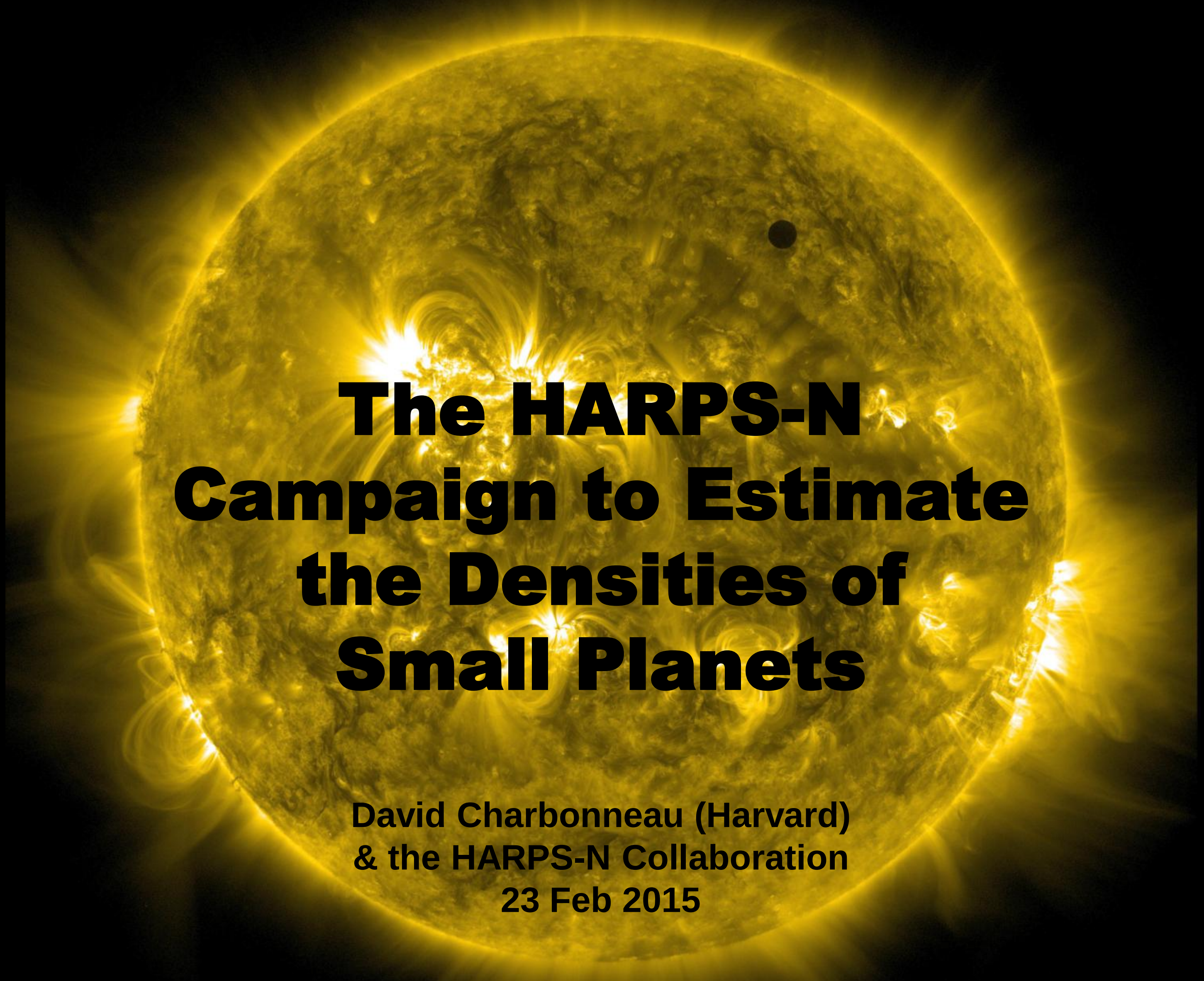
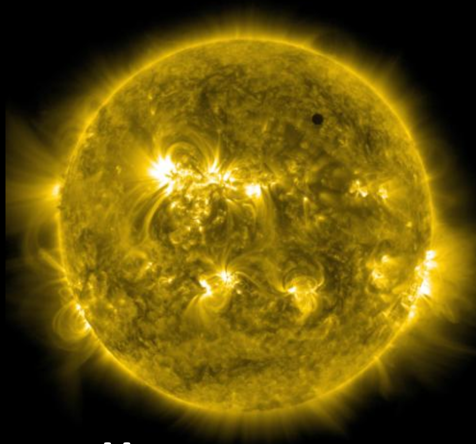


The HARPS-N Campaign to Estimate the Densities of Small Planets

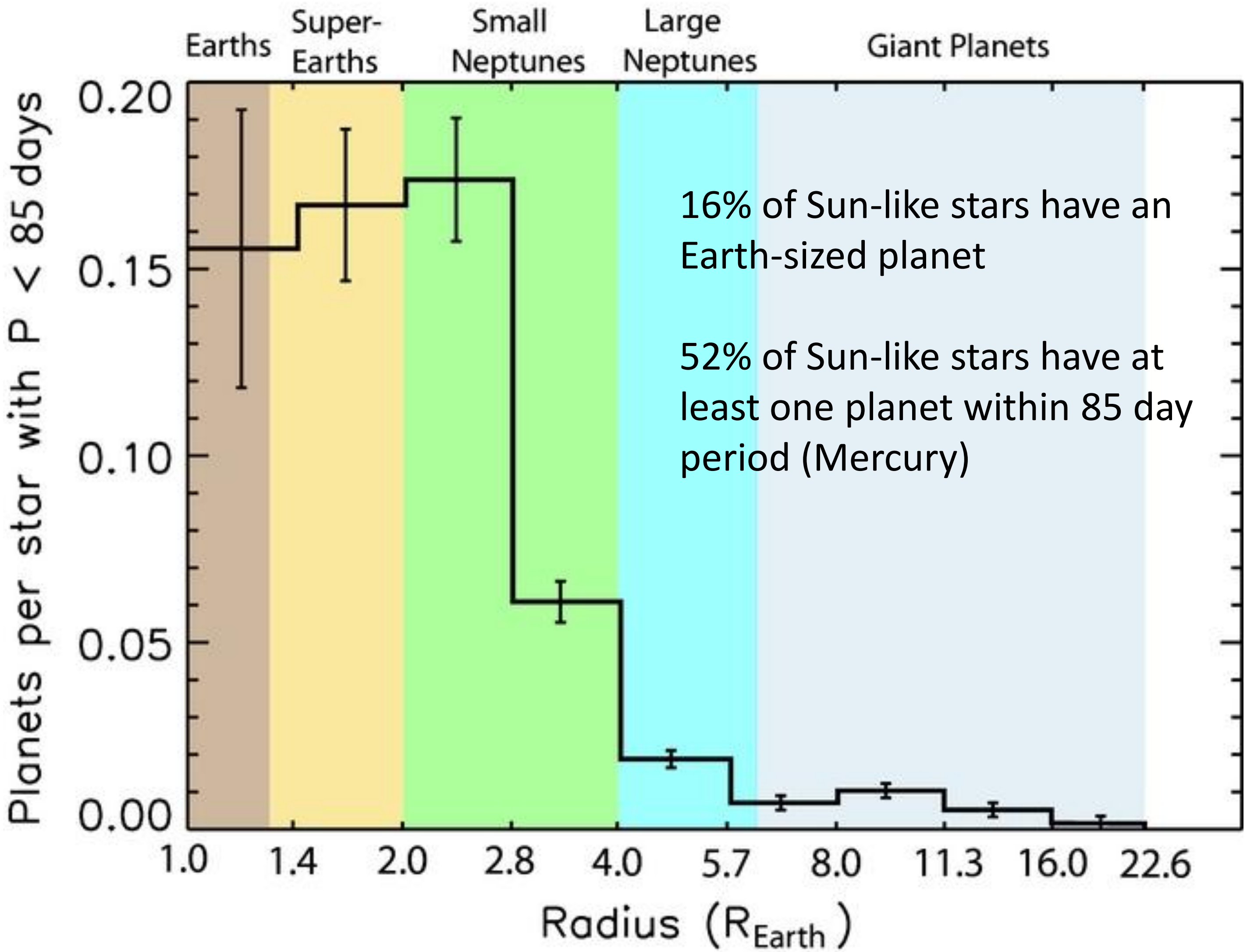
David Charbonneau (Harvard)
& the HARPS-N Collaboration
23 Feb 2015

Questions for Today



- What are the likely compositions of small planets?
- Is there a maximum mass for an exo-analog of a terrestrial planet?
- What are the prospects for improving our knowledge in the next 3 years?

The Planet Radius Distribution for Sun-Like Stars

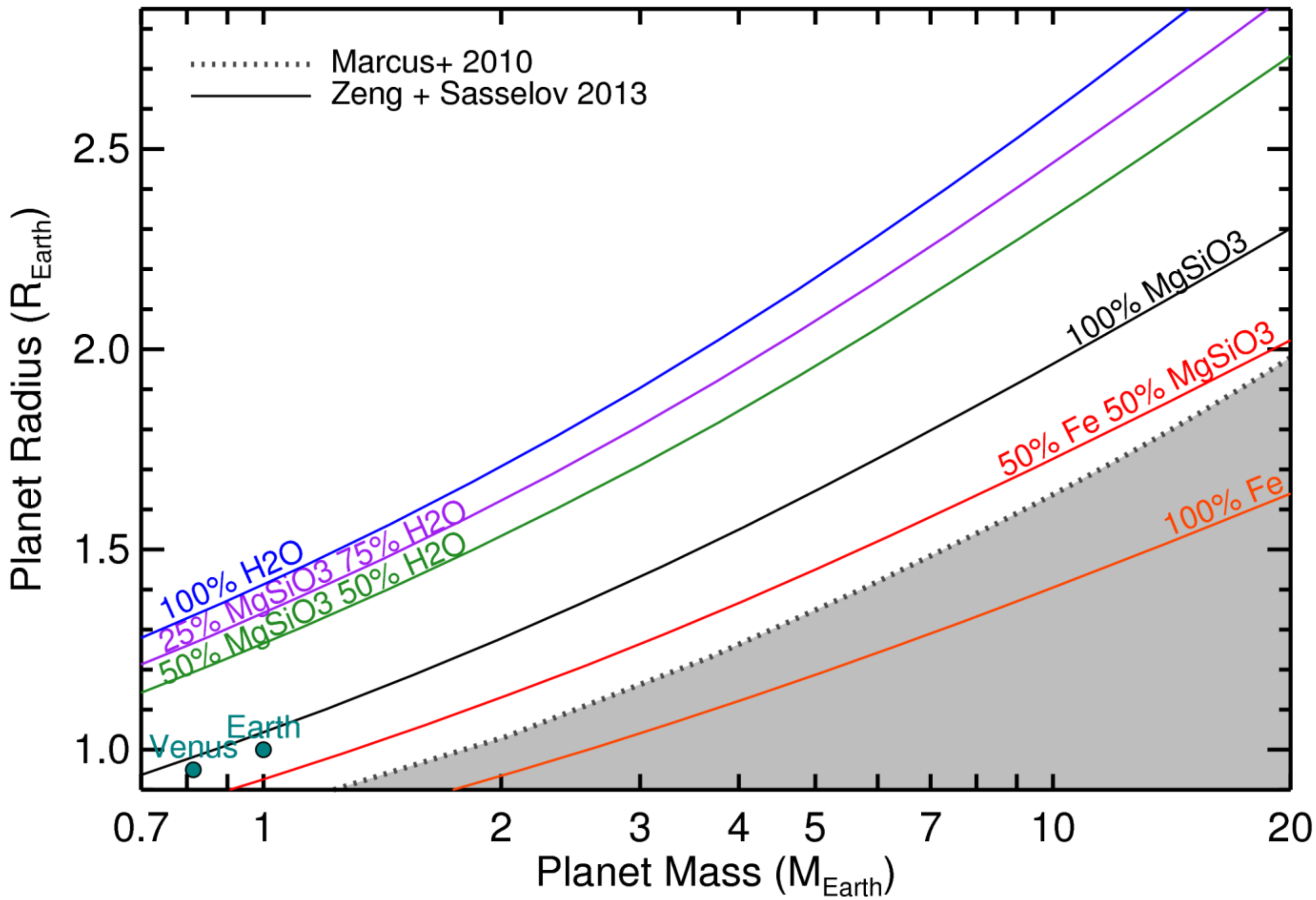


16% of Sun-like stars have an Earth-sized planet

52% of Sun-like stars have at least one planet within 85 day period (Mercury)

Fressin, Torres, Charbonneau et al. (2013)

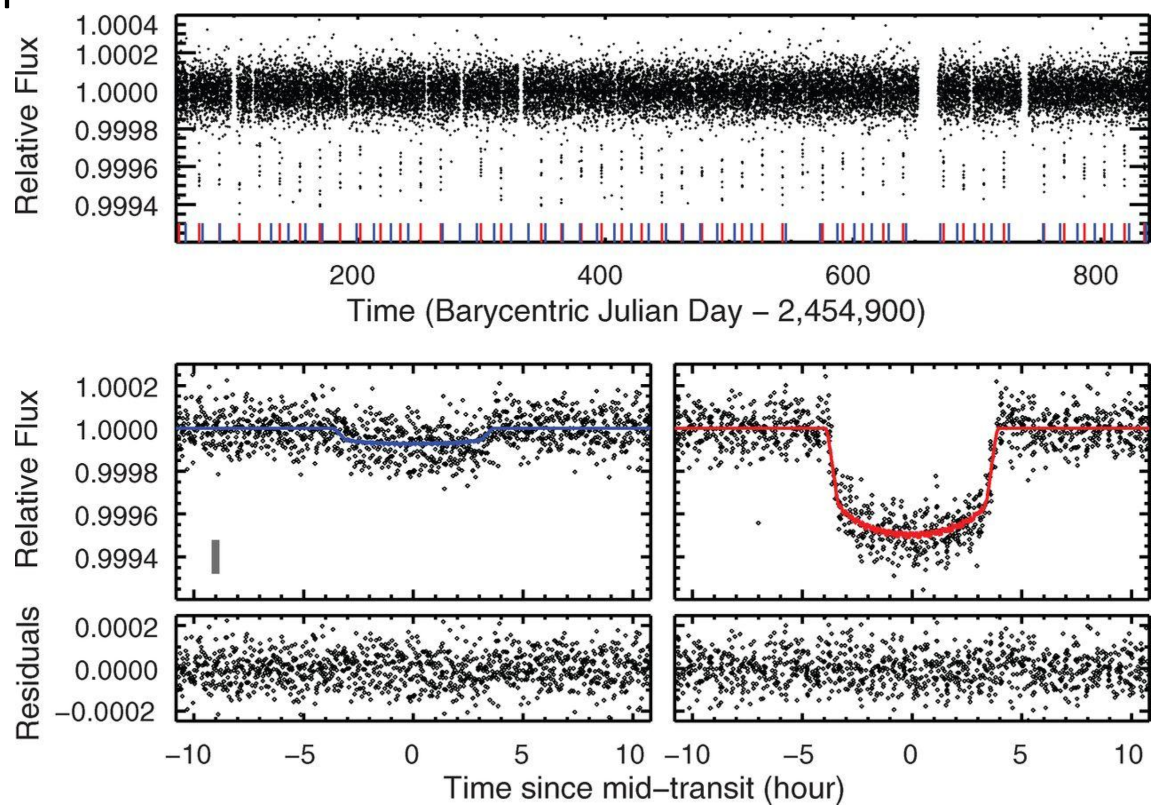
Towards Precise Constraints on the Mass-Radius Diagram below 2.5 Earth Radii



Dressing, Charbonneau, et al. to appear in ApJ (2015)

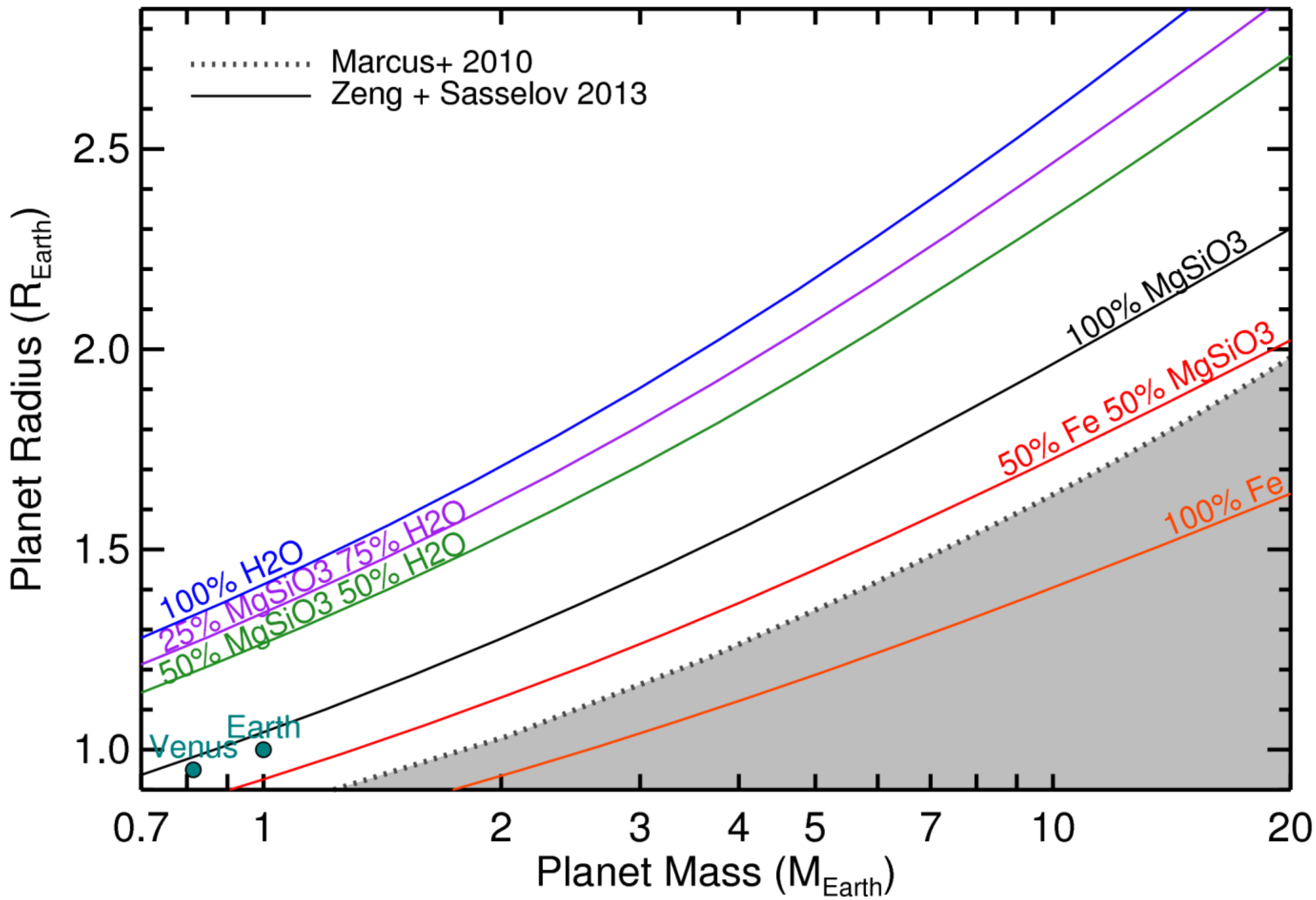
Masses from Transit Timing Variations

- Kepler-36b has two planets in 13.8d and 16.2d orbit (6:7)
- Precise constraints on stellar mass and radius from asteroseismology (ρ_{star}=0.25 +/- 0.02 ρ_{sun}) and stellar spectroscopy
- Masses (4.5 & 8.1 M_{earth}) indicate very different compositions despite similar insolation



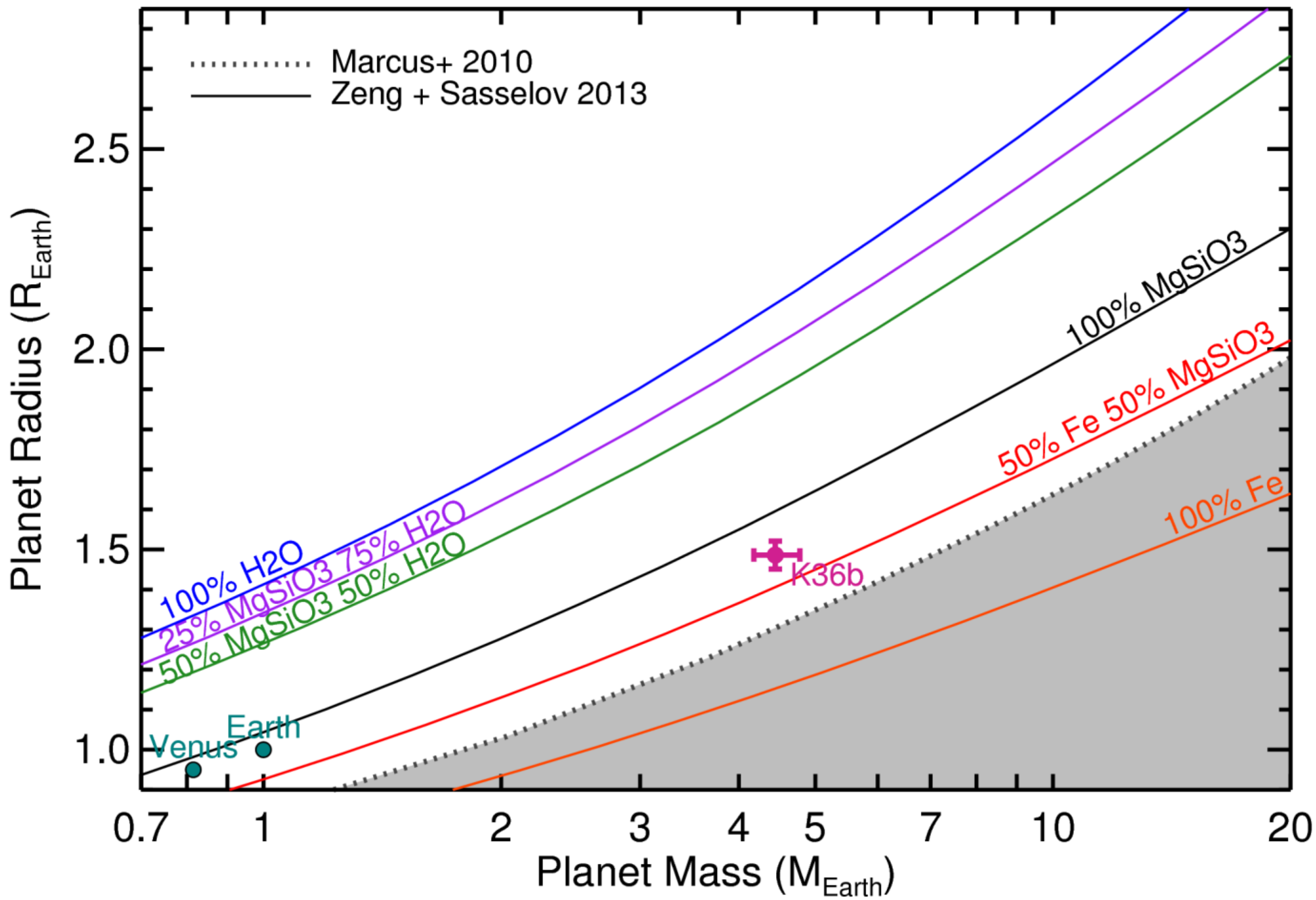
Carter et al. Science (2012)

Towards Precise Constraints on the Mass-Radius Diagram below 2.5 Earth Radii



Dressing, Charbonneau, et al. to appear in ApJ (2015)

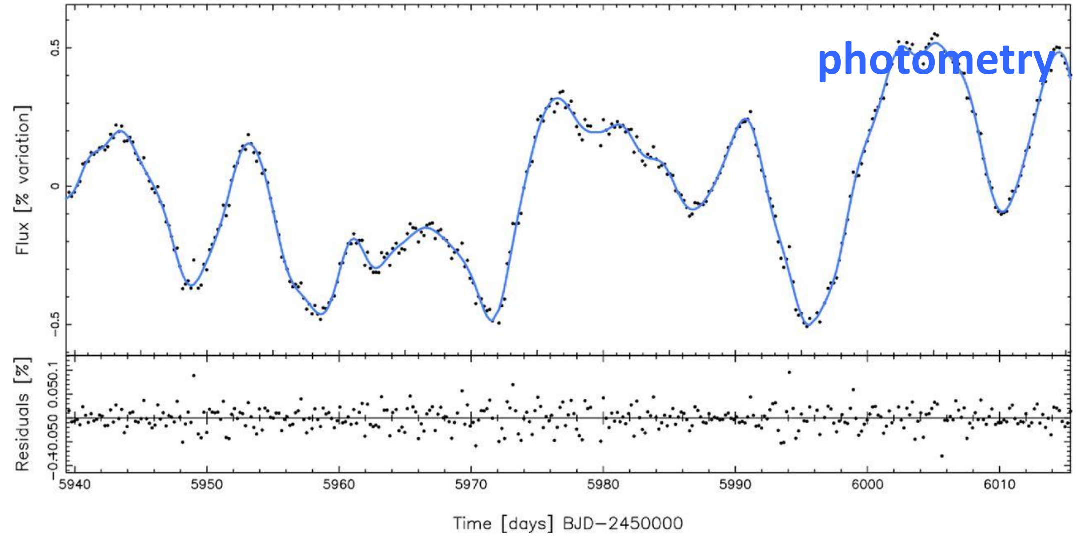
Only planet smaller than 2.5 R_{earth} with a mass from timing variations & precision < 20%. Future missions unlikely to yield more due to short time baselines.

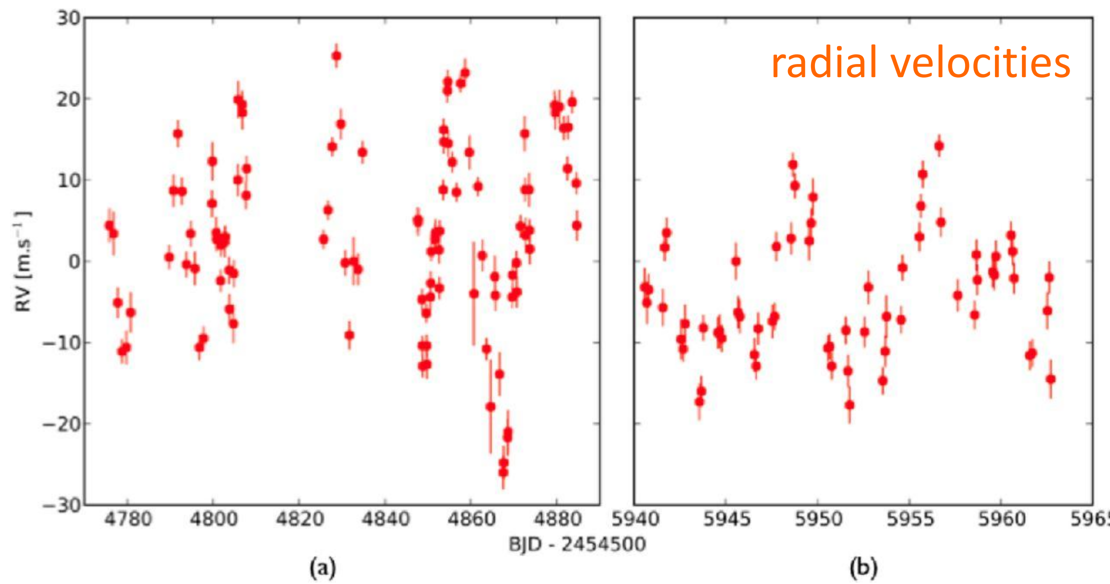


Dressing, Charbonneau, et al. to appear in ApJ (2015)

Masses from Radial Velocities: CoRoT-7

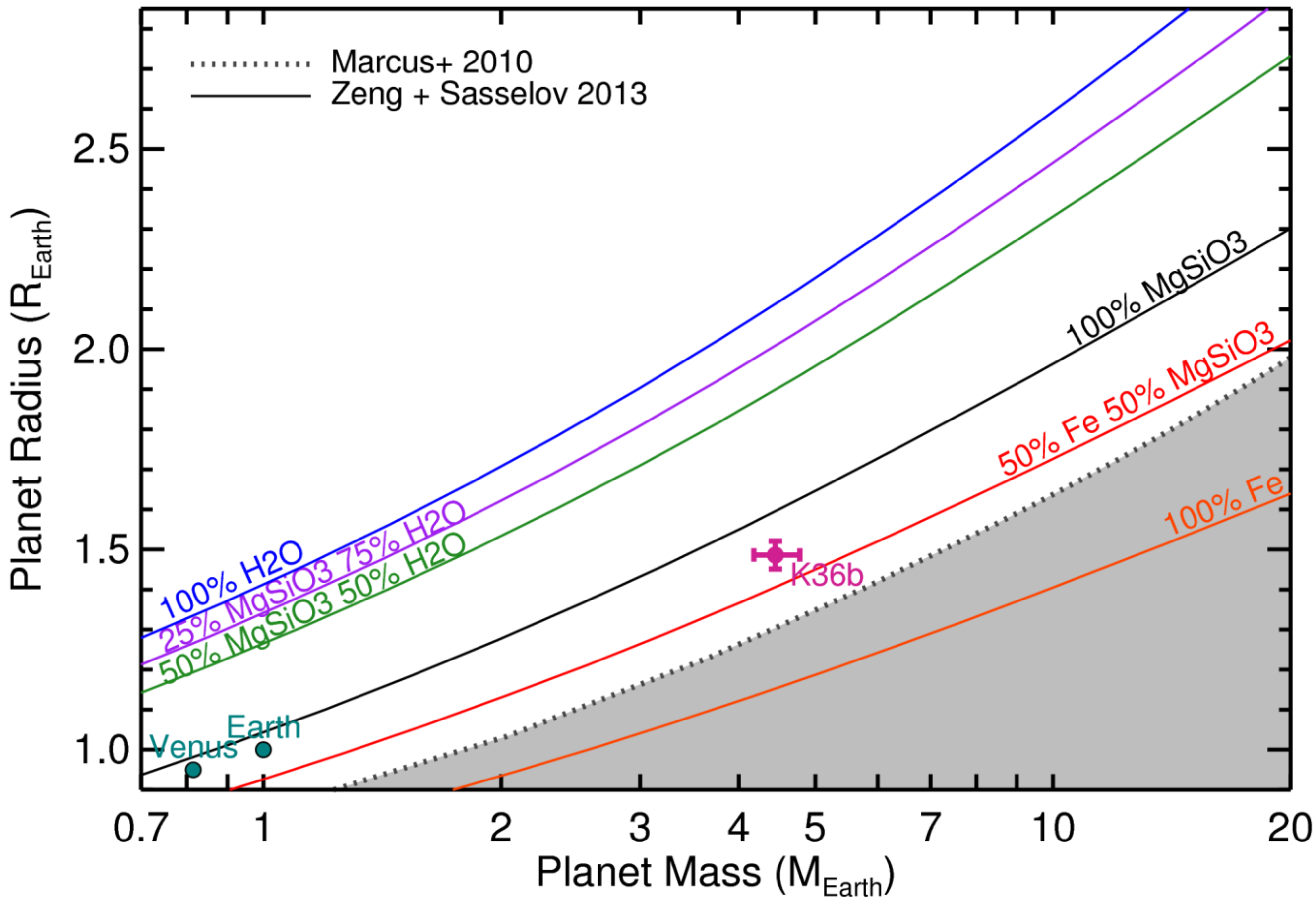
- CoRoT-7b first transiting planet smaller than 2.5 R_{earth}
- Large variations in photometry (2%) and radial velocity (20 m/s) due to spots and convection
- Haywood et al. (2014) modeled simultaneous photometry + radial velocities to improve estimate of planet mass
- Enormous investment of telescope time to overcome noisy star





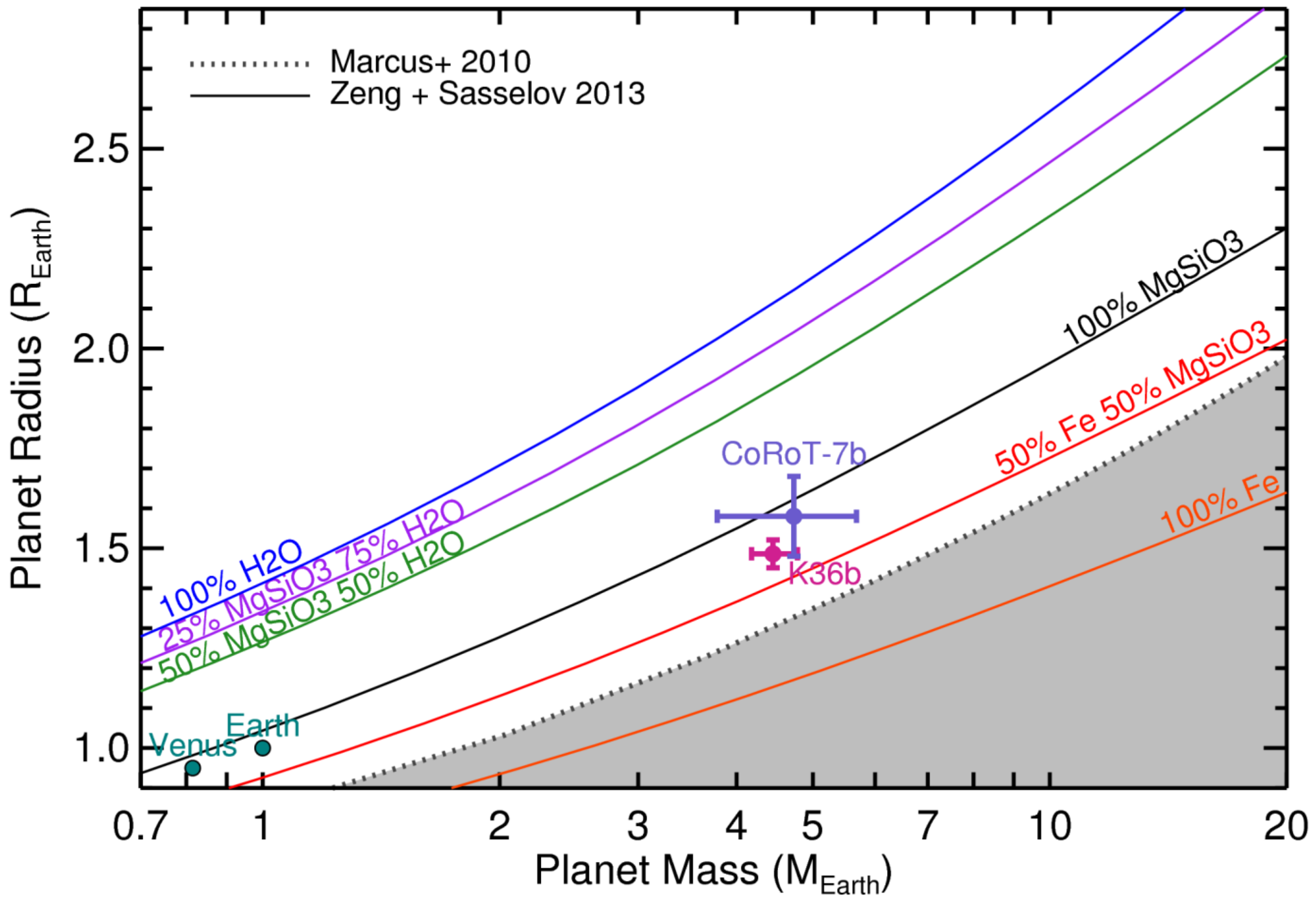
Leger et al. A&A (2009); Queloz et al. A&A (2009); Haywood et al. MNRAS (2014)

Towards Precise Constraints on the Mass-Radius Diagram below 2.5 Earth Radii



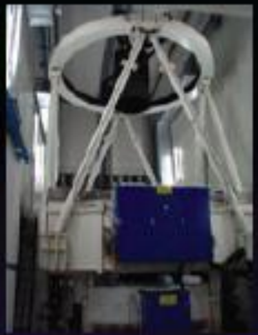
Dressing, Charbonneau, et al. to appear in ApJ (2015)

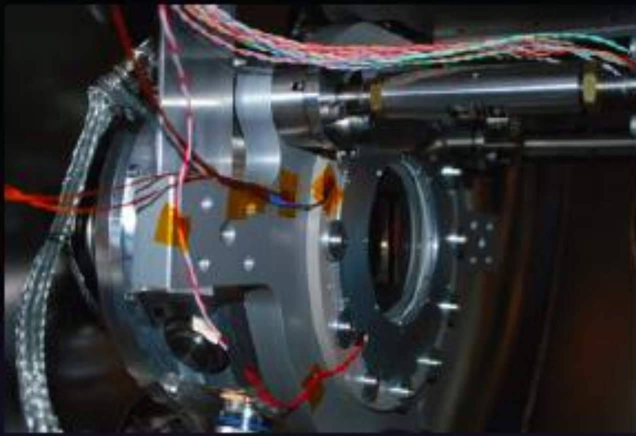
Stellar variability precludes efficient mass measurement. Only planet smaller than 2.5 R_{earth} from CoRoT: Kepler observes in northern hemisphere, which southern spectrograph cannot see.



Dressing, Charbonneau, et al. to appear in ApJ (2015)

HARPS-N

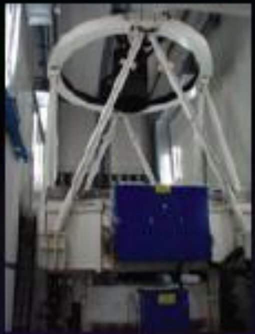


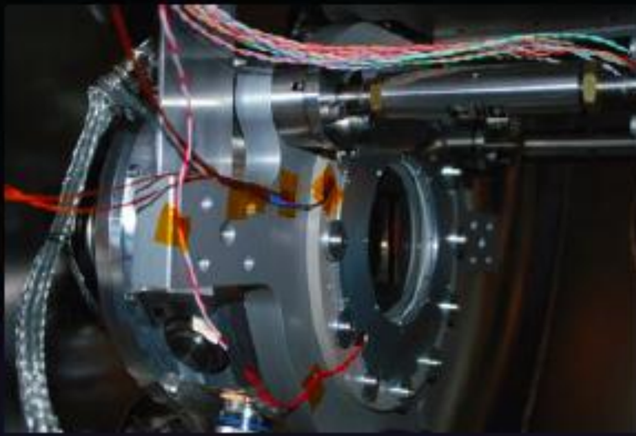


Partnership between Geneva Observatory, Harvard-Smithsonian Center for Astrophysics, Italian National Institute for Astrophysics, Univ. of St. Andrews, Edinburgh, and Queens Univ Belfast.

Located at 3.6m Italian Galileo Telescope on the island of La Palma, Spain.

HARPS-N





High resolution (R=115,000) highly stabilized optical spectrograph.

Similar to HARPS-S, but improvements include octagonal fibers (better scrambling) and monolithic 4096x4096 CCD.

80 guaranteed nights per year.

HARPS-N Target Selection Tiger Team

- An effort to select the most profitable Kepler candidates for radial velocity monitoring

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- Begin with all bright stars hosting a planet <3 R_{earth} & P<50d

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- Conduct photometric analysis and reject variables

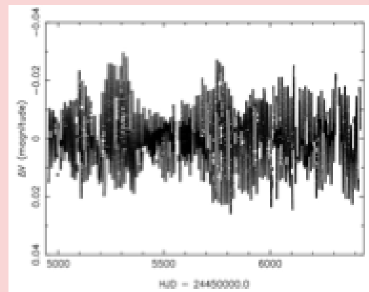
HARPS-N Target Selection Tiger Team

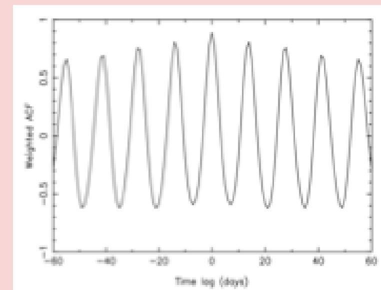
Object name & notes on photometric and expected spectroscopic stellar variability	Kepler lightcurve, all quarters (LC)	Autocorrelation function (ACF) of LC	Lomb-Scargle periodogram of LC

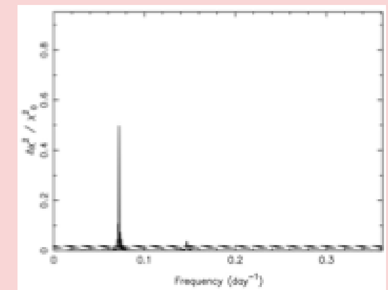
KOI 678 (Kepler-211)

- High photometric variability. As a rule of thumb, 1 mmag photometric variability translates into 2 m/s RV rotational modulation
- Strong sidelobes in ACF suggest presence of long-lived active regions on stellar surface

→ OK only for short period planets (Hatzes et al. 2011, Pepe et al. 2013)



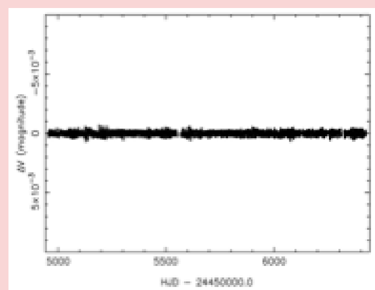


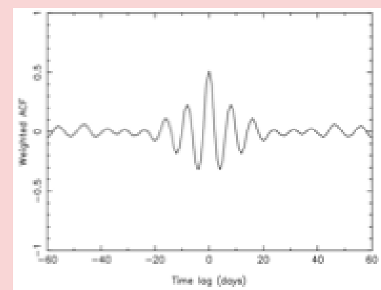


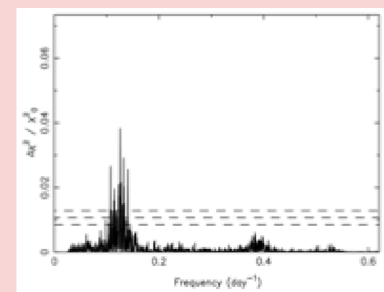
KOI 262 (Kepler-50)

- Short stellar rotation period (~ 8 days)
- ACF displays high amplitude of first sidelobe relative to main peak.

→ Likely fast rotator, RV follow up impossible





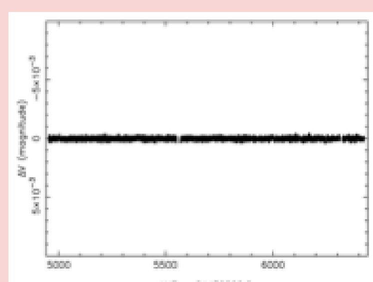


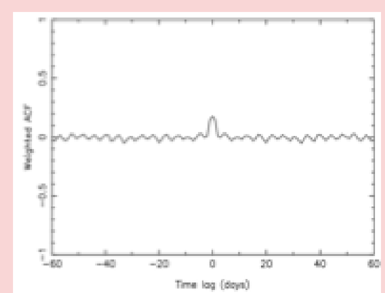
KOI 4462

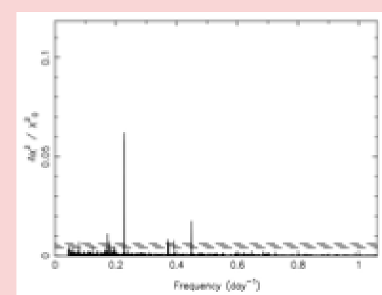
- High levels of photometric variability over short timescales ("8-hour flicker", see Bastien et al. 2013) indicate high levels of granulation-related noise

→ RV will be affected by granulation noise

- Sharp peaks in periodogram suggesting stellar pulsations and T=7675K → possible A star







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- Conduct photometric analysis and reject variables

- Rank survivors by telescope time to achieve 15% mass measurement (assuming variety of mass-radius relations)

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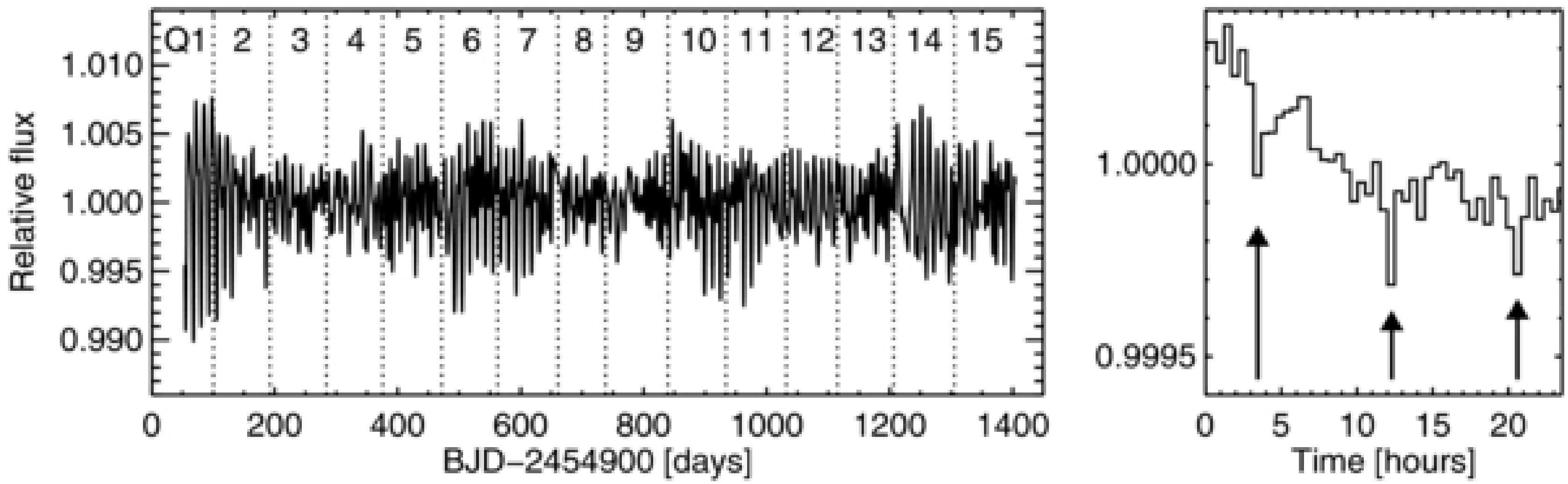
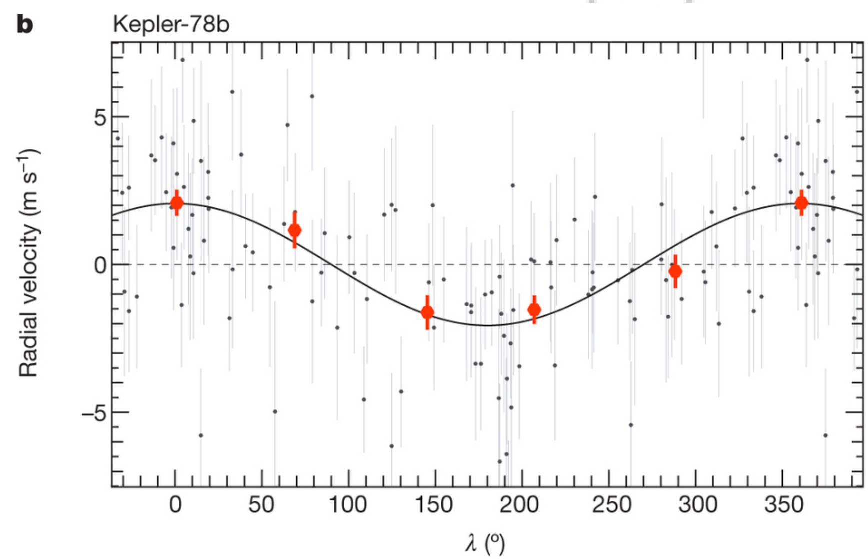
- Favor stars with asteroseismic characterization
- Conduct photometric analysis and reject variables
- Rank survivors by telescope time to achieve 15% mass measurement (assuming variety of mass-radius relations)
- Allocate time to achieve this until 40 telescope nights are expended

System 1: Kepler-78

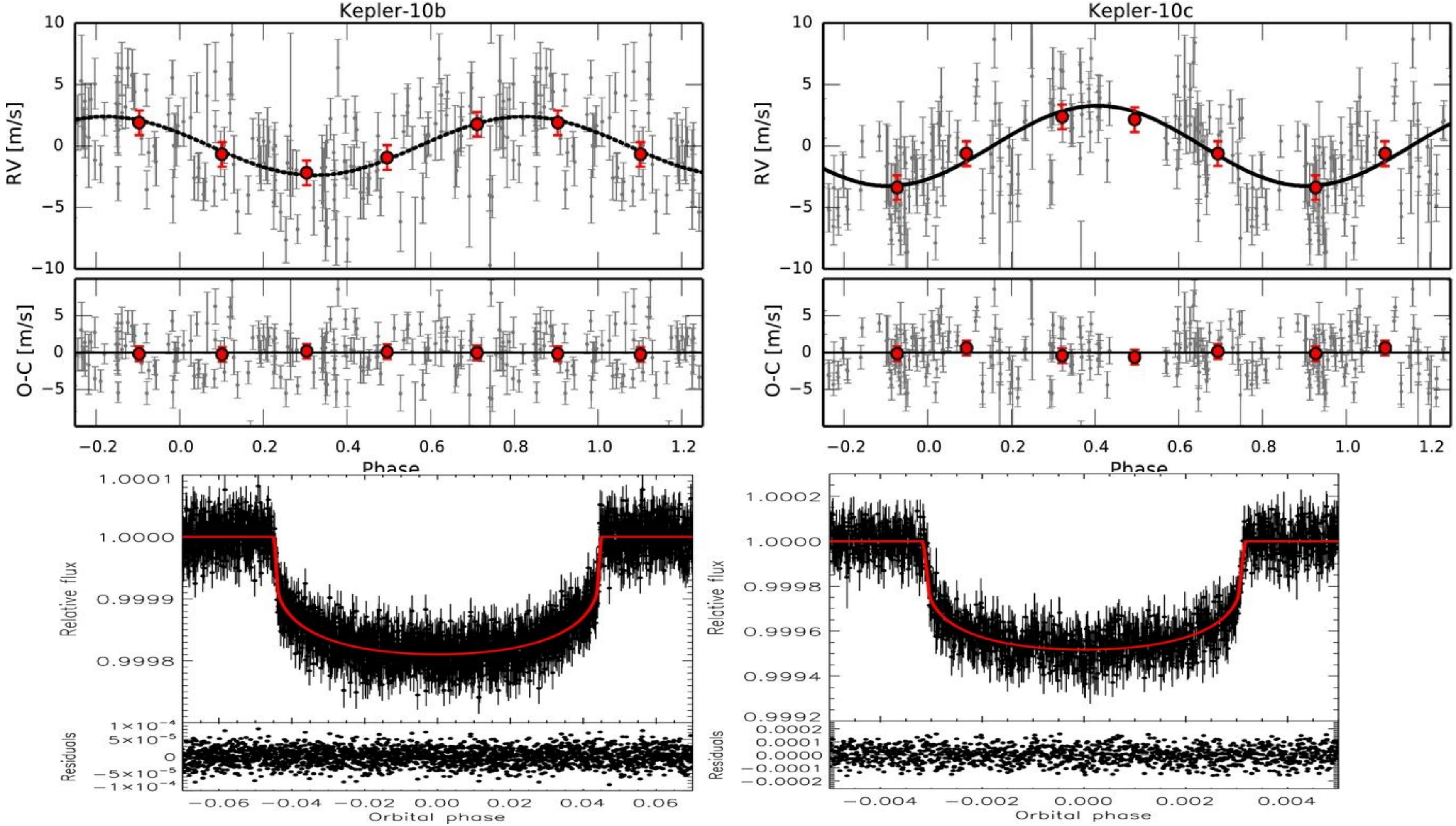




- Planet only slightly larger than Earth
- Very short period of 8.1 hrs means radial velocity amplitude is measurable
- Independent measurement by Keck/HIRES (Howard et al. Nature 2014)

Sanchis-Ojeda et al. ApJ (2013)
Pepe et al. Nature (2013)
Howard et al. Nature (2013)

System 2: Kepler-10

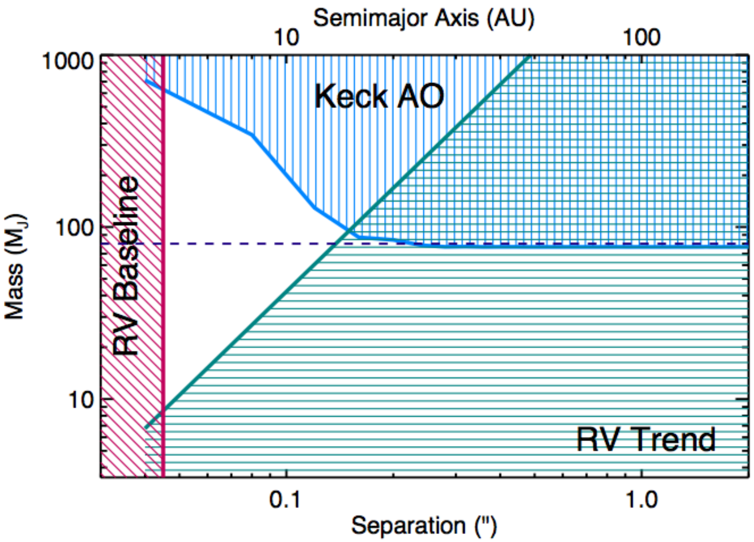


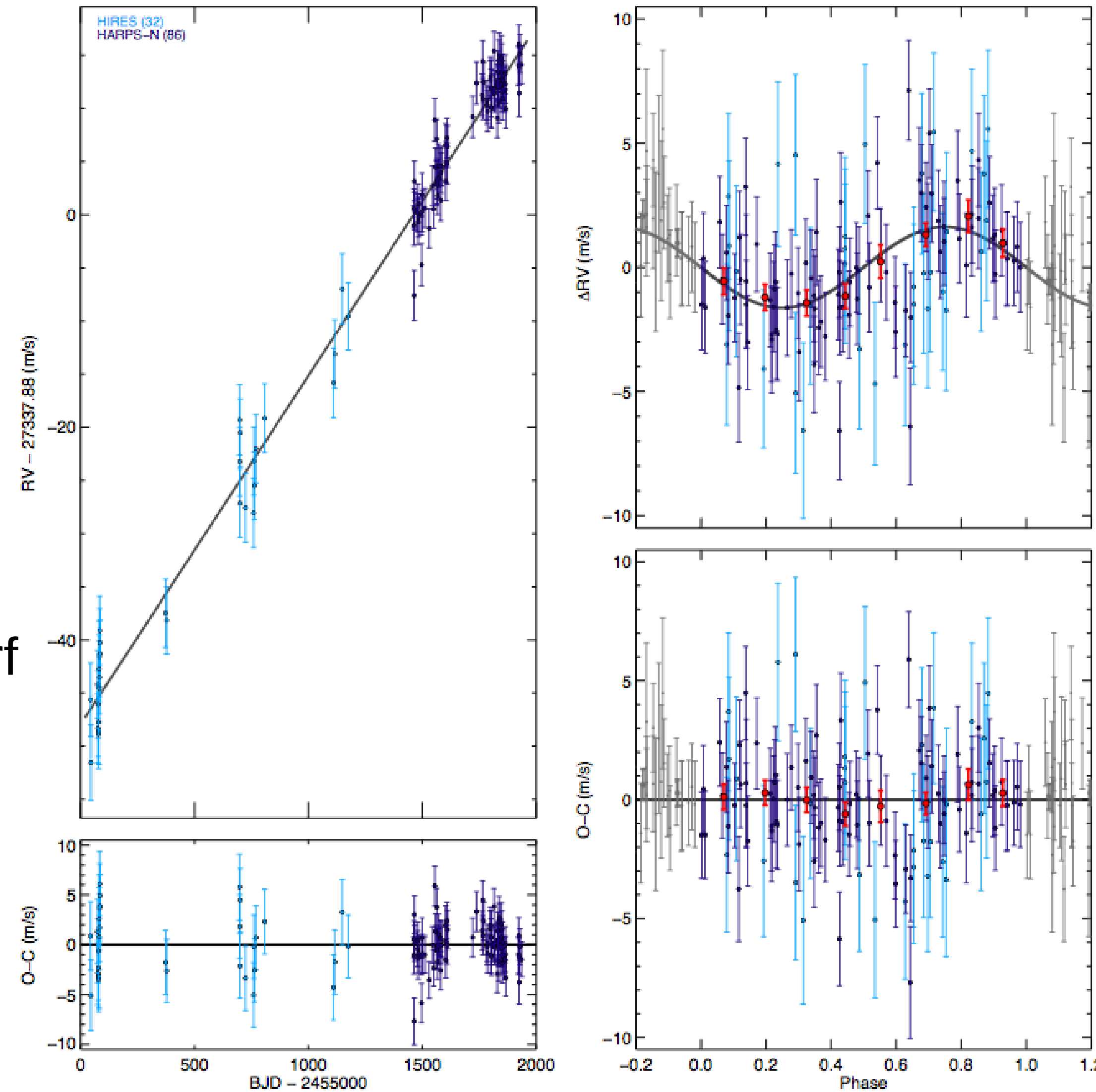
- Two planets:
  1.47 R_{earth} at P=0.8d & 2.35 R_{earth} at P=45d
- Very old system: 10.6 +/- 1.4 Gyr

Batalha et al. ApJ (2011)
Dumusque et al. ApJ (2014)

System 3: Kepler-93

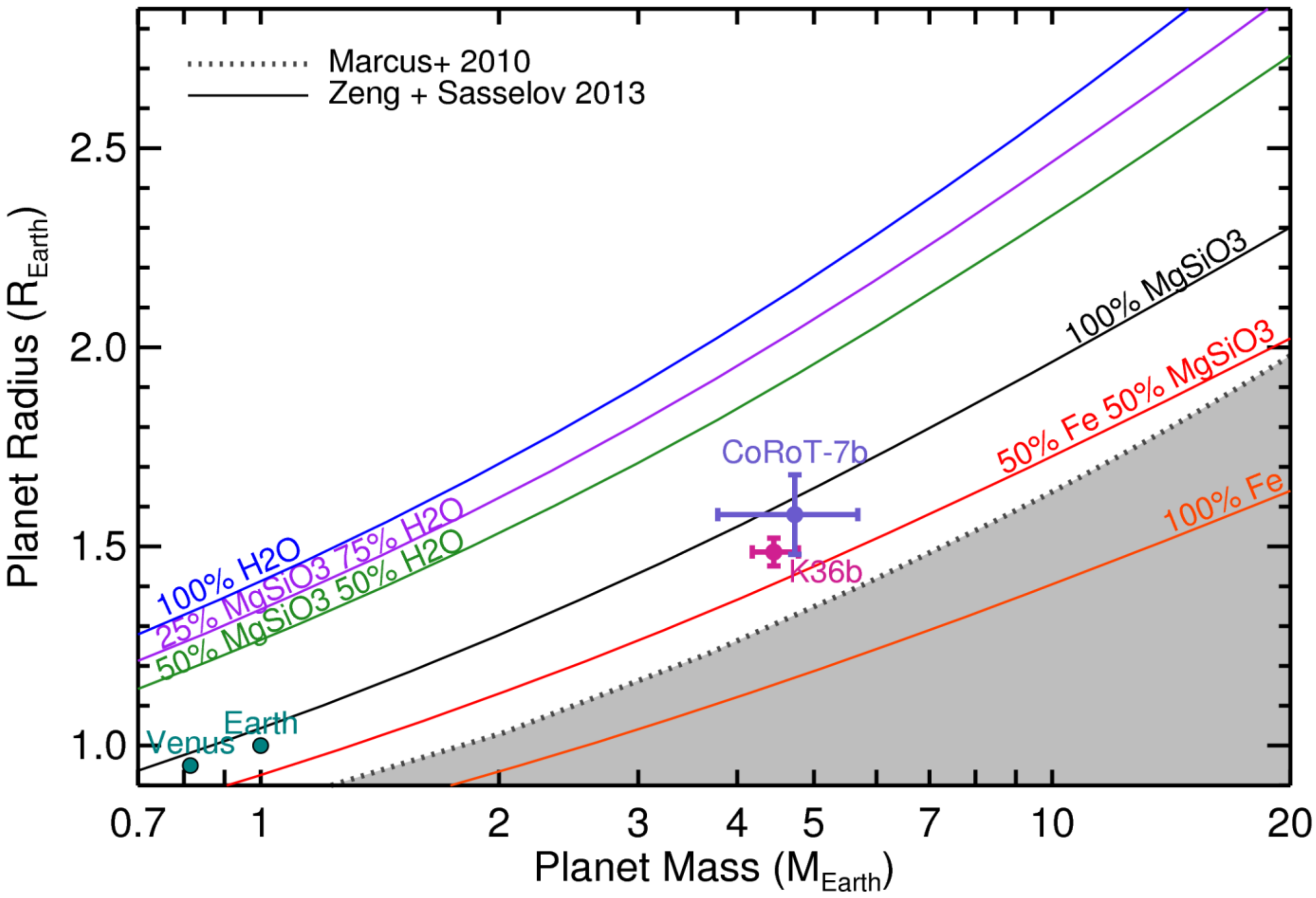
- Asteroseismic study makes this the most precisely measured exoplanet radius 1.48 R_{earth} +/- 120km
- Trend indicates brown dwarf or stellar companion





Dressing et al. to appear in ApJ (2013)
Ballard et al. (2013)

Towards Precise Constraints on the Mass-Radius Diagram below 2.5 Earth Radii



Dressing, Charbonneau, et al. to appear in ApJ (2014)

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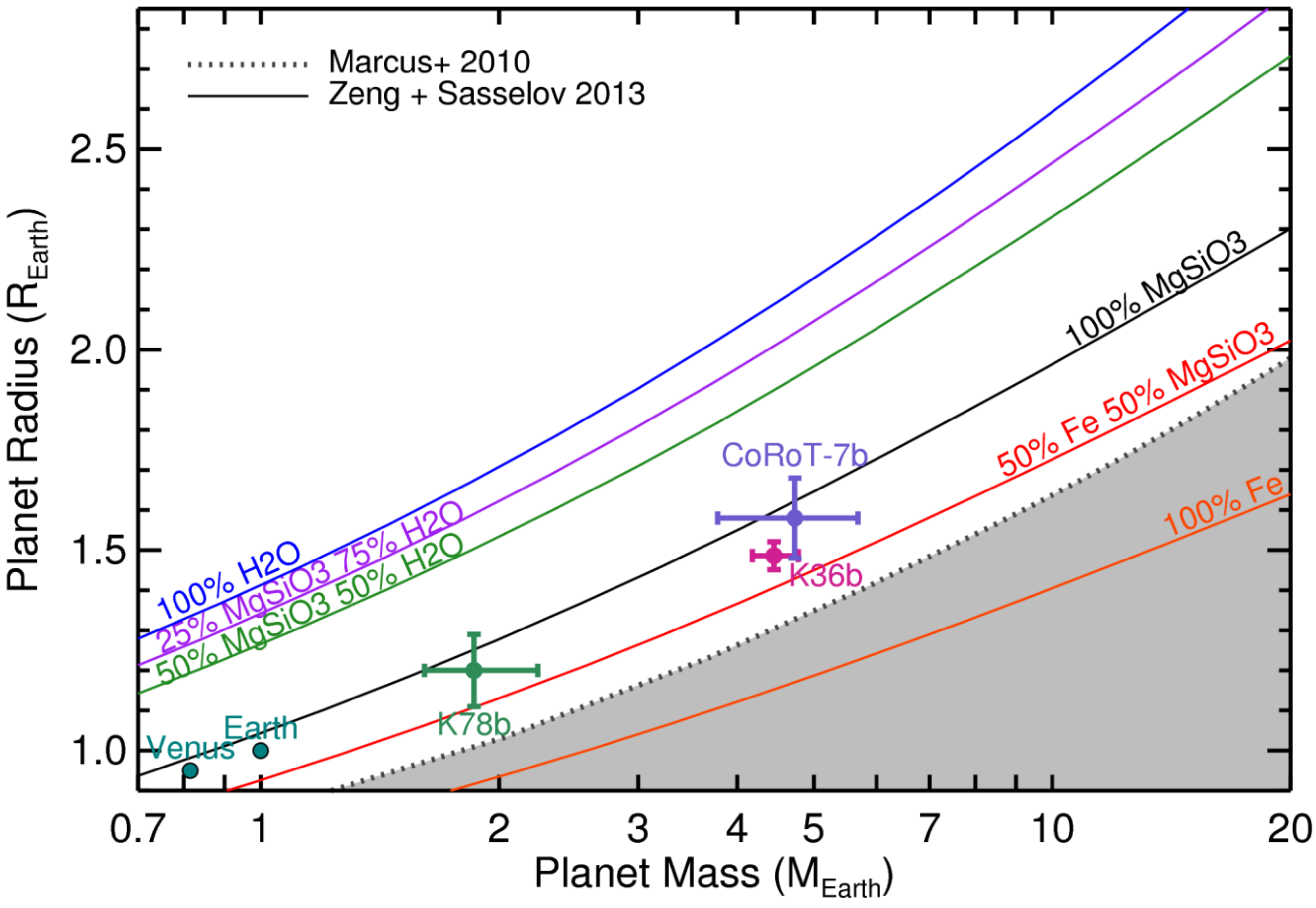

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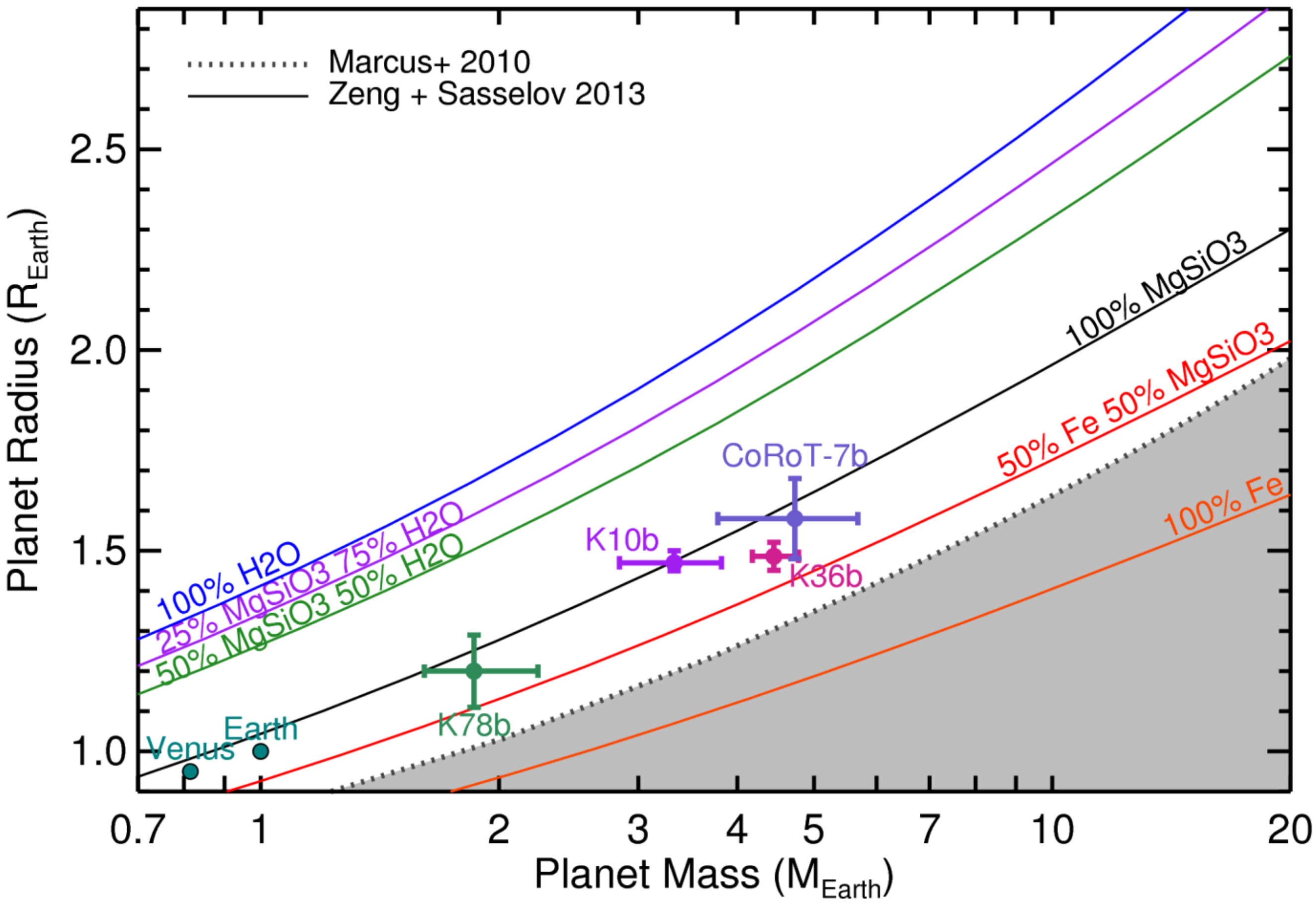

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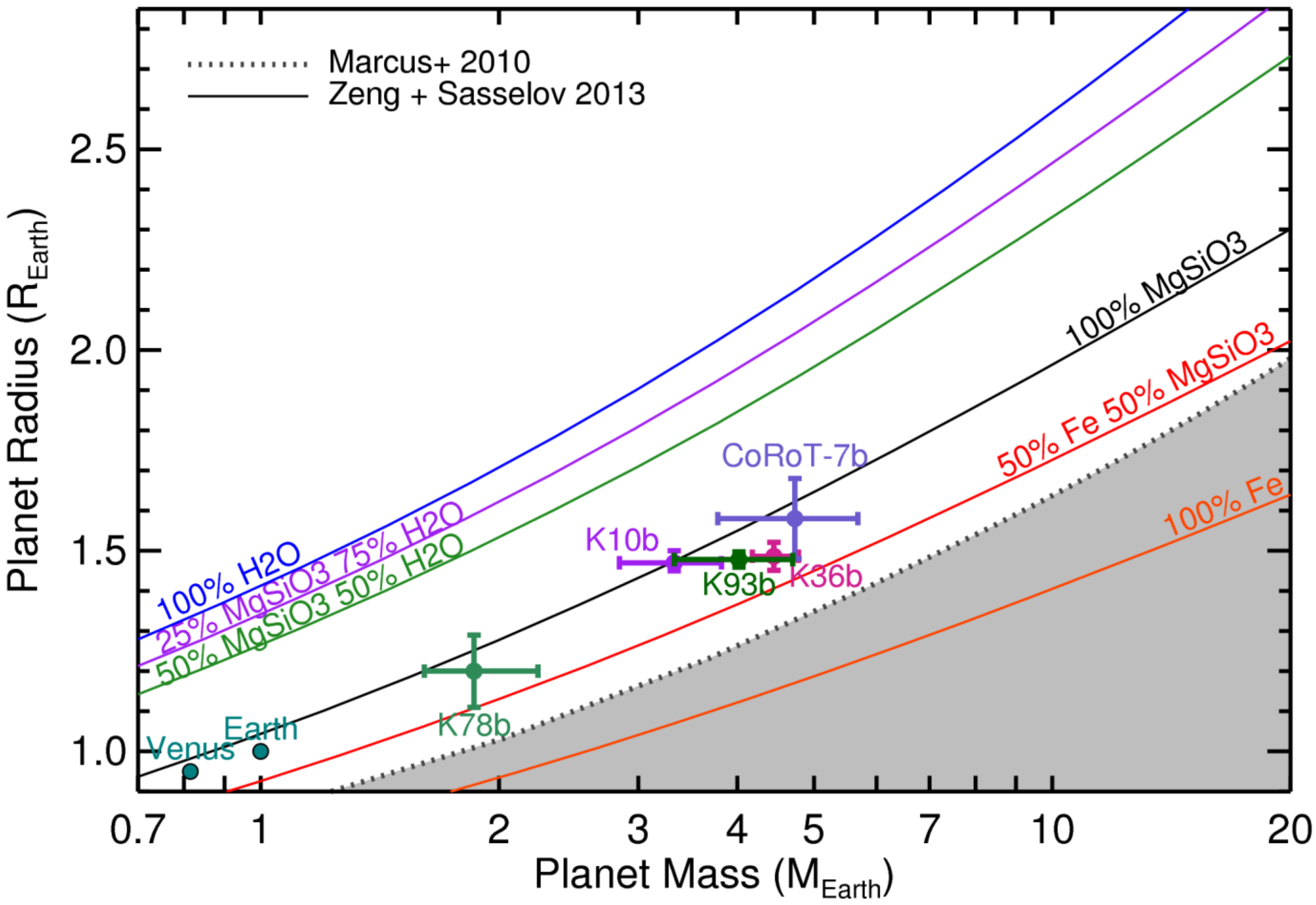

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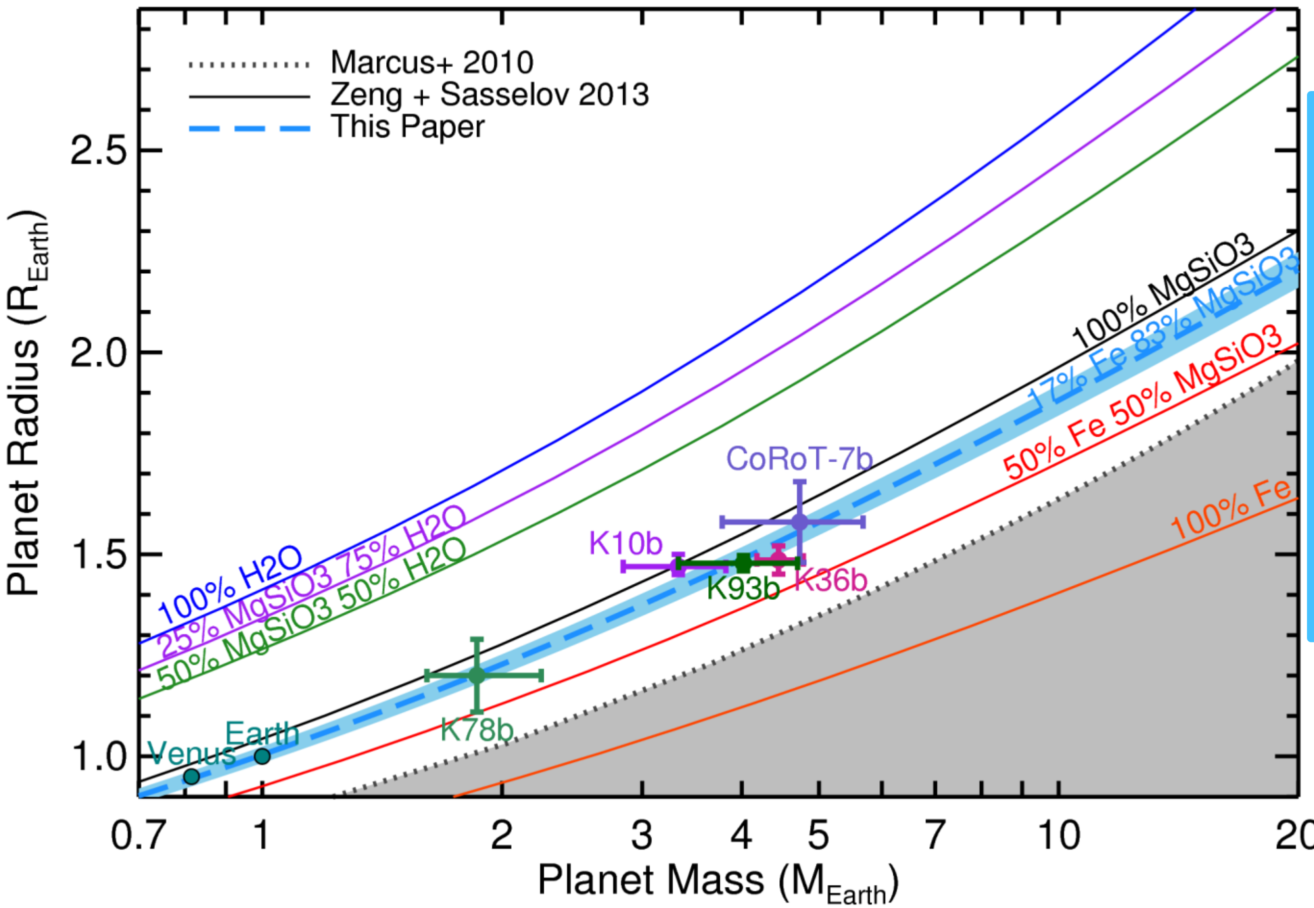

Width set by observed variation in Mg/Si/Fe ratios in local planet hosts

Grasset et al. (2009)

Dressing, Charbonneau, et al. to appear in ApJ (2014)

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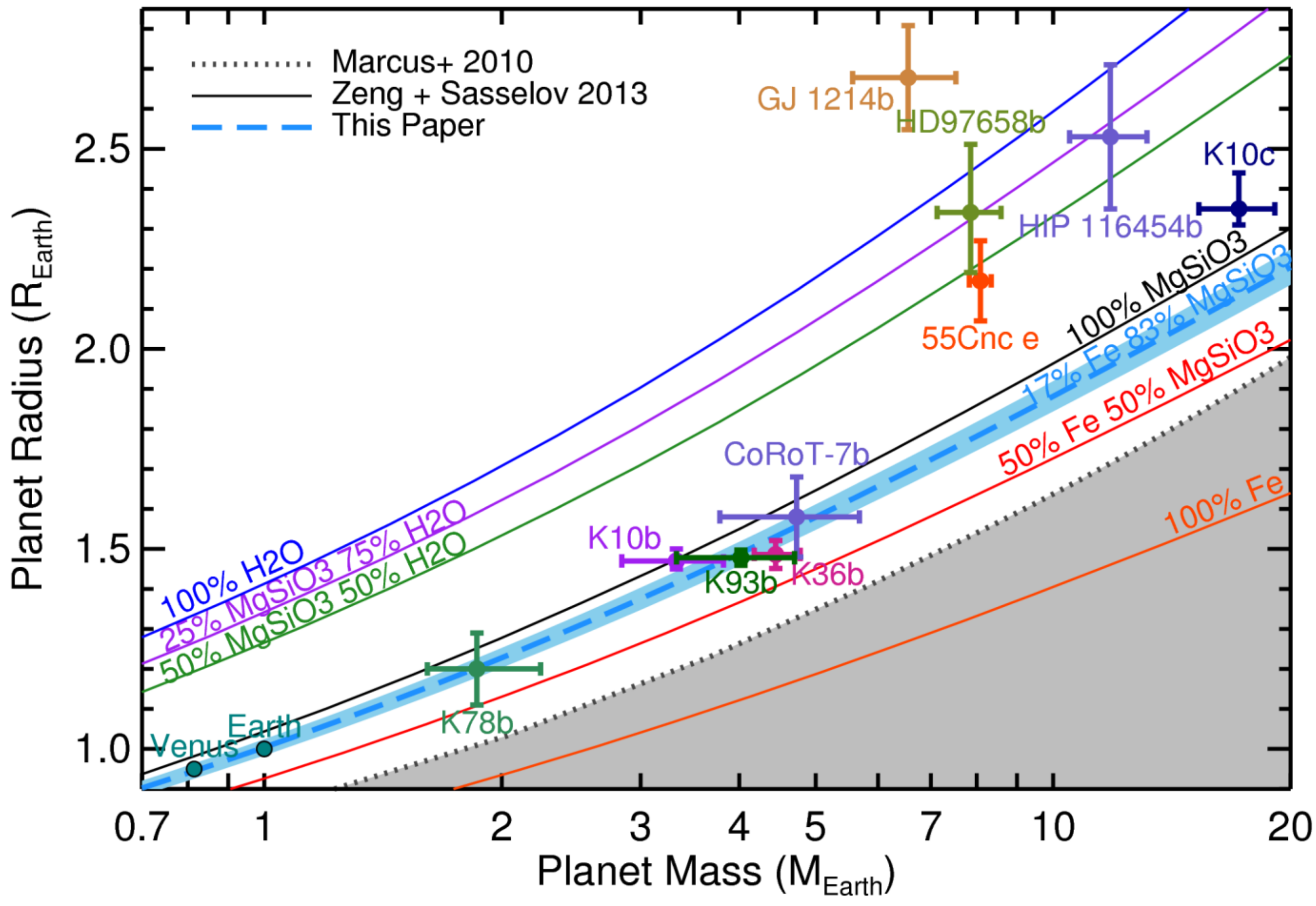
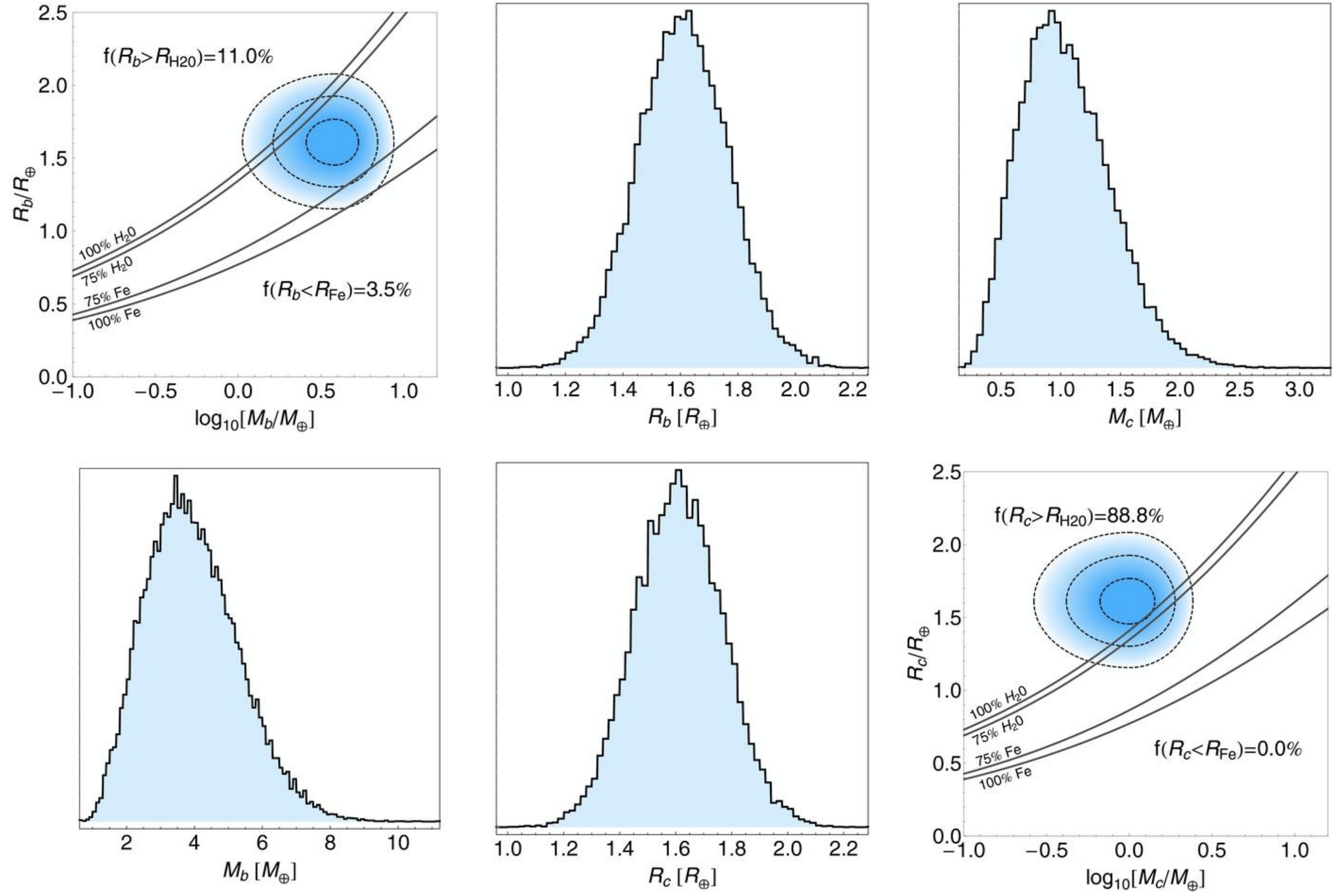


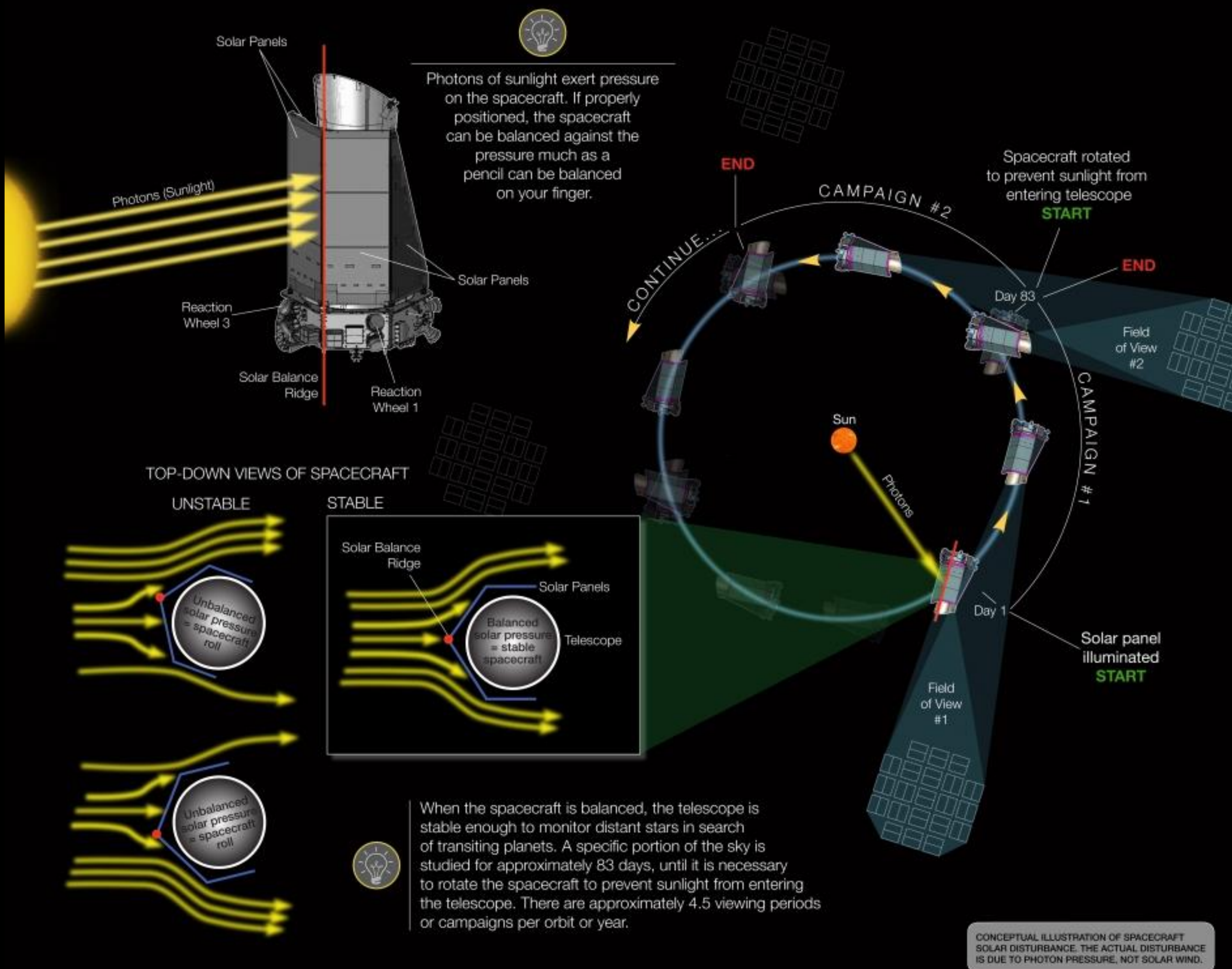
Dressing, Charbonneau, et al. to appear in ApJ (2014)

Low-density and Small Planets? The Case of KOI-314

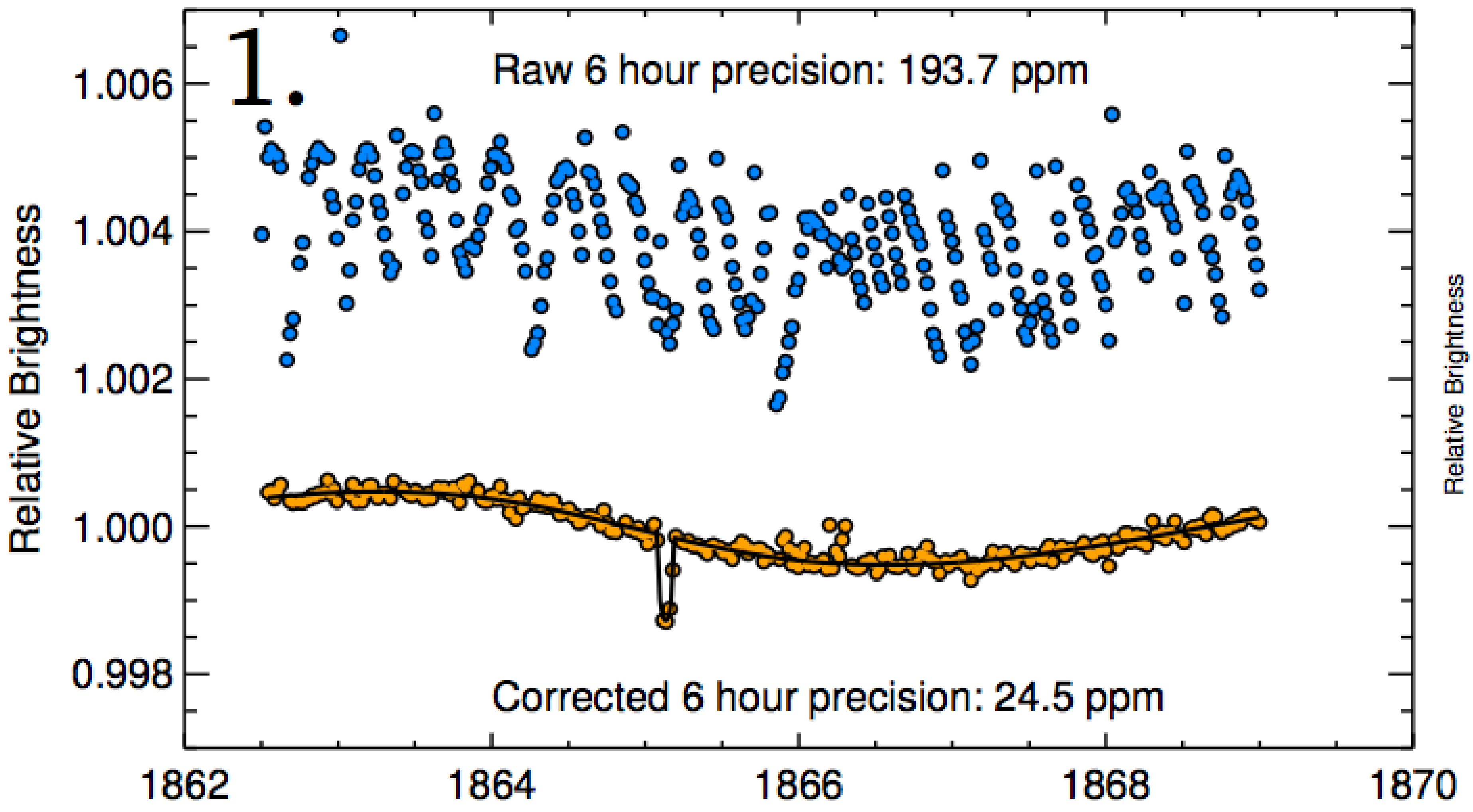


Kipping et al. ApJ (2014)

Kepler's Second Light: How K2 Will Work

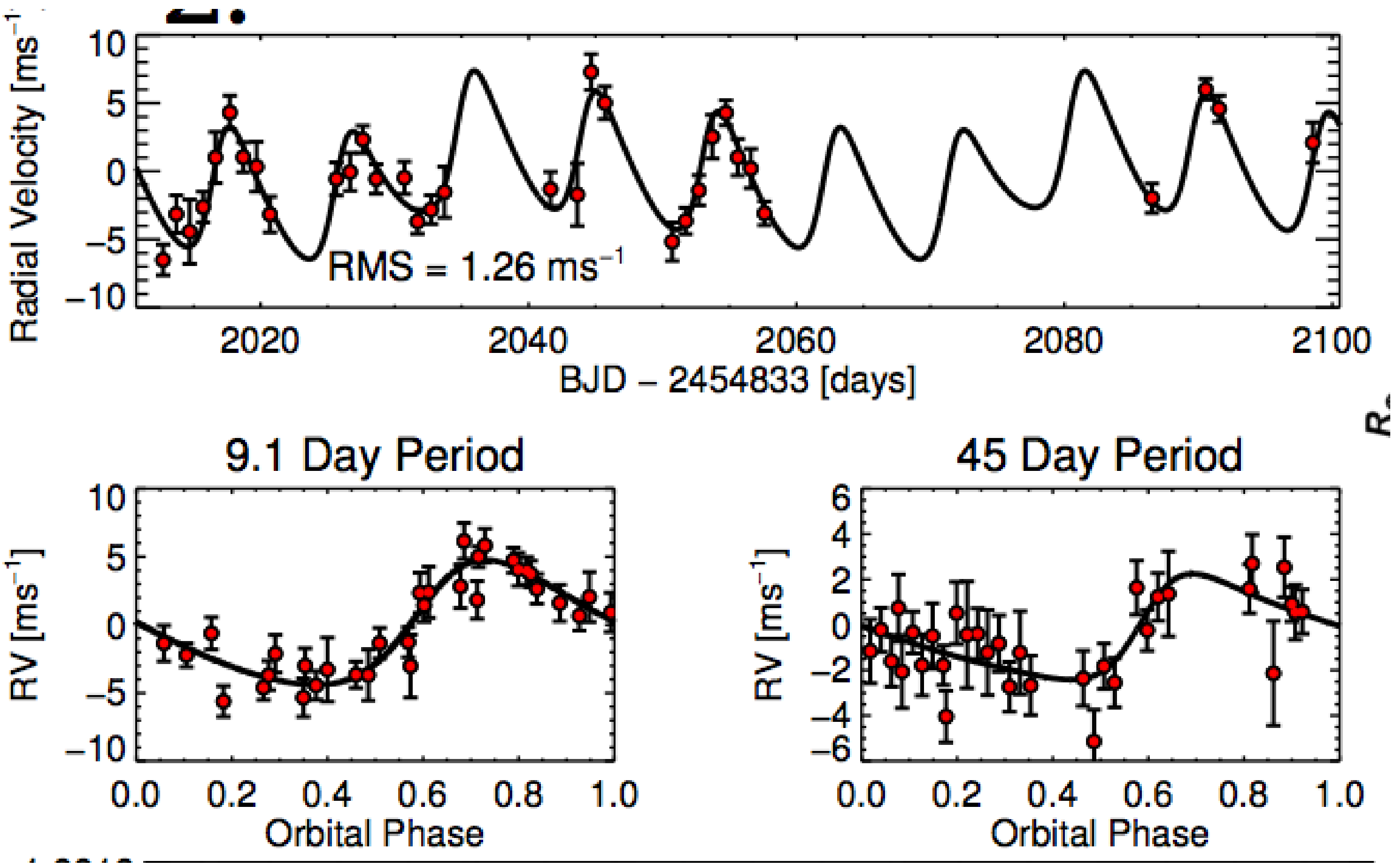


First Planet Discovery with K2 Mission and HARPS-N



Vanderburg, Montet, Johnson et al. ApJ (2015)

HIP116454: Bright, Nearby Star hosting a transiting 10.6 M_{earth} planet



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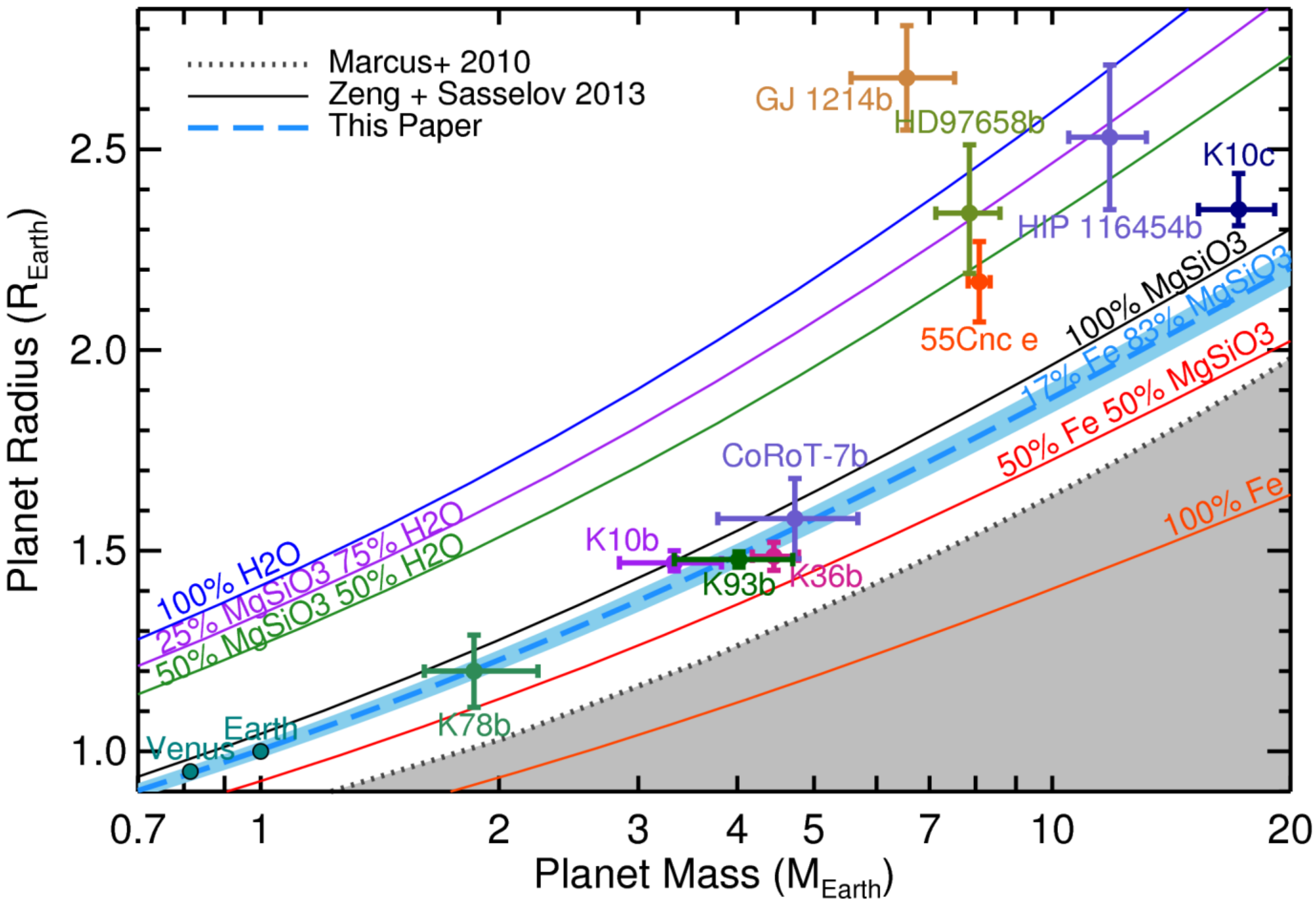

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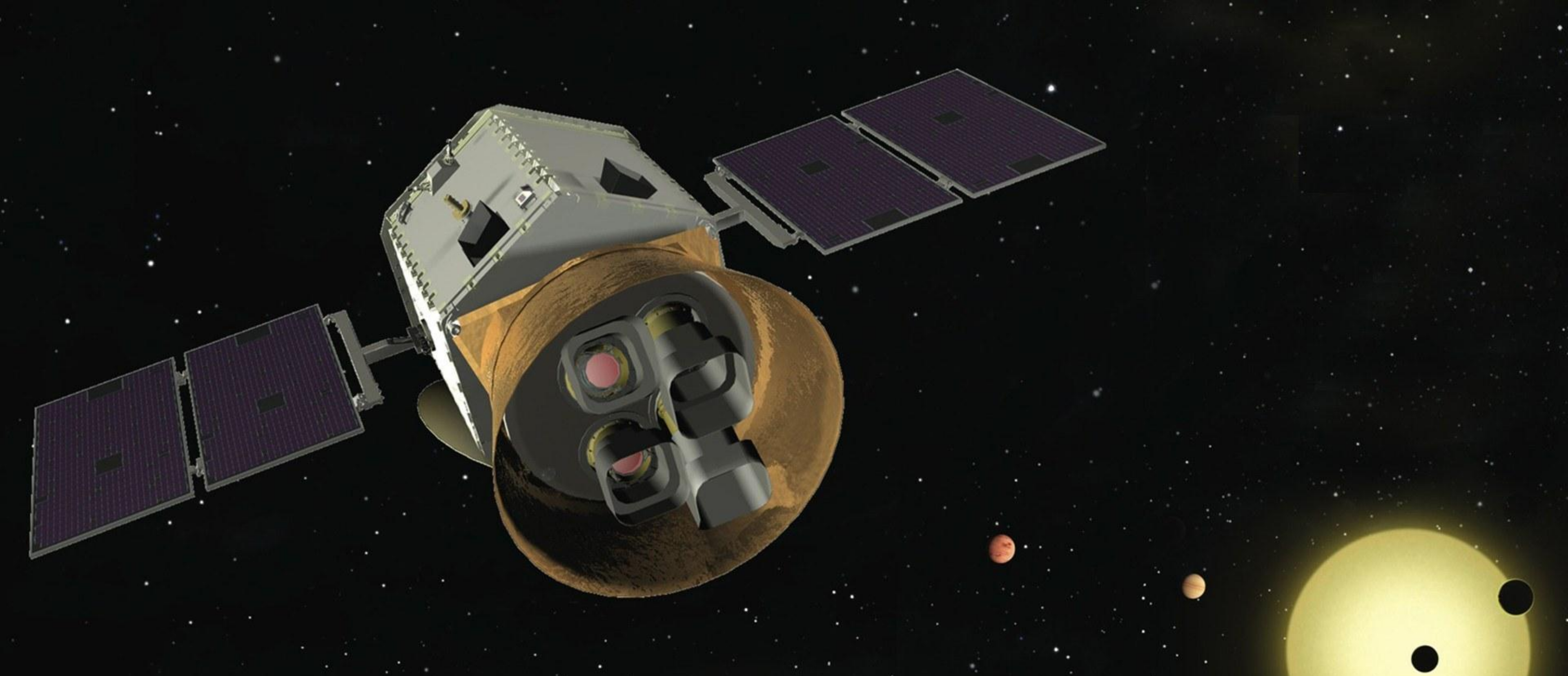
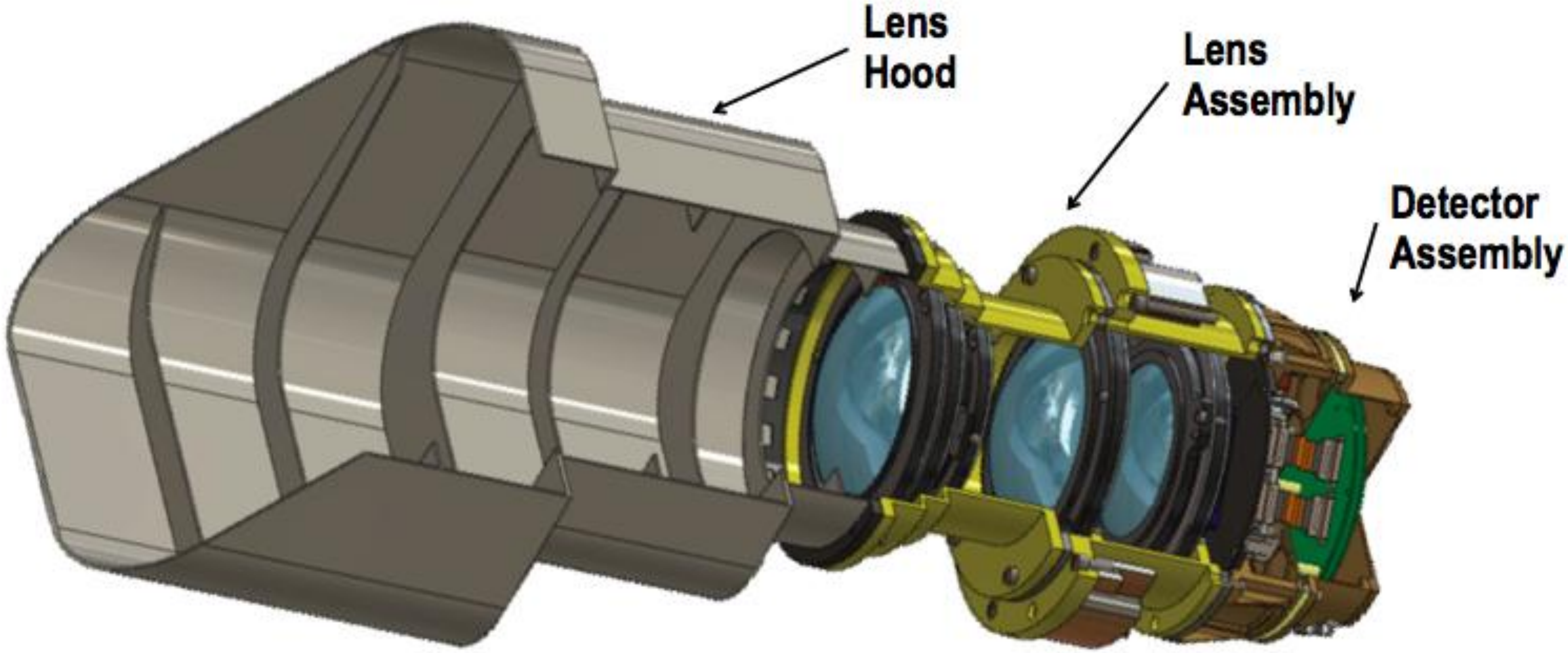


The NASA TESS Mission

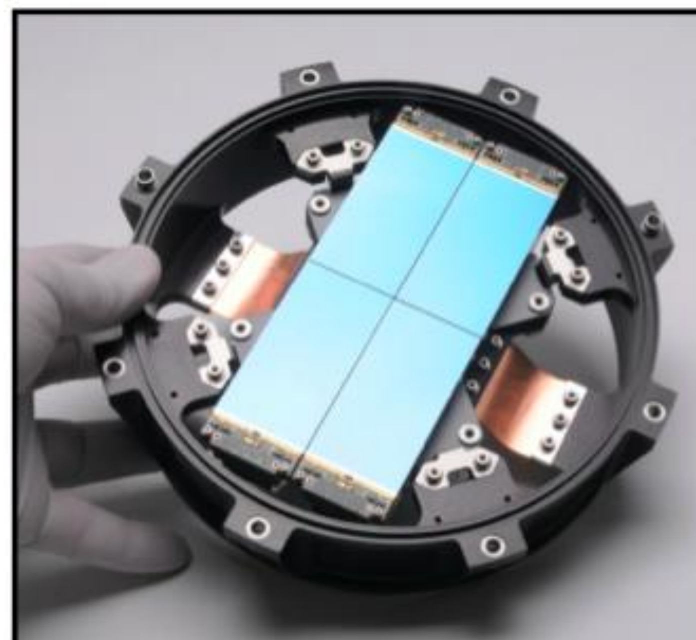
MIT, Orbital Sciences, Harvard-Smithsonian Center for Astrophysics

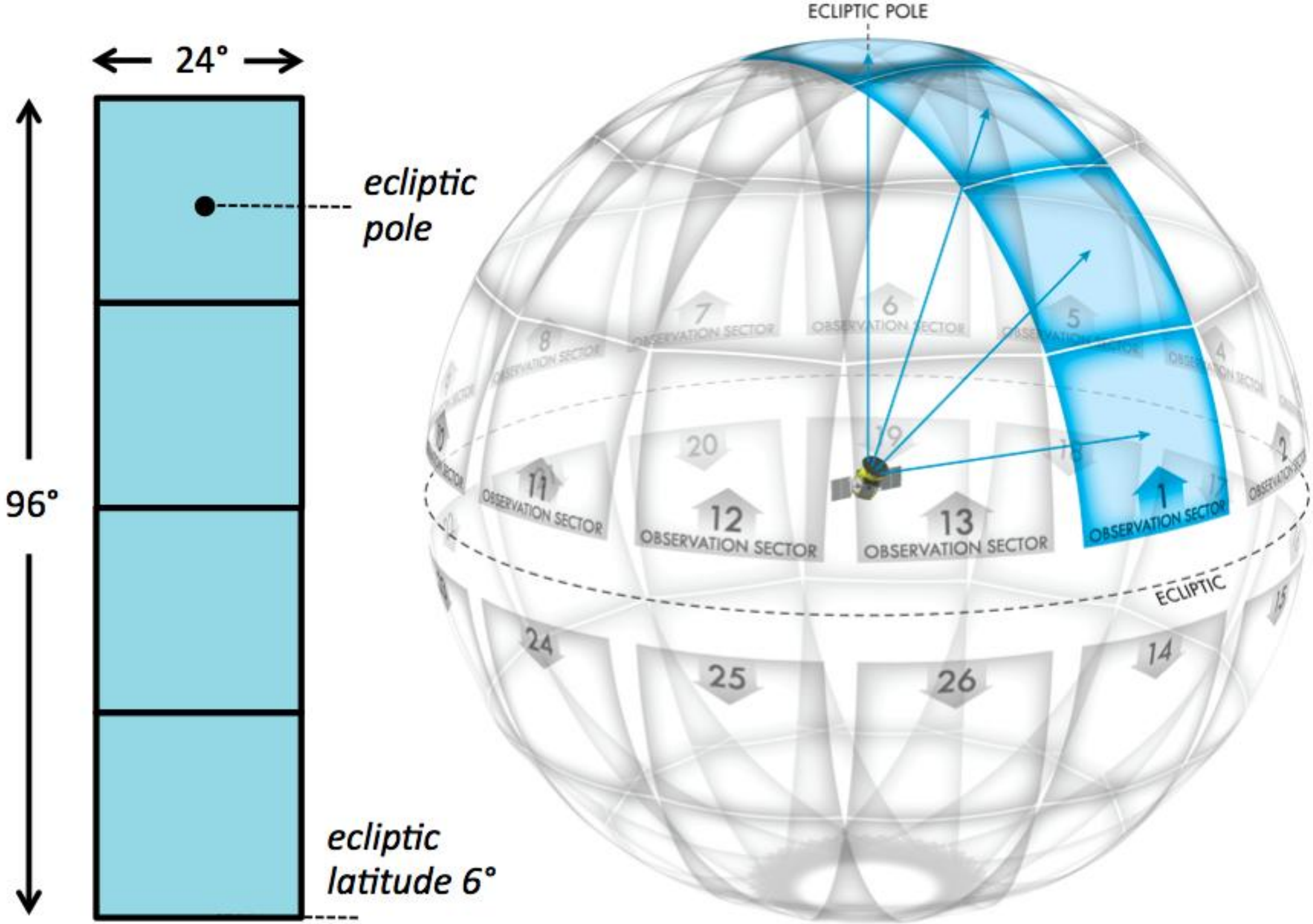
Launch in 2017, 2 year mission (1 year per hemisphere) + 2 year extension
Monitor 500,000 stars brighter than V=12

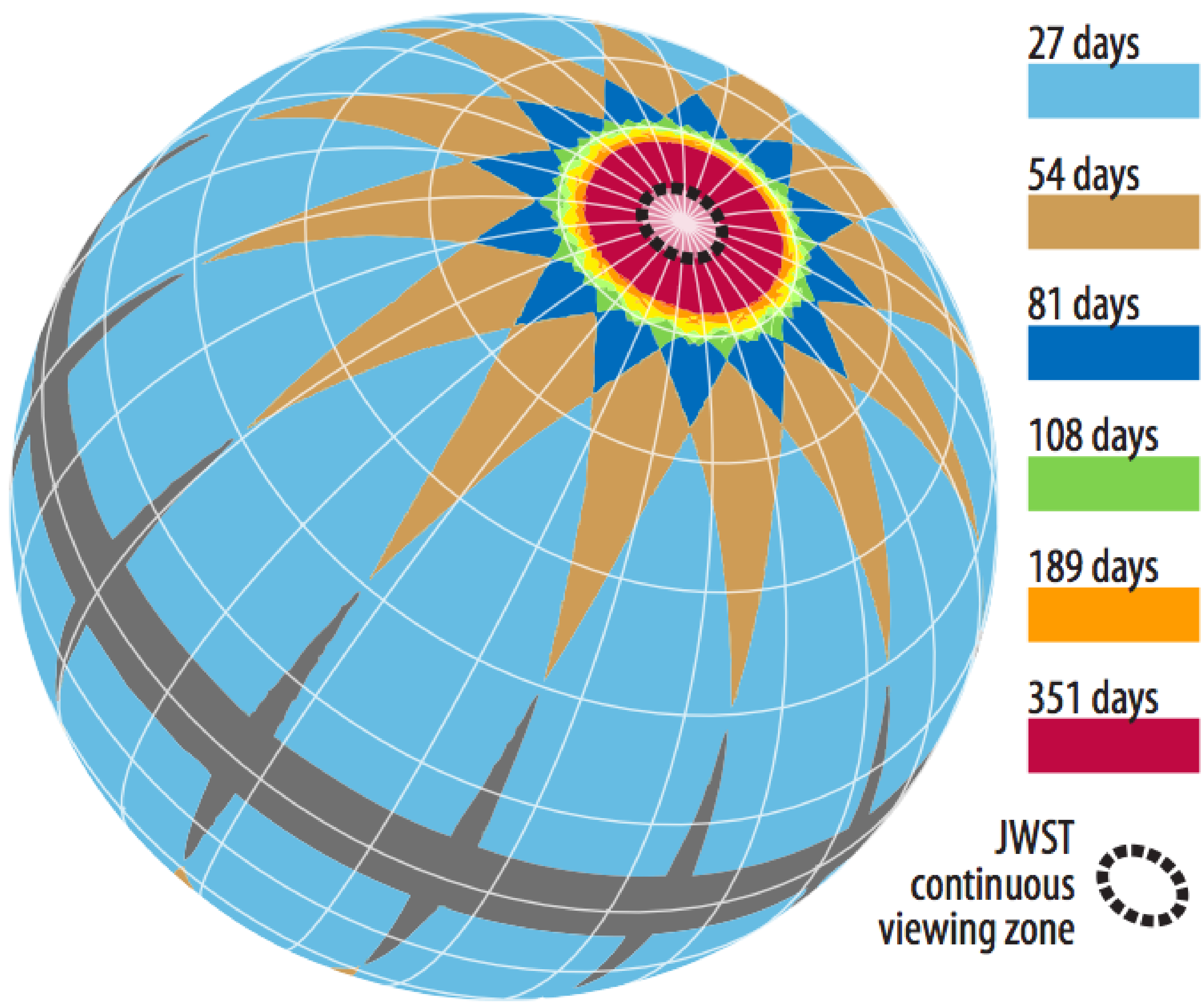
TESS will discover 1000+ small exoplanets transiting the closest, brightest stars and publicly release these immediately for all to study.



Entrance pupil diameter	10.5 cm
Bandpass	600-1000 nm
Field of view	24° x 24°
Cadence for target stars	2 min
Cadence for full frame images	30 min



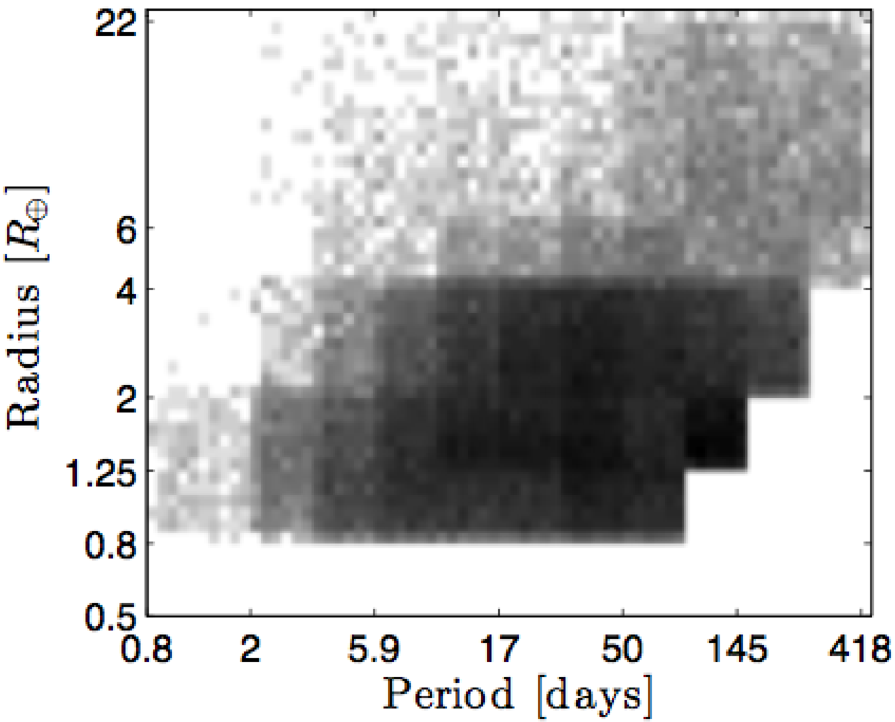

24°
96°
ecliptic pole
ecliptic latitude 6°
ECLIPTIC POLE
7 OBSERVATION SECTOR
6 OBSERVATION SECTOR
5
8 OBSERVATION SECTOR
20
19
11 OBSERVATION SECTOR
12 OBSERVATION SECTOR
13 OBSERVATION SECTOR
1 OBSERVATION SECTOR
2
ECLIPTIC
24
25
26
14



27 days
54 days
81 days
108 days
189 days
351 days
JWST
continuous
viewing zone

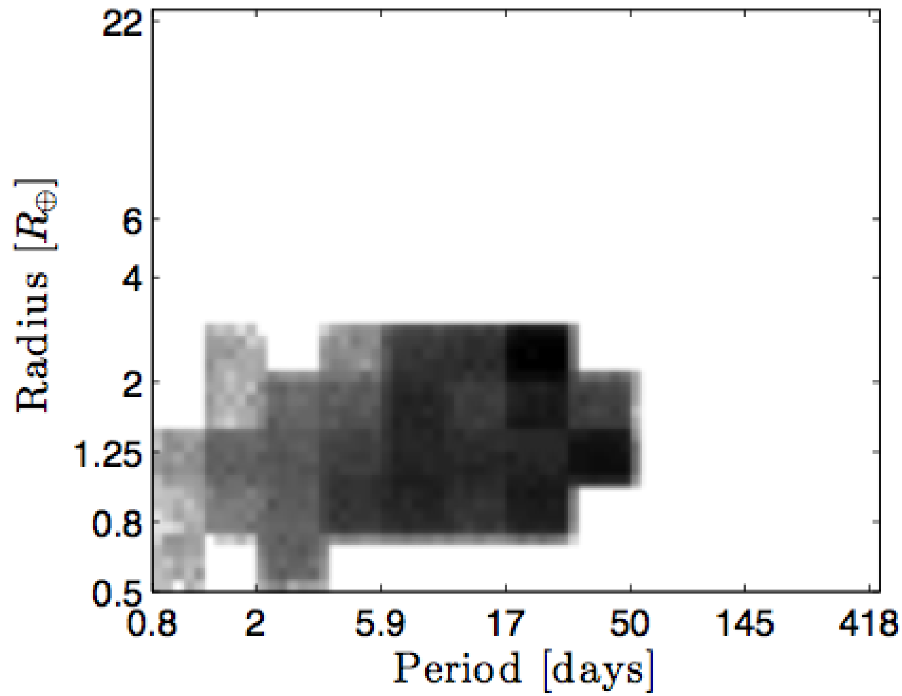
Simulated planets

FGK dwarfs



Fressin et al. (2013)

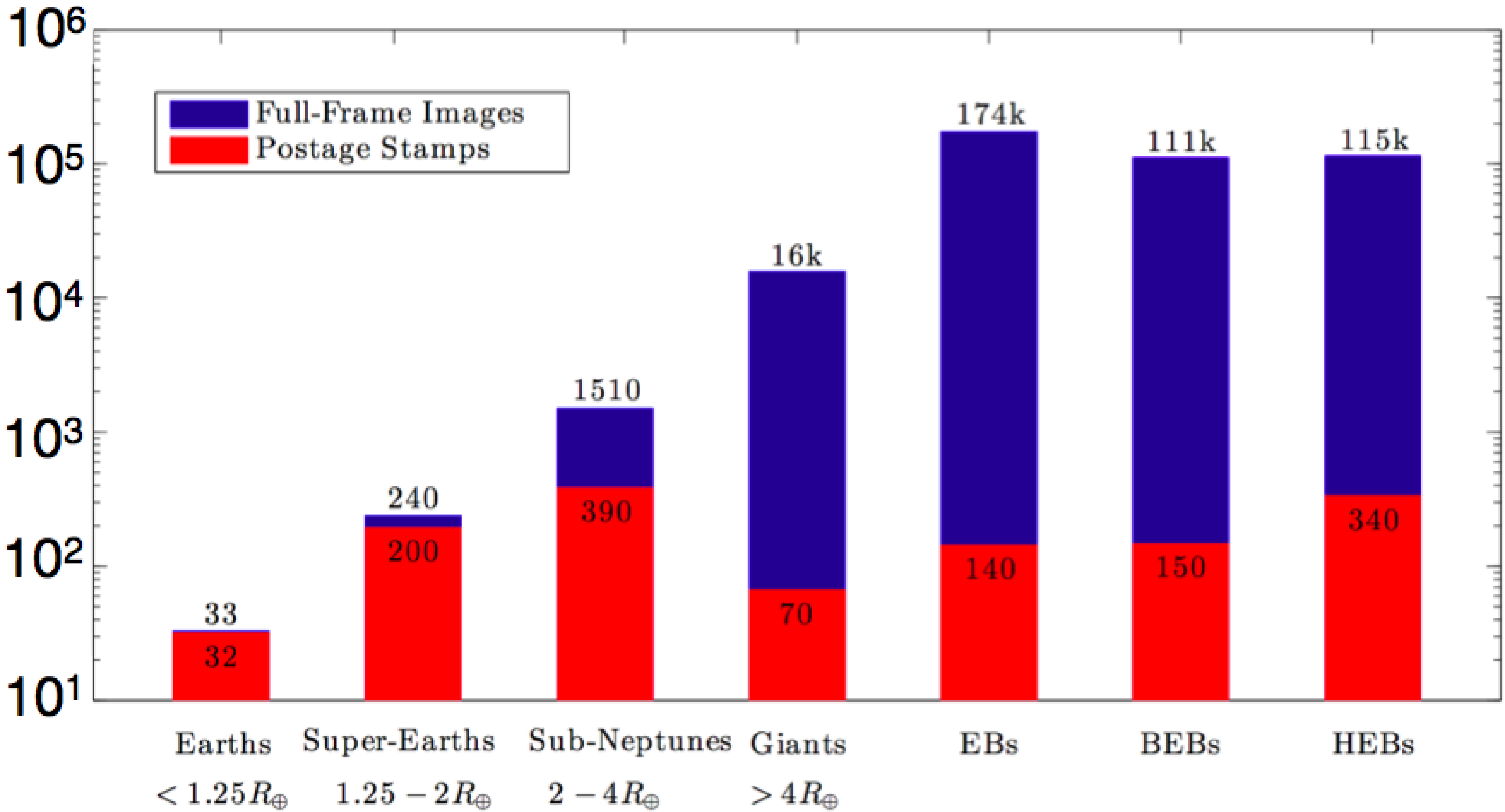
M dwarfs



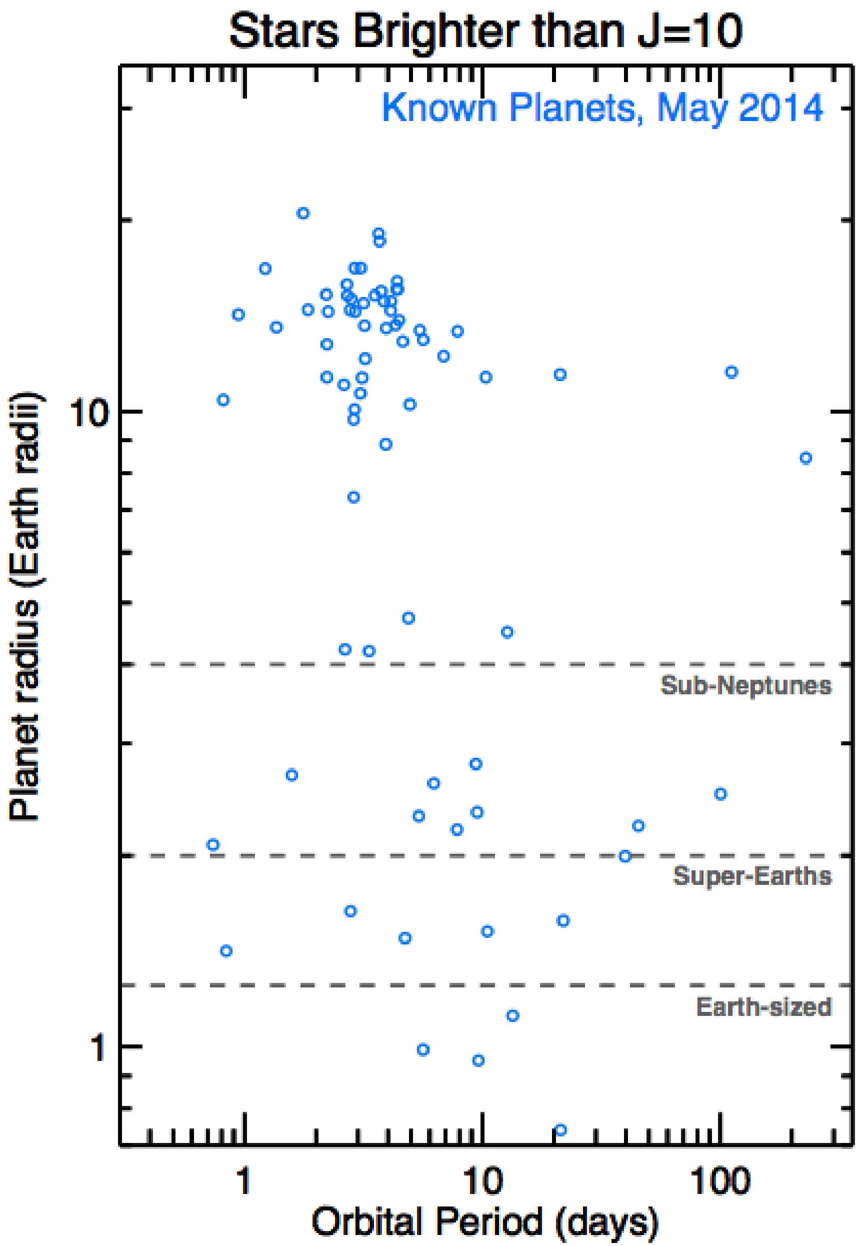
Dressing & Charbonneau (2013)

Sullivan et al., in prep.

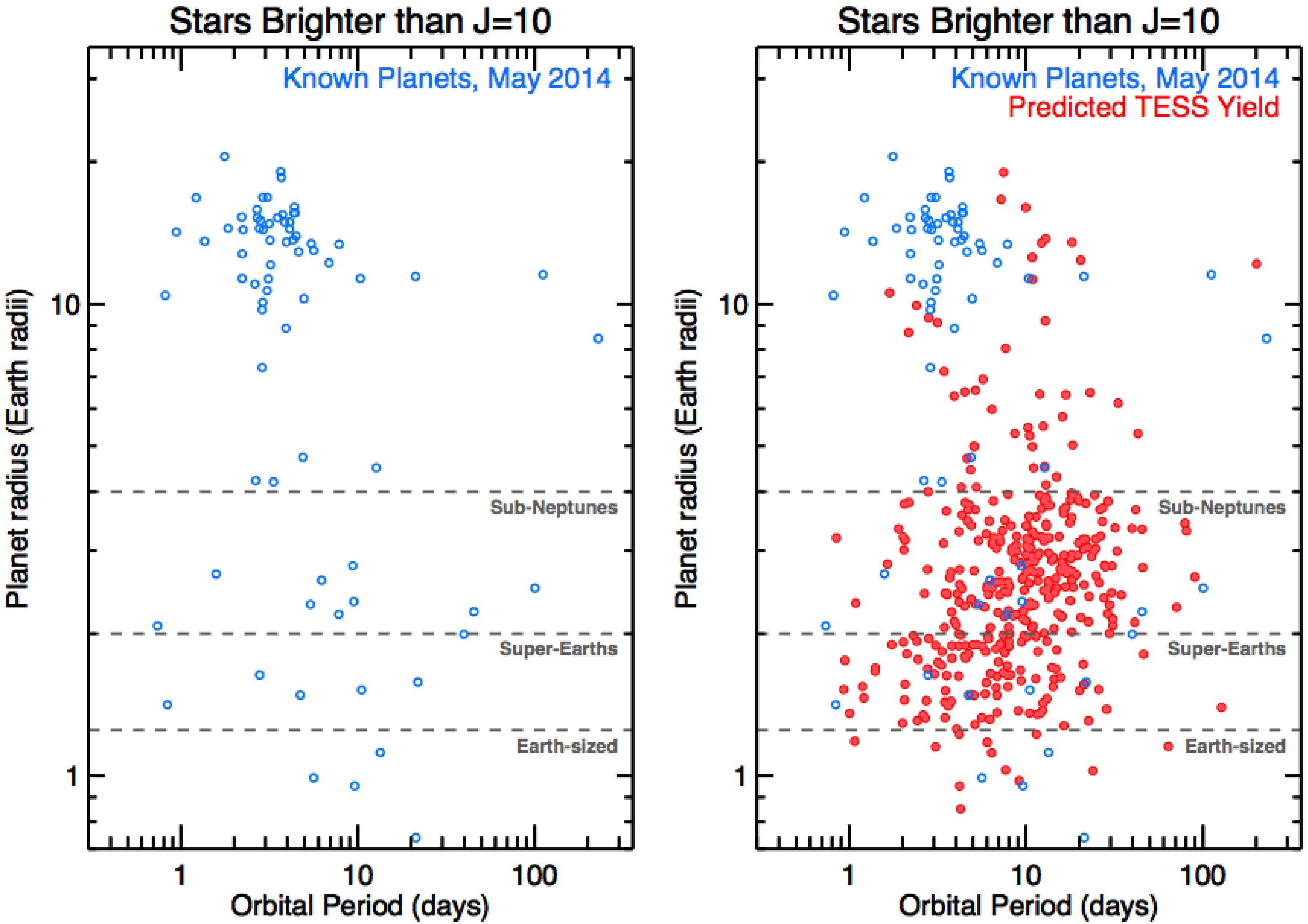
Simulated TESS detections



Sullivan et al., in prep.



Stars Brighter than J=10
Known Planets, May 2014
Planet radius (Earth radii)
10
1
Sub-Neptunes
Super-Earths
Earth-sized
1
10
100
Orbital Period (days)


Stars Brighter than J=10
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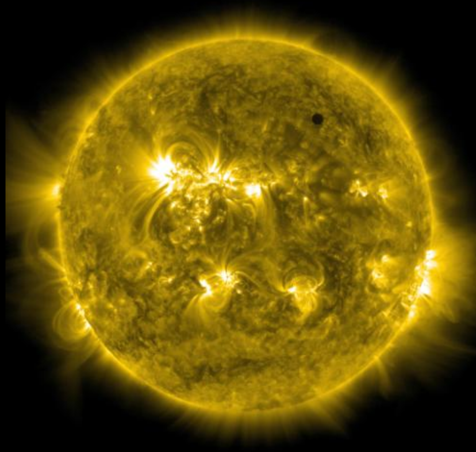
Planet radius (Earth radii)
Orbital Period (days)
Sub-Neptunes
Super-Earths
Earth-sized
10
1
1
10
100
Stars Brighter than J=10
Known Planets, May 2014
Predicted TESS Yield
Planet radius (Earth radii)
Orbital Period (days)
Sub-Neptunes
Super-Earths
Earth-sized
10
1
1
10
100

Conclusions



- When we restrict to planets with precise masses and radii:
  - All dense planets 1 < M_{Earth} < 6 are consistent with an Earth-like composition
  - There are NO such planets more massive than 8 M_{Earth}:
    Such planets require significant amounts of volatiles or H/He

- The NASA TESS Mission will discover 300 Earths and super-Earths that transit nearby stars: Perhaps 5 of these will be habitable planets in the continuous viewing zone of the James Webb Space Telescope.