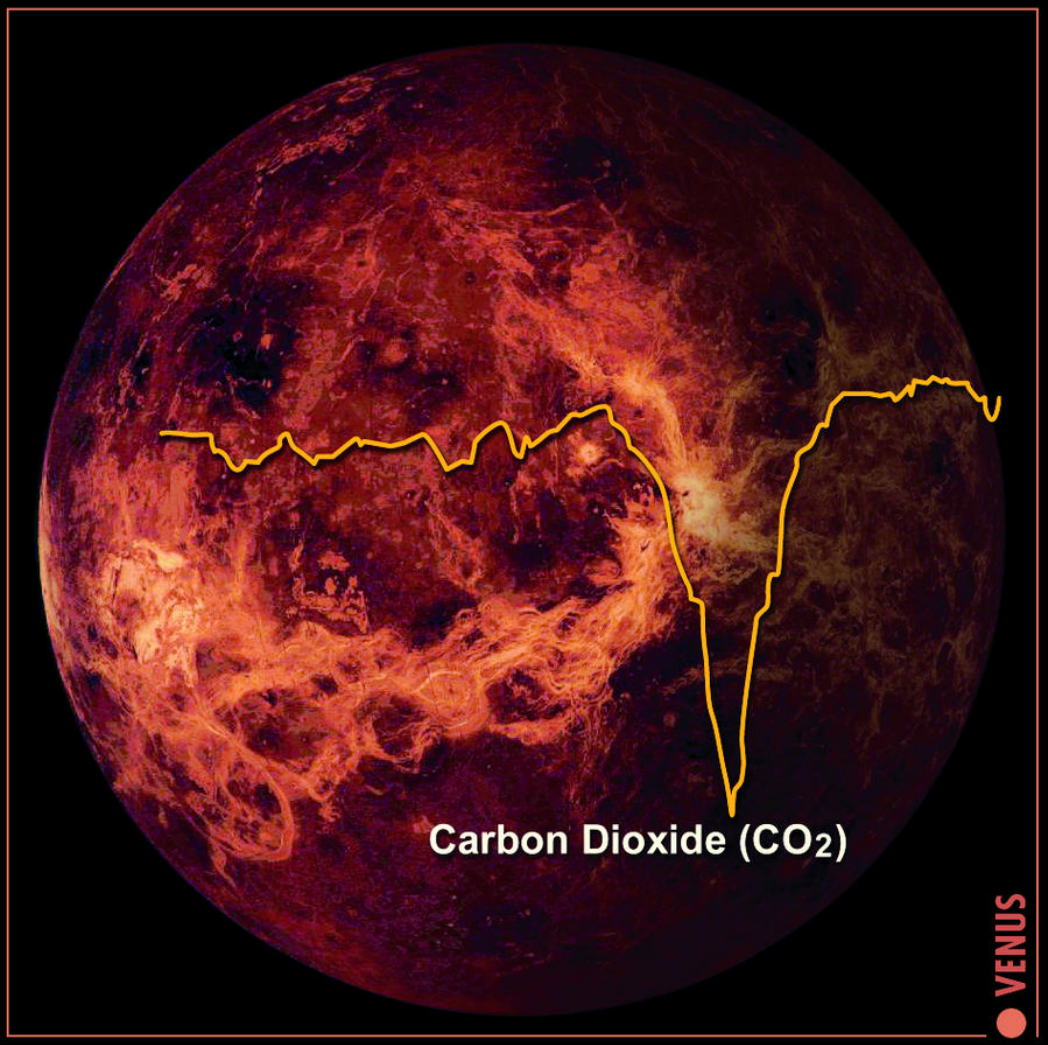
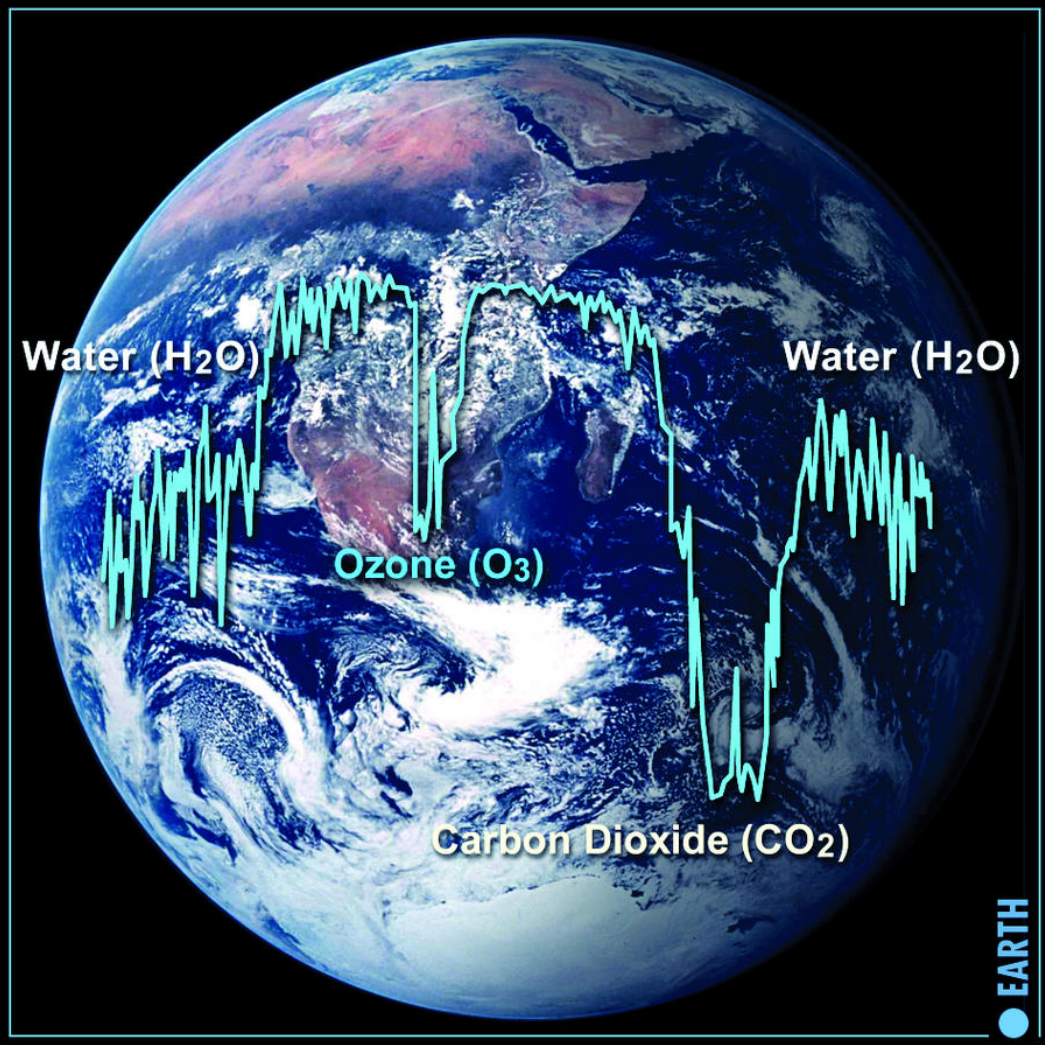
Planetary Habitability



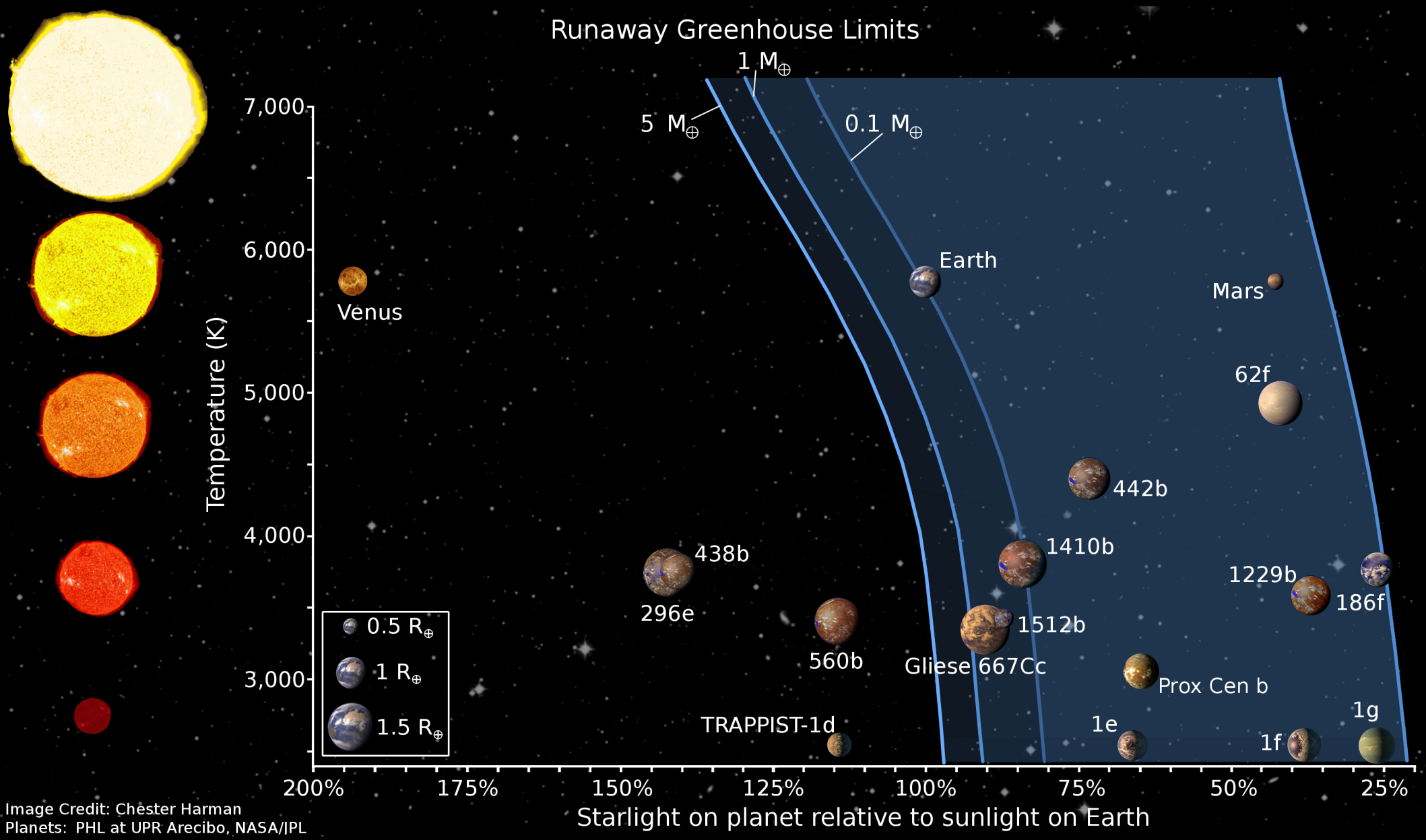


Stephen Kane

UNIVERSITY OF CALIFORNIA
UC RIVERSIDE

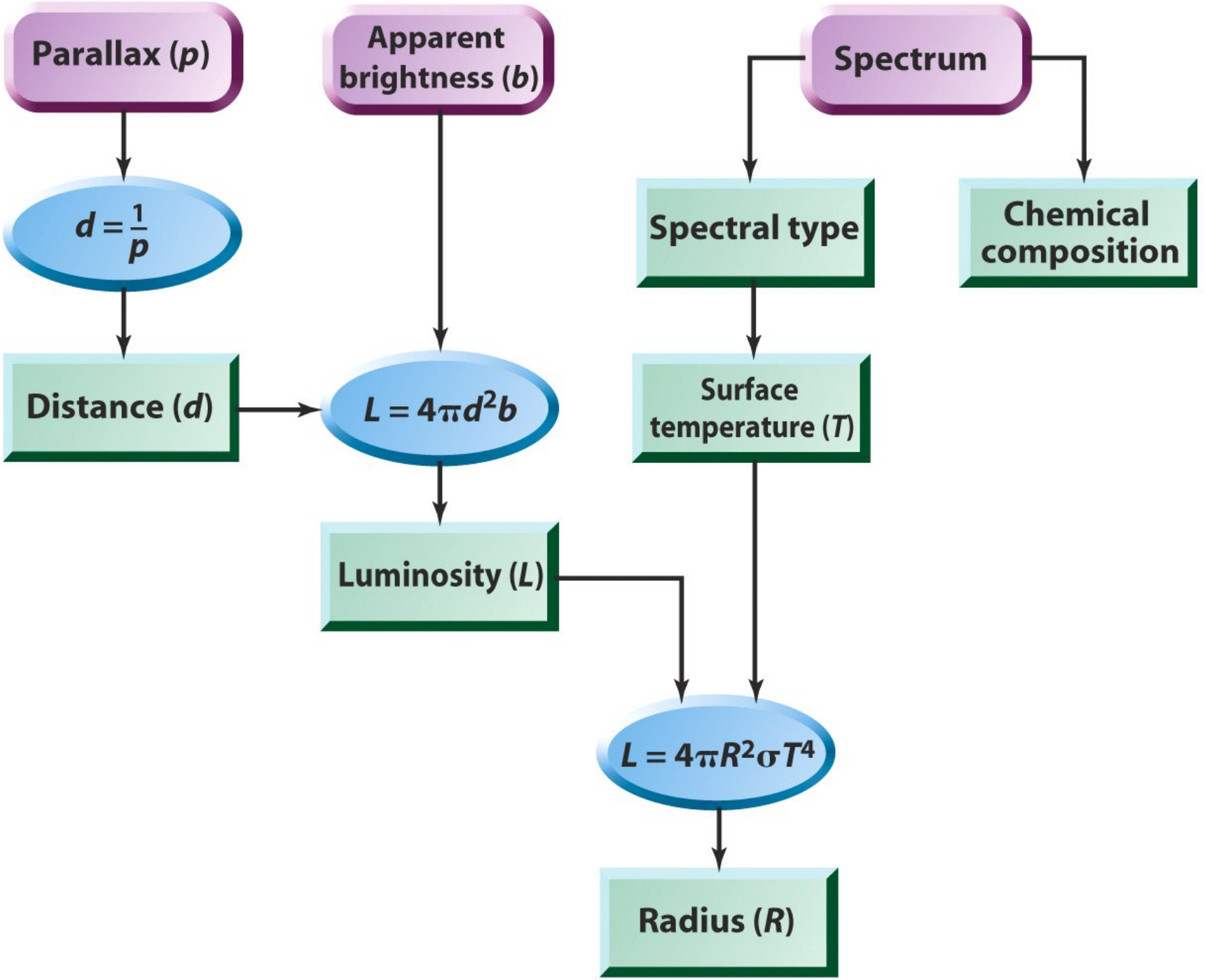
Topics

- Lecture 1 – Introduction
- Lecture 2 – Habitability Factors
- Lecture 3 - Stars
- Lecture 4 – Planetary Atmospheres
- Lecture 5 – Planetary Interiors
- Lecture 6 – Planetary Energy Balance
- Lecture 7 – Habitable Zone I
- Lecture 8 – Habitable Zone II
- Lecture 9 – Earth as a Living Planet
- Lecture 10 – Mars
- Lecture 11 – Icy Moons
- Lecture 12 – Venus
- Lecture 13 – Mercury & the Moon
- Lecture 14 – The Role of Giant Planets
- Lecture 15 – Stellar Influences
- Lecture 16 – Magnetic Fields
- Lecture 17 – Milankovitch Cycles
- Lecture 18 – Geological Cycles
- Lecture 19 – The Next Steps
- Lecture 20 – Summary/Discussion

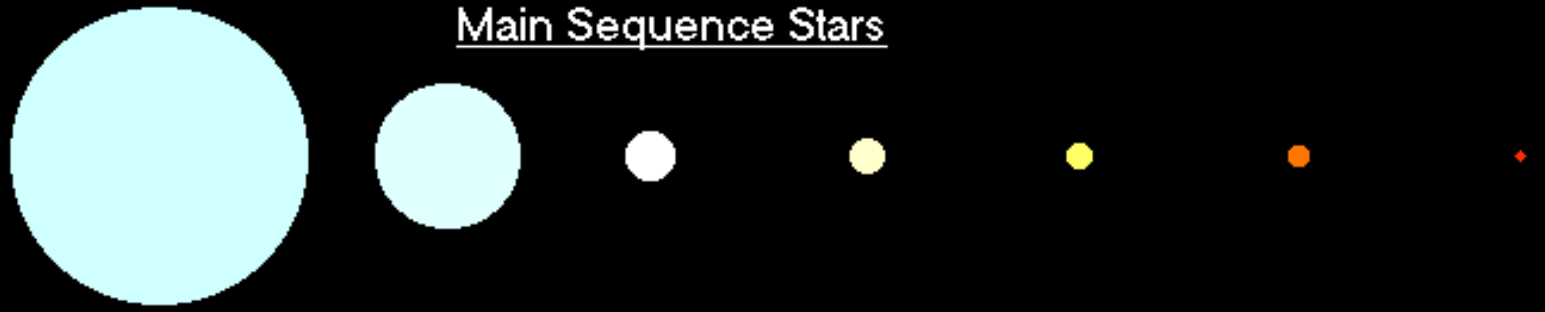


Kopparapu et al. “Habitable Zones around Main-sequence Stars: Dependence on Planetary Mass”, 2014, ApJ, 787, L29

Flowchart of Key Stellar Parameters



Main Sequence Stars



Spectral Type:	O	B	A	F	G	K	M
Temperature:	40 000K	20 000K	8500K	6500K	5700K	4500K	3200K
Radius (Sun=1):	10	5	1.7	1.3	1.0	0.8	0.3
Mass (Sun=1):	50	10	2.0	1.5	1.0	0.7	0.2
Luminosity (Sun=1):	100 000	1000	20	4	1.0	0.2	0.01
Lifetime (million yrs):	10	100	1000	3000	10 000	50 000	200 000
Abundance:	0.00001%	0.1%	0.7%	2%	3.5%	8%	80%

Giant Stars

Low mass stars near the end of their lives.

Spectral Type:	Mainly G, K or M
Temperature:	3000 to 10 000K
Radius (Sun=1):	10 to 50
Mass (Sun=1):	1 to 5
Luminosity (Sun=1):	50 to 1000
Lifetime (million yrs):	1000
Abundance:	0.4%

White Dwarfs

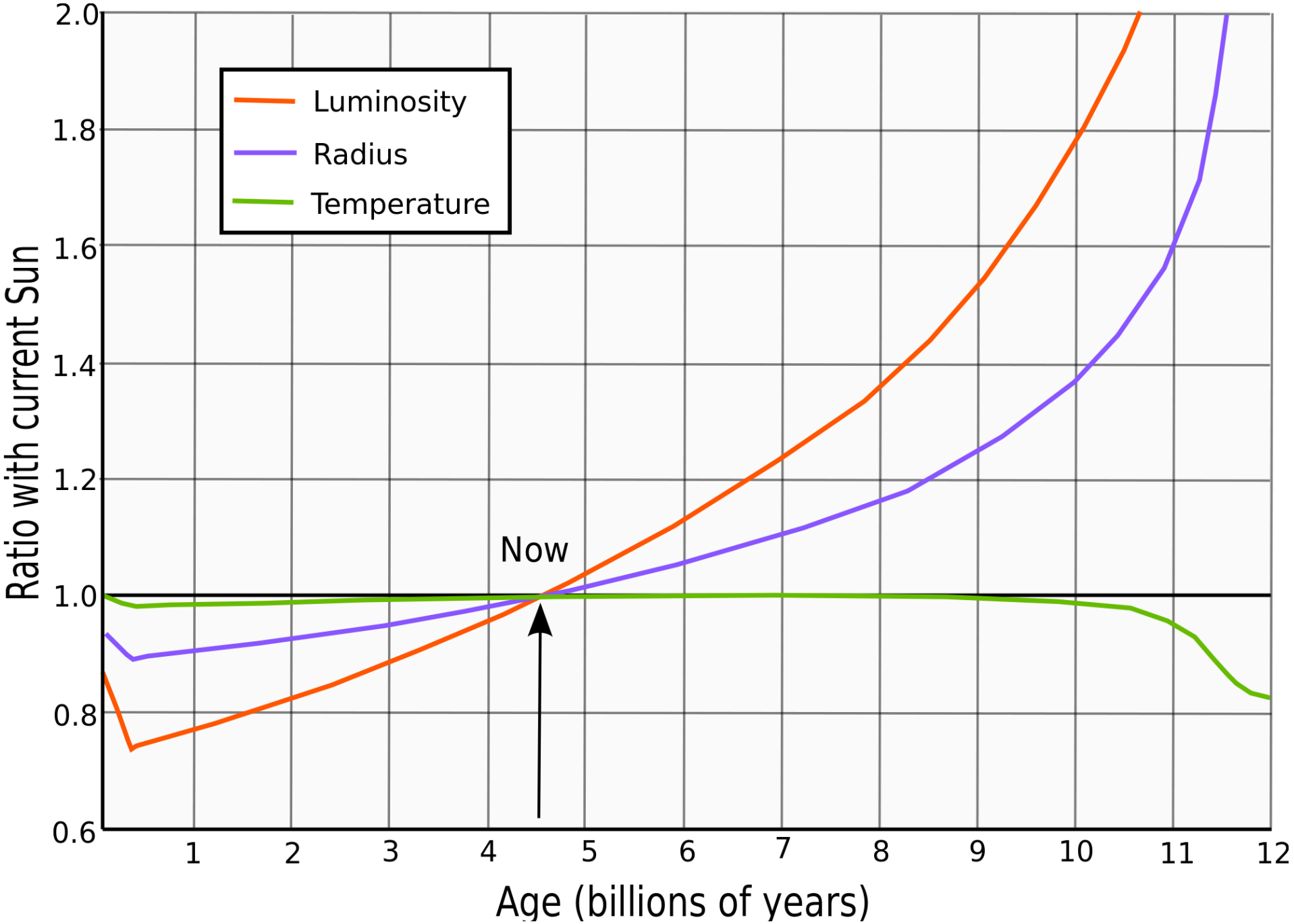
Dying remnant of an imploded star.

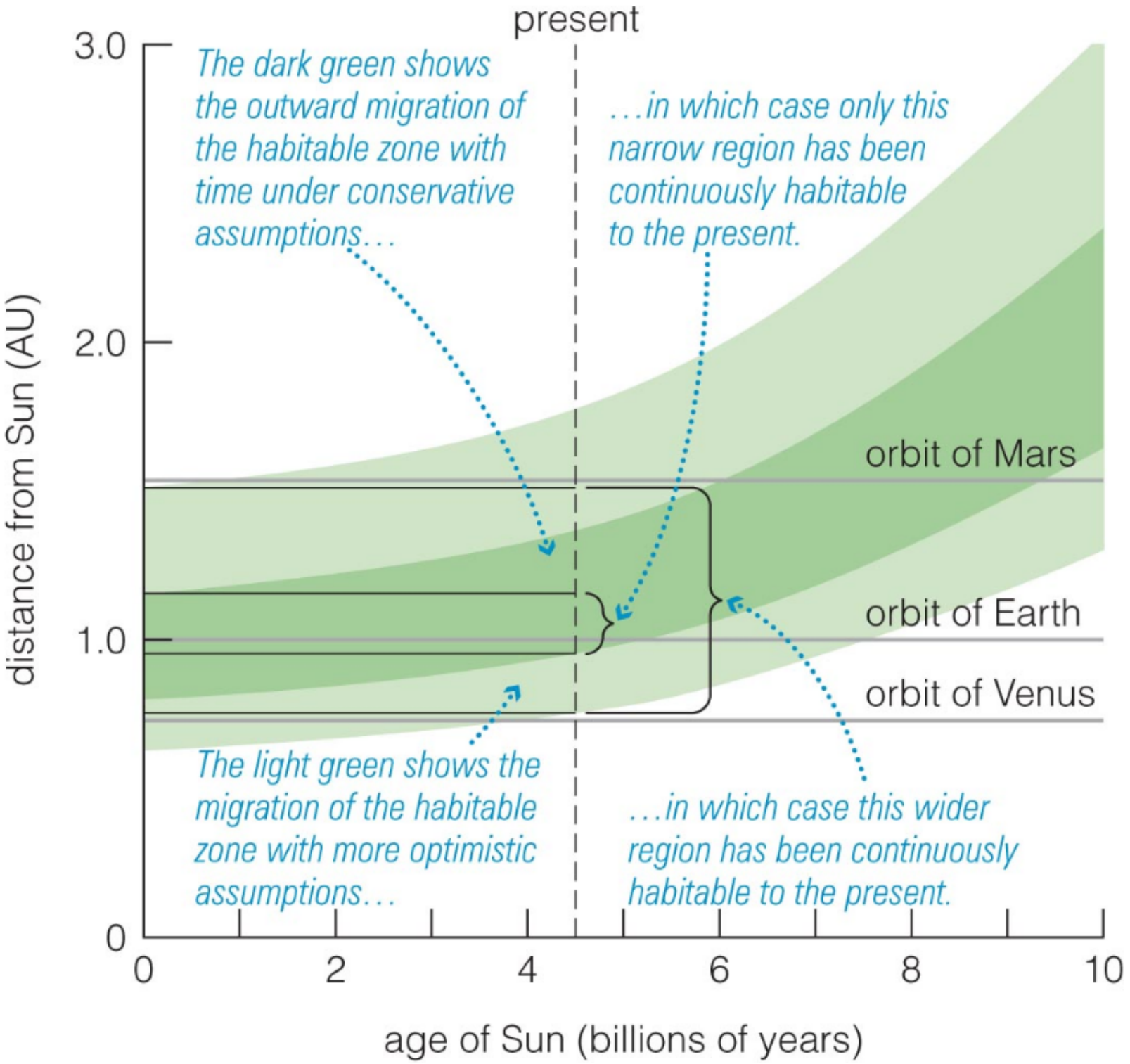
Spectral Type:	D
Temperature:	Under 80 000K
Radius (Sun=1):	Under 0.01
Mass (Sun=1):	Under 1.4
Luminosity (Sun=1):	Under 0.01
Lifetime (million yrs):	–
Abundance:	5%

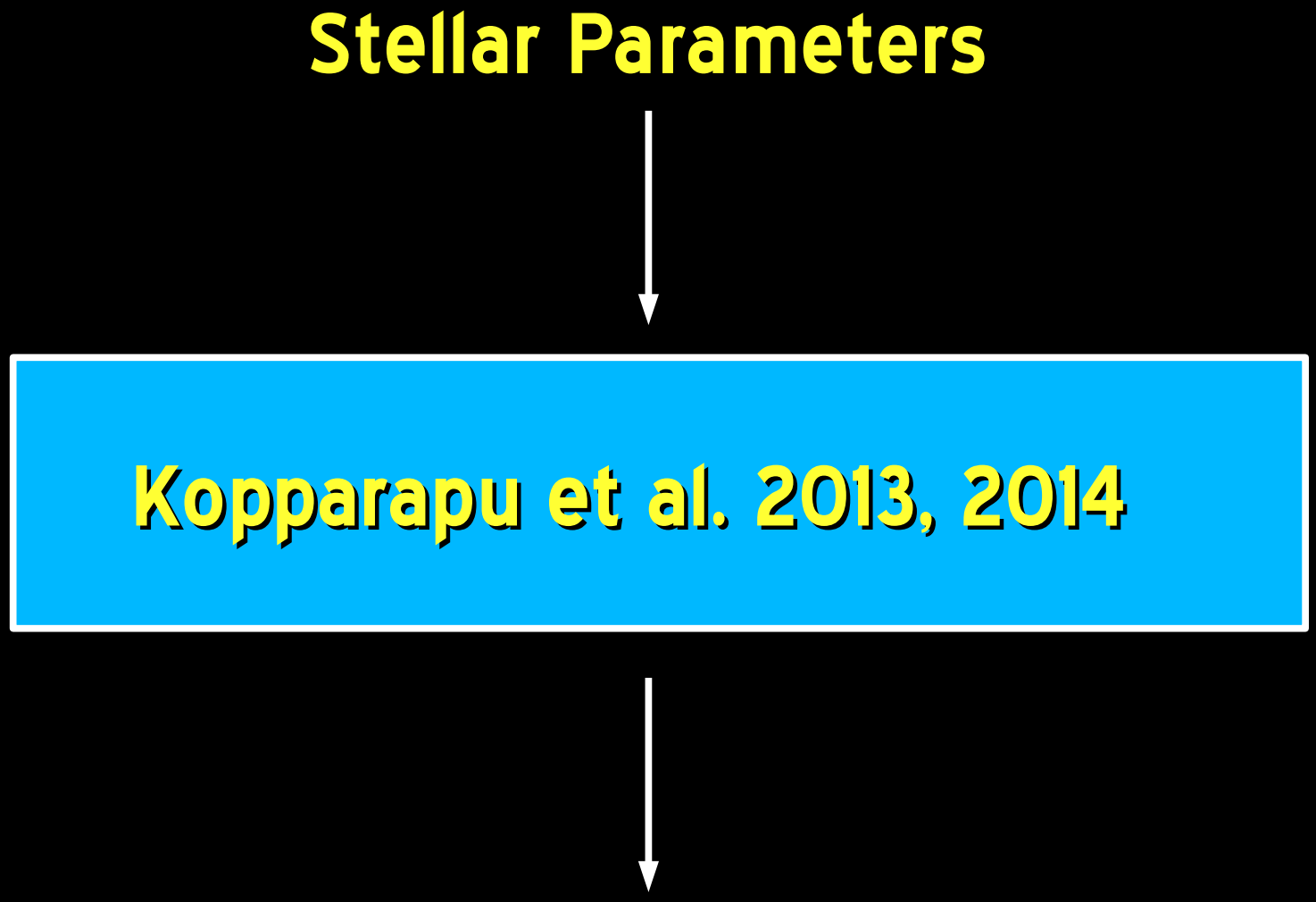
Supergiant Stars

High mass stars near the end of their lives.

Spectral Type:	O, B, A, F, G, K or M
Temperature:	4000 to 40 000K
Radius (Sun=1):	30 to 500
Mass (Sun=1):	10 to 70
Luminosity (Sun=1):	30 000 to 1000 000
Lifetime (million yrs):	10
Abundance:	0.0001%


Luminosity
Radius
Temperature
Now
Ratio with current Sun
Age (billions of years)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
1
2
3
4
5
6
7
8
9
10
11
12


present
3.0
2.0
1.0
0
distance from Sun (AU)
The dark green shows the outward migration of the habitable zone with time under conservative assumptions…
…in which case only this narrow region has been continuously habitable to the present.
orbit of Mars
orbit of Earth
orbit of Venus
The light green shows the migration of the habitable zone with more optimistic assumptions…
…in which case this wider region has been continuously habitable to the present.
0
2
4
6
8
10
age of Sun (billions of years)



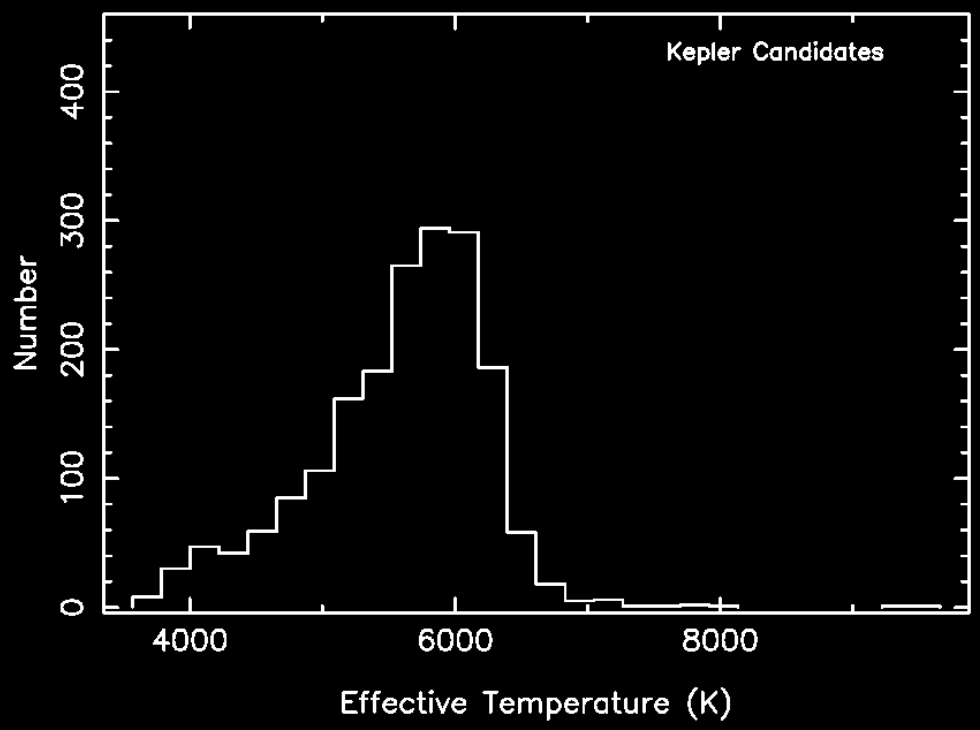
Kane, “Habitable Zone Dependence on Stellar Parameter Uncertainties”, 2014, ApJ, 782, 111

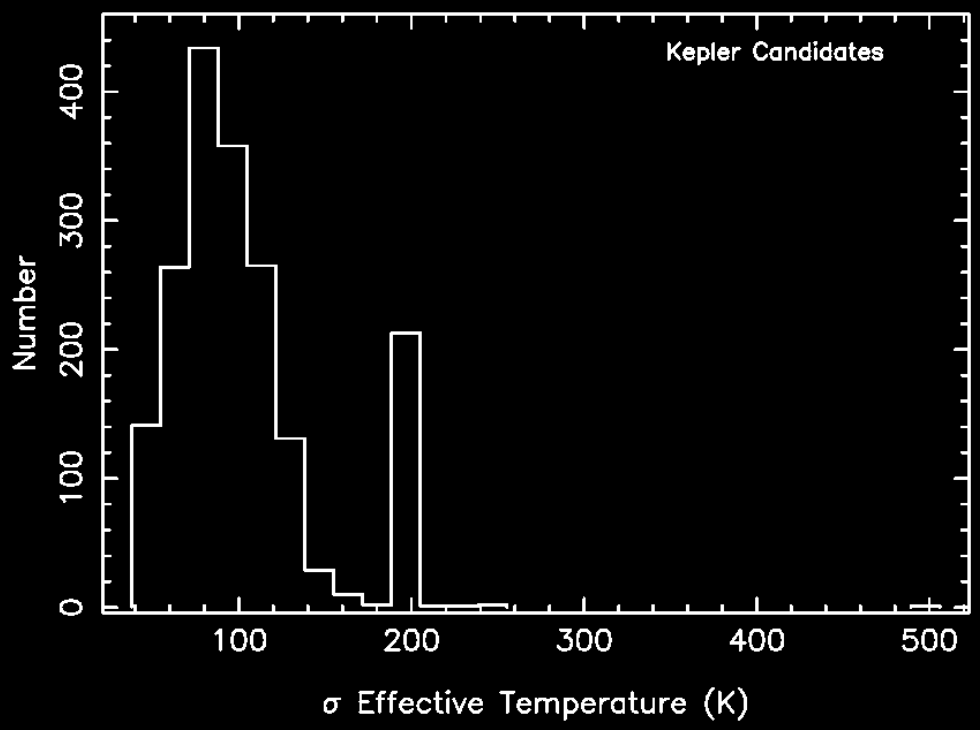
Stellar Parameters +/- X

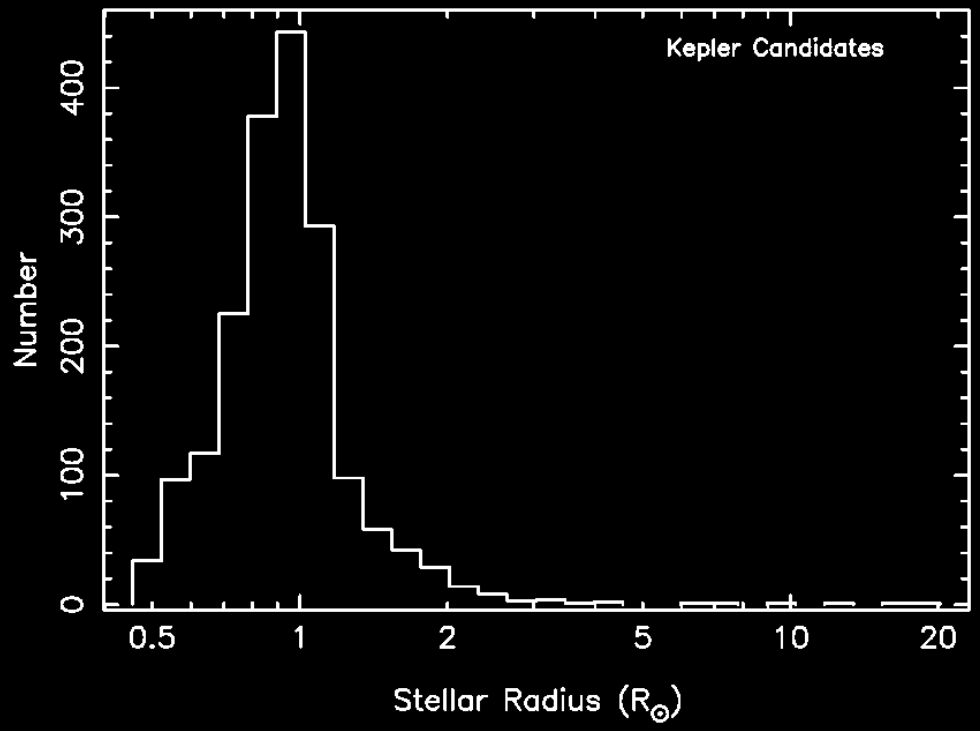
Kopparapu et al. 2013, 2014

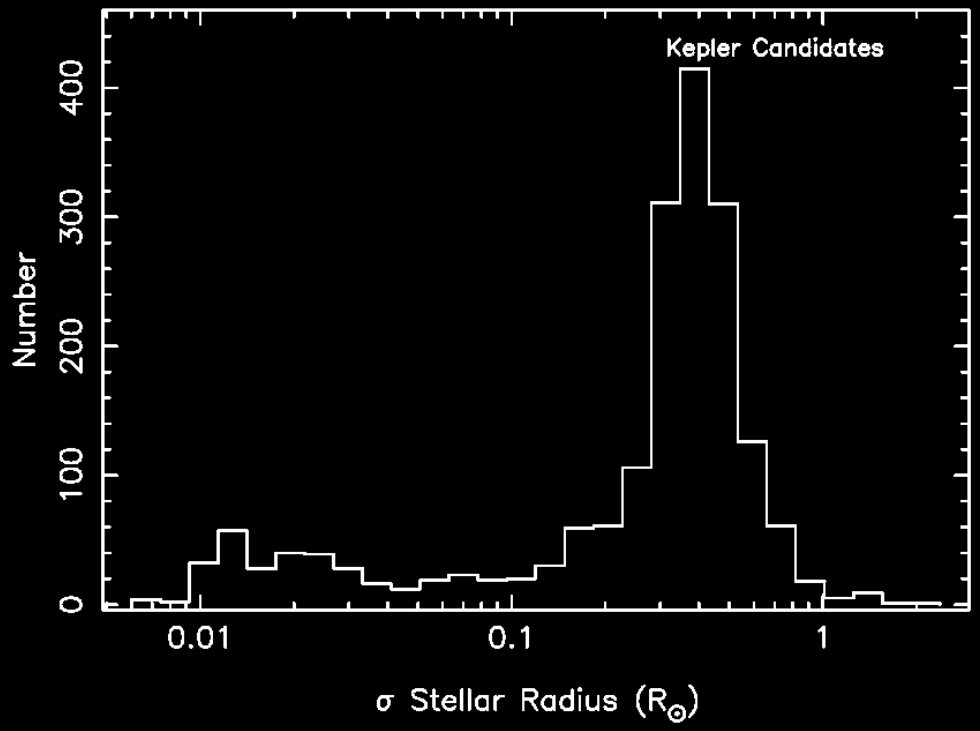
Habitable Zone Boundaries +/- Y

Kane, “Habitable Zone Dependence on Stellar Parameter Uncertainties”, 2014, ApJ, 782, 111

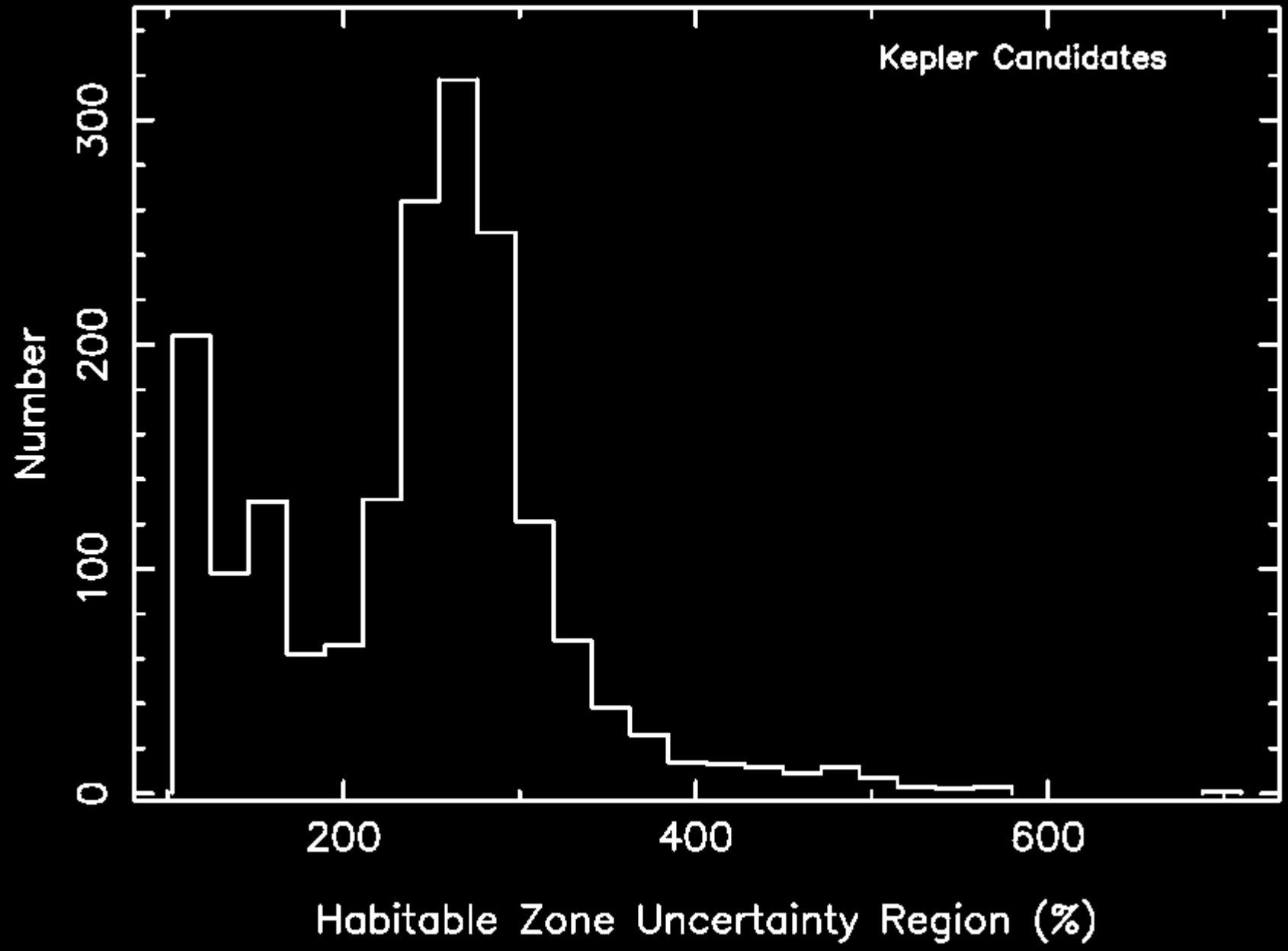

Kepler Candidates
Number
0
100
200
300
400
4000
6000
8000
Effective Temperature (K)


Kepler Candidates
Number
0
100
200
300
400
100
200
300
400
500
σ Effective Temperature (K)

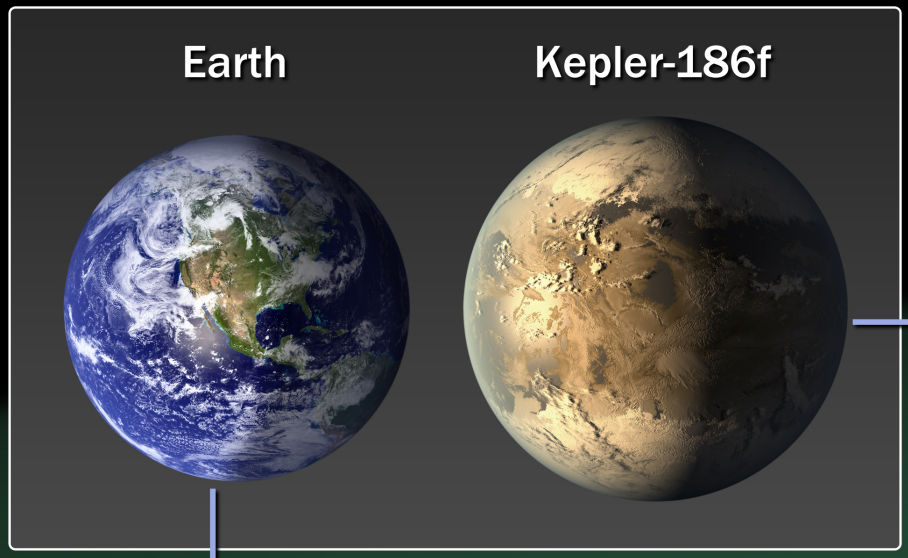

Kepler Candidates
Number
0
100
200
300
400
0.5
1
2
5
10
20
Stellar Radius (R⊙)

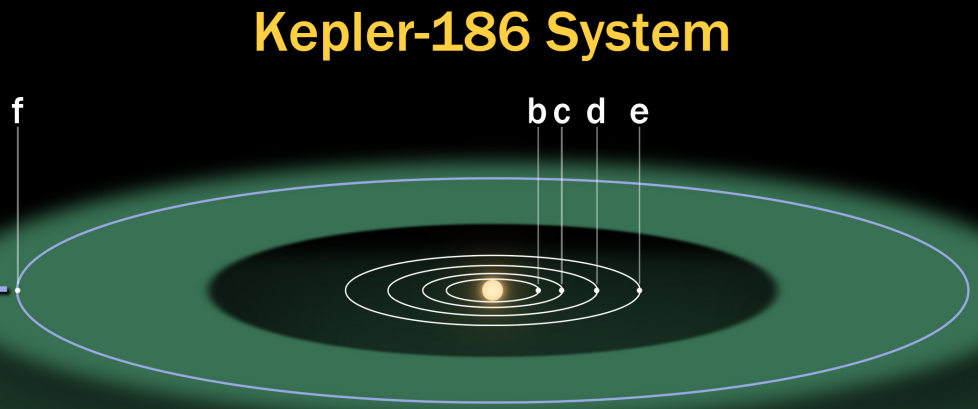

Kepler Candidates
Number
0
100
200
300
400
0.01
0.1
1
σ Stellar Radius (R⊙)

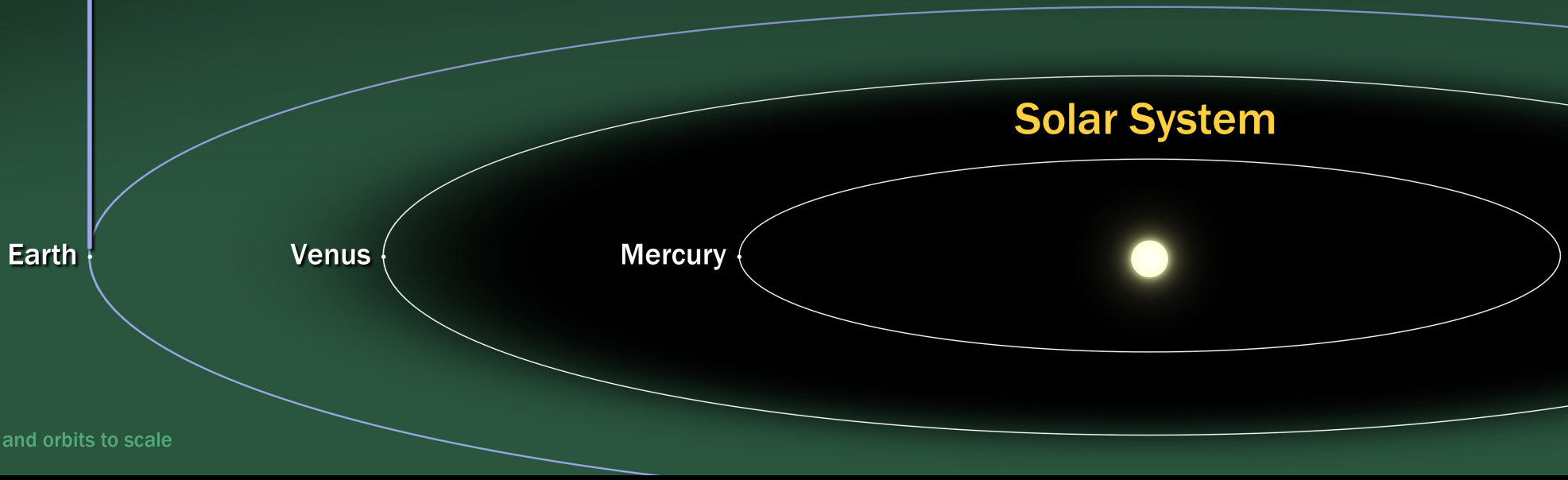
Where are the Habitable Zone Boundaries?



Kane, “Habitable Zone Dependence on Stellar Parameter Uncertainties”, 2014, ApJ, 782, 111

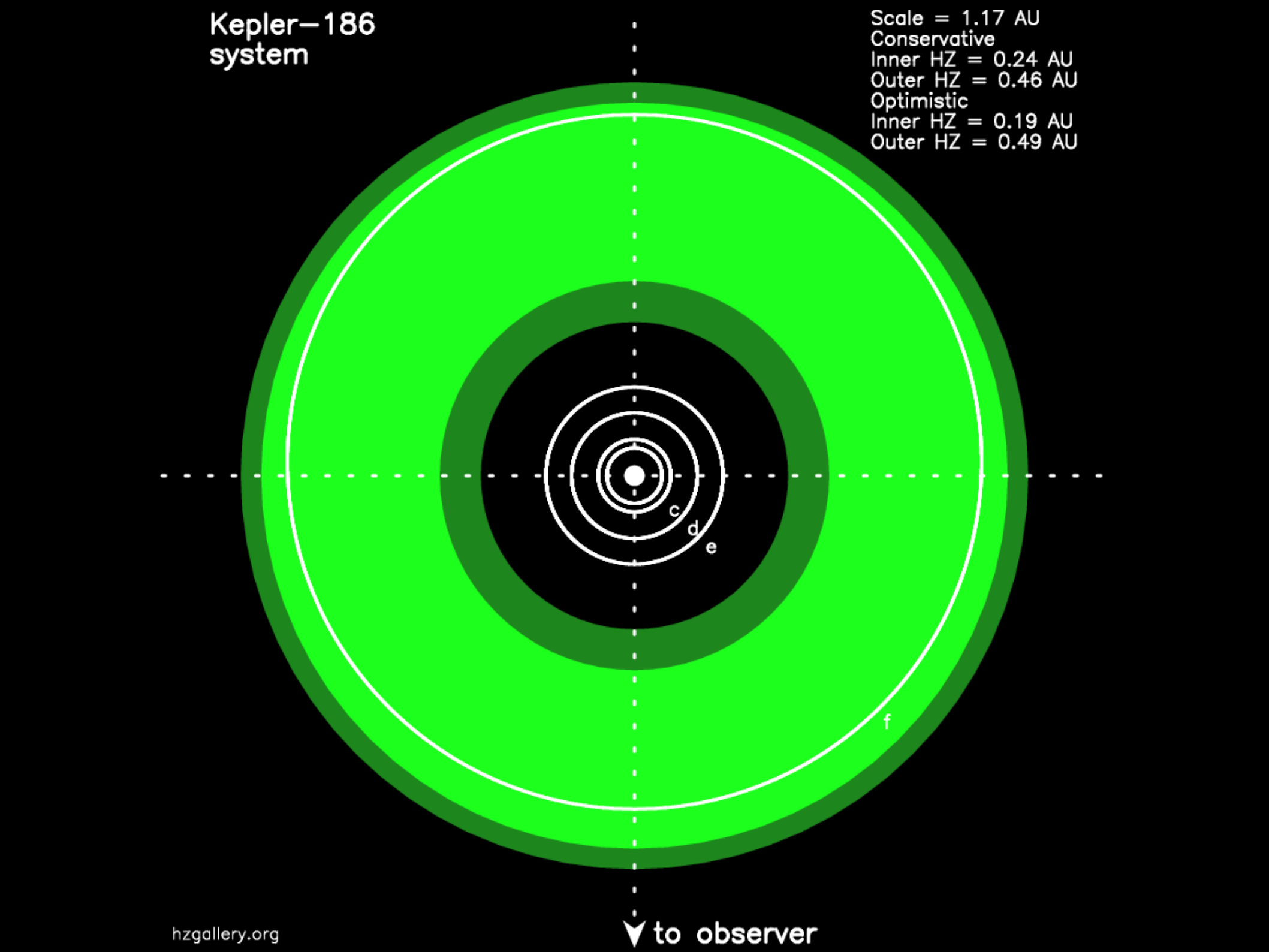


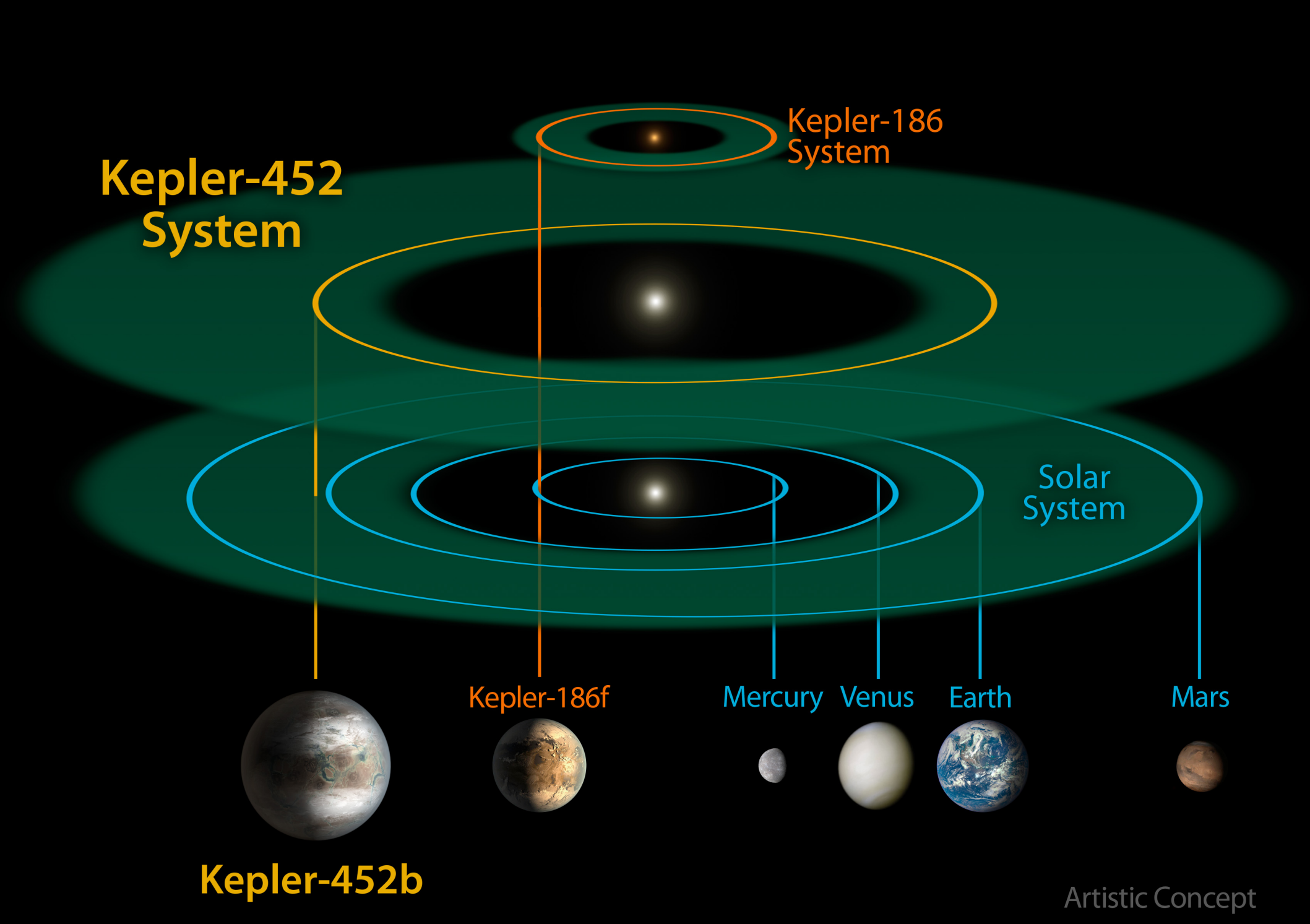




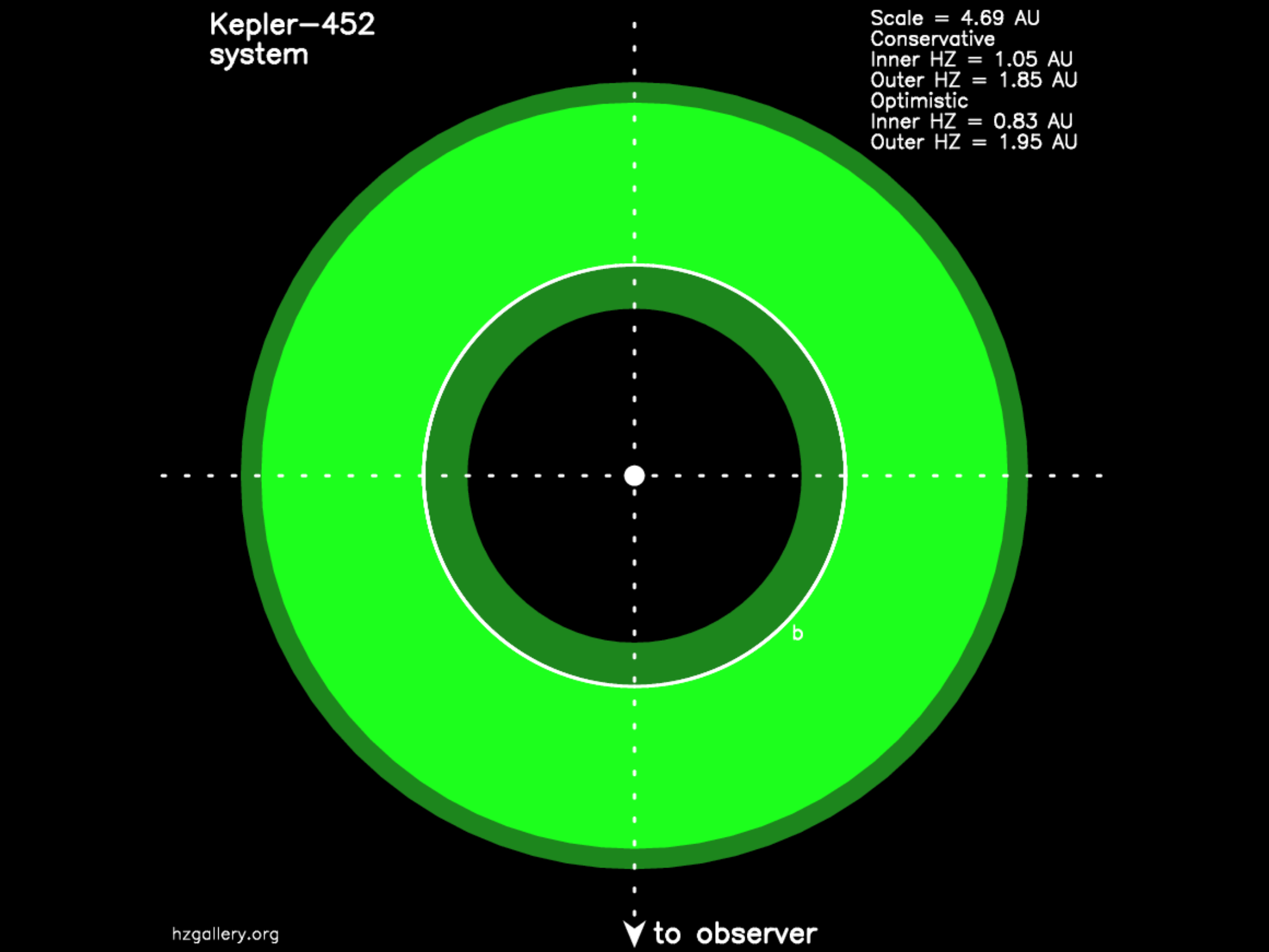
Planets and orbits to scale

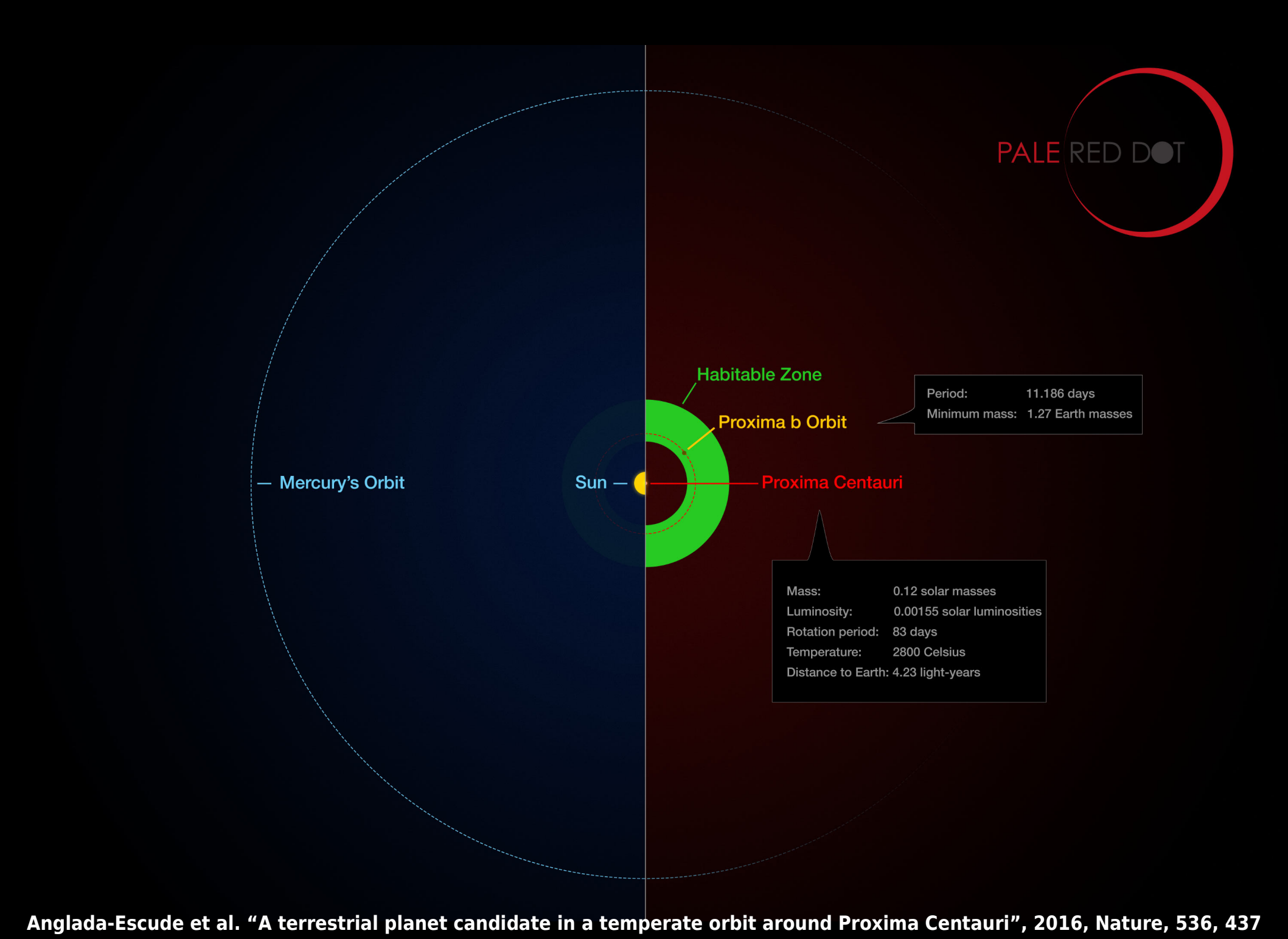
Quintana et al. “An Earth-Sized Planet in the Habitable Zone of a Cool Star”, 2014, Science, 344, 277


Kepler–186
system
Scale = 1.17 AU
Conservative
Inner HZ = 0.24 AU
Outer HZ = 0.46 AU
Optimistic
Inner HZ = 0.19 AU
Outer HZ = 0.49 AU
c
d
e
f
hzgallery.org
to observer

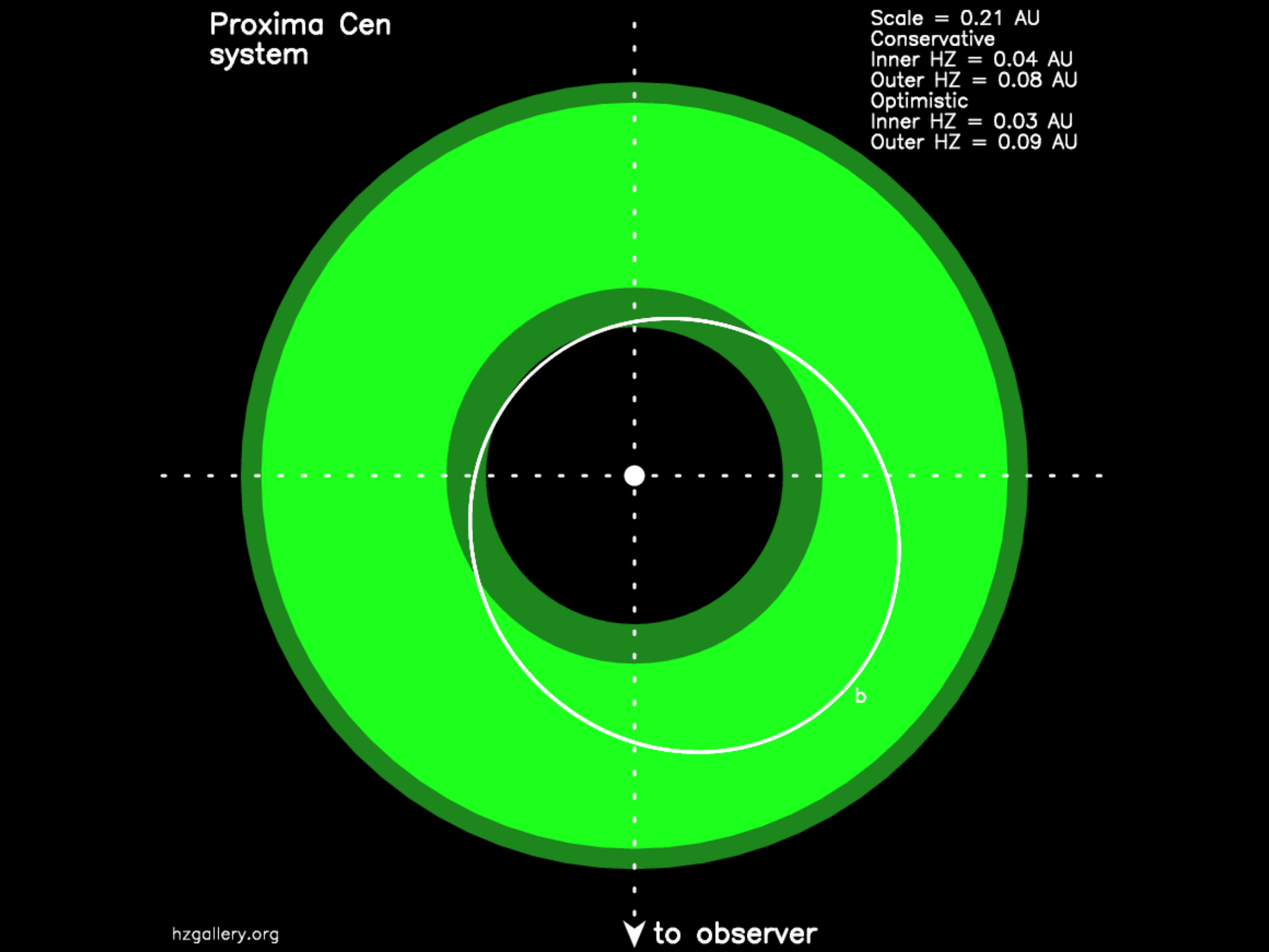


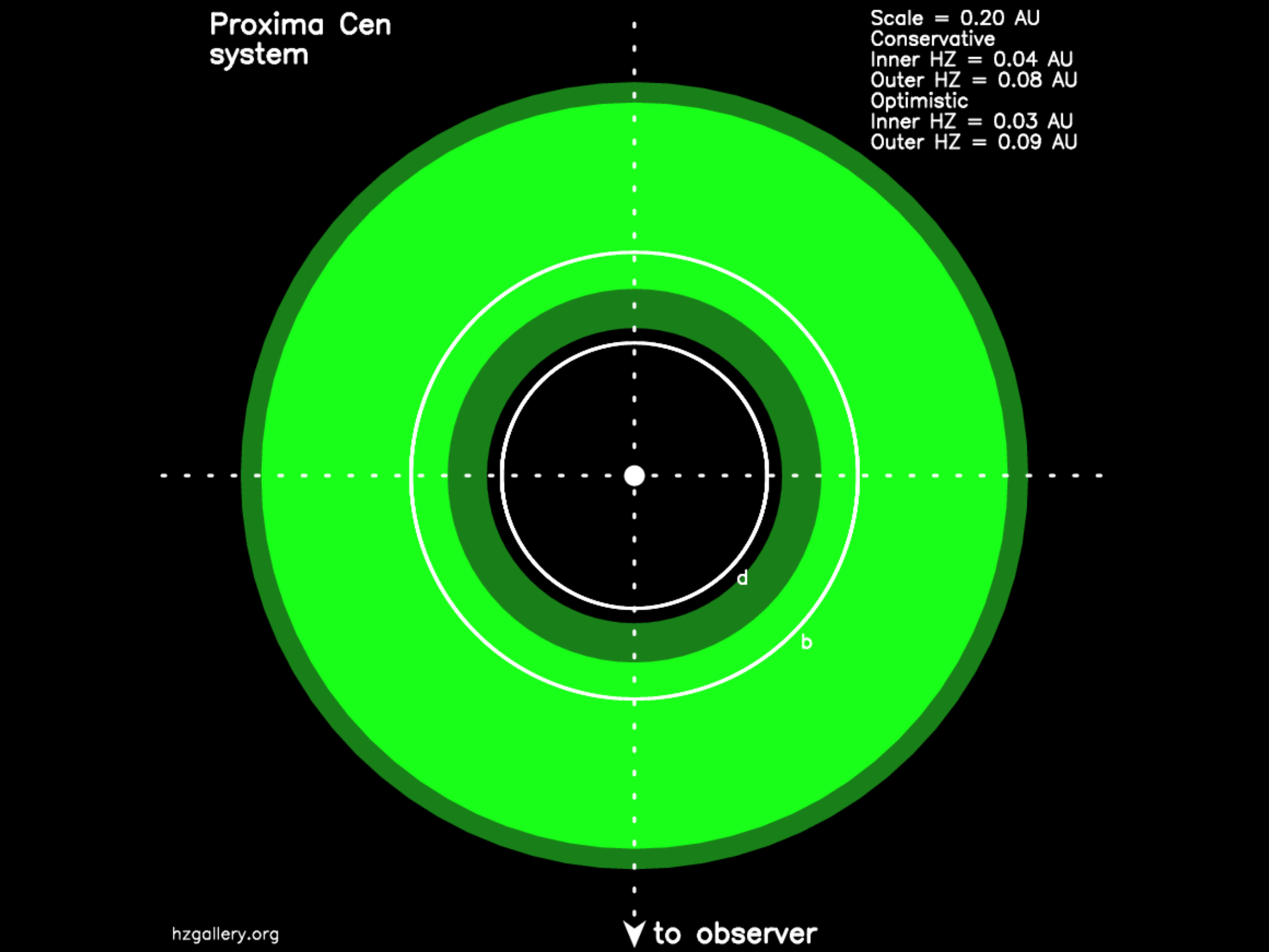
Jenkins et al. “Discovery and Validation of Kepler-452b: A 1.6 R⊕ Super Earth Exoplanet in the Habitable Zone of a G2 Star”, 2015, AJ, 150, 56

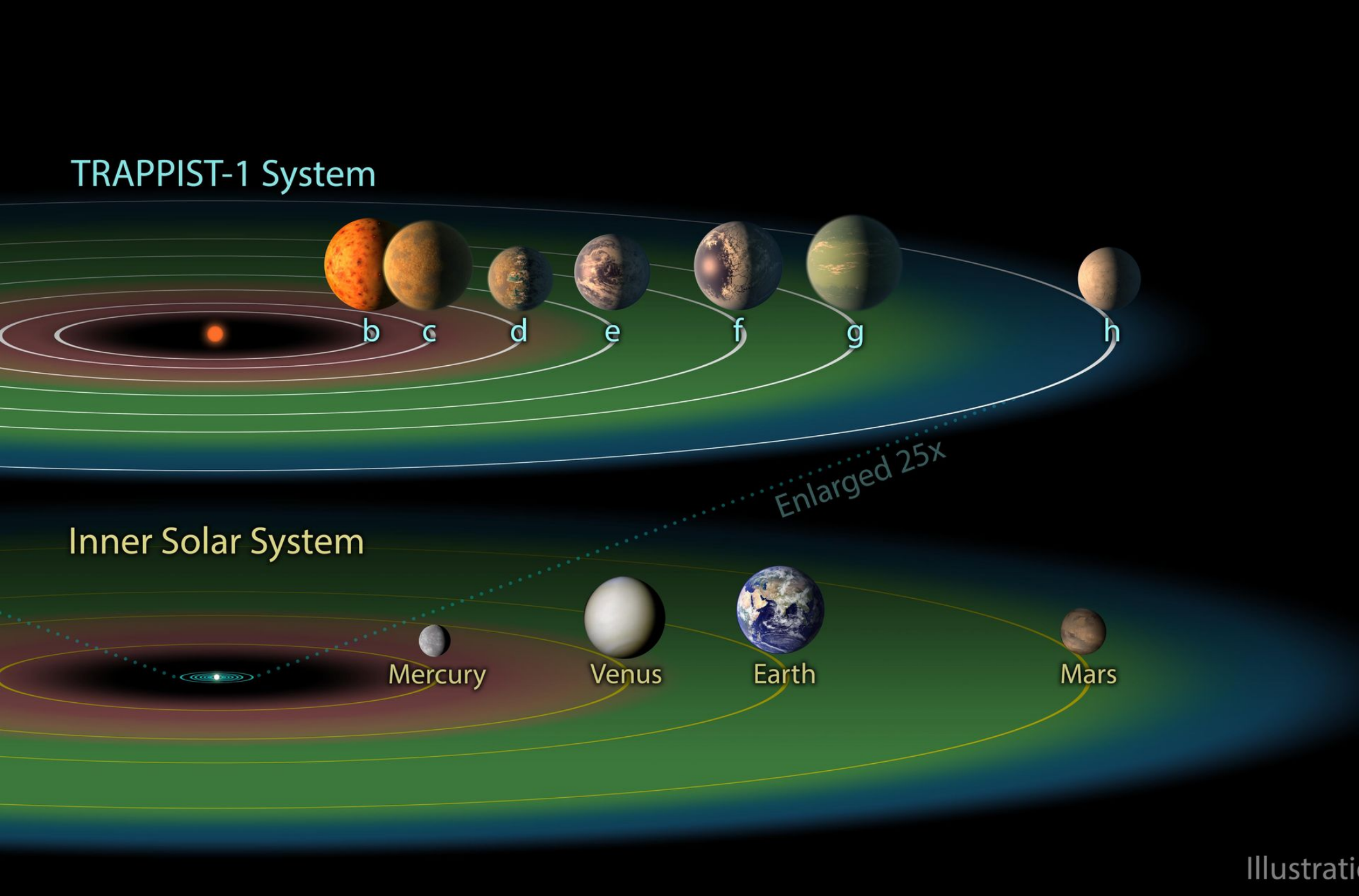

Kepler–452
system
Scale = 4.69 AU
Conservative
Inner HZ = 1.05 AU
Outer HZ = 1.85 AU
Optimistic
Inner HZ = 0.83 AU
Outer HZ = 1.95 AU
b
hzgallery.org
to observer



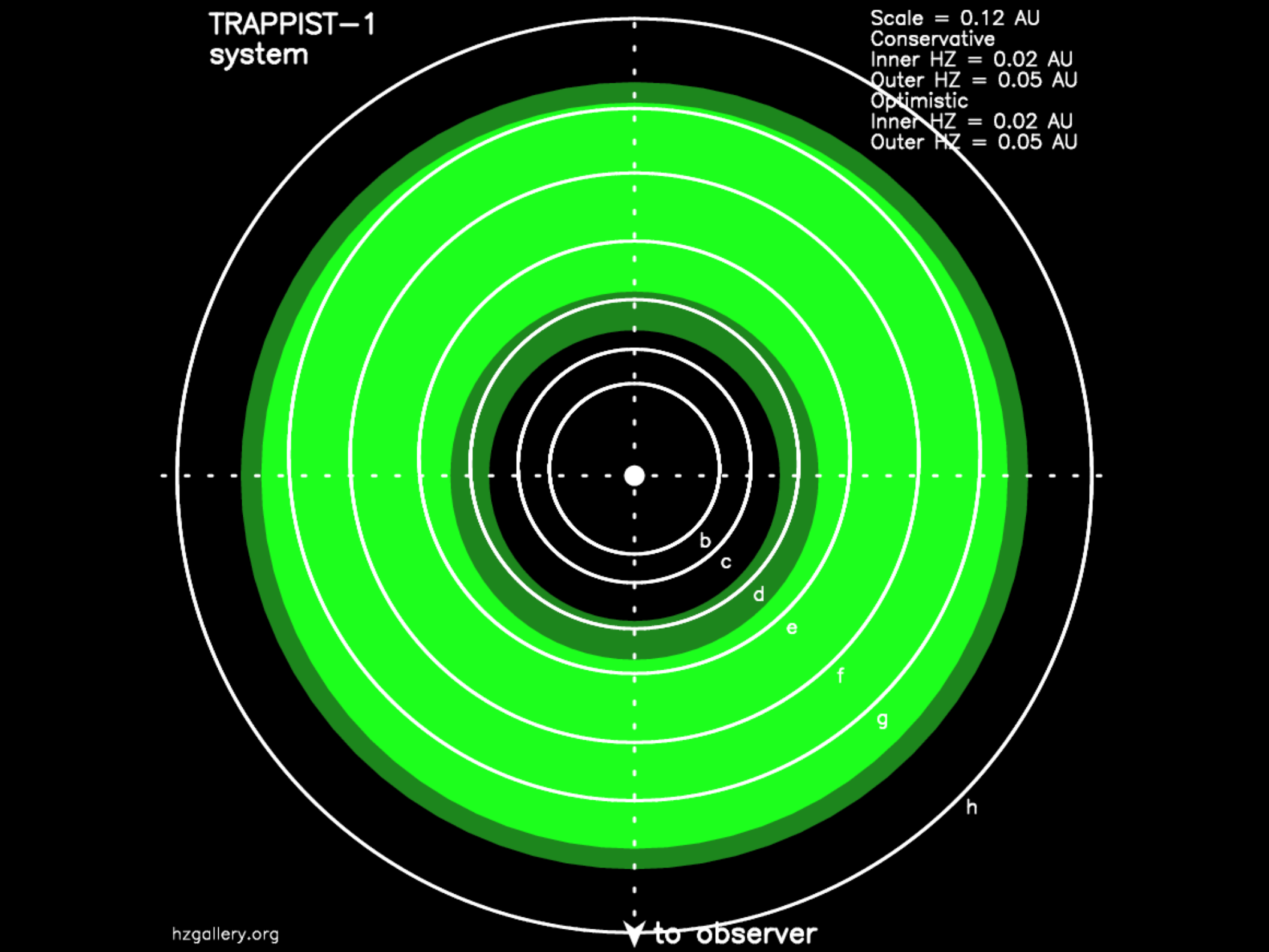
Anglada-Escude et al. "A terrestrial planet candidate in a temperate orbit around Proxima Centauri", 2016, Nature, 536, 437


Proxima Cen system
Scale = 0.21 AU
Conservative
Inner HZ = 0.04 AU
Outer HZ = 0.08 AU
Optimistic
Inner HZ = 0.03 AU
Outer HZ = 0.09 AU
b
hzgallery.org
to observer

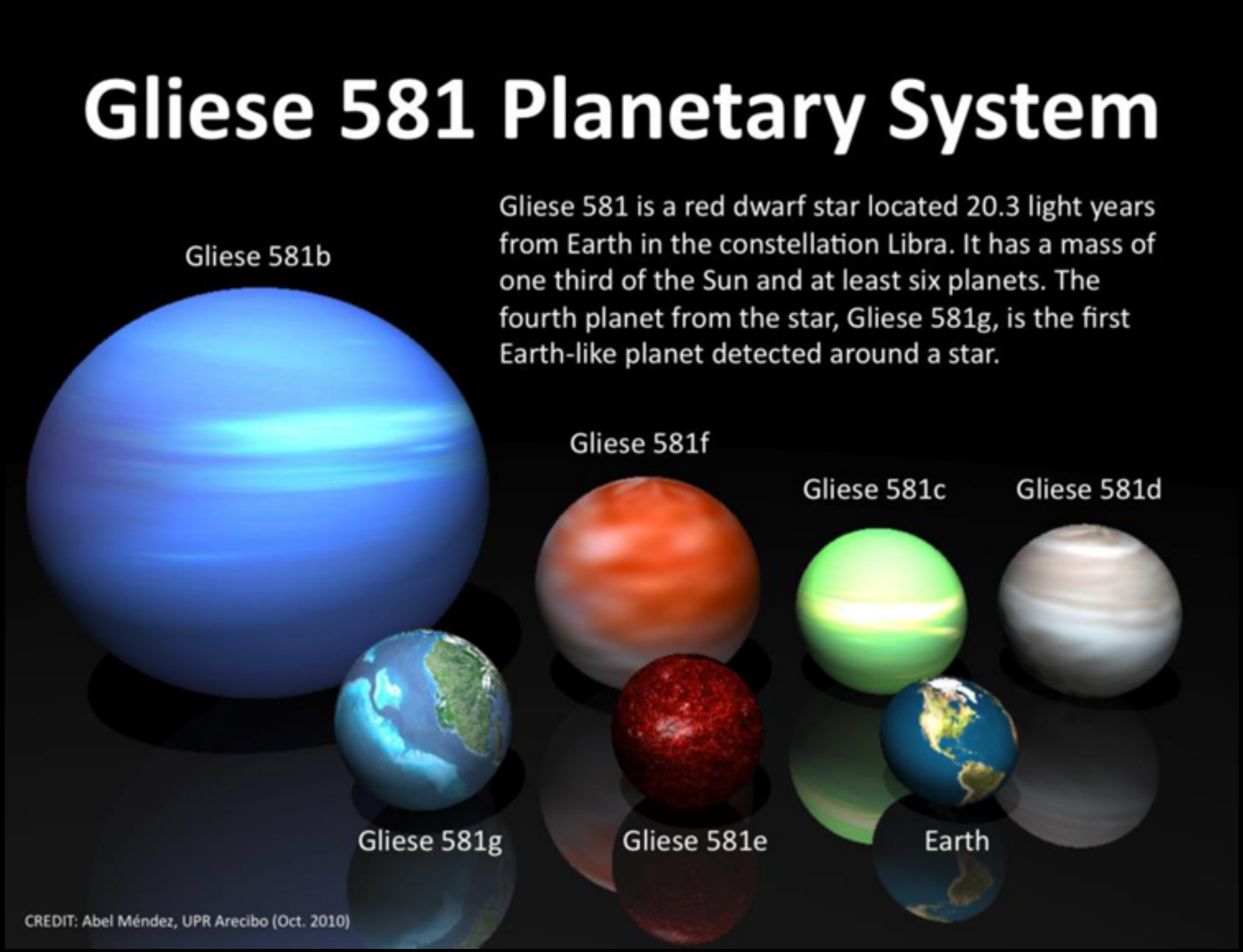

Proxima Cen system
Scale = 0.20 AU
Conservative
Inner HZ = 0.04 AU
Outer HZ = 0.08 AU
Optimistic
Inner HZ = 0.03 AU
Outer HZ = 0.09 AU
d
b
hzgallery.org
to observer

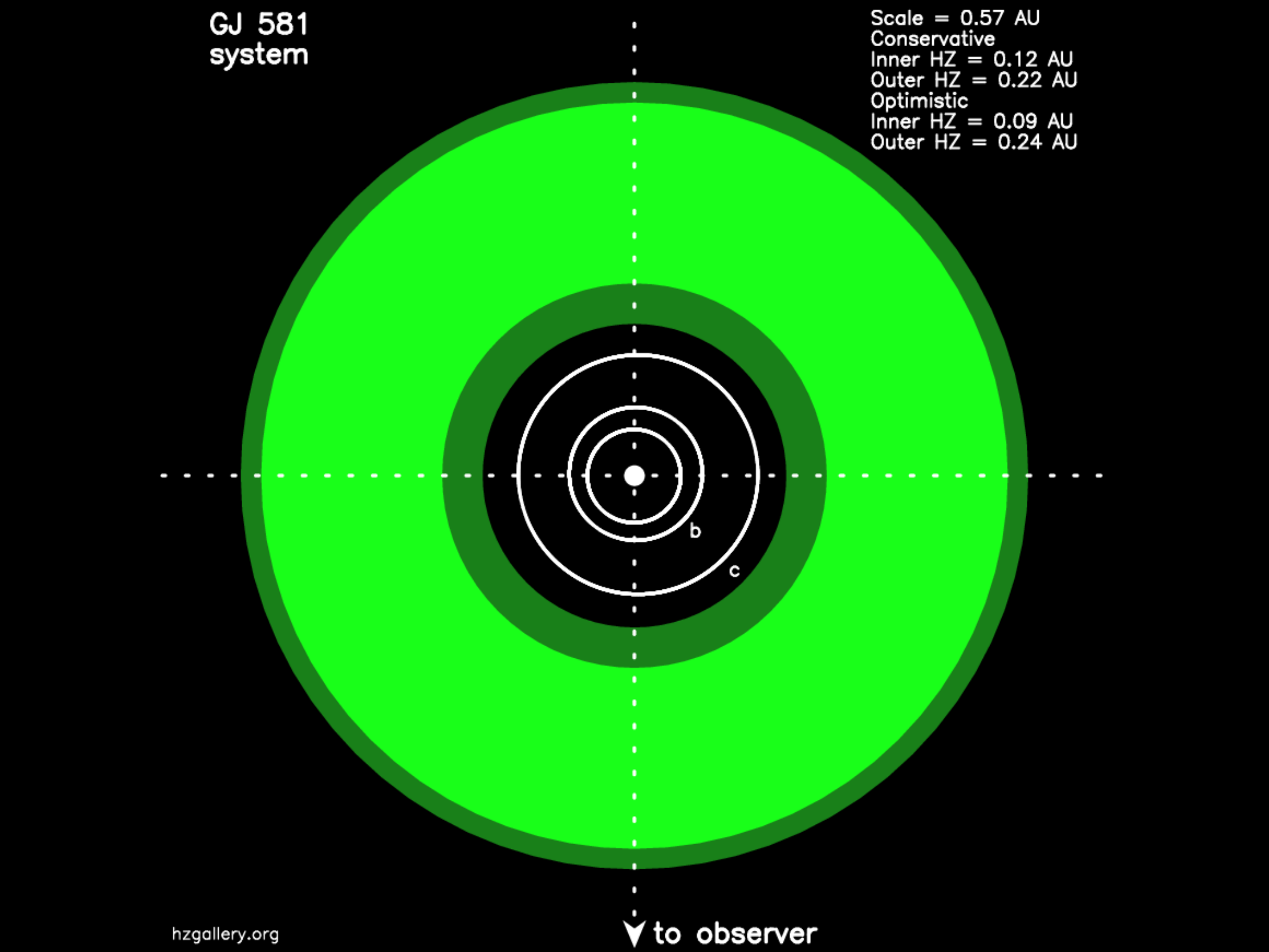


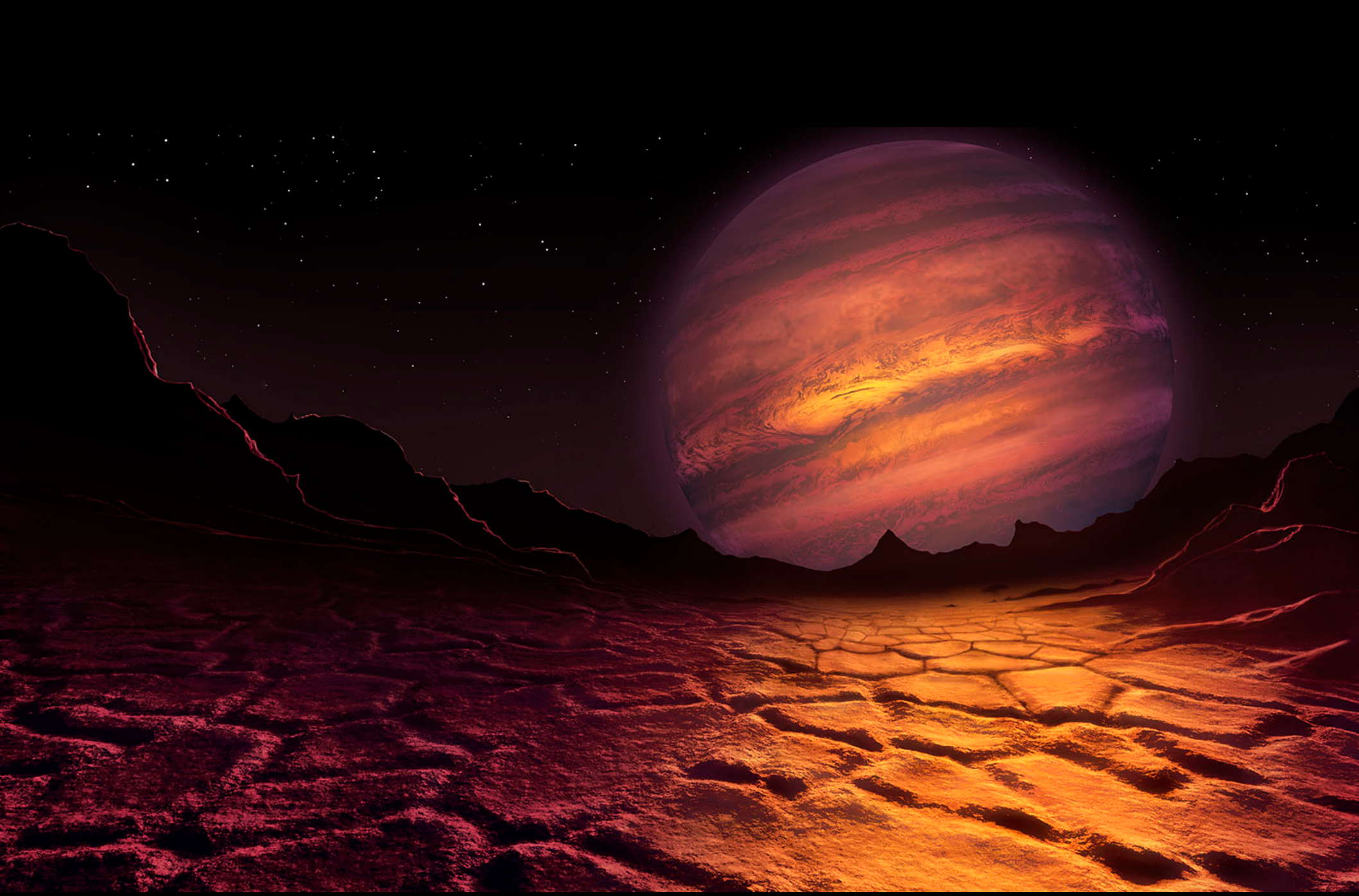
Gillon et al. “Temperate Earth-sized planets transiting a nearby ultracool dwarf star”, 2016, Nature, 533, 221

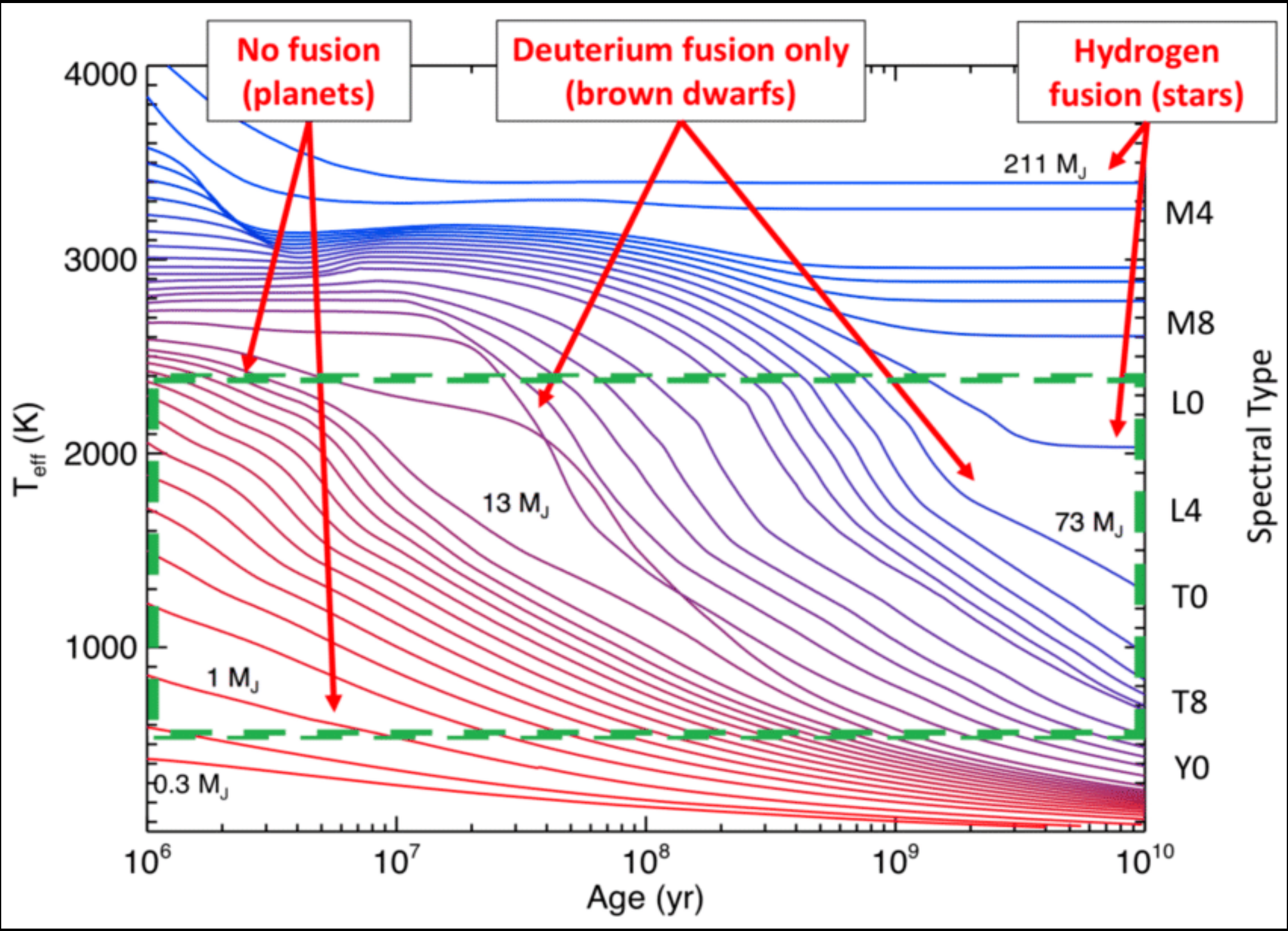

TRAPPIST−1
system
Scale = 0.12 AU
Conservative
Inner HZ = 0.02 AU
Outer HZ = 0.05 AU
Optimistic
Inner HZ = 0.02 AU
Outer HZ = 0.05 AU
b
c
d
e
f
g
h
to observer
hzgallery.org

Gliese 581 Planetary System




GJ 581
system
Scale = 0.57 AU
Conservative
Inner HZ = 0.12 AU
Outer HZ = 0.22 AU
Optimistic
Inner HZ = 0.09 AU
Outer HZ = 0.24 AU
b
c
hzgallery.org
to observer




No fusion (planets)
Deuterium fusion only (brown dwarfs)
Hydrogen fusion (stars)
211 M$_J$
13 M$_J$
73 M$_J$
1 M$_J$
0.3 M$_J$
4000
3000
2000
1000
T$_{eff}$ (K)
M4
M8
L0
L4
T0
T8
Y0
Spectral Type
10^6
10^7
10^8
10^9
10^{10}
Age (yr)

A CATALOG OF KEPLER HABITABLE ZONE EXOPLANET CANDIDATES

Stephen R. Kane[1], Michelle L. Hill[1], James F. Kasting[2], Ravi Kumar Kopparapu[3], Elisa V. Quintana[4], Thomas Barclay[4], Natalie M. Batalha[4], William J. Borucki[4], David R. Ciardi[5], Nader Haghighipour[6], Natalie R. Hinkel[1,7], Lisa Kaltenegger[8], Franck Selsis[9,10], Guillermo Torres[11]

[1]Department of Physics & Astronomy, San Francisco State University, 1600 Holloway Avenue, San Francisco, CA 94132, USA

[2]Department of Geosciences, Penn State University, 443 Deike Building, University Park, PA 16802, USA

[3]NASA Goddard Space Flight Center, 8800 Greenbelt Road, Mail Stop 699.0 Building 34, Greenbelt, MD 20771, USA

[4]NASA Ames Research Center, Moffett Field, CA 94035, USA

[5]NASA Exoplanet Science Institute, Caltech, MS 100-22, 770 South Wilson Avenue, Pasadena, CA 91125, USA

[6]University of Hawaii-Manoa, Honolulu, HI 96822, USA

[7]School of Earth & Space Exploration, Arizona State University, Tempe, AZ 85287, USA

[8]Department of Astronomy, Cornell University, Ithaca, NY, USA

[9]Univ. Bordeaux, LAB, UMR 5804, F-33615, Pessac, France

[10]CNRS, LAB, UMR 5804, F-33615, Pessac, France

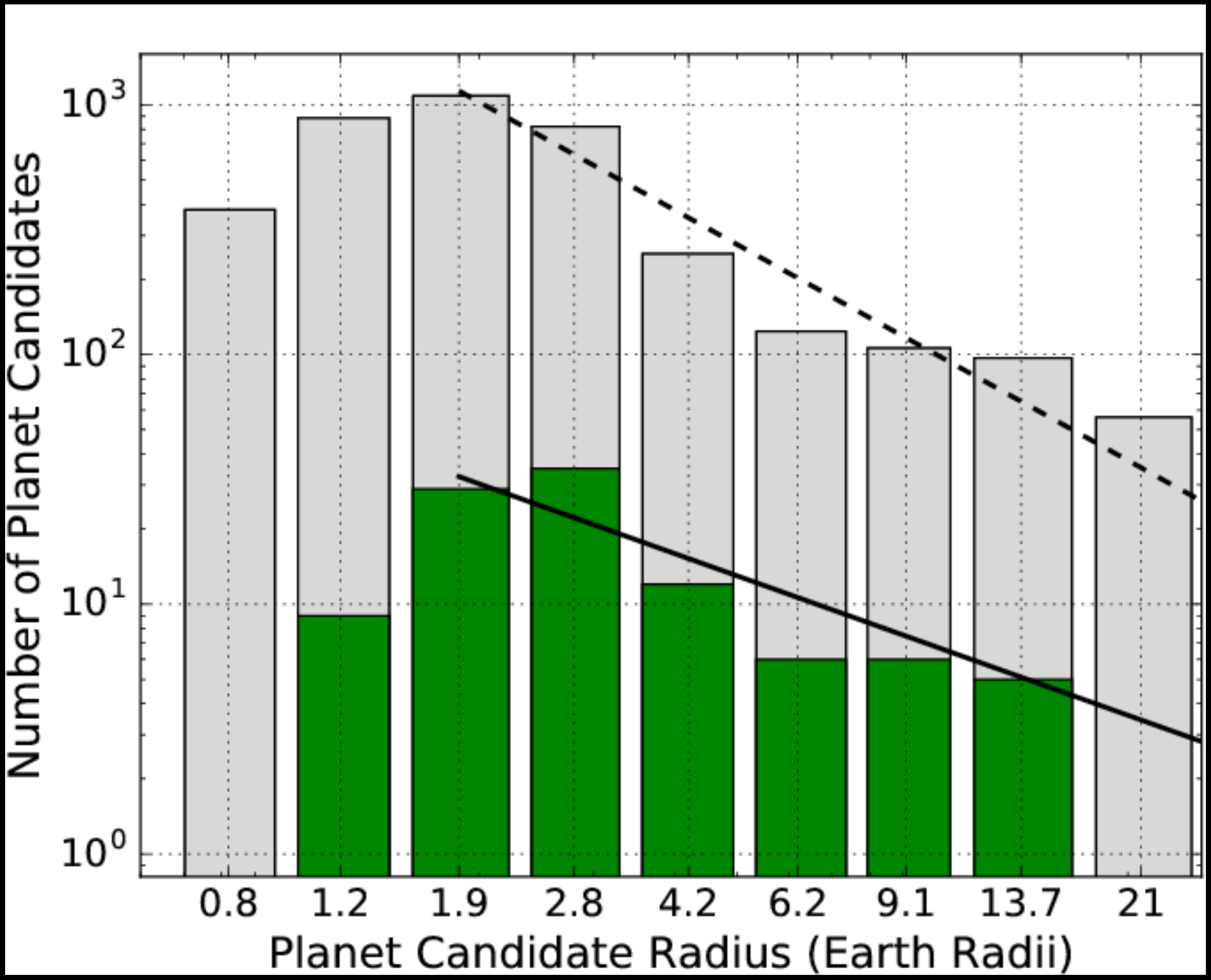
[11]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

ABSTRACT

The NASA *Kepler* mission has discovered thousands of new planetary candidates, many of which have been confirmed through follow-up observations. A primary goal of the mission is to determine the occurrance rate of terrestrial-size planets within the Habitable Zone (HZ) of their host stars. Here we provide a list of HZ exoplanet candidates from the *Kepler* Data Release 24 Q1-Q17 data vetting process. This work was undertaken as part of the *Kepler* Habitable Zone Working Group. We use a variety of criteria regarding HZ boundaries and planetary sizes to produce complete lists of HZ candidates, including a catalog of 104 candidates within the optimistic HZ and 20 candidates with radii less than two Earth radii within the conservative HZ. We cross-match our HZ candidates with the Data Release 25 stellar properties and confirmed planet properties to provide robust stellar parameters and candidate dispositions. We also include false positive probabilities recently calculated by Morton (2016) for each of the candidates within our catalogs to aid in their validation. Finally, we performed dynamical analysis simulations for multi-planet systems that contain candidates with radii less than two Earth radii as a step toward validation of those systems.

Keywords: astrobiology – astronomical databases: miscellaneous – planetary systems – techniques: photometric

Kepler Habitable Zone Catalog



Kepler Habitable Zone Catalog

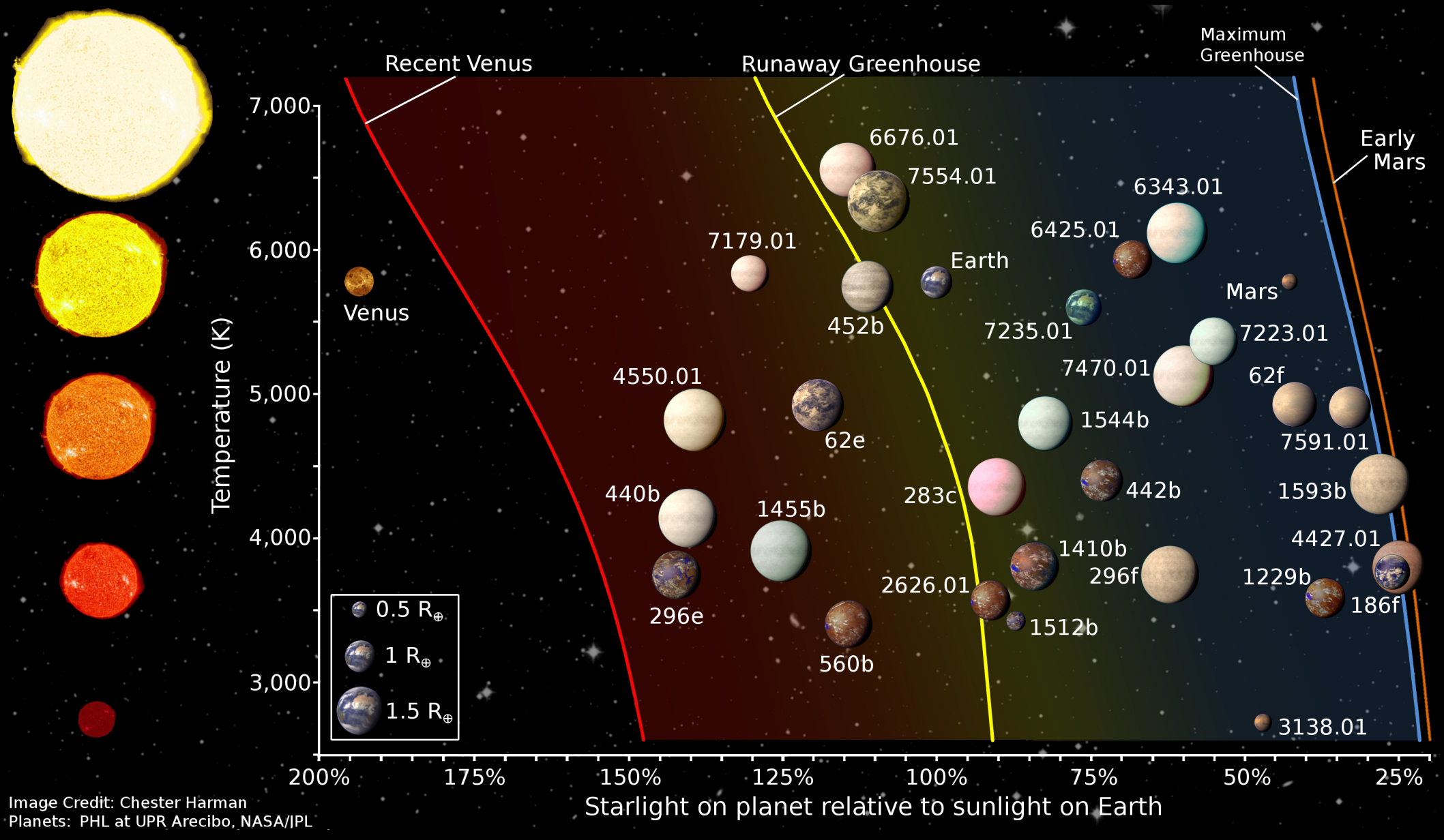


Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/IPL

Kane et al. "A Catalog of Kepler Habitable Zone Exoplanet Candidates", 2016, ApJ, 830, 1
Hill et al. "A Catalog of Habitable Zone Exoplanets", 2023, AJ, 165, 34

The Astronomical Journal, 165:34 (16pp), 2023 February https://doi.org/10.3847/1538-3881/aca1c0

A Catalog of Habitable Zone Exoplanets

Michelle L. Hill[1], Kimberly Bott[1], Paul A. Dalba[1,2,6], Tara Fetherolf[1,7], Stephen R. Kane[1], Ravi Kopparapu[3,4,5], Zhexing Li[1], and Colby Ostberg[1]
[1] Department of Earth and Planetary Sciences, University of California Riverside, 900 University Avenue, Riverside, CA 92521, USA; mhill012@ucr.edu
[2] Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA
[3] NASA NExSS Virtual Planetary Laboratory, Seattle, WA, USA
[4] Blue Marble Space Institute of Science, Seattle, WA, USA
[5] NASA Goddard Space Flight Center, Greenbelt, MD, USA
Received 2022 May 19; revised 2022 October 13; accepted 2022 October 14; published 2023 January 5

Abstract

The search for habitable planets has revealed many planets that can vary greatly from an Earth analog environment. These include highly eccentric orbits, giant planets, different bulk densities, relatively active stars, and evolved stars. This work catalogs all planets found to reside in the habitable zone (HZ) and provides HZ boundaries, orbit characterization, and the potential for spectroscopic follow-up observations. Demographics of the HZ planets are compared with a full catalog of exoplanets. Extreme planets within the HZ are highlighted, and how their unique properties may affect their potential habitability is discussed. Kepler-296 f is the most eccentric $\leqslant 2\,R_{\oplus}$ planet that spends 100% of its orbit in the HZ. HD 106270 b and HD 38529 c are the most massive planets ($\leqslant 13\,M_{\rm J}$) that orbit within the HZ, and are ideal targets for determining the properties of potential hosts of HZ exomoons. These planets, along with the others highlighted, will serve as special edge cases to the Earth-based scenario, and observations of these targets will help test the resilience of habitability outside the standard model. The most promising observational HZ target that is known to transit is GJ 414 A b. Of the transiting, $\leqslant 2\,R_{\oplus}$ HZ planets, LHS 1140 b, TRAPPIST-1 d, and K2-3 d are the most favorable. Of the nontransiting HZ planets, HD 102365 b and 55 Cnc f are the most promising, and the best nontransiting candidates that have $\leqslant 2\,R_{\oplus}$ are GJ 667 C c, Wolf 1061 c, Ross 508 b, Teegarden's Star b, and Proxima Cen b.

Unified Astronomy Thesaurus concepts: Exoplanet astronomy (486); Exoplanet catalogs (488); Exoplanets (498); Planet hosting stars (1242); Habitable planets (695); Habitable zone (696); Astrobiology (74); Radial velocity (1332); Transits (1711); Observational astronomy (1145)

Supporting material: machine-readable table