OSHER
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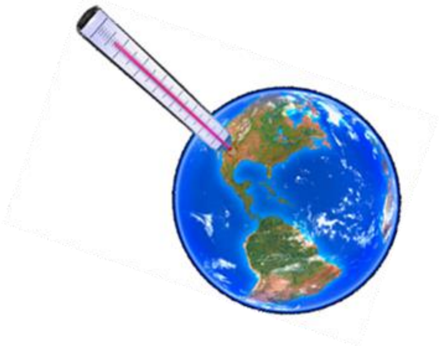
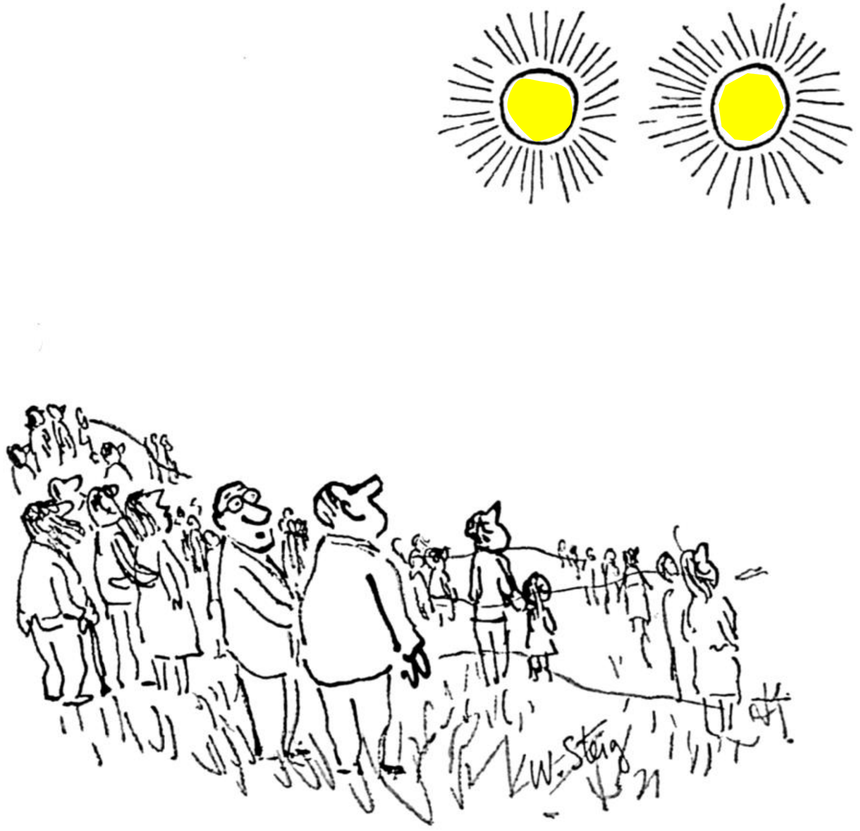




"It looks as if our troubles are only beginning."

New Yorker 3 Dec 2018

Demystifying Climate Change

Session 2

Our Goldilocks Earth:
A Radiative Balancing Act

OLLI at Illinois

Spring 2021

D. H. Tracy

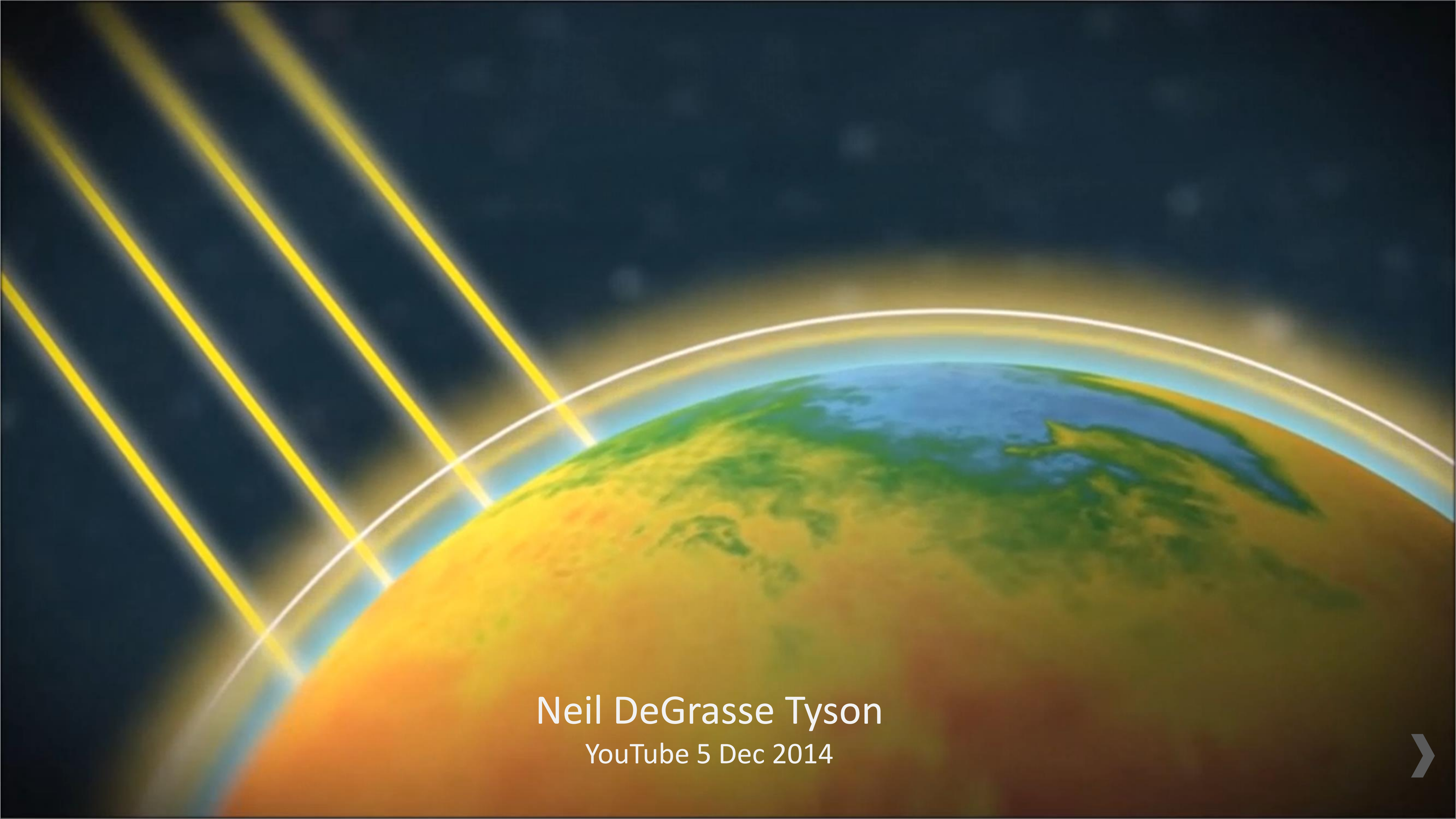
Course Outline

1. Building Blocks: Some important concepts
2. **Our Goldilocks Earth: a Radiative Balancing Act**
3. The Role of the Atmosphere: Greenhouse Gases & Clouds
4. Dynamics of the Earth System: Oceans, Atmosphere, Biosphere, Cryosphere, People, Plate Tectonics
5. Natural Variability of the Climate, short and long term. Ice Ages
6. Carbon Dioxide and other Greenhouse Gases: where do they come from, where do they go, how are they regulated?
7. Impacts and Future Projections for Global Warming -- Uncertainties
8. Adaptation and Amelioration Strategies. The Climate debate. Policy options.

Today’s Discussion: 50 second Version

Neil DeGrasse Tyson

YouTube 5 Dec 2014



Neil DeGrasse Tyson

YouTube 5 Dec 2014

Our Goldilocks Earth ♁

$T_{eff} = 254$ K (-2°F)

$T_{surf} = 288$ K (59°F) +13%

Global
Averages

Why?

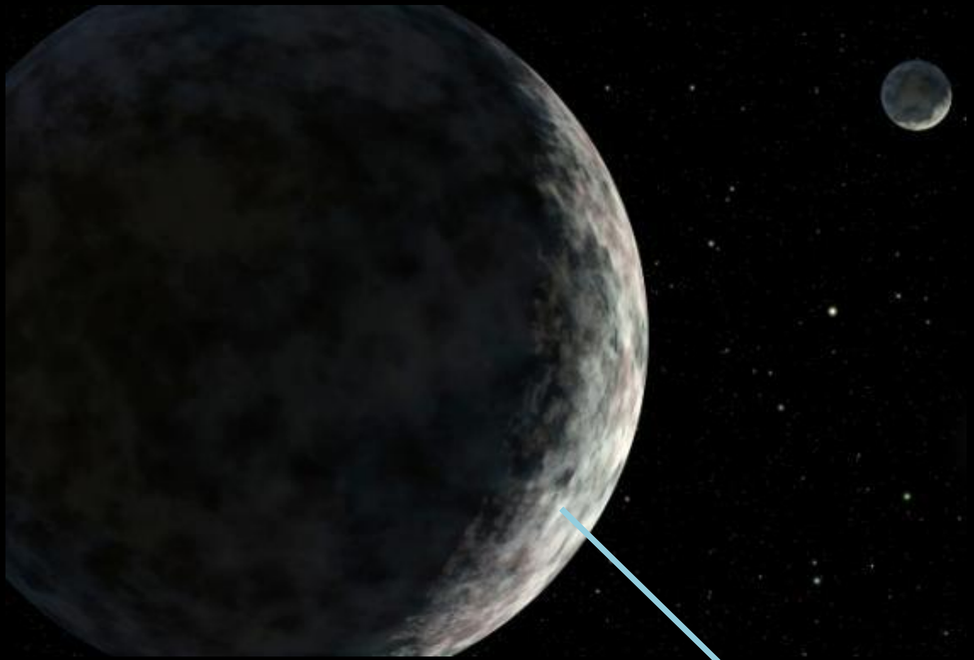
Turn Off the Sun ♁

T_{eff} = 254 K (-2°F)

T_{surf} = 288 K (59°F)

Turn Off the Sun ♁

Turn Off the Sun



30 Ft thick coating of frozen air

T_{eff} = 36 K (-395°F)

T_{surf} = 36 K (-395°F)

Why does it only cool down to 36K? Why not colder?

Turn Off the Sun ♁

$T_{eff} = 36\ K$ (-395°F)

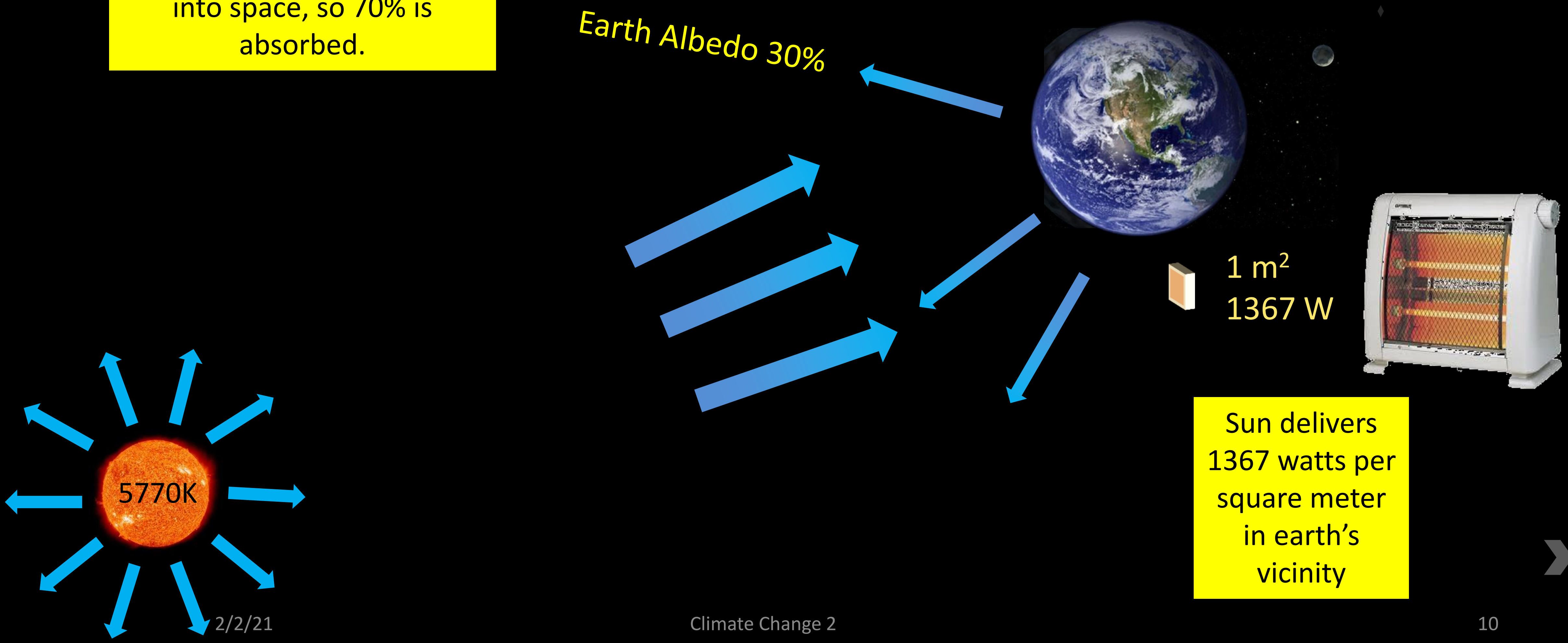
$T_{surf} = 36\ K$ (-395°F)

30 Ft thick
coating of
frozen air

The core is still hot from earths creation, and from radioactive decay.
This geothermal heat keeps the surface slightly warm

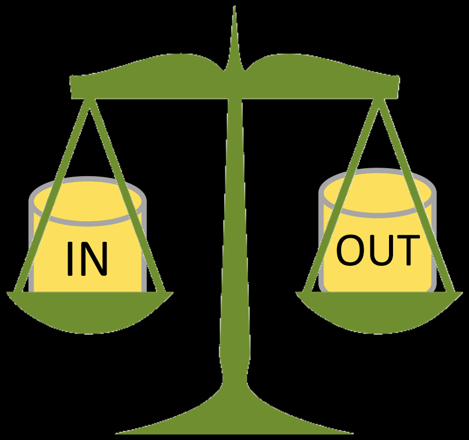
Turn the Sun Back On

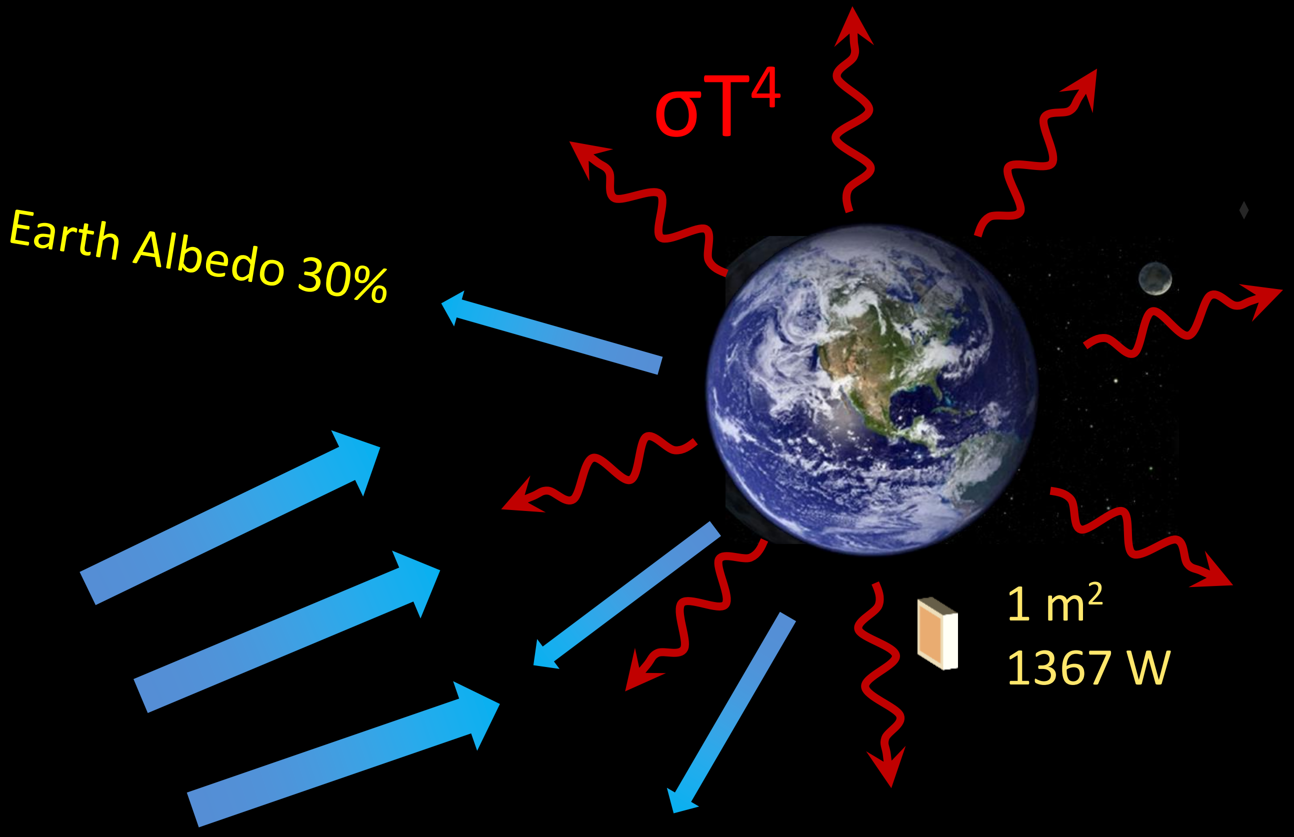
30% of the sunlight hitting the earth is reflected back into space, so 70% is absorbed.

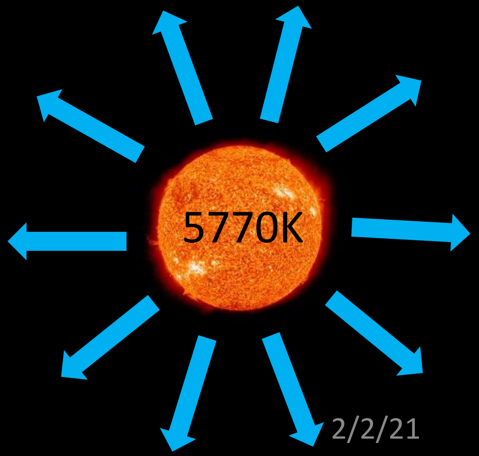


Sun delivers 1367 watts per square meter in earth's vicinity

Sun is Back On



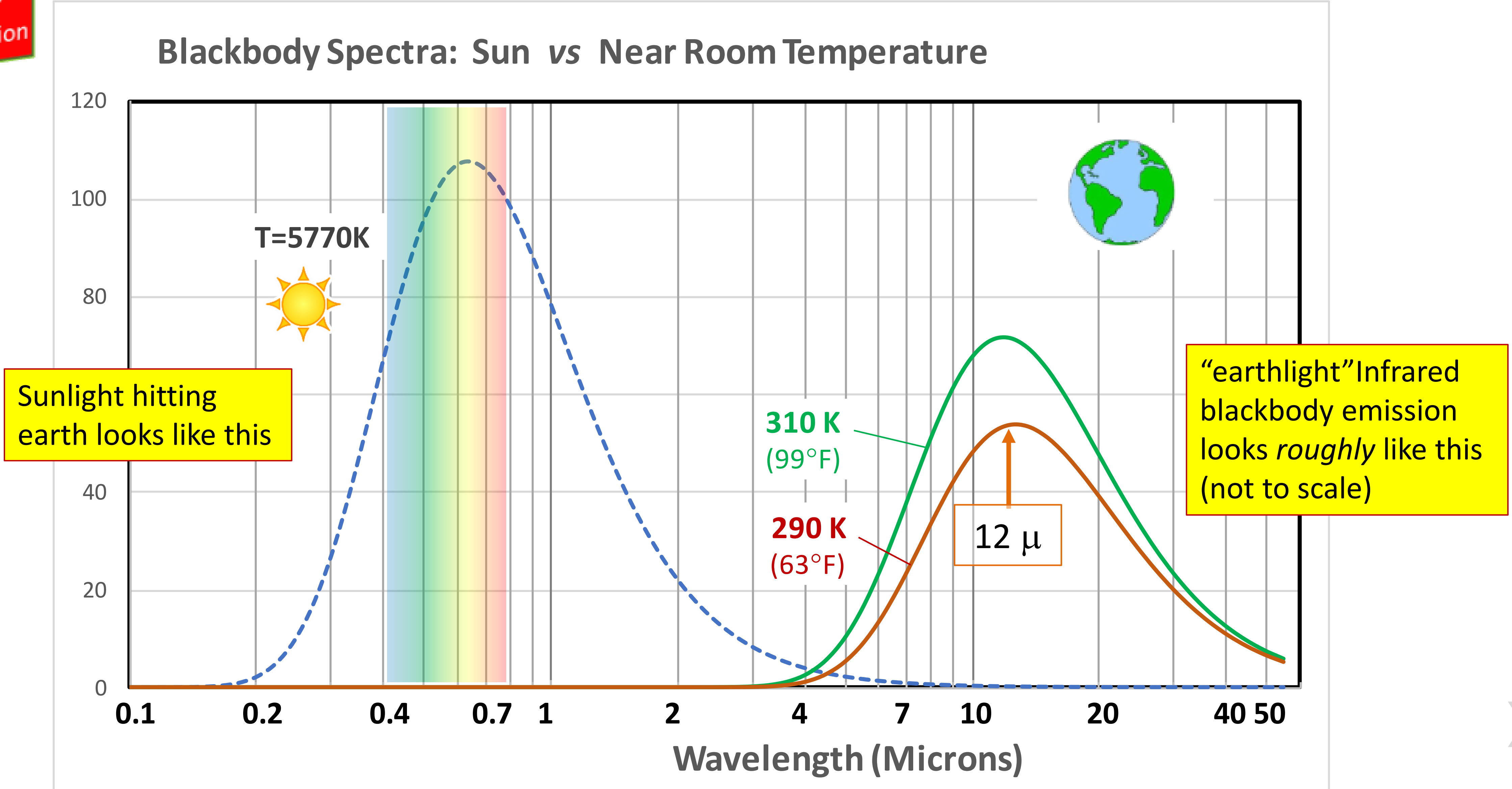




The incoming sun heat must be balanced approximately by Blackbody IR emission from the earth into space. That depends on T^4 ! So eventually earth's apparent temperature must adjust.

6 BB Radiation

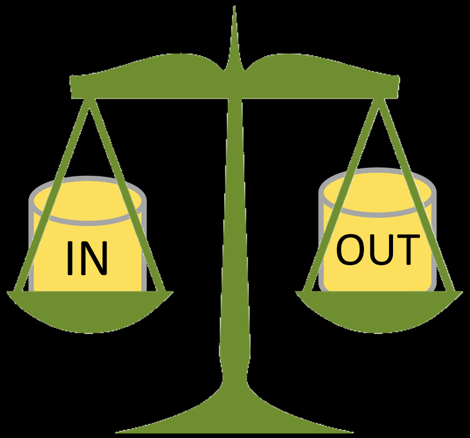
Solar Radiation *vs.* Earth Radiation

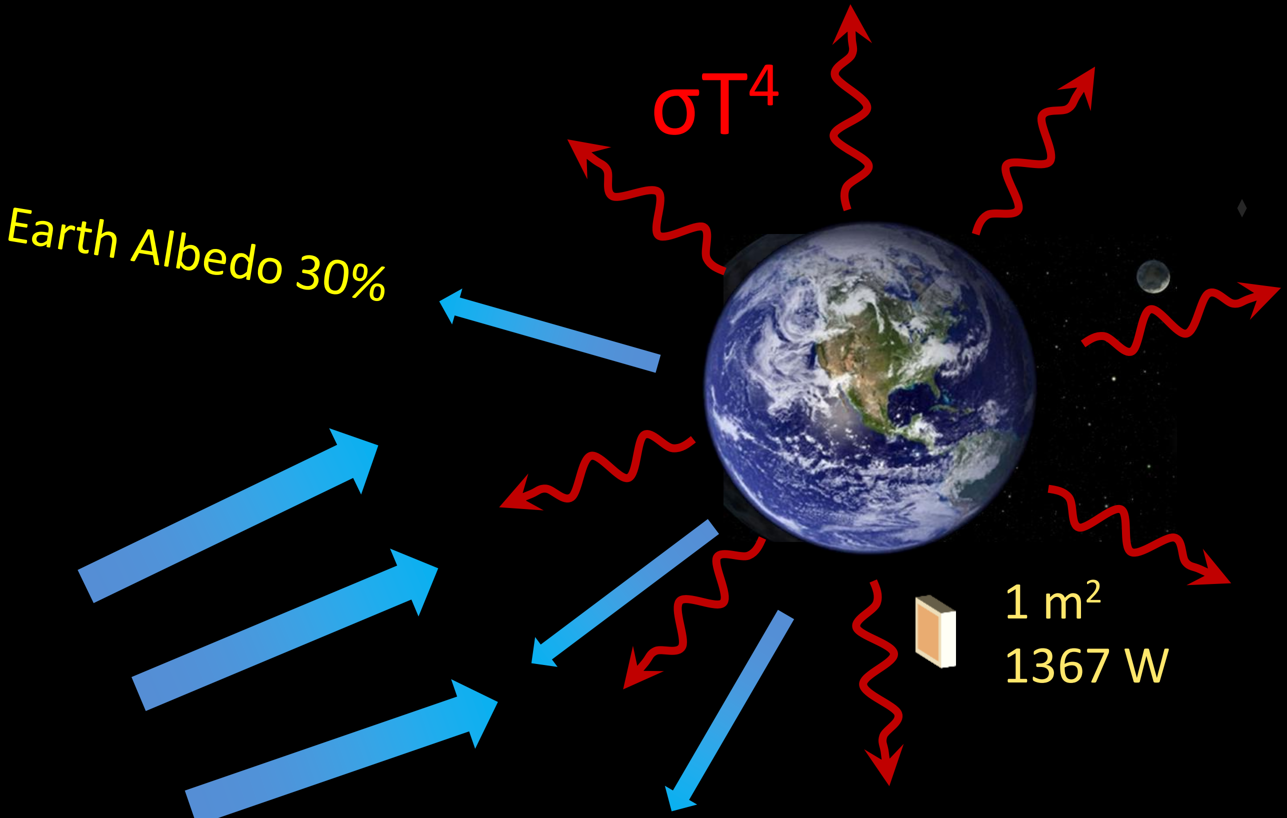


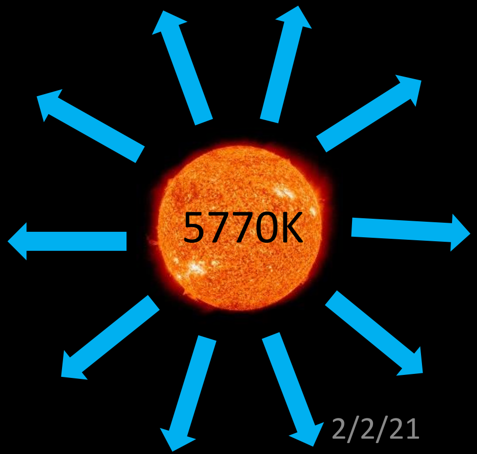
Sunlight hitting earth looks like this

"earthlight" Infrared blackbody emission looks *roughly* like this (not to scale)

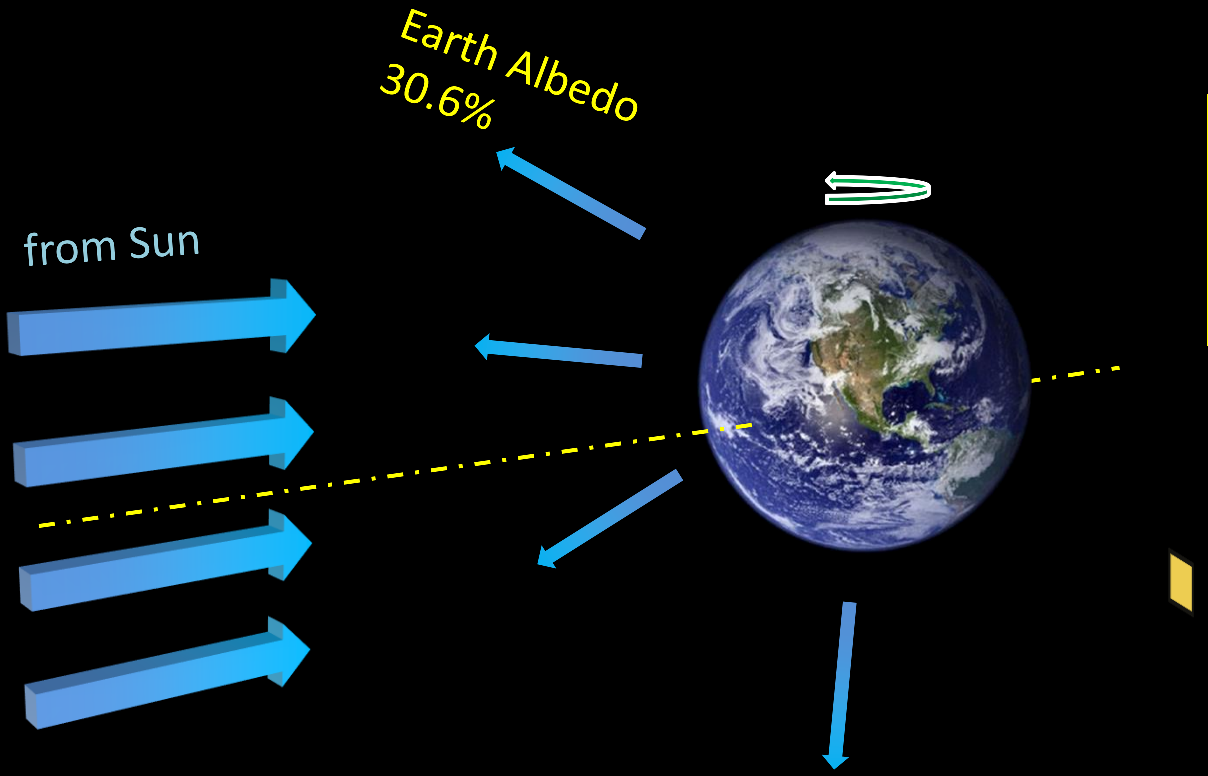
Turn the Sun Back On







How much sunlight does each square meter absorb?



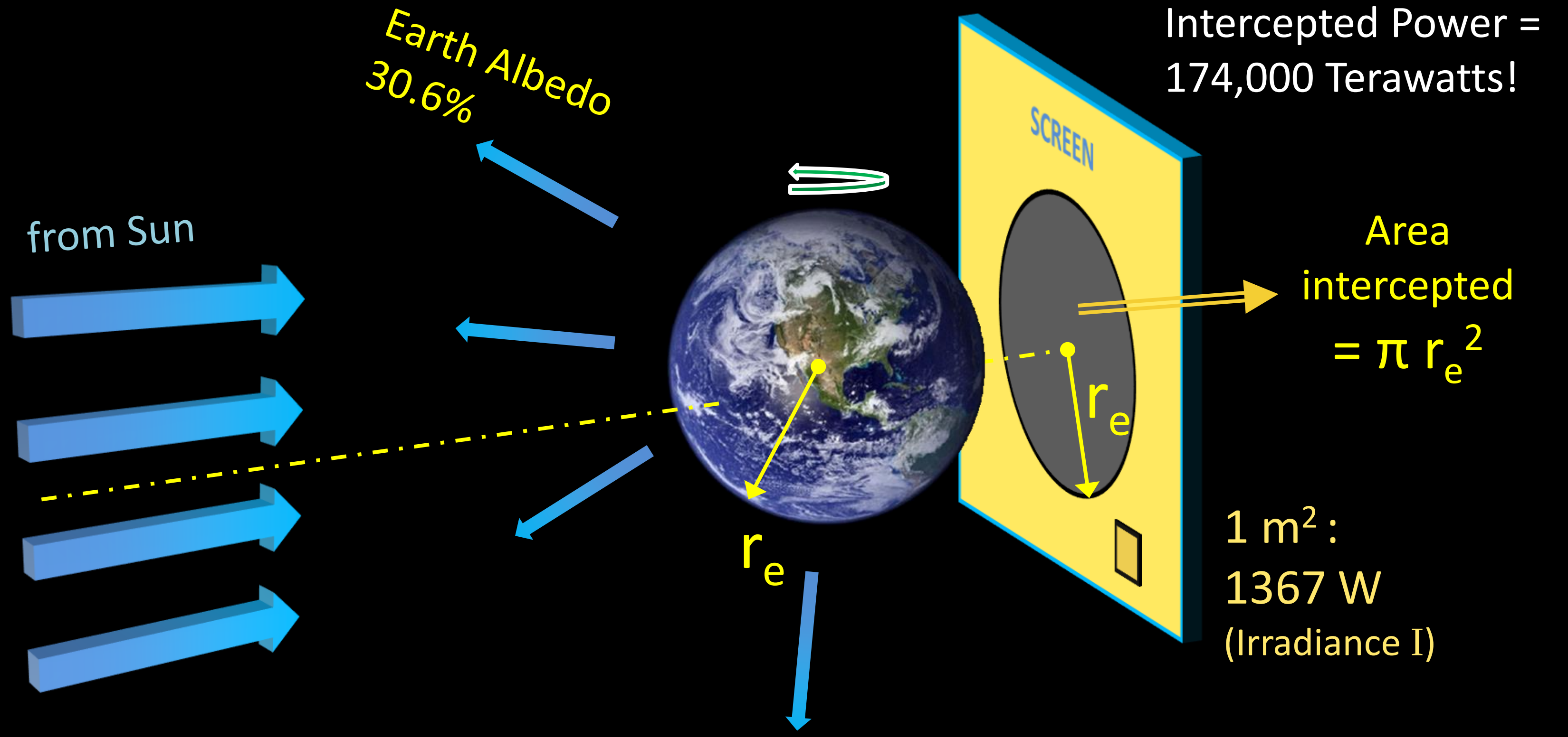
from Sun

Earth Albedo
30.6%

Note that earth spins, so sunlight hits only during daytime

1 m^2 :
1367 W
(Irradiance I)

How much sunlight does each square meter absorb?



Intercepted Power =
174,000 Terawatts!

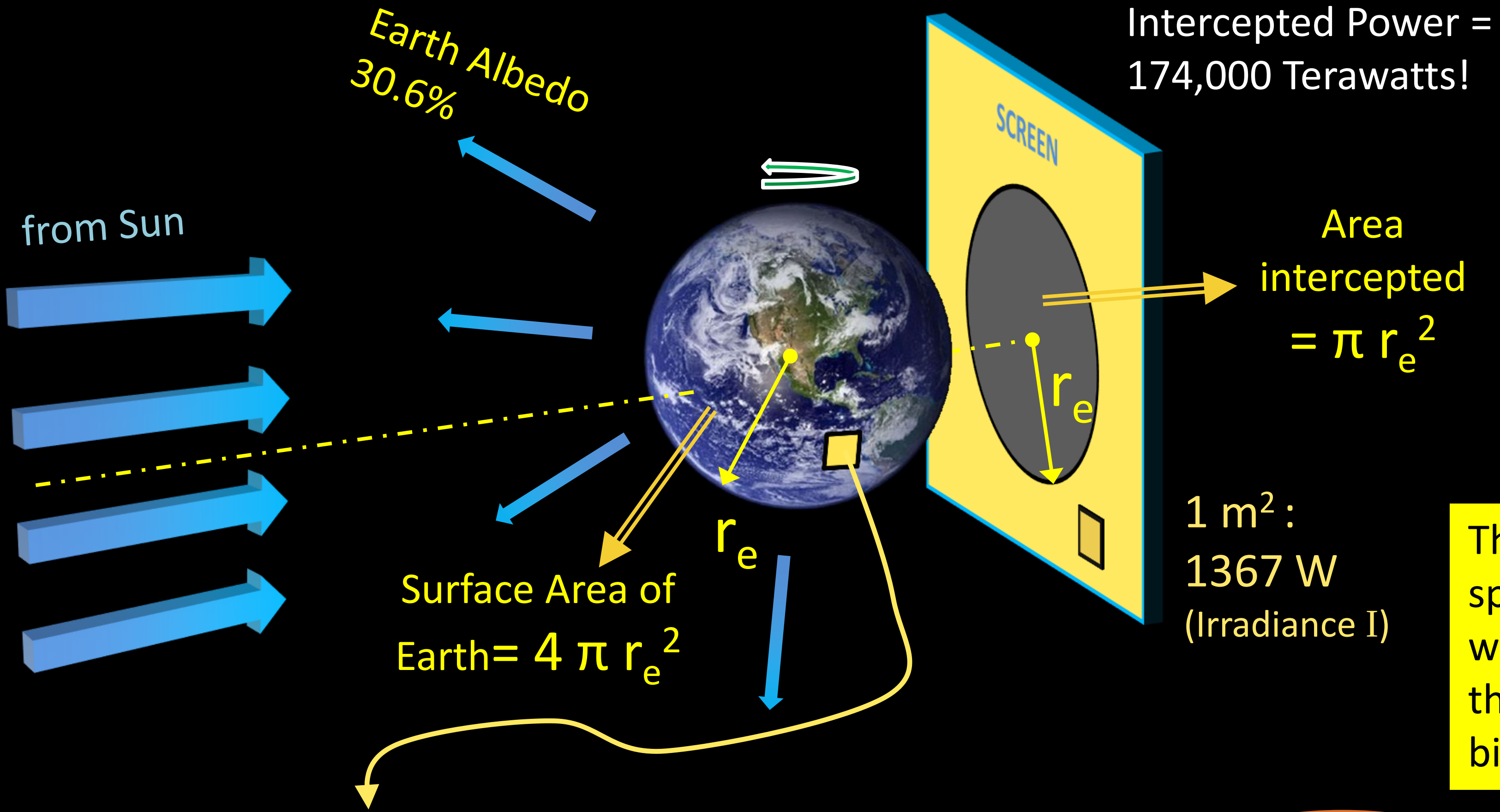
Credit for
Shadow Idea:
David Archer

Area
intercepted
$= \pi r_e^2$

$1\ m^2$:
1367 W
(Irradiance I)

An easy way to figure out how much heat is absorbed from the sunlight is to consider a screen just behind the earth. The shadow area directly gives us the amount of intercepted solar radiation. [But only 70% of this is actually absorbed]

How much sunlight does each square meter absorb?



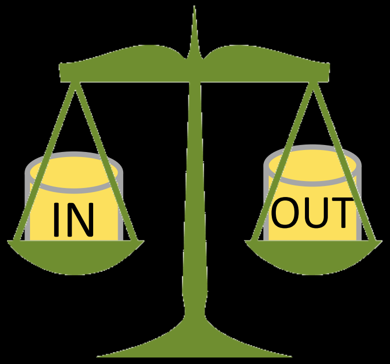
Credit for
Shadow Idea:
David Archer

This absorbed heat is spread out over the whole surface area of the Earth, which is 4x bigger than its shadow!

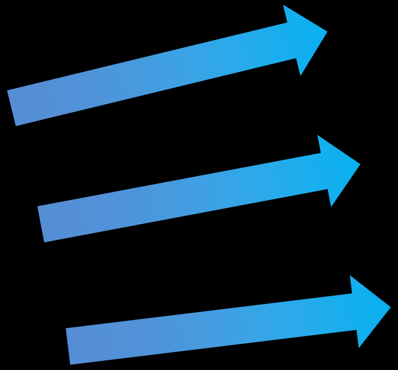
Average solar heat delivered
to *each m²* on earth

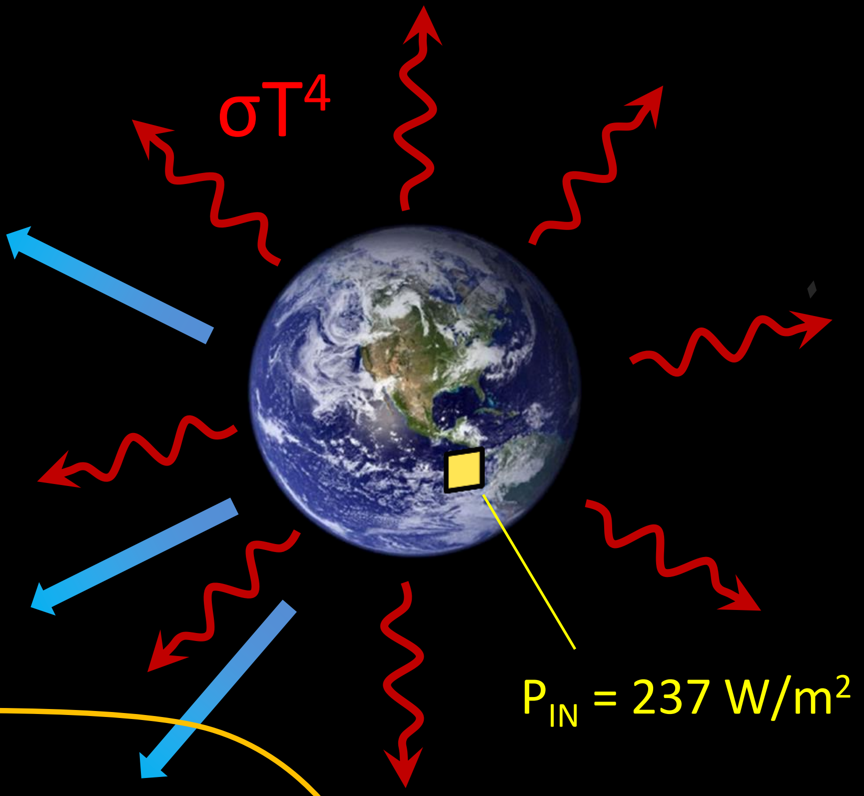
$$= \frac{1367\ W/m^2}{4}[1-0.306] \boxed{\cong 237\ W/m^2}$$

So What Effective Temperature Does This Imply?



The required energy balance gives us a very simple equation for the needed effective Temperature.

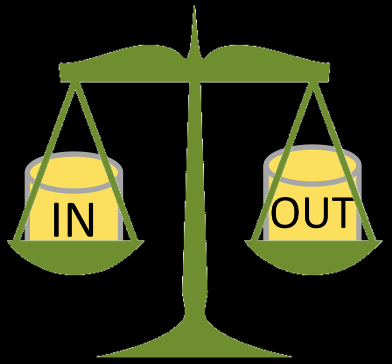


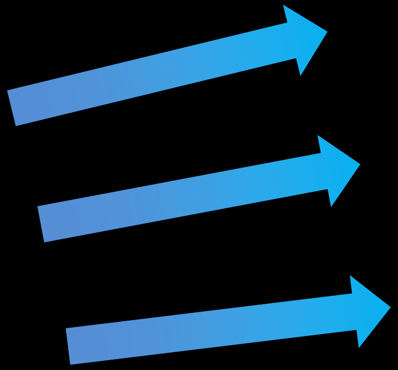


$$P_{OUT} = 237\ W/m^2 = \sigma\, T_{EFF}^4$$

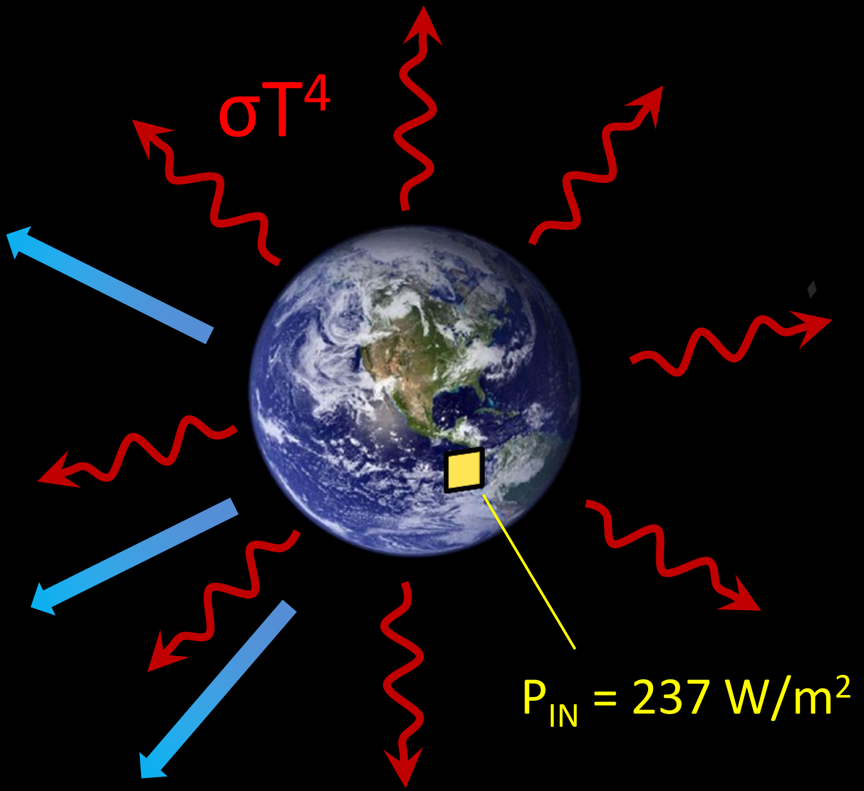
$\sigma = 5.67 \times 10^{-8}\ W/m^2/K^4$
(Stefan-Boltzmann Const)

So What Effective Temperature Does This Imply?





We can then easily calculate the effective Temperature as -2 ° F This is the temperature seen from outside the earth – also known as "Skin Temperature"



$P_{IN} = 237\ W/m^2$

$$P_{OUT} = 237\ W/m^2 = \sigma\, T_{EFF}^4$$

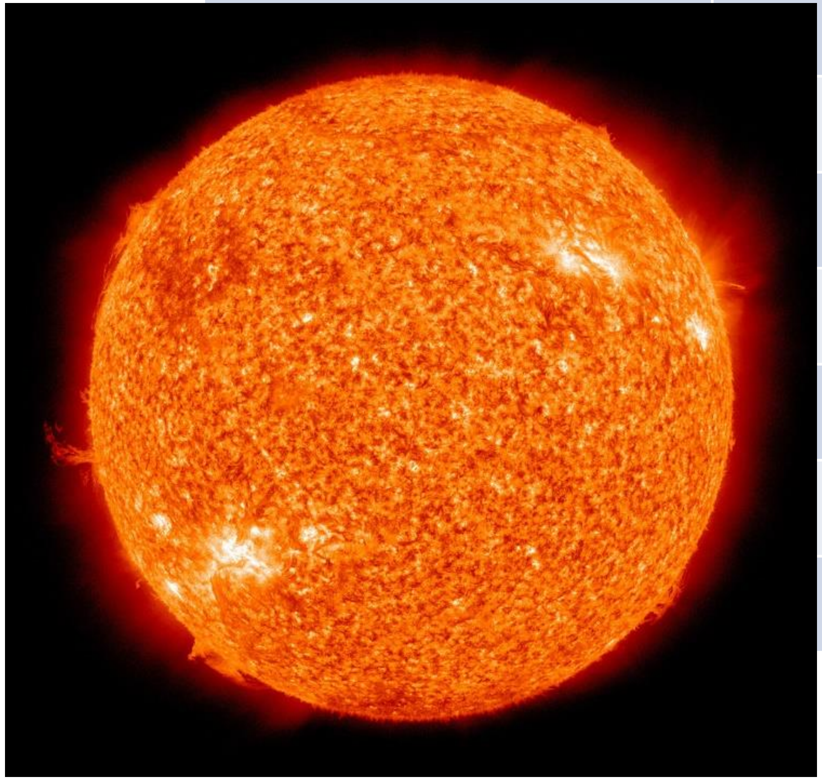
$$T_{EFF} = \sqrt[4]{237/\sigma}\ \boxed{= 254\ ^\circ K}\quad -2\ ^\circ F$$

"Skin Temp."

$\sigma = 5.67 \times 10^{-8}\ W/m^2/K^4$
(Stefan-Boltzmann Const)

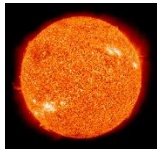
What Are the Heat Sources for Earth?

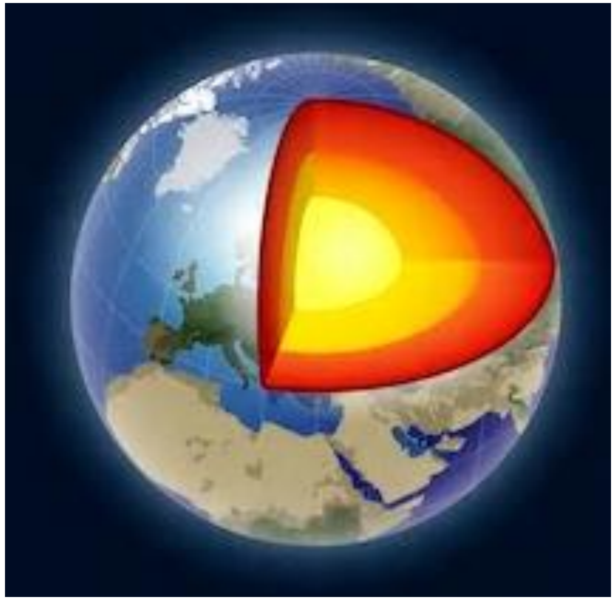
Source	Total Power	Power/sq m
	(TW)	*W/m^2*
Sun	120,900	237

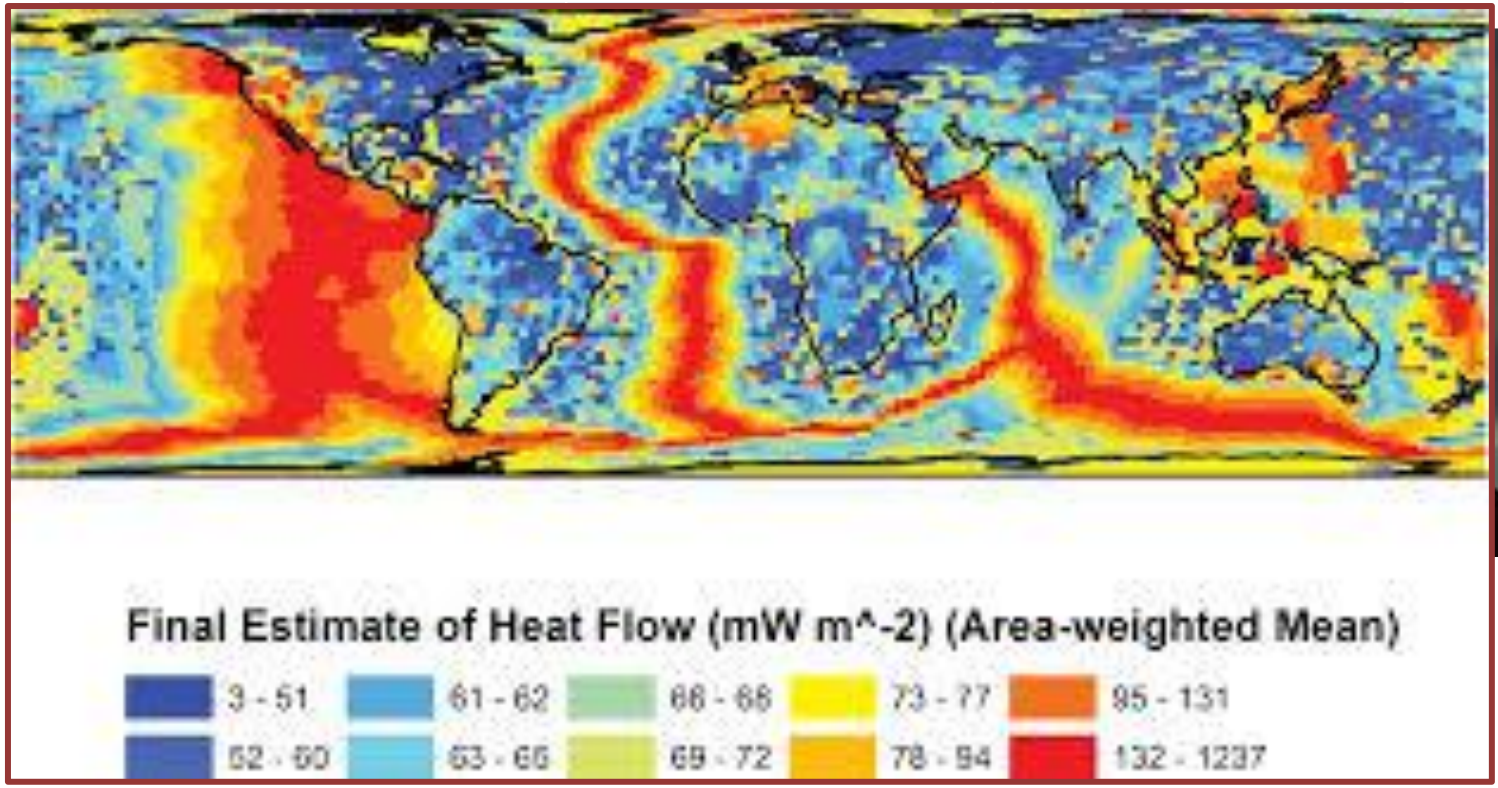


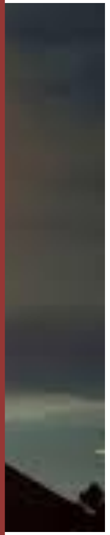
What Are the Heat Sources for Earth?

Source	Total Power	Power/sq m
	(TW)	*W/m^2*
Sun	120,900	237
Geothermal	45	0.088

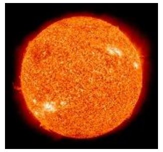


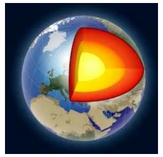




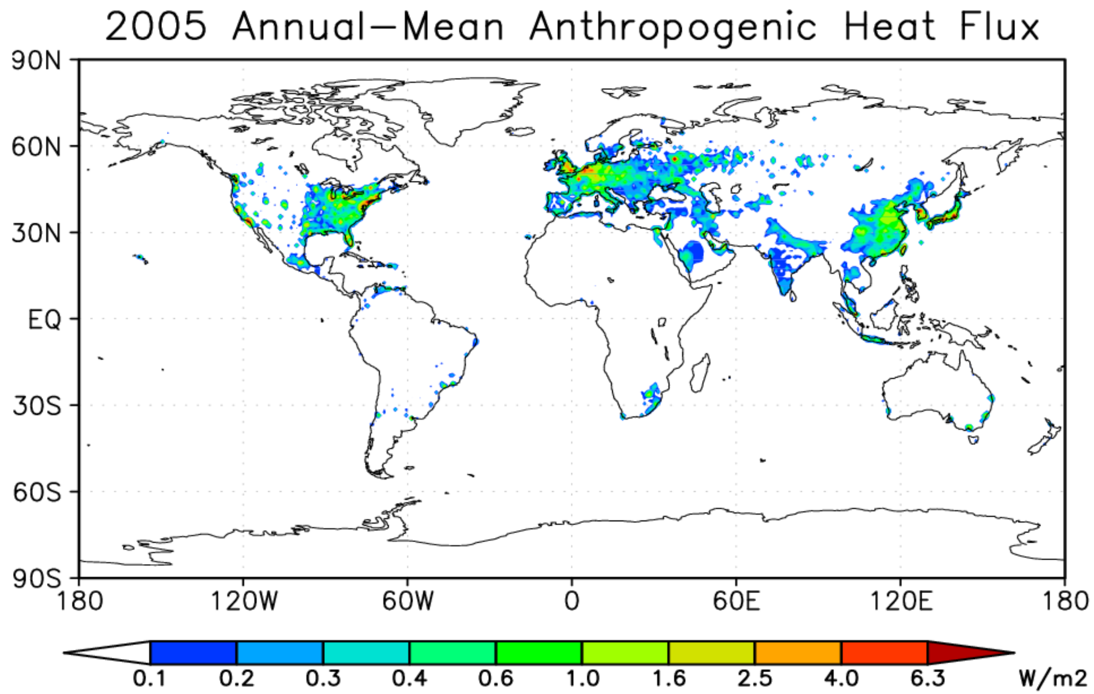


What Are the Heat Sources for Earth?



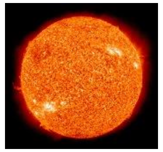


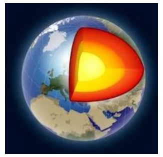
Source	Total Power	Power/sq m
	(TW)	*W/m^2*
Sun	120,900	237
Geothermal	45	0.088
Human Activity	≈ 17	0.033



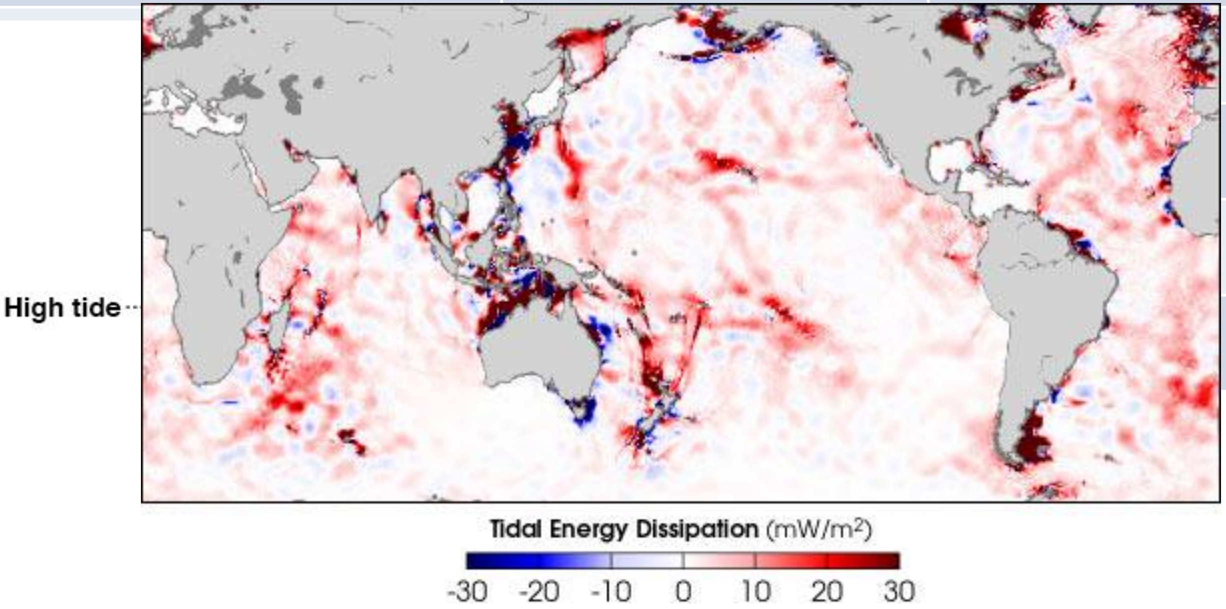
This is the *directly* generated human heat (e.g. nuclear power plants, burning fuels, etc.), ***not*** the indirect effect of CO2 emissions, etc.

What Are the Heat Sources for Earth?

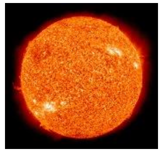


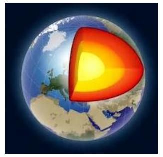


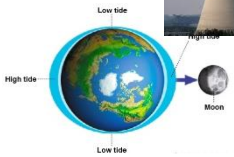
Source	Total Power	Power/sq m
	(TW)	*W/m²*
Sun	120,900	237
Geothermal	45	0.088
Human Activity	≈ 17	0.033
Tides	≈ 4	0.008



What Are the Heat Sources for Earth?



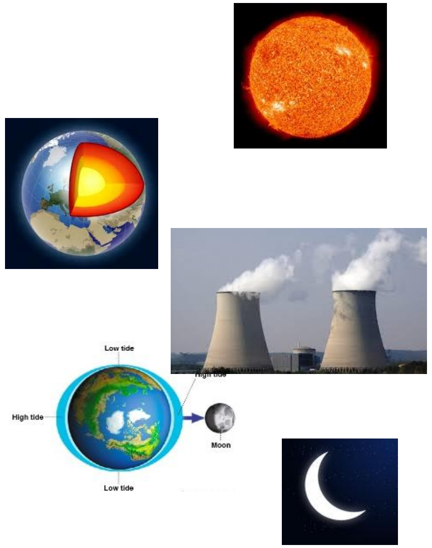




Source	Total Power	Power/sq m
	(TW)	*W/m²*
Sun	120,900	237
Geothermal	45	0.088
Human Activity	≈ 17	0.033
Tides	≈ 4	0.008
Moonlight*	≈1.8	0.0035

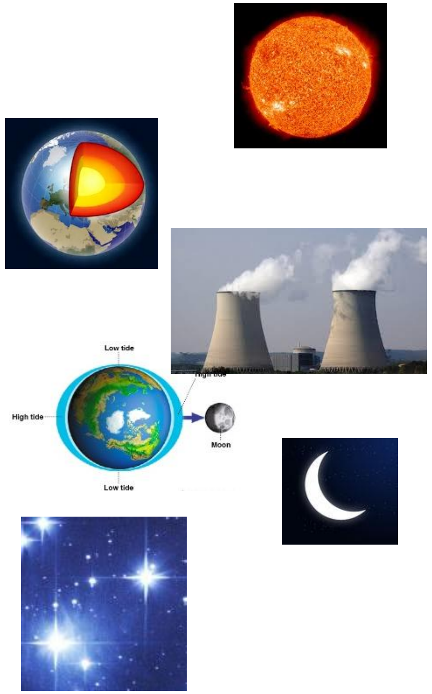
* Includes IR emission from hot face!

What Are the Heat Sources for Earth?



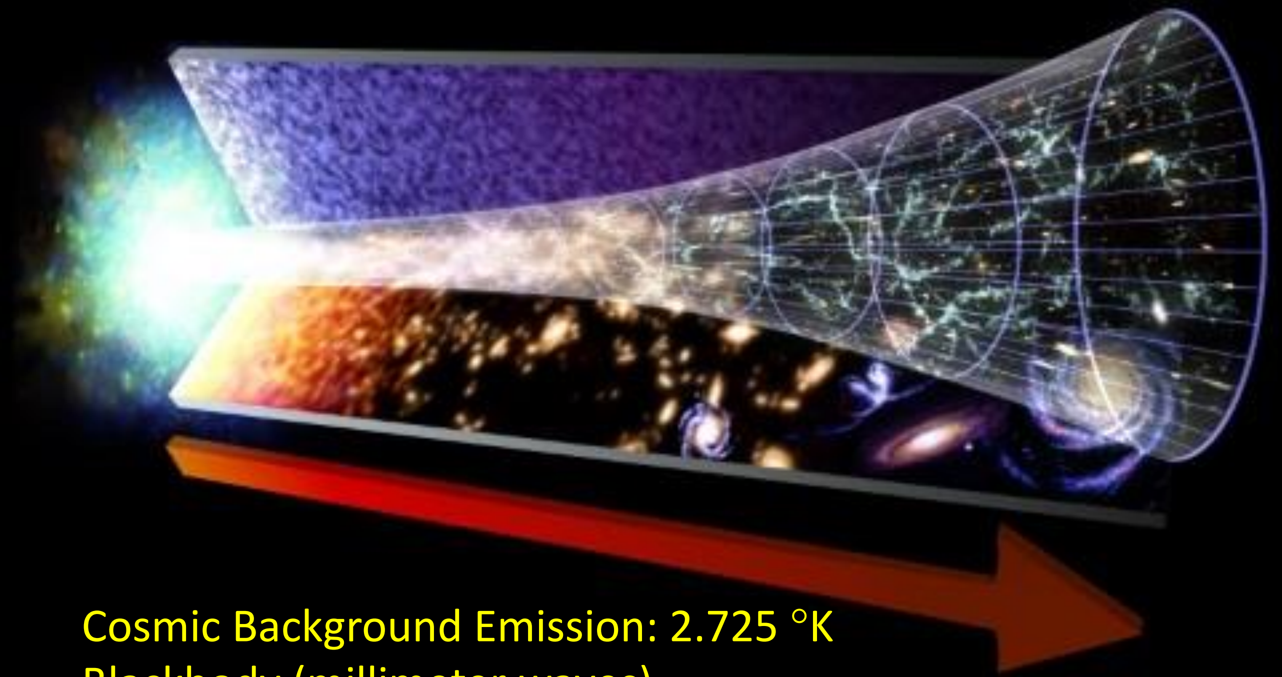
Source	Total Power	Power/sq m
	(TW)	*W/m²*
Sun	120,900	237
Geothermal	45	0.088
Human Activity	≈ 17	0.033
Tides	≈ 4	0.008
Moonlight*	≈1.8	0.0035
Starlight	≈0.005	0.00001

What Are the He



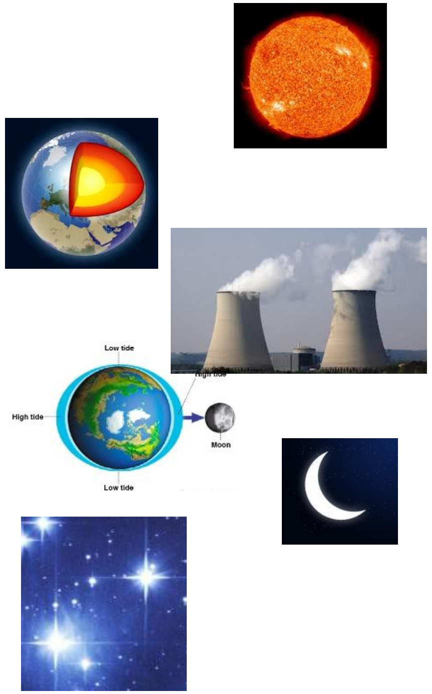
Source		
Sun		
Geotherma		
Human Activi		
Tides		
Moonlight*		
Starlight		
CBE	0.0016	0.0000031
Totals	121,000	237.13

Relic of the Big Bang

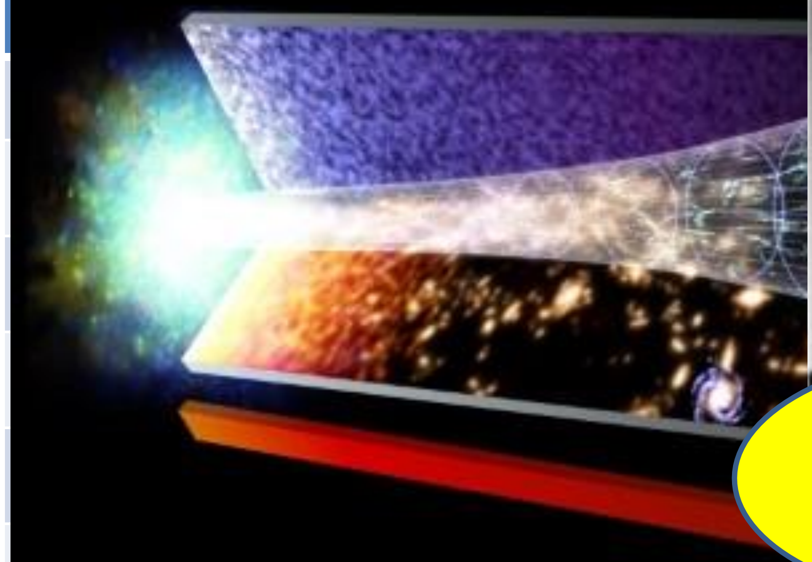


Cosmic Background Emission: 2.725 °K
Blackbody (millimeter waves)

What

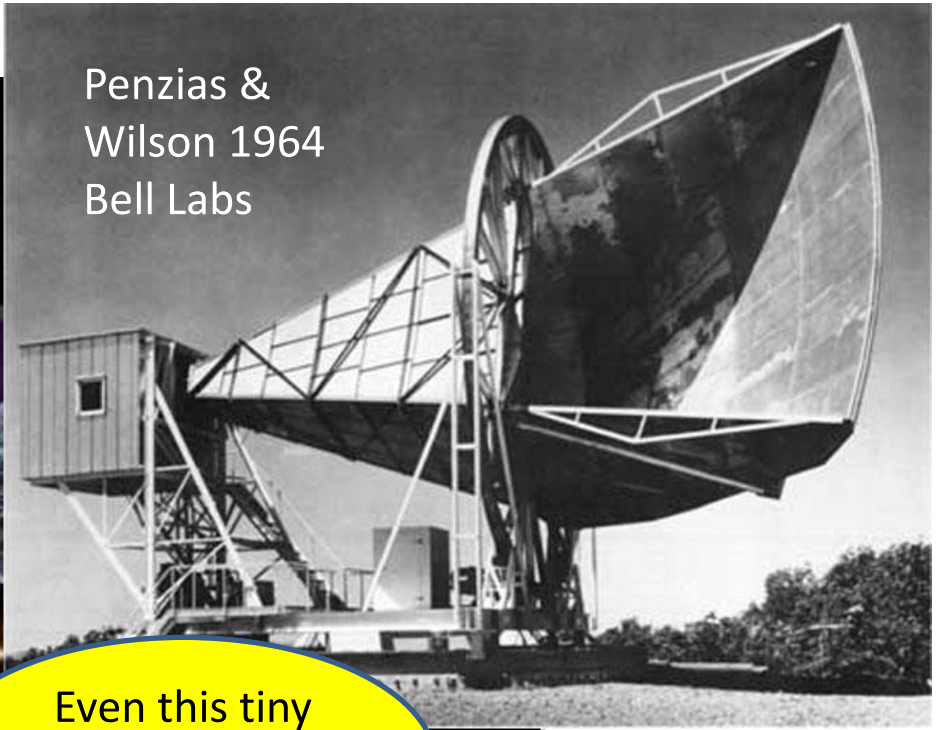


Relic of the Big Bang



Cosmic Background Emission: 2.725 °K Blackbody (millimeter waves)

Penzias & Wilson 1964 Bell Labs



Even this tiny amount = 1.6 Gigawatts!

CBE	0.0016	0.0000031
Totals	121,000	237.13

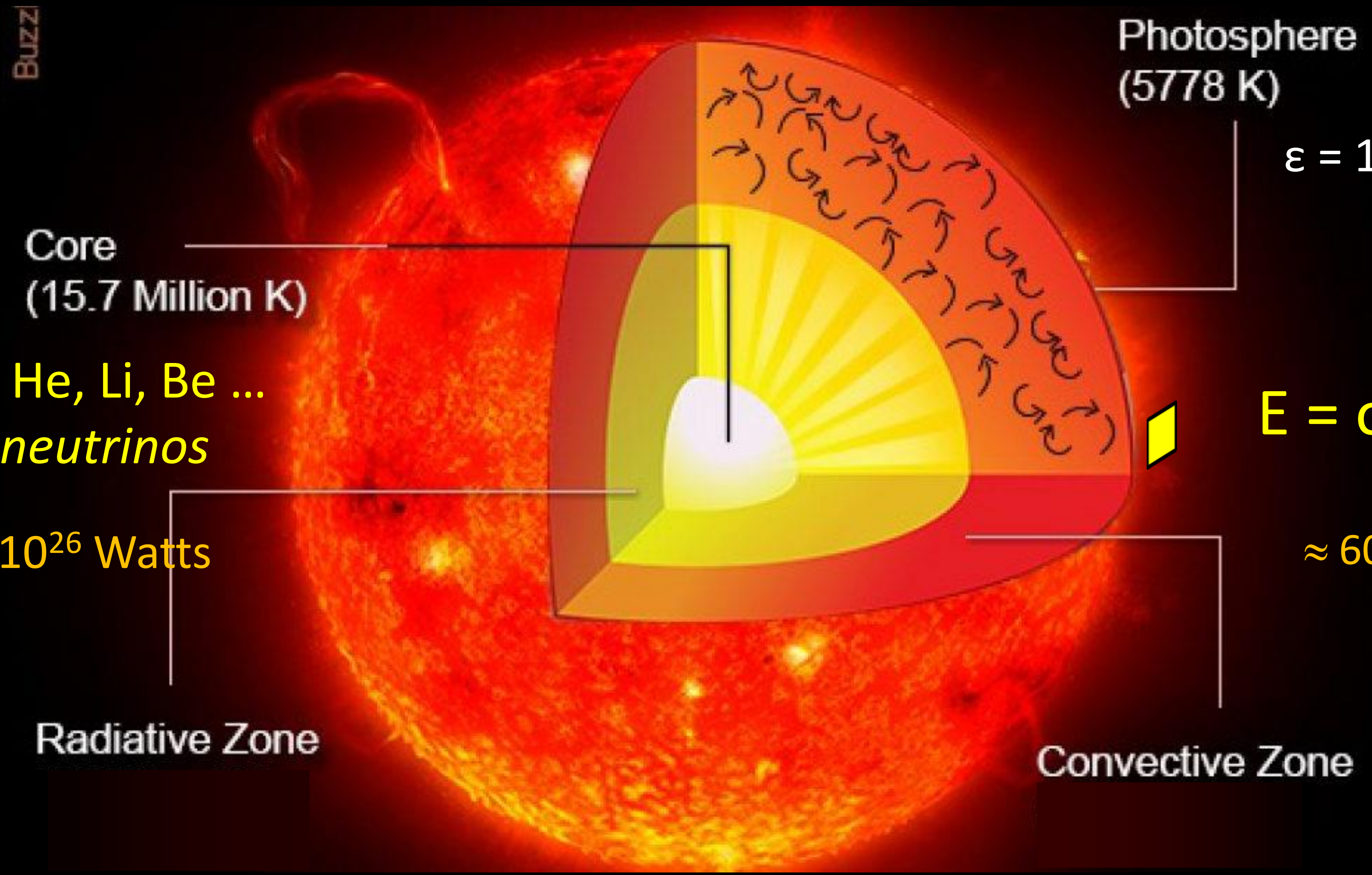
What Are the Heat Sources for Earth?

What Are the Heat Sources for Earth?

The sun is virtually the whole story…

Source	Total Power	Power/sq m
	(TW)	*W/m²*
Sun	120,900	237
Geothermal	45	0.088
Human Activity	≈ 17	0.033
Tides	≈ 4	0.008
Moonlight*	≈1.8	0.0035
Starlight	≈0.005	0.00001
CBE	0.0016	0.0000031
Totals	121,000	237.13

Our Sun – A fusion reactor



$\varepsilon = 100\%$

H → He, Li, Be …
+ *neutrinos*

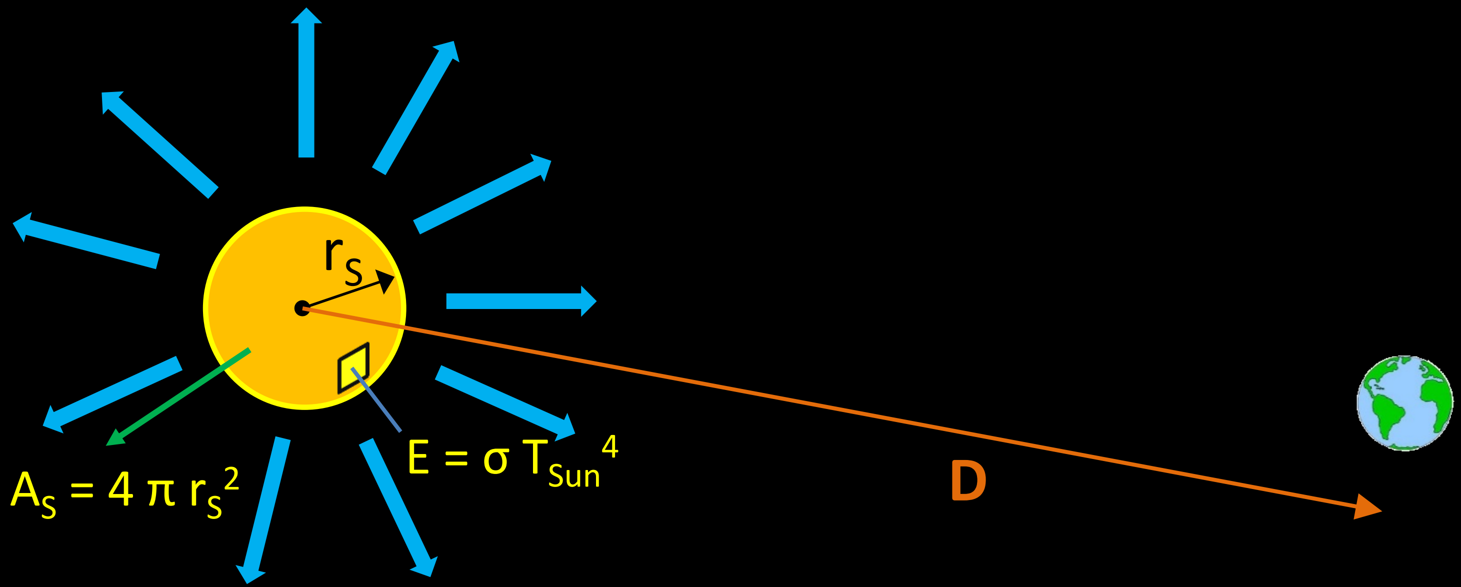
$\sim 4 \times 10^{26}$ Watts

$E = \sigma T_{Sun}^{4}$ W/m^2

≈ 60 Megawatts / m^2 !

How Much Sunlight Reaches Earth?

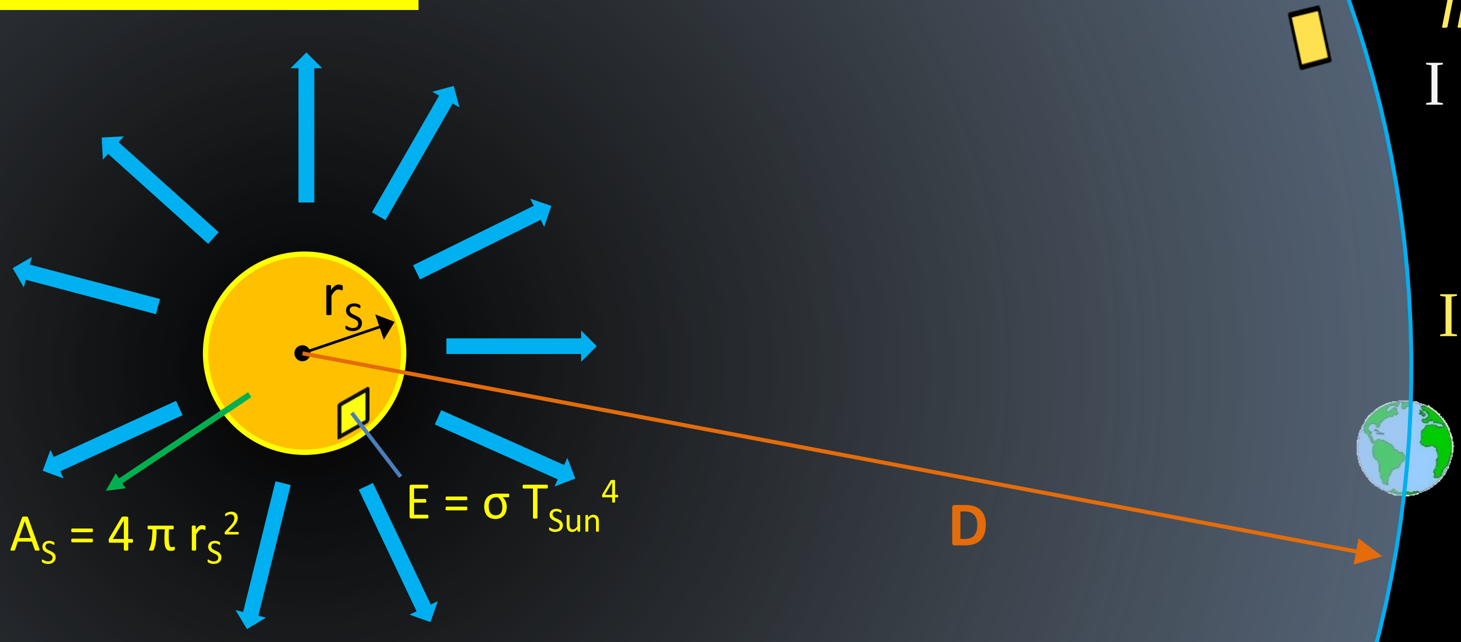
Start by figuring out the total energy output of the sun, called its Luminosity….



Total Power *Luminosity* $L = E A_S$ watts

How Much Sunlight Reaches Earth?

Then spread this heat out over a huge spherical shell at the distance of the Earth. Doing the accounting, get 1367 Watts per square meter near the earth…



$A_S = 4\pi r_S^2$

$E = \sigma T_{Sun}^4$

$A_{bubble} = 4\pi D^2$

Light hitting each square meter=

Irradiance

$I = L / A_{bubble}$

watts/m²

$$I = \sigma T_{Sun}^4 \left[\frac{r_S}{D}\right]^2 = 1367 \text{ W/m}^2$$

Total Power *Luminosity* $L = E A_S$ watts

How Much Sunlight Reaches Earth?

Curiously, we don't actually have to know how big the sun is, or how far away it is. All we need to do is measure its apparent angular size, which anyone can do. it is about 0.5 degrees, same as the moon.

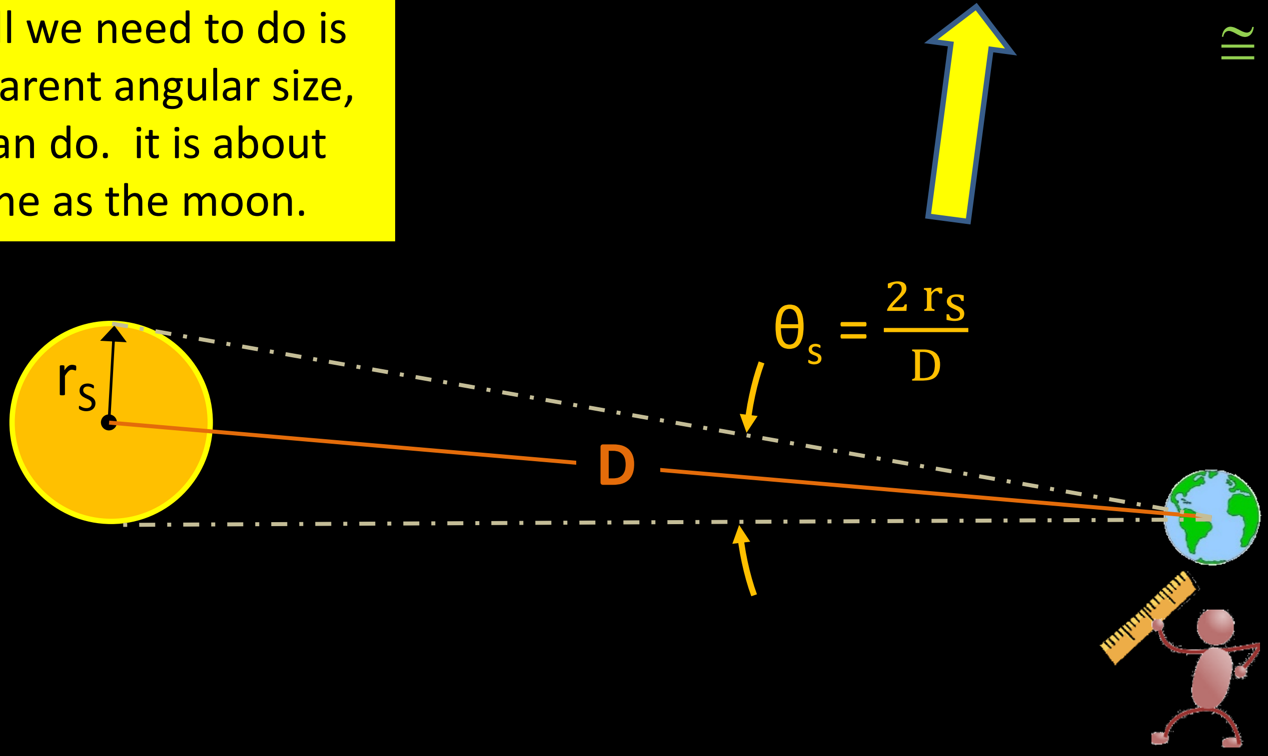
$$I = \sigma\, T_{\text{Sun}}^{4} \left[\frac{r_S}{D}\right]^{2}$$

Light hitting each square meter=

Irradiance

at Earth

≅ 1367 W/m^2



$$\theta_s = \frac{2\, r_S}{D}$$

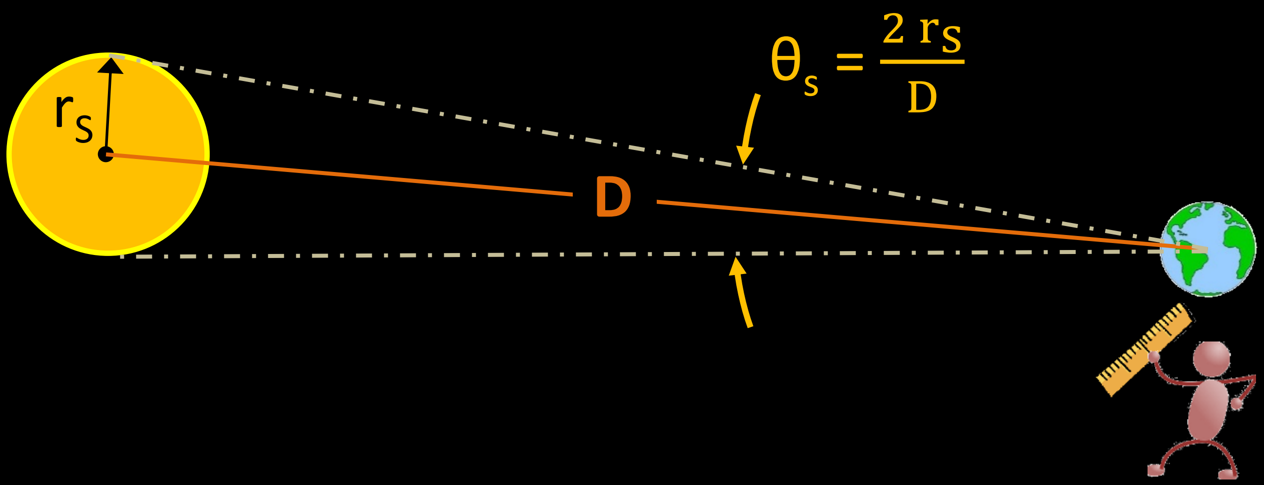
How Much Sunlight Reaches Earth?

So we can get a formula for the Irradiance of the sun at any location just in terms of the Sun's temperature and apparent angular size θ_S. We do not need to know how far away the sun is…

$$I = \sigma\, T_{Sun}^4 \left[\frac{r_S}{D}\right]^2$$

Light hitting each square meter= *Irradiance* at Earth

$$\boxed{I = \sigma\, T_{Sun}^4 [\theta_s/2]^2 \cong 1367\ \mathrm{W/m^2}}$$

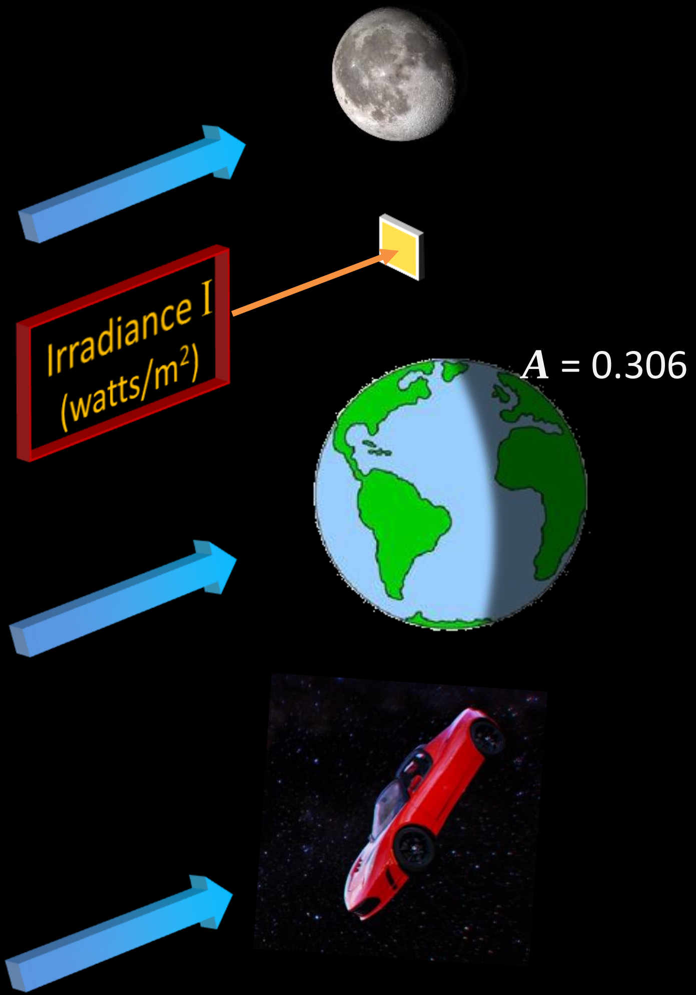


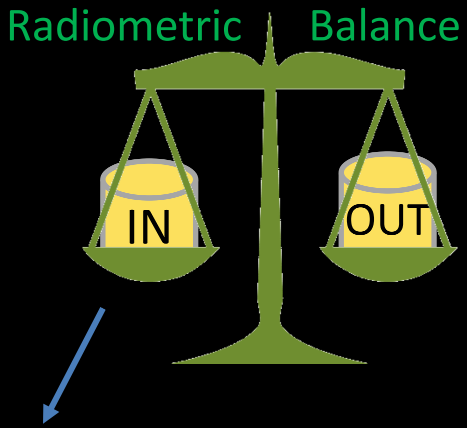
Take a deep breath…

A bit complicated, but definitely not Rocket Science!

Equilibrium Effective Temperature
for Objects in Space

- “Bond” Albedo ***A***
- IR Emissivity ε ≈ 1





For each
square meter
of surface

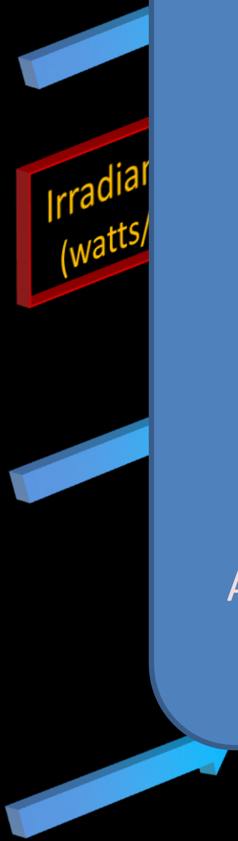
$$\frac{\boldsymbol{I}}{4}[1-A]$$

$$\boxed{I = \sigma\, T_{Sun}^4 [\theta_s /2]^2}$$

Equilibrium Effective Temperature

Radiometric Balance

For each
square meter
of surface



Albedo*:

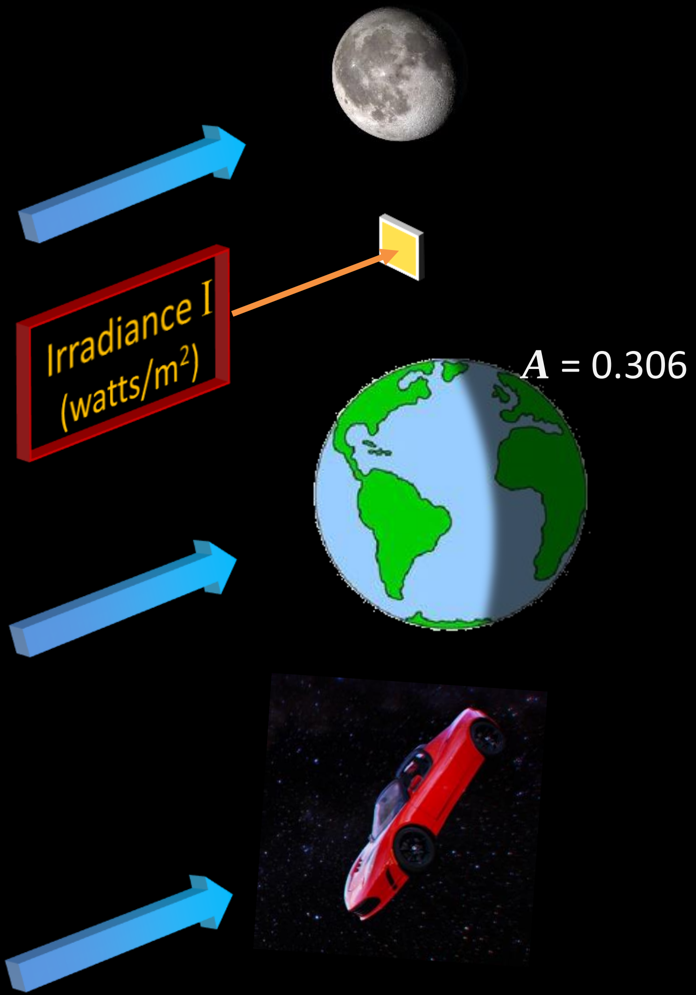
Fraction of sunlight *reflected* by planet
(and therefore not absorbed)

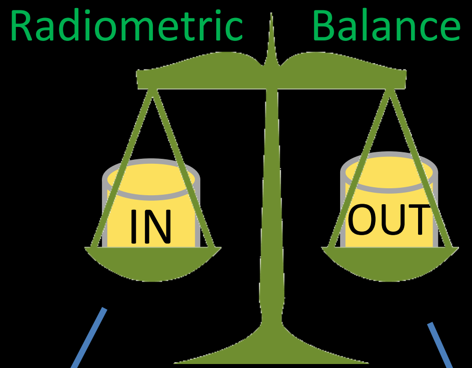
1.0	.77	.30	.25	.11	0
No Absorption	Venus	Earth	Mars	Moon	100% Absorption

* Bond Albedo

Equilibrium Effective Temperature

- “Bond” Albedo $\boldsymbol{A}$
- IR Emissivity $\varepsilon \approx 1$





For each
square meter
of surface

$$\frac{\boldsymbol{I}}{4}[1-A] \quad = \quad \sigma\, T_{eff}^{4}$$

$$\boxed{T_{eff} = \tfrac{1}{2}\, T_{sun} \sqrt{\theta_s}\, \sqrt[4]{(1-A)}}$$

$$I = \sigma\, T_{Sun}^{4} [\theta_s /2]^2$$

So we get a fairly simple formula for figuring out the T_{EFF} of bodies knowing only the Sun’s temperature, its apparent angular size, and the body’s Albedo!

Equilibrium Effective Temperature

$$T_{eff} = \frac{1}{2} Tsun \sqrt{\theta_s} \sqrt[4]{(1-A)}$$

“Skin Temperature”

We can easily calculate T_{EFF} for a bunch of heavenly bodies, and compare with NASA’s numbers….

Bare Rocks:
(No atmosphere)

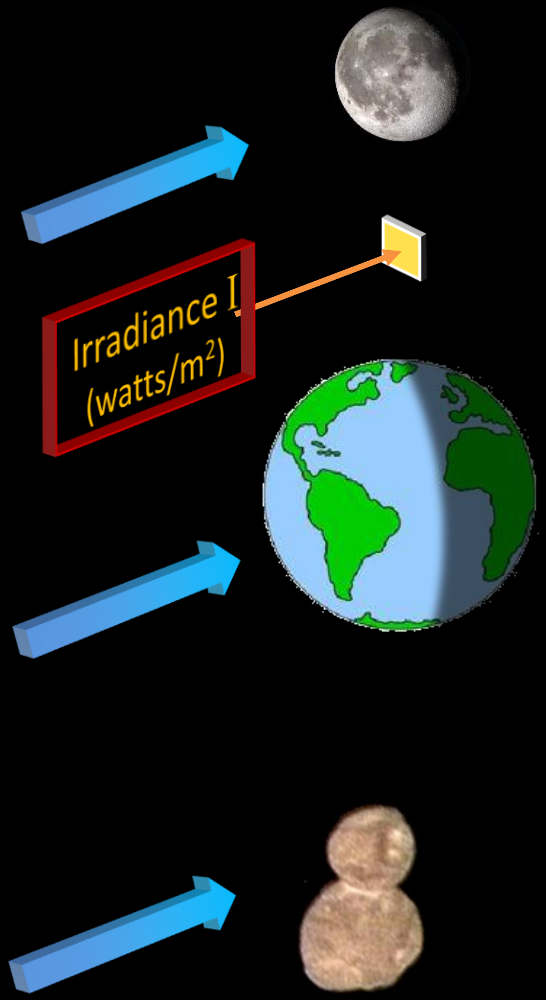
Average Surface Temperature T_{SURF} *is the same as* T_{eff}

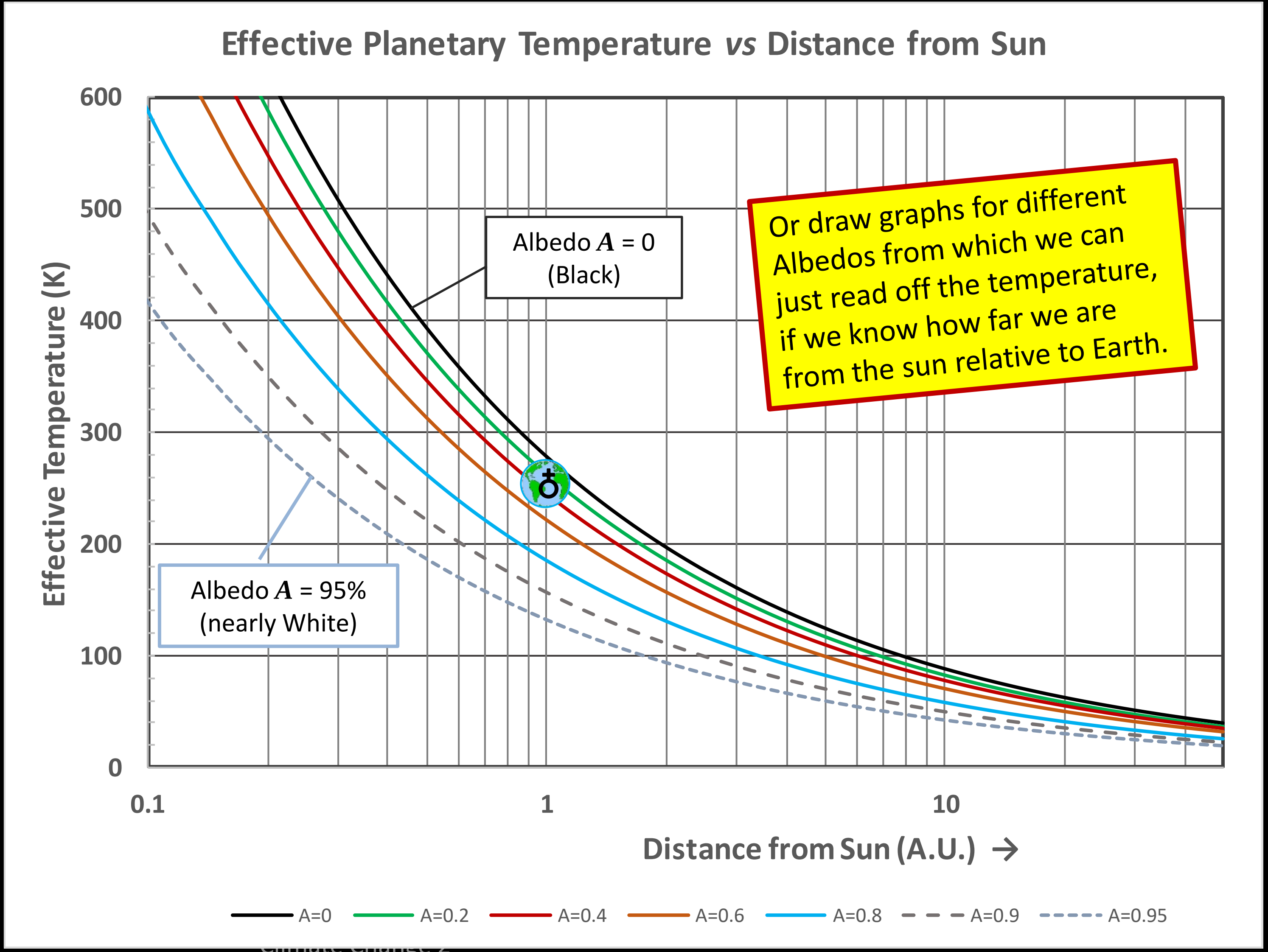
Body	T_{SUN}	θ_S Apparent Sun Dia.	D_{rel} Relative Distance	*A** Bond Albedo	T_{EFF}		
					Calculated		*NASA**
Units	*°K*	*deg*	*A.U.*		*°K*	*°F*	*°K*
Mercury	5770	1.377°	*0.39*	0.068	439	331	*439.6*
Venus	5770	0.737°	*0.72*	0.77	227	-52	*226.6*
Earth	5770	0.533°	*1.0*	0.306	254	-2	*254.0*
Moon	5770	0.533°	*1.0*	0.11	270	27	*270.4*
Mars	5770	0.350°	*1.52*	0.25	210	-82	*209.8*
Uranus	5770	0.028°	*19.2*	0.30	58	-355	*58.1*
Ultima-Thule	5770	0.012°	*44.5*	0.09 (est)	41	-386	*?*

*https://nssdc.gsfc.nasa.gov/planetary/factsheet/

Equilibrium Effective Temperature

$$T_{eff} = \frac{1}{2}\,Tsun\,\sqrt{\theta_s}\;\sqrt[4]{(1-A)}$$

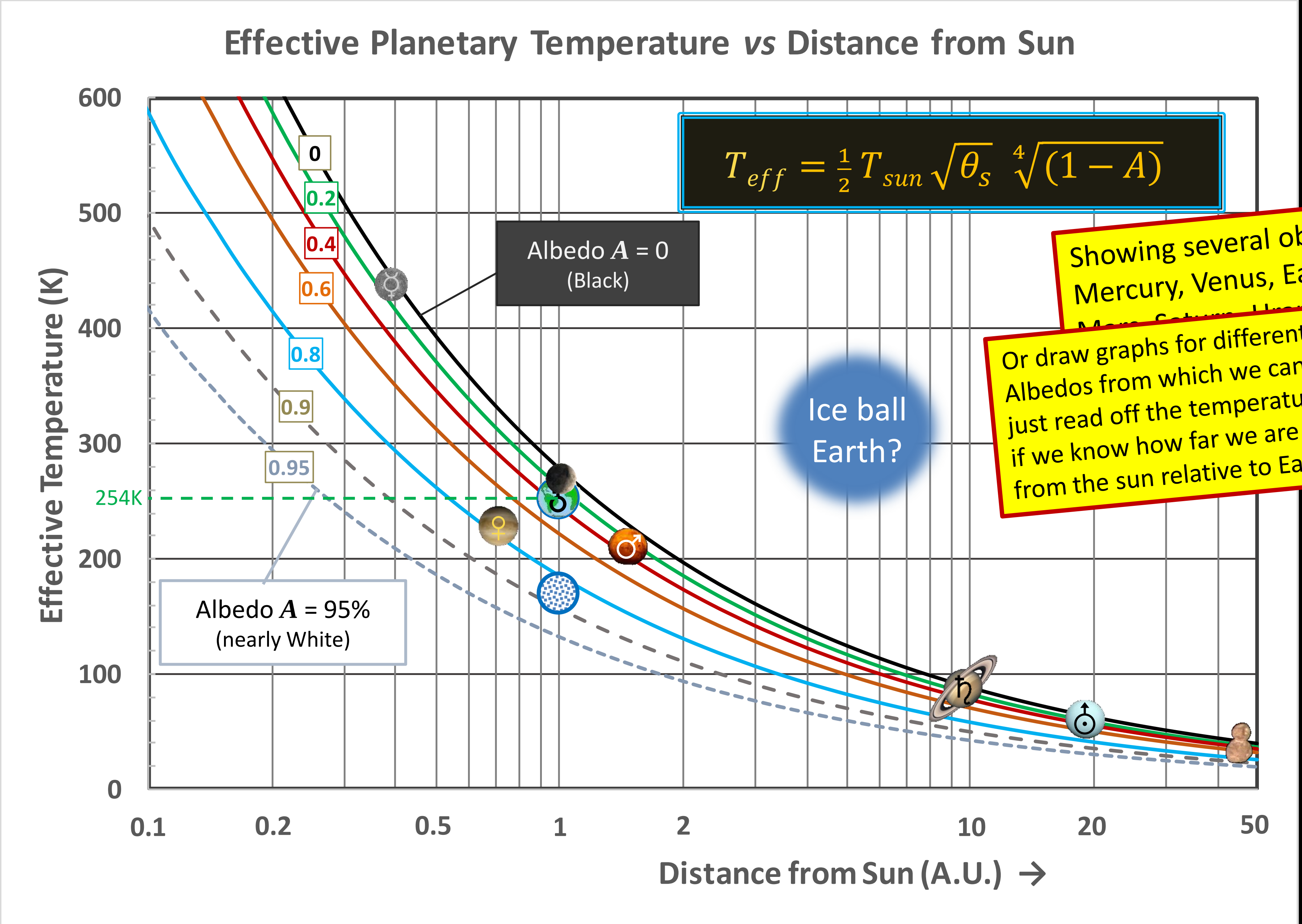



Effective Planetary Temperature *vs* Distance from Sun

Albedo ***A*** = 0
(Black)

Albedo ***A*** = 95%
(nearly White)

Or draw graphs for different Albedos from which we can just read off the temperature, if we know how far we are from the sun relative to Earth.



$$T_{eff} = \tfrac{1}{2} T_{sun} \sqrt{\theta_s}\ \sqrt[4]{(1-A)}$$

Showing several objects:
Mercury, Venus, Earth,
Mars, Saturn, Uranus
rth”
to

Or draw graphs for different
Albedos from which we can
just read off the temperature,
if we know how far we are
from the sun relative to Earth.

A Tale of Two Planets

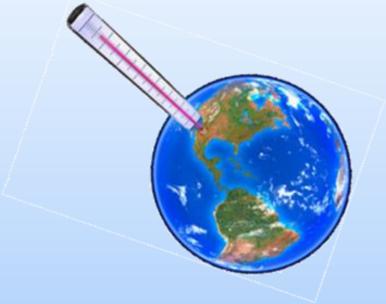
♀

So now we understand the Skin Temperatures of Venus and Earth, based on their Albedos and distance from the sun.

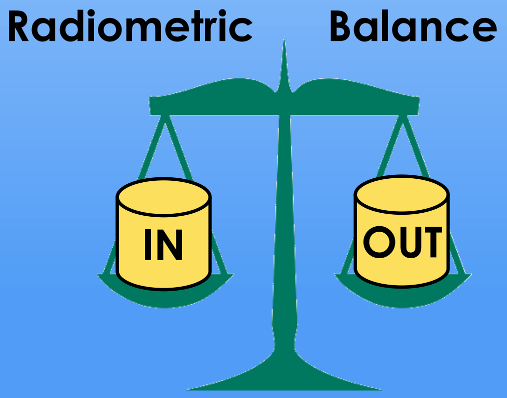
♁

77%	Albedo	30%
-51 °F	Effective *(Apparent Ave.)* Temperature	**-2 °F**

Questions about Earth’s basic Effective Temperature?

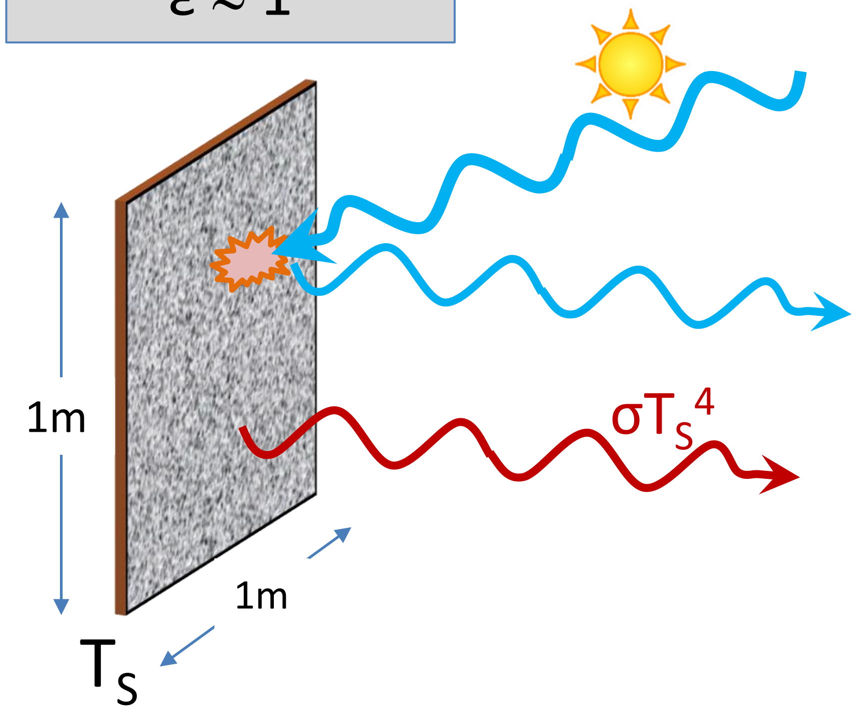


Why is it about -2 ^{o}F ?



Radiative Greenhouse Effect

Albedo A = 0.5
$\varepsilon \approx 1$

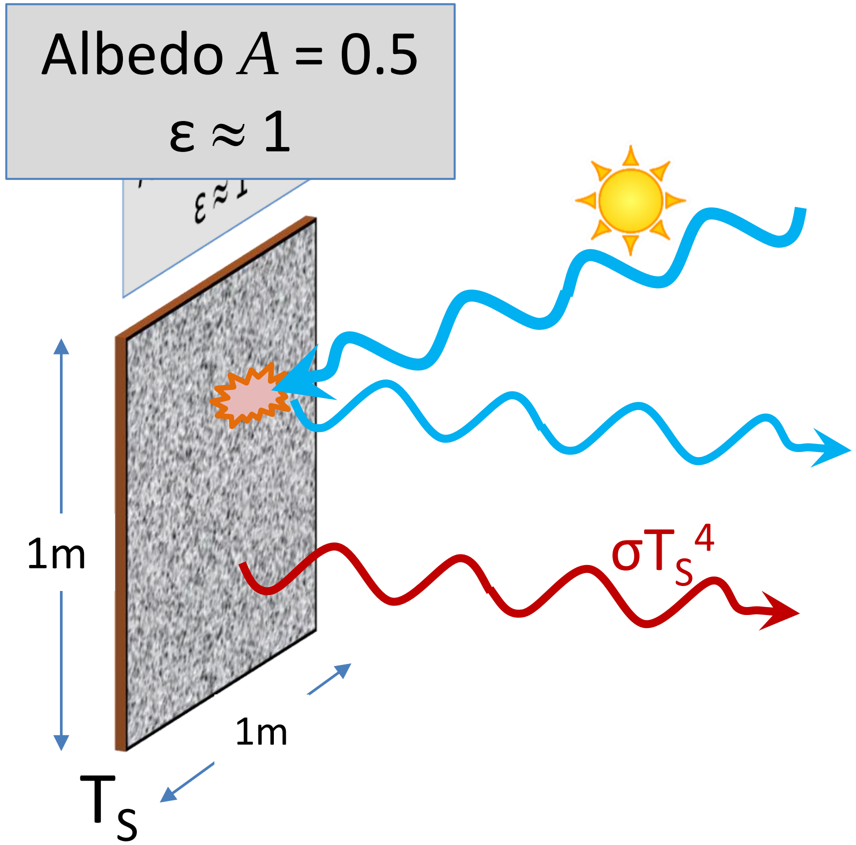


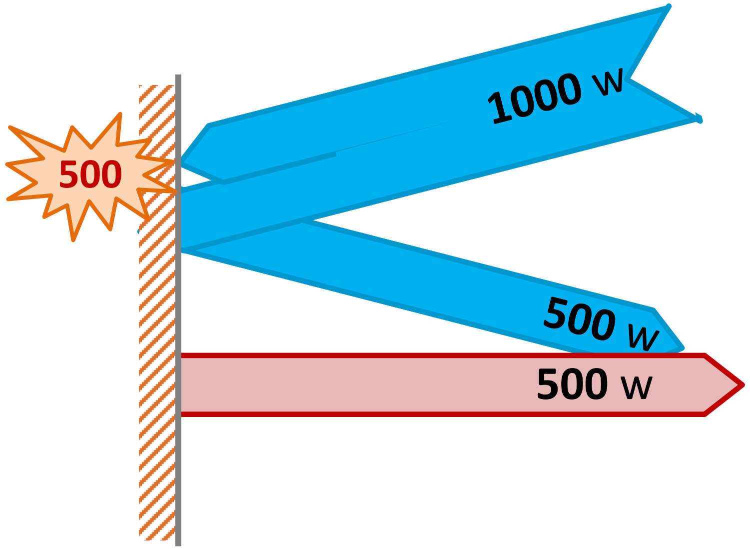
To see how the Greenhouse effect works, imagine we have square meter of surface with Albedo 50%. 1000 W/m2 of sunlight is coming in, 50% of which is absorbed as heat.
Depending on its temperature, the surface also emits some amount of Blackbody IR radiation.

VACUUM

σ = 56.7 nW / m^2 /K^4

Radiative Greenhouse Effect





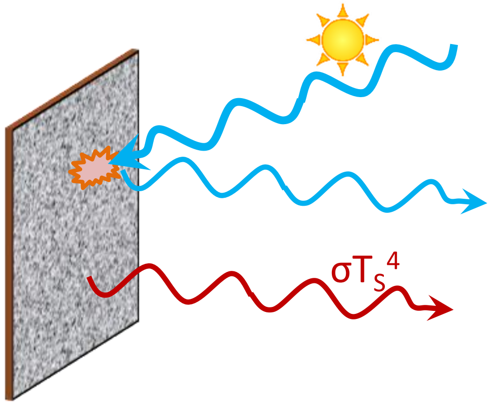
T_S = 306 K (92°F)

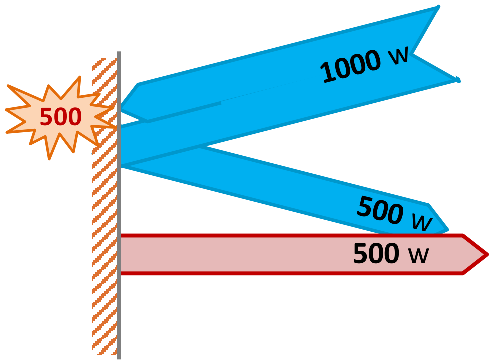
VACUUM

σ = 56.7 nW / m^2 /K^4

In order to achieve equilibrium, since the surface absorbs 500 watts of sunlight, it must be able to emit 500 watts of IR radiation.
Thus its temperature must be T_S=306K

Radiative Greenhouse Effect

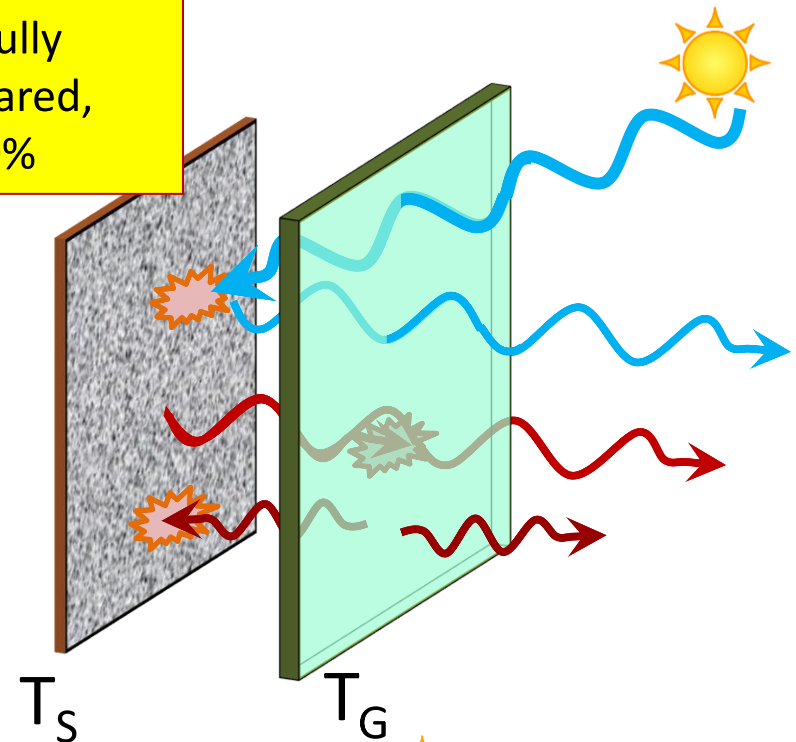


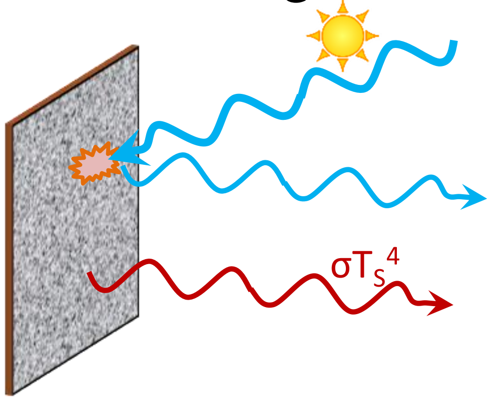


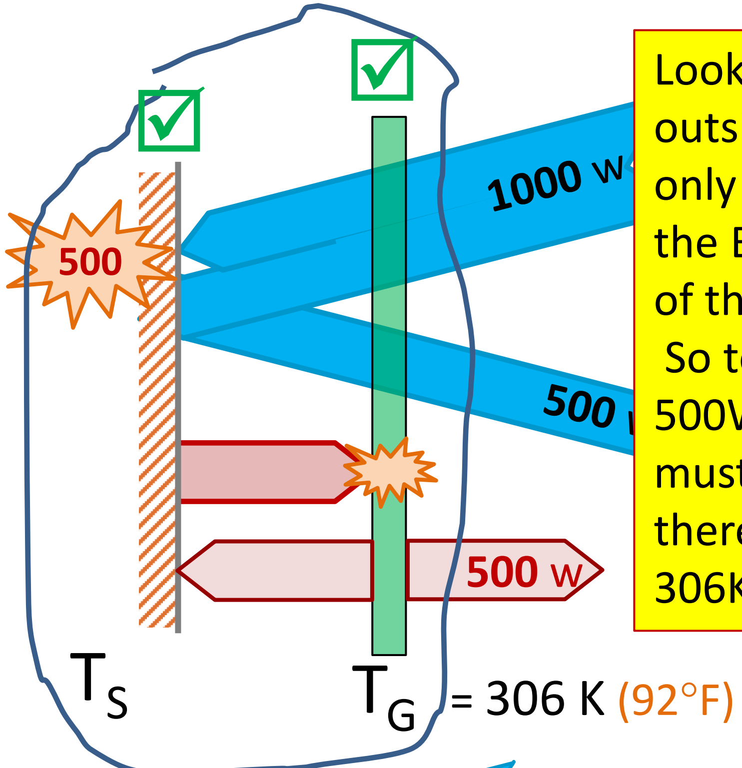
T_S = 306 K (92°F)

Radiative Greenhouse Effect

Now let's put a sheet of glass in front of the surface. Glass fully absorbs LW Infrared, emissivity = 100%

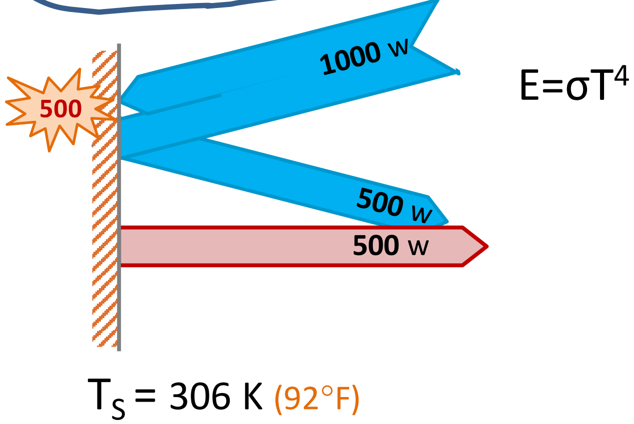






T_G = 306 K (92°F)

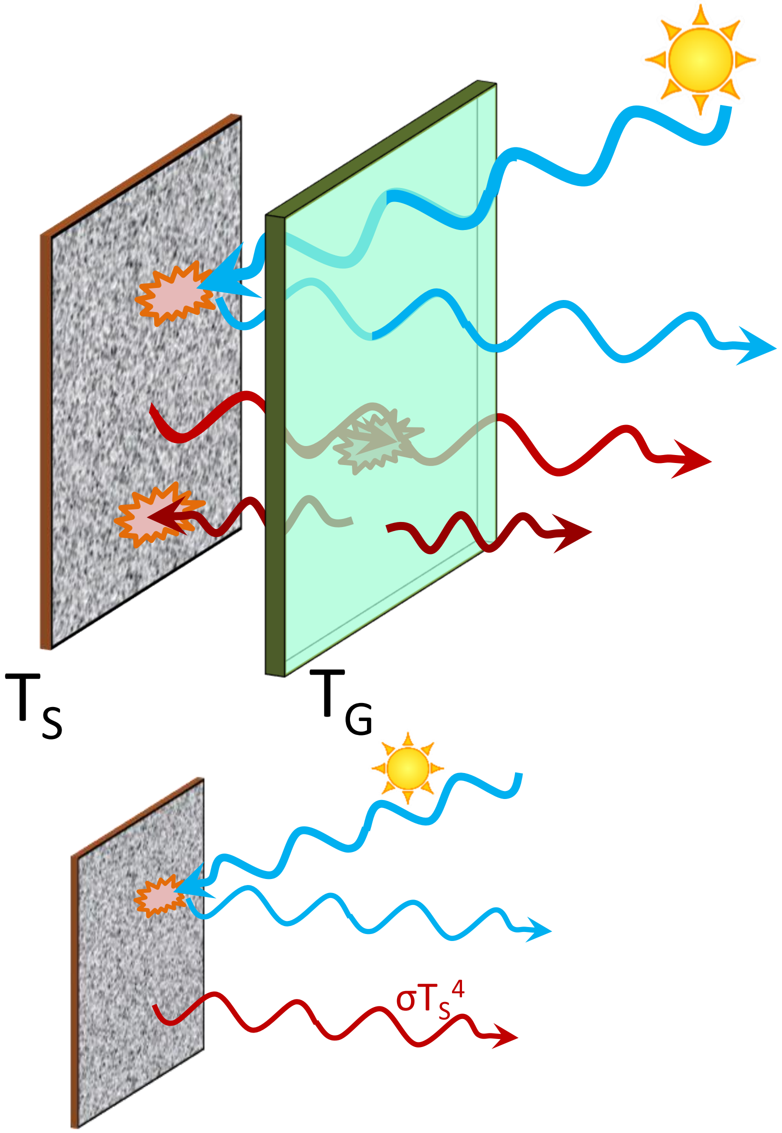
Looking from the outside (space), the only IR is coming from the BlackBody emission of the glass sheet.
So to balance the 500W of sunlight, it must emit 500W and therefore has the same 306K temperature!

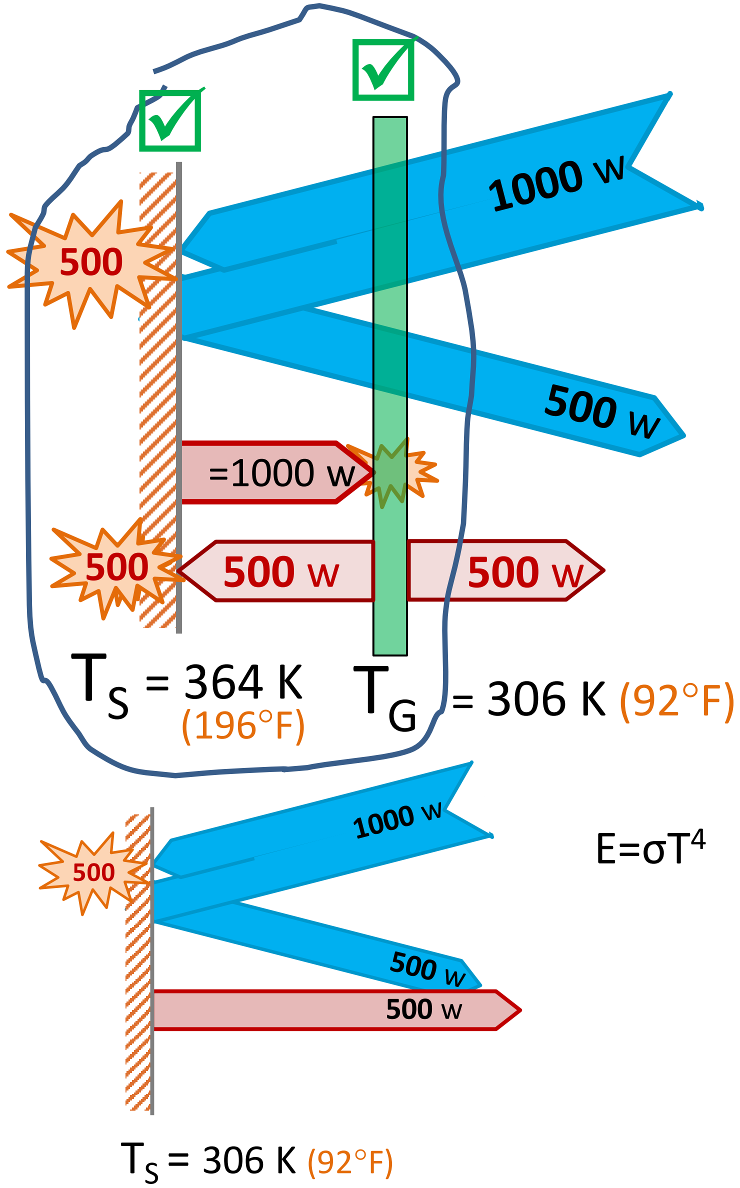


$E=\sigma T^4$

T_S = 306 K (92°F)

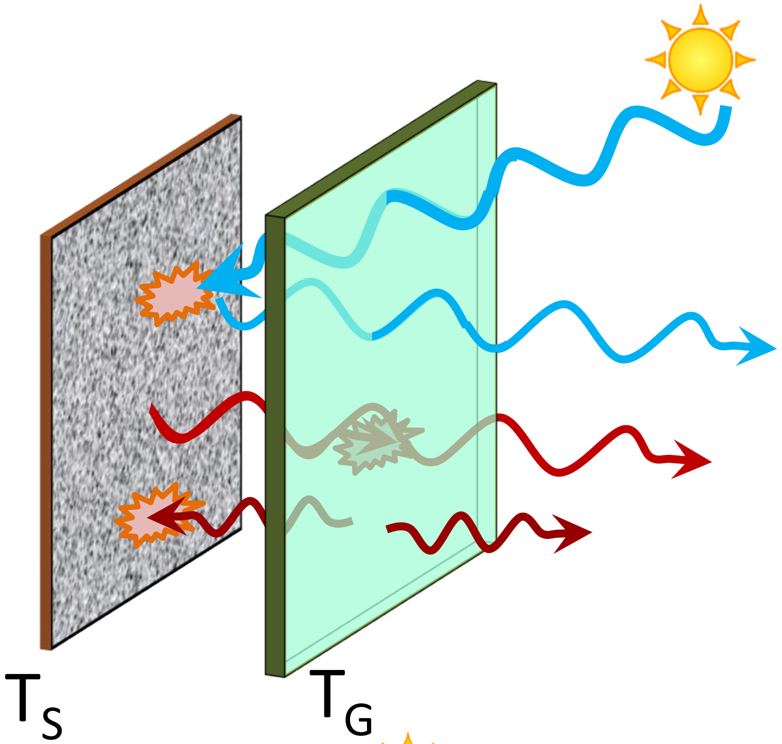
Radiative Greenhouse Effect

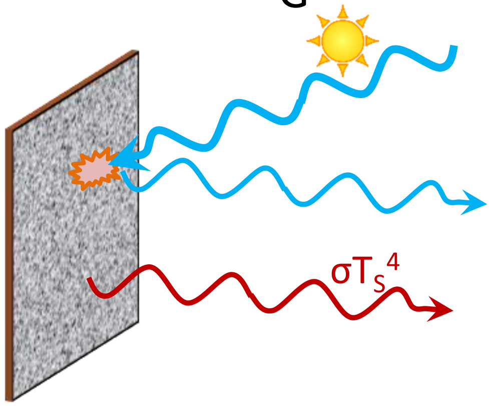


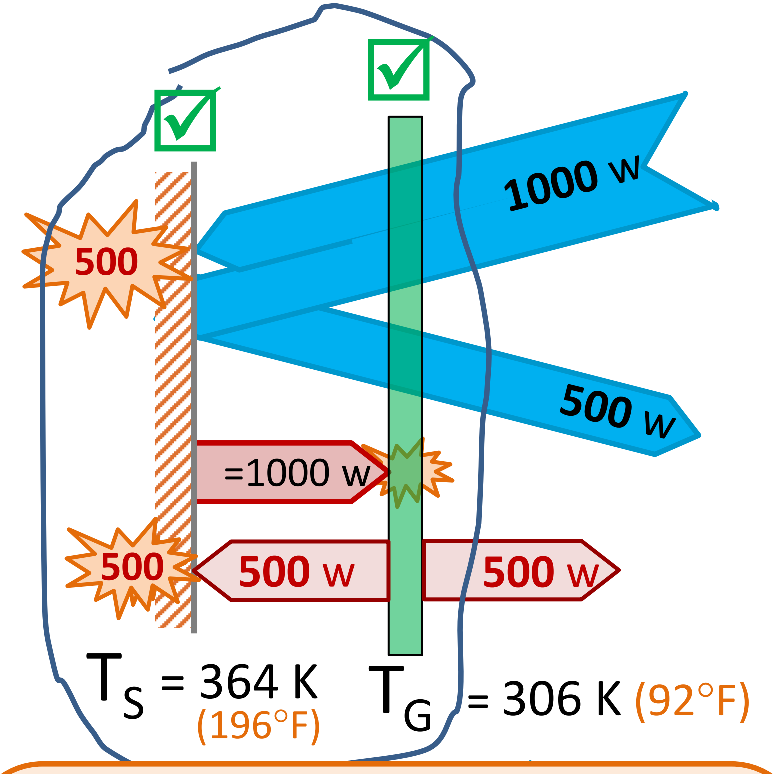


The glass must also emit 500W back towards the surface, where it is entirely absorbed. Thus surface is now getting 1000 watts total heat.
It must then warm up so it emits 1000W, which means the temperature is 364K.

Radiative Greenhouse Effect







T_S = 364 K (196°F)

T_G = 306 K (92°F)

It turns out that the Surface is warmed up by 19%, and this is true regardless of its Albedo!

19%

Power Doubled

$E=\sigma T^4$

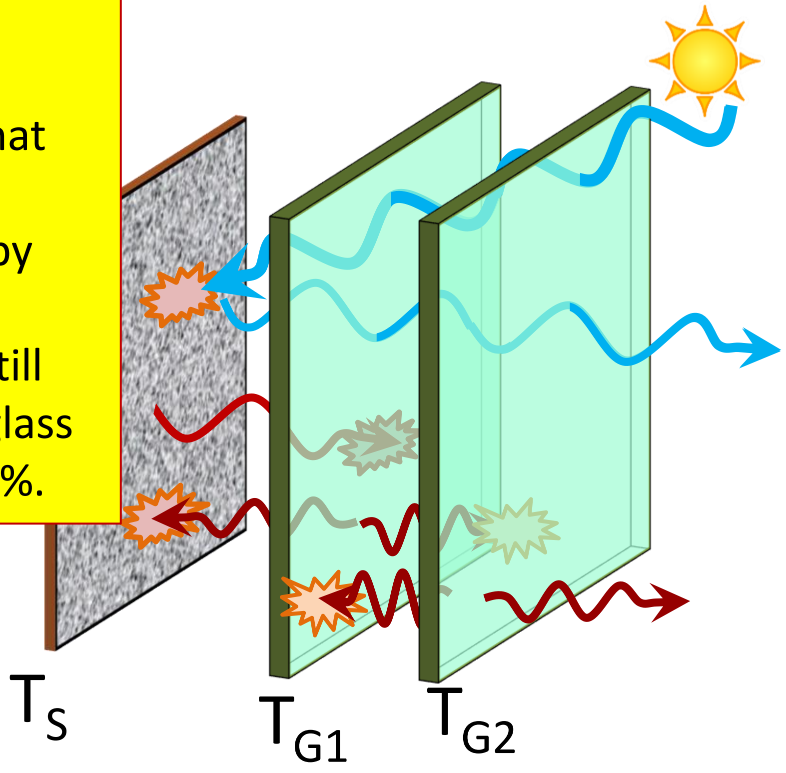
... *so* T^4 must ***double***

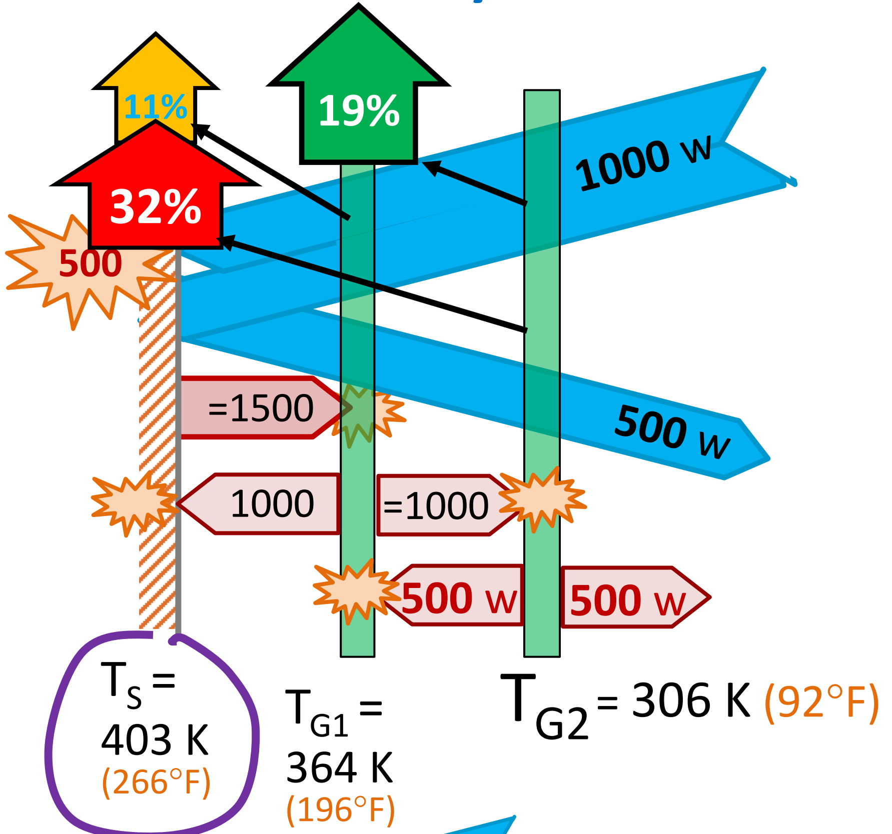
... so T increases by $\sqrt[4]{2} \approx$ **1.19**

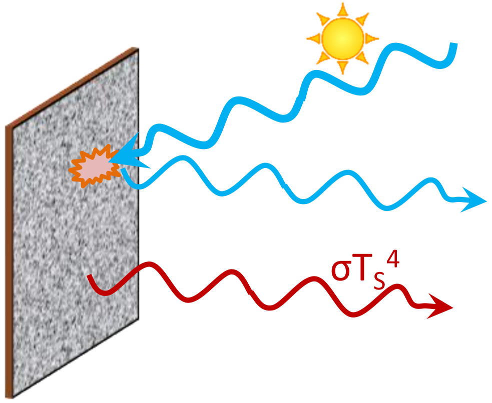
Regardless of *A* !

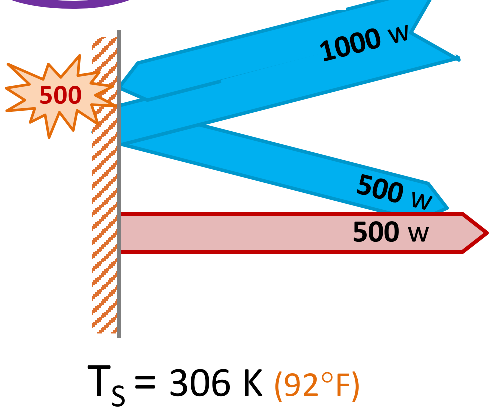
Radiative Greenhouse Effect: 2 Layers

What if we use 2 sheets of glass (still in a Vacuum!)
Then it turns out that the Surface temperature rises by 32%!
The outer glass is still 306K, and the 2nd glass sheet warms up 19%.



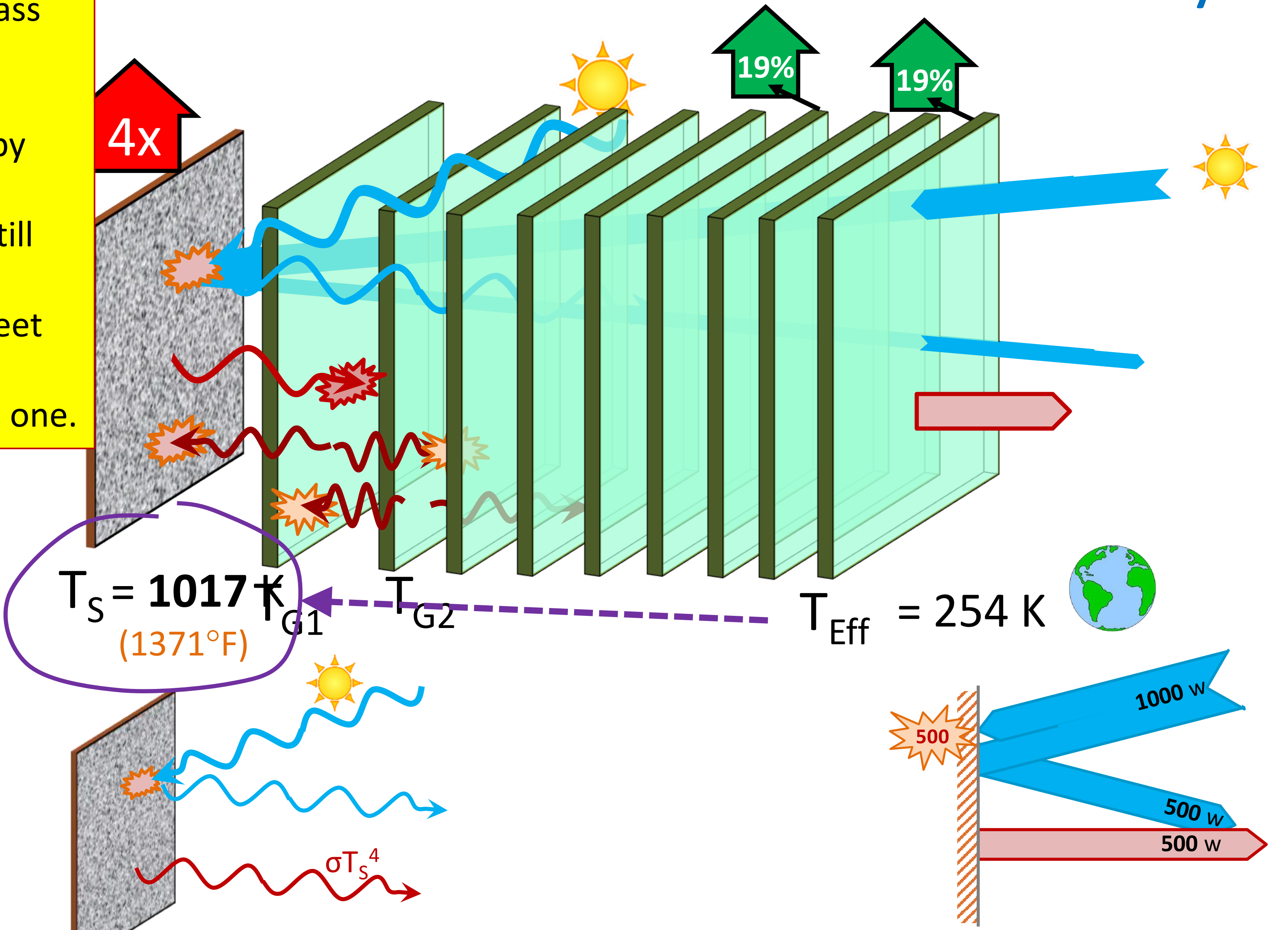






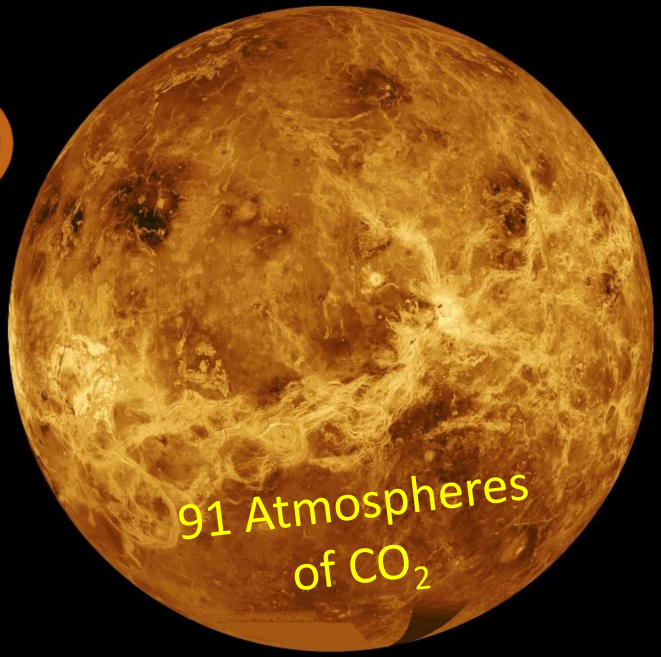
Radiative Greenhouse Effect: n = 9 Layers

With 9 sheets of glass (still in a Vacuum!), the Surface temperature rises by 400%! Super hot. The outer glass is still 306K, and each successive glass sheet warms up by 19% above the previous one.



A Tale of Two Planets: Down at the Surface

♀



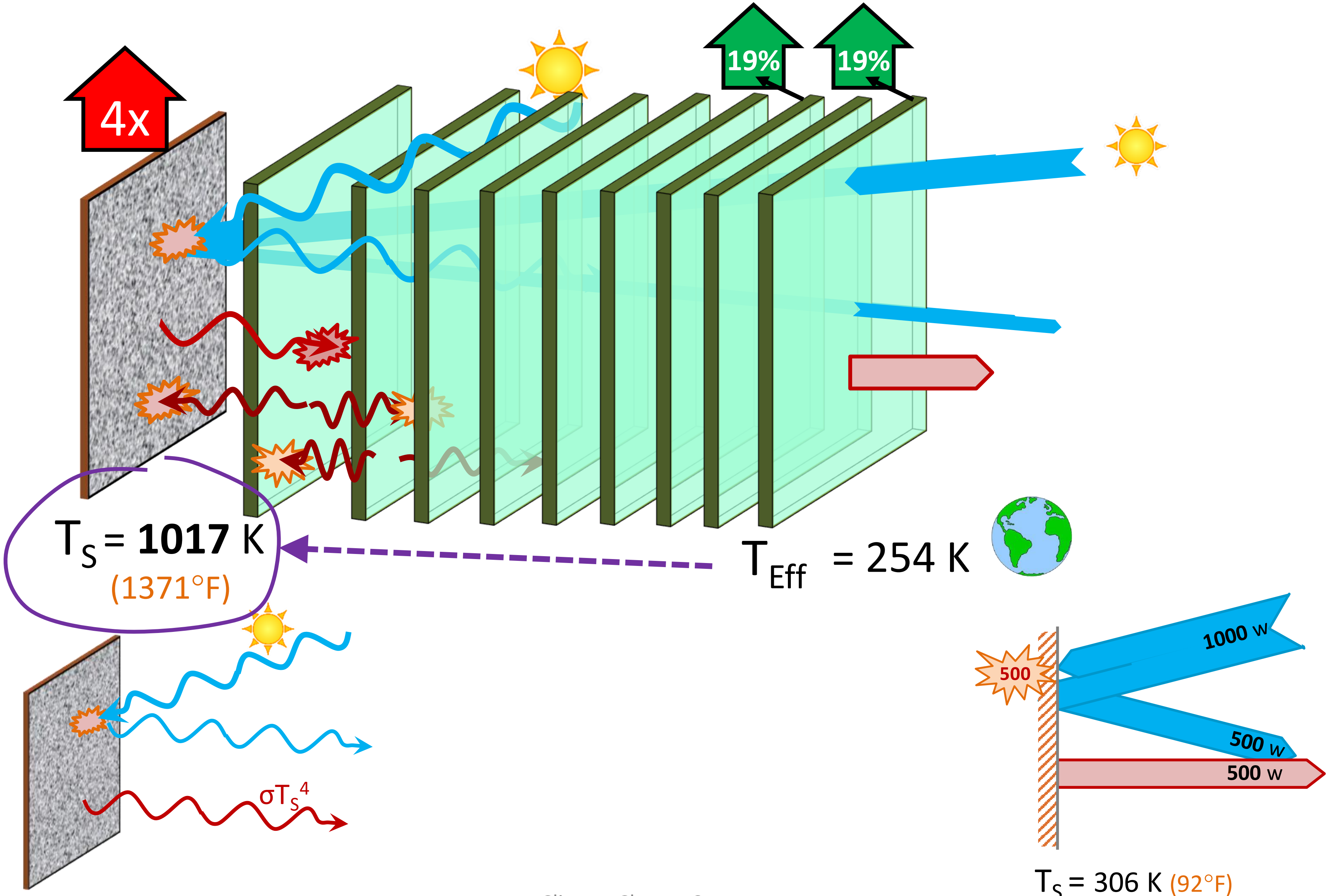
91 Atmospheres of CO_2

Not hard to see how Venus Surface gets to 867F via multi-level Greenhouse Effect

♁

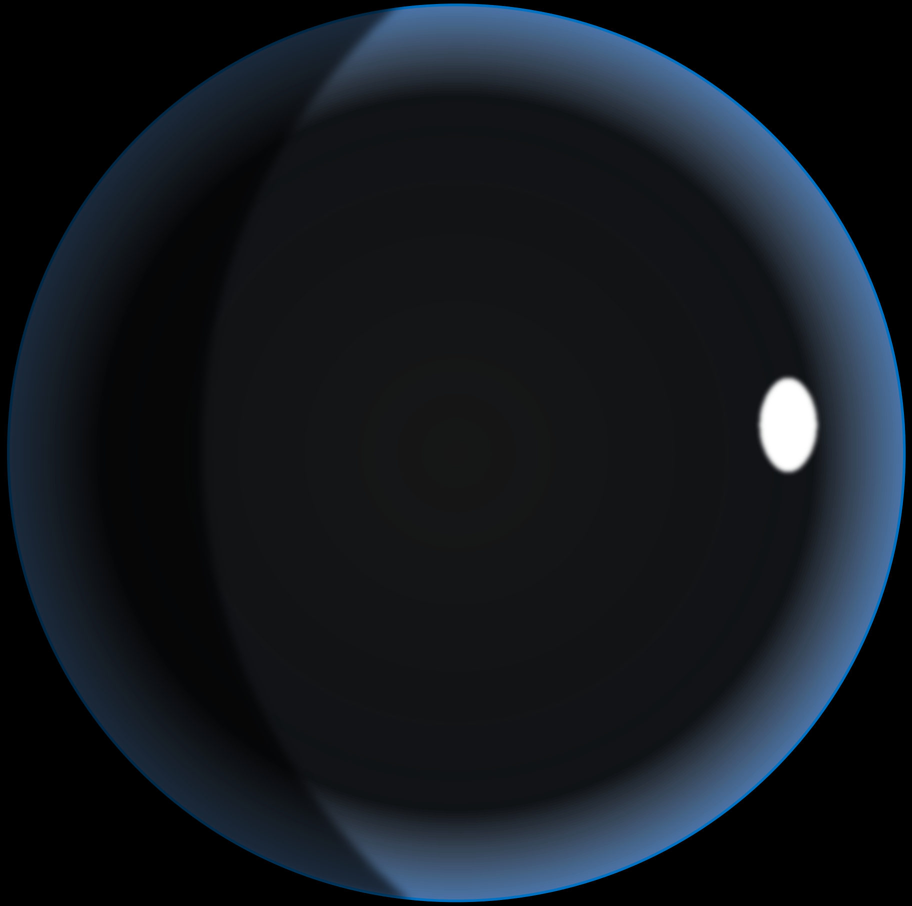
867 °F	Average Surface Temperature	59 °F

Radiative Greenhouse Effect: n = 9 Layers



T_S = 306 K (92°F)

Crystal Earth?

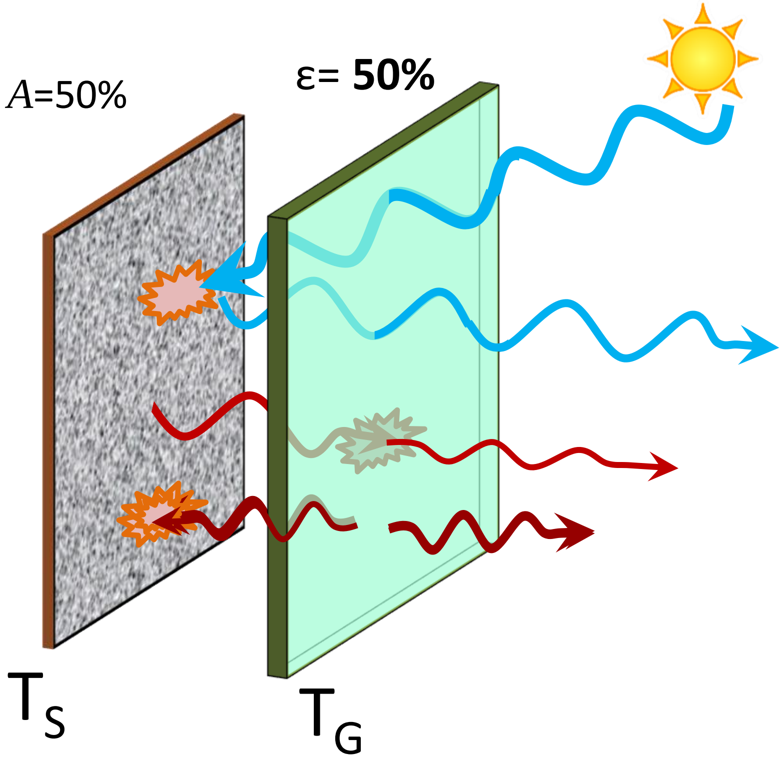


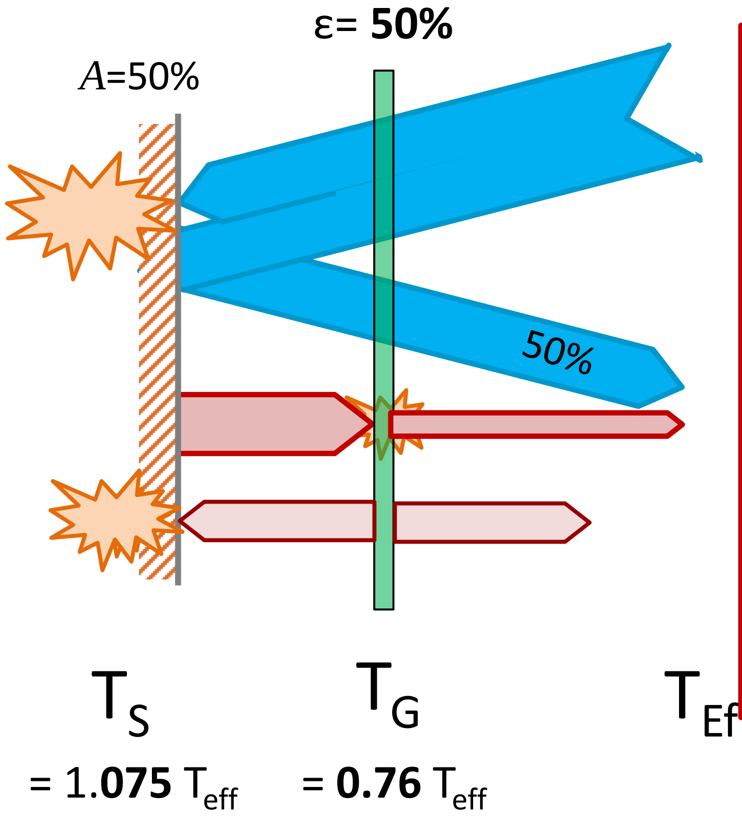
Crystal Earth?

Crystal Earth?

Radiative Greenhouse Effect: Thin 'Glass'

Atmospheric layers are *not* fully IR absorbing like glass! Lets look at "thin glass" which is partially absorbing, say emissivity of 50%. This means half the IR from the surface gets through it.

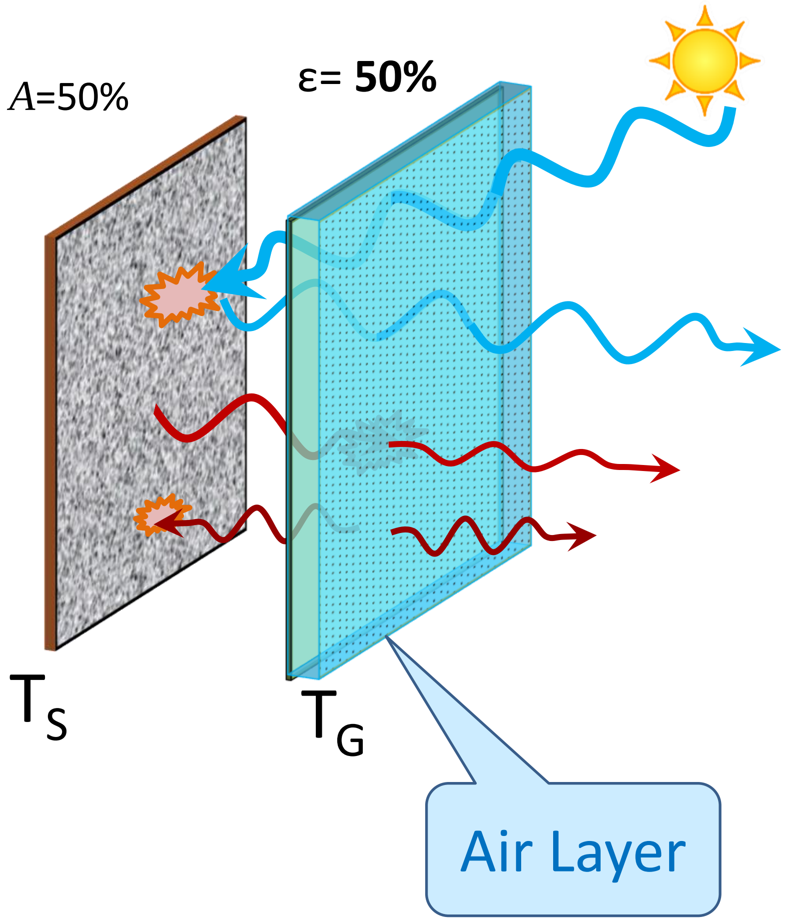


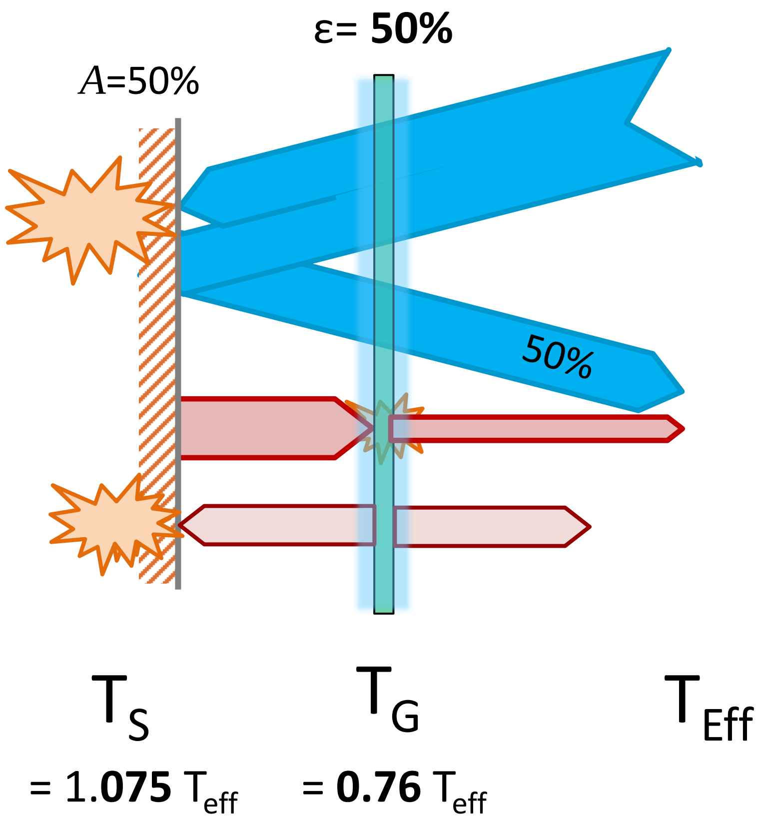


When we do the radiation balance logic, the needed 500W of IR radiation to space comes partly from the surface and partly from the thin glass. The surface temperature rise is only 7.5%, and the glass is very cold.

Radiative Greenhouse Effect: Thin Air?

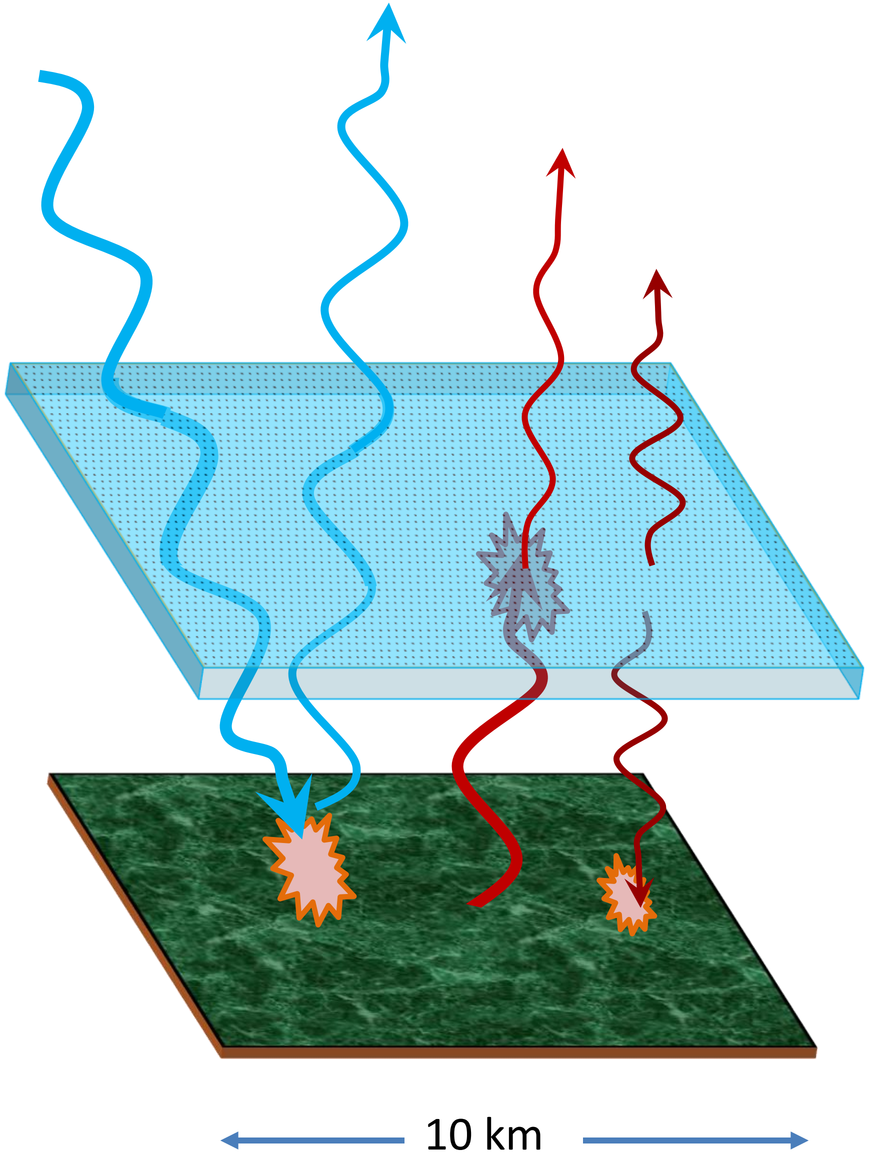
We can imagine that the “thin glass” is actually an air layer containing some IR absorbing gas.....



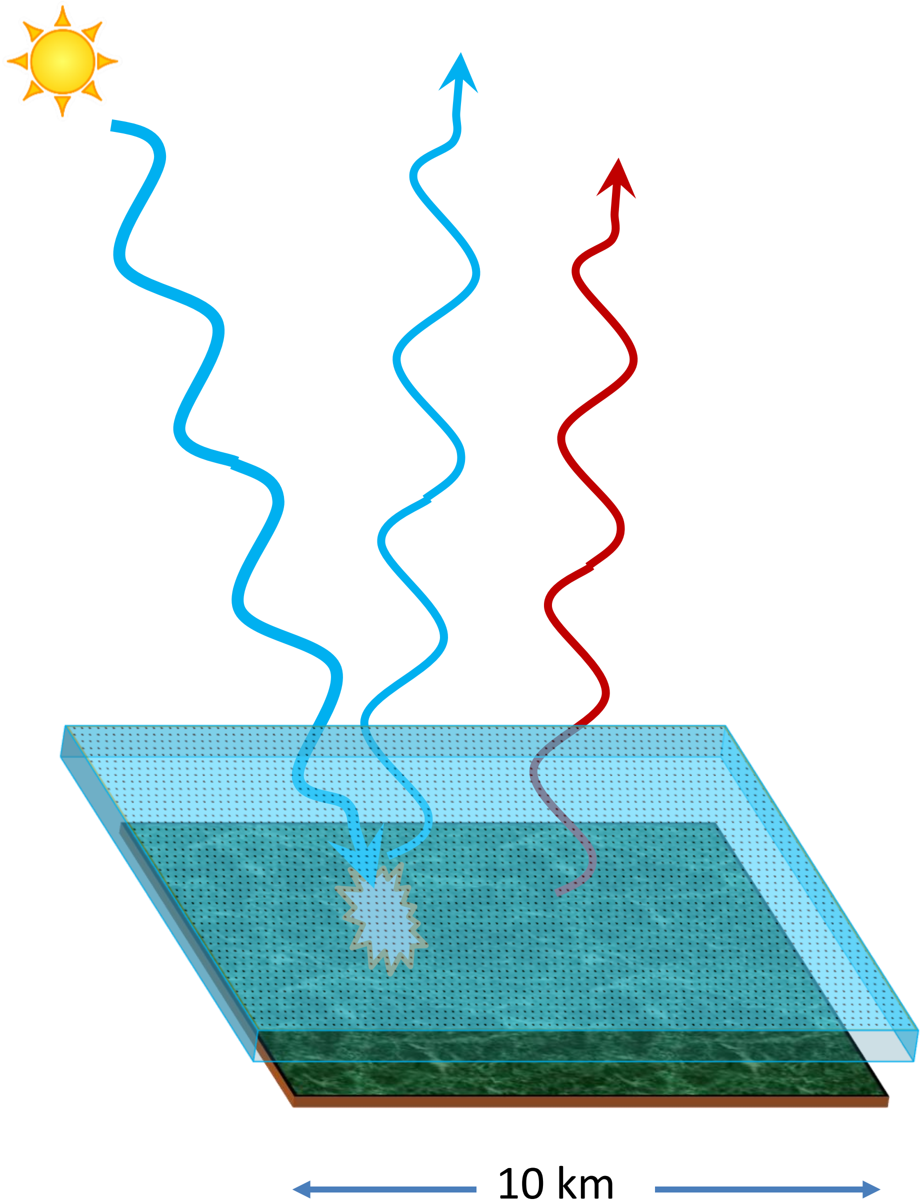


Radiative Greenhouse Effect: Thin Air?

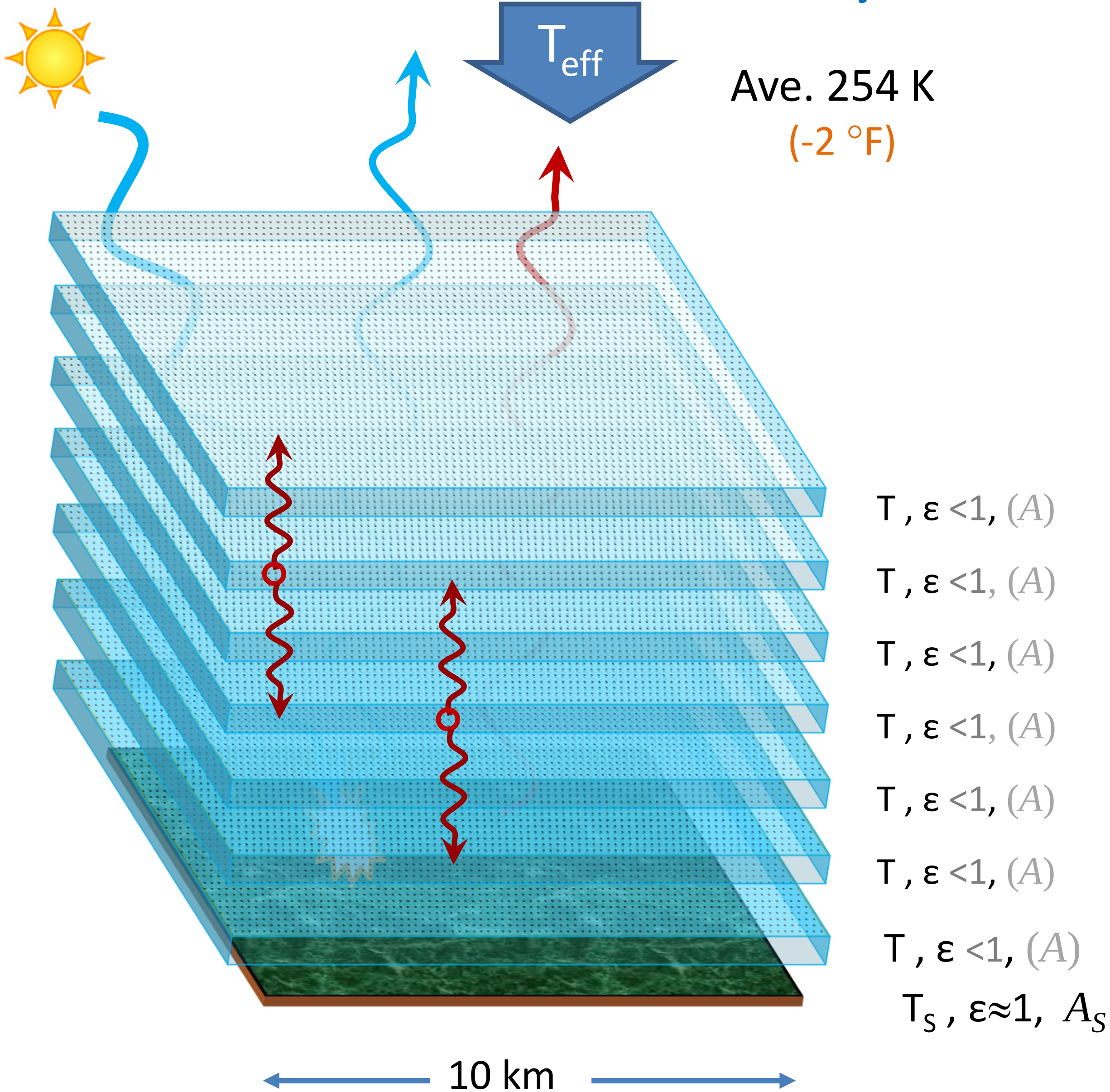
To see how this applies to our earth, imagine turning the surface 90deg and enlarging it to 10km square. Put layers of air above it which are partially transparent to IR. Note that we are no longer in vacuum….



Radiative Greenhouse Effect: Thin Air?



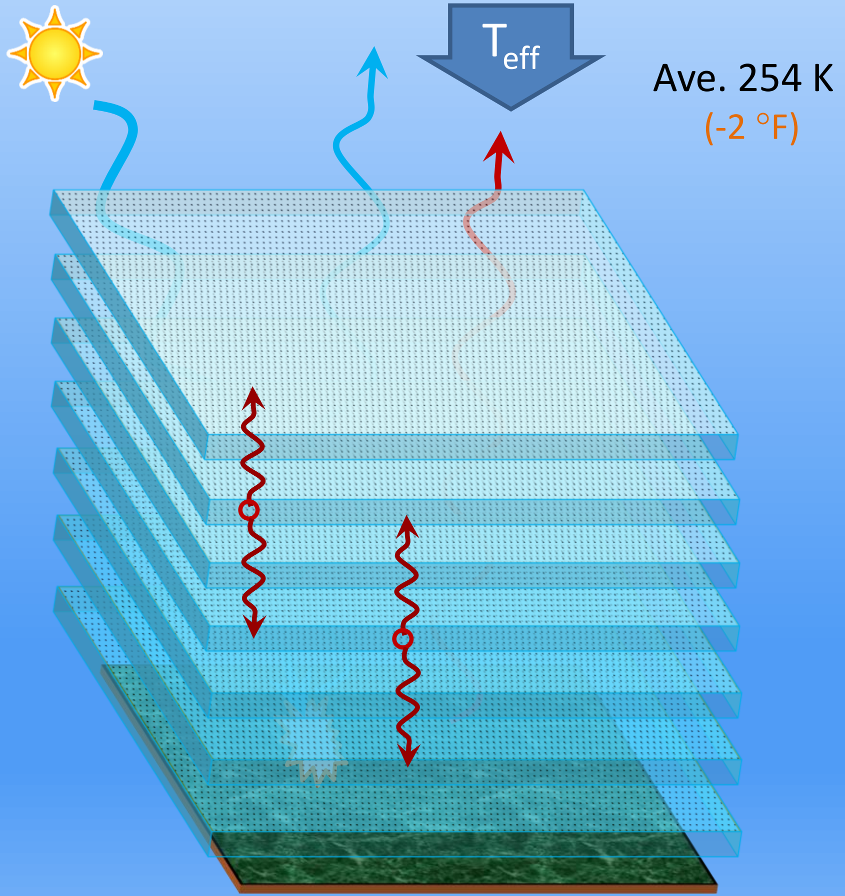
Radiative Greenhouse Effect: Layers of Air



Problem:
No Vacuum between Layers

Each air layer has a temperature T, an IR emissivity that is less than 100%, and maybe an albedo due to clouds.
The outside skin temperature remains at 254K, but the surface can be much warmer.

Questions about Earth's basic Greenhouse Effect?



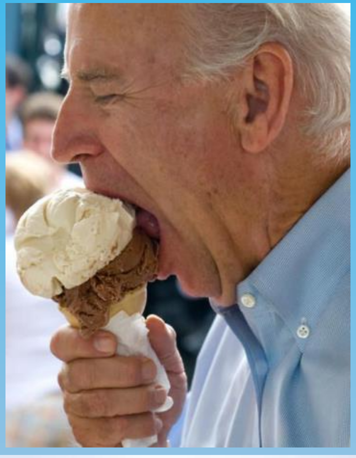
Modes of Heat Transfer

- Radiative
  - Photons

MAJOR

- Thermal Conduction
  - Molecule to molecule energy transfer

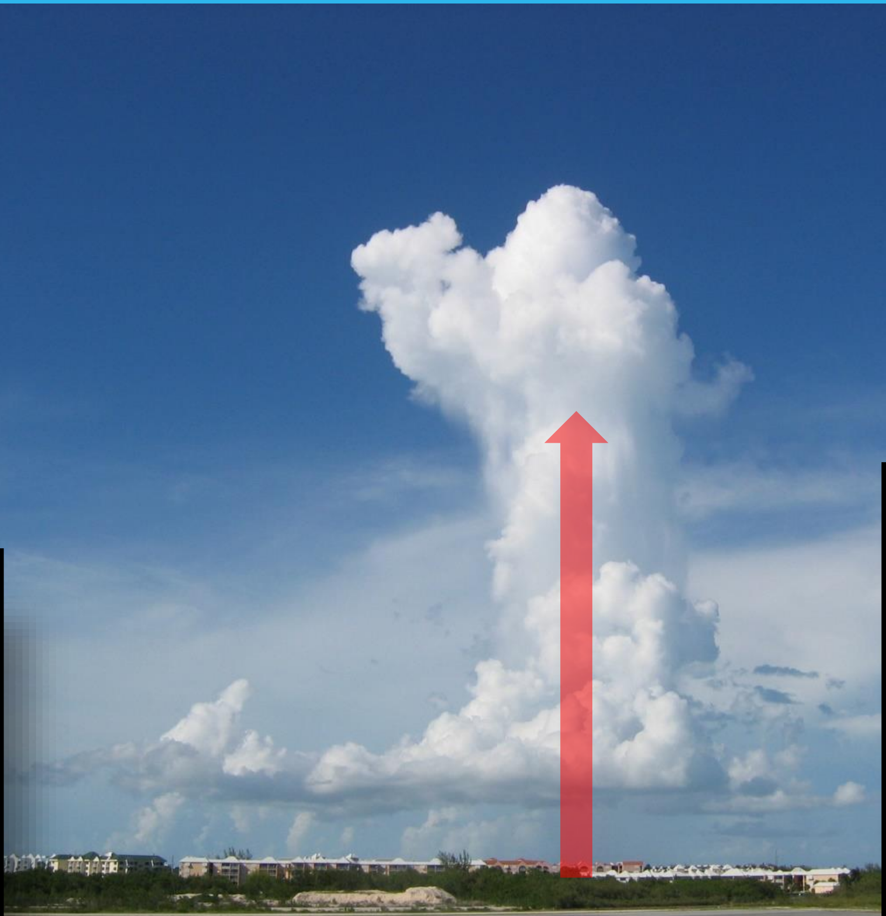
MINOR

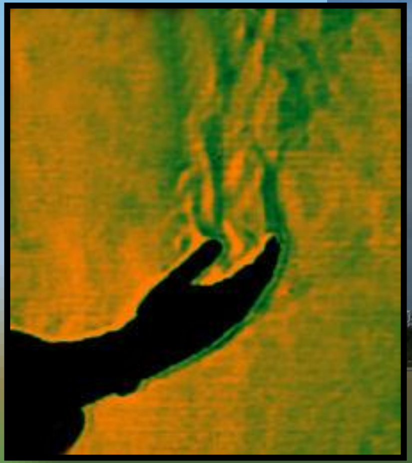


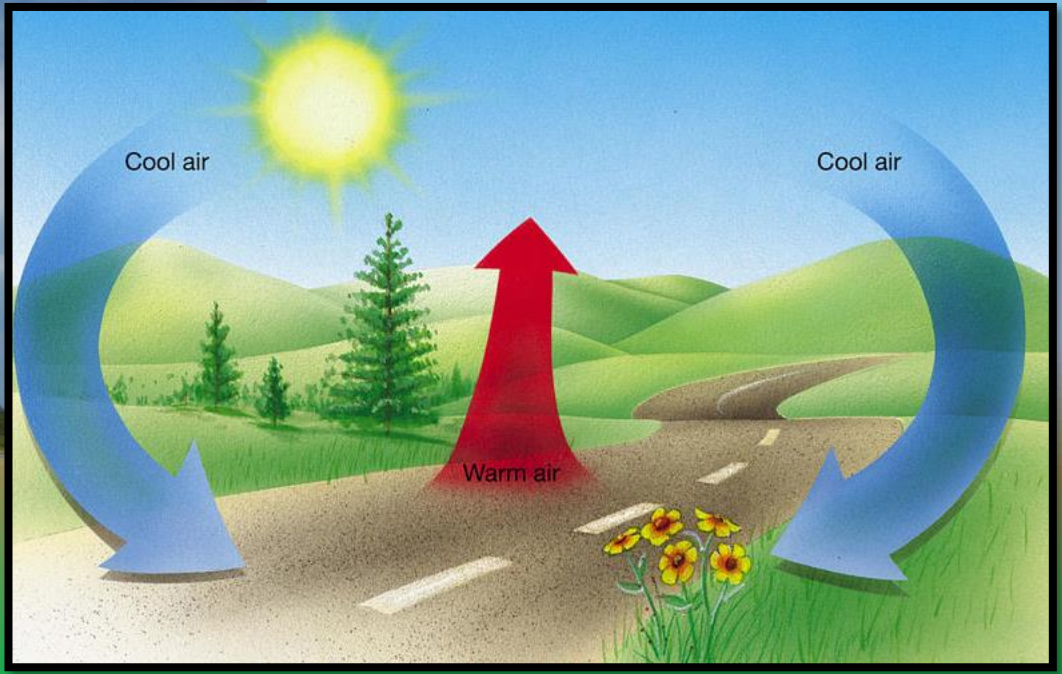
- Thermal Convection
  - Carrying heat via fluid motion
  - Often gravity-driven

MAJOR

Modes of Heat Transfer:
Thermal Convection by Gravity

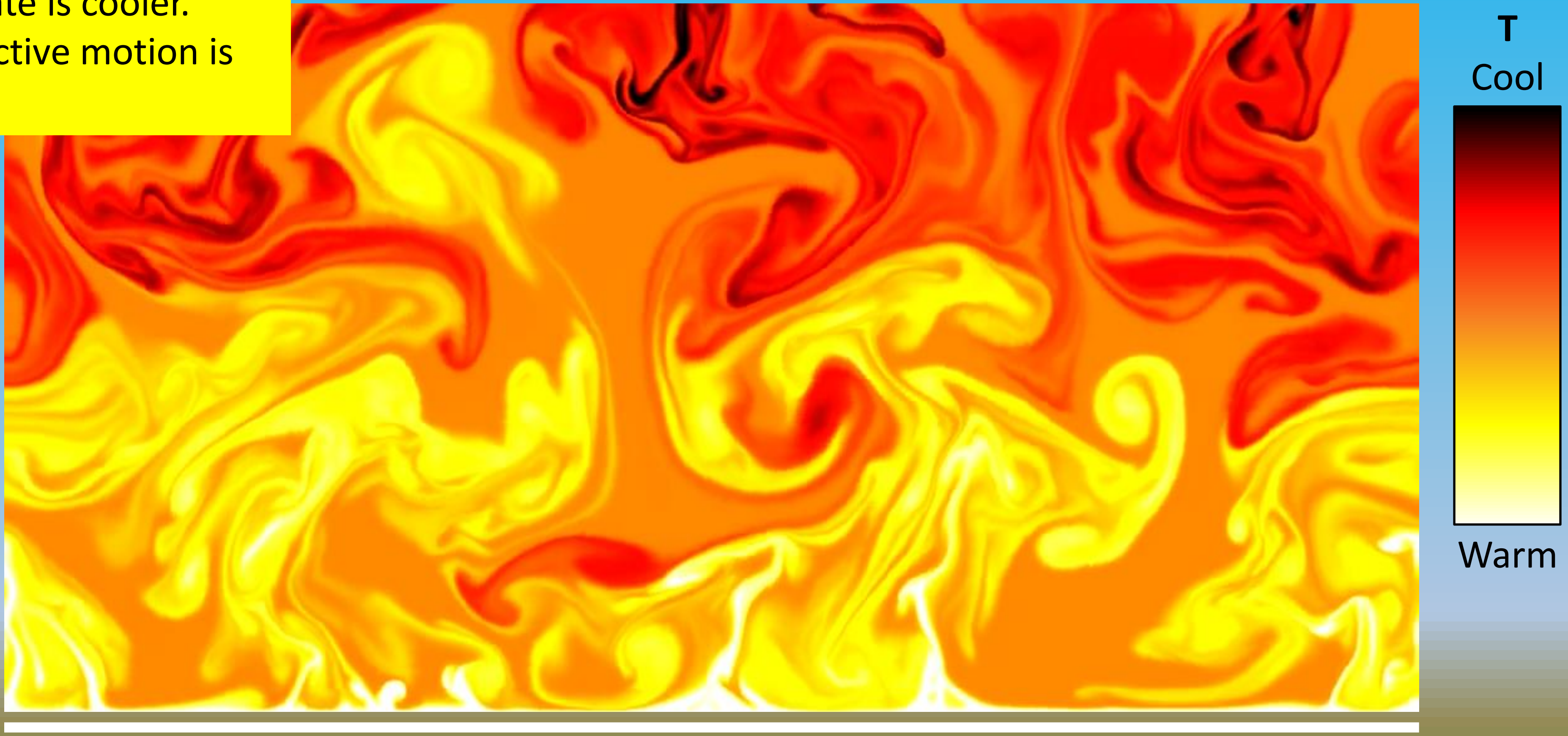






Thermal Convection

Numerical simulation of thermal gravity convection in an unspecified fluid. The bottom plate is hot, the top plate is cooler. The convective motion is chaotic.



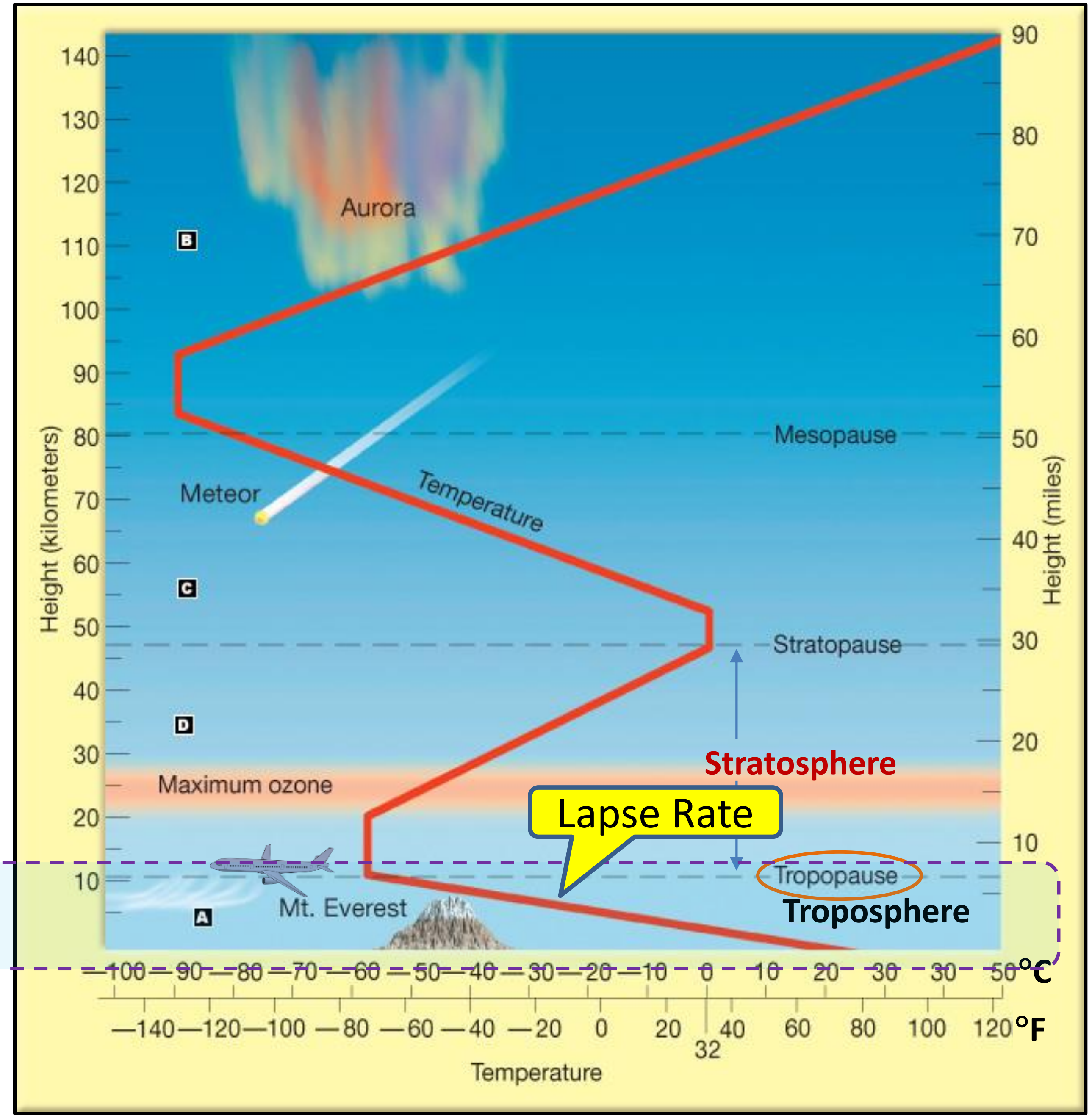
by TurbulenceTeam (2010)

Temperature Profile of the Atmosphere

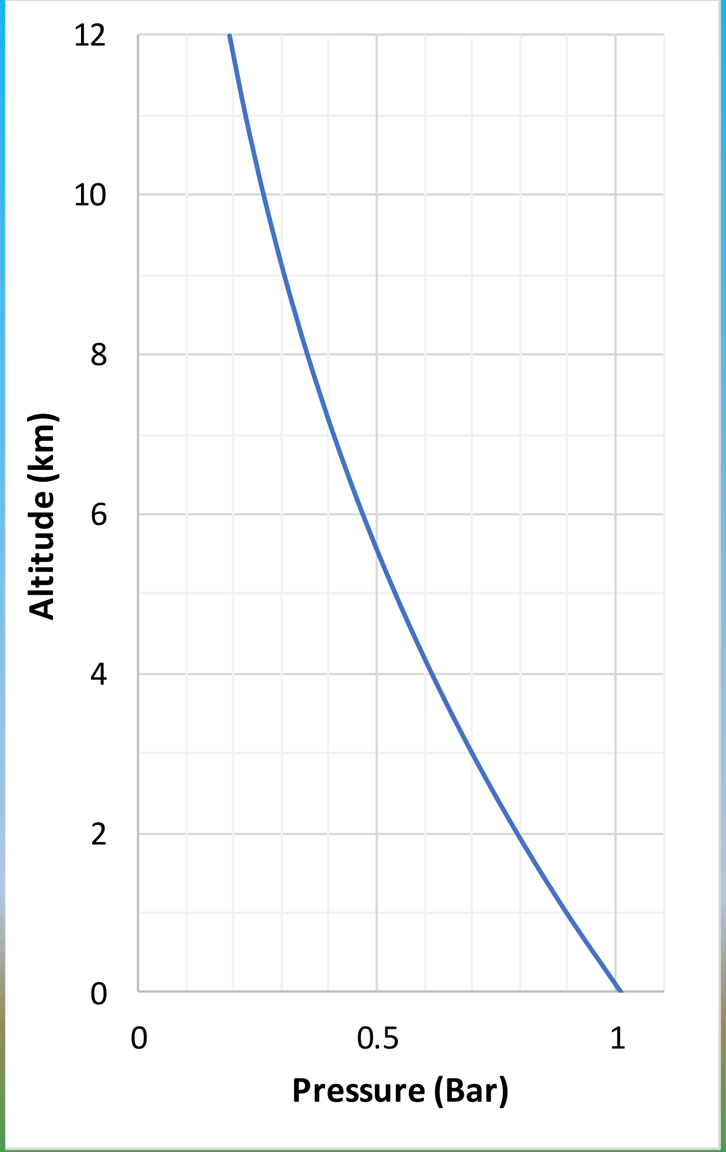
Not much air up here

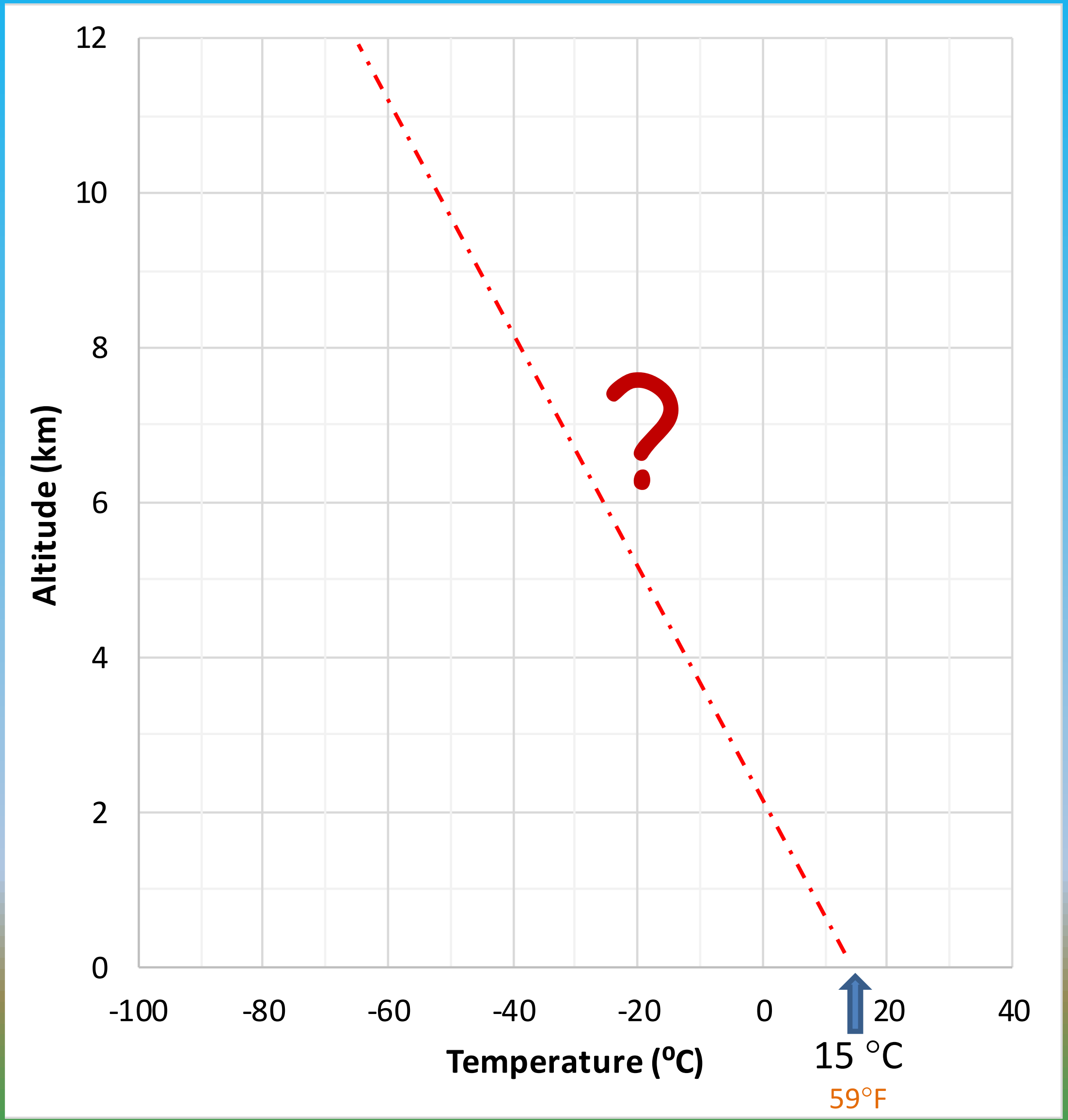
Solar **UV** Absorption Reigns

Thermal Convection Reigns

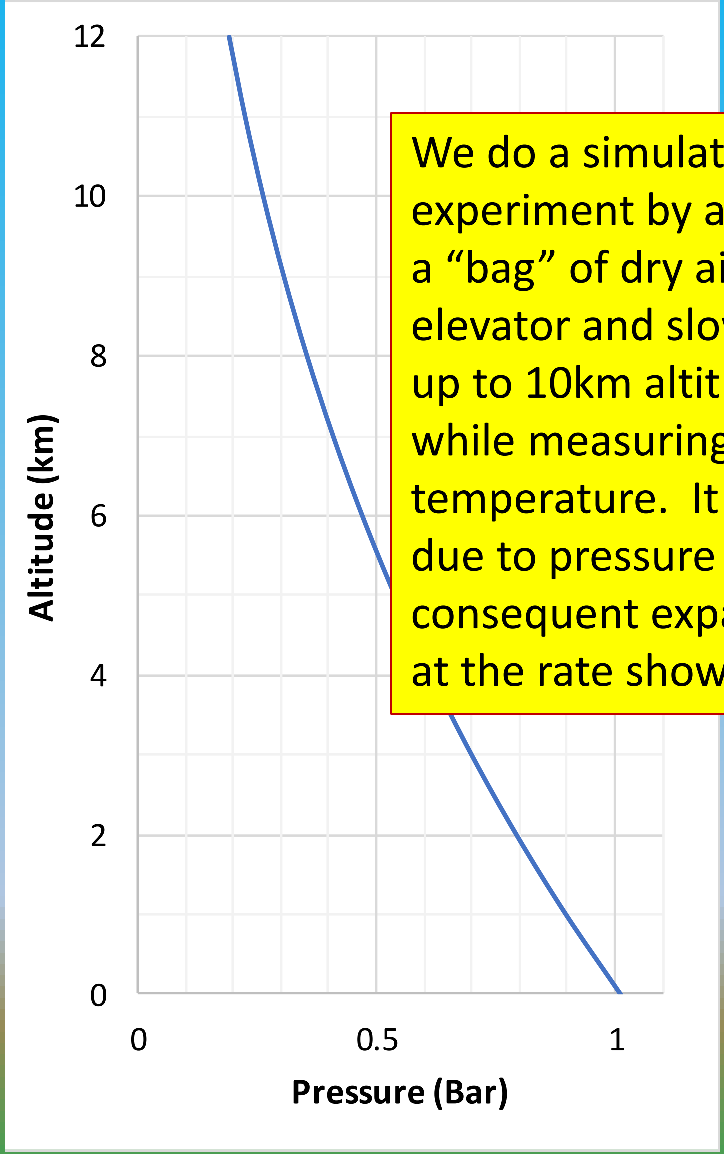


Lapse Rate in Troposphere

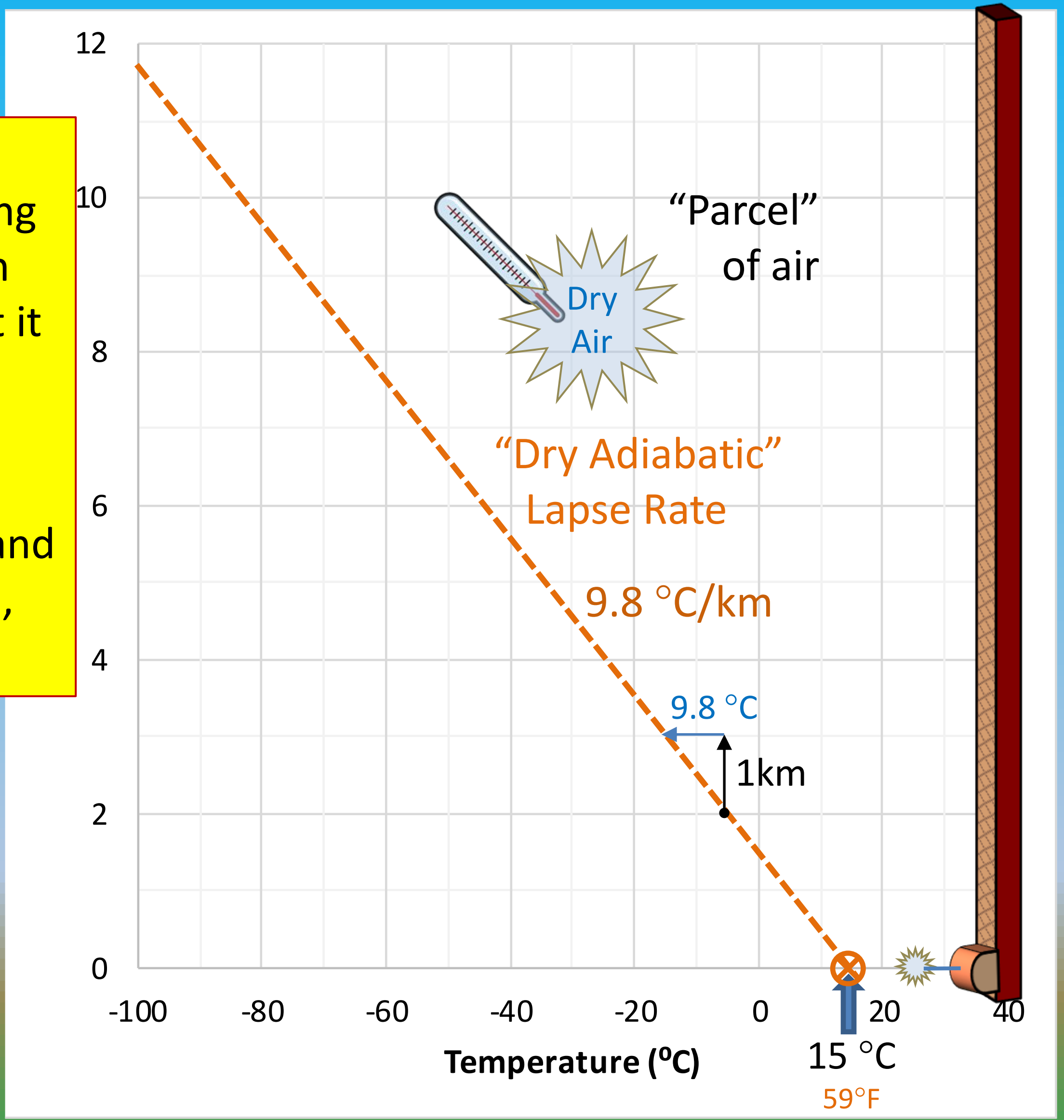




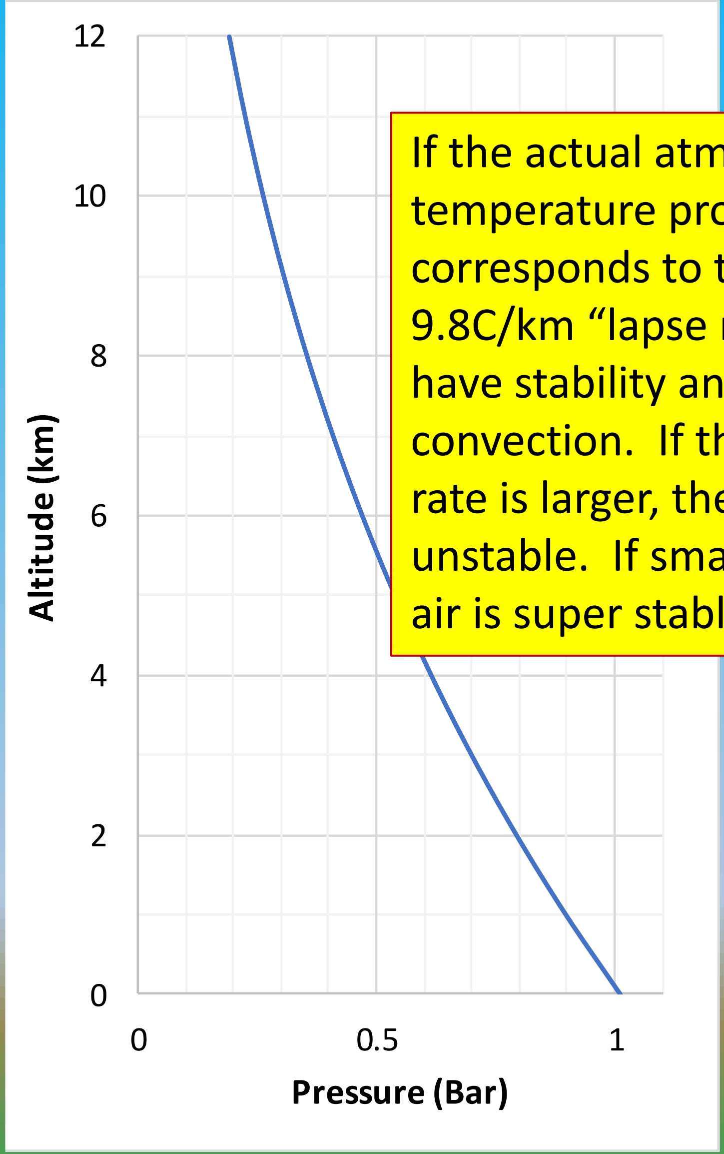
Lapse Rate in Troposphere



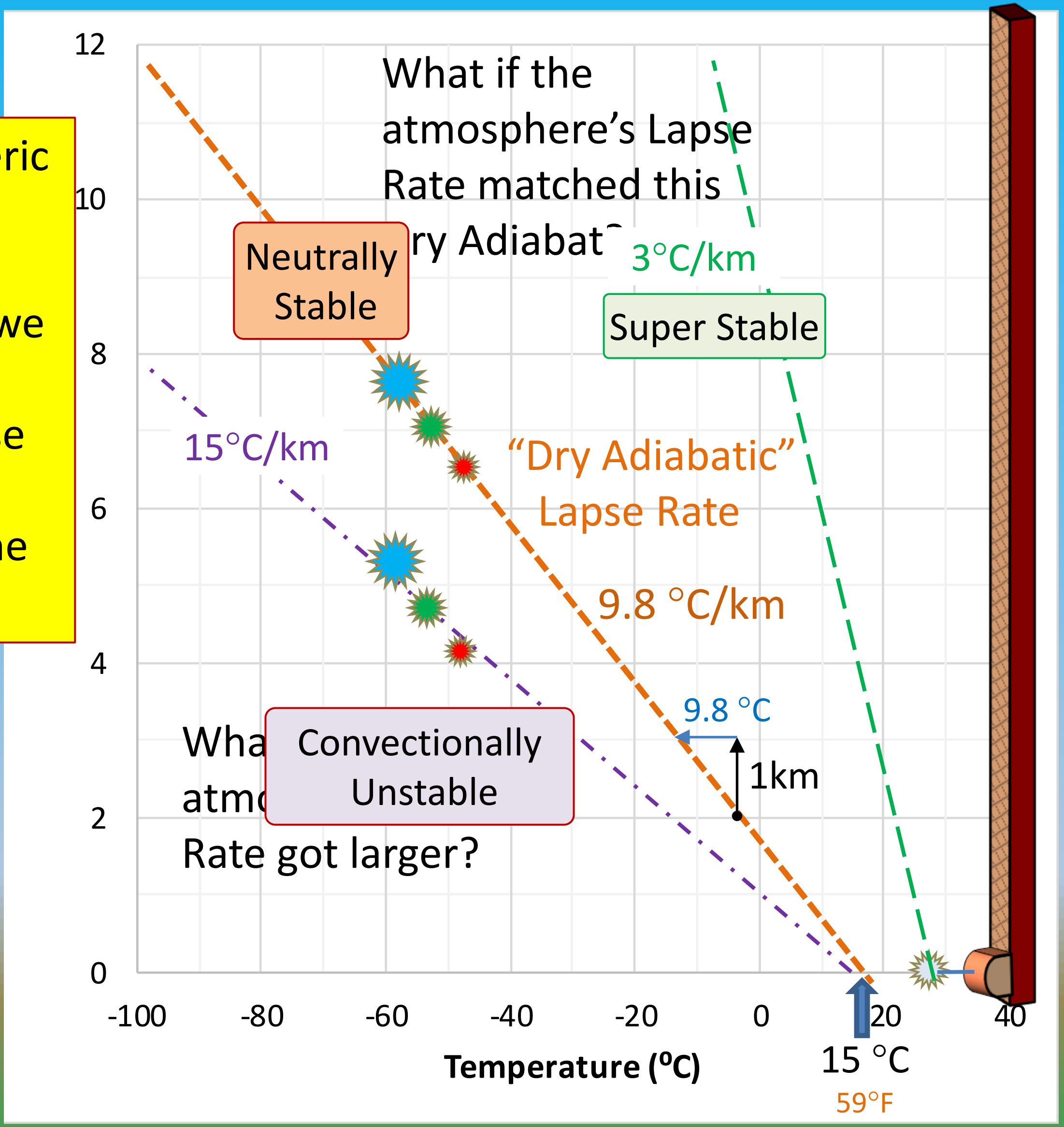
We do a simulated experiment by attaching a "bag" of dry air to an elevator and slowly lift it up to 10km altitude while measuring its temperature. It cools due to pressure drop and consequent expansion, at the rate shown.



Lapse Rate in Troposphere

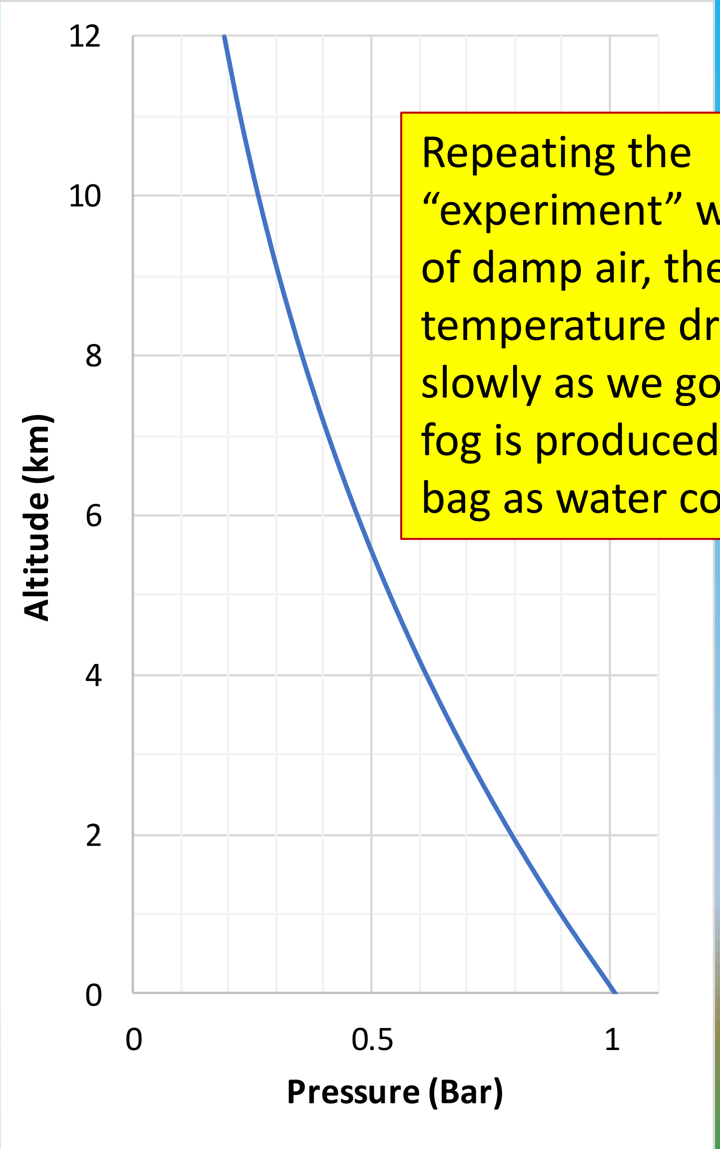


If the actual atmospheric temperature profile corresponds to this 9.8C/km "lapse rate", we have stability and no convection. If the lapse rate is larger, the air is unstable. If smaller, the air is super stable.

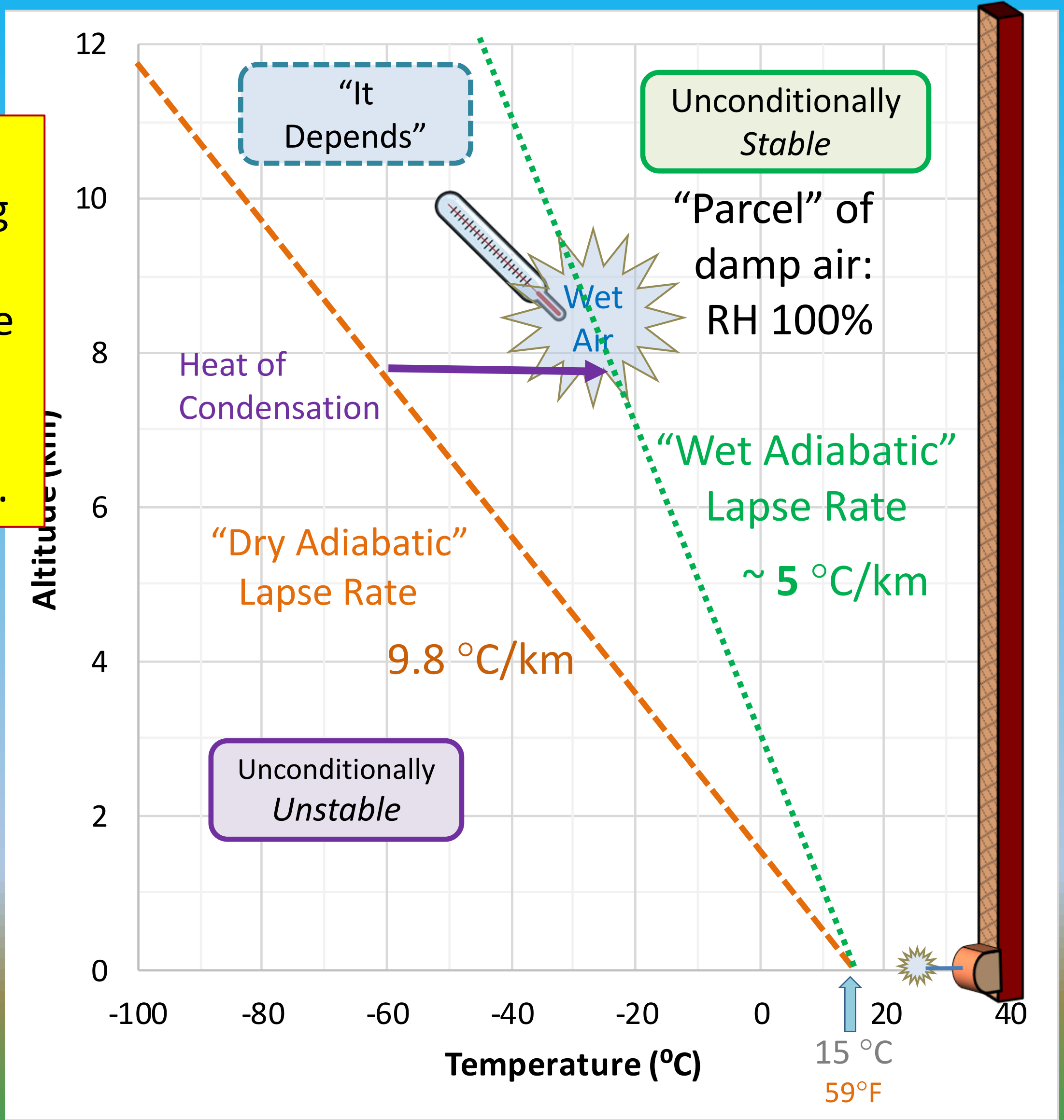


But air is wet…..

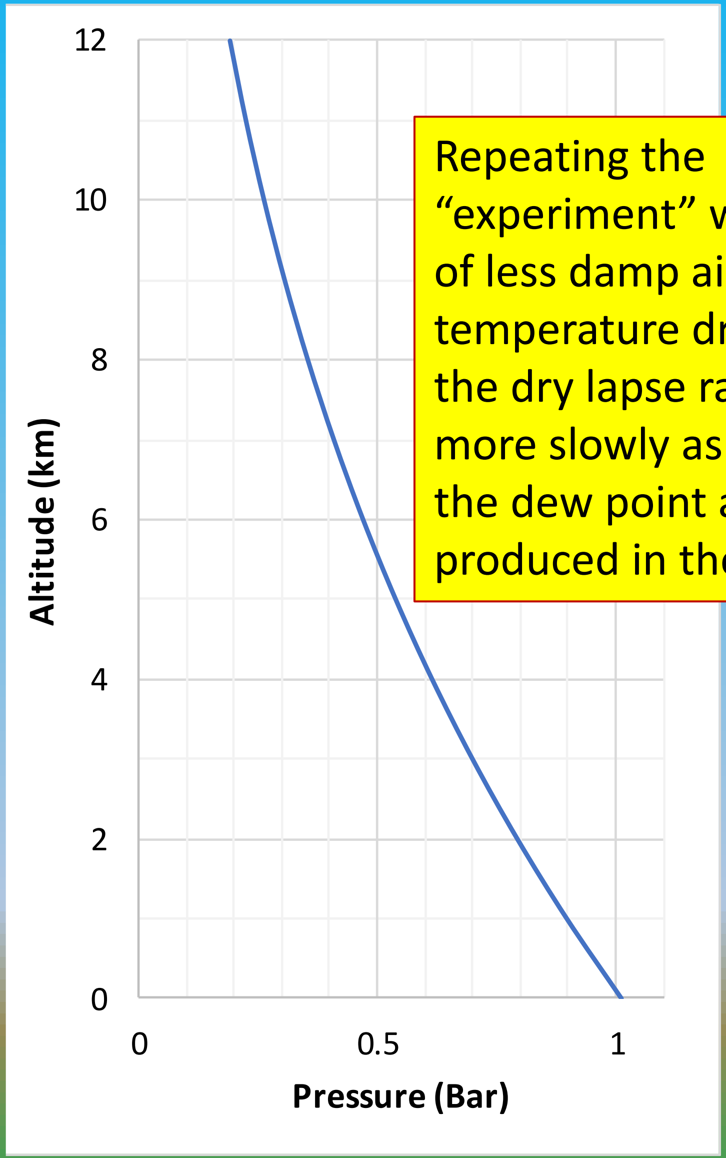
Lapse Rate in Troposphere



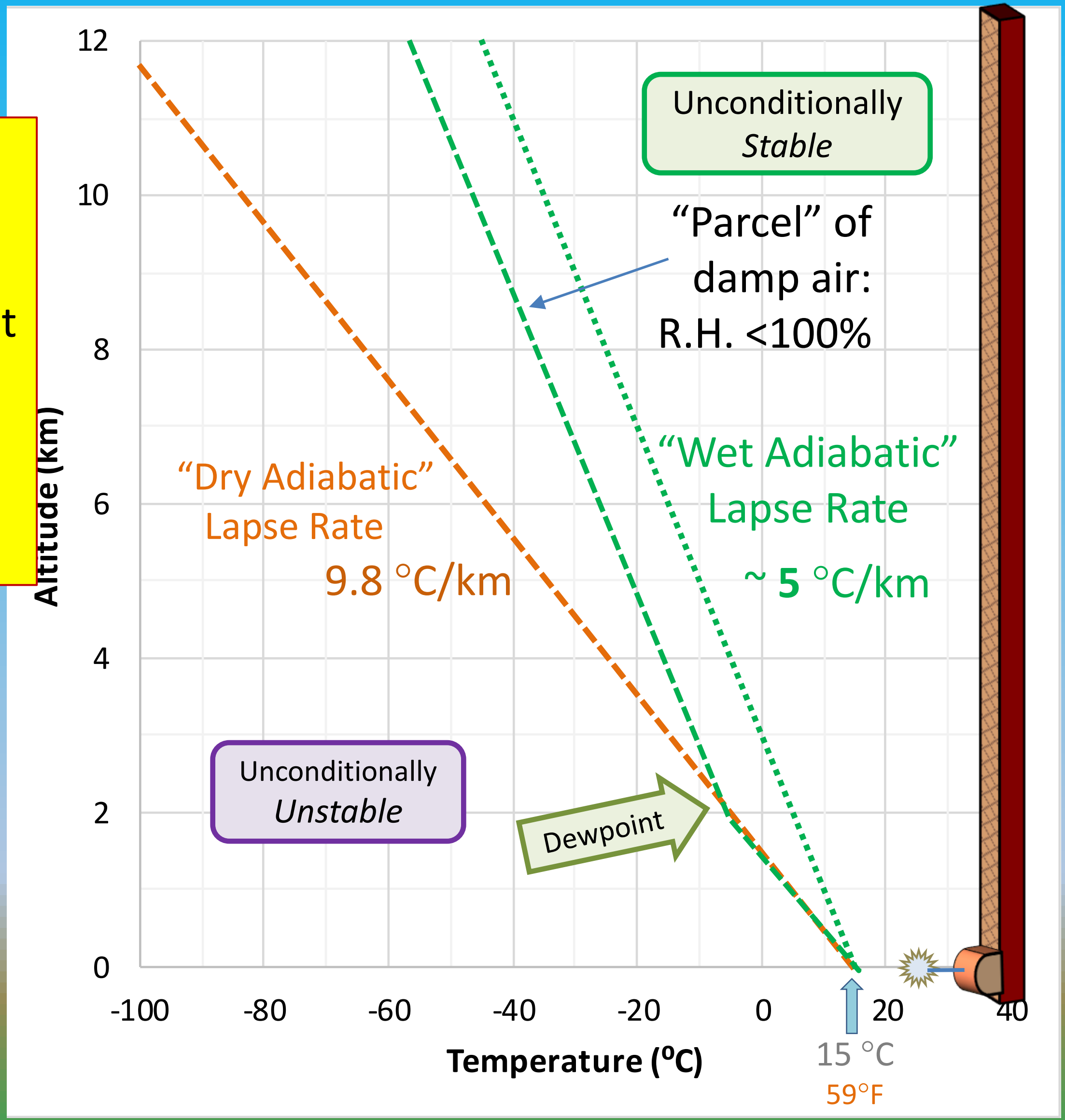
Repeating the "experiment" with a bag of damp air, the temperature drops more slowly as we go up, and fog is produced in the bag as water condenses.



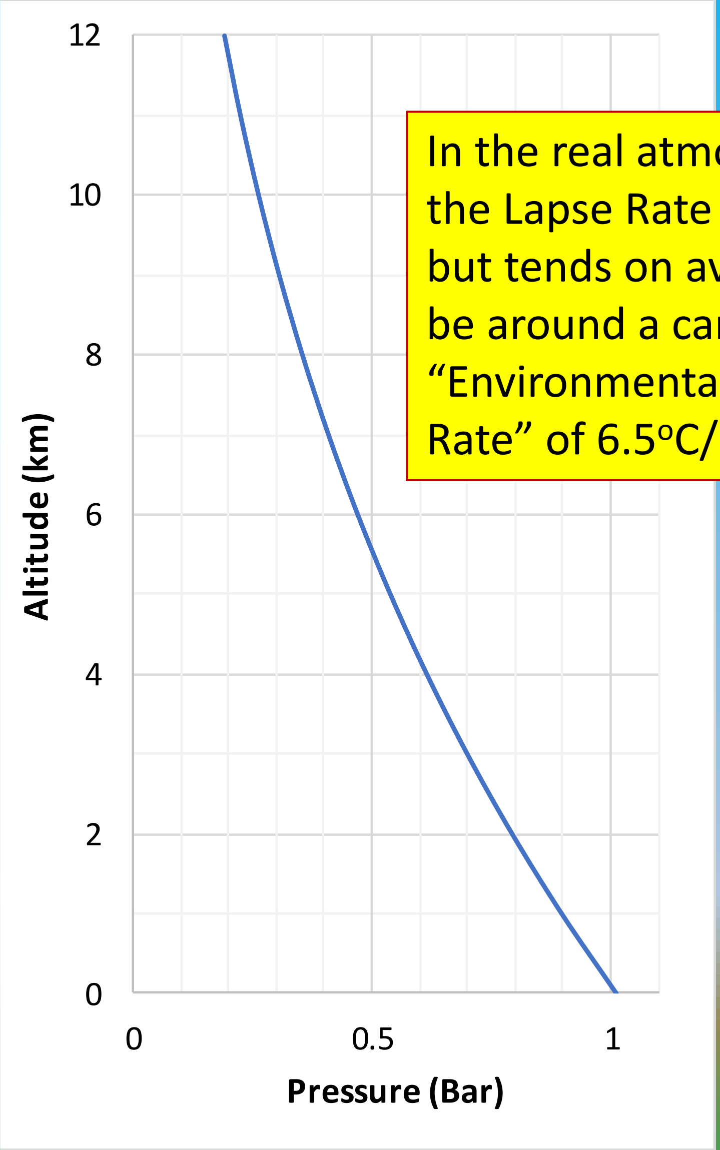
Lapse Rate in Troposphere



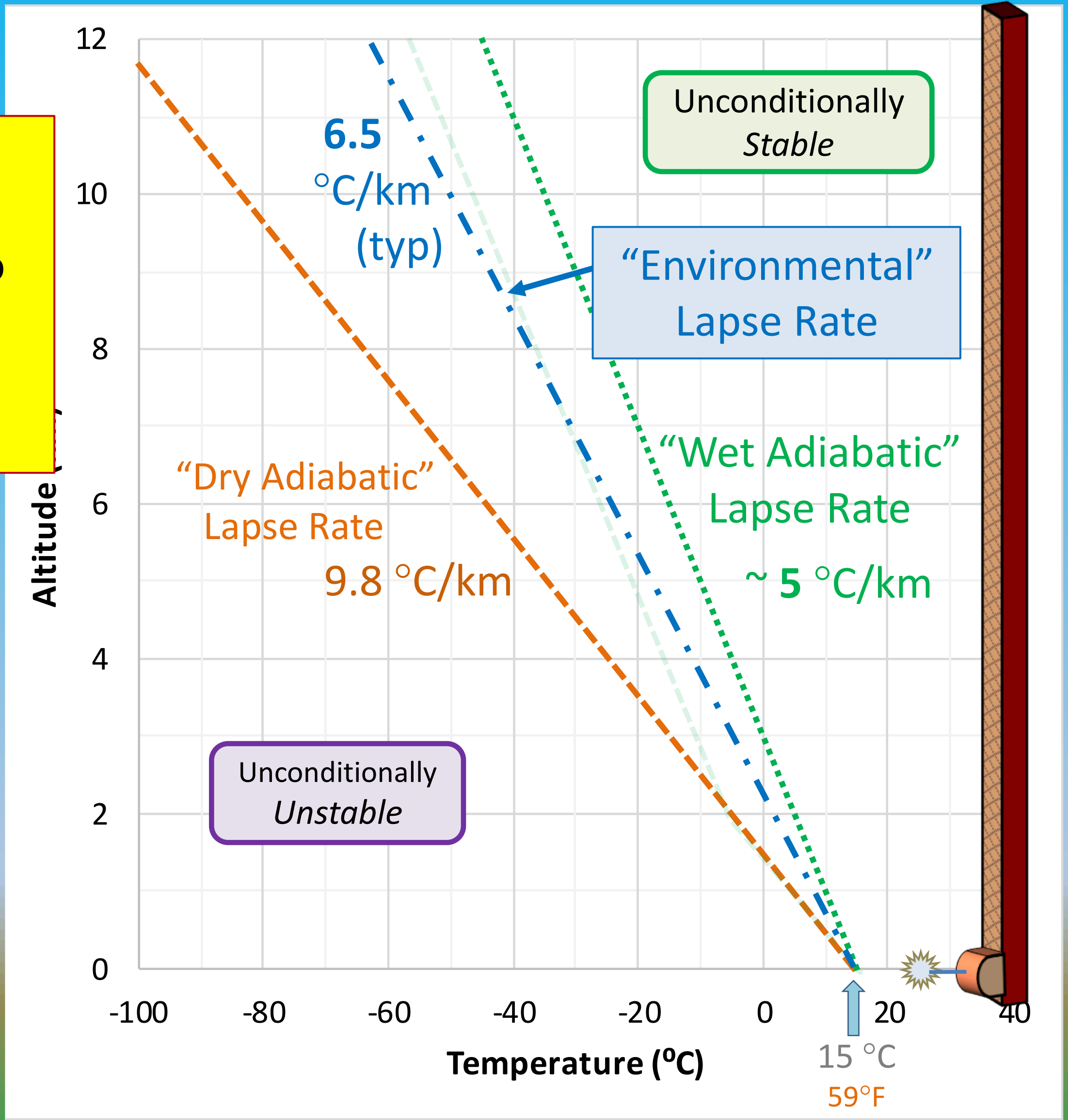
Repeating the "experiment" with a bag of less damp air, the temperature dropsfirst at the dry lapse rate, then more slowly as we reach the dew point and fog is produced in the bag.



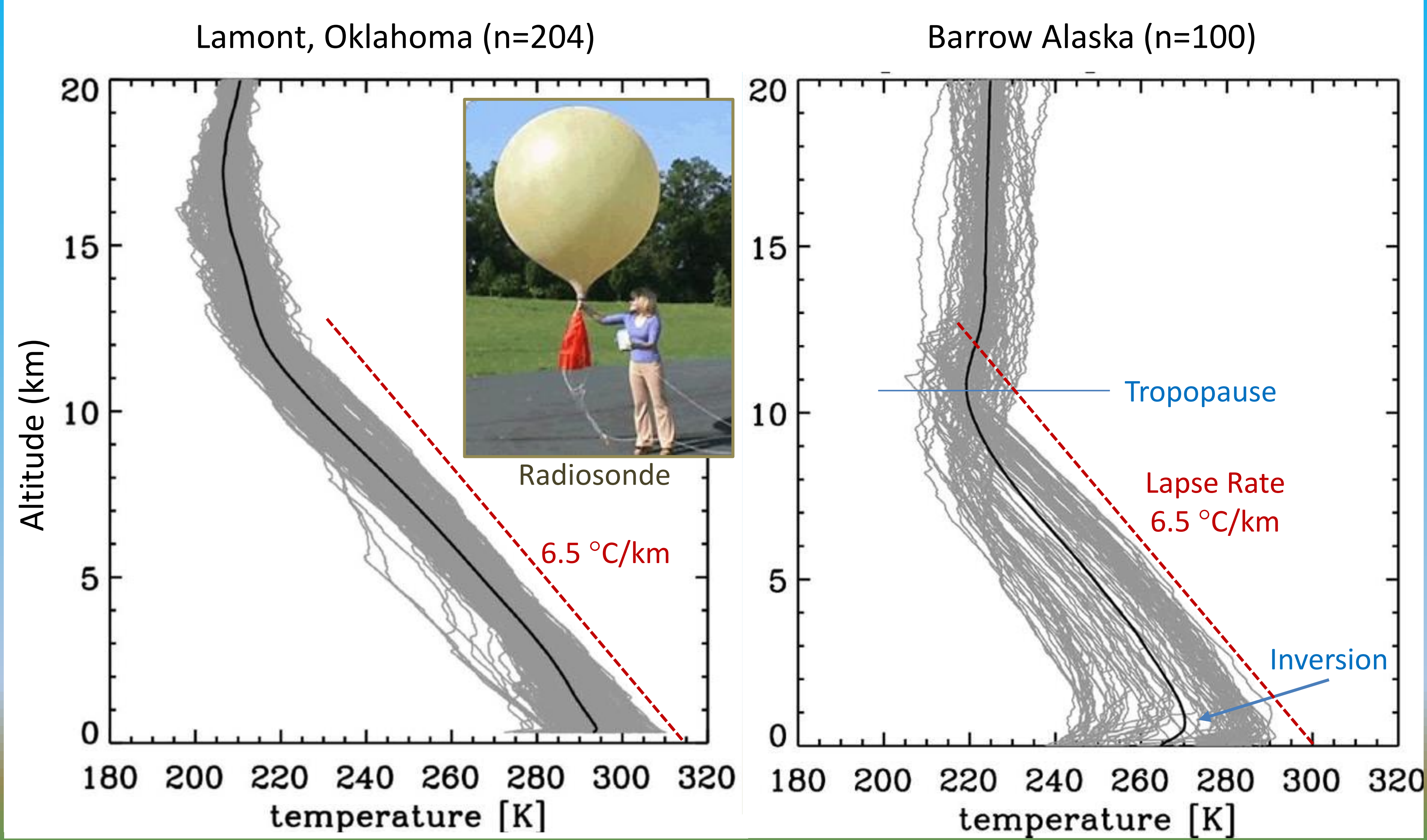
Lapse Rate in Troposphere



In the real atmosphere, the Lapse Rate varies, but tends on average to be around a canonical "Environmental Lapse Rate" of 6.5°C/km.

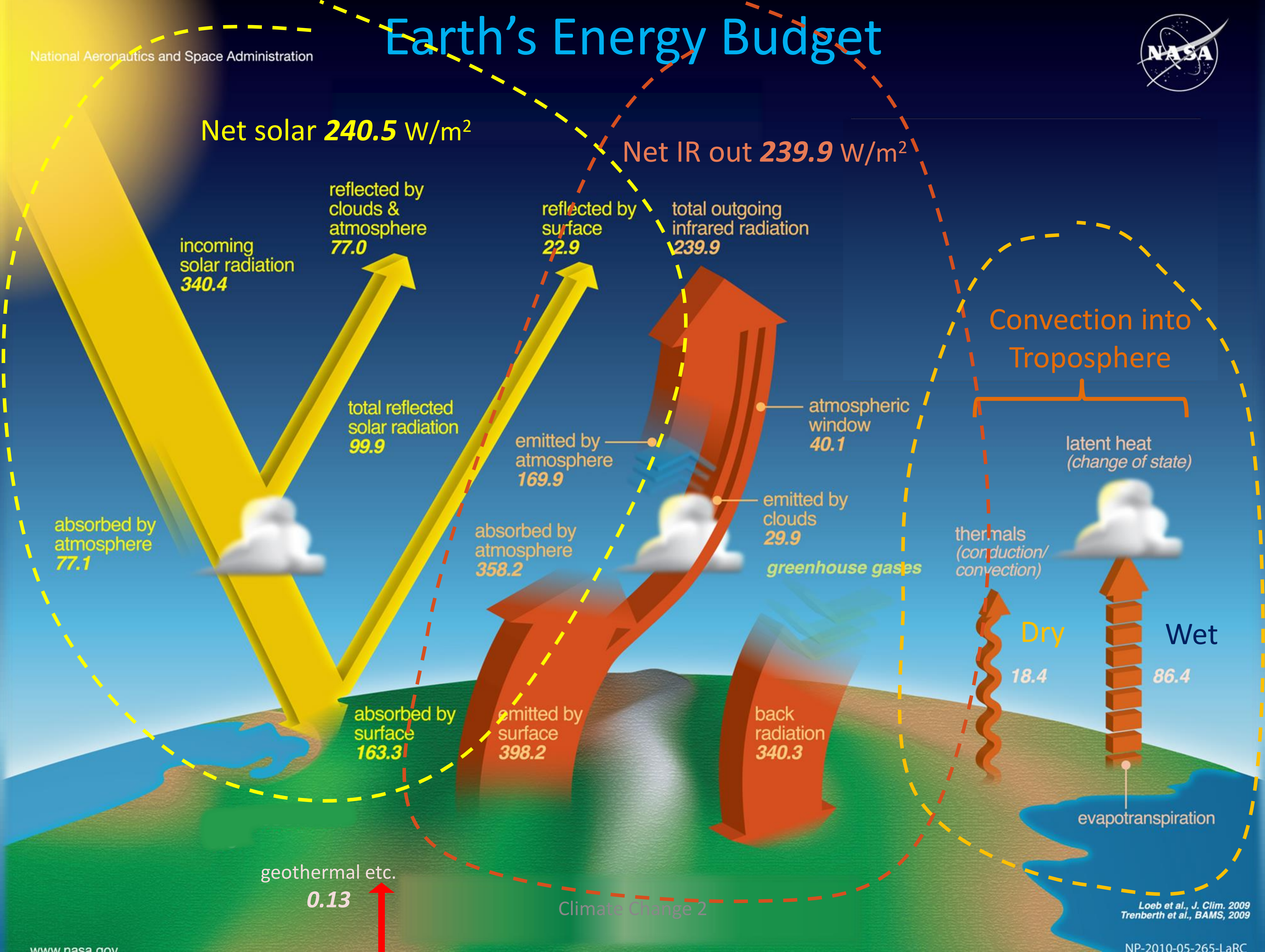


Actual Temperature Profiles in Troposphere



from Payne et. al., IEEE Trans. on Geoscience & Remote Sensing **46** (2008)

Earth’s Energy Budget



Net solar **240.5** W/m^2

Net IR out **239.9** W/m^2

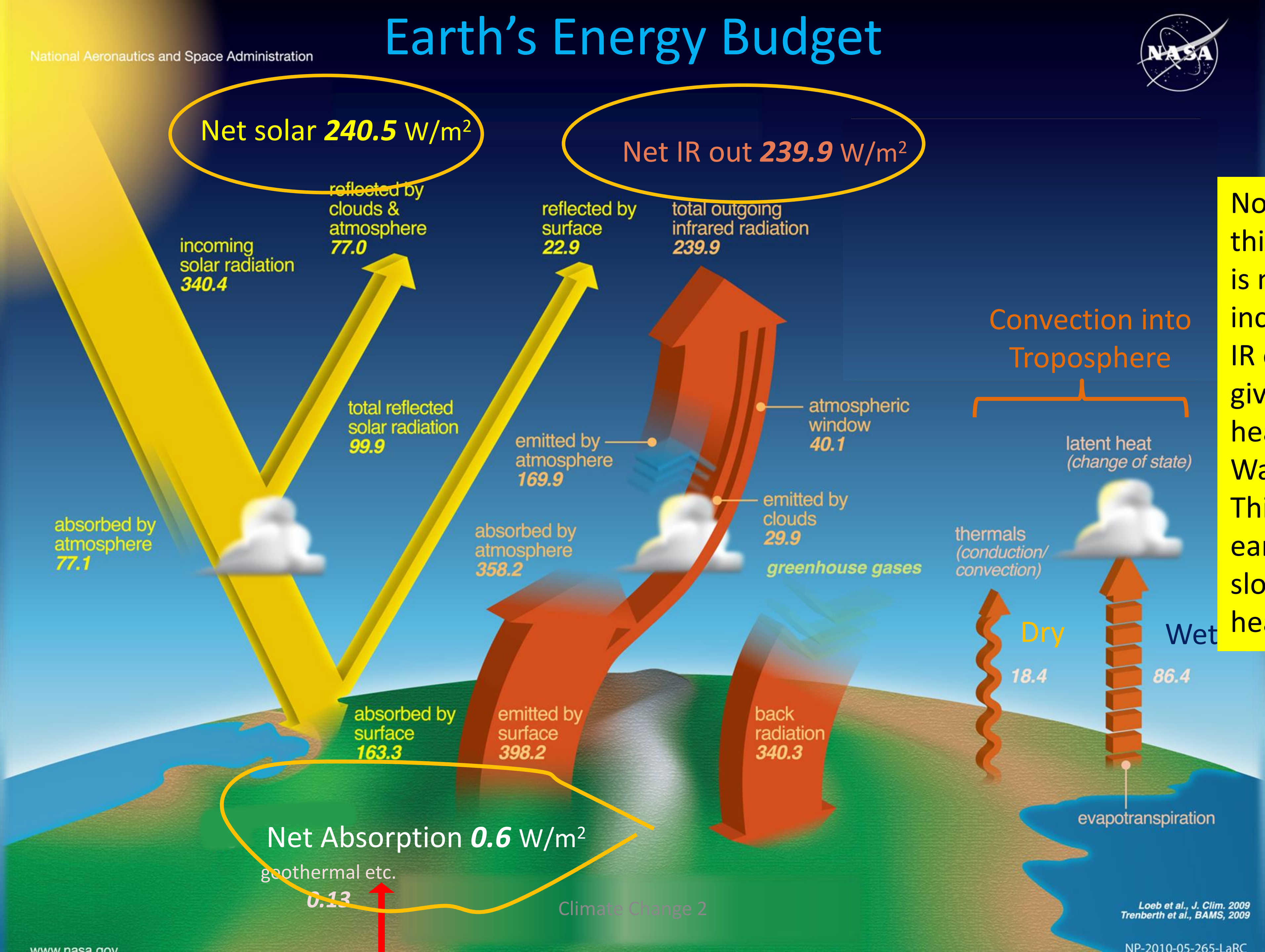
Convection into Troposphere

Dry

Wet

geothermal etc.
0.13

Earth’s Energy Budget



Net solar ***240.5*** W/m^2

Net IR out ***239.9*** W/m^2

Convection into Troposphere

Dry

Wet

Net Absorption ***0.6*** W/m^2

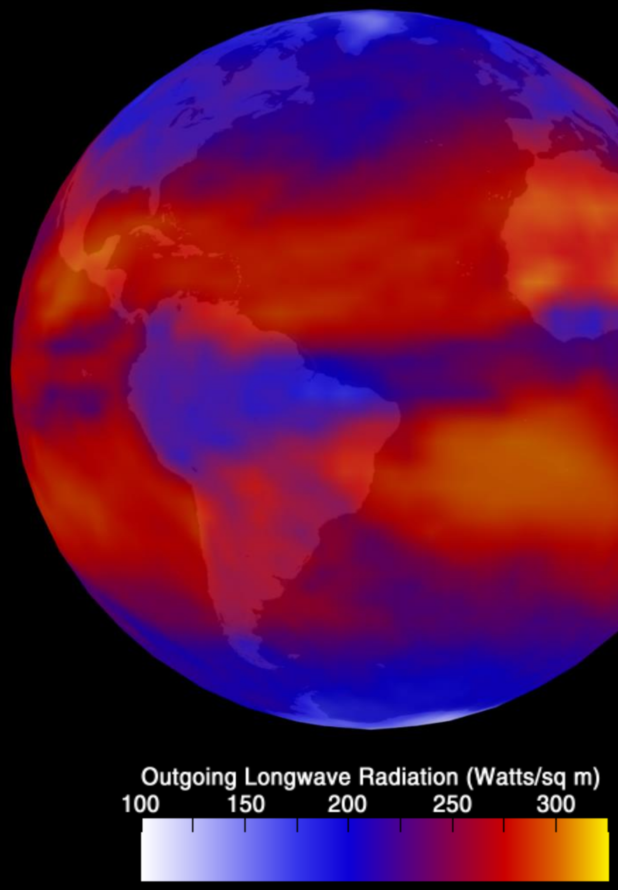
geothermal etc.

0.13

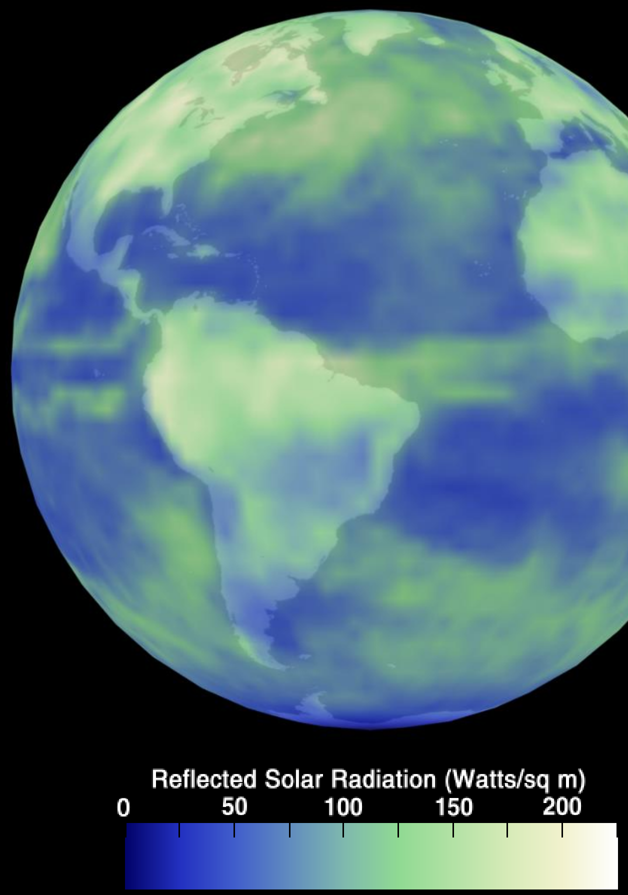
Note that in this case, there is more Solar incoming than IR outgoing, giving a net heating of 0.6 Watts/m2. This means the earth must be slowing heating up.

Satellite Measurements of Outgoing Earth Radiation

LW IR Outgoing Radiation



Solar Reflected Radiation



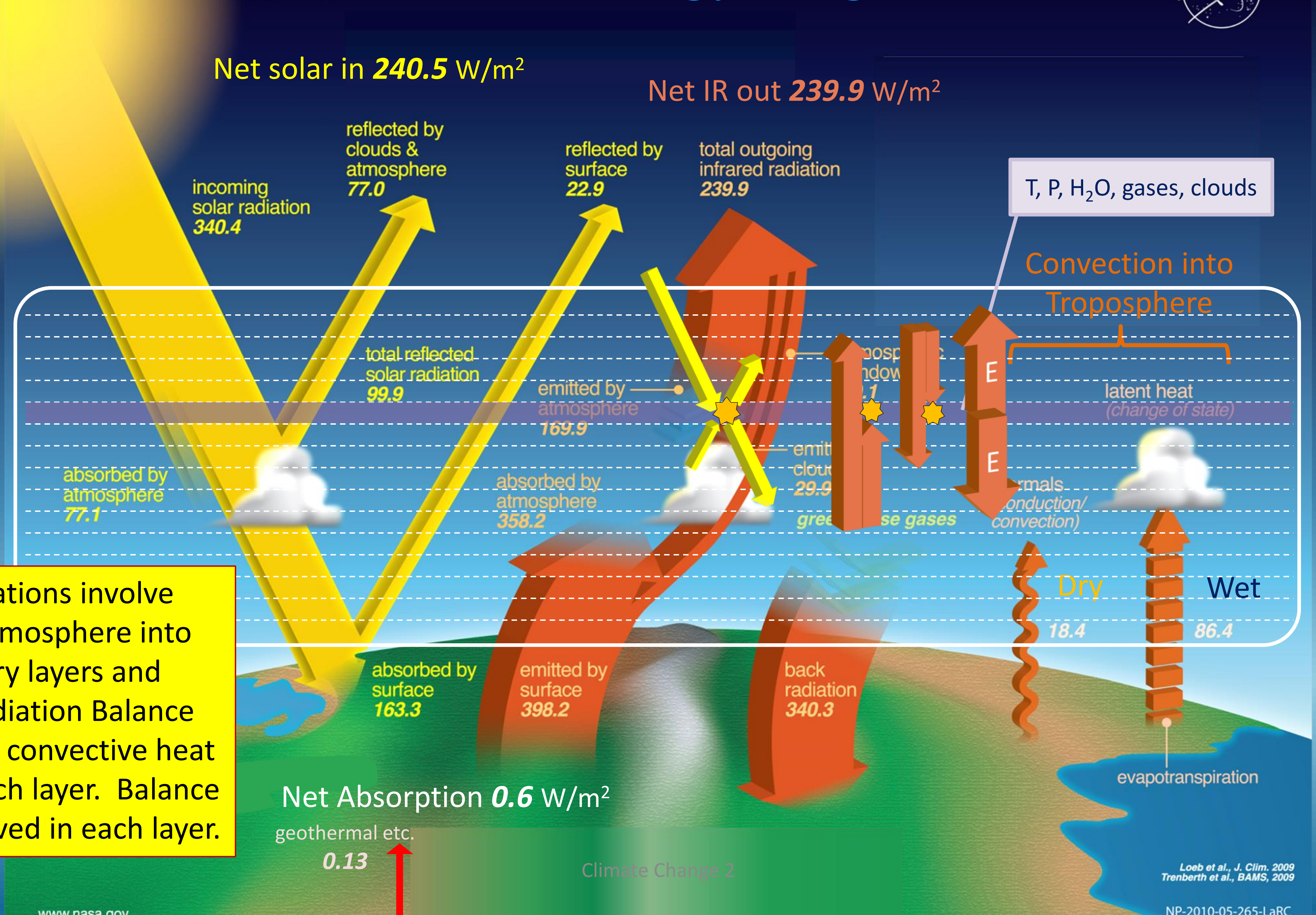
Note that both outgoing IR and reflected Solar are non-uniform and time dependent. Up to now we have be discussing averages.

Apr 2001

CERES Satellite Data

ceres.larc.nasa.gov/press_releases_images.php

Earth’s Energy Budget



Net solar in ***240.5*** W/m^2

Net IR out ***239.9*** W/m^2

T, P, H_2O, gases, clouds

Convection into Troposphere

E

E

Dry

Wet

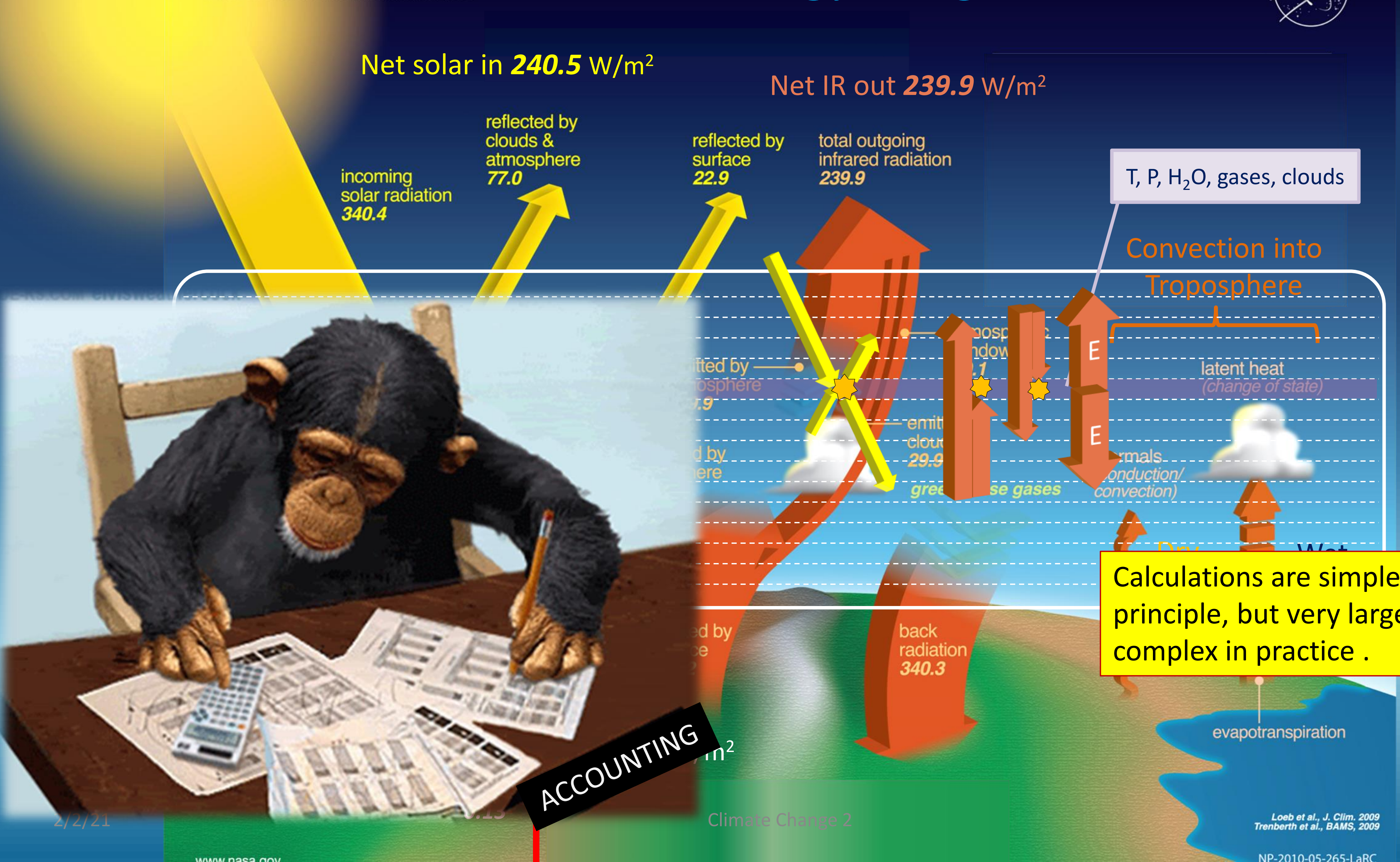
Climate calculations involve dividing the atmosphere into many imaginary layers and calculating Radiation Balance (together with convective heat transfer) in each layer. Balance must be achieved in each layer.

Net Absorption ***0.6*** W/m^2

geothermal etc.

0.13

Earth’s Energy Budget



Net solar in ***240.5*** W/m^2

Net IR out ***239.9*** W/m^2

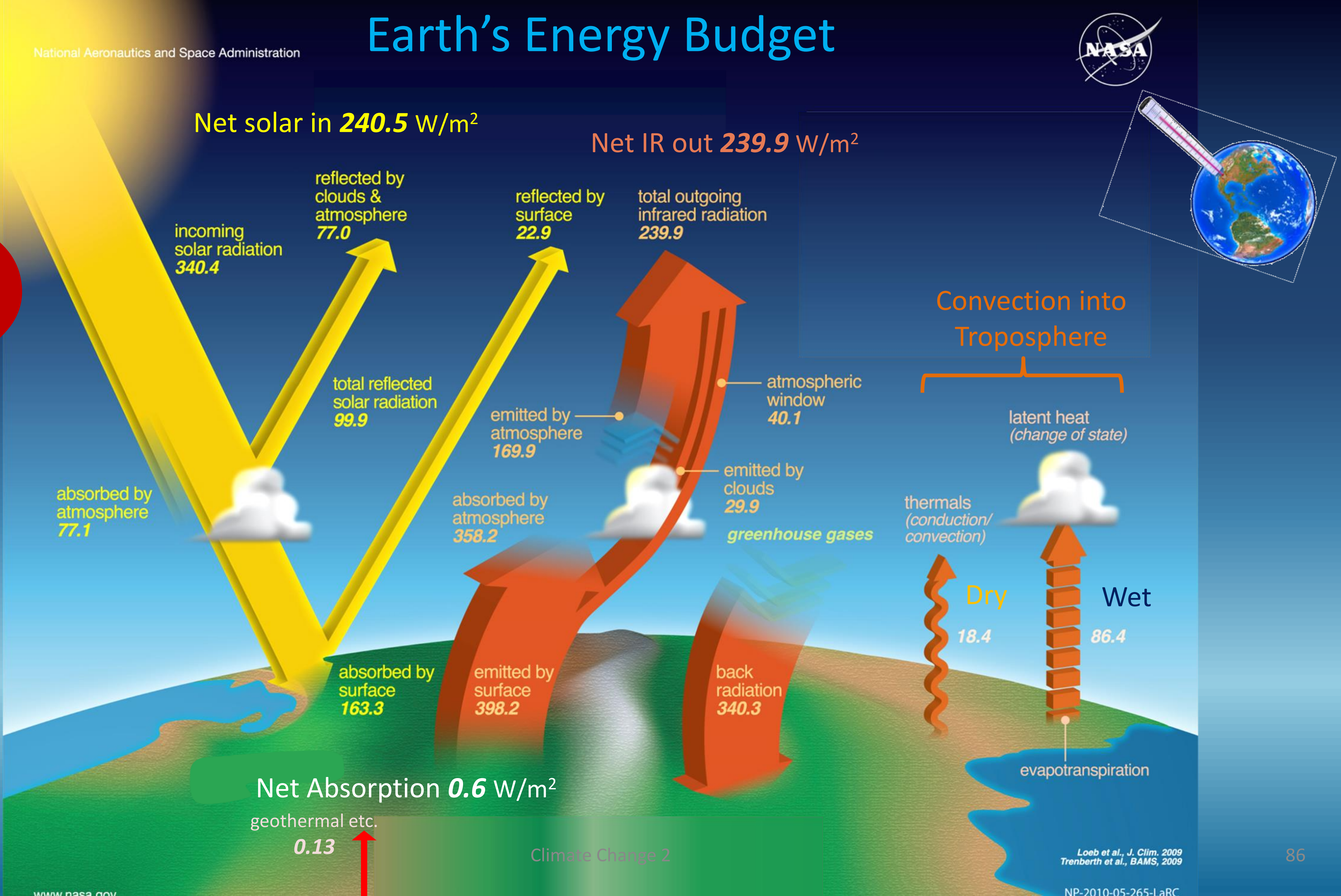
T, P, H_2O, gases, clouds

Convection into Troposphere

Calculations are simple in principle, but very large and complex in practice .

Loeb et al., J. Clim. 2009
Trenberth et al., BAMS, 2009

Earth’s Energy Budget



Net solar in ***240.5*** W/m^2

Net IR out ***239.9*** W/m^2

Convection into Troposphere

Dry

Wet

Net Absorption ***0.6*** W/m^2

geothermal etc.

0.13

Course Outline

1. Building Blocks: Some basic concepts
2. Our Goldilocks earth: a radiative balancing act
3. The Atmosphere and its Gases. Modeling the climate system
4. Wild cards: the roles of clouds and aerosols
5. The Dynamic Earth System: Oceans, atmosphere, biosphere, cryosphere, people, plate tectonics
6. Natural Variability of the climate, short and long term. Ice ages
7. Carbon Dioxide, Water and other greenhouse gases: Where do they come from, where do they go, how are they regulated?
8. Future Projections: Impacts of GW and the uncertainties. Amelioration strategies.