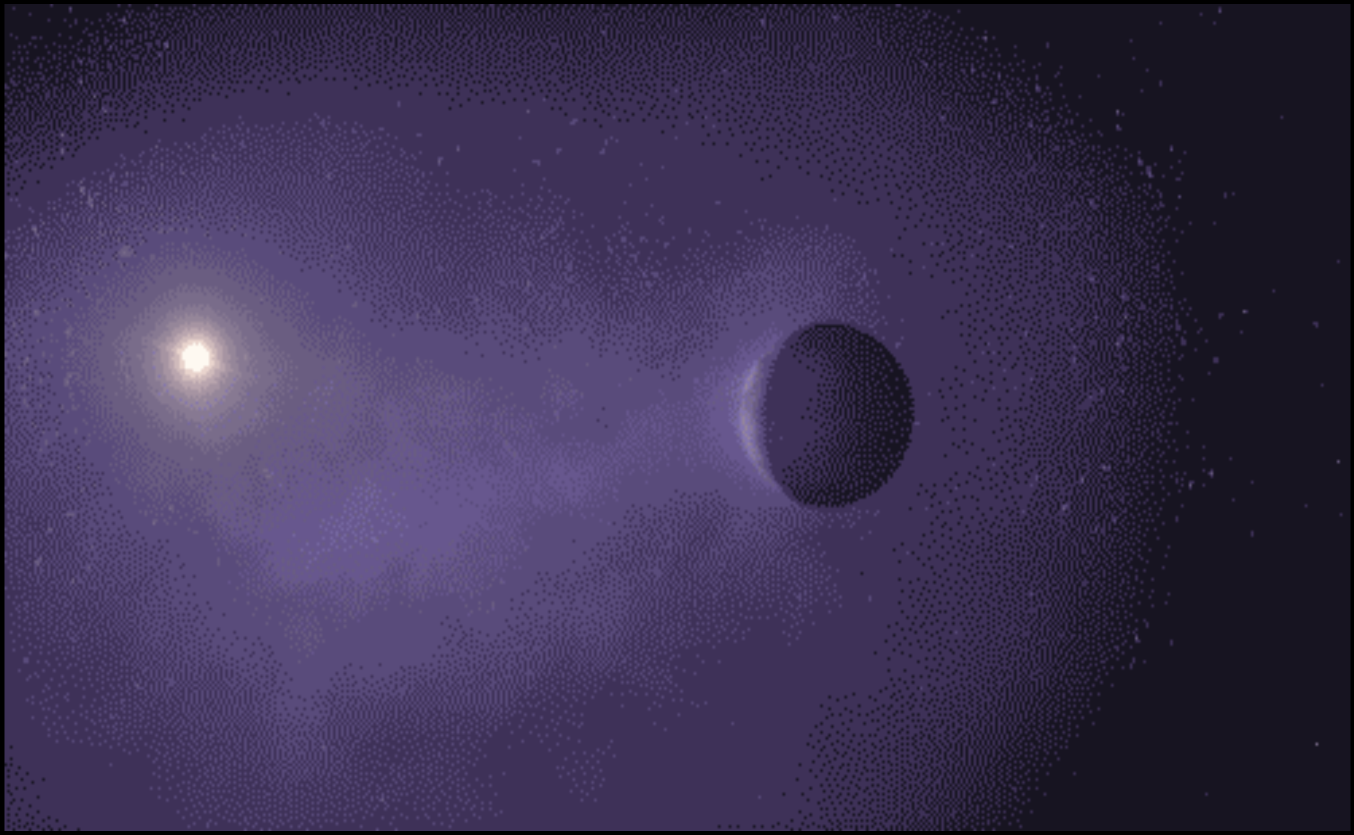
Lecture 4 -

Heating/ Cooling -

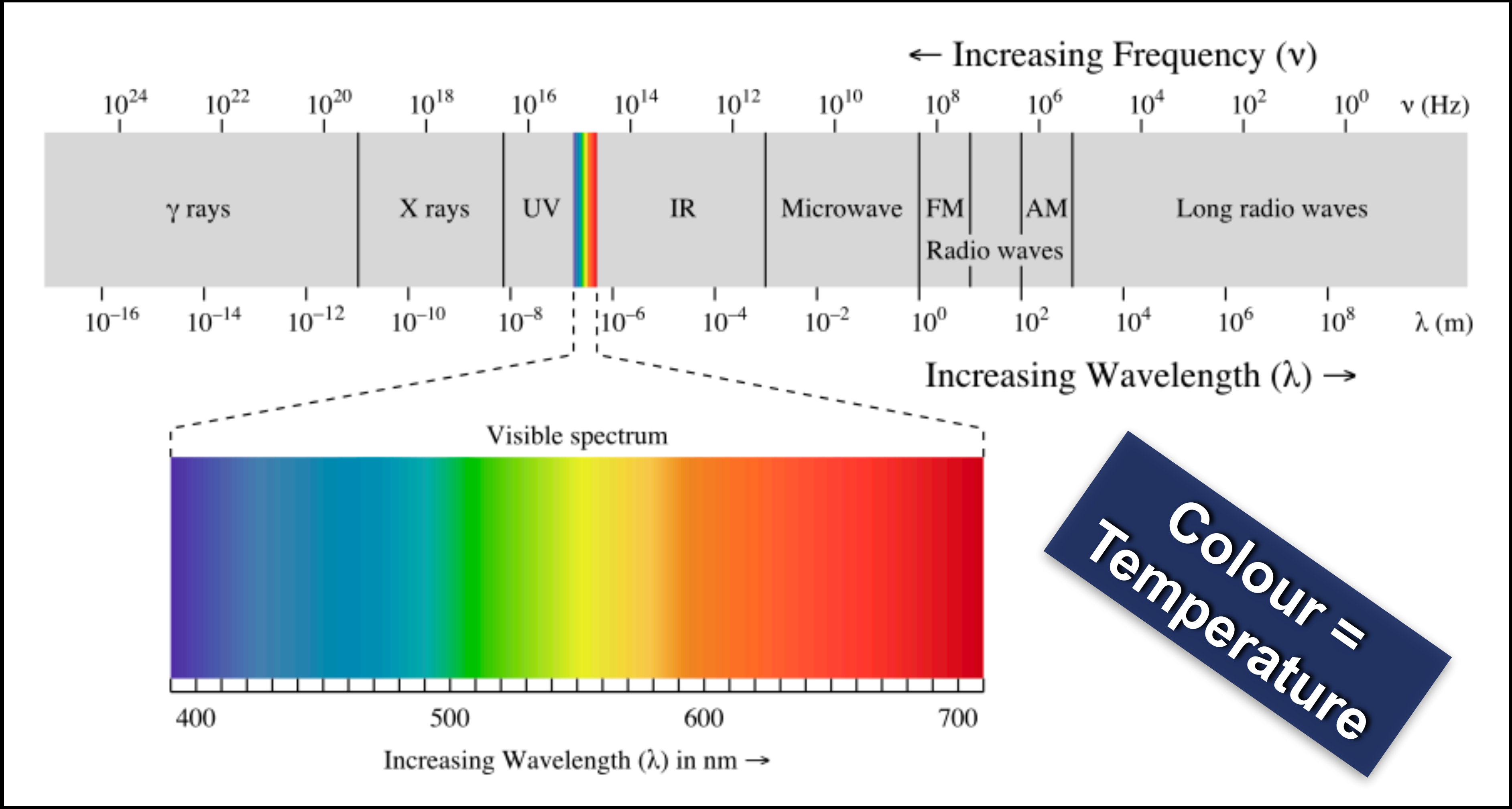
Star-Planet Interactions



Learning Objectives – Heating/Cooling - Star-Planet Interactions

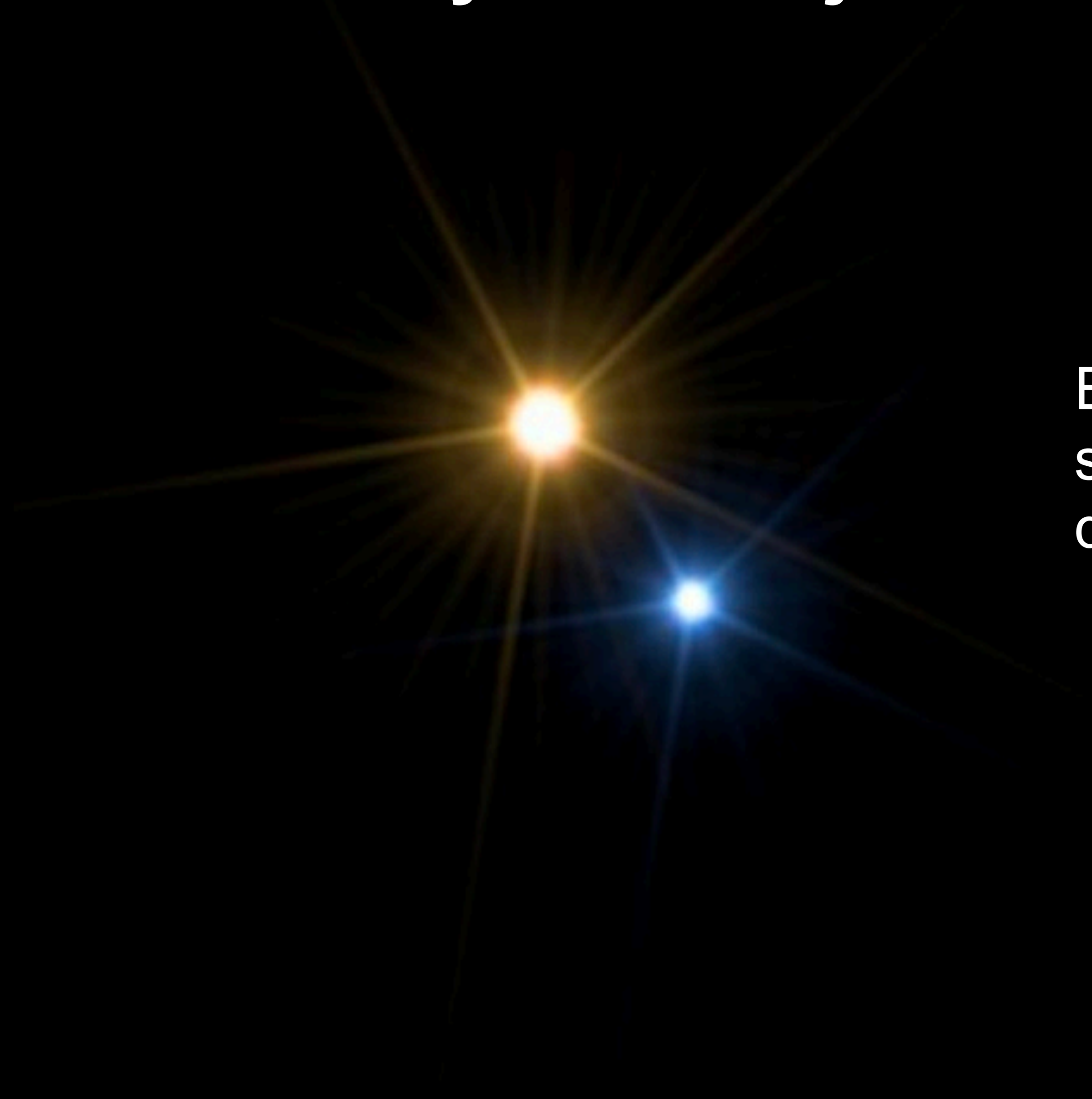
1) Understand the definition and the emission spectra of blackbodies
2) Calculate the luminosity of a blackbody and the peak wavelength of its emission spectrum
3) Understand the quantities that determine a planet's equilibrium temperature
4) Recite examples of physical processes that result in planetary atmospheric escape along with the quantities that determine their efficacy
5) Understand a planet's cooling mechanism and how its cooling timescale depends on the planet's size

Blackbody Radiation

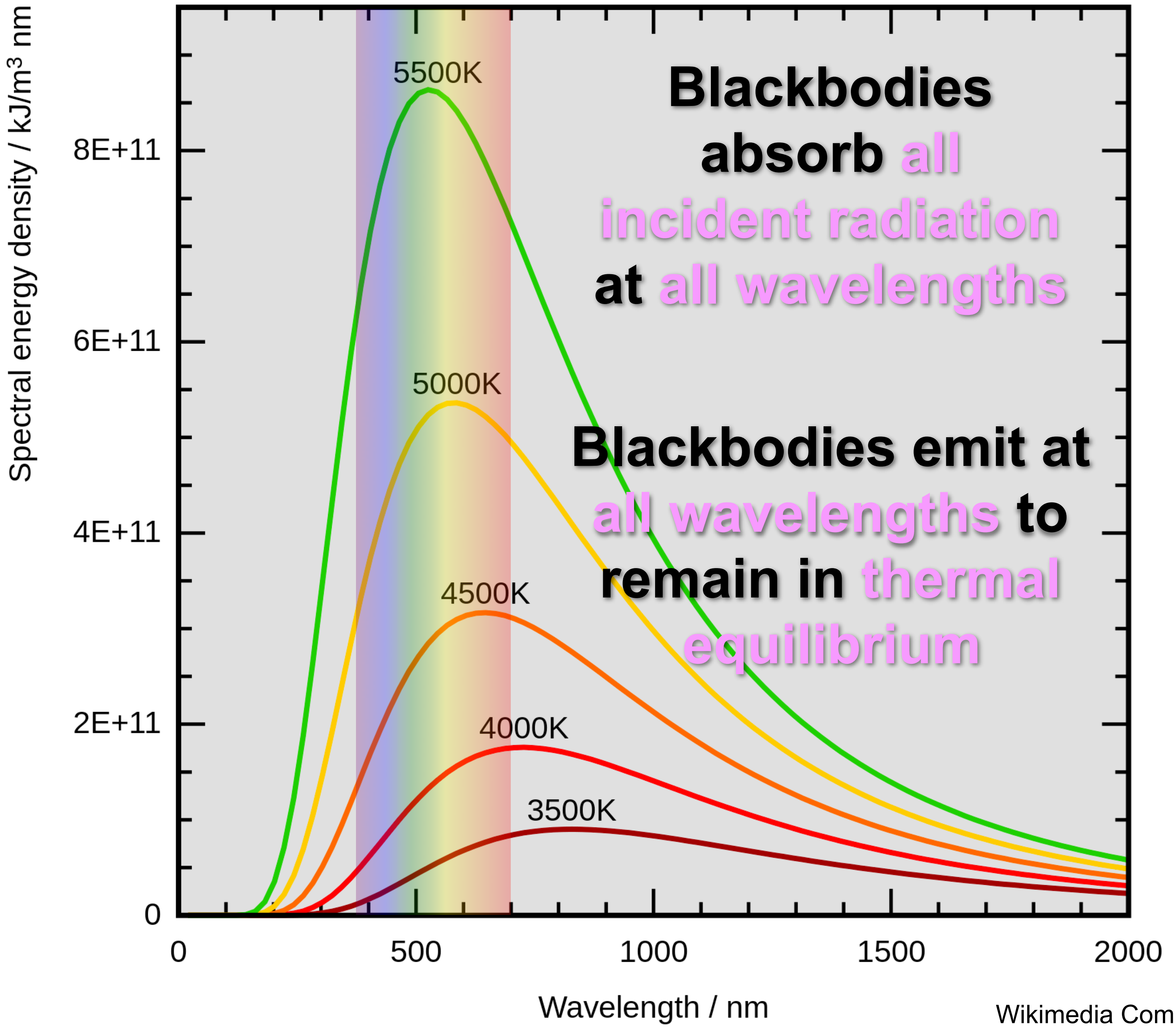


Colour = Temperature

Relationship between the colour of light emitted by a hot object and its temperature



E.g. Albireo - a double star showing clearly distinct colors



Blackbodies absorb all incident radiation at all wavelengths

Blackbodies emit at all wavelengths to remain in thermal equilibrium

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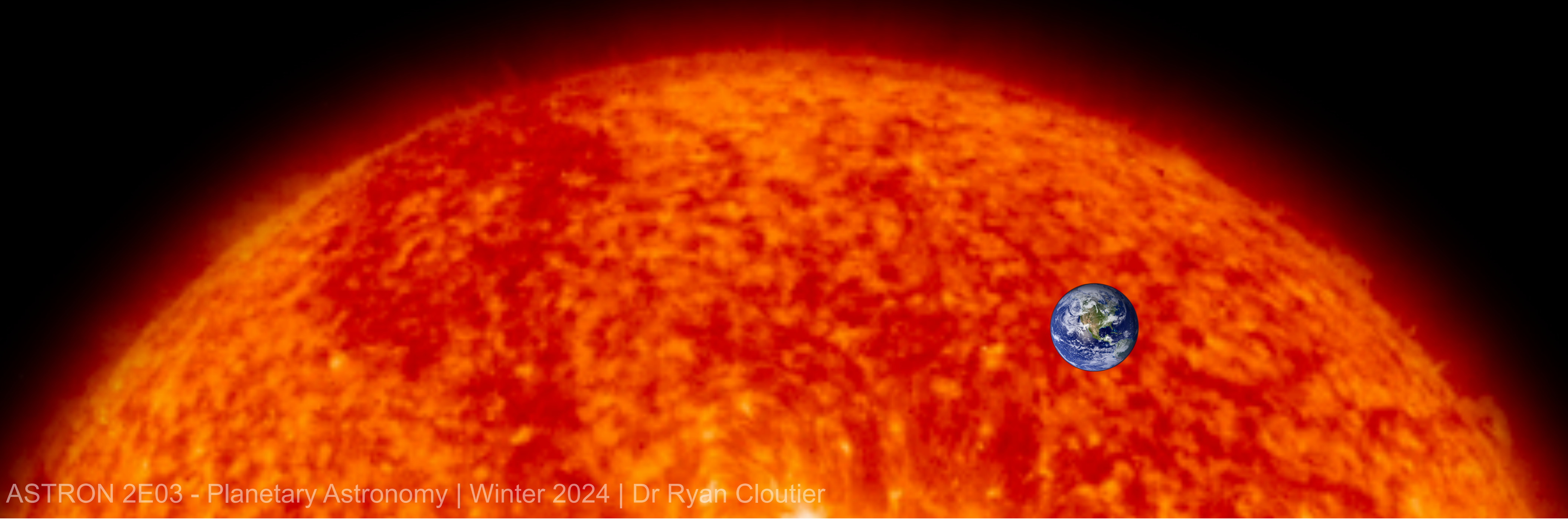
Wein’s displacement law

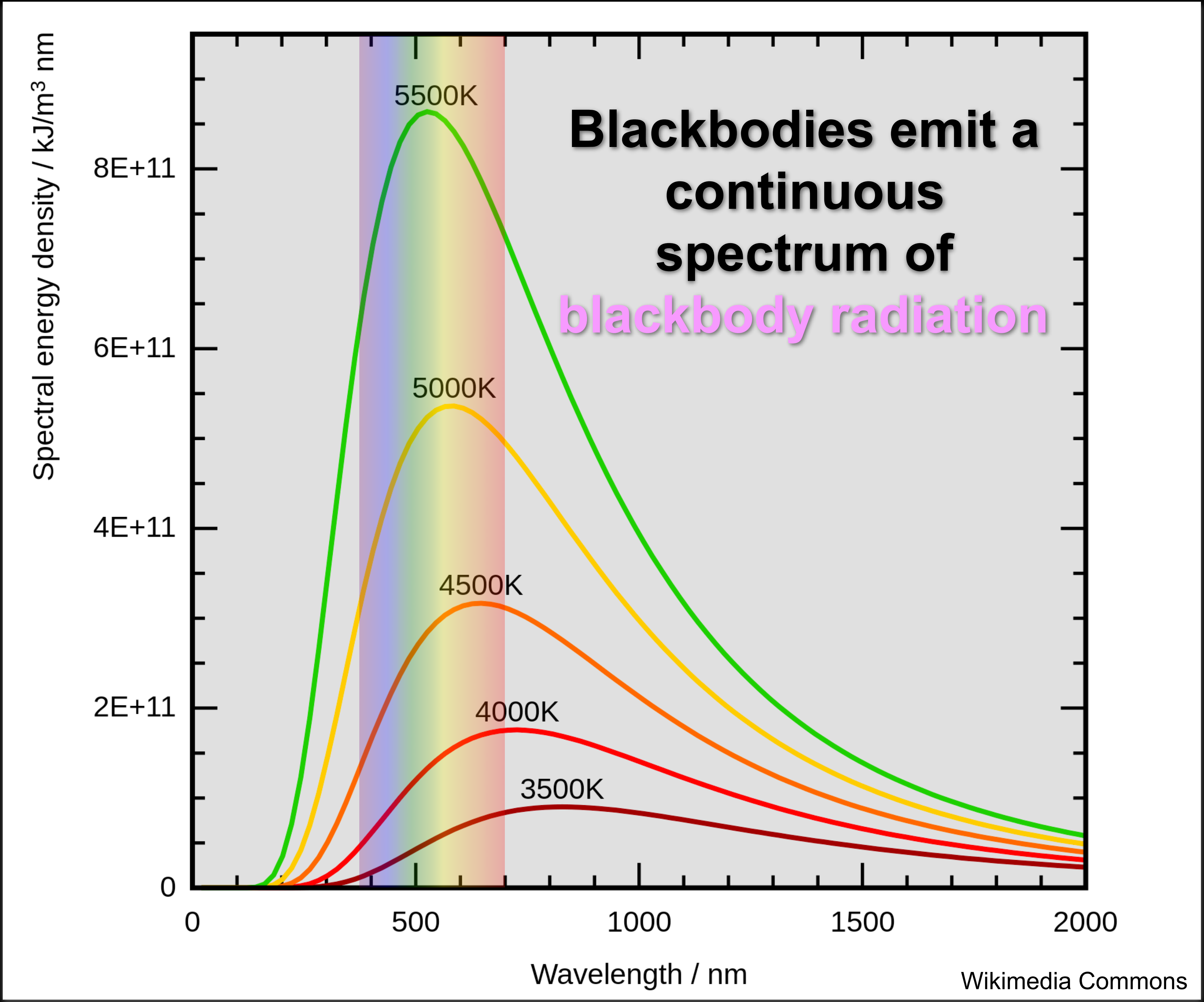
$$\lambda_{\rm peak} = \frac{b}{T} = \frac{2898\,\mu{\rm m~K}}{T}$$

TPS Activity

The Sun’s BB curve peaks at a wavelength of about 0.5 microns whereas the Earth’s BB curve peaks at about 10 microns.

How much hotter is the Sun’s surface compared to the Earth?





Blackbodies emit a continuous spectrum of blackbody radiation

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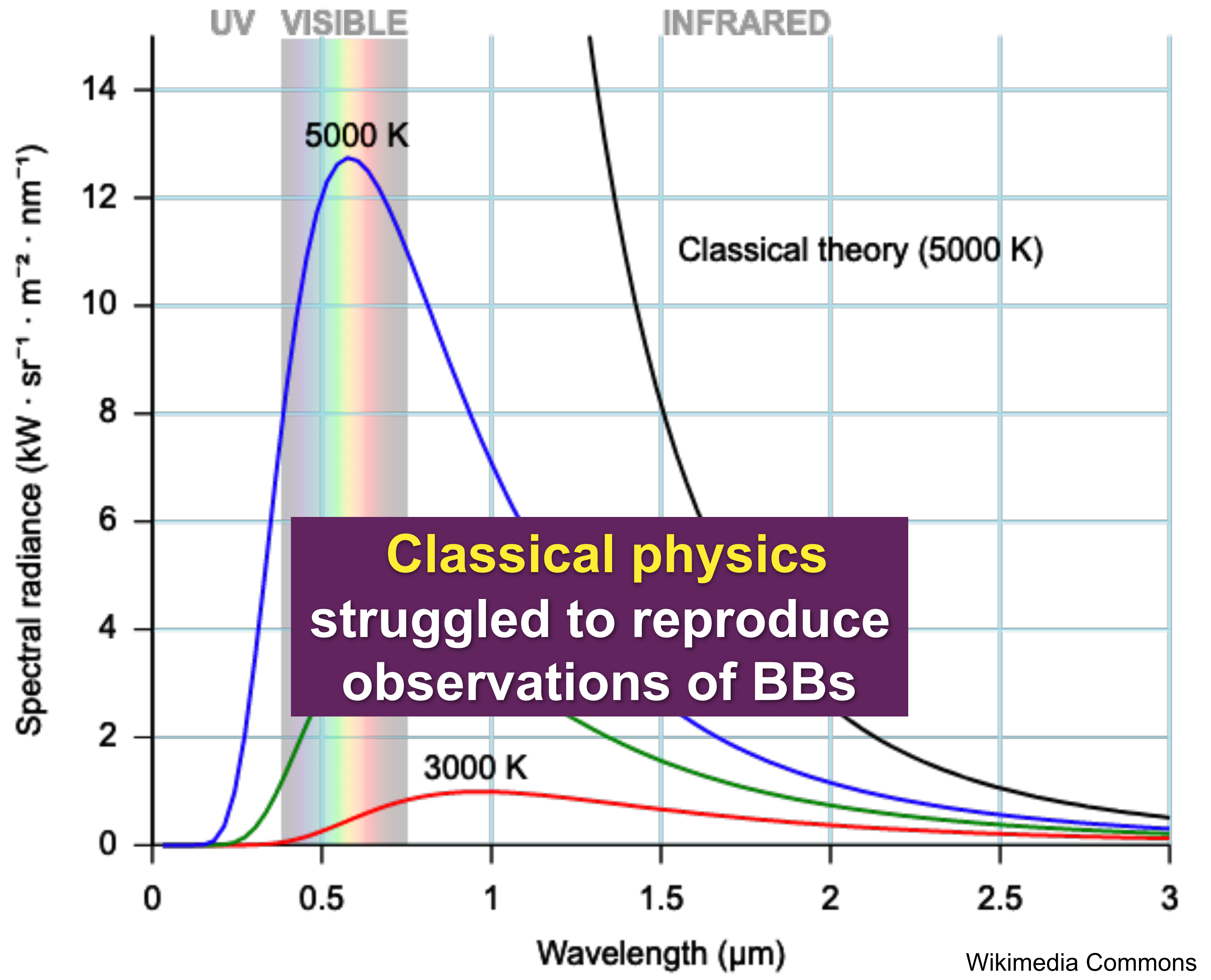

Classical physics struggled to reproduce observations of BBs

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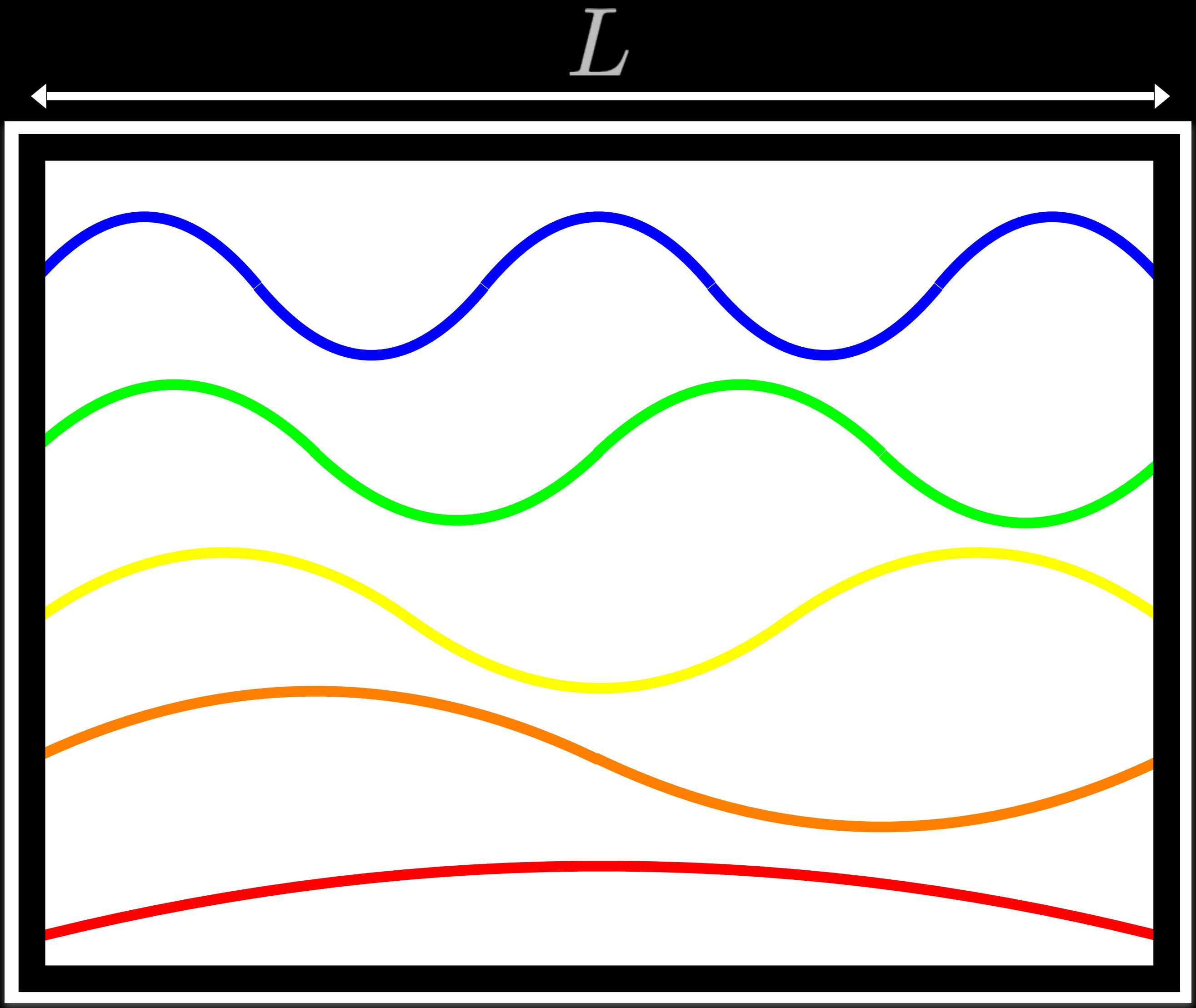
Problem: the ultraviolet catastrophe

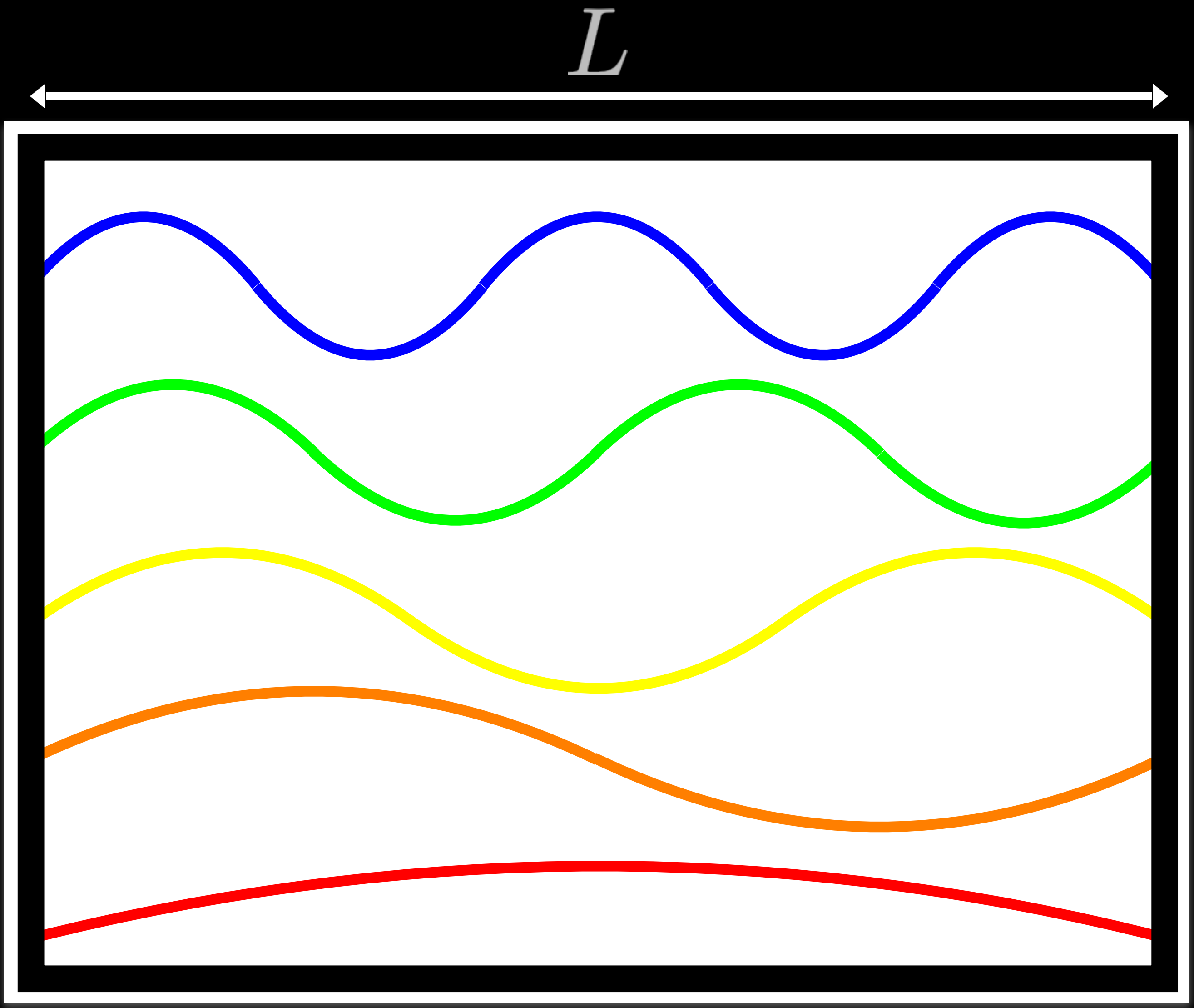
- Consider an oven with length *L* and filled with blackbody radiation in thermal equilibrium

- Classically, this radiation is a set of standing waves with wavelengths 2L, L, 2L/3, L/2, 2L/5, etc

- For a thermalized system, all waves have equal energies = $k_B * T$

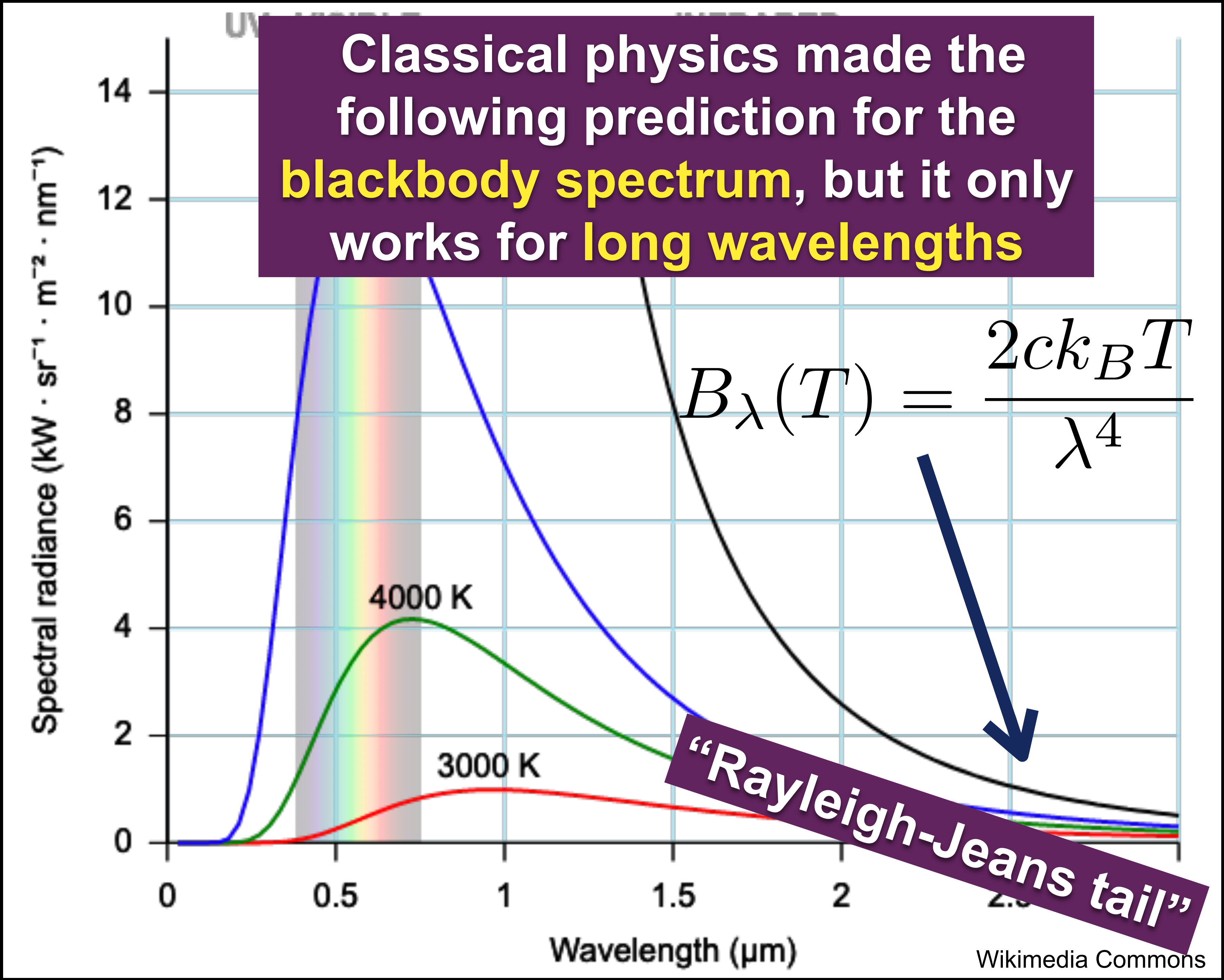


Problem: the ultraviolet catastrophe



Ultraviolet catastrophe: with an infinite number of decreasing wavelengths, this system would have an unlimited amount of blackbody radiation energy from short wavelength standing waves

Classical physics made the following prediction for the **blackbody spectrum**, but it only works for **long wavelengths**



$$B_\lambda(T) = \frac{2ck_BT}{\lambda^4}$$

"Rayleigh-Jeans tail"

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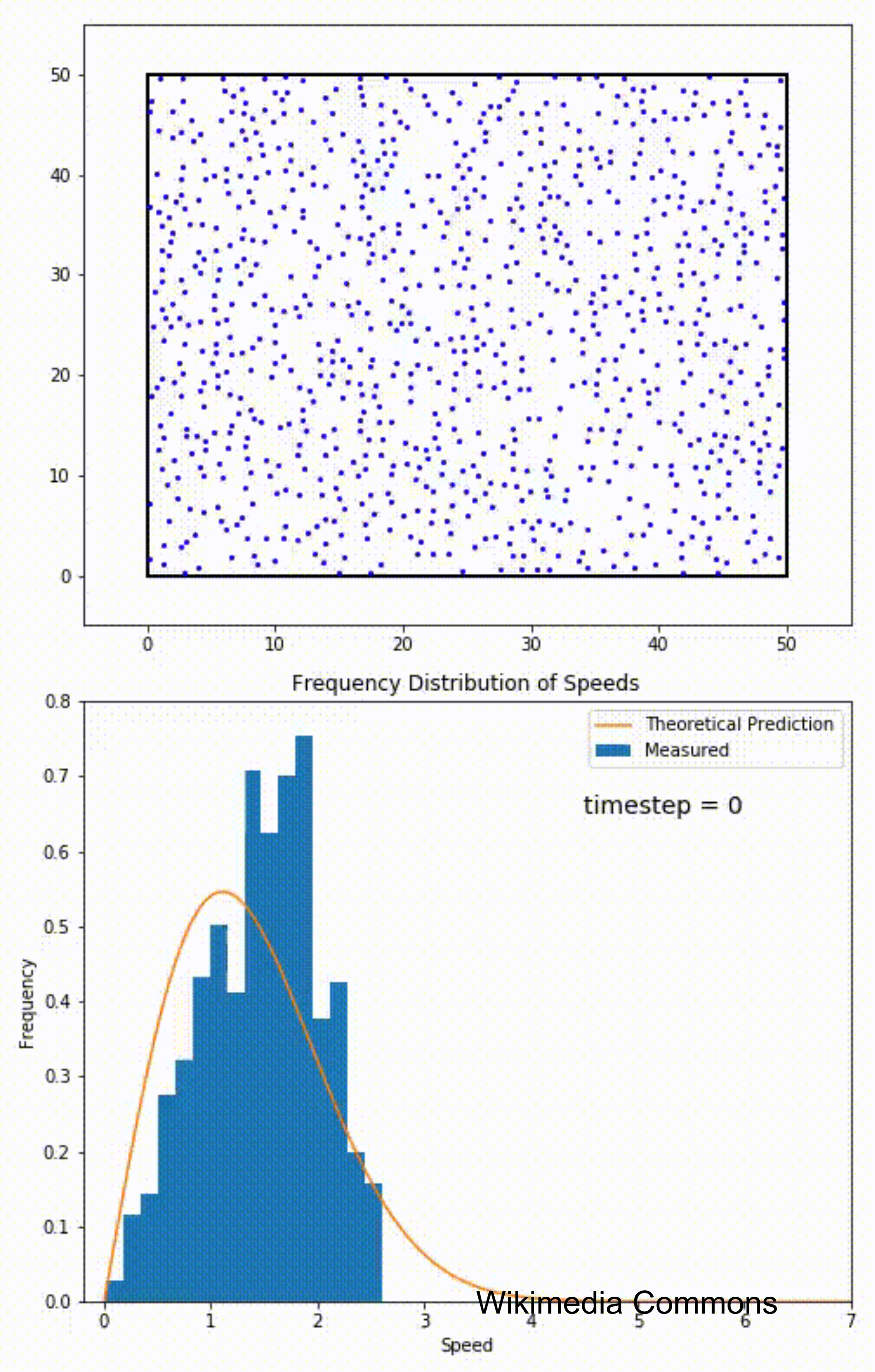
Aside:

Maxwell-Boltzmann distribution

$$\left(\frac{dN}{dv}\right)_{m,T} = v^2\left(\frac{m}{2\pi k_B T}\right)^{3/2} \times \exp\left(-\frac{mv^2}{2k_B T}\right)$$



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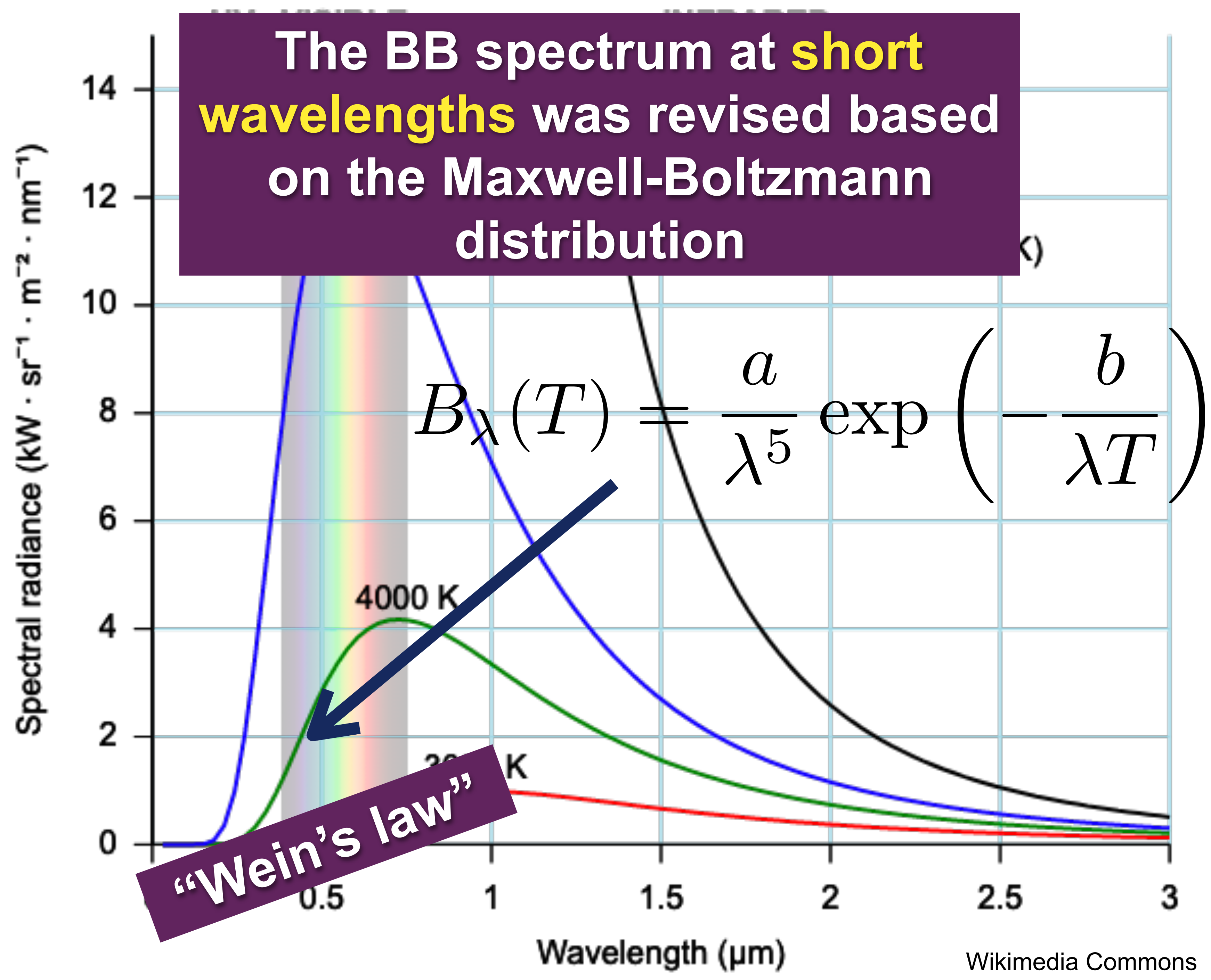
The BB spectrum at **short wavelengths** was revised based on the Maxwell-Boltzmann distribution



$$B_\lambda(T) = \frac{a}{\lambda^5}\exp\left(-\frac{b}{\lambda T}\right)$$

“Wein’s law”

Wikimedia Commons

German physicist Max Planck modified Wein’s law to fit the BB curve at all wavelengths, thus avoiding the ultraviolet catastrophe

$$B_\lambda(T) = \left(\frac{a}{\lambda^5}\right)\frac{1}{e^{b/\lambda T}}$$

$$\rightarrow B_\lambda(T) = \left(\frac{a}{\lambda^5}\right)\frac{1}{e^{b/\lambda T} - 1}$$

$$\rightarrow B_\lambda(T) = \left(\frac{2hc^2}{\lambda^5}\right)\frac{1}{e^{hc/\lambda k_B T} - 1}$$

The Planck function

Requires that standing waves have **quantized energy**, not arbitrary energy

Quantized radiation waves are known as **photons** (i.e. “particles” of light)

One quantum of energy is

$$E = h\nu$$

where ν is the oscillating frequency

$$\nu = \frac{c}{\lambda}$$

and *h* became known as **Planck’s constant**

TPS Activity

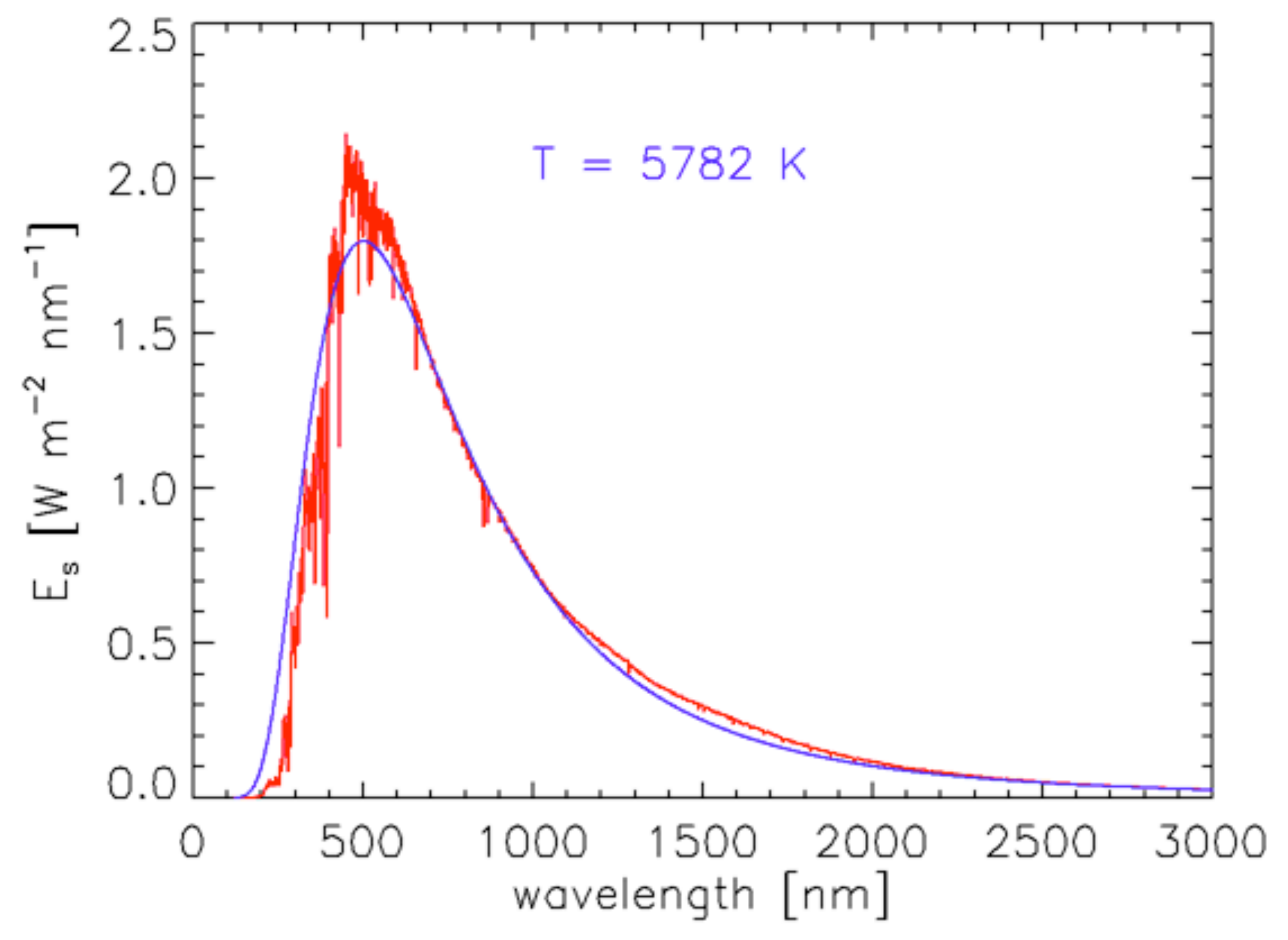
Rescale the expression for photon energy *E* to the following form:

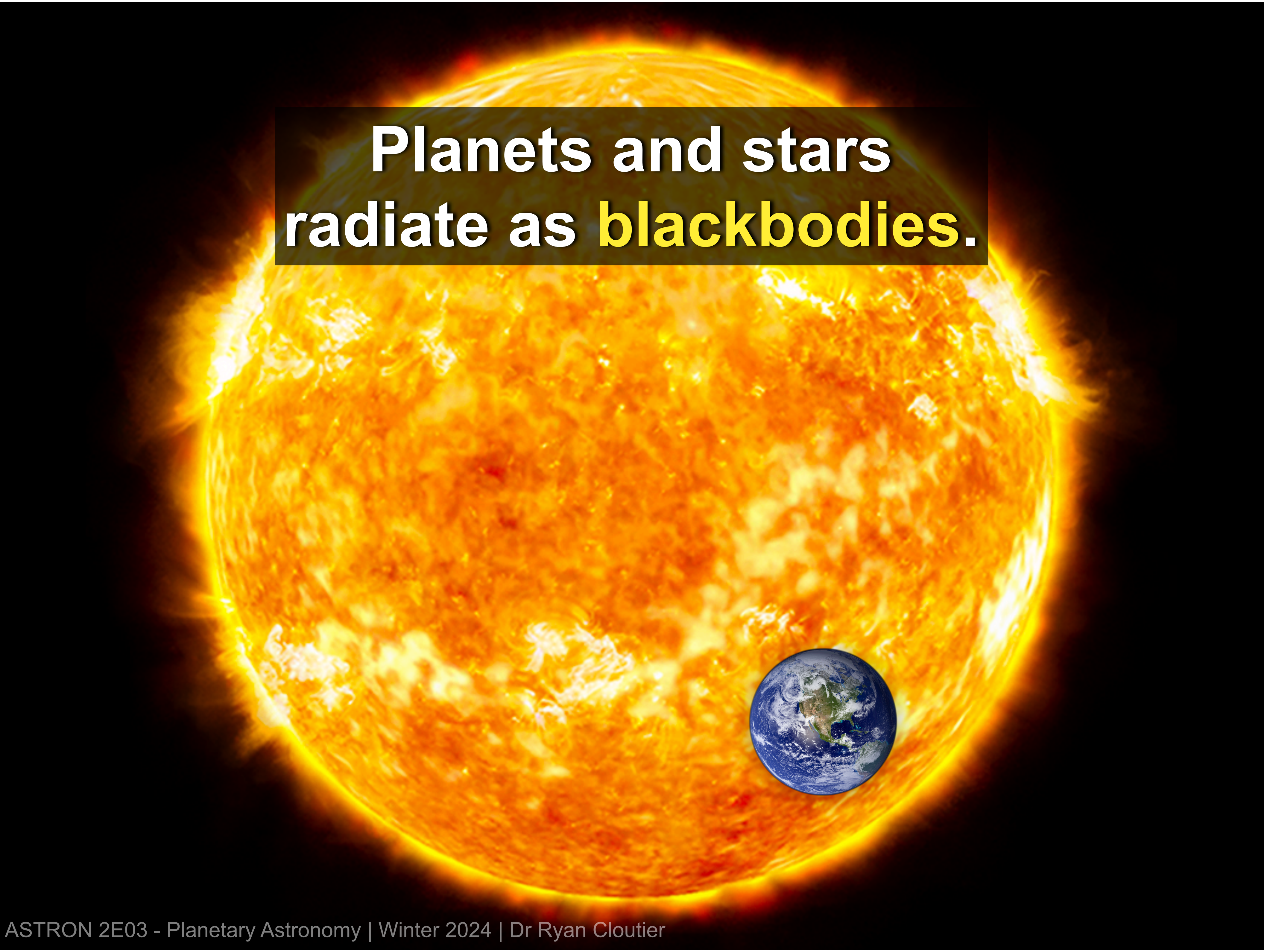
$$E = \frac{hc}{\lambda} \rightarrow x \, \text{Joules} \left(\frac{\lambda}{\text{nm}} \right)^{-1}$$

(i.e. solve for *x* in units of Joules)

Stars are only approximate blackbodies

- The continuum of the solar spectrum well-described as a blackbody curve
- But it does show additional complexity from atmospheric absorbers (e.g. H, O, Mg, Fe, etc)
- We will ignore absorption for now





Planets and stars radiate as **blackbodies**.

Stefan-Boltzmann equation

$$L = A\sigma T^4$$

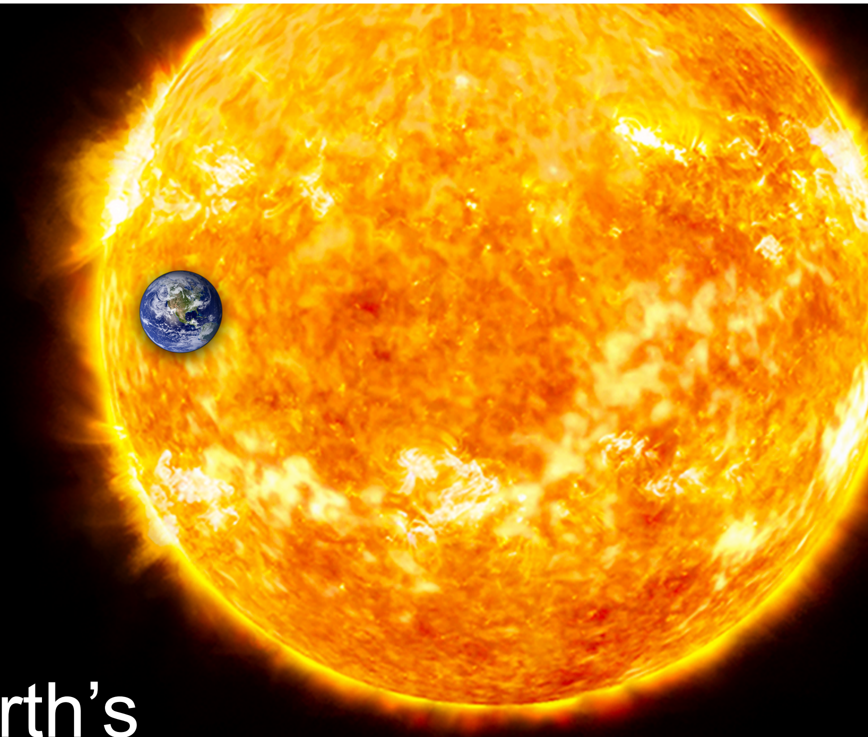
L:
Luminosity
[energy/time]

***A*: Surface area**

***T*: Temperature**

σ: Stefan-Boltzmann constant

TPS Activity



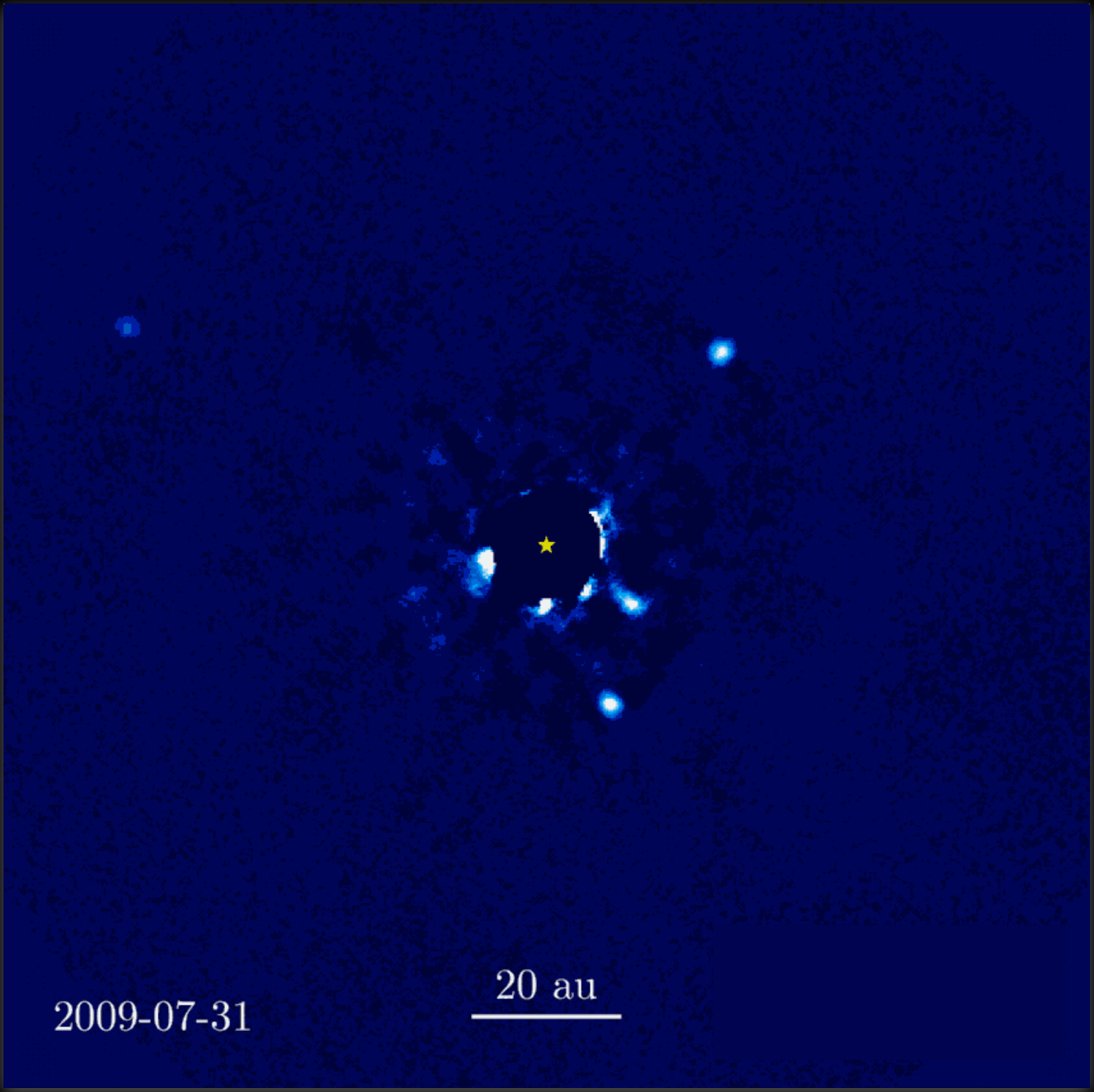
$$L = A\sigma T^4$$

If the Sun's radius is 100x the Earth's and it's surface is ~20x hotter,

how much more luminous is the Sun compared to the Earth?

Remember how direct imaging is hard?

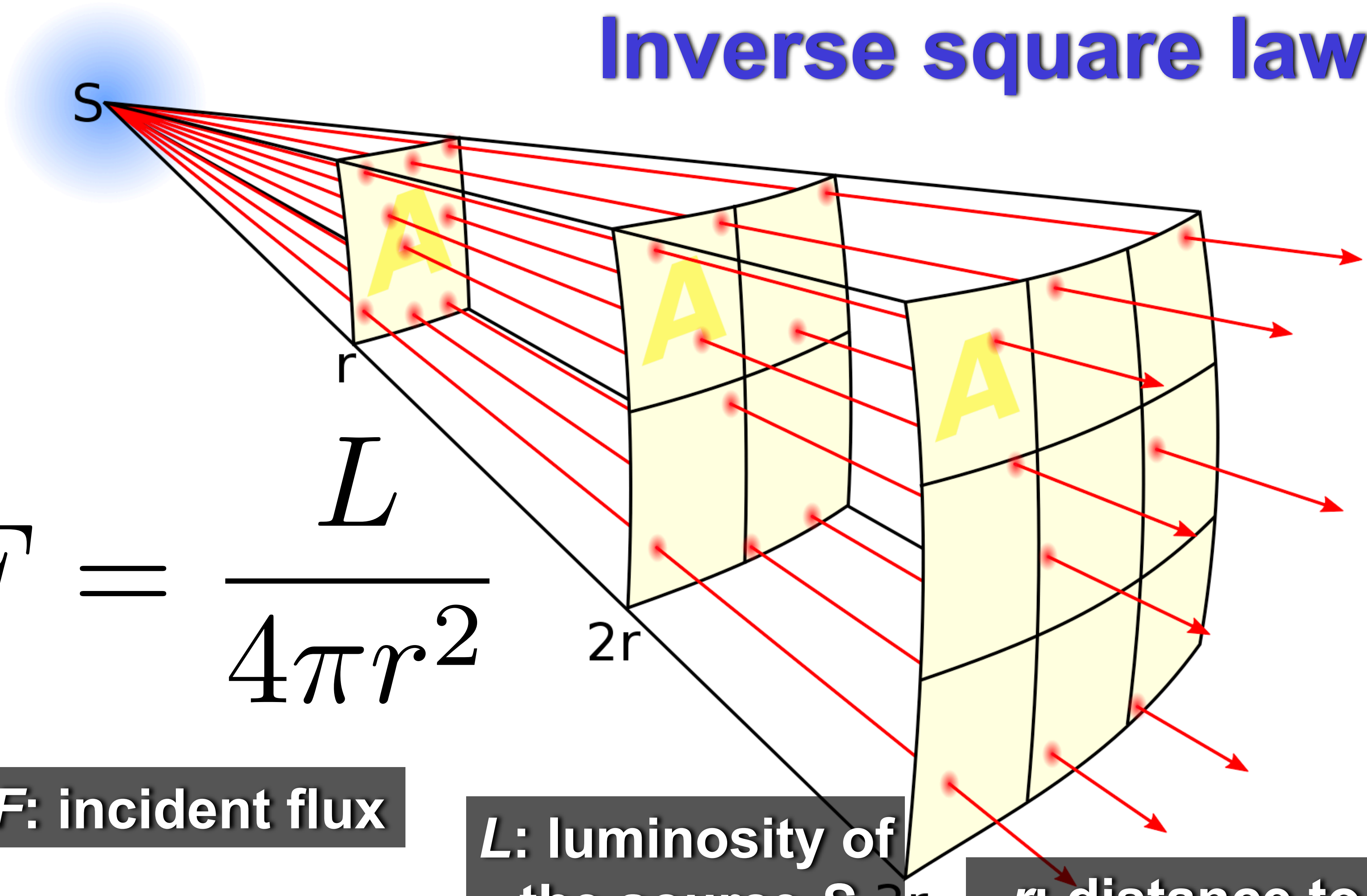
$$\frac{L_\oplus}{L_\odot} \sim 10^{-9}$$



Stars and planets are spheres…

$$L = A\sigma T^4 \rightarrow 4\pi R^2\sigma T^4$$

Inverse square law



$$F = \frac{L}{4\pi r^2}$$

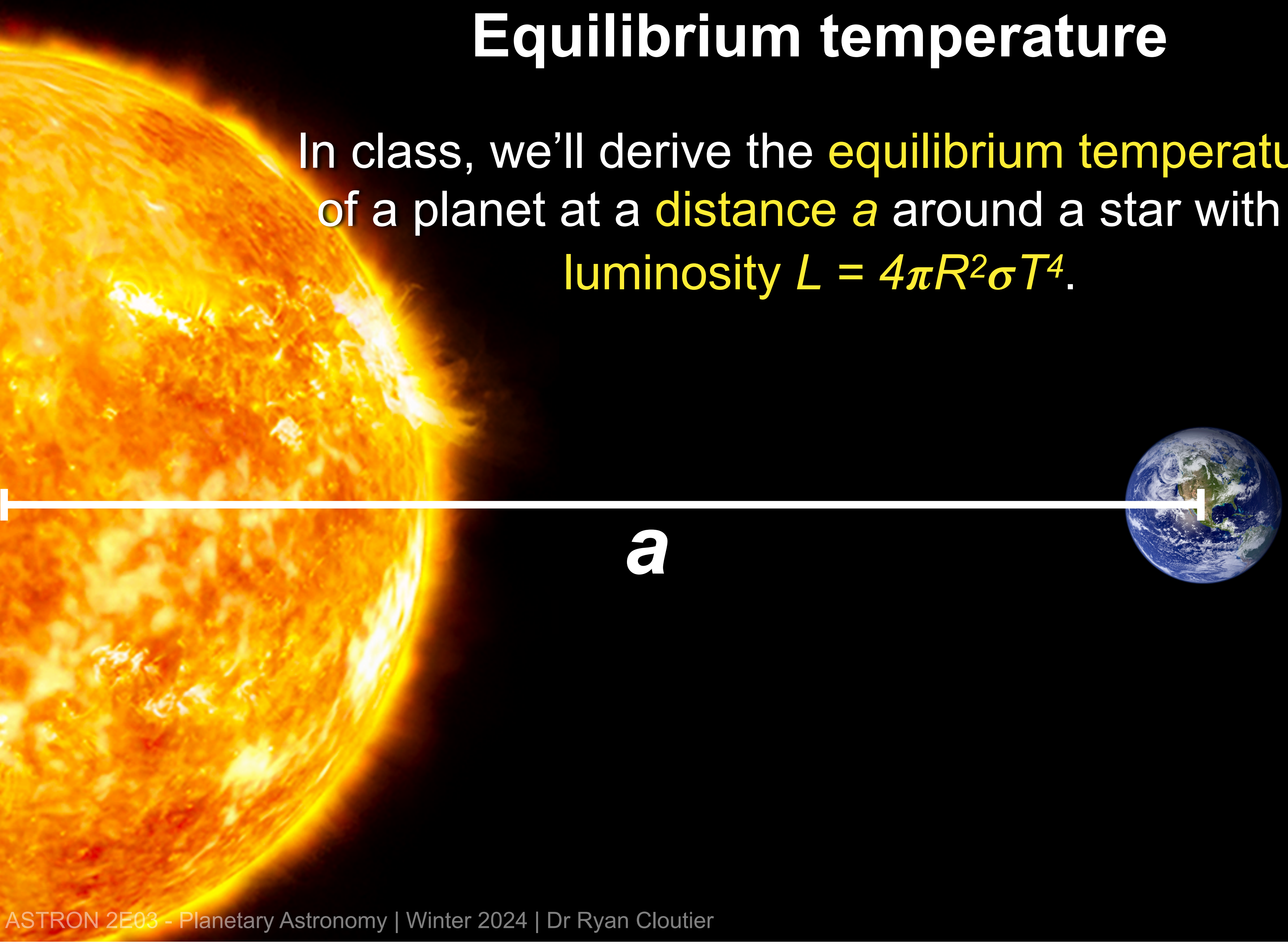
F: **incident flux**

L: **luminosity of the source *S***

r: **distance to the source *S***

Equilibrium temperature

In class, we'll derive the equilibrium temperature of a planet at a distance *a* around a star with a luminosity $L = 4\pi R^2\sigma T^4$.

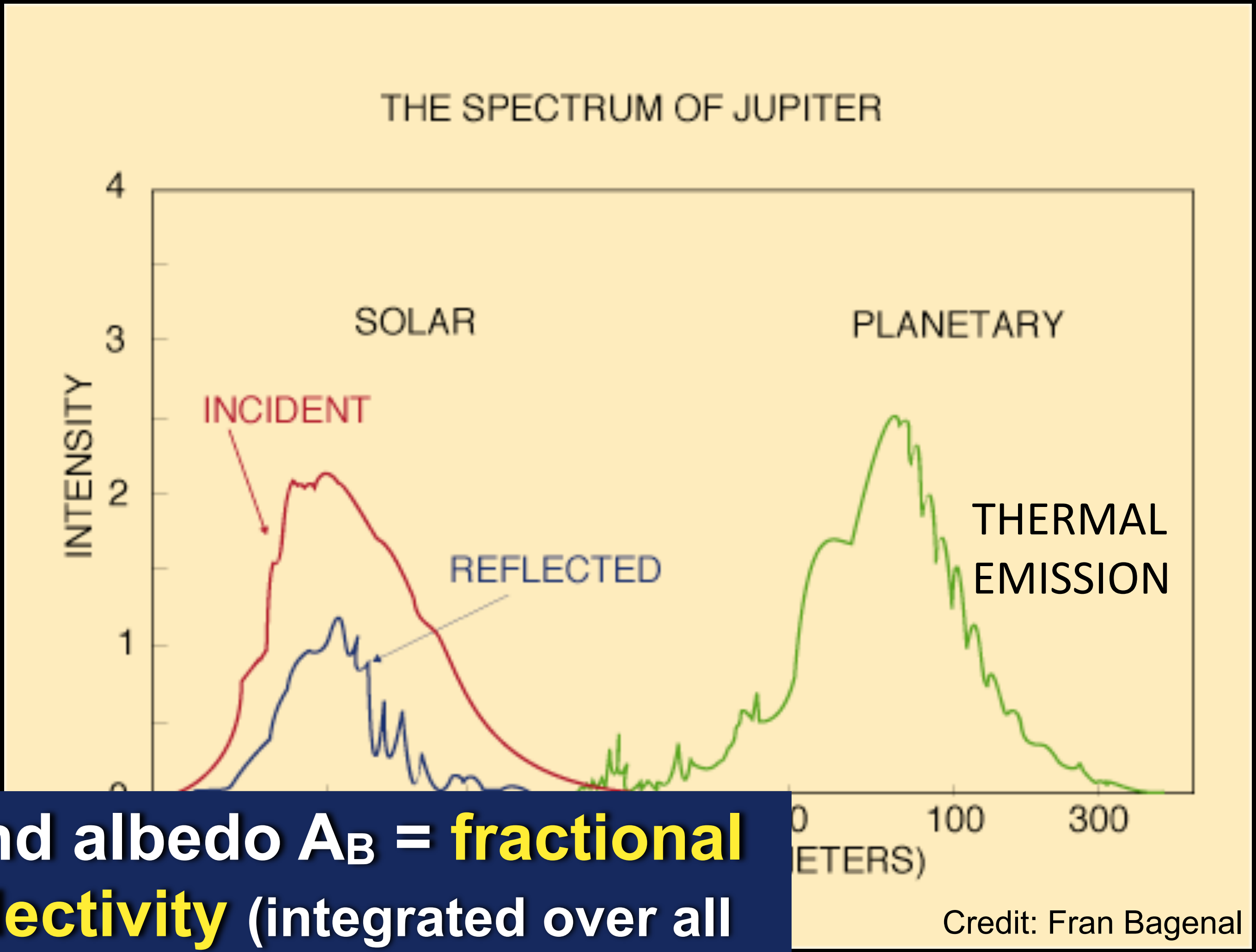


Equilibrium temperature

$$T_{eq} = T_{eff}\sqrt{\frac{R_\star}{2a}}$$

But this assumes that planets are perfect blackbodies that **absorb all incident radiation**

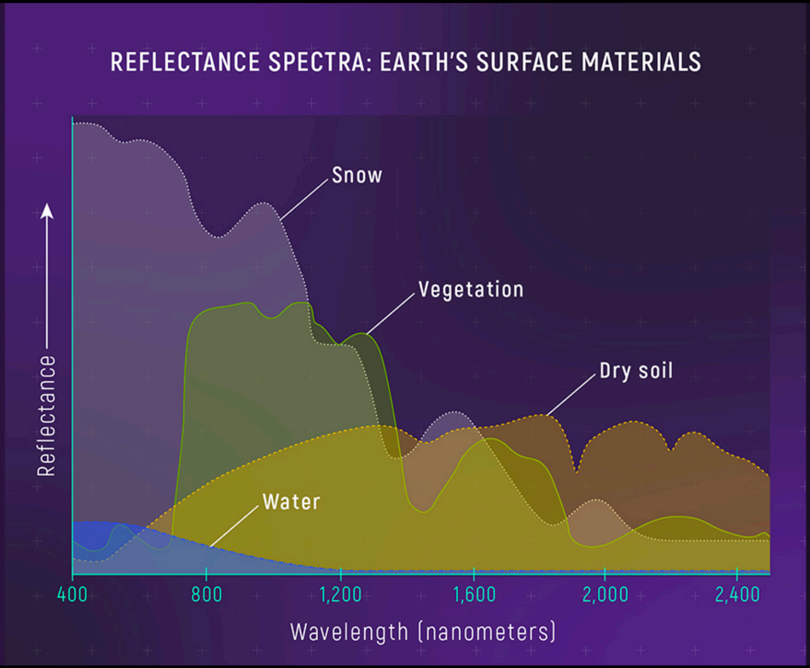
Planets reflect some light



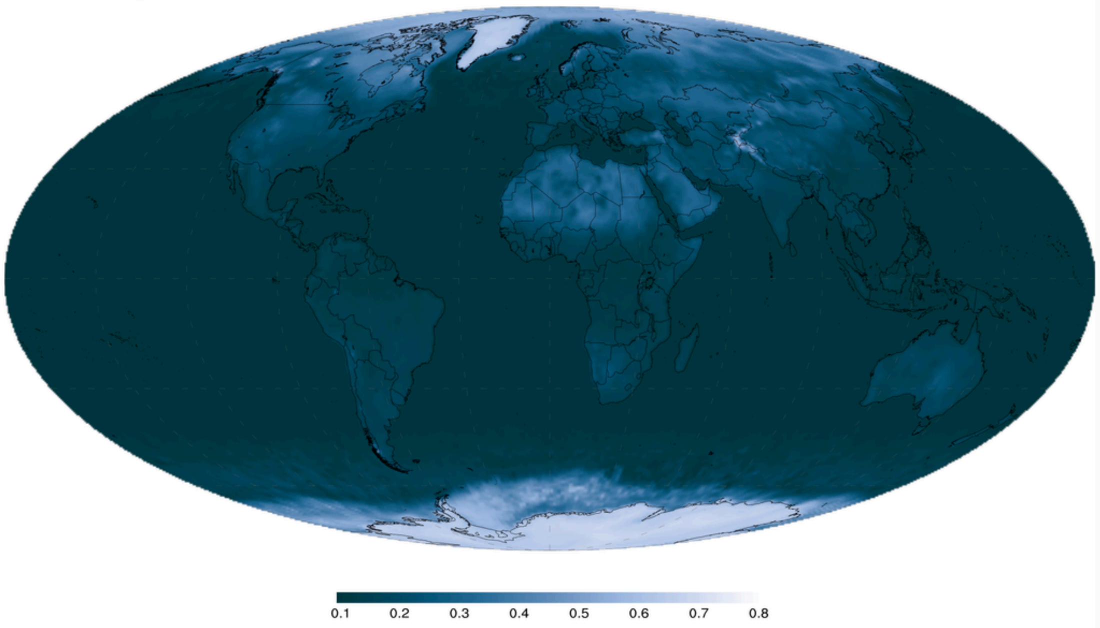
Credit: Fran Bagenal

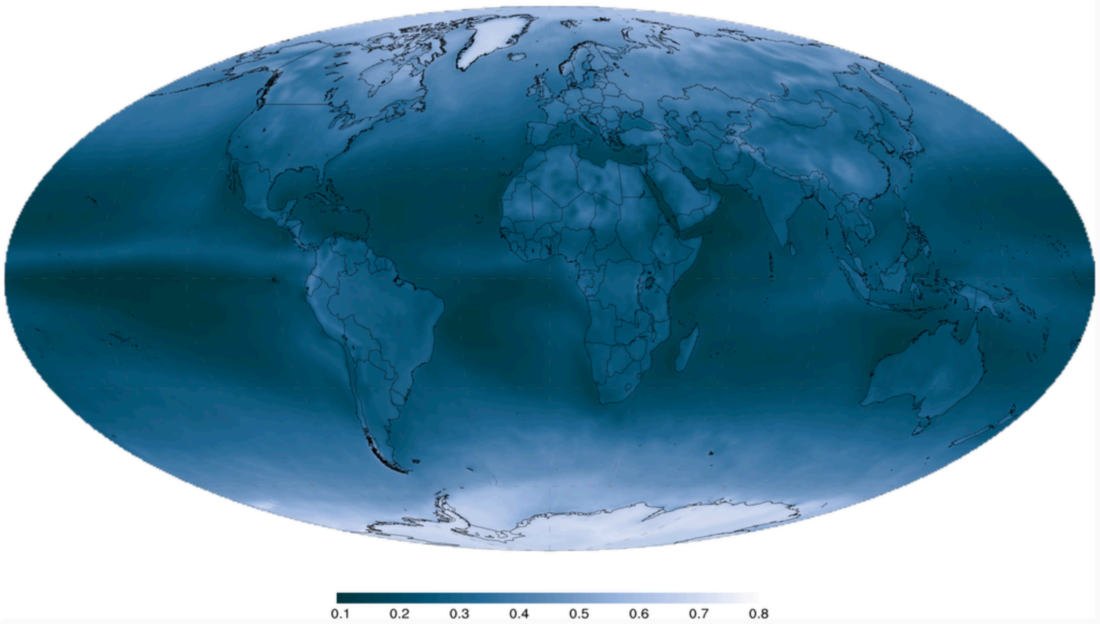
Bond albedo A_B = fractional reflectivity (integrated over all wavelengths)

Continents, ice, clouds, etc. have **different albedos**


REFLECTANCE SPECTRA: EARTH'S SURFACE MATERIALS

NASA


Clear Sky Albedo


Total Sky Albedo

(modified) Equilibrium temperature

$$P_{in} = \frac{L_\star}{4\pi a^2}(\pi R_p^2)$$

$$\rightarrow \frac{L_\star}{4\pi a^2}(\pi R_p^2)(1 - A_B)$$

$$\rightarrow T_{eq} = (1 - A_B)^{1/4}\, T_{eff}\sqrt{\frac{R_\star}{2a}}$$

(modified) Equilibrium temperature

$$
\begin{aligned}
T_{eq} &= (1 - A_B)^{1/4}\, T_{eff} \sqrt{\frac{R_\star}{2a}} \\
&= 279\,\mathrm{K}\,(1 - A_B)^{1/4} \left(\frac{T_{eff}}{5780\,\mathrm{K}}\right) \left(\frac{R_\star}{R_\odot}\right)^{1/2} \left(\frac{a}{\mathrm{au}}\right)^{-1/2}
\end{aligned}
$$

TPS Activity

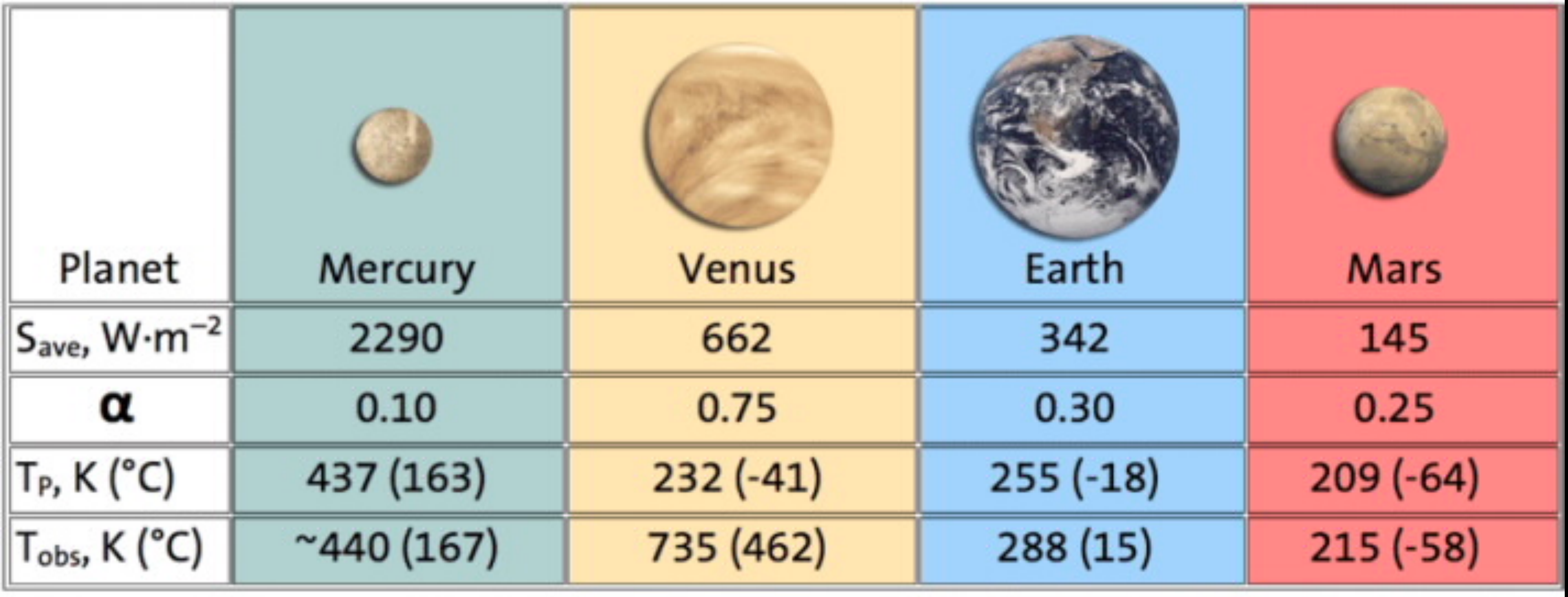
$$T_{eq} = 279\,\mathrm{K}\,(1 - A_B)^{1/4} \left(\frac{T_{eff}}{5780\,\mathrm{K}}\right) \left(\frac{R_\star}{R_\odot}\right)^{1/2} \left(\frac{a}{\mathrm{au}}\right)^{-1/2}$$

Earth’s Bond albedo is 0.33.

What is Earth’s equilibrium temperature?

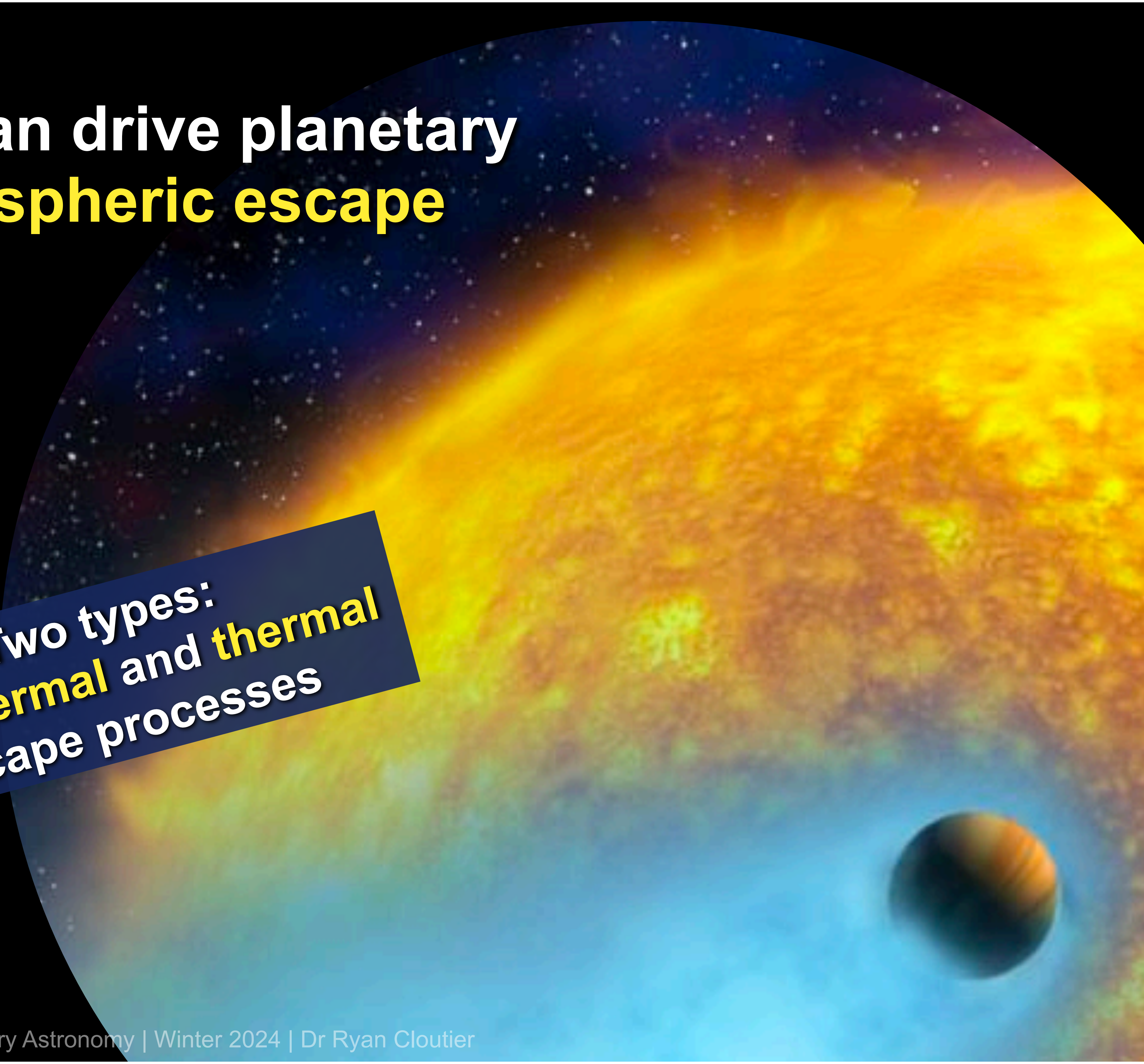
How does this compare to its surface temperature?

Bond albedos (α) in the inner solar system



Planet	Mercury	Venus	Earth	Mars
S_{ave}, W·m^{-2}	2290	662	342	145
α	0.10	0.75	0.30	0.25
T_P, K (°C)	437 (163)	232 (-41)	255 (-18)	209 (-64)
T_{obs}, K (°C)	~440 (167)	735 (462)	288 (15)	215 (-58)

Stars can drive planetary atmospheric escape



Two types: non-thermal and thermal escape processes

Non-thermal escape process

A physical process that results in the full or partial loss of a planet's atmosphere and that is *not driven by heating the atmospheric gas

***often driven by interactions between a planet's magnetic field and energetic particles from the host star (i.e. the stellar wind)**

Non-thermal escape process

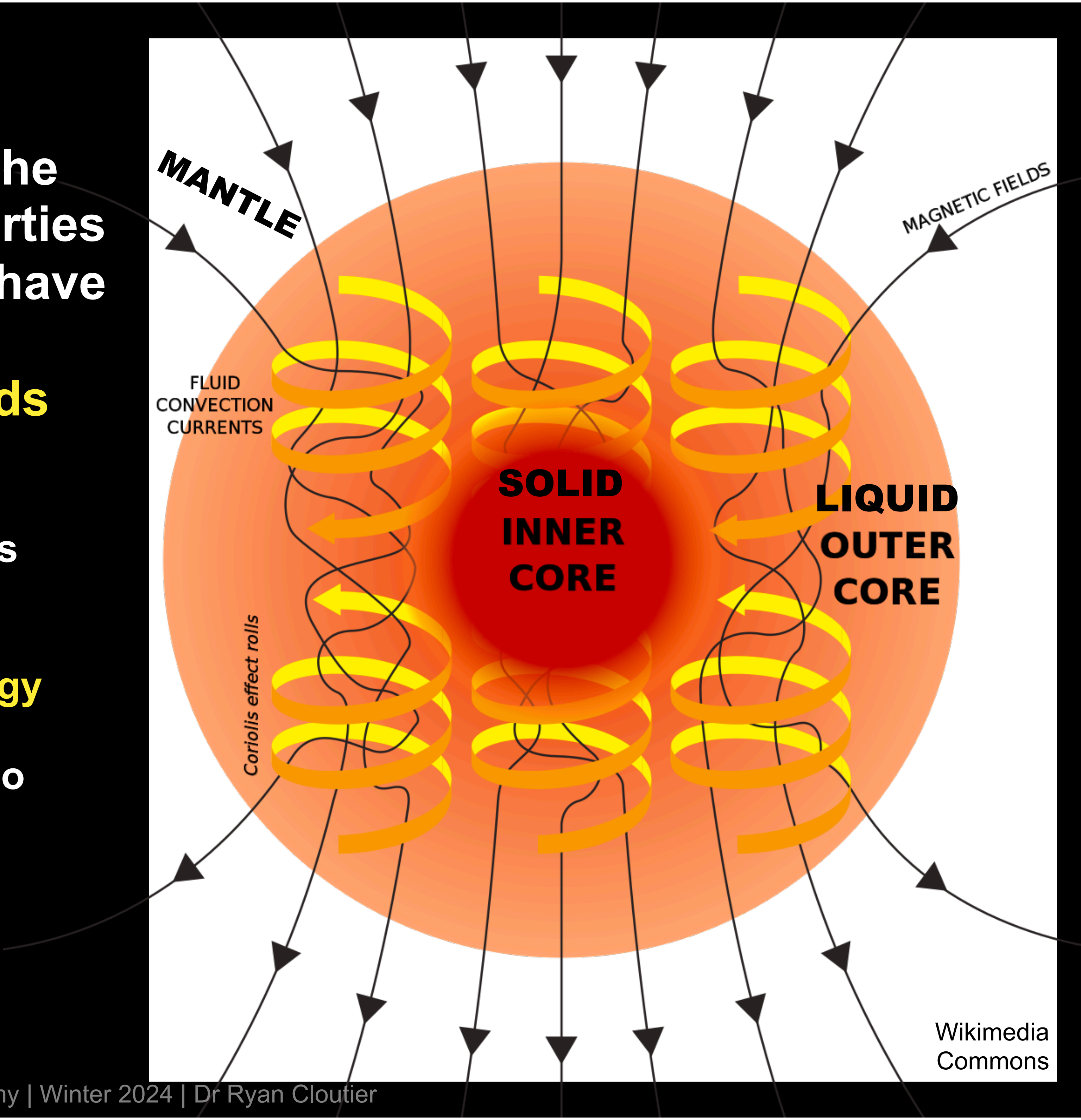
A physical process that results in the full or partial loss of a planet's atmosphere and that is *not driven by heating the atmospheric gas

***another example is planetary collisions,**

but in this lecture we're focusing on star-planet interactions

Planets with the following properties are believed to have large-scale magnetic fields

- an interior that is
  - conductive
  - convective
- has kinetic energy (from rotation) to drive the dynamo



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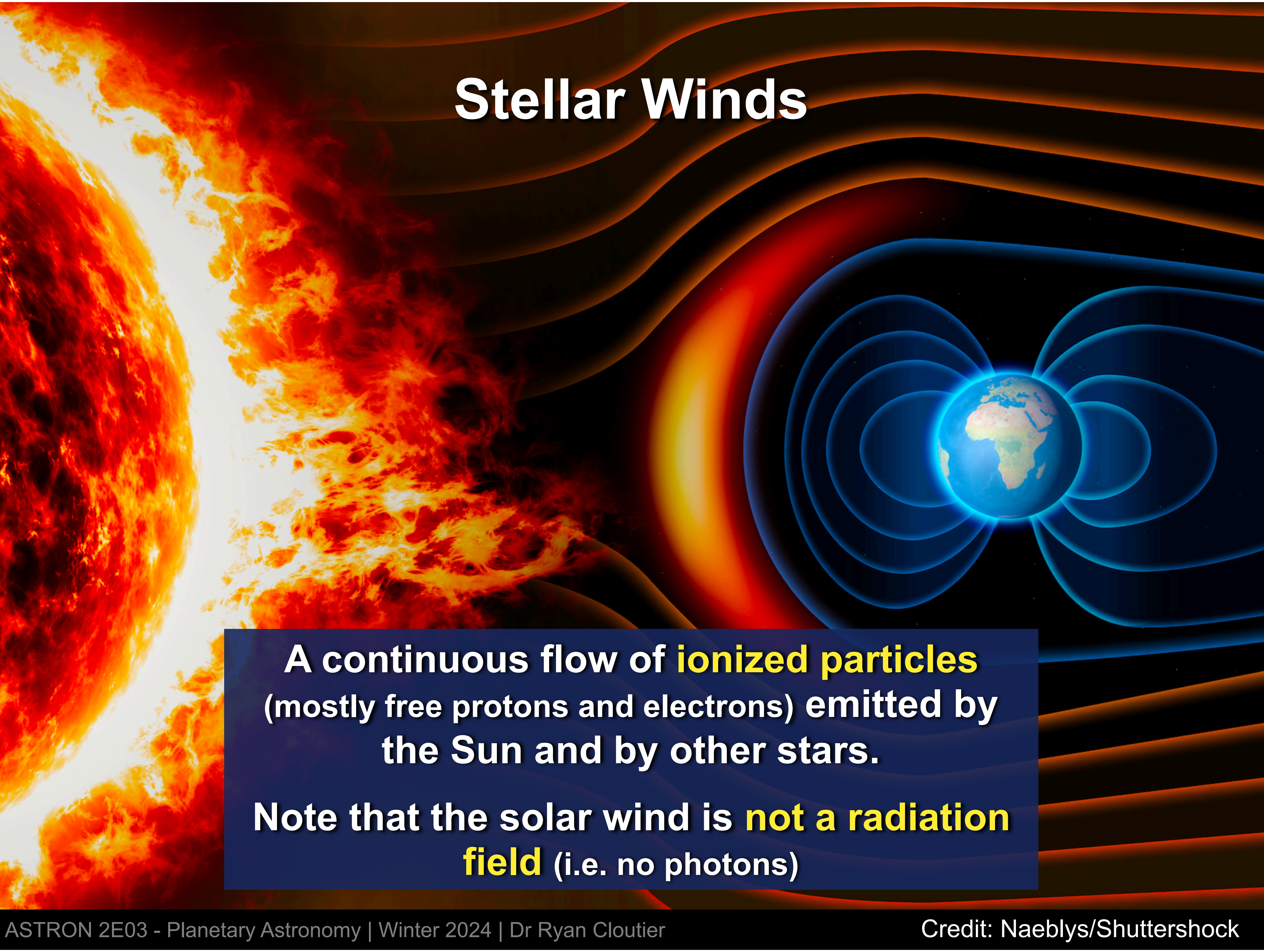
Stellar Winds



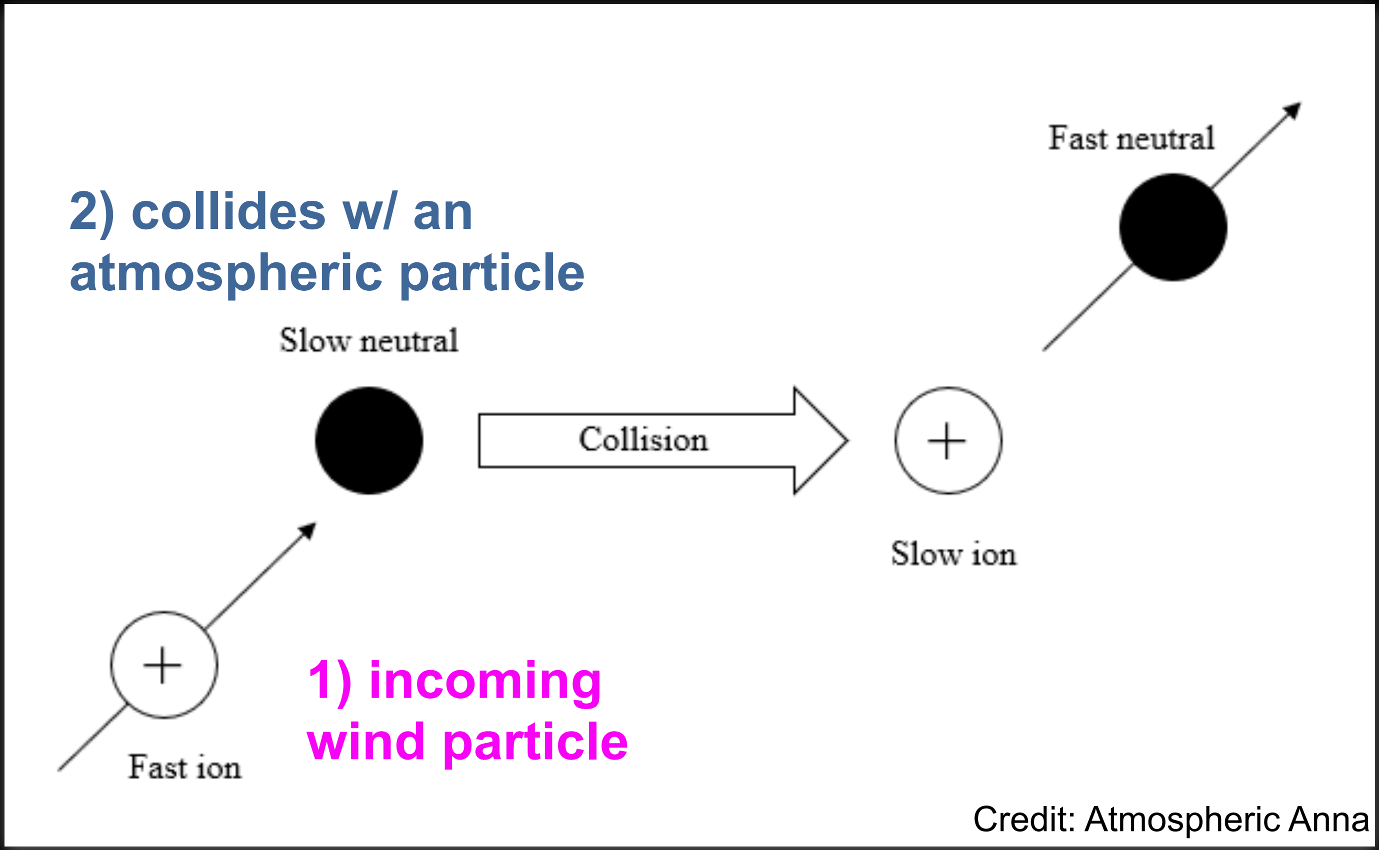
A continuous flow of **ionized particles** (mostly free protons and electrons) emitted by the Sun and by other stars.

Note that the solar wind is **not a radiation field** (i.e. no photons)

Credit: Naeblys/Shuttershock

Charge exchange and sputtering from stellar wind particles to planetary atmospheric particles can results in atmospheric escape…

Charge exchange and sputtering from stellar wind particles to planetary atmospheric particles can results in atmospheric escape…

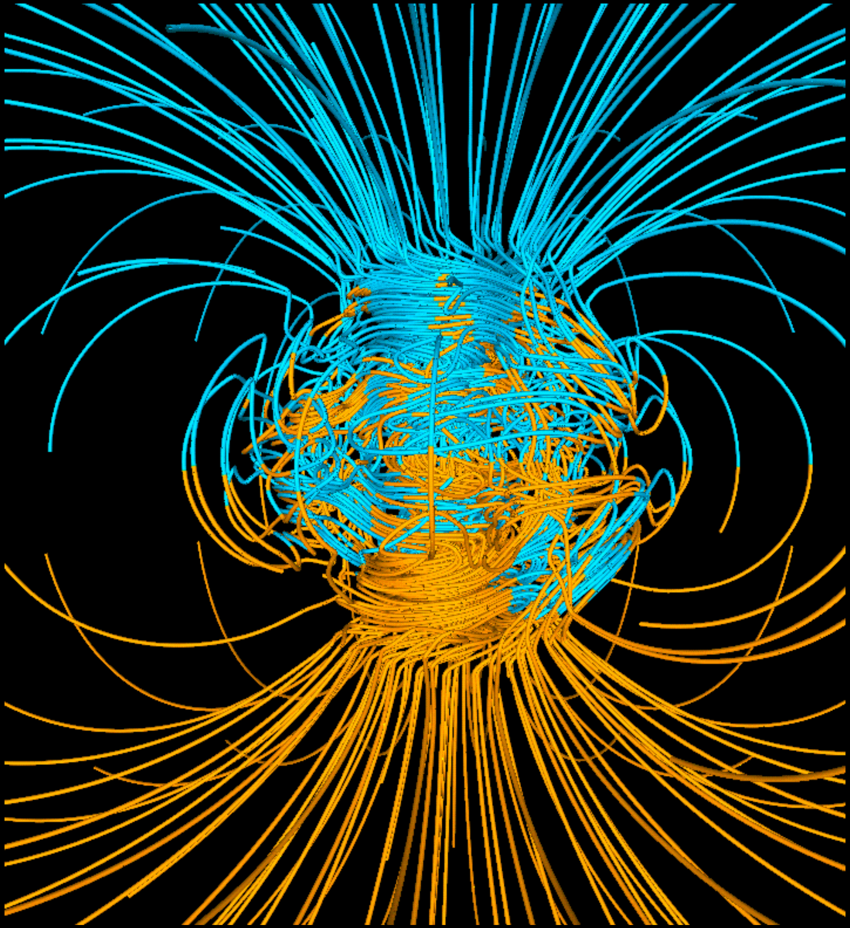


Credit: Atmospheric Anna

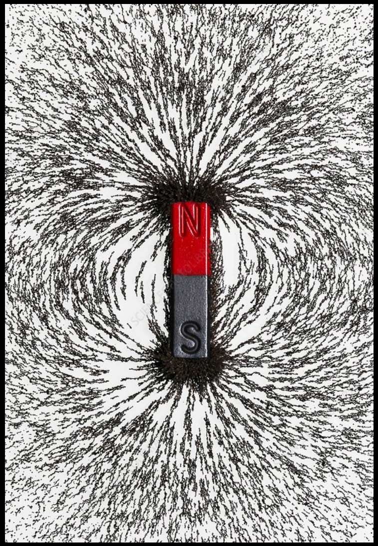
3) momentum is transferred to the atmospheric particle, which can **escape**

4) the now low-momentum wind particle is **trapped by the Earth's magnetic field**

Charge exchange and sputtering from stellar wind particles to planetary atmospheric particles can results in atmospheric escape…

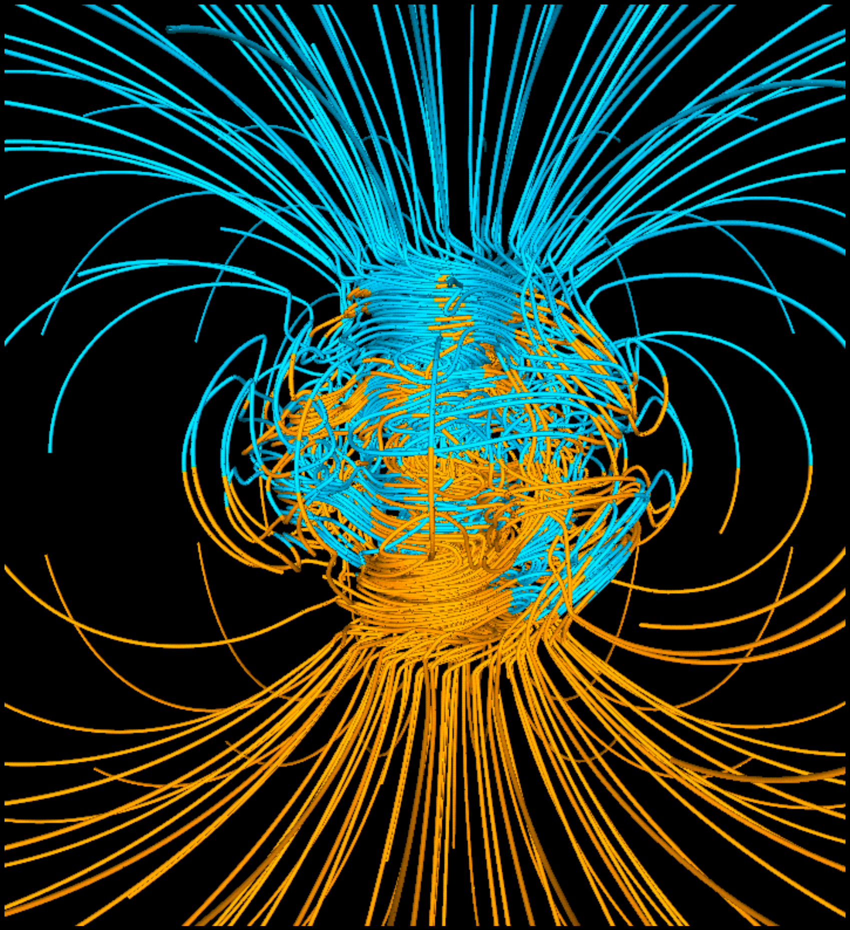


Earth's magnetic field behaves like a large scale **bar magnetic**



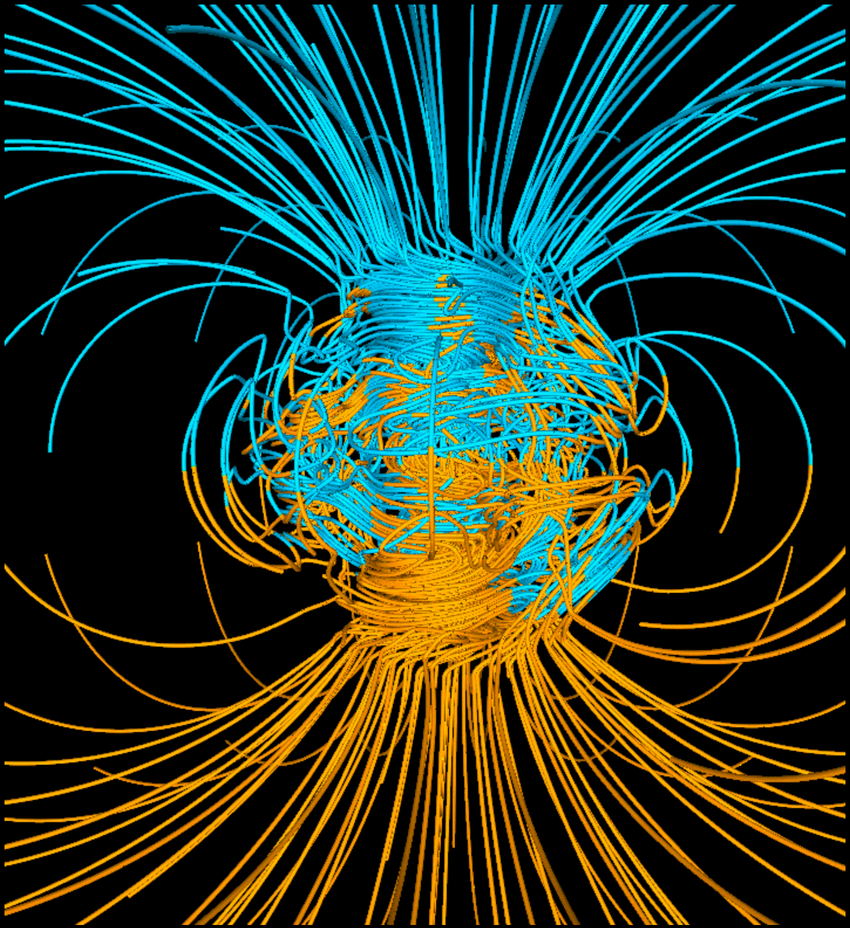
Credit: Cordelia Malloy

Charge exchange and sputtering from stellar wind particles to planetary atmospheric particles can results in atmospheric escape…



Most of these field lines are **closed**, which traps the slow ions from the stellar wind

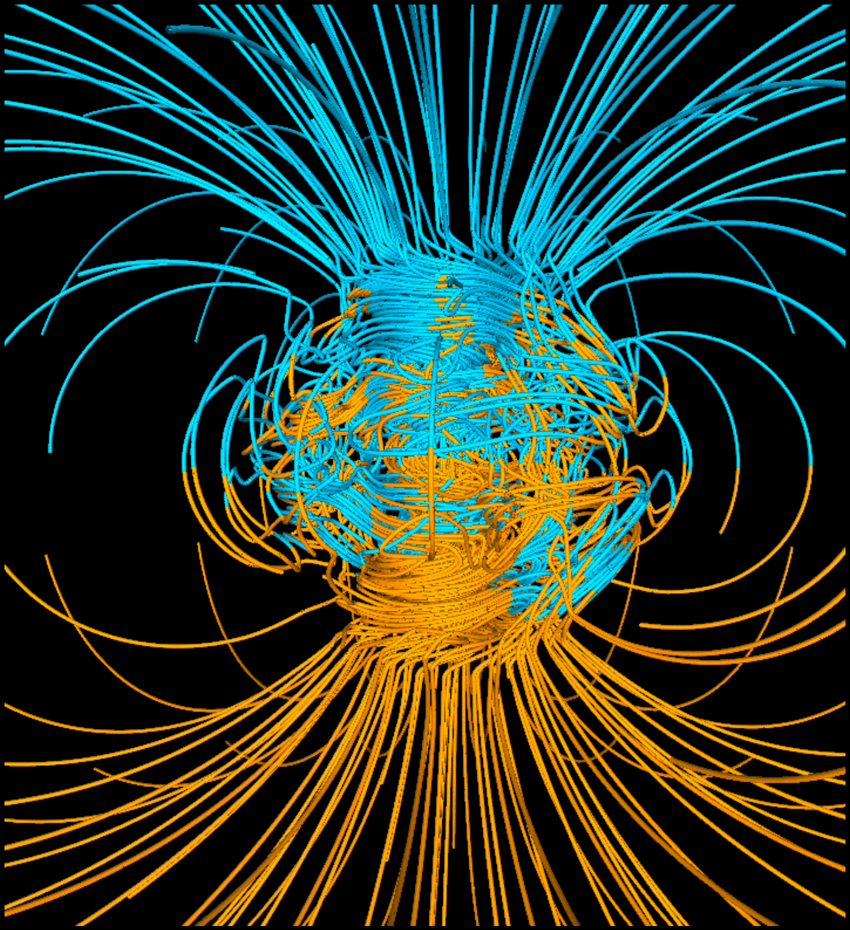
Charge exchange and sputtering from stellar wind particles to planetary atmospheric particles can results in atmospheric escape…



Charge exchange accounts for the majority of the atmospheric loss on the Earth today

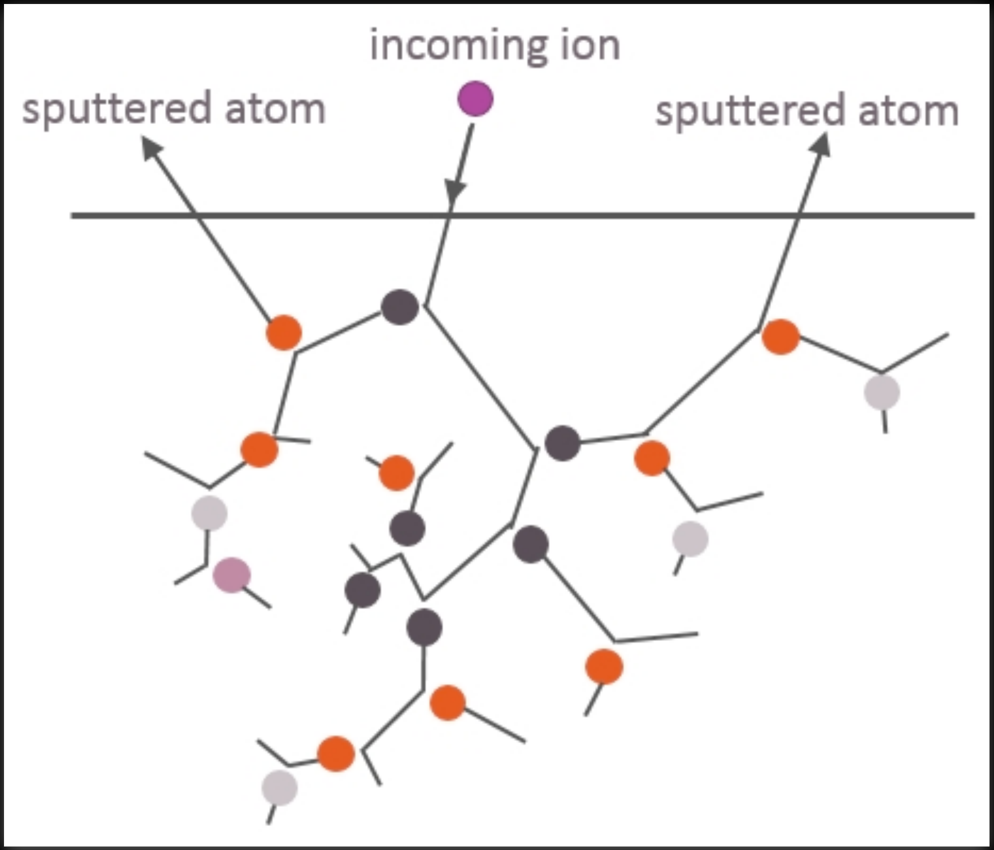
But magnetic field lines are not closed at the poles

Therefore, there are some slow moving ions produced by charge exchange that do escape at the poles as they are directed away by open field lines



This mass loss process is known as the polar wind

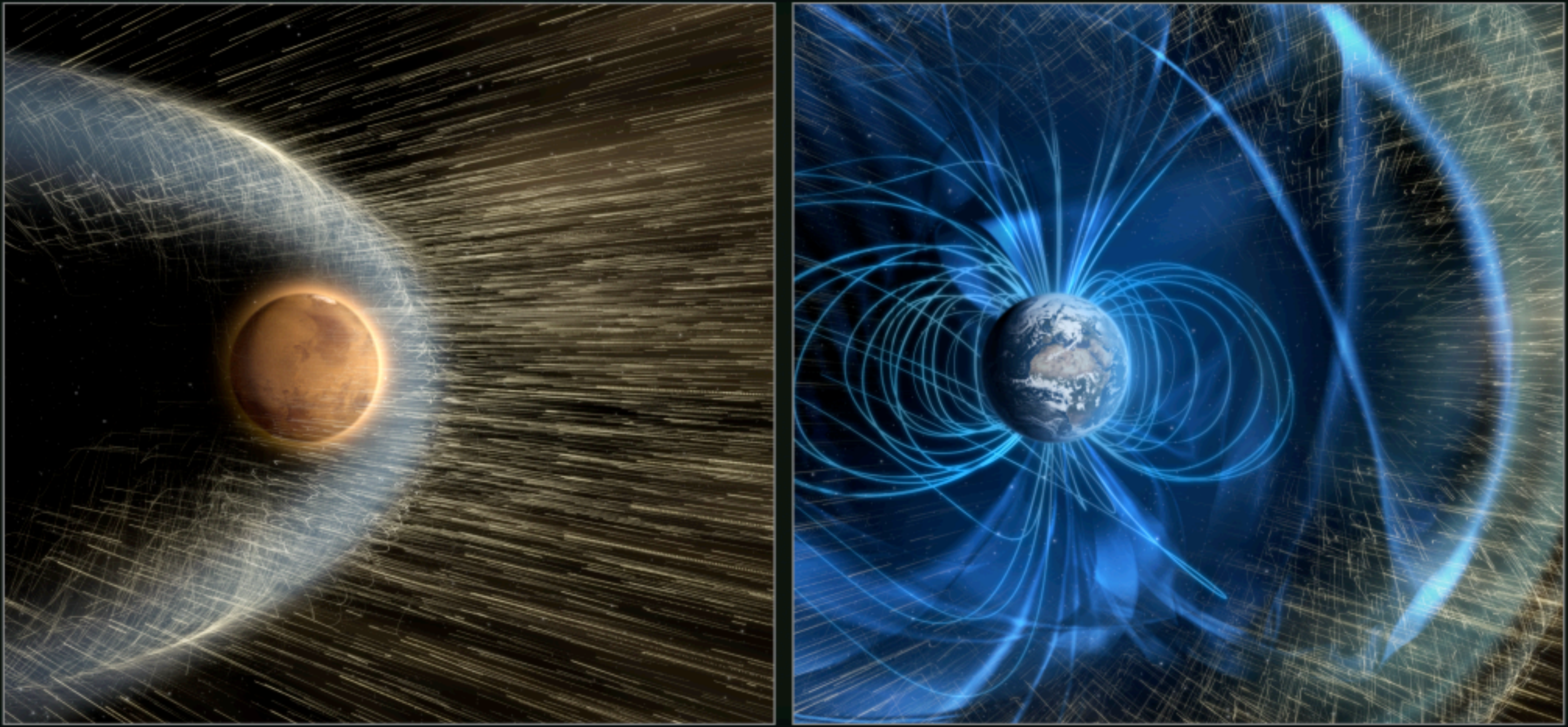
Charge exchange and sputtering from stellar wind particles to planetary atmospheric particles can results in atmospheric escape…



Credit: Polygon Physics

- momentum exchange between an coming wind particle and and an upper atmospheric layer produces a collisional cascade
- momentum propagates through the material and can result in a sputtered atom that escapes

Strong **magnetic fields** help shield a planet's atmosphere from the **stellar wind**



NASA/Goddard Space Flight Center

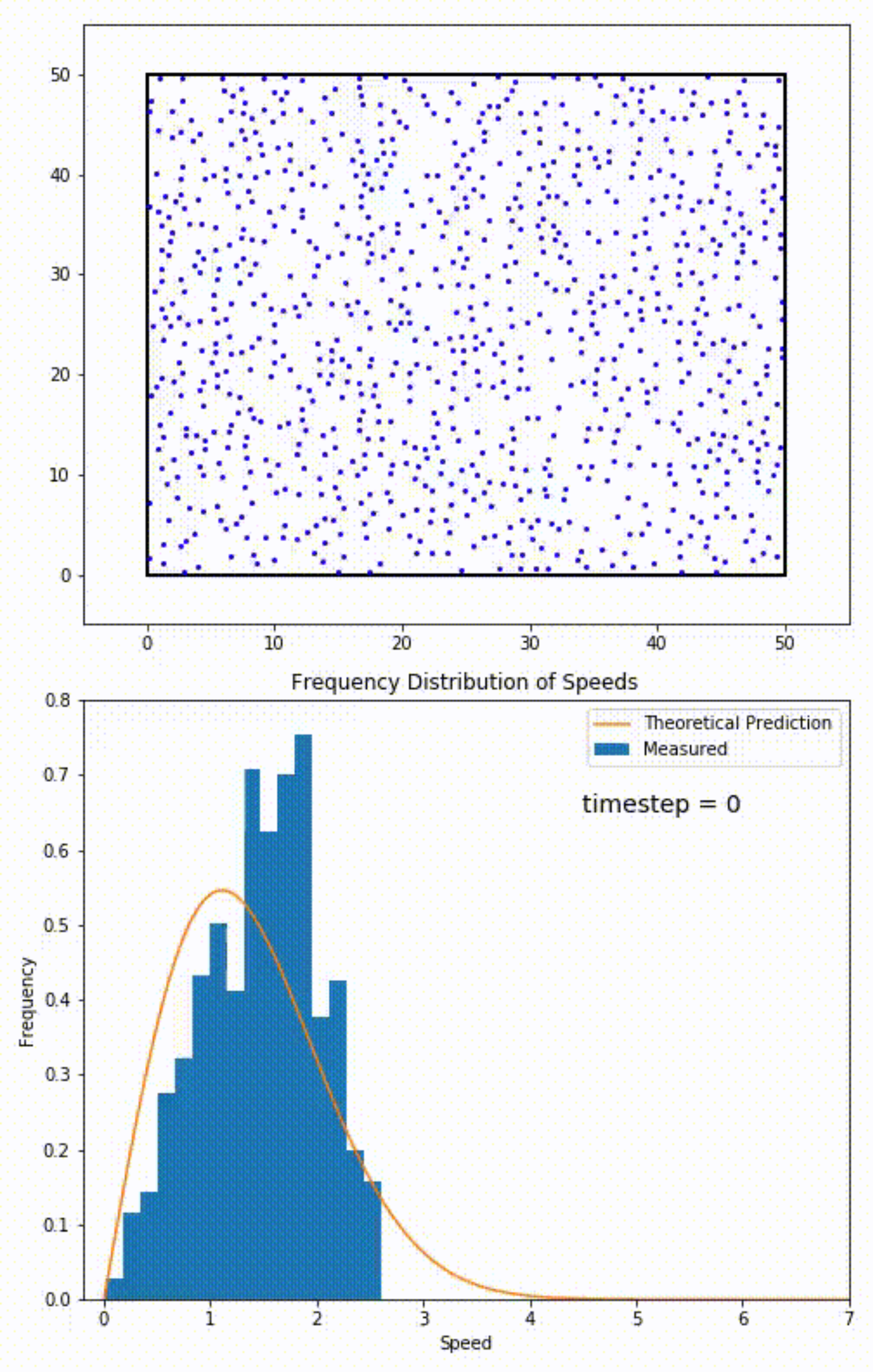
Thermal escape process

A physical process that results in the full or partial loss of a planet’s atmosphere and that is driven by heating the atmospheric gas

Thermal Escape I:
Jeans escape

Recall the
Maxwell-Boltzmann distribution

$$\left(\frac{dN}{dv}\right)_{\boxed{m,T}} = v^2 \left(\frac{m}{2\pi k_B T}\right)^{3/2} \times \exp\left(-\frac{mv^2}{2k_B T}\right)$$

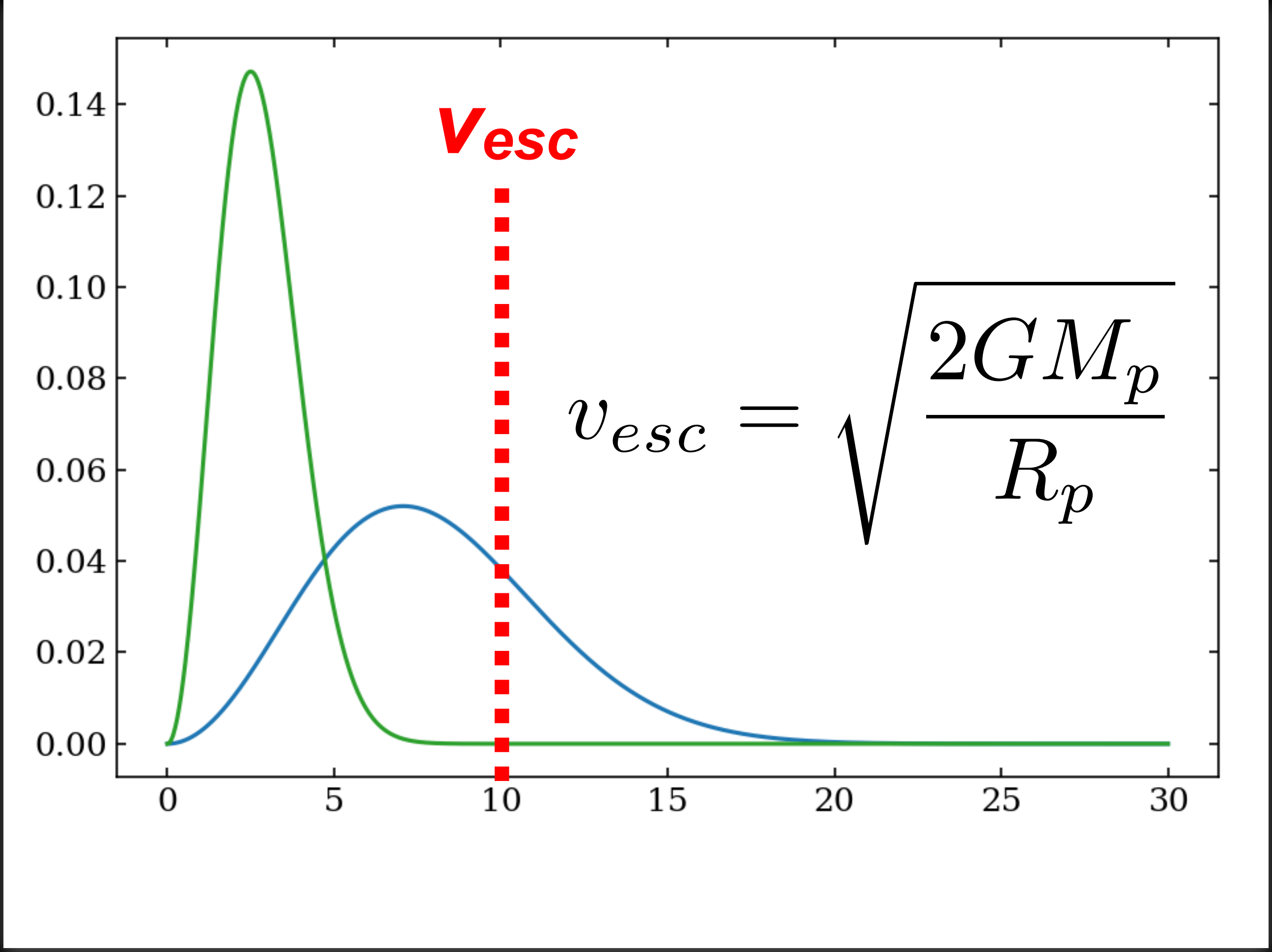


Thermal Escape I: Jeans escape

Recall a planet's escape velocity (see lecture 2)

$$v_{esc} = \sqrt{\frac{2GM_p}{R_p}}$$

For gas in the uppermost layers of a planet's atmosphere where $T_{gas} \sim T_{eq}$, thermal velocities may exceed and v_{esc} and gas particles are lost to space



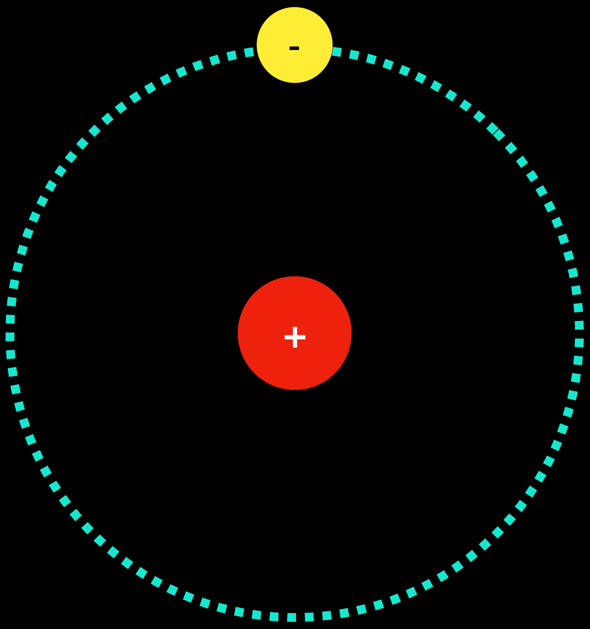
$$v_{esc} = \sqrt{\frac{2GM_p}{R_p}}$$

Jeans escape efficiency is moderated by v_{esc}, the gas particle mass, and gas temperature

Mean molecular weight, μ = average particle mass in units of the mass of hydrogen atom

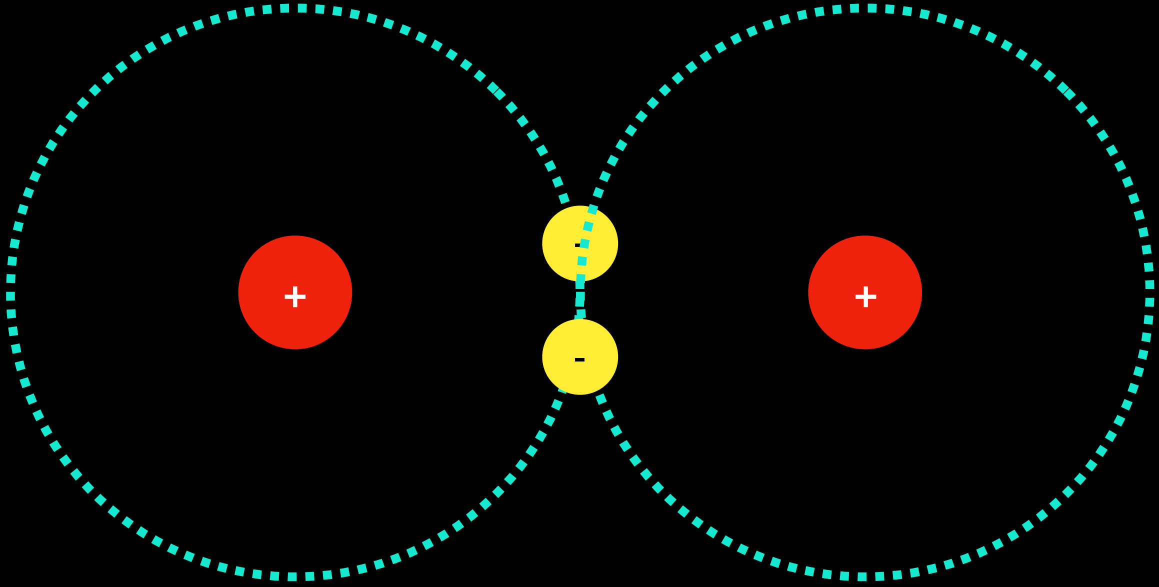
For atomic hydrogen, H

$\mu = 1$



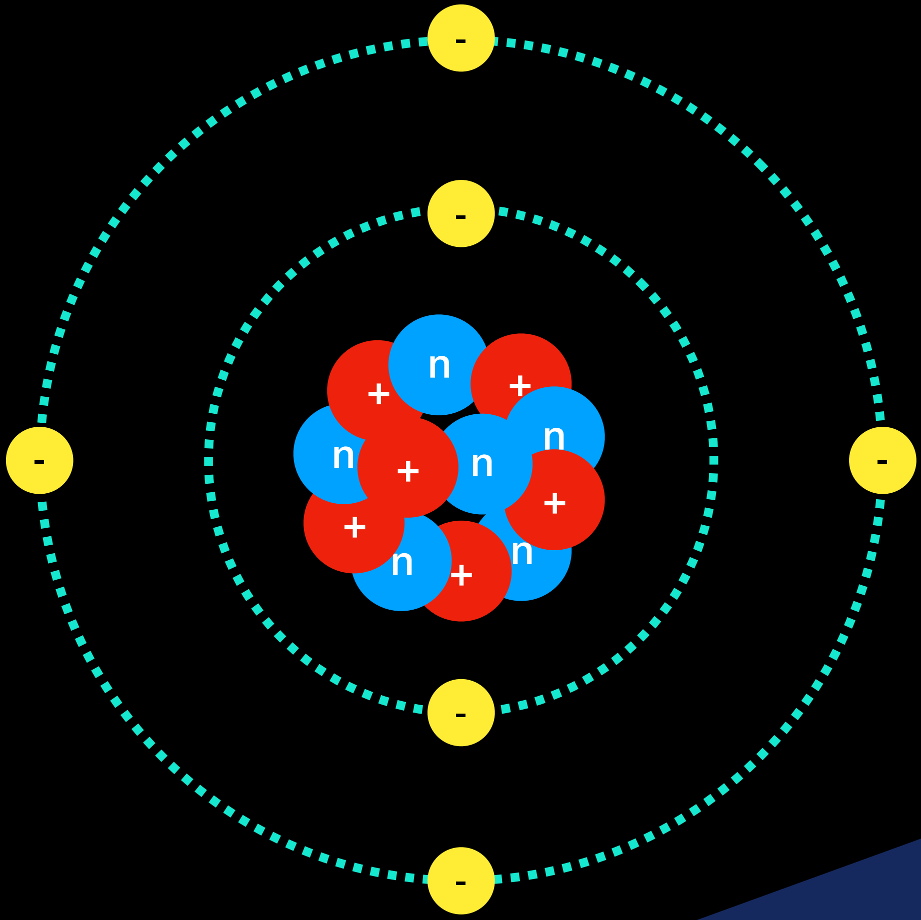
For molecular hydrogen, H_2

$\mu = 2$



For atomic carbon, C

$\mu = 12$

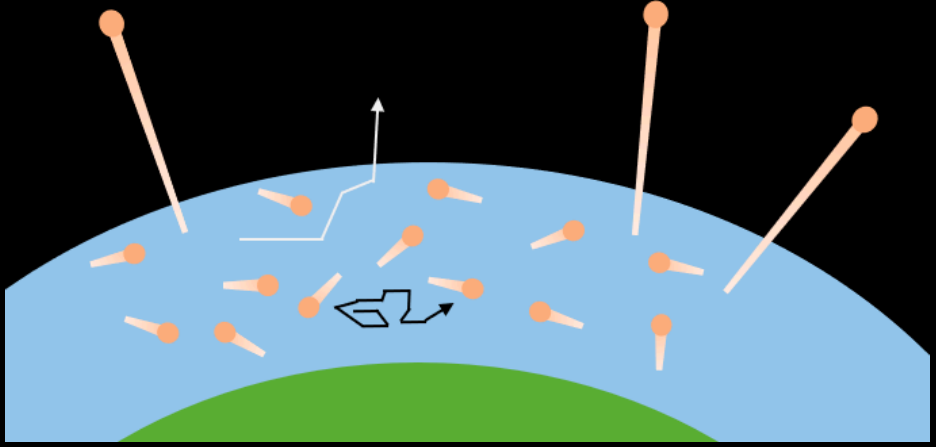


Note:

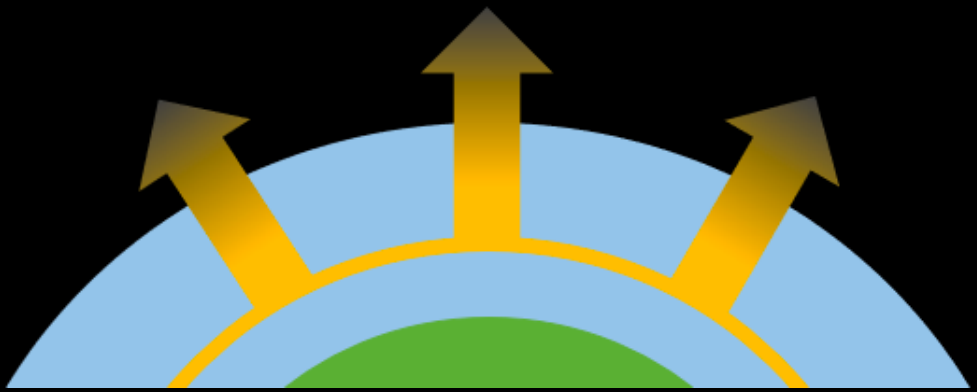
$m_{electron} << m_{proton} \sim m_{neutron}$

Thermal Escape II:
Hydrodynamic escape

Like Jeans escape, atmospheric gas particles are heated and can escape the planet's gravity



Unlike Jeans escape, instead of losing individual atoms or molecules, rapid heating drives a **bulk outward flow** of material



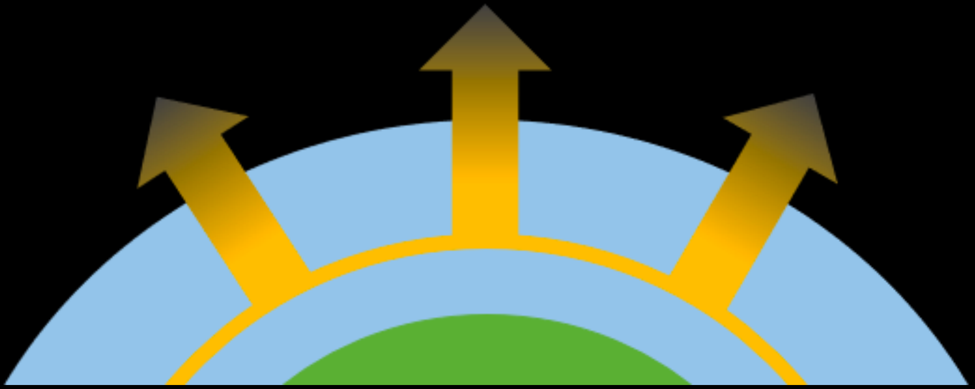
Credit: Atmospheric Anna

Thermal Escape II:
Hydrodynamic escape

Like Jeans escape, atmospheric gas particles are heated and can escape the planet’s gravity

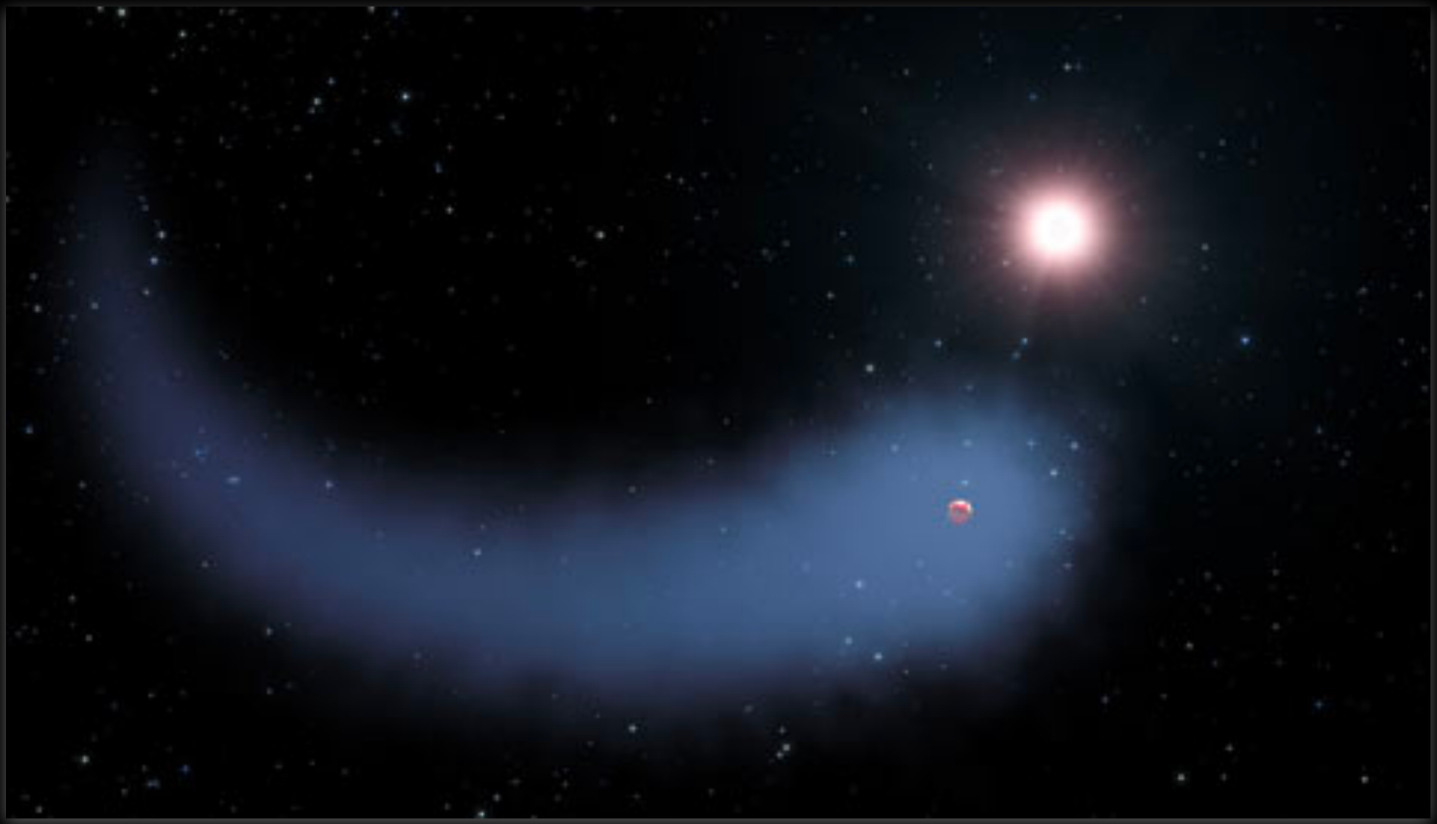
A powerful heating sources is X-ray and UV photons from the host star

Unlike Jeans escape, instead of losing individual atoms or molecules, rapid heating drives a **bulk outward flow** of material



Credit: Atmospheric Anna

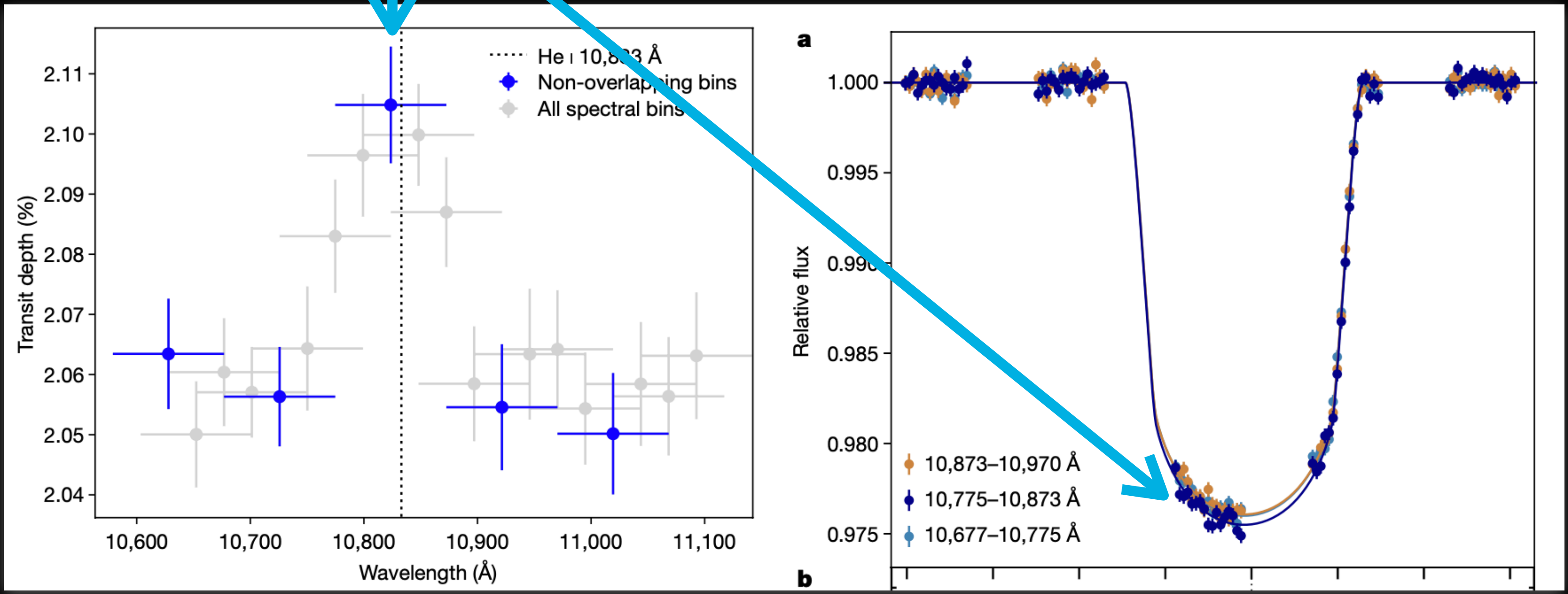
A hydrodynamically-driven outward flow can be seen as a trail of material as the evaporating planet orbits its host star



NASA/ESA

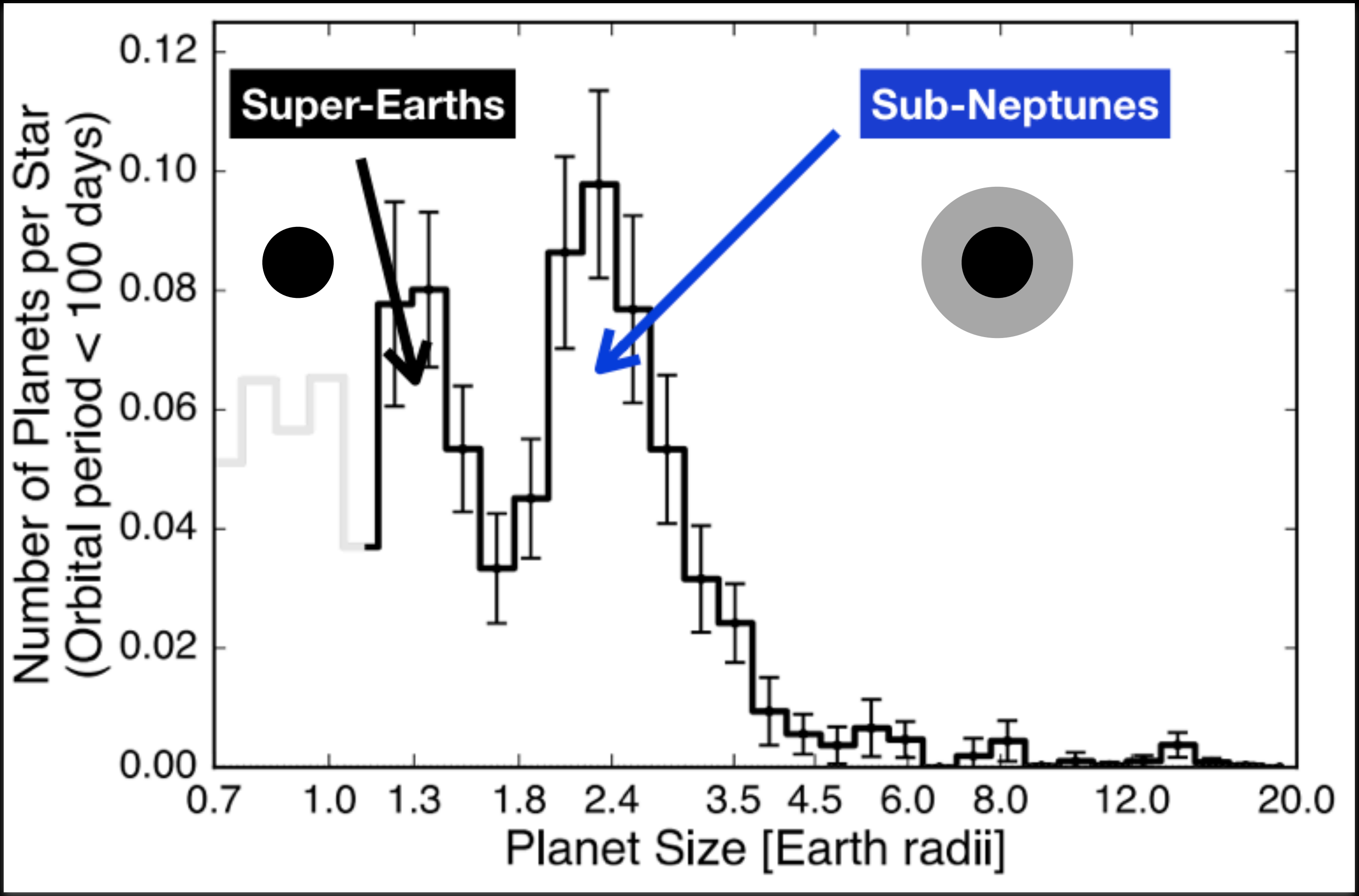
Light weight He atoms are more easily lost than heavier molecules in a planet’s upper atmosphere

Astronomers have witnessed ongoing hydrodynamic escape via excess He absorption at 1083 nm in a handful of hot exoplanets



Spake et al 2018

Hydrodynamic escape can explain a major feature in the planet size distribution of close-in exoplanets: The Radius Valley

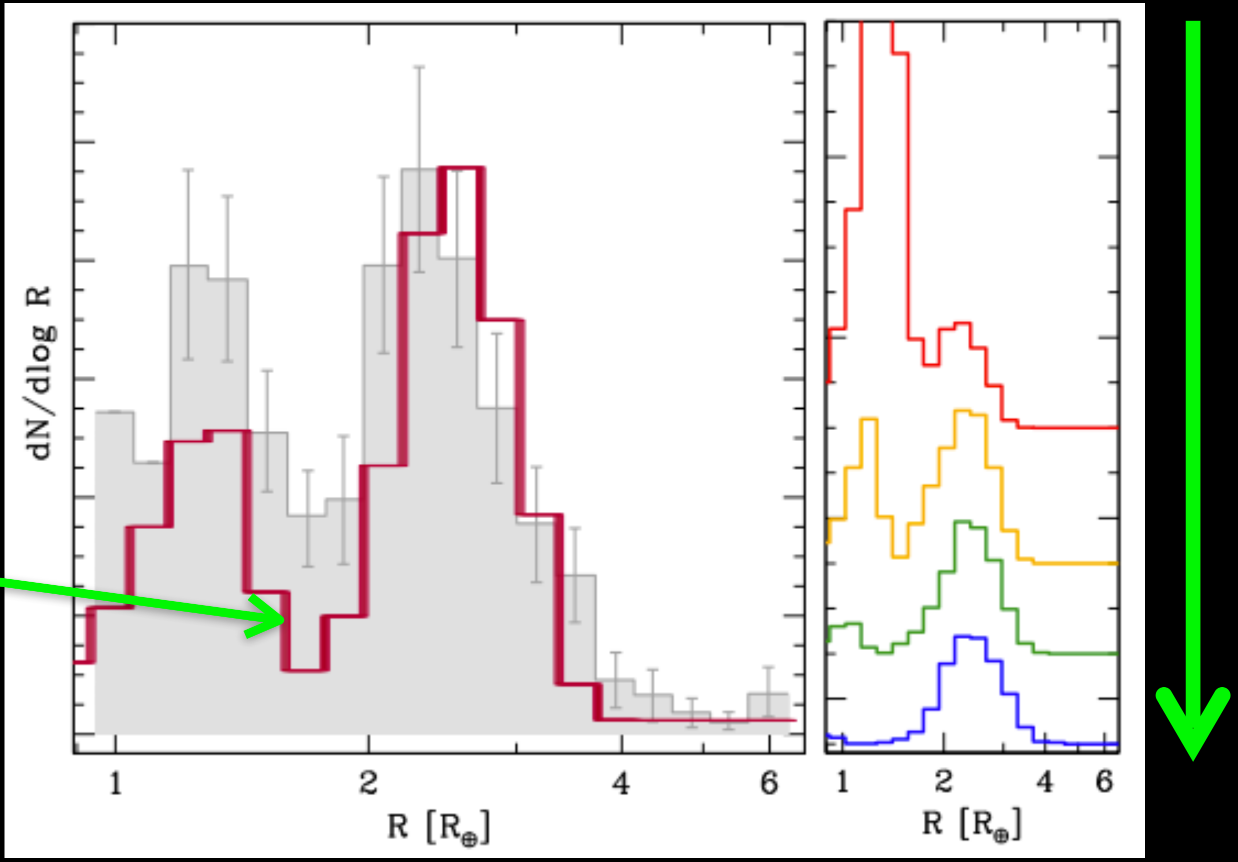


Fulton et al 2017

XUV-driven hydrodynamic escape

Decreasing XUV instellation produces fewer super-Earths

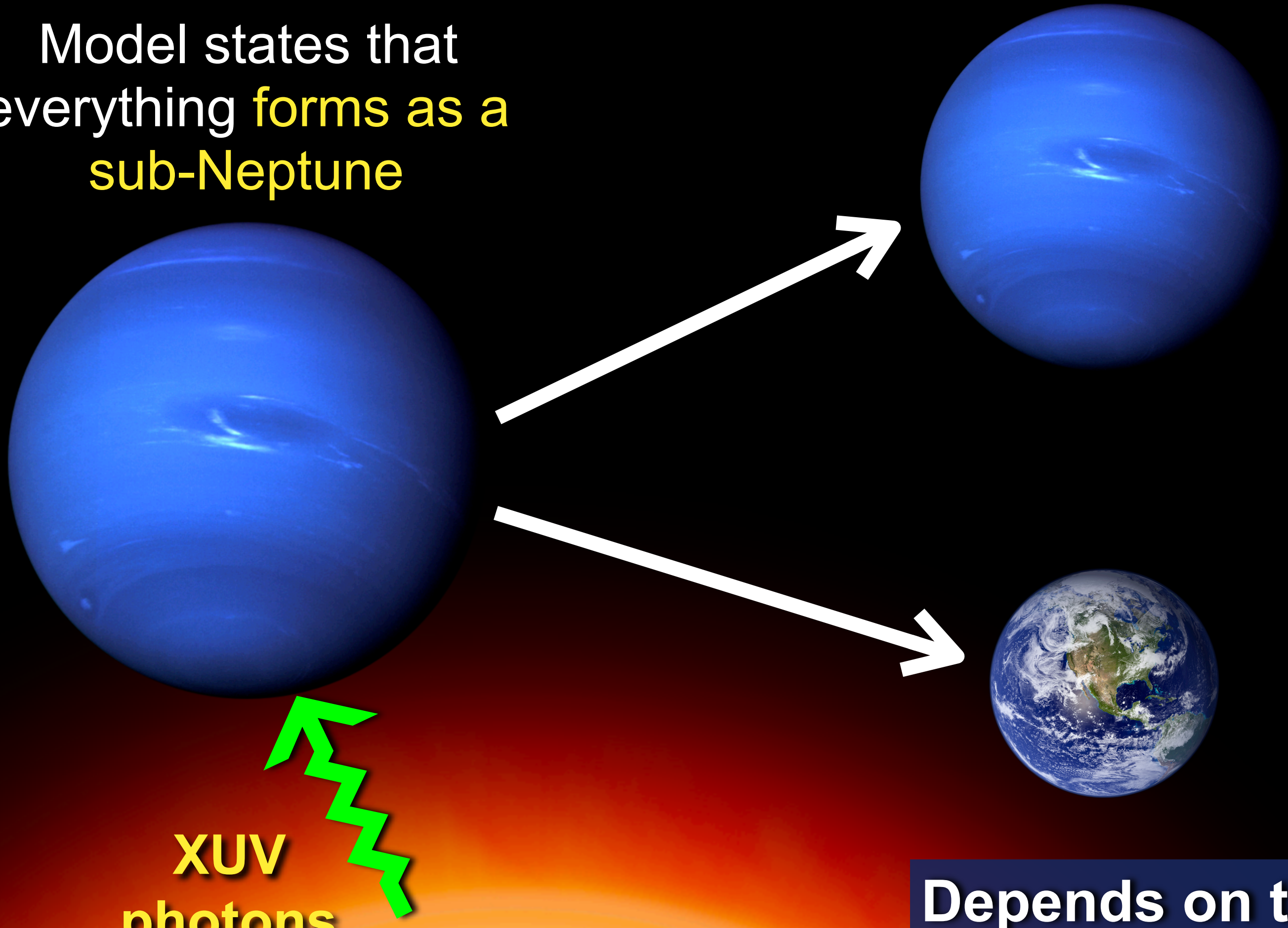
Models of XUV-driven heating and subsequent hydrodynamic escape can reproduce the Radius Valley



Owen & Wu 2017

XUV-driven hydrodynamic escape

Model states that everything forms as a sub-Neptune



XUV heating results in either partial or complete atmospheric loss

Depends on the planet's semi-major axis and surface gravity
(i.e. its mass)

A closing note on understanding the impact of atmospheric escape on exoplanets:

Thermal escape processes depend on planetary heating by radiation from the host star

→ Our telescopes are good at seeing radiation (i.e. light)

But non-thermal escape processes depend on the stellar wind

→ We can’t directly observe ions in stellar winds because they’re composed of mostly free protons and electrons, not light

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It is very difficult to assess the importance of non-thermal escape processes on exoplanets

Summary of planetary **heating and cooling** processes discussed so far

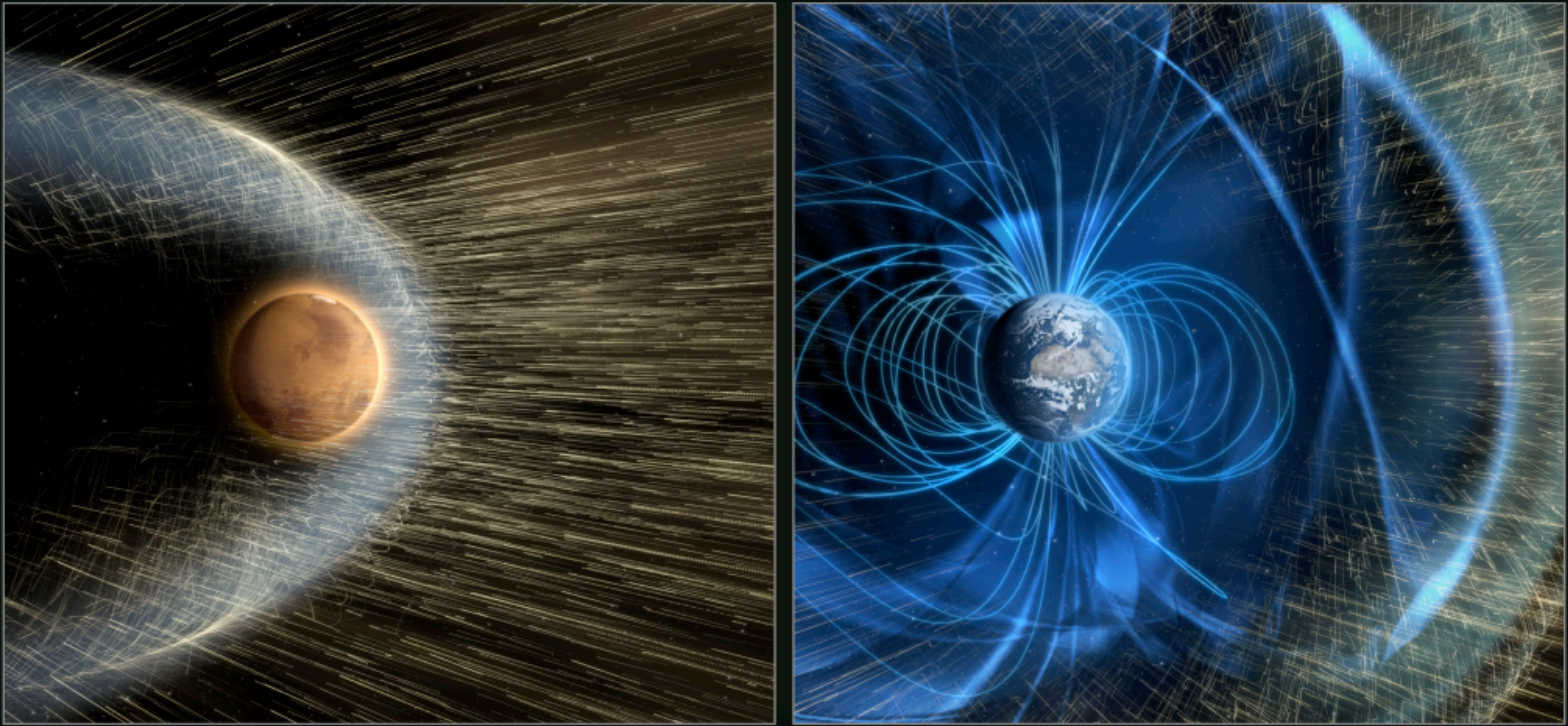
Heating	Cooling
T_{eq} is set by the host star's **blackbody radiation**	~~Planet's can resist heating by having a high albedo or a large-scale magnetic field, but this isn't really cooling~~
XUV heating, which can drive a hydrodynamic flow	Planets radiate as **blackbodies** at their T_{eq}
Stellar wind particles impart energy via collisions with atmospheric particles	
Tidal heating (see lecture 3)	

Planet size determines its cooling timescale

In class, we'll derive the following scaling between a planet's cooling timescale and its radius

$$t_{\rm cool} \propto R_p$$

Mars’ small size is the reason its interior is no longer molten and why it has a **weak magnetic field**



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