Tides and Tidal Forces

So far, we’ve been making a major unspoken assumption: that the energy to power life must come from stars.

Credit: pxhere.com

We’ve also been assuming that terrestrial planets are the ‘natural’ habitat for life.

Credit: NASA/Kepler

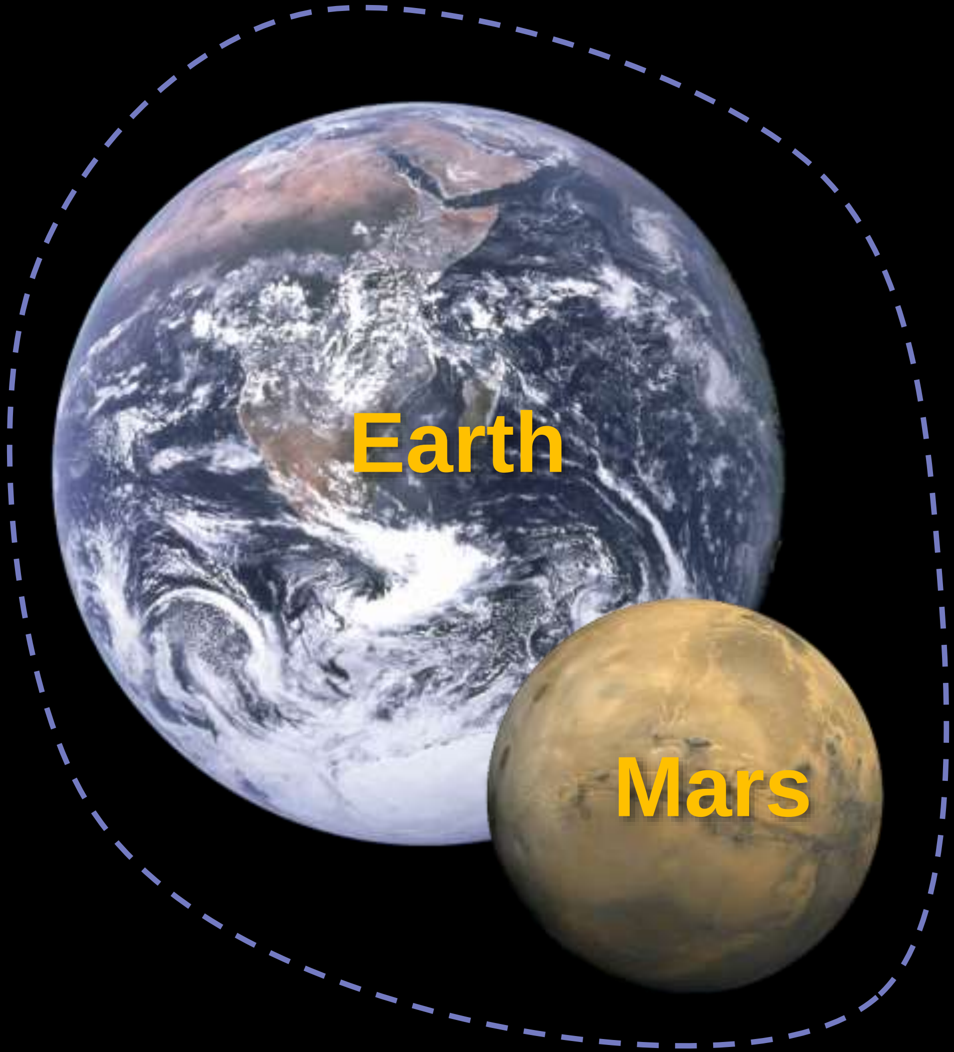
What if either or both of these assumptions is wrong?

Maybe *really* wrong.

We know that starlight isn't the only way to keep a world warm.

Other energy sources for life might include chemical reactions, radioactive decay, and tides.

In most of the places in our solar system that seem to have liquid water, that water is kept liquid not by sunlight, but by tides.



Energy to keep water liquid comes mainly from sunlight

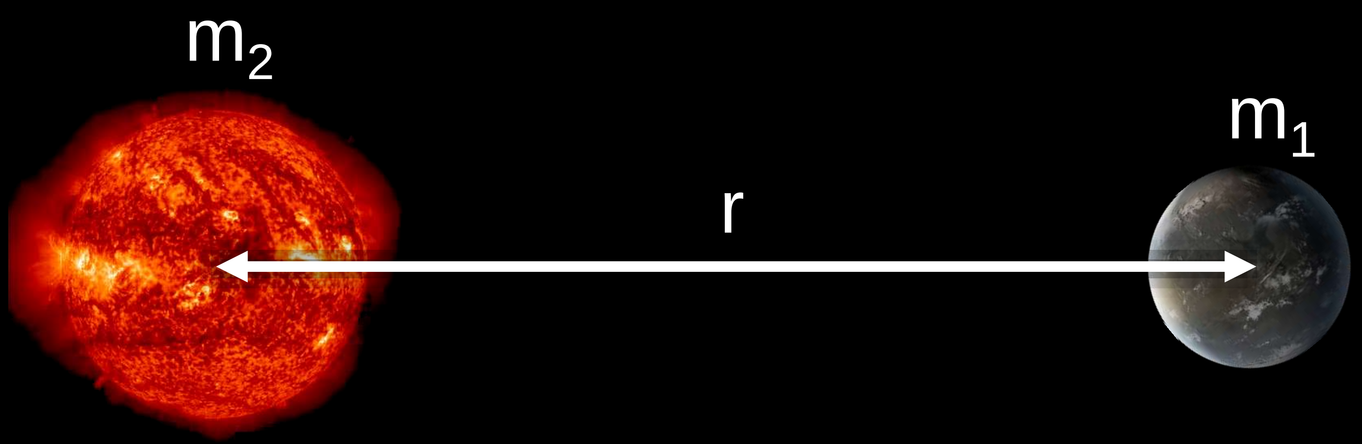
Energy to keep water liquid comes mainly from tides

Credit: NASA

If tides are such an important source of energy, we may need to completely rethink our notion of habitable zones.

But what exactly are tides and how do they supply energy to a planet or moon?

To understand tides, we need to remember that the force of gravity **depends on distance:**



$$F_{gravity} = \frac{Gm_1 m_2}{r^2}$$

Concept Check

Which of the following correctly describes the relationship between the force of gravity from the Earth felt by your head and your feet?

A. Your head feels stronger gravity
B. Your feet feel stronger gravity
C. They both feel the same force of gravity because the force of gravity at the surface of the Earth is constant

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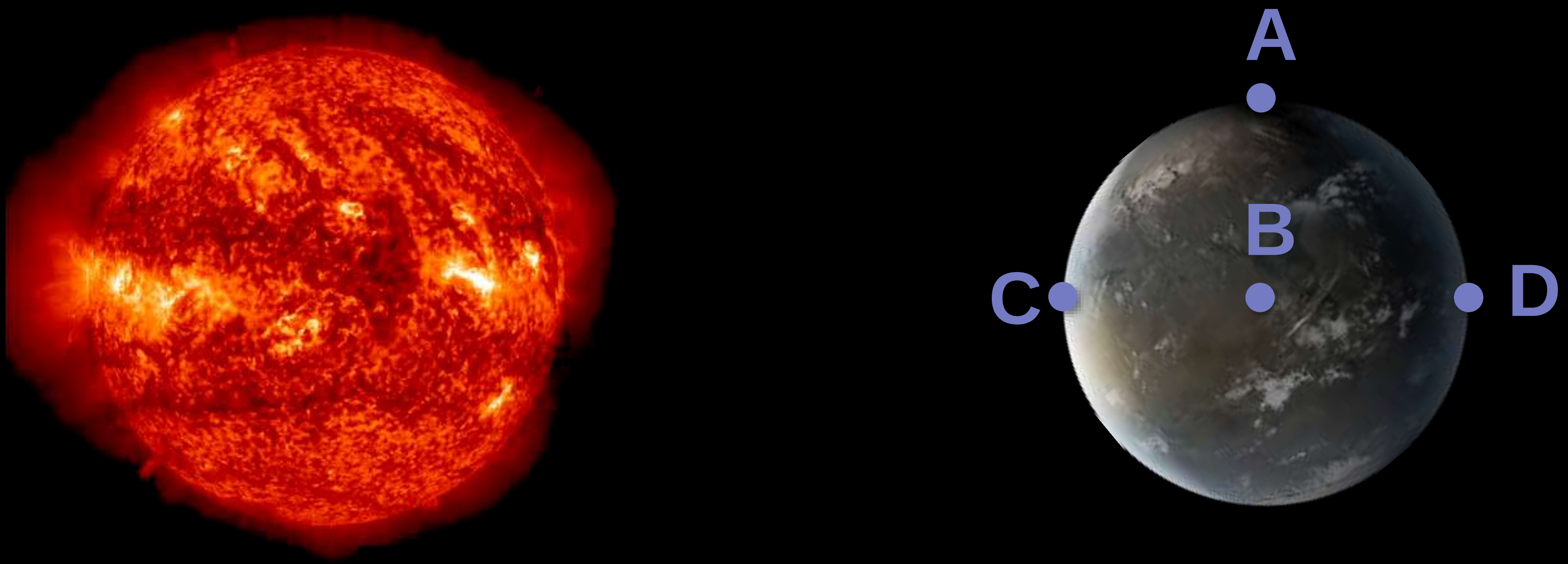
When you stand on the surface of the Earth, your feet are closer to the centre of mass of Earth than your head is. So, your feet feel a stronger force of gravity than your head does.

Credit: NASA/Robert Markowitz

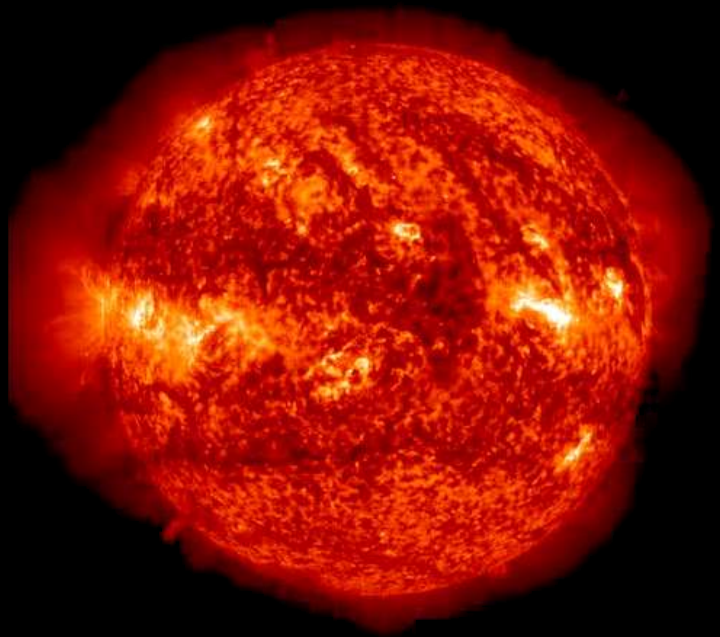
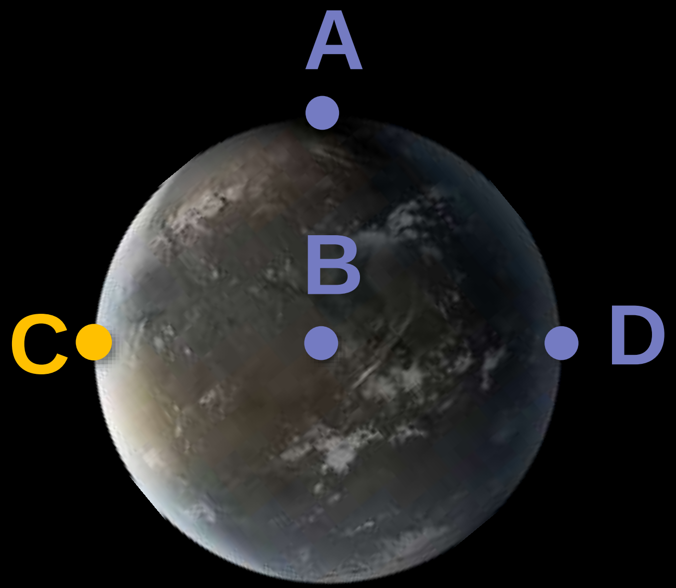
Concept Check

Which point on the planet feels the strongest force of gravity from the star?



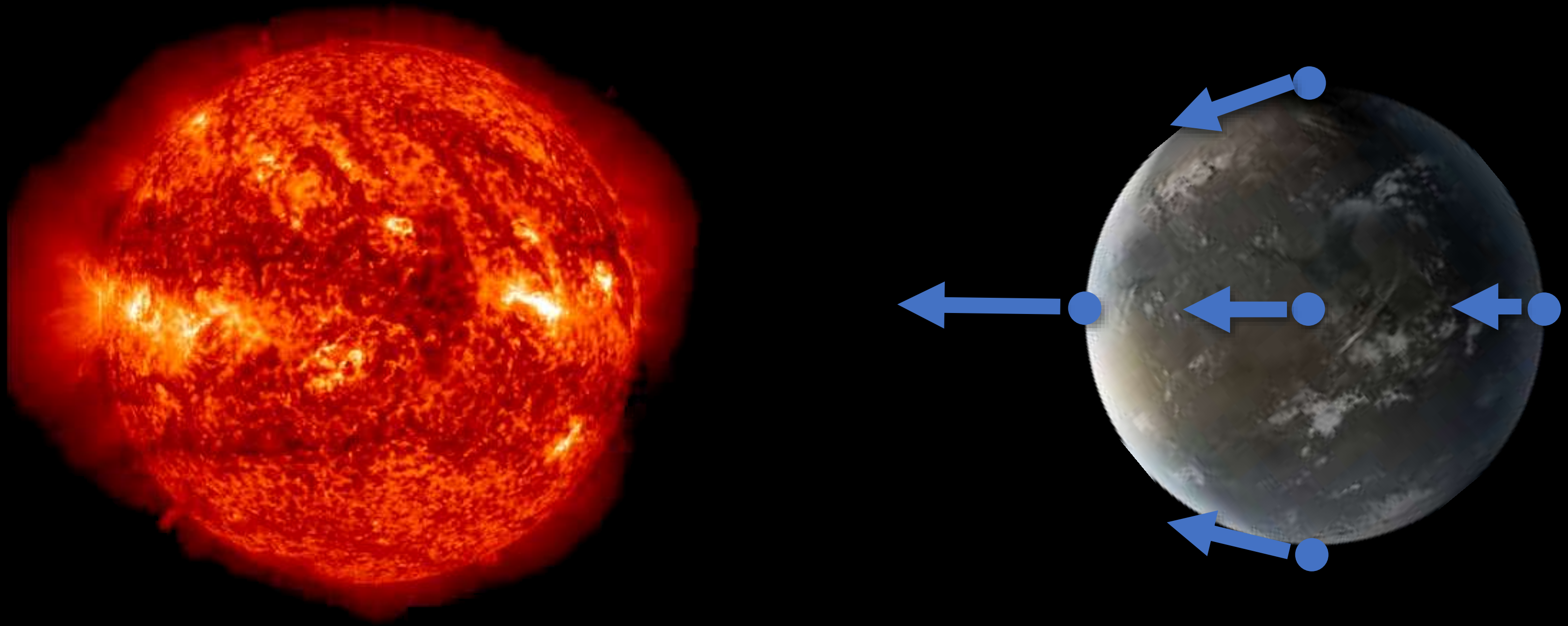
Concept Check

Which point on the planet feels the strongest force of gravity from the star?

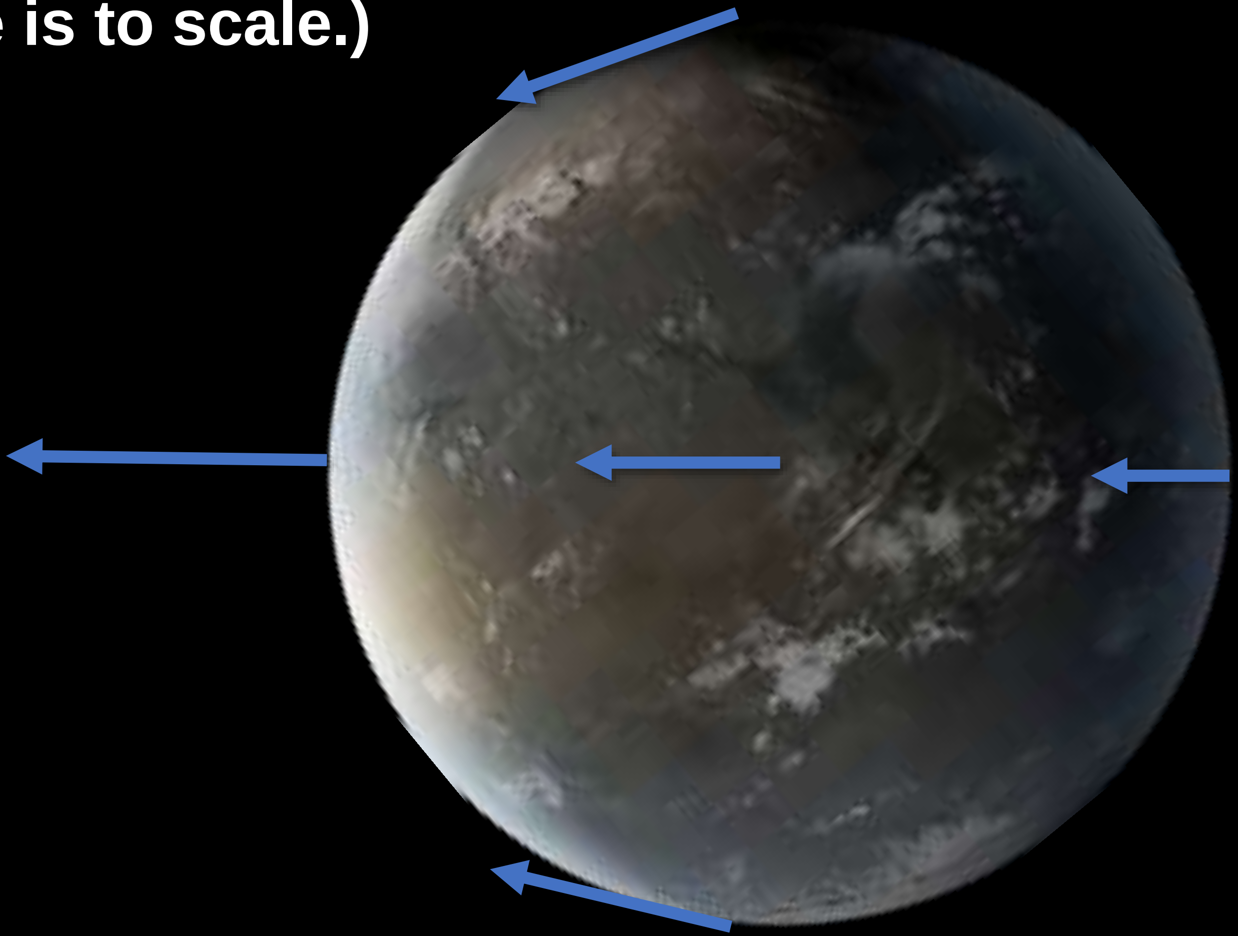



These differences in the force of gravity between two points are called tidal forces.

The force of gravity from a star varies from point to point on a planet orbiting that star.

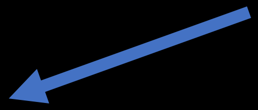


Blue arrows show the actual force of gravity from the planet's star. The force always points toward the star. (Nothing here is to scale.)



We want to visualize <u>differences</u> in the force of gravity from point to point, not the force of gravity itself.

Vectors are added by connecting them tip to tail:



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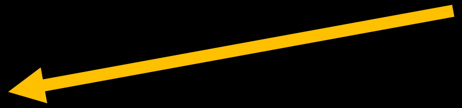
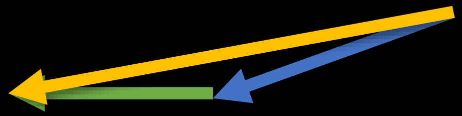


because



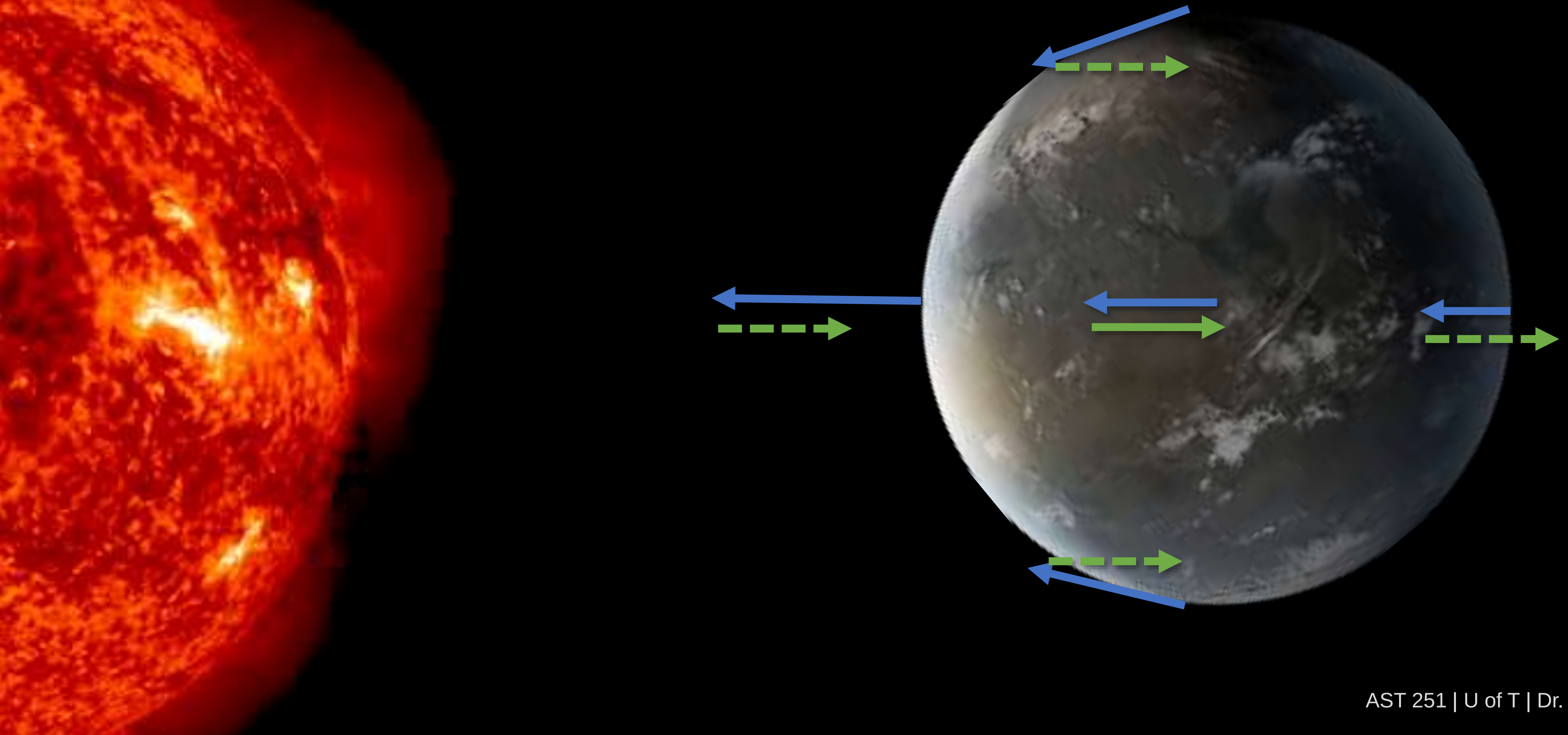
add the green vector to the blue one by connecting the tip of blue to the tail of green

Vectors can be subtracted by reversing the subtracted one before adding it:

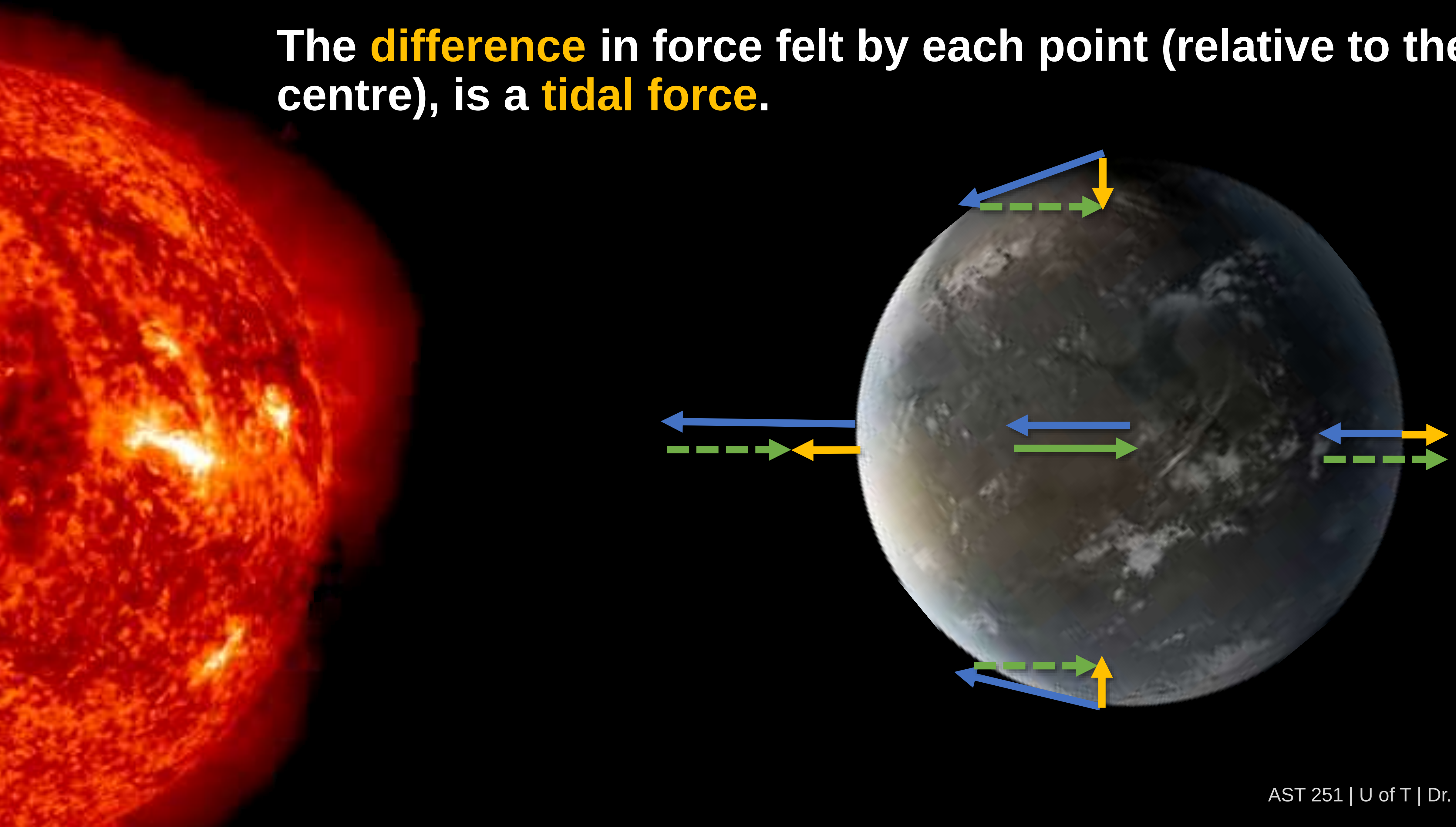
add the green vector to the blue one by connecting the tip of blue to the tail of green

reverse the green vector to subtract it from the blue one

Let's subtract the force of gravity felt by the centre of the planet from all of the other forces felt at other points on the planet.

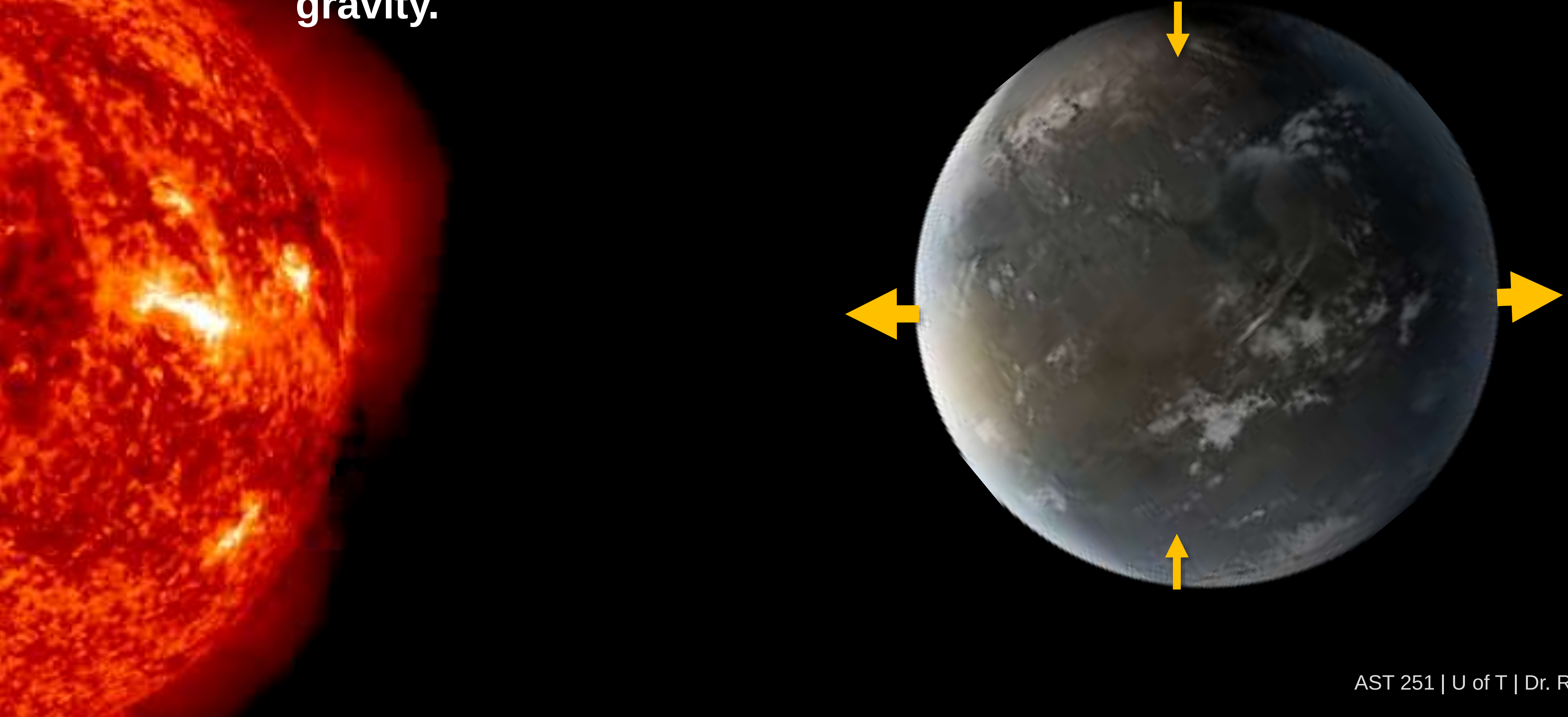


The **difference** in force felt by each point (relative to the centre), is a **tidal force**.



Erase everything except the tidal forces. These are the forces of gravity felt at each point compared to the force of gravity felt at the centre of the planet (compared to itself, the centre feels no gravity, so it has no tidal force arrow).

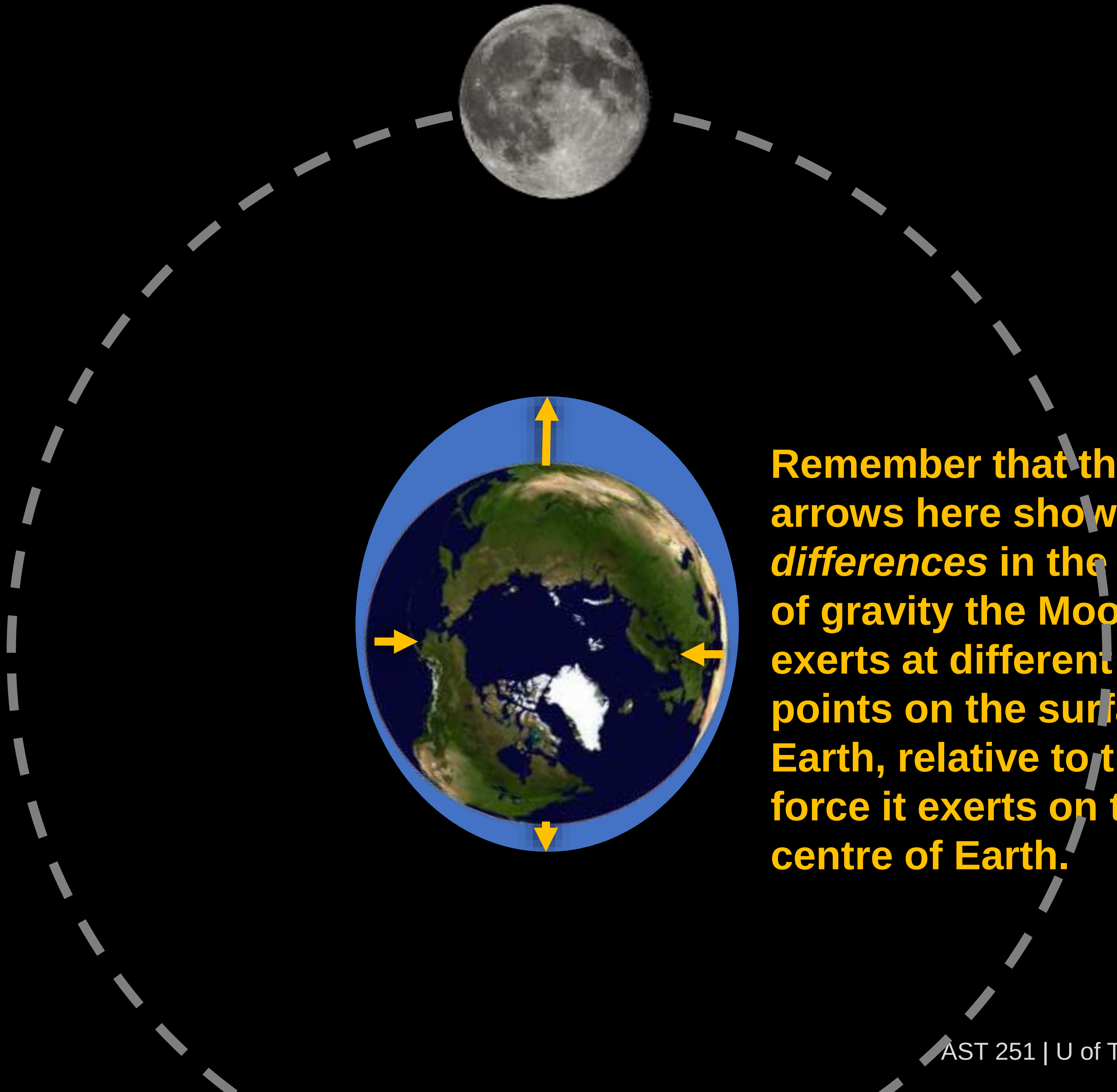
Note that on the sides of the planet facing toward and away from the star the title forces push *away* from the planet. These aren't real actual forces of gravity, just *differences* in the force of gravity.



Tidal forces <u>aren’t a new force</u>, separate from gravity.

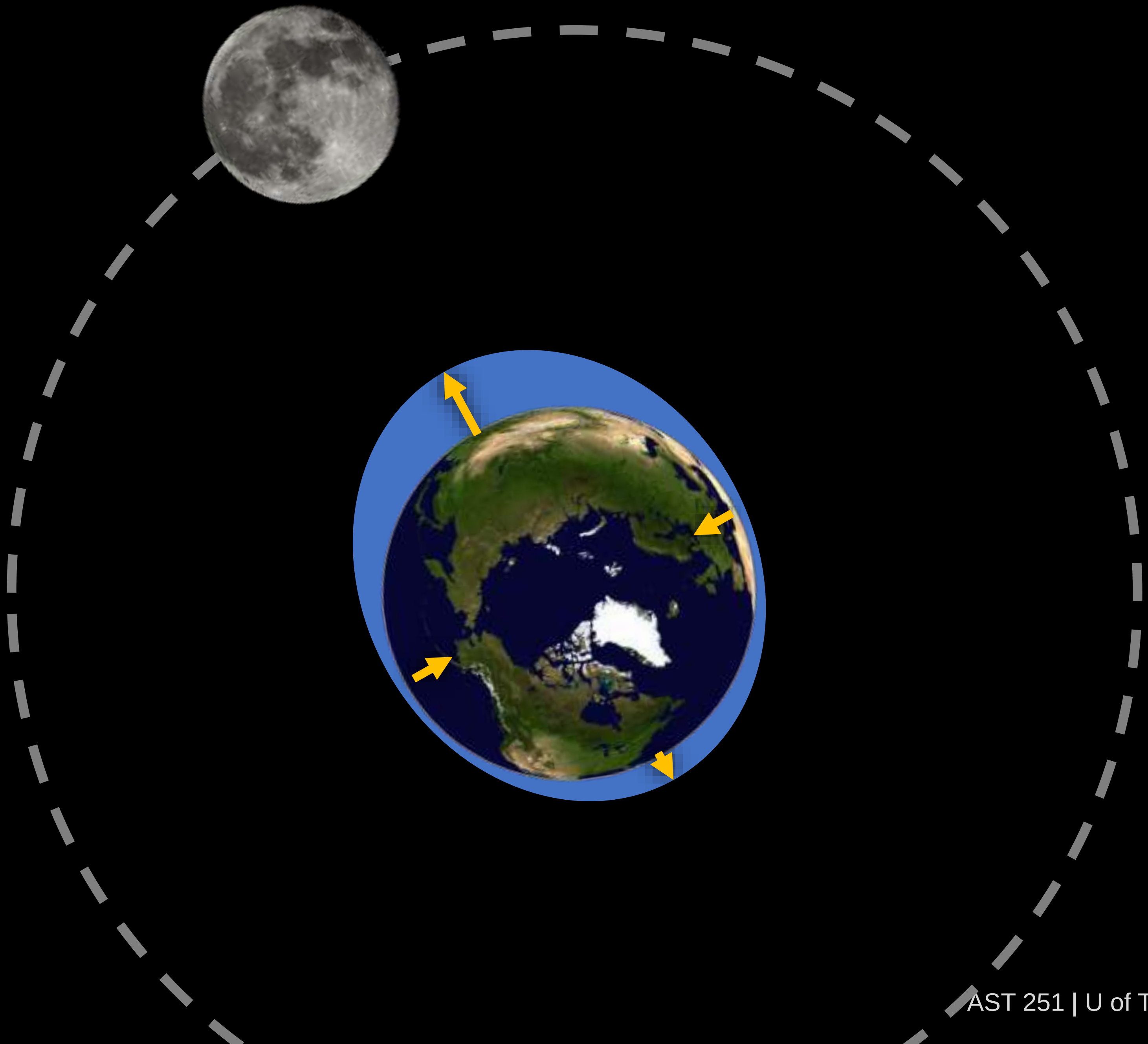
Remember: they’re just differences in the force of gravity from one place to another.

The tidal gravity of the Moon produces ocean tides on Earth.



Remember that the arrows here show *differences* in the force of gravity the Moon exerts at different points on the surface of Earth, relative to the force it exerts on the centre of Earth.

The tidal bulges move as the Moon moves in its orbit.



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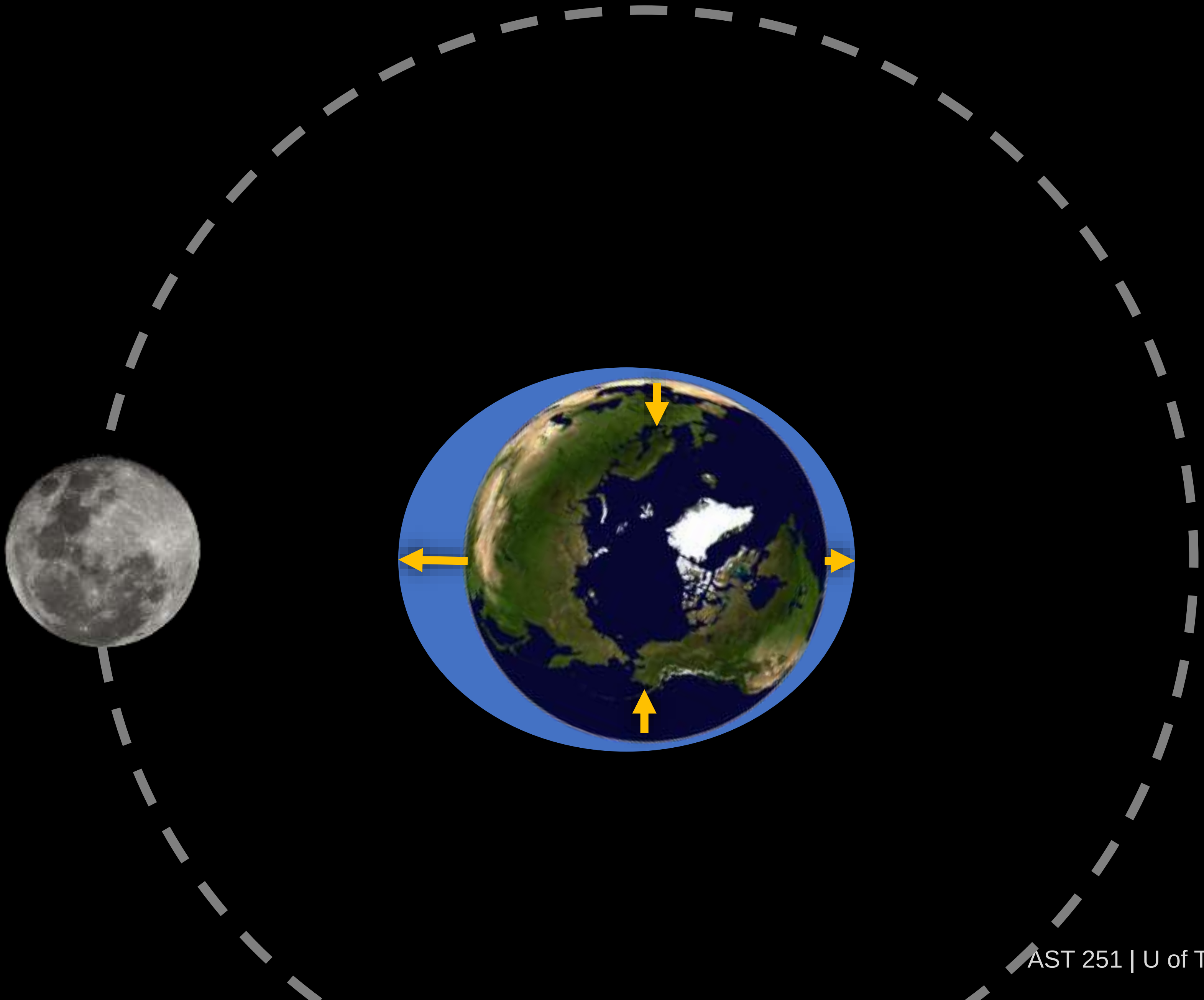
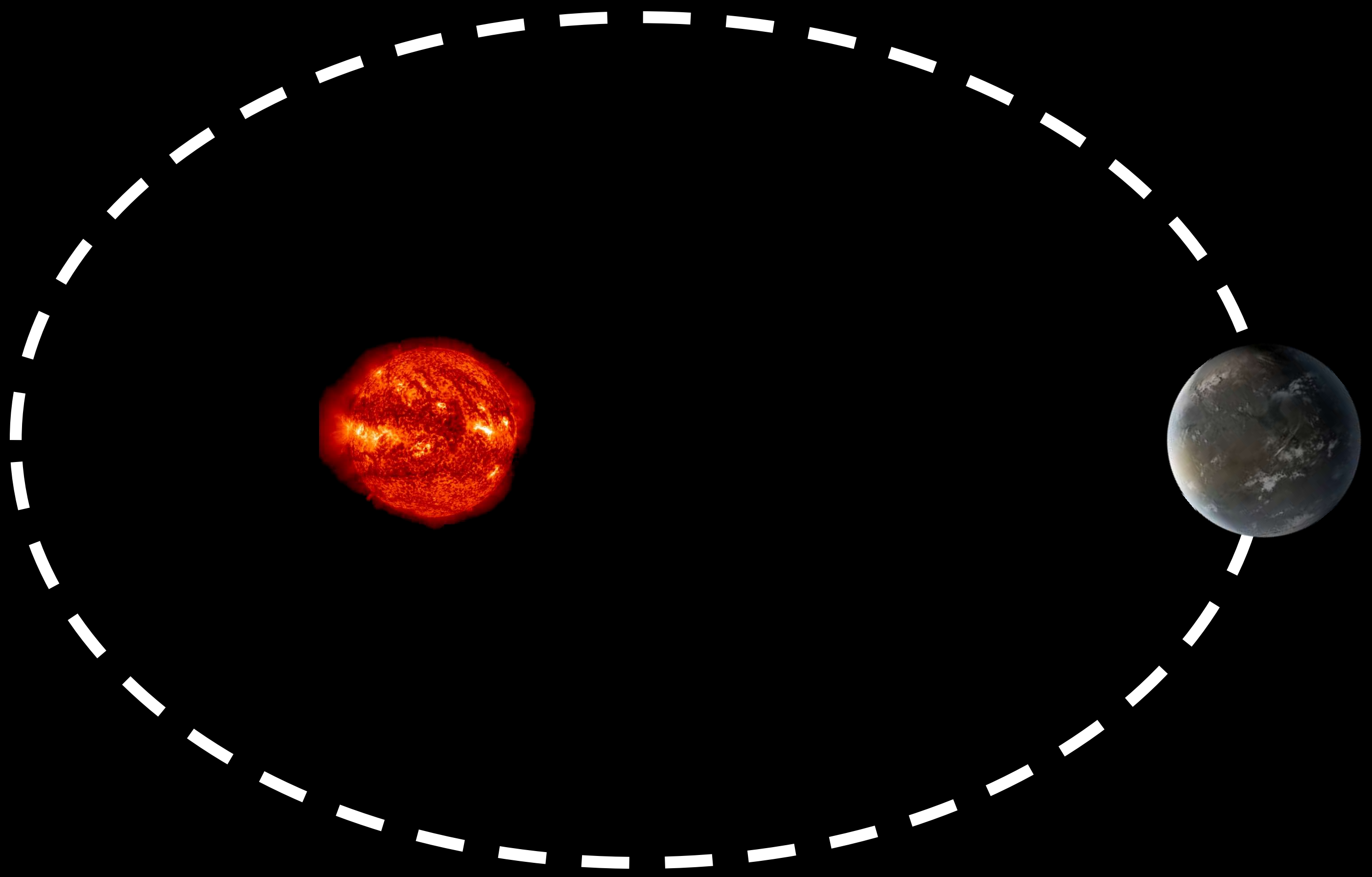


Tidal Heating of Moons

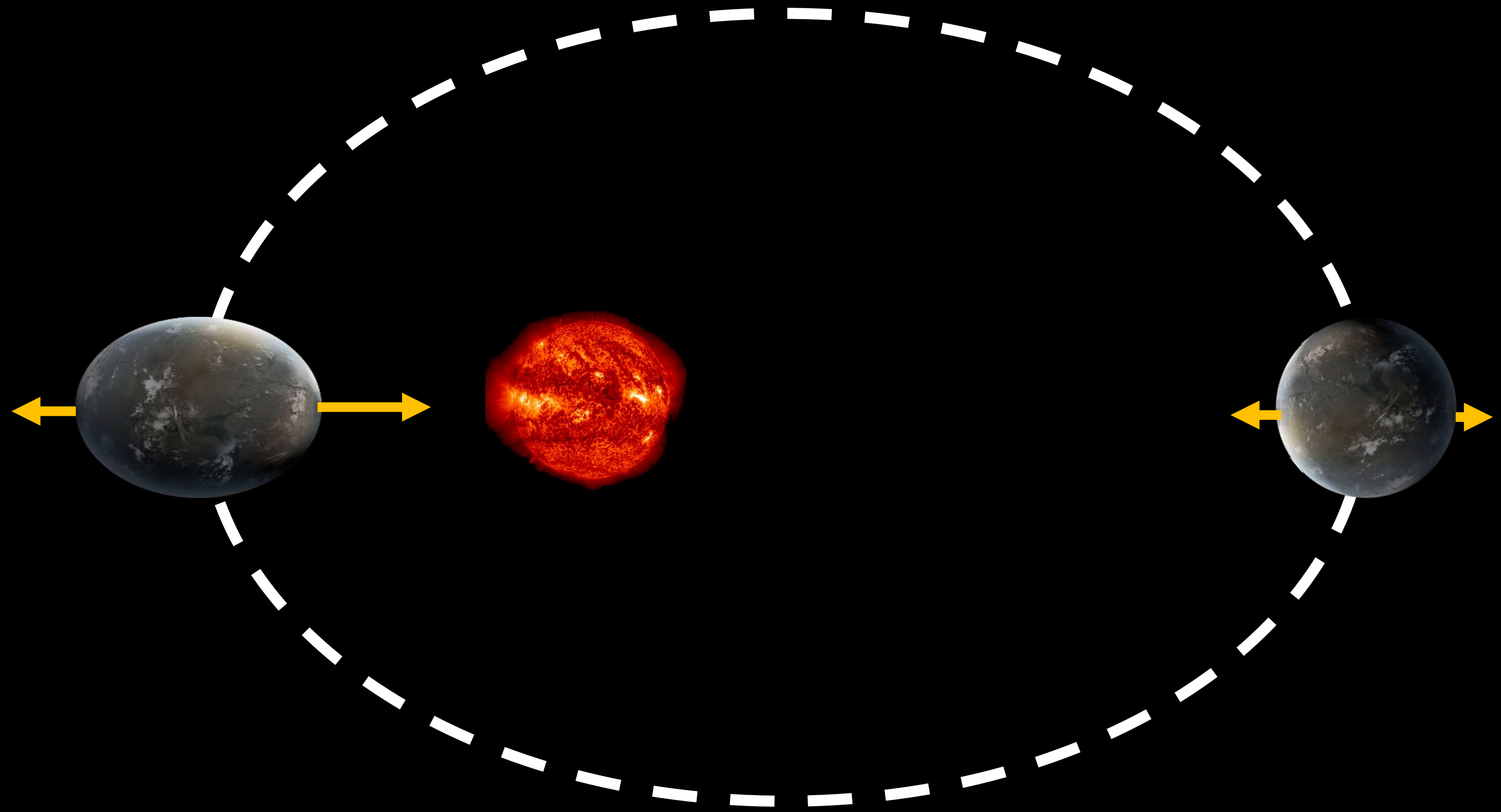
Tidal forces physically deform planets and moons, stretching their fluid AND solid components.

Consider a planet in an eccentric orbit. The changing distance between the planet and its parent star means that the tidal force varies with time, causing the planet to “flex”.

As a planet in an eccentric orbit approaches its star, the tidal forces increase, causing the planet to physically deform (the effect is greatly exaggerated here).



Top-down view of an eccentric orbit

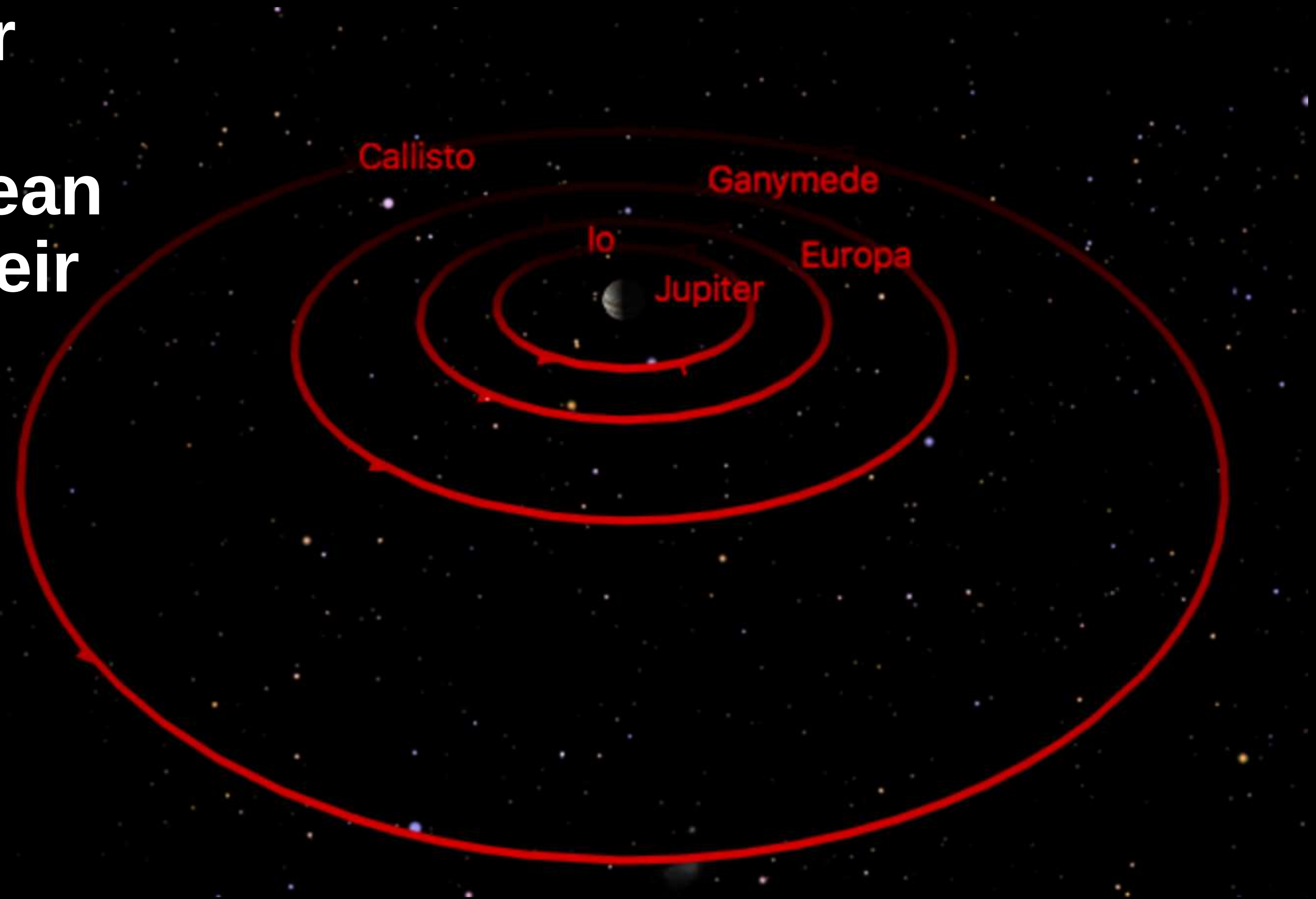


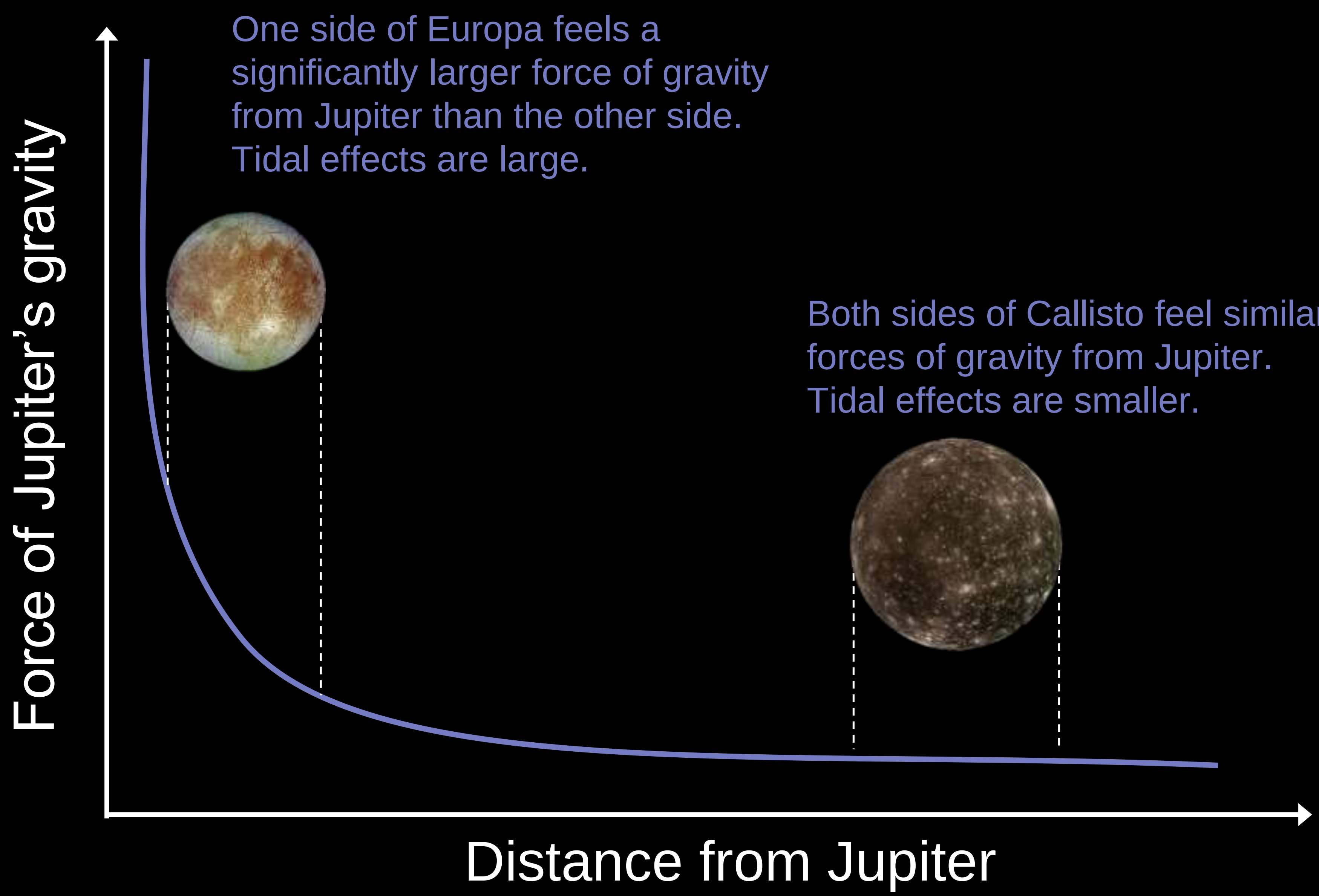
Top-down view of an eccentric orbit. Tidal flexing is hugely exaggerated here.

Tidal effects are felt by all bodies in an orbiting system, whether they be stars, planets, or moons.

They are often very important among moons of Jovian planets.

Jupiter has four large moons, called the Galilean moons, after their discoverer.

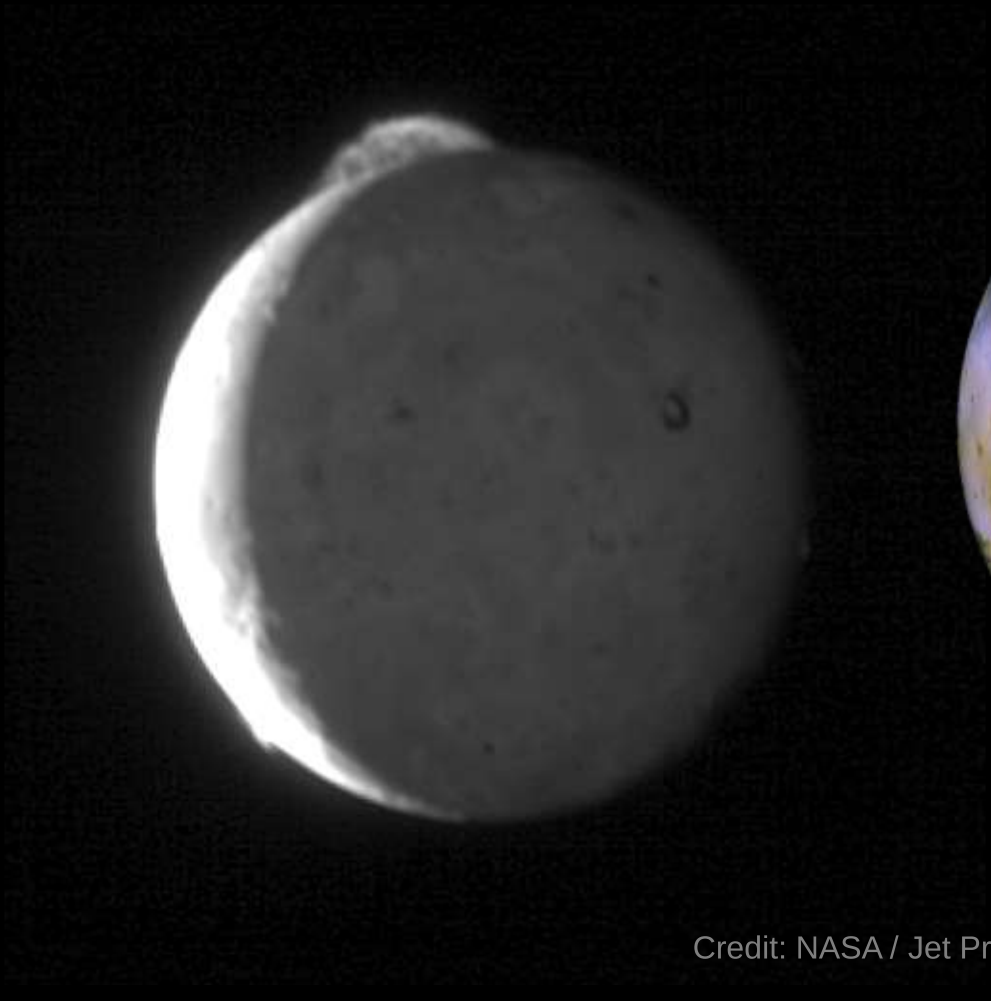


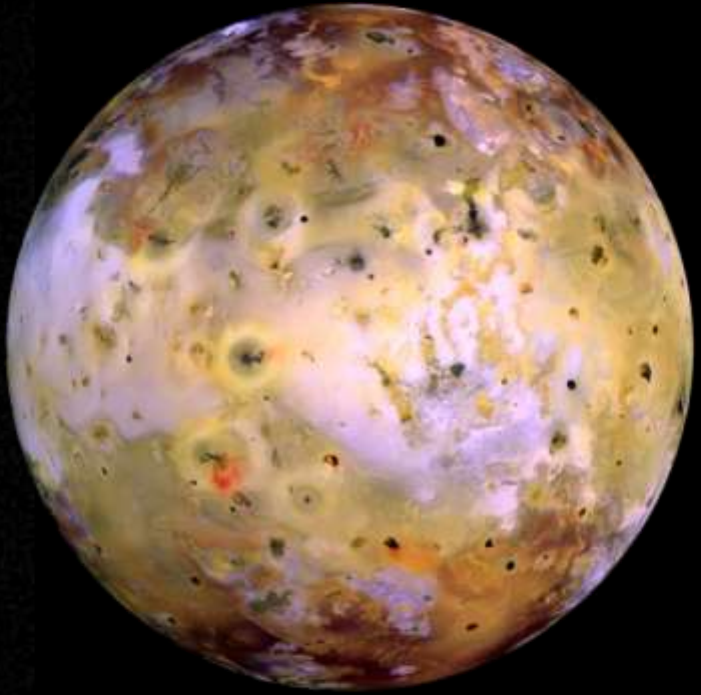

One side of Europa feels a significantly larger force of gravity from Jupiter than the other side. Tidal effects are large.
Both sides of Callisto feel similar forces of gravity from Jupiter. Tidal effects are smaller.
Force of Jupiter’s gravity
Distance from Jupiter

Europa and its shadow against the background of Jupiter’s Great Red Spot.

The friction caused by the constant flexing of the Galilean moons is enough to keep at least three of them partially liquid inside.

Io, the innermost Galilean moon, is seen here with its Tvashtar volcano erupting. Io is the most volcanically active object in the solar system.





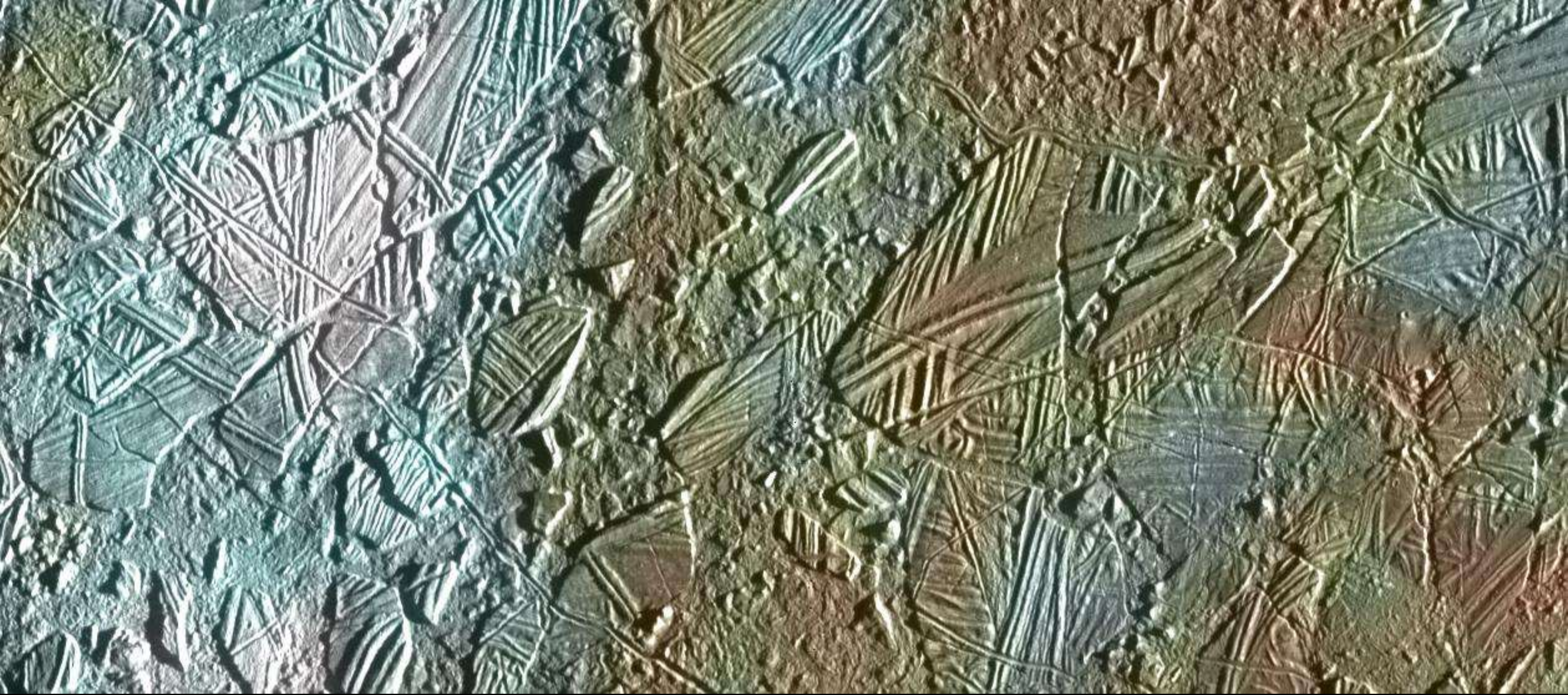
Credit: NASA / Jet Propulsion Lab-Caltech

Europa is an icy moon with no significant atmosphere.

Credit: NASA / Jet Propulsion Lab-Caltech / SETI Institute

The network of cracks on Europa’s surface testify to active geology—it has something like plate tectonics, where the plates are sheets of ice moving around on a liquid water “mantle”.

Credit: NASA / Jet Propulsion Lab-Caltech / SETI Institute

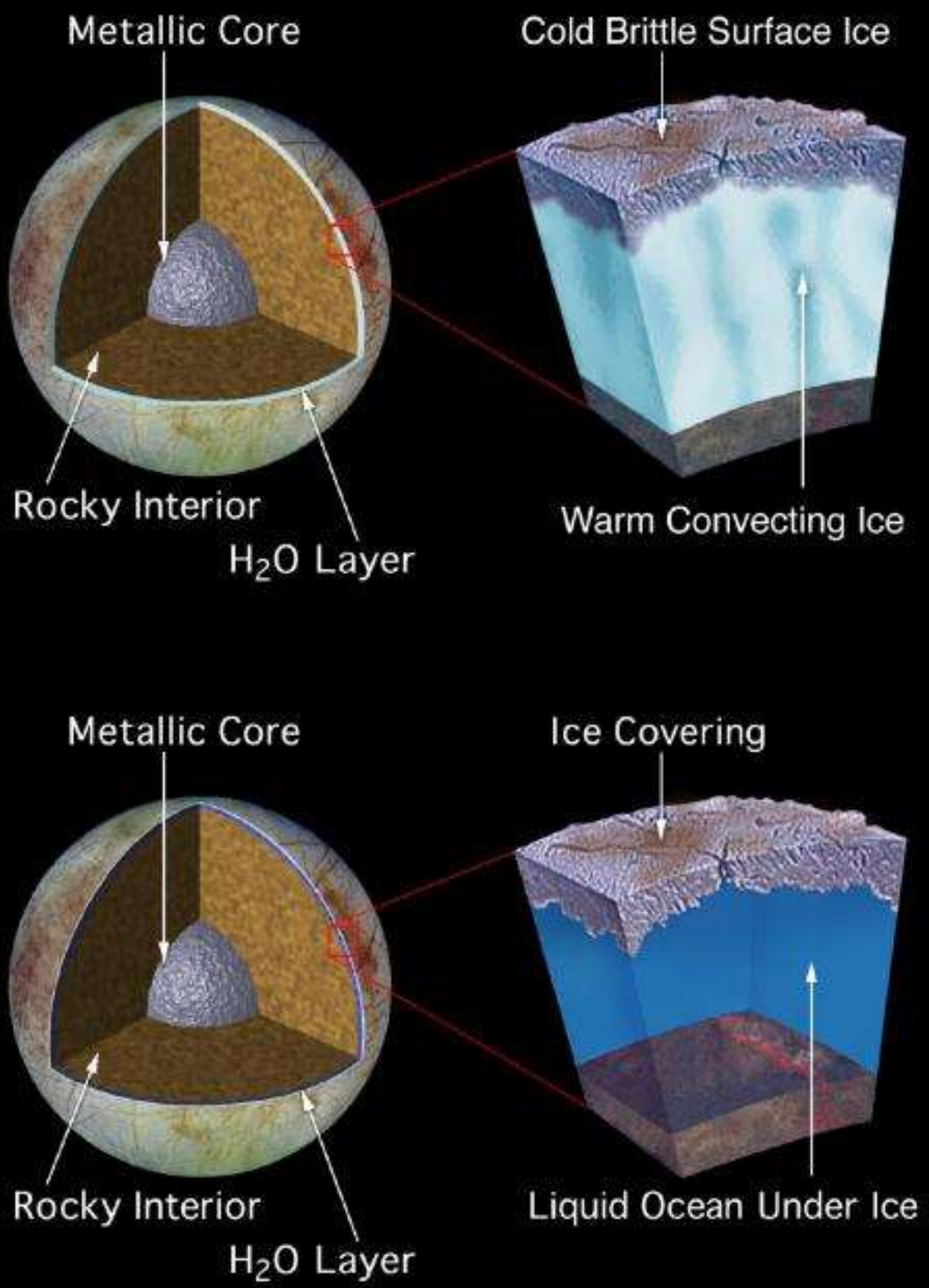


“Chaos terrain” on Europa is interpreted as the result of interactions between surface ice and thin “lenses” of liquid water trapped beneath the surface (Schmidt et al., Nature, 2011)

Credit: NASA /JPL/University of Arizona

Two models for the interior of Europa.

It’s possible that the volume of liquid water inside Europa exceeds all the oceans on Earth.



Credit: NASA /JPL

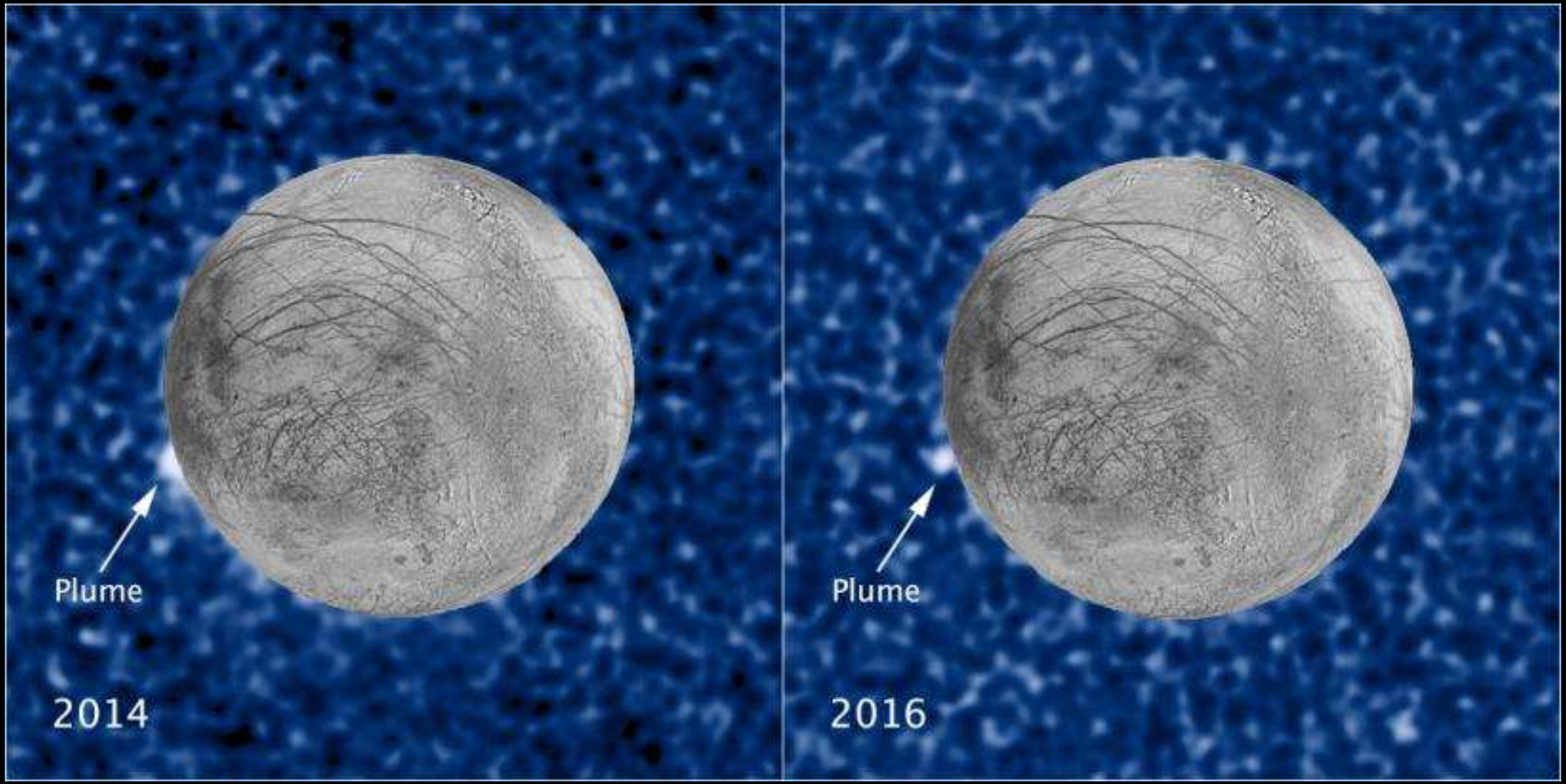
Because of the virtually certain presence of some amount of liquid water, Europa is a prime target for searches for life.

We **might not be able to live there, but probably other organisms could.**

Europa landers have been contemplated, but how would we drill through all that ice? Also, we need to worry about forward contamination by Earth life.

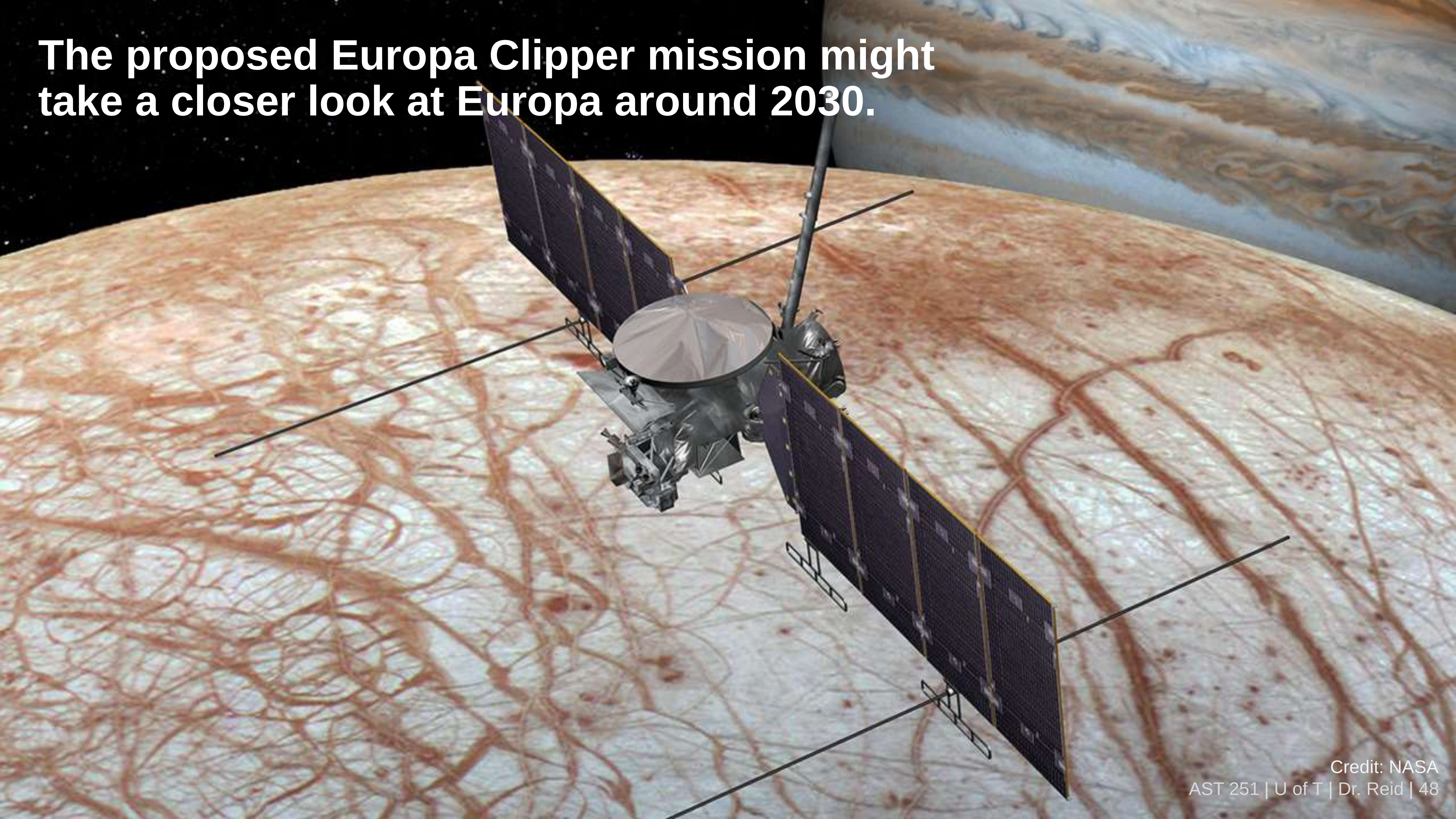
Credit: NASA / Jet Propulsion Lab-Caltech

Conveniently, Europa erupts plumes of (presumably) water into space, which might make sample collection easier.



Credit: NASA/ESA/W. Sparks (STScI)/USGS Astrogeology Science Center

The proposed Europa Clipper mission might take a closer look at Europa around 2030.

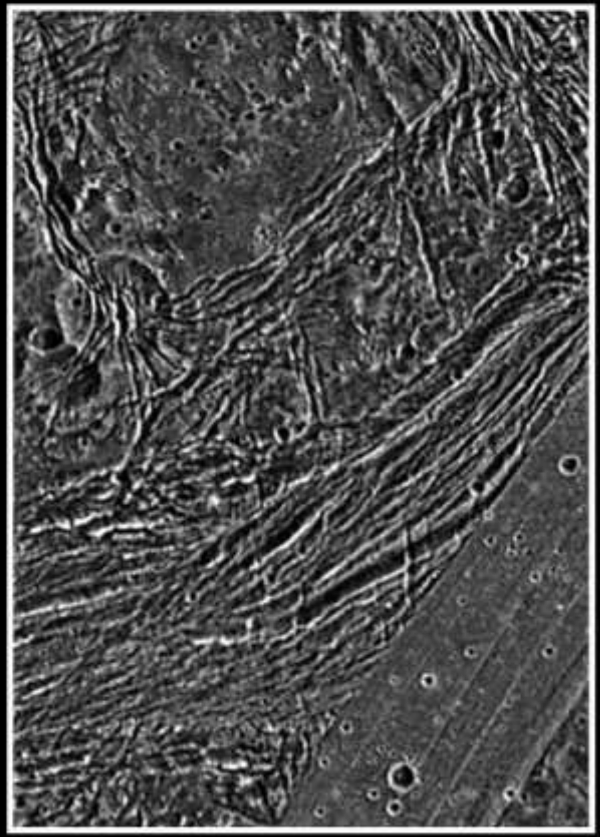


Credit: NASA

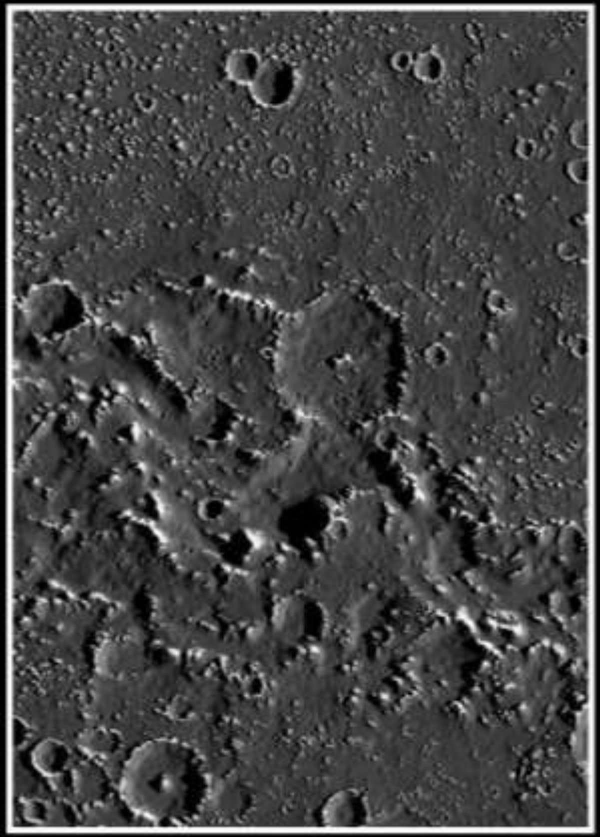
The outer two Galilean moons, Ganymede and Callisto, may also have large amounts of liquid water.

Credit: NASA

Europa



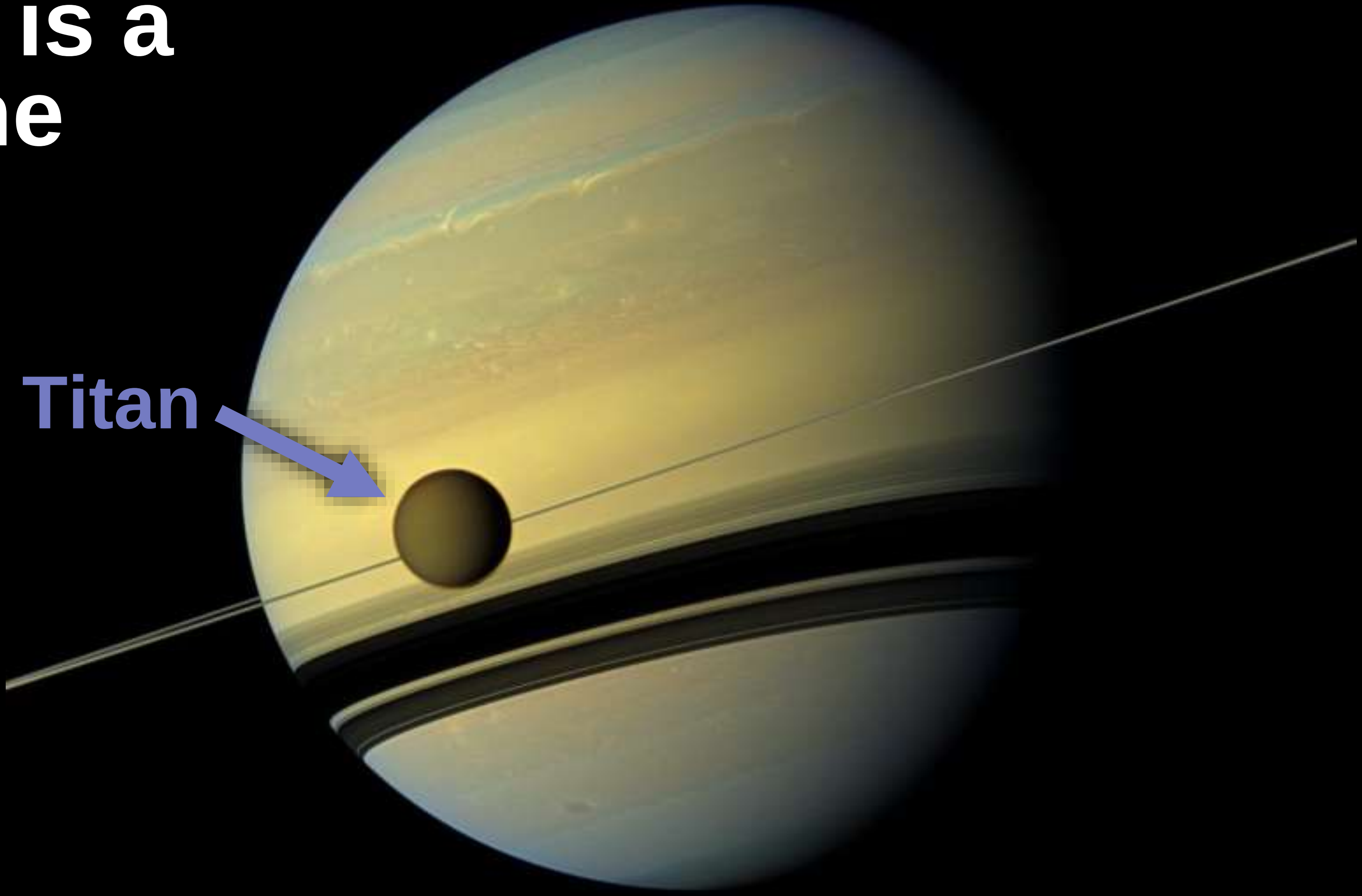
Ganymede



Callisto

Tidal heating is a common feature among the moons of Jovian planets.

Titan, the largest moon of Saturn, is a bit larger than the planet Mercury.

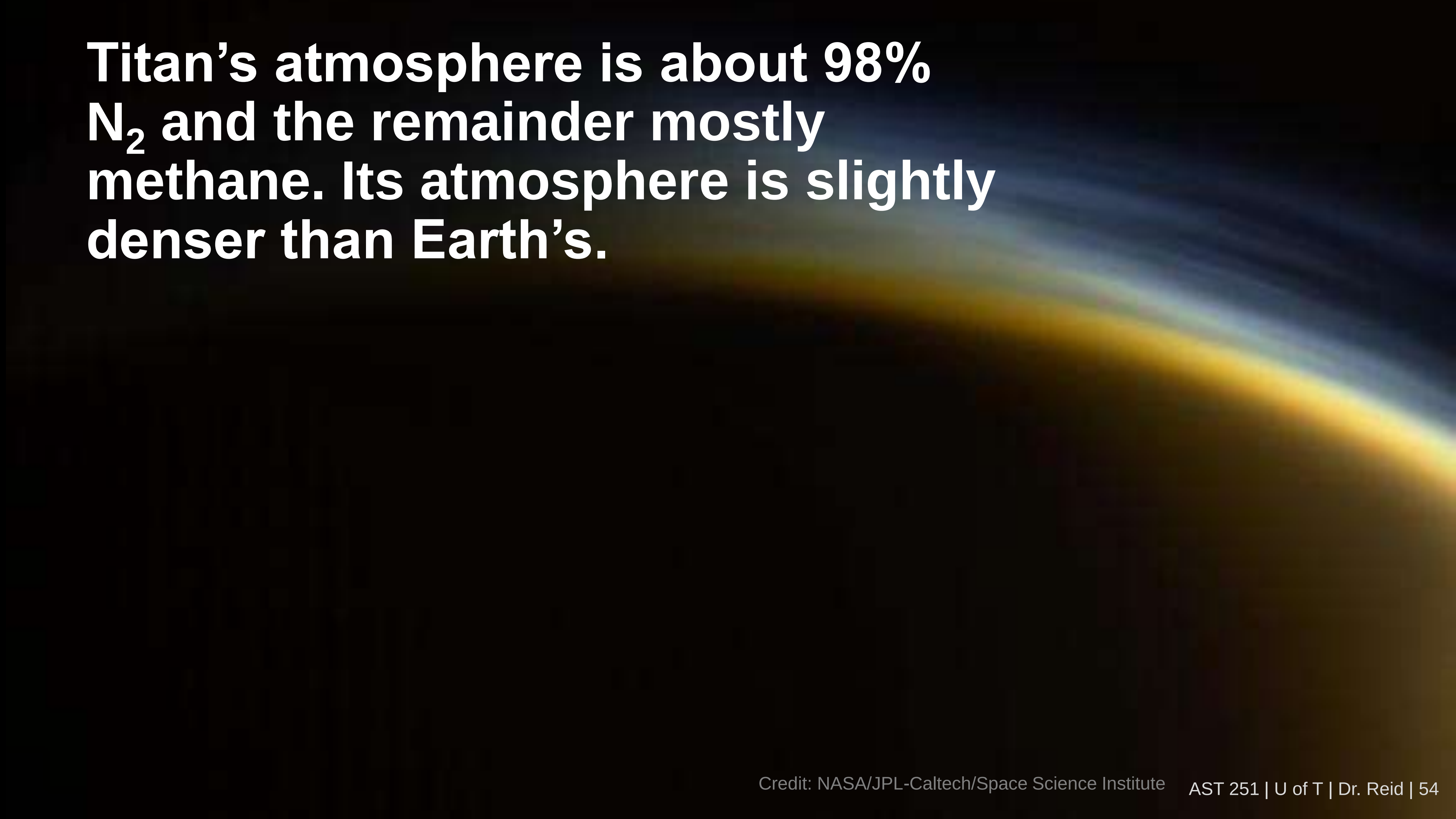


Credit: NASA /Cassini

Titan and Rhea as seen by Cassini. What differences do you notice between them?

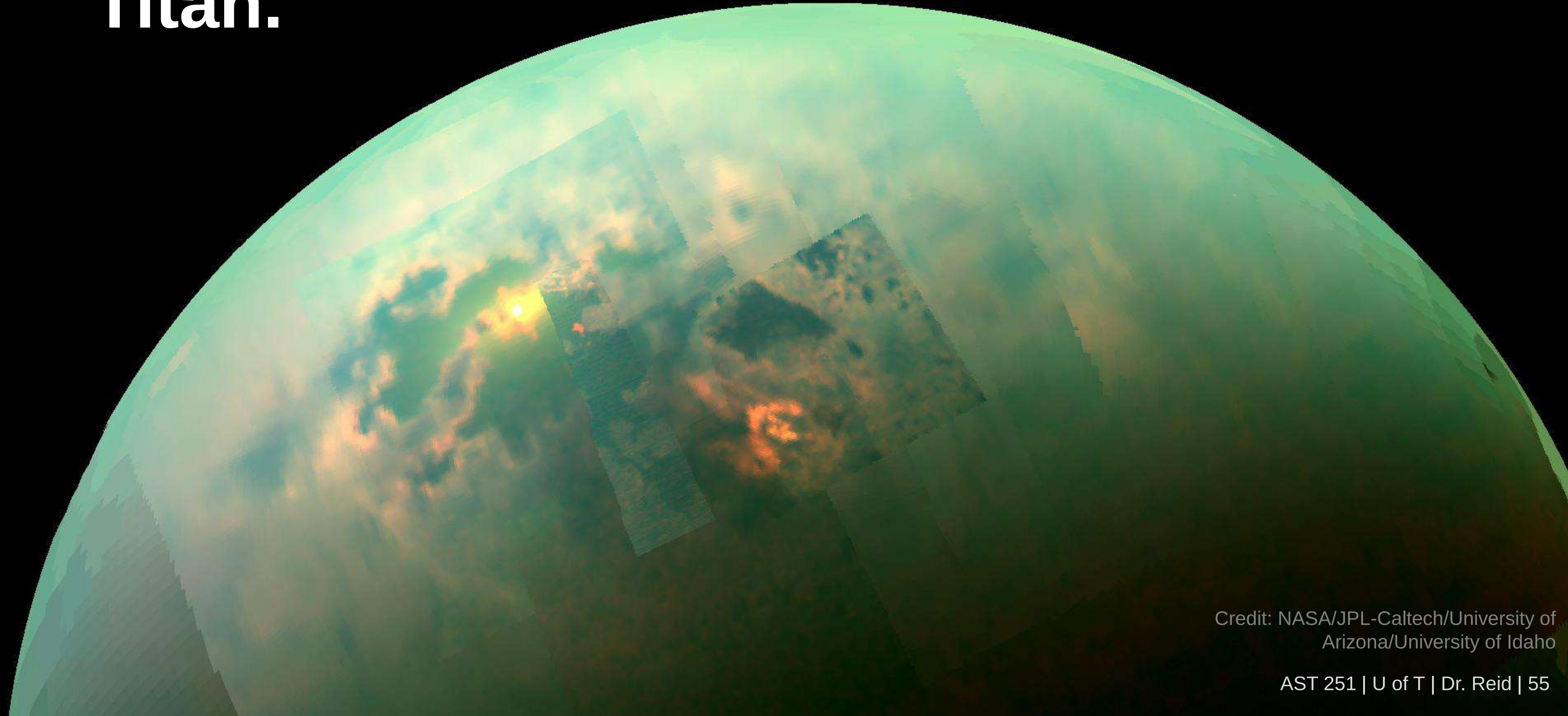
Credit: NASA/JPL-Caltech/Space Science Institute

Titan's atmosphere is about 98% N_2 and the remainder mostly methane. Its atmosphere is slightly denser than Earth's.



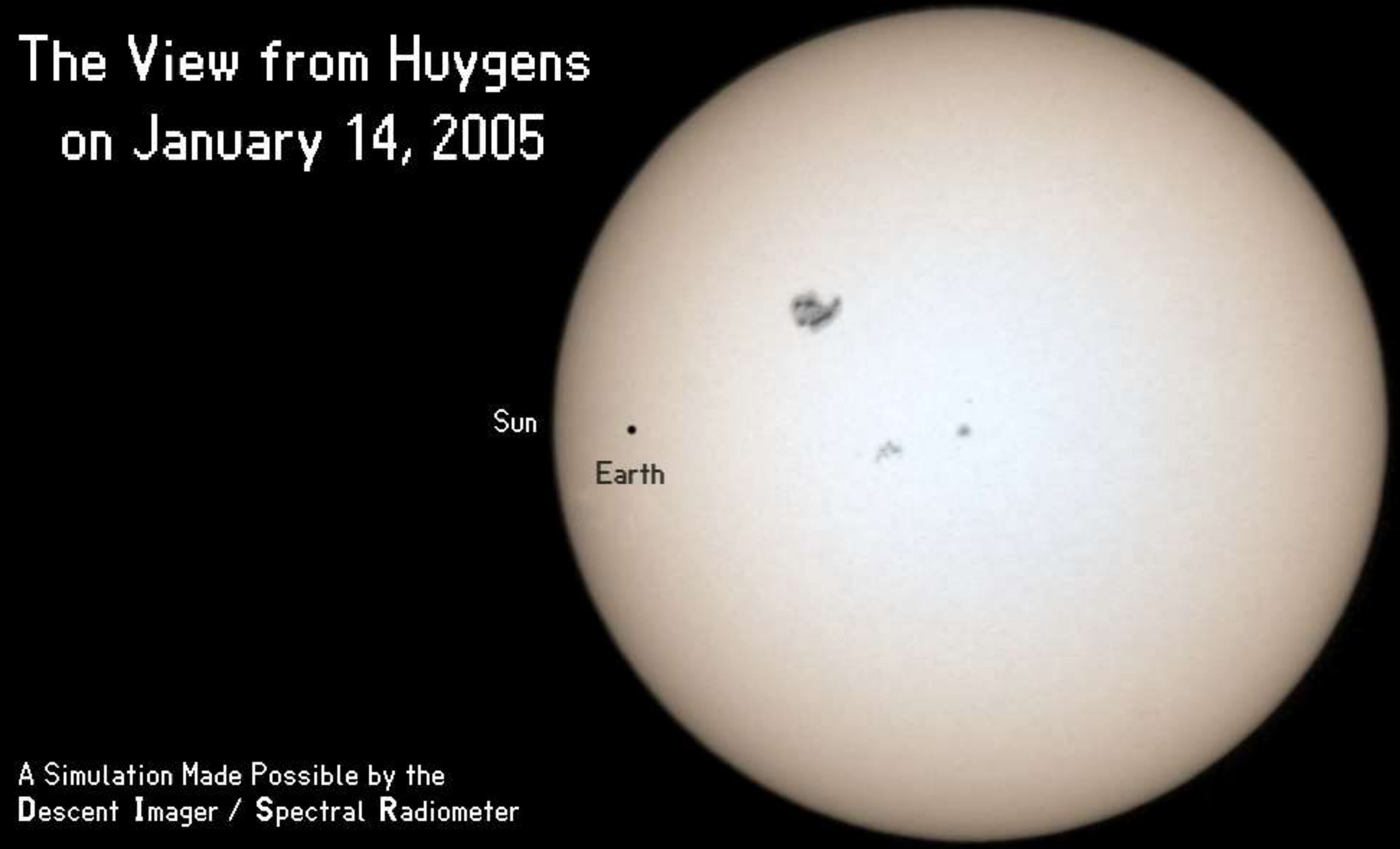
Credit: NASA/JPL-Caltech/Space Science Institute

Sunlight glinting off lakes on Titan.

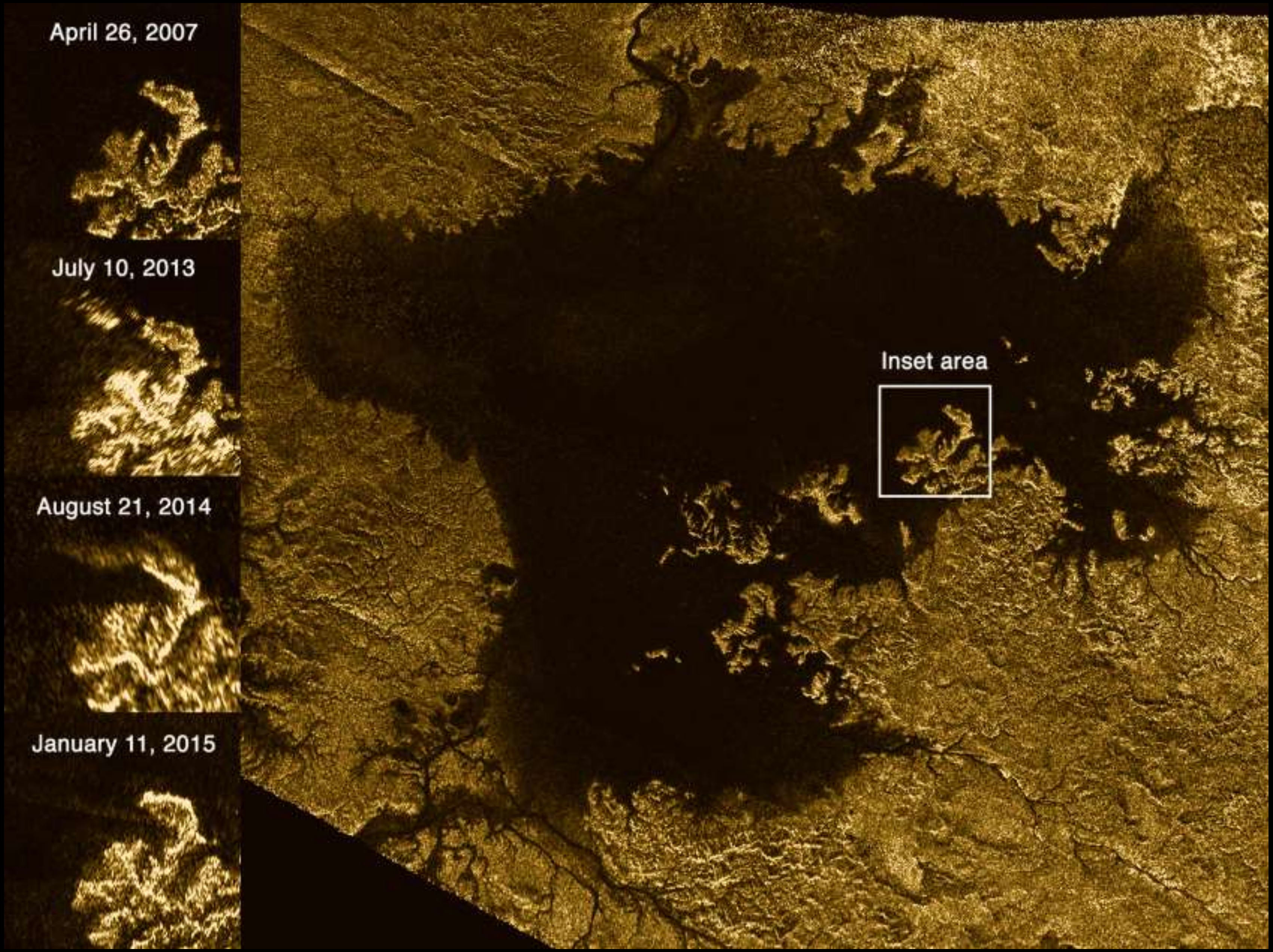


Credit: NASA/JPL-Caltech/University of Arizona/University of Idaho

In 2005, the Cassini spacecraft dropped its Huygens lander onto Titan.

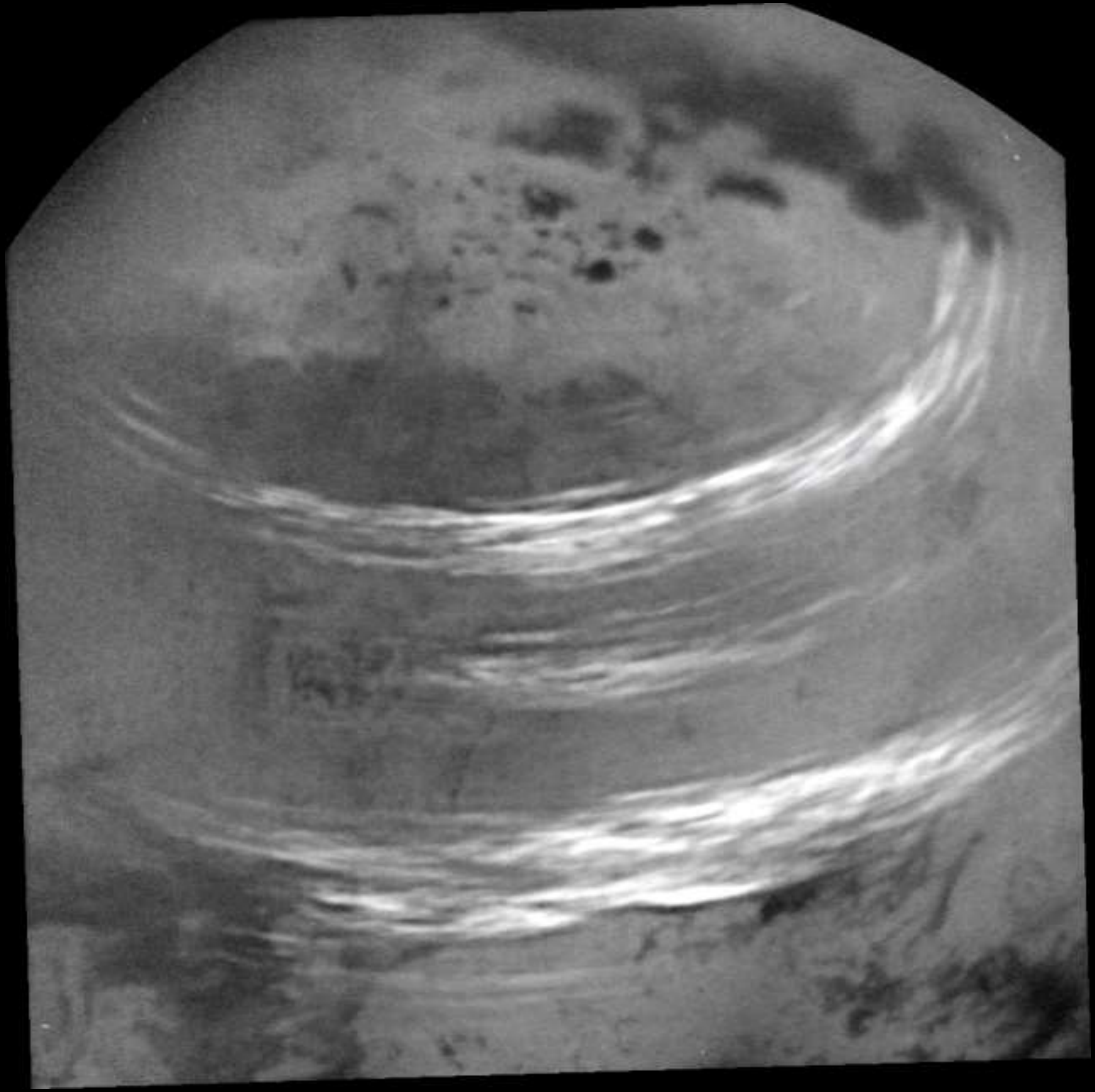


Titan has surface lakes of liquid hydrocarbons, which are always evolving. This one is 50% larger than Lake Superior.



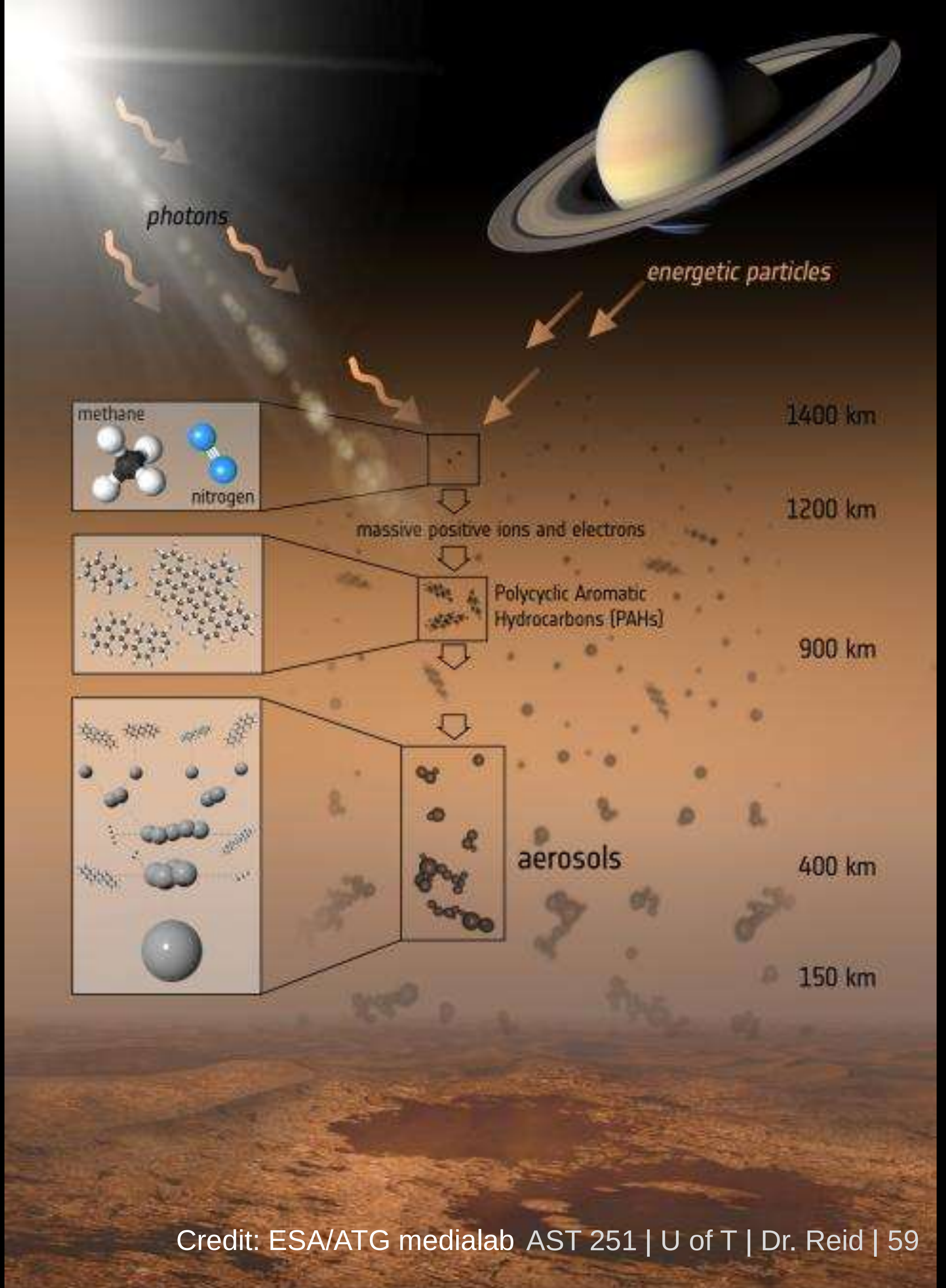
Credit: NASA/JPL-Caltech/ASI

Titan has prominent clouds of methane (CH_4) which appear to fuel complex chemistry.

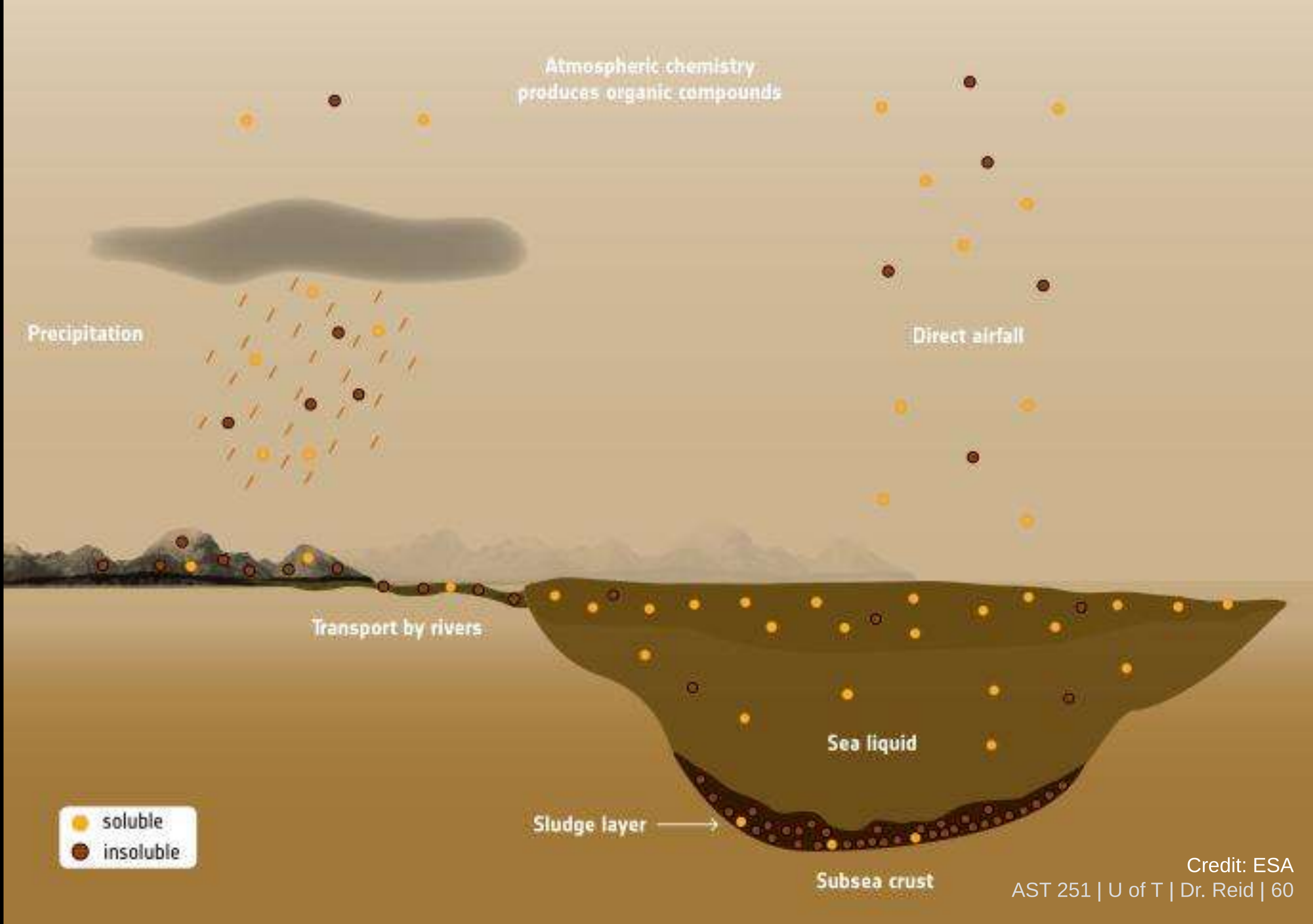


Credit: NASA/JPL-Caltech/Space Science Institute

Chemical reactions taking place between N_2 and CH_4 in the atmosphere of Titan appear to produce simple organic chemicals which then rain down onto its surface and accumulate in its lakes.



Credit: ESA/ATG medialab


Atmospheric chemistry
produces organic compounds
Precipitation
Direct airfall
Transport by rivers
Sea liquid
Sludge layer
Subsea crust
soluble
insoluble

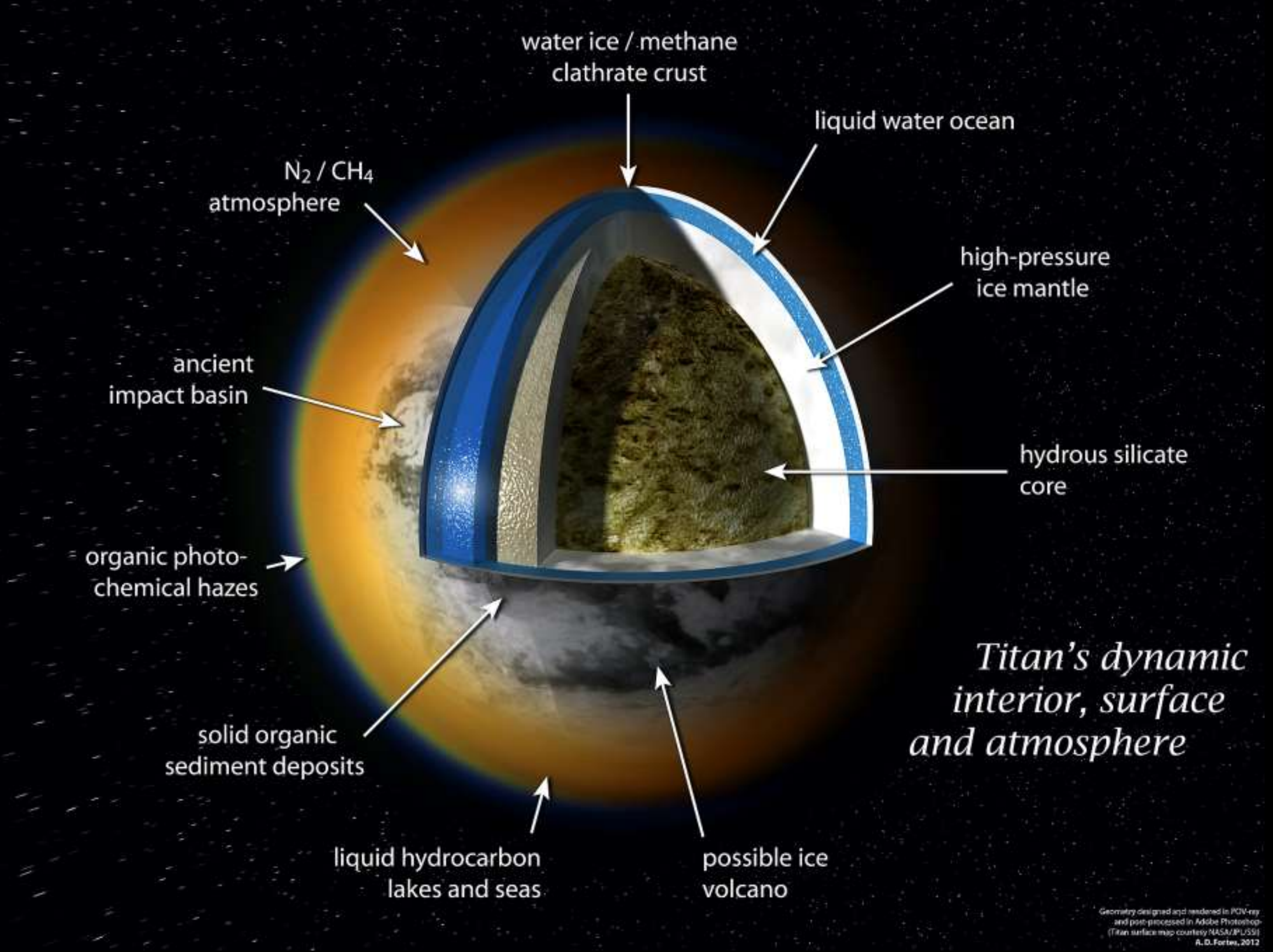
Credit: ESA

Titan's surface temperature is a frigid -180°C, but this is about 12 degrees warmer than it would be without the greenhouse effect of its atmospheric methane.

(McKay, Pollack, & Courtin, Science, 1991)

Titan's crust is mainly water ice.

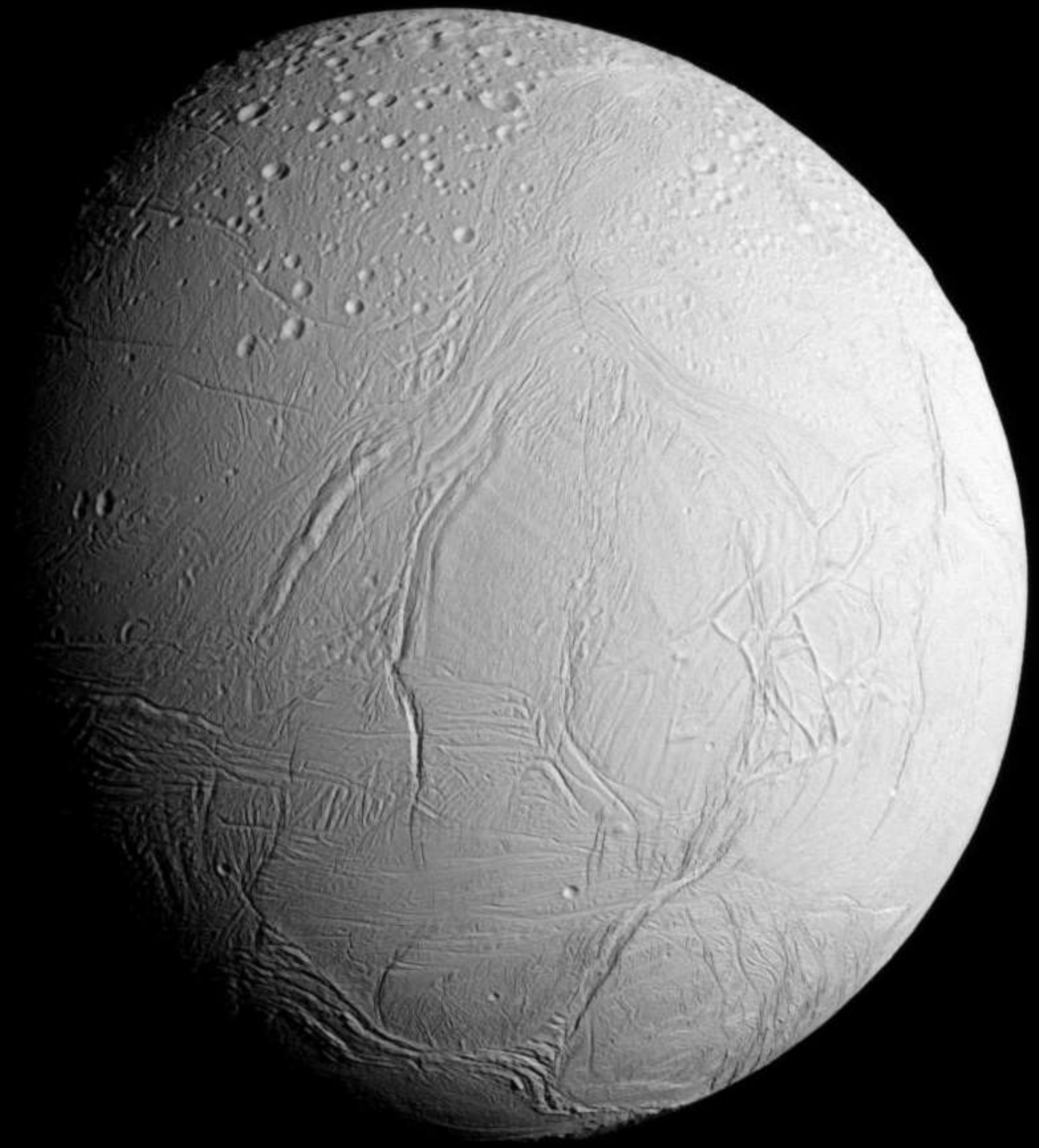
However, tidal heating produced by Saturn probably permits a subsurface ocean of liquid water.


water ice / methane clathrate crust
liquid water ocean
N_2 / CH_4 atmosphere
high-pressure ice mantle
ancient impact basin
hydrous silicate core
organic photo-chemical hazes
Titan's dynamic interior, surface and atmosphere
solid organic sediment deposits
liquid hydrocarbon lakes and seas
possible ice volcano

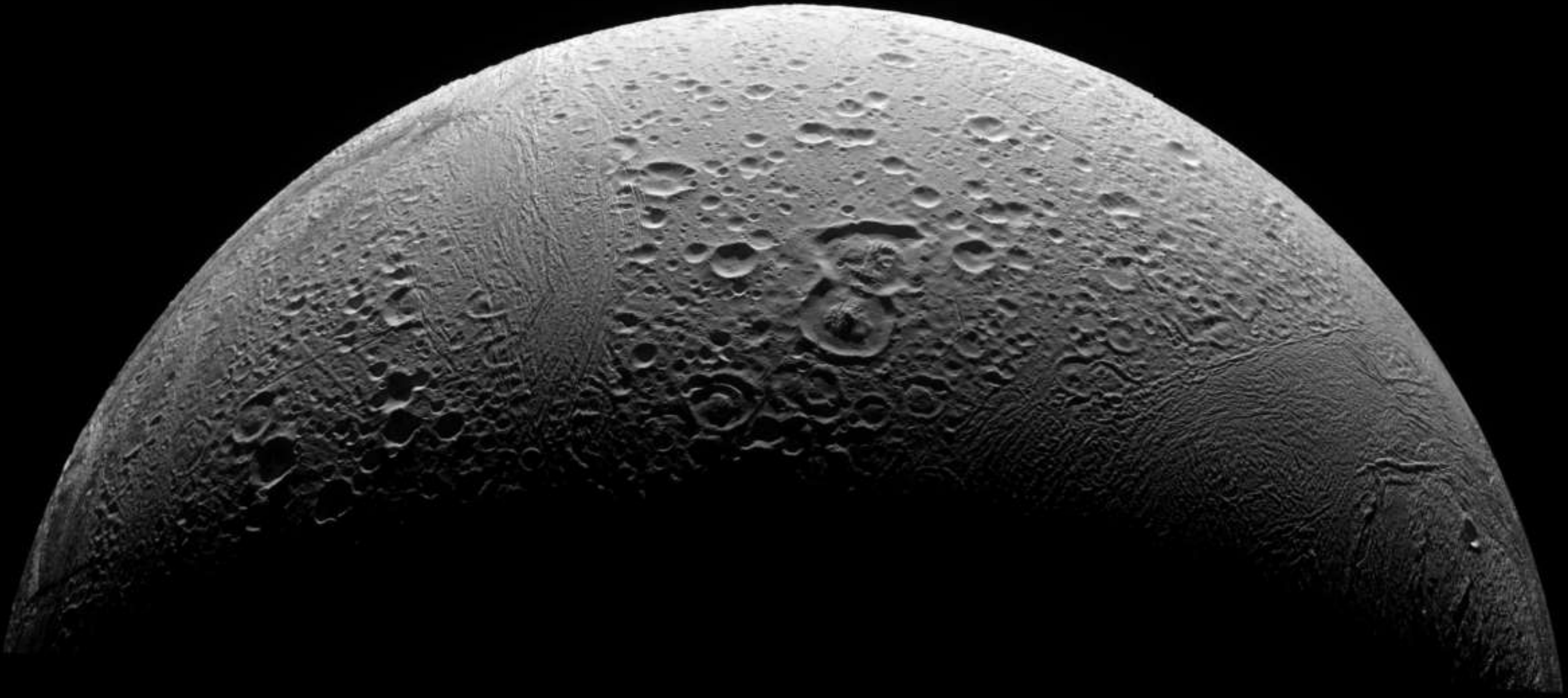
So, Titan may be *the only body in the solar system* with large quantities of two different solvents that could both potentially form a basis for life.

The more we learn about Titan, the more some people think we should skip Mars and head for Titan as soon as possible.

Saturn has another watery moon, Enceladus.

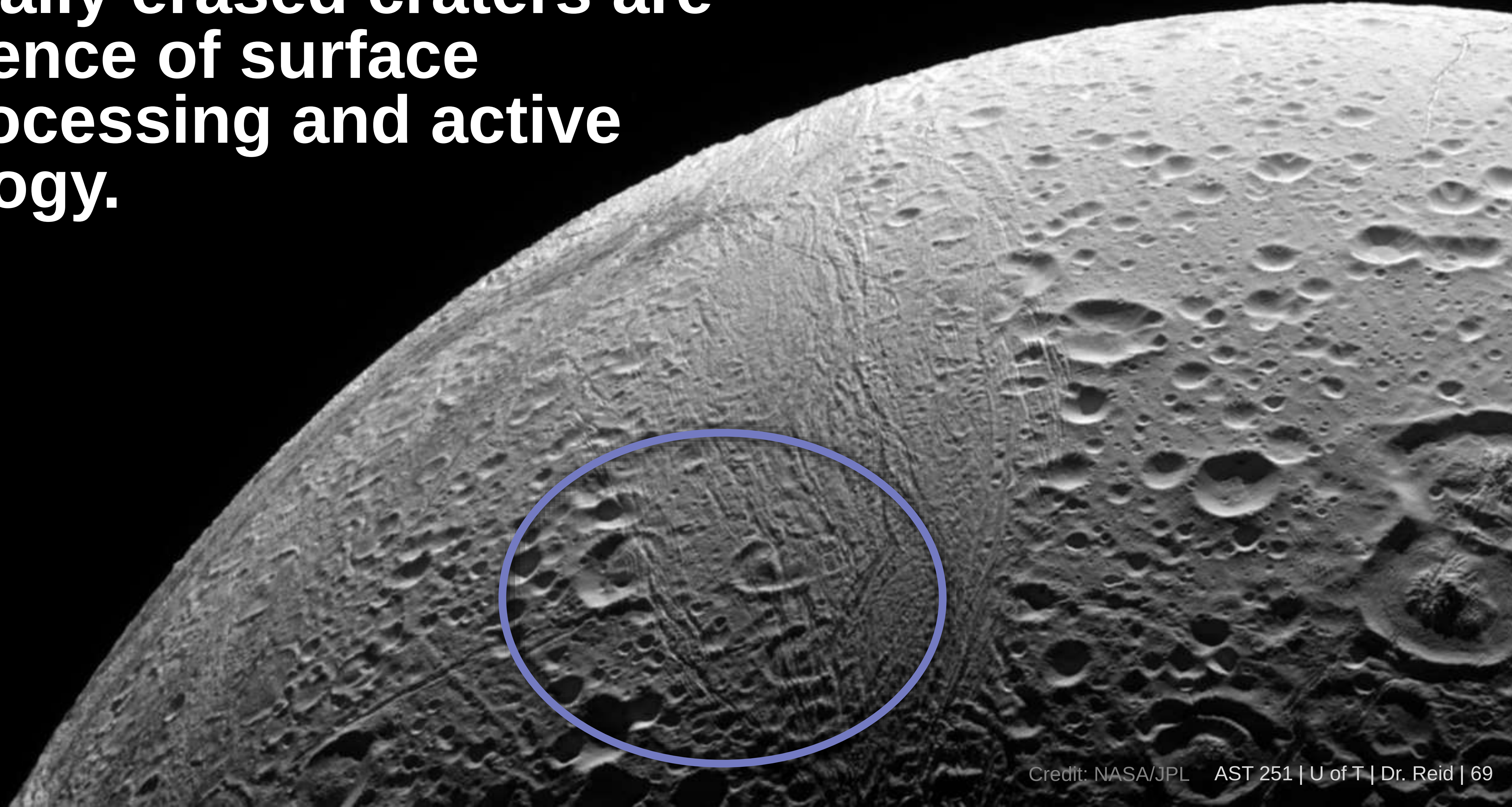


Credit: NASA/JPL



Credit: NASA/JPL

artially erased craters are vidence of surface eprocessing and active eology.

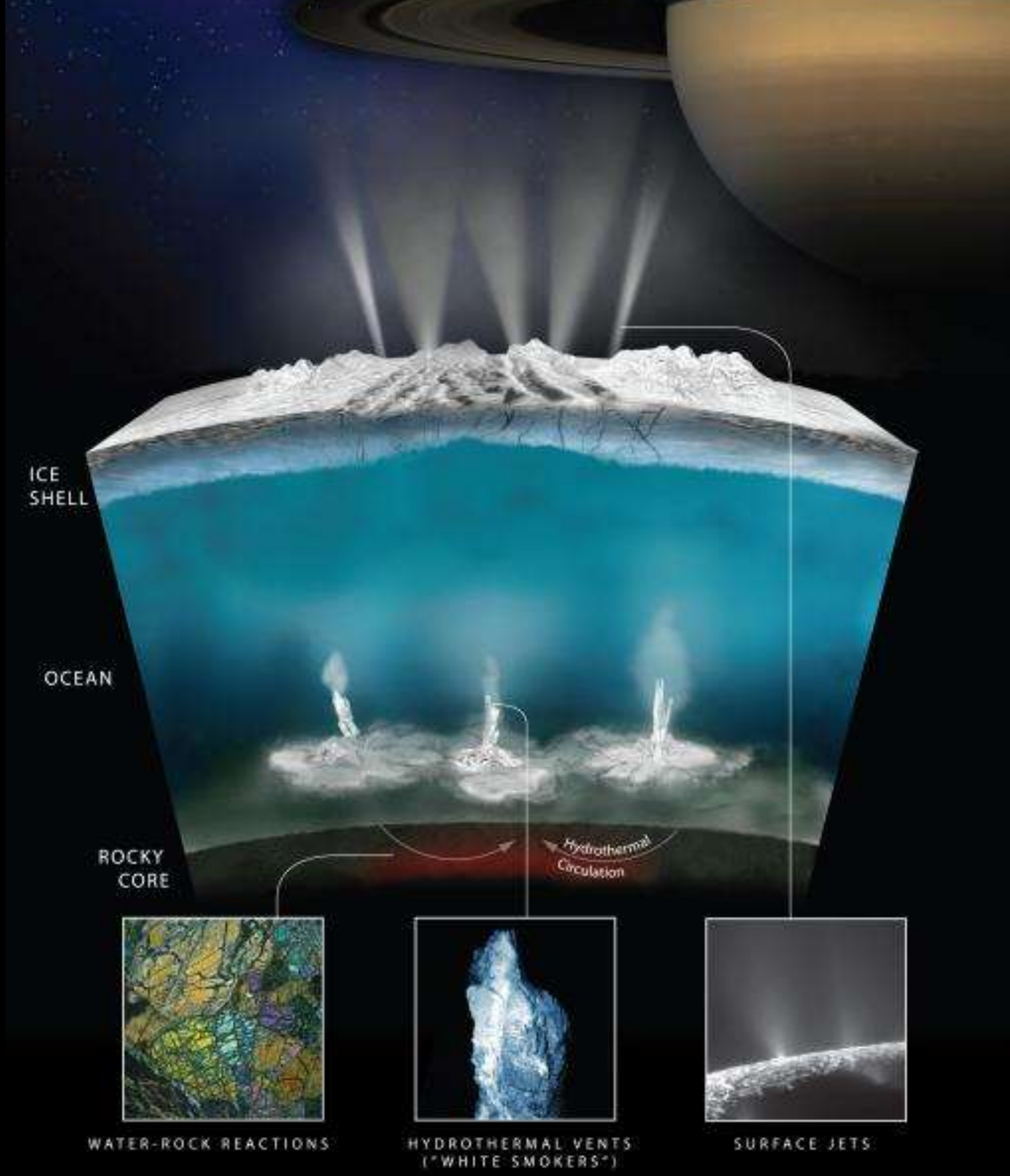

Credit: NASA/JPL

Enceladus has watery plumes erupting from its south pole.

Credit: NASA/JPL-Caltech

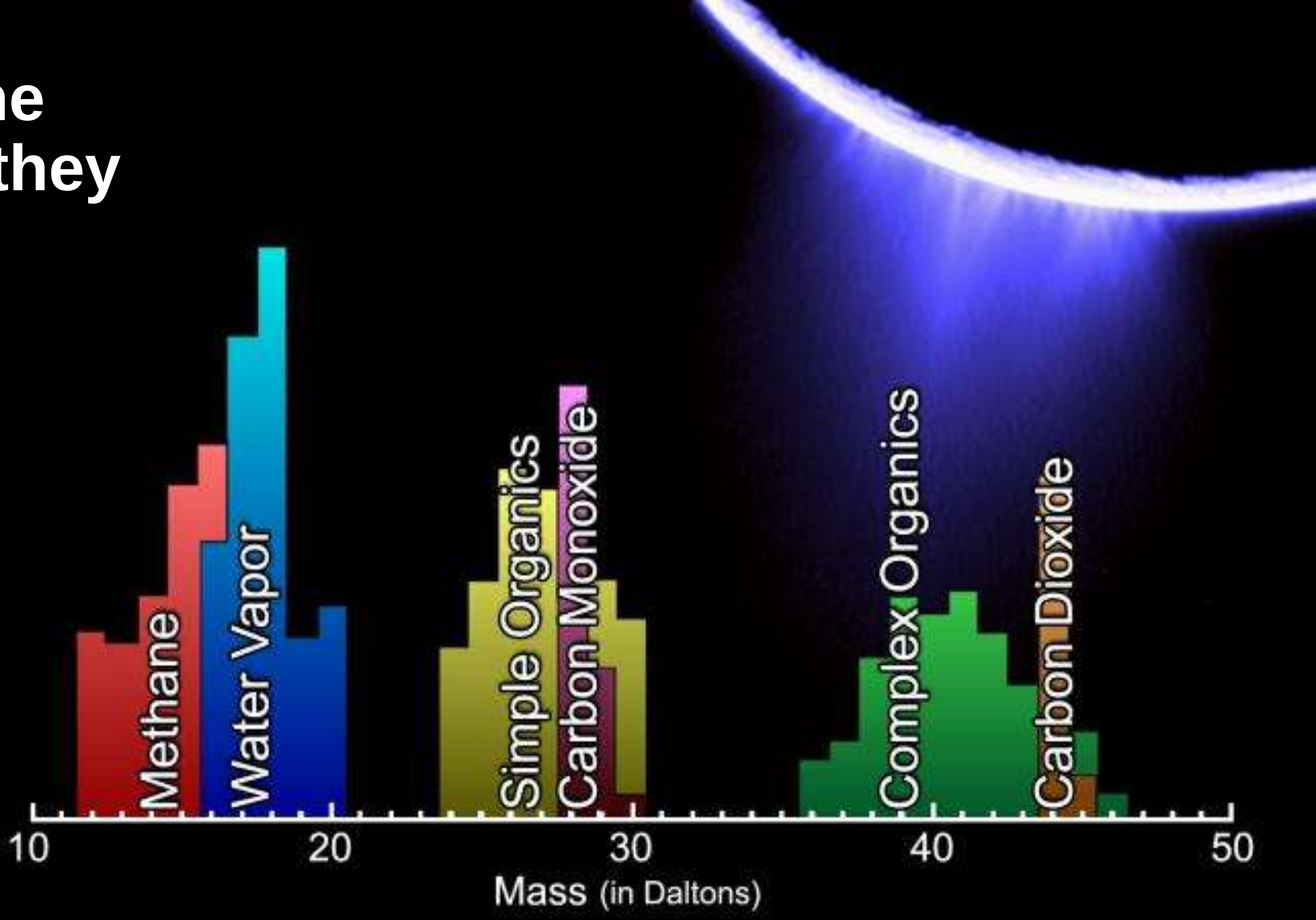
Material in the plumes appears to originate from hydrothermal vents where Enceladus' ocean contacts its rocky core—a similar environment to where life may have formed on Earth.

(Hsu et al., Nature, 2015)



Credit: NASA/JPL-Caltech/Southwest Research Institute

Spectroscopy of the plumes show that they contain organic molecules.



Credit: NASA/JPL-Caltech/Southwest Research Institute

By now, you should be wondering why we spent all this time talking about possible dribbles of water on Mars when there are at least *five moons* believed to have liquid water oceans.

And the answer is: we are really attached to Mars for historical and emotional reasons.

It’s also easier to get to than the Jovian moons, so we can study it more often and at lower cost.

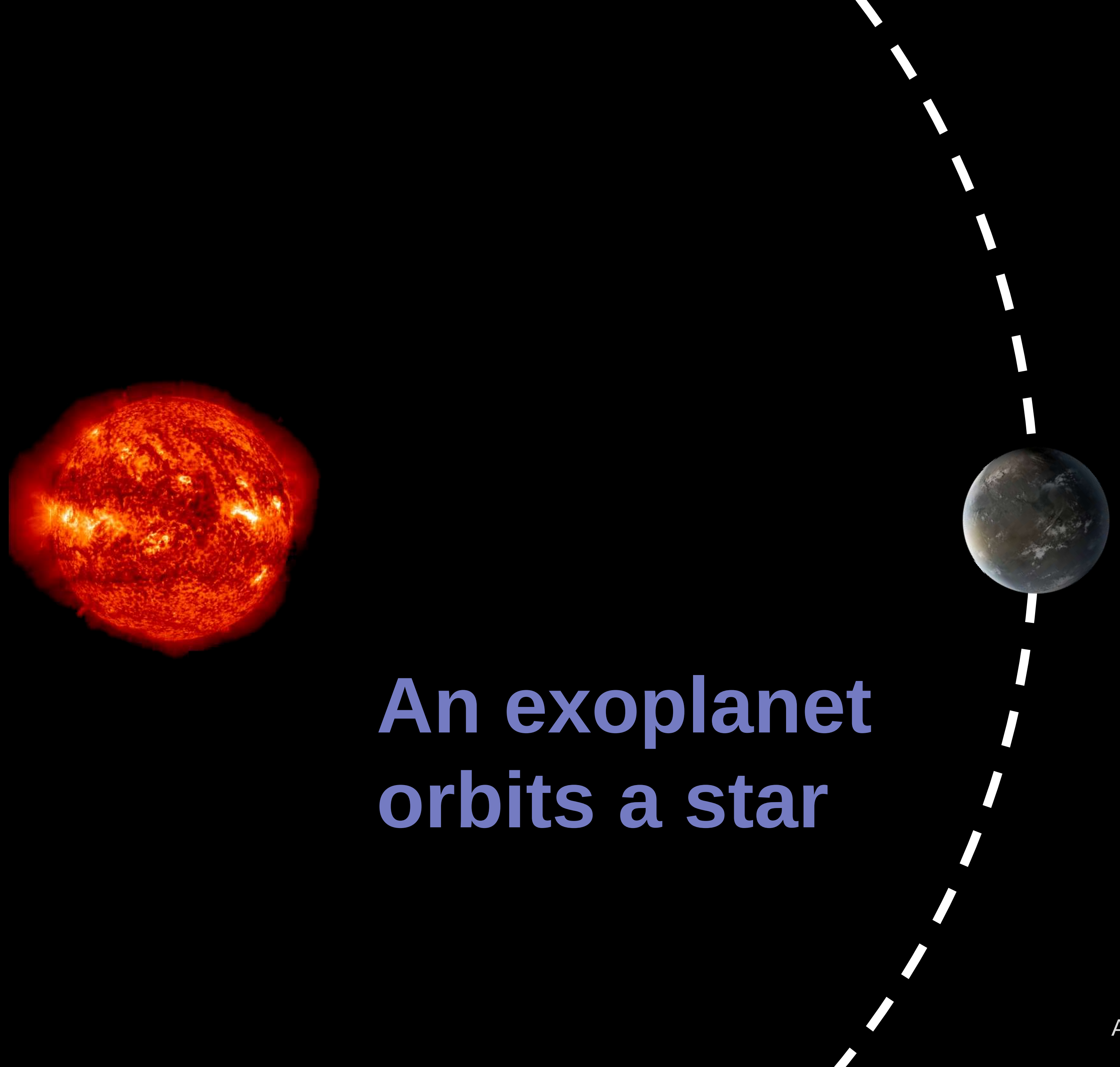
Tidal Locking of Planets and Moons

Tides may be a huge boon to life, providing the energy for it to survive where it otherwise could not.

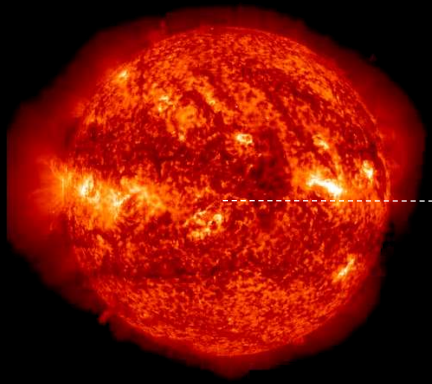
But there is a downside to tides.

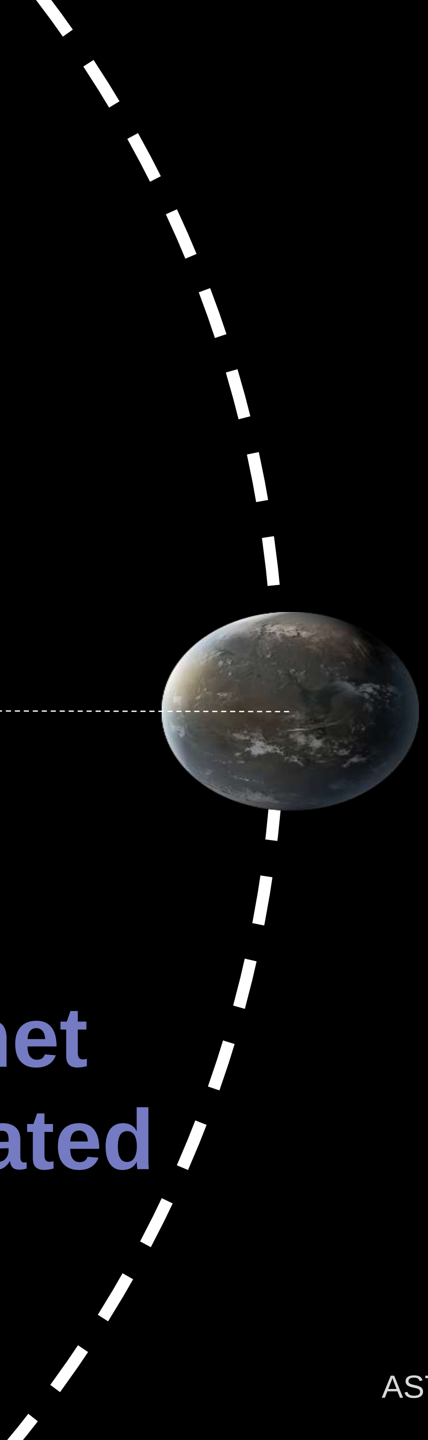
Tidal interactions between two bodies can result in them becoming tidally locked.

Tidal locking is why the same side of the Moon always faces Earth.

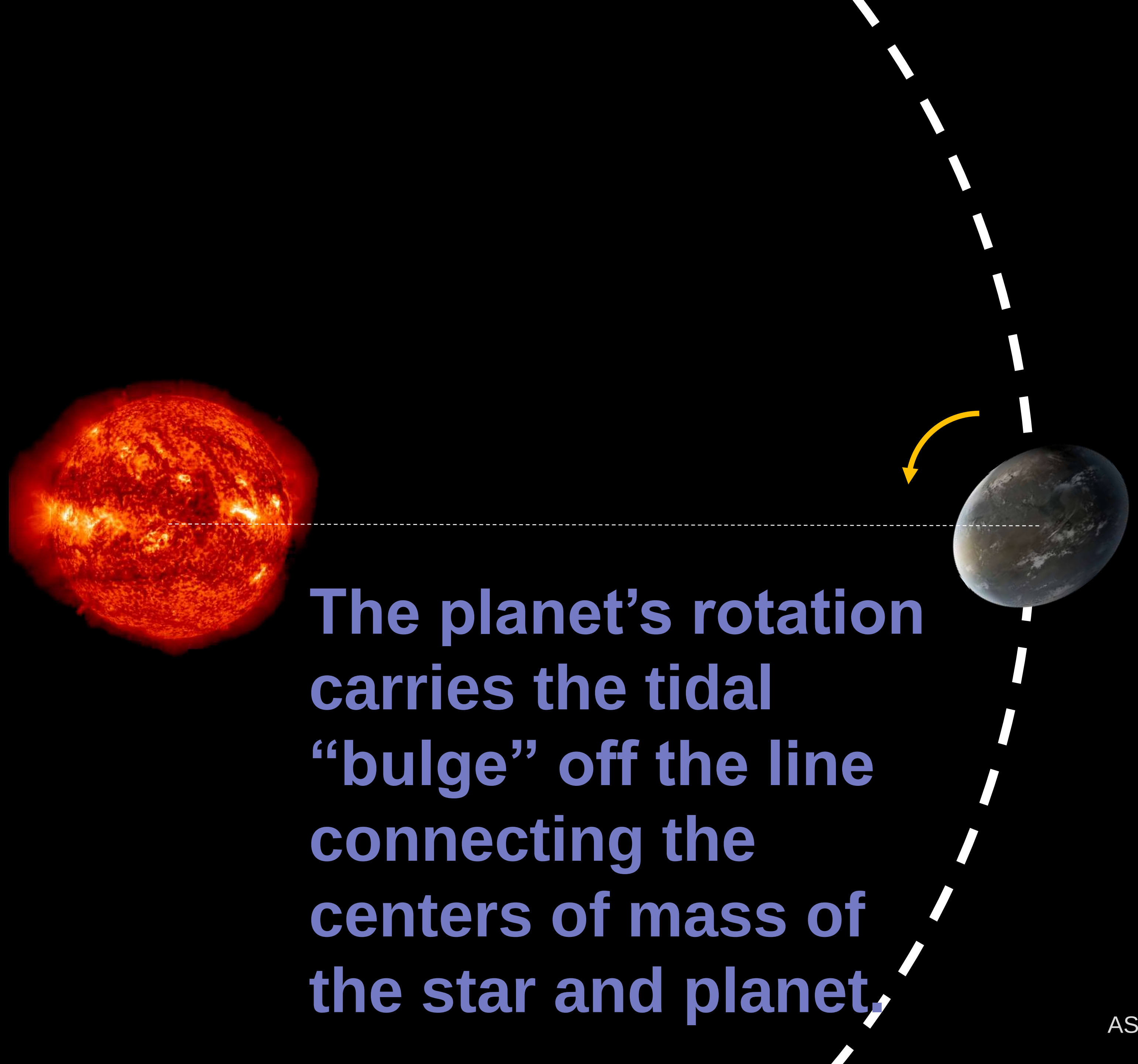


An exoplanet orbits a star

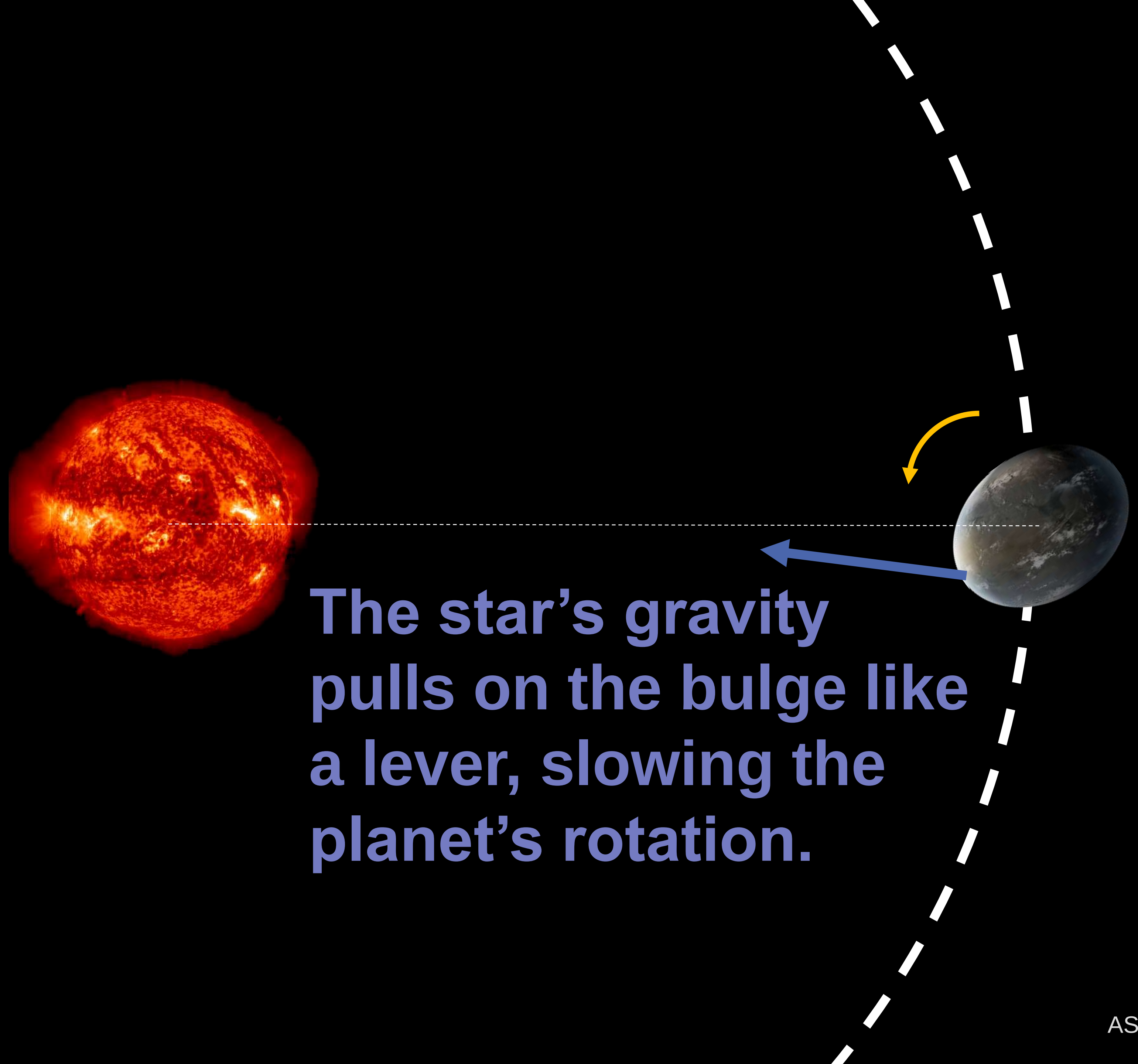


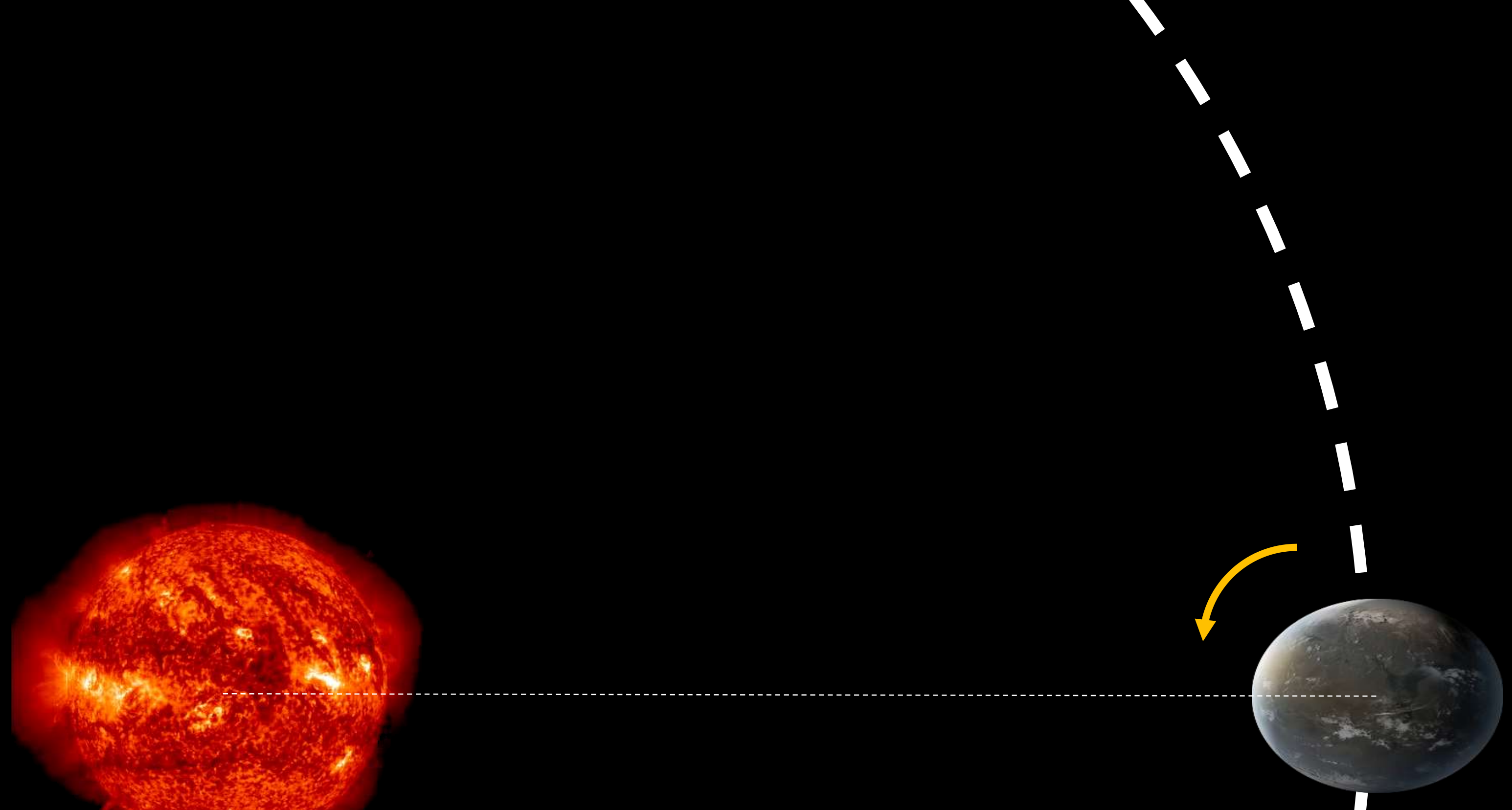


The star’s tidal gravity slightly deforms the planet (hugely exaggerated for clarity)



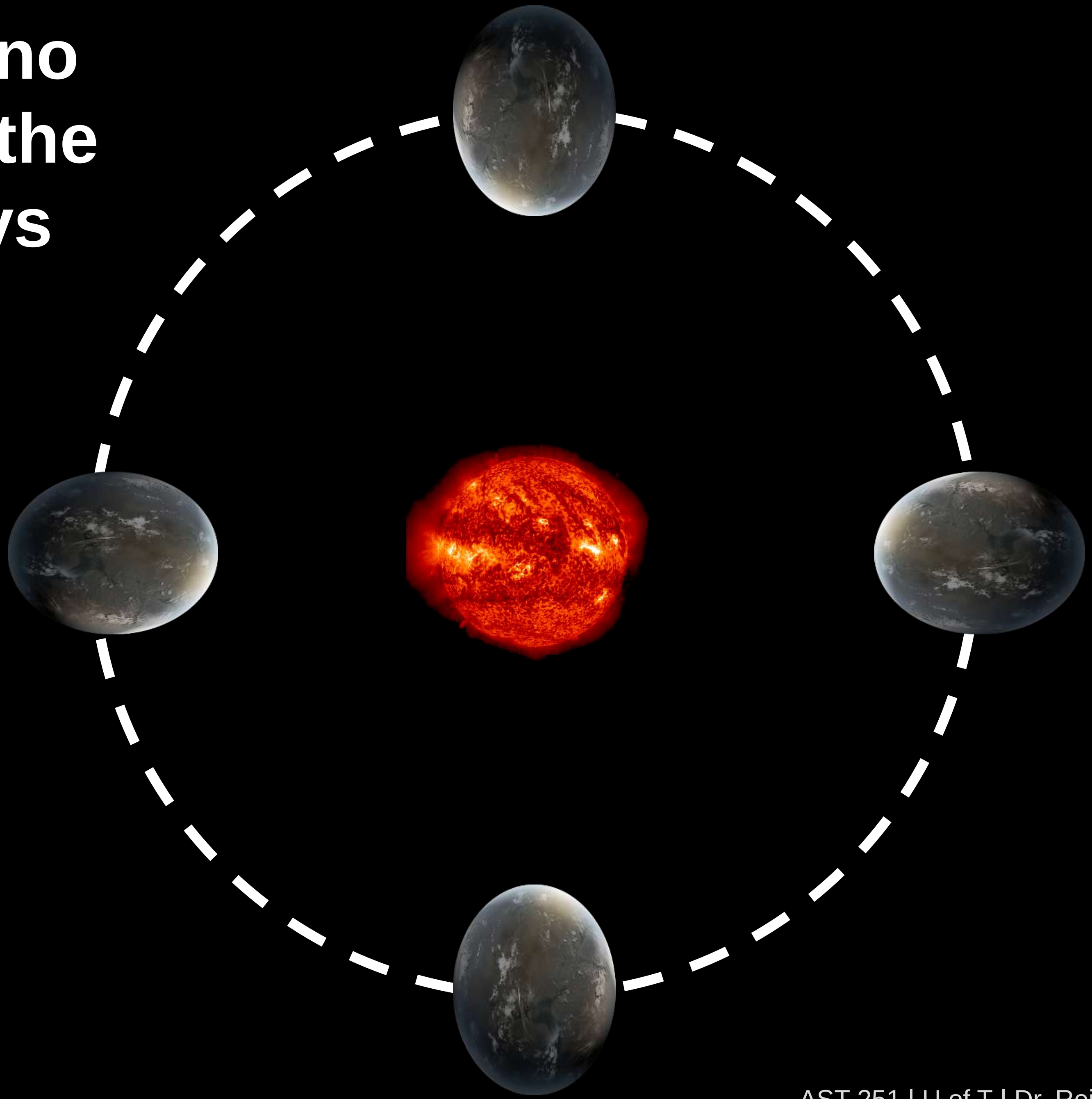
The planet’s rotation carries the tidal “bulge” off the line connecting the centers of mass of the star and planet.


The star’s gravity pulls on the bulge like a lever, slowing the planet’s rotation.



Eventually, the bulge becomes permanently aligned with the star. At this point, the planet is no longer rotating relative to the star. Its orbital and rotational periods are equal.

From then on, the planet no longer rotates relative to the star. The same side always faces the star.



The special case in which tidal locking causes an object's orbital period to equal its rotational period is called synchronous rotation (there are other more complicated forms of tidal locking).

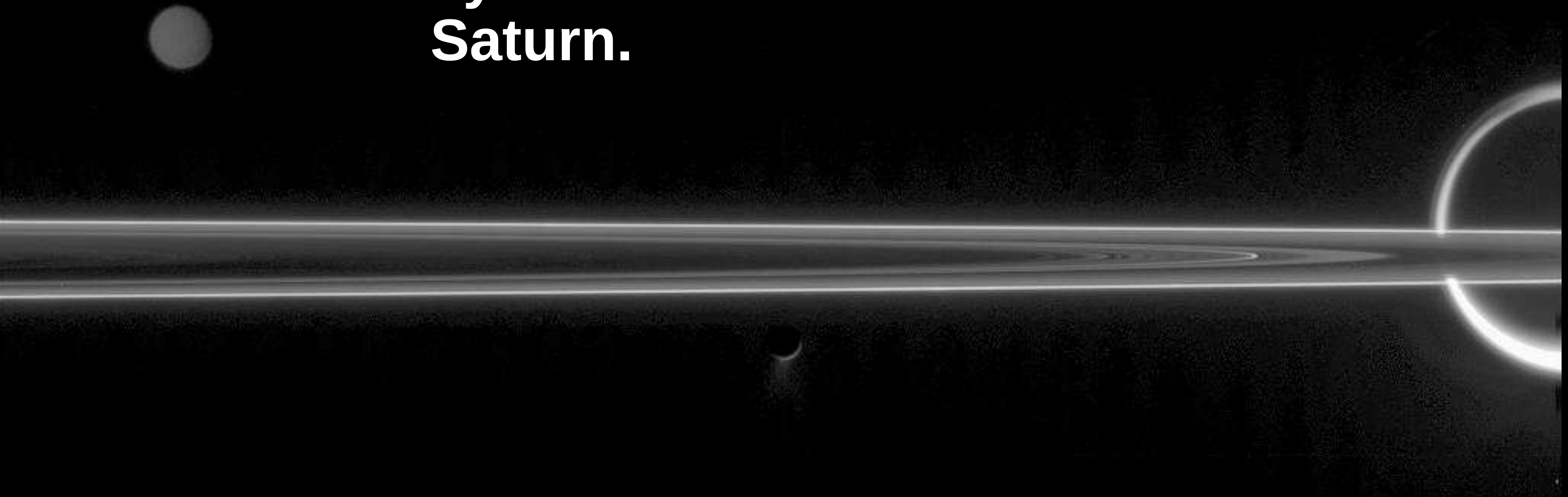
The Moon is in synchronous rotation around Earth: every month, the Moon spins once on its axis (relative to the distant stars) and goes around Earth once.

Most large moons are tidally locked to their parent planets, usually in synchronous rotation.

Io, Europa, Ganymede, and Callisto are in synchronous rotation around Jupiter.

Credit: NASA/JPL/DLR

Enceladus and Titan are in synchronous rotation around Saturn.



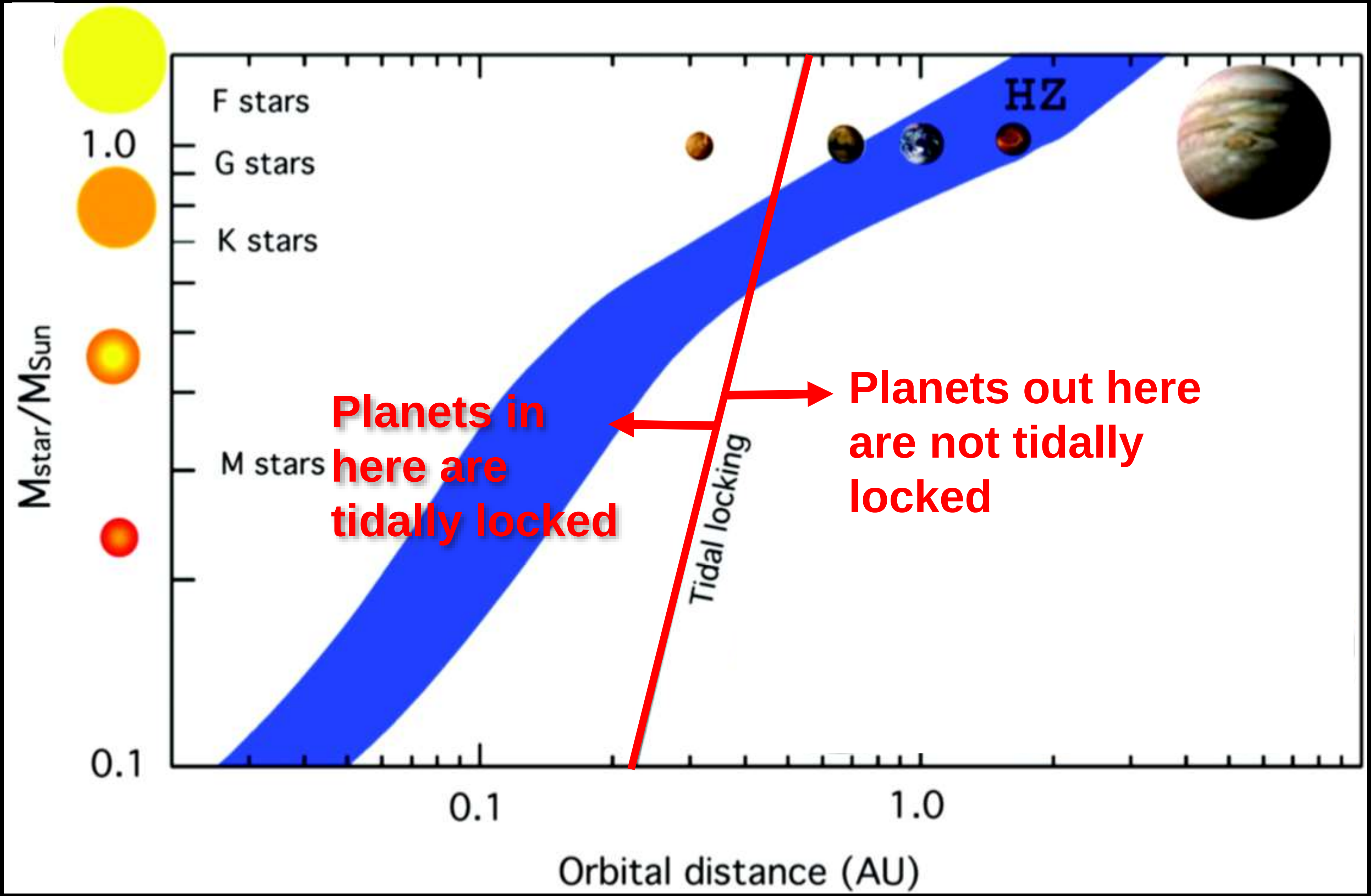
Credit: NASA

Pluto and its moon Charon are in mutual synchronous rotation.

Credit: NASA/JHUAPL/SwRI

The strength of tidal interactions falls rapidly with distance (as the inverse cube of the distance), so two objects have to be fairly close together to be tidally locked.

This means that exoplanets which orbit close to their parent stars are likely to be tidally locked.

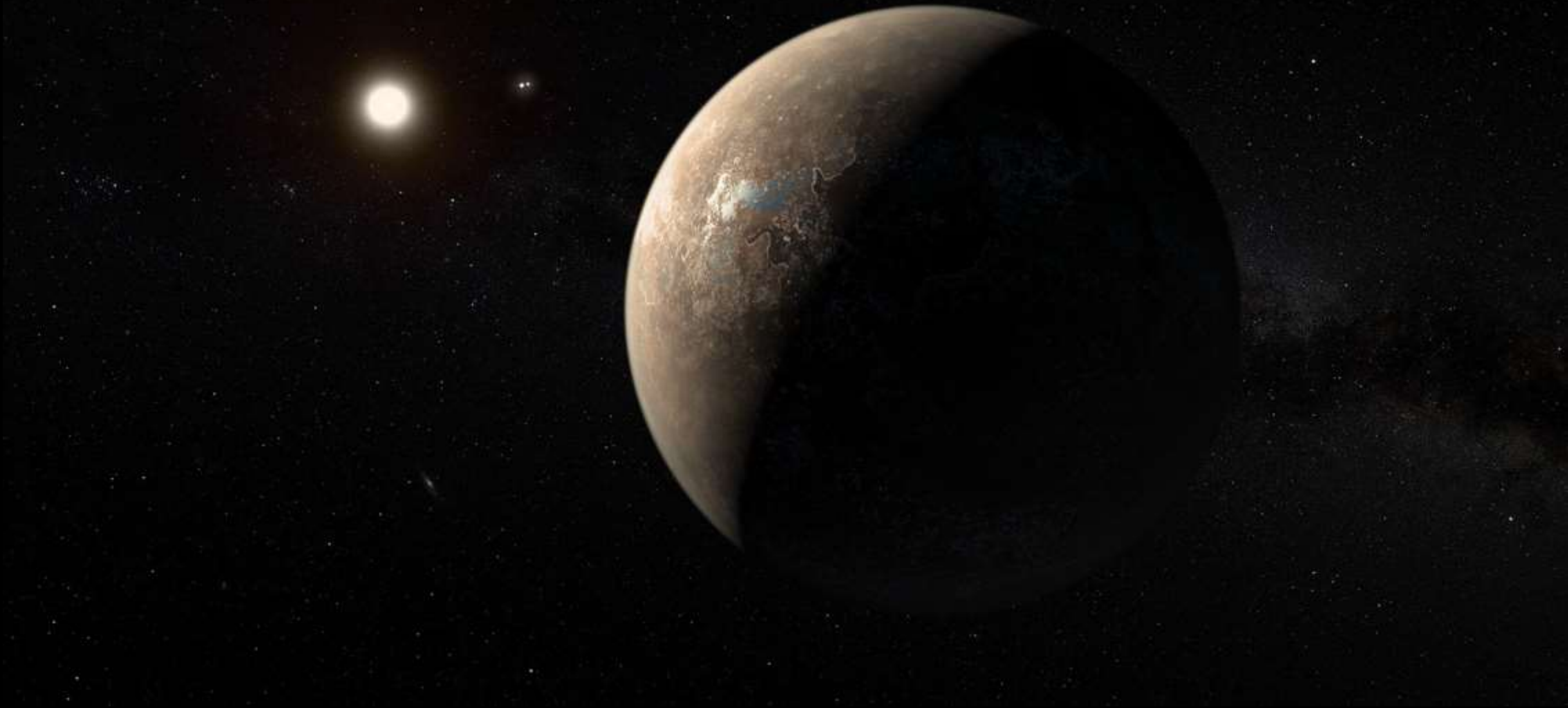


Credit: Kaltenegger et al., 2010

The TRAPPIST-1 planets may all be in synchronous rotation.

Credit: NASA/JPL-Caltech

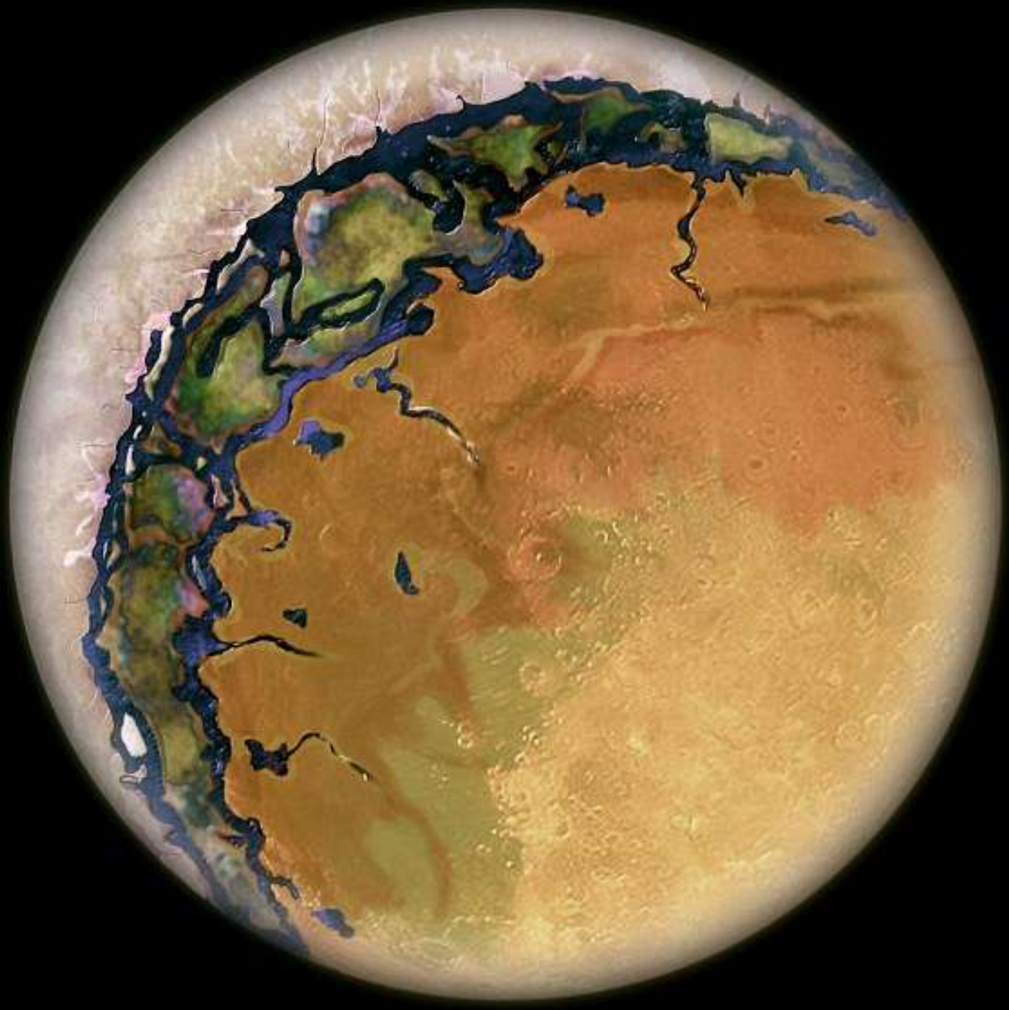
Proxima Centauri b is probably tidally locked.



Credit: ESO

What would life be like on a synchronously rotating planet?

Perhaps such planets would have a narrow habitable strip between the boiling day and freezing night sides.



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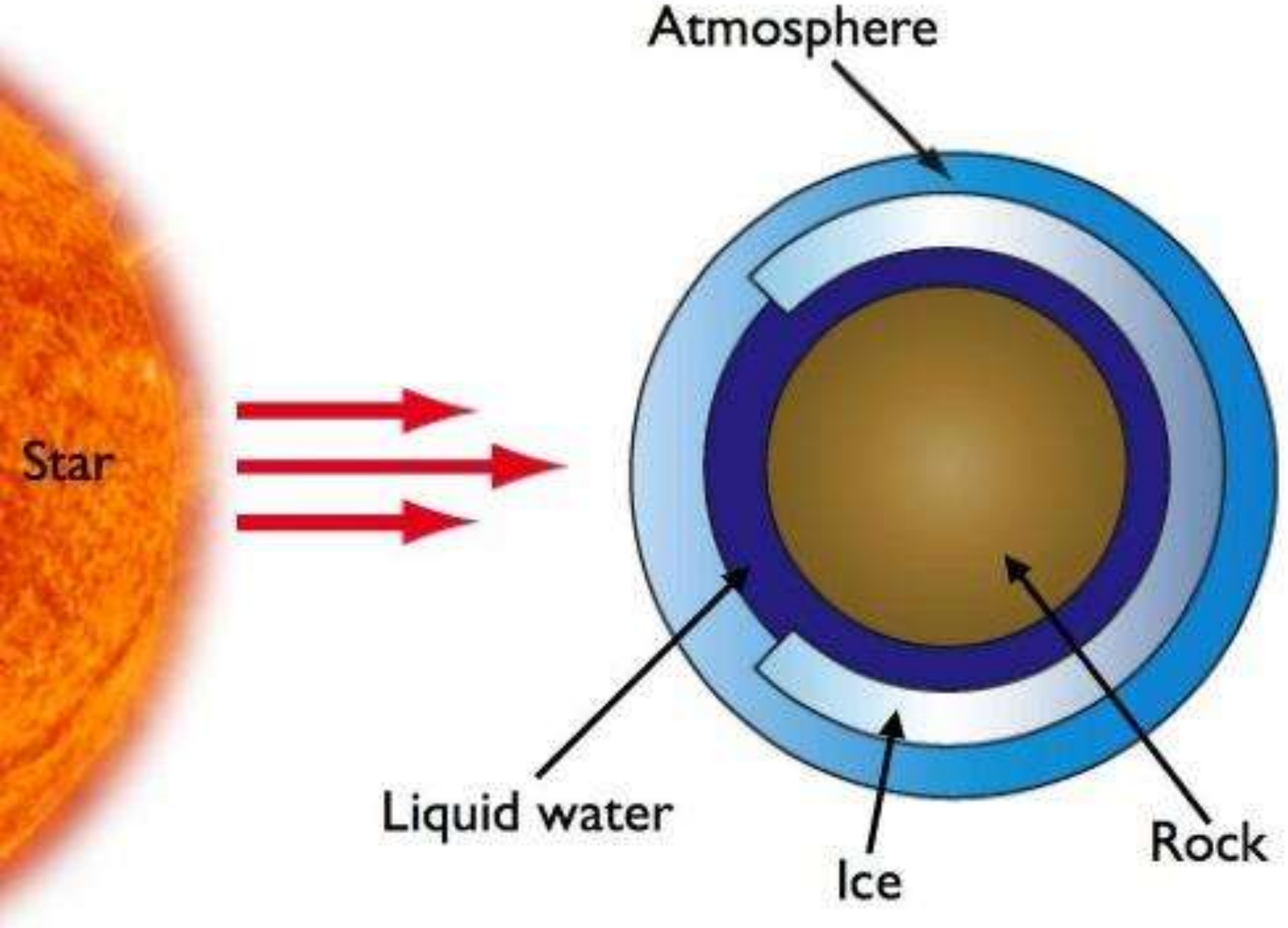

Perhaps ocean worlds might be frozen, except for a patch on the day side. Sometimes these are called “eyeball planets.”

Credit: nautil.us

In our own solar system, liquid water seems to be kept liquid more often by tidal forces than by sunlight.

So, perhaps we should be looking for habitable exomoons more than habitable exoplanets!

What about the moons of warm Jovians? Maybe there are gas giants out there with multiple warm, watery moons.

Credit: Celestia/Frizaven

In Summary

- **Moons of giant planets can be kept warm over the long term by tidal heating.**
- **Tidal heating sustains apparently long-lasting liquid water on several moons in our solar system.**
- **Tidal locking may limit the habitability of exoplanets orbiting smaller stars with narrow habitable zones.**