ASTR 380
Habitable Zone

"I've located the source of all that annoying spam we've been receiving...preparing to destroy."

ASTR 380
Habitable Zone

Summary of best chances for life in Solar System
What is meant by habitable?
What distances from the Sun could the Earth be and
still be habitable?
What can we learn from Earth's temperature
history, distant past and current?
Relevance of mass of planet
Relevance of mass of star
Relevance of age of star.

ASTR 380
Habitable Zone

The habitable zone around a star is the range of locations around a star where life based on liquid water could exist.

By this definition, the habitable zone is based on an Earth-like planet, Earth-like life and water.

We will stretch this a little by allowing for modest changes in the CO_2 content of the atmosphere.

Note the habitable zone is not the same as the human comfort zone…. Worlds with average temperatures of 1 C or 30 C, compared to our 14 C, are allowed.

Continuously Habitable Zone

- A refinement: as we will see, stars change their luminosity with time
- Therefore, a more restrictive requirement that has been suggested is that a planet must be in the habitable zone for its entire history, not just at one point
- Is this reasonable?

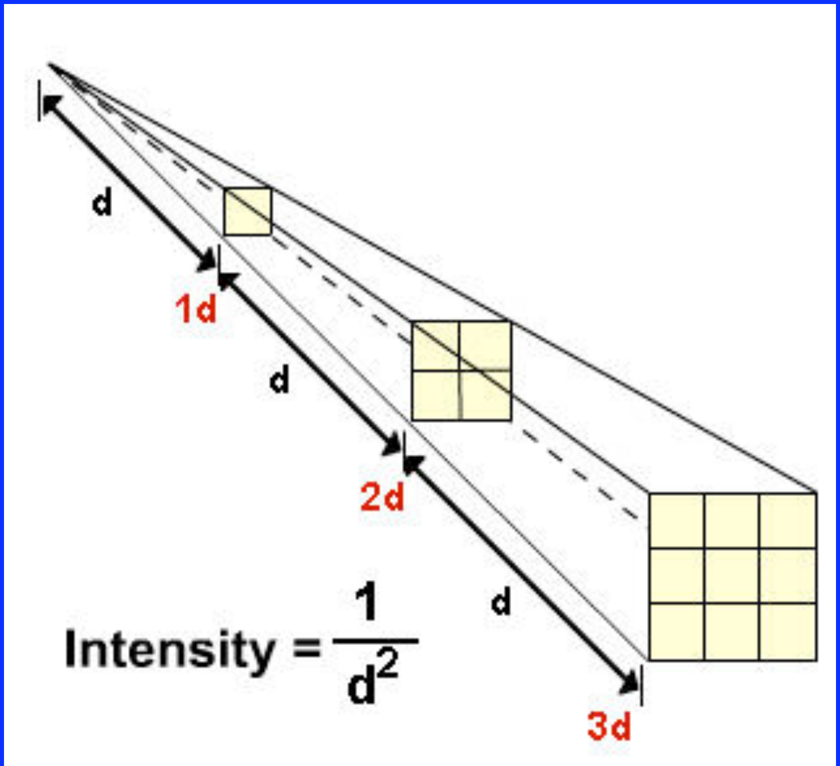
ASTR 380
Habitable Zone

The only planet in the habitable zone in the current Solar System is the Earth.

How much closer or farther from the Sun could the Earth be and still be habitable?

Background: Radiation Intensity

- The intensity of light diminishes like the inverse square of the distance from source
- Why? Same light, but spread over area that goes like the square of the distance from the source

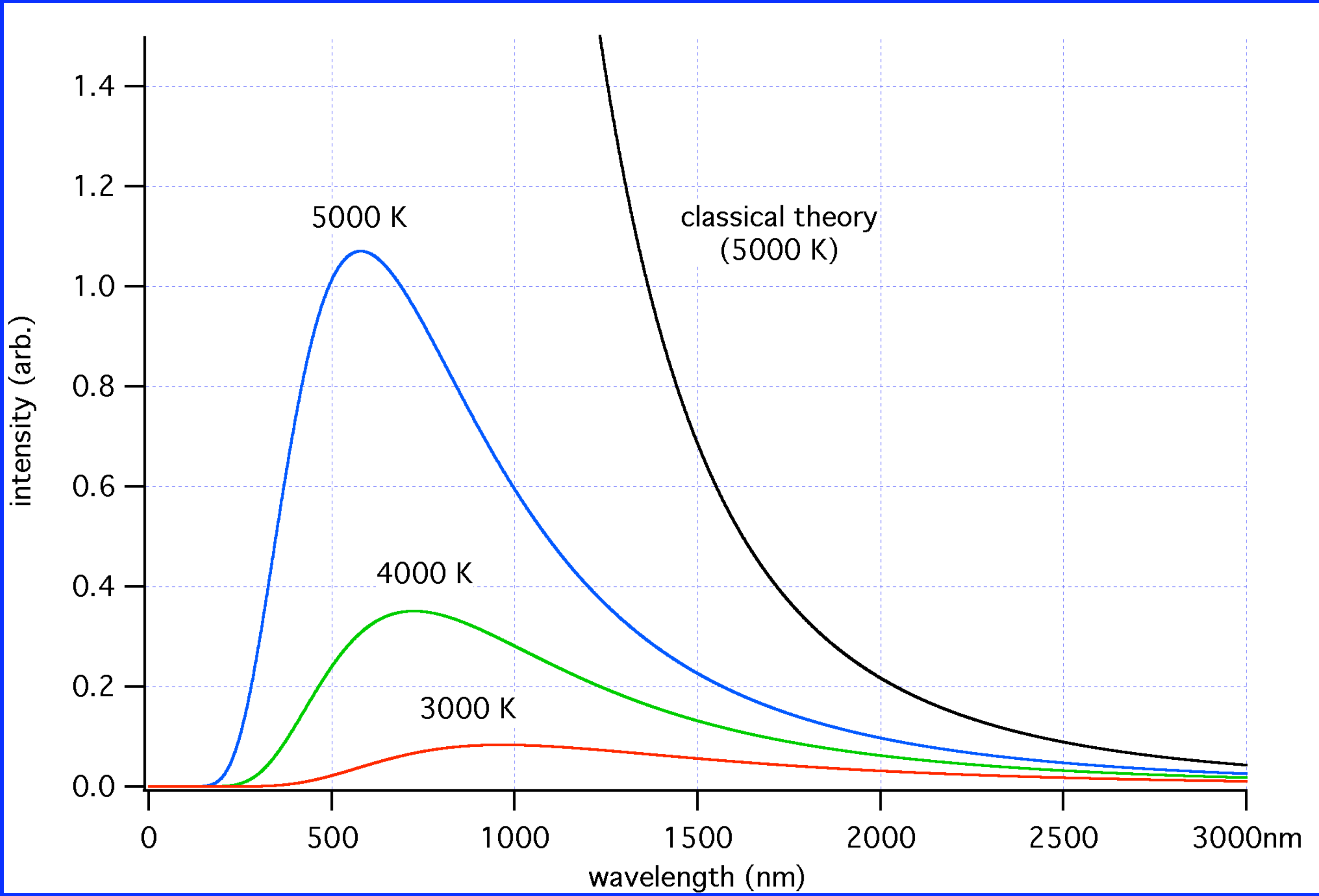


http://www.e-radiography.net/radtech/i/inverse%20square%20law.jpg

Examples of Intensity

- Mercury's average distance from Sun is 0.39 times Earth's
  Average intensity $1/(0.39)^2=6.6$ times Earth's
- Mars's average distance from Sun is 1.52 times Earth's
  Average intensity $1/(1.52)^2=0.43$ times Earth's
- But how does this translate into temperature?

Temperature vs. Intensity



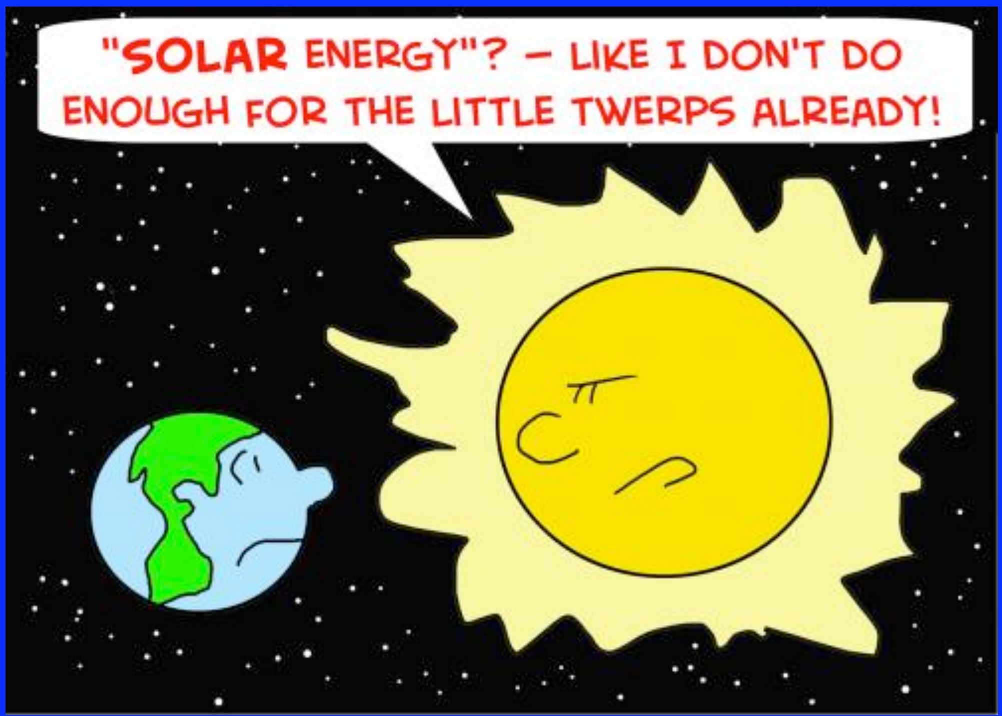
http://www.goiit.com/upload/2009/9/5/2669bfc0a49e880f2dabd261bca06506_1418968.png

Temperature vs. Intensity

- If all else is equal (which it isn't), the radiated luminosity is proportional to the temperature to the fourth power: $L \sim T^4$
- Therefore, if a planet radiates away all the energy it gets from its star, the temperature of the planet should scale as $T \sim L^{1/4}$
- Let's see how this works for Earth...

Calculation for the Earth

- Putting in the right numbers, we predict an average surface temperature of 281 K
- Real value: 287 K. Pretty close; is this the right track?

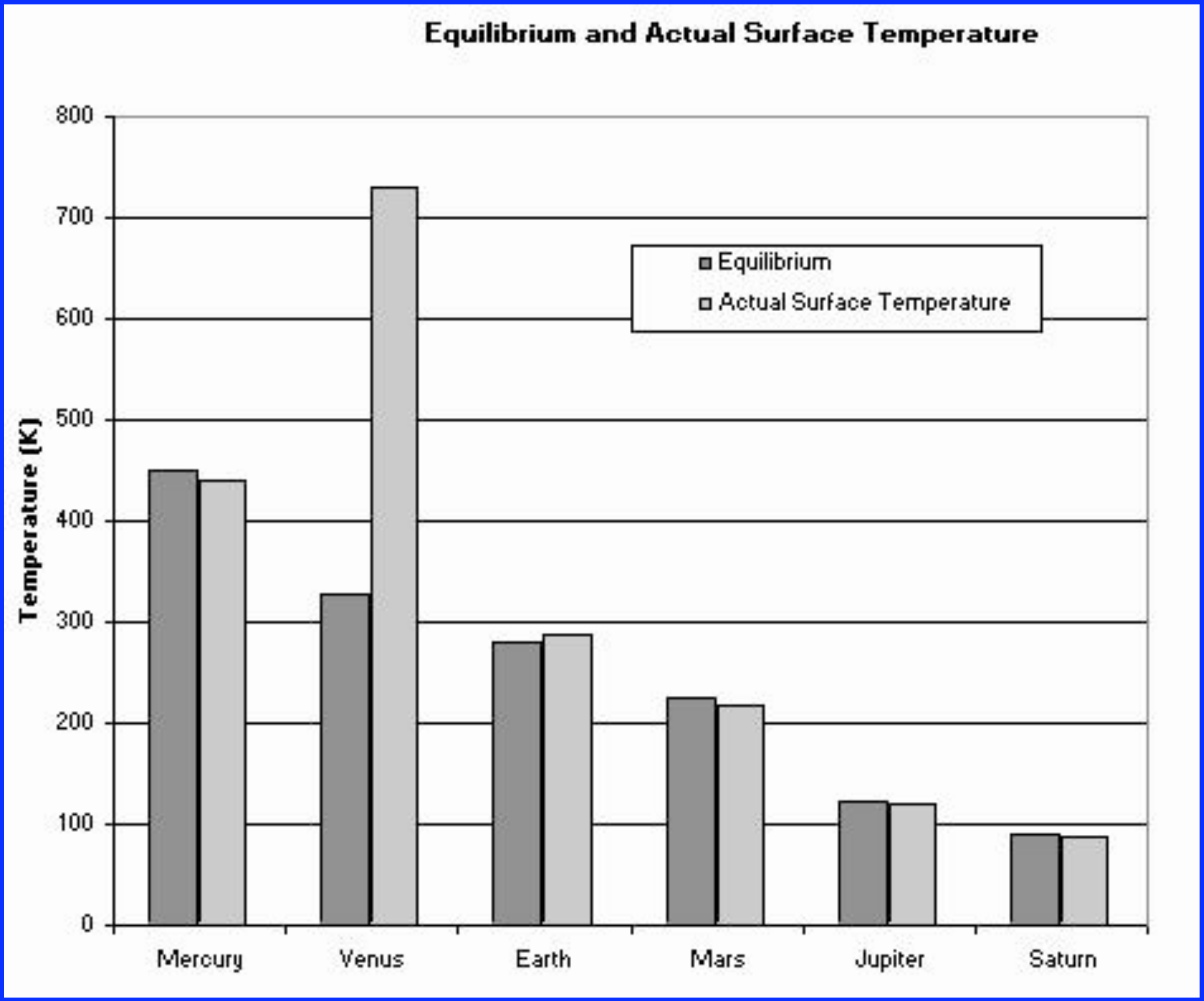


http://www.toonpool.com/user/997/files/solar_energy_earth_sun_twerps_234435.jpg

Combining Distance, Temperature

- Recall that the luminosity absorbed by a planet scales as $1/d^2$ (d is the distance)
- The luminosity radiated scales as T^4, if the planet absorbs all the luminosity
- Thus $T^4 \sim 1/d^2$, or $T \sim 1/d^{1/2}$, i.e., $T \sim d^{-1/2}$
- How does this prediction compare with what we see?

Predicted vs. Actual Temperature



http://physics.lakeheadu.ca/courses/Astro/2310/PlanetGraphs/temp.jpg

How Did We Do?

- Pretty well, right, except for Venus?
- Yes, but there are two effects that we have not yet included that can play a major role
- What are they?

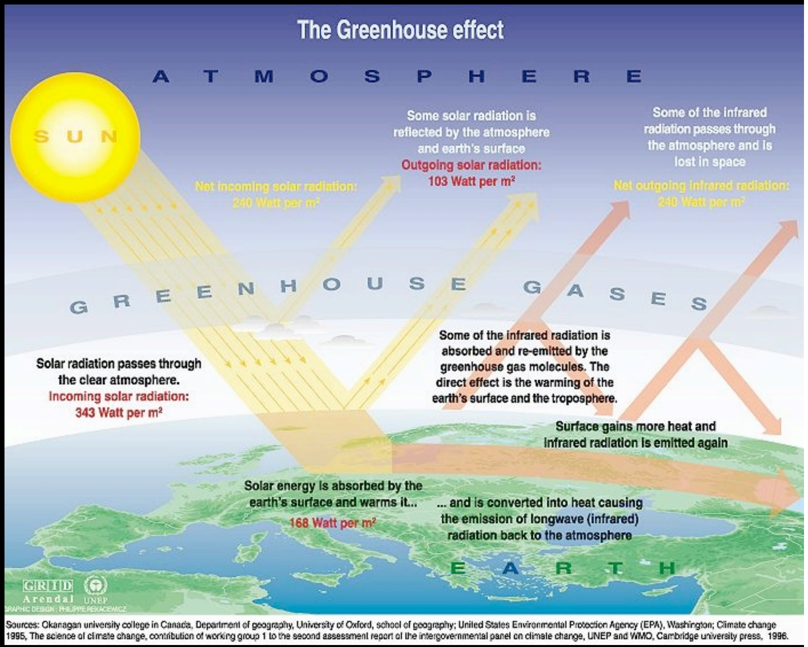
How Did We Do?

- Pretty well, right, except for Venus?
- Yes, but there are two effects that we have not yet included that can play a major role
- What are they?
  Albedo: planets can reflect some fraction of radiation back into space without absorbing
  Greenhouse effect: atmosphere can trap radiation, heating further (Venus!!)

ASTR 380
Habitable Zone

The inner boundary for the Earth is set by overheating.

As you move the Earth inward…
-- it receives more solar energy
-- which increases the temperature
-- which increases water vapor
-- which is a greenhouse gas
-- which traps the heat
-- which increases the temperature



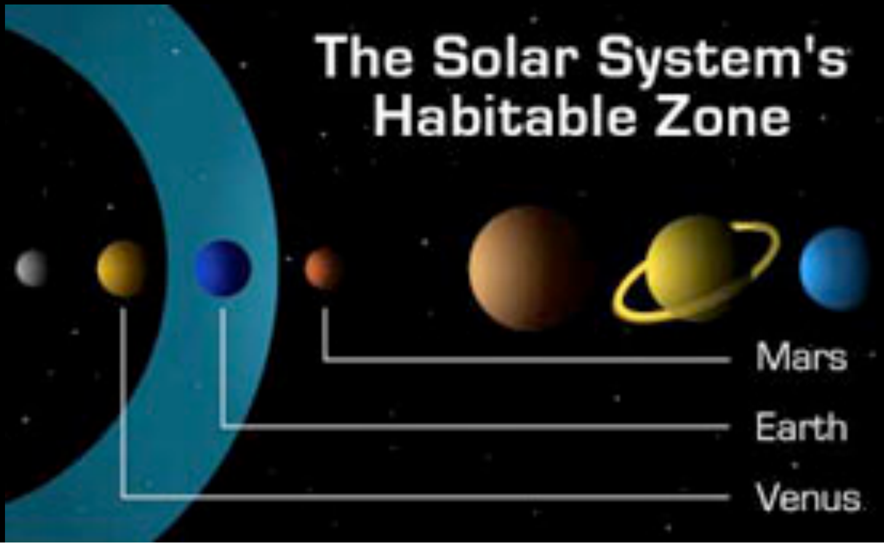
A positive feedback loop which pushes the temperature up and up

ASTR 380
Habitable Zone

The inner boundary for the Earth is set by overheating.

The most liberal estimate allows the Earth to be as close as 0.84 AU.

The more conservative estimate allows the Earth to only be as close as 0.95 AU.



ASTR 380
Habitable Zone

The inner boundary for the Earth might also be set
by the early CO_2 rich atmosphere of the Earth…

If the Earth was too close at that time, perhaps liquid water would never have formed, so the CO_2 in the atmosphere would never have been locked into rocks.

The inner boundary for this is likely around 0.9 AU.

ASTR 380
Habitable Zone

The outer boundary for the Earth is set by the need to keep the temperature high enough for liquid water.

The temperature of a planet is set by the balance between the energy received from the Sun and the energy emitted by the planet by virtue of being warm.

Energy in = Energy out

"Energy in" decreases with distance squared from the Sun

"Energy out" decreases as planet temperature to the fourth power -- roughly.

ASTR 380
Habitable Zone

The outer boundary for the Earth is set by the need to keep the temperature high enough for liquid water.
Freezing temp: 273 K

Current global average temperature = 14 C = 287 K

Distance from Sun	Solar energy	Temperature
1 AU	100 %	287
1.05 AU	90.6%	280
1.1 AU	83%	274
1.15 AU	75%	267

Clearly there is a problem with freezing by 1.15 AU

Albedo

- Also note that the temperature depends on the reflectivity, or albedo, of Earth
- Ice reflects most light, so lots of ice means colder temperatures
- One might think this would result in a runaway (Snowball Earth), but Earth also has internal heat sources

Albedo

- Values for planets run from 0.11 (Mercury; only 11% of light is reflected back) to 0.65 for Venus (65% of light reflected back)
- If albedo is α, equilibrium temperature should scale as $(1-\alpha)^{1/4}$
- Over 0.11 to 0.65 range, would imply a range of 20% in temperature; big! Equivalent of factor of 1.6 in distance

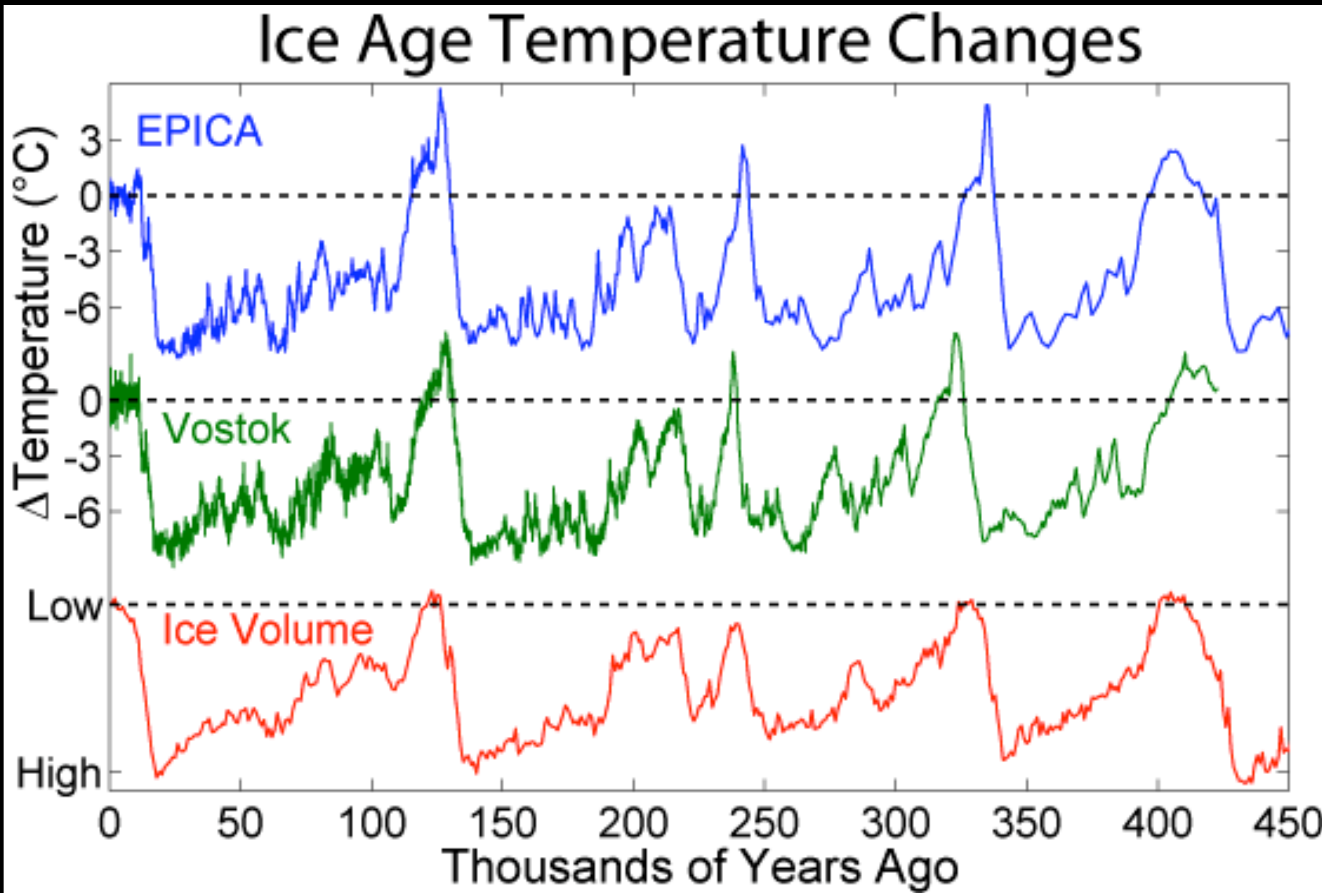
ASTR 380
Habitable Zone

But this really underestimates the problem for precisely Earth-like conditions… because it does not account for changes in the Earth in response to the temperature.

Fortunately the Earth's historical record provides evidence of how our planet reacts to global changes…. And we are doing more experiments today with CO_2 emission!

We can estimate global temperature in the distant past from geological records, measurements of ^{18}O content in sediments, and other chemical tracers.

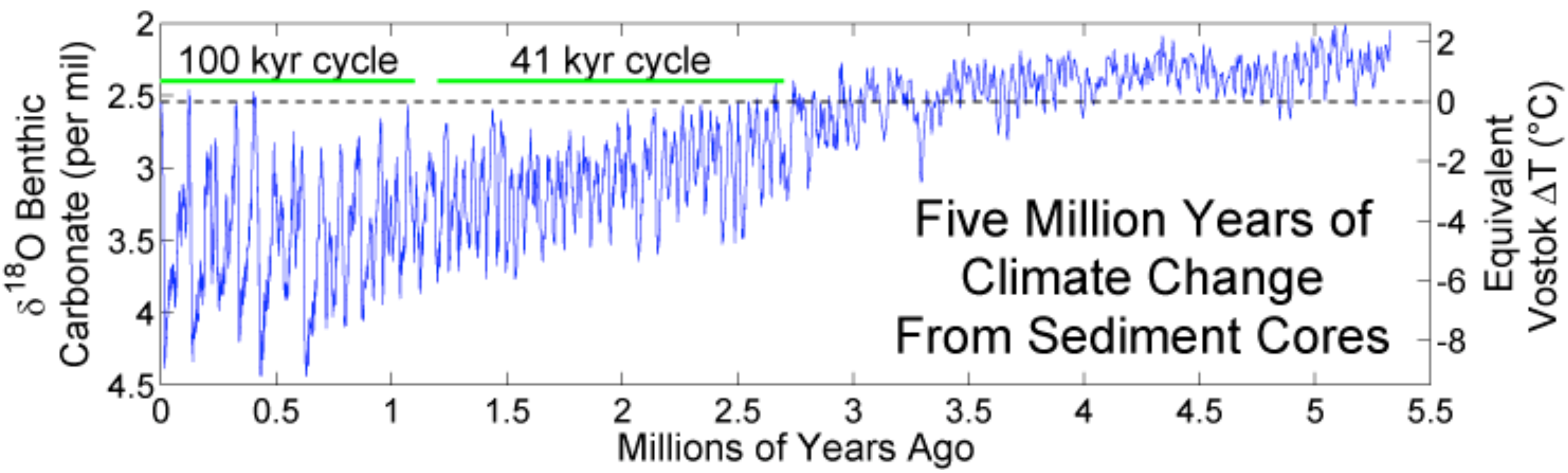
ASTR 380
Habitable Zone



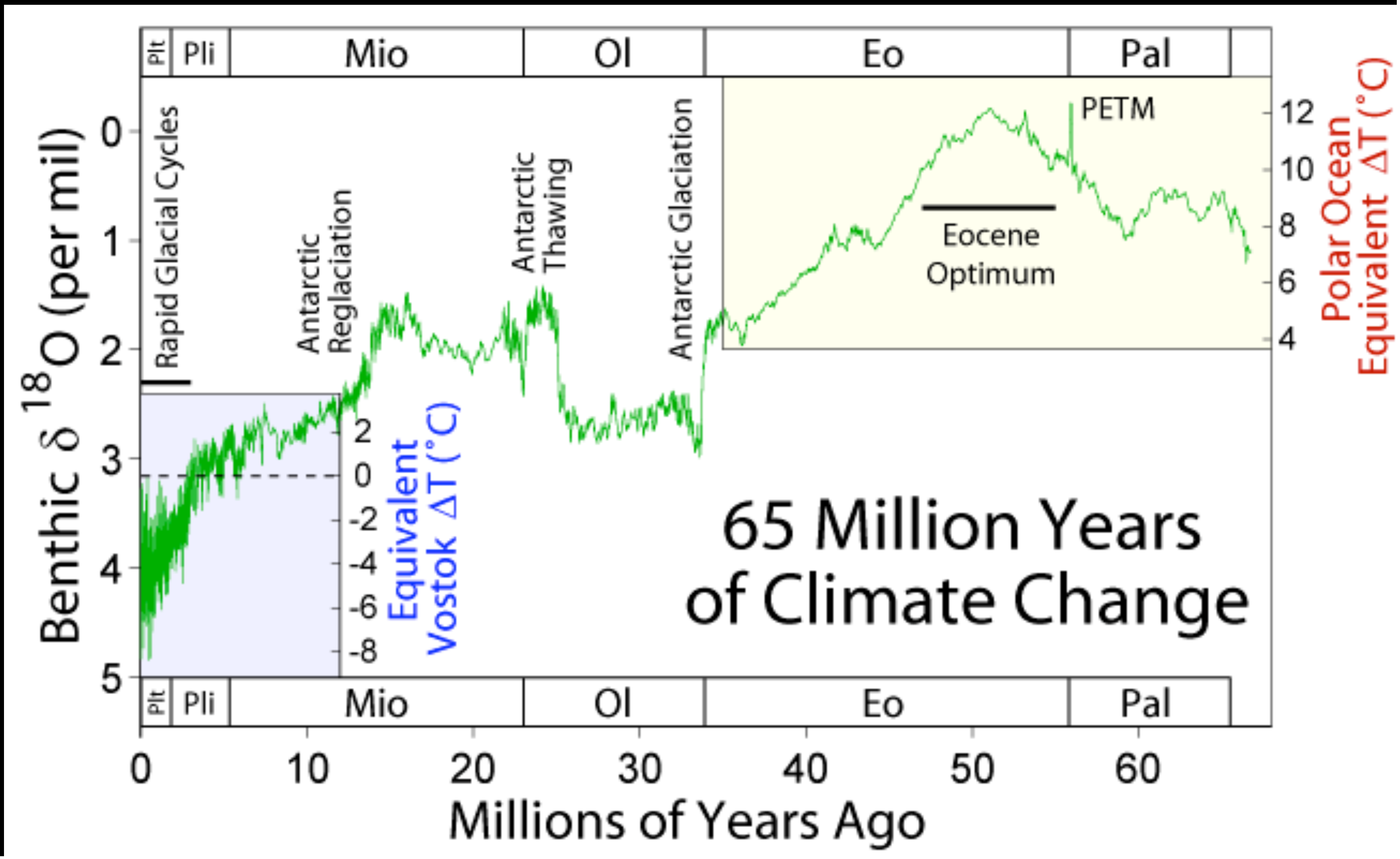
ASTR 380
Habitable Zone

Artic and Antarctic ice cores provide valuable records of the atmospheric composition and average temperature over several 100,000 years.

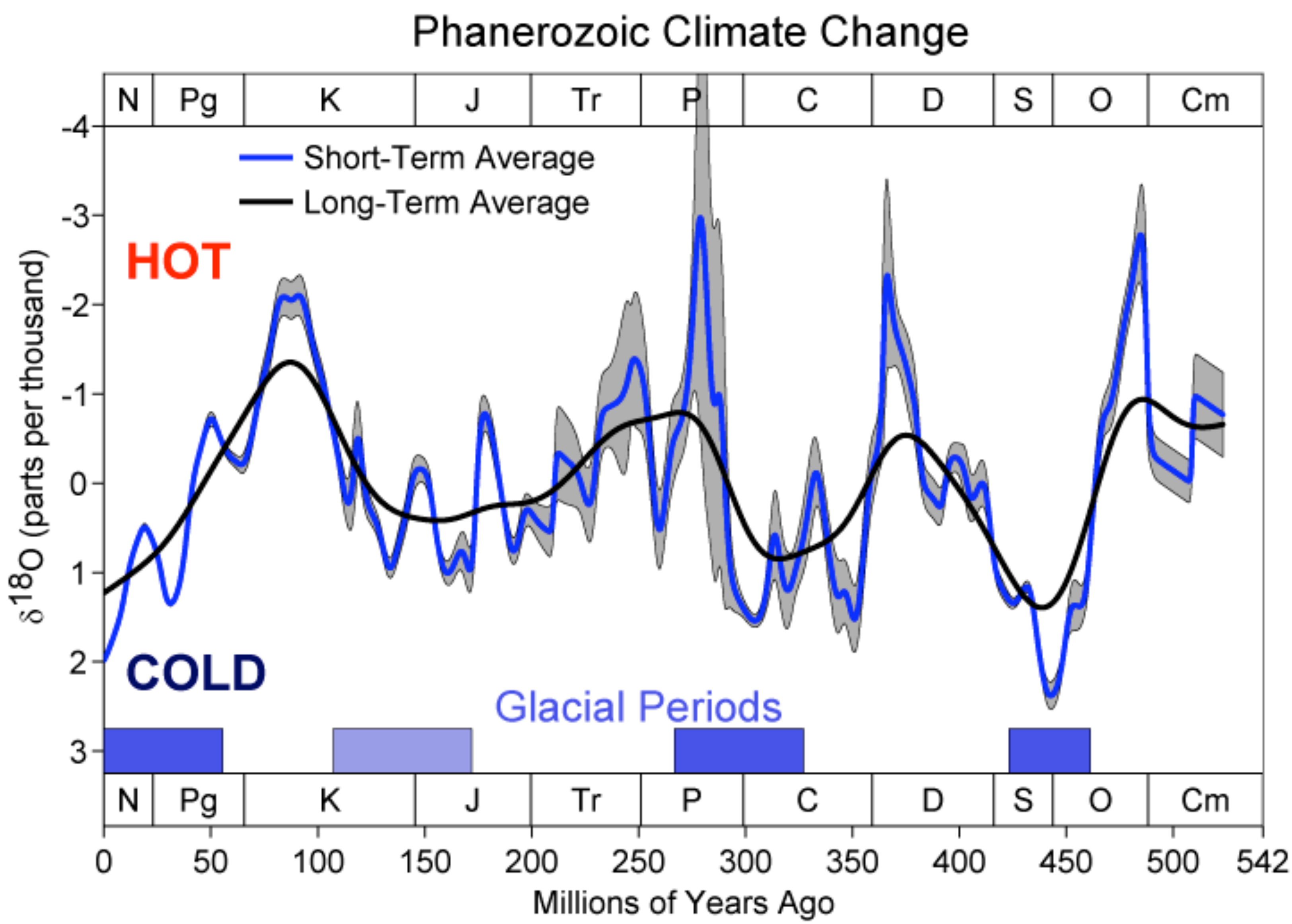
Sediments can stretch back millions of years.



ASTR 380
Habitable Zone

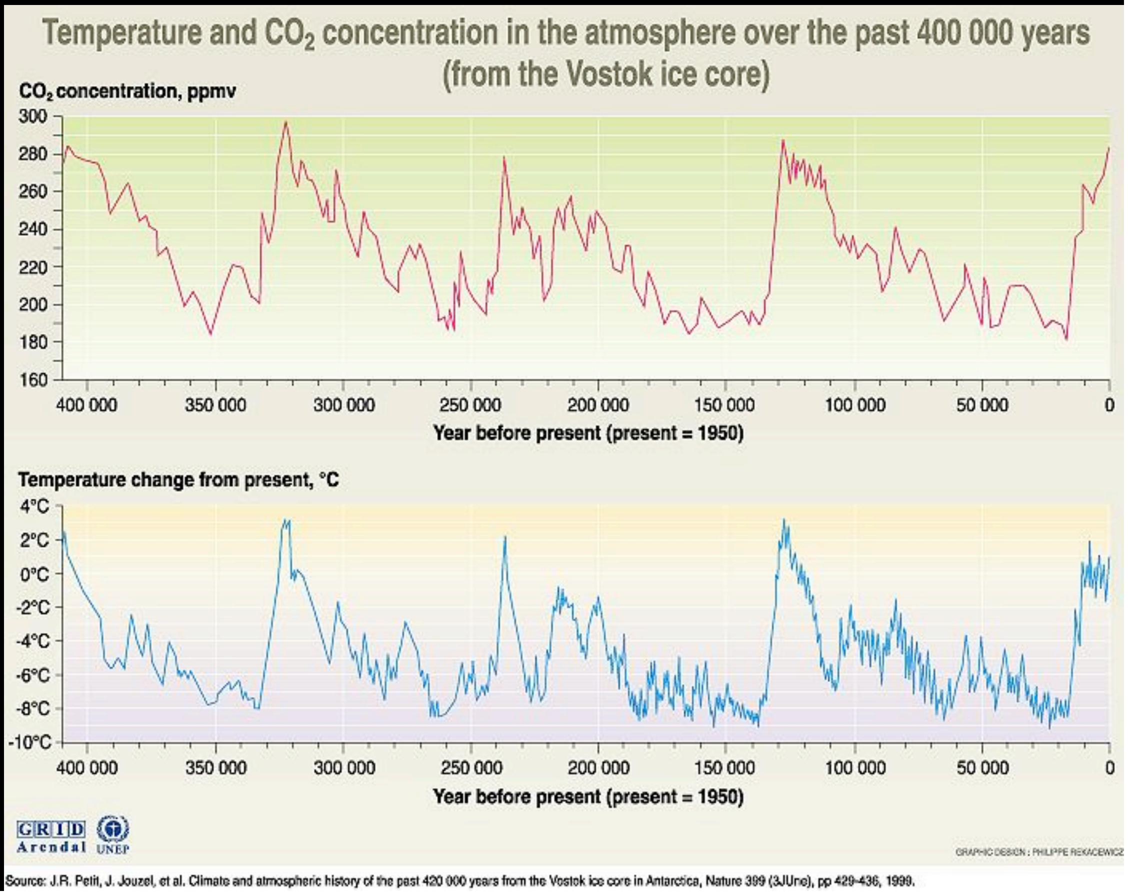


ASTR 380
Habitable Zone



ASTR 380
Habitable Zone

The actual temperature of the Earth depends on:
- -- CO_2 content of atmosphere
- -- ice coverage
- -- continental location
- -- ocean currents
- -- Sun's brightness



ASTR 380
Habitable Zone

There is a global feedback loop that acts on geological timescales.

Too hot?

-- more rain means more CO_2 locked into rock

-- decreases greenhouse effect

Too cold?

-- more ice cover kills plants and decreases rain

-- natural CO_2 from volcanoes not removed

-- increased greenhouse effect

But these regulating mechanisms act on 100,000 year timescales and only within limits.

ASTR 380
Habitable Zone

Runaway greenhouse:

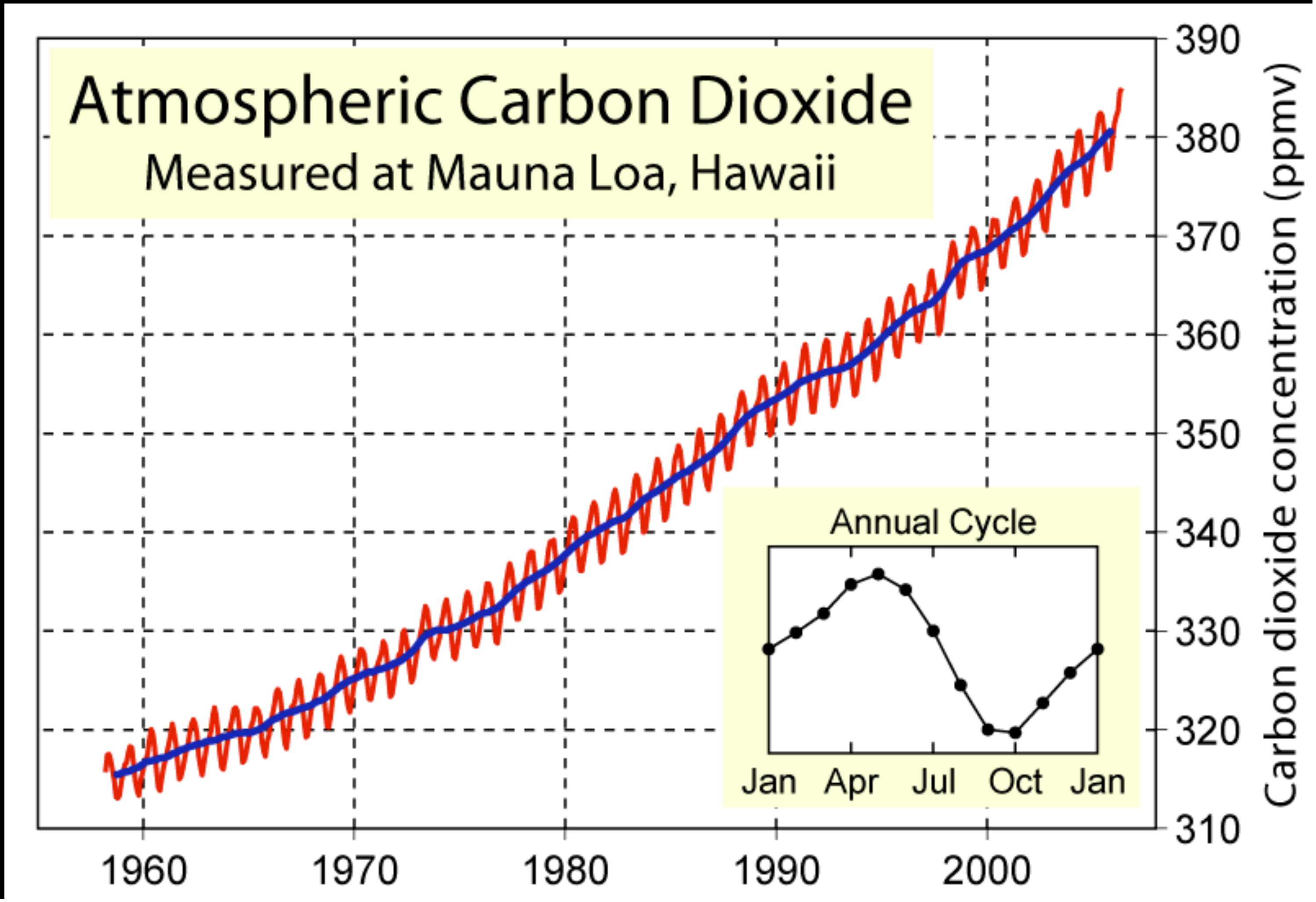
-- too much CO_2 or increase solar energy
-- temperature increases increasing water vapor
-- more greenhouse effect
-- higher temperature and more greenhouse effect

Runaway snowball

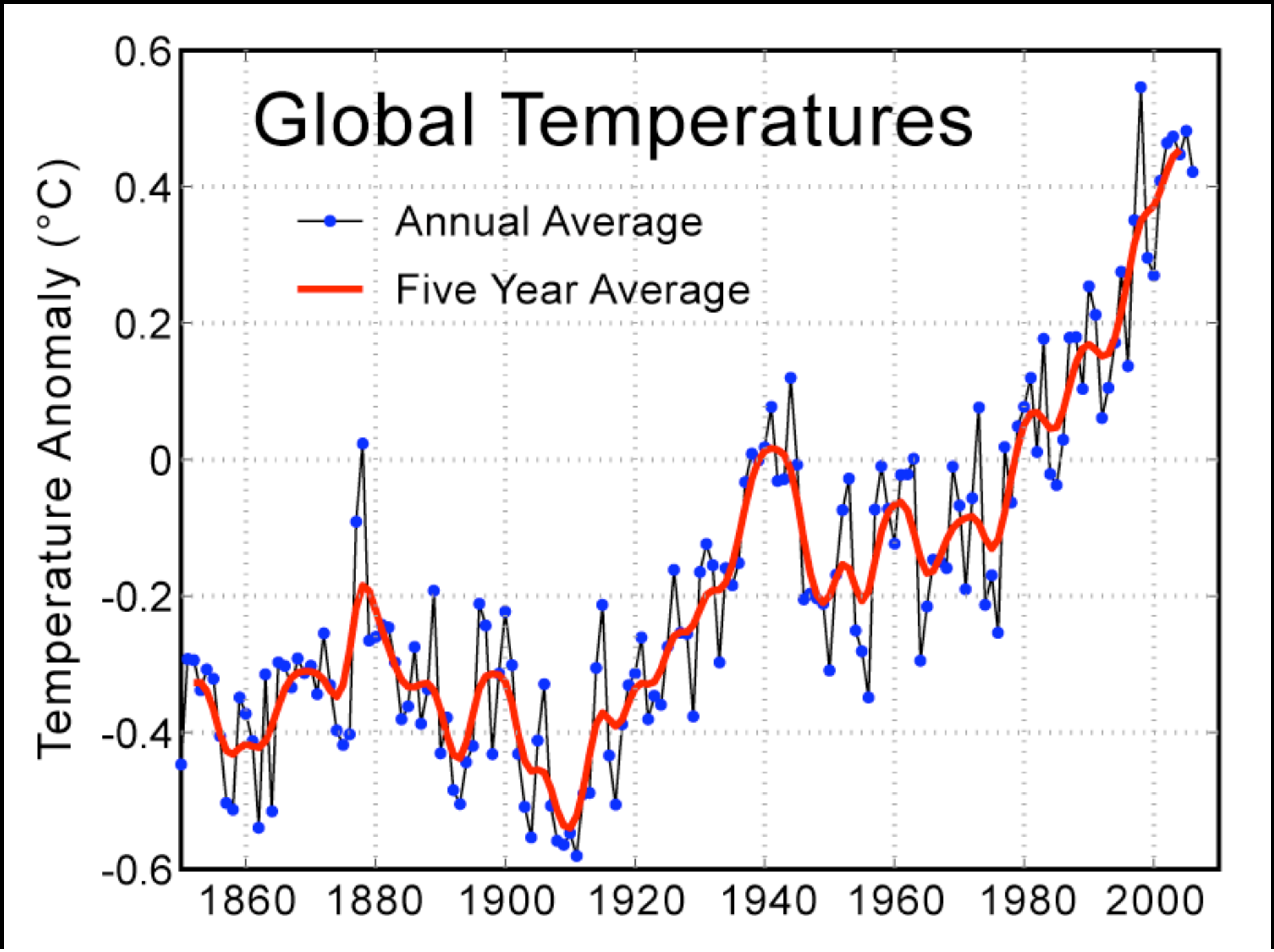
-- too little greenhouse effect or dimmer Sun
-- ice cover increases reflecting light
-- reduced heating
-- more ice and more reflected light – less heating

ASTR 380
Habitable Zone

Our current experiment with CO_2 increases!

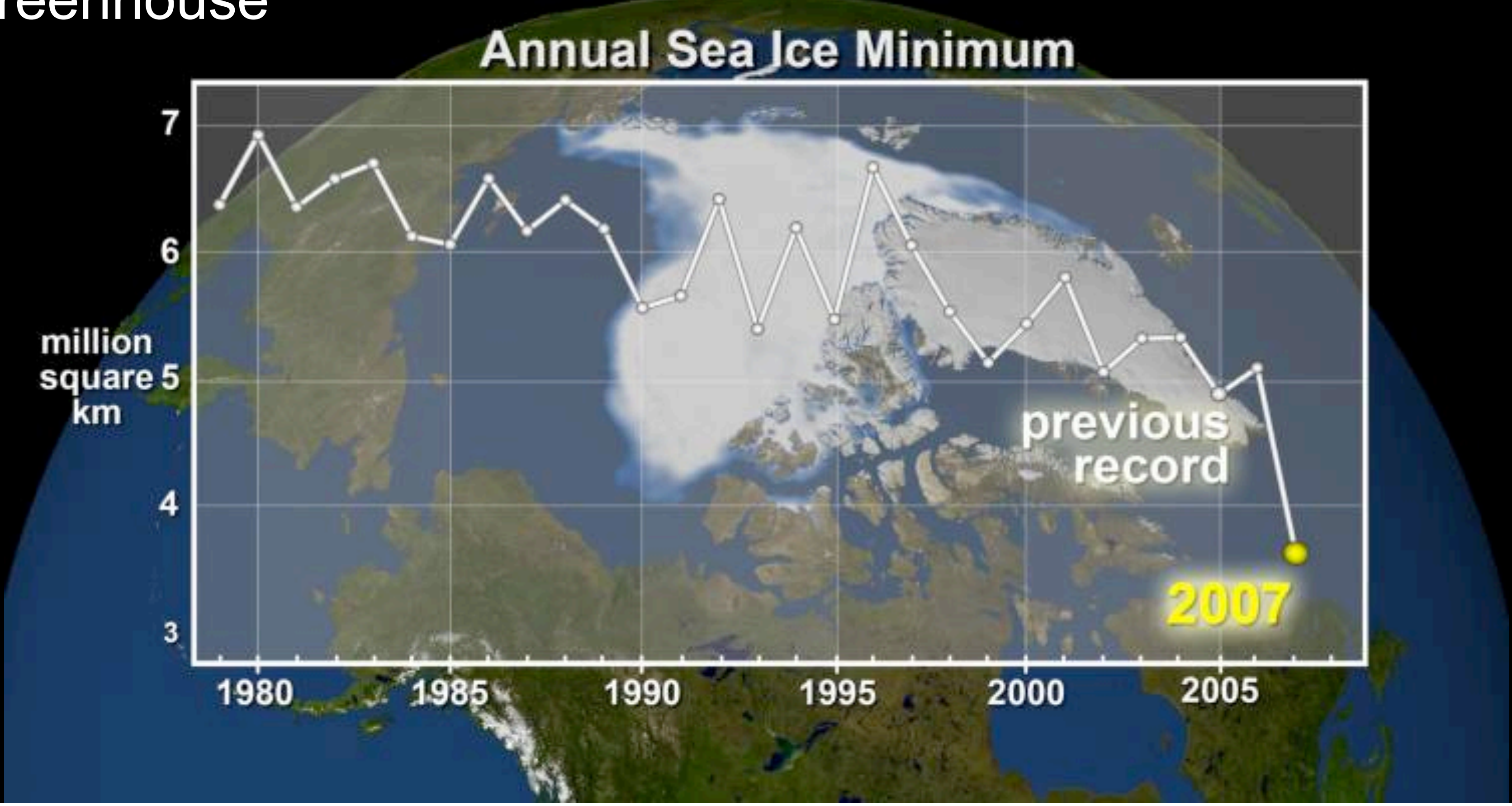


ASTR 380
Habitable Zone

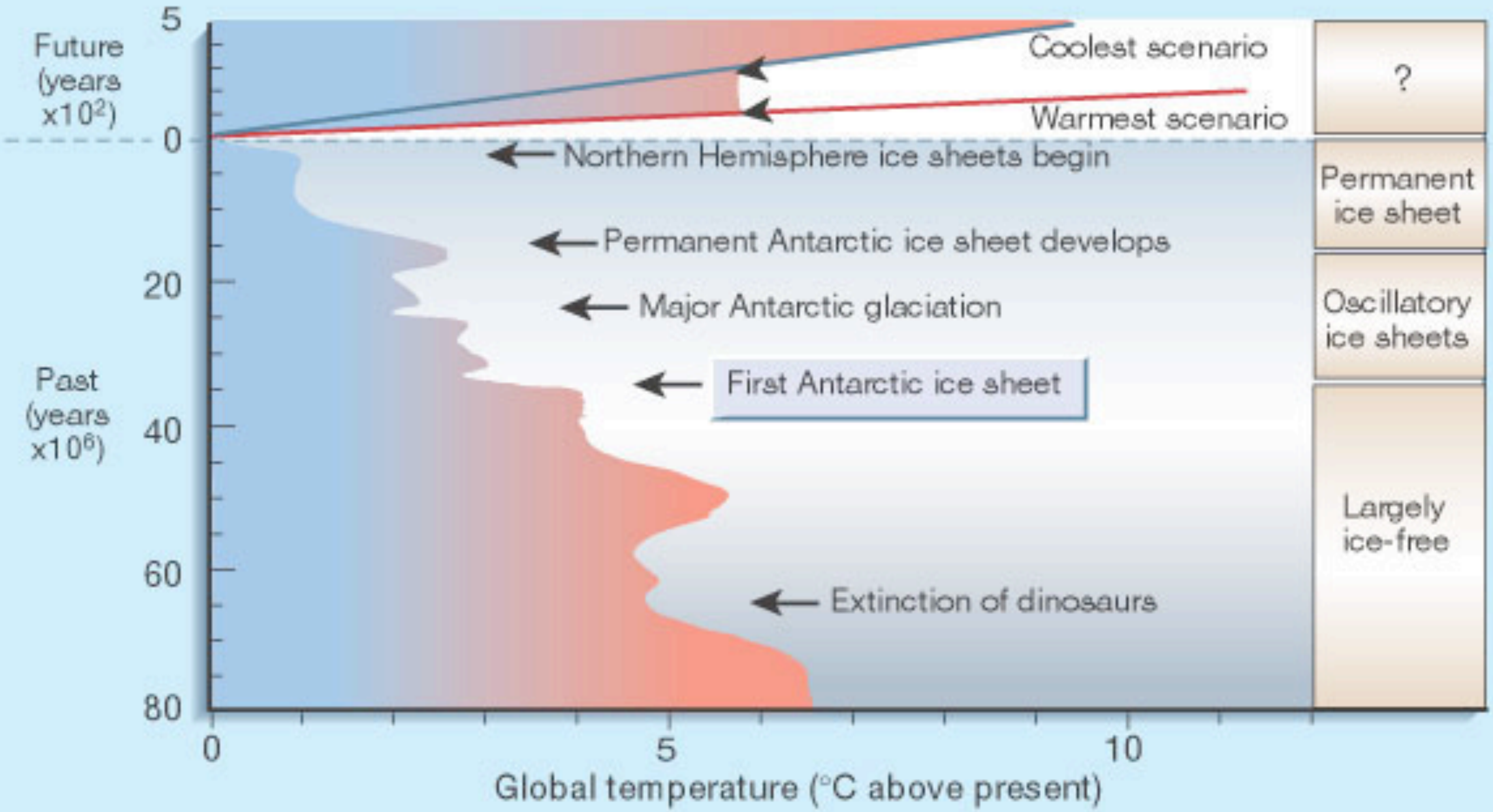


ASTR 380
Habitable Zone

So we are in the loop of…. More CO_2… gives more heating.. Which melts ice… which increases the heating… which may also release methane and CO_2 locked in permafrost.. More greenhouse

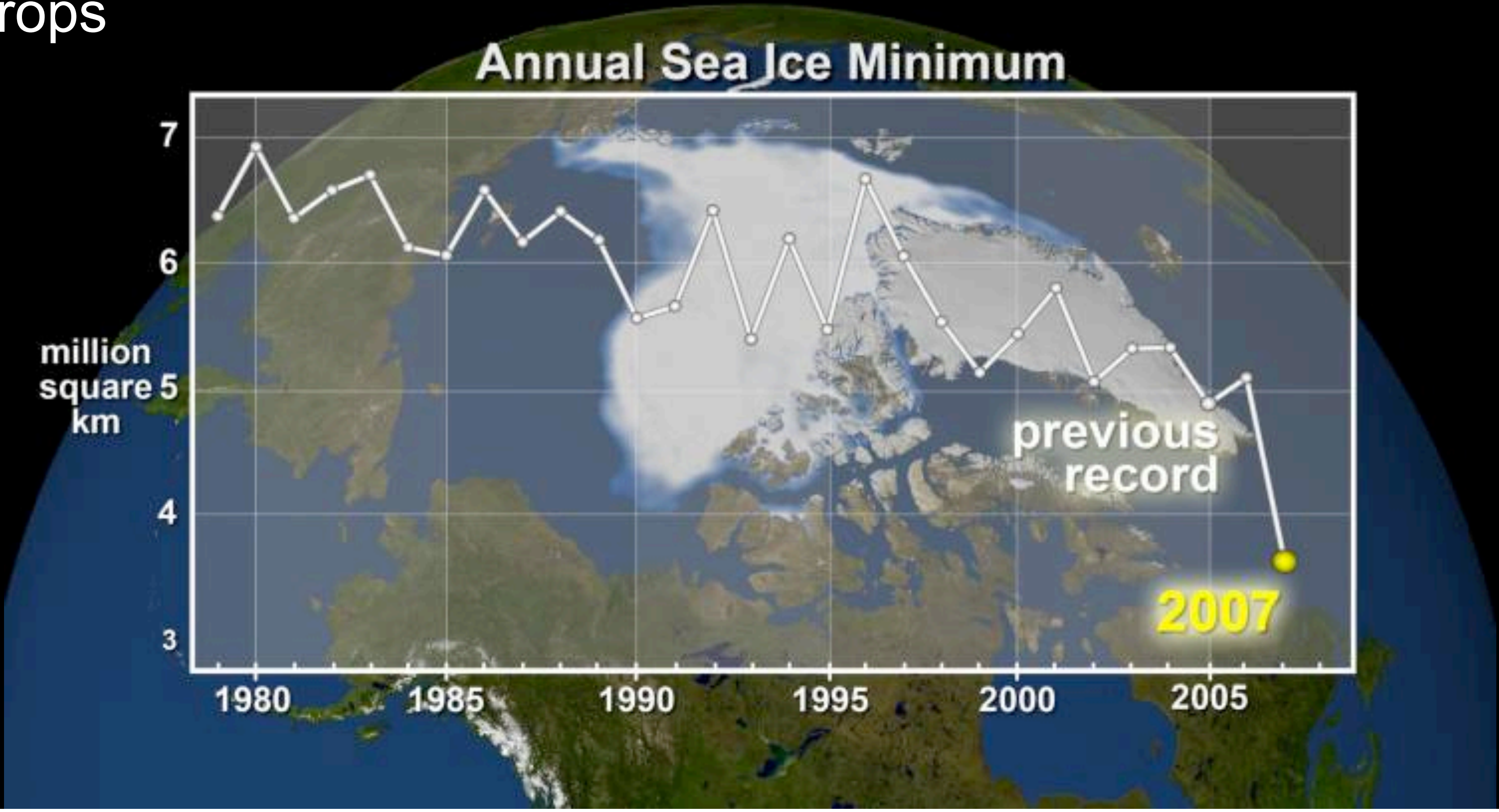


ASTR 380
Habitable Zone



ASTR 380
Habitable Zone

How does the Earth deal with this? Humans die. CO_2 production decreases. Excess CO_2 is gradually locked back into rocks and sequestered in plant matter… temperature drops



ASTR 380
Habitable Zone

Returning to our habitable zone question….

For the Earth, increasing the CO_2 by 60 parts per million increases the global temperature by 0.6 C

If we want Earth-like conditions at 1.15 AU, we need to increase the global temperature by 20 C using greenhouse gases… so going from 380 parts per million currently to about 2500 parts per million would likely do it! That is an abundance of only 0.25%. The atmosphere is still mostly N_2 and O_2

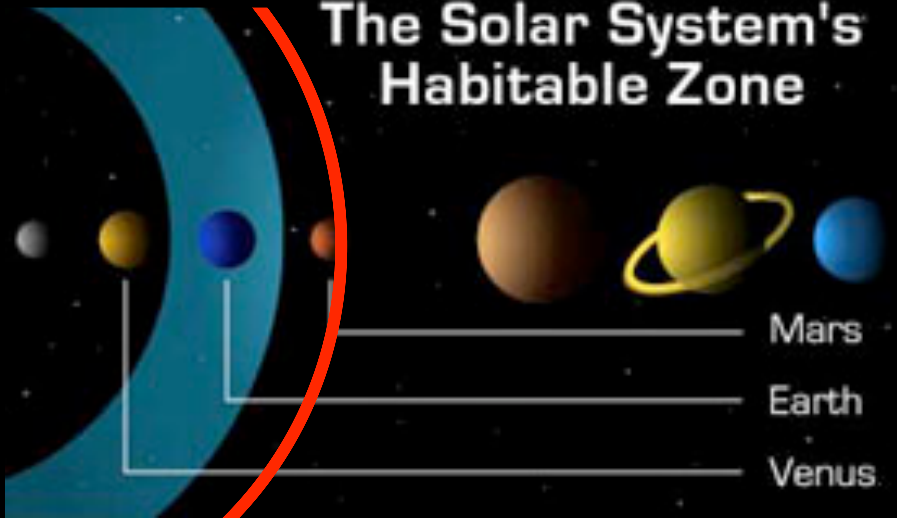
It is estimated that one could retain Earth-like conditions with a strong CO_2 atmosphere out to 1.4 to 1.7 AU.

ASTR 380
Habitable Zone

In summary:

The strict habitable zone for the Earth (as is) is roughly 0.9 to 1.1 AU.

If we allow different CO_2 abundance to control the greenhouse effect, the range likely extends from 0.85 to 1.4 AU and maybe even 1.7 AU.



ASTR 380
Habitable Zone

Mass of the planet also matters:

-- mass controls the amount of atmosphere retained
-- affects amount of continuing volcanic activity
-- may change the amount of water retained.

Too small mass:
-- too thin atmosphere
-- core solidifies so volcanic activity gone

Too big mass:
-- retains hydrogen atmosphere – extremely thick

Likely happy mass: 0.5 to a few Earth masses

ASTR 380
Habitable Zone

Mass of Star matters:

More massive stars are brighter:

-- habitable zone moves out from star to larger radius
because "energy in = energy out"

Less massive stars are dimmer:

-- habitable zone moves to small radius.

ASTR 380
Habitable Zone

Tidal effects

If a planet is close enough to its host star, then the gravity of the star tends to:

- Make the planet’s orbit more circular
- Make the planet rotate with the same period it orbits

This latter is called “tidal locking”, and happens only for planets very close to their star.
But that’s required if the star is very low mass

ASTR 380
Habitable Zone

The Age of the Star matters:

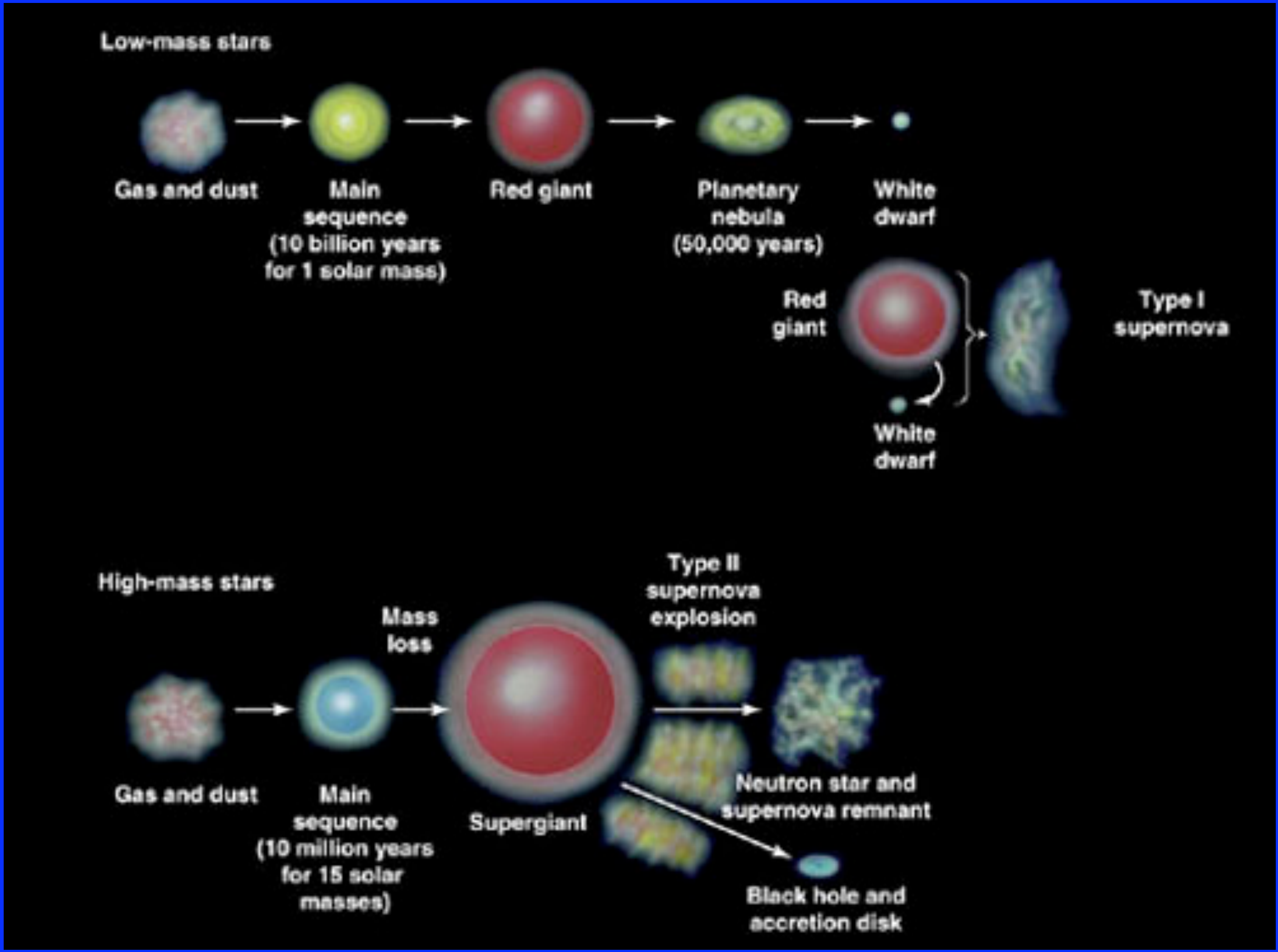
Younger stars are dimmer:

-- zone is closer to star

Older stars are brighter:

-- zone is farther from star

A given planet may change between being habitable and non-habitable as the star ages



http://www.redorbit.com/modules/reflib/article_images/6_dac4e7d6b8fb5cf3a1458d796b90d7a9.jpg

ASTR 380
Habitable Worlds

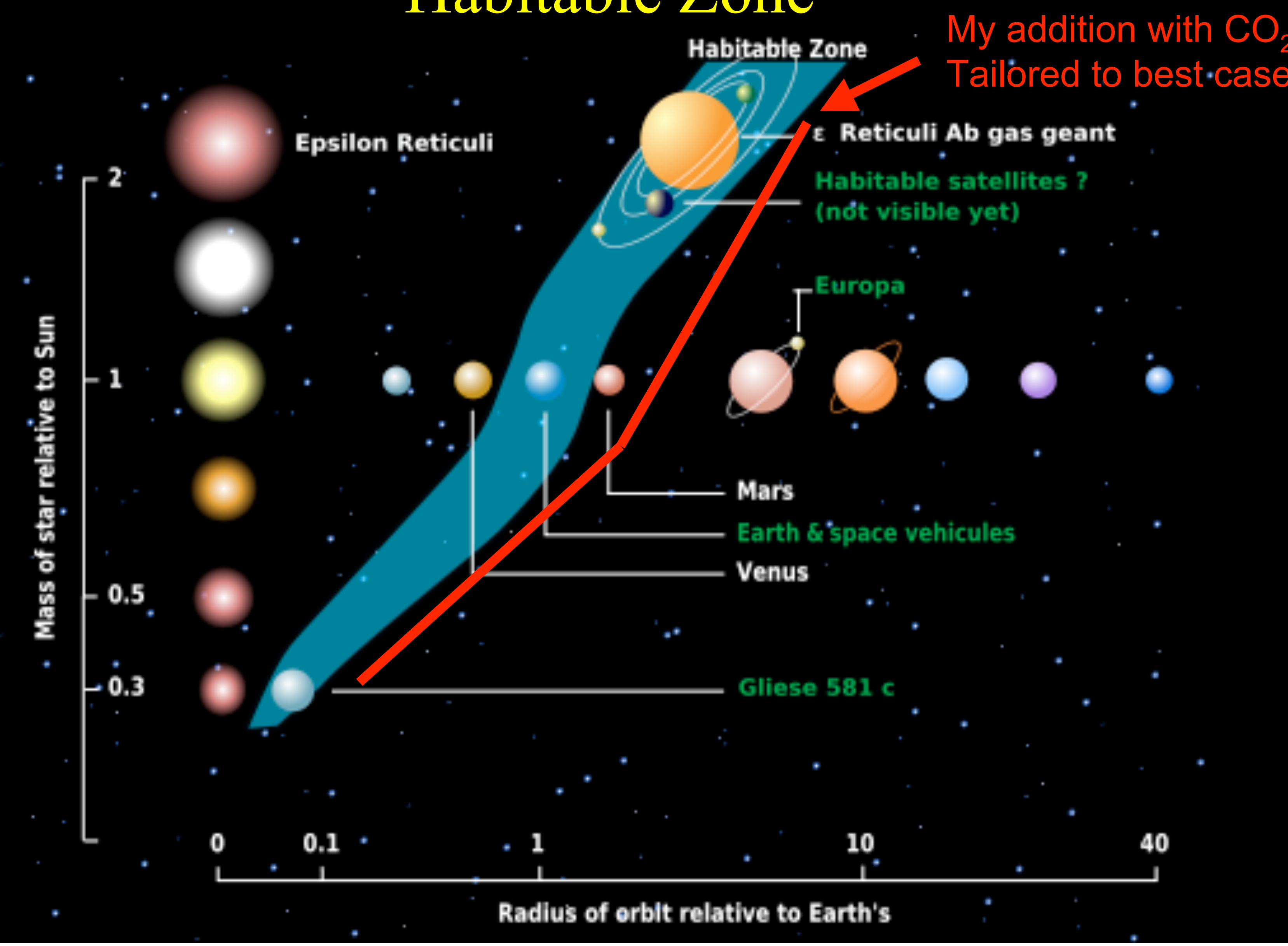
We can also think of habitable worlds which exist beyond the formal habitable zone…

-- ice covered worlds which have sub-surface oceans heated by tidal heating or volcanic activity.
Europa, Ganymede?

-- methane oceans on cold planets or moons

-- ????

ASTR 380
Habitable Zone



Debate: Habitable Zone

- How important is the habitable zone?
- First point of view: habitable zone is essential for at least the development of complex life
- Second point of view: not true; even complex life could develop far outside the traditional habitable zone

Summary

- As always, we are limited by the one example we know
- But if liquid water in quantity is needed, there is a relatively narrow region that will suffice
- Can be extended by greenhouse effects or internal heat caused by tidal stresses or cooling, or by albedo