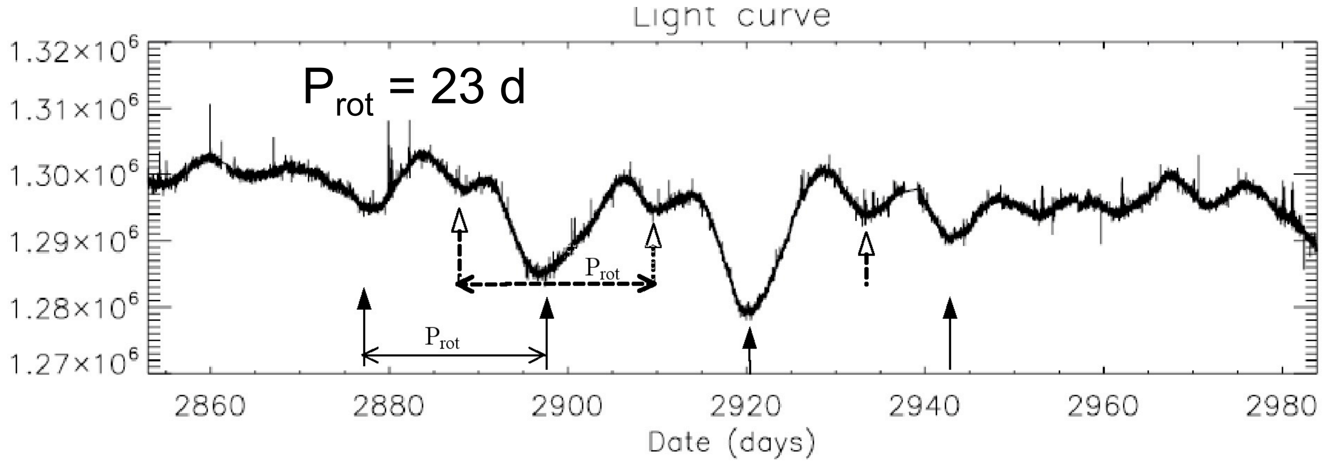
100
10
1
.1
.01
.1
1
10
100
Density (gm cm⁻³)
Mass (M_Jupiter)
8b
13b
20b
ρ ~ M^1.17
R ~ M^−0.06

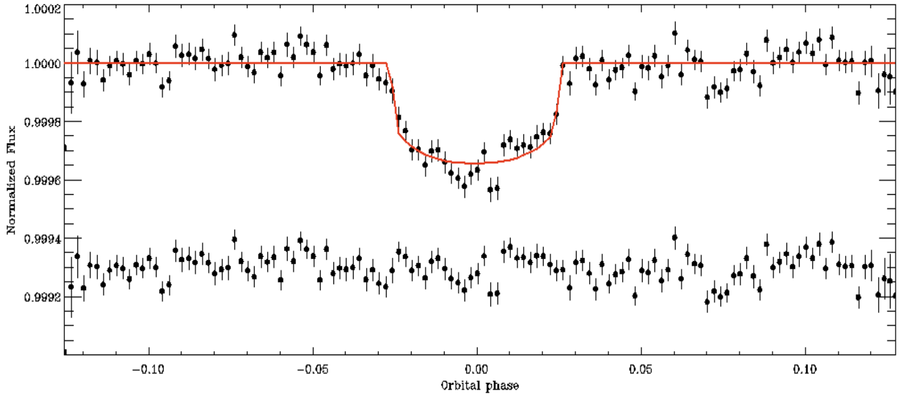

CoRoT-1b
OGLE-TR-133b
CoRoT-3b
Jupiter
CoRoT-3b : Radius = Jupiter, Mass = 21.6 Jupiter
CoRoT-1b : Radius = 1.5 Jupiter, Mass = 1 Jupiter
OGLE-TR-133b: Radius = 1.33 Jupiter, Mass = 85 Jupiter
Modified From H. Rauer

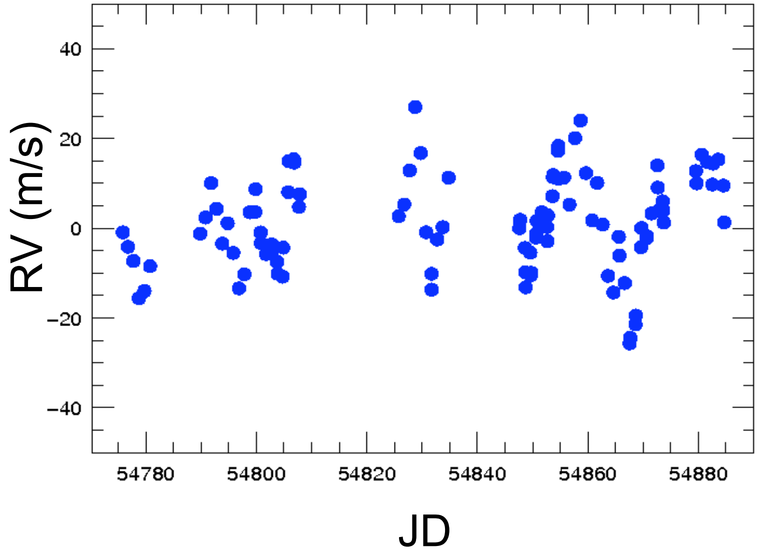
Close-in Rocky Planets

The first transiting „Rocky“ Planet

CoRoT-7b







P_{rot} (stellar) = 23 d

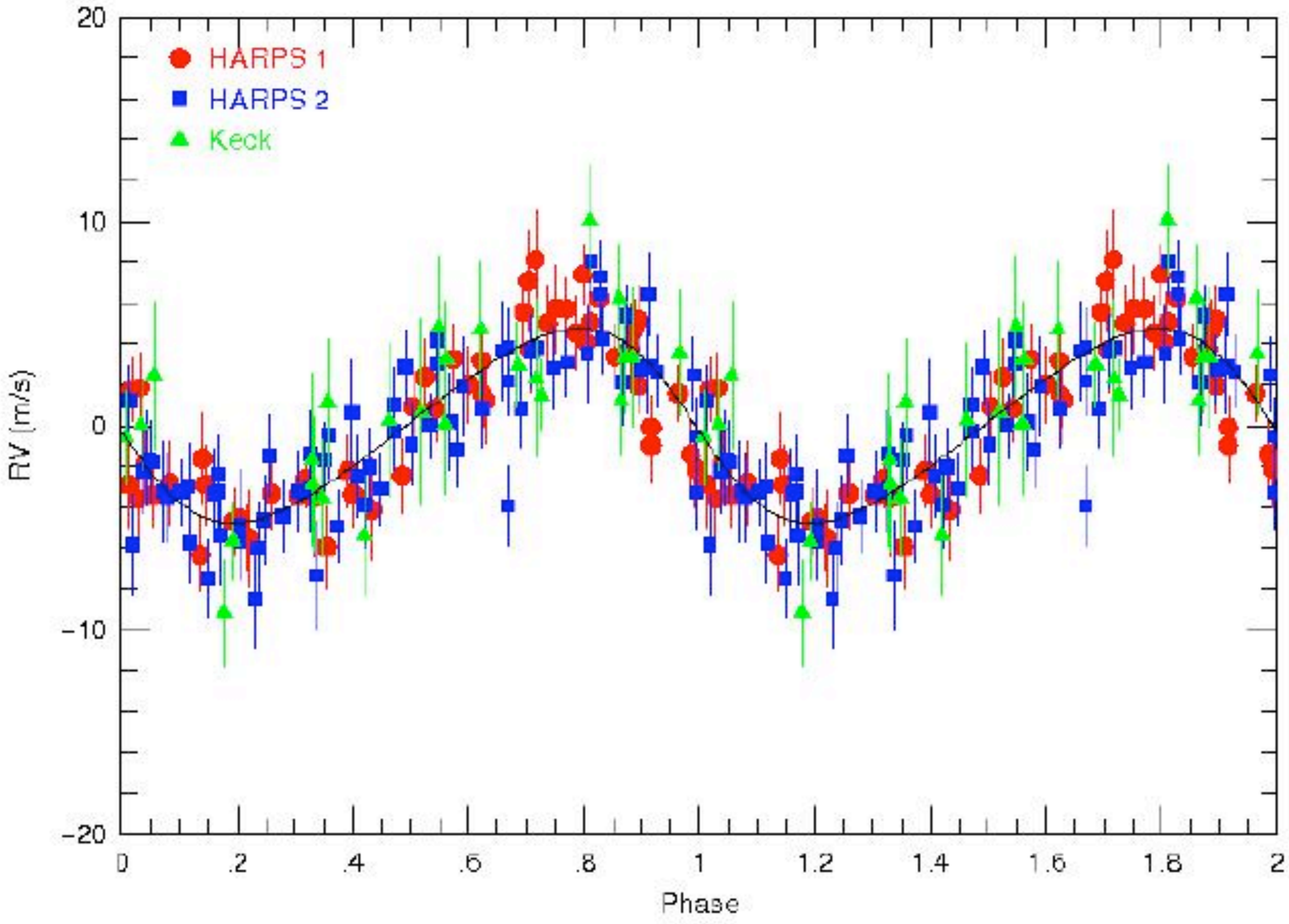
P_{planet} = 0.85 d

Depth = 0.035%

Radius = 1.6 R_E

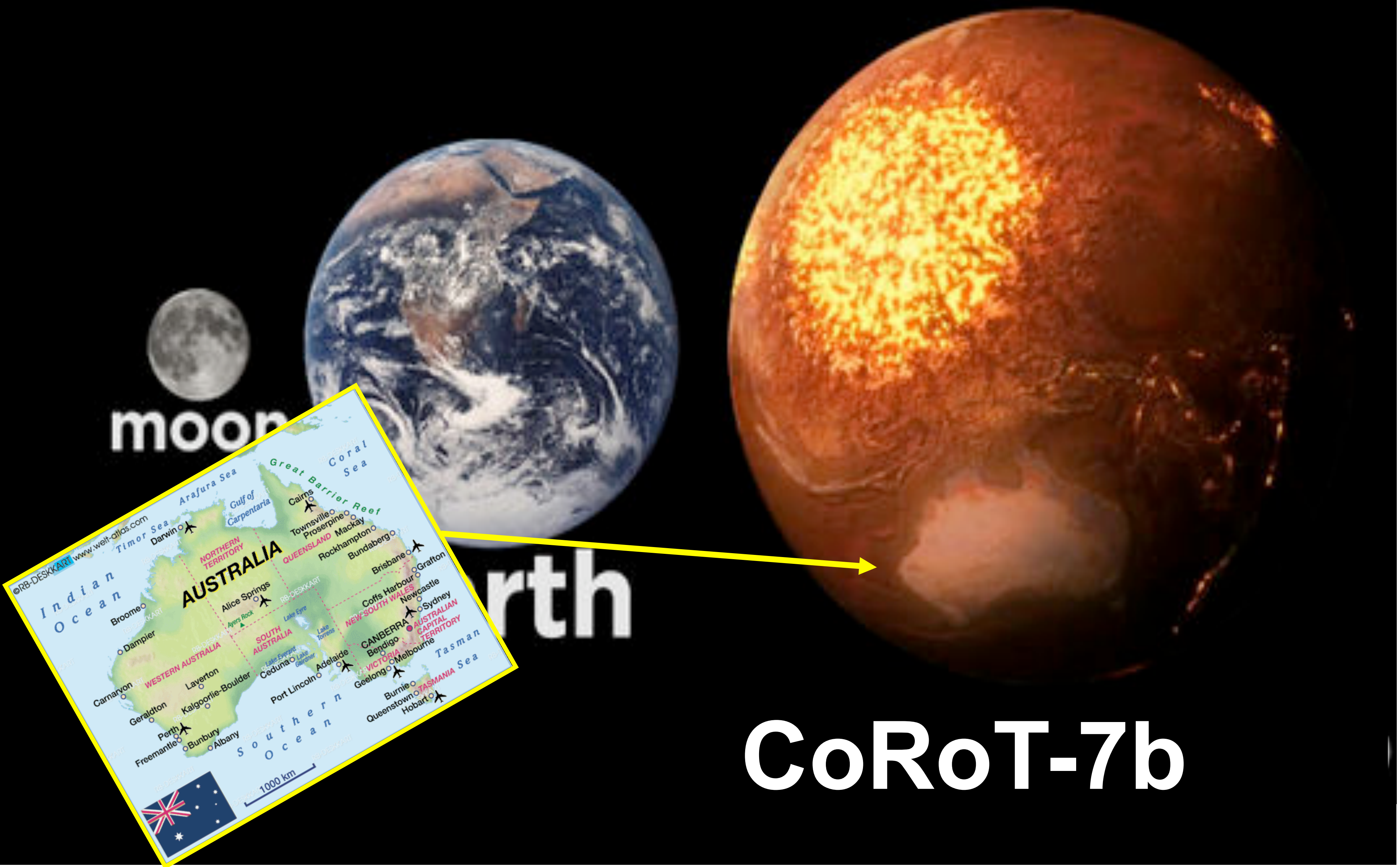
The Velocity variation of CoRoT 7b after removing the activity variations

CoRoT-7b

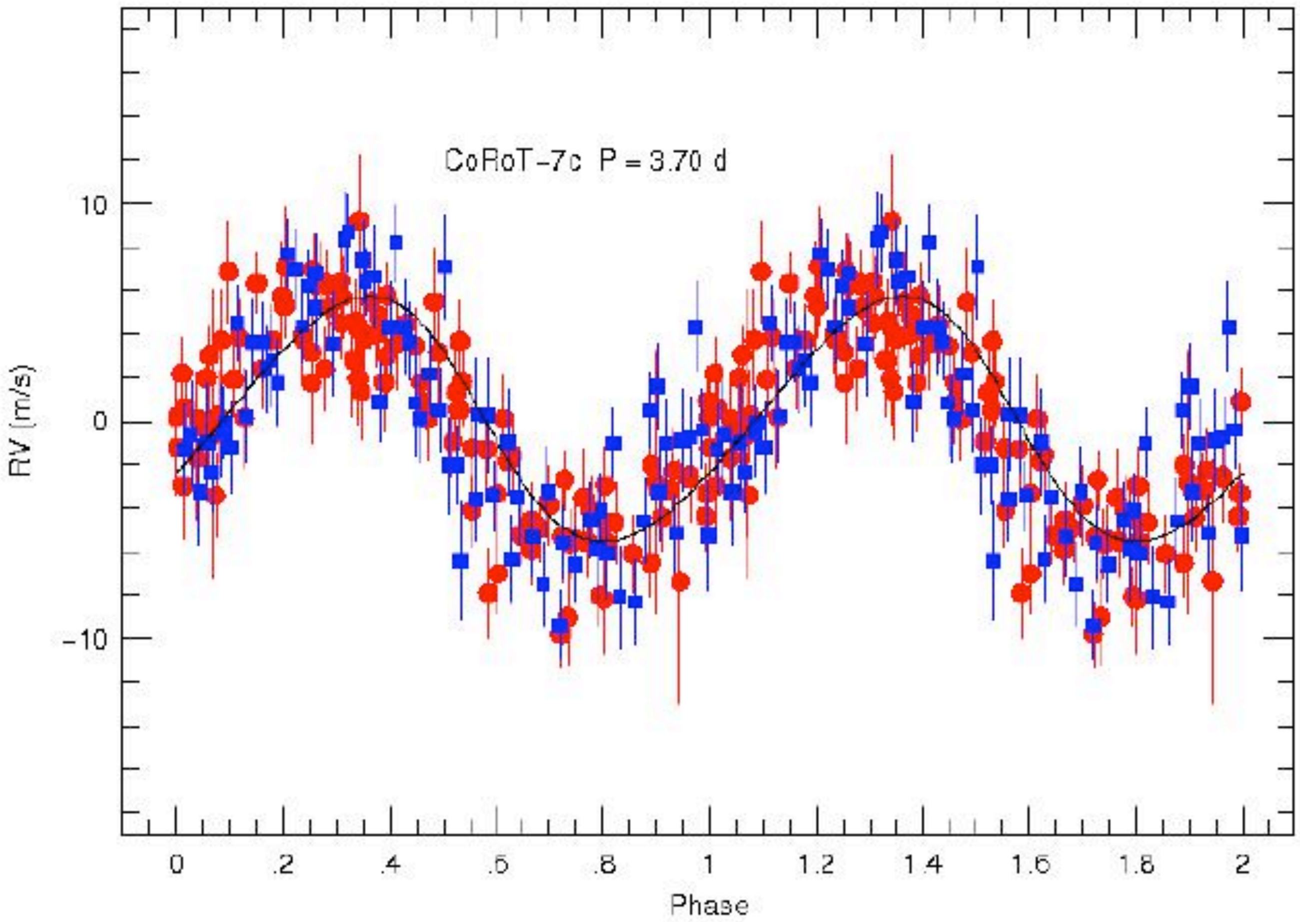


Mass = 7.3 M_E ρ =8.8 gm cm^{-3}

CoRoT-7b


CoRoT-7b
AUSTRALIA
Indian Ocean
Timor Sea
Arafura Sea
Gulf of Carpentaria
Coral Sea
Great Barrier Reef
Tasman Sea
Southern Ocean
NORTHERN TERRITORY
QUEENSLAND
WESTERN AUSTRALIA
SOUTH AUSTRALIA
NEW SOUTH WALES
VICTORIA
TASMANIA
AUSTRALIAN CAPITAL TERRITORY
CANBERRA
Darwin
Cairns
Townsville
Alice Springs
Brisbane
Sydney
Melbourne
Adelaide
Perth
Hobart
1000 km

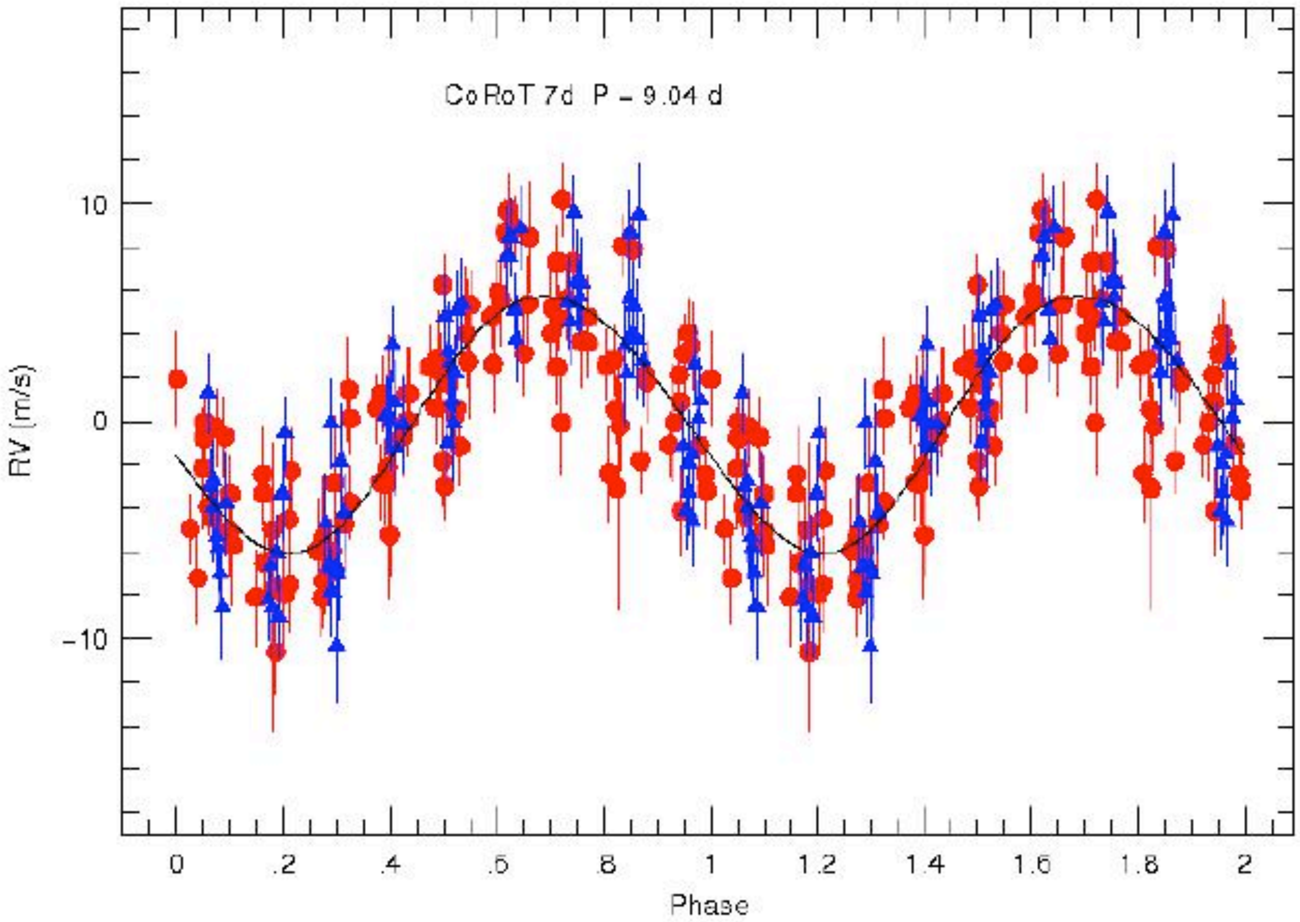
CoRoT-7c



P = 3.7 Days

Mass = 12.4 M_E

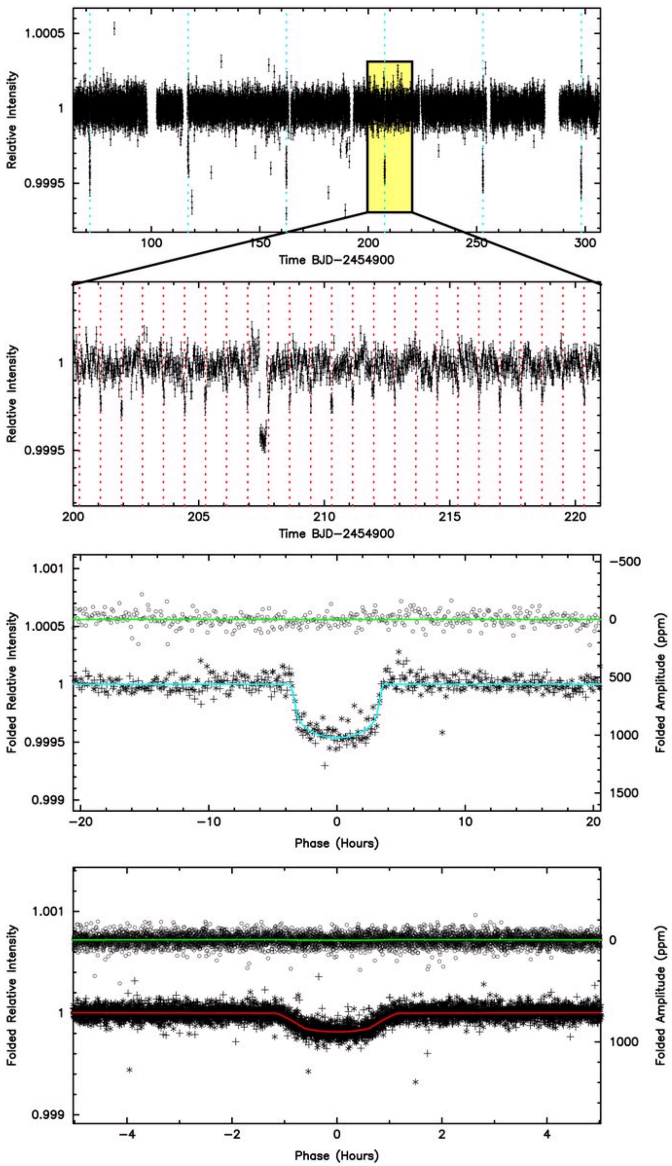
CoRoT-7d

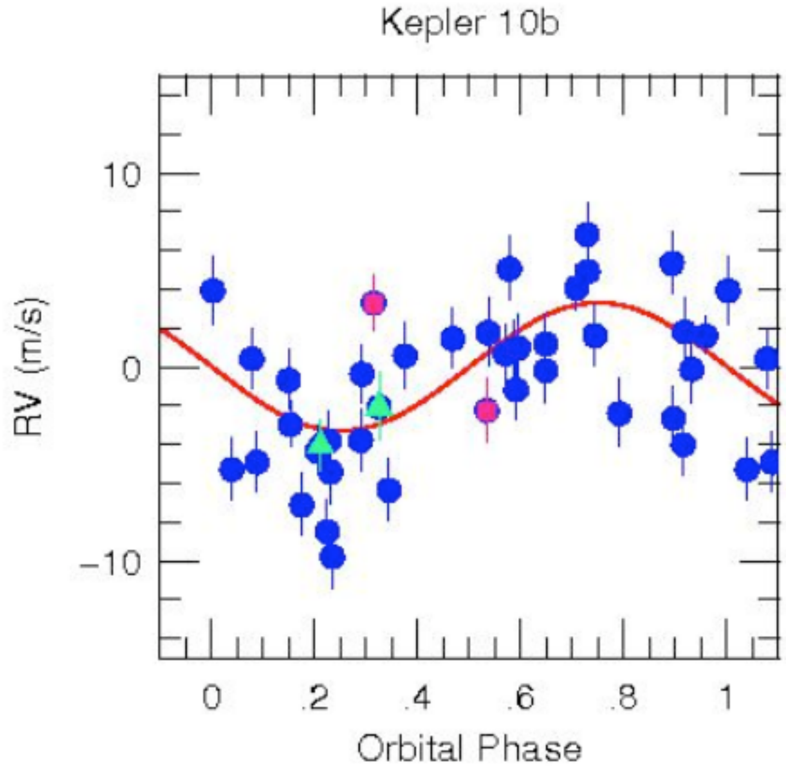


P = 9 Days

Mass = 16.7 M_E

Kepler-10b the twin of CoRoT-7b



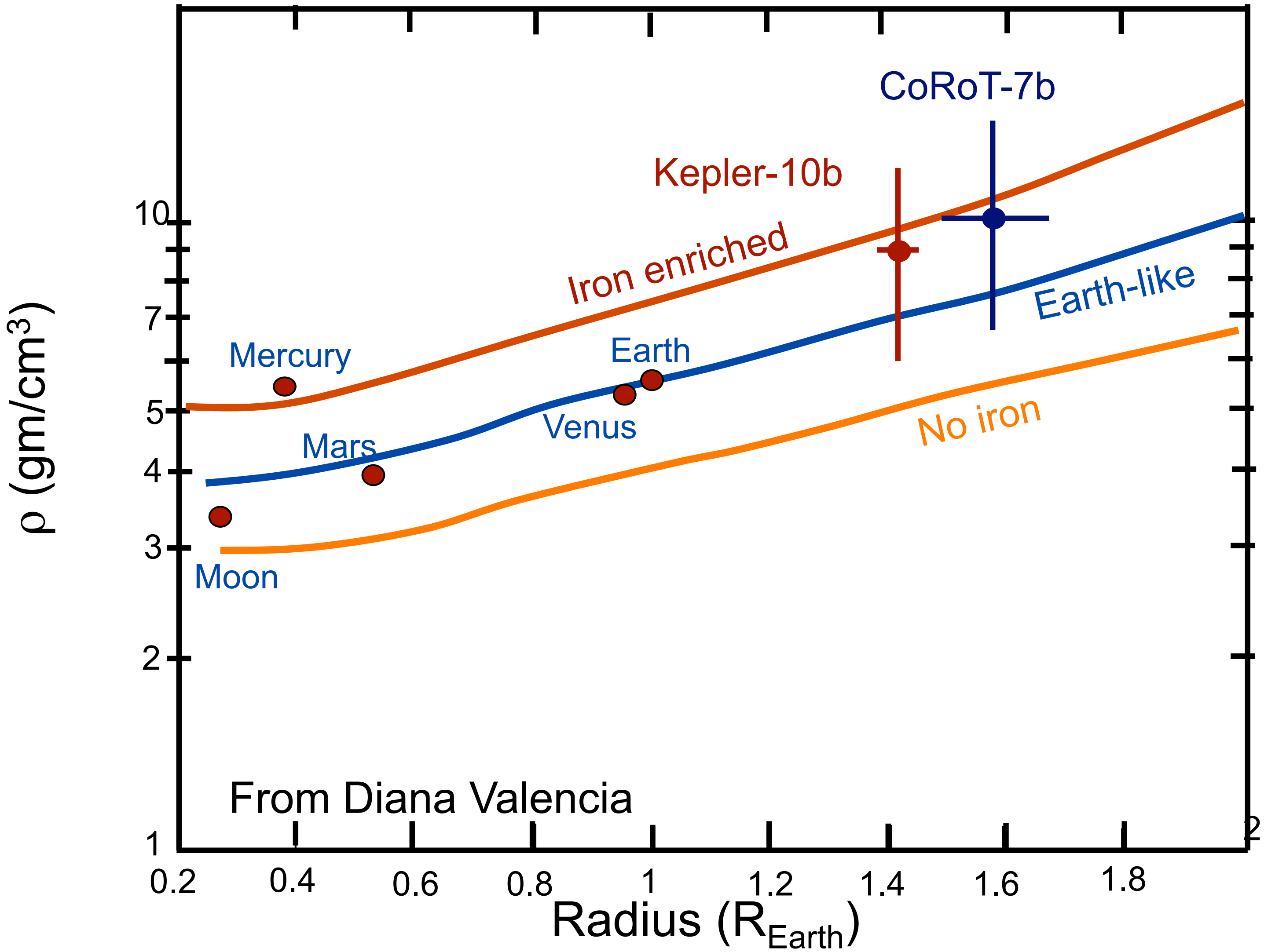


Orbital Period: 0.84 d

Radius: 1.4 R_{Earth}

Mass = 4.6 M_{Earth}

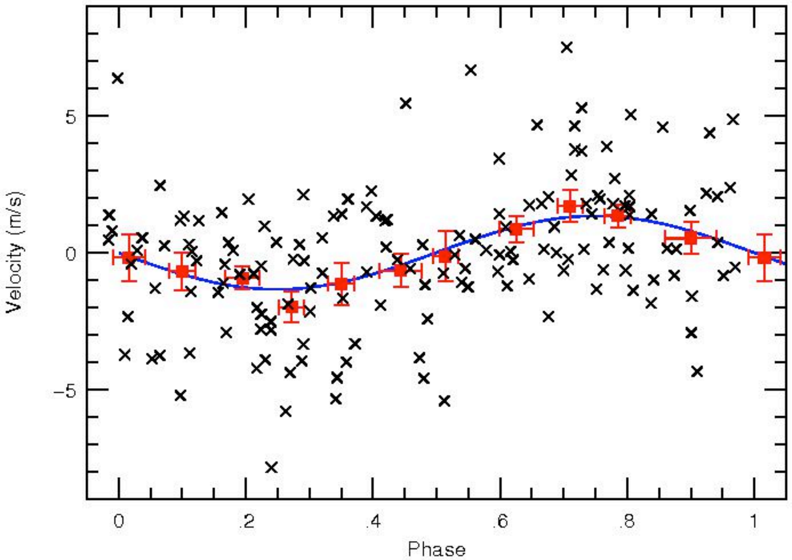
The Inner Structure of Kepler-10b and CoRoT-7b

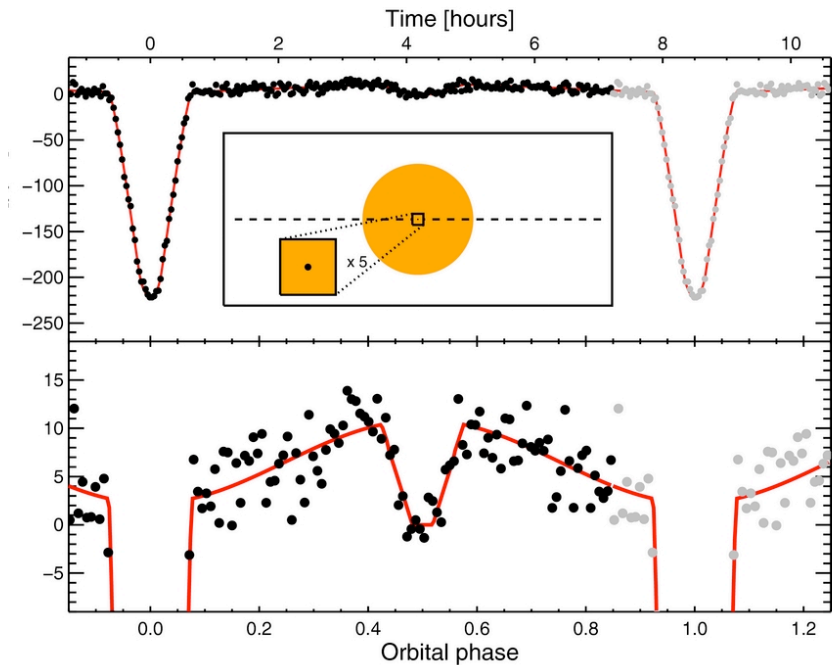


CoRoT-7b and Kepler 10b likely iron enriched Wagner et al. 2012

The Earth-mass Planet Kepler-78b

Transit detection: Sanchis-Ojeda et al 2013
Keck Velocity Measurements: Howard et al. 2013
HARPS-N Velocity Measurements: Pepe et al. 2013





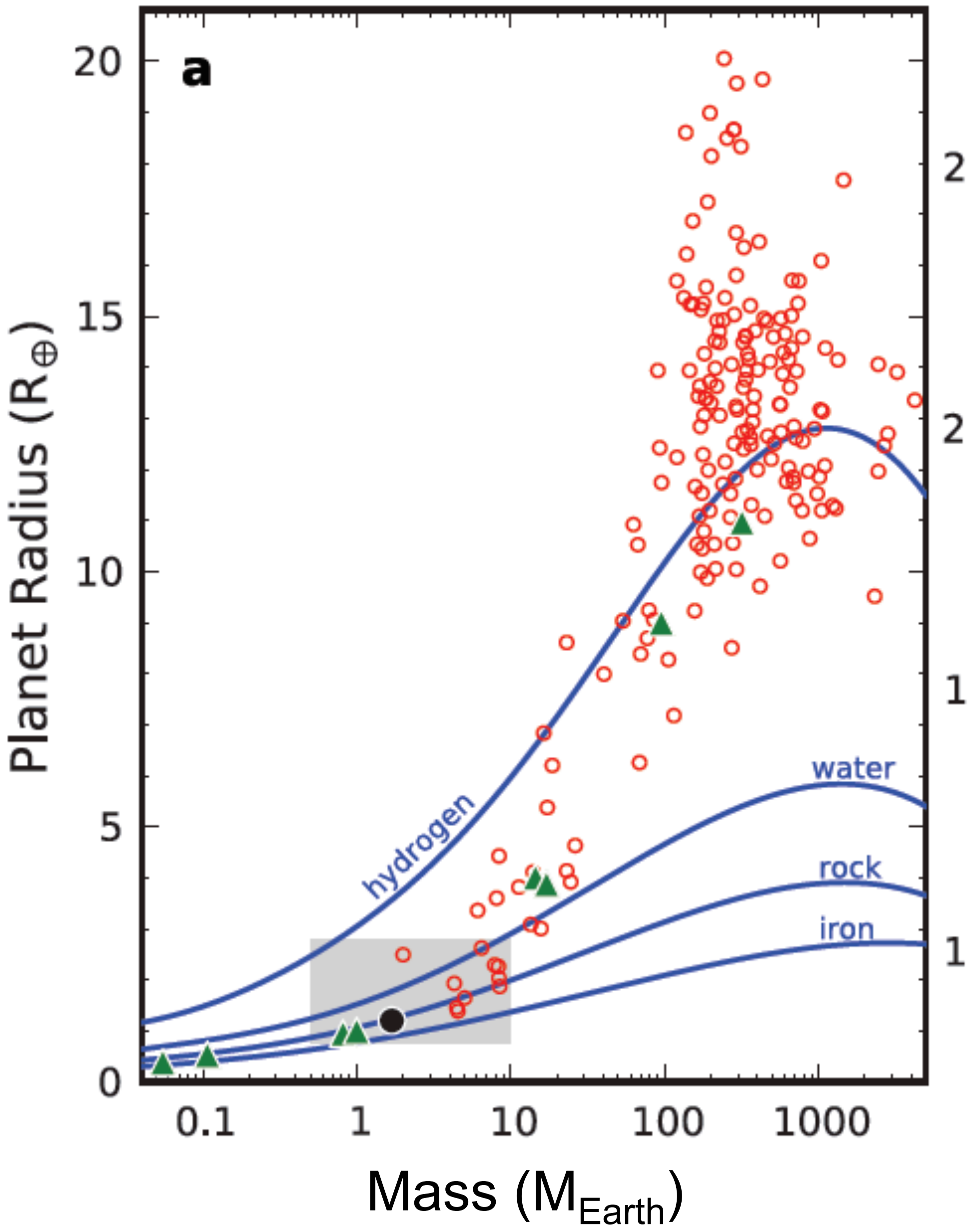
$M = 1.31 \pm 0.24\ M_{Earth}$

density = 4.5 ± 2.1 gm cm^{-3}

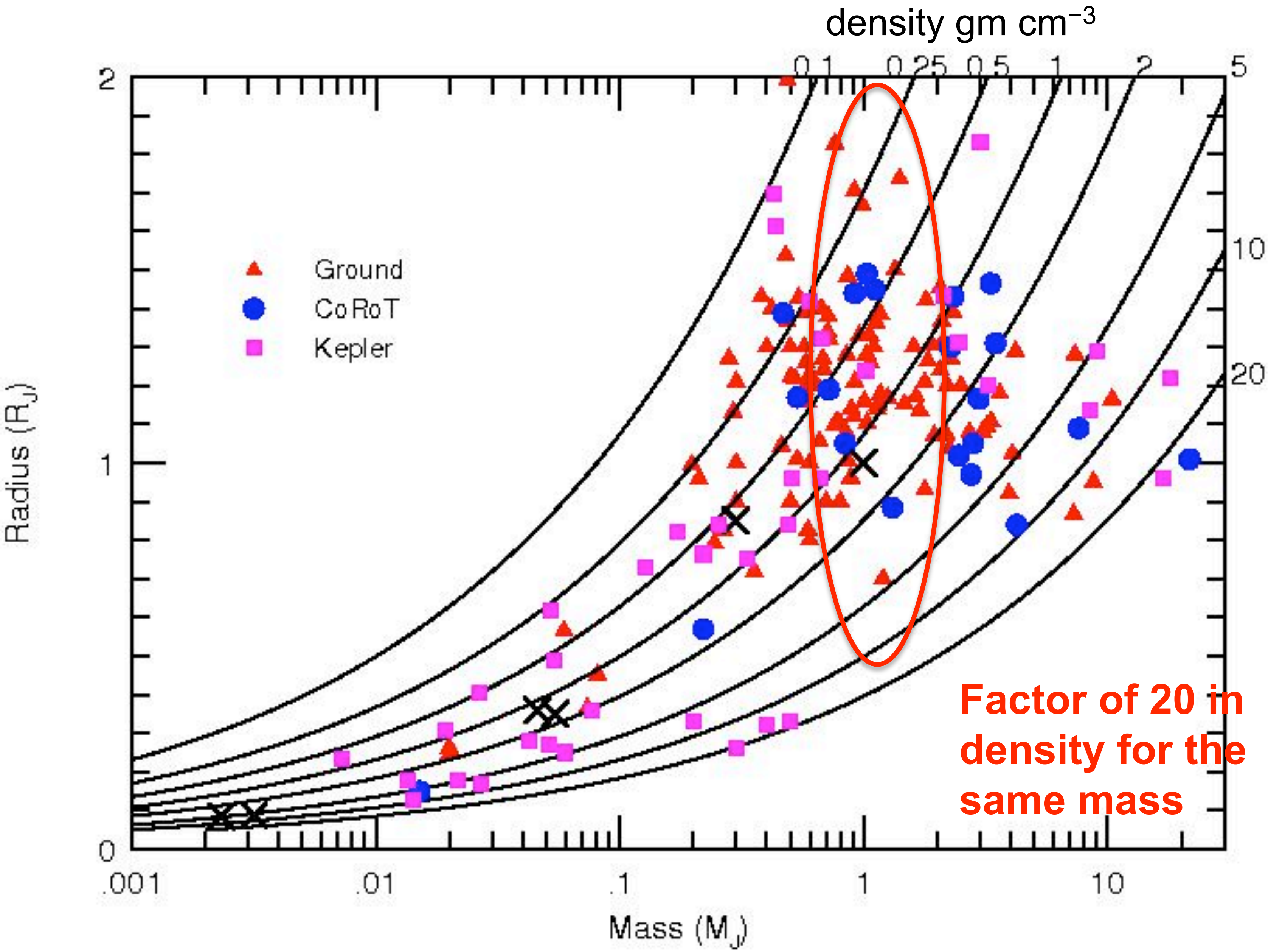
$R = 1.16 \pm 0.19\ R_{Earth}$
T_{planet} = 2300 – 3100 K

Orbital Period = 8.5 hours!
Orbital distance = 0.01 AU (2.1 Stellar Radii)

Howard et al. 2013

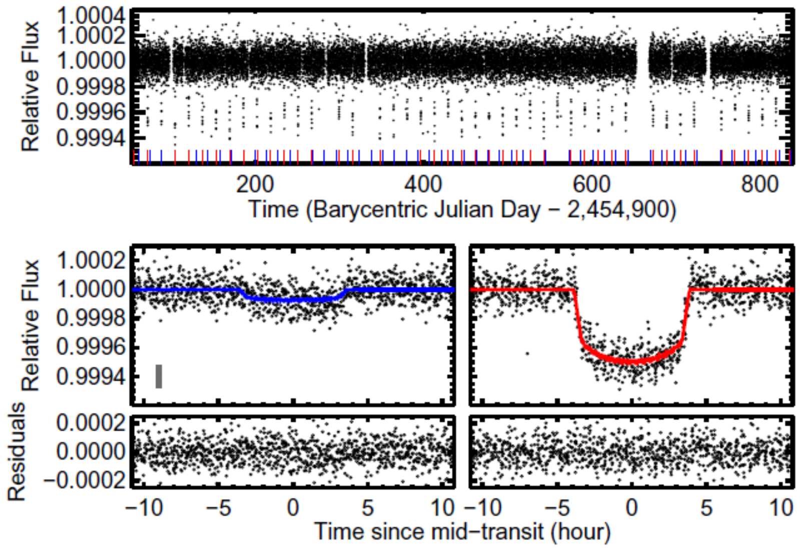


Diversity in Density


density gm cm⁻³
0.1
0.25
0.5
1
2
5
10
20
Ground
CoRoT
Kepler
Radius (RJ)
2
1
0
.001
.01
.1
1
10
Mass (MJ)
Factor of 20 in density for the same mass

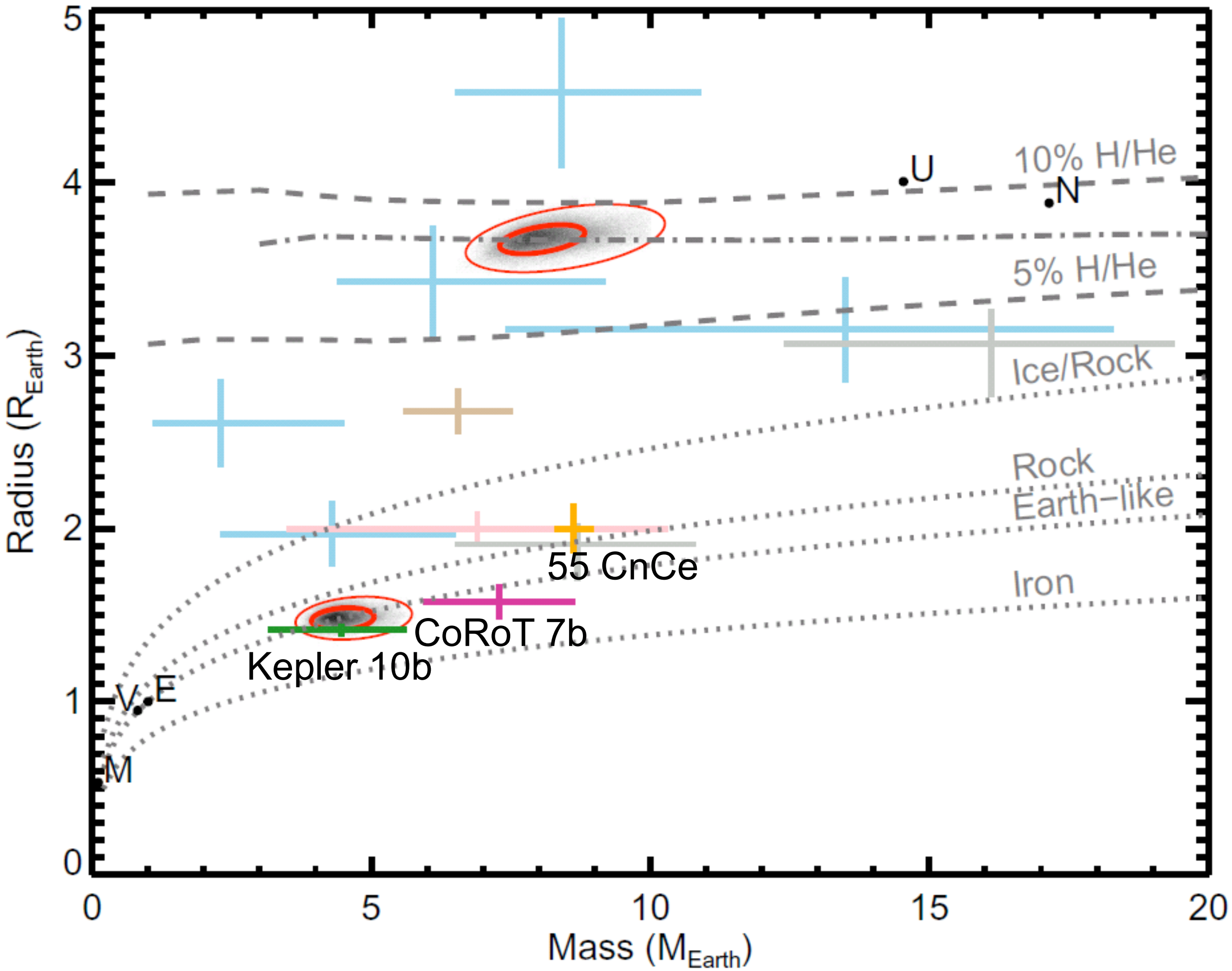
Kepler-36: A Pair of Planets with Neighboring Orbits and Dissimilar Densities

Joshua A. Carter[1]+*, Eric Agol[2]+*, William J. Chaplin[3],



Star	
Mass, $M_\star$ ($M_\odot$)	1.071 ± 0.043
Radius, $R_\star$ ($R_\odot$)	1.626 ± 0.019
Mean Density, $\rho_\star$ (g cm^{-3})	0.3508 ± 0.0056
Stellar Effective Temperature, $T_{\rm eff}$ (K)	5911 ± 66
Planet b	
Time of Transit, T_b (BJD)	$2454960.9753^{+0.0055}_{-0.0058}$
Period, P_b (day)	$13.83989^{+0.00082}_{-0.00060}$
Orbital Semimajor Axis, a_b (AU)	0.1153 ± 0.0015
Mass, M_b ($M_\oplus$)	$4.45^{+0.33}_{-0.27}$
Radius, R_b ($R_\oplus$)	1.486 ± 0.035
Mean Density, ρ_b (g cm^{-3})	$7.46^{+0.74}_{-0.59}$
Equilibrium Temperature, $T_{\rm eq,b}$ (K)	978 ± 11
Planet c	
Time of Transit, T_c (BJD)	$2454955.9132^{+0.0011}_{-0.0010}$
Period, P_c (day)	$16.23855^{+0.00038}_{-0.00054}$
Orbital Semimajor Axis, a_c (AU)	0.1283 ± 0.0016
Mass, M_c ($M_\oplus$)	$8.08^{+0.60}_{-0.46}$
Radius, R_c ($R_\oplus$)	3.679 ± 0.054
Mean Density, ρ_c (g cm^{-3})	$0.89^{+0.07}_{-0.05}$
Equilibrium Temperature, $T_{\rm eq,c}$ (K)	928 ± 10

A diversity in densities



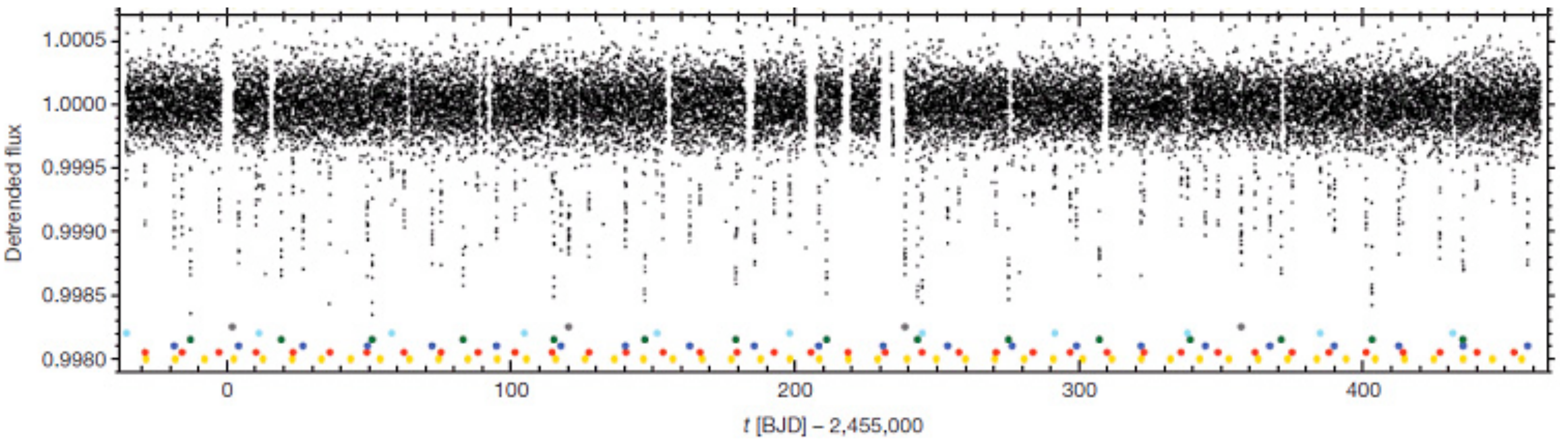
- a_1 = 0.1153 AU, a_2 =0.1283 AU, a difference of 10%
- m_1 = 4.4 M_E, m_2 = 8.1 M_E, ~ 2x
- ρ_1 = 7.46 gm cm^{-3} ρ_2 = 0.89, ~ 8x
- In situ formation: How can two planets formed in the same part of the protoplanetary disk have such different densities?
- Migration?

Planetary Systems

Kepler-11: A transiting 6 Planet System

A closely packed system of low-mass, low-density planets transiting Kepler-11

Jack J. Lissauer[1], Daniel C. Fabrycky[2], Eric B. Ford[3], William J. Borucki[1], Francois Fressin[4], Geoffrey W. Marcy[5], Jerome A. Orosz[6], Jason F. Rowe[7], Guillermo Torres[4], William F. Welsh[6], Natalie M. Batalha[8], Stephen T. Bryson[1], Lars A. Buchhave[9], Douglas A. Caldwell[7], Joshua A. Carter[4], David Charbonneau[4], Jessie L. Christiansen[7], William D. Cochran[10], Jean-Michel Desert[4], Edward W. Dunham[11], Michael N. Fanelli[12], Jonathan J. Fortney[2], Thomas N. Gautier III[13], John C. Geary[4], Ronald L. Gilliland[14], Michael R. Haas[1], Jennifer R. Hall[15], Matthew J. Holman[4], David G. Koch[1], David W. Latham[4], Eric Lopez[2], Sean McCauliff[15], Neil Miller[2], Robert C. Morehead[3], Elisa V. Quintana[7], Darin Ragozzine[4], Dimitar Sasselov[4], Donald R. Short[6] & Jason H. Steffen[16]



Six Transiting Planets

M = 4.2 M_E

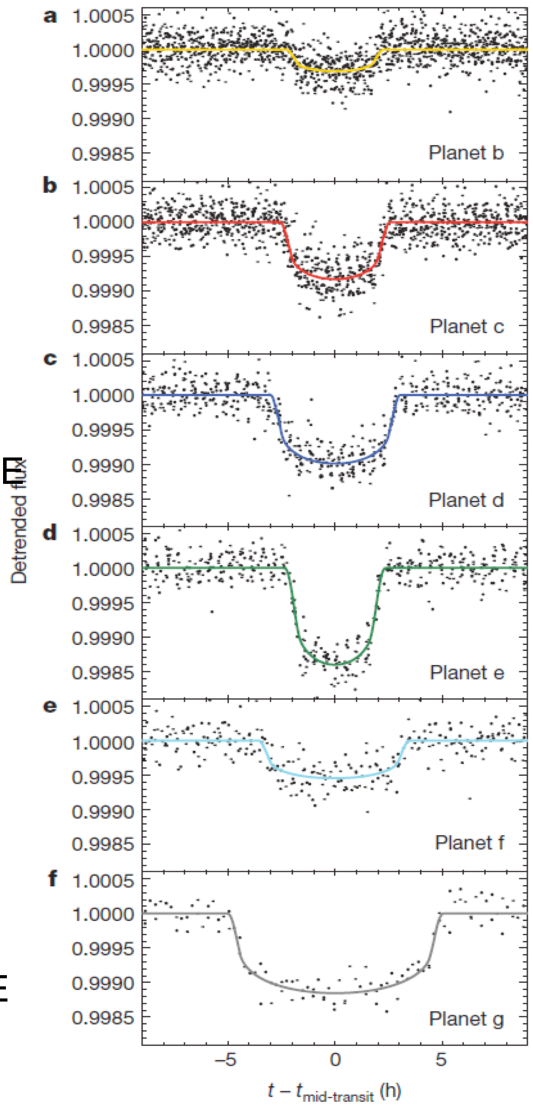
M = 13 M_E

M = 6.36 M_E

M = 8.3 M_E

M = 2.2 M_E

M < 300 M_E



Kepler-11b : P=10.3 d

Kepler-11c : P= 13.02 d

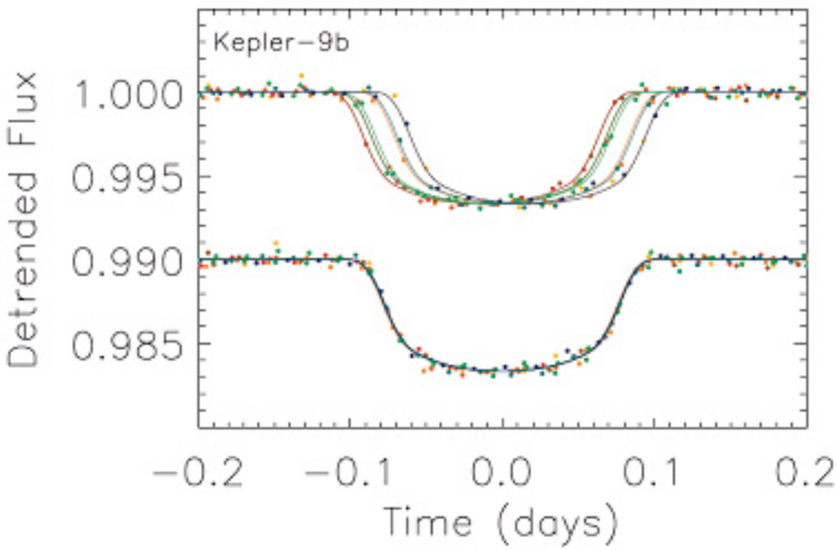
Kepler-11d : P= 22.69 d

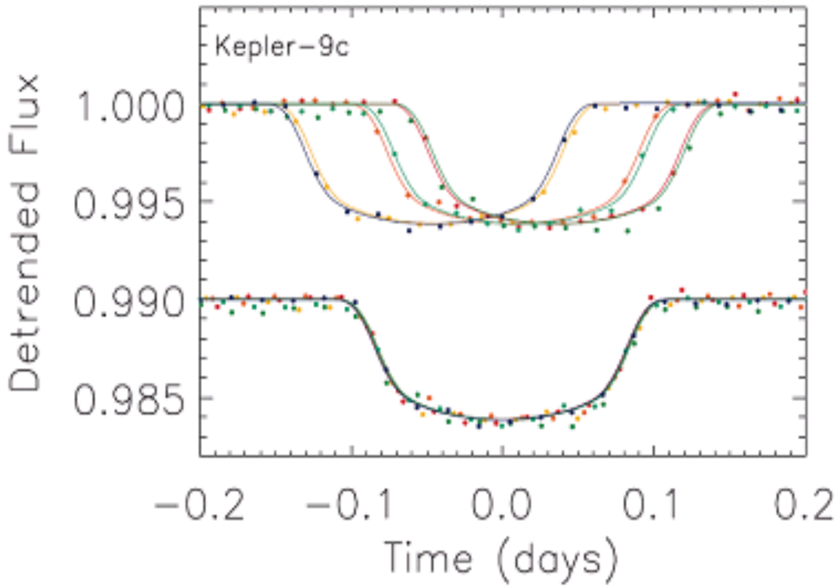
Kepler-11e : P= 32 d

Kepler-11f : P =46.7 d

Kepler-11g : P=118.3 d

Dynamical Determinations of the Mass through Transit Timing Variations (TTVs)





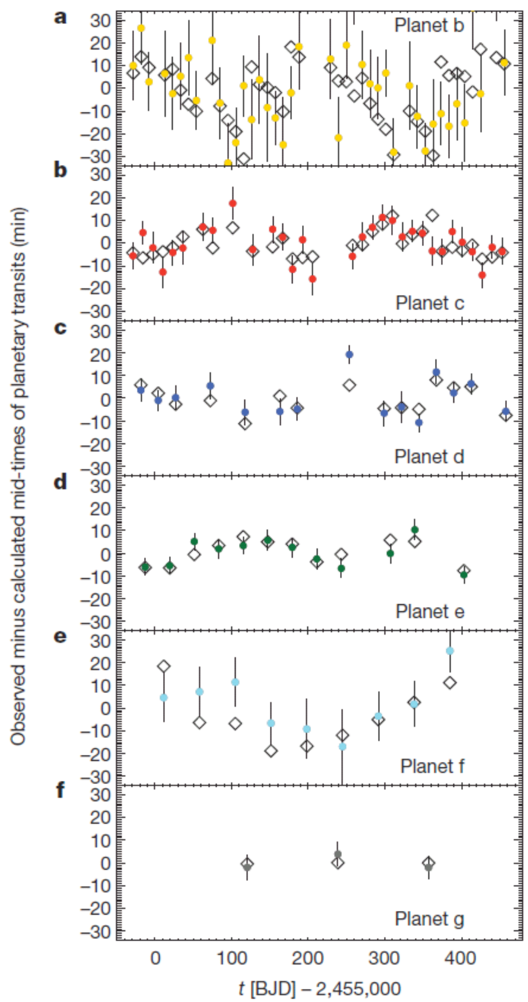
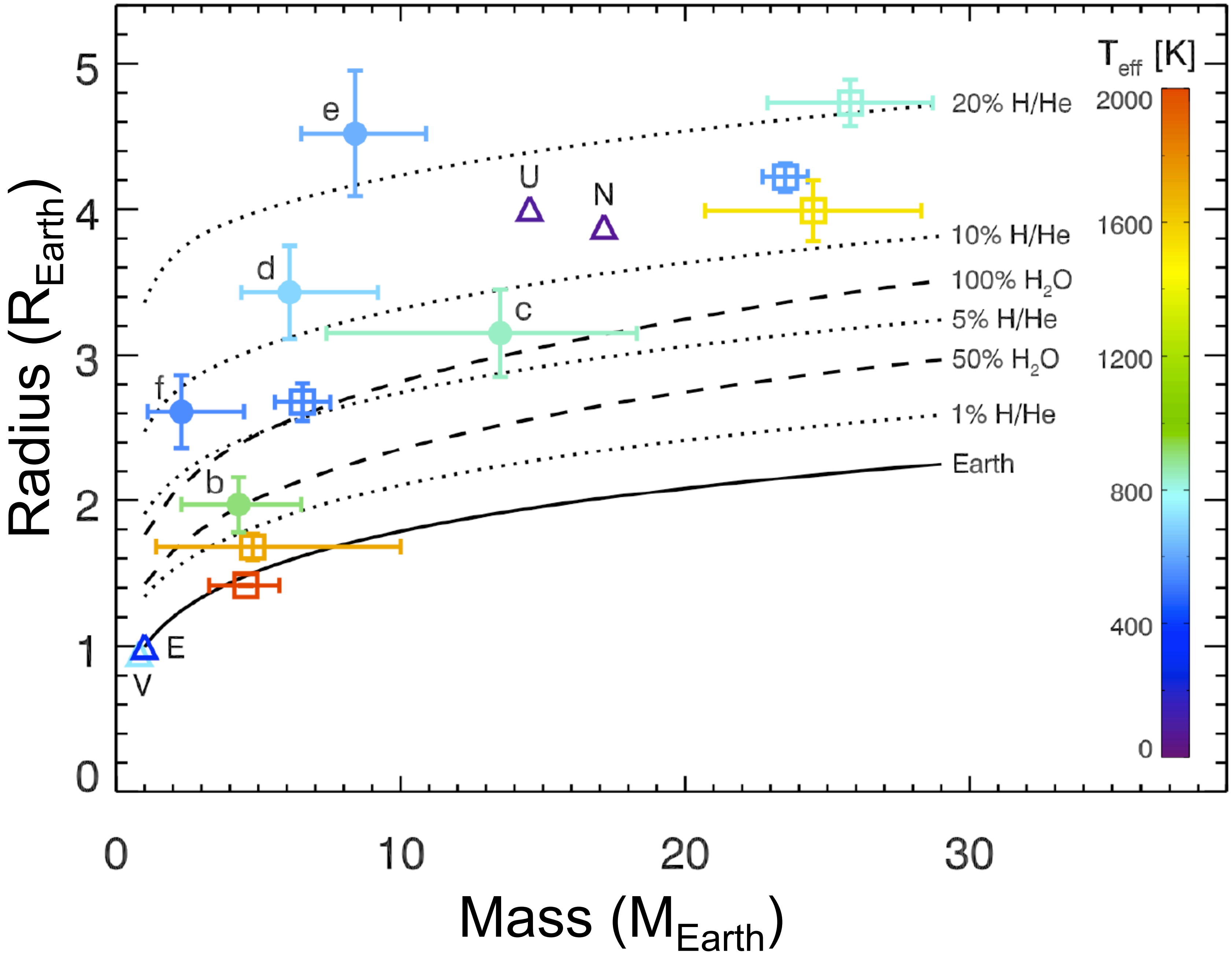
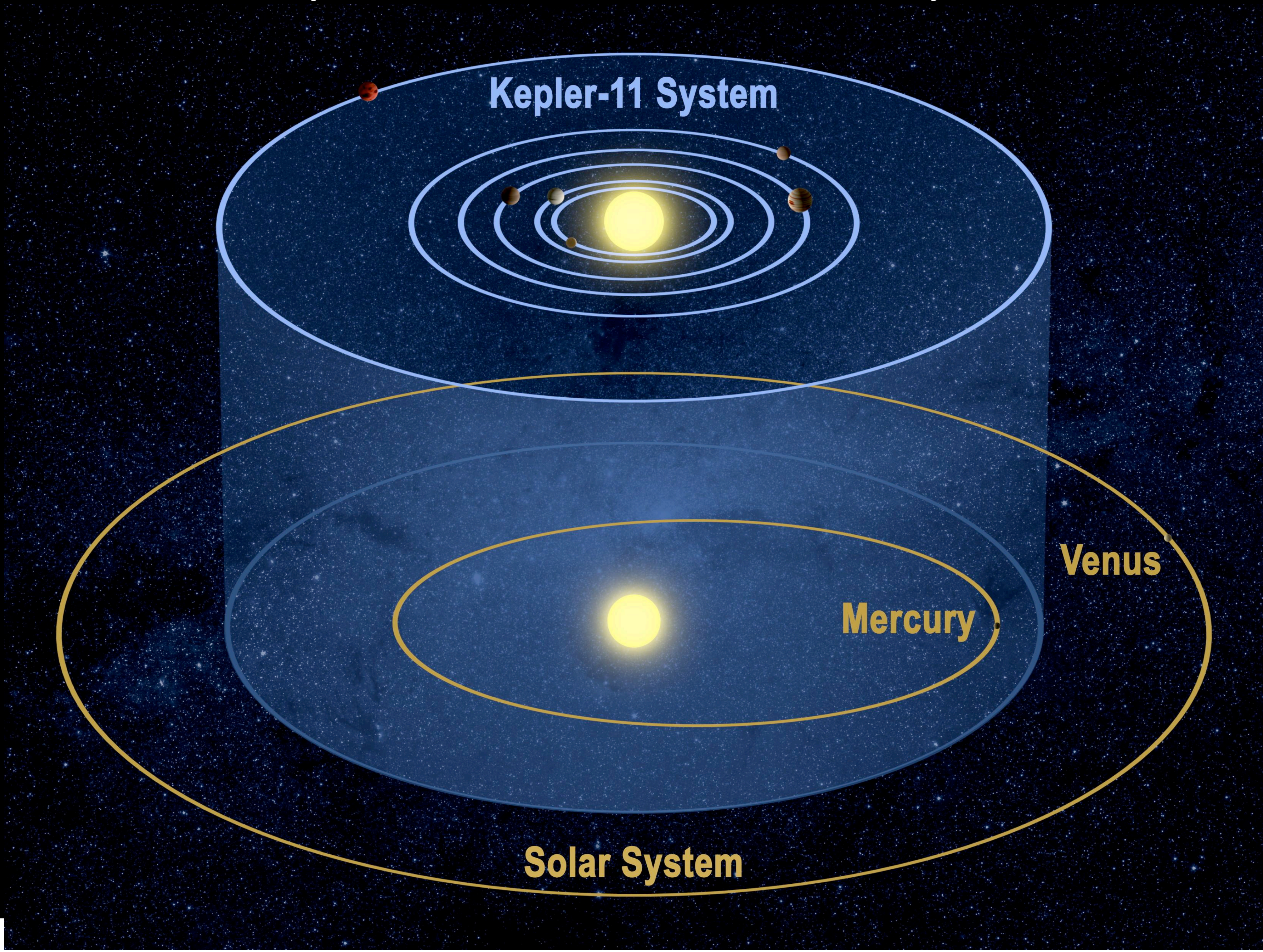


Figure 3 | Transit timing variations and dynamical fits. Observed mid-times of planetary transits (see section 3 of the Supplementary Information for transit-fitting method and Supplementary Table 2 for transit times) minus a calculated linear ephemeris, are plotted as dots with 1σ error bars; colours correspond to the planetary transit signals in Figs 1 and 2. The times derived from the 'circular fit' model described in Supplementary Table 4 are given by the open diamonds. Contributions of individual planets to these variations are shown in Supplementary Fig. 6a.



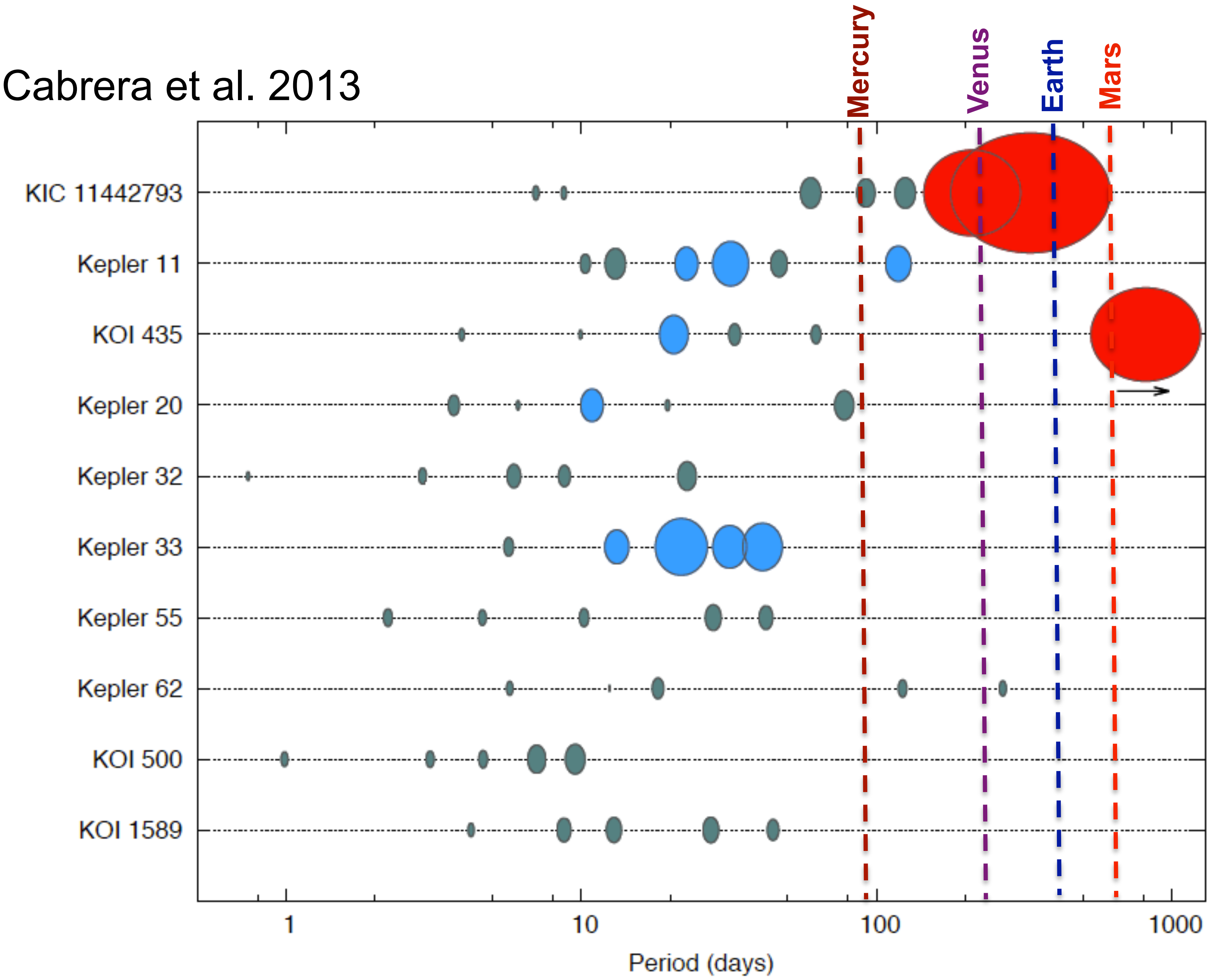
Radius (R_{Earth})
Mass (M_{Earth})
0
10
20
30
0
1
2
3
4
5
e
d
c
f
b
U
N
E
V
20% H/He
10% H/He
100% H_2O
5% H/He
50% H_2O
1% H/He
Earth
T_{eff} [K]
2000
1600
1200
800
400
0

Comparison to our Solar System

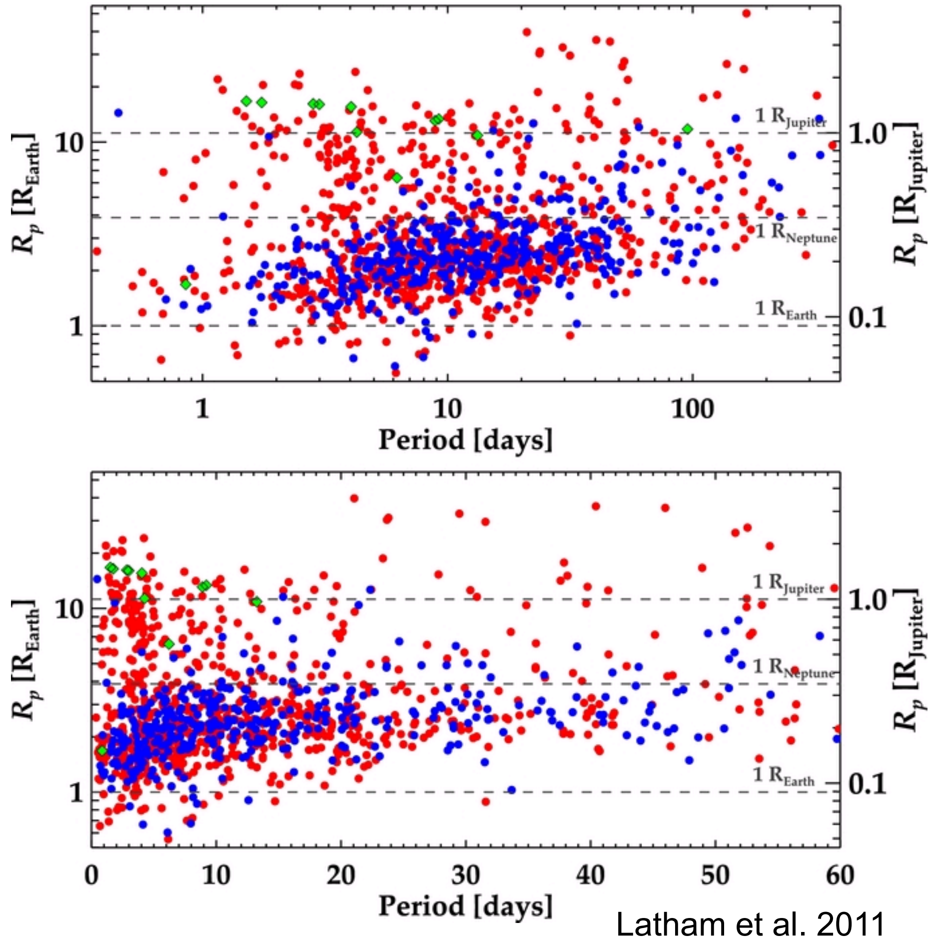


KIC 11442793: Record Holder with 7 planets

Cabrera et al. 2013



Single versus Multiple Planets

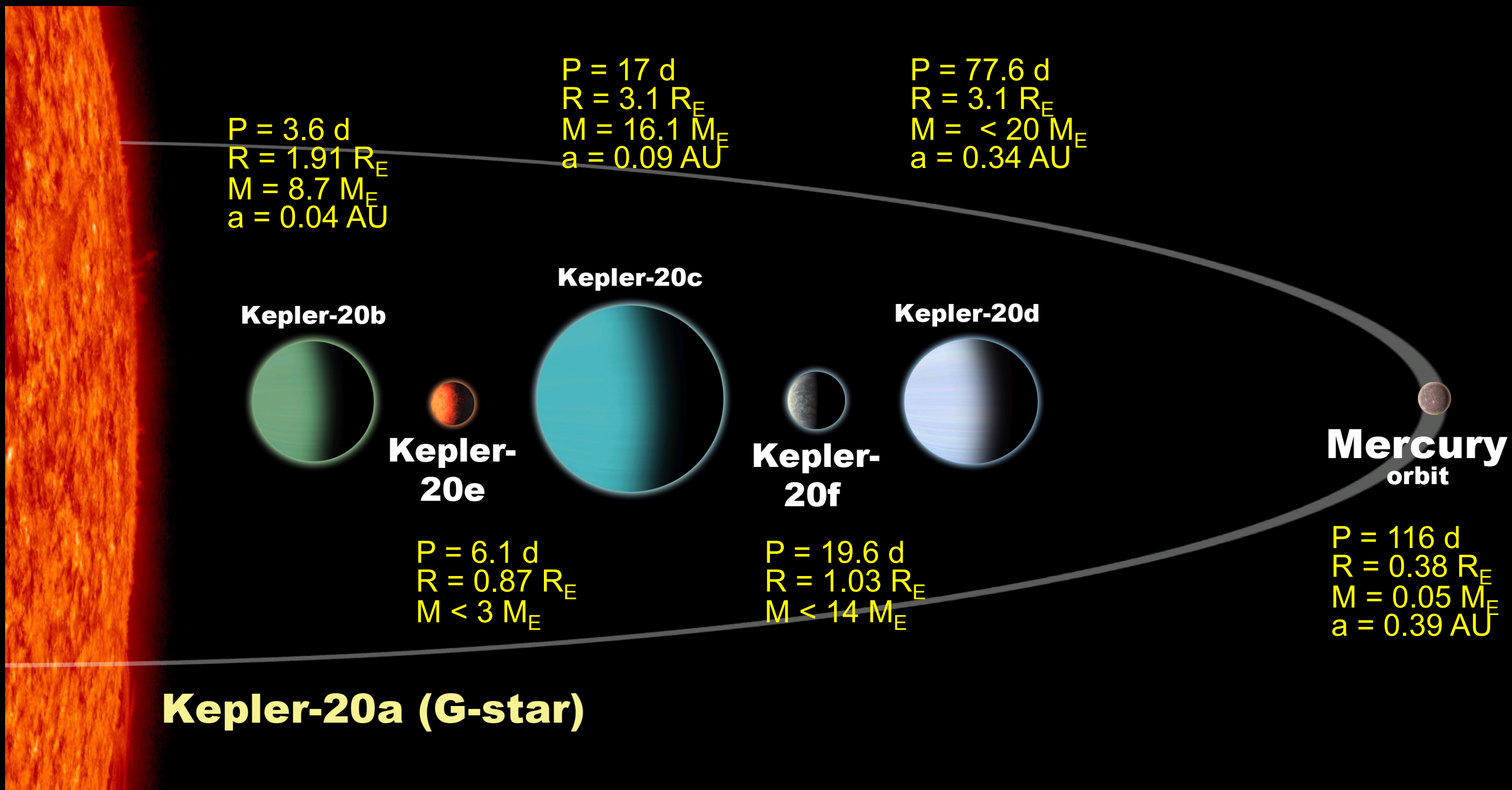


Latham et al. 2011

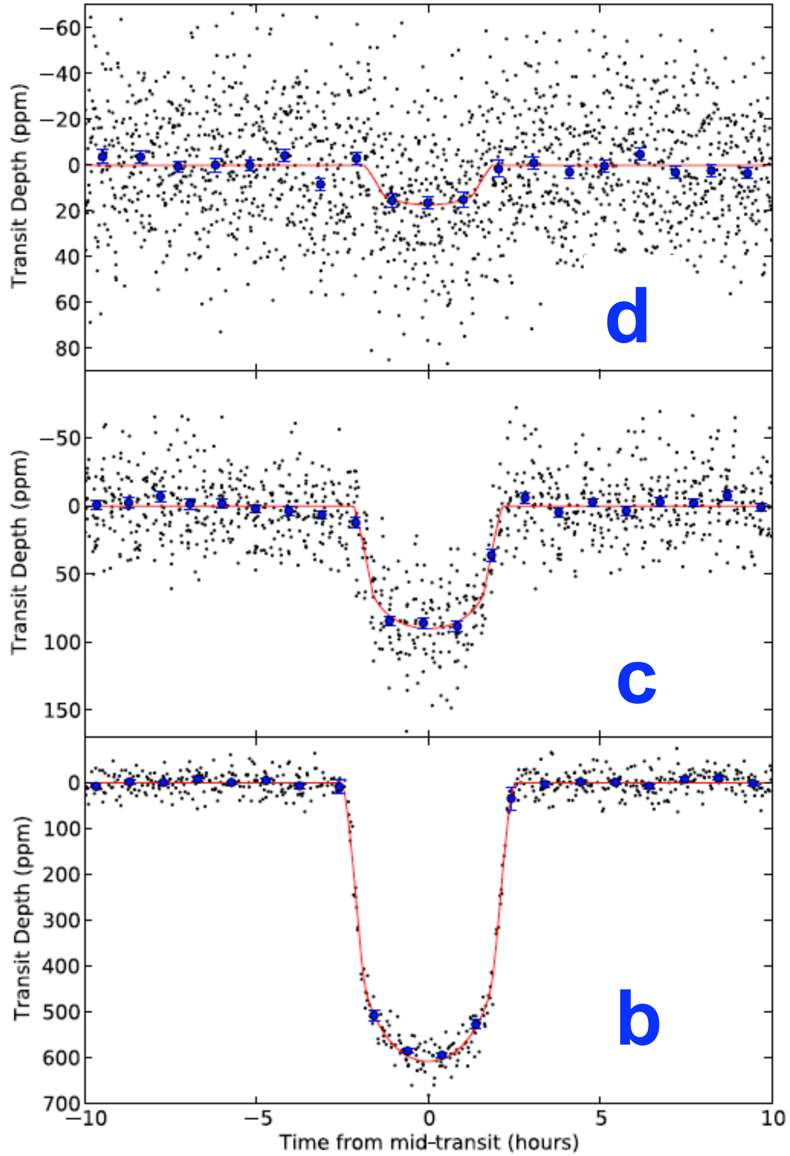
Red: single transits, Blue: multiple transits.

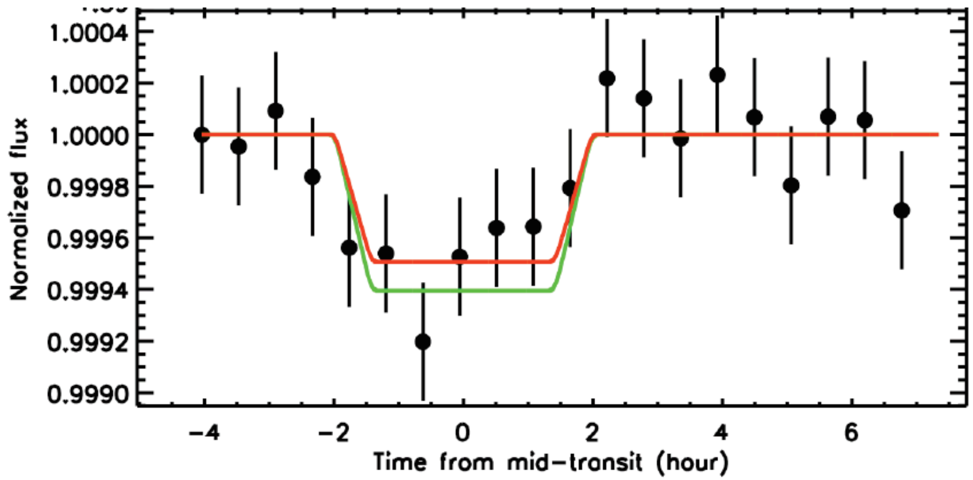
Single planets come in all sizes, but there are relatively few giant planets in transiting multiple system

Kepler 20 b, c, d, e, f: A Planet System with 2 Earth-sized Planets



Kepler 37d – The smallest Exoplanet





$R = 0.74\ R_{Earth}$

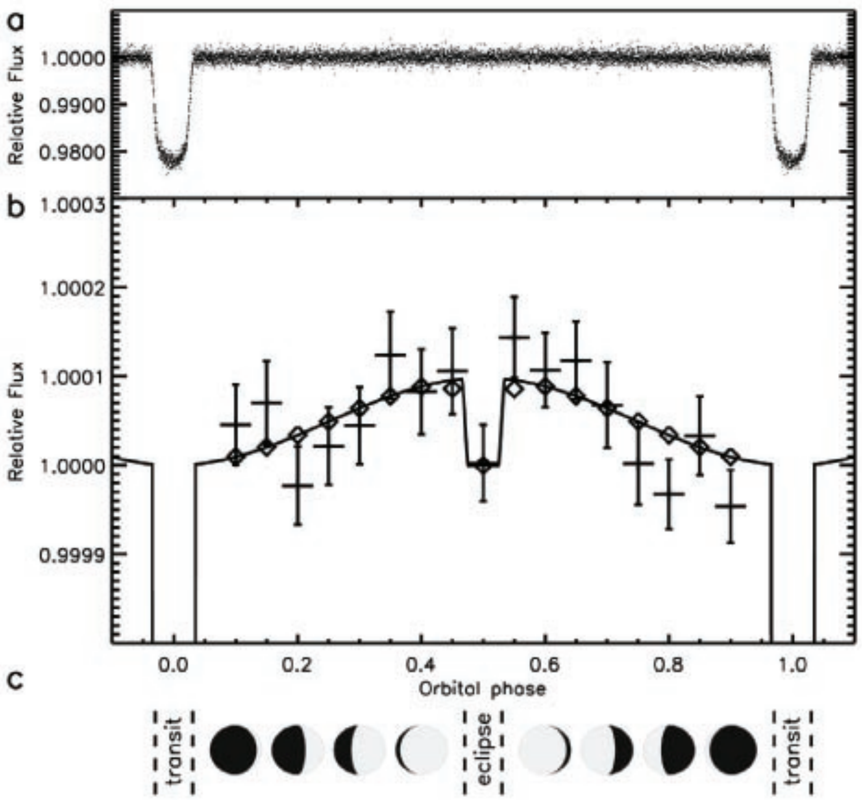
$P = 21.3$ d

$R = 2\ R_{Earth}$

$P = 13.4$ d

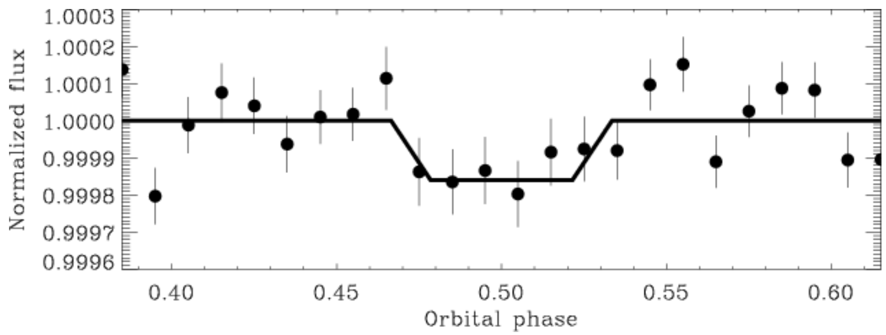
Reflected Light from the Planet

CoRoT-1b:
Secondary Transit und Phase Curve



Snellen et al. 2009

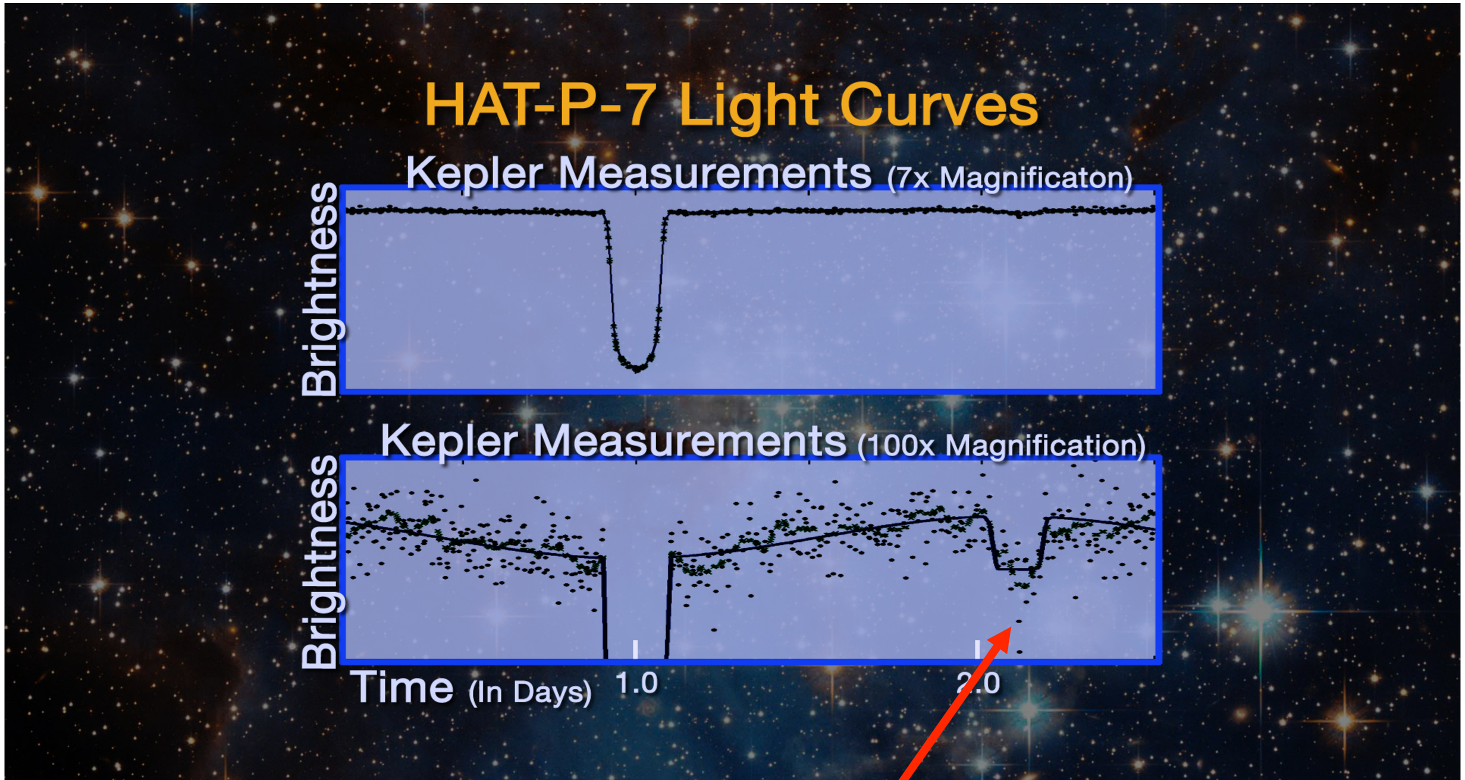
The first detection of the phase curve and secondary transit in the optical.



Alonso et al. 2009

P = 1,5 Days T = 2.100° C

Kepler does this better:



The detection of the secondary transit demonstrated that Kepler should easily detect the transit of an Earth-size planet

Albedo Measurements of Exoplanets

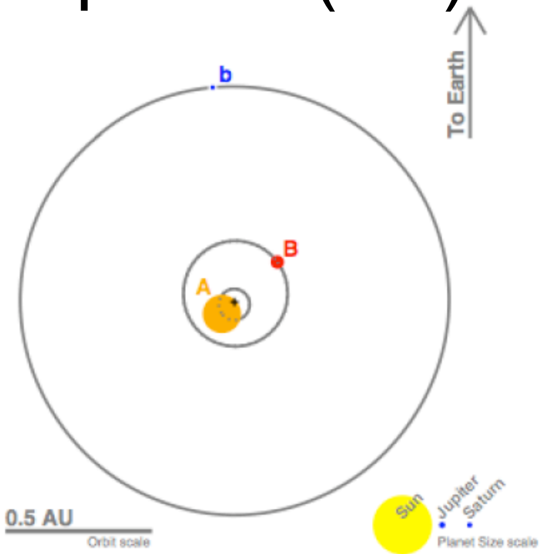
Planet	Albedo (geometric)	T_{eq} (K)	Reference
HD 209458 b	< 0.08 (3σ)	1550	Rowe et al. 2008
HD 75289A b	< 0.12 (3σ)	1260	Leigh et al. 2003
CoRoT-1 b	< 0.20 (3σ)	2330	Snellen et al. 2010
CoRoT-2 b	0.09 ± 0.04	1910	Alonso et al. 2010
HAT-P-7 b	0.12 ± 0.02	2220	Christiansen et al. 2010,
Kepler-5 b	0.12 ± 0.04	1868	Desert al. 2011,
Kepler-6 b	0.11 ± 0.04	1500	Desert al. 2011
Kepler-7b	0.32 ± 0.03	1750	Demory et al. 2011
Earth	0.37		
Jupiter	0.52		
Moon	0.12		

Close-in giant planets are dark!

Planets in Binary Star Systems

Kepler‘s Circumbinary Planets

Kepler 16(AB)b

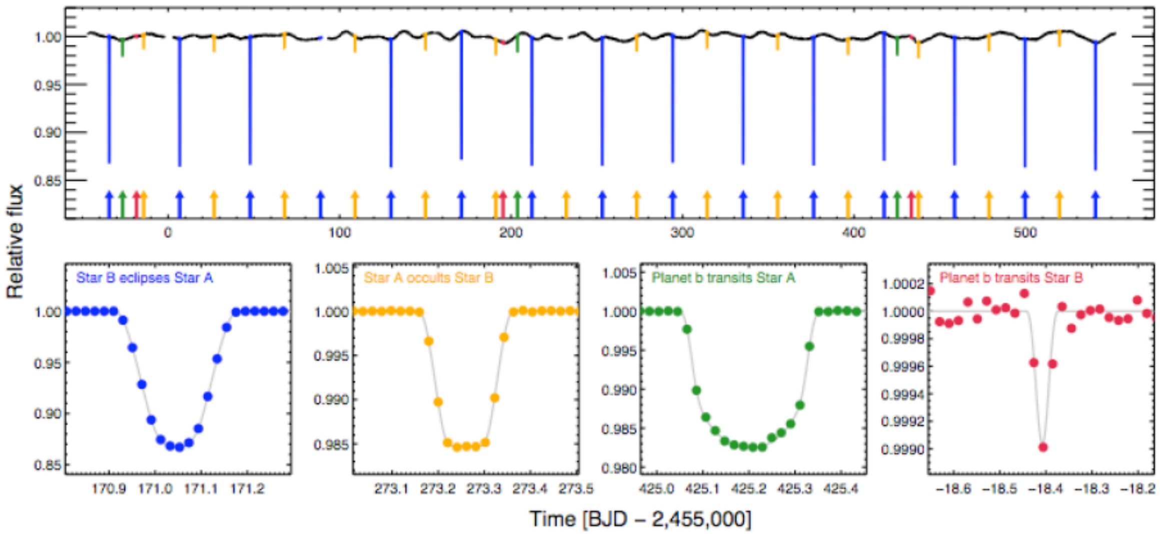


P_{binary} = 41 days

P_{planet} = 229 days

M_{planet} = 0.33 M_J

R_{planet} = 0.75 R_J



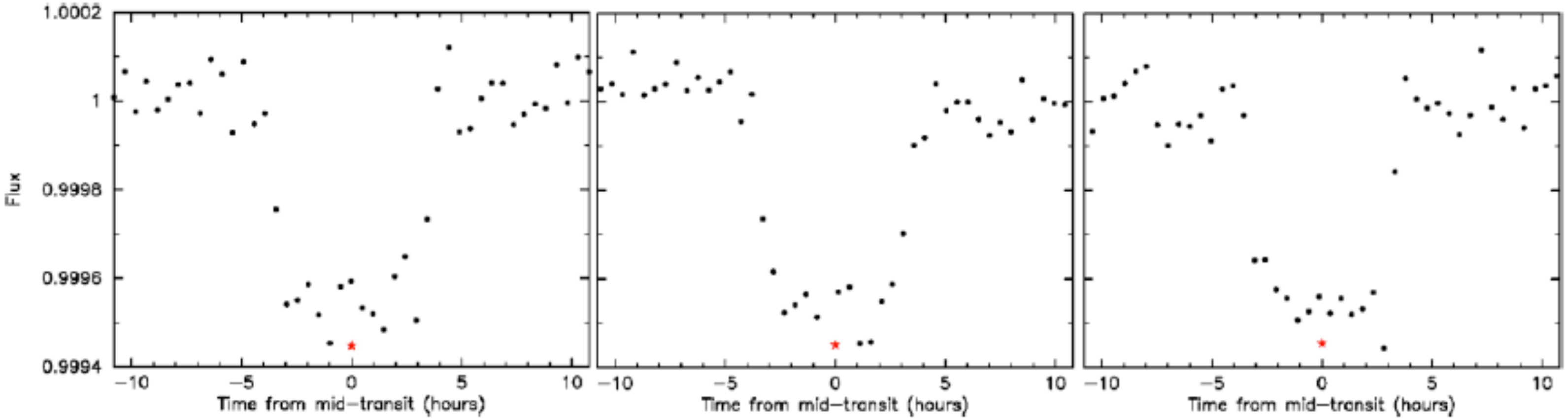
The Circumbinary Planets

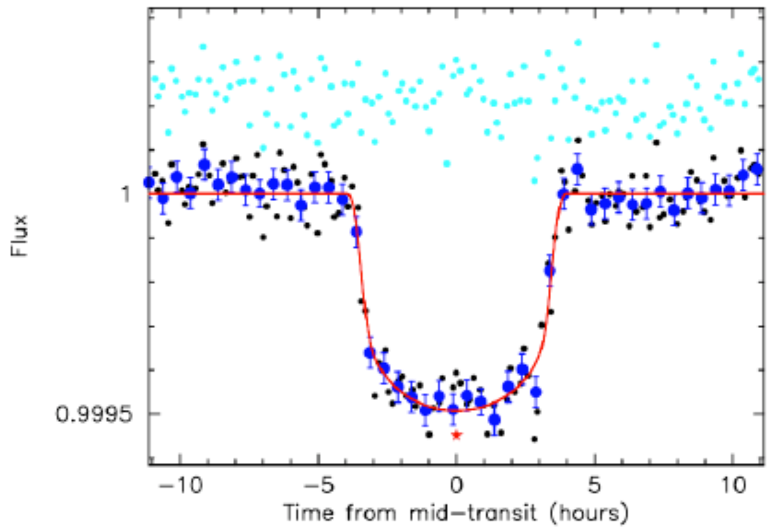
Binary	Planet b	Planet c
$M_A = 1.04\ M_\odot$	$P_b = 49.5$ d	$P_c = 303$ d
$M_B = 0.36\ M_\odot$	$R_b = 2.98\ R_{Earth}$	$R_c = 4.61\ R_{Earth}$
$P_{AB} = 7.44$ d		

Orosz, Welsh, Carter et al. Science 2012

Planets in the Habitable Zone

Kepler-22b: „Super-Earth“ in the Habitable Zone





Radius = 2,38 R_{Earth}

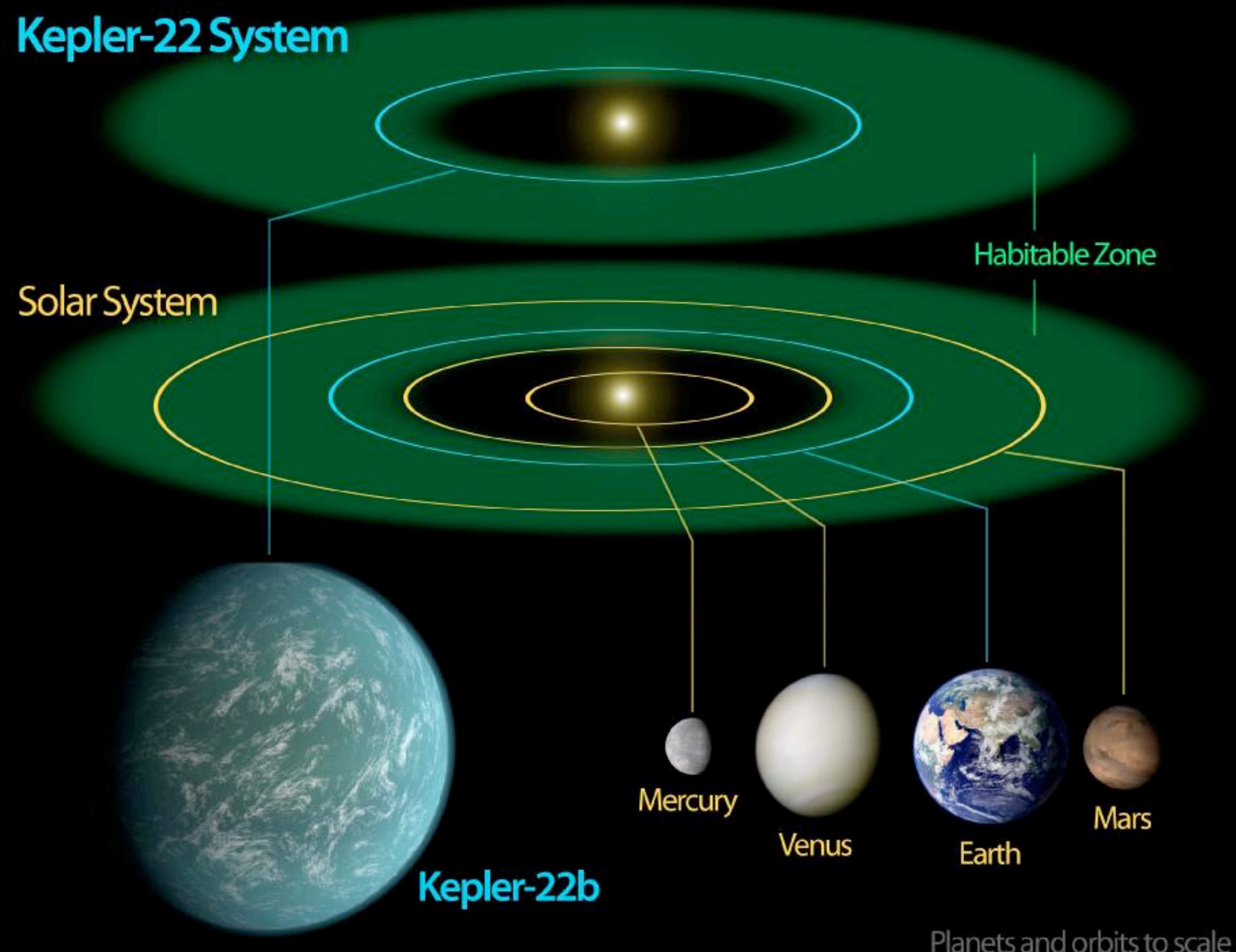
Mass < 36 M_{Earth}

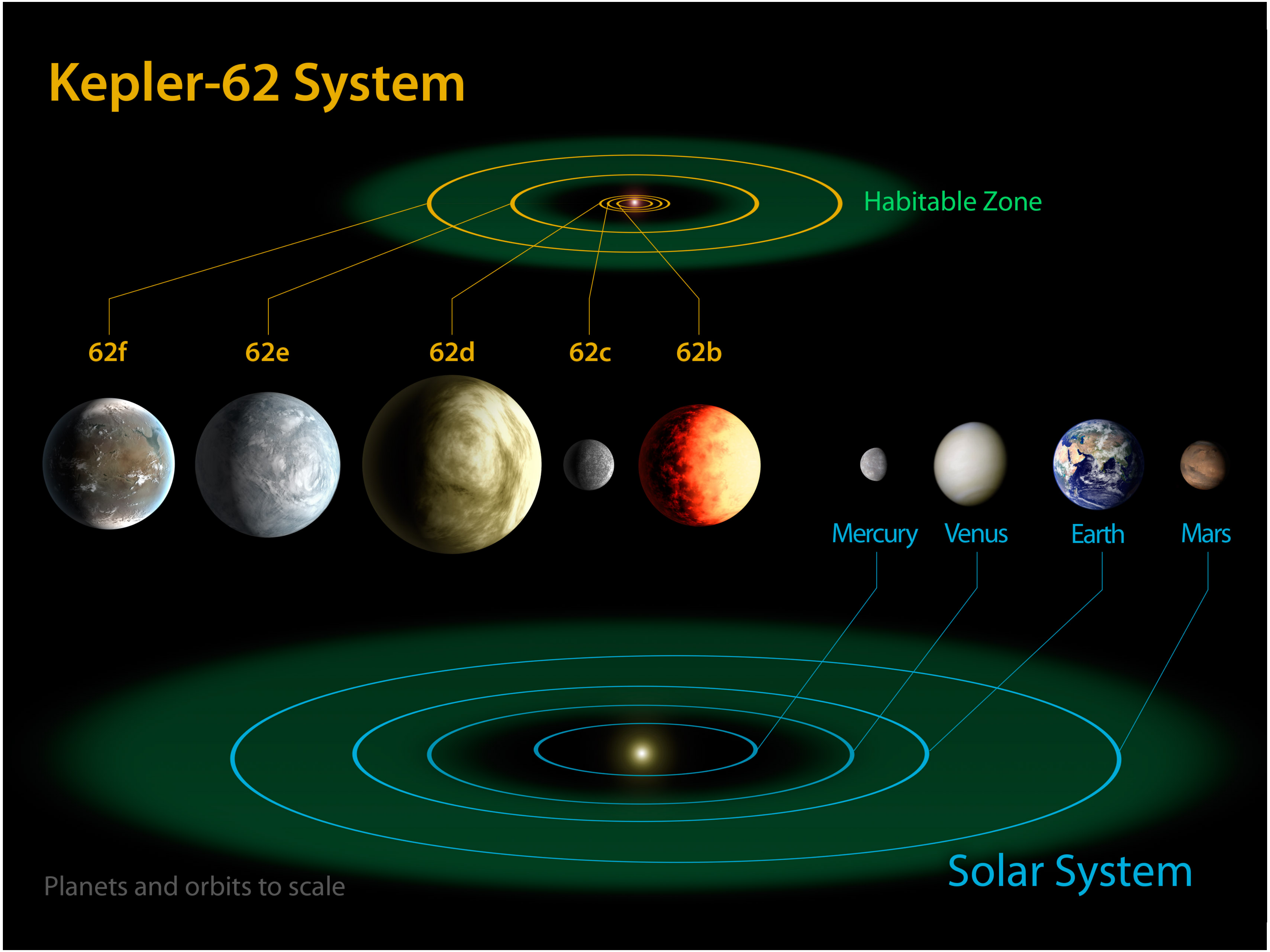
Period = 290 Days

Distance to Star = 0,89 AU

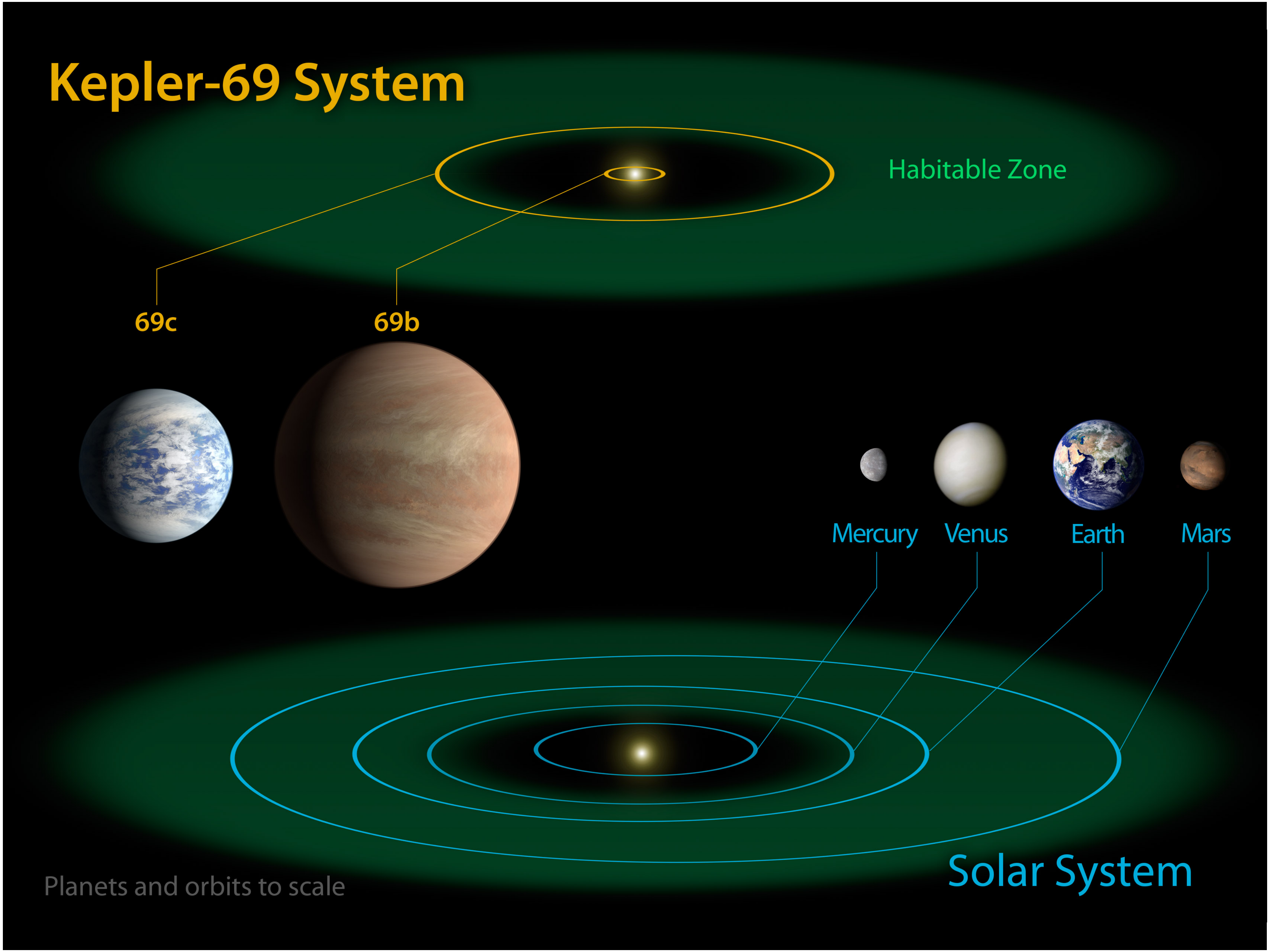
Temperature = 262 K

Compared to Solar System

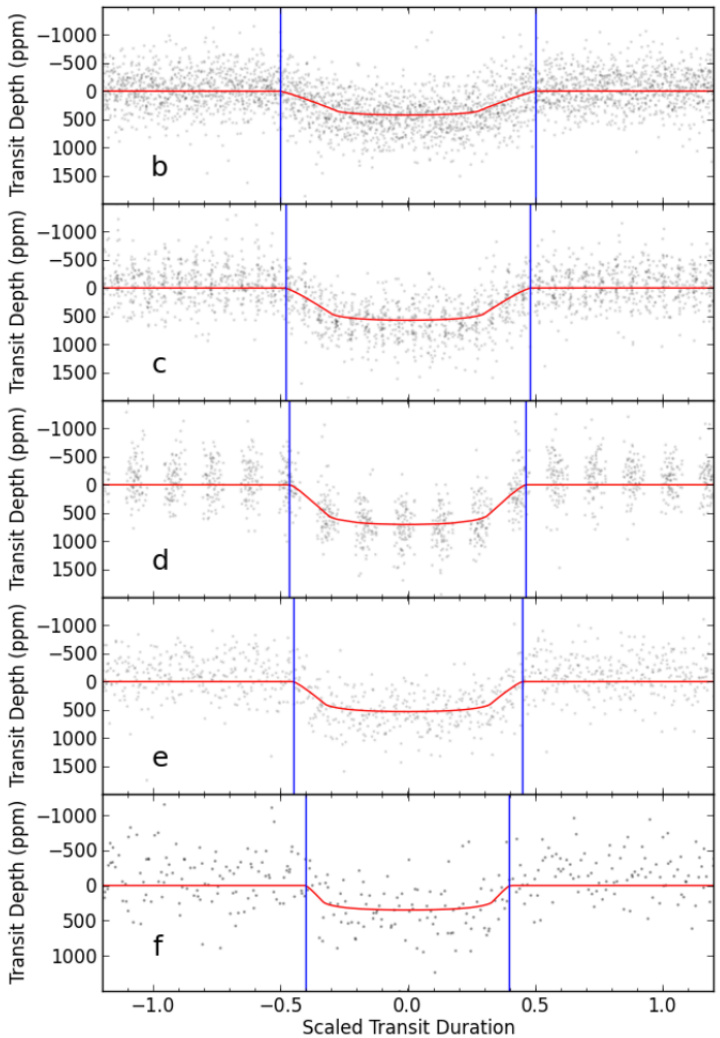




Kepler-62 System
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale


Kepler-69 System
Habitable Zone
69c
69b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale

Kepler's „First" Habitable Earth-sized Planet



$R = 1.07 \pm 0.12\ R_{earth}$

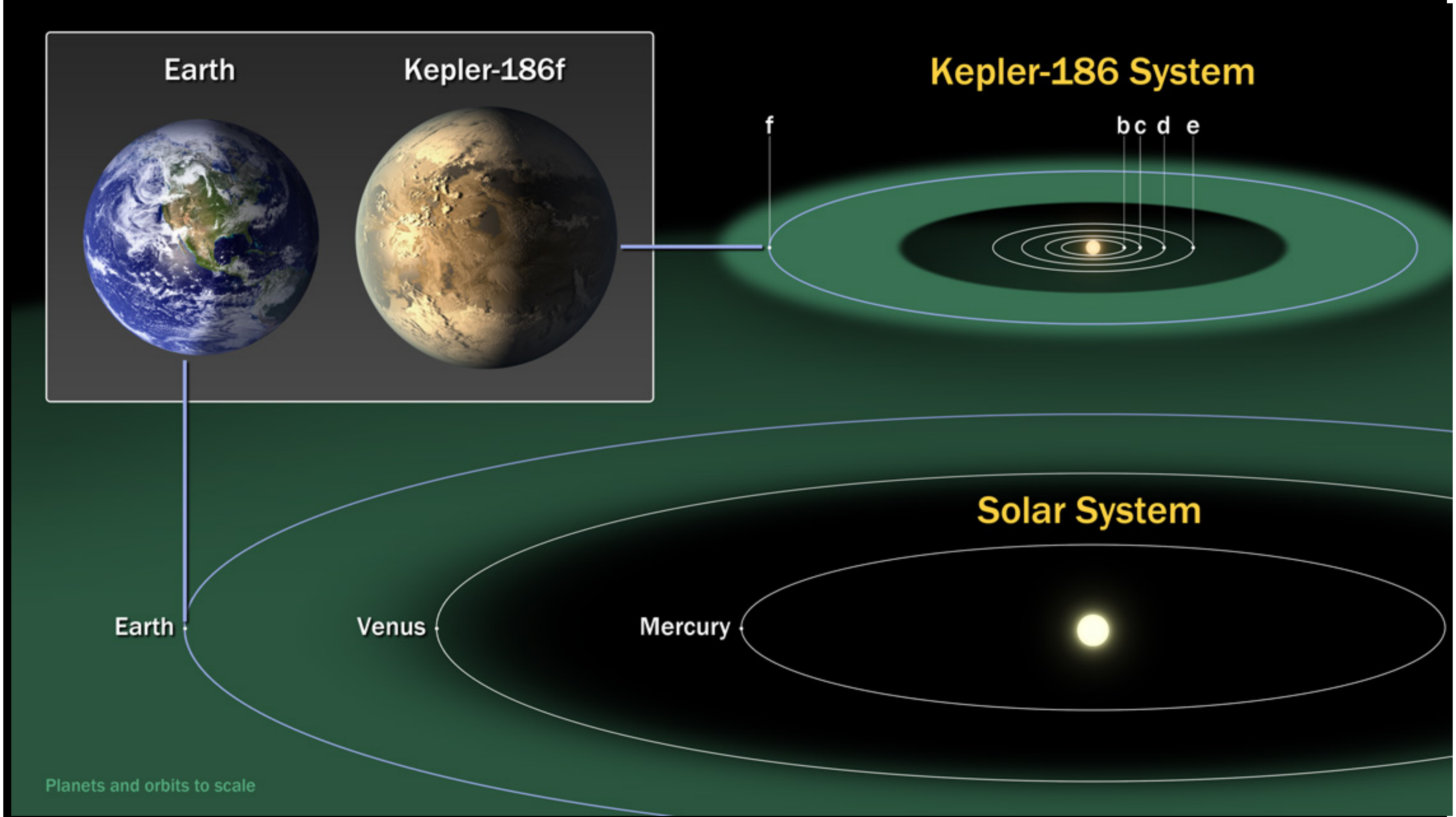
$R = 1.25 \pm 0.14\ R_{earth}$

$R = 1.40 \pm 0.16\ R_{earth}$

$R = 1.27 \pm 0.15\ R_{earth}$

$R = 1.11 \pm 0.14\ R_{earth}$

Kepler‘s „First“ Habitable Earth-sized Planet



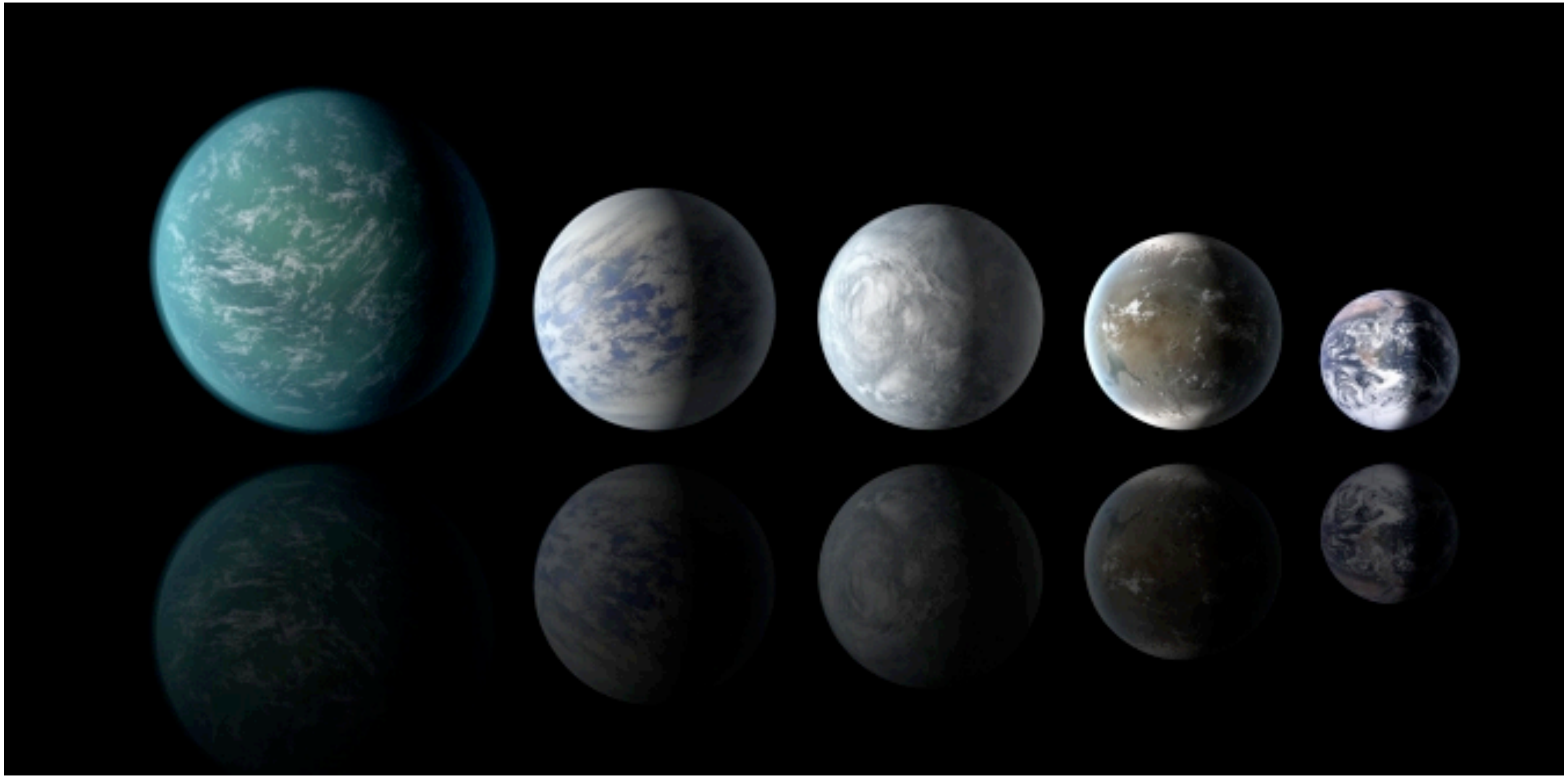
NASA‘s Public Relations (Marketing) Machine

December 5, 2011: Kepler-22b
“NASA’s Kepler Mission Confirms its **First** Planet in the Habitable Zone of a Sun-like Star”

April 18, 2013: Kepler-62e,f and Kepler-69c
“Earth-Like Planets Found in Habitable Zone around Kepler-62, Kepler 69”
“These planets are not like anything in our solar system. They have endless oceans.”

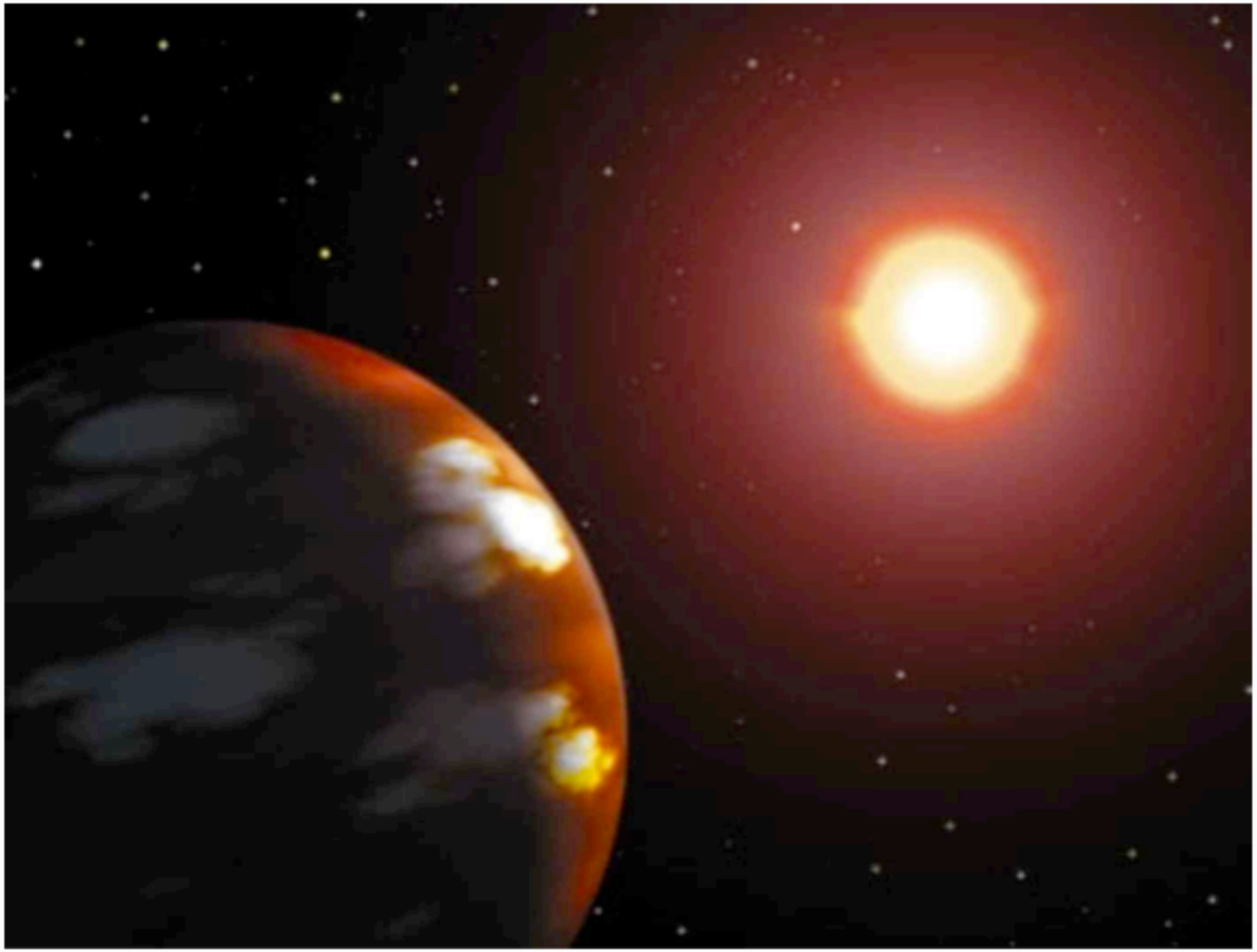
April 17, 2014: Kepler-168f
“NASA’s Kepler Discovers **First** Earth-like Planet in the Habitable Zone of Another Star”

Kepler’s lineup of “Habitable Planets” before Kepler 186f (the “first”)



New Planet Discovered 400 Light Years Away From Public's Interest

NEWS IN PHOTOS · Science & Technology · Science · Space · ISSUE 41·34 · Aug 24, 2005

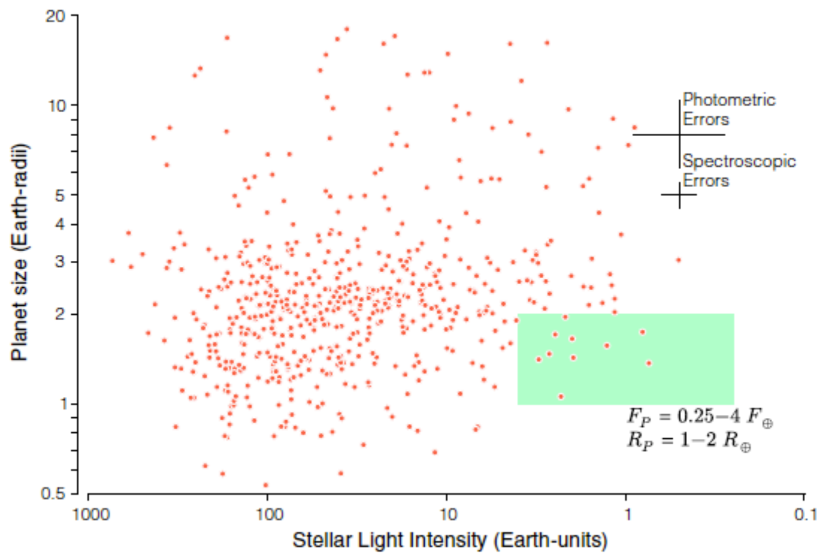


What about η_{Earth} (fraction of stars with rocky planets in the habitable zone)?

From Petigura et al. (Kepler Conference 2013):

- Independent analysis of Kepler light curves
- 603 small planet candidates found, 10 in Habitable Zone
- Detection bias assessed with simulations inserting and recovering simulated planets
- Spectroscopy of the Host Stars with P > 100 d

The Answer (?):



l planets (dots) in a 2D domain similar to Figs. 1 and 2. Here, the 2D domain has orbital period replaced by stellar light intensity, incider

22 ± 8% of stars have planets with radii 1-2 R_E, and incident stellar flux 0.25-4 F_E

4 F_E ➔ 0.5 AU

0.25 F_E ➔ 2 AU

Kepler observed 100.000 stars, should have found ~100 planets, but only 10 real detections ➔ factor of 10 correction

➔ If your "experiment" is not detecting most of the planets, you need to design one that does

Status of CoRoT

- On 7 March 2009 one DPU lost (2 CCDs)
- On 2 November 2013 second DPU lost, just before the start of the second extended mission
- All efforts to revive have failed.
- Operations will formally end mid-2015
- > 160.000 light curves

Status of Kepler

- In July 2012 one reaction wheel lost
- On 14 May 2013 second reaction wheel lost just before the start of the extended mission
- Precision pointing lost unable to collect high precision light curves for a long time
- Efforts to revive reaction wheels have stopped
- 150.000 light curves at start, 100.000 light curves over 4 years.

The Space Transit Search Graveyard

“Rumors of my death were greatly exaggerated.”

SuperCoRoT

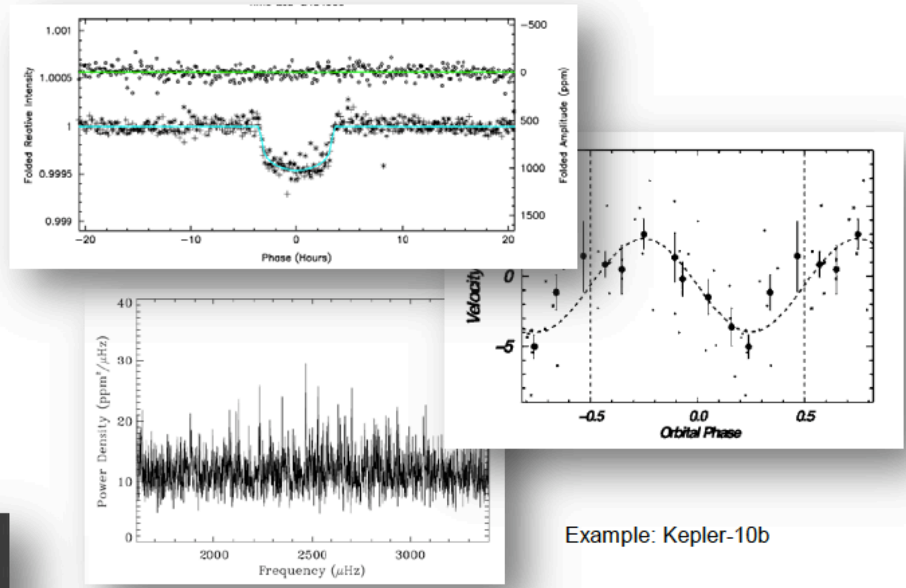
- 2 Reaction Wheels + Thrusters for positioning
- Look in Ecliptic where solar wind has minimum effect
- Observe a field of 10.000 – 20.000 stars for 40-80 days, move to the next field
- 4-6 fields per year
- precision ~ 3×10^{-4}

The PLATO Mission

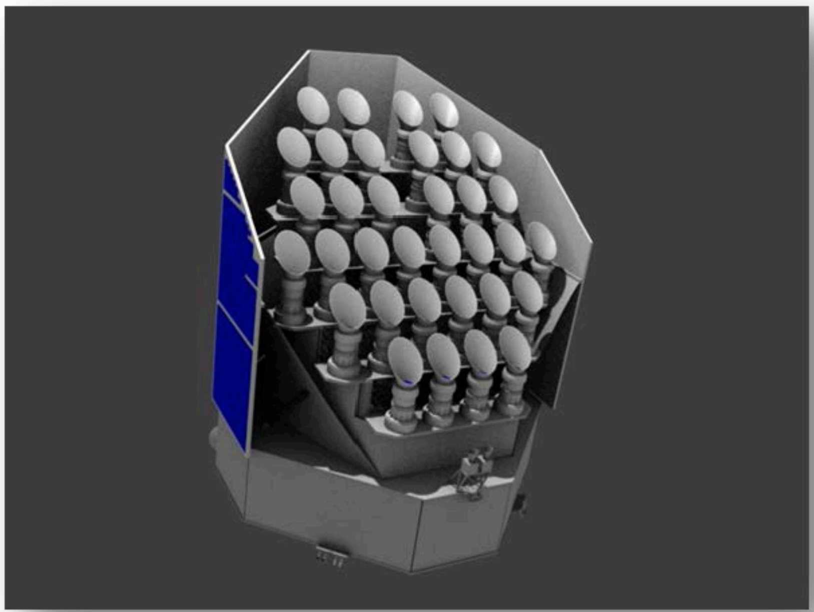
Mission **approved** for ESA M3 launch selection

PLATO :

- planets around bright stars
- astroseismology of hosts
- ultra-high precision
- very wide field



Example: Kepler-10b



Accuracy:

An Earth around a Sun :

- radius up to 2%
- mass up to 10%
- age known to 10%

The Legacy of CoRoT and Kepler

1. The most precise light curves and thus best measurements of exoplanet radii and densities. 200 Confirmed planets, ~3000 candidate planets
2. Unbiased detections: Every transiting planet down to Superearth (Earth) detected, unlike ground based surveys that only find the largest exoplanets
3. First transiting rocky planet found by CoRoT (7b) and its twin by Kepler (10b)
4. Rocky planets in “ultra-short” period orbits < 1 d (Kepler 78b: 8.5 hours!)

The Legacy of CoRoT and Kepler

5. Smallest Planet (1.4 R_{Moon}) found by Kepler
6. Multi-planet, compact superearth systems are common
7. More Neptunes-size than Jupiter-size planets
8. Multi-system: Neptunes and Superearths, Single: Jupiters, Neptunes, and Superearths
9. Circumbinary planets are common

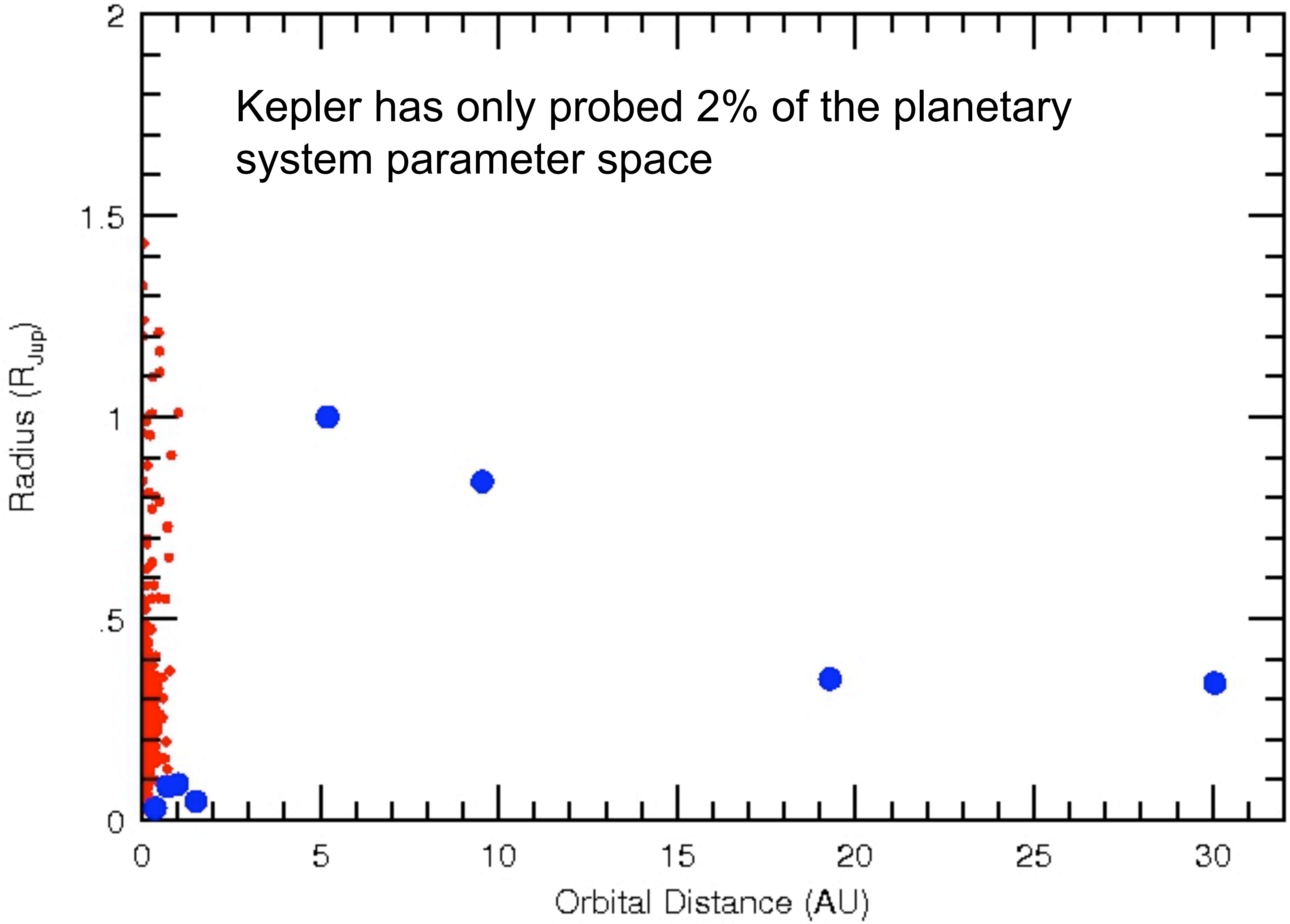
The Legacy of CoRoT and Kepler

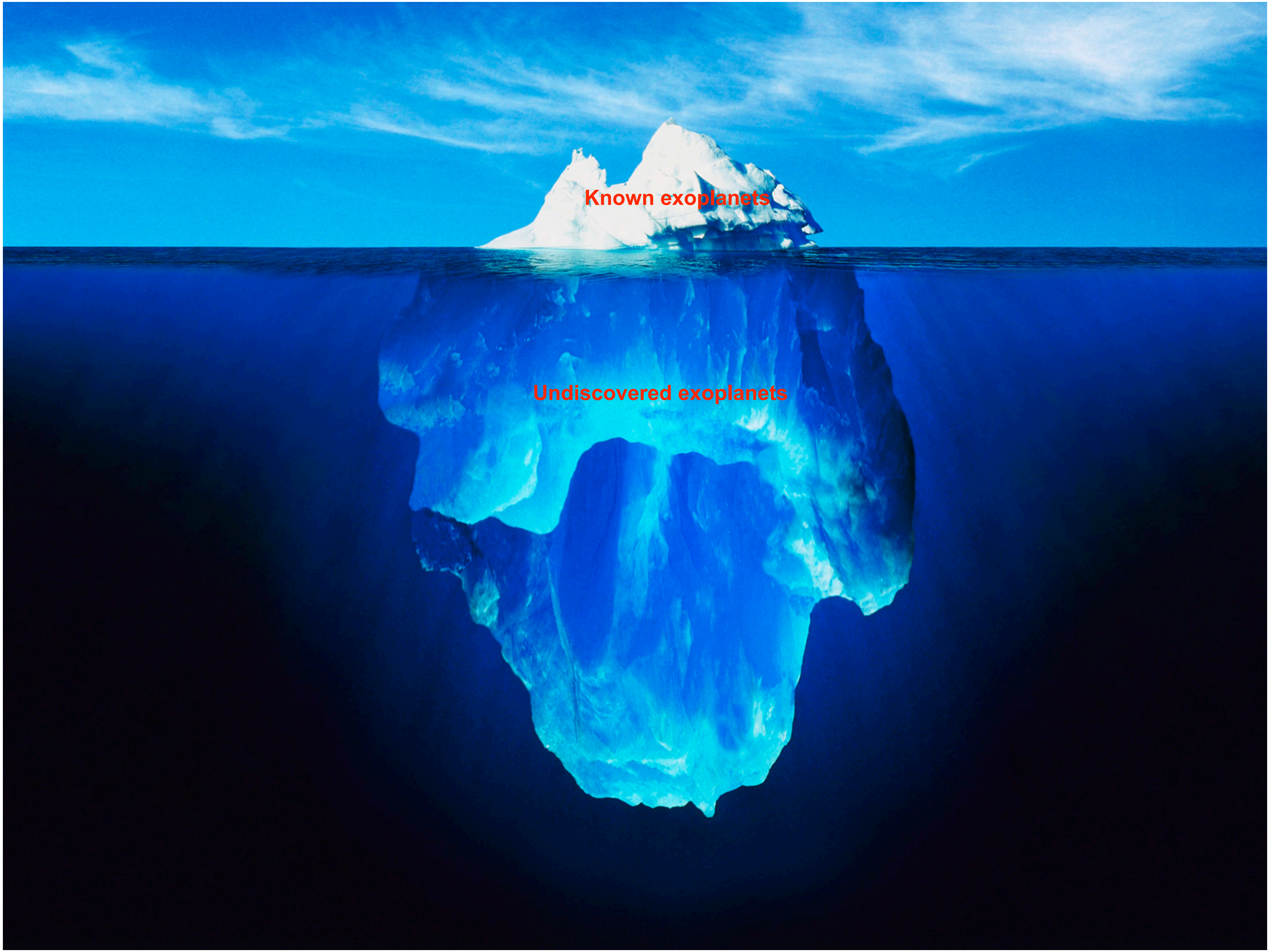
10. May be a diversity in densities, even for adjacent planets ➔ need for PLATO
11. First rough estimate of η_{Earth} (22%) but a more accurate value is needed ➔ PLATO
12. Lots of stellar astrophysics ➔ not just exoplanet missions!

We are still searching for a planetary system like ours!

“A transit mission’s got to know its limitations.”

Kepler Parameter Space




Known exoplanets
Undiscovered exoplanets

Thank you for your attention!