Habitable Zones for Exomoons Around Exoplanets

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Why exomoons are important

(1) Mars-sized moons in the stellar HZs may be as common as terrestrial HZ planets, as suggested by observations of the *Kepler* telescope (see plot below).

(2) Detection methods are now able to find moons a few times the mass of Mars (0.1 $M_\oplus$) and as small as Ganymede (0.4 $R_\oplus$) in the *Kepler* data [1,2].

(3) Moons are likely tidally locked to their planets. They cannot be tidally locked to the star and thus avoid the danger of unstable atmospheres and climates.

(4) Moons give unprecedented insights into planet formation.

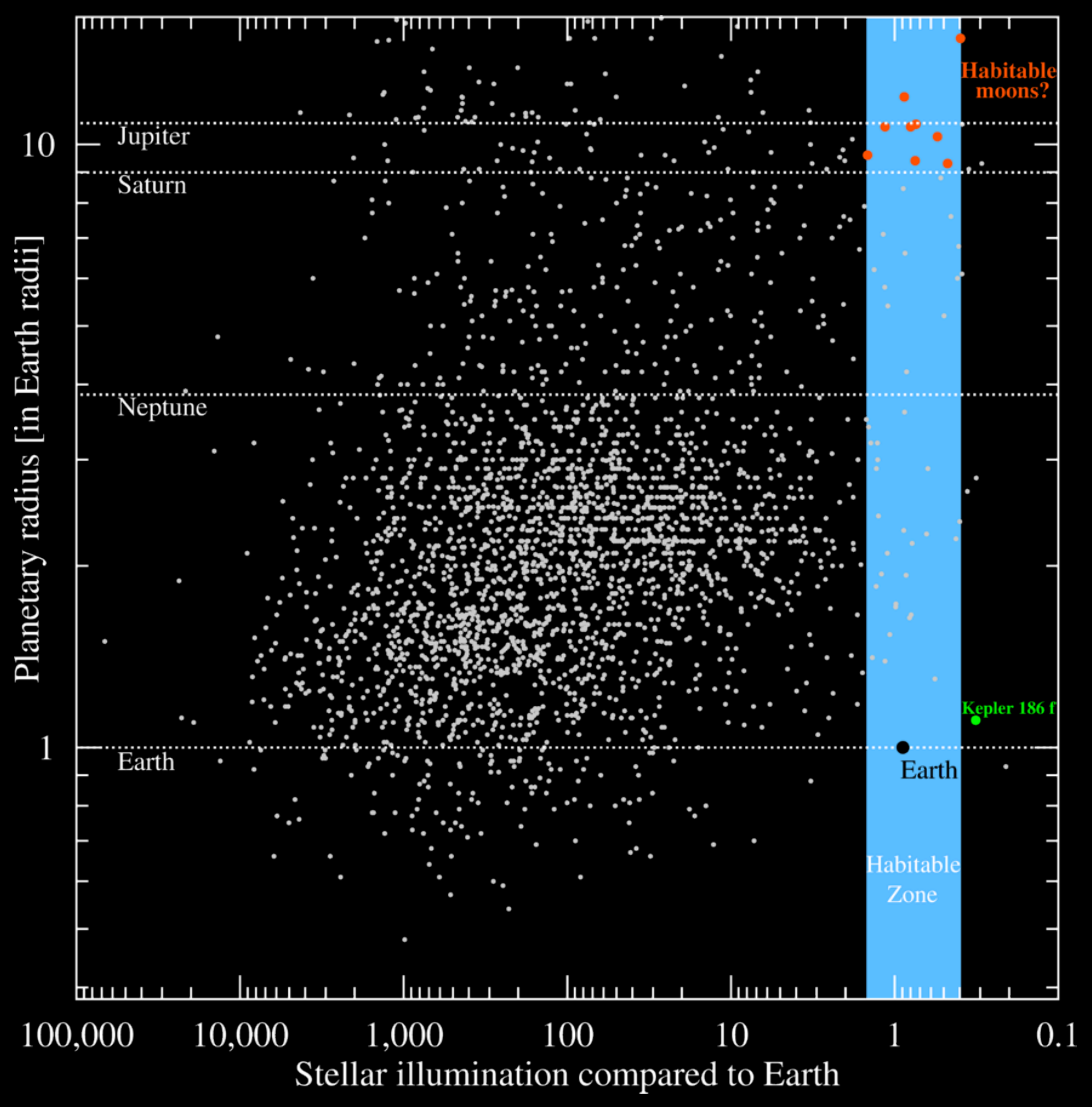

Figure 1 shows the radii and the stellar illumination for about 2700 out of the 3600 planet candidates detected by the *Kepler* telescope as of late 2013 [3]. About one hundred exoplanets and candidates have been discovered in the habitable zones (HZs) around their stars, most of which are substantially larger than Earth. While these planets are likely not habitable themselves, their moons might be. The blue stripe indicates the stellar HZ of FGKM dwarfs stars [4]. Orange dots in the HZ indicate super-Saturn candidates, which may be orbited by massive moons that formed in the circumplanetary disks.

Formation scenarios for habitable moons

Even the biggest moon in the solar system, Ganymede, has a mass of only ~0.025 $M_\oplus$. Yet, to hold a substantial atmosphere in the HZ, a terrestrial body needs at least the mass of Mars [5]. Such big moons might form around exoplanets via

(1) In-situ accretion in the disks around young giant planets. The total mass available for moon formation is ~10^{-4} times the planetary mass [6,7]. To form a Mars-mass moon, a planet with about 5 $M_{\rm Jup}$ is required (orange dots in Fig. 1).

(2) Capture: Massive planets several AU from their stars have large Hill spheres, in which they can capture by-passing objects into moons [8,9].

(3) Giant impacts: Projectiles and targets a few times the masses of Mars and Earth, respectively, might create scaled-up versions of the Earth-Moon binary. Mars-sized moons around super-Earths are a compelling scenario, given the high abundance of super-Earths (see Fig. 1 and note Kepler-186f).

Energy budgets on moons

Planetary habitability is mostly determined by stellar irradiation, which defines the stellar HZ. However, the moons of giant planets also receive

(1) stellar reflected light from the planet [10],

(2) plus thermal emission from the planet [11],

(3) and moons closer than ~10 planetary radii around a gas giant experience substantial tidal heating, possibly making a moon uninhabitable [10 – 14].

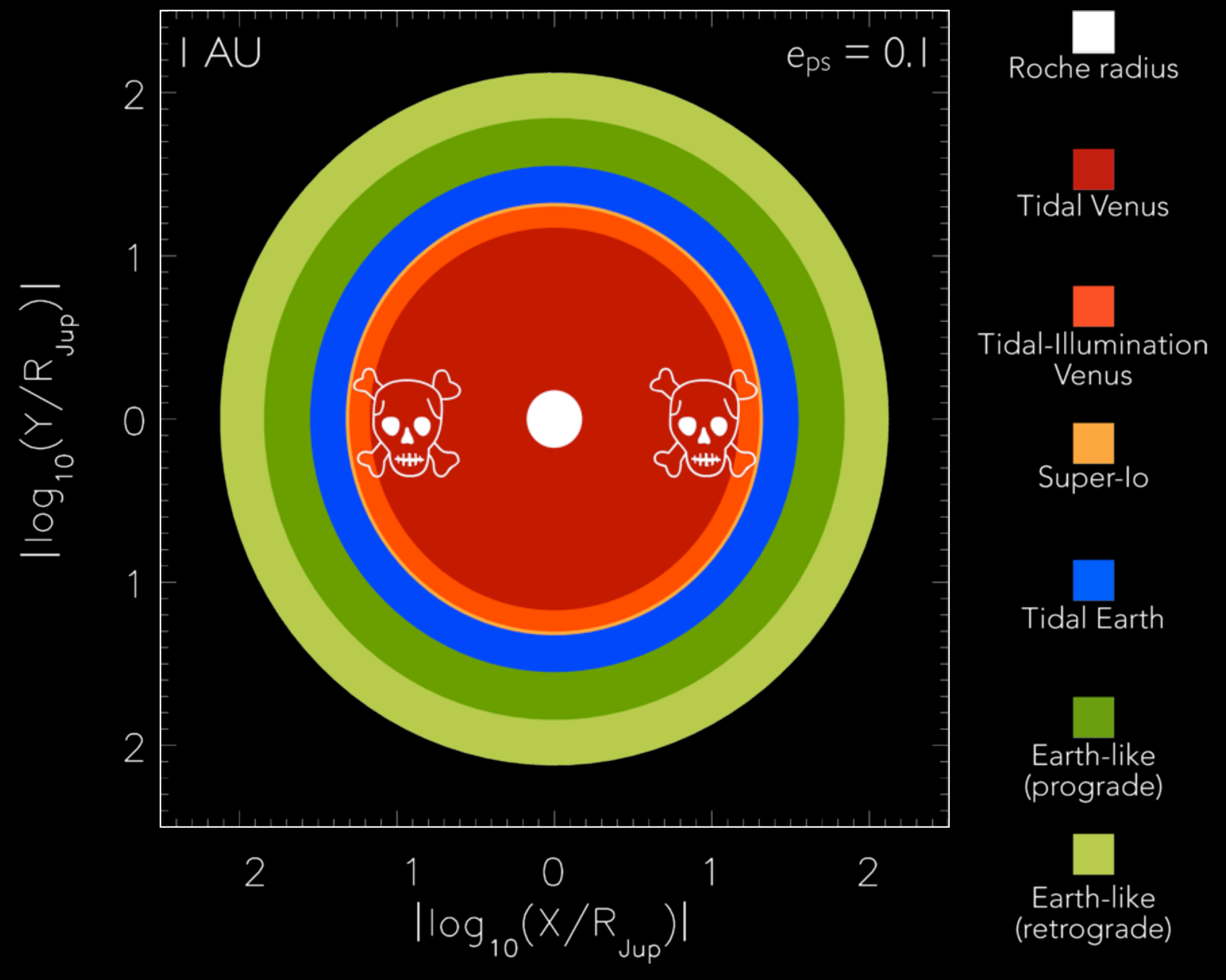

Figure 2 shows what we call a circumplanetary exomoon menagerie [11] around a 500 Myr old 13 Jupiter-mass planet 1 AU from a Sun-like star. The planet is in the center, colored shells depict the habitability status of a hypothetical Earth-sized moon with an orbital eccentricity of 0.1. In the Tidal Venus case, tidal heating alone initiates an runaway greenhouse (RG) on the moon. In the Tidal-Illumination Venus state, tidal heat plus illumination (stellar & planetary) trigger a RG. In the Super-Io scenario, tidal heating is >2 W/m^2, but the moon could be habitable. In the Tidal Earth shell, tidal heating is <2 W/m^2, but still non-zero. In the green orbits, tidal heating is negligible, and prograde (light) or retrograde (dark) moons are stable.

Finding exomoons in the stellar habitable zone

The orbital sampling effect (OSE) emerges in the phase-folded light curve of a transiting planet with moons after a few dozen transits [2]. Statistically, a moon appears more often at large *apparent* separations from its planet, which creates an extra distortion in the average transit shape. In multi-satellite systems, each moon creates its own OSE, allowing the characterization of multi-moon systems. The OSE is sensitive sub-Earth-sized moons in the stellar HZs around quiet M and K dwarf stars.

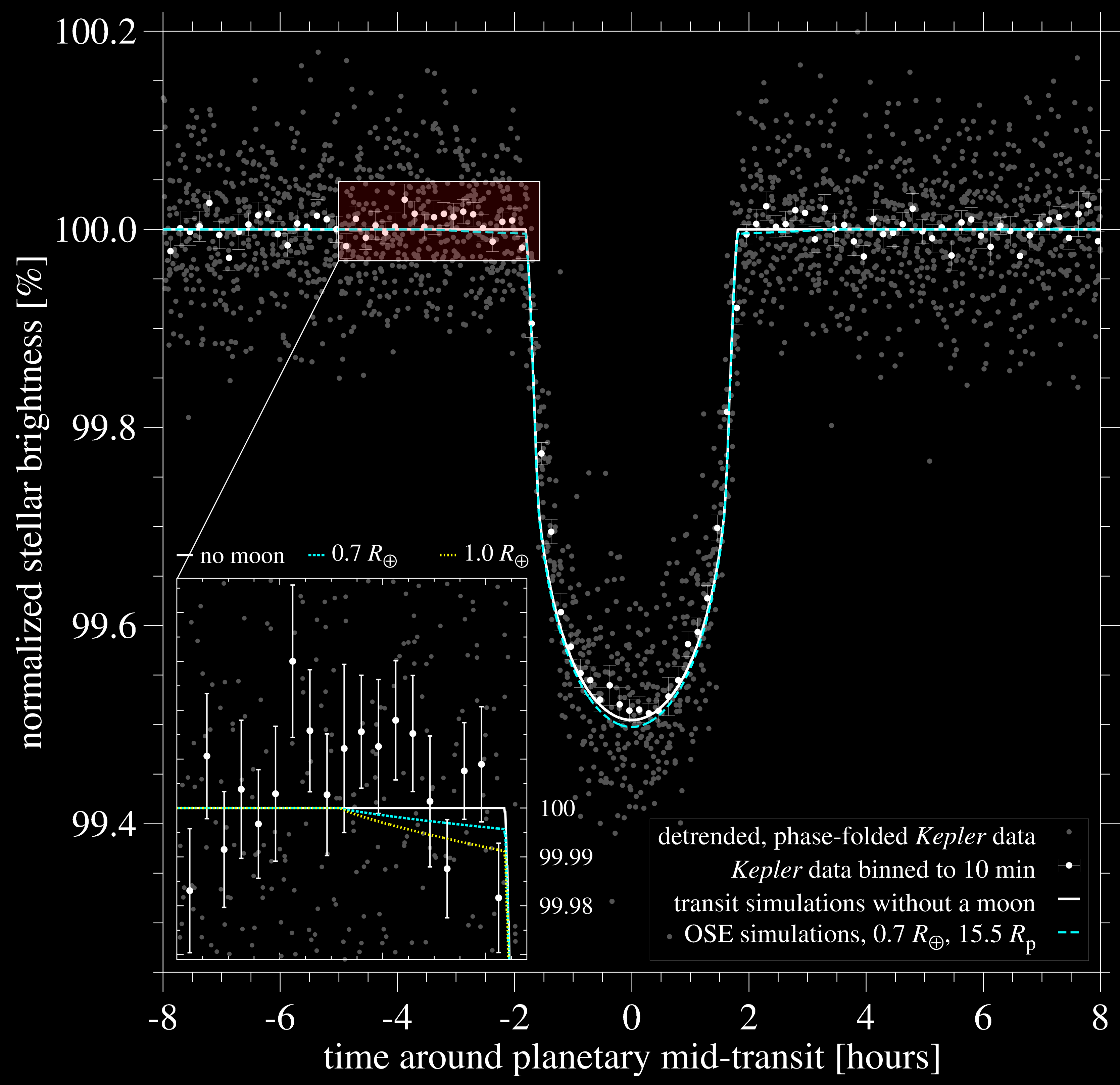

Figure 3 shows the phase-folded light curve of Kepler-229c, a 4.8 $R_\oplus$ planet around a 0.7 $R_\odot$ star in a 17-day orbit. Gray dots are the original *Kepler* data, white dots with error bars shows the data binned to 20 min. A white solid line shows our "no moon" transit model, the blue dashed line shows the OSE model for a hypothetical super-Mars-sized moon (0.7 $R_\oplus$) at 15.5 planetary radii from the planet (like Ganymede around Jupiter). The inset shows an additional example of an Earth-sized moon. Both moon models are only meant to visualize the effect of the OSE (note the ordinate scale in the inset). A statistical OSE analysis of the data is still in the works.

References

[1] Kipping+ (2012) *ApJ* 750, 115. arxiv:1201.0752
[2] Heller (2014) *ApJ* 787, 14. arxiv:1403.5839
[3] Batalha+ (2013) *ApJS* 204, 24. arxiv:1202.5852
[4] Kopparapu+ (2013) *ApJ* 765, 131. arxiv:1301.6674
[5] Williams+ (1997) *Nature* 385, 234.
[6] Canup & Ward (2006) *Nature* 441, 834.
[7] Heller & Pudritz (2015) *A&A* 578, A19. arxiv:1504.01668
[8] Agnor & Hamilton (2006) *Nature* 441, 192.
[9] Williams (2013) *AsBio* 13, 315.
[10] Heller & Barnes (2013) *AsBio* 13, 18. arXiv:1209.5323
[11] Heller & Barnes (2015) *IJA* 14, 335. arxiv:1311.0292
[12] Reynolds, McKay, & Kasting (1987) *AdSpR* 7, 125.
[13] Heller & Armstrong (2014) *AsBio* 14, 50. arxiv:1401.2392
[14] Heller (2012) *A&A* 545, 8. arxiv:1209.0050

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