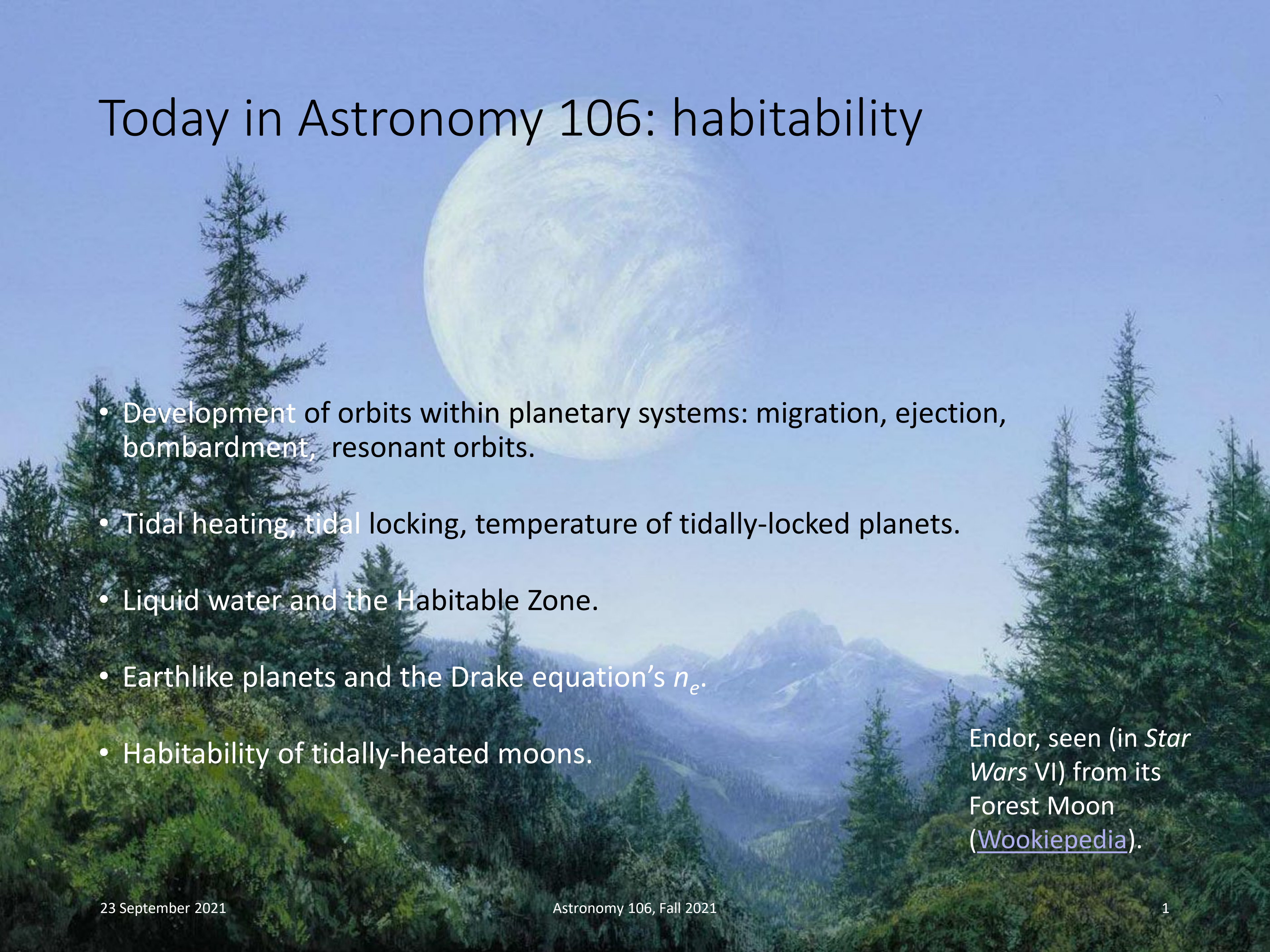


Today in Astronomy 106: habitability

- Development of orbits within planetary systems: migration, ejection, bombardment, resonant orbits.
- Tidal heating, tidal locking, temperature of tidally-locked planets.
- Liquid water and the Habitable Zone.
- Earthlike planets and the Drake equation's n_e.
- Habitability of tidally-heated moons.

Endor, seen (in *Star Wars* VI) from its Forest Moon (Wookiepedia).

Review. An exoplanet is found in orbit around a 0.5 solar mass star, with orbital period 36.525 days. What is its orbital radius, in AU?

A. 0.17 AU

B. 0.79 AU

C. 3.7 AU

D. 4.6 AU

E. None of these

Review. The luminosity of the 0.5 solar-mass star is 0.063 solar luminosities. What is the temperature of the cloudtops or surface of this exoplanet, if its albedo is earthlike *(A* = 0.37)*?*

A. 279 K

B. 301 K

C. 325 K

D. 383 K

E. None of these

Evolution of planetary-system architecture

After planets form they begin, with the gravitational forces they exert, to perturb the orbits and rotation of smaller Solar-system bodies and each other. This results in

- orbital **migration**: the large-scale changing of planetary orbits.
- capture into, or ejection from, **resonant orbits**.
- systematic **ejection** of small planetesimals, sometimes *en masse*.
- **tidal locking**: the slowing of rotation of a body due to tidal forces by another, orbiting body.

These effects influence the habitability of given planets and the existence in a planetary system of habitable planets.

Planets move each other around

Planets are constantly under the influence of the gravity of each other as well as that of the central star.

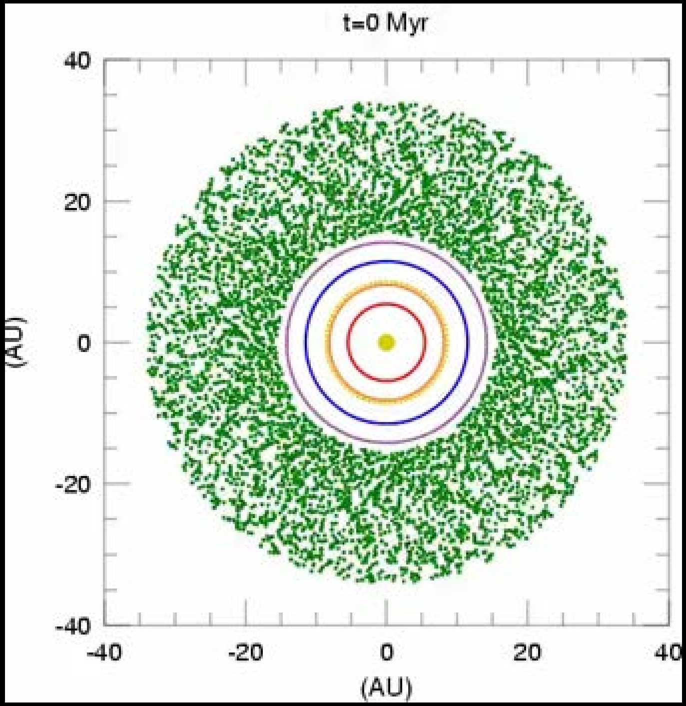
- The effects are largest, of course, when they are closest together in their (generally elliptical) orbits, because the gravitational force are steeply dependent upon distance.
- Thus you can think of each body suffering an impulsive "tug" – technical term **perturbation** – at closest approach.
- If closest approach happens in the **same place** in each orbit – a situation in which the orbits of the two are called **resonant** – the perturbations can build up over time to large differences, instead of tending to average out.
- If the orbital periods of two bodies have a ratio very close to a ratio of integers (whole numbers), they are resonant.

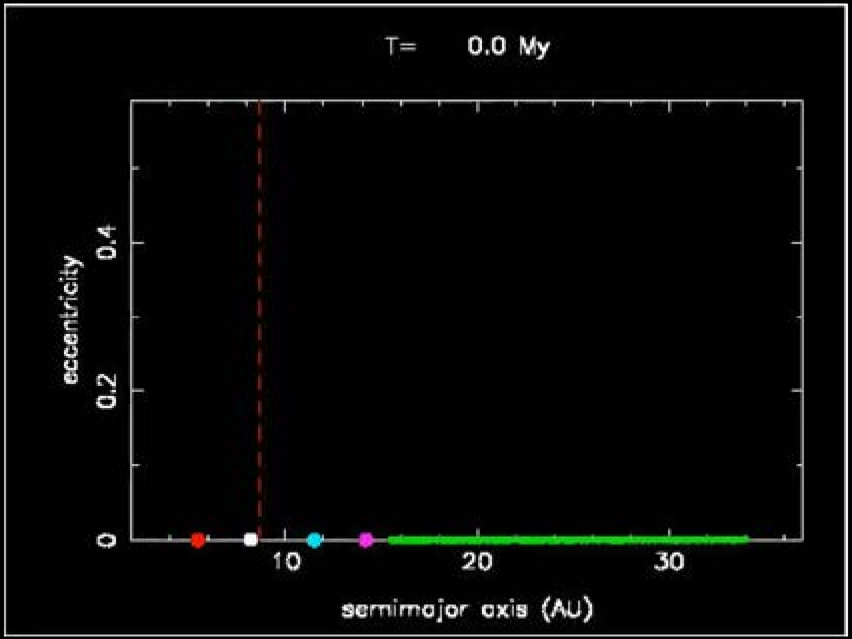
Planets move each other around (continued)

- Thus planets, especially giant ones, can force each other to change orbits drastically.
  - Even large ones, but …
  - … especially smaller bodies. If a giant planet migrates by a substantial amount, small bodies are subject to ejection or consumption.
  - **Example**: the early history of our Solar system, according to the Nice model by Allesandro Morbidelli and coworkers. See next page.

    Main events:
    - perturbation of Jupiter and Saturn by each other migrate these planets outward.
    - Saturn resonantly perturbs Neptune.
    - Neptune and Uranus swap orbits, ejecting 99% of the smaller bodies.

The Nice model of our solar system's development





Hal Levison, SwRI

Alessandro Morbidelli, CAO

Stars can slow the rotation of planets

And planets can slow the rotation of their moons, but let's concentrate on stars and planets for the moment.

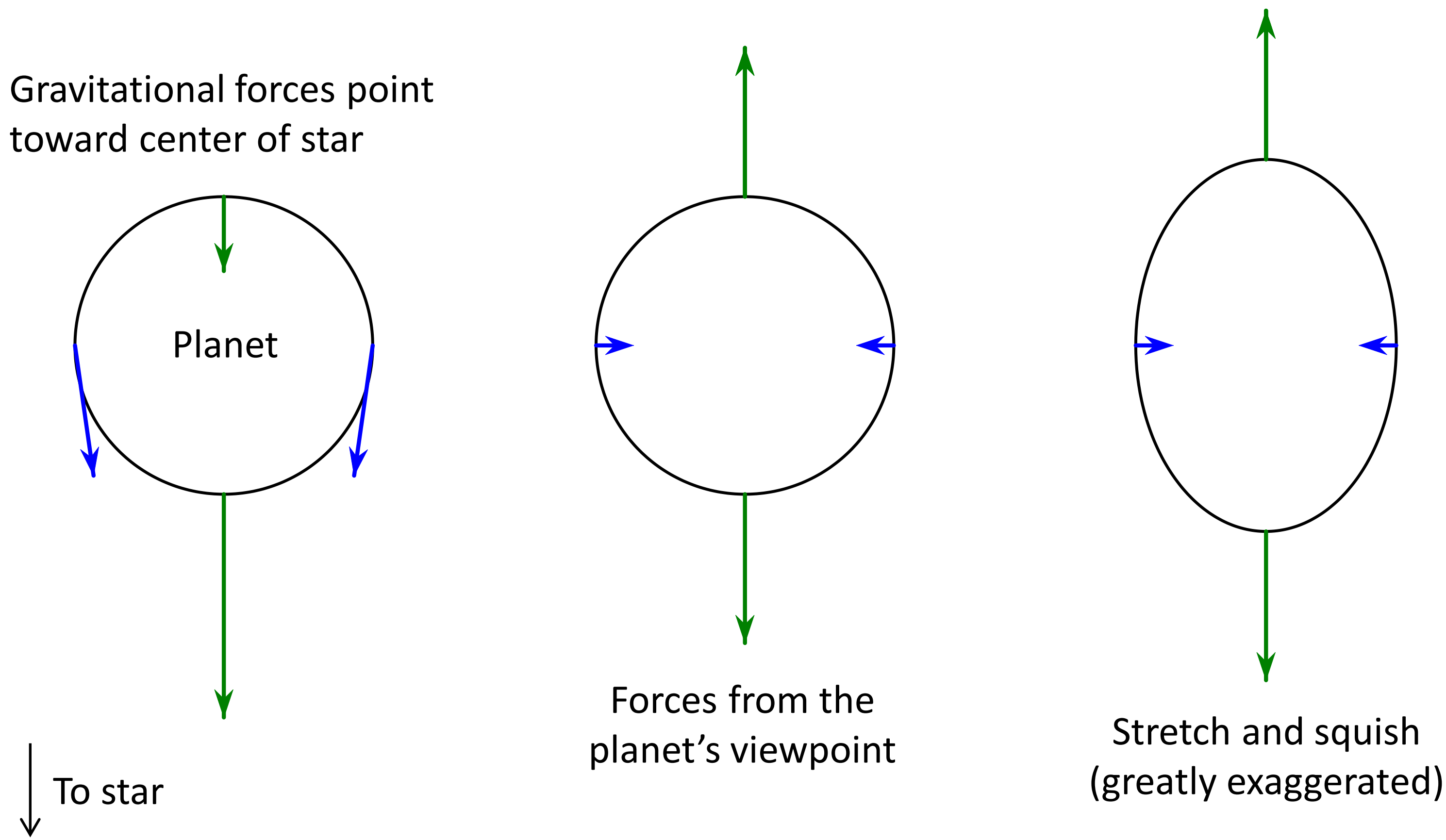
- Terminology: **rotation** is spinning about an axis, and **revolution** is motion in an orbit. Earth **rotates** about its axis, and **revolves** around the Sun.

Though planets are many diameters away from their stars, their diameters are not so small as to be ignorable.

- As planet and star orbit each other, they tug on each other's near side significantly harder than the far side.
- They also tug each other's right and left sides closer together.
- These force differences are known as **tides**.
- When two bodies pass each other, they stretch and compress in response to the tidal forces, and relax back to their previous shapes after the perturbation is over.

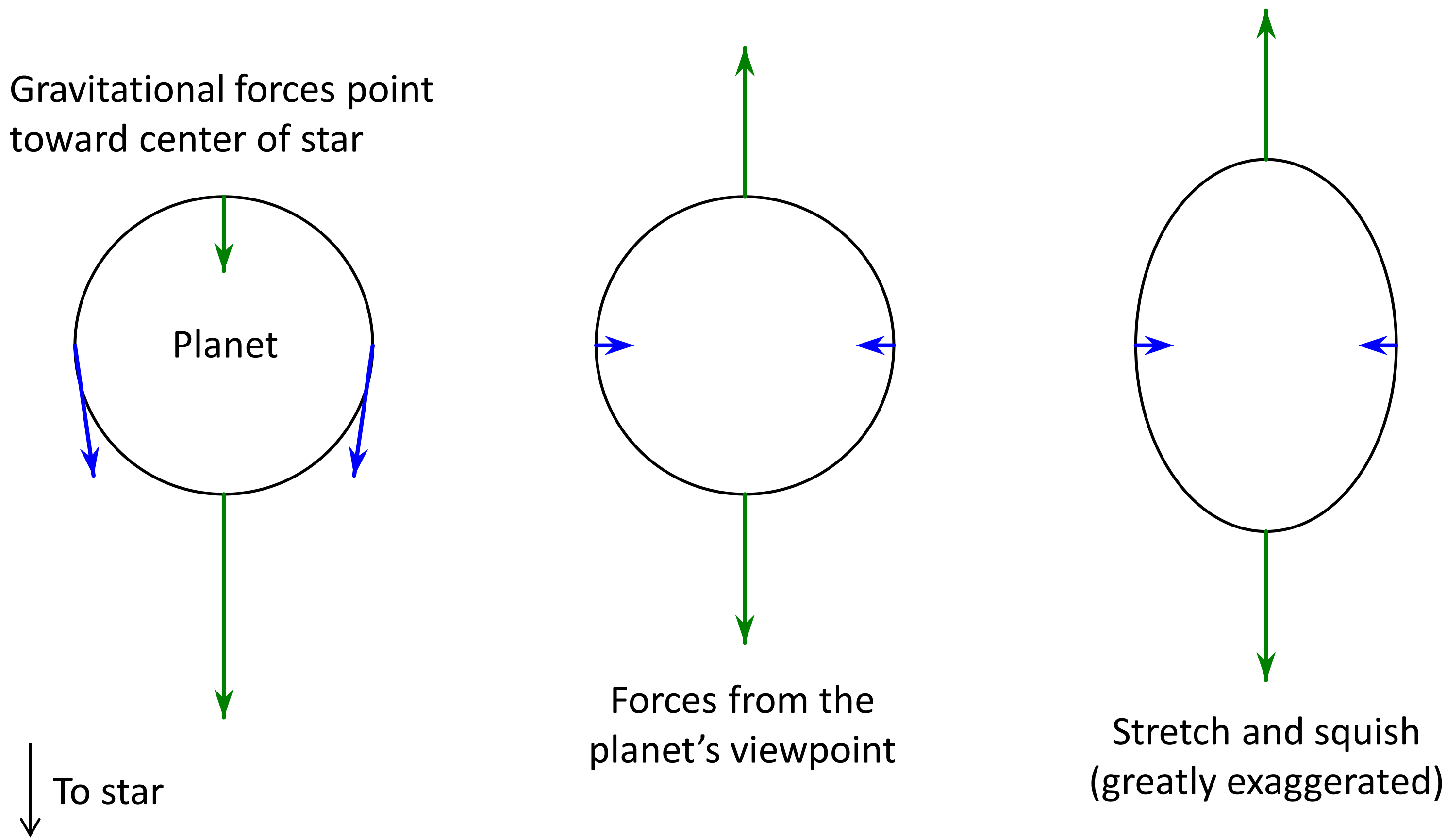
Tidal forces and tidal stretching

- The force of gravity decreases sharply with increasing distance, and a spherical mass exerts the force as if all its mass lies at its center.



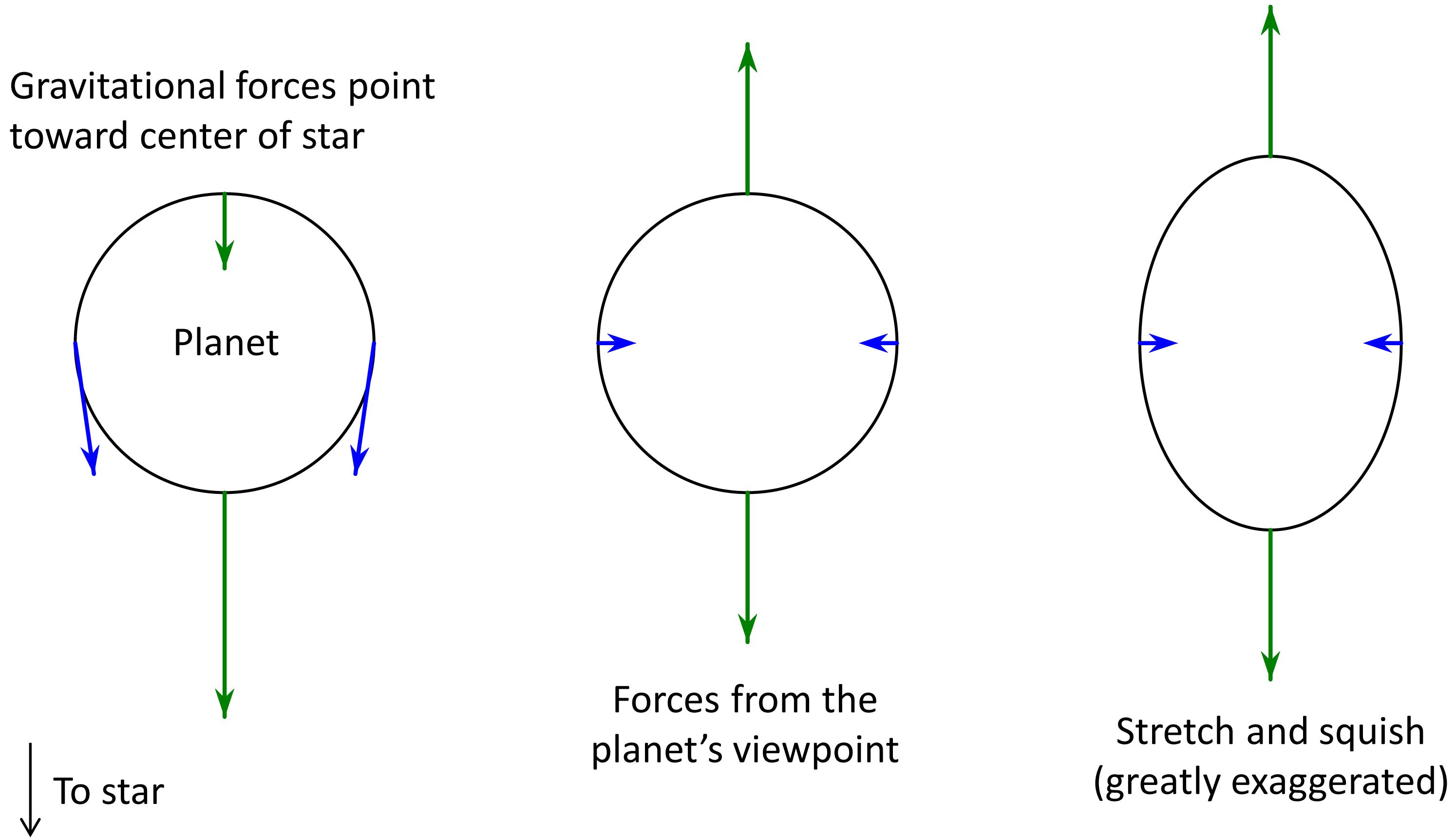
Tidal forces and tidal stretching (continued)

- Thus the planet is **stretched in the direction toward the other body, as the near side gets tugged harder than the far side…**



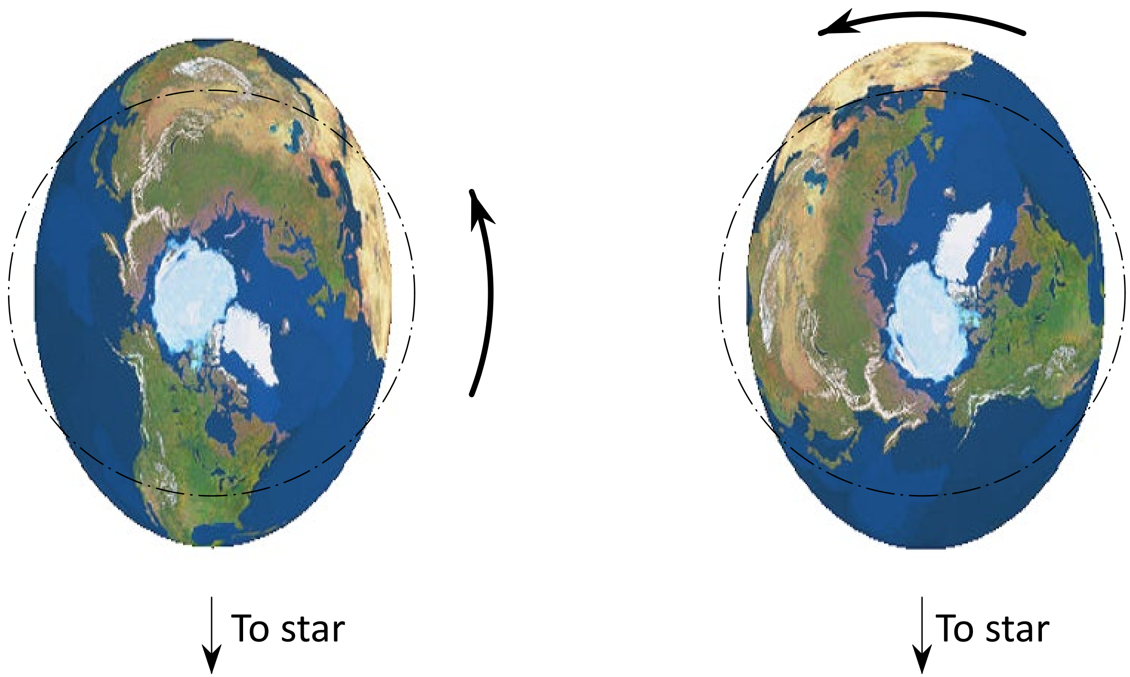
Tidal forces and tidal stretching (continued)

- and is **squished in the perpendicular direction by the convergence of the forces at the other body's center.**



Tidal forces and tidal stretching (continued)

- The **stretch and squish stay fixed in the direction toward the other body**, so if the planet rotates faster than it revolves, every point on the surface will be pushed up twice a day from the stretch, and down twice a day from the squish.



Stretch and squish greatly exaggerated

Tidal locking (continued)

- It takes work to stretch/compress the planet, and not all the energy springs back when the forces decrease.
  - Friction and viscosity within the planet dissipate some of the energy as heat, which is then (blackbody-) radiated away.
- Because the tidal heating depends upon the state of rotation of the body as well as its orbit, radiation of the tidal heat drains the rotational and orbital energy.
- **Thus the planet (or moon) rotates more slowly** and **drifts to larger orbital distance**.
- Eventually (in 1-100 Myr), this results in a special relation, such as equality, between the orbital and rotation period, corresponding to the minimum of tidal heating. This is called tidal **locking**.

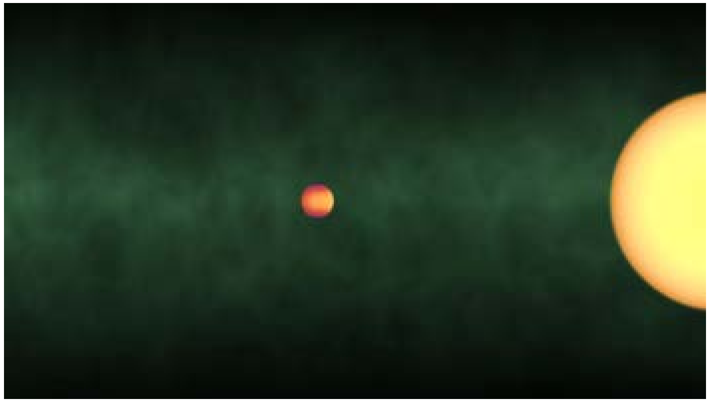
Tidal locking (continued)

- This happens a lot, in star-planet systems and in planet-moon systems:
  - The Moon is tidally locked: it rotates once per revolution around Earth.
  - Pluto and its largest moon Charon are **mutually** tidally locked: each rotates once every 6.4-day revolution.
  - All the large moons of Jupiter and Saturn are tidally locked.
  - **Planets in orbits very close to their stars will tend to be tidally locked**. (Mercury, for example.)
  - Tidal locking changes their starlight-heating situations.

Temperatures of fast and slow rotators

Implications for the temperature of a revolving body that is mainly heated by starlight:

- If a body rotates faster than it can cool off – is a **fast rotator** – its surface will have a fairly uniform temperature, therefore given by the formula for dust grains (see lecture, 16 September).
  - Earth and Mars are fast rotators, for example.
- If alternatively it is a **slow rotator**, it may have hot and cold sides.
  - If tidally locked in circular orbit around its star, it **will** have **permanently** hot and cold sides.



Tim Pyle, SSC

Temperatures of fast and slow rotators (continued)

- For a slow rotator, the maximum temperature, which is *generally* reached at the substellar ("noon") point, is

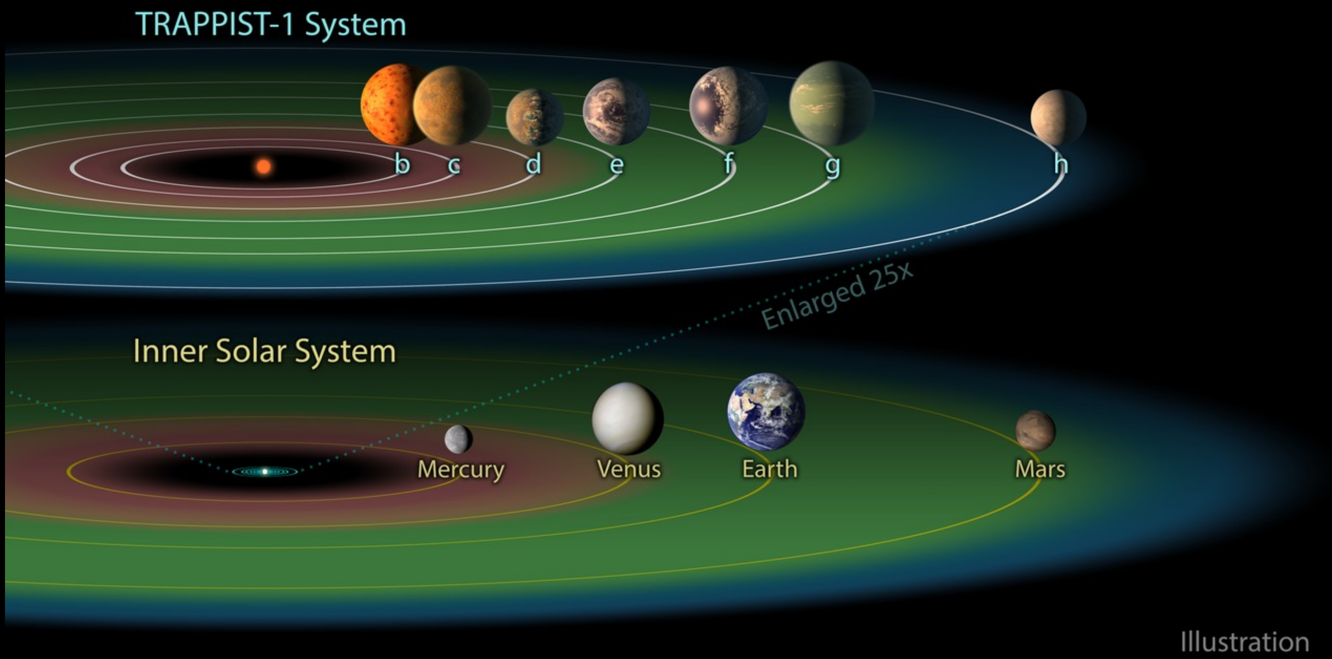
$$\boxed{T=\left(\frac{(1-A)L}{4\pi\sigma r^2}\right)^{\frac{1}{4}}=394\ \mathrm{K}\times\left(\frac{(1-A)L\left[L_\odot\right]}{\left(r[\mathrm{AU}]\right)^2}\right)^{\frac{1}{4}}}$$

You need to understand how to use this equation.

- Fortunately it's the same as the last equation, with 394 K replacing 279 K.
  - Or, if you prefer, with 4π replacing 16π.

Mid-lecture break.

- Homework #2 is due Monday, 7:00 PM.
- **Quiz #1 takes place in class on Tuesday, on WeBWorK. Bring your laptop to class that day. Stay tuned for a Practice Quiz #1**



Habitable zones, in our Solar system and the TRAPPIST-1 system. (NASA/SSC)

The habitable zone

Since the interstellar medium already provides infant solar systems with the basic, and some processed, ingredients of life, the next basic requirement for habitability is for the ingredients to have the right temperature.

- What's the right temperature? Clues from Earth:
  - Simple organisms are not killed by prolonged exposure to temperatures *slightly* below the freezing point of water, or *slightly* above the boiling point. (These beasts are called **extremophiles.**)
  - Complex organisms are most abundantly found in habitats between freezing and boiling.
- That is, Earth suggests that **liquid water** promotes habitability by organic chemical/water-based life.

The habitable zone (continued)

- Is this unwarranted geocentrism, to presume that life requires water? Not necessarily:
  - As we will discuss in a few weeks, chemistry in liquids is **by far** the fastest way for life to evolve.
  - Usually this means having a solvent: a liquid for other molecules to dissolve in, that can facilitate their reactions.
  - Water is **by far** the most abundant solvent molecule in protoplanetary disks, and chemically is a great solvent.
  - The temperature range within which water is liquid overlaps that of many other solvent candidates, like methanol and ammonia.
- Still, we have to be wary of this possible bias.

The habitable zone (continued)

- The most common definition of habitability in a planetary system is that water exists permanently in liquid form on a suitable planet.
    - That is T = 273 – 373 K under normal pressure conditions on Earth, and this range is often taken.
    - The water need not be exposed on the surface; if it is, the planet better have an atmosphere.
- Such planets are found this far from their stars (see lecture, 16 September):

$$r[\mathrm{AU}] = \left(\frac{T_0}{T}\right)^2 \sqrt{(1-A)L[L_\odot]}$$

where T_0 = 279 K for fast rotators and 394 K for slow ones, and T runs from 273 to 373 K, if the planets are just “large dust grains.”

The greenhouse effect

Real planets are not large dust grains: they often have atmospheres.

- Recall that the reasoning above gives only T = 249 K for the Earth (lecture, 16 September). This is the temperature of the cloud tops; it's warmer down below. Why?

- Because the atmosphere is transparent at shorter wavelengths (visible, ultraviolet,…) at which stars emit lots of light.

    - This light heats the surface directly.

    - But the extra energy can't escape so quickly. The surface radiates at the same infrared wavelengths at which the atmosphere is opaque.

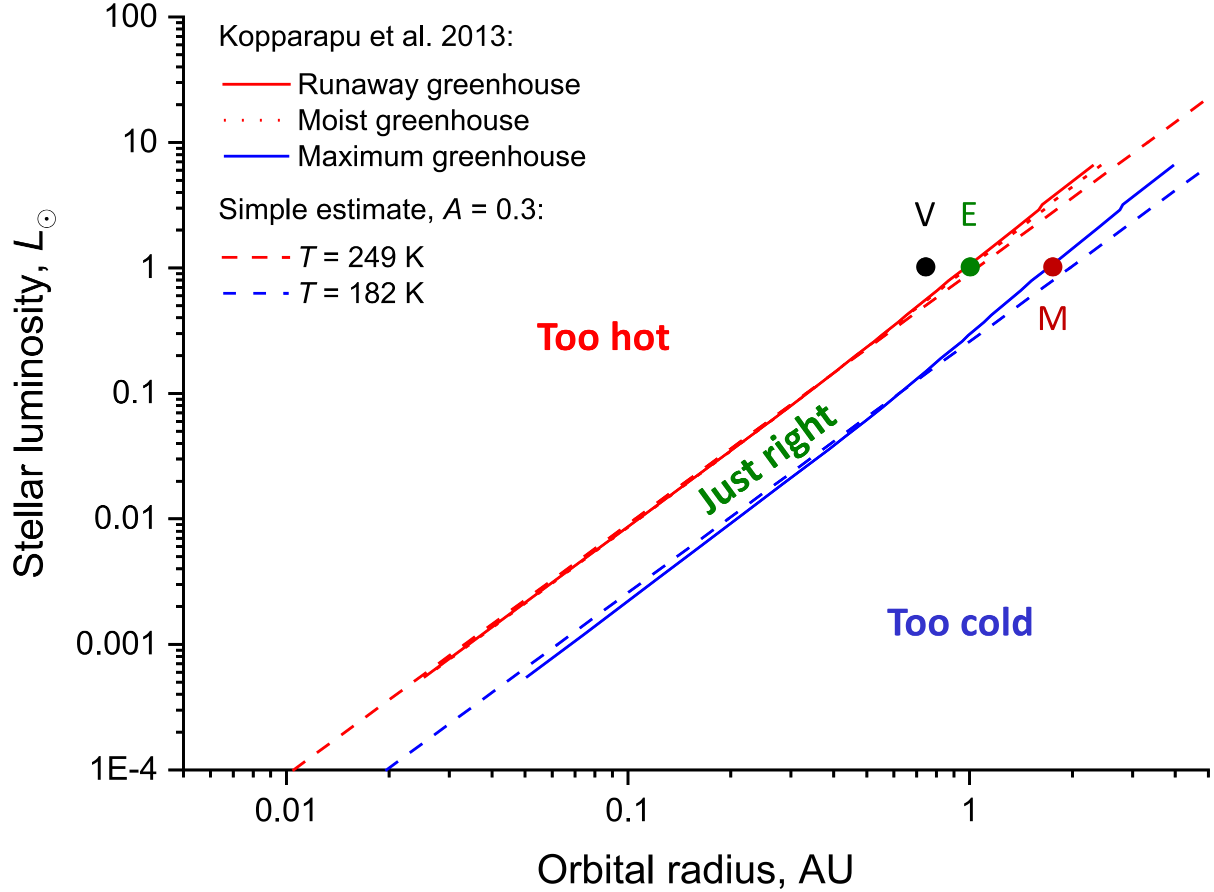
    - Thus the surface is warmer than the cloudtops.

- This is called the **greenhouse effect.** We will describe it more completely toward the end of the semester.

The habitable zone (continued)

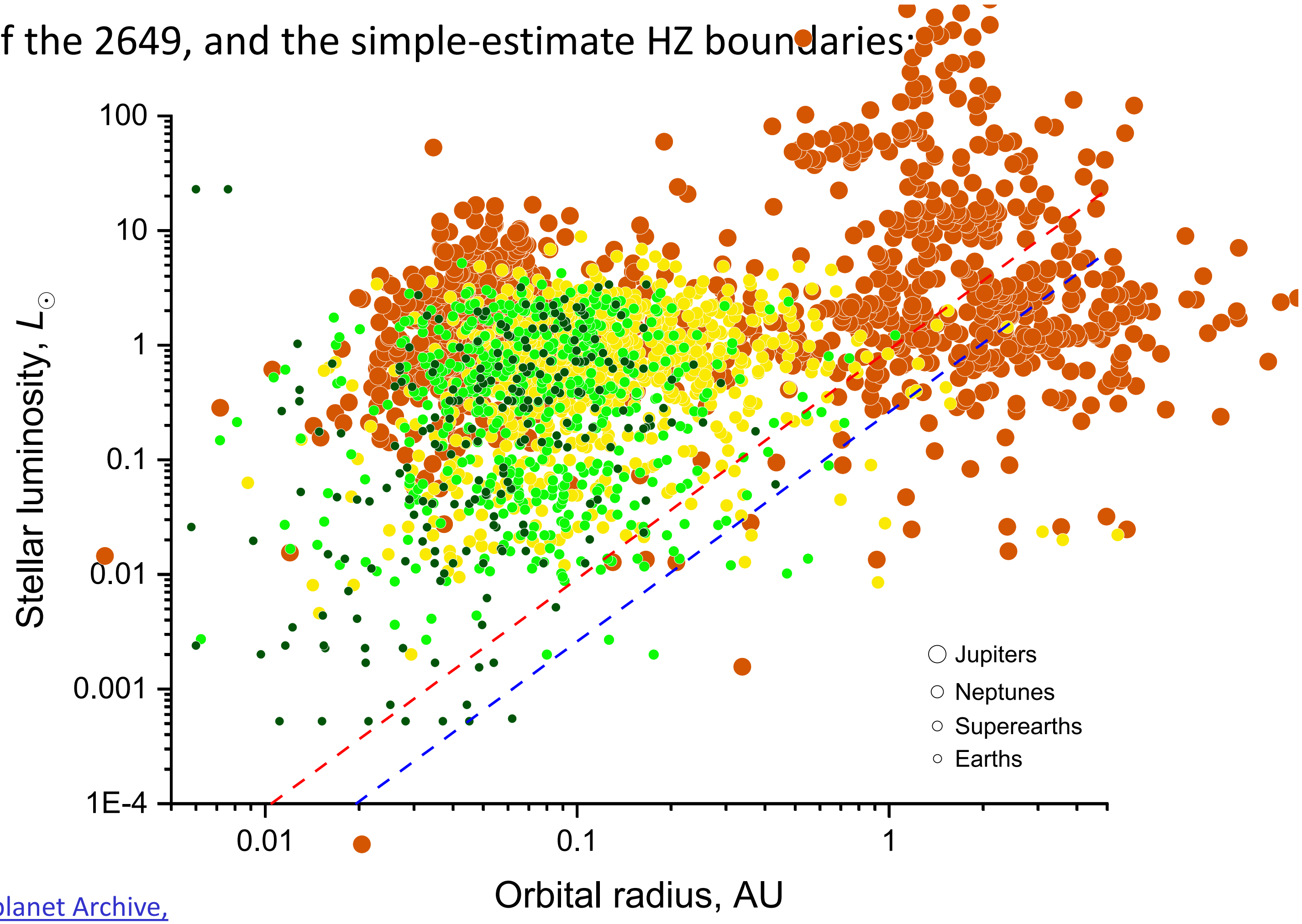
- A simple but realistic estimate of the extent of the habitable zone is obtained using A = 0.3 and the equations we know, and to take the temperature bounds to be ***T* = 182 K and 249 K**.
  - By this criterion, 142 of today's 2649 confirmed, classifiable planets lie in the habitable zone.
    - Classifiable = we know orbit, mass and radius of planet, and the properties of the host star.
  - Many are giant planets, but any rocky moons with atmospheres would be habitable.
- The simple estimates agrees well with the state of the art in atmospheric models applied to habitability (Kopparapu et al. 2013), which account for the greenhouse effect and produce surface temperatures of 273 K and 373 K.

The habitable zone (continued)



The habitable zone (continued)

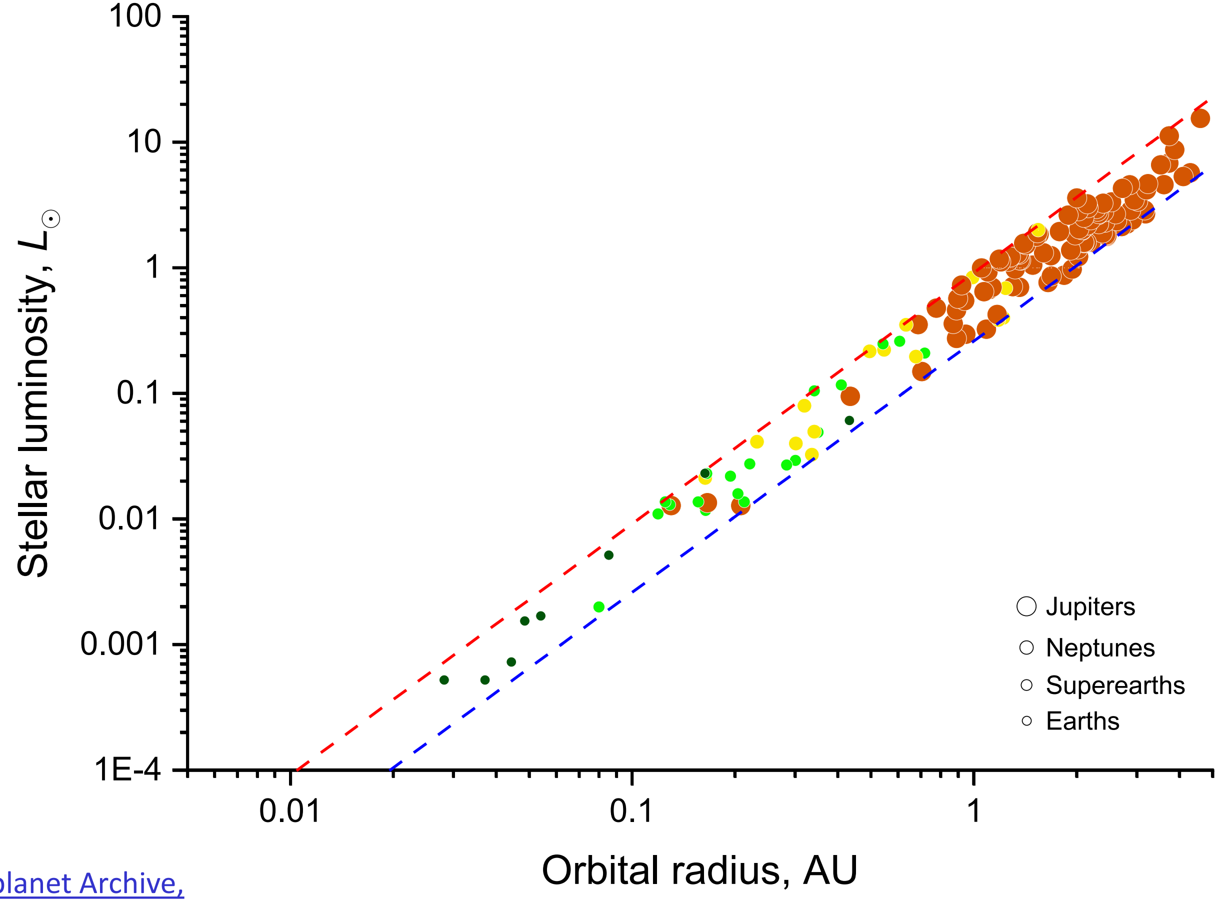
Most of the 2649, and the simple-estimate HZ boundaries:



Data:
[NASA Exoplanet Archive, 22 September 2021]

The habitable zone (continued)

142 lie within the HZ boundary, 16 of them closer than 40 light years.



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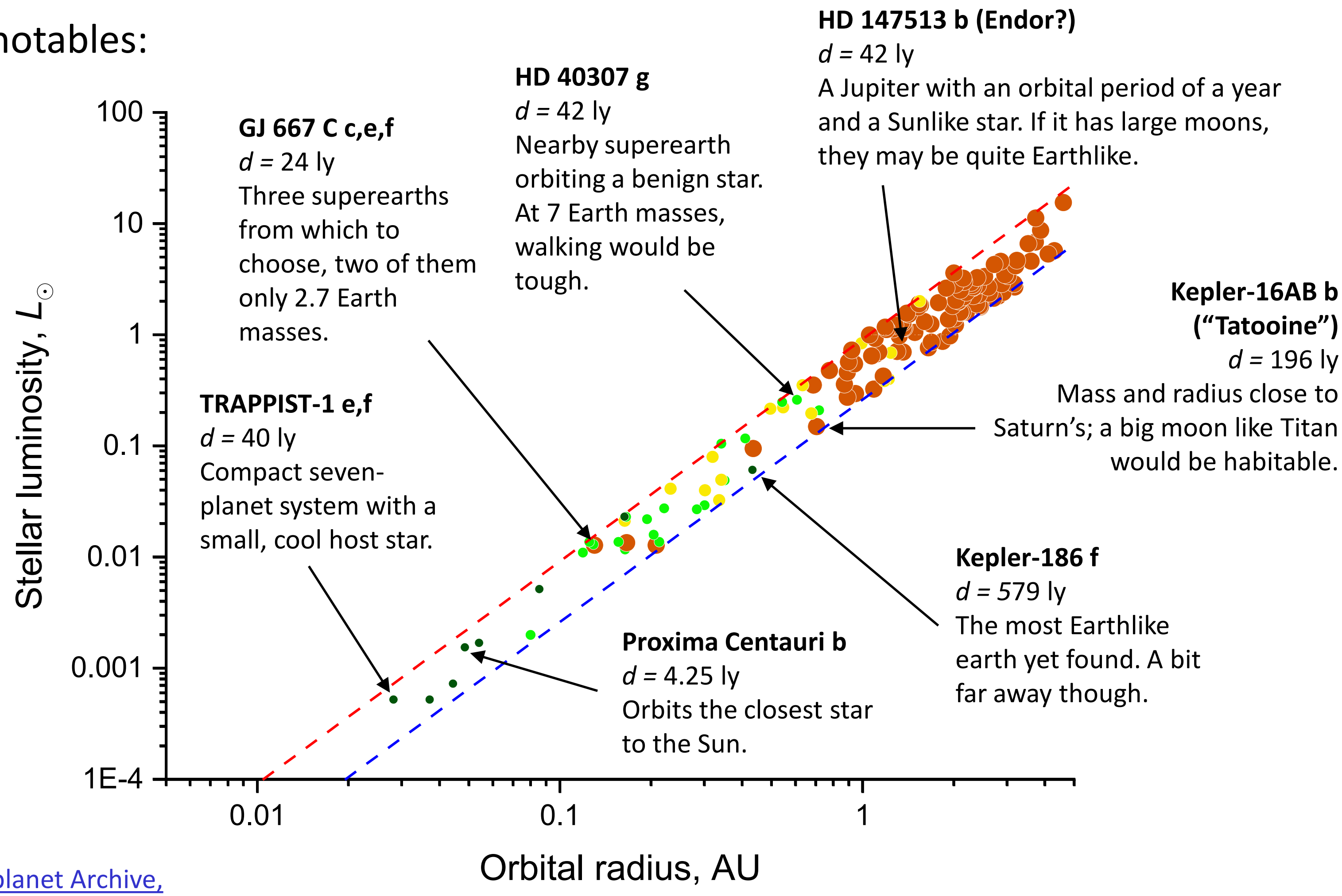
[NASA Exoplanet Archive, 22 September 2021]

The habitable zone (continued)

Some notables:



Data:
[NASA Exoplanet Archive, 22 September 2021]

The habitable zone (continued)

Tatooine

Lucasfilm

Drake's n_e: what fraction of planetary systems have habitable planets?

This is what the NASA *Kepler* mission was designed to measure, and it has succeeded.

- Originally the n_e factor was supposed to count Earth-like planets, meaning habitable ones. Now, with such unsuspected things as super-earths and abundant tidally-locked planets, and the trickiness of the greenhouse effect, there's more context required around the numbers.
- Earths and super-earths are more abundant around low-mass, cool stars ("M") than around Sun-like (G-K) stars:

G-K: 46%±3% of stars have E or SE (Silburt et al. 2015)

M: 56%±6% of stars have E, 46%±7% SE
(Dressing & Charbonneau 2015)

Drake's n_e: what fraction of planetary systems have habitable planets? (continued)

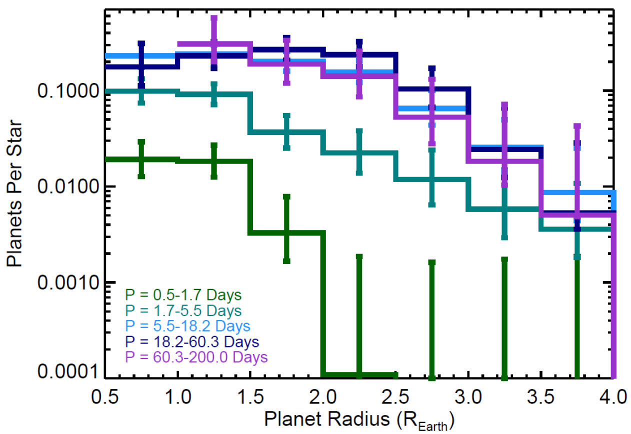
- Within the habitable zone as modelled by Kopparapu et al. 2013, the fraction of stars possessing planets is

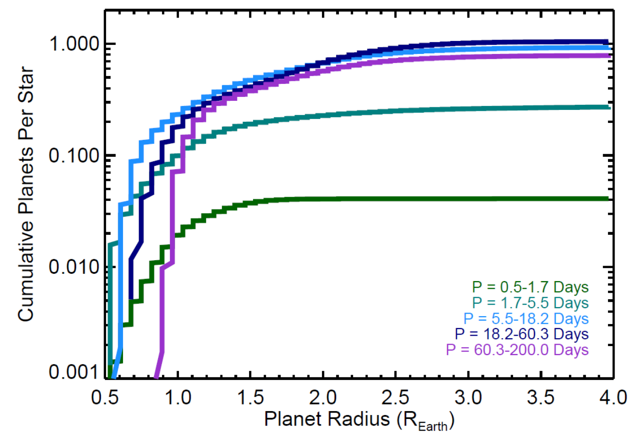
  G-K stars: 6% Earths, 17% SE (Silburt et al. 2015)

  M stars: 16% E, 12% SE (Dressing & Charbonneau 2015)

- Splitting the difference in % and ignoring the difference in E/SE, we will adopt

  $\boxed{n_e = 0.25}$ (25%)





Dressing & Charbonneau 2015

So, ignoring habitable moons of giant planets, about how many stars would we have to visit on the average to find one habitable planet?

A. 1

B. 2

C. 4

D. 8

E. 16

F. 32

G. 64

H. 128

Habitability outside the habitable zone

- We chose starlight as the energy source above because it is generally provided at a steady rate for billions of years, and other heat sources are not. All but one, anyway:
  - Tidal heating of suitably-placed moons and planets can be significant sources of energy for as long as they rotate rapidly and/or don't have circular orbits.
  - On the one hand, as the moon or planet radiates away the energy, the rotation slows and the orbit circularizes over time, reducing the tidal heating to zero. But on the other…
  - If something can force a suitably-placed planet or moon to rotate or follow an elliptical orbit permanently, the tidal heating would be permanent.

Habitability outside the habitable zone (cont'd)

- And something can: perturbations of moons and planets on each other's orbit can result in orbits being locked into orbital resonance.

- Since there's an attractive impulse at closest approach, and since for resonant orbits this happens in the same spot in the orbit every time, these **resonantly-locked** orbits can't be precisely circular.

- Thus tidal heating can be permanent, and substantial.

- This is the case for the large moons of Jupiter and Saturn, particularly **Io, Europa and Ganymede** (orbital periods in ratio 1-2-4).
  - Permanently liquid water further away from the star than the habitable zone!

- We will discuss this further when our talk turns to the search for life elsewhere within the Solar system.