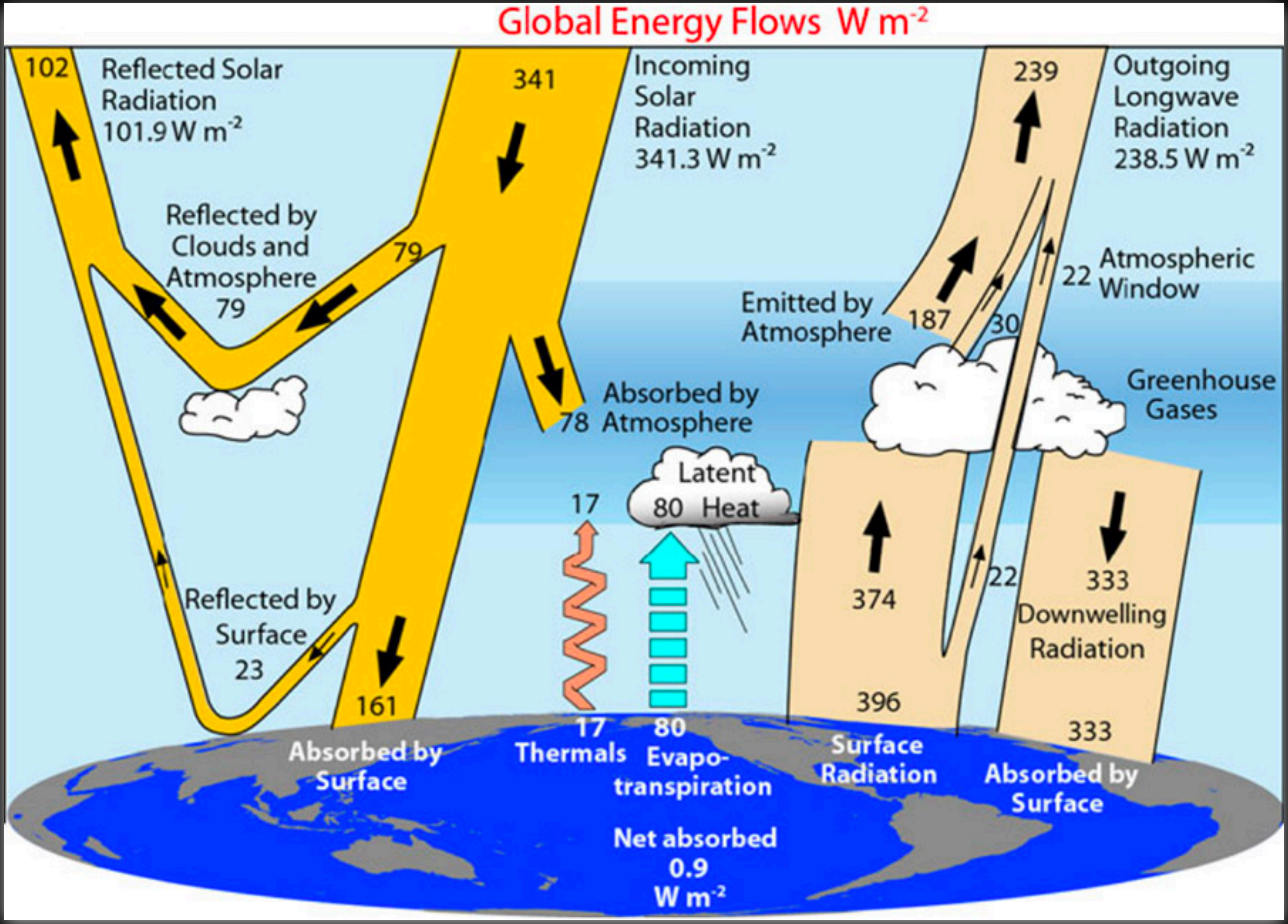
Lecture 5 - Heating/Cooling
The Greenhouse Effect



Kevin Trenberth, John Fasullo and Jeff Kiehl

Learning Objectives - Heating/Cooling

The Greenhouse Effect

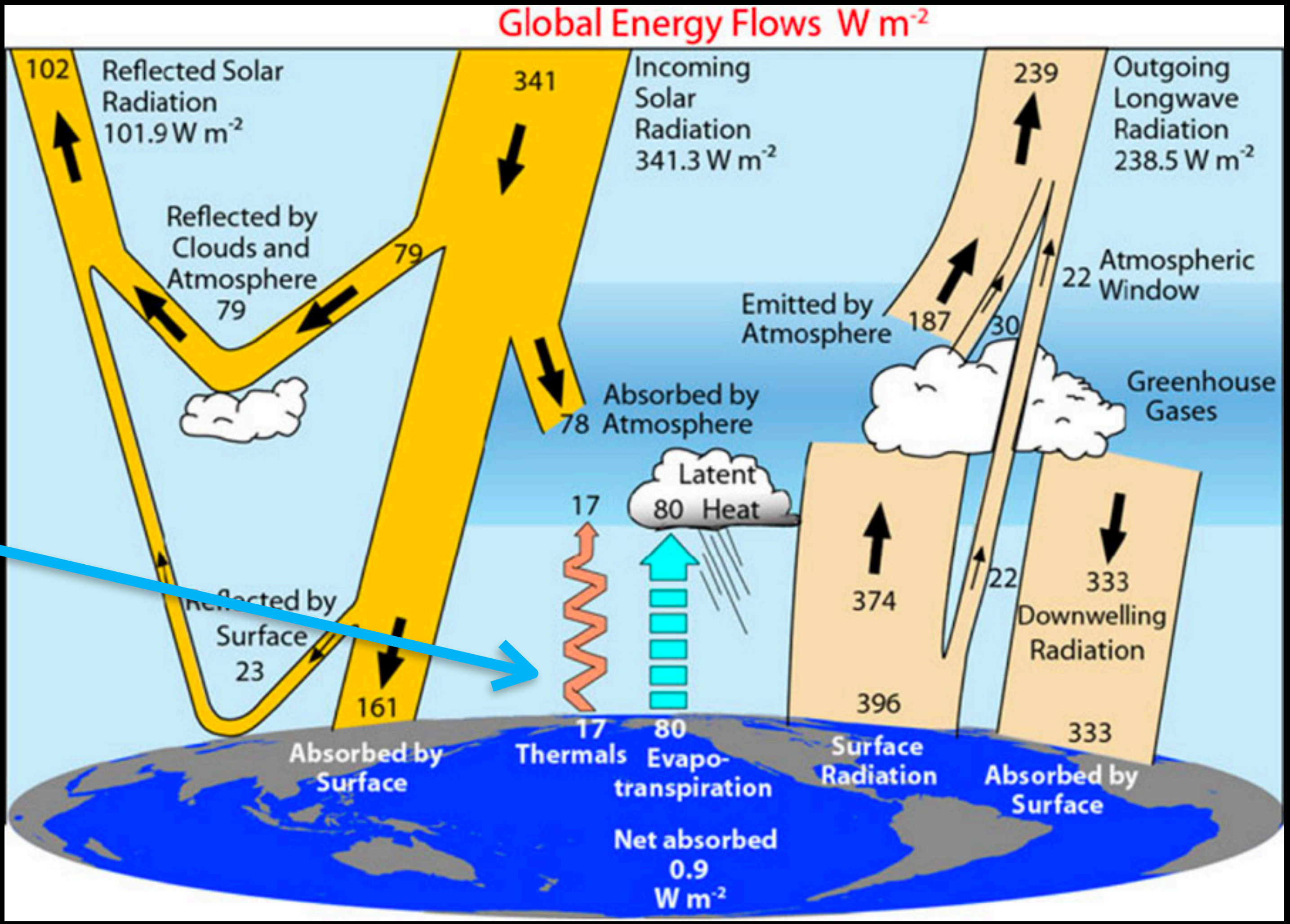
1) List examples of radiative forcing processes that impact the energy budgets of planetary atmospheres
2) Define the greenhouse effect and describe its impact
3) Understand and replicate the toy model of the GH effect with an arbitrary number of absorbing layers
4) Compare and contrast the GH effect on the Earth and Venus to the exoplanet population
5) List the steps in the Carbon-Silicate cycle on Earth

Radiative Forcing

Any physical process that alters the energy budget of a planet's atmosphere

Cooling processes

- albedo
- blackbody radiation



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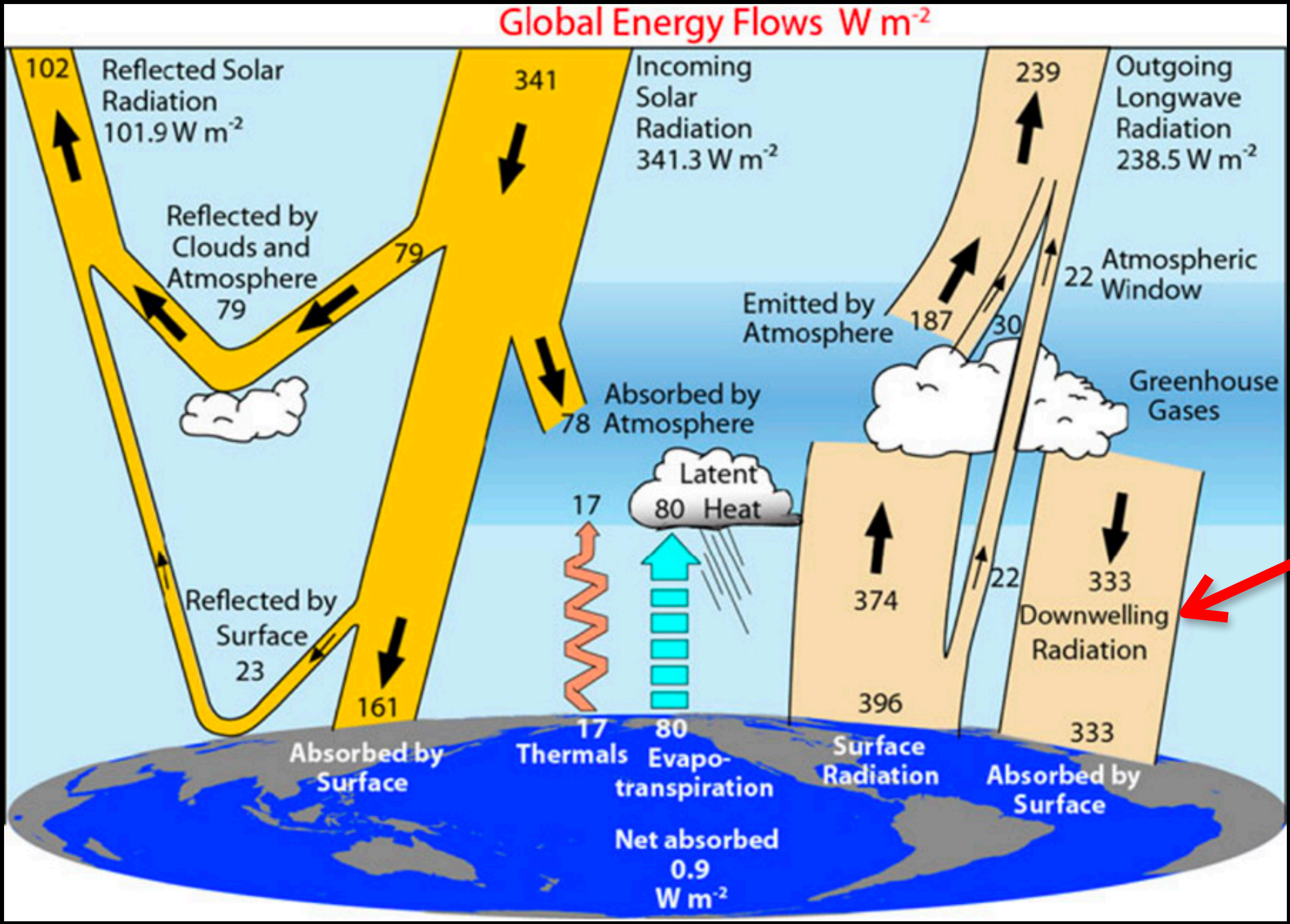
Radiative Forcing

Any physical process that alters the energy budget of a planet's atmosphere



Heating processes

- incident stellar flux
- GH effect

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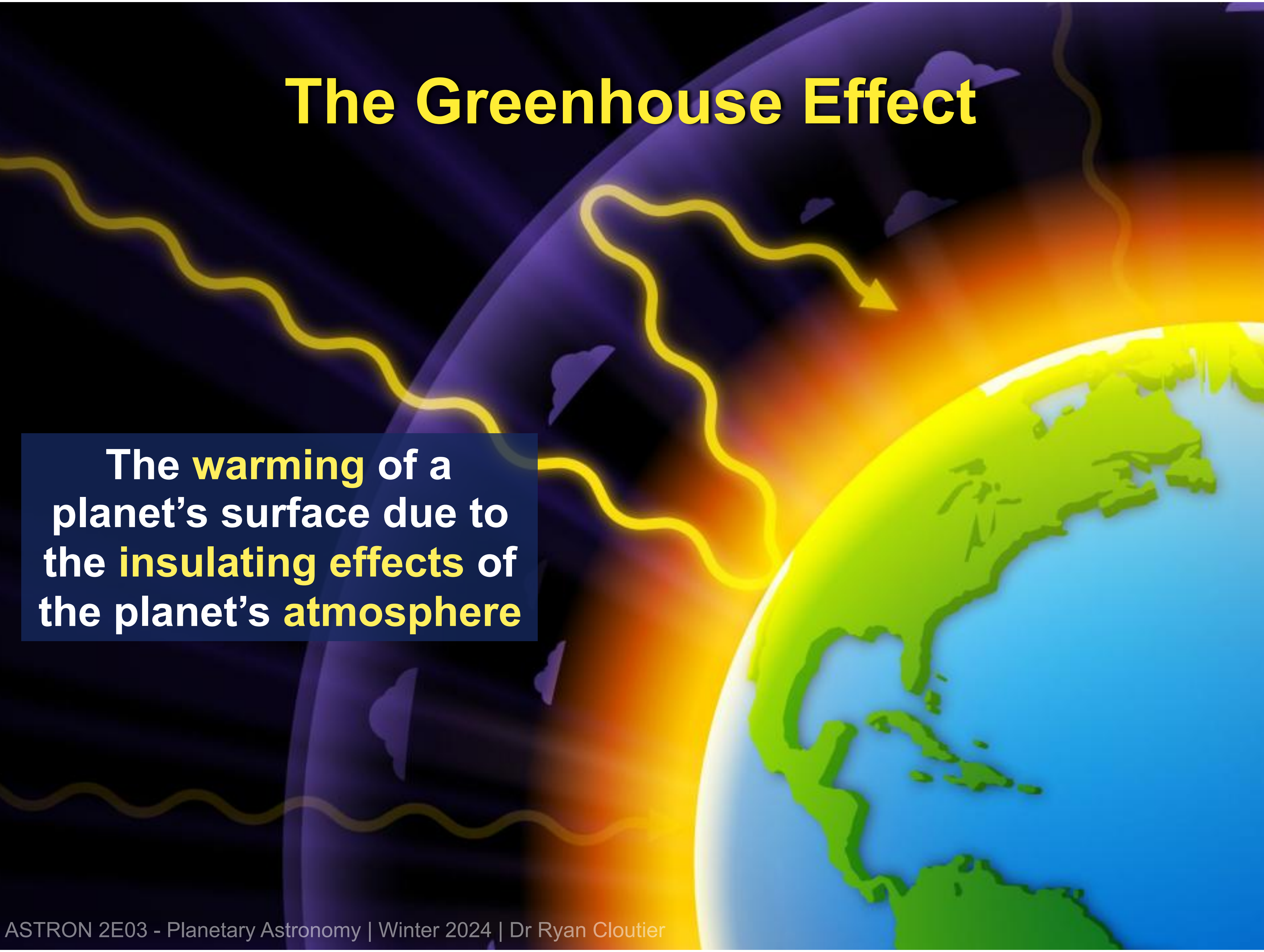
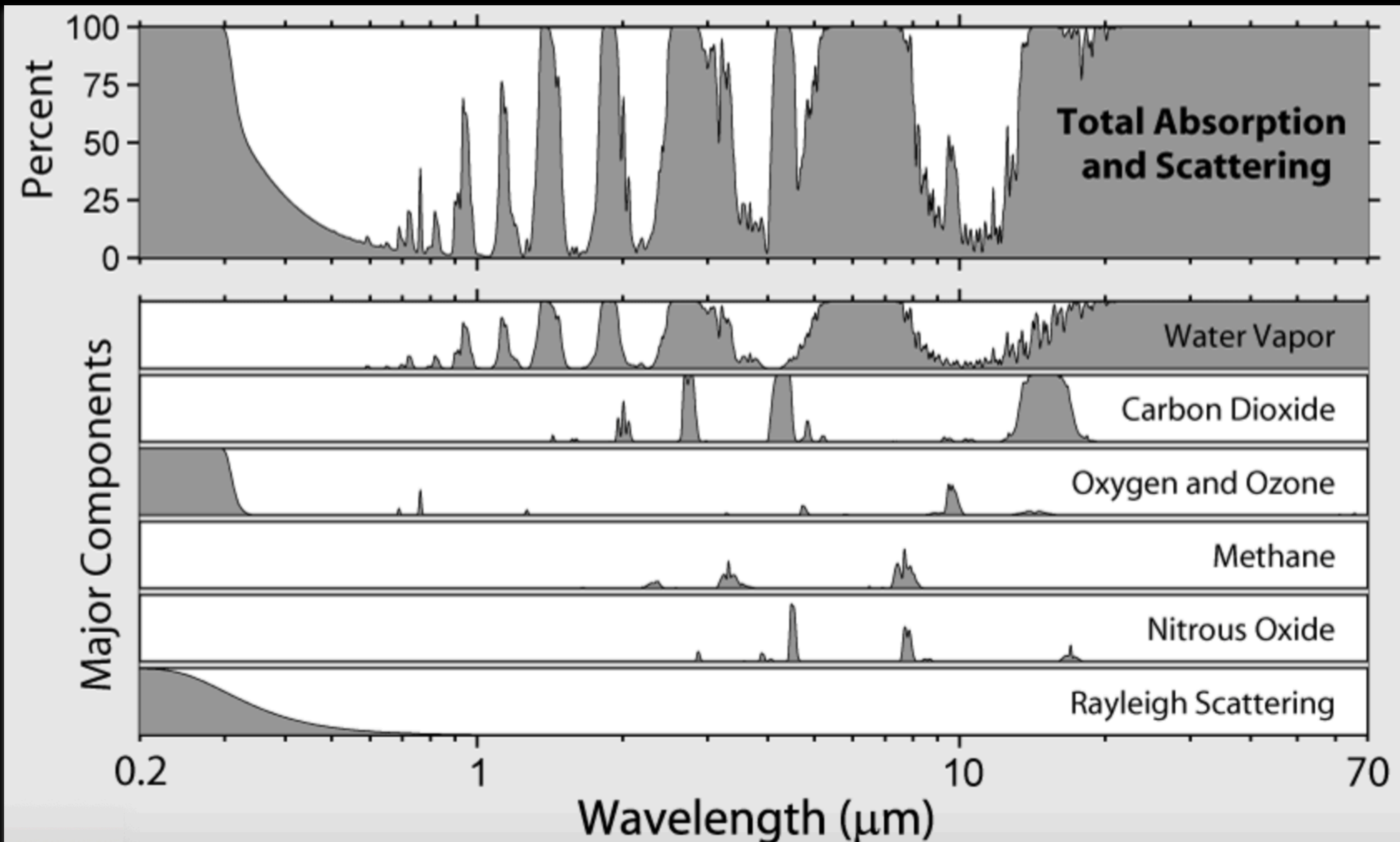
The Greenhouse Effect



The warming of a planet's surface due to the insulating effects of the planet's atmosphere

Atmospheric transmission: GH gases



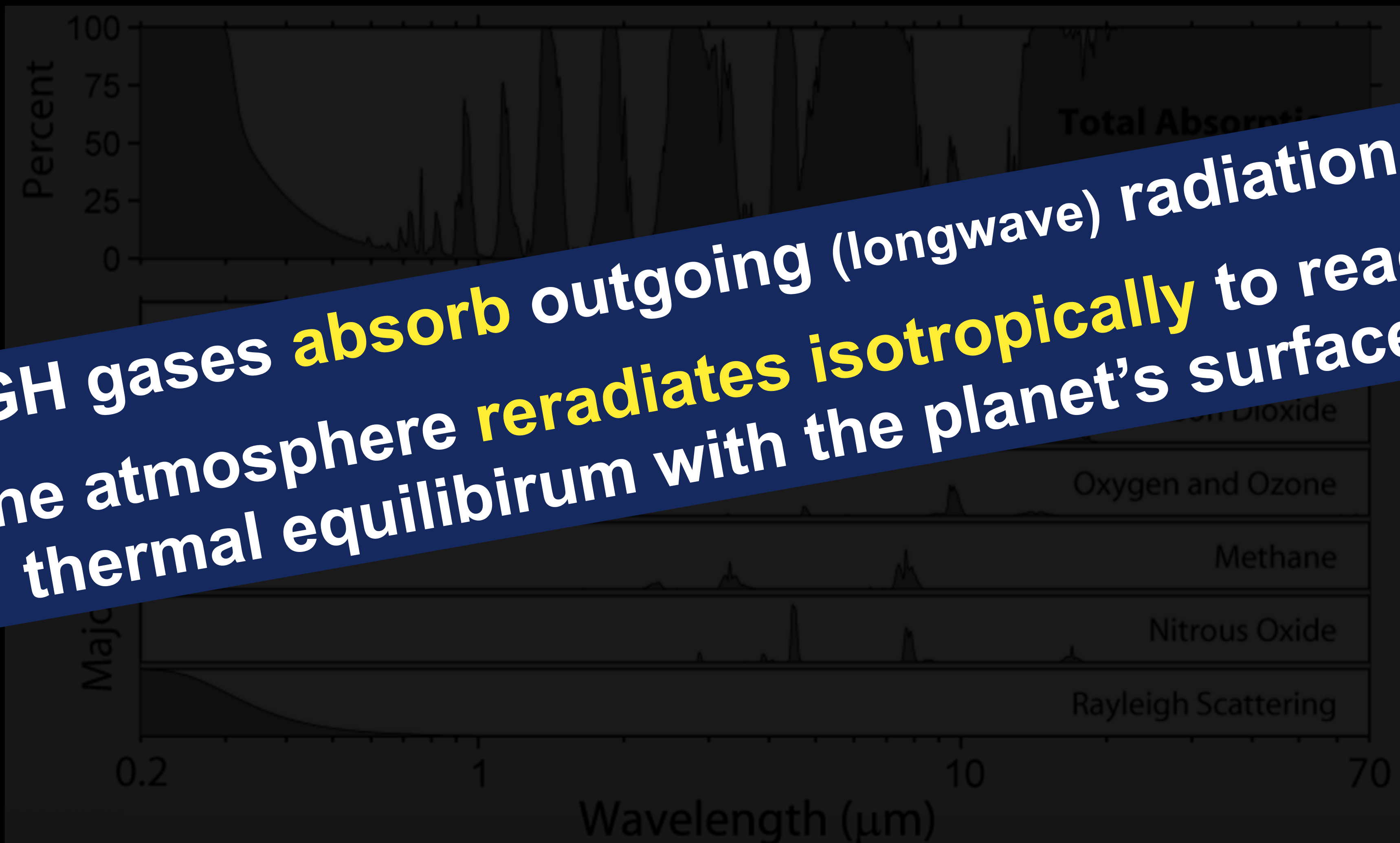
Recall a planet's equilibrium temperature

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

For the Earth, $T_{eq,\oplus}$ ~ 252 K (-21 °C)

Whereas $T_{surf,\oplus}$ ~ 288 K (15 °C)

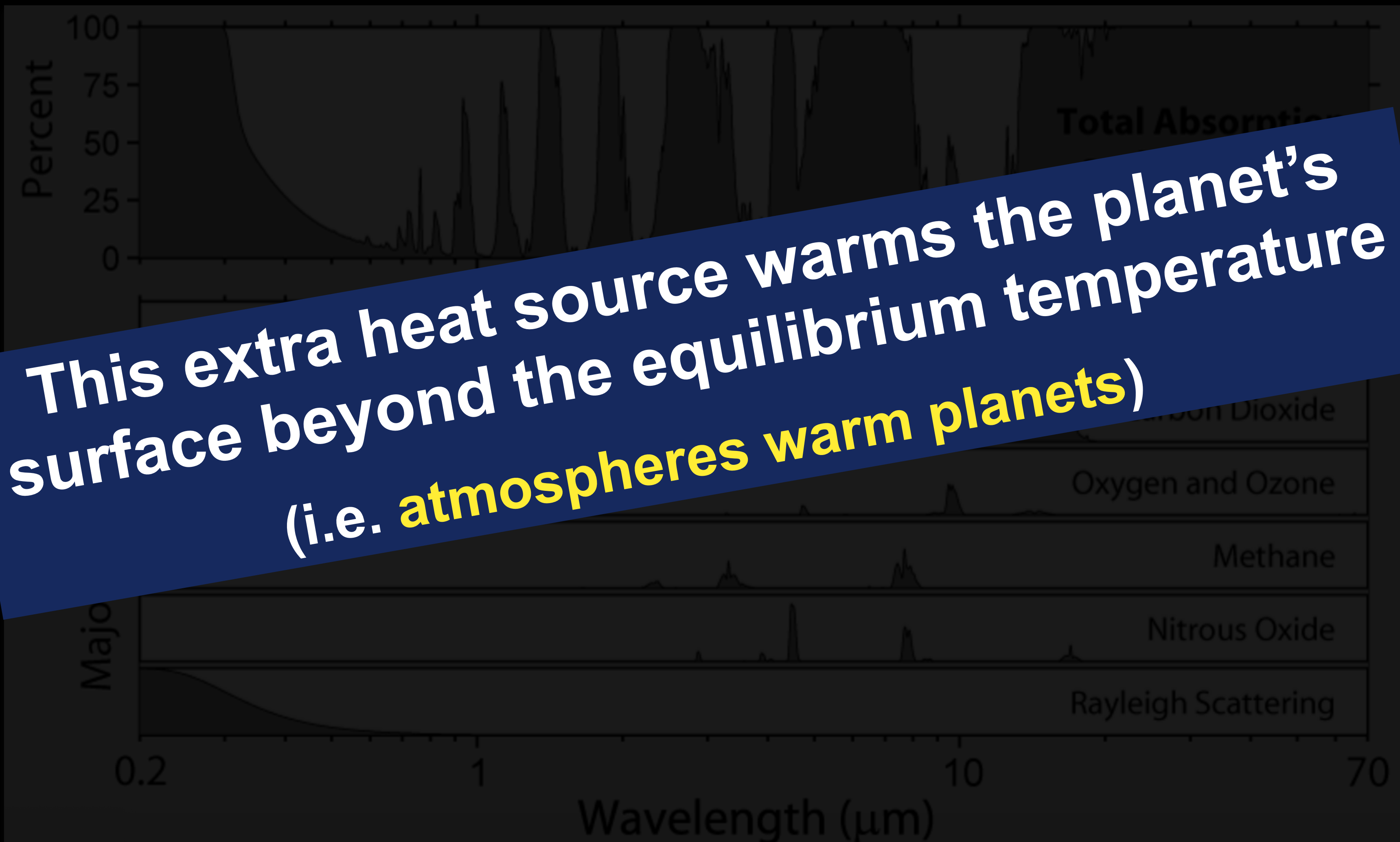
Atmospheric transmission: GH gases



GH gases absorb outgoing (longwave) radiation.

The atmosphere reradiates isotropically to reach thermal equilibirum with the planet's surface

Atmospheric transmission: GH gases



This extra heat source warms the planet's surface beyond the equilibrium temperature

(i.e. atmospheres warm planets)

Before we explore a toy model of the GH effect, recall the incident stellar flux is

$$F = \frac{L_\star}{4\pi a^2}$$

For the Earth:

$$S_0 = \frac{L_\odot}{4\pi(1\,\mathrm{au})^2}$$

$$= 1362\,\mathrm{W m^{-2}}$$

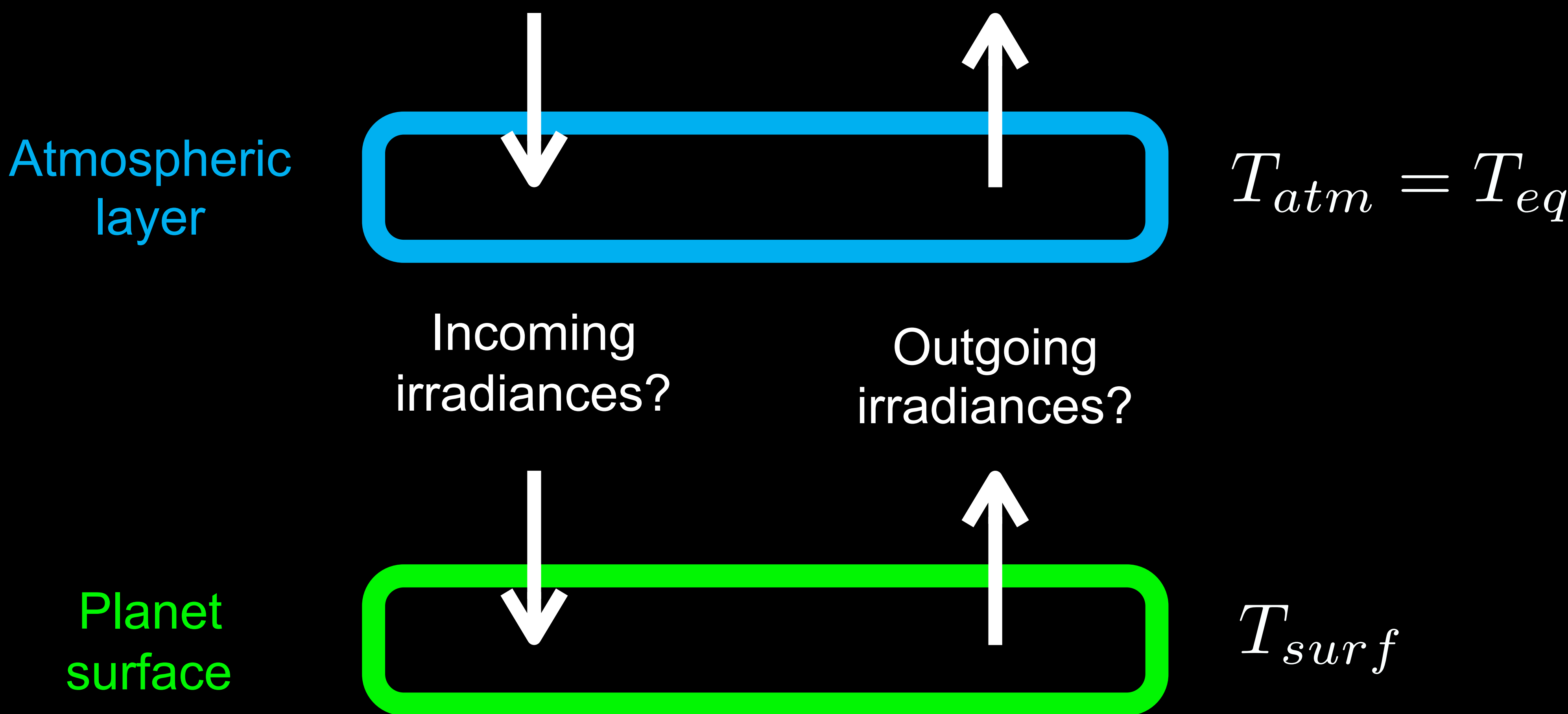
S_0 is known as the solar constant

TPS Activity

Recall our derivation of T_{eq} from Lecture 4, which began by setting the incident power on a planet's cross-section equal to the power out.

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

Toy model of the GH effect



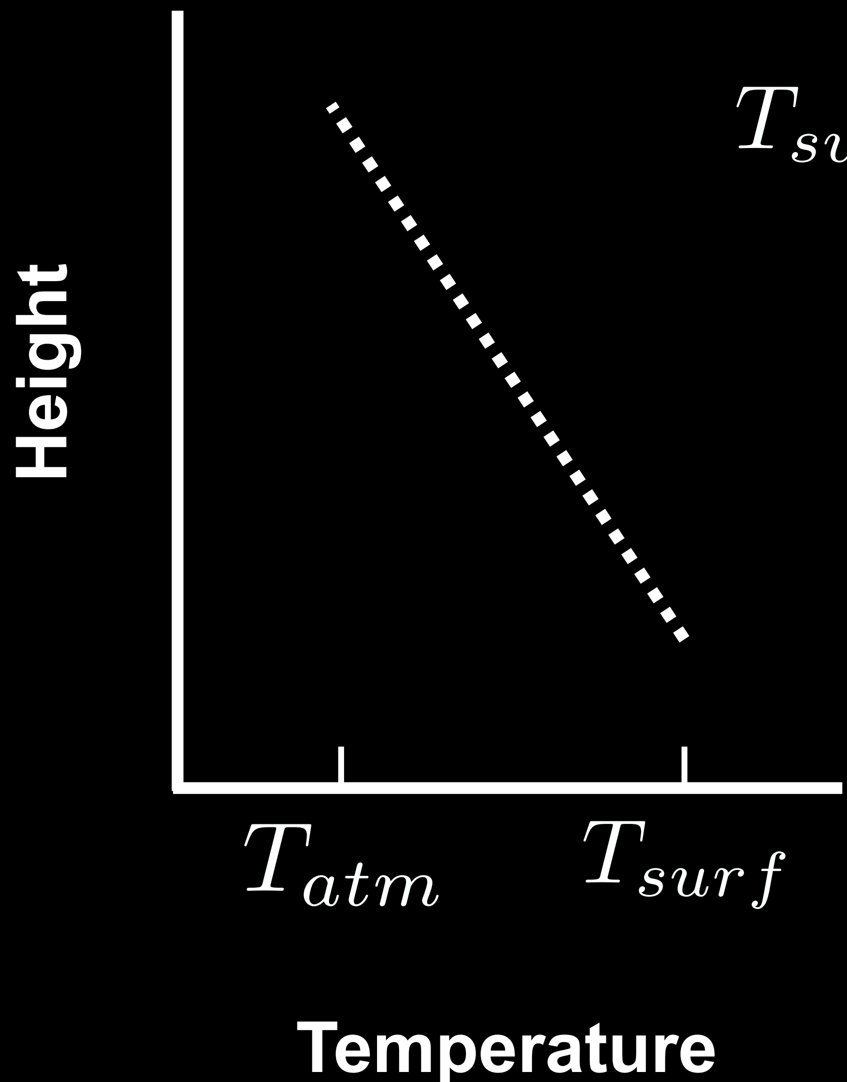
Toy model of the GH effect

In class, we'll show that the planet's surface temperature in the presence of an absorbing atmospheric layer is

$$T_{surf} = \left(\frac{2S}{\sigma}\right)^{1/4}$$

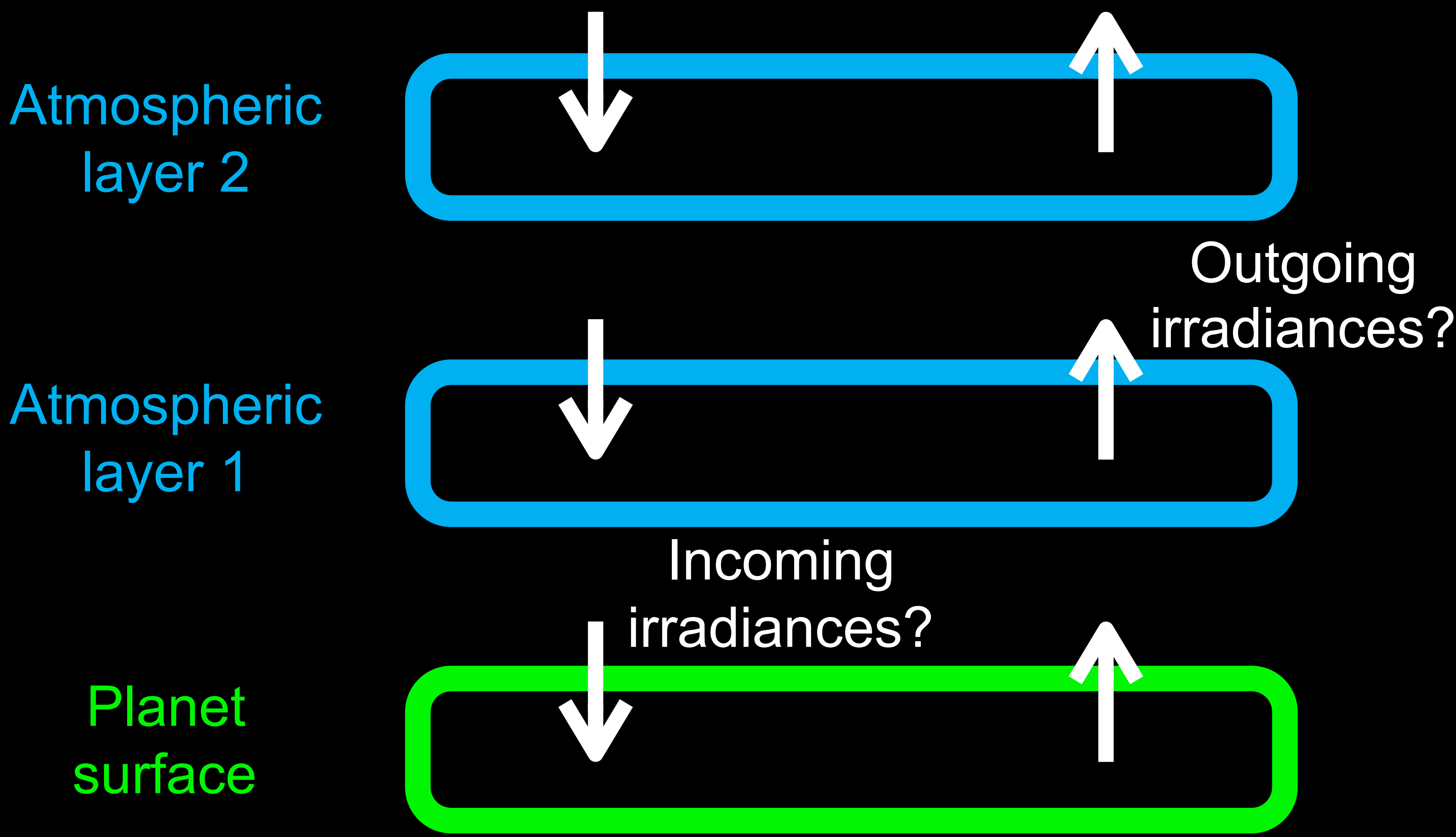
$$\sim 1.19\, T_{atm}$$

Toy model of the GH effect



$$T_{surf} \sim 1.19\, T_{atm}$$

(extended) Toy model of the GH effect



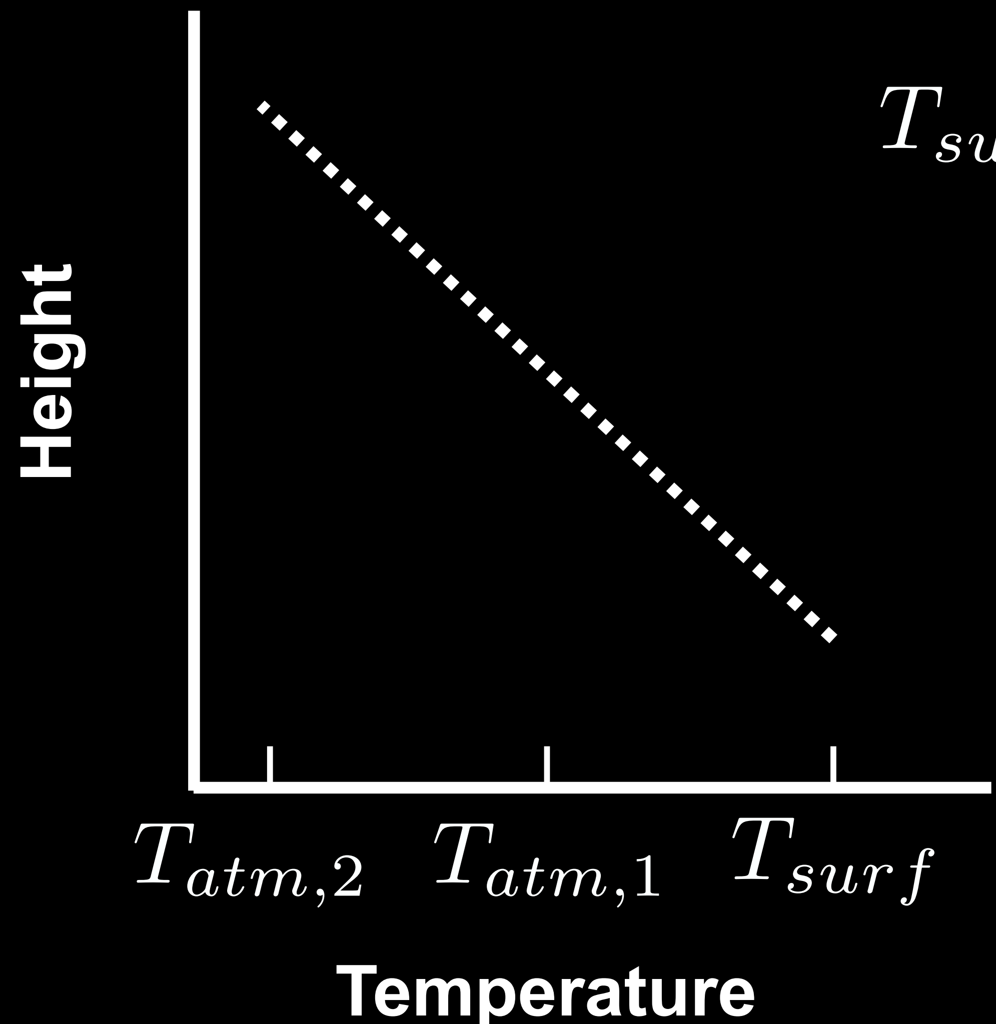
(extended) Toy model of the GH effect

In class, we'll show that the planet's surface temperature in the presence of n=2 absorbing atmospheric layers is

$$T_{surf} = \left(\frac{3S}{\sigma}\right)^{1/4}$$

$$\sim 1.32\,T_{atm,2}$$

(extended) Toy model of the GH effect



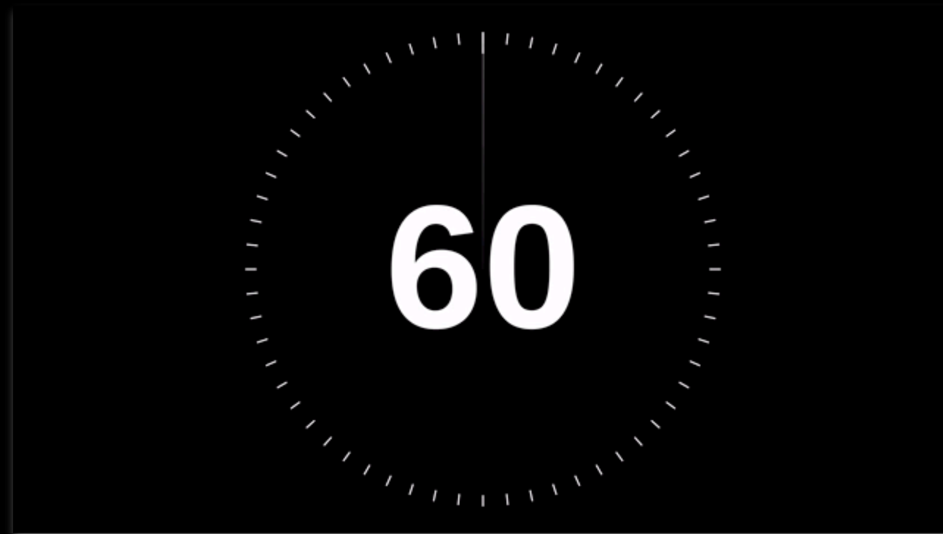
$$T_{surf} \sim 1.32\, T_{atm,2}$$

General form of *T_{surf}* from our toy model with *n* atmospheric layers

$$T_{surf} = \left[\frac{(n+1)S}{\sigma}\right]^{1/4}$$

$$= (n+1)^{1/4}\, T_{atm,n}$$

TPS Activity



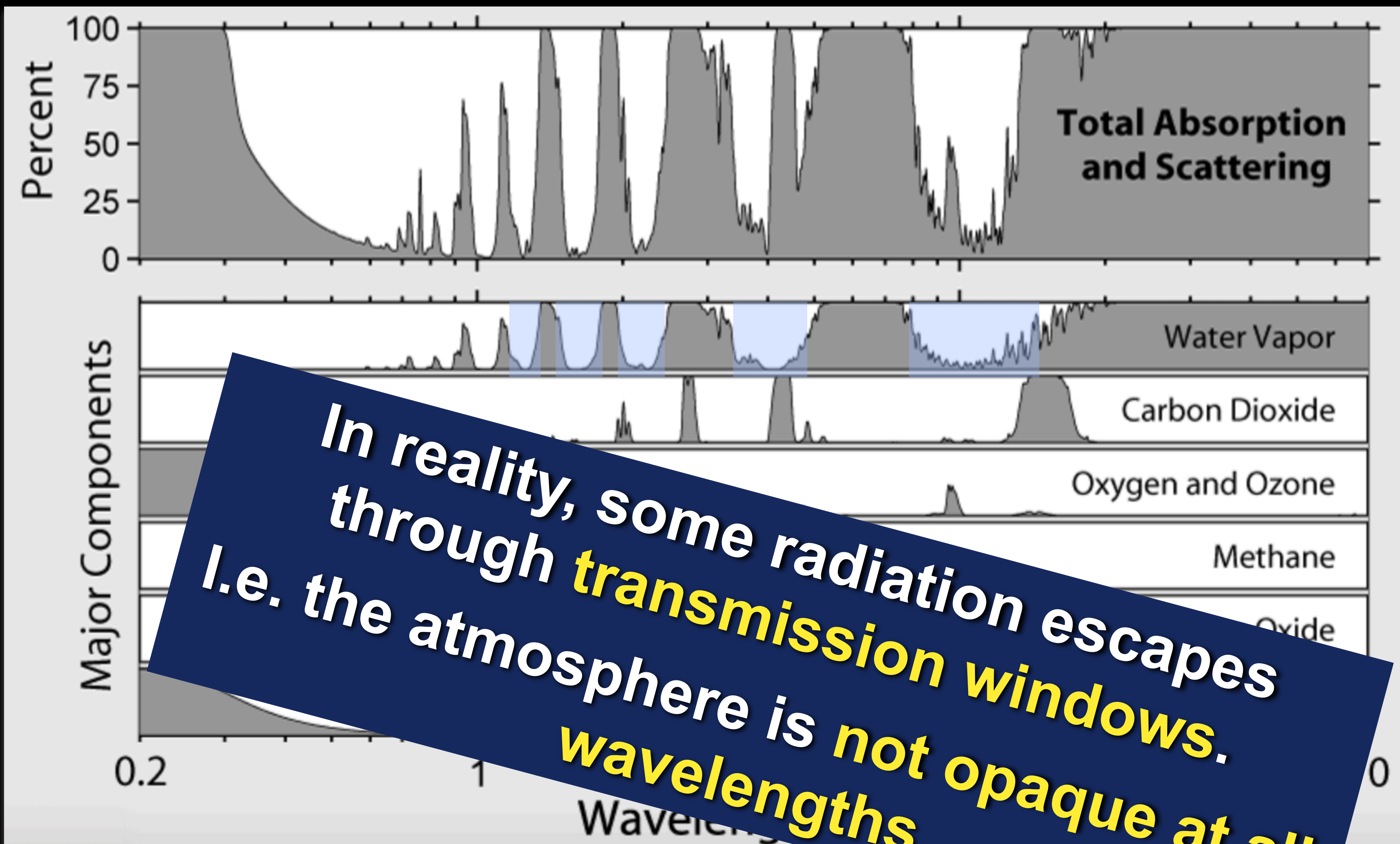
How many absorbing atmospheric layers are needed to describe the Earth?

Recall that

T_{eq} = 252 K
T_{surf} = 288 K

$$T_{surf} = (n+1)^{1/4}\, T_{atm,n}$$

Recall that our toy model assumed that **all** outgoing longwave radiation was **absorbed** by the atmosphere



In reality, some radiation escapes through transmission windows.
I.e. the atmosphere is not opaque at all wavelengths

TPS Activity

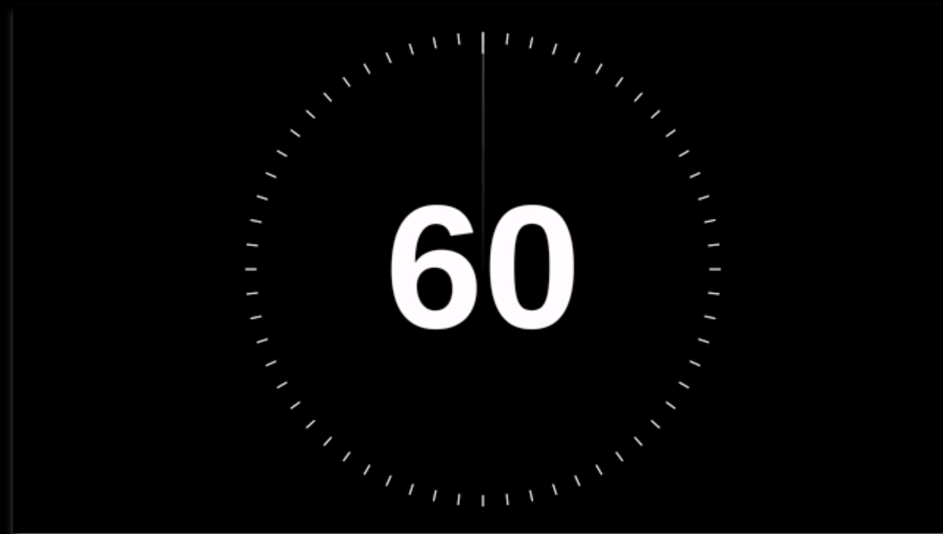
How many absorbing atmospheric layers are needed to describe Mars?

Note that

T_{eq} = 210 K
T_{surf} = 215 K

$$T_{surf} = (n+1)^{1/4}\, T_{atm,n}$$

TPS **Activity**



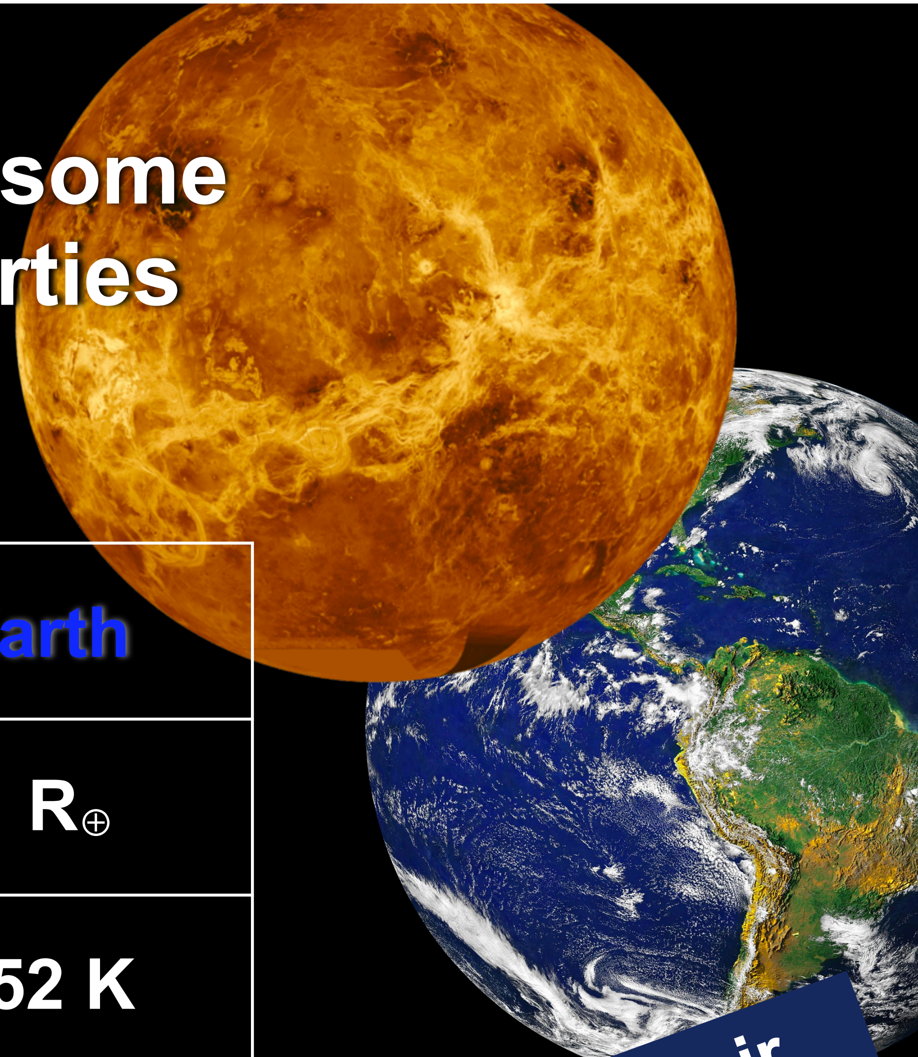
How many absorbing atmospheric layers are needed to describe Venus?

Note that

T_{eq} = 233 K
T_{surf} = 737 K

$$T_{surf} = (n+1)^{1/4}\, T_{atm,n}$$

Venus and the Earth have some remarkably similar properties

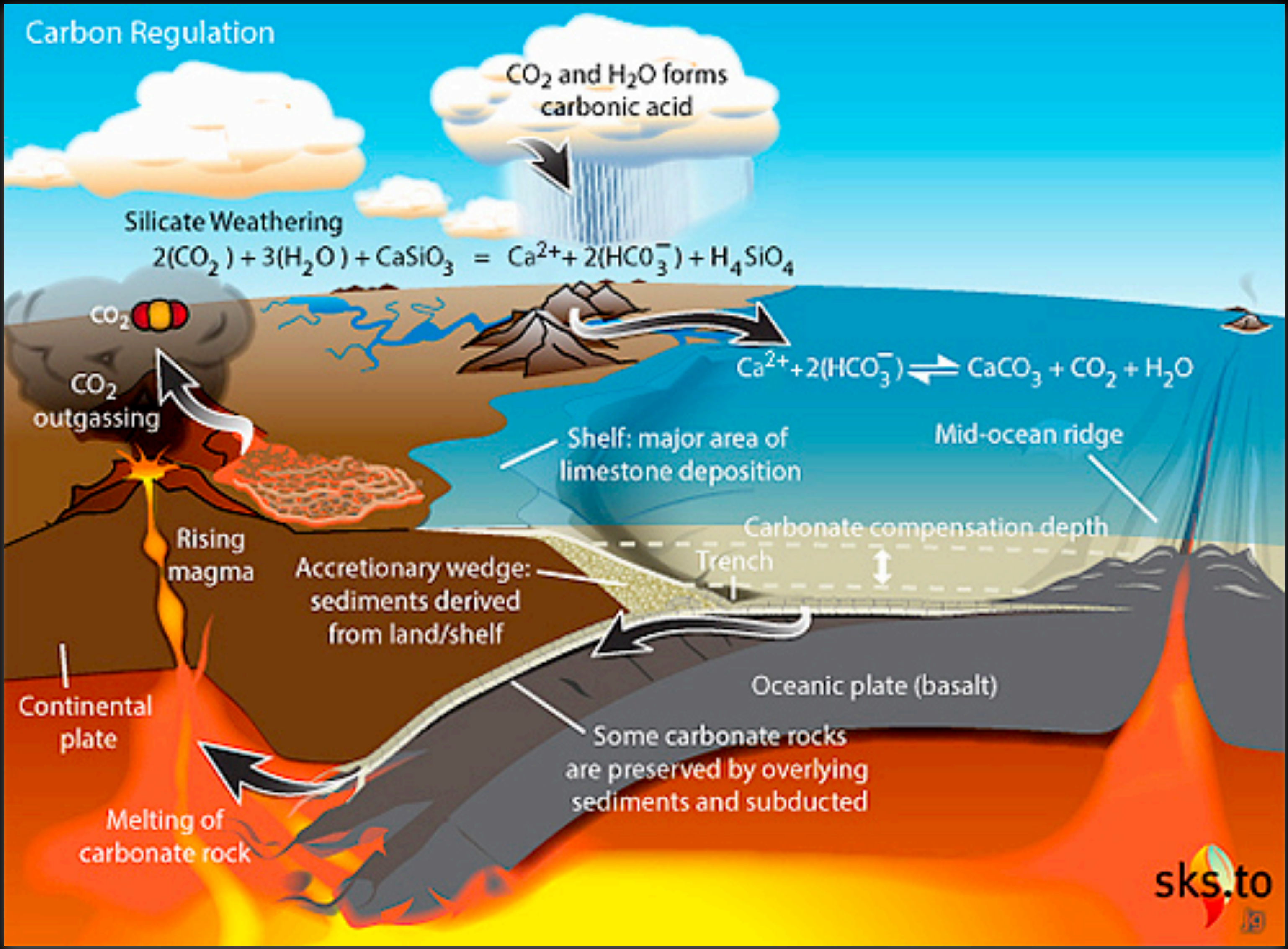


	Venus	Earth
Planet radius	0.95 $R_{\oplus}$	1 $R_{\oplus}$
Equilibrium temperature	233 K	252 K
Surface temperature	737 K	288 K

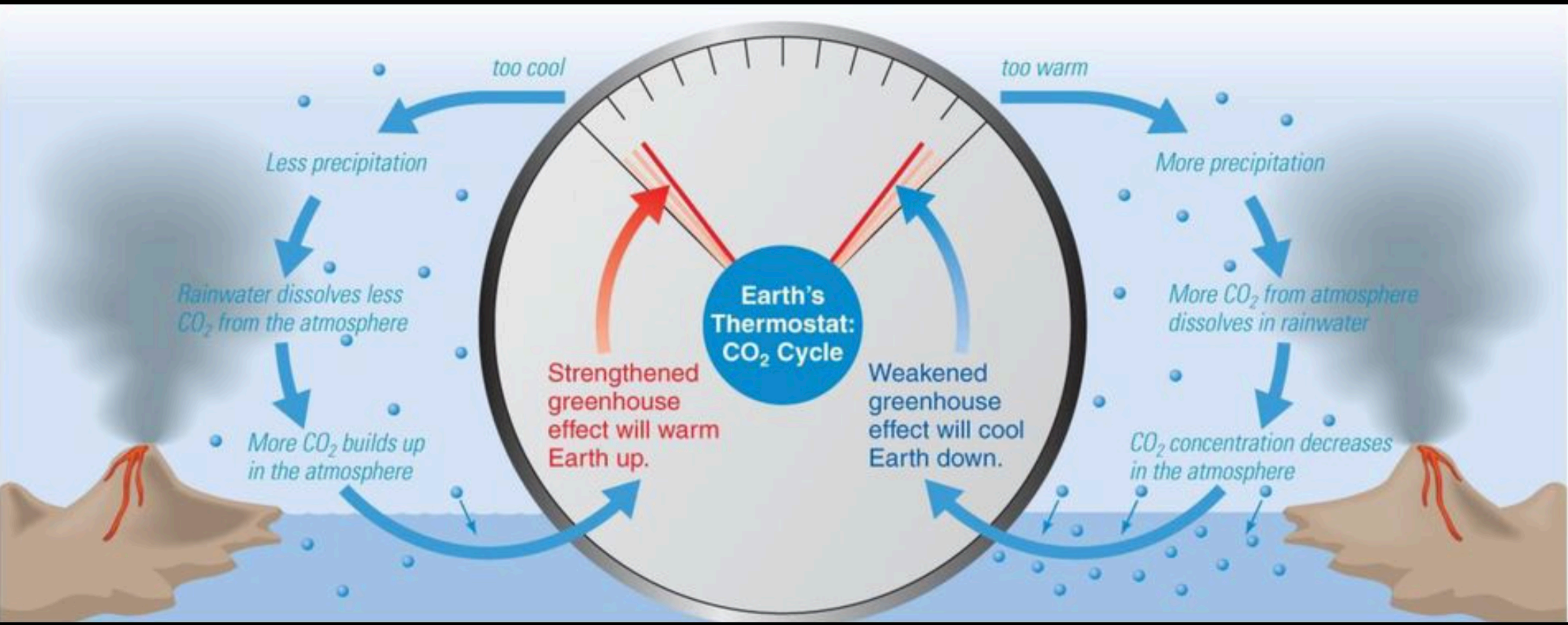
What differed between their evolutionary histories that led to this large difference in T_{surf}?

The Carbon-Silicate Cycle

A geochemical process that helps regulate the Earth's temperature



Credit: John Garrett

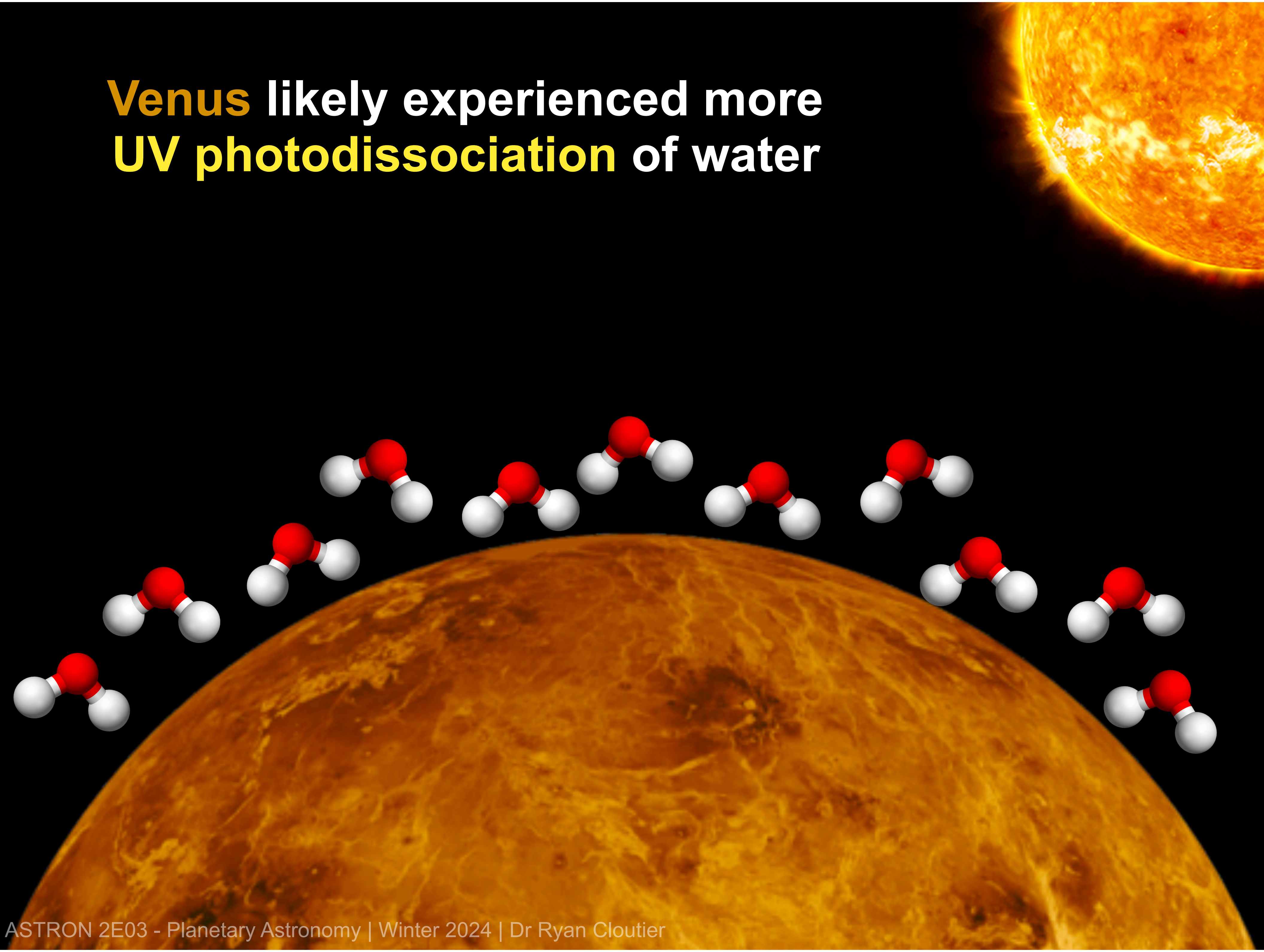


Credit: Pearson Education Inc

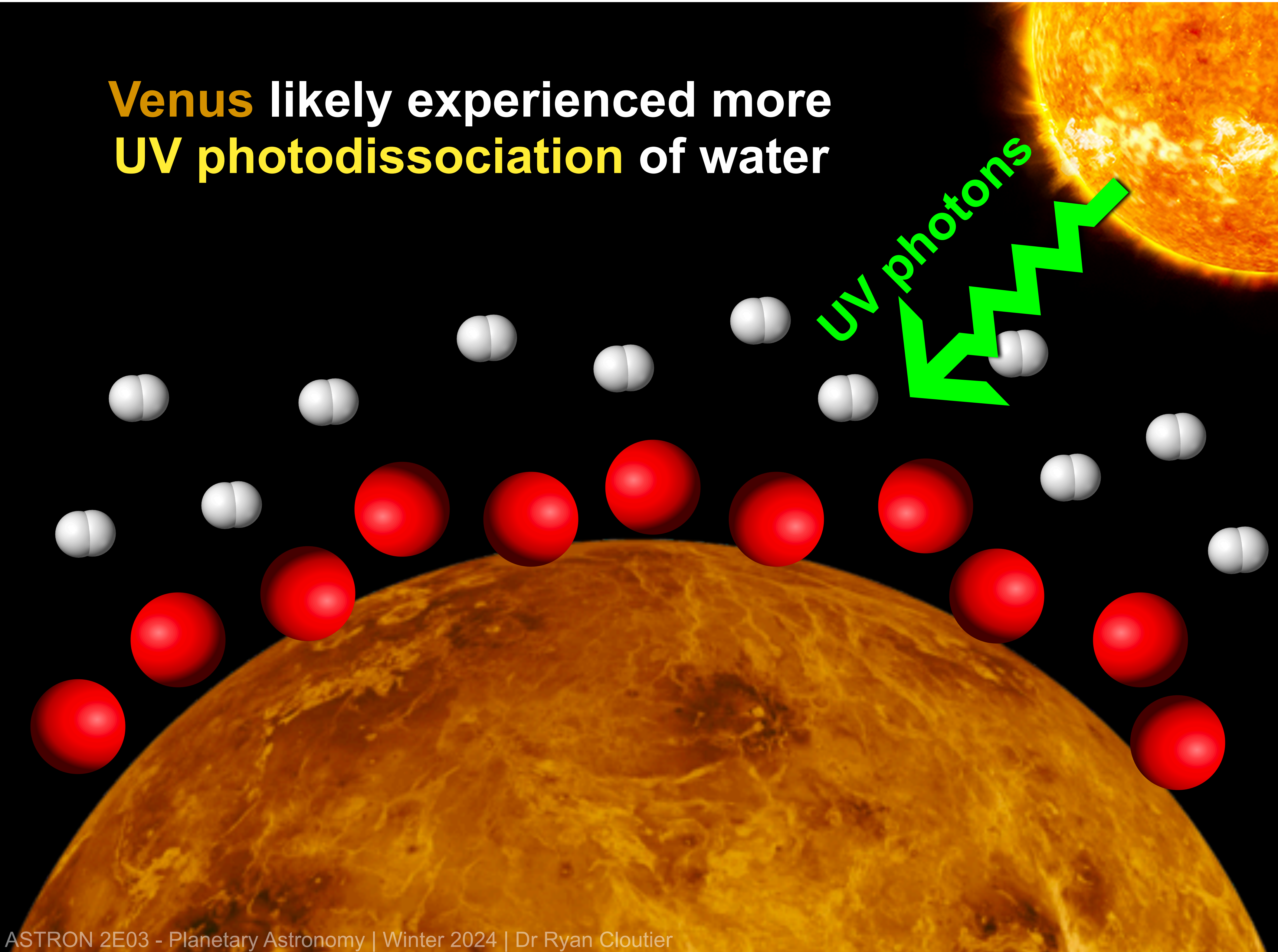
This is an example of a **negative feedback** process

Fluctuations that cool the planet are geochemically “corrected” back to its equilibrium state

Conversely, a positive feedback process would amplify the temperature perturbation and continue to drive the system away from its previous state

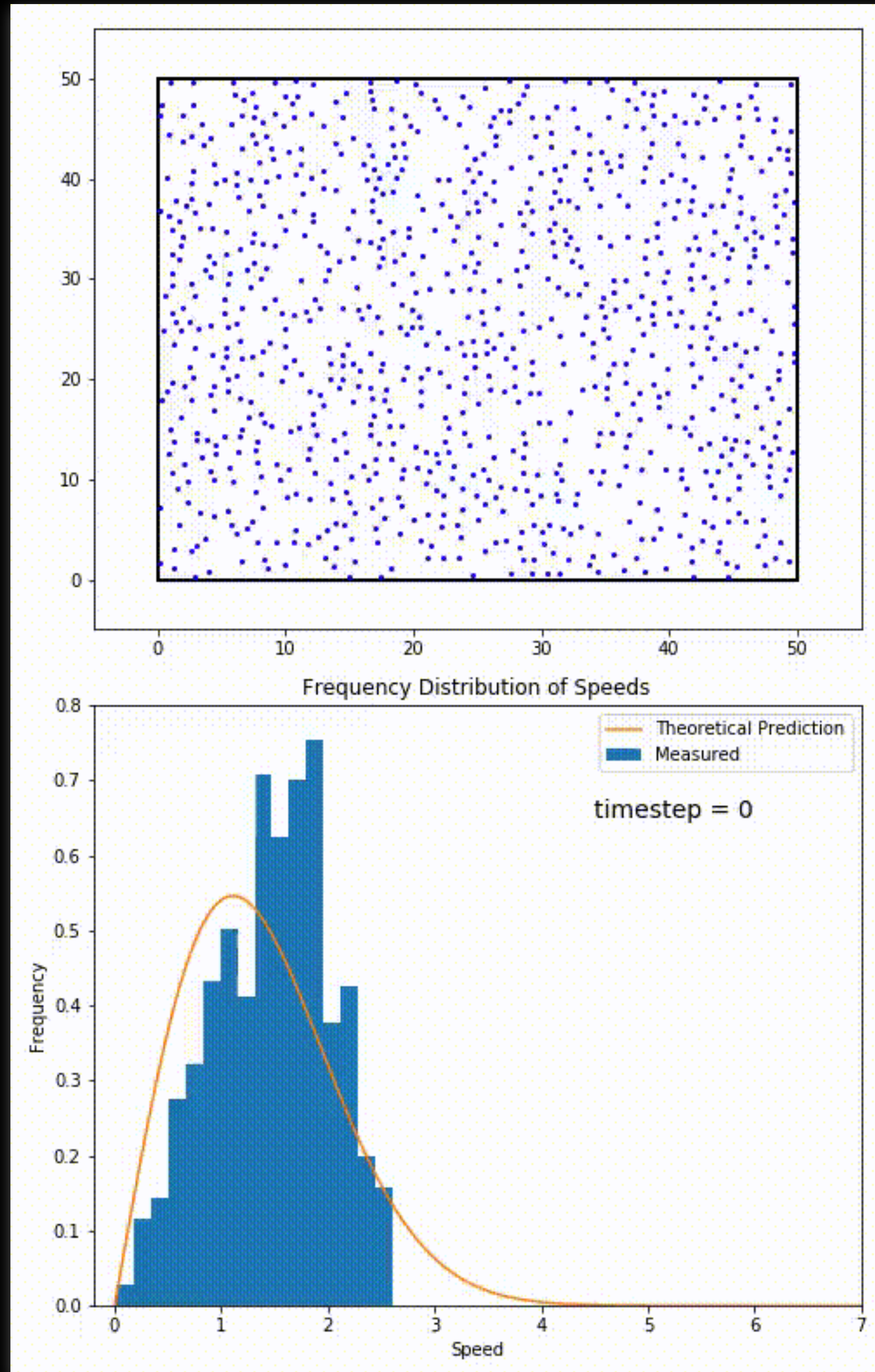

Venus likely experienced more
UV photodissociation of water

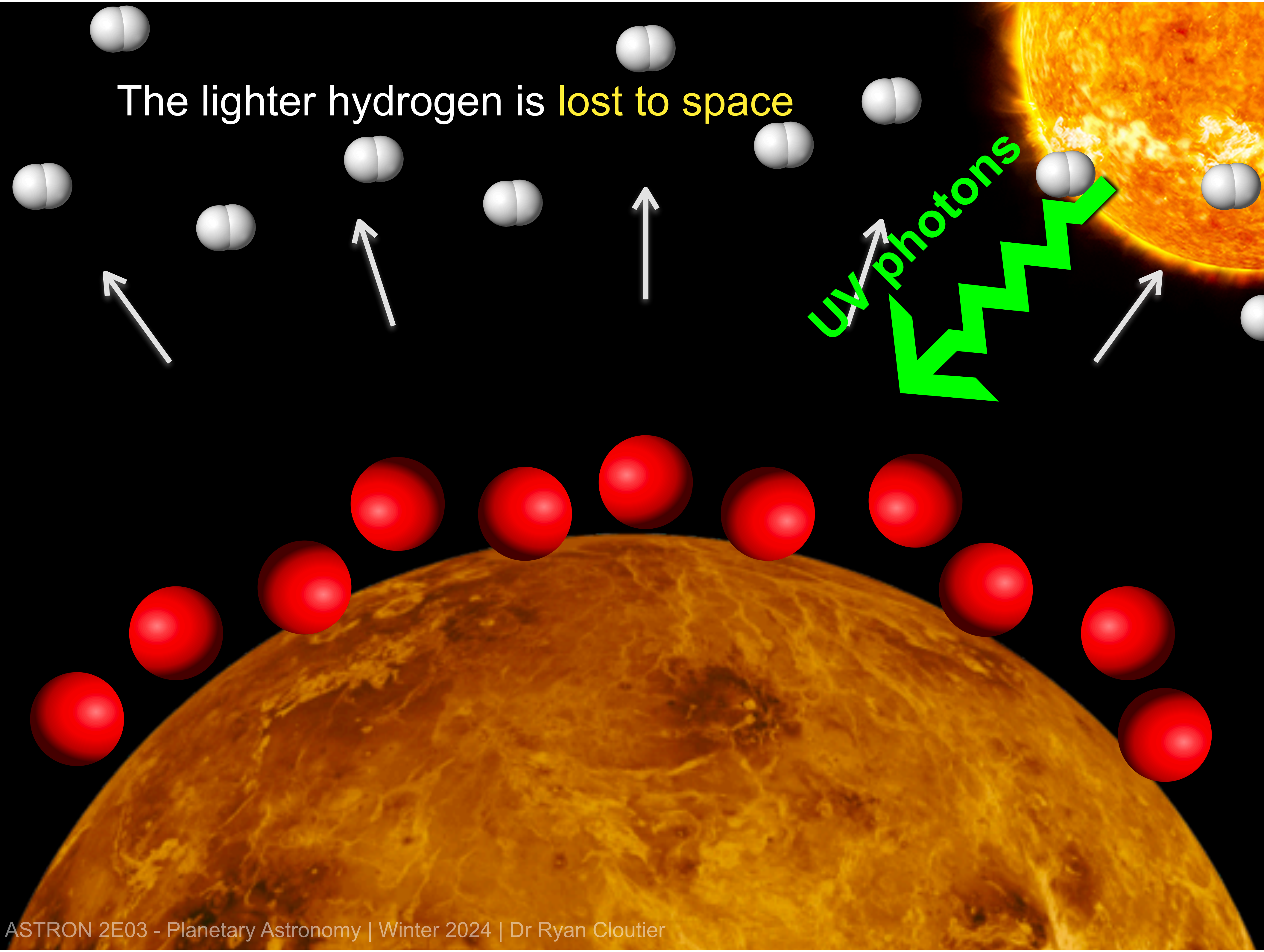
Venus likely experienced more UV photodissociation of water



Recall the **Maxwell-Boltzmann distribution**

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




The lighter hydrogen is lost to space
UV photons

The **absence of water** would have shut off a C-Si cycle on **Venus**, allowing volcanic CO_2 to build up and...

...resulting in a **runaway GH effect**

Runaway greenhouses may be extremely common