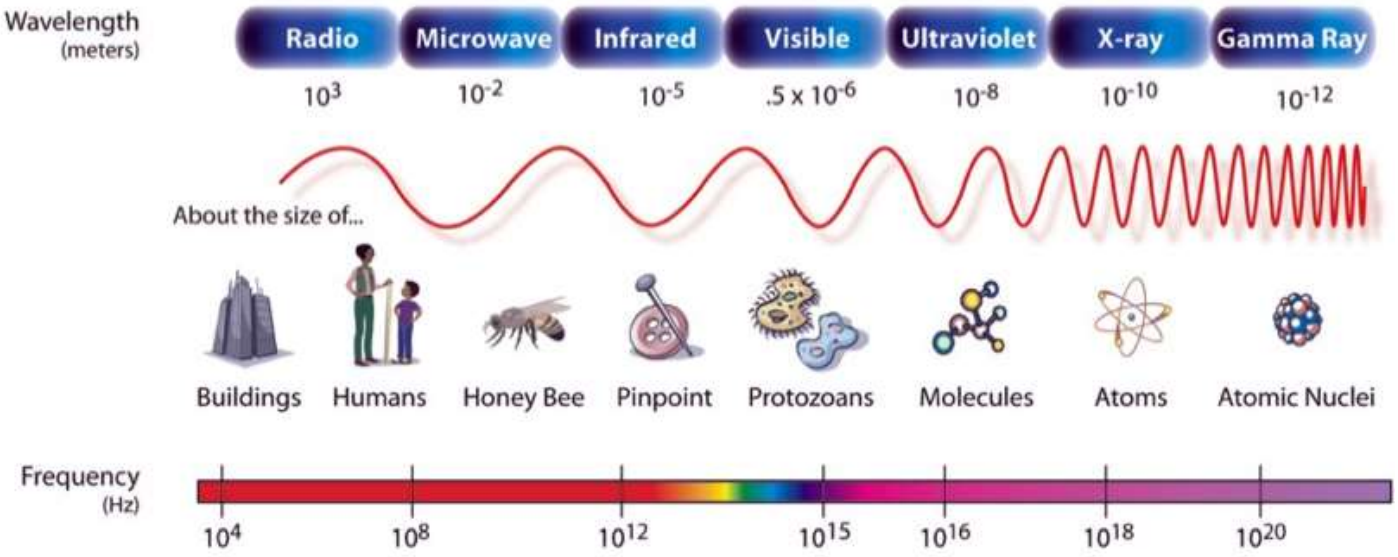
All are electromagnetic waves!



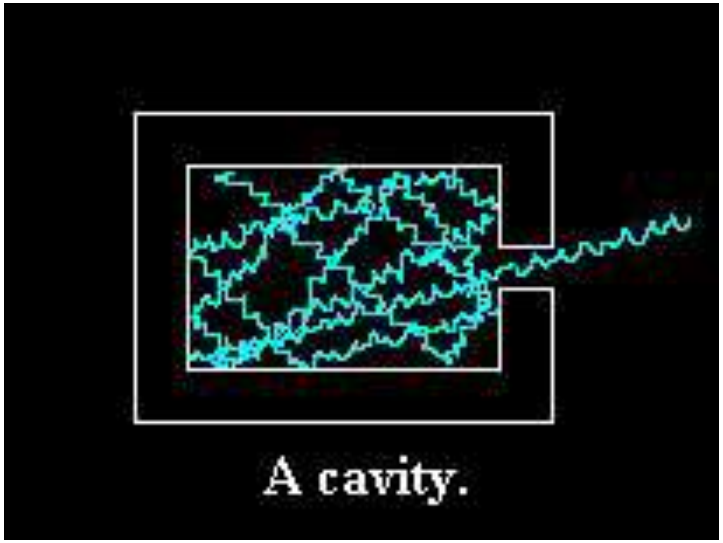
Characteristics:

- Speed of waves = 3.00×10^{8} m/s
- Can travel through vacuum

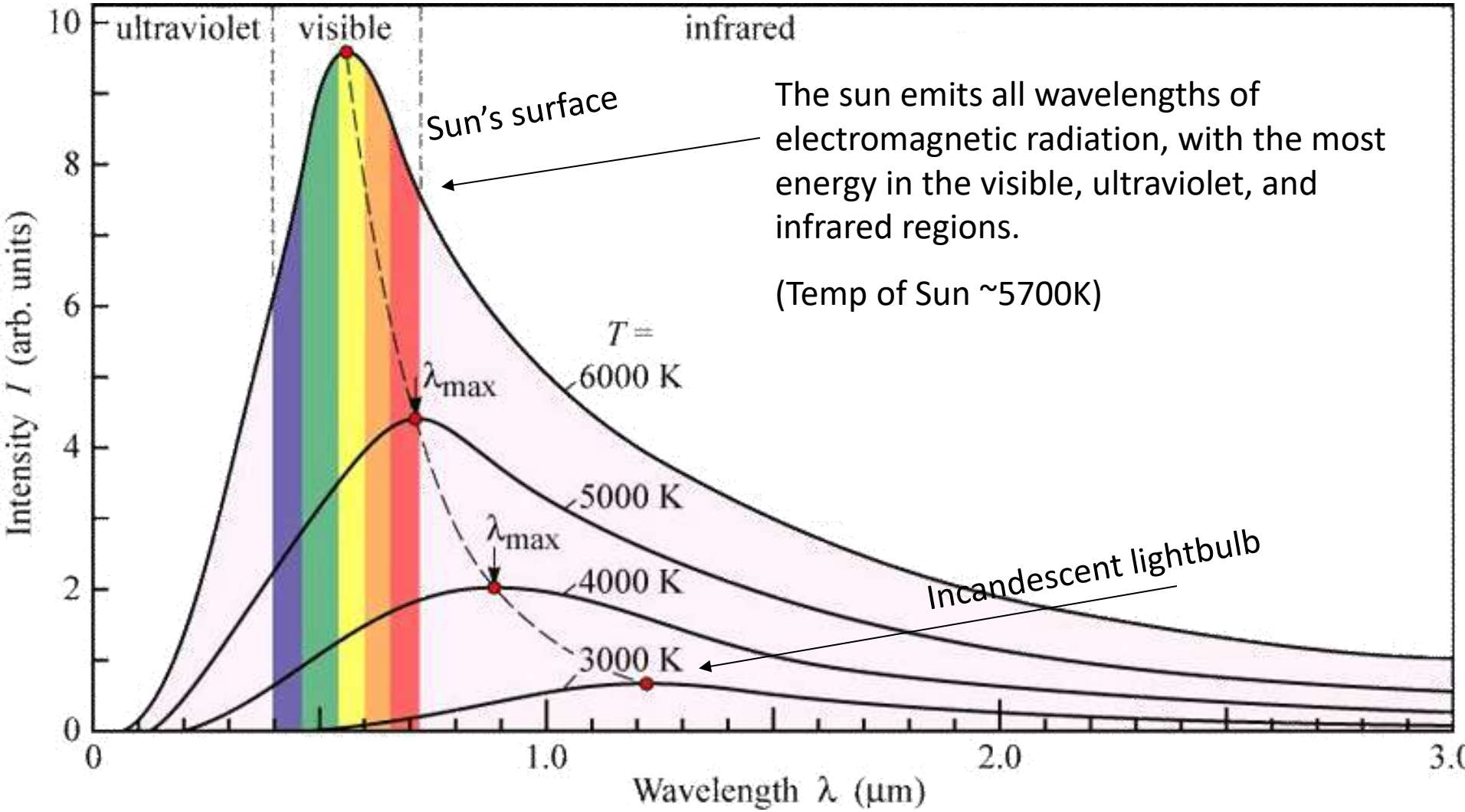
Thermal (Heat) Radiation

A “blackbody” is material/object that does not reflect any light: It is perfectly black.

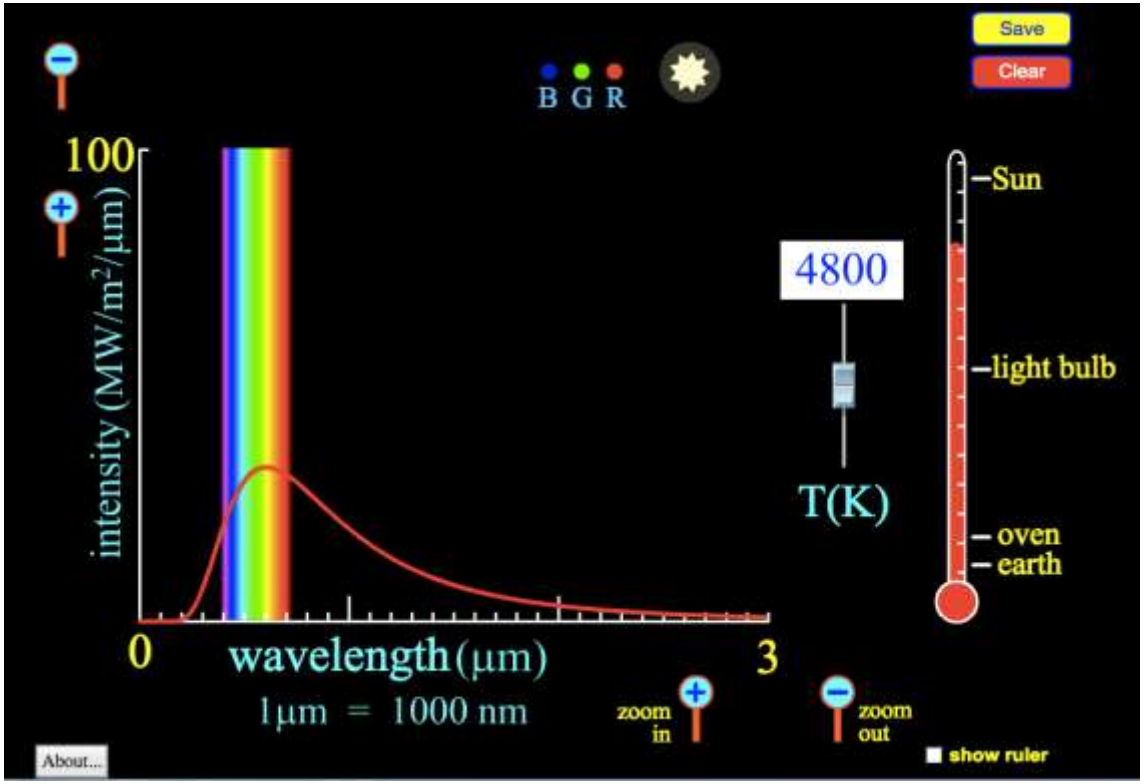
Thermal (Heat) Radiation



- A blackbody is material/object that does not reflect any light: It is perfectly black.
- Can be realized by using a cavity with a hole in it: Light going in will never come back out.
- When heated to higher and higher temperatures, the aperture will emit light, first infrared, then visible: red, orange, yellow, white, blueish.
- This is called “blackbody radiation”.

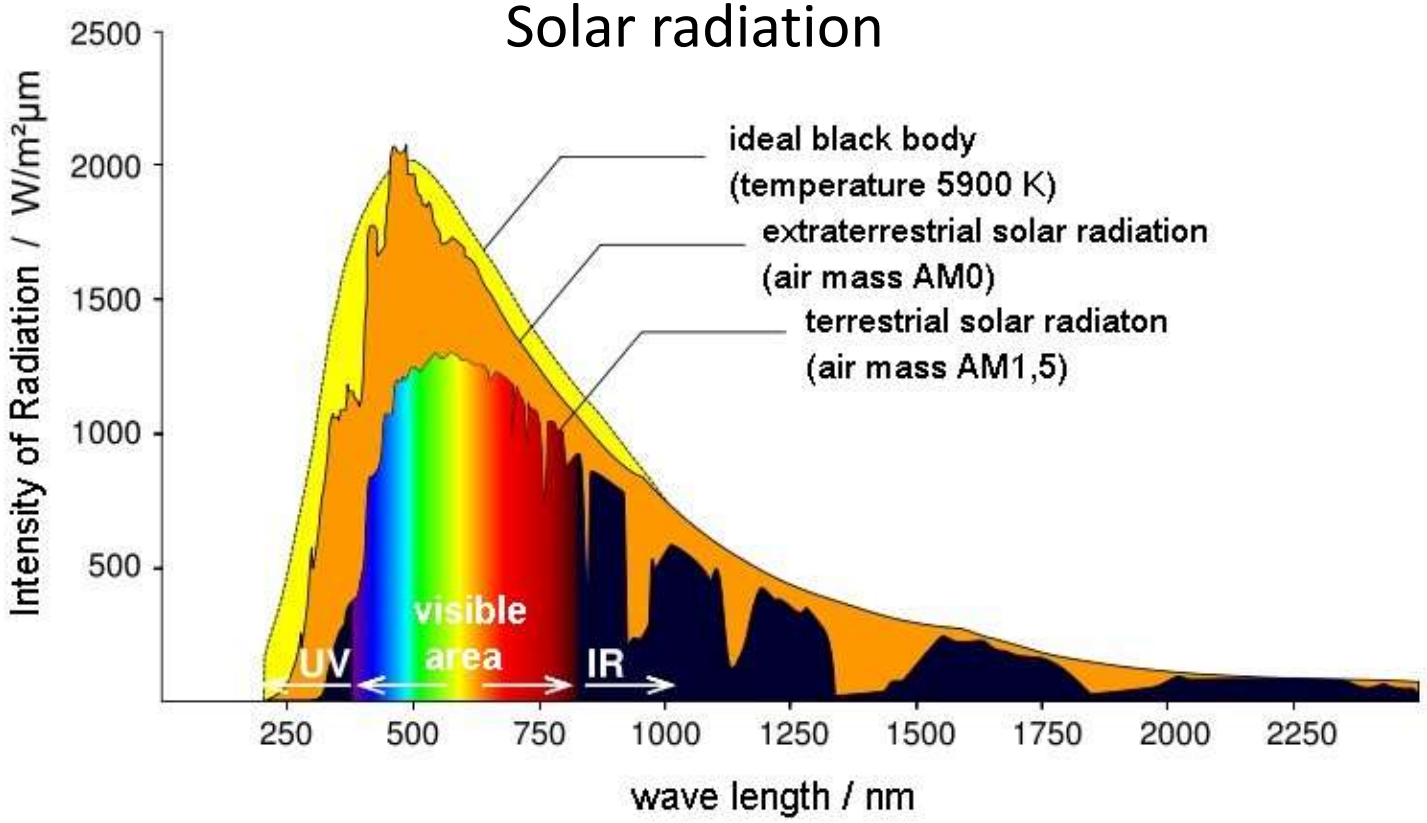

ultraviolet
visible
infrared
Sun's surface
The sun emits all wavelengths of electromagnetic radiation, with the most energy in the visible, ultraviolet, and infrared regions.
(Temp of Sun ~5700K)
T =
6000 K
5000 K
4000 K
3000 K
λmax
λmax
Incandescent lightbulb
Intensity I (arb. units)
Wavelength λ (μm)
0
2
4
6
8
10
0
1.0
2.0
3.0

https://phet.colorado.edu/sims/html/blackbody-spectrum/latest/blackbody-spectrum_en.html



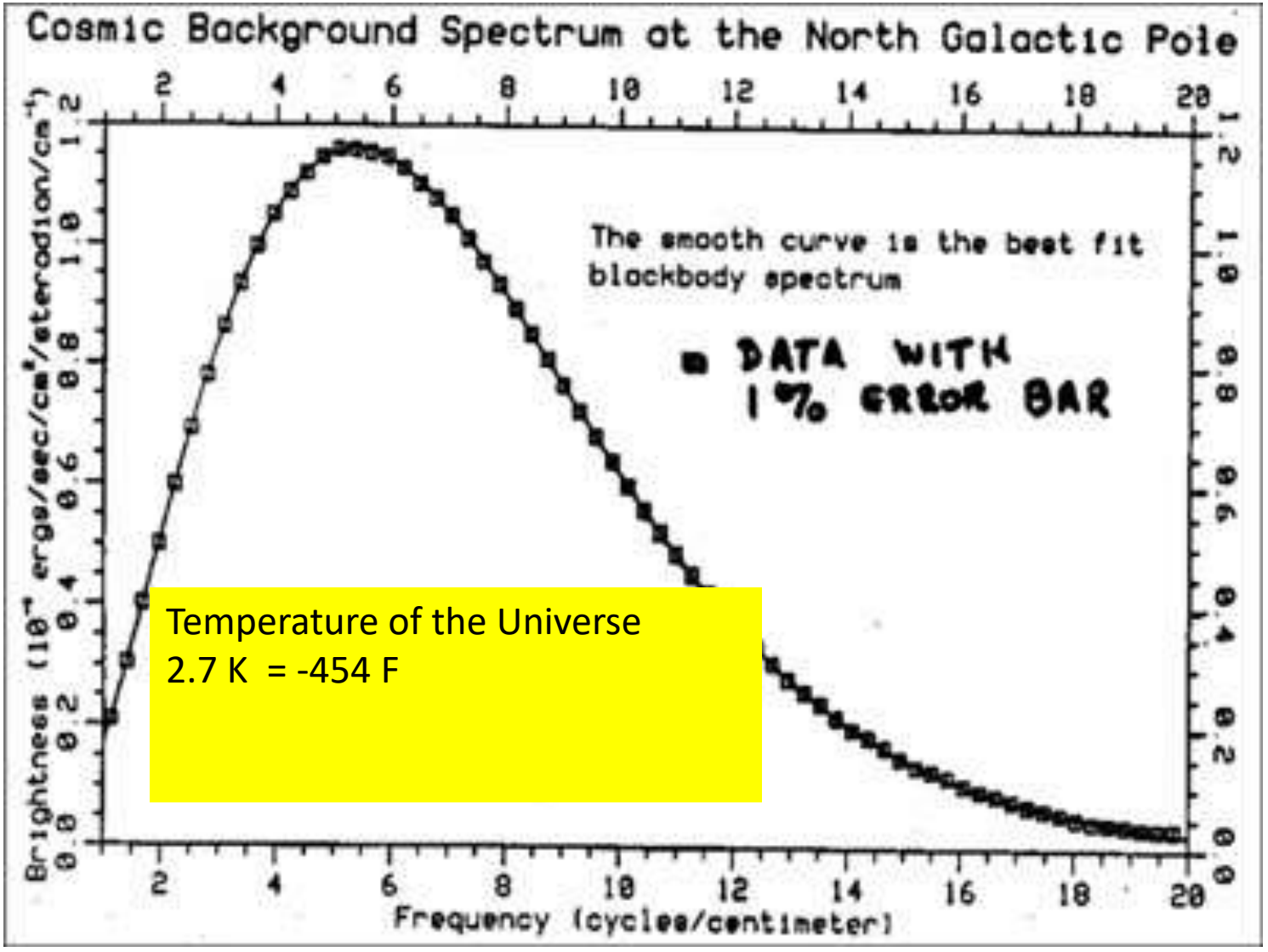
Do non-black bodies emit thermal radiation?
Yes, but spectrum depends on properties of object.
For blackbody, only the temperature matters!

Increasing frequency



Increasing wavelength

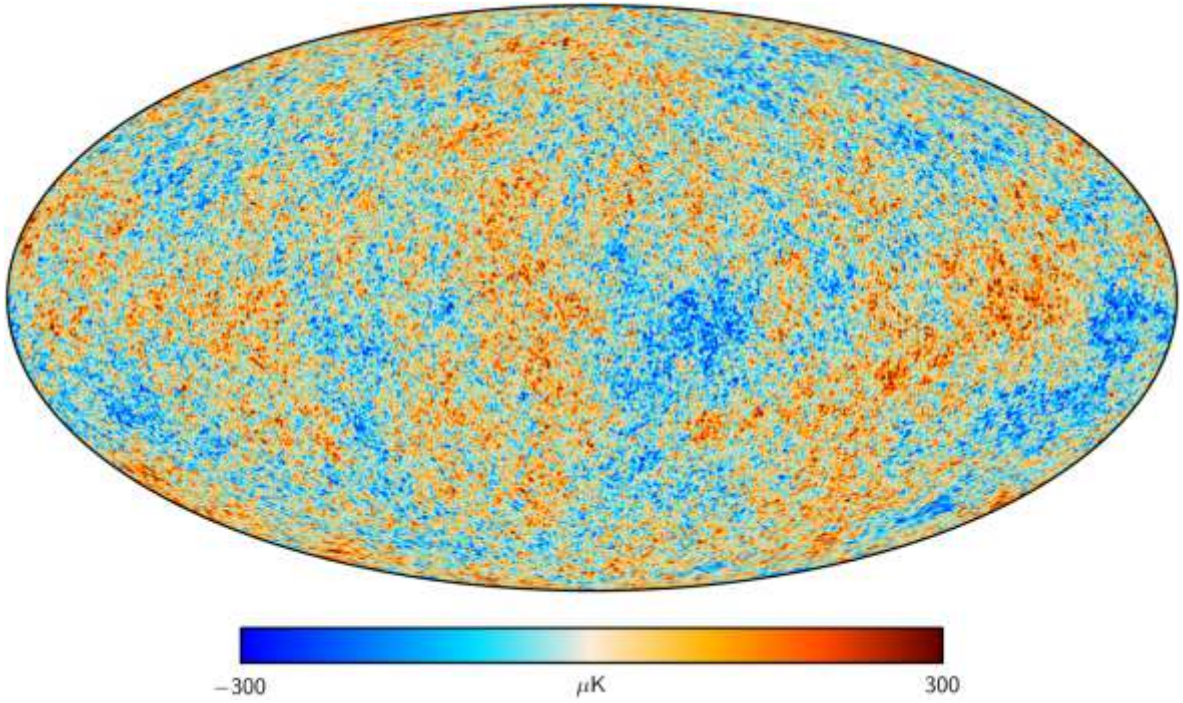
Entire Universe is a blackbody



Entire Universe is a blackbody

- This is a map of the cosmic microwave background (CMB). It is the most precisely known thermal emission (blackbody) spectrum, with a temperature of ~2.7 K.

https://www.cosmos.esa.int/web/planck



Clicker

The radiation emitted by an ideal blackbody cavity depends on

A) How radioactive it is
B) How black it is
C) On its material
D) On its temperature
E) On the color of the paint inside

Clicker

The radiation emitted by an ideal blackbody cavity depends on

A) How radioactive it is

B) How black it is

C) On its material

D) On its temperature

E) On the color of the paint inside

Clicker

If one object is emitting reddish light, and another is emitting bluish light, which one is hotter (higher temperature)?

A) The heavier object
B) The reddish object
C) The bluish object
D) Both are at the same temperature
E) It depends on how far away the object is

Clicker

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A) The heavier object

B) The reddish object

C) The bluish object

D) Both are at the same temperature

E) It depends on how far away the object is

Clicker

What is the significance of "black" in "blackbody"? Why don't we have a celebrated law for "whitebody radiation", "redbody radiation", "greenbody radiation", or whatever your favorite color is? And what about the Fifty Shades of Grey?

a) Physicists are boring. They cannot appreciate the beauty of colors. Or shades of grey.

b) Only black bodies radiate thermal radiation. Other colors won't.

c) Each color has its own radiation law. The non-black laws require understanding of the theory of QCD (quantum chromodynamics, chromos = color).

d) We don't discriminate between black bodies and white bodies. All bodies are subject to the same law!

e) The radiation inside any closed cavity, no matter what the color of the material, is identical to that emitted from a perfect black body.

Clicker

What is the significance of "black" in "blackbody"? Why don't we have a celebrated law for "whitebody radiation", "redbody radiation", "greenbody radiation", or whatever your favorite color is? And what about the Fifty Shades of Grey?

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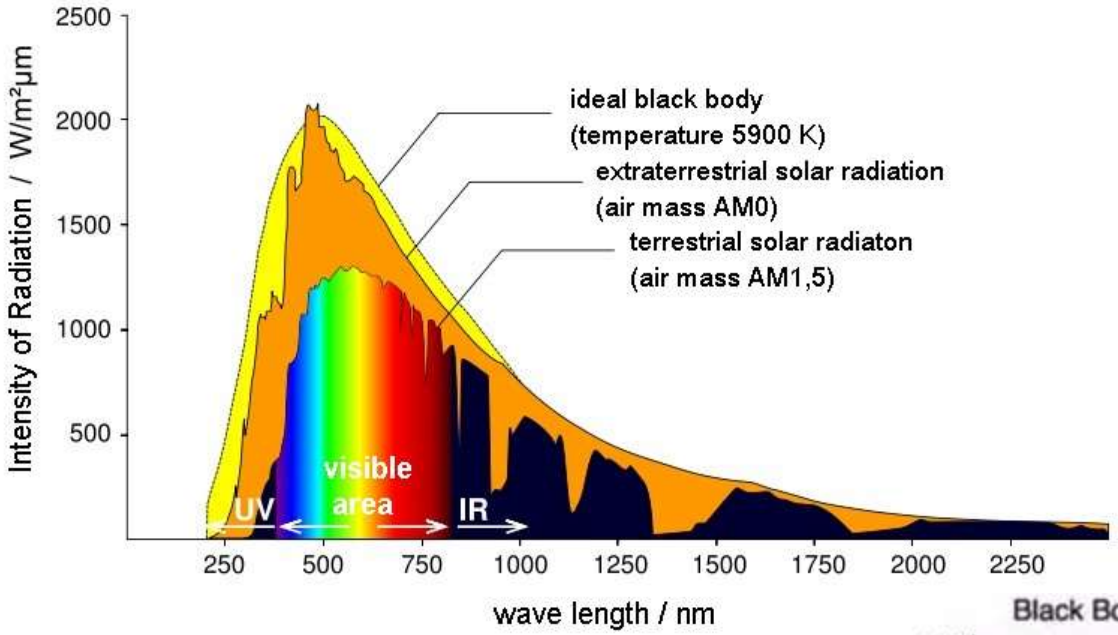
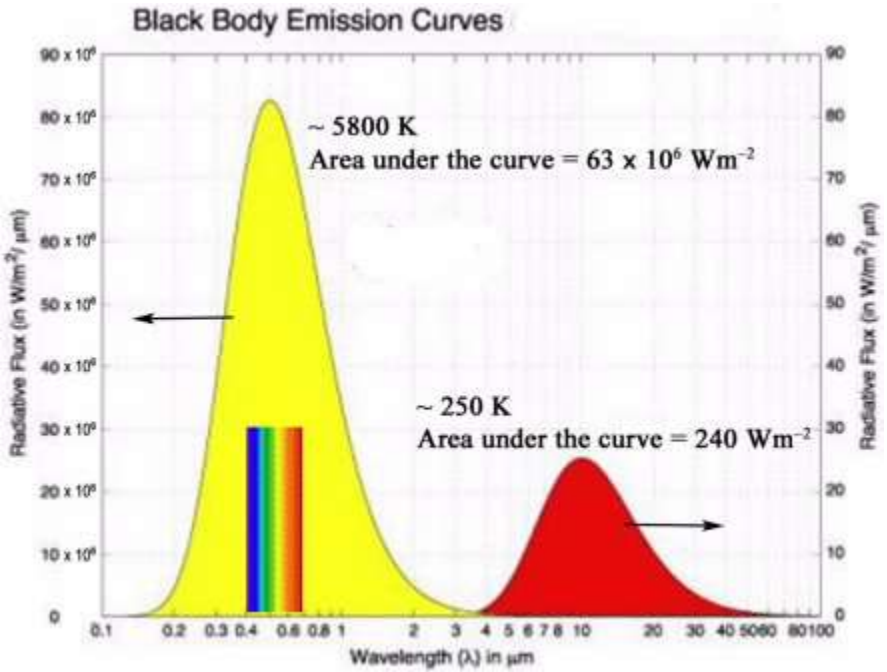
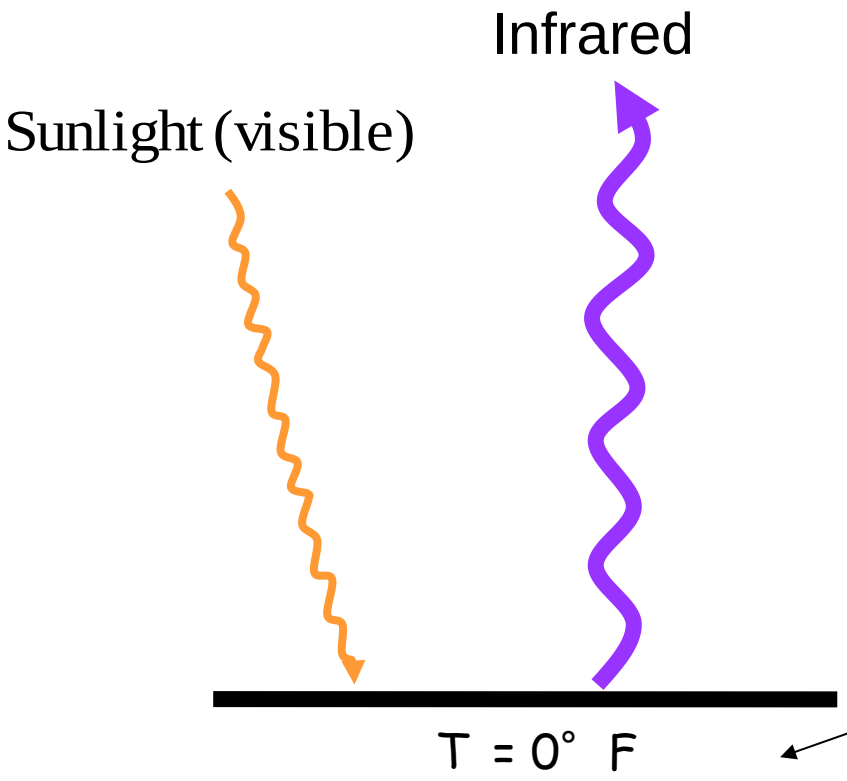
Sun and Earth Emission Spectra





What is the Greenhouse Effect?

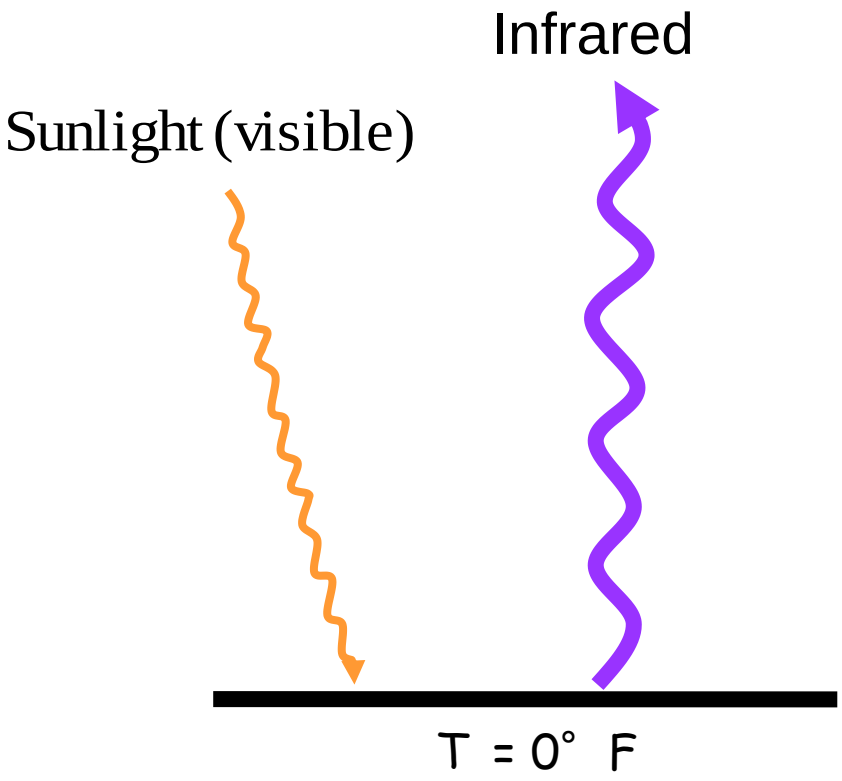


If NO greenhouse effect!

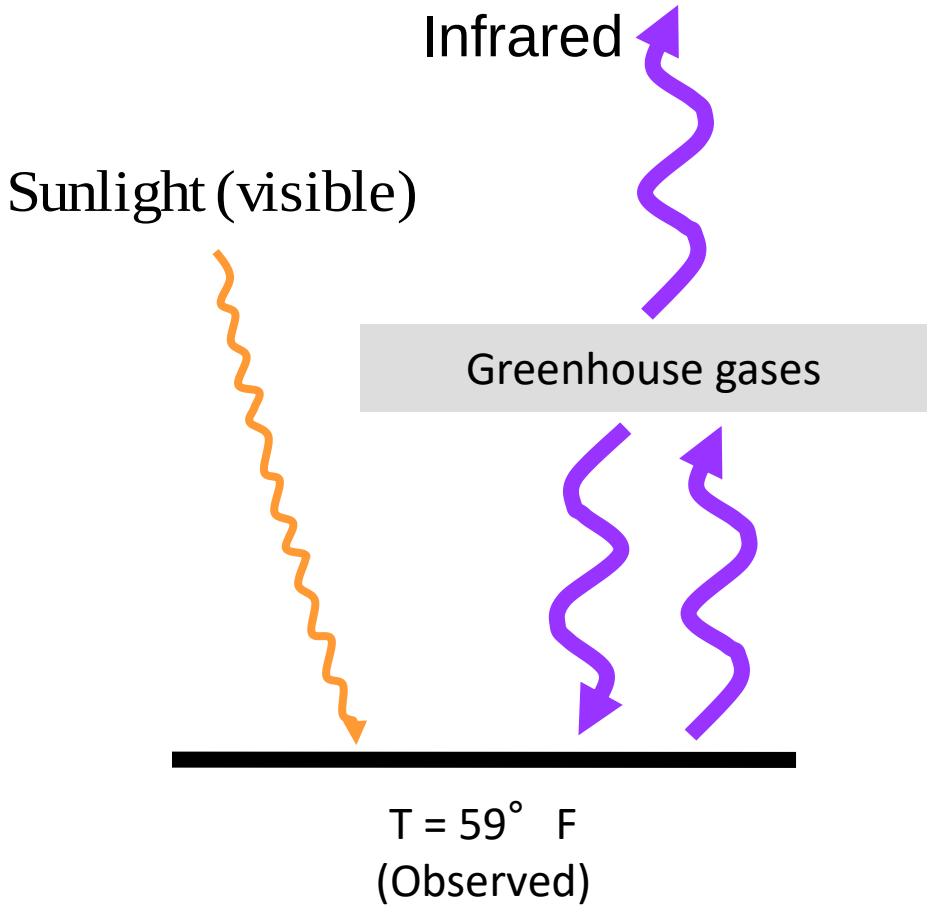
- The Earth must radiate back into space ALL the energy it receives.
  - 31% of incoming solar energy is reflected right back.
  - 69% is absorbed by the atmosphere +surface.

  → 120 x 10^{15} Watts
- The temperature at the Earth's surface is set by how many Watts have to be radiated back into space.

No Greenhouse Effect



With Greenhouse Effect



Greenhouse effect saves us!

Atmosperic composition

Nitrogen (N_2)	77.8%	
Oxygen (O_2)	20.8%	
Argon (Ar)	0.9%	
Water vapor (H_2O)	0.4%	4000 ppm (average)
Carbon dioxide (CO_2)		390 ppm
Neon (Ne)		18 ppm
Helium (He)		5 ppm
Methane (CH_4)		1.8 ppm
Nitrous oxide (N_2O)	0.3 ppm	
Ozone (O_3)		0.0 to 0.07 ppm
Nitrogen dioxide (NO_2)		0.02 ppm

Greenhouse gases absorb IR!

All of the above are transparent to visible light

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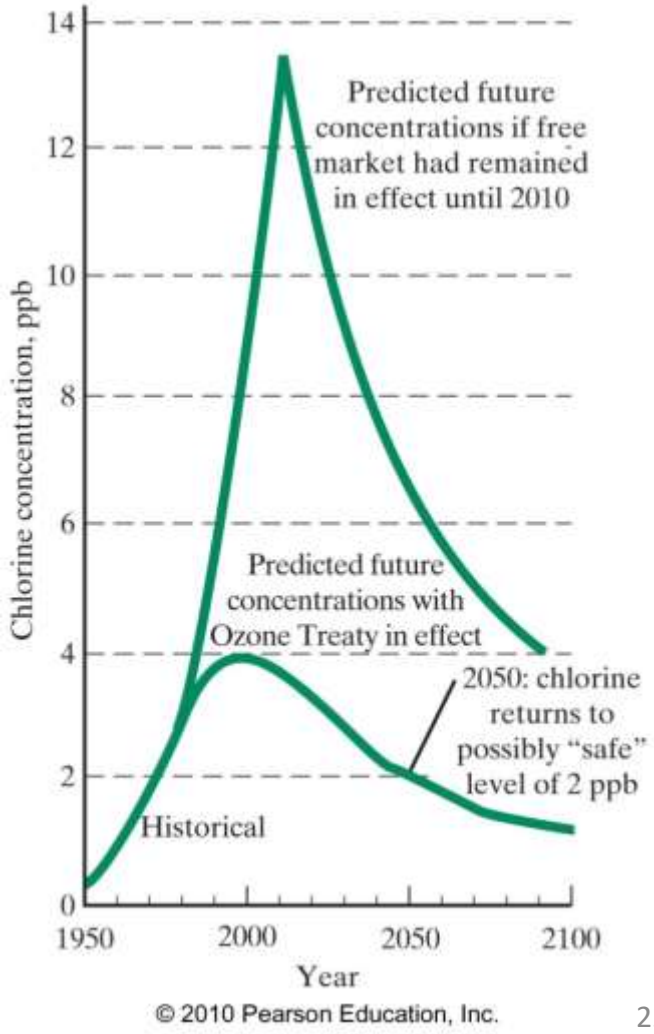
Absorbs UV !

Ozone Depletion

- Ozone naturally protects us against harmful UV
- CFCs (chlorofluorocarbons) from spray cans, perfumes, refrigerants, etc., were destroying atmospheric ozone
- International treaty of 1987 has largely solved the problem

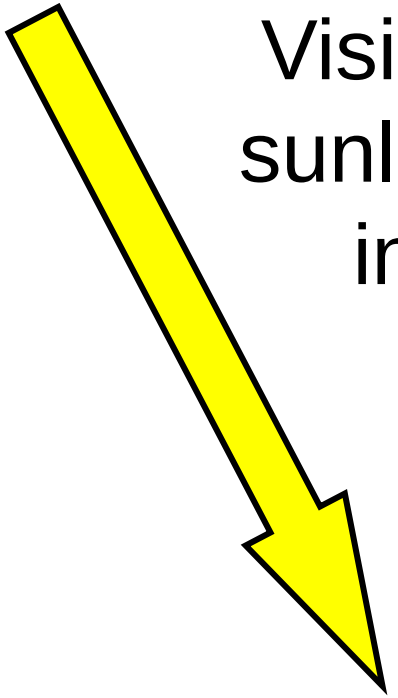


Ozone Depletion

Lessons:

- Trace gases in the atmosphere can be extremely important
- Once produced, they last for a long time (decades)
- Ordinary market forces do not work to control the problem
- International treaty action needed
- Prevented millions of skin cancer deaths worldwide 1990-2050

No Greenhouse Effect

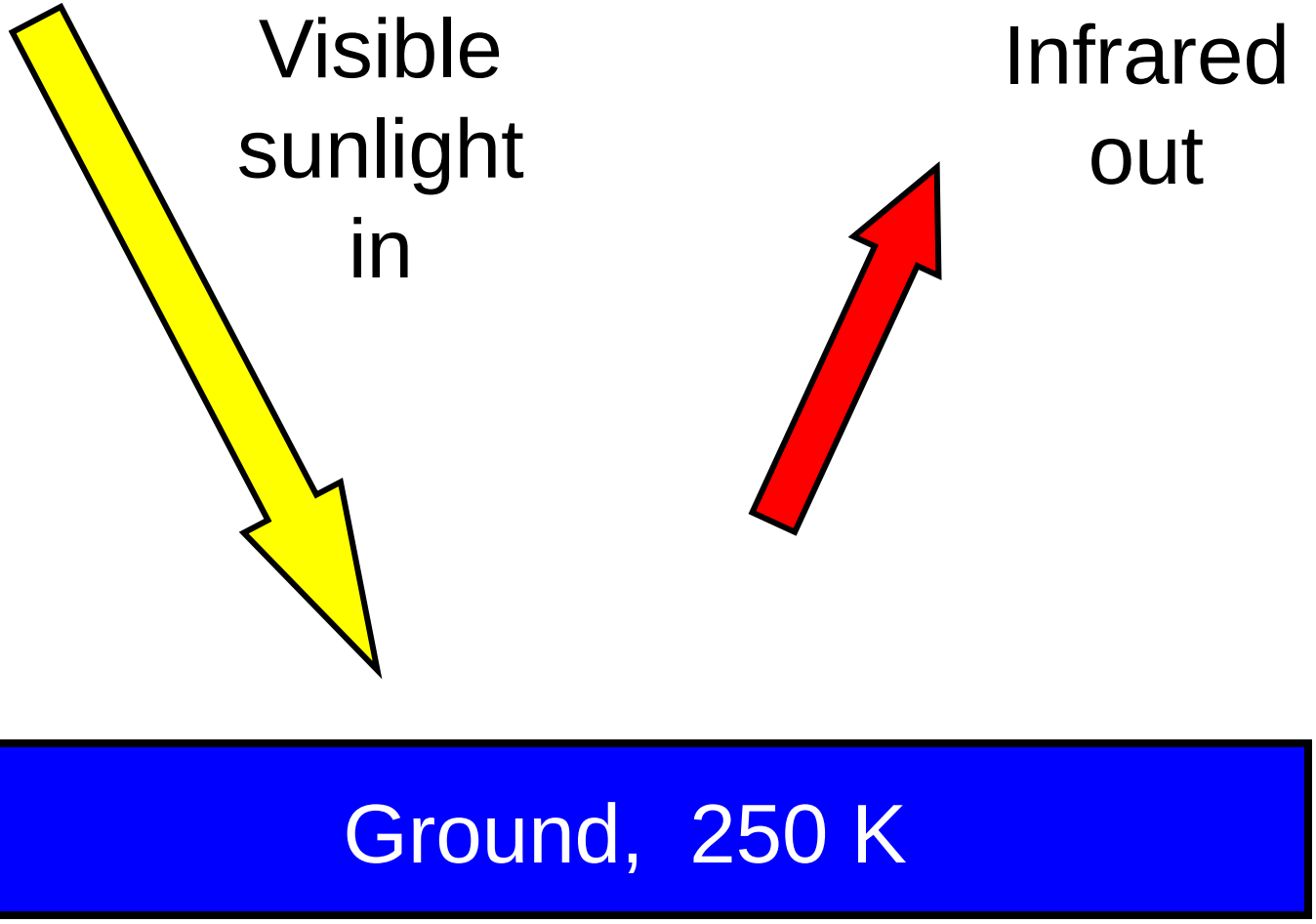


Visible sunlight in

Ground, 200 K

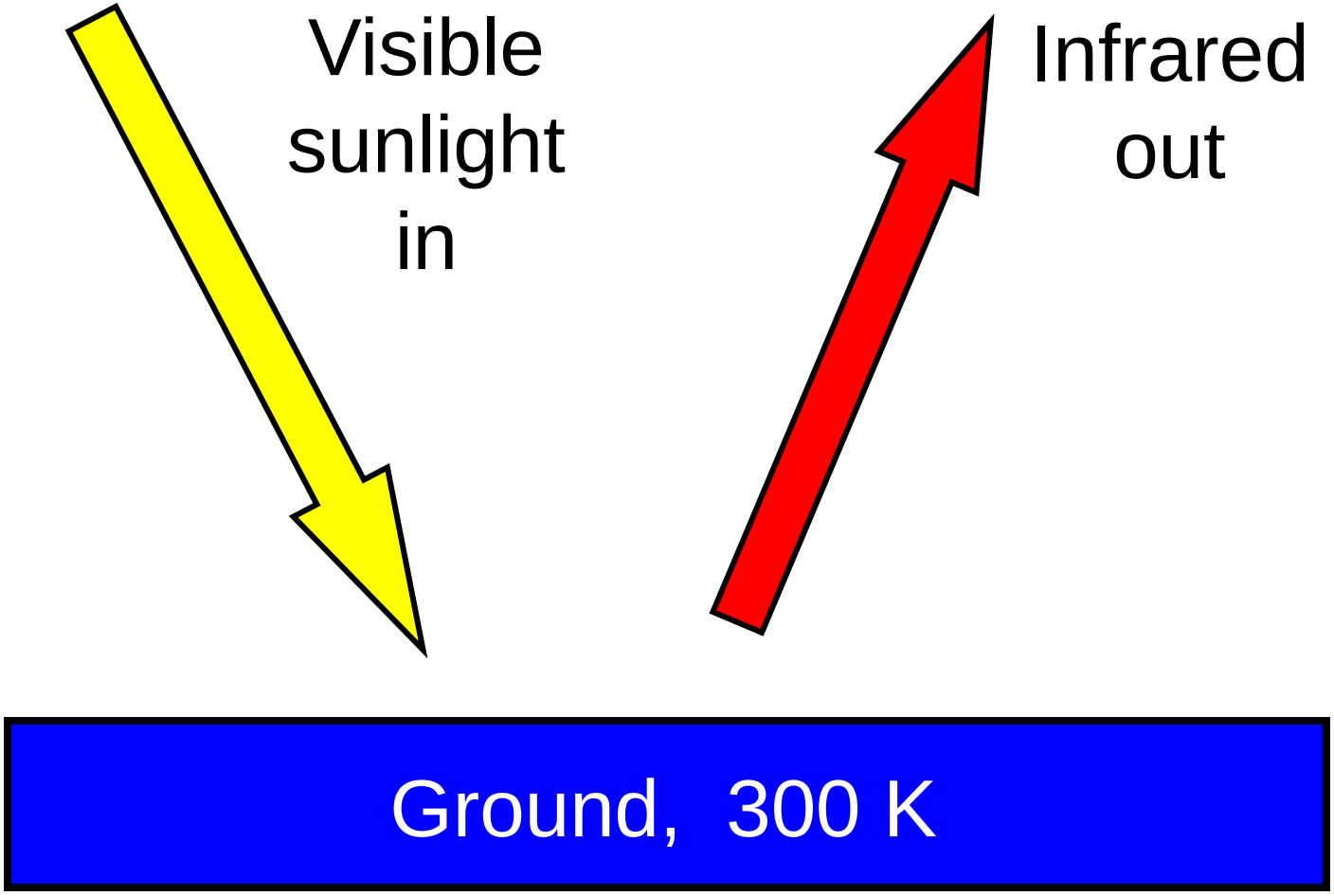
WARMING

No Greenhouse Effect



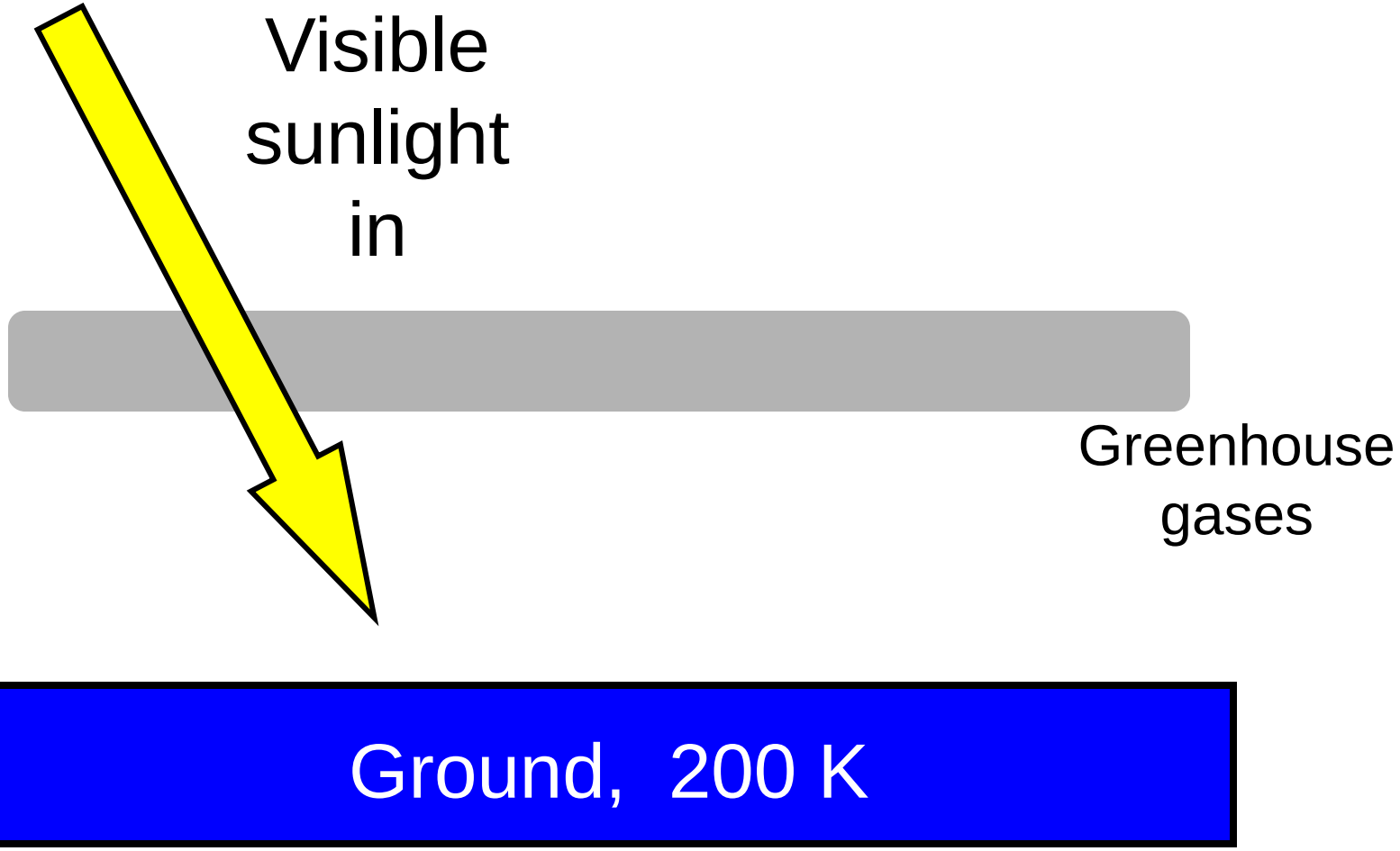
WARMING MORE SLOWLY

No Greenhouse Effect



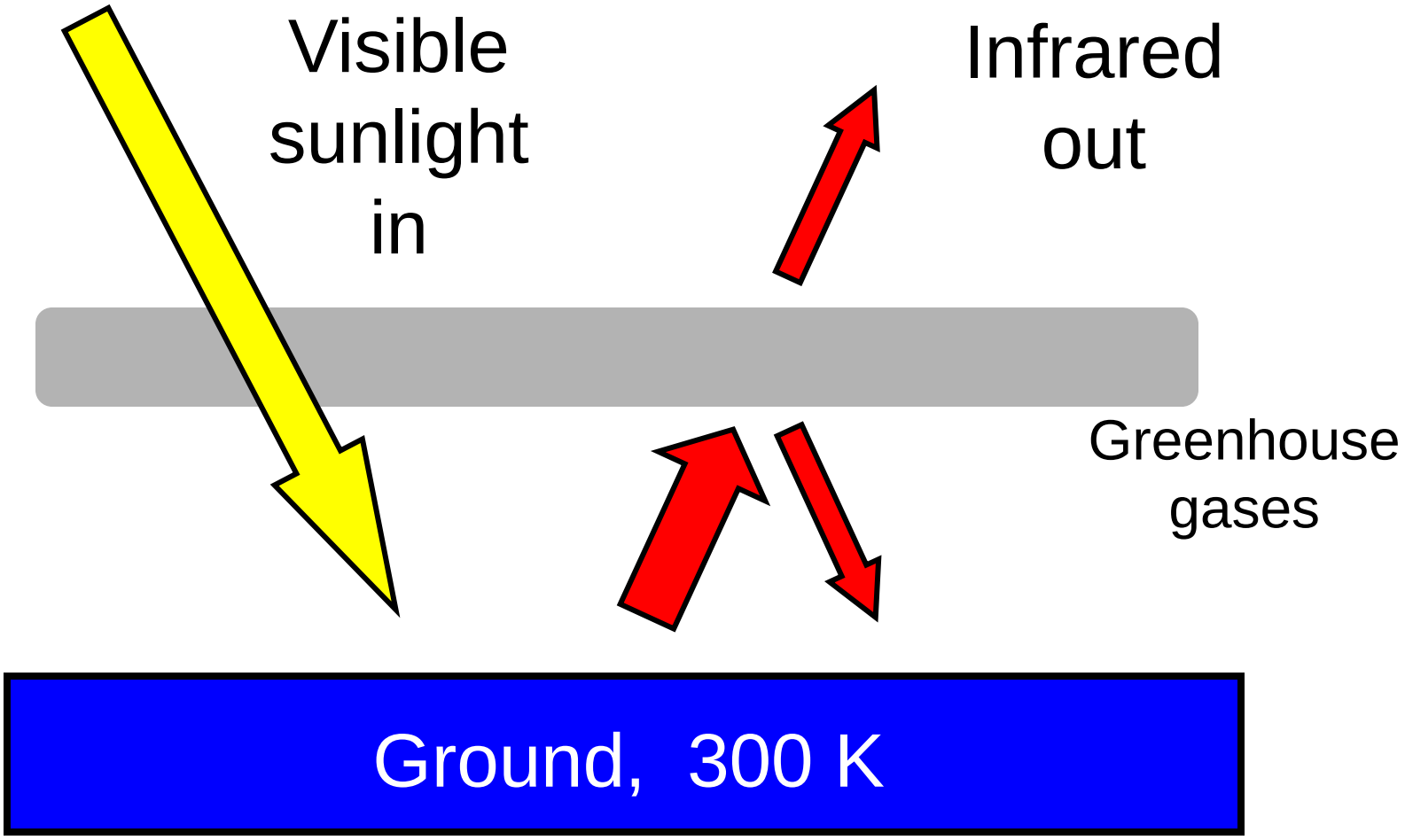
NO LONGER WARMING

With Greenhouse Effect



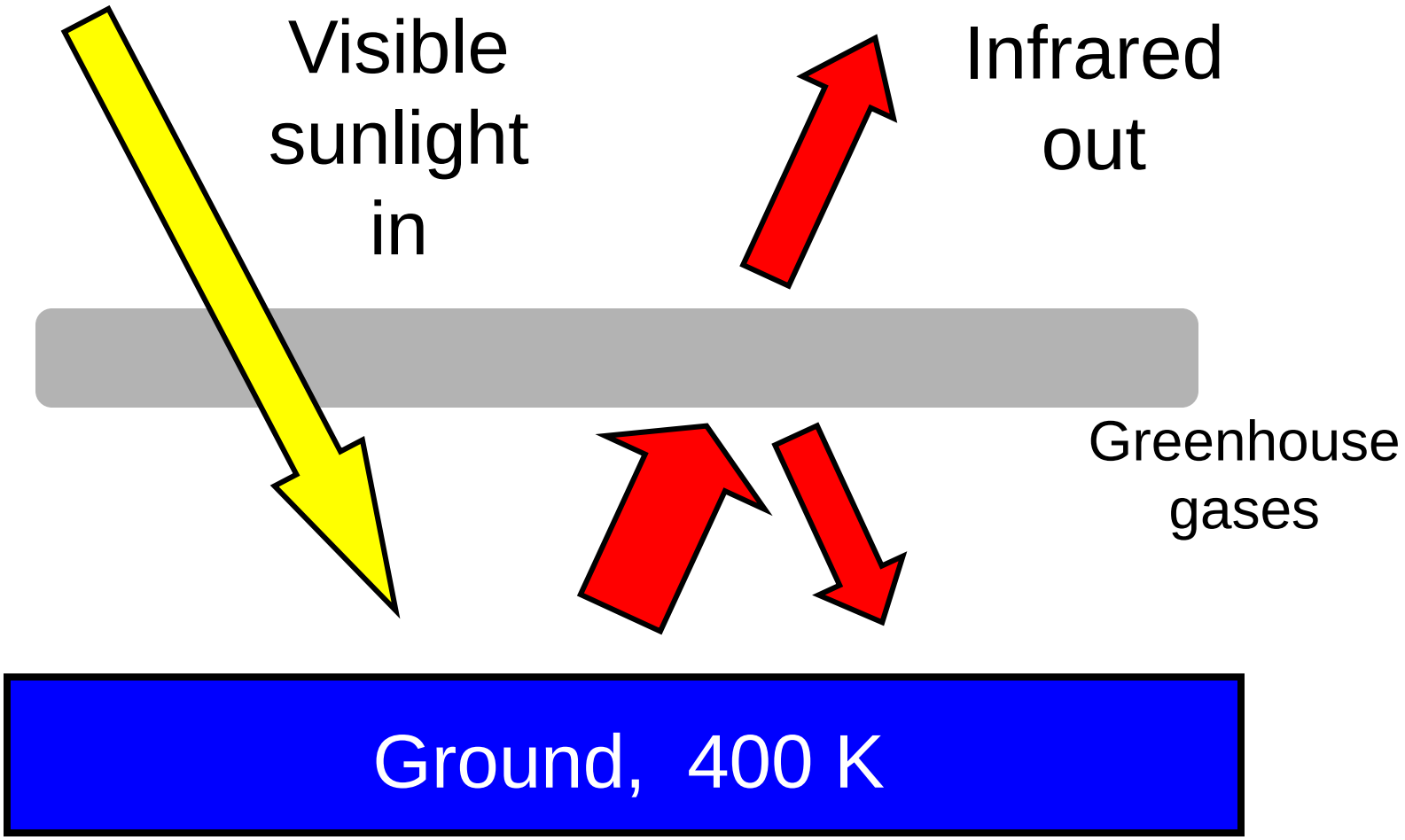
WARMING

With Greenhouse Effect



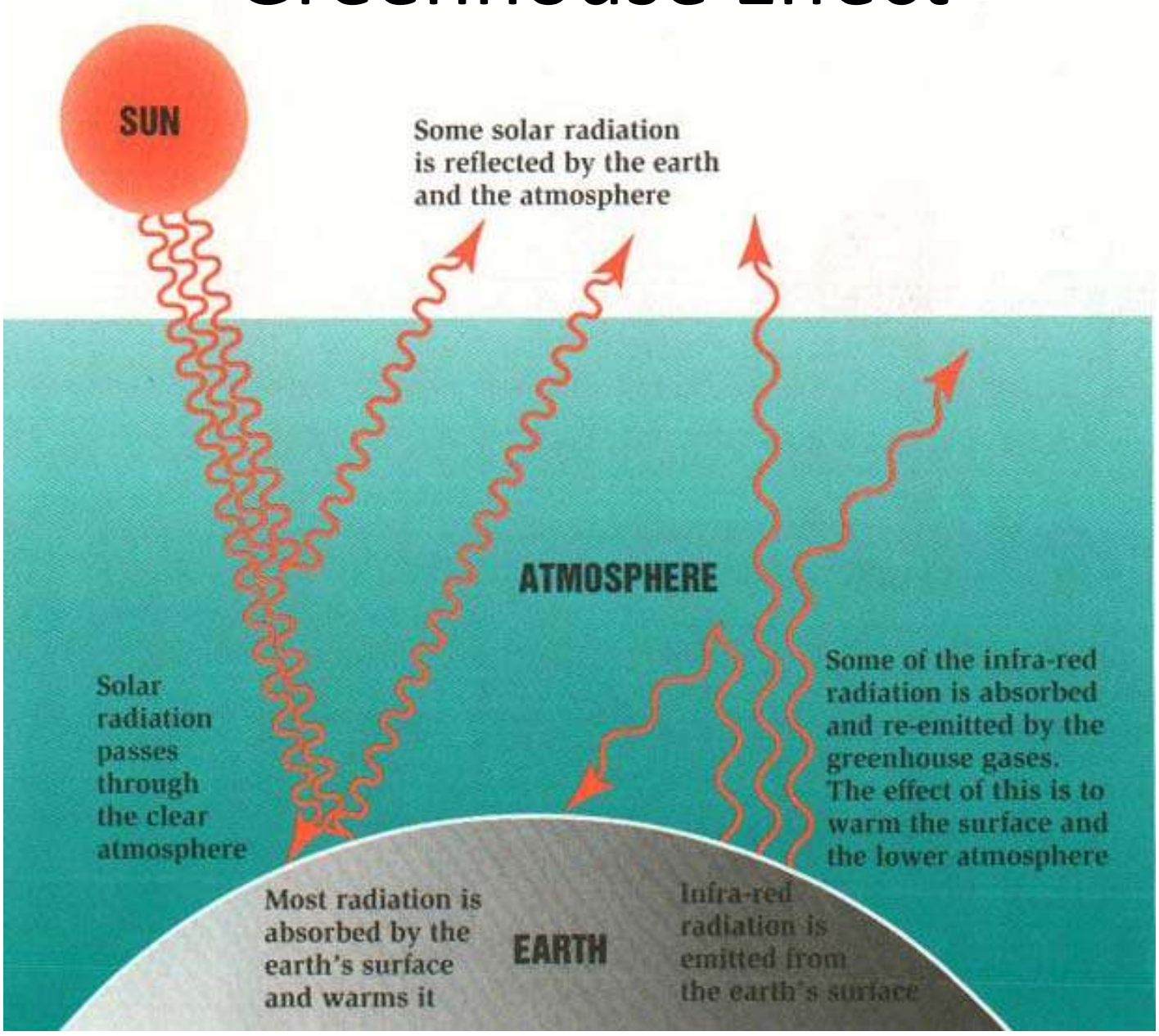
WARMING

With Greenhouse Effect

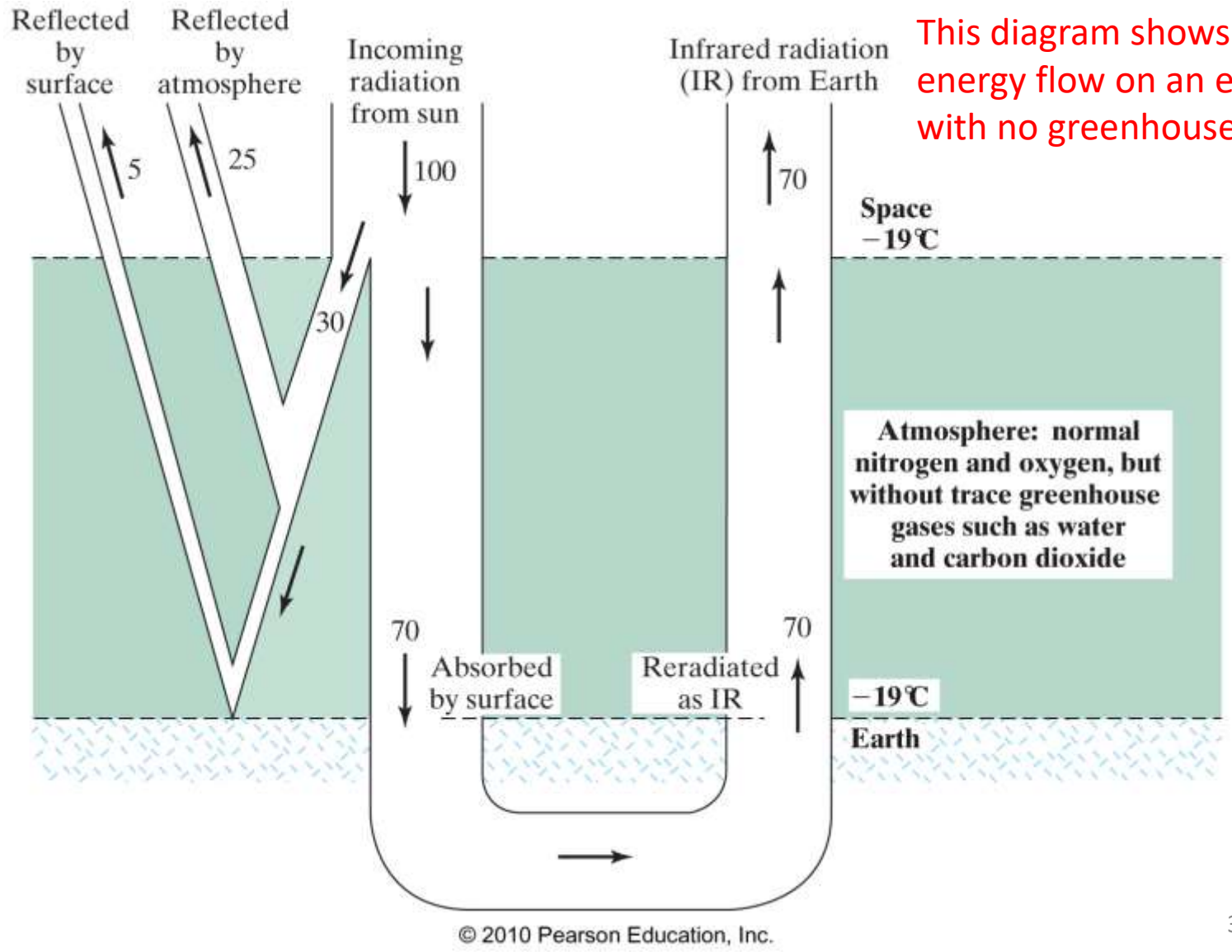


NO LONGER WARMING

Greenhouse Effect



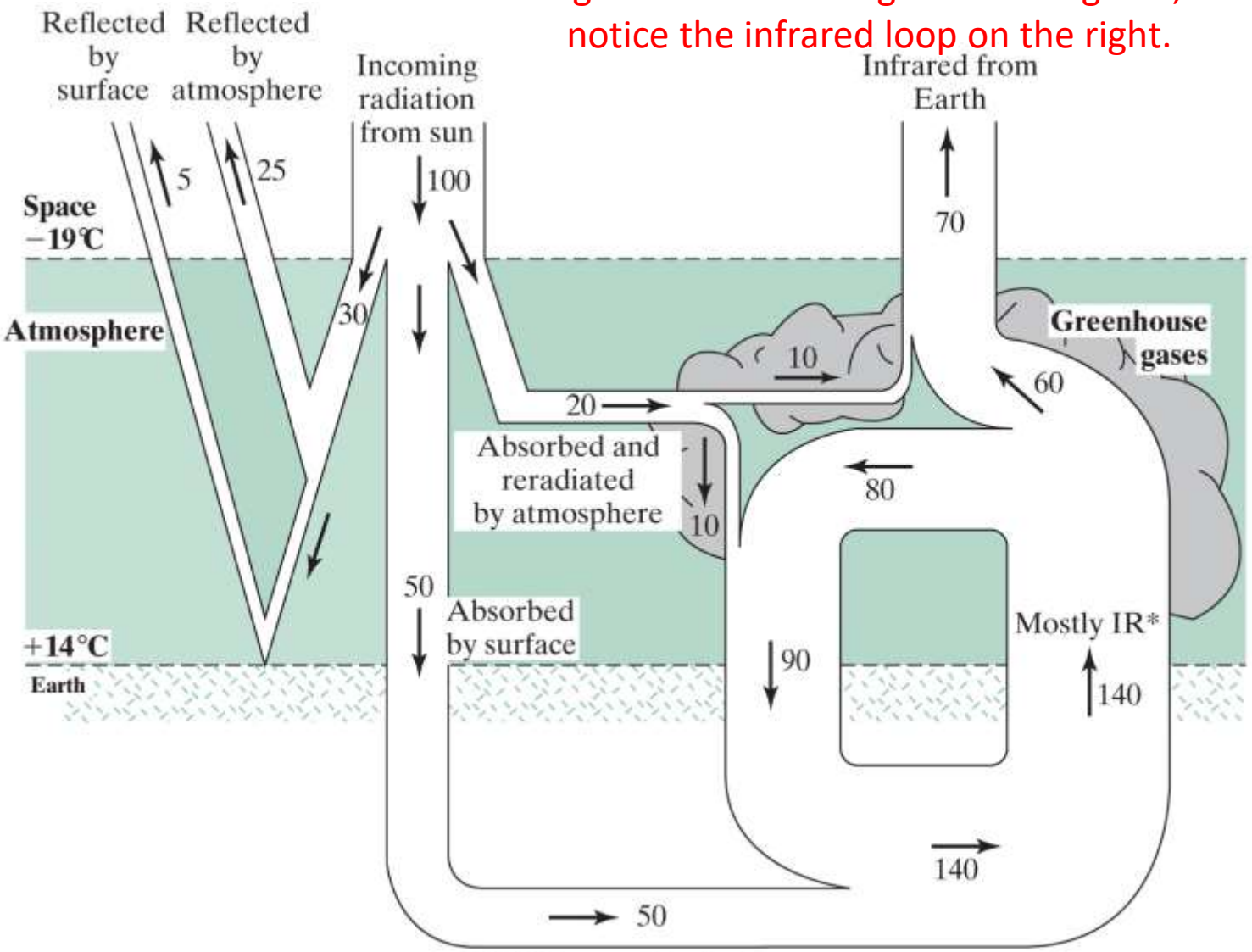
No Greenhouse Effect



This diagram shows the energy flow on an earth with no greenhouse gases.

With Greenhouse Effect

This diagram includes the greenhouse gases; notice the infrared loop on the right.



Planet surface temperatures

	Estimate, No Greenhouse Effect	Actual
Venus 	–40 °F	900 °F
Earth 	0 °F	60 °F
Mars 	–80 °F	–80 °F

Greenhouse effect

- The greenhouse effect is a natural process
- It is essential to life on earth as we know it
- So what is the problem?
- Answer: We are increasing the greenhouse gases in the atmosphere to unprecedented levels!

Greenhouse Gases

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Water vapor (H_2O)	0.4%	4000 ppm (average)
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Ozone (O_3)		0.0 to 0.07 ppm
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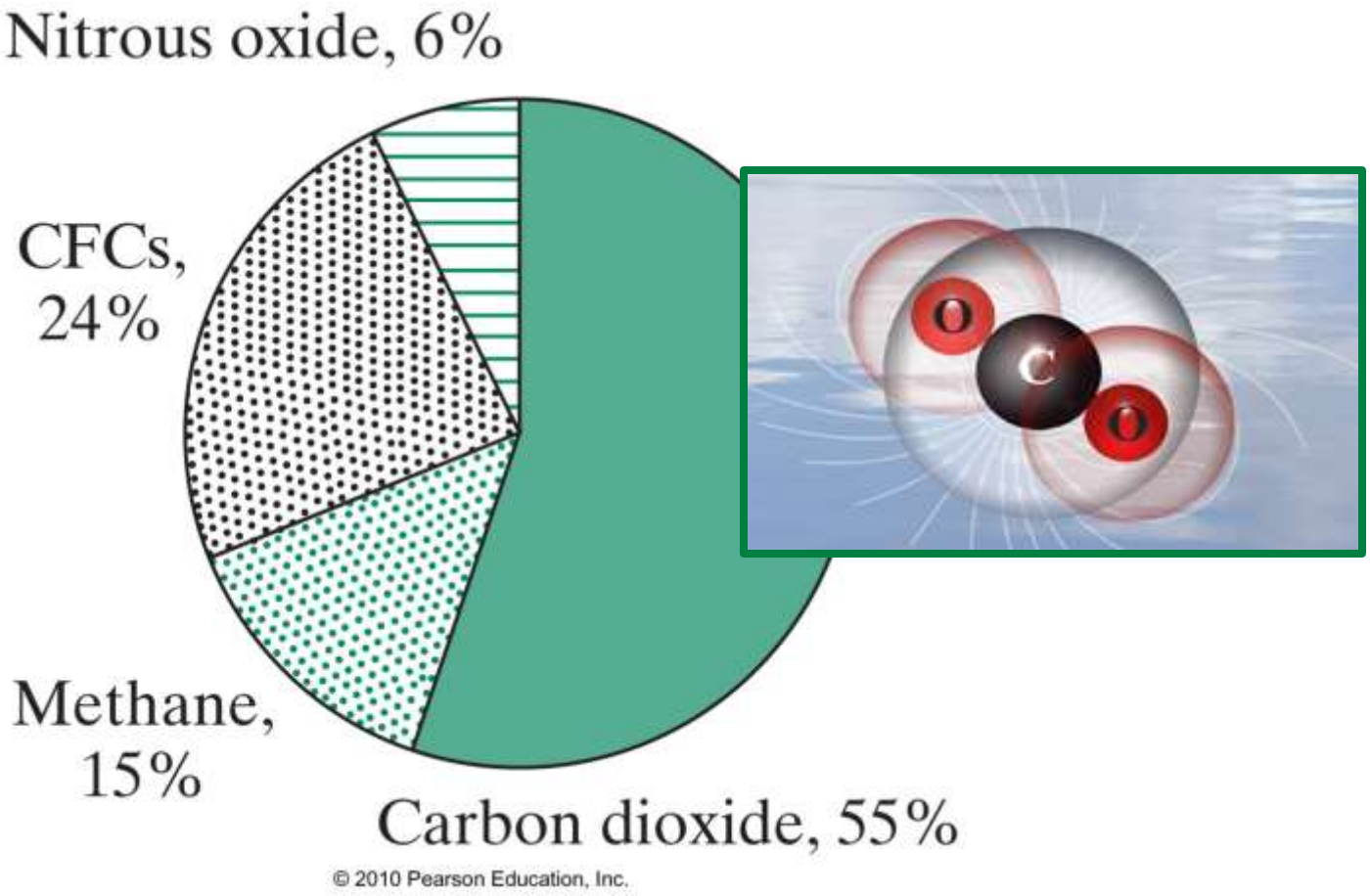
Naturally self-regulated

Increasing due to human activity

Greenhouse Gases



Percentages indicate contribution to global warming

Clicker

Which statement is *false*?

A) Increasing the greenhouse gases in the atmosphere of a planet tends to raise its temperature

B) The greenhouse effect is a natural phenomenon that has been going on for millions of years

C) The greenhouse effect is based on infrared light arriving from the sun, and leaving in the form of visible light

D) Water vapor is a greenhouse gas

E) Carbon dioxide is a greenhouse gas

Clicker

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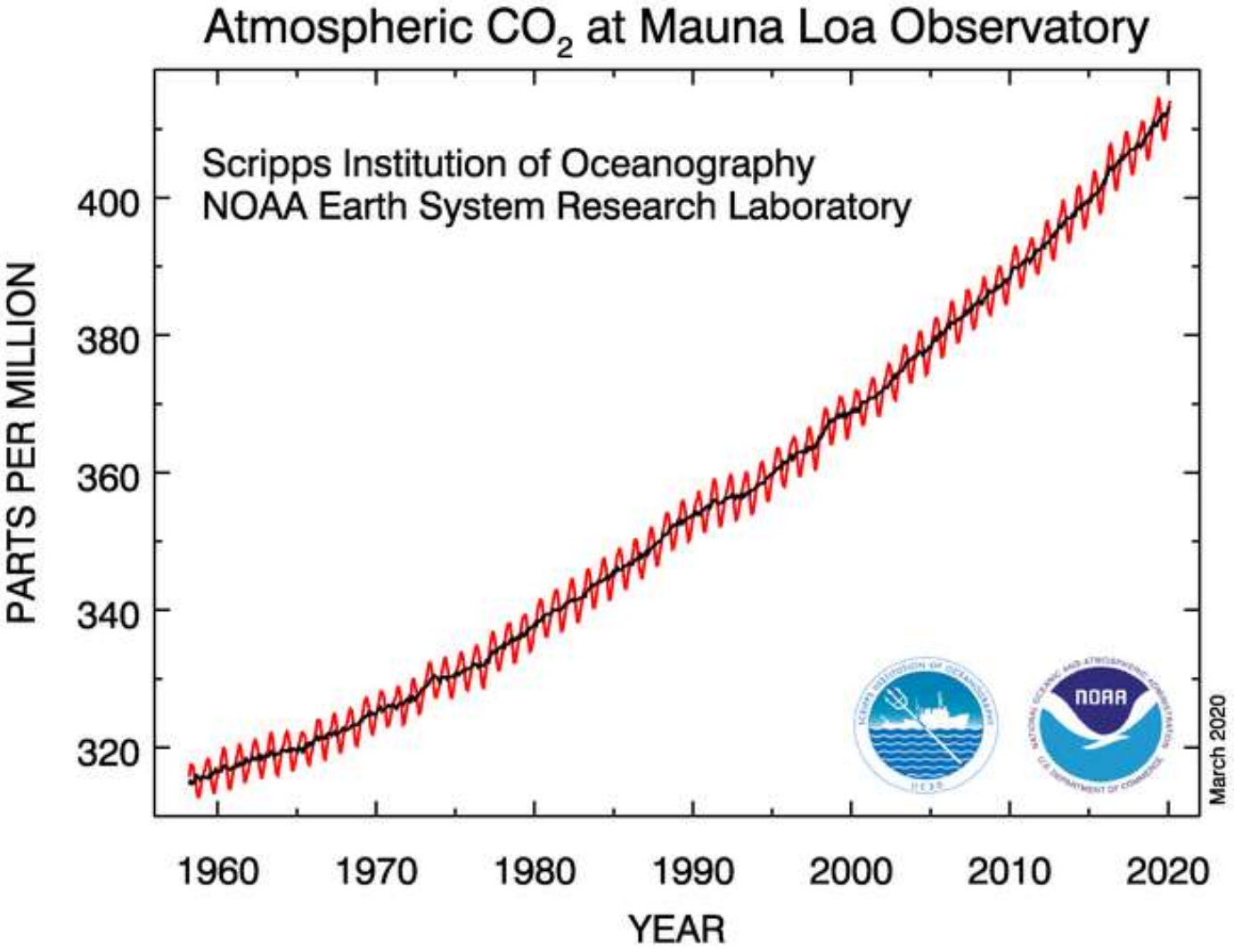
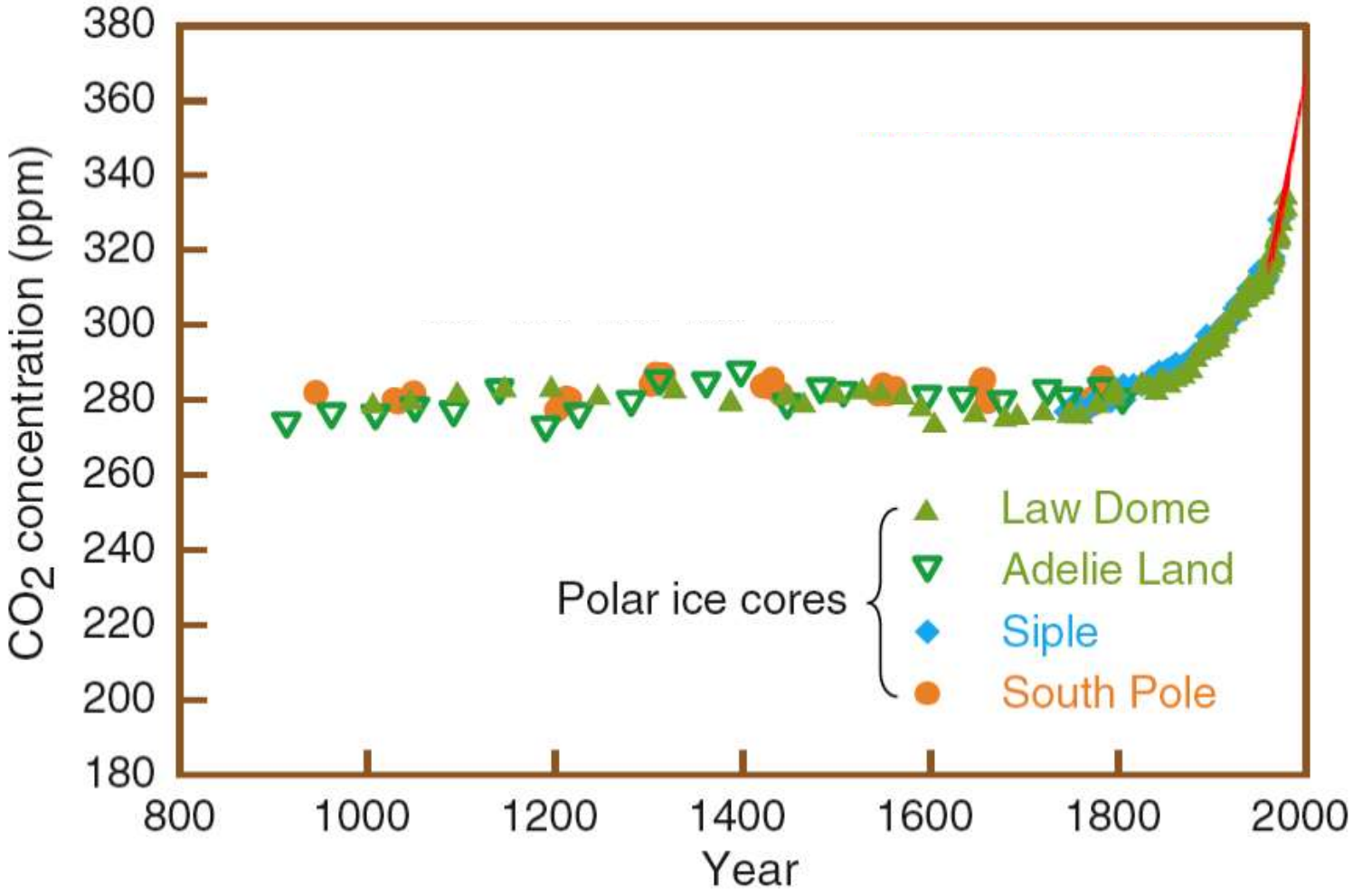


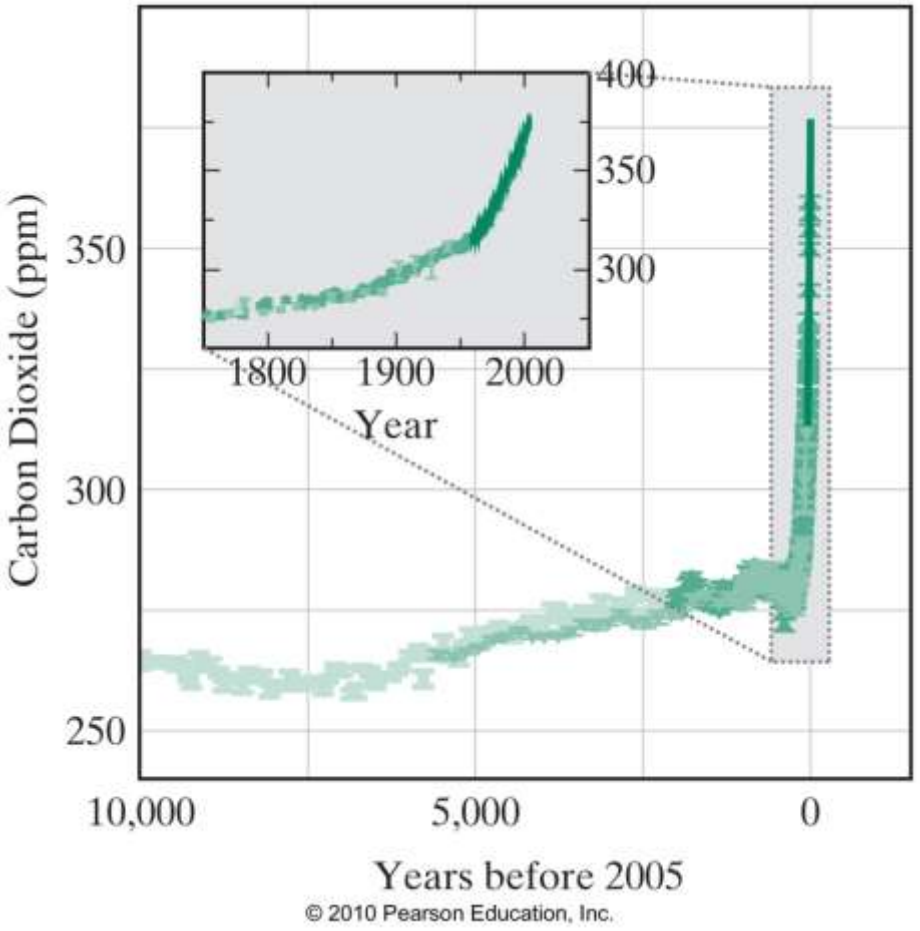
https://www.esrl.noaa.gov/gmd/ccgg/trends/

ATMOSPHERIC CARBON DIOXIDE IS INCREASING

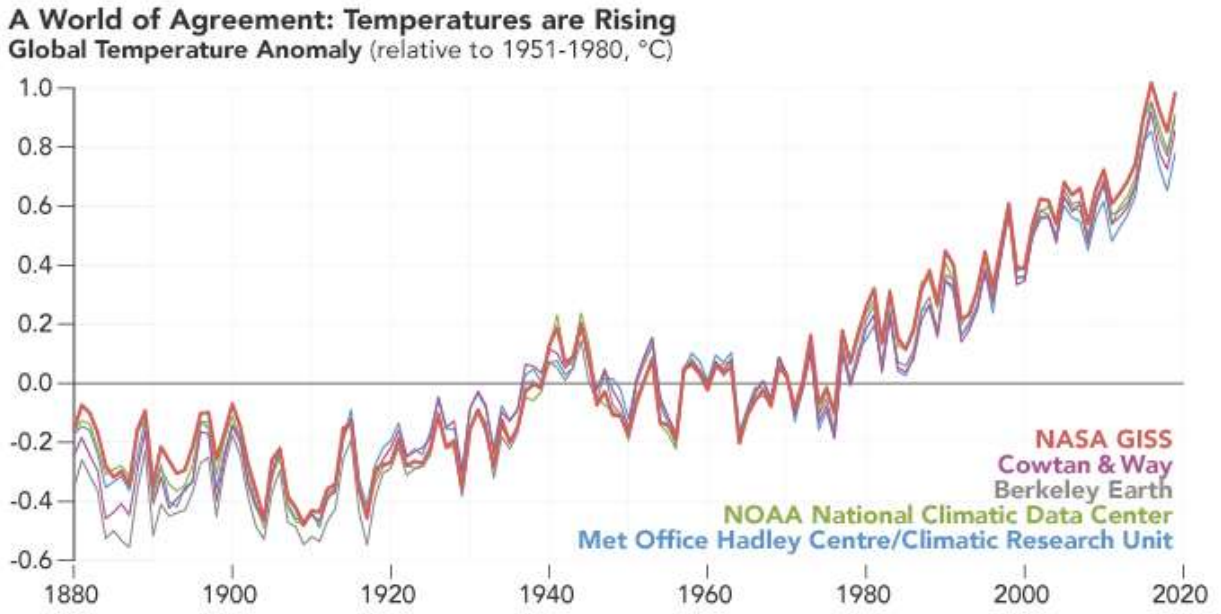


Atmospheric Carbon Dioxide is Increasing

The atmospheric concentration of carbon dioxide has increased dramatically since 1750, making the relationship between carbon dioxide and warming evident.

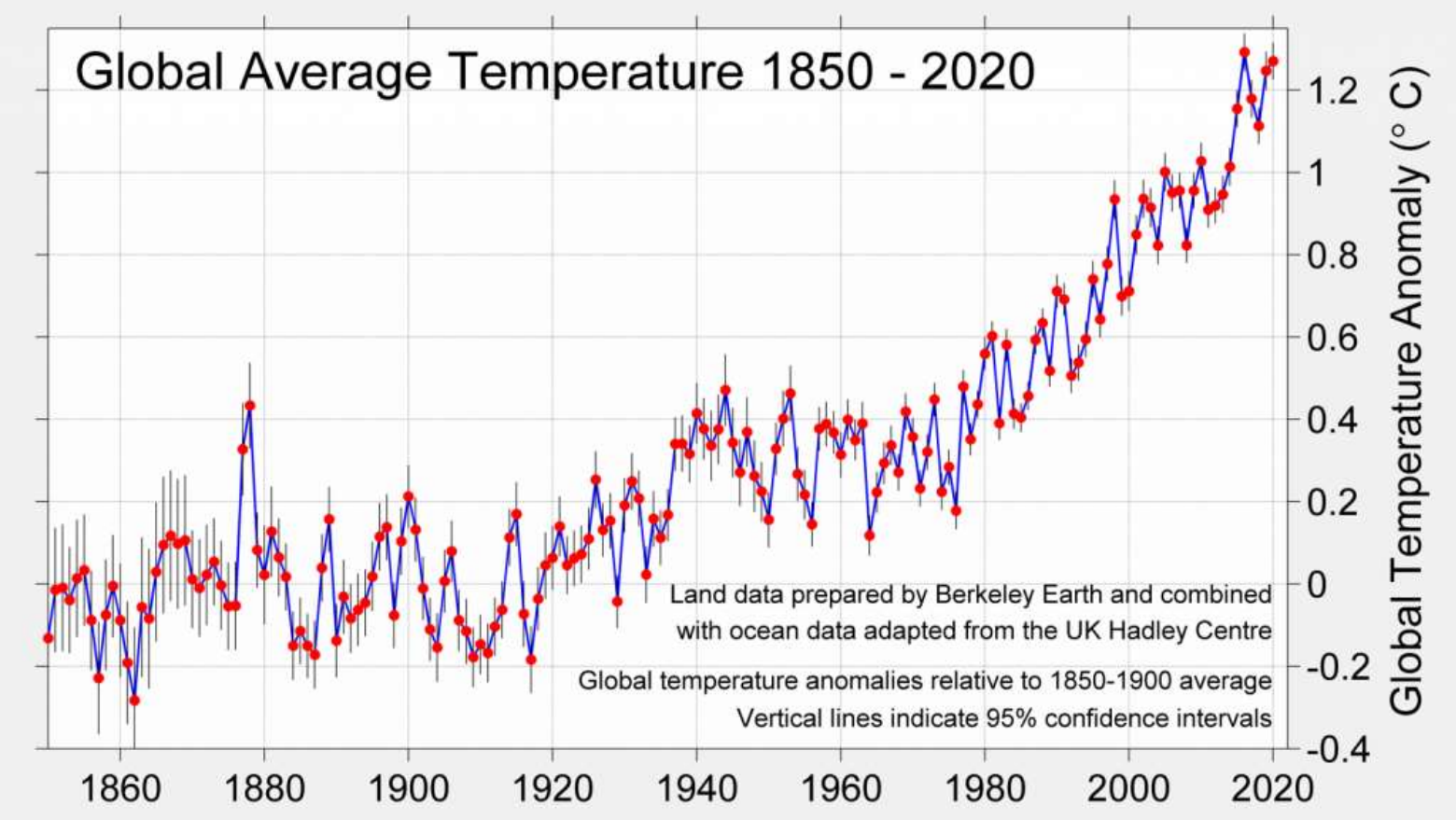


Average global temperature

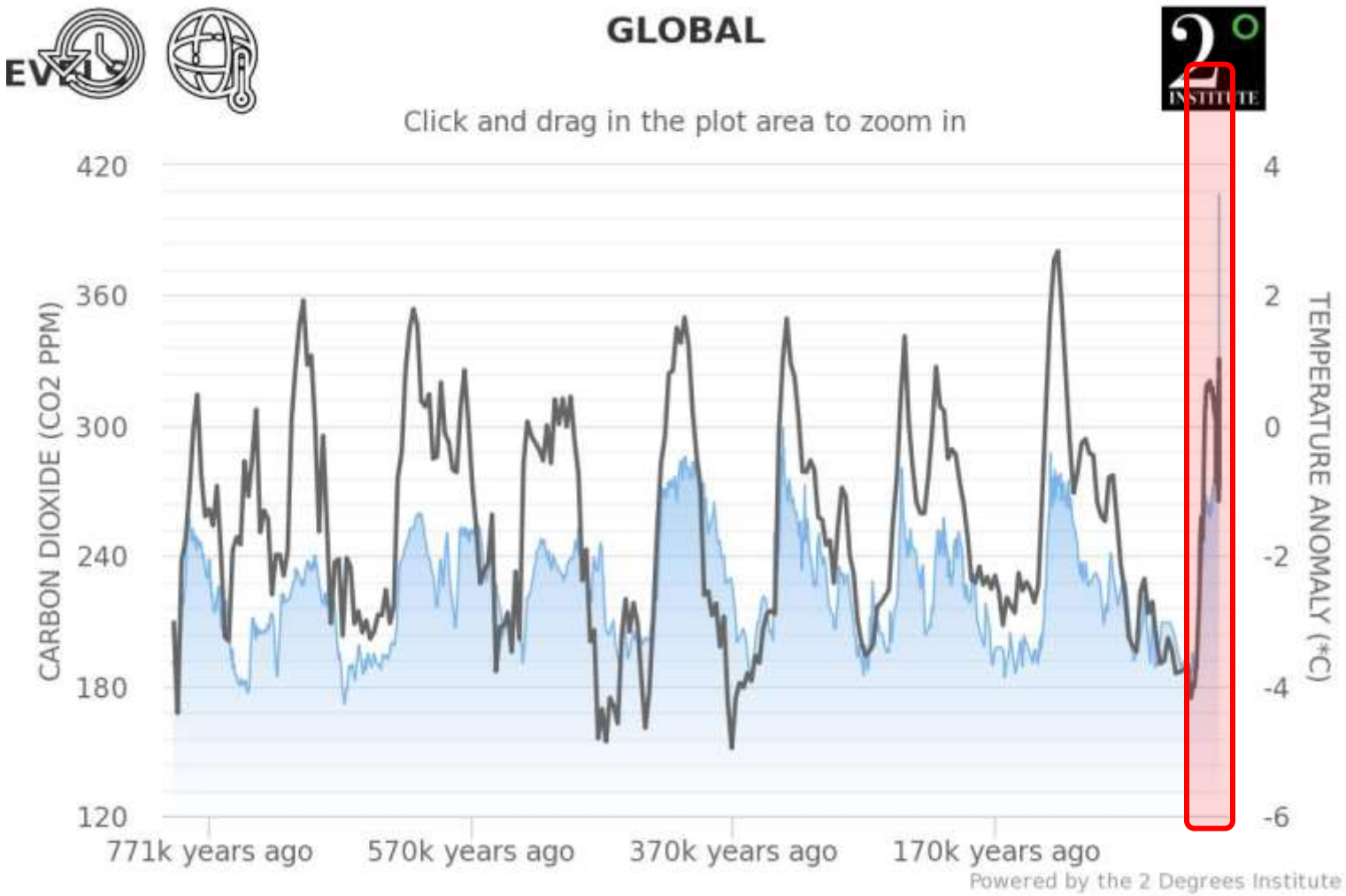


https://earthobservatory.nasa.gov/world-of-change/global-temperatures

Average global temperature



Including Data from Ice Cores



Civilized human history!

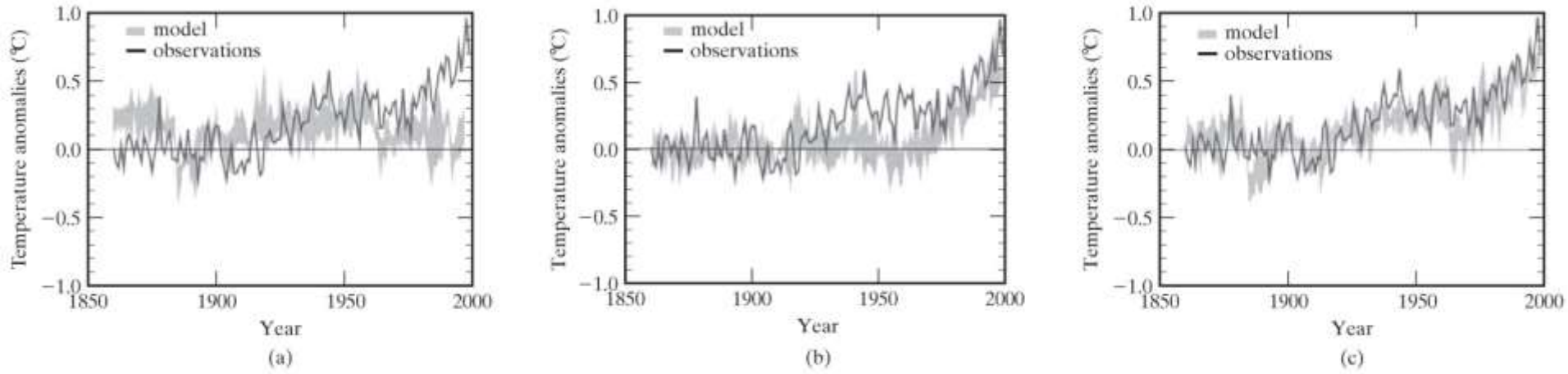
https://www.co2levels.org/

The big questions

- Is recent global temperature rise due to human CO_2 emissions?

  ("Is climate change caused by humans?")
- How much will future human CO_2 emissions increase global temperatures?
- What will be the consequences?
- What can we do about it?

We rely on computer models

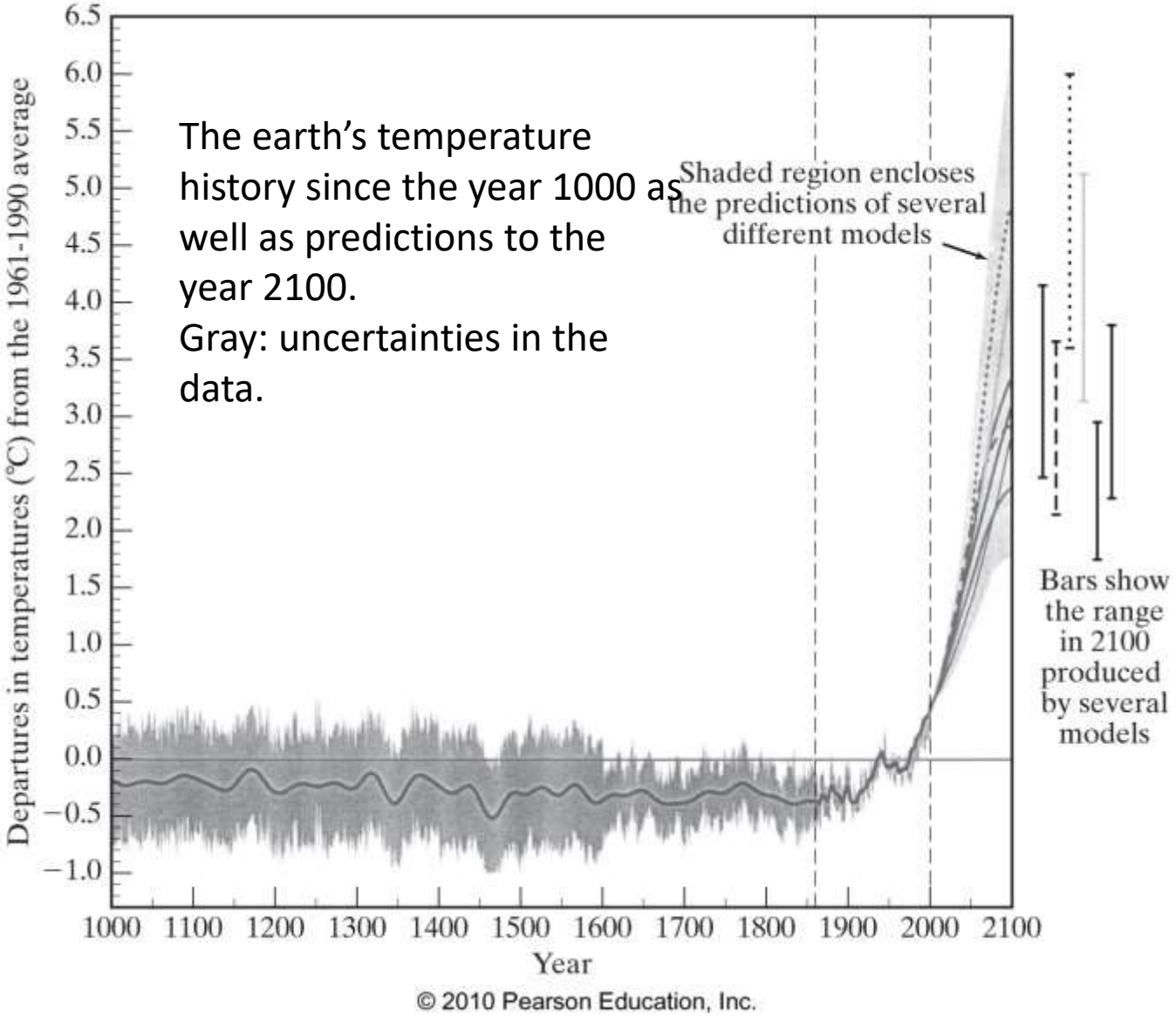


These graphs show climate model predictions (gray) compared to measurements (solid black).

Graph on the right shows the best-fit climate model with observed temperatures since 1860.

This best-fit model includes both natural and human sources of carbon dioxide.

Future temperature rise?

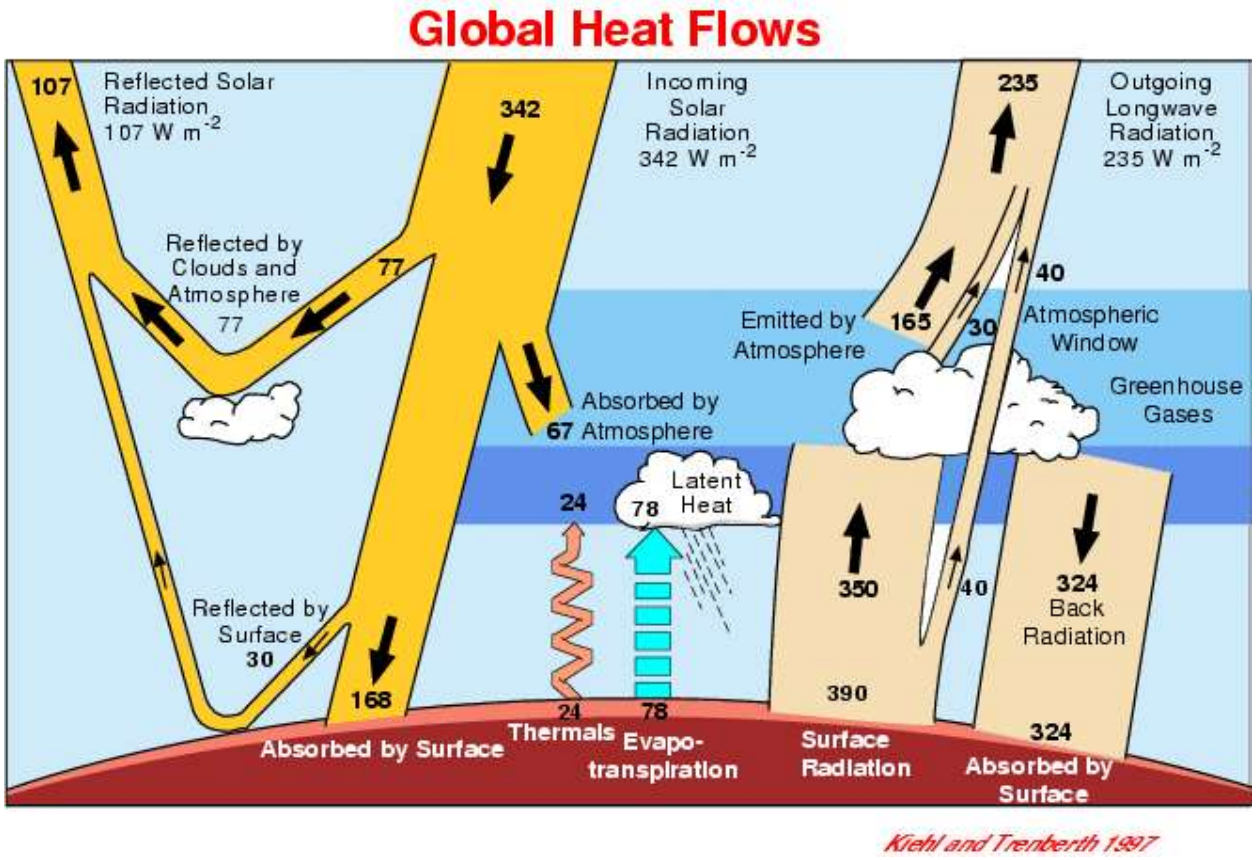


Future temperature rise?

Uncertainties:

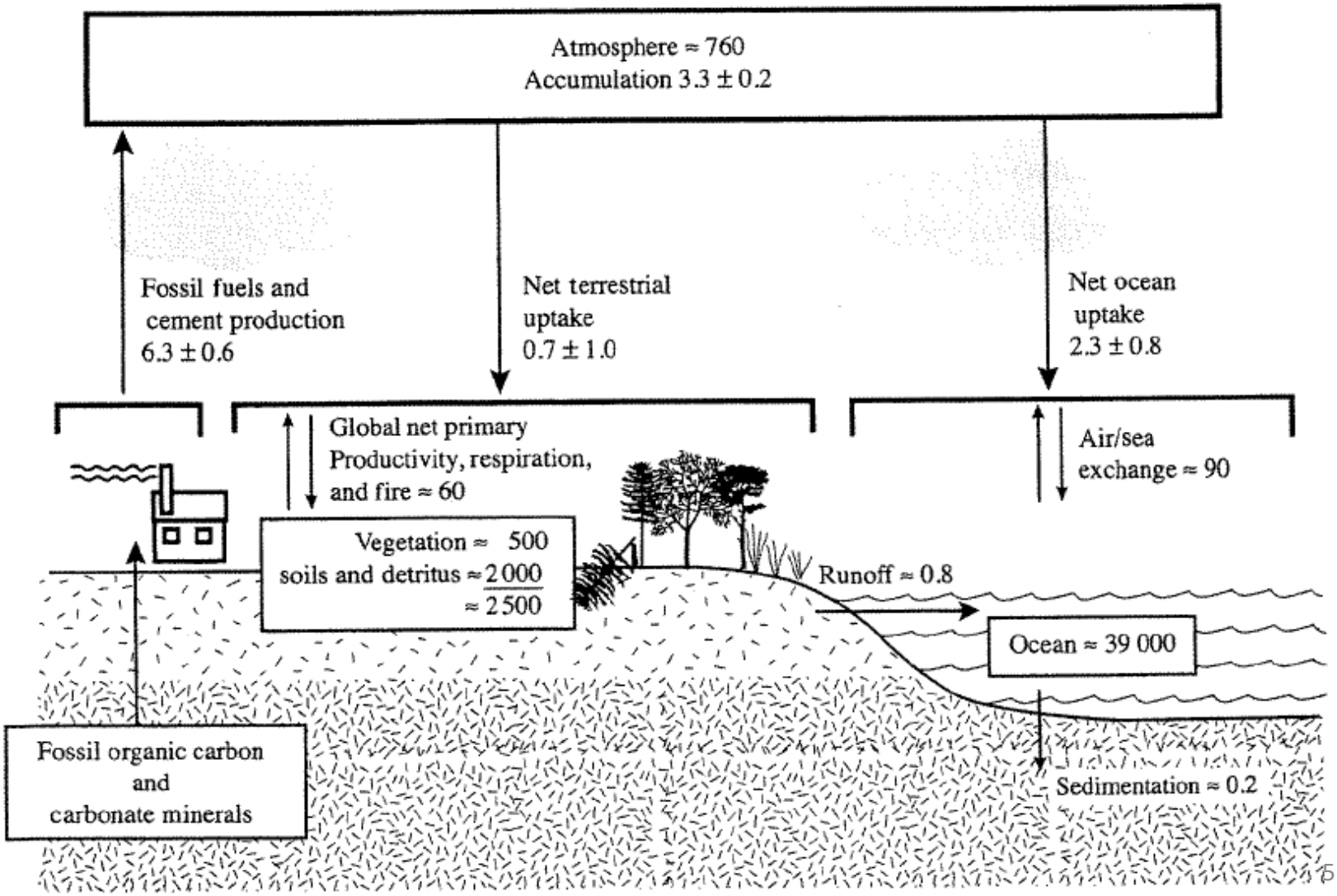
- Carbon cycle
- Cloud cover
- Climate models
- Ocean circulation

Cloud cover and the greenhouse effect



Clouds have both warming and cooling effects.
Clouds near the ground: Sun blocking dominates.
Clouds at high altitude: Greenhouse effect dominates.

Carbon cycle



The big questions

- Is recent global temperature rise due to human CO_2 emissions?

  Yes, with 95% confidence.

- How much will future human CO_2 emissions increase global temperatures?

  Unknown! Probably a lot…

- What will be the consequences?

  Many, some of them bad:

  Drought, crop failures

  Wildfires

  Floods

  Hurricanes

  Polar Ice Cap Melting

  Sea Level Rise

  Some might also be beneficial, but hard to predict.

- What can we do about it?

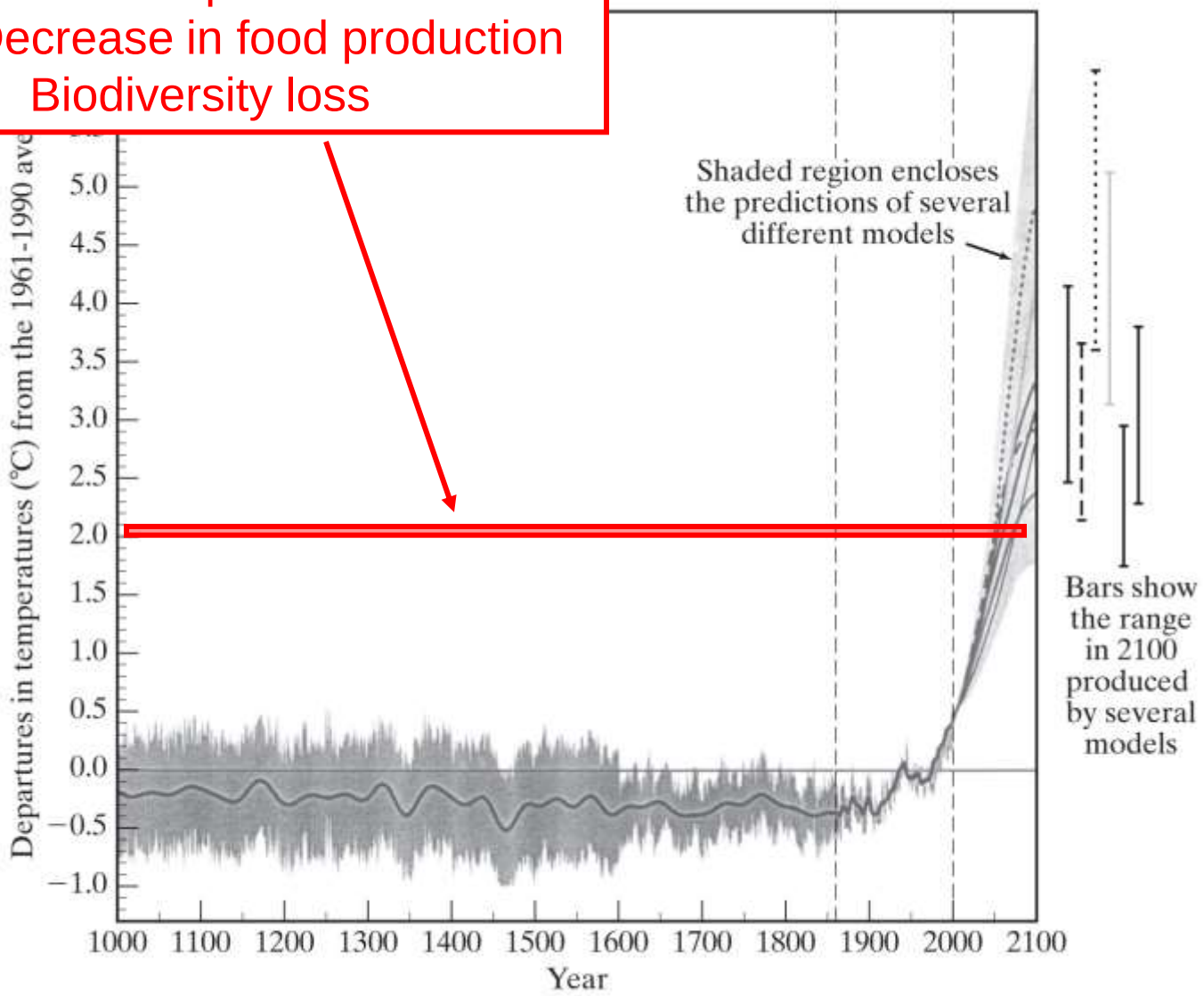
  A lot, if we decide to get serious!

Consequences?

- Changing local climates?
- Collapse of permafrost (Alaska)?
- More severe weather? Hurricanes?
- Melting glaciers (Greenland, Antarctica)?
- Disappearing arctic ice caps?
- Extinction of polar bears, other species?
- Rising sea levels?
- Flooded cities, coastal plains?
- Human costs: dislocations, war, famine…?

Consequences?

Above this line: Expect sea level rise
Shift / Decrease in food production
Biodiversity loss



How do we fix it?

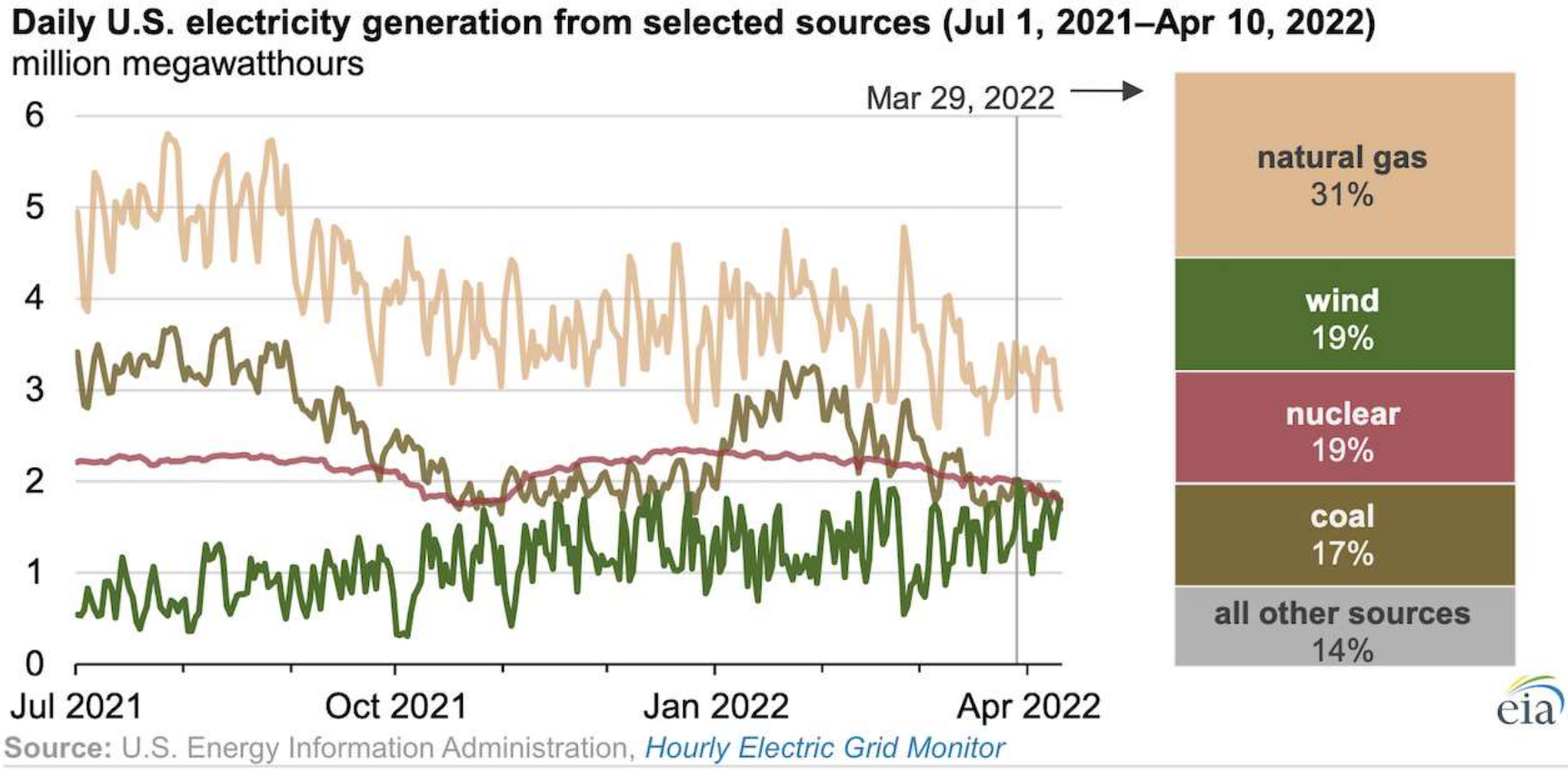
Everybody has a favorite answer!

- Solar power (**photovoltaics**, solar thermal)
- **Wind power**
- Hydroelectric power
- **Electric cars**
- **Grid battery storage**
- Geothermal energy
- Electric trains, ships, airplanes
- Nuclear power
- Tidal power
- ...

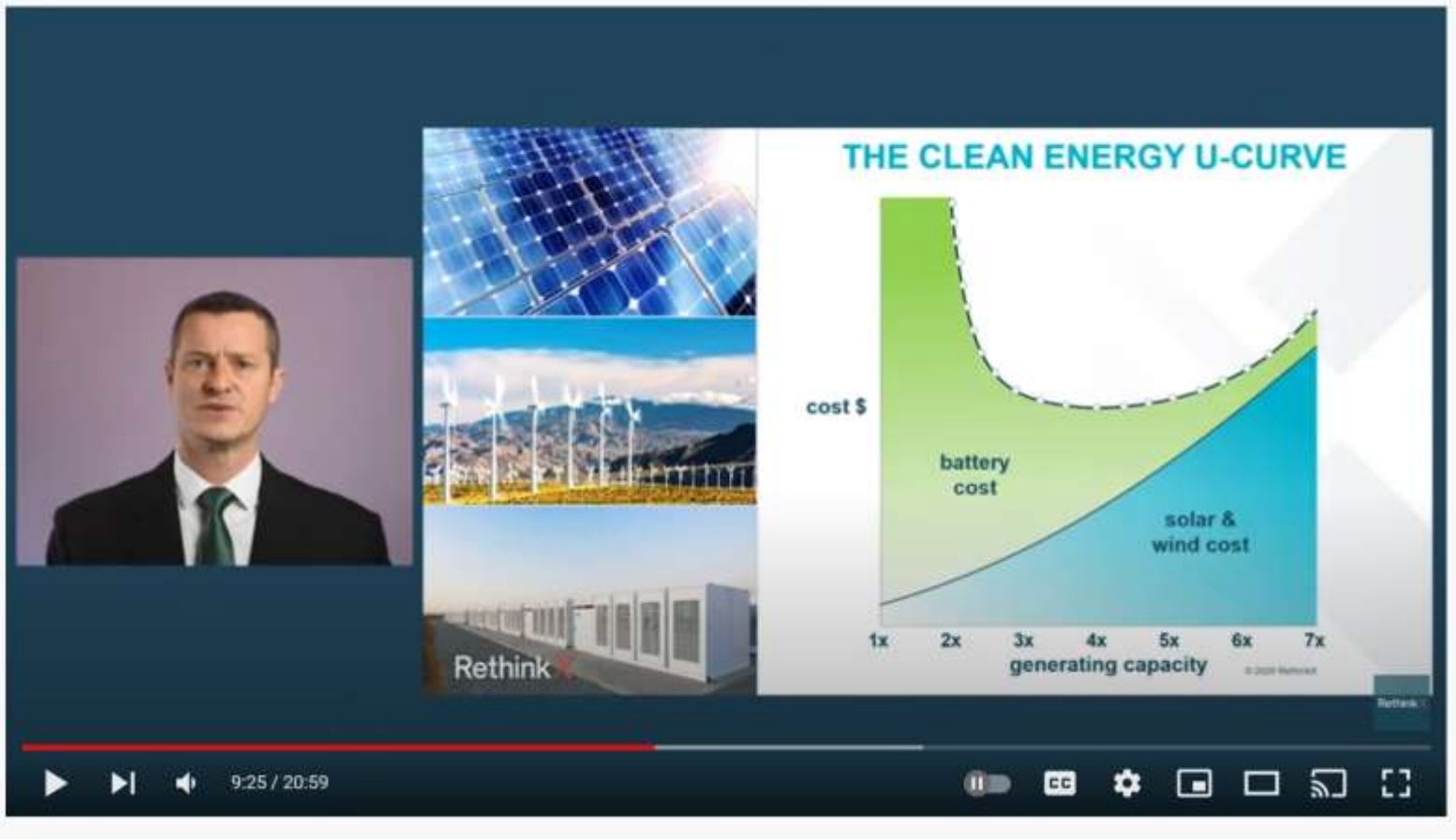
Benefits of Electric Cars

- No tailpipe emissions.
- Less pollution, reduced greenhouse gases.
- Much cheaper to fuel!
- Convenience: Charge at home, skip gas stations!
- Performance, handling, acceleration: fun to drive!
- Safety: large mass, low center of gravity, impact absorbing front “crumple zone” (no engine).
- Lower cost of ownership: Little maintenance required (few moving parts!)
- Much higher resale value!

US electricity generation



Solar, Wind + Battery Storage for Electricity



2:00 to 11:00