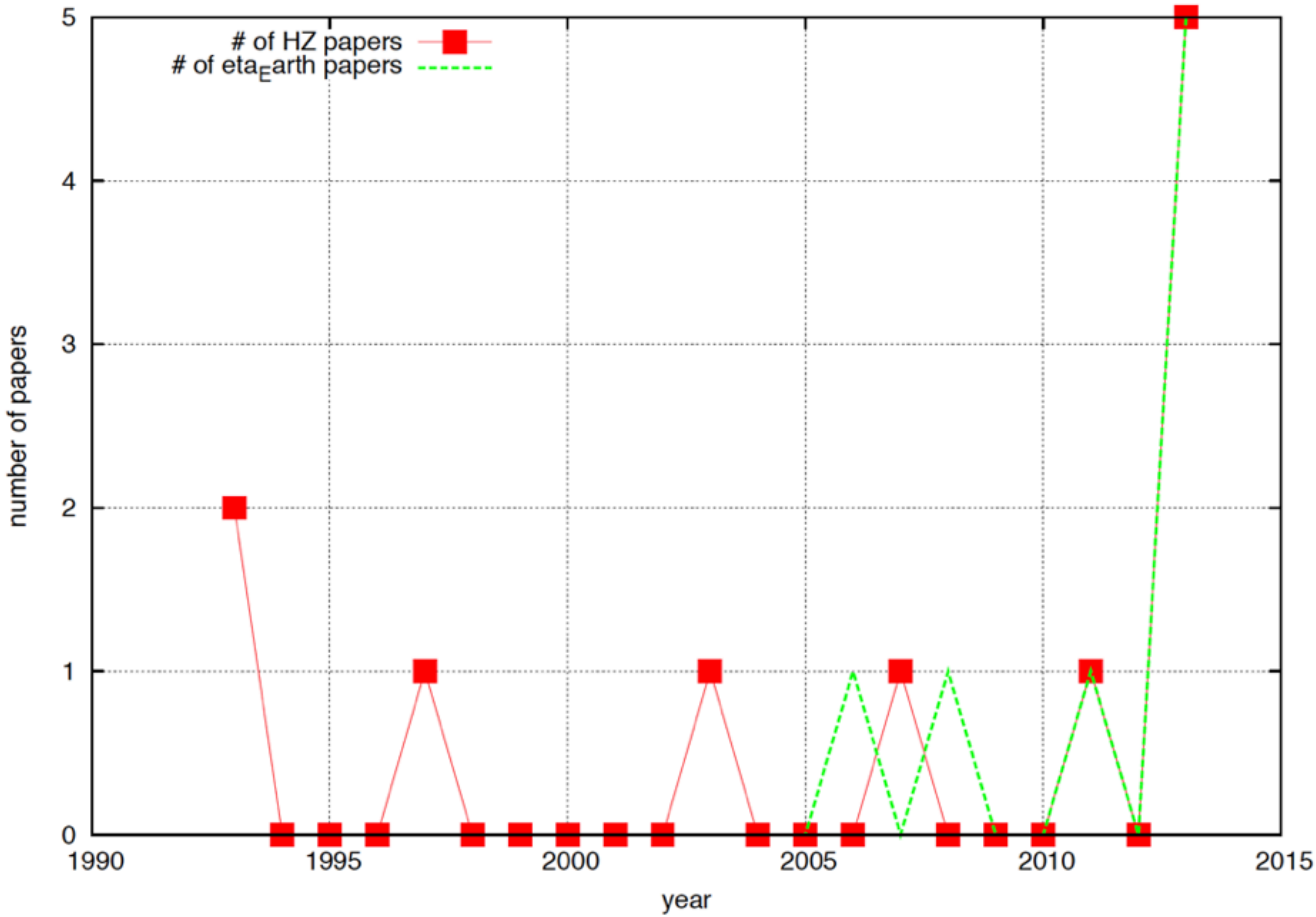
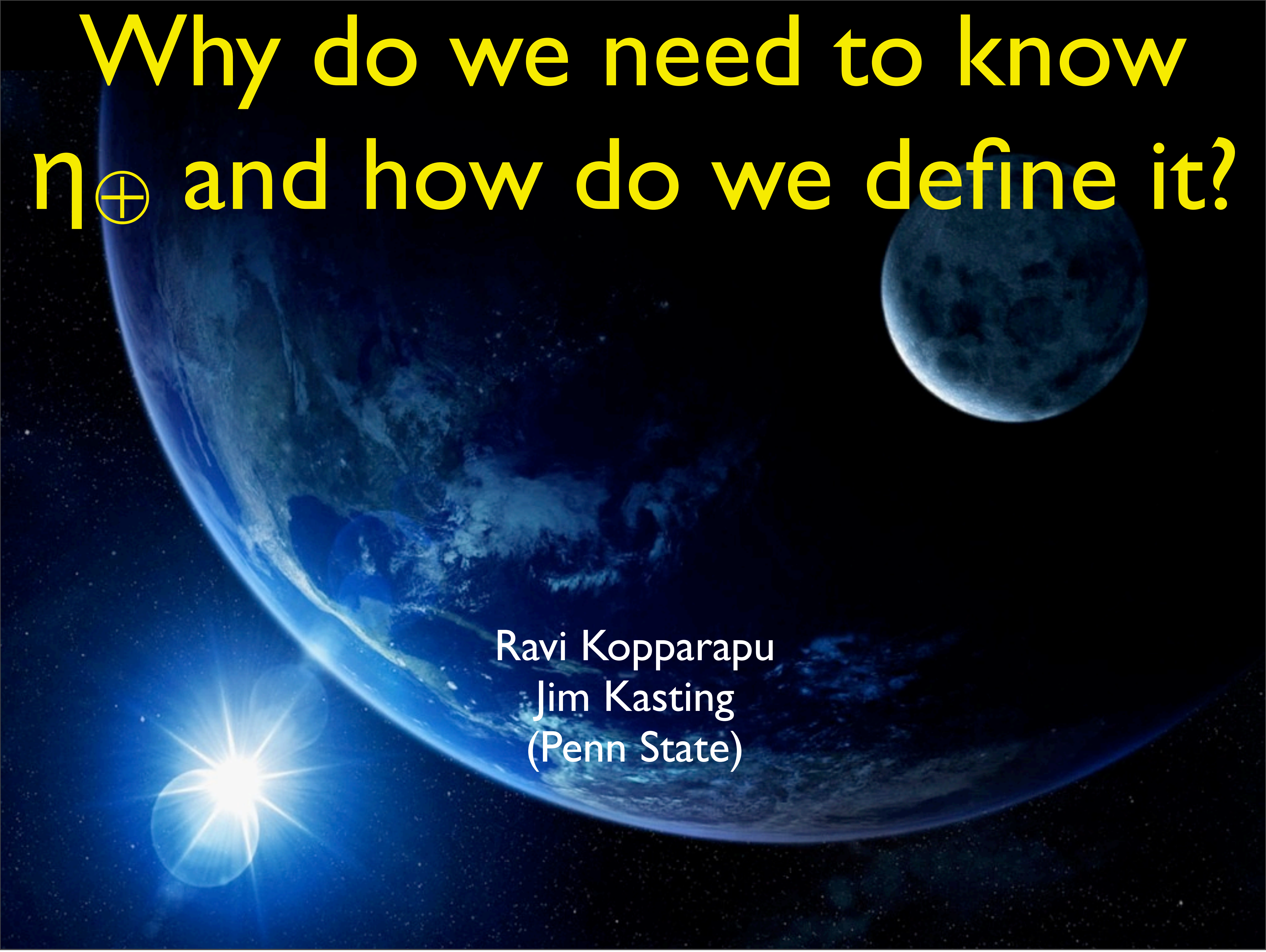


# of HZ papers
# of eta$_E$arth papers
number of papers
year
0
1
2
3
4
5
1990
1995
2000
2005
2010
2015

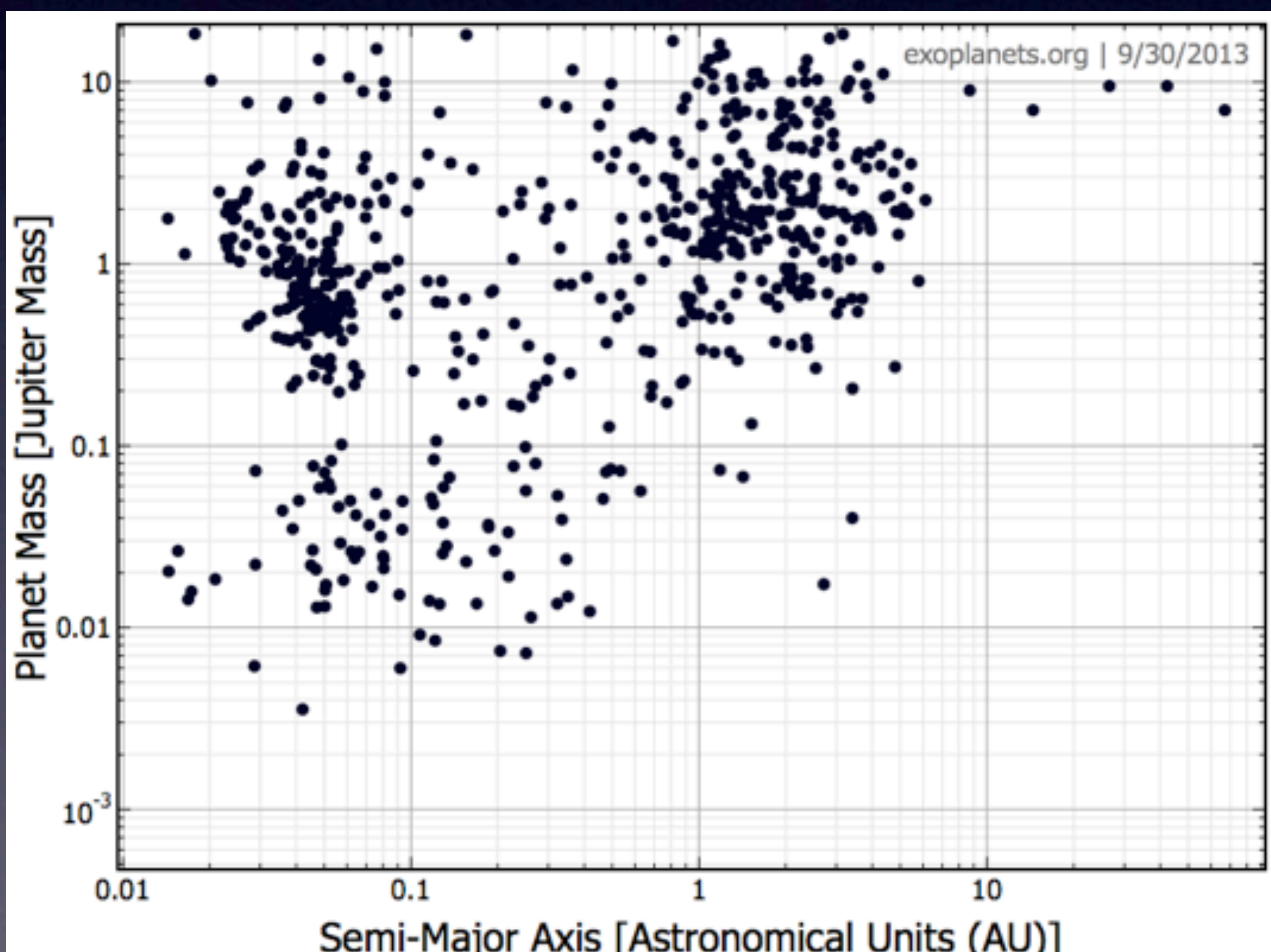
Why do we need to know $\eta_{\oplus}$ and how do we define it?

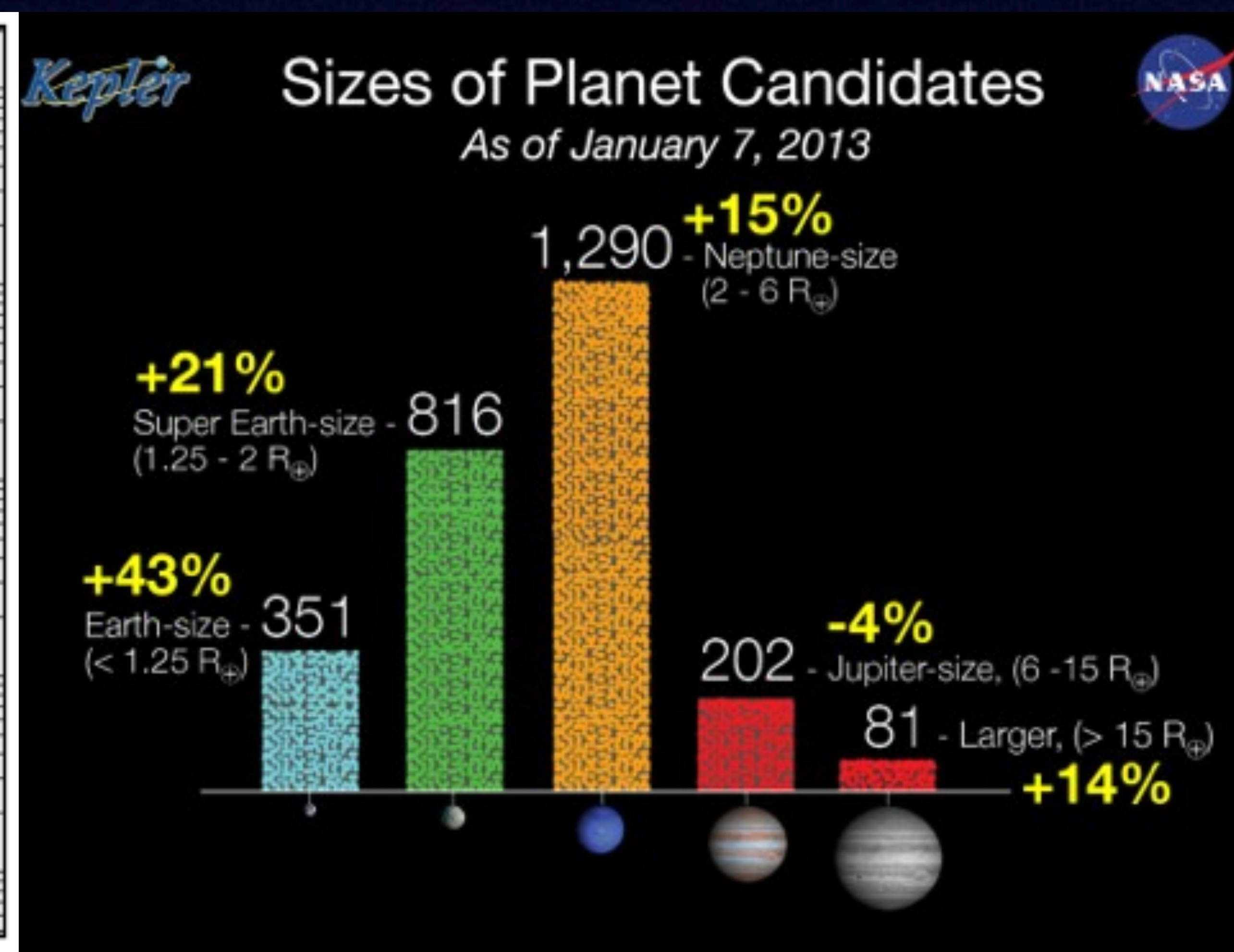


Ravi Kopparapu
Jim Kasting
(Penn State)

Exoplanet Discoveries

- 732 total confirmed planets from all detection methods[1]
- 3588 unconfirmed *Kepler* planet candidates[2]



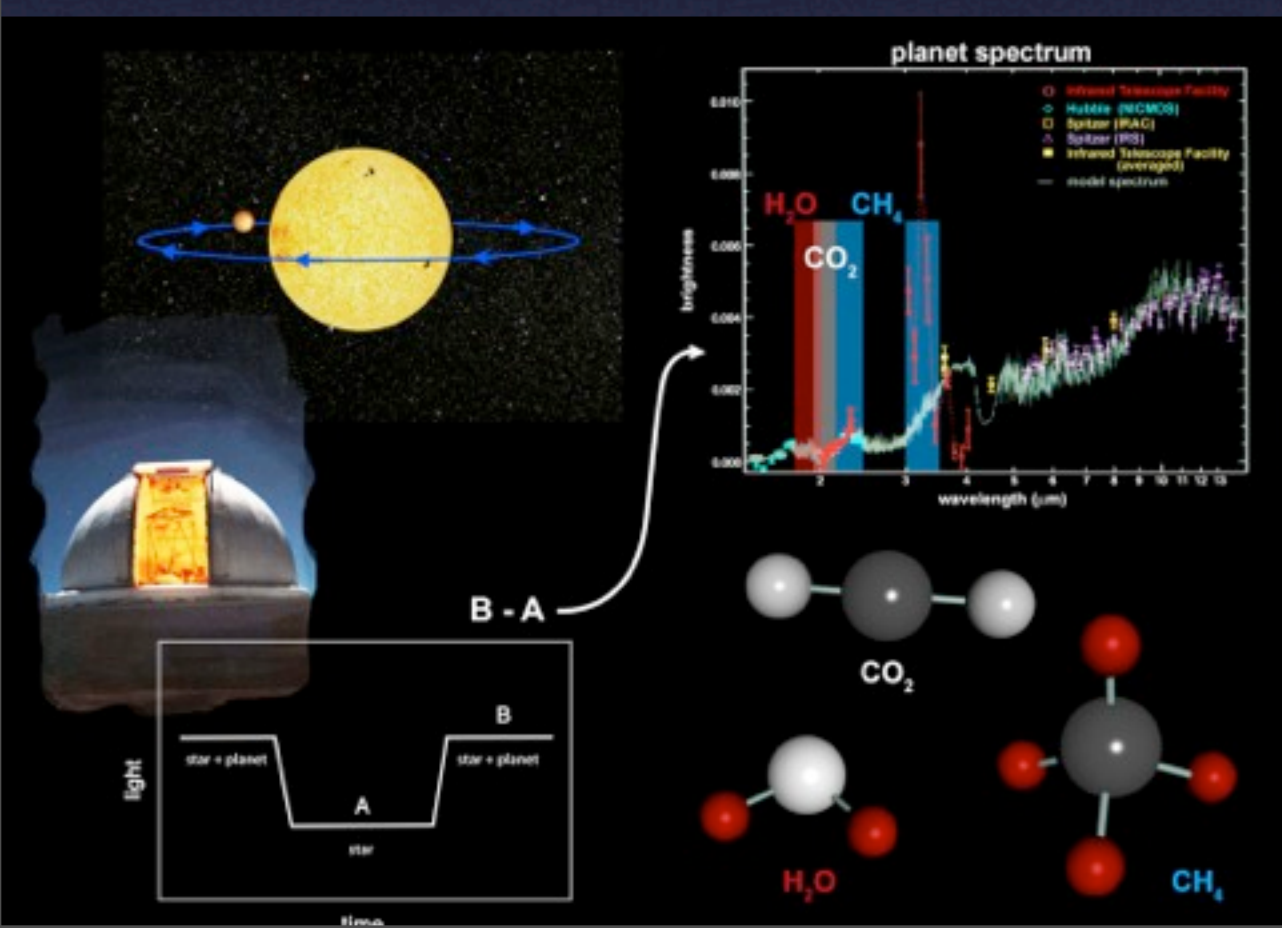


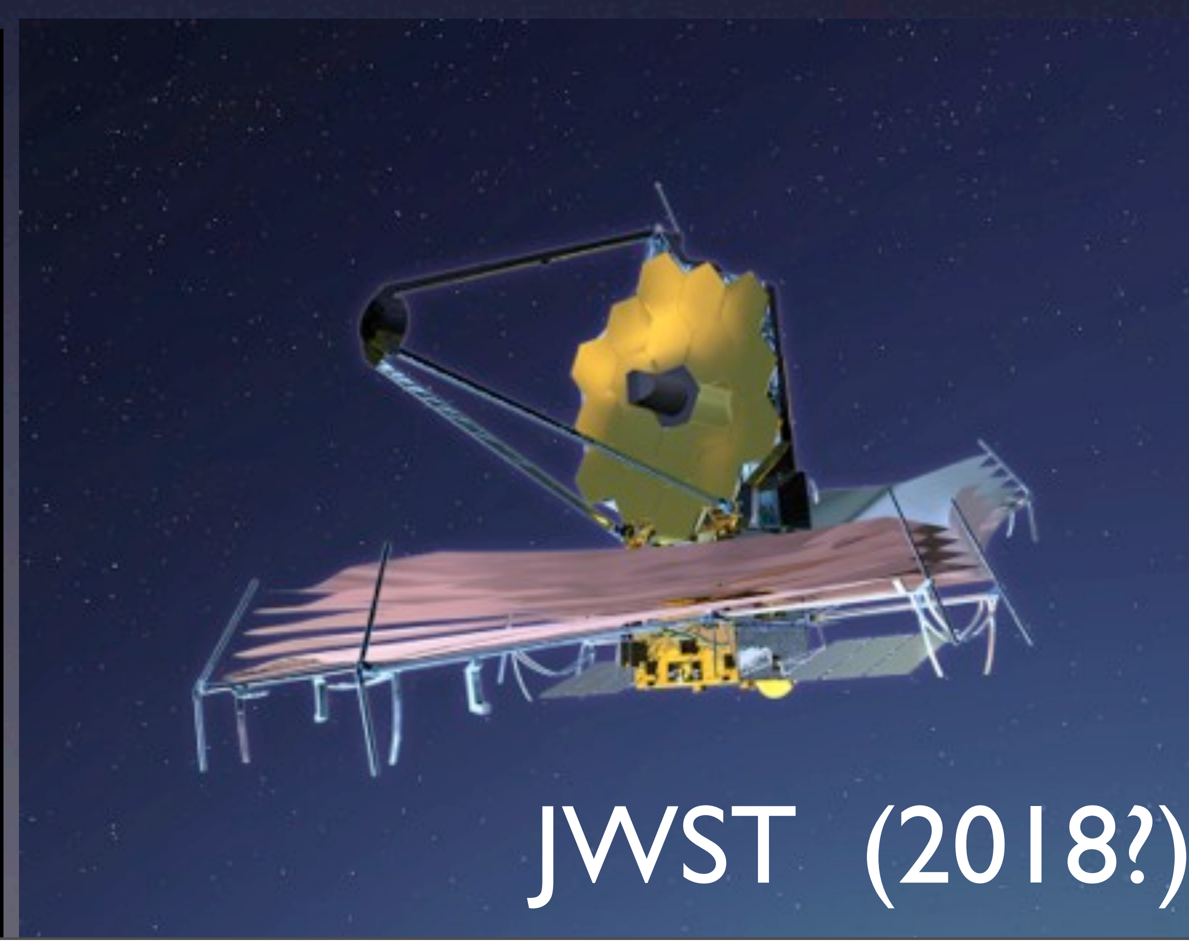
[1] exoplanets.org

[2] http://kepler.nasa.gov/Mission/discoveries/candidates/

Exoplanet Characterization

- Ground-based, HST & Spitzer observations have characterized hot-Jupiters and hot-Neptunes (thermal profiles, atmospheric abundances and circulation)
- JWST can *potentially* characterize (HZ?) super-Earths around M-dwarfs





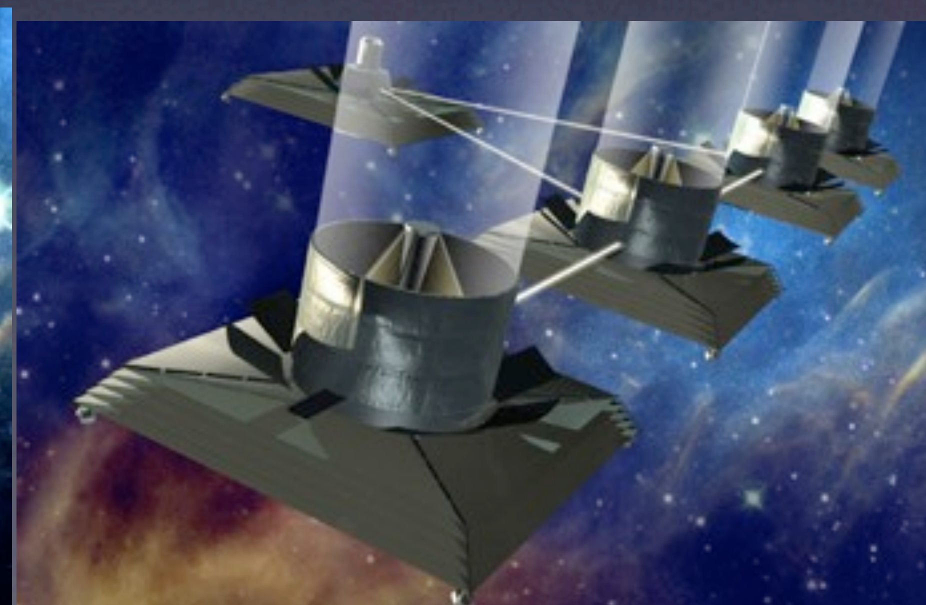
Exoplanet Characterization

(The habitable planet flavor)

- Spectroscopic biomarkers (O_2, O_3, CH_4, NH_3?) by direct imaging of potential habitable worlds around F, G, K stars

TPF-C

TPF-I



TPF-O

Size of the telescope

(from TPF-C STDT report)

- One requirement is that TPF-C must be able to look at an Earth-size planet at 1 AU from a Sun like star at 10 parsec.
- At this distance the angular separation θ of an Earth-like planet = 100 mas.
- At an inner working angle of ~ 60 mas, and λ ~ 0.5 micron, the (circular) diameter 'D' of the telescope is ~ 8 m (assuming $\theta \sim 4\lambda/D$)

How many stars to search?

- The number of stars to search (N_{stars})depends on $\eta_\oplus$
- $\eta_\oplus$: Fraction of *observed* stars that have at least one terrestrial size/mass planet within their habitable zone[1].
- Terrestrial: 0.5 - 2 $R_\oplus$, 0.3-10 $M_\oplus$
- Habitable Zone[2]: Circumstellar region where liquid water can exist on the surface of a planet

[1] TPF-C Science and Technology Definition Team report
[2] Kasting et al.(1993)

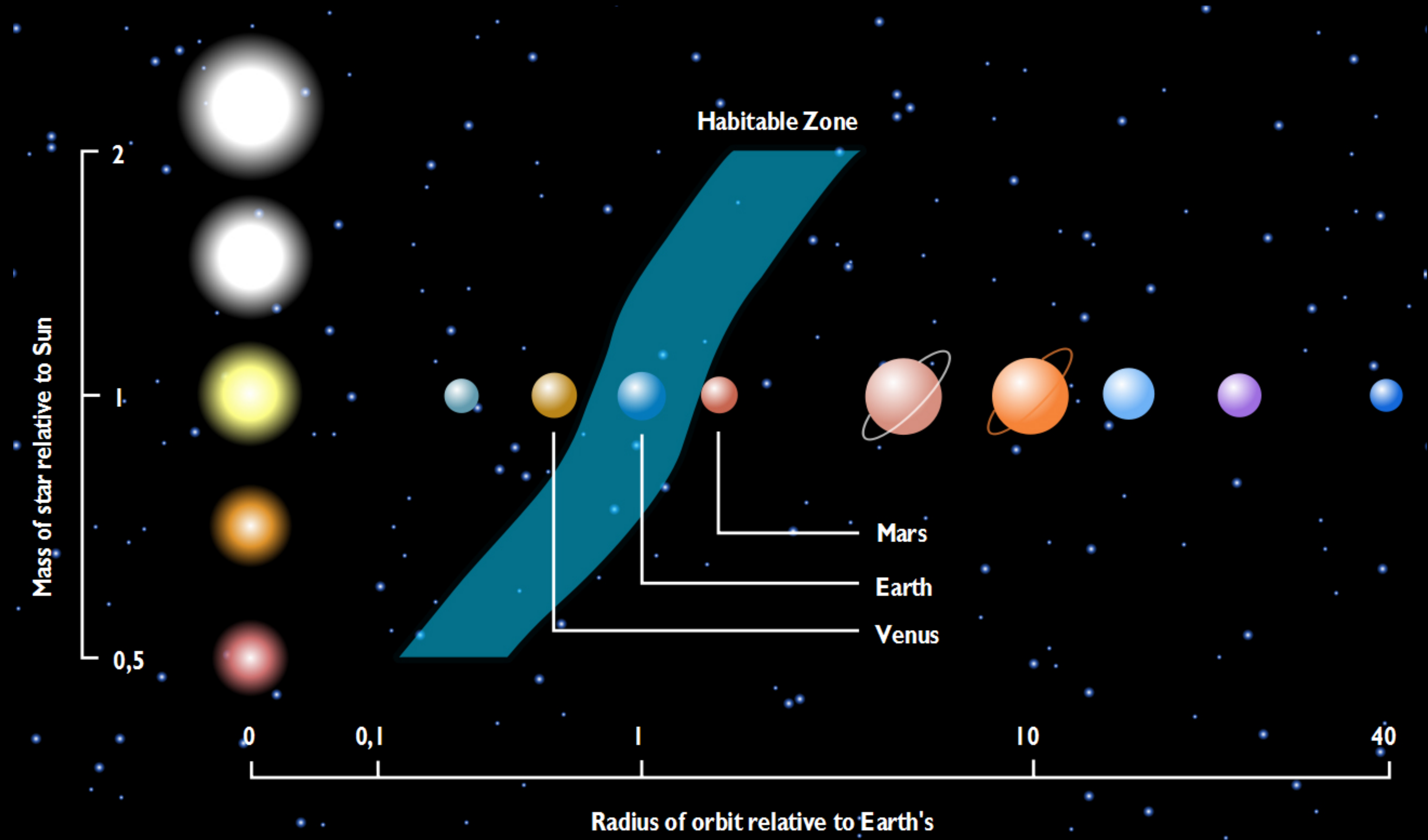
How many stars to search?

- The expected number of potentially habitable planets $N = \eta_{\oplus} . N_{stars}$. This assumes 100% complete search of each star's entire HZ.
- Assuming $\eta_{\oplus}$ = 0.1, and requiring that N = 3, the number of stars to be searched is $N_{stars} \sim 30$
- For 90% completeness, $N_{stars} \sim 30/0.9 \sim 33$, to have an expected number N = 3
- A sample of ~30 stars can provide an upper bound on $\eta_{\oplus}$

How many stars to search?

- If a 100% search of 30 stars HZ reveals no planets, then the probability that $\eta_\oplus \geq 0.1$ would be $(1\text{-}0.1)^{30} = 0.9^{30} \sim 0.04$
- So we can say with >95% certainty that $\eta_\oplus \leq 0.1$
- This does not mean that the mission should only search around nearest 30 stars
- The same expectation value of potential habitable planets, and the same upper limit on $\eta_\oplus$, can be derived if the HZ search completeness ~ 50% around 60 stars

The ZAMS habitable zone



- The liquid water habitable zone, as defined by Kasting et al. (1993). Figure applies to zero-age-main-sequence stars
- The habitable zone is relatively *wide* because of the negative feedback provided by the carbonate-silicate cycle

http://www.dlr.de/en/desktopdefault.aspx/tabid-5170/8702_read-15322/8702_page-2/

Inner edge of the HZ

(Kasting et al. 1993)

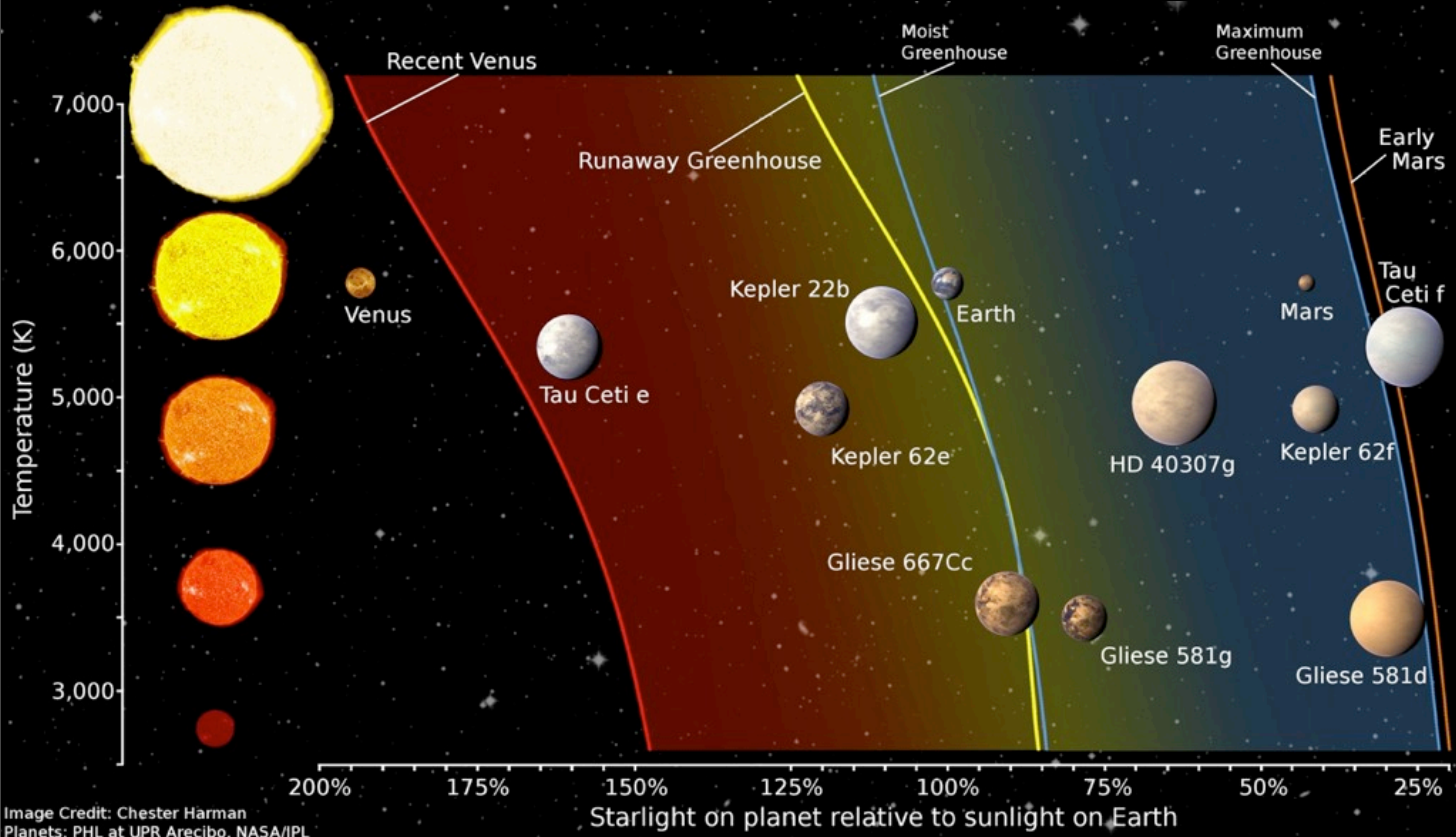
- Moist greenhouse: Water is lost by photodissociation and escape of hydrogen to space
- Runaway Greenhouse: All surface water is evaporated
- Recent Venus: Empirical estimate based on the observation that Venus has already lost its water prior to ~ 1 by years ago

Outer edge of the HZ

(Kasting et al. 1993)

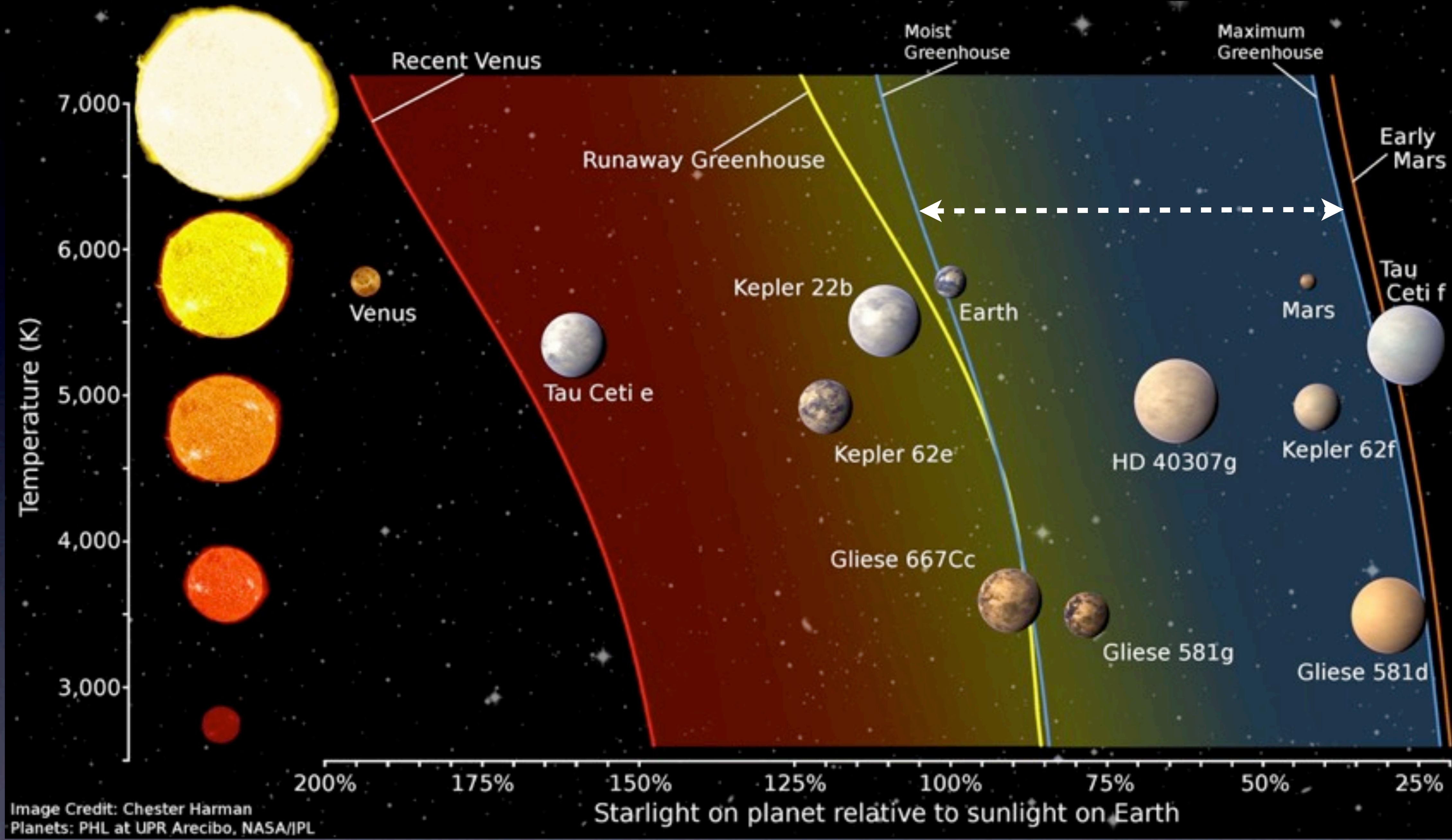
- Maximum Greenhouse: The maximum greenhouse effect of a CO_2-H_2O atmosphere
- Early Mars: Empirical estimate based on the inferred presence of liquid water on Mars' surface at or before 3.8 Ga

Revised Habitable Zones



Kopparapu, Ramirez, Kasting et al.(2013), ApJ, 765, 131

Revised Habitable Zones

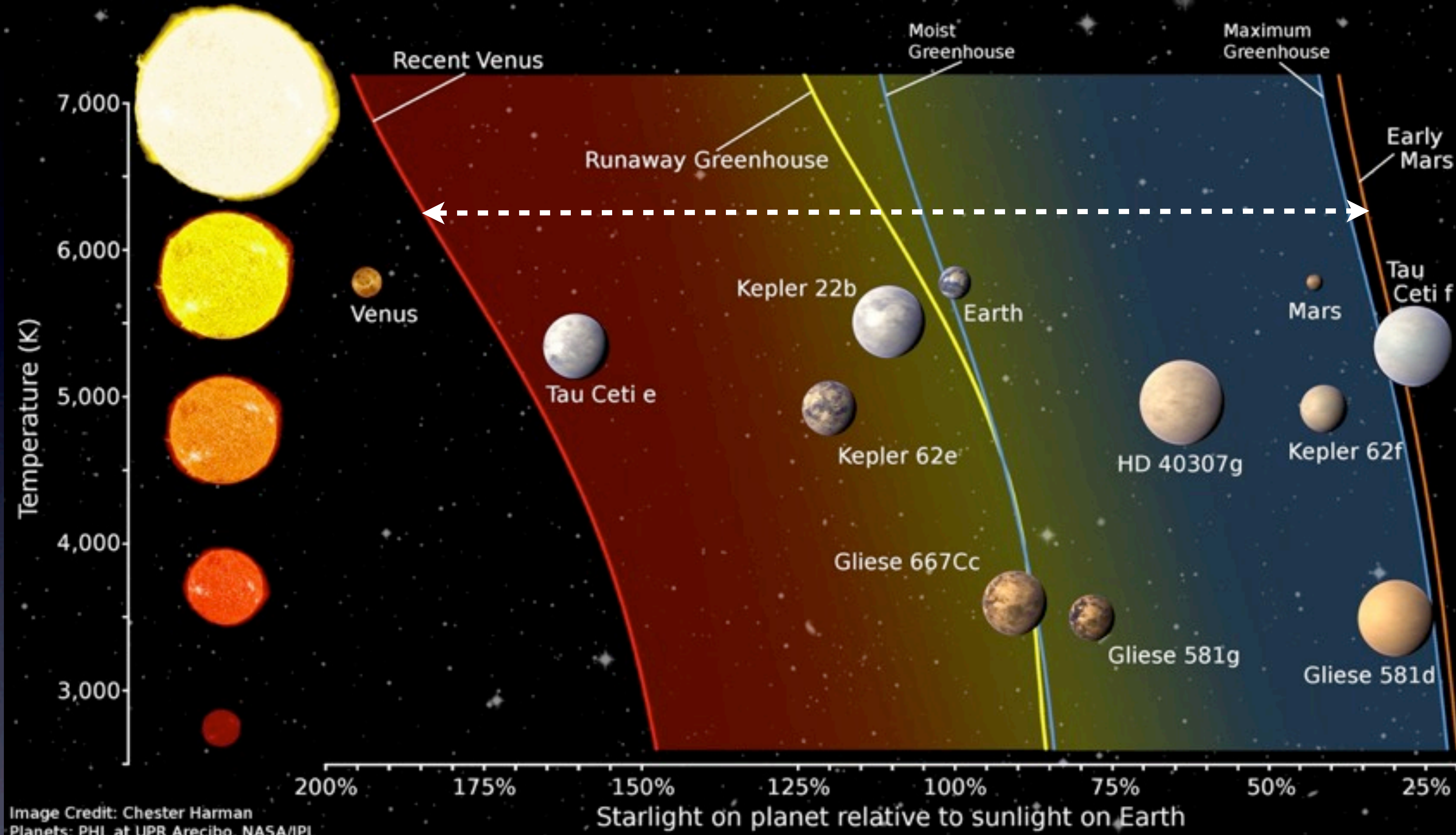


Conservative HZs:

Moist greenhouse (inner edge), Maximum greenhouse (outer edge)

Kopparapu, Ramirez, Kasting et al.(2013), ApJ, 765, 131

Revised Habitable Zones



<u>Optimistic HZs:</u>

Recent Venus (inner edge), Early Mars (outer edge)

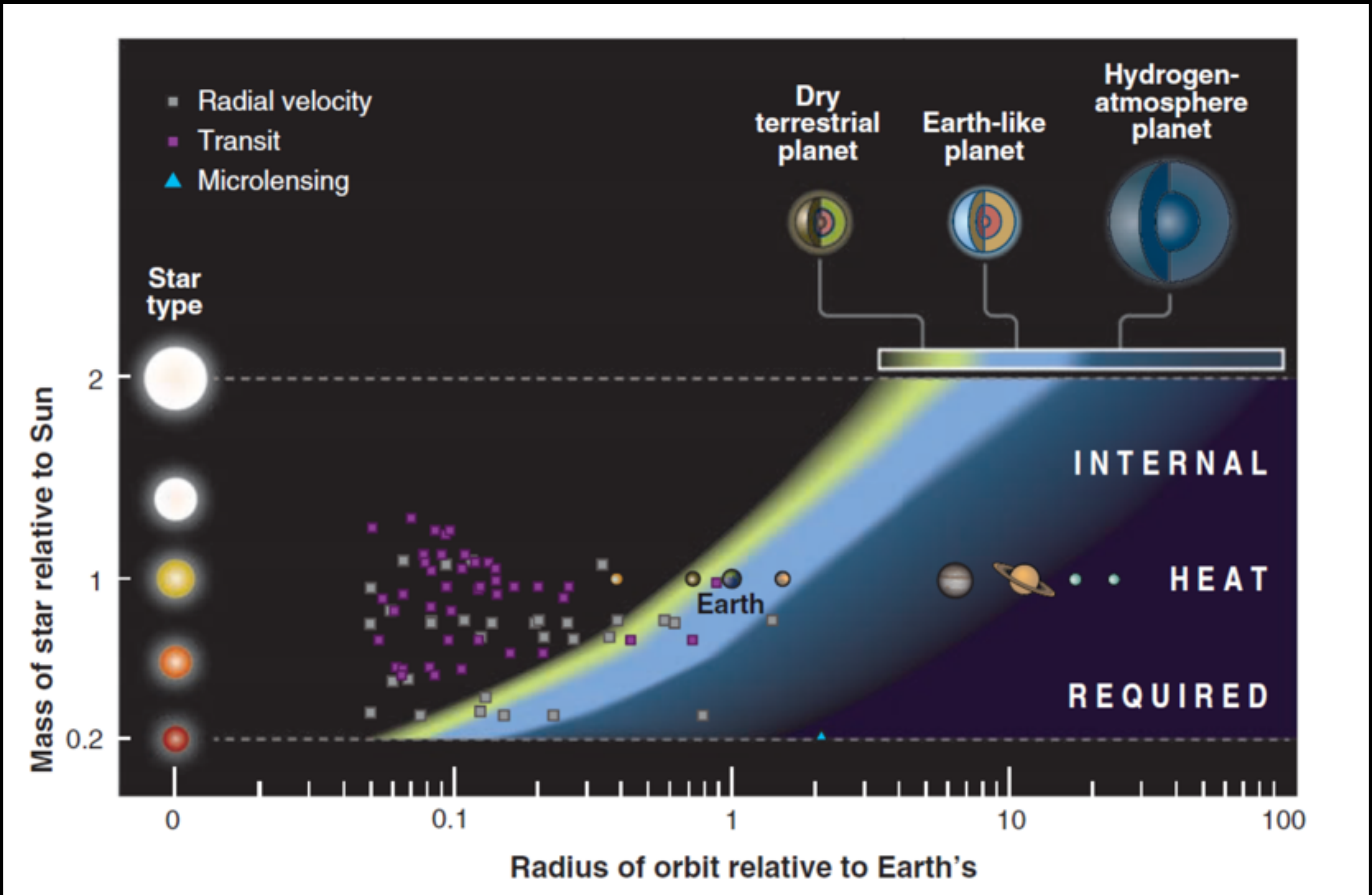
Kopparapu, Ramirez, Kasting et al.(2013), ApJ, 765, 131

Other studies

- Yang, Cowan & Abbot(2013) used 3D GCM models to show that the inner HZ can extend closer to the star for tidally locked planets around M-stars.
- Pierrehumbert & Gaidos(2011) showed that the outer edge of the HZ could be as far out as 10 AU. The particular planet envisioned is a 3-M_E super-Earth with a captured 40-bar H_2 atmosphere
- Abe et al.(2011) used 3D GCM models to show that dry planets can be habitable closer to their star
- Zsom et al.(2013) used 1D models to argue that low relative humidity planets have wider HZs*

*Certain conditions and restrictions apply

Wider HZs ?



S. Seager, Science, April, 2013

- It was suggested that the outer edge of the HZ could be as far out as 10 AU. and the inner edge as close as 0.5 AU around a Sun-like star.

Which HZ limits to use?

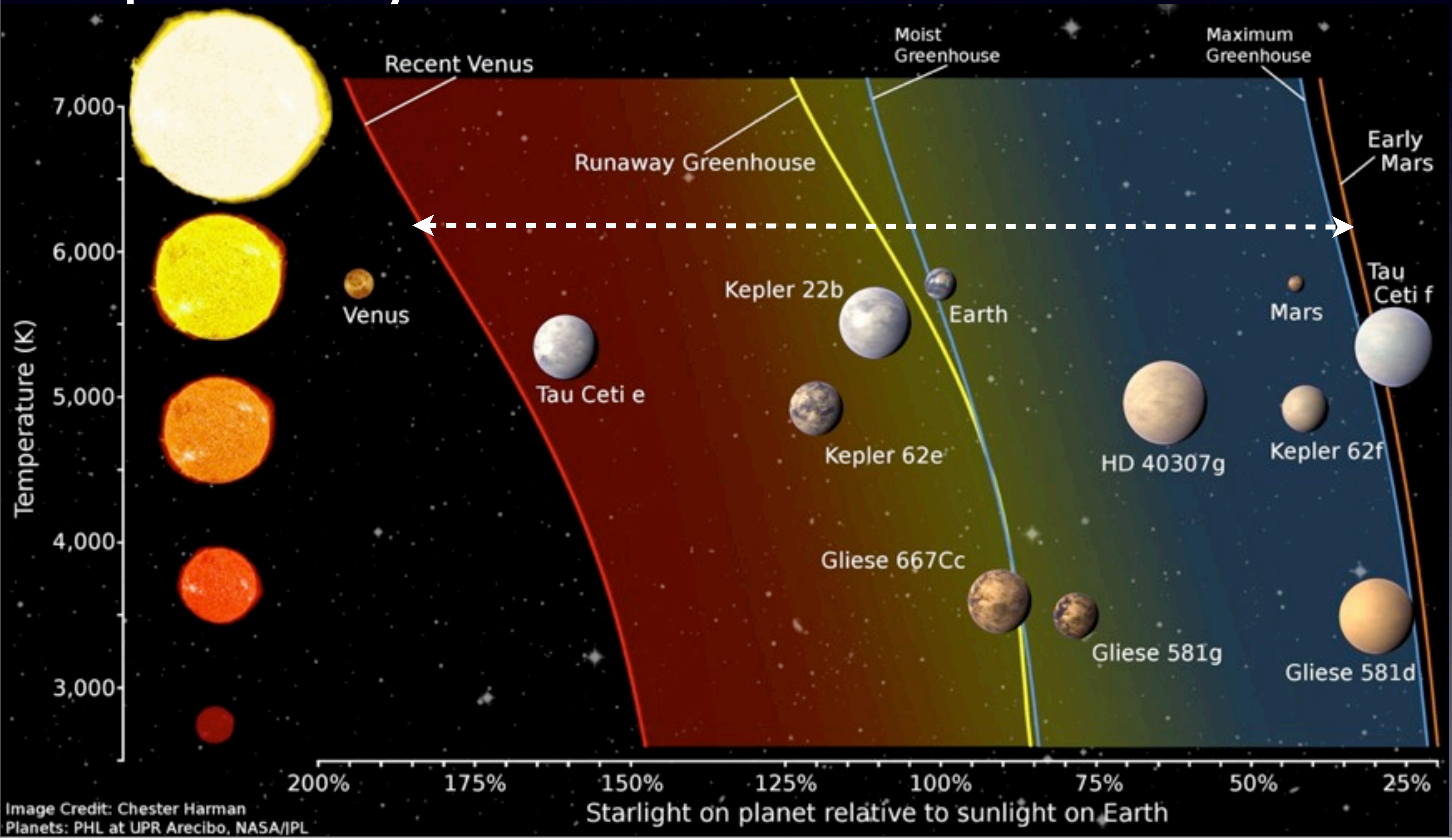
- Both conservative and optimistic estimates are useful, but for different purposes.
- A conservative estimate of the HZ means a conservative (lower) $\eta_{\oplus}$ estimate, so more target stars (N_{stars}) need to be searched to find expected number of planets ($N = \eta_{\oplus} \cdot N_{stars}$)
- A larger N_{stars} means observing at larger distances, so probably a bigger telescope is needed.
- If this conservative estimate of $\eta_{\oplus}$ is larger than previous estimates of ~ 0.1 from TPC STDT, then a telescope < 8m may suffice.

Which $\eta_{\oplus}$ limits to use?

- A TPF-C like mission also needs to distinguish the light from the planet and exozodi. TPF STDT suggested a minimum telescope diameter of 4m based on Solar System exozodi levels.
- An accurate estimate of $\eta_{\oplus}$ for F, G, K-stars can give a more precise answer on the size of the telescope
- Traub(2012) *conservative* estimate of $\eta_{\oplus}$ for G-stars ~0.25 from 136 days of Kepler data (This estimate is more than twice the TPF STDT value of 0.1 for an 8m telescope)

Which $\eta_\oplus$ limits to use?

- Once a telescope size is determined, an optimistic estimate of the HZ should be used to not miss any potentially habitable worlds.



η_{Earth} for M/late-K stars

- Earth size (0.5 – 1.4 R_{Earth}): $0.15^{+0.13}_{-0.06}$ Dressing & Charbonneau (2013)

- Earth size (0.5 – 1.4 R_{Earth}): $0.48^{+0.12}_{-0.24}$ (Conservative)

  $0.53^{+0.08}_{-0.17}$ (Optimistic)

- Earth size (0.5 – 2.0 R_{Earth}): $0.51^{+0.10}_{-0.20}$ (Conservative)

  $0.61^{+0.07}_{-0.15}$ (Optimistic)

  Kopparapu (2013)

- Earth size (0.8-2.0 R_{Earth}): $0.46^{+0.18}_{-0.15}$ (Optimistic) ***Gaidos (2013)***

- **Bonfils et al.(2011)** radial velocity optimistic estimate: $0.41^{+0.54}_{-0.13}$

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In summary

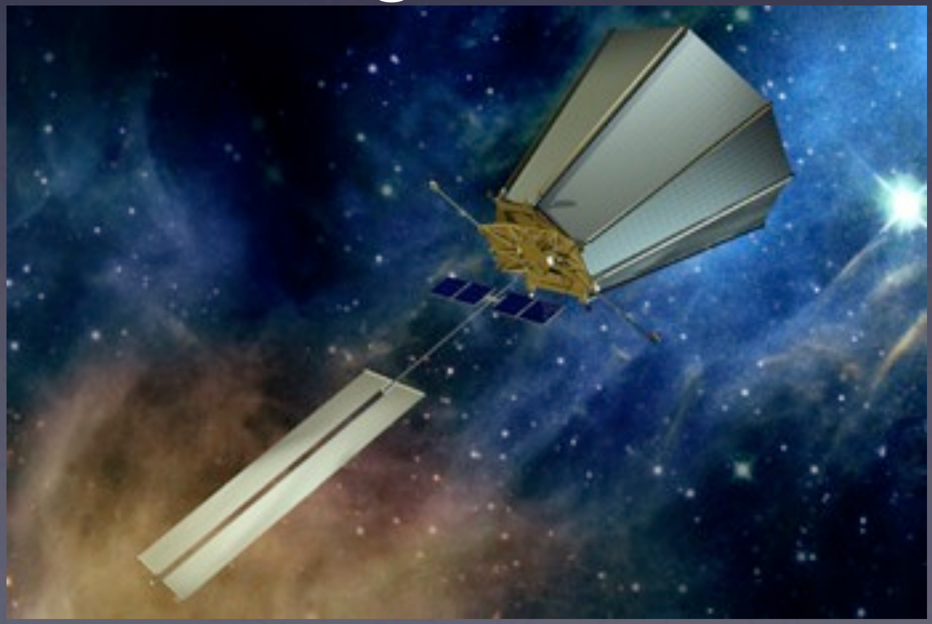
- Why do we need to know $\eta_{\oplus}$?

•One of the main goals of *Kepler* mission is to determine $\eta_{\oplus}$. What do we do with that number?

•To determine the size of a direct imaging telescope we need to build.

•To find out the number of stars that we need to search for potentially habitable planet(s)

But one has to be careful about not overestimating $\eta_{\oplus}$.



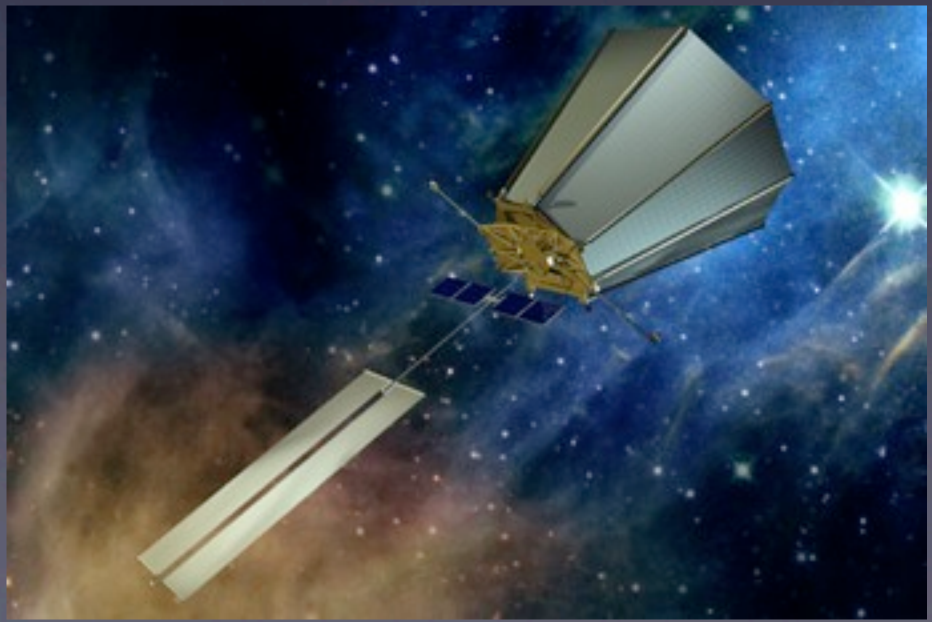
In summary

- How do we define $\eta_\oplus$?

•Conservative estimates can be used for the design of the telescope so that it is not undersized
•Optimistic estimates are upper limits on the frequency of potential habitable planets.

Provide upper and lower bounds of $\eta_\oplus$

Recent analysis of *Kepler* data suggests that $\eta_\oplus$ for M/late-K stars is in the 0.4-0.5 range.



Analysis of longer dataset is critical in deriving a more accurate estimate for F, G stars

- Online Habitable Zone calculator:
- http://www3.geosc.psu.edu/~ruk15/planets/

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

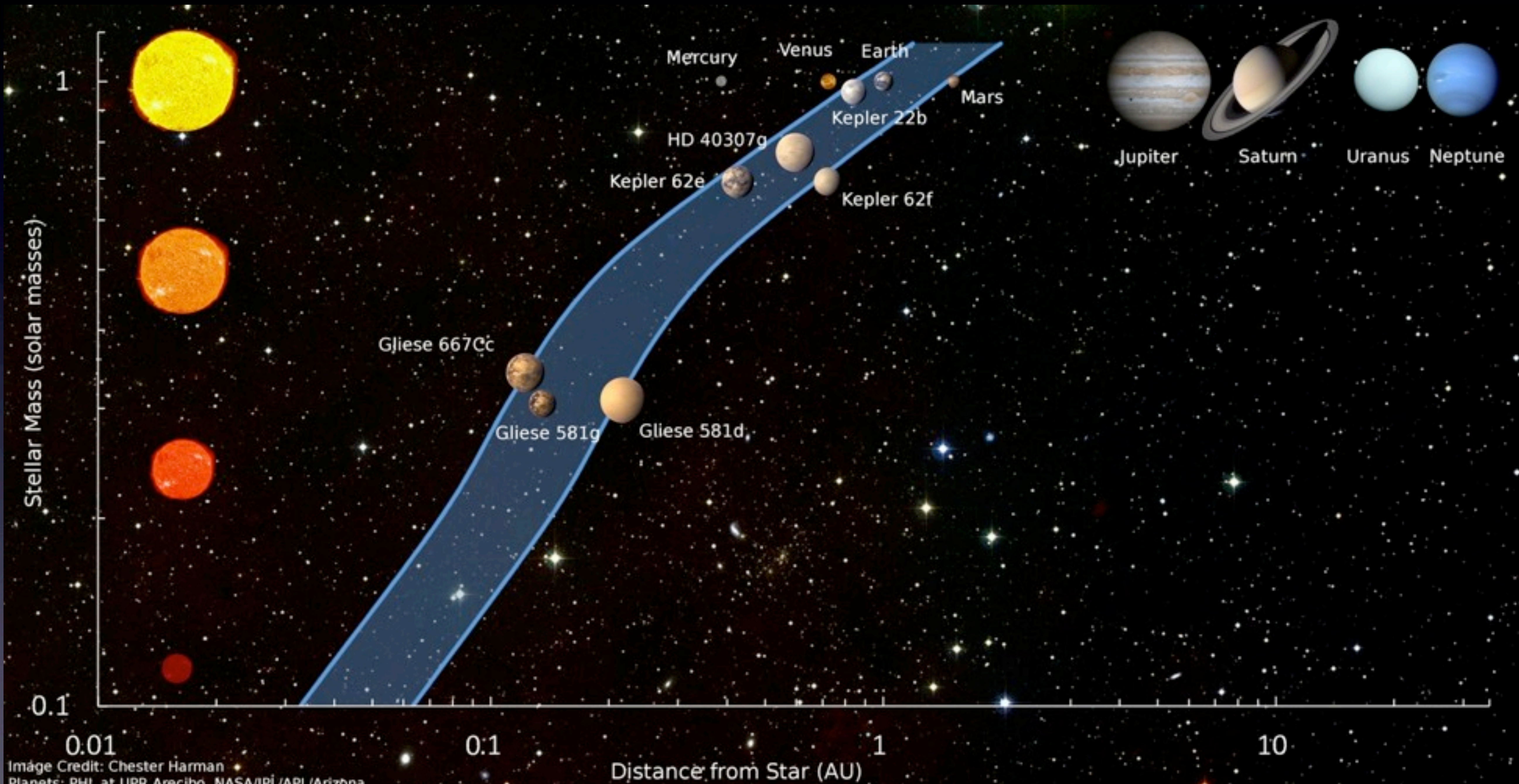
Optimistic habitable zone limits	***Stellar flux compared to the Sun***	***HZ distance from the star (AU)***
Inner HZ - Recent Venus limit	1.7763	0.7503
Outer HZ - Early Mars limit	0.3207	1.7658

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

Revised Habitable Zones
(ZAMS)



•Note that the HZ is ~21% wider for M stars than for G stars. This is because Rayleigh scattering by CO2 is important near the outer edge