We thank the IRTF TAC & the Caltech TAC for enabling these follow-up observations and the K2 Guest Observer Office for supporting our numerous K2 proposals.

From Red Dwarfs to Pale Blue Dots: Searching for Potentially Habitable Planets in the Galaxy with Kepler, K2, TESS, & Beyond

Courtney Dressing

NASA Sagan Fellow at Caltech

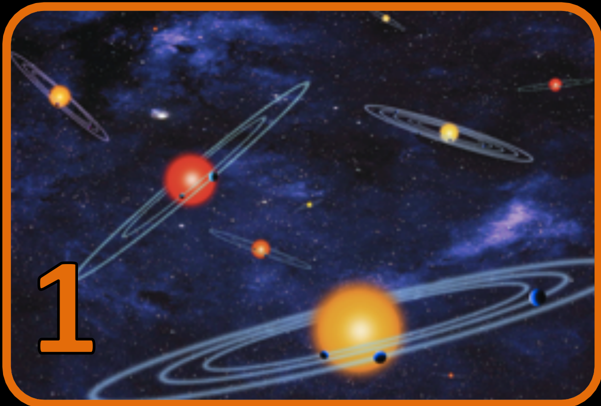
LUVOIR Seminar

November 30, 2016

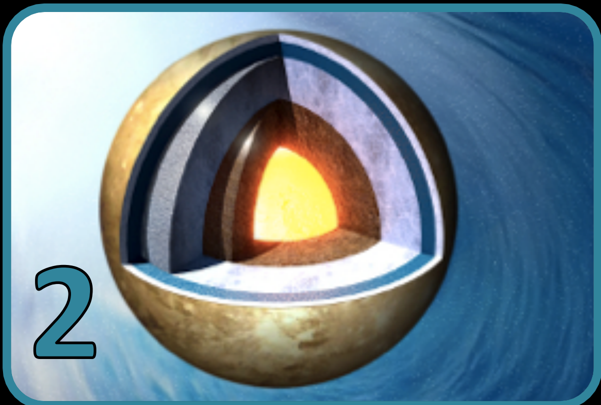
Collaborators: Elisabeth Newton, Josh Schlieder, Andrew Vanderburg, Ian Crossfield, Arturo Martinez, Heather Knutson, David Charbonneau, the K2 California Consortium, & the HARPS-N Consortium

The Big Question: ***Are we alone?***

Questions Addressed Today



How **common** are *planets orbiting low-mass stars* ?



How **diverse** are the *compositions of small planets* ?

How can we **identify** *potentially habitable planets* ?

Transit Observations Reveal Planet Sizes

Radial Velocity Observations Reveal Planet Masses

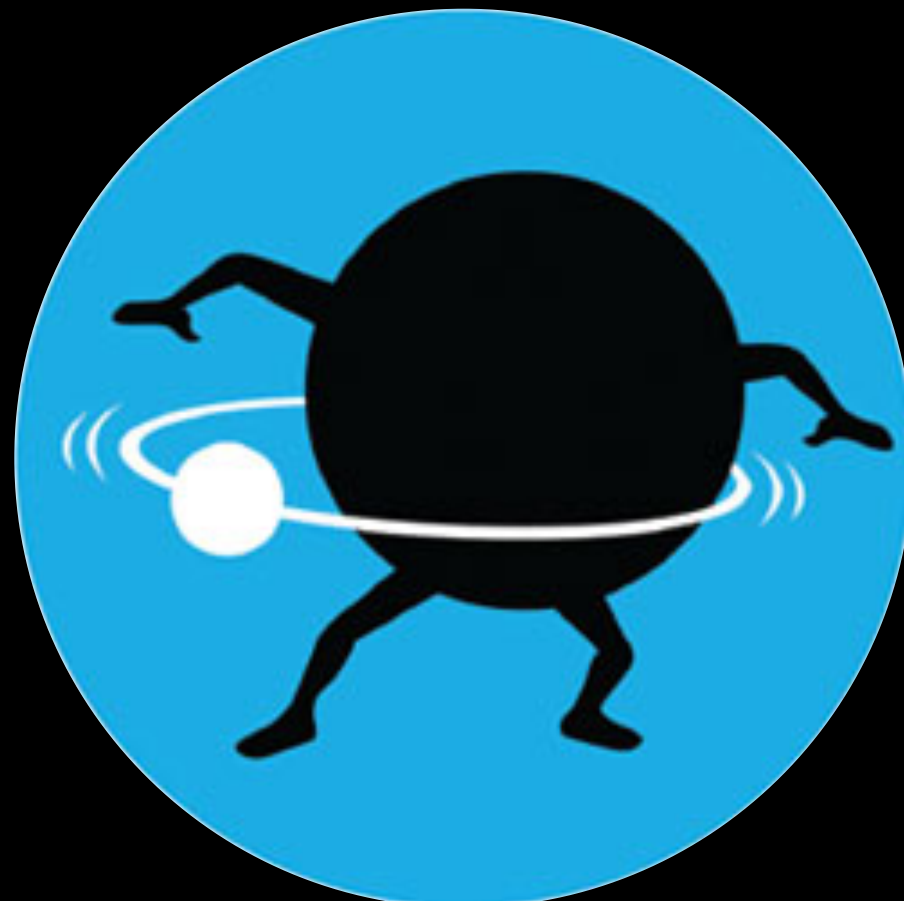
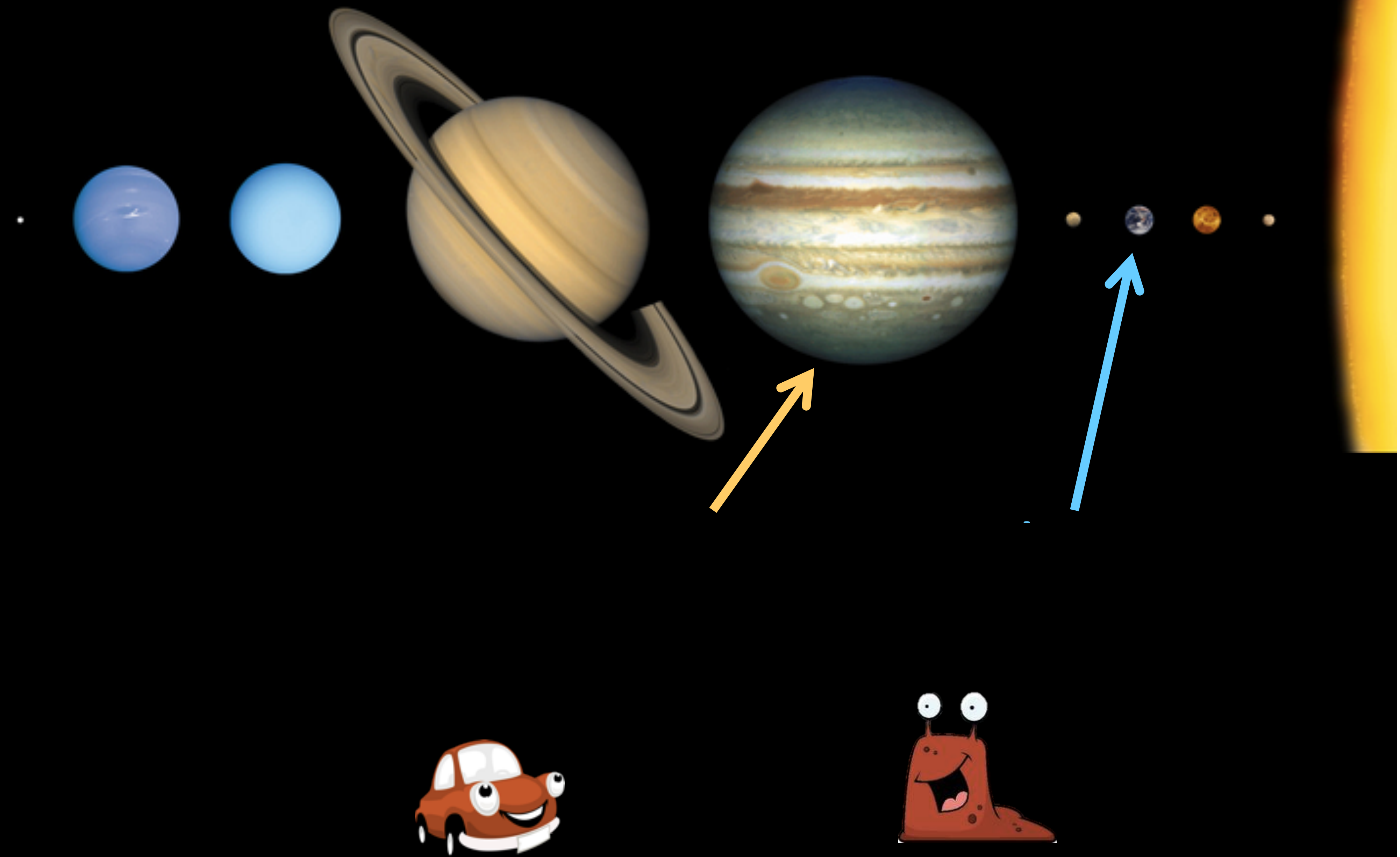
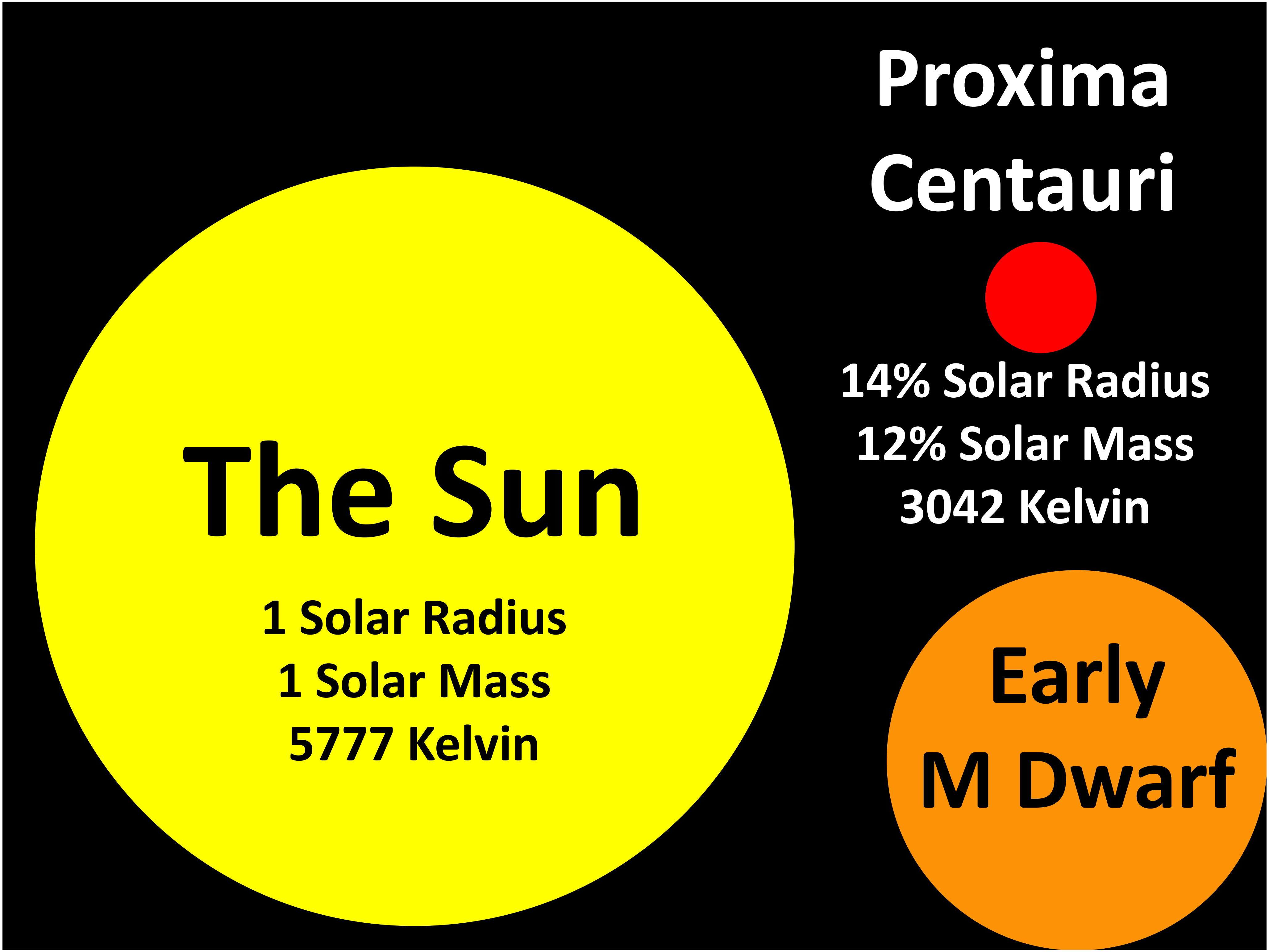
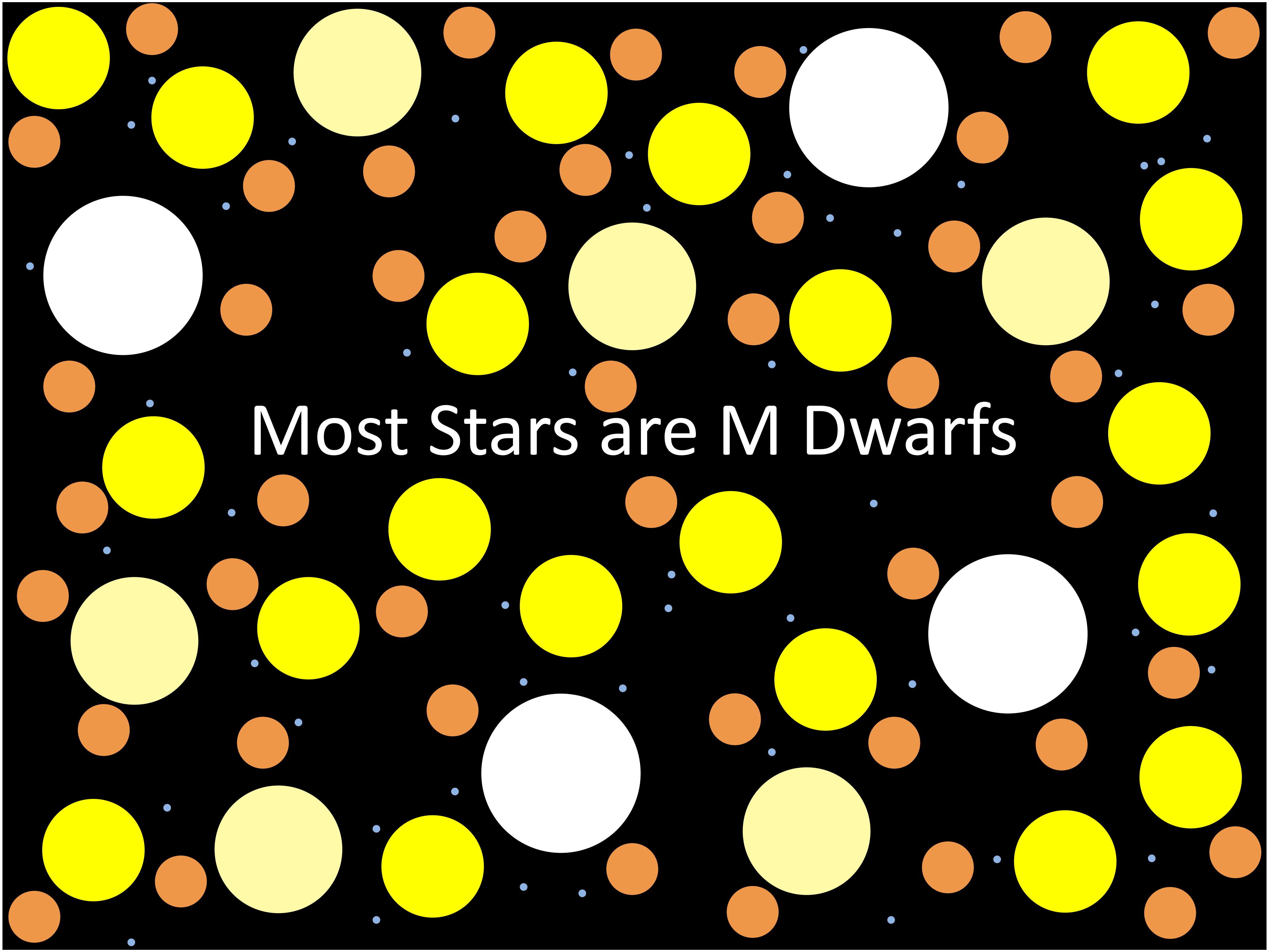


Image credit: NASA/SDO, Scientific American

How detectable are these signals?



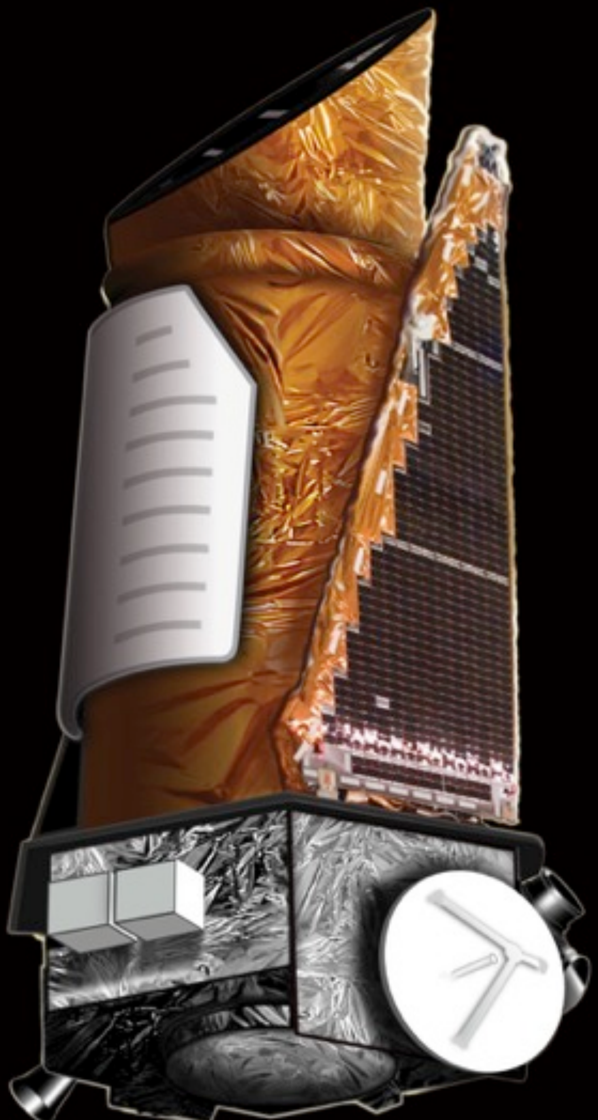

Proxima
Centauri
14% Solar Radius
12% Solar Mass
3042 Kelvin
The Sun
1 Solar Radius
1 Solar Mass
5777 Kelvin
Early
M Dwarf

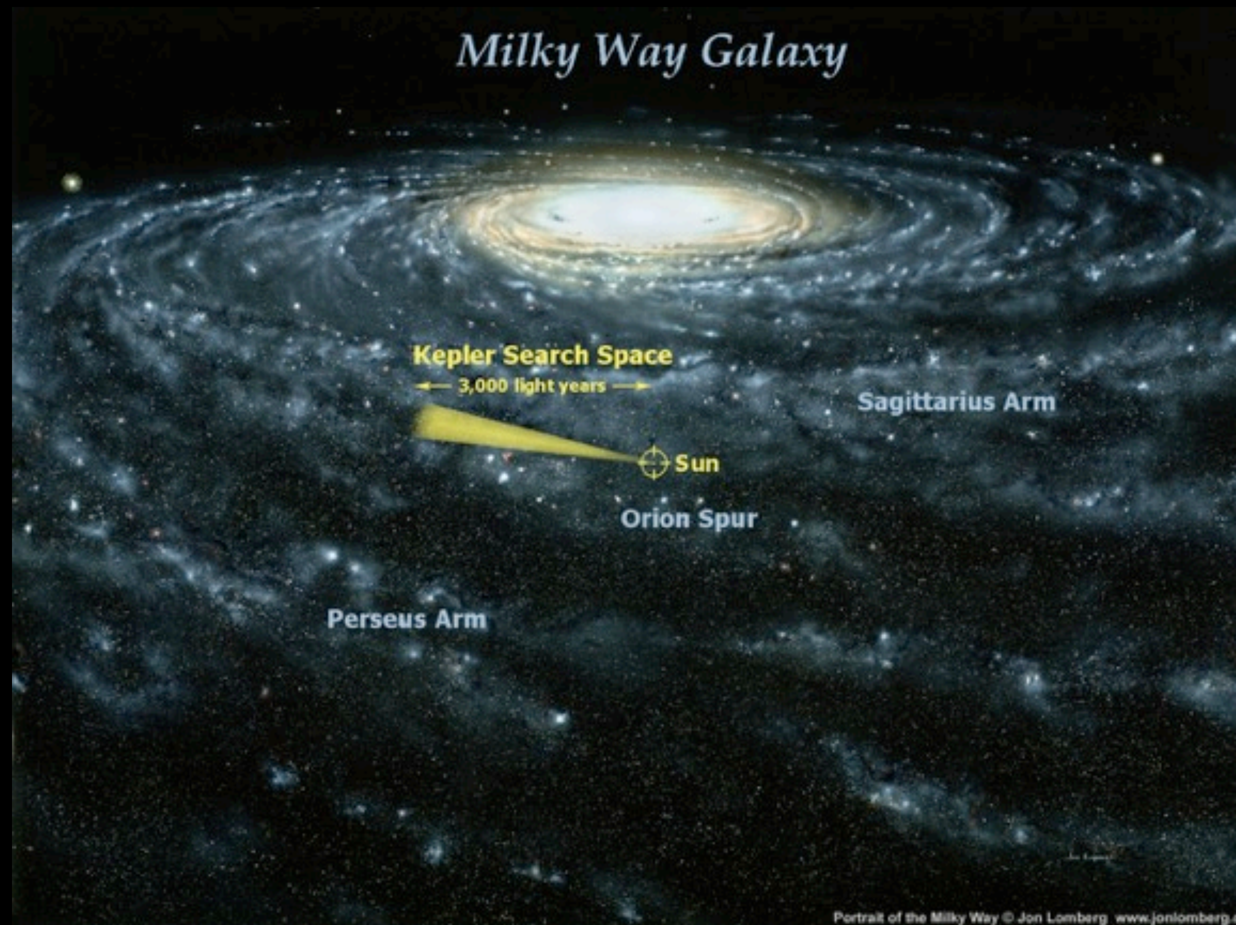

Most Stars are M Dwarfs


Most Stars are M Dwarfs


Most Stars are M Dwarfs
How many planets orbit these stars?

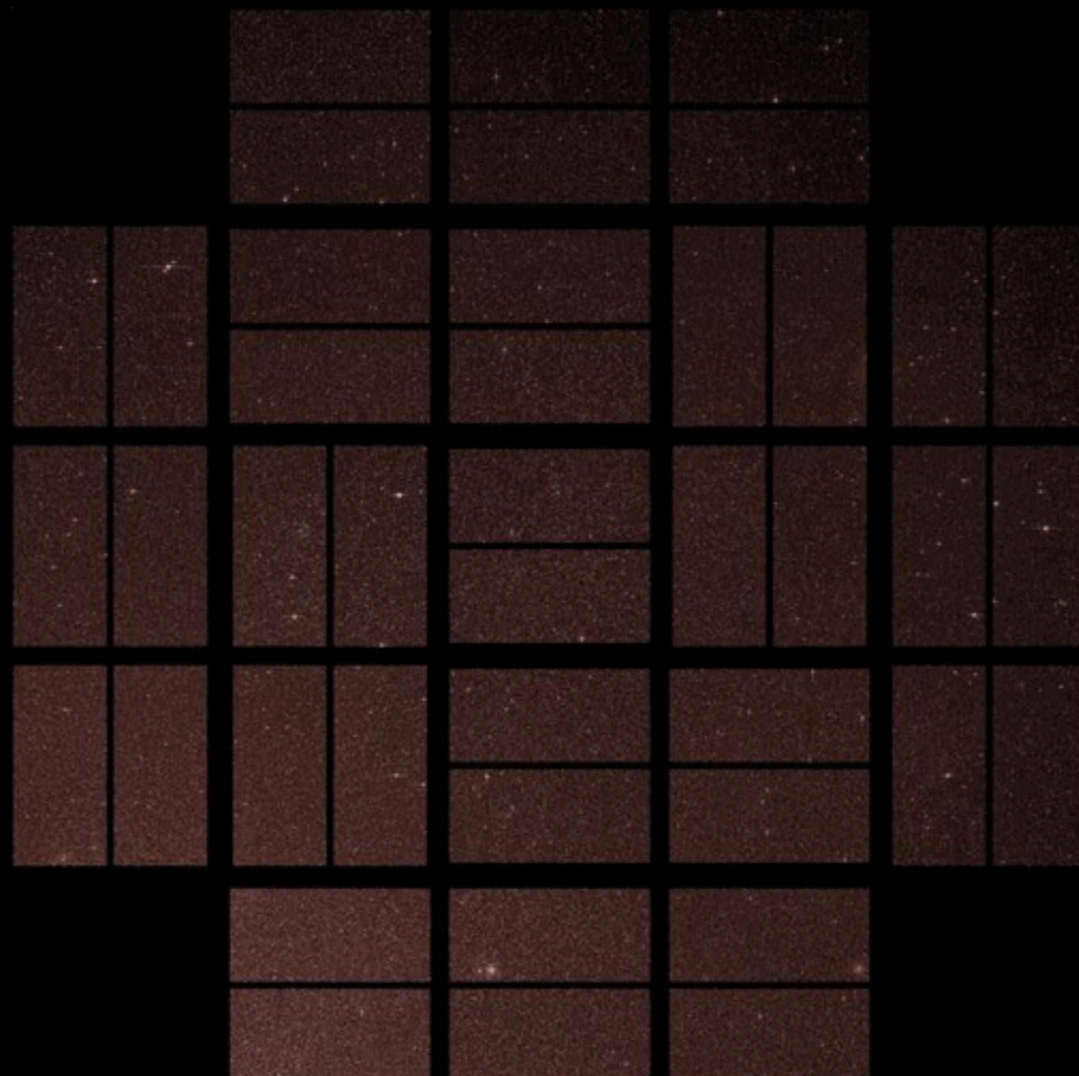
The *Kepler* Mission: 2009 - 2013





Credit: NASA/*Kepler* mission

Kepler Looked for Planets Orbiting These Stars

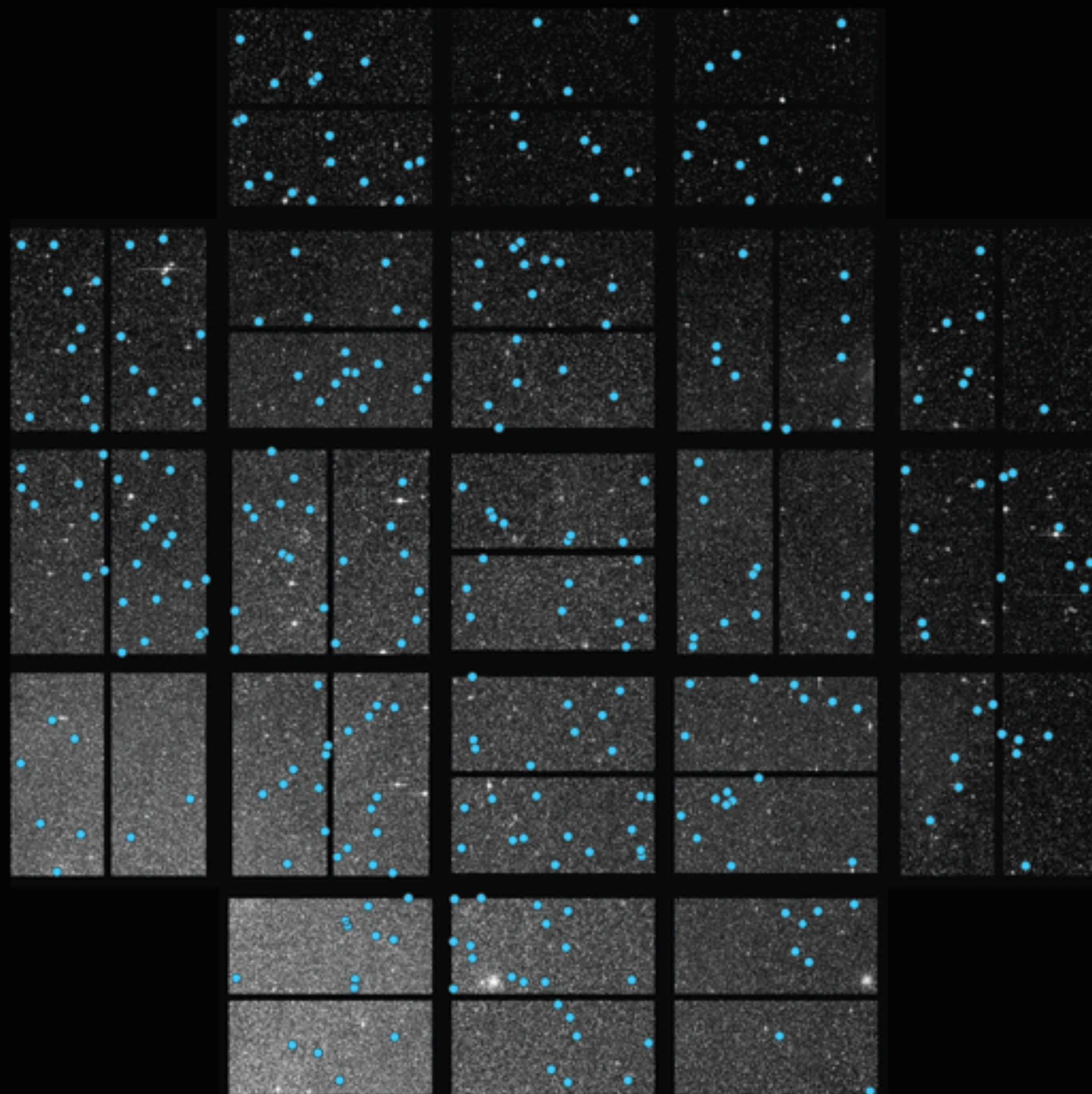


Credit: NASA/*Kepler* mission

Locations of Kepler Planet Candidates

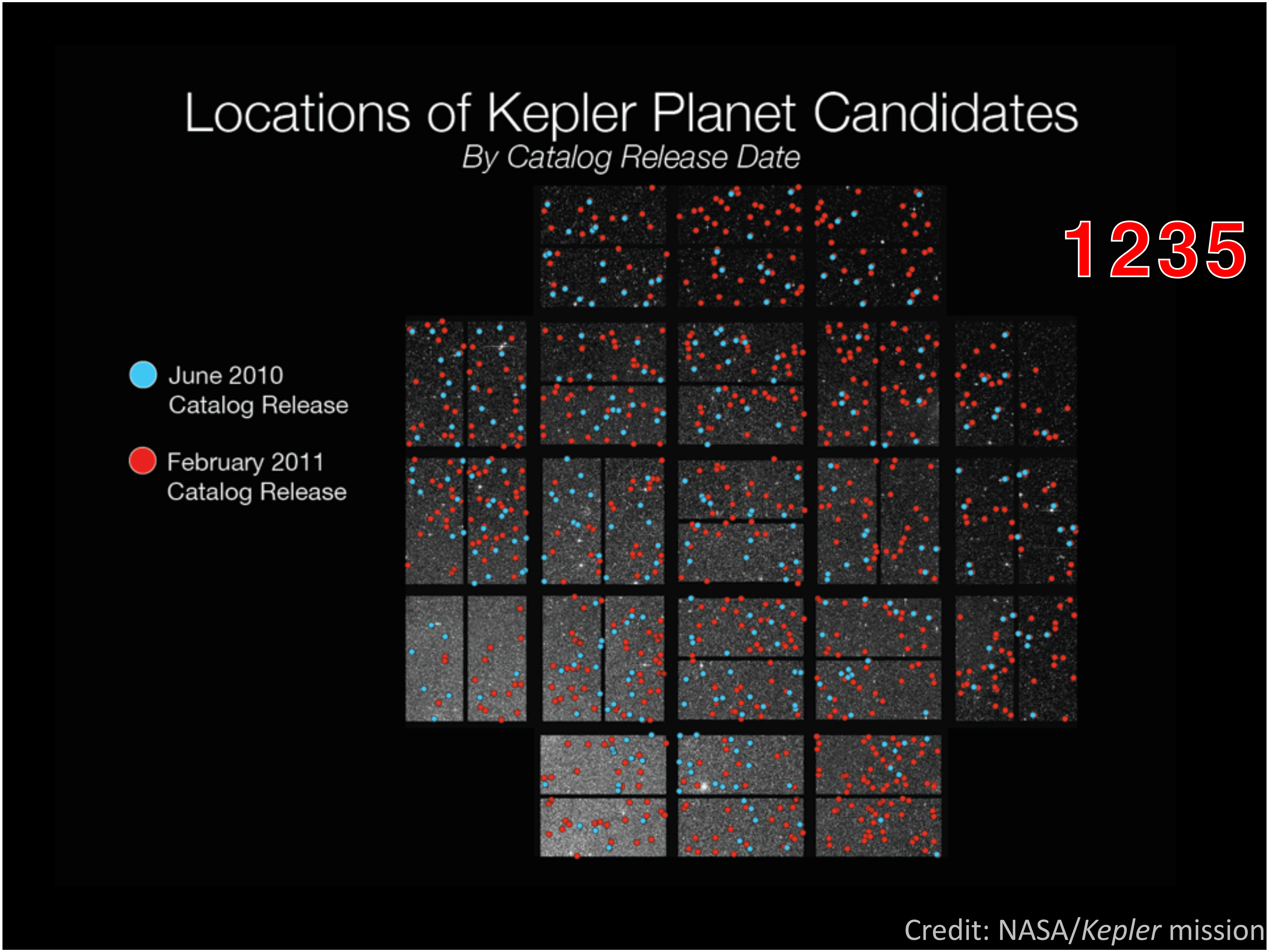
By Catalog Release Date

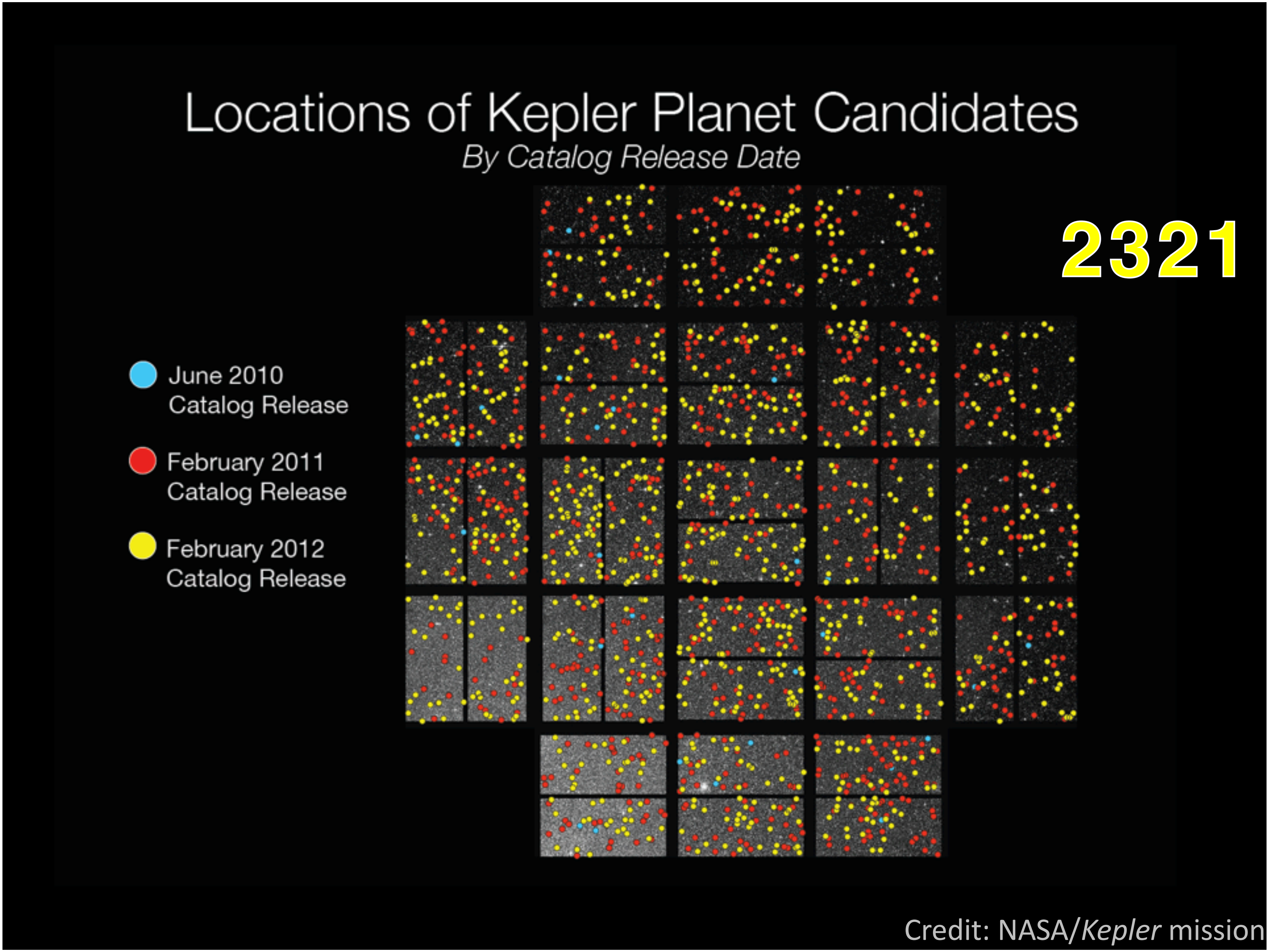
312



June 2010 Catalog Release

Credit: NASA/*Kepler* mission


Locations of Kepler Planet Candidates
By Catalog Release Date
1235
June 2010
Catalog Release
February 2011
Catalog Release
Credit: NASA/Kepler mission


Locations of Kepler Planet Candidates
By Catalog Release Date
2321
June 2010
Catalog Release
February 2011
Catalog Release
February 2012
Catalog Release
Credit: NASA/Kepler mission

Locations of Kepler Planet Candidates

As of January 7, 2013

2740

- Earth-size
- Super-Earth size 1.25 - 2.0 Earth-size
- Neptune-size 2.0 - 6.0 Earth-size
- Giant-planet size 6.0 - 22 Earth-size

Total Today: 4696!

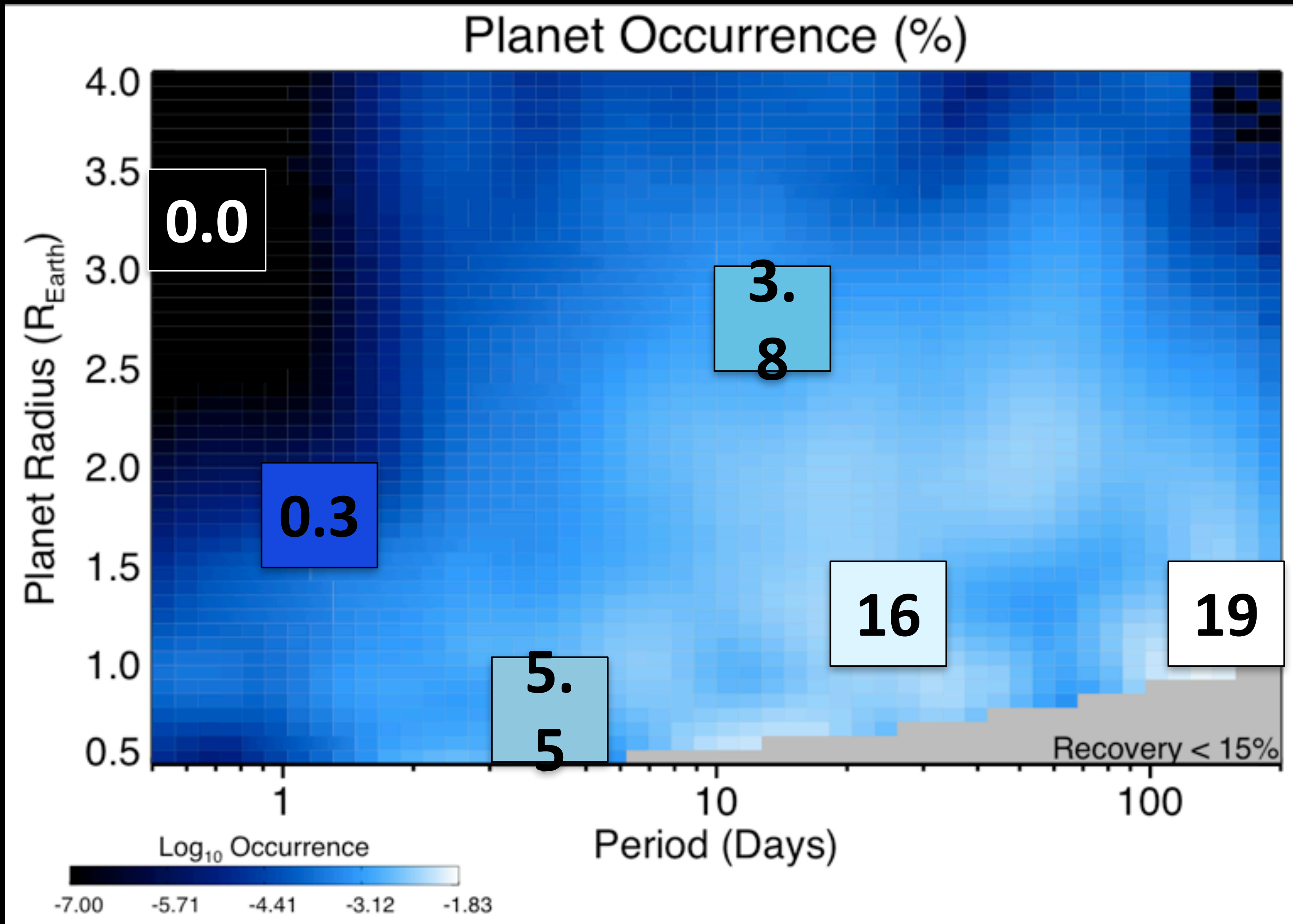
Credit: NASA/*Kepler* mission

# of Planets = # of Planet Candidates – # of False Positives

$$\textit{Planet Occurrence Rate} = \frac{\boxed{\text{Number of Planets}}}{\boxed{\text{Number of Stars “Searched”}}}$$

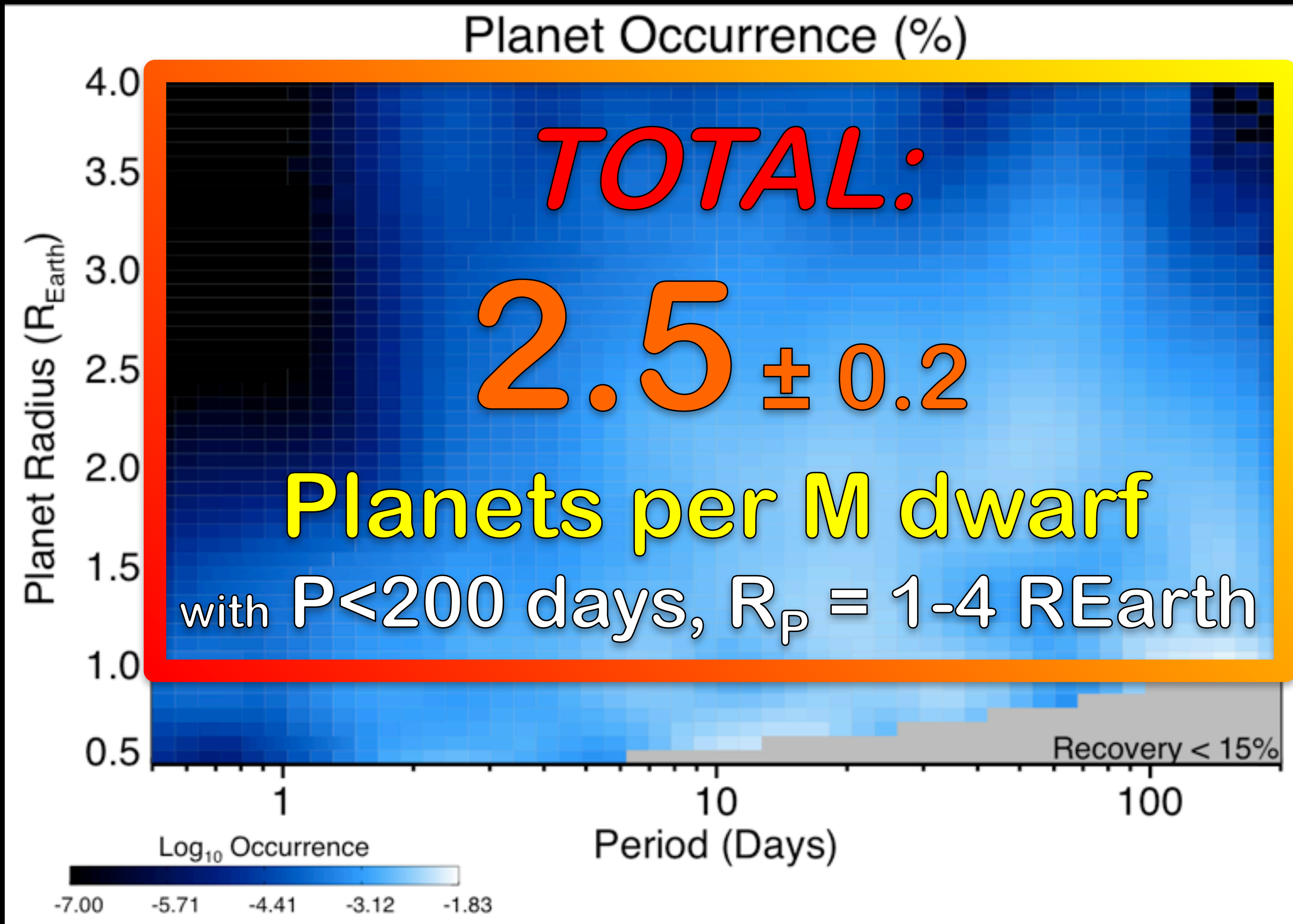
Transit detectability depends on stellar and planetary properties

Smaller Planets Are More Prevalent



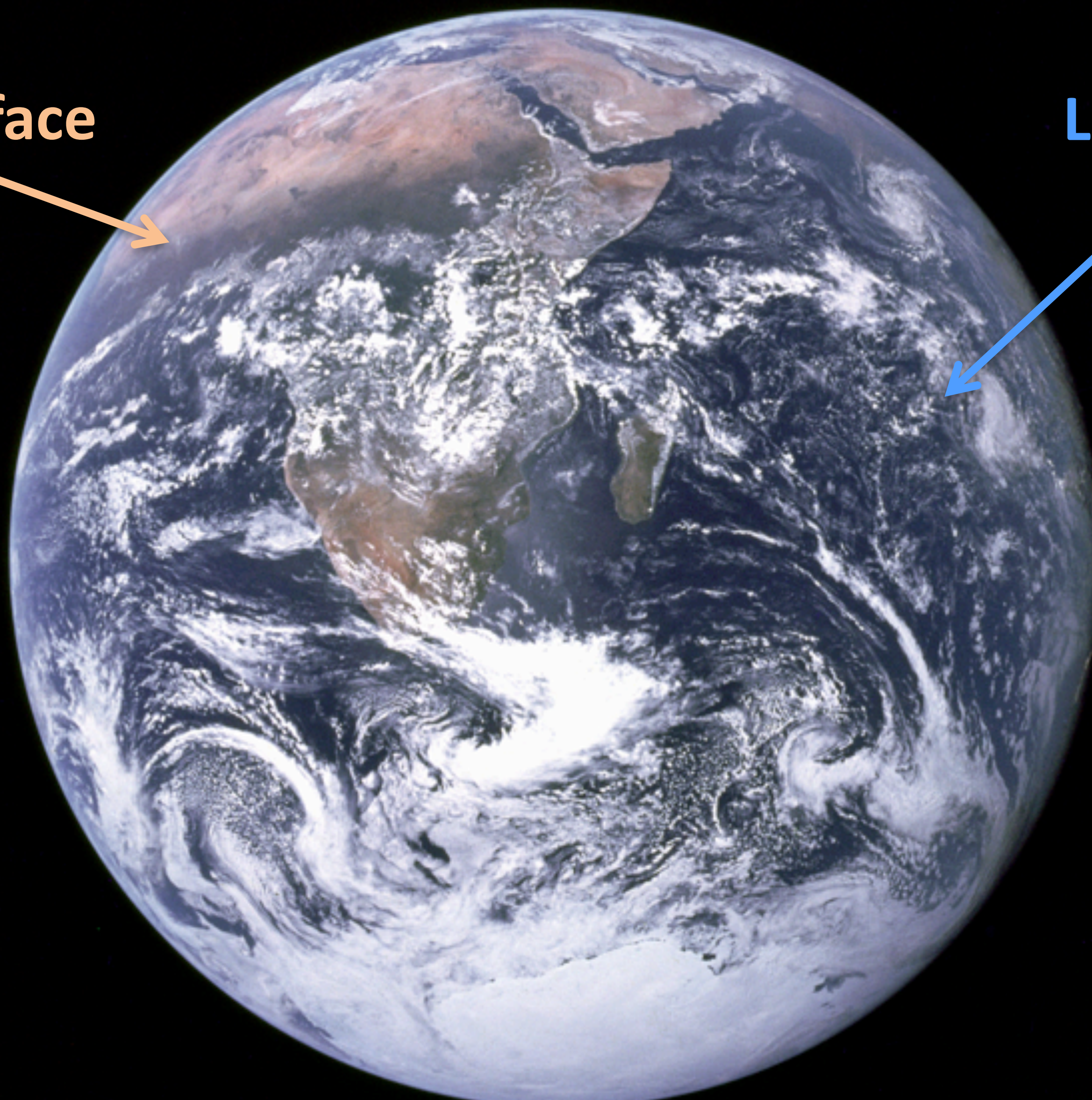
Dressing & Charbonneau 2015, ApJ, 807, 45

Planets Orbiting Low-Mass Stars are Common



Dressing & Charbonneau 2015, ApJ, 807, 45

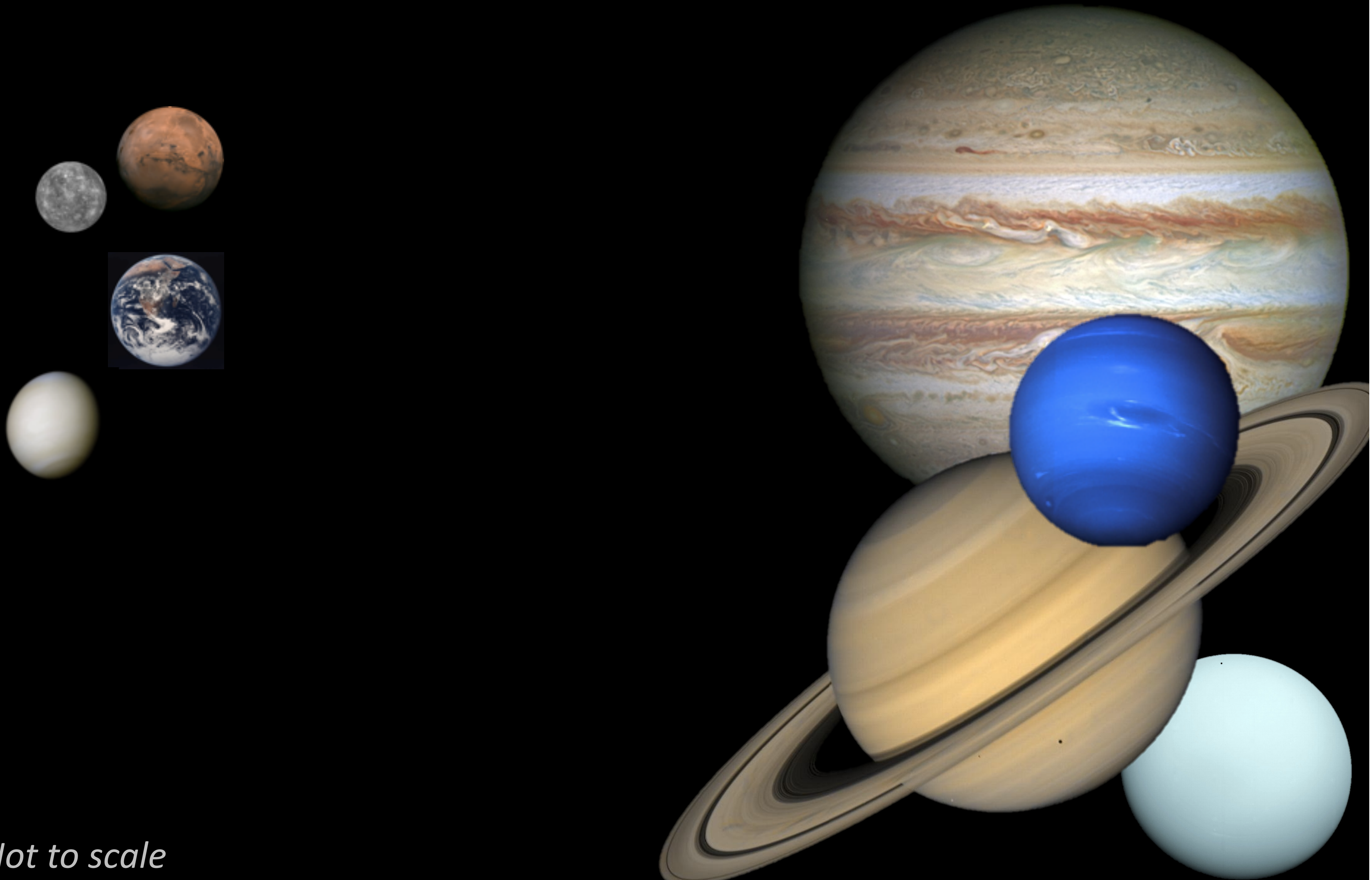
Are any of these planets habitable?



How large can a rocky planet be?

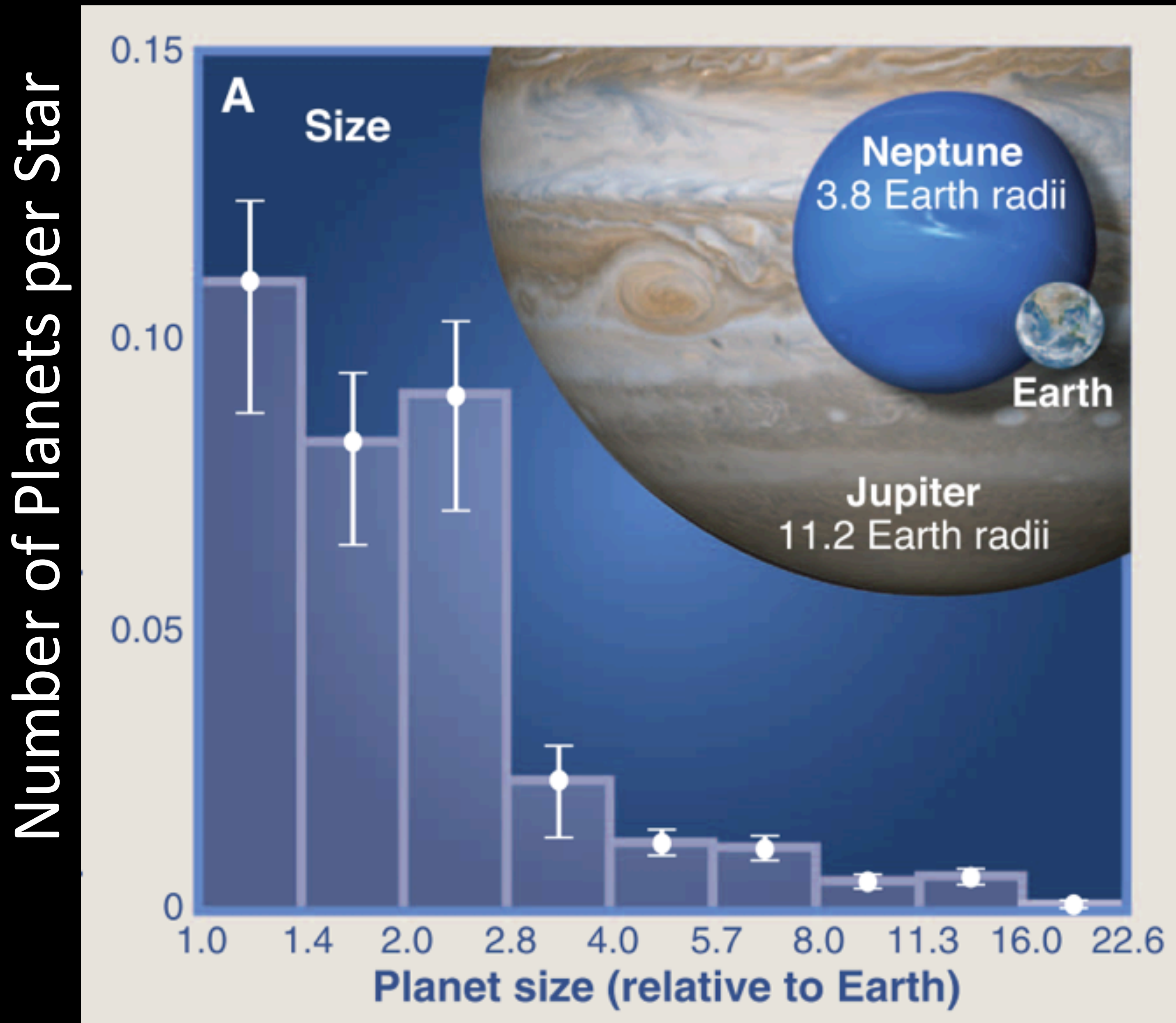
Image credit: NASA/Apollo 17

Our Solar System has Two Types of Planets



Not to scale

Planets 2-4x Larger than Earth are Common



Howard 2013, Science, 340, 572

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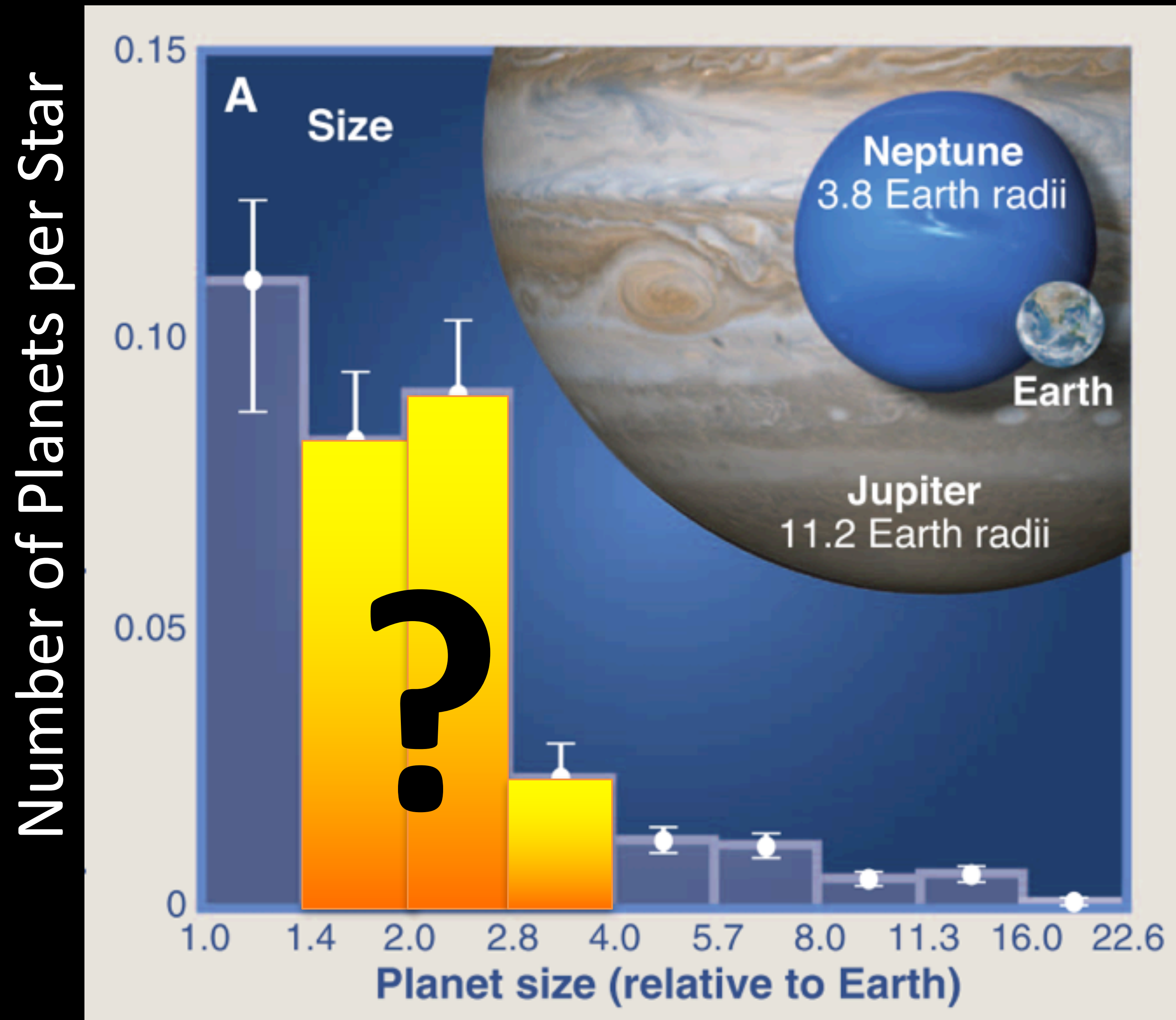
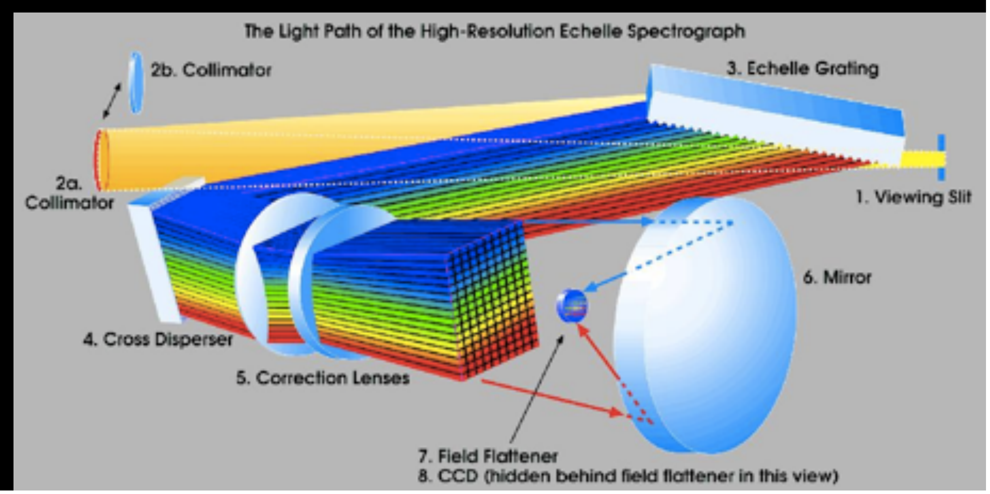


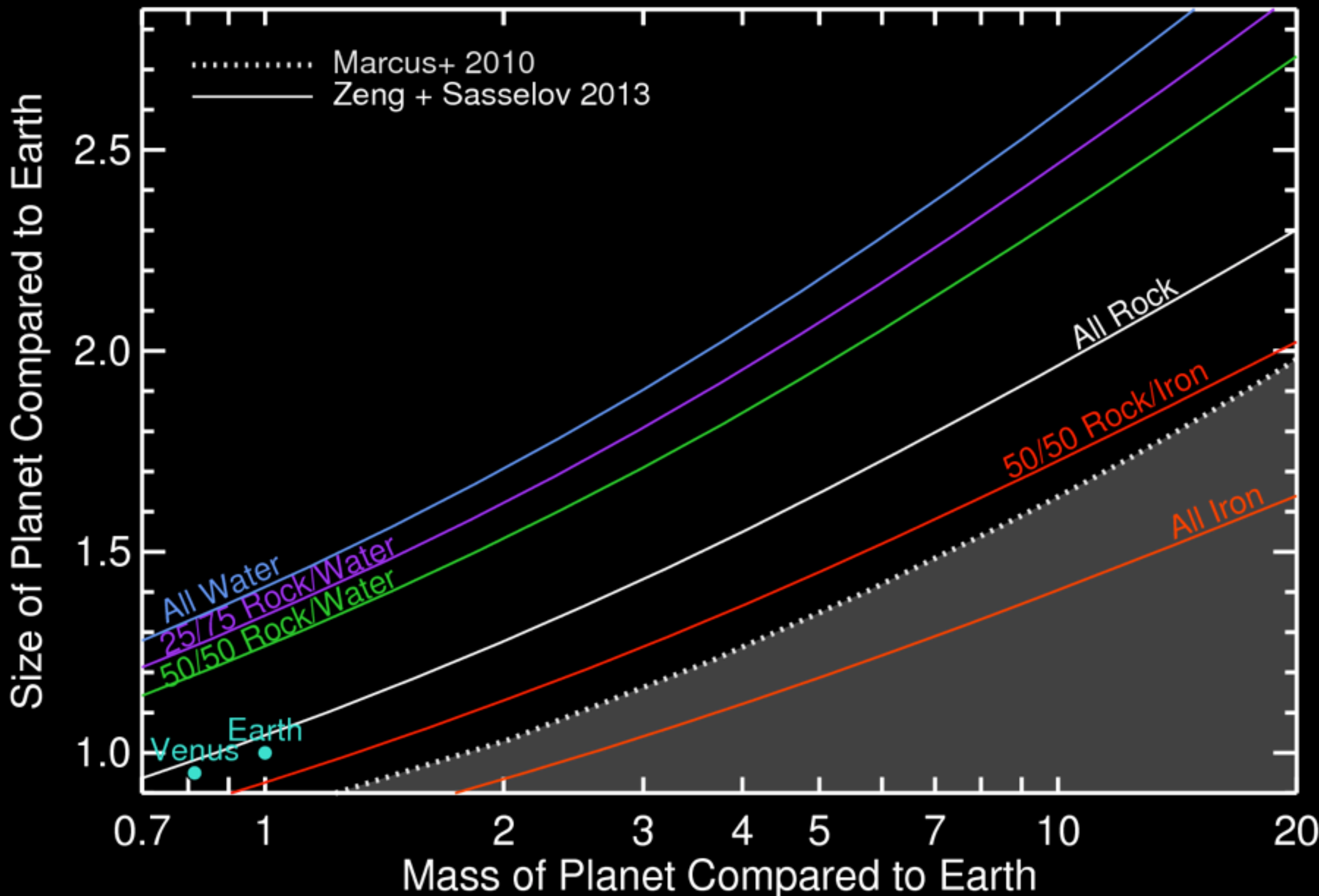
Howard 2013, Science, 340, 572

RV Observations of Transiting Planets Constrain the Densities of Small Worlds

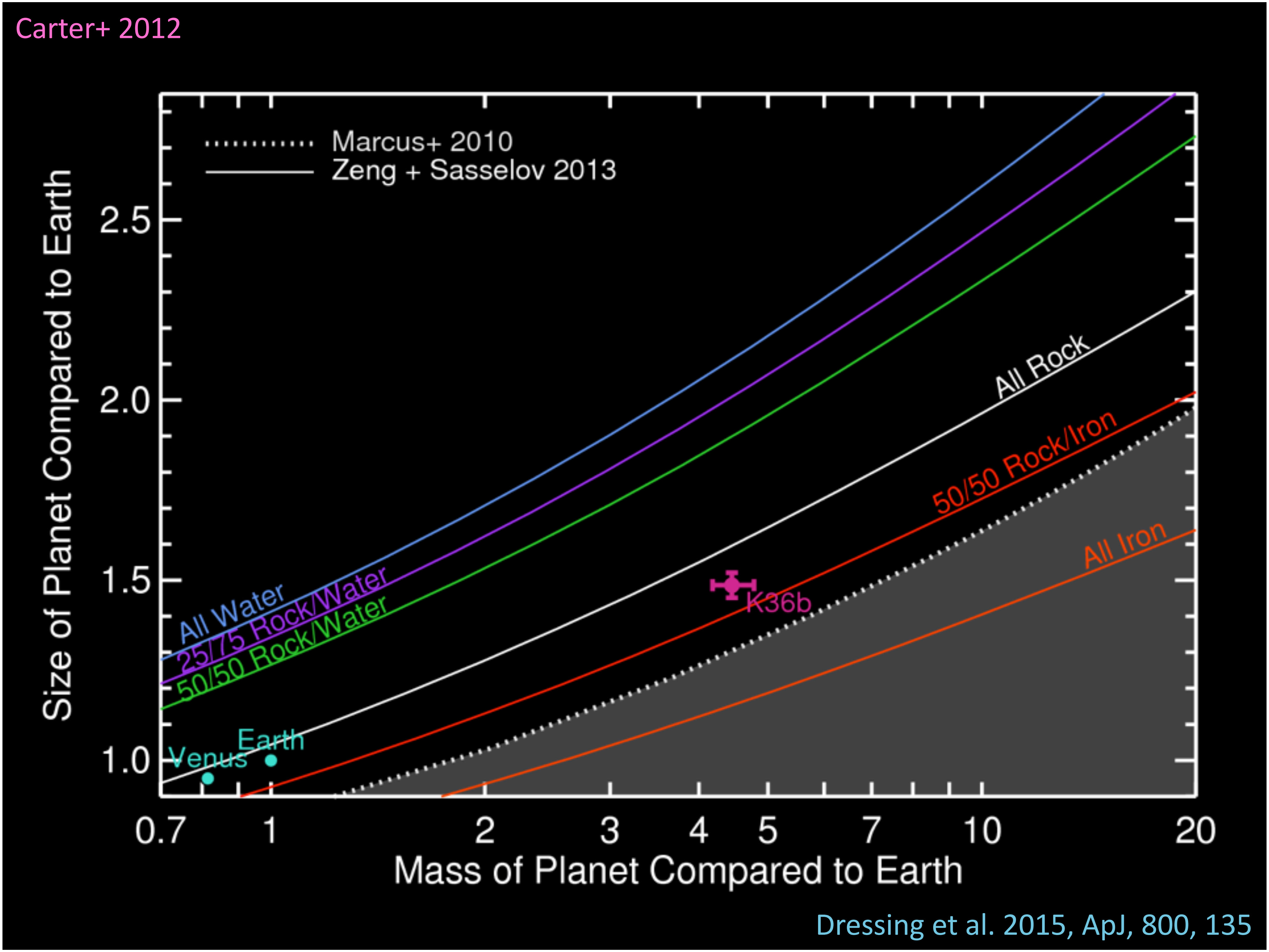
HARPS-N at TNG

HIRES at Keck





Dressing et al. 2015, ApJ, 800, 135


Carter+ 2012
Marcus+ 2010
Zeng + Sasselov 2013
All Water
25/75 Rock/Water
50/50 Rock/Water
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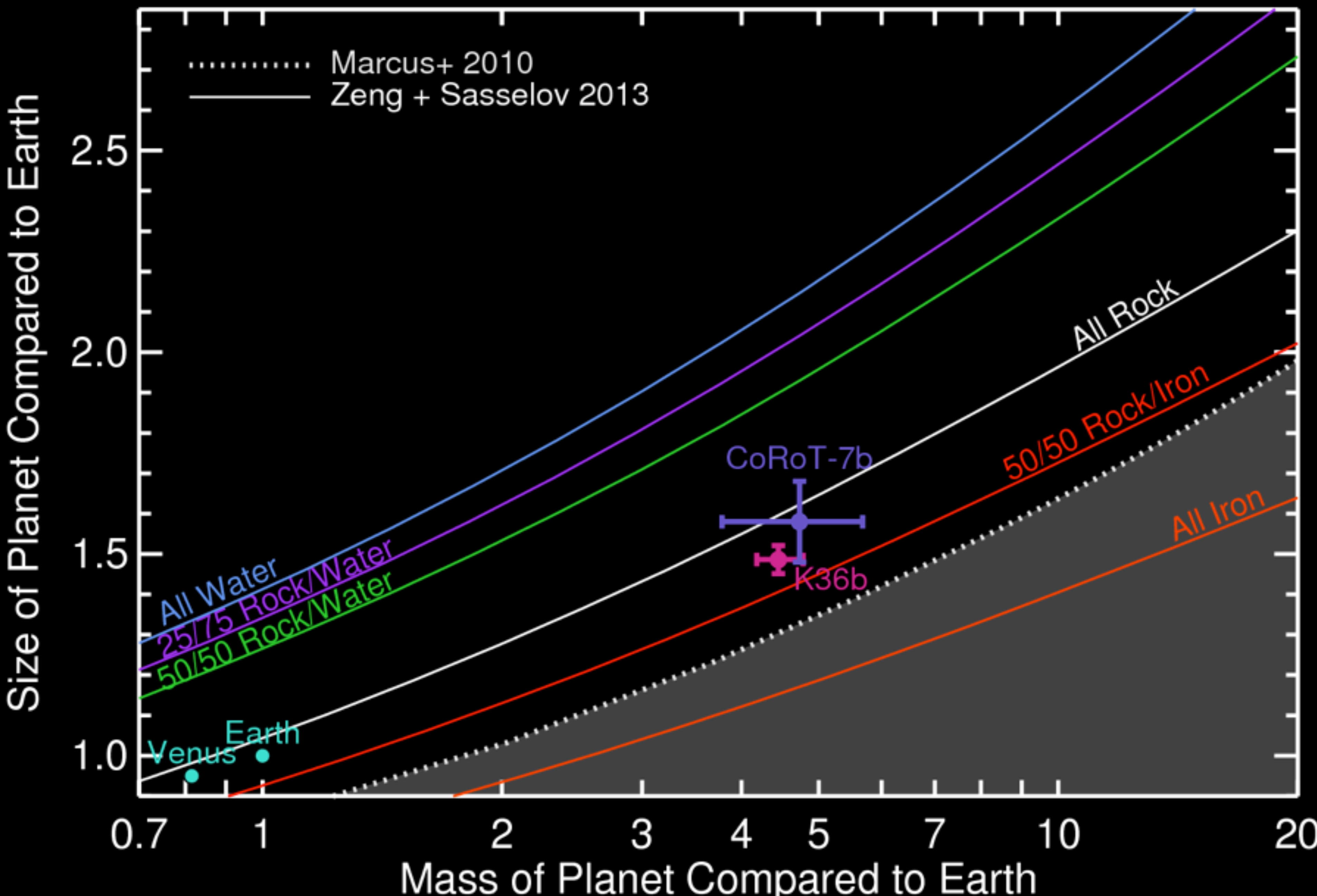
K36b
Venus
Earth
Size of Planet Compared to Earth
2.5
2.0
1.5
1.0
0.7
1
2
3
4
5
7
10
20
Mass of Planet Compared to Earth
Dressing et al. 2015, ApJ, 800, 135

Carter+ 2012, Barros+ 2014, Haywood+ 2014,



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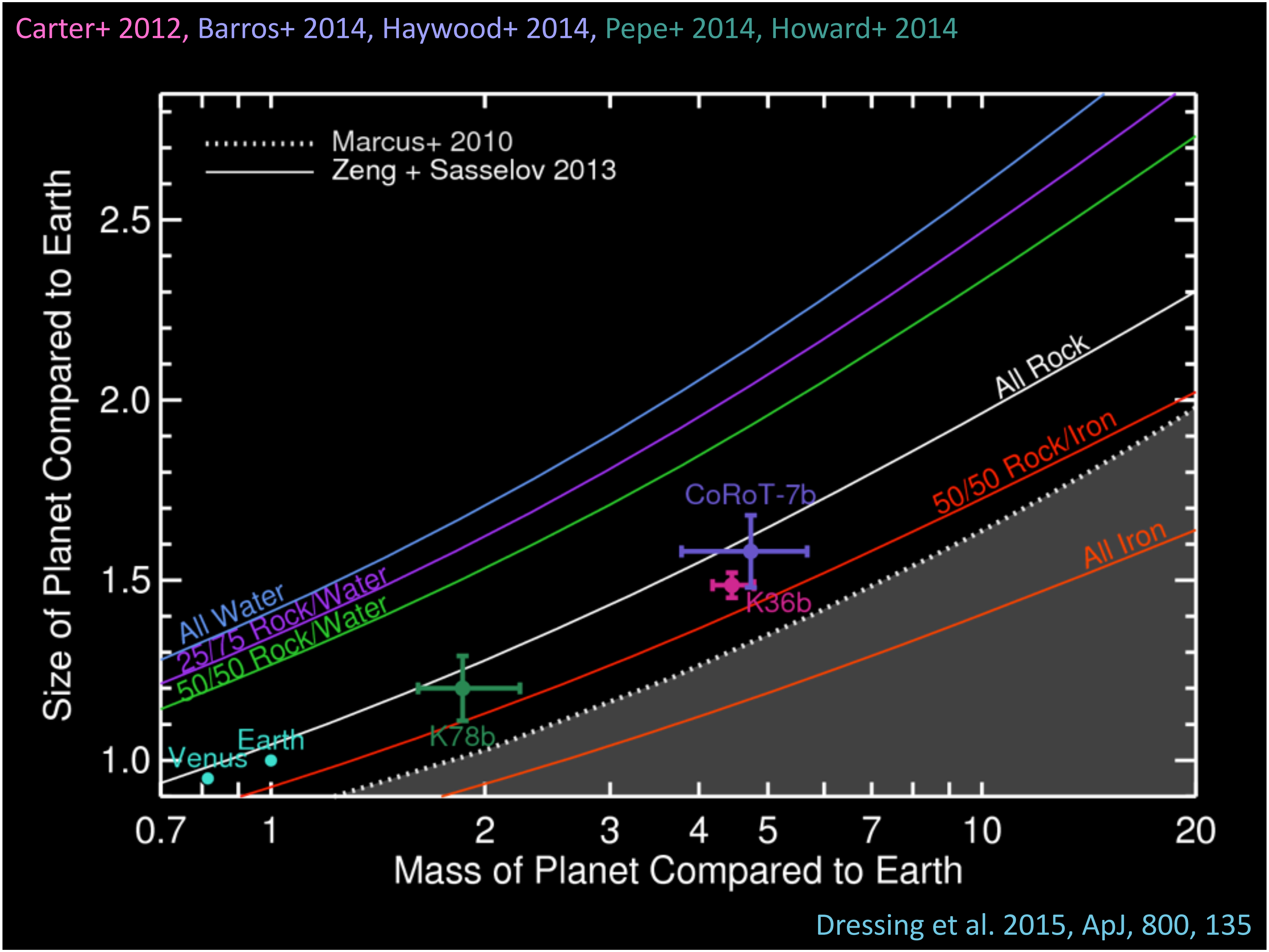
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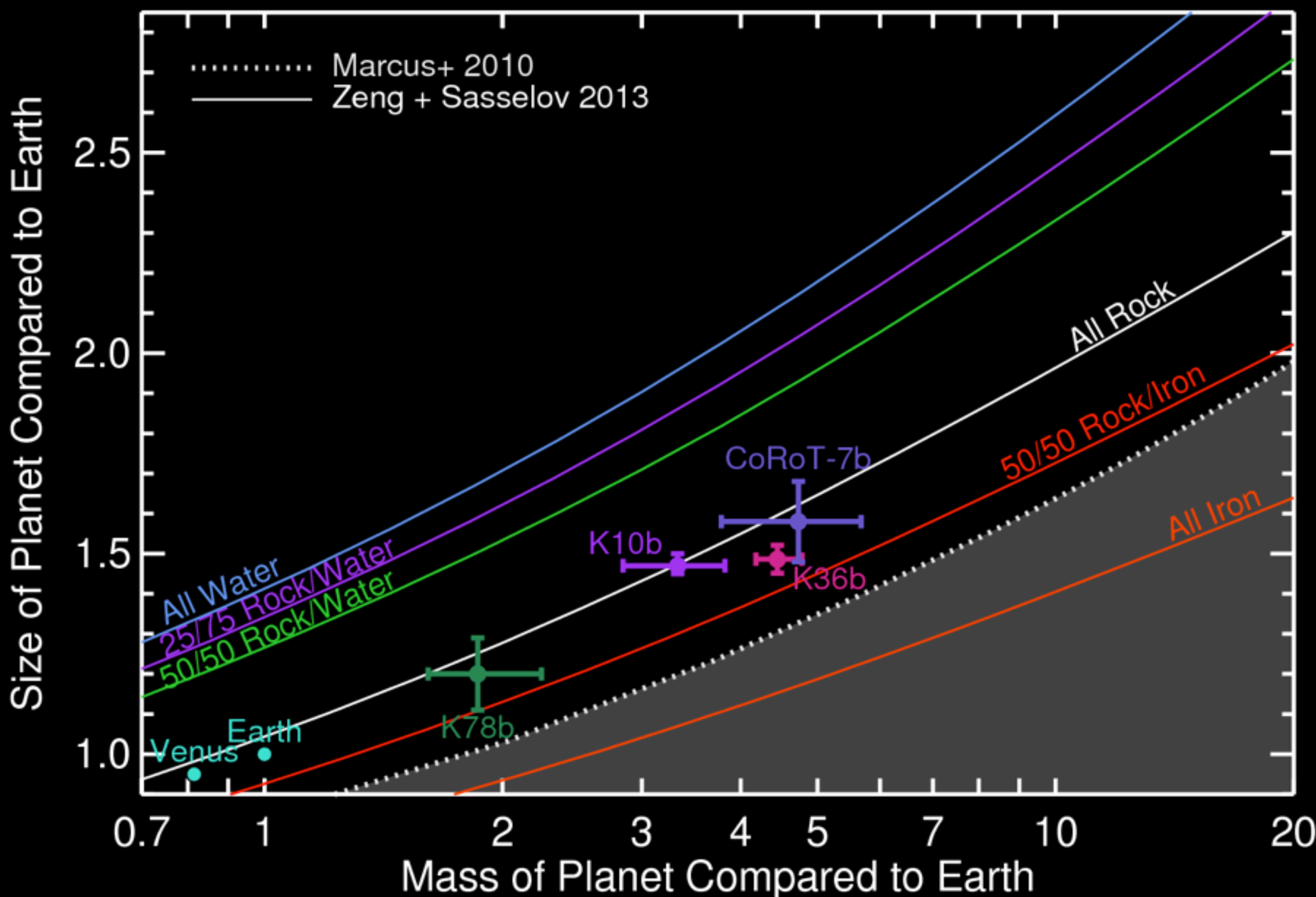

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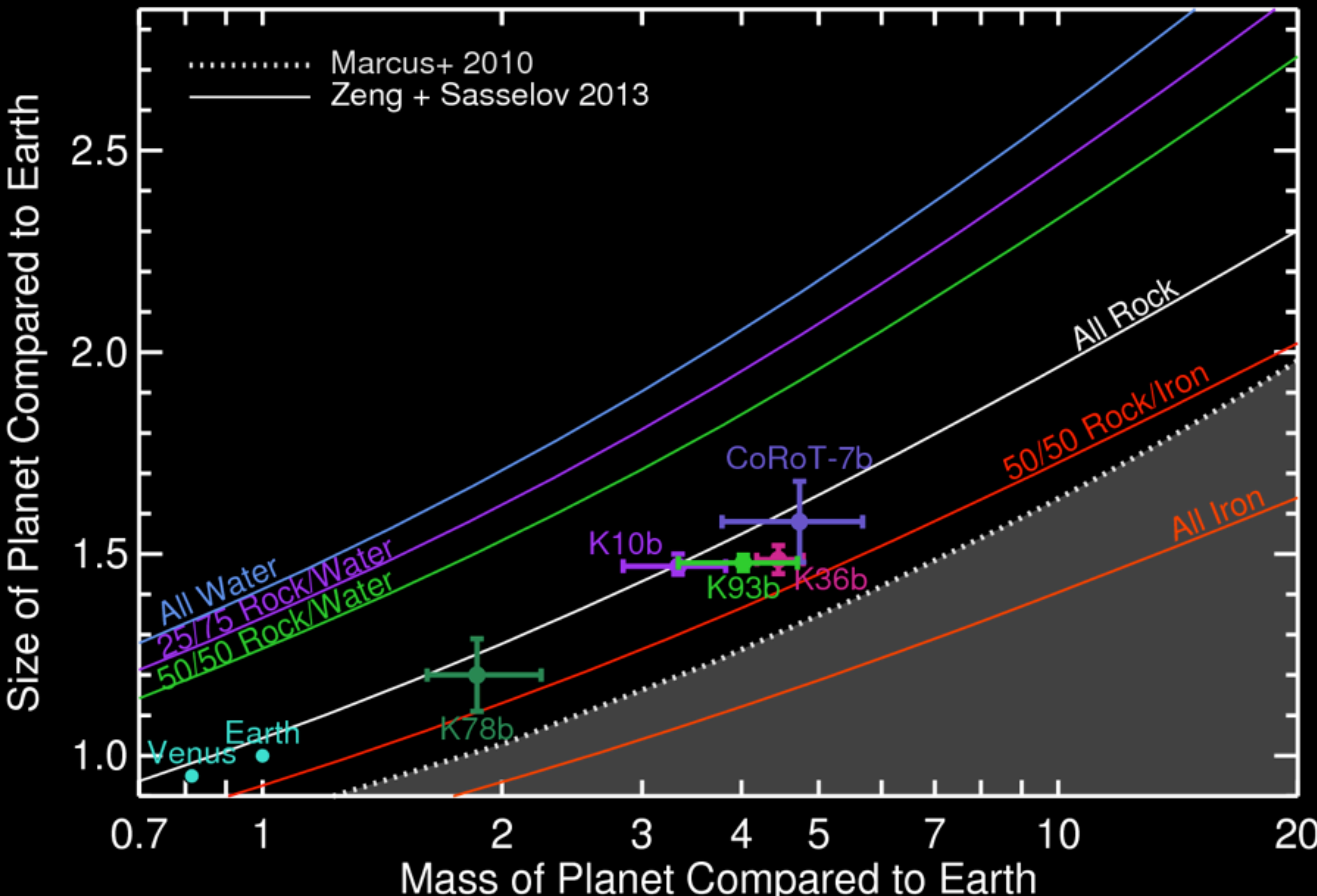

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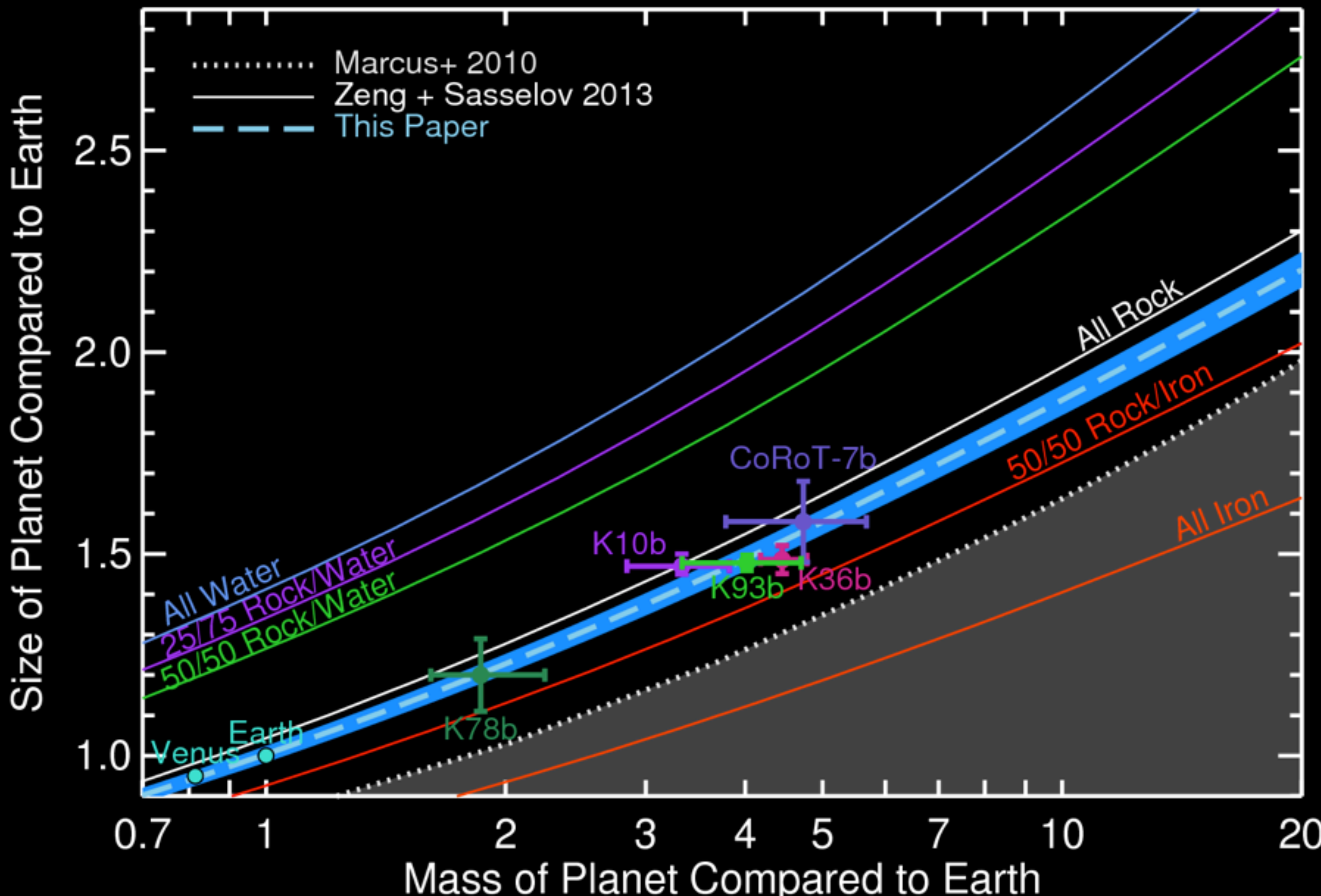

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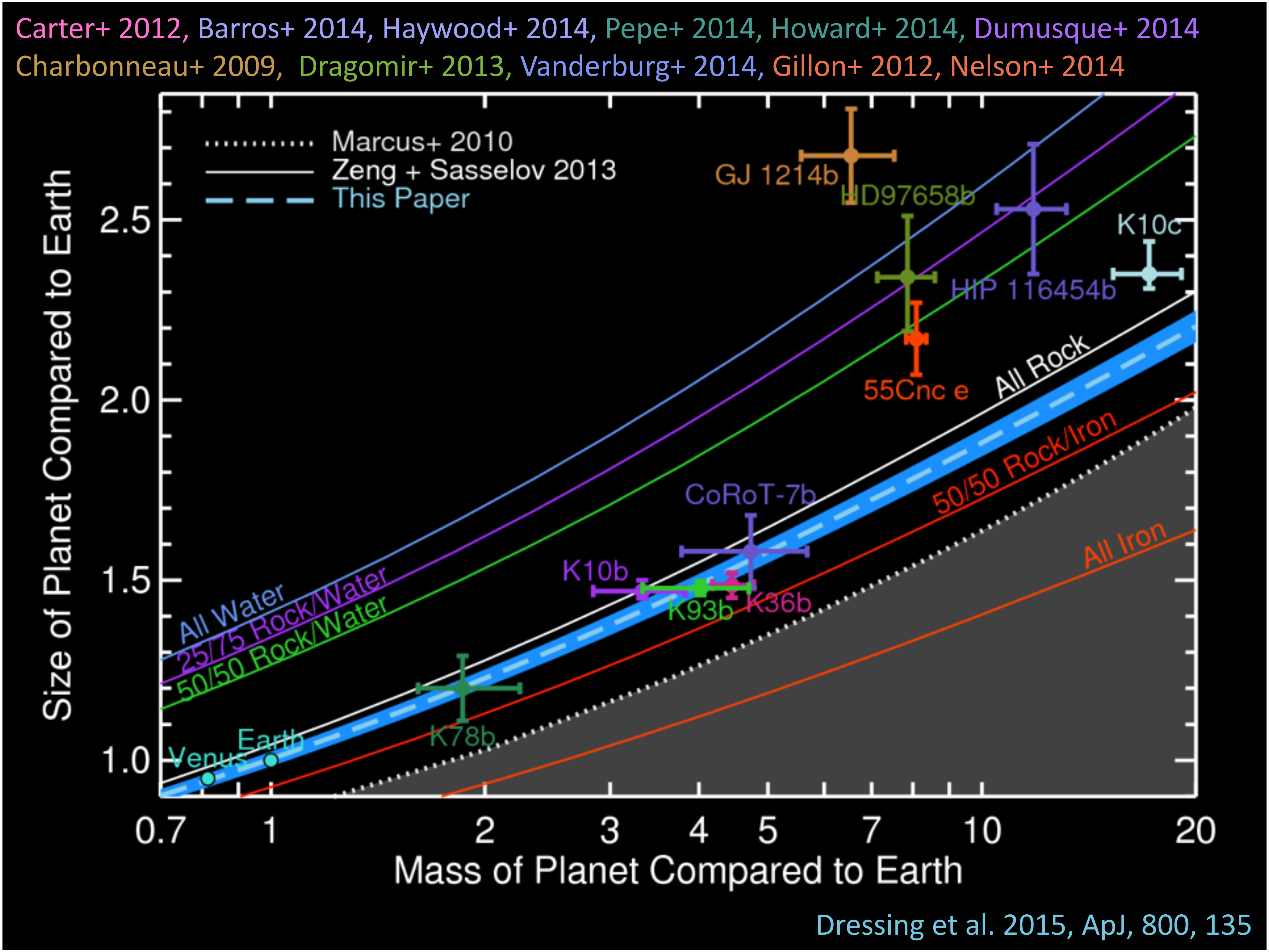

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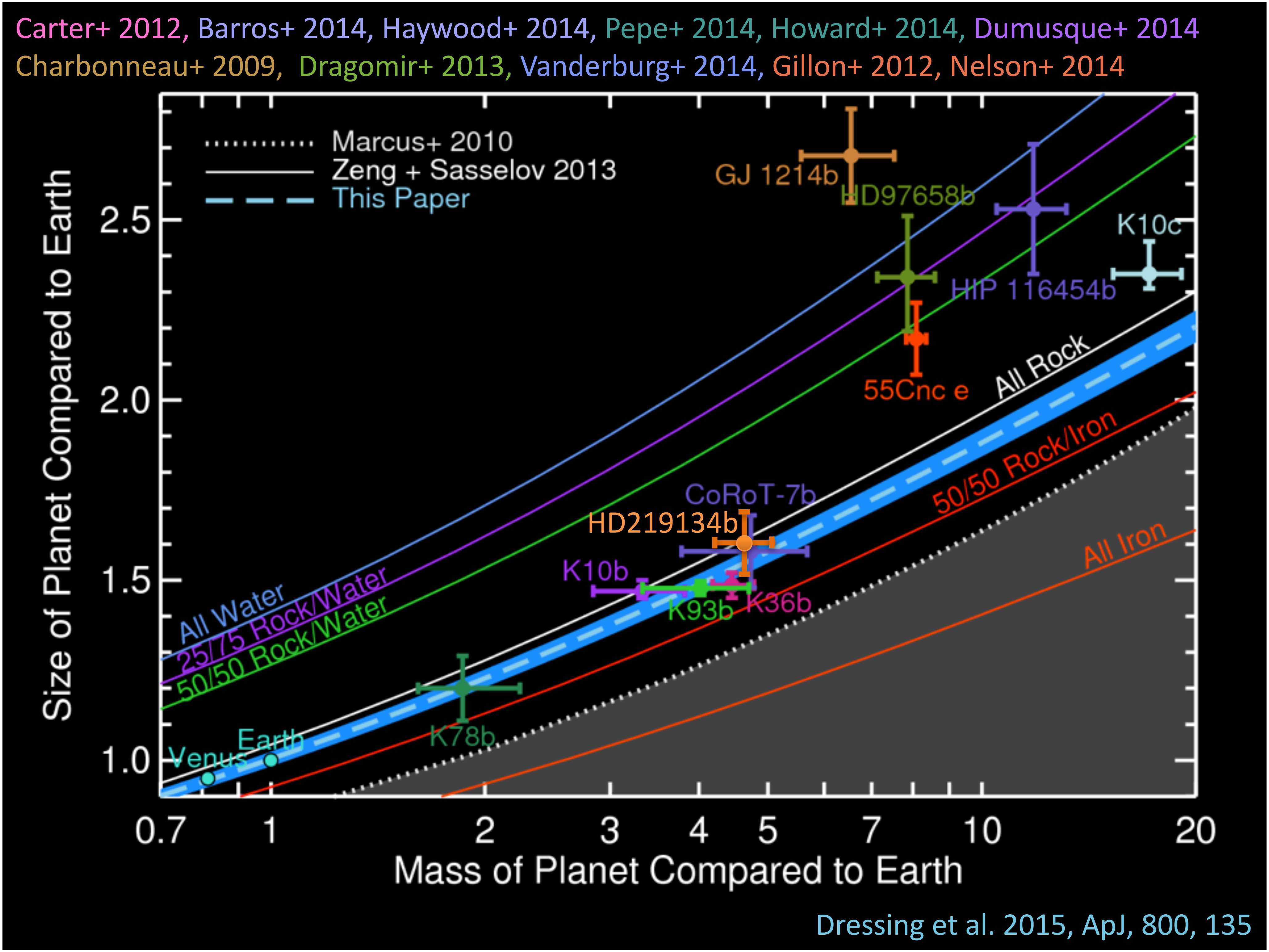

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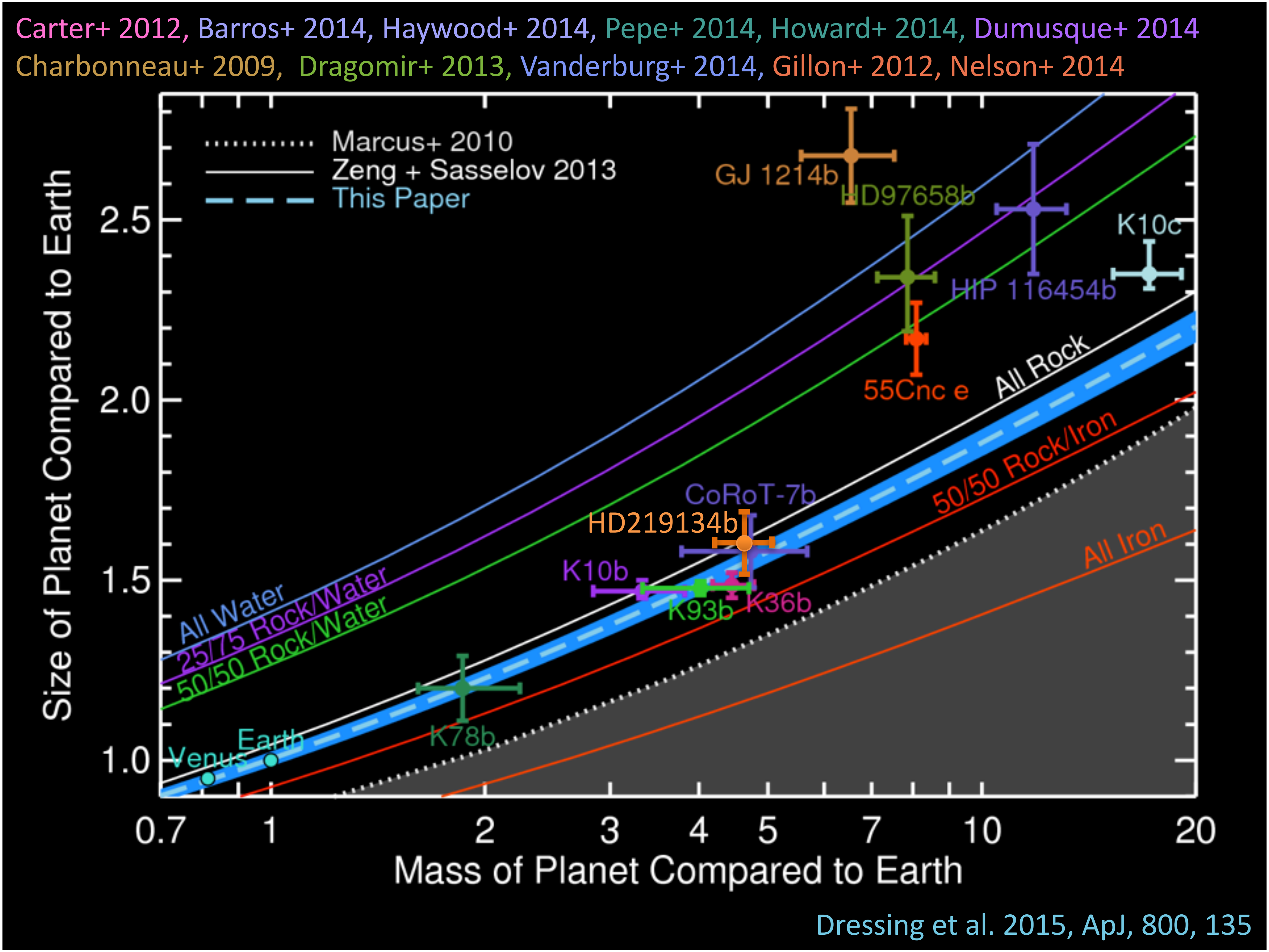

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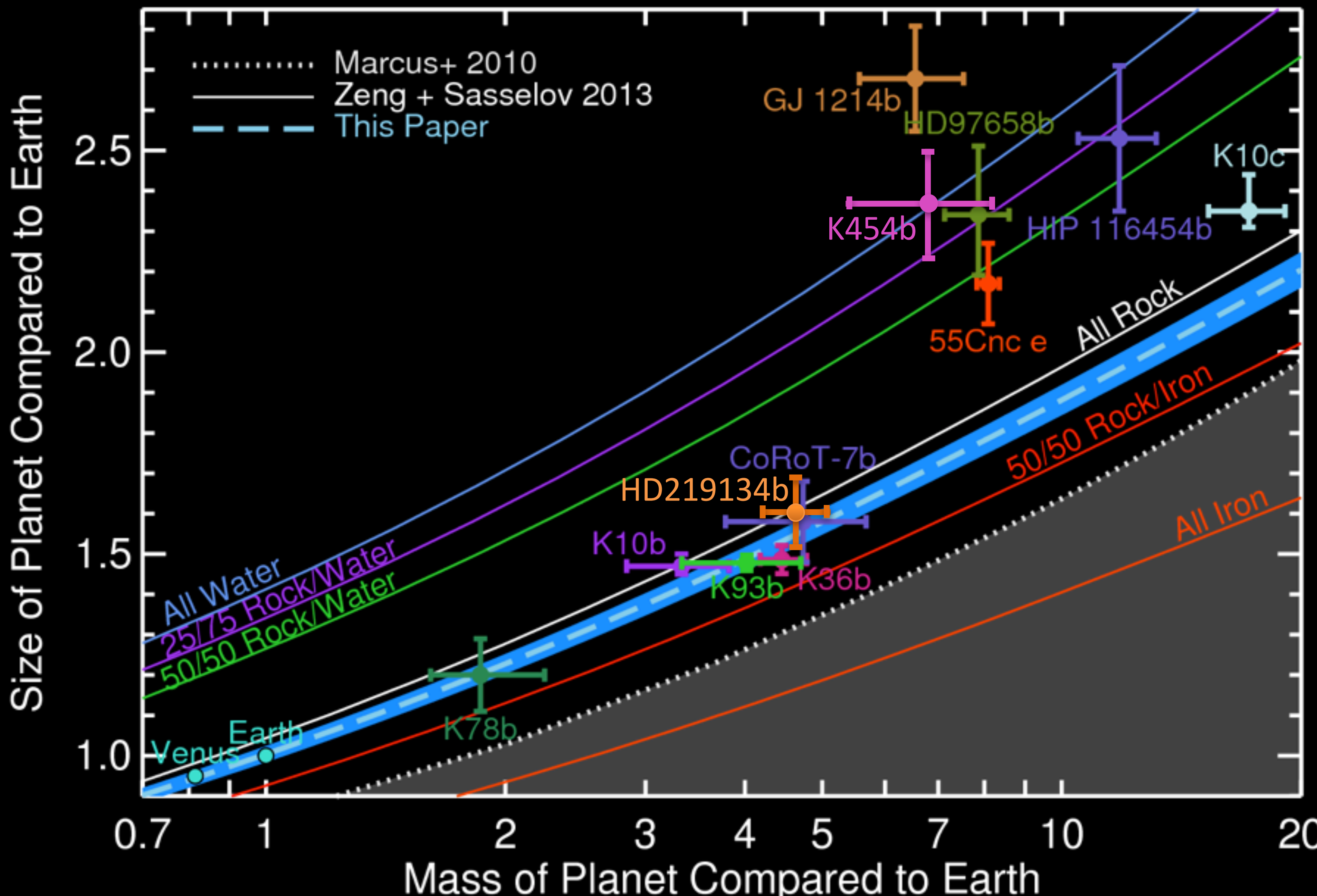

Dressing et al. 2015, ApJ, 800, 135

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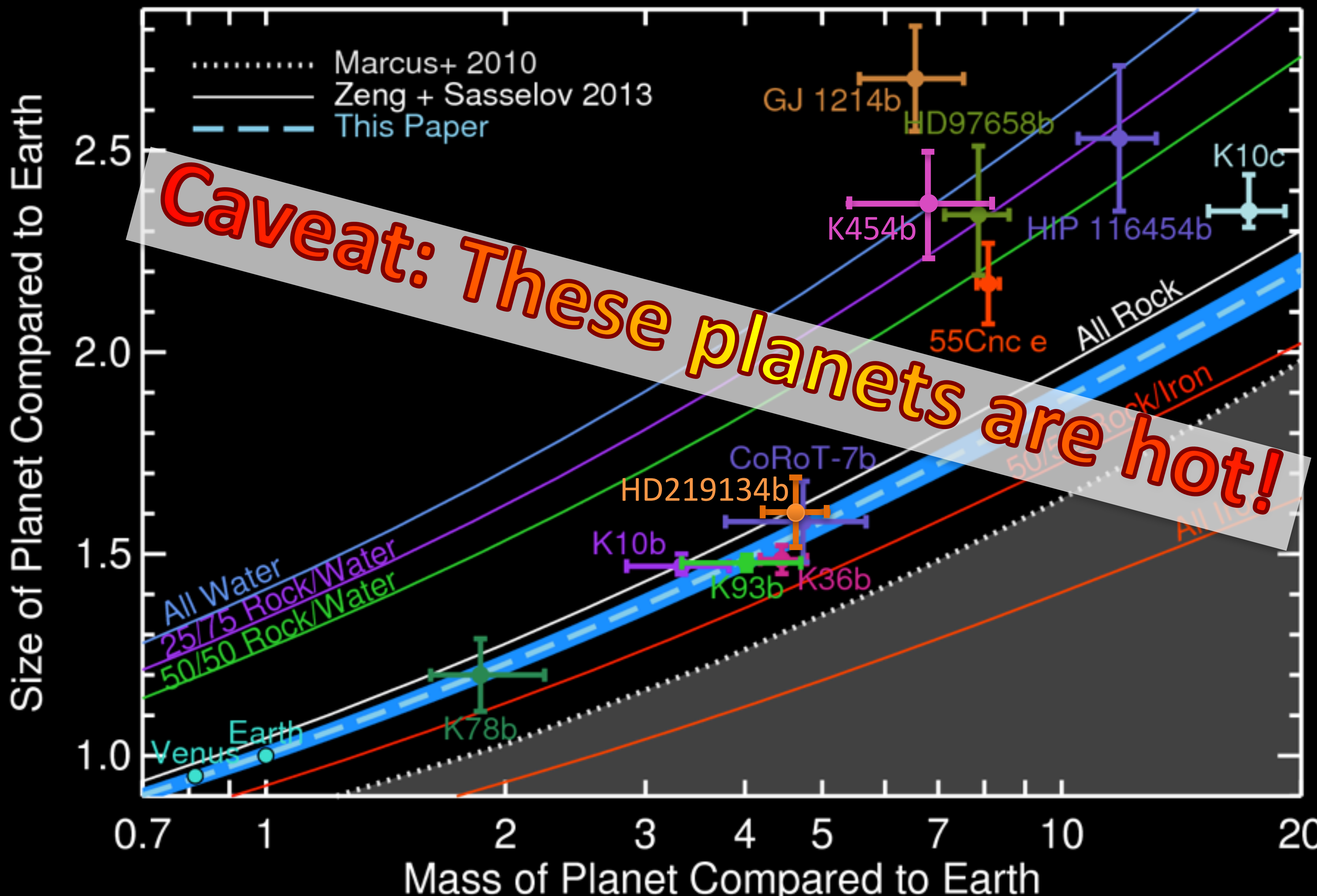
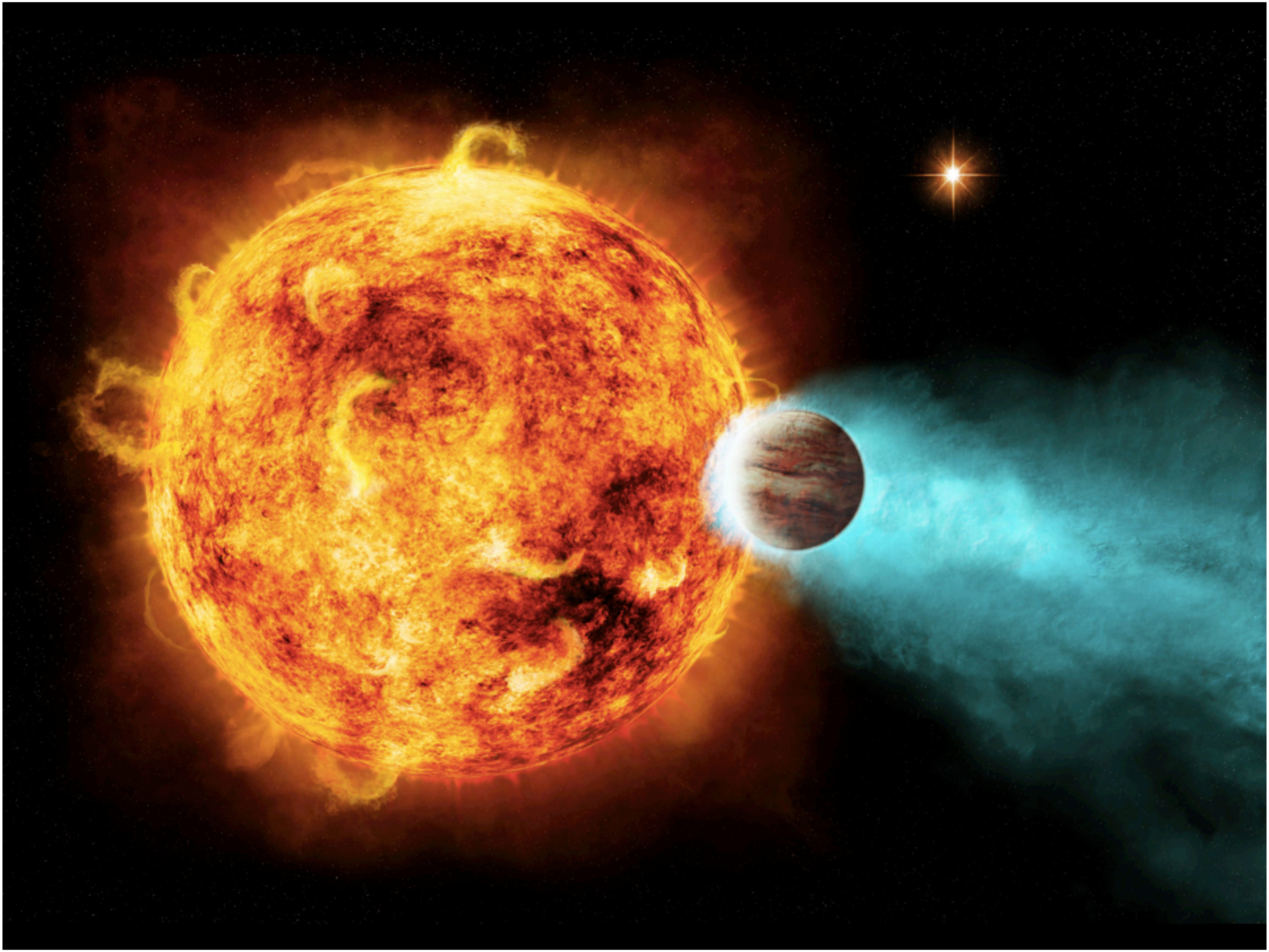


For cooler planets, see Weiss et al. 2013;
Weiss & Marcy 2014; Rogers 2015; Wolfgang & Lopez 2015

Dressing et al. 2015, ApJ, 800, 135



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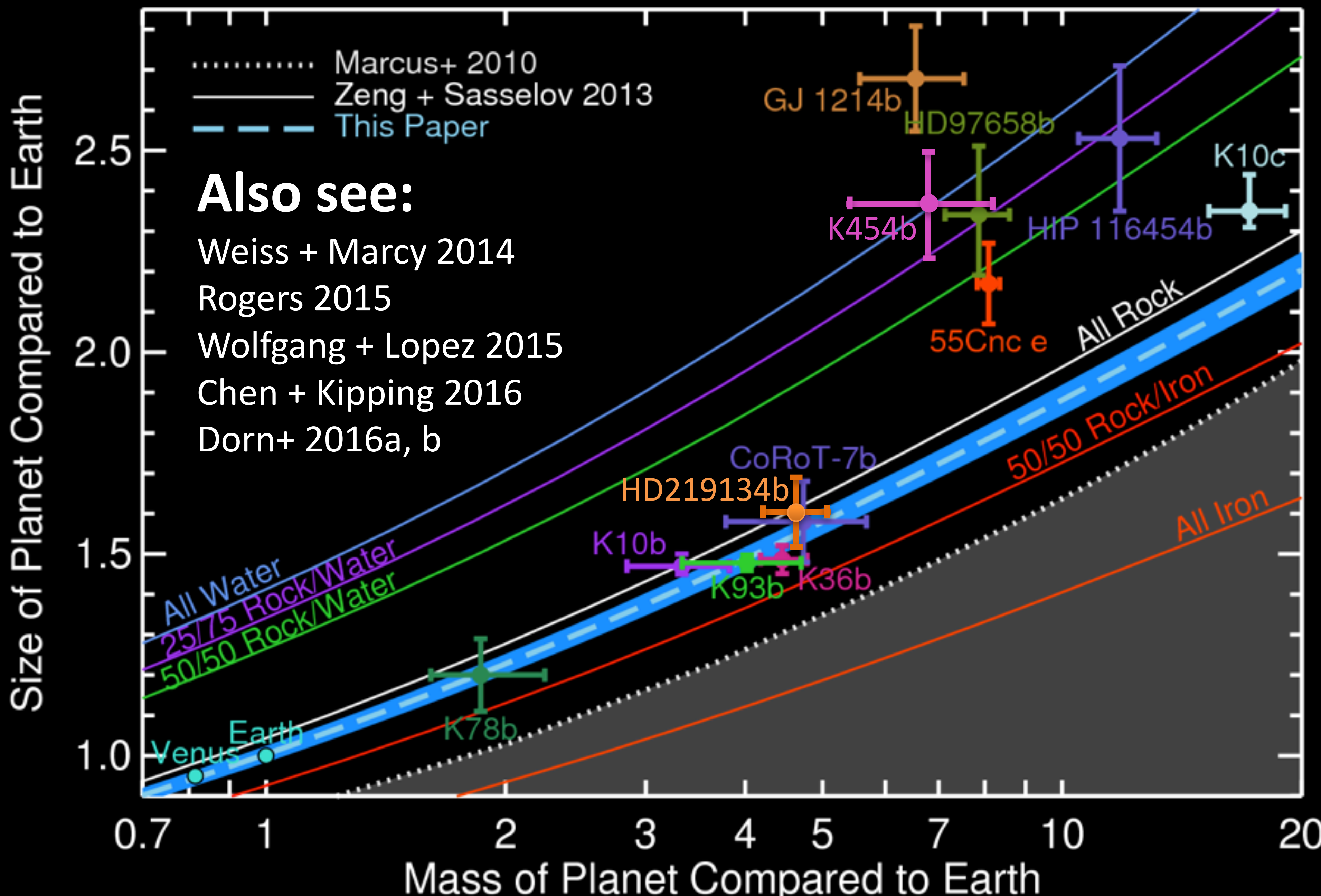
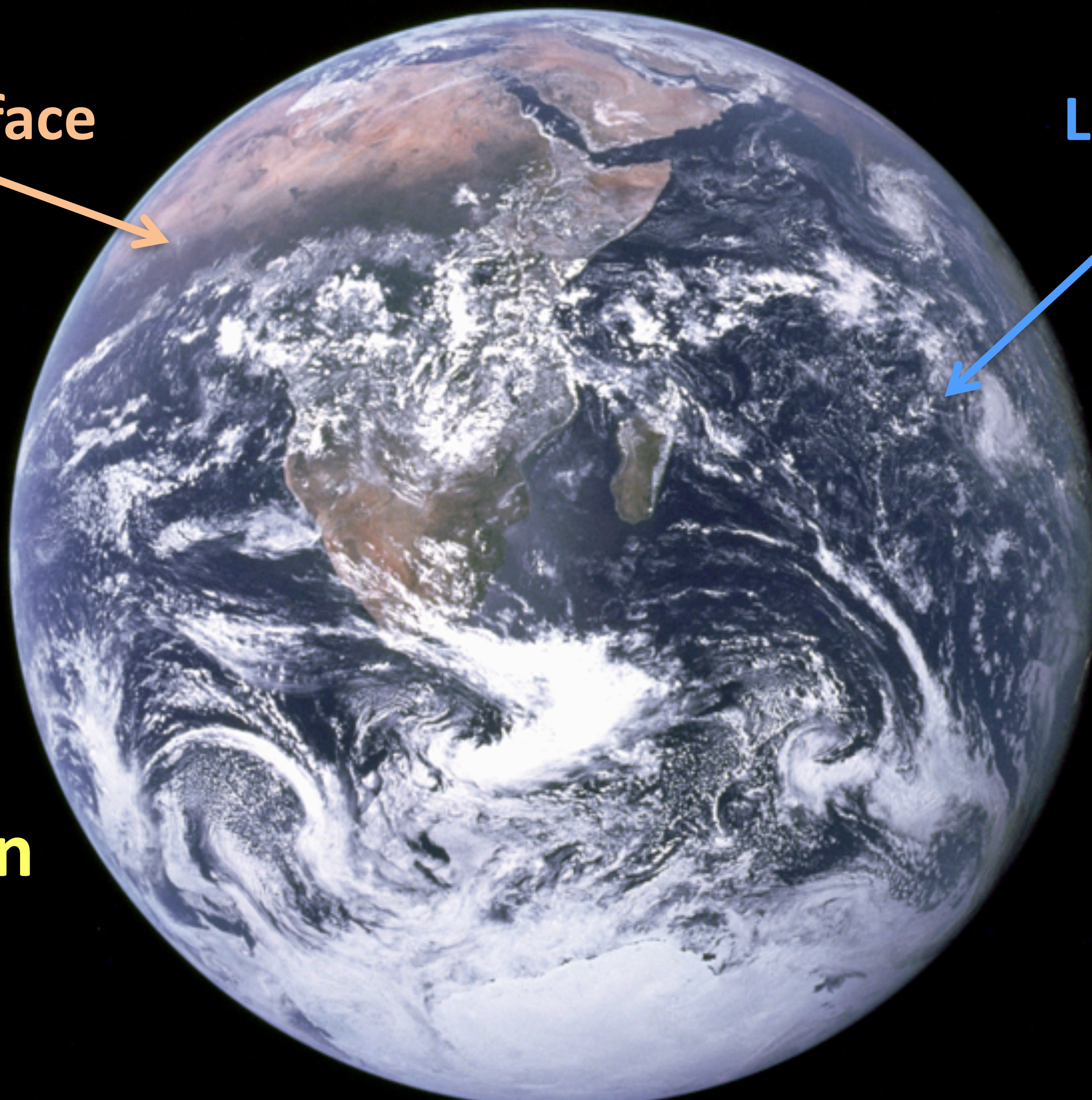


Dressing et al. 2015, ApJ, 800, 135

Are any of these planets habitable?

Rocky Surface

Liquid Water



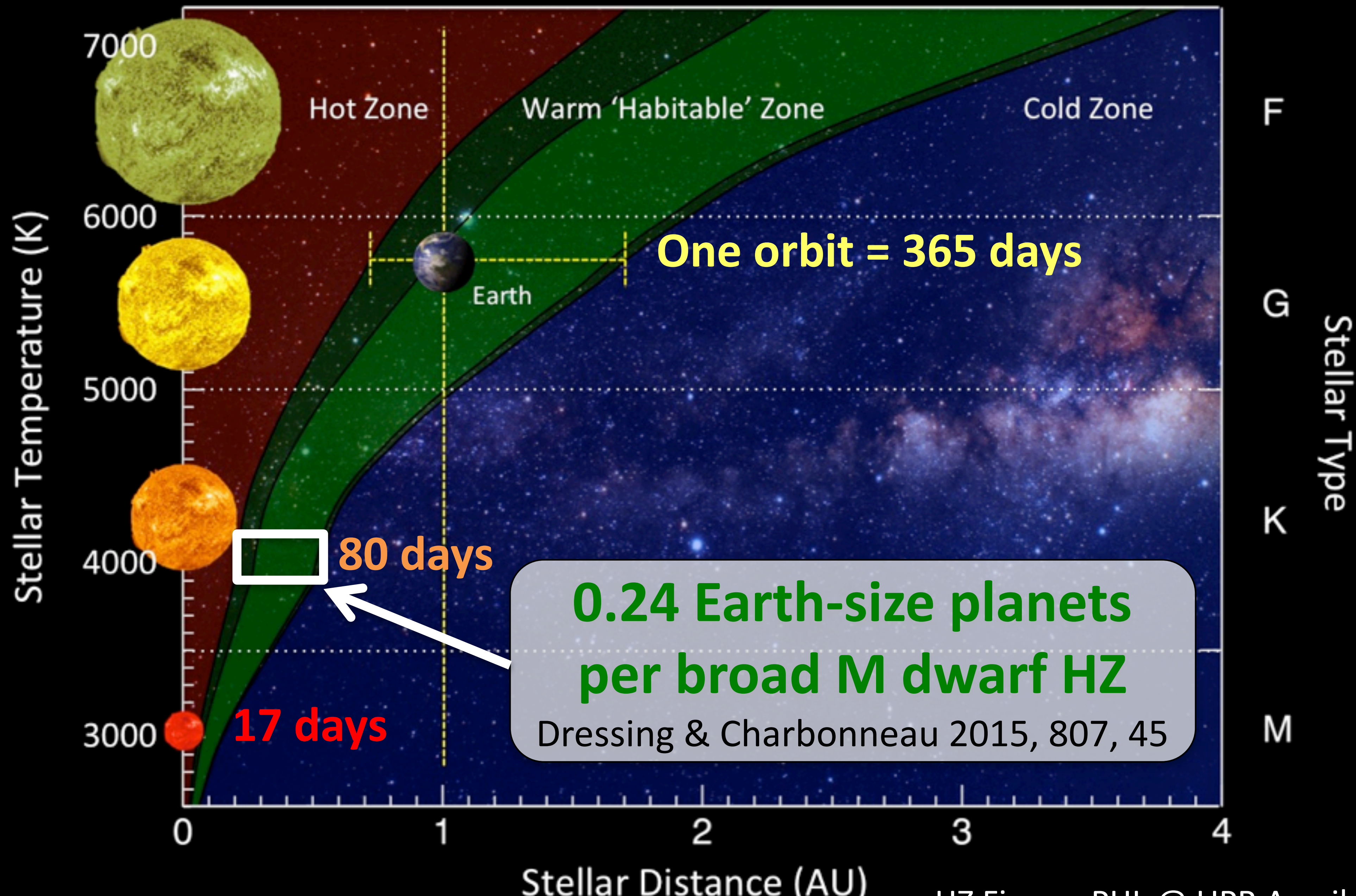
Is there an upper limit on the size of a rocky planet?

Look for planets **smaller than 1.7 Earth Radii**

Look for planets with **temperate climates**

Image credit: NASA/Apollo 17

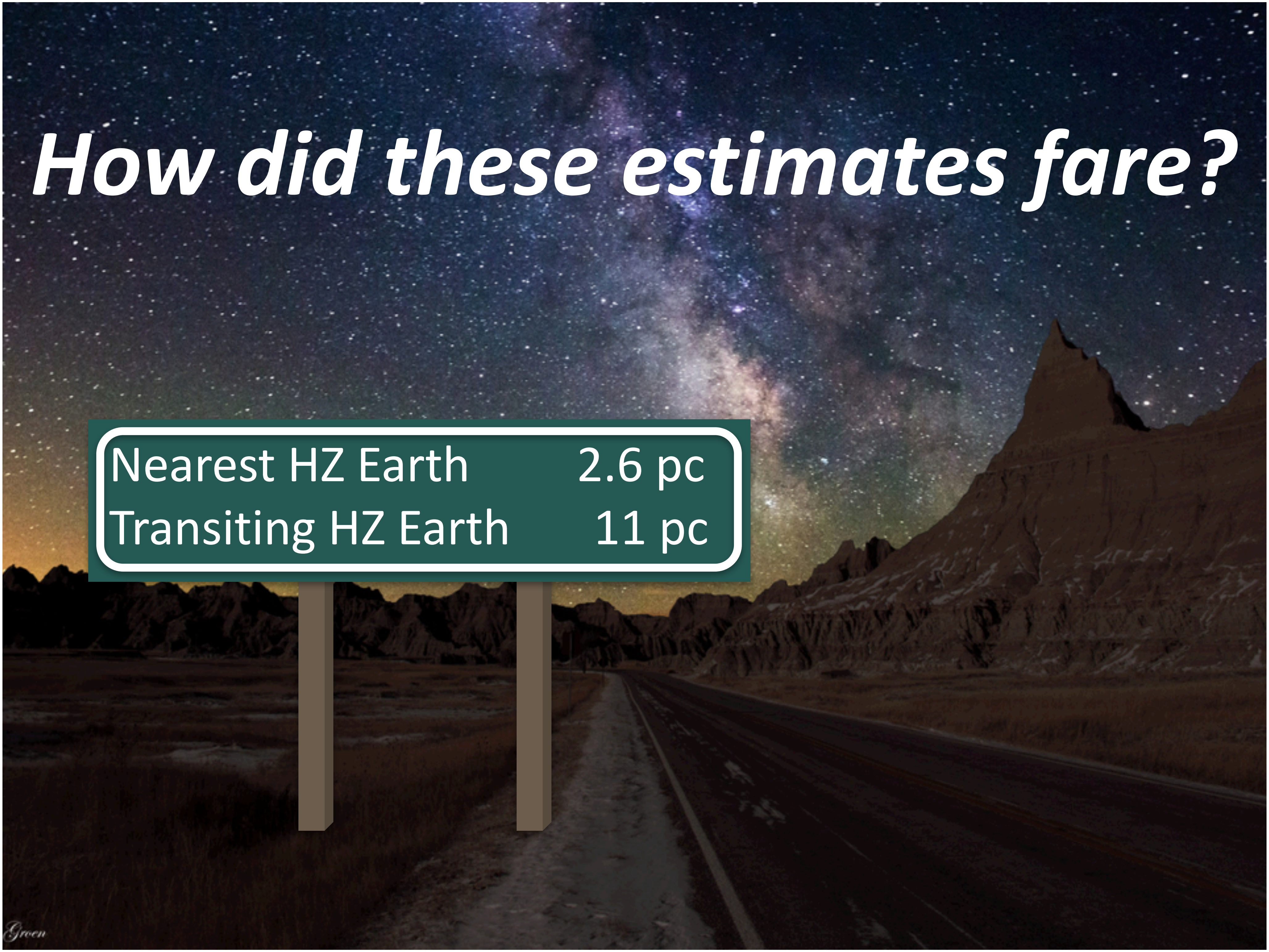
Likely Locations of Habitable Worlds



HZ Figure: PHL @ UPR Arecibo


Nearest HZ Earth 2.6 pc
Transiting HZ Earth 11 pc
Groen

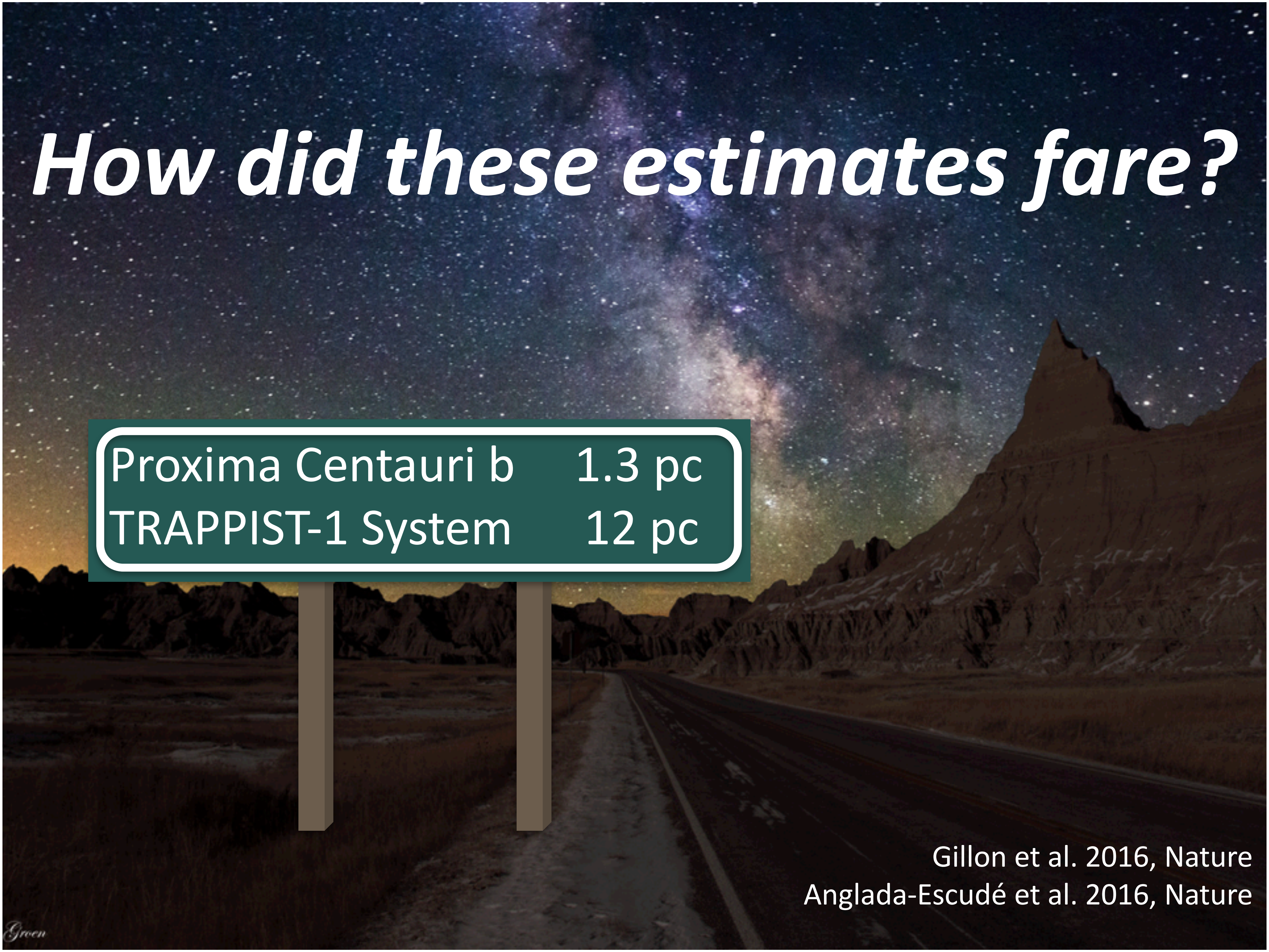
How did these estimates fare?



How did these estimates fare?

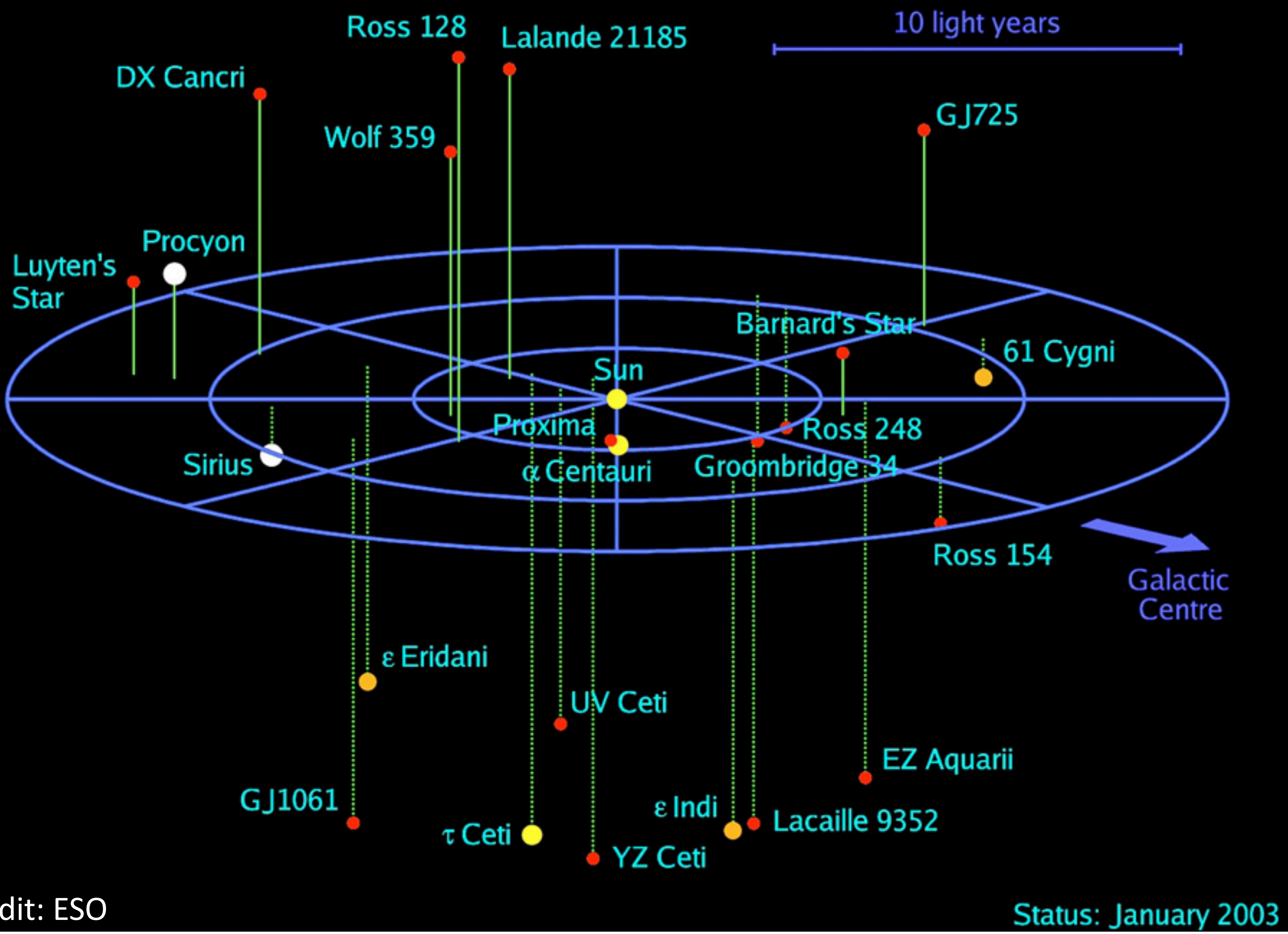
Gillon et al. 2016, Nature

How did these estimates fare?

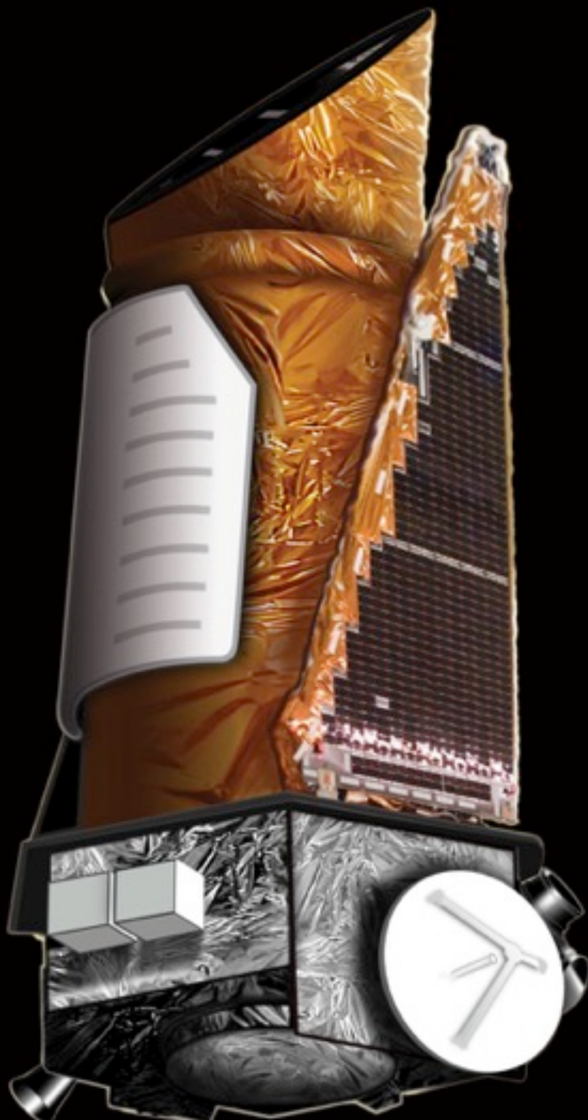


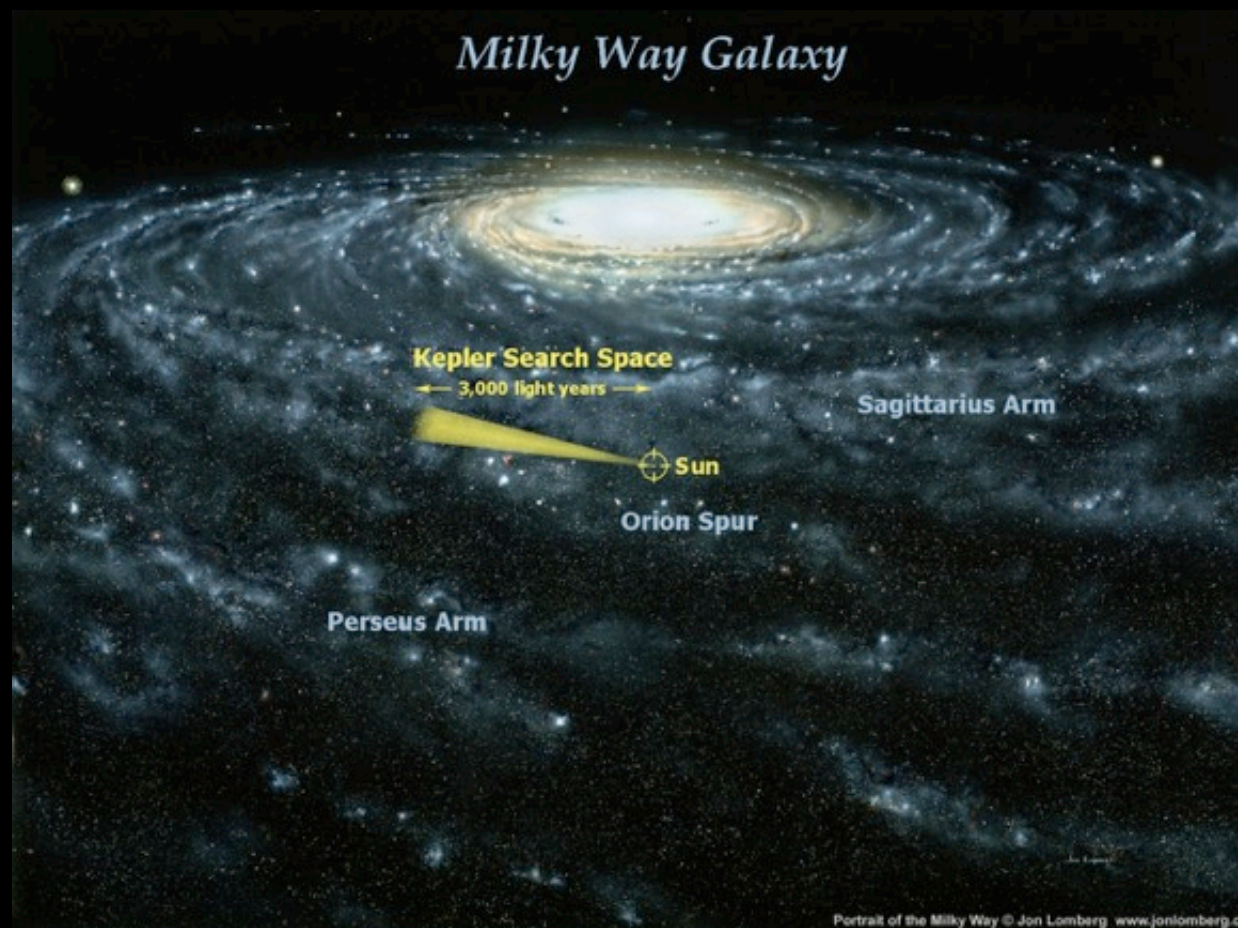
Gillon et al. 2016, Nature
Anglada-Escudé et al. 2016, Nature

Do our other neighbors host potentially habitable planets?



Credit: ESO

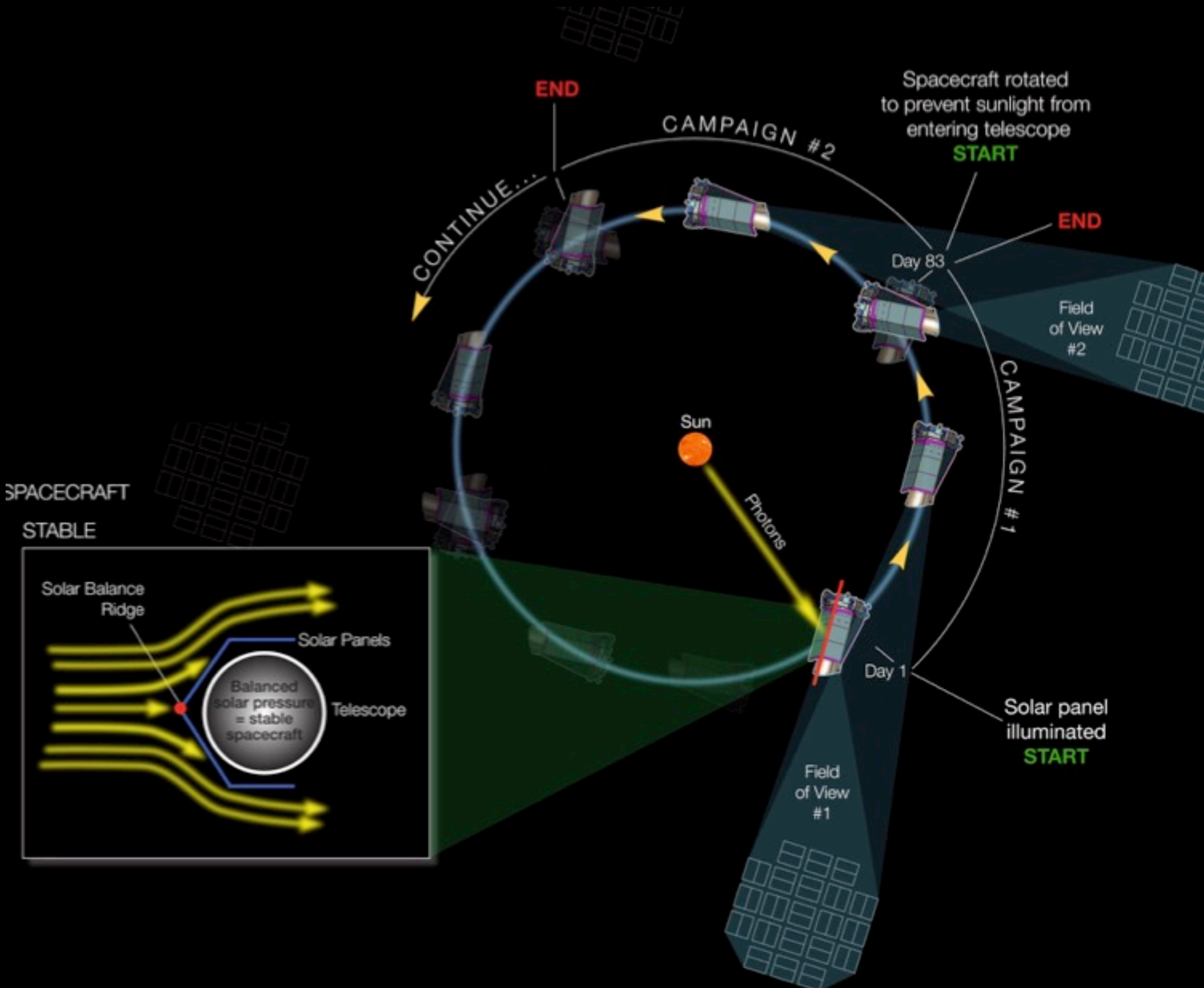




Credit: NASA/*Kepler* mission

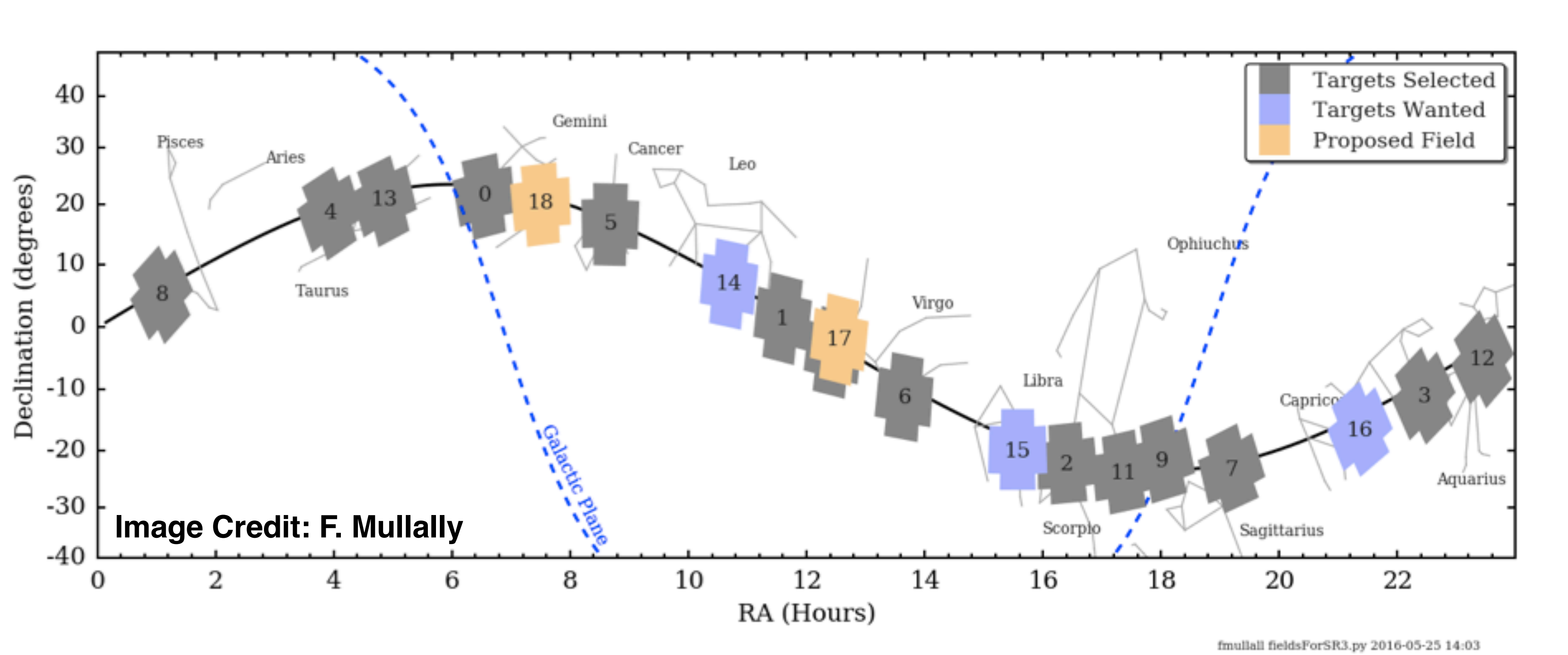
Credit: NASA/*Kepler* mission

Each K2 Campaign Lasts Roughly 80 Days

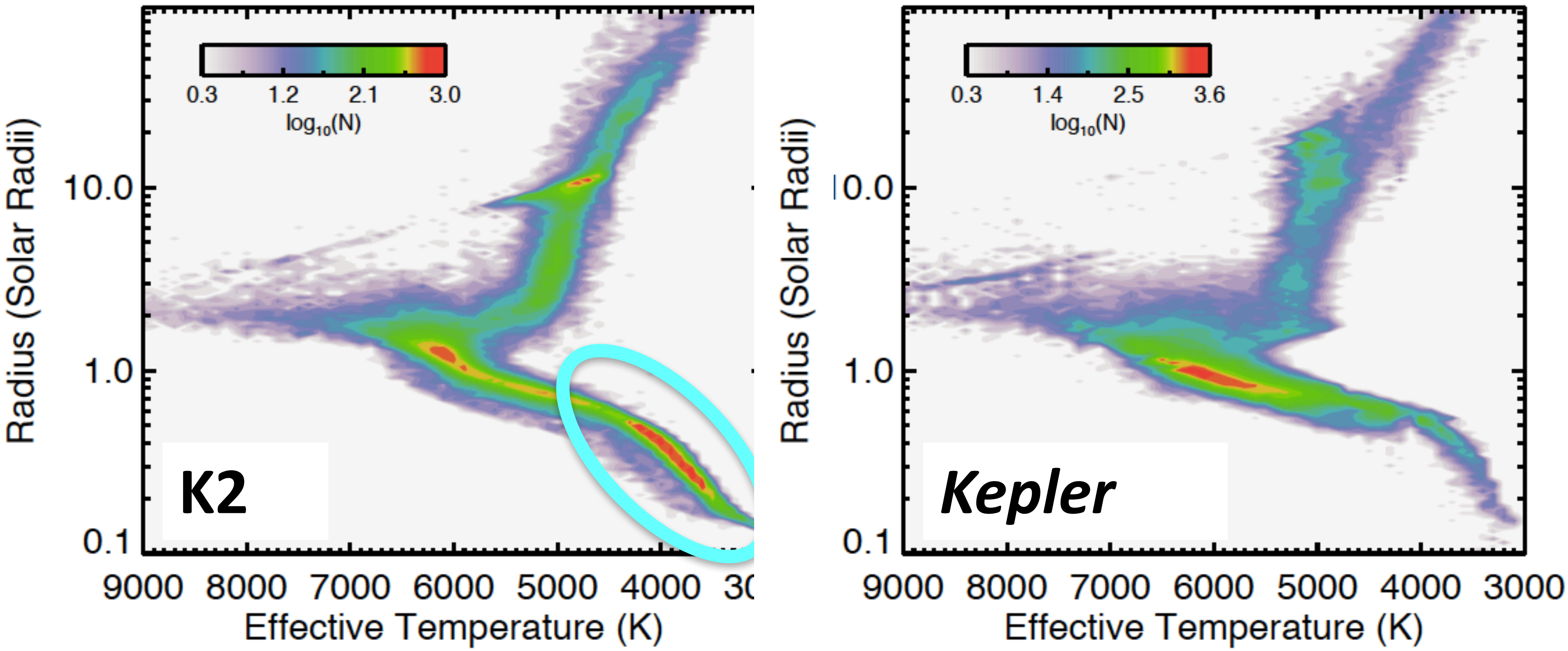


http://www.nasa.gov/kepler/keplers-second-light-how-k2-will-work

Where is K2 Looking?



K2 is Observing Many Small Stars



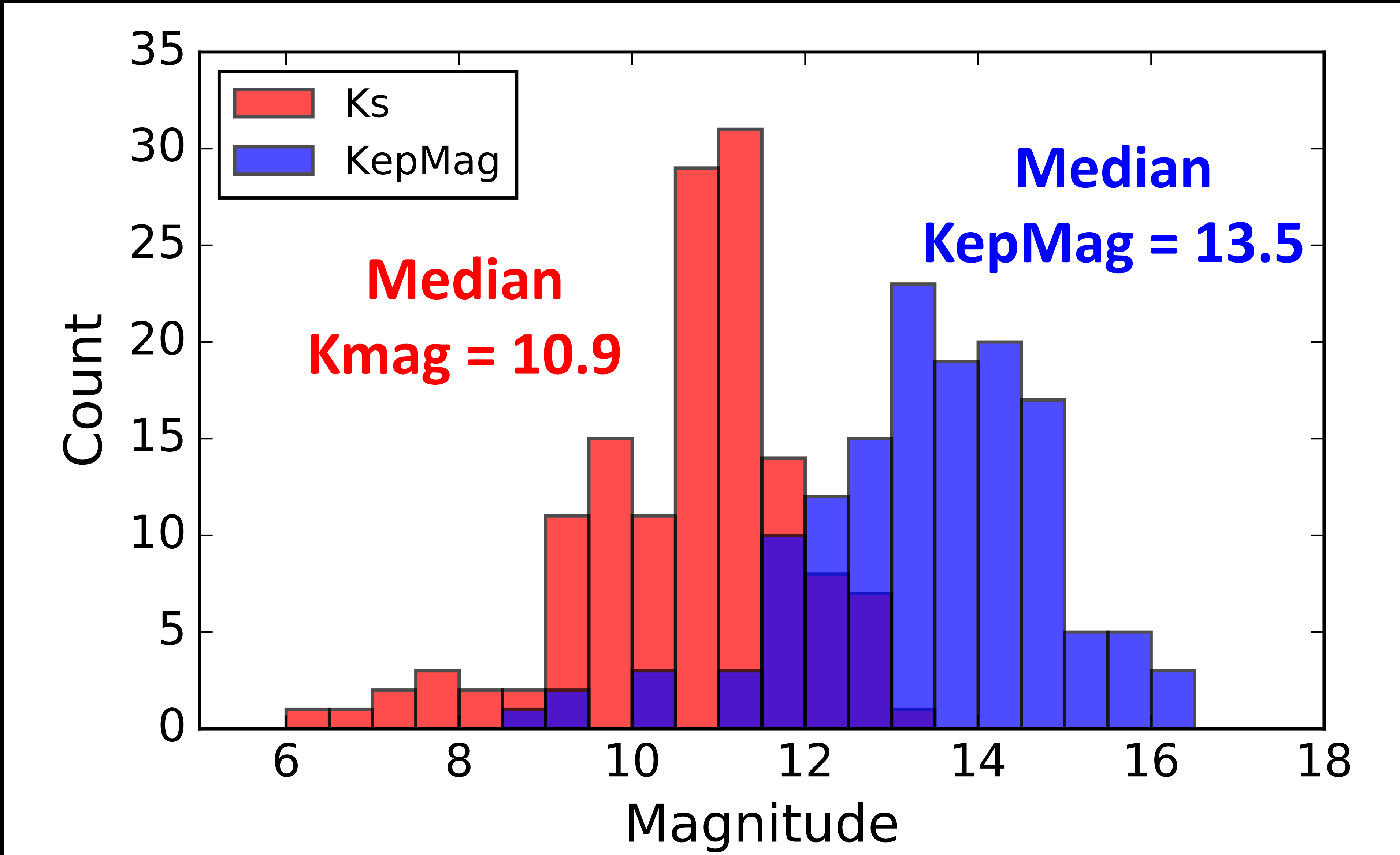
41% of selected K2 targets are K and M dwarfs

Huber et al. 2016, ApJS, 224, 2

Near-Infrared Spectroscopy Enables Host Star Characterization

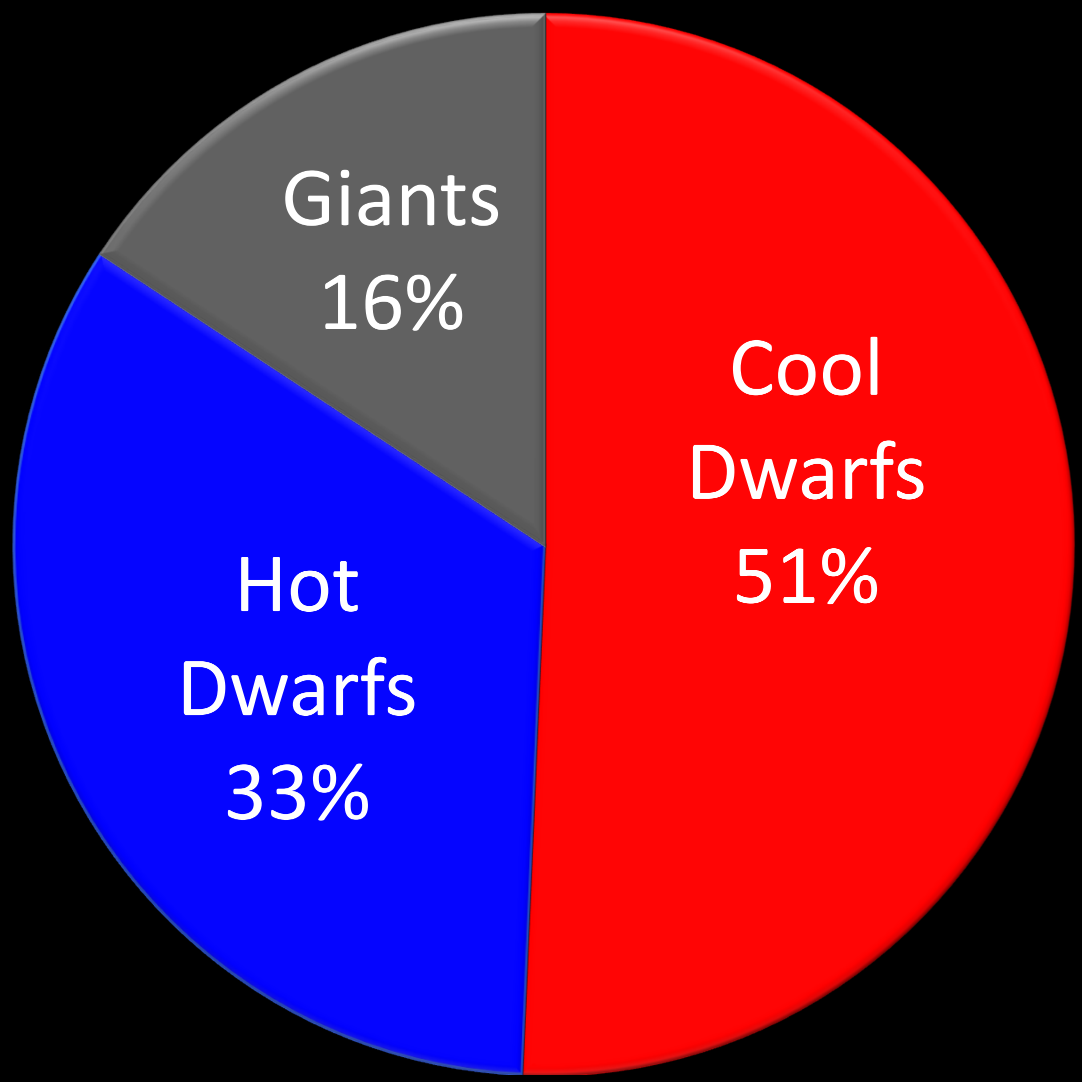
IRTF/SpeX		Palomar 200”/TripleSpec
21 (mostly partial)	Nights Observed	**7** (5 clear, 2 bad weather)
1 partial	Upcoming Nights	**2 full**
0.7 – 2.55 microns (SXD mode)	Wavelength Coverage	1.0 – 2.4 microns
2000 (SXD mode with 0.3x15” slit)	Spectral Resolution	2500 – 2700 (1x30” slit)
3.0 meters	Telescope Aperture	200” = 5.1 meters

We Concentrate on Bright Targets

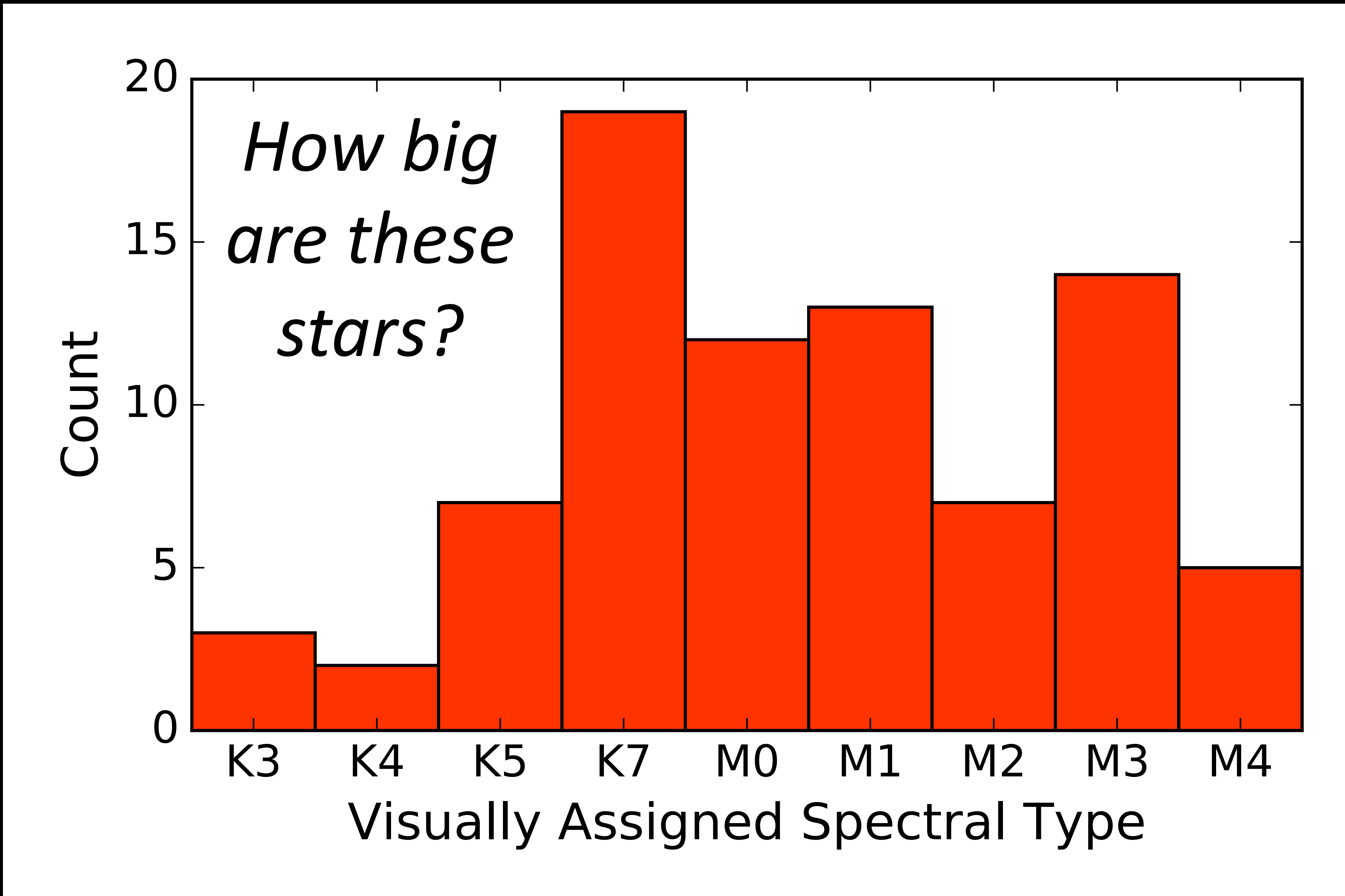


Dressing et al. 2016a, accepted to ApJ

Only 51% of our targets are actually Low-mass Dwarfs

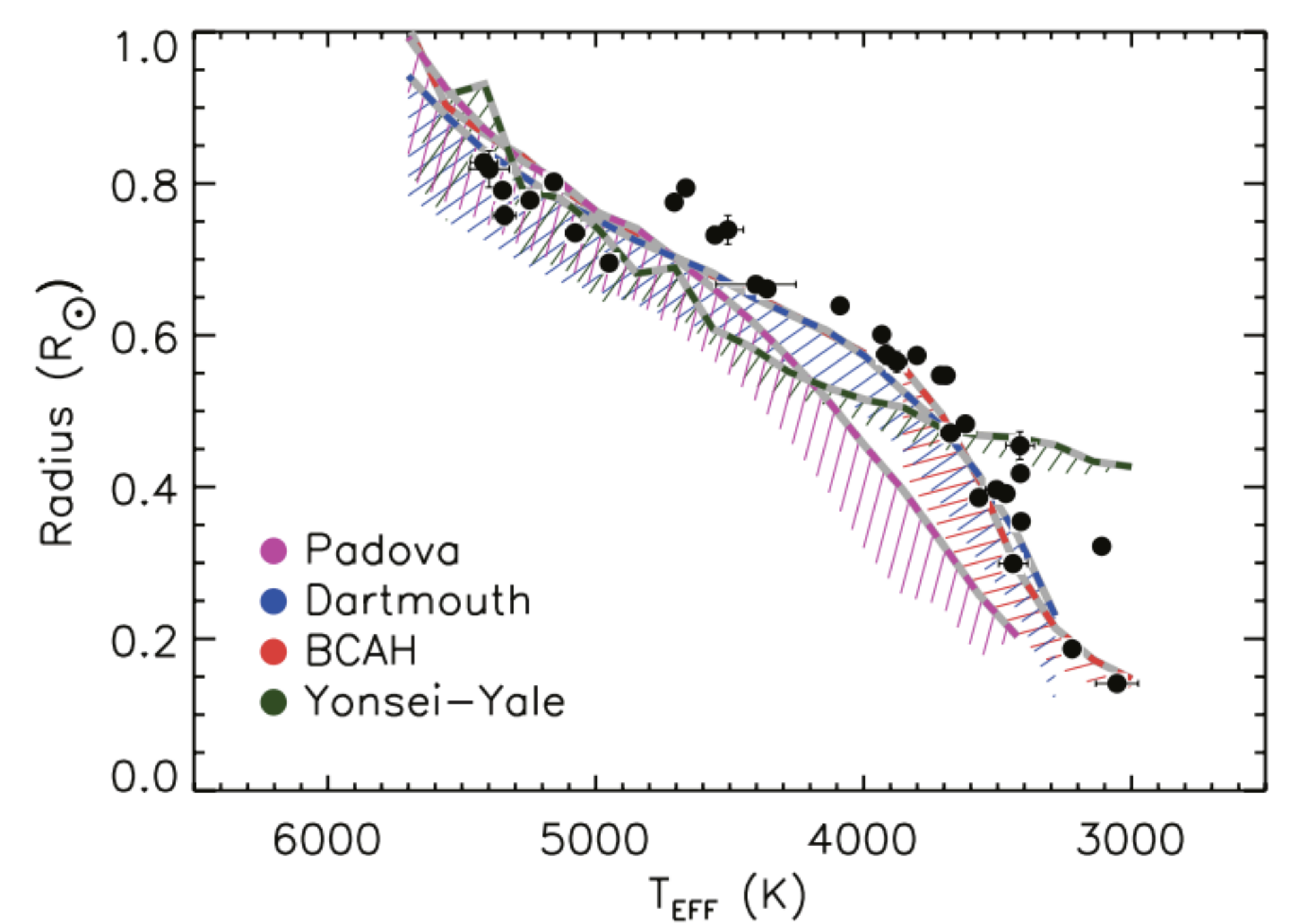


The Cool Dwarf Sample Extends from K3 – M4



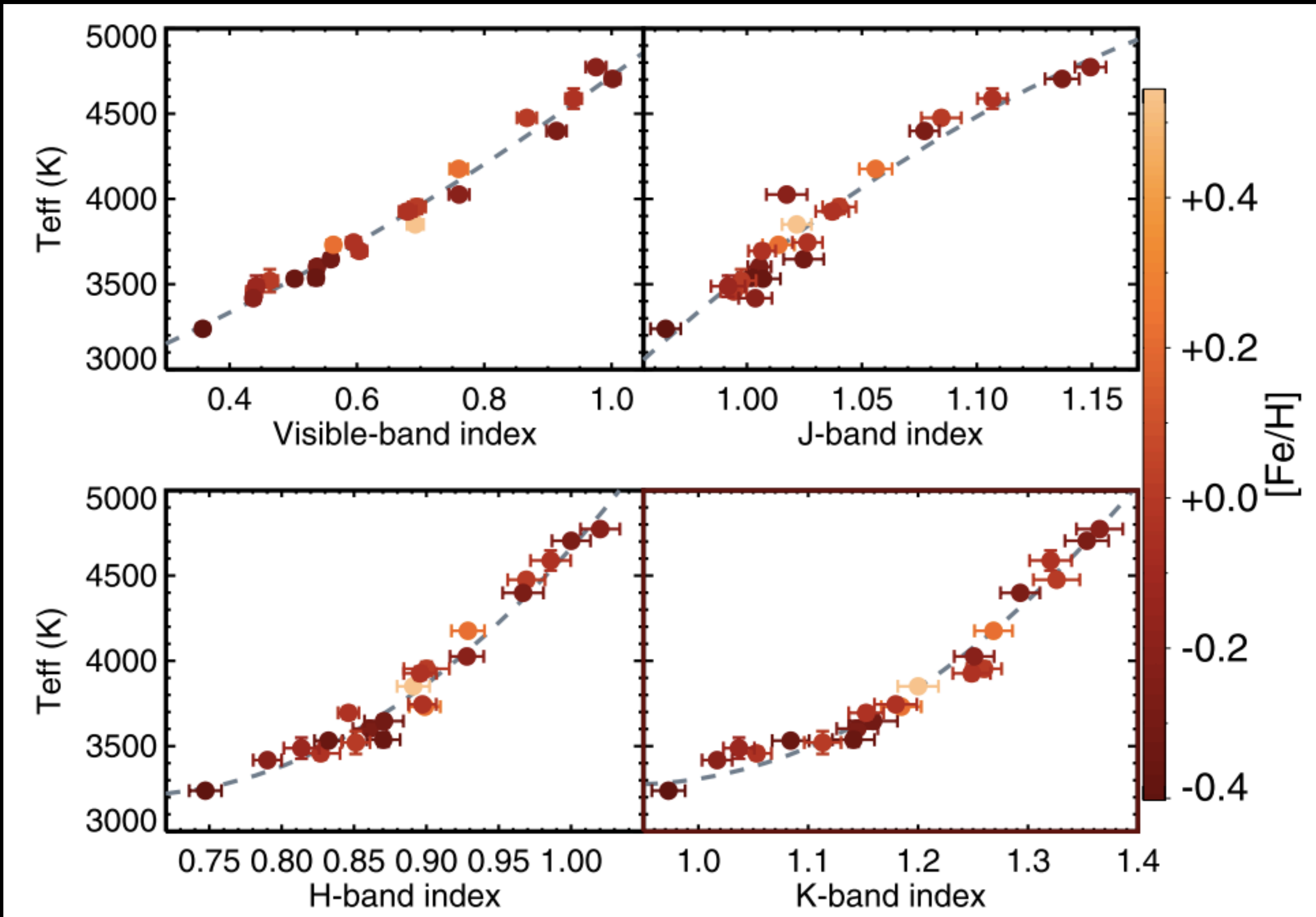
Dressing et al. 2016a, accepted to ApJ

Stellar Models Underestimate the Radii of Low-Mass Stars



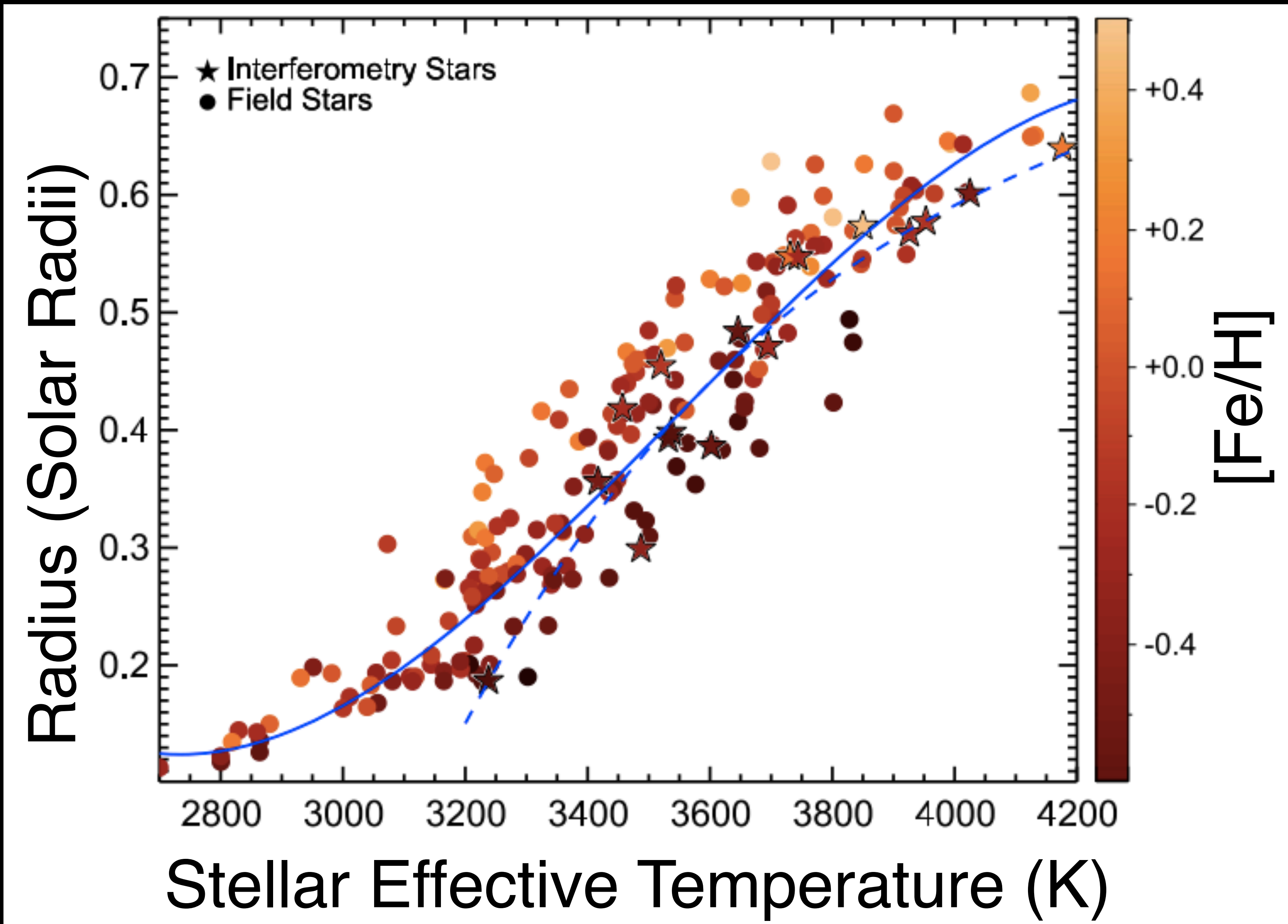
Boyajian et al. 2012, ApJ, 757, 112

Estimate **Stellar Effective Temperatures** using Features in J, H, & K Bands



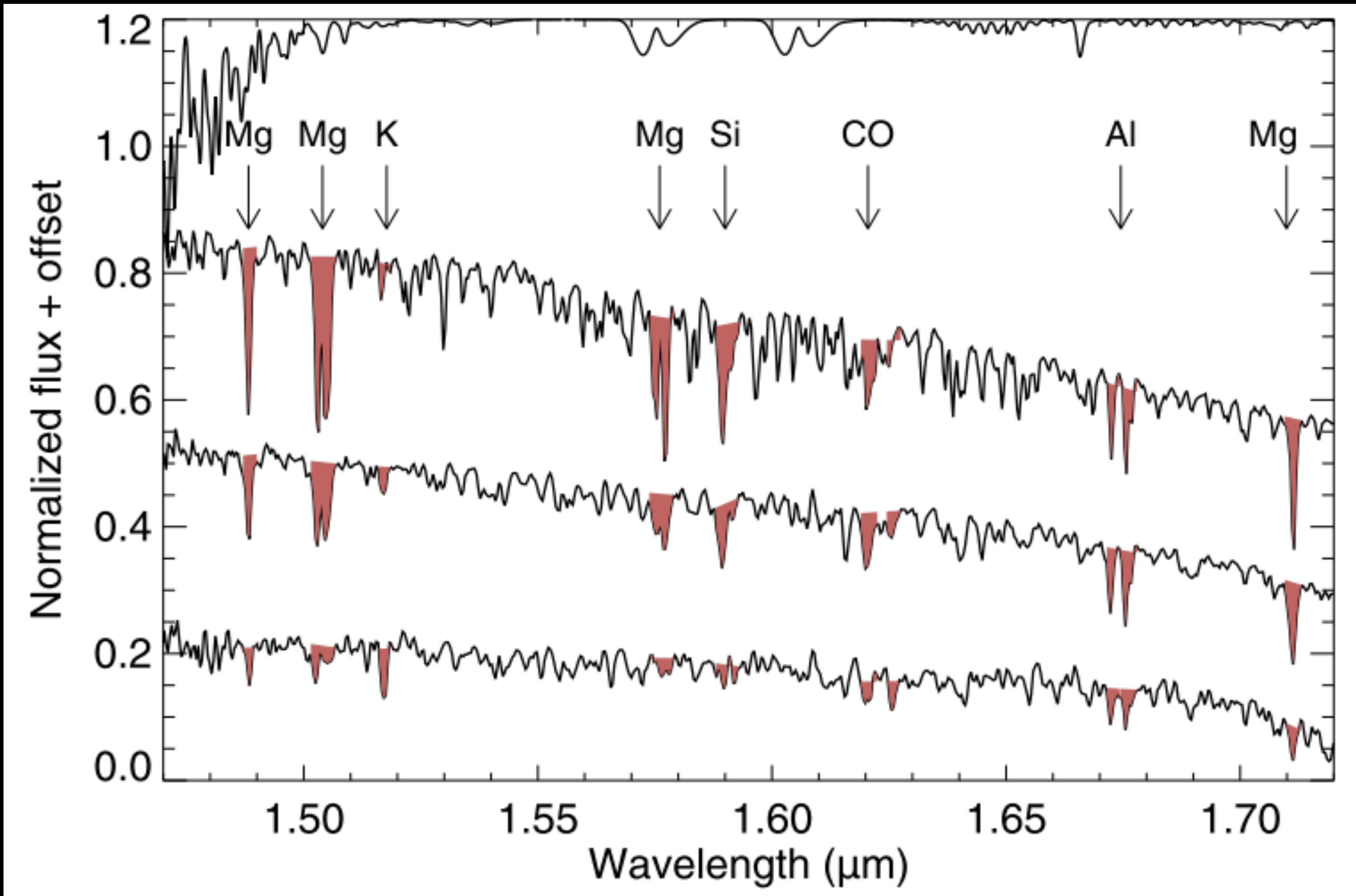
Mann et al. 2013, ApJ, 779, 118

Estimate **Stellar Radii** from Effective Temperatures & Metallicities



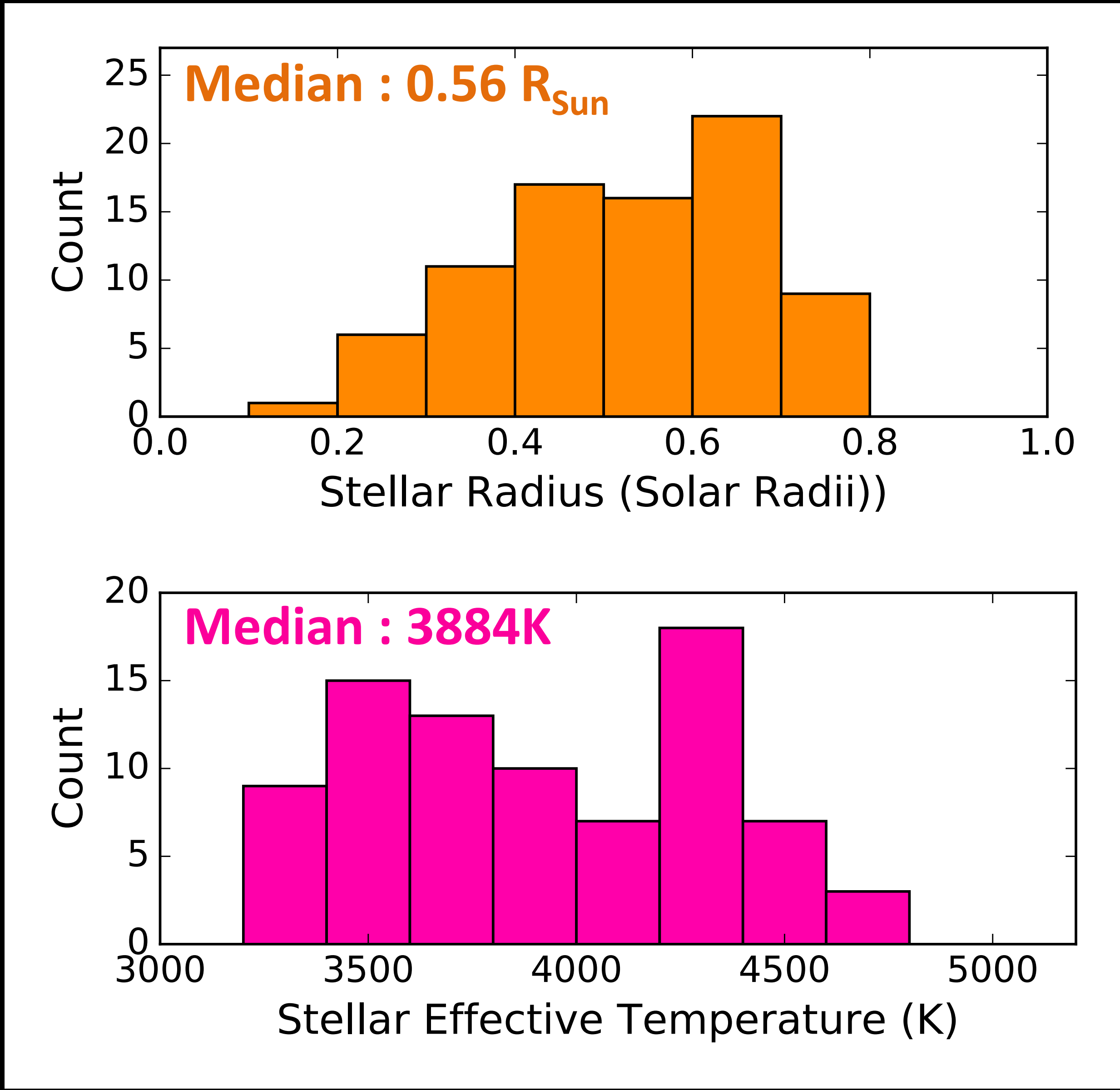
Mann et al. 2015, ApJ, 804, 64

Alternate Approach: Directly Estimate **Temperatures, Luminosities,** and **Radii** Using H-Band Features



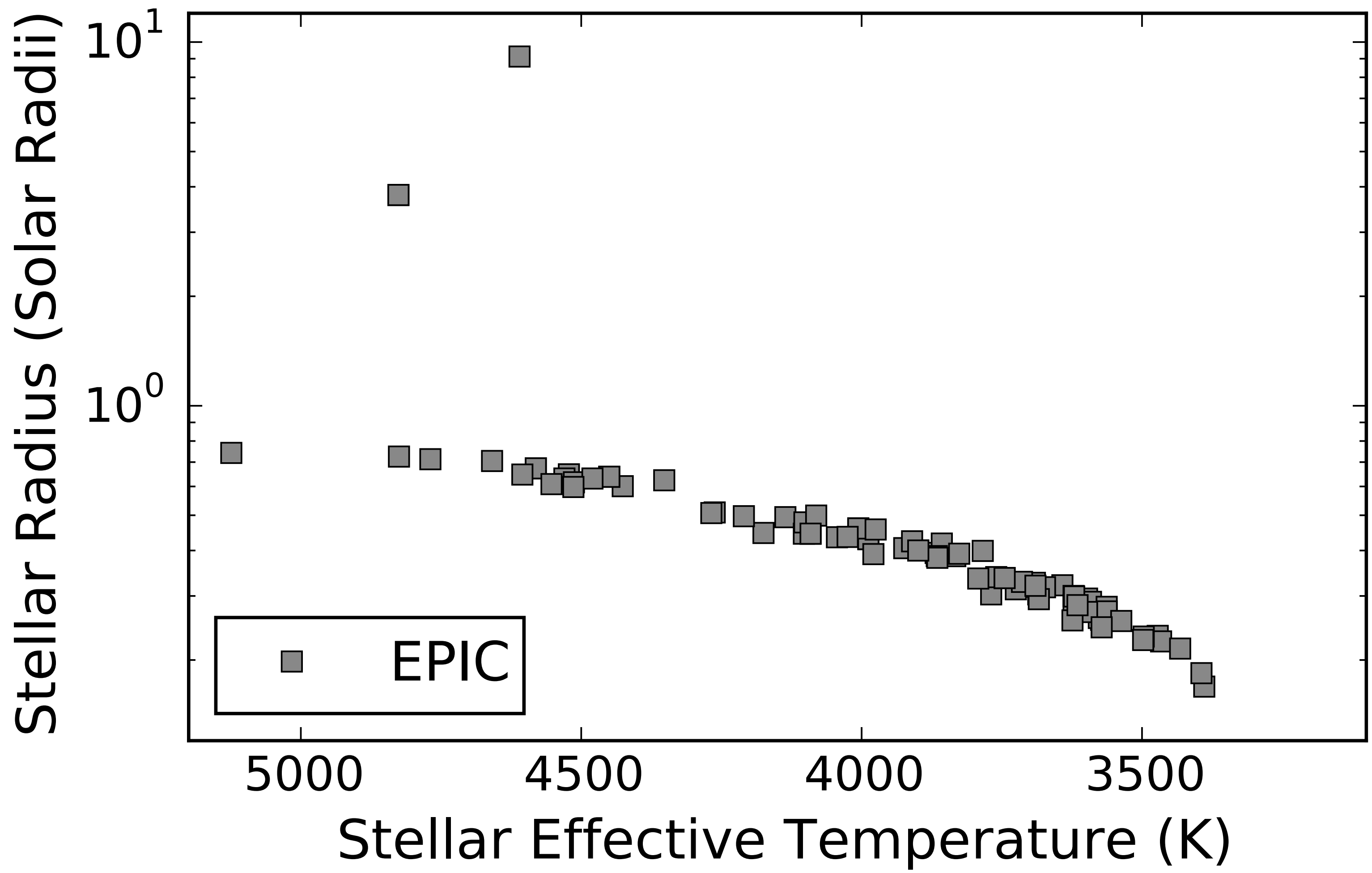
Newton et al. 2015, ApJ, 800, 85

Our Typical Cool Dwarfs are Roughly 0.6 R_{Sun}



Dressing et al. 2016a, accepted to ApJ

Most stars are larger than previously estimated ($\Delta R_* = +0.13 R_{Sun} = 34\%$)



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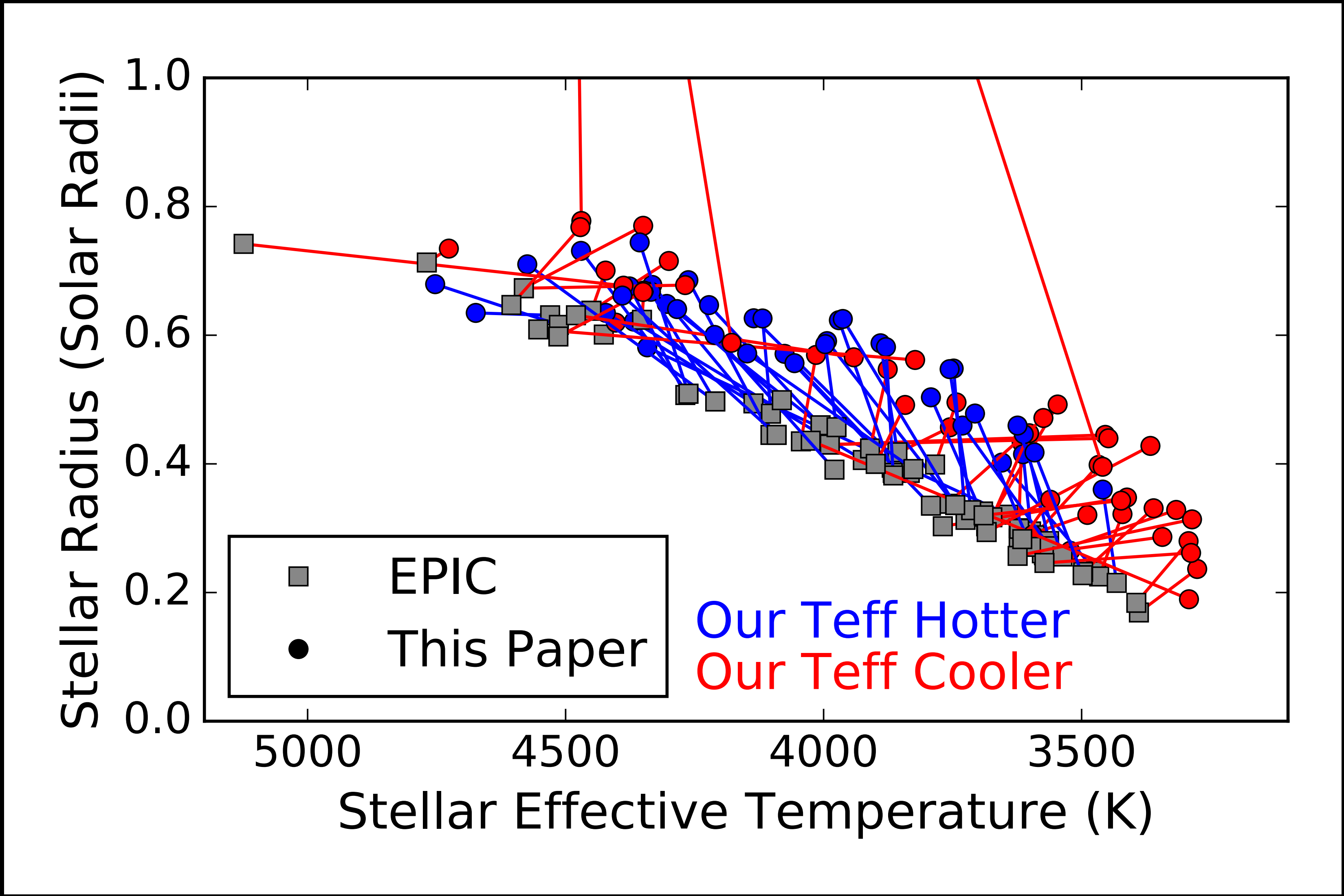
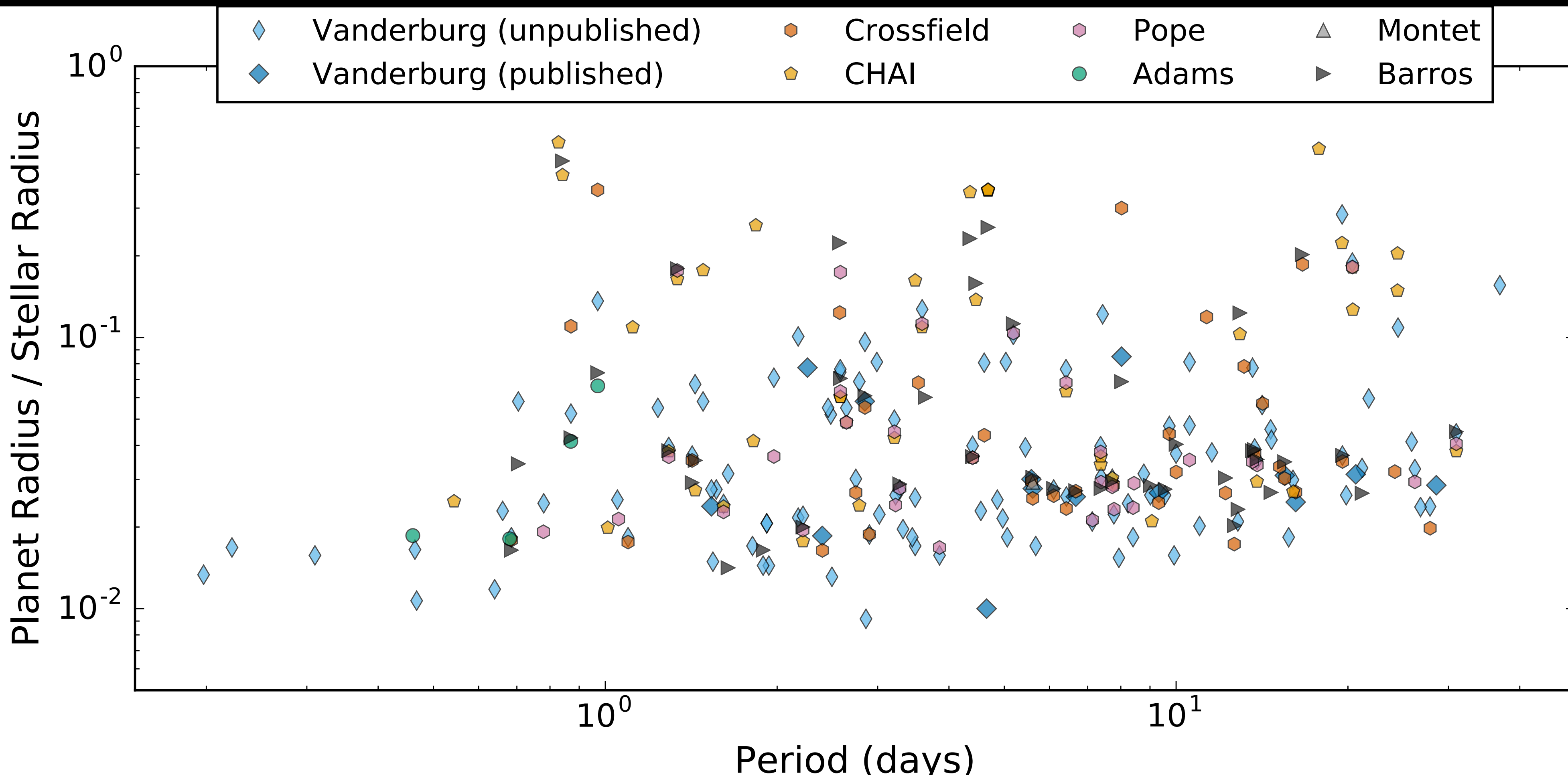


Dressing et al. 2016a, accepted to ApJ

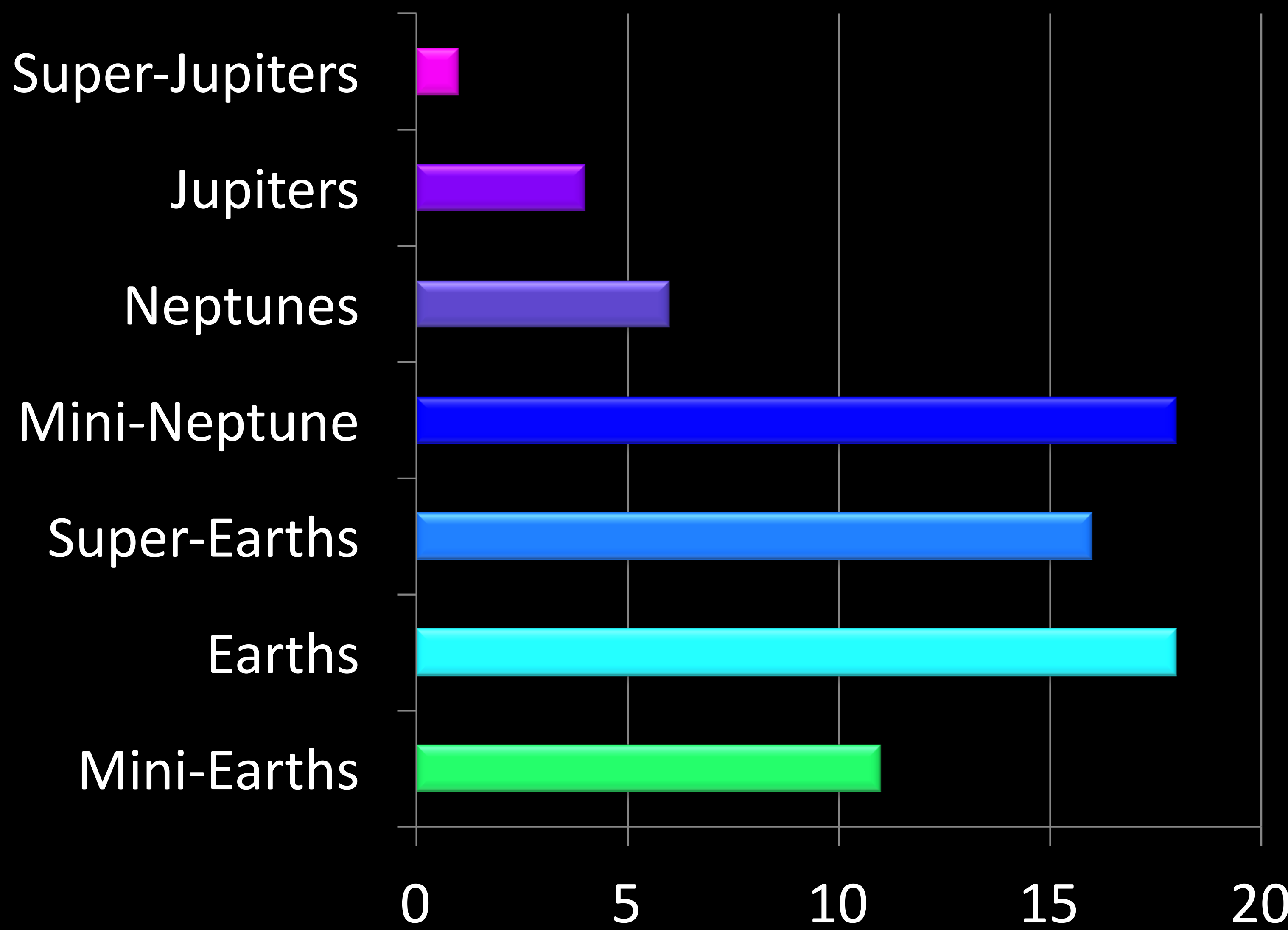
We Use the Revised Stellar Radii to Update the Radii of the Associated Planet Candidates



Dressing et al. 2016b (in prep)

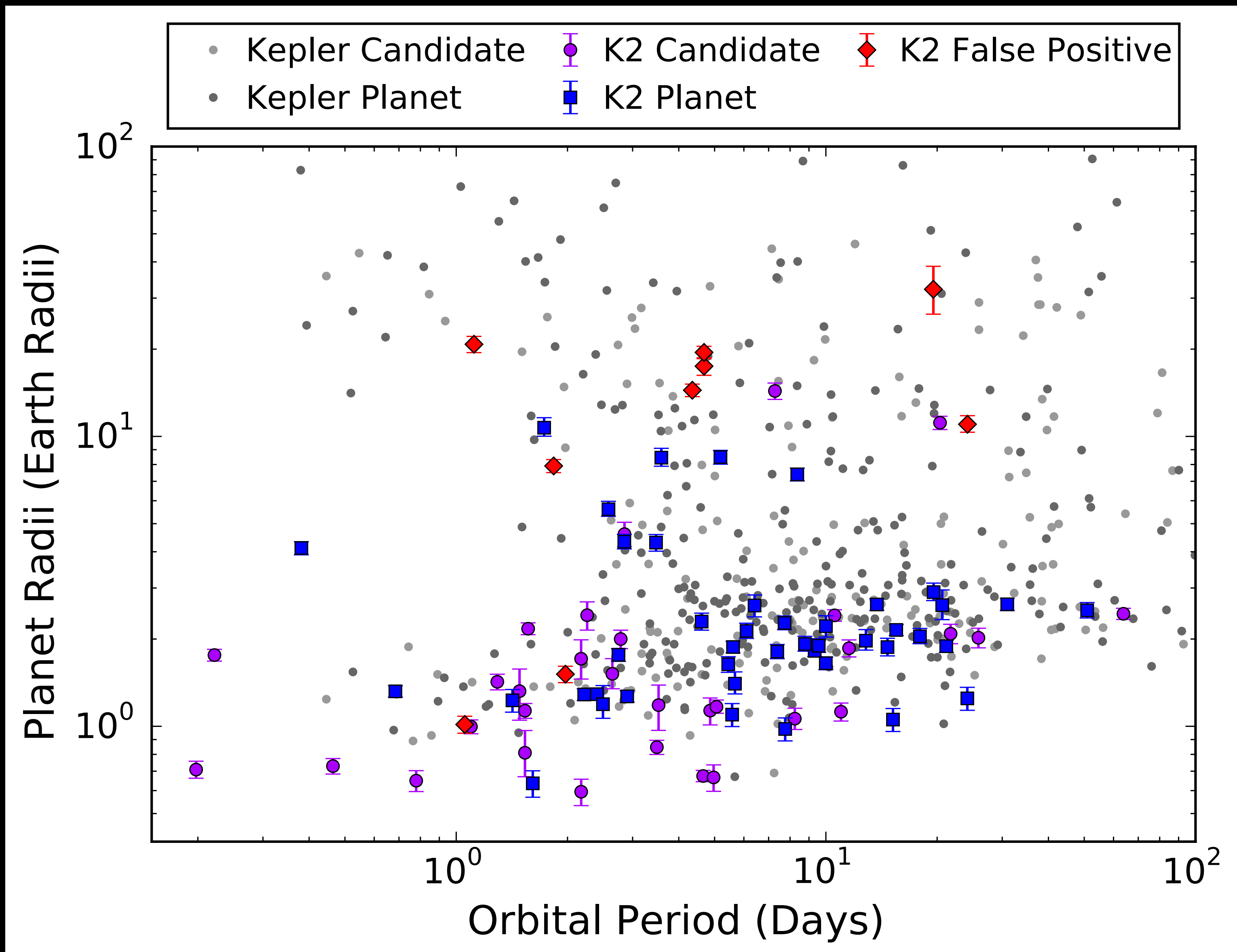
Published planets from Adams+ 2016, AJ accepted, arXiv:1603.06488; Barros+ 2016, A&A accepted, arXiv:1607.02339, Crossfield+ 2016, ApJ accepted, arXiv:1607.05263; Montet+ 2015, 809, 25; Pope+ 2016, MNRAS accepted, arXiv:1606.01264; Vanderburg+ 2016, ApJS, 222, 14

Most of our Planets are Small



Dressing et al. 2016b (in prep)

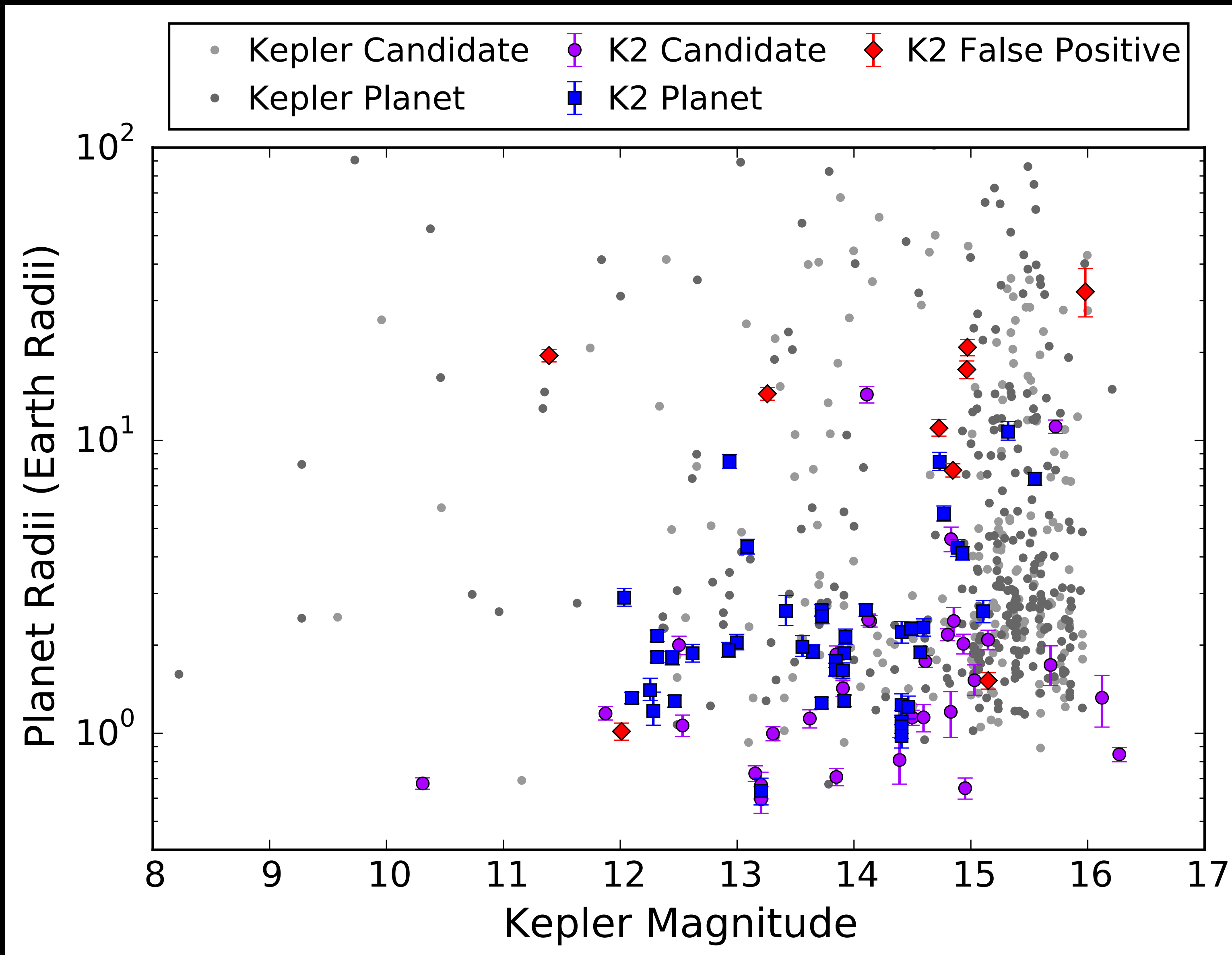
Our K2 Planet Sample Is Similar to the *Kepler* Planet Sample…



Kepler Candidates & Planets: NASA Exoplanet Archive

Dressing et al. 2016b (in prep)

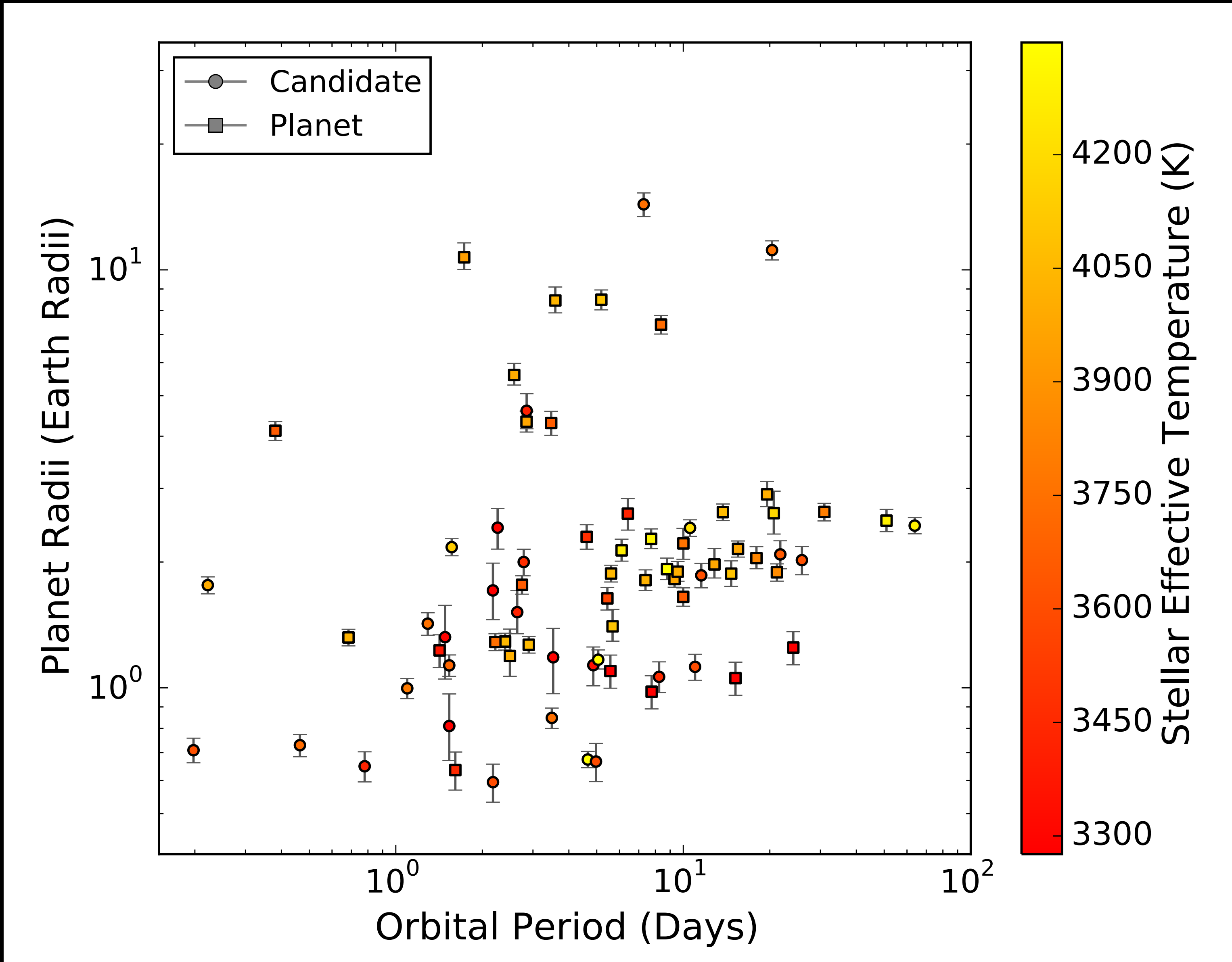
…but the K2 planets generally orbit brighter stars



Kepler Candidates & Planets: NASA Exoplanet Archive

Dressing et al. 2016b (in prep)

Our Smaller Planets Tend to Orbit Cooler Stars (consistent with expected detection bias)



Dressing et al. 2016b (in prep)

Spectra are Expensive!

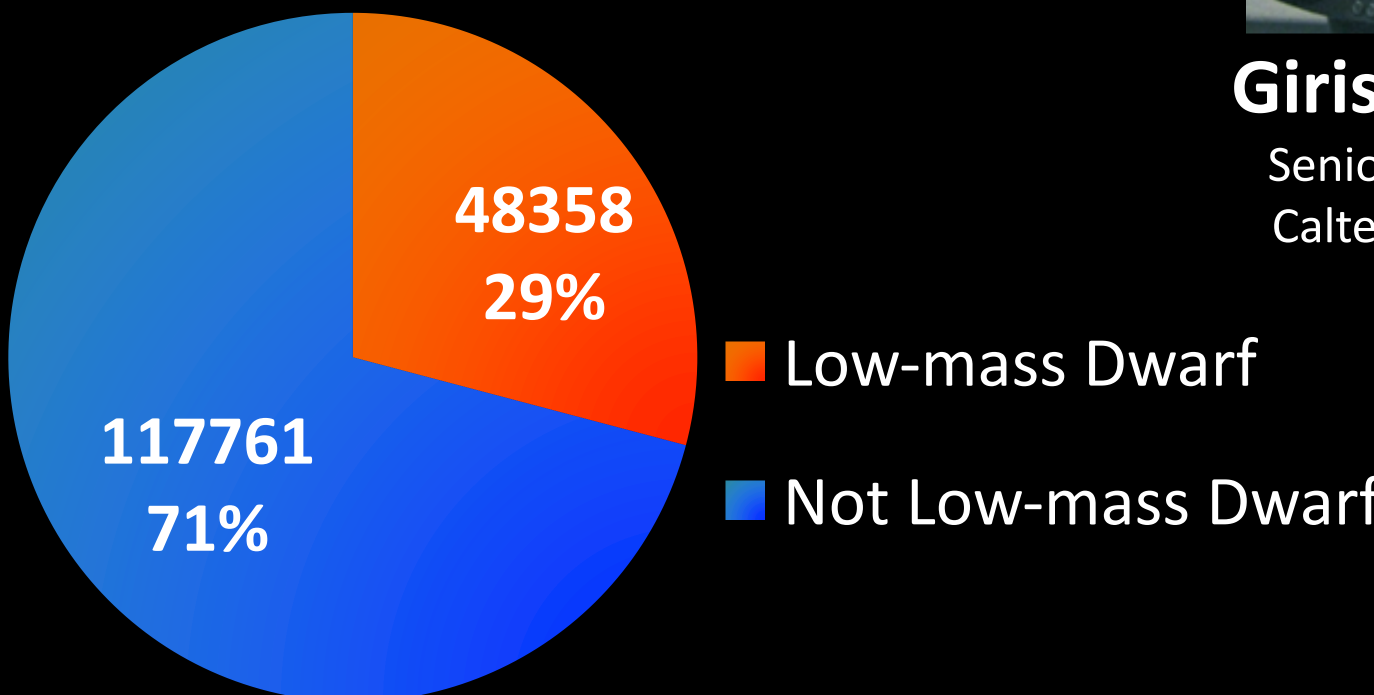
How can we classify the full K2 M dwarf sample?

- Trained random forest using spectroscopically-classified stars
- Reported probabilities that individual targets are M dwarfs

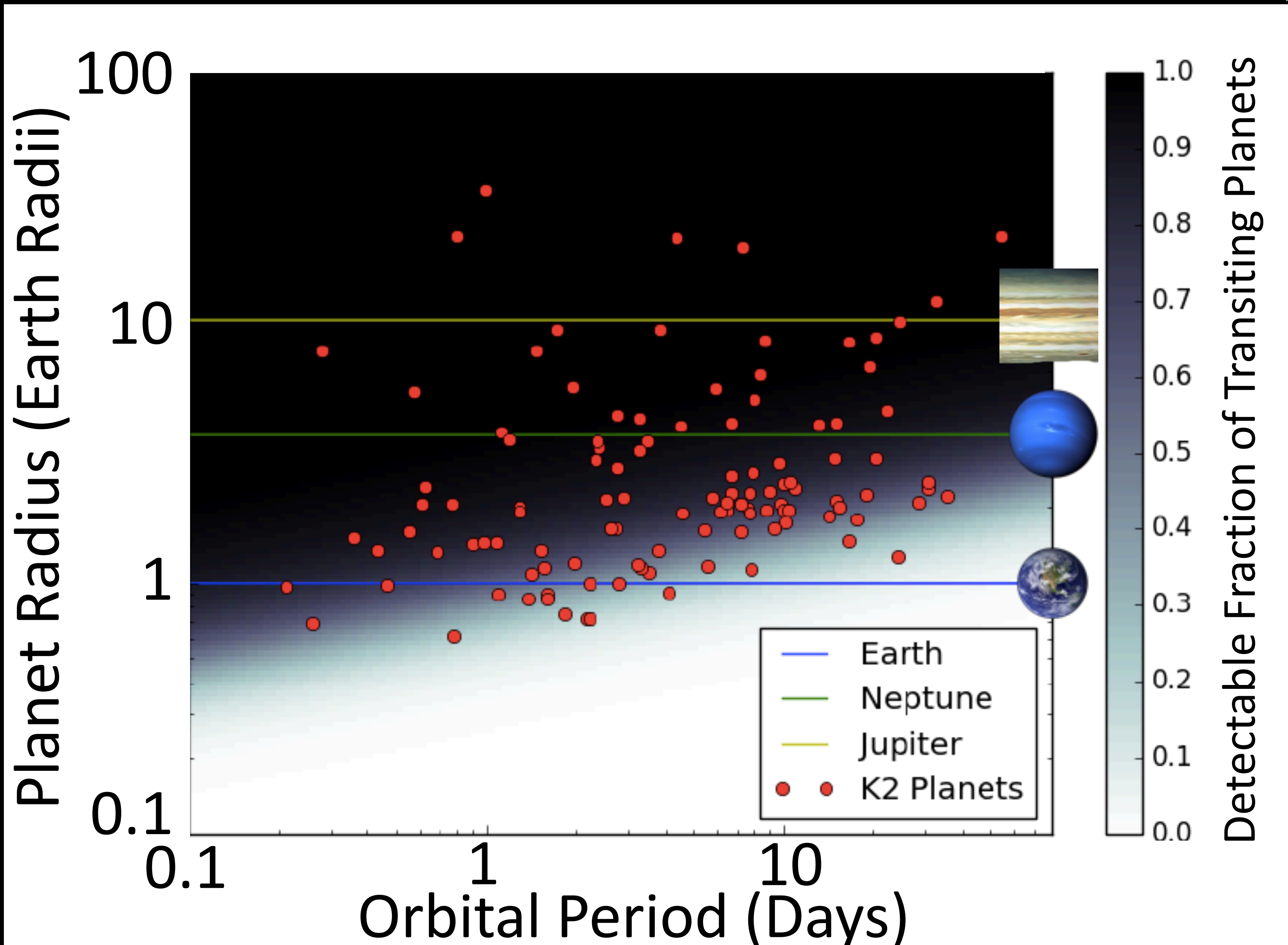
Girish Duvvuri

Senior at Wesleyan

Caltech SURF 2016



Girish Estimated K2's Sensitivity to Planetary Systems Orbiting M Dwarfs



Typical K2 M dwarfs host 1.2 small planets with periods < 50 days

Size Range:	Period < 10 Days	Period 10 – 50 Days
Smaller than Earth	0.21	0.07
Earth – Neptune	0.35	0.45
Neptune - Jupiter	0.07	0.07

Looking toward the future:

A Pathway for the Discovery & Characterization of Potentially Habitable Worlds

Pathway to Earth 2.0

Constrain planet frequencies ✔

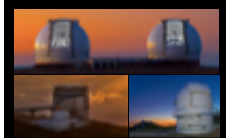


Figure out which sizes of planets are rocky ✔ for hot planets

(Work in progress for cool planets)

Find cool potentially habitable planets

Measure masses to identify rocky worlds

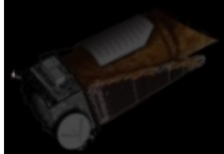
Determine atmospheric compositions

Search for biosignatures

Perform detailed characterization

Up Next!

Pathway to Earth 2.0



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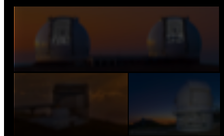

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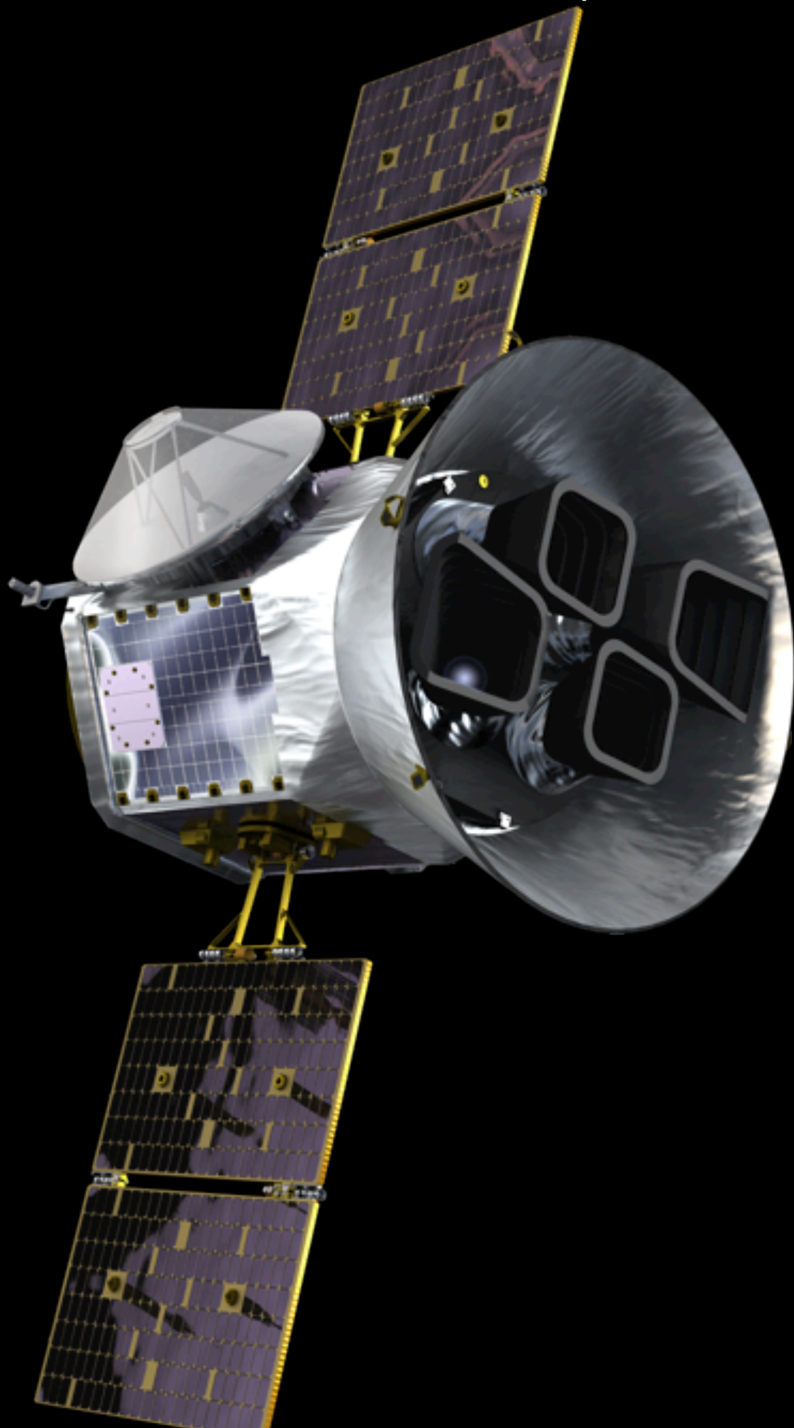
TESS Slides from Zach Berta-Thompson



TESS

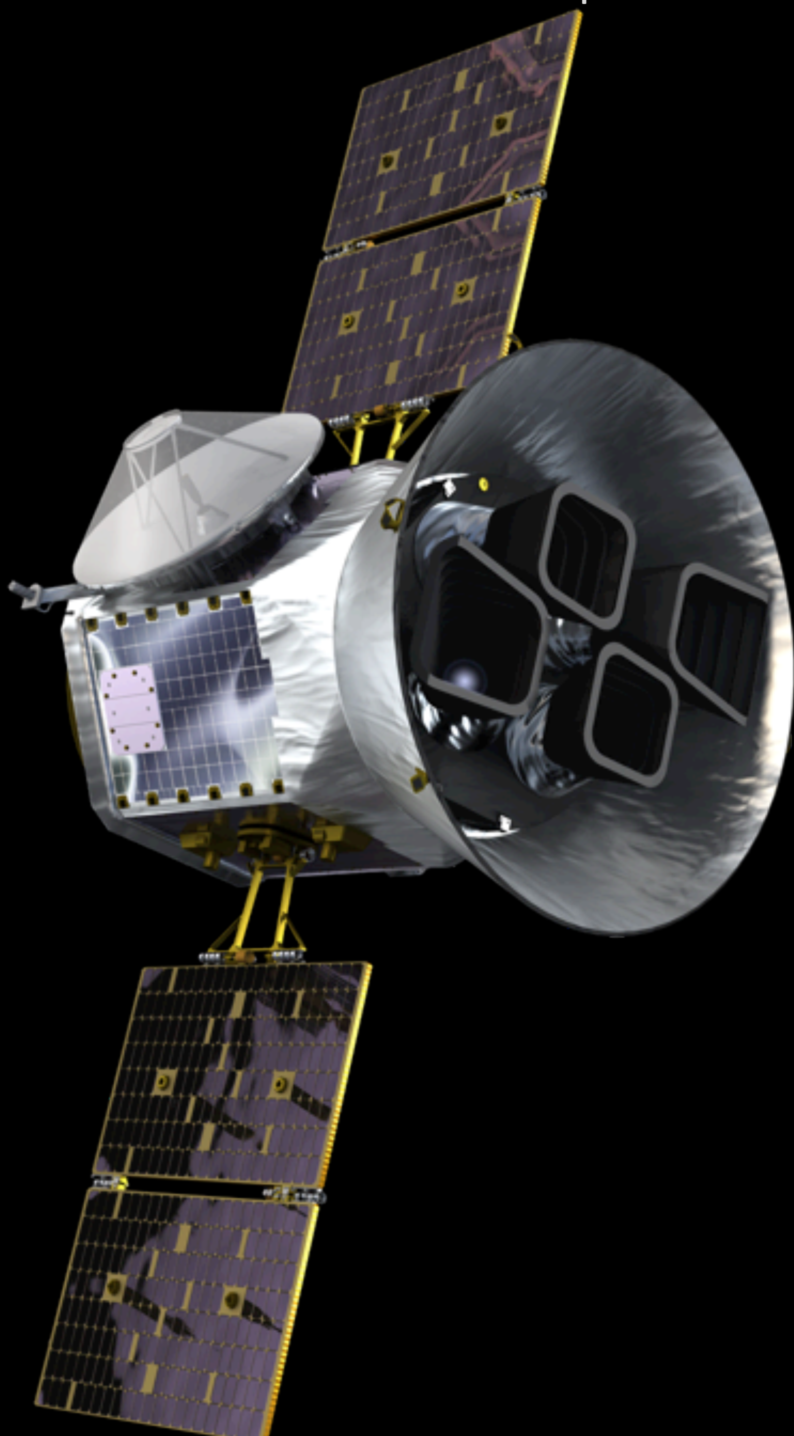
Explorer Mission

*launch in **2017**, to find hundreds of nearby small exoplanets amenable to detailed characterization*

Ricker et al., *JATIS*, (2014)

TESS Slides from Zach Berta-Thompson

TESS

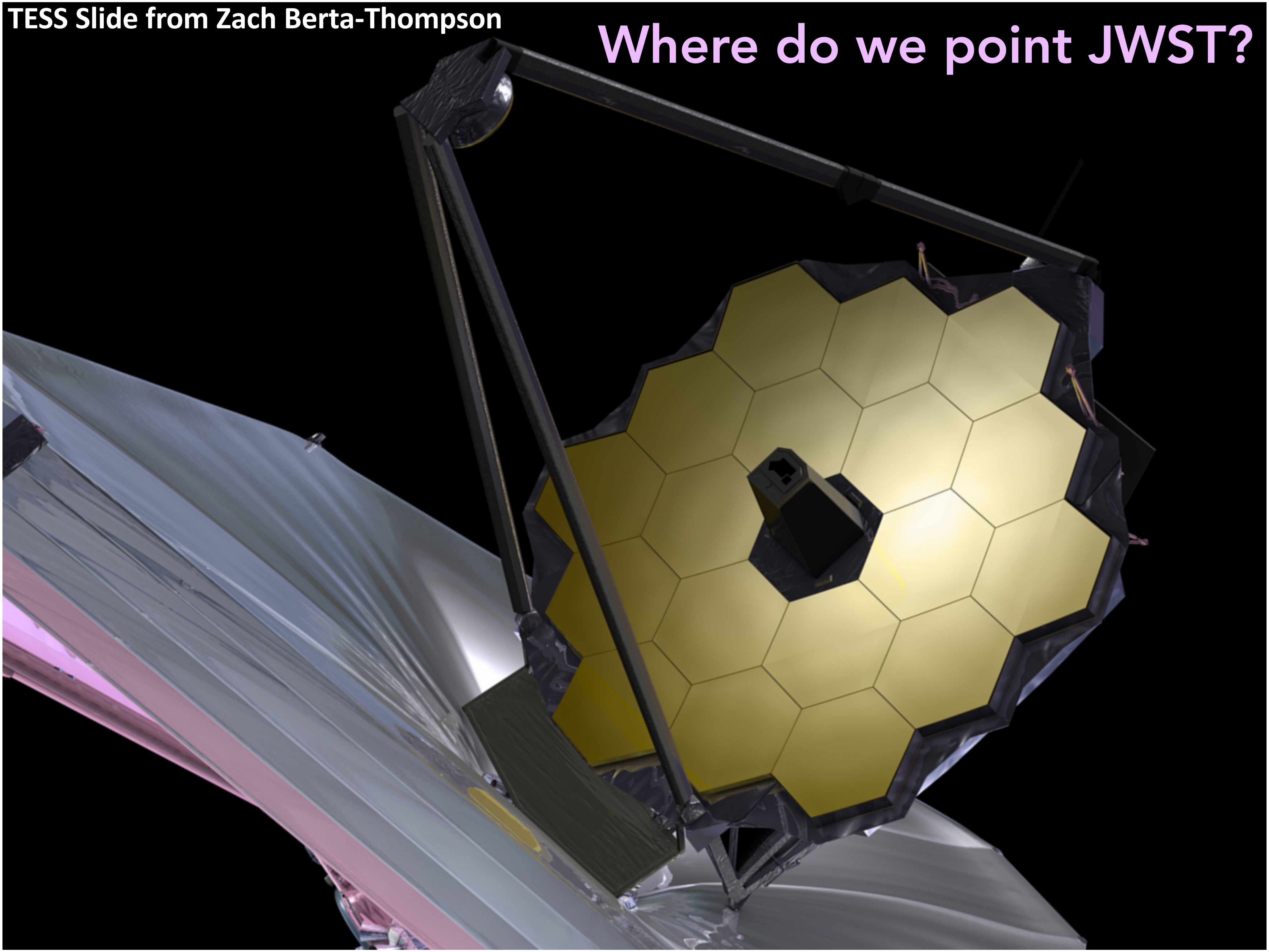


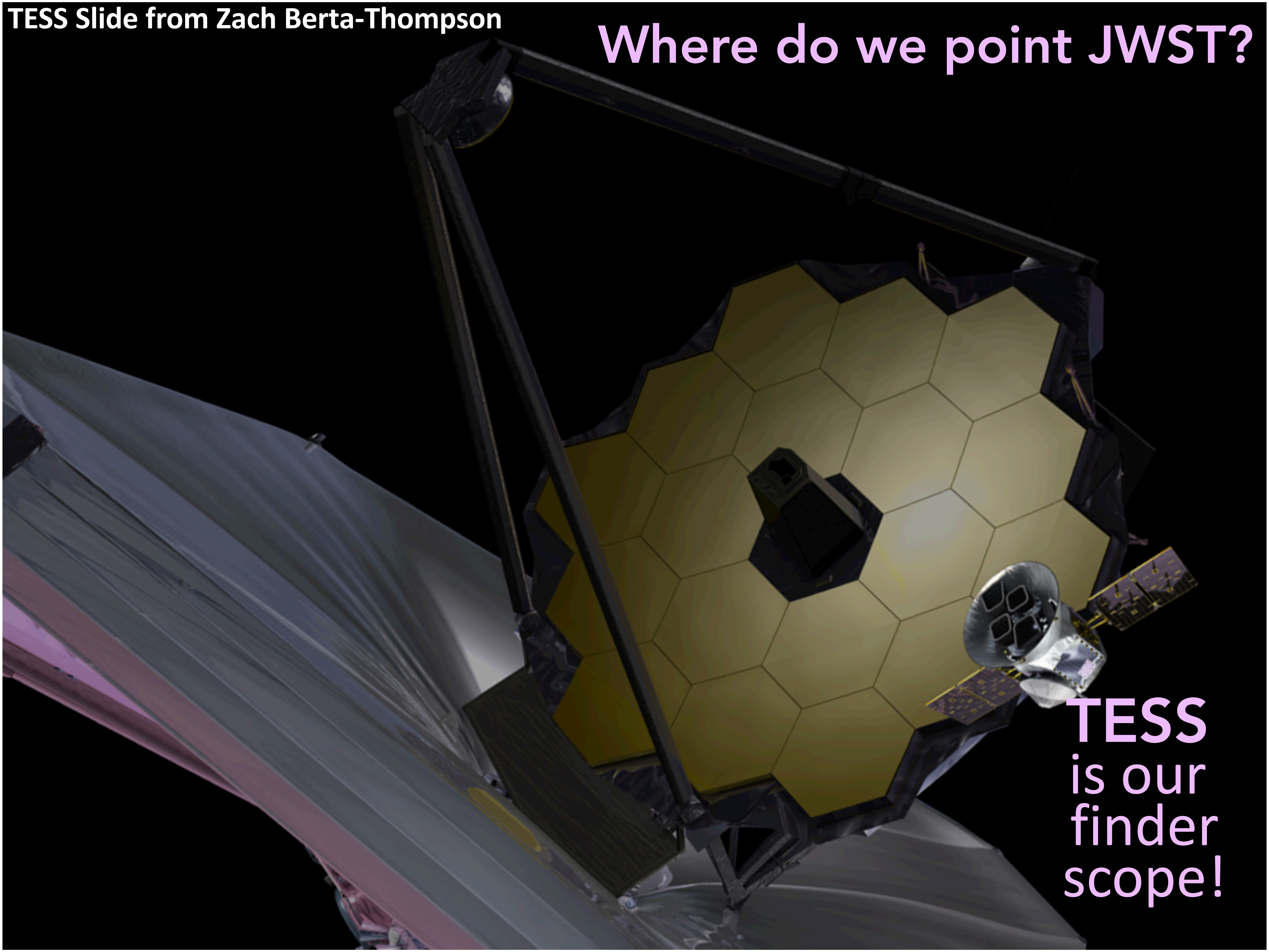
George Ricker (P.I.)
Roland Vanderspek (Deputy P. I.)
Massachusetts Institute of Technology

science center shared between
MIT + Harvard/Smithsonian CfA

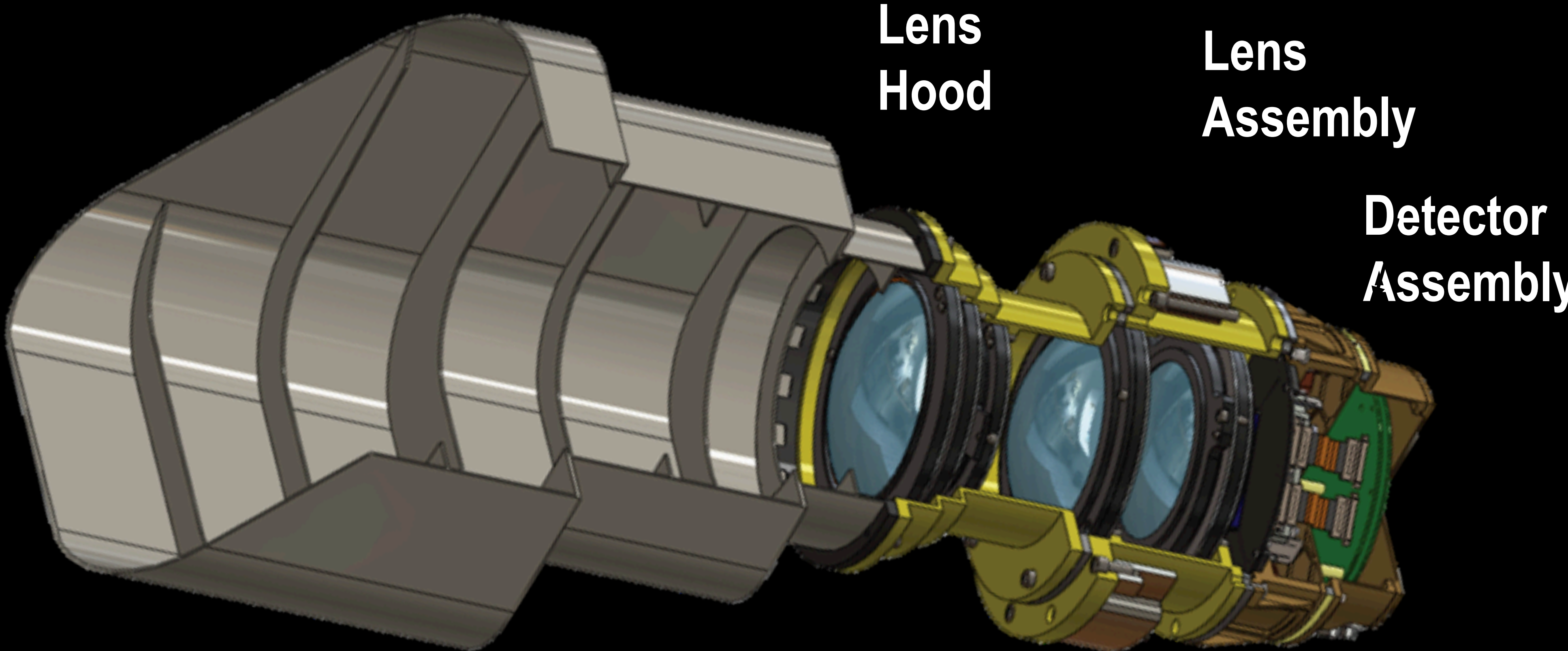
collaboration including:
NASA Goddard, NASA Ames, MIT Lincoln Lab, Orbital Sciences, STScI, SAO, MPIA-Germany, Las Cumbres Observatory, Geneva Observatory, OHP-France, University of Florida, Aarhus University-Denmark, Harvard College Observatory, Vanderbilt University

Ricker et al., *JATIS*, (2014)


TESS Slide from Zach Berta-Thompson
Where do we point JWST?

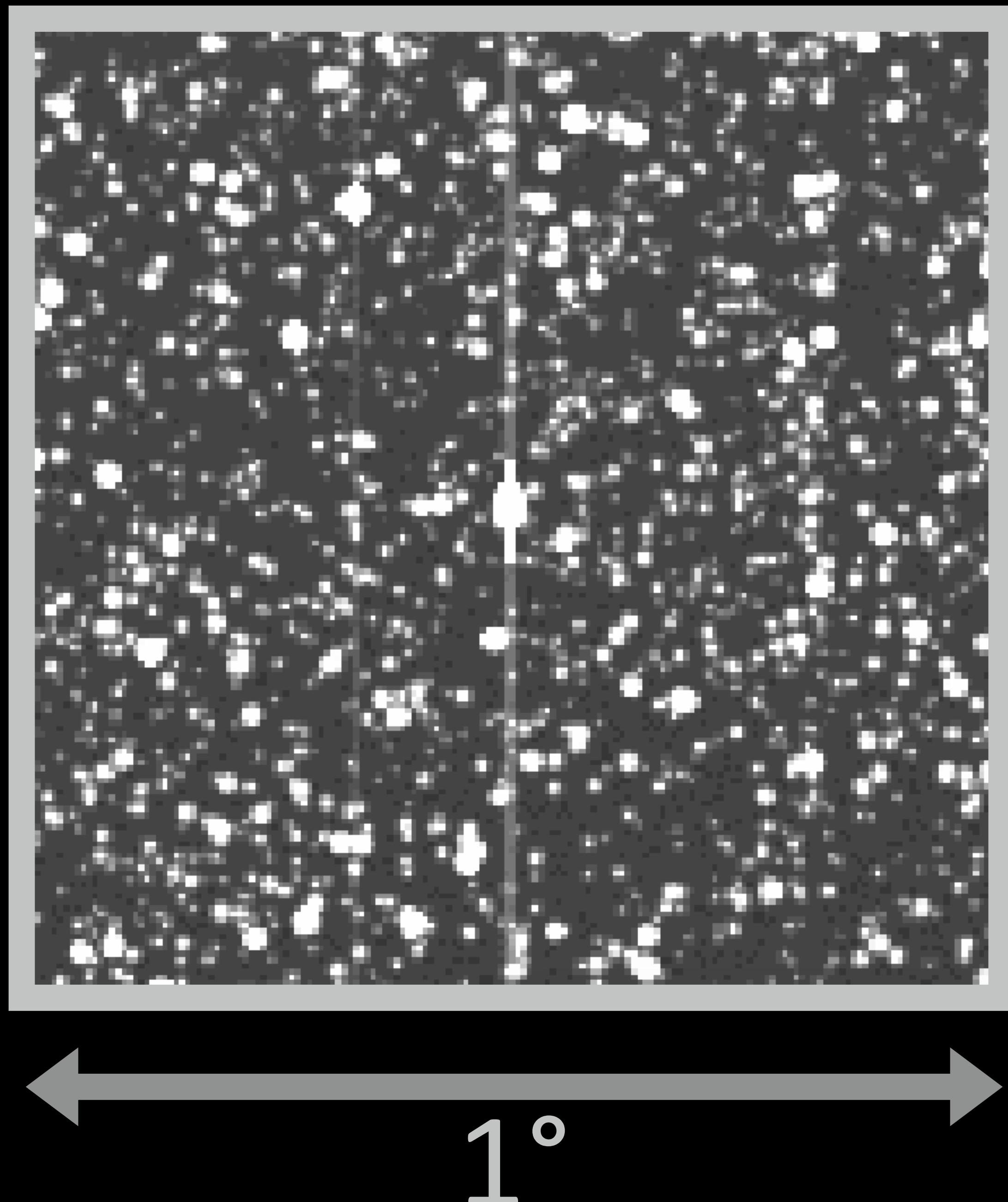

TESS Slide from Zach Berta-Thompson
Where do we point JWST?
TESS
is our
finder
scope!

TESS Slide from Zach Berta-Thompson



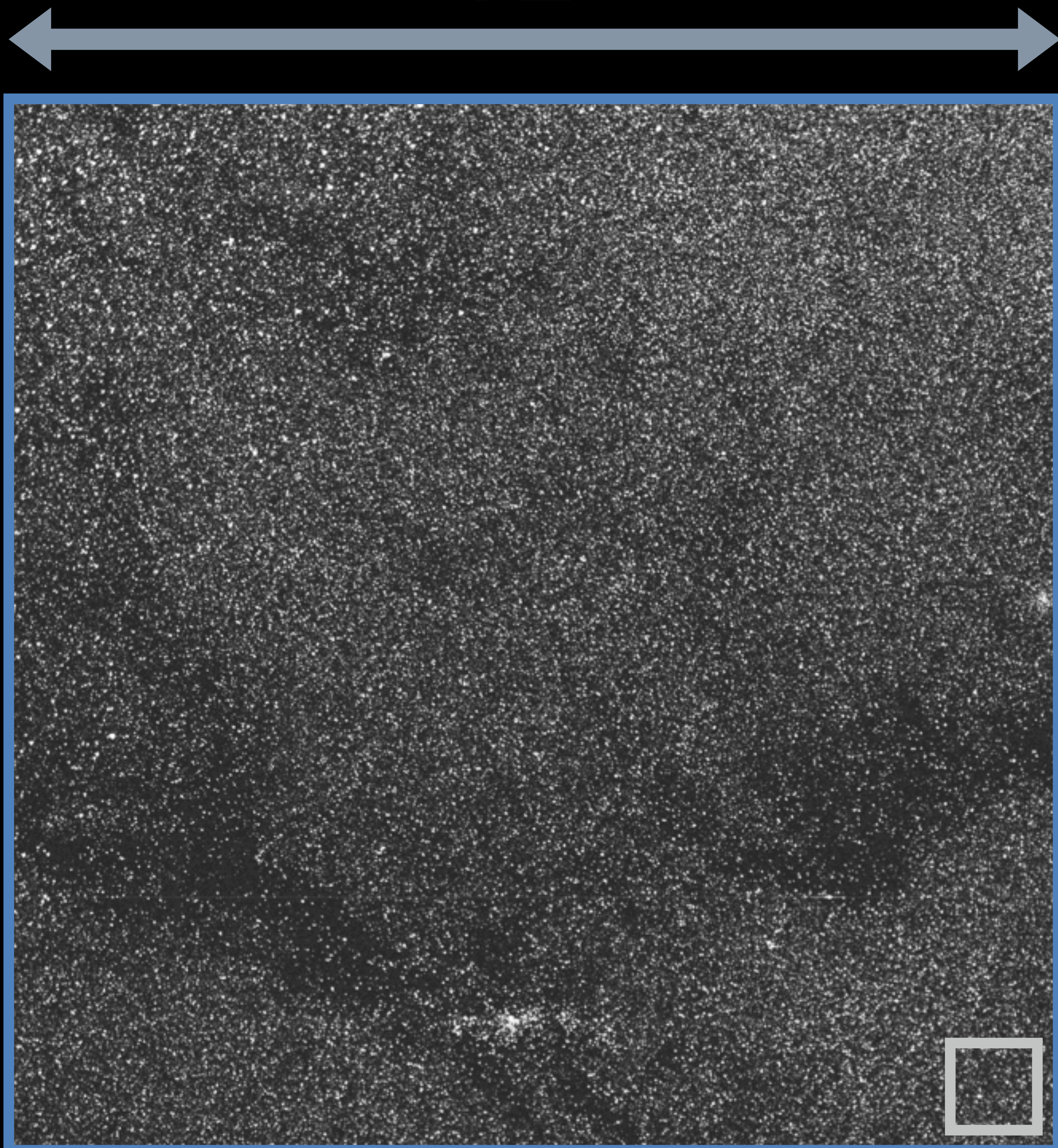
10.5 cm diameter, 24°x24° field of view

Ricker et al. (2014), Sullivan et al. (2015)



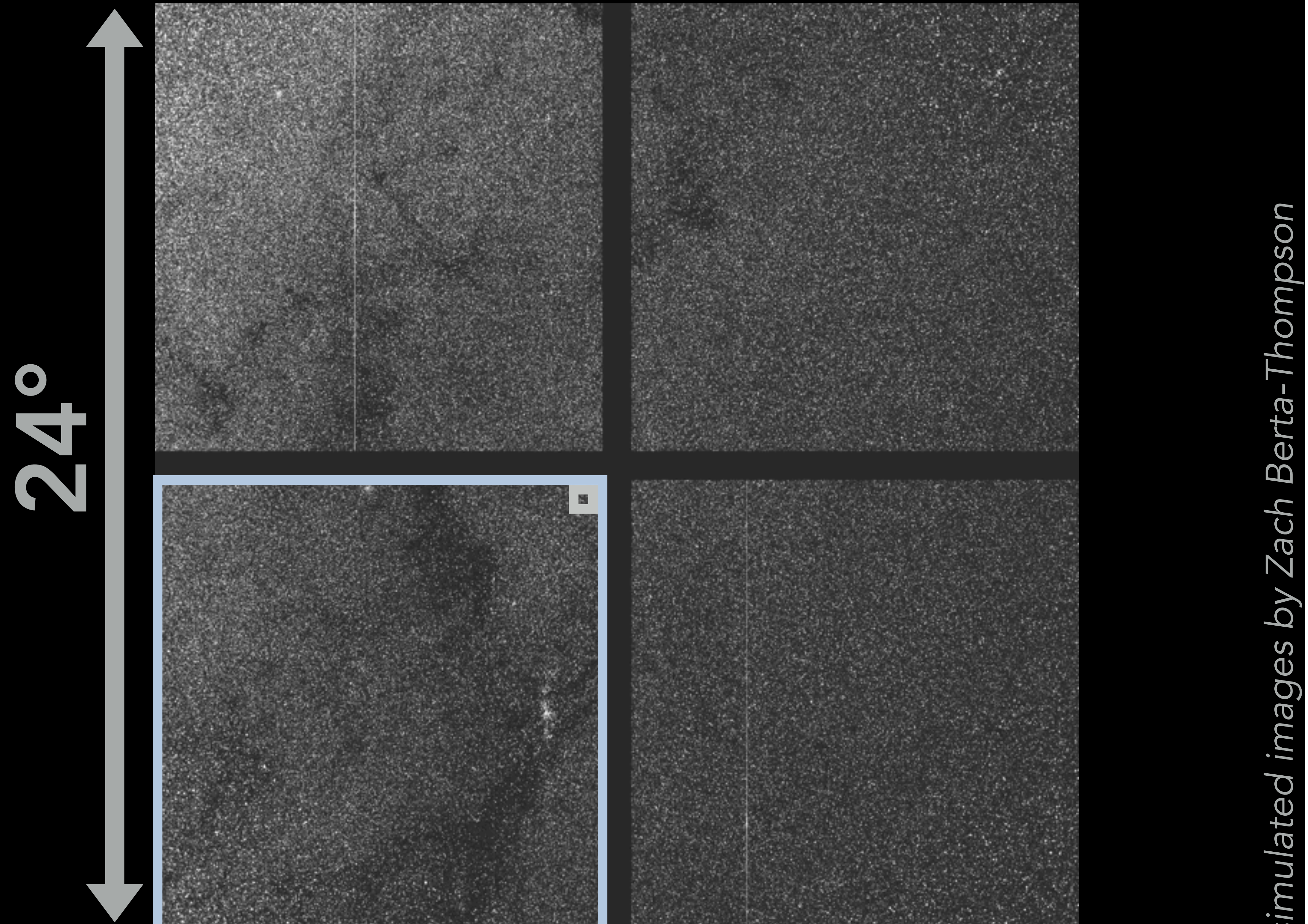
simulated images by Zach Berta-Thompson

one CCD:
12°



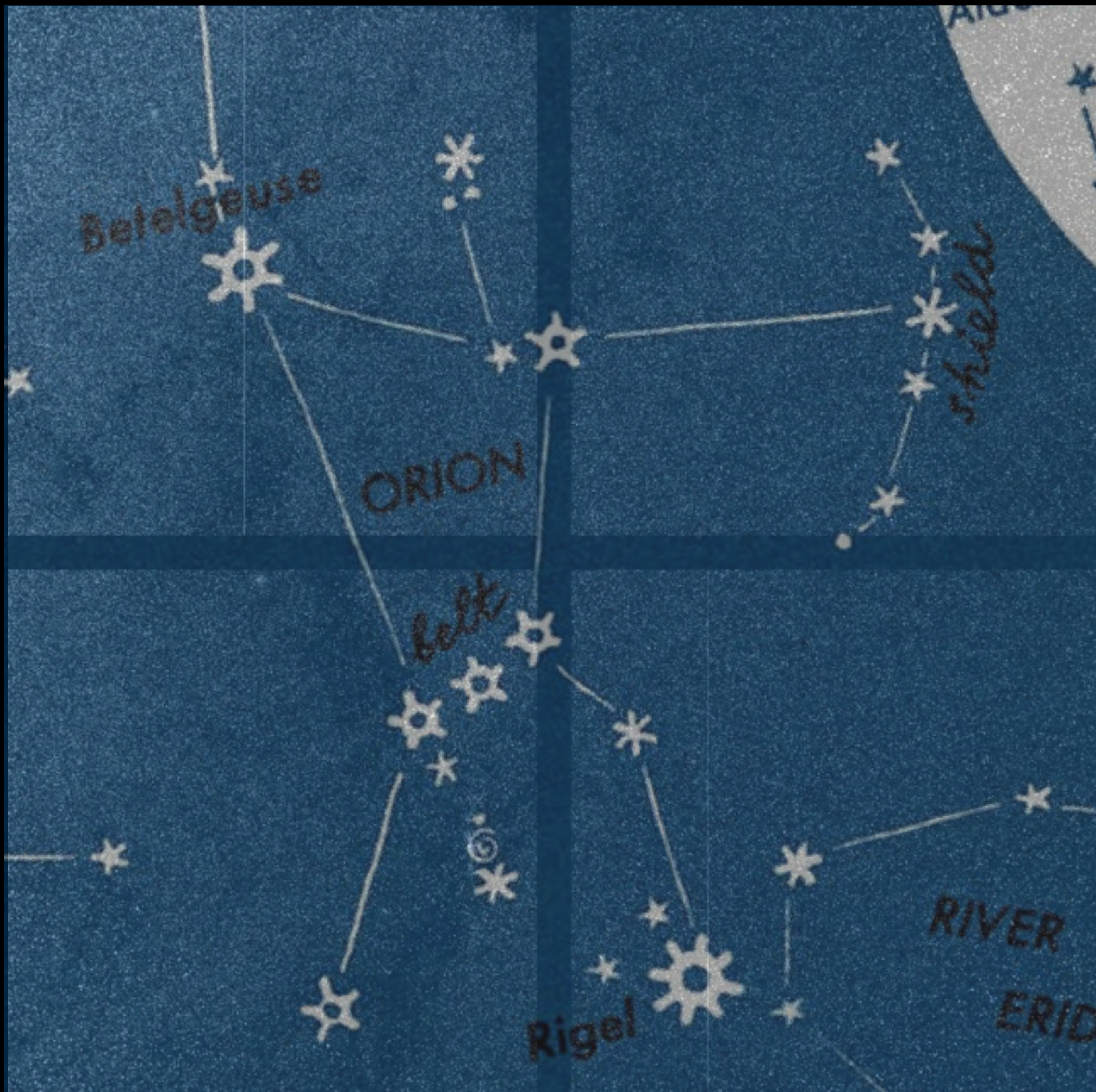
simulated images by Zach Berta-Thompson

FOV from one TESS camera:



FOV from one TESS camera:

24°



constellations by H. A. Rey

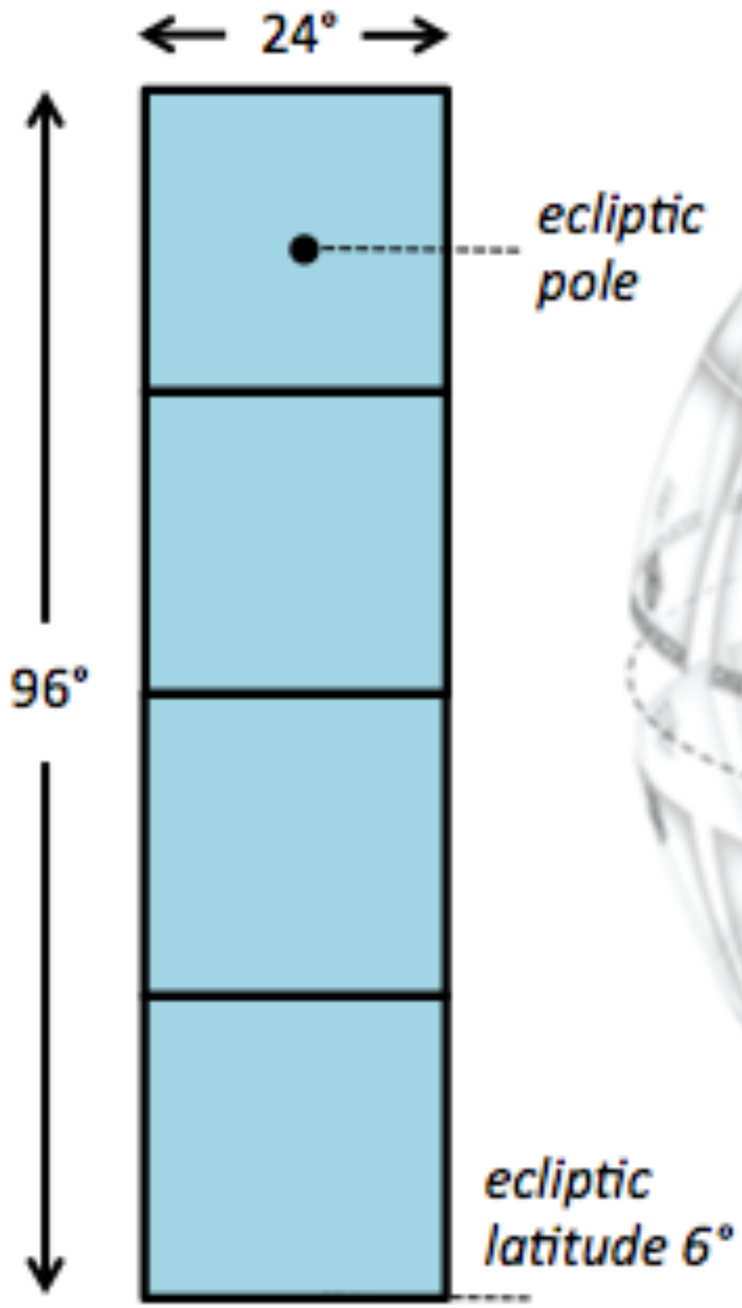
Slide by Zach Berta-Thompson

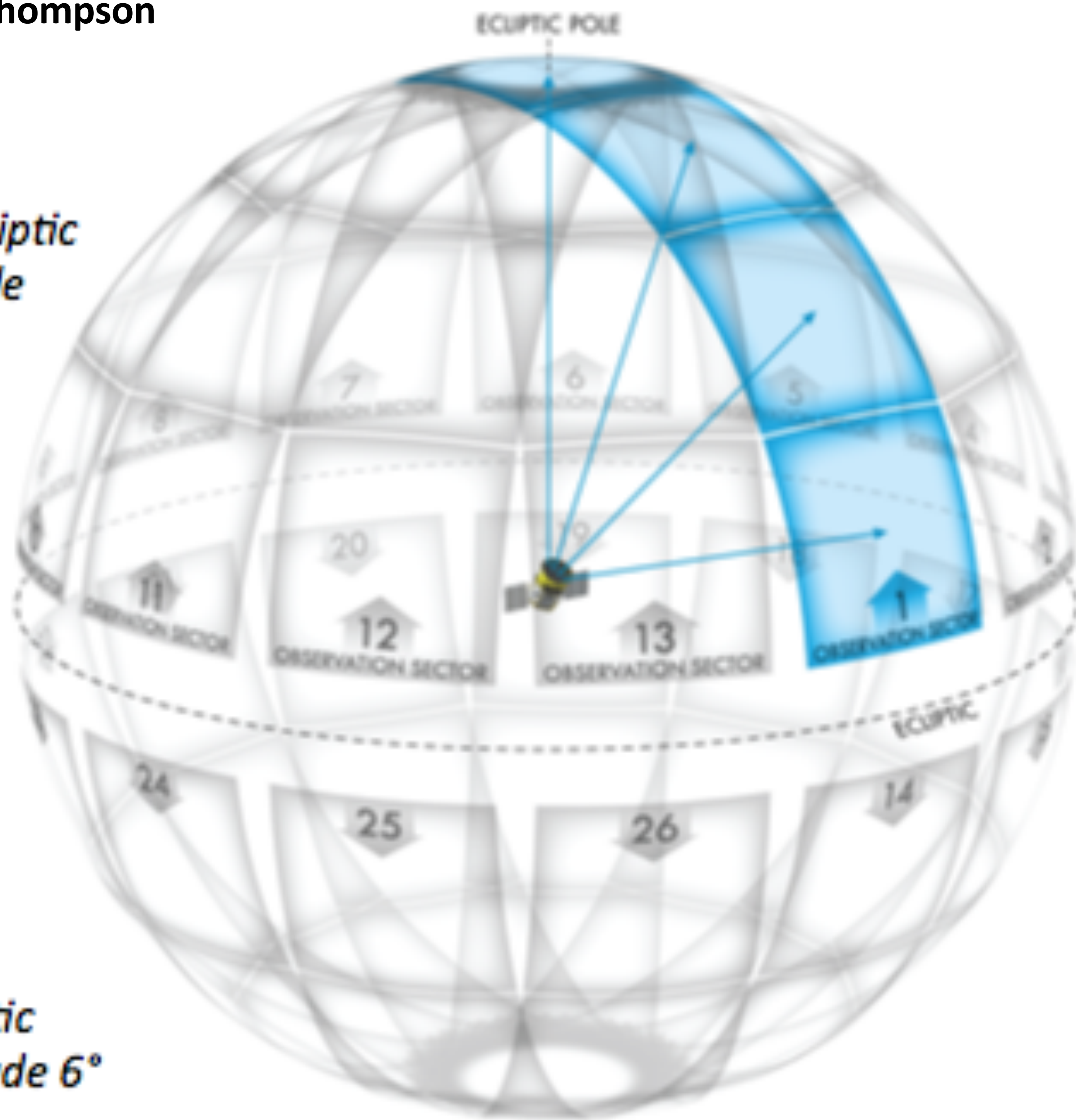
TESS Slides from Zach Berta-Thompson

4 cameras

Ricker et al. (2014), Sullivan et al. (2015)

TESS Slides from Zach Berta-Thompson





Ricker et al. (2014), Sullivan et al. (2015)

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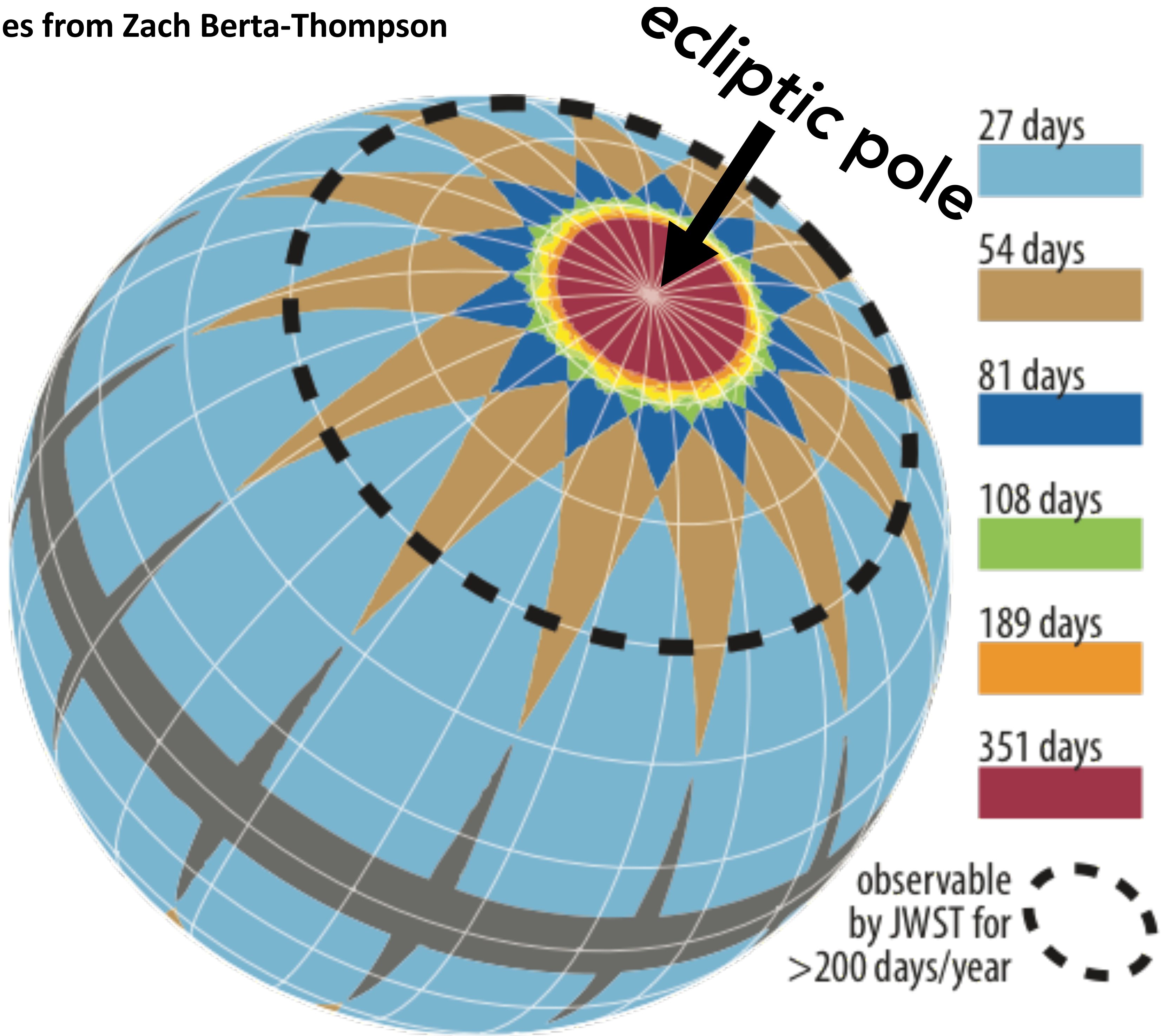
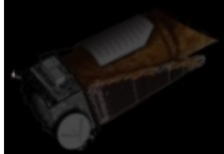


Ricker et al. (2014), Sullivan et al. (2015)

Play TESS Movie

Pathway to Earth 2.0



Constrain planet frequencies ✔

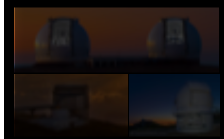
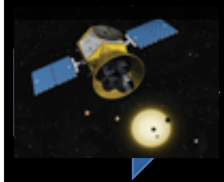


Figure out which sizes of planets are rocky ✔ for hot planets

(Work in progress for cool planets)



Find cool potentially habitable planets

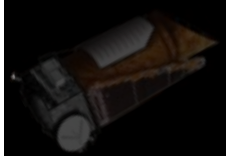
Measure masses to identify rocky worlds

Determine atmospheric compositions

Search for biosignatures

Perform detailed characterization

Pathway to Earth 2.0



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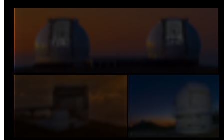

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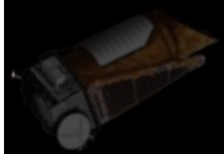

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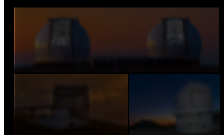

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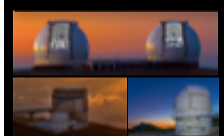

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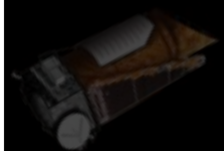

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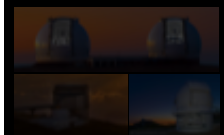

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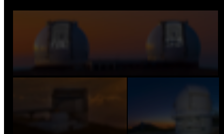

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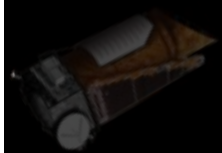

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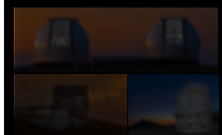

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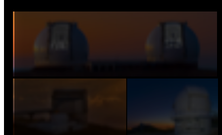

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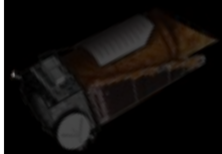

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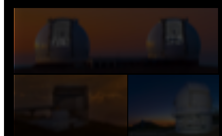

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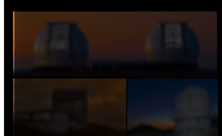

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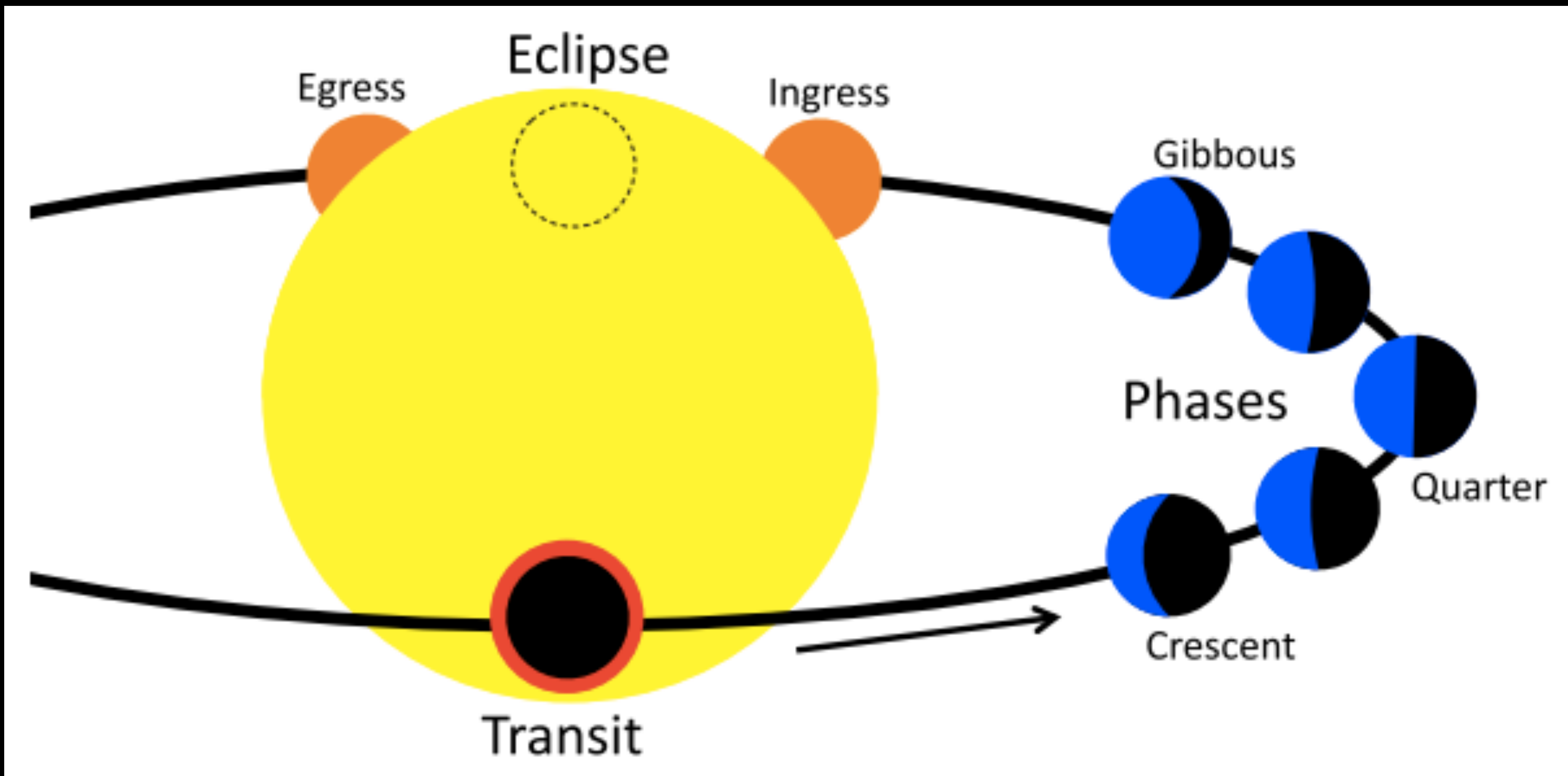
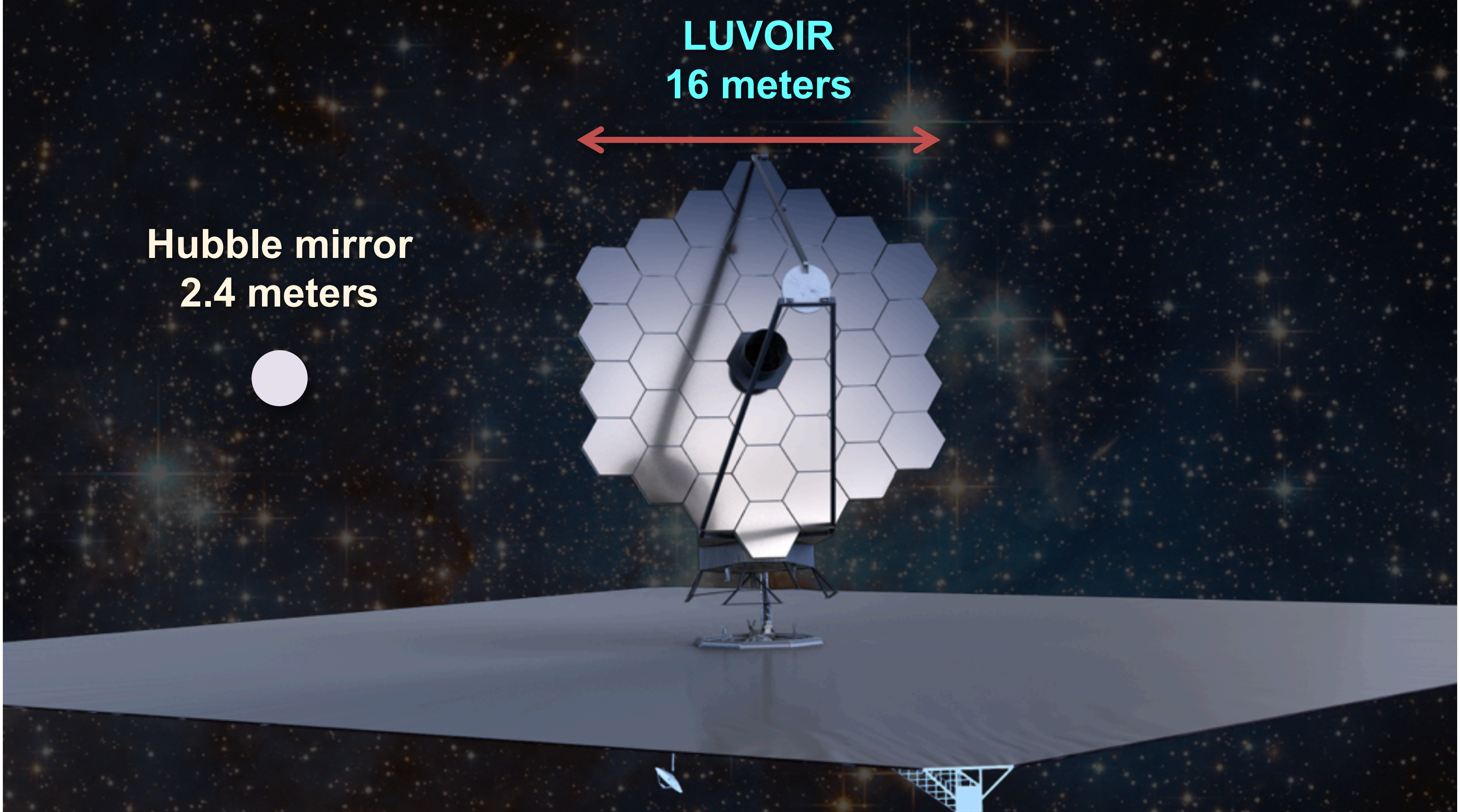
Transits, Eclipses, and Phase Curves of Exoplanets Reveal Atmospheric Properties

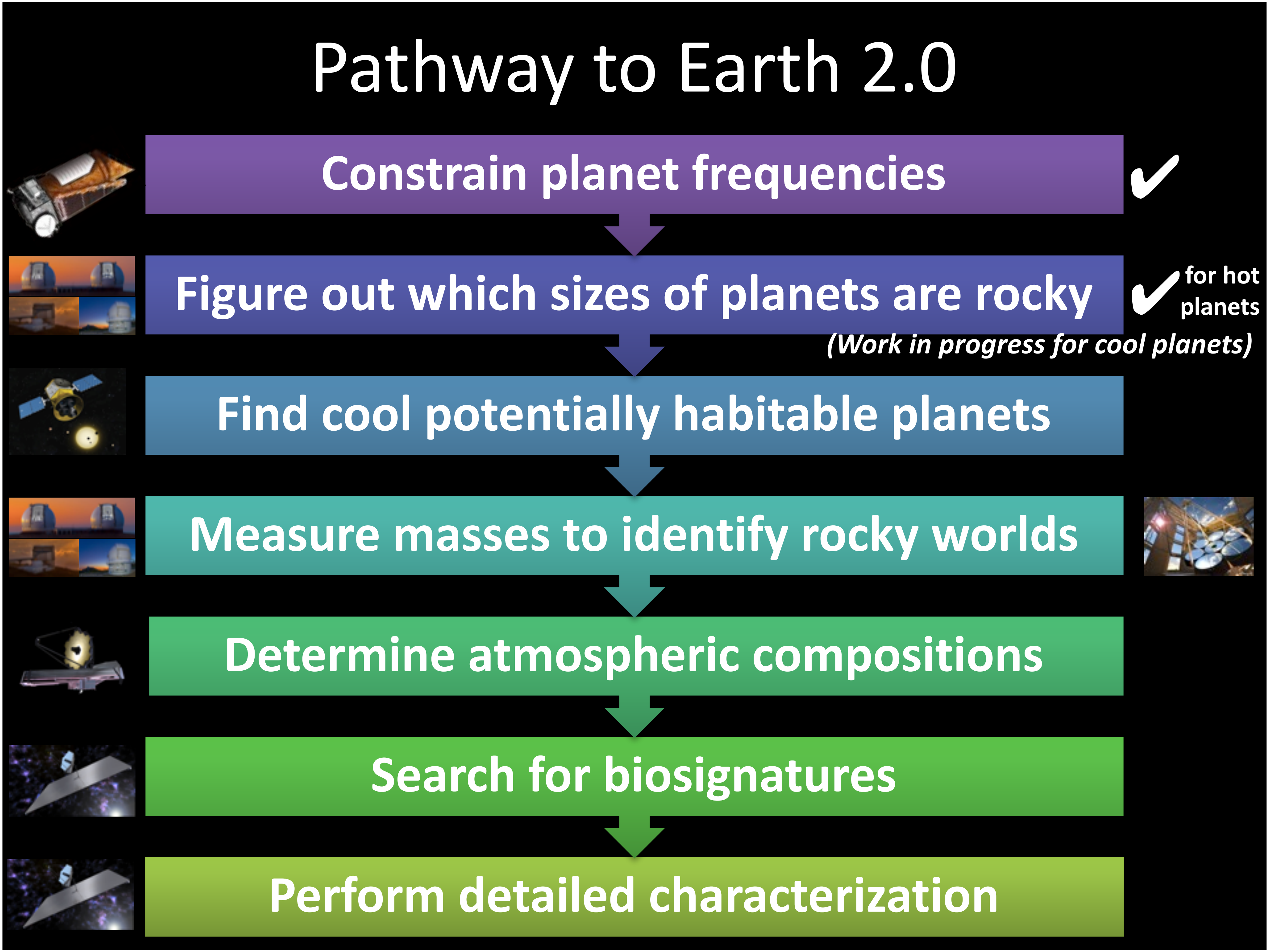


Cowan et al. 2015, PASP, 127, 311

LUVOIR will Assess Planetary Habitability



This is one possible architecture for LUVOIR



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✔
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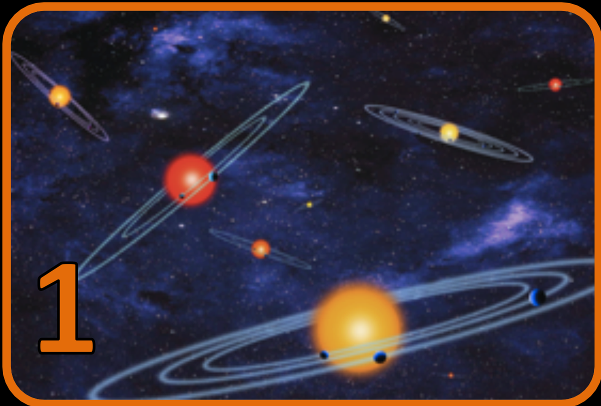
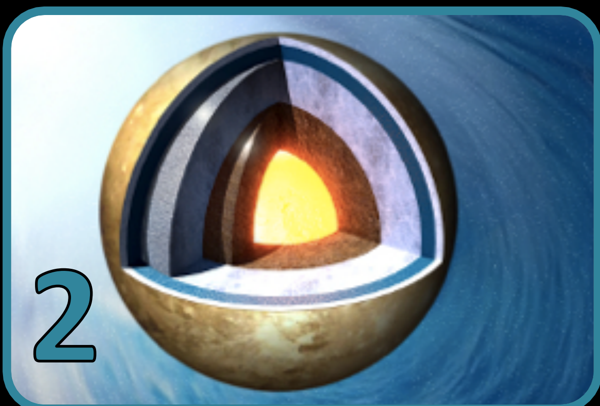
Big Picture Summary



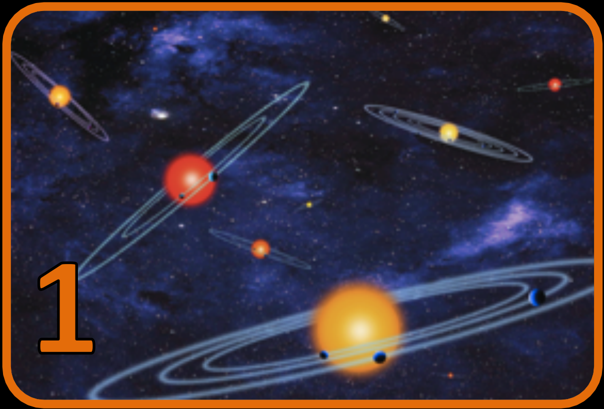
How **common** are *planets orbiting low-mass stars* ?



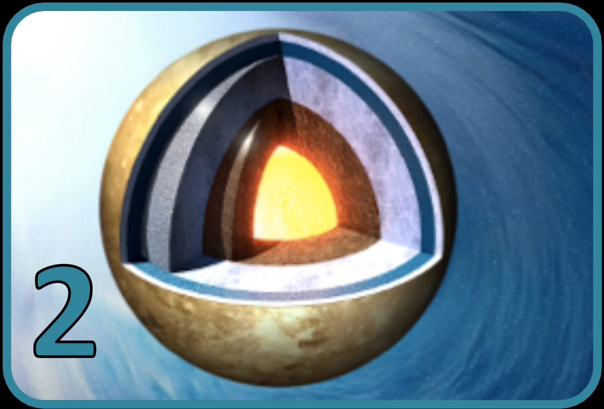
How **diverse** are the *compositions of small planets* ?

How can we **identify** *potentially habitable planets* ?

Big Picture Summary



- **2.5 small planets** per M dwarf
- **0.25 Earth-like planets** per M dwarf



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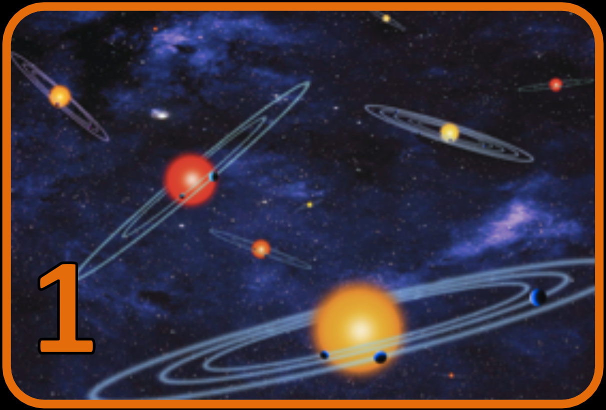

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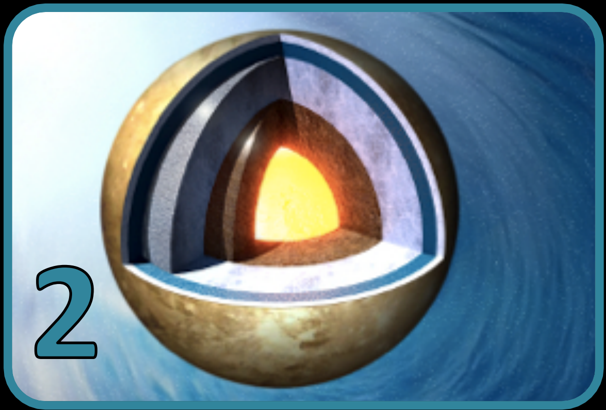

- Highly-irradiated small planets have **Earth-like compositions**
- **Larger planets** require **volatiles**

How can we **identify** ***potentially habitable planets*** **?**

Big Picture Summary

- **2.5 small planets** per M dwarf
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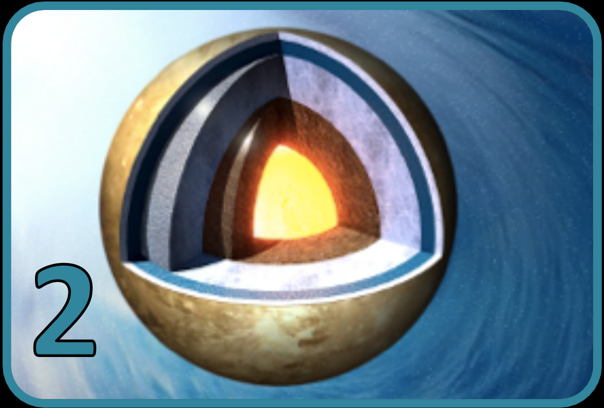

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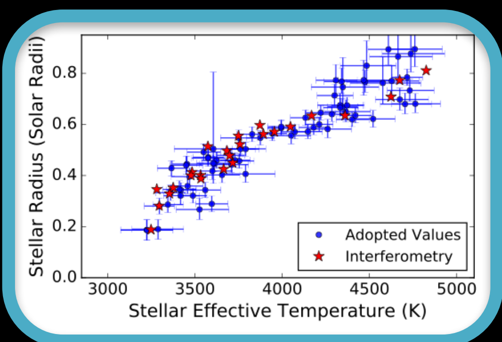
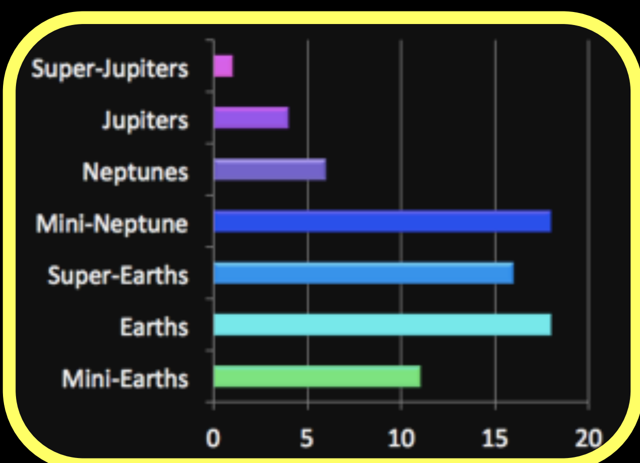
- **Planet detection** with **K2 + TESS**
- **Follow-up** with **JWST + ELTs**
- **Biosignatures** with **LUVOIR?**

K2 Highlights

- We've acquired **NIR spectroscopy of 144 possible low-mass stars** hosting K2 planet candidates
- **51%** of our targets are actually **low-mass dwarfs**



- Classified stars using **empirical relations** based on **interferometry** (Newton+ 2015, Mann+ 2013)
- Our **revised stellar radii** are **6-39% larger**



- **63 planets** are **smaller than Neptune**
- **3 planets** are **in or near** the **habitable zone**
- **Red dwarfs** have lots of **small planets!**

K2 planets are great for follow-up studies!

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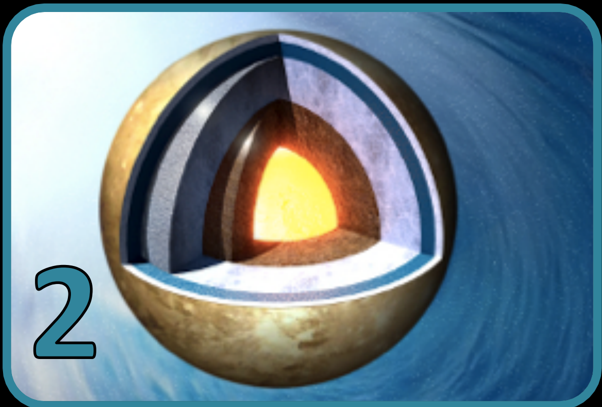
Big Picture Summary

- **2.5 small planets** per M dwarf
- **0.25 Earth-like planets** per M dwarf

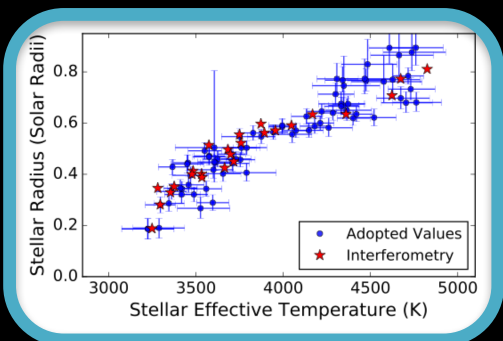


- Highly-irradiated small planets have **Earth-like compositions**
- **Larger planets** require **volatiles**

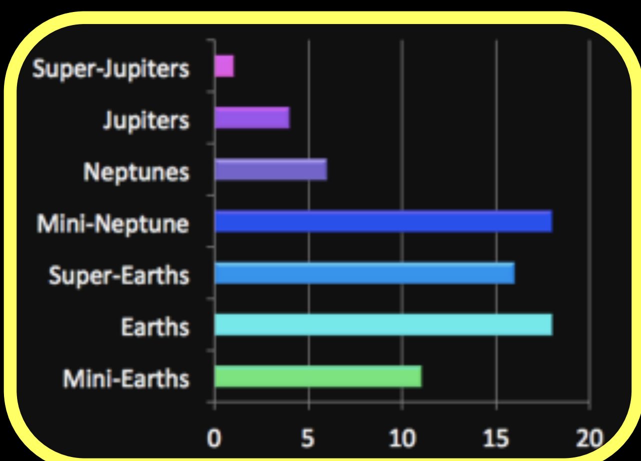
- **Planet detection** with **K2 + TESS**
- **Follow-up** with **JWST + ELTs**
- **Biosignatures** with **LUVOIR?**

K2 Highlights

- We've acquired **NIR spectroscopy of 144 possible low-mass stars** hosting K2 planet candidates
- **53%** of our targets are actually **low-mass dwarfs**



- Classified stars using **empirical relations** based on **interferometry** (Newton+ 2015, Mann+ 2013)
- Our **revised stellar radii** are **6-39% larger**



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ADDITIONAL SLIDES

Most TESS Planets will be Inside the IWA

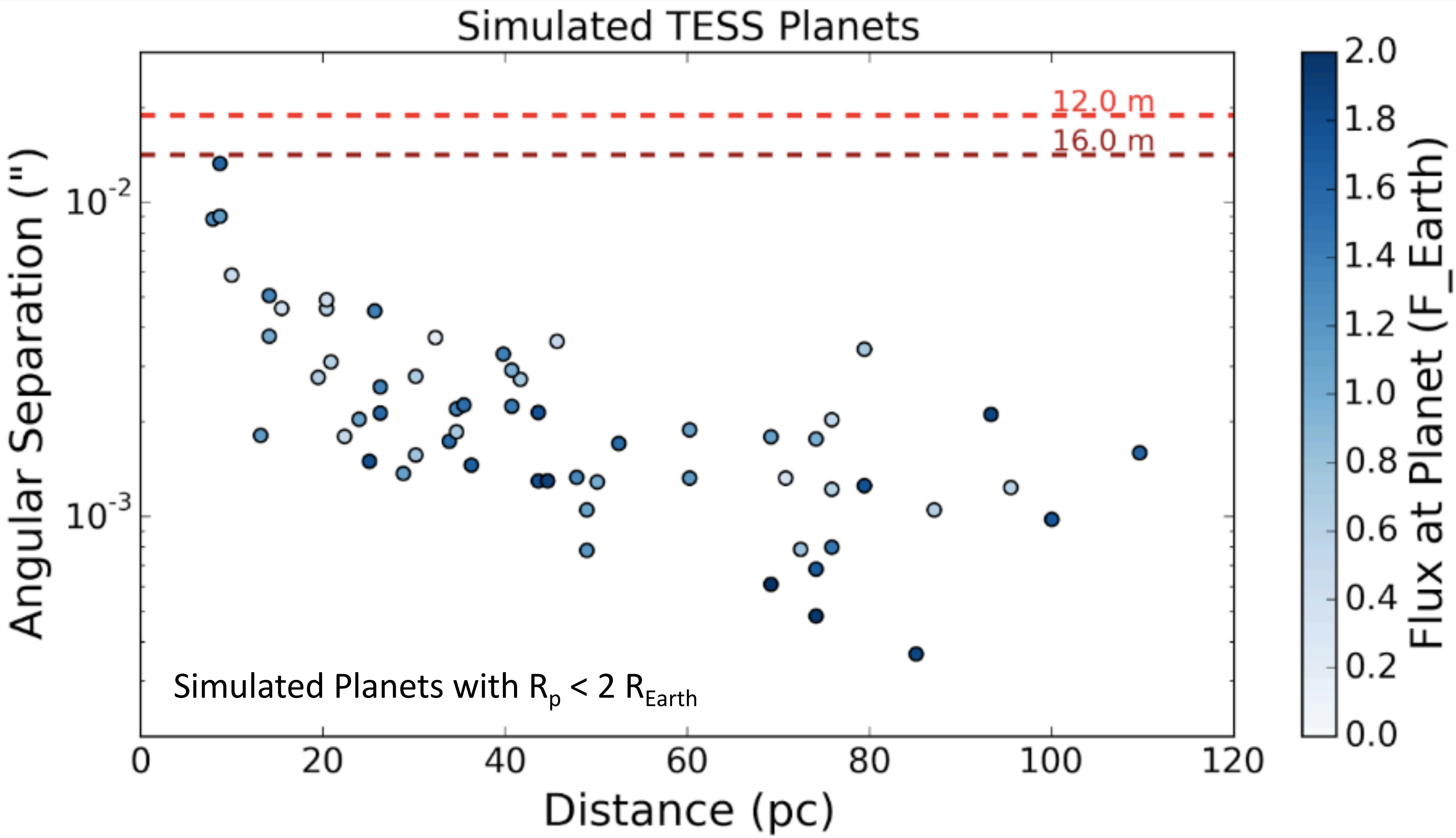


Figure 2.1.1 from the Habitability Science Case
Simulated Planets from Sullivan et al. (2015)

Some M Dwarf HZs will be Accessible

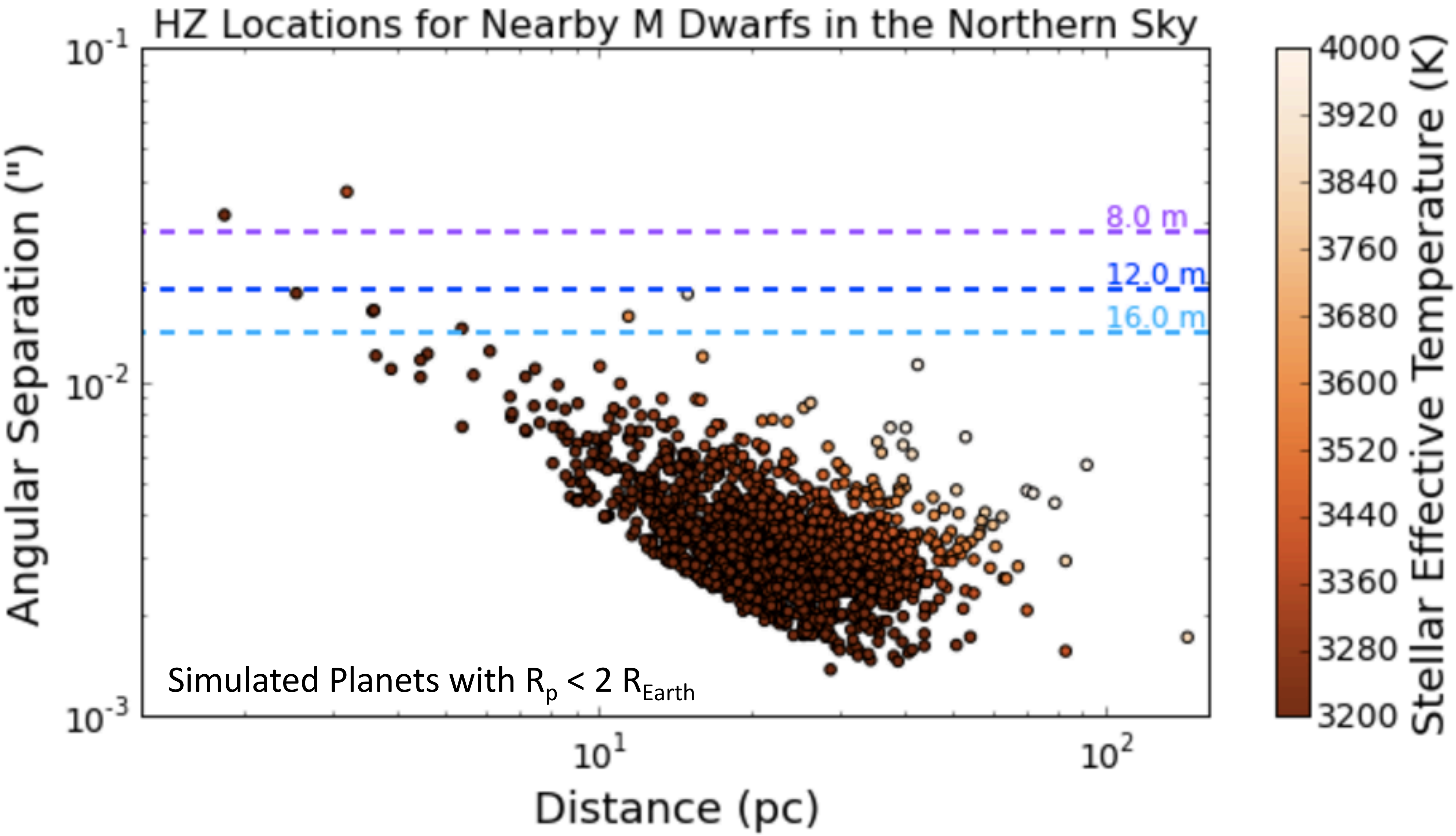
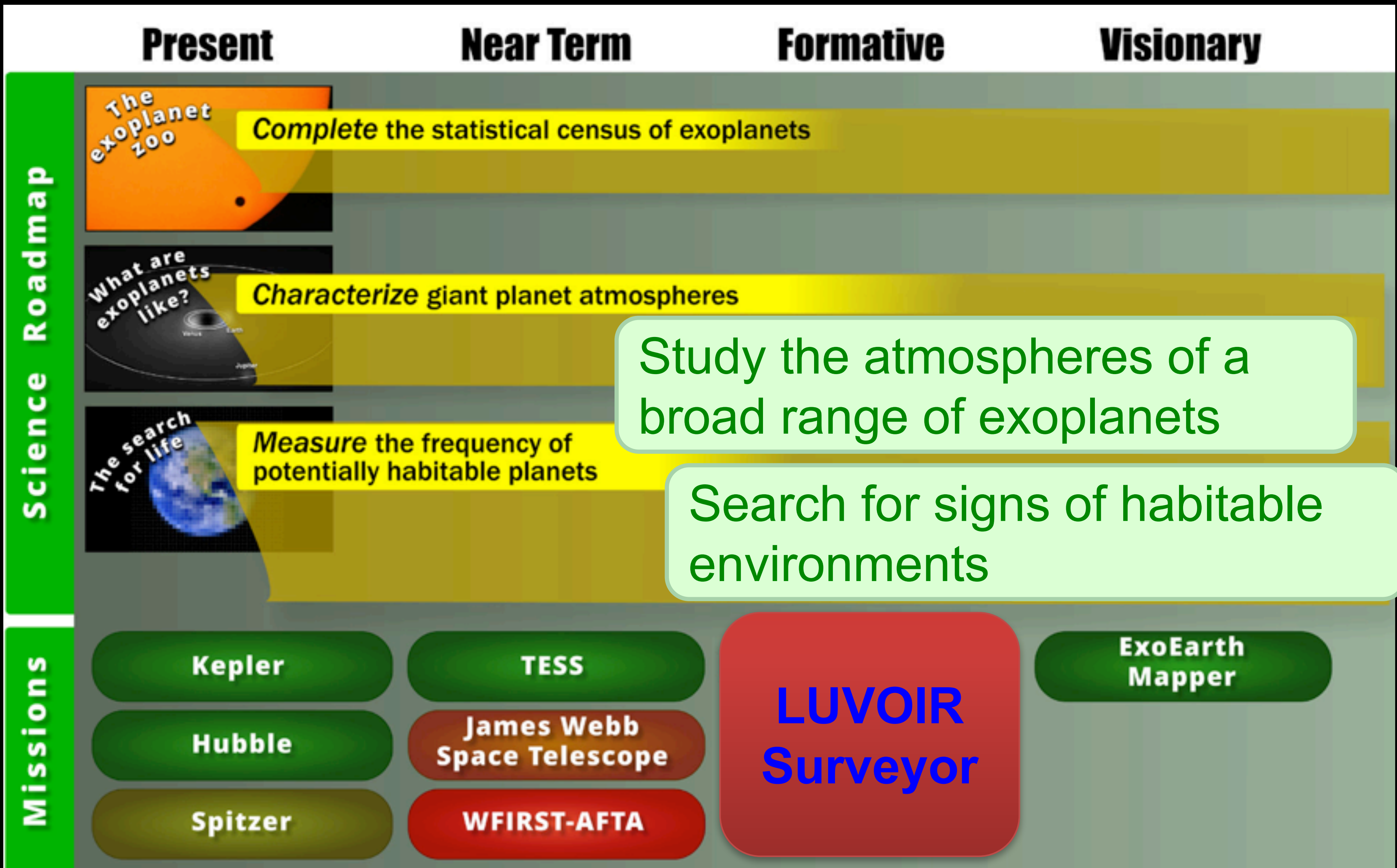
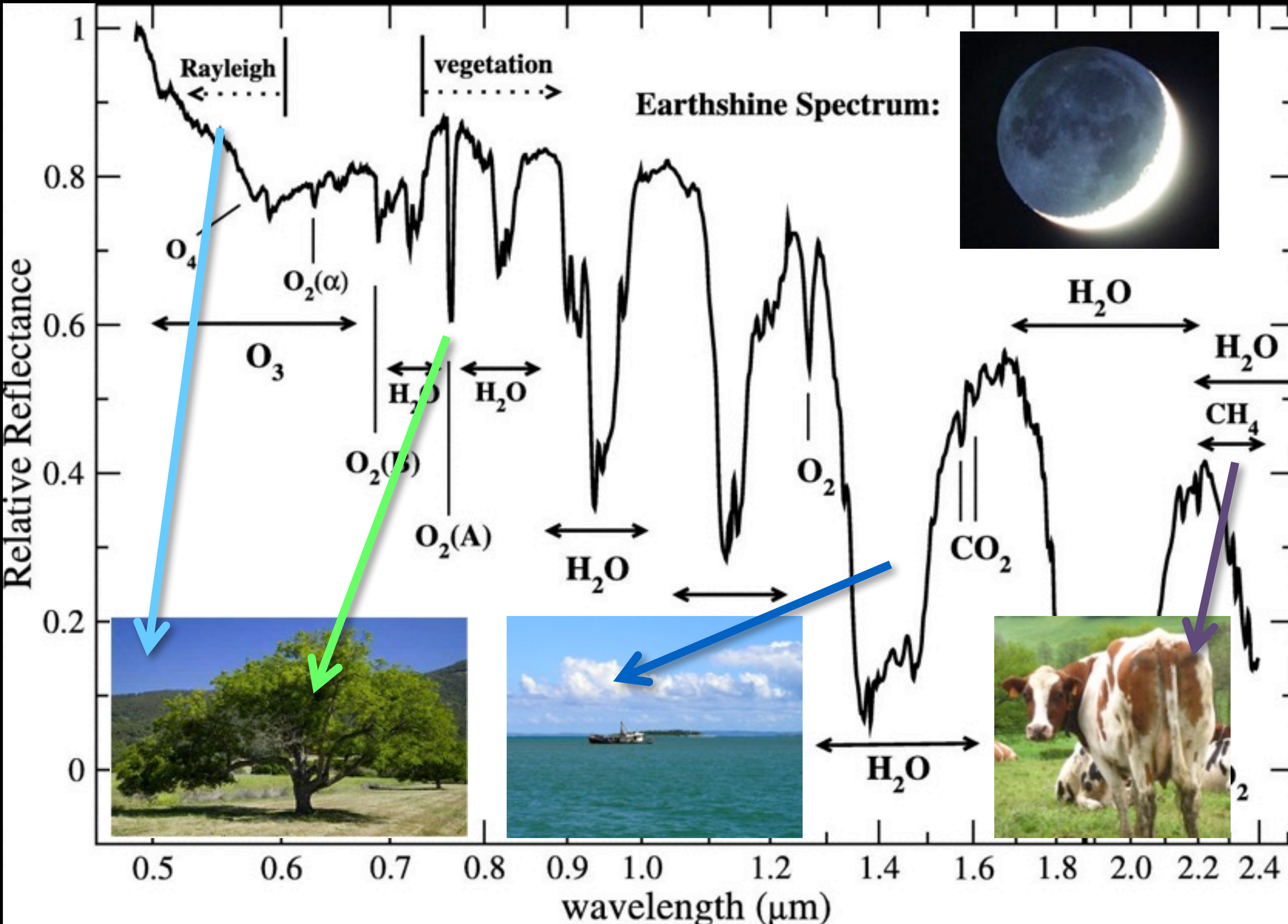


Figure 2.1.2 from the Habitability Science Case
Stars from Dittmann et al. (2015)

Exoplanet science goals in Roadmap

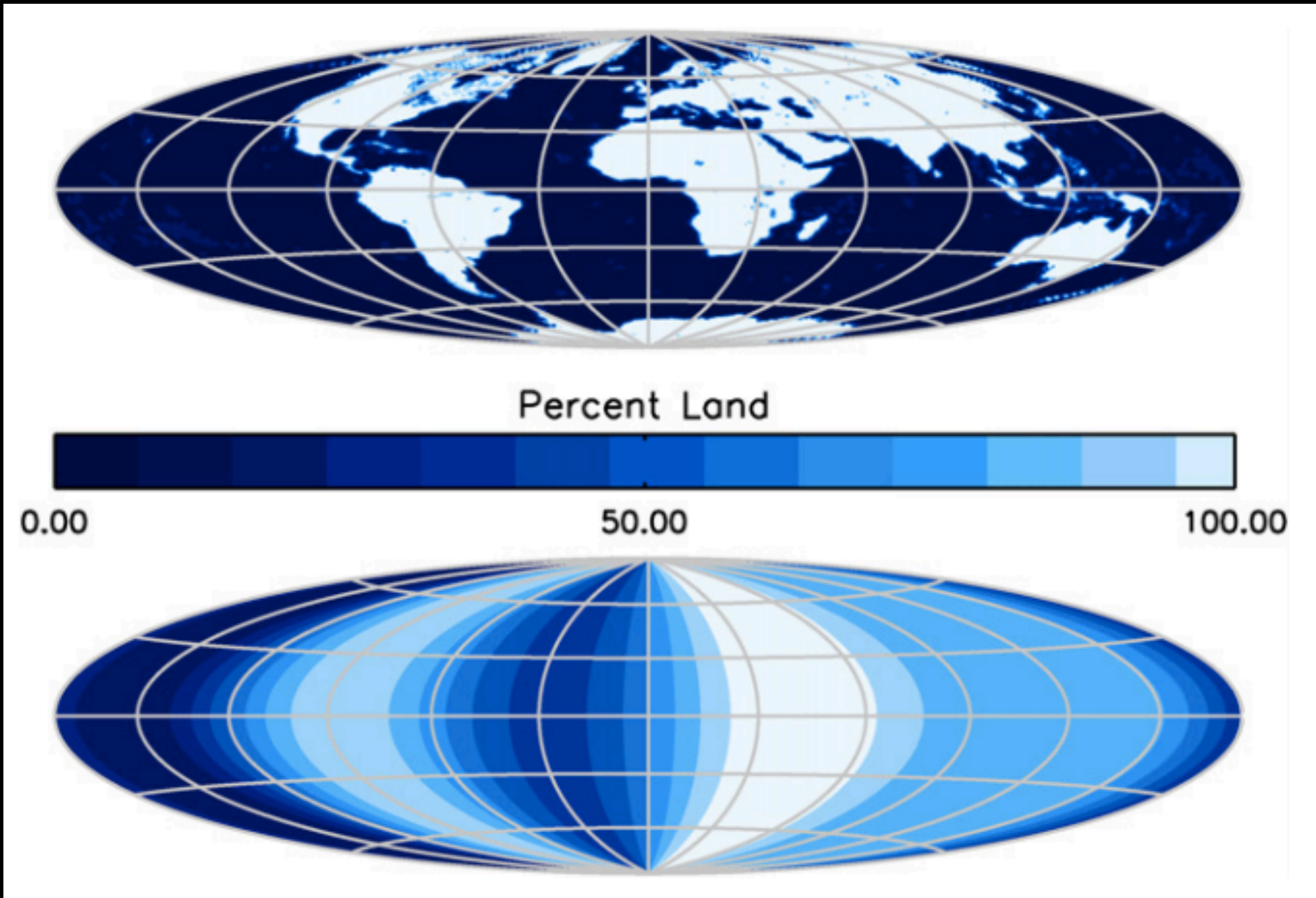


How do we detect life on an exoplanet?



Turnbull et al. (2006)

Observations with Large Space Telescopes Could Generate Coarse Surface Maps



Cowan et al. 2009, ApJ, 700, 915

The M Dwarf Advantage

Detectability of Earth-like planet	Sun	*Kepler* M dwarf	Typical M dwarf
Orbital Period (days)	365	80	17
Transit Probability (%)	0.46	0.89	1.41
Transit Depth (ppm)	84	250	1890
Doppler Wobble (cm/s)	9	21	85

Spectroscopic investigations could expose potentially habitable worlds