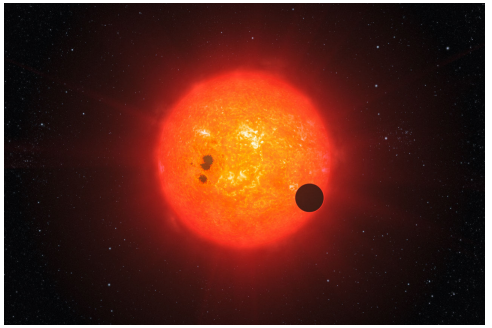
The Intervening Decade

David Charbonneau, Harvard University

ESO E-ELT Exoplanet Workshop, 5 February 2014

My Goals for Today



- Define the characteristics of an Earth-like planet
- Summarize our knowledge of the occurrence of Earth-like planets
- Survey searches for nearby transiting Earth-like planets
- Situate the E-ELT in its likely 2024 exoplanet landscape

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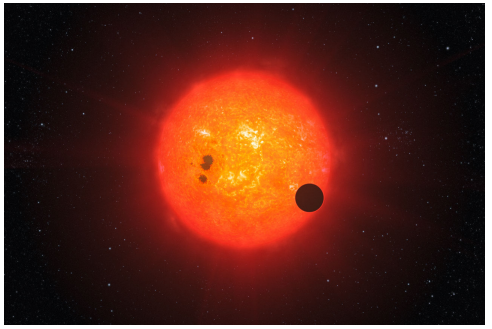

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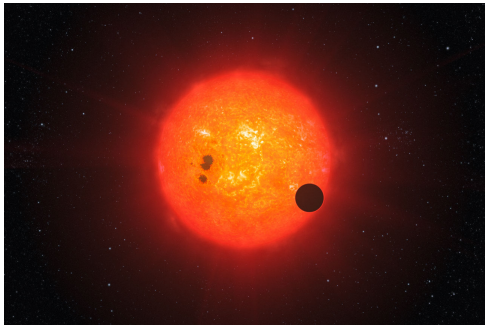

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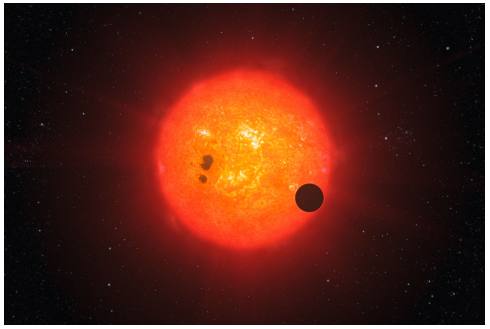

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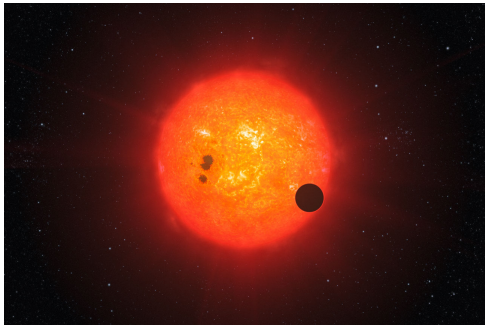

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Earth-Like

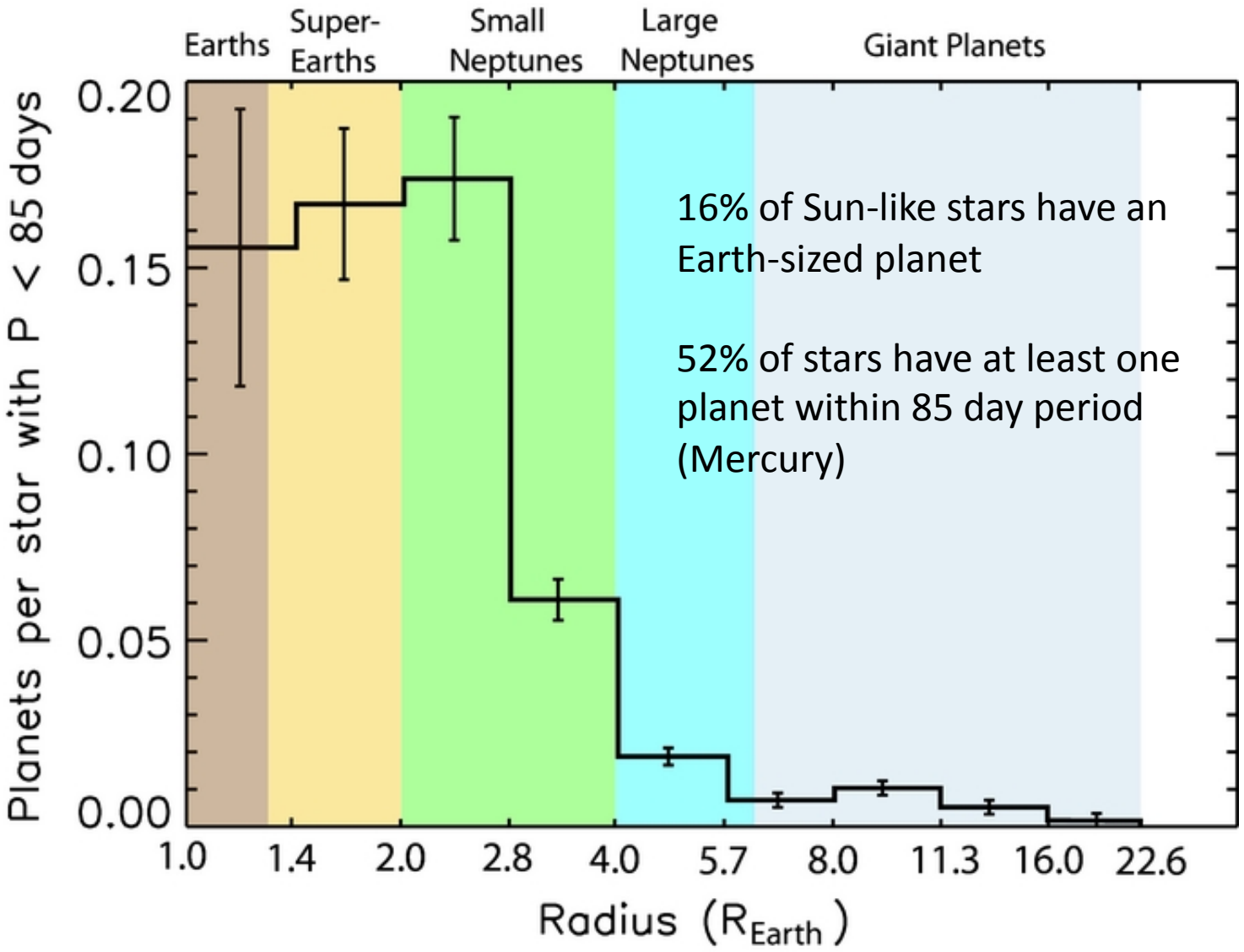
What is the range of radii over which planets are rocky?

(a question for observers)

What is the range of insolation over which planets have liquid surface water?

(a question for theorists)

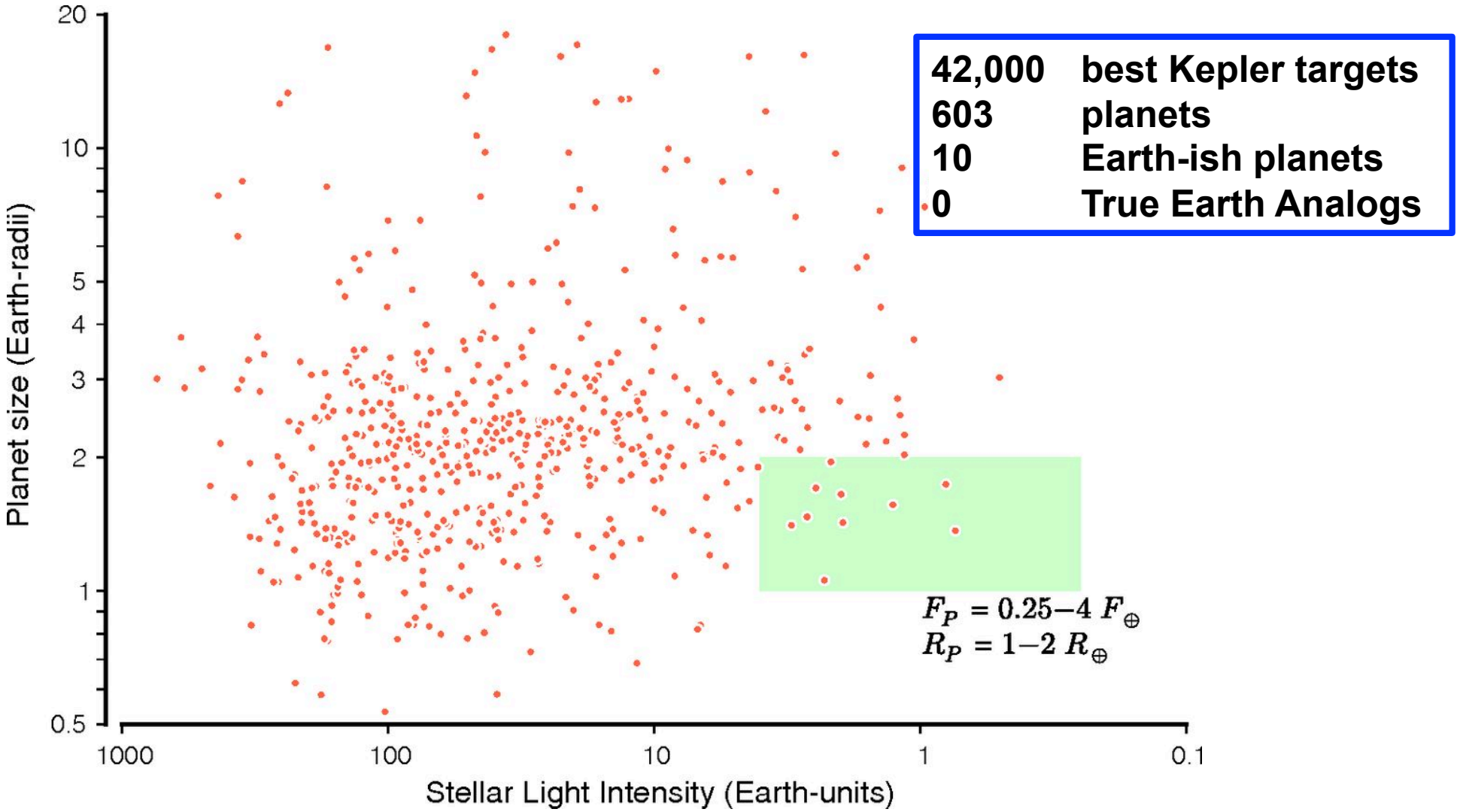
The Planet Radius Distribution



Fressin, Torres, Charbonneau et al. (2013)

(Two Slides Redacted)

How Common Are Earths Around Sun-like Stars?



Petigura, Howard & Marcy (2013)

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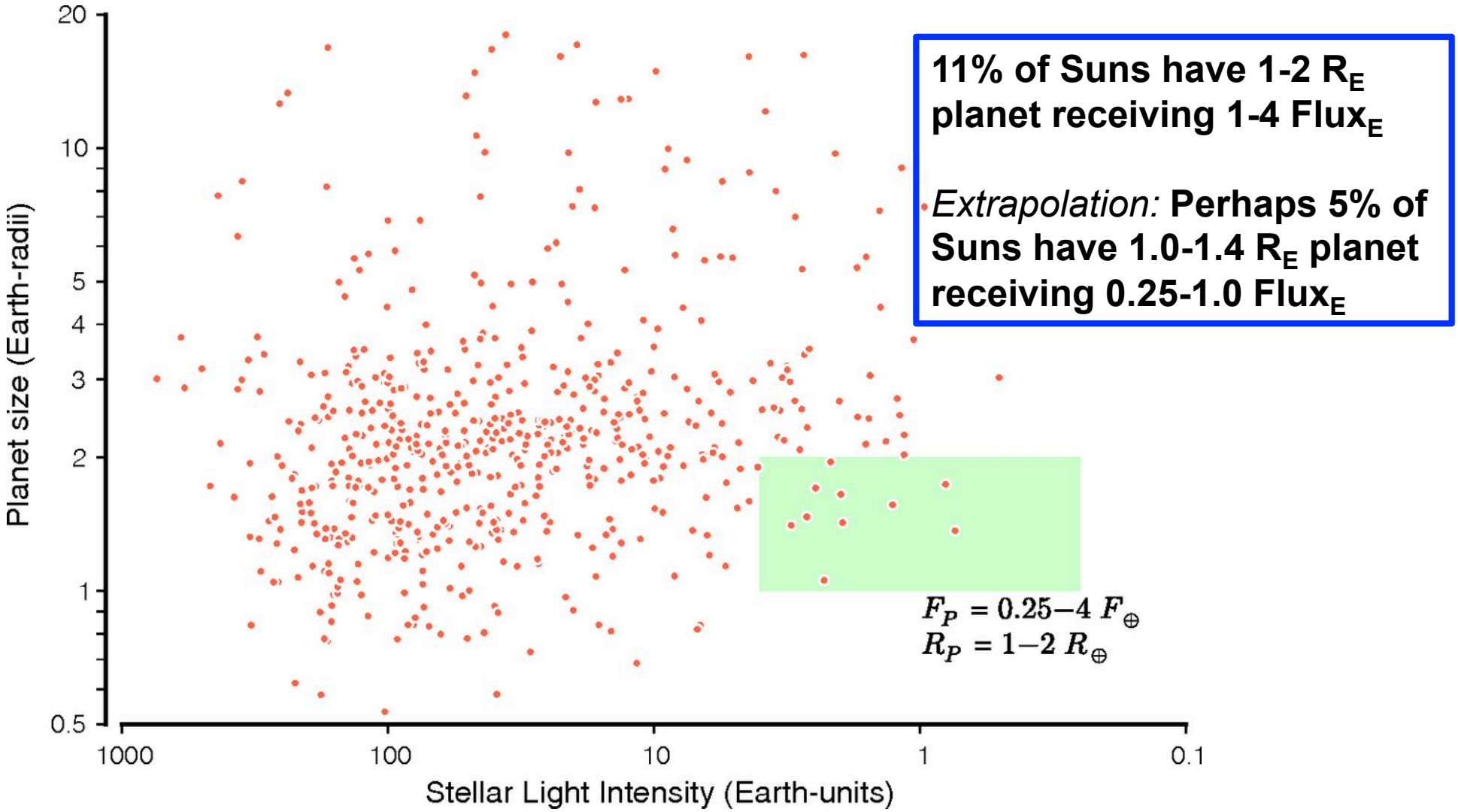
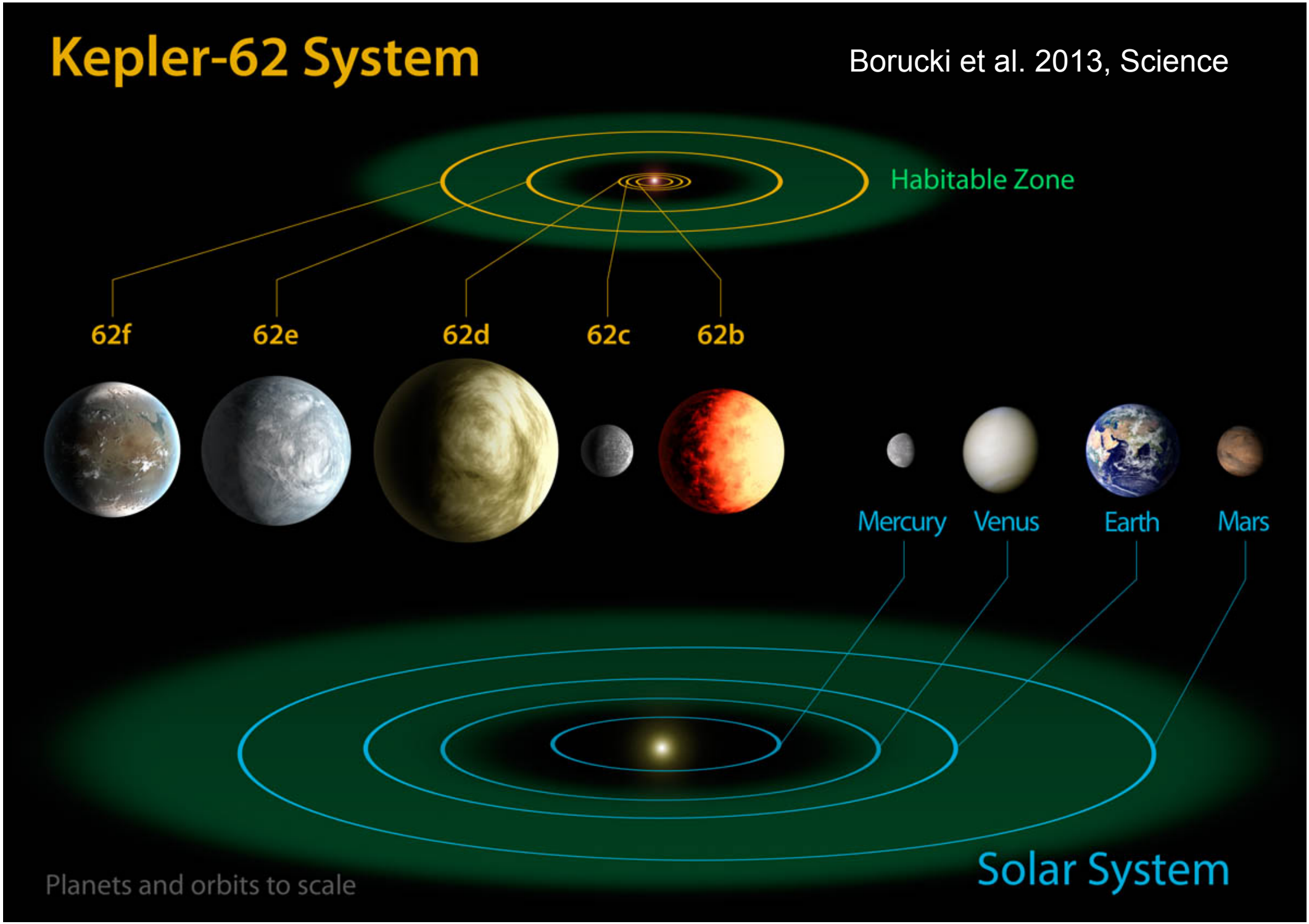


11% of Suns have 1-2 R_E planet receiving 1-4 $Flux_E$

Extrapolation: **Perhaps 5% of Suns have 1.0-1.4 R_E planet receiving 0.25-1.0 $Flux_E$**

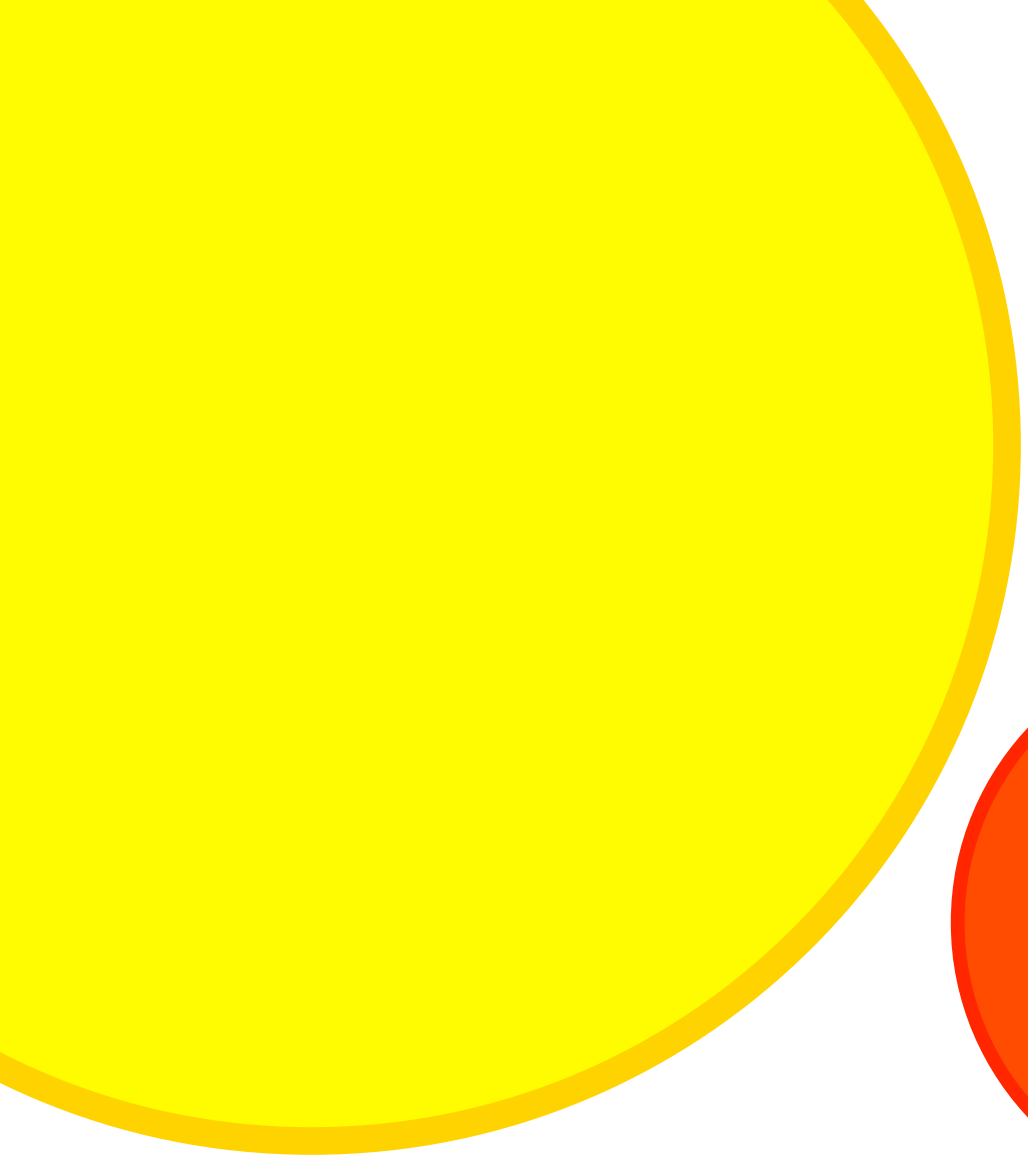
Petigura, Howard & Marcy (2013)


Kepler-62 System
Borucki et al. 2013, Science
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale

M Dwarf Properties

--sizes to scale--

0.07 < mass < 0.6 M_{sun}

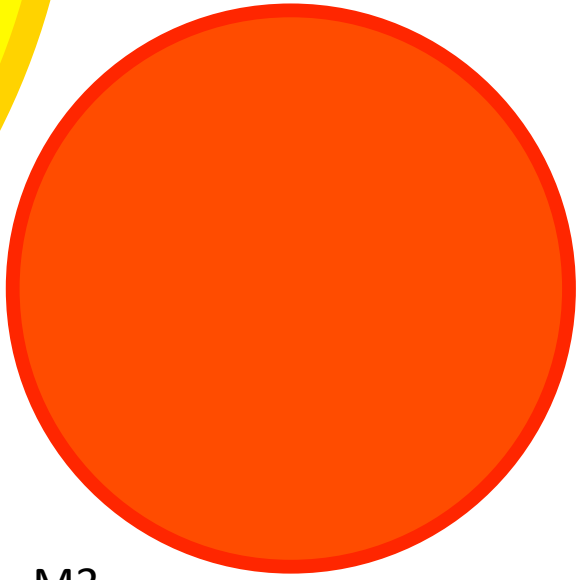


G2

M = 1 M_{sun}

R = 1 R_{sun}

T = 5800 K



M3

M = 0.45 M_{sun}

R = 0.45 R_{sun}

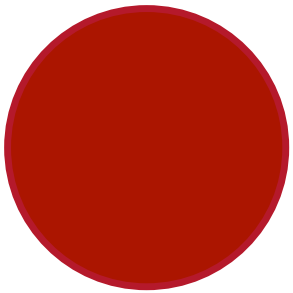
T = 3500 K

M6

M = 0.12 M_{sun}

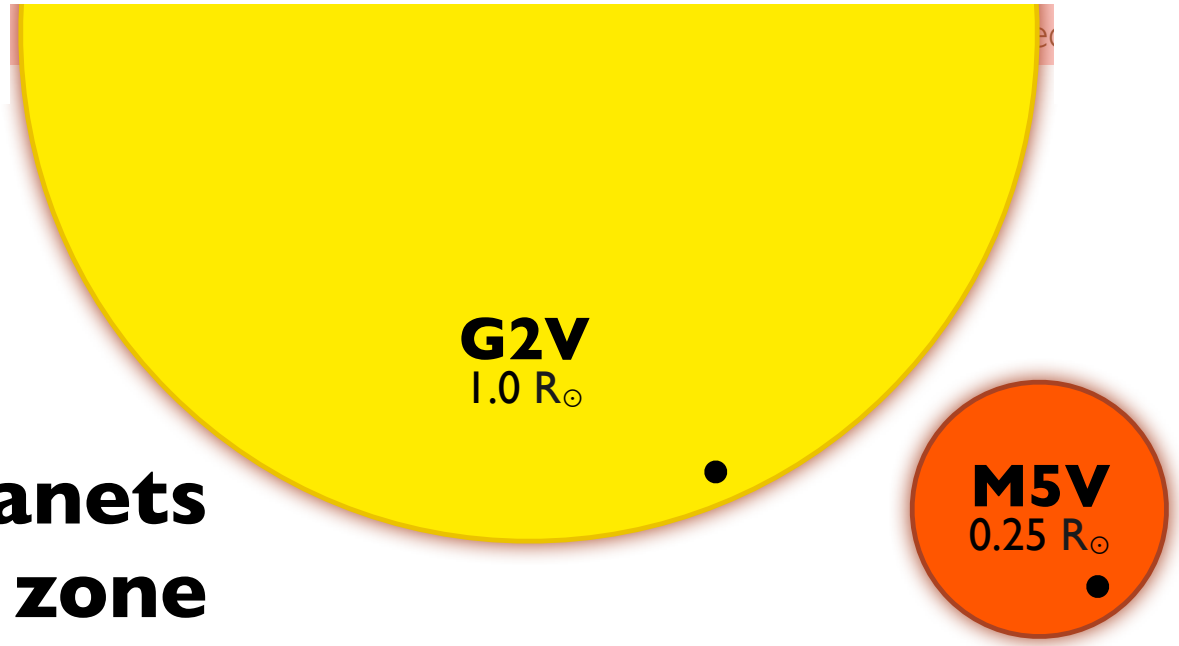
R = 0.18 R_{sun}

T = 2900 K



Earth

Slide by Jacob Bean



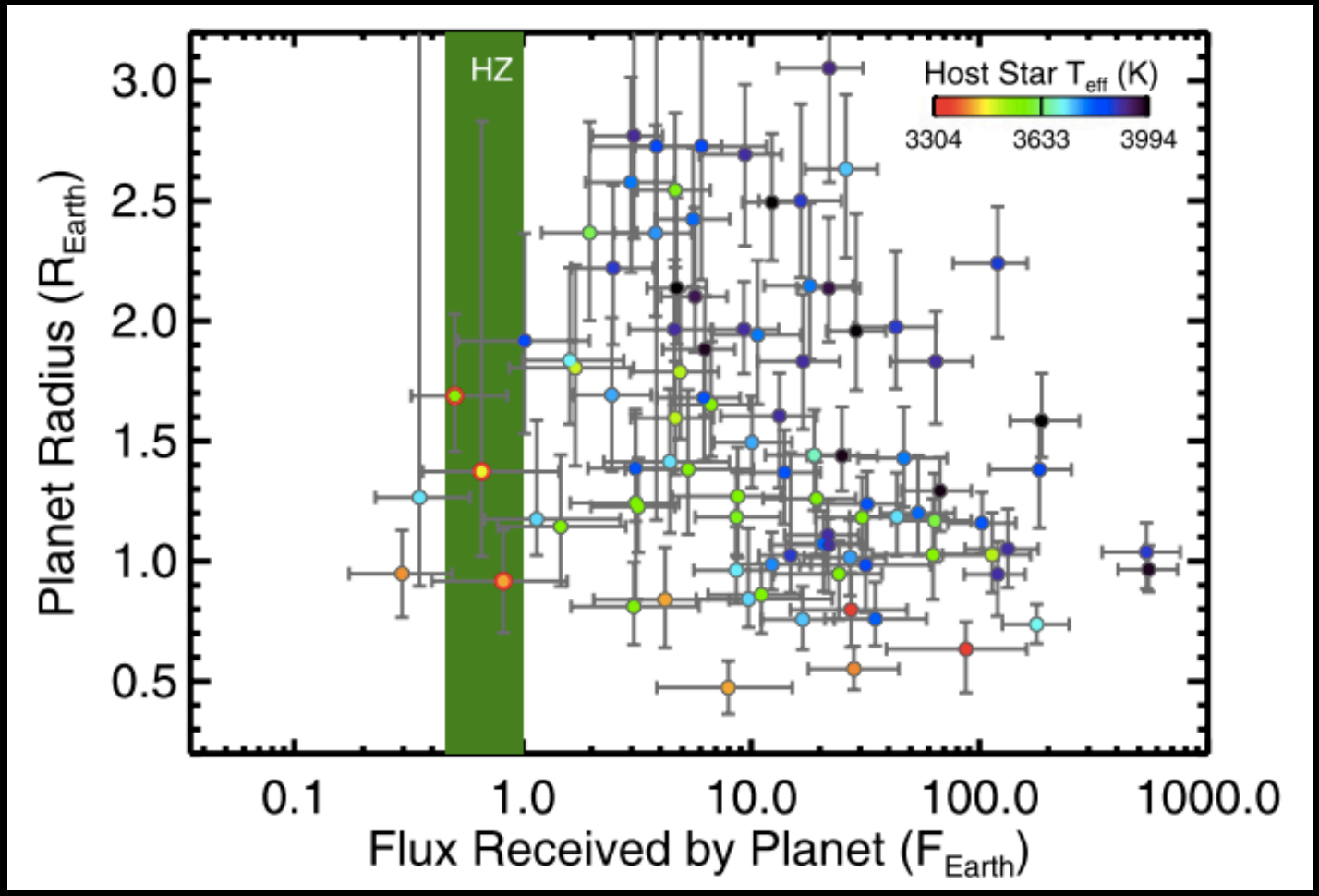
super-Earth planets in the **habitable zone**

2 $R_\oplus$, 7 $M_\oplus$, Earth-like insolation

transit depth =	**0.03%**	**0.5%**
Doppler wobble =	**60 cm/s**	**5 m/s**
transit probability =	**0.5%**	**1.5%**
orbital period =	**1 year**	**2 weeks**

Nutzman & Charbonneau (2008)

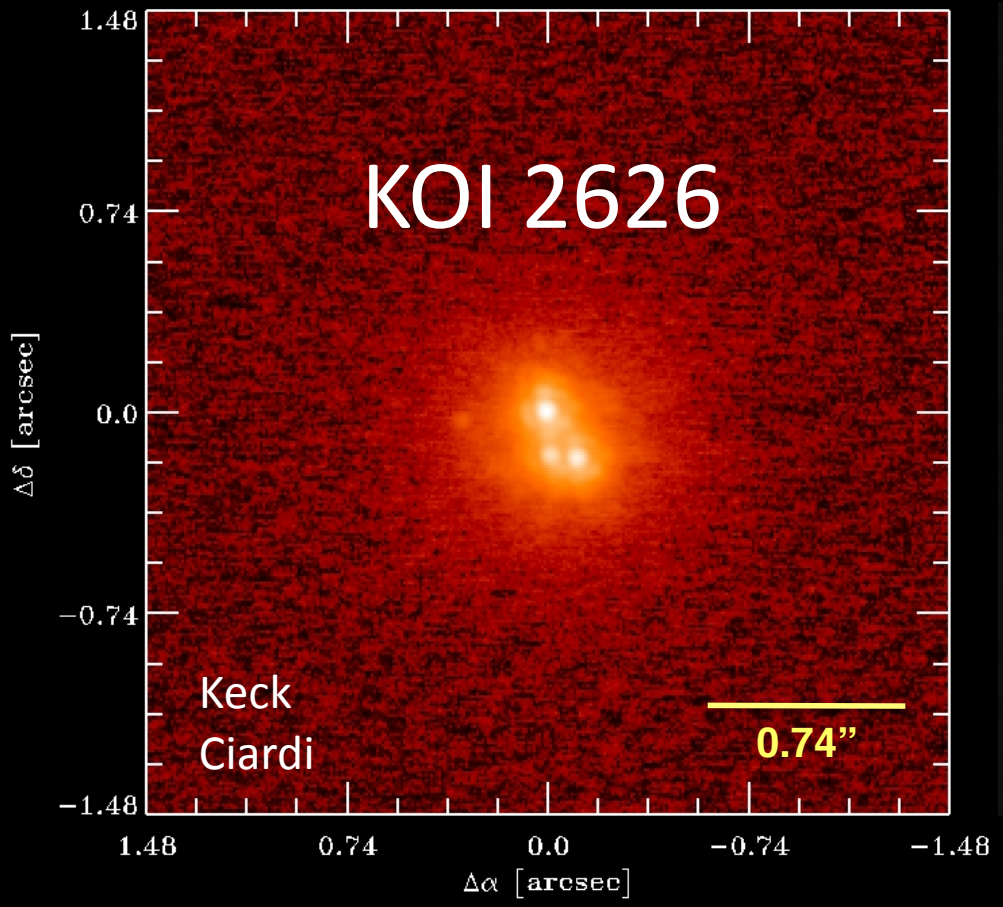
M Dwarf Planet Occurrence Estimate using Kepler Q1-Q6 Data

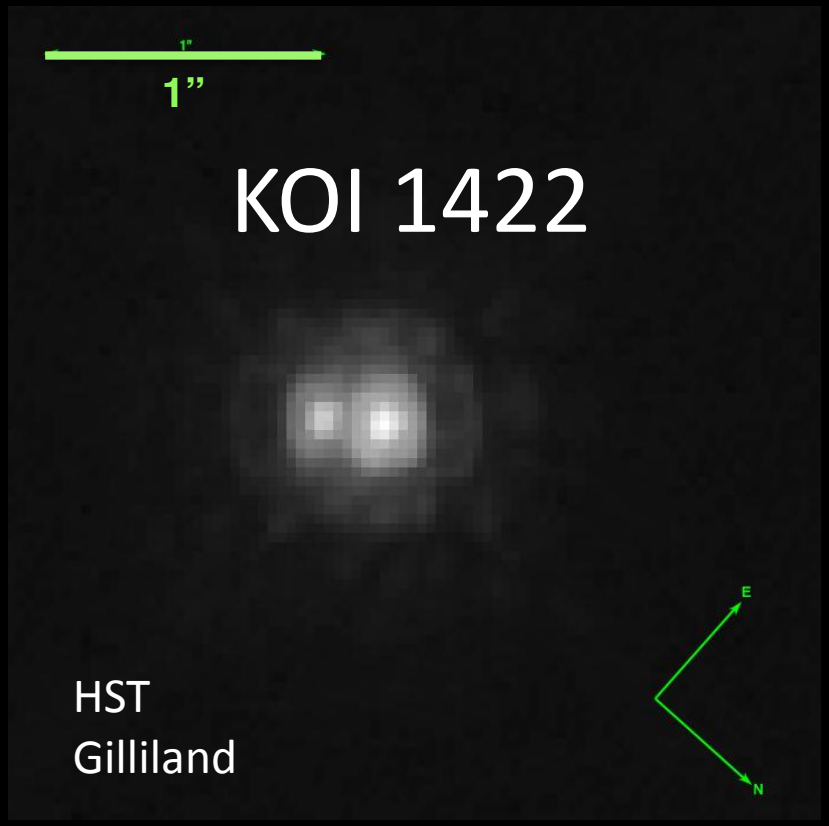


0.15 (+0.13/-0.06) **Earth-size planets per HZ**

Dressing & Charbonneau 2013, *ApJ*, 767, 95

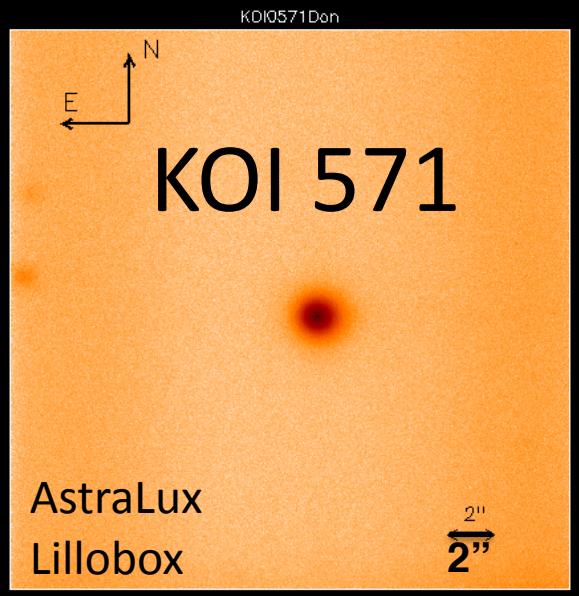
Follow-Up Images of Potentially Habitable KOIs

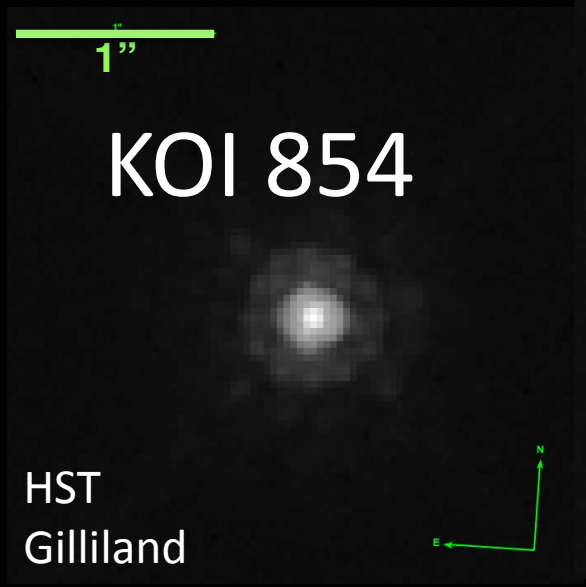


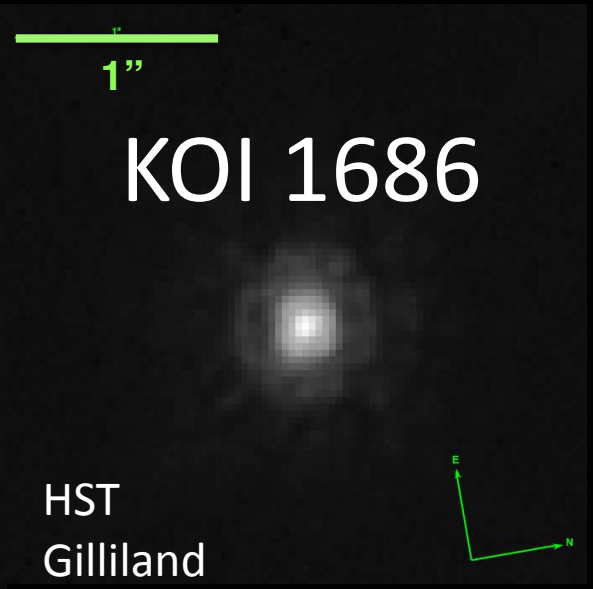


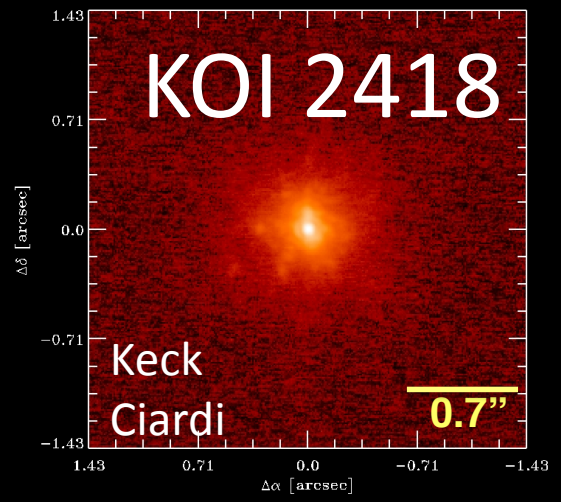
CFOP
Kepler Community Follow-up Observing Program

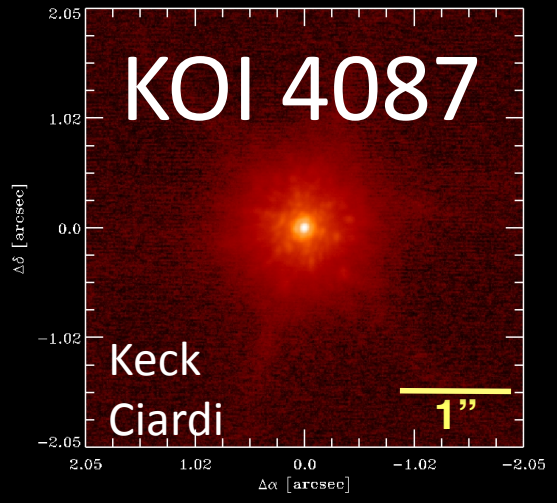
Follow-Up Images of Potentially Habitable KOIs







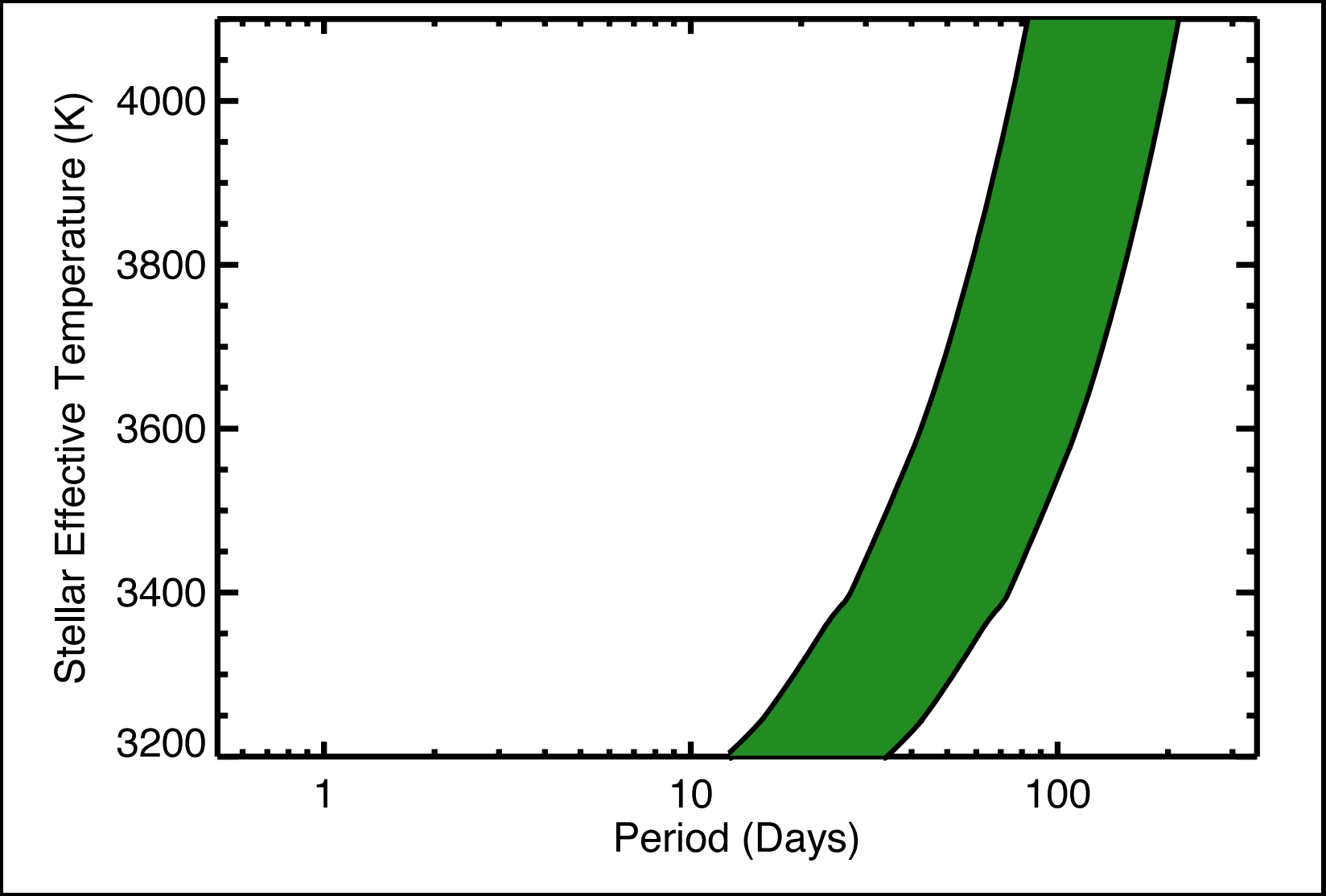




All images from the Kepler Community Follow-up Observing Program (CFOP) website

(Two Slides Redacted)

Updated Estimate Using Q1-12 Data & New HZ Boundaries



HZ: Kopparapu et al. 2013, *ApJ* 765: 131

Stellar Models: Dotter et al. 2008, *ApJS*, 178, 89

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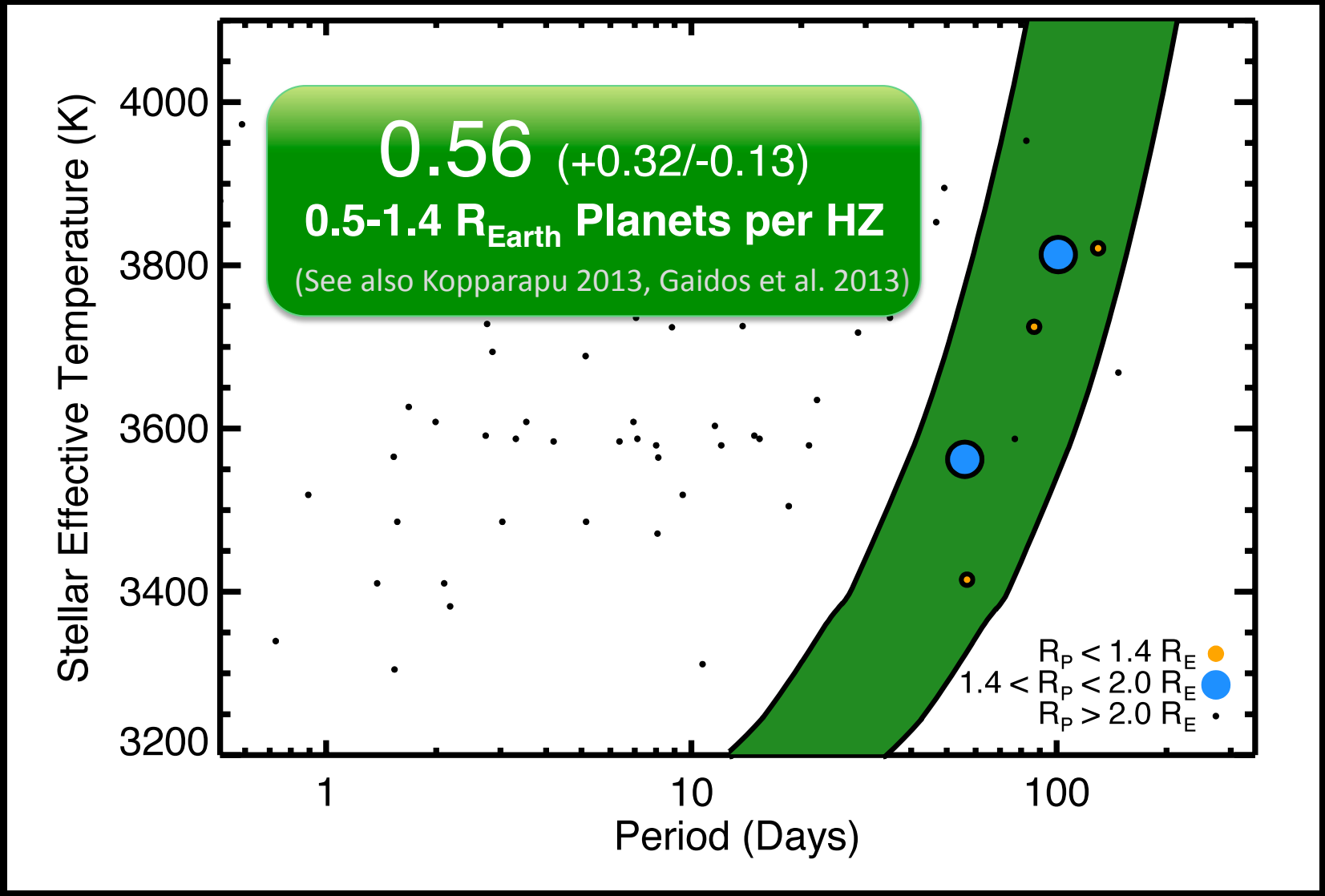


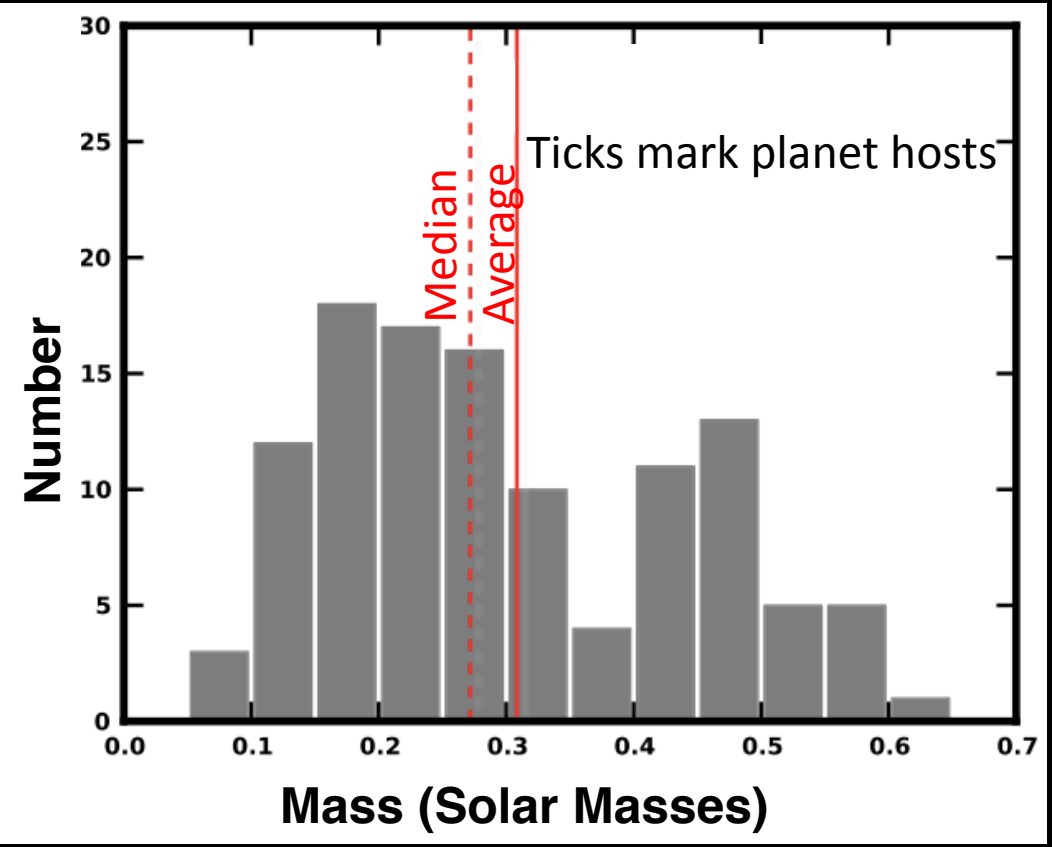
Planet Candidates: Q1-Q12 KOI List

HZ: Kopparapu et al. 2013, *ApJ* 765: 131

Stellar Models: Dotter et al. 2008, *ApJS*, 178, 89

Bonfils et al. 2013: Sensitivity

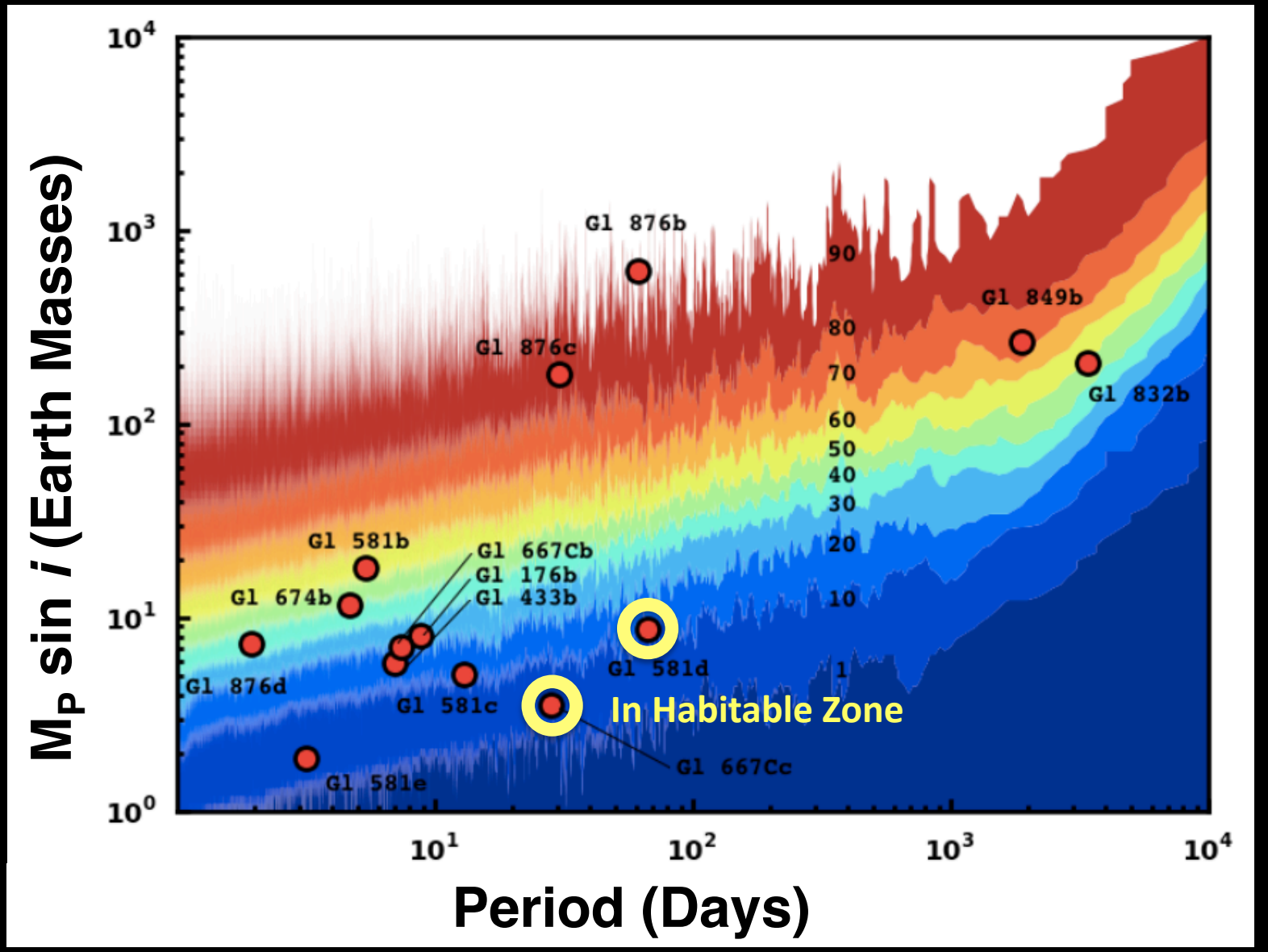
- 6-year RV search with HARPS
- 102 M Dwarfs in volume-limited sample



Found
14 planets
orbiting
8 stars

Bonfils et al. 2013, *A&A*, 549, A109

Bonfils et al. 2013: Sensitivity



Bonfils et al. 2013, *A&A*, 549, A109

Bonfils et al. 2013: Habitable Zone

- Two planets within Habitable Zone (Selsis et al. 2007) with $1 < m \sin i < 10$ M_{Earth}
  - Gl 581d
  - Gl 667Cc
- Sensitive to HZ planets orbiting 4.84 stars
- Occurrence rate = 0.41 (+0.54/-0.13) HZ planets per star

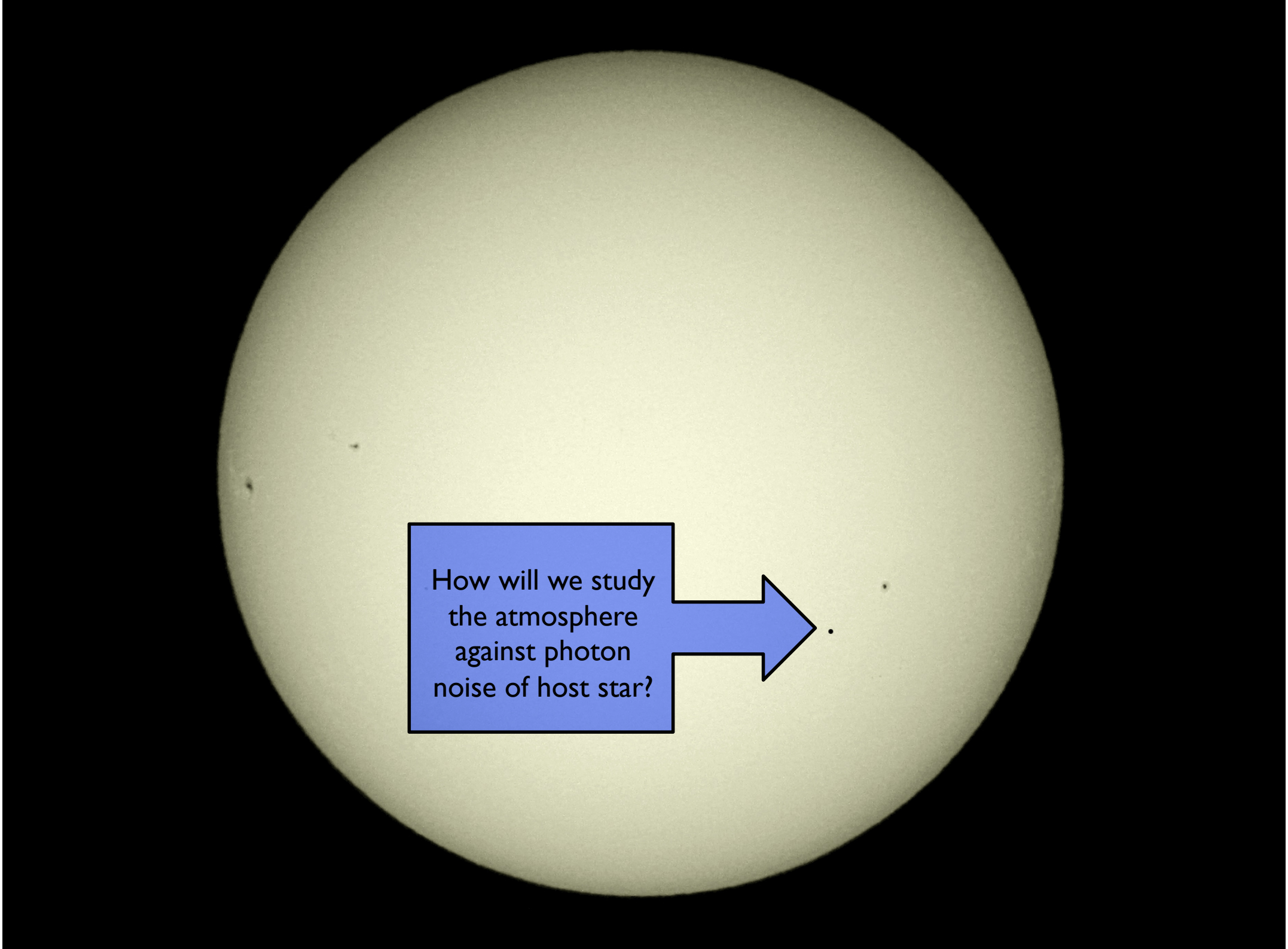
Bonfils et al. 2013, *A&A*, 549, A109

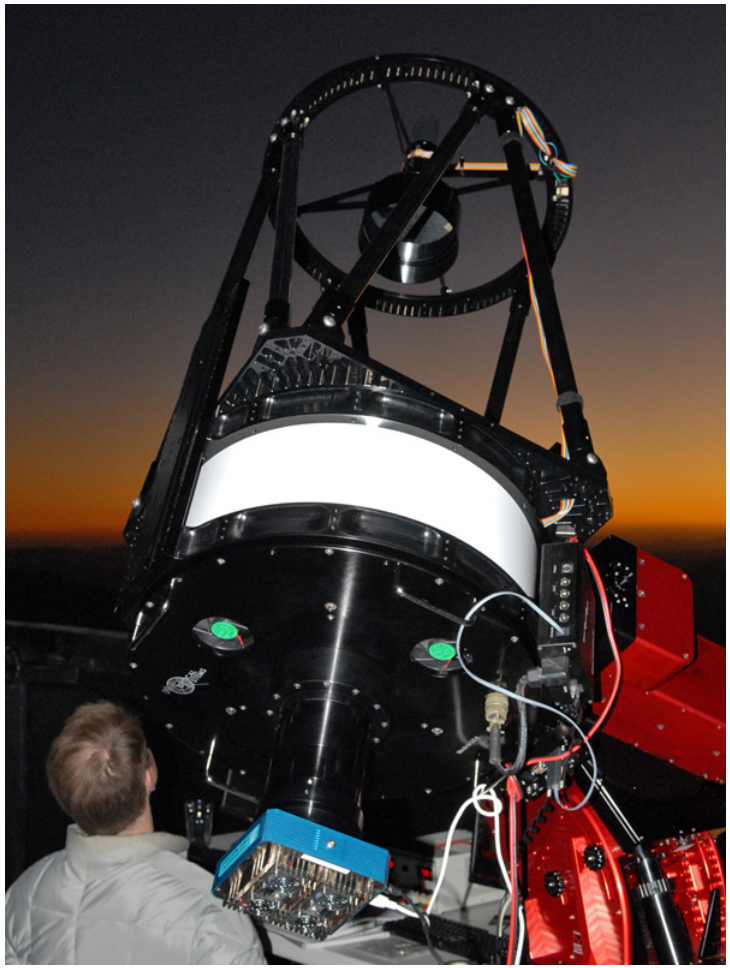
Number of Earths per HZ

Paper	Eta Earth	HZ Inner Edge	HZ Outer Edge	Planet Properties
Bonfils+ 2013	**0.41** (+0.54/-0.13)	Recent Venus (Selsis +2007)	Early Mars (Selsis+ 2007)	$1 < m \sin I < 10$ M_{Earth}
Gaidos 2013	**0.46** (+0.18/-0.15)	50% Clouds (Selsis+ 2007)	50% Clouds (Selsis+ 2007)	$R_P > 0.8$ R_{Earth}
Kopparapu 2013 (Conservative)	**0.48** (+0.12/-0.24)	Moist Greenhouse (Kopparapu+ 2013)	Max Greenhouse (Kopparapu+ 2013)	$0.5 < R_P < 1.4$ R_{Earth}
Kopparapu 2013 (Optimistic)	**0.61** (+0.07/-0.15)	Recent Venus (Kopparapu+ 2013)	Early Mars (Kopparapu+ 2013)	$0.5 < R_P < 2$ R_{Earth}
Dressing & Charbonneau 2013	**0.15** (+0.13/-0.06)	Water Loss (Kasting+ 1993)	CO_2 Condensation (Kasting+ 1993)	$0.5 < R_P < 1.4$ R_{Earth}
Dressing & Charbonneau (in prep)	**0.56** (+0.32/-0.13)	Moist Greenhouse (Kopparapu+ 2013)	Max Greenhouse (Kopparapu+ 2013)	$0.5 < R_P < 1.4$ R_{Earth}
Dressing & Charbonneau (in prep)	**0.66** (+0.25/-0.12)	Moist Greenhouse with Clouds (Yang+ 2013)	Max Greenhouse (Kopparapu+ 2013)	$0.5 < R_P < 1.4$ R_{Earth}

The Story So Far

- Nearly all planets smaller than 1.5 R_E are rocky. Some planets as large as 2.0 R_E are rocky.
- We *haven't* measured the rate of Earth-like planets around Sun-like stars, but extrapolation puts this number at 5-11%.
- We *have* measured the rate of Earth-like planets around early M-dwarfs. It ranges from 15–60% depending on your definition of the habitable zone.
- The most probable distance for the closest transiting habitable planet is 9 pc, but it could be as far as 20 pc (95% confidence, 0.15 occurrence rate).


How will we study the atmosphere against photon noise of host star?



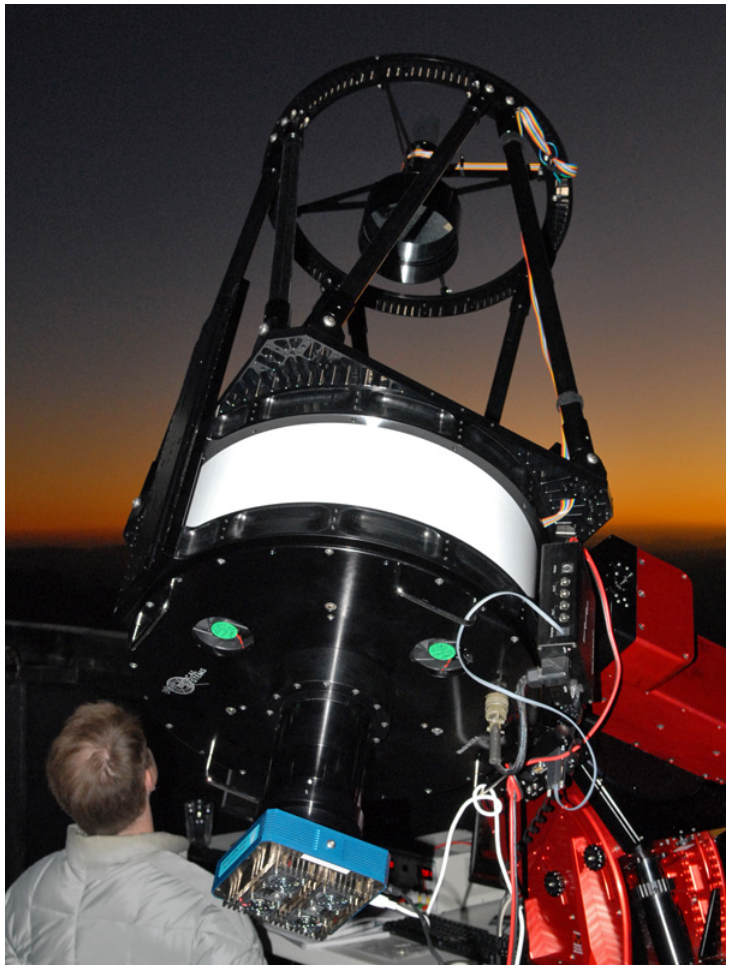
The MEarth Project

Nutzman & Charbonneau 2008; Berta et al. 2013

- Using 8 X 40cm telescopes, we are surveying the 2000 nearest low-mass stars for planets as small as 2 R_{Earth} orbiting within the habitable zone.
- **MEarth is different: Monitor stars sequentially & detect transits in progress**

THE PRIMARY PURPOSE OF MEARTH
IS TO FIND THE IDEAL TARGETS FOR CHARACTERIZATION
WITH THE ELTs and JWST

The MEarth Project



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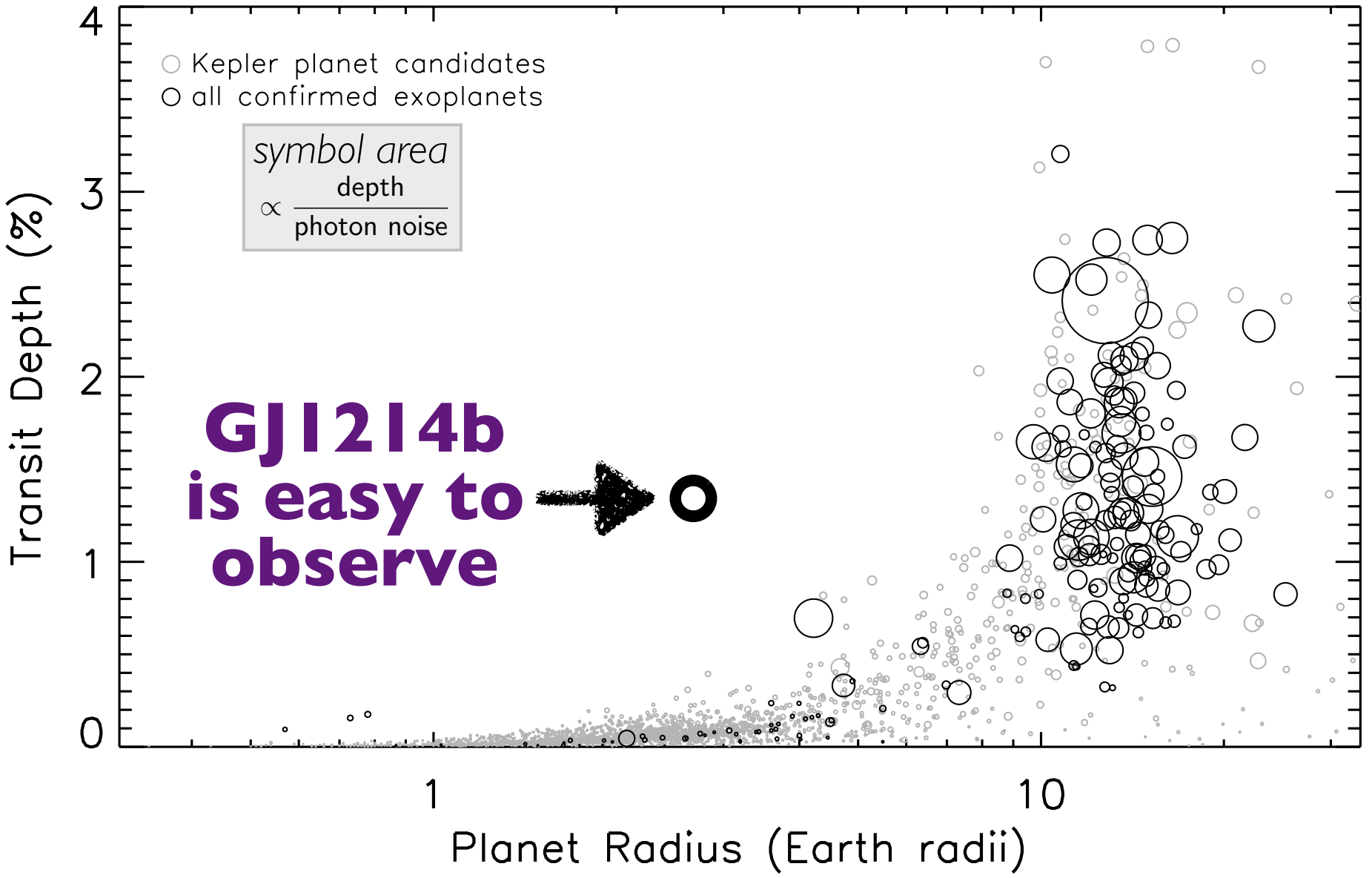
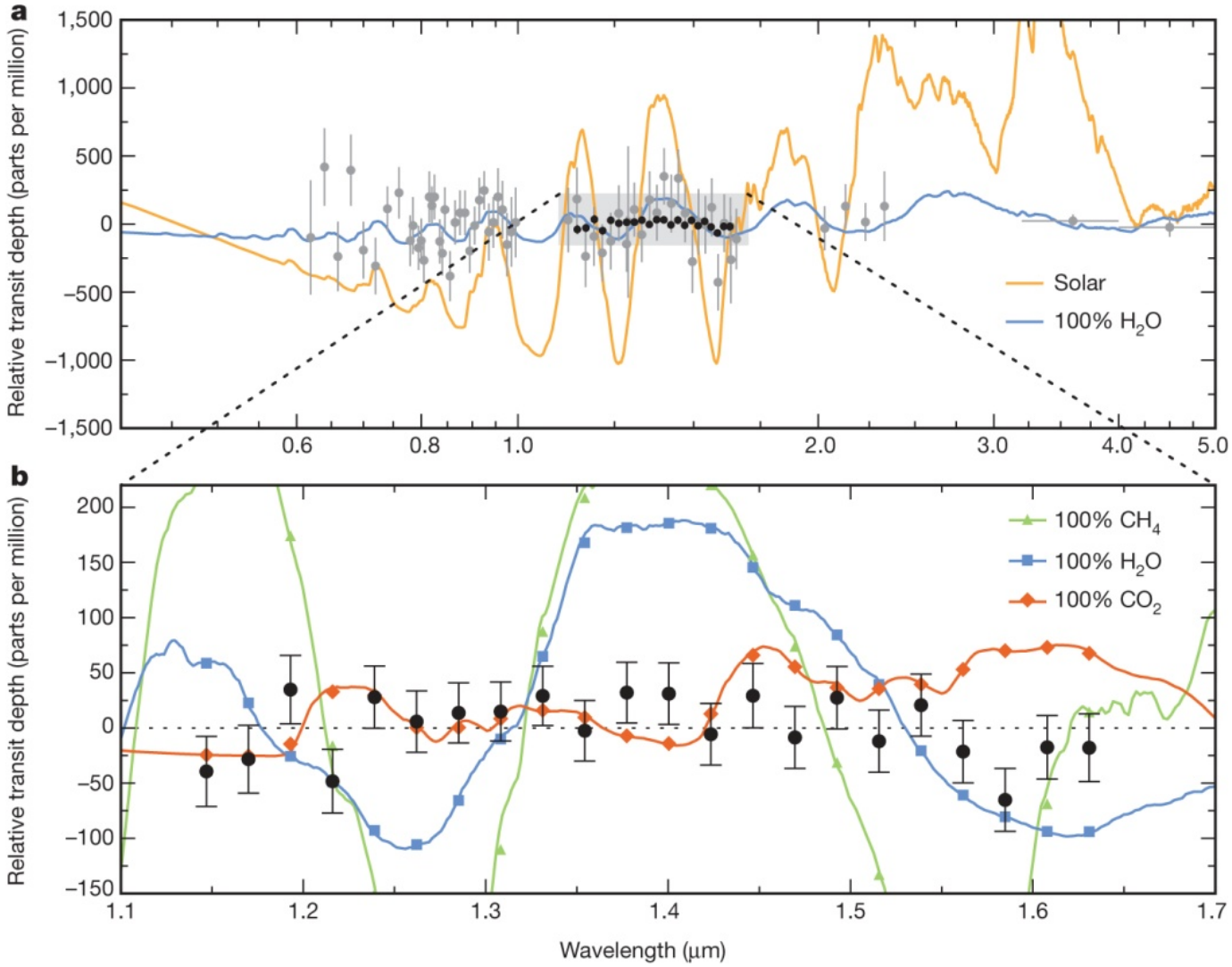


Berta, Charbonneau, et al. 2012

The GJ1214b Hubble Deep Field

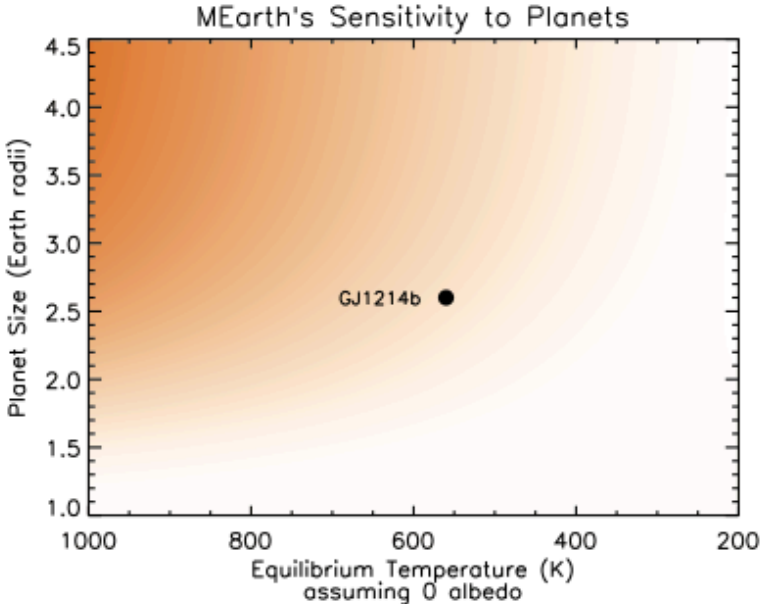


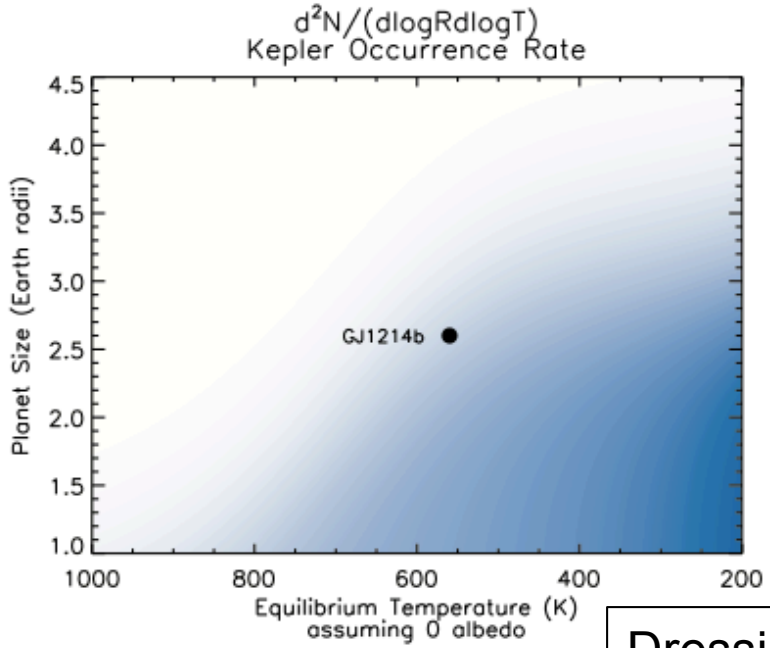
Kreidberg, Bean, et al. 2014 Nature

MEarth-South at Cerro Tololo
Operational as of January 2014

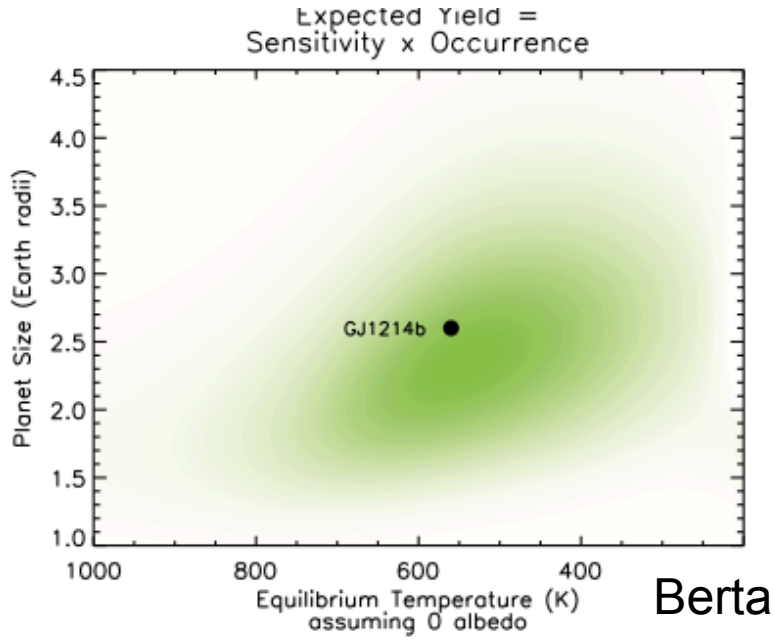
(Graphic redacted)

So, can we find smaller planets?





Dressing & Charbonneau (2013)



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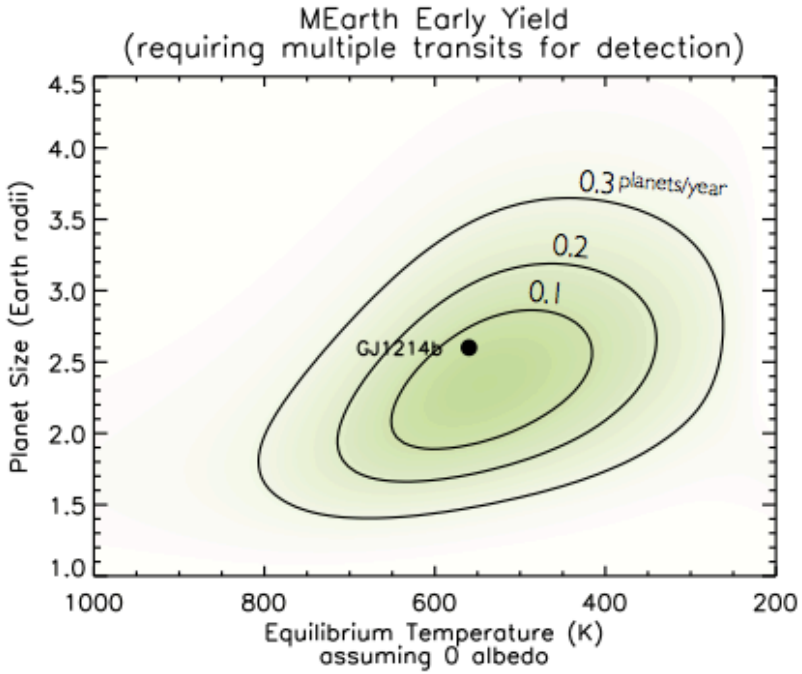
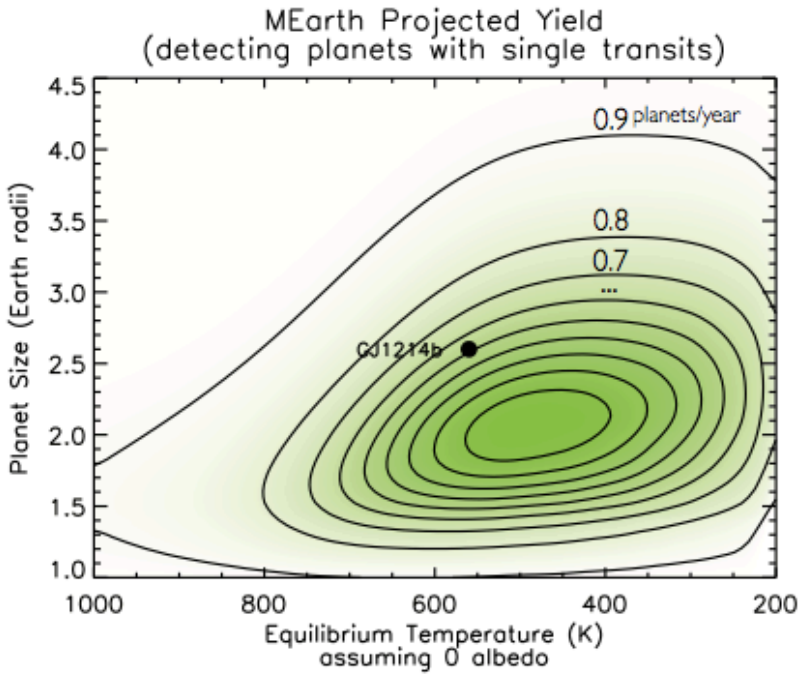




Can we do better?

Berta, Irwin, Charbonneau (2013)

Many Ground-Based Surveys Will Target Habitable Planets Orbiting M-Dwarfs

- *Transits:*
  - MEarth-North & MEarth-South
  - SPECULOOS
  - ExTrA
  - APACHE
- *Radial Velocities:*
  - Penn State Habitable Planet Finder
  - CARMENES
  - SPIROU

Note lack of M-dwarf (red or nIR) radial velocity survey in southern hemisphere

TESS Science Goals and Drivers

MIT-led Mission: NASA, Orbital Sciences, Harvard-SAO

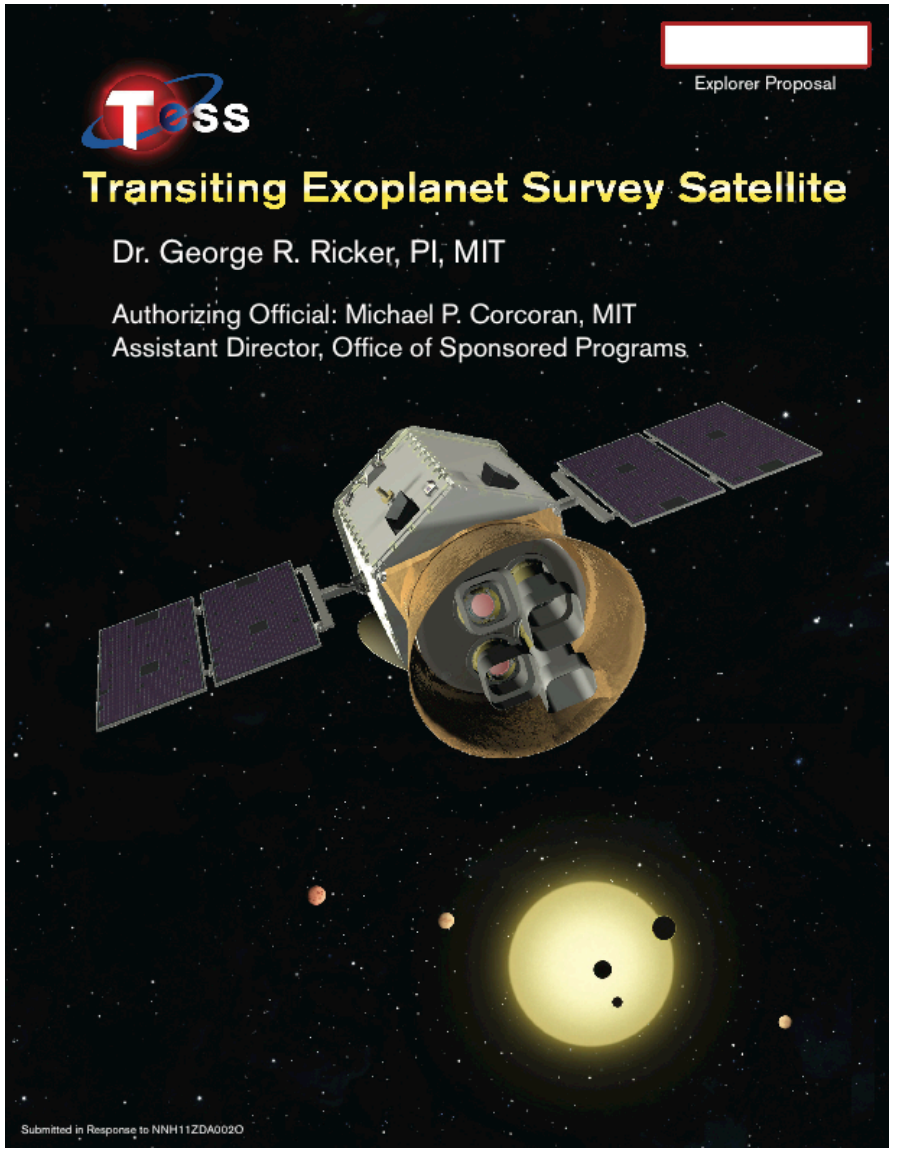
Discover Transiting Earths and SuperEarths around Bright, Nearby Stars

- Rocky planets
- Water worlds
- Habitable zone planets

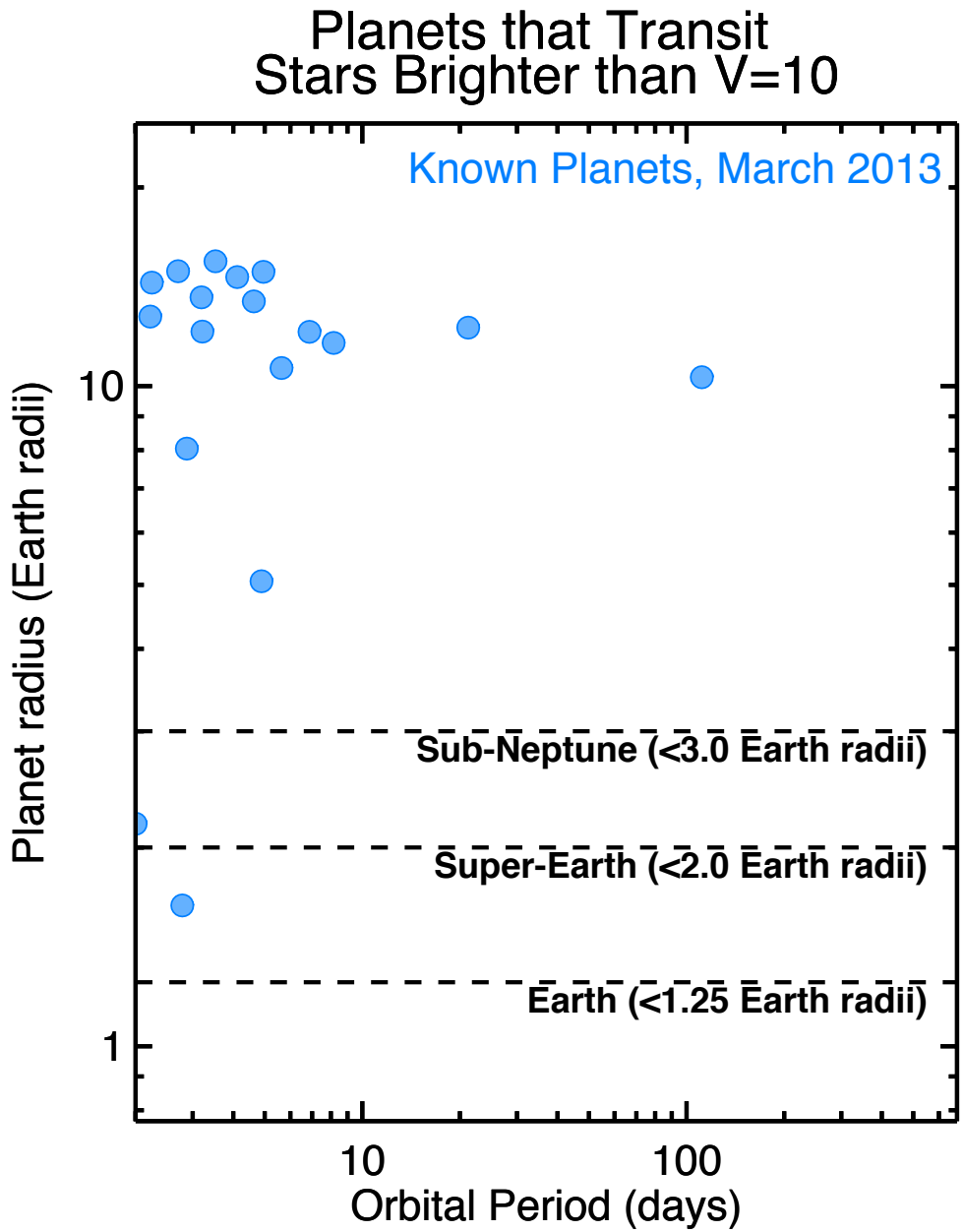
Discover 1000+ Exoplanets

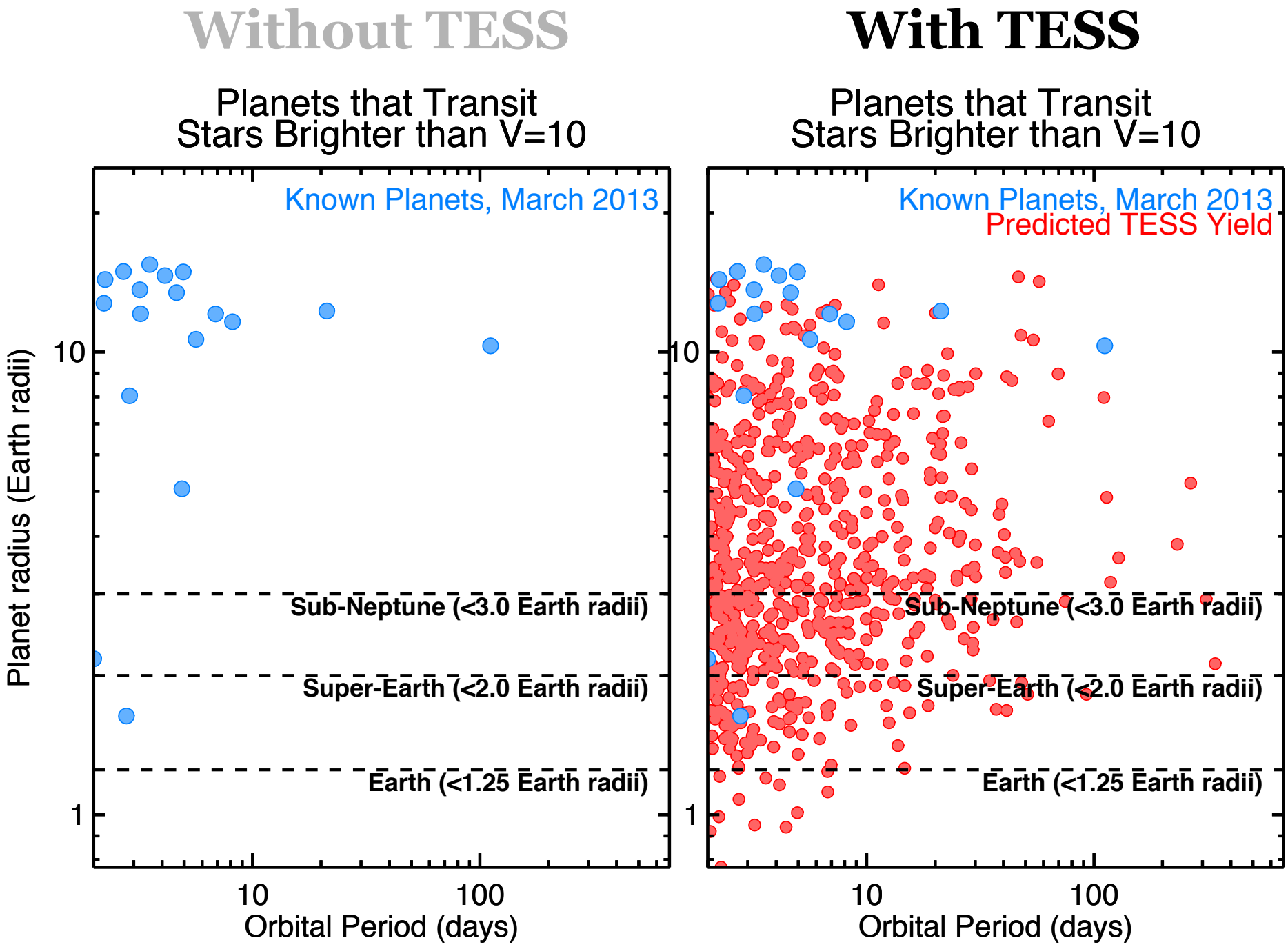
All Sky Survey of Bright Stars

- ~40000 deg^2 (~400 x Kepler)
- F, G, K dwarf stars: 4.5 to 12 magnitude
- M stars known within 50 pc (= 150 l-yr)
- 500,000 stars in two years

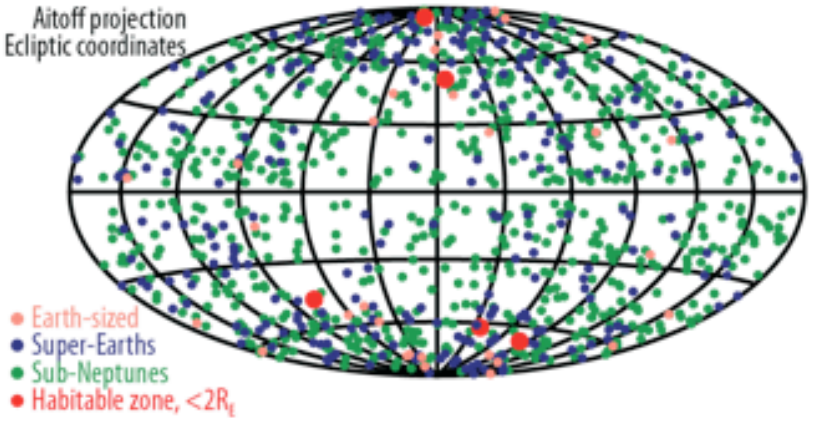


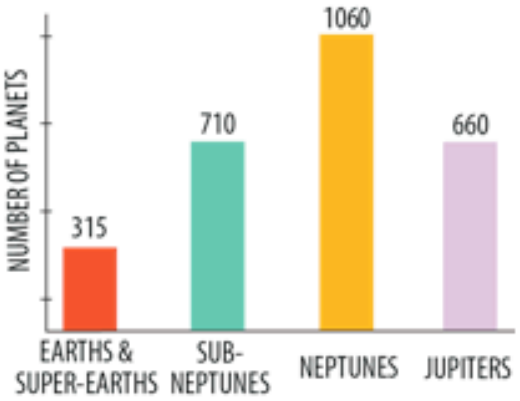
Without TESS

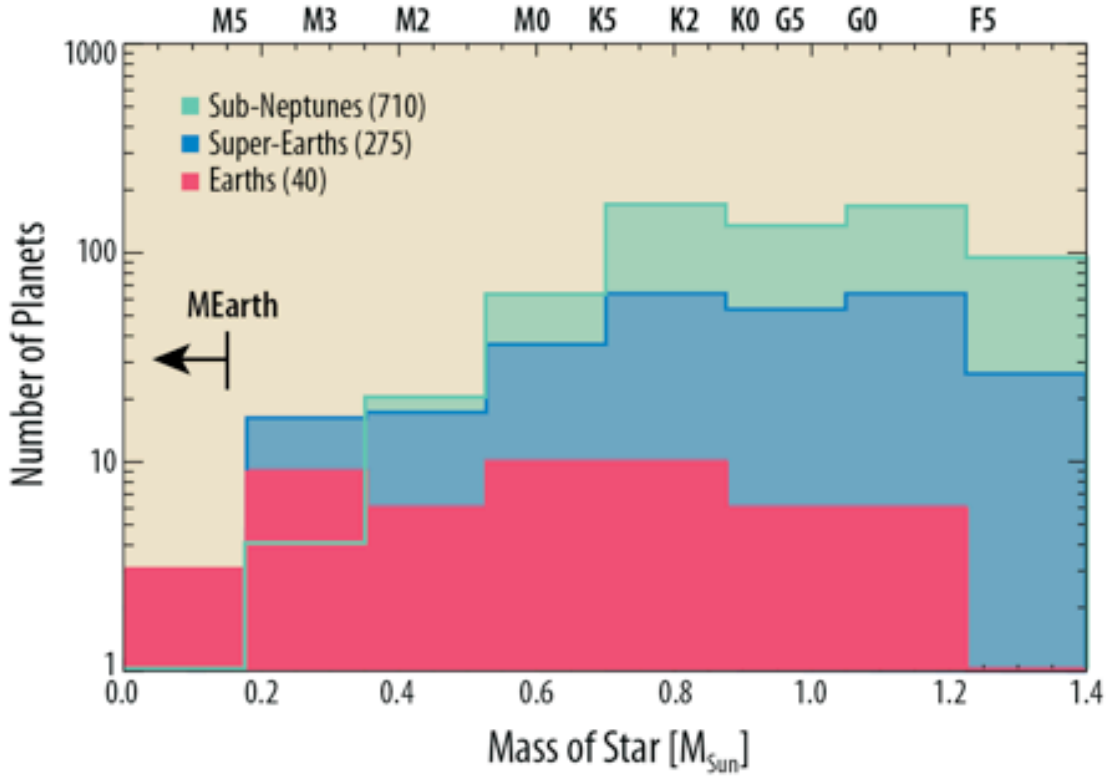



Without TESS
With TESS
Planets that Transit
Stars Brighter than V=10
Known Planets, March 2013
Predicted TESS Yield
Sub-Neptune (<3.0 Earth radii)
Super-Earth (<2.0 Earth radii)
Earth (<1.25 Earth radii)
Planet radius (Earth radii)
10
1
10
100
Orbital Period (days)

Predicted Science Yield from TESS Mission

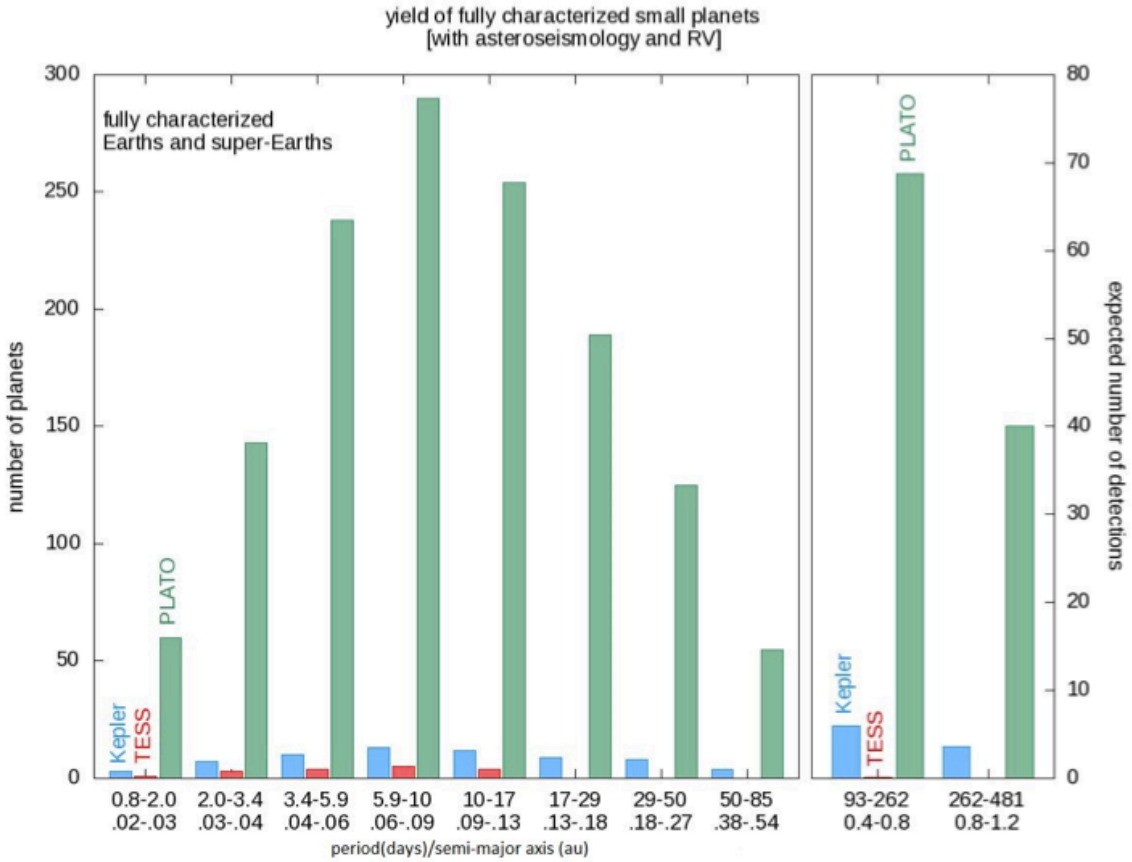


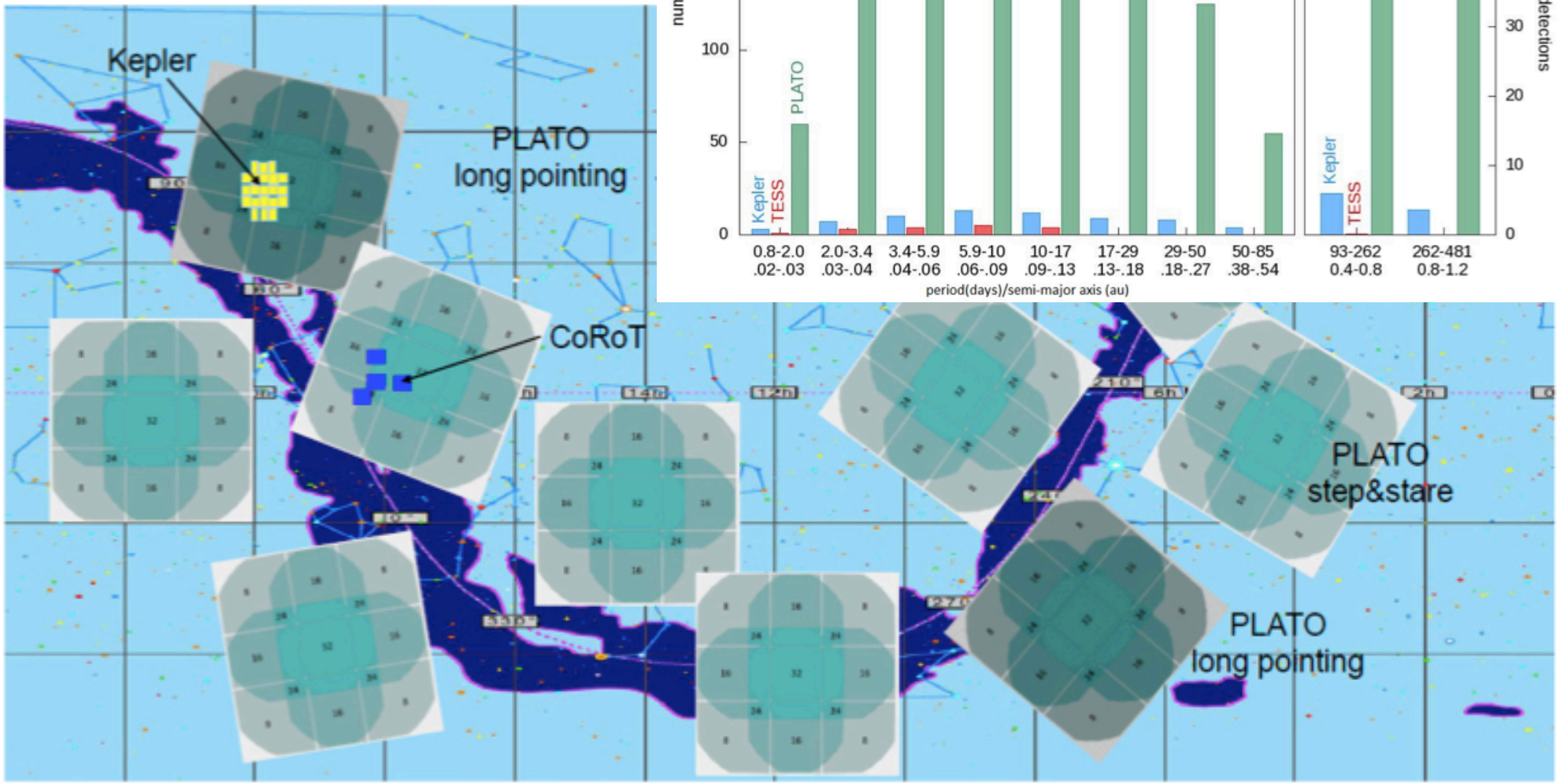




TESS Will Discover ~300 Earths + SuperEarths

PLATO:
Radii, Masses, & Asteroseismology
$4 < m_V < 11$





FINDING EXTRATERRESTRIAL LIFE USING GROUND-BASED HIGH-DISPERSION SPECTROSCOPY

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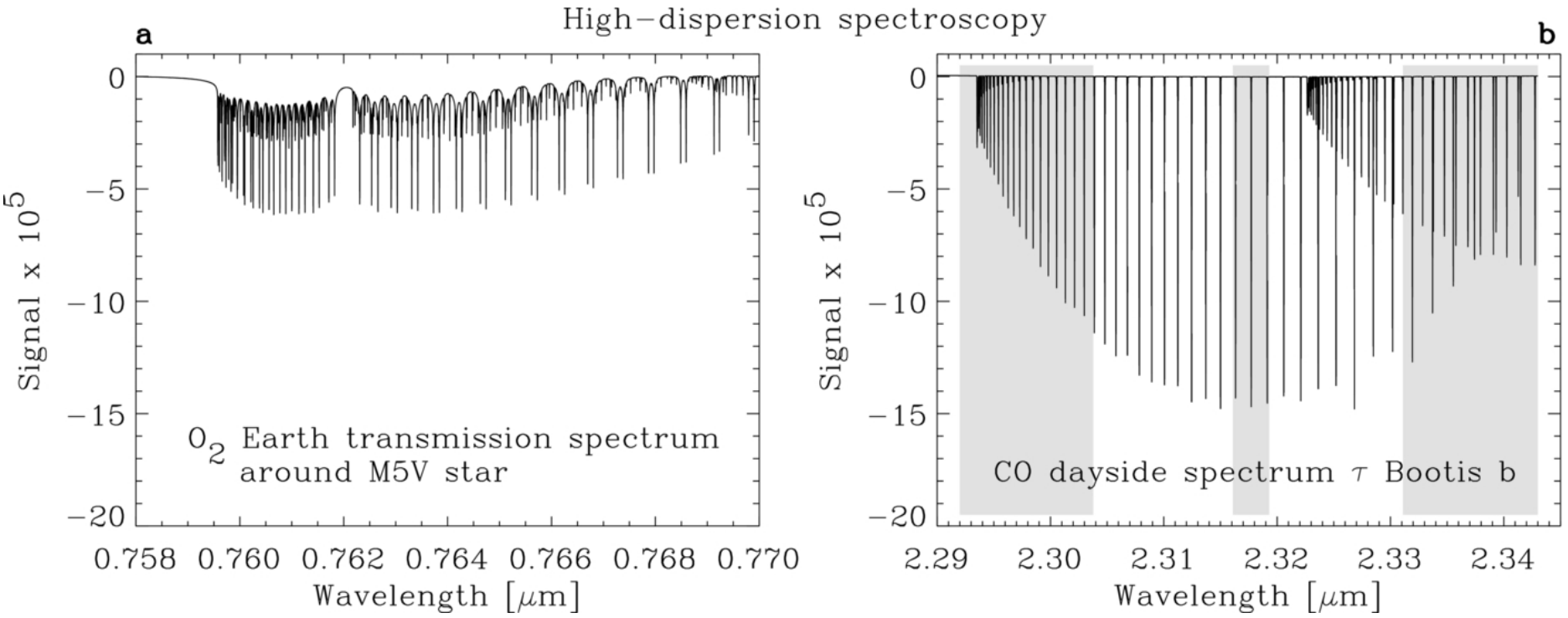
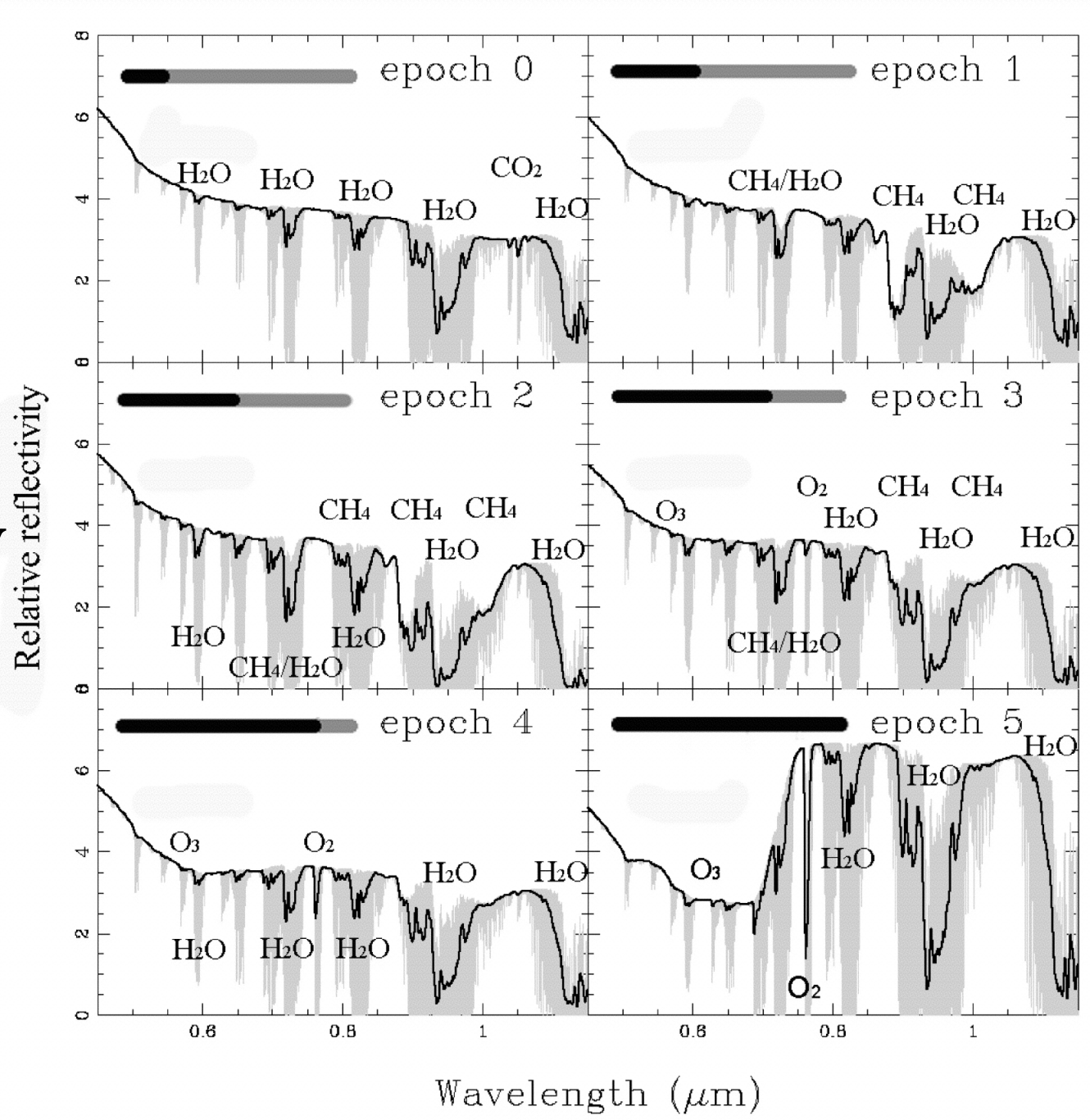


If Earth-like planets are common around M-dwarfs, then ELTs can search for oxygen.

Giant Magellan Telecope: GCLEF (optical) first first-light instrument
European ELT: HIRES (optical and nIR) and METIS (mid IR)

Evolution of Atmospheric Bio-signatures

Age from TESS & PLATO asteroseismology



Kaltenegger, Traub & Jucks (2007)

Summary

Doppler, Transit & Atmospheric Landscape is Evolving Rapidly

- Developments since Feb 5th, 2013:
  - Discovery that Earth-like planets are very common around M-dwarfs
  - End of primary NASA Kepler Mission
  - Selection of NASA TESS Mission
  - Atmosphere of 6 M_E planet studied at level of 30 ppm
  - First measurement of mass of Earth-sized planet (Kepler-78b)
  - Favorable recommendation of PLATO Mission to ESA
  - *Selection of CHEOPS – but OK that is old news (16 months ago)*

- E-ELT and instrument science cases MUST take these developments into account and anticipate similarly rapid progress 2014-2024

- Are the scientific goals sufficiently ambitious?
  - *Search for biomarkers on HZ planets orbiting M-dwarfs?*
  - *Such an instrument would surely be very high-R, very stable: retain precise RV?*
  - *Image spectroscopy of transiting planets planets (masses and radii known)?*

- *How do we compete with JWST?* ***vs*** *What can JWST do for the E-ELT?*