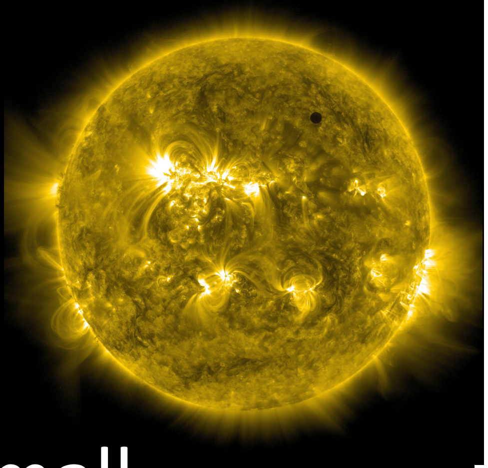
The Compositions of Small Planets

David Charbonneau (Harvard)

29 June 2015

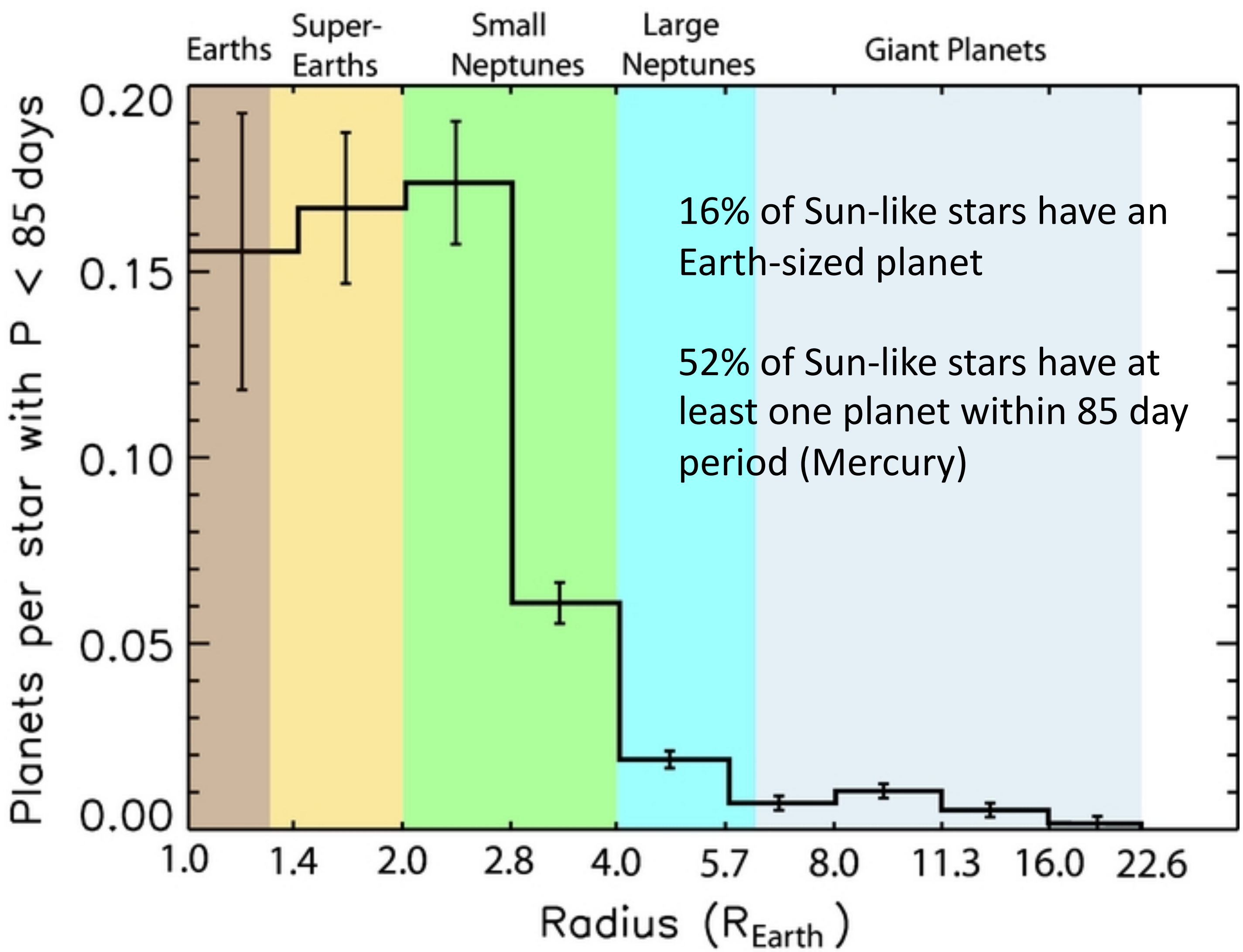
Questions for Today



- What are the likely compositions of small planets?
  - Can low-mass planets accrete a H/He envelope?
  - Is there a maximum mass for an exo-analog of a terrestrial planet?

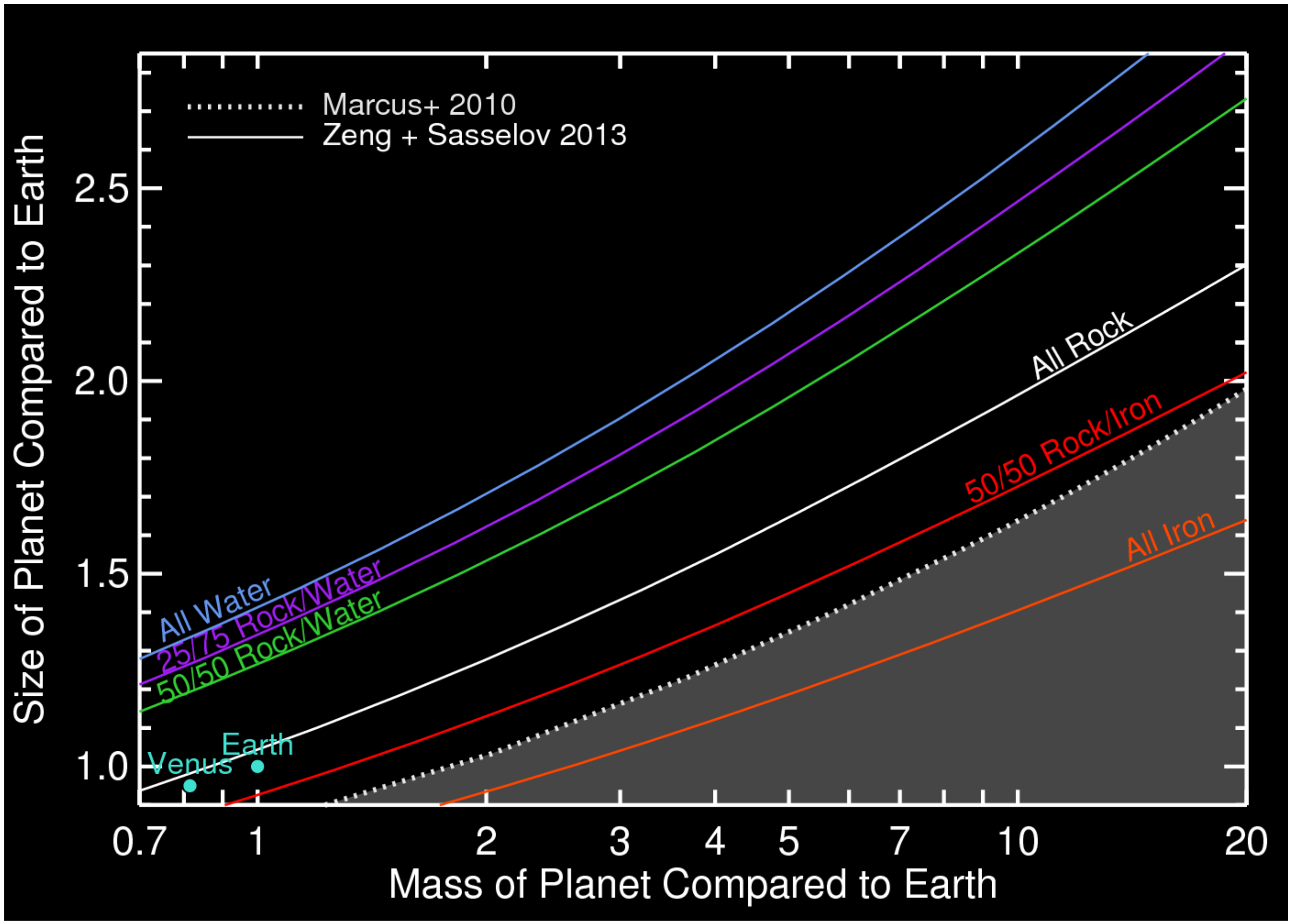
- What are the prospects for improving our knowledge in the next 3 years?

The Planet Radius Distribution for Sun-Like Stars



Fressin, Torres, Charbonneau et al. (2013)

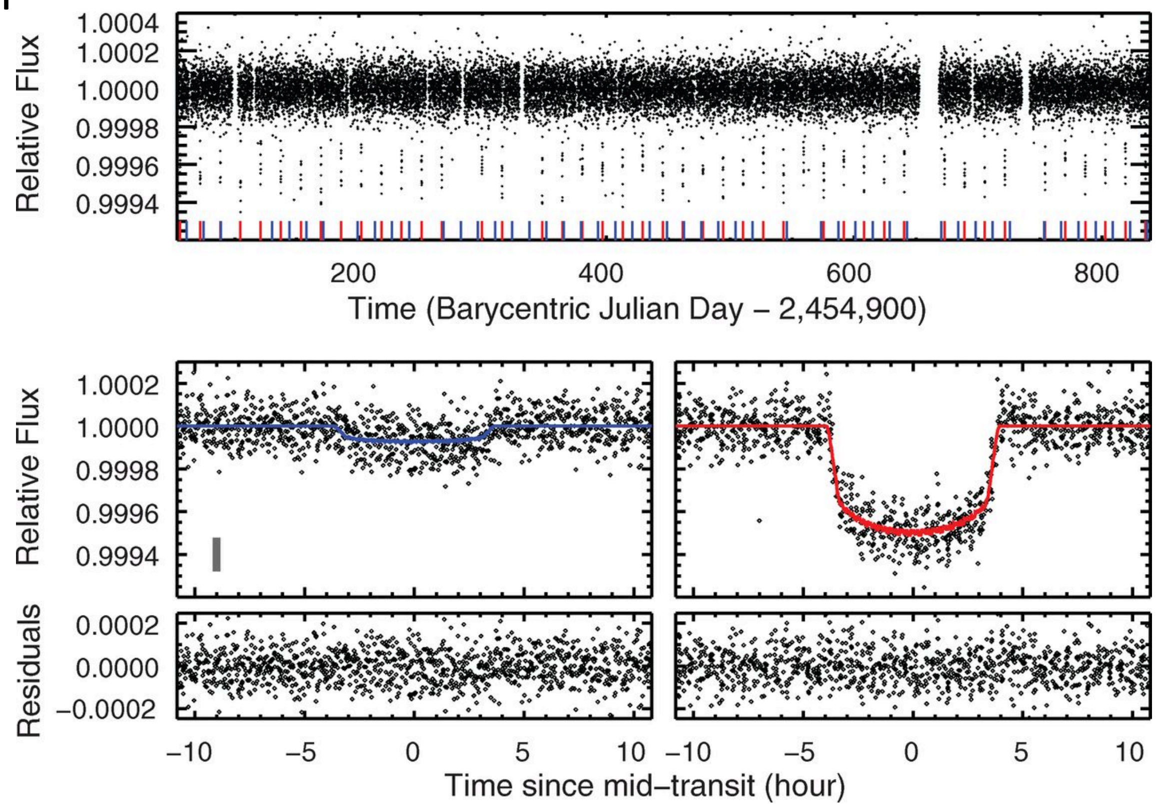
Towards Precise Constraints on the Mass-Radius Diagram below 2.8 Earth Radii



Dressing, Charbonneau, et al. 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)

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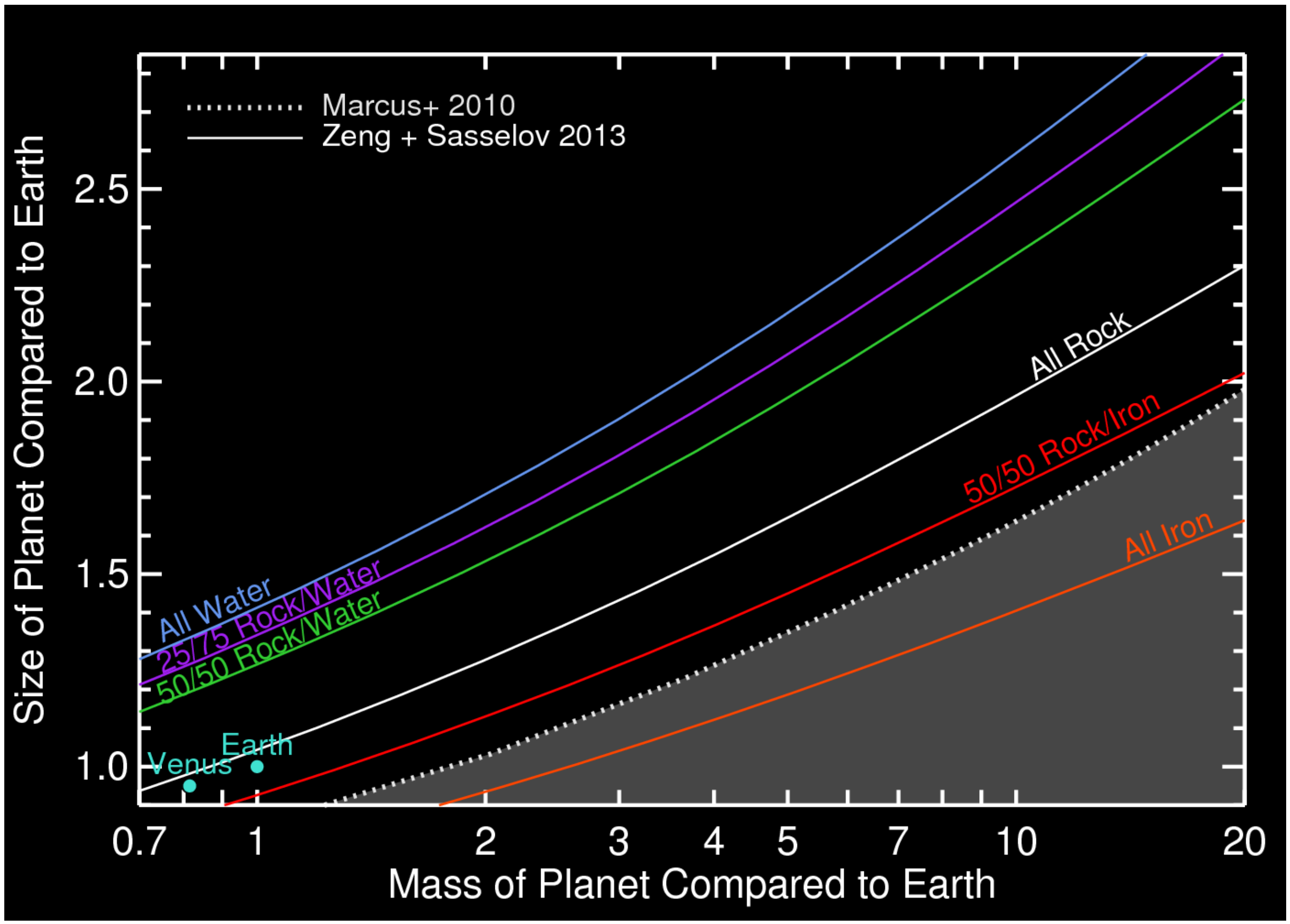
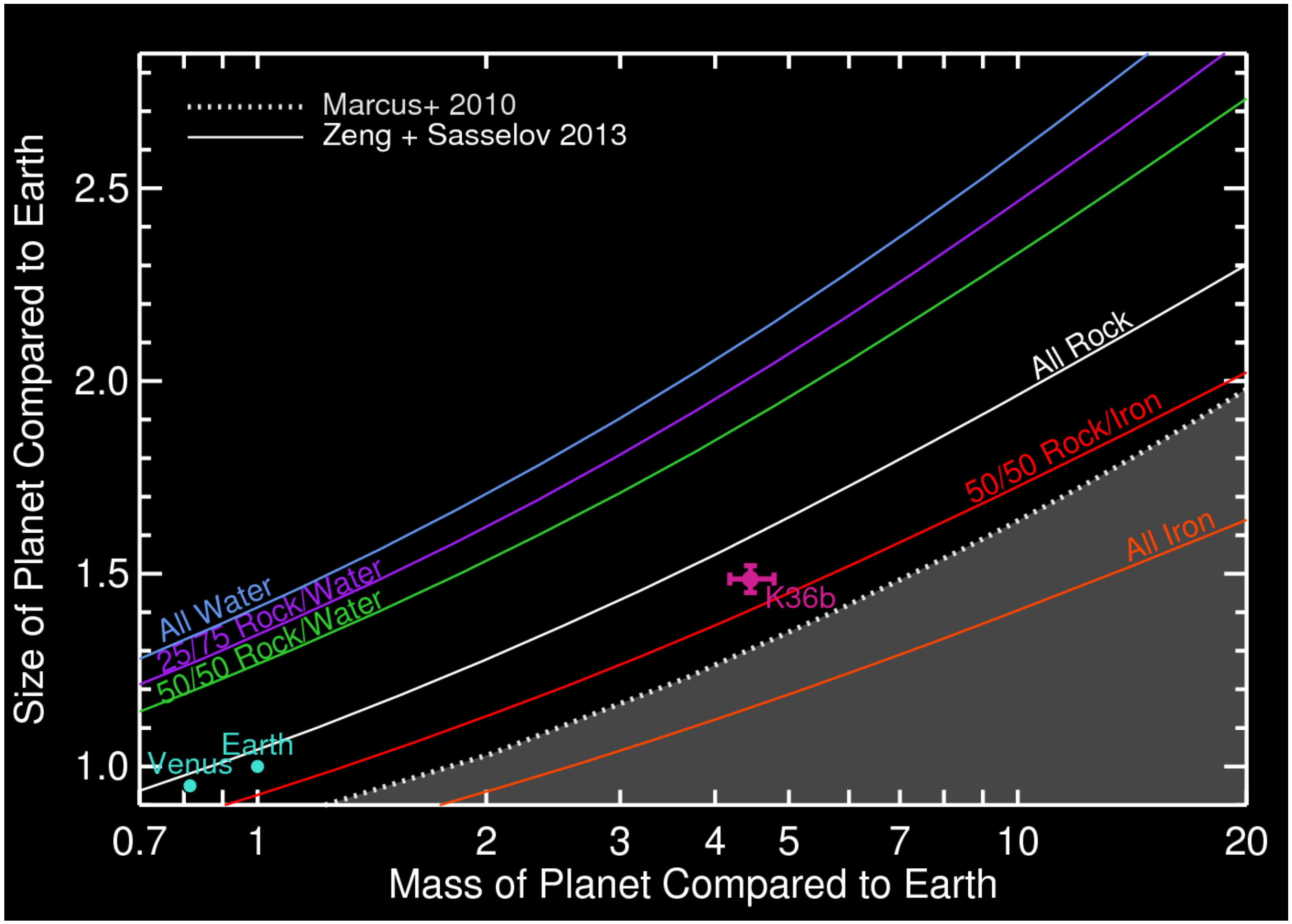
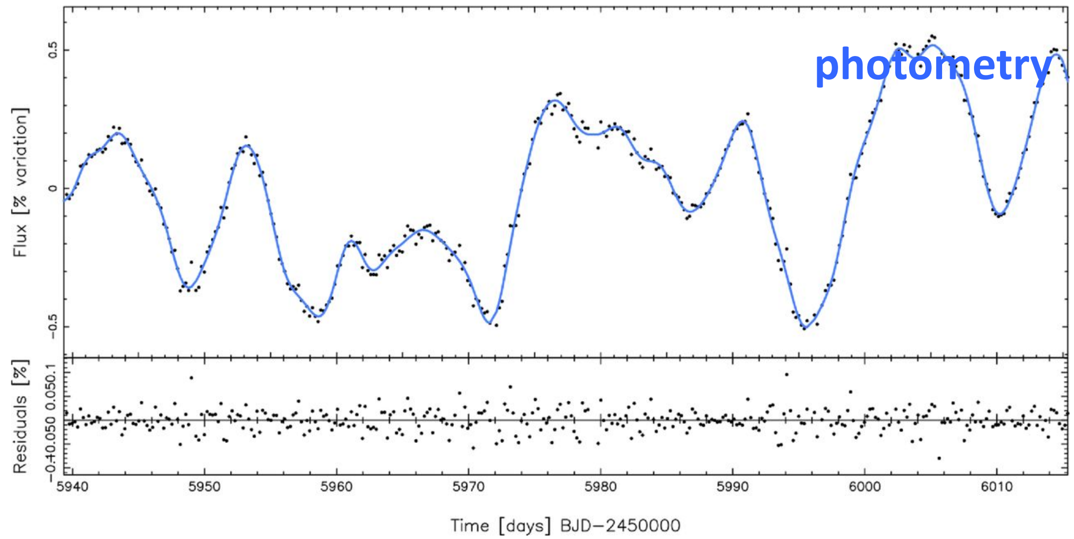


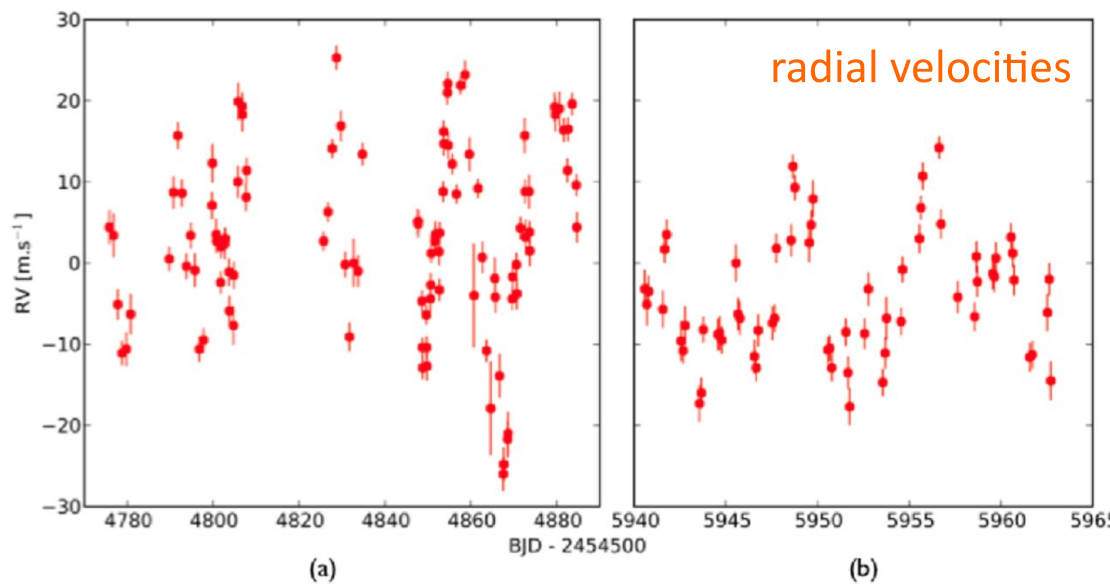
Only planet smaller than 2.8 R_{earth} with a mass from timing variations & precision < 20%. Future missions unlikely to yield more due to short time baselines.



Masses from Radial Velocities: CoRoT-7

- CoRoT-7b first transiting planet smaller than 2.8 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)

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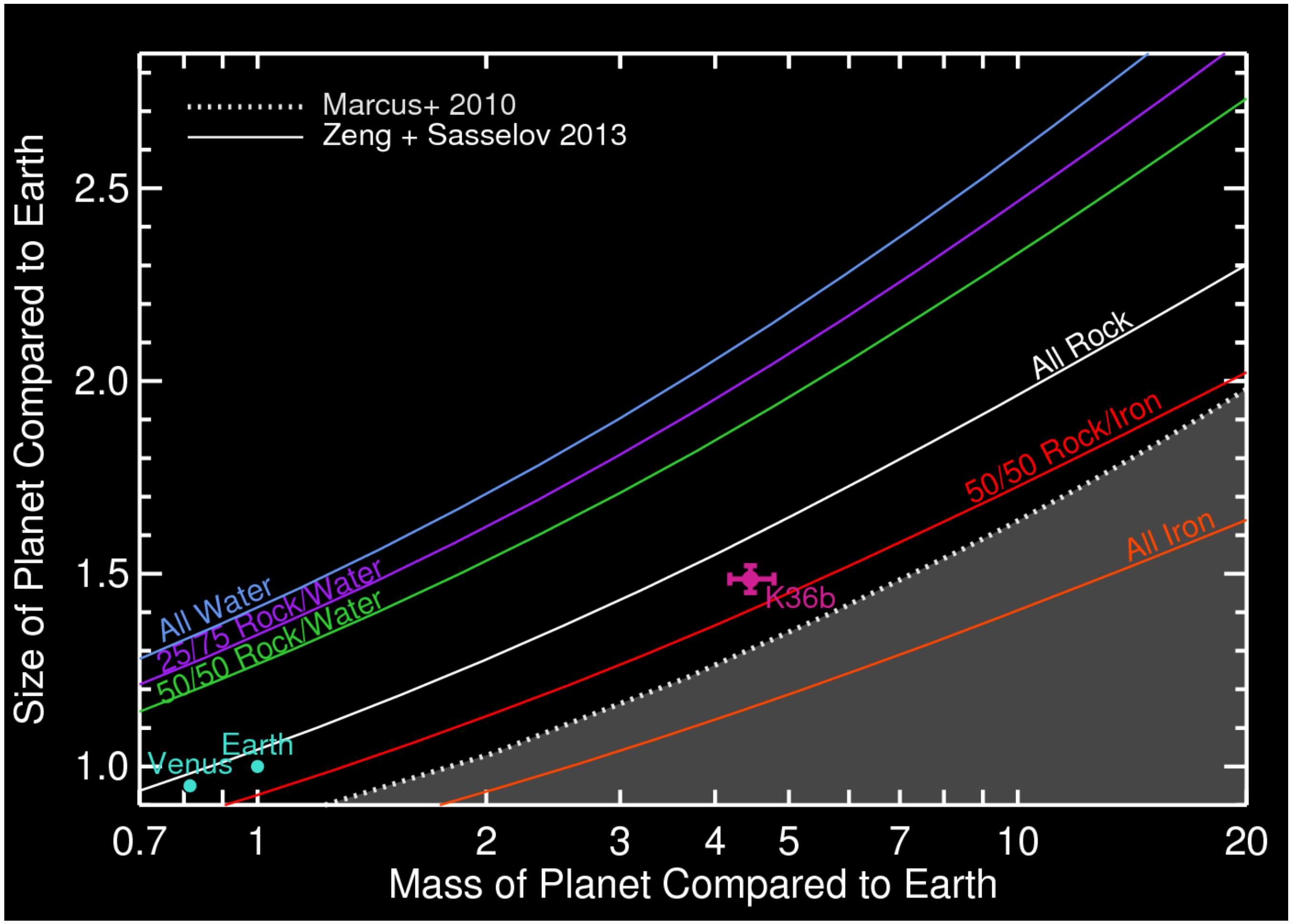
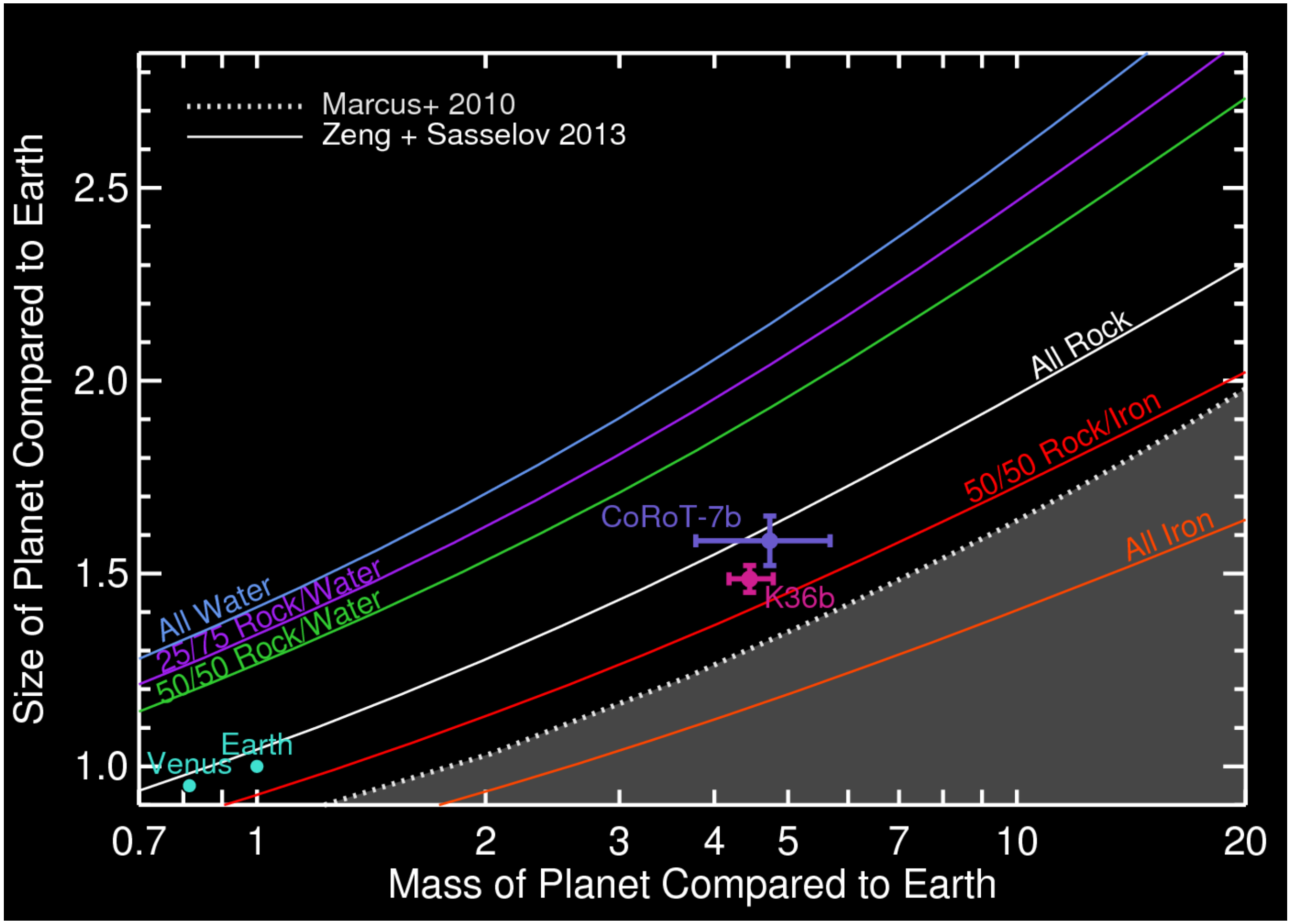
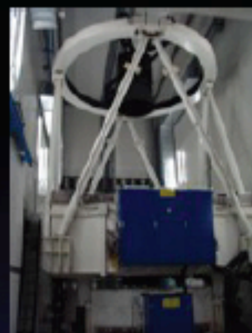
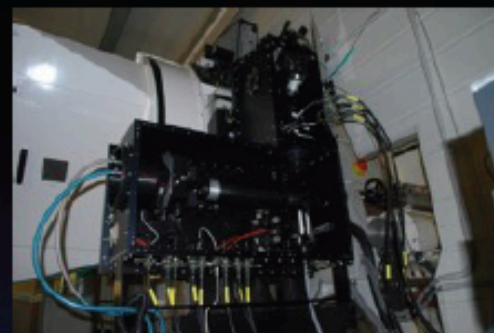


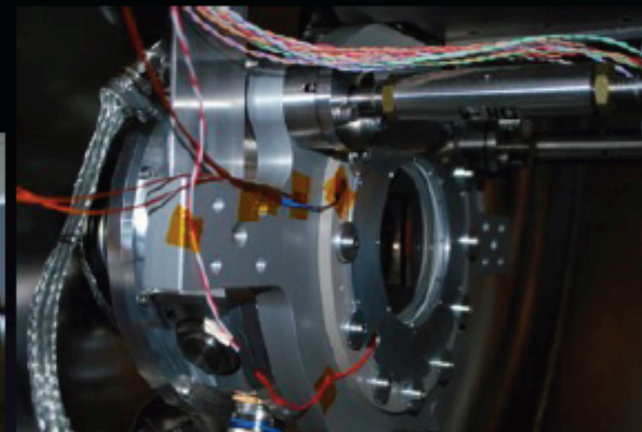
Stellar variability precludes efficient mass measurement. Only planet smaller than 2.5 R_{earth} from CoRoT: Kepler observes in northern hemisphere, which southern spectrograph cannot see.



HARPS-N



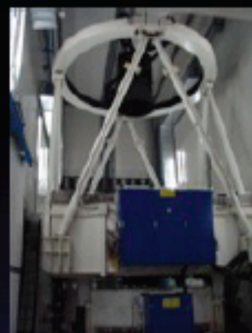
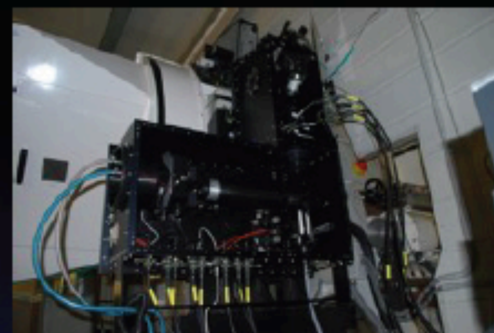
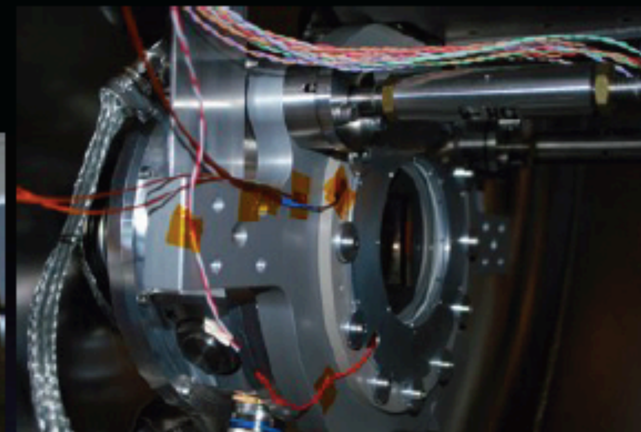


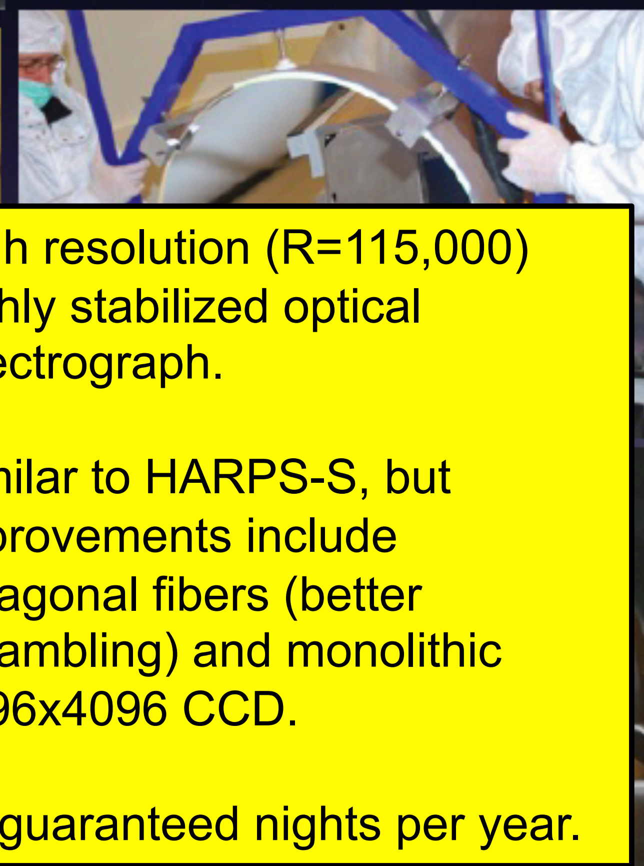


Partnership between Geneva Observatory, Harvard-Smithsonian Center for Astrophysics, Italian National Institute for Astrophysics, Univ. of St. Andrews, Edinburgh, and Queens Univ Belfast.

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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- Conduct photometric analysis and reject variables

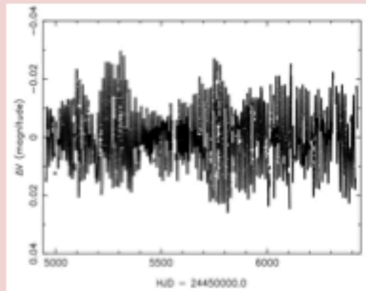
HARPS-N Target Selection Tiger Team

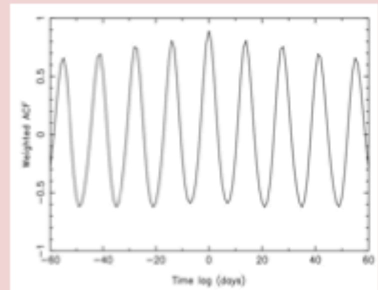
Object name & notes on photometric and expected spectroscopic stellar variability	Kepler lightcurve, all quarters (LC)	Autocorrelation function (ACF) of LC	Lomb-Scargle periodogram of LC

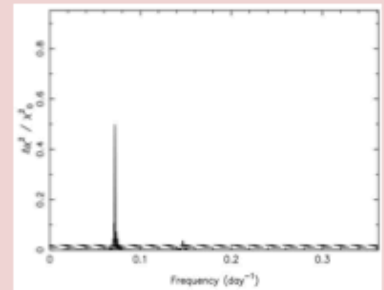
KOI 678 (Kepler-211)

- 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)



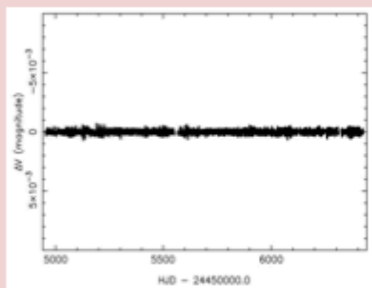


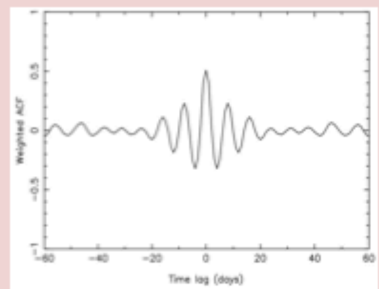


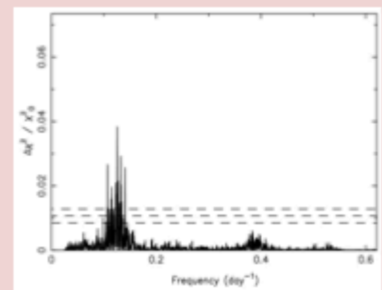
KOI 262 (Kepler-50)

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

→ Likely fast rotator, RV follow up impossible





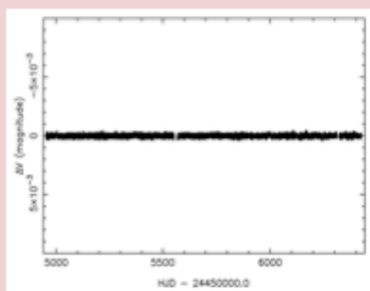


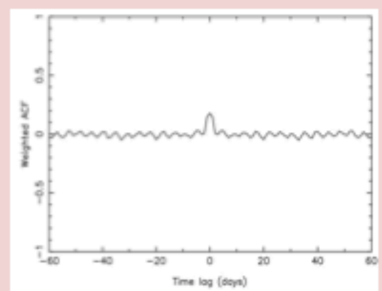
KOI 4462

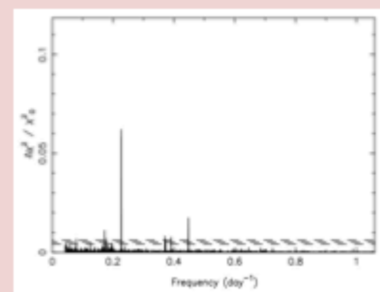
- High levels of photometric variability over short timescales ("8-hour flicker", see Bastien et al. 2013) indicate high levels of granulation-related noise

→ 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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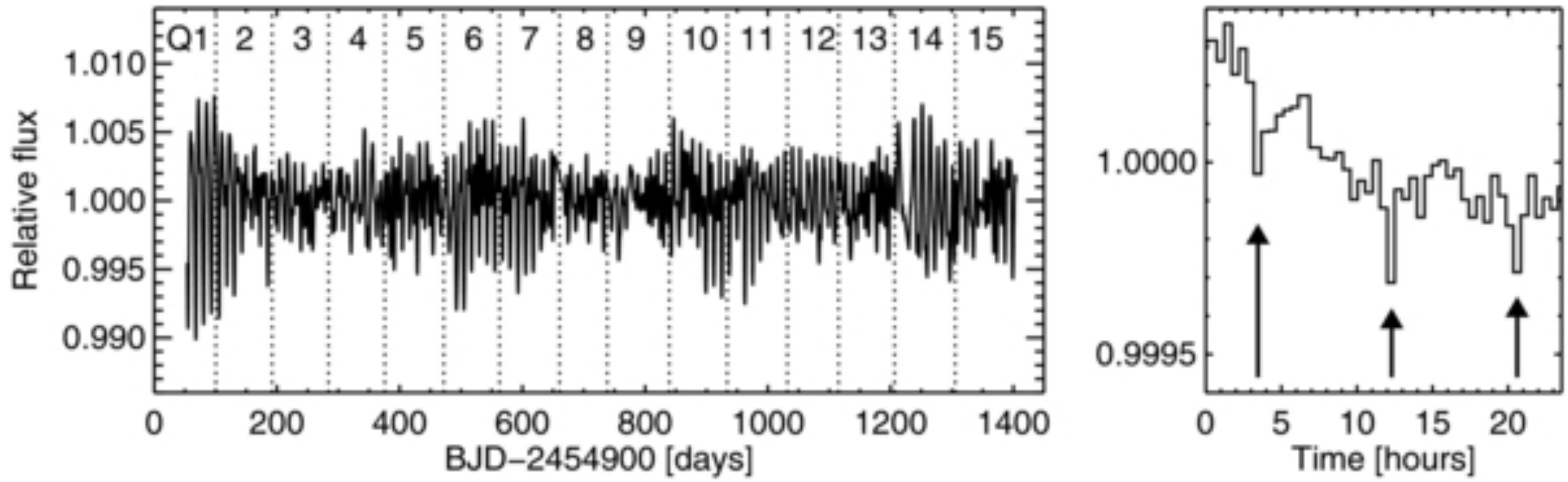
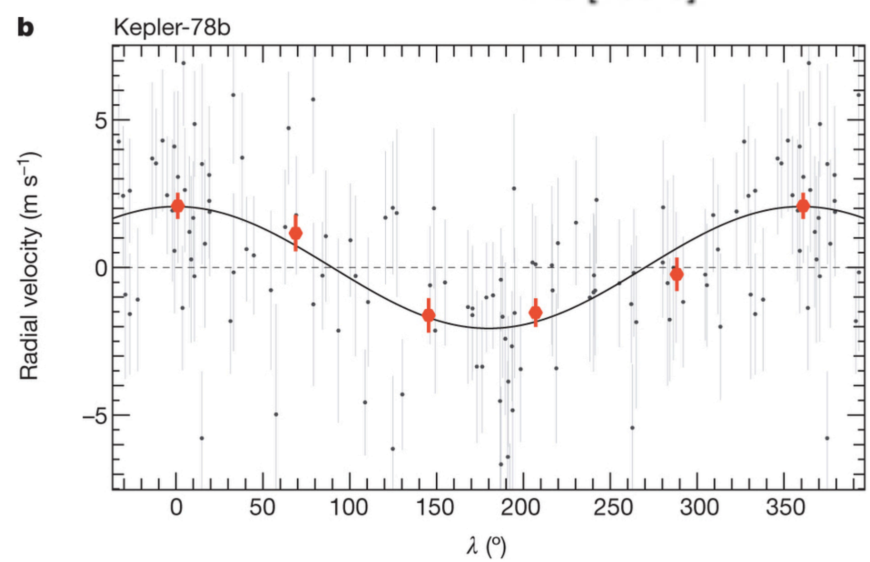
- Allocate time to achieve this until 40 telescope nights are expended

System 1: Kepler-78

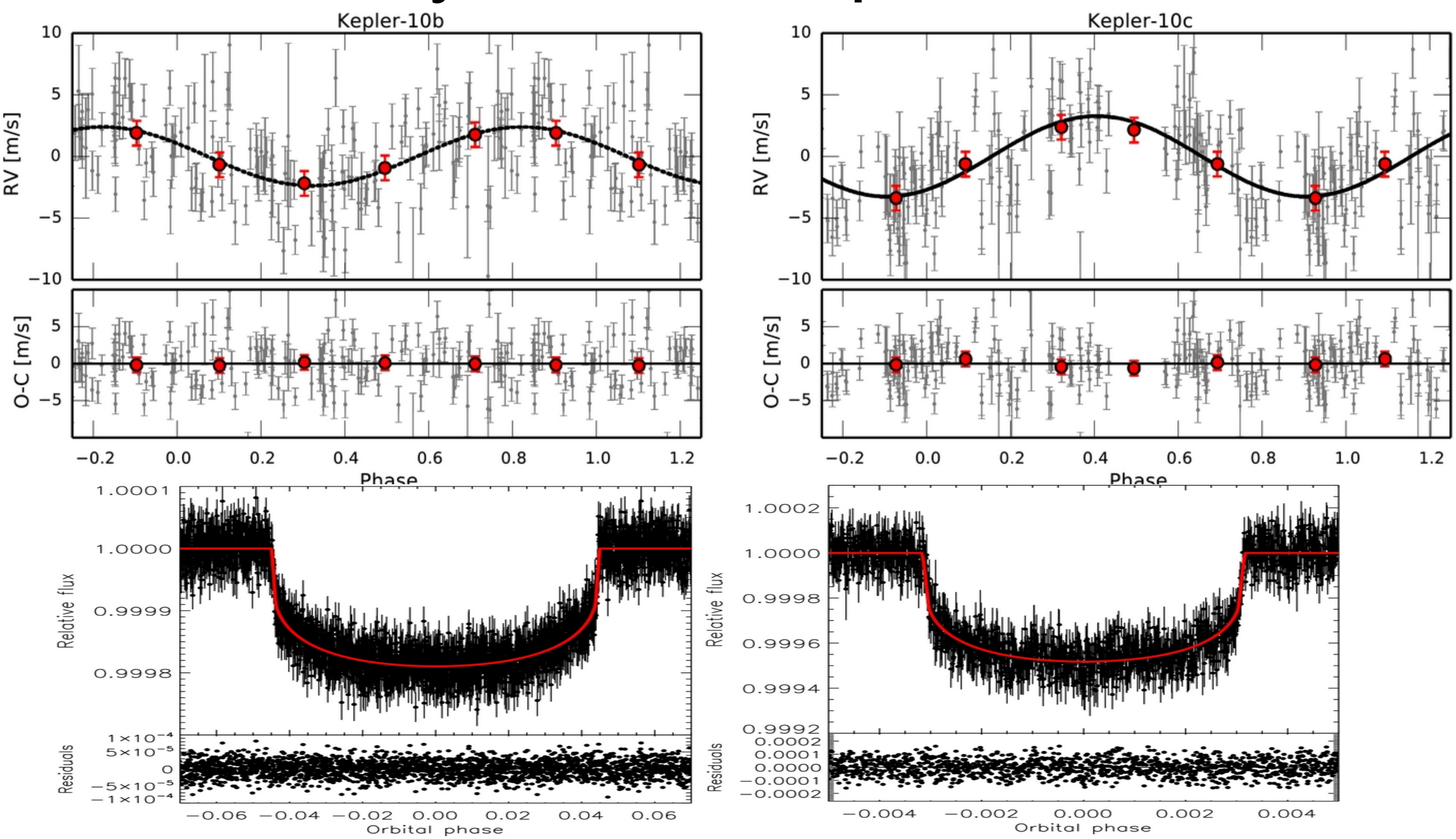




- Planet only slightly larger than Earth
- Very short period of 8.1 hrs means radial velocity amplitude is measurable
- Independent measurement by Keck/HIRES (Howard et al. Nature 2014)

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

System 2: Kepler-10

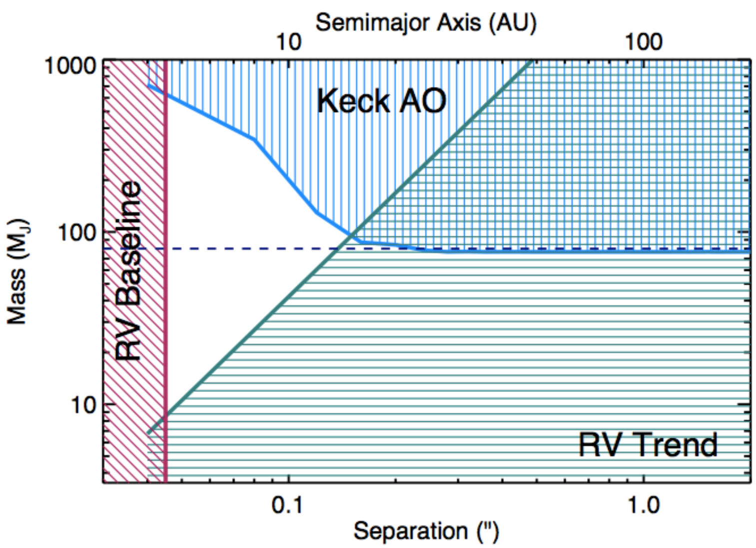


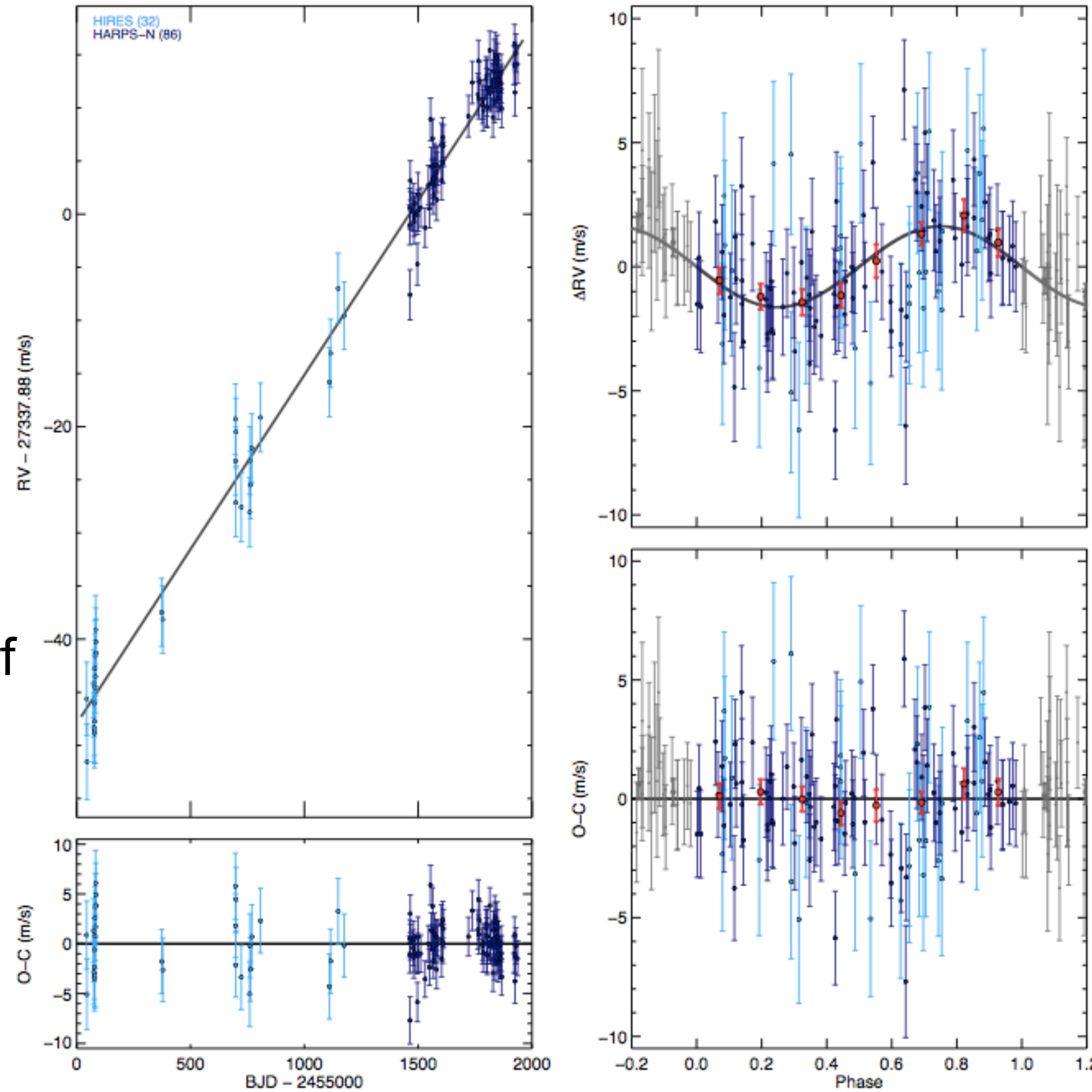
- Two planets:
  1.47 R_{earth} at P=0.8d & 2.35 R_{earth} at P=45d
- Very old system: 10.6 +/- 1.4 Gyr

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. ApJ (2015)
Ballard et al. ApJ (2014)

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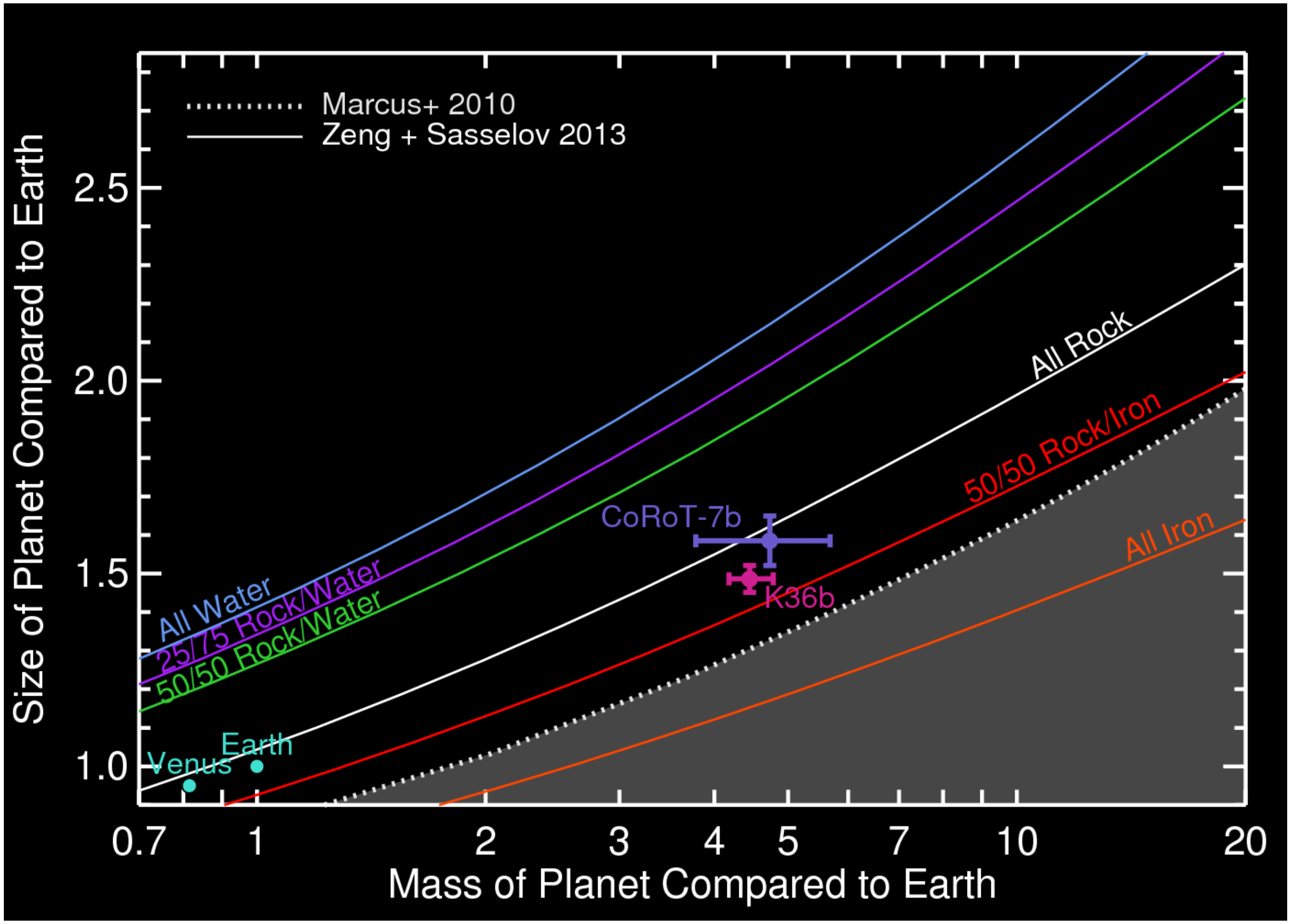

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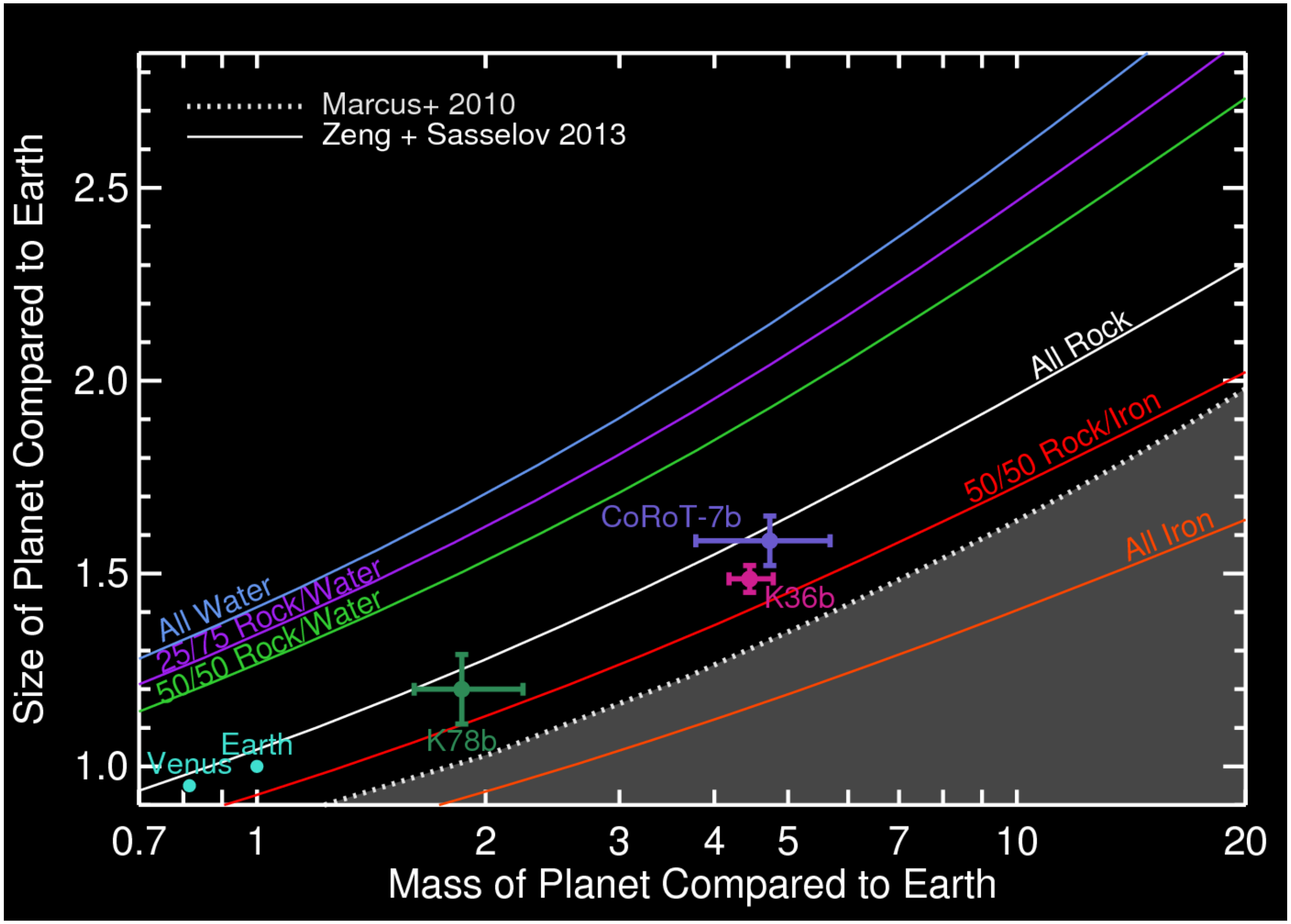

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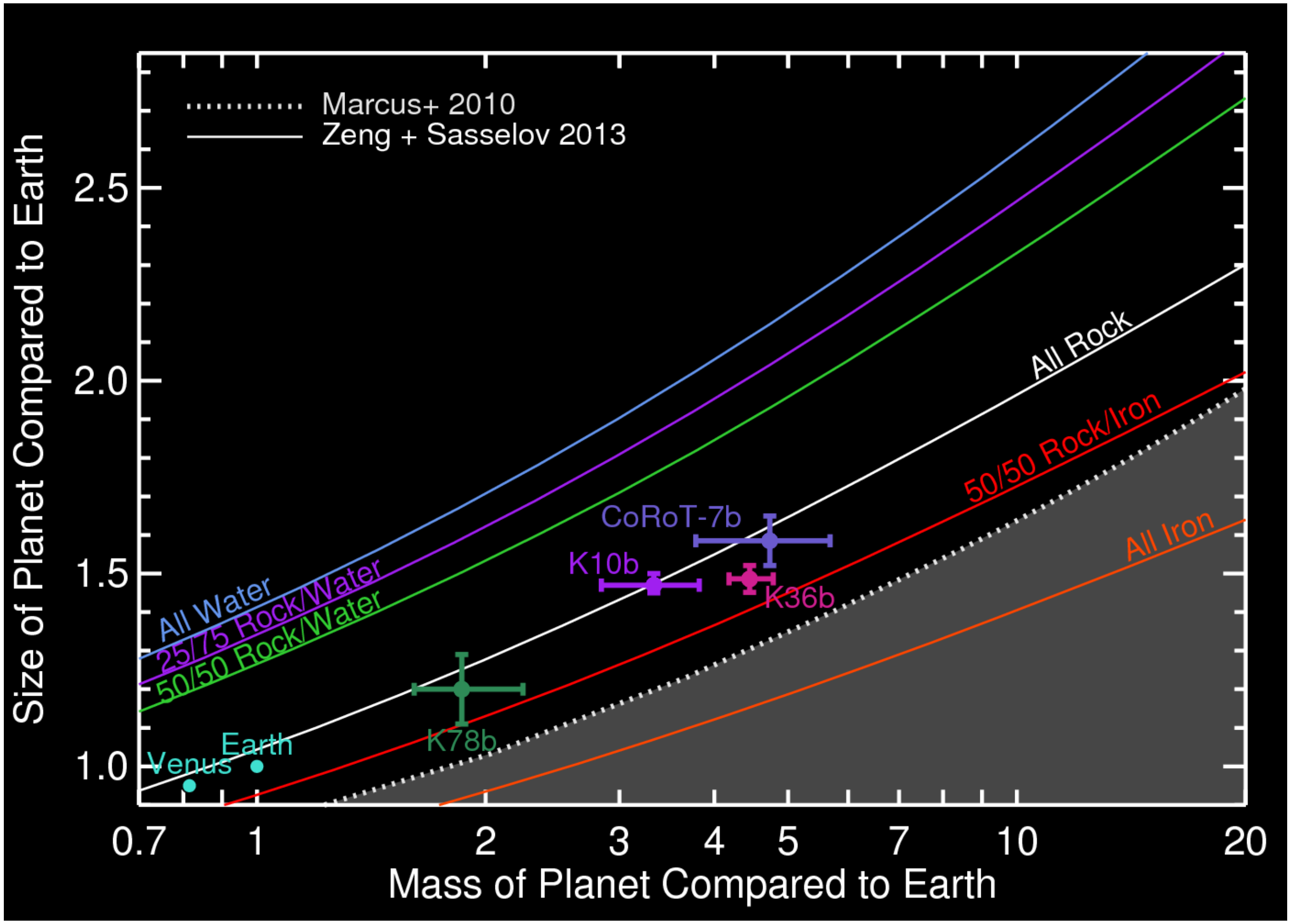

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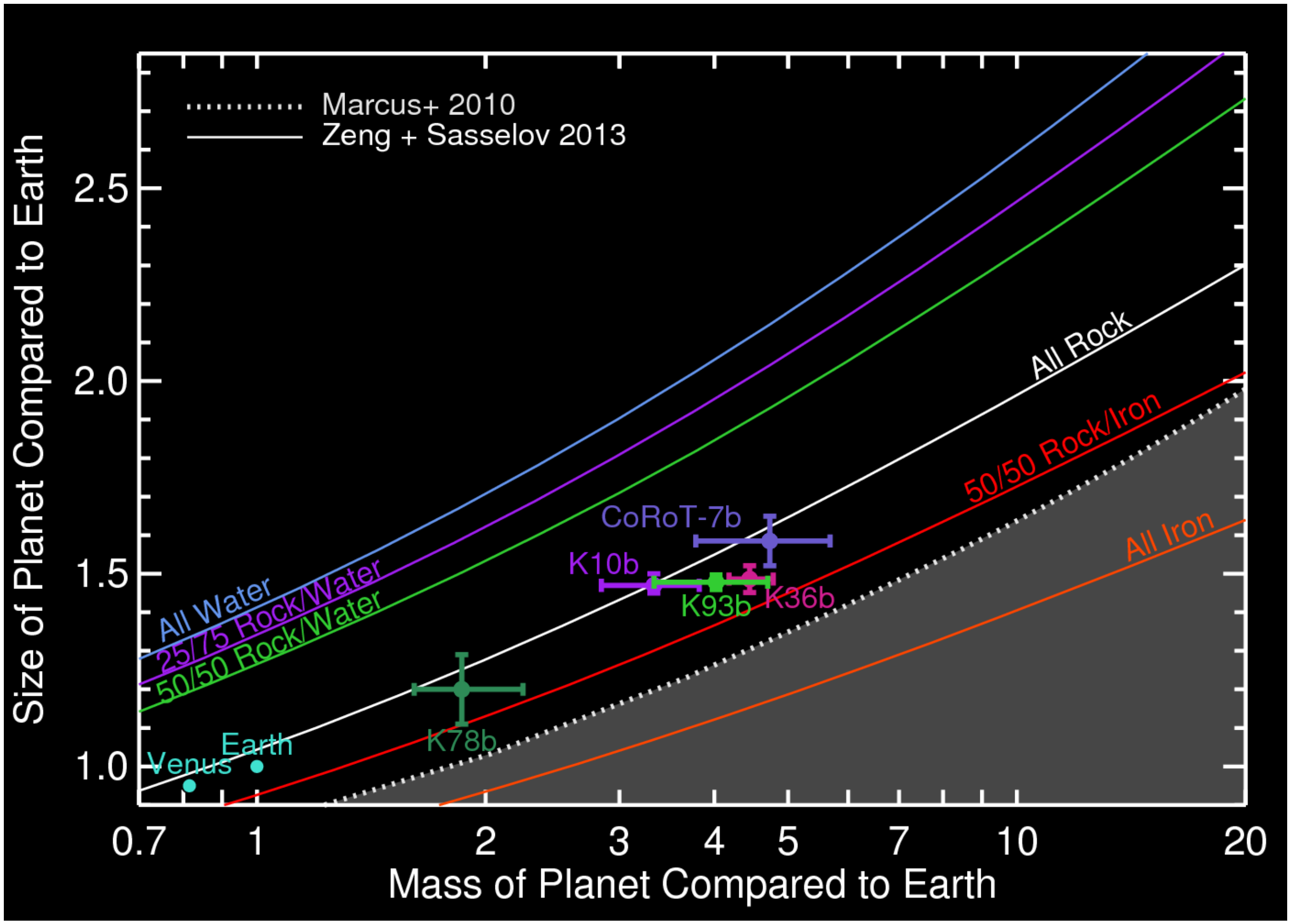

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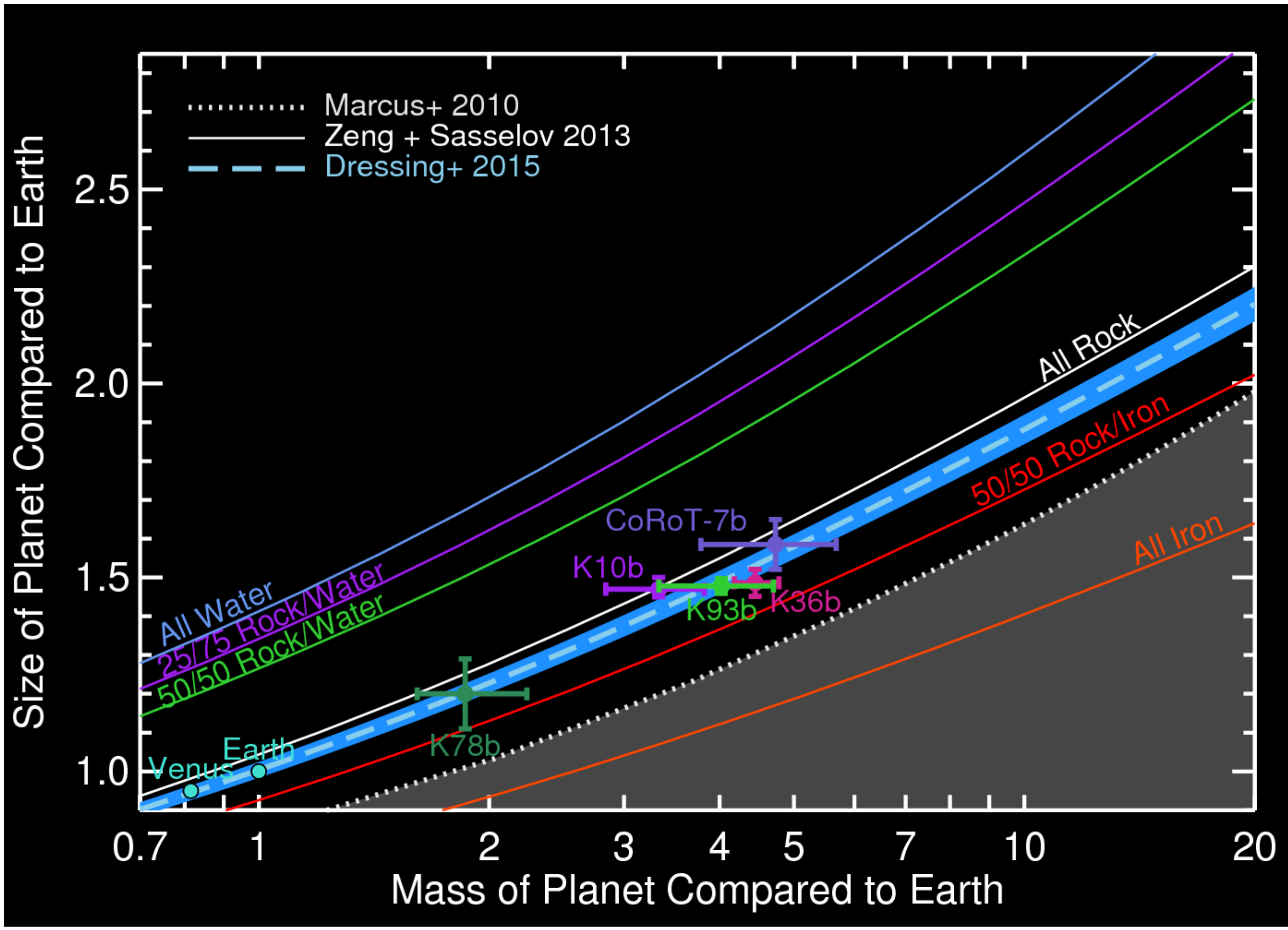


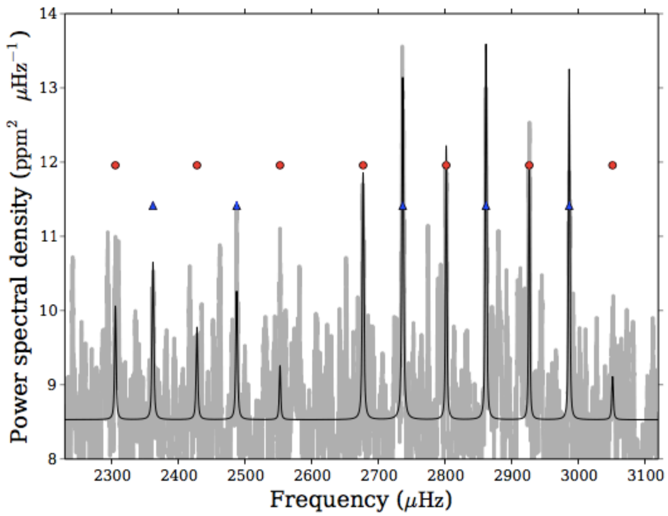
Dressing, Charbonneau, et al. ApJ (2015)

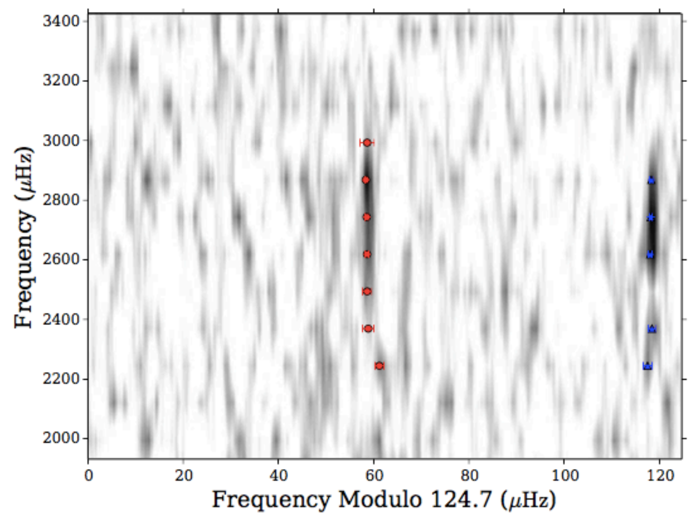
Width set by observed variation in Mg/Si/Fe ratios in local planet hosts

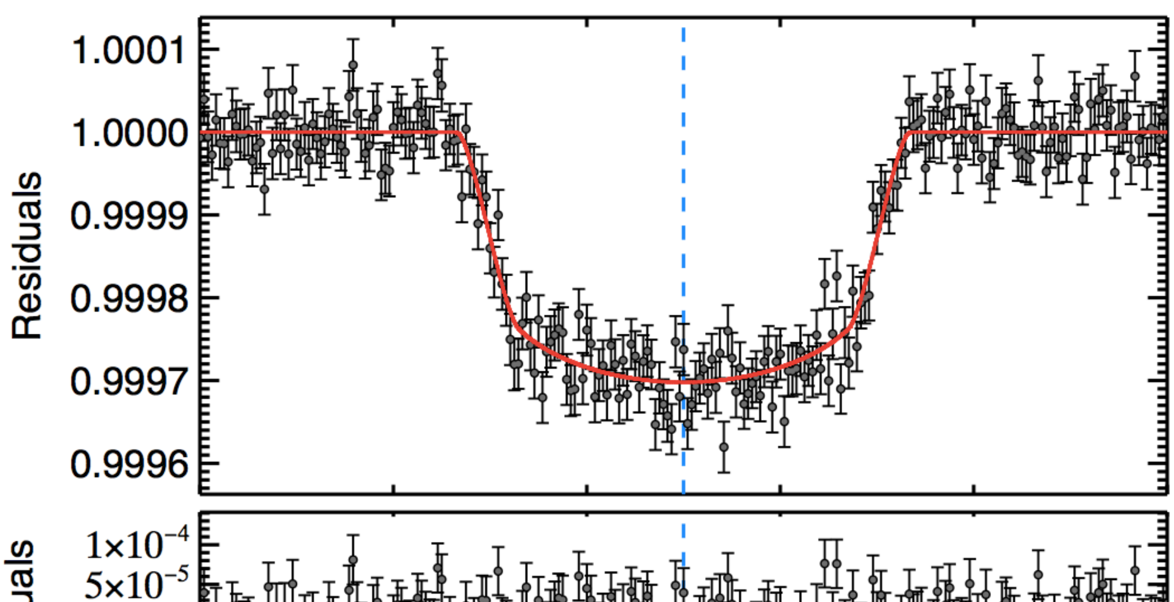
Grasset et al. (2009)

System 4: KOI-273

Initially selected for 1.88 R_{Earth} planet + 10.6d orbit: Interesting region of M-R diagram. New asteroseismic study (Chaplin, Huber, and colleagues) yields precise stellar radius 1.066 +/- 0.012 R_{Sun} and age 5.25 +/- 1.40 Gyr.





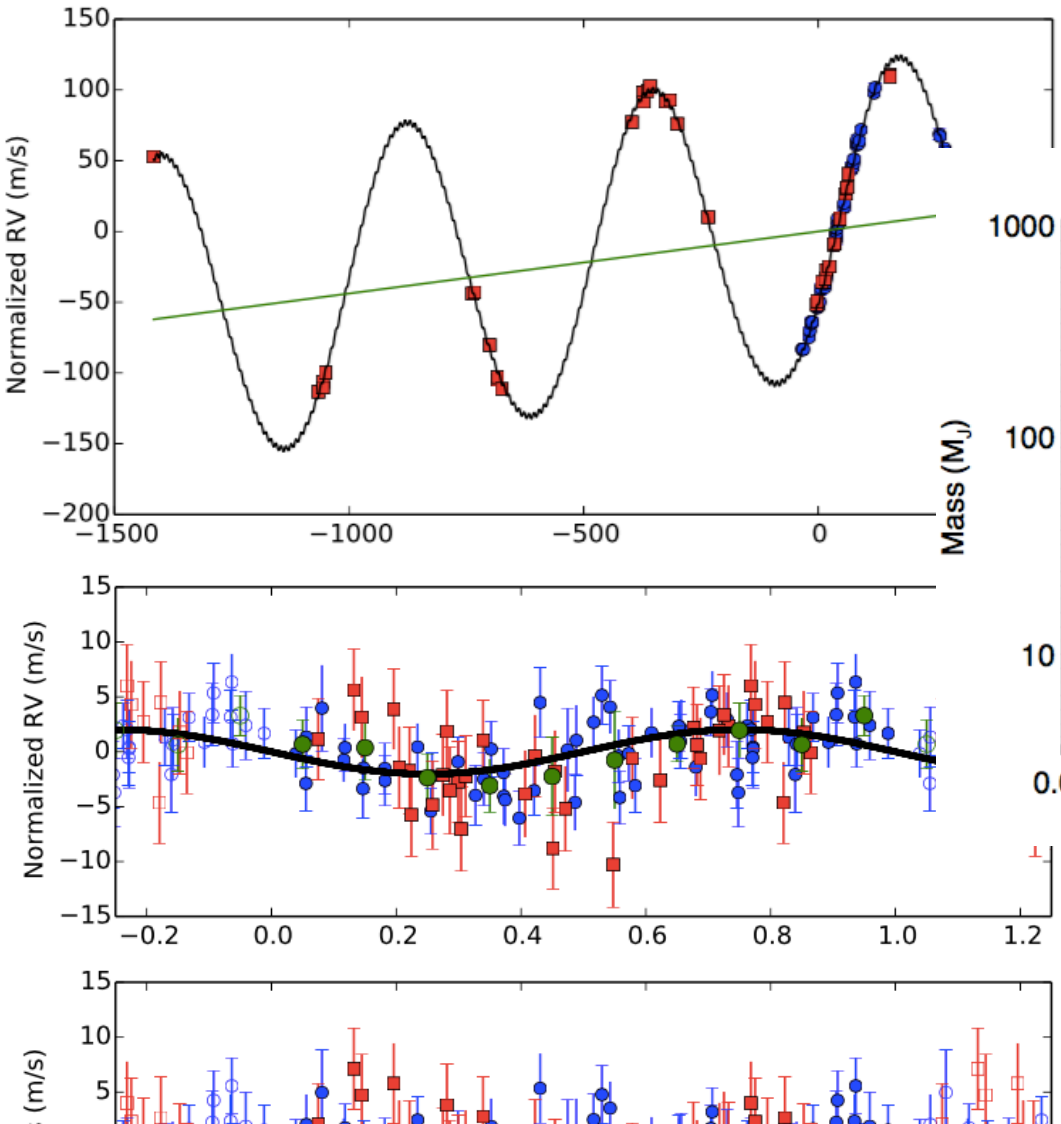


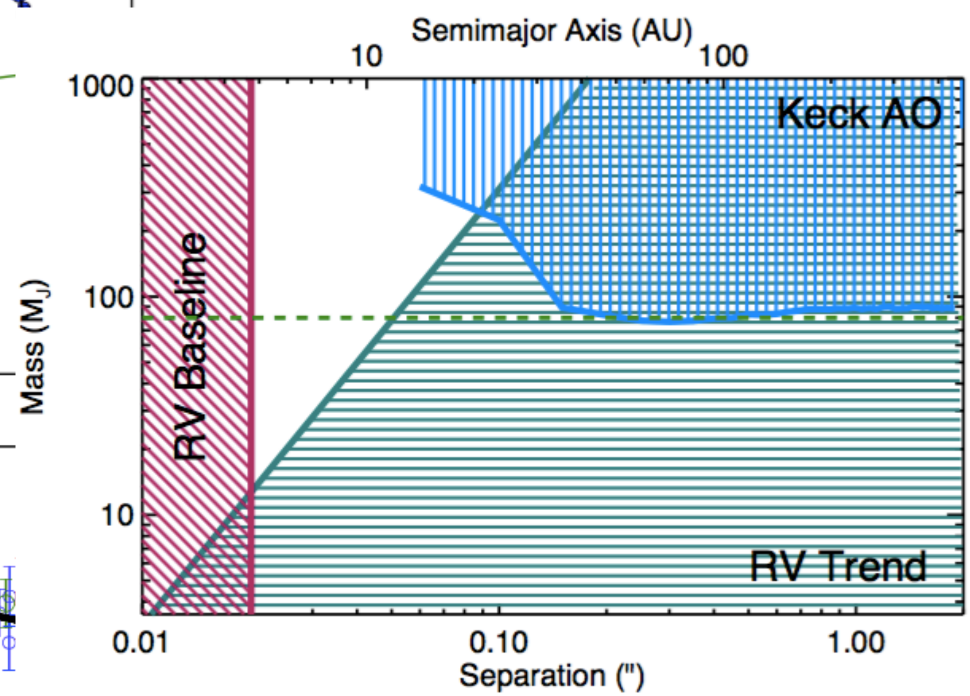
New fits to LC obtain precise, but larger planet radius of 2.37 +/- 0.13 R_{Earth}

Gettel, Charbonneau, et al. submitted to ApJ (2015)

System 4: KOI-273

HARPS-N collaboration with Marcy, Howard, Isaacson (Keck/HIRES). Transiting planet has a mass of 7.1 +/- 1.4 MEarth and is accompanied by 4.4 MJup companion in 524d nearly circular orbit, and massive body with P > 10 yr.





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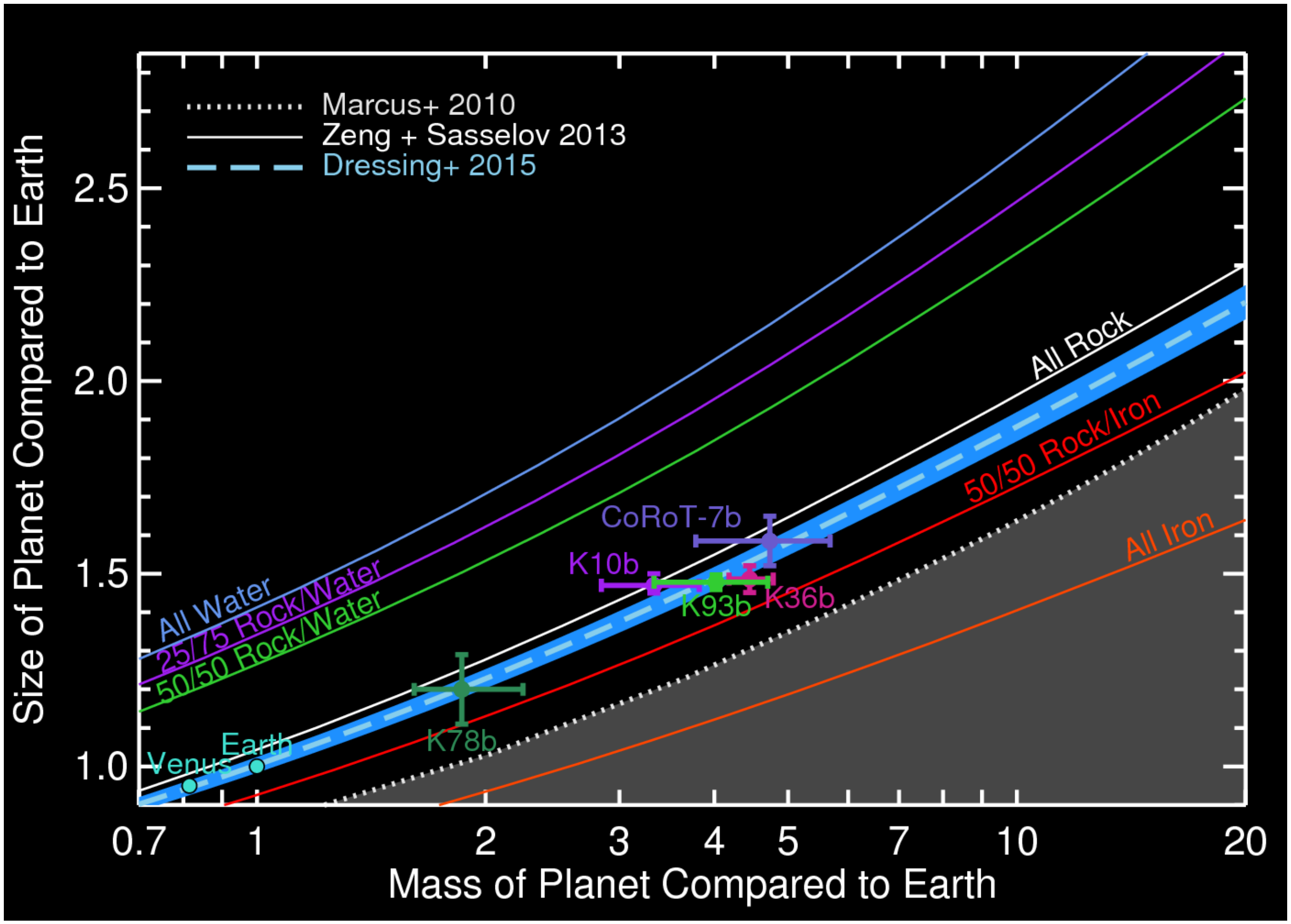
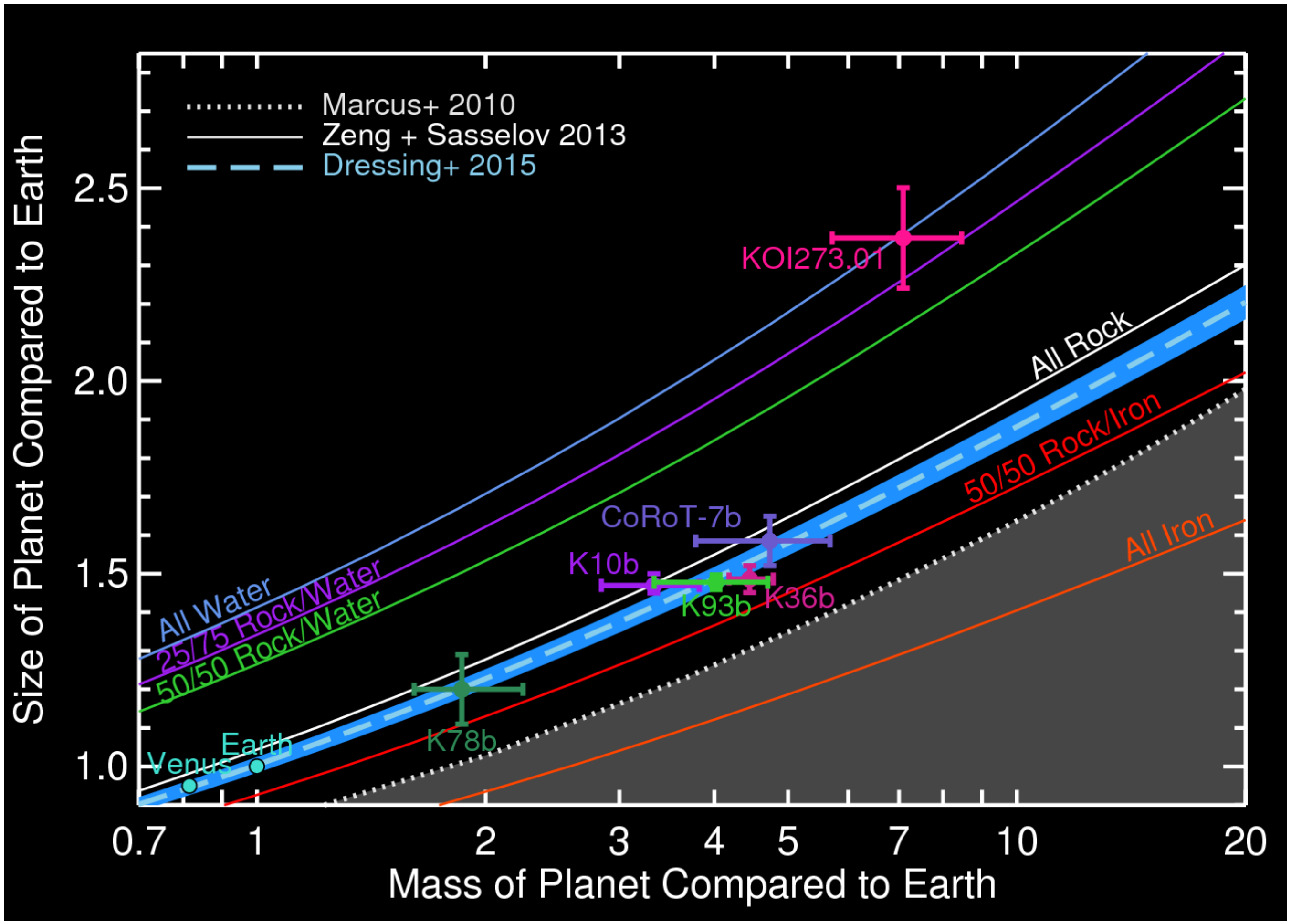
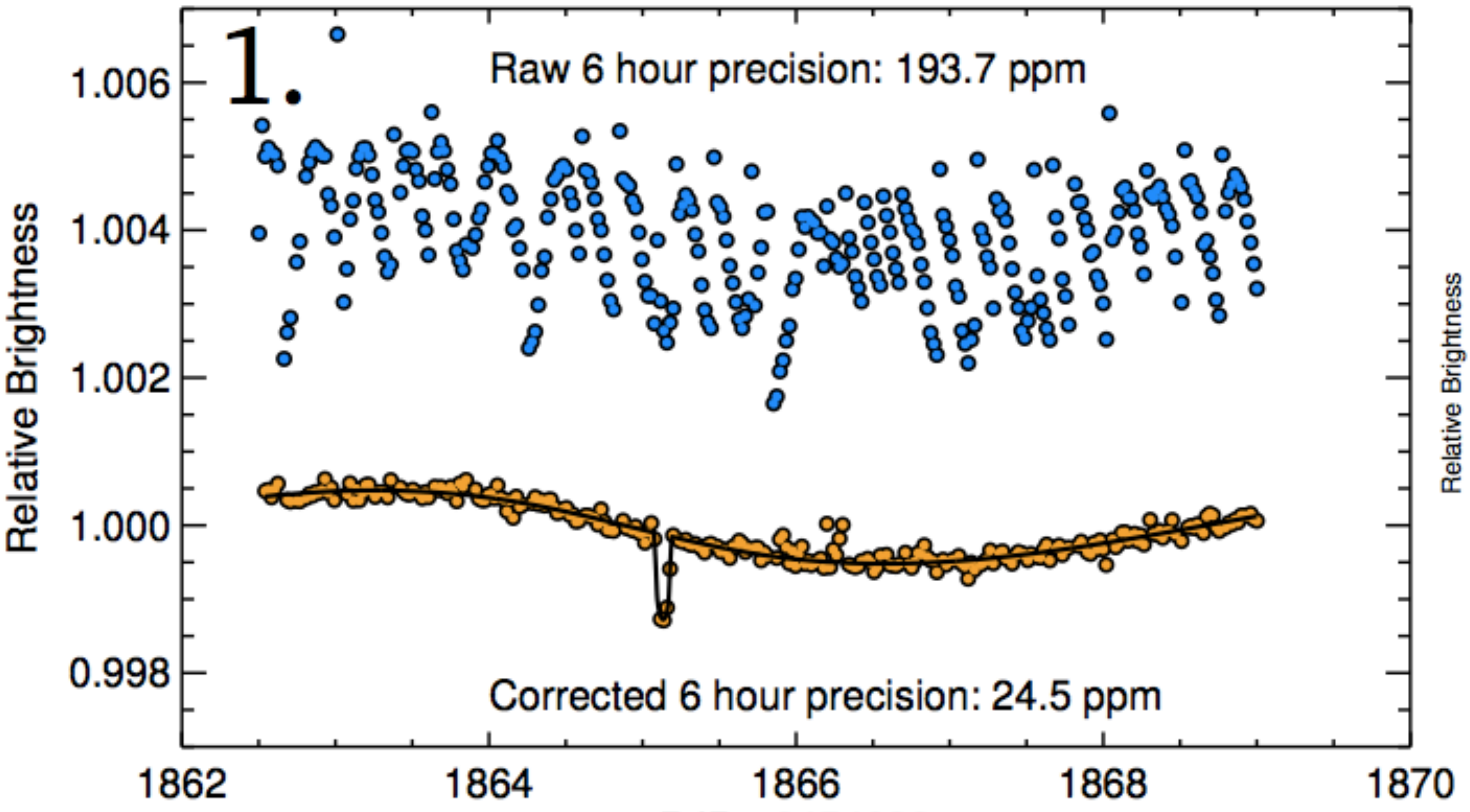


KOI-273b requires the presence of a significant fraction of volatiles and/or H/He



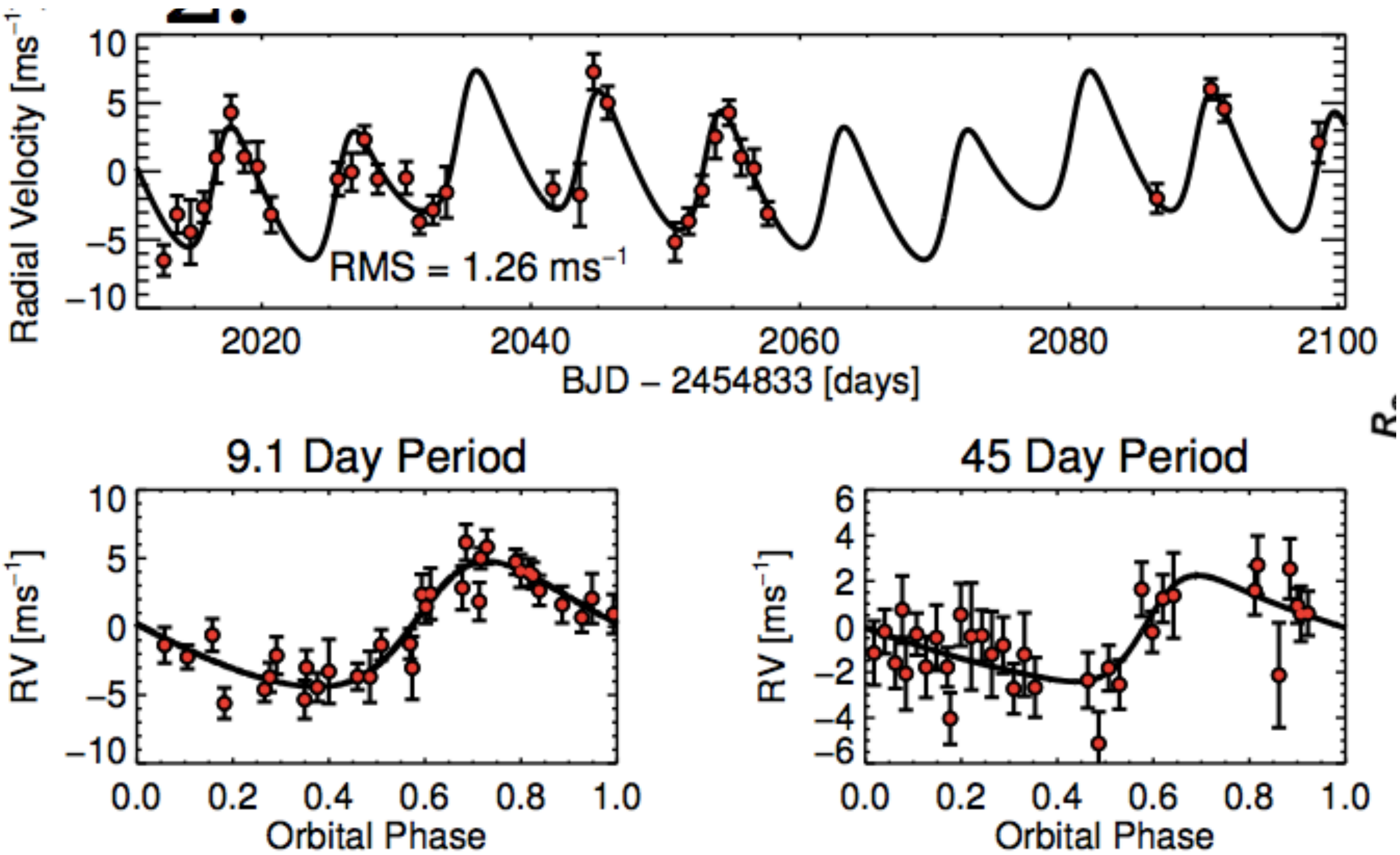
Gettel, Charbonneau, et al. submitted to ApJ (2015)

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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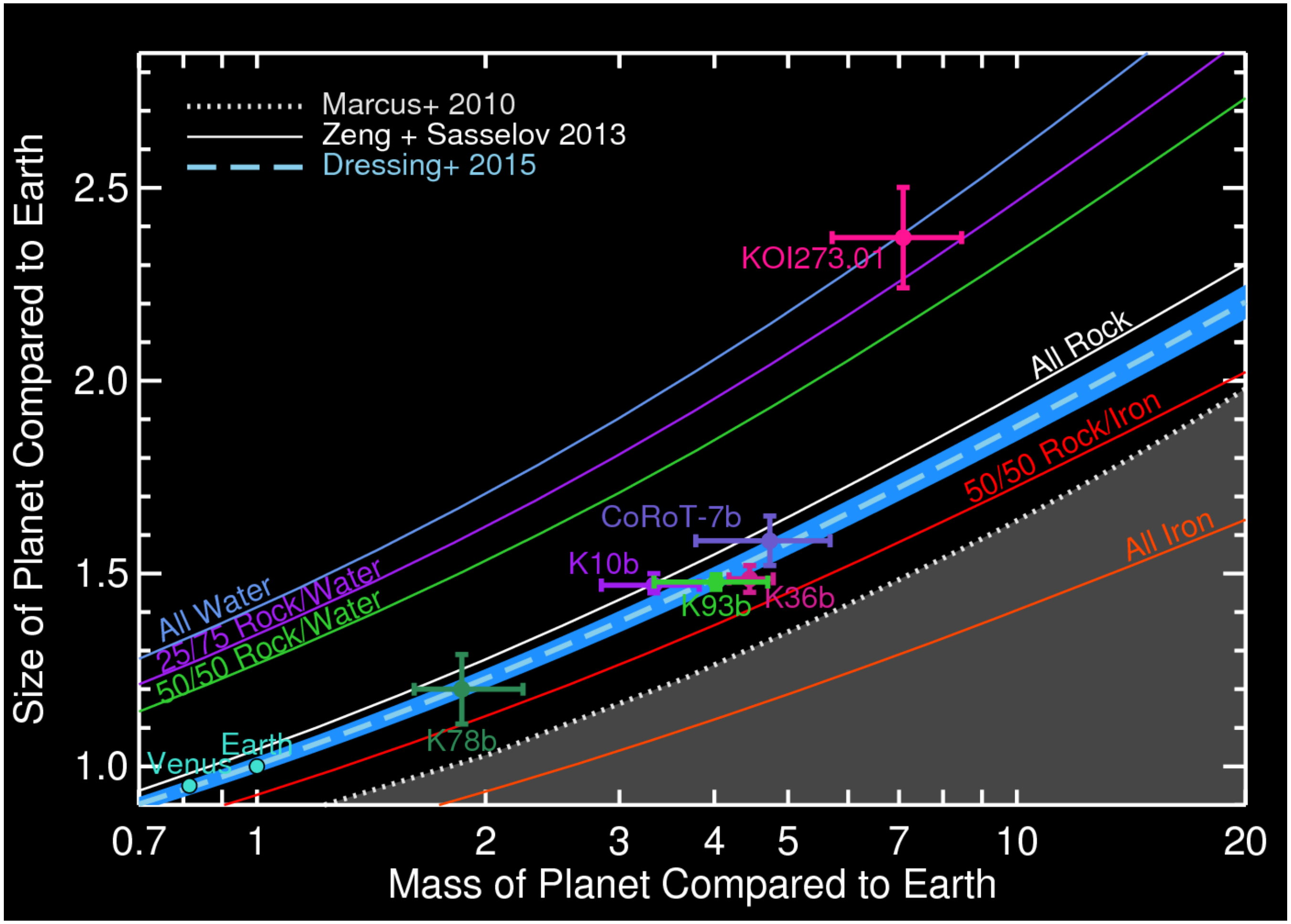
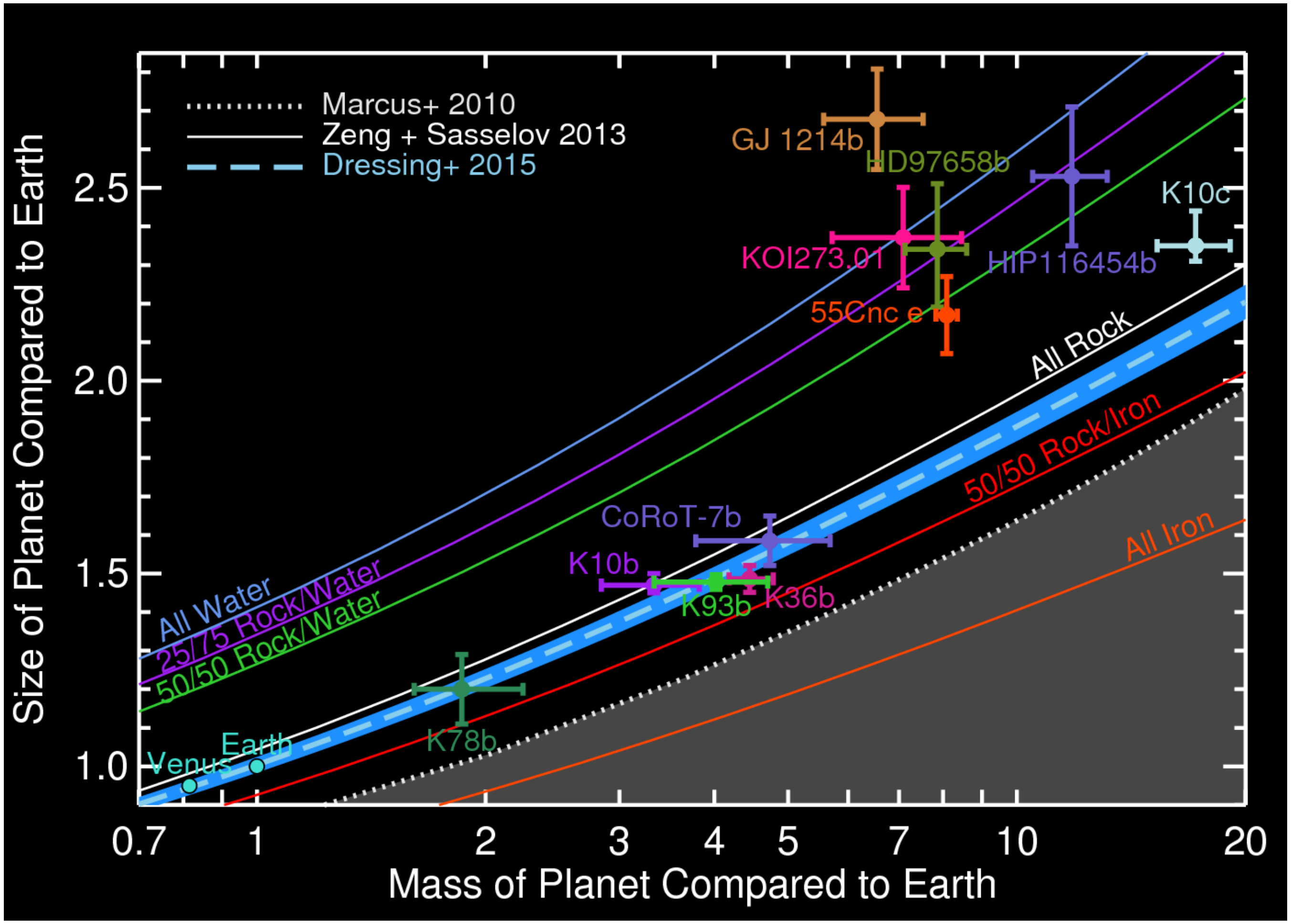
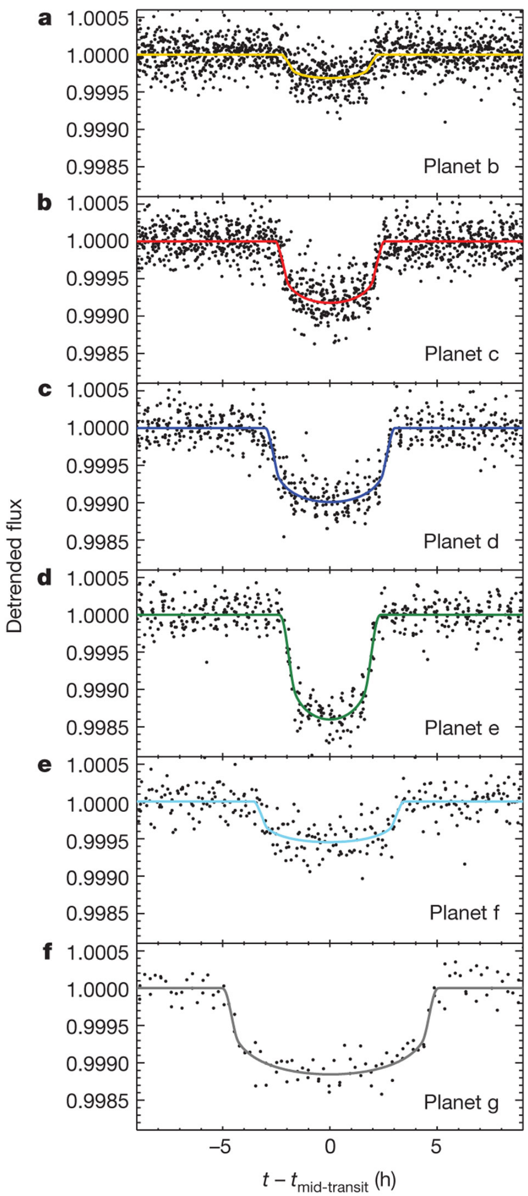
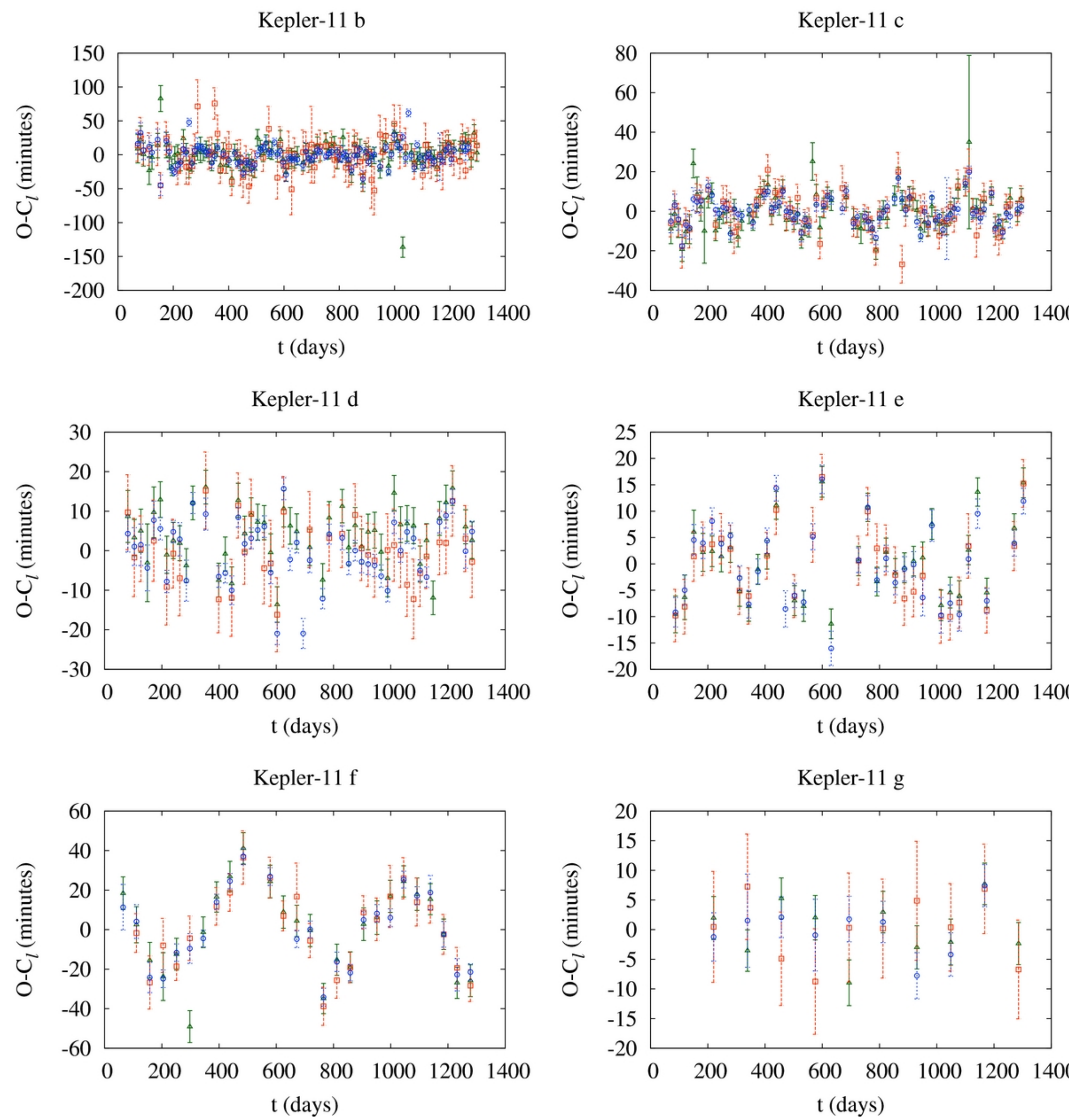


There are no terrestrial planets more massive than 7 M_{Earth}, despite the ease of measuring their masses



Kepler-11: Puffy Planets

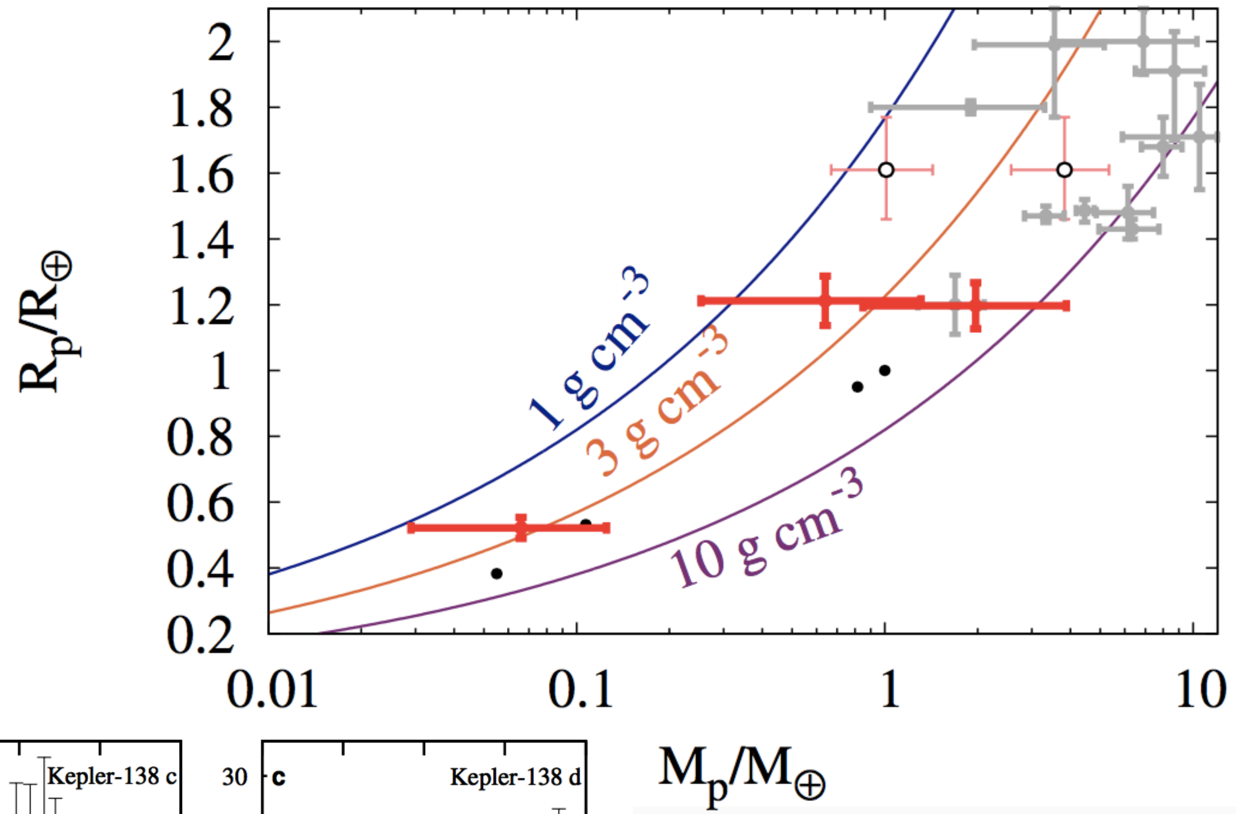


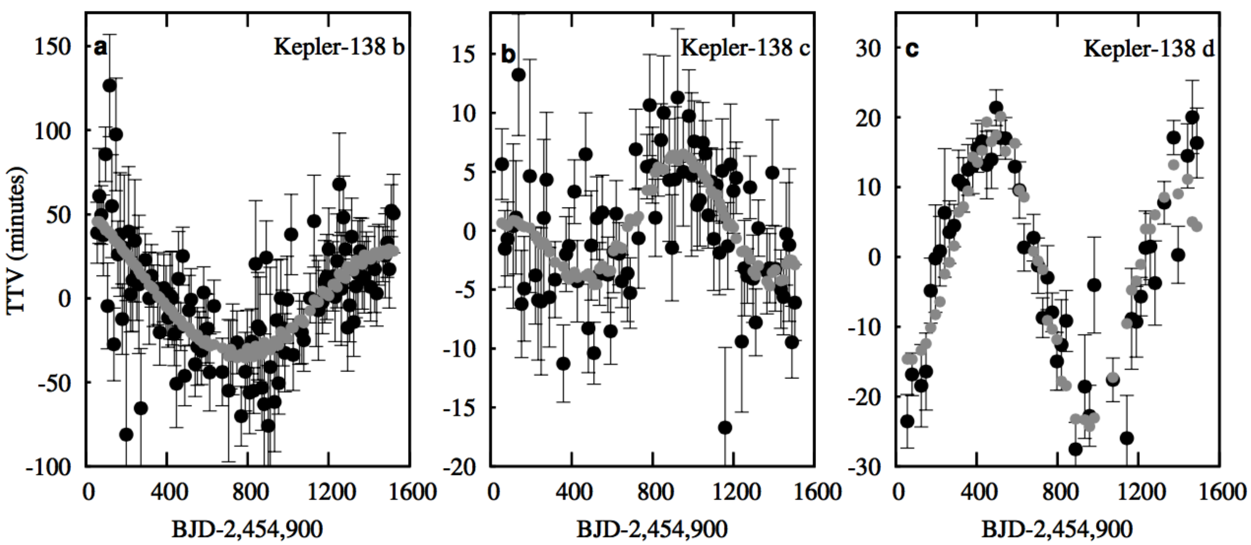


Lissauer et al. Nature 2011; Lissauer et al. 2013

Low-density and Small Planets

KOI-314 = Kepler-138





Kipping et al. ApJ (2014)

Jontof-Hutter et al. Nature (2015)

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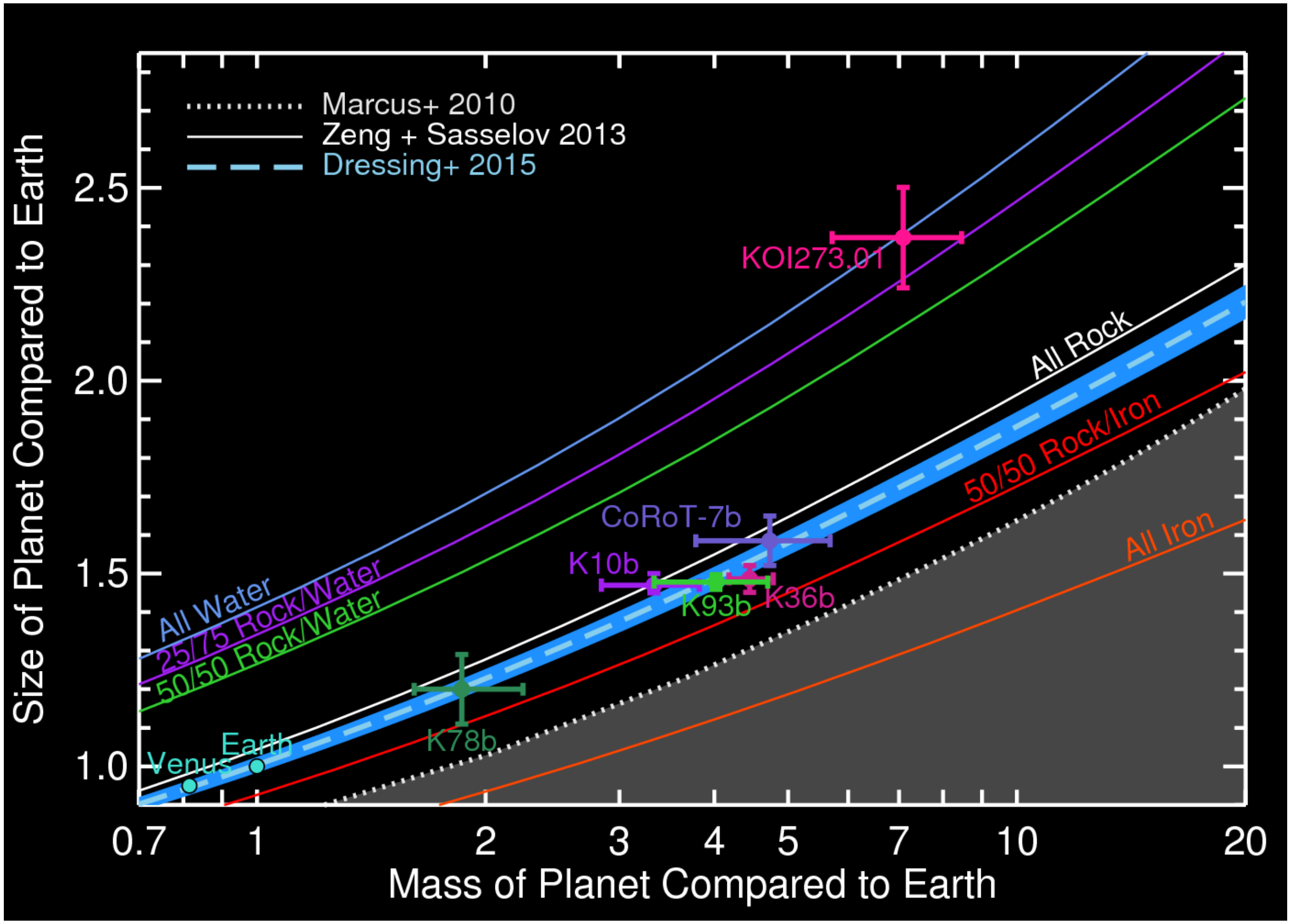
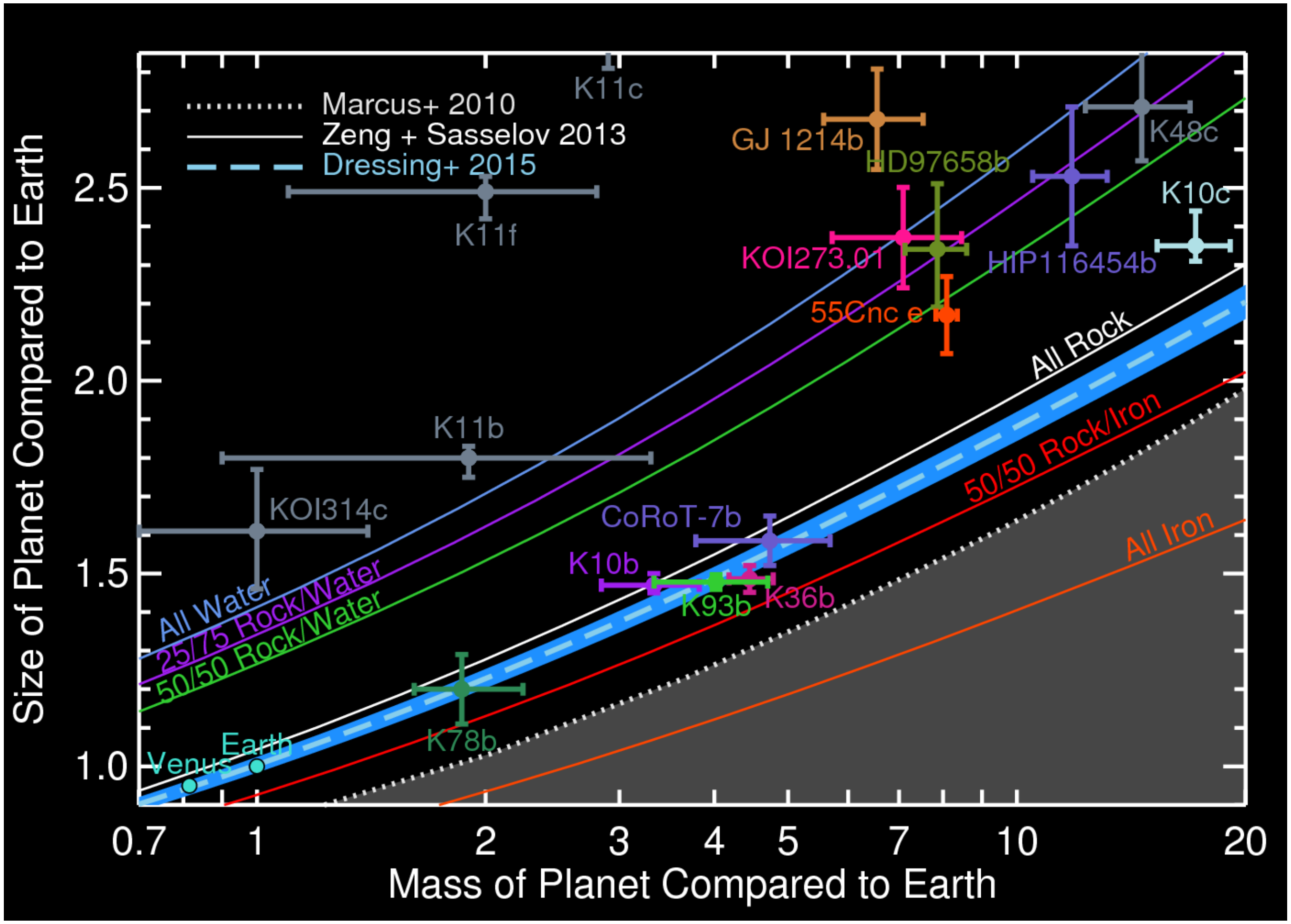
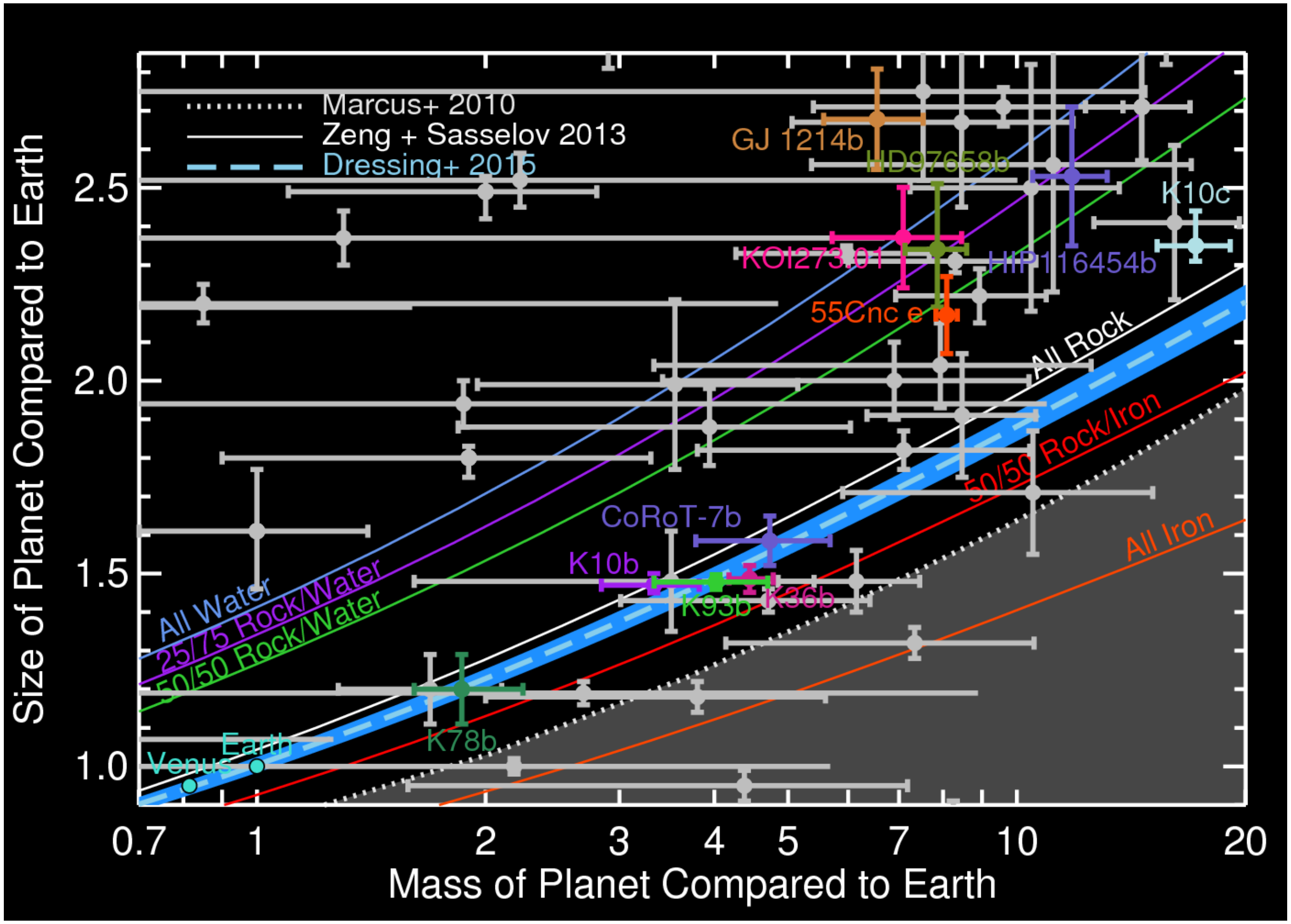


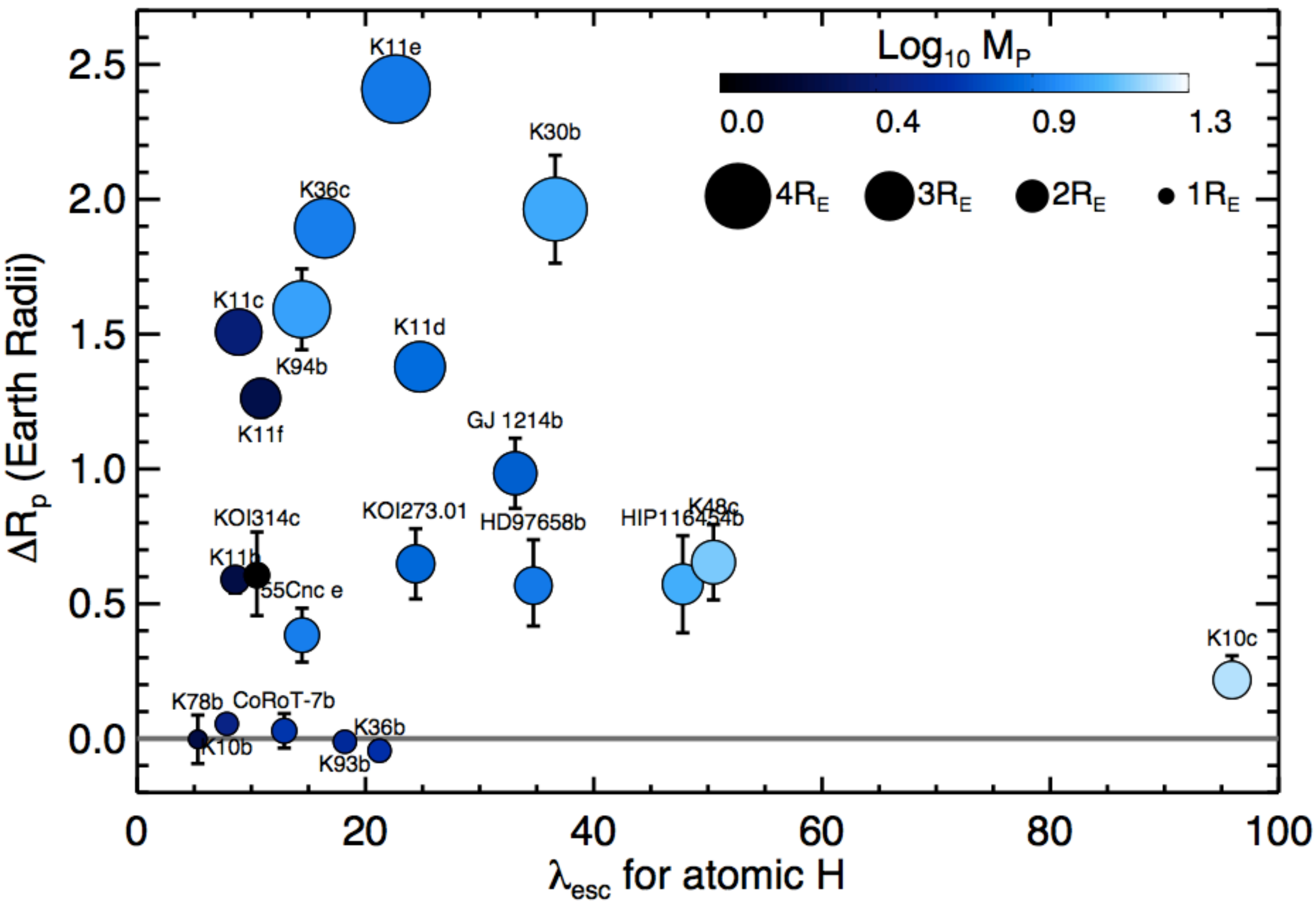
TTVs Grant Access to Mass Determinations of Planets Inaccessible to RV



Compilation of Weiss & Marcy (2014) and Subsequent Work: There are Many Small Planets with Mass Measurements within Reach

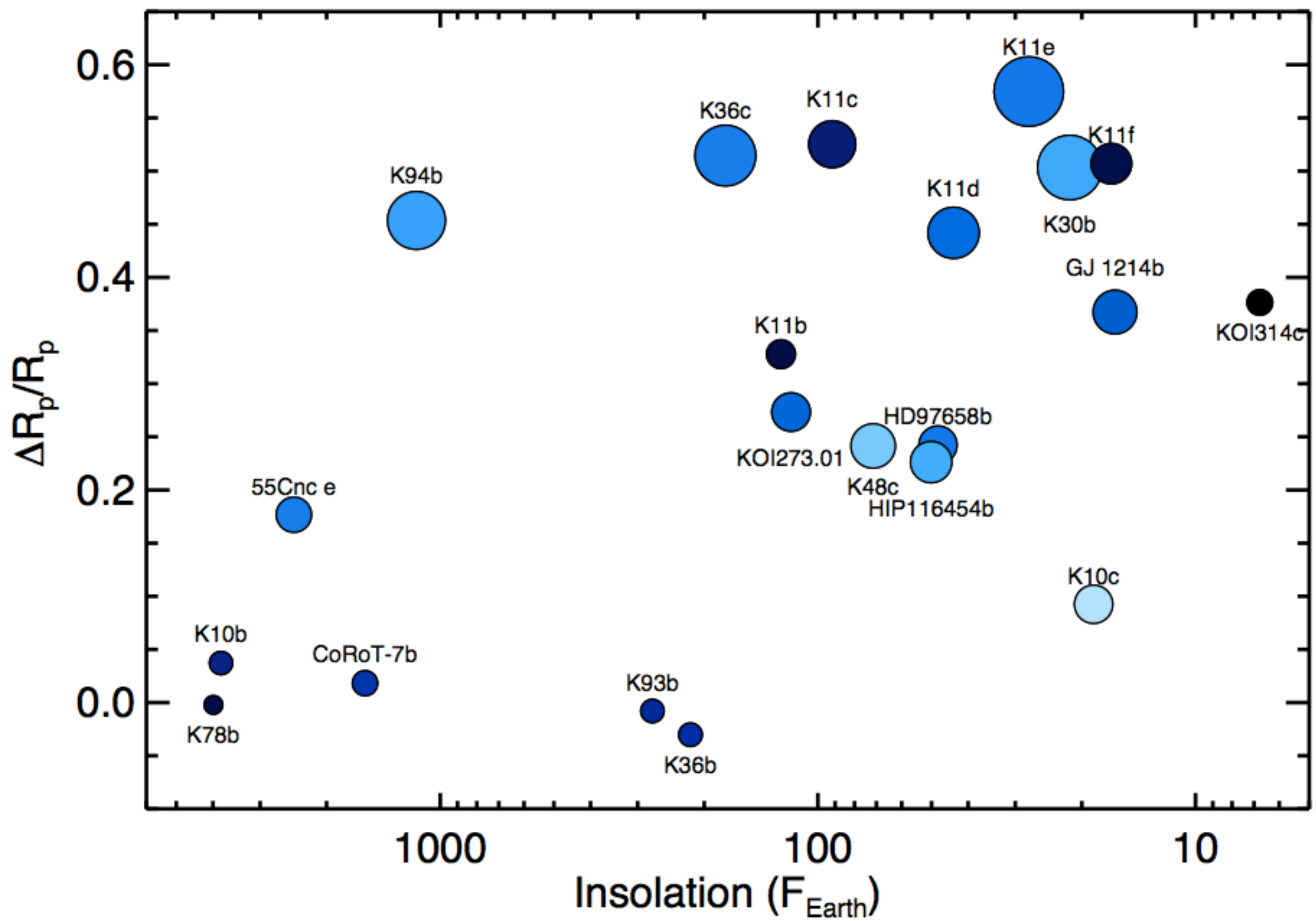


Composition vs Insolation and Mass will Inform Models of Accretion and Retention of Gas: Next talk by Eric Lopez



Plot from Gettel, Charbonneau et al. submitted to ApJ 2015

Composition vs Insolation and Mass will Inform Models of Accretion and Retention of Gas: Next talk by Eric Lopez



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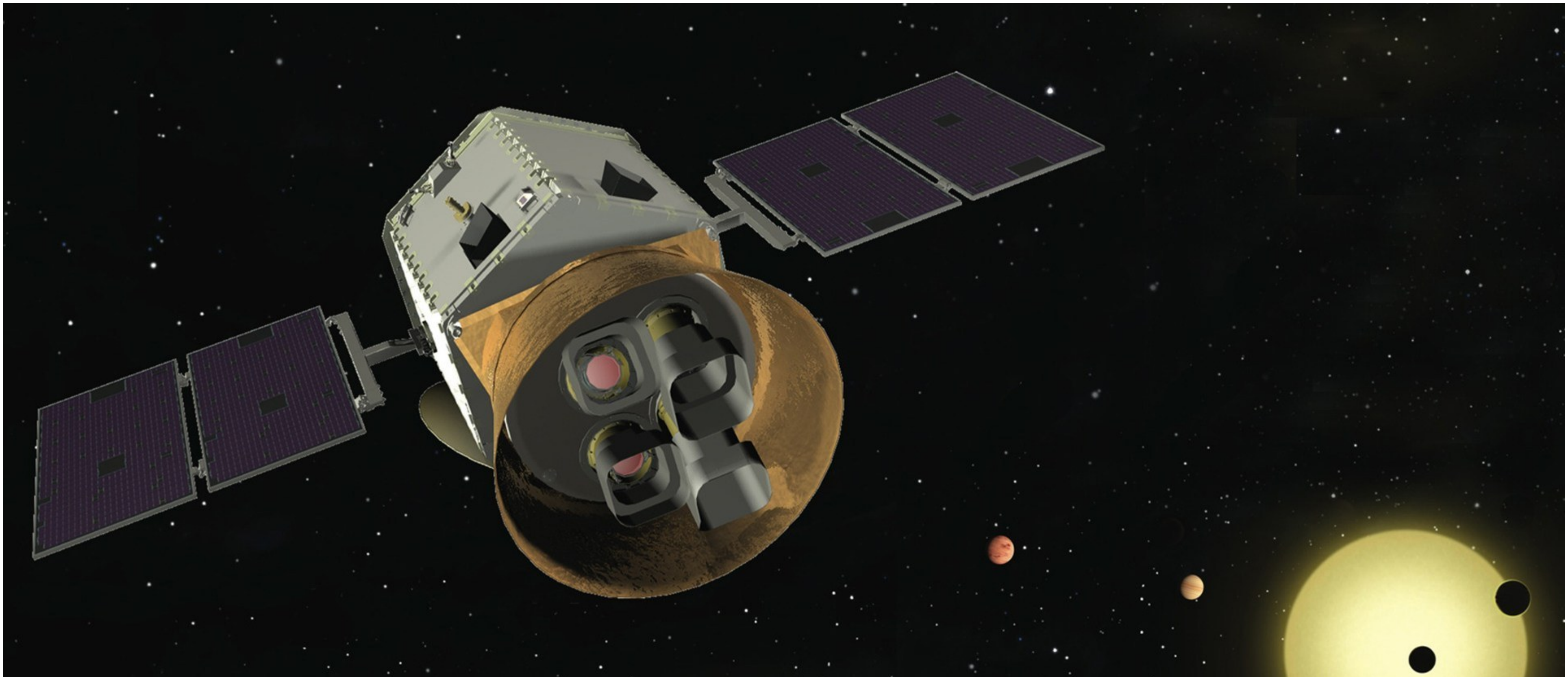
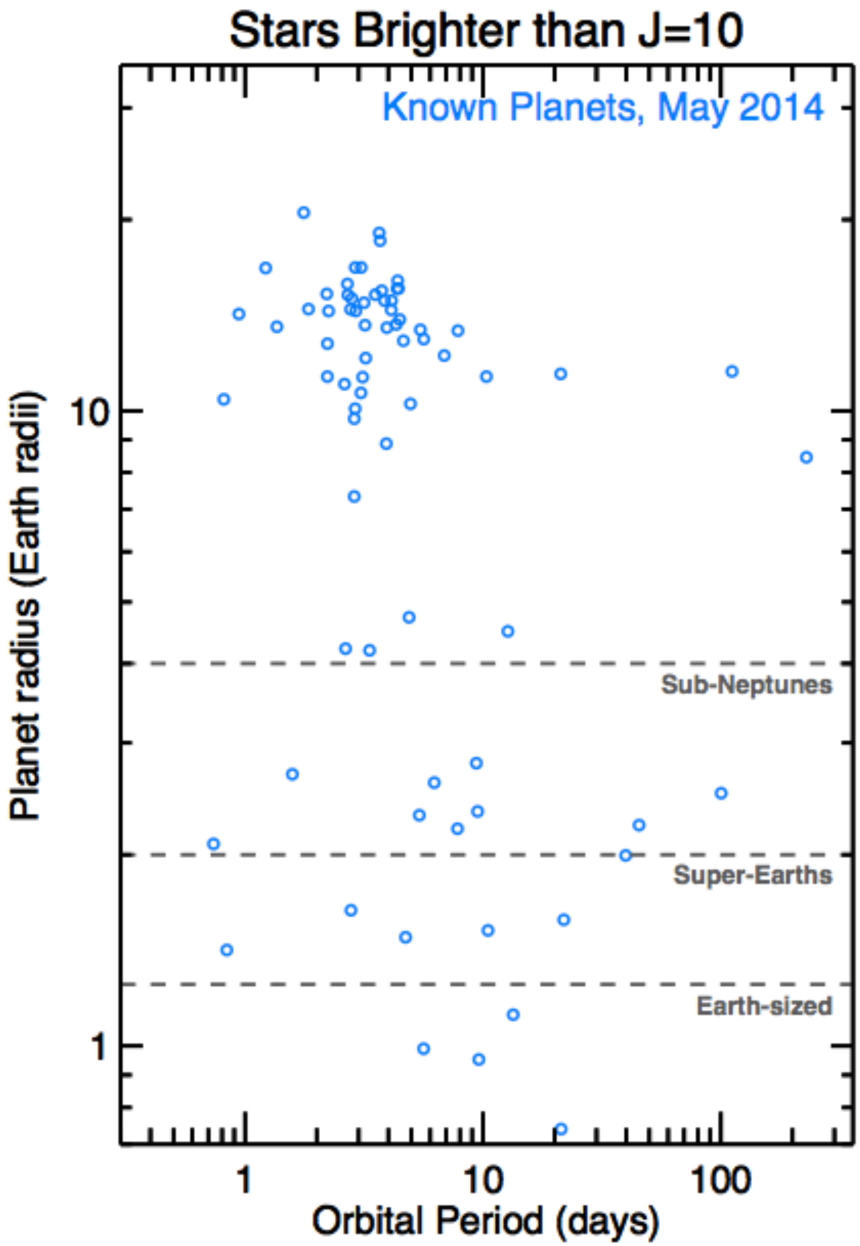


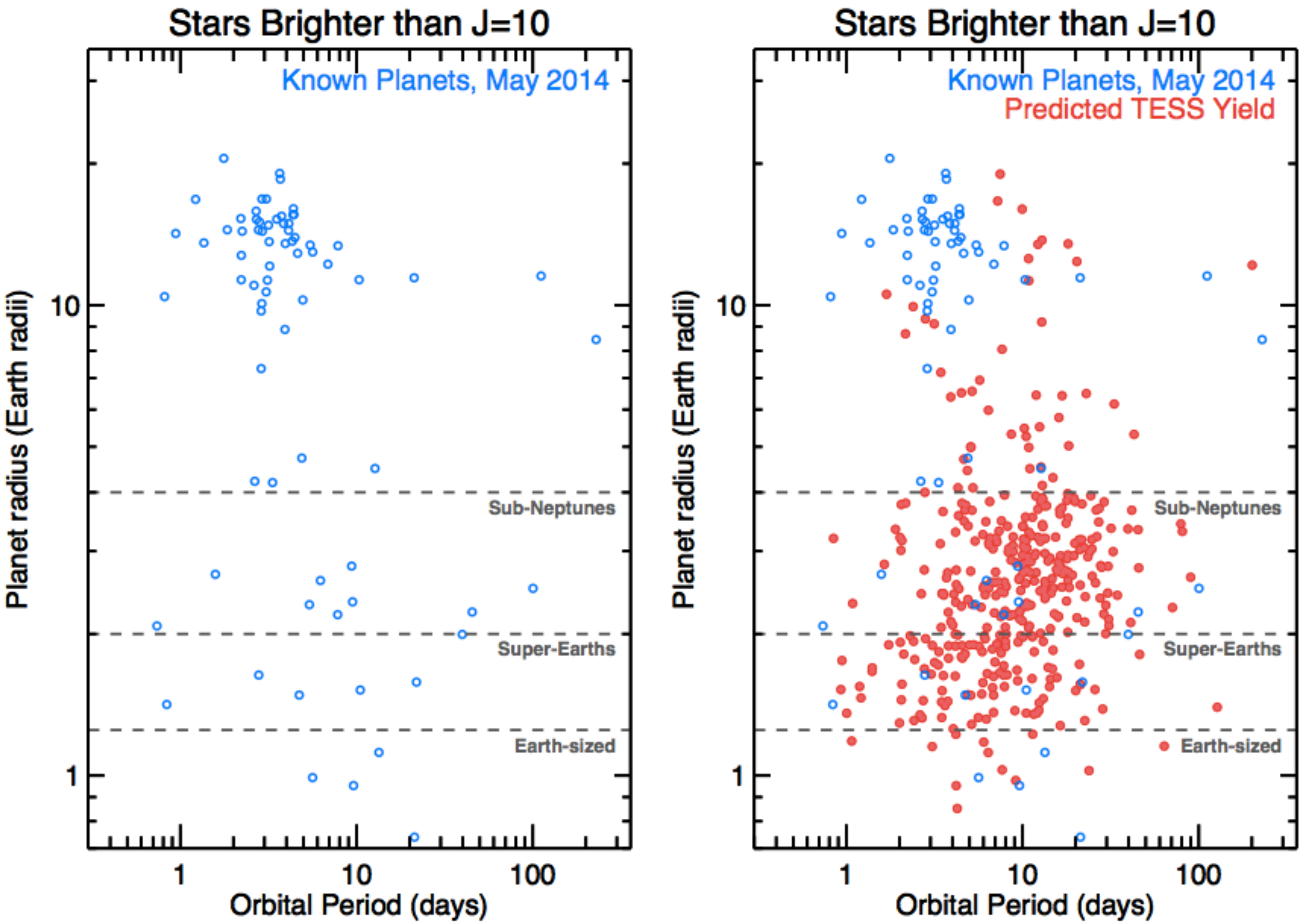
The NASA TESS Mission

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.


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

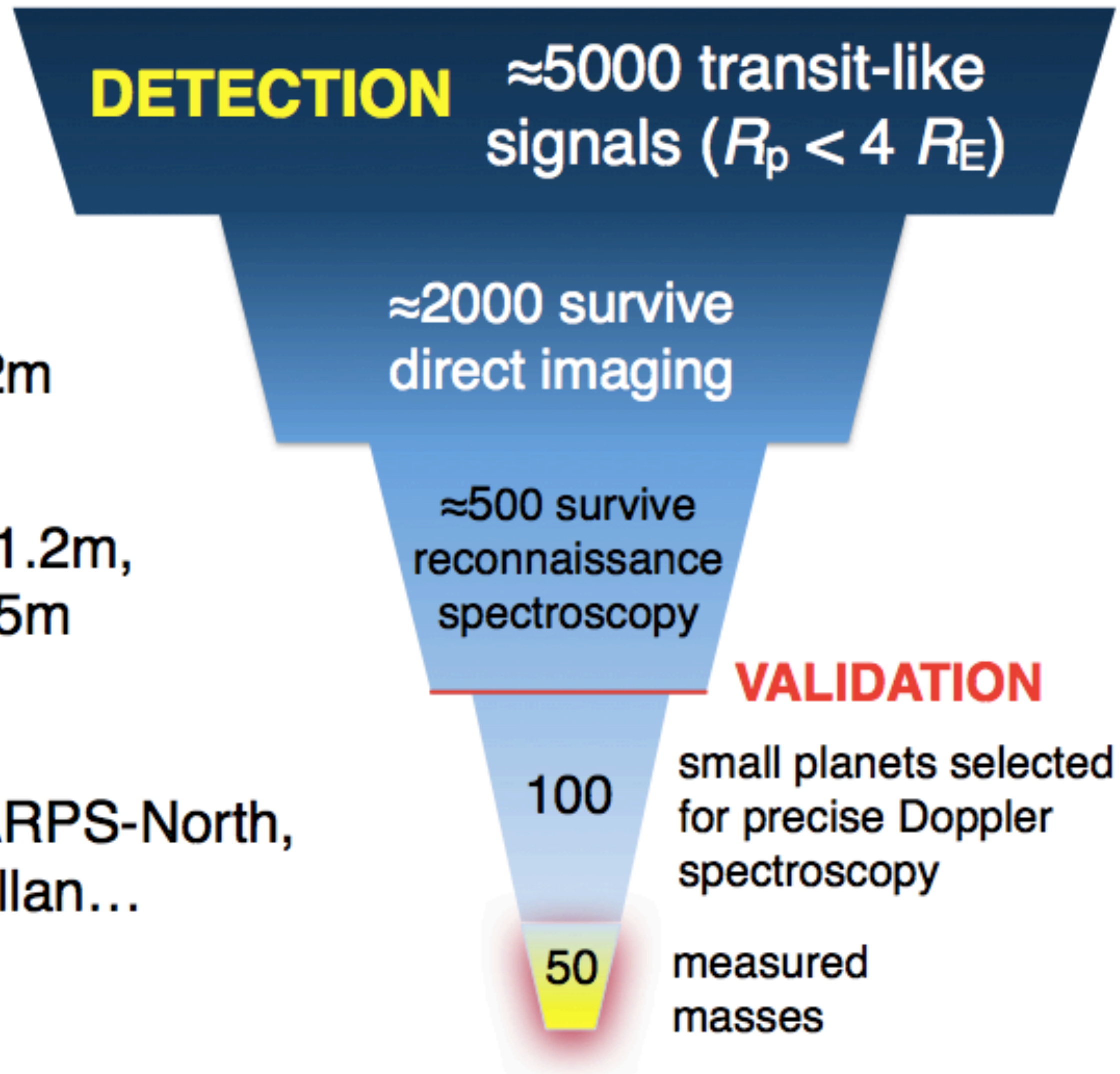
Ground-based follow-up program

TESS data delivered to MAST within 4 months

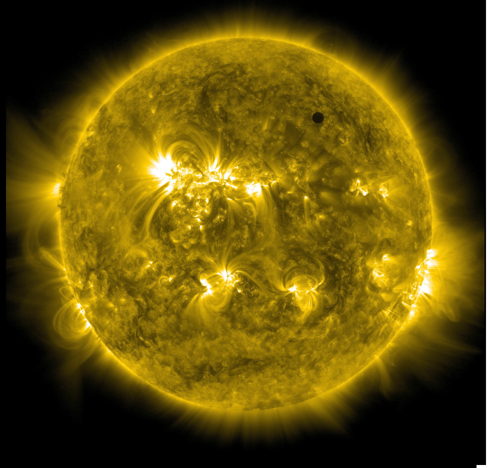
LCOGT, MEarth,
Euler 1.2m, FLWO 1.2m

LCOGT, Euler 1.2m,
OHP, FLWO 1.5m

HARPS, HARPS-North,
Keck, Magellan…



Conclusions



- There are no planets > 7 M_{Earth} with a high density corresponding to an Earth-like composition
- Across 1 – 6 M_{Earth}, there are both planets with H/He envelopes, and planets with Earth-like densities.
  - The rocky group display no intrinsic scatter about the predictions from the Earth composition curve. It would be fascinating to see whether deviations correlate with stellar elemental abundances.
  - The relationship between the presence of a H/He envelope and the distance from the star points to fruitful constraints on the processes of accretion and retention of such envelopes.
- The NASA TESS Mission will discover 300 nearby Earths and super-Earths. Precise densities as a function of insolation and age will inform our understanding of formation and evaporation, and permit a prediction of which planets (at greater separations) are habitable.

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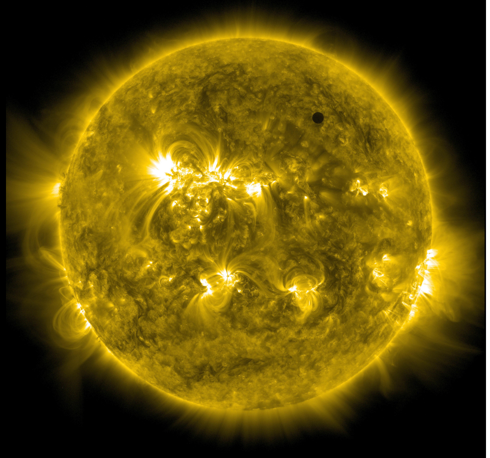

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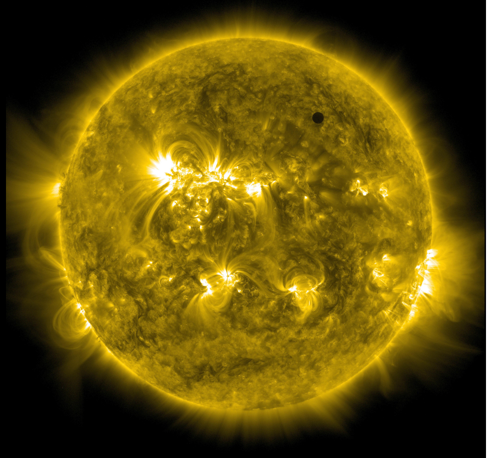

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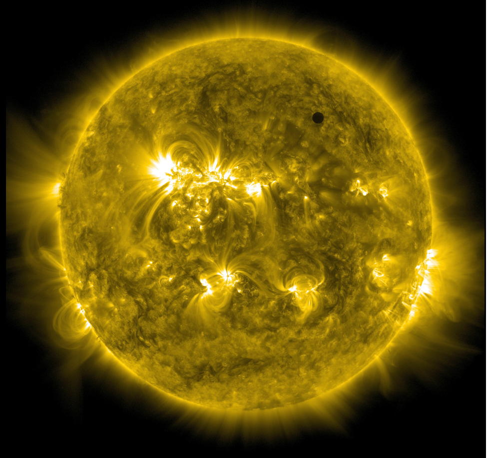

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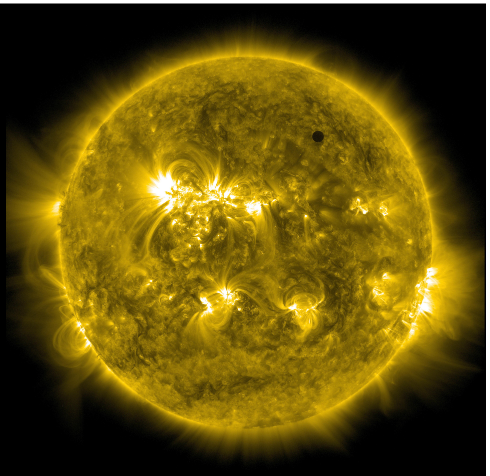

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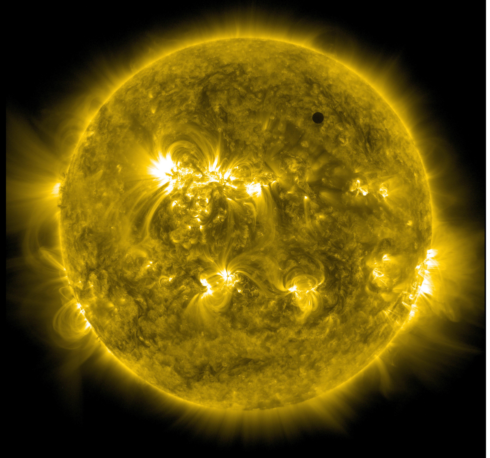

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