Astrobiology
An Overview

Markus Kissler-Patig

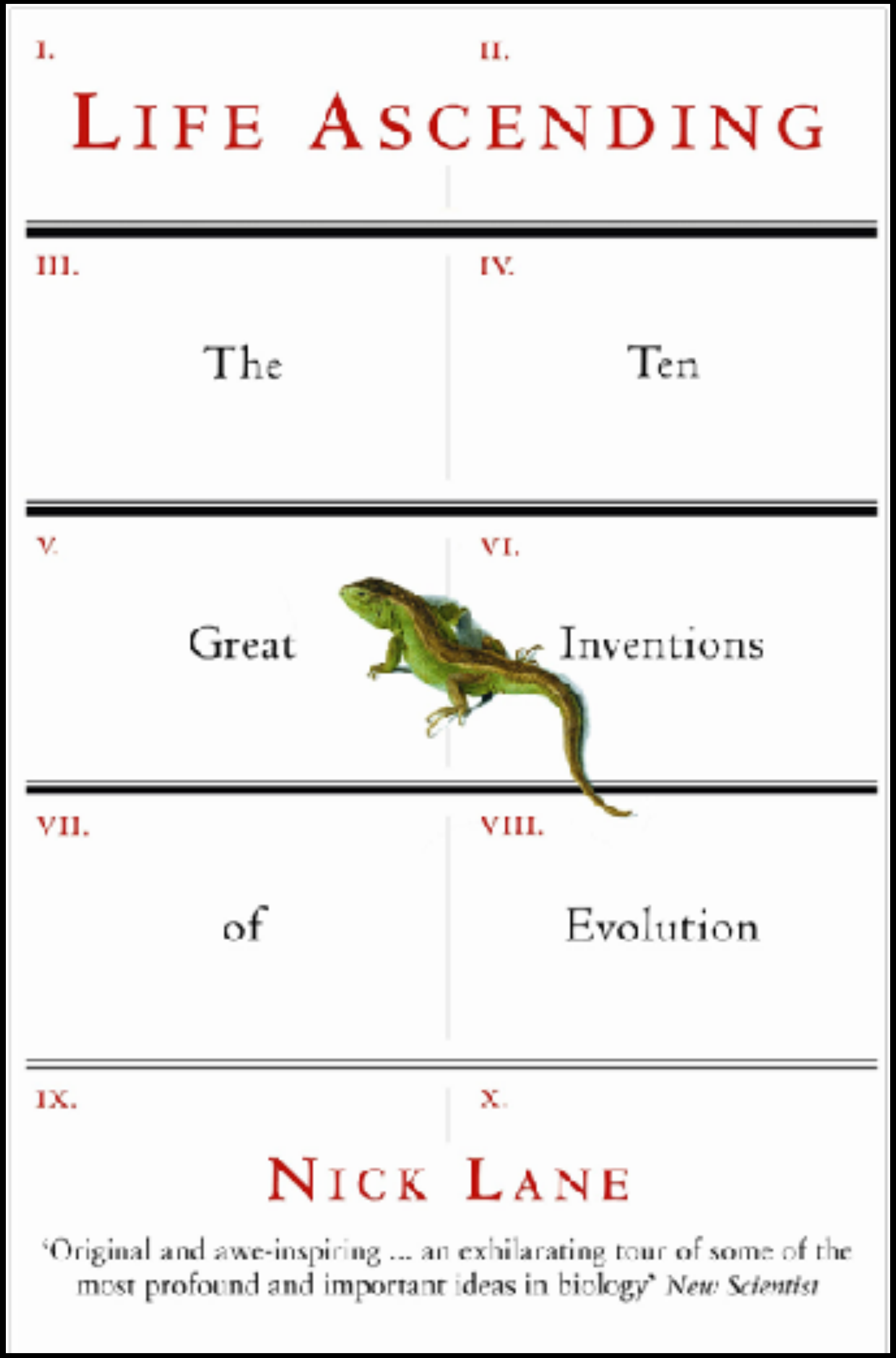
IMPRS Graduate School 🙂

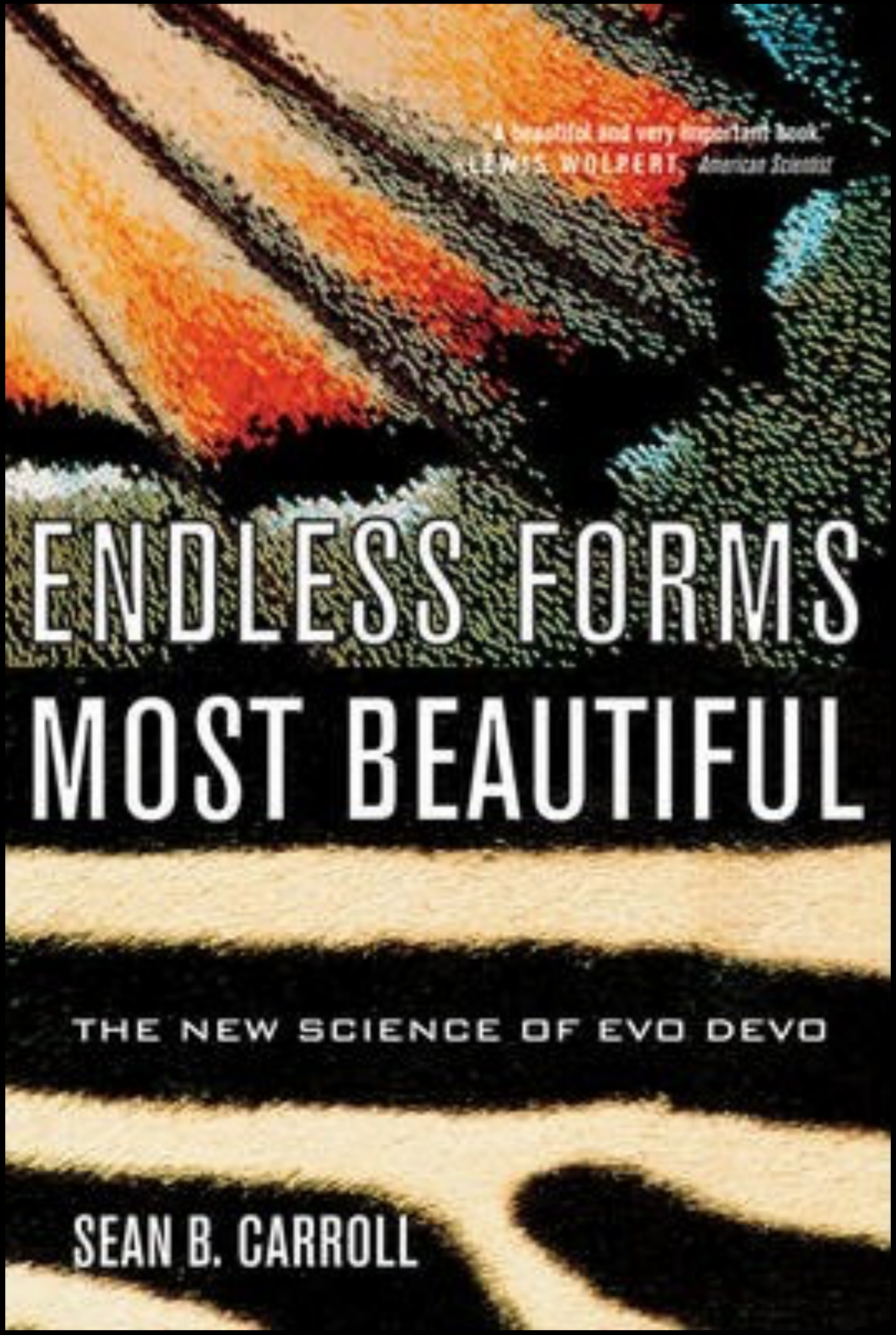
November 20-24, 2023

Daily: 10:00-12:00 & 13:00-14:00

https://www.cosmos.esa.int/web/astrobio/imprs-2023

Books mentioned yesterday:





Astrobiology
An Overview

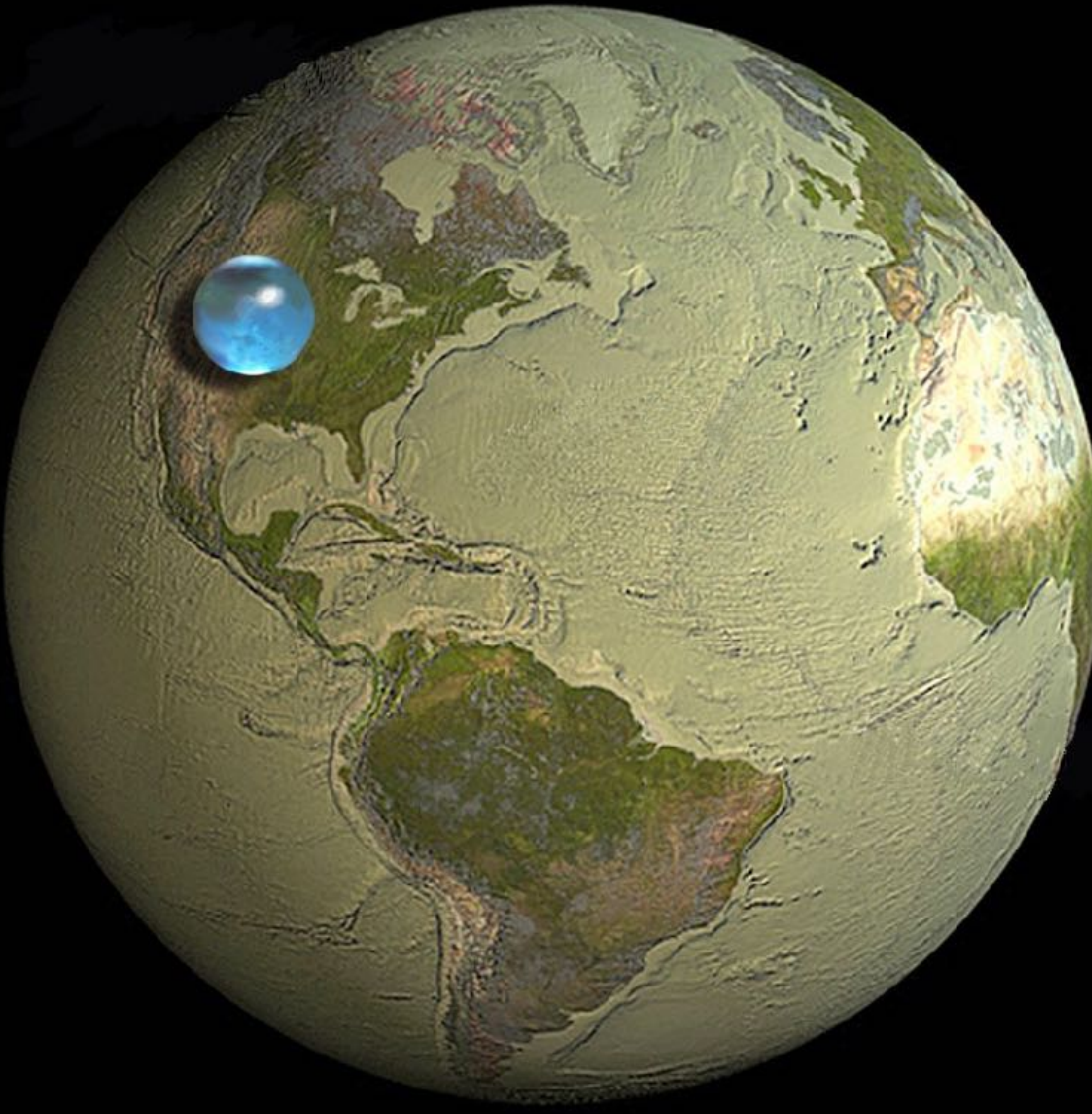
Day 2

Earth Climate History; Mars and Venus Climates

https://www.cosmos.esa.int/web/astrobio/imprs-2023

Monday November 20	Day 1: Definition of Life; Origin of Life; Evolution of Life; Limits of Life 10:00-12:00 & 13:00-14:00
Tuesday November 21	Day 2: Earth Climate History; Mars and Venus Climates 10:00-12:00 & 13:00-14:00 OLD SEMINAR ROOM
Wednesday November 22	Day 3: Habitable Places in the Solar System; Mars; Moons of Giant Planets 10:00-12:00 & 13:00-14:00
Thursday November 23	Day 4: Habitable Places beyond the Solar System; Exoplanets properties; Biosignatures 10:00-12:00 & 13:00-14:00
Friday November 24	Day 5: Search for Extraterrestrial Intelligence; Alien Biochemistry 10:00-12:00 & 13:00-14:00

Basics of Climate

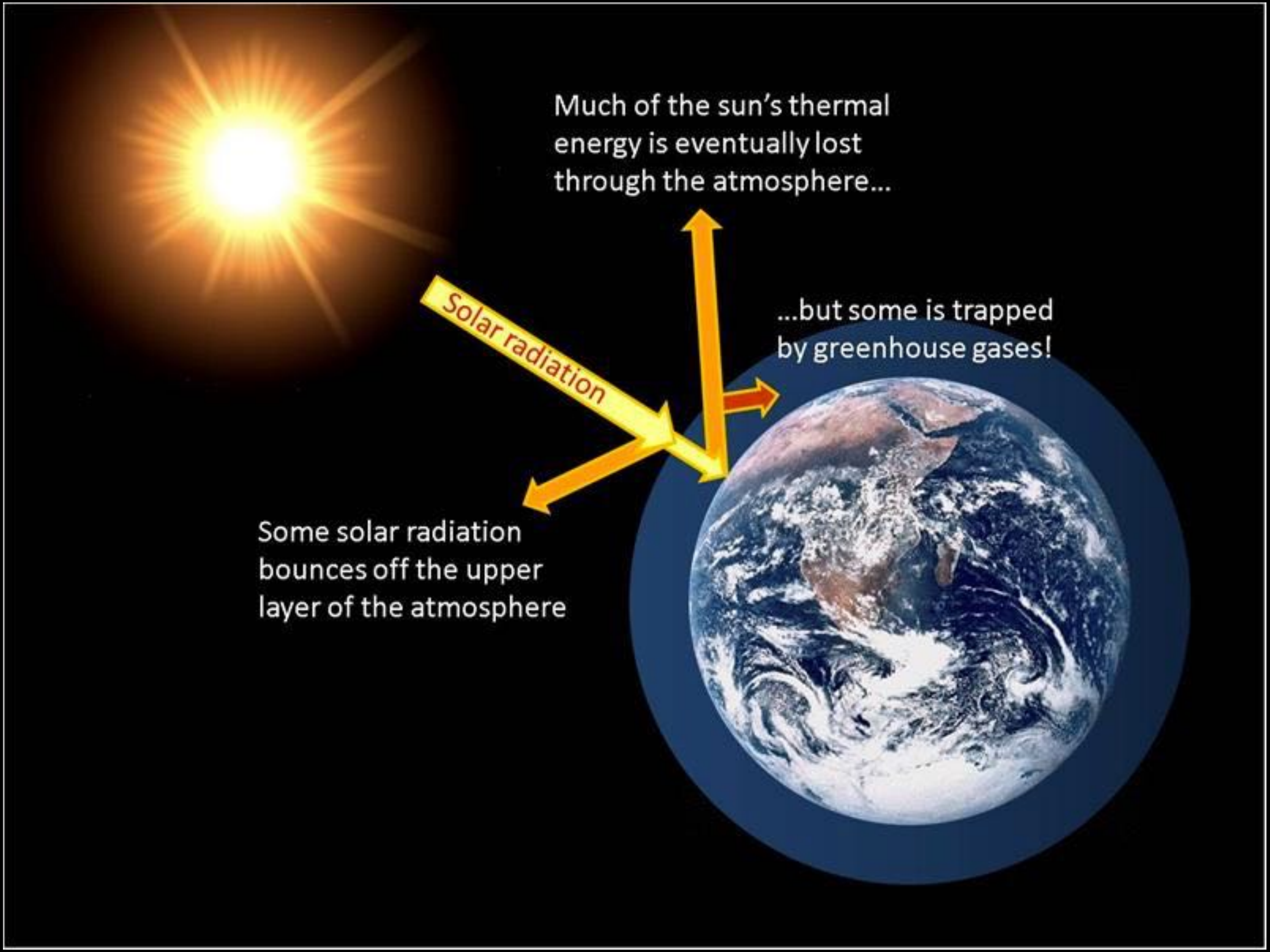


If Earth were a black body heated by the Sun:

$T_{eff} = 255K$ assuming 0.3 Albedo

But $T_{surf} \sim 288K$

Two heat sources: the sun + the heated atmosphere



Which is the most important Greenhouse gas for Earth's climate?

If Earth were a black body heated by the Sun:

$T_{eff} = 255K$ assuming 0.3 Albedo

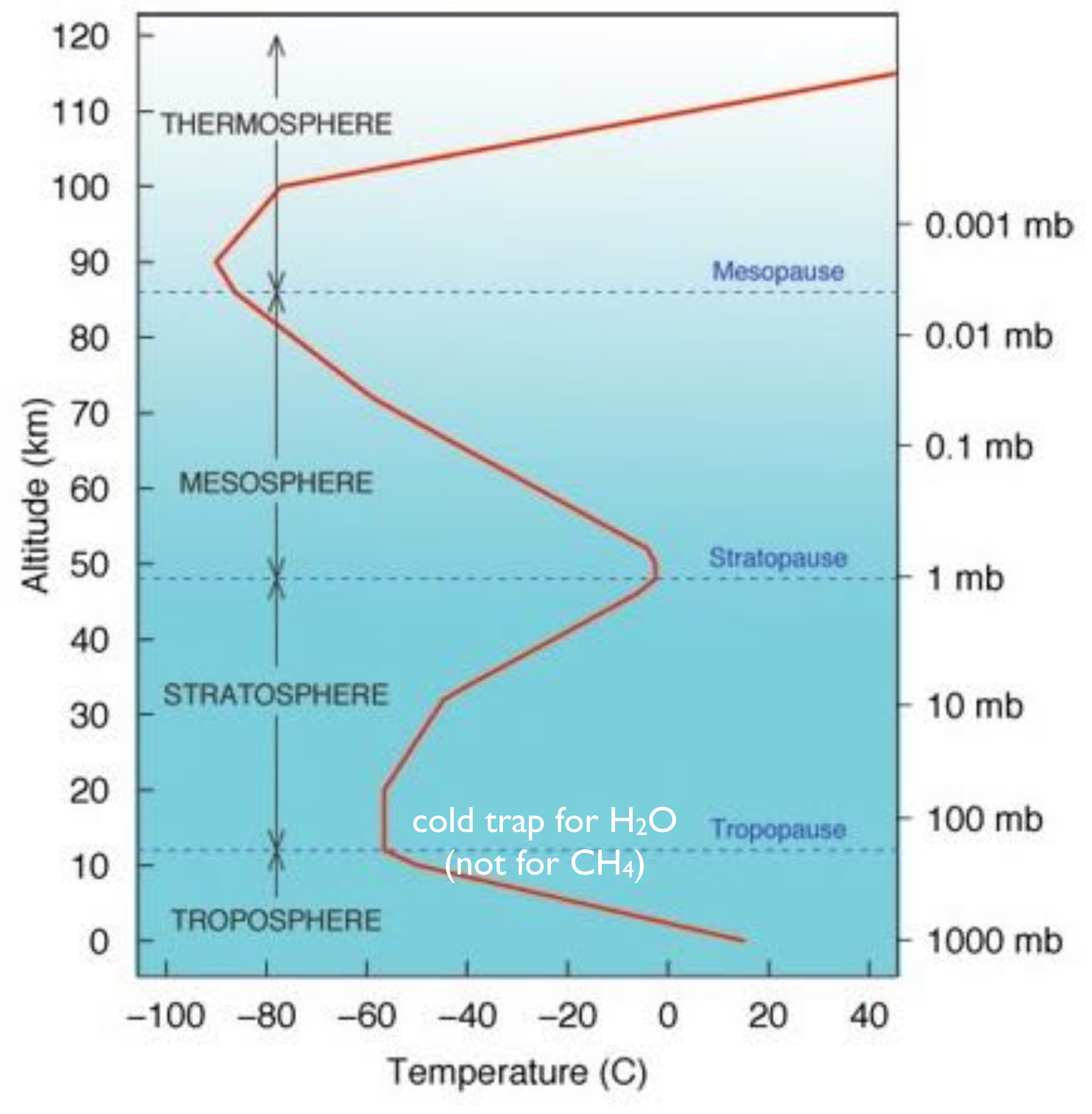
But $T_{surf} \sim 288K$

The Greenhouse effect contributes ~33K

(20K H_2O, 10K CO_2, 2-3K CH_4,N_2O,O_3,CFCs)

The Temperature of the planet depends (to first order) on only three factors:

- The Solar flux (geometry, solar physics)
- The Albedo (80% due to clouds, very difficult to model!)
- The Greenhouse effect (atmospheric composition)

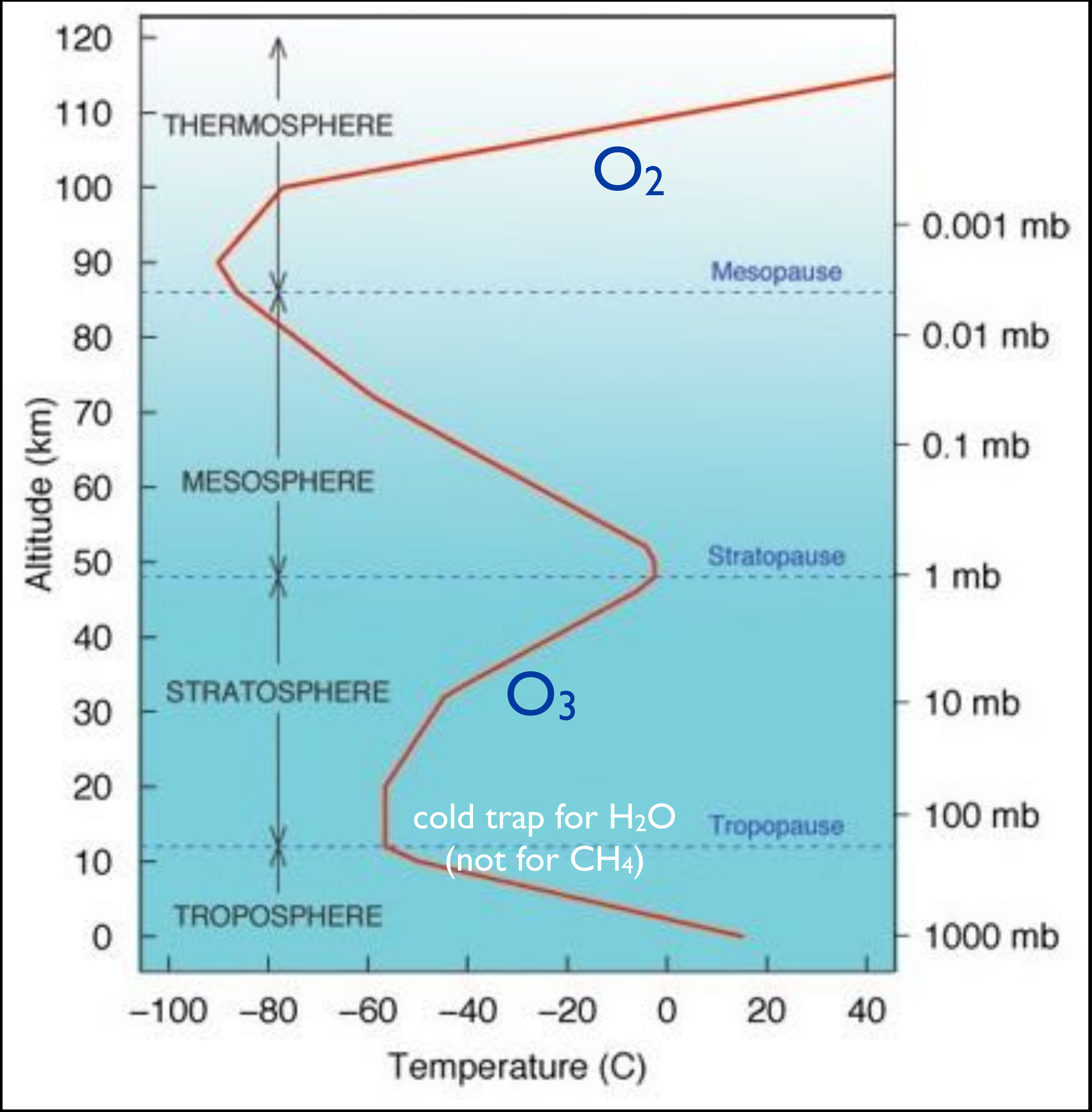


120
110
100
90
80
70
60
50
40
30
20
10
0
Altitude (km)
THERMOSPHERE
MESOSPHERE
STRATOSPHERE
TROPOSPHERE
Mesopause
Stratopause
Tropopause
0.001 mb
0.01 mb
0.1 mb
1 mb
10 mb
100 mb
1000 mb
−100
−80
−60
−40
−20
0
20
40
Temperature (C)
cold trap for H_2O
(not for CH_4)

Grimsvötn: ashes 8-12 km high, H_2O up to 20km

May 2011

At which altitude is the Ozone layer?



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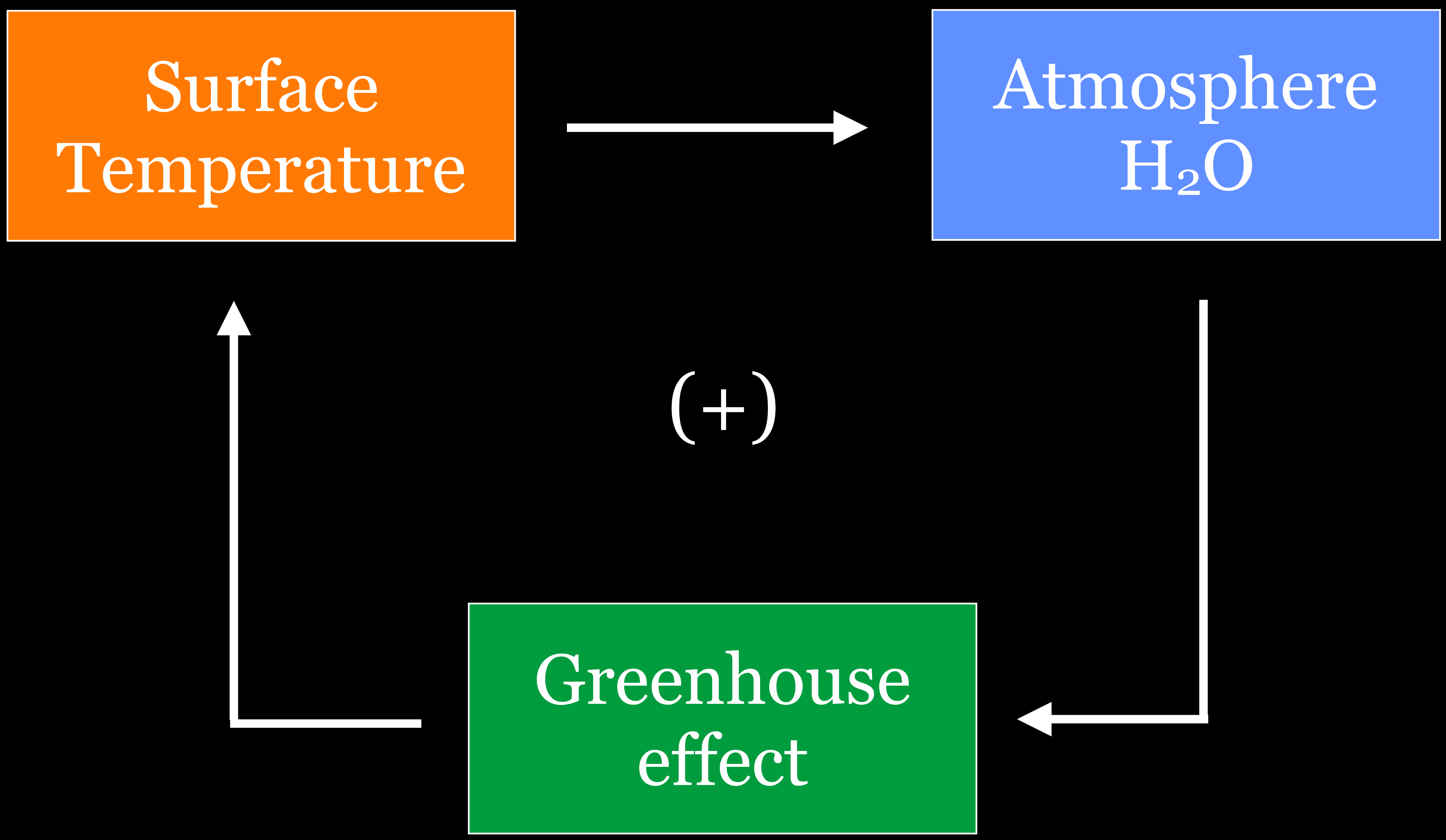
1000 mb
O_2
O_3
cold trap for H_2O
(not for CH_4)
−100 −80 −60 −40 −20 0 20 40
Temperature (C)

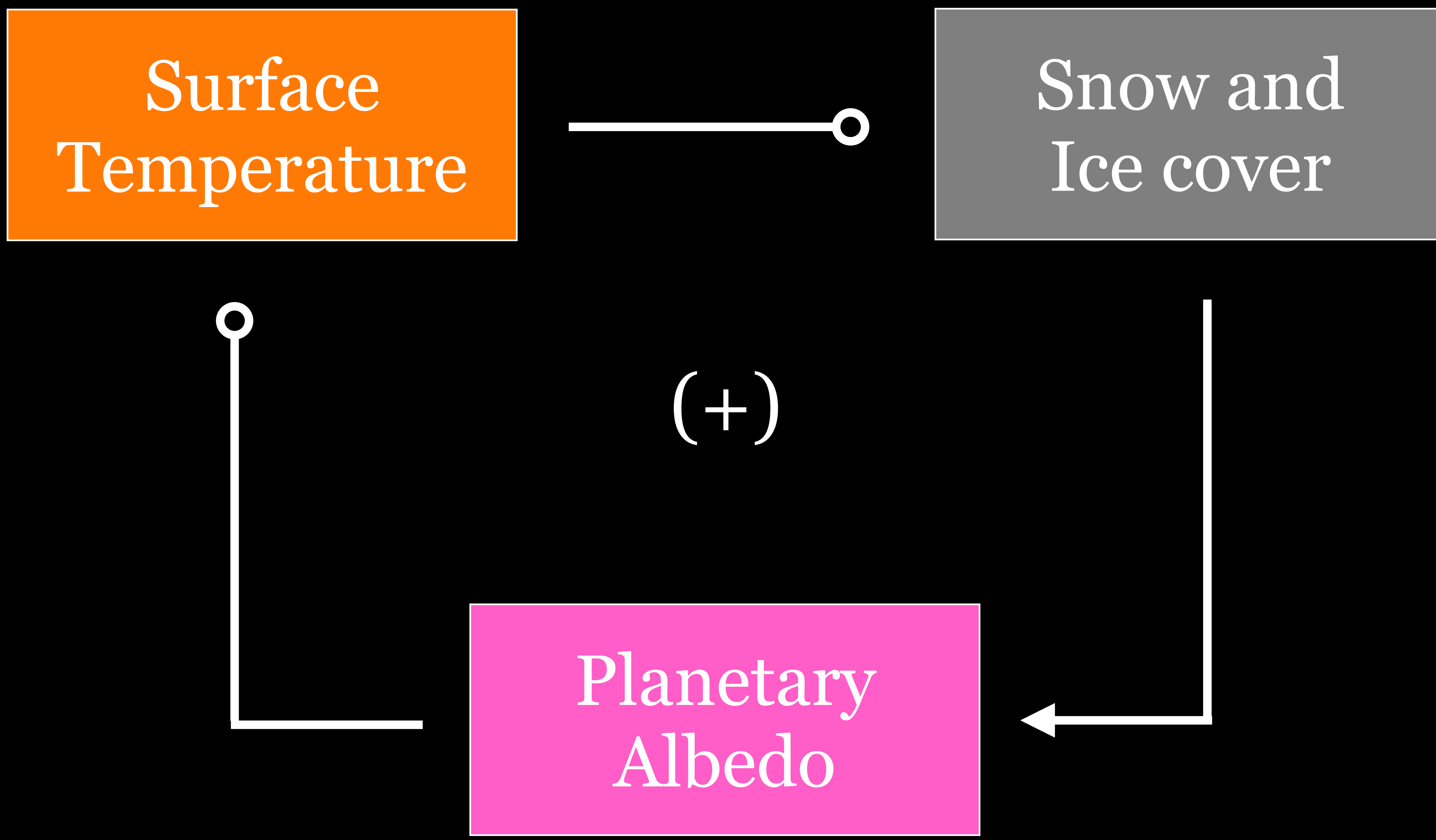
Climate Feedback loops

Solar flux variations

Greenhouse variations



Albedo variations



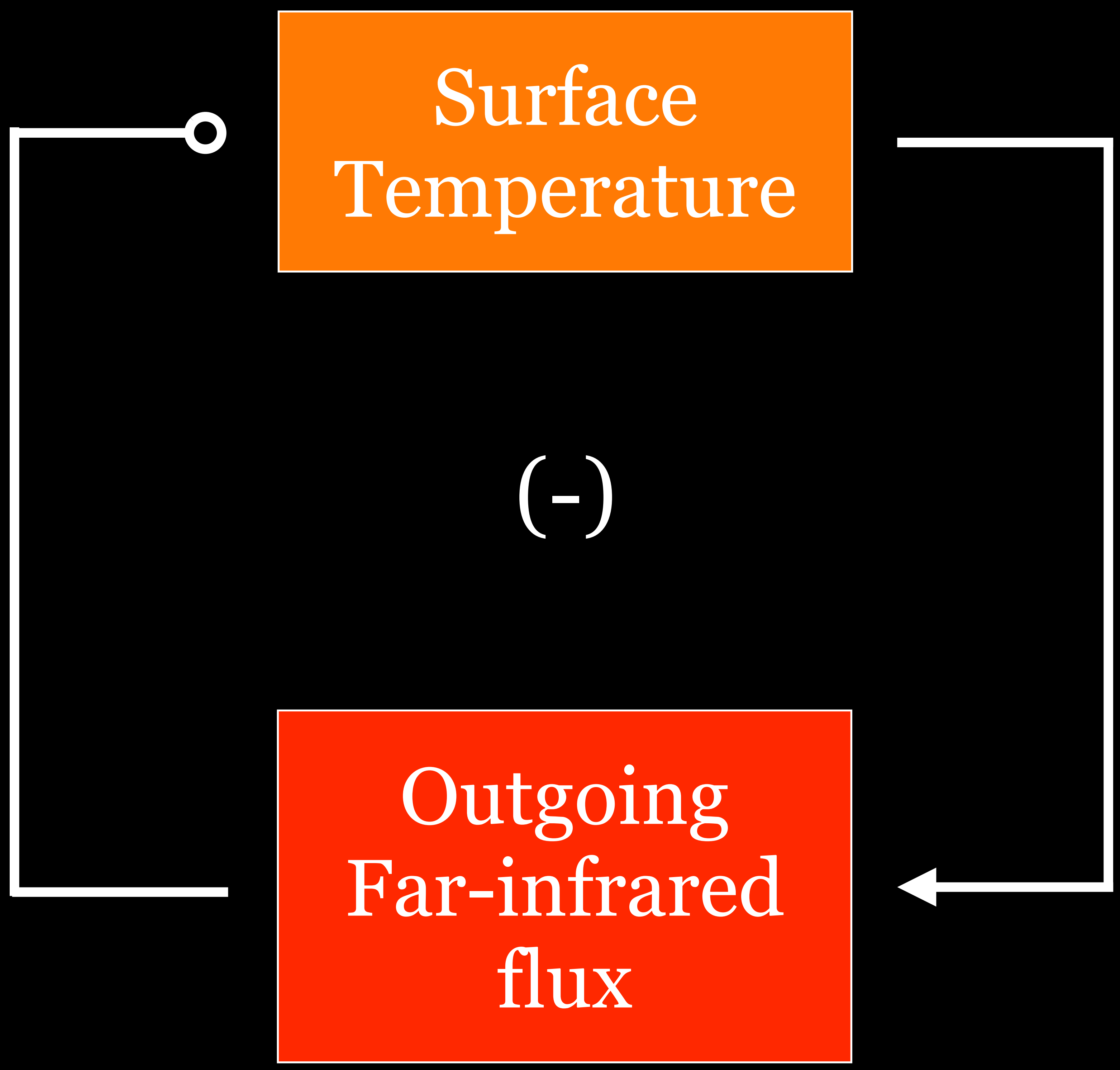
Gained in importance in the last 2 Myr

POSITIVE (+) Feedback loops are unstable

But the climate on Earth is stable...

⇒ There must be NEGATIVE (-) feedback loops that stabilize the climate (at least on short time scales)

Provides short-term stability

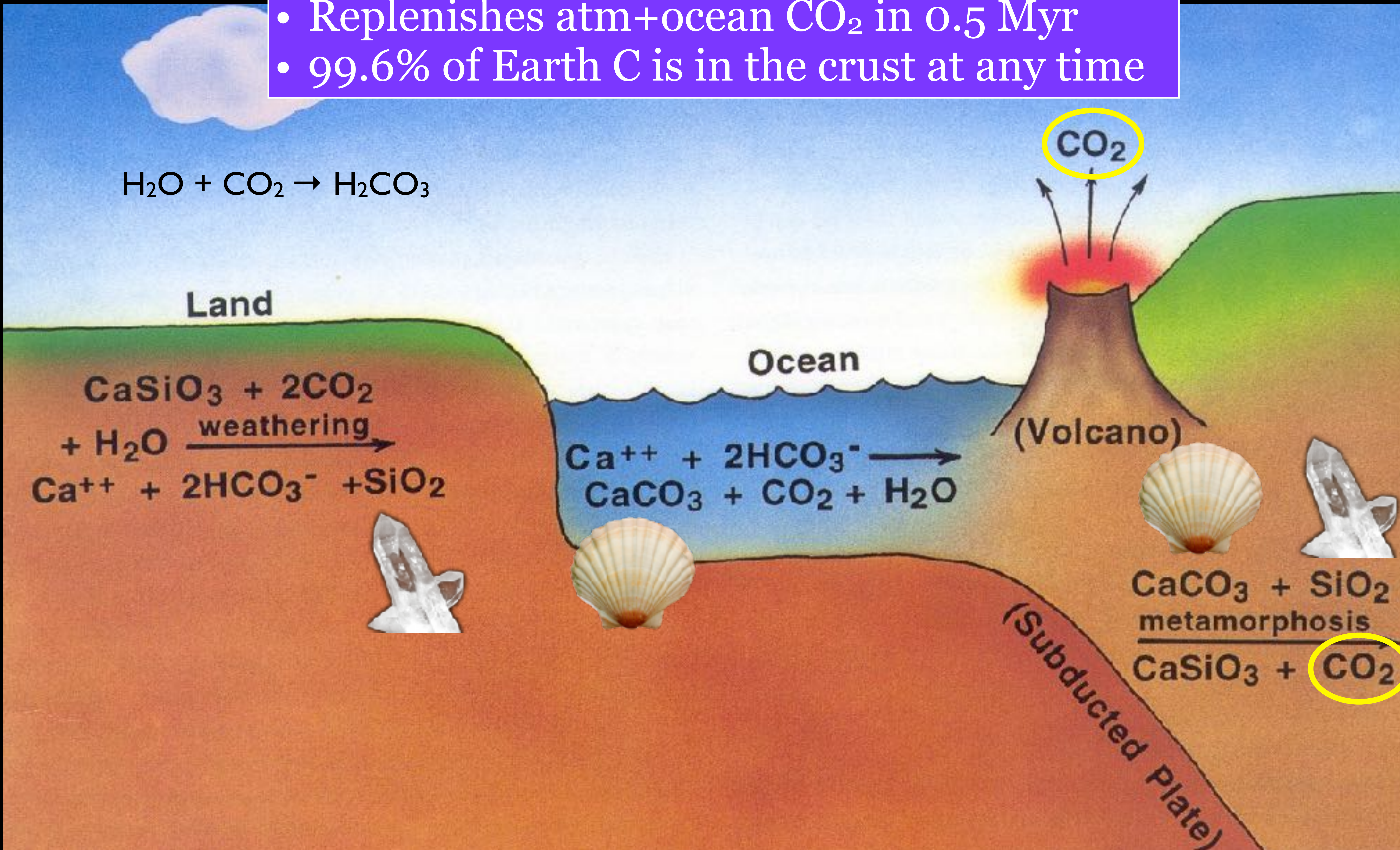


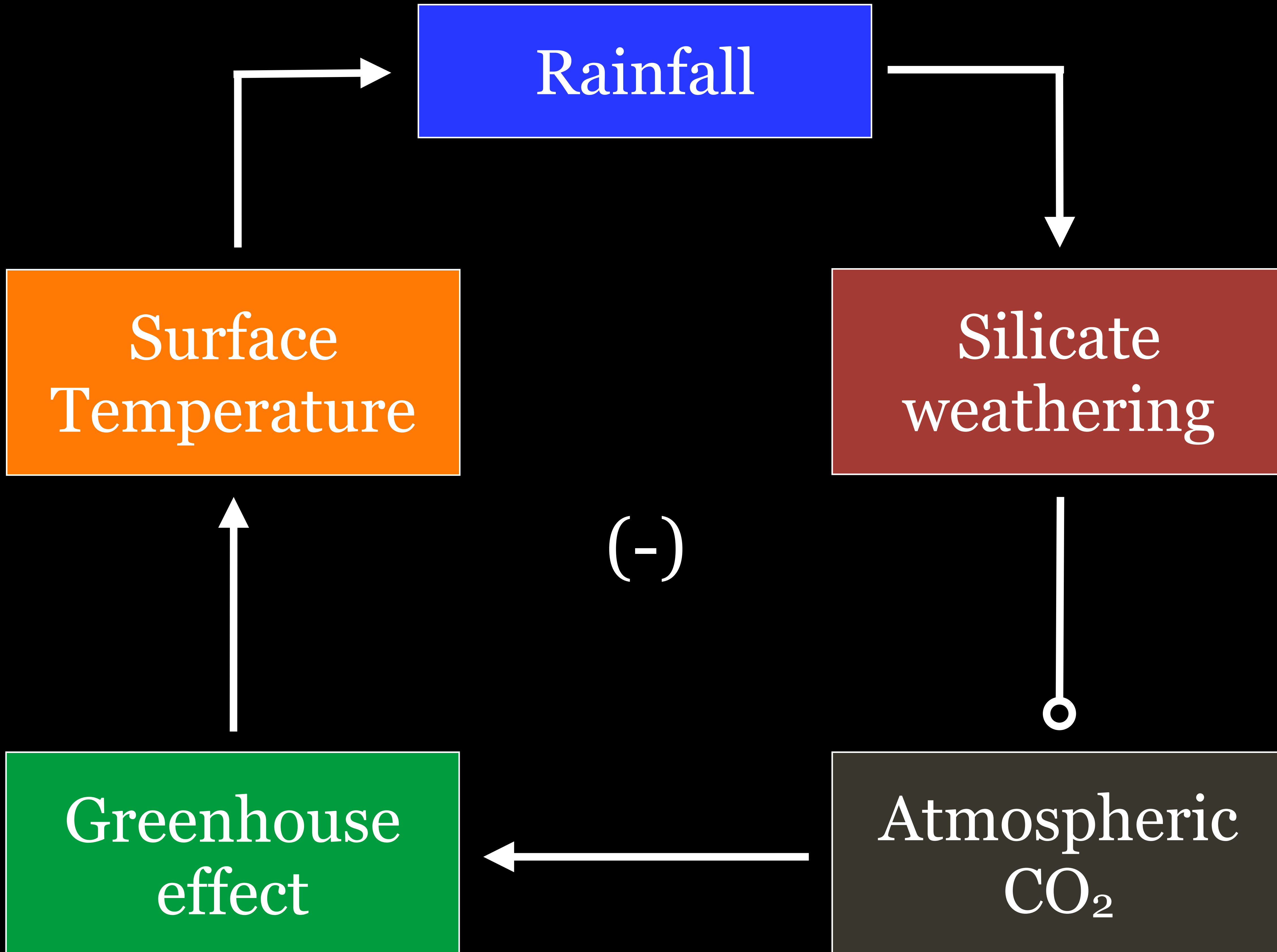
‘Faint Young Sun’ Problem

Do we have evidence for a long-term stabilizing process?

Carbonate-Silicate Cycle

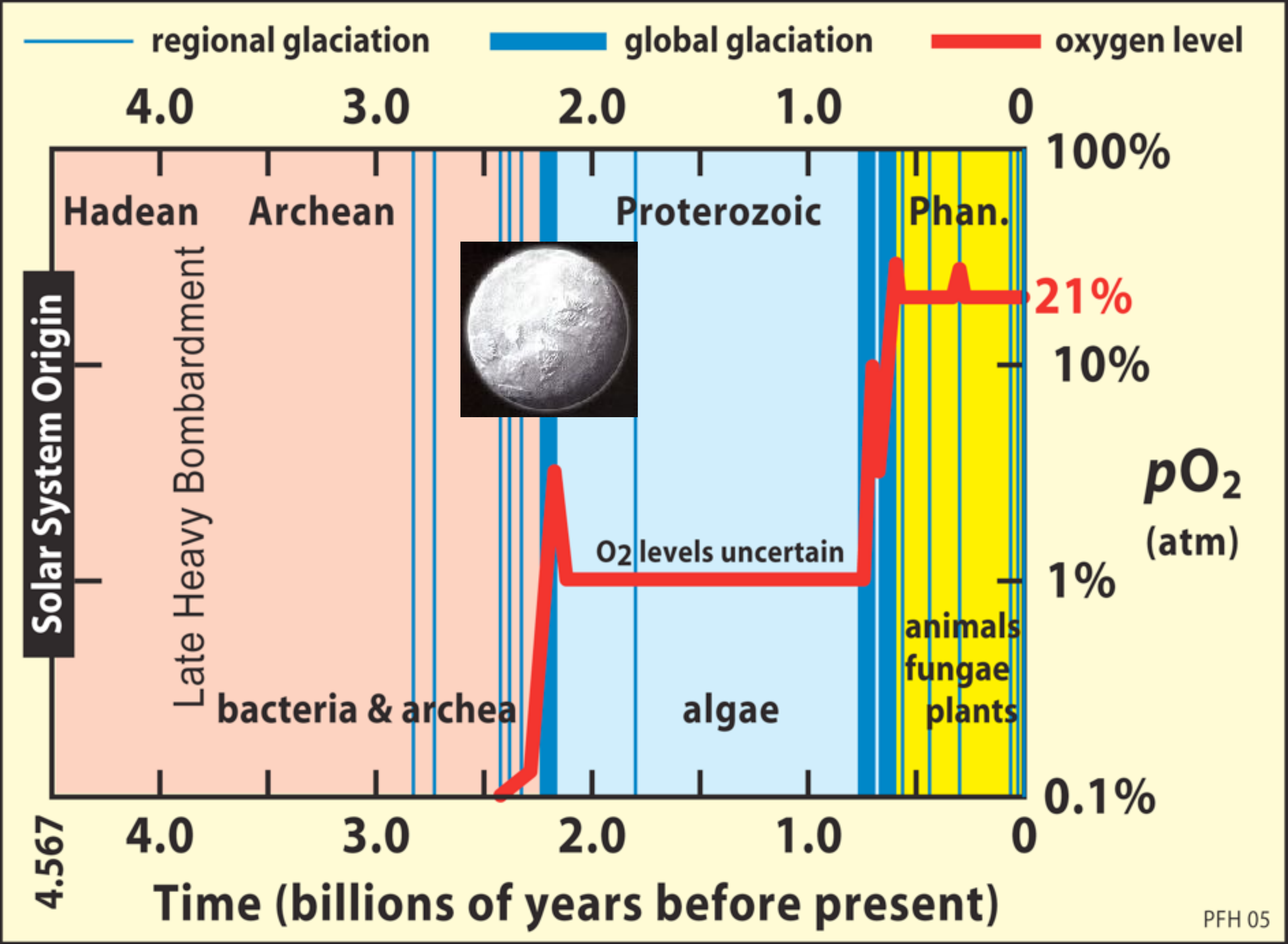
- 200 Myr timescale
- Replenishes atm+ocean CO_2 in 0.5 Myr
- 99.6% of Earth C is in the crust at any time





Provides long-term climate stability

Climate Crisis


regional glaciation
global glaciation
oxygen level
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4.567
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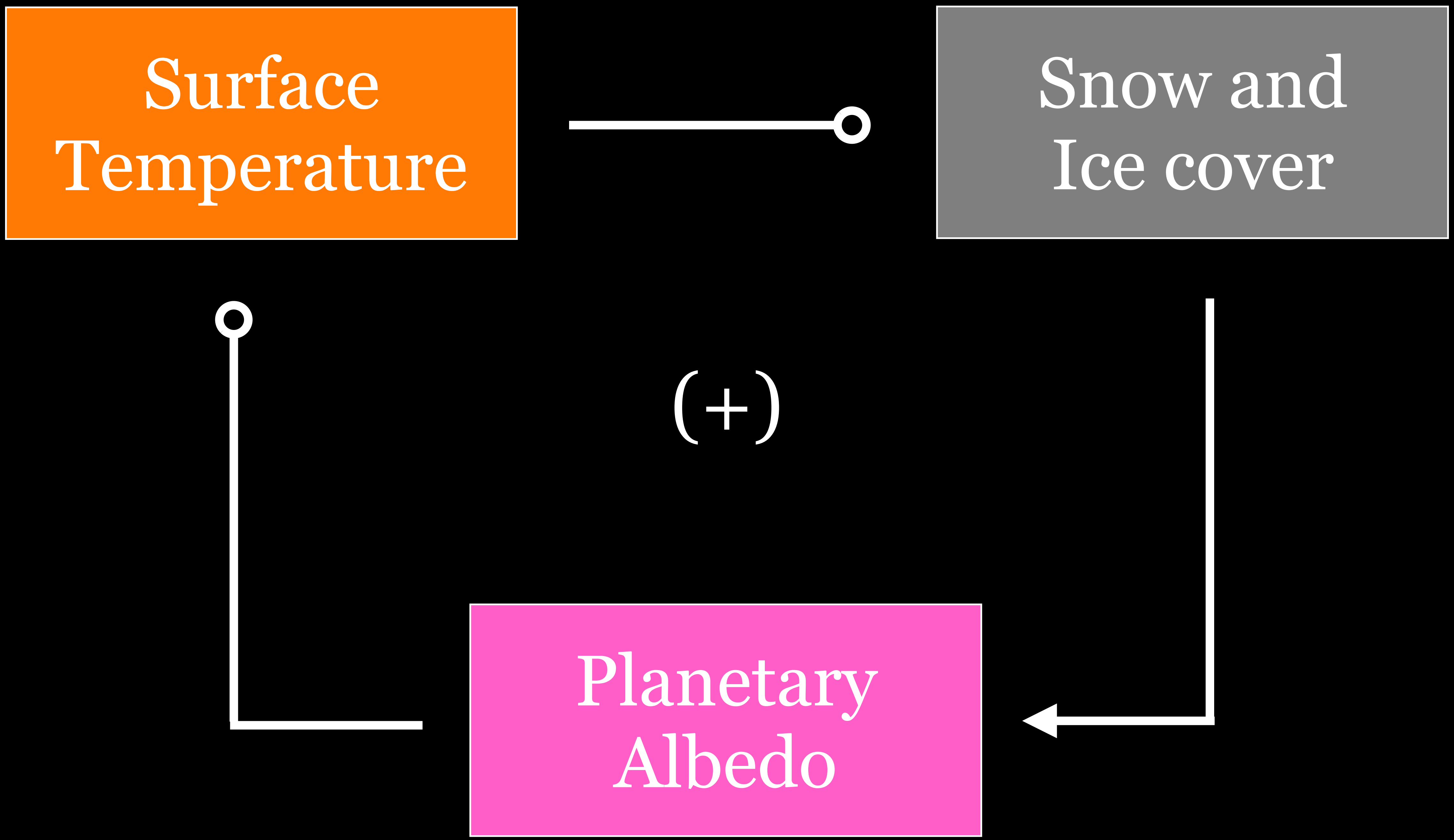
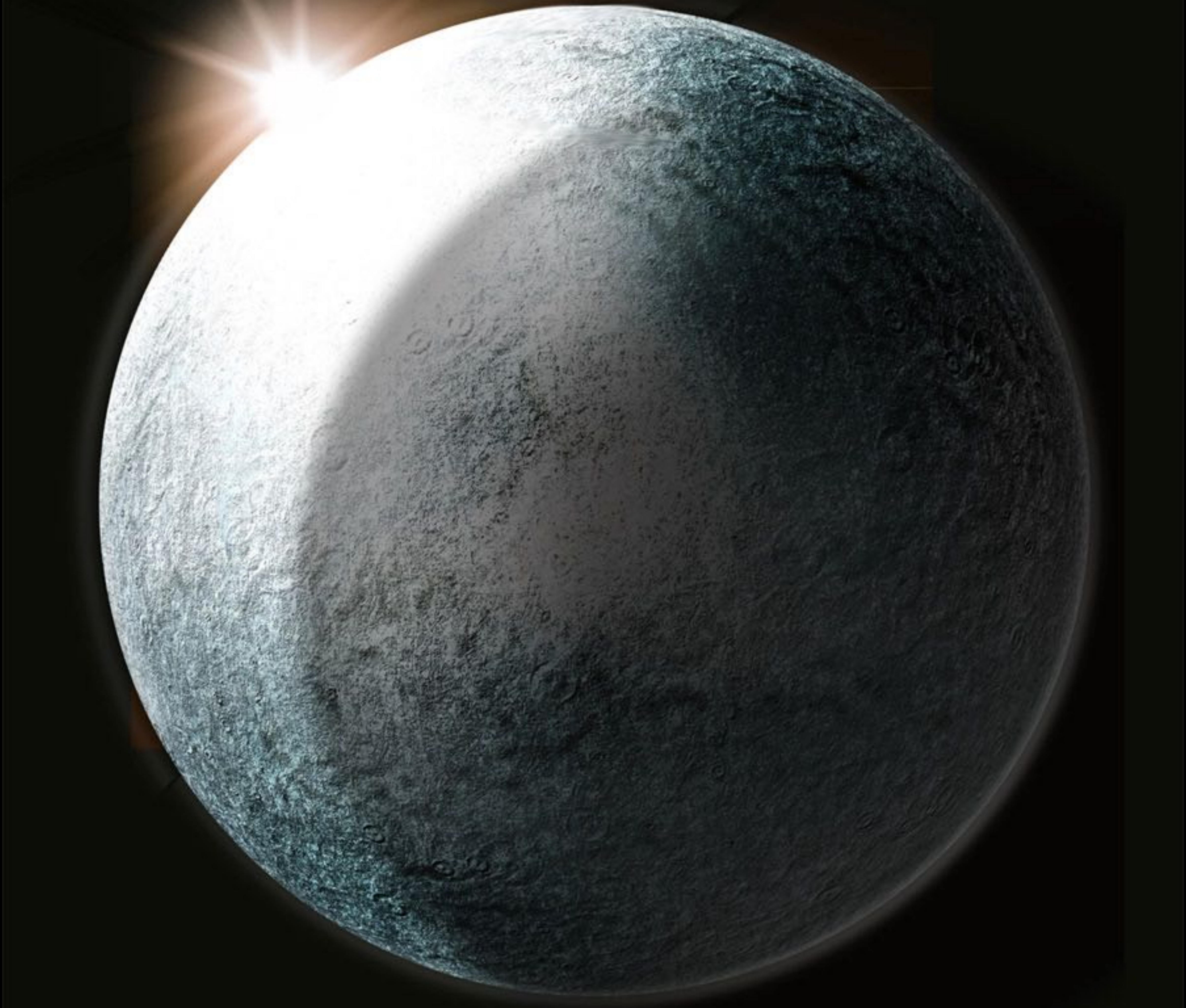
Time (billions of years before present)
PFH 05

Snowball Earth


Surface Temperature
Snow and Ice cover
(+)
Planetary Albedo



Geological evidence (Glaciers) for 3 total Glaciations

- First ~2.4-2.2 Ga (very unstable weather)

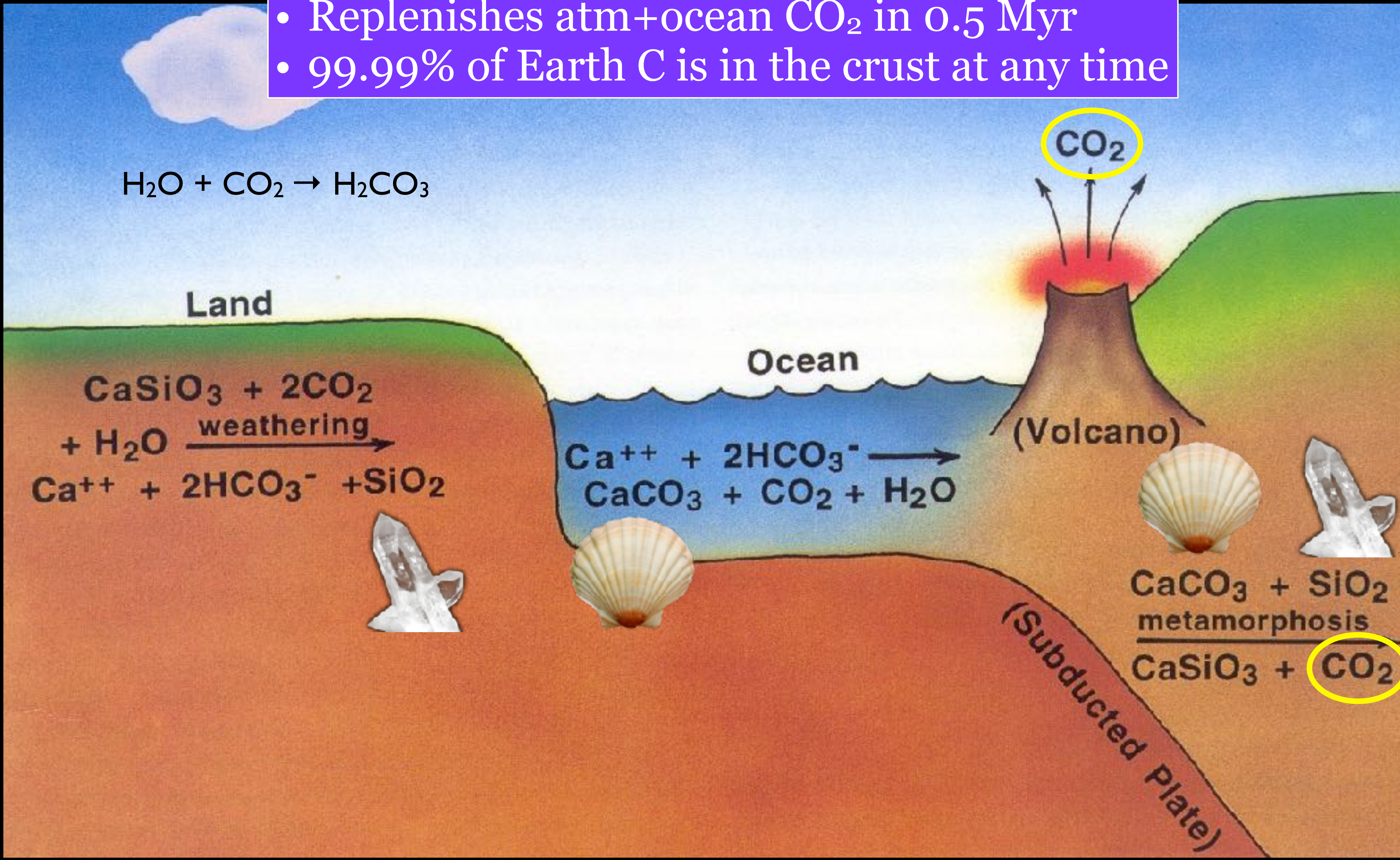
  O_2 ↗ → CH_4 ↘ → Greenhouse effect ↘

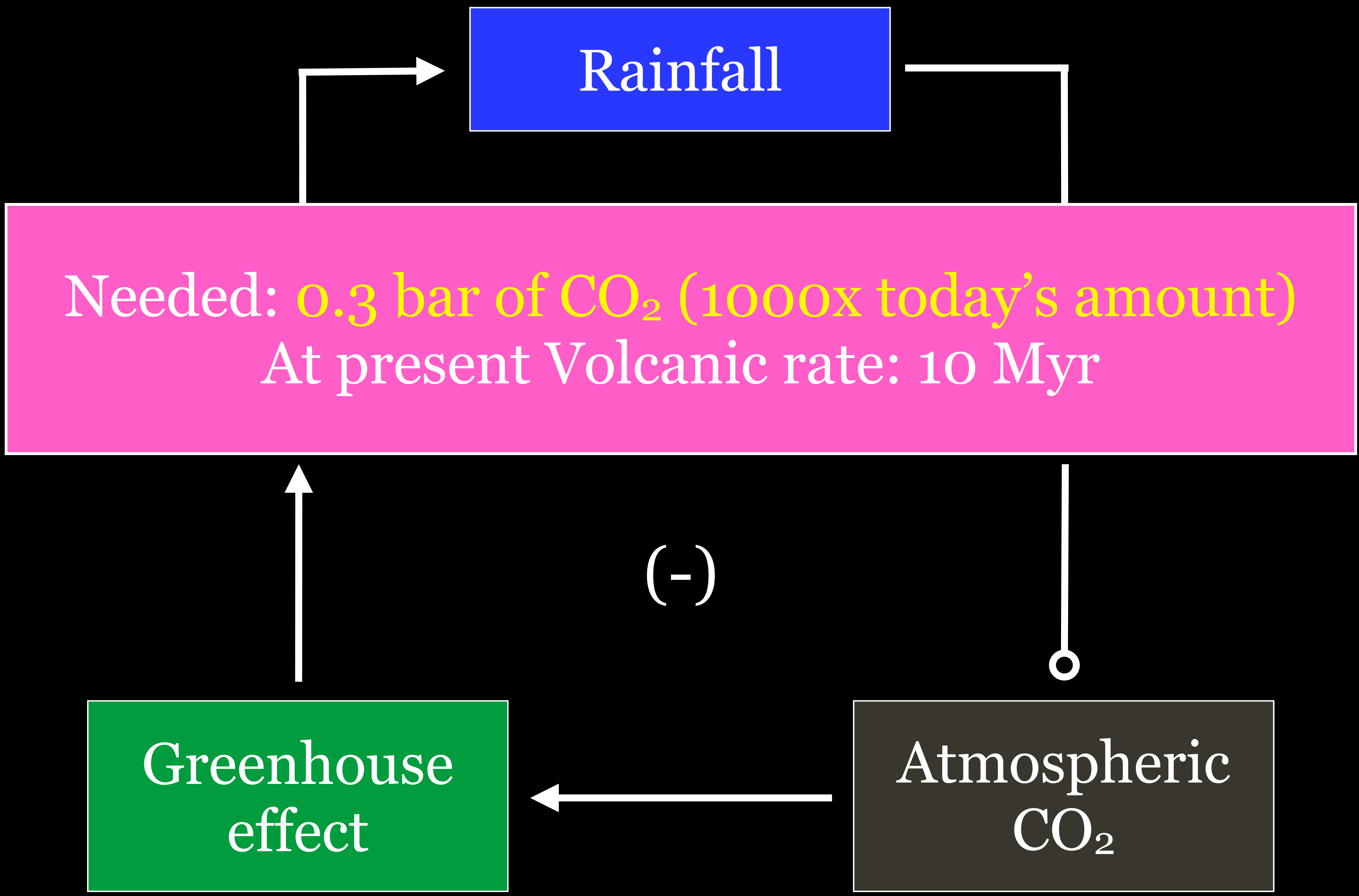
- Next 720 Ma and 580 Ma

How did we get out of it?

Carbonate-Silicate Cycle

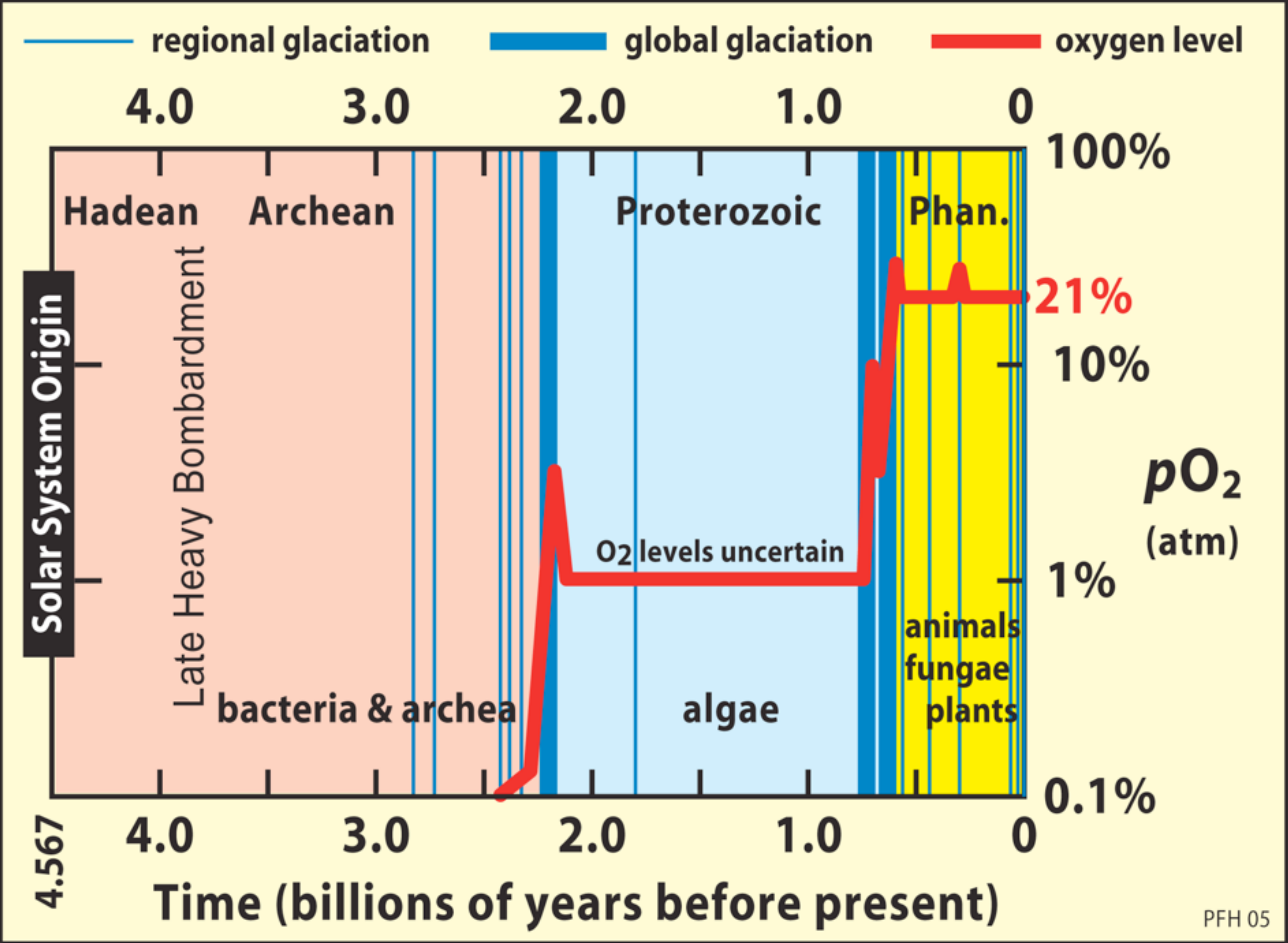
- 200 Myr timescale
- Replenishes atm+ocean CO_2 in 0.5 Myr
- 99.99% of Earth C is in the crust at any time




Rainfall
Needed: 0.3 bar of CO_2 (1000x today's amount)
At present Volcanic rate: 10 Myr
(-)
Greenhouse effect
Atmospheric CO_2

The Rise of Oxygen

Co-evolution of Oxygen and Life



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Time (billions of years before present)
PFH 05

Pre-biotic Oxygen

All the primordial atmosphere was lost during impacts

It was replaced (prior to 4.2 Ga) by a secondary atmosphere (Volcanic out-gassing, late-accretion)

Liquid water was present on the surface by then (Geological evidence)
→ Atmospheric pressure was approaching 1 bar
→ Greenhouse was possible

4.5-4.4 Ga <4.4Ga

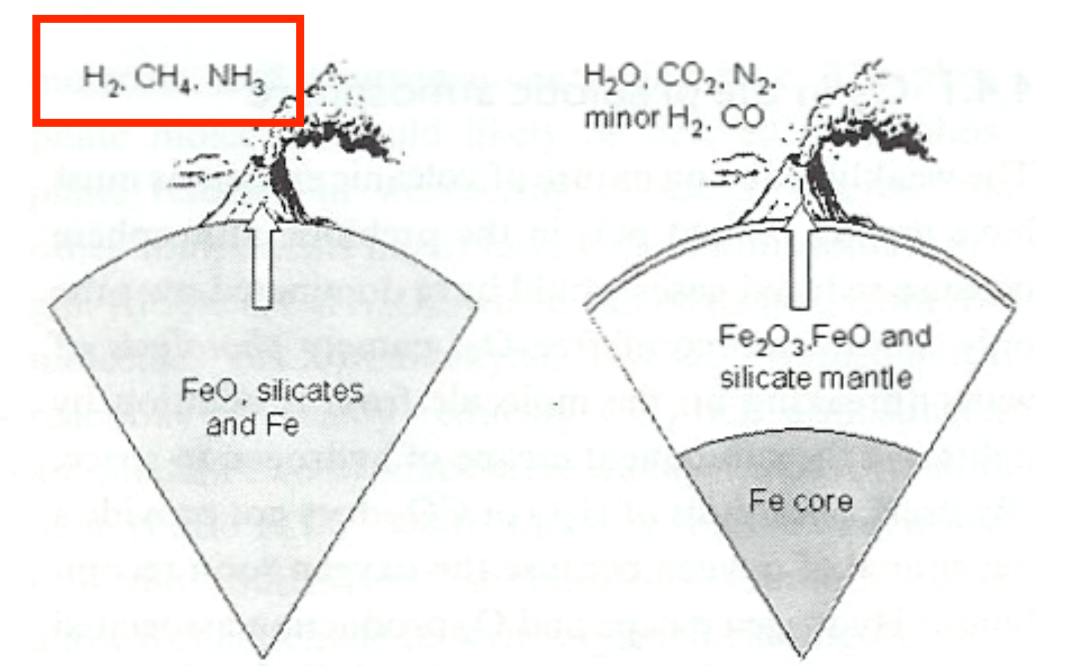


FIGURE 4.7 (Left) During 4.4–4.5 Ga when the mantle was Fe-rich during core formation, reduced volcanic gases were introduced into the atmosphere. (Right) From 4.4 Ga onwards, after the Earth had differentiated into a core, mantle, and crust, a weakly reducing mixture of volcanic gases fed the atmosphere.

Core-Mantle-Crust structure formed in the first 100 Myr

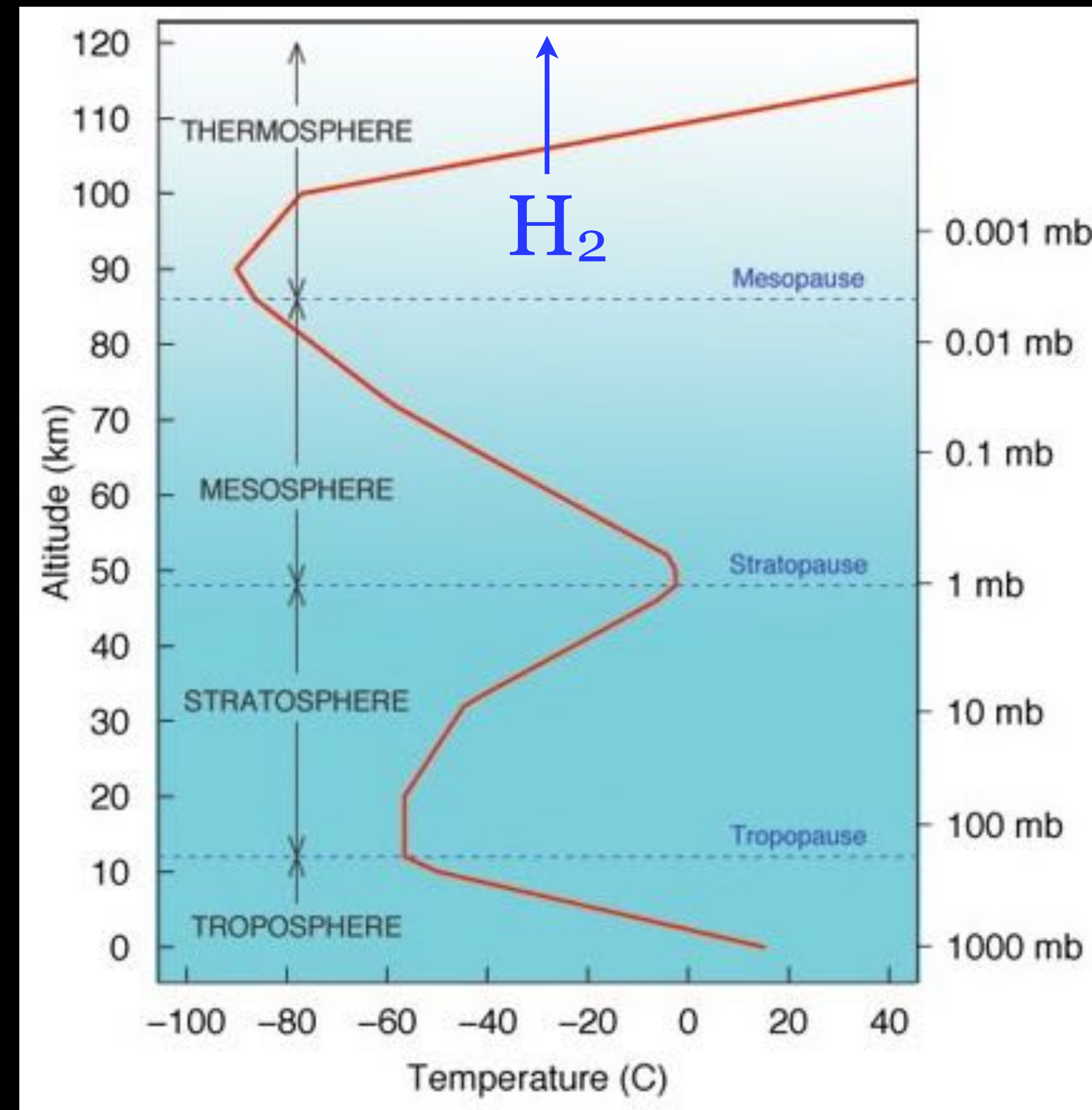
Where did the first abiotic O_2 in the atmosphere come from?

Only source: photolysis of H_2O and CO_2

but fast recombination

Solution: H_2 escapes

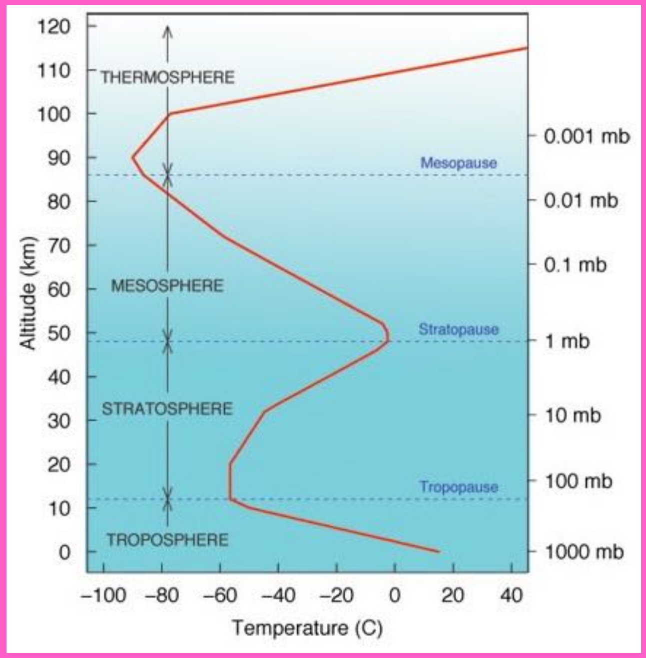
10-40% Thermal escape	60-90% Non-thermal escape



Around ~3.9 Ga, the atmosphere reached an oxidation state close to today's value

What was the fraction of oxygen in the Earth atmosphere prior to Life?

What did the temperature profile of the atmosphere look like?

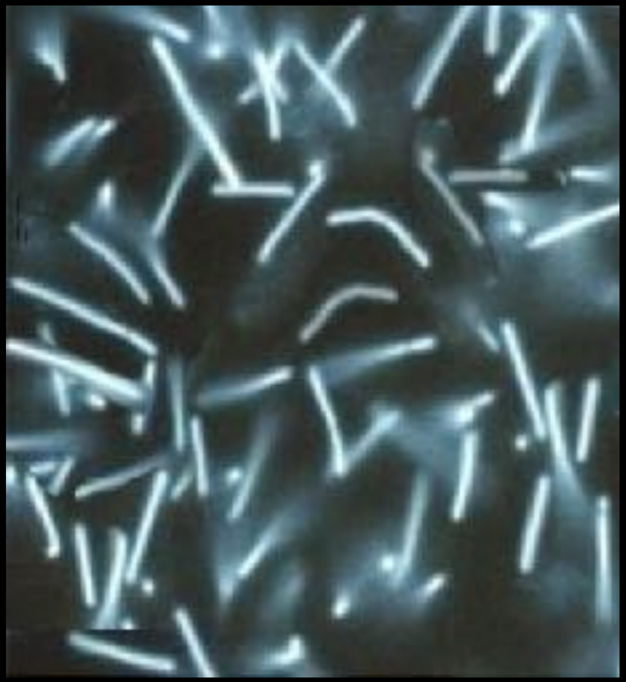


Effects of primitive life on the atmosphere

Life modulates the most important volatiles in the atmosphere: H_2, CO_2, N_2 and O_2

Methanogens regulate H_2 and CO_2

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$



consume H_2 and reject CH_4 → Greenhouse ↗ → weathering ↗ → CO_2 in the atmosphere ↘

Carbon gets bound to inorganic/organic matter

All organisms metabolize N_2
(If they can get it in soluble form…)

N_2 - Nitrogen is essential for life (DNA, RNA, proteins)

But: very few organisms can metabolize N_2 directly from the atmosphere

Solution: $N_2 + CO_2 \rightarrow 2NO + 2\,CO$
(with the help of lightning in the atmosphere)

NO is soluble in water (HNO), can be fixed (anaerobic) and then be used by organisms

Take a break…

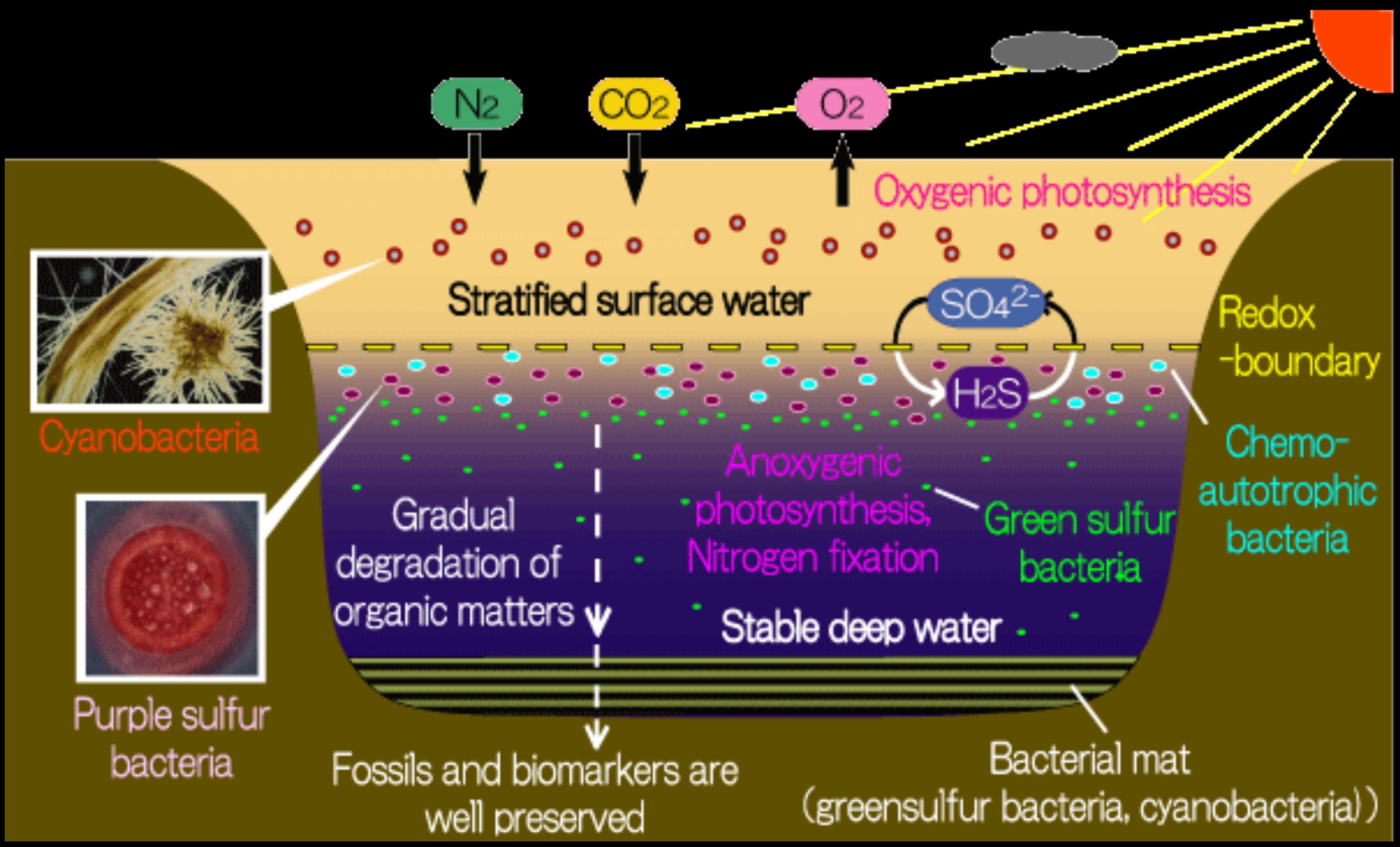
The first Rise of Oxygen

Anoxygenic Photosynthesis

- pre-dates Oxygen photosynthesis (probably 3.5-3.2 Ga)

- principle: use sunlight to extract protons (H^+) from H_2S, store energy in ATP, and use it to extract C by reducing CO_2

e.g. $2H_2S + CO_2 + h\nu \rightarrow CH_2O + H_2O + 2S$

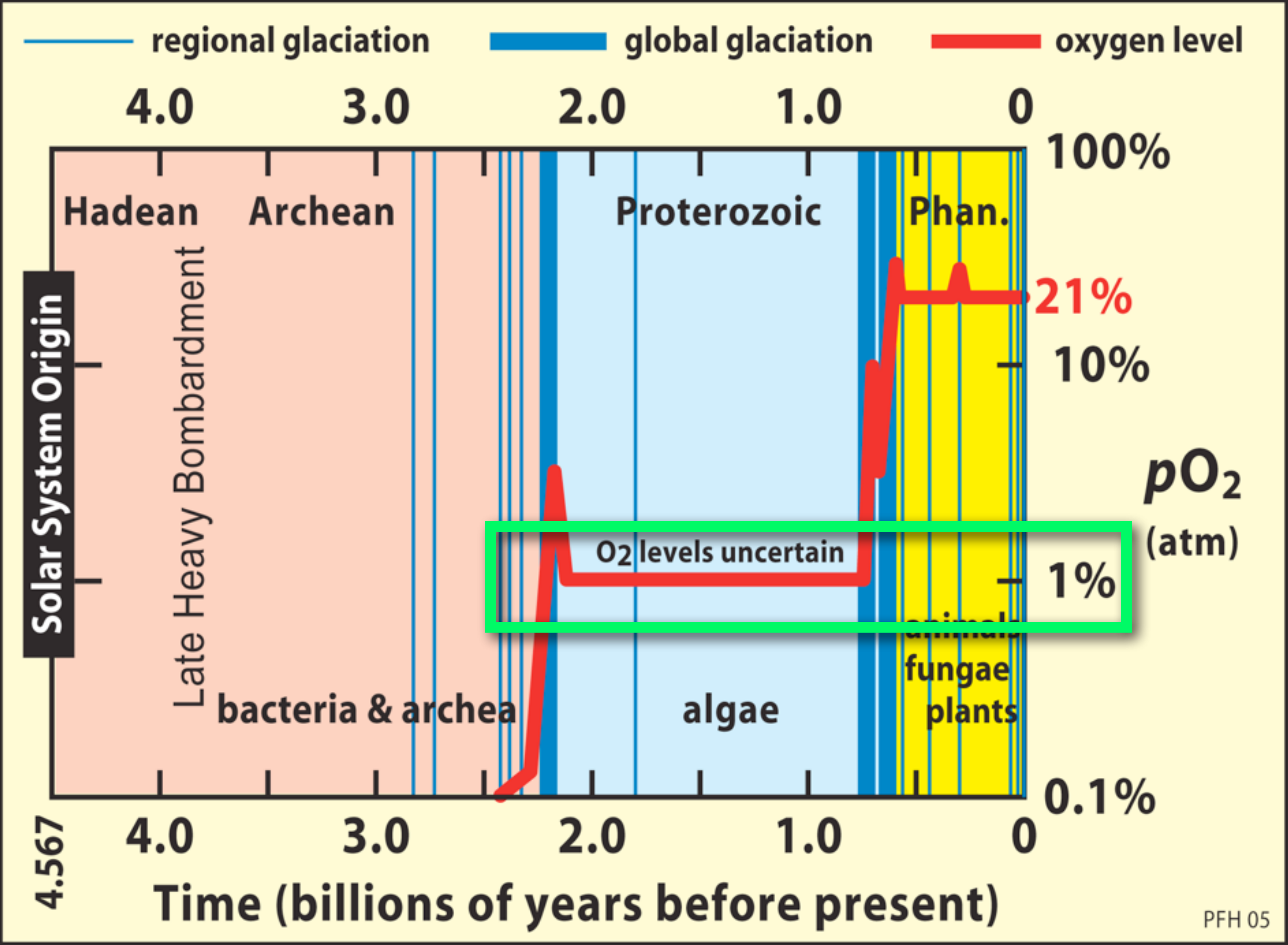


There are no pockets of “old” atmosphere left. How can we trace the early atmosphere?

How old are the oldest ice cores?

Geological evidence for O_2 in atmosphere

Palo Duro Canyon, Texas



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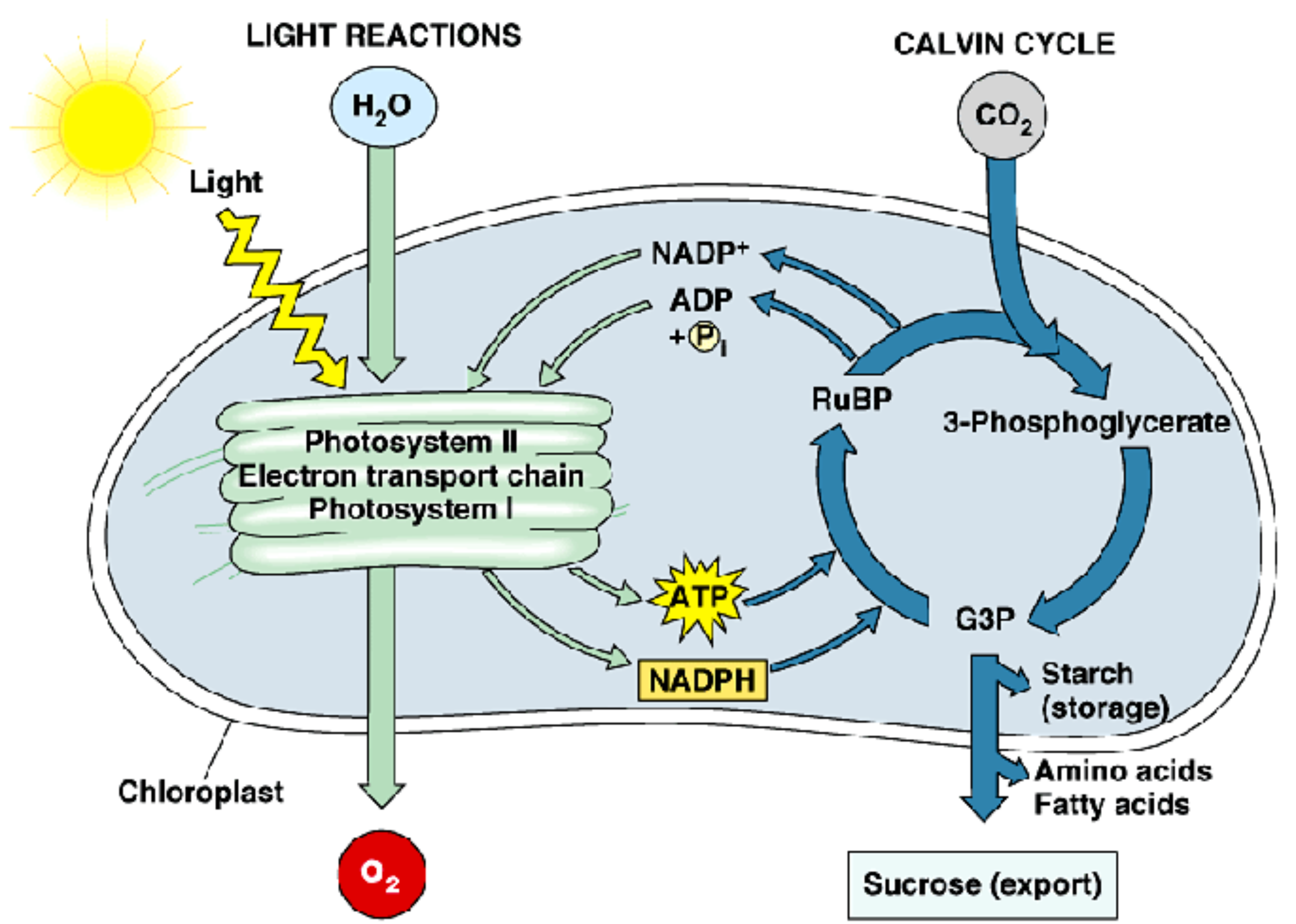
Time (billions of years before present)
PFH 05

Oxygenic Photosynthesis

- probably invented ~2.7 Ga (evidence in Stromatolites)
- principle: use sunlight to extract protons (H^+) from H_2O, store energy in ATP, and use it to extract C by reducing CO_2

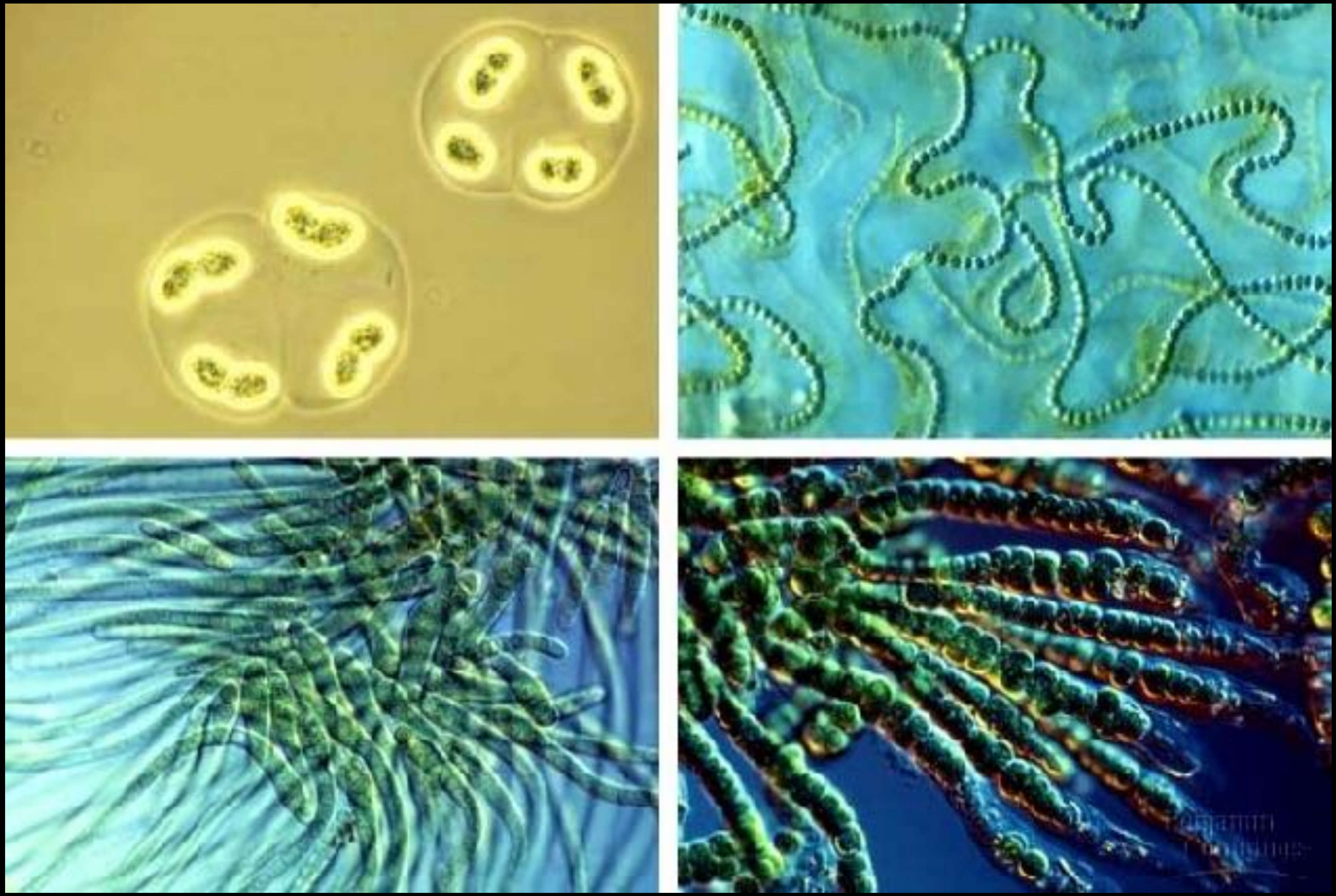


First to use it: Cyanobacteria

Found 0.3-0.4 Gyr before the rise of Oxygen!

Main trick needed: overcome toxic O_2

Today found as Chloroplast in Eukaryotes



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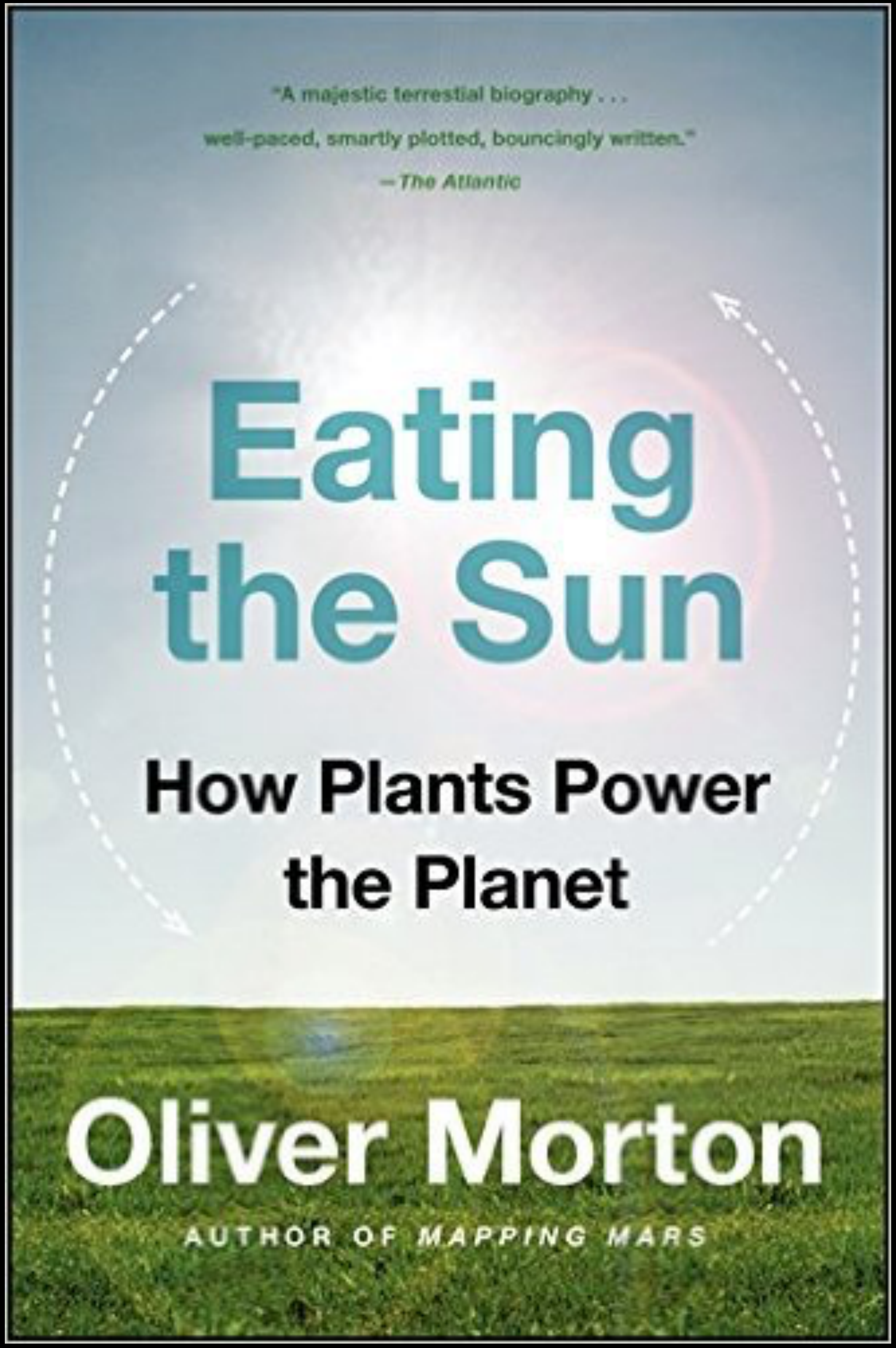
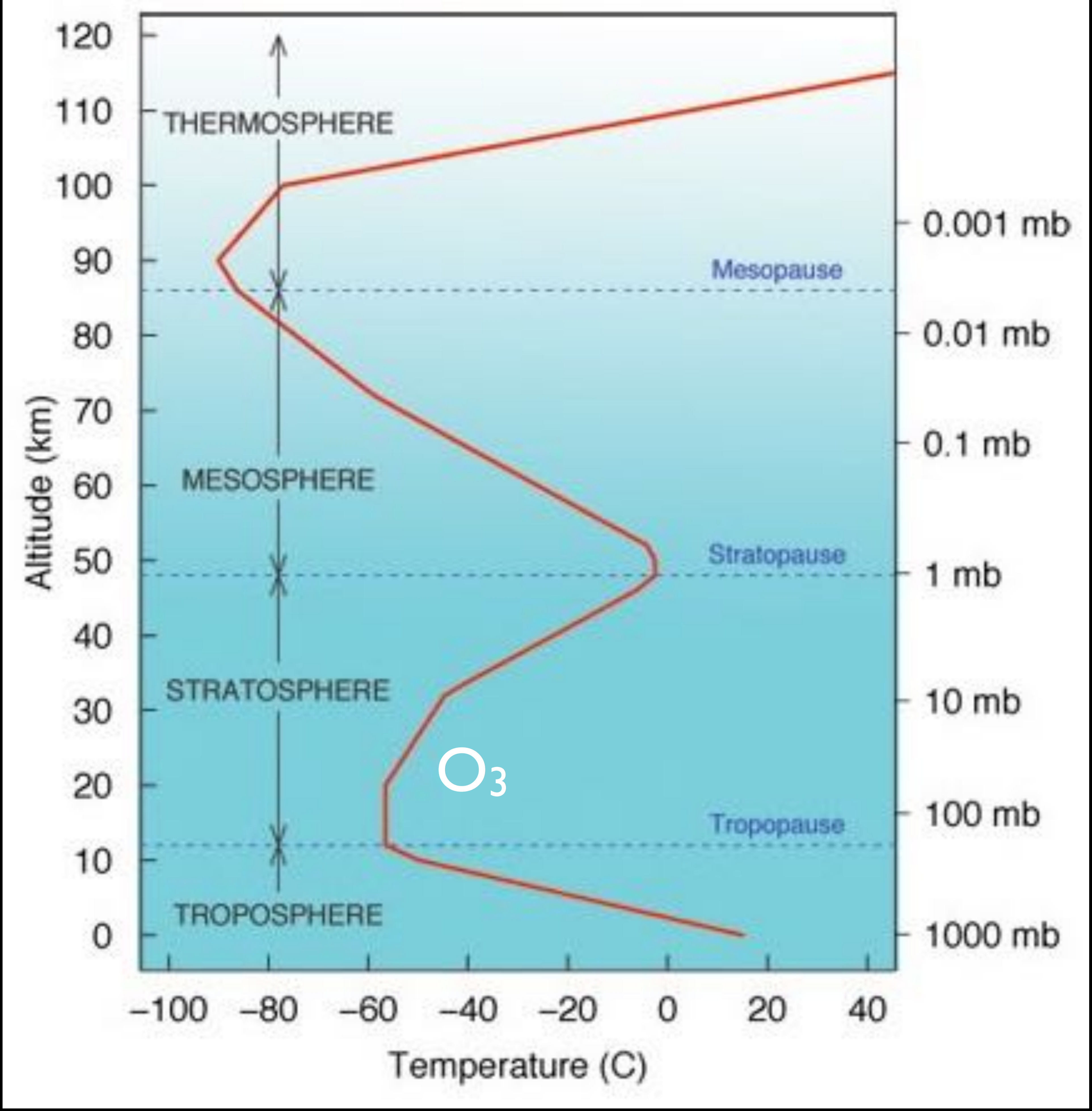


With Oxygen comes Ozone…

What is the effect of Ozone on the stratosphere?

Why is Ozone important for Life?



THERMOSPHERE
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O_3
Altitude (km)
Temperature (C)
0.001 mb
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10 mb
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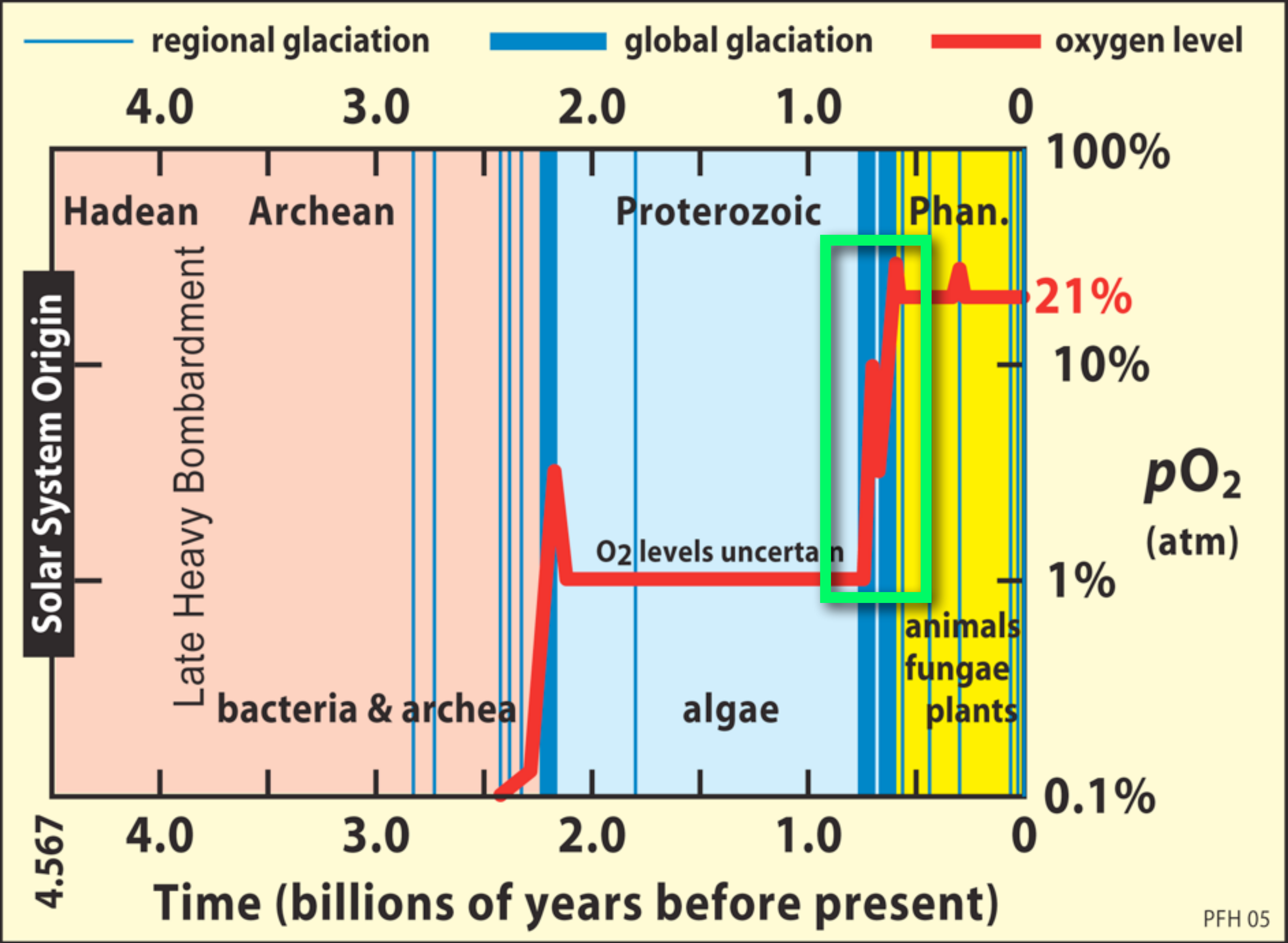
1000 mb

The Ozone shield → allows life at the surface

The Ozon layer appeared with the rise of Oxygen (~2.4-2.3 Ga ago) in the lower Stratosphere (10-20km)

CO_2 protects < 200nm
O_3 protects 200-300 nm (already at 1% of todays O_2)

The next Rise of Oxygen



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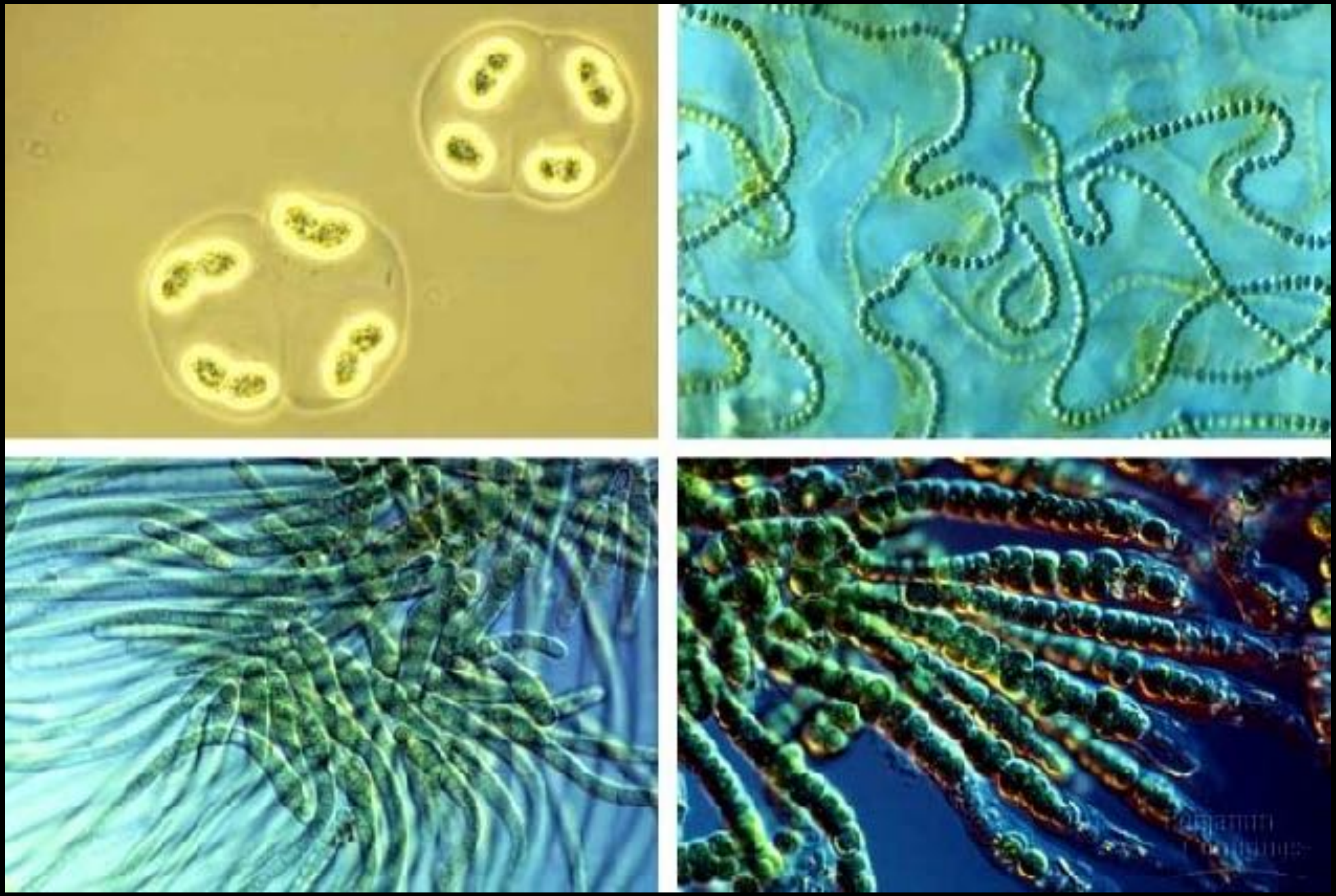
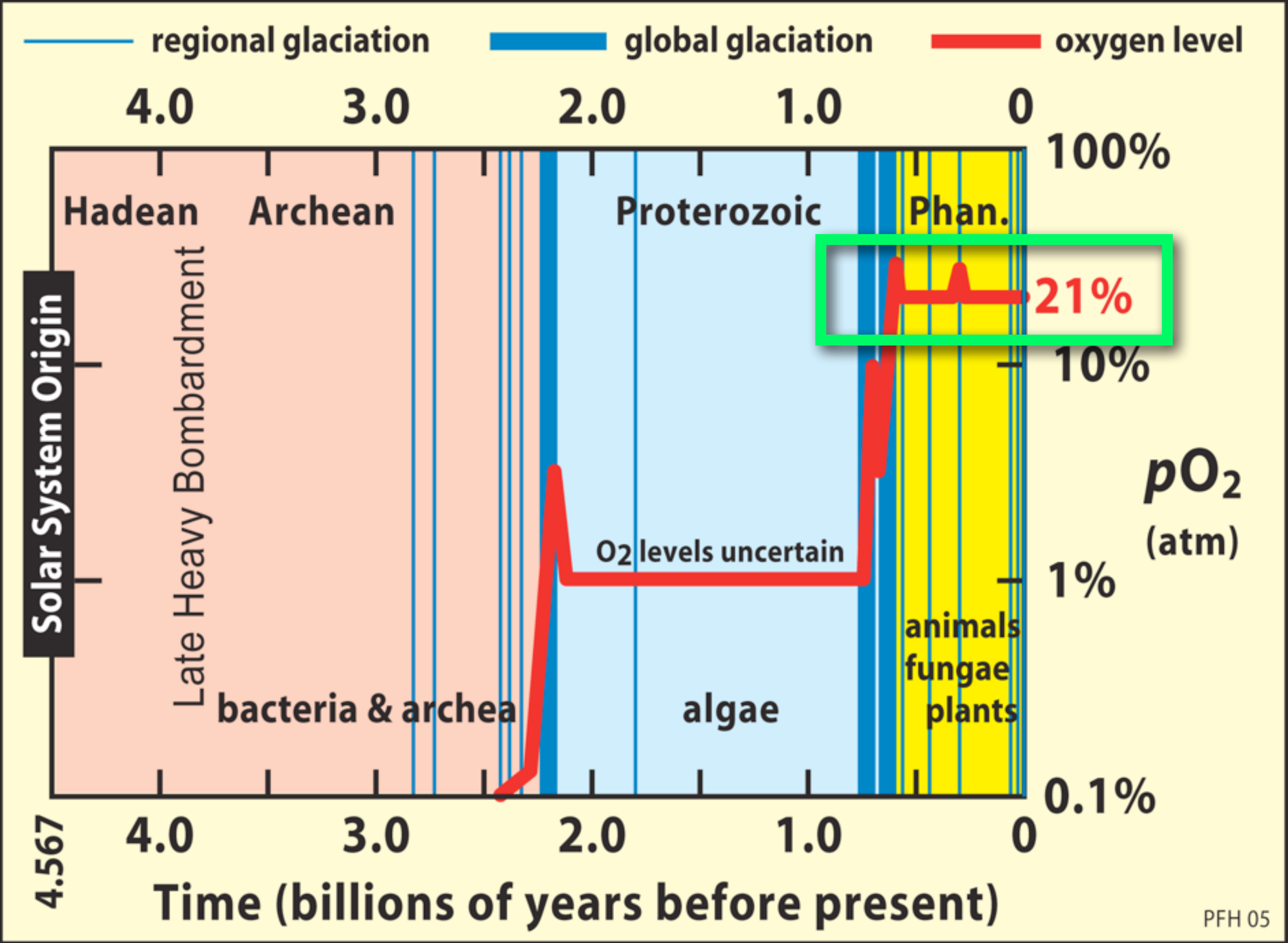
Time (billions of years before present)
PFH 05

Most likely, organism with Oxygenic Photosynthesis expanded rapidly after a (near) total glaciation...



Who are the main producers of oxygen today?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When is a Planet “habitable”?

When would you claim
that a planet is habitable?

Water is important

- For all biological processes
- For stability of the climate
- For short-term temperature stability (heat capacity)

In order to detect LIFE in the atmosphere
it is a lot easier if it is on the surface of the Planet

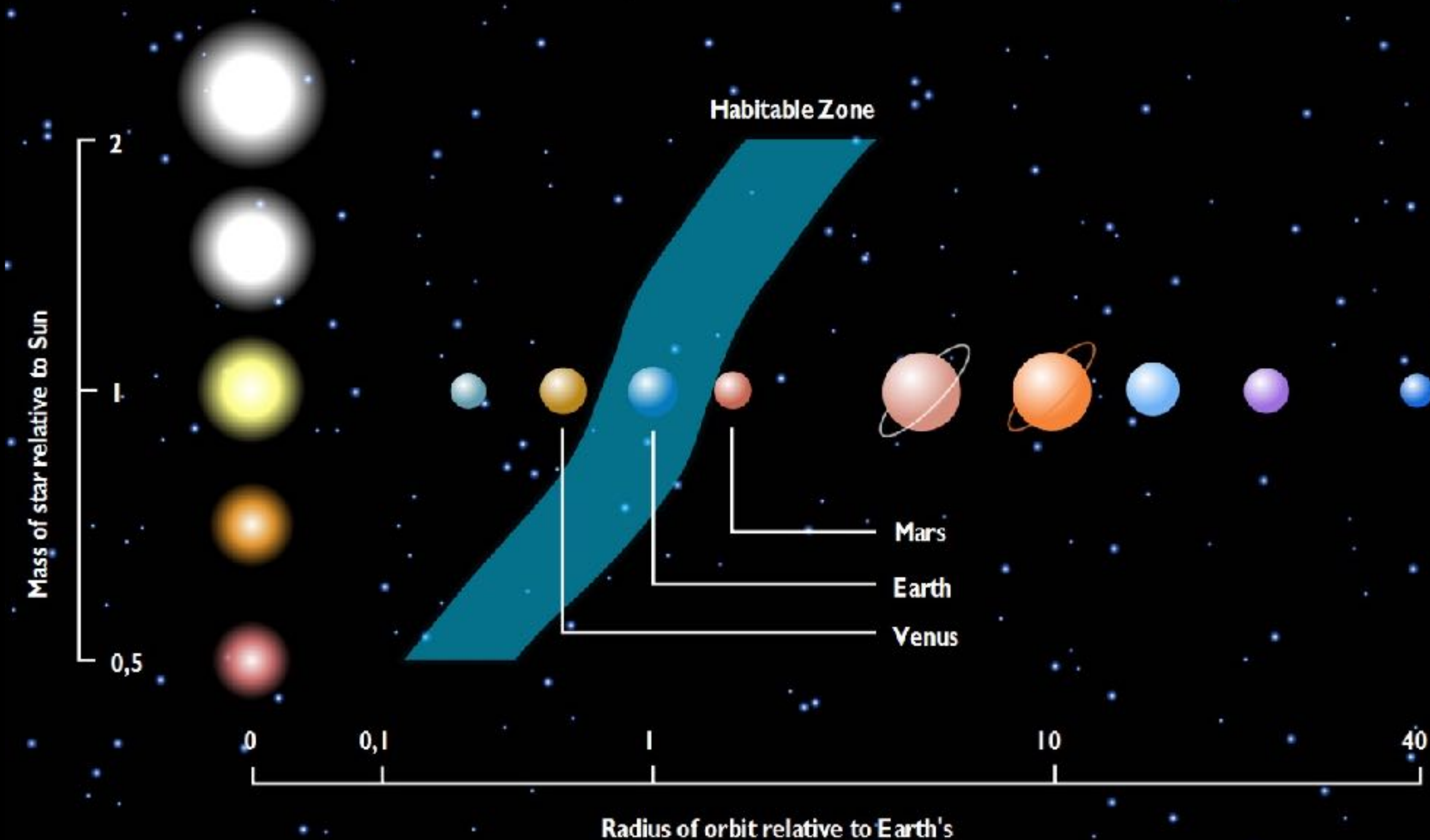
Start the search
where Water is liquid on the surface

A planet is habitable if it provides the environment, materials and processes that are advantageous for the formation and long-term evolution of life

The Habitable zone was first know as
“Liquid Water Belt” (Shapley 1953),
“Ecosphere around the Sun” (Strughold 1953), before
“Habitable zone” (Su-Shu Huang 1959)

Often Human-centric view for life as we know it

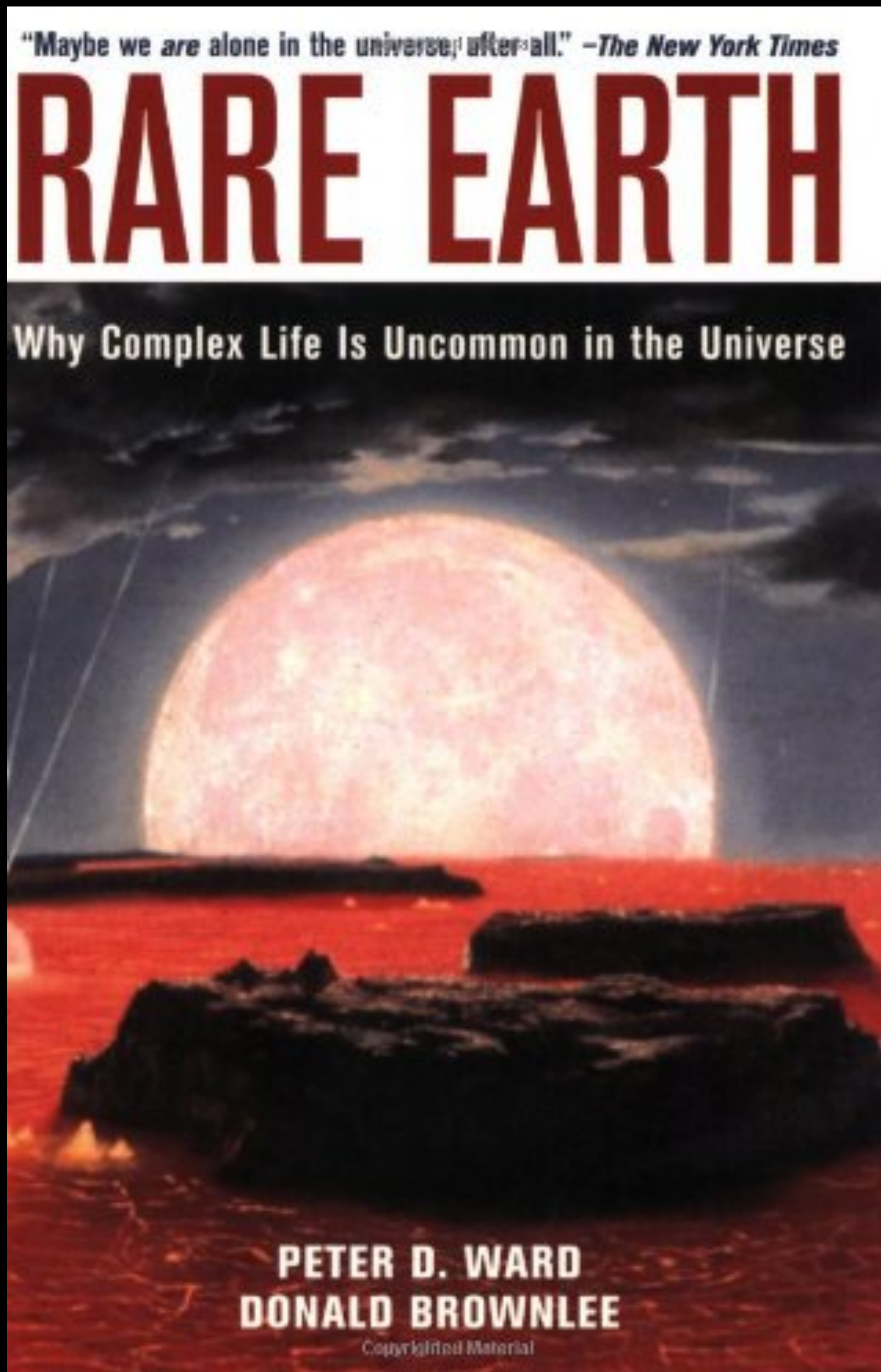
Habitability is more than “liquid water on surface”

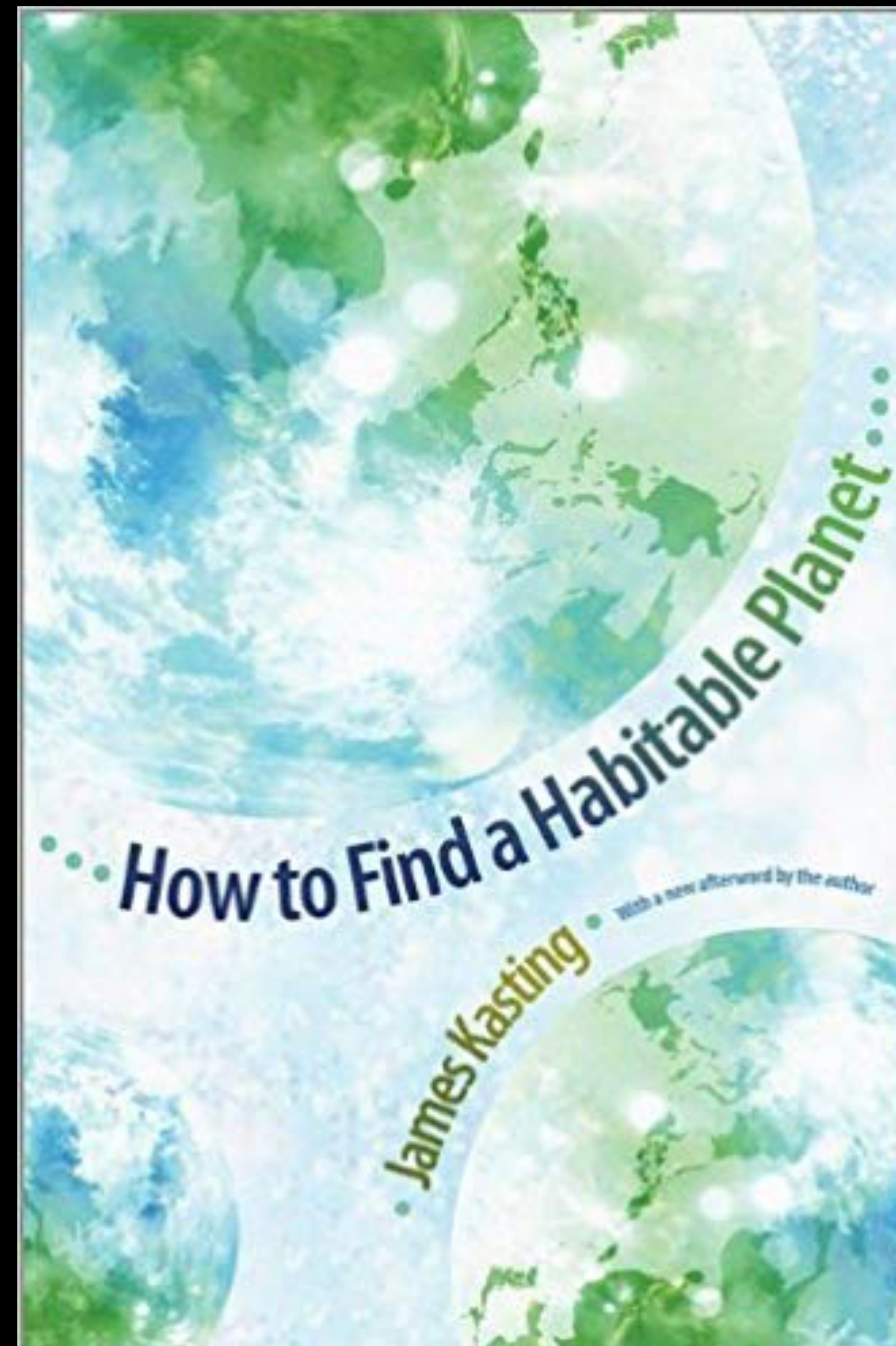

Habitable Zone
Mass of star relative to Sun
2
1
0,5
Mars
Earth
Venus
0
0,1
1
10
40
Radius of orbit relative to Earth's

Why should we search on Venus and Mars, when they are outside the “habitable zone”?

Other Factors that influence Habitability...

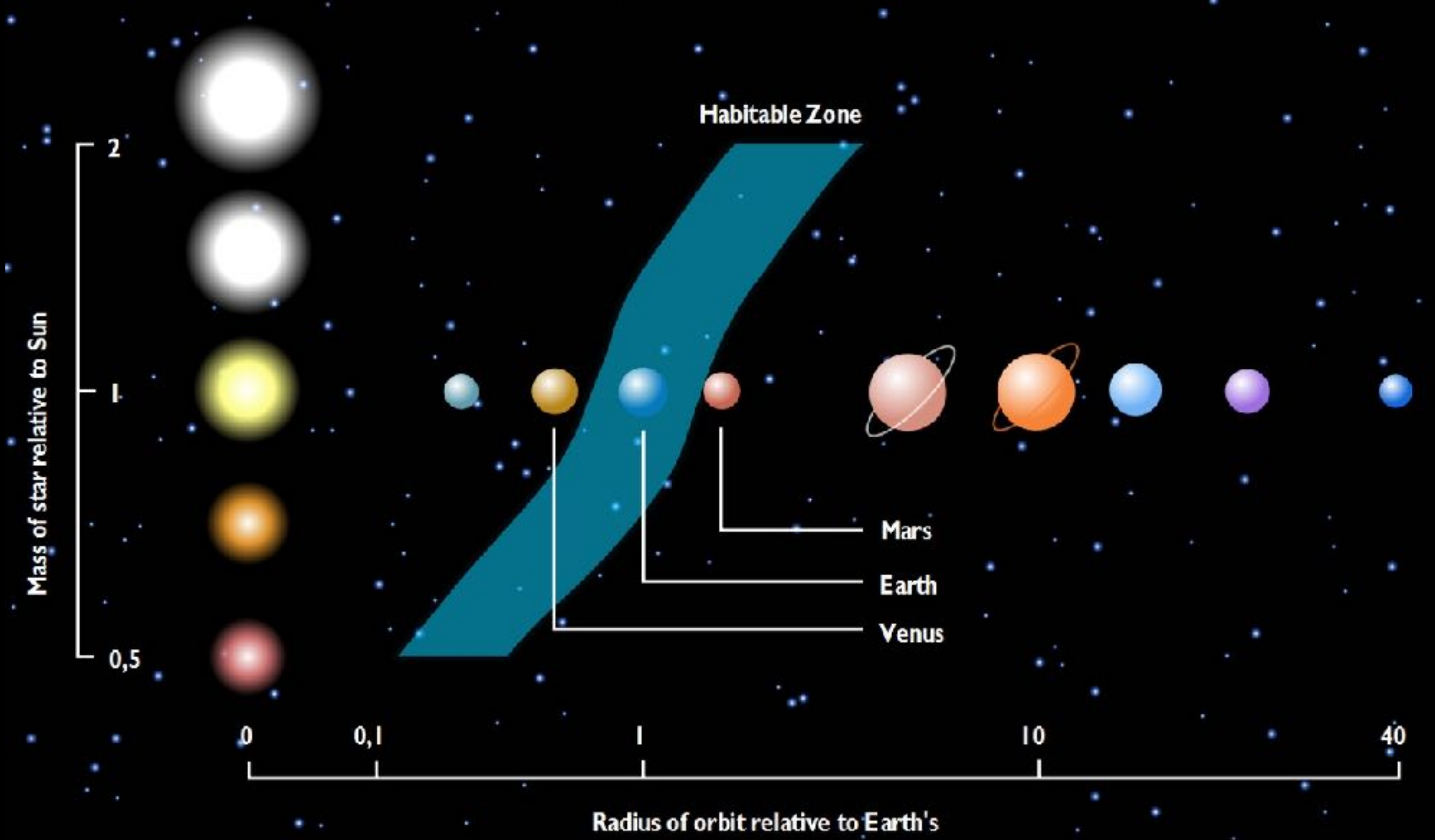
Re-considering…





Lunch break…

Runaway Greenhouse:
The Evolution of Venus


Habitable Zone
Mass of star relative to Sun
2
1
0,5
Mars
Earth
Venus
0
0,1
1
10
40
Radius of orbit relative to Earth's

Venus: Earth "Sister"

Distance from Sun: 0.72 AU
Mass: 81% of Earth

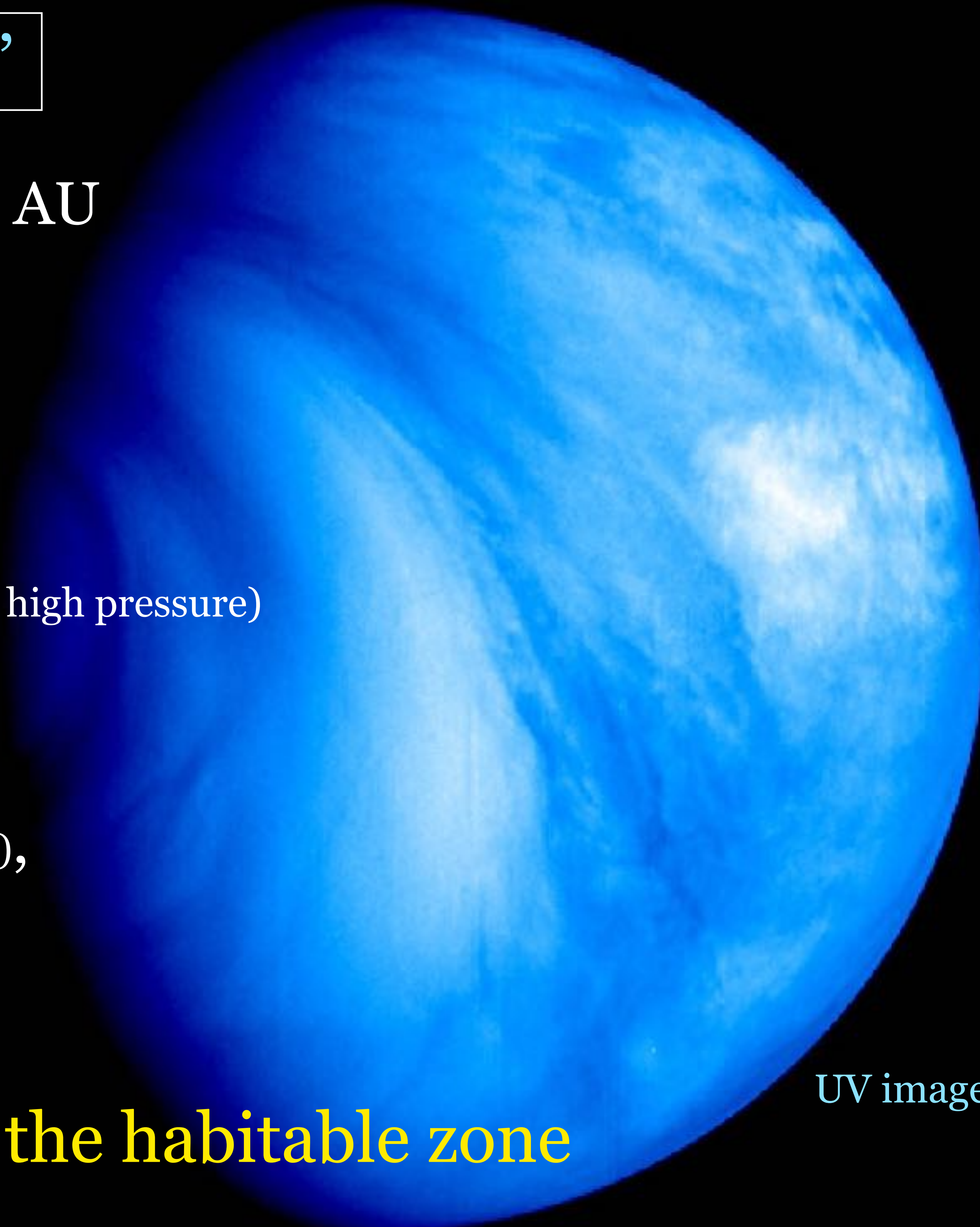
But....

T_{surf} = 460 ^{o}C
(too hot for liquid water, even under high pressure)

P_{surf} ~ 93 bars

ATM: CO_2 (96.5%), N_2 (3.5%),

traces of SO_2, H_2O, CO
leading to H_2SO_4 rain

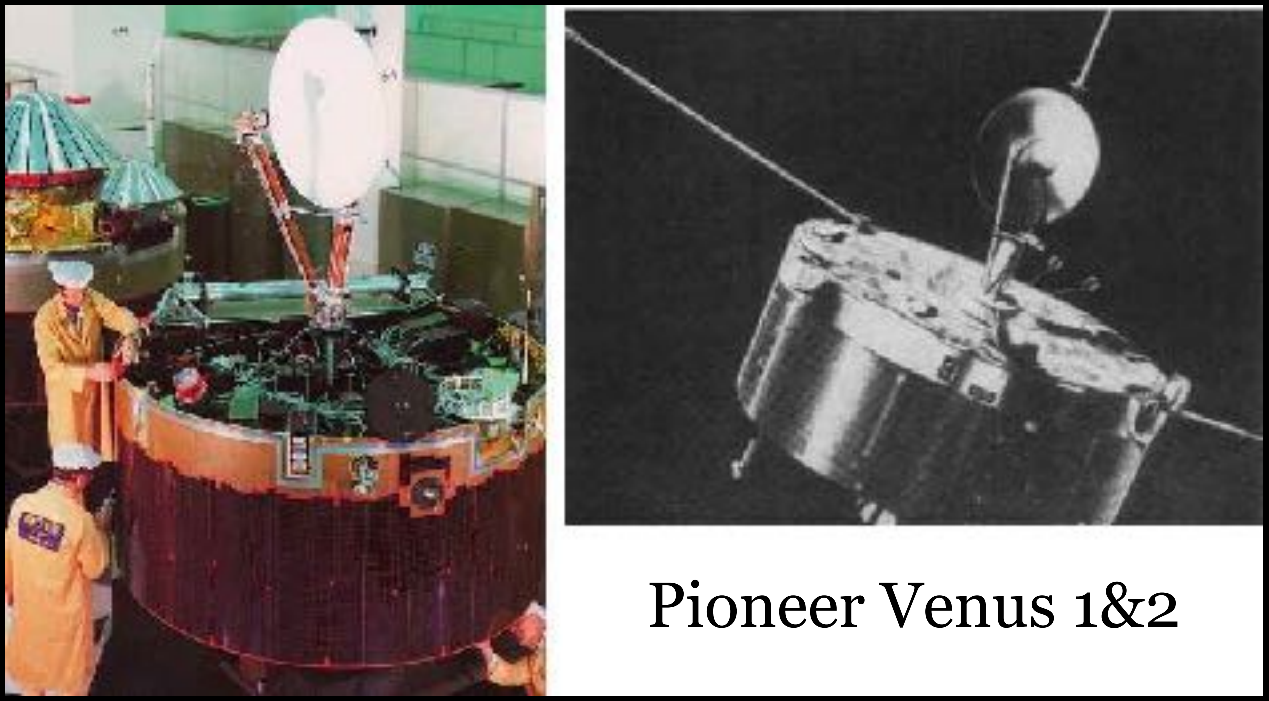


UV image

Secure inner limit of the habitable zone

Did Venus start wet or dry?

Pioneer Venus (1977/1978):



today: only 10^{-3} x Earth H_2O
(in atm 30 ppm vs. 1000-40,000 ppm)

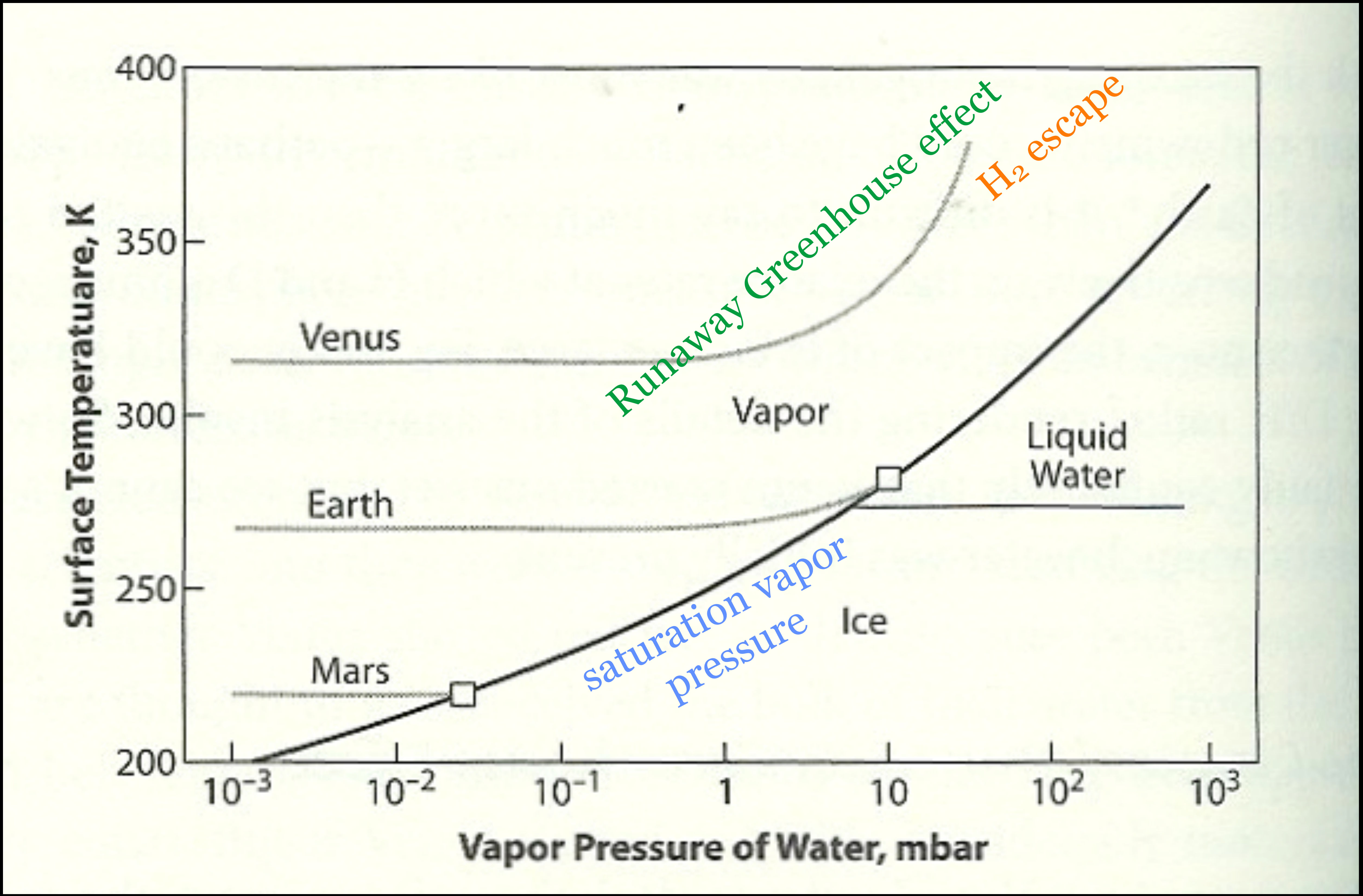
but D/H ratio: 150 x Earth

H^+ escapes, D^+ (heavier) less…

Venus started with surface water!

How much is unclear…

A simple model based on no initial atmosphere, pure H_2O volcanism, and all albedos = Mars' albedo = 0.17



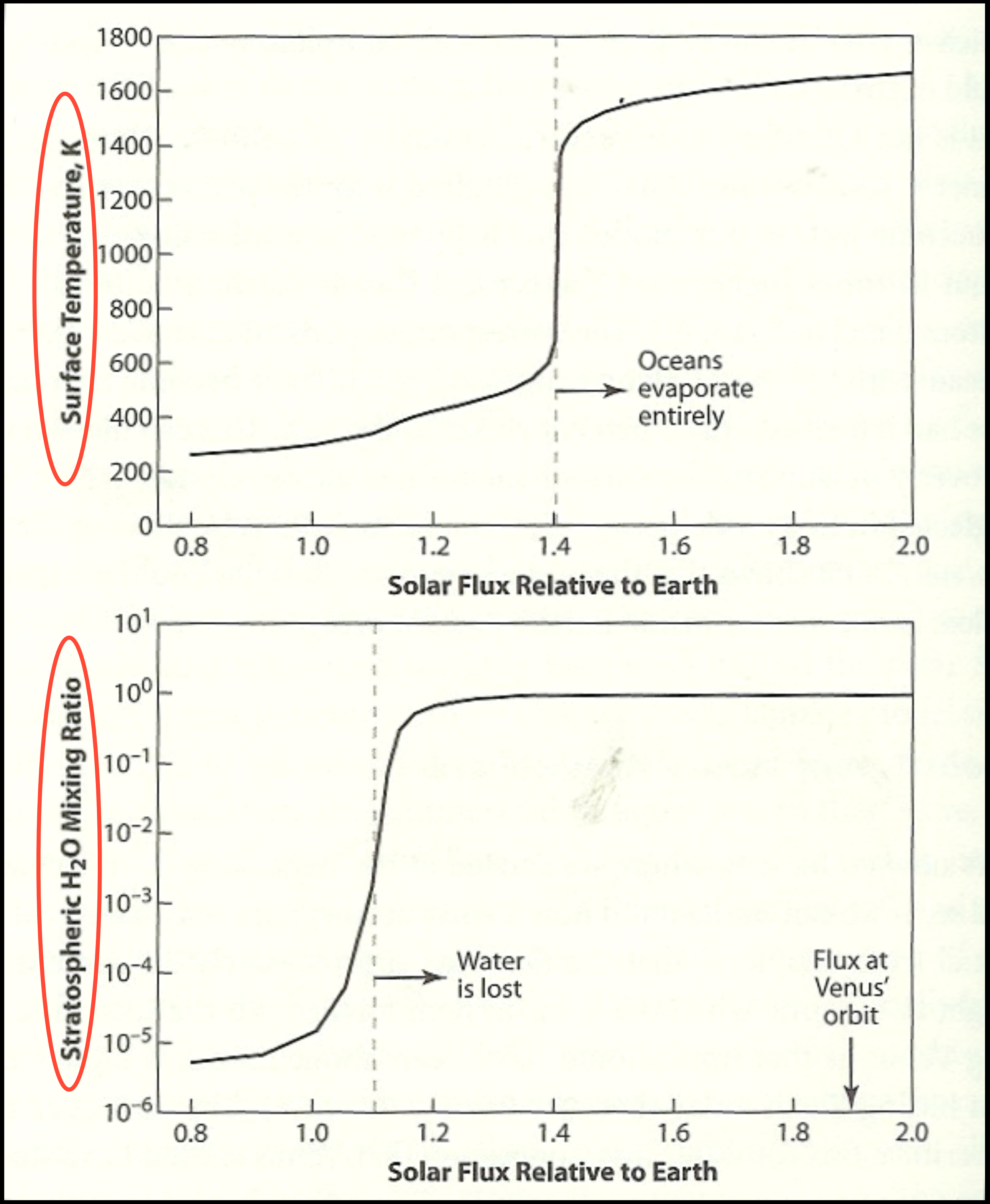
How much more radiation flux from the Sun does Venus get (at 0.72 AU) than Earth?

Gedankenexperiment: moving Earth closer to the sun

At ~1.4 x Earth solar flux (i.e. 0.85 AU):
Runaway Greenhouse
Oceans evaporate entirely

At ~1.1 x Earth solar flux (i.e. 0.95 AU):
The tropopause is lifted (from 10-15km to 150km)
A wet stratosphere develops and H_2O is lost

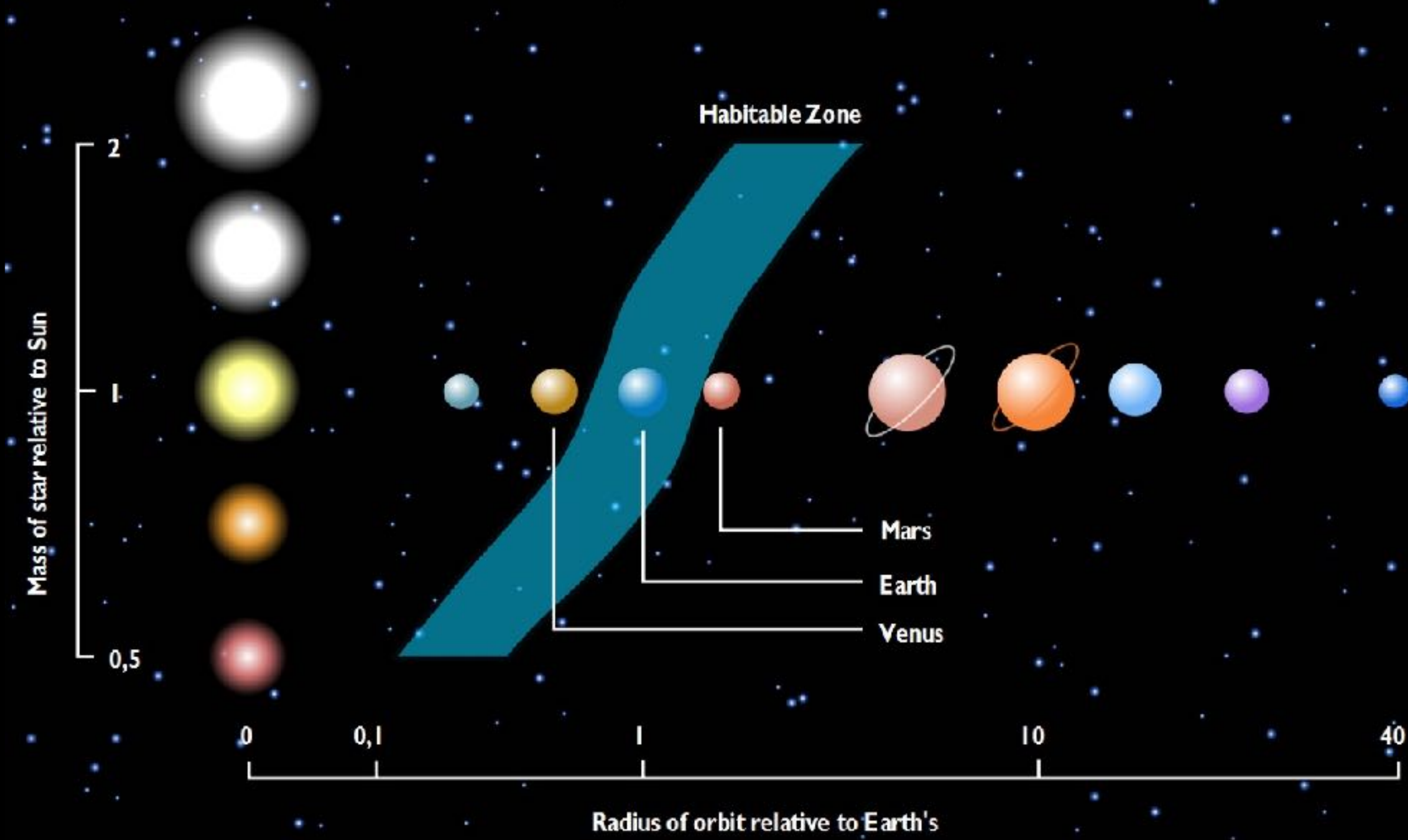
This is the inner edge of the Habitable Zone



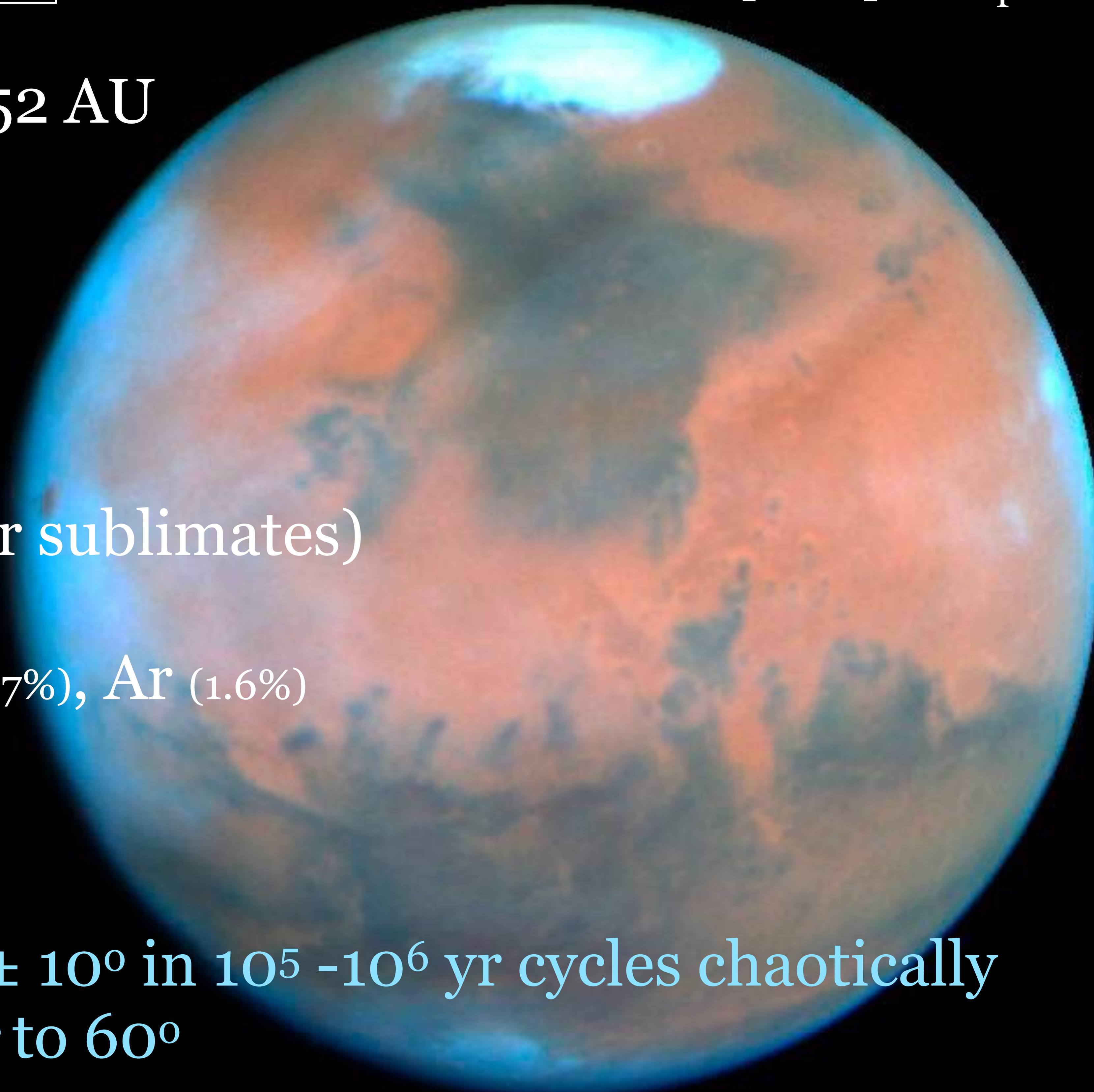
cold trap is lost
Ozone is destroyed

Climate History of Mars

How did the inner/outer edge vary as a function of time?


Habitable Zone
Mass of star relative to Sun
2
1
0,5
Mars
Earth
Venus
0
0,1
1
10
40
Radius of orbit relative to Earth's

Mars: the red planet



Distance from Sun: 1.52 AU
Mass: 11% of Earth

and….

T_{surf} = -55 ^{o}C
P_{surf} ~ 6-8 mbar (water sublimates)

ATM: CO_2 (95.3%), N_2 (2.7%), Ar (1.6%)

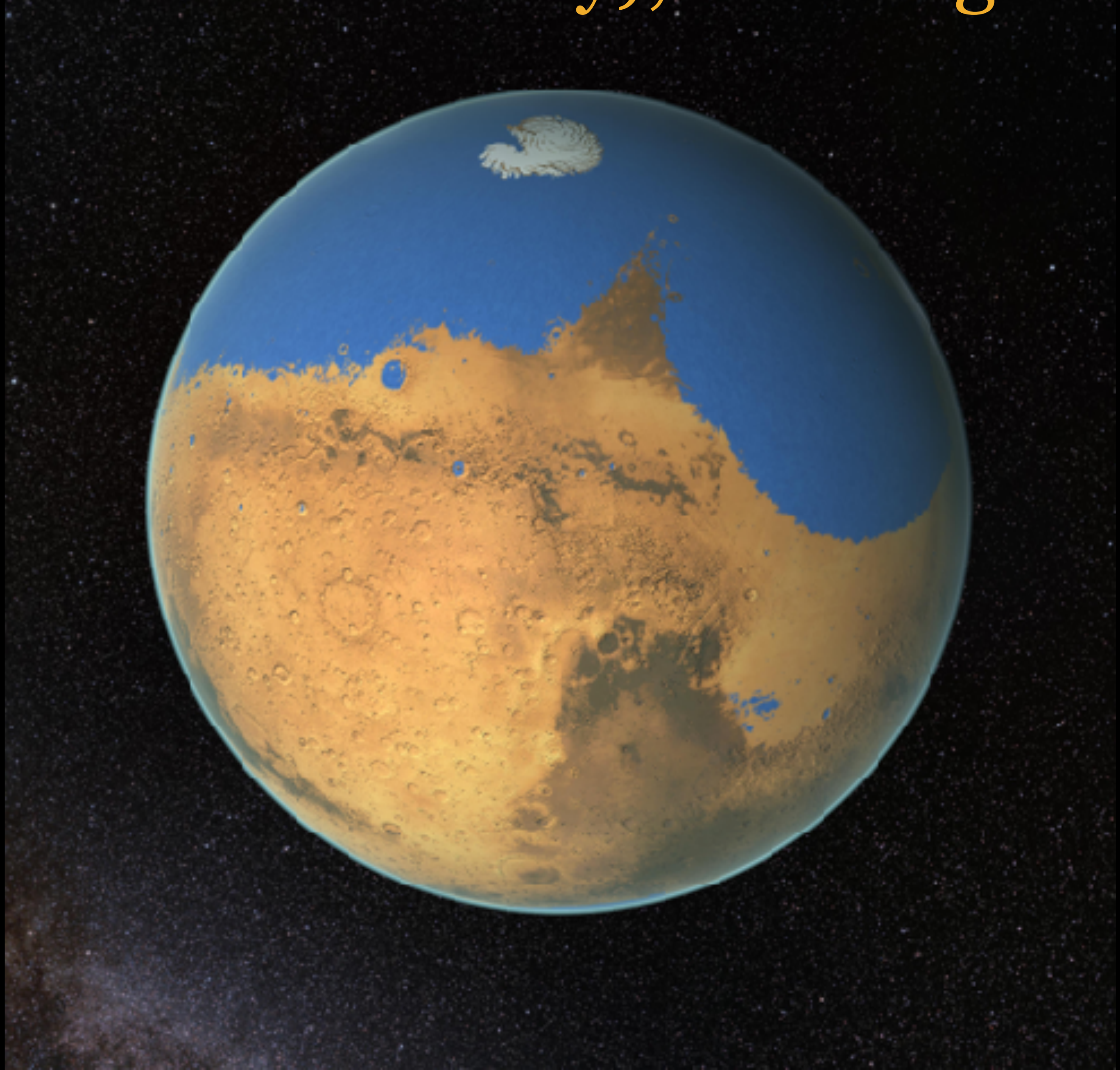
traces of O_2, CO, H_2O

Obliquity changes by ± 10^{o} in 10^5 -10^6 yr cycles chaotically and can range from 0^{o} to 60^{o}

Did it ever rain on Mars?

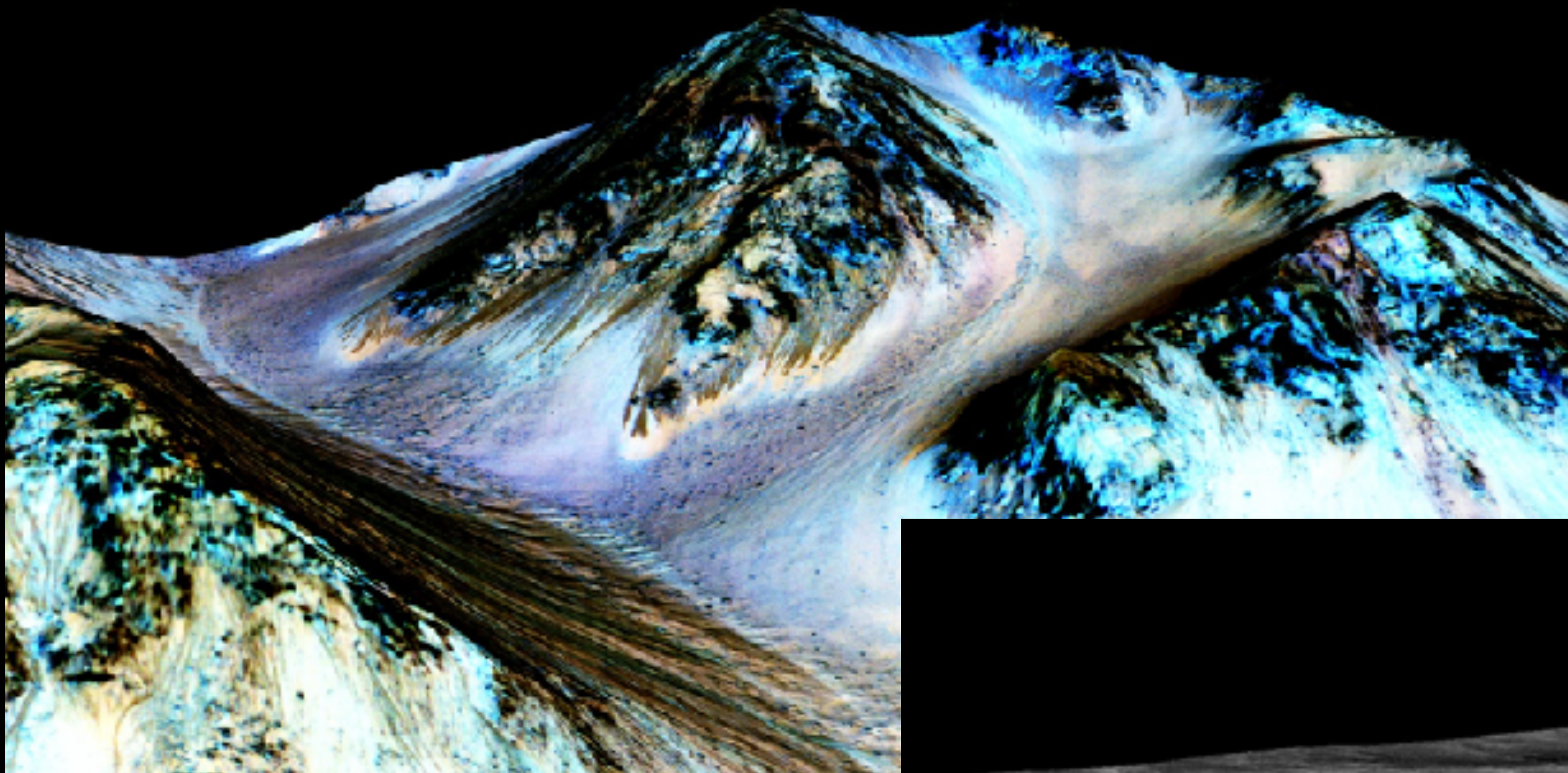
Comparison of HDO with H_2O in water on Mars today vs. Mars meteorites dating from 4.5 Ga ago

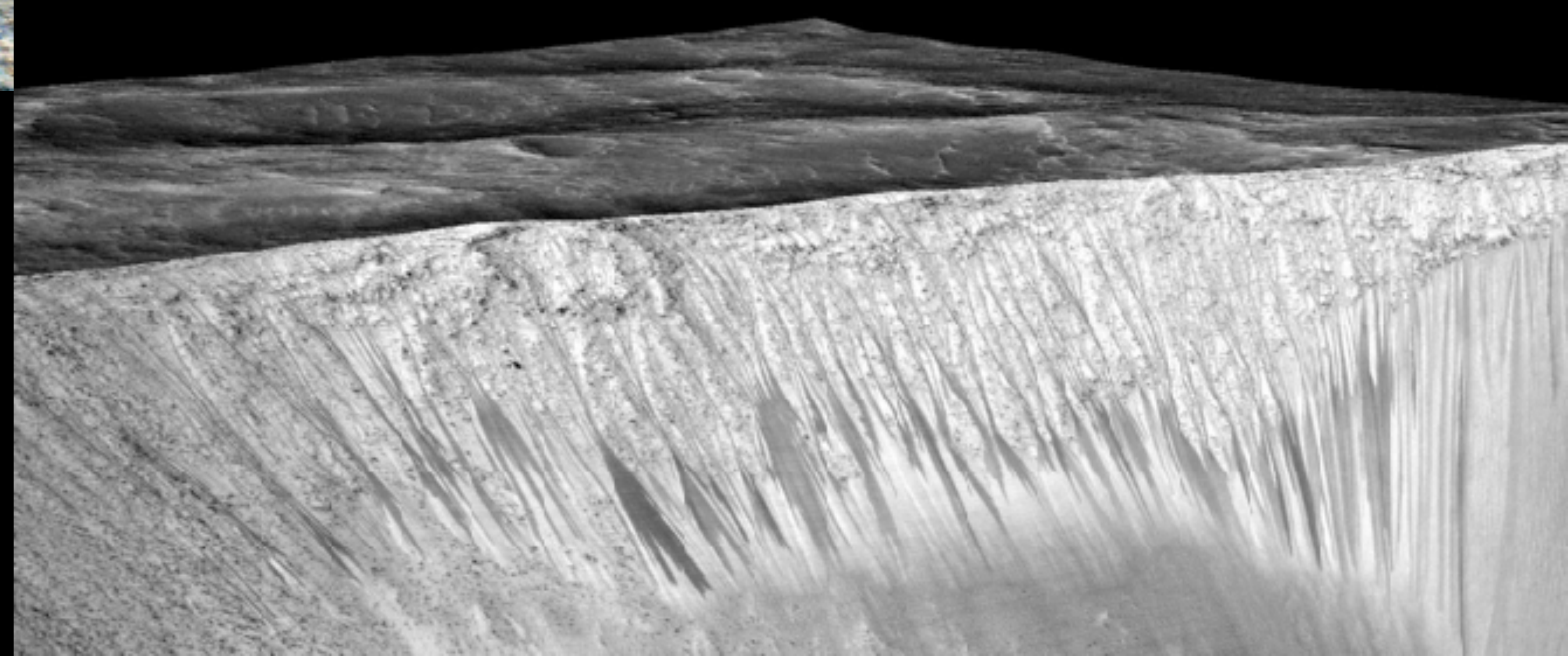
Deduced that 20 million km^3 of water were liquid (1/70 of the amount on Earth today), covering 20% of Mars



Did it ever rain on Mars?

The Mars Reconnaissance Orbiter, in 2015, confirmed evidence that water flows on Mars today (hydrated minerals in the slopes of the Hale crater)





Could early Mars have been warm?

Earth analogy: early Greenhouse gases were CO_2 and CH_4

CO_2 : through Volcanism ✔

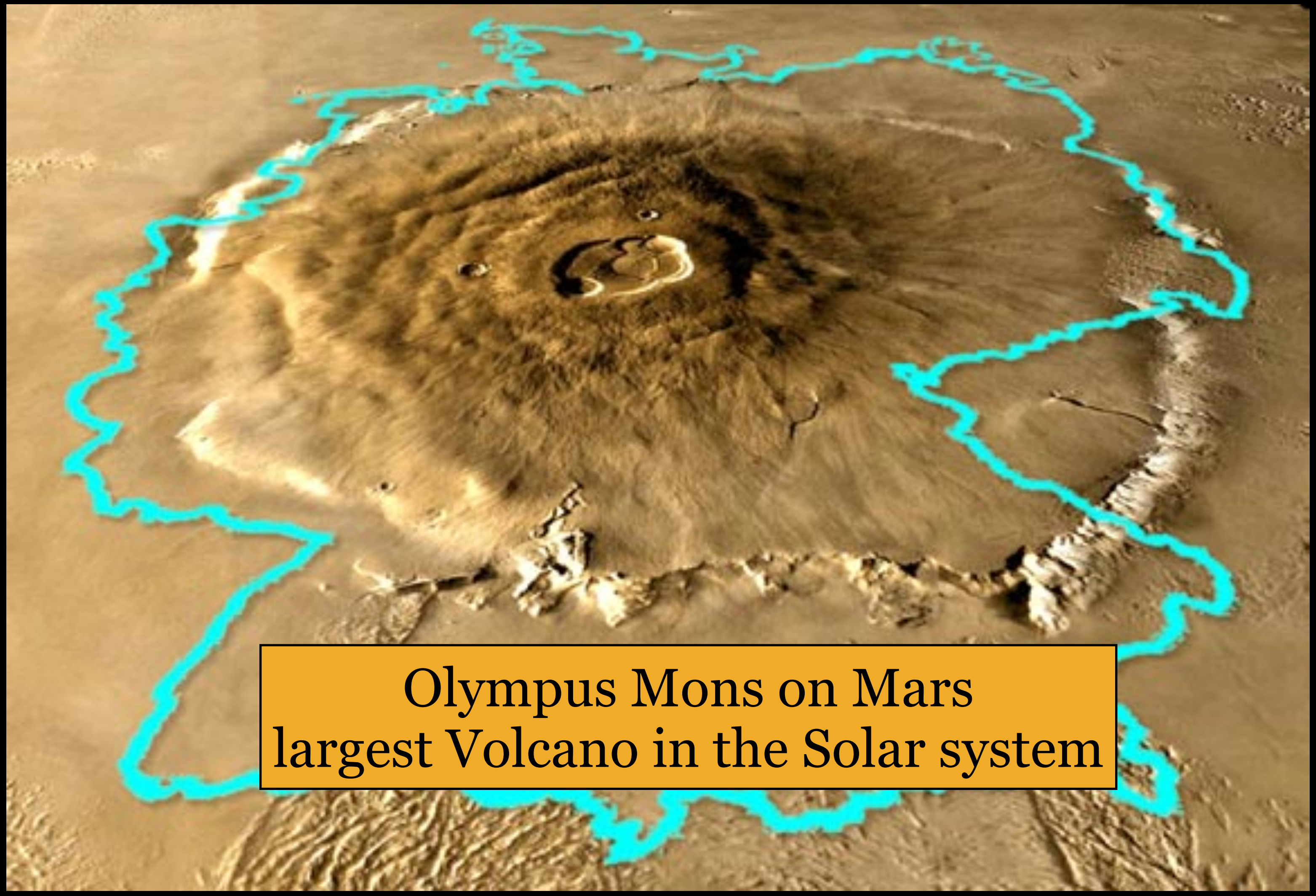
CH_4 : abiotic? biotic (methanogens)? ✔

SO_2 : Volcanic origin but unstable in the atmosphere ✖
(Note: leads to H_2SO_3 and acid surface, explains absence of carbonates)

but...
at <3.8 Ga and 1.52 AU, Solar intensity was 32% of Earth today

→ Max. T_{surf} ~ 225K (-48°C)

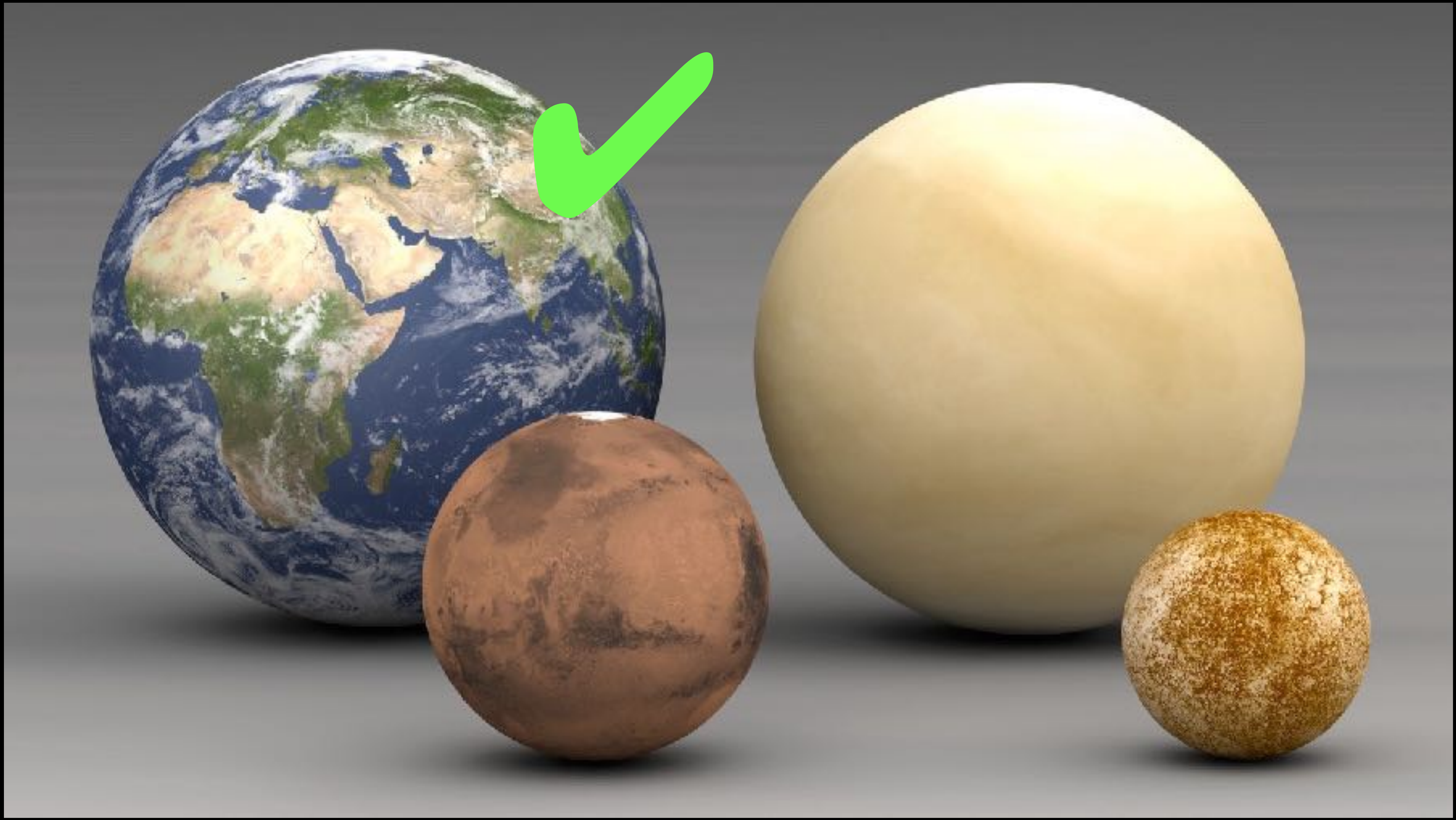
Today Volcanism stopped on Mars



If this were not the case (if Mars were more **massive** and had tectonic activity) there would be enough CO_2

At ~0.7 x Earth solar flux (i.e. 1.2 AU): CO_2 condenses to clouds and the greenhouse effect is reduced

The outer edge of the Habitable Zone is fuzzy but around 1.5 AU



In the Solar System:

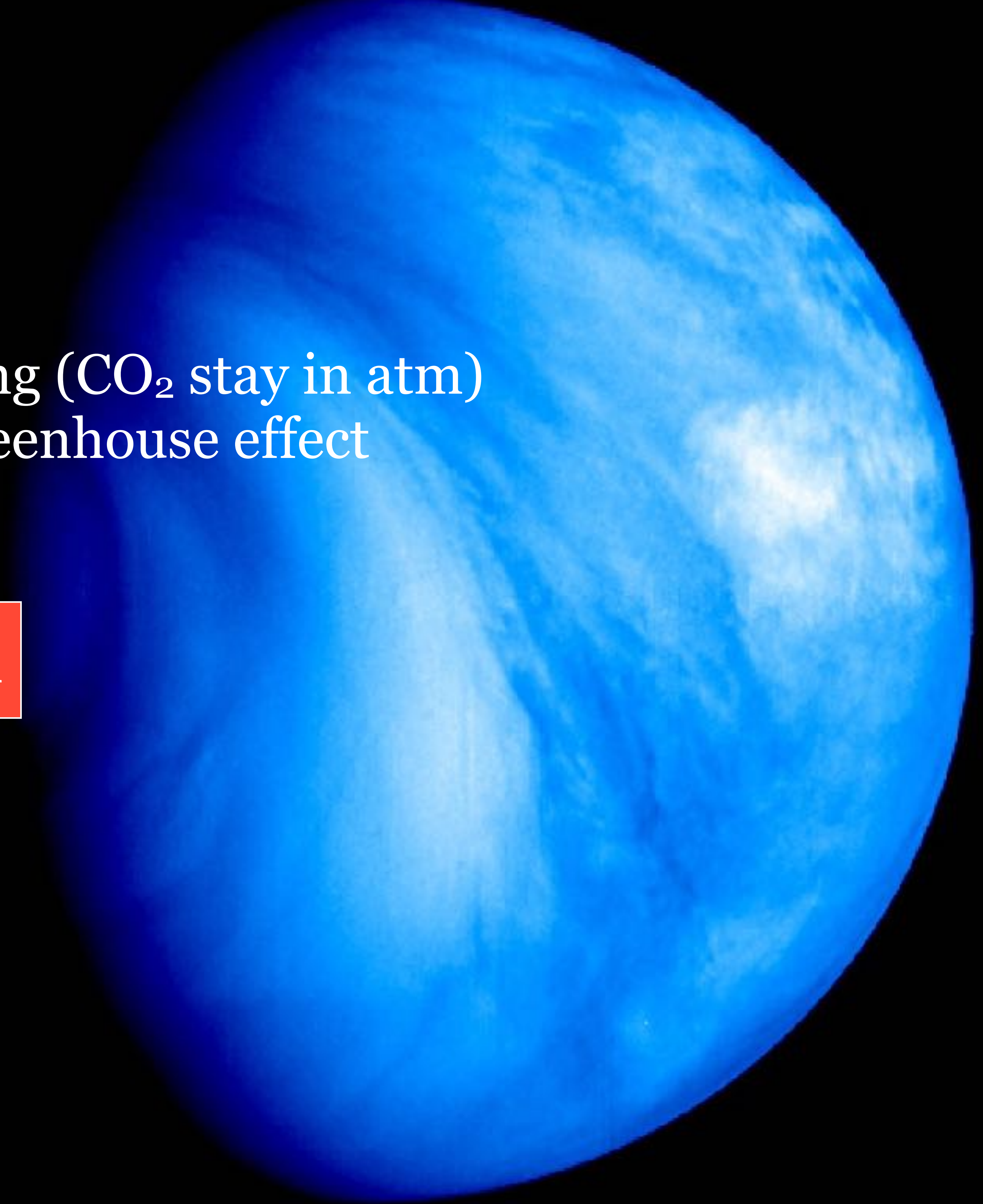
The inner edge of the Habitable Zone is around ~0.9 AU

The outer edge is fuzzy but around ~1.5 AU

Venus

- Close to Sun
- Lost its H_2O
- No weathering (CO_2 stay in atm)
- Runaway Greenhouse effect

$T_{surf} \sim 730K$



Mars

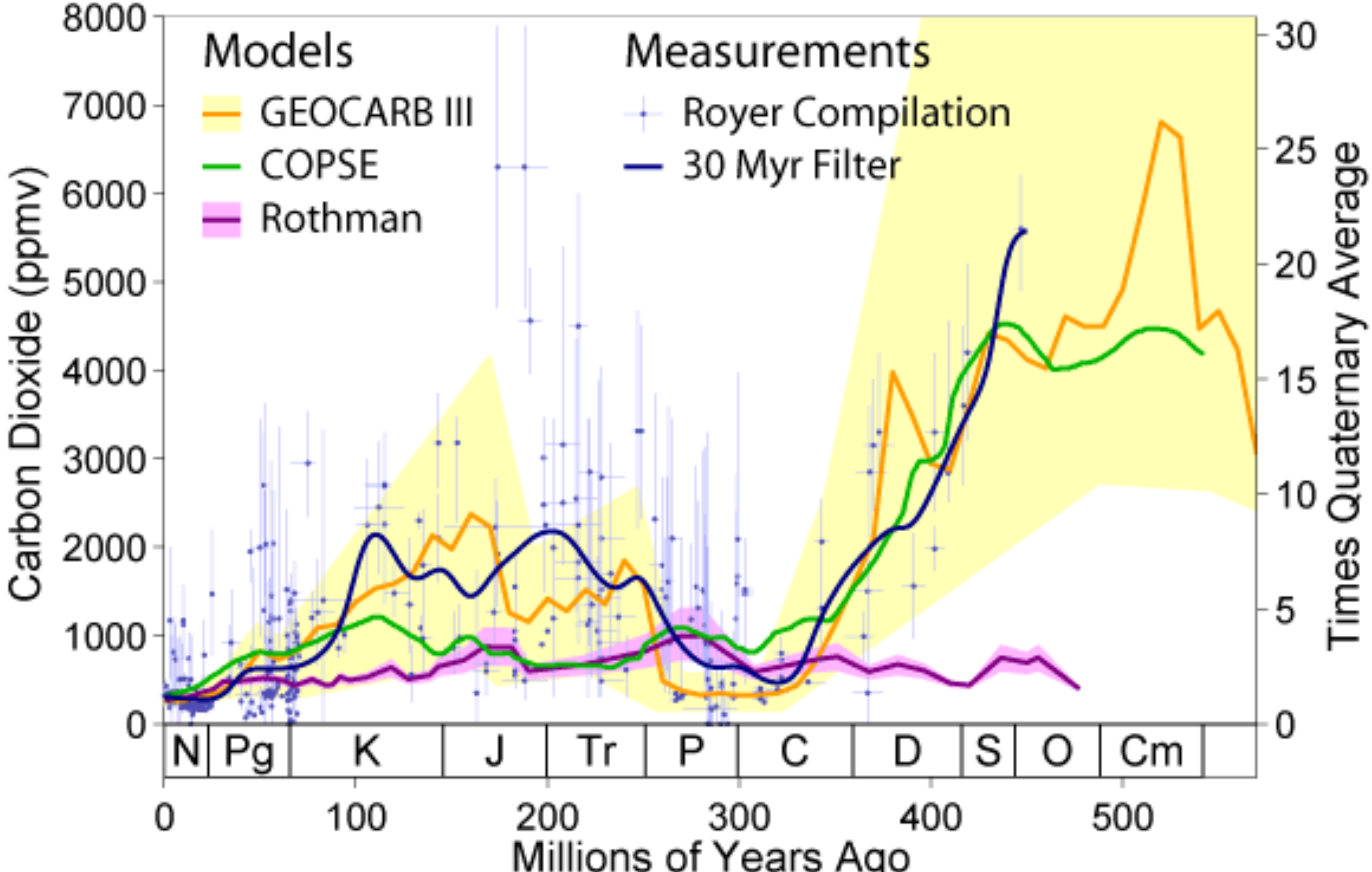
- Too far, too small (10% of Earth-mass)
- Volcanic activity stopped quickly (no CO_2 production)
- Lost its atmosphere
- No Greenhouse effect

$T_{surf} \sim 218$ K

What about the climate on Mercury?

The Future of Earth

Phanerozoic Carbon Dioxide



What will be the long-term consequence on the climate of today's raise in CO_2?

And the consequence for Life on Earth?

Current: CO_2 ~400 ppm

(CO_2 is an efficient Rayleigh scattered = higher Albedo)

If we burned all fossil reserves: 1400-2000 ppm

→ higher Greenhouse (compensated partly by higher albedo: no runaway process)

→ T_{surf} + ~8°C (sea level + ~80m)

Even at Venus CO_2 concentration: T_{surf} ~230°C but Pressure ↗ (100 bar) → Water remains liquid

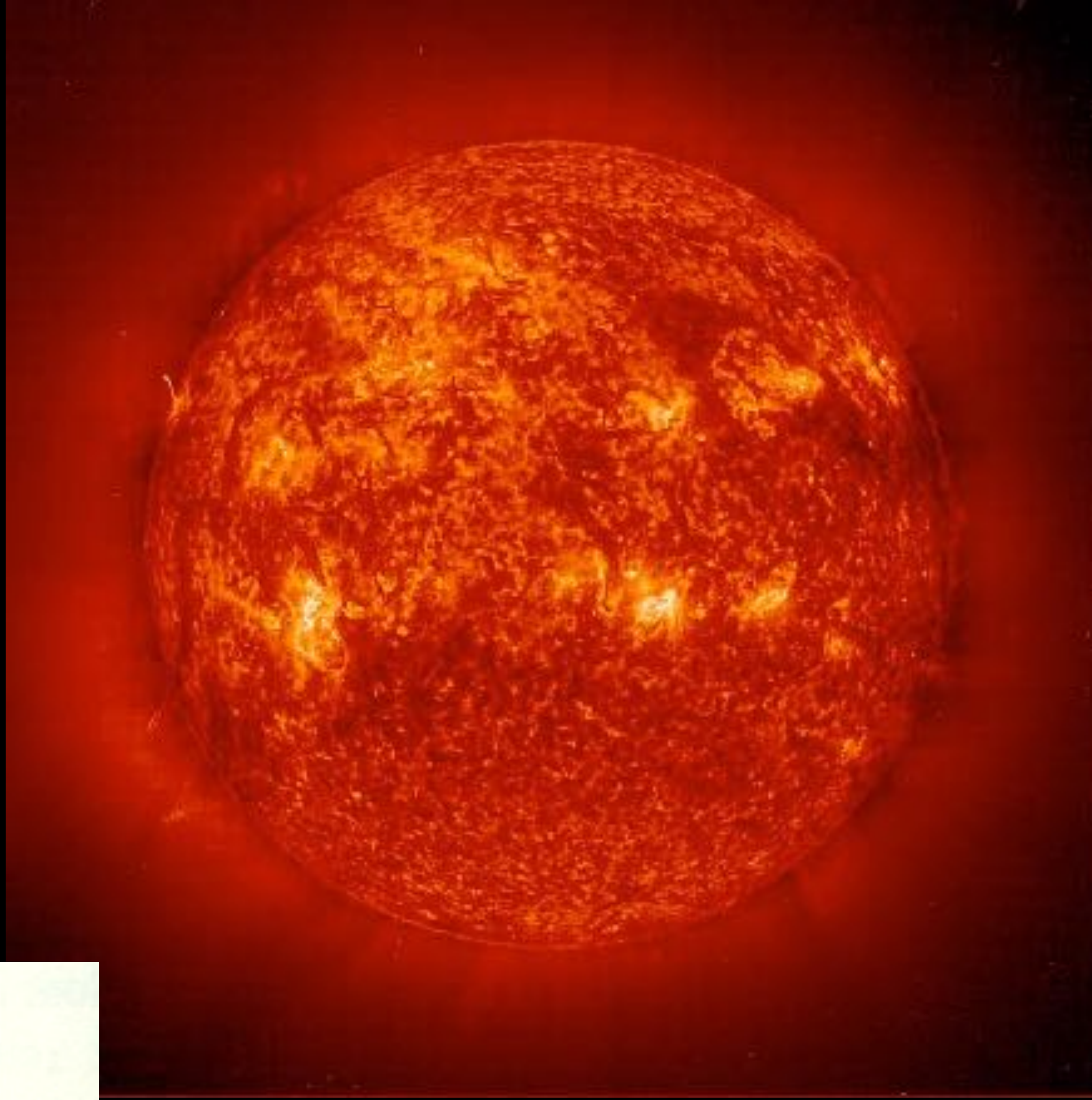
Today, Earth cannot lose its water

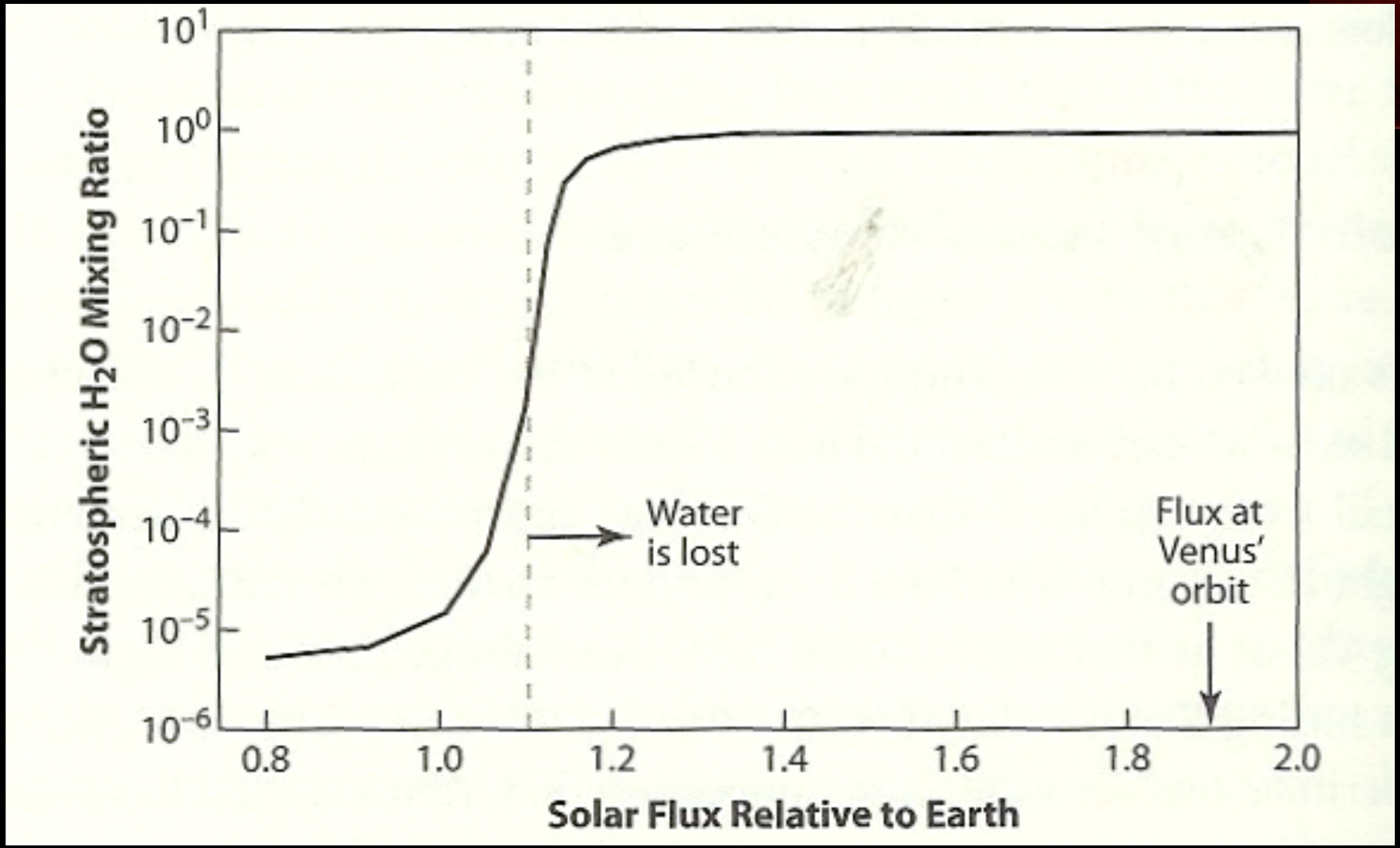
(Humans would nevertheless feel very uncomfortable)

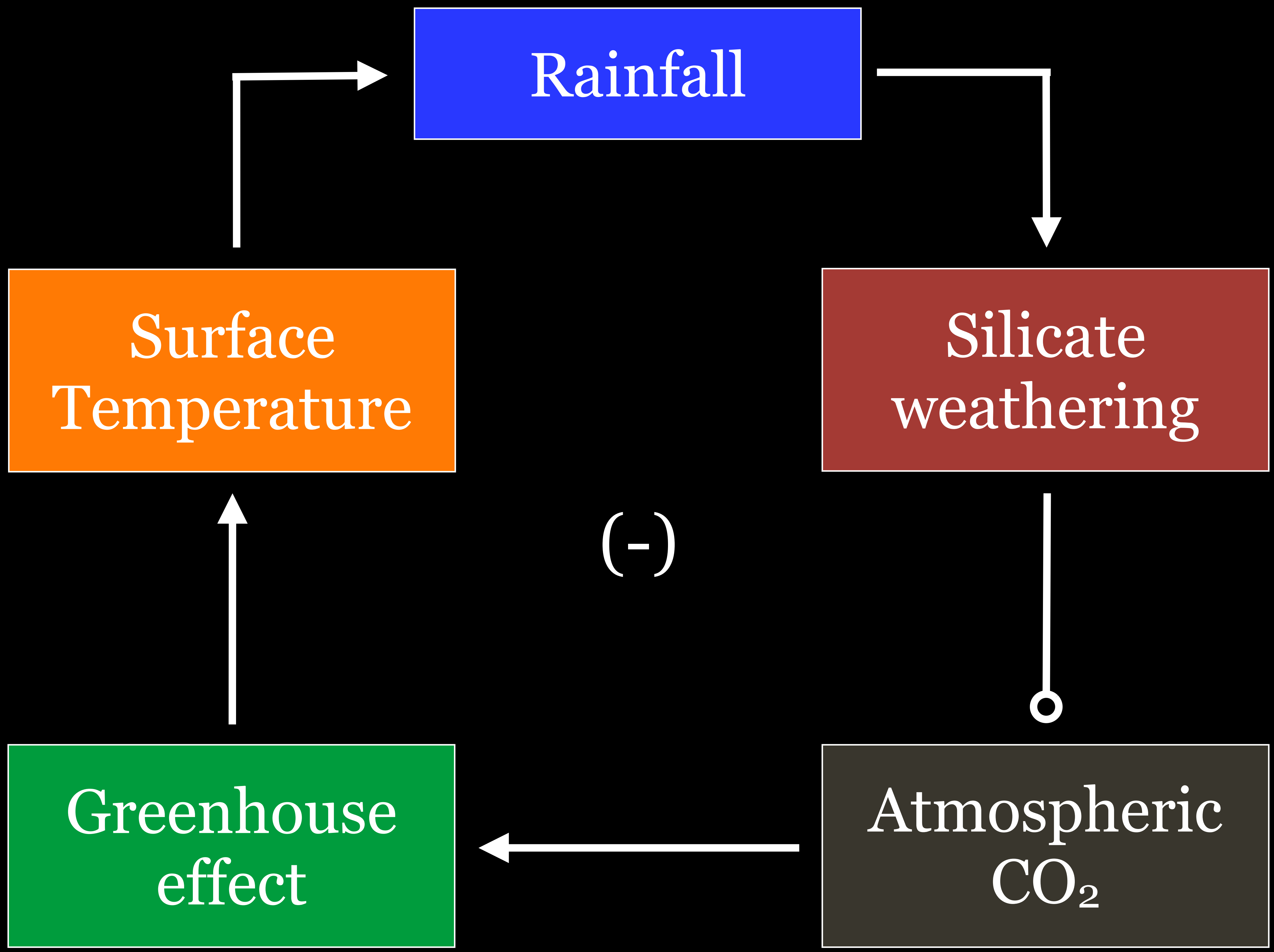
But what about in ~1 Gyr time?

Solar luminosity up by 10%

⇒ Earth loses its water
but how fast?







Provides long-term climate stability

What will happen?

(ignore the short term human-made CO_2)

Solar luminosity ↗ → weathering increases → CO_2 ↘

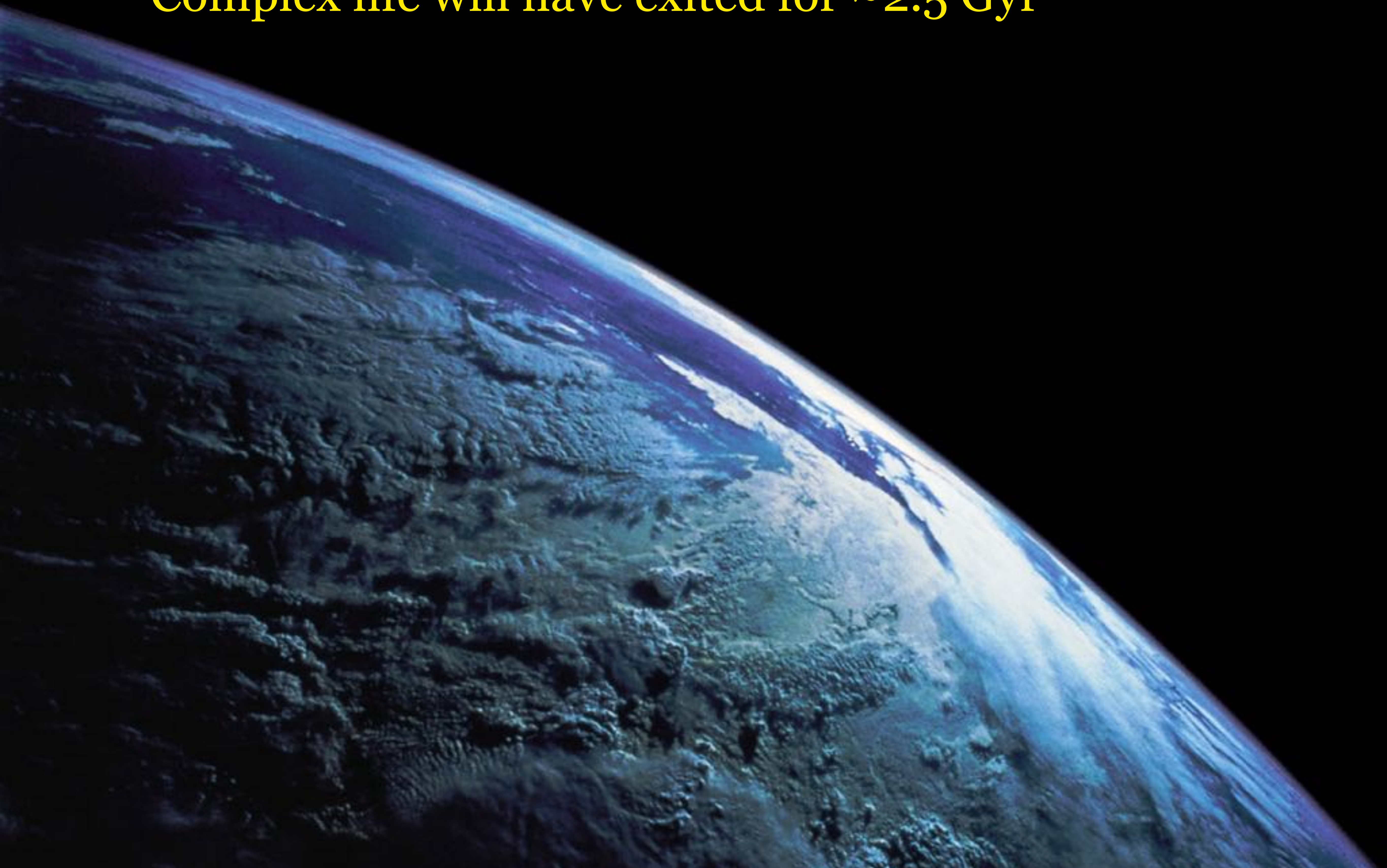
- at 150 ppm CO_2 (after 500 Myr) C3 plants die
  C3 plants: all trees, most crops [95%]

- at 10 ppm CO_2 (after 900 Myr) C4 plants die
  C4 plants: tropical plants, corn, sugar cane [5%]

The atmosphere becomes thin (low pressure) and H_2O gets lost over a few 100 Myr

Earth lifetime with surface H_2O will have been ~5.5 Gyr

Complex life will have exited for ~2.5 Gyr



Take home ideas from day 2

- Solar flux, albedo, greenhouse effect
- Feedback loops drive the climate
- Life modulates the most important volatiles in the atmosphere
- Oxygen appeared with photosynthesis
- Habitability is (currently) linked to liquid water
- Venus experienced a runaway greenhouse effect
- Mars never developed a greenhouse atm

Homework:

- Watch the BBC documentary ‘Earth - The Power of the Planet’, episode 2 ‘Atmosphere’ (http://documentaryheaven.com/atmosphere-earth-the-power-of-the-planet/)
  If motivated, look at episodes 1 and 5: ‘Volcano’ and ‘Rare Earth’
- Read one (or both) Chapters of ‘The Emerald Planet’ by D.Beerling
  Start with ‘Oxygen and the lost world of giants’, and if motivated, continue with ‘Nature’s Green Revolution’

Monday November 20	Day 1: Definition of Life; Origin of Life; Evolution of Life; Limits of Life 10:00-12:00 & 13:00-14:00
Tuesday November 21	Day 2: Earth Climate History; Mars and Venus Climates 10:00-12:00 & 13:00-14:00 OLD SEMINAR ROOM
Wednesday November 22	Day 3: Habitable Places in the Solar System; Mars; Moons of Giant Planets 10:00-12:00 & 13:00-14:00
Thursday November 23	Day 4: Habitable Places beyond the Solar System; Exoplanets properties; Biosignatures 10:00-12:00 & 13:00-14:00
Friday November 24	Day 5: Search for Extraterrestrial Intelligence; Alien Biochemistry 10:00-12:00 & 13:00-14:00

The End for Today

Thank you!