EARTH-LIFE
SCIENCE
INSTITUTE

Tokyo Institute
of Technology

Earth-Life Science C: Planets

Instructors:

- Hidenori Genda
- John Hernlund
- Shigeru Ida
- Hiroyuki Kurokawa

Report assignment of the previous lecture

1. Given the mean surface temperature, $T = 288$ K, and the mean molecular mass, $\bar{m} = 29.0 \times 10^{-3}/6.02 \times 10^{23}$ kg, Estimate the scale height of Earth's atmosphere. Answer with two significant digits.

$$H = \frac{k_B T}{\bar{m} g} \simeq 8.4 \text{ km}.$$

2. Estimate the pressure at the top of Mt. Everest (8,849 m). You can use the pressure at the sea level = 1.013×10^5 Pa, and the scale height from Q1. Answer with two significant digits.

Given the height $z = 8{,}849$ m and the surface pressure $p_0 = 1.013 \times 10^5$ Pa, the pressure at the top is,

$$p(z) = p_0 \exp(-z/H) \simeq 3.5 \times 10^4 \text{ Pa}.$$

Hernlund

- Lecture 1: The present-day Earth (Tuesday, 4 October)
- Lecture 2: Earth's history (Friday, 7 October)
- Lecture 3: Exploration of the Solar System (Tuesday, 11 October)

Kurokawa

- Lecture 4: Planetary structure and equations (Friday, 14 October)
- Lecture 5: Planetary atmospheres (Tuesday, 18 October)
- Lecture 6: Climate evolution, volatile cycling, and biogeochemical cycling (Friday, 21 October)

Ida

- Lecture 7: Planet formation ~~(Tuesday, 1 November)~~ Friday, 28 October
- Lecture 8: Satellite formation (Friday, 4 November)
- Lecture 9: Origins of organic materials (Tuesday, 8 November)

Genda

- Lecture 10: Water delivery to Earth (Friday, 11 November)
- Lecture 11: Stellar evolution (Tuesday, 15 November)
- Lecture 12: Exoplanet observations (Friday, 18 November)

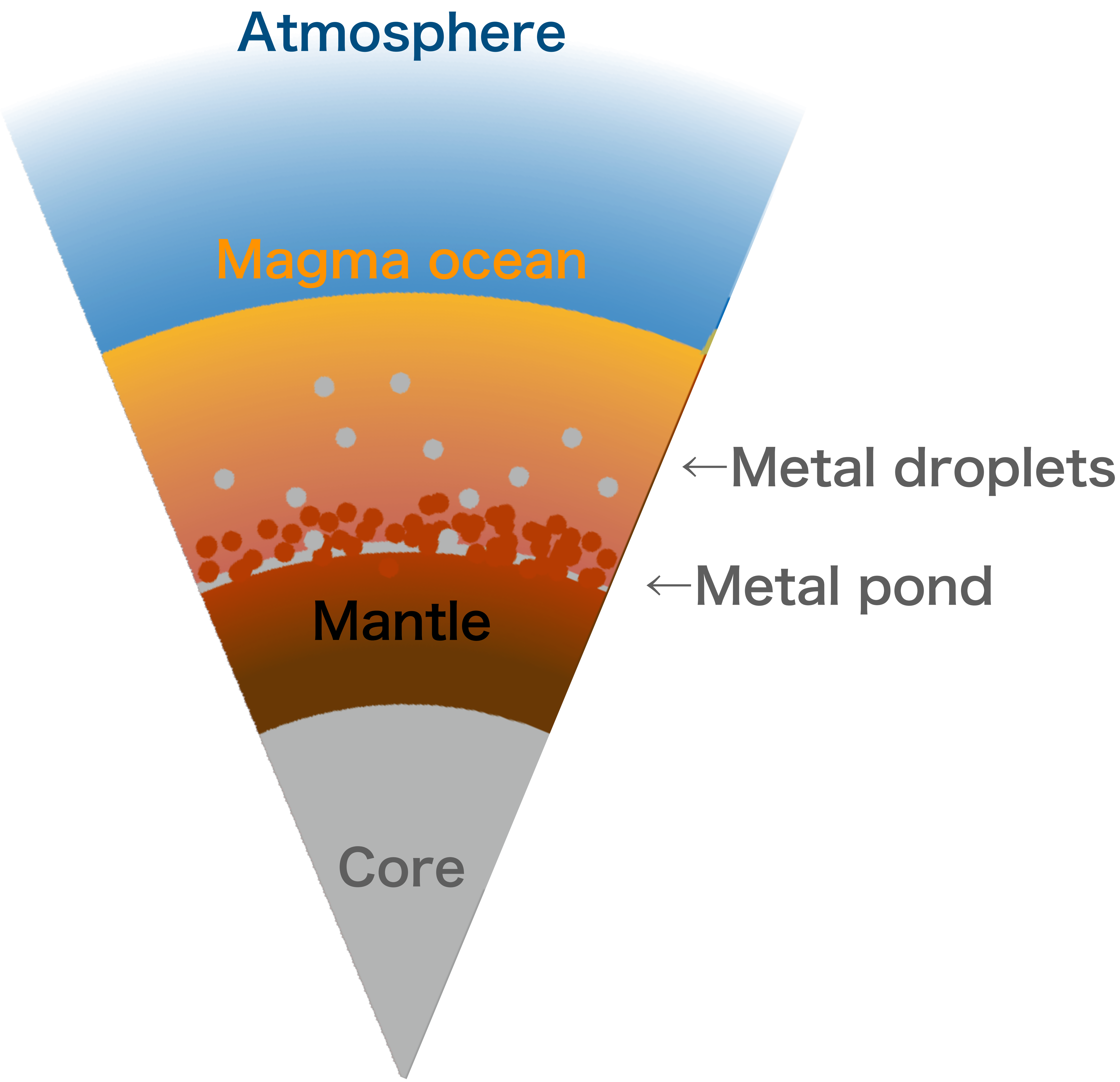
All

- Lecture 13: Summary and future prospects (Tuesday, 22 November)

Planets born hot

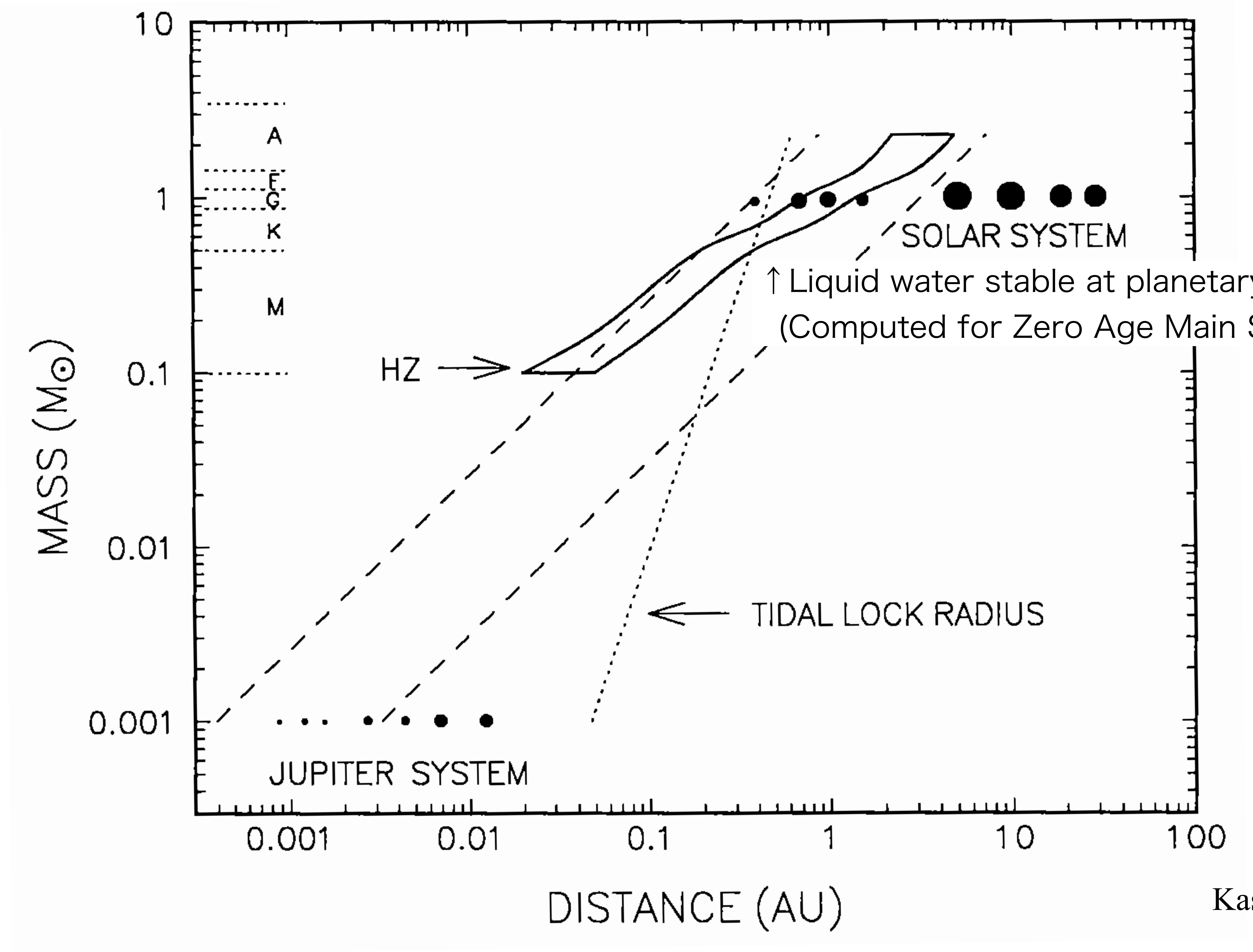
Credit: Alan Brandon/*Nature*

Differentiation



- Magma ocean: Molten rock layer
- Differentiation to form a core
  - Metal droplet settling
    - Size ~1 cm (Rubie et al. 2003, *Earth Planet. Sci. Lett.*)
  - Accumulate on top of solidified mantle
  - Because of the density difference, the metal pond finally becomes unstable and be transported to the core
  - Light elements have likely to be partitioned in the core at this stage

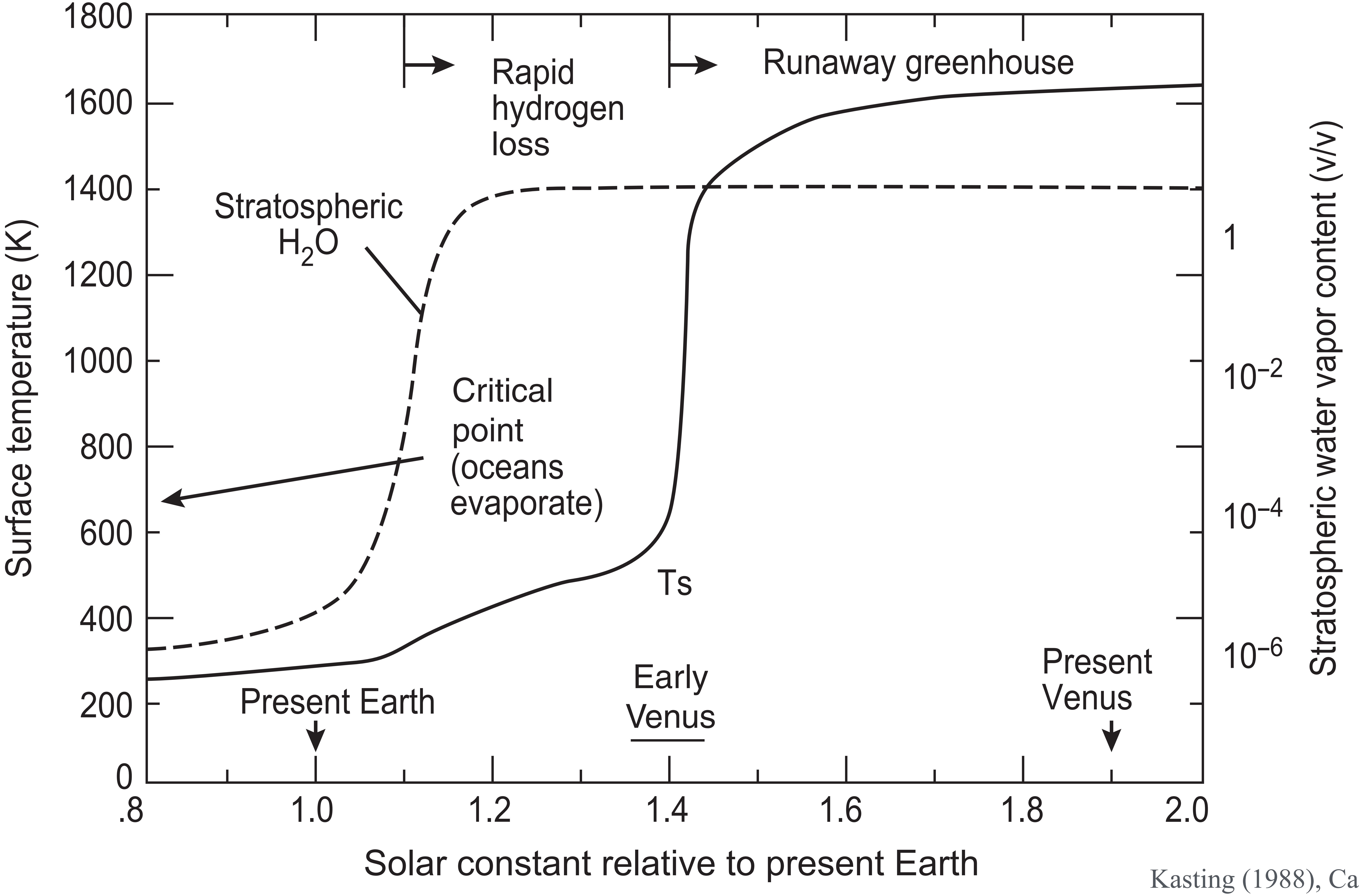
Habitable Zone (HZ)



↑ Liquid water stable at planetary surfaces
(Computed for Zero Age Main Sequence)

Kasting et al. (1993) *Icarus*

Atmospheric response to different irradiation levels

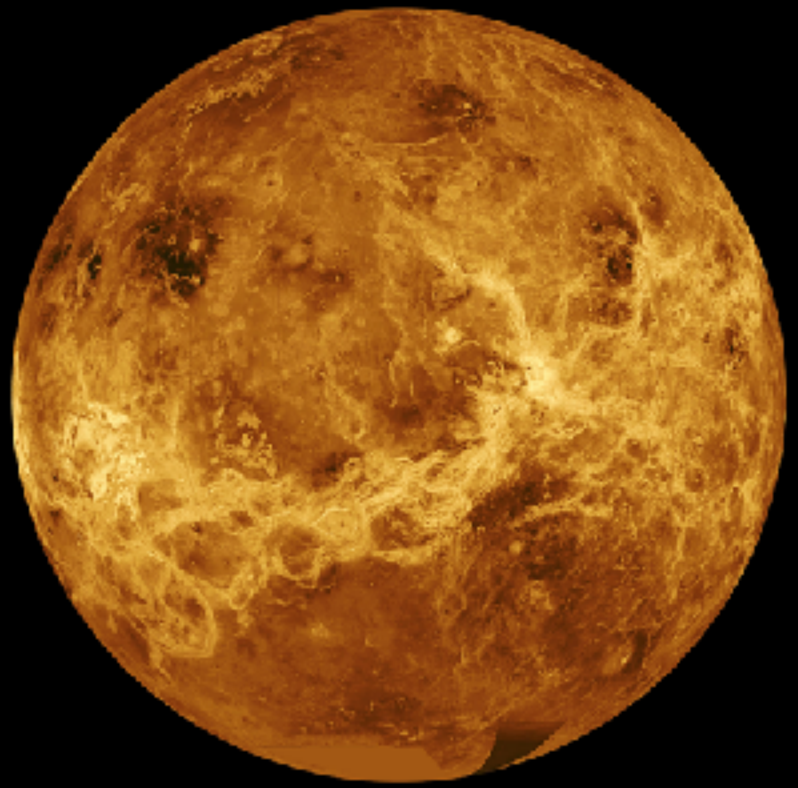


Kasting (1988), Catling & Kasting (2017)

Bifurcation of early Venus and Earth

Magma ocean planet

Dry Venus



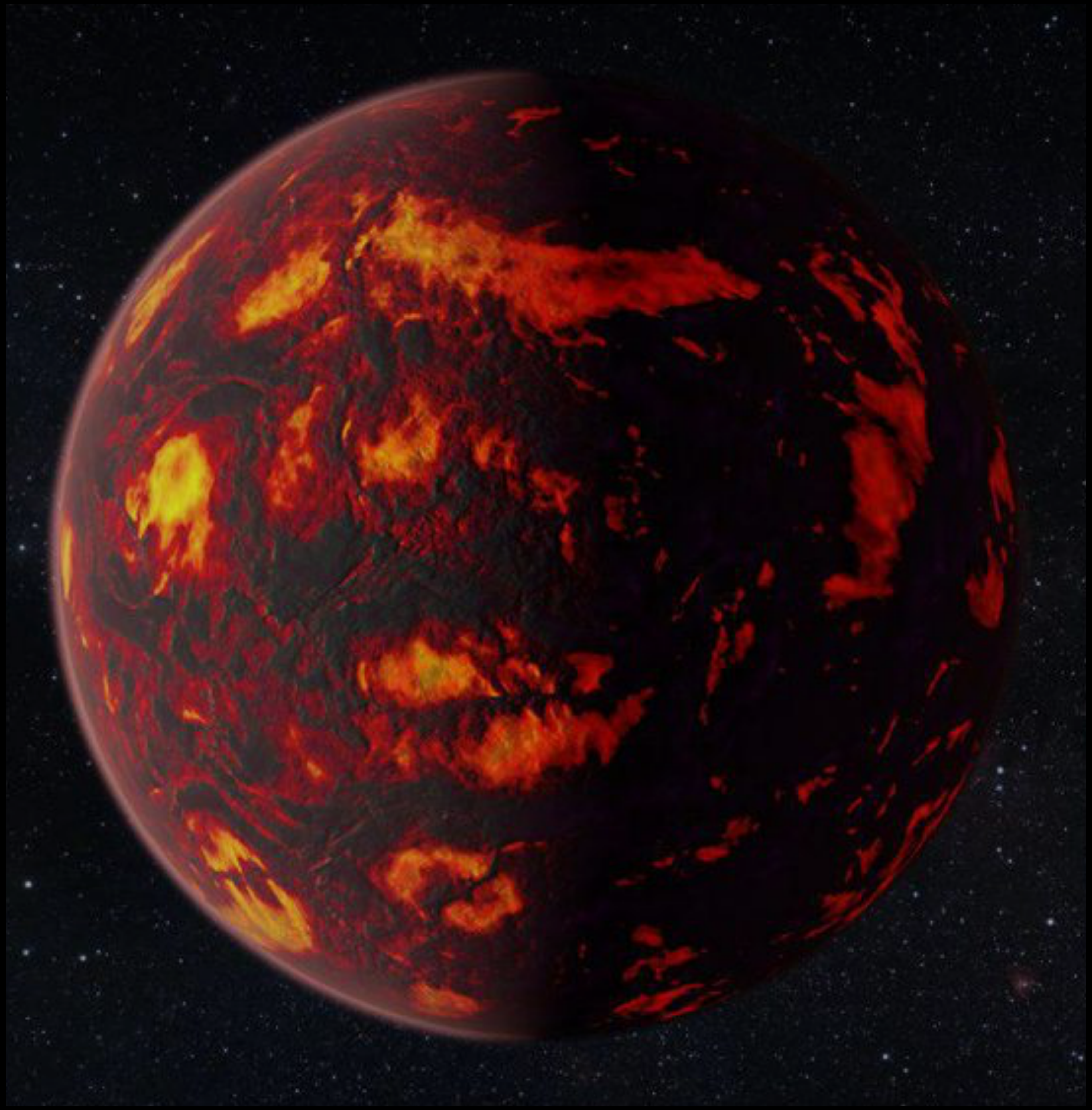
- Venus have never had an ocean (runaway greenhouse state) or had only a short-life-time ocean
- Water lost to space

-----------Inner boundary of the habitable zone ----------

Wet Earth

- Once Earth cooled down, an ocean formed
- Water loss to space is limited as the upper atmosphere is dry

Earth's atmosphere right after MO solidification



- Solubilities of C and N in the magma is low
  → Partitioning more into the atmosphere than in the mantle
  (e.g., Hirschmann 2016)
- Present-day Earth's mantle+crust contain
  CO_2: a few hundreds bar, N_2: a few bar

→ **Earth had a Venus-like atmosphere?**

Carbonate-silicate cycle

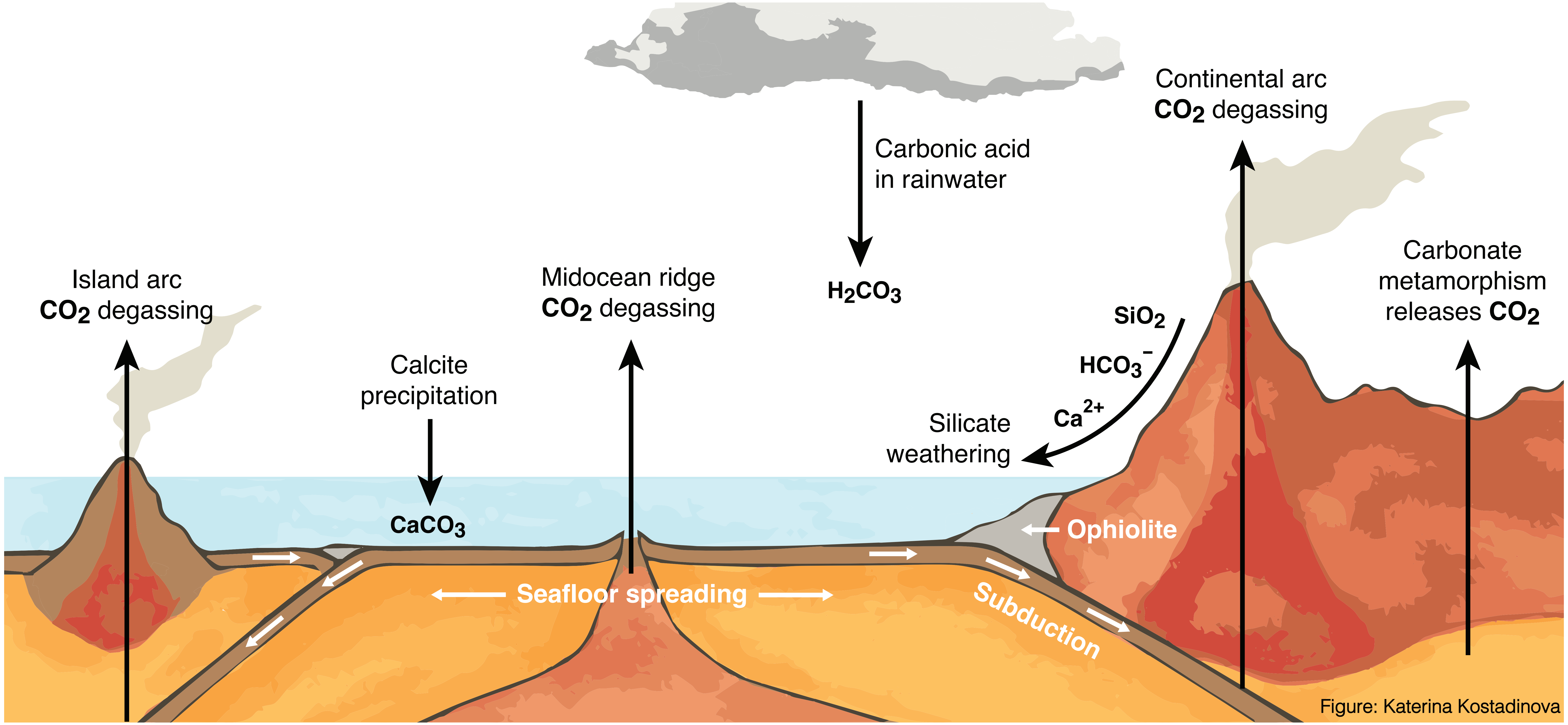
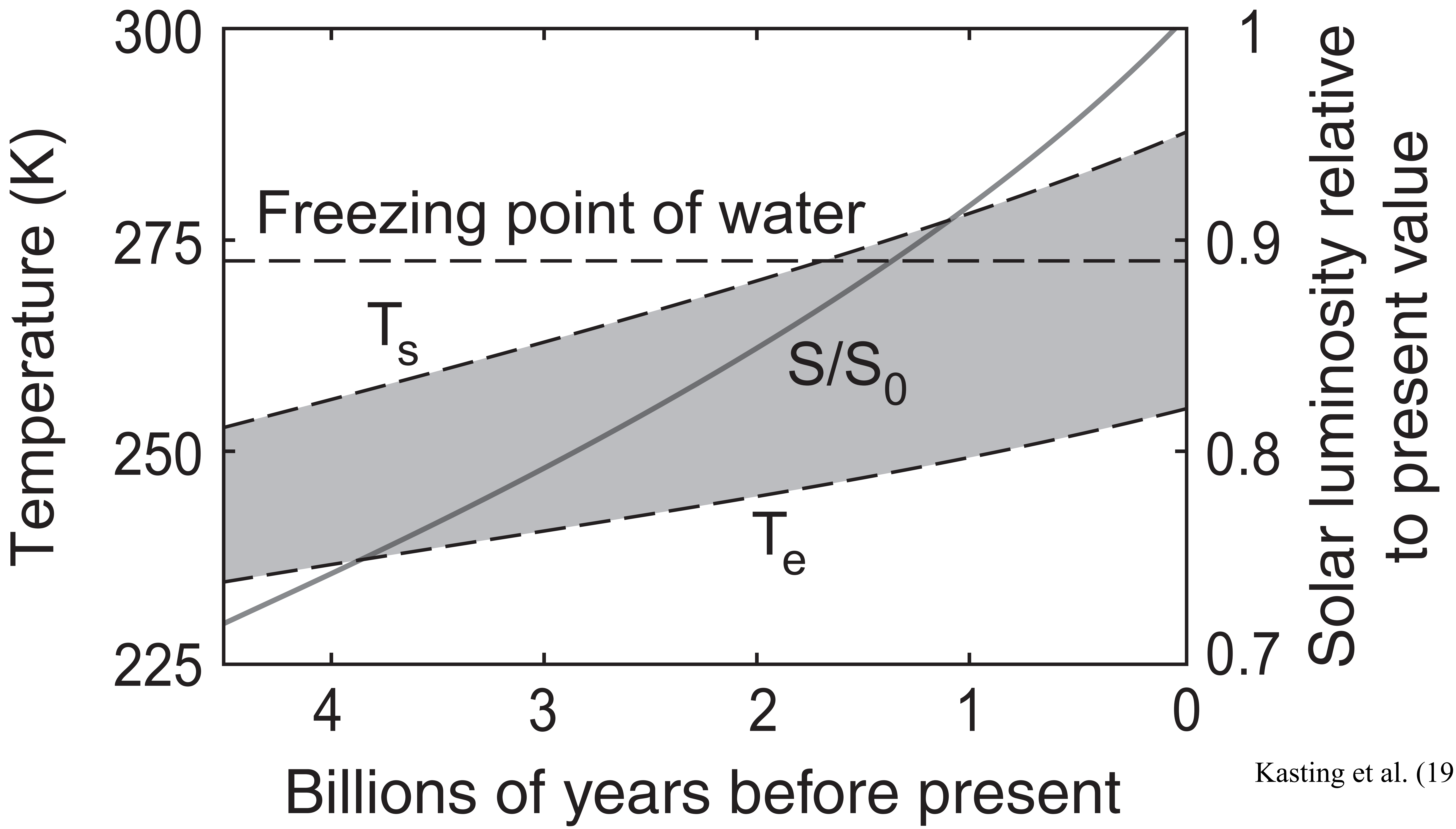


Figure: Katerina Kostadinova

- CO_2 cycles between the atmosphere and interior (timescale $\sim 10^{6-7}$ yrs)
- The primordial dense CO_2 atmosphere likely removed by this cycle

Evolution of the solar luminosity and Earth's climate



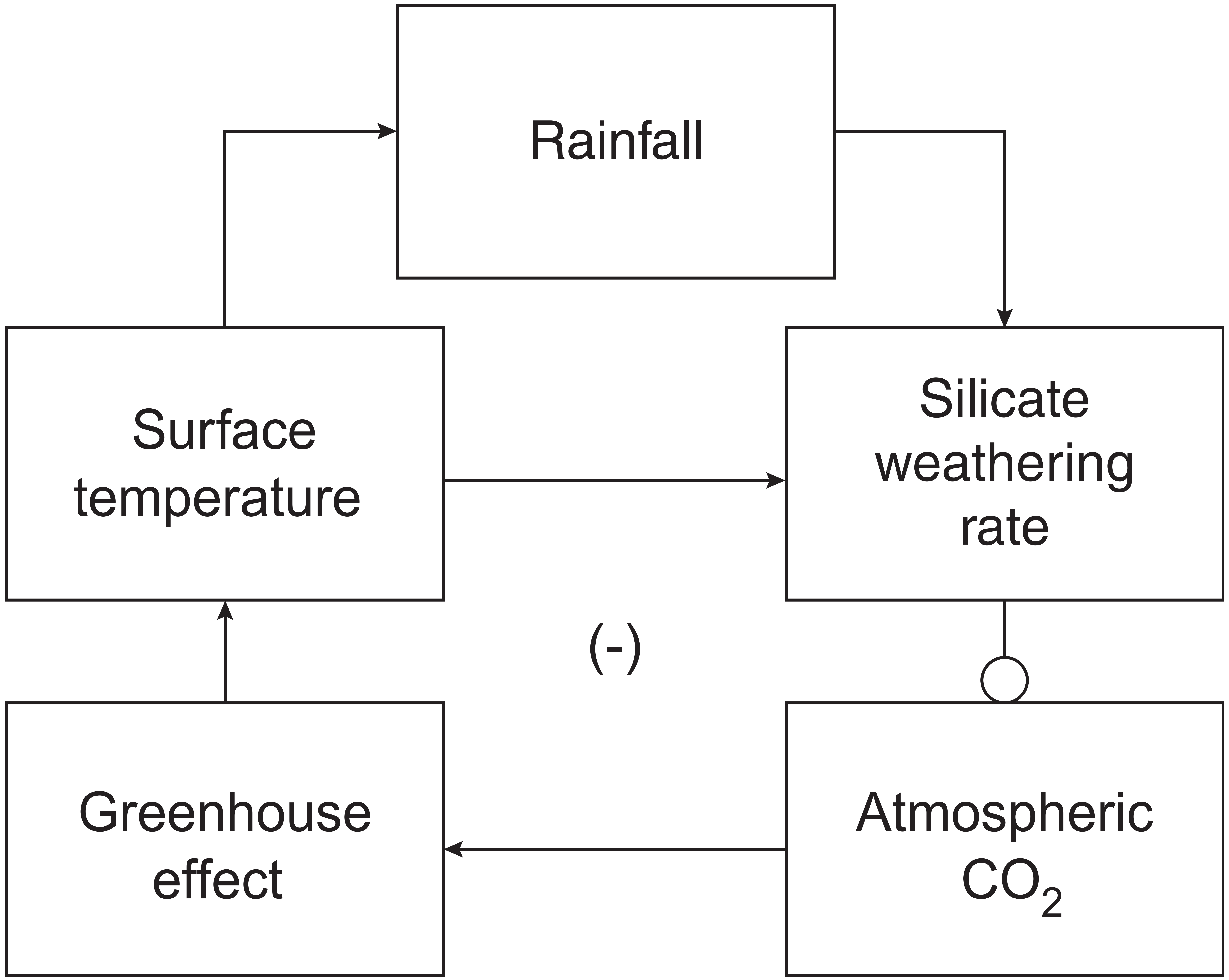
Kasting et al. (1988) *Scientific Am.*

The Faint Young Sun Paradox (Segan & Muller 1972, *Science*)

If the atmospheric composition had been unchanged with time, early earth would have been frozen

↔ Incompatible with the geologic record

Climate stabilization by carbonate-silicate cycle

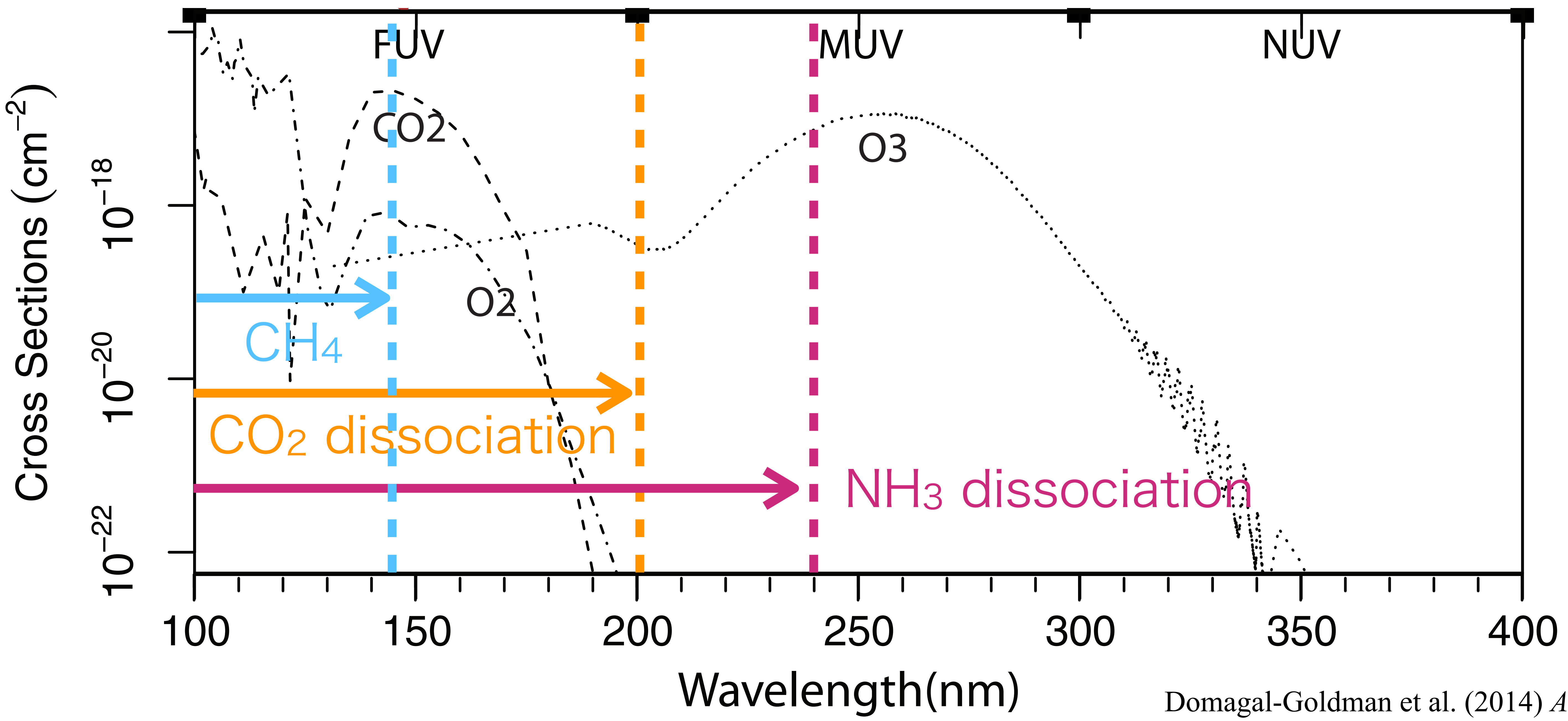


Kasting (2010)

- The carbonate-silicate cycle moderates temperature changes due to external influences (including the solar luminosity evolution) (Walker et al. 1981)
- This negative feedback is thought to have compensated the faint young sun

A reducing atmosphere on early Earth?

- Preferred before the development of modern planet formation theory…
- Beneficial for prebiotic organic chemistry (Miller's experiments)
- A CH_4-NH_3 atmosphere can compensate the faint young sun, but…
  - Chemical equilibrium with the magma ocean leads to a CO_2-N_2 atmosphere
  - NH_3 is short-lived due to photodissociation (Kasting, 1982; Kuhn & Atreya, 1979)



Domagal-Goldman et al. (2014) *Astrophys. J.*

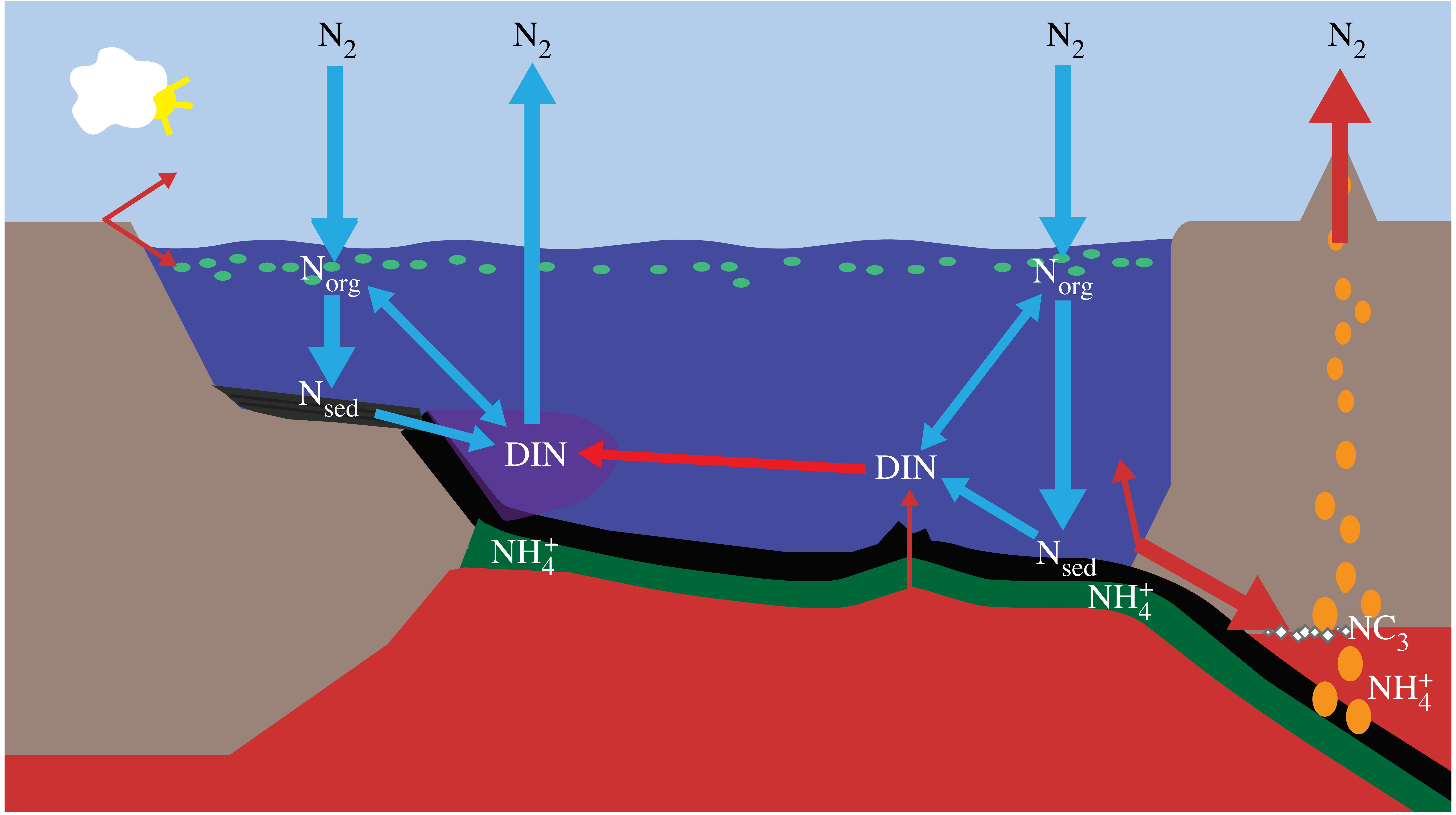
Late accretion and its influence on climate

- Lunar crater record and geochemical signature (highly siderophile elements) in Earth's mantle suggest early Earth had been bombarded by frequent impacts
- A transient reducing atmosphere could have formed after such impacts

Biogeochemical cycling

- Life is not just a consequence of abiotic cycling of matters
- Both biotic and abiotic processes take part in cycling of elements including C, H, N, O, P, and S

An example: deep N cycling initiated by biotic N_2 fixation

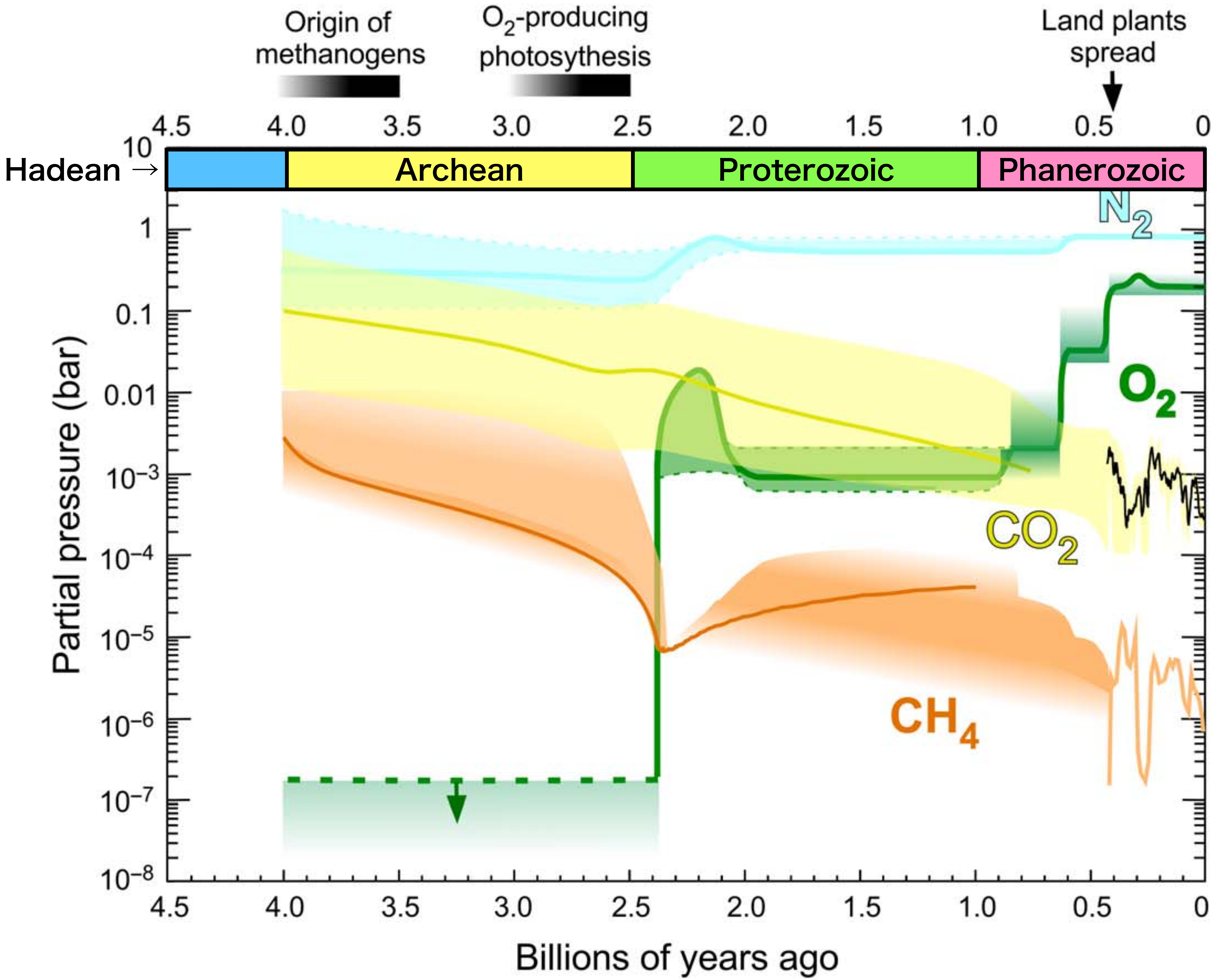


Zerkle (2018)

Earth-Life coevolution

- The Great Oxidation Event at 2.4 Ga is the most well-known example of biotic impacts on Earth’s environment
- A CH_4-rich atmosphere caused by methanogens (microorganisms that produce CH_4) in the Archean is another possibility
- Atmospheric N_2 level as well?
- We actually do not know how Earth would look like if life never emerged on Earth…

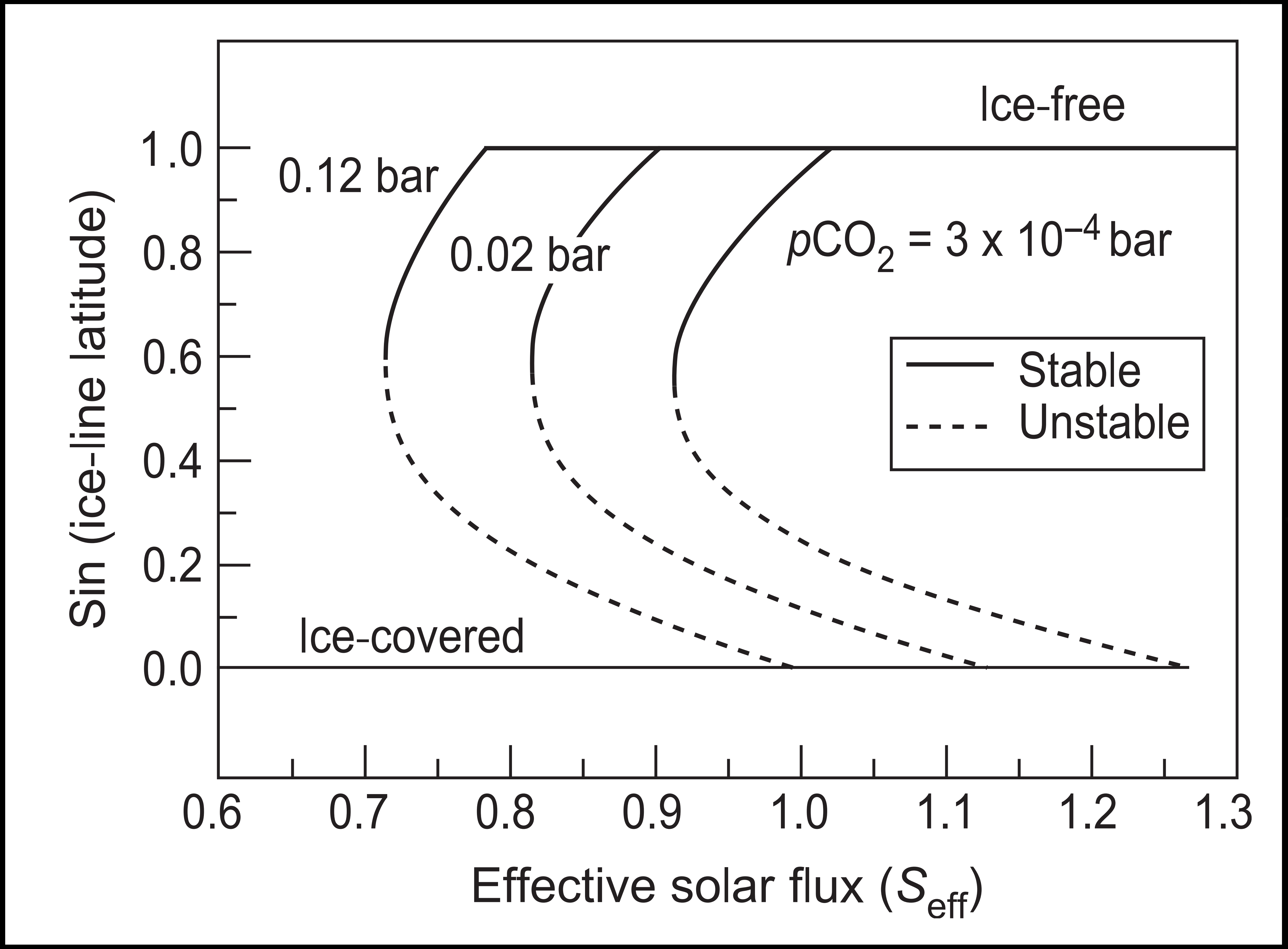
Hypothetical Archean Earth covered by organic haze
‘Pale Orange Dot’ (Arney et al. 2016)



Catling & Zahnle (2020)

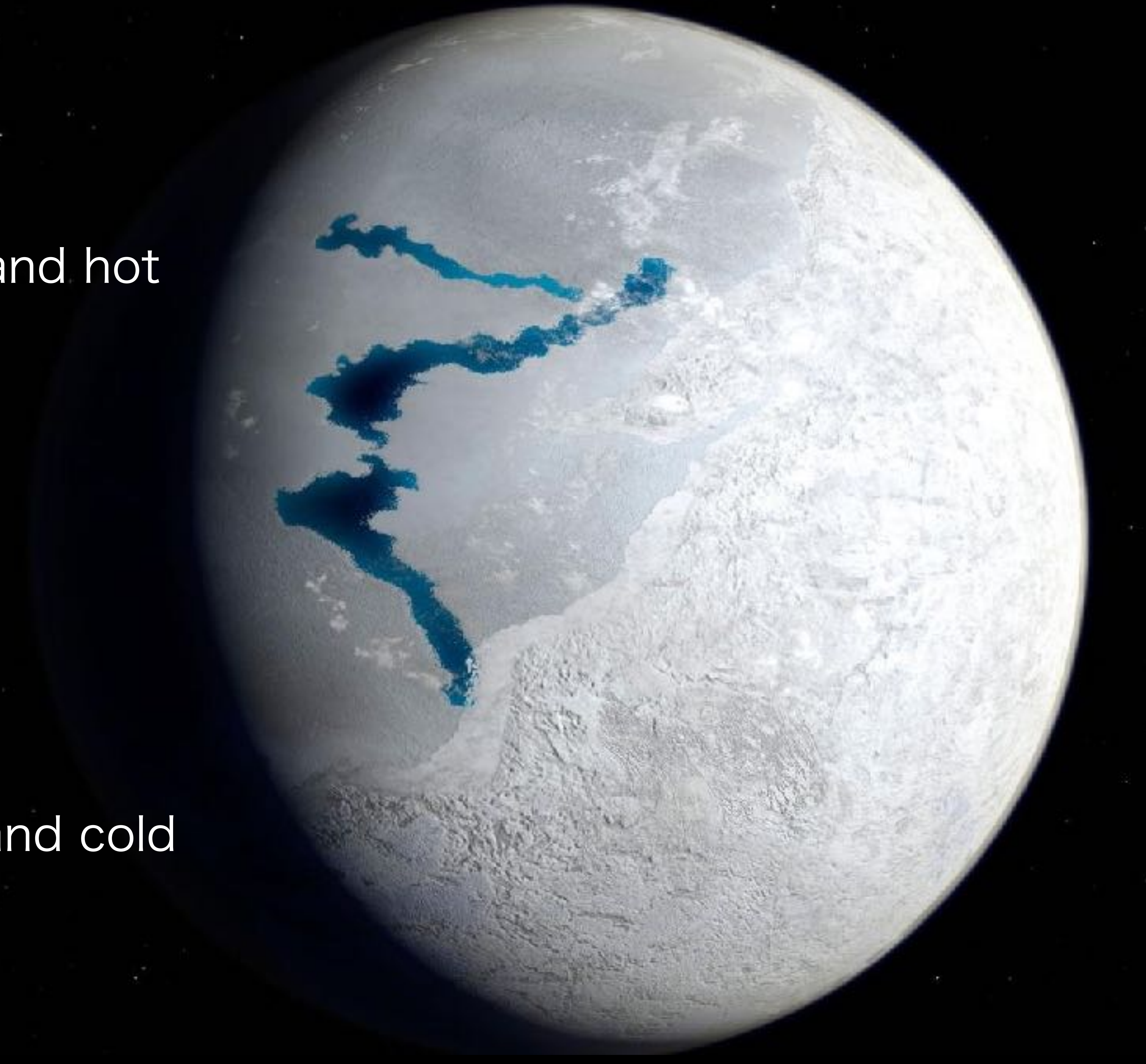
Snowball Earth

Multiple equilibrium solutions for Earth's climate



← Low albedo and hot

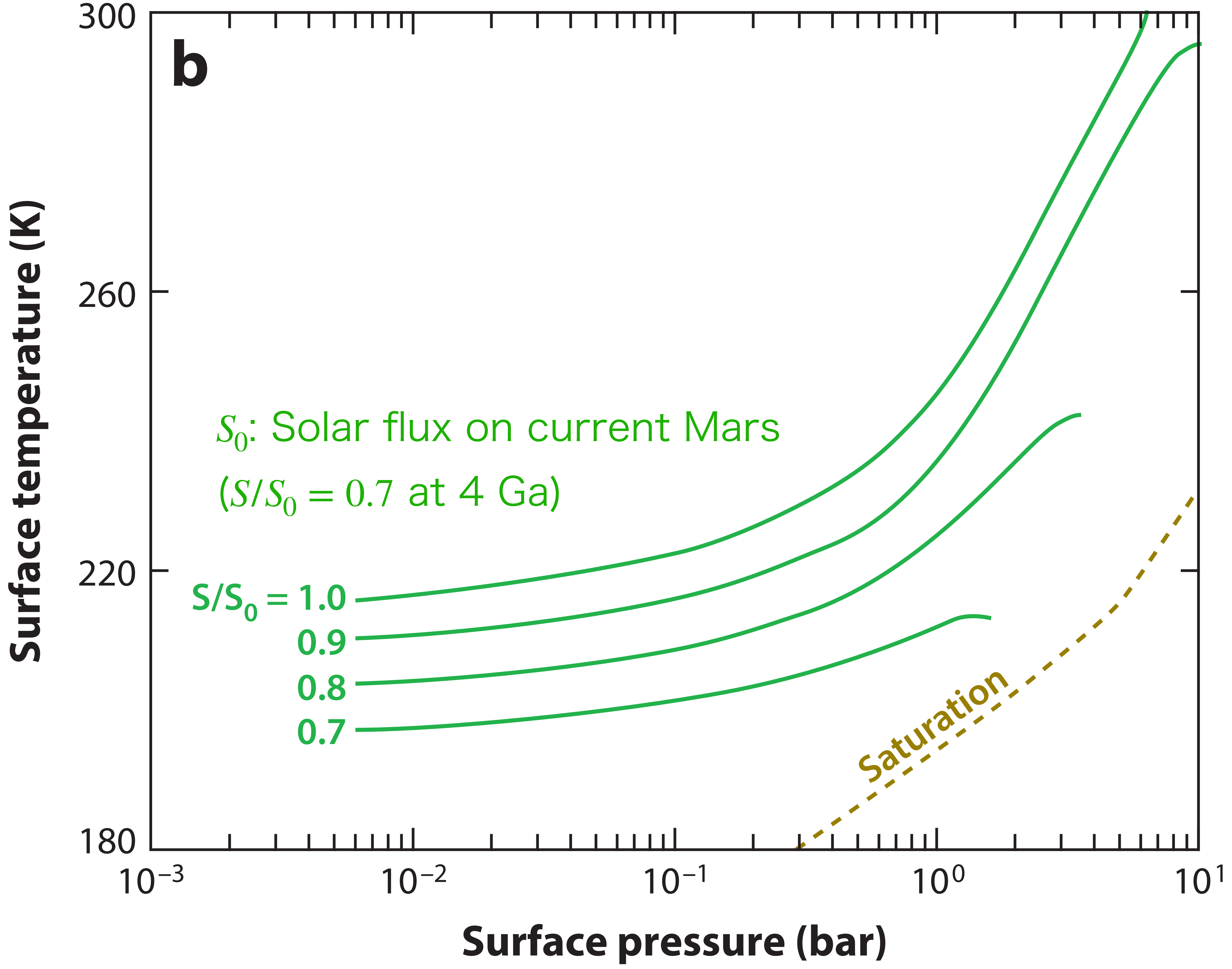
← High albedo and cold



- Geologic record show that Earth experienced snowball events
- Ice-albedo feedback allows such climate to be stable

Outer boundary of habitable zone

Surface temperature as a function of surface pressure of the CO_2 atmosphere

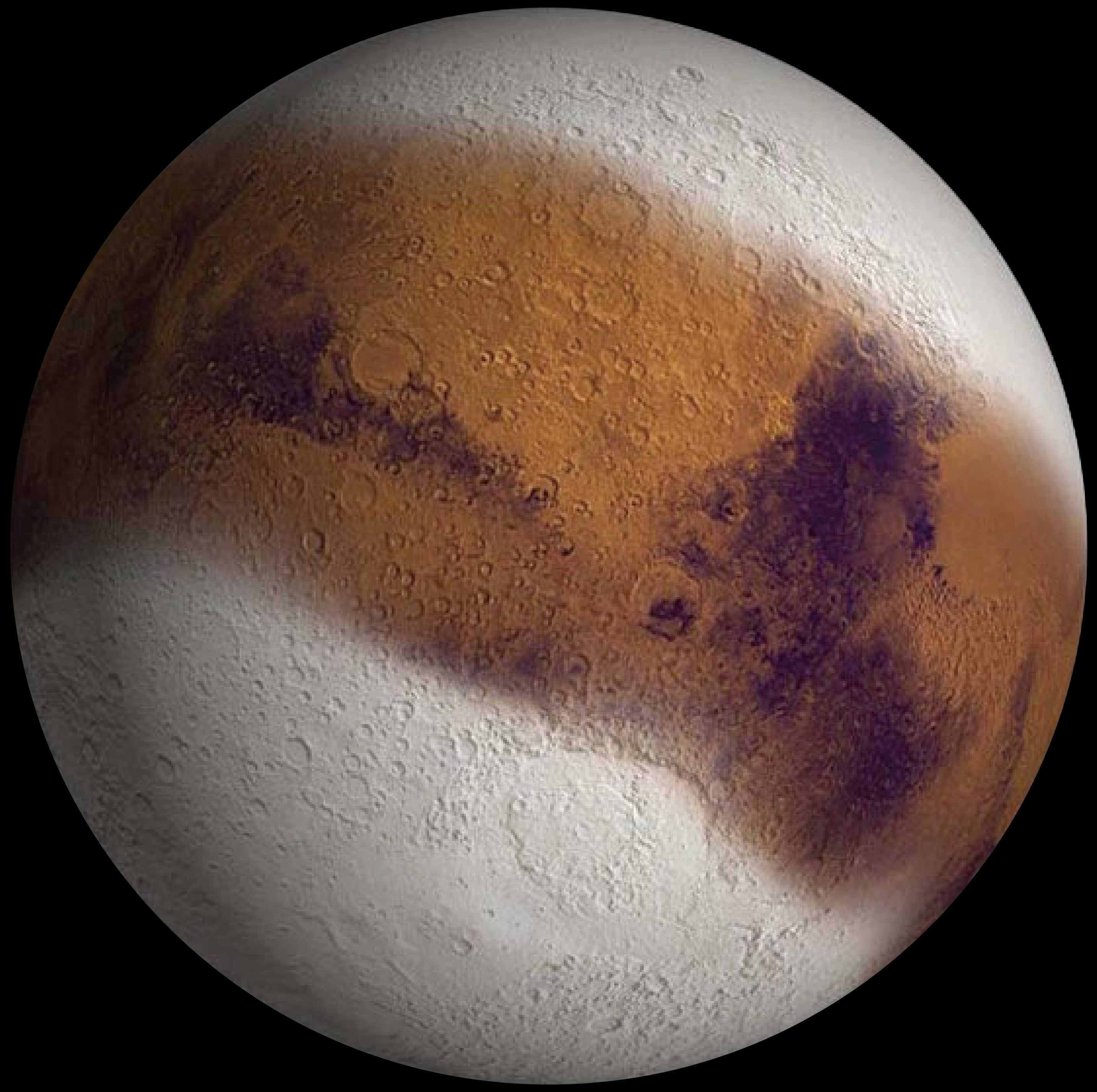


Wordsworth (2016)

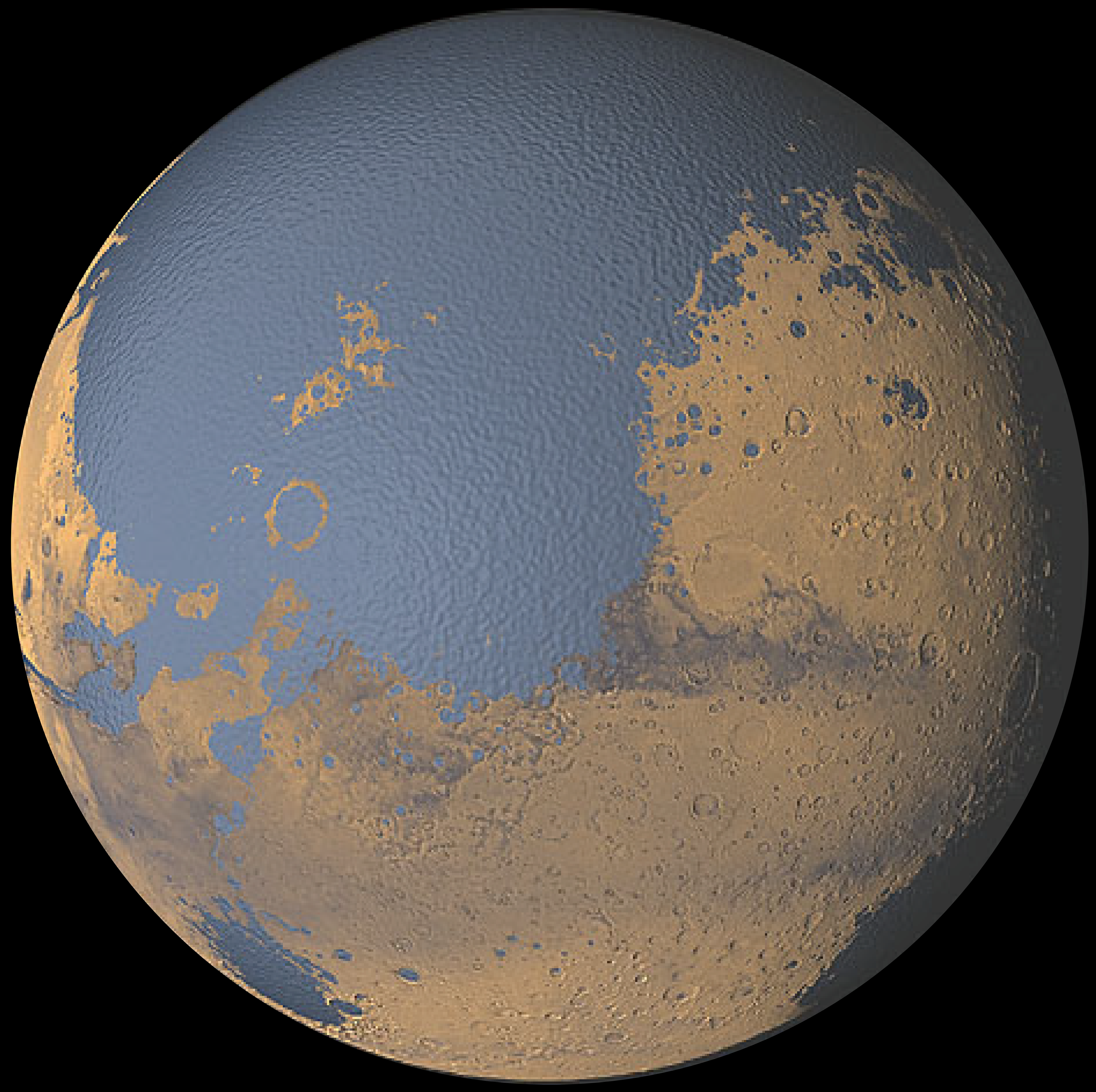
- Generally, the HZ depends on the atmospheric composition (greenhouse effect)
- For CO_2 atmospheres, condensation of CO_2 (atmospheric collapse) limits the extent of the outer edge of the HZ
- Early Mars is outside the HZ for planets with CO_2 atmospheres

Early Mars' climate

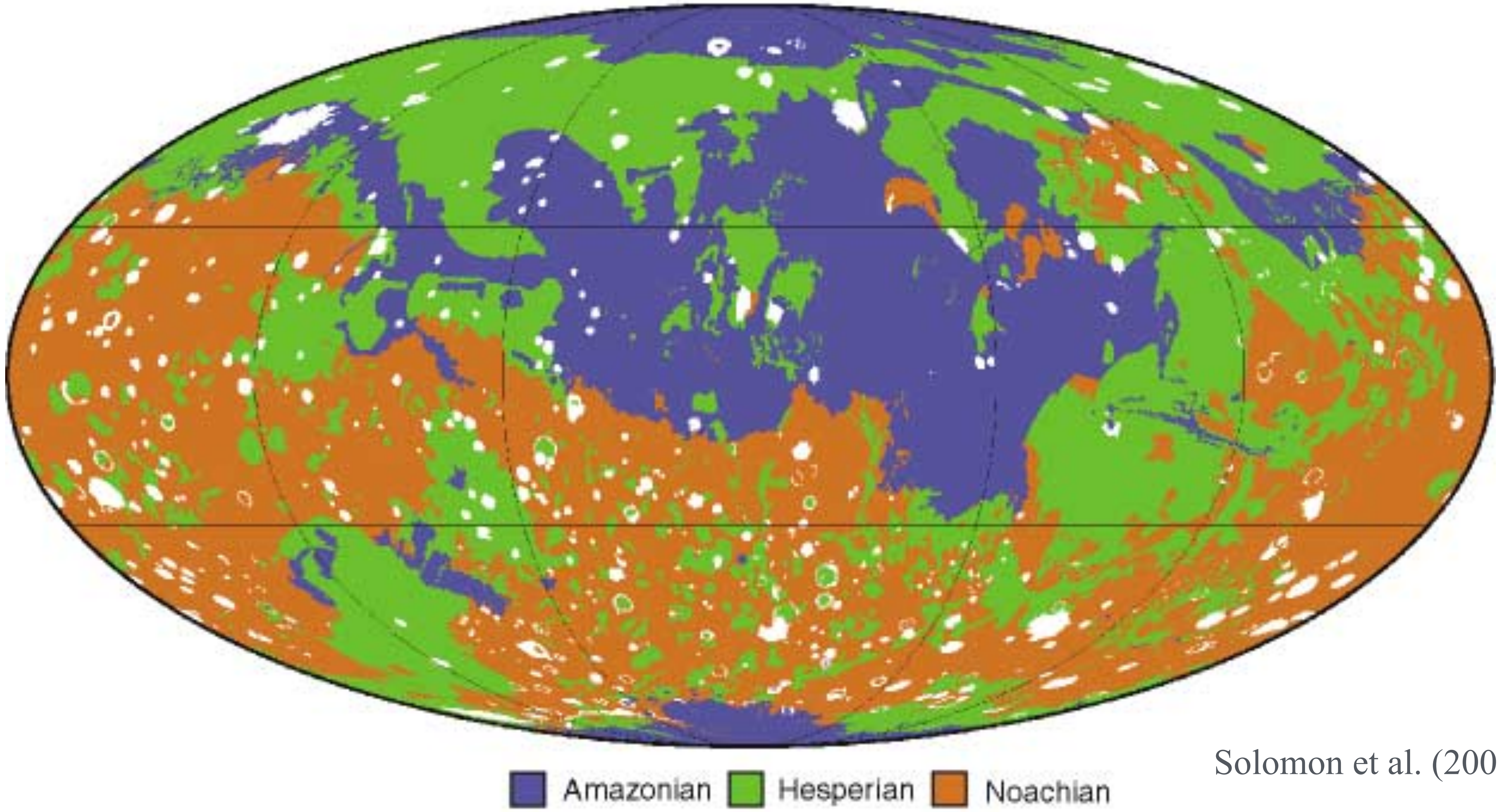
No (limited) additional greenhouse gas
→ Frozen early Mars



Sufficient additional greenhouse gas
→ Ocean-covered early Mars



Mars surface age



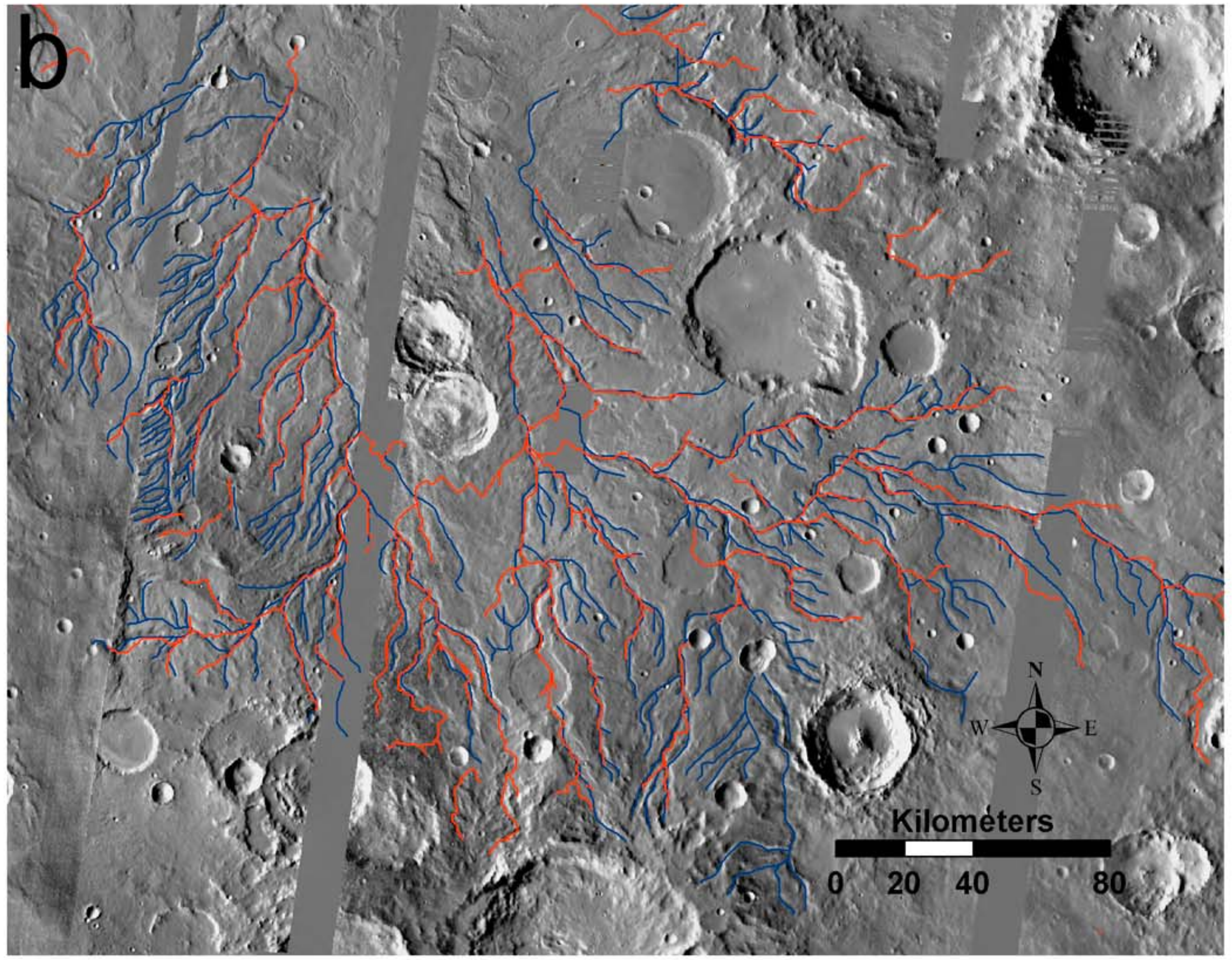
Pre-Noachean	4.5 to 4.2 Ga
Noachean	4.2 to (3.7–3.5) Ga
Hesperian	(3.7–3.5) to (3.3–2.9) Ga
Amazonian	(3.3–2.9) Ga to Present

Solomon et al. (2005) *Nature*

- Lack of plate tectonics → Old crust still remains
  cf.) Earth's oceanic crust ~0.1 Ga, continental crust ~2 Ga
- Southern hemisphere: old high-lands, Northern hemisphere: yound low-lands

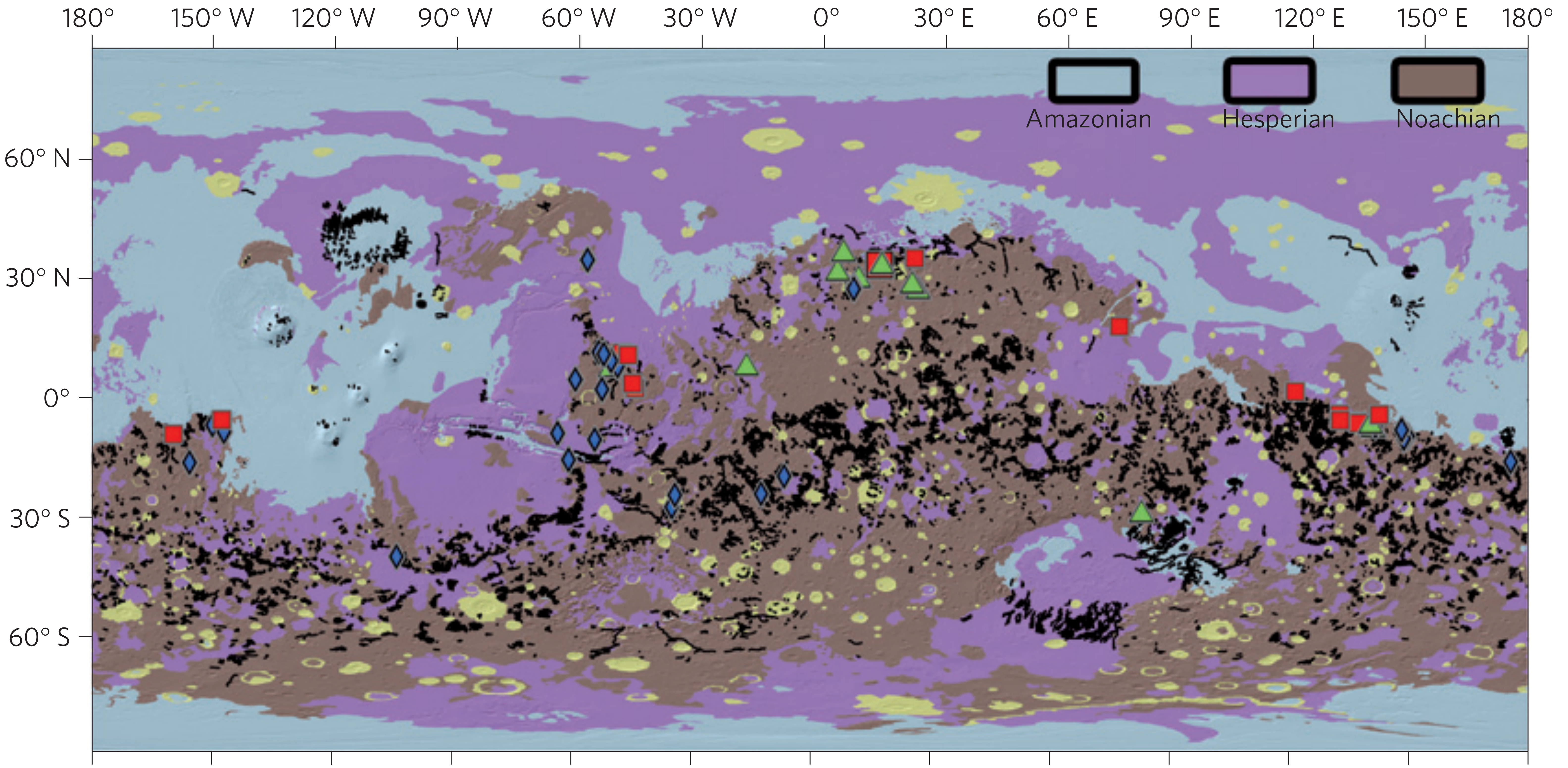
Mars’ valley network

Vellay network mapping



Hynek et al. (2010) *J. Geophys. Res.*

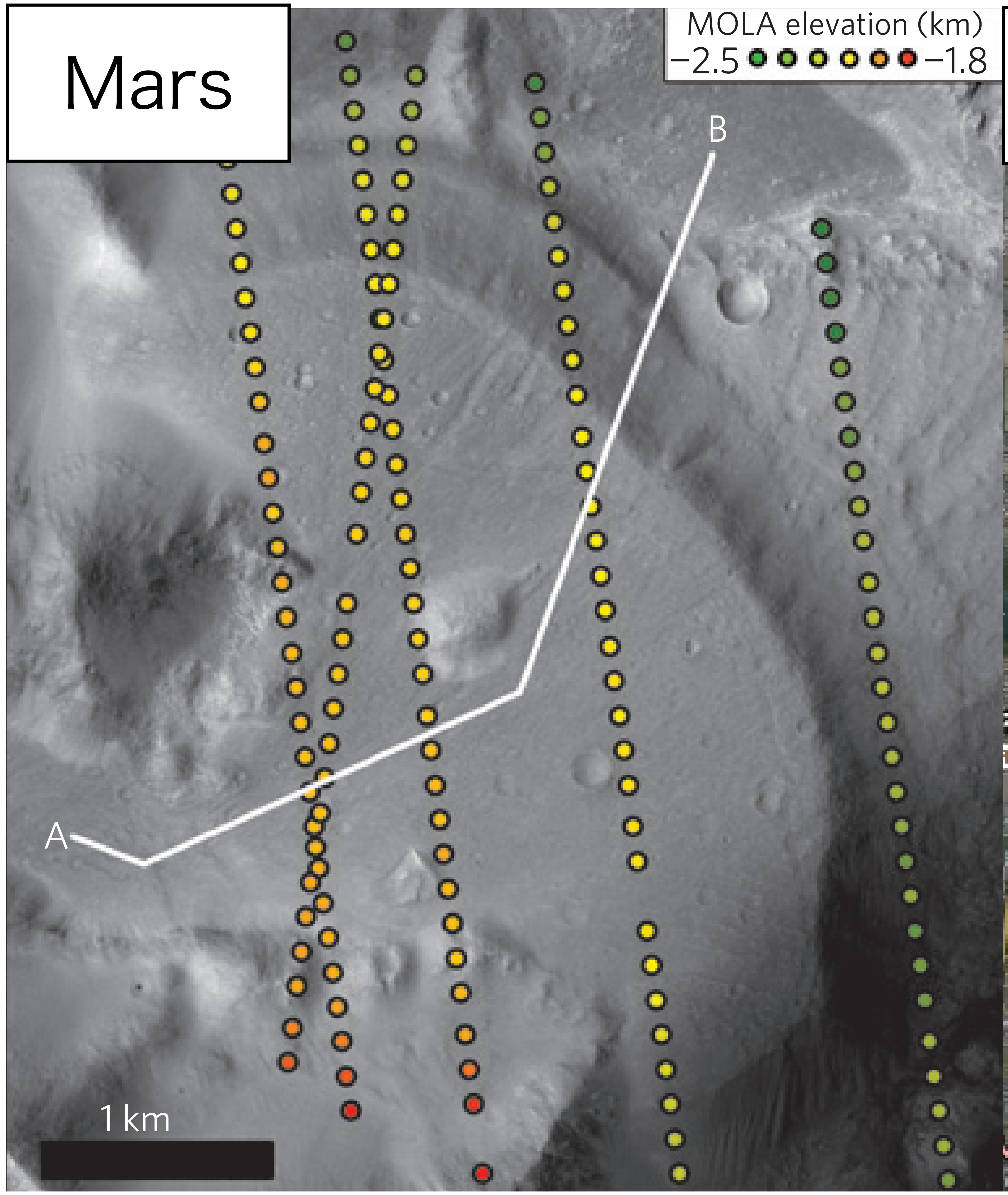
Valley network distribution (black)



Di Achille & Hynek (2010) *Nature Geosci.*

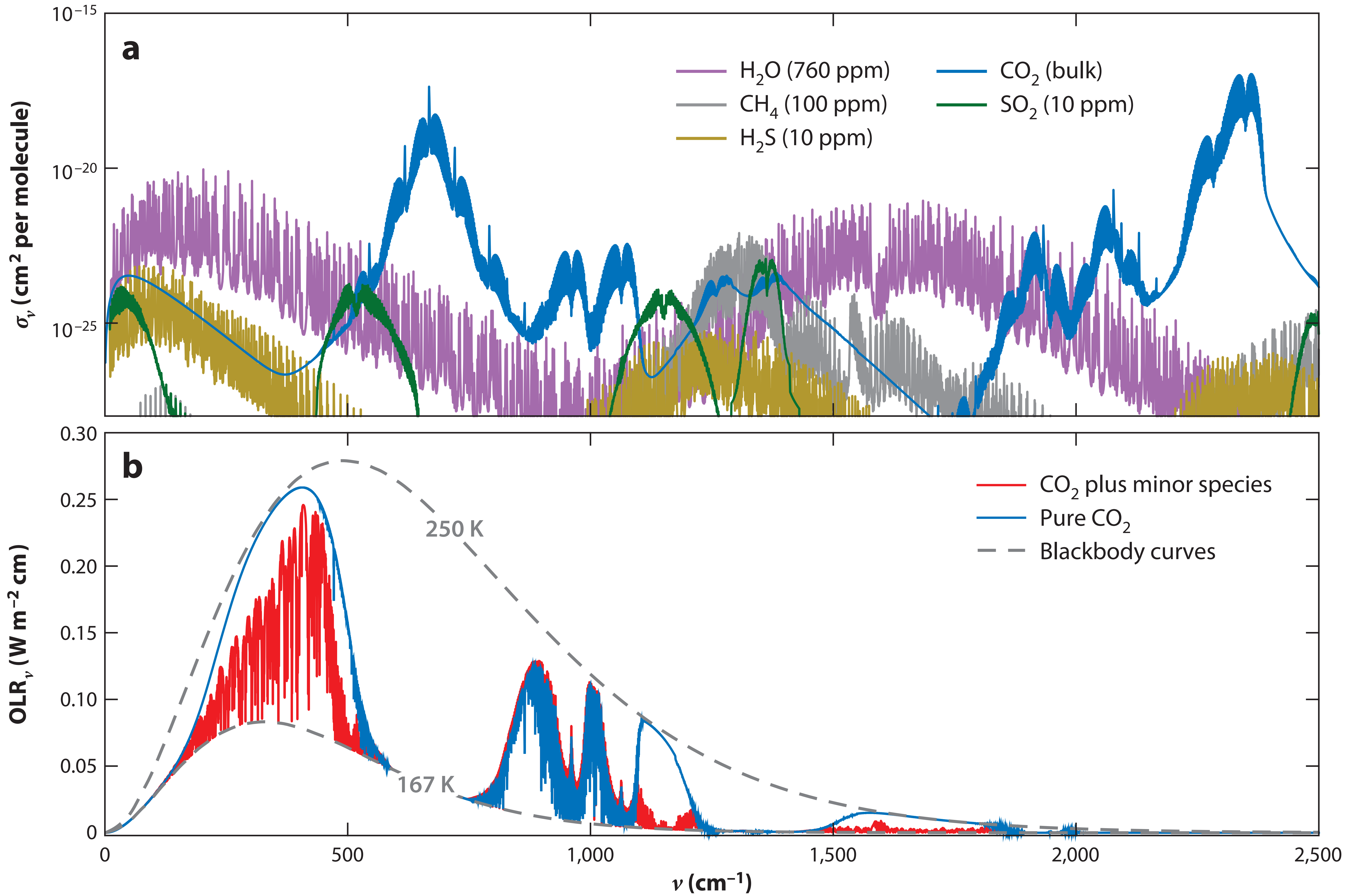
- Formed in the Noachean (4.2–3.5 Ga)
- Requires > 10^5 yr of water flow (Kite et al. 2019, *Space Sci. Rev.*) → There were transient warm periods at least

Delta

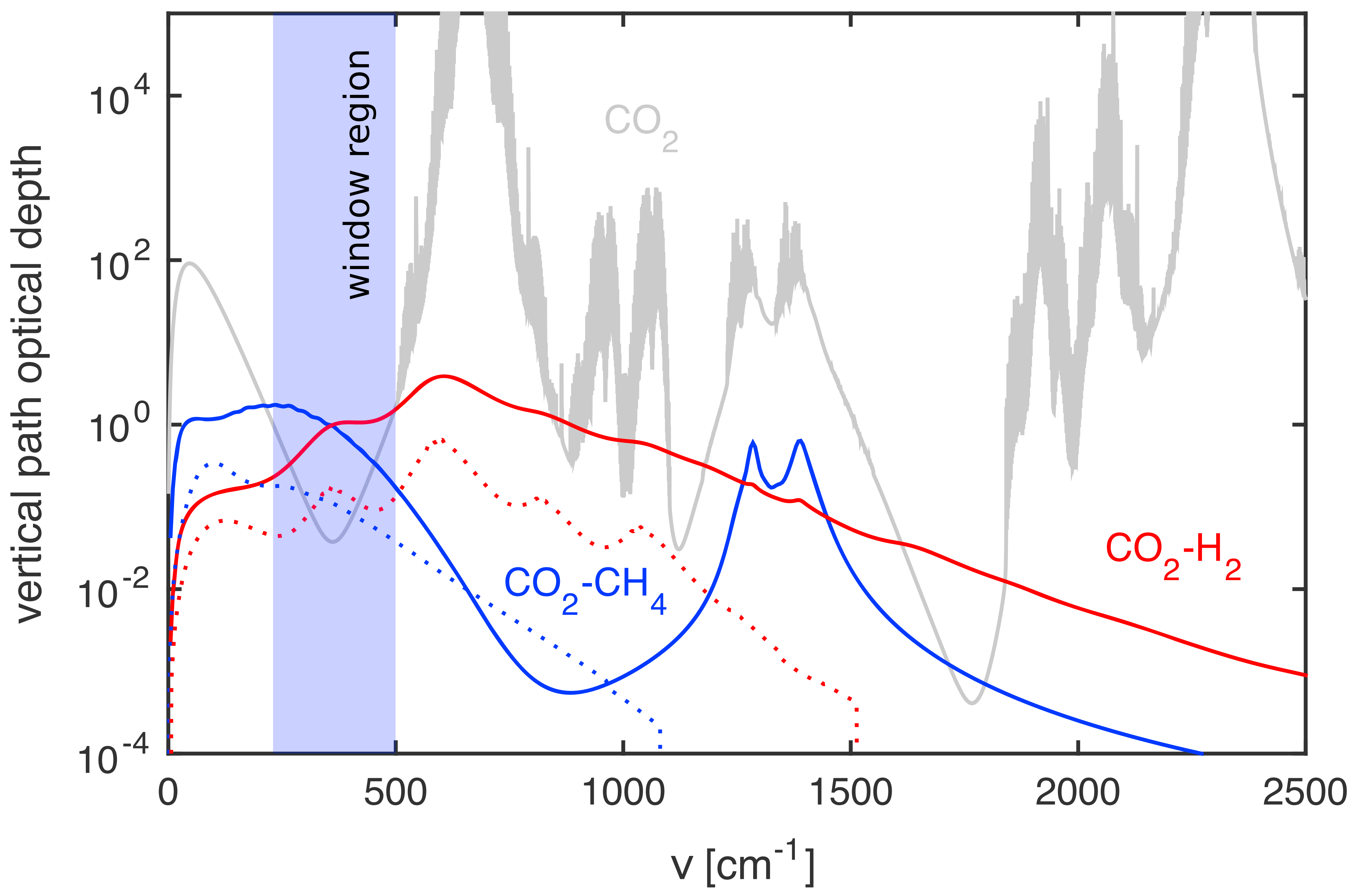


Di Achille & Hynek (2010) *Nature*

Greenhouse gas to warm early Mars



Wordsworth (2016) *Annu. Rev. Earth Planet. Sci.*



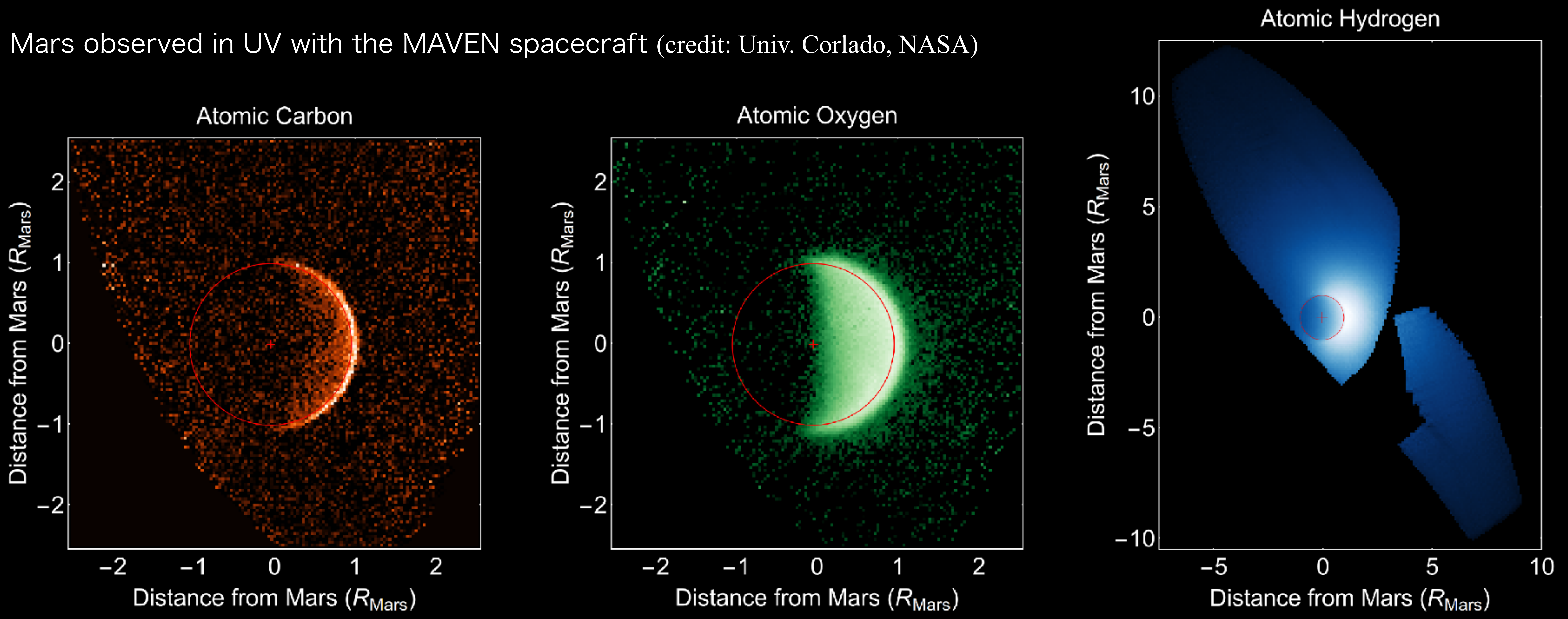
Wordsworth et al. (2017) *Geophys. Res. Lett.*

Which molecules can cover the window of the CO_2 atmosphere?

→ **CO_2-H_2 collision-induced absorption**, SO_2 (short-lived), H_2S (short-lived)

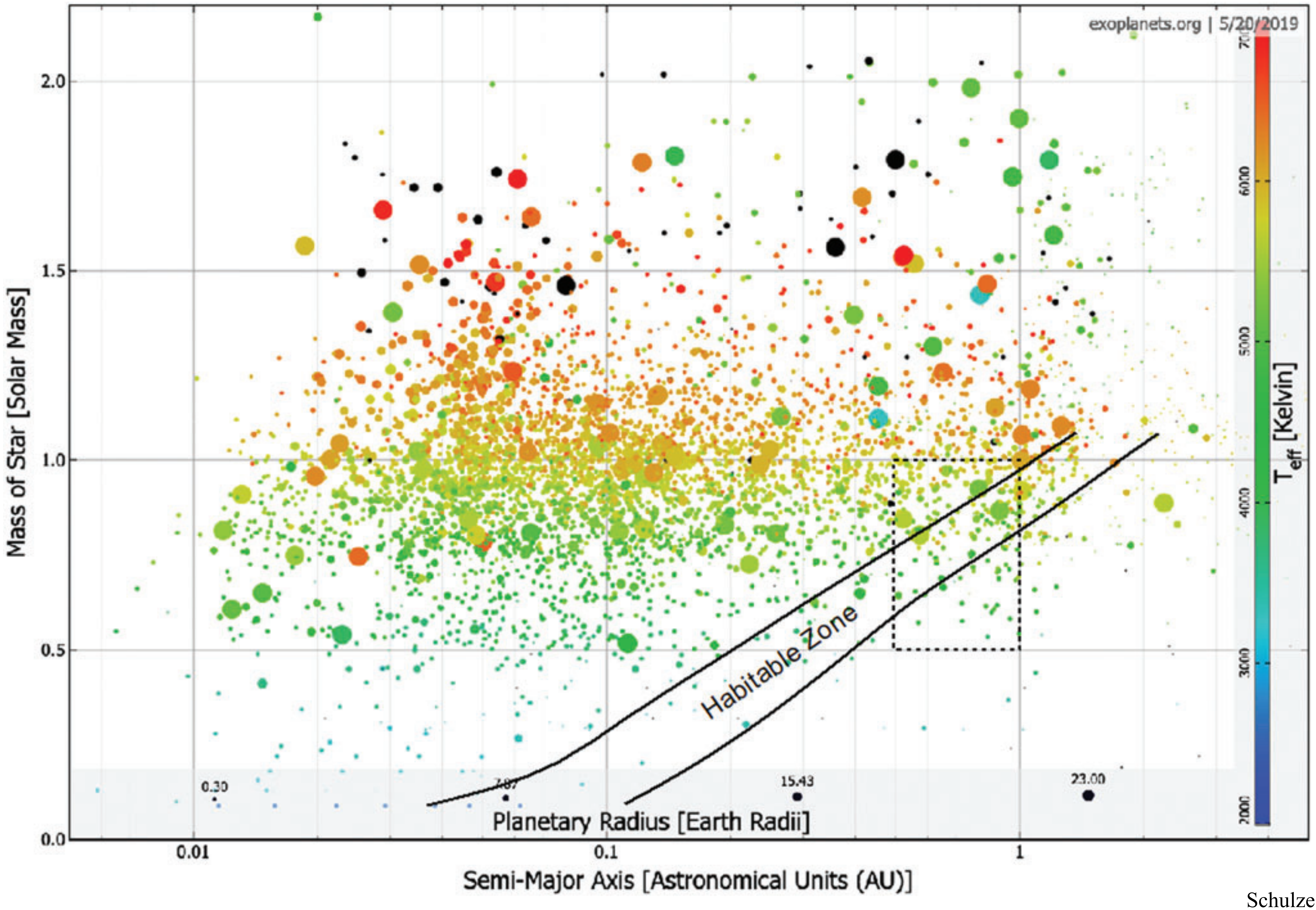
Water and atmosphere lost to space?

Mars observed in UV with the MAVEN spacecraft (credit: Univ. Corlado, NASA)



The absence of magnetic field → Atmospheric escape due to the solar wind

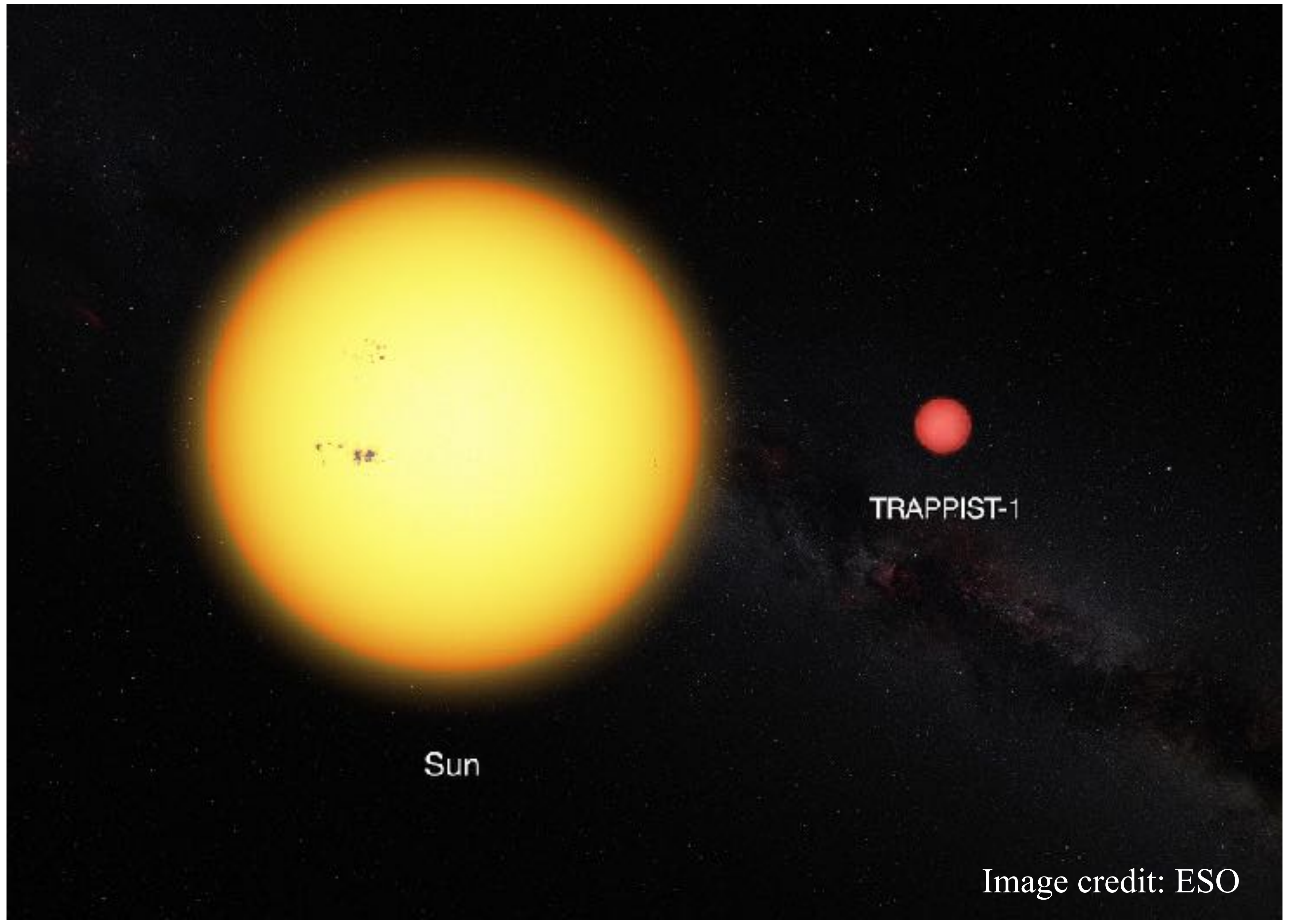
Potentially habitable exoplanets



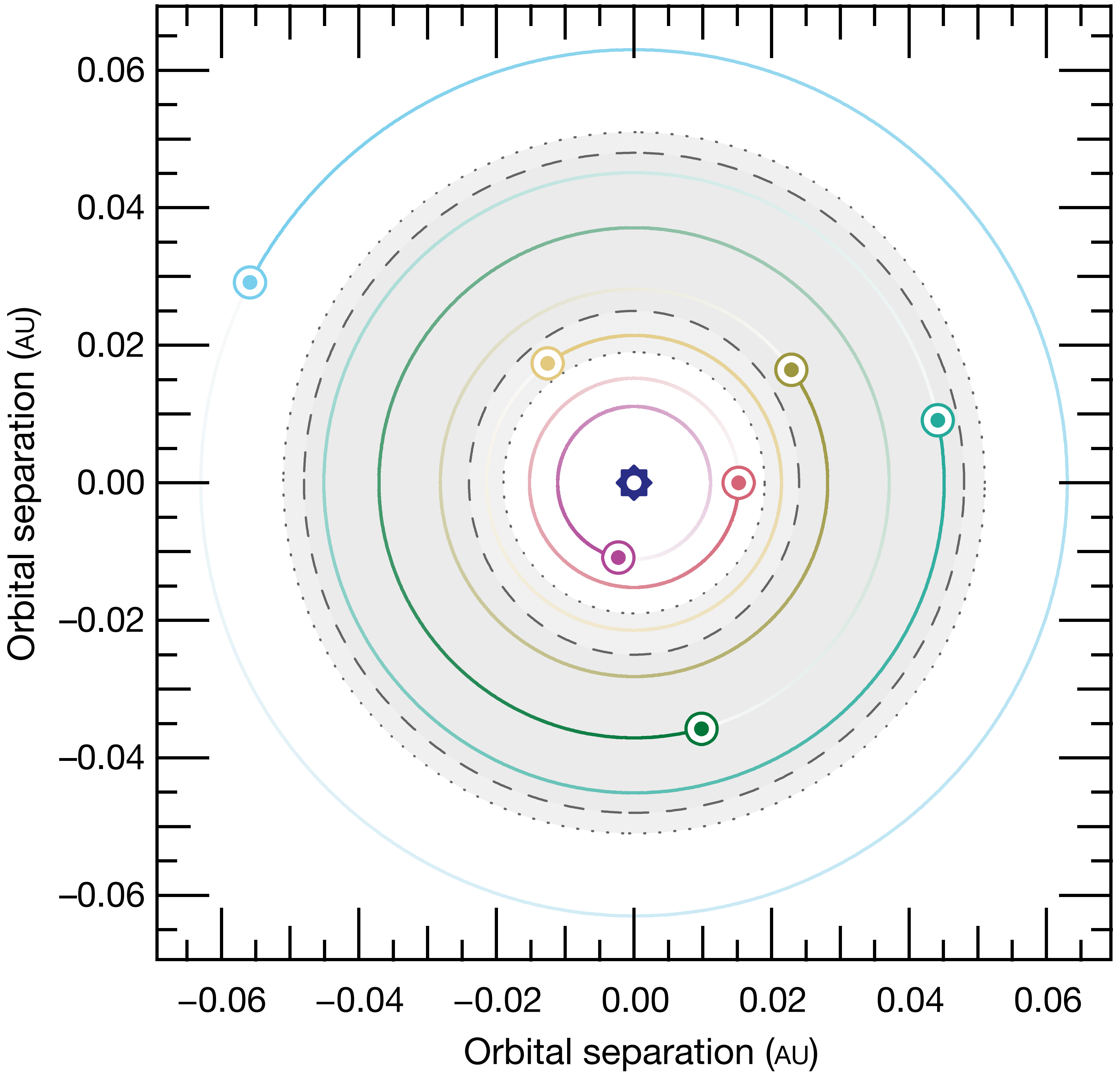
Schulze-Makuch et al. (2020) *Astrobiology*

Planets around M-type stars

Sun vs. TRAPPIST-1 (0.09 $M_\odot$, M-type)



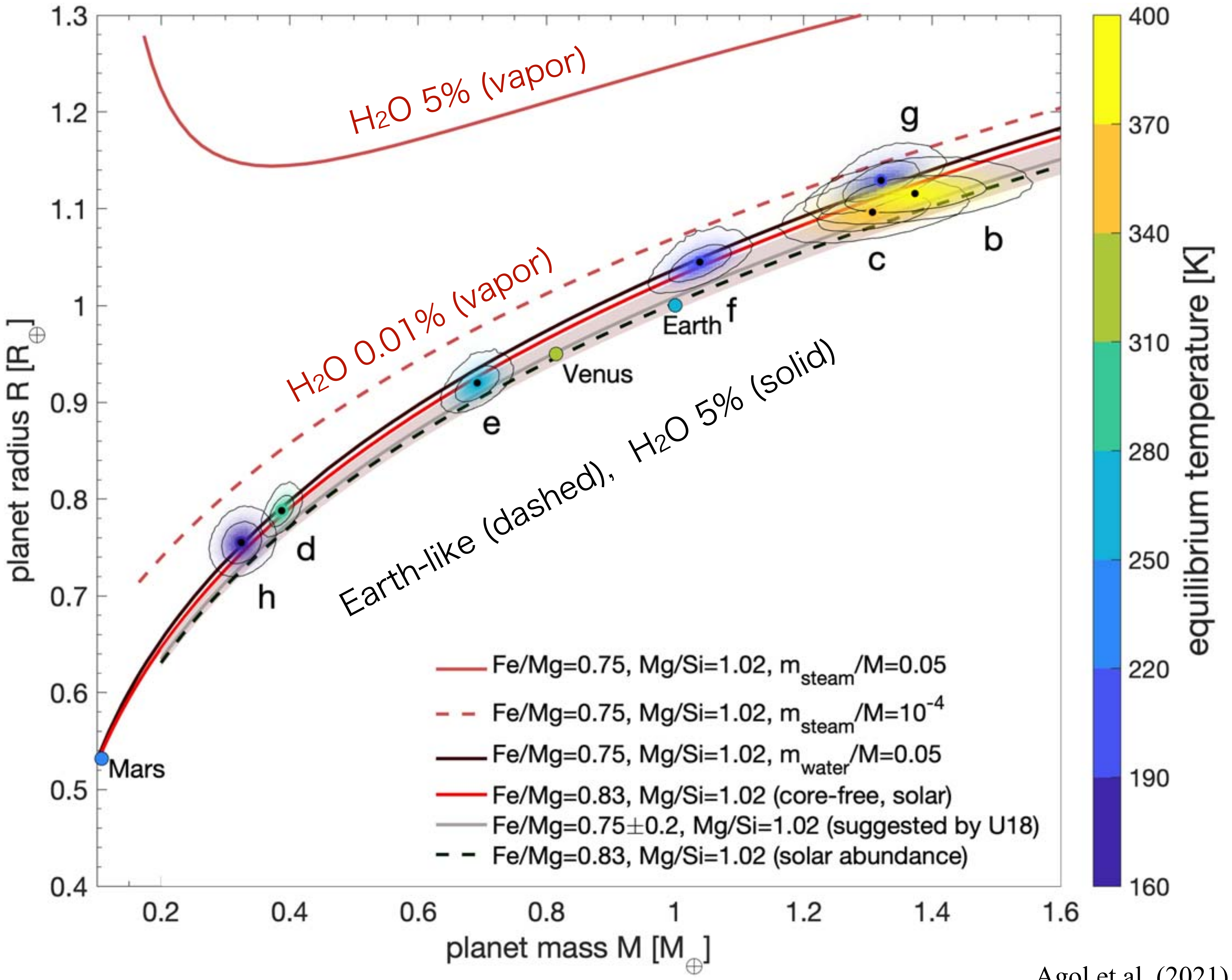
TRAPPIST-1 planets (solid) and the habitable zone (dashed)



Gillon et al. (2017)

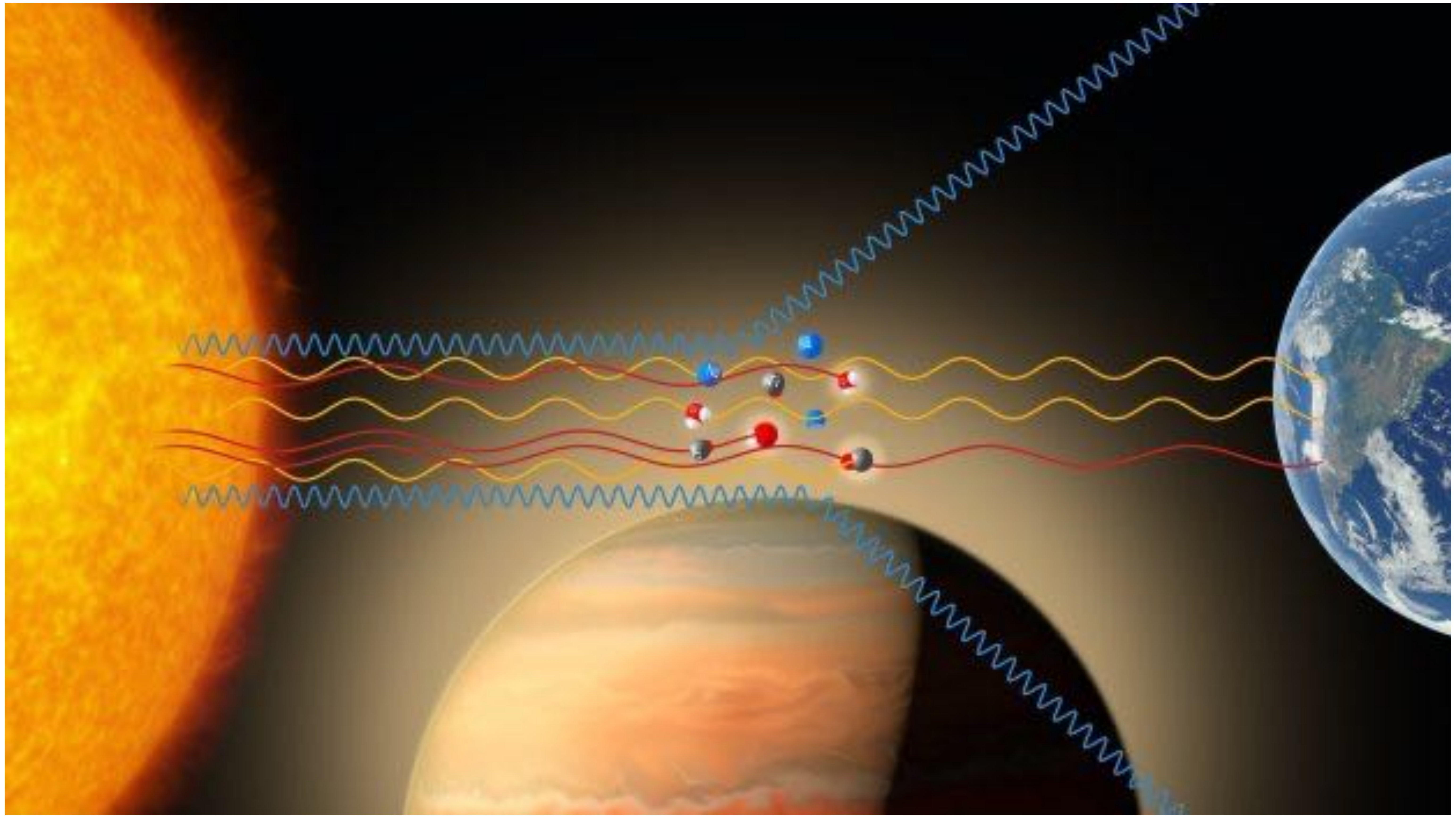
- The majority of solar neighbors are M-type stars
- Three planets (e, f, g) in TRAPPIST-1 system (12 pc from the sun) are in its habitable zone

Mass-radius relation

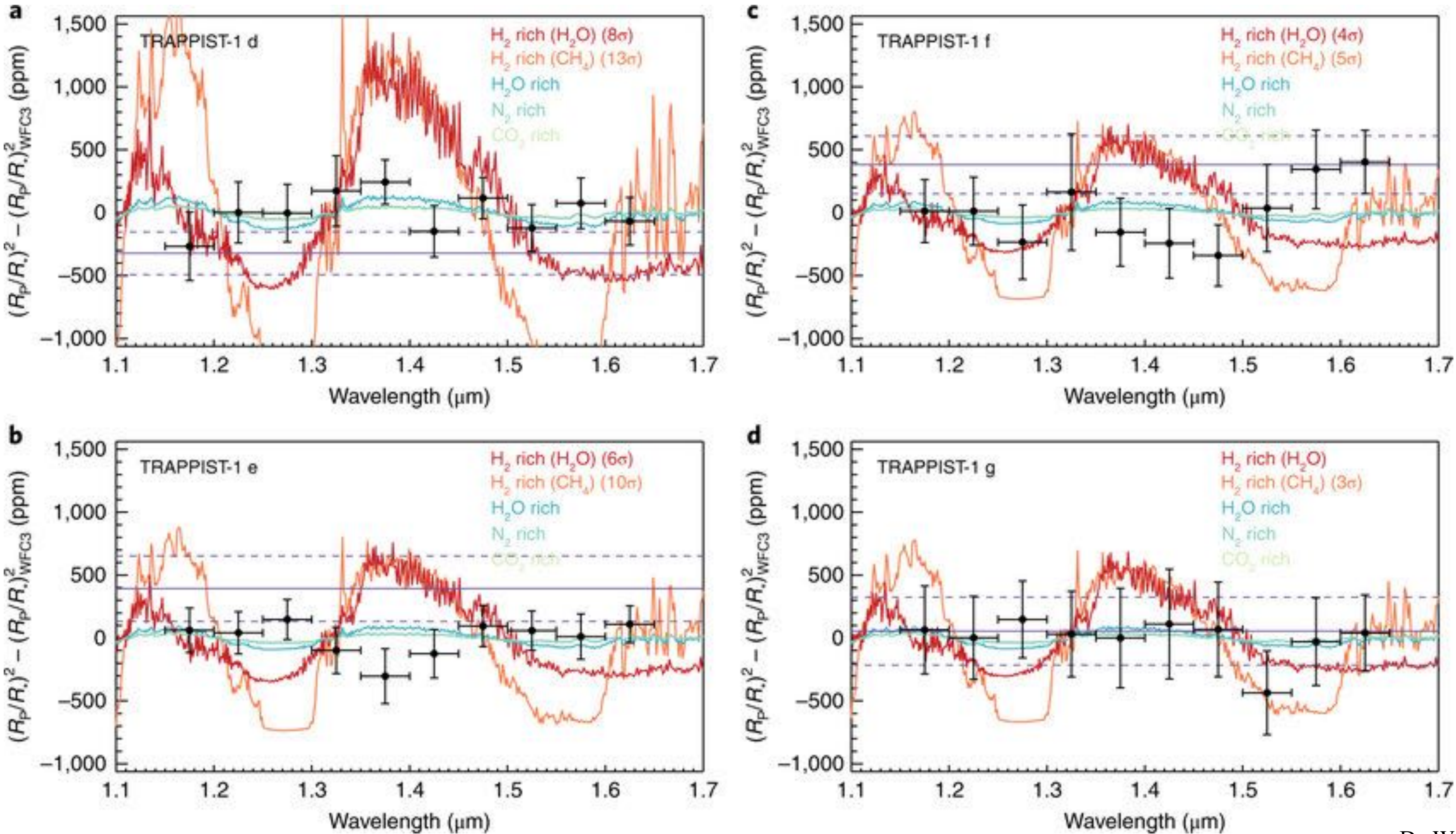


Agol et al. (2021)

Transmission spectra

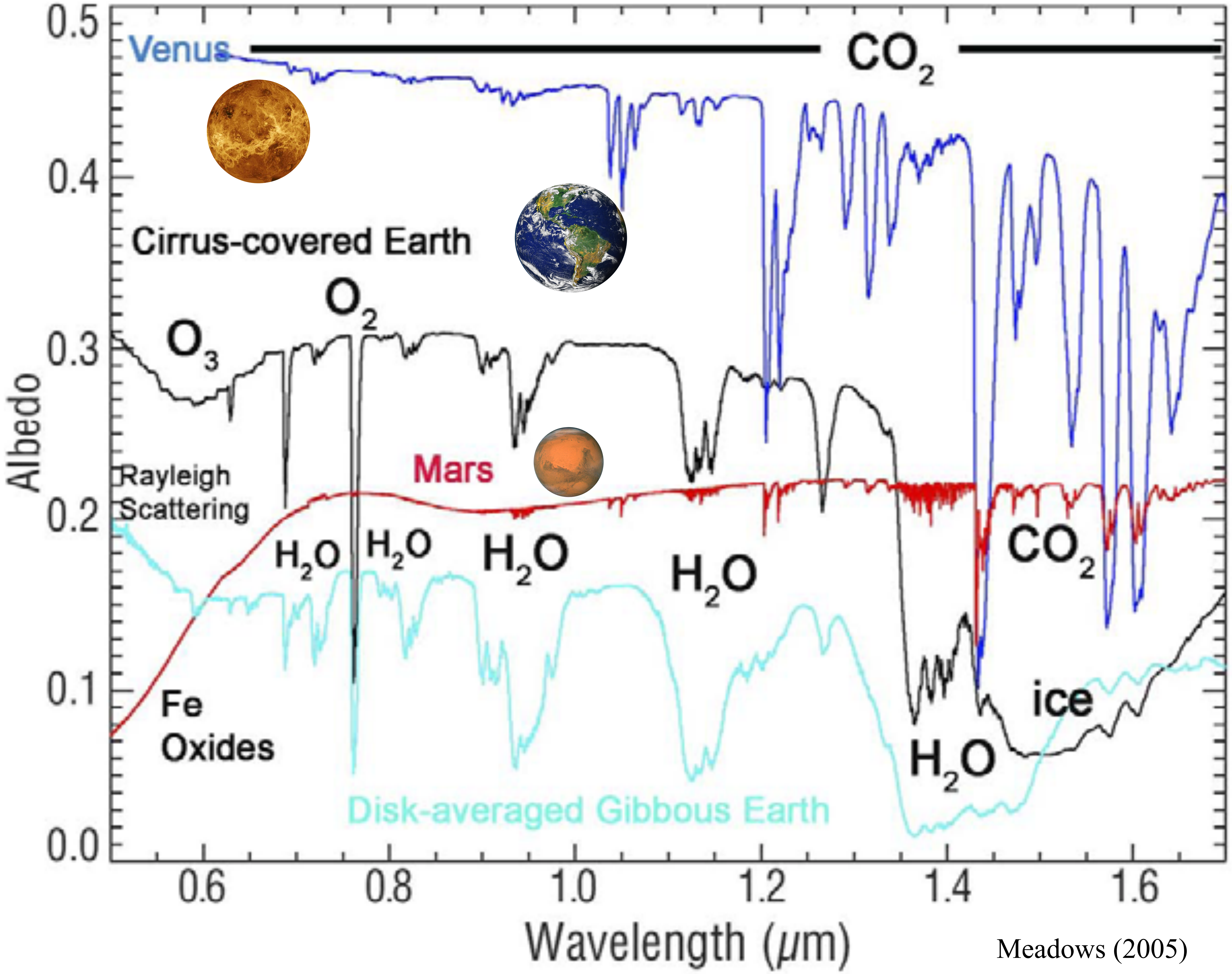


Transmission spectra of TRAPPIST-1 planets



De Wit et al. (2018)

Biosignature



Meadows (2005)

Non-equilibrium chemistry driven by photodissociation

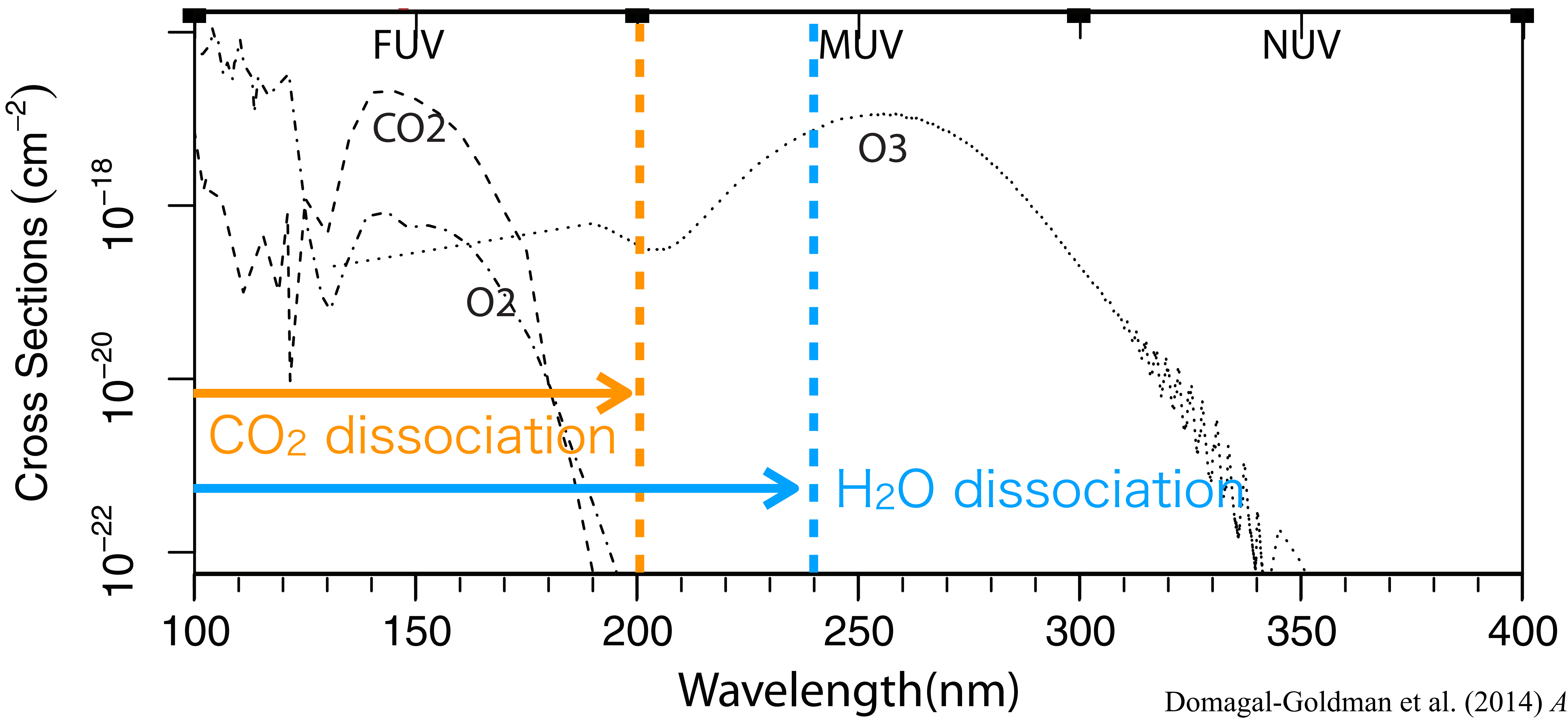
- **Radicals** produced by photodissociation drive non-equilibrium chemistry
  - Species with unpaired electrons in the outermost shell: such as OH, Cl, O

- Production of OH
  - Earth: $O_3 + h\nu\ (\lambda < 310\ \mathrm{nm}) \rightarrow O_2 + O(^1D)$ — (1), $H_2O + O(^1D) \rightarrow OH + OH$ — (2)
  - Mars: $H_2O + h\nu\ (\lambda < 240\ \mathrm{nm}) \rightarrow OH + O$ — (3)

- Free energy of radicals obtained from photons propagates through reactions
  - e.g., $CH_4 + OH \rightarrow CH_3 + H_2O$ — (4)

- Eventually thermalized either by disproportionation reaction or recombination by three-body reaction.
  - e.g., $OH + HO_2 \rightarrow H_2O + O_2$ — (5), $NO_2 + OH + M \rightarrow HNO_3 + M$ — (6)

$H_2O(OH)$ stabilize CO_2



Domagal-Goldman et al. (2014) *Astrophys. J.*

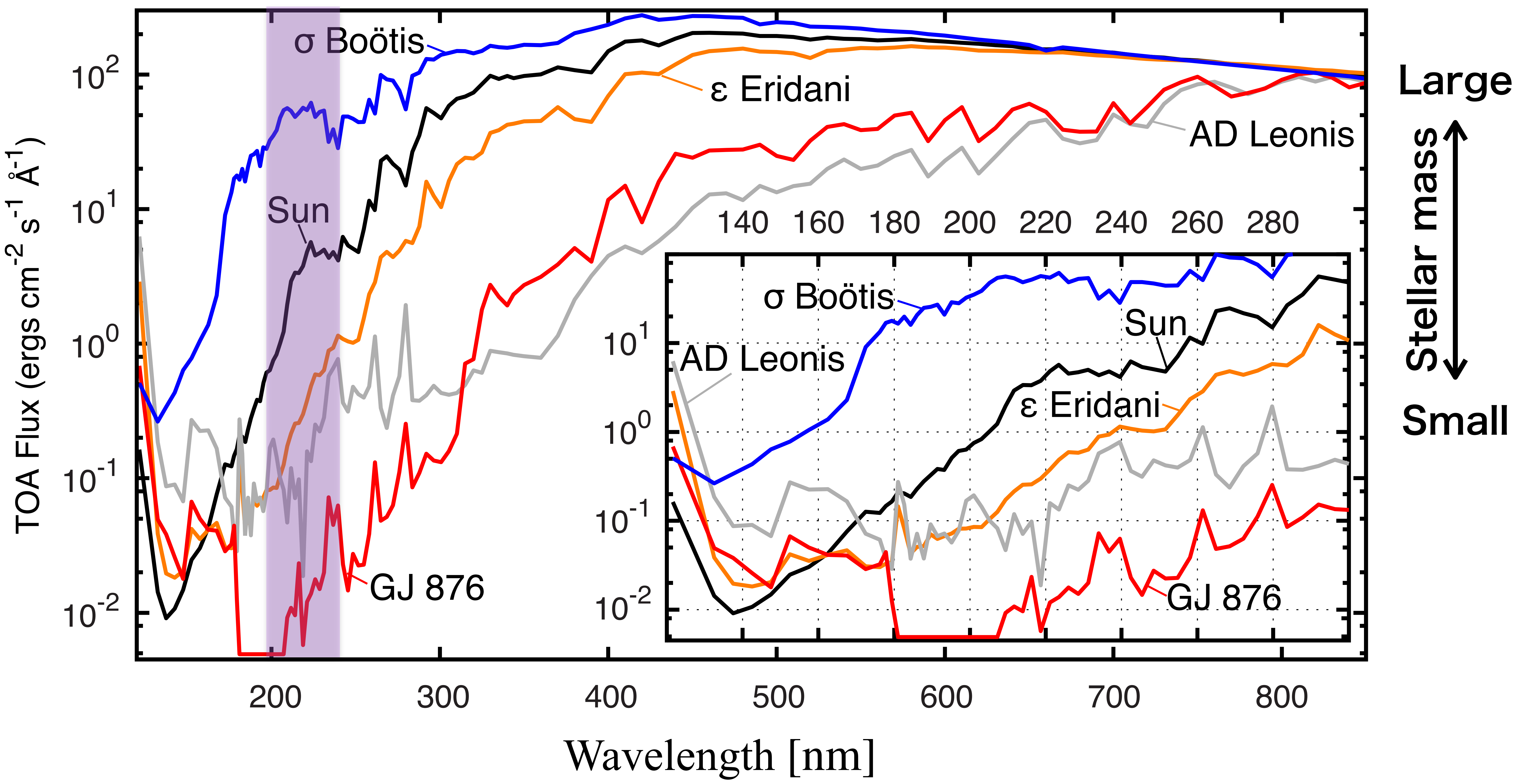
CO_2 dissociates with < 200 nm UV: $CO_2 + h\nu \rightarrow CO + O$ — (1)

Its reverse reaction is slow: $CO + O + M \rightarrow CO_2 + M$ — (2) (*spin-forbidden reaction*)

H_2O dissociates with: < 240 nm UV: $H_2O + h\nu \rightarrow OH + H$ — (3)

This OH radical oxidizes CO: $CO + OH \rightarrow CO_2 + H$ — (4)

Photochemical instability of CO_2 atmosphere?



Emission spectra of stars

- σ Boötis: F-type
- Sun: G-type
- ε Eridiani: K-type
- ADLeonis, GJ 876: M-type

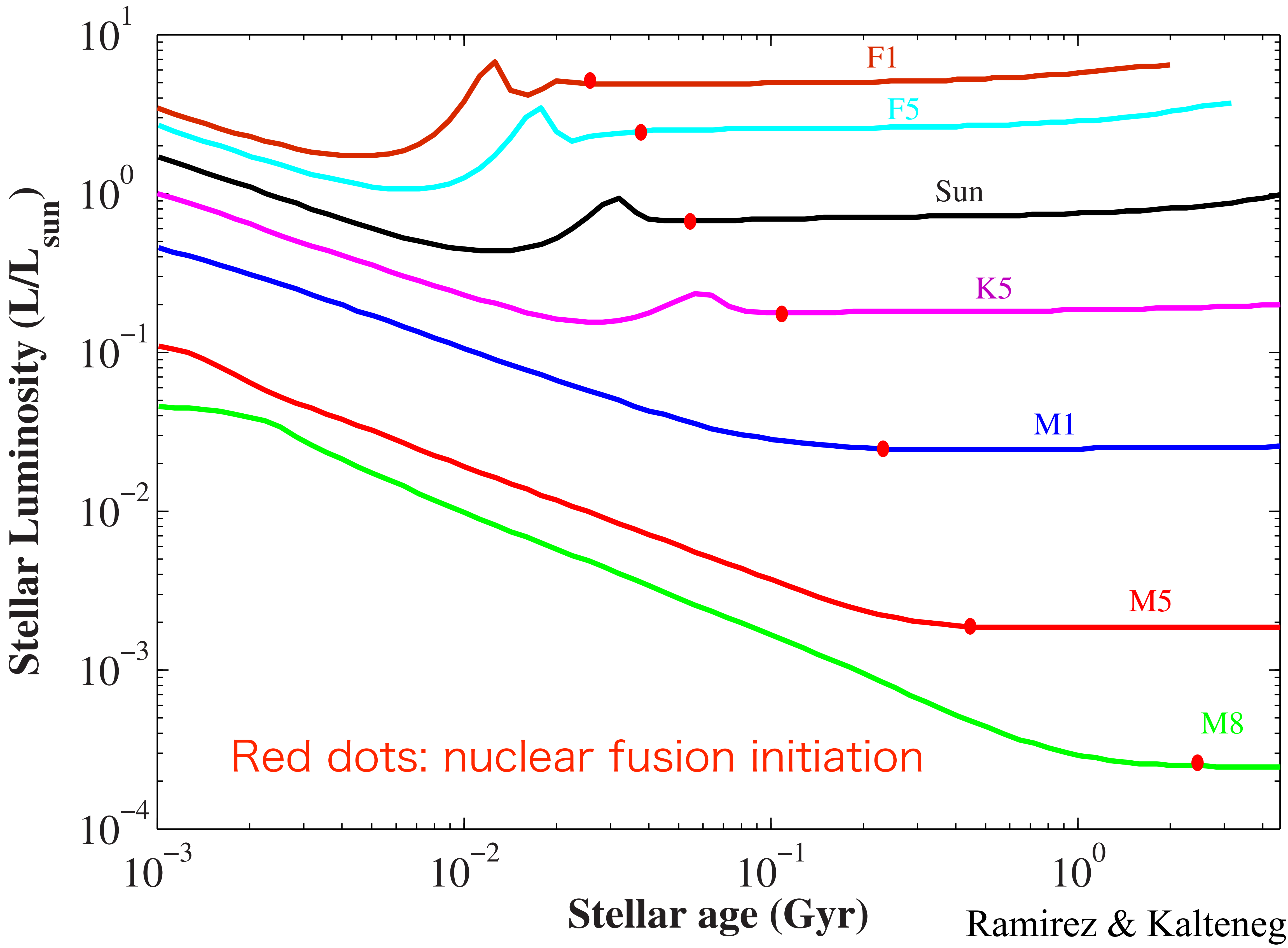
Harman et al. (2015) *Astrophys. J.*

- The difference in stellar emission spectra influences planetary environments via photochemistry
- M-type stars are dimmer in H_2O-dissociation wavelengths (200 – 240 nm) → CO+O_2 atmosphere？

(e.g., Tian et al. 2014)

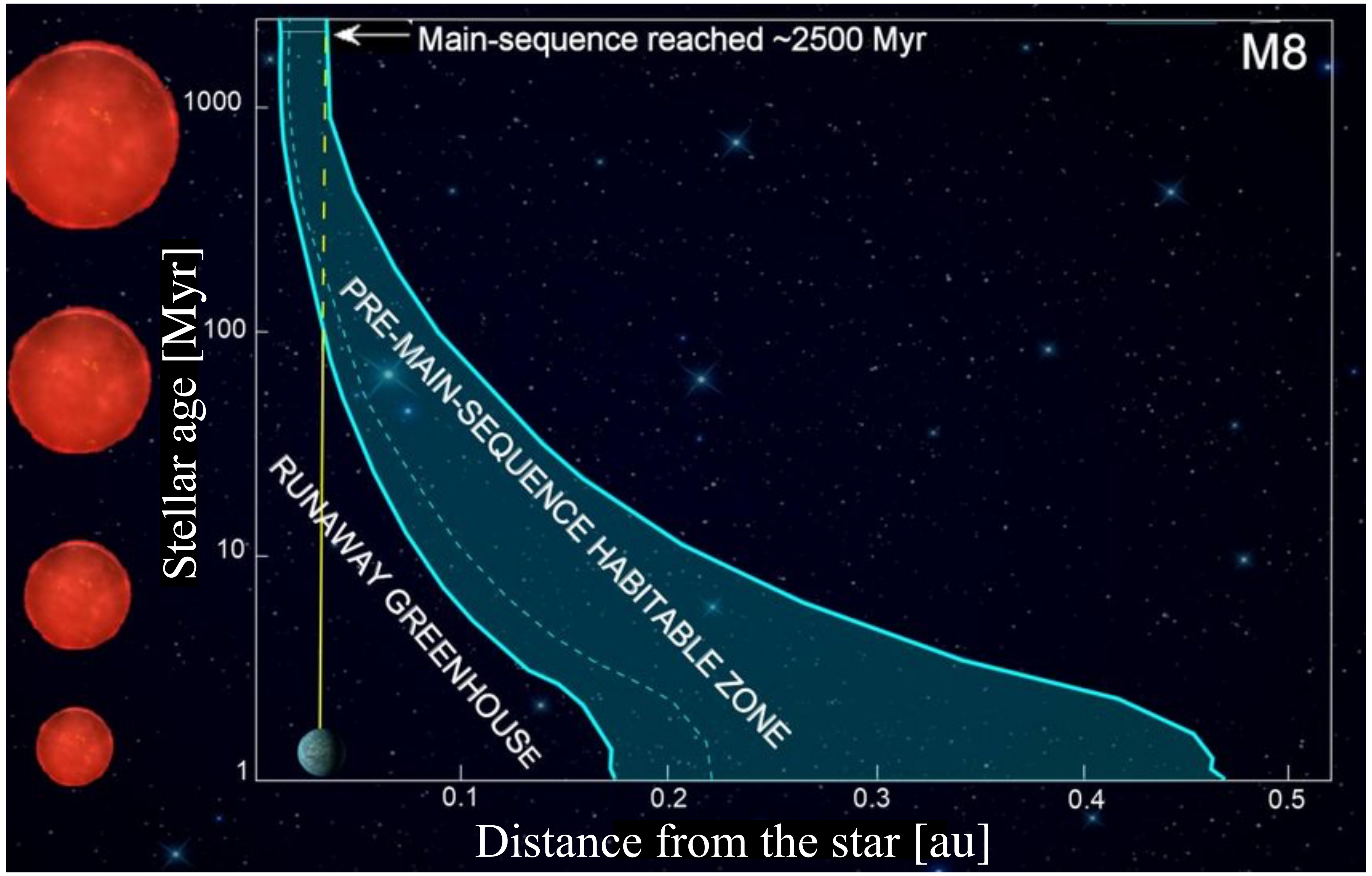
Stellar evolution

Luminosity evolution for different stellar types



Ramirez & Kaltenegger (2014)

How the HZ evolves around a M-type stars



Ramirez (2018)

- M-type stars stay ~Gyr as pre-main-sequence stars with higher luminosities
- Planets in HZs of M-type stars experience Venus-like water loss?

Summary

- Planets born hot: magma ocean state and planetary differentiation
- Orbital locations with respect to the HZ dominantly control planetary evolution
- Venus: the runaway greenhouse state and water loss
- Earth: formation of the ocean and CO_2 drawdown as carbonate rock
- Mars: CO_2 ice formation, intermittent warm climates with additional greenhouse gas?
- Stellar effects: atmospheric escape, photochemistry, luminosity evolution
- Extrasolar rocky planets will show more variety of evolution?

Report assignment

Summarize your answers into a short report and submit it by the beginning of the next lecture (either directly, to my post-box, or by e-mail to hiro.kurokawa@elsi.jp).

Earth's crust contains 3.6×10^{20} kg of carbonate rock (mainly $CaCO_3$) which ultimately originates from Earth's early atmosphere (mainly CO_2) right after magma ocean solidification. Given that the atmospheric surface pressure is proportional to the atmospheric mass, estimate the surface pressure of the early atmosphere. You can use current Earth's surface pressure = 1.0×10^5 Pa and atmospheric mass = 5.1×10^{18} kg.