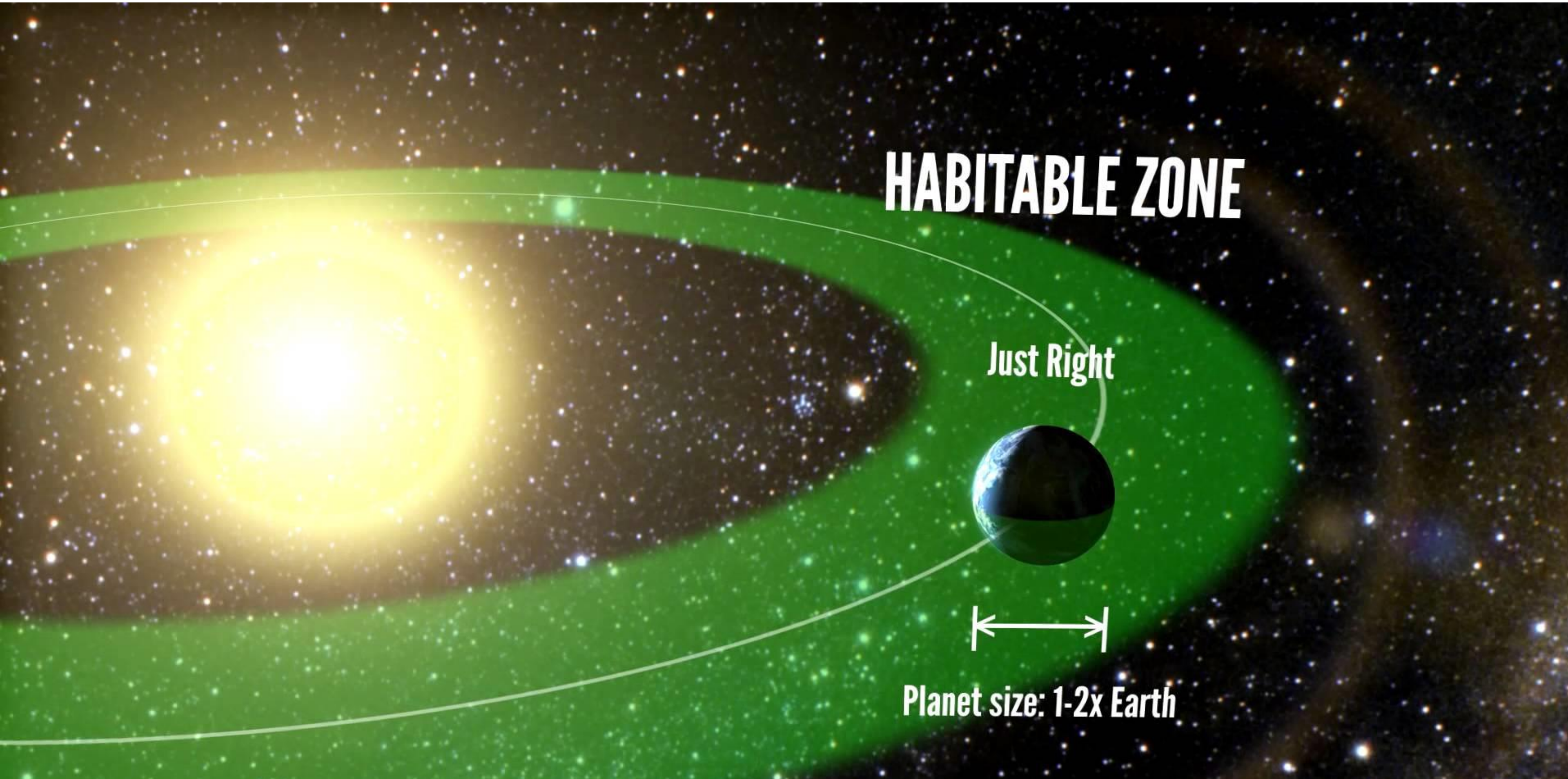
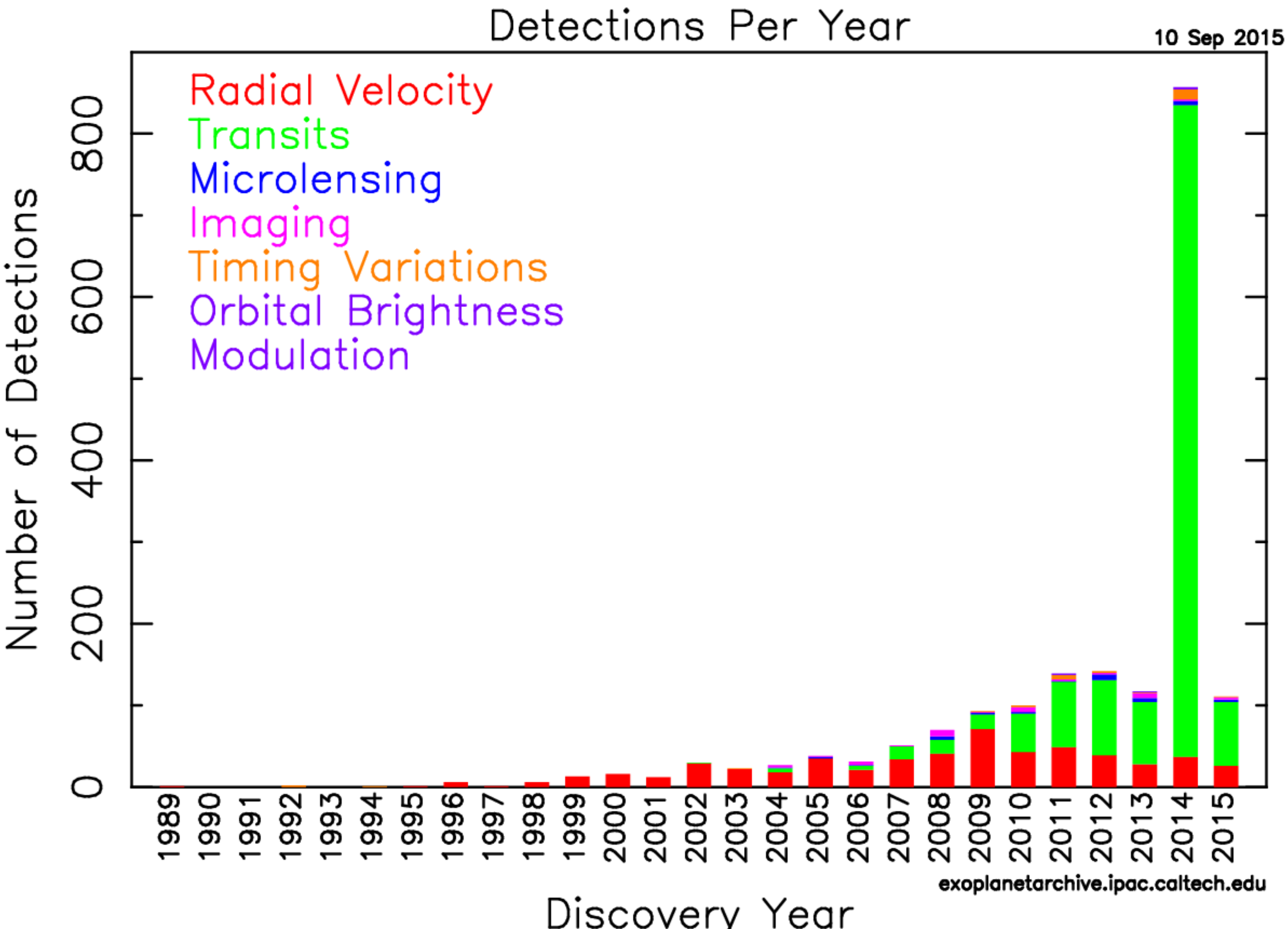
ExoPlanets:
The Era of Comparative Planetology



A. Sozzetti
INAF – Osservatorio Astrofisico di Torino

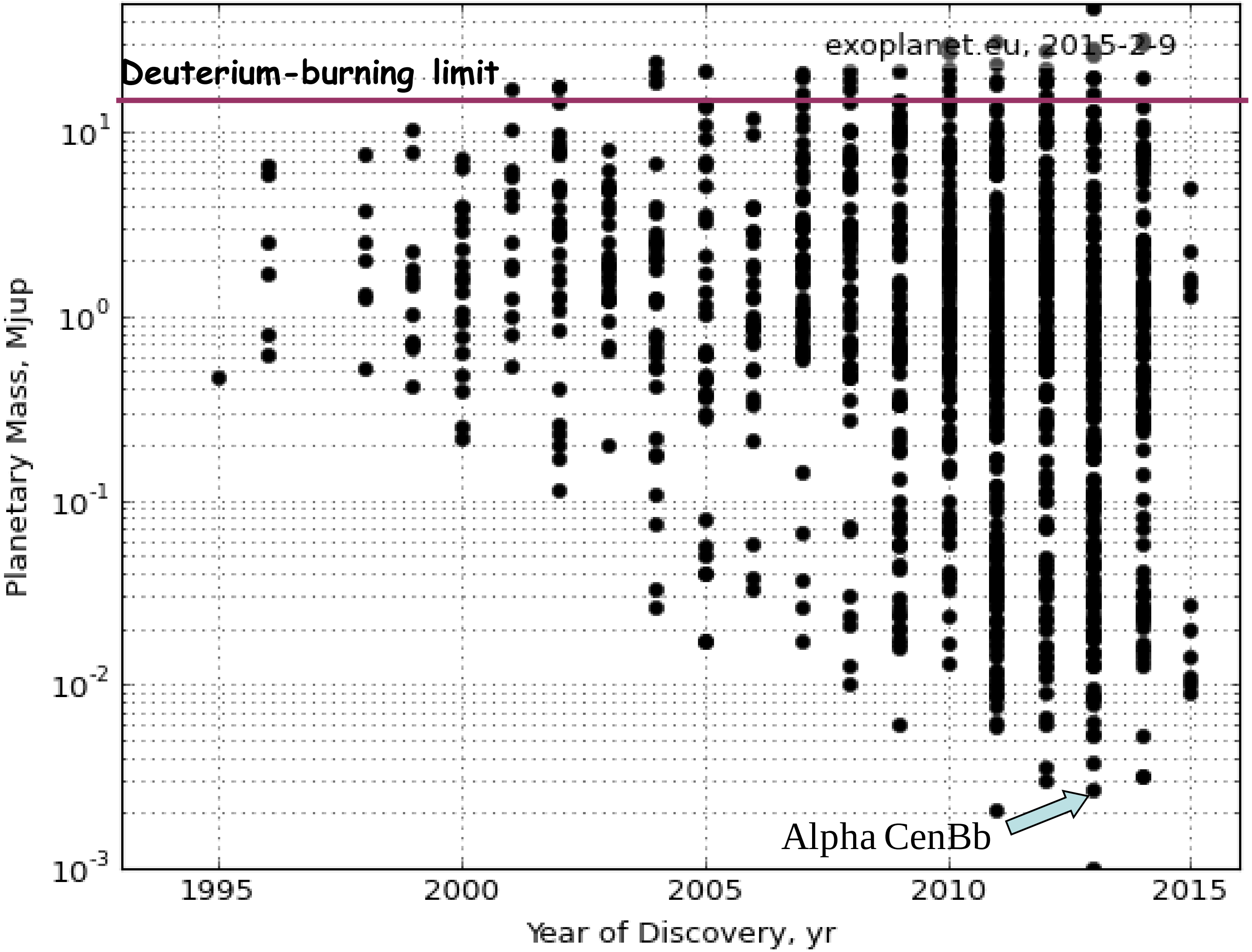
Exoplanetary Population



High-Precision RVs

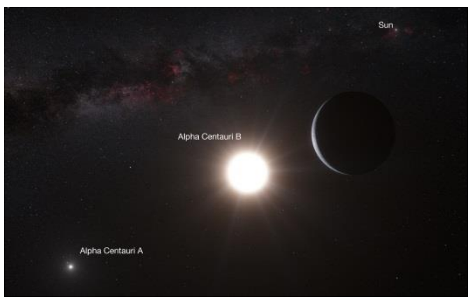
- 1-m/s precision measurements (1 km/s for binary work)
- Fundamental for transiting candidates confirmation (mass determination)
- Long-term surveys (e.g. HARPS) critical for uncovering planet properties, frequencies, and correlations with the hosts' characteristics
- The discovery of planets with Earth's mass (not radius) already made!

The Radial Velocity 'Revolution'

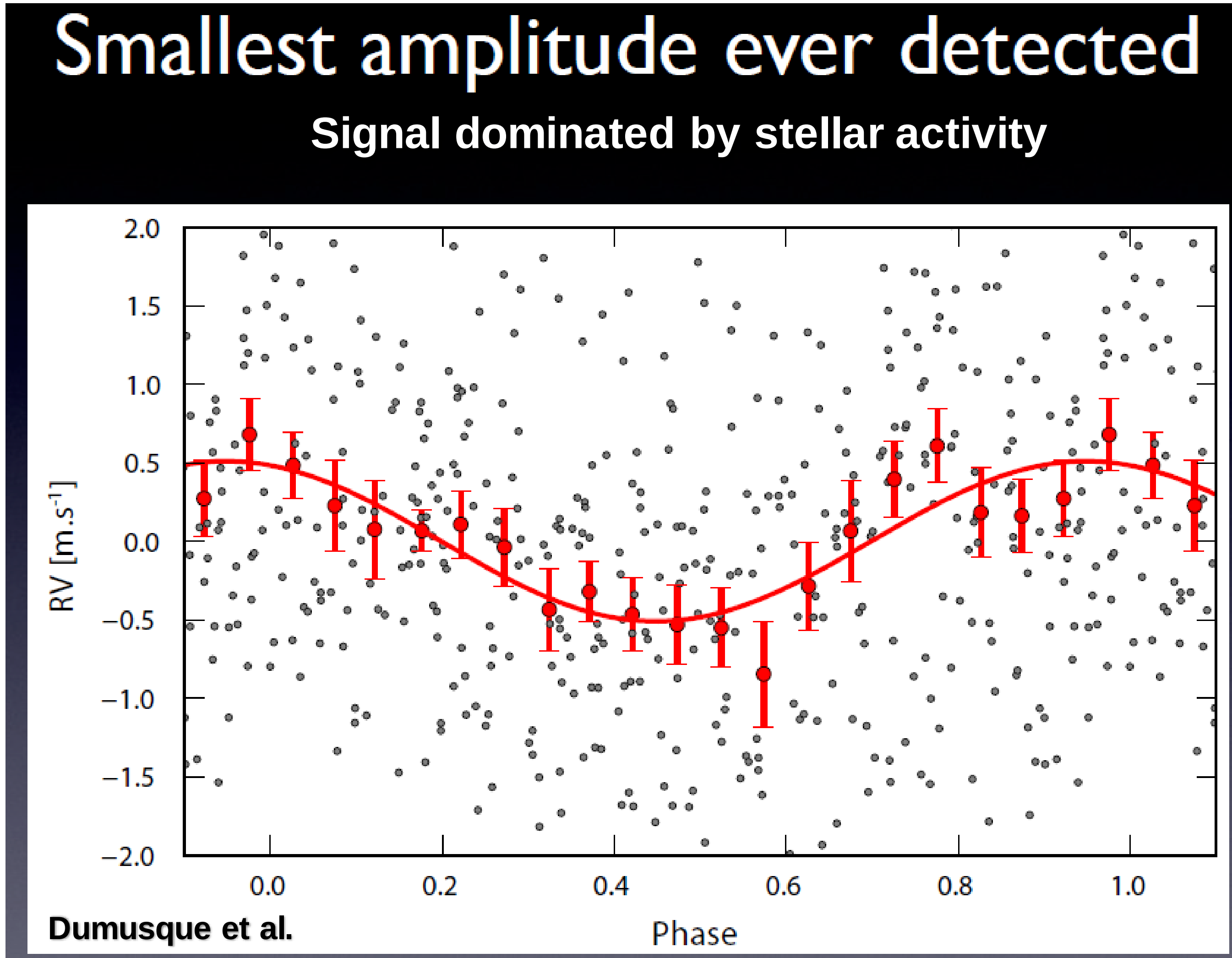


α Cen Bb:
The First Earth-(minimum)mass Planet

P = 3.236 days
K = 51 cm/s
M_{pl} sin(I)= 1.1 M_E

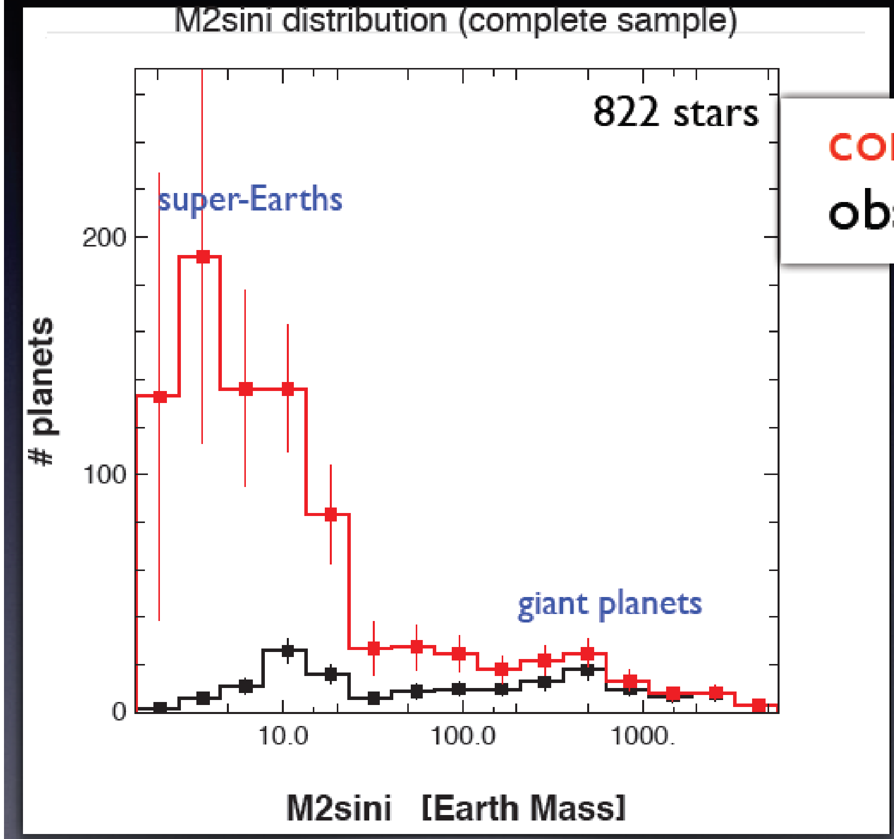


460 RVs!

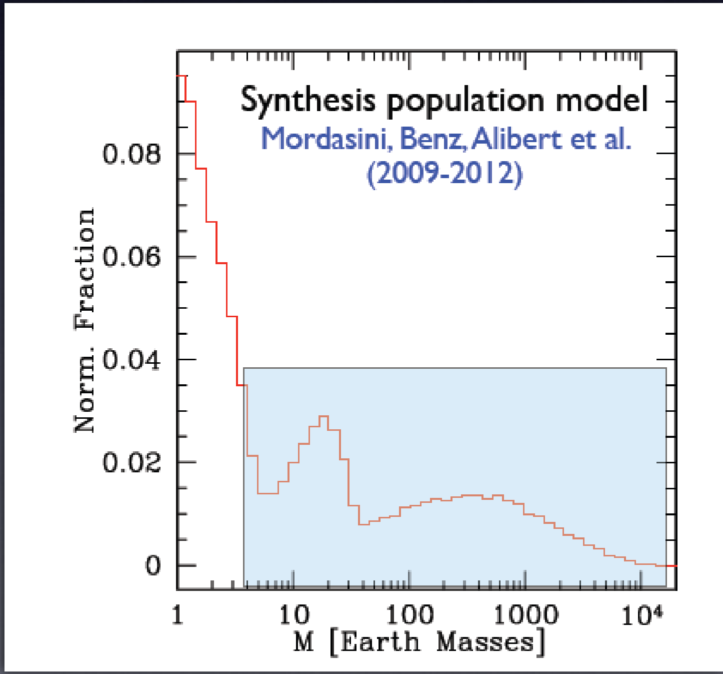


Mass distribution

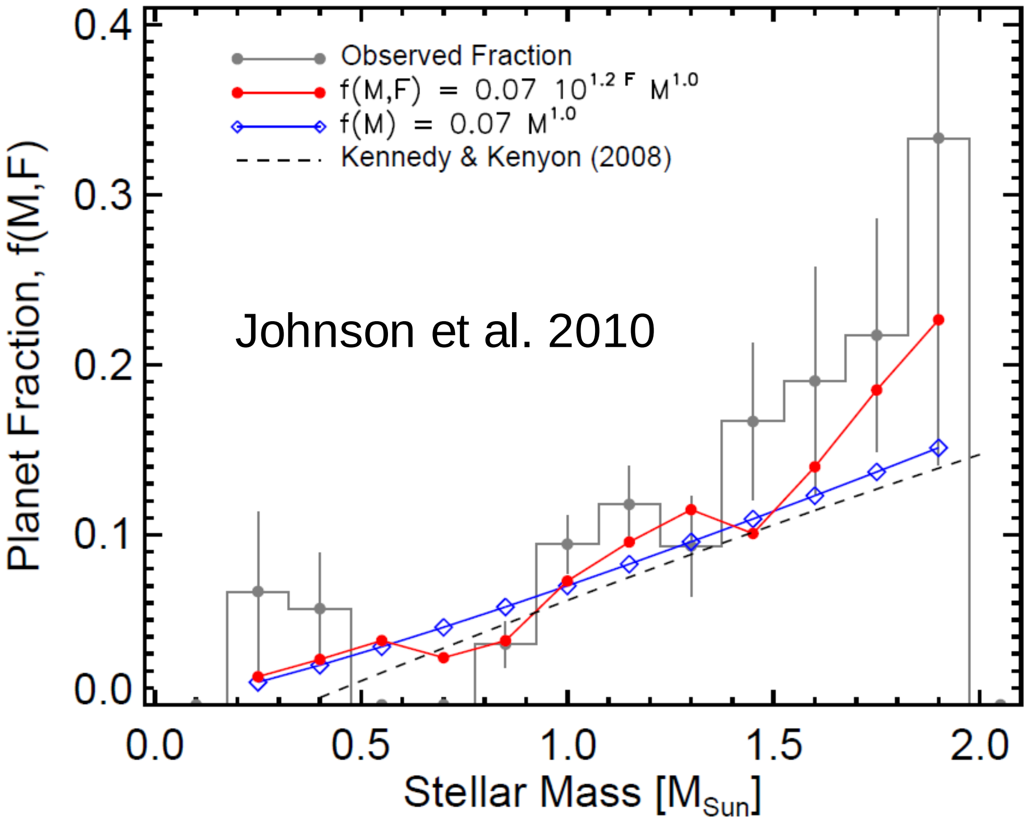
with incompleteness correction

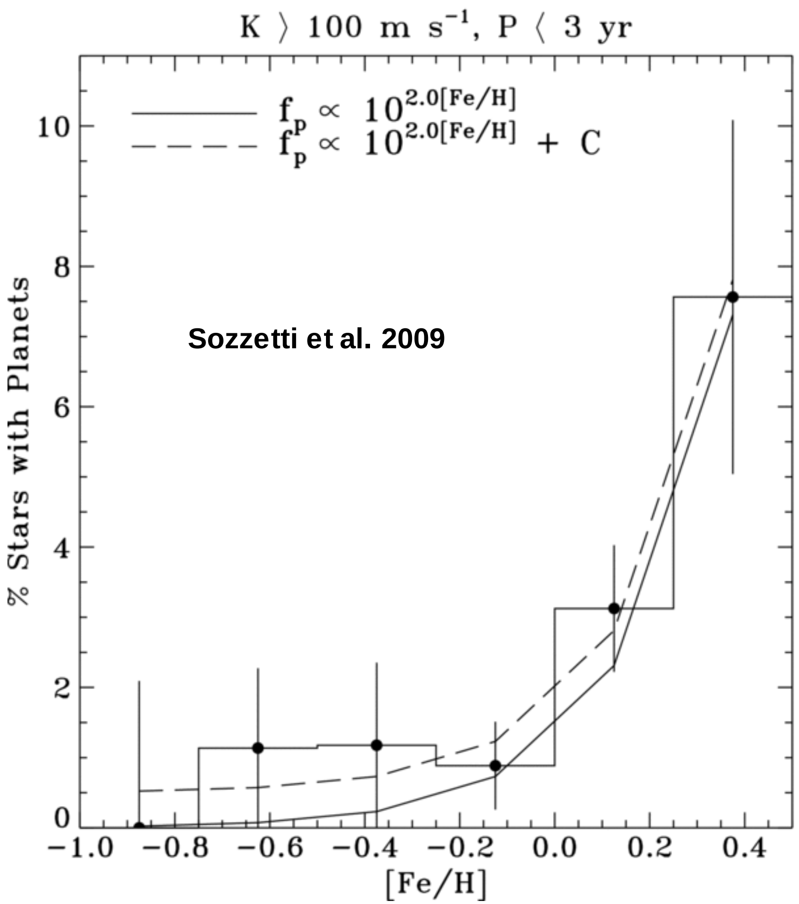


corrected
observed



Planet – Host Star Connection





Critical tests of competing giant planet formation models

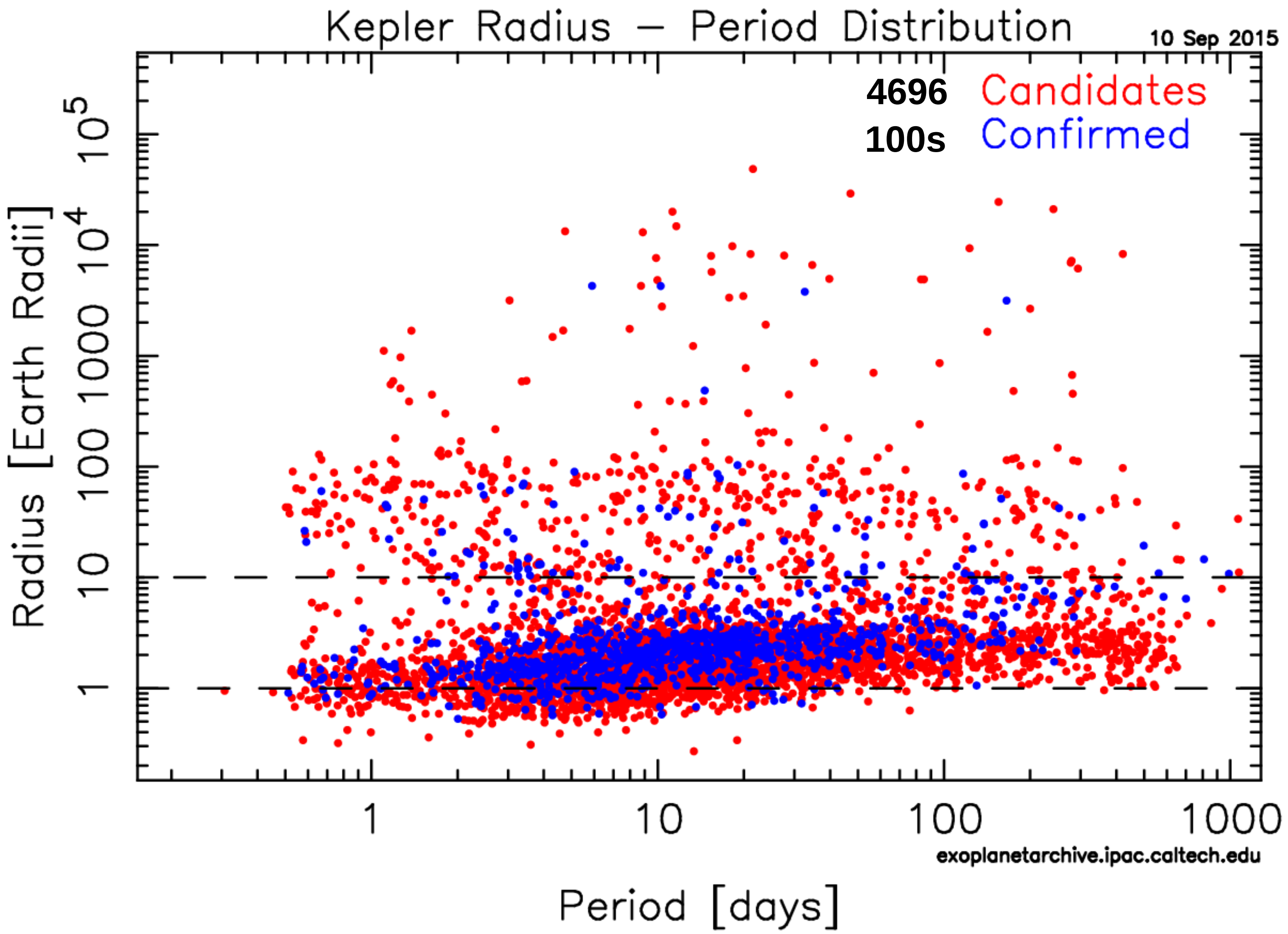
Terrestrial-type planets do not seem to follow the trend…

Transiting Planets: A Treasure Trove

- **Learn about the history of planet migration**
- **Learn about the architecture of multiple systems**
- **Learn about the physical structure and composition of exoplanets**
- **Learn about the structure, chemistry, and dynamics of atmospheres**

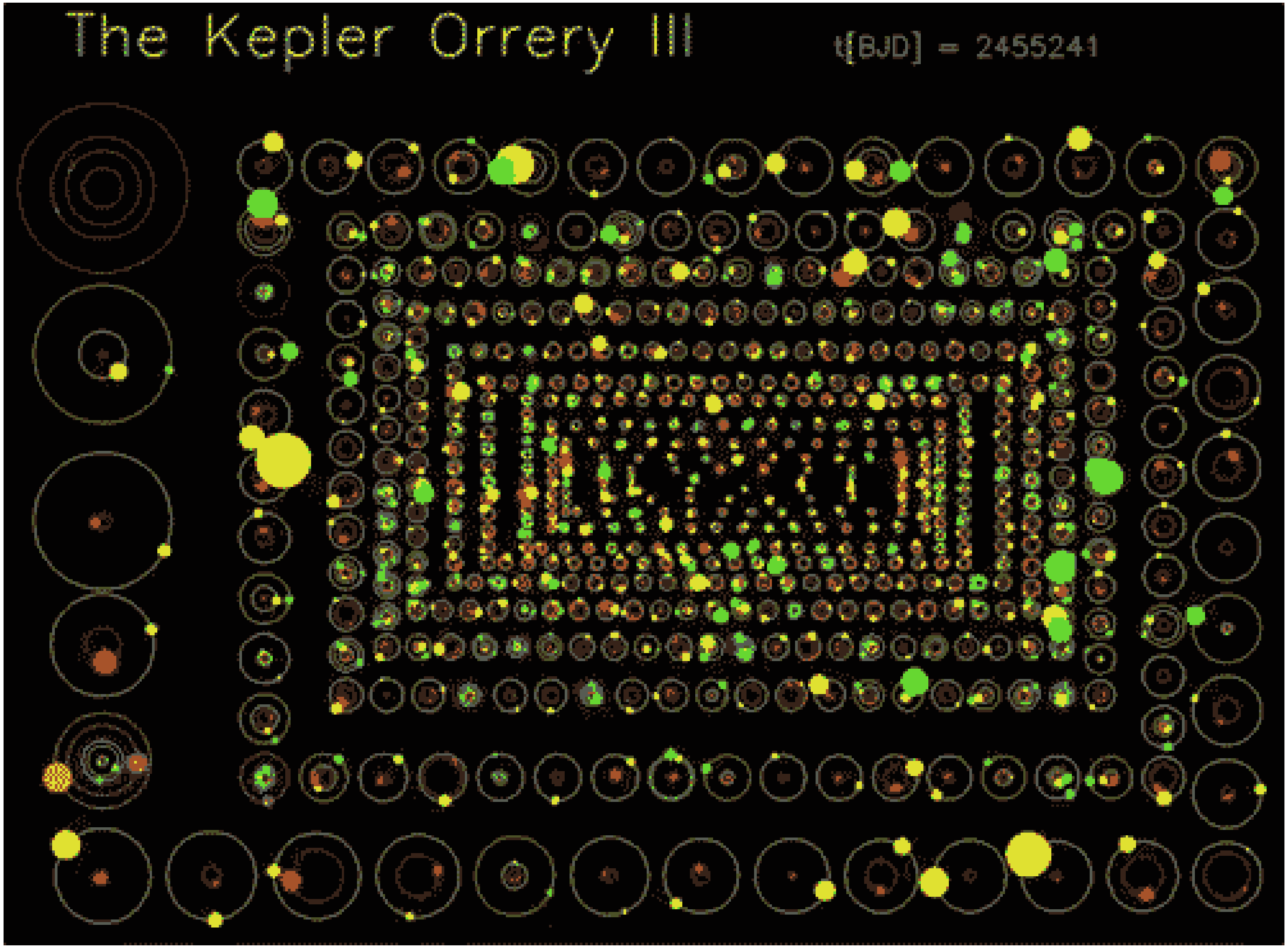
Tens of ground-based surveys, two highly successful space projects

The Kepler 'Revolution'



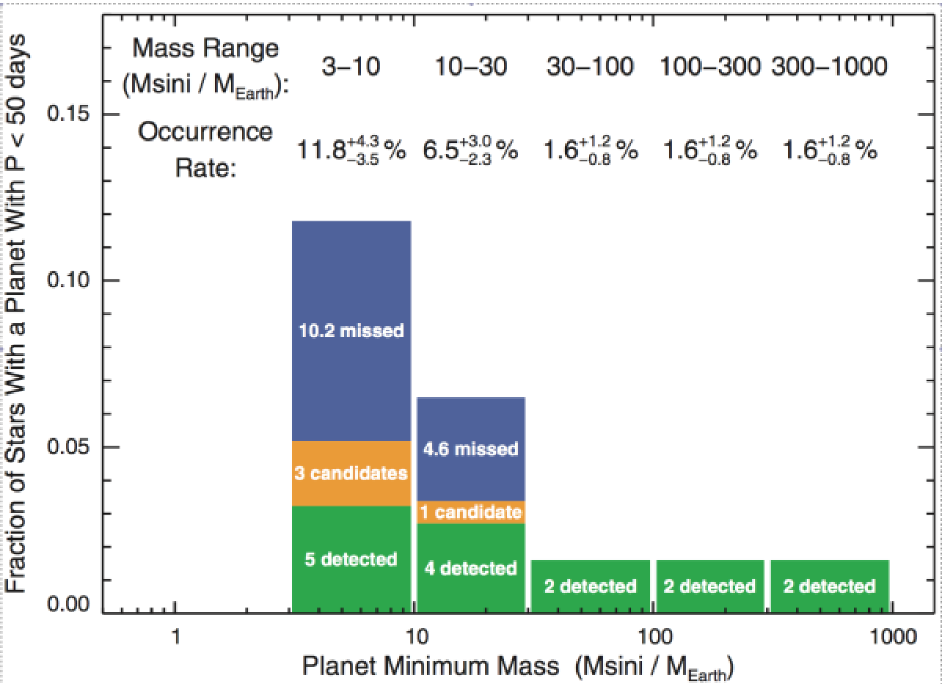
From the ground: 1 mmag precision at best / Kepler's: 20 ppm!

Multiple-Planet Systems



100s' of 'flat' systems, the vast majority with small radii. Most are real!

Frequencies: Kepler vs. RVs



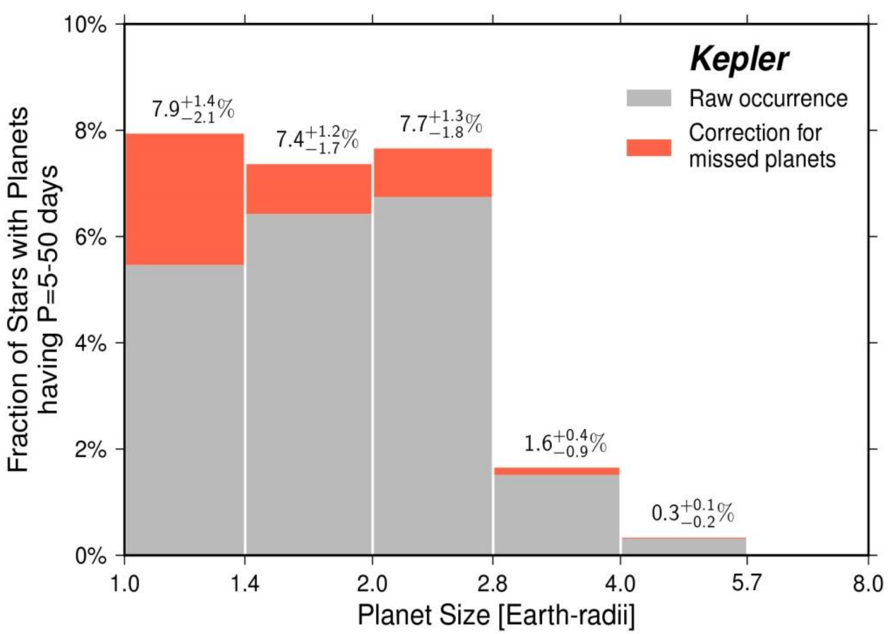
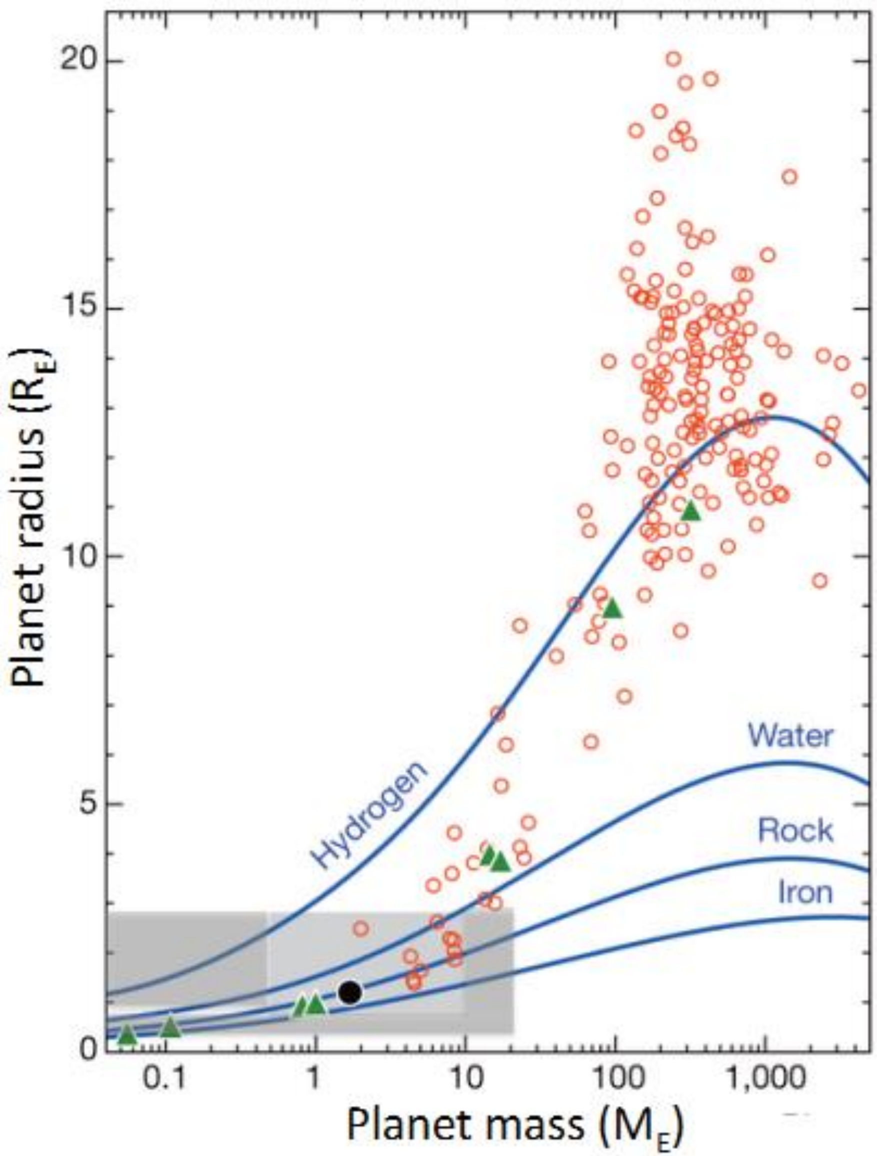


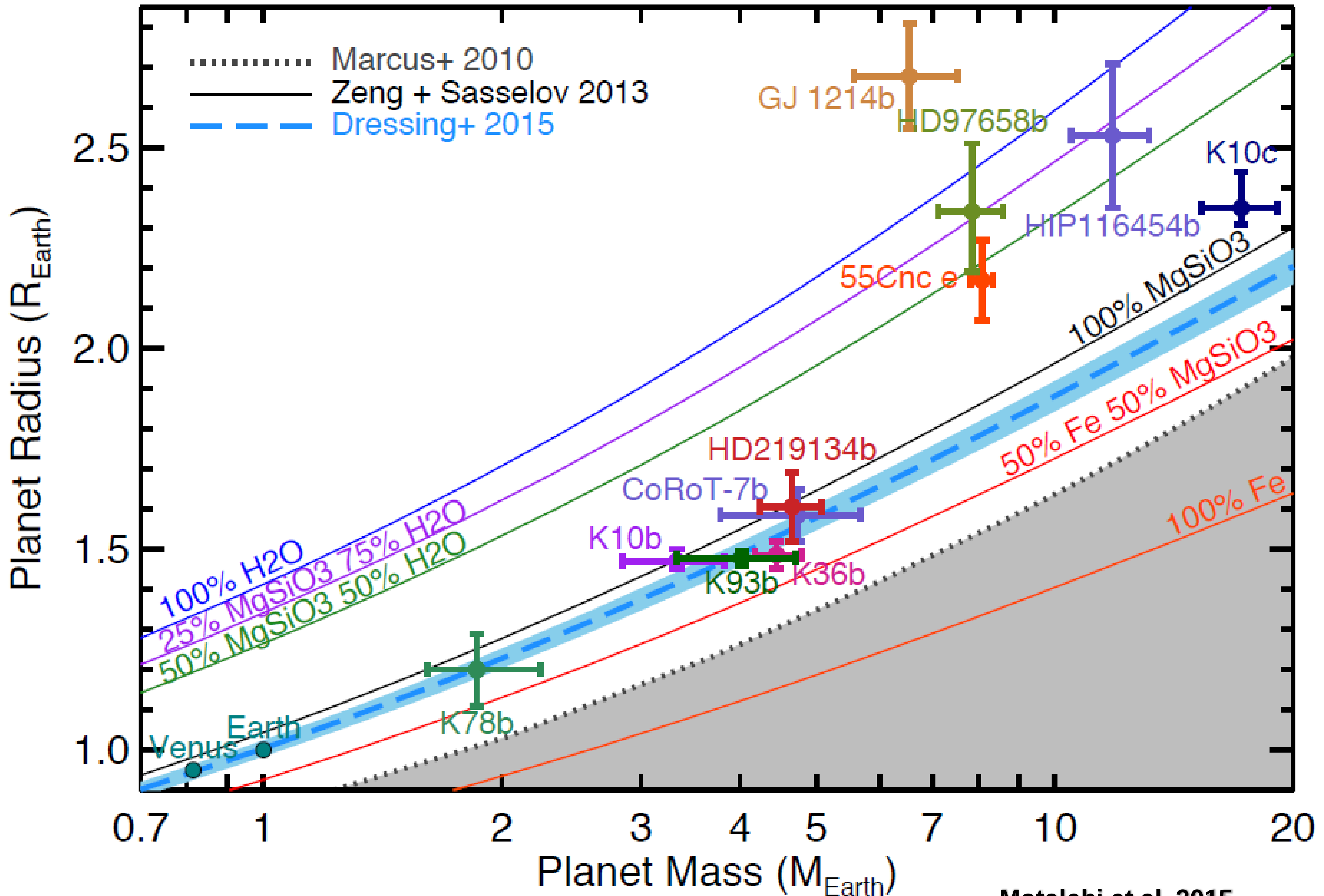
Table 1. Planet occurrence rates around FGK stars

Study	Technique	Period range	Size range	Occurrence [%]
Wright et al. (2012)	Doppler	< 10 d	$> 30\ M_\oplus$	1.20 ± 0.38
Mayor et al. (2011)	Doppler	< 11 d	$> 50\ M_\oplus$	0.89 ± 0.36
Cumming et al. (2008)	Doppler	< 5.2 yr	$>100\ M_\oplus$	8.5 ± 1.3
		<100 d	$>100\ M_\oplus$	2.4 ± 0.7
Howard et al. (2010)	Doppler	<50 d	3–$10\ M_\oplus$	$11.8^{+4.3}_{-3.5}$
		<50 d	10–$30\ M_\oplus$	$6.5^{+3.0}_{-2.3}$
Mayor et al. (2011)	Doppler	<50 d	3–$10\ M_\oplus$	16.6 ± 4.4
		<50 d	10–$30\ M_\oplus$	11.1 ± 2.4
		<10 yr	$>50\ M_\oplus$	13.9 ± 1.7
Fressin et al. (2013)	Transit	<10 d	6–$22\ R_\oplus$	0.43 ± 0.05
		<85 d	0.8–$1.25\ R_\oplus$	16.6 ± 3.6
		<85 d	1.25–$2\ R_\oplus$	20.3 ± 2.0
		<85 d	2–$4\ R_\oplus$	19.9 ± 1.2
		<85 d	1.25–$22\ R_\oplus$	52.3 ± 4.2
Petigura et al. (2013)	Transit	5–100 d	1–$2\ R_\oplus$	26 ± 3
		5–100 d	8–$16\ R_\oplus$	1.6 ± 0.4

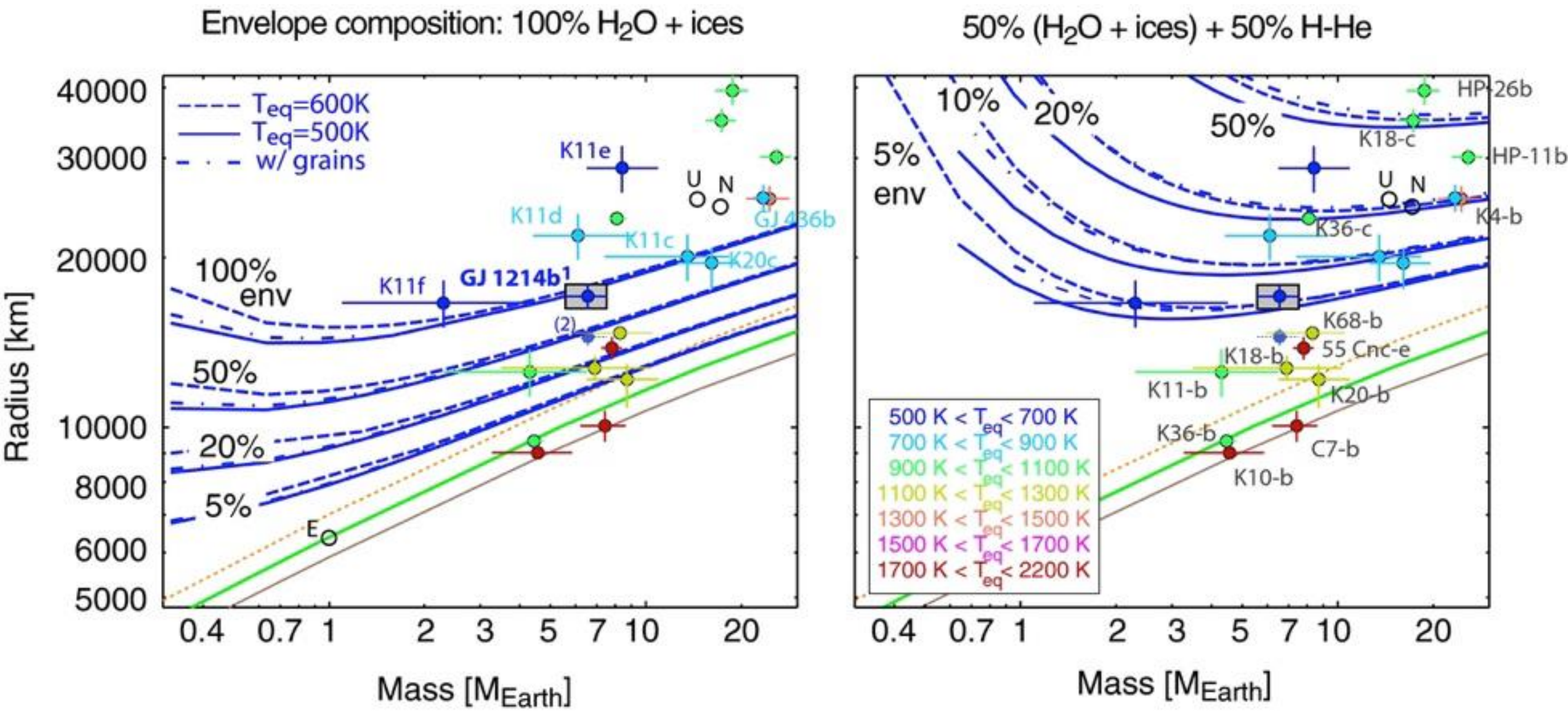
Winn & Fabrycky 2015

The Mass-Radius Relationship



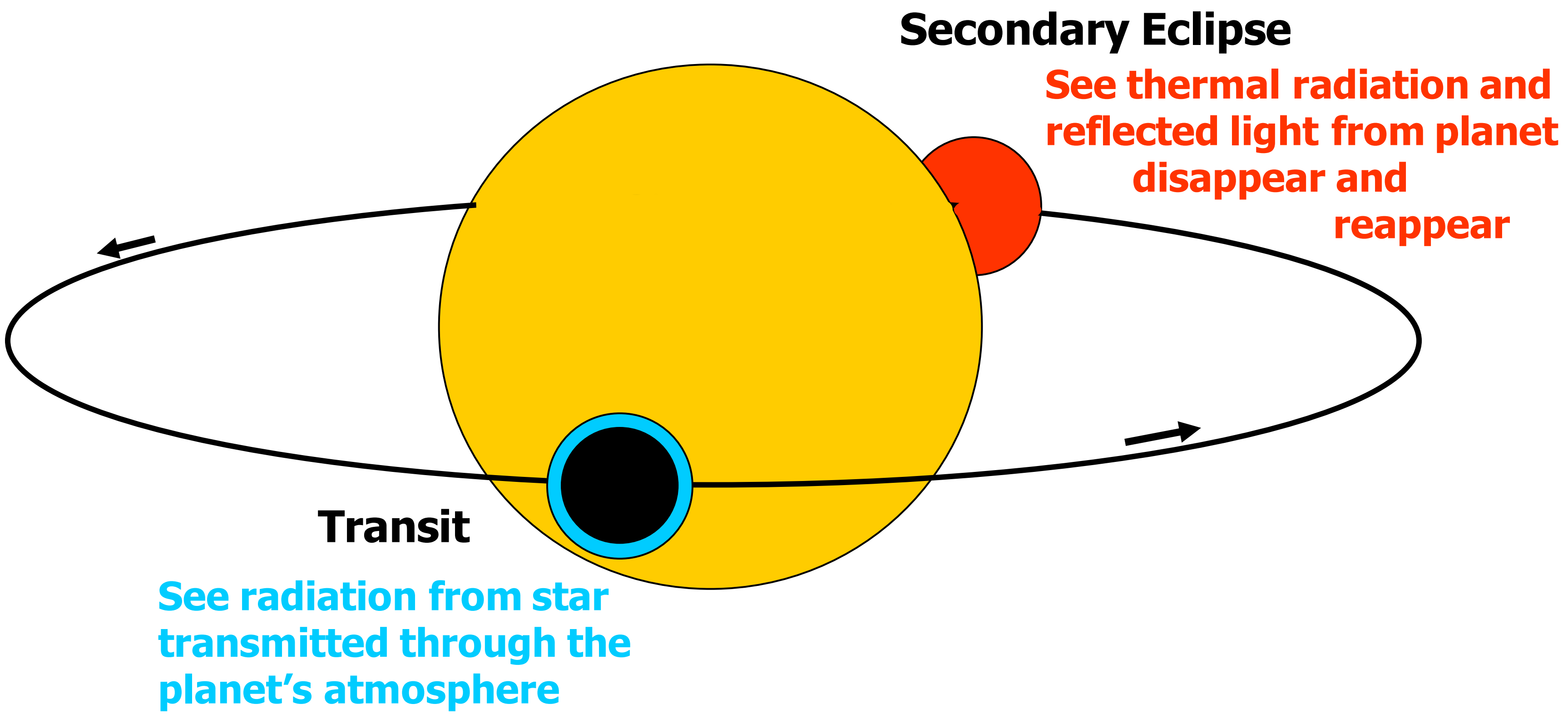


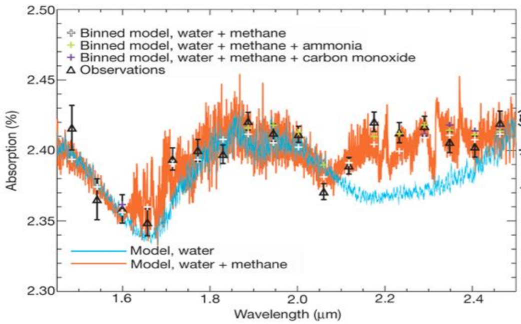
Motalebi et al. 2015

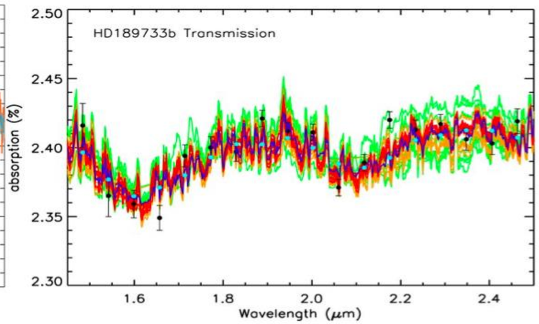


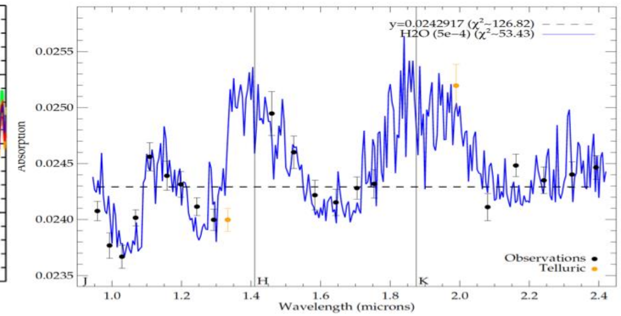
Envelope composition: 100% H_2O + ices
50% (H_2O + ices) + 50% H-He
T_{eq}=600K
T_{eq}=500K
w/ grains
Radius [km]
Mass [M_{Earth}]
100% env
50%
20%
10%
5% env
K11e
K11d
K11c
K11f
GJ 1214b
GJ 436b
K20c
U
N
E
HP-26b
K18-c
HP-11b
K4-b
K36-c
K68-b
55 Cnc-e
K18-b
K11-b
K20-b
K36-b
C7-b
K10-b
500 K < T_{eq} < 700 K
700 K < T_{eq} < 900 K
900 K < T_{eq} < 1100 K
1100 K < T_{eq} < 1300 K
1300 K < T_{eq} < 1500 K
1500 K < T_{eq} < 1700 K
1700 K < T_{eq} < 2200 K

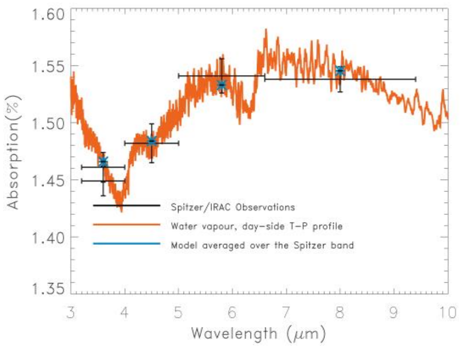
Transits Allow Studies of the Atmospheres That Are Not (Yet) Possible for Non-Transiting Planets

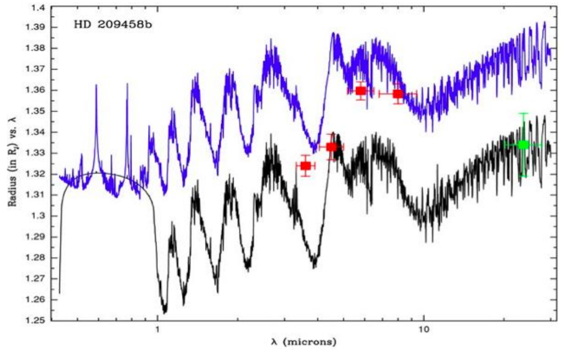


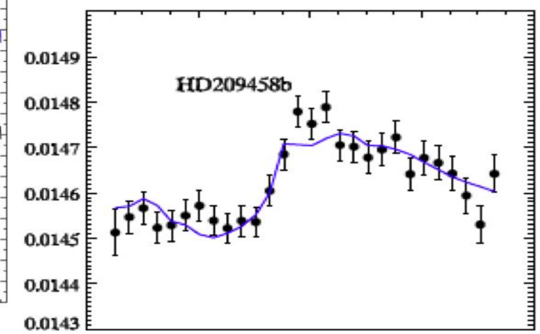


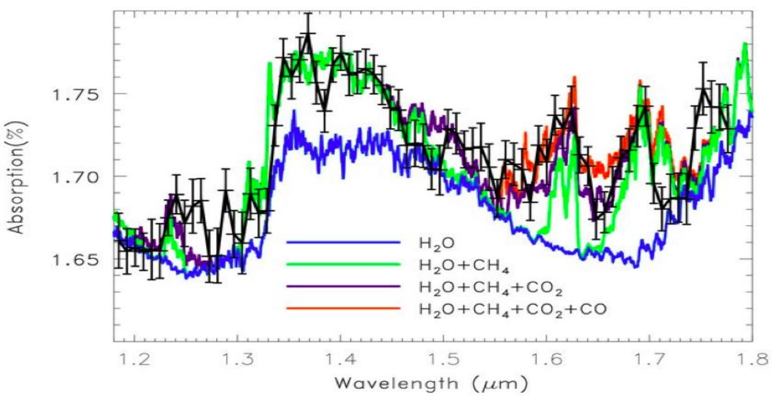


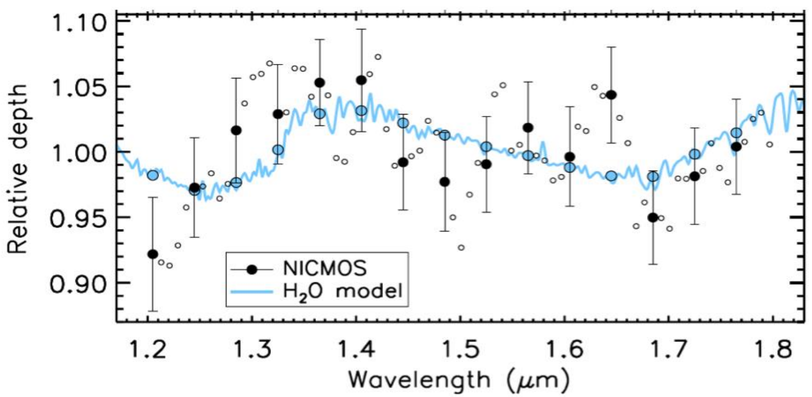






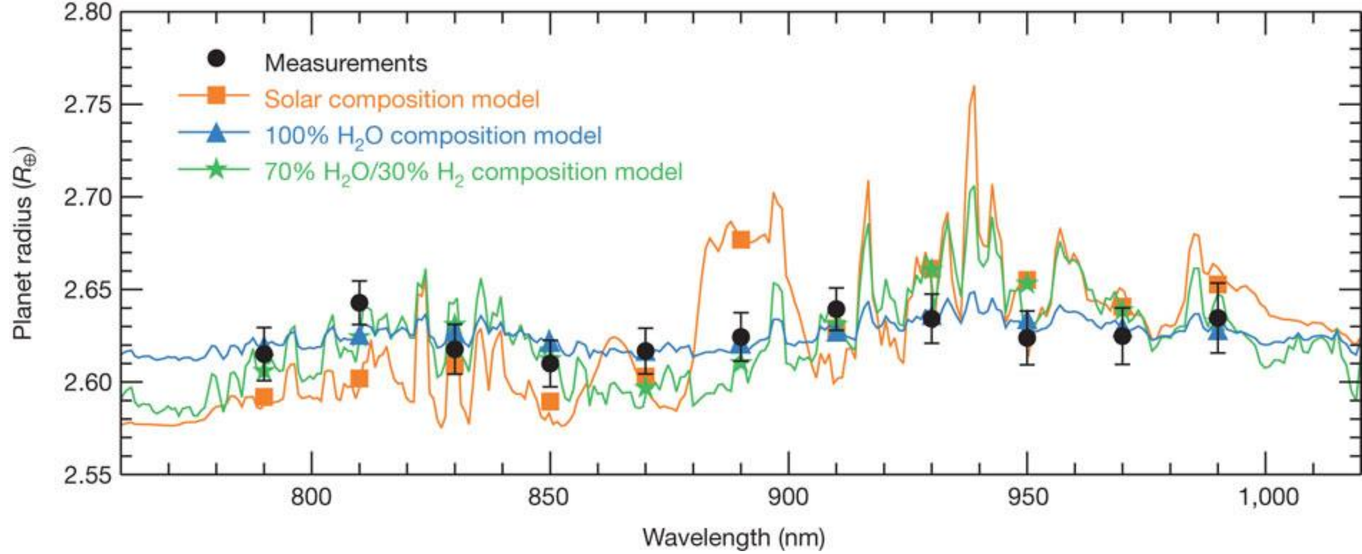


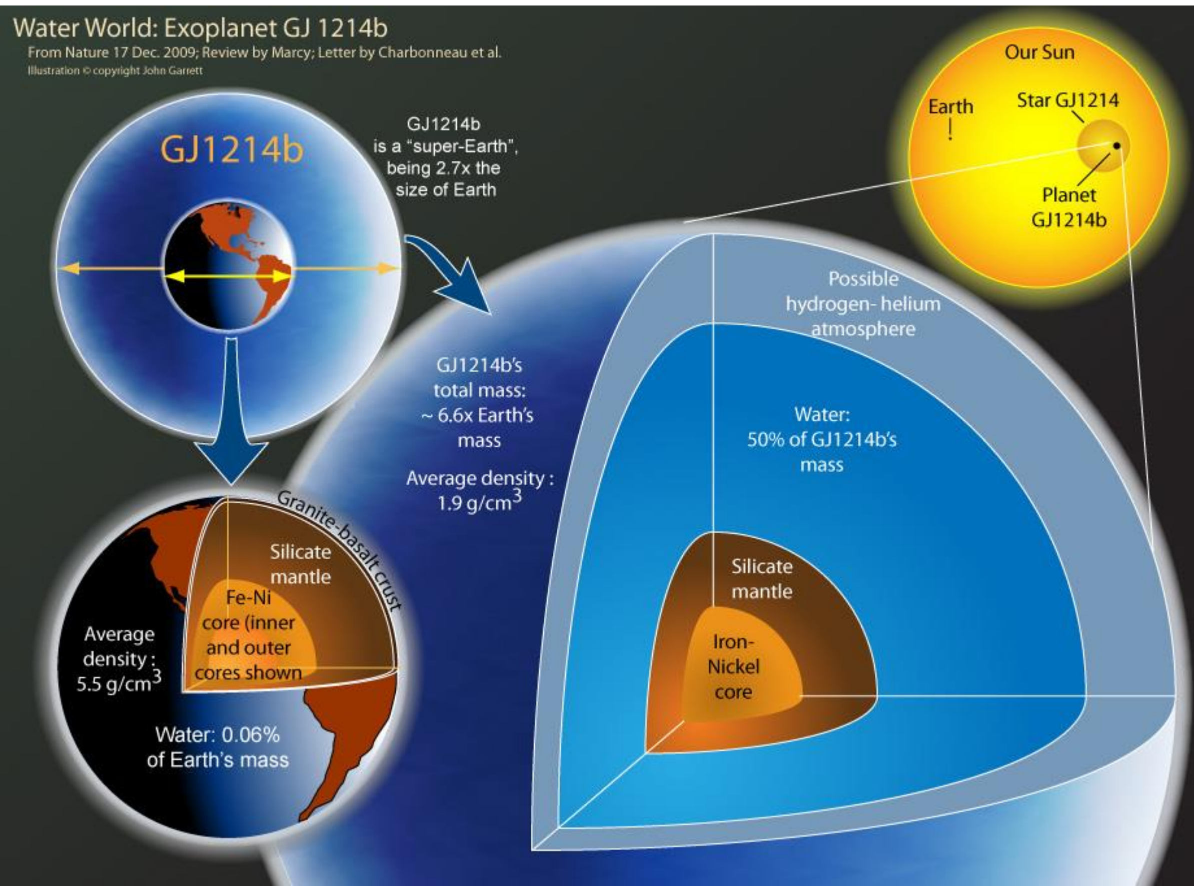




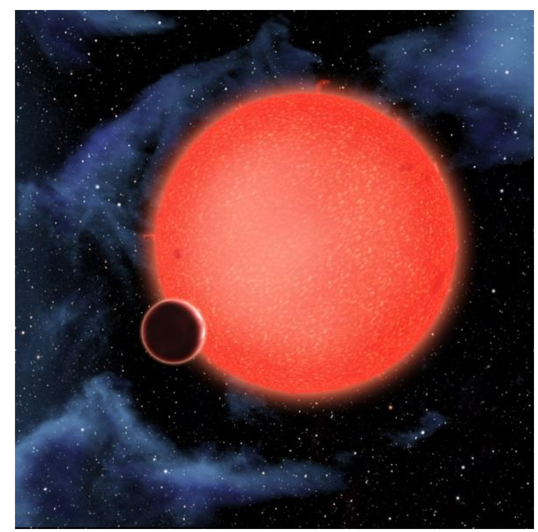
Swain *et al*., 2008; Madhu & Seager, 2009; Danielski et al., 2013; Beaulieu et al., 2010; Burrows et al., 2011; Deming et al., 2013; Tinetti et al., 2010; Crouzet et al., 2012

GJ 1214b

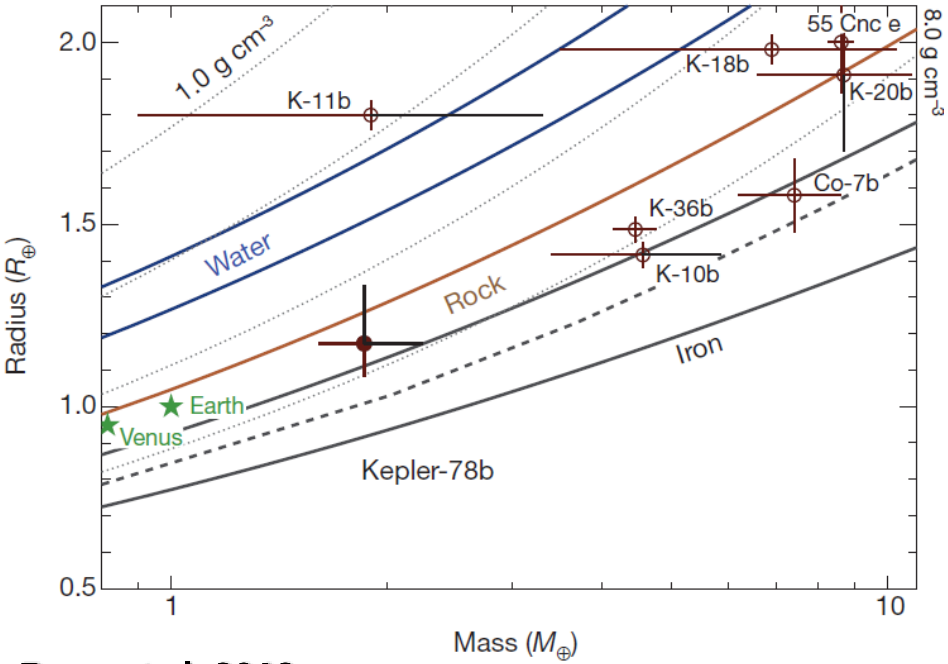




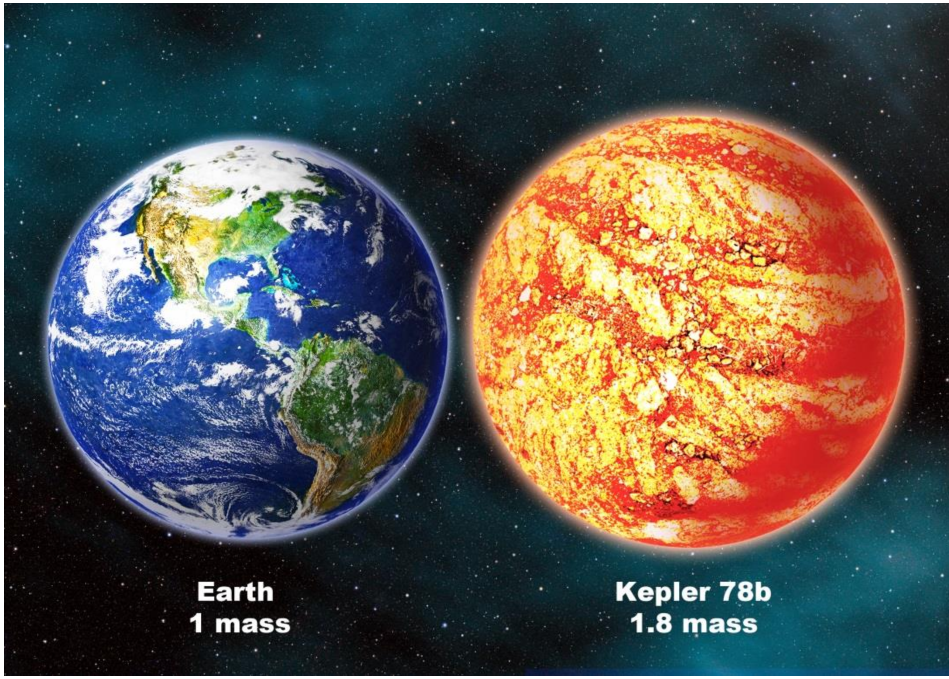
A 'cool' Super-Earth around an M4.5 dwarf



Kepler-78b: The closest thing to Earth ever detected!

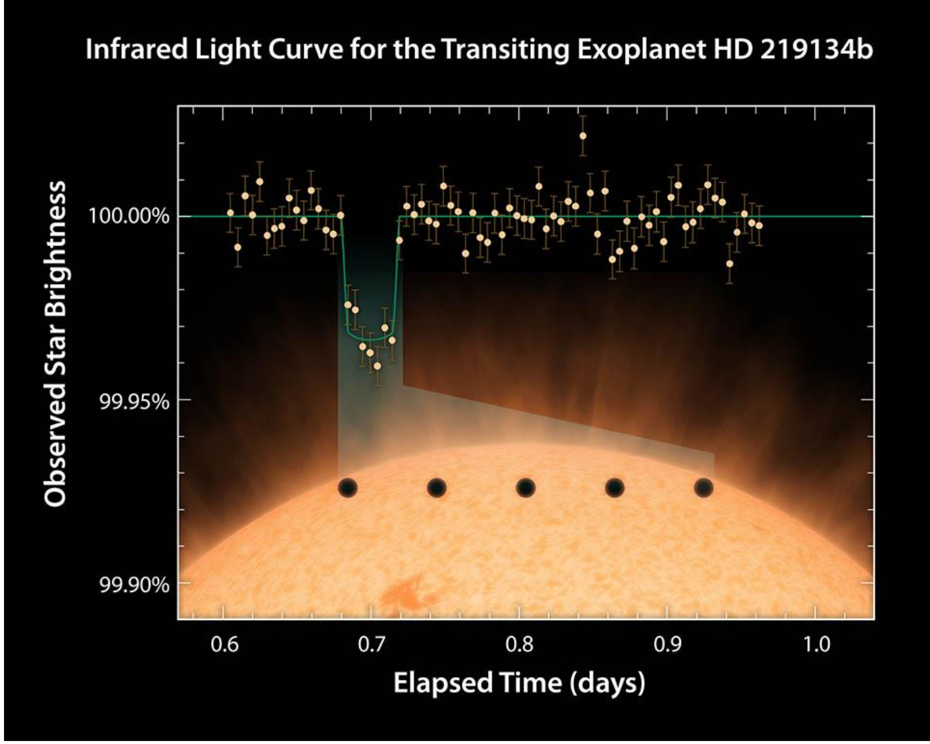


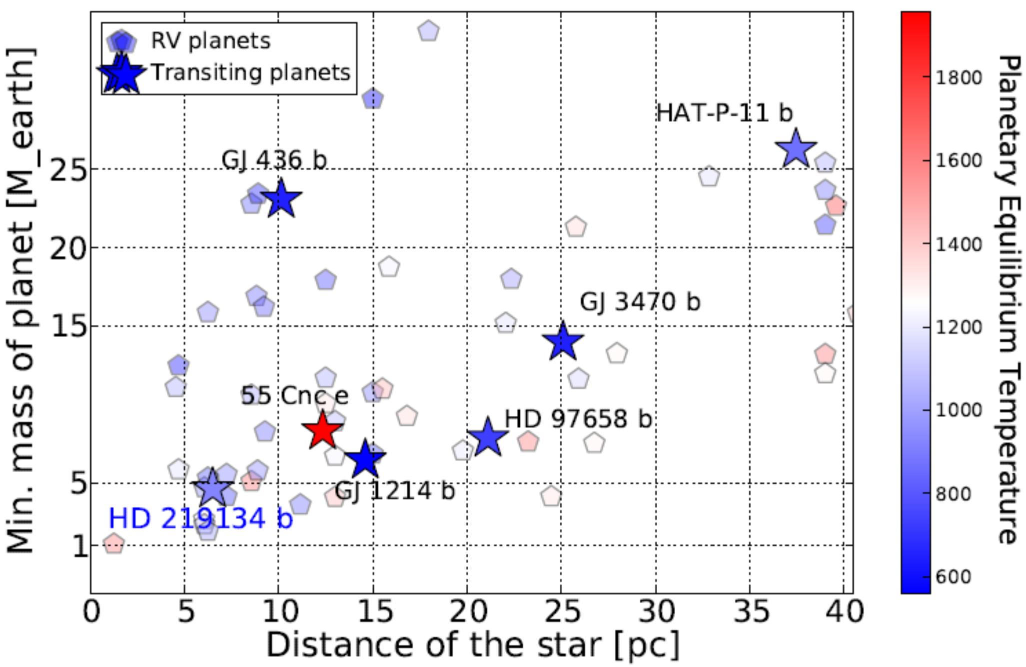
Pepe et al. 2013



But: P=8.5 hrs, T_{eq} =3000 K
Alas… Far From Habitable!

HD219134b:
A transiting Super Earth at 6.5 pc from the Sun!

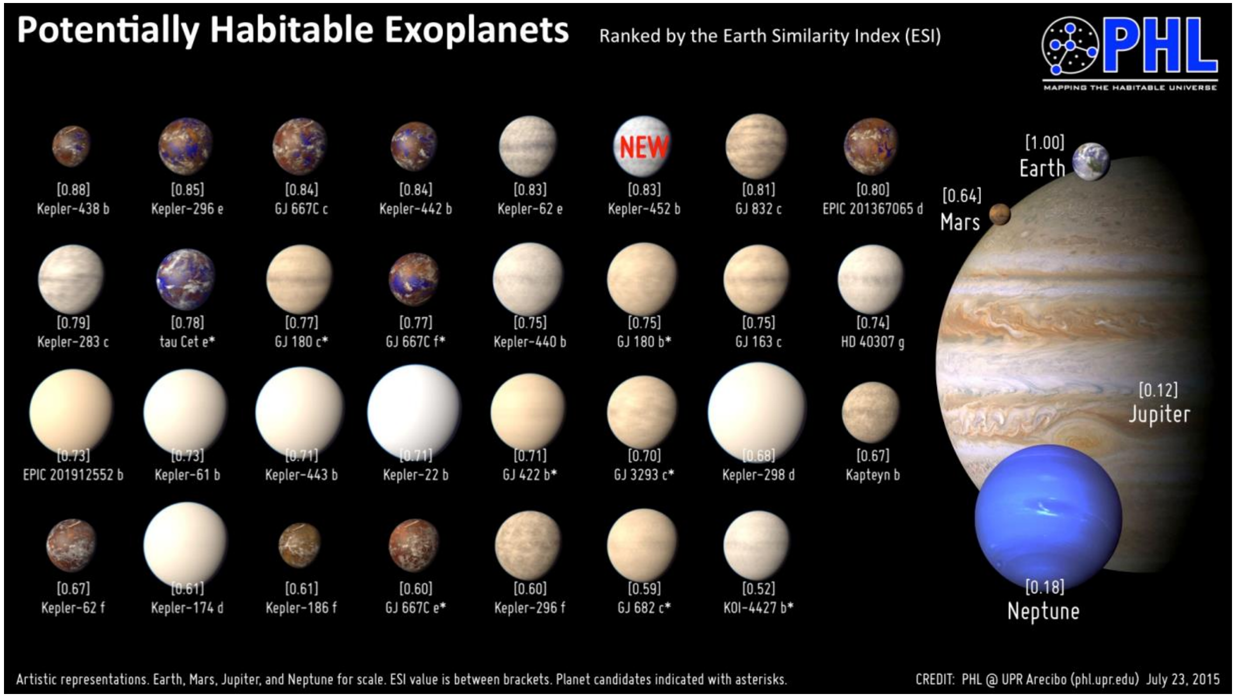




It is likely rocky indeed, but it orbits its K dwarf with P= 3.1 d…

Motalebi et al. 2015

‘Habitable’ Planets?



*** Typically orbiting stars smaller than our Sun**

*** In some cases, only minimum mass estimates available, no radius measurements**

*** In other cases, only radii are measured, masses are unknown**

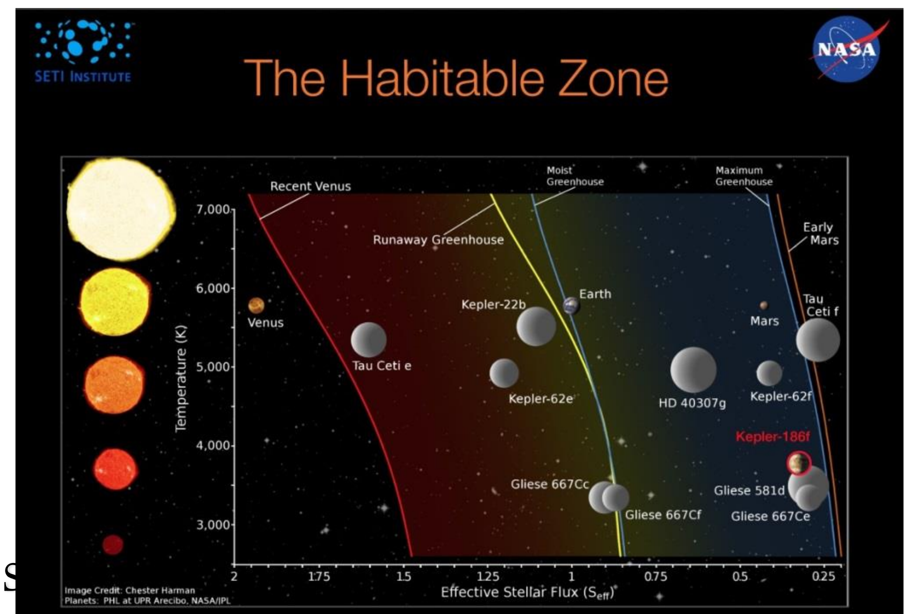


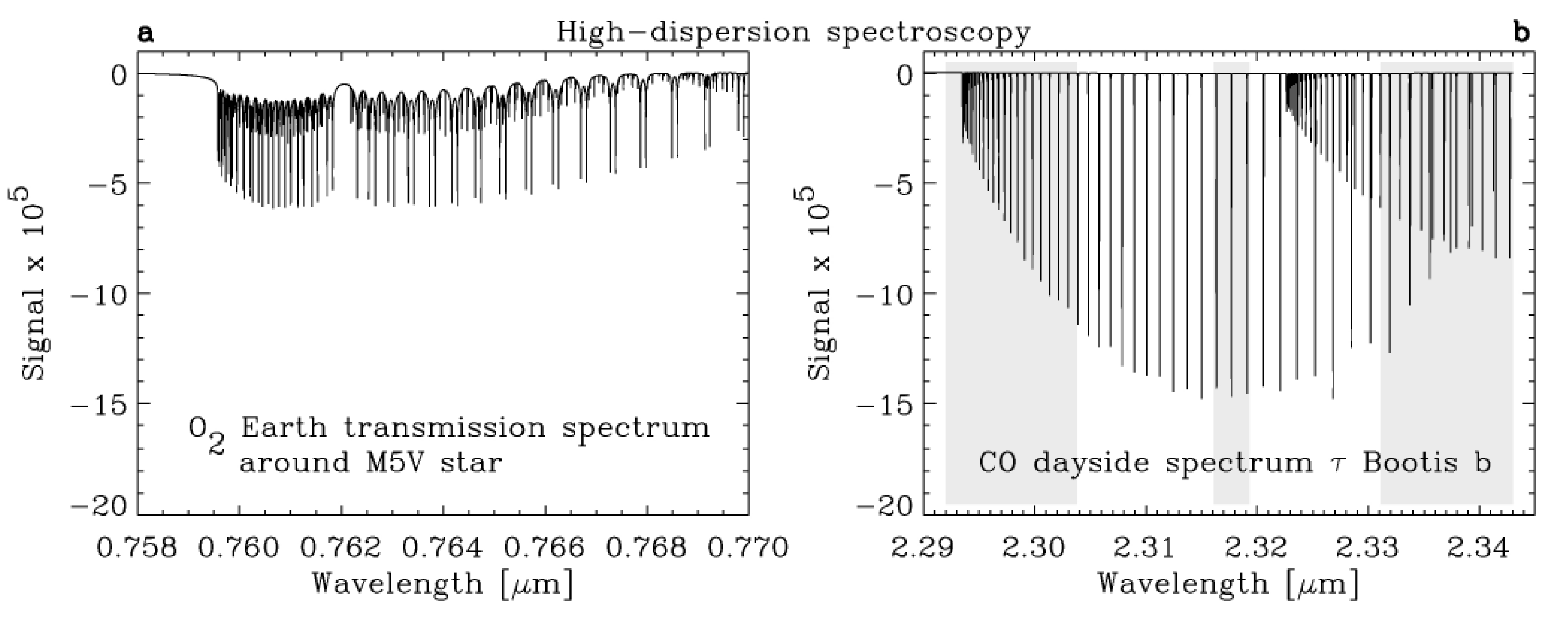
Table 2. Occurrence rates of "Earth-like planets"

Type of star	Type of planet	Approx. HZ boundaries* $[S/S_{\oplus}]$	Occurrence rate [%]	Reference
M	1-10 $M_{\oplus}$	0.75-2.0	41^{+54}_{-13}	1
FGK	0.8-2.0 $R_{\oplus}$	0.3-1.8	$2.8^{+1.9}_{-0.9}$	2
FGK	0.5-2.0 $R_{\oplus}$	0.8-1.8	34 ± 14	3
M	0.5-1.4 $R_{\oplus}$	0.46-1.0	15^{+13}_{-6}	4
M	0.5-1.4 $R_{\oplus}$	0.22-0.80	48^{+12}_{-24}	5
GK	1-2 $R_{\oplus}$	0.25-4.0	11 ± 4	6
FGK	1-2 $R_{\oplus}$	$0.25\text{-}4.0^{\dagger}$	$\sim 0.01^{\dagger}$	7
FGK	1-4 $R_{\oplus}$	0.35-1.0	$6.4^{+3.4}_{-1.1}$	8
G	0.6-1.7 $R_{\oplus}$	0.51–1.95	$1.7^{+1.8}_{-0.9}$	9

Winn & Fabrycky 2015

Note. — References: (1) Bonfils et al. (2013), (2) Catanzarite & Shao (2011), (3) Traub (2012), (4) Dressing & Charbonneau (2013), (5) Kopparapu (2013), (6) Petigura et al. (2013), (7) Schlaufman (2014), (8) Silburt et al. (2014), (9) Foreman-Mackey et al. (2014). In column 3, S refers to the incident flux of starlight on the planet, and $S_{\oplus}$ to the Earth's insolation. All these works are based on *Kepler* data except (1) which is based on the HARPS Doppler survey, and (7) which is based on both *Kepler* and the Keck Doppler survey. *In many cases the actual HZ definitions used by the authors were more complex; please refer to the original papers for details. †The result is much lower than the others because the author also required the Earth-sized planet to have a long-period giant-planet companion.

Extremely Large Telescopes



Stellar type	R_* [R_{sun}]	M_* [M_{sun}]	a_{HZ} [au]	Prob [%]	P_{HZ} [days]	Dur. [hrs]	I (η_e=1) [mag]	Line Contrast	SNR σ	Time (yrs)
G0-G5	1.00	1.00	1.000	0.47	365.3	13	4.4 - 6.1	2×10^{-6}	1.1-2.5	80-400
M0-M2	0.49	0.49	0.203	1.12	47.7	4.1	7.3 - 9.1	8×10^{-6}	0.7-1.5	20-90
M4-M6	0.19	0.19	0.058	1.52	11.8	1.4	10.0-11.8	5×10^{-5}	0.7-1.7	4-20

Snellen et al. 2013

Brightest expected systems

SNR for ELT in 1 transit

Comparative Exoplanetology

- **Orbital elements, mass distributions, multiplicity**
- **Correlations amongst planetary parameters and between planet characteristics and frequencies and the properties of the stellar hosts (M_*, [Fe/H])**
- **Internal structure, atmospheric composition and circulation (and ultimately habitability)**

→ **Putting our Solar System in Context!**