Biases of the Radial Velocity Method

Concept Check

Given what you know about the radial velocity method, which of the following types of planets should be most easily detected using this method?

A. A massive planet with a low semimajor axis
B. A massive planet with a high semimajor axis
C. A low-mass planet with a low semimajor axis
D. A low-mass planet with a high semimajor axis

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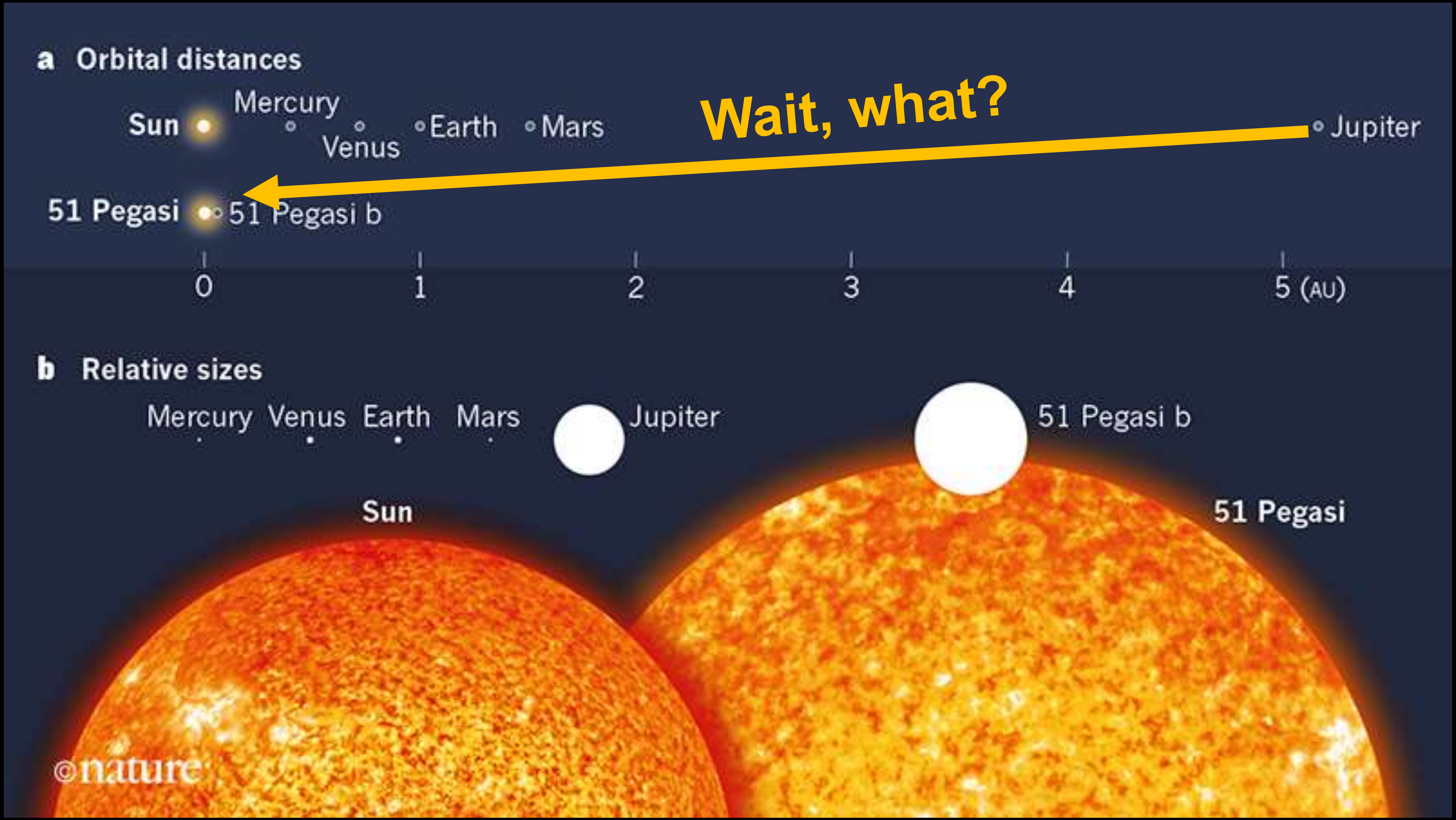
$$v_{radial} \cong \sqrt{\frac{G}{a(1-e^2)M_{star}}}M_{planet}$$

$$v_{radial} \propto \frac{M_{planet}}{\sqrt{a}}$$

Higher planet (M_{planet}) combined with low semimajor axis (a) produces the largest radial velocity.

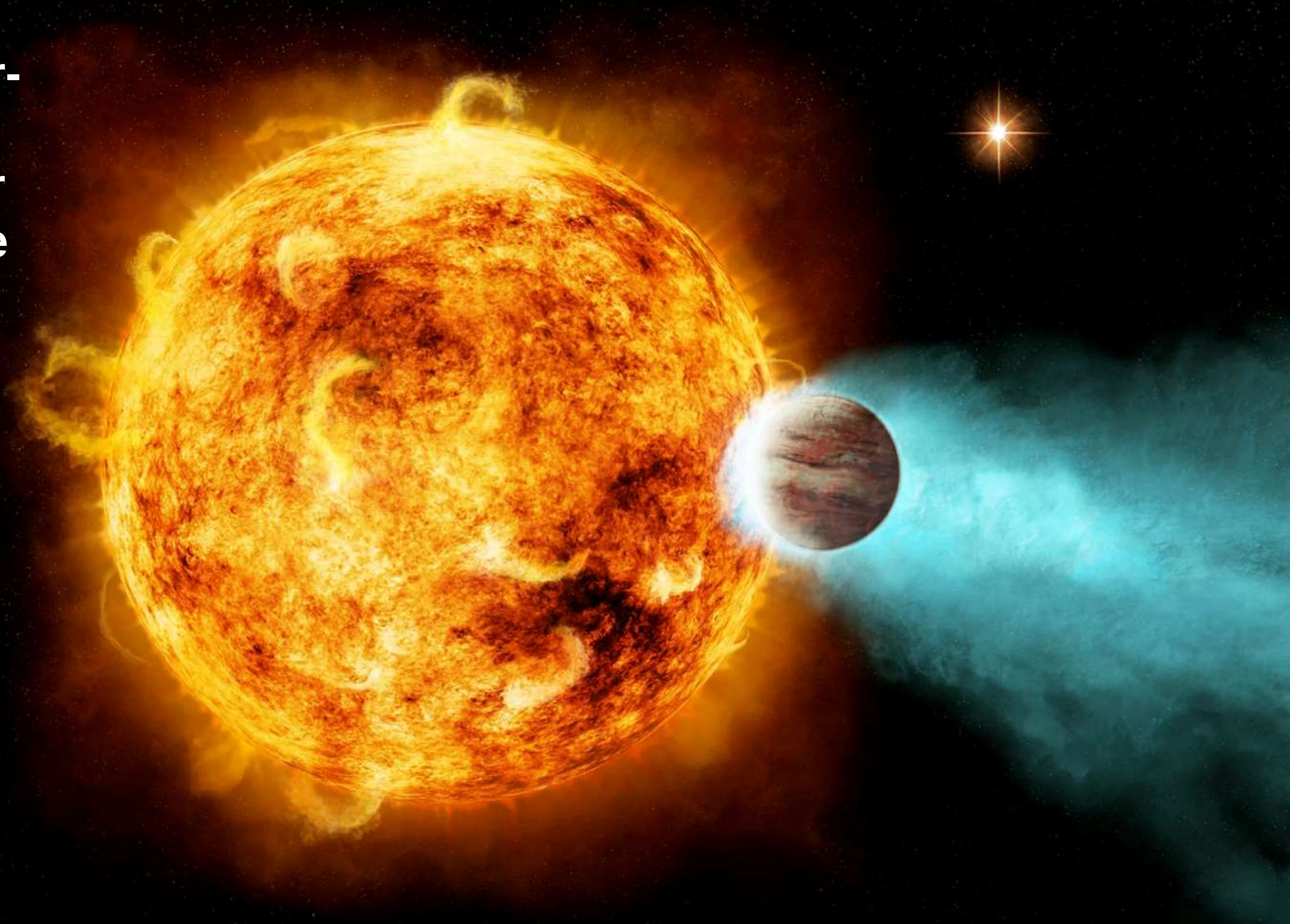
The radial velocity method was the first method to find an exoplanet orbiting a Sun-like star—51 Pegasi b.

But it wasn't the kind of planet anyone expected…



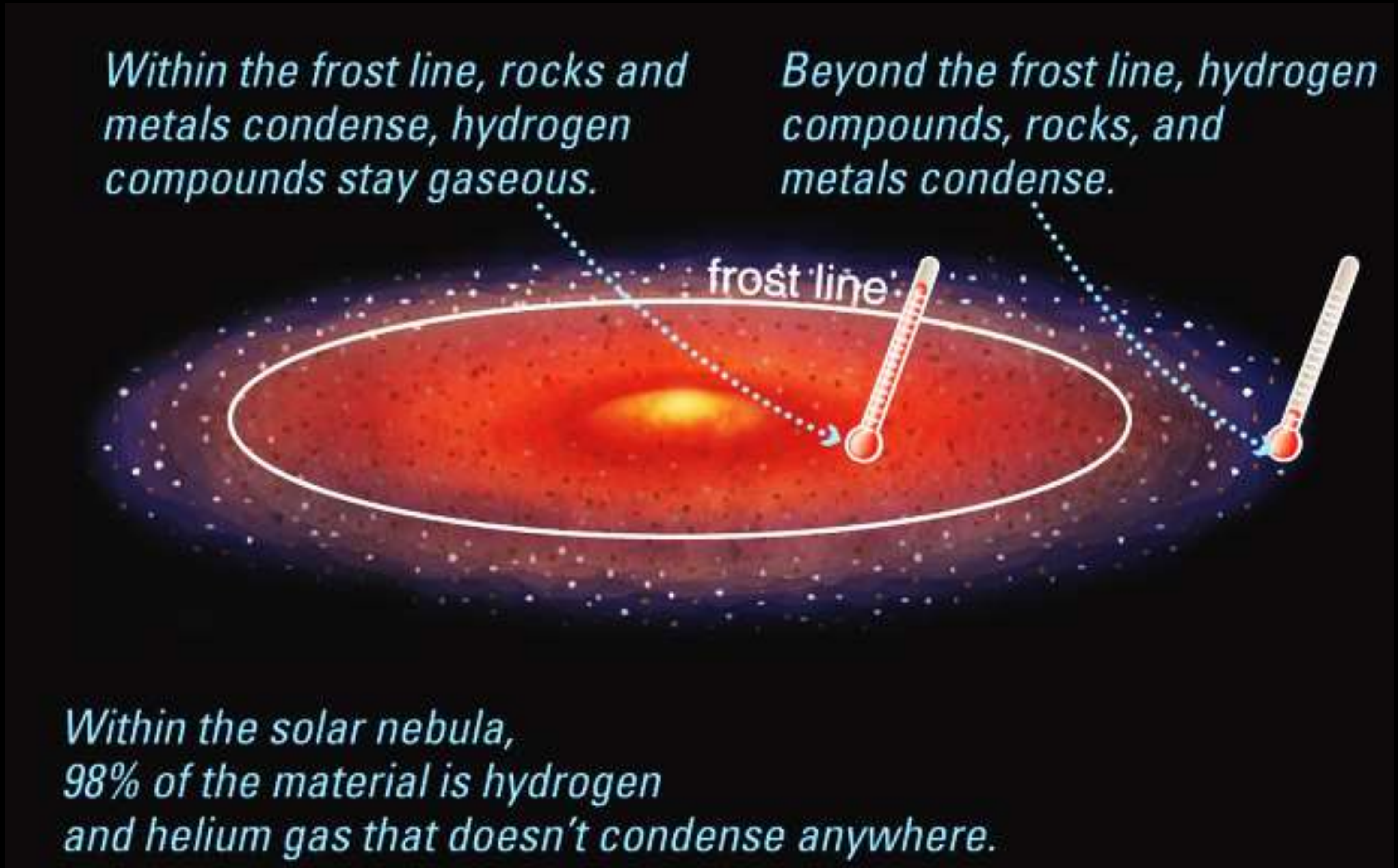
Credit: Nature Magazine

51 Pegasi b is a Jupiter-sized planet orbiting closer to its parent star than Mercury orbits the Sun. It was the first known hot Jupiter.



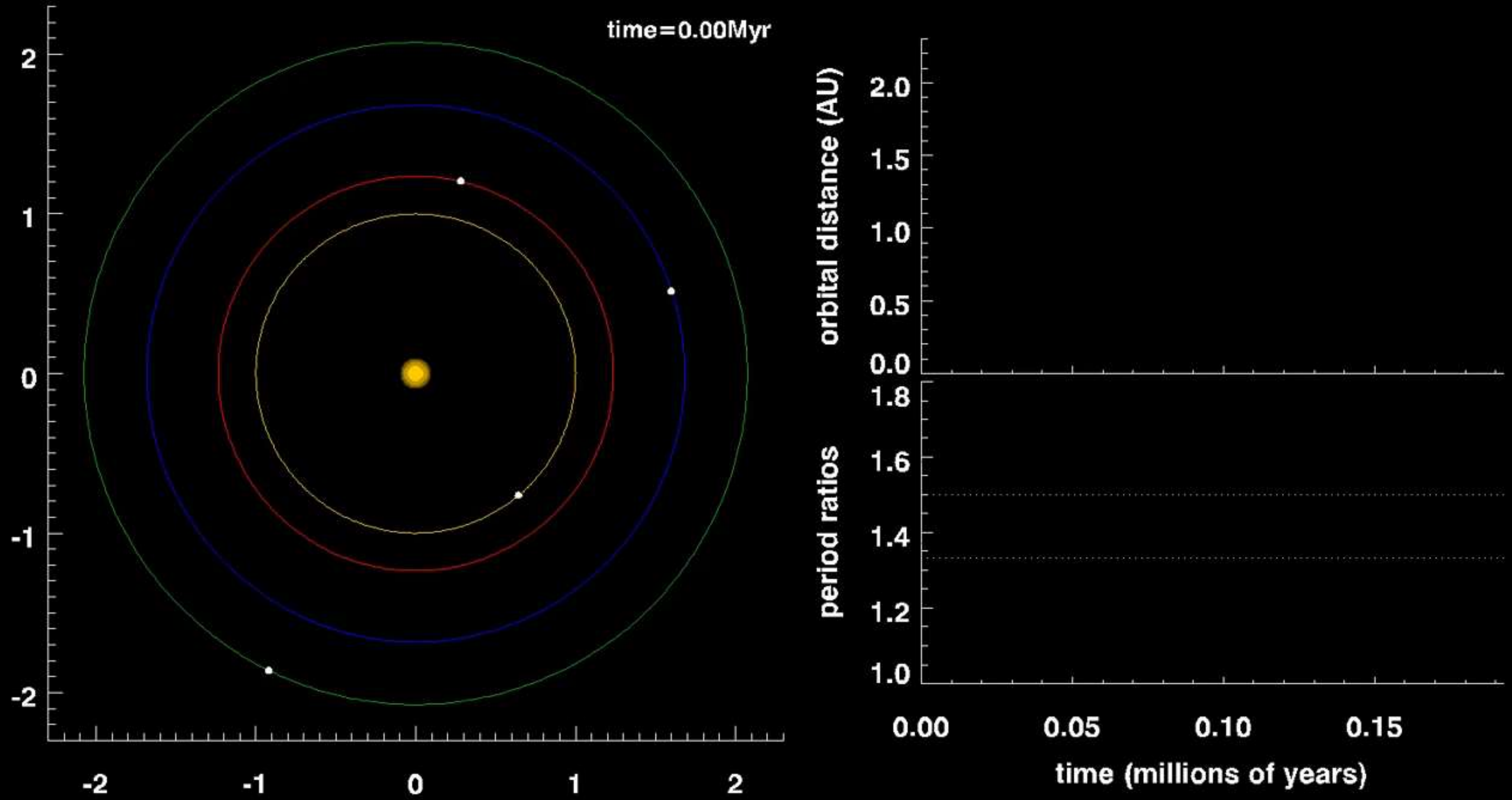
Credit: NASA/Ames/JPL-Caltech

Hot Jupiters were a surprise because giant planets should form in the outer reaches of a solar system, beyond the frost line.



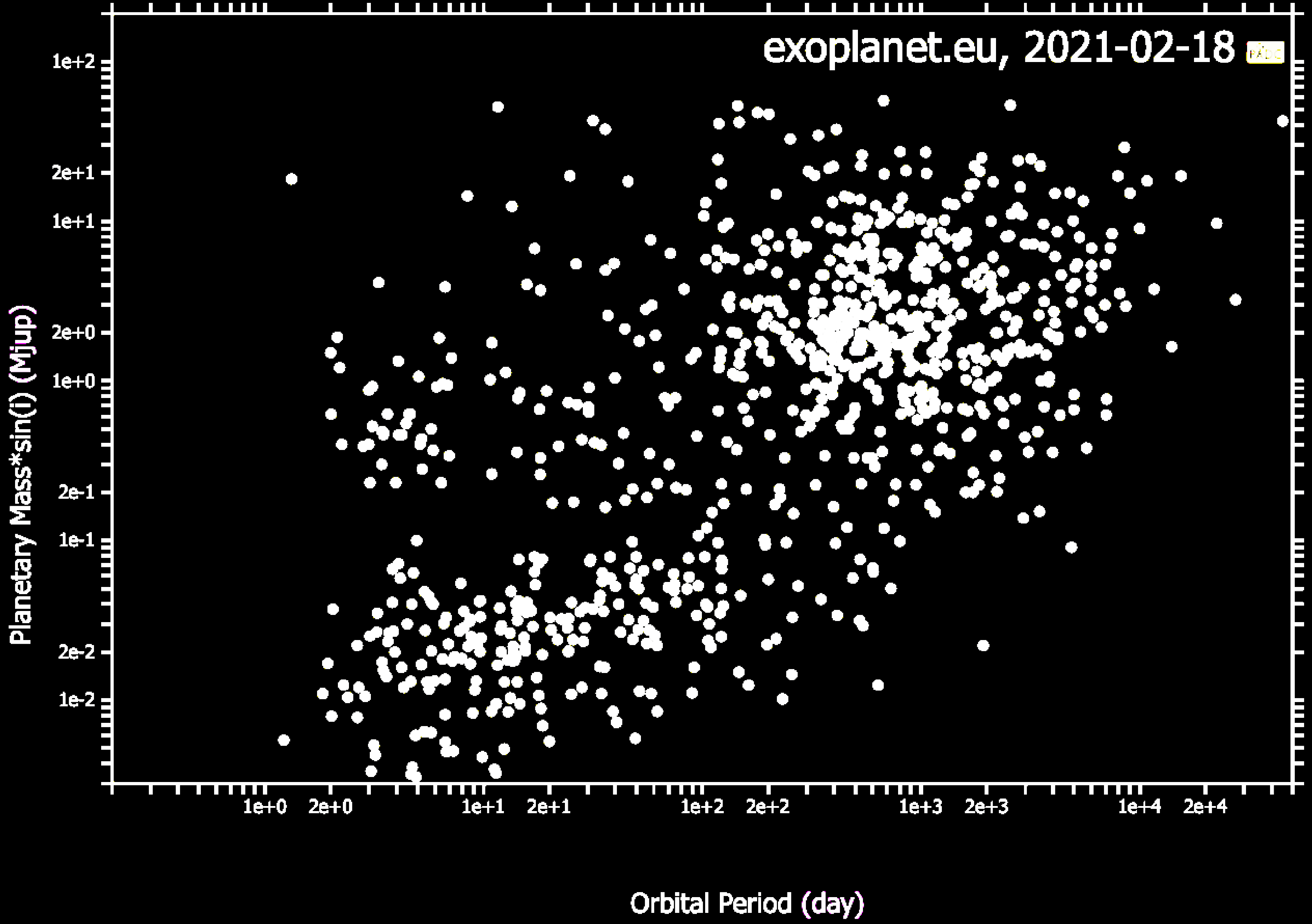
Credit: Pearson Education

We now understand that there are several mechanisms by which giant planet can migrate from beyond the frost line in toward the star. Sadly, this probably spells doom for the inner terrestrial planets in these systems.

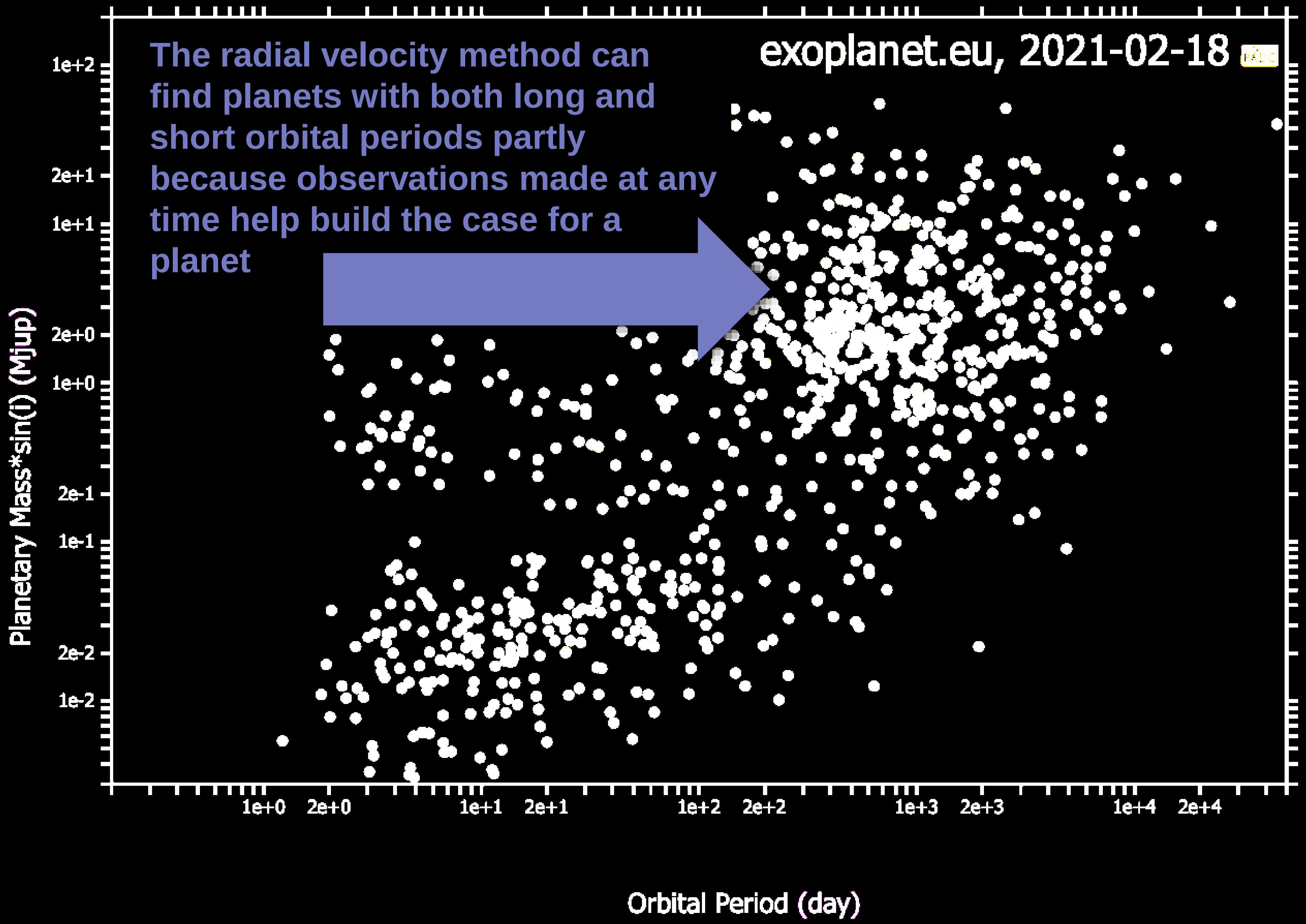


Credit: Mills & Fabrycky, UChicago

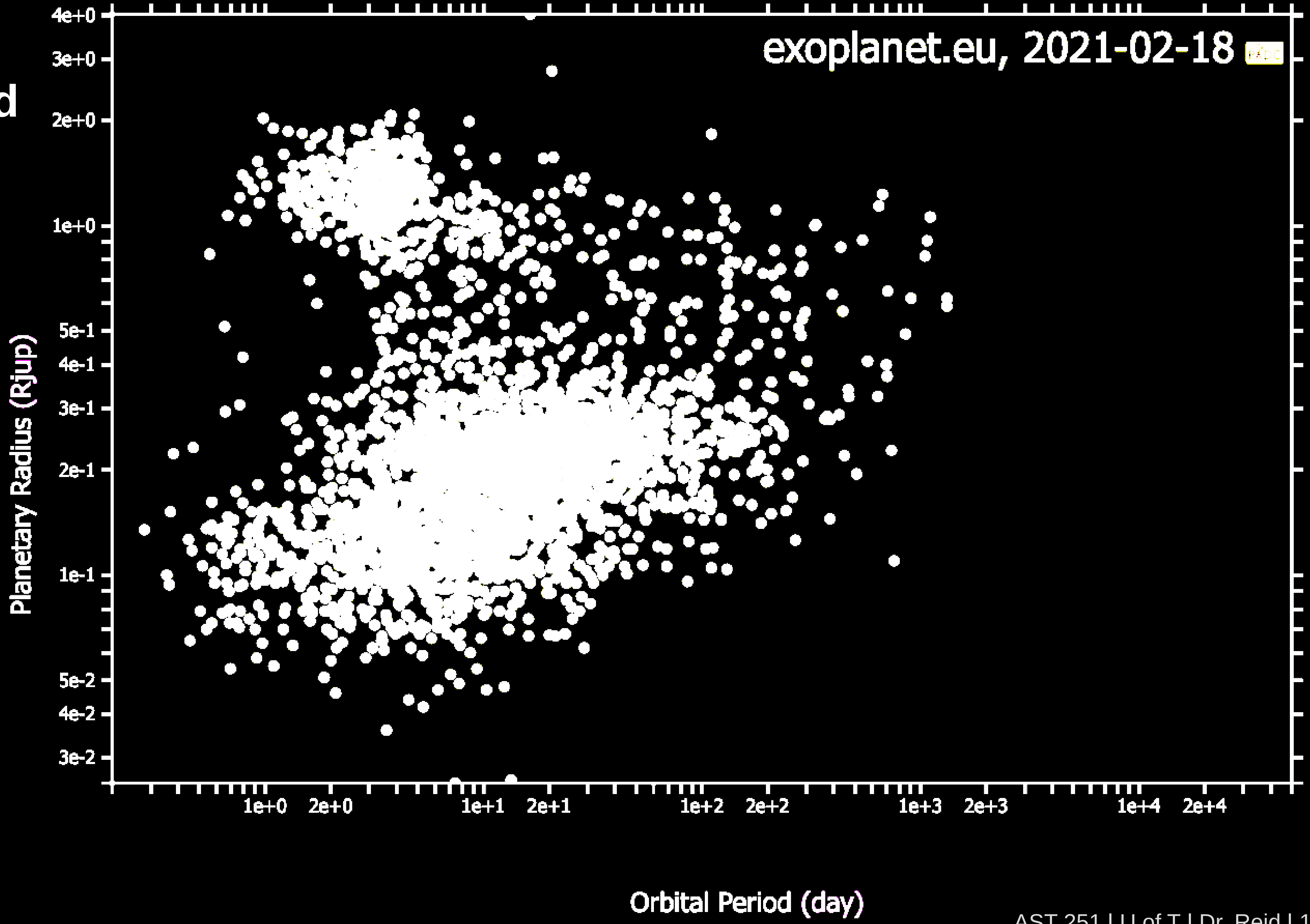
Mass*sin(i) vs period for planets detected using the radial velocity method



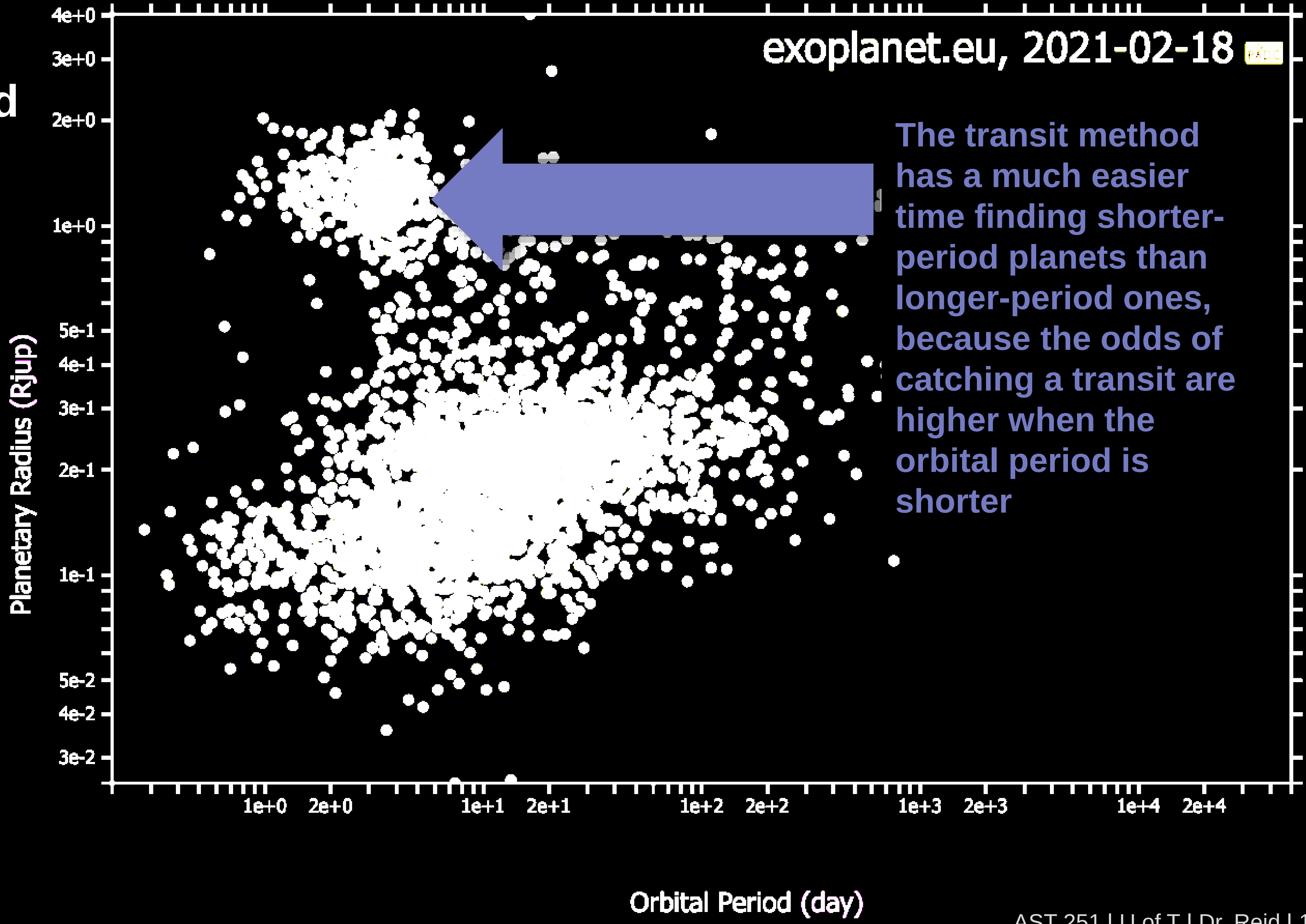
Mass*sin(i) vs period for planets detected using the radial velocity method



Radius vs period for planets detected using the transit method

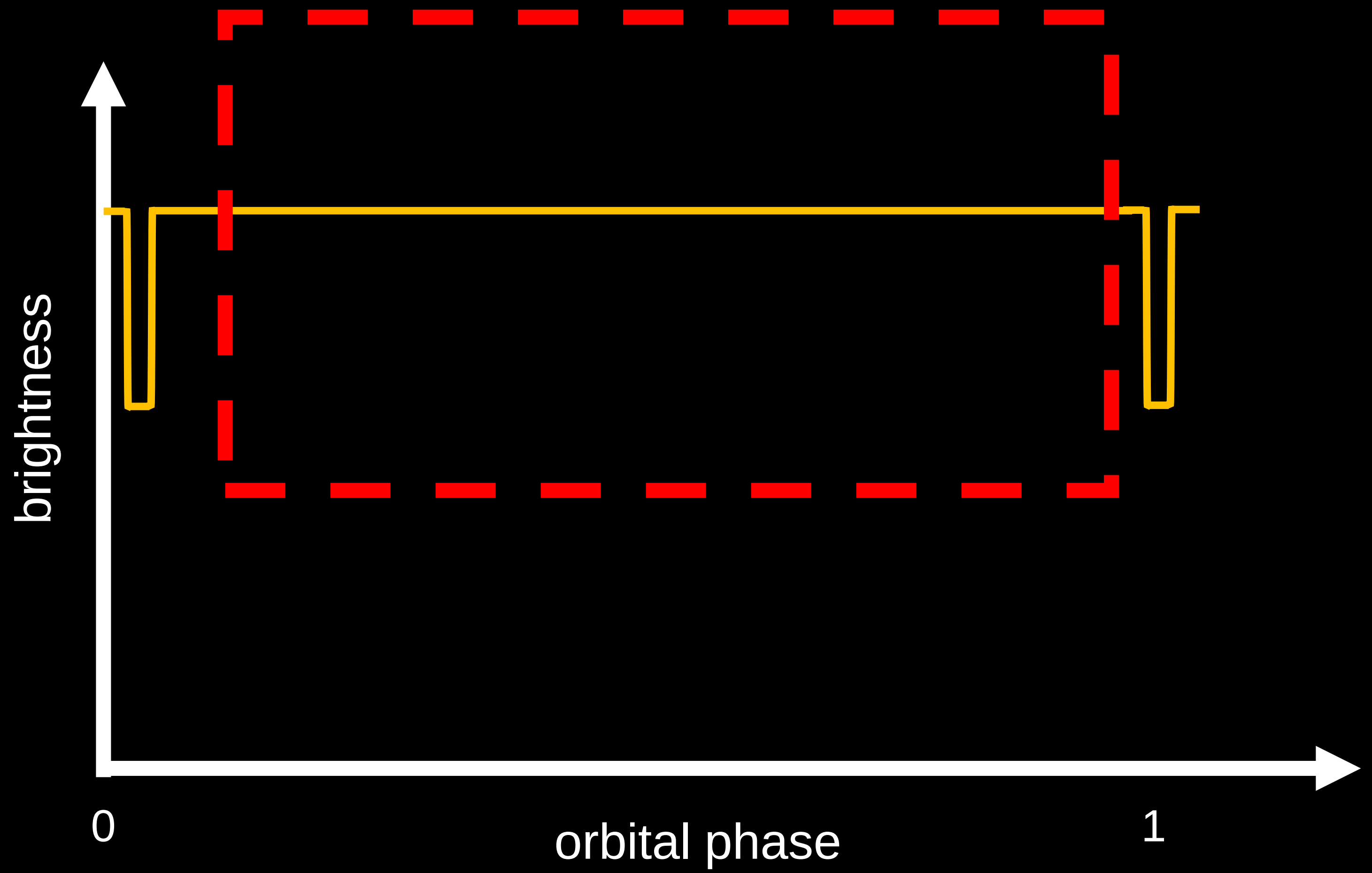


Radius vs period for planets detected using the transit method

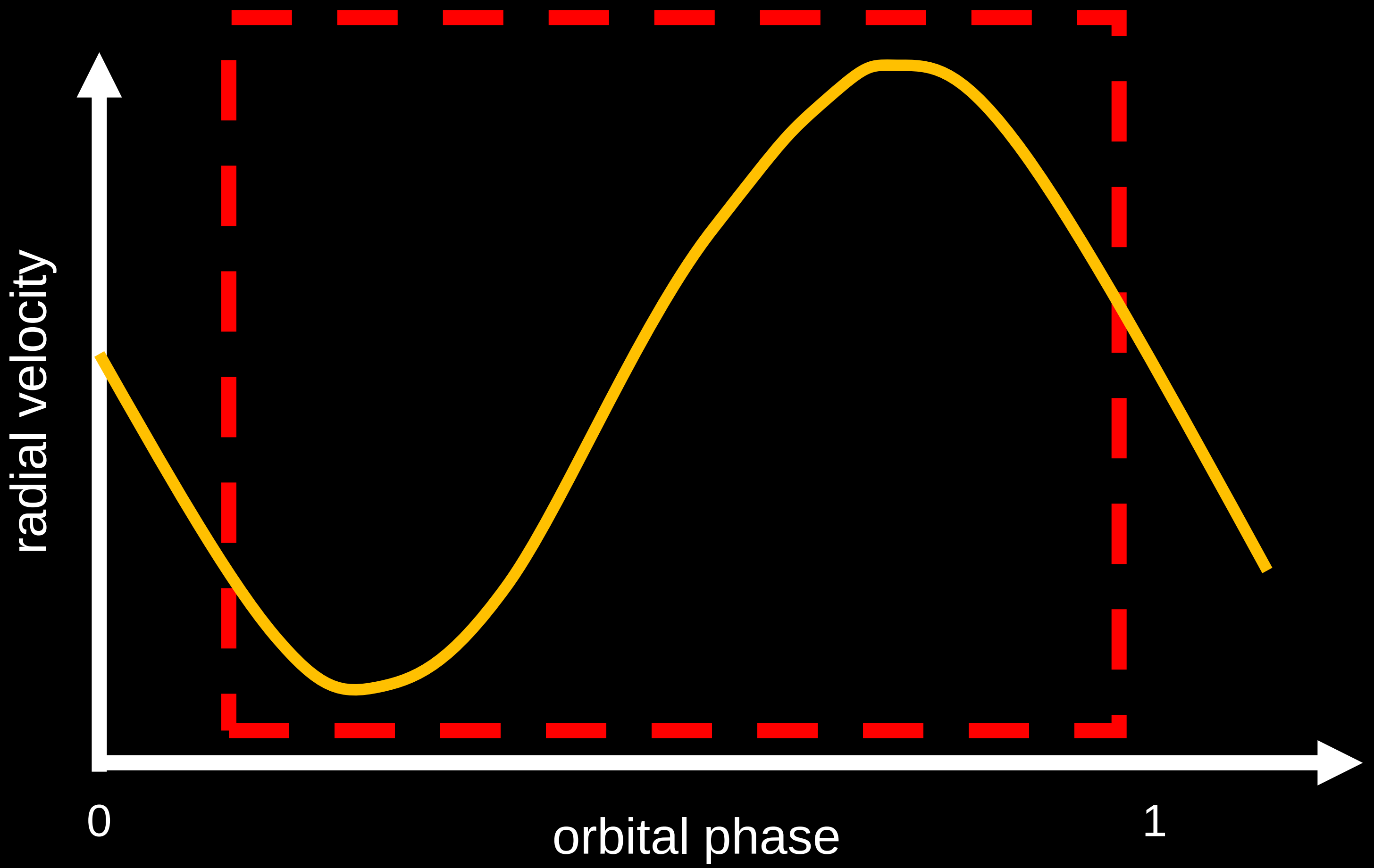


The transit method has a much easier time finding shorter-period planets than longer-period ones, because the odds of catching a transit are higher when the orbital period is shorter

Observing a transiting planetary system for a large fraction of one orbit may not capture even a single transit.



However, the radial velocity method can pick up signs of a planet in less than one orbital period (although several orbits would usually be required to confirm the detection).

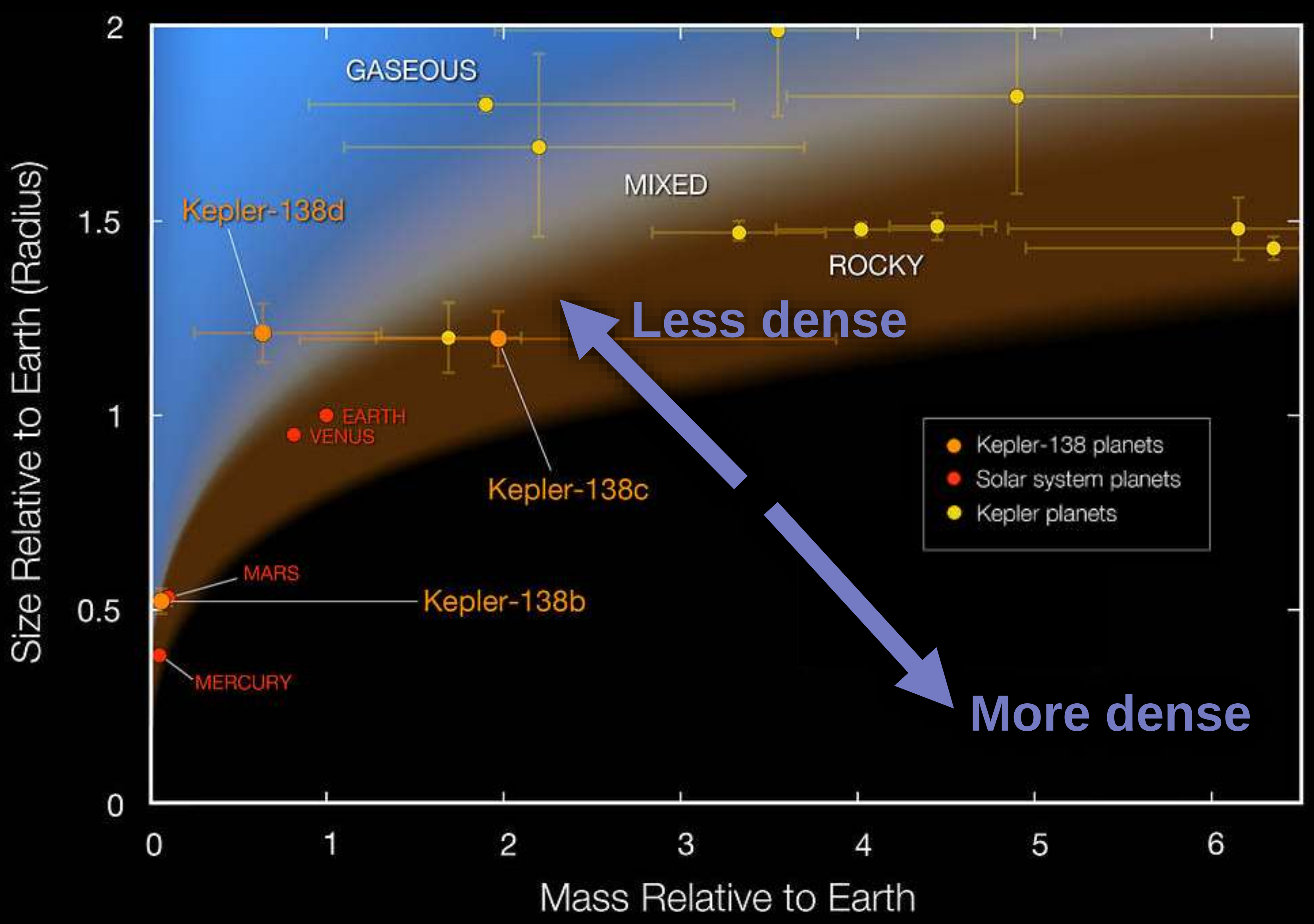


Combining Detection Methods

To determine which planets might be habitable, we need to know much more than just their size or their mass.

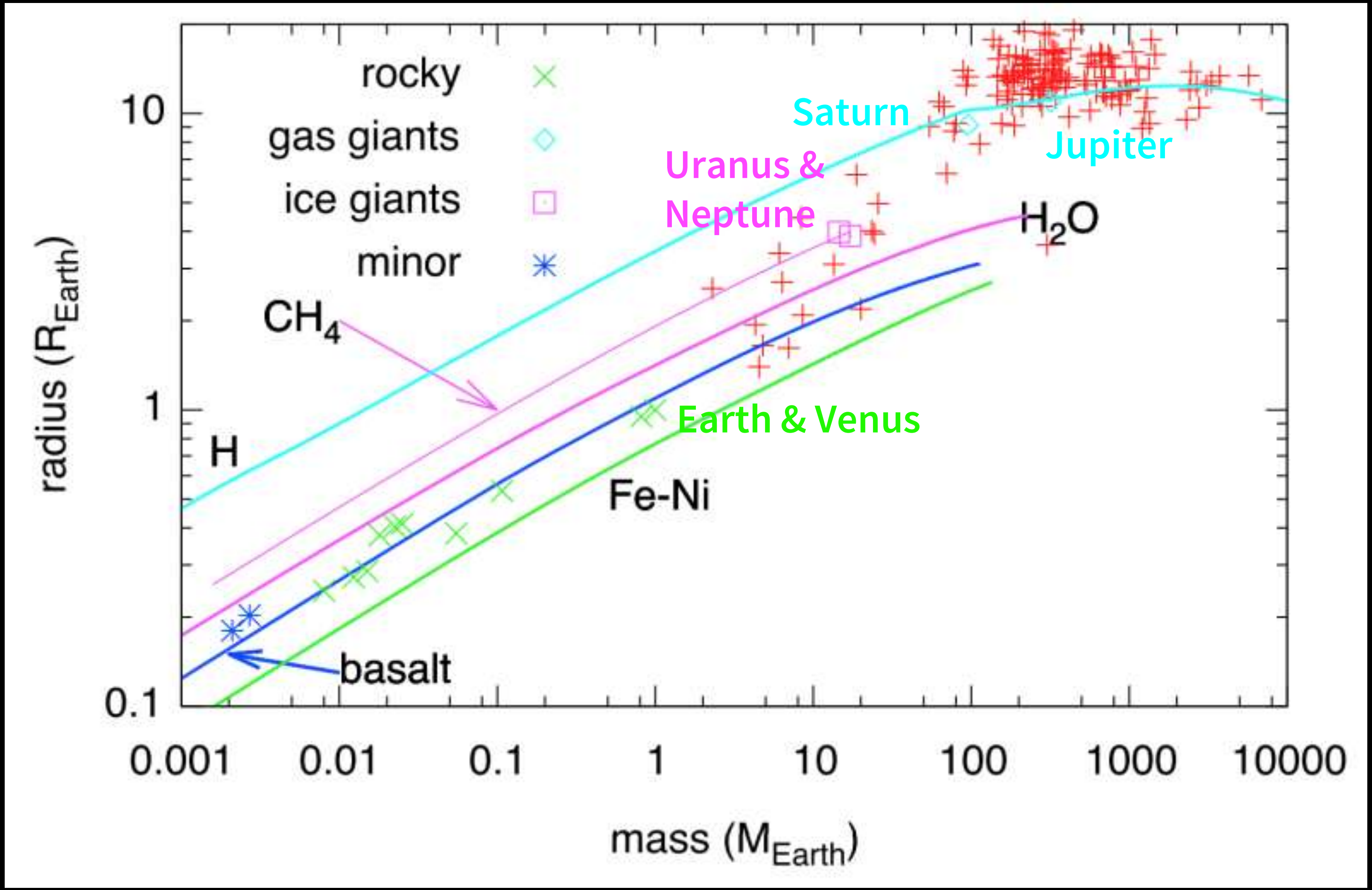
With the planet mass from the radial velocity method and the planet radius from the transit method, we can compute the density of a planet.

Plotting mass versus radius gives us a sense of the likely composition of planets, whether gaseous, rocky, or in between.

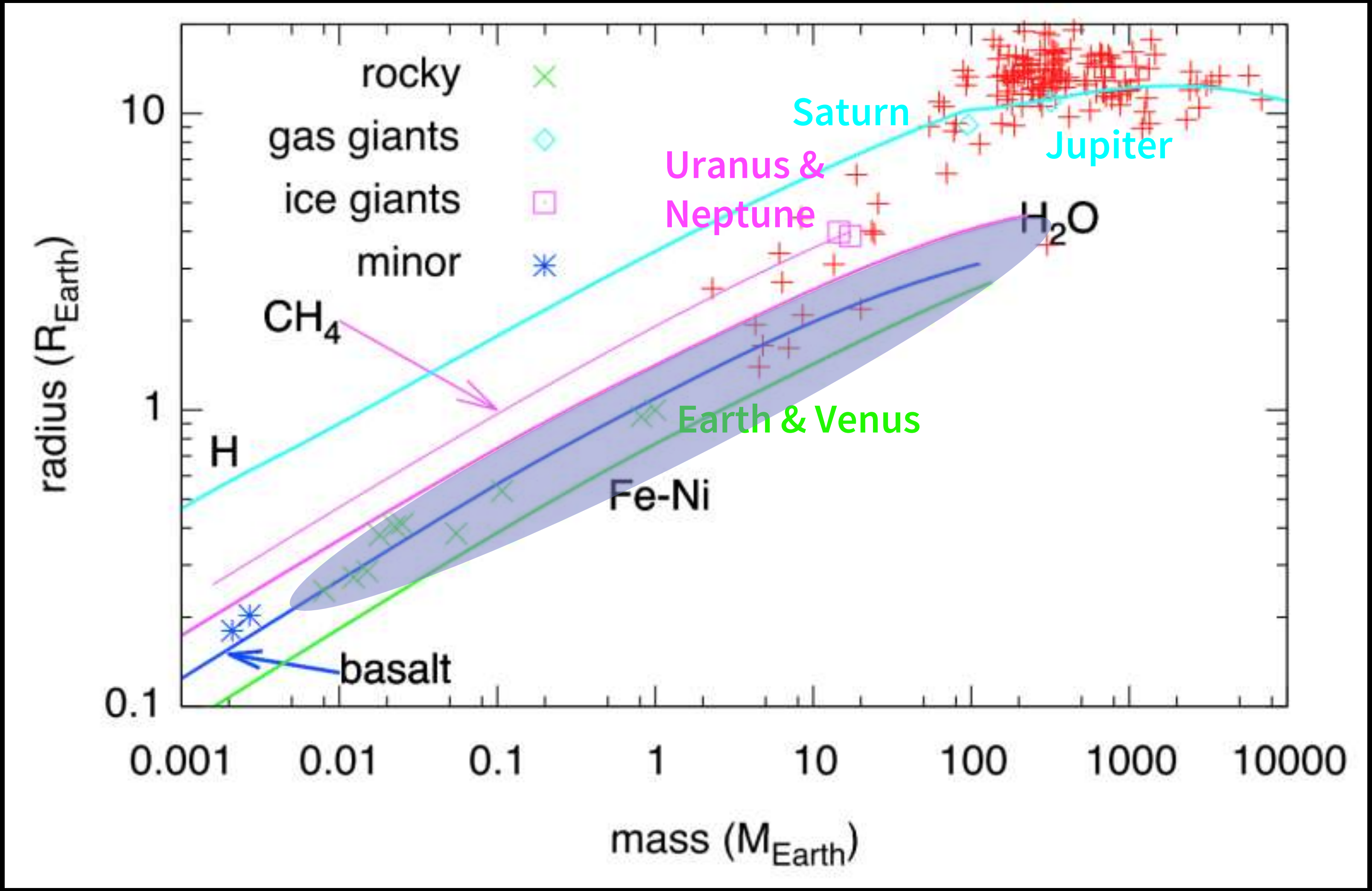


Credit: NASA Ames/W Stenzel

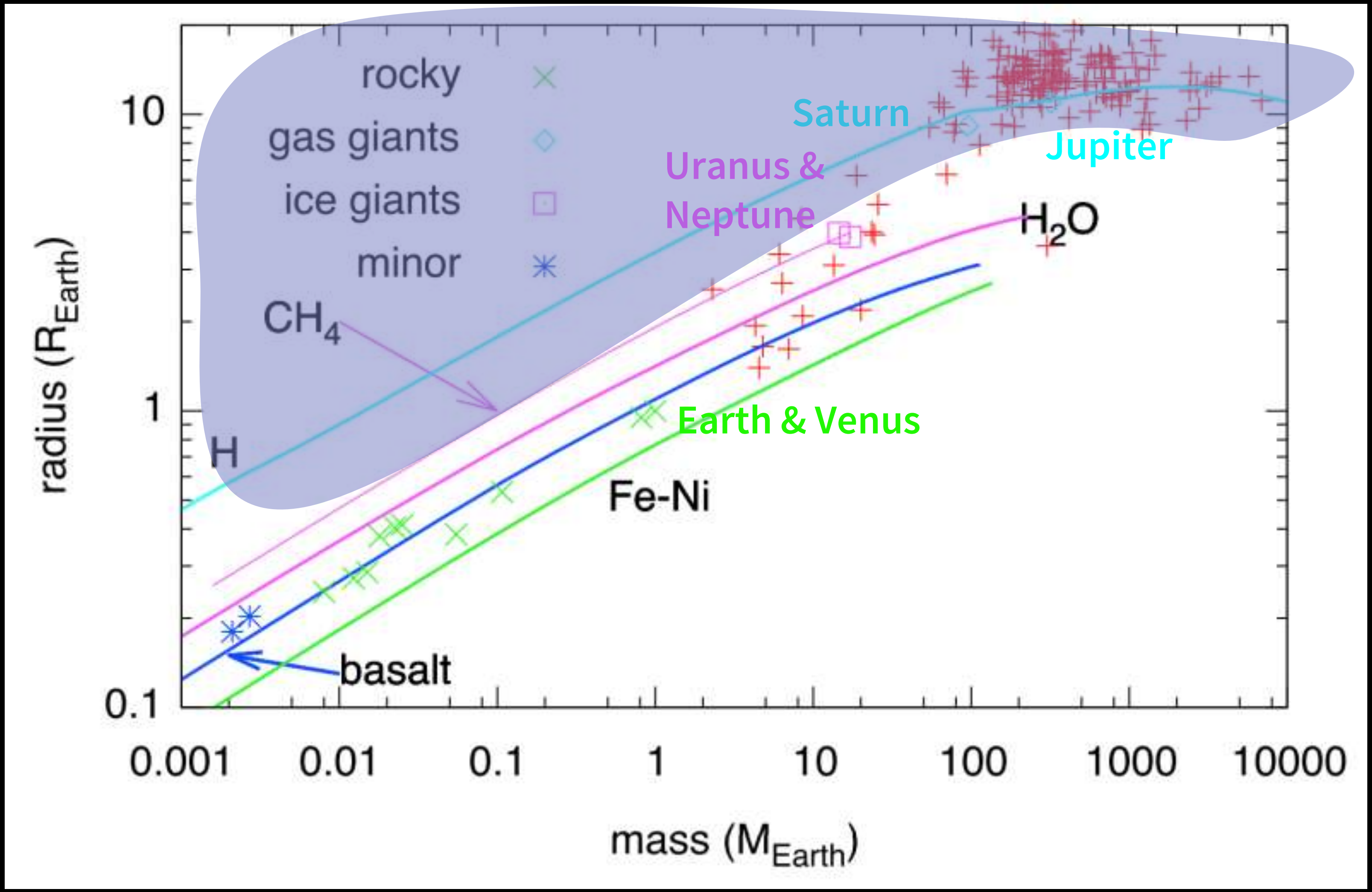
Mass-radius relationships for a wider range of planet types, with exoplanets plotted in red and solar system objects in other colours. (Swift et al., ApJ, 2012)



Exoplanets in the shaded region could be similar to Earth in their bulk properties, but notice that uninhabitable Venus lies in this region as well.



Meanwhile, planets in the upper portion of the diagram are more likely to be gaseous, and therefore probably uninhabitable to life like us.



Concept Check

Which of the following properties of an exoplanet can be obtained directly from the radial velocity method but not from the conventional transit method?

A. mass
B. orbital semimajor axis
C. radius
D. equilibrium temperature
E. atmospheric composition

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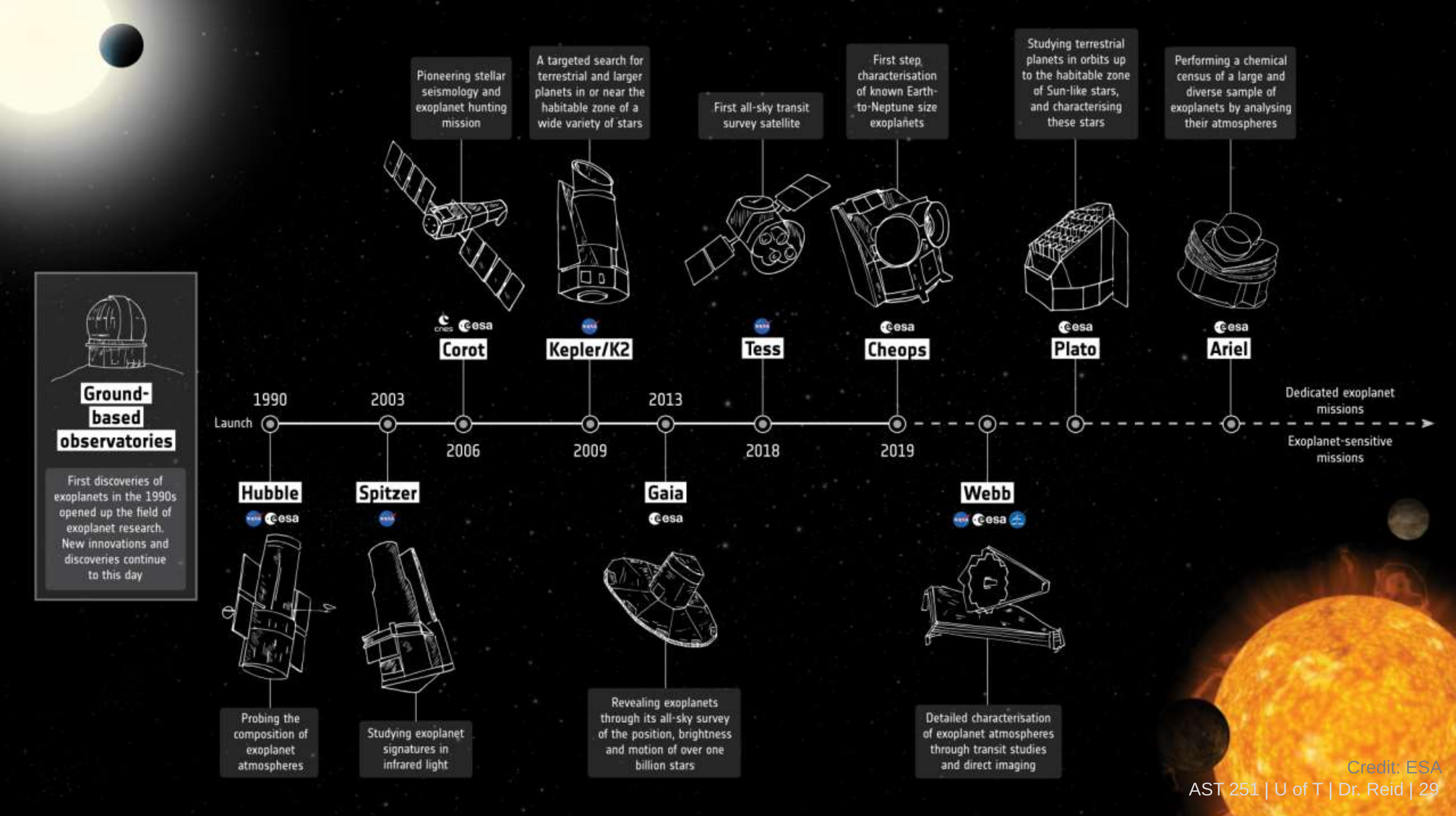
The Future of Exoplanet Searches

After all of this discussion about *detecting* exoplanets, what we really want is to know whether they are *habitable*.

Establishing habitability is extremely challenging with current technologies. So, several new space telescopes are being built.


Ground-based observatories
First discoveries of exoplanets in the 1990s opened up the field of exoplanet research. New innovations and discoveries continue to this day
Launch
1990
2003
2006
2009
2013
2018
2019
Pioneering stellar seismology and exoplanet hunting mission
Corot
A targeted search for terrestrial and larger planets in or near the habitable zone of a wide variety of stars
Kepler/K2
First all-sky transit survey satellite
Tess
First step characterisation of known Earth-to-Neptune size exoplanets
Cheops
Studying terrestrial planets in orbits up to the habitable zone of Sun-like stars, and characterising these stars
Plato
Performing a chemical census of a large and diverse sample of exoplanets by analysing their atmospheres
Ariel
Dedicated exoplanet missions
Exoplanet-sensitive missions
Hubble
Probing the composition of exoplanet atmospheres
Spitzer
Studying exoplanet signatures in infrared light
Gaia
Revealing exoplanets through its all-sky survey of the position, brightness and motion of over one billion stars
Webb
Detailed characterisation of exoplanet atmospheres through transit studies and direct imaging

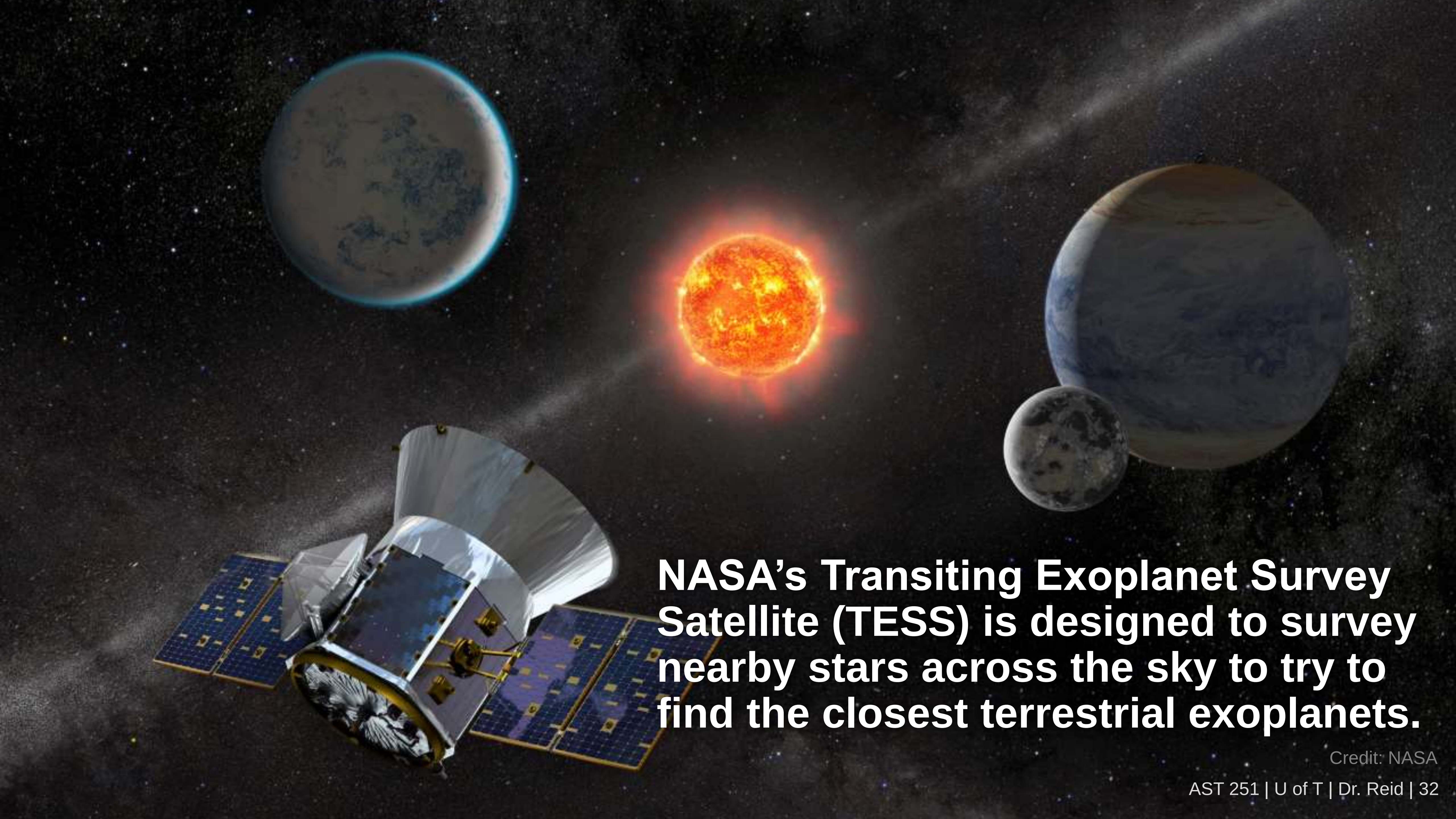
Credit: ESA

Perhaps the biggest uncertainty in establishing habitability is an exoplanet's atmosphere.

Venus and Earth are nearly the same size and mass, but Venus' thick CO_2 atmosphere renders it uninhabitable.

Credit: NASA

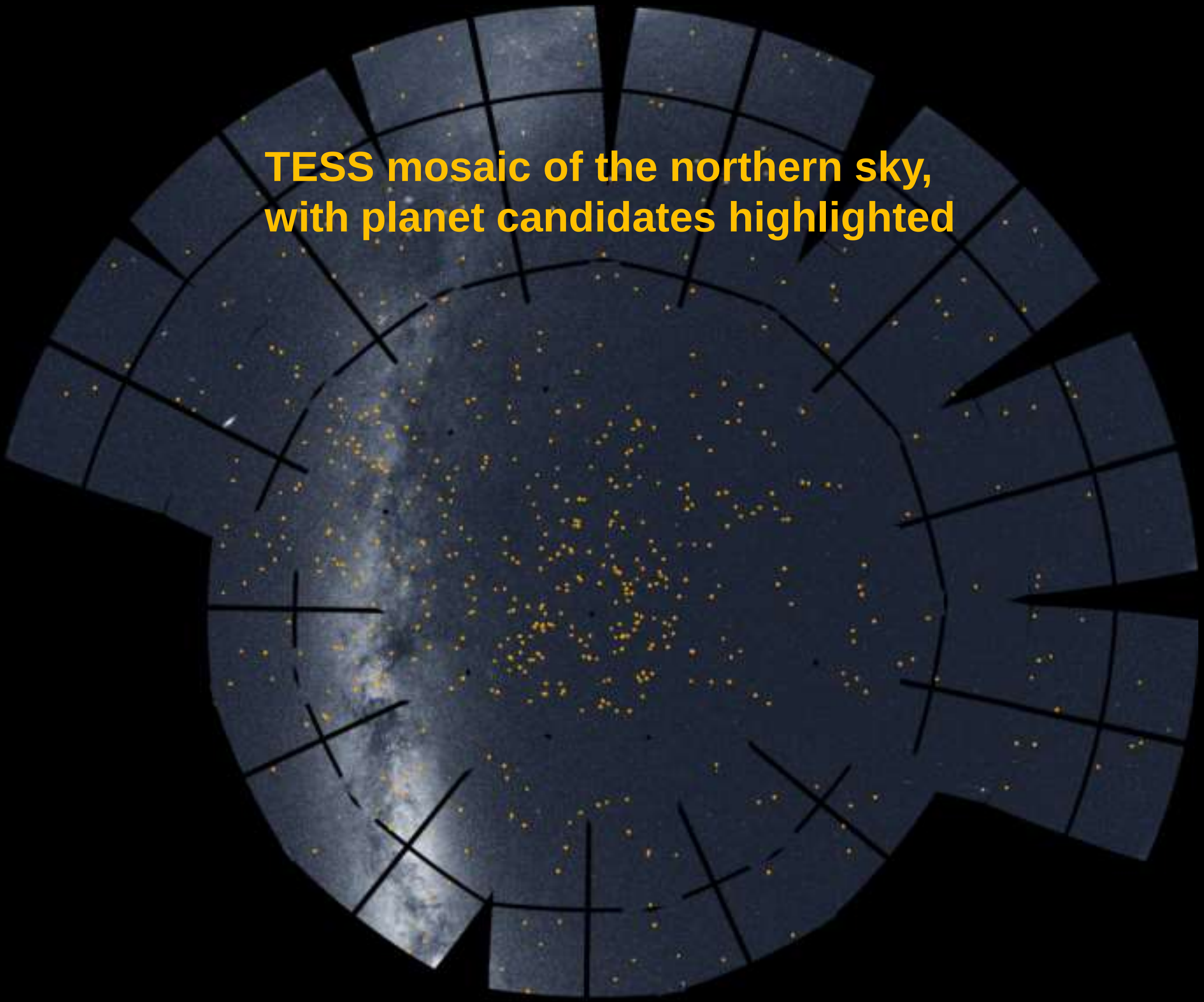
A major challenge in characterizing exoplanet atmospheres is that many of the planets detected so far are simply too far away.



NASA’s Transiting Exoplanet Survey Satellite (TESS) is designed to survey nearby stars across the sky to try to find the closest terrestrial exoplanets.

Credit: NASA

Credit: NASA



The Kepler space telescope stared at a small patch of sky continuously for years.

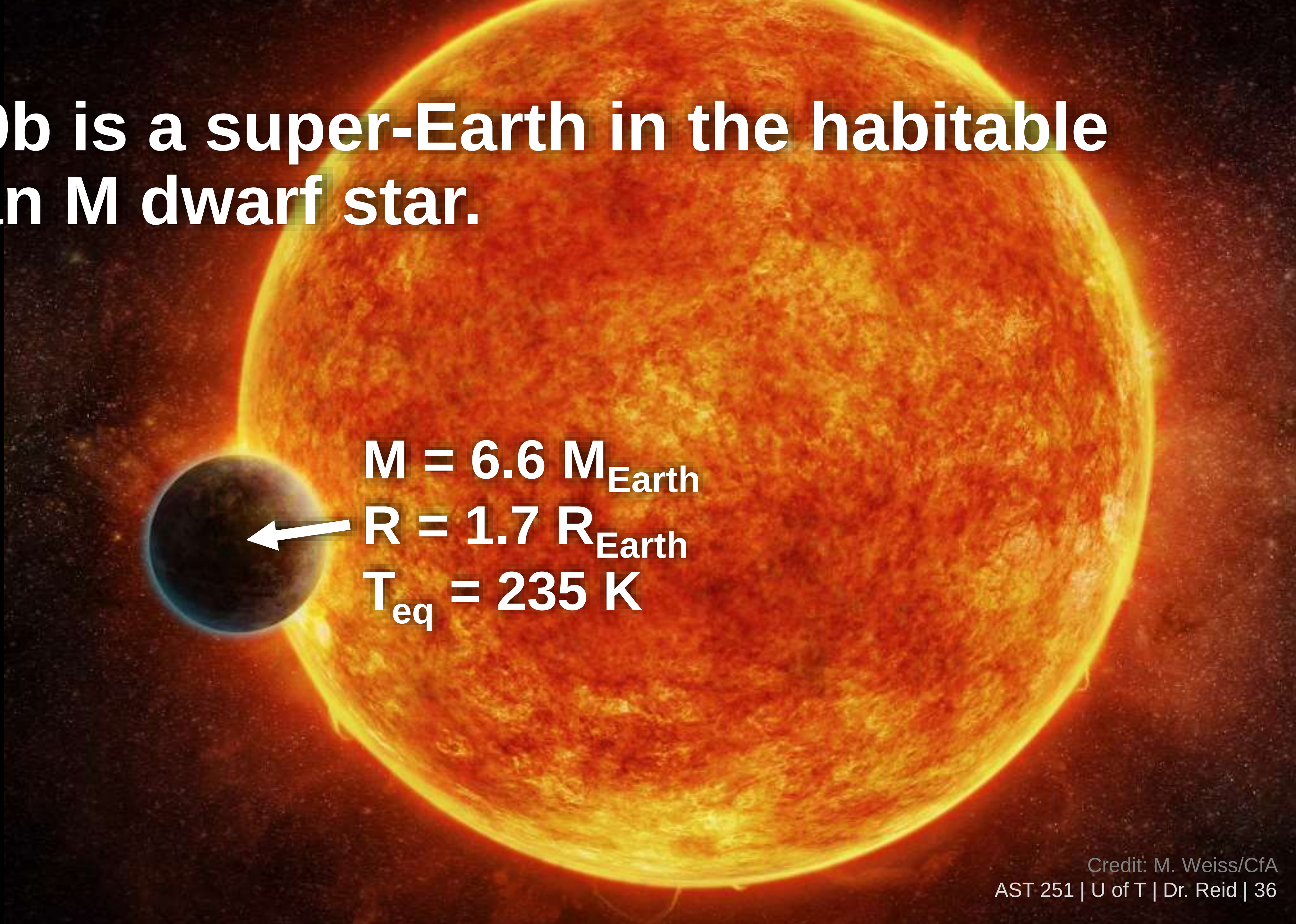
TESS stared at each patch of sky for only 27 days, but will cover 85% of the sky, including thousands of nearby G, K, and M stars.

Credit: NASA

The European Space Agency’s CHEOPS telescope will use the transit method to very precisely measure the sizes of known exoplanets, allowing us to calculate their densities very accurately. It will also search for exoplanet moons and rings.

Credit: ESA

LHS 1140b is a super-Earth in the habitable zone of an M dwarf star.



Credit: M. Weiss/CfA

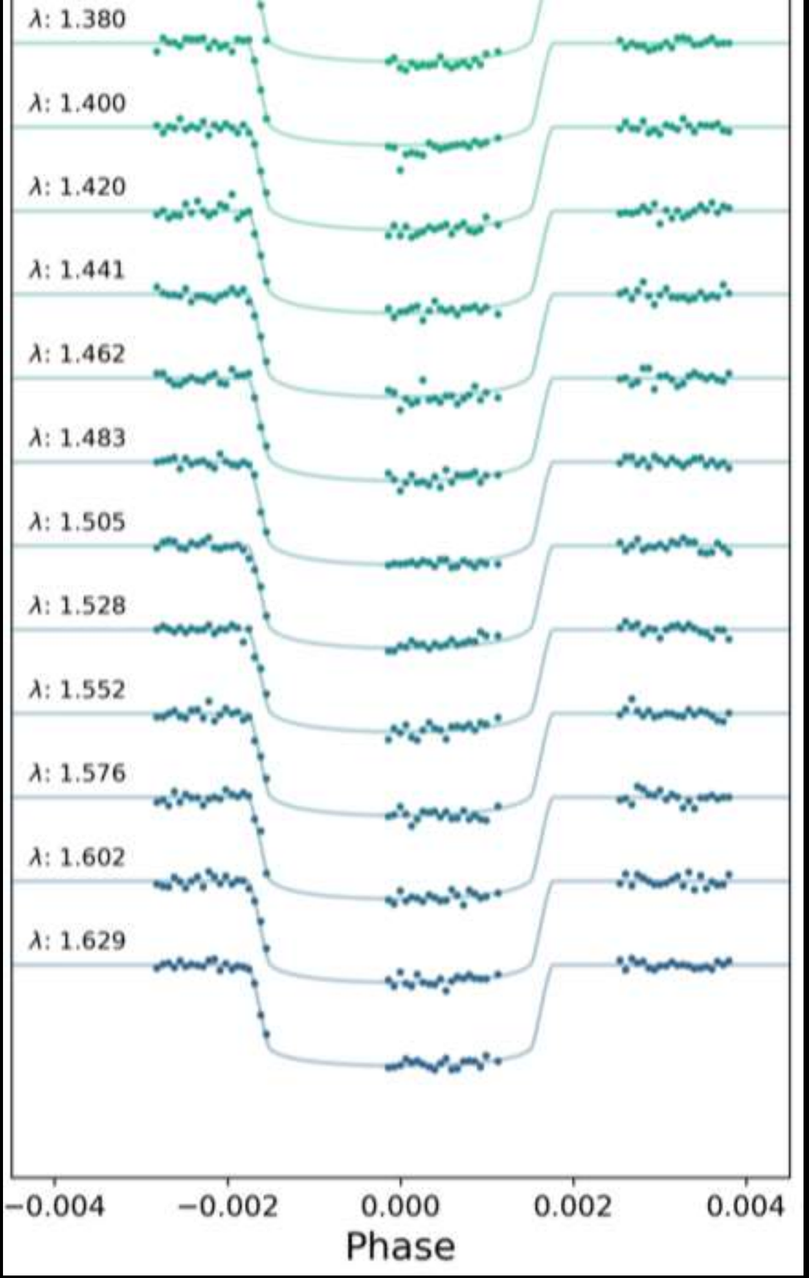
The James Web Space Telescope (JWST) will follow up on TESS planets to try to characterize their atmospheres. What can we expect to find?

Credit: NASA

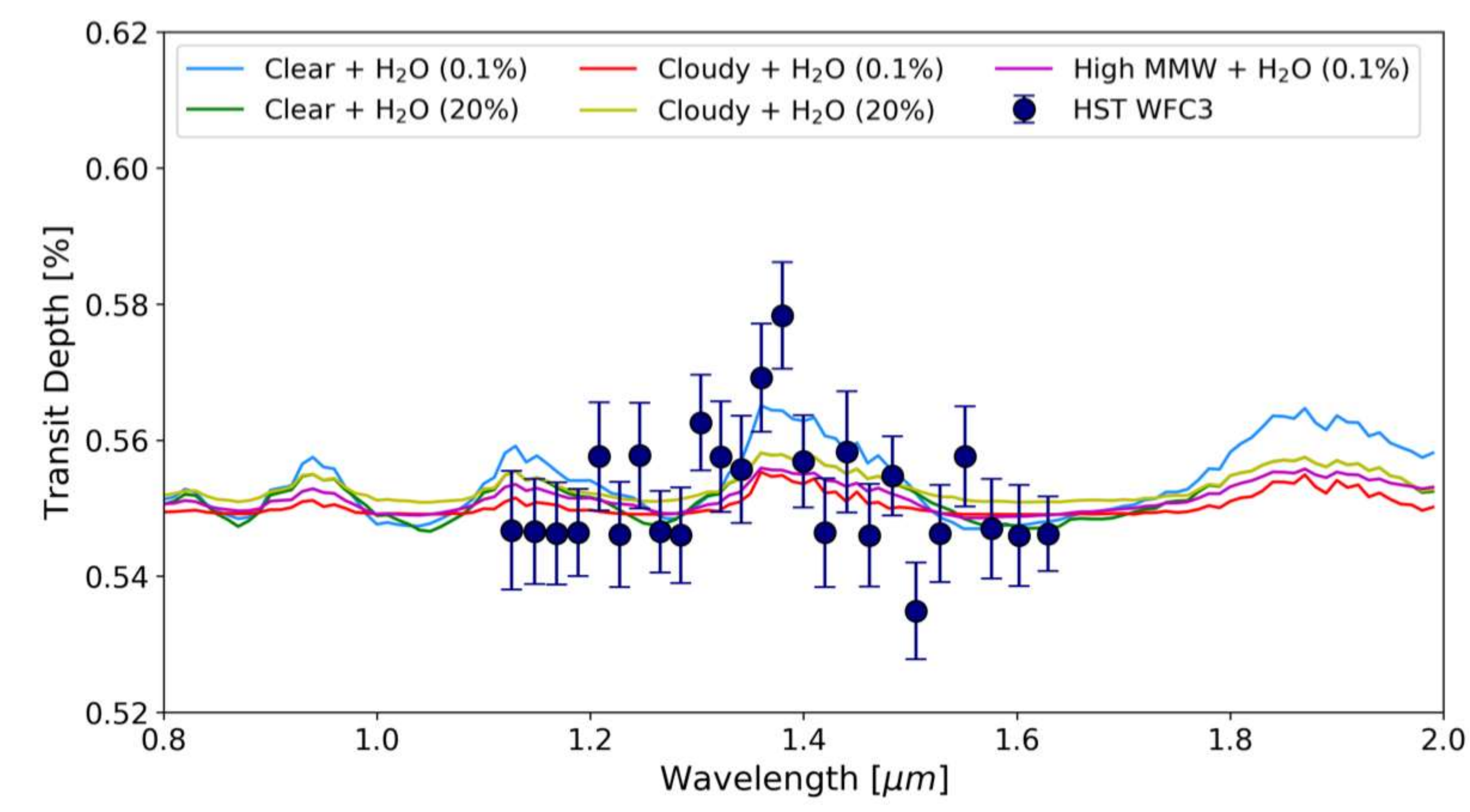
From theoretical models, we would expect LHS 1140b to have a transparent H/He atmosphere. But what else is mixed in?

Credit: ESO/spaceengine.org

Edwards et al. (2020) used the Hubble Space Telescope to do transit spectroscopy on LHS 1140b. They measured the transit depth at many wavelengths (λ) and measured tiny differences in depth.

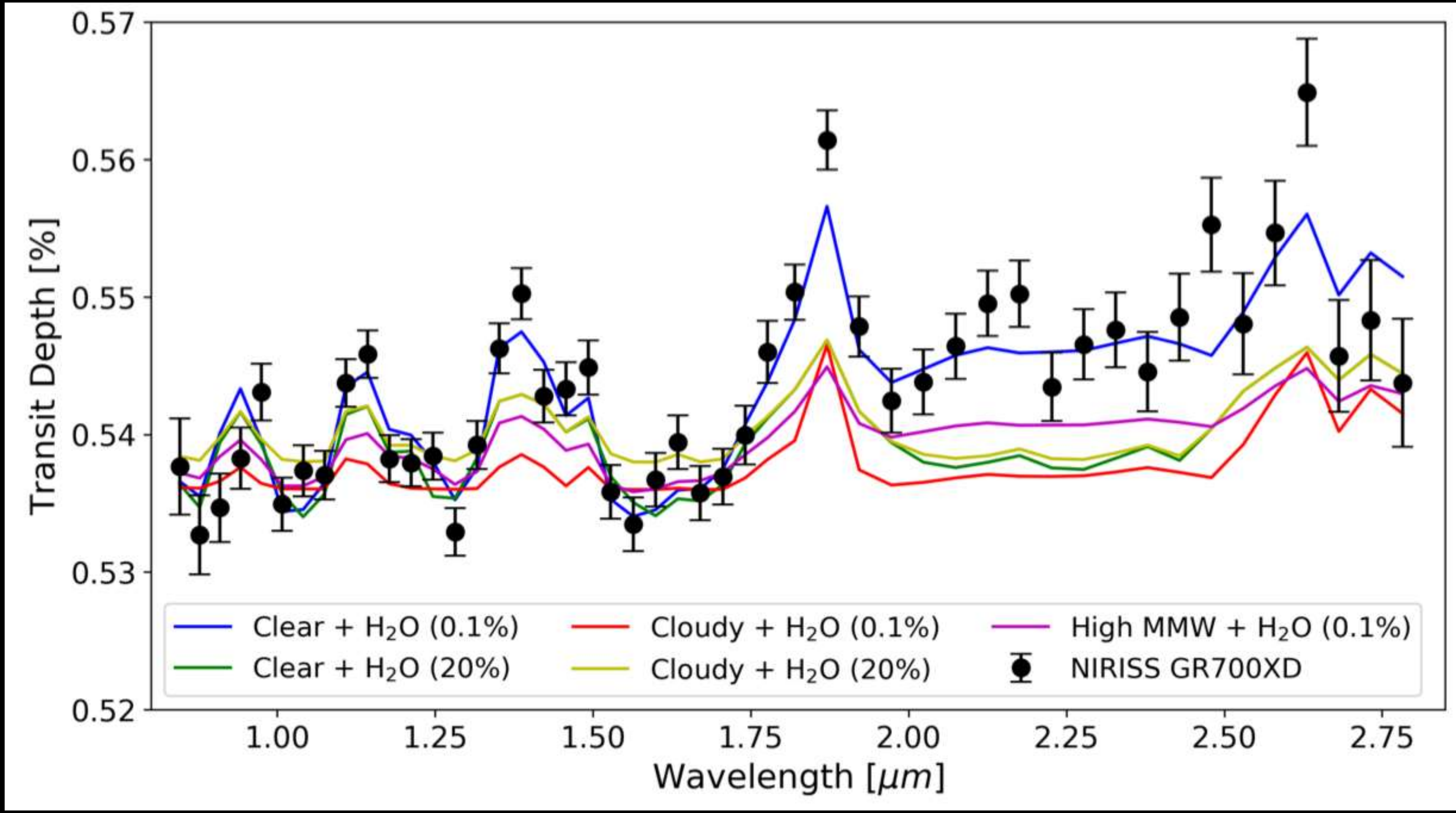


This is essentially the best that can be done with current telescopes, and what it reveals is that there may be water in this planet's atmosphere.



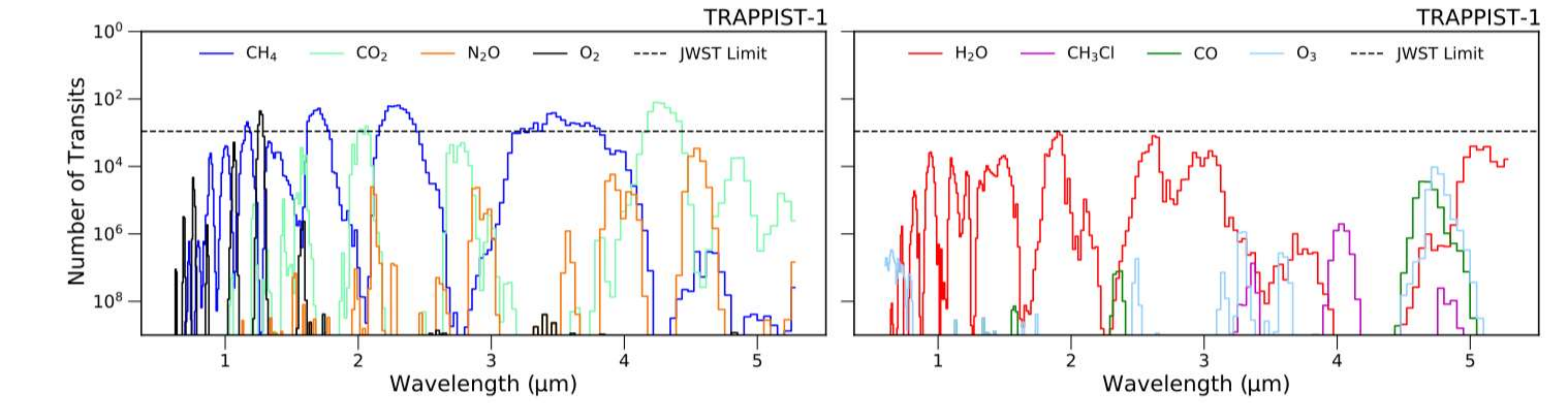
Credit: Edwards et al. (2020)

With JWST, it should be possible to improve these measurements and make finer distinctions between atmospheric models.



Credit: Edwards et al. (2020)

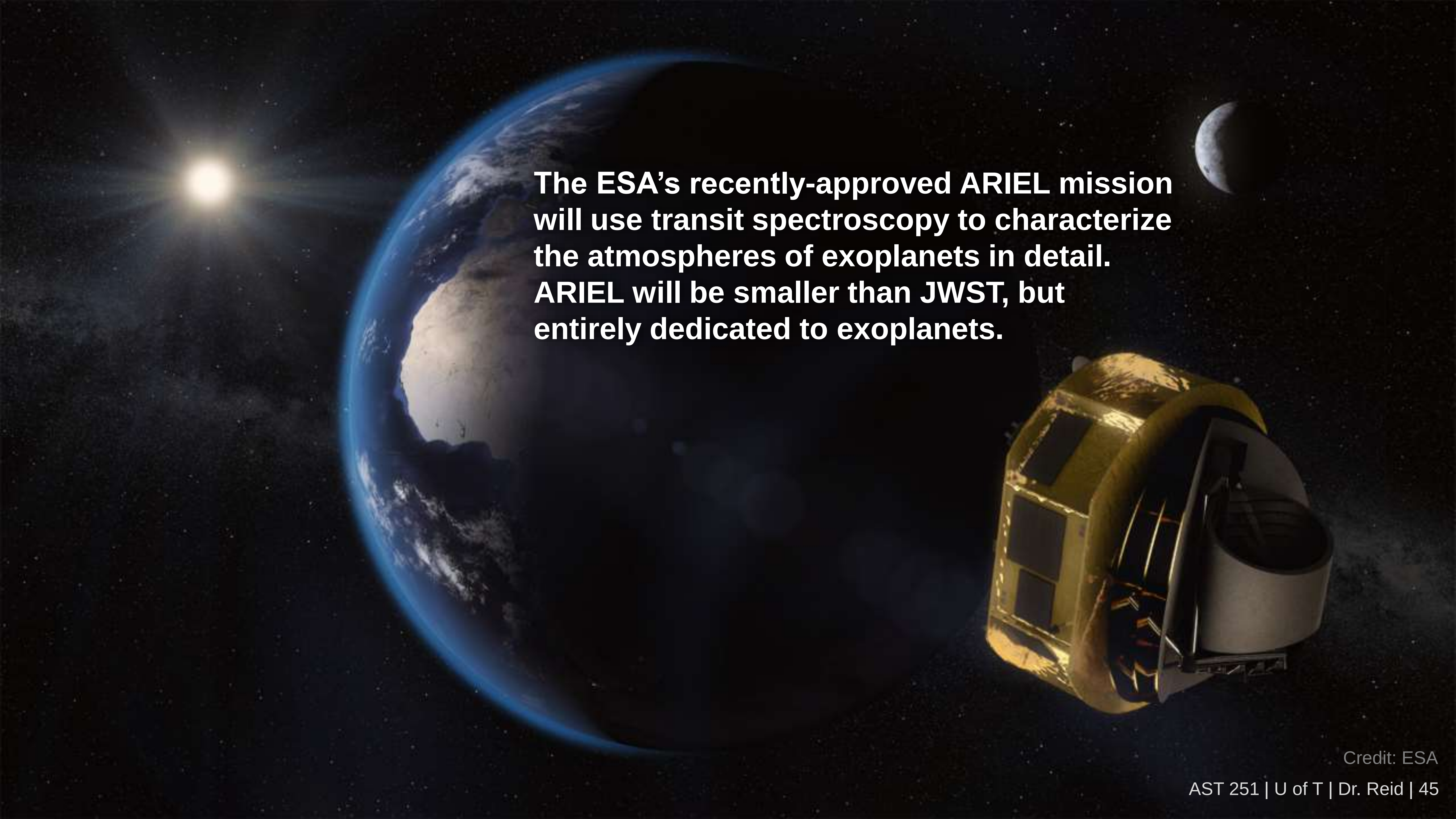
What about characterizing the atmospheres of Earth-like exoplanets? Will JWST be able to do that?



Number of transits required for JWST to detect various molecules in the atmosphere of an Earth-like planet if the planet were orbiting the star TRAPPIST-1. The maximum number of transits JWST could see in its 10-year lifetime is shown by the dashed line. (Gialuca et al., 2021)

The ESA’s 2026 PLATO mission will use the transit method to find Earth-sized planets orbiting in the habitable zones of Sun-like stars. These will be ideal for atmospheric characterization.

Credit: OHB System AG



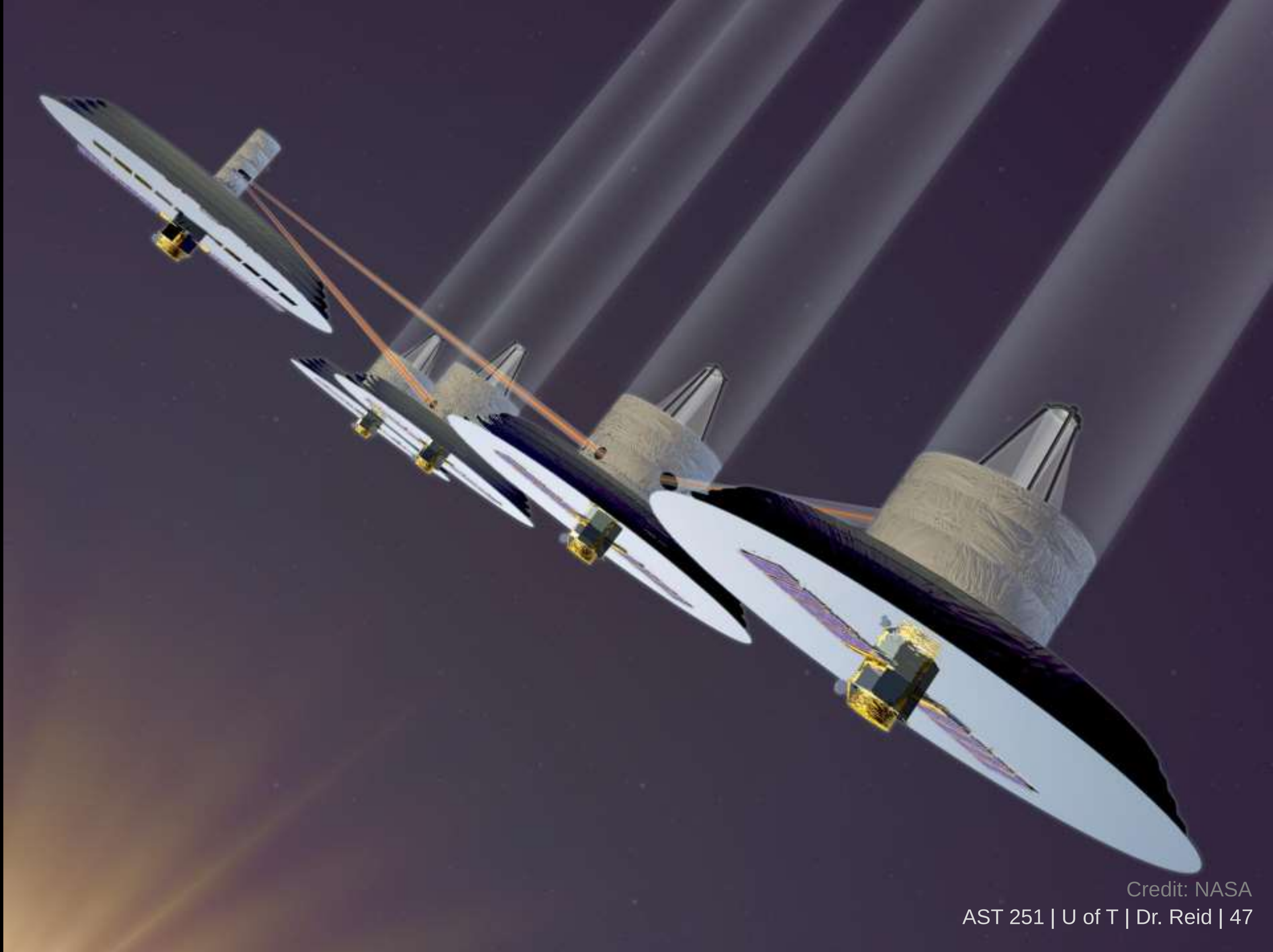
The ESA's recently-approved ARIEL mission will use transit spectroscopy to characterize the atmospheres of exoplanets in detail. ARIEL will be smaller than JWST, but entirely dedicated to exoplanets.

Credit: ESA

NASA’s Nancy Grace Roman telescope will be a multi-purpose telescope, intended to study dark energy, but also capable of detecting extremely low mass planets using the gravitational microlensing method. It will also find free-floating or “rogue” planets in interstellar space.

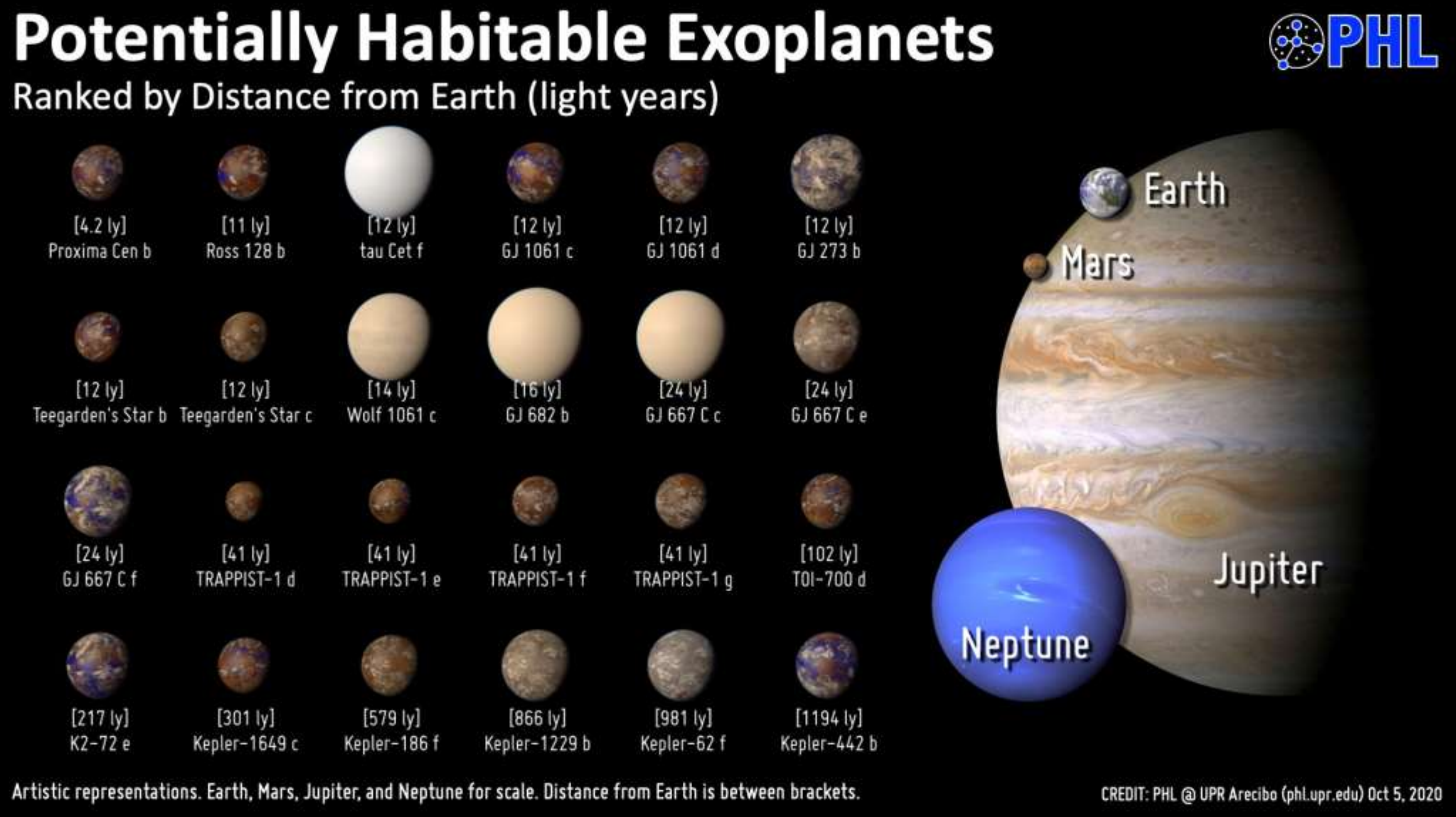
Credit: NASA

The cancelled Terrestrial Planet Finder mission would have directly imaged Earth-sized exoplanets in the habitable zones of nearby stars. One of the main challenges to building it is the technology needed to maintain precise positioning of the satellites.



Credit: NASA

In summary, what can we say about our knowledge of habitable planets?


Potentially Habitable Exoplanets
Ranked by Distance from Earth (light years)
PHL
[4.2 ly] Proxima Cen b
[11 ly] Ross 128 b
[12 ly] tau Cet f
[12 ly] GJ 1061 c
[12 ly] GJ 1061 d
[12 ly] GJ 273 b
[12 ly] Teegarden's Star b
[12 ly] Teegarden's Star c
[14 ly] Wolf 1061 c
[16 ly] GJ 682 b
[24 ly] GJ 667 C c
[24 ly] GJ 667 C e
[24 ly] GJ 667 C f
[41 ly] TRAPPIST-1 d
[41 ly] TRAPPIST-1 e
[41 ly] TRAPPIST-1 f
[41 ly] TRAPPIST-1 g
[102 ly] TOI-700 d
[217 ly] K2-72 e
[301 ly] Kepler-1649 c
[579 ly] Kepler-186 f
[866 ly] Kepler-1229 b
[981 ly] Kepler-62 f
[1194 ly] Kepler-442 b
Earth
Mars
Jupiter
Neptune
Artistic representations. Earth, Mars, Jupiter, and Neptune for scale. Distance from Earth is between brackets.
CREDIT: PHL @ UPR Arecibo (phl.upr.edu) Oct 5, 2020

Name	Type	Mass (M_E)	Radius (R_E)	Flux (S_E)	T_{eq} (K)	Period (days)	Distance (ly)	ESI
001. Teegarden's Star b	M-Warm Terran	≥1.05	—	1.15	264	4.9	12	0.95
002. TOI-700 d (N)	M-Warm Terran	—	1.14	0.87	246	37.4	101	0.93
003. K2-72 e	M-Warm Terran	—	1.29	1.11	261	24.2	217	0.90
004. TRAPPIST-1 d	M-Warm Subterran	0.41	0.77	1.14	263	4.0	41	0.90
005. Kepler-1649 c (N)	M-Warm Terran	—	1.06	0.75	237	19.5	301	0.90
006. Proxima Cen b	M-Warm Terran	≥1.27	—	0.70	228	11.2	4.2	0.87
007. GJ 1061 d (N)	M-Warm Terran	≥1.64	—	0.69	218	13.0	12	0.86
008. GJ 1061 c (N)	M-Warm Terran	≥1.74	—	1.45	275	6.7	12	0.86
009. Ross 128 b	M-Warm Terran	≥1.40	—	1.48	280	9.9	11	0.86
010. GJ 273 b	M-Warm Terran	≥2.89	—	1.06	258	18.6	12	0.85
011. TRAPPIST-1 e	M-Warm Terran	0.62	0.92	0.66	230	6.1	41	0.85
012. Kepler-442 b	K-Warm Terran	—	1.35	0.70	233	112.3	1193	0.84
013. Wolf 1061 c	M-Warm Terran	≥3.41	—	1.30	271	17.9	14	0.80
014. GJ 667 C c	M-Warm Terran	≥3.81	—	0.88	247	28.1	24	0.80
015. GJ 667 C f	M-Warm Terran	≥2.54	—	0.56	221	39.0	24	0.77
016. Kepler-1229 b	M-Warm Terran	—	1.40	0.49	213	86.8	865	0.73
017. TRAPPIST-1 f	M-Warm Terran	0.68	1.04	0.38	200	9.2	41	0.68
018. Kepler-62 f	K-Warm Terran	—	1.41	0.41	204	267.3	981	0.68
019. Teegarden's Star c	M-Warm Terran	≥1.11	—	0.37	199	11.4	12	0.68
020. Kepler-186 f	M-Warm Terran	—	1.17	0.29	188	129.9	579	0.61
021. GJ 667 C e	M-Warm Terran	≥2.54	—	0.30	189	62.2	24	0.60
022. tau Cet f	G-Warm Terran	≥3.93	—	0.32	190	636.1	12	0.58
023. TRAPPIST-1 g	M-Warm Terran	1.34	1.13	0.26	181	12.4	41	0.58
024. GJ 682 b	M-Warm Terran	≥4.40	—	0.31	190	17.5	16	0.57

Credit: PHL @ UPR Arecibo

Rogue Planets

So far, we've been assuming that all planets orbit stars. However, there are several methods by which planets can be ejected from their original solar systems and thrown into interstellar space.

We call these rogue planets.

This object, named CFBDSIR J214947.2-040308.9, is either a massive rogue planet or a failed star.

Credit: ESO/P. Delorme

In September 2020, astronomers using the gravitational microlensing technique detected what may be a terrestrial rogue planet (Mroz et al., 2020)

Credit: NASA/JPL-Caltech/R. Hurt (Caltech-IPAC)

You might think that, without a star for energy, there’s no way a rogue planet could be habitable.

We’ll return to this point…

What would it be like to visit—or live on—a planet with no star?