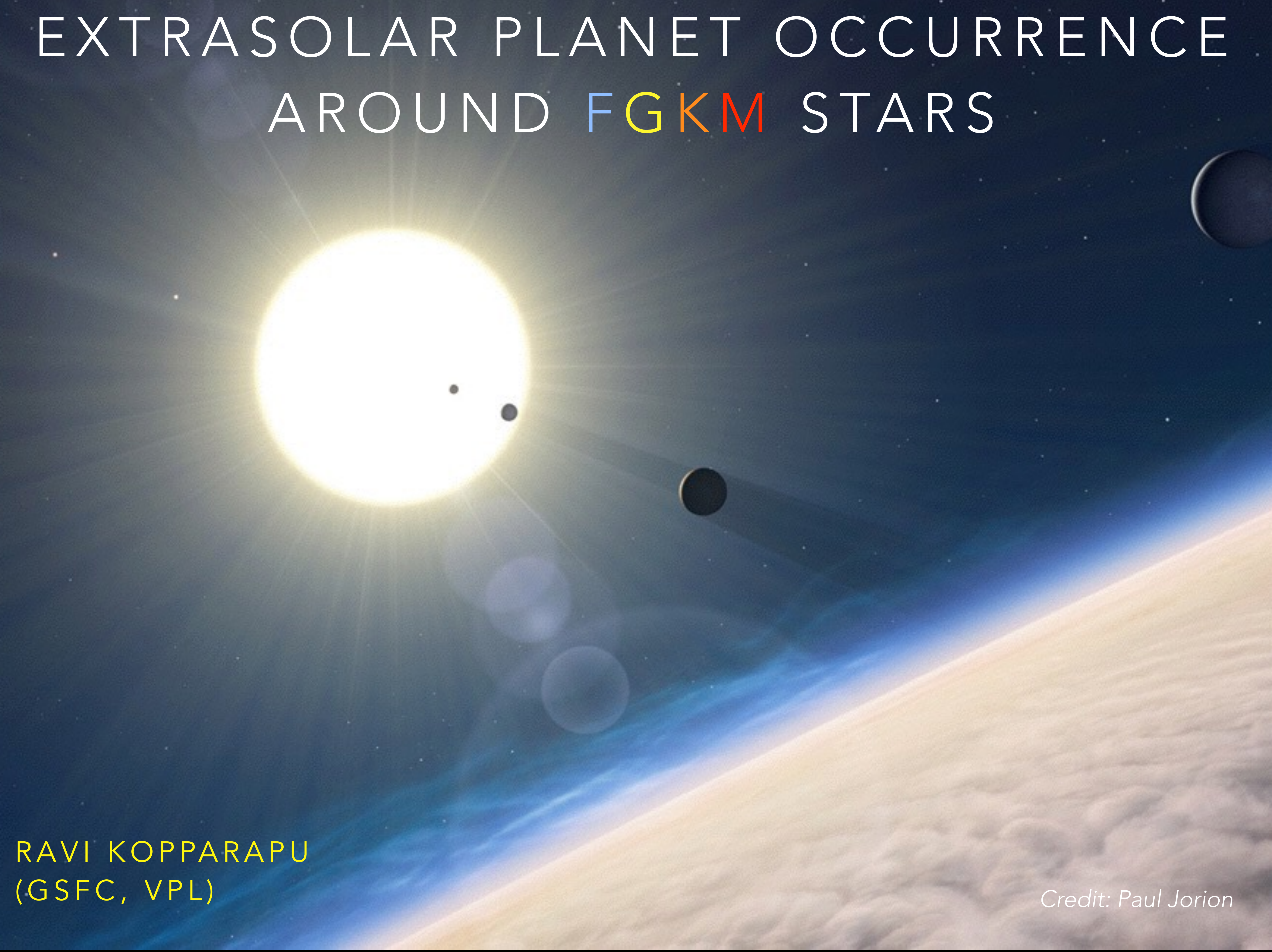
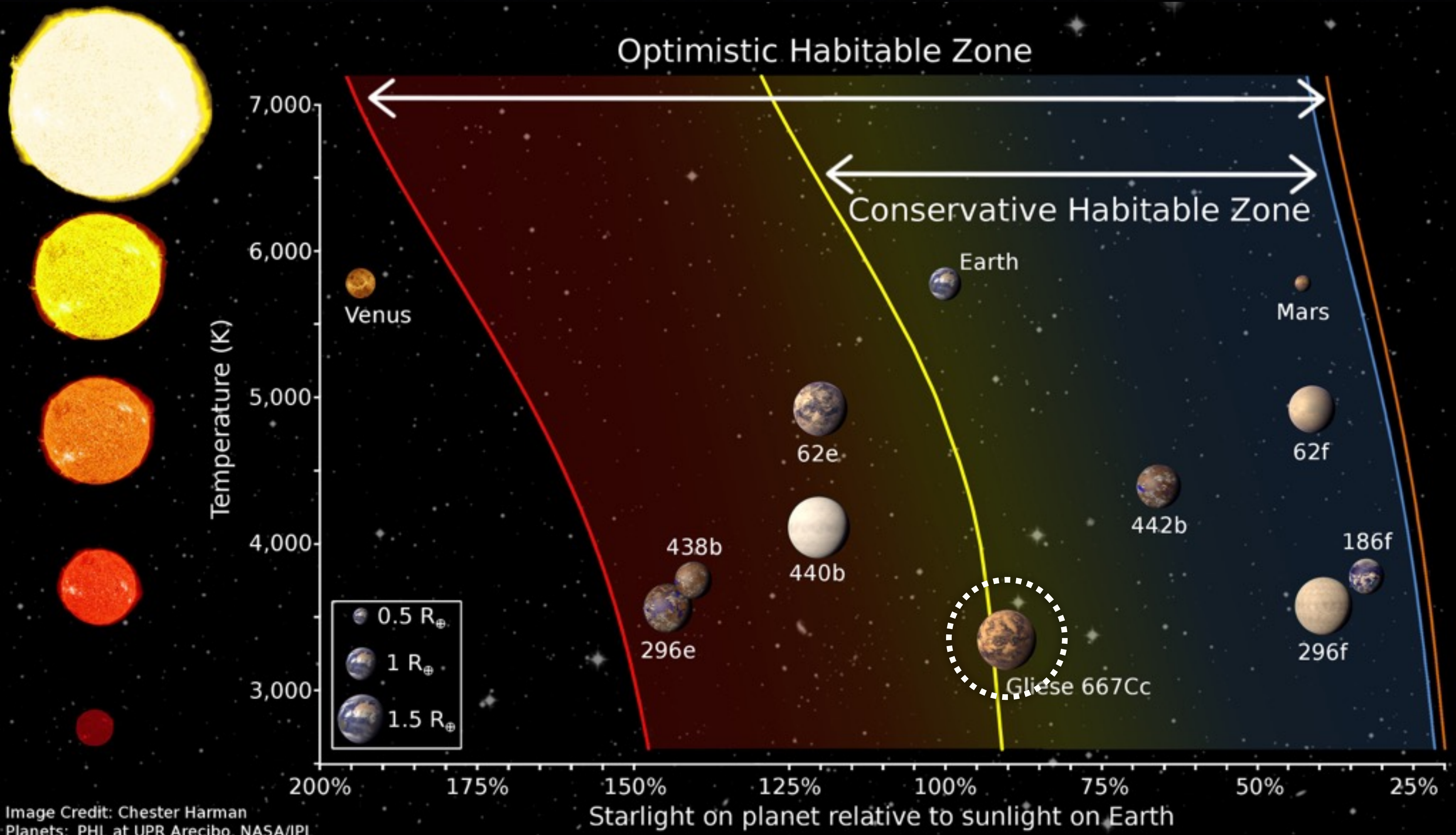
EXTRASOLAR PLANET OCCURRENCE AROUND FGKM STARS



RAVI KOPPARAPU
(GSFC, VPL)

Credit: Paul Jorion

Revised Habitable Zones

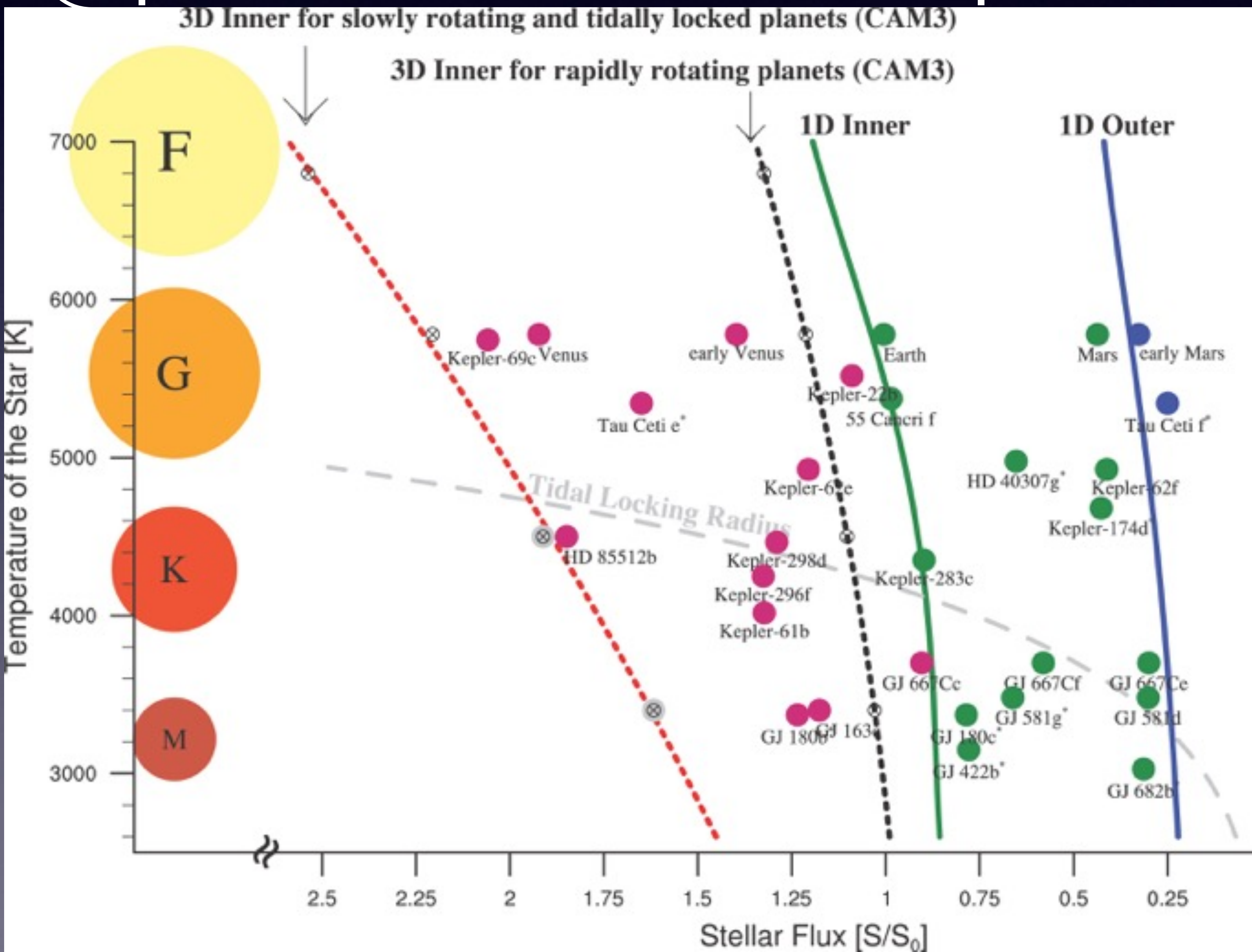


Kopparapu et al.(2013), Astrophysical Journal, 765, 131

Kopparapu et al.(2014), Astrophysical Journal Letters, 787, L29

HZs around M-stars are wider?

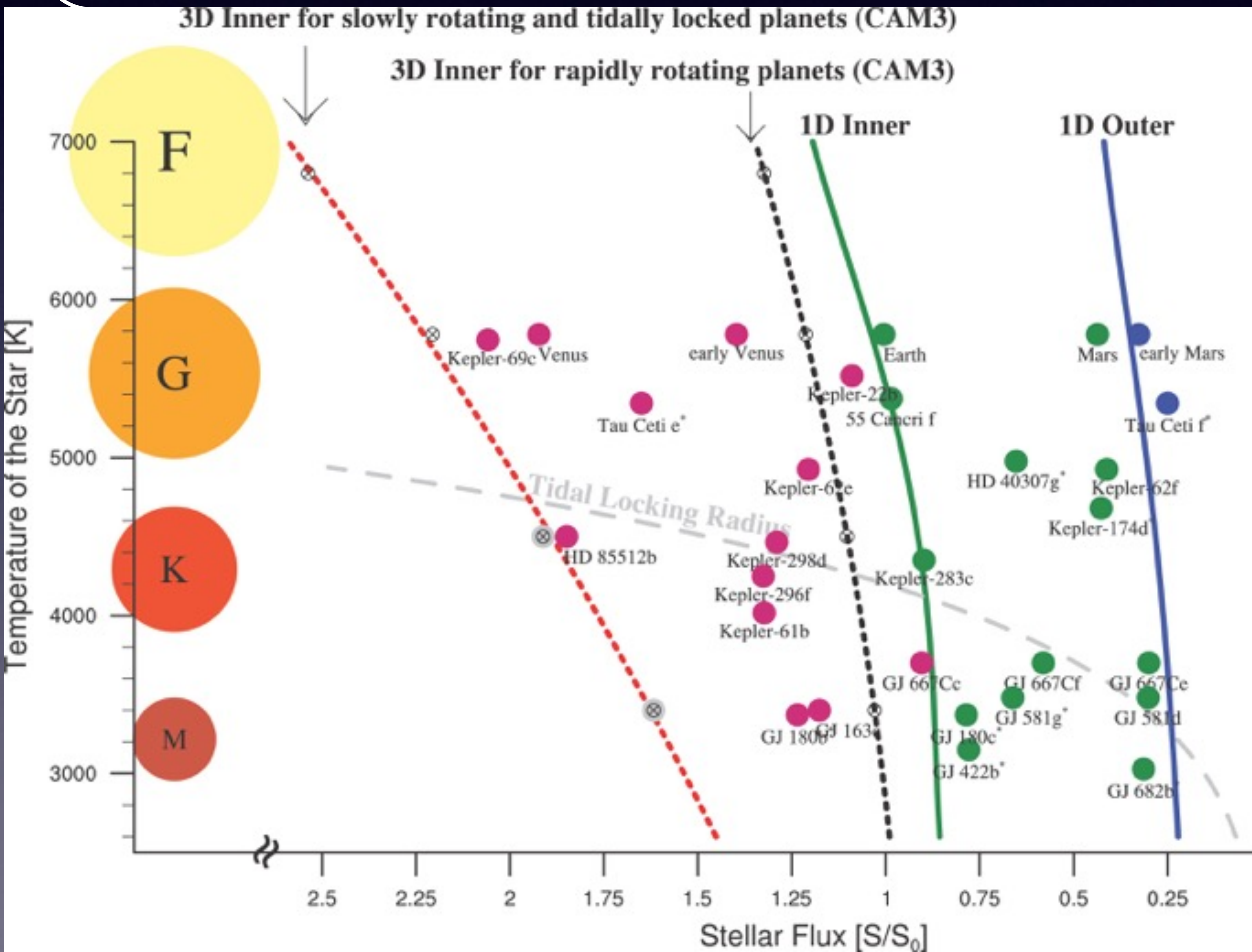
- 3D GCM models show that the inner HZ can extend ~ 2 times closer to the star for synchronously rotating planets around M-stars, compared to 1-D models.



Yang et al.(2014)

HZs around M-stars are wider?

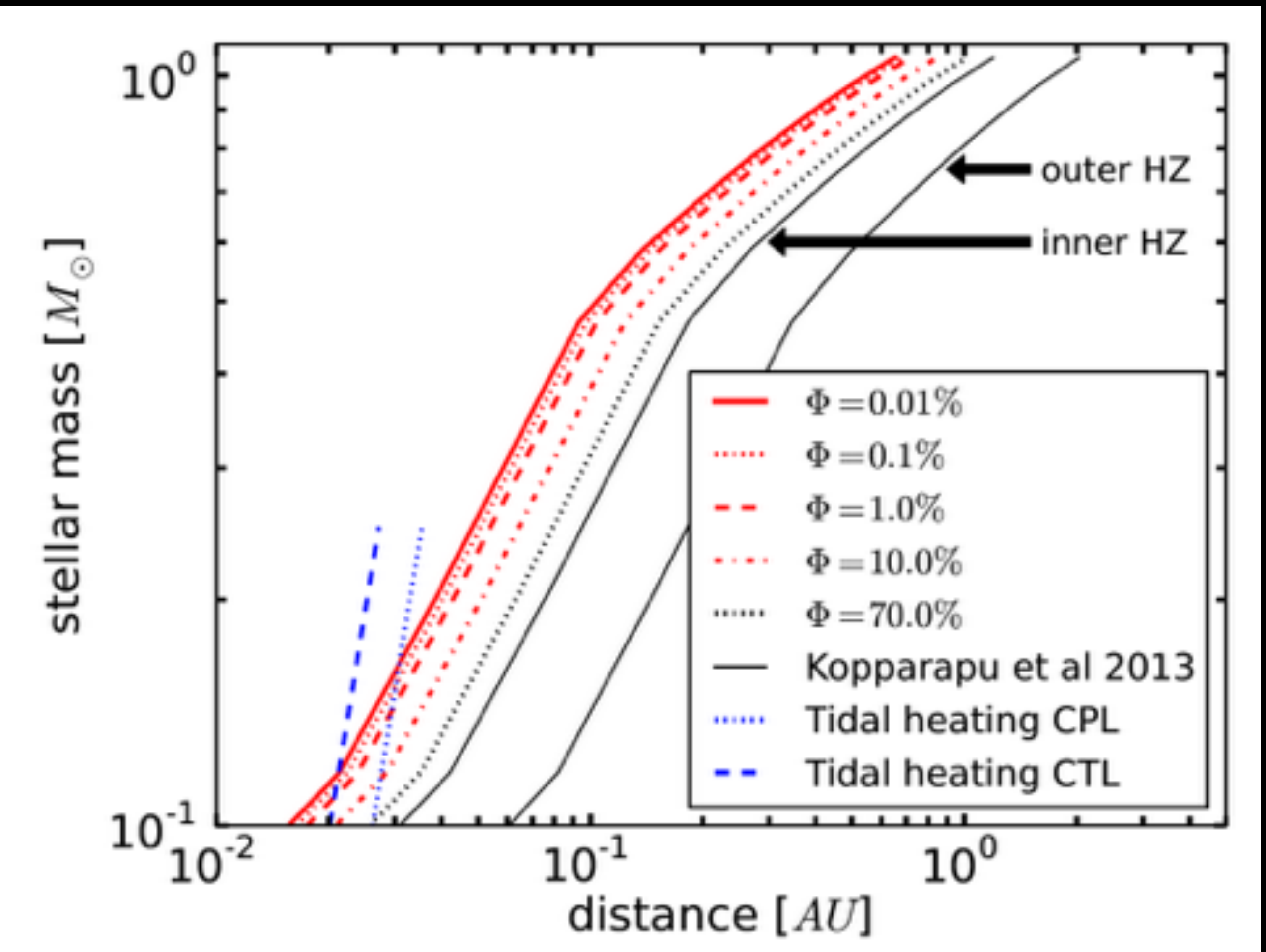
- A word of caution….!! Inconsistent orbital periods.
- They assumed 60 day orbital periods ***for all*** K & M stars!



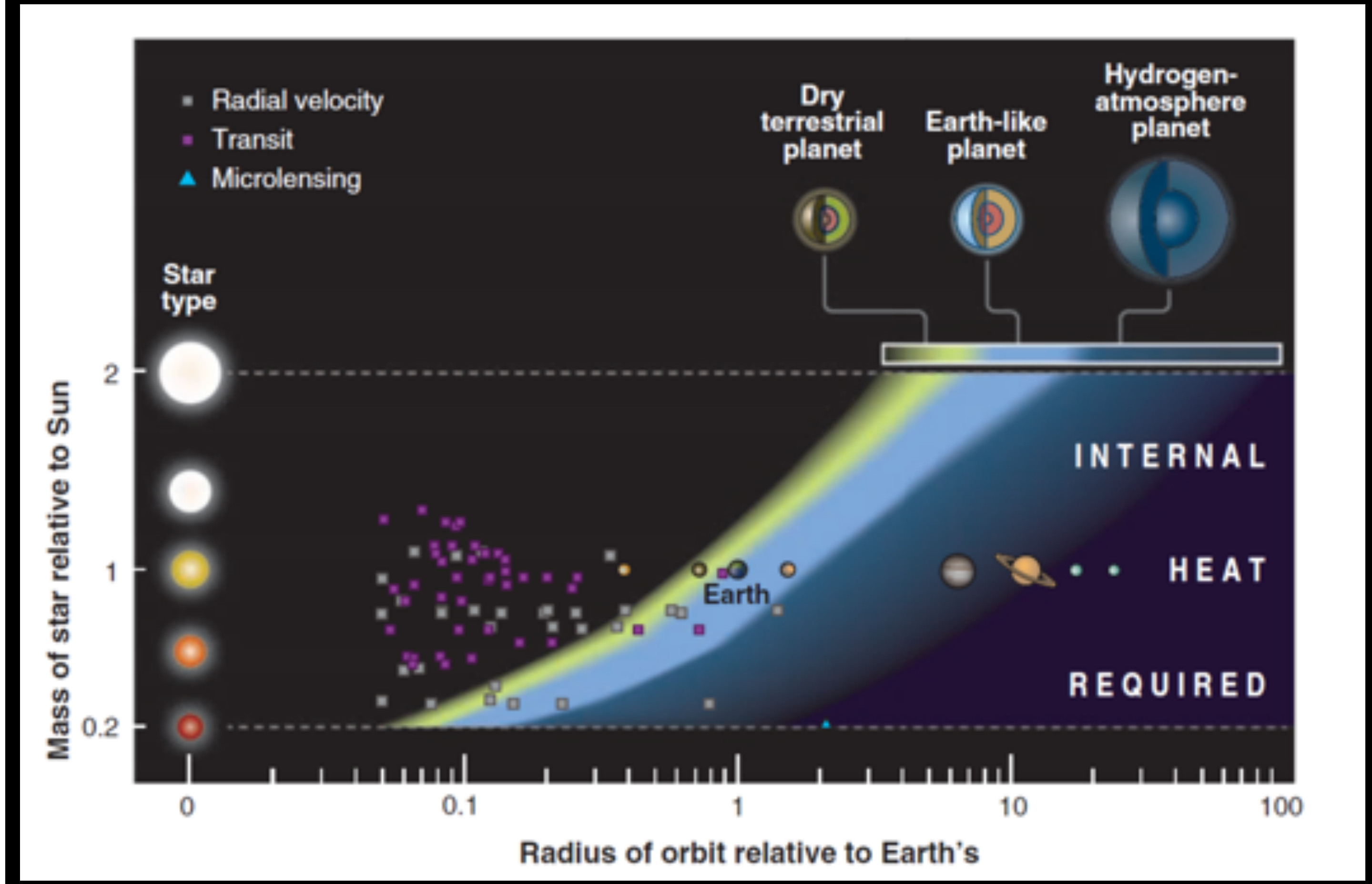
Clouds dominate the sunny side of tidally locked planets orbiting M and late-K stars, raising their albedos

Yang et al.(2014)

WIDER HABITABLE ZONES?



Zsom, Seager et al.(2013), ApJ, 778, 109



S. Seager,Science, April, 2013

- It was suggested that the inner edge is as close as 0.38 AU (orbit of Mercury!!) around a Sun-like star, for a 'Dry' planet.
- We showed that the Lifetime of an Earth 'ocean' is ~ 400 years.
- Kasting, Kopparapu, Ramirez, Harman (2014), PNAS

The HARPS search for southern extra-solar planets★,★★,★★★

XXXI. The M-dwarf sample

X. Bonfils[1,2], X. Delfosse[1], S. Udry[2], T. Forveille[1], M. Mayor[2], C. Perrier[1], F. Bouchy[3,4], M. Gillon[5,2], C. Lovis[2], F. Pepe[2], D. Queloz[2], N. C. Santos[6], D. Ségransan[2], and J.-L. Bertaux[7]

ABSTRACT

Context. Searching for planets around stars with different masses helps us to assess the outcome of planetary formation for different initial conditions. The low-mass M dwarfs are also the most frequent stars in our Galaxy and potentially therefore, the most frequent planet hosts.

Aims. We present observations of 102 southern nearby M dwarfs, using a fraction of our guaranteed time on the ESO/HARPS spectrograph. We observed for 460 h and gathered 1965 precise (~1–3 m/s) radial velocities (RVs), spanning the period from Feb. 11, 2003 to Apr. 1, 2009.

Methods. For each star observed, we derive a time series and its precision as well as its variability. We apply systematic searches for long-term trends, periodic signals, and Keplerian orbits (from one to four planets). We analyze the subset of stars with detected signals and apply several diagnostics to discriminate whether the observed Doppler shifts are caused by either stellar surface inhomogeneities or the radial pull of orbiting planets. To prepare for the statistical view of our survey, we also compute the limits on possible unseen signals, and derive a first estimate of the frequency of planets orbiting M dwarfs.

Results. We recover the planetary signals of 9 planets announced by our group (Gl 176 b, Gl 581 b, c, d & e, Gl 674 b, Gl 433 b, Gl 667C b, and Gl 667C c). We present radial velocities confirming that GJ 849 hosts a Jupiter-mass planet, plus a long-term radial-velocity variation. We also present RVs that precise the planetary mass and period of Gl 832b. We detect long-term RV changes for Gl 367, Gl 680, and Gl 880, which are indicative of yet unknown long-period companions. We identify candidate signals in the radial-velocity time series of 11 other M dwarfs. Spectral diagnostics and/or photometric observations demonstrate however that these signals are most probably caused by stellar surface inhomogeneities. Finally, we find that our survey is sensitive to a few Earth-mass planets for periods up to several hundred days. We derive a first estimate of the occurrence of M-dwarf planets as a function of their minimum mass and orbital period. In particular, we find that giant planets ($m \sin i$ = 100–1000 $M_\oplus$) have a low frequency (e.g. $f \lesssim 1\%$ for P = 1–10 d and $f = 0.02^{+0.03}_{-0.01}$ for P = 10–100 d), whereas super-Earths ($m \sin i$ = 1–10 $M_\oplus$) are likely very abundant ($f = 0.36^{+0.25}_{-0.10}$ for P = 1–10 d and $f = 0.52^{+0.50}_{-0.16}$ for P = 10–100 d). We also obtained $\eta_\oplus = 0.41^{+0.54}_{-0.13}$, which is the frequency of habitable planets orbiting M dwarfs ($1 \le m \sin i \le 10$ $M_\oplus$). For the first time, $\eta_\oplus$ is a direct measure and not a number extrapolated from the statistics of more massive and/or shorter-period planets.

Bonfils et al.(2013) • $\eta_\oplus$ = 41% (Gl 667Cc + Gl ~~581d~~)

THE OCCURRENCE OF POTENTIALLY HABITABLE PLANETS ORBITING M DWARFS ESTIMATED FROM THE FULL KEPLER DATASET AND AN EMPIRICAL MEASUREMENT OF THE DETECTION SENSITIVITY

COURTNEY D. DRESSING[1,2] AND DAVID CHARBONNEAU[1]

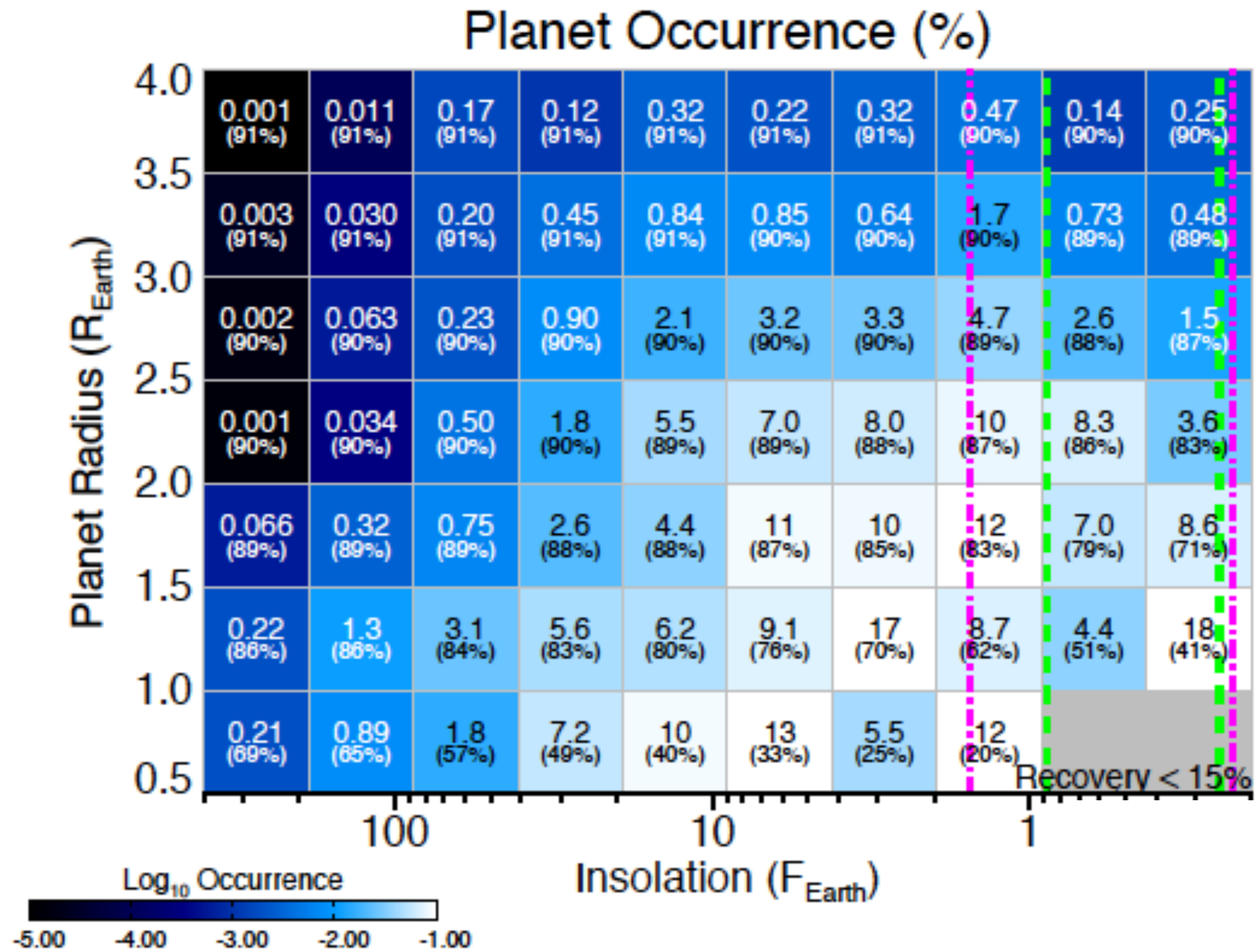
(Dated: May 27, 2015)
Draft version May 27, 2015

ABSTRACT

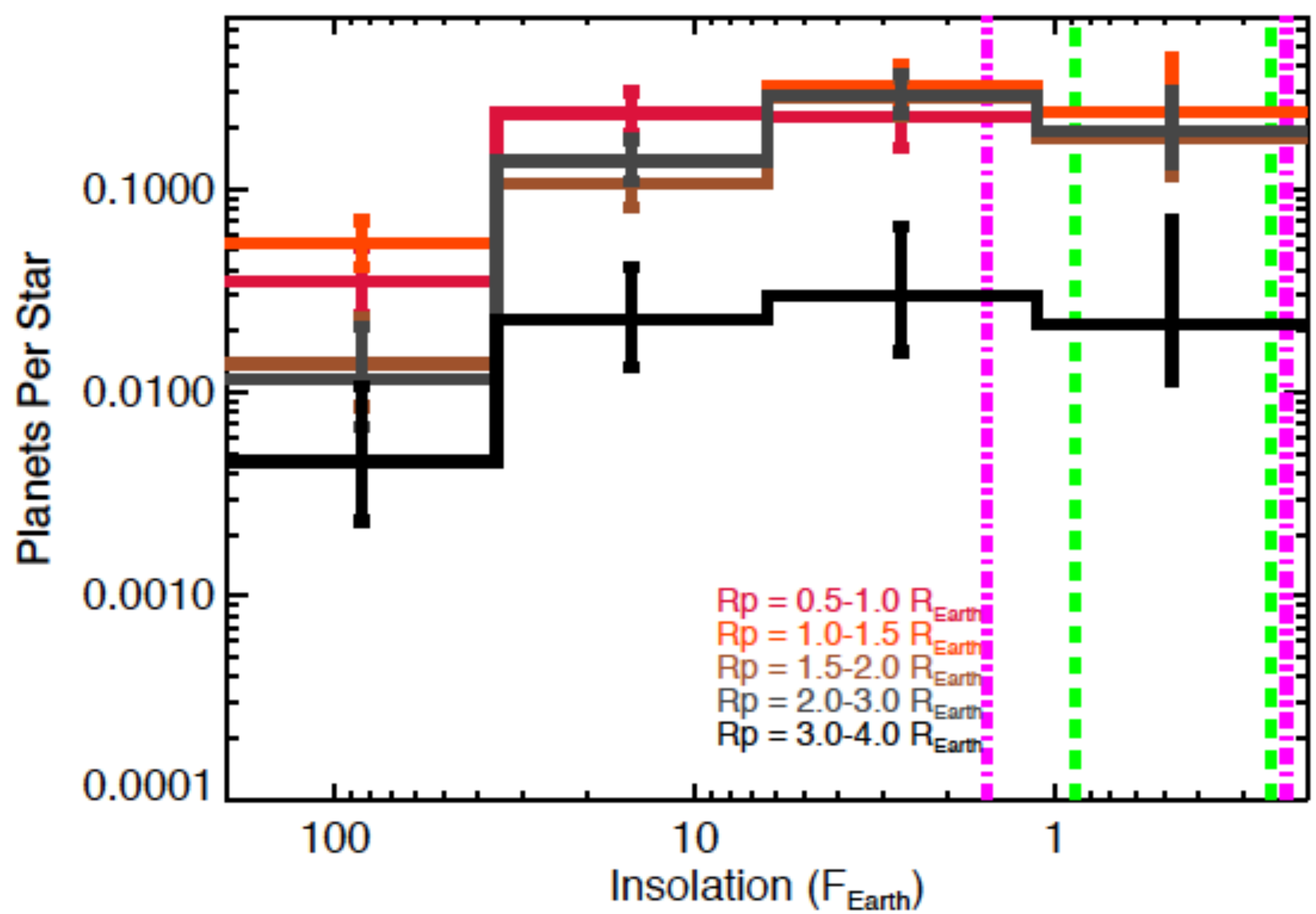
We present an improved estimate of the occurrence rate of small planets orbiting small stars by searching the full four-year *Kepler* data set for transiting planets using our own planet detection pipeline and conducting transit injection and recovery simulations to empirically measure the search completeness of our pipeline. We identified 156 planet candidates, including one object that was not previously identified as a *Kepler* Object of Interest. We inspected all publicly available follow-up images, observing notes, and centroid analyses, and corrected for the likelihood of false positives. We evaluated the sensitivity of our detection pipeline on a star-by-star basis by injecting 2000 transit signals into the light curve of each target star. For periods shorter than 50 days, we find $0.56^{+0.06}_{-0.05}$ Earth-size planets ($1 - 1.5\,R_\oplus$) and $0.46^{+0.07}_{-0.05}$ super-Earths ($1.5 - 2\,R_\oplus$) per M dwarf. In total, we estimate a cumulative planet occurrence rate of 2.5 ± 0.2 planets per M dwarf with radii $1 - 4\,R_\oplus$ and periods shorter than 200 days. Within a conservatively defined habitable zone based on the moist greenhouse inner limit and maximum greenhouse outer limit, we estimate an occurrence rate of $0.16^{+0.17}_{-0.07}$ Earth-size planets and $0.12^{+0.10}_{-0.05}$ super-Earths per M dwarf habitable zone. Adopting the broader insolation boundaries of the recent Venus and early Mars limits yields a higher estimate of $0.24^{+0.18}_{-0.08}$ Earth-size planets and $0.21^{+0.11}_{-0.06}$ super-Earths per M dwarf habitable zone. This suggests that the nearest potentially habitable non-transiting and transiting Earth-size planets are 2.6 ± 0.4 pc and $10.6^{+1.6}_{-1.8}$ pc away, respectively. If we include super-Earths, these distances diminish to 2.1 ± 0.2 pc and $8.6^{+0.7}_{-0.8}$ pc.

Dressing and Charbonneau (2015)

- $\eta_\oplus$ = 16% (revised down from 48% Kopparapu(2013) Q1-Q6 data)



Planet Occurrence (%)
Planet Radius (R_{Earth})
Insolation (F_{Earth})
Log$_{10}$ Occurrence
-5.00 -4.00 -3.00 -2.00 -1.00
Recovery < 15%



Planets Per Star
Insolation (F_{Earth})
Rp = 0.5-1.0 R_{Earth}
Rp = 1.0-1.5 R_{Earth}
Rp = 1.5-2.0 R_{Earth}
Rp = 2.0-3.0 R_{Earth}
Rp = 3.0-4.0 R_{Earth}

Prevalence of Earth-size planets orbiting Sun-like stars

Erik A. Petigura[a,b,1], Andrew W. Howard[b], and Geoffrey W. Marcy[a]

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Contributed by Geoffrey W. Marcy, October 22, 2013 (sent for review October 18, 2013)

Determining whether Earth-like planets are common or rare looms as a touchstone in the question of life in the universe. We searched for Earth-size planets that cross in front of their host stars by examining the brightness measurements of 42,000 stars from National Aeronautics and Space Administration's *Kepler* mission. We found 603 planets, including 10 that are Earth size ($1-2\ R_\oplus$) and receive comparable levels of stellar energy to that of Earth ($0.25-4\ F_\oplus$). We account for *Kepler's* imperfect detectability of such planets by injecting synthetic planet–caused dimmings into the *Kepler* brightness measurements and recording the fraction detected. We find that 11 ± 4% of Sun-like stars harbor an Earth-size planet receiving between one and four times the stellar intensity as Earth. We also find that the occurrence of Earth-size planets is constant with increasing orbital period (*P*), within equal intervals of log*P* up to ~200 d. Extrapolating, one finds $5.7^{+1.7}_{-2.2}$% of Sun-like stars harbor an Earth-size planet with orbital periods of 200–400 d.

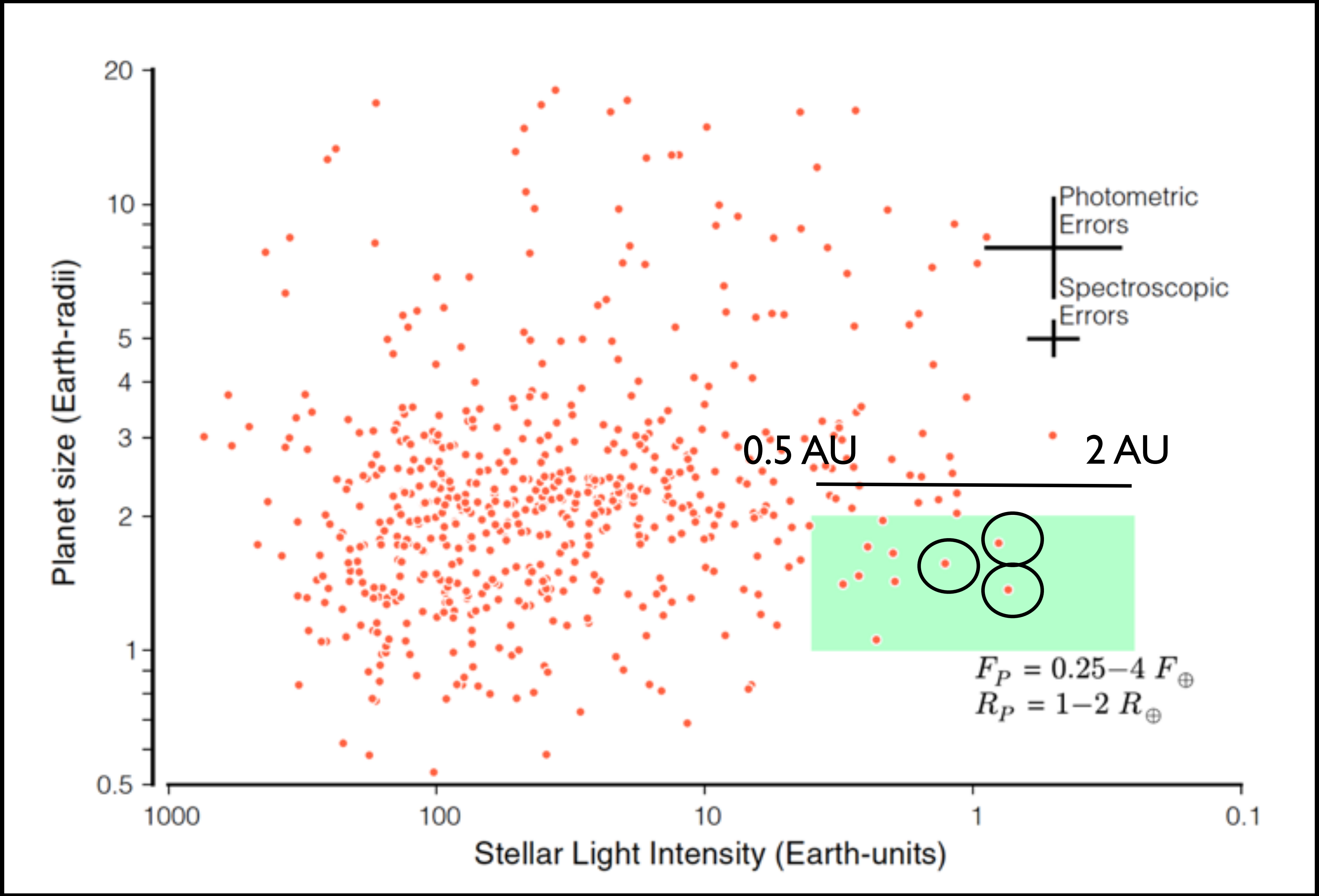
We searched for transiting planets in *Kepler* brightness measurements using our custom-built TERRA software package described in previous works (6, 9) and in *SI Appendix*. In brief, TERRA conditions *Kepler* photometry in the time domain, removing outliers, long timescale variability (>10 d), and systematic errors common to a large number of stars. TERRA then searches for transit signals by evaluating the signal-to-noise ratio (SNR) of prospective transits over a finely spaced 3D grid of orbital period, P, time of transit, t_0, and transit duration, ΔT. This grid-based search extends over the orbital period range of 0.5–400 d.

TERRA produced a list of "threshold crossing events" (TCEs) that meet the key criterion of a photometric dimming SNR ratio SNR > 12. Unfortunately, an unwieldy 16,227 TCEs met this criterion, many of which are inconsistent with the periodic dimming profile from a true transiting planet. Further vetting was performed by automatically assessing which light curves were consistent with

Petigura et al.(2013)

- $\eta_\oplus$ = 22% *

4 times flux (0.5 AU) is too high. Surface water is unstable (~few hundred years lifetime).



4 times flux (0.5 AU) is too high. Surface water is unstable (~few hundred years lifetime).

Only 3 planets with 1-2 RE within the conservative HZ limits

η_{Earth} for late-G and K stars

Table 1. Occurrence of small planets in the habitable zone

HZ definition	a_{inner}	a_{outer}	$F_{P,inner}$	$F_{P,outer}$	f_{HZ} (%)
Simple	0.5	2	4	0.25	22
Kasting (1993)	0.95	1.37	1.11	0.53	5.8
Kopparapu et al. (2013)	0.99	1.70	1.02	0.35	8.6
Zsom et al. (2013)	0.38		6.92		26*
Pierrehumbert and Gaidos (2011)		10		0.01	~50†

*Zsom et al. (17) studied the inner edge of the habitable zone. Here we adopt an outer edge of 2 AU from the Simple model.
†Pierrehumbert and Gaidos (18) studied the outer edge of the habitable zone. Here we adopt an inner edge of 0.5 AU from the Simple model. Extrapolation out to 10 AU is severely underconstrained. This estimate is highly uncertain and is included for completeness.

Petigura et al.(2013), PNAS

$\eta_{\oplus}$ for "solar-like" (GK spectral type) is probably closer to ~10% (using current *Kepler* data)...but....

DRAFT VERSION JUNE 25, 2014
Preprint typeset using LaTeX style emulateapj v. 12/16/11

A STATISTICAL RECONSTRUCTION OF THE PLANET POPULATION AROUND KEPLER SOLAR-TYPE STARS

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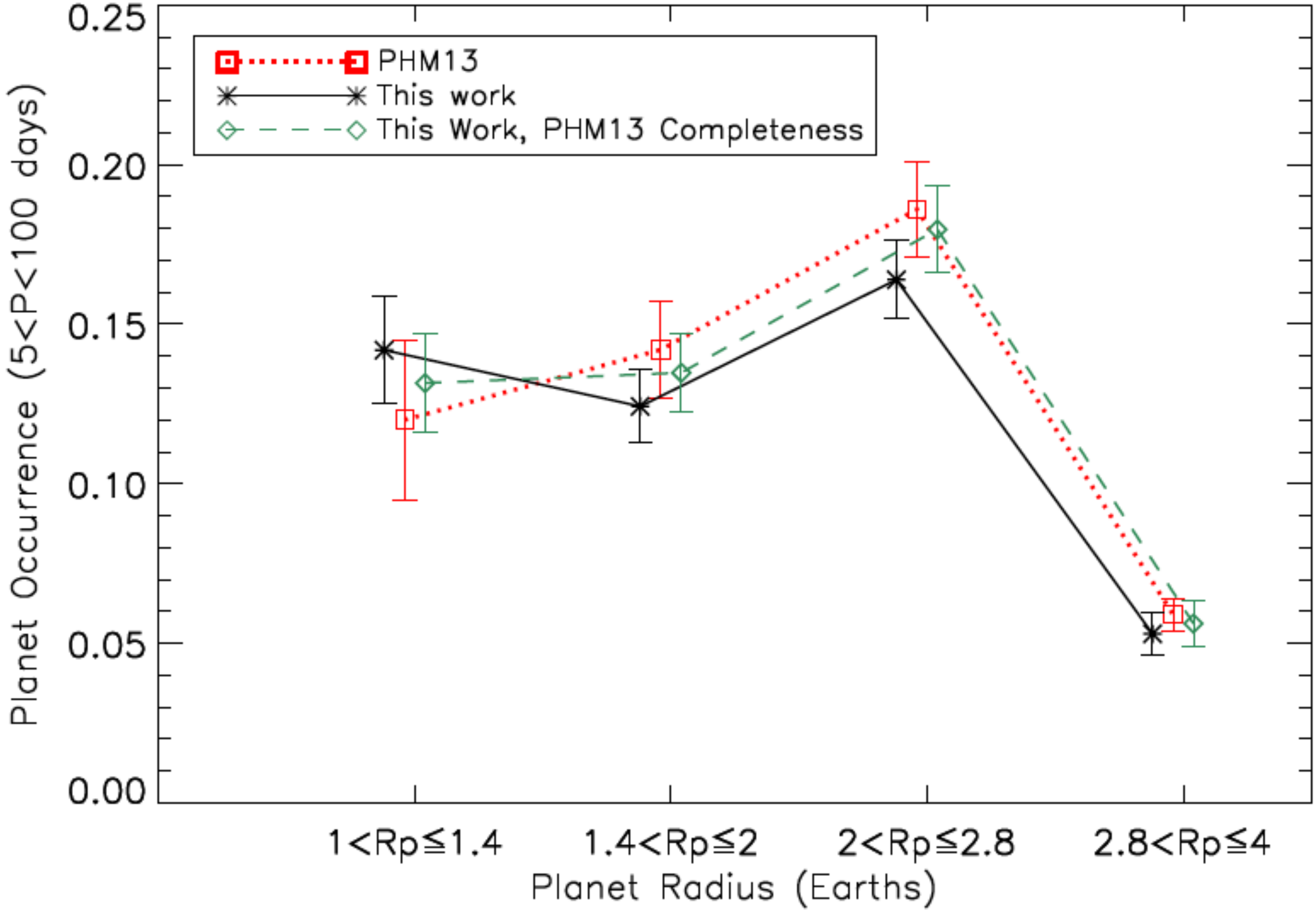
[2]Department of Geology & Geophysics, University of Hawai'i at Mānoa, Honolulu, HI 96822 USA
Draft version June 25, 2014

ABSTRACT

Using the most recent Kepler catalog, we reconstruct the occurrence rate of small (Neptune-sized or below) planets as a function of orbital period and planet radius, taking careful account of various detection biases. We analyze a sample of $76,000$ Sun-like stars and their associated planet candidates with periods between 20 and 200 days, and sizes between 1 and $4R_\oplus$. Such planets have likely experienced little photoevaporation, and may reflect the "primordial" planet population. Assuming that the size distribution of planets are independent of their orbital periods (and vice versa), we conclude that Kepler planets are preferentially peaked at $2-2.8R_\oplus$, with their numbers decreasing gradually toward smaller sizes. These planets are found roughly uniformly in logarithmic period. The average number of planets per star, in the stated period and size ranges, is 0.46 ± 0.03. This number rises by ~ 0.2 if one includes planets inward of 20 days. Upon extrapolation we obtain an occurrence rate, for Earth-like planets within the "habitable zone" (as calculated by 1-D climate models), of $6.4^{+3.4}_{-1.1}\%$. We discuss the astrophysical implications of our results.

In our study, we introduce a number of novel statistical approaches, including the adoption of the "iterative simulation" technique (in addition to the standard MCMC technique), incorporation of uncertainties in planet radii, and an improved consideration of detection bias. Our results largely agree with those from an earlier work by Petigura et al. (2013), based on different statistical treatments and noise models. However, this agreement masks two substantial underlying discrepancies that (to first order) cancel each other out.

- $\eta_\oplus = 6.4\%$ (+3.4, -1.1)



Silburt et al.(2015)

The Astrophysical Journal, 795:64 (12pp), 2014 November 1 doi:10.1088/0004-637X/795/1/6

EXOPLANET POPULATION INFERENCE AND THE ABUNDANCE OF EARTH ANALOGS FROM NOISY, INCOMPLETE CATALOGS

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Received 2014 June 11; accepted 2014 September 3; published 2014 October 14

ABSTRACT

No true extrasolar Earth analog is known. Hundreds of planets have been found around Sun-like stars that are either Earth-sized but on shorter periods, or else on year-long orbits but somewhat larger. Under strong assumptions, exoplanet catalogs have been used to make an extrapolated estimate of the rate at which Sun-like stars host Earth analogs. These studies are complicated by the fact that every catalog is censored by non-trivial selection effects and detection efficiencies, and every property (period, radius, etc.) is measured noisily. Here we present a general hierarchical probabilistic framework for making justified inferences about the population of exoplanets, taking into account survey completeness and, for the first time, observational uncertainties. We are able to make fewer assumptions about the distribution than previous studies; we only require that the occurrence rate density be a smooth function of period and radius (employing a Gaussian process). By applying our method to synthetic catalogs, we demonstrate that it produces more accurate estimates of the whole population than standard procedures based on weighting by inverse detection efficiency. We apply the method to an existing catalog of small planet candidates around G dwarf stars. We confirm a previous result that the radius distribution changes slope near Earth's radius. We find that the rate density of Earth analogs is about 0.02 (per star per natural logarithmic bin in period and radius) with large uncertainty. This number is much smaller than previous estimates made with the same data but stronger assumptions.

- rate denisty= 2%

$$\Gamma_\oplus = \Gamma(\ln P_\oplus,\ \ln R_\oplus) = \left. \frac{dN}{d\ln P\ d\ln R} \right|_{R=R_\oplus,\ P=P_\oplus} .$$

That is, $\Gamma_\oplus$ is the rate density of exoplanets around a Sun-like star (expected number of planets per star per natural logarithm of period per natural logarithm of radius), evaluated at the period and radius of Earth.

In Equation (20), we use the symbol Γ instead of the more commonly used η since we define "Earth analog" in terms of measurable quantities with no mention of habitability or composition. This might seem unsatisfying but the composition of an exoplanet is notoriously difficult to measure even with large uncertainty and any definition of habitability is still extremely subjective. With this in mind, we stick to the observable definition for this article.

TERRESTRIAL PLANET OCCURRENCE RATES FOR THE *KEPLER* GK DWARF SAMPLE

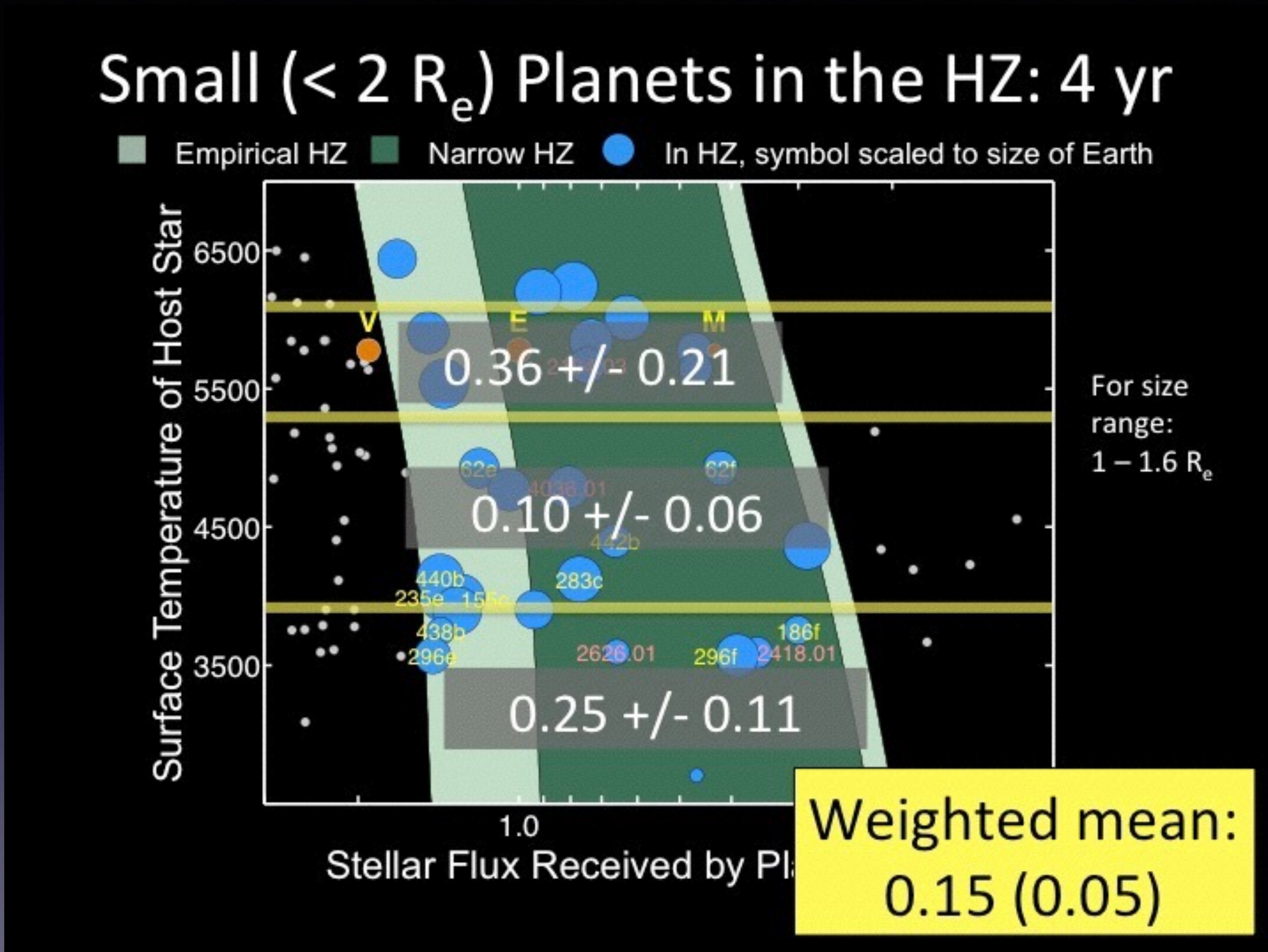
Christopher J. Burke[1], Jessie L. Christiansen[2], F. Mullally[1], Shawn Seader[1], Daniel Huber[3,4,5], Jason F. Rowe[1], Jeffrey L. Coughlin[1], Susan E. Thompson[1], Joseph Catanzarite[1], Bruce D. Clarke[1], Timothy D. Morton[6], Douglas A. Caldwell[1], Stephen T. Bryson[7], Michael R. Haas[7], Natalie M. Batalha[7], Jon M. Jenkins[7], Peter Tenenbaum[1], Joseph D. Twicken[1], Jie Li[1], Elisa Quintana[1], Thomas Barclay[8], Christopher E. Henze[7], William J. Borucki[7], Steve B. Howell[7], Martin Still[8]

Submitted

ABSTRACT

We measure planet occurrence rates using the planet candidates discovered by the Q1-Q16 *Kepler* pipeline search. This study examines planet occurrence rates for the *Kepler* GK dwarf target sample for planet radii, $0.75 \leq R_{\rm p} \leq 2.5\ R_{\oplus}$, and orbital periods, $50 \leq P_{\rm orb} \leq 300$ days, with an emphasis on a thorough exploration and identification of the most important sources of systematic uncertainties. Integrating over this parameter space, we measure an occurrence rate of F_0=0.77 planets per star, with an allowed range of $0.3 \leq F_0 \leq 1.9$. The allowed range takes into account both statistical and systematic uncertainties, and values of F_0 beyond the allowed range are significantly in disagreement with our analysis. We generally find higher planet occurrence rates and a steeper increase in planet occurrence rates towards small planets than previous studies of the *Kepler* GK dwarf sample. Through extrapolation, we find that the one year orbital period terrestrial planet occurrence rate, $\zeta_{1.0}$=0.1, with an allowed range of $0.01 \leq \zeta_{1.0} \leq 2$, where $\zeta_{1.0}$ is defined as the number of planets per star within 20% of the $R_{\rm p}$ and $P_{\rm orb}$ of Earth. For G dwarf hosts, the $\zeta_{1.0}$ parameter space is a subset of the larger $\eta_{\oplus}$ parameter space, thus $\zeta_{1.0}$ places a lower limit on $\eta_{\oplus}$ for G dwarf hosts. From our analysis, we identify the leading sources of systematics impacting *Kepler* occurrence rate determinations as: reliability of the planet candidate sample, planet radii, pipeline completeness, and stellar parameters.

Number of planets per star in 1 year orbit ~10%
(with an allowed range of 1% to 200%)



Courtesy: Batalha, N

Key objectives and questions:

1. Propose standard nominal conventions, definitions, and units for occurrence rates/distributions to facilitate comparisons between different studies.

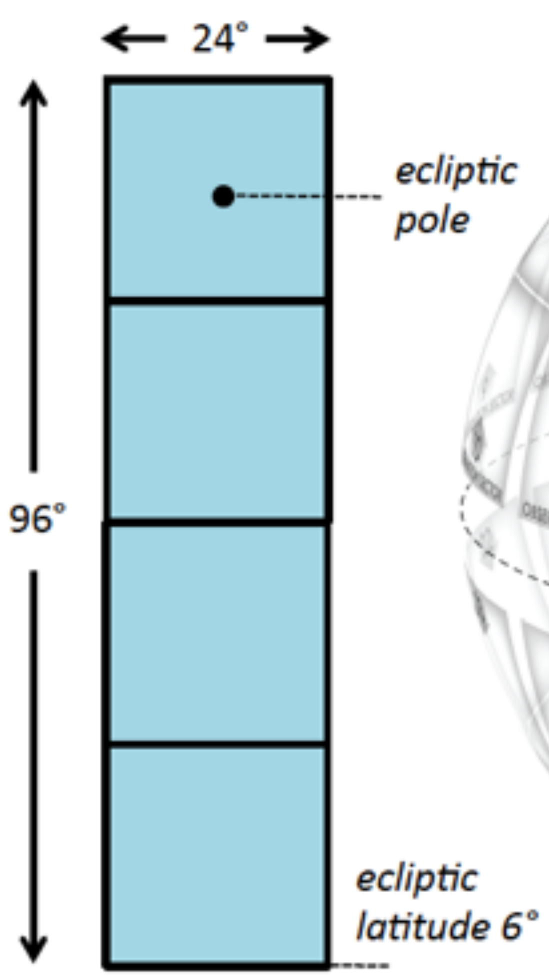
2. Do occurrence estimates from different teams/methods agree with each other to within statistical uncertainty? If not, why?

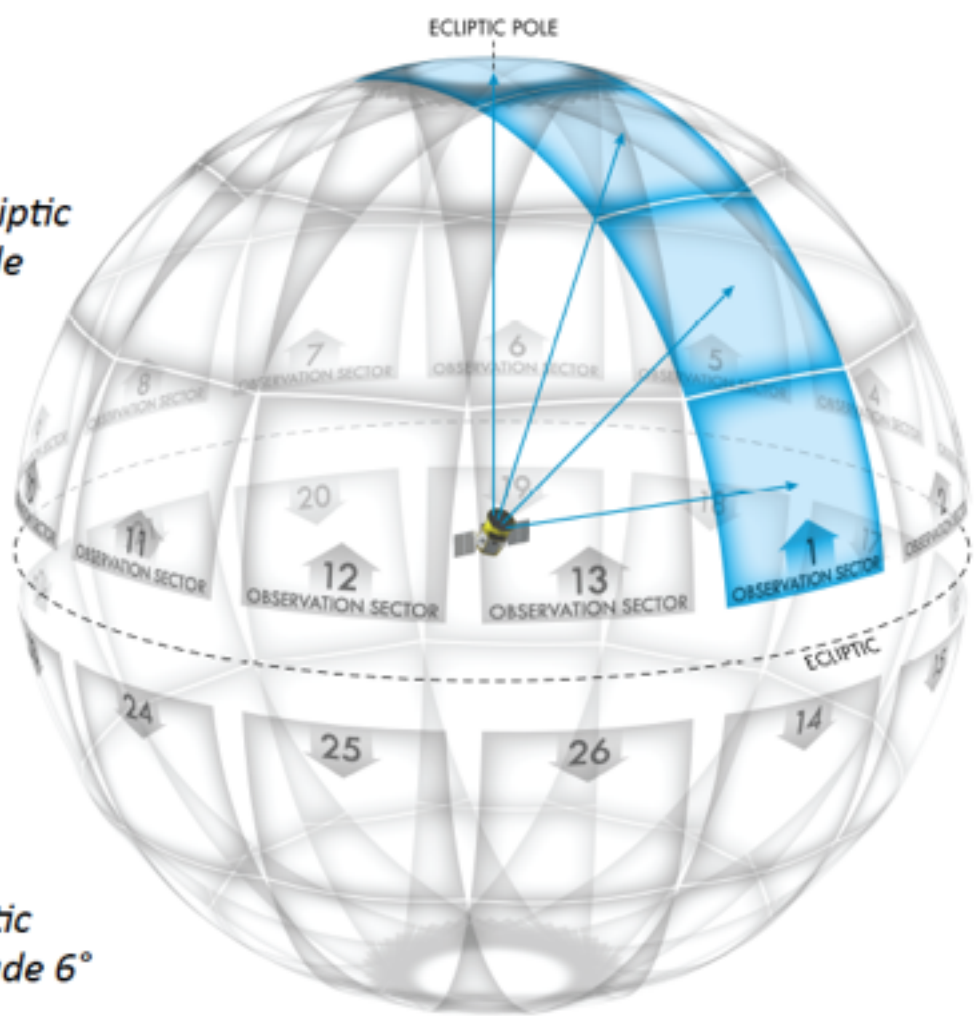
3. For occurrence rates where extrapolation is still necessary, what values should the community adopt as standard conventions for mission yield estimates?

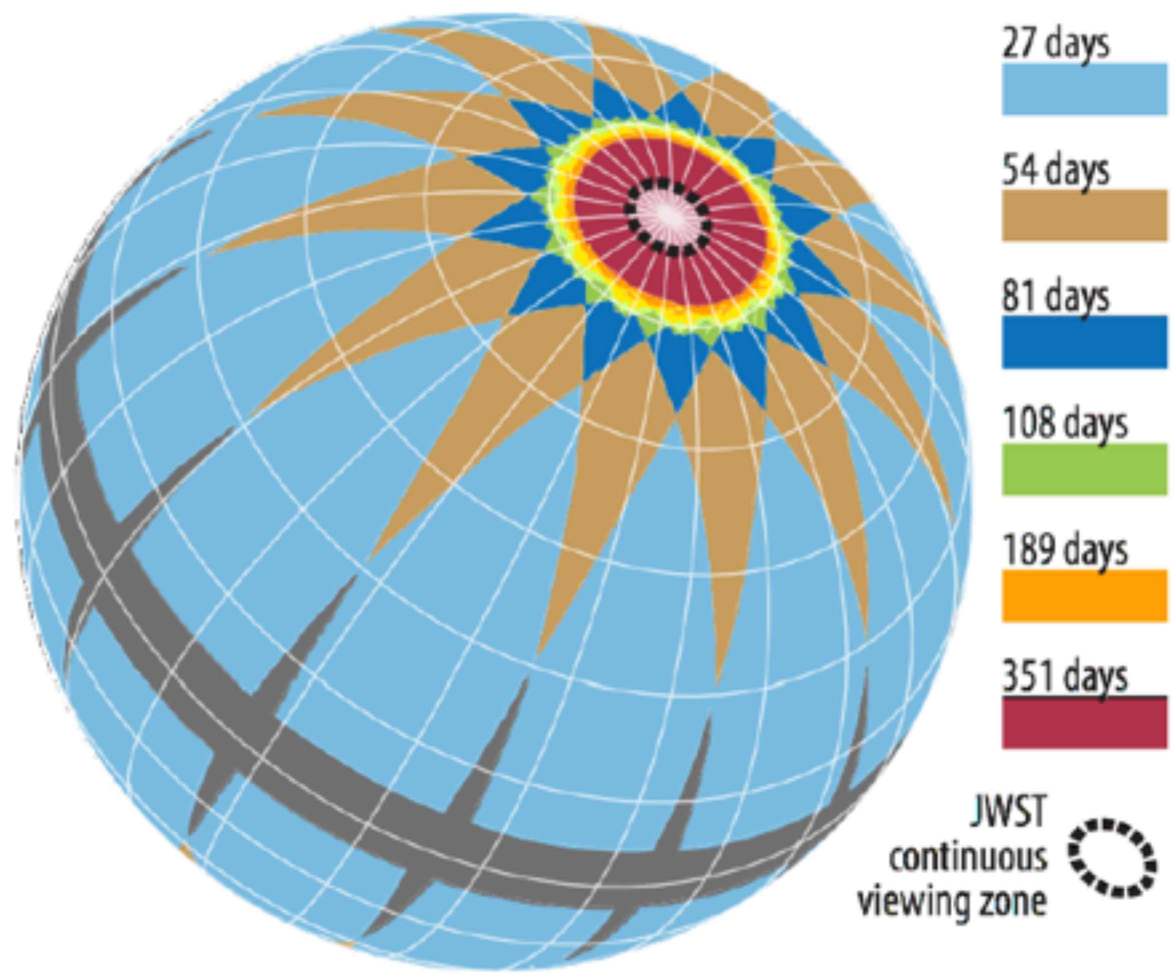
Rus Belikov and Chris Stark.

TESS

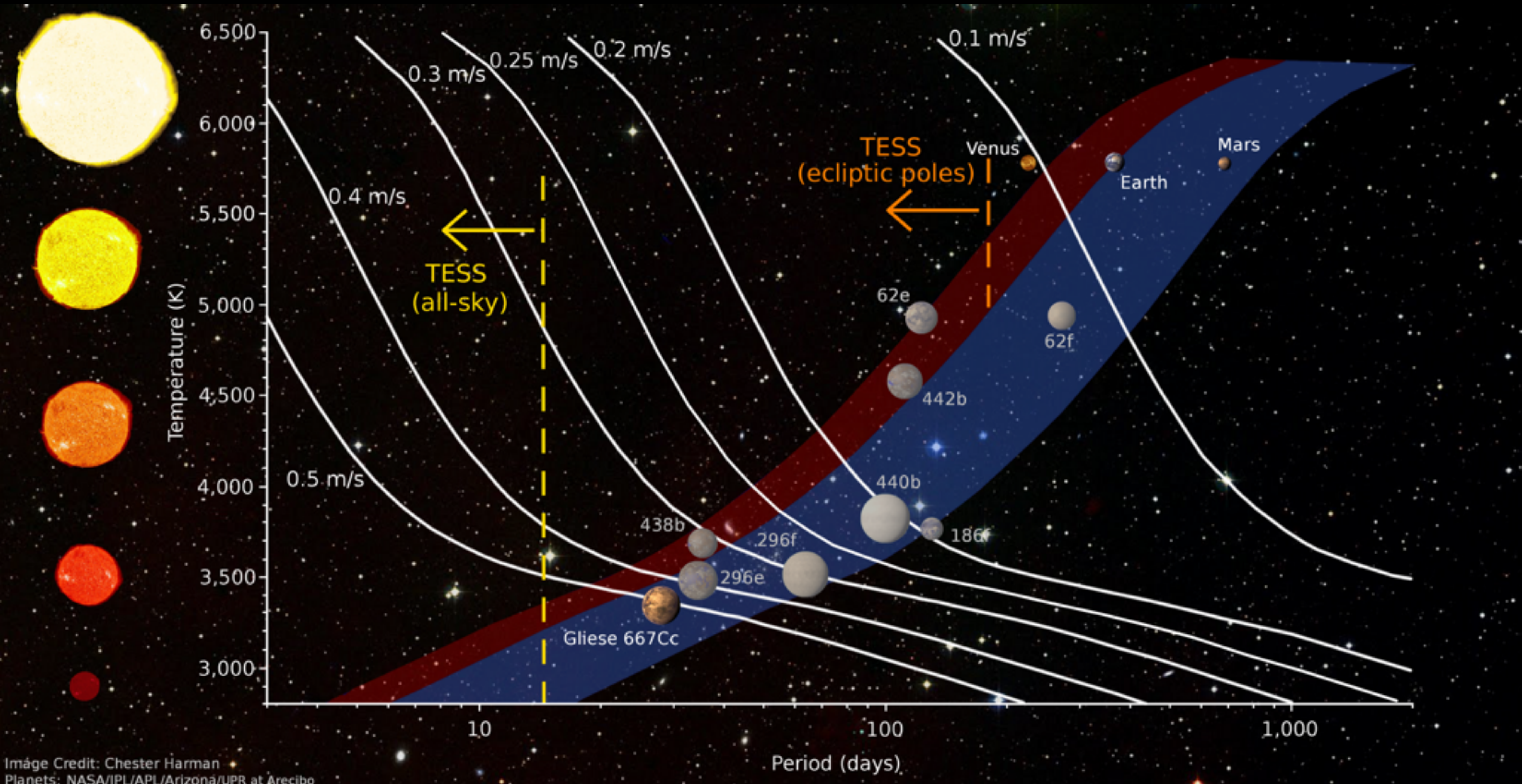
(TRANSITING EXOPLANET SURVEY SATELLITE)







RV SENSITIVITY OF HZ PLANETS



$\eta_{♀}$

Submitted for publication in the Astrophysical Journal Letters
Preprint typeset using LaTeX style emulateapj v. 11/10/09

ON THE FREQUENCY OF POTENTIAL VENUS ANALOGS FROM KEPLER DATA

Stephen R. Kane[1], Ravi Kumar Kopparapu[2,3,4,5,6], Shawn D. Domagal-Goldman[7]

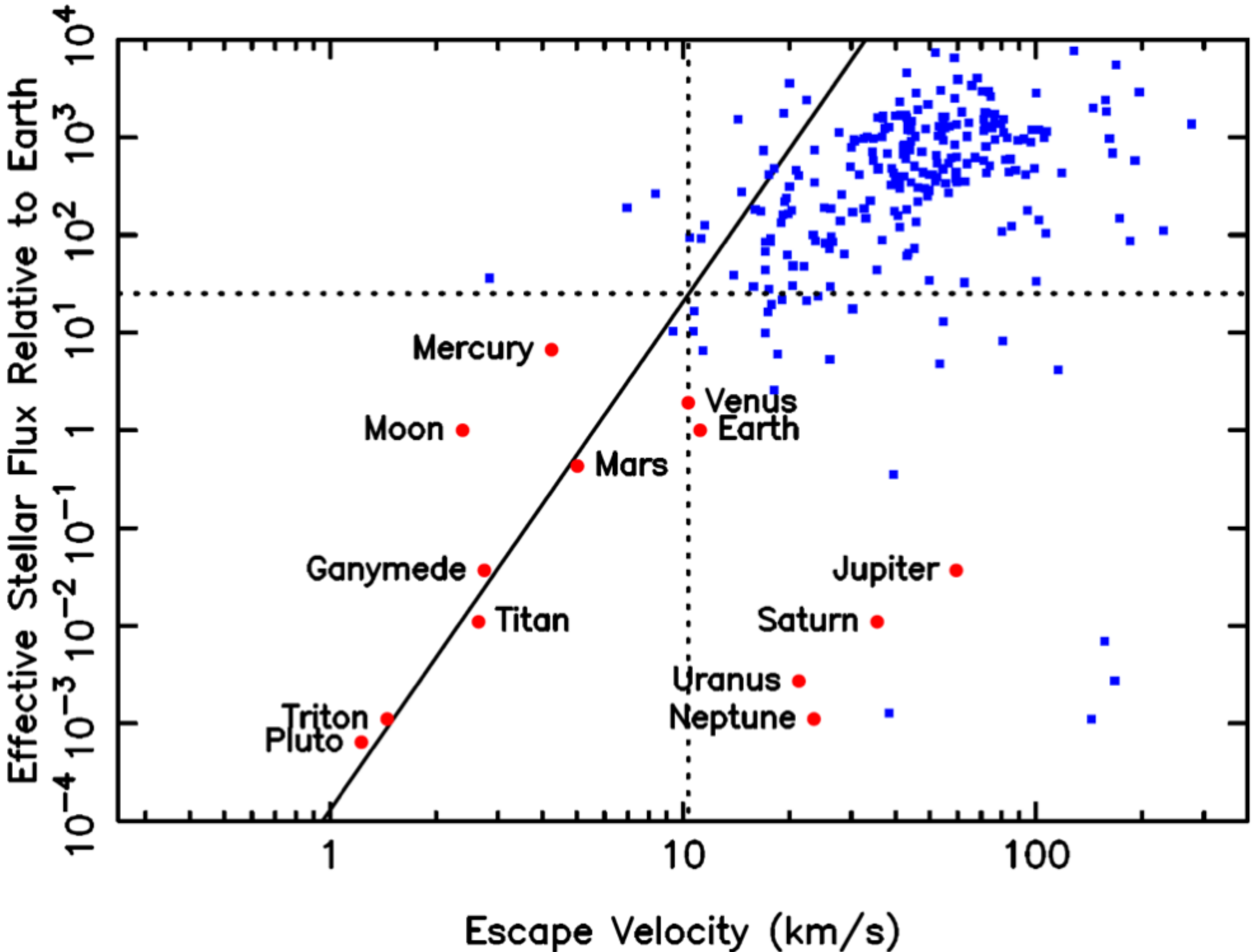
Submitted for publication in the Astrophysical Journal Letters

ABSTRACT

The field of exoplanetary science has seen a dramatic improvement in sensitivity to terrestrial planets over recent years. Such discoveries have been a key feature of results from the *Kepler* mission which utilizes the transit method to determine the size of the planet. These discoveries have resulted in a corresponding interest in the topic of the Habitable Zone (HZ) and the search for potential Earth analogs. Within the Solar System, there is a clear dichotomy between Venus and Earth in terms of atmospheric evolution, likely the result of the large difference ($\sim$ factor of two) in incident flux from the Sun. Since Venus is 95% of the Earth's radius in size, it is impossible to distinguish between these two planets based only on size. In this paper we discuss planetary insolation in the context of atmospheric erosion and runaway greenhouse limits for planets similar to Venus. We define a "Venus Zone" (VZ) in which the planet is more likely to be a Venus analog rather than an Earth analog. We identify 43 potential Venus analogs with an occurrence rate ($\eta_{♀}$) of $0.32^{+0.05}_{-0.07}$ and $0.45^{+0.06}_{-0.09}$ for M dwarfs and GK dwarfs respectively.

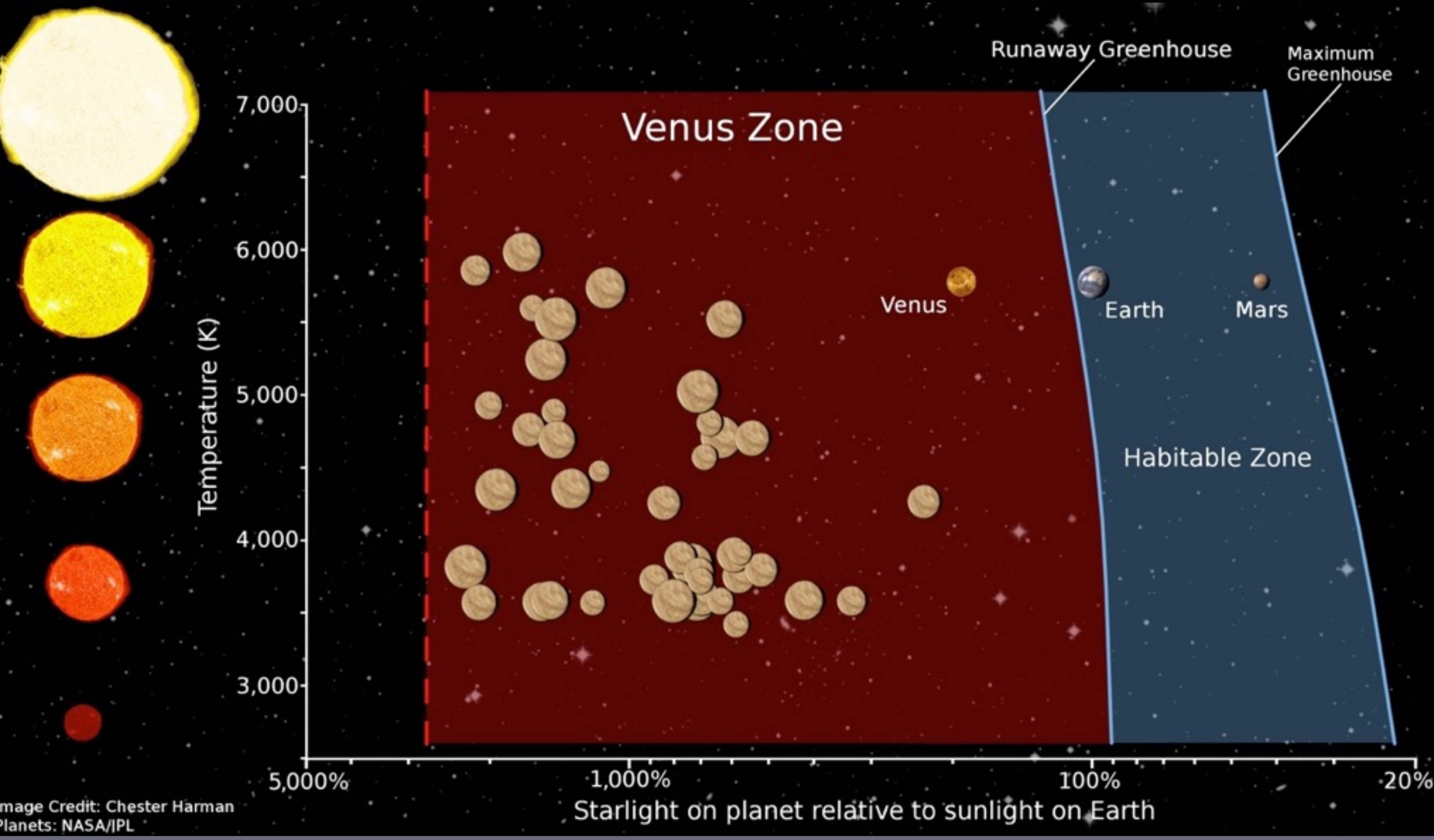
Subject headings: astrobiology – planetary systems – planets and satellites: individual (Venus)

Kane, Kopparapu & Domagal-Goldman (2014), ApJLetters in press, arXiv:1409.2886

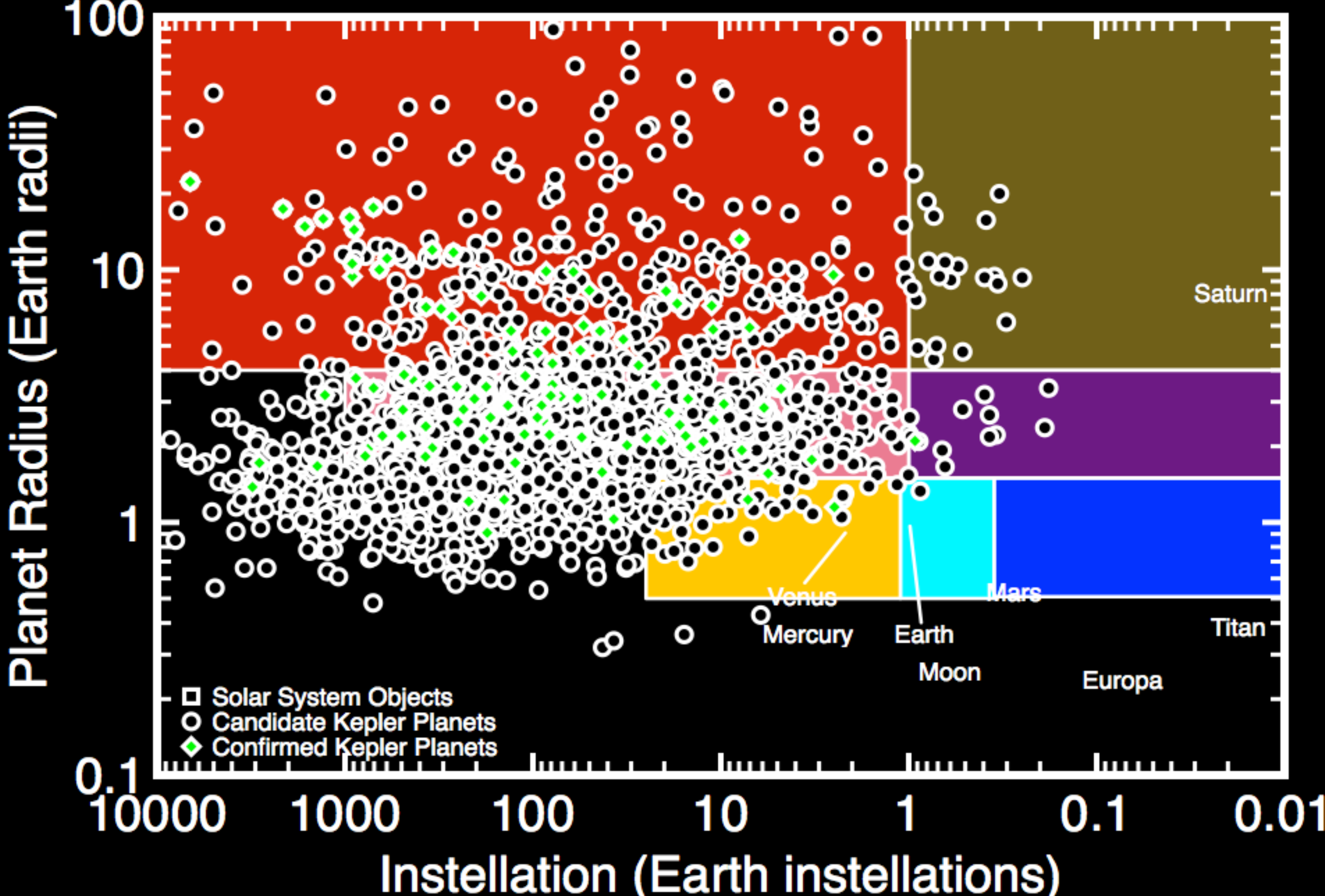


Effective Stellar Flux Relative to Earth
Escape Velocity (km/s)
Mercury
Venus
Earth
Moon
Mars
Ganymede
Titan
Triton
Pluto
Jupiter
Saturn
Uranus
Neptune

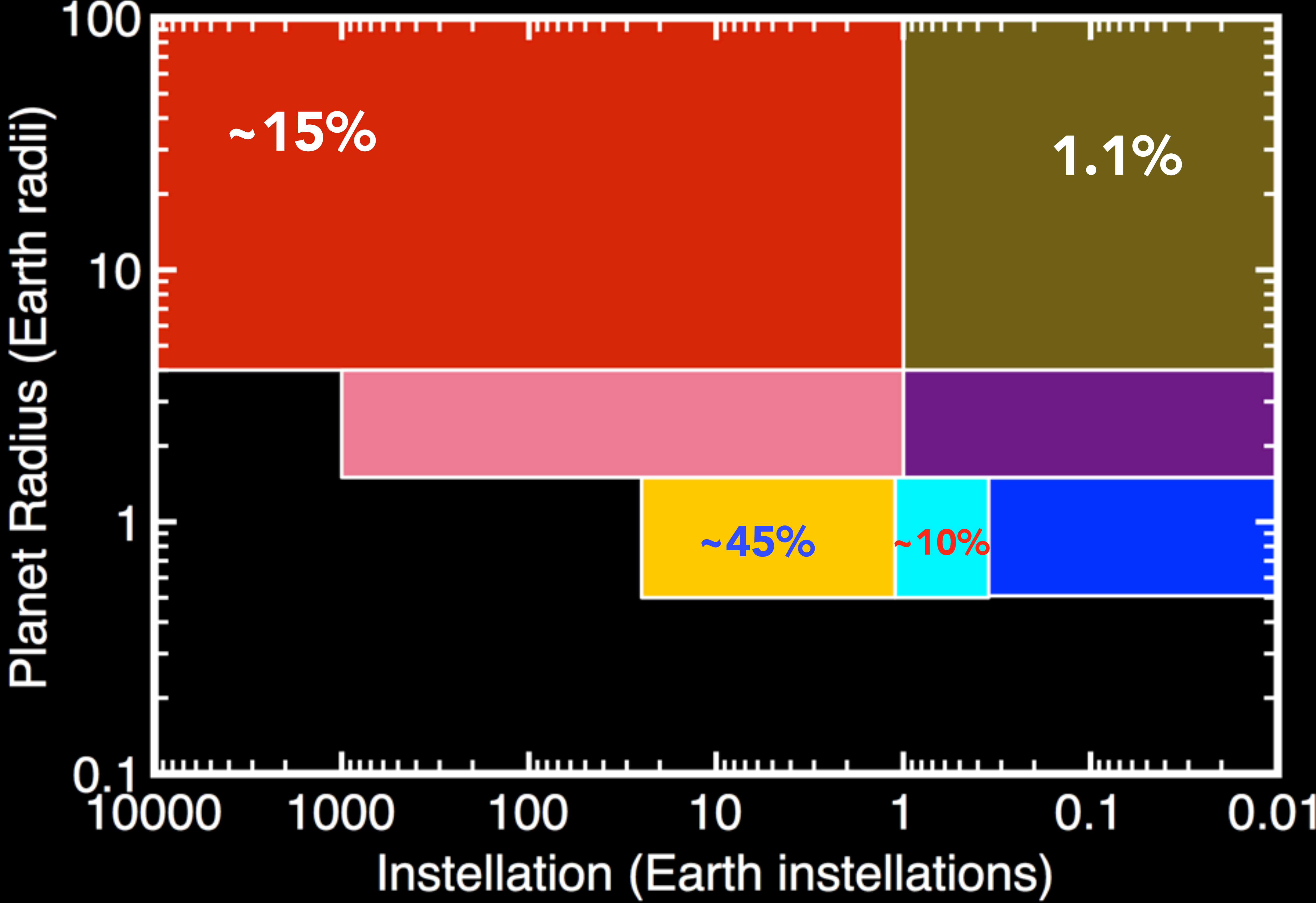
Occurrence of Venus Analogs



Kane, Kopparapu & Domagal-Goldman (2014), ApJLetters



Planet Radius (Earth radii)
100
10
1
0.1
10000
1000
100
10
1
0.1
0.01
Instellation (Earth instellations)
Saturn
Venus
Mars
Mercury
Earth
Titan
Moon
Europa
Solar System Objects
Candidate Kepler Planets
Confirmed Kepler Planets



~15%
1.1%
~45%
~10%
100
10
1
0.1
10000
1000
100
10
1
0.1
0.01
Planet Radius (Earth radii)
Instellation (Earth instellations)