THE (SURFACE) LIQUID WATER ZONE

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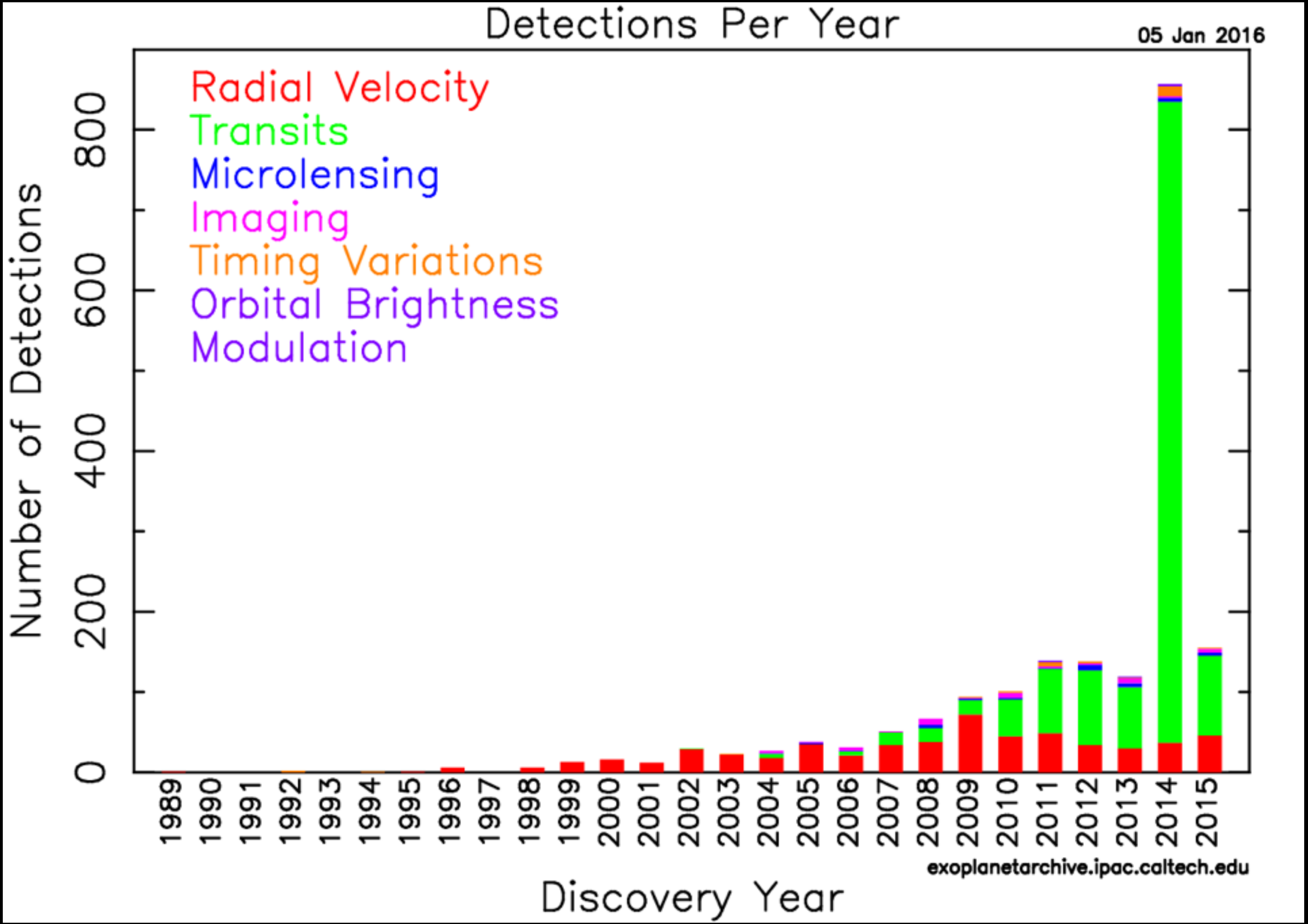
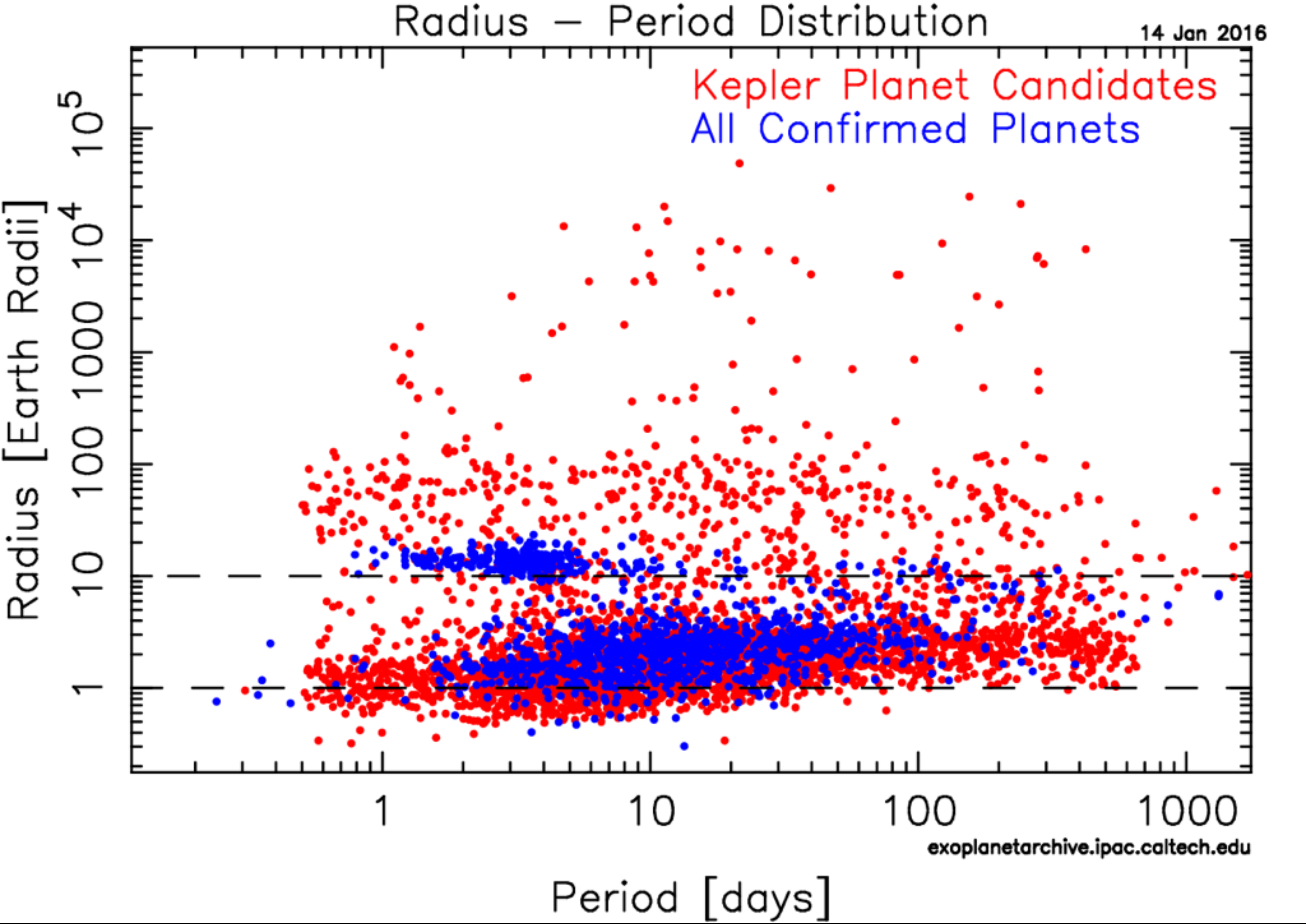
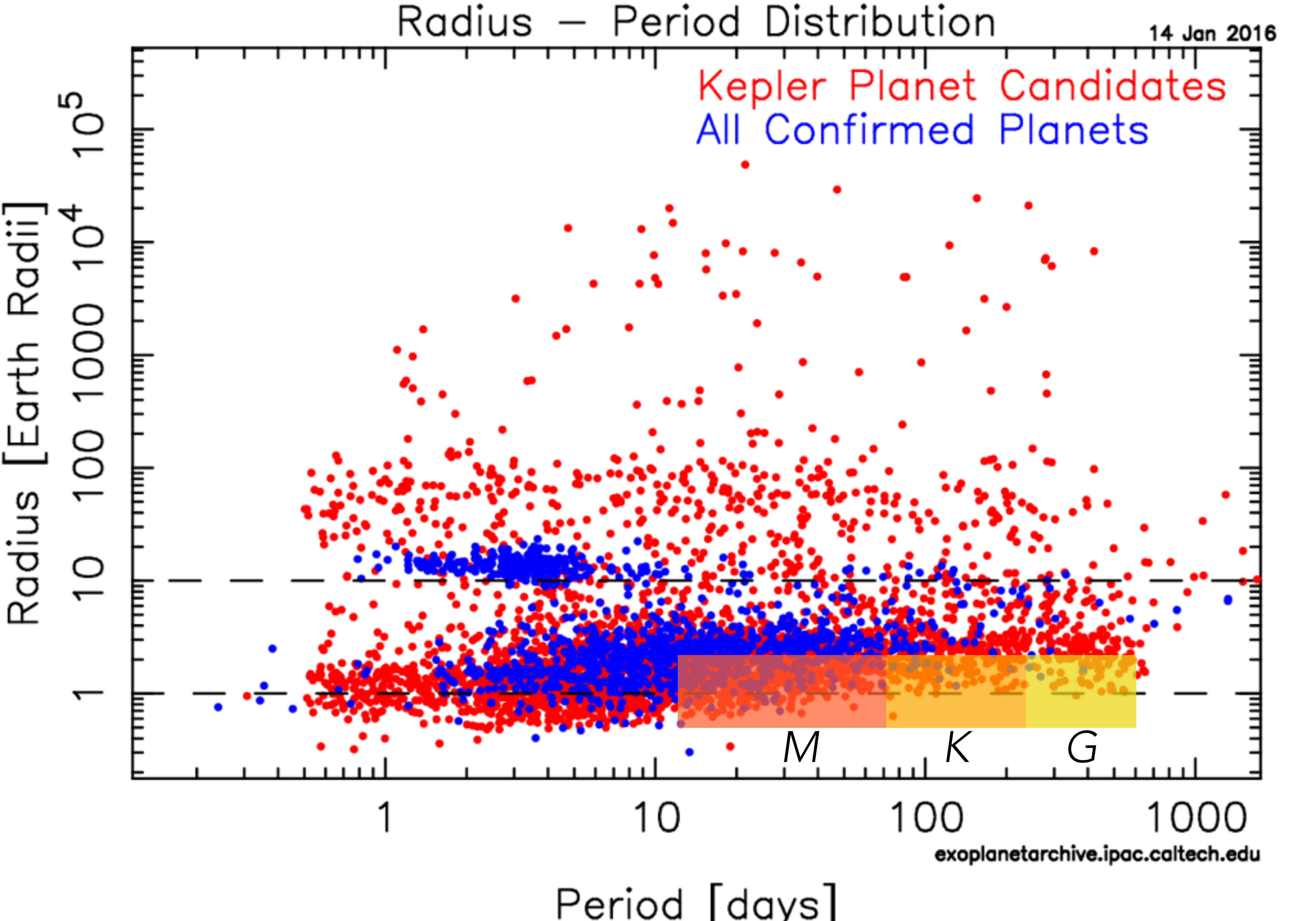
EXOPLANET DETECTIONS

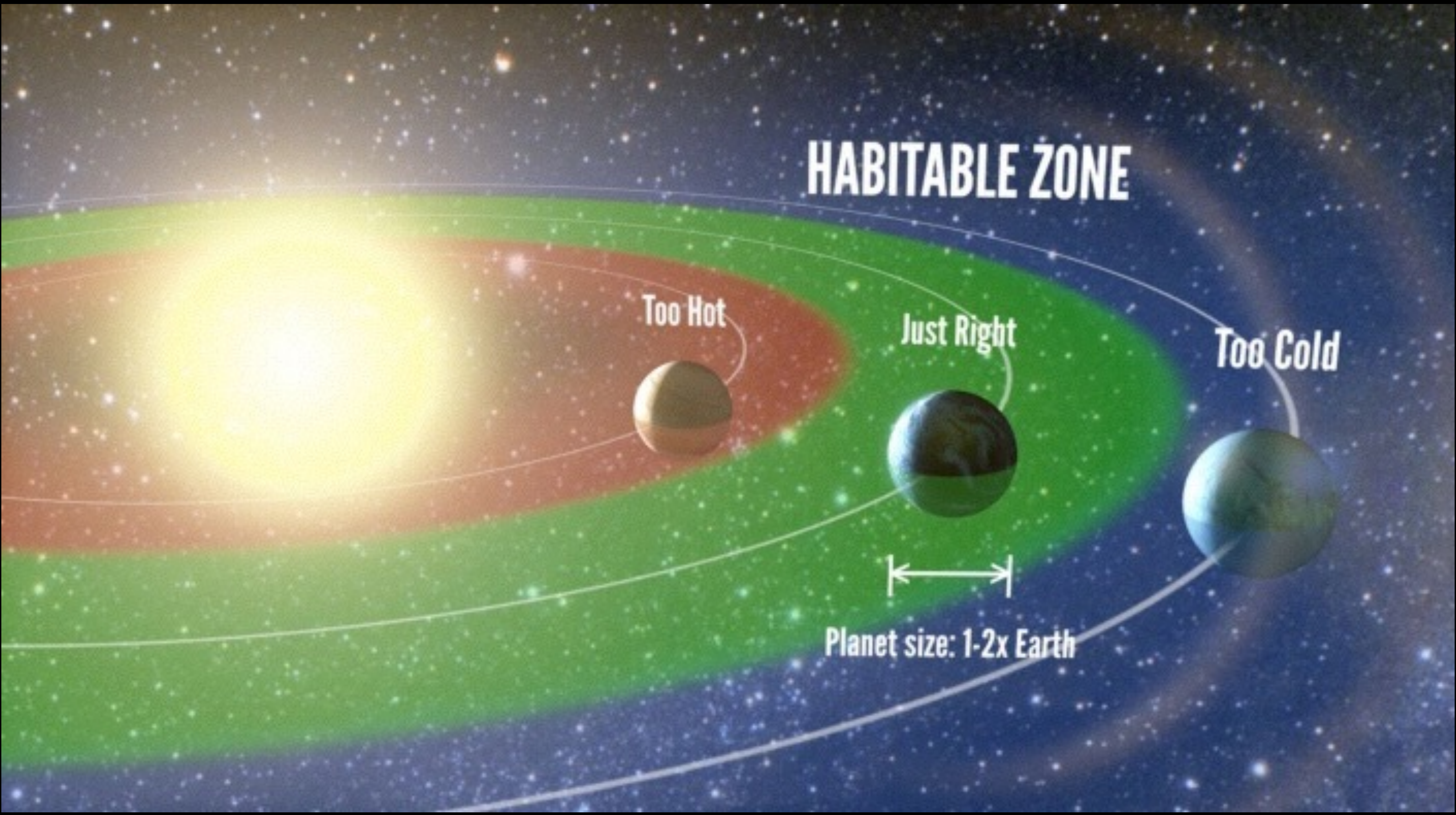




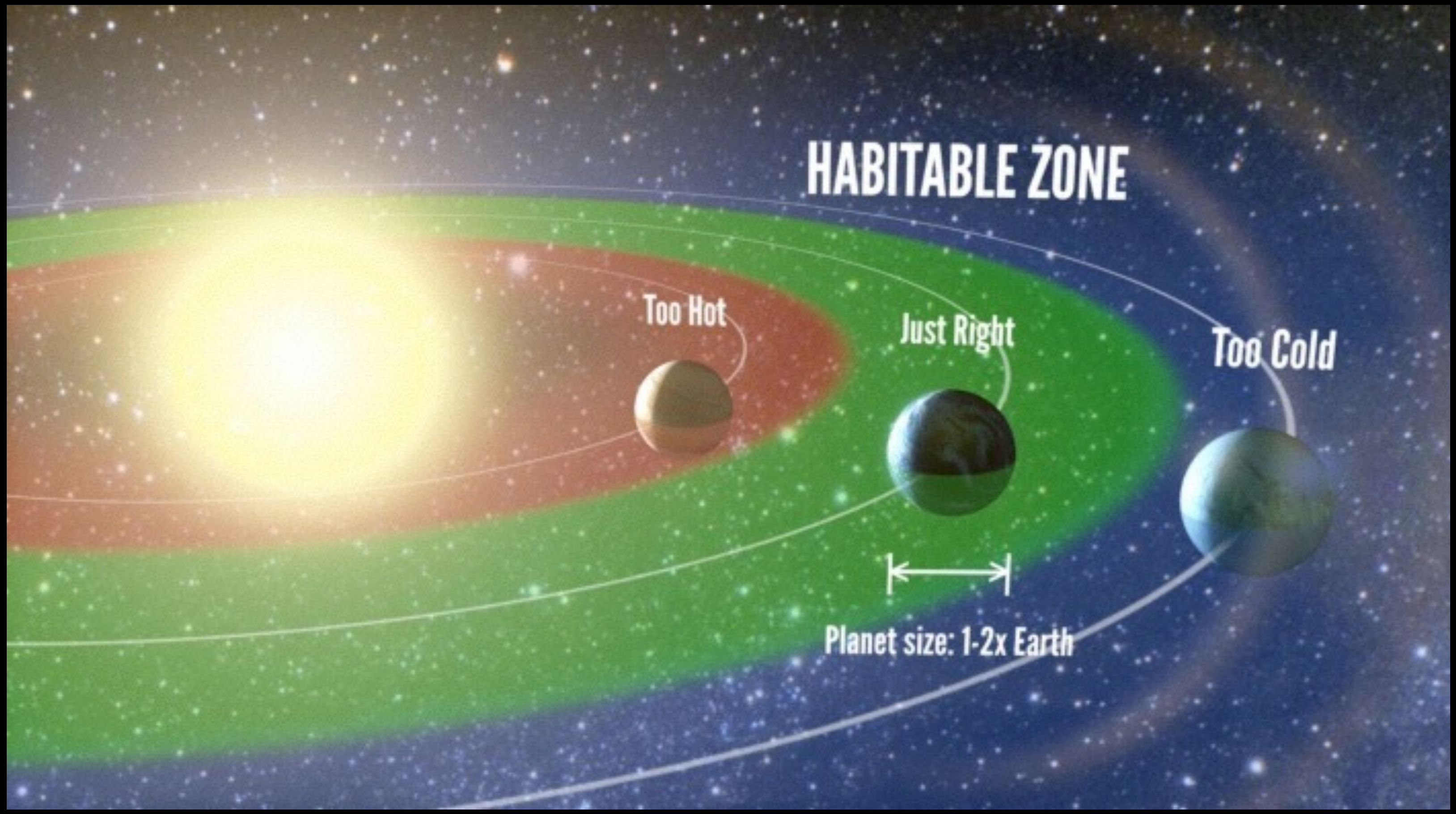
Radius – Period Distribution
14 Jan 2016
Kepler Planet Candidates
All Confirmed Planets
Radius [Earth Radii]
1
10
100
1000
10^4
10^5
1
10
100
1000
Period [days]
exoplanetarchive.ipac.caltech.edu



Radius – Period Distribution
14 Jan 2016
Kepler Planet Candidates
All Confirmed Planets
Radius [Earth Radii]
Period [days]
1
10
100
1000
10^4
10^5
M
K
G
exoplanetarchive.ipac.caltech.edu



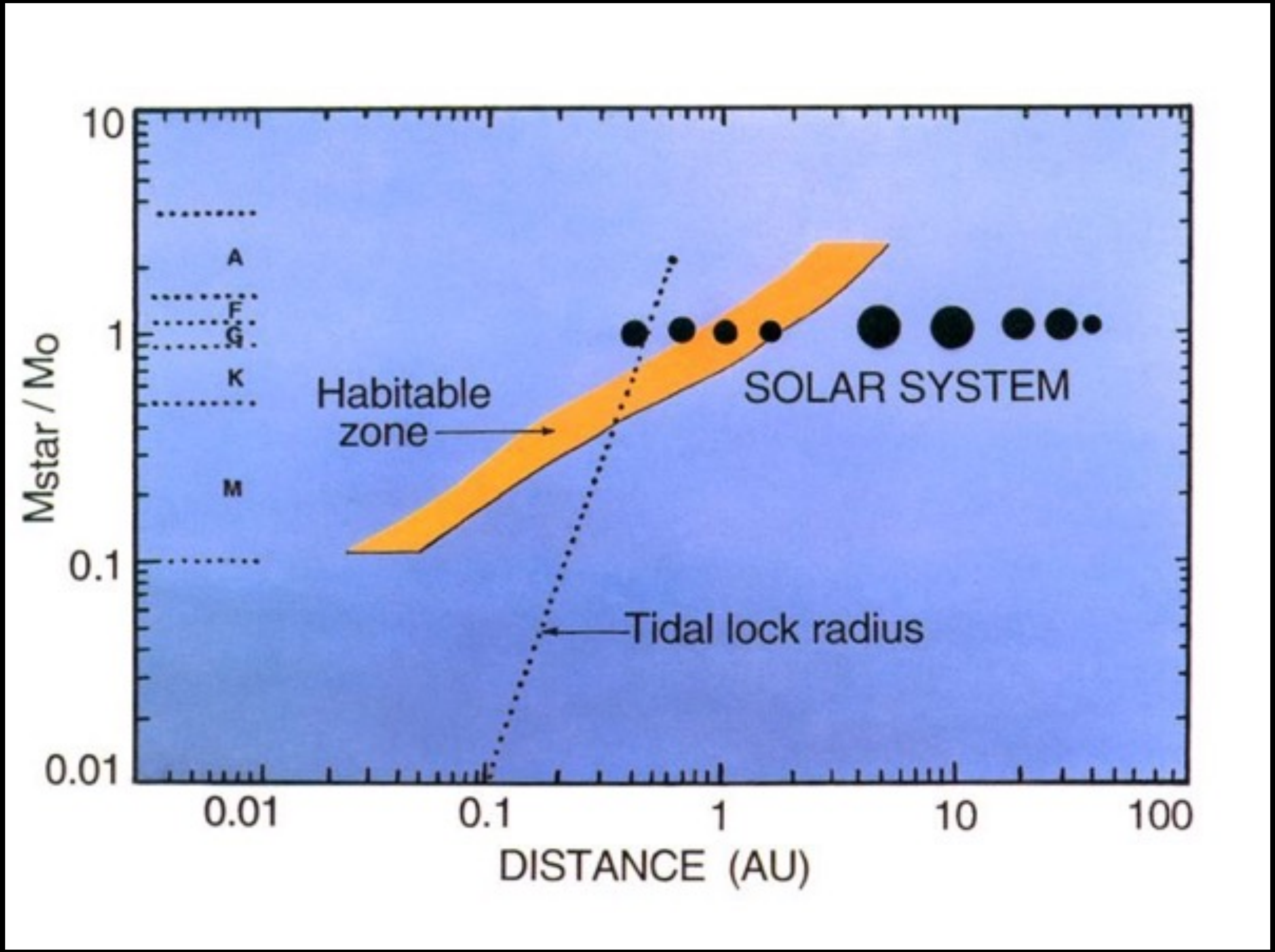
Circumstellar region where a terrestrial size/mass planet with a "suitable" atmosphere can maintain liquid-water on it's surface.



Circumstellar region where a terrestrial size/mass planet with a "suitable" atmosphere can maintain liquid-water on it's surface.

This definition of HZ has little to do with habitability. It is a subset of a larger definition of "The" habitable zone where life can arise (irrespective of detectability)

WHAT ARE THE HZS AND WHERE ARE THEY?



Solar system HZ:
Inner edge: 0.95 AU
Outer edge: 1.67 AU

1-D climate model assuming an Earth-like planet with H_2O dominated atmospheres at the inner edge, and CO_2 dominated atmospheres at the outer edge (N_2 background gas)

Kasting, Whitmire & Reynolds (1993)

WHAT ARE THE HZS AND WHERE ARE THEY?

Inner edge

Moist greenhouse: The ocean remains liquid, but the stratosphere becomes wet, leading to rapid photodissociation of water and escape of hydrogen to space.

Runaway greenhouse: The atmosphere becomes opaque to outgoing long-wave radiation, preventing the planet to cool. Thus climate warms uncontrollably until *all* surface water has evaporated.

For habitability purpose, Moist greenhouse (or "water-loss") limit is more relevant to the inner edge of the HZ

WHAT ARE THE HZS AND WHERE ARE THEY?

Outer edge

Maximum greenhouse: Atmospheric CO_2 should build up as the planet cools. There is a limit at which the CO_2 starts to condense, and Rayleigh scattering by CO_2 raises the planet's albedo competing with the greenhouse effect

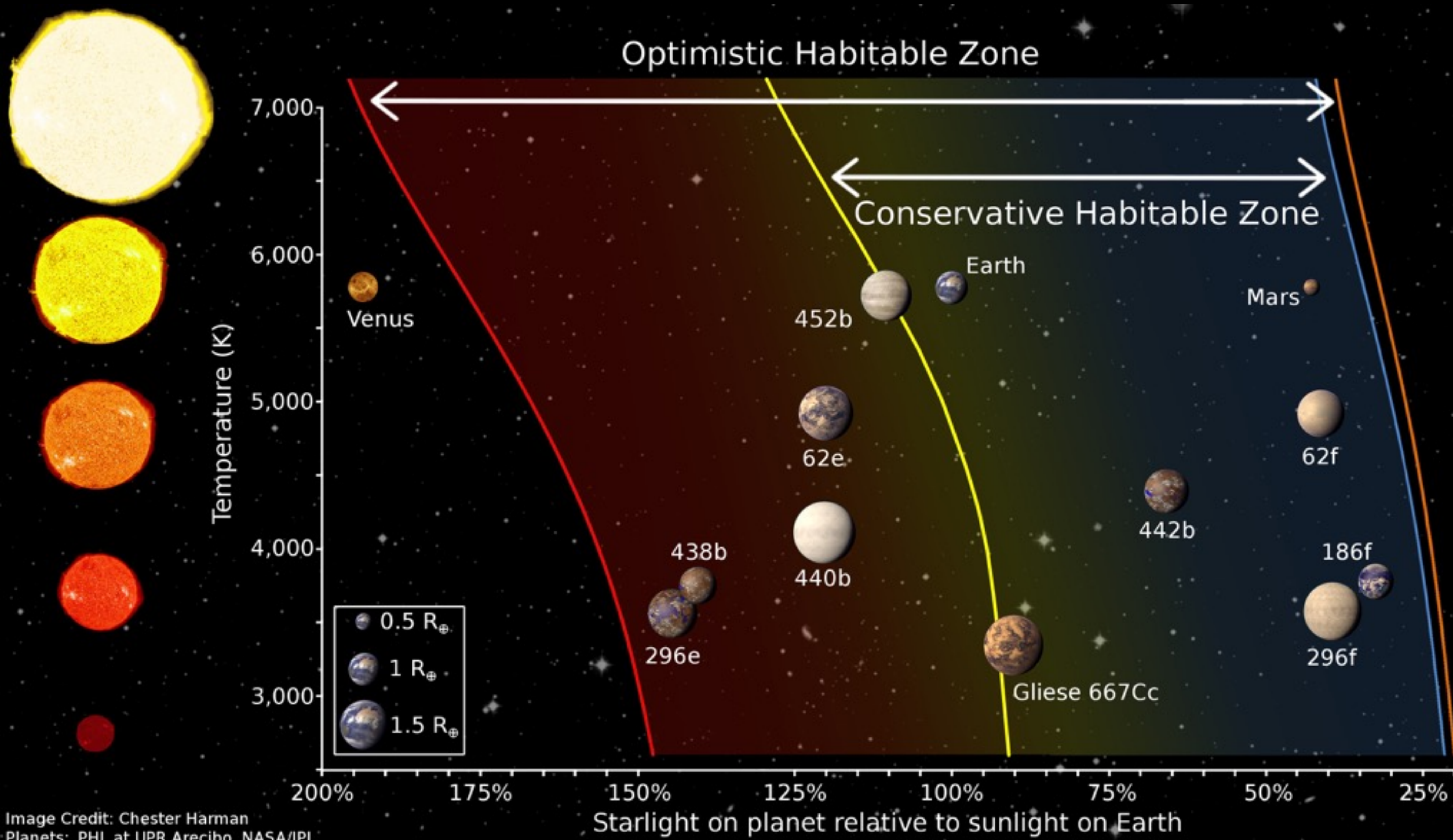
This leads to the "*maximum*" greenhouse limit that CO_2 can produce.

UPDATED CLIMATE MODEL

Updated Absorption coefficients updated from LBL databases ,HITRAN 2008 &HITEMP 2010

Inner edge: 0.97~0.99AU
Outer edge: 1.68 AU

Kopparapu et al.(2013), ApJ, 765, 131
Kopparapu (2013), ApJ Letters, 767, L8
Kopparapu et al.(2014), ApJ Letters, 787, L29
Kasting et al.(2014), PNAS, 111,35


Optimistic Habitable Zone
Conservative Habitable Zone
Temperature (K)
7,000
6,000
5,000
4,000
3,000
Venus
452b
Earth
Mars
62e
62f
442b
438b
440b
186f
296e
296f
Gliese 667Cc
0.5 $R_\oplus$
1 $R_\oplus$
1.5 $R_\oplus$
200%
175%
150%
125%
100%
75%
50%
25%
Starlight on planet relative to sunlight on Earth
Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/JPL

ONLINE HABITABLE ZONE CALCULATOR

Calculation of Habitable Zones

Enter stellar effective temperature and luminosity (Default is Sun).

If you don't know the luminosity, just enter T_{eff} and keep luminosity = 0.

That will give you just Habitable stellar flux boundaries.

(If you want to calculate HZs for a number of stars, download this fortran code)

After entering the values in each box, just click inside each box to obtain the results.

T_{eff} (K) 5780 Stellar Luminosity (solar units) 1

Conservative habitable zone limits	***Stellar flux compared to the Sun***	***HZ distance from the star (AU)***
Inner HZ - Moist Greenhouse (waterloss) limit	1.0146	0.9928
Outer HZ - Maximum Greenhouse limit	0.3507	1.6886

Optimistic habitable zone limits	***Stellar flux compared to the Sun***	***HZ distance from the star (AU)***
Inner HZ - Recent Venus limit	1.7763	0.7503
Outer HZ - Early Mars limit	0.3207	1.7658

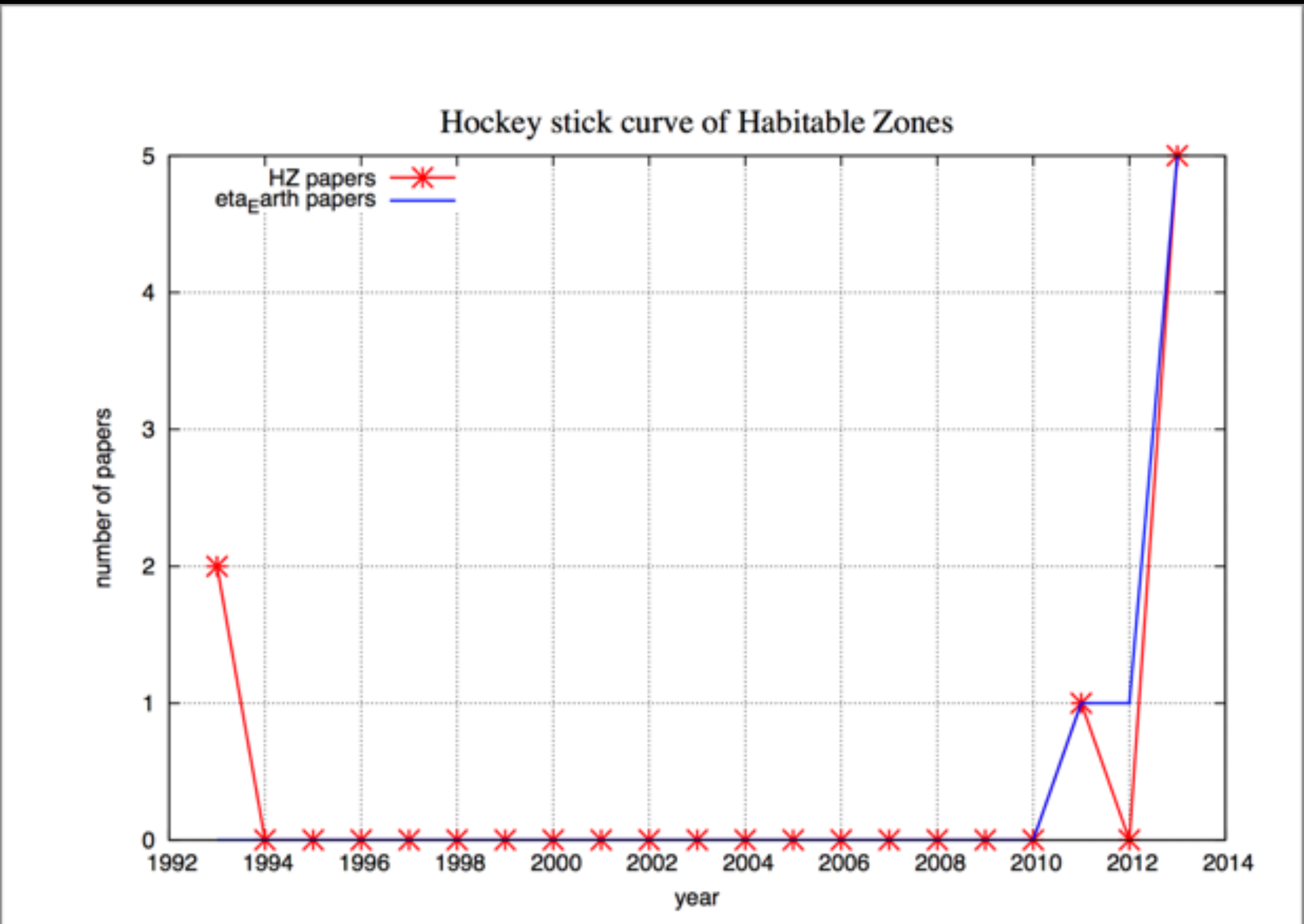
Runaway Greenhouse limit 1.0385 0.9813 AU

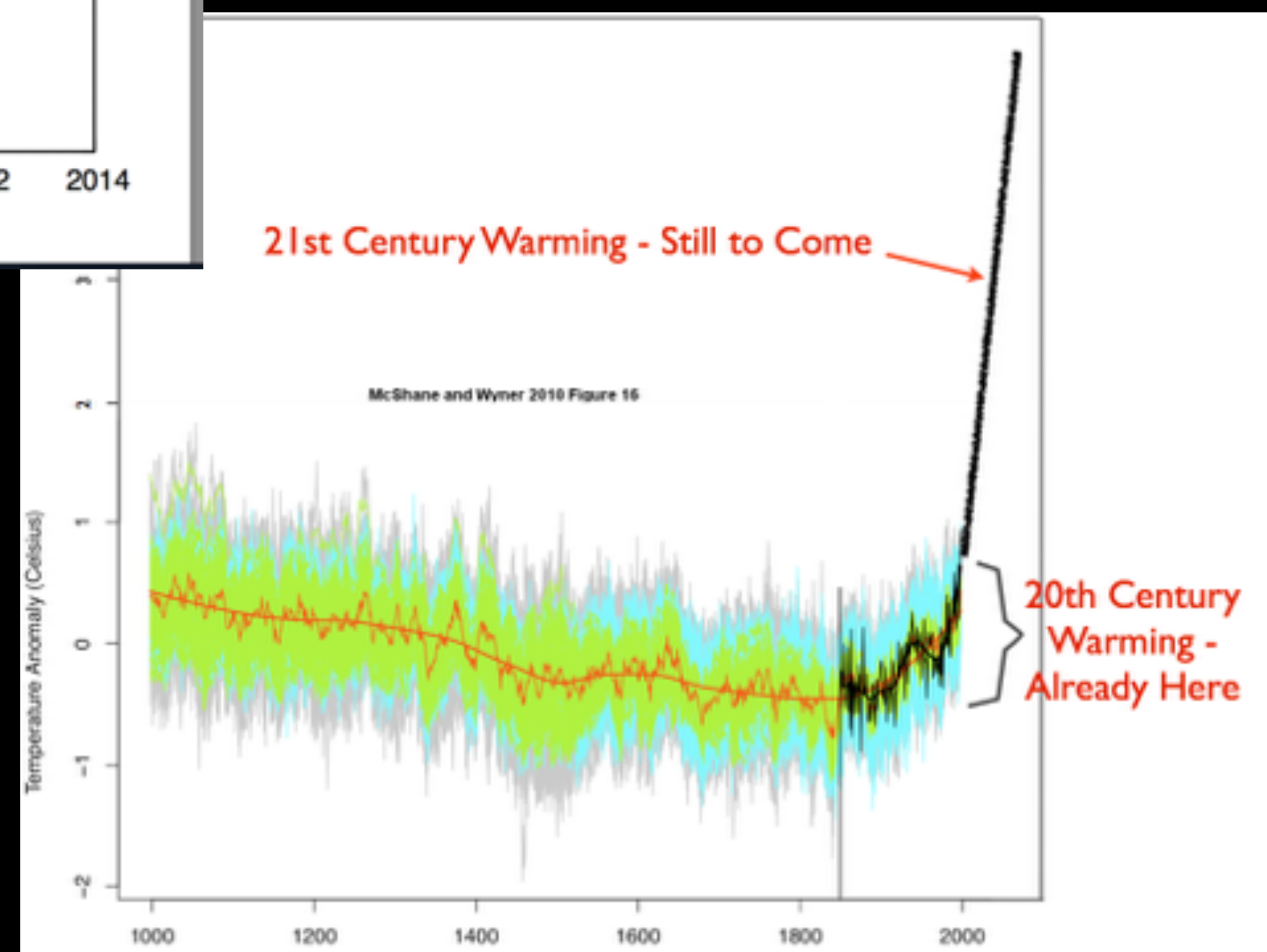
If you use this calculator or the FORTRAN code, please cite the following publication:

"Habitable Zones Around Main-Sequence Stars: New Estimates" by Kopparapu et al.(2013), *Astrophysical Journal, 765, 131* arXiv link

http://depts.washington.edu/naivpl/sites/default/files/hz.shtml

http://www3.geosc.psu.edu/~ruk15/planets/


Hockey stick curve of Habitable Zones
HZ papers
eta$_E$arth papers
number of papers
year
0
1
2
3
4
5
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014

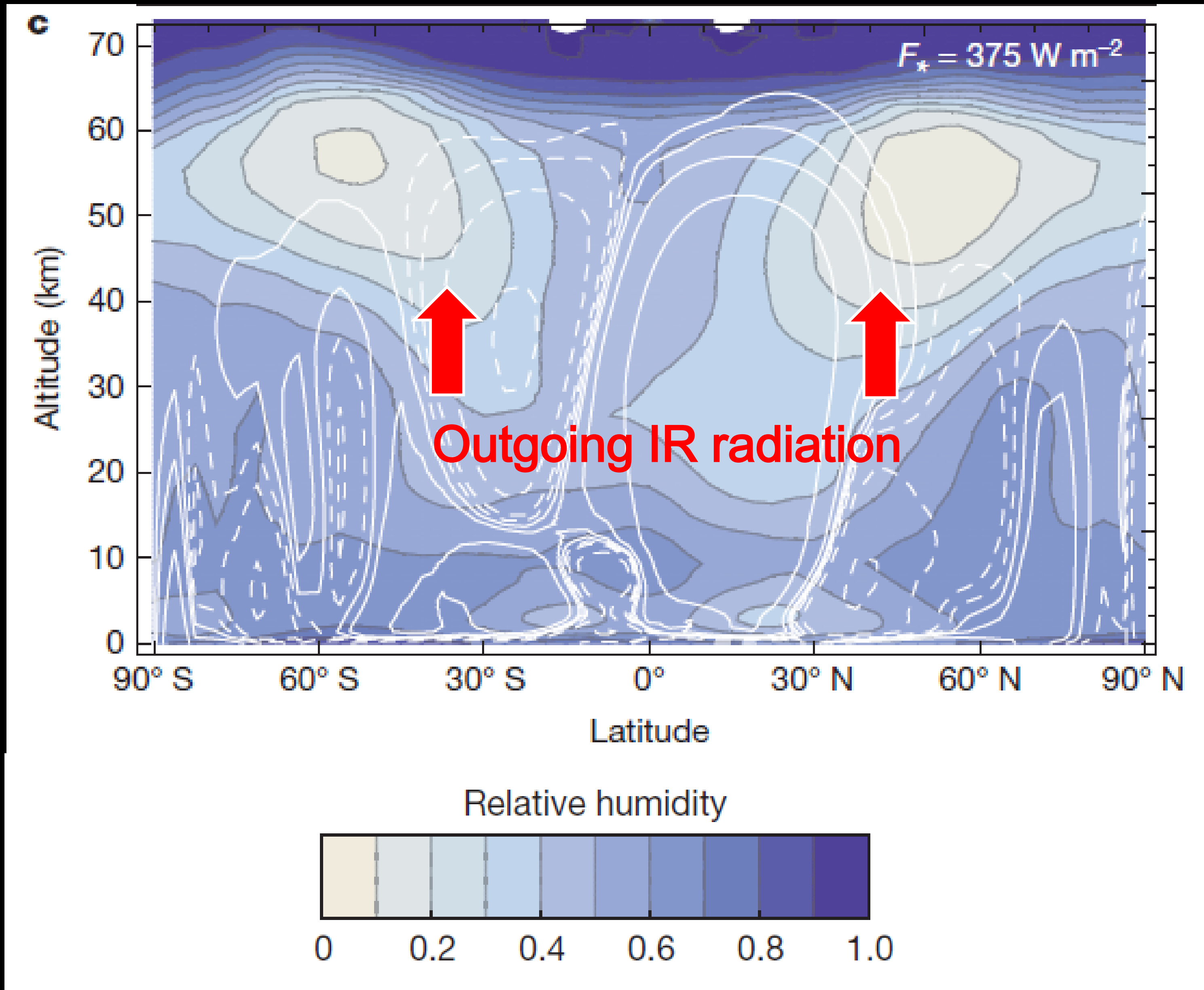

21st Century Warming - Still to Come
McShane and Wyner 2010 Figure 16
20th Century Warming - Already Here
Temperature Anomaly (Celsius)
1000
1200
1400
1600
1800
2000

3-DMODELING OF HZ BOUNDARIES

The runaway greenhouse threshold distance is increased to 0.95 AU because the tropical Hadley cells radiate IR to space, thus cooling the planet.

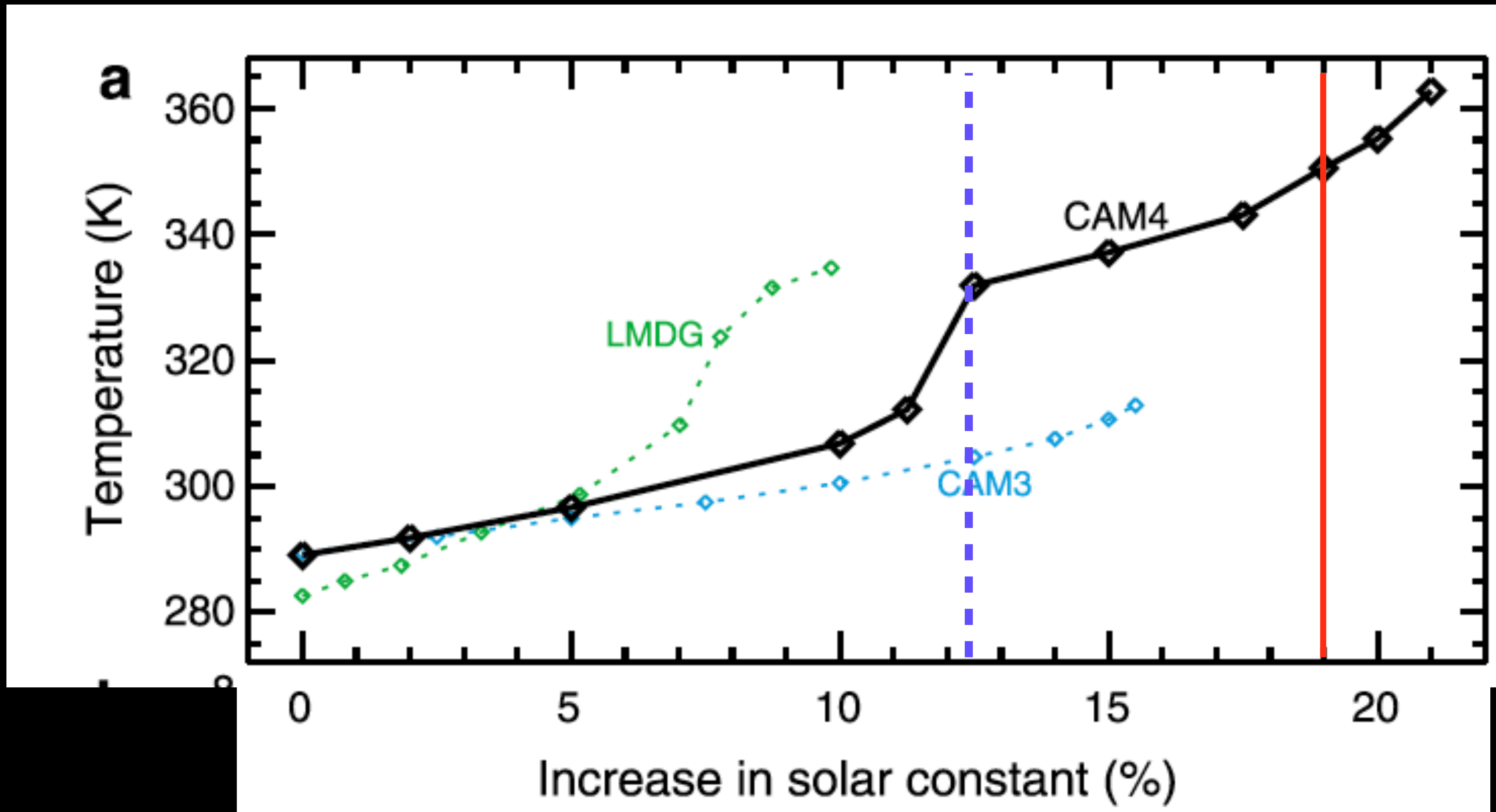
But they did not find moist greenhouse limit.

However….
(Kasting, Kopparapu & Chen(2015)) show that indeed moist-greenhouse is possible.



Leconte et al.(2013)

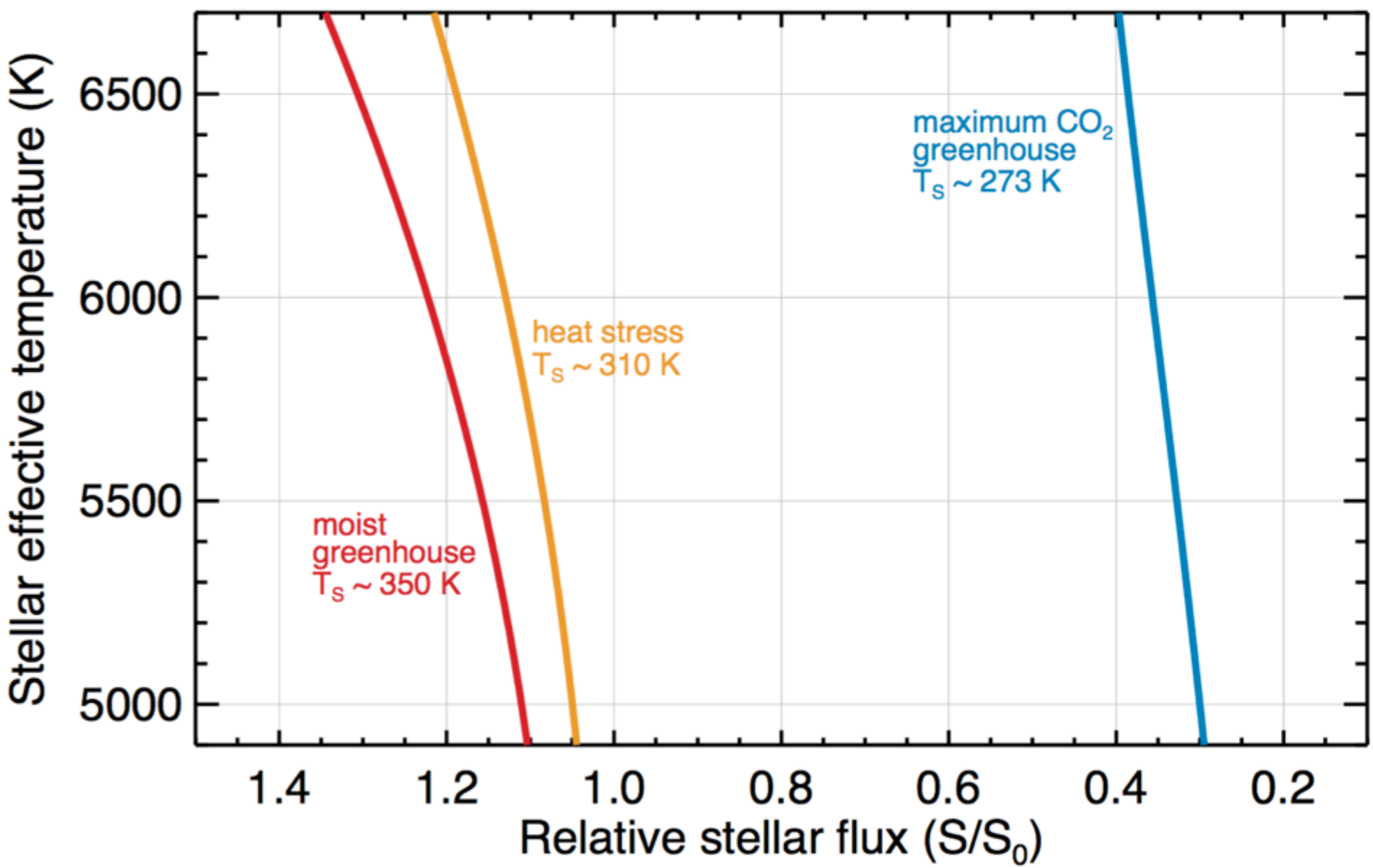
3-DMODELING OF HZ BOUNDARIES



Wolf & Toon(2015)

Moist greenhouse at 0.92 AU (19% S_0, Red)

Heat Stress/climate transition at 0.94 AU (12.5% S_0, Blue)

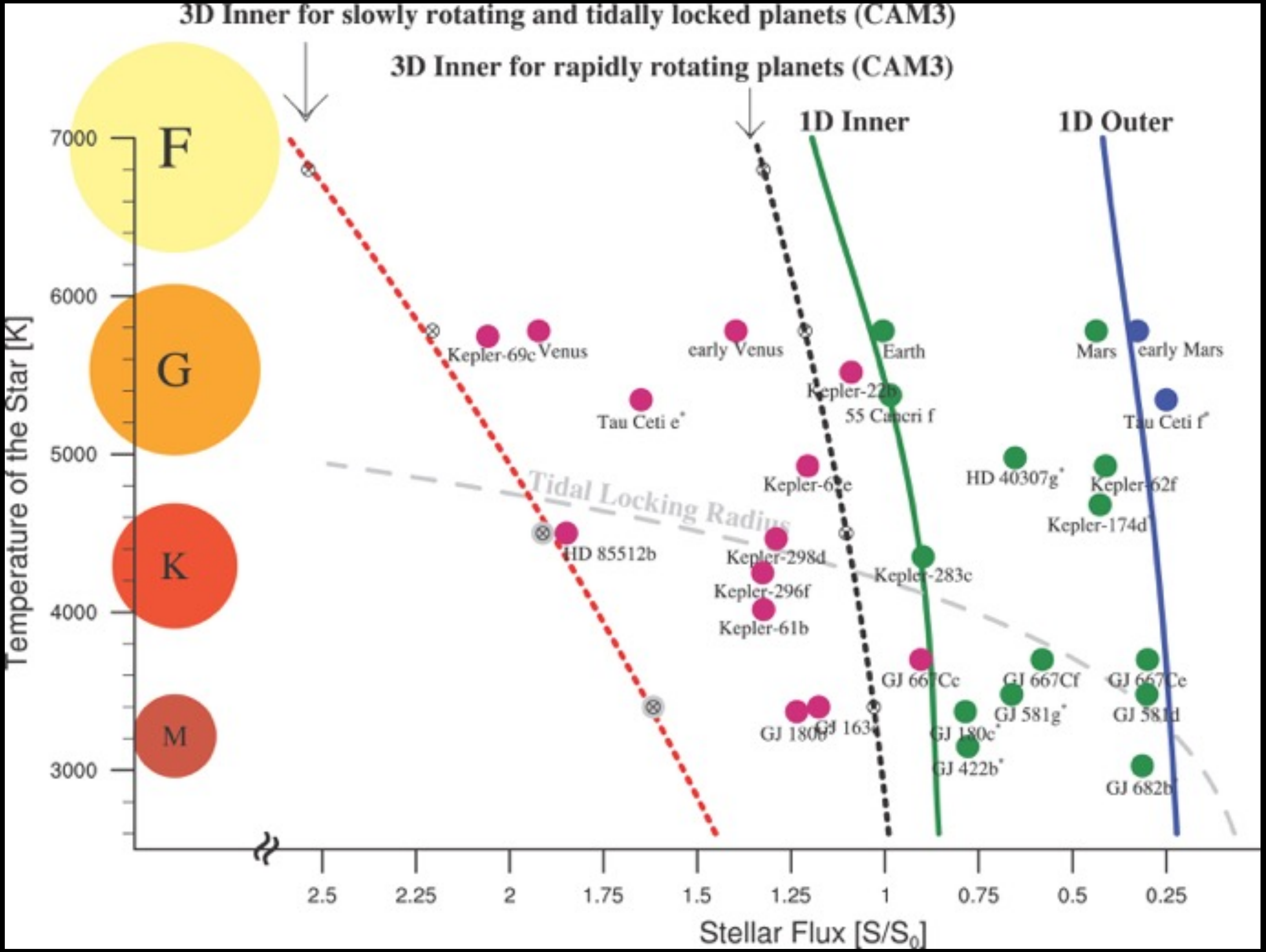


Stellar effective temperature (K)
6500
6000
5500
5000
1.4
1.2
1.0
0.8
0.6
0.4
0.2
Relative stellar flux (S/S_0)
maximum CO_2 greenhouse
$T_S \sim 273$ K
heat stress
$T_S \sim 310$ K
moist greenhouse
$T_S \sim 350$ K

3-D MODELS FOR M AND K-DWARF HZS

- The inner HZ can extend ~ 2 times closer to the star for synchronously rotating planets around MK-dwarfs.

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



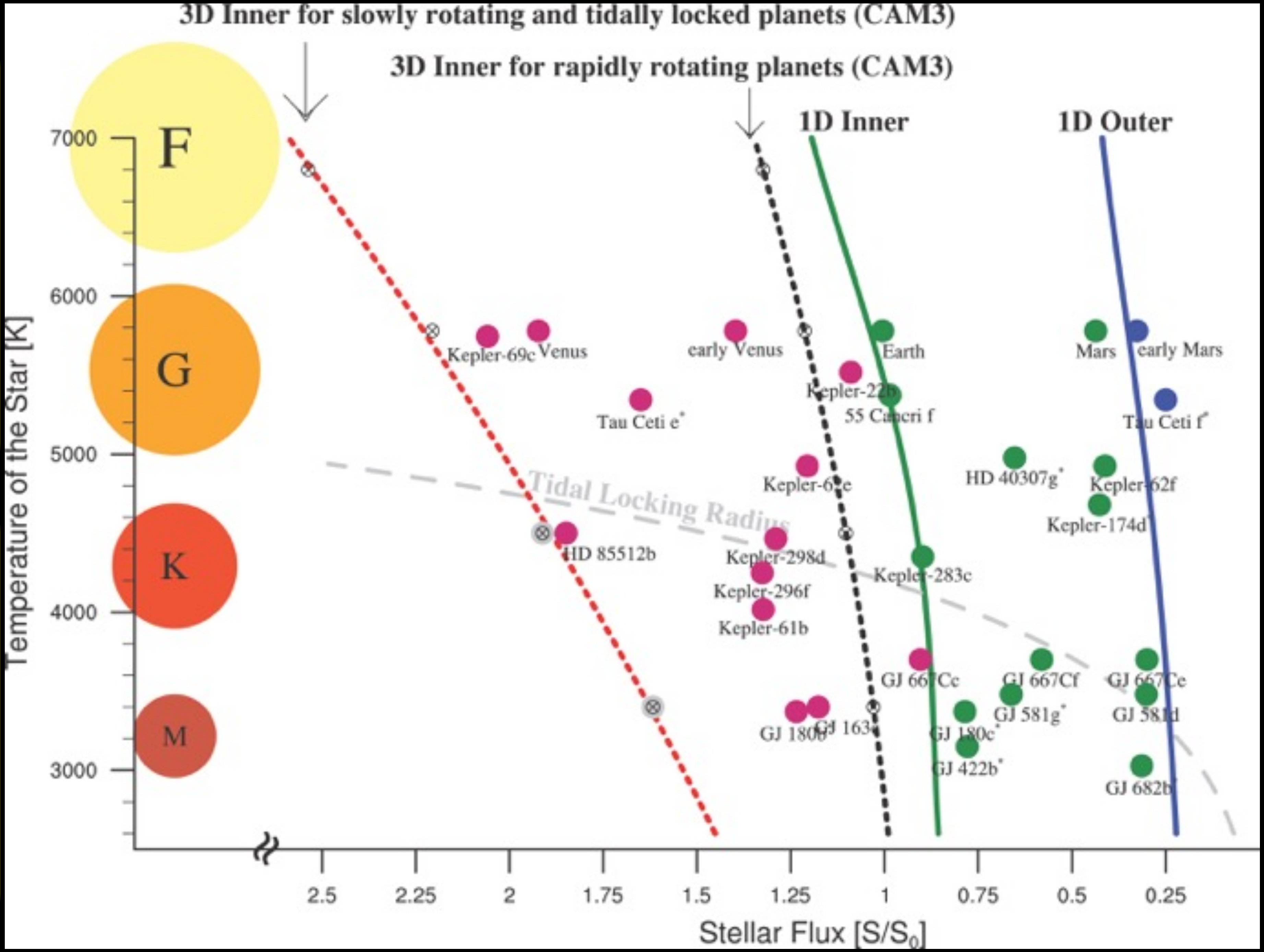
Yang et al.(2014)

But…their inner edge is not the moist greenhouse limit (Last converged stable simulation)

3-D MODELS FOR M AND K-DWARF HZS

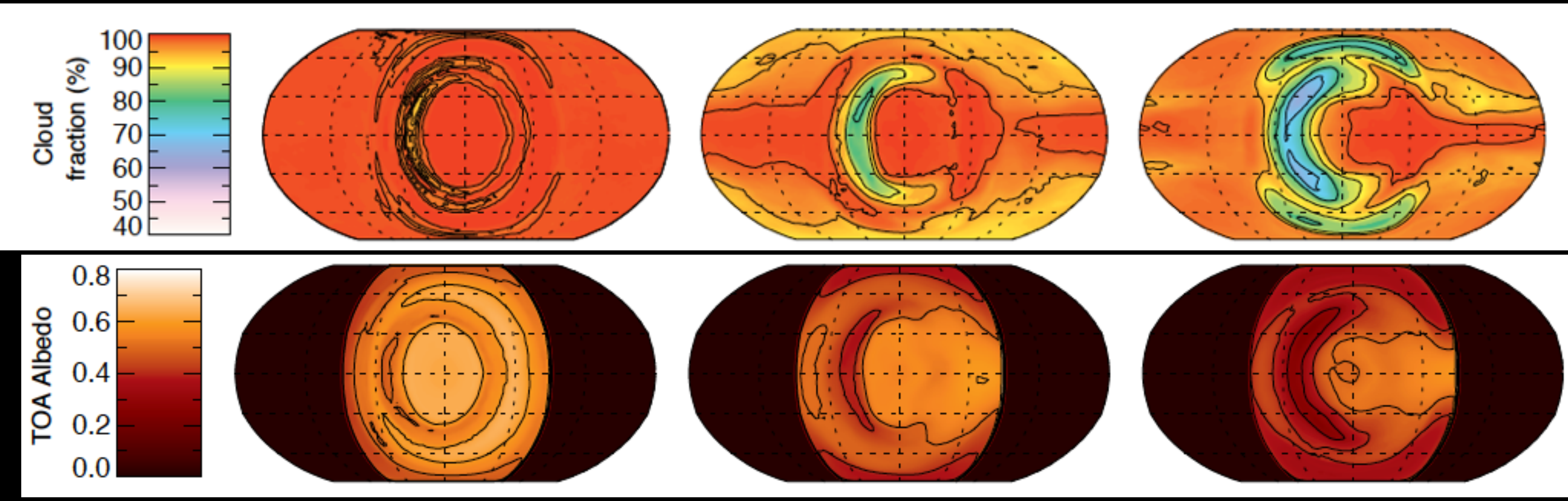
- A word of caution: They assumed 60 day orbital periods ***for all*** planets around M-dwarfs

- Violates Kepler's laws, if synchronous rotation is assumed



Yang et al.(2014)

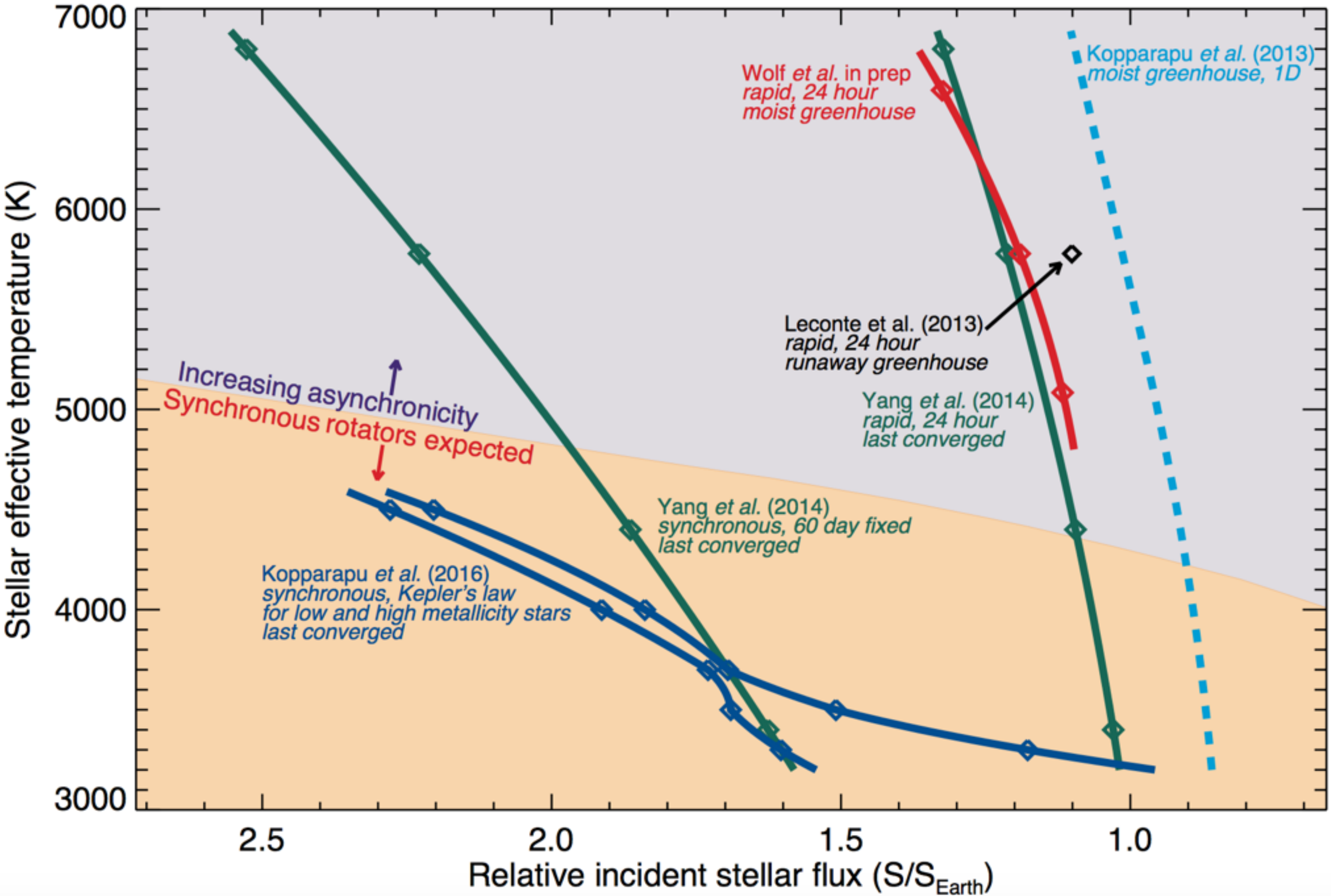
But…their inner edge is not the moist greenhouse limit (Last converged stable simulation)



Kopparapu et al.(2016)

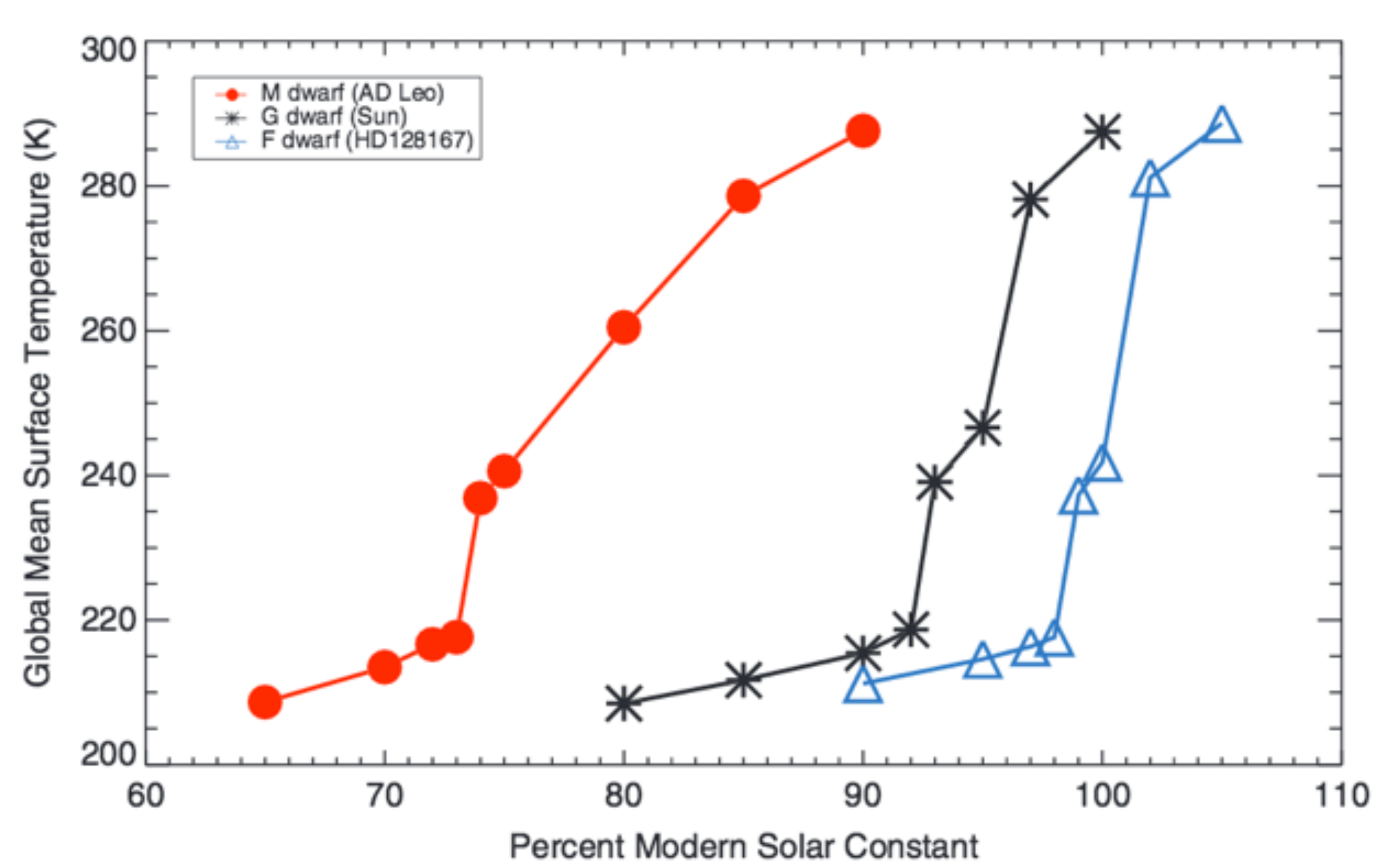
In general, we reproduce the physical mechanism of substellar clouds. But, If correct orbital/rotational periods are used, the substellar clouds smear up to a degree, and reduce the albedo.

INNER EDGE OF THE HZ



3-D OUTER EDGE OF THE HZ

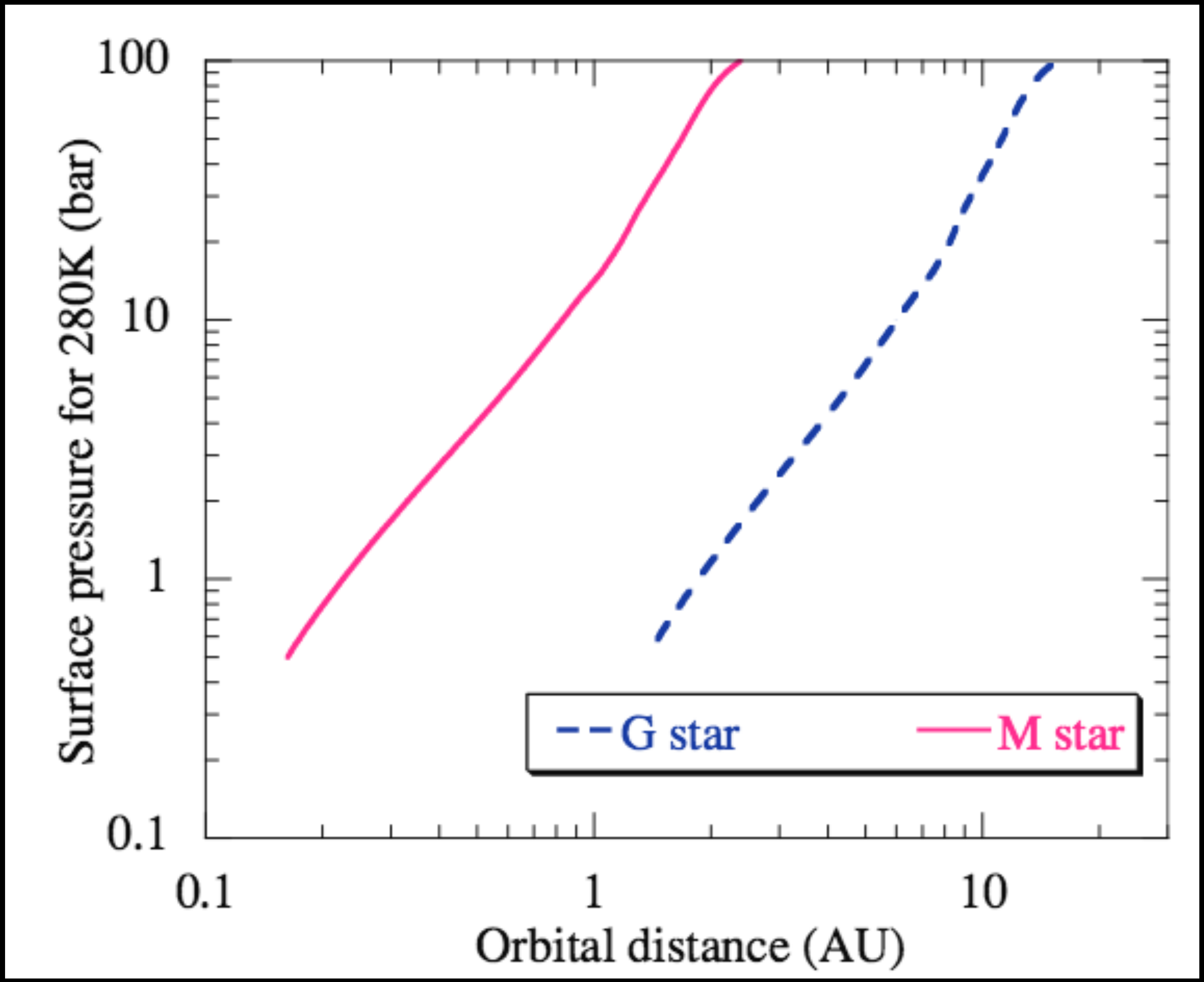
- Planets around M-dwarfs are less susceptible to snowball episodes.
- Lower albedo of ice and snow at near-IR wavelengths, in addition to near-IR absorption by atmospheric CO2, water vapor and water clouds



Shields et al.(2013)

HYDROGEN HABITABLE ZONES

- 40 bars of pure H_2 on a three Earth-mass planet can maintain a surface temperature of 280 K out to 10 AU around a G-dwarf!
- Collision induced absorption of H_2 provides greenhouse effect



Pierrehumbert & Gaidos (2011)

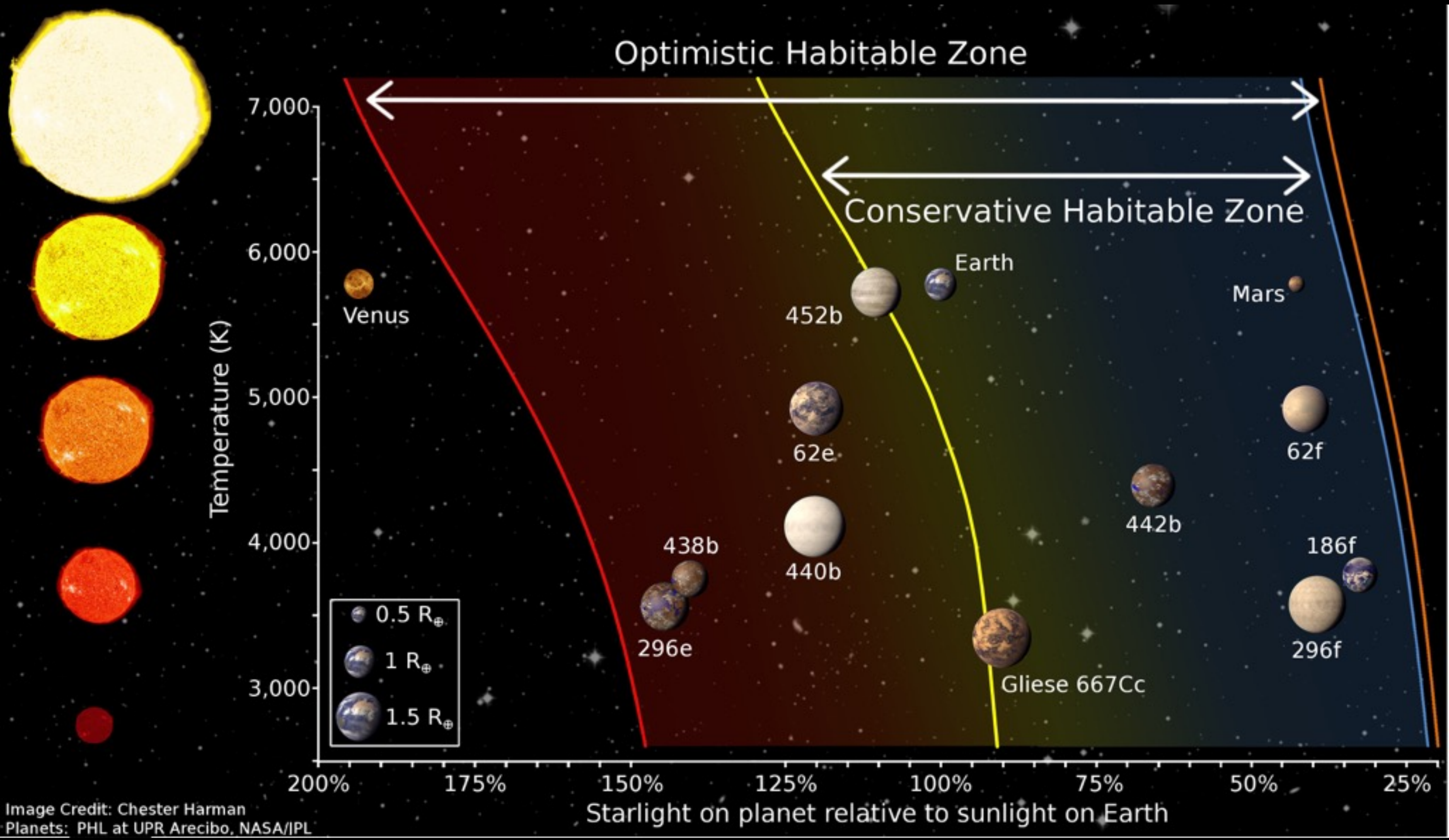
WHICH HZS TO USE?

- What is the purpose?
- Every model has a utility depending on the need.
- Advances in modeling techniques means an evolution of HZ estimates.

HZ models =

APPLICATIONS OF HZS

- Discover potential habitable planets (around which star)? Some models have results only for G-stars
- Climate studies (atmospheric circulation, dynamics, convection, energy transport)?
- Calculate occurrence rates of Earth-size/mass planets (again, around what spectral types?)
- What do we want to do with the occurrence rates? Design a direct imaging mission for bio-signature detection.



http://depts.washington.edu/naivpl/sites/default/files/hz.shtml

http://www3.geosc.psu.edu/~ruk15/planets/