The Habitable Zone

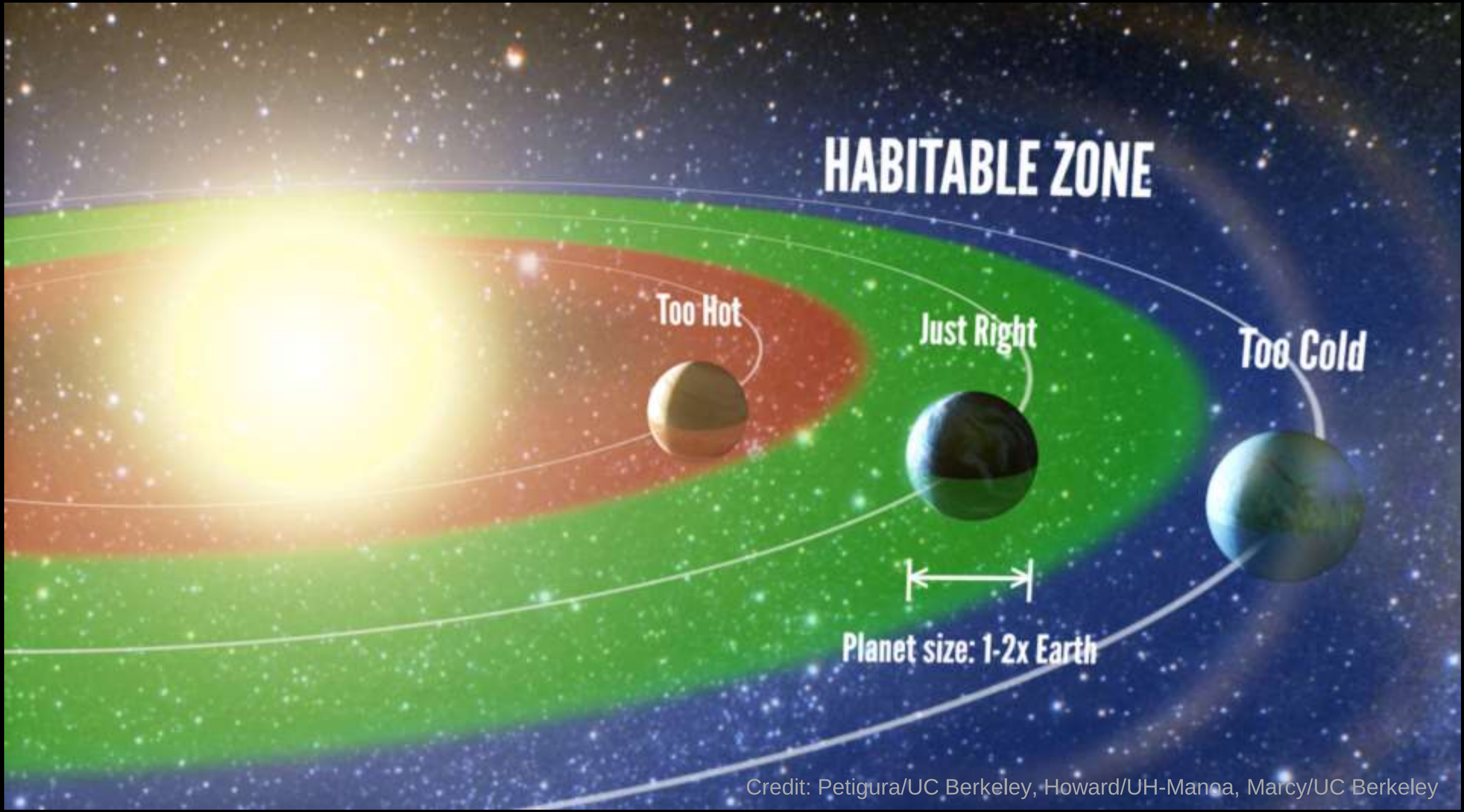
What makes a world “habitable” to life-like-us?

“Follow the water”

To begin, we will define a **habitable planet** as one on whose surface water can remain liquid for long periods of time.

Later, we will critique this definition and expand it.

The **habitable zone** around a star is the range of distances from the star within which habitable planets can exist.

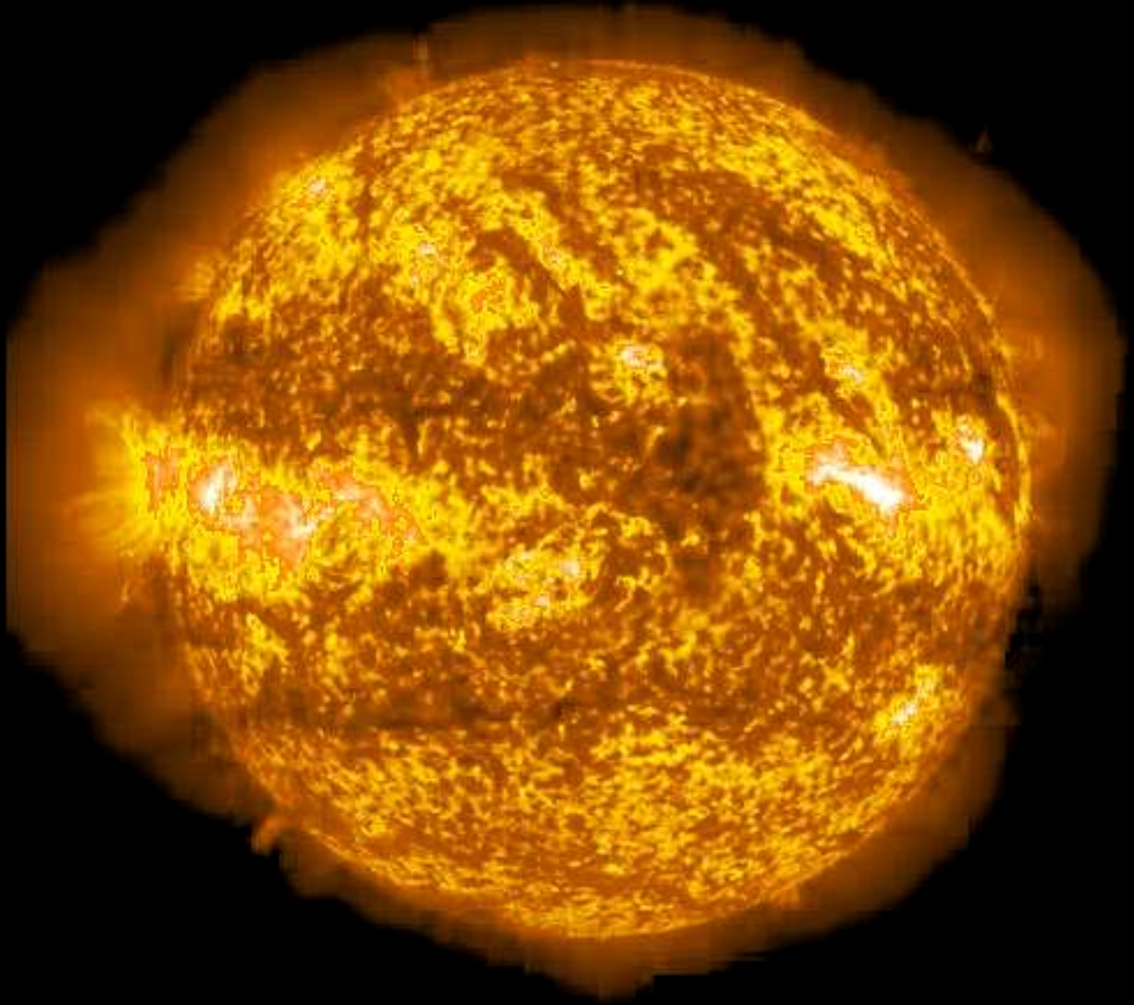


The habitable zone is sometimes called the “Goldilocks zone”.

Let’s develop a simple model that will allow us to calculate the boundaries of the Sun’s habitable zone.

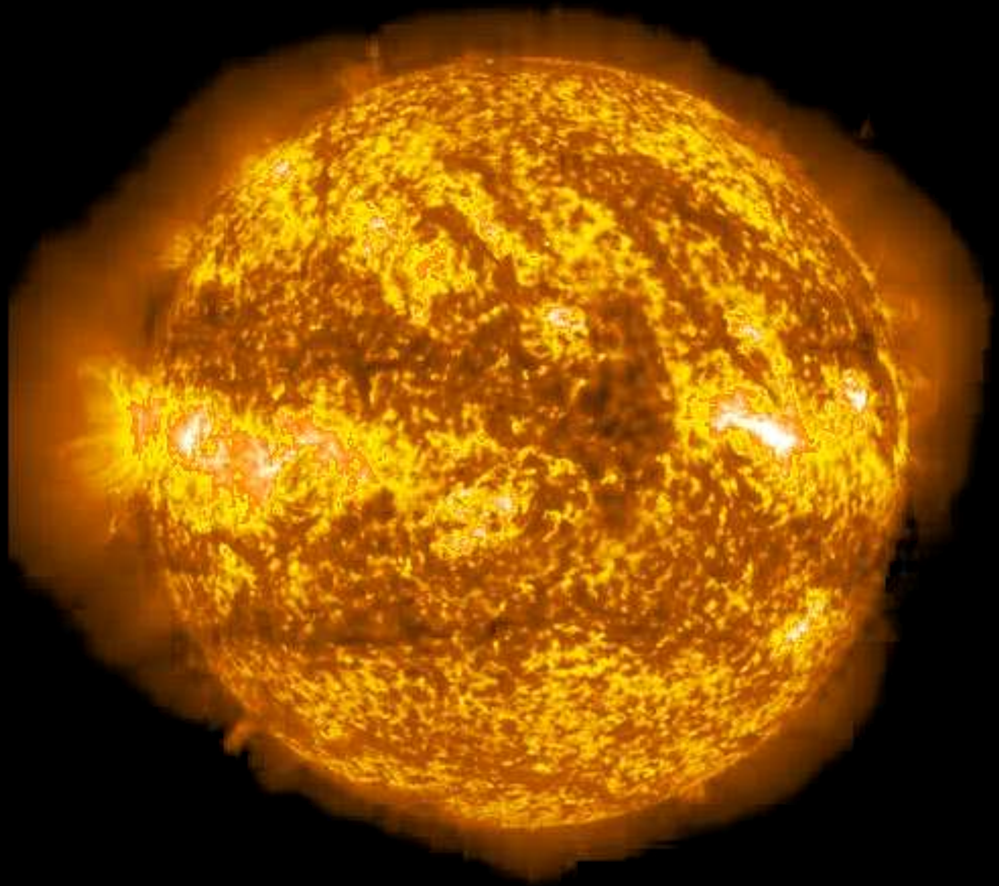
In this simple model, the boundaries of the habitable zone depend exclusively on the equilibrium temperature of the planet.

incandescent lightbulb = 100 W



The Sun = 3.8×10^{26} W

Credit: NASA



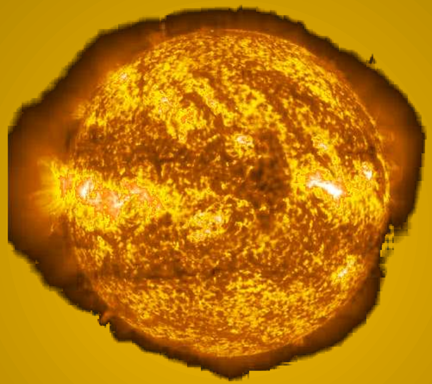
The energy output of the Sun is 3.8×10^{26} W.

In physics, “energy per unit time” is called “power”.

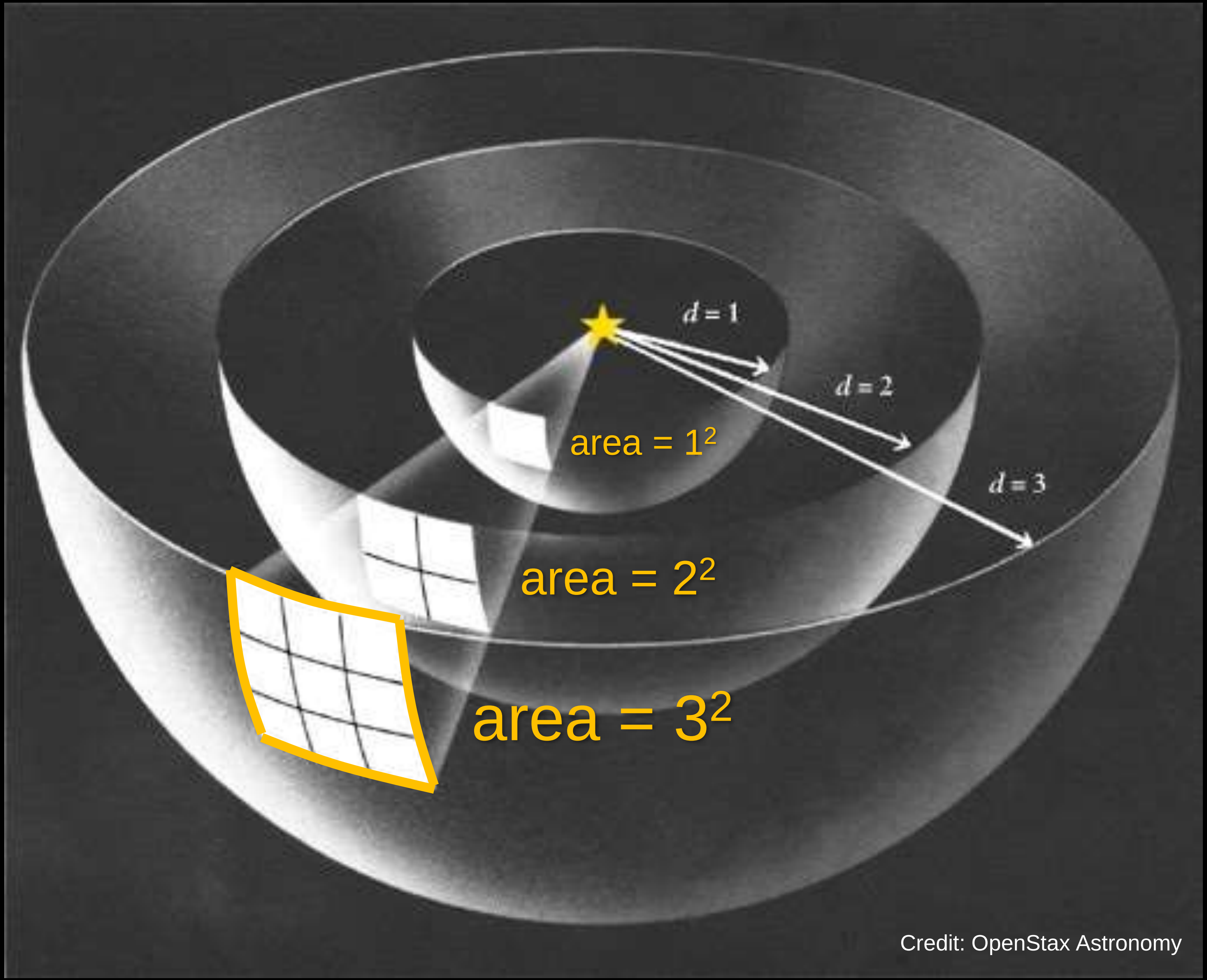
In astronomy, we call this the Sun’s luminosity, $L_\odot$

($\odot$ is the symbol meaning “Sun”)

Credit: NASA

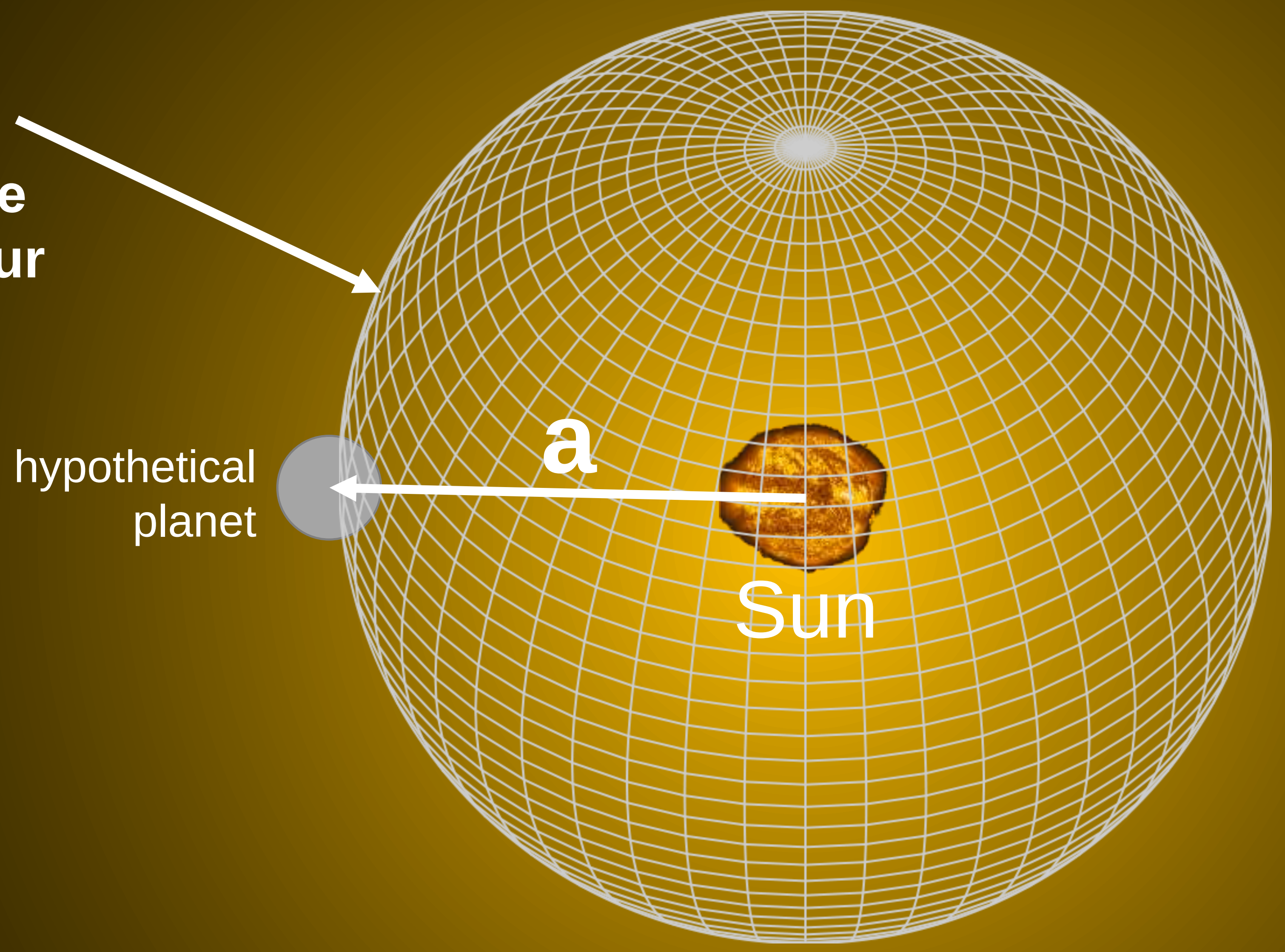


If we imagine that the Sun radiates this energy equally in every direction, then we can use the inverse square law to calculate how much energy a planet receives.



d = 1
d = 2
d = 3
area = 1^2
area = 2^2
area = 3^2
Credit: OpenStax Astronomy

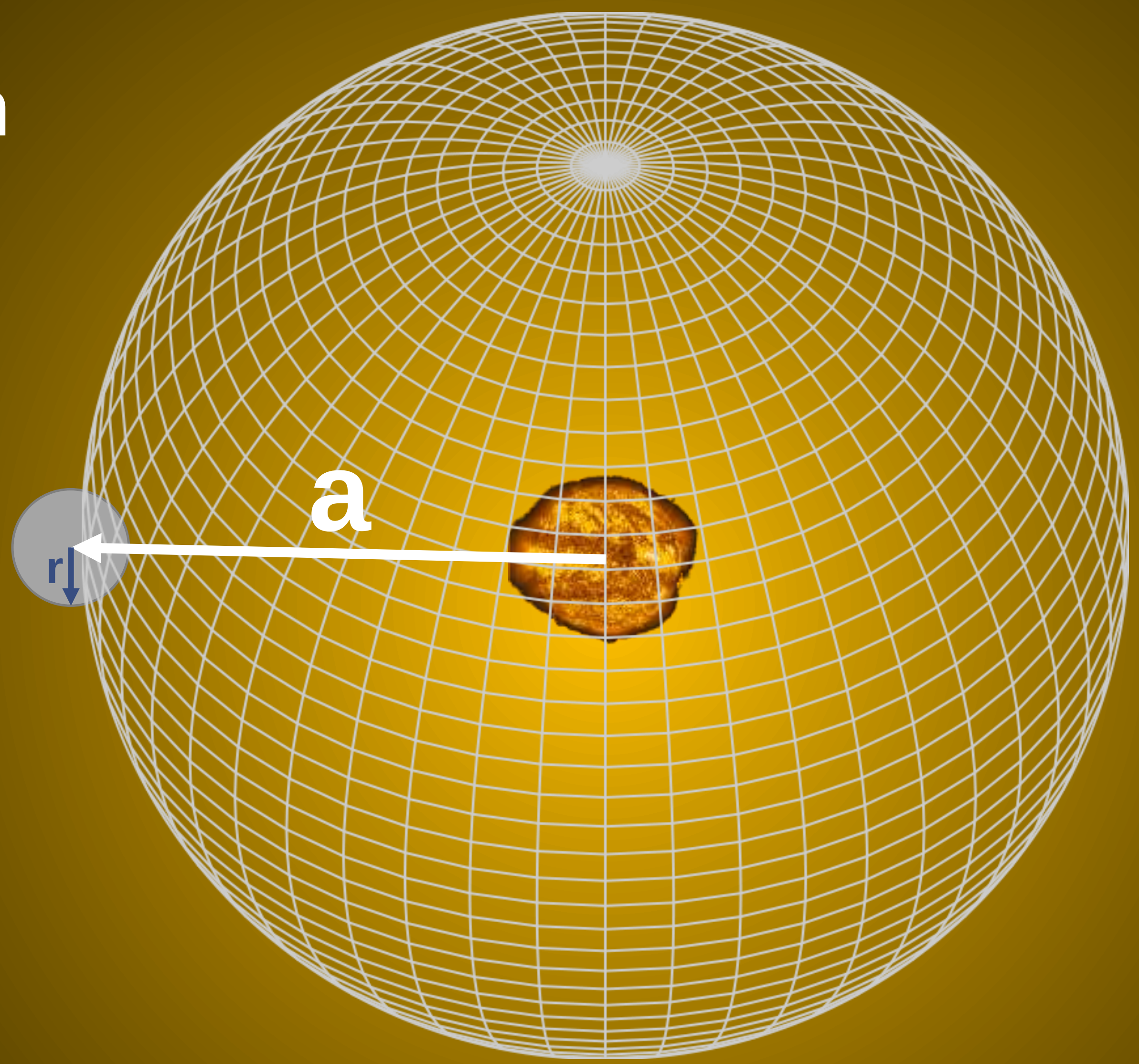
The Sun radiates light into a sphere with a surface area of $4\pi a^2$, where ‘a’ is the distance between the star and our imaginary planet.



What fraction of the Sun's total radiated power does the planet intercept?

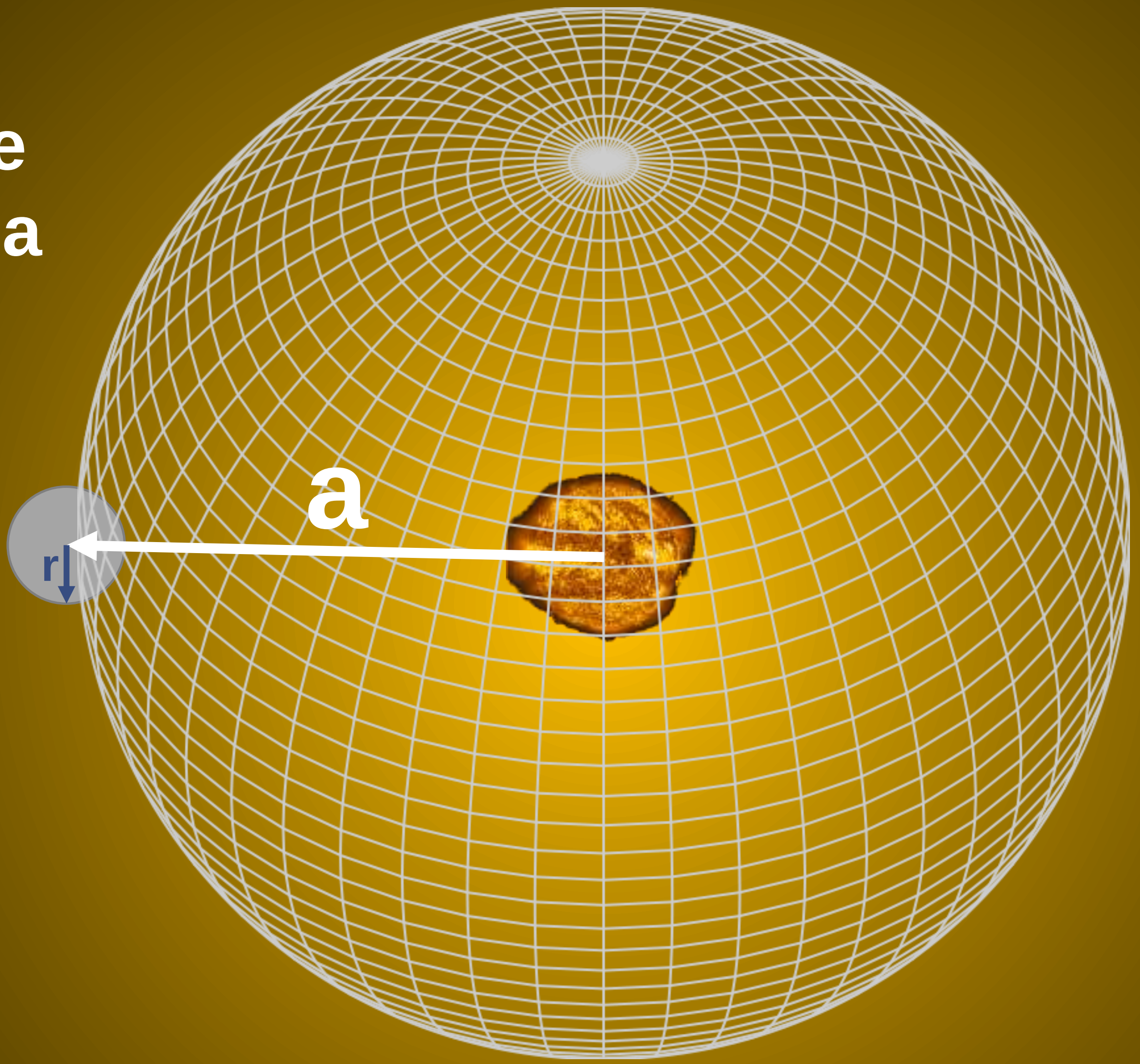
(This is analogous to asking how much of the light from a light bulb your body absorbs if you stand near the bulb.)

A planet of radius ‘r’ blocks light in proportion to its cross-sectional area, πr^2



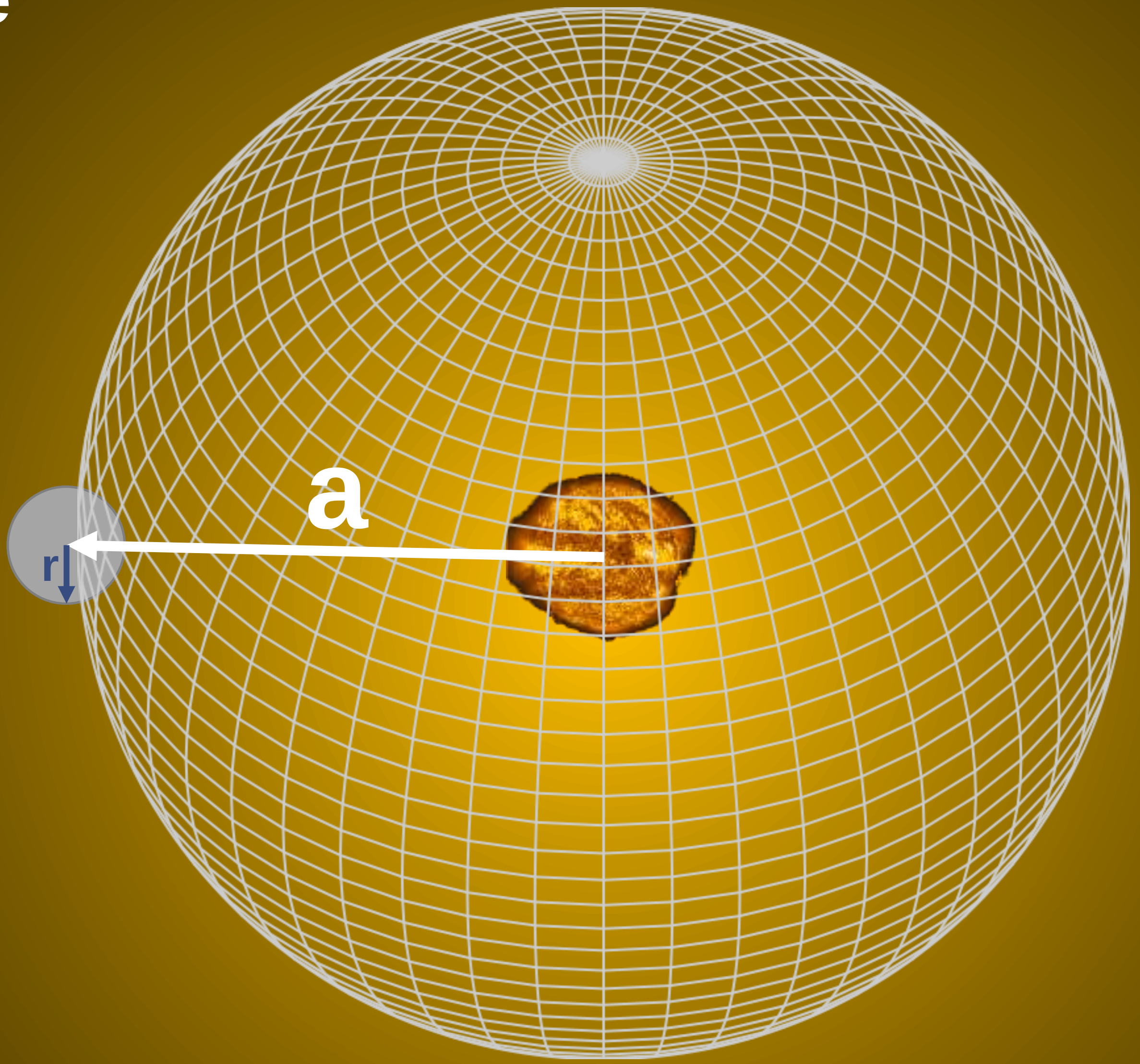
The fraction of the Sun's light intercepted by the planet just the cross-sectional area of the planet divided by the total area into which the star is emitting light:

$$P_{in} = \frac{(\text{cross}-\text{sectional area of planet})}{(\text{area the star is emitting light into})} L_{\odot}$$



So the power received by the planet, P_{in}, as a fraction of the total power emitted by the Sun, $L_\odot$ is:

$$P_{in} = \frac{\pi r^2}{4\pi a^2} L_\odot$$



What happens to the light that falls on the planet?

Does the planet absorb it all? Reflect some? Absorb then re-radiate some?

To start, let's assume that the planet has a uniform surface which reflects some fraction of the light it receives.

Venus: A ≈ 0.75

Earth: A ≈ 0.3

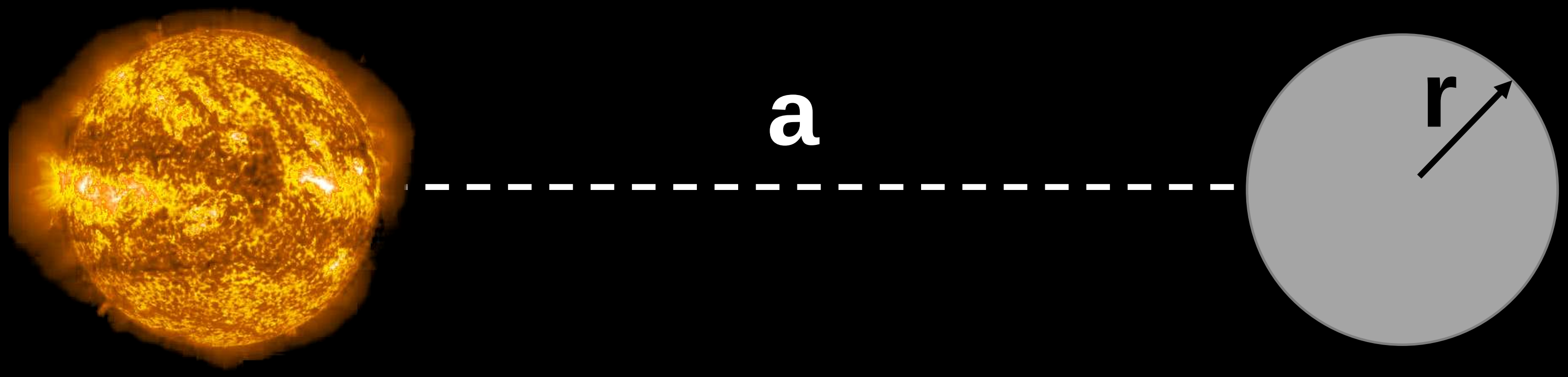
Bond albedo, A:
the fraction of the light falling on a planet that is reflected back to space.

A = 0 → perfectly black (absorbs all light)

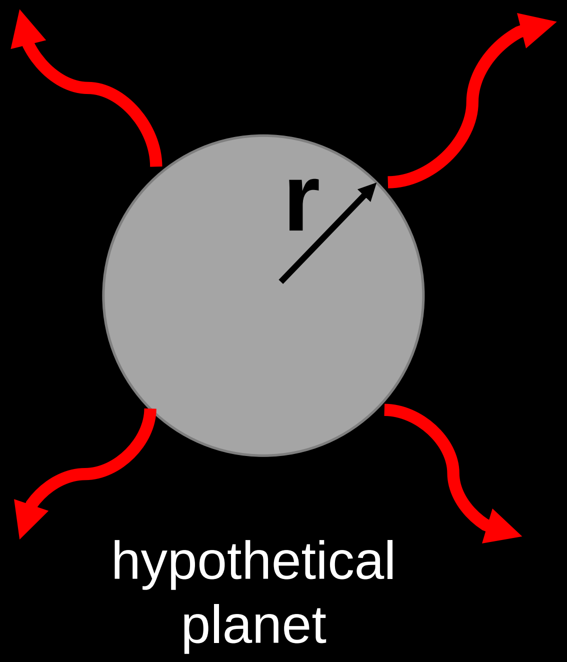
A = 1 → perfectly white (reflects all light)

Credit: NASA & NASA/Caltech/JPL/Mattias Malmer

We adjust our result to account for the albedo of our test planet:

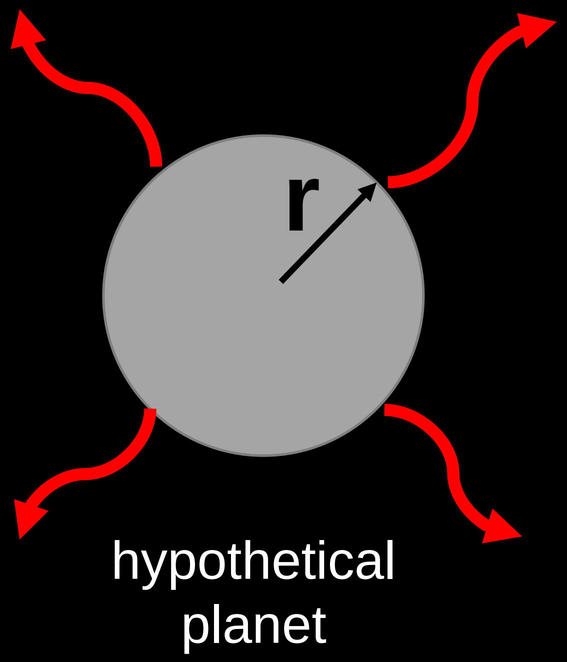


$$P_{in} = \underbrace{(1 - A)}_{\text{new term to account for planet's reflectivity}} \frac{\pi r^2}{4\pi a^2} L_\odot$$



If the planet didn’t release some of the energy it absorbed, it would heat up indefinitely.

In actuality, the surface absorbs sunlight, then re-radiates it at other wavelengths (mainly infrared).

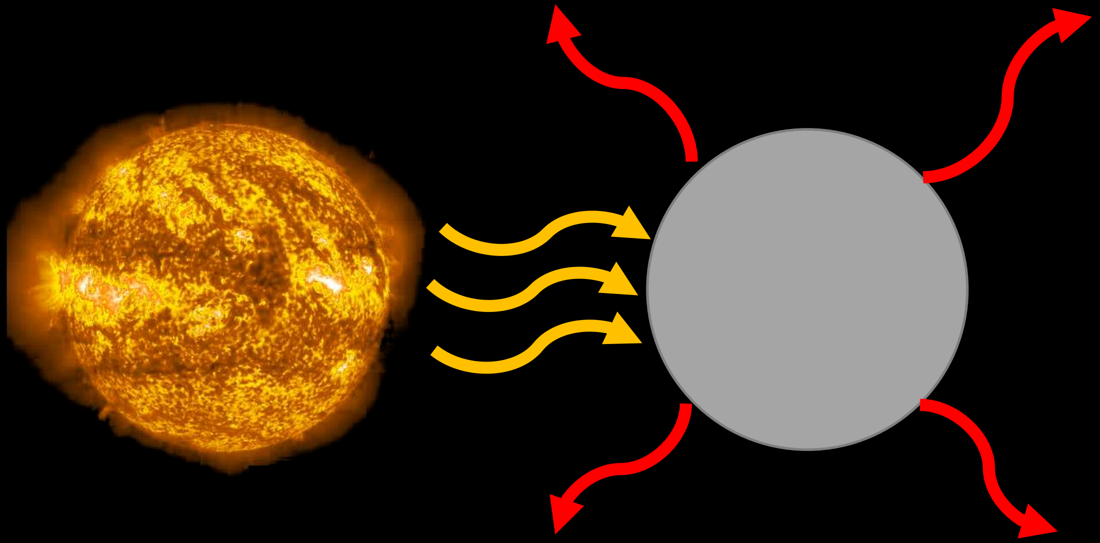


The amount it radiates away depends on its surface area, $4\pi r^2$, and its temperature, T:

$$P_{out} = 4\pi r^2 \sigma T^4$$

(This comes from the physics of "blackbodies", which we won't go into, but you can look it up if you're curious. σ is the Stefan-Boltzmann constant.)

For a planet in equilibrium (meaning maintaining a constant temperature), all of the energy received is eventually re-radiated, so $P_{in} = P_{out}$:



$$P_{in} = P_{out}$$

Plug in our two expressions for power and solve for temperature:

$$P_{in} = P_{out}$$

$$(1 - A)\frac{L_{\odot}}{4\pi a^2}\pi r^2 = 4\pi r^2 \sigma T^4$$

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

So, in this simple model, we can calculate a planet's equilibrium temperature if we know the:

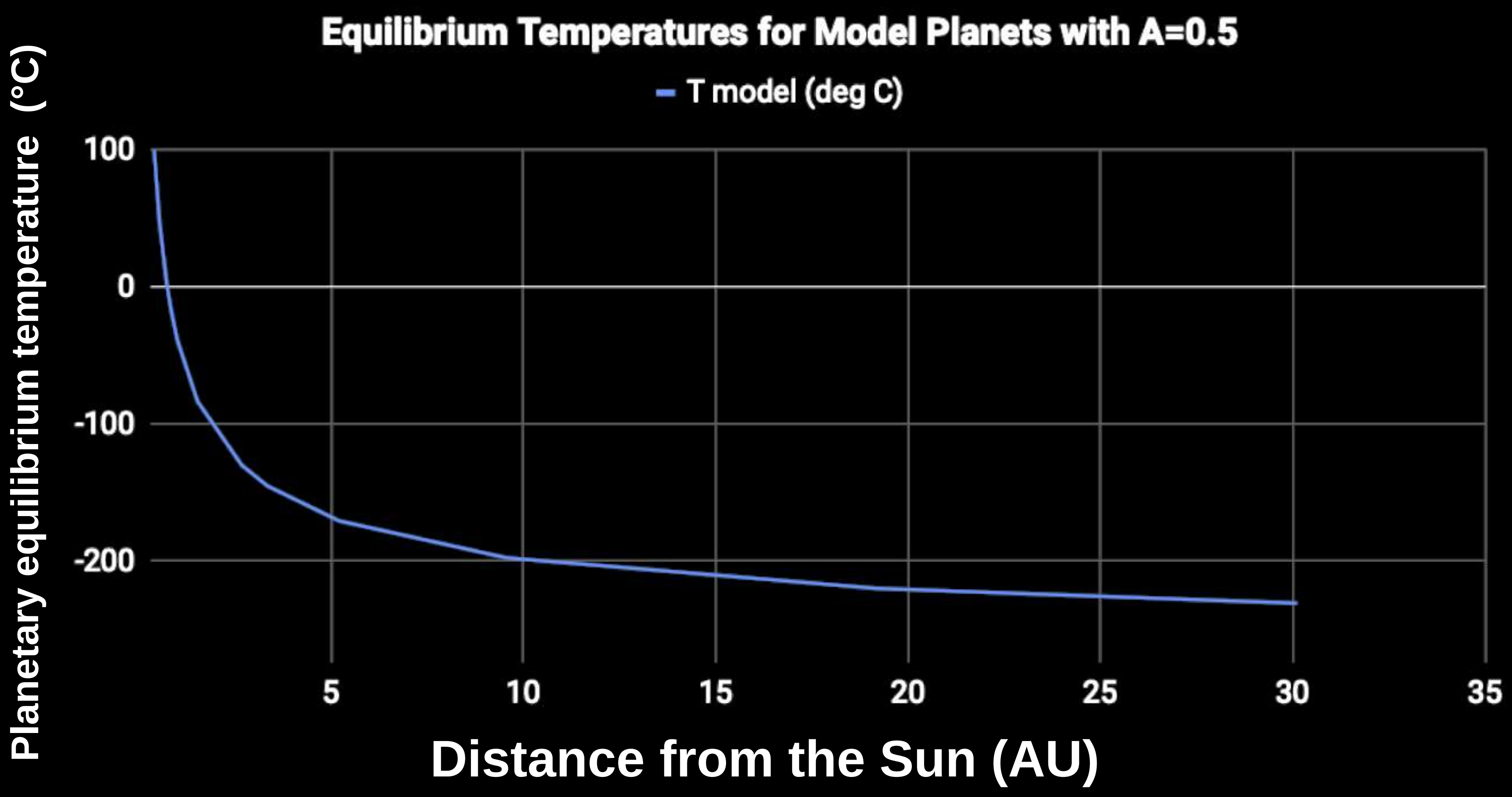
- luminosity of the star it orbits, L ($L_\odot$ for the Sun)
- planet's Bond albedo, A
- planet's orbital semi-major axis, a

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

Stefan-Boltzmann constant, σ

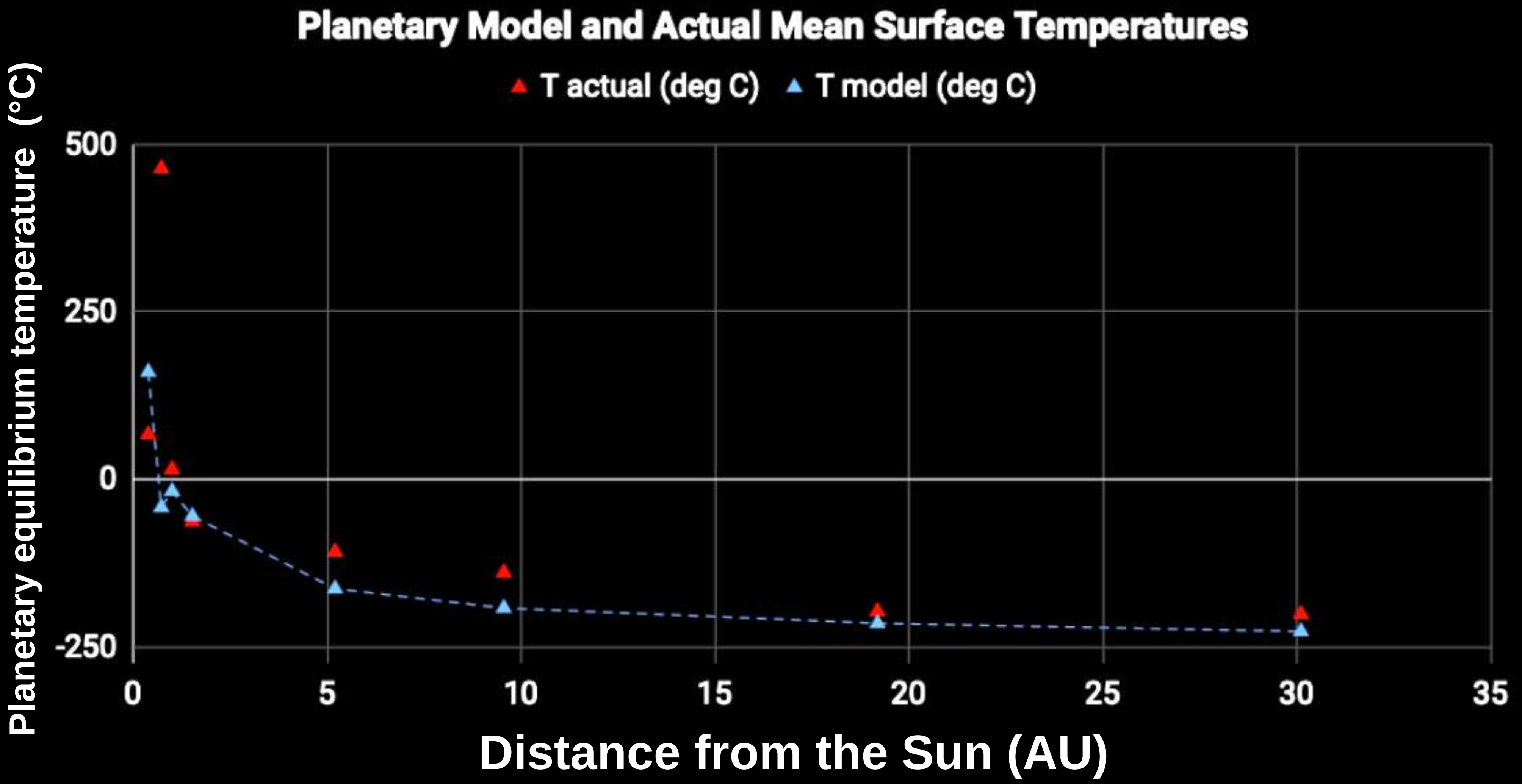
The limits of the habitable zone in our simple model are based on the equilibrium temperature of the planet.

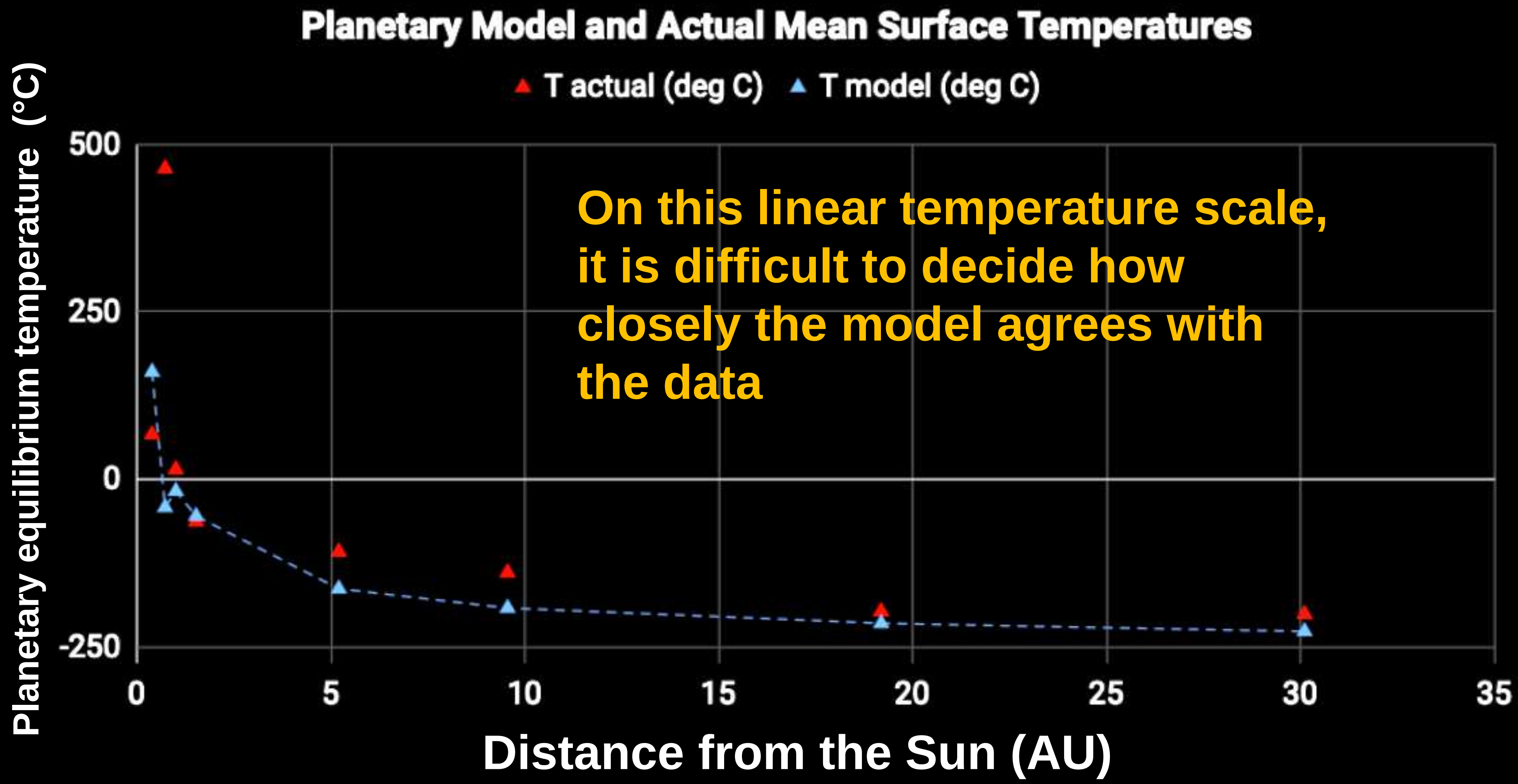
So, we can use the preceding formula to calculate the width of the habitable zone.


Equilibrium Temperatures for Model Planets with A=0.5
T model (deg C)
100
0
-100
-200
5
10
15
20
25
30
35
Planetary equilibrium temperature (°C)
Distance from the Sun (AU)

Remember that this is a simplified model.

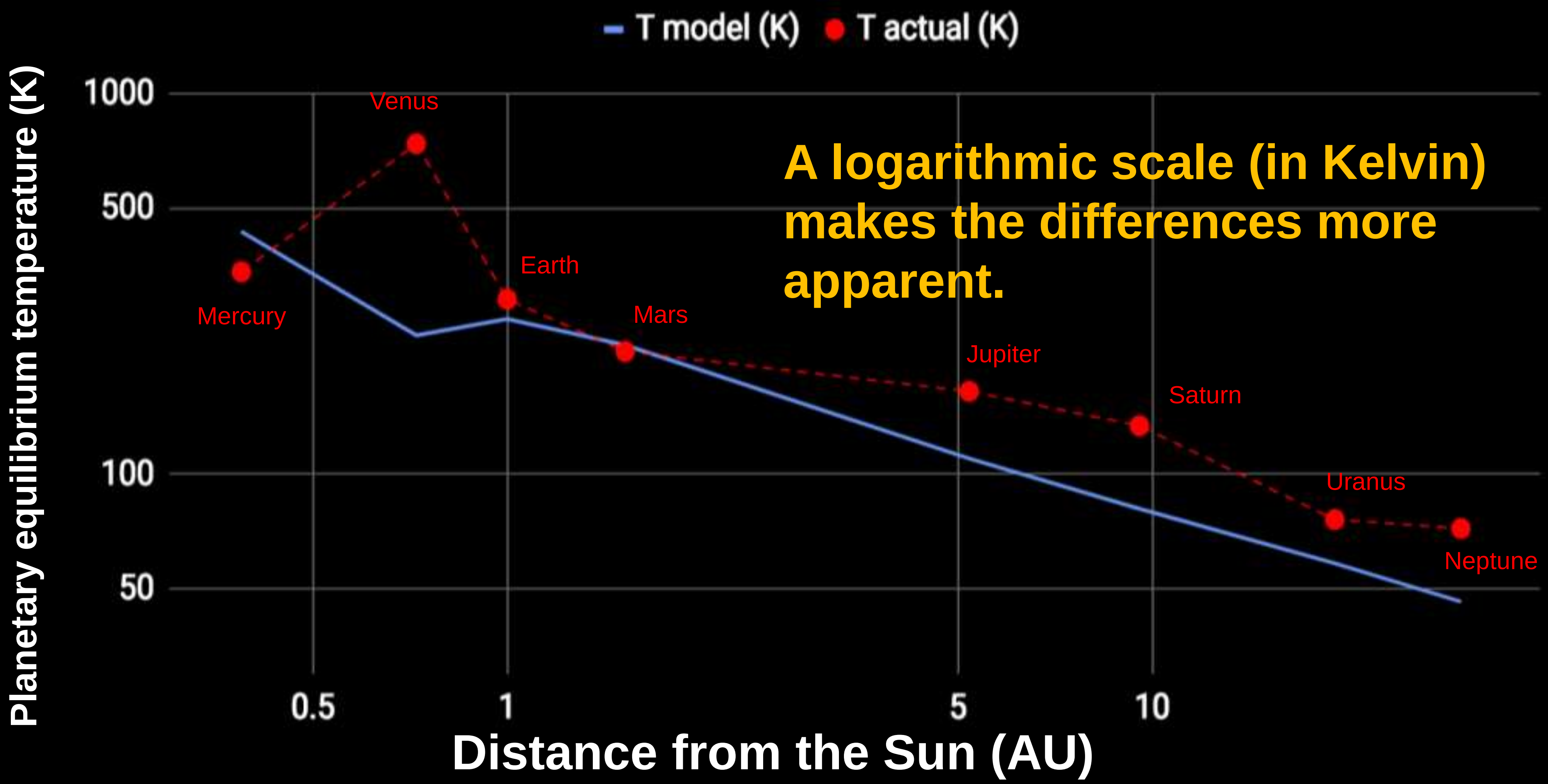
How well does it work for the planets of our solar system?


Planetary Model and Actual Mean Surface Temperatures
T actual (deg C)
T model (deg C)
Planetary equilibrium temperature (°C)
500
250
0
-250
0
5
10
15
20
25
30
35
Distance from the Sun (AU)



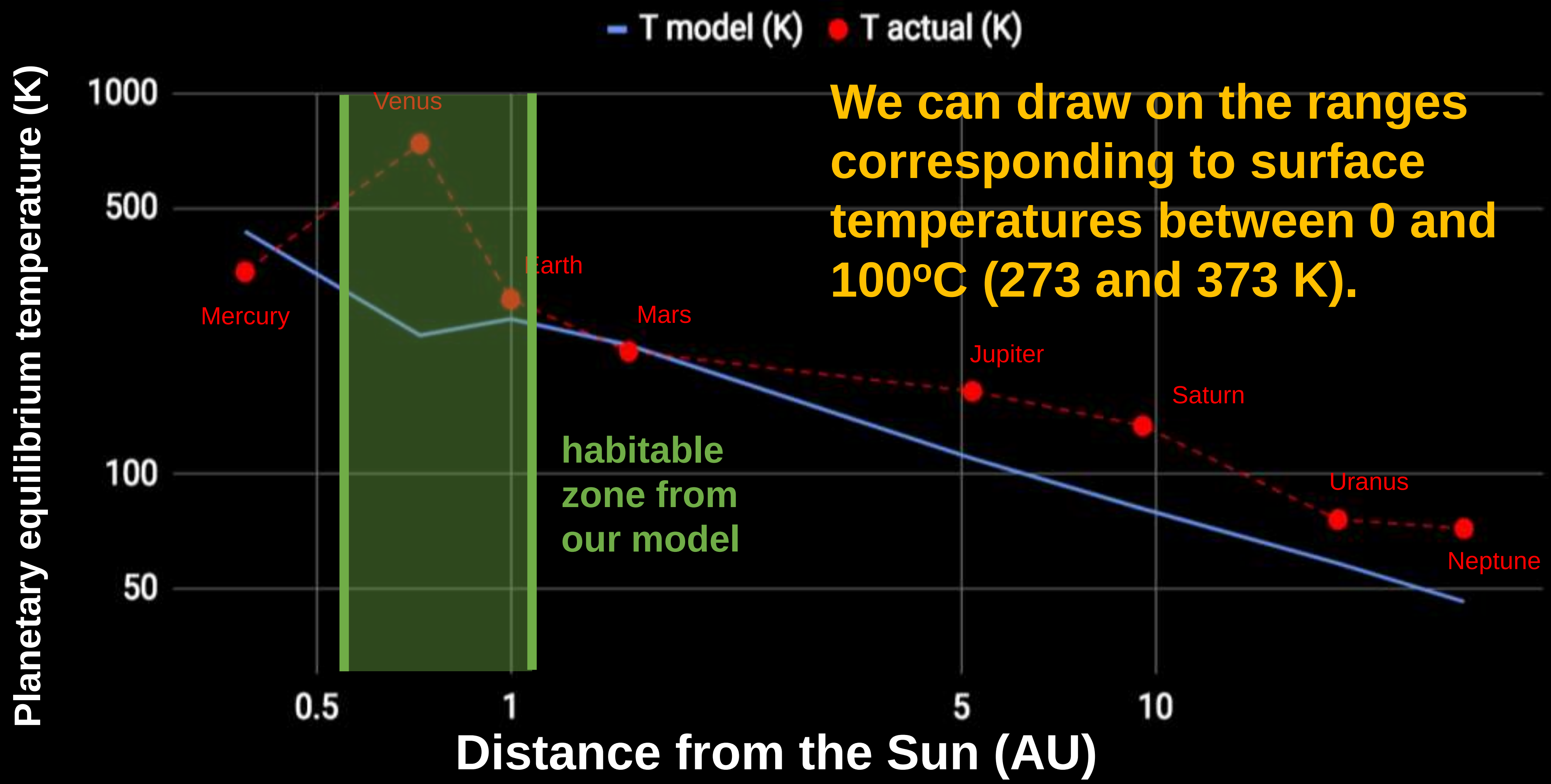
Planetary Model and Actual Mean Surface Temperatures
T actual (deg C)
T model (deg C)
500
250
0
-250
0
5
10
15
20
25
30
35
Planetary equilibrium temperature (°C)
Distance from the Sun (AU)
On this linear temperature scale, it is difficult to decide how closely the model agrees with the data

Planetary equilibrium temperatures for planets in our solar system

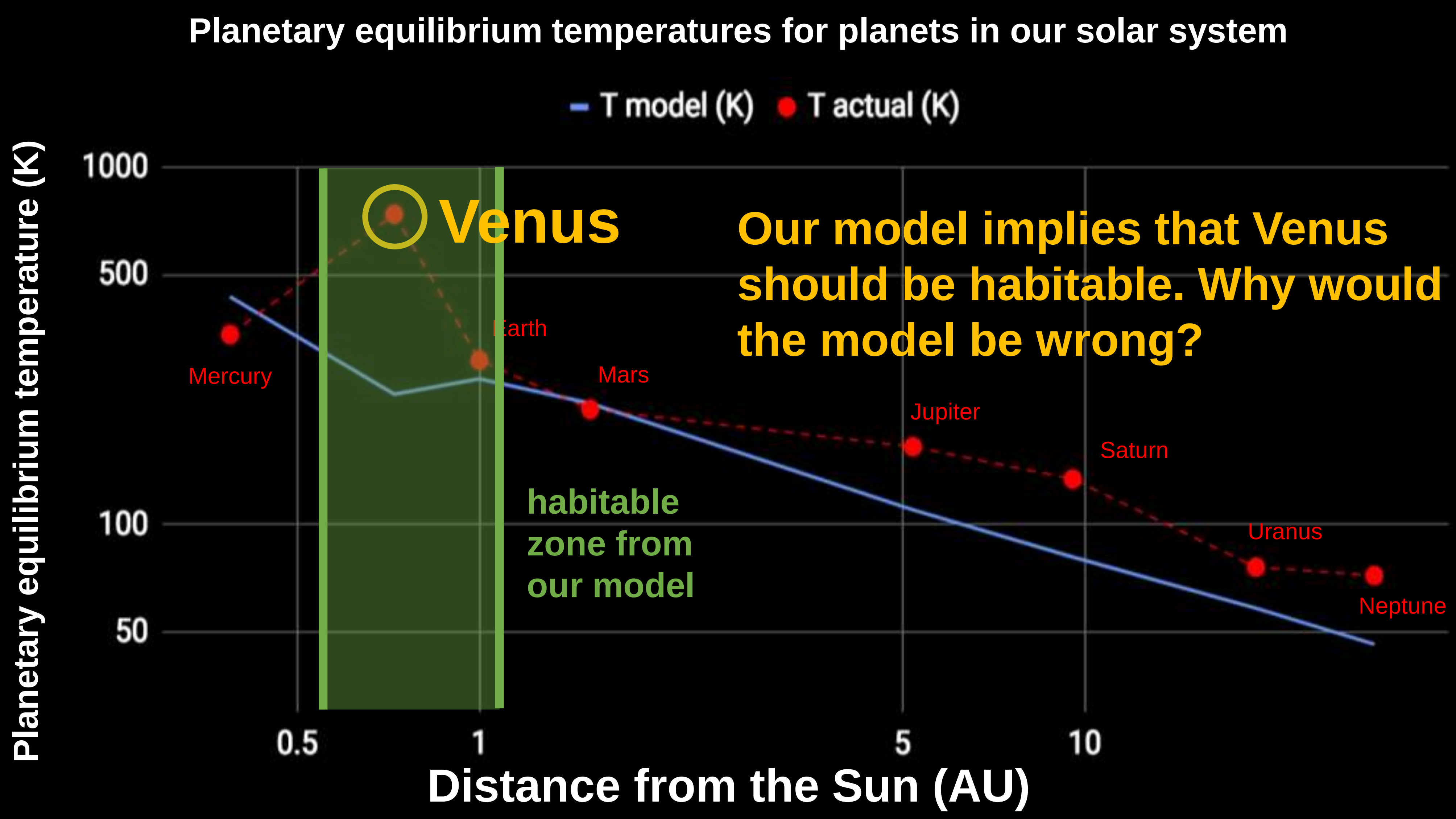


A logarithmic scale (in Kelvin) makes the differences more apparent.

Planetary equilibrium temperatures for planets in our solar system

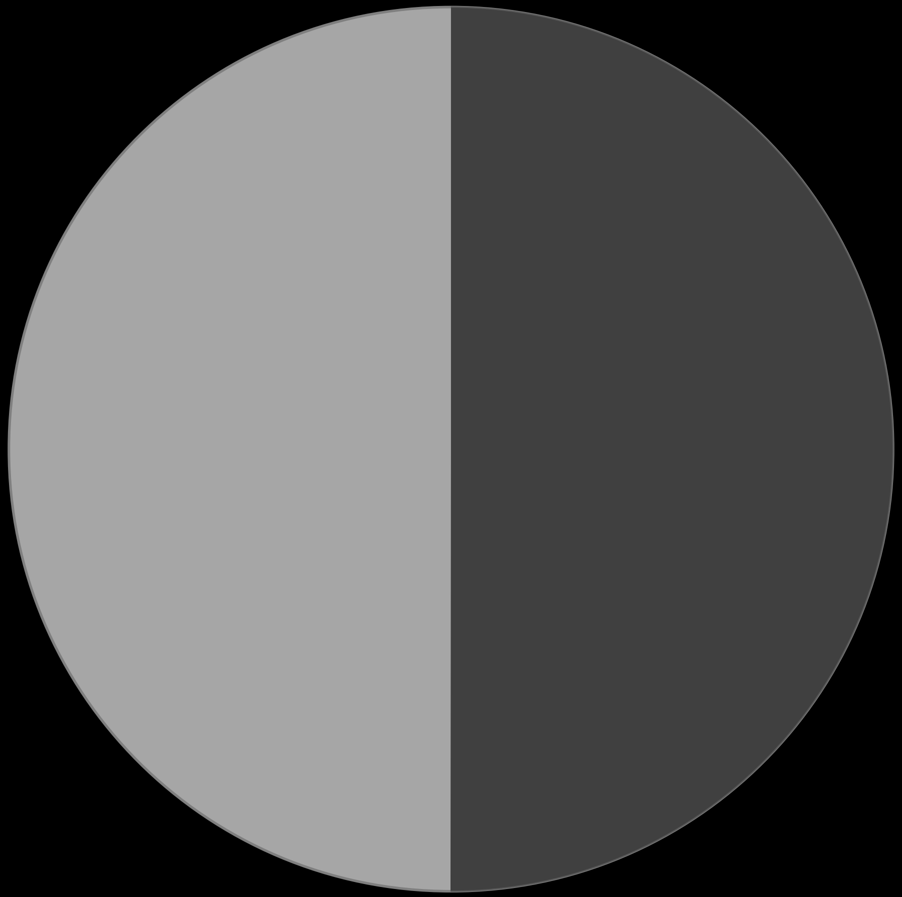


We can draw on the ranges corresponding to surface temperatures between 0 and 100ºC (273 and 373 K).


Planetary equilibrium temperatures for planets in our solar system
T model (K)
T actual (K)
Planetary equilibrium temperature (K)
1000
500
100
50
0.5
1
5
10
Distance from the Sun (AU)
Venus
Mercury
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
habitable zone from our model
Our model implies that Venus should be habitable. Why would the model be wrong?

Venus has an immensely thick CO_2 atmosphere which has caused a runaway greenhouse effect.

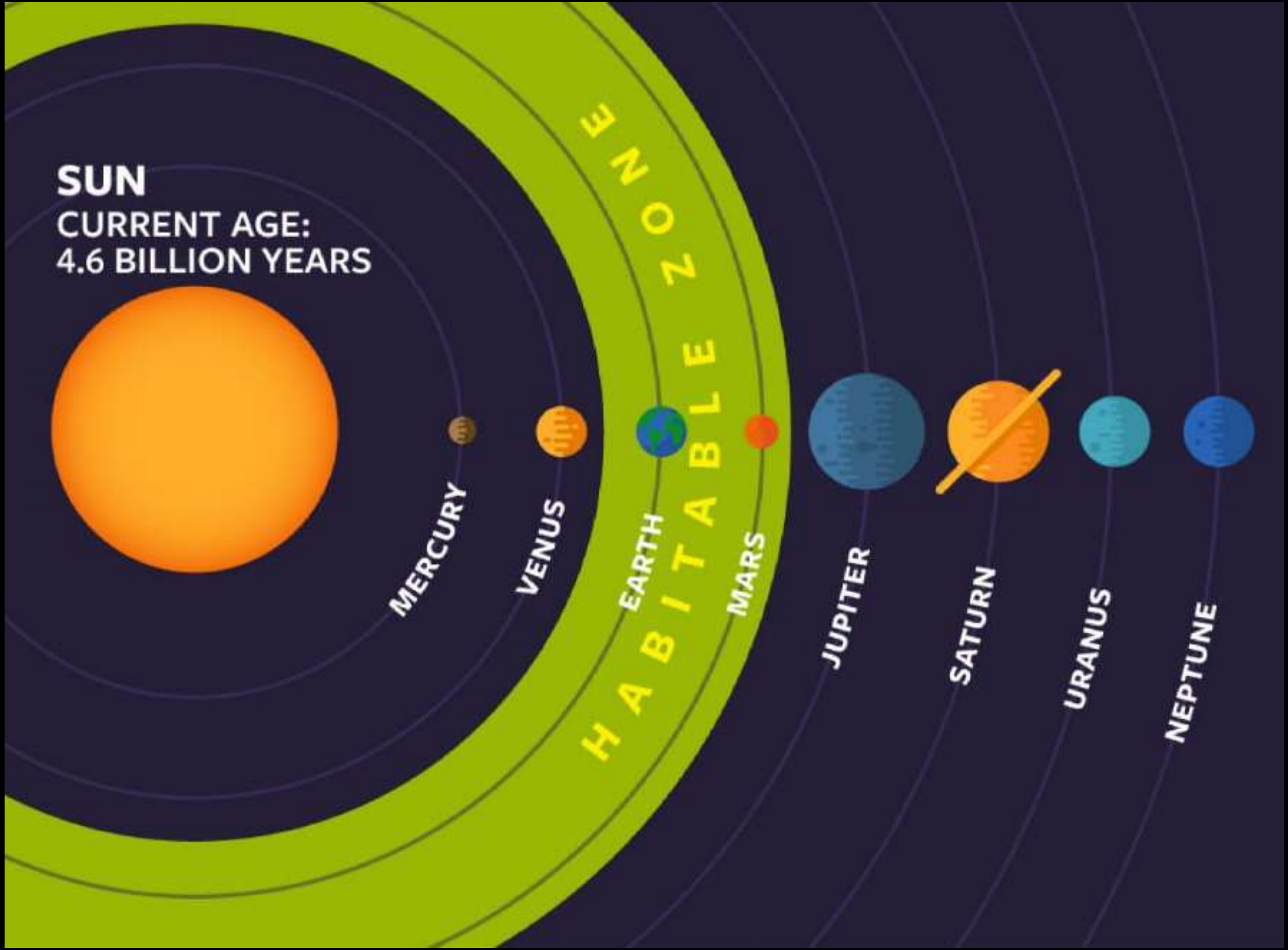
Credit: NASA



Our model ignored planetary atmospheres, except for a very approximate accounting via the albedo.

Modern attempts to define the **habitable zone** around a star try to account for atmospheric effects.

This is why, in textbooks, Venus is not in the HZ, but Mars sometimes is.



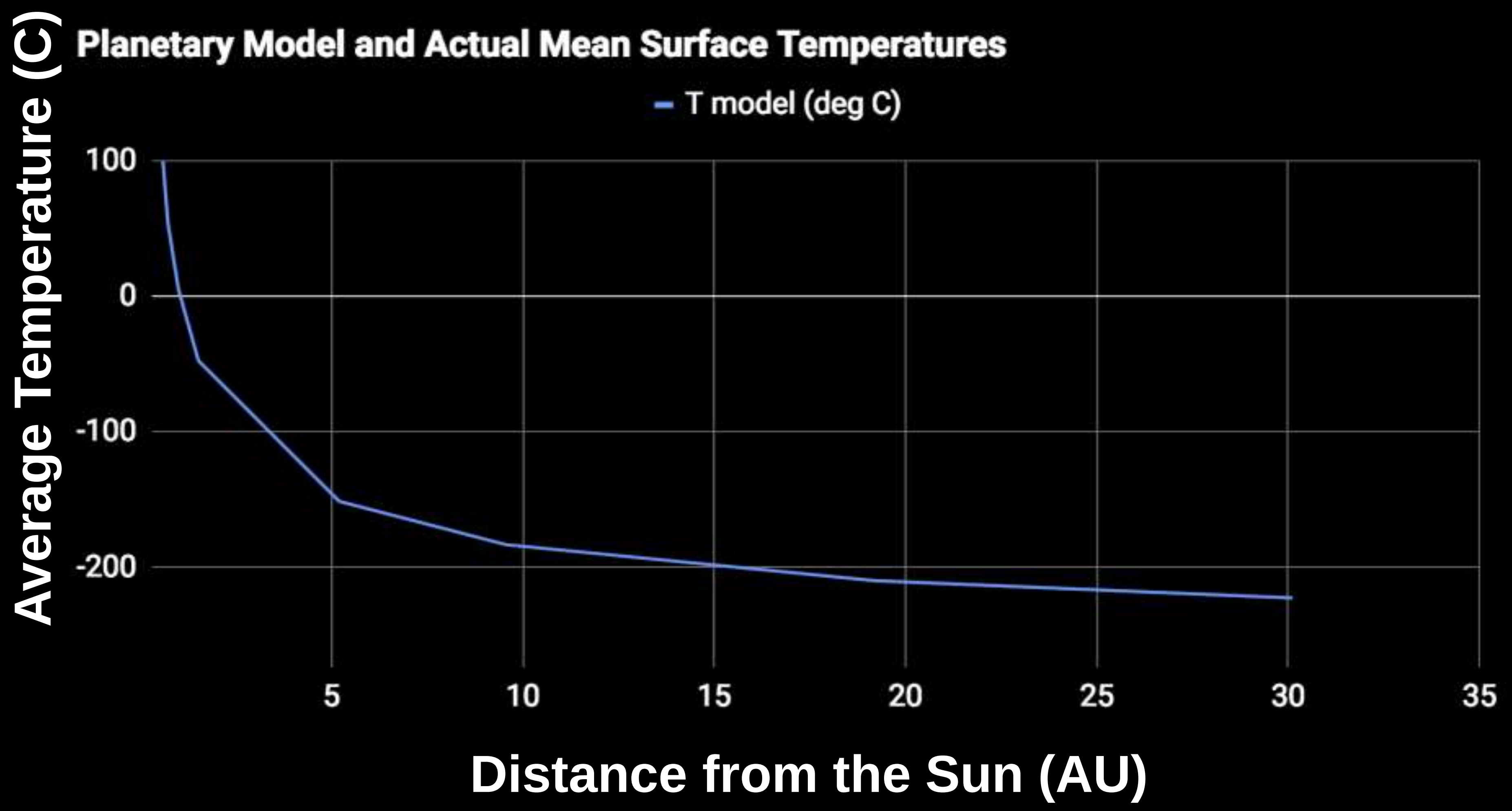
Credit: Carl Sagan Institute

Concept Check

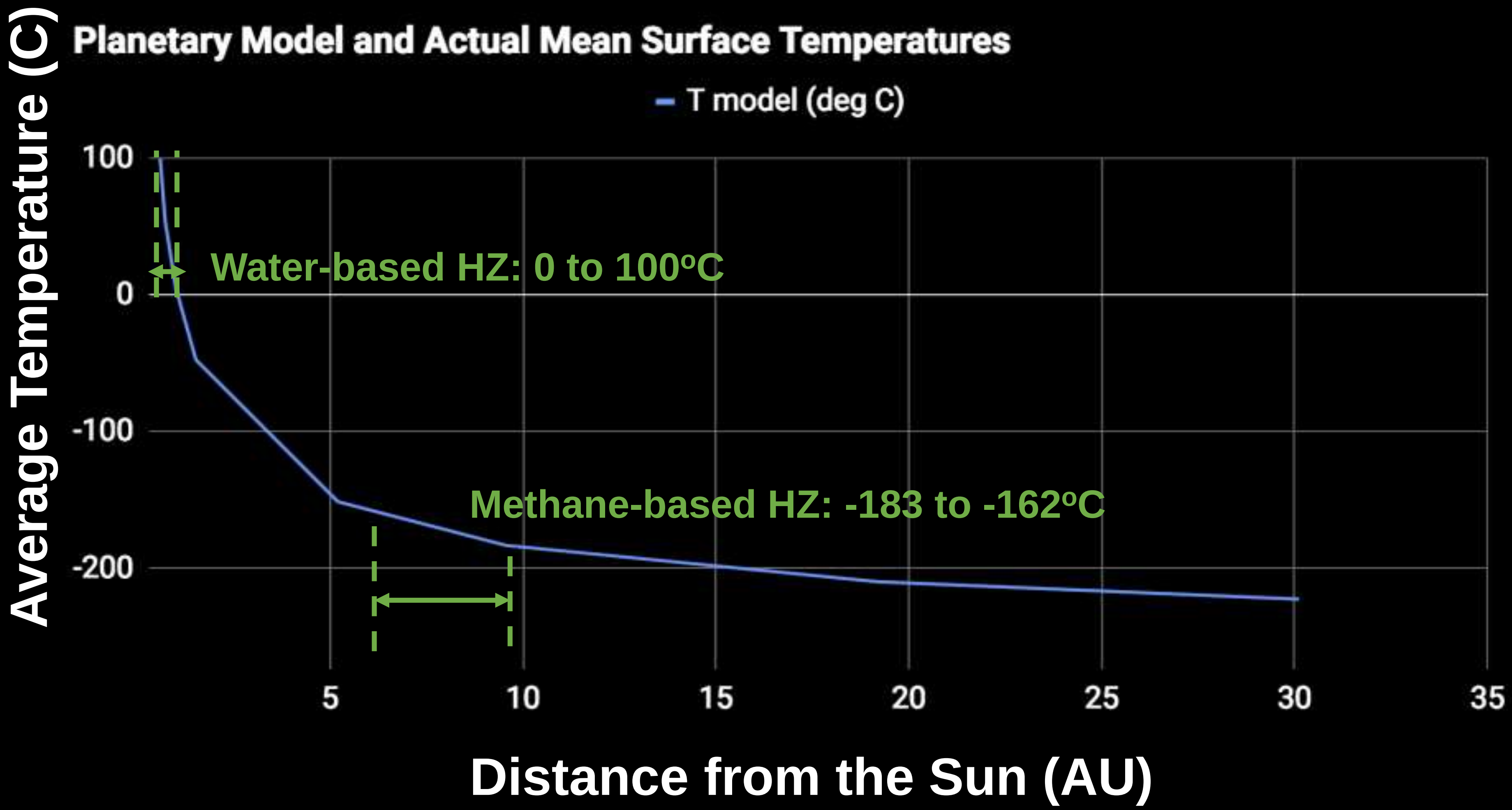
We have calculated a habitable zone for life that depends on water. How would the habitable zone change if we computed it for life based on methane, which has melting and boiling points of -183°C and -162°C?

Pause and try to sketch the result.

Concept Check



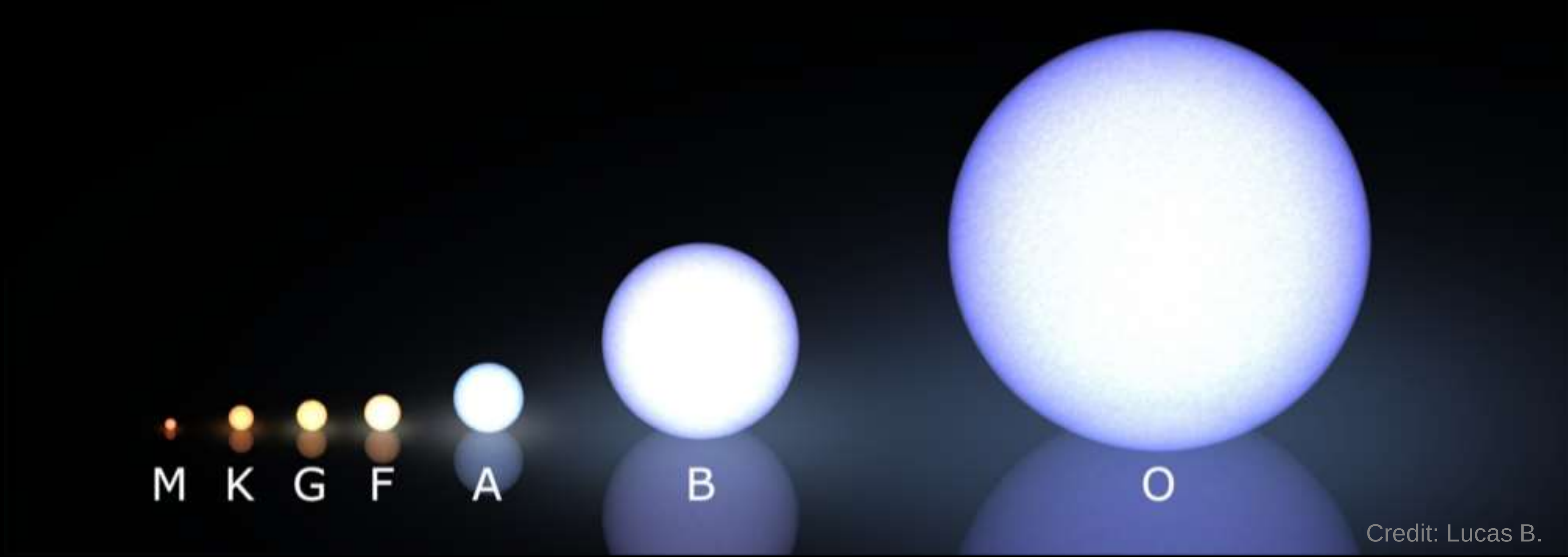
Concept Check



An Introduction to Stars

So far, we have been treating stars as generic sources of energy.

However, stars come in a wide variety of types, each of which affects the habitability of its planets differently.



Credit: Lucas B.

Our limited human vision makes it difficult to tell that stars come in a variety of colours.

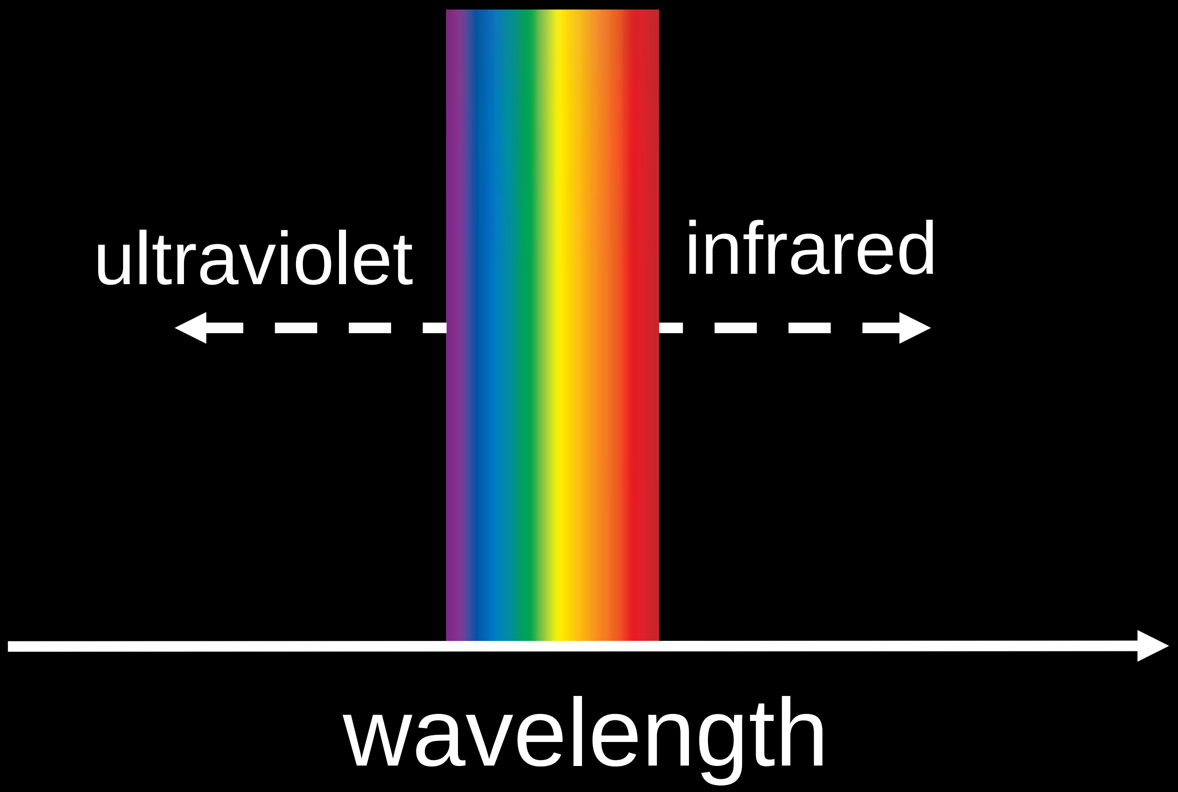
Credit: NASA/ESA

You can verify this with the unaided eye by looking at the constellation Orion

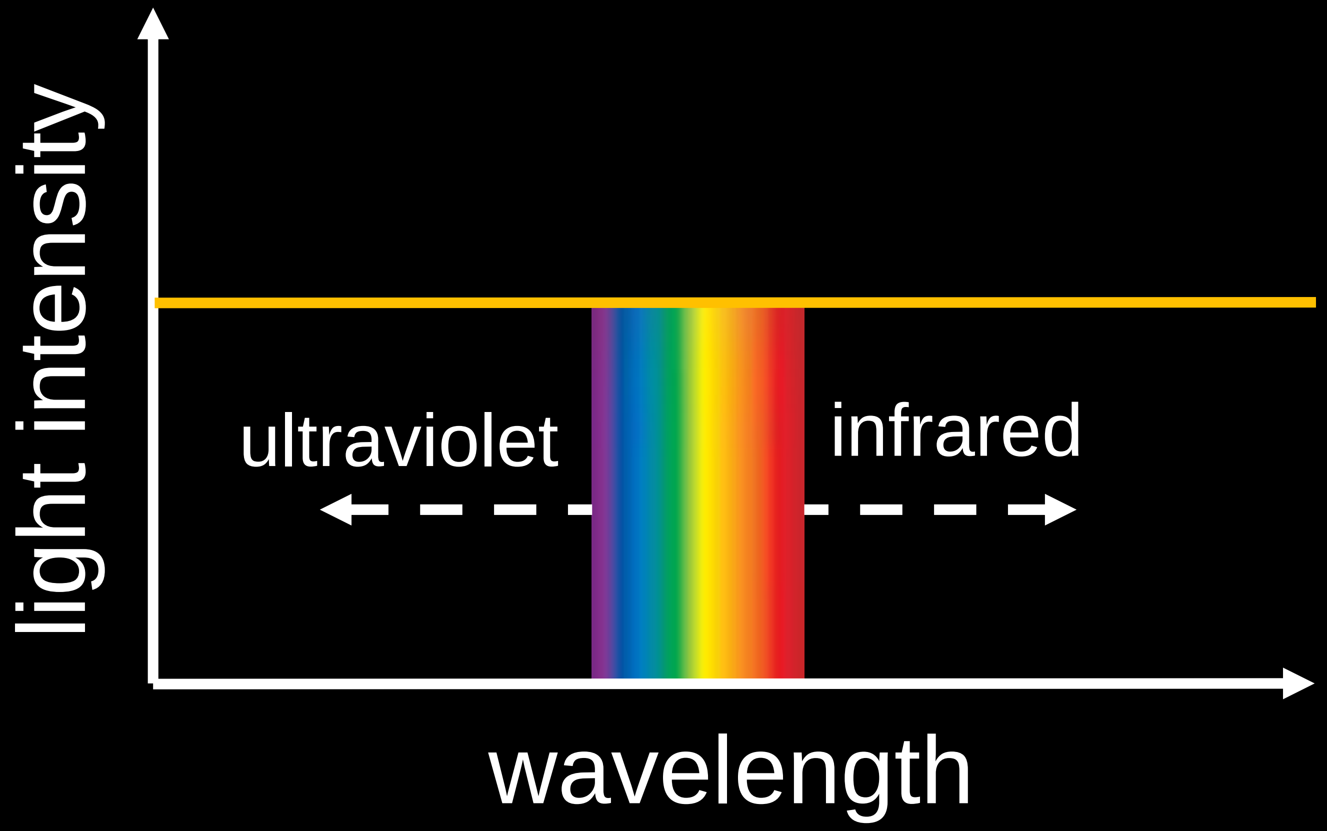
Credit: Matthew Spinelli

All stars emit light of all colours.

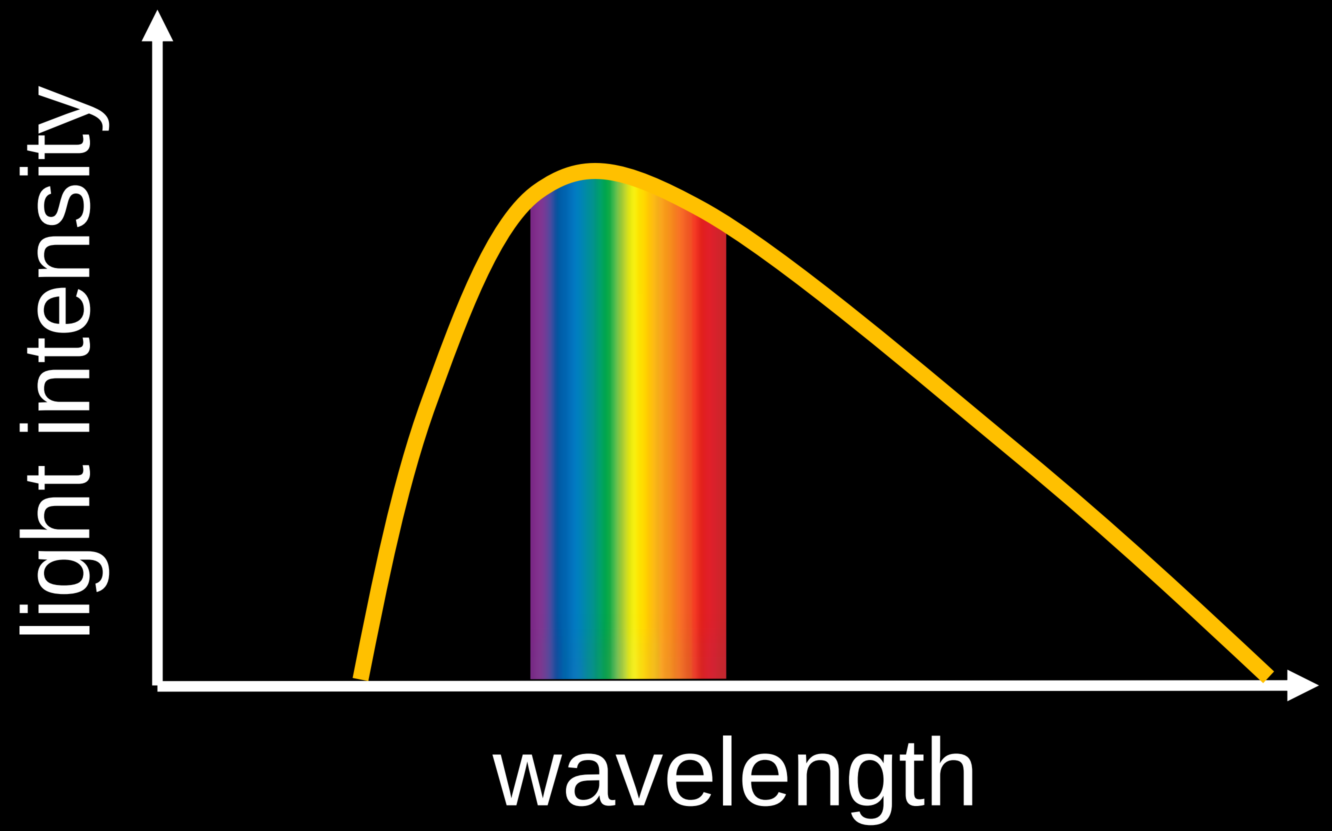
Which colours they emit the most of depends on their surface temperature.



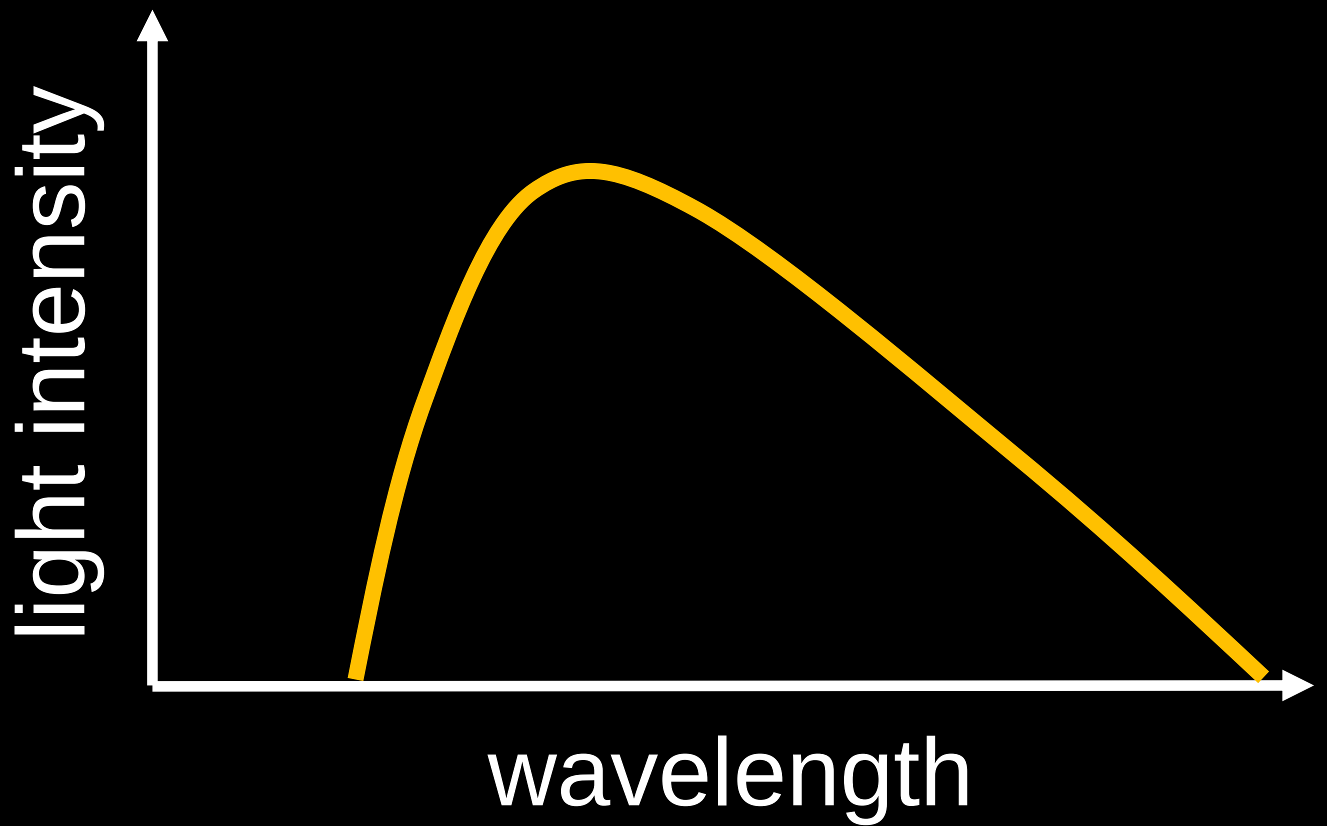
Visible light represents a small part of the electromagnetic spectrum.



All dense objects emit a continuous spectrum of light (that is, some light of every colour with no gaps).



However, real objects don’t emit equal quantities of all wavelengths.

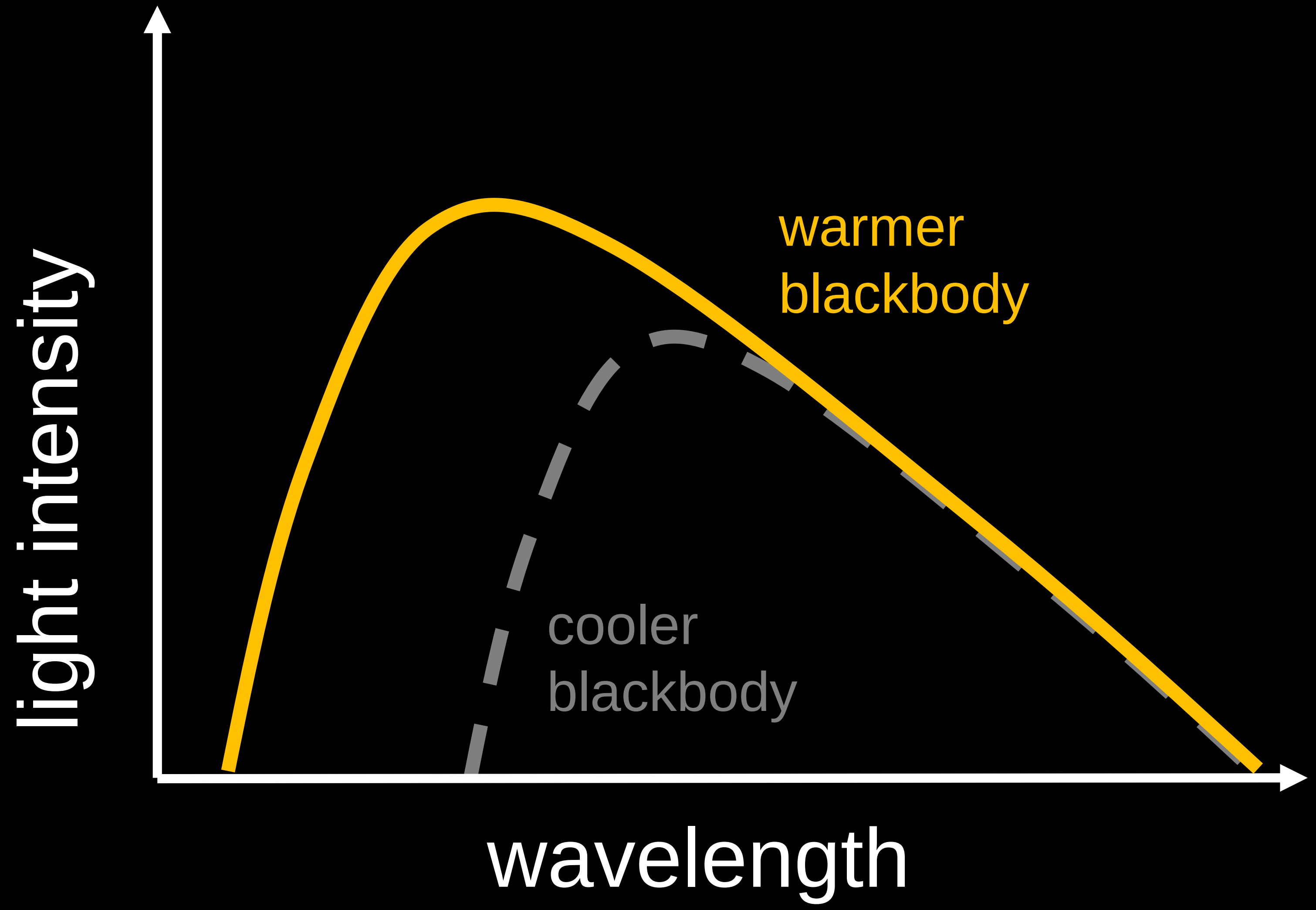


We call this curve the blackbody curve. It describes how any dense object (whether solid, liquid, or gas) emits light.

As you heat up a dense object (a "blackbody") it emits:

1. more light overall

2. a higher fraction of that light at shorter wavelengths



In the late 1800s, when astronomers were first recording spectra of stars, they didn't understand why the spectra looked the way they did.

They put them into alphabetic categories: A, B, C, D, etc.

Credit: NOAO/AURA/NSF

Astronomer Annie Jump Cannon personally studied more than 200,000 spectra. She removed many categories and reordered the rest: OBAFGKM

Credit: Smithsonian Institution Archives

O B A F G K M

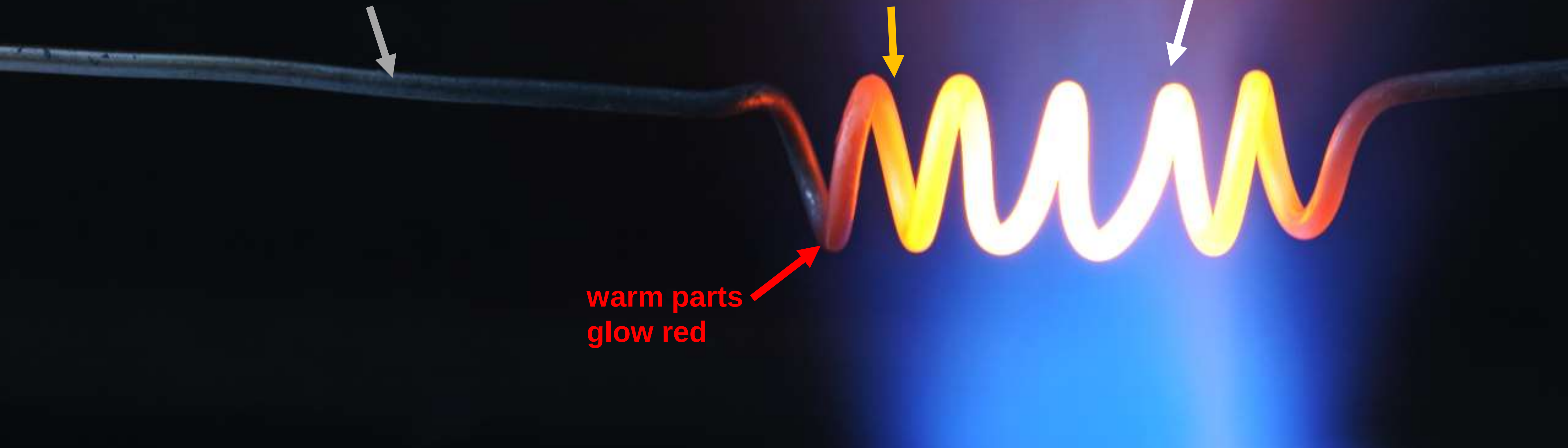
O B A F G K M

Stellar spectral types

Only **B**ungling
Astronomers **F**orget
Generally **K**nown
Mnemonics

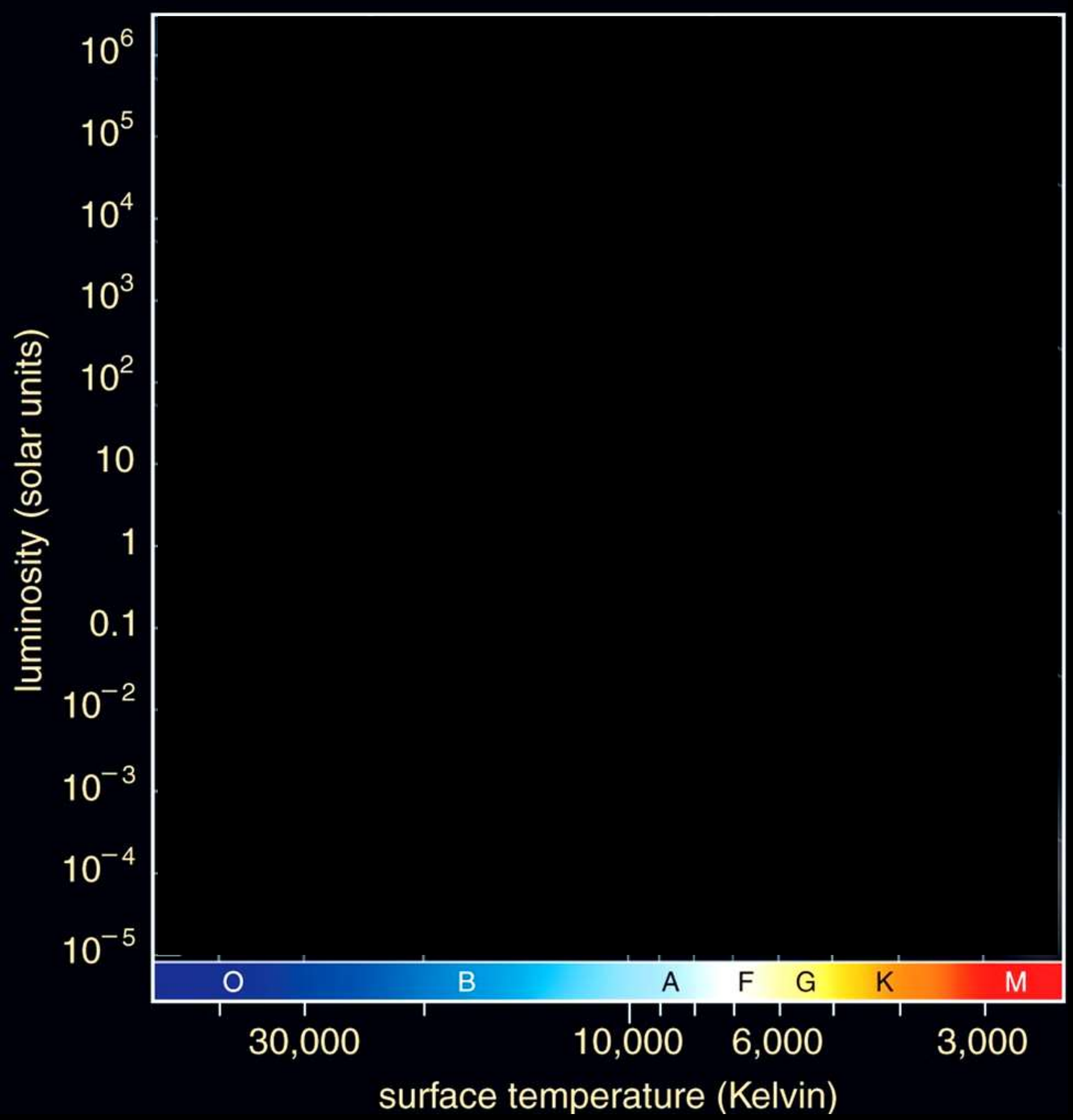
Because stars are blackbodies, their colours are entirely determined by their surface temperatures.

Heating up dense objects, such as this wire, causes them to turn first red, then orange, then yellow, then white, and finally blue. (the blue flame is caused by a different effect)



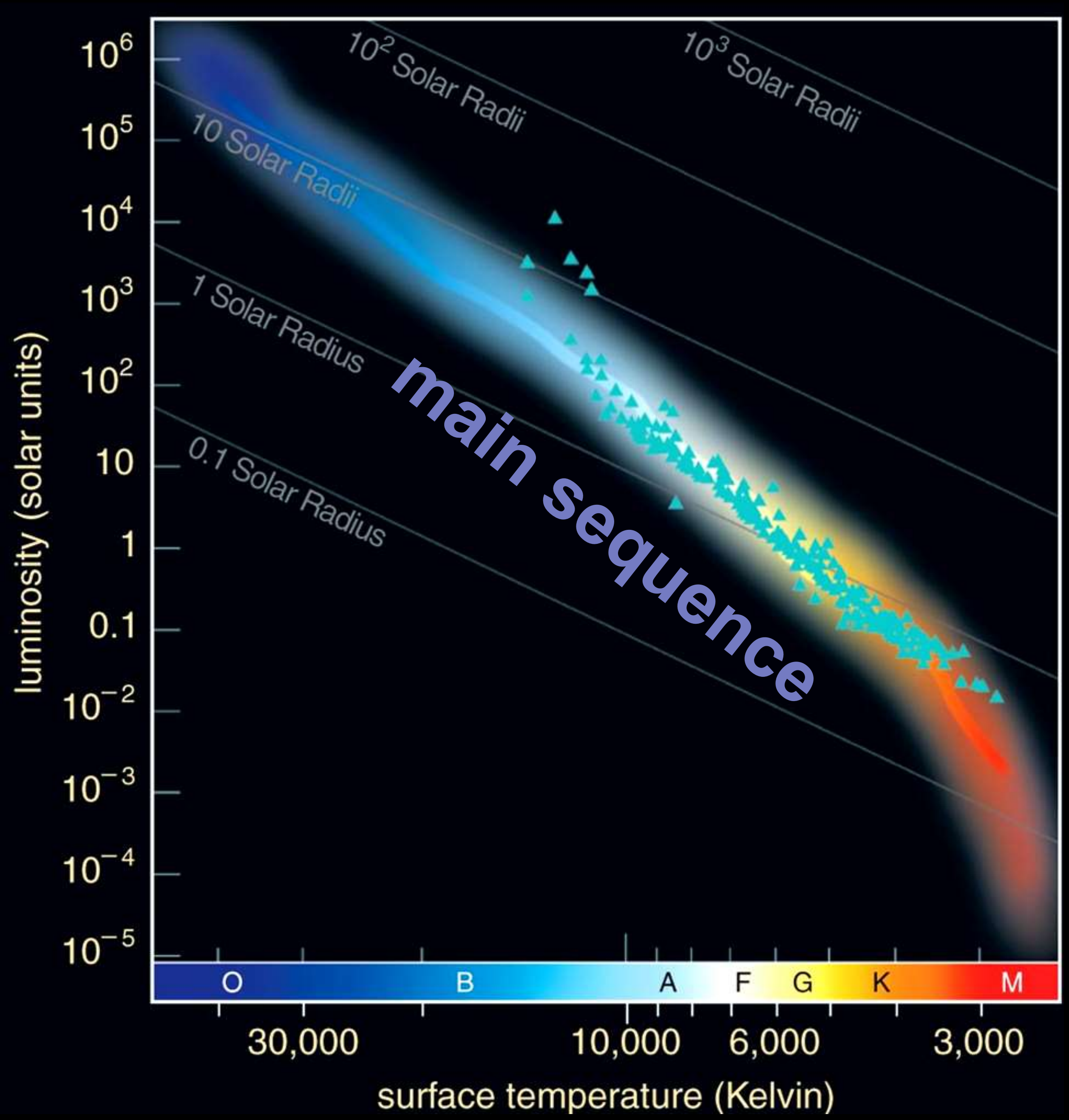
O	B	A	F	G	K	M
>30,000 K	20,000 K	8500 K	6500 K	5500 K	4000 K	3000 K

If we plot temperature (or spectral type, or colour) vs. luminosity, we find that stars naturally form groups.



The axes for a Hertzsprung-Russell or HR diagram

Credit: Pearson Education

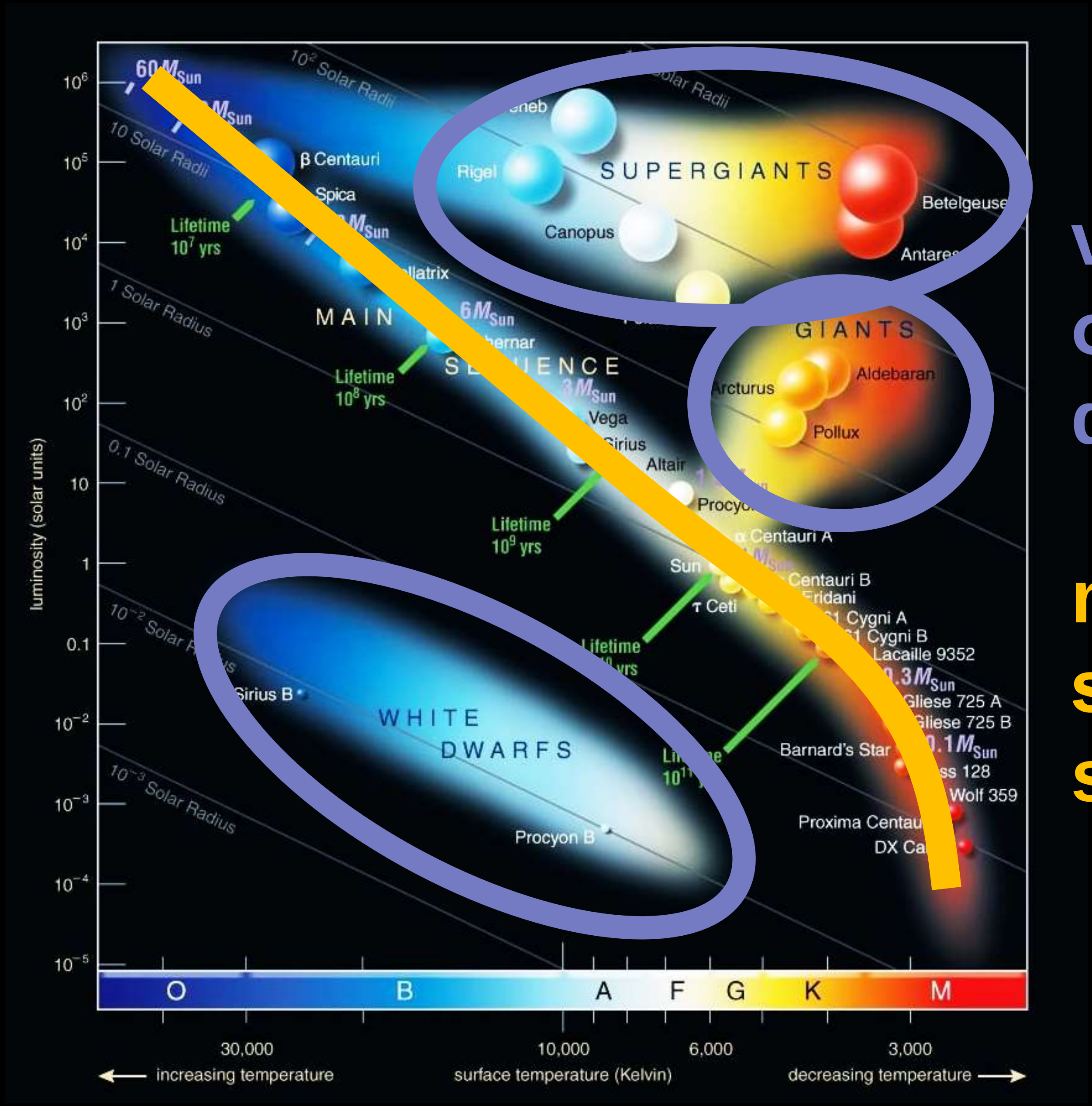


The band of stars through the middle of the diagram is called the **main sequence**

Credit: Pearson Education

Main sequence stars are those that are still fusing hydrogen in their cores.

We say they are “alive”, but we don’t mean this literally.



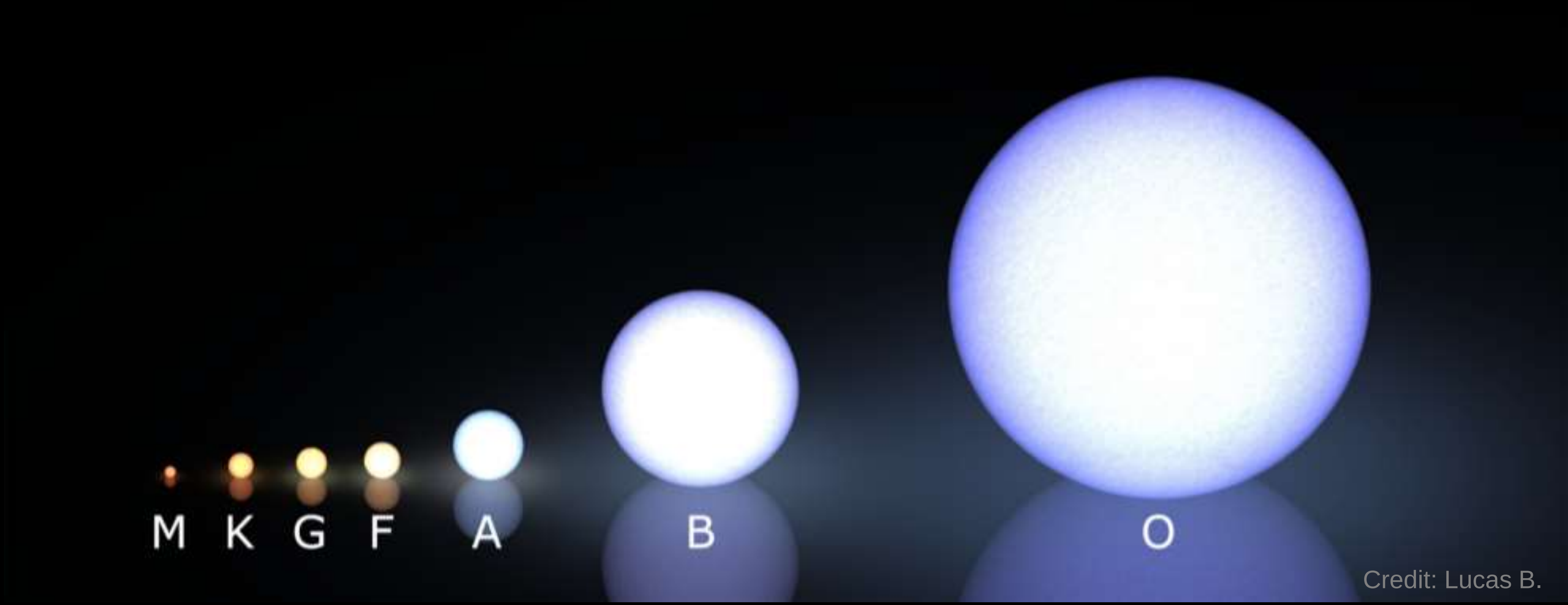
various groups of "dead" or dying stars

main sequence stars ("living" stars)

Credit: Pearson Education

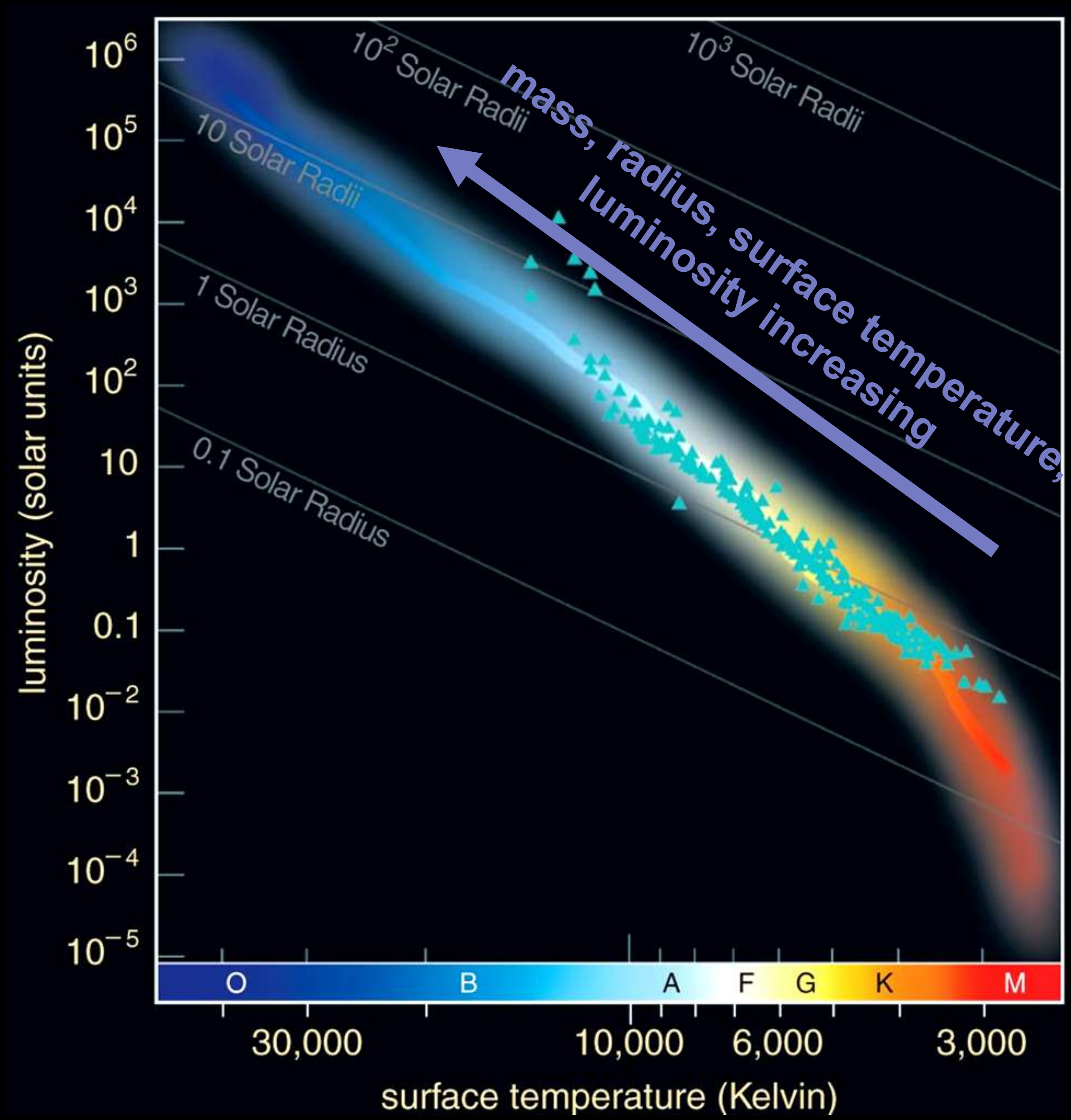
Note that, *on the main sequence*, all blue stars are large and luminous while all red stars are small and dim.

(This ONLY applies to main-sequence stars. Dying or dead stars can be large and red or small and blue.)



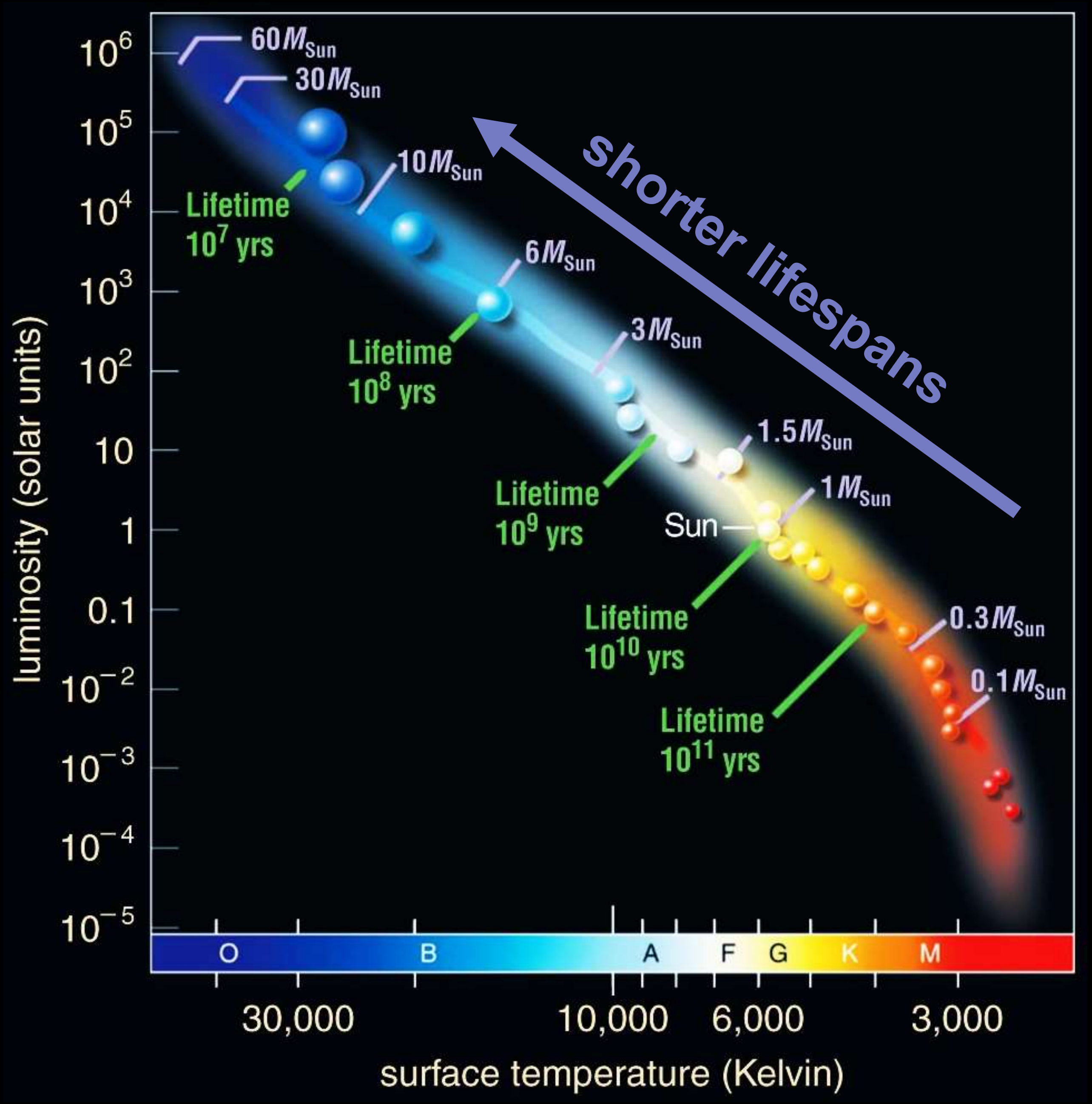
Credit: Lucas B.

Along the main sequence, the mass, radius, surface temperature, and luminosity of stars increase as we move from M to O.



Credit: Pearson Education

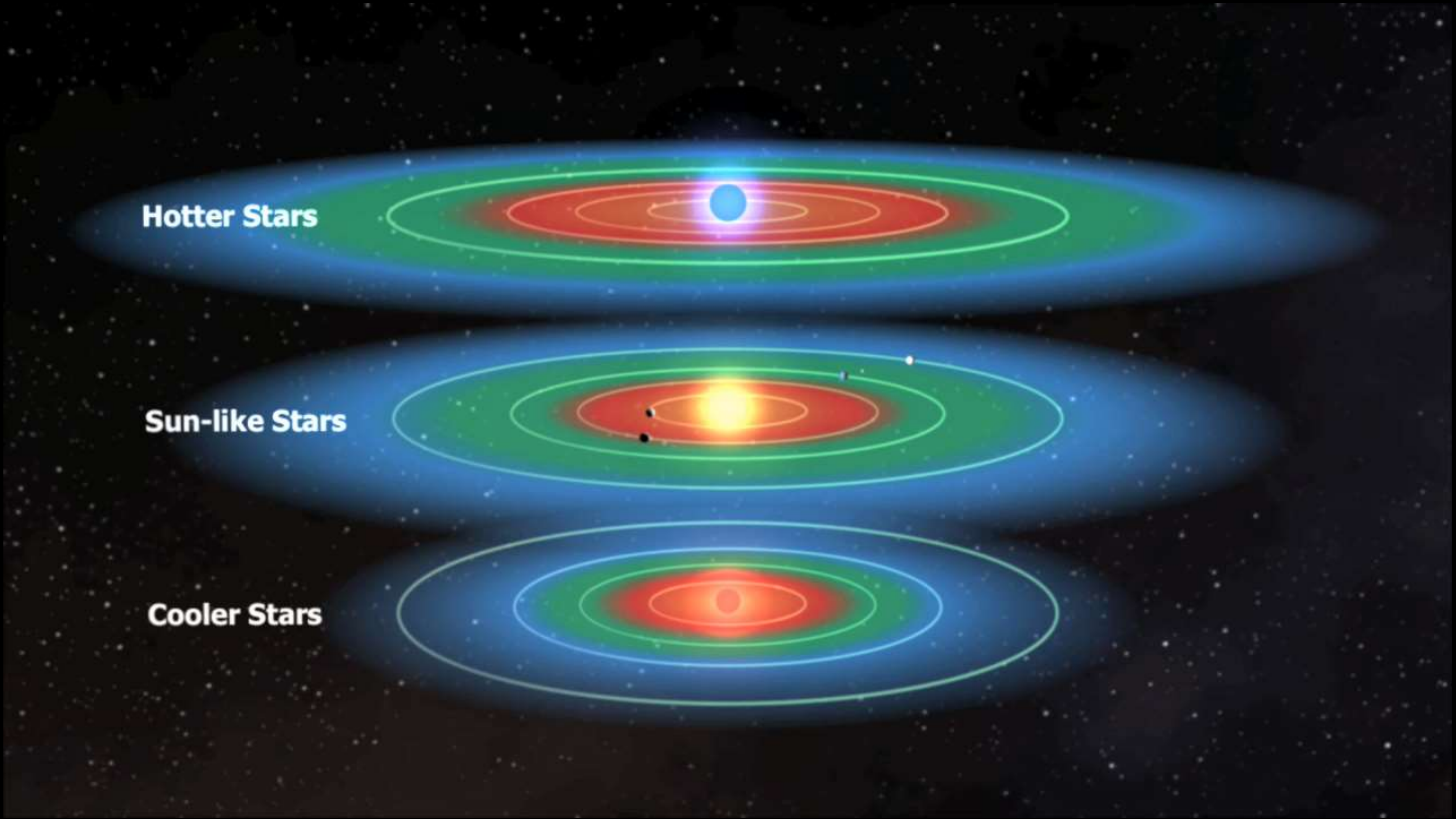
Their total lifespans decrease in that same direction because more massive stars burn their fuel at a very high rate—more than enough to offset that they have more fuel to burn.



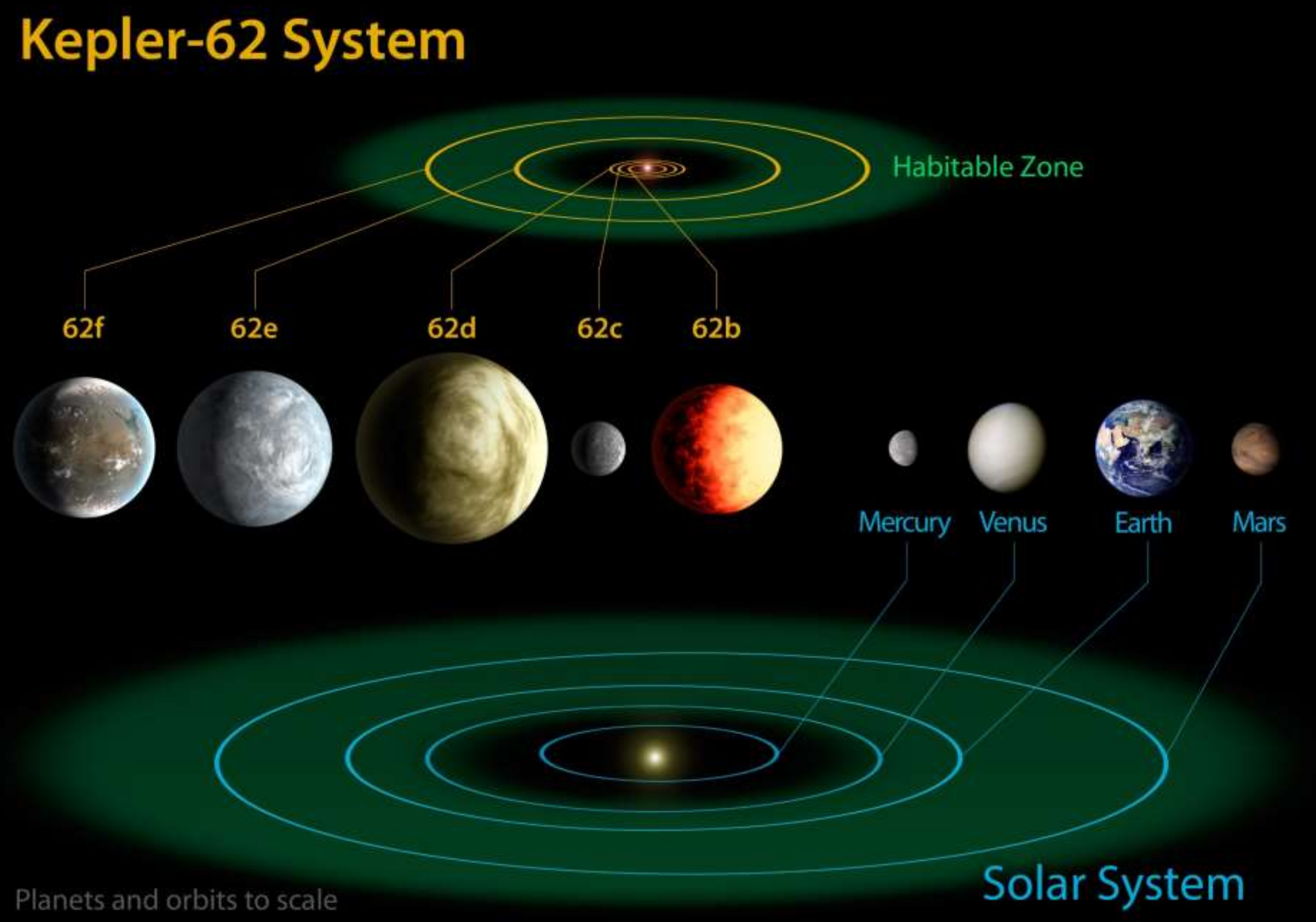
Credit: Pearson Education

The Effect of Stars on Planetary Habitability

How does the nature of the star a planet orbits affect the habitability of that planet?

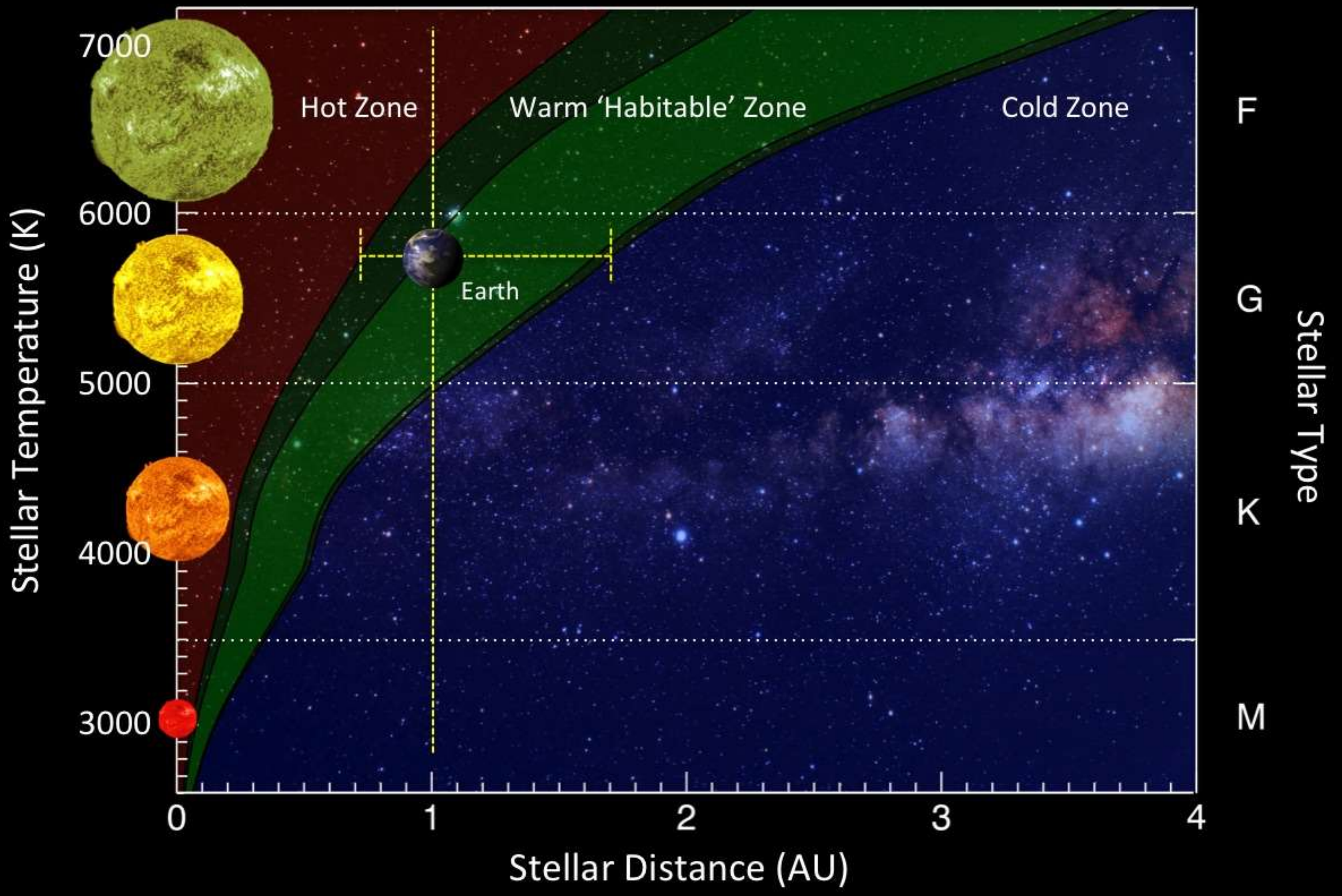


Credit: NASA



Kepler-62 System
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale

Habitable Zone of Main Sequence Stars



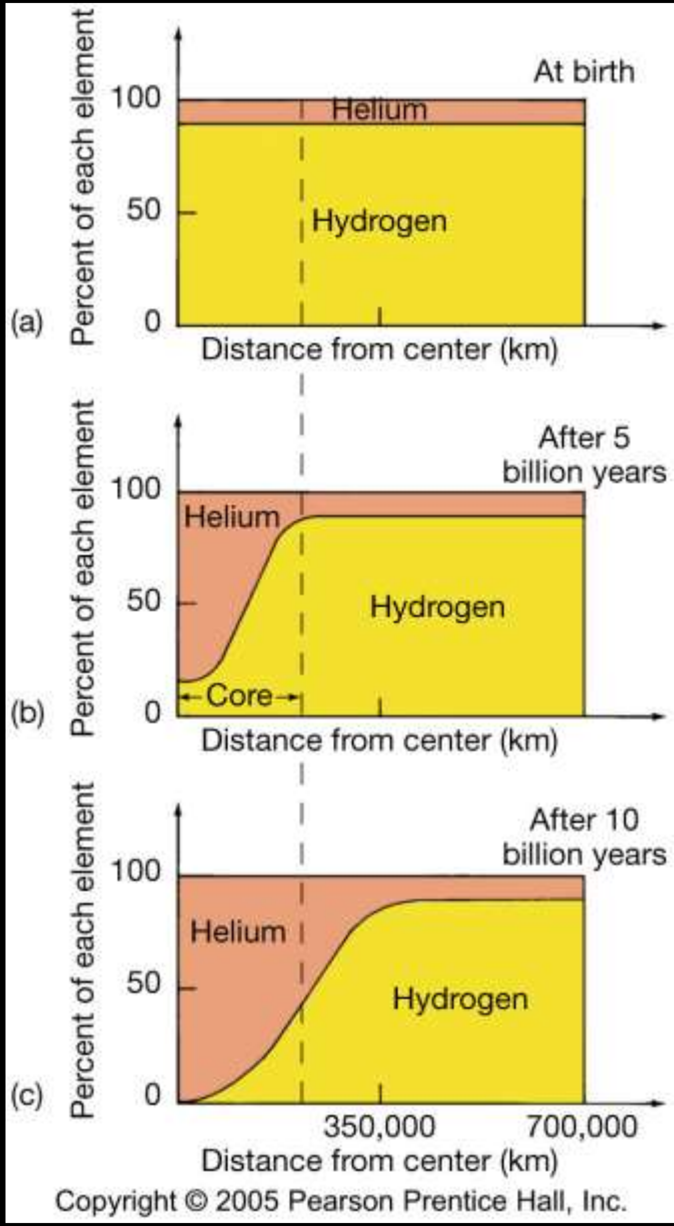
CREDIT: PHL @ UPR Arecibo

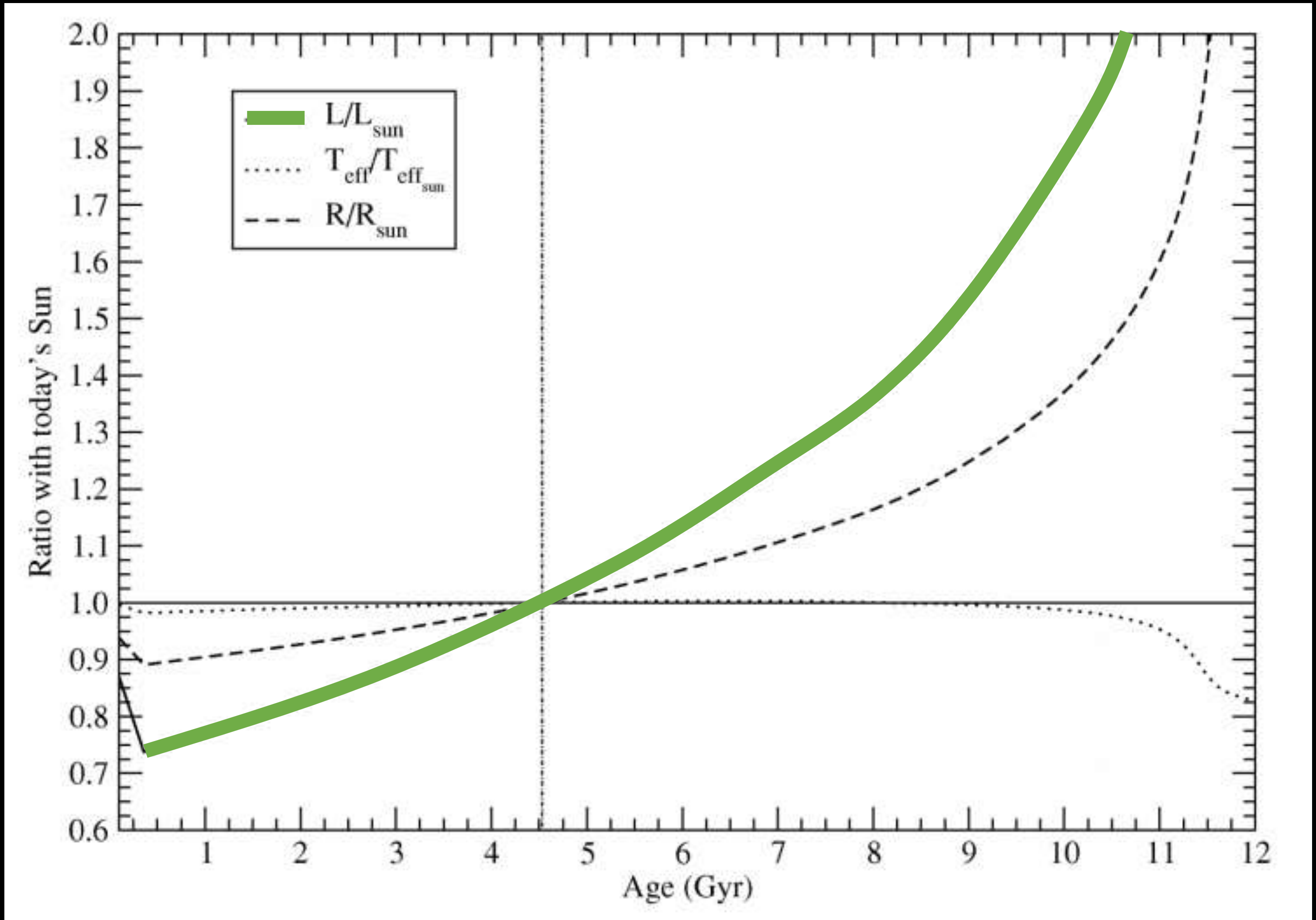
So, our first conclusion is that the location and width of the habitable zone varies with stellar spectral type.

How is the lifespan of a star related to the habitability of its planets?

Main sequence stars produce energy by fusing hydrogen in their cores.

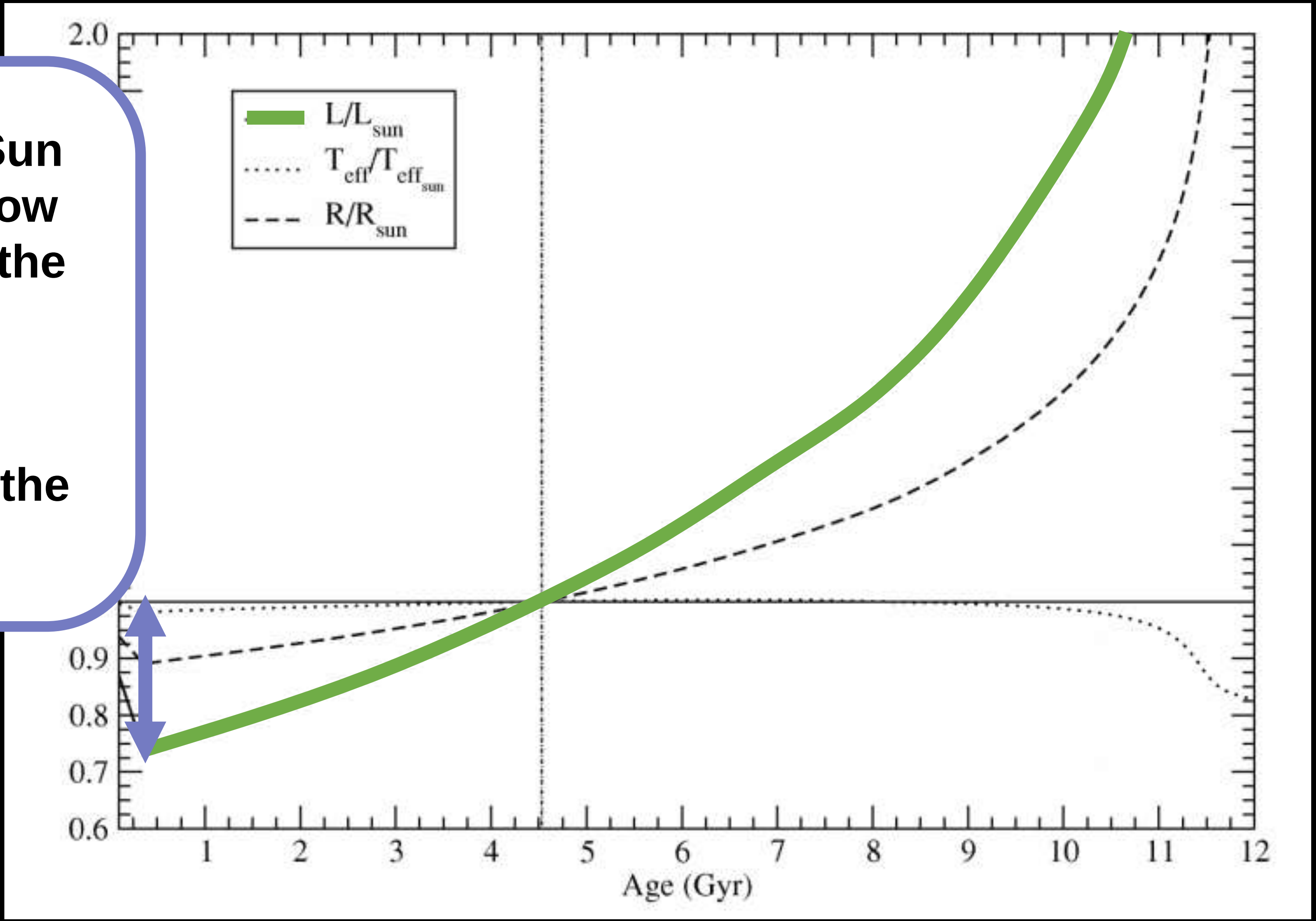
Stars of spectral class G, like the Sun, will run out of core hydrogen about 10 Gy after they form.





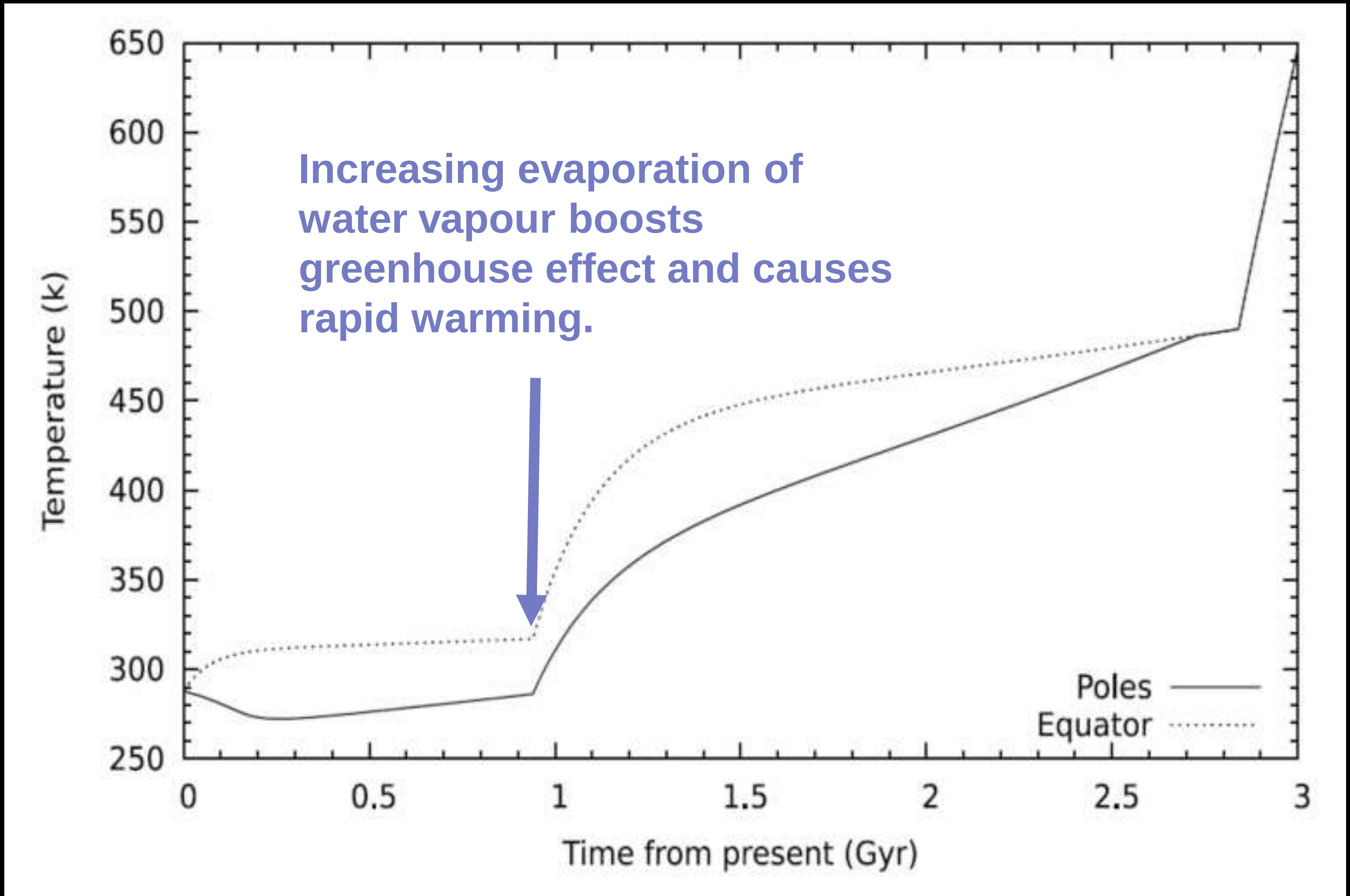
As the Sun ages, its luminosity is slowly rising. (Ribas, 2010)

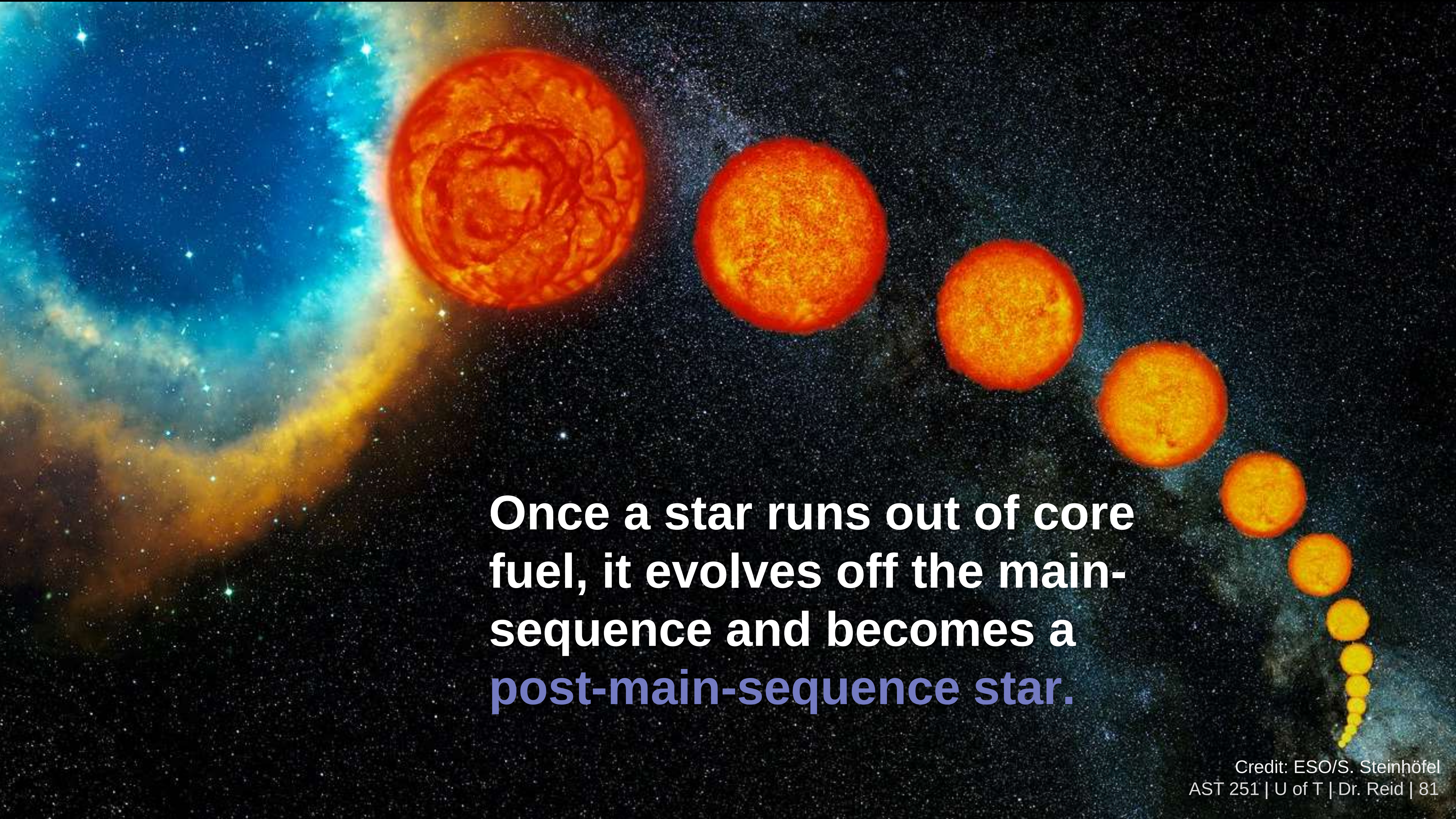
Aside: **the luminosity of the Sun billions of years ago was as low as 70% its present value, yet the geologic record is clear that Earth was warm enough to sustain liquid water and eventually, life. This is called the Faint Young Sun paradox.**



As the Sun ages, its luminosity is slowly rising. (Ribas, 2010)

The Sun's rising luminosity will probably render Earth uninhabitable to complex life within about a billion years. (O'Malley-James et al., 2013)



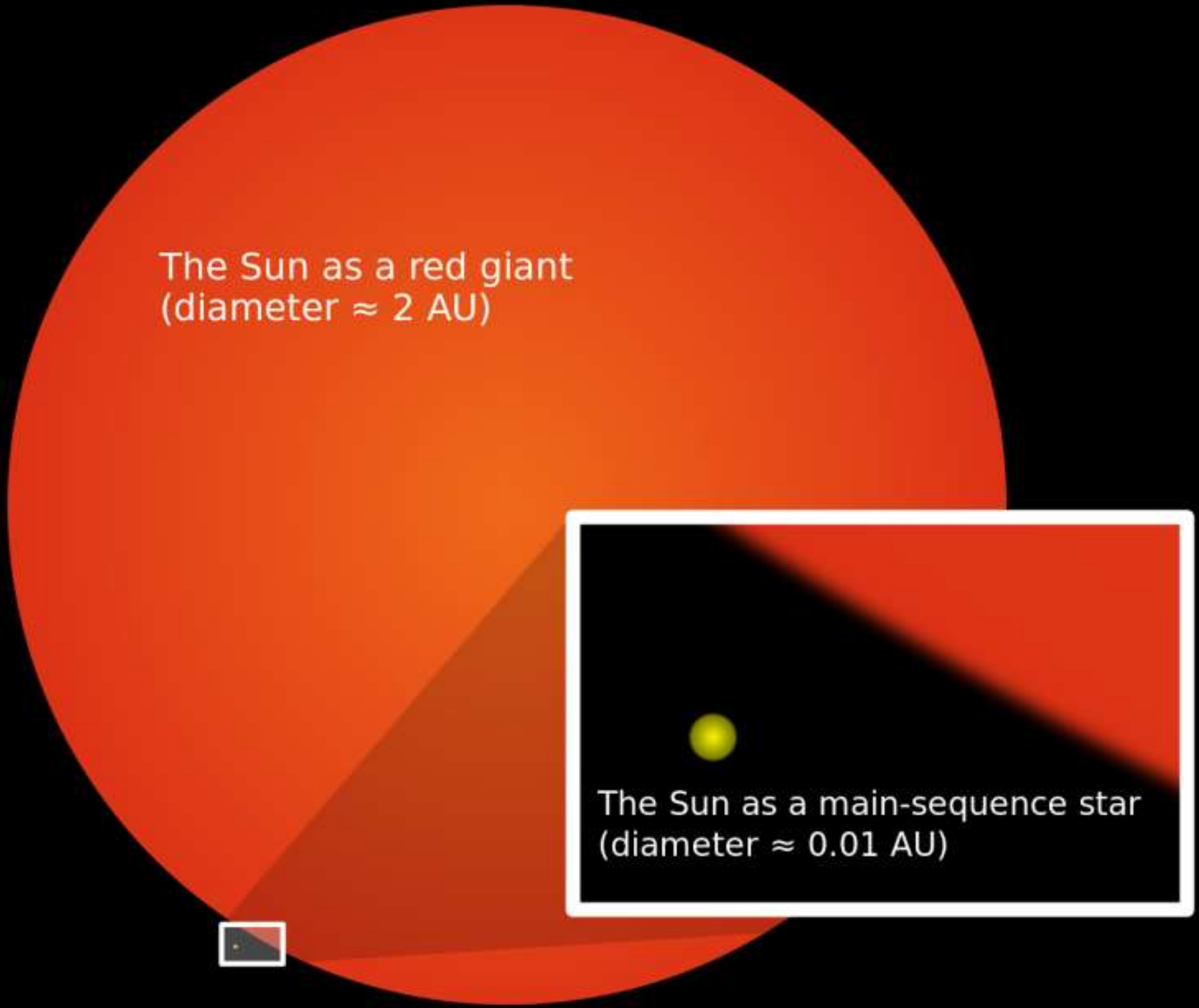


Once a star runs out of core fuel, it evolves off the main-sequence and becomes a post-main-sequence star.

Credit: ESO/S. Steinhöfel

Post main sequence stellar evolution is very complex, so we will greatly simplify it.

Low-mass stars (those < 8 $M_{\odot}$, classes M-A) expand to become red giants before ejecting their outer layers to form confusingly named "planetary nebulae", then shrinking to become white dwarfs.



Credit: Wikimedia Commons; Oona Räisänen

The Helix Nebula, a planetary nebula left over after the death of a low-mass star.

Credit: NASA, NOAO, ESA, the Hubble Helix Nebula Team, M. Meixner (STScI), and T.A. Rector (NRAO)

The transition from red giant to white dwarf + planetary nebula is not an explosion.

Low-mass stars do not explode when they die.

Massive stars (those > 8 $M_{\odot}$, including all O stars and some B stars) also become red giants but then they DO explode as supernovae.

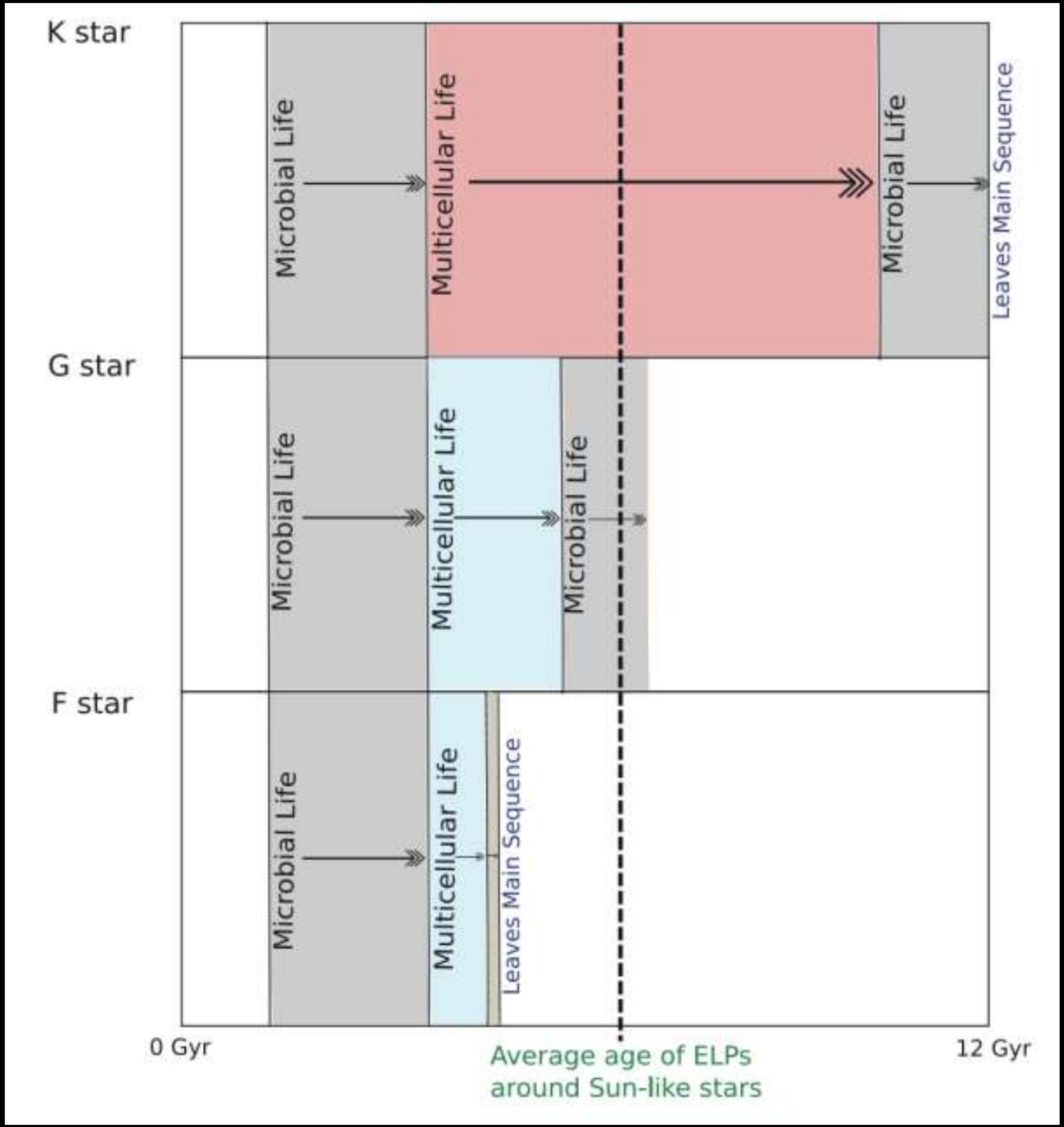
www.eso.org

As a star approaches the red giant stage, rising luminosity would likely cause a runaway greenhouse effect on its planets, rendering them uninhabitable.

Ultimately, a planet’s atmosphere could evaporate into space or the planet itself could be engulfed by its parent star.

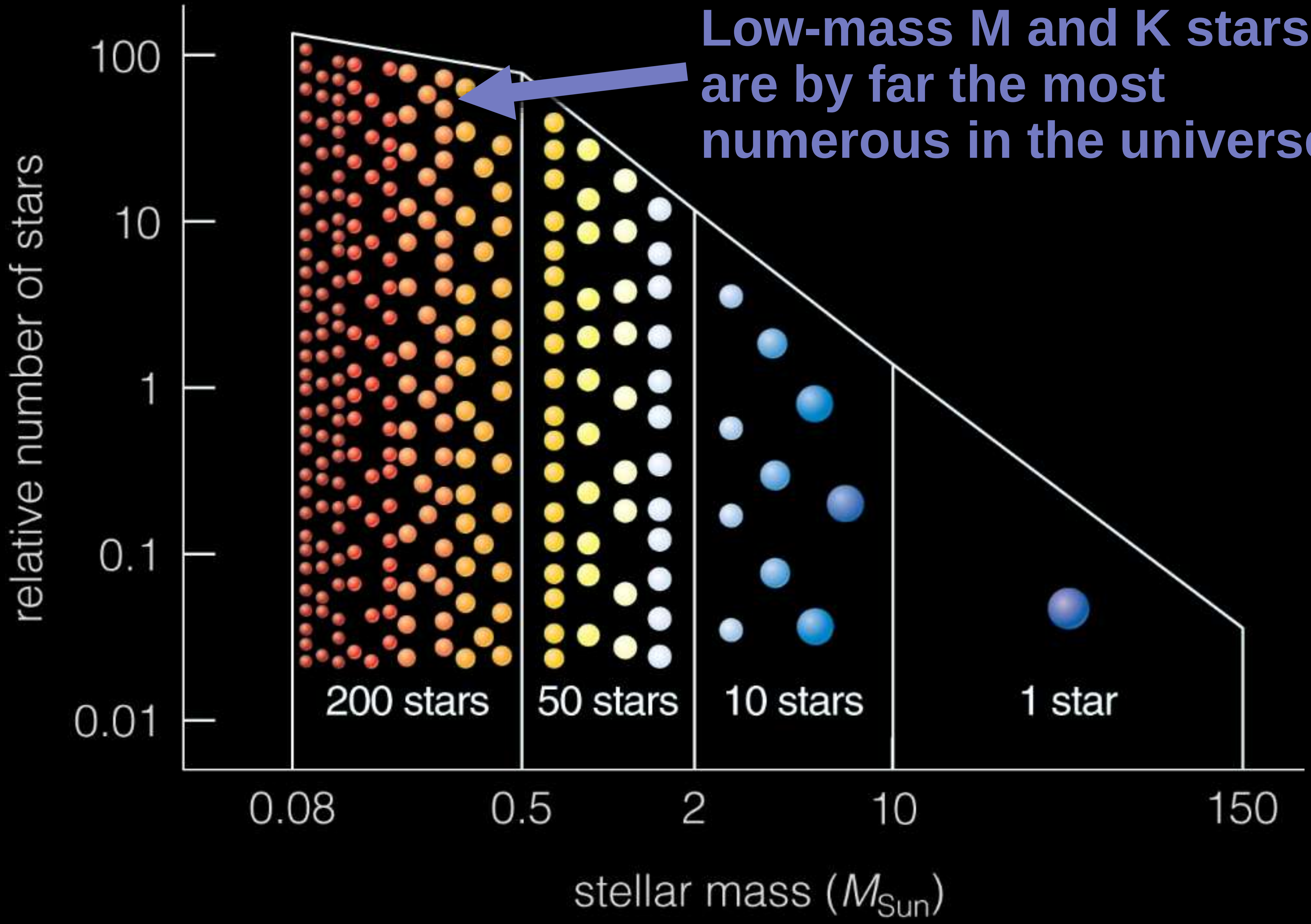
Credit: David A. Aguilar (CfA)

In principle, complex life could endure much longer on planets orbiting long-lived cool stars, such as M and K stars.

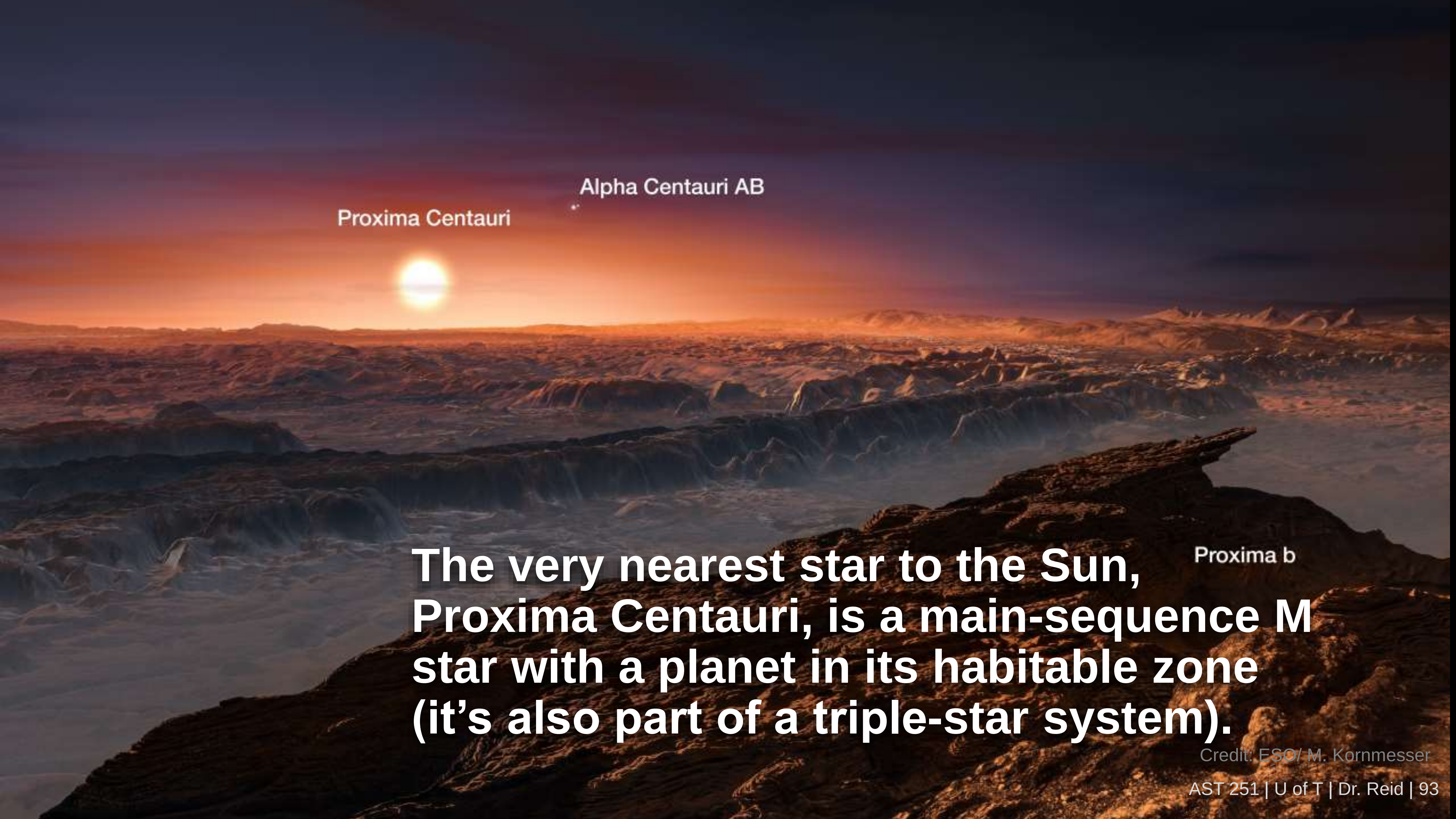


Credit: O’Malley-James et al., 2013

Low-mass M and K stars are by far the most numerous in the universe



Credit: Pearson Education



The very nearest star to the Sun, Proxima Centauri, is a main-sequence M star with a planet in its habitable zone (it's also part of a triple-star system).

Credit: ESO/ M. Kornmesser

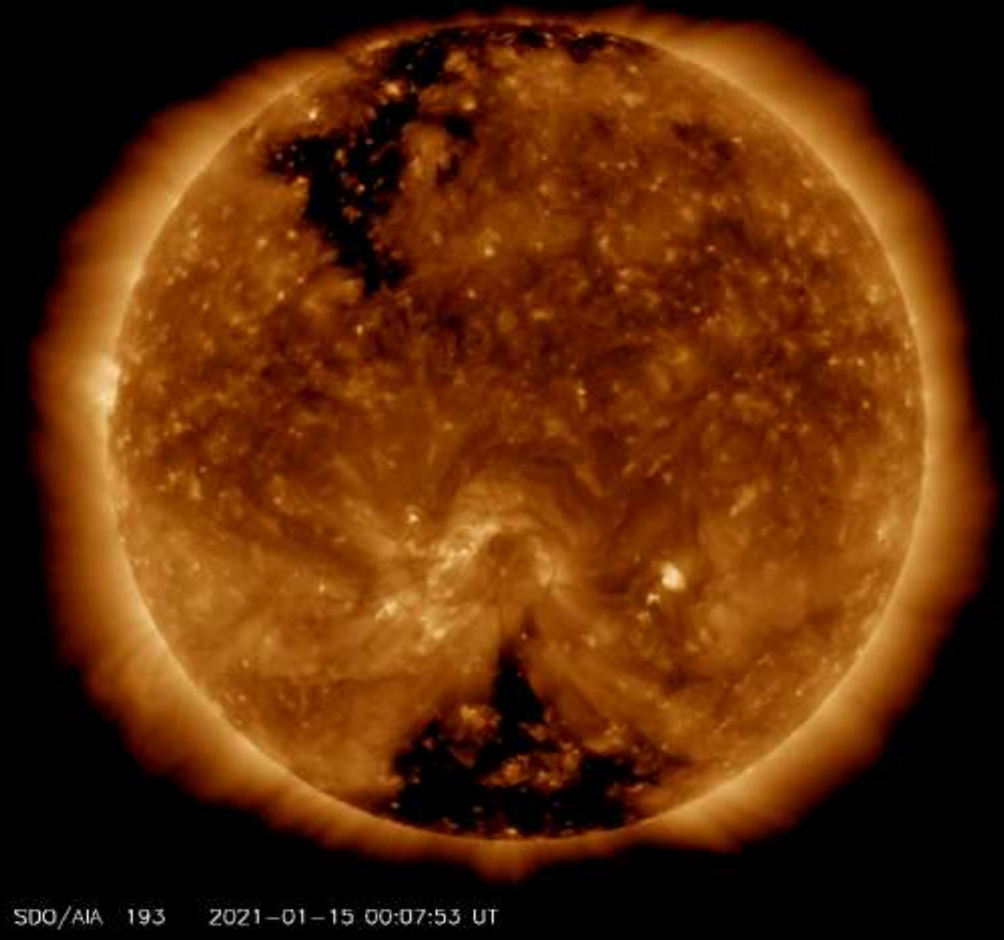
Perhaps most life in the universe is on planets orbiting M and K stars, not G stars like the Sun?

But we have not yet accounted for stellar activity and stellar variability.

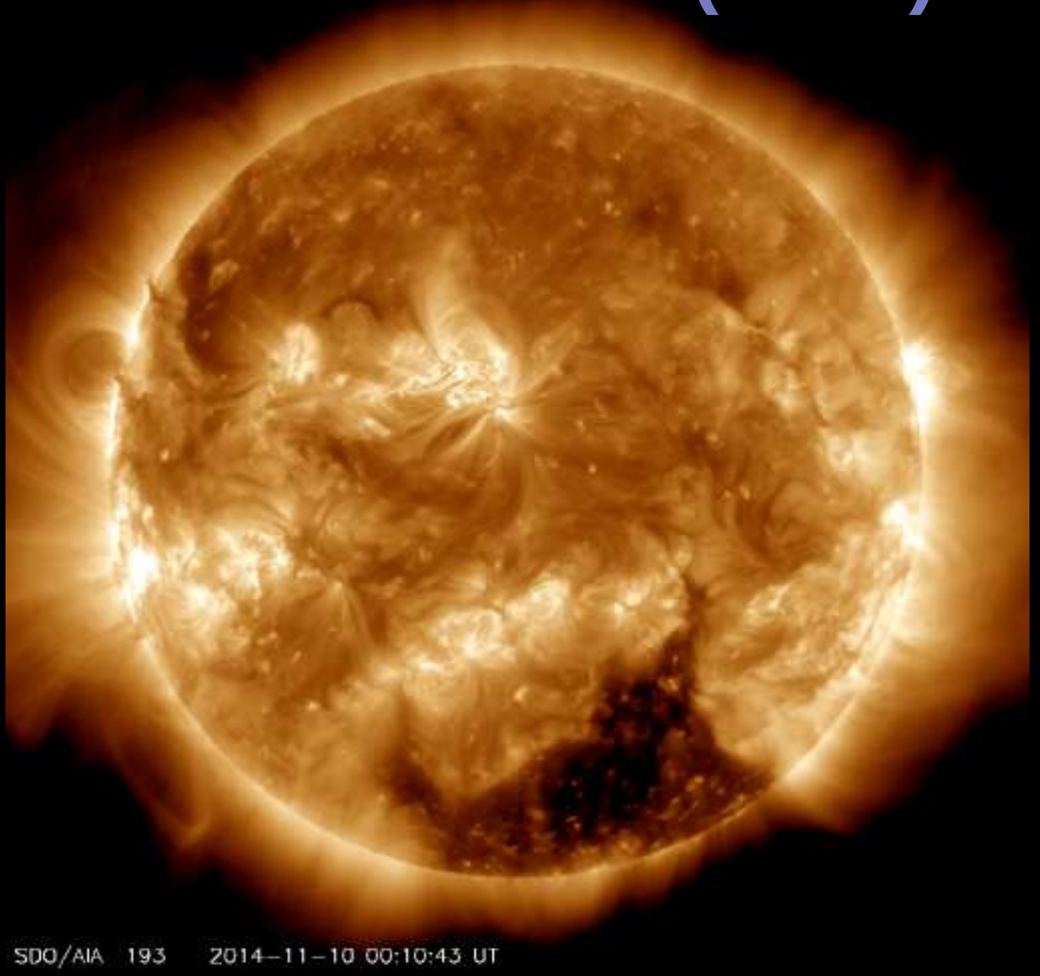
The Sun goes through an 11-year cycle of activity.

During the Sun's active state, Earth is bombarded by more intense radiation that can (rarely)pose hazards to life.

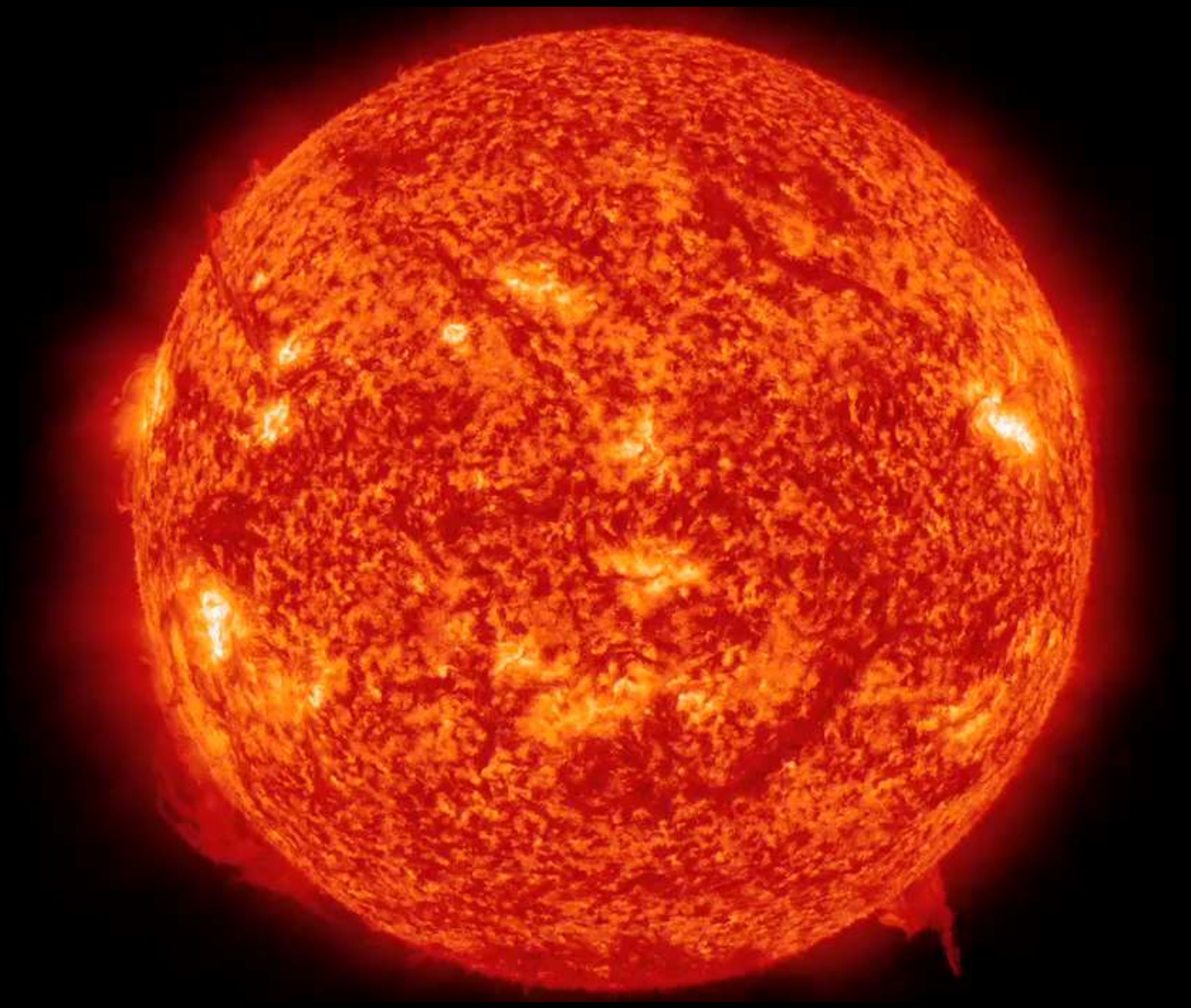
quiescent Sun (2021)



active Sun (2014)



Credit: SDO


Credit: NASA/SDO

Unfortunately, many M stars are flare stars, which are far more active than the Sun.

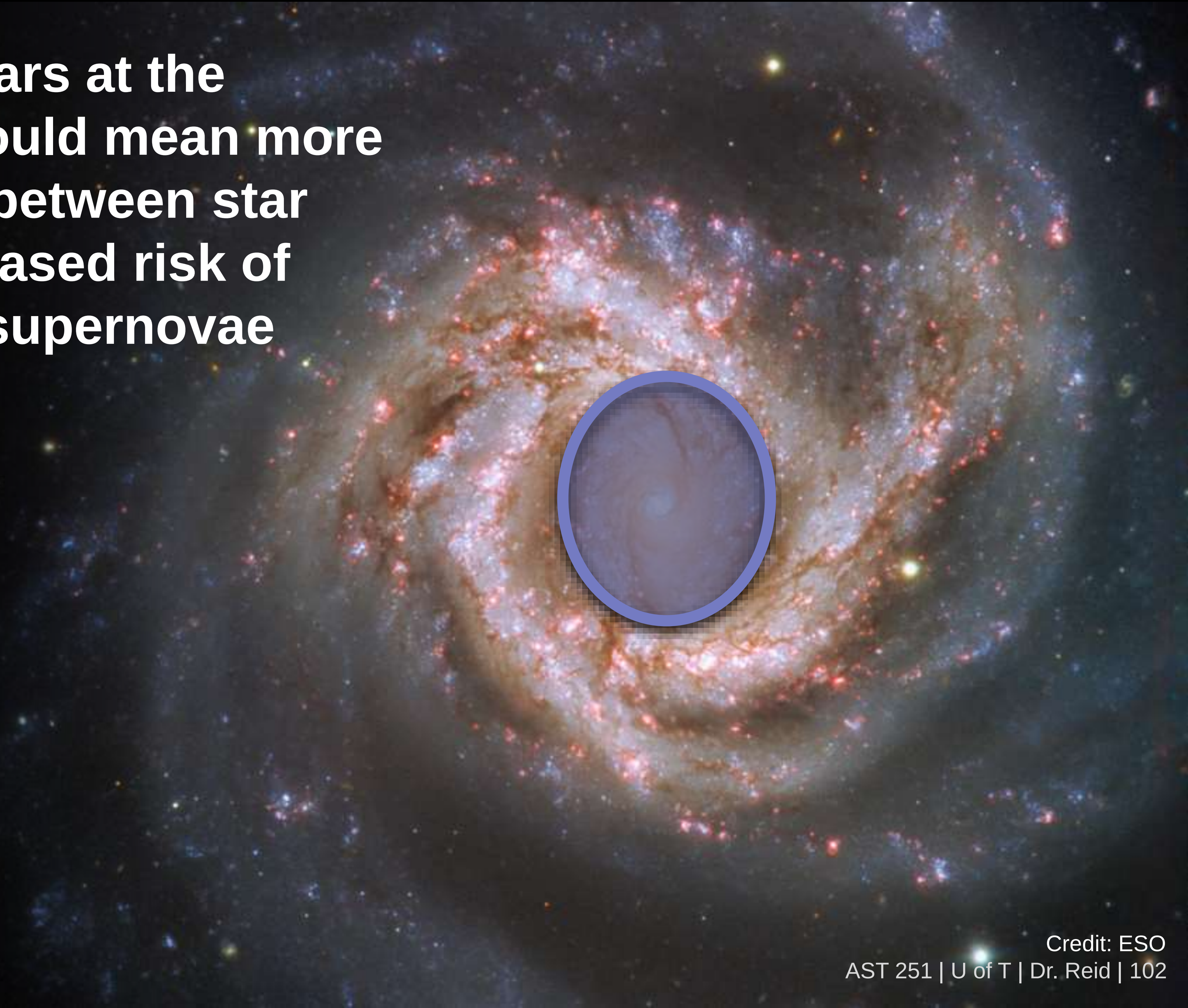
Their brightness can double or more for periods of minutes to hours, which may make them less suitable host stars for life-bearing planets.

So, to assess habitability, we need to consider the properties of each star individually, not just its spectral type.

Galaxies may also have galactic habitable zones

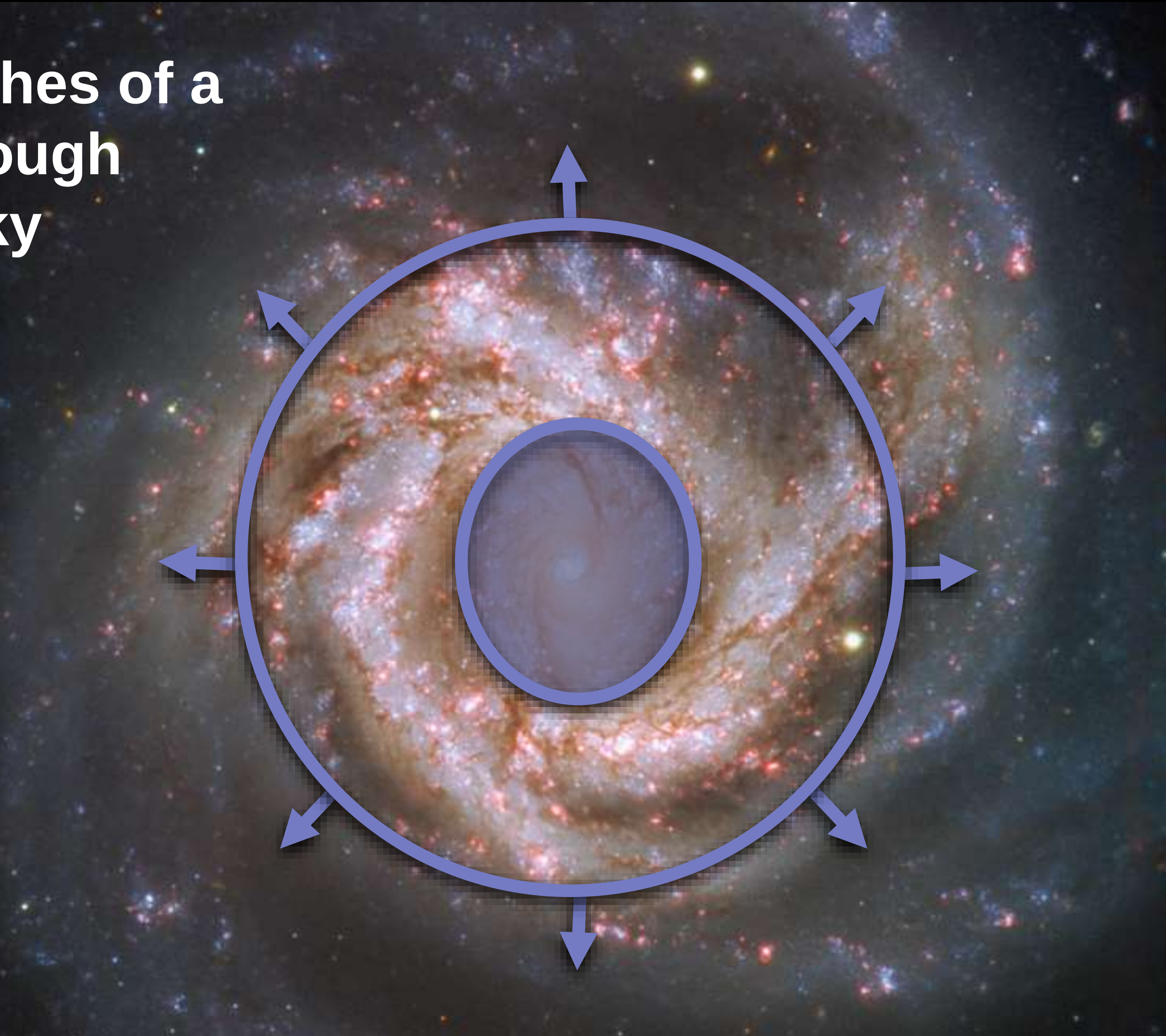
Credit: ESO

The high density of stars at the centres of galaxies would mean more frequent interactions between star systems, and an increased risk of damage from nearby supernovae



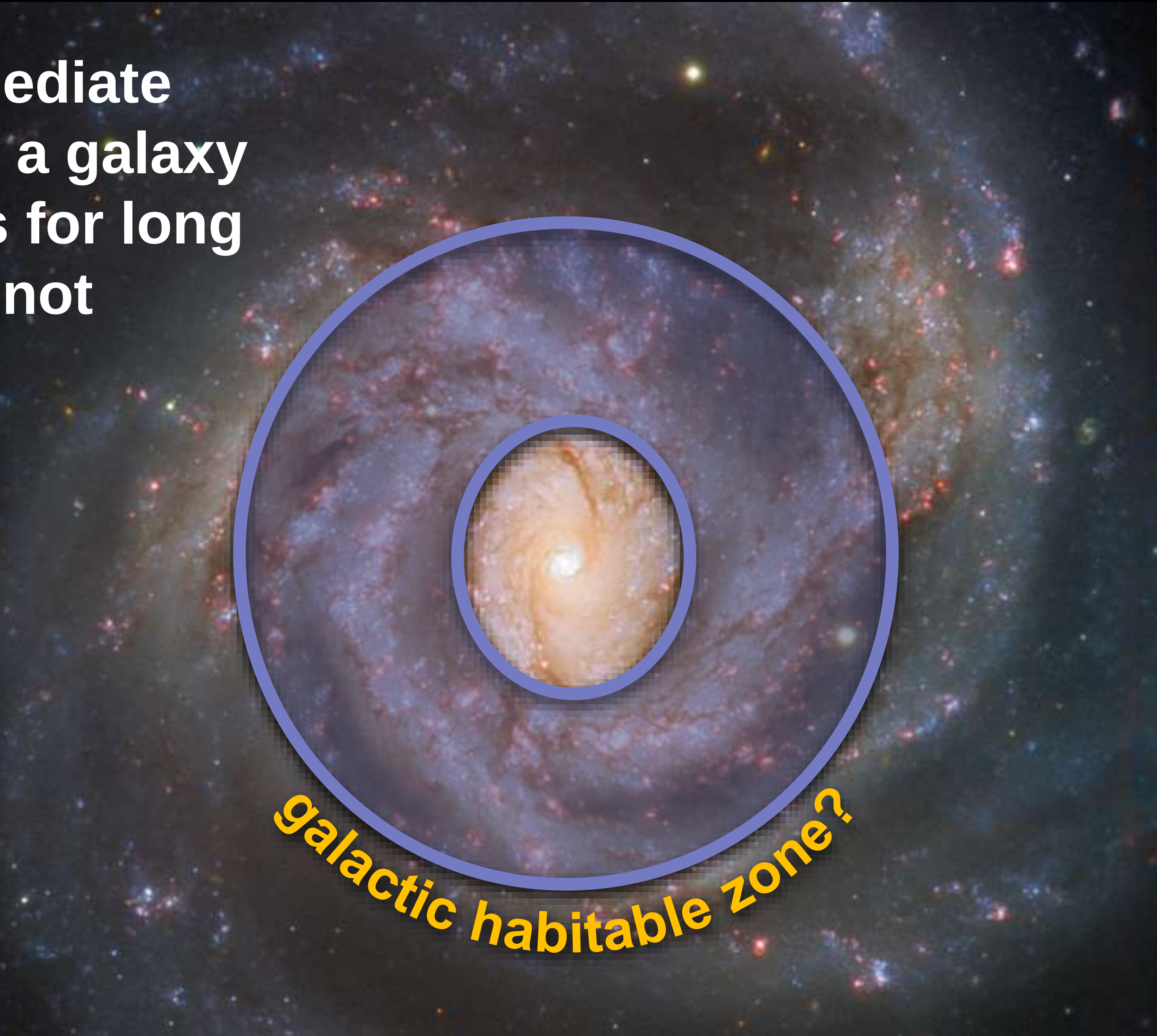
Credit: ESO

Meanwhile, in the outer reaches of a galaxy, there may not be enough heavy elements to form rocky planets.



Credit: ESO

Perhaps only stars at intermediate distances from the centre of a galaxy can host life-bearing planets for long periods of time. This idea is not universally accepted.



Credit: ESO