Climate Limit Cycling and Implications for Exoplanet Habitability

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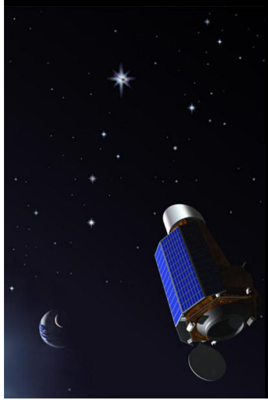

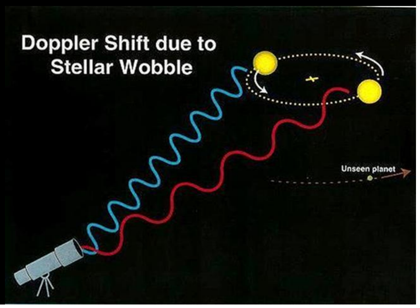

Exoplanets and "Big Data"

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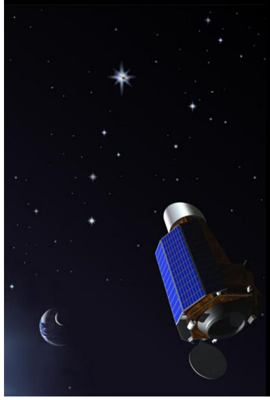
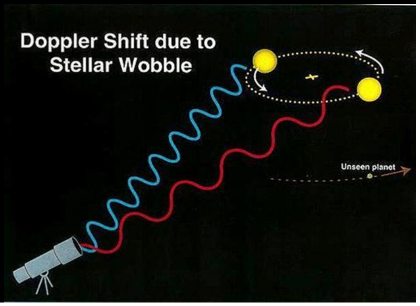




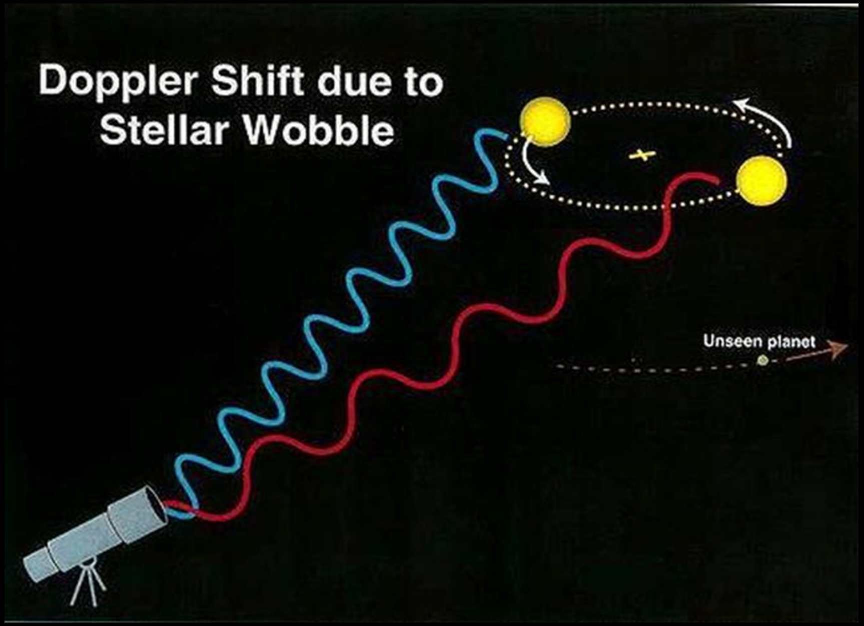
Talk outline

- Part 1: Introduction to exoplanet detection methods and the Kepler dataset
  - This is where "Big Data" comes in
- Part 2: (Very brief) The liquid water habitable zone
- Part 3: (Also brief) The future of exoplanet exploration

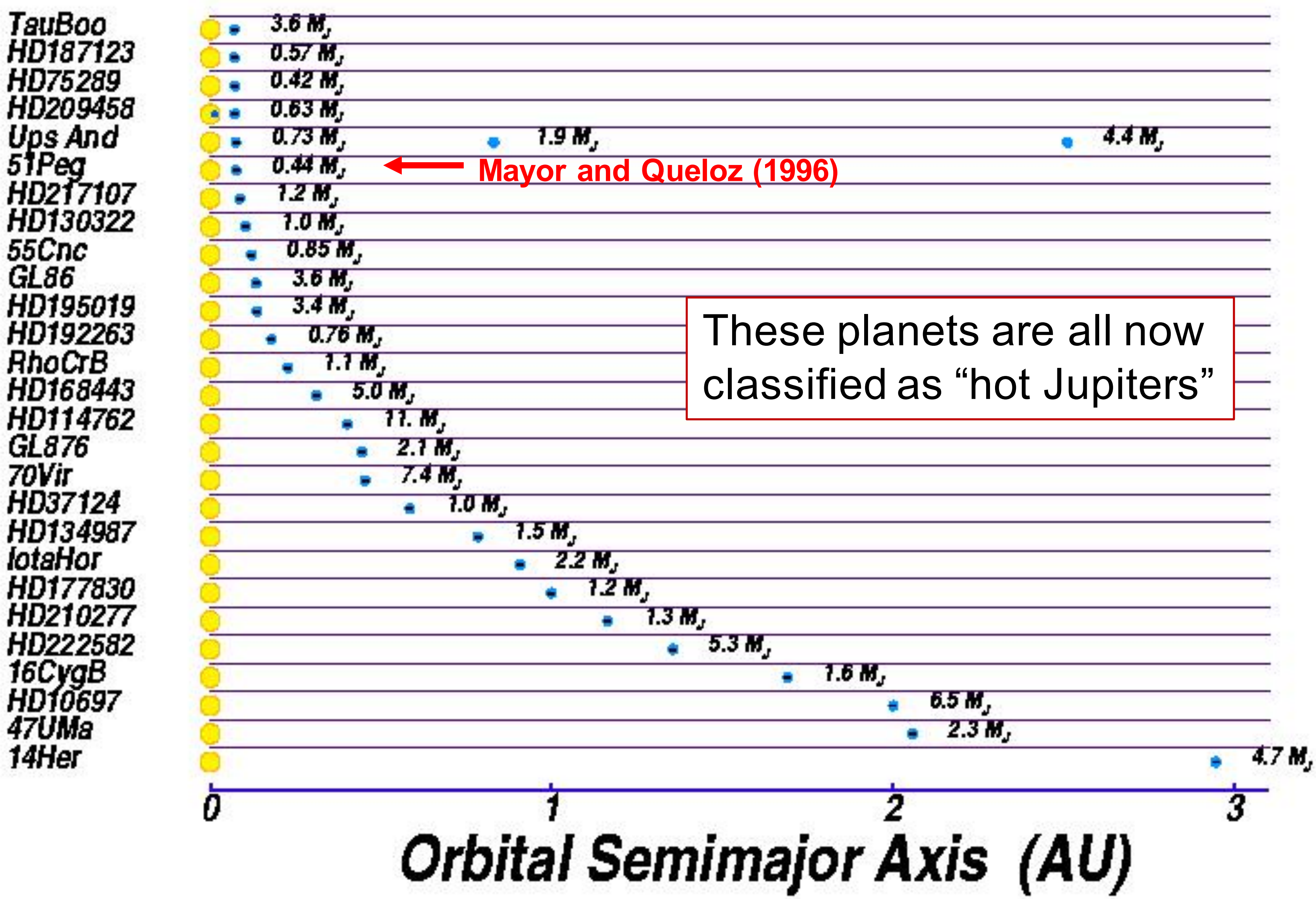
Part 1: Exoplanet detection methods

The radial velocity (Doppler) method

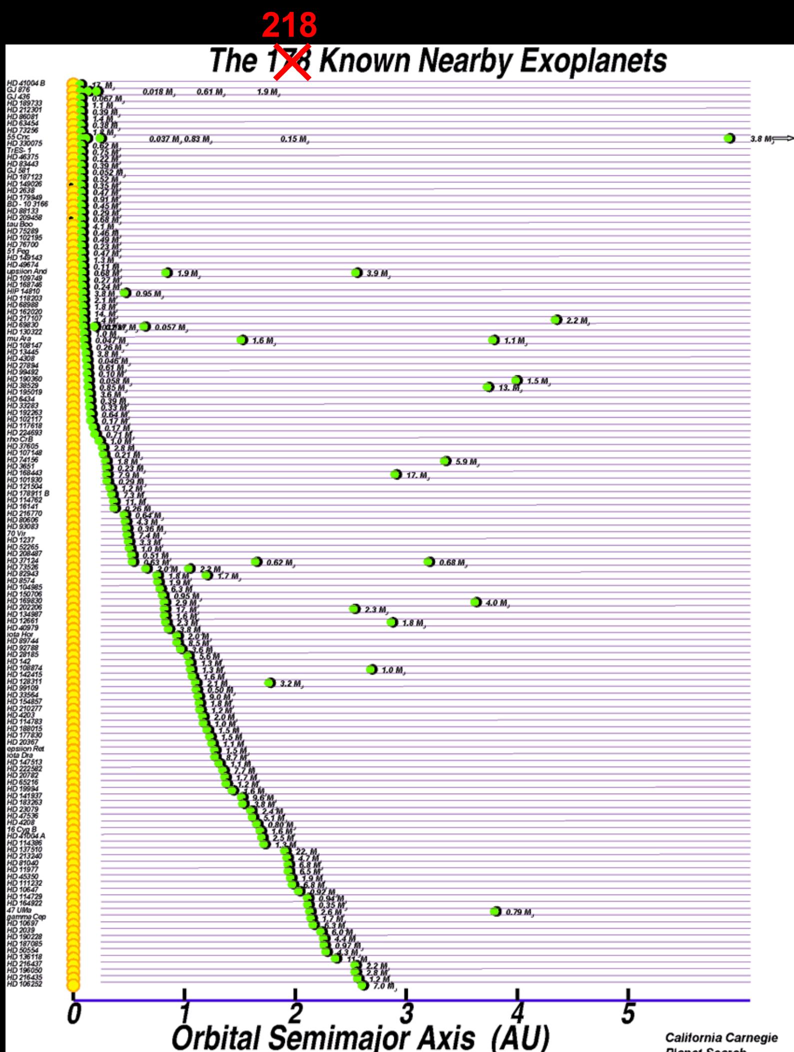
- Up until 2009, most exoplanets were found using the radial velocity (or Doppler) method
- The first such exoplanet, 51 Peg b, was discovered by Michel Mayor and Didier Queloz in 1996
- This method yields only a minimum mass for the planet because the orbital inclination is generally unknown



G. Marcy and P. Butler
(circa 2002)



Known extrasolar planets



http://exoplanets.org/massradiiframe.html

- 218 extrasolar planets identified as of April 4, 2007
  - 206 by radial velocity
  - 4 microlensing
  - 4 direct imaging
  - 4 pulsar planets
  - 20 multiple planet systems
- None of these planets are very interesting, however, from an astrobiological standpoint

Info from *Extrasolar Planets Encyclopedia* (Jean Schneider, CNRS)

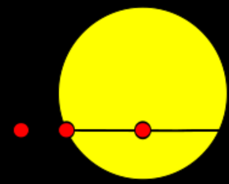
Kepler Mission

- This space-based telescope will point at a patch of the Milky Way and monitor the brightness of ~160,000 stars, looking for *transits* of Earth-sized (and other) planets
- 10^{-5} precision *photometry*
- 0.95-m aperture capable of detecting Earths
- Launched: March 5, 2009
- Died (mostly): April, 2013

http://www.nmm.ac.uk/uploads/jpg/kepler.jpg

Transit method

- The light from the star dims if a planet passes in front of it
- Jupiter's diameter is 1/10th that of the Sun, so a Jupiter transit would diminish the sunlight by 1%
- Earth's diameter is 1% that of the Sun, so an Earth transit decreases sunlight by 1 part in 10^4
- The plane of the planetary system must be favorably oriented
  - Transit probability is R_*/a, where R_* is the star's radius and a is the planet's orbital distance
  - Transit probability for our own Earth is 0.5%



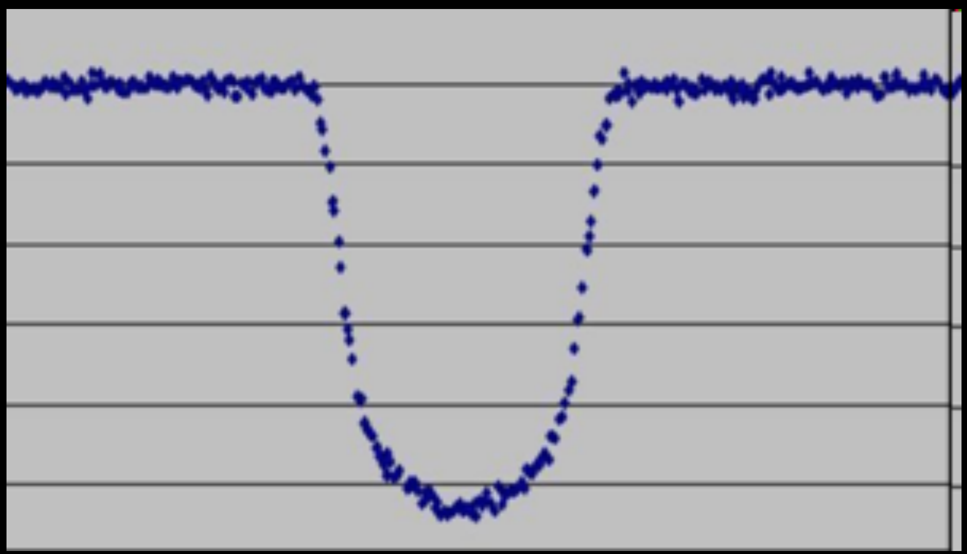
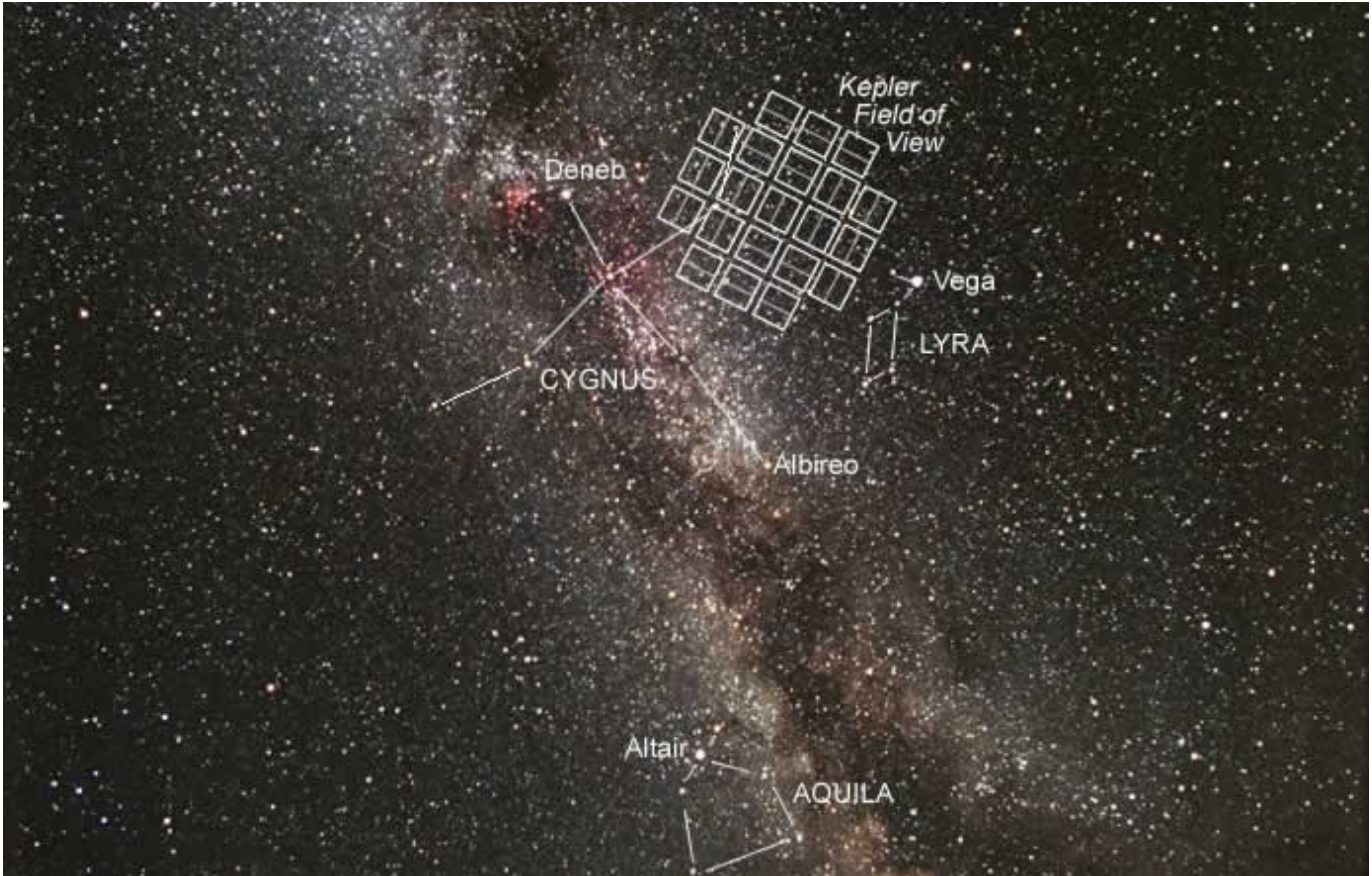


Image from Wikipedia

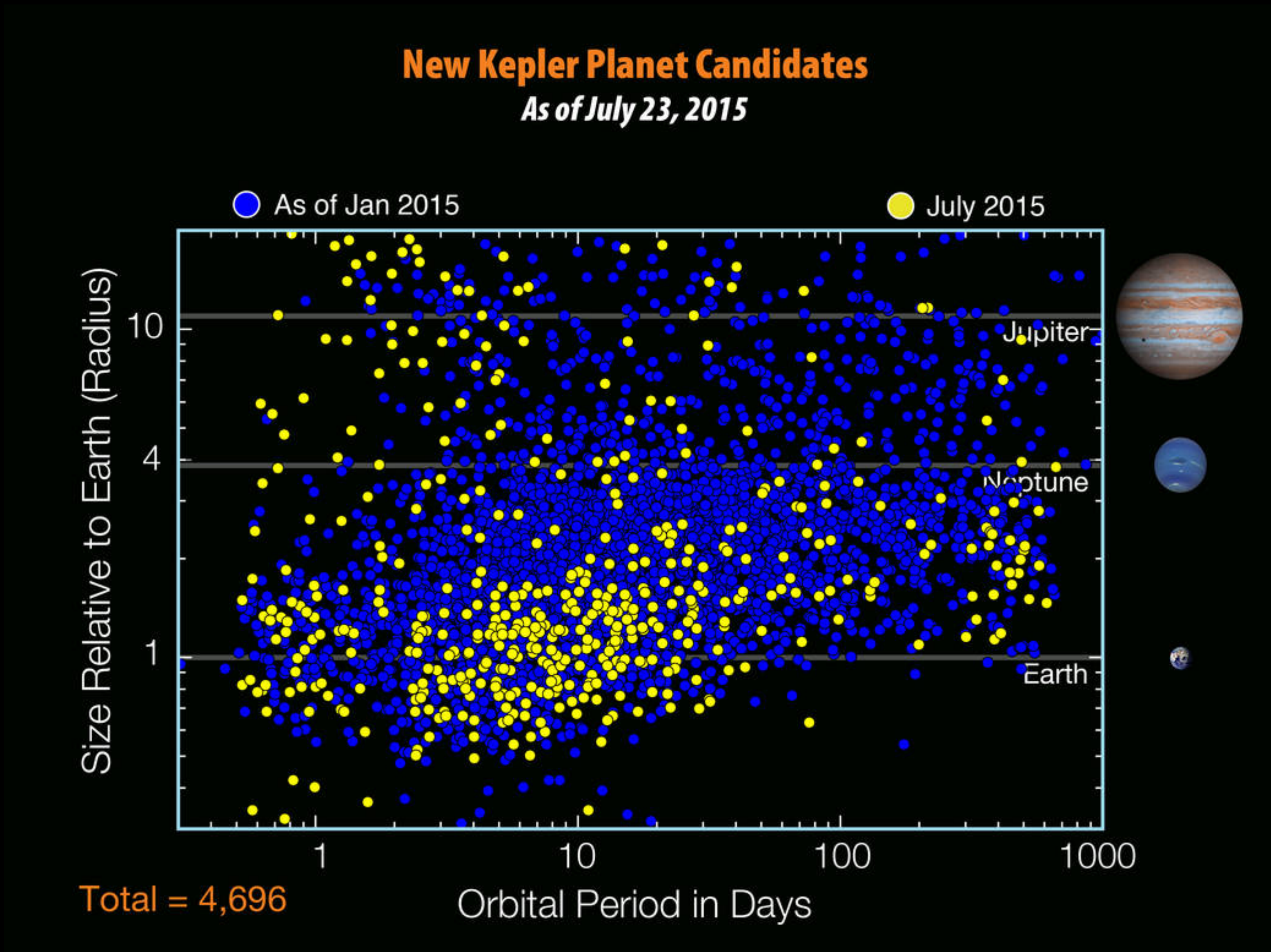


Kepler target field: The stars in this field range from a few hundred to a few thousand light years in distance

Kepler and 'Big Data'

- Kepler monitored 160,000 stars for 4 years with a long-cadence interval of ~30 minutes
- The number of data points is thus: 160,000 stars $\times$ 4 yr $\times$ 525,600 min/yr / 30 min $\approx 1.1 \times 10^{10}$, or 11 billion
- This was enough to do some pretty impressive statistics on exoplanets

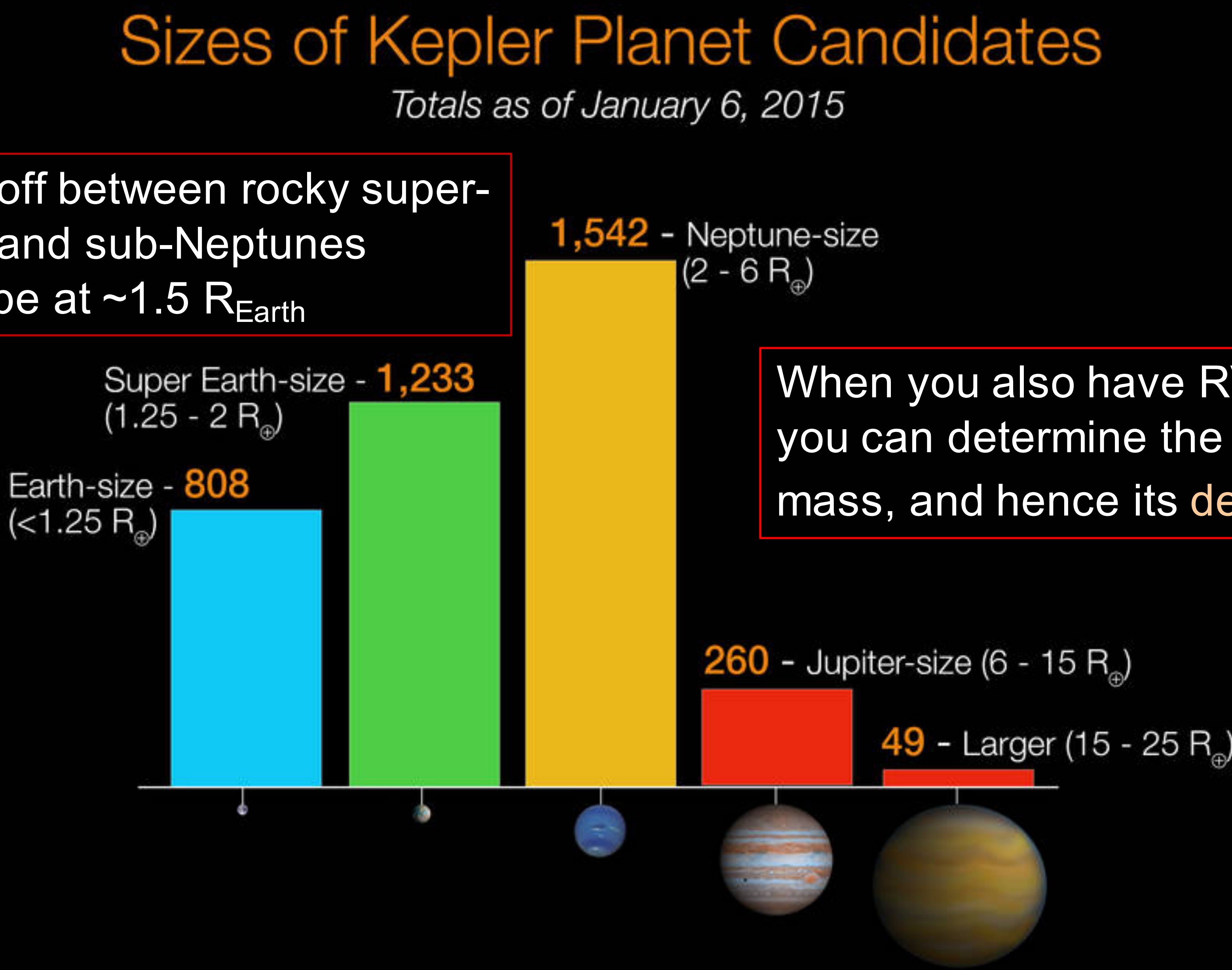
http://www.nmm.ac.uk/uploads/jpg/kepler.jpg



- 4,696 planet candidates; 2,325 confirmed (as of May, 2016)
- More than ¾ of the exoplanets observed by Kepler have sizes between Earth and Neptune, and hence are not represented in our own Solar System

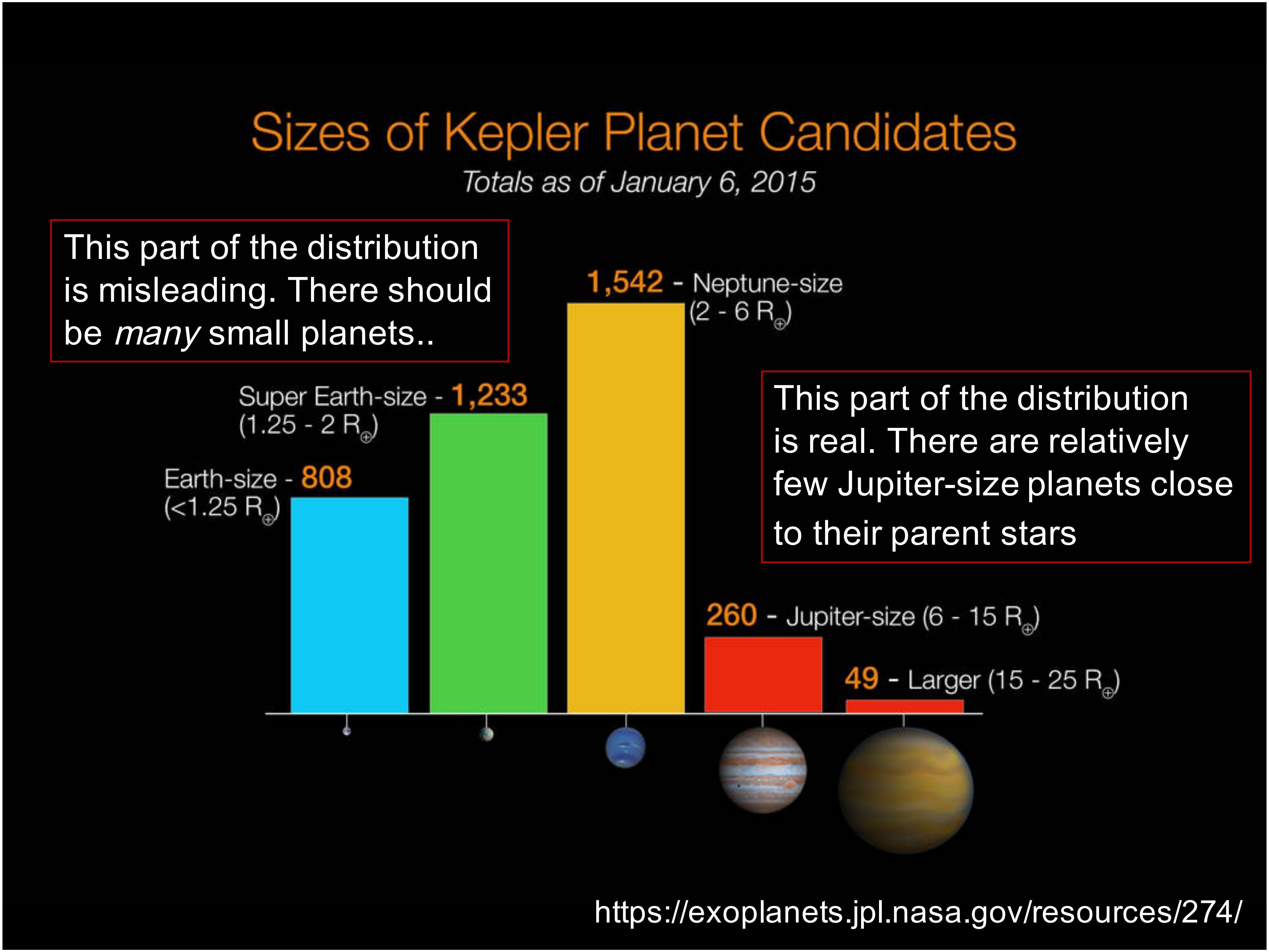
http://www.nasa.gov/mission_pages/kepler/news/kepler-461-new-candidates.html

The cutoff between rocky super-Earth's and sub-Neptunes should be at ~1.5 R_{Earth}



When you also have RV data, you can determine the planet's mass, and hence its density

https://exoplanets.jpl.nasa.gov/resources/274/



Sizes of Kepler Planet Candidates
Totals as of January 6, 2015
This part of the distribution is misleading. There should be *many* small planets..
1,542 - Neptune-size (2 - 6 R⊕)
Super Earth-size - 1,233 (1.25 - 2 R⊕)
Earth-size - 808 (<1.25 R⊕)
This part of the distribution is real. There are relatively few Jupiter-size planets close to their parent stars
260 - Jupiter-size (6 - 15 R⊕)
49 - Larger (15 - 25 R⊕)
https://exoplanets.jpl.nasa.gov/resources/274/

Estimates for η_{Earth}

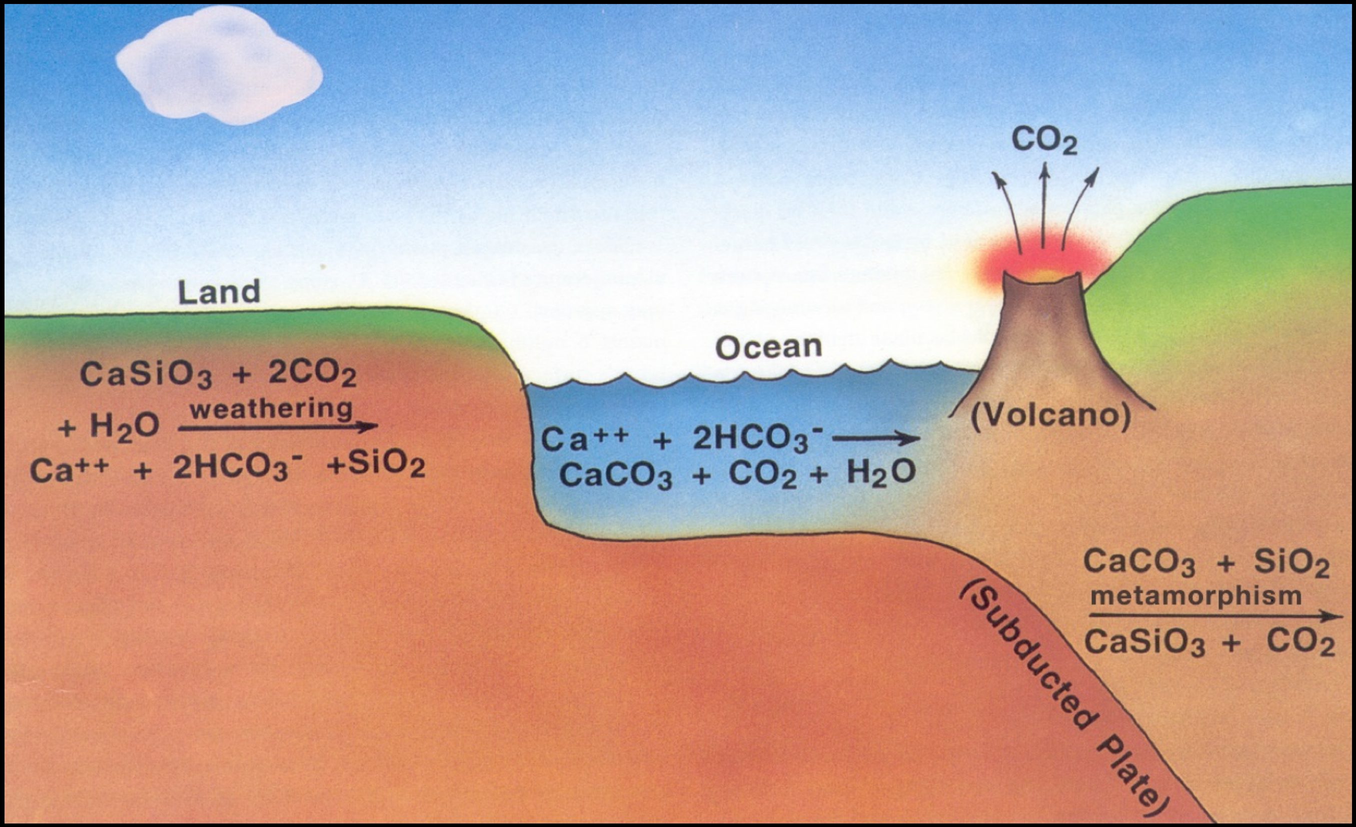
- η_{Earth}—the fraction of stars that have at least one rocky planet in their *habitable zone*
  - Measuring η_{Earth} turned out to be more difficult than anticipated for Kepler because most G stars are more active than the Sun
  - Best estimate for η_{Earth} from Kepler is ~0.15 (N. Batalha, unpublished)

- Part 2: The liquid water habitable zone

Boundaries of the habitable zone (HZ)

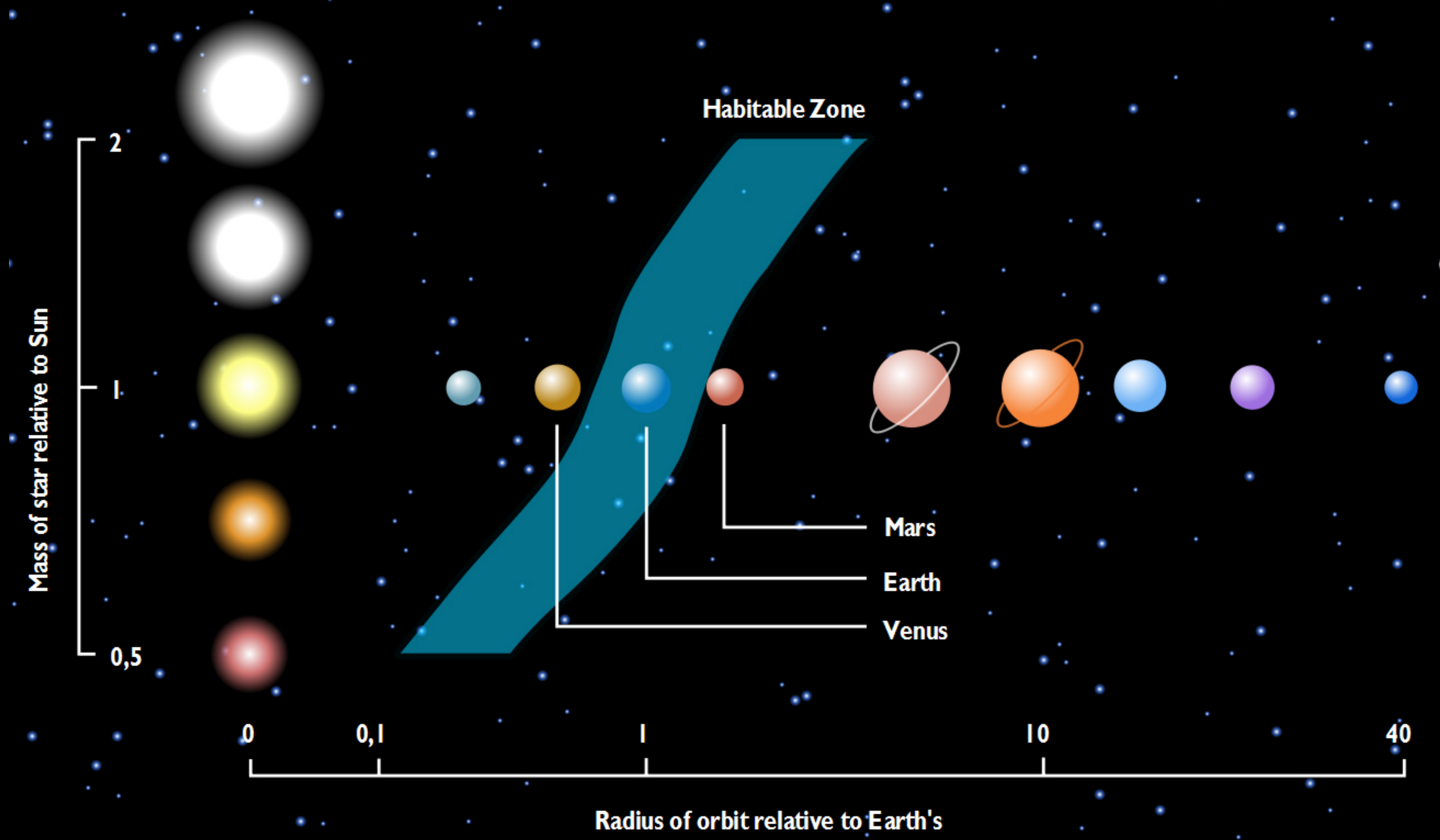
- Inner edge is determined by loss of water via runaway or moist greenhouse effect
  - 'Moist greenhouse' is when the stratosphere becomes wet even though an ocean is still present
- Outer edge is determined by the point at which CO_2 condensation/Rayleigh scattering begin to overwhelm the CO_2-H_2O greenhouse effect
  - We call this the 'maximum greenhouse' limit

The carbonate-silicate cycle



- The habitable zone is relatively wide because of negative feedbacks in the carbonate-silicate cycle: Atmospheric CO_2 should build up as the planet cools
- Higher CO_2 is also at least part of the problem to the faint young Sun problem on Earth

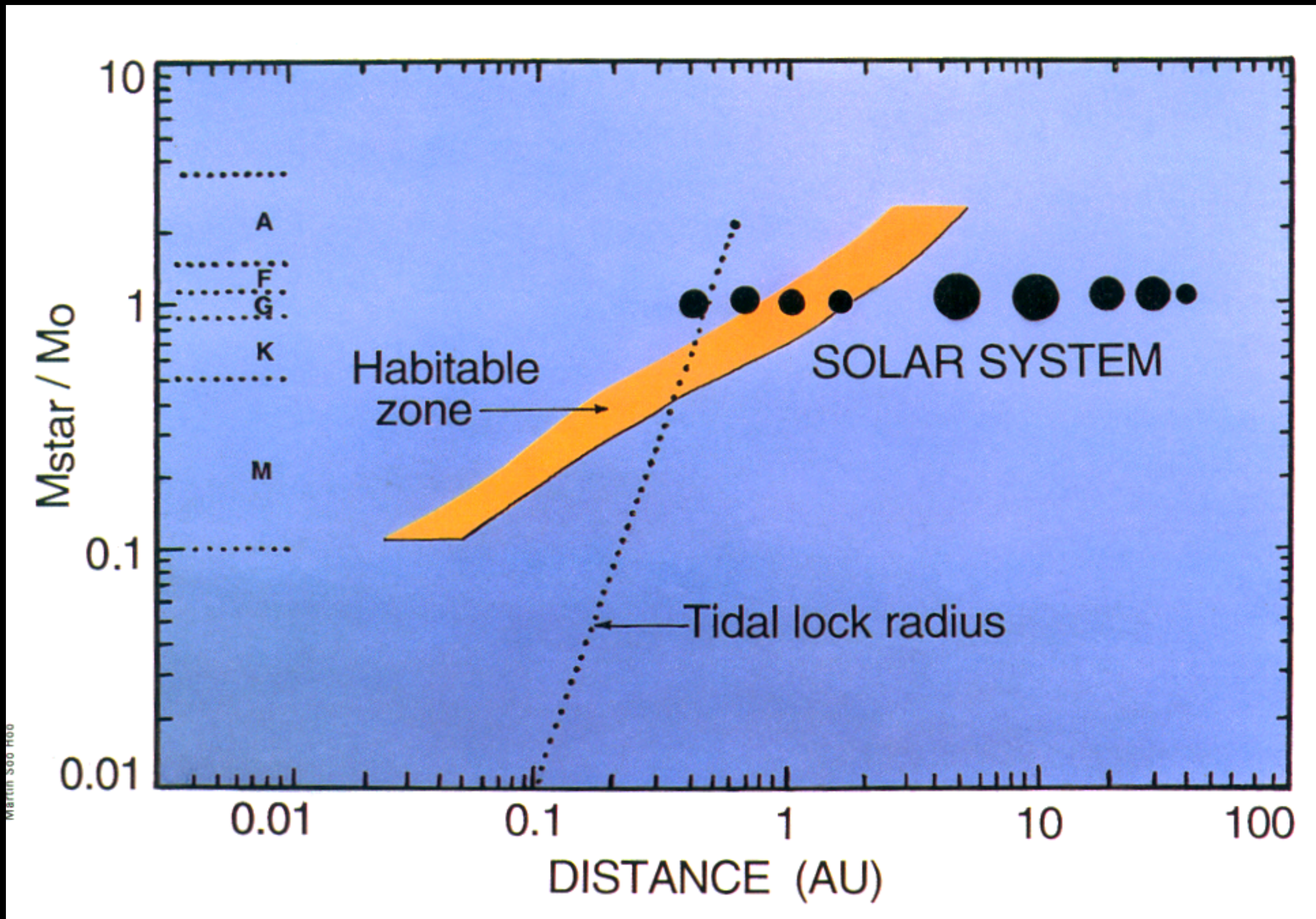
The ZAMS habitable zone



- When CO_2-climate feedback is taken into account, one gets a habitable zone that is fairly wide compared to the mean planetary spacing
- Figure applies to zero-age-main-sequence stars; the HZ moves outward with time because all main sequence stars brighten as they age

Diagram adapted from J. F. Kasting et al., Icarus (1993)

ZAMS habitable zones



- Older diagram: Not quite as pretty as the other one, but it illustrates the tidal locking problem for planets around late K and M stars

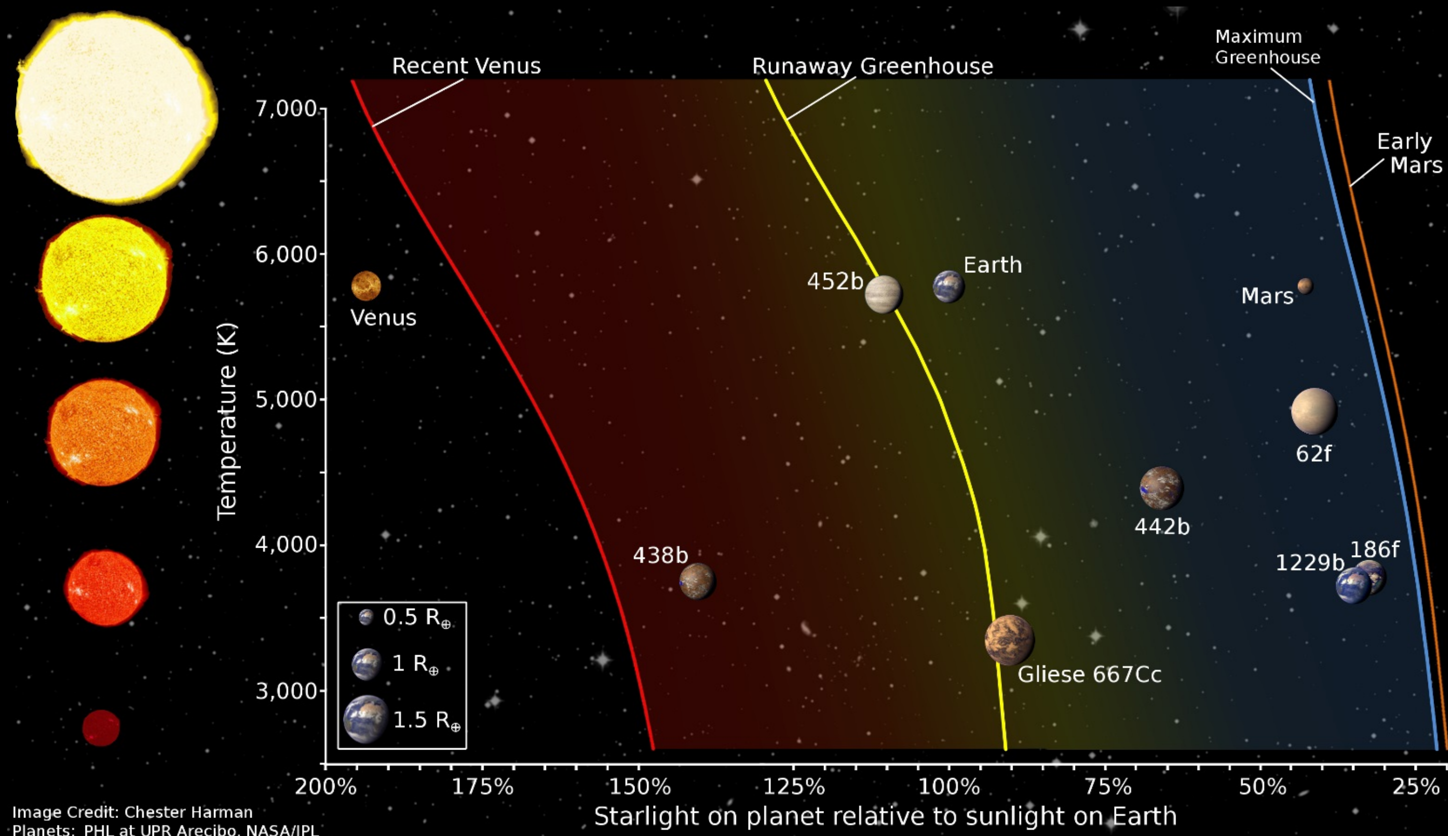
Kasting et al., *Icarus* (1993)

Recent improvements to models of the habitable zone

- My students, Ravi Kopparapu, Ramses Ramirez, and others have refined and extended these original HZ calculations
- Colin Goldblatt (U. Victoria) showed that new H_2O absorption coefficients (from HITEMP, rather than HITRAN) make a big difference in warm, moist atmospheres, moving the inner edge outwards
- Recent studies show that 3-D climate modeling leads to new insights
  - Leconte et al. (Nature, 2013) showed that the inner edge moves inwards because of 'radiator fin' behavior of the tropical Hadley cells (an idea borrowed from Ray Pierrehumbert)
  - Yang et al. (Ap.J., 2013) showed that the inner edge moves way inwards for tidally locked planets orbiting M stars because they become nearly 100% cloud-covered on their daysides

Updated habitable zone

(Kopparapu et al., 2013, 2014)



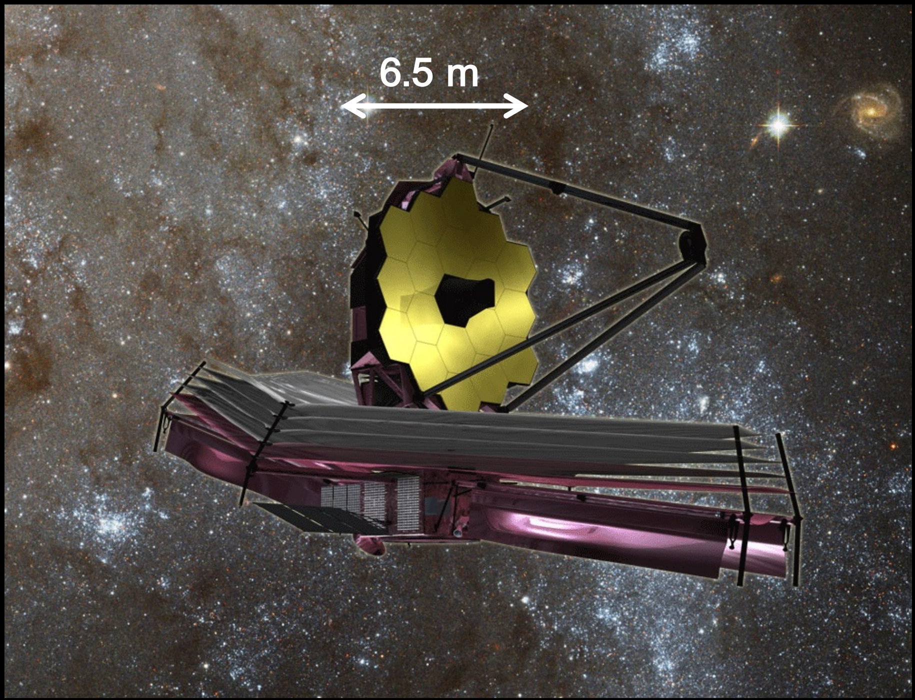
- Note the change in the x-axis from distance units to stellar flux units. This makes it easier to compare where different planets lie
- The exoplanets represent objects identified either by ground-based RV measurements or by NASA's Kepler Space Telescope (using transits)

Figure credit: Sonny Harman

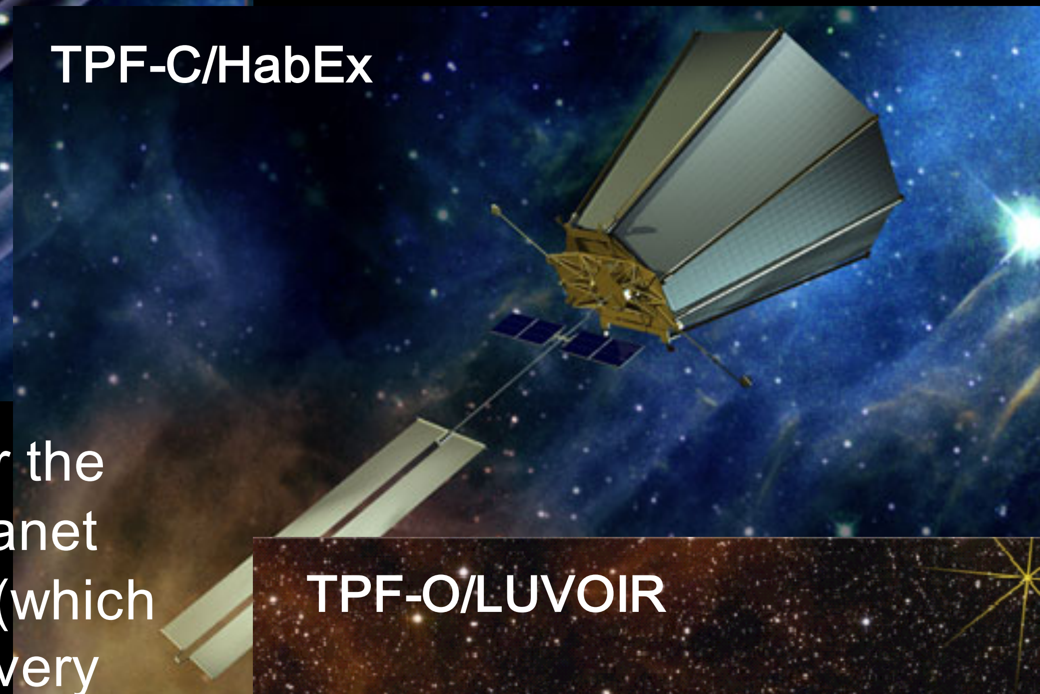
- Part 3: The future of exoplanet exploration

JWST and TESS

- NASA's James Webb Space Telescope, scheduled for launch in 2018, could in principle characterize Earth-size planets using transit spectroscopy
  - NASA's TESS mission, which launches in 2017, will look for transiting habitable zone planets around nearby stars in hopes of providing targets for JWST
- In practice, characterizing Earth-size planets is a scientific long-shot
- We want instead to look for non-transiting planets using *direct imaging..*



NASA's James Webb Space Telescope



- Direct imaging means looking for the light reflected or emitted by a planet when it is beside its parent star (which is hard to do because stars are very bright, and planets are dim)
- Such missions have been studied previously under the name of TPF (Terrestrial Planet Finder)
- With such a telescope, we could also look for spectroscopic biomarkers (O_2, O_3, CH_4) and try to infer whether life is present on such planets

Conclusions

- The Kepler dataset has produced a quantum leap in our knowledge of exoplanets
  - We now know that planets are common
- The habitable zone is relatively wide because of the negative feedback between CO_2 and climate
  - (Not discussed) Habitable zones for complex (animal) life may be narrower because of limit cycling behavior in the outer regions of the HZ
- JWST *may* provide spectra of transiting Earth-like planets within the next few years
- In the not-too-distant future (~20 years), we hope to find and characterize Earth-sized planets around nearby stars using direct imaging

- Backup slides

- *But,* this analysis overlooks a phenomenon that *could* have been important on early Earth and that *should* be important on at least some Earth-like planets around other stars…

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Climate stability of habitable Earth-like planets

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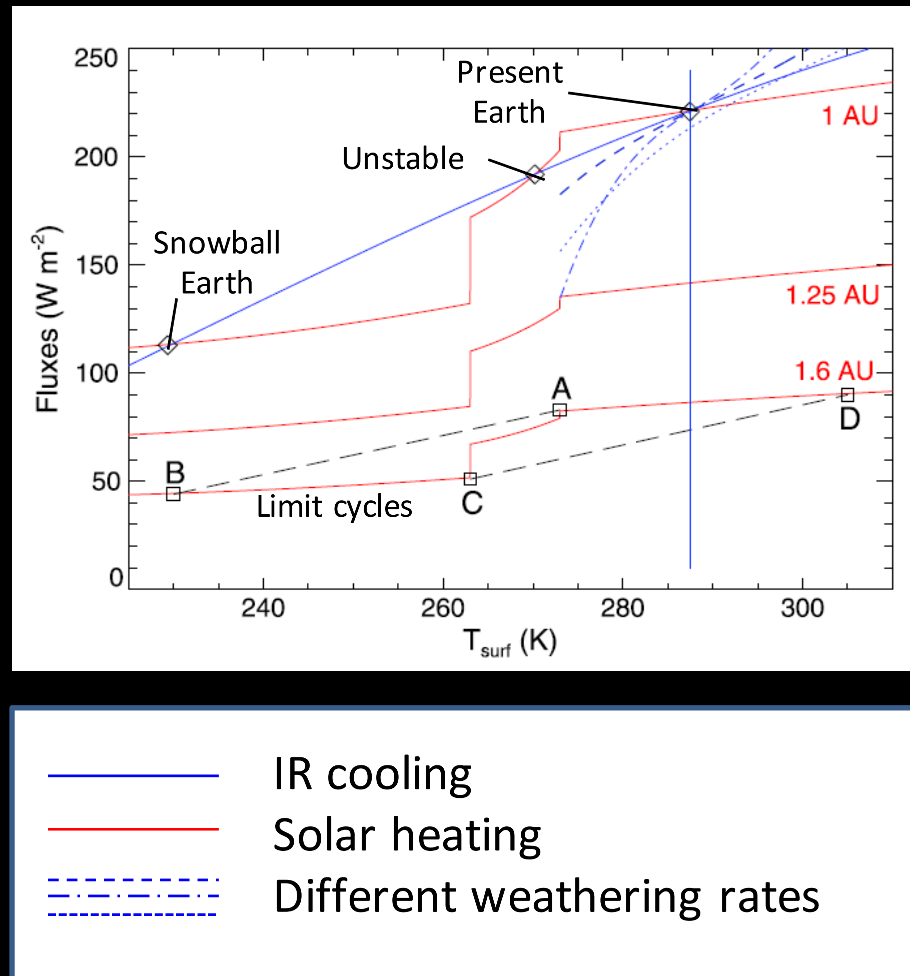
- A new paper by Kristen Menou shows that planets near the outer edge of the habitable zone should *not* have stable, warm climates, despite the influence of the carbonate-silicate cycle. Rather, they are predicted to undergo climate limit cycles, alternating between globally glaciated and ice-free states
- Surface temperature (T_S) and pCO_2 are coupled in two ways:
  1. T_S depends on pCO_2 through the greenhouse effect
  2. pCO_2 depends on T_S via its effect on the silicate weathering rate
- See also Kadoya and Tajika (ApJ, 2014), along with earlier papers by Tajika, referenced therein

Limit cycles on poorly lit planets

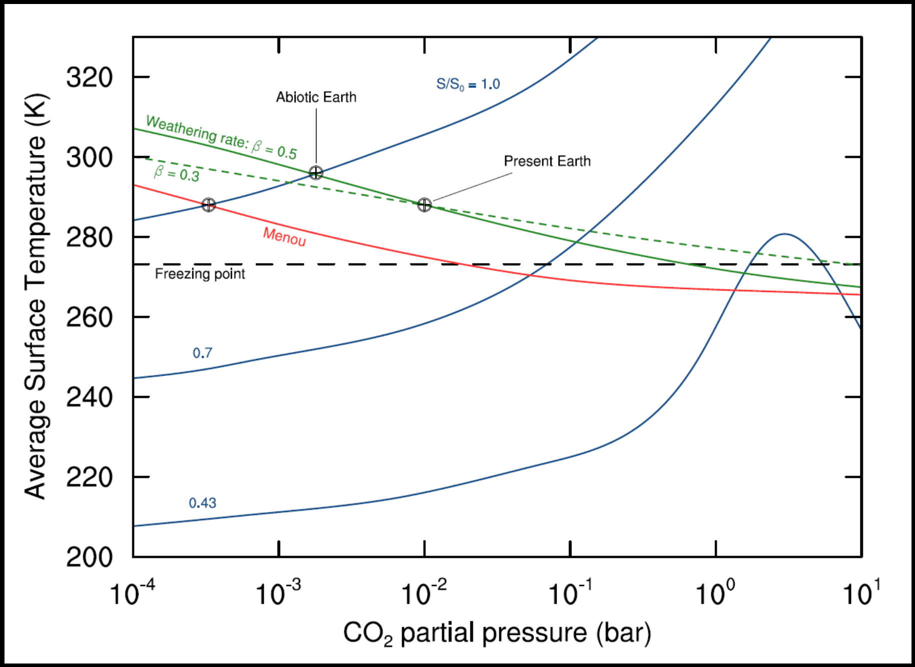
- An Earth-like planet at 1 AU from its parent star has a stable, warm climate state. Snowball climate states exist, but they go away because of volcanic CO_2 buildup
- An Earth-like planet at 1.6 AU has *no* stable states but, rather, cycles between warm and cold (Snowball) climate states



K. Menou, EPSL (2015)

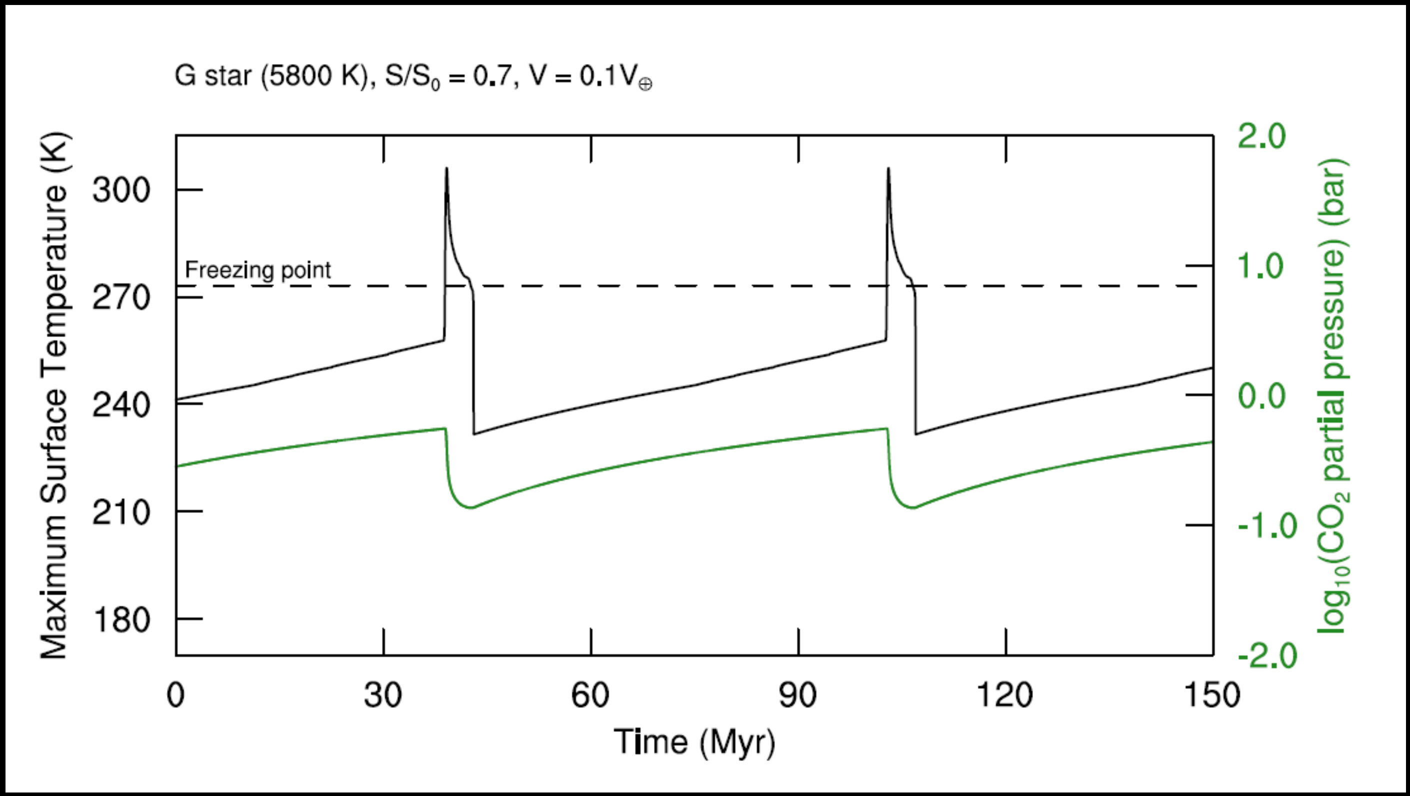
Our new limit cycle figure

- We have tried to illustrate this behavior in a different way
  - Stable climate states are achieved when the surface temperature curves (green and red) intersect the weathering rate curve *above* the freezing point of water
  - Limit cycles are predicted when the intersection occurs *below* the freezing point



Haqq-Misra et al., ApJ, submitted

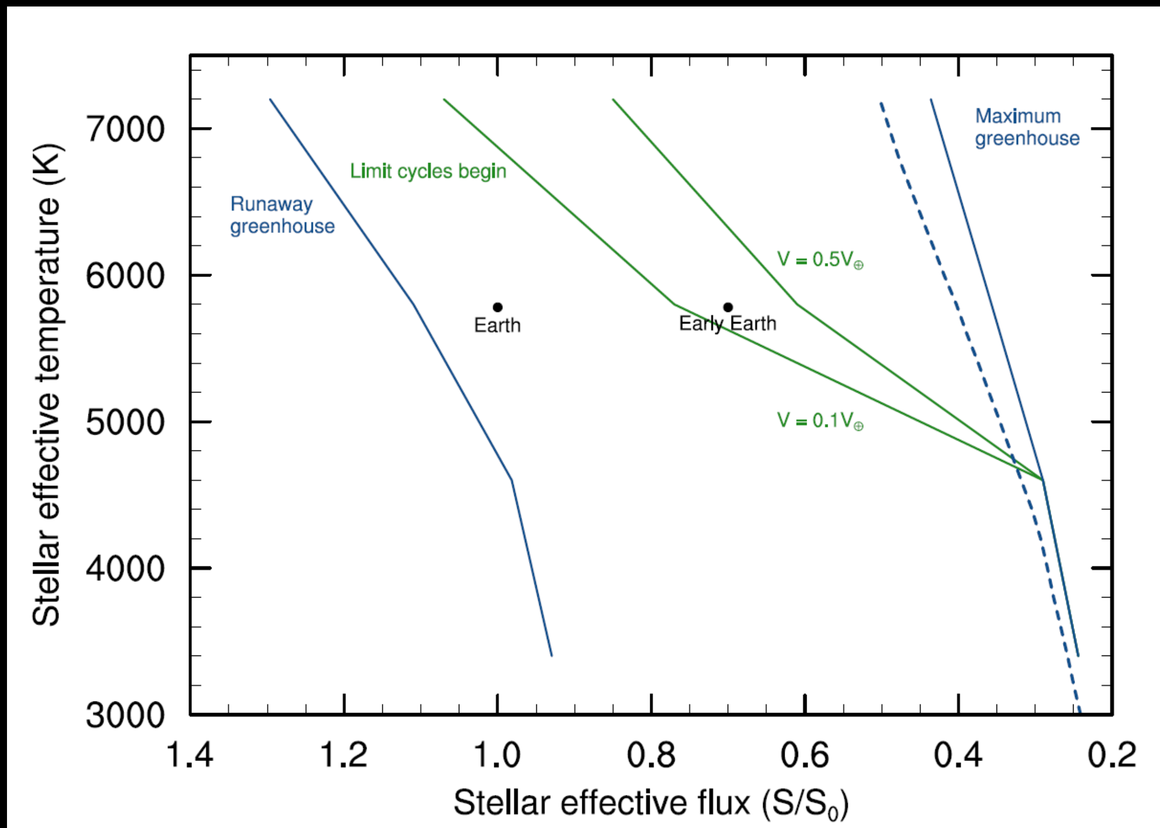
Example of a limit cycle



Haqq-Misra et al., ApJ, submitted

- This shows limit cycling behavior in our model for a planet orbiting a G star with 70% of current solar luminosity and a low volcanic outgassing rate (0.1 times Earth's value)
- T_{surf} represents the maximum surface temperature, which occurs in the tropics in this model

Limit cycling near the HZ outer edge

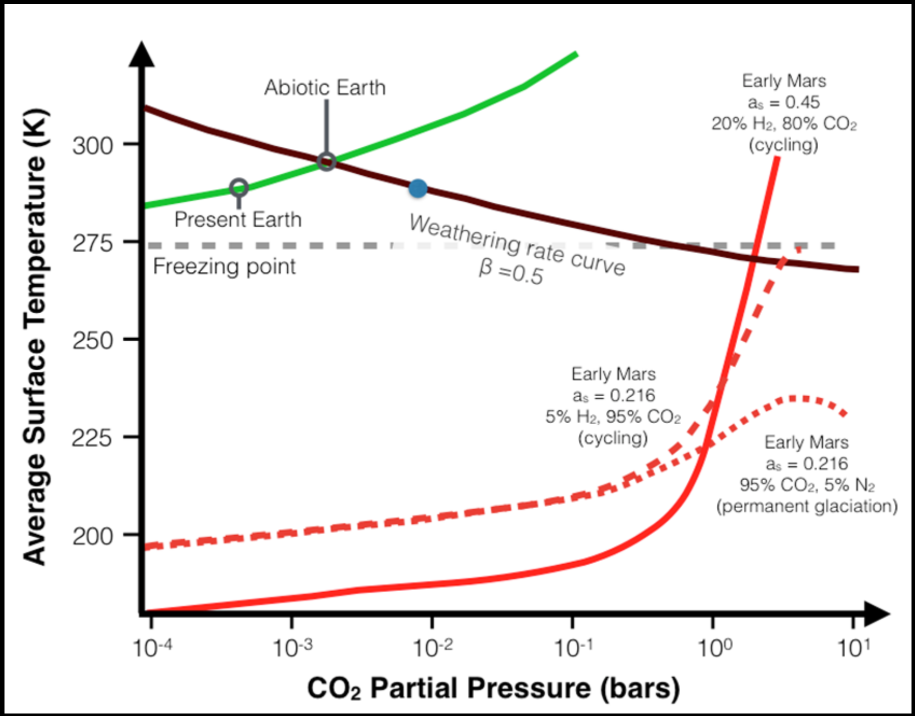


- Bottom line: Limit cycles only occur in our model for planets with low volcanic outgassing rates
- This phenomenon may still have implications for the existence of complex (animal) life, including intelligent life

Haqq-Misra et al., ApJ, submitted

Limit cycling on early Mars

- We think that early Mars may also have been in the limit cycling regime
- On early Mars, we need to supplement the greenhouse effect of CO_2 with H_2 to make it warm (Ramirez et al., Nature Geo., 2014)
- This paper is the latest addition to a longstanding debate about the climate on early Mars



Batalha et al., EPSL, submitted