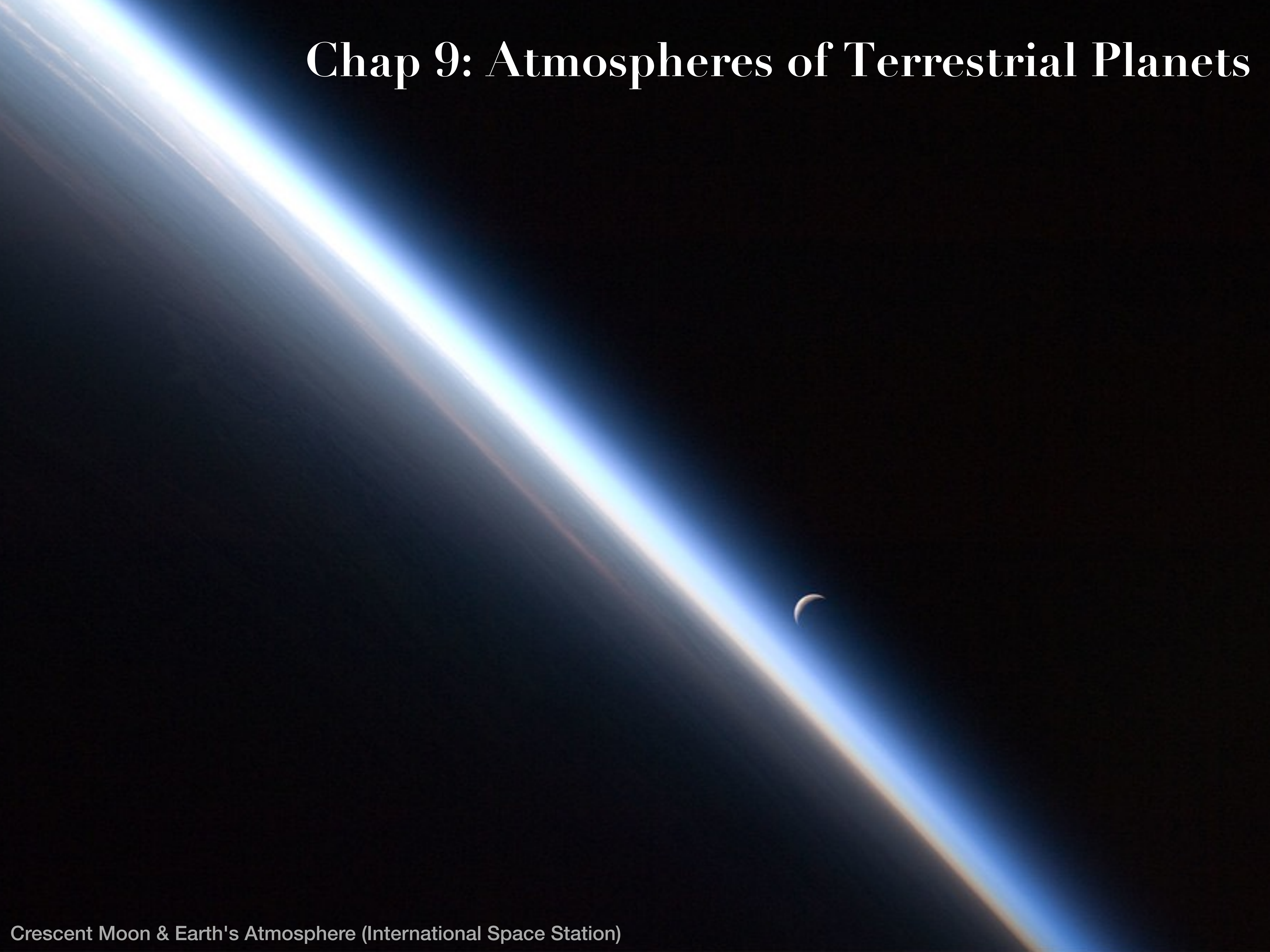
Chap 9: Atmospheres of Terrestrial Planets



Crescent Moon & Earth's Atmosphere (International Space Station)

Chap 9: Atmospheres of Terrestrial Planets

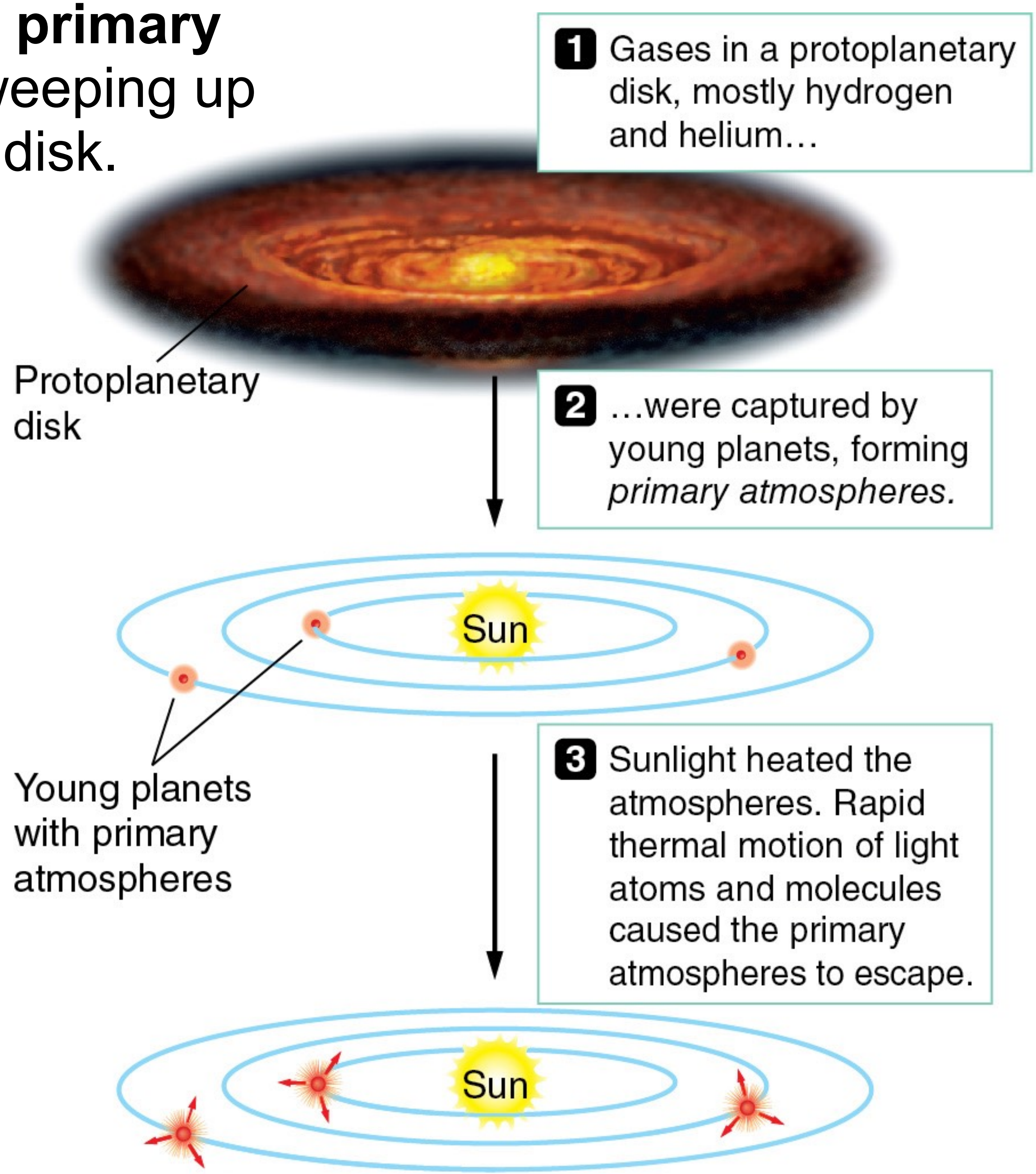
- How did the terrestrial planets' atmospheres form?
  - Primary and secondary atmospheres
  - Atmosphere retention: mean molecular velocity & magnetosphere
- How do we understand the density structure of the atmosphere?
  - Hydrostatic equilibrium under isothermal condition
- How has Earth's atmosphere been changed over time?
  - Oh, life has changed everything!
- Climate effects from astronomical, geological, and biological mechanisms

The Origin of Atmospheres

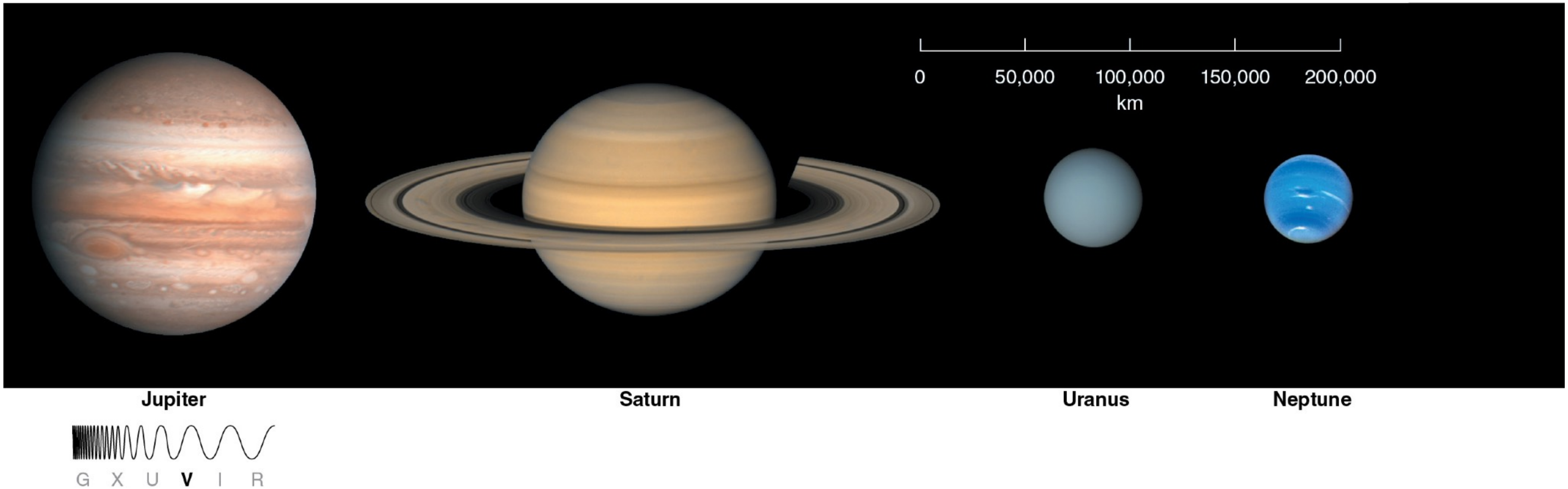
a brief history

Primary/Primitive Atmospheres from Accretion

- New planets formed **primary atmospheres** by sweeping up gas in the accretion disk.

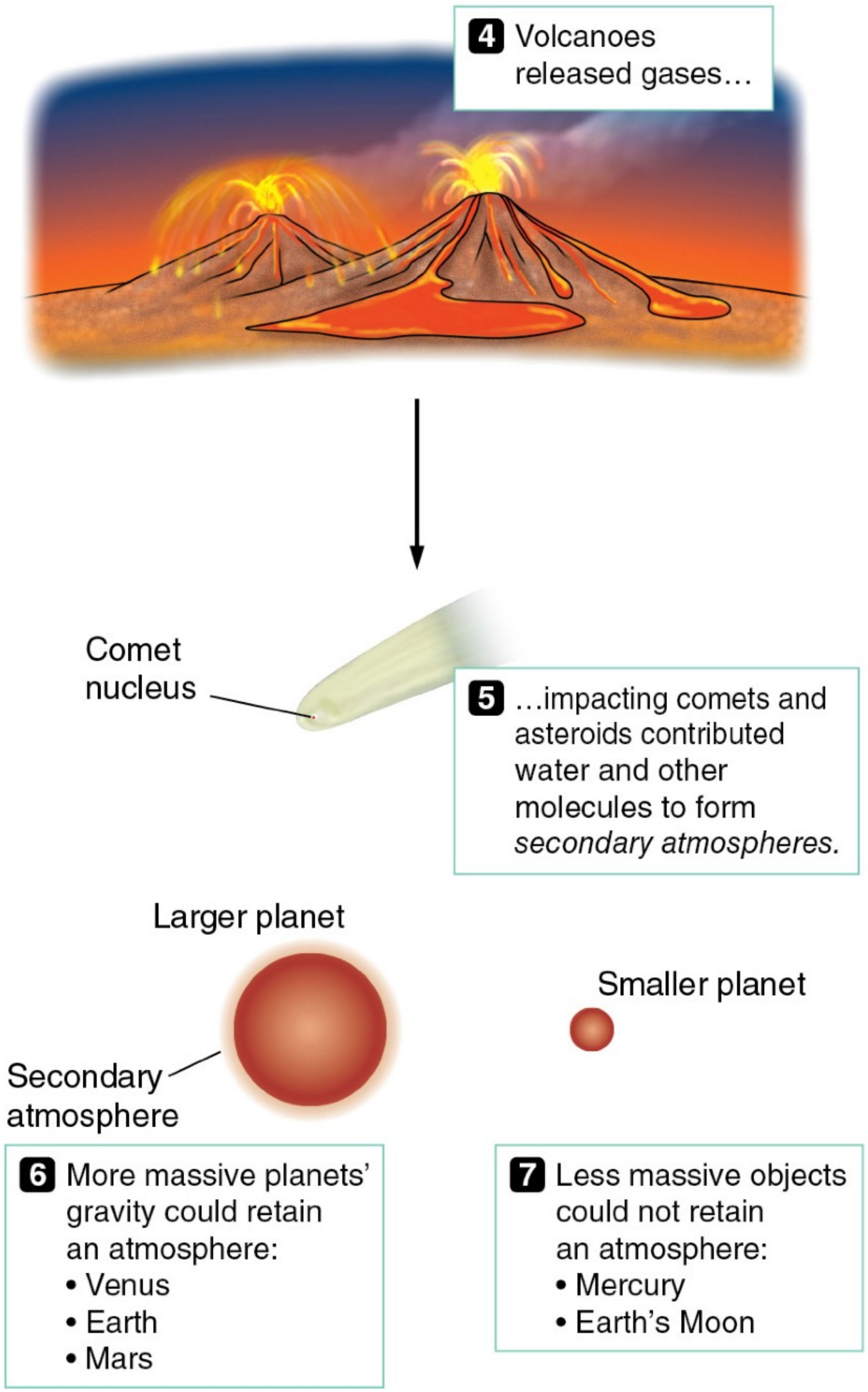


Primary/Primitive Atmospheres are retained in the Giant Planets



- The Gas Giants have no solid surfaces. We just see the cloud layers in the atmospheres.
- They are called giant planets because of their mass—from 14.5 Earth masses (Uranus) to 318 (Jupiter)—and also their physical size.

Secondary Atmospheres from volcanism and small bodies



- **All terrestrial bodies lost their primary atmospheres.**
- **Secondary atmospheres** were acquired later by:
  - **volcanism**
  - **comet impacts**
- Only Venus, Earth, and Mars have significant secondary atmospheres.
- Mercury and the Moon have no significant atmosphere.

The Condensation Process (Minerals)

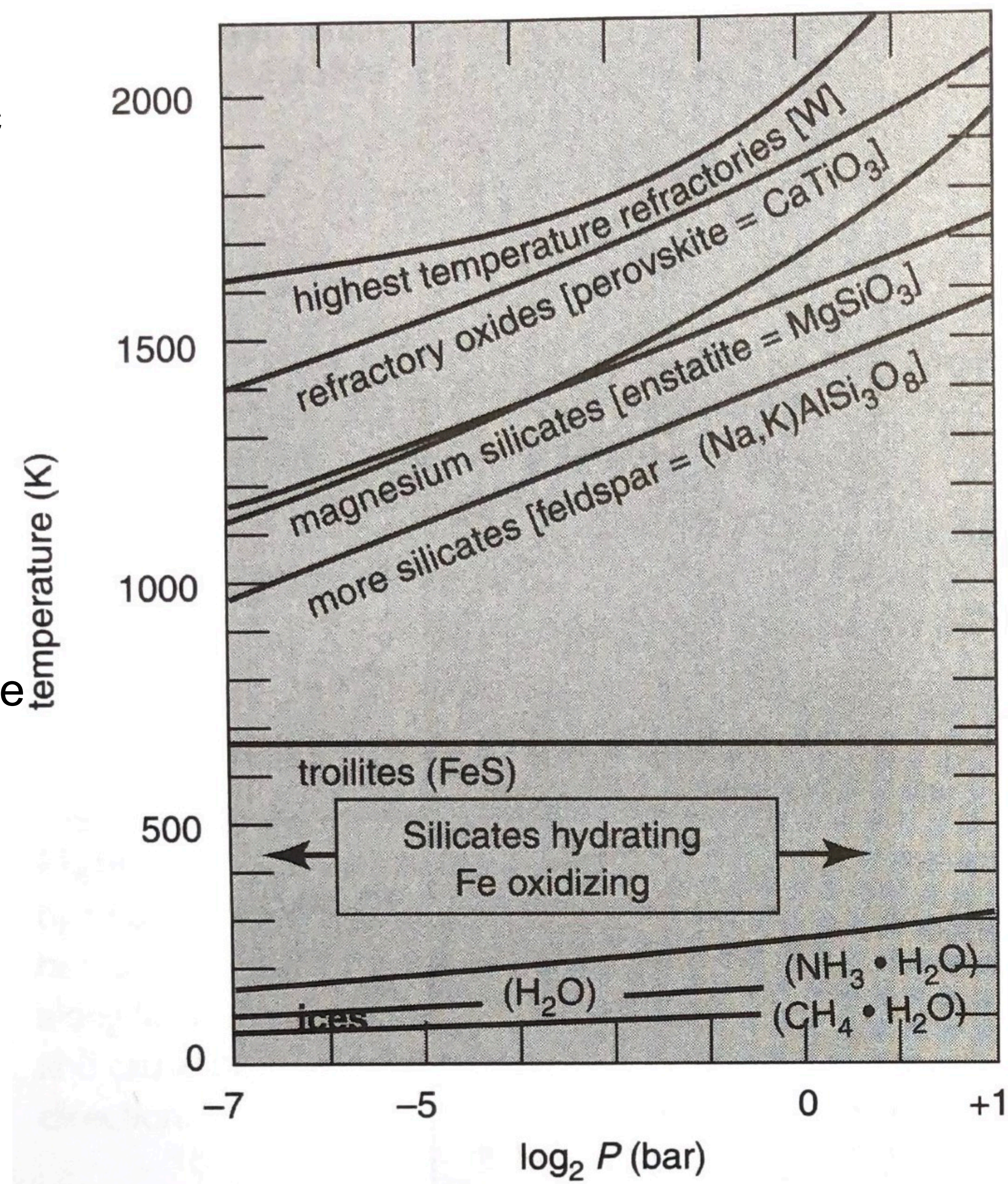
As elements condense out of the solar cocoon nebula, they form solid microscopic mineral grains in the following sequence:

1. High temperature refractories (e.g., Tungsten [W], spinel [$MgAl_2O_4$], and perovskite [$CaTiO_3$])

2. Nickel-Iron alloy, and Silicates (e.g., olivine [Fe_2SiO_4 and Mg_2SiO_4]).

3. Carbonaceous condensates (graphite-like material mixed with organic molecules and silicates)

4. Ices (**500 > T > 200 K, hydrated minerals [serpentine - hydrated olivine]**; T < 200 K, ices of water, ammonia, methane, and hydrated ices; T < 170 K, surface ice)



Hartmann05 Fig 5-5: Condensation of minerals

Volcanism releases volatiles: Volcán de Fuego, GUATEMALA

Meteorite Bombardment: remember the sodium-layer laser guide stars in adaptive optics?

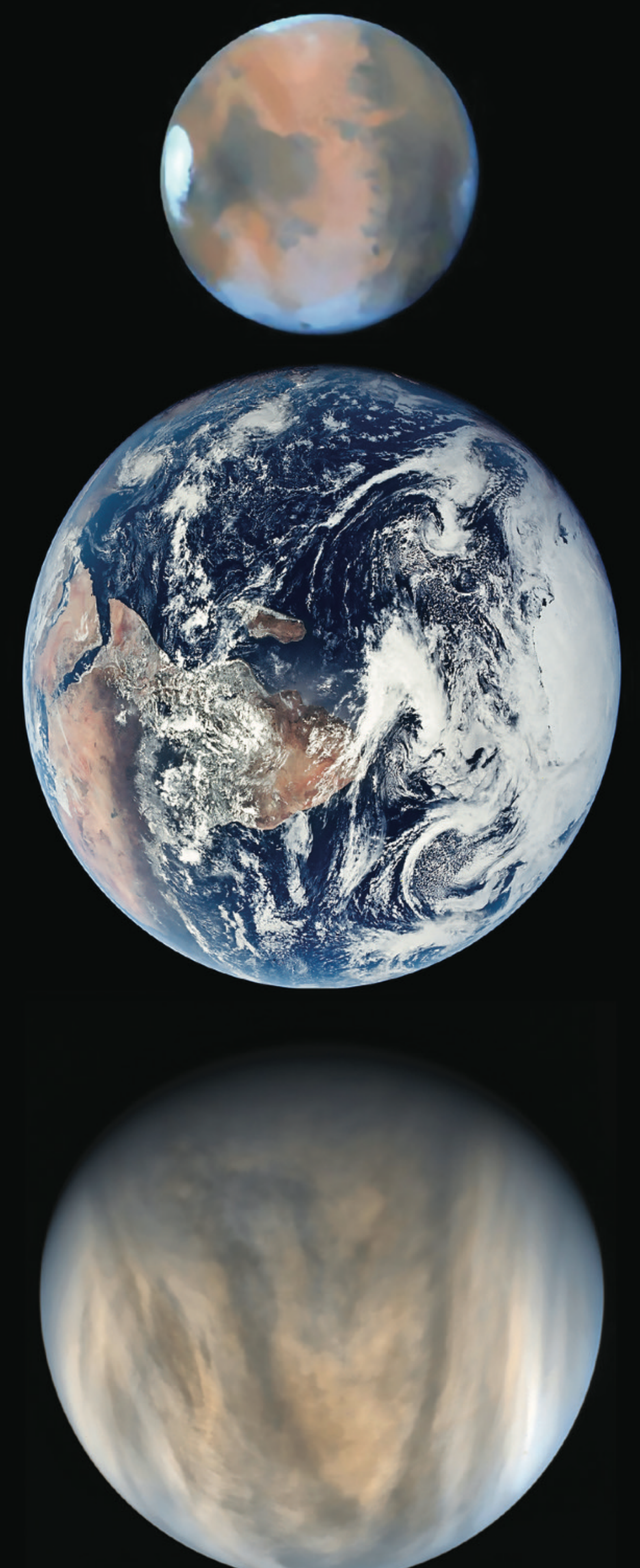
- Sodium layer: 90 km high, 10 km thick (mesosphere). Origin - micrometeorites

TABLE 9.1

Atmospheres of the Terrestrial Planets

Physical Properties and Composition

	PLANET		
Property	Venus	Earth	Mars
Surface Pressure (bars)	92	1.0	0.006
Atmospheric Mass (kg)	4.8×10^{20}	5.1×10^{18}	2.5×10^{16}
Surface Temperature (K)	740	288	210
Carbon Dioxide (%)	96.5	0.041	95.3
Nitrogen (%)	3.5	78.1	2.7
Oxygen (%)	0.00	20.9	0.13
Water (%)	0.002	0.1 to 3	0.02
Argon (%)	0.007	0.93	1.6
Sulfur Dioxide (%)	0.015	0.02	0.00



Summary: the Accretion, Loss, and Regeneration of Atmospheres

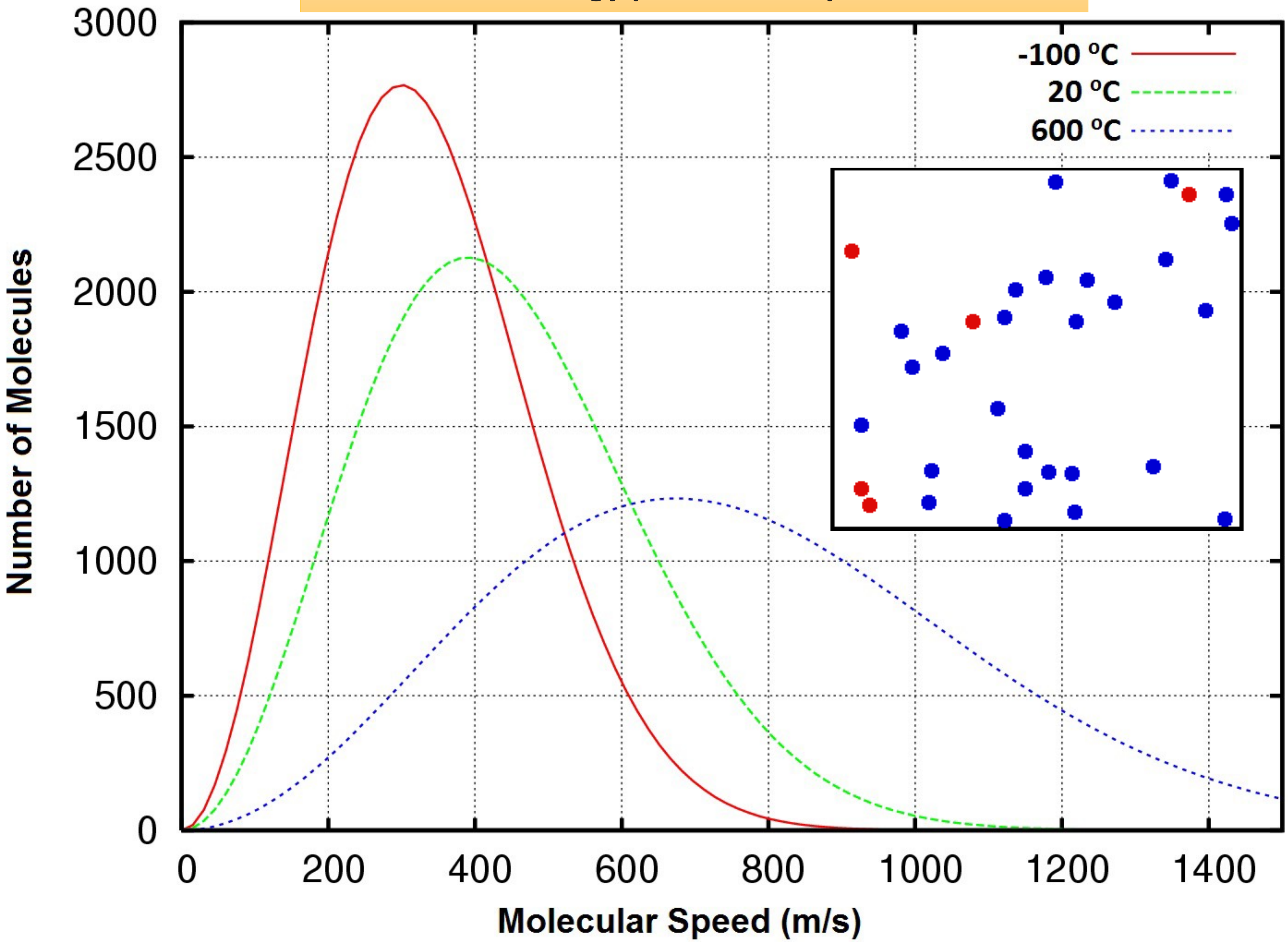
- The **primary atmosphere** is the gas initially gathered from the disk.
  - This is primarily hydrogen and helium (low mass gases).
  - The process of gathering atmosphere is called **core accretion–gas capture**.
- **Secondary atmospheres** occur around some low-mass planets because the initial atmosphere is lost.
  - The low-mass planets do not have enough gravity to keep the initial atmosphere from escaping.
  - **Volcanoes** emit heavy gases from the planetary interiors that the planet can hold onto for a very long time.
  - **Comets & asteroids** bring water and other volatiles to planets, which evaporate and add to the secondary atmosphere.

The Retention of Atmospheres

molecular velocity vs. escape velocity

Velocities of Gas Molecules in the Atmosphere: Boltzmann Distribution

Mean Kinetic Energy per Particle: $\mu m_H v^2/2 = 3kT/2$

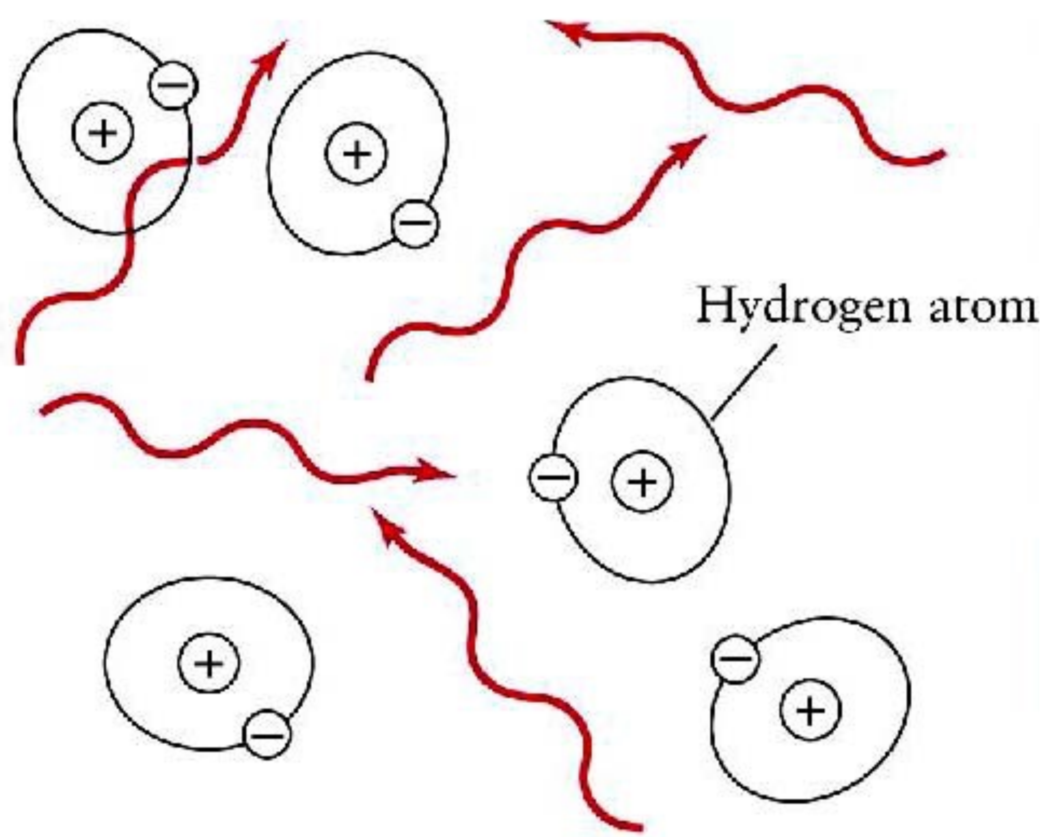


The Mean Molecular Weight/Mass

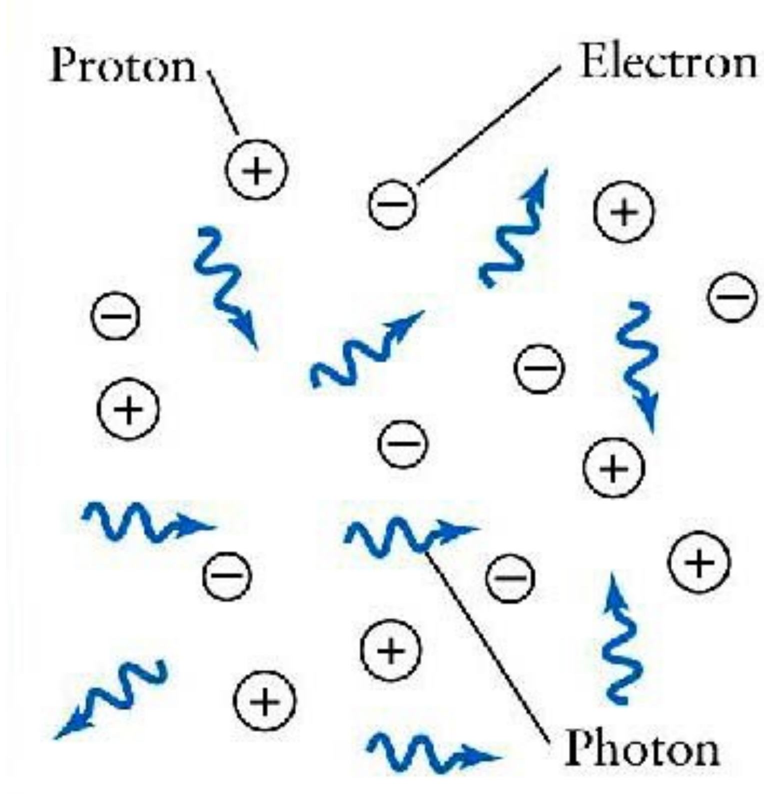
$$\mu = \frac{M_{\rm gas}/N_{\rm particle}}{m_H} = \frac{\bar{m}}{m_H}$$

Examples:

- neutral atomic hydrogen gas: μ = 1
- ionized atomic hydrogen gas: μ = 0.5
- what is the mean molecular weight/mass (μ) of pure CO_2 gas?



neutral atomic hydrogen



ionized hydrogen

Working It Out 9.1: Atmosphere Retention – 1

Mean Kinetic Energy per Particle: $\mu m_H v^2/2 = 3kT/2$

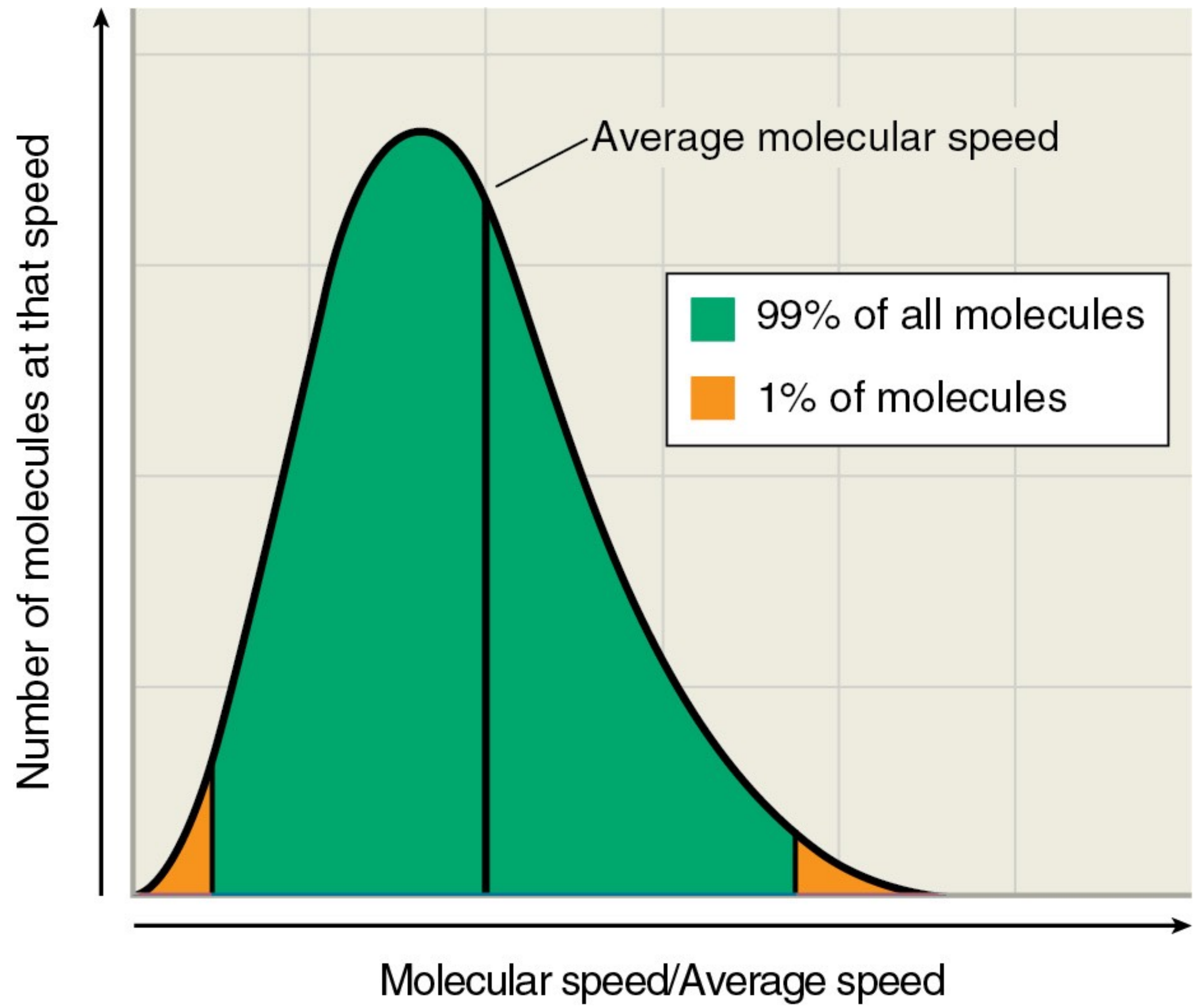
- The temperature of a gas is a measure of the average kinetic energy of its molecules. With the average kinetic energy, we can calculate the average velocity if we know the mean molecular weight (mu).
- How does the **mean velocity** of the CO_2 molecules (mu=44) at 27 C (300 K) compare with the **escape velocity** from the surface of the Earth?
- Constants: k = 1.38e-23 J/K, m_H = 1.67e-27 kg

$$\bar{v}_{\text{molecule}} = \sqrt{\frac{3kT}{\mu m_H}} = 0.4\ \text{km/s}\left(\frac{T}{300\ \text{K}}\right)^{0.5}\left(\frac{\mu}{44}\right)^{-0.5}$$

$$v_{\text{esc}} = \sqrt{\frac{2GM}{R}} = 11.2\ \text{km/s}\left(\frac{M}{M_{\text{Earth}}}\right)^{0.5}\left(\frac{R}{R_{\text{Earth}}}\right)^{-0.5}$$

Working it Out 9.1: Atmosphere Retention – 2

- If the speed of a gas molecule is significantly less than a planet's escape speed, it will be more easily retained.
- The speed is related to the temperature and the mean molecular mass — **lighter gas (e.g., H) move faster than heavier gas (e.g., Ar, Ne)**
- If **the mean molecular speed is less than 1/6 of the escape speed**, the planet will be able to retain this gas in its atmosphere.



Venus, Earth, and Mars – 2

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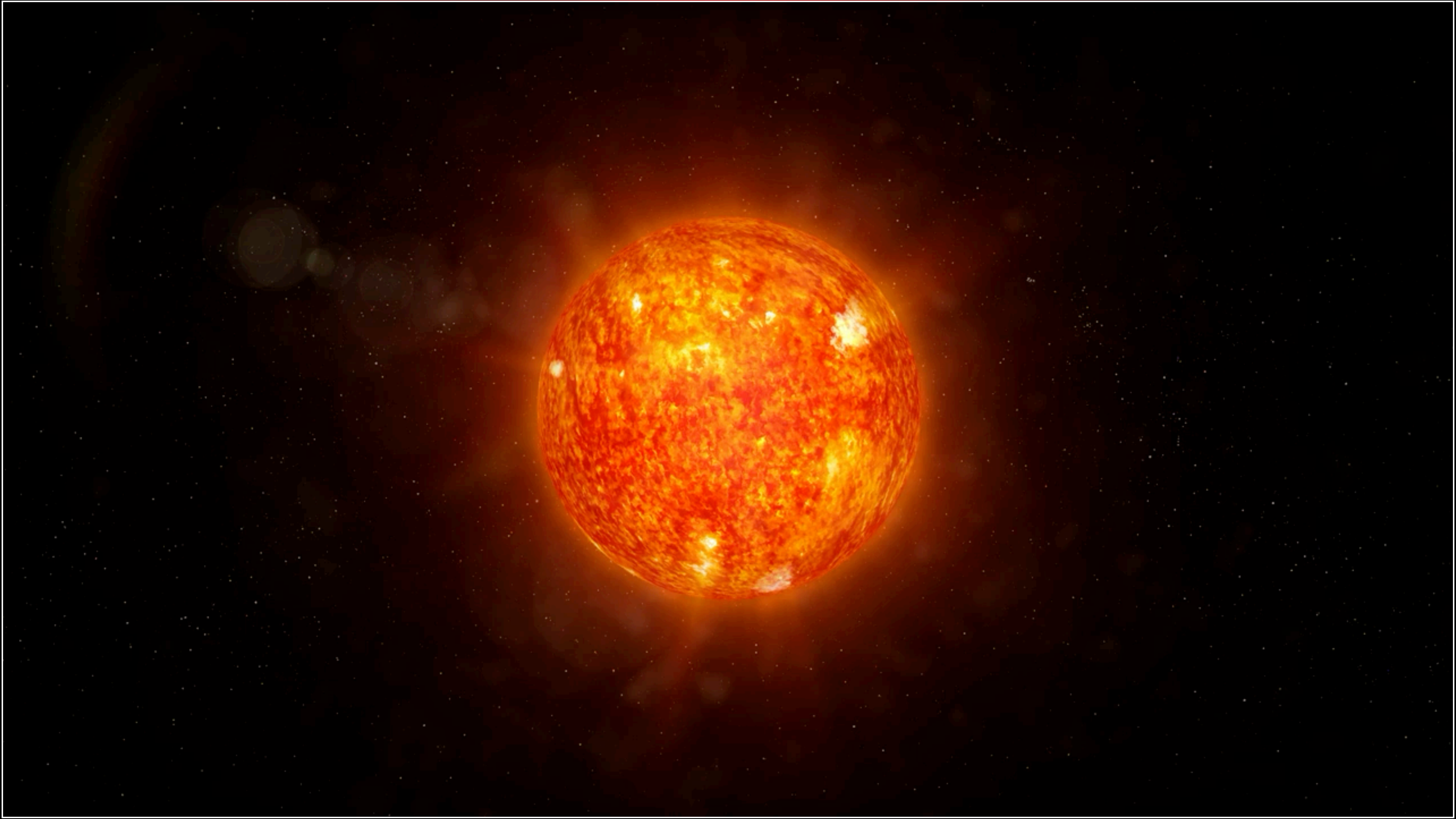
- Earth has about 200 times more atmospheric mass than Mars, and Venus has almost 100 times more atmospheric mass than Earth.
- The difference with Mars is from the differences in the amount of surface gravity.
- Venus and Earth (being bigger) were able to keep more atmosphere than Mars.

The Retention of Atmospheres

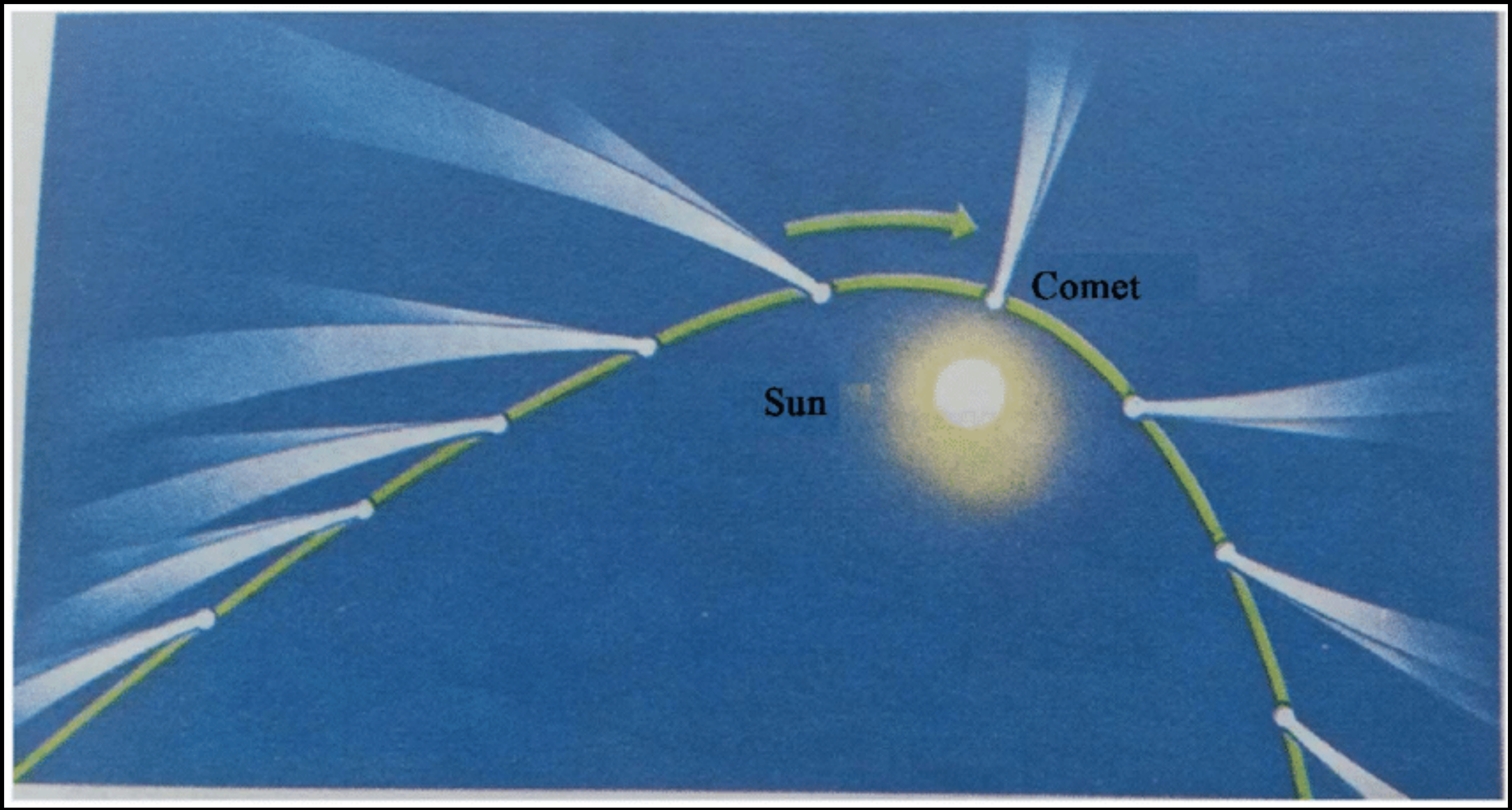
solar wind & the importance of the magnetosphere

The Solar Wind

The solar wind is ionized gas emitted from the Sun flowing radially outward through the solar system and into interstellar space.



Solar winds blow a comet's tails away from the Sun



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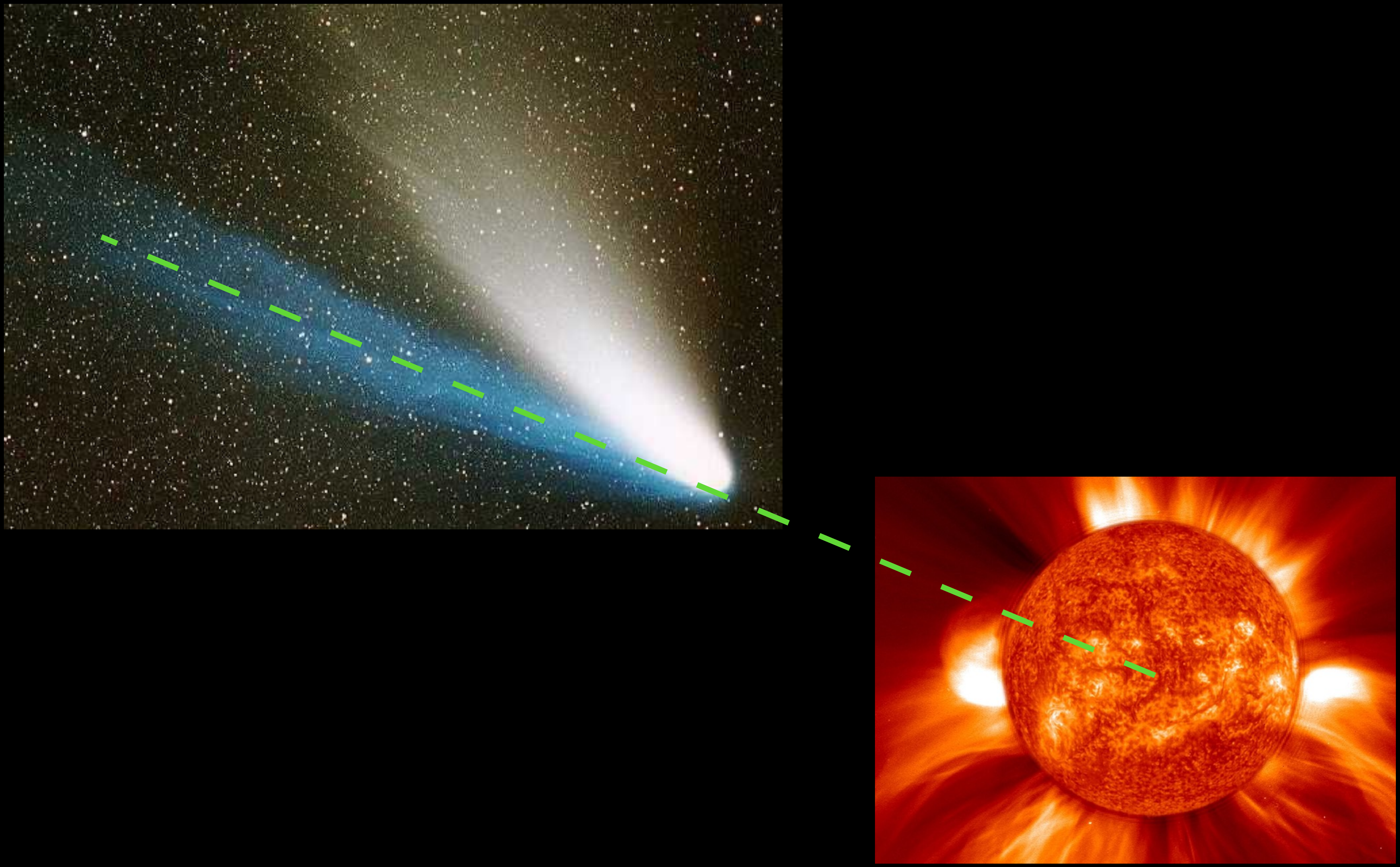
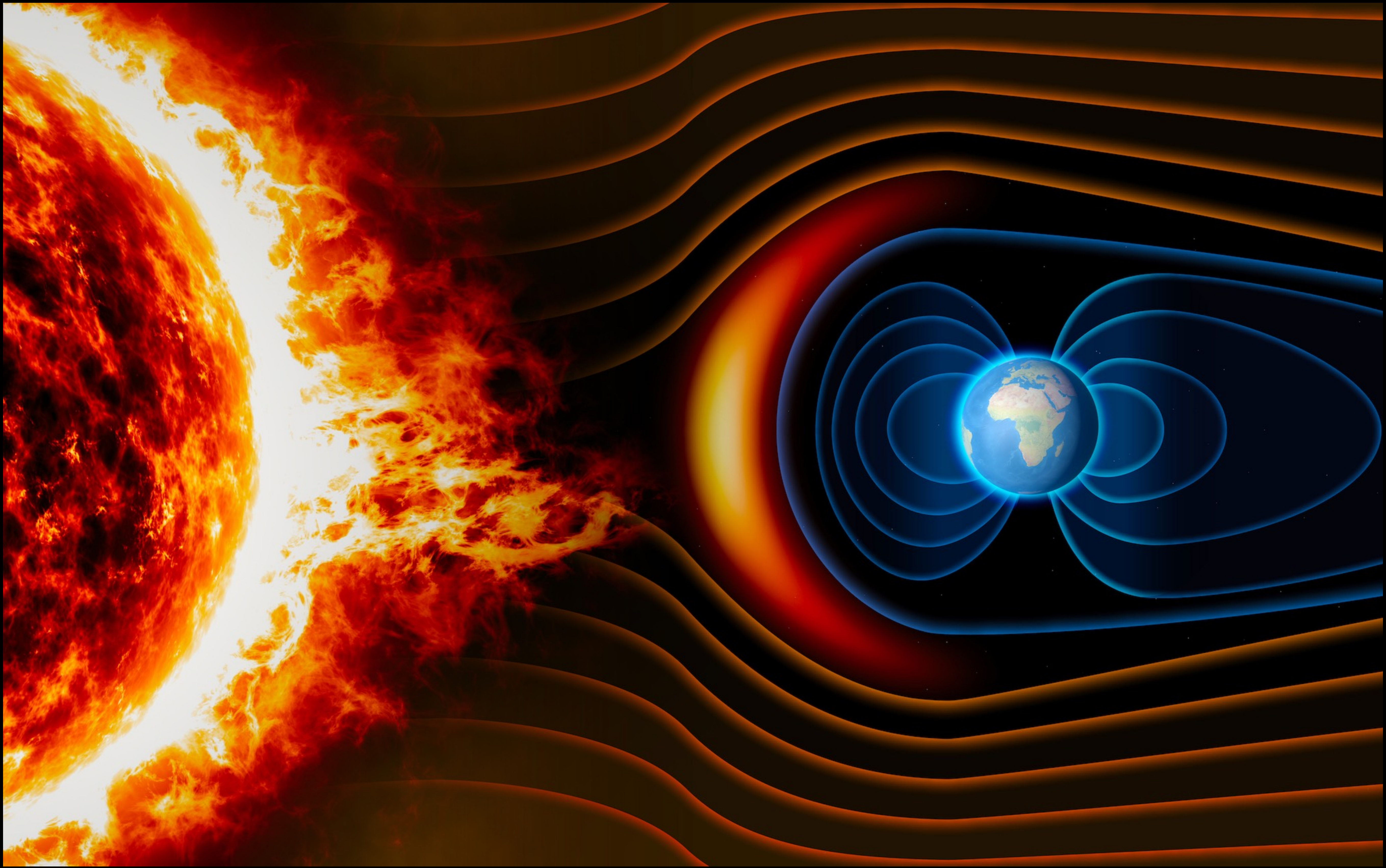
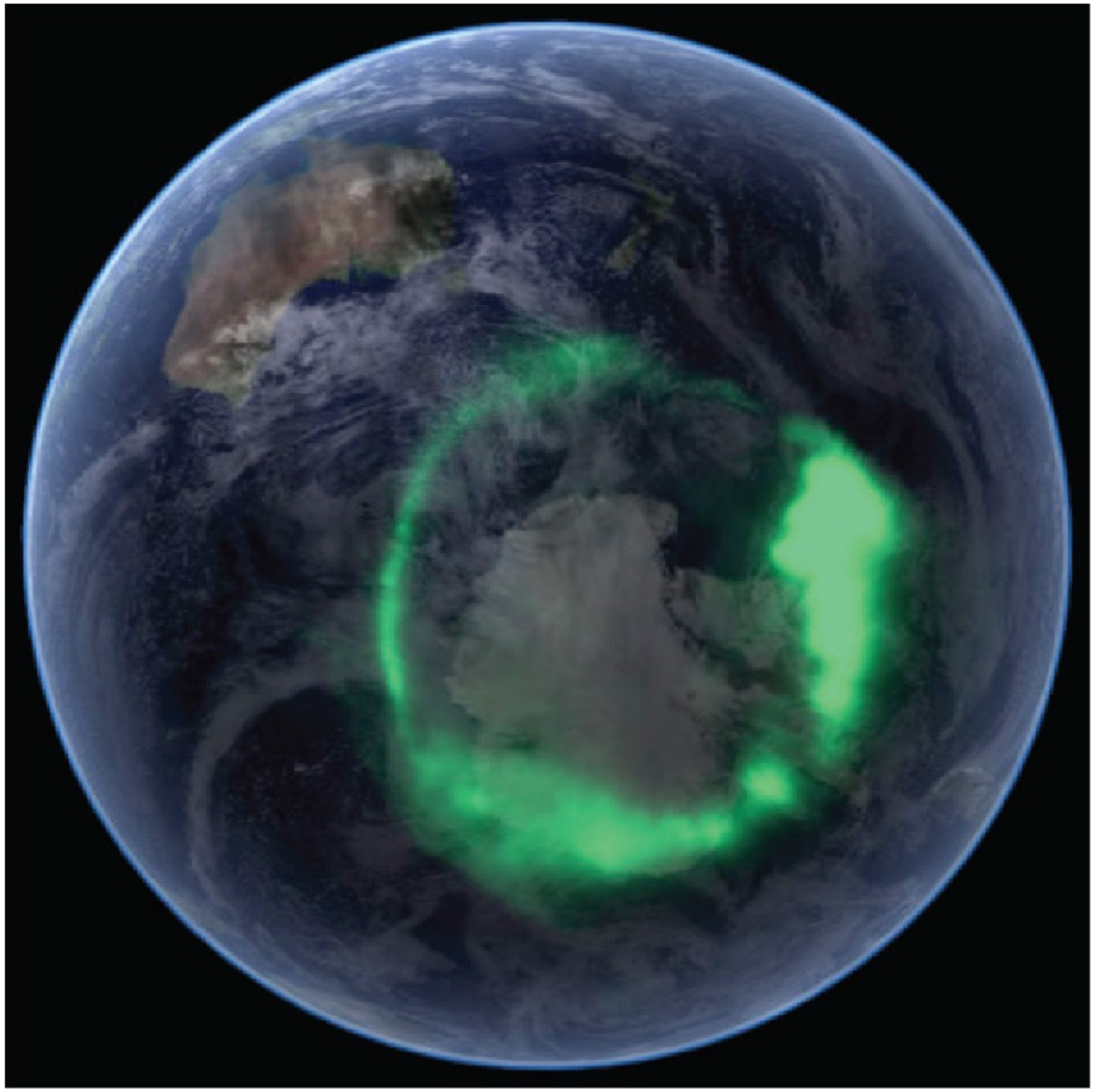
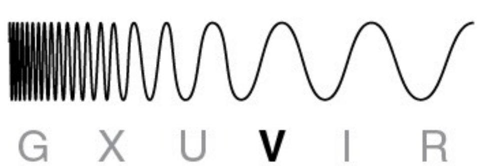


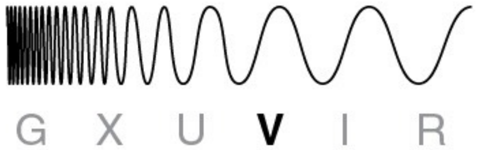
Without the Earth's Magnetosphere, the Earth's atmosphere would have been blown away by the solar winds



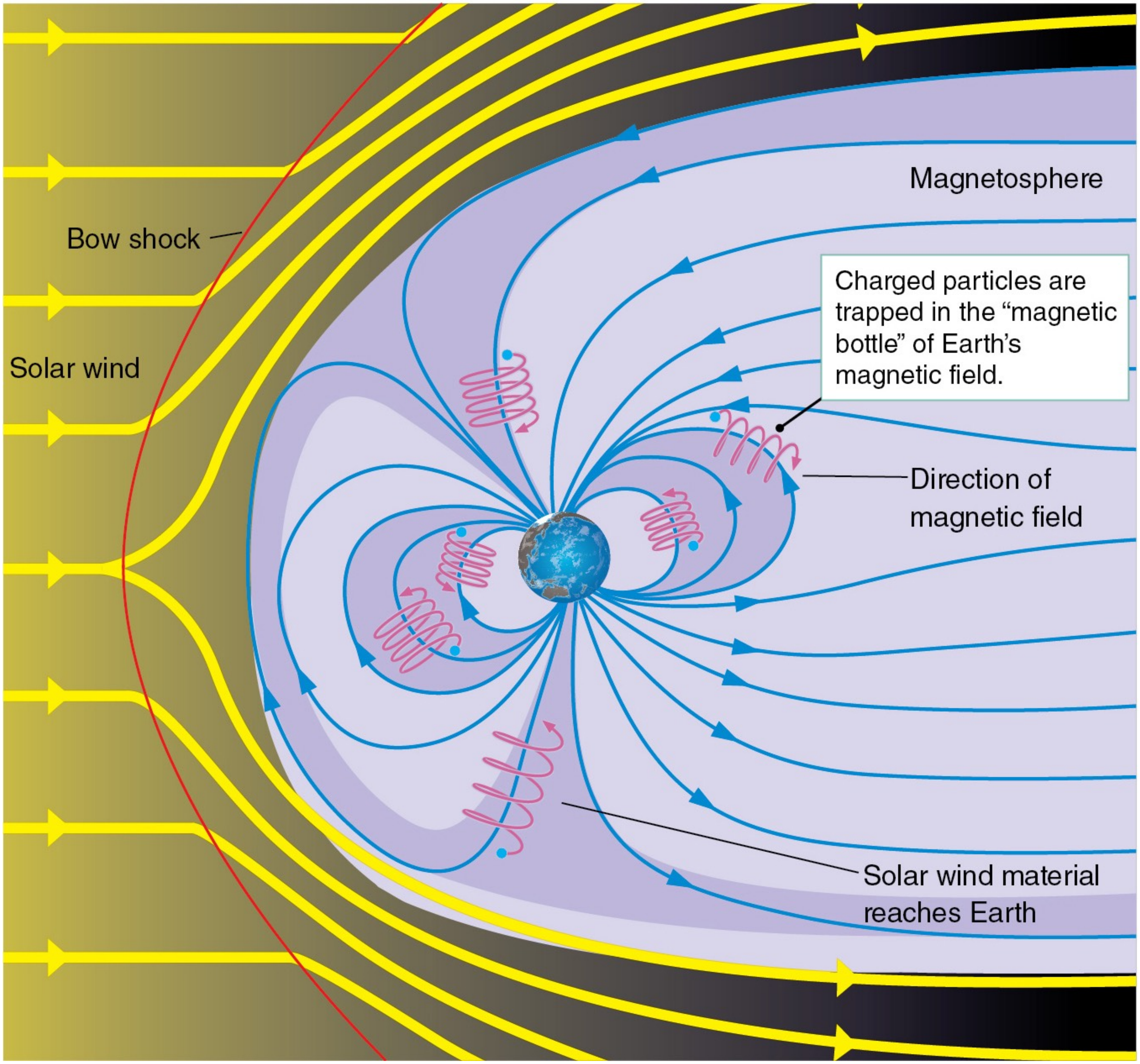
Particles from the solar wind collide with the upper atmosphere, creating auroras



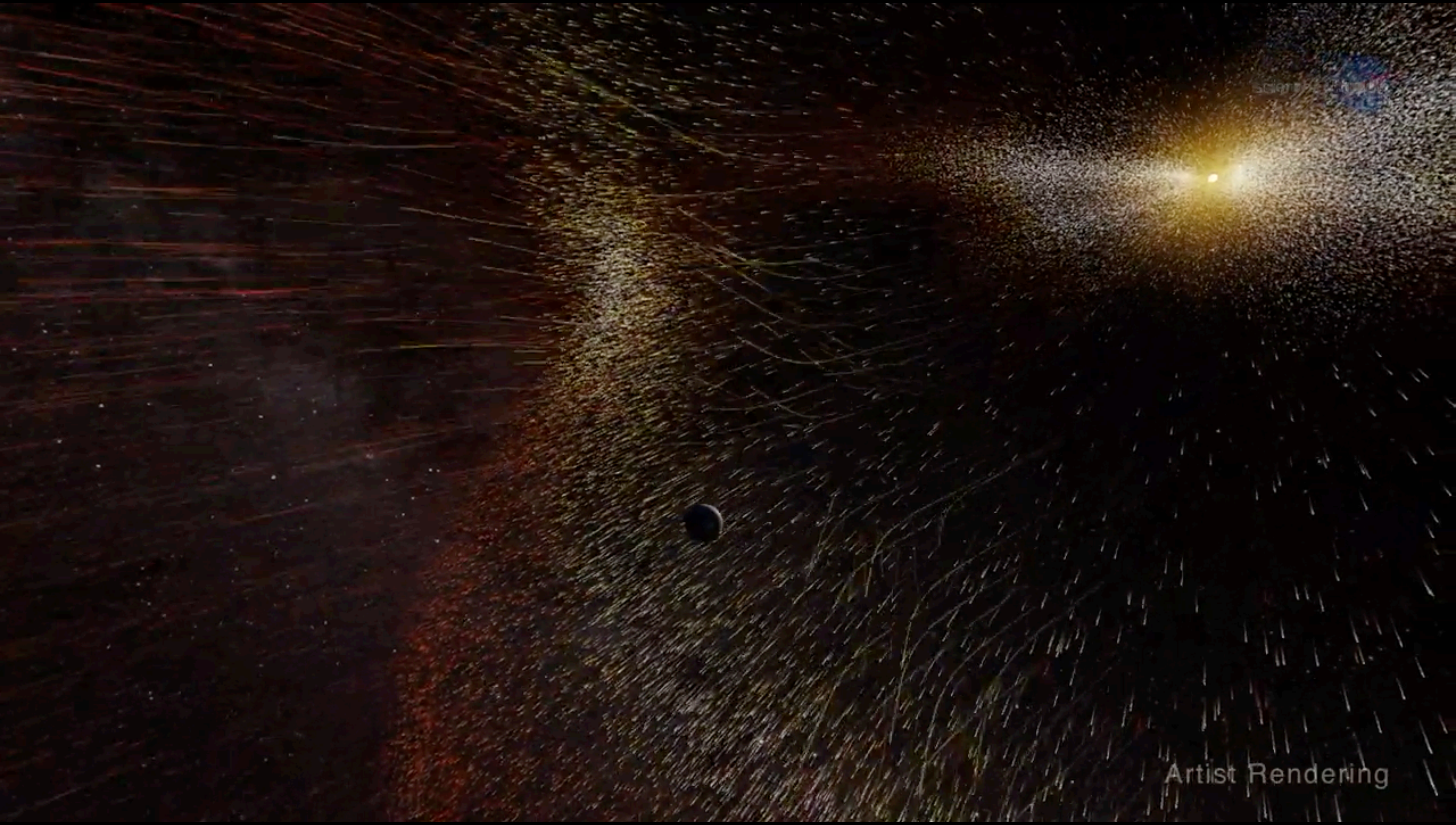




- Earth's **magnetosphere** extends out to 10 R_{Earth}, much larger than the atmosphere (~0.015 R_{Earth})
- It blocks much of the solar wind, trapping the charged particles from the Sun, protecting our atmosphere.



Solar winds Interactions with Earth’s Magnetosphere



Recap of Atm Part 1

The Accretion, Loss, and Regeneration of Atmospheres

- The **primary atmosphere** is the gas initially gathered from the disk.
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  - The process of gathering atmosphere is called **core accretion–gas capture**.
- **Secondary atmospheres** occur around some low-mass planets because the initial atmosphere is lost.
  - The low-mass planets do not have enough gravity to keep the initial atmosphere from **escaping**.
  - **Volcanoes** emit volatiles from the planetary interiors that were incorporated in solid rock form during the condensation phase (e.g., hydrated minerals like **serpentine**).
  - **Comets & asteroids** bring water and other volatiles to planets, which evaporate and add to the secondary atmosphere.

Atmosphere Retention - Primary Atmosphere

- The temperature of a gas is a measure of the average kinetic energy of its molecules. With the average kinetic energy, we can calculate the average velocity if we know the mean molecular weight (mu).
- How does the **mean velocity** of the **H_2 molecules** (mu=?) at **600 K** compare with the **escape velocity** from the surface of the Earth?
- Constants: k = 1.38e-23 J/K, m_H = 1.67e-27 kg

$$\bar{v}_{\mathrm{molecule}} = \sqrt{\frac{3kT}{\mu m_H}} = 0.4\ \mathrm{km/s}\ \left(\frac{T}{300\ \mathrm{K}}\right)^{0.5} \left(\frac{\mu}{44}\right)^{-0.5}$$

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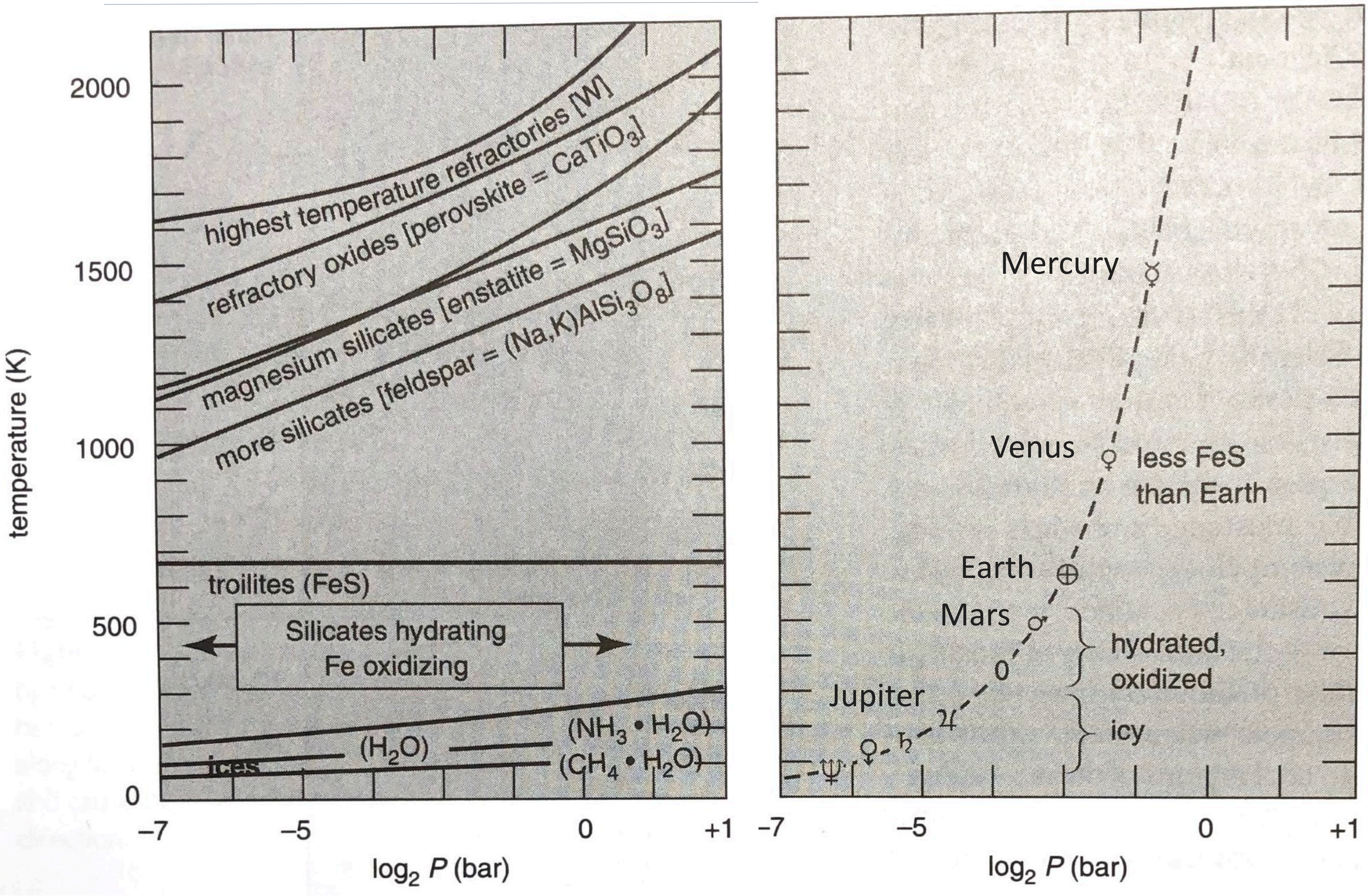
A model of Temperature Gradient + Condensation + Stellar Wind can explain the distance-dependency of the chemical composition



Hartmann05 Fig 5-5: Condensation of minerals

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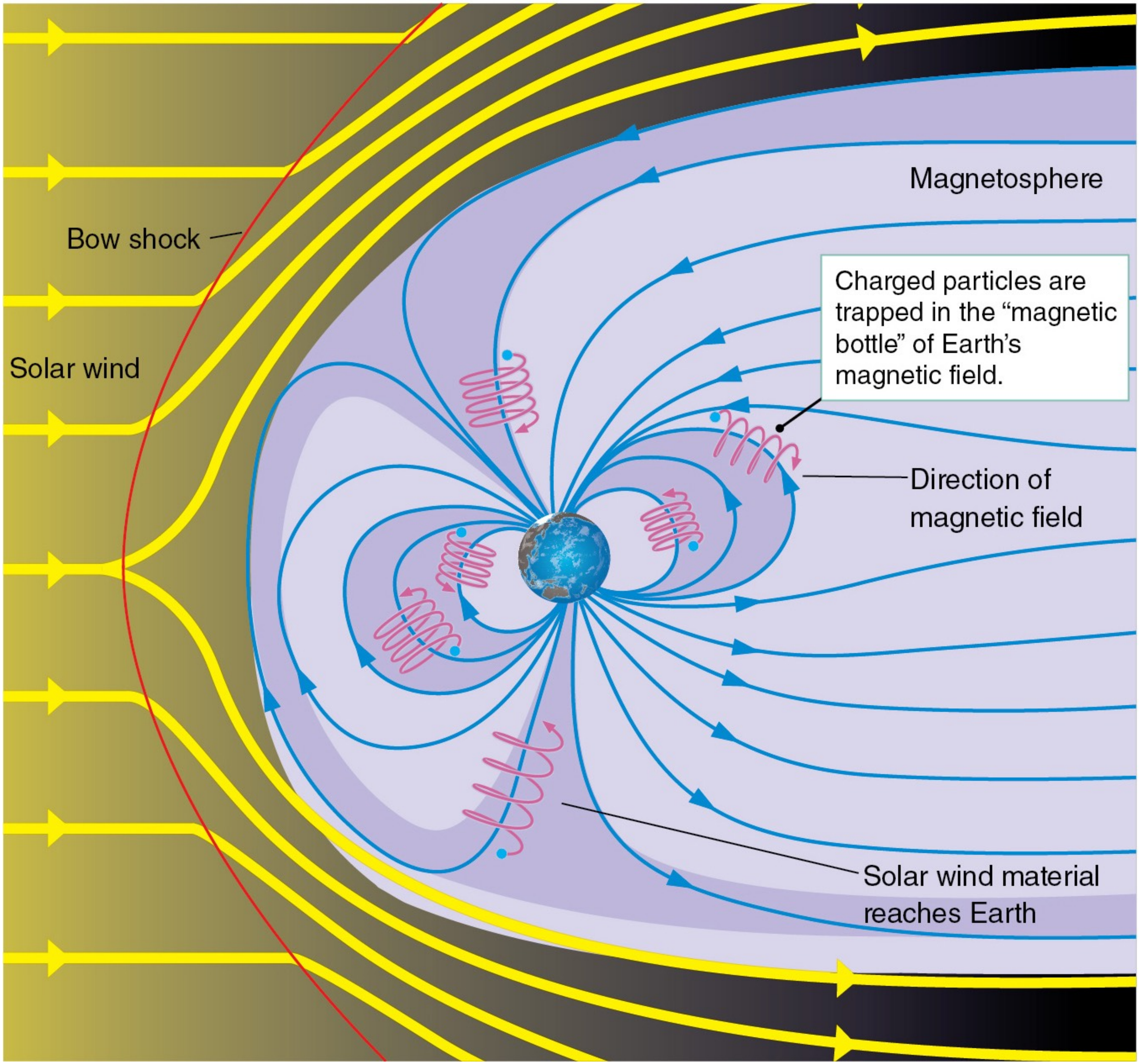


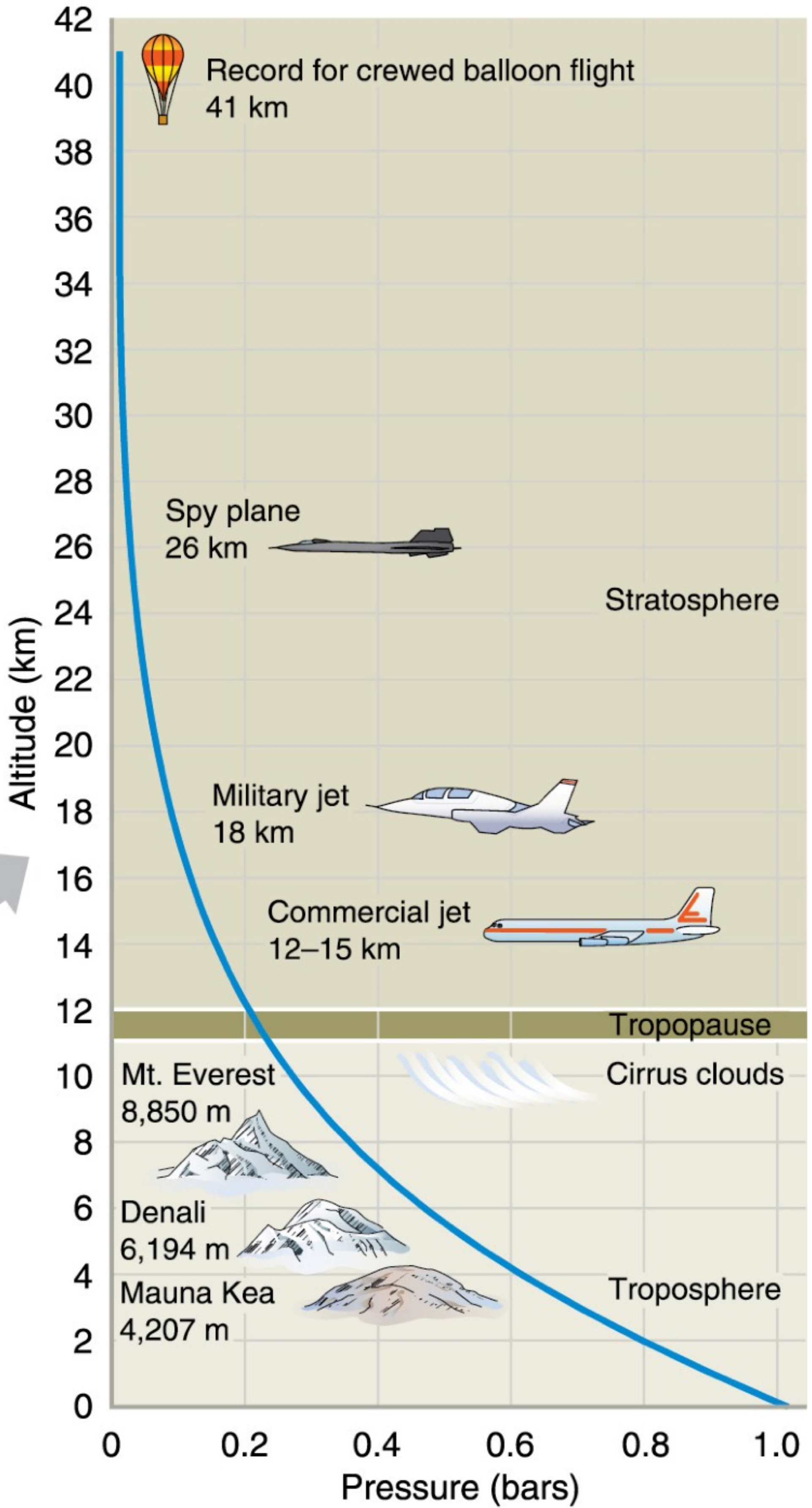
Understanding the vertical density structure of the atmosphere

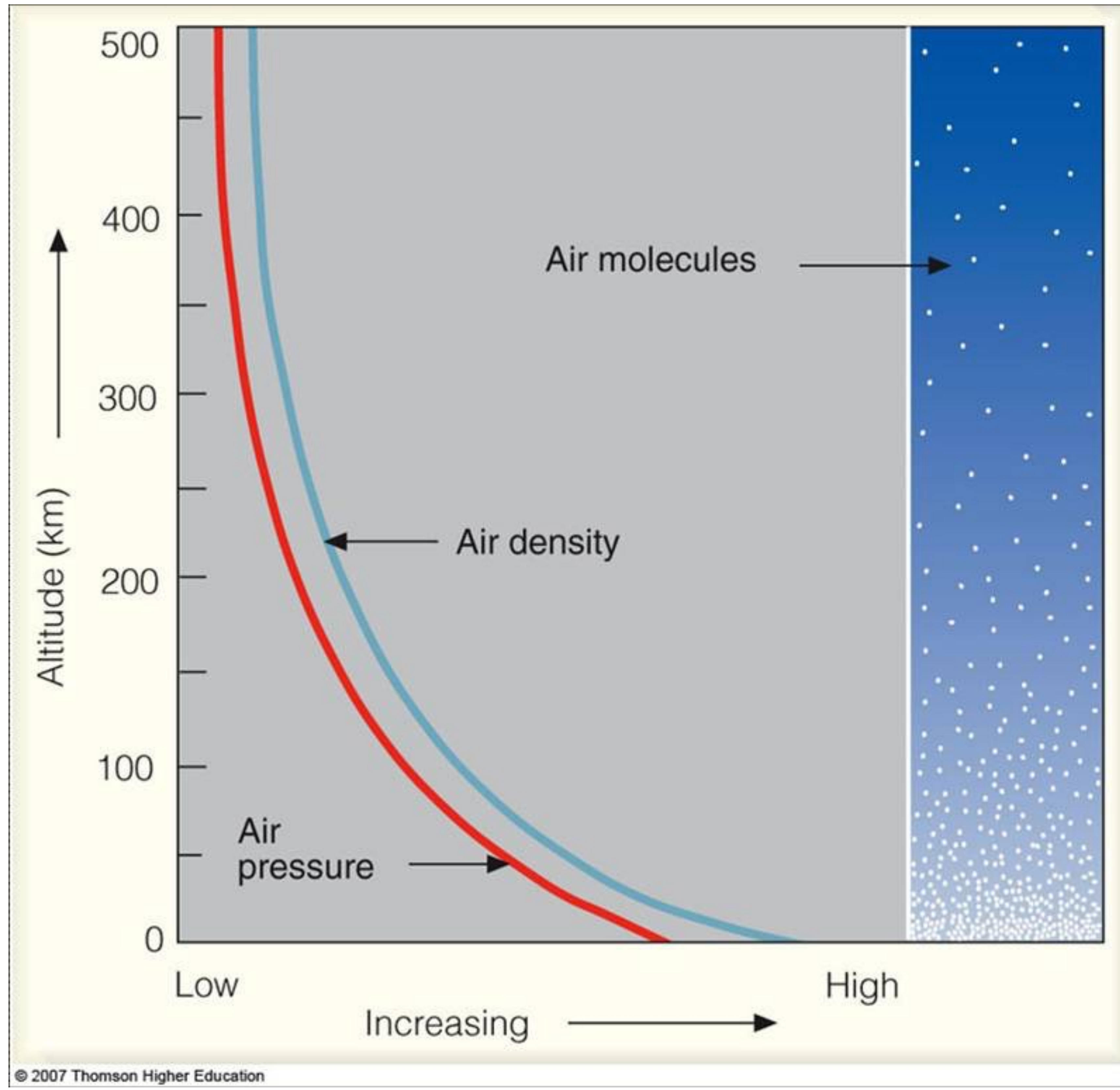
ideal gas law, hydrostatic equilibrium, & isothermal

The higher you go, the less air there is, why?

Pressure & Density Profile of Earth's Atmosphere

$$\frac{P}{P_0} = \frac{n}{n_0} = \exp(-\frac{h}{h_S})$$





Ideal Gas Law & Mean Molecular Weight

The law states that pressure is 2/3 of the kinetic energy density:

$$P = nkT = \left(\frac{\rho}{\mu m_H}\right)kT$$

where in the above we expressed the particle number density (n) as the ratio between the mass density (ρ) and the mean particle mass (μm_H).

These quantities are related in the following way given the definition of the mean molecular weight:

$$\mu m_H = \bar{m} = \frac{M}{N} = \frac{\rho}{n}$$

The equation above shows the importance of the mean molecular weight in the conversion between mass density and number density.

Mean Molecular Weight of Mixed Gas

- What need to be known? the mean molecular weight of each component (μ_i), and their percentages by volume (f_i^v)

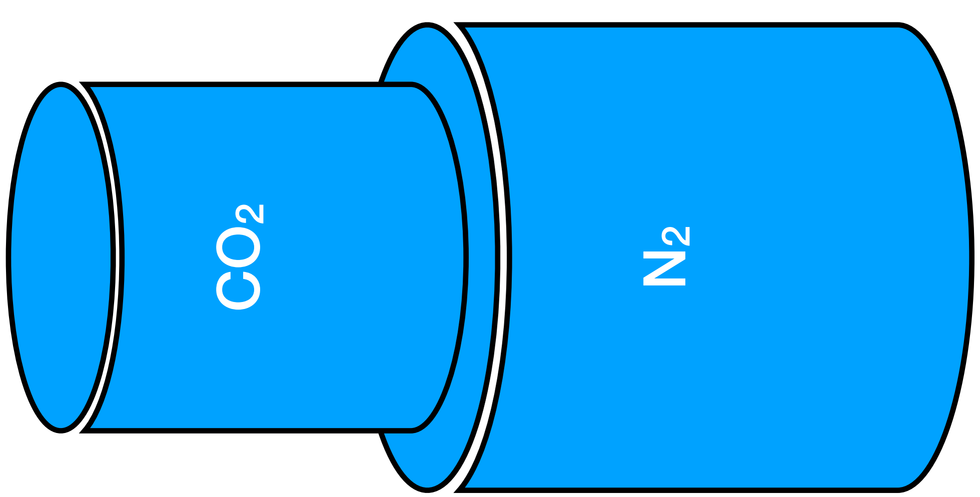
$$\mu = \sum_i \mu_i f_i^v$$

Practice:

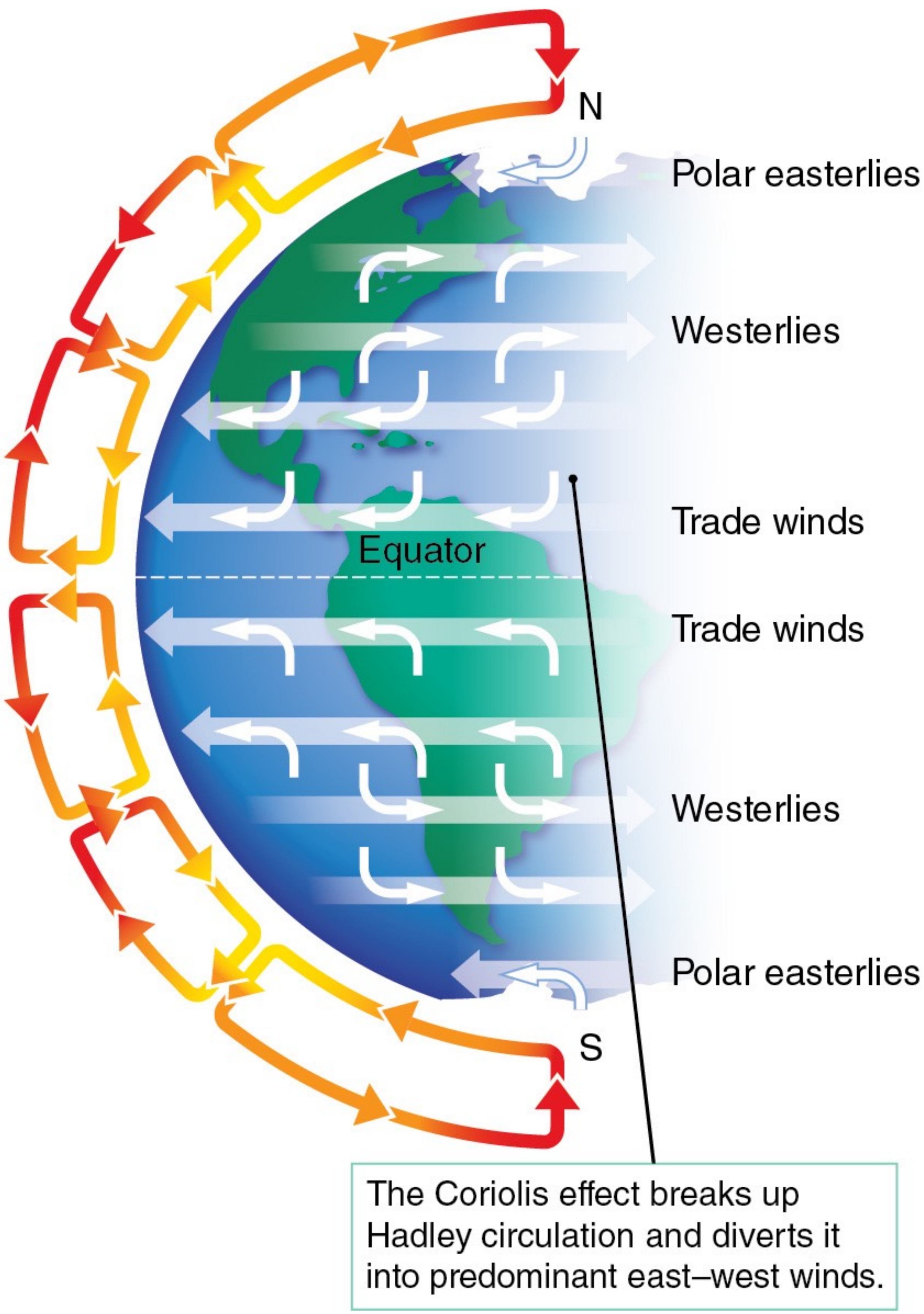
- CO_2: μ = 44

- N_2: μ = 28

- What is the mean molecular weight of a mixed gas consisting of 40% CO_2 & 60% N_2 (by volume)?

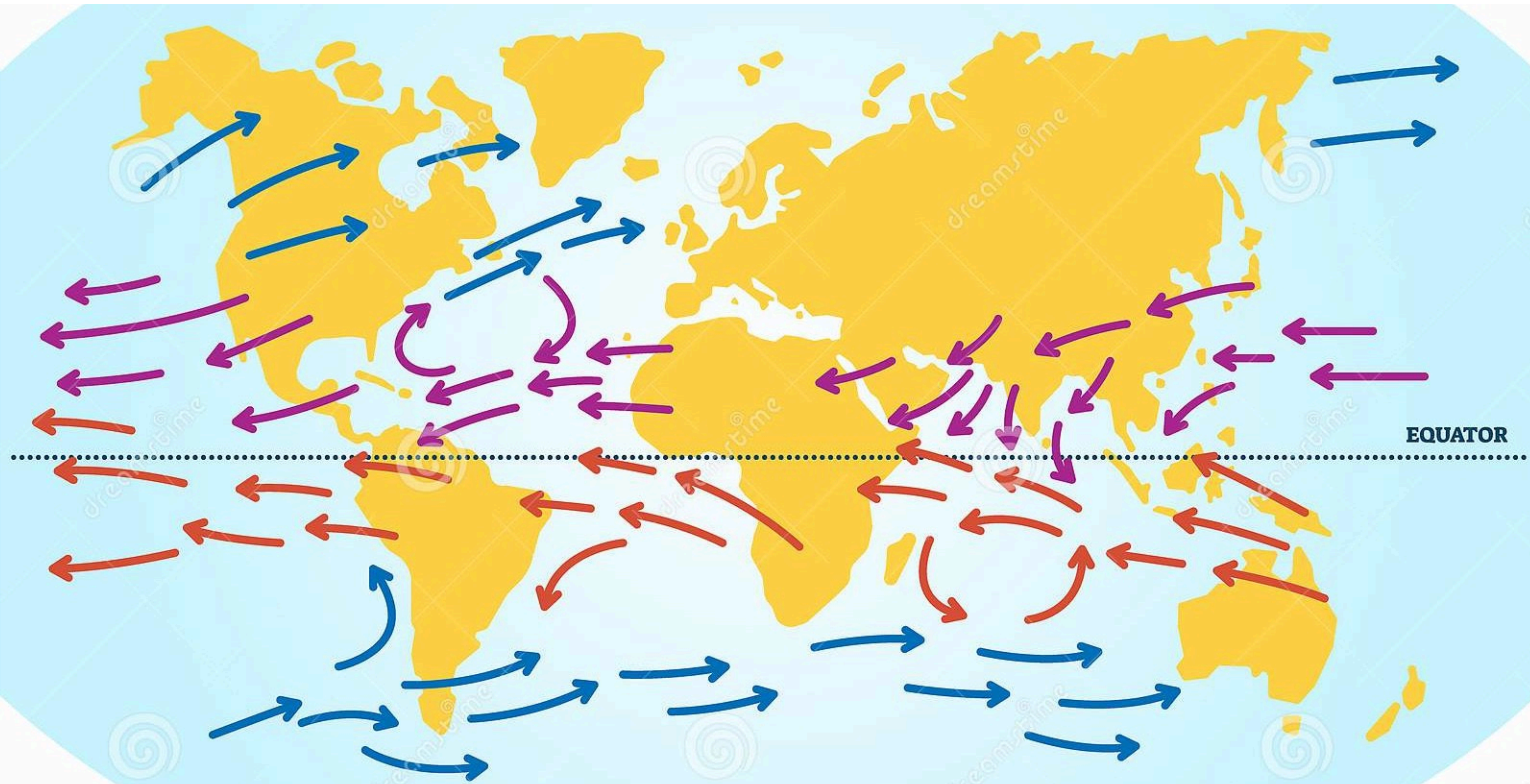


Winds and Circulation

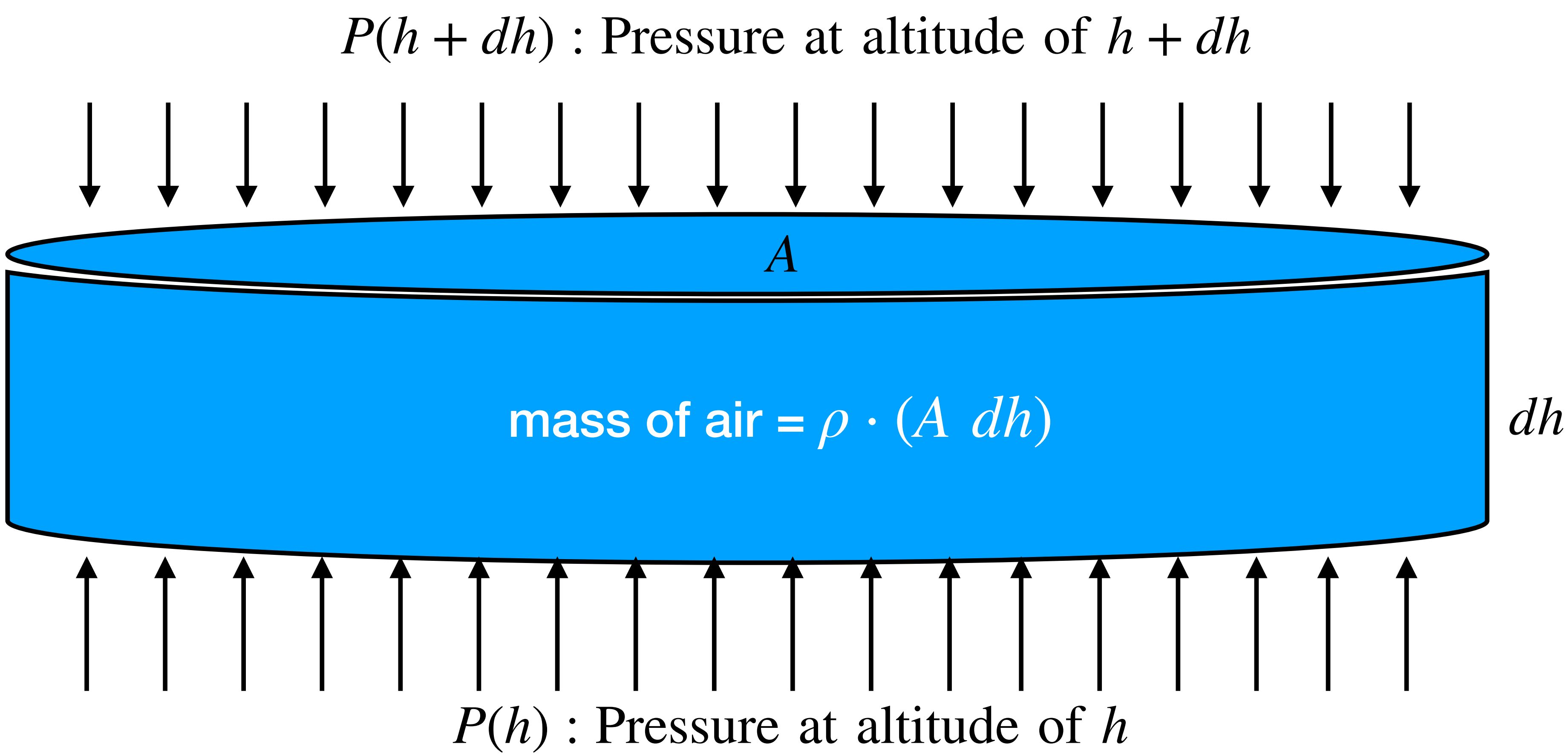


- **Convection** distributes surface heating.
- **Hadley circulation** transports heat between the equator and poles with **global winds**
- The Earth rotates fast enough to break up the large convection cells into smaller ones via the **Coriolis effect**.
- The Coriolis effect creates **zonal winds**, which blow in the east–west direction

A Map of the Trade Winds



Hydrostatic Equilibrium Derivation



- consider the force balance in a packet of air at an altitude of **h**. The packet has a cylindrical shape with an area of **A** and an infinitesimal height of **dh**
- this packet of air can stay stationary because of a force balance
  - upward force from pressure = $[P(h) - P(h+dh)] \cdot A = -\, dP \cdot A$
  - downward gravitational force = $\rho \cdot (A\ dh) \cdot g$

Hydrostatic Equilibrium Derivation

- consider the force balance in a packet of air at an altitude of **h**. The packet has a cylindrical shape with an area of **A** and an infinitesimal height of **dh**
- this packet of air can stay stationary because of a **force balance**
  - upward force from pressure = $[P(h) - P(h + dh)] \cdot A = - dP \cdot A$
  - downward gravitational force = $\rho \cdot (A \ dh) \cdot g$
- Equating the two forces means **hydrostatic equilibrium**:

$$-dP = \rho \ g \ dh \Rightarrow$$

$$-d(nkT) = (\mu m_H n) \ g \ dh$$

where we have applied the **ideal gas law** and expressed mass density as number density. If the temperature is constant, i.e., the **isothermal condition**, we can take *kT* out of the differentiation, and we can also move n to the left side (assuming also **thin atmosphere** so that *g* is constant):

$$\frac{dn}{n} = - \frac{\mu m_H g}{kT} \ dh$$

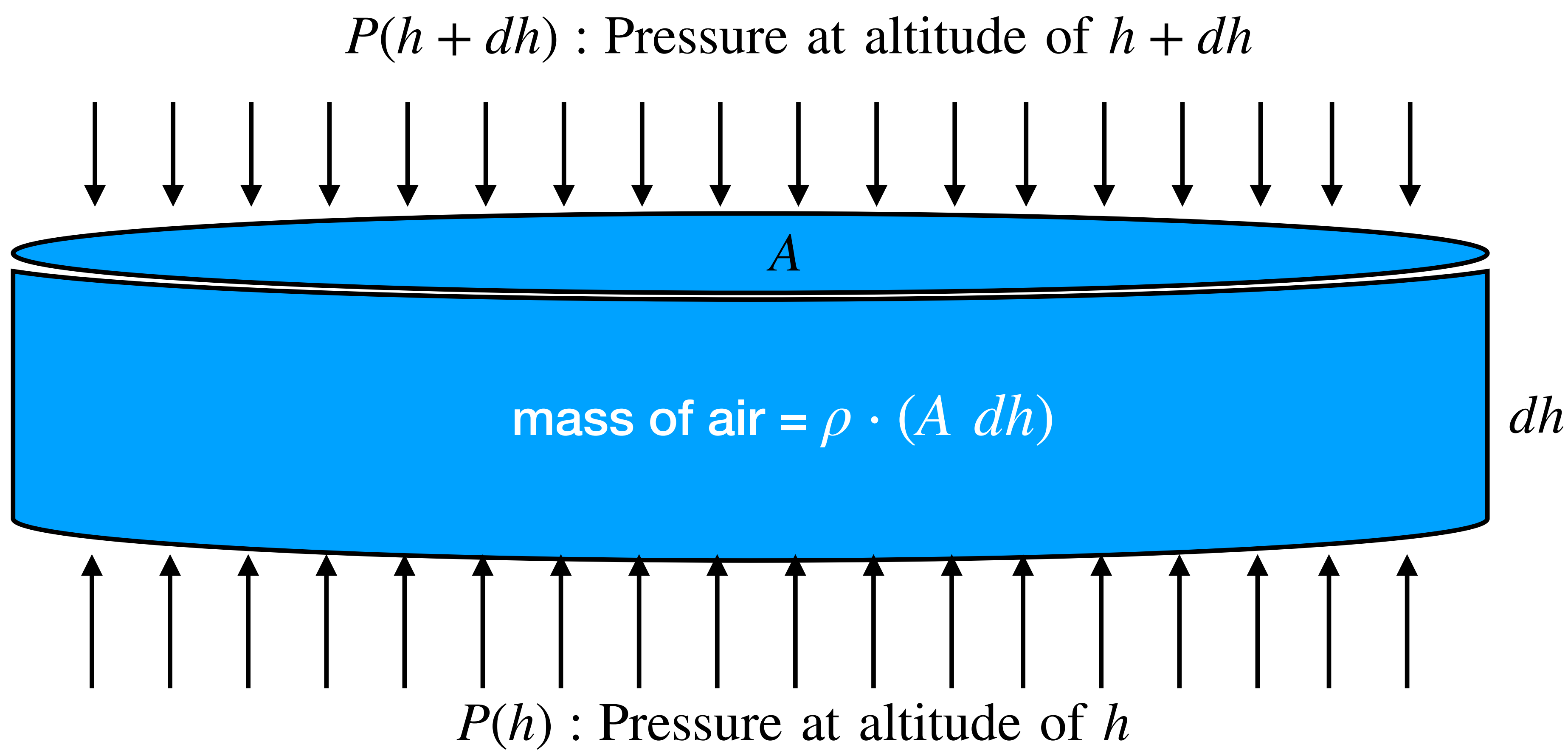
- Integrating both side from altitude of *0* to altitude of *h*, we have a solution:

$n(h) = n_0 \exp\left(- \frac{h}{h_S} \right)$ where $h_S = \frac{kT}{\mu m_H g}$ is the **scale height**.

Recap: Understanding the vertical density structure of the atmosphere

ideal gas law, hydrostatic equilibrium, & isothermal

Hydrostatic Equilibrium Derivation



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Hydrostatic Equilibrium Derivation

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Practice: Calculate the scale height of N_2

$$n(h) = n_0 \exp\left(-\frac{h}{h_S}\right) \text{ where } h_S = \frac{kT}{\mu m_H g} \text{ is the **scale height**.}$$

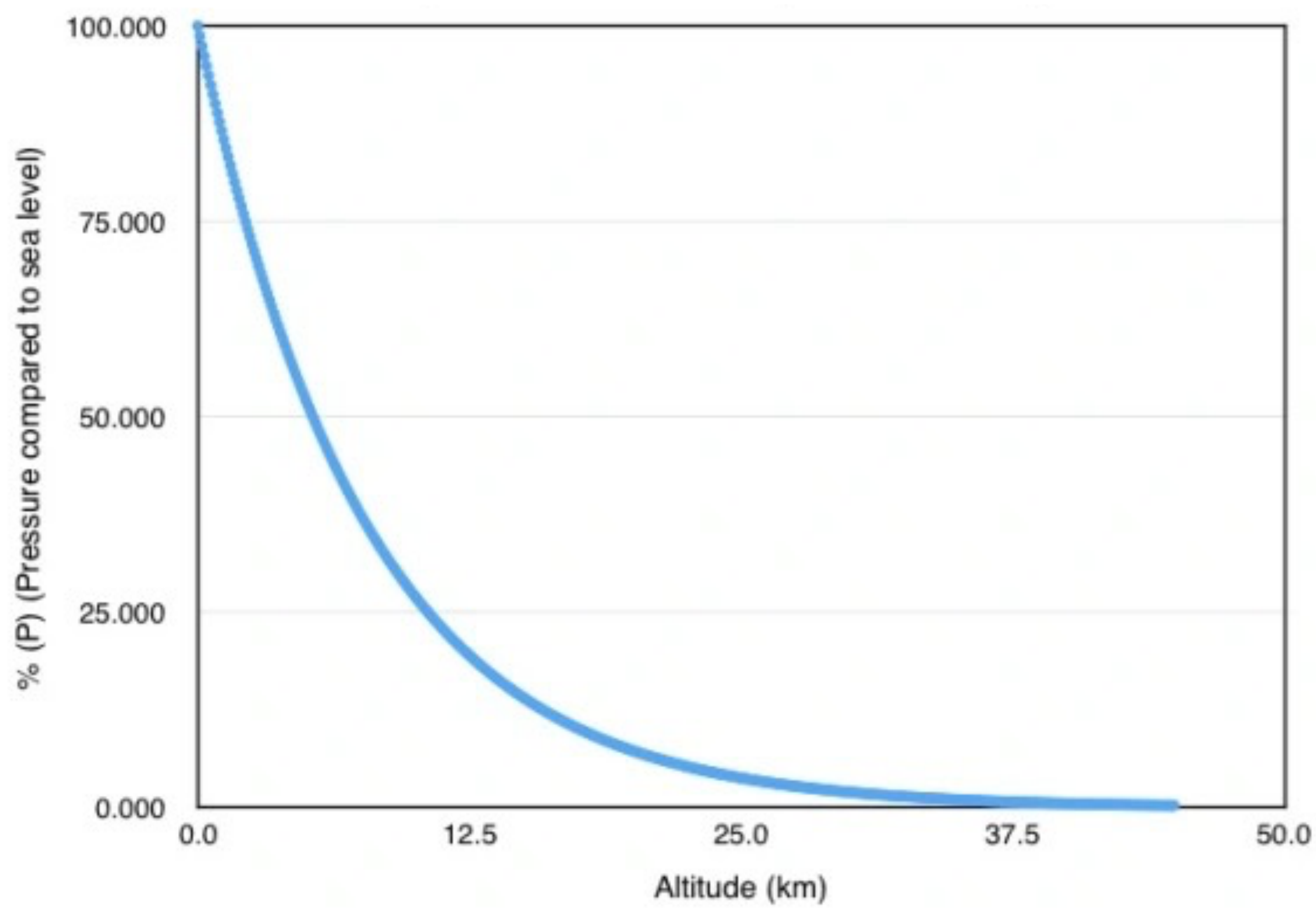
For an 100% N_2 atmosphere, mu = ?.

Assume a mean temperature of 280 K (+7 C).

Constants: k = 1.38e-23 J/K, m_H = 1.67e-27 kg, g = 9.8 m/s^2, e = 2.718

1. What's the scale height?
2. What are the N_2 densities at 1x and 3x the scale height if its density at sea level (n_0) is set to be at 1 unit (~10^{25} m^{-3}).

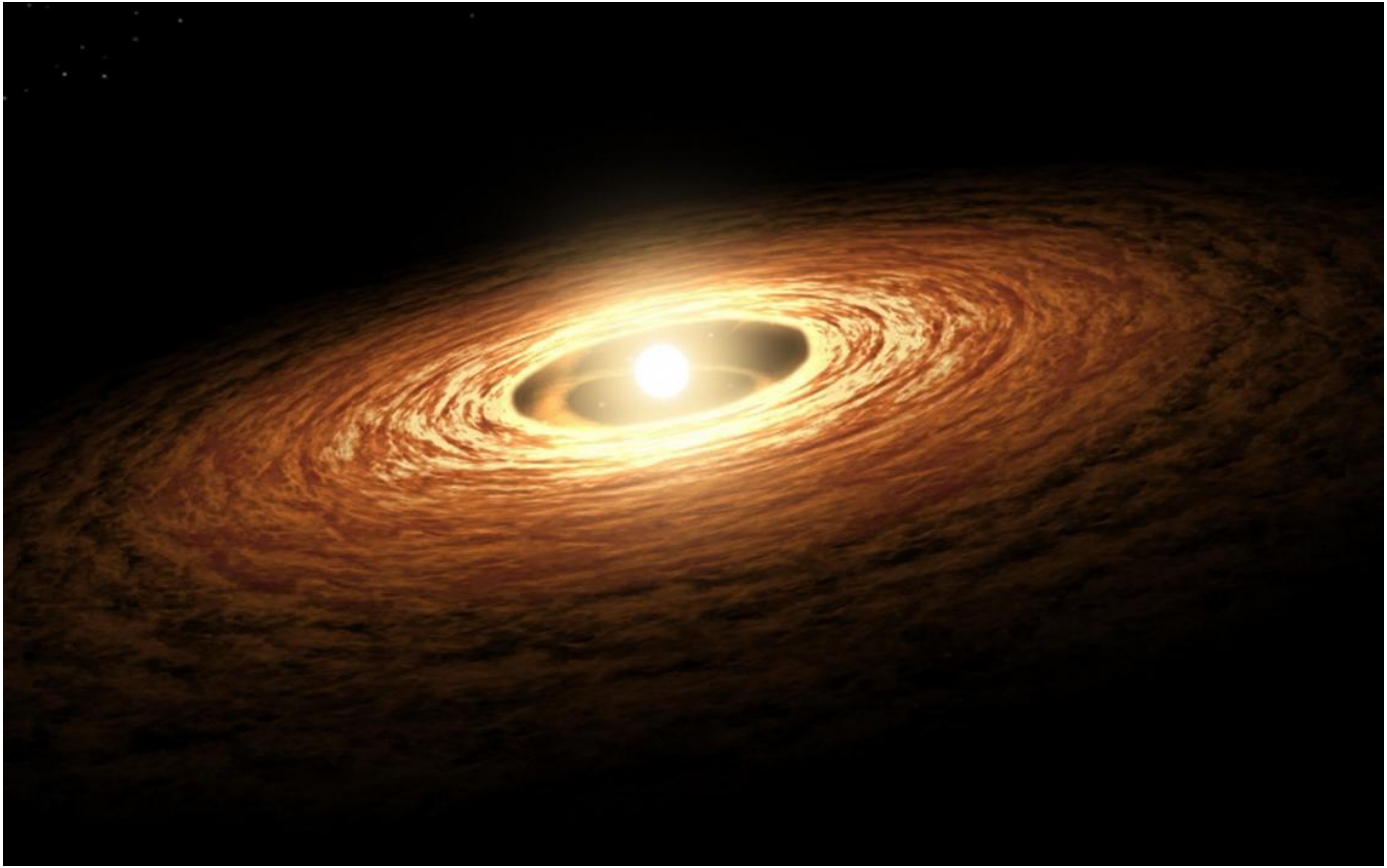
Answer: 8.4 km, 0.37 unit at 1 h_s, 0.05 unit at 3 h_s



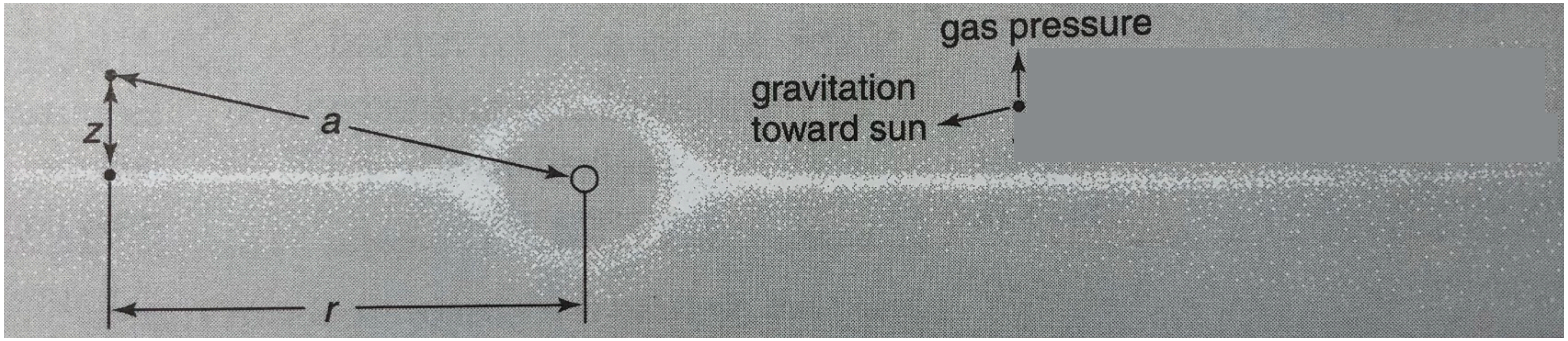
Understanding the vertical density structure of the protoplanetary disks

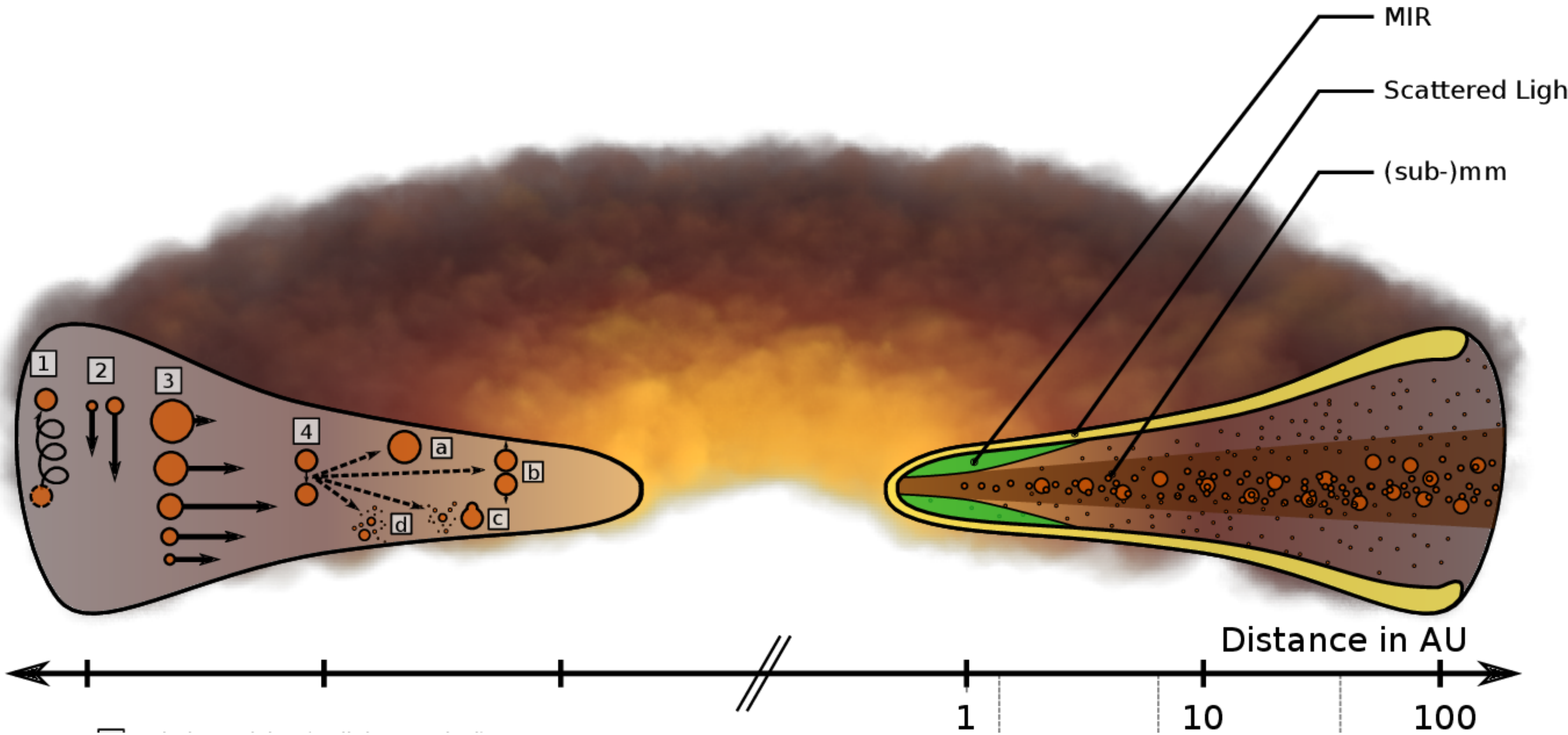
ideal gas law, hydrostatic equilibrium, & isothermal

Vertical density structure of proto-planetary disks



Vertical density structure of proto-planetary disks



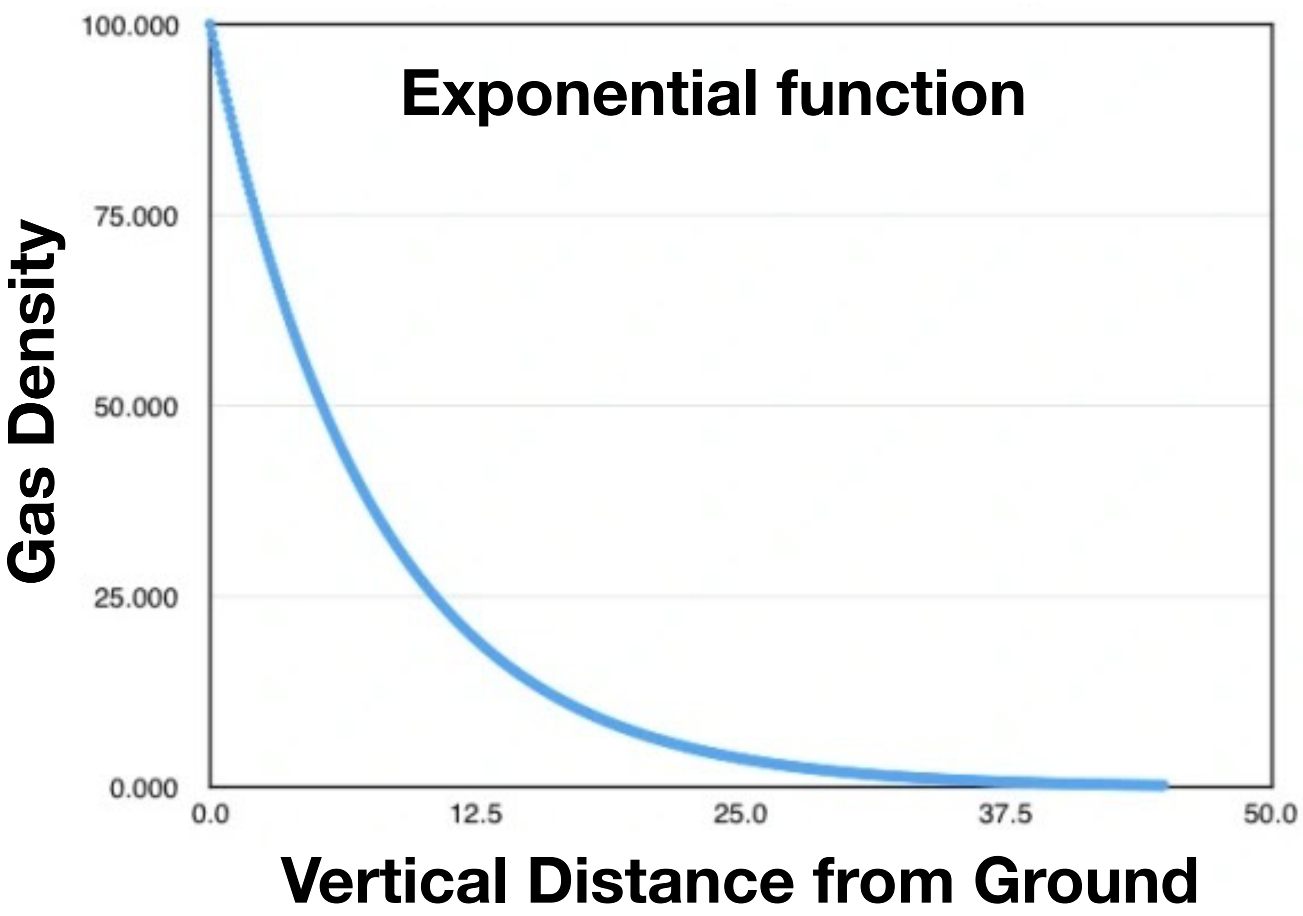


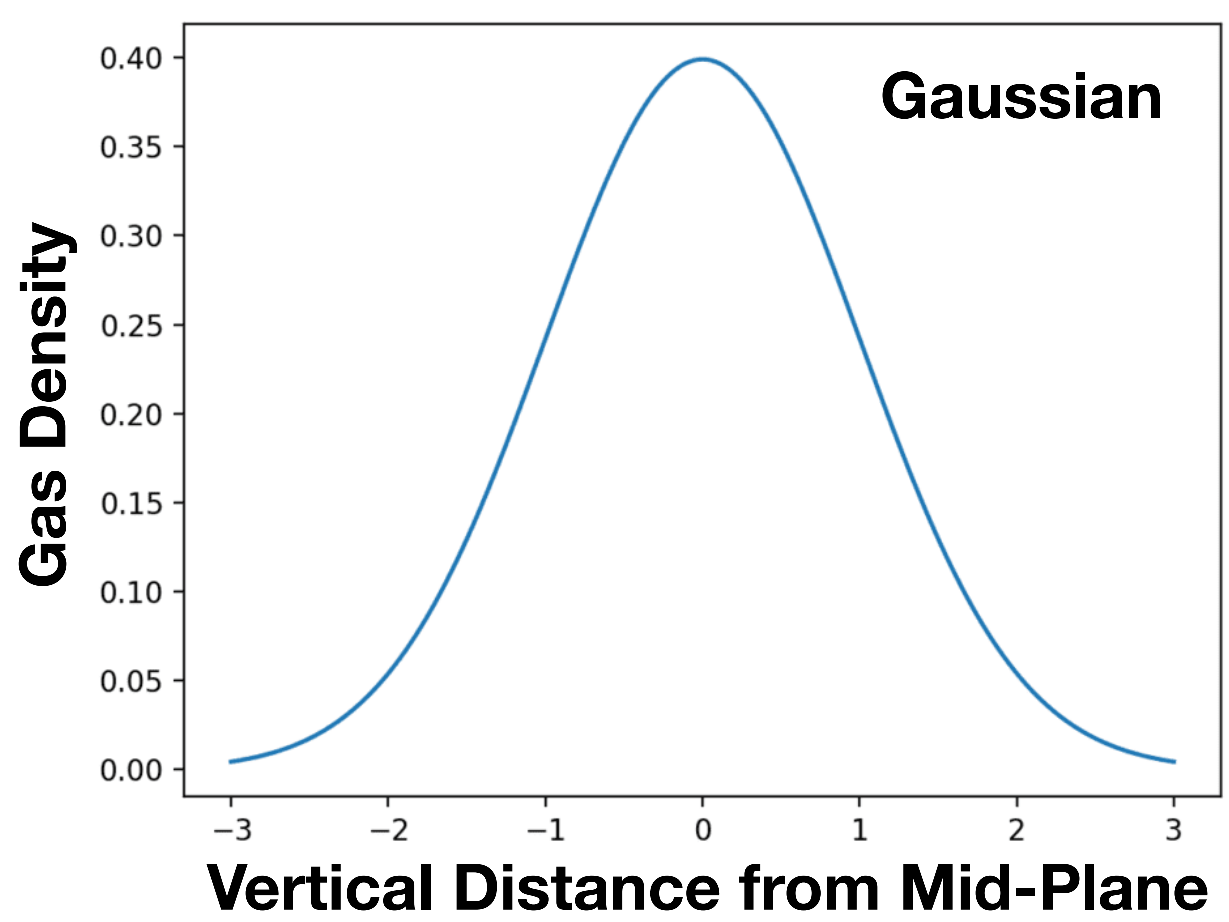
Vertical density structure of proto-planetary disks

Instead of an exponential function, it follows a Gaussian function

proto-planetary disk: $$\frac{n}{n_0} = \exp\left(-\frac{h^2}{h_S^2}\right) \text{ where } h_S = \sqrt{\frac{2kTr^3}{\mu m_H G M^\star}}$$

thin atmosphere: $$\frac{n}{n_0} = \exp\left(-\frac{h}{h_S}\right) \text{ where } h_S = \frac{kT}{\mu m_H g}$$





The Evolution of Earth’s Atmosphere

terraforming the early Earth

Why is the Earth's atmosphere so different, if not unique?

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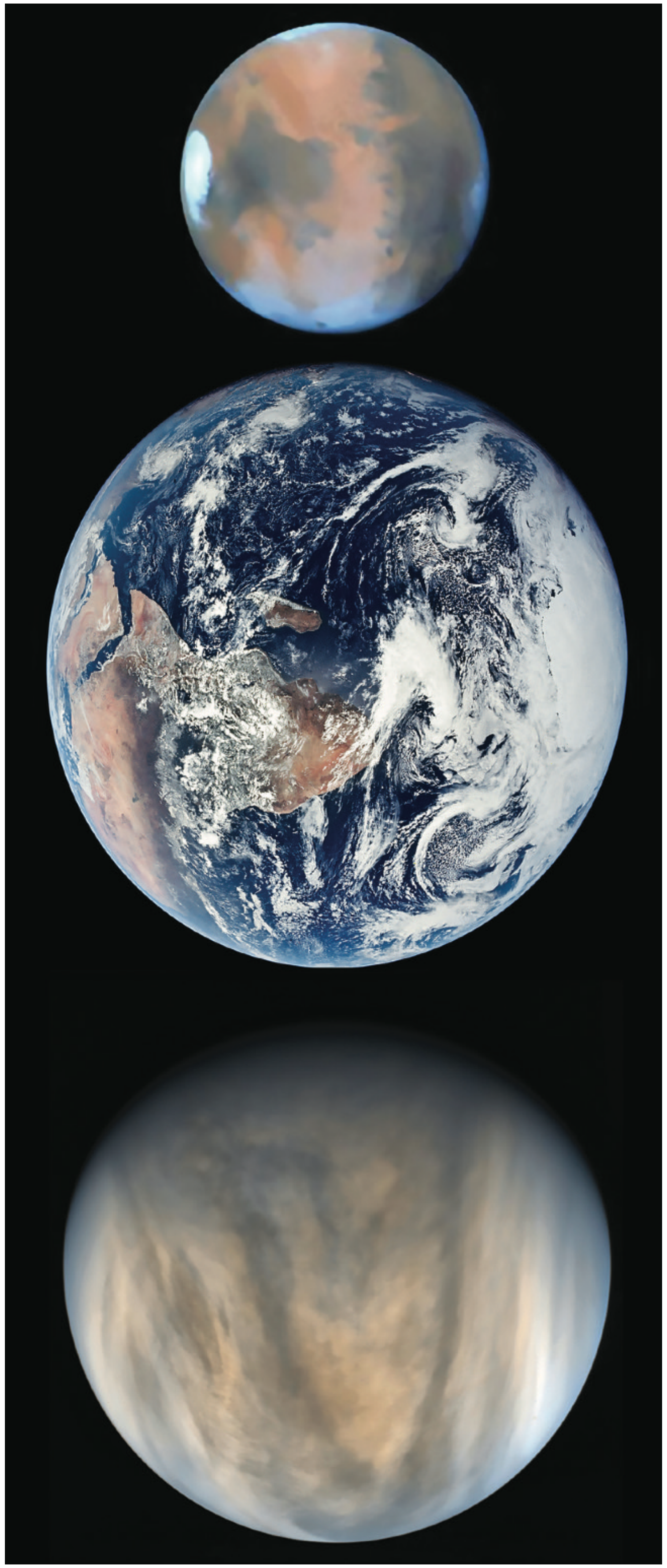
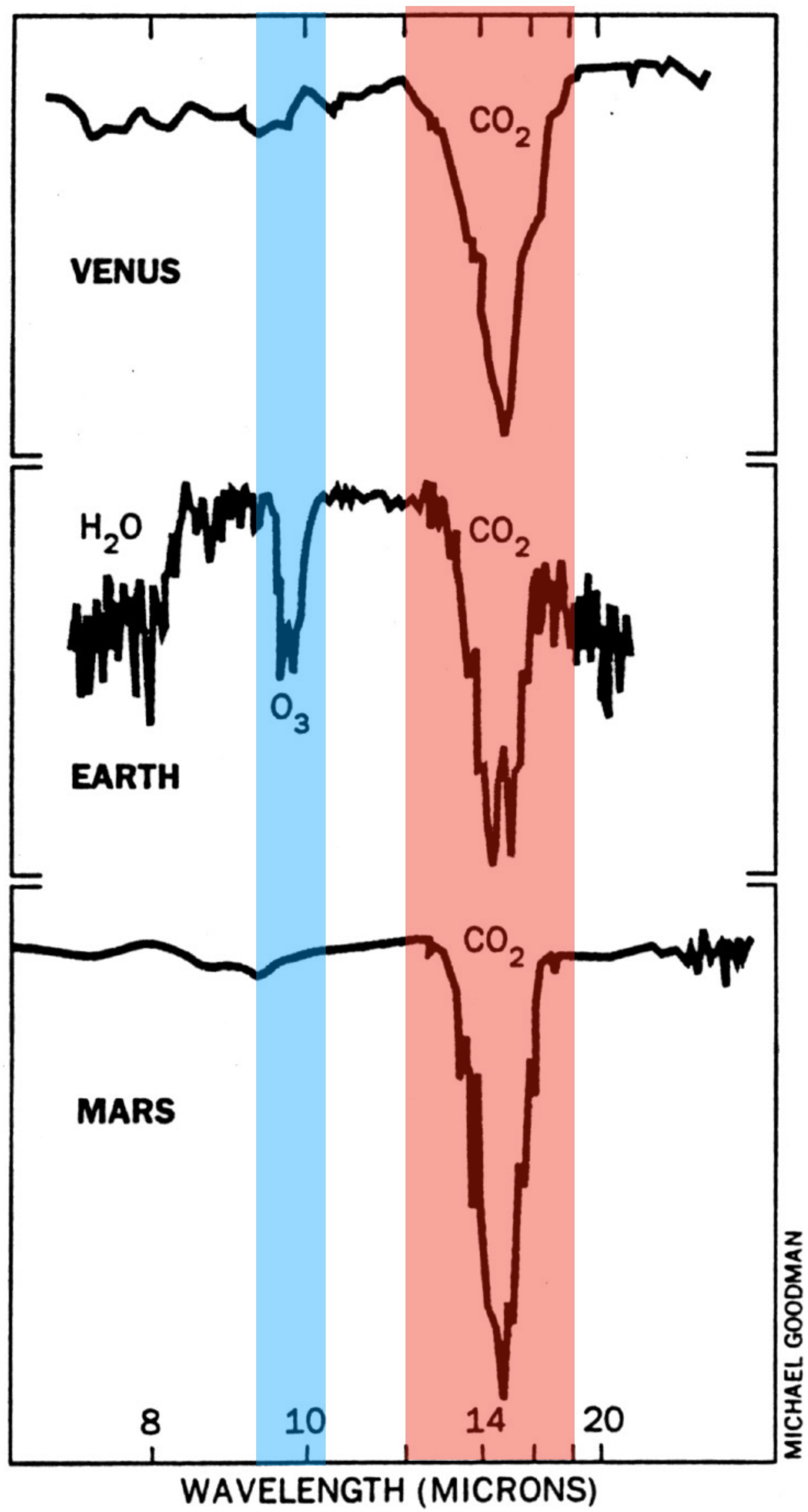
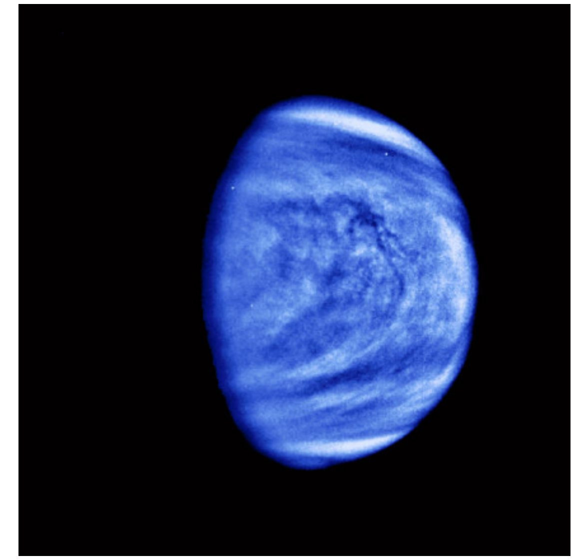
Nitrogen (%)	3.5	78.1	2.7
Oxygen (%)	0.00	20.9	0.13
Water (%)	0.002	0.1 to 3	0.02
Argon (%)	0.007	0.93	1.6
Sulfur Dioxide (%)	0.015	0.02	0.00



The 9.7-micron Biomarker in the mid-Infrared spectra

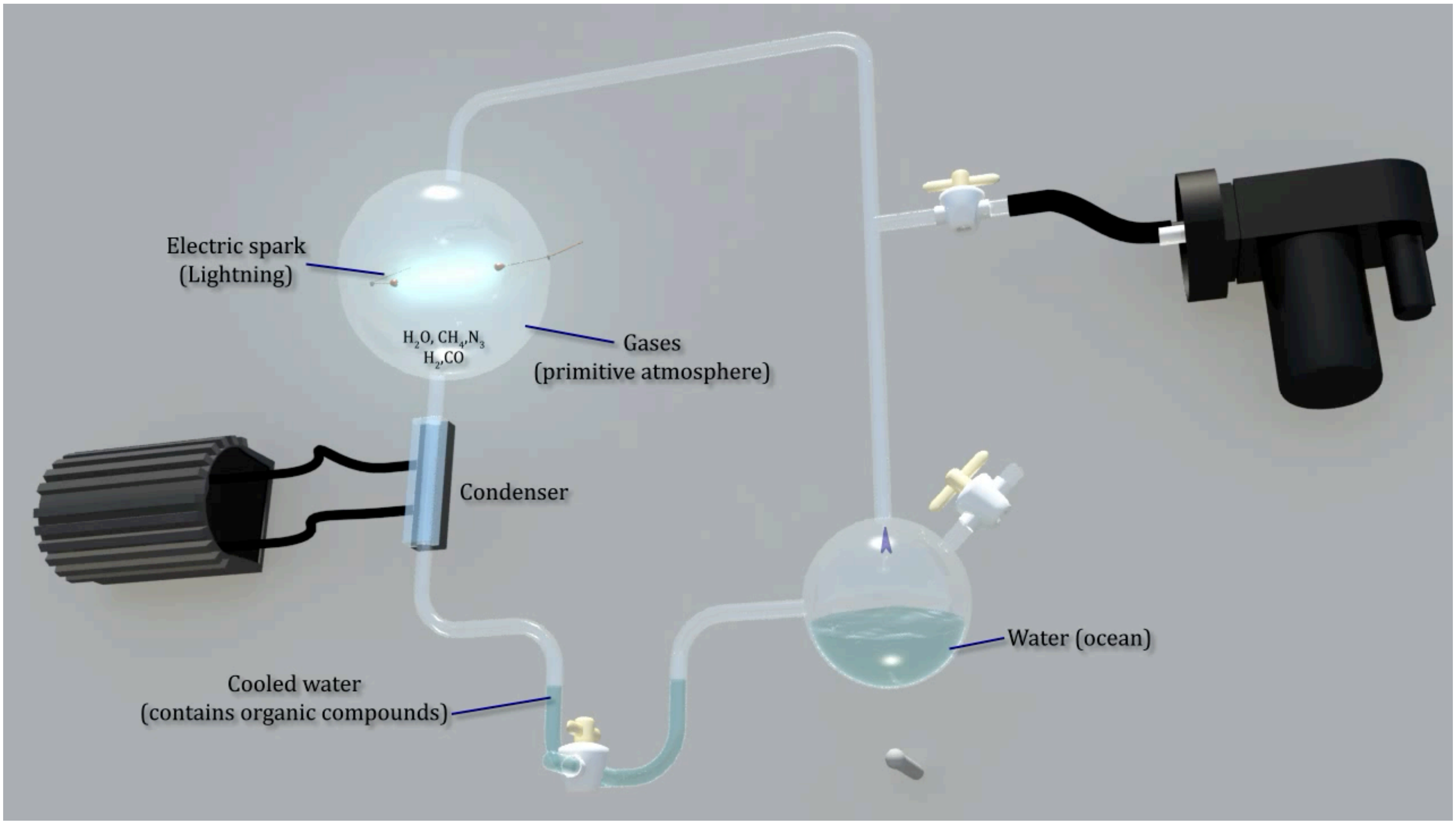




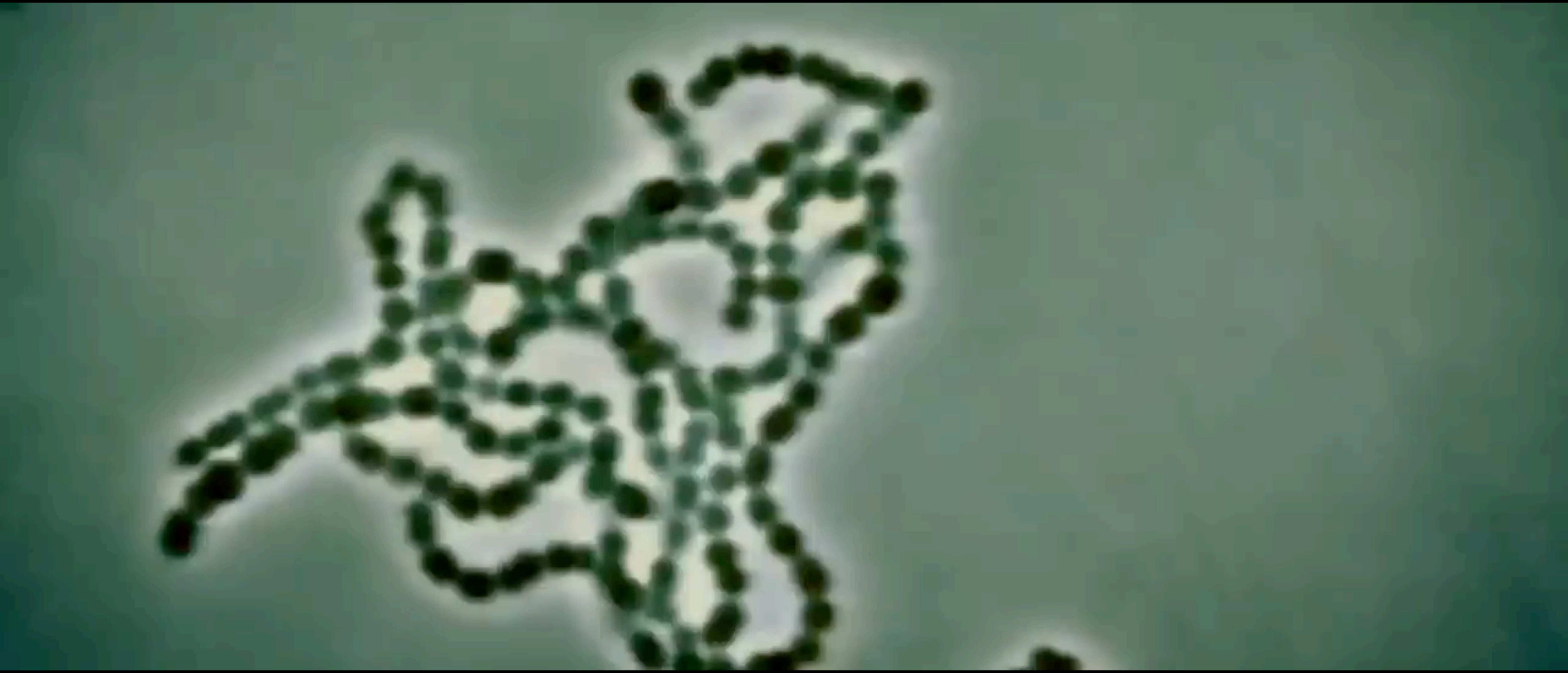
Miller-Urey Experiment (1952)

A chemistry experiment that simulated the conditions in the atmosphere of the early Earth
Goal: to test the hypothesis of the chemical origin of life.

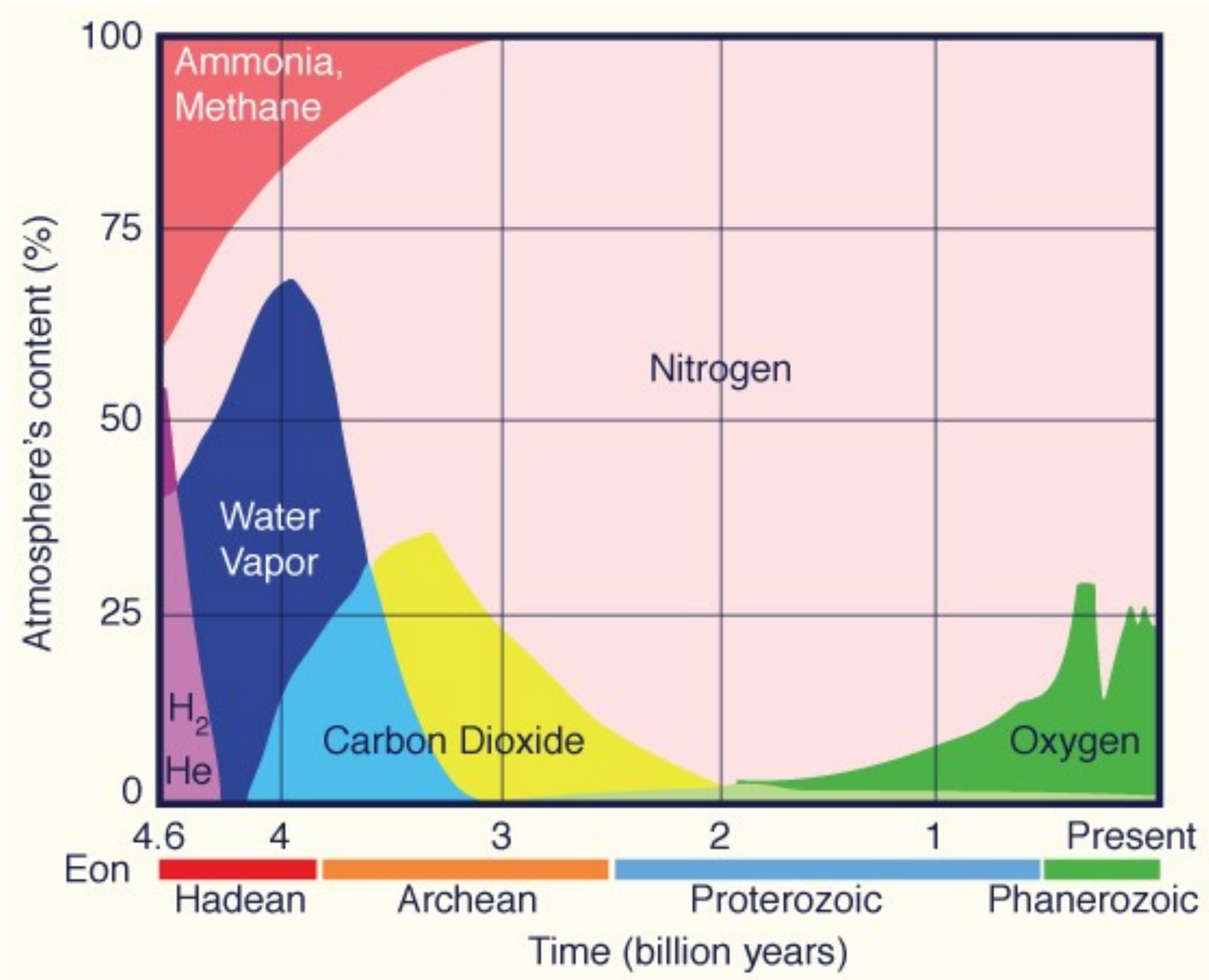
Result: Over 20 different **amino acids** (building blocks of protein and genetic code) were produced from simple gas mixtures of **CH_4, NH_3, H_2O, and H_2**, after only 1 week



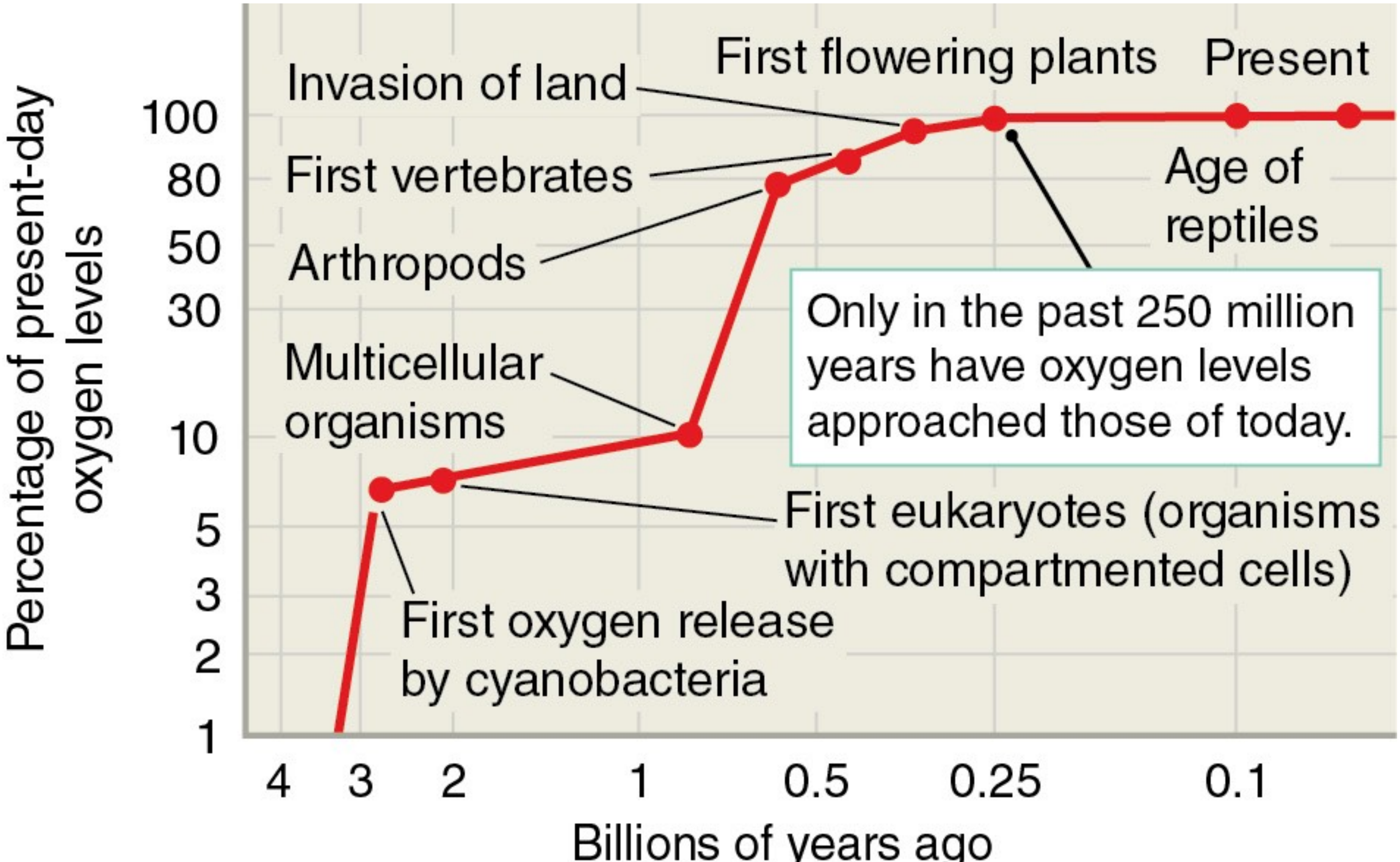
our story in one minute: a spark of life changed everything!



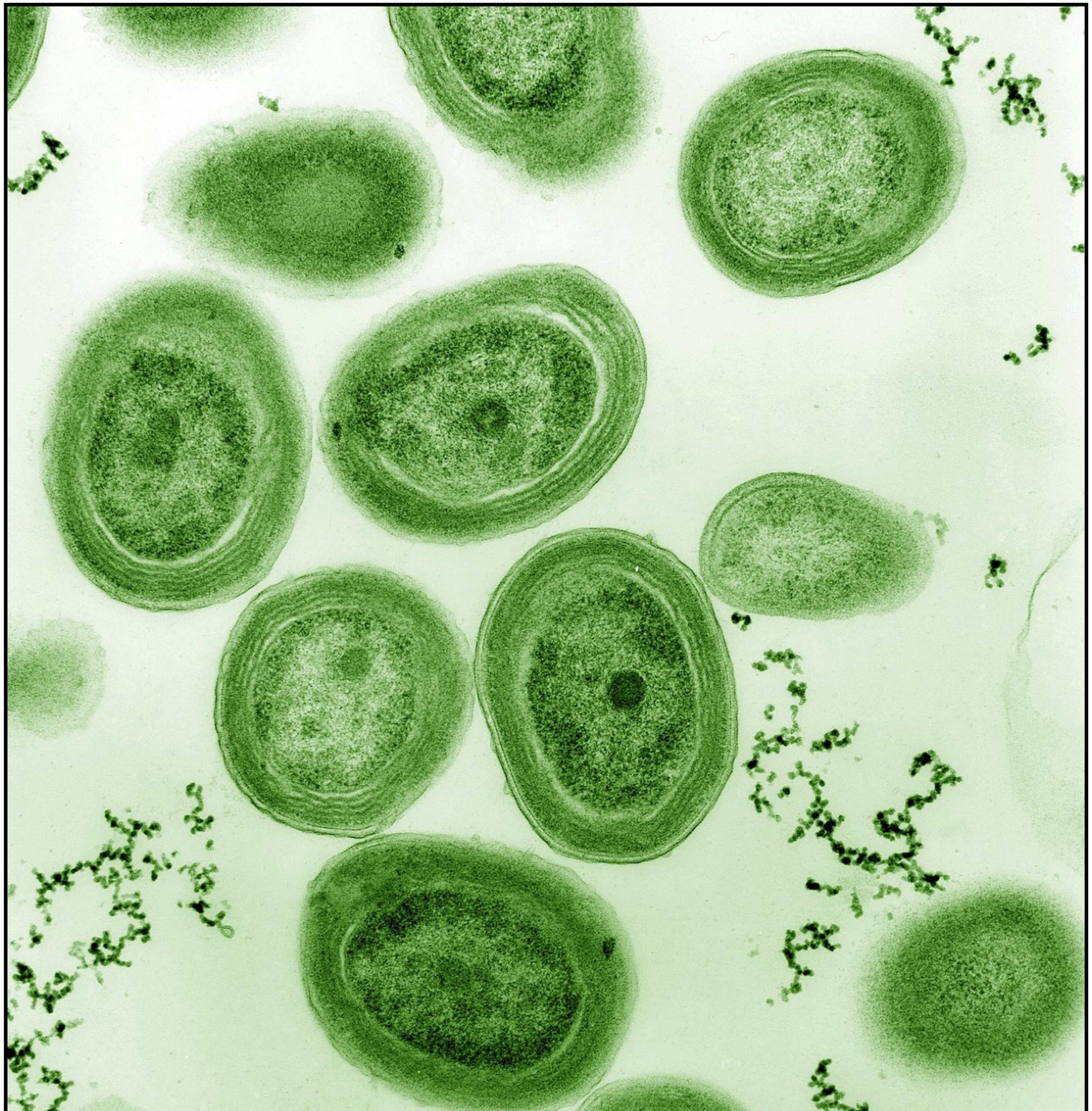
The Evolution of the Earth's Atmospheric Composition



Oxygen Level in Earth's Atmosphere vs. Time (log-scale)



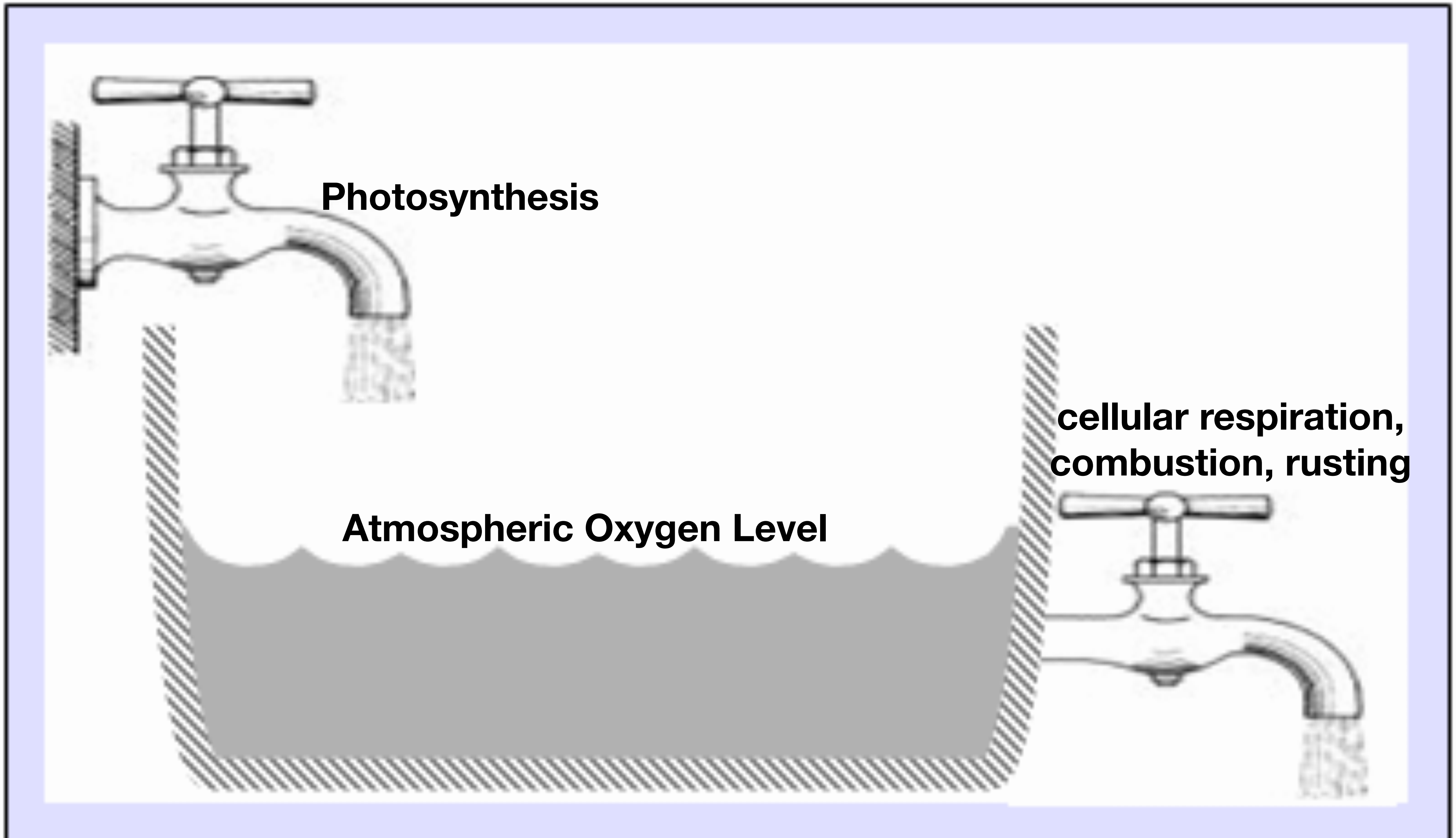
Marine cyanobacteria (aka blue-green algae) is an important group of Phytoplankton, which accounts for half of the oxygen production today



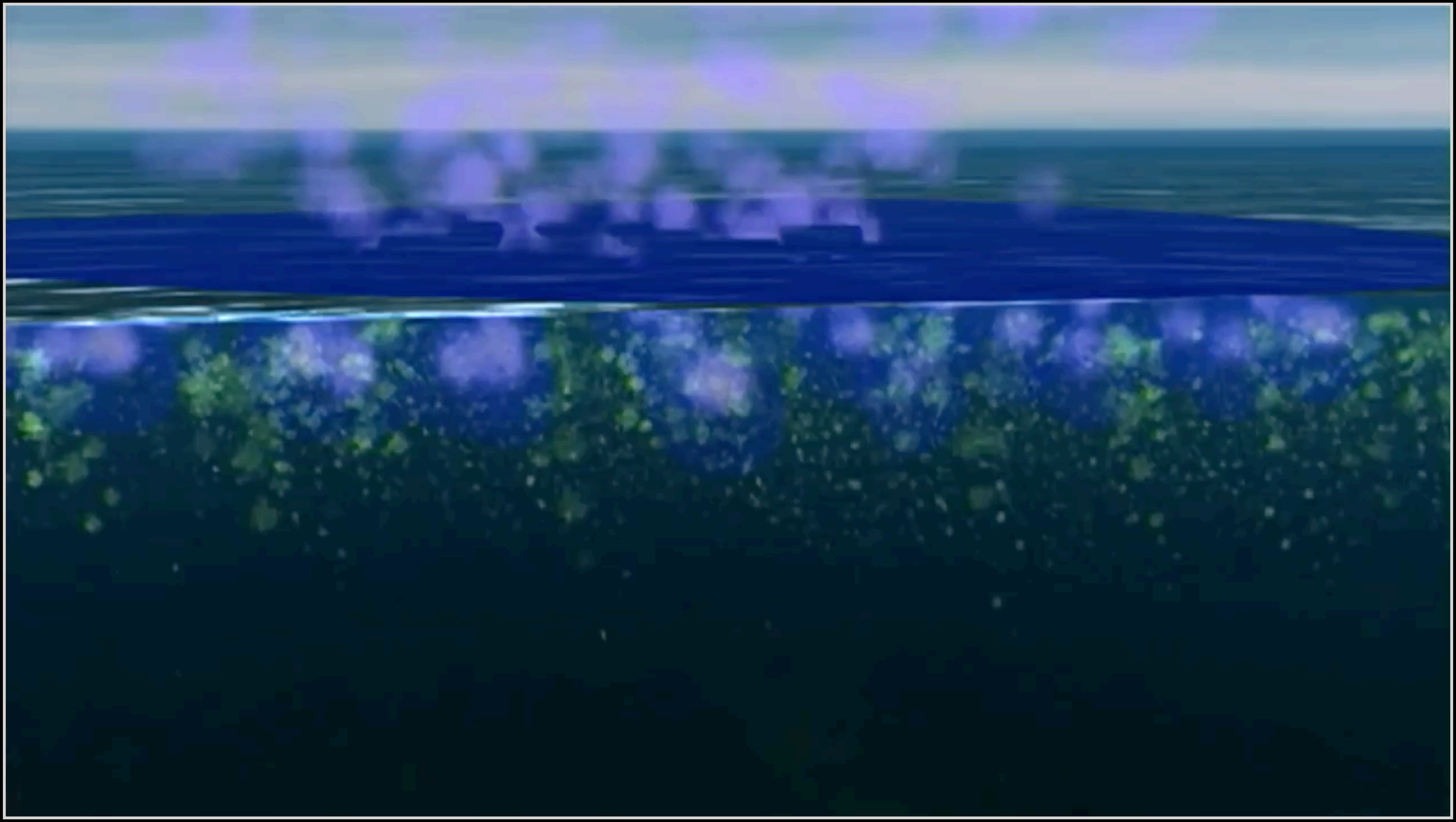
Prochlorococcus, a marine cyanobacterium just 0.6-um across, produced much of the world's oxygen

The Oxygen level in the atmosphere works like a bathtub

- The level of O_2 in the atmosphere depends on the relative strength between the inflow (production) rate and the outflow (consumption) rate



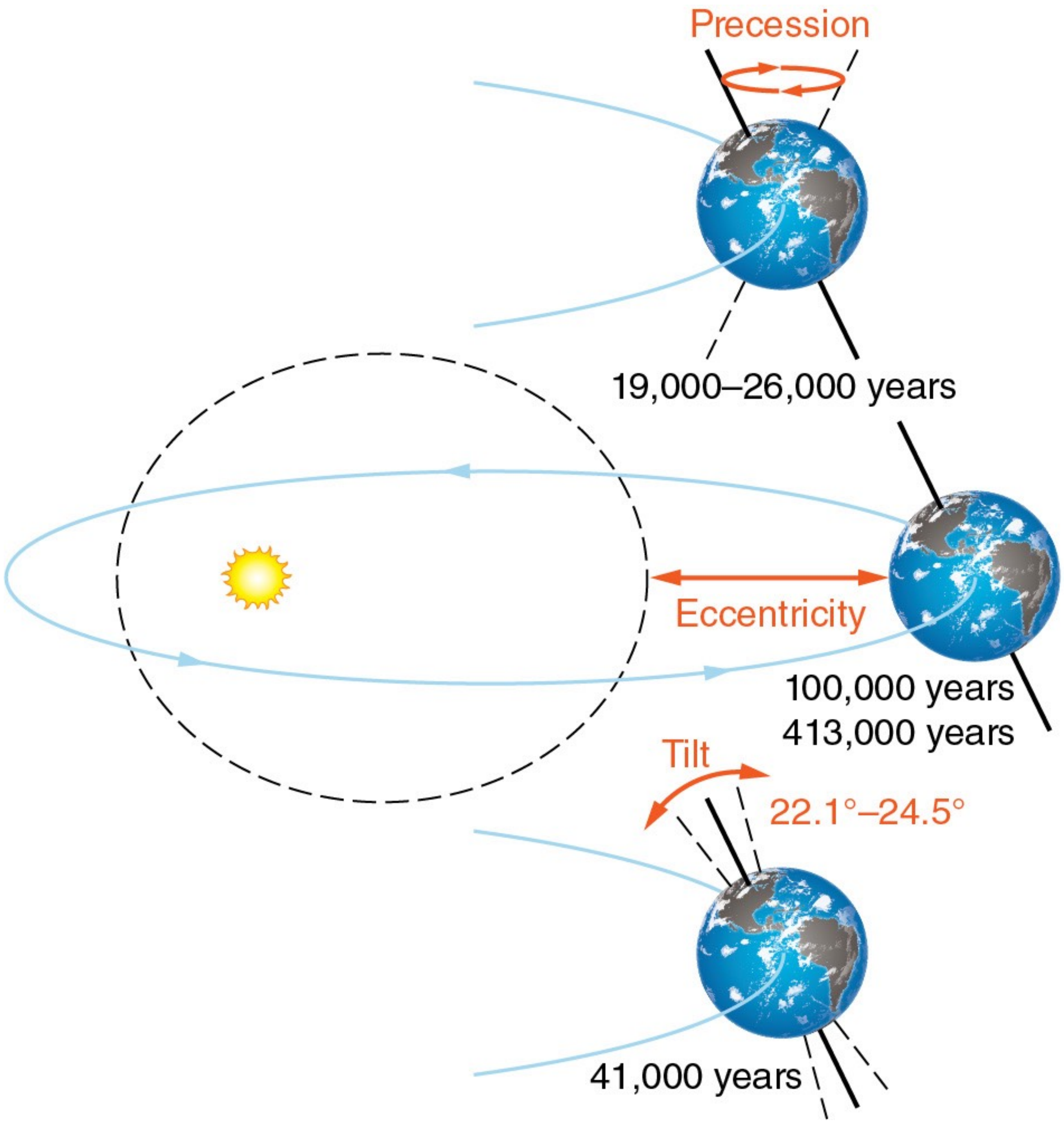
To maintain the Oxygen level, we need Oxygen production from Phytoplankton’s photosynthesis, but its population is decreasing as the ocean warms



Natural & Human Factors affecting the Condition of the Earth's atmosphere

an extension of "Milankovitch Cycles" (Ch02_Part6)

Milankovitch Cycles and Astronomical Mechanisms

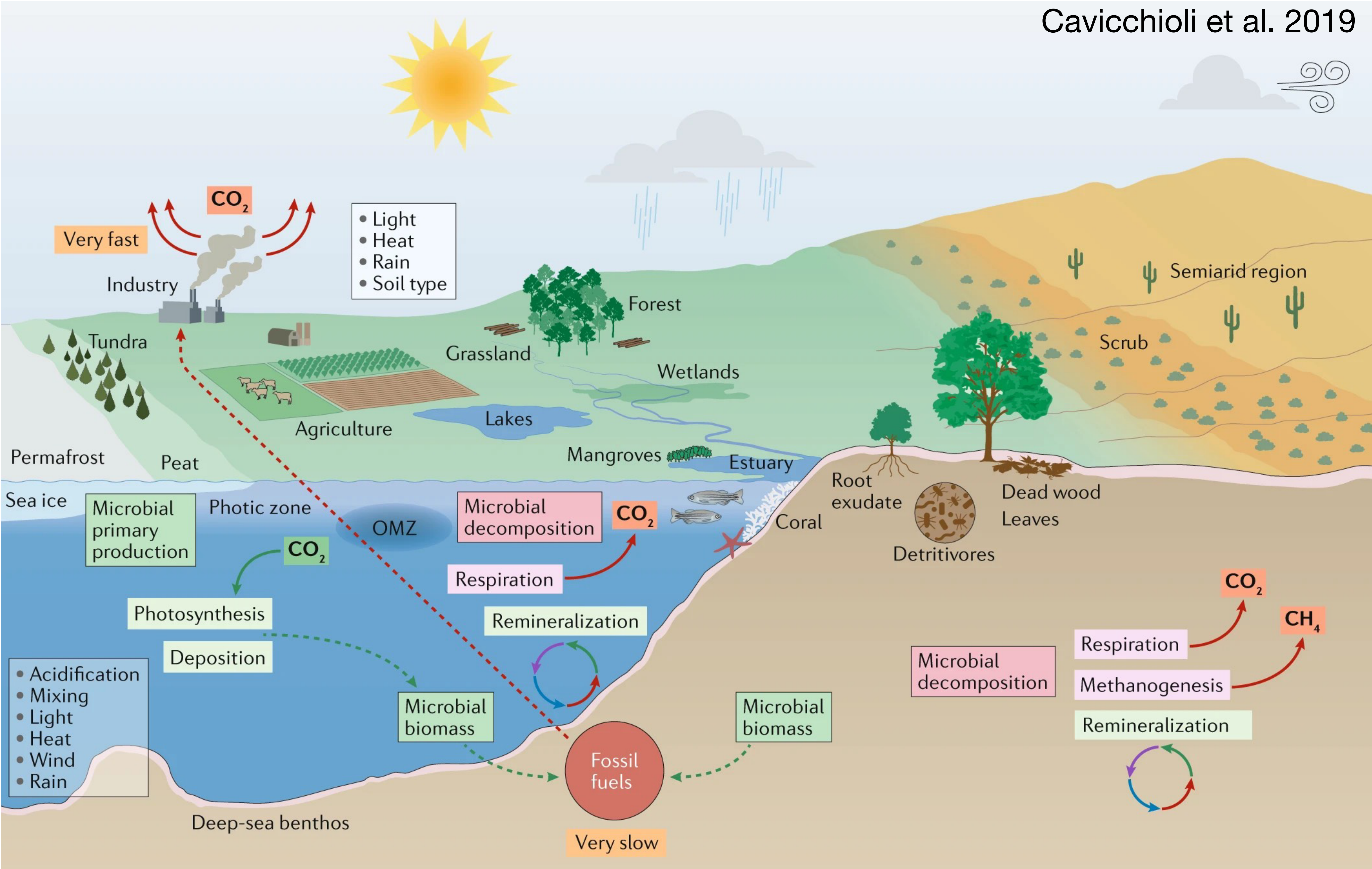


- **Climate** is the average state of an atmosphere.
- It can be affected by ***astronomical***, ***geological***, and ***biological*** mechanisms.
- **Astronomical mechanisms** that influence climate are changes in the average solar power received from the Sun.
  - **Solar luminosity**
  - **Orbit eccentricity**
  - **Spin obliquity**
  - **Spin precession**

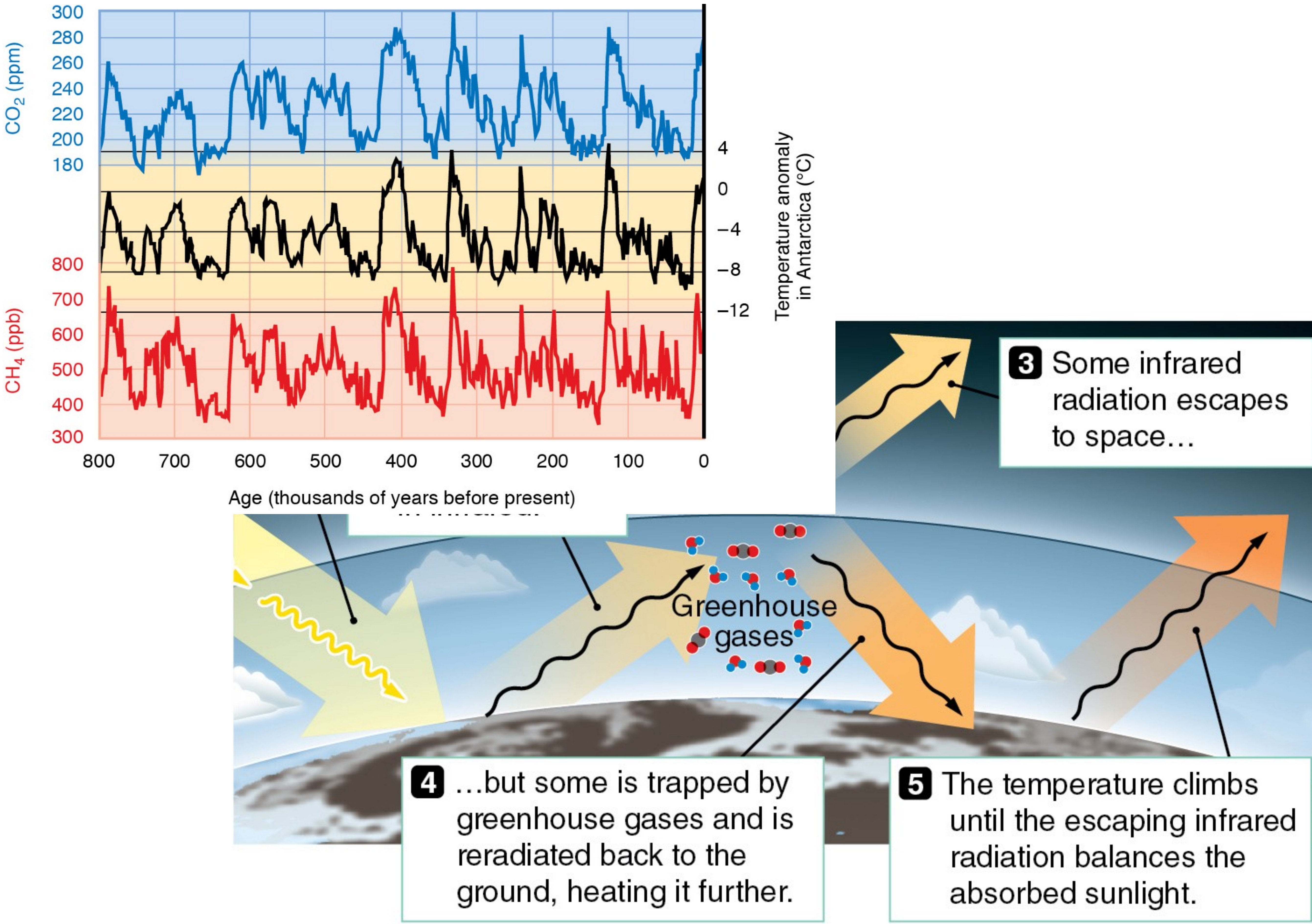
Climate and Biological Mechanisms, incl. Human Activity (Agriculture & Industry)

- Biological mechanisms are photosynthesis by bacteria and plants, methane by-products, and human activity.

Cavicchioli et al. 2019

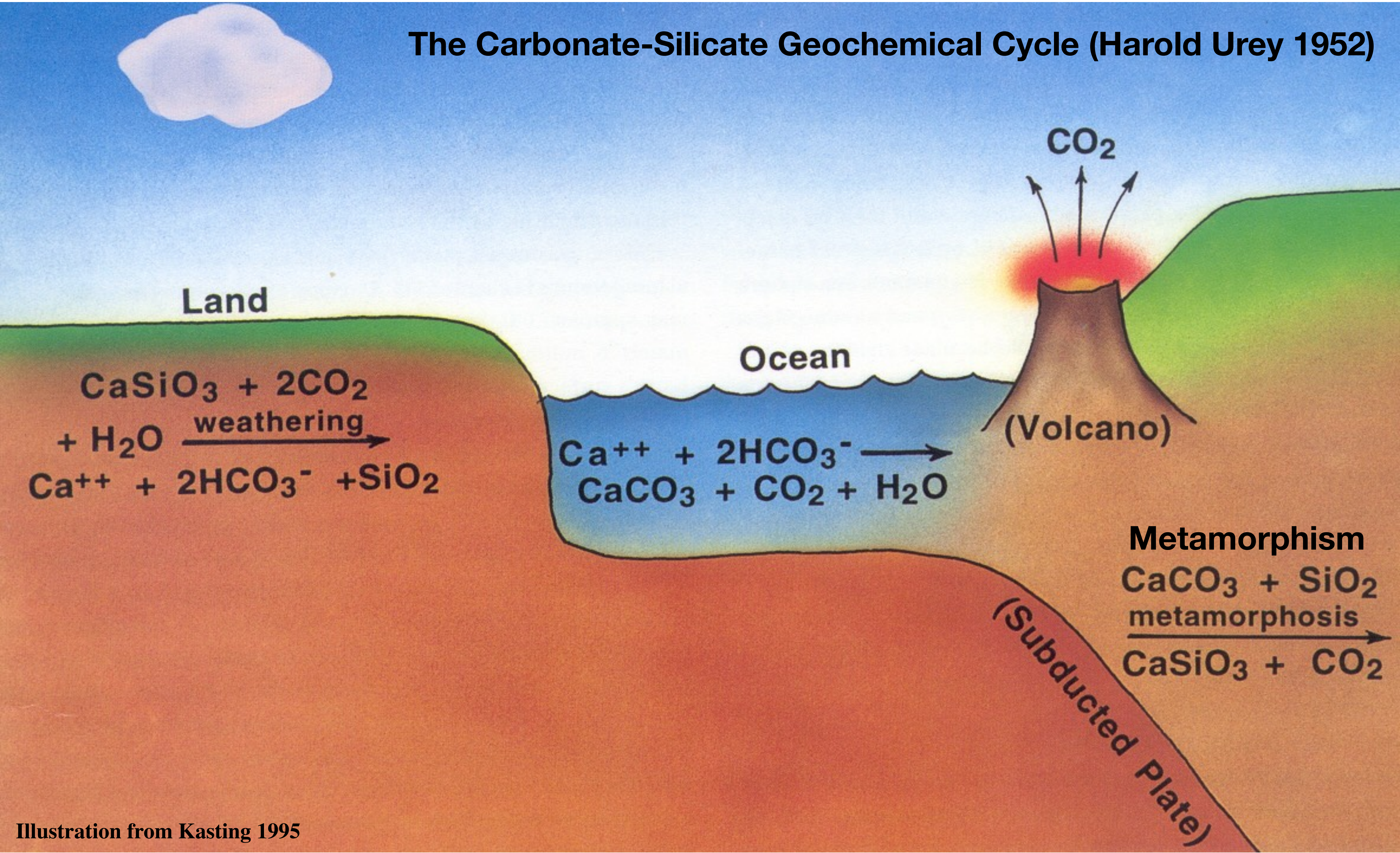


The Correlation between Greenhouse Gas Concentration and Temperature



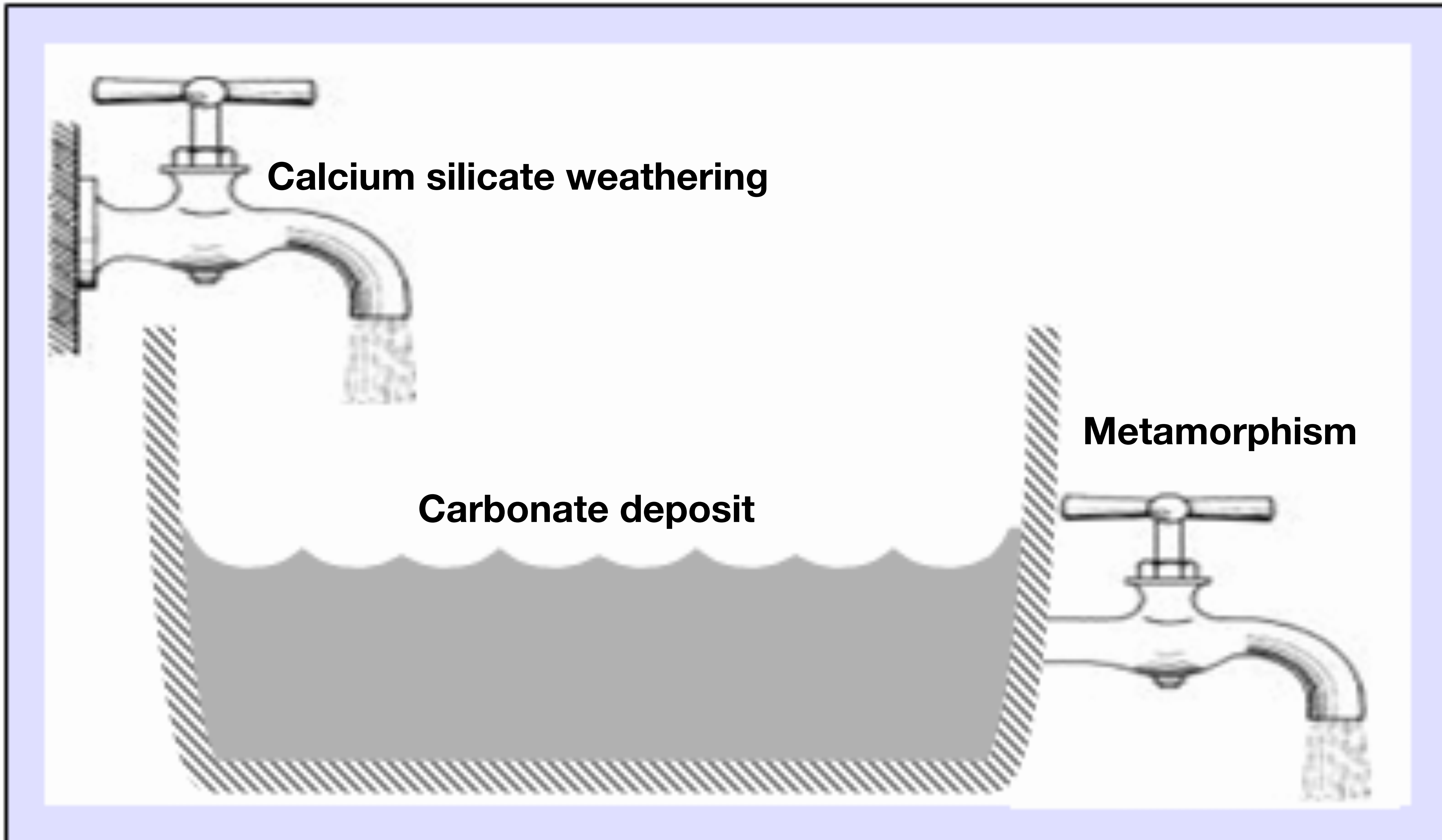
Geological Mechanisms: Longterm Cycles

- volcanic and tectonic activity on million-year time scales.

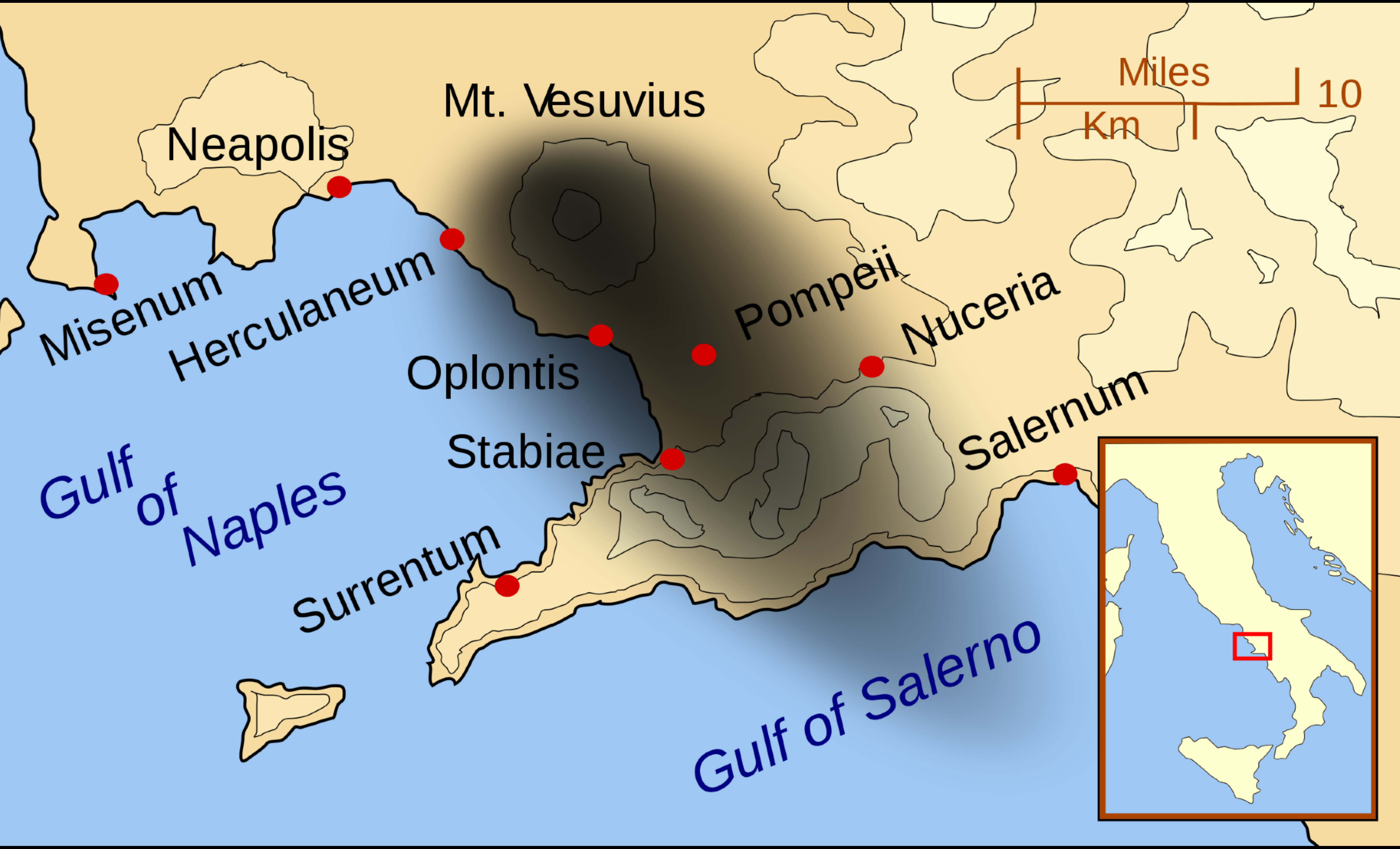


The Carbonate-Silicate Cycle works also like a bathtub

- The level of CO_2 locked in the carbonate reservoir depends on the inflow and outflow rates
- the carbonate reservoir level anti-correlates with the atmospheric CO2 level



The Burial of Pompeii, Roman Empire, 79 AD



The Burial of Pompeii, Roman Empire, 79 AD

Pompeii, with Vesuvius towering in the background

Chile’s Puyehue Eruption in 2011

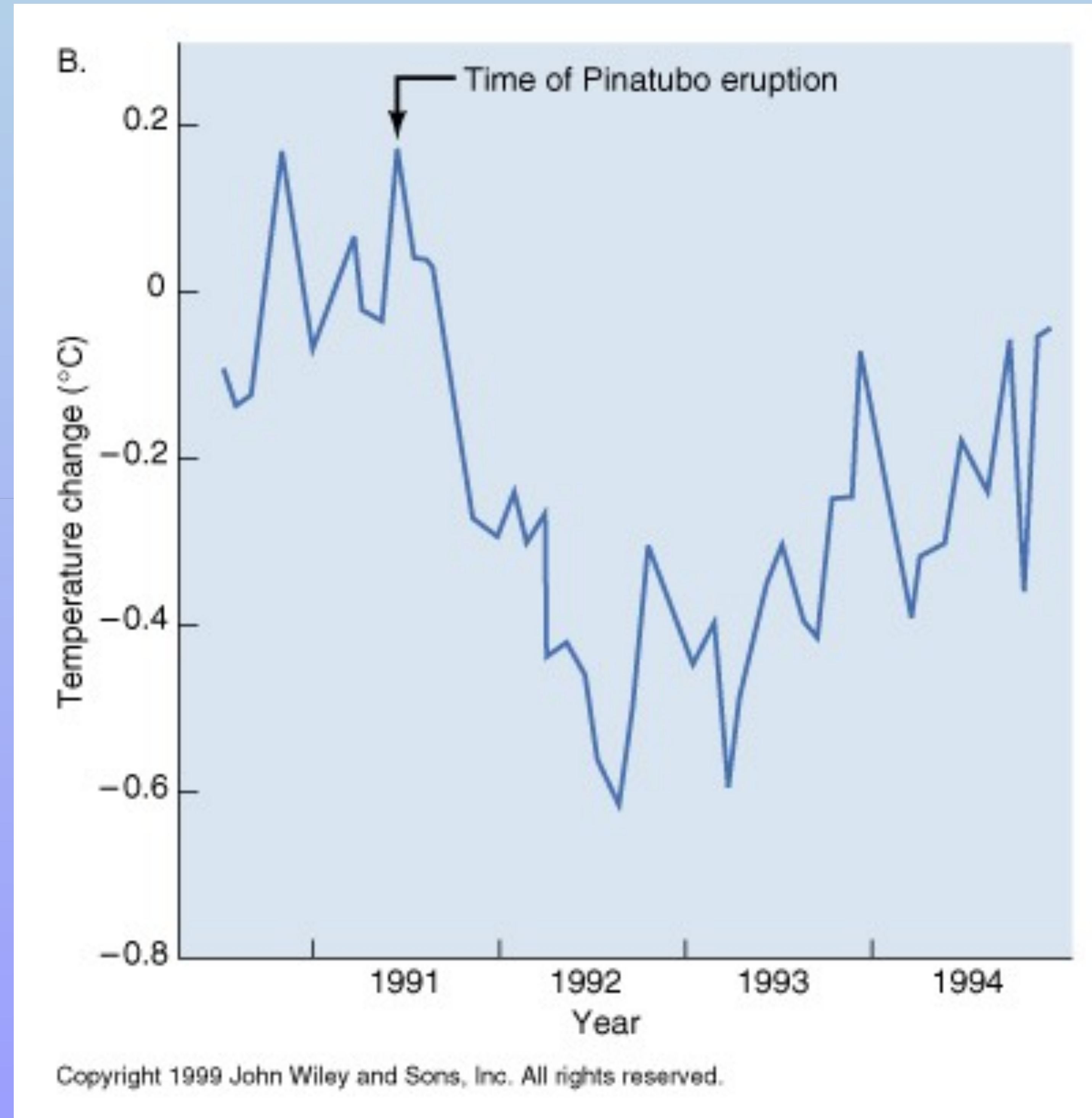
Puyehue Volcano in March 2015

Geological mechanisms - volcanic eruptions

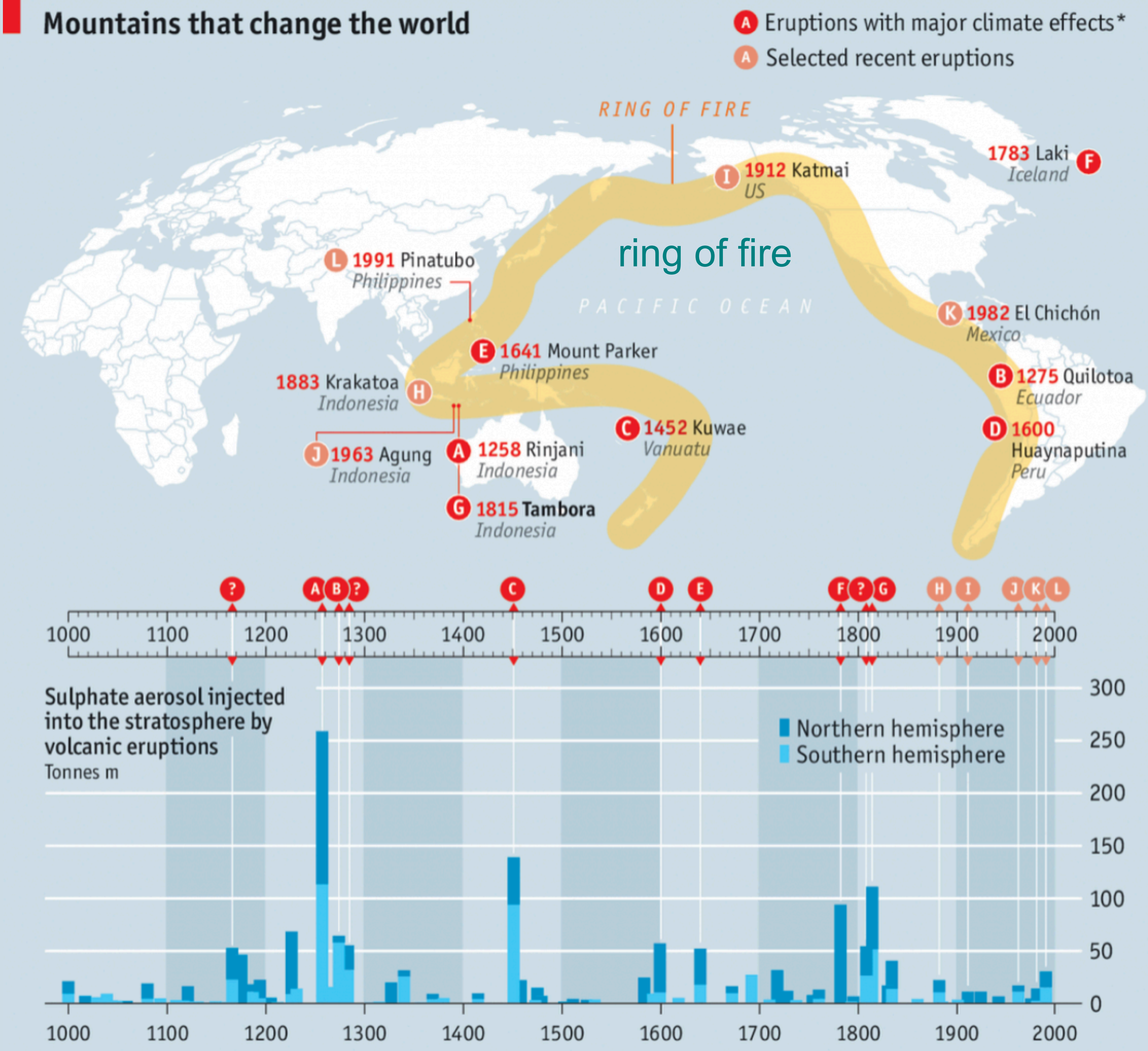
Mt. Pinatubo, Philippine, June 1991

Effects of volcanic eruptions on global temperature can be felt on really short timescale, a few years

Mt. Pinatubo eruption
June, 1991 (Phillipines)



Mountains that change the world



Crescent Moon & Earth's Atmosphere (International Space Station)

Drake Equation:
How long can a civilization exist before its self-destruction?

$$N = R * f_p * n_e * f_l * f_i * f_c * L$$

- $R_* = 10\ \text{yr}^{-1}$ (100 billion star formed over 10 billion years)
- $f_p = 0.5$ (one half of all stars formed will have planets)
- $n_e = 0.2$ (20% chance of hosting life-supporting planets)
- $f_l = 1$ (100% of the above will develop life)
- $f_i = 1$ (100% of the above will develop intelligent life)
- $f_c = 1$ (100% of the above will develop advanced civilizations)

$$N \approx L_{\text{year}}$$

Orion Spacecraft, Earth, and the Moon, Nov 28, 2022

- Constants: k = 1.38e-23 J/K, m_H = 1.67e-27 kg, e = 2.718

Chap 9: Equations

$$\mu = \sum_i \mu_i f_i^v$$

$$P = nkT = \left(\frac{\rho}{\mu m_H}\right) kT \qquad \mu m_H = \bar{m} = \frac{M}{N} = \frac{\rho}{n}$$

$$n(h) = n_0 \exp\left(-\frac{h}{h_S}\right) \text{ where the scale height is:}$$

$$h_S = \frac{kT}{\mu m_H g} = 7.4 \text{ km} \left(\frac{T}{280\ K}\right)\left(\frac{32}{\mu}\right)\left(\frac{9.8\ \text{m/s}^2}{g}\right)$$

$$\bar{v}_{\text{molecule}} = \sqrt{\frac{3kT}{\mu m_H}} = 0.4 \text{ km/s} \left(\frac{T}{300 \text{ K}}\right)^{0.5}\left(\frac{\mu}{44}\right)^{-0.5}$$

$$v_{\text{esc}} = \sqrt{\frac{2GM}{R}} = 11.2 \text{ km/s} \left(\frac{M}{M_{\text{Earth}}}\right)^{0.5}\left(\frac{R}{R_{\text{Earth}}}\right)^{-0.5}$$