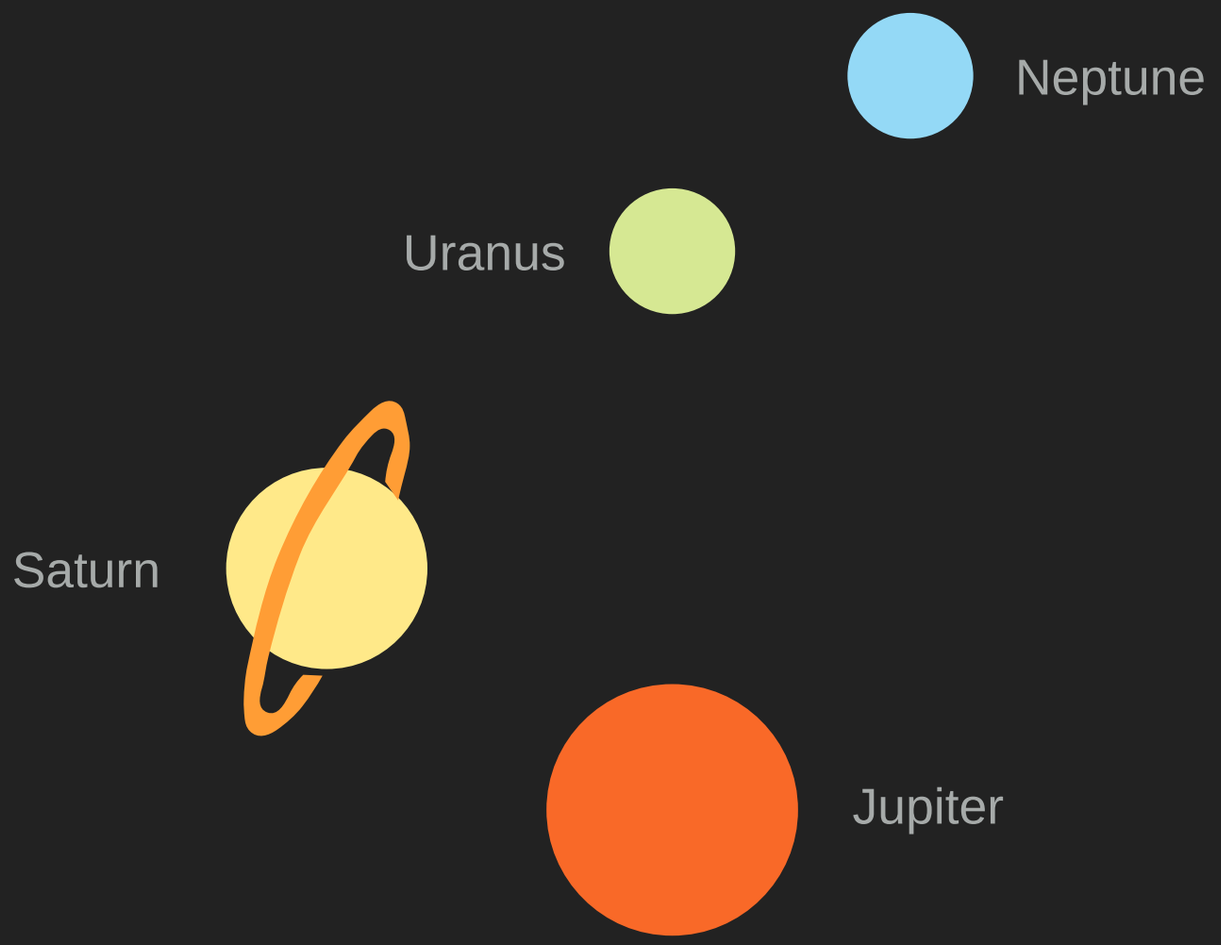
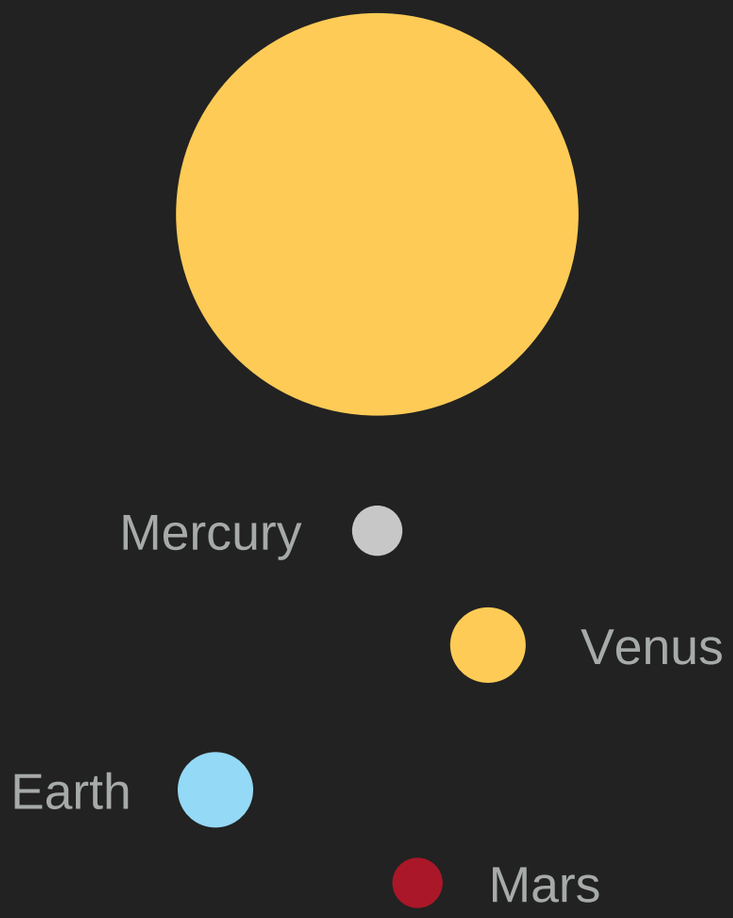
Hunting Habitable Shadows

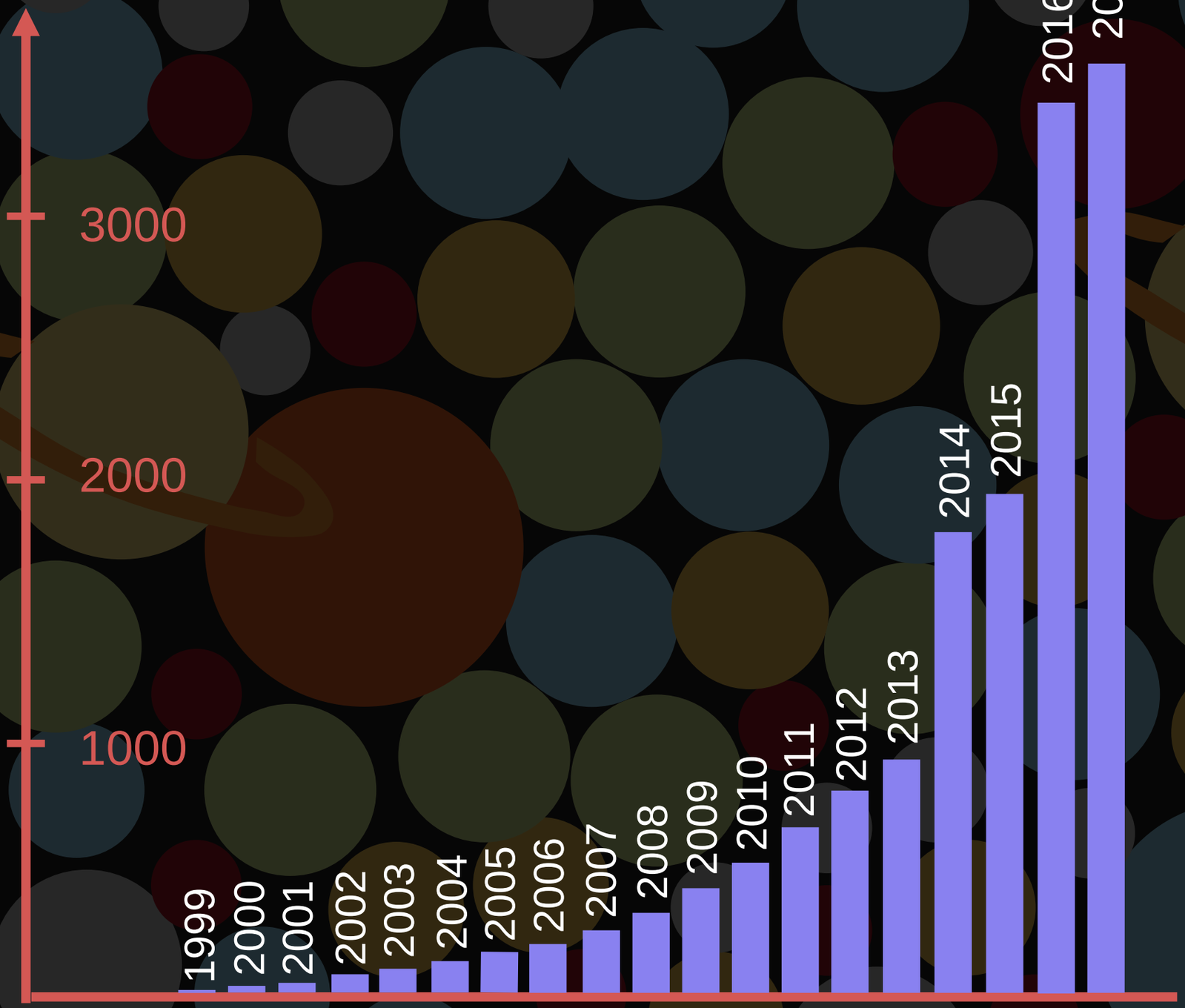
Elizabeth Tasker

JAXA Explore to Realize


Neptune
Uranus
Saturn
Jupiter


Mercury
Venus
Earth
Mars

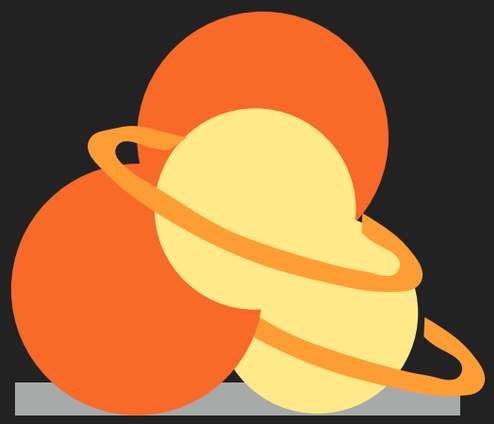

Saturn



Our first generation of planet hunting instruments gave us numbers

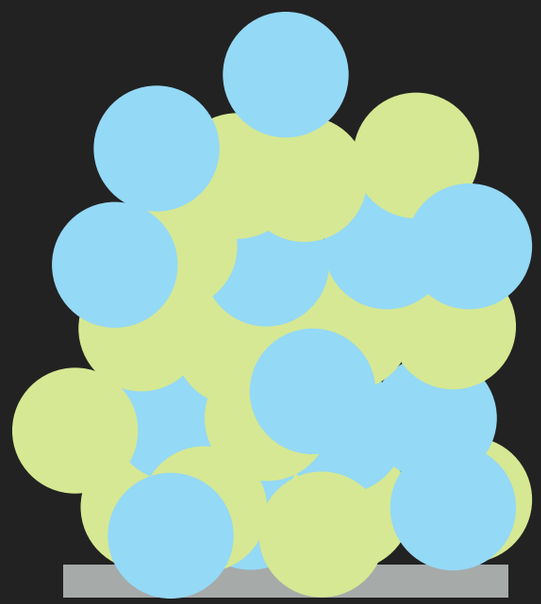
https://exoplanetarchive.ipac.caltech.edu

5%



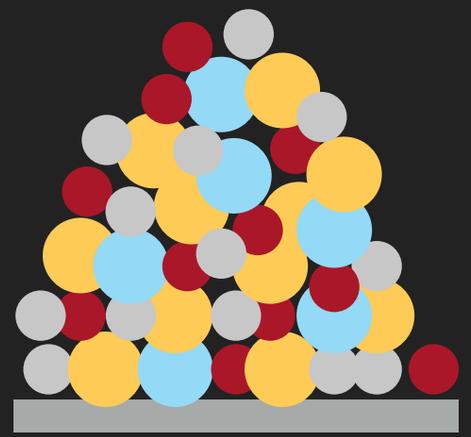
$R_p > 15R_\oplus$

55%



$2R_\oplus < R_p < 15R_\oplus$

40%



$R_p < 2R_\oplus$

https://exoplanetarchive.ipac.caltech.edu

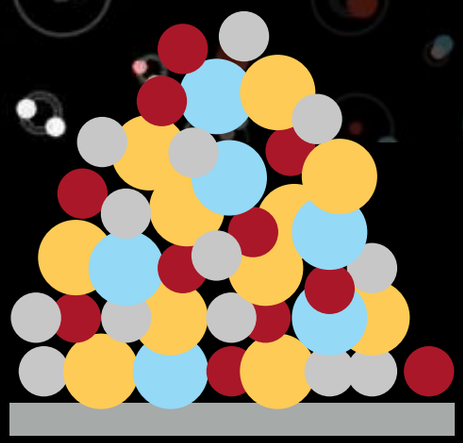
Jupiter
Neptune
Earth
Mercury

1250 Lava
1000
750 Surface of Venus
500 Mercury
250 Earth

Planet Equilibrium Temperature (K)

Kepler Orrery IV
23 Nov 2010
By Ethan Kruse
@ethan_kruse

Solar System

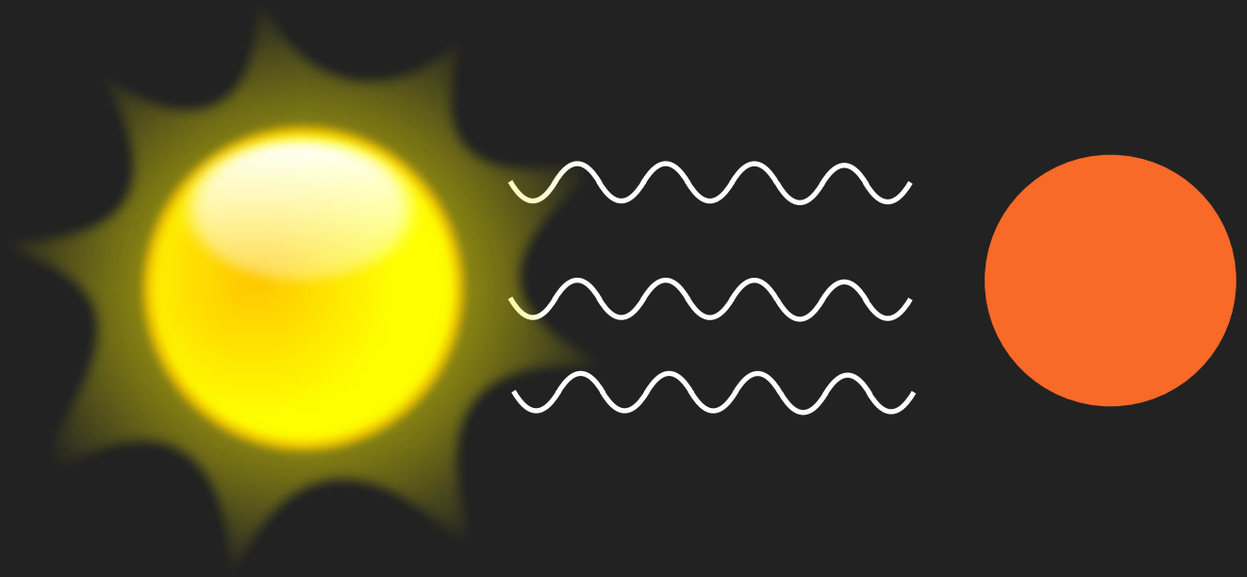


Could any be habitable?

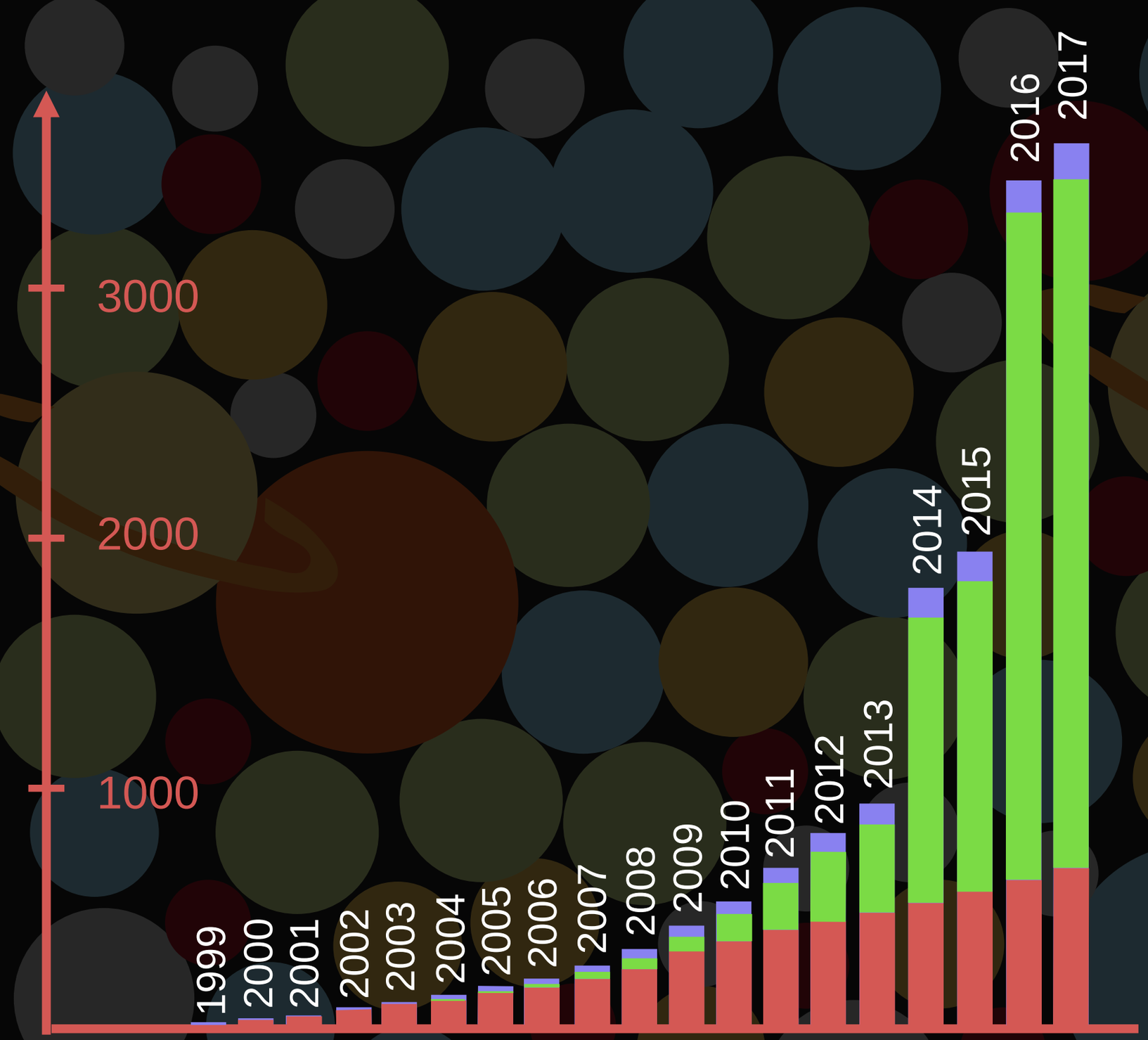
Current instruments yields < 3 planet properties:

Planet radius

Planet mass



Amount of radiation from star

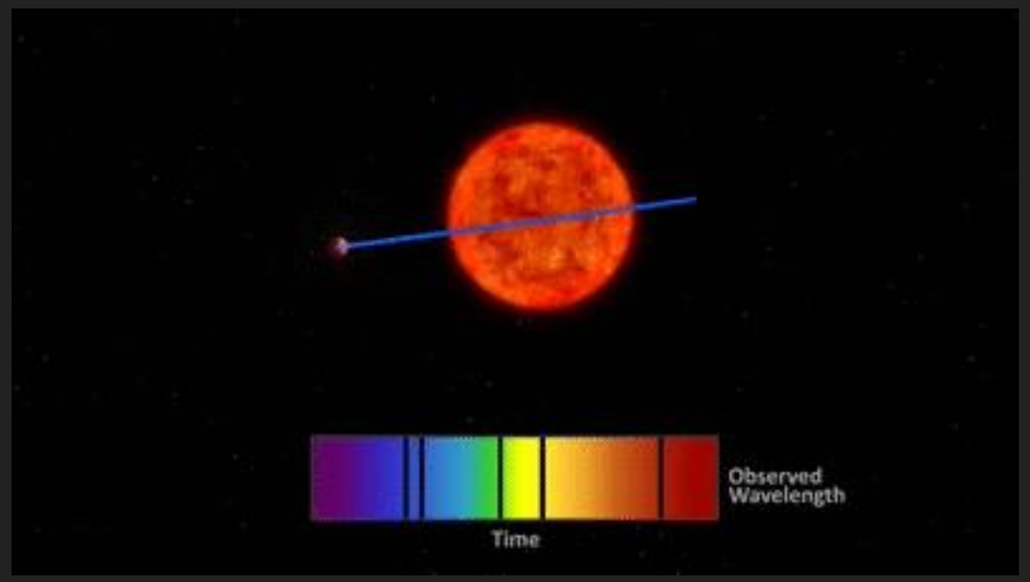


https://exoplanetarchive.ipac.caltech.edu

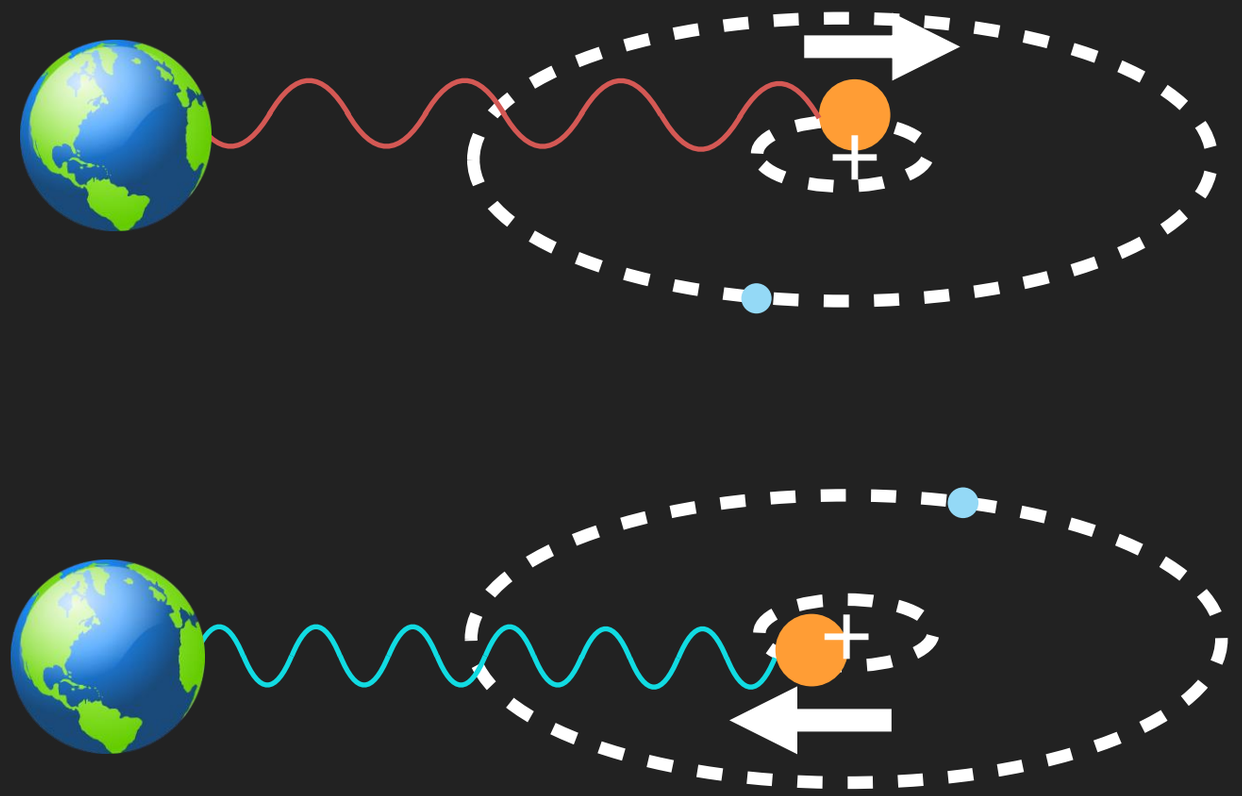
Transit
Radial velocity
Other

96% exoplanets found by either the radial velocity or transit technique

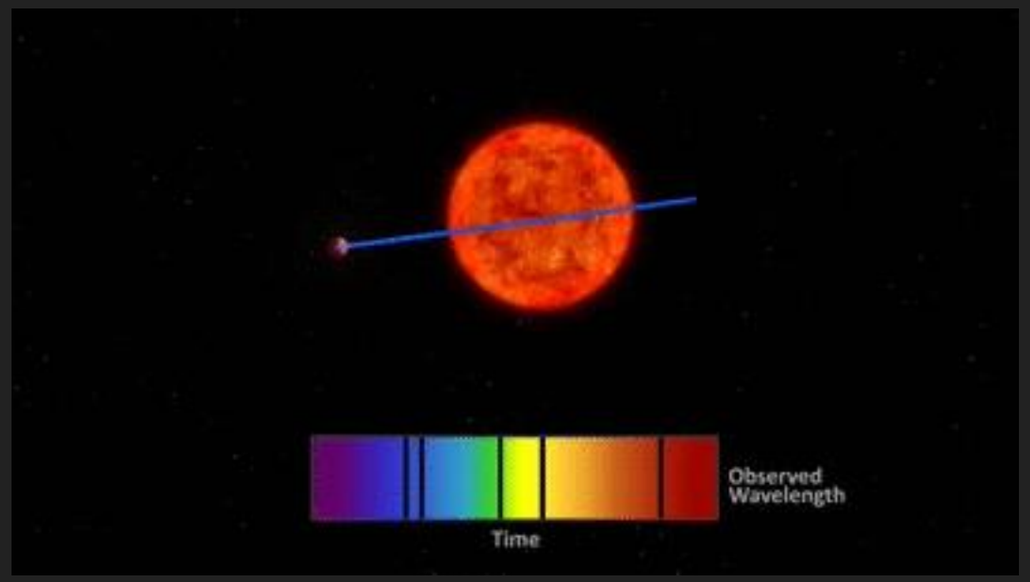
Radial velocity
or
Doppler wobble



Orbit with planet causes the star to wobble, causing a periodic shift in wavelength

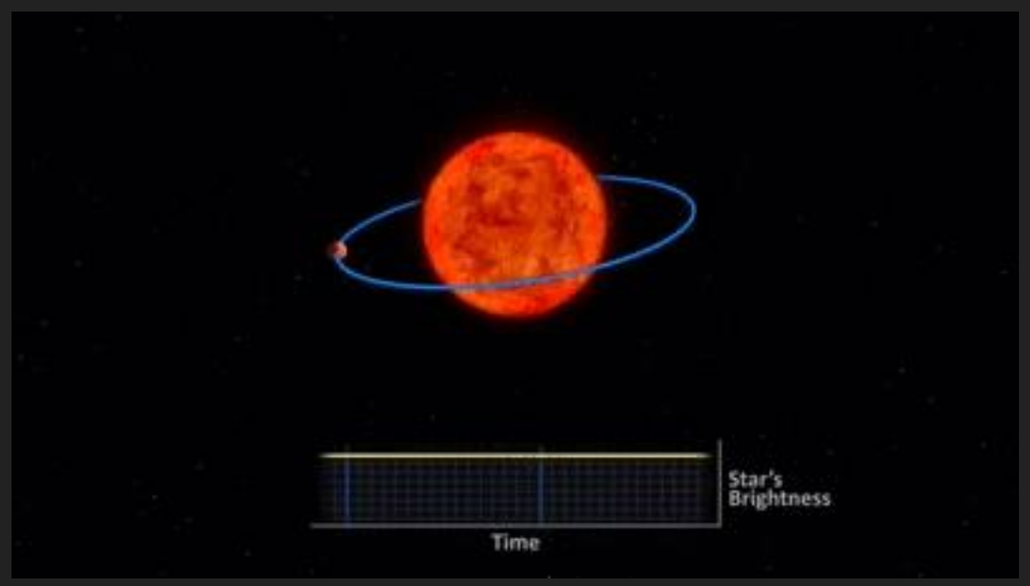


Radial velocity
or
Doppler wobble



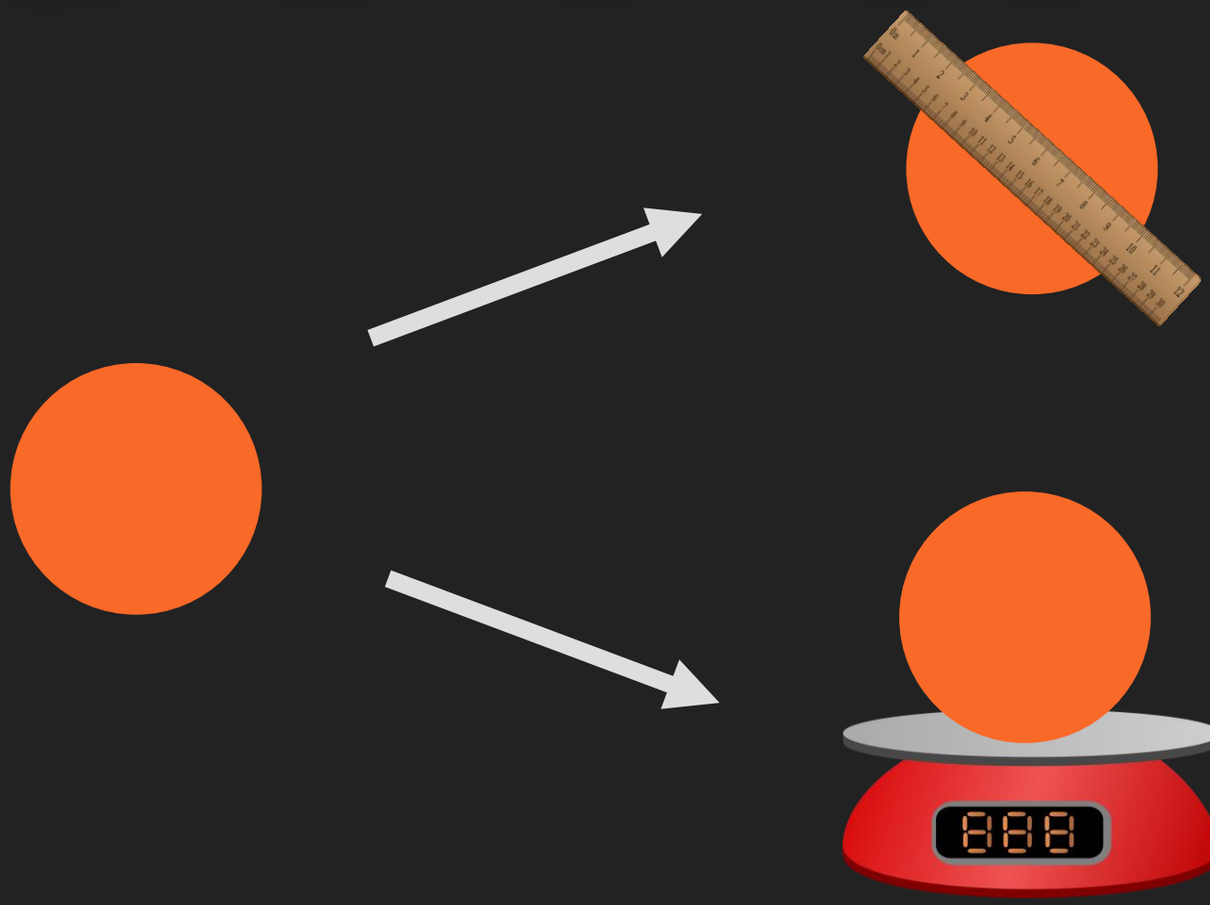
Orbit with planet causes the star to wobble, causing a periodic shift in wavelength

Transit



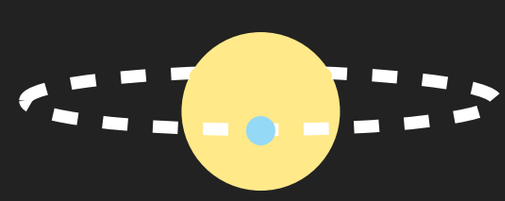
Dip in light as planet crosses our line of sight to the star

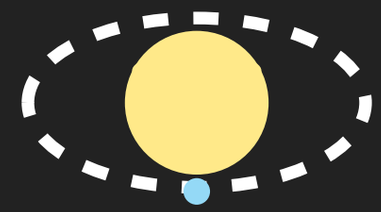
Typically, < 2 planet properties:



Planet radius

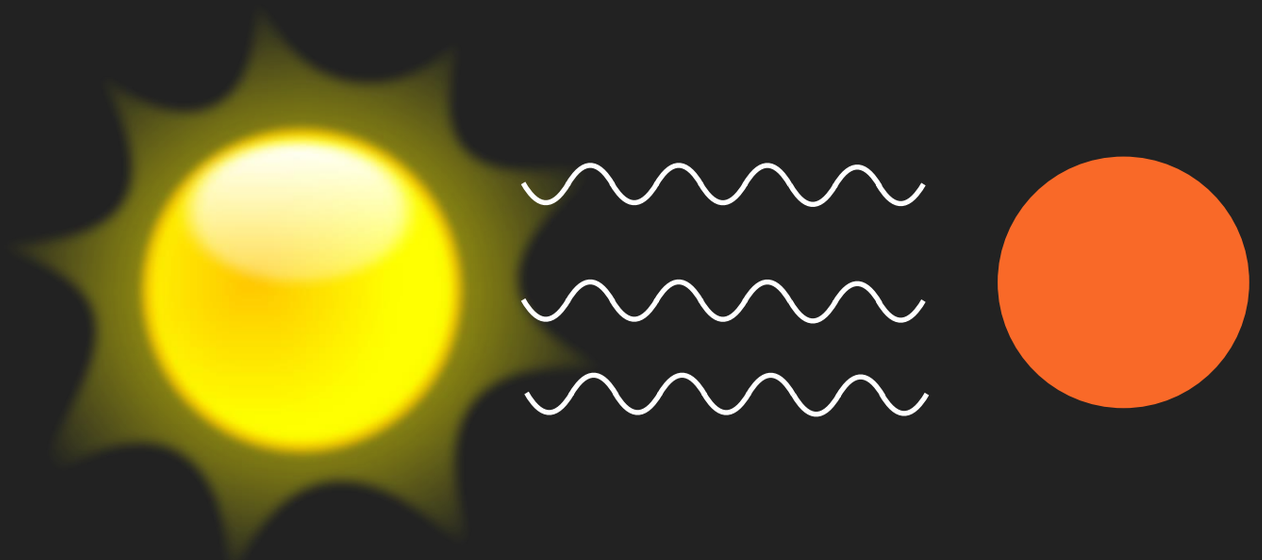
Planet (minimum) mass



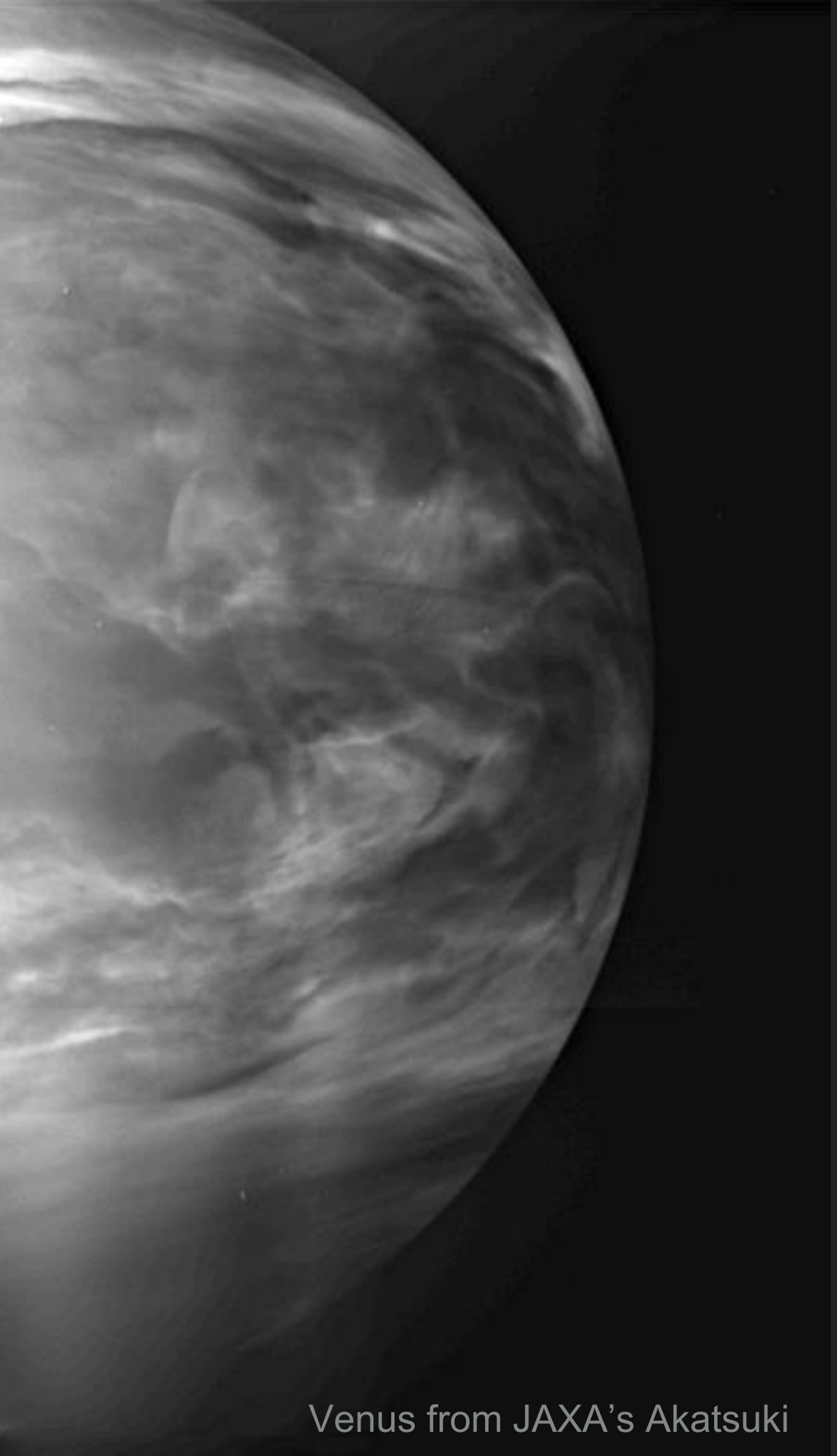


m sin (i) = mass

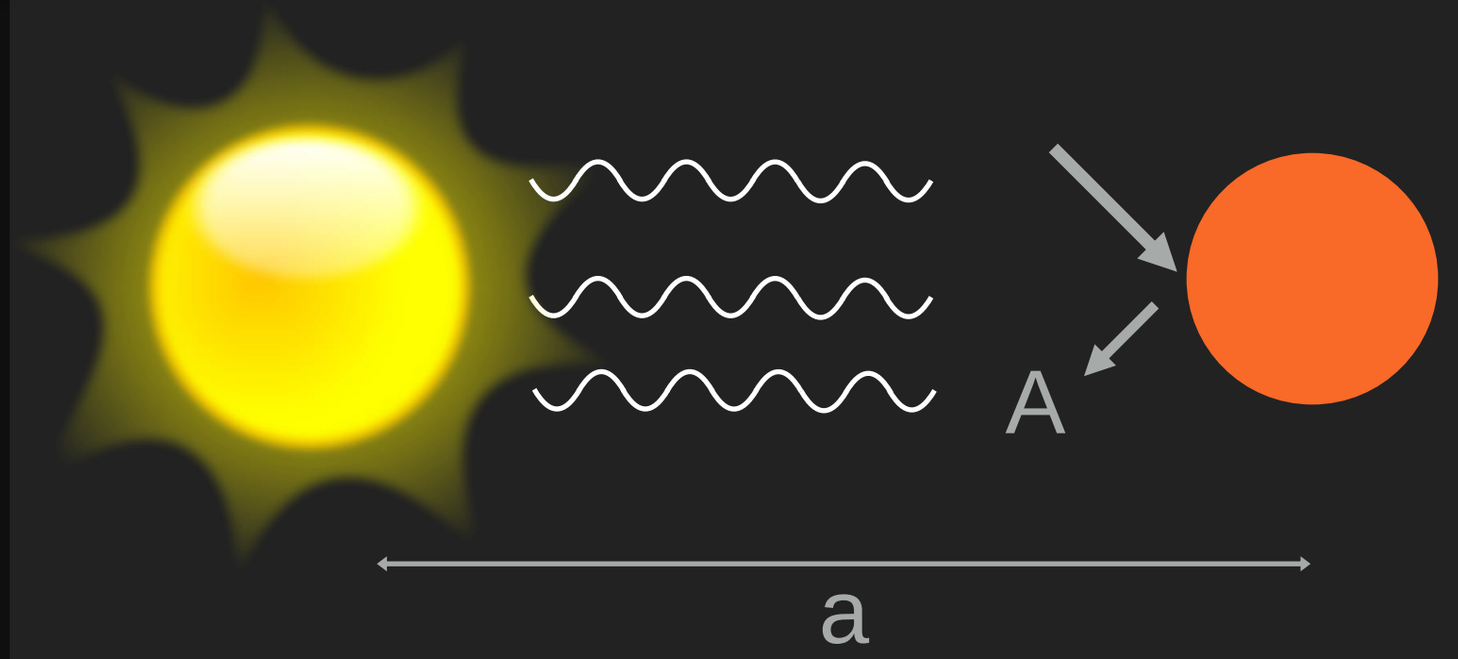
m sin (i) << mass



Amount of radiation from star



Venus from JAXA's Akatsuki



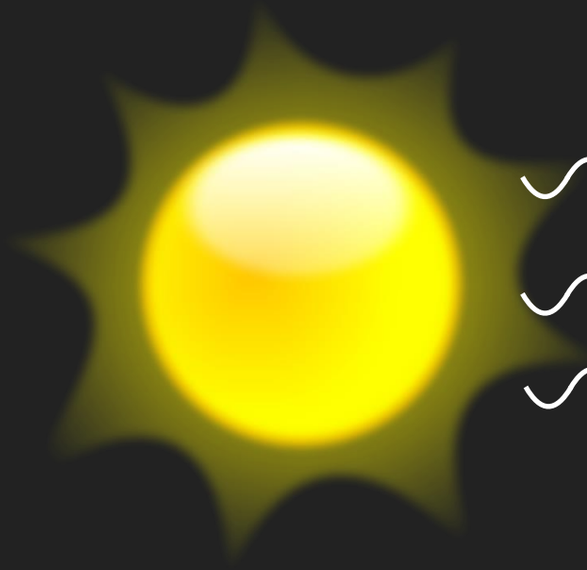
$$T_{\text{eq}} = \left[\frac{L_*}{16\pi\sigma a^2}\right]^{1/4} \times (1-A)^{1/4}$$

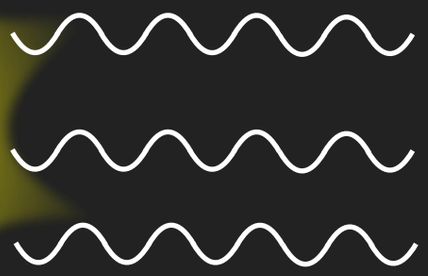
T_{eq} $= 5°\text{C}$ $-18°\text{C}$

T_{s} $= 15°\text{C}$

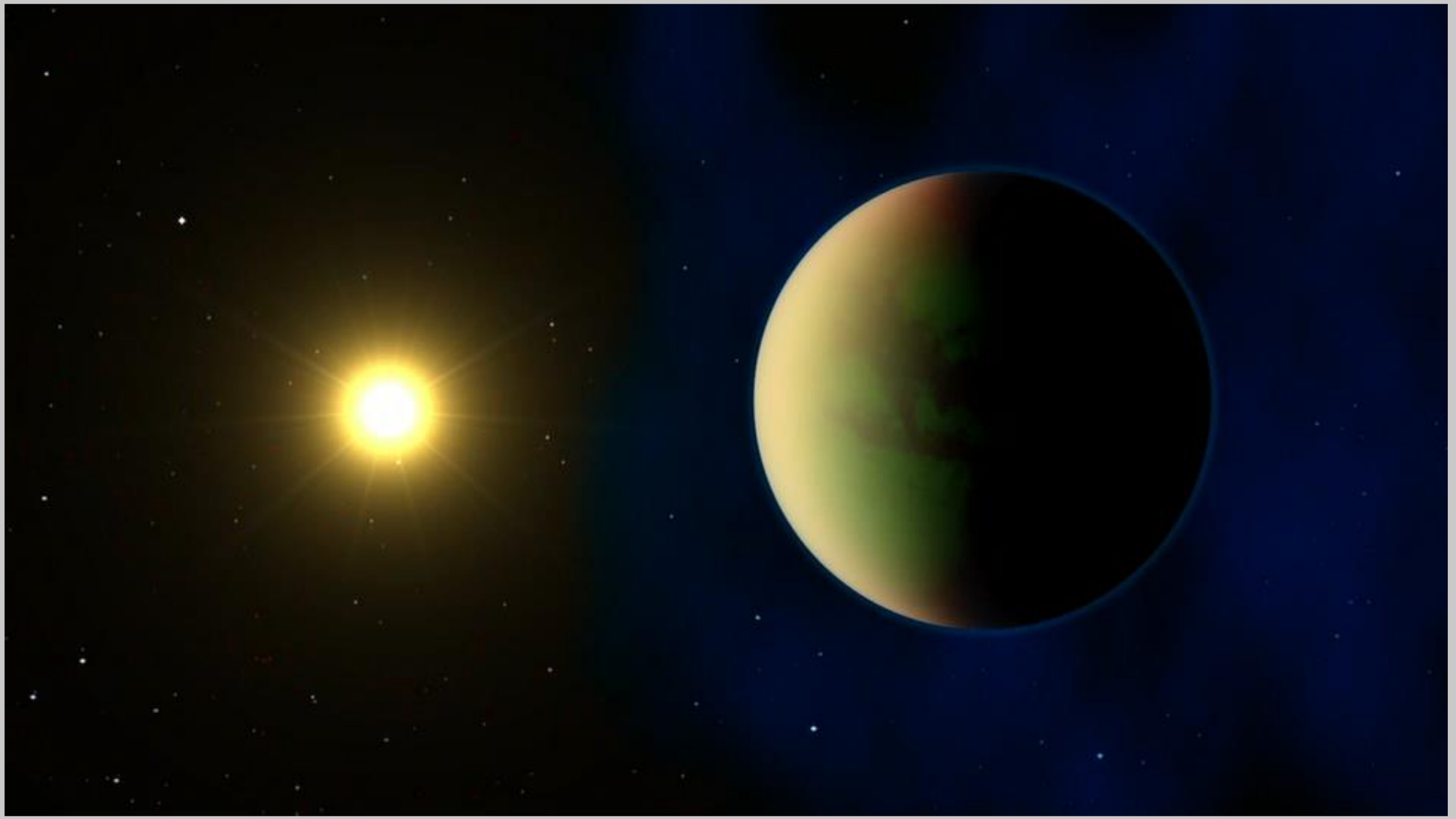
T_{eq} $= 54°\text{C}$ $-42°\text{C}$

T_{s} $= 460°\text{C}$



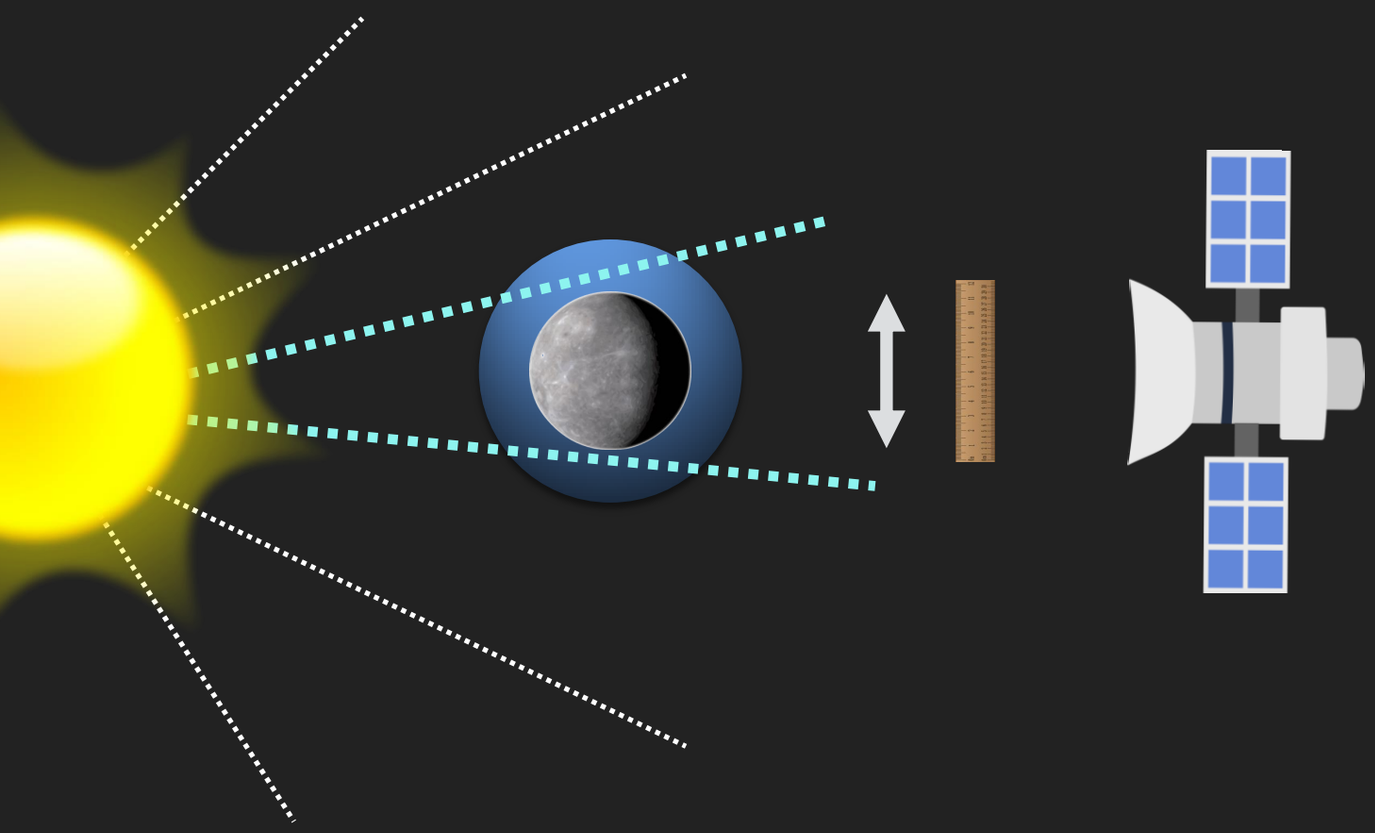


None of these measurable properties directly relate to surface conditions



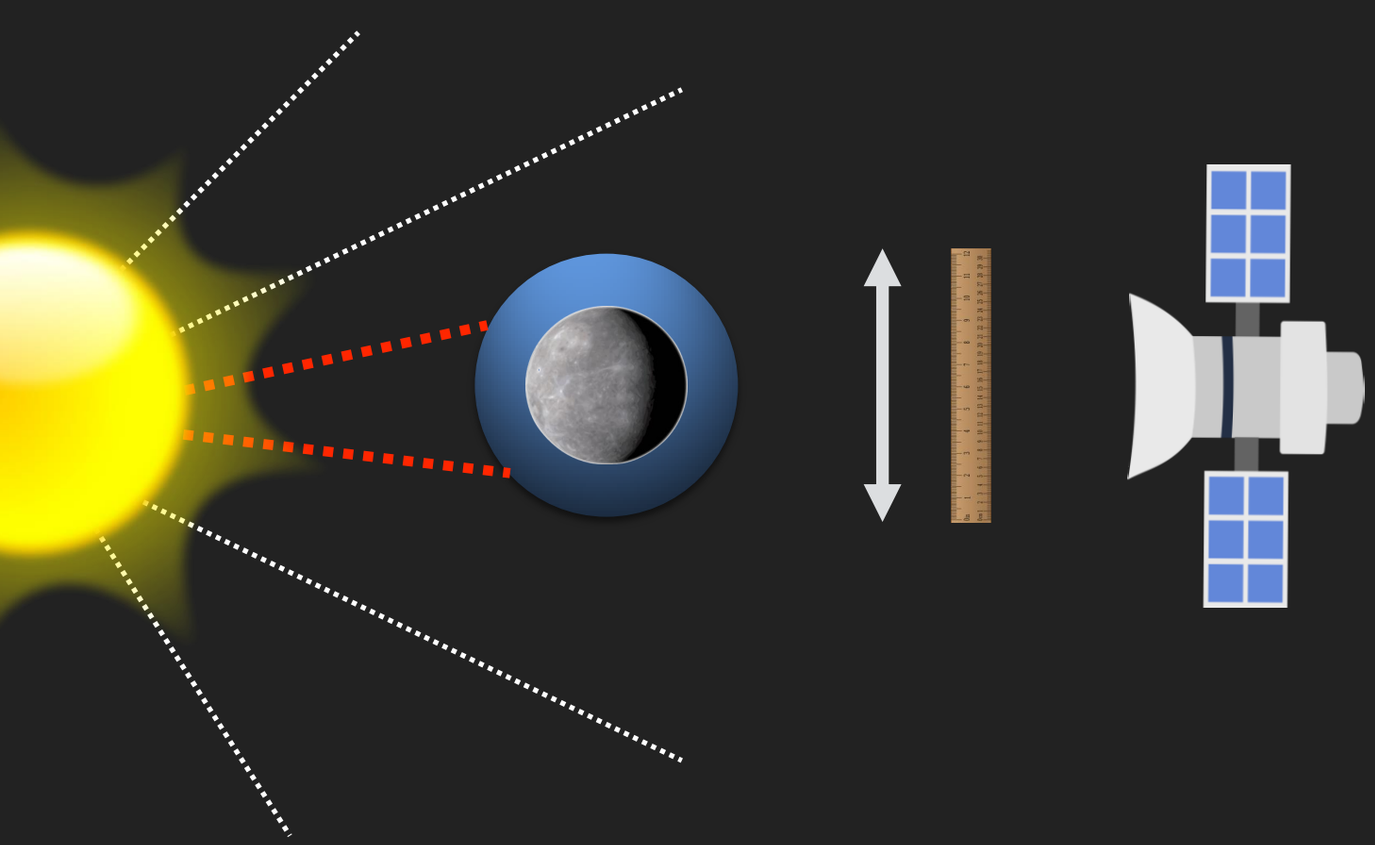
NASA GSFC

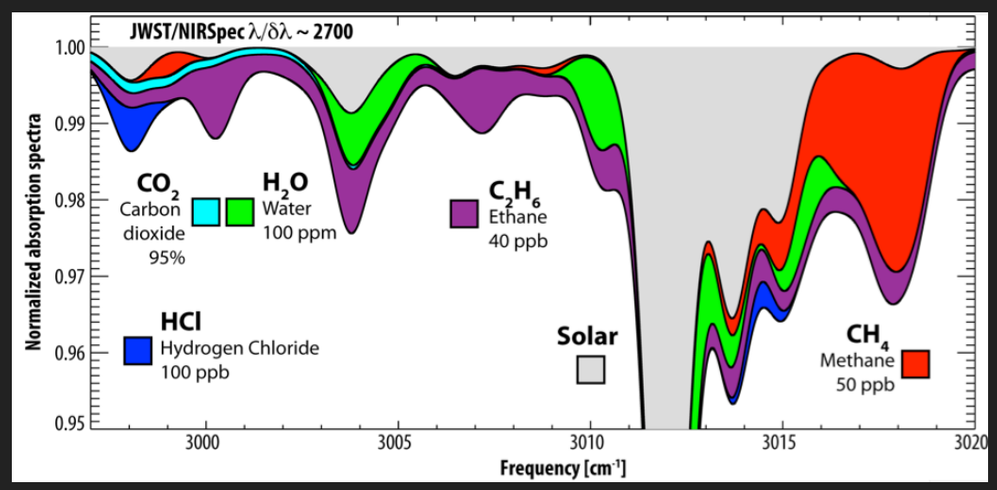
Our next generation of instruments aim at atmospheric composition



Atmospheric composition gives opacity variations with frequency.

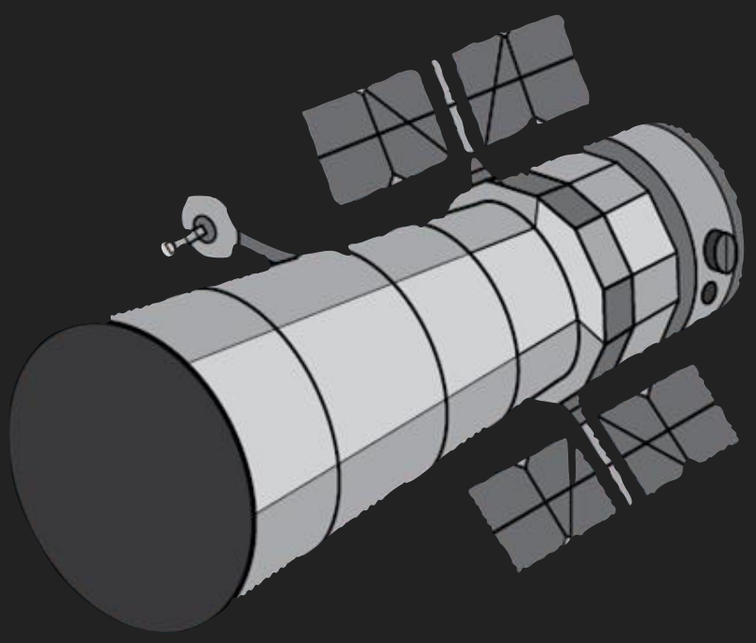
Measured planet size increases at opaque frequencies





Villanueva, NASA/GSFC
(simulated Mars JWST detection)

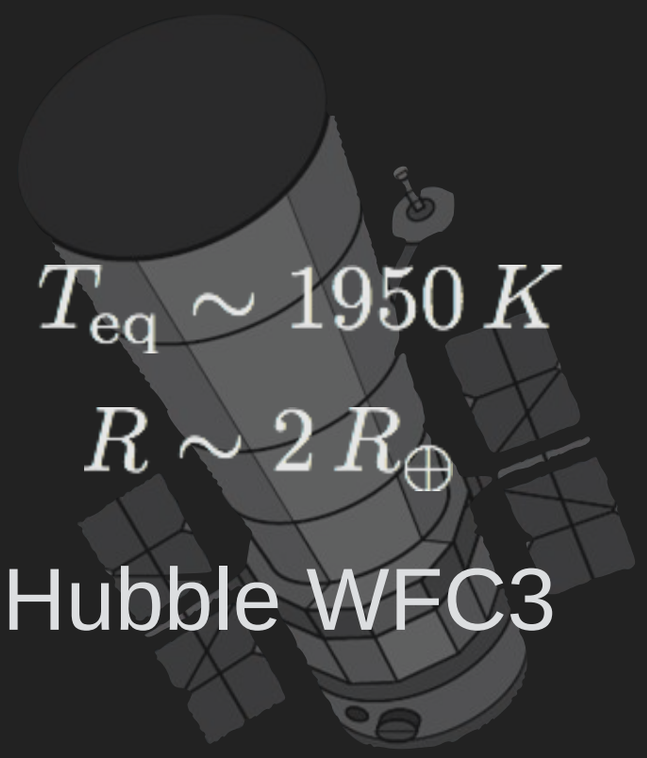
Atmospheric spectra



$T_{\mathrm{eq}} \sim 600\,K$

$R \sim 4\,\mathrm{R}_{\oplus}$

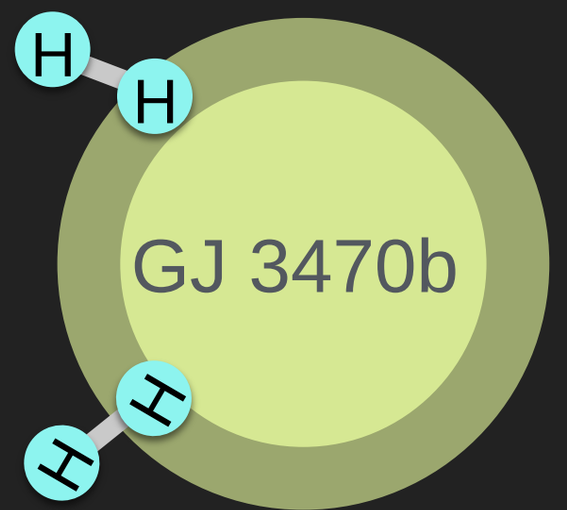
NASA IRTF



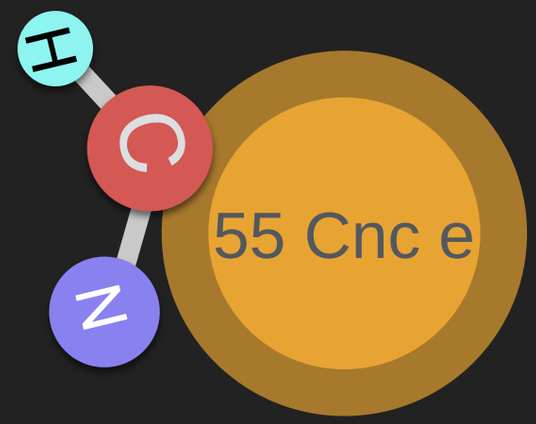
$T_{\mathrm{eq}} \sim 1950\,K$

$R \sim 2\,R_{\oplus}$

Hubble WFC3



Biddle et al, 2014

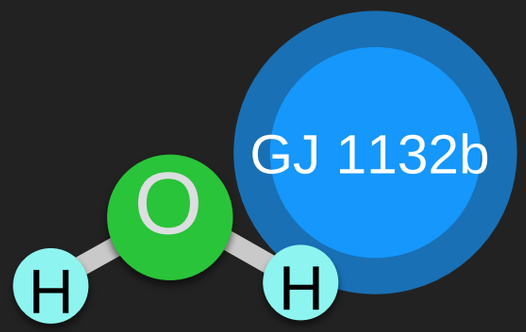


Tsiaras et al, 2016

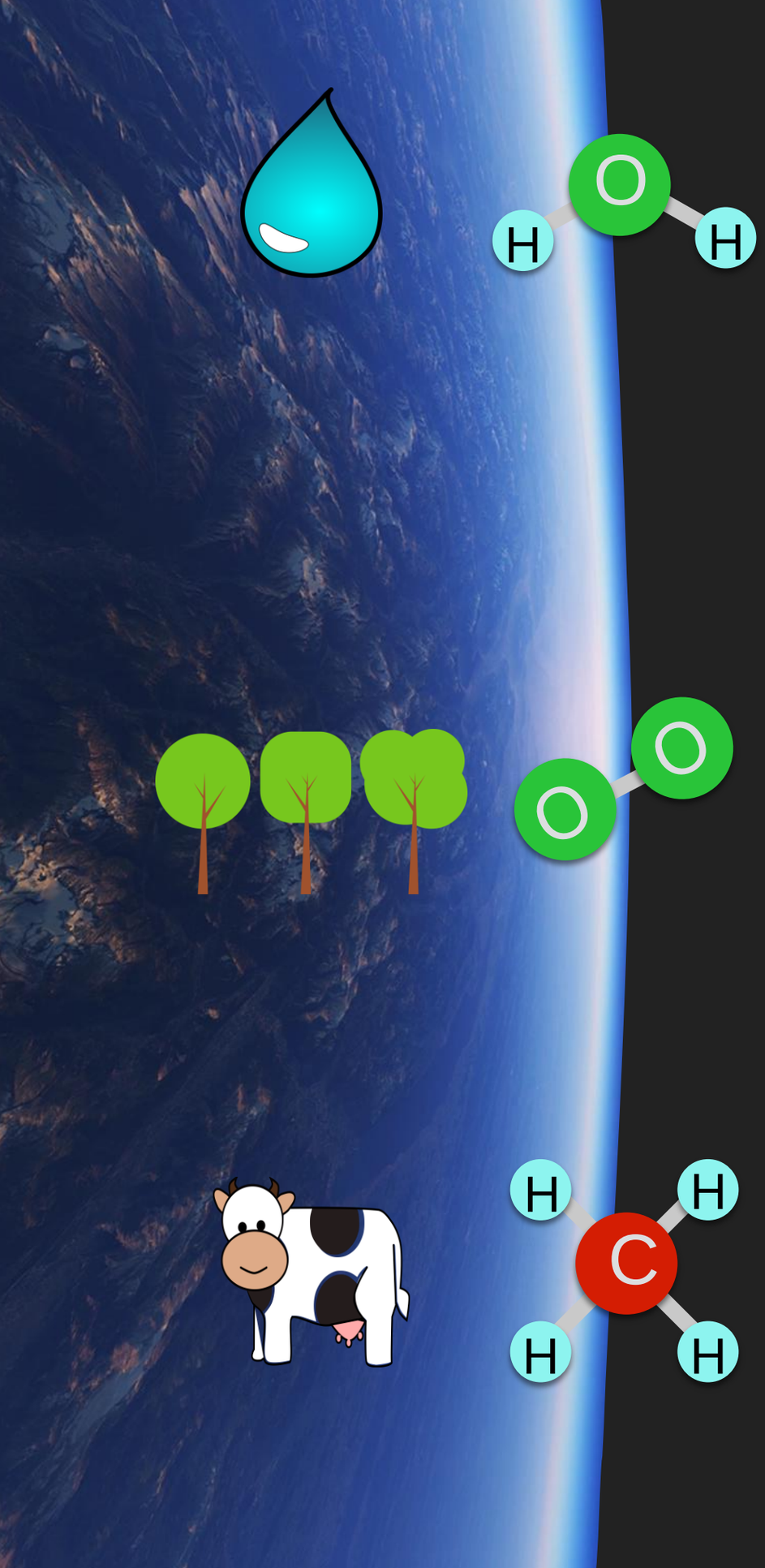
$T_{\mathrm{eq}} \sim 644\,K$

$R \sim 1.2\,R_{\oplus}$

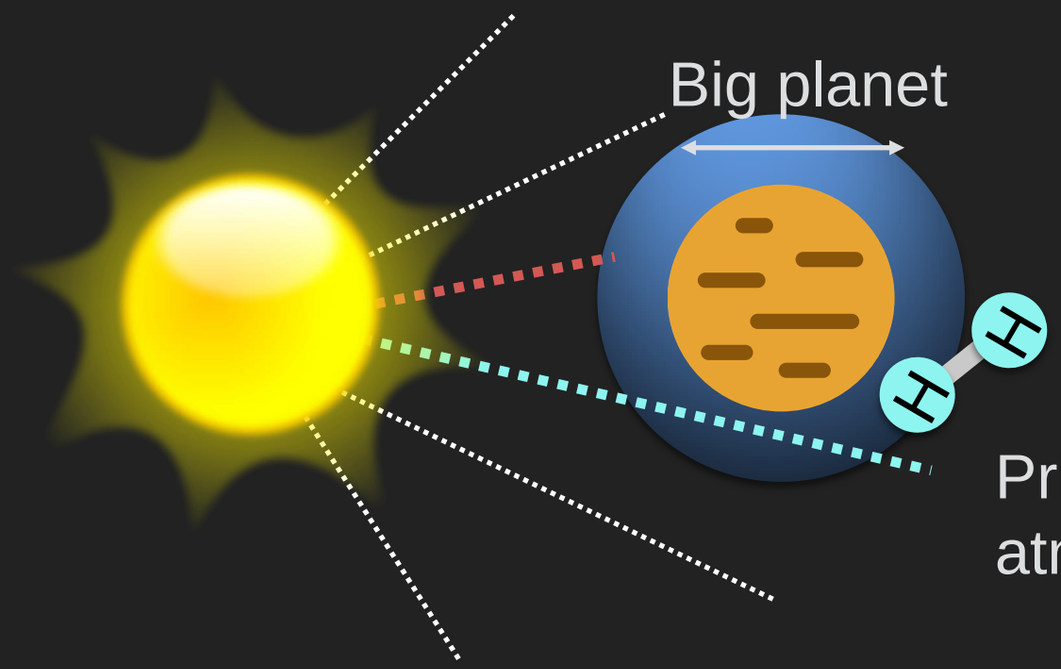
MPG/ESO

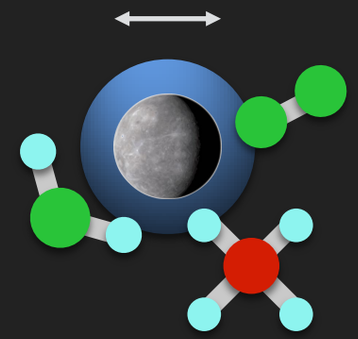


Southworth et al, 2017



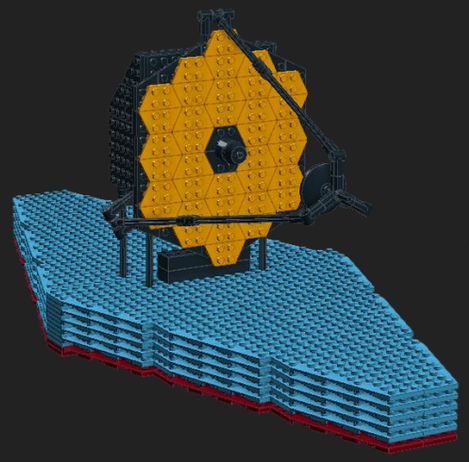
Sagan et al, Nature 1993





close orbit

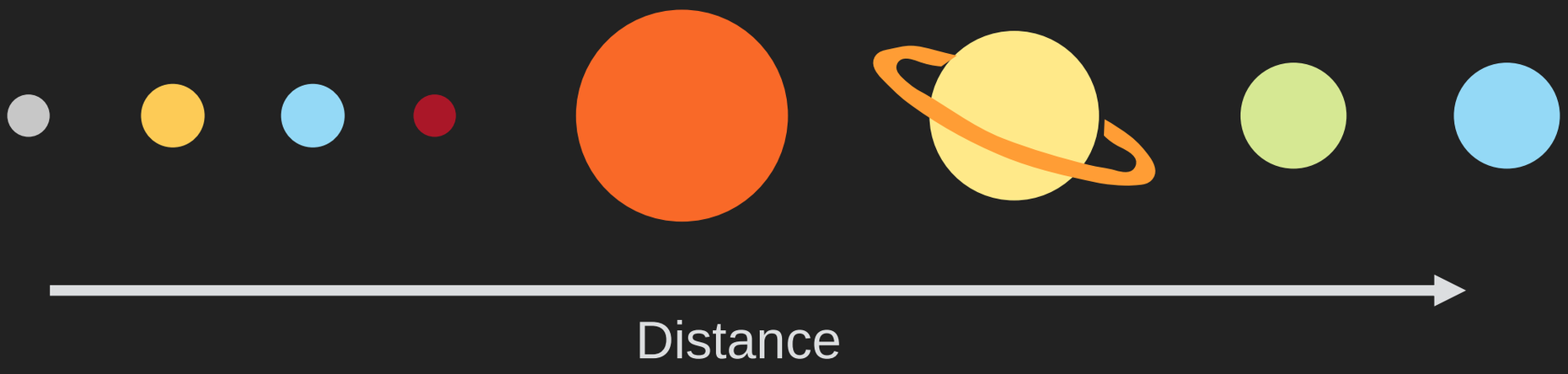
longer orbit



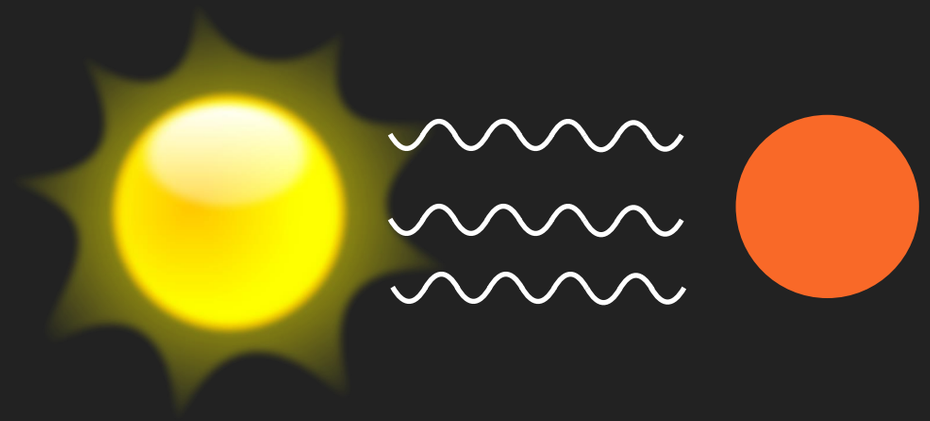
Many targets possible

Long observation times,
few targets only

With a lifetime ~5.5 years for the JWST, how do we choose the handful of Earth-sized targets for observations?

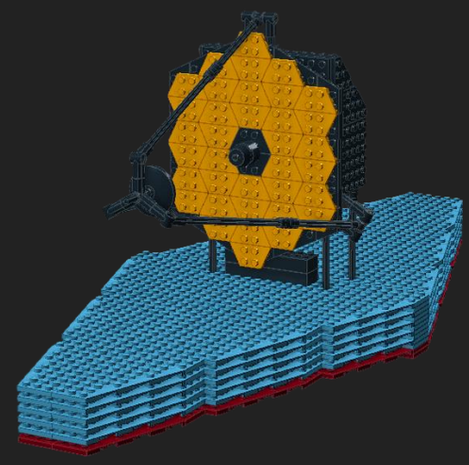

Distance

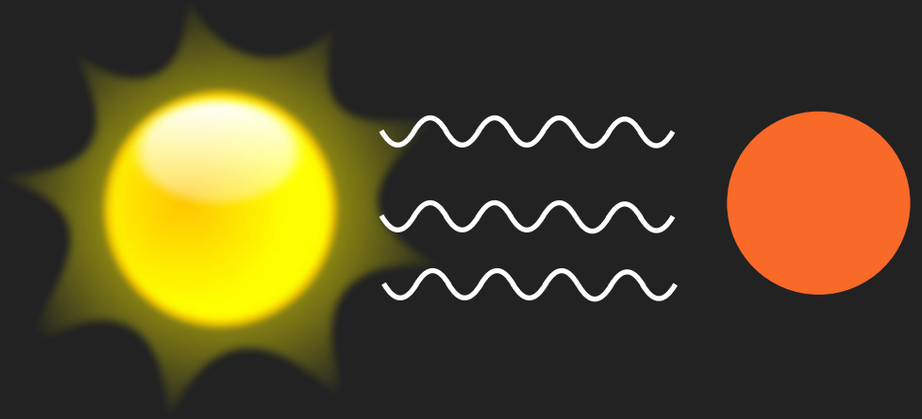
Rank by most interesting target for habitability



Priority

… without knowing any surface properties





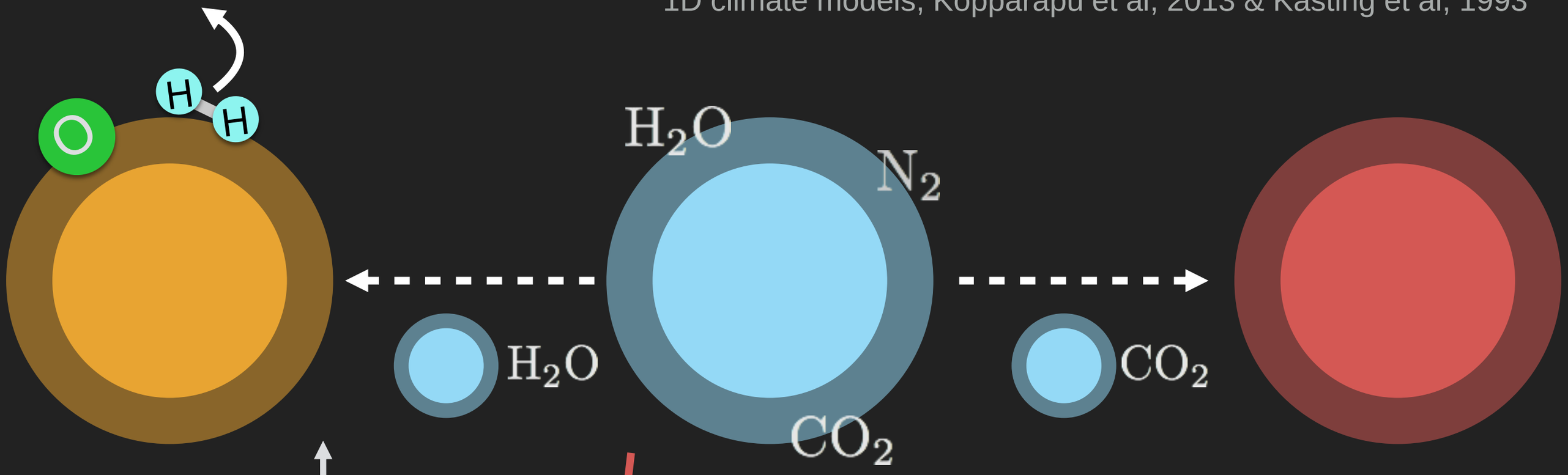
Easiest to recognise Earth-like life
(water & carbon-based chemistry)

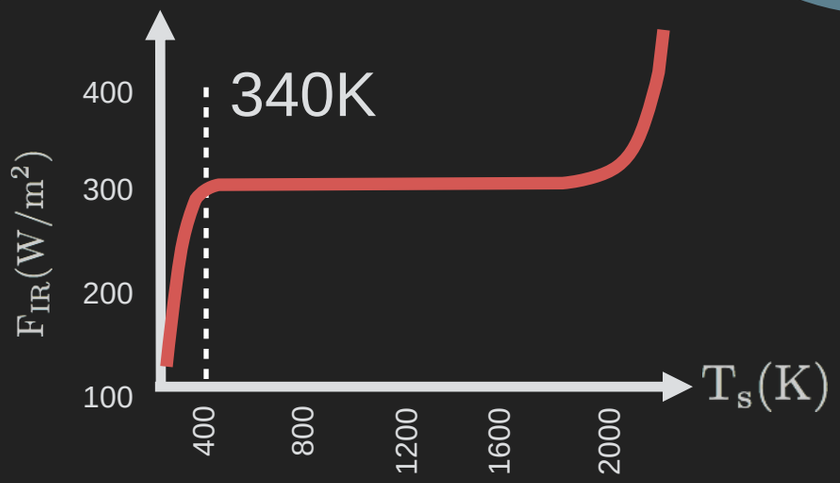
Needs to be detectable
(surface water needed)

How much insolation does an Earth-like planet need?

“Habitable Zone”

1D climate models, Kopparapu et al, 2013 & Kasting et al, 1993

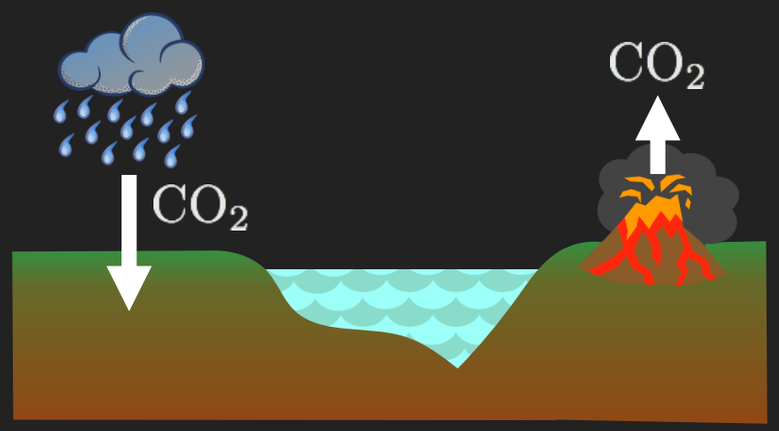




Atmosphere becomes opaque to IR as water vapour increases

Water in the upper atmosphere is lost through photo-evaporation

Moist greenhouse limit



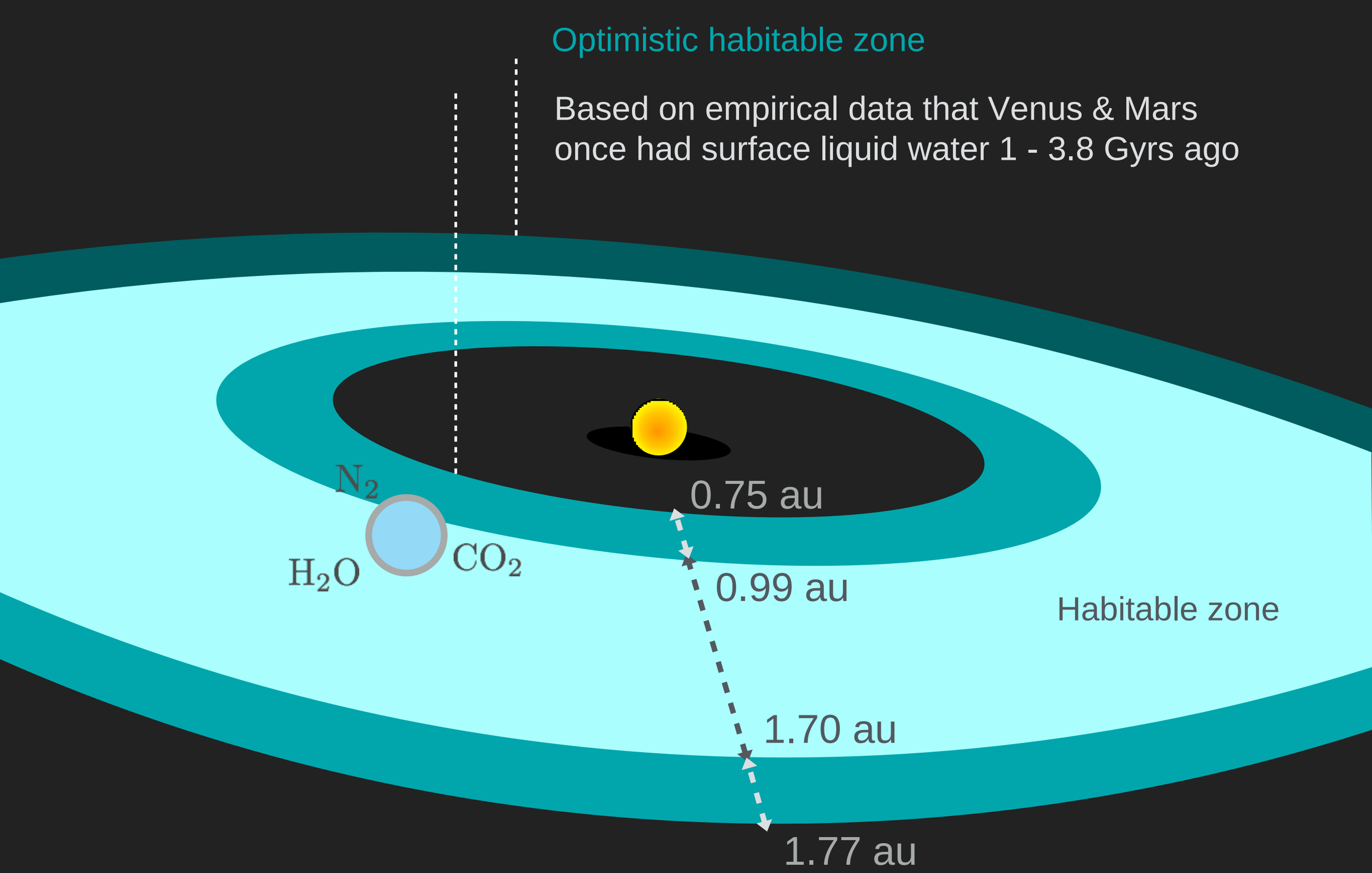
Carbon-silicate feedback cycle fails as CO_2 condenses.

Dense CO_2 atmosphere gives a high planet albedo due to Rayleigh scattering.

Maximum greenhouse limit

Optimistic habitable zone

Based on empirical data that Venus & Mars once had surface liquid water 1 - 3.8 Gyrs ago



(Kopparapu et al, 2013)

The Habitable Zone

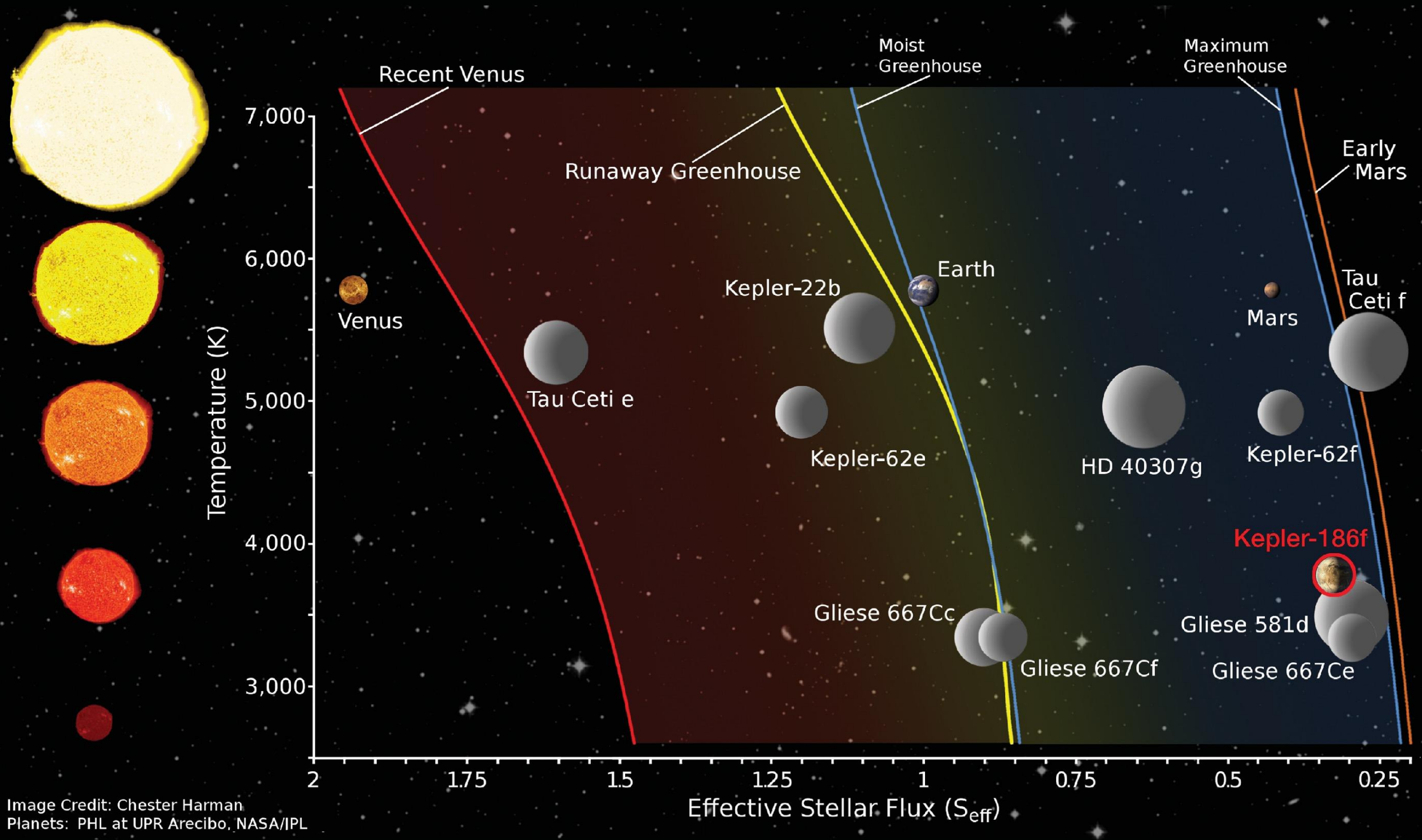
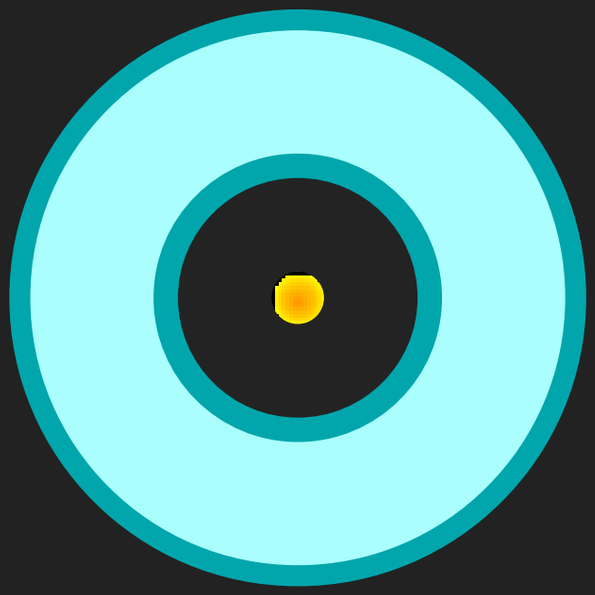
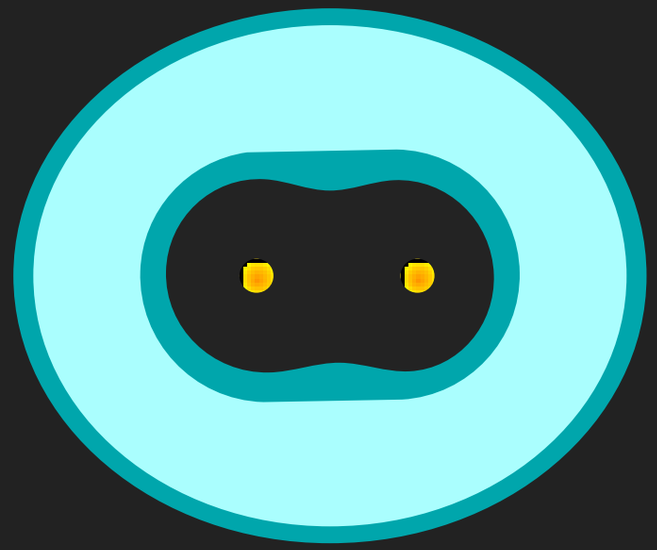


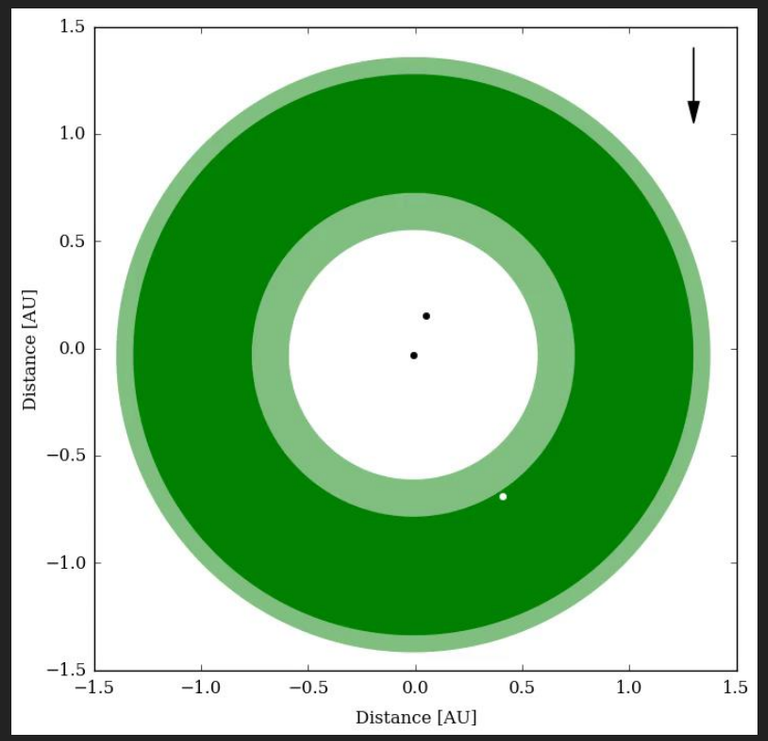
Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/IPL

Habitable zones around binary star systems

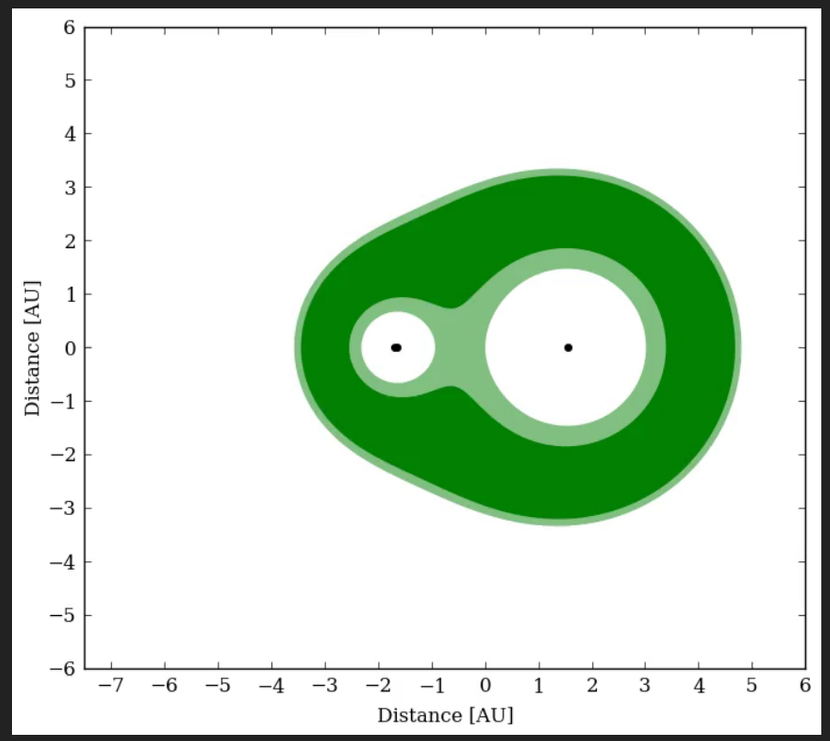




Kepler 453b



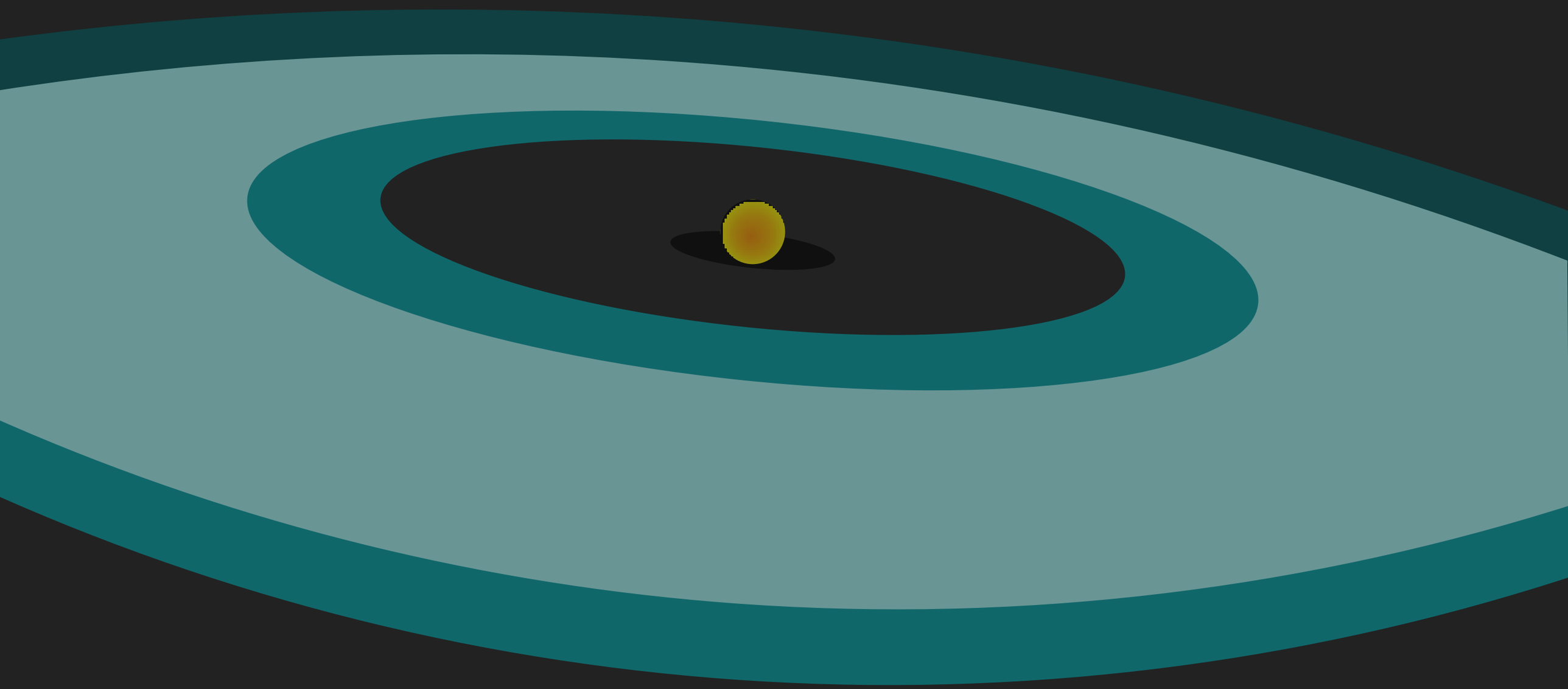
multi-component system: KIC 4150611



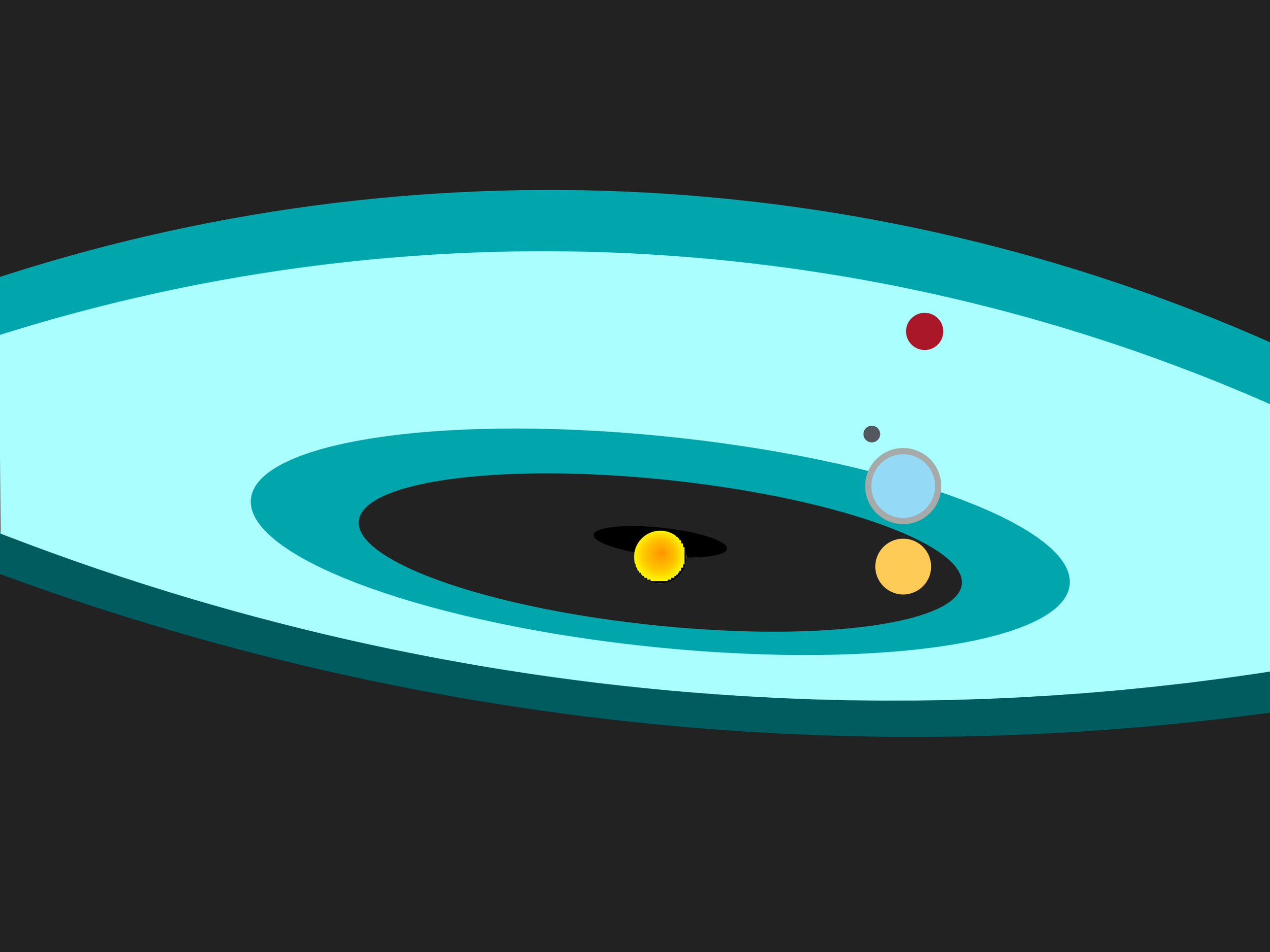
http://astro.twam.info/hz/

(Muller & Haghighipour, 2014)

Limitations of the HZ

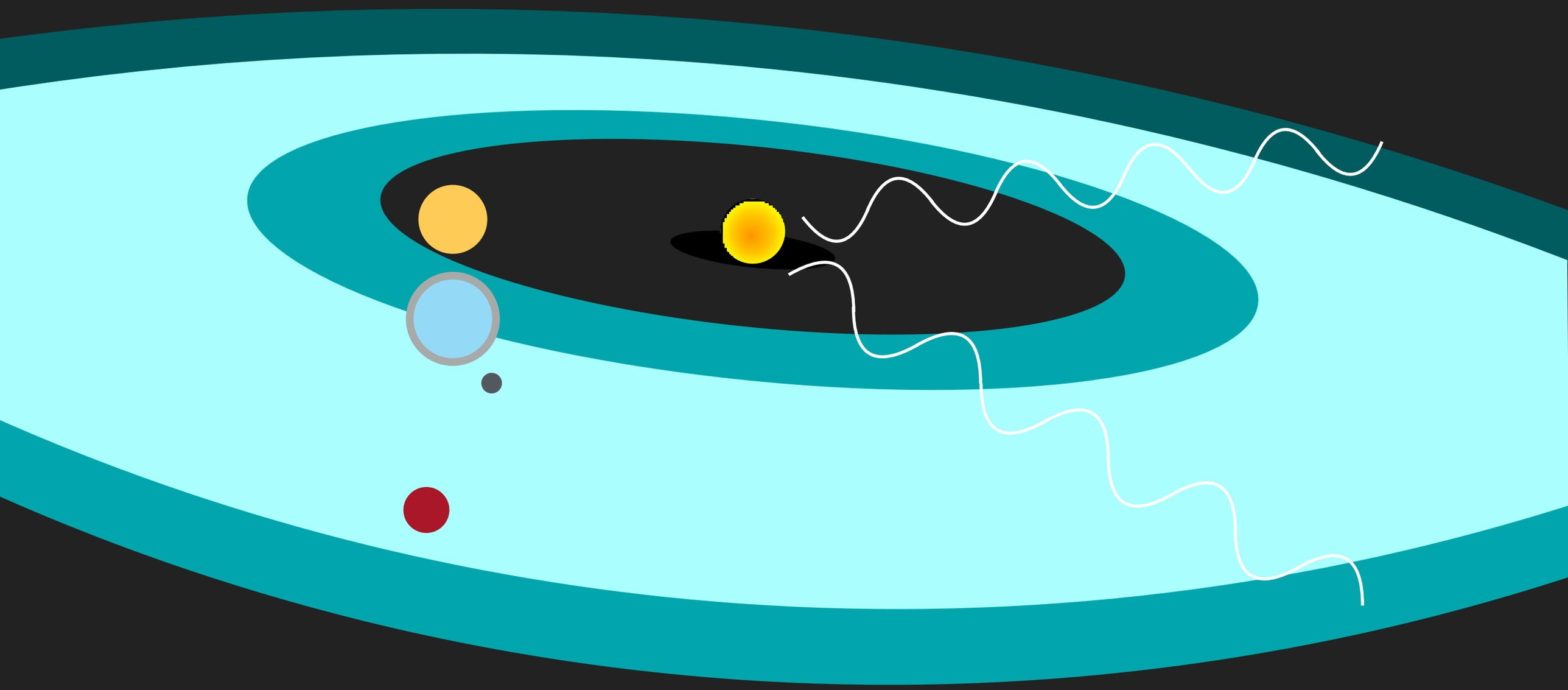


(a.k.a. 101 ways to die in the HZ)



HZ location depends only on the star

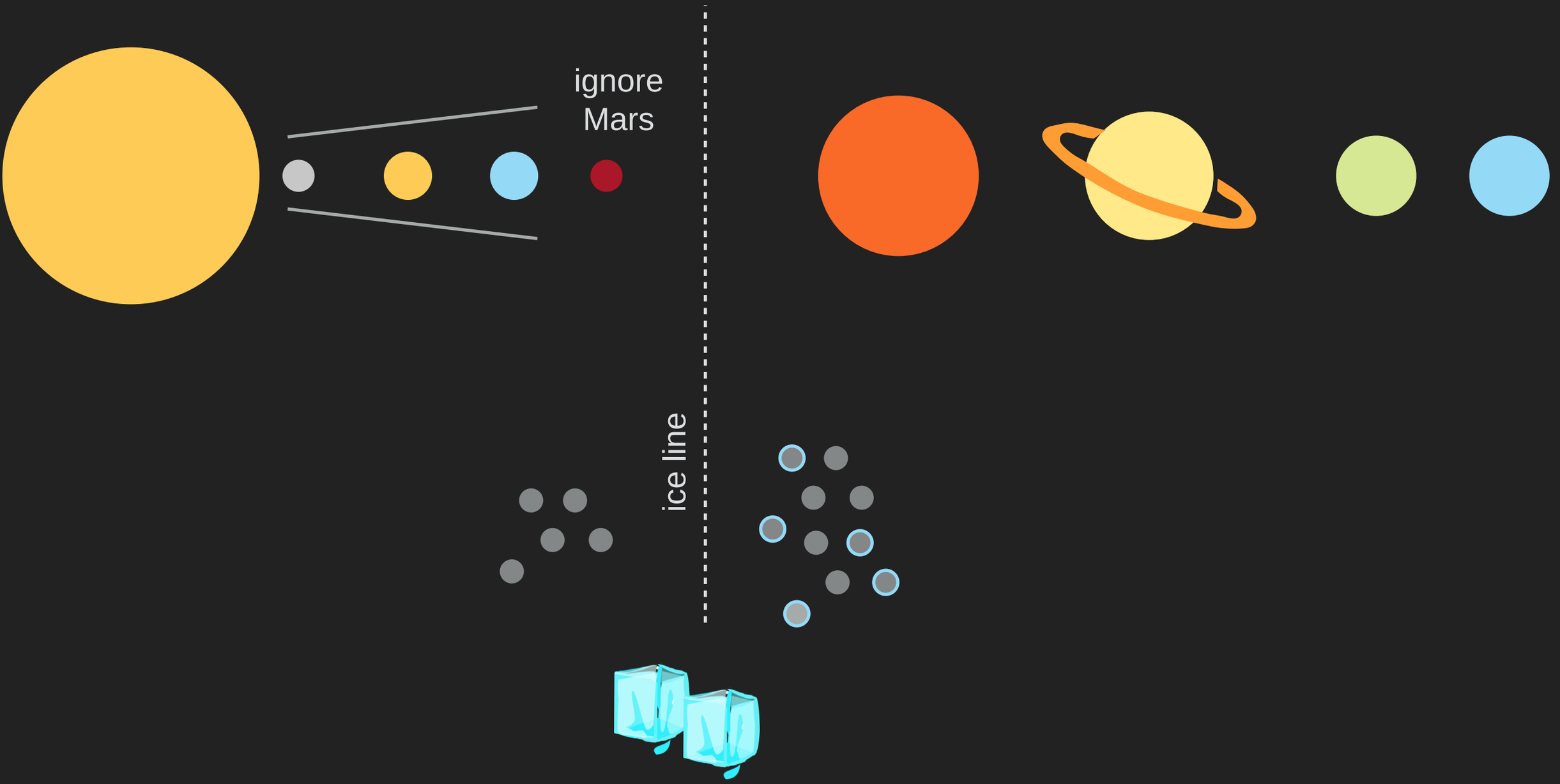
Any planet can sit inside the HZ



Only for an Earth-like planet is this location connected with supporting liquid surface water.

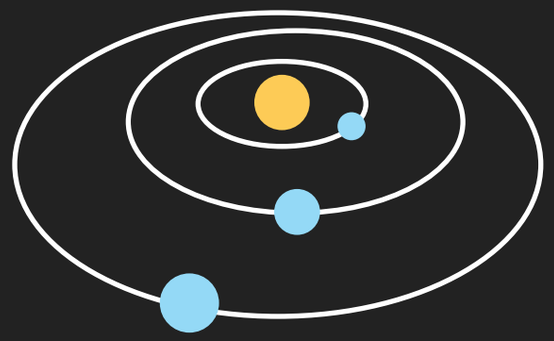
But if you form in an Earth-like location…

… aren’t you likely to be Earth-like?

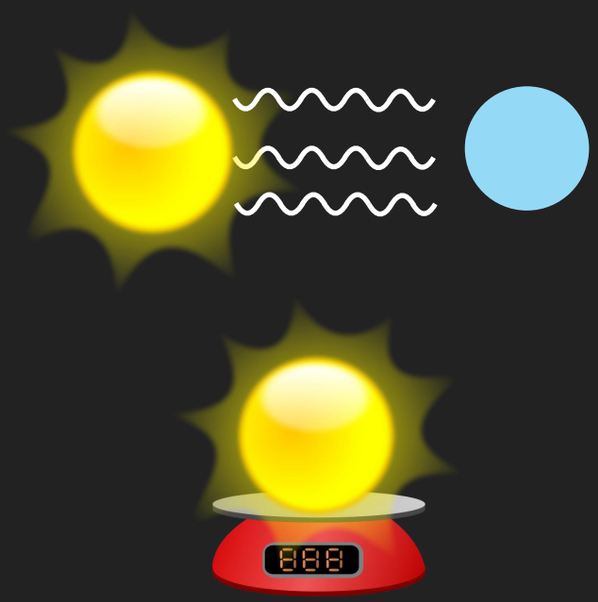


Our Solar System suggests ‘yes’

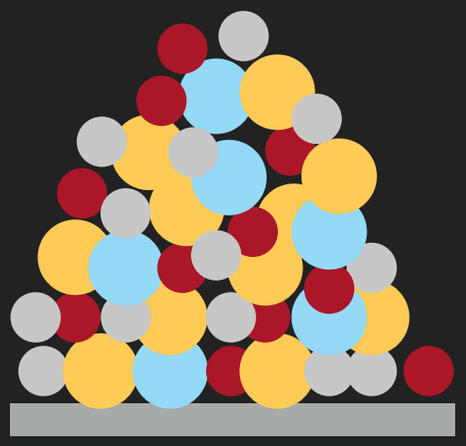
… but exoplanets tell a different story.

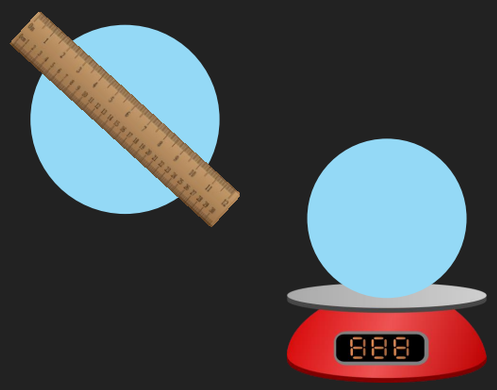


While we lack detail about individual planets…

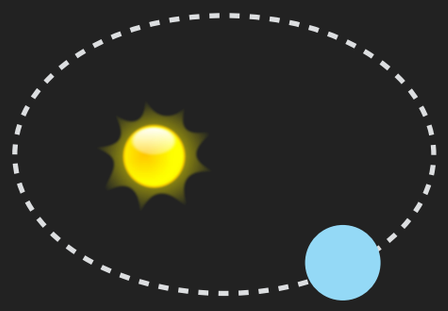


Size and orbits of >3,500 planets enables statistics





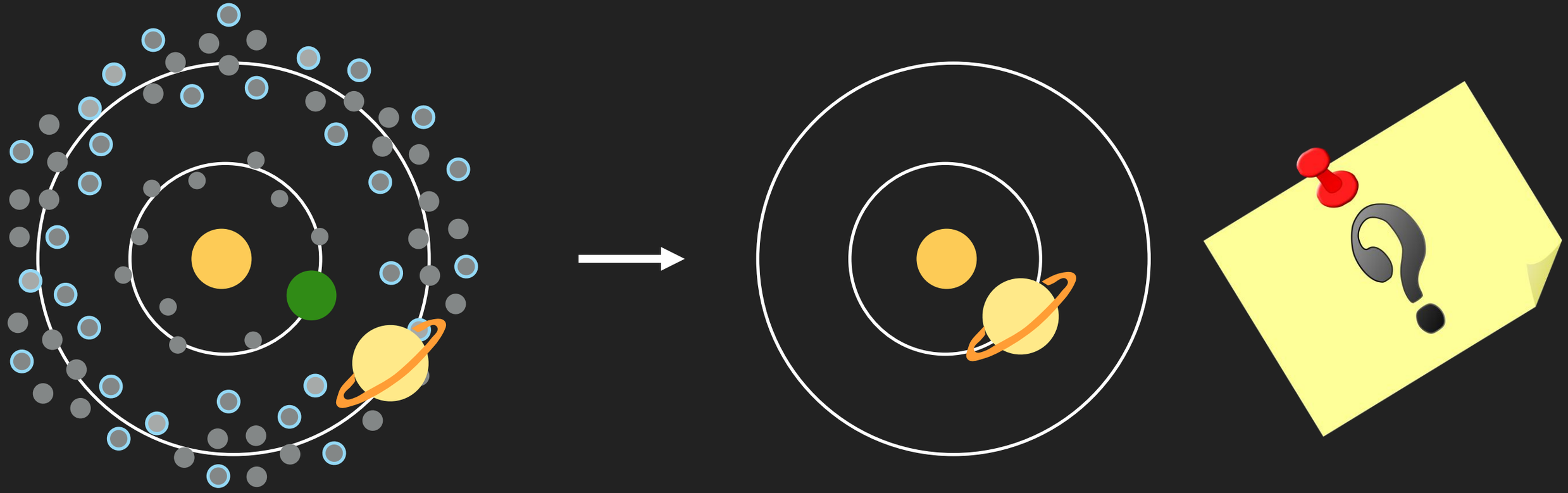
Revealed a lot about planet formation

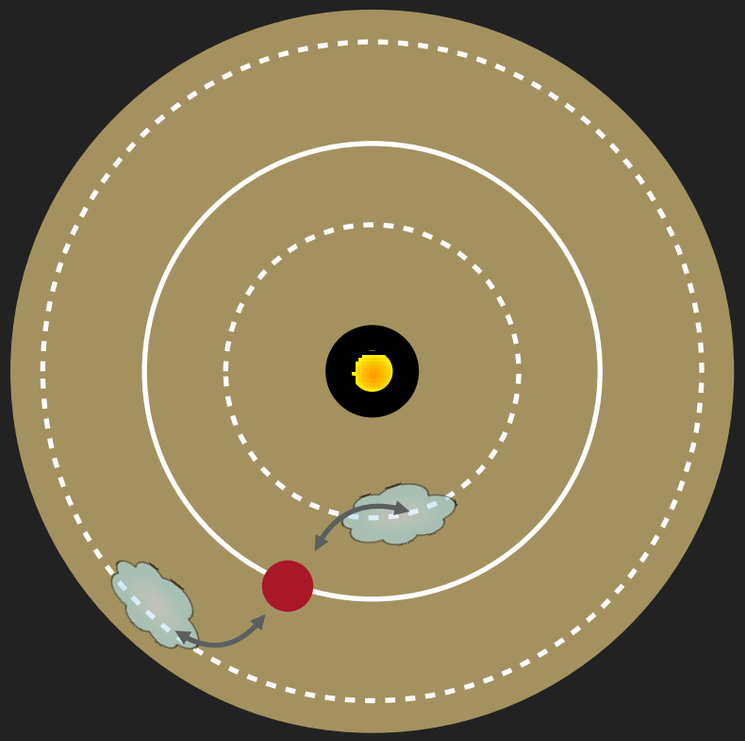


Hot Jupiters:

First planets found around Sun-like stars

Gas giants on very close-in orbits



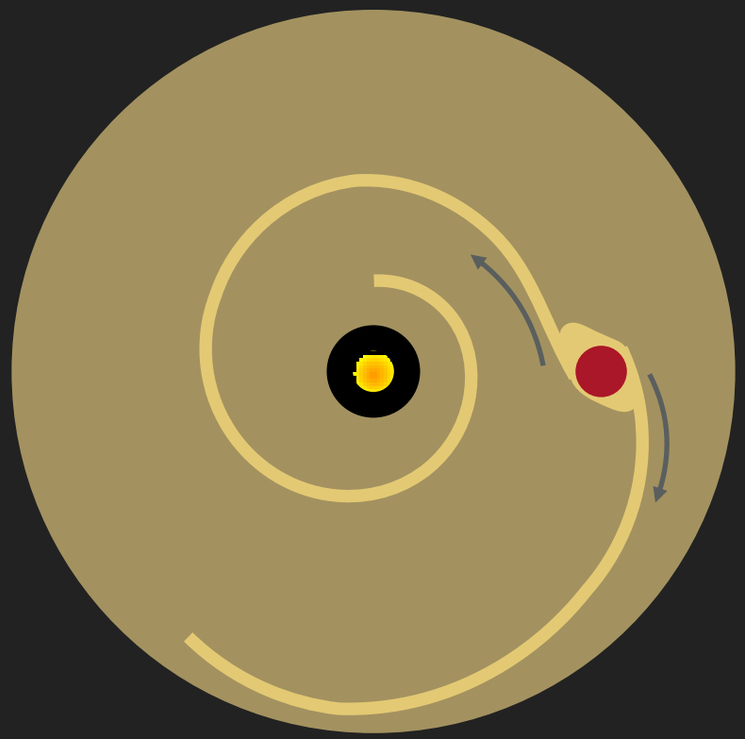


inner
gas:
+torque

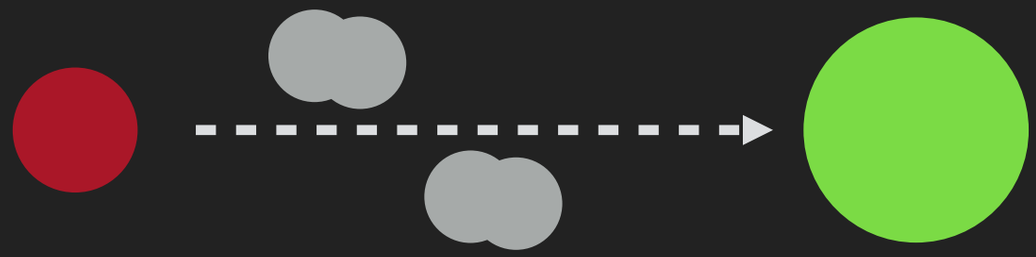
outer gas:
-torque

2 arm wake excited at Lindblad resonances

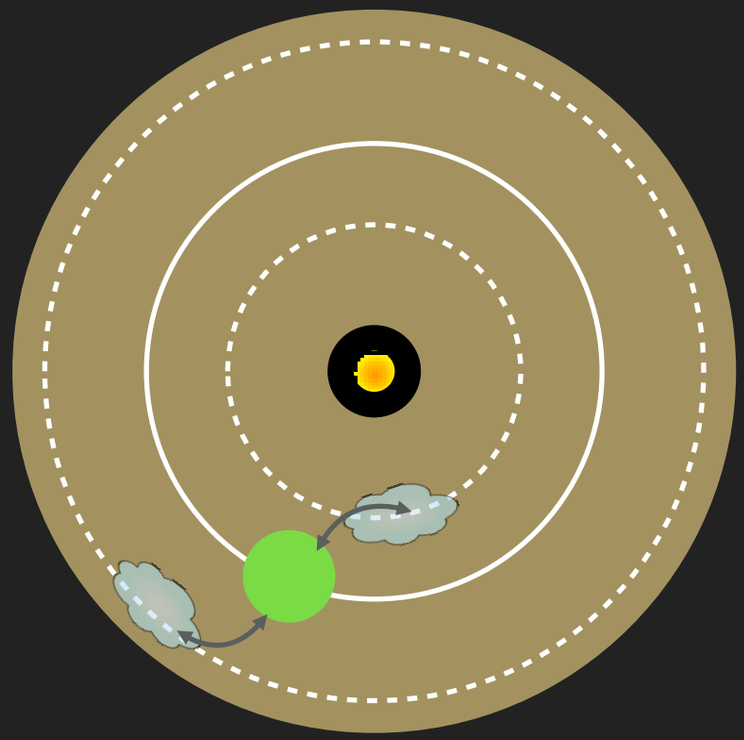
Sum of torques typically causes inward motion of the planet



Type I migration

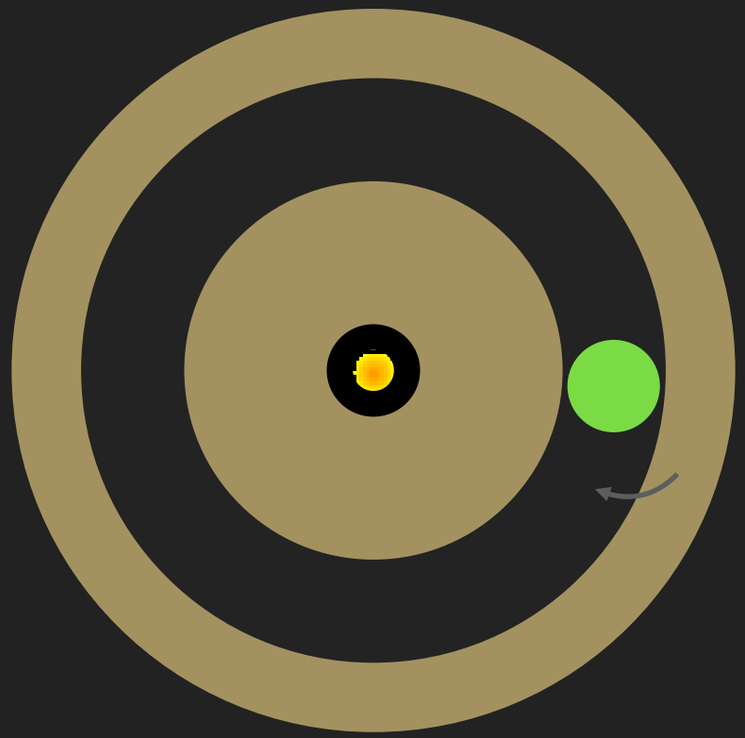


Planet grows, angular momentum exchange with the gas increases

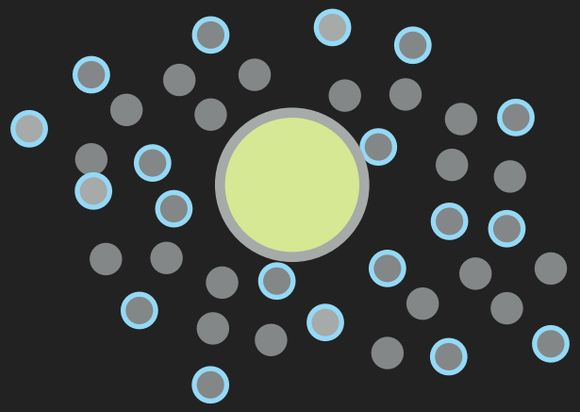


And a gap around the planet forms

Inward motion due to viscous gas flow into gap



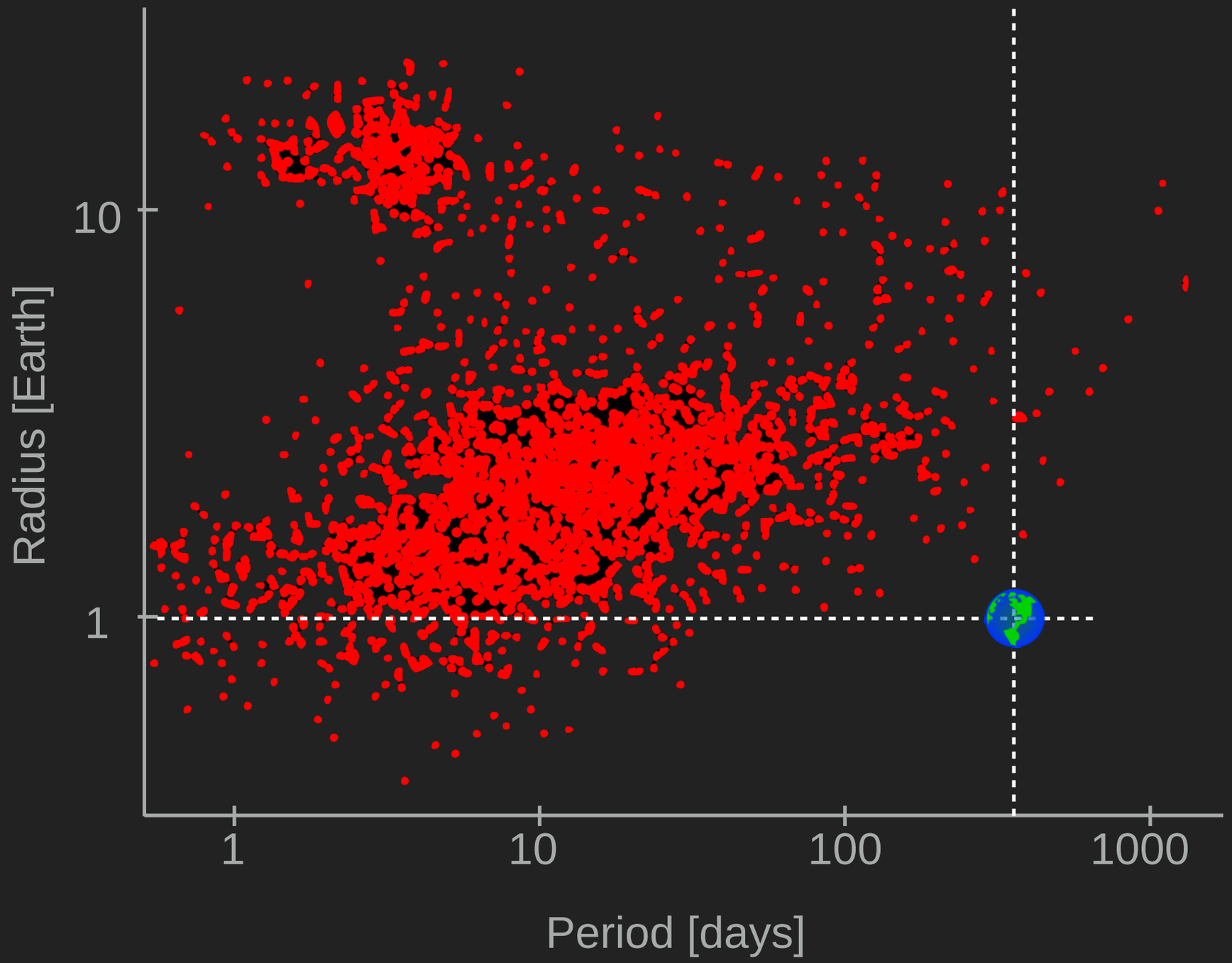
Type II migration



Planet can form beyond the ice line.

Migrate inwards to become a hot Jupiter.

Migration is common



Major architect of planetary systems

Important consequences for habitability

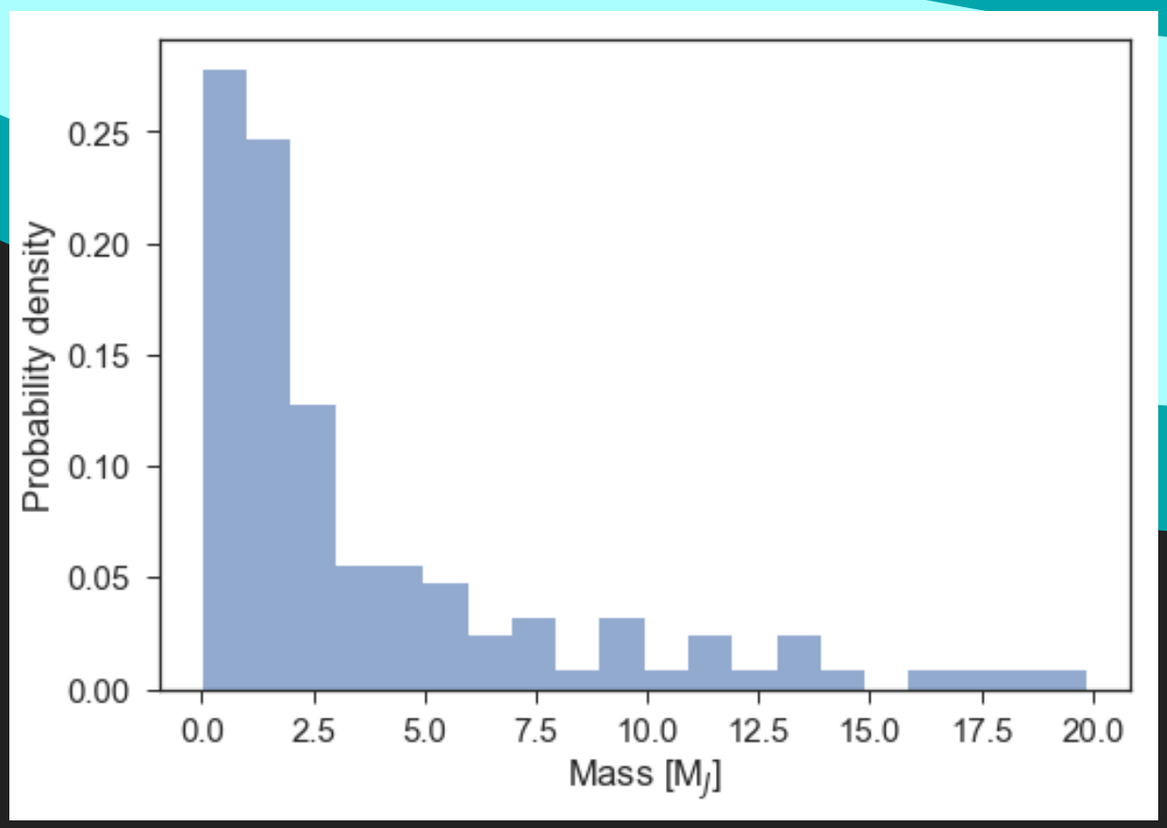
https://exoplanetarchive.ipac.caltech.edu

$R_p < 1.6\,R_\oplus$

$M_p < 6\,M_\oplus$

$t_{HZ} > 0$

- Kepler-1229b
- Kepler-186f
- Kepler-442b
- Kepler-62e
- Kepler-62f
- GJ 832c
- TRAPPIST-1e
- TRAPPIST-1f
- TRAPPIST-1g
- Prox Cen b
- Ross 128b

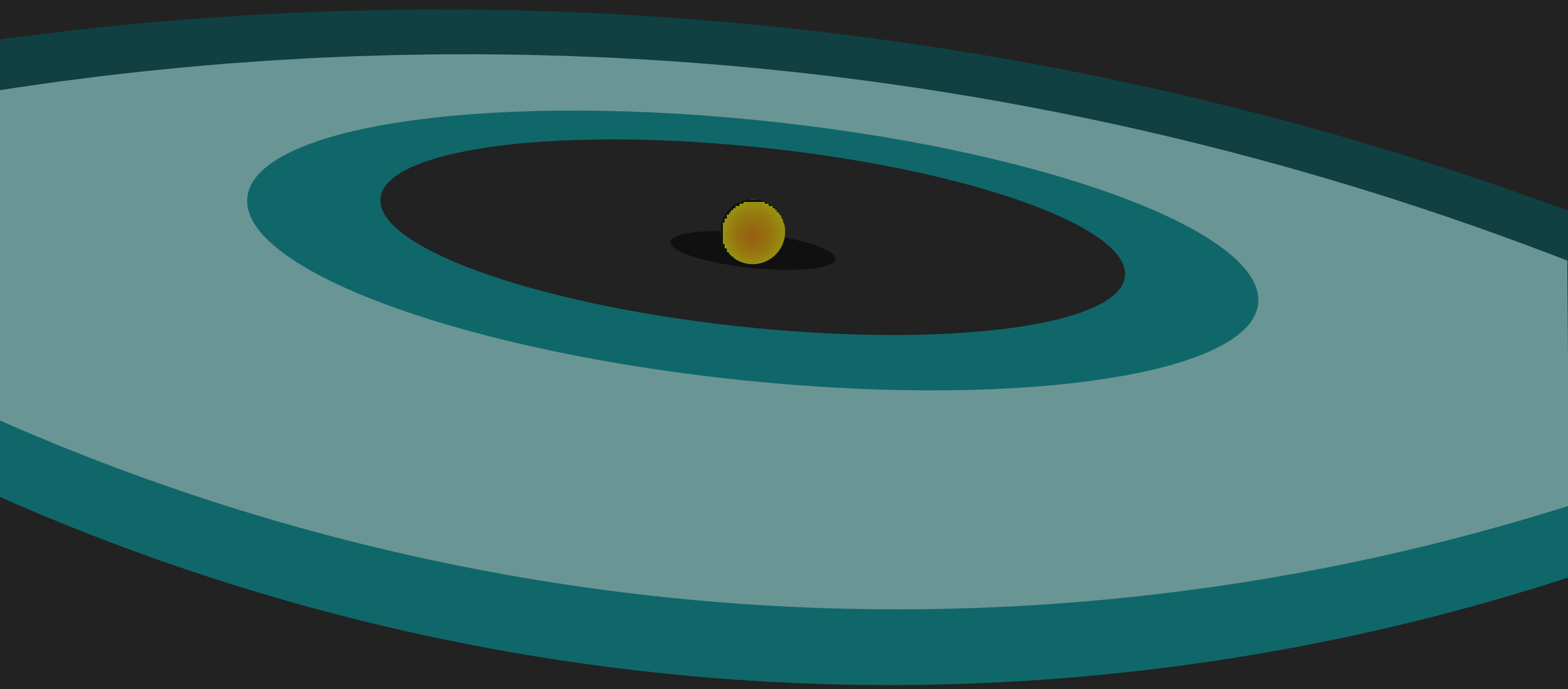


15 : 1

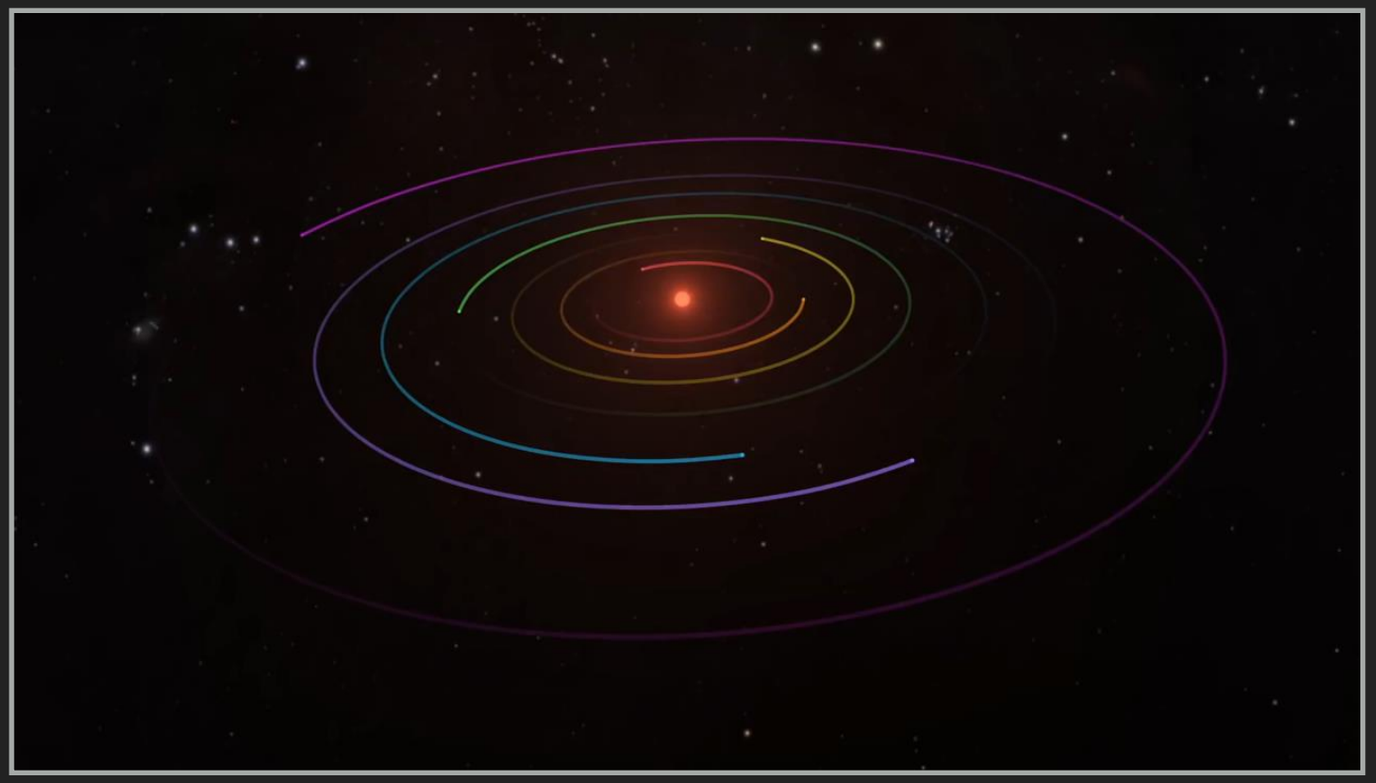
Non-rocky : rocky

http://www.hzgallery.org/ (Kane & Gelino, 2010)

Another Earth is expected to be in the HZ



But planets within the HZ are not all expected to be like Earth

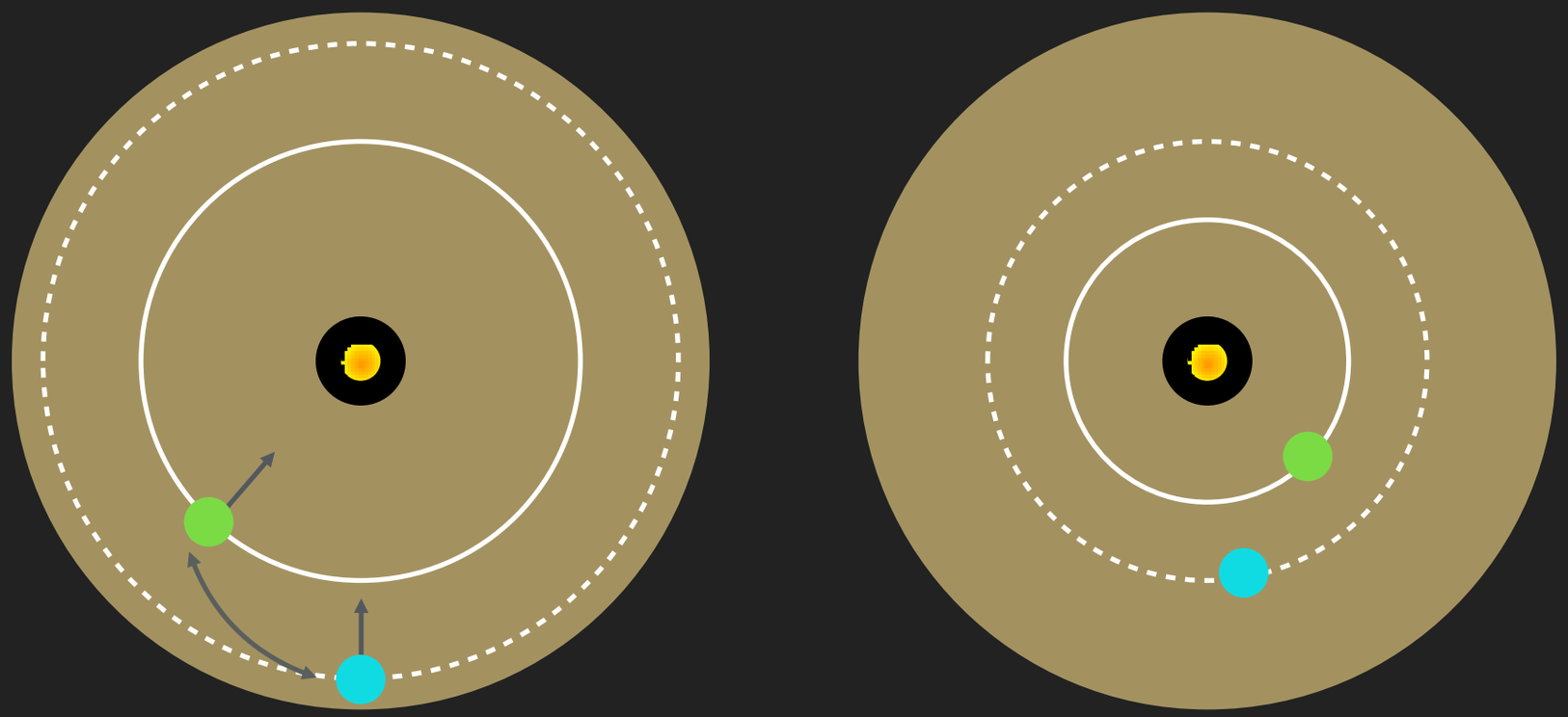


NASA/JPL

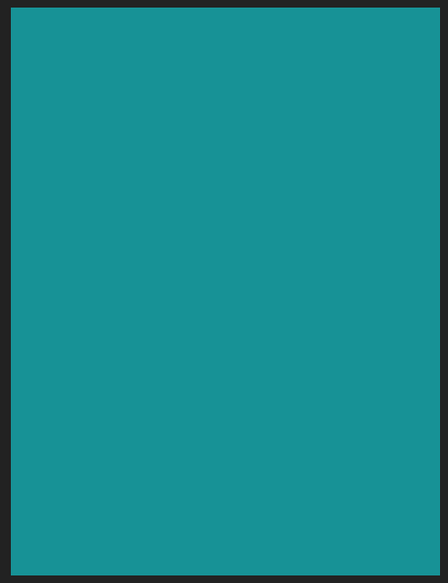
TRAPPIST-1 planets are in resonance

24 15 9 6 4 3 2

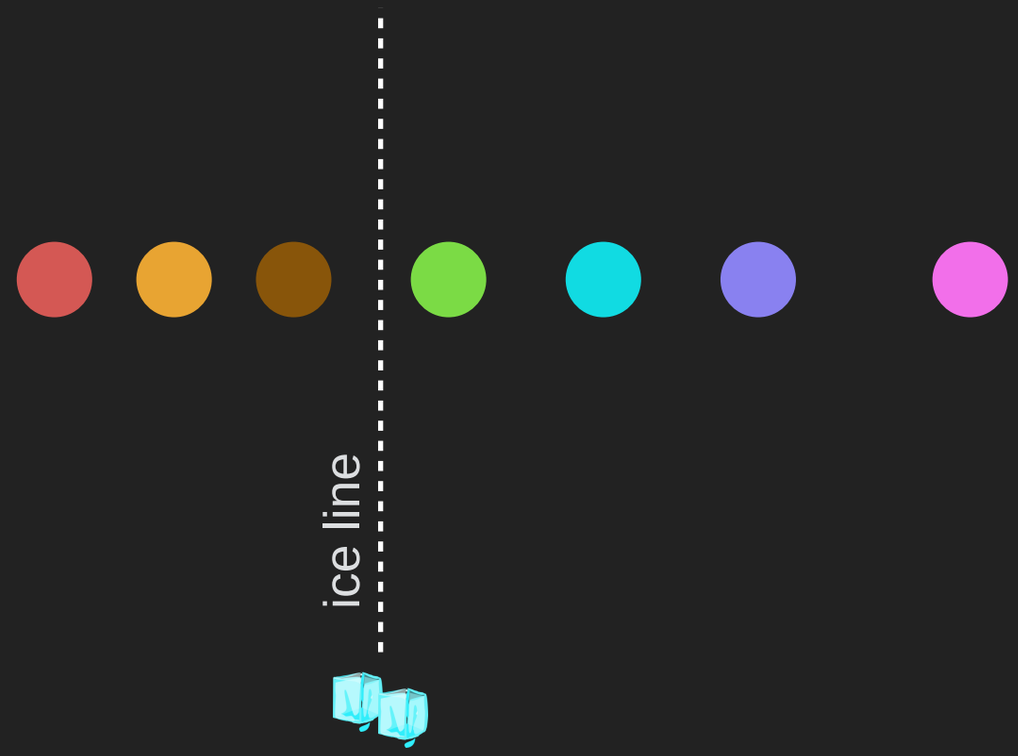
orbits



Thought to happen during migration

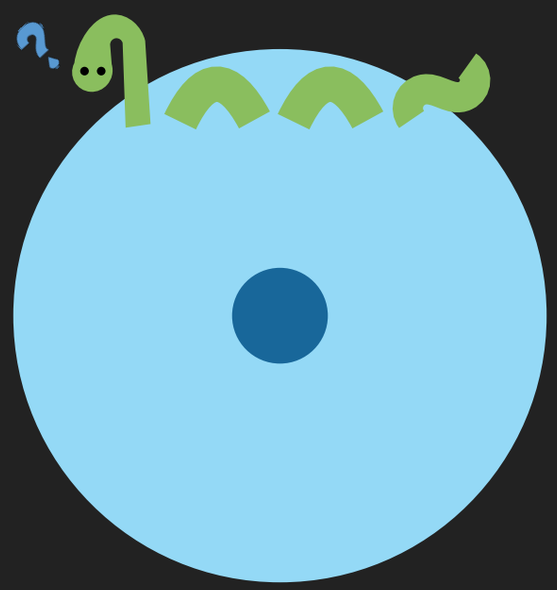


habitable zone



If Trappist-1 planets formed beyond the ice line

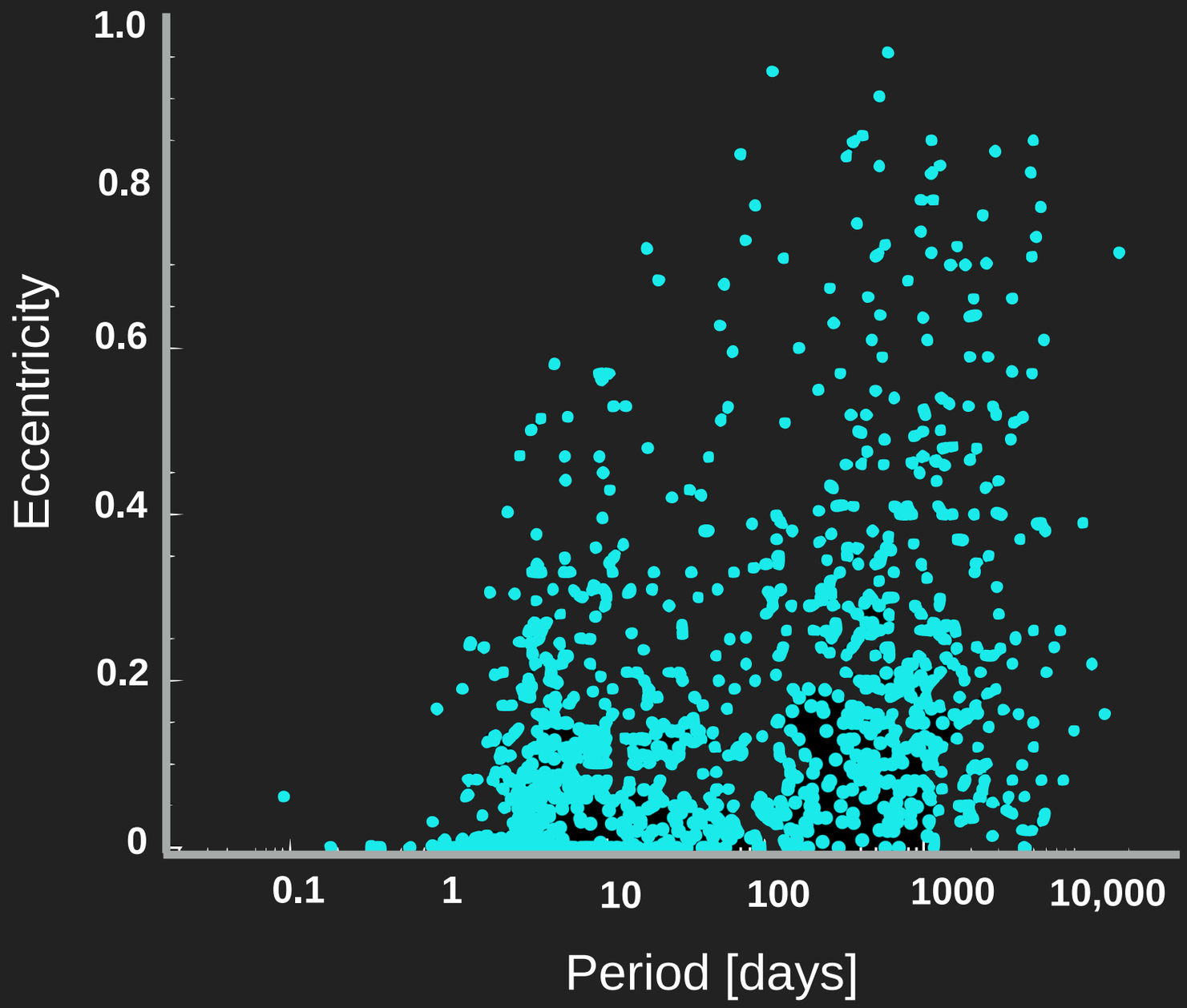
Then they may be water worlds, with hundreds of oceans more water than Earth



Water worlds are not Earth-like

Are they habitable? ⟶ Steve Dasch’s talk

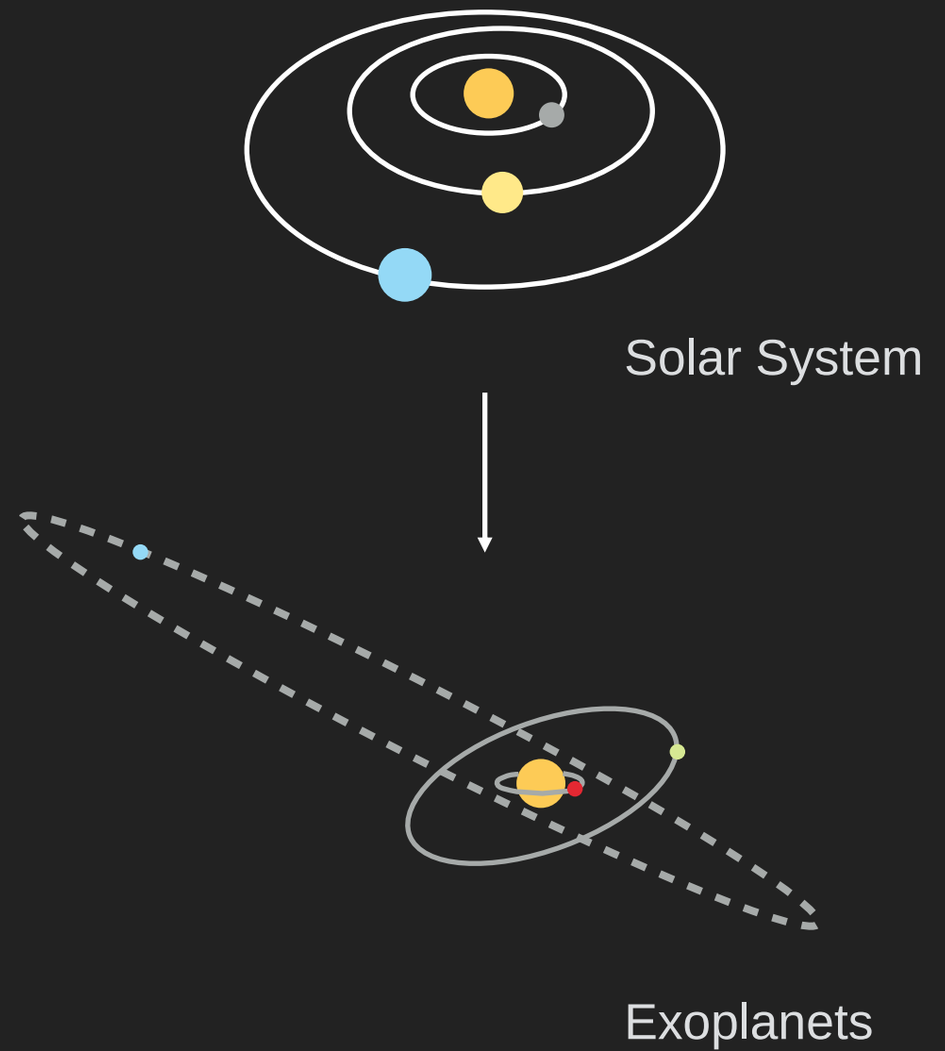
Planet eccentricity > 0

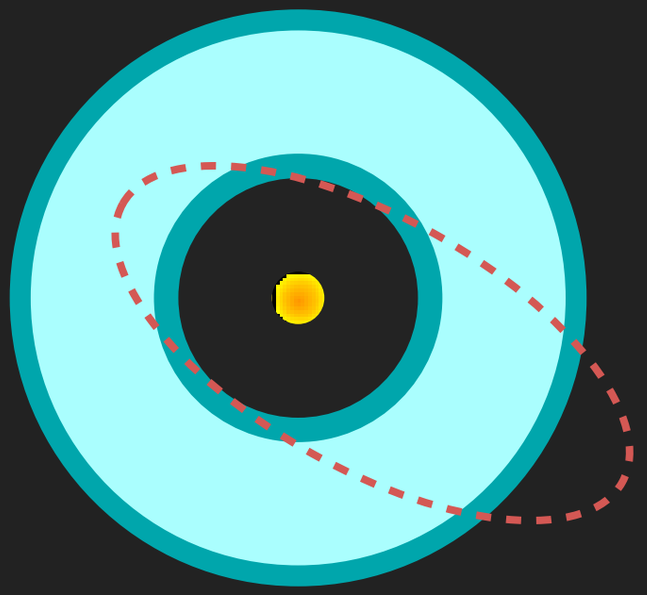


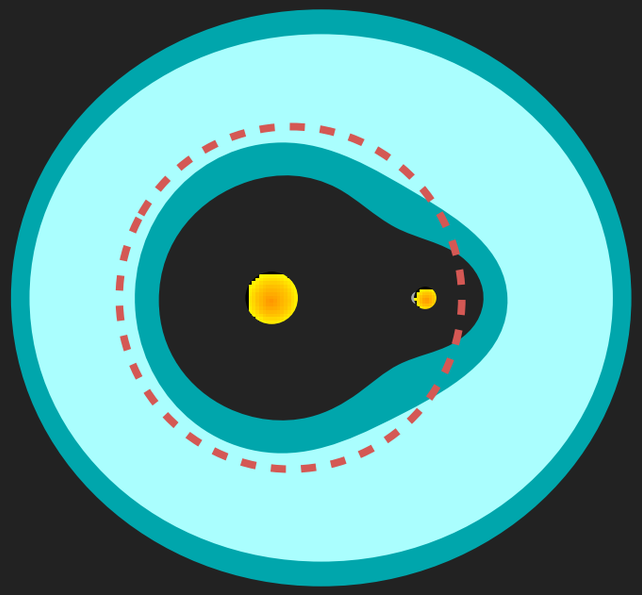
Average eccentricity of

planets > 100 days / 1 au

e ~ 0.26

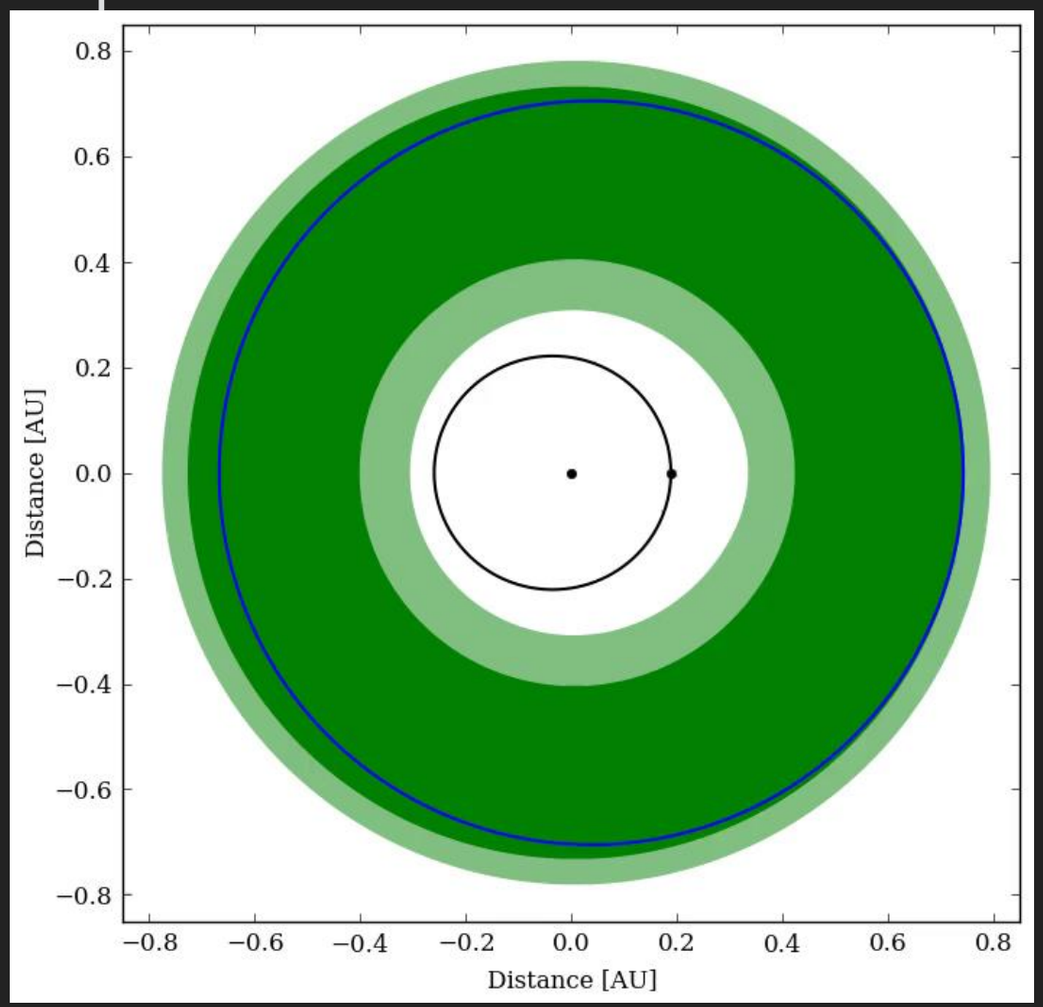


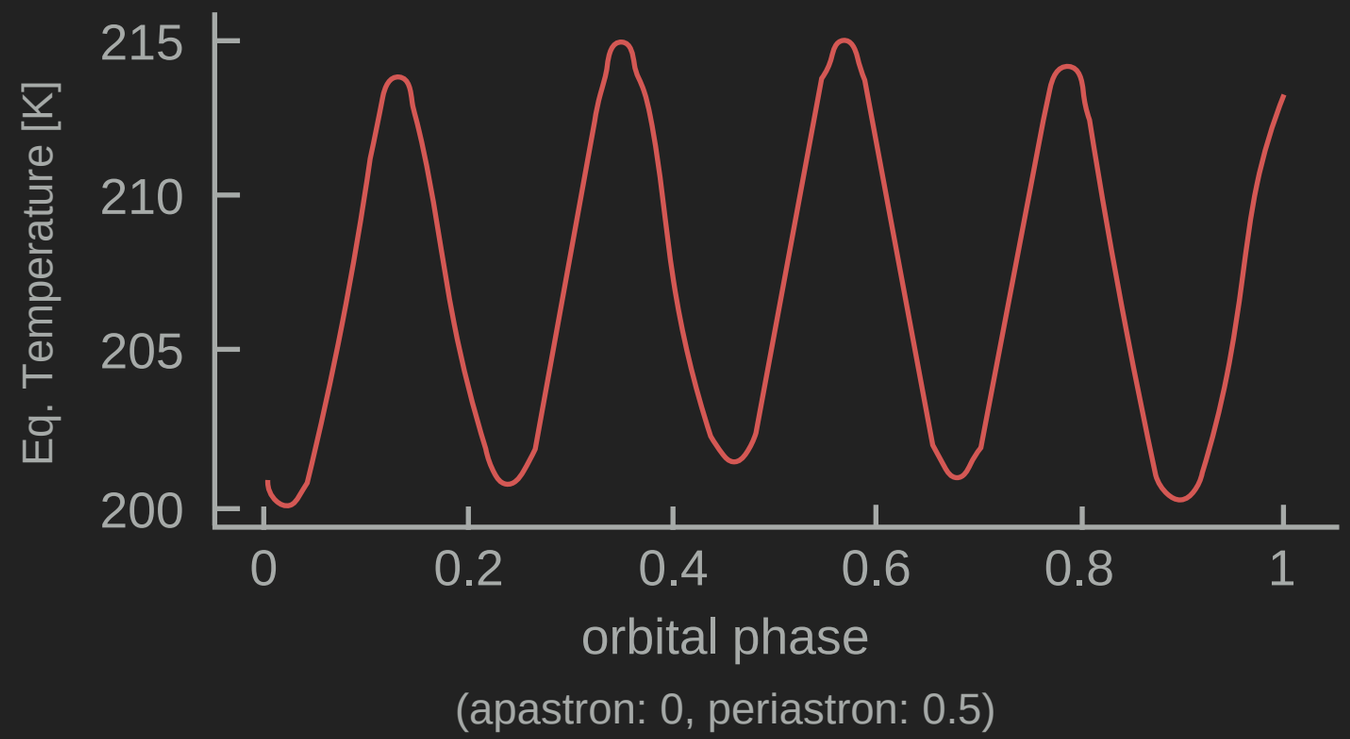




Eccentric orbits or multi-star systems cause planets to move in & out of the HZ

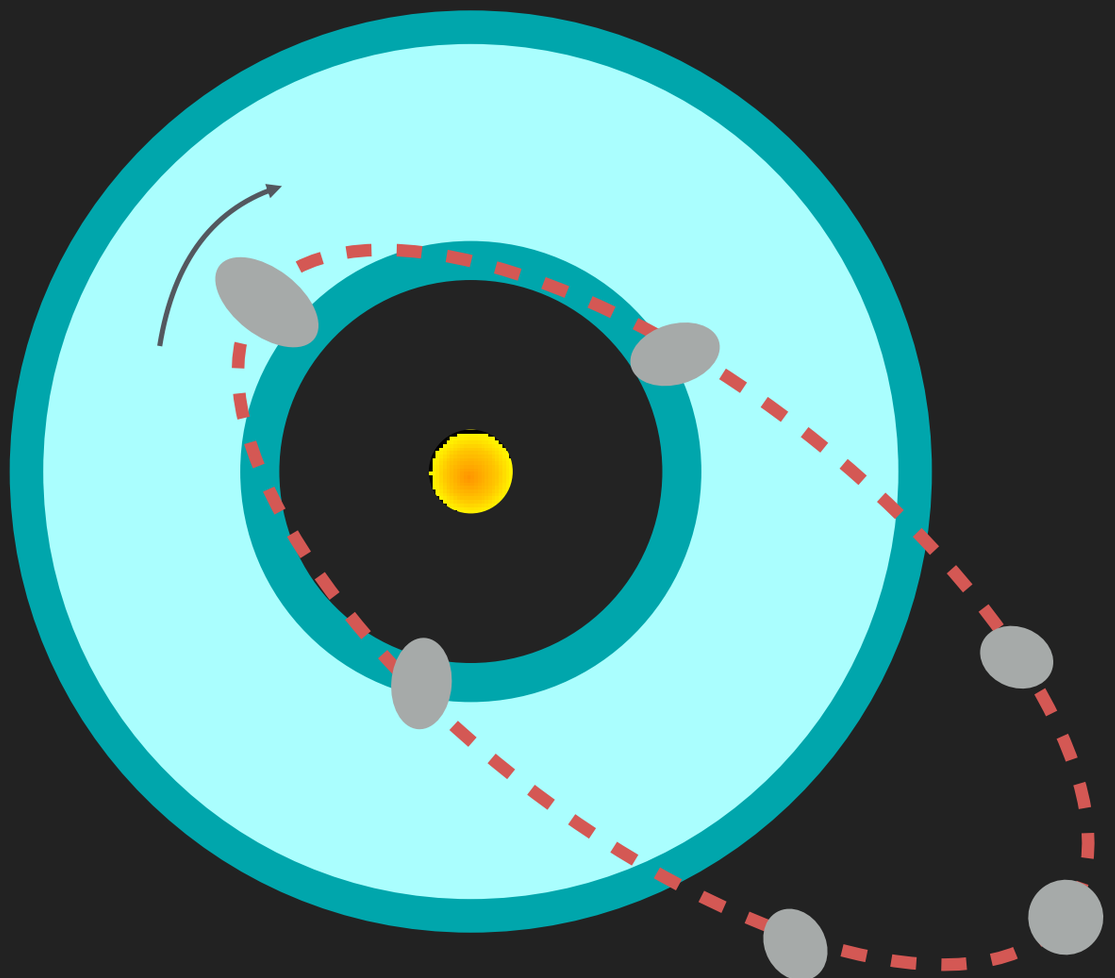
Kepler-16 b





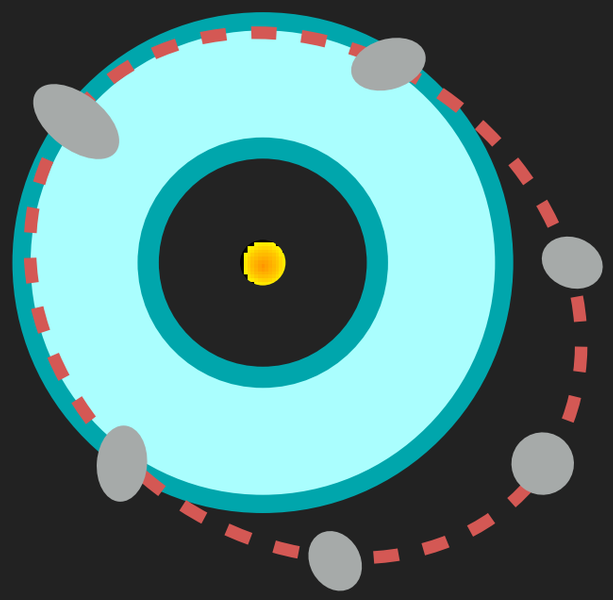
(Kane & Hinkel, 2013)

http://astro.twam.info/hz/

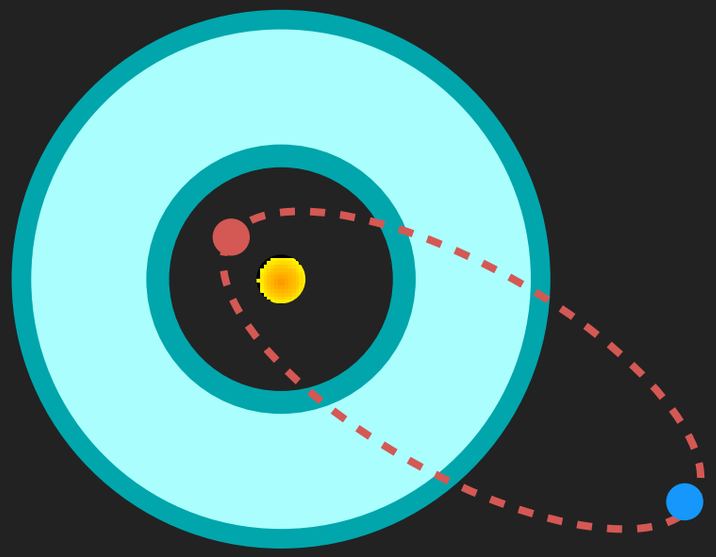


Eccentric orbits can also tidally heat a planet

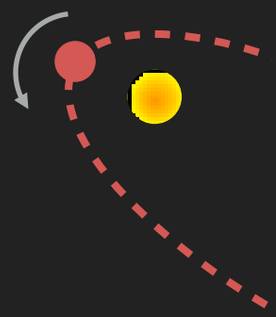
The planet is flexed as its distance from the star changes



For a mildly eccentric orbit, the most clement climate might be just outside the HZ



Can life survive extreme seasons?



Planet moves fast close to the star, so scorching summer is short

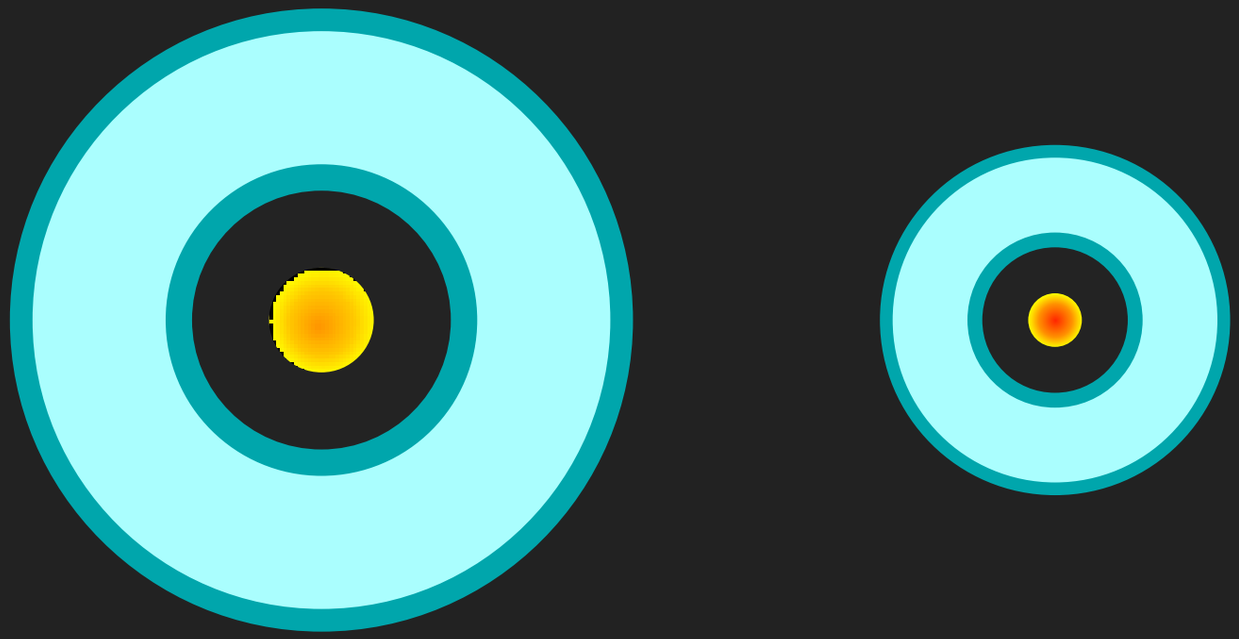
Might be able to retain water

If $< F > \sim F_{\mathrm{HZ}}$

(Williams & Pollard, 2002)

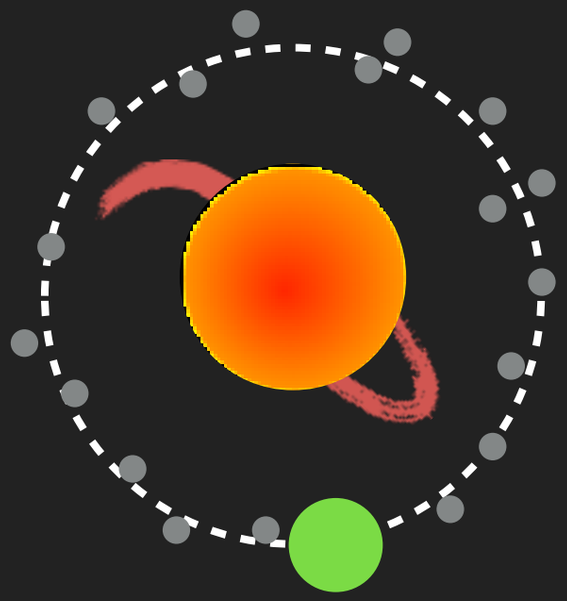
Life might hibernate during inhospitable spells

(Kane et al. 2012)



HZ around dim M-dwarf stars is much closer-in

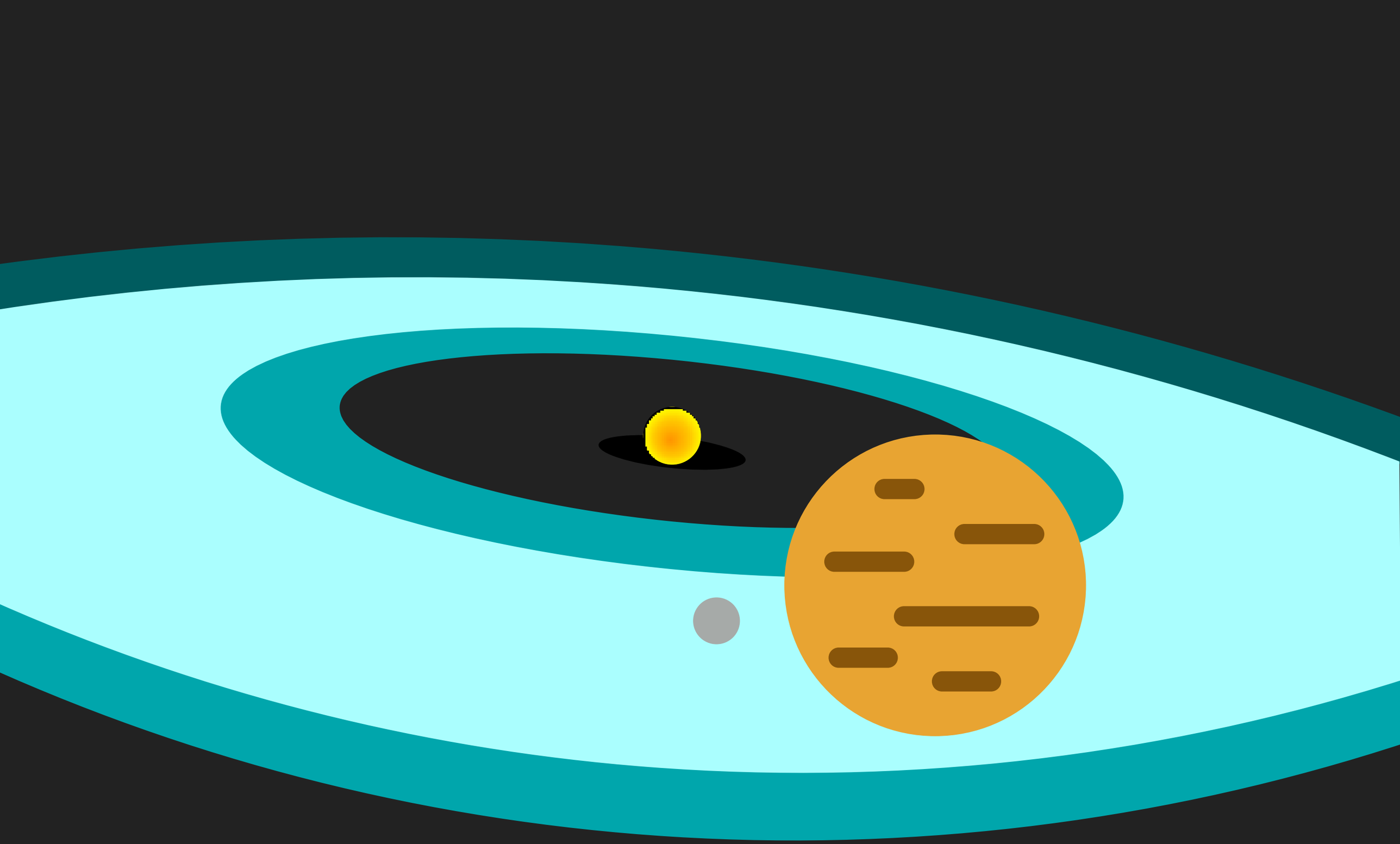
Planets easier to detect



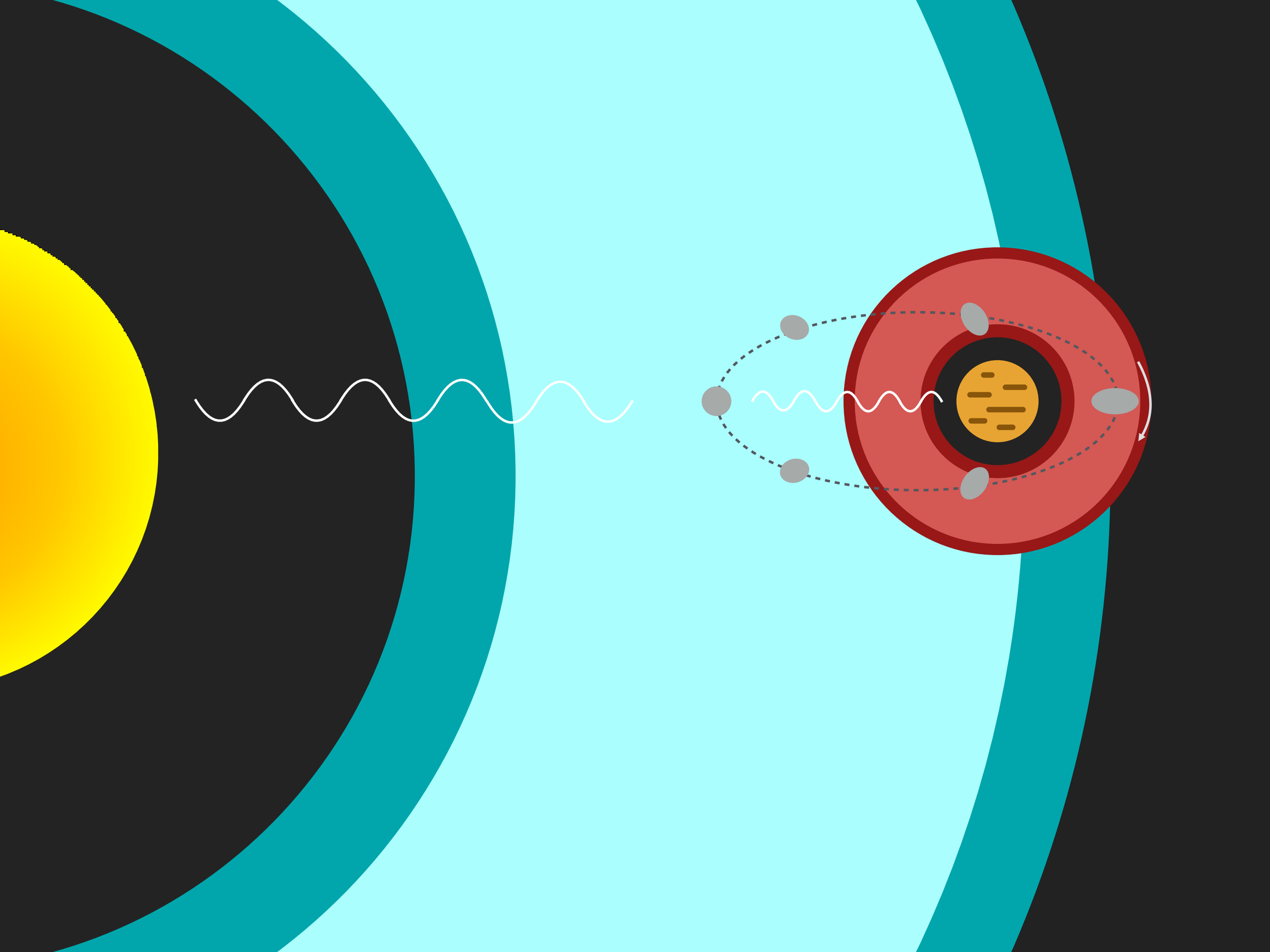
Young M-dwarf stars are rambunctious

On short orbits, planet formation is swift

Planet may be sterilised



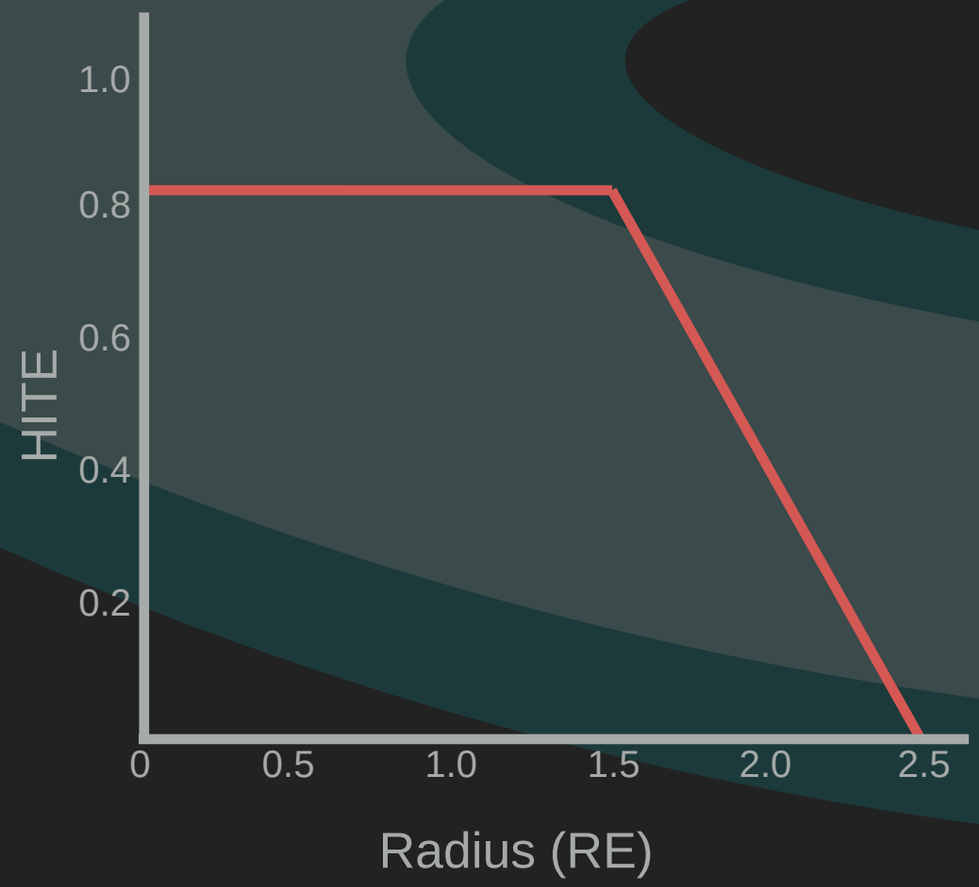
Could an Earth-sized moon be habitable?

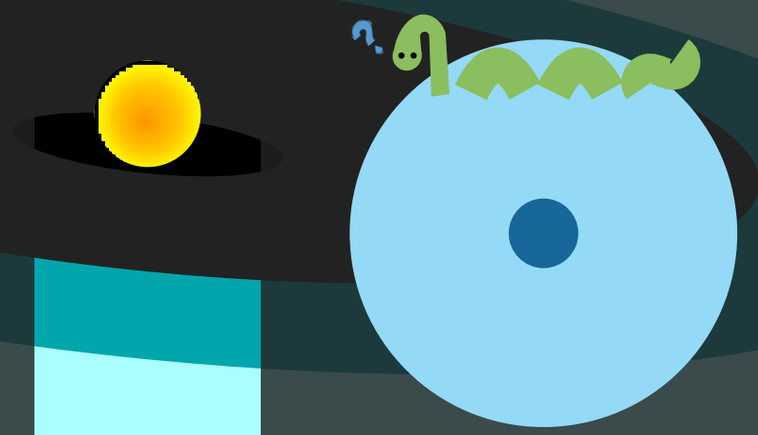


The Habitability Index for Transiting Exoplanets (HITE)

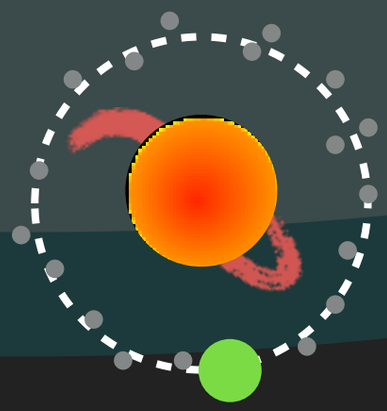
$$H = \frac{\sum h_{\mathrm{HITE,j}} p_j(e)}{\sum p_j(e)} p_{\mathrm{rocky}}$$

Removes gas planets from target selection

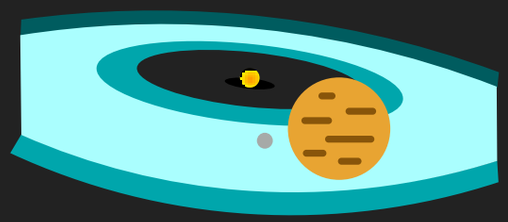




Wouldn't rule out an Earth-sized water world

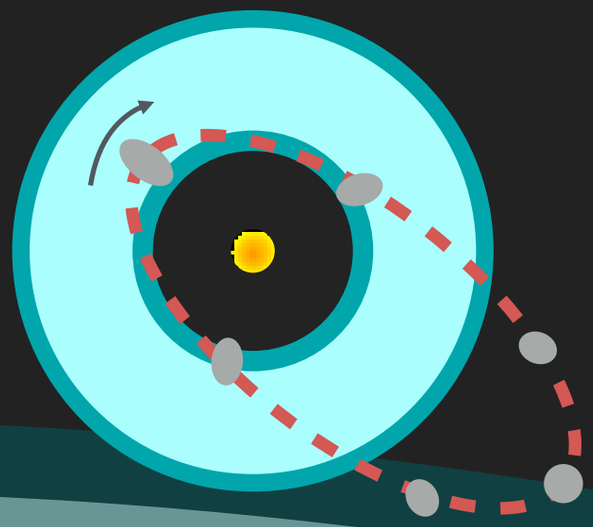


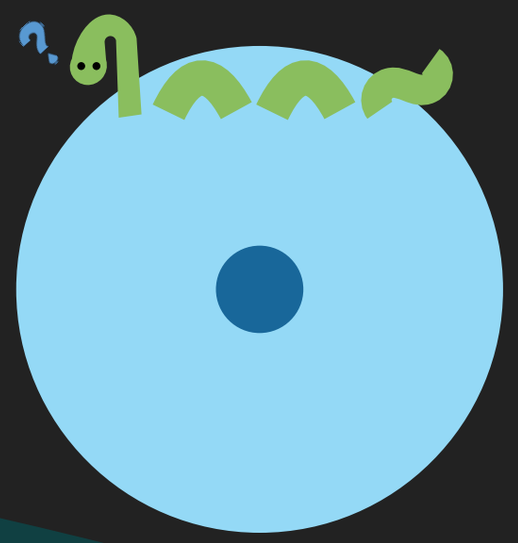
or stérilisation from stellar radiation



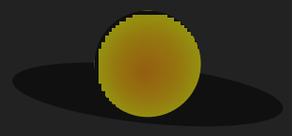
or additional forms of heating

(Barnes, Meadows & Evans, 2015)



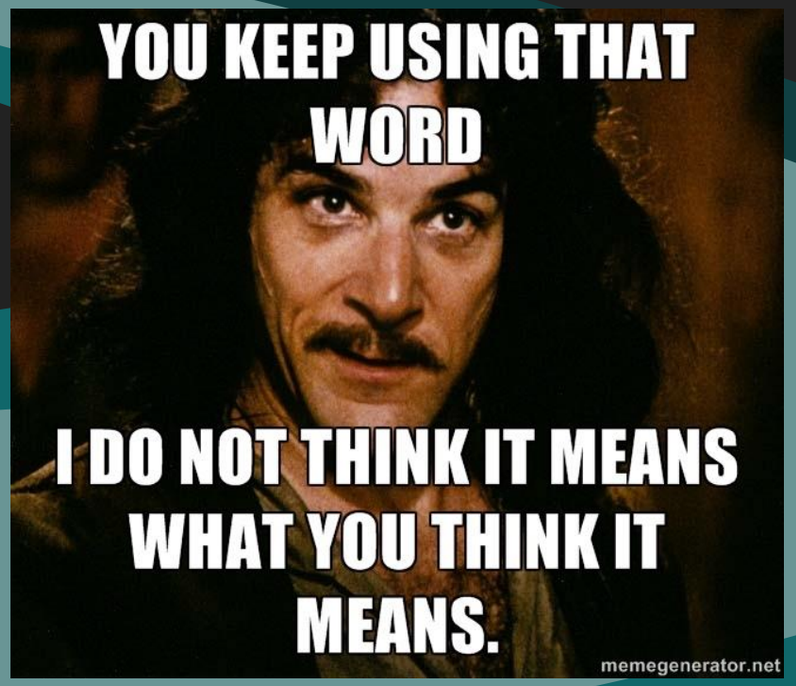


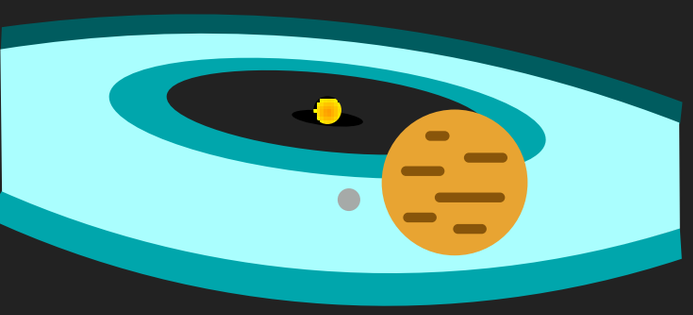
Habitable

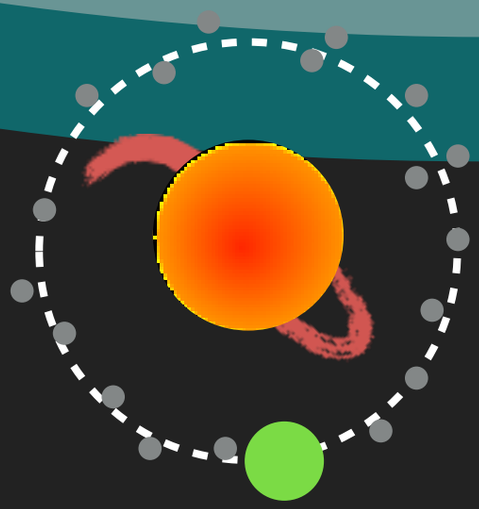


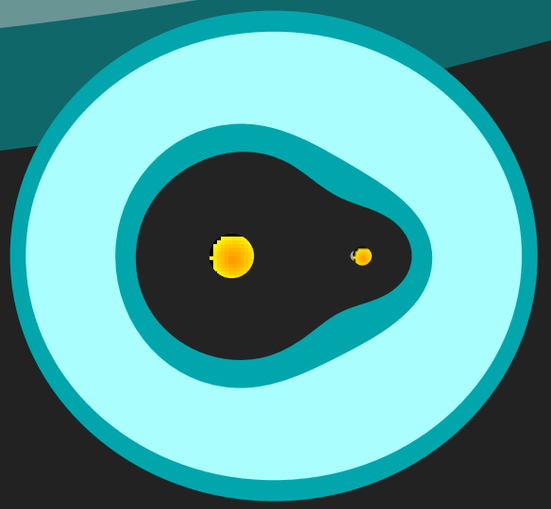
No quantitive measure of habitability

Just our best attempts at target selection









that variable interstellar medium density can affect the astrosphere of planetary systems, changing the level of shielding to cosmic rays.

Exoplanets are often rated on the Earth Similarity Index (ESI Schulze-Makuch et al. 2011), which measures the similarity of a planet to Earth based on its radius, bulk density, escape velocity and surface temperature. In this work we consider the host stars of the most Earth-like exoplanets defined by this index, as found in the Habitable Exoplanets Catalogue[1]. To allow this sample, we limit ou *pler* mission, giving a sa

"most Earth-like exoplanets"

The emergence of "life as we know it" requires stars for two reasons. Stars are needed to produce the heavy elements (carbon, oxygen and so on, up to iron) out of which rocky planets and the molecules of life are made. Stars also provide a heat source for powering the chemistry of life on the surface of their planets. Each star is surrounded by a habitable zone where the surface temperature of a planet allows liquid water to exist. The approximate distance of the habitable zone, $r_{\rm HZ}$, is obtained by equating the heating rate per unit area from the stellar luminos $T_{\rm HZ} \sim 300$ K, namely (L

… habitable zone where the surface temperature of a planet allows liquid water to exist

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trosphere of planetary systems, changing the level of s
ing to cosmic rays.

Exoplanets are often rated on the Earth Similarit
dex (ESI Schulze-Makuch et al. 2011), which measure
similarity of a planet to Earth based on its radius, bulk

Space

'Second Earth' exoplanet found just outside our Solar System could harbour alien life

Proxima b has a temperature suitable for liquid water to exist

INDEPENDENT News Voices Culture Lifestyle Tech Sport Daily Edition Charity Appeal

News › Science

Earth 2.0: What we know about Kepler 452b, the most Earth-like planet ever discovered

an Earth, slightly larger, could have liquid water on the surface and it's 1,400

Friday 24 July 2015

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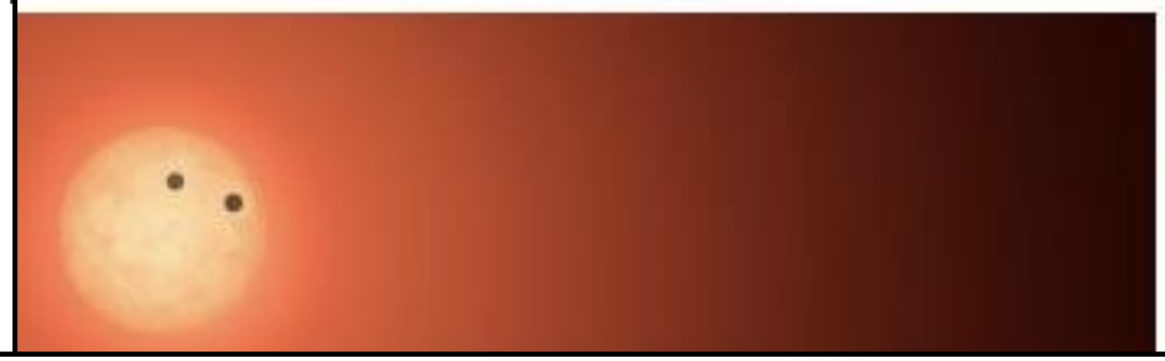
The Prospects for Life on TRAPPIST-1 Keep Getting Better

Maddie Stone



Another Earth? THESE Five Exoplanets That Are Quite Like Our Mother Earth!

1 APR , 2016

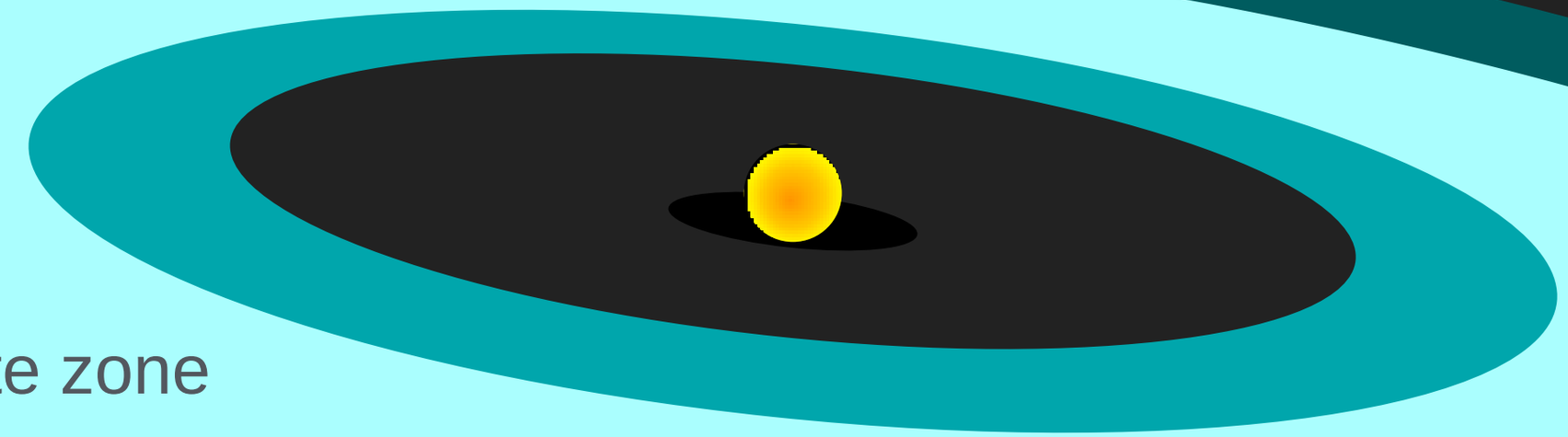
537 SHARES | 534 | 0 | 1 | 1 | 1 | 0

Space research is a fascinating field. Searching new planets and stars and galaxies, studying the existing ones, comparing two different celestial bodies etc. are some of the interesting aspects of it. One of the fixation of space scientists is searching planets similar to Mother Earth. Finding a planet and life (or even probability of life) on it has been a fetish since long for these scientists. The habitability of these planets is calculated on the

Space

Kepler-442b is more habitable than Earth

Can we use a better term?

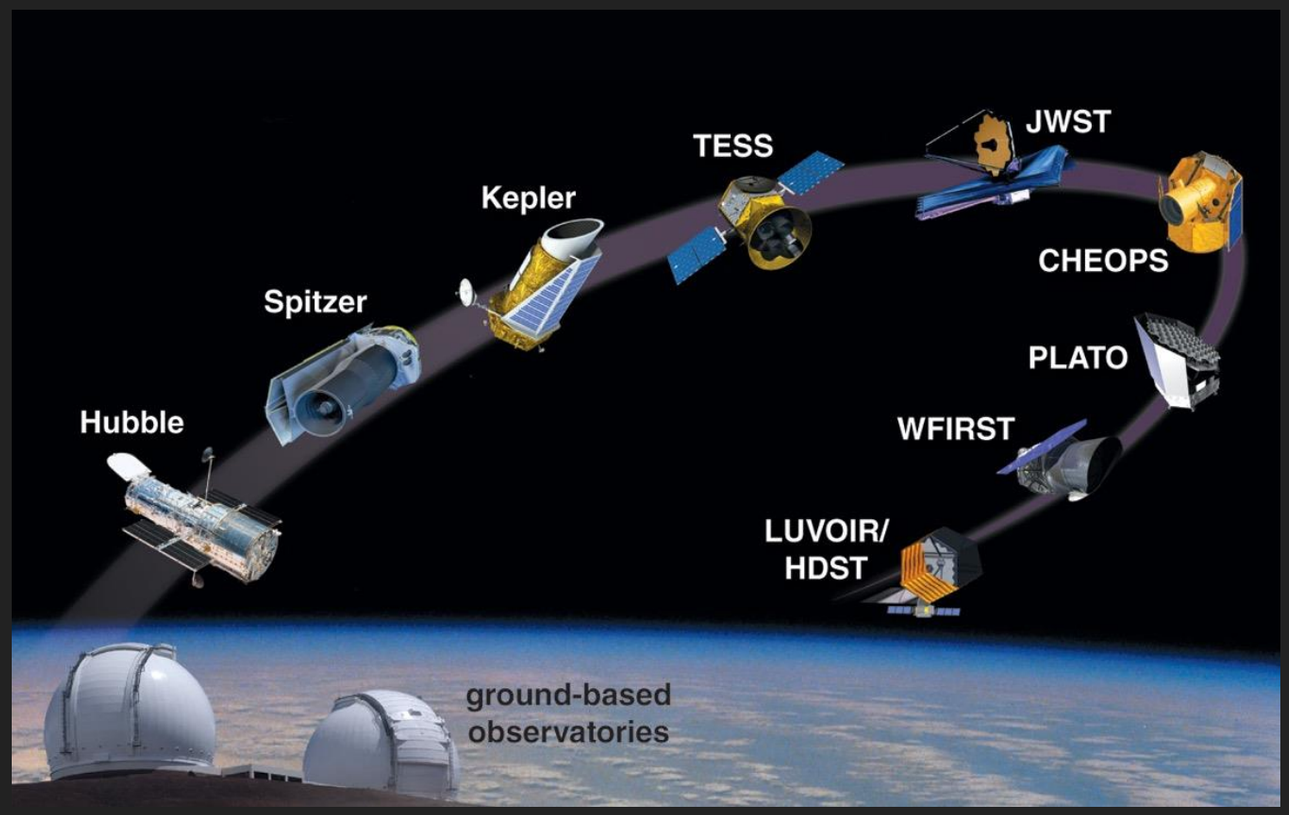


Temperate zone

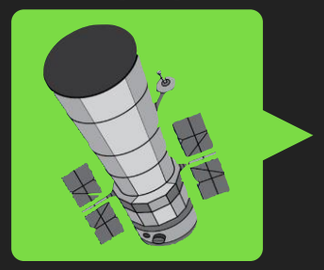
Hunting zone

High-priority zone

We may be on the brink of finding life on another world

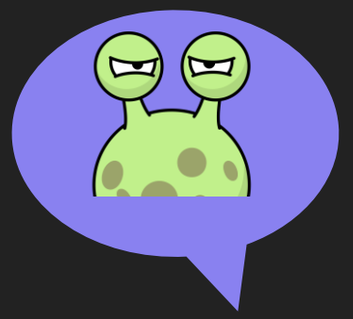


Astrophysics



Geophysics

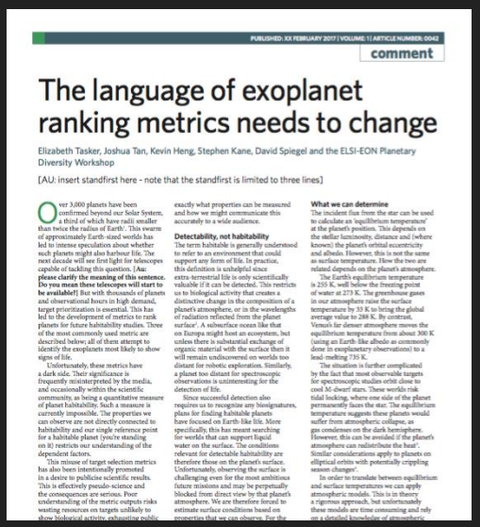
Biology



But it’s going to take all of us

And we don’t use the same jargon

Let’s watch our language.



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comment

The language of exoplanet ranking metrics needs to change

Elizabeth Tasker, Joshua Tan, Kevin Heng, Stephen Kane, David Spiegel and the ELSI-EON Planetary Diversity Workshop

[AU: insert standfirst here - note that the standfirst is limited to three lines]

Over 3,000 planets have been confirmed beyond our Solar System, a third of which have radii smaller than twice the radius of Earth[1]. This swarm of approximately Earth-sized worlds has led to intense speculation about whether such planets might also harbour life. The next decade will see first light for telescopes capable of tackling this question. [Au: **please clarify the meaning of this sentence. Do you mean these telescopes will start to be available?**] But with thousands of planets and observational hours in high demand, target prioritization is essential. This has led to the development of metrics to rank planets for future habitability studies. Three of the most commonly used metric are described below; all of them attempt to identify the exoplanets most likely to show signs of life.

Unfortunately, these metrics have a dark side. Their significance is frequently misinterpreted by the media, and occasionally within the scientific community, as being a quantitative measure of planet habitability. Such a measure is currently impossible. The properties we can observe are not directly connected to habitability and our single reference point for a habitable planet (you're standing on it) restricts our understanding of the dependent factors.

This misuse of target selection metrics has also been intentionally promoted in a desire to publicise scientific results. This is effectively pseudo-science and the consequences are serious. Poor understanding of the metric outputs risks wasting resources on targets unlikely to show biological activity, exhausting public

exactly what properties can be measured and how we might communicate this accurately to a wide audience.

Detectability, not habitability

The term habitable is generally understood to refer to an environment that could support any form of life. In practice, this definition is unhelpful since extra-terrestrial life is only scientifically valuable if it can be detected. This restricts us to biological activity that creates a distinctive change in the composition of a planet's atmosphere, or in the wavelengths of radiation reflected from the planet surface[2]. A subsurface ocean like that on Europa might host an ecosystem, but unless there is substantial exchange of organic material with the surface then it will remain undiscovered on worlds too distant for robotic exploration. Similarly, a planet too distant for spectroscopic observations is uninteresting for the detection of life.

Since successful detection also requires us to recognize any biosignatures, plans for finding habitable planets have focused on Earth-like life. More specifically, this has meant searching for worlds that can support liquid water on the surface. The conditions relevant for detectable habitability are therefore those on the planet's surface. Unfortunately, observing the surface is challenging even for the most ambitious future missions and may be perpetually blocked from direct view by that planet's atmosphere. We are therefore forced to estimate surface conditions based on properties that we can observe. For the

What we can determine

The incident flux from the star can be used to calculate an 'equilibrium temperature' at the planet's position. This depends on the stellar luminosity, distance and (where known) the planet's orbital eccentricity and albedo. However, this is not the same as surface temperature. How the two are related depends on the planet's atmosphere.

The Earth's equilibrium temperature is 255 K, well below the freezing point of water at 273 K. The greenhouse gases in our atmosphere raise the surface temperature by 33 K to bring the global average value to 288 K. By contrast, Venus's far denser atmosphere moves the equilibrium temperature from about 300 K (using an Earth-like albedo as commonly done in exoplanetary observations) to a lead-melting 735 K.

The situation is further complicated by the fact that most observable targets for spectroscopic studies orbit close to cool M-dwarf stars. These worlds risk tidal locking, where one side of the planet permanently faces the star. The equilibrium temperature suggests these planets would suffer from atmospheric collapse, as gas condenses on the dark hemisphere. However, this can be avoided if the planet's atmosphere can redistribute the heat[3]. Similar considerations apply to planets on elliptical orbits with potentially crippling season changes[4].

In order to translate between equilibrium and surface temperatures we can apply atmospheric models. This is in theory a rigorous approach, but unfortunately these models are time consuming and rely on a detailed knowledge of atmospheric

Earth -size is not Earth -like

but Earth -size is Venus -size

The optimistic edges of the HZ are based on empirical data.

Why is Venus so awful?