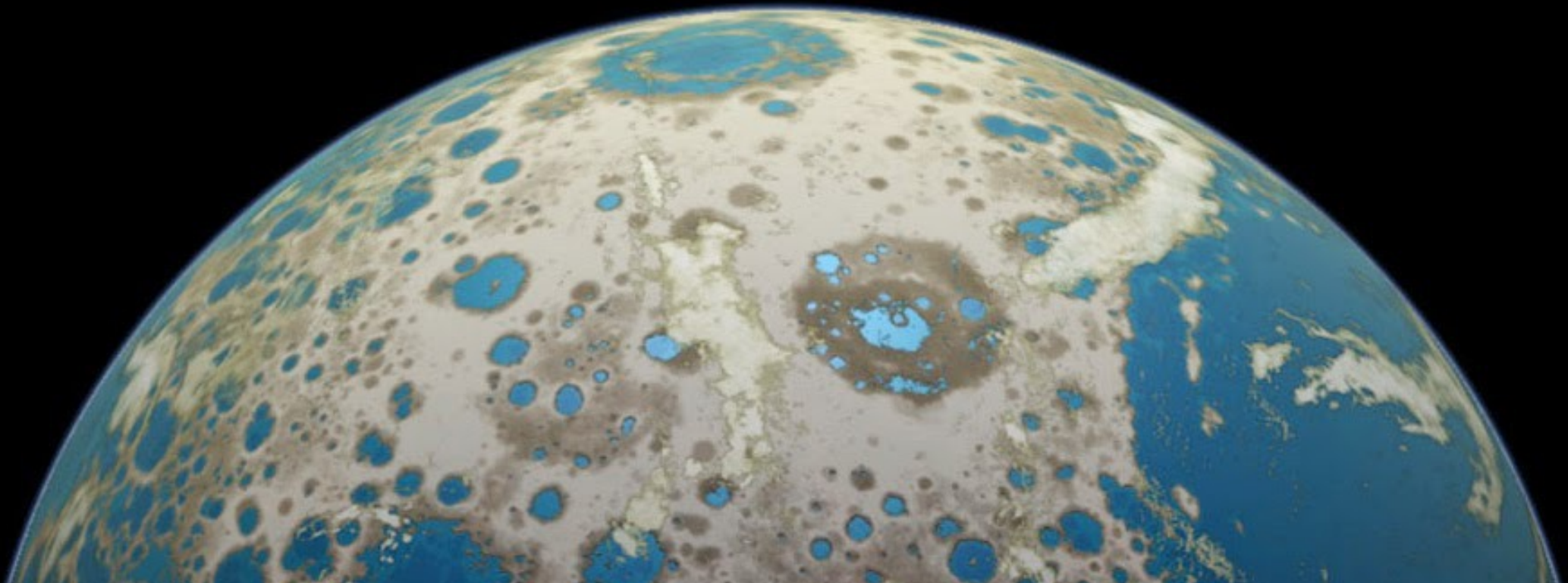


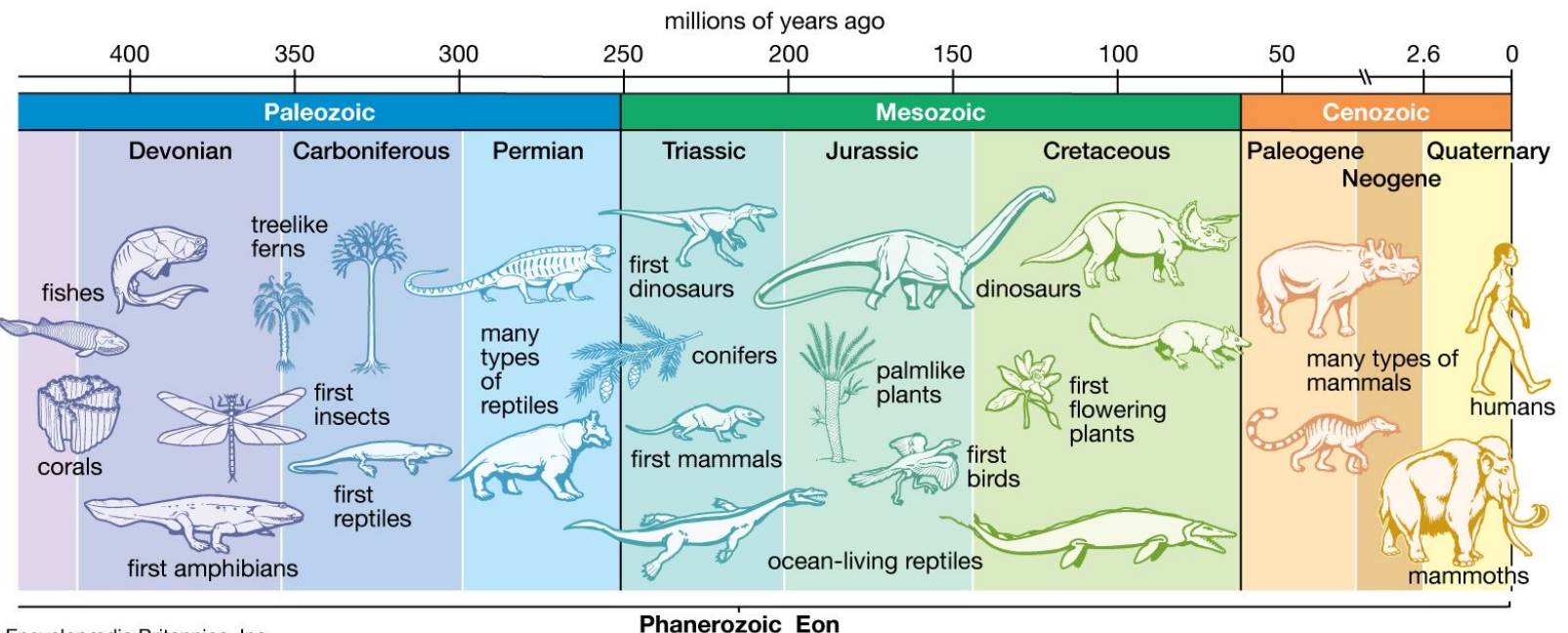
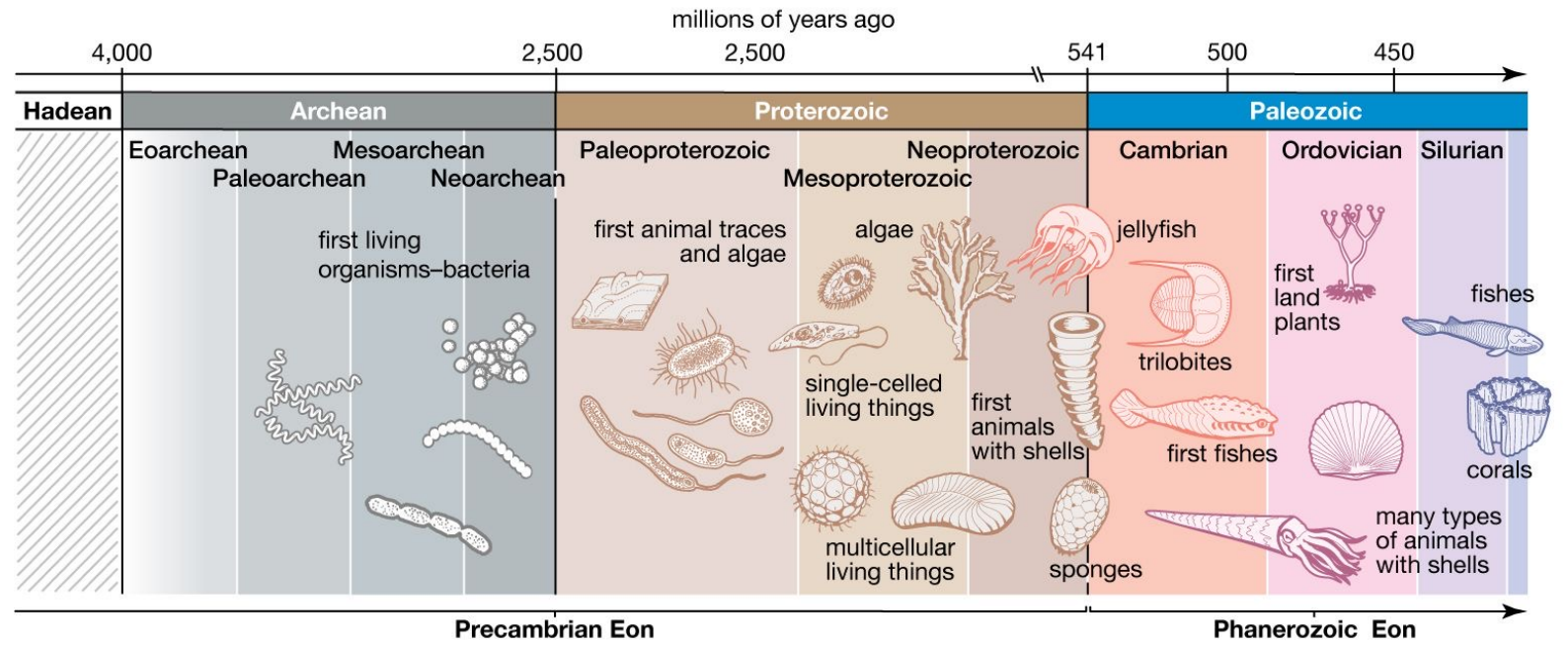
On the origin of Life on Earth

Hans Dembinski, TU Dortmund



Overview

- Earth formed **4.5 Ga** ago
- **Life** appeared **4 Ga** ago at end of Hadean eon
- How did organisms develop from non-living matter?



© Encyclopædia Britannica, Inc.

<https://www.britannica.com/science/life/Life-on-Earth>

Hadean eon



Hadean eon

- First oceans **4.4 Ga** ago
- 230 °C surface temperature
- Anaerobic atmosphere
 - CO₂, N₂
 - 27 bar

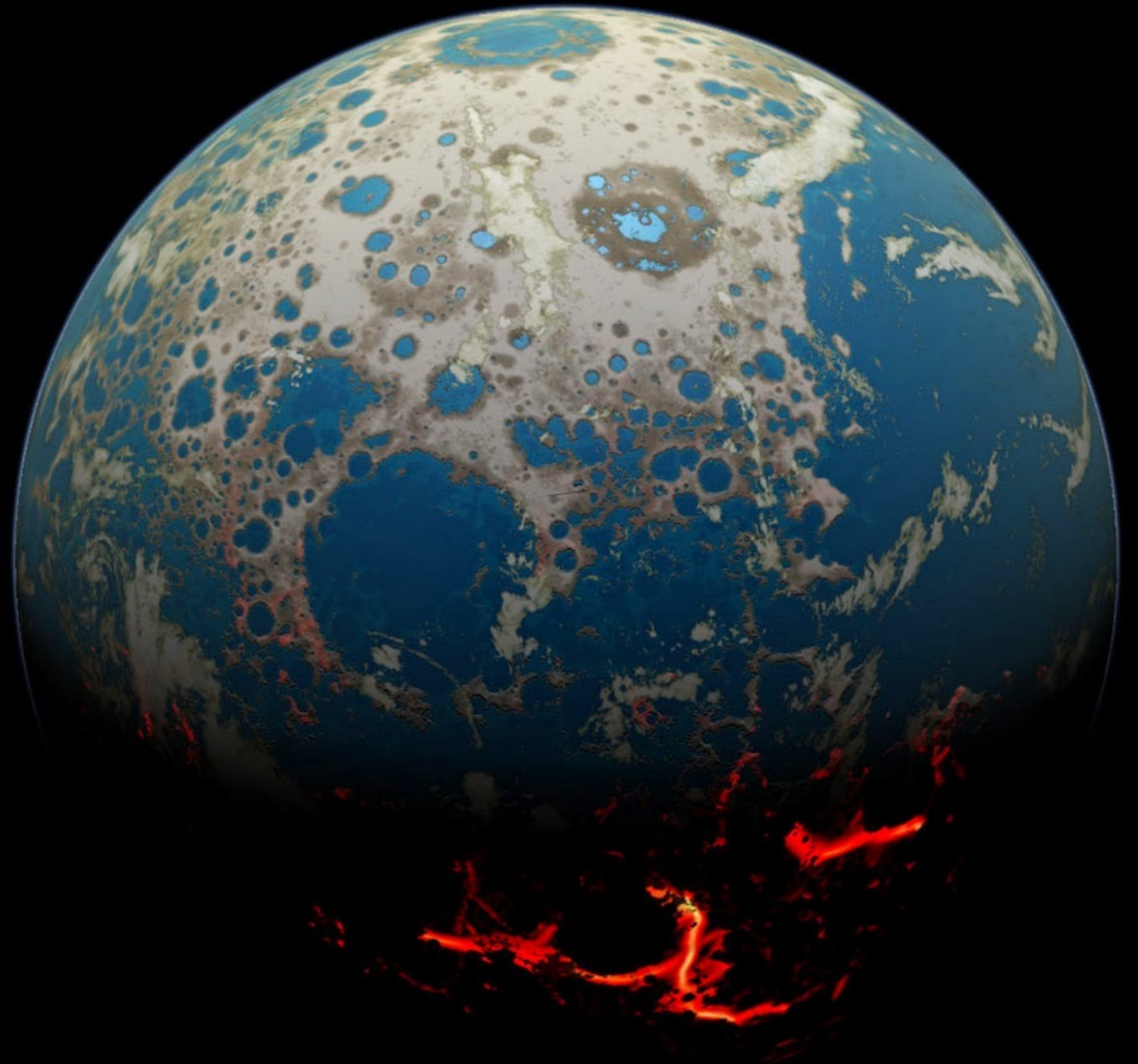


Image credit: Simone Marchi

Hadean eon: How bad was it?

- **Formation of Moon 4.4 Ga ago:**
impact of Mars-sized dwarf planet

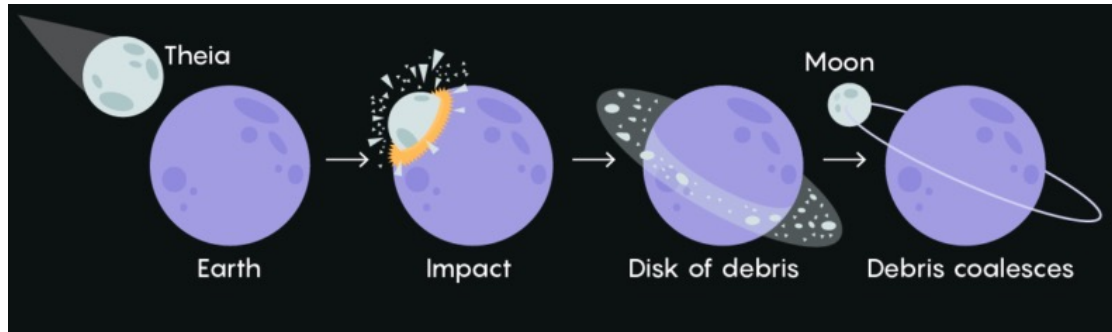
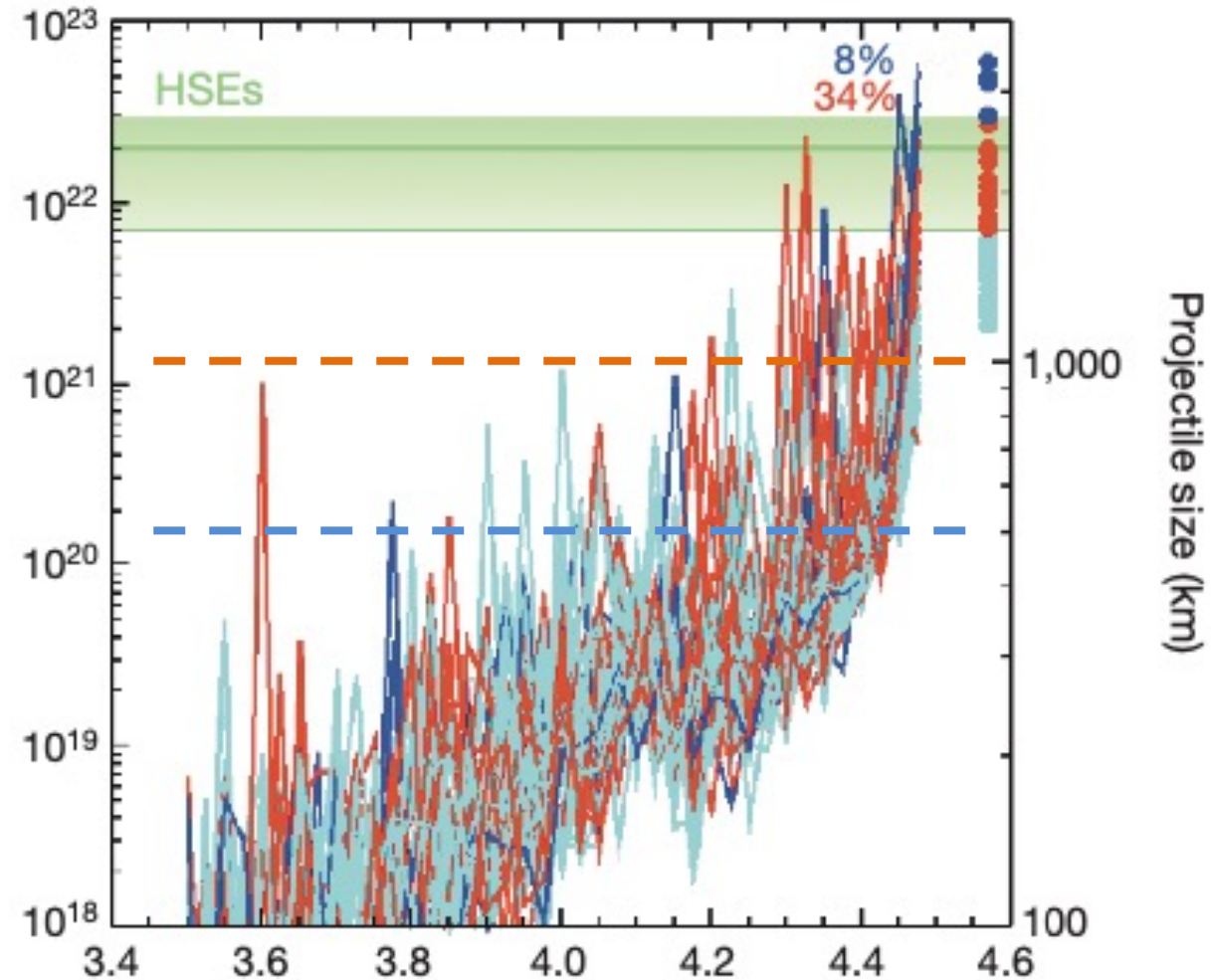


image credit: <https://commons.wikimedia.org/w/index.php?curid=72720188>

- Catastrophic bombardment till ≈ 3.8 Ga ago
 - ▶ **Impactors** with >1000 km size capable of **global serialization**
 - ▶ **Impactors** with >500 km size capable of **global ocean vaporization**

Marchi et al (2014) Nature **511**, Issue 7511, pp. 578-582



Oldest known rocks

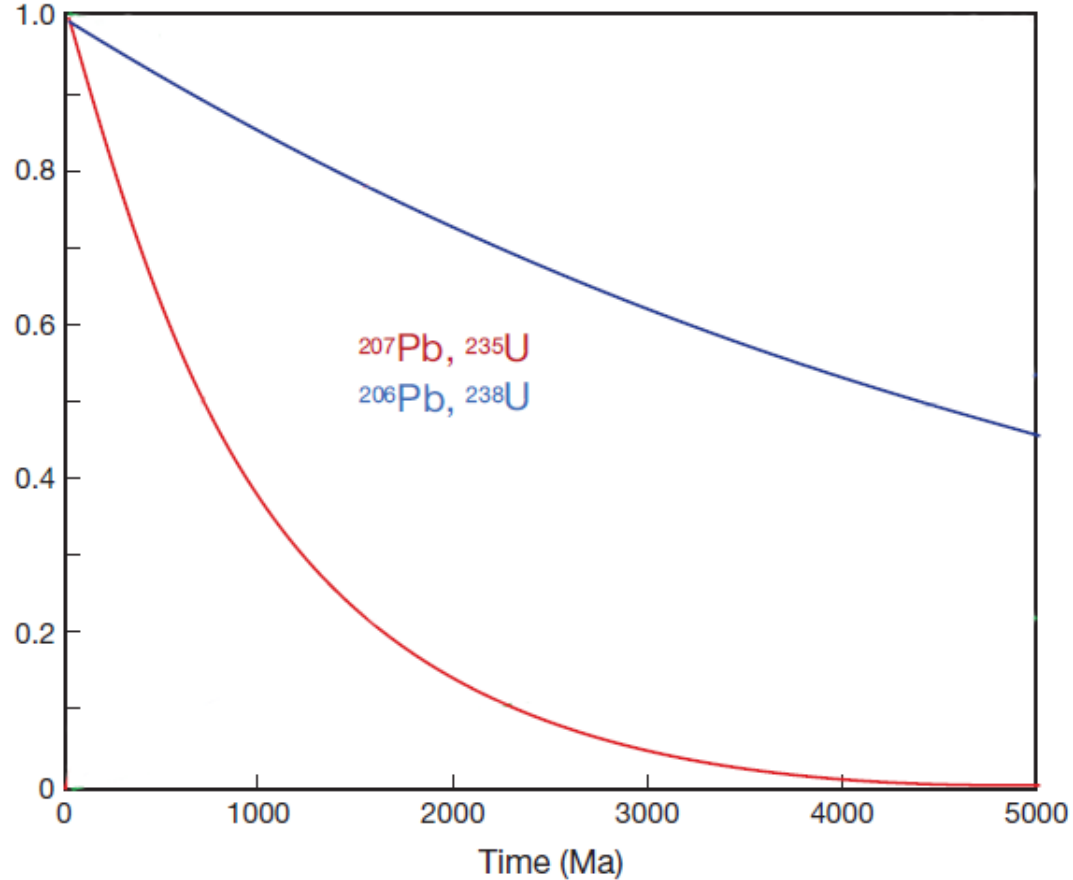


Jack Hills, Western Australia

image credit: <https://alchetron.com/Jack-Hills>

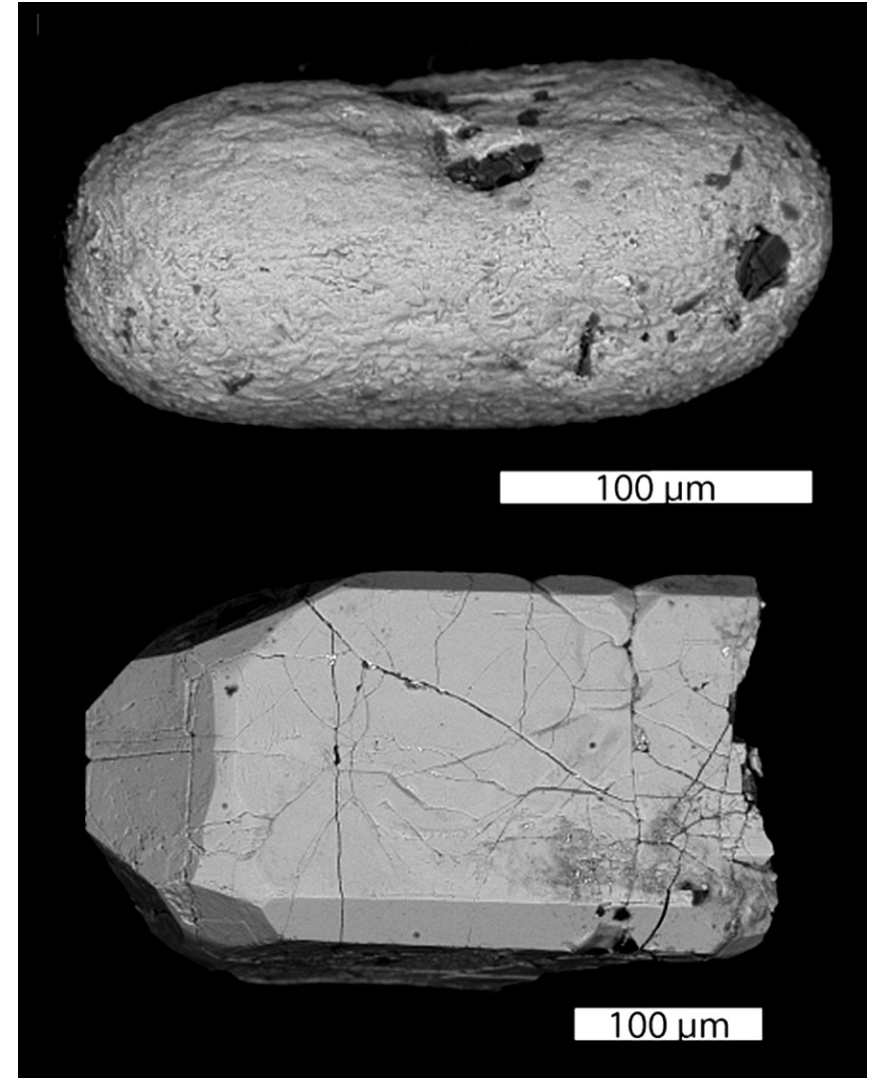
Zircon radiometric dating

image credit: <https://www.gsoc.org/news/2020/12/07/zircon>



- Zircons on formation
 - Free of lead
 - Traces of uranium embedded in crystal lattice
- U/Pb ratio to determines age to precision 0.1-1%

Zircons from Hadean **4.404 ± 0.008 Ga**
Jack Hills, Western Australia
Wilde et al. (2001), Nature **409** (6817): 175–178



Earliest fossils: Stromatolites

Modern stromatolites, Shark Bay, Western Australia



Stromatolite fossil from Pilbara region
Western Australia

Duda et al, PLoS One. 2016; 11(1): e0147629



Modern cyanobacterial mat,
Salty lake on the White Sea, Russia

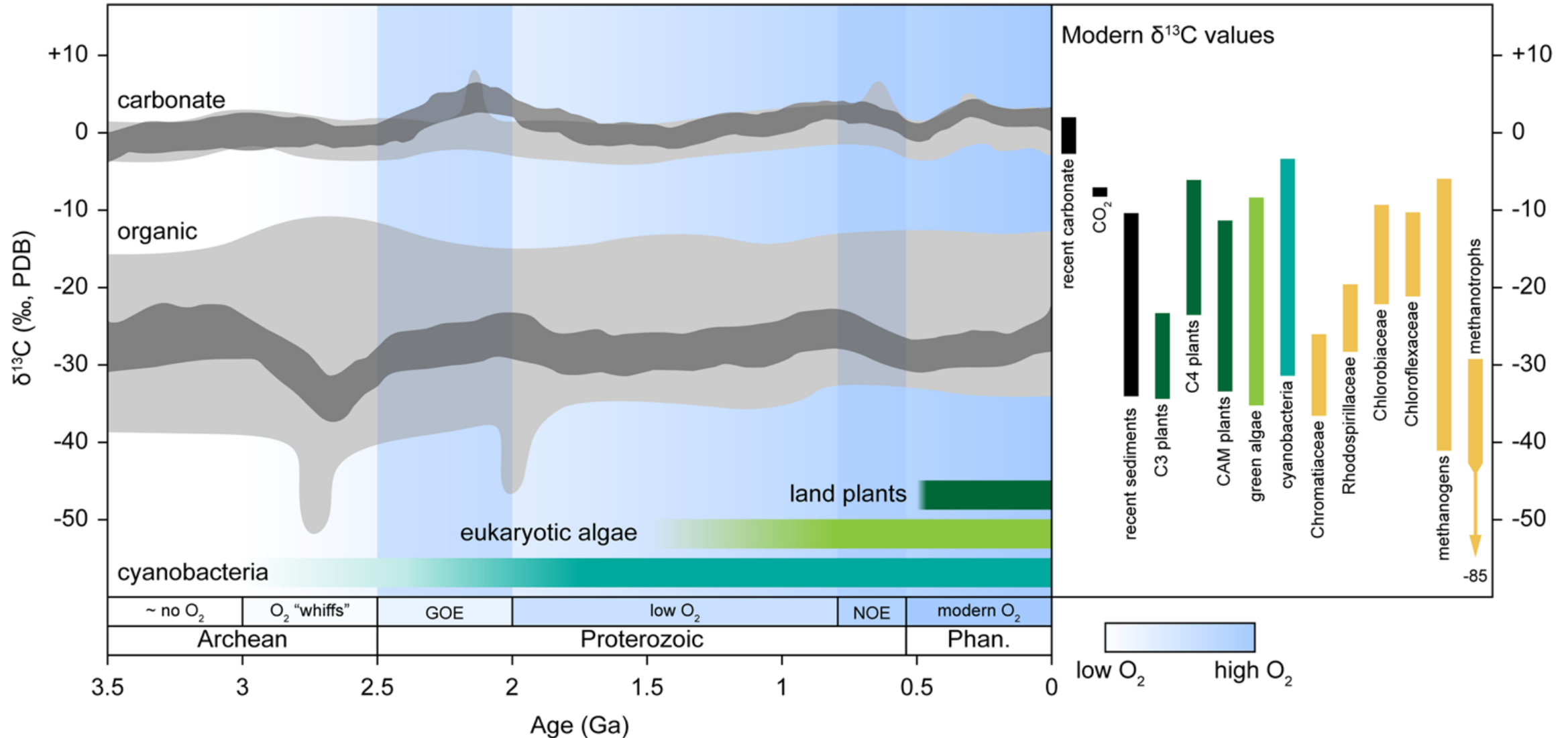
- Stromatolites are formed by microbial mats
- Earliest stromatolites from **3.5 Ga** ago

image credit: https://en.wikipedia.org/wiki/Microbial_mat#/media/File:Cyanobacterial-algal_mat.jpg, https://en.wikipedia.org/wiki/Stromatolite#/media/File:Stromatolites_in_Sharkbay.jpg

Earliest fossils: Organic carbon

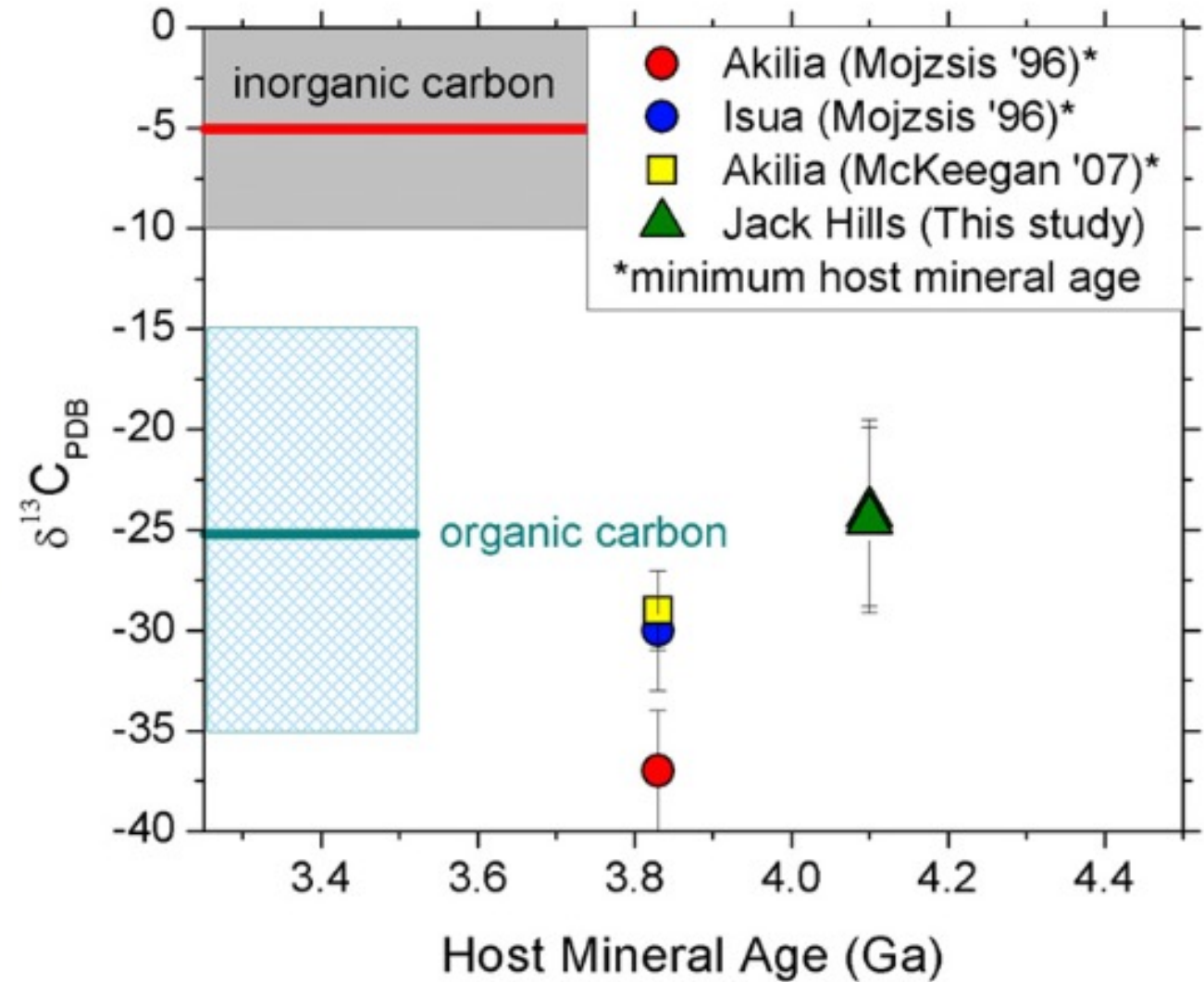
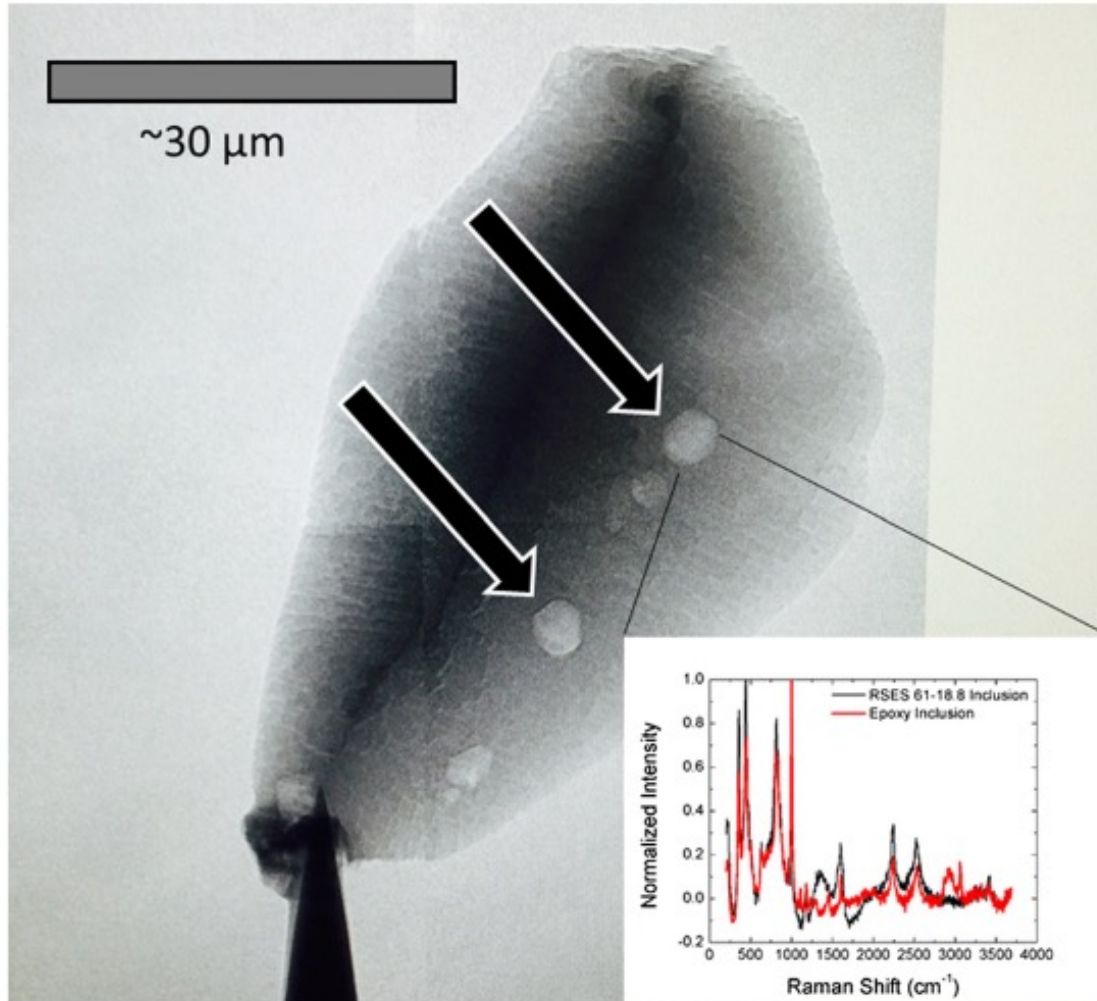
$\delta^{13}\text{C}$ = normalized $^{13}\text{C}/^{12}\text{C}$ ratio to PDB standard

Garcia, Cavanaugh, Kacar, The ISME Journal volume 15, pages 2183–2194 (2021)



Earliest fossils: Organic carbon

Bell, Boehnke, Harrison, Mao (2015) Proc. Natl. Acad. Sci. USA **112**(47) 14518-14521



Modern cells

Eukaryotes

Nucleus with DNA

Organelles

Sexual reproduction

Plants

Animals

Fungi

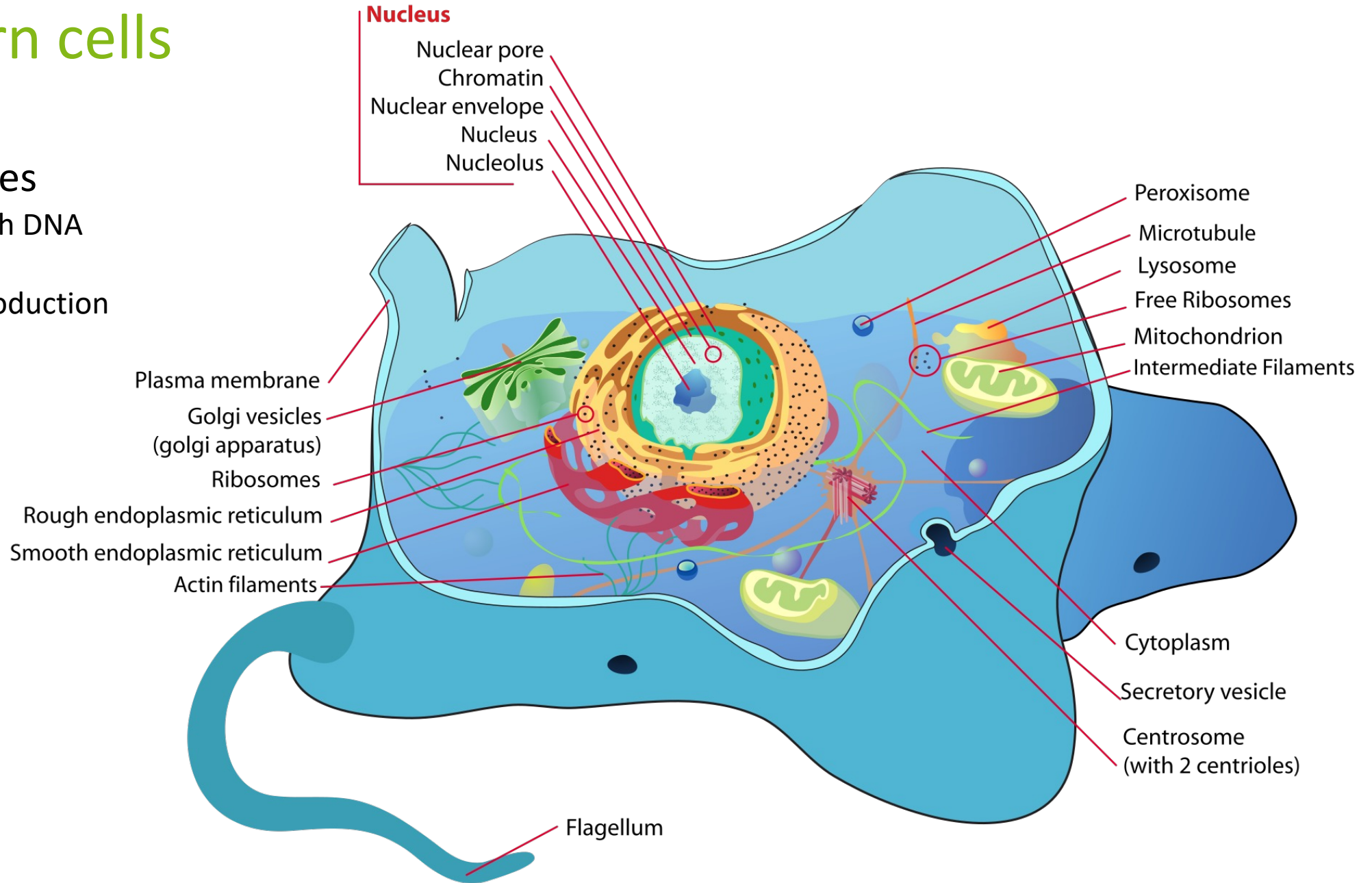


image credit: [https://en.wikipedia.org/wiki/Cell_\(biology\)](https://en.wikipedia.org/wiki/Cell_(biology))

Earliest cells

Prokaryotes

Free DNA

No organelles

Frequent horizontal gene transfer

Bacteria

Archaea

Eukaryotes evolved from archaea

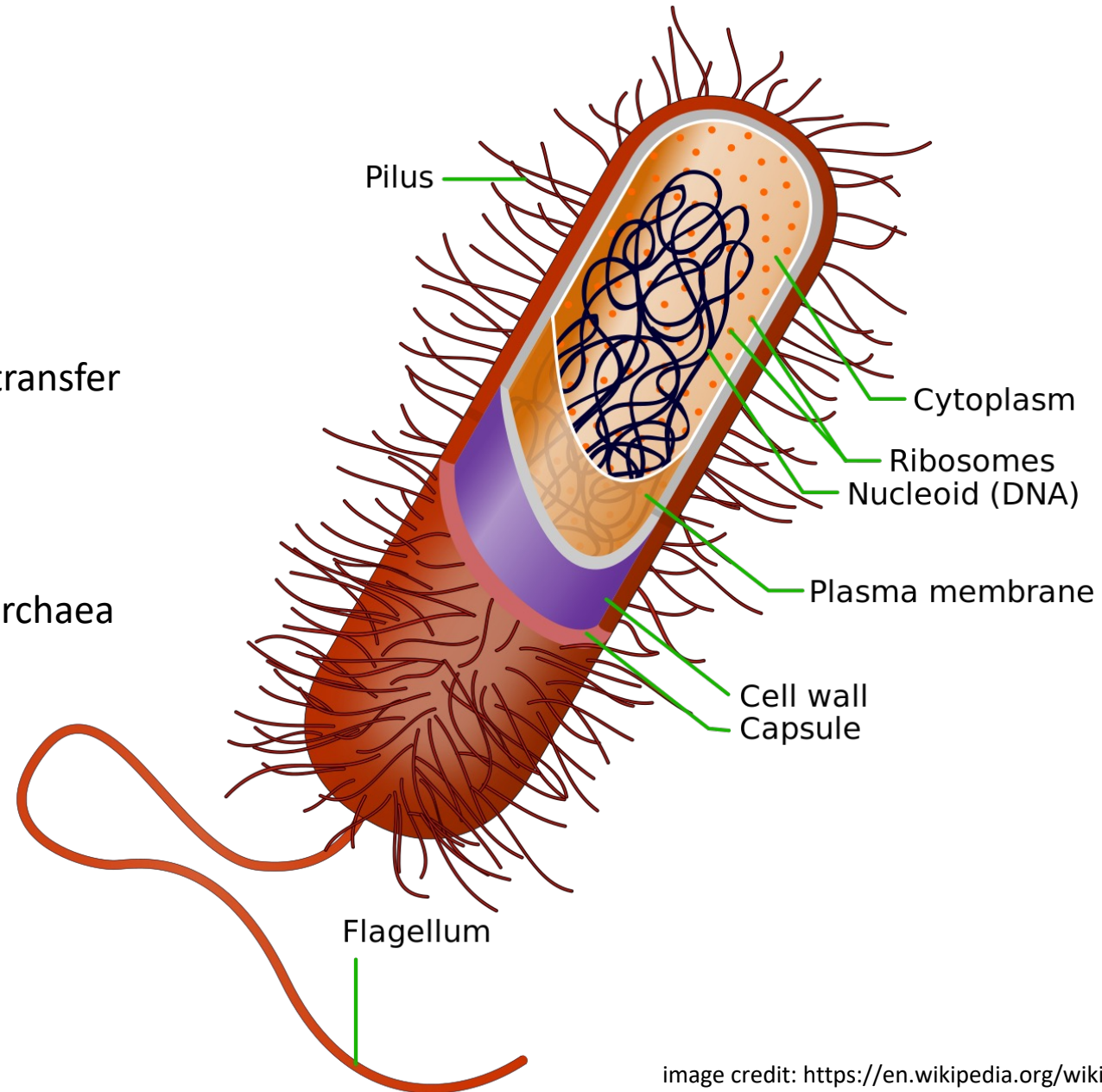
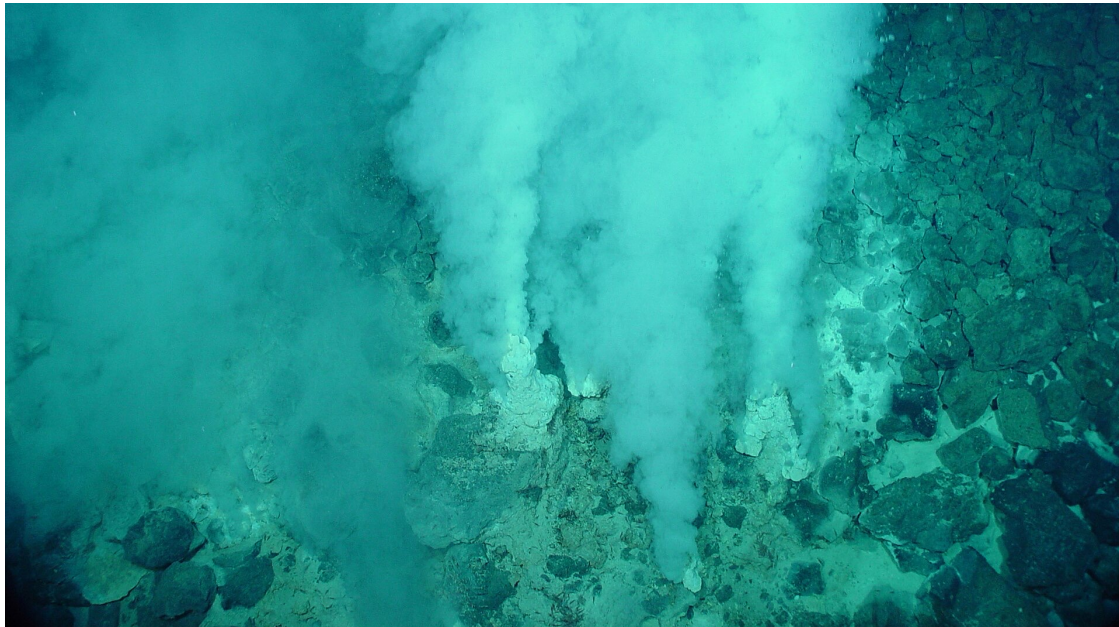


image credit: [https://en.wikipedia.org/wiki/Cell_\(biology\)](https://en.wikipedia.org/wiki/Cell_(biology))

Last Universal Common Ancestor (LUCA)

- Reconstruction of ancient genes
 - ▶ 30 genes common to all life
 - ▶ 355-11000 genes if allowing for some loss
- Anaerobic thermophile with DNA and simple cell wall?
Weiss et al. (2016) Nature Microbiology. 1 (9): 16116



White smokers at Champagne Vent, Eifuku, Japan

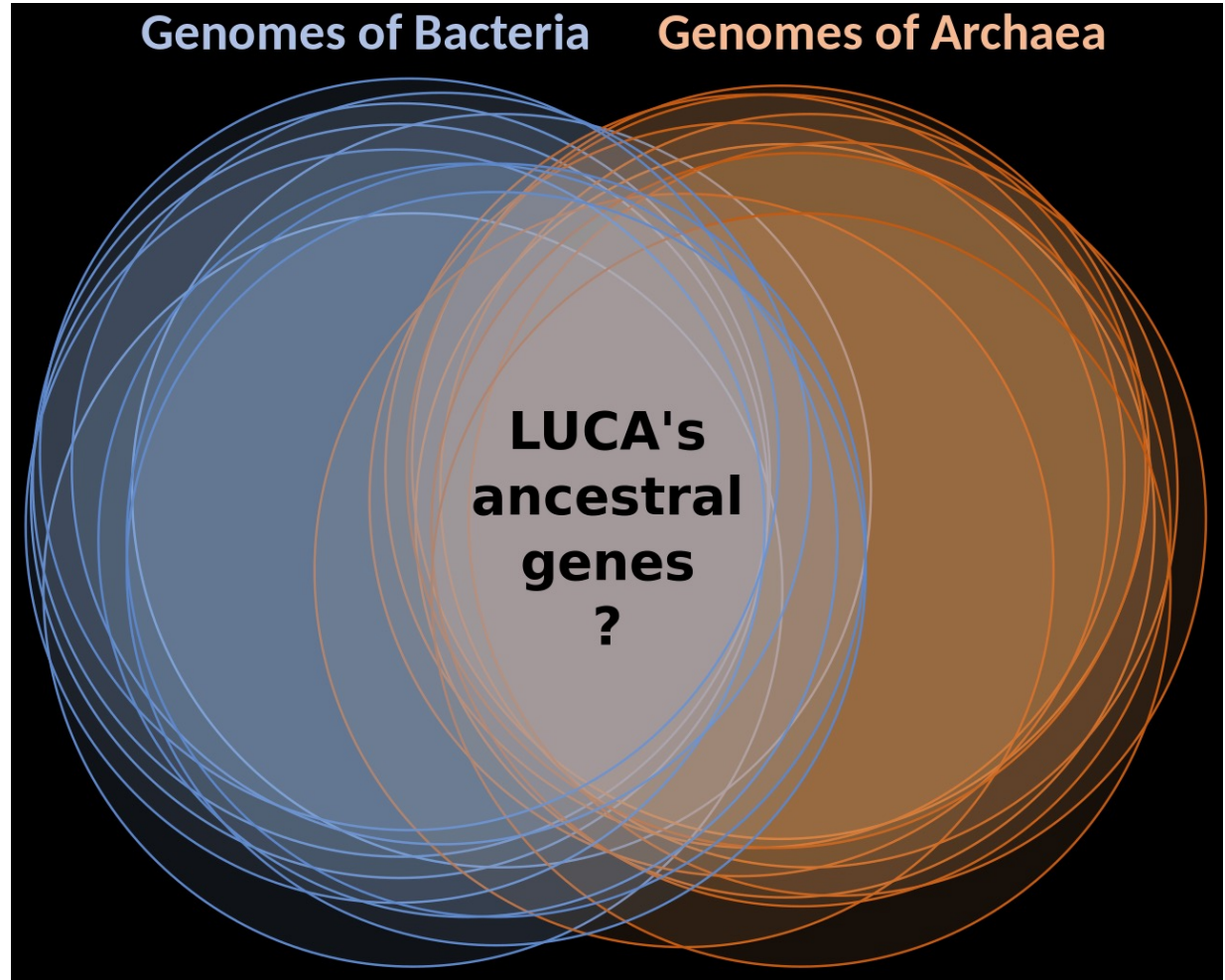


image credit: <https://commons.wikimedia.org/w/index.php?curid=119941737>

LUCA dating

- Recent studies suggested increasingly ancient time for the LUCA from **3.5 to 3.8 Ga ago**

- Molecular clock model: 4.50 ± 0.02 Ga ago**

Betts et al. (2018) Nature Ecology & Evolution **2**: 1556–1562

- ▶ Rate of molecular evolution roughly constant
- ▶ "Clock ticks": Neutral changes to DNA

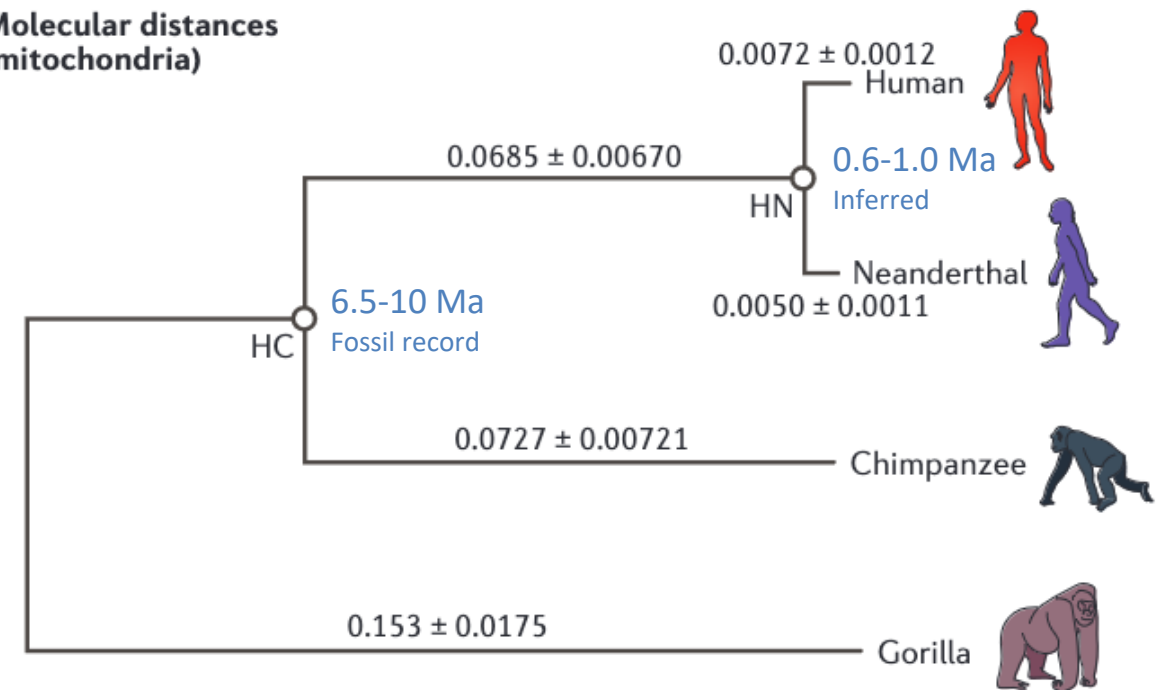
- Puzzling! Reminder:**

- ▶ Moon-forming impact **4.4 Ga ago**
- ▶ Potentially sterilizing impacts until **3.8 Ga ago**

- Life before the LUCA?

dos Reis, Donoghue, Yang (2016) Nature Reviews **17**: 71-80

Molecular distances
(mitochondria)



Abiogenesis

Life: **self-sustaining chemical system capable of Darwinian evolution**

<https://astrobiology.nasa.gov/research/life-detection/about>



Habitable
world

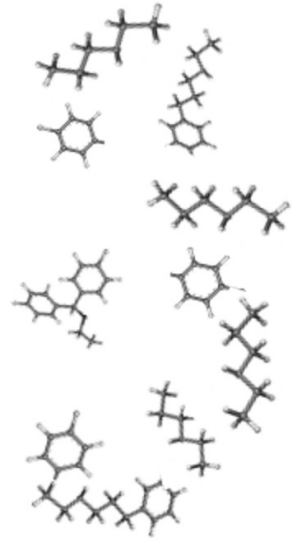


image credit: <https://en.wikipedia.org/wiki/Abiogenesis>

Abiogenesis

Life: **self-sustaining chemical system capable of Darwinian evolution**

<https://astrobiology.nasa.gov/research/life-detection/about>



Habitable
world



Prebiotic
synthesis



image credit: <https://en.wikipedia.org/wiki/Abiogenesis>

Abiogenesis

Life: **self-sustaining chemical system capable of Darwinian evolution**

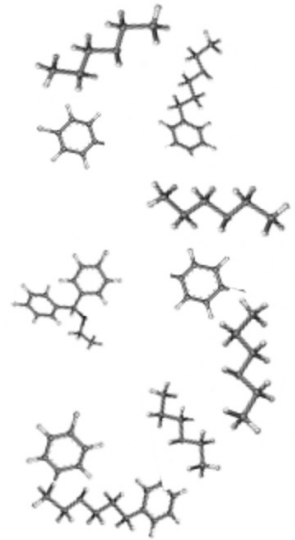
<https://astrobiology.nasa.gov/research/life-detection/about>



Habitable
world



Prebiotic
synthesis



Polymers,
vesicles

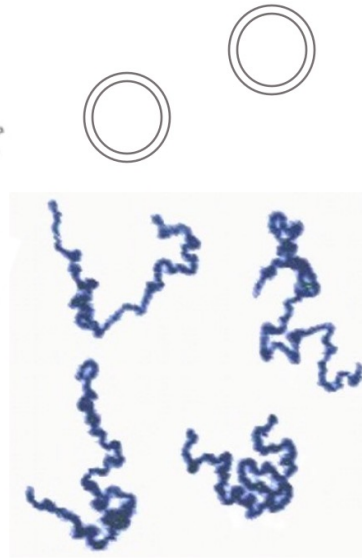
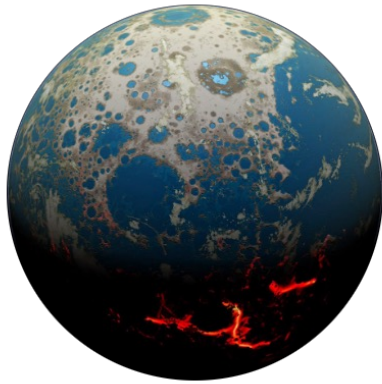


image credit: <https://en.wikipedia.org/wiki/Abiogenesis>

Abiogenesis

Life: **self-sustaining chemical system capable of Darwinian evolution**

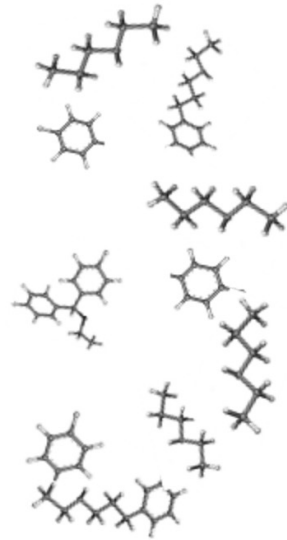
<https://astrobiology.nasa.gov/research/life-detection/about>



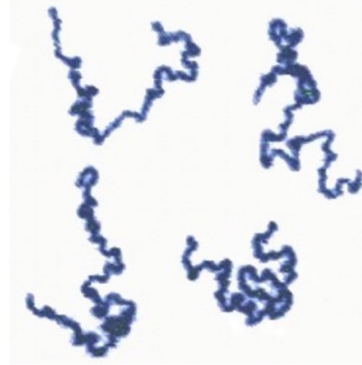
Habitable
world



Prebiotic
synthesis



Polymers,
vesicles



... Protocells? .

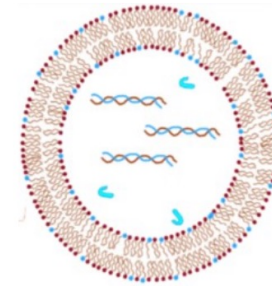


image credit: <https://en.wikipedia.org/wiki/Abiogenesis>

Abiogenesis

Life: self-sustaining chemical system capable of Darwinian evolution

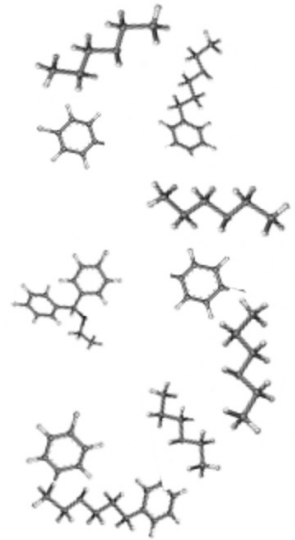
<https://astrobiology.nasa.gov/research/life-detection/about>



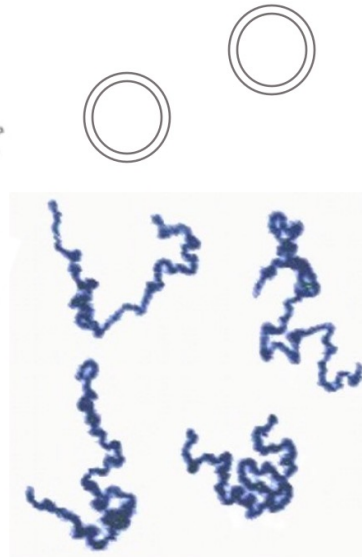
Habitable world



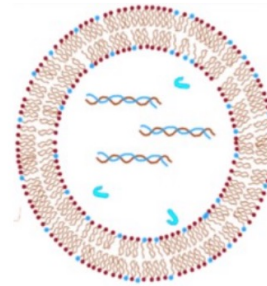
Prebiotic synthesis



Polymers, vesicles



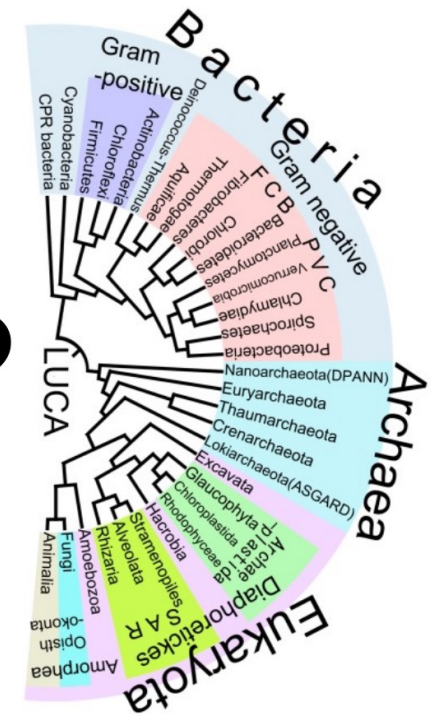
... Protocells? ...



???



LUCA



Diversity of life

image credit: <https://en.wikipedia.org/wiki/Abiogenesis>

Miller-Urey experiment

Miller (1952) *Biochimica et Biophysica Acta*. **23**: 480–489

- Simulation of prebiotic atmosphere
- **Simple** amino acids form spontaneously (building blocks of proteins)

Glycine

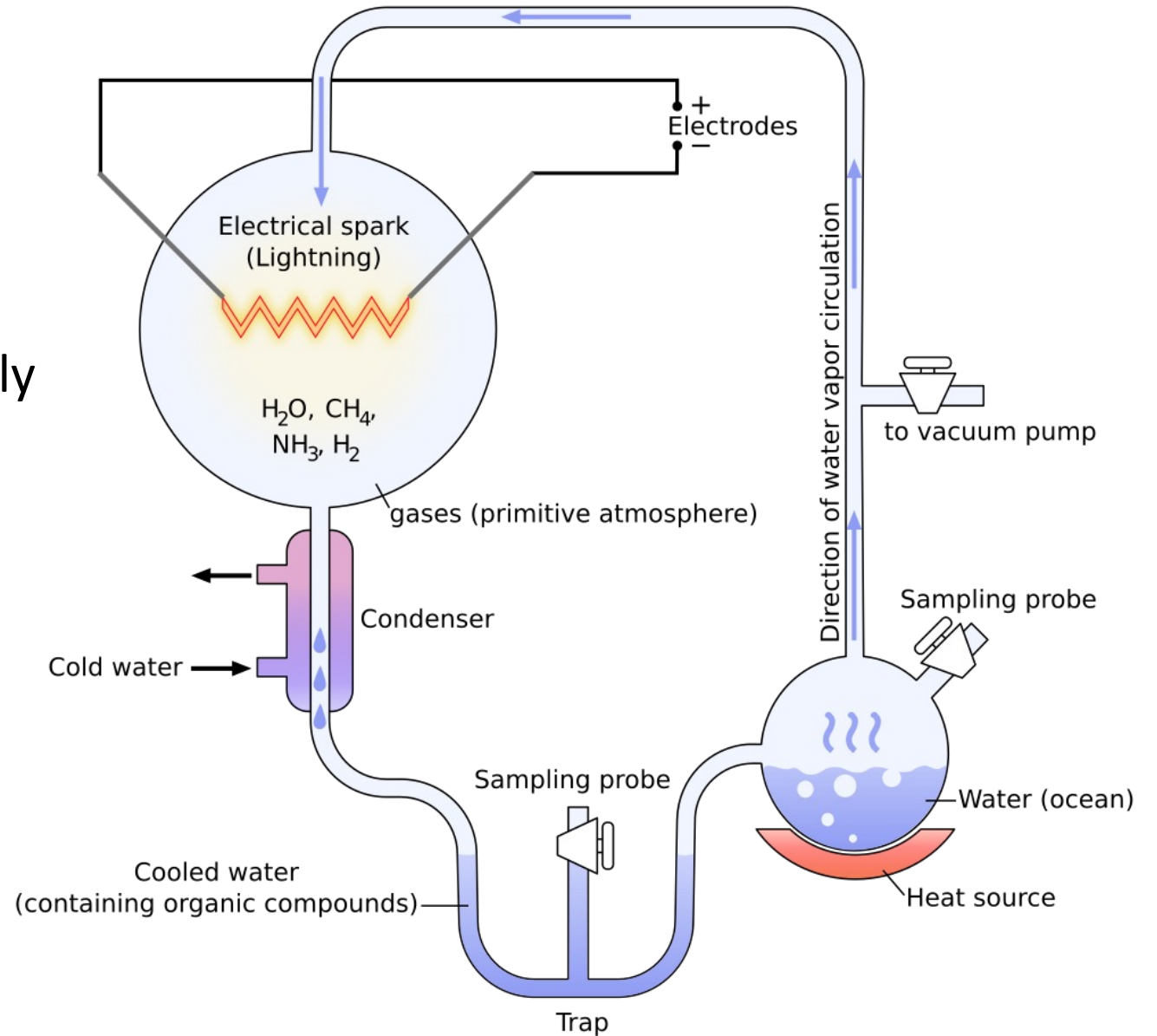
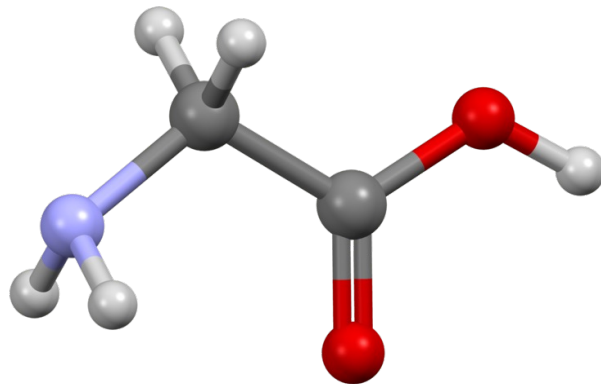
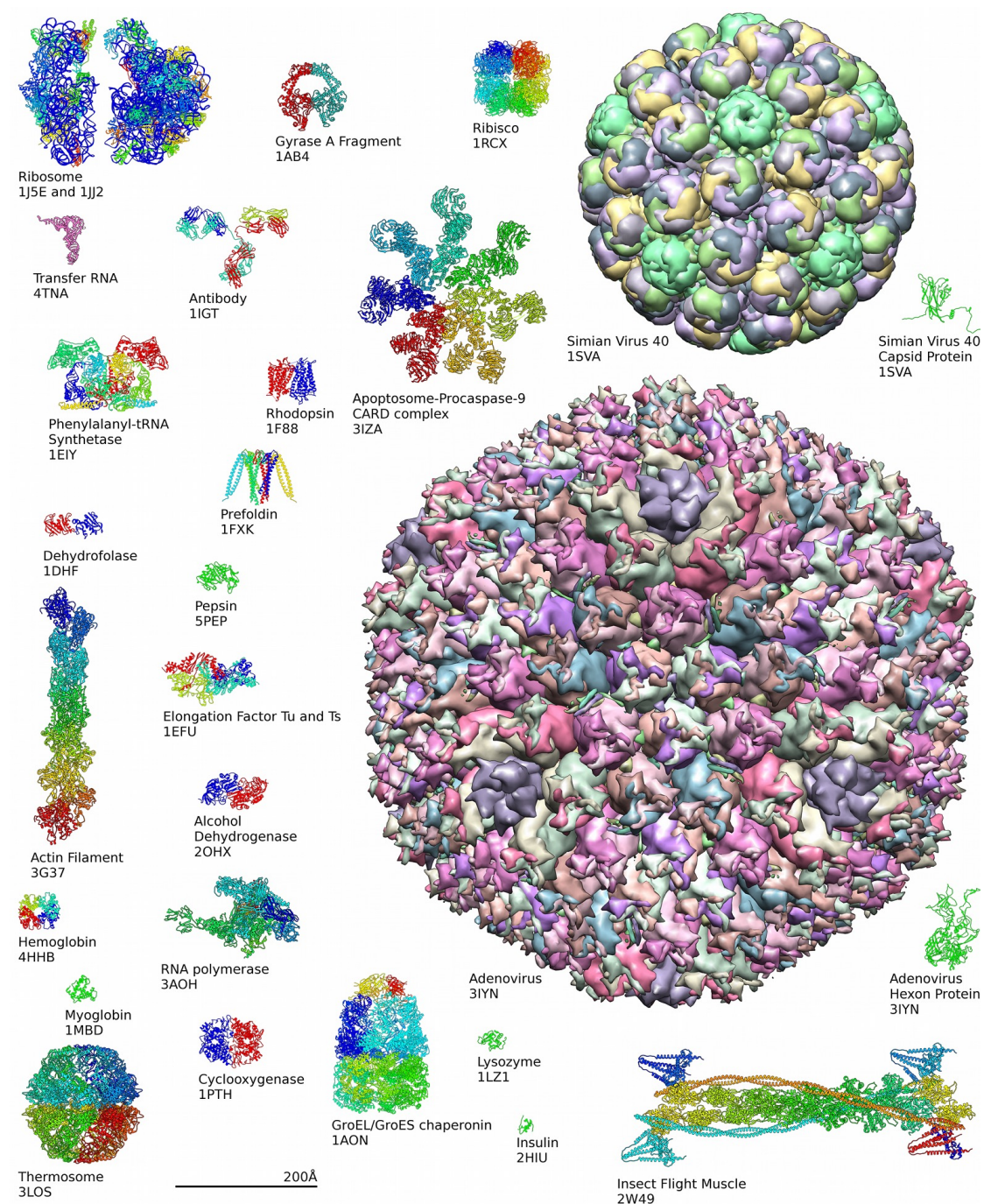


image credit: <https://commons.wikimedia.org/w/index.php?curid=3500500>, <https://commons.wikimedia.org/w/index.php?curid=98162935>

Biomolecules

- Biomolecules tend to be **large, complex & highly specialized**
- Must be evolved
- Example: Ribosome
 - ▶ Synthesizes proteins from RNA code
 - ▶ 20-30 nm diameter
 - ▶ 10k-100k atoms

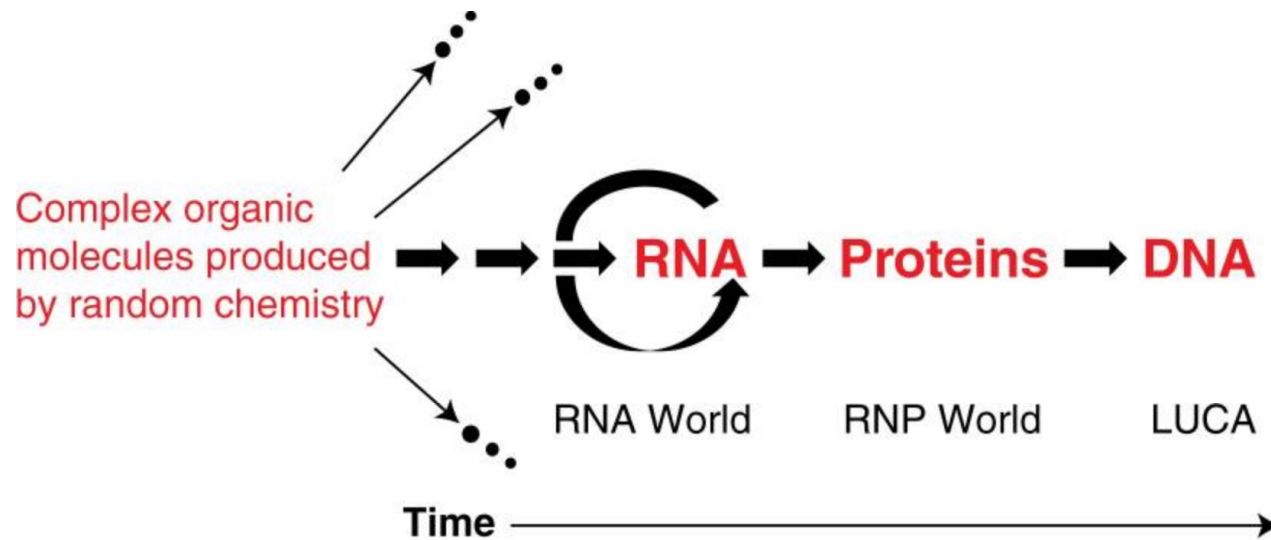


Examples of protein structures from the Protein Data Bank
Protein Data Bank, Nucleic Acids Res. 47 (D1): 520–528

RNA world

Cech, Cold Spring Harb (2012) Perspect Biol. 4(7): a006742

Robertson & Joyce, Cold Spring (2012) Harb Perspect Biol. 4(5): a003608



- RNA can self-replicate & catalyze biochemistry
 - DNA replaced RNA as information carrier
 - Proteins replaced RNA as catalyst
- Possible "living" molecular fossil: Ribosome

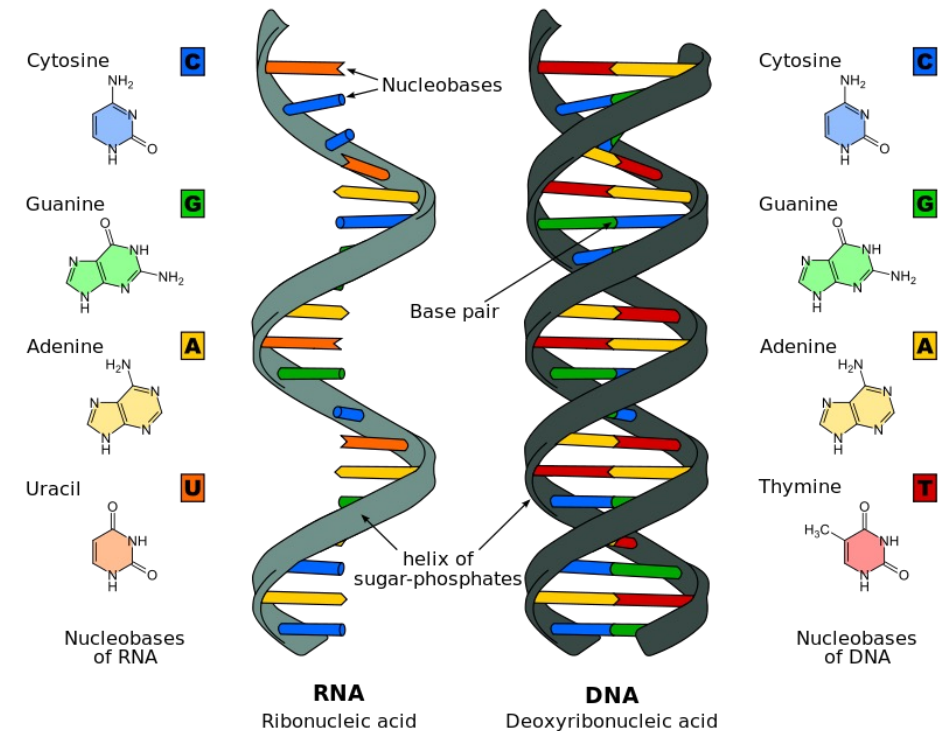
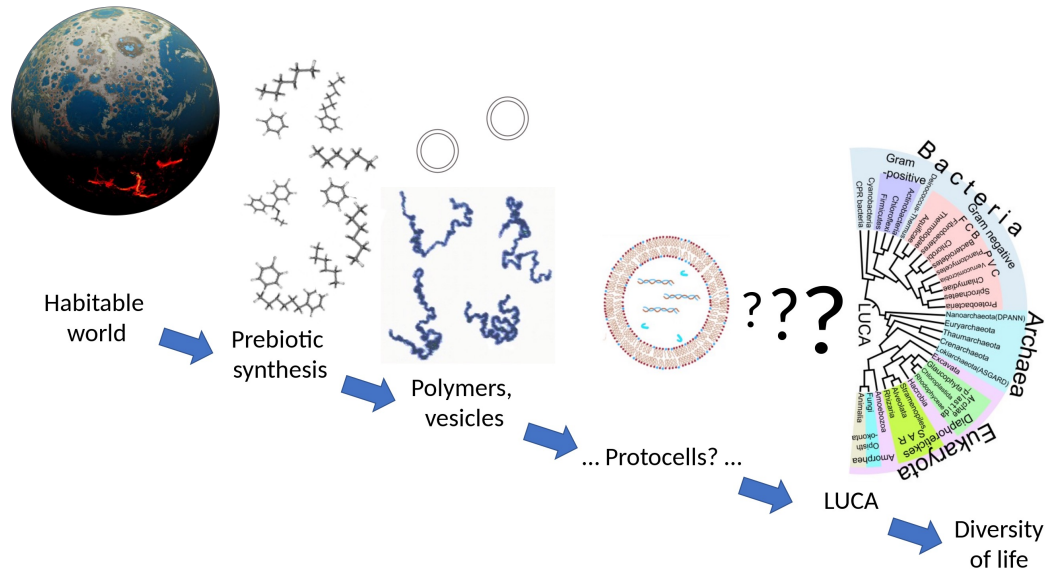


image credit: https://en.wikipedia.org/wiki/RNA_world

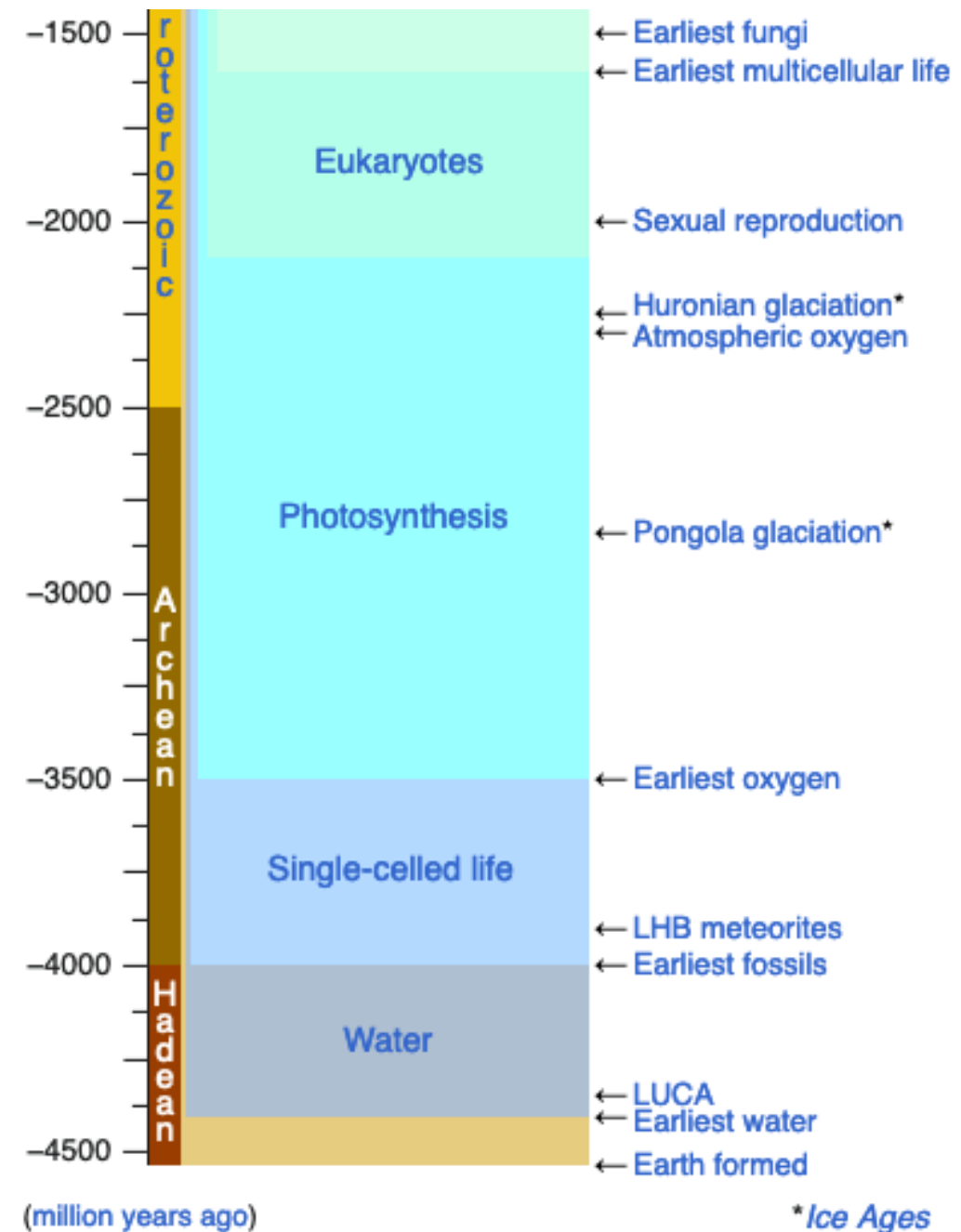
De Novo hypothesis

- Life developed on Earth via abiogenesis



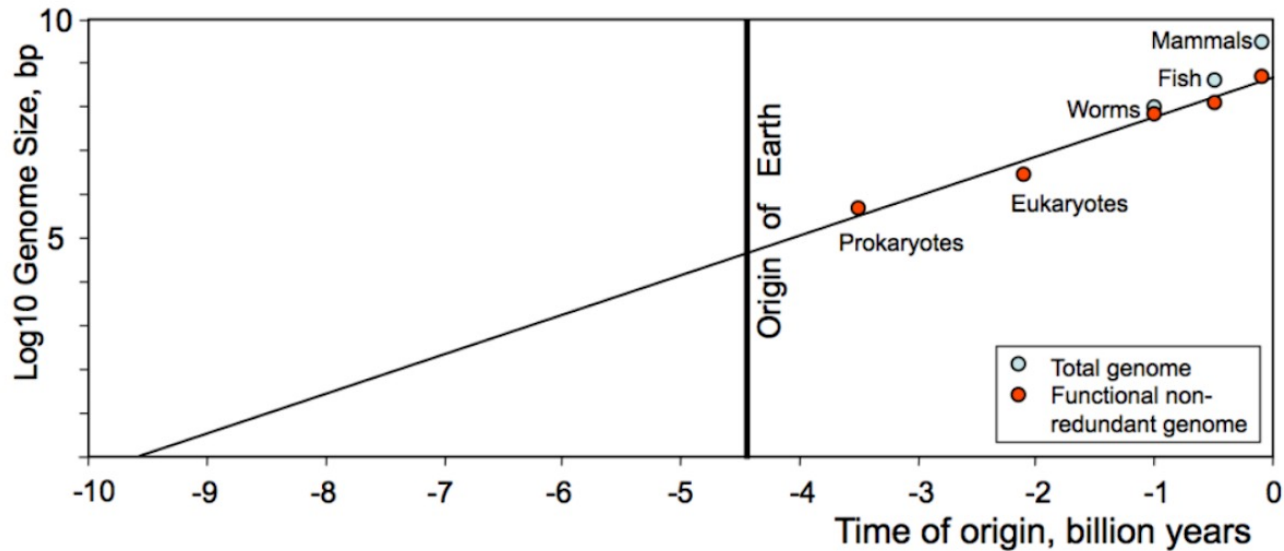
- Origin puzzle**

- ▶ Hadean eon was hostile to life, still cells evolved *almost immediately*
- ▶ **No time for evolution in RNA world**
- ▶ To put this into perspective:
 $\Delta T \approx 2 \text{ Ga}$ from prokaryotes to eukaryotes

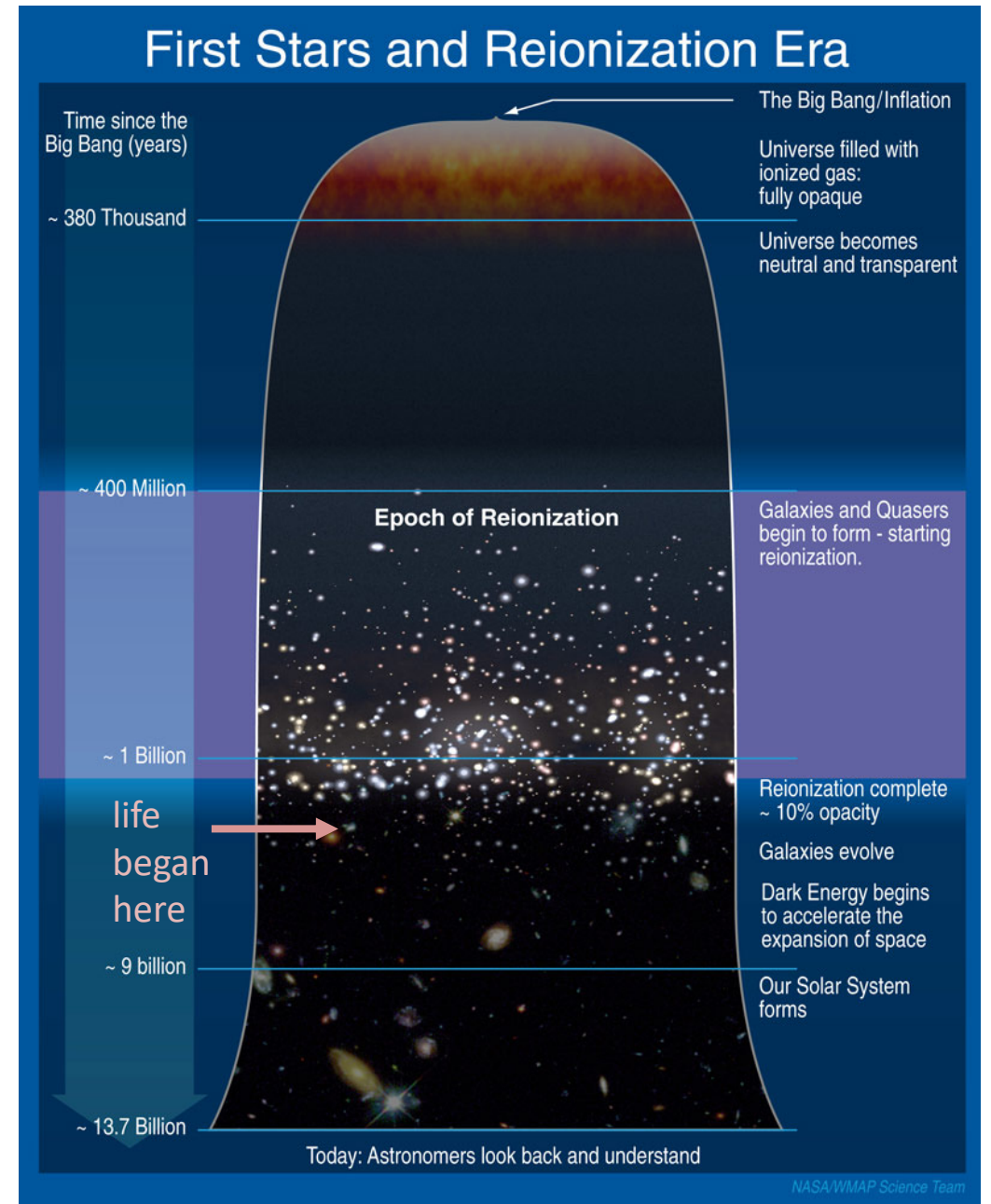


Genome size argument

Sharov & Gordon, <https://arxiv.org/abs/1304.3381>



- Back-extrapolation of genome size puts origin of life to **3-4 Ga** after Big Bang
- Captivating idea, but is it conceivable?



Requirements for life

- Life's elements

- ▶ H, C, N, O
- ▶ Traces of P, Cu, B, Si, Fe ...

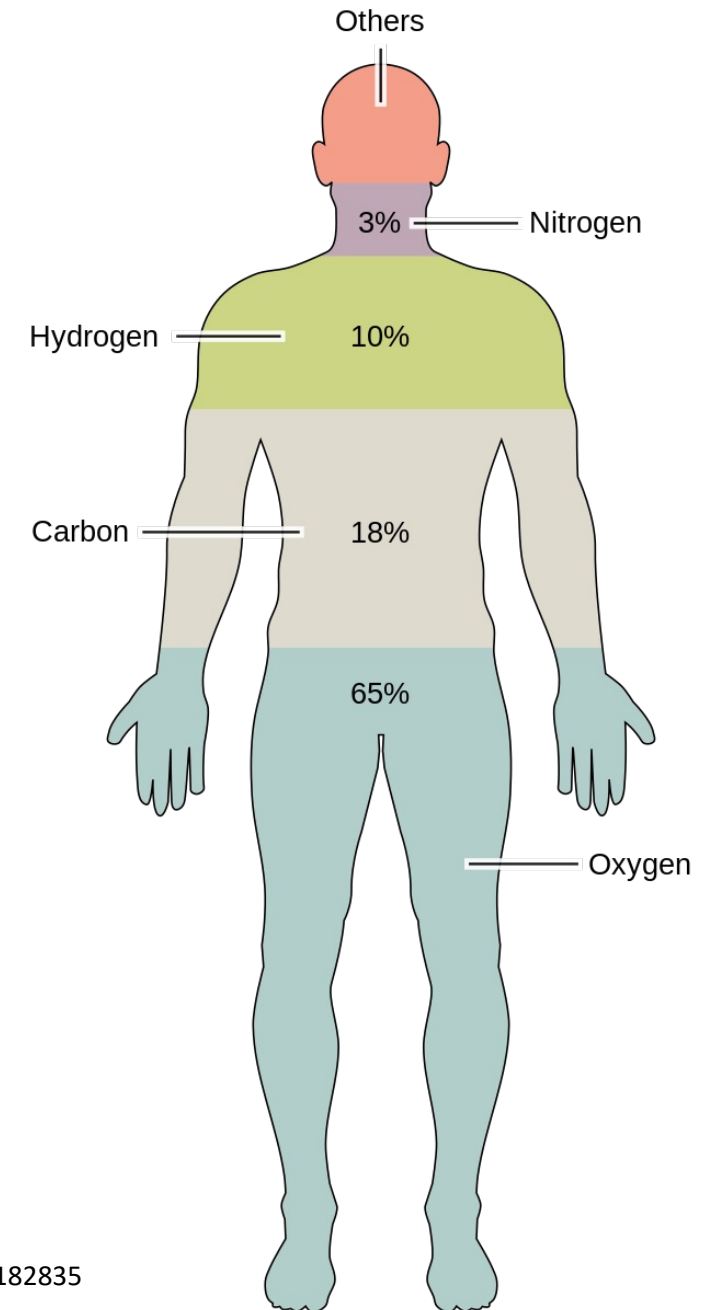


image credit: <https://commons.wikimedia.org/w/index.php?curid=46182835>

Requirements for life

- Life's elements
 - H, C, N, O
 - Traces of P, Cu, B, Si, Fe ...
- Liquid water $T = 0-100\text{ }^{\circ}\text{C}$

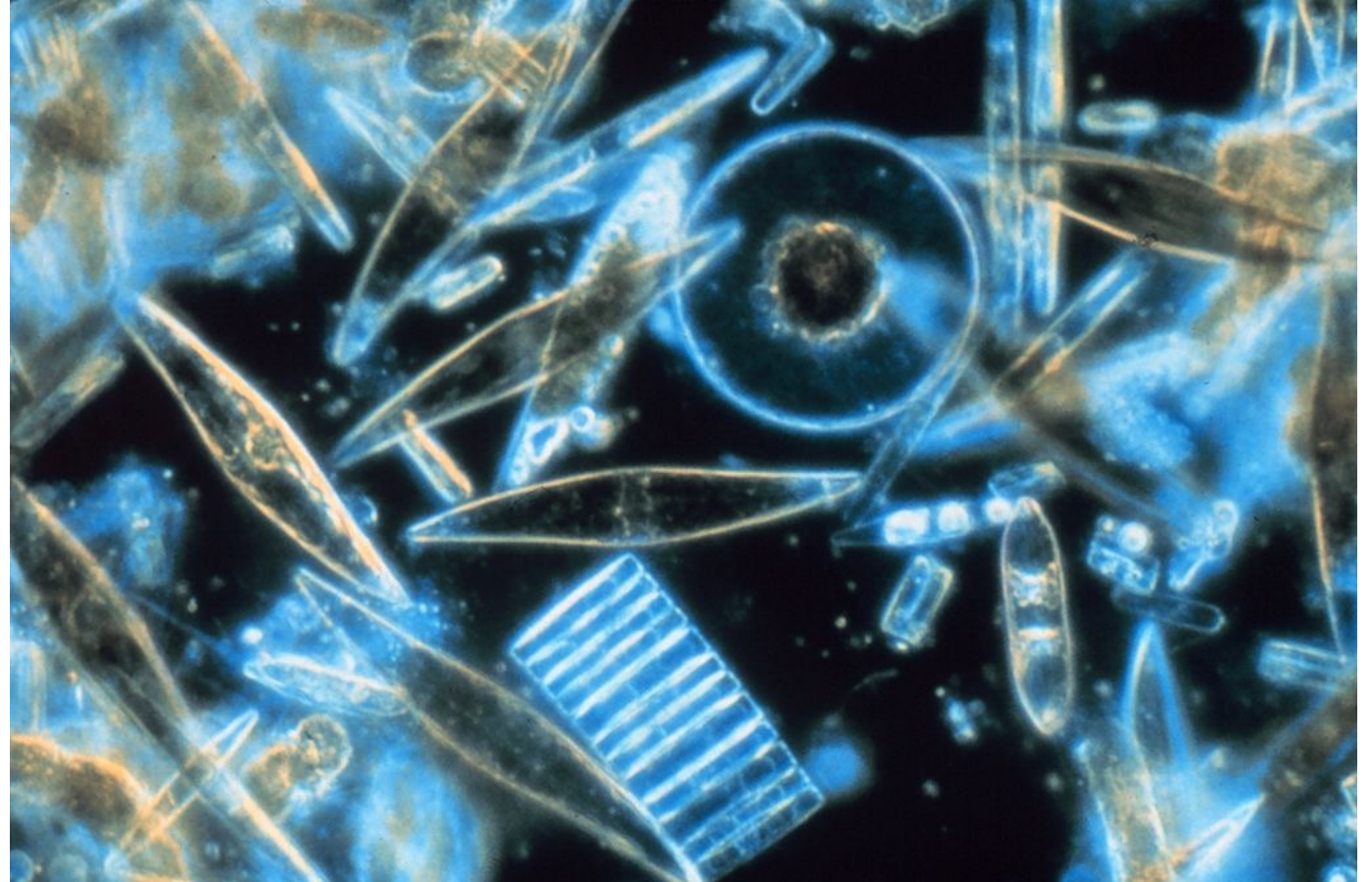


image credit: <https://commons.wikimedia.org/w/index.php?curid=246319>

Requirements for life

- Life's elements
 - H, C, N, O
 - Traces of P, Cu, B, Si, Fe ...
- Liquid water $T = 0-100\text{ }^{\circ}\text{C}$
- Thermodynamic free energy



image credit: <https://commons.wikimedia.org/w/index.php?curid=36691633>

Requirements for life

- Life's elements
 - H, C, N, O
 - Traces of P, Cu, B, Si, Fe ...
- Liquid water $T = 0-100\text{ }^{\circ}\text{C}$
- Thermodynamic free energy
- Protection from lethal radiation: UV light, cosmic rays

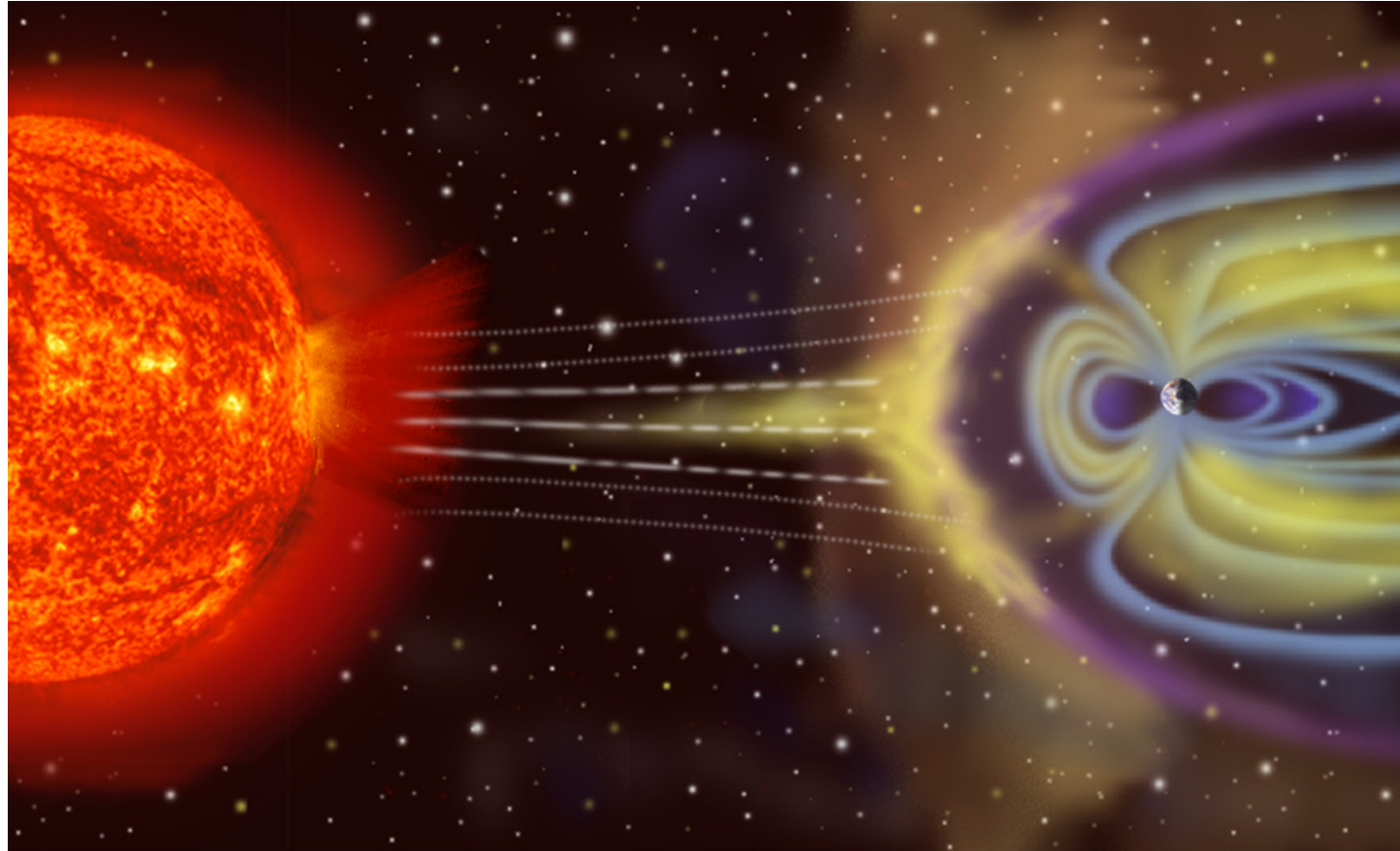
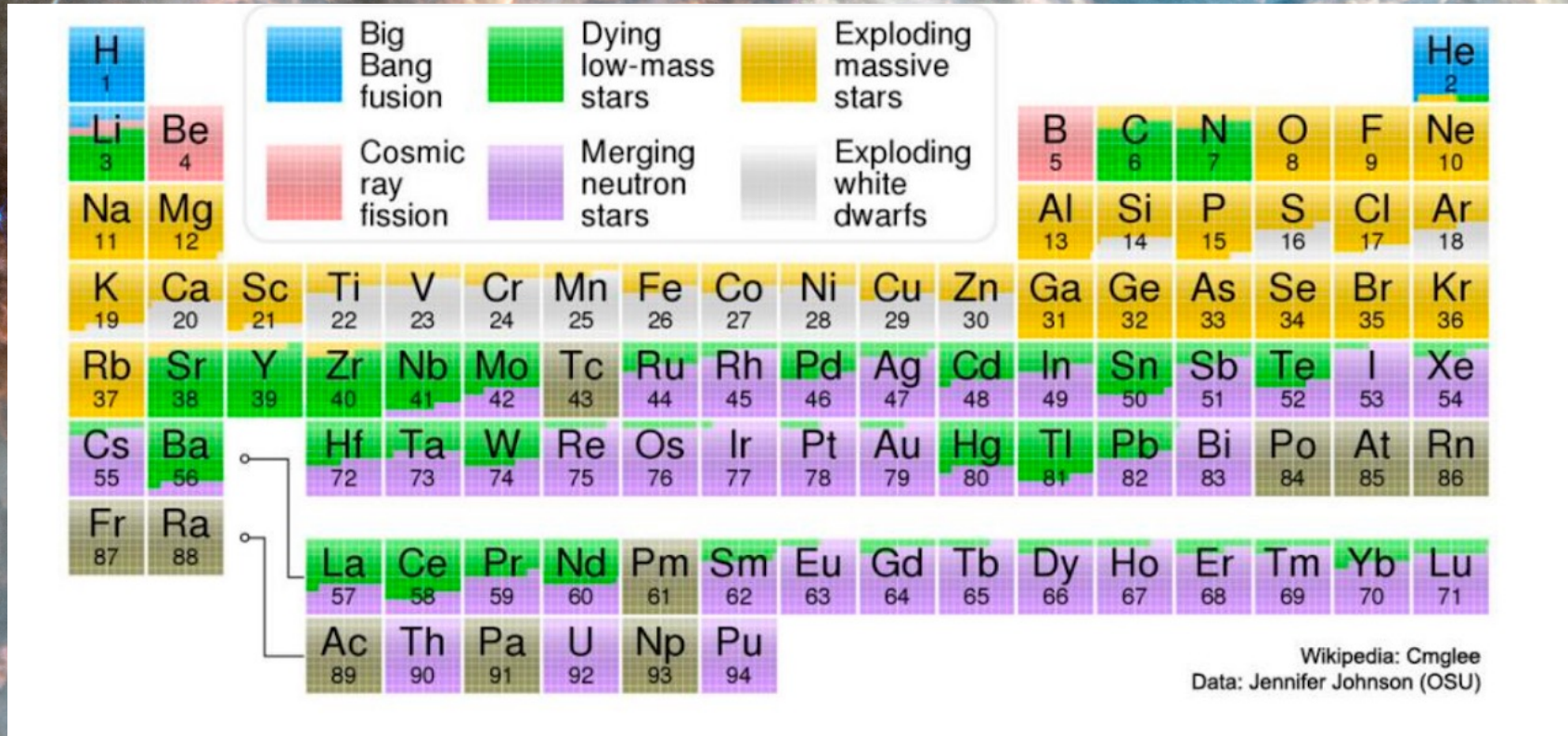


image credit: https://www.esa.int/ESA_Multimedia/Images/2007/10/The_Sun-Earth_connection

Earliest life?

Crab nebula
SN 1054

Deaths of first stars generated life's elements



First stars

- Population III, never directly observed
- Formed $> 0.2-0.3$ Ga
- Probably very massive with short life-times 2-5 Ma



HD 140283 "Methuselah star", population II, born < 2 Ga, 190 ly away

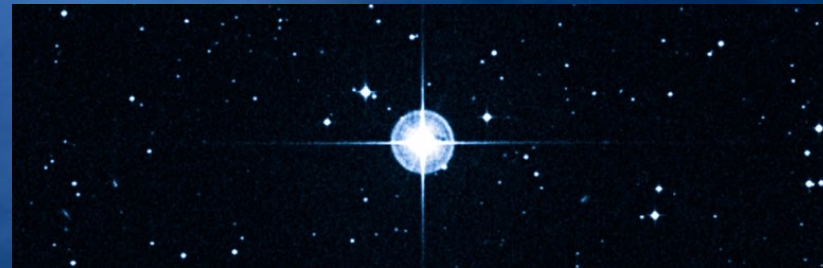


image credit: <https://commons.wikimedia.org/w/index.php?curid=25275489>

OK: life could have developed
3-4 Ga after Big Bang

Life in Solar System before Earth?

No

- Solar system formed **4.6 Ga** ago by collapse of **molecular cloud**
- Planets and asteroids also formed at this time

Life in molecular cloud?

Wilson & Johnston (1994) Lecture Notes in Physics 439
Springer Berlin Heidelberg

- 10-30 atoms per cm^3
- $T = \mathbf{O(10) K}$
- Gas
 - Mostly H_2 , CO
 - Water (ice), **simple organic molecules** (e.g. methanol)
- Dust
 - Shielding from UV light
 - Chemical catalyst
- Clouds dissolve & change rapidly $\Delta T \approx \mathbf{10 Ma}$



Cloud which broke off from
Carina nebula

No

Interesting chemistry 😊

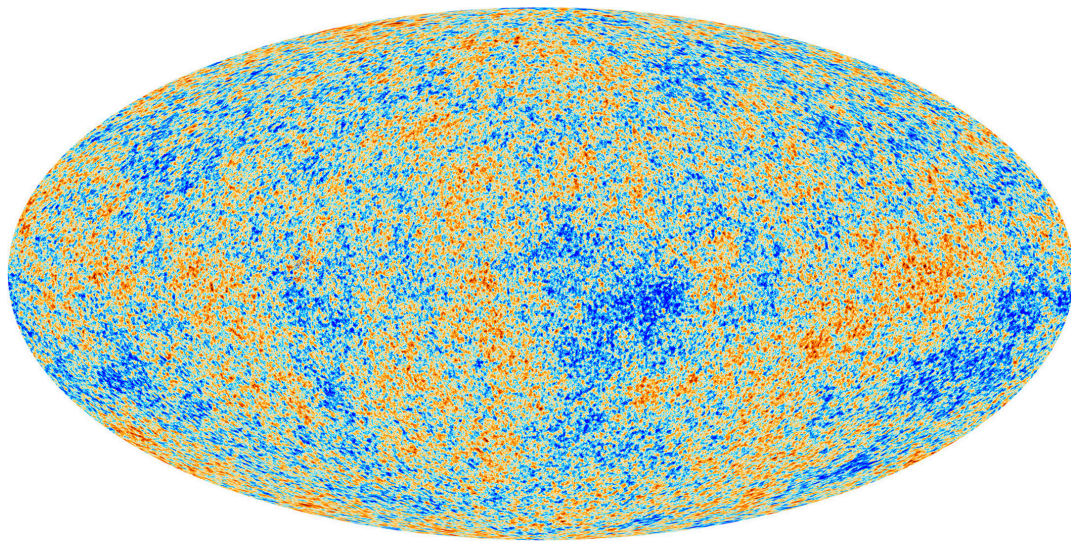
Protection from UV light 😊

No liquid water 😞

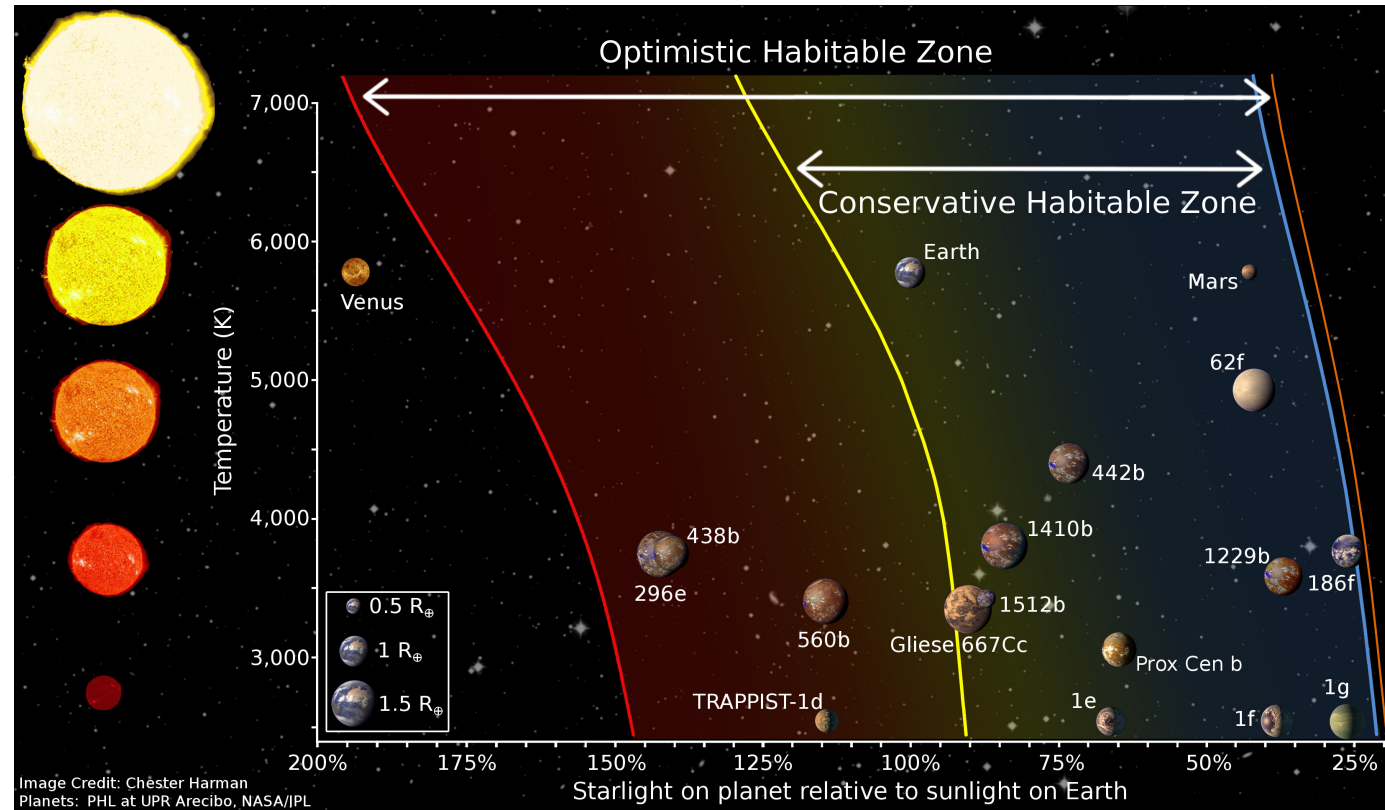
Too unstable 😞

Life on exoplanets?

- Rocky planets
 - ▶ Potential for liquid water
 - 24 out of 5600 exoplanets in habitable zone
<https://exoplanetarchive.ipac.caltech.edu/>
 - ▶ Protection from lethal radiation
- No known exoplanets with life
 - ▶ But potential for detection



https://www.esa.int/Science_Exploration/Space_Science/Planck/Planck_and_the_cosmic_microwave_background

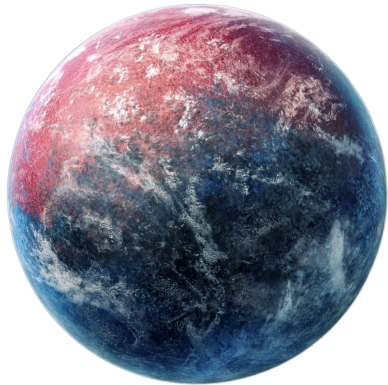


- Fun fact: Universe was "habitable" everywhere at **10-17 Ma** after Big Bang (but no stars or planets then)

Panspermia hypothesis

<https://en.wikipedia.org/wiki/Panspermia>

Abiogenesis on habitable exoplanet



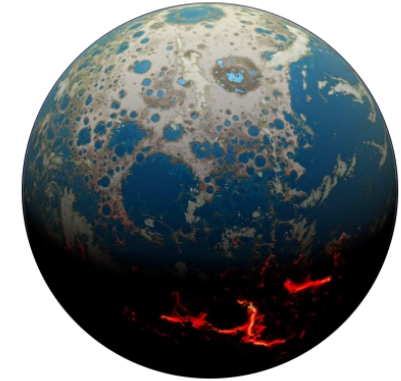
planetary
ejection



travel in interstellar space for > 0.1 Ma

atmospheric
entry

Hadean Earth, 4.5 Ga ago



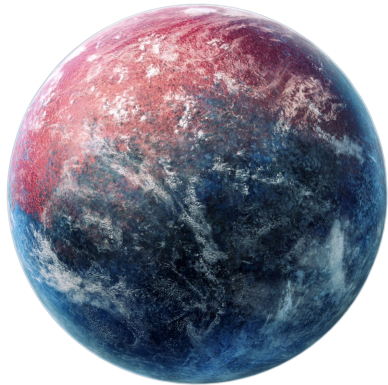
- Radiopanspermia

- ▶ Microscopic lifeforms (< 1.5 μm) accelerated by radiation pressure
- ▶ Fast interstellar travel & soft atmospheric entry 😊
- ▶ Exposure to vacuum & lethal radiation 😞

Panspermia hypothesis

<https://en.wikipedia.org/wiki/Panspermia>

Abiogenesis on habitable exoplanet



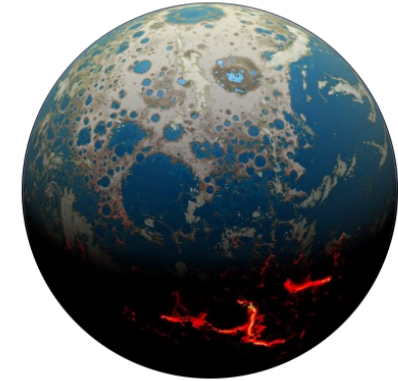
planetary
ejection



travel in **interstellar space** for > 0.1 Ma

atmospheric
entry

Hadean Earth, 4.5 Ga ago



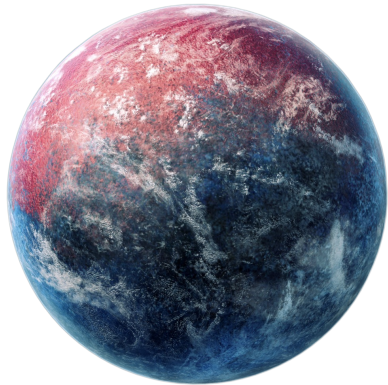
- **Lithopanspermia**

- ▶ Transport of hibernating or even living organisms in **asteroids & comets** conceivable
 - Size > 1 m protects interior from cosmic radiation
 - Liquid water from radioactive decay
- ▶ Some microorganisms survived simulated planetary ejection and atmospheric entry
Horneck et al (2008) *Astrobiology* 8(1): 17-44; Fajardo-Cavazos et al, *Astrobiology* 5(6): 726-736

Panspermia hypothesis

<https://en.wikipedia.org/wiki/Panspermia>

Abiogenesis on habitable exoplanet



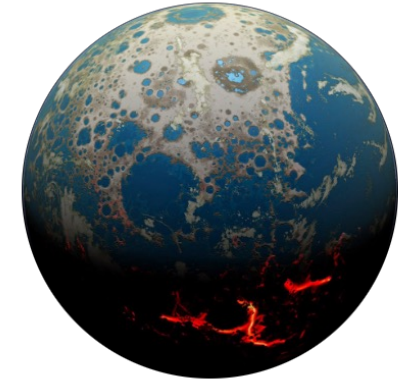
planetary ejection



travel in interstellar space for > 0.1 Ma

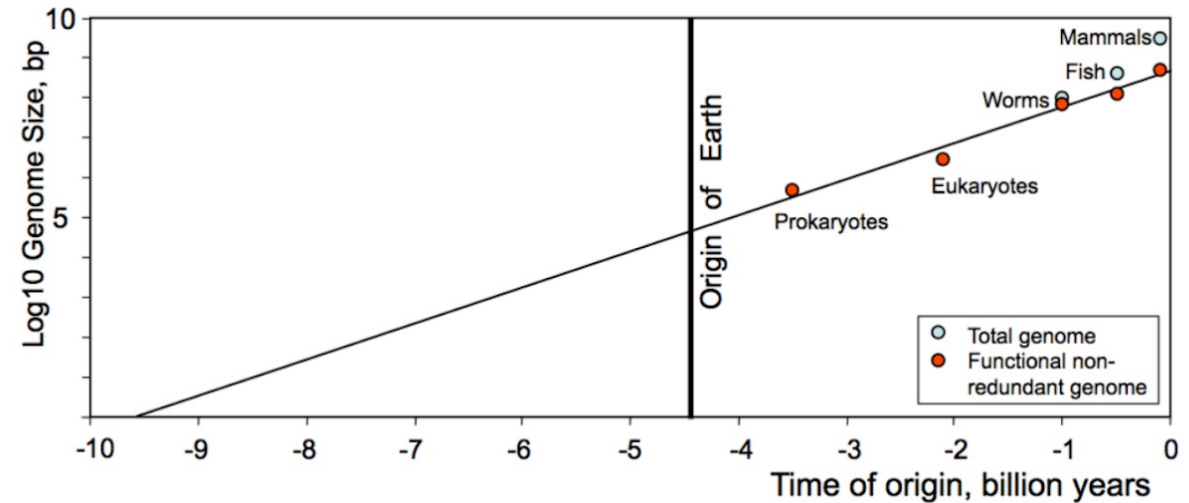
atmospheric entry

Hadean Earth, 4.5 Ga ago



- Directed panspermia

- ▶ Previously evolved intelligent life seeds planets
- ▶ No complex life expected 5 Ga ago



Space-faring microbes?

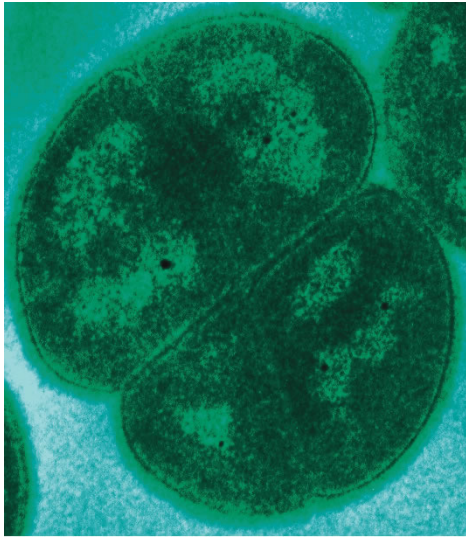


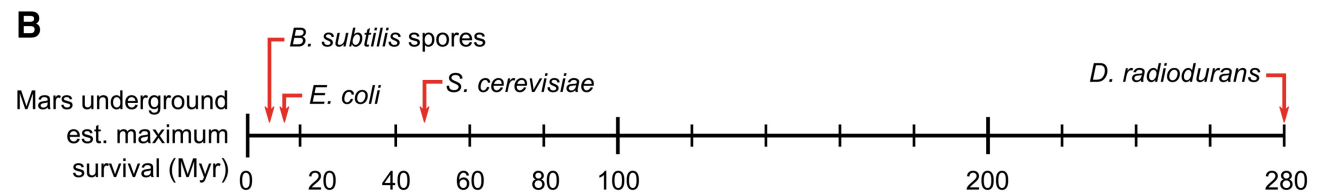
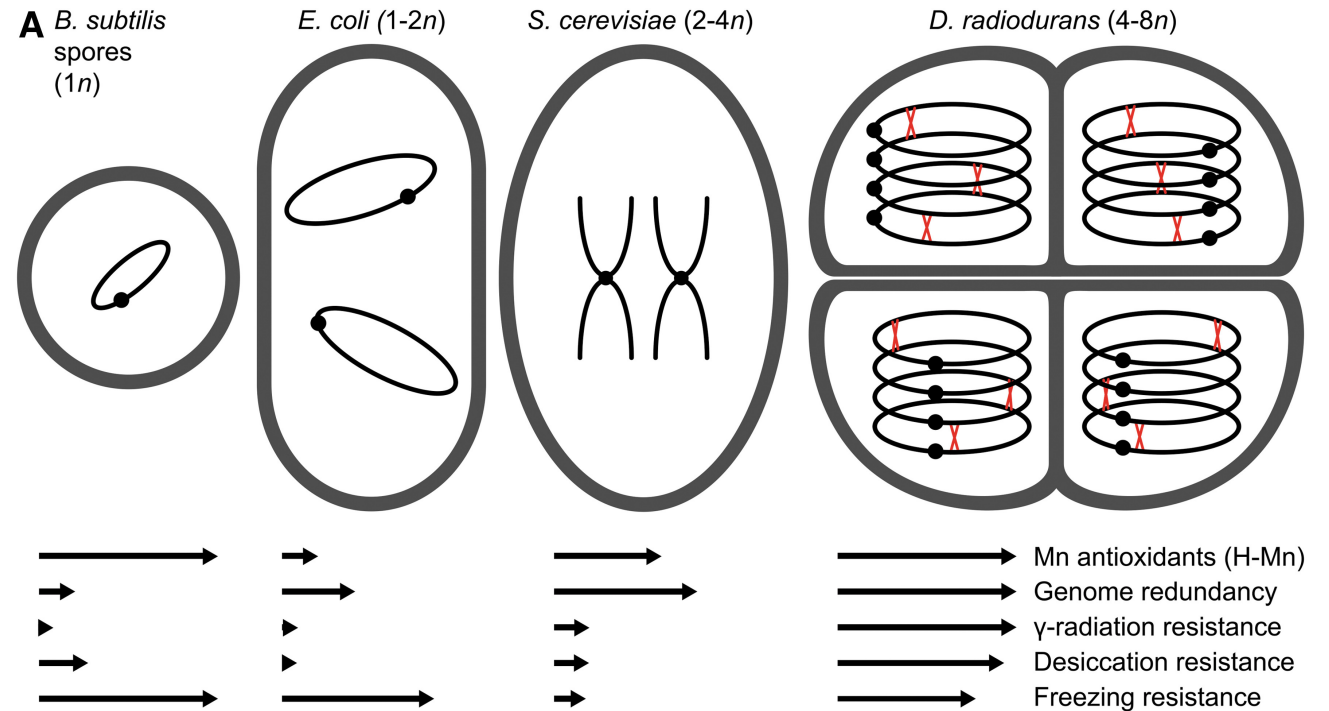
image credit: <https://commons.wikimedia.org/w/index.php?curid=157172>

Deinococcus radiodurans

- Survived outer space for **3 years**
- Survived up to **140 kGy** of radiation
 - 5 Gy lethal to humans
- If sufficiently shielded, may survive dehydrated & frozen for **280 Ma**

Kawaguchi et al (2020) Front Microbiol. **11**: 2050
 Nature Microbiology **7** (4): 465-466
 Horne et al (2022) Astrobiology **22**(11): 1337-1350

Horneck et al (2008) Astrobiology **8**(1): 17-44



Conclusions



- Microbial life should be common in the universe, it either...
 - ▶ Develops rapidly via abiogenesis on barely habitable worlds OR
 - ▶ Developed long ago and already spread everywhere through space

Conclusions



- If genome size argument is correct...
 - ▶ We are among the **first intelligent lifeforms** in the universe
 - ▶ Potential solution to the Fermi Paradox: **Where is everybody?**

Conclusions



- Panspermia hypothesis is testable
 - Search for Earth-like microbes on Mars or Titan

A microscopic image showing a variety of biological structures, likely spores or cells, stained in shades of blue and yellow. The structures are diverse in shape, including elongated, pointed forms, circular structures with dark centers, and rectangular structures with internal striations. The background is dark, making the stained structures stand out.

Thank you for listening!

Backup

Theia impact

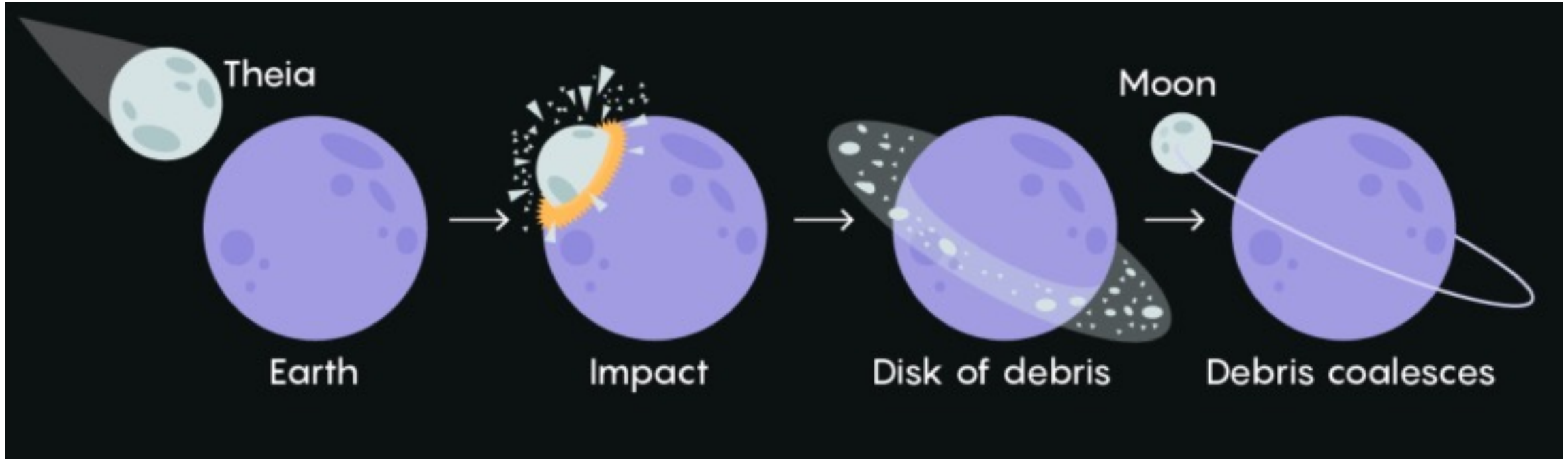
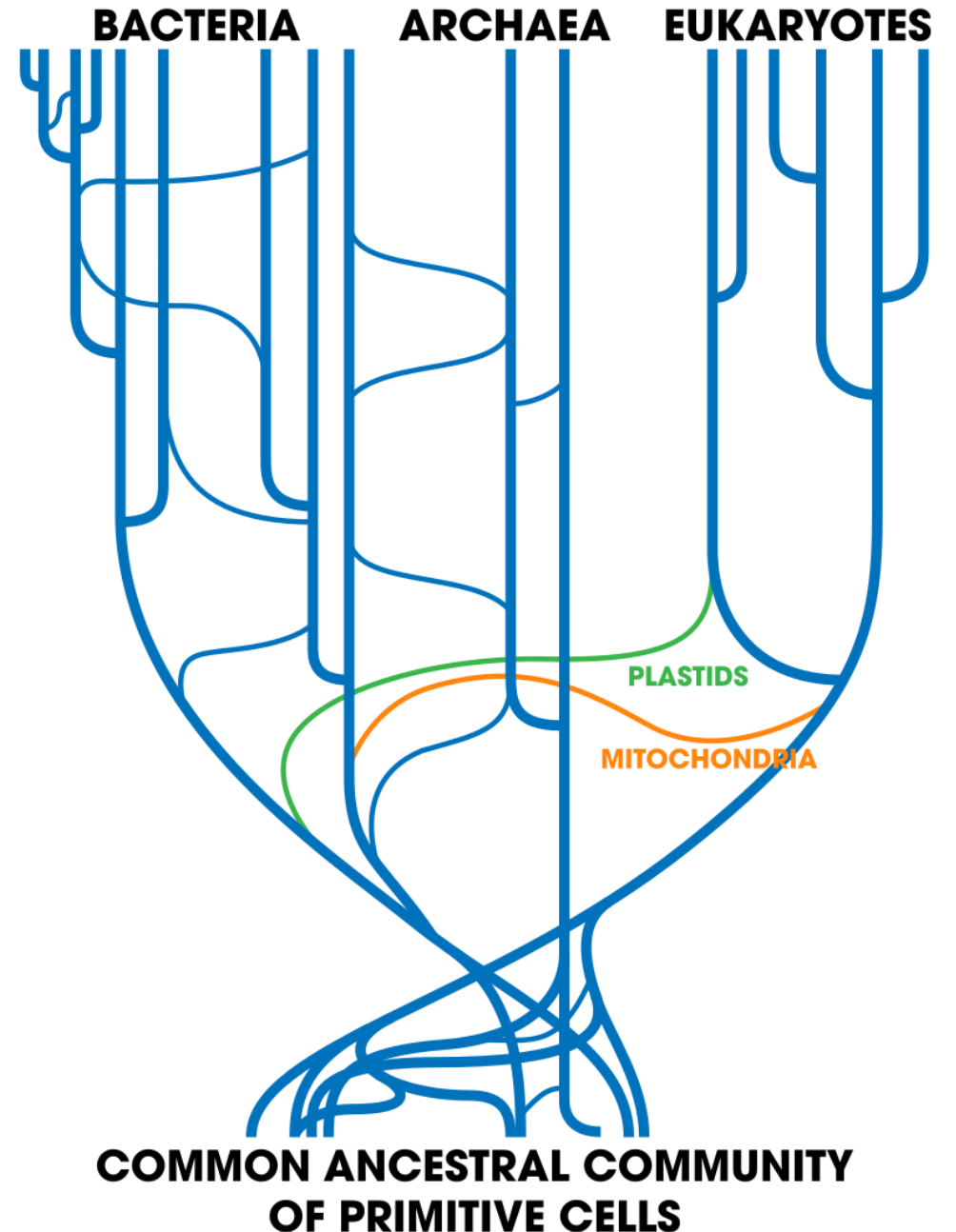


image credit: <https://commons.wikimedia.org/w/index.php?curid=72720188>

- https://en.wikipedia.org/wiki/File:ARC-20221004-AAV3443-MoonOrigin-Social-NASAWeb-1080p_medium.oggtheora.ogg

Web-like root

- Tree of evolution
 - Vertical gene transfer: Inheritance
 - Horizontal gene transfer
 - Today: antibiotics resistance in bacteria
 - Common among early life-forms
- LUCA may have been community of pre-cells with frequent gene exchange



Smets, Barkay, Tamar (2005) Nature Reviews Microbiology **3** (9) 675–678

Late heavy bombardment hypothesis Gomes et al (2005) Nature. **435** (7041): 466–469

3.8 – 4.1 Ga ago

Jupiter

Saturn

Neptune

Uranus

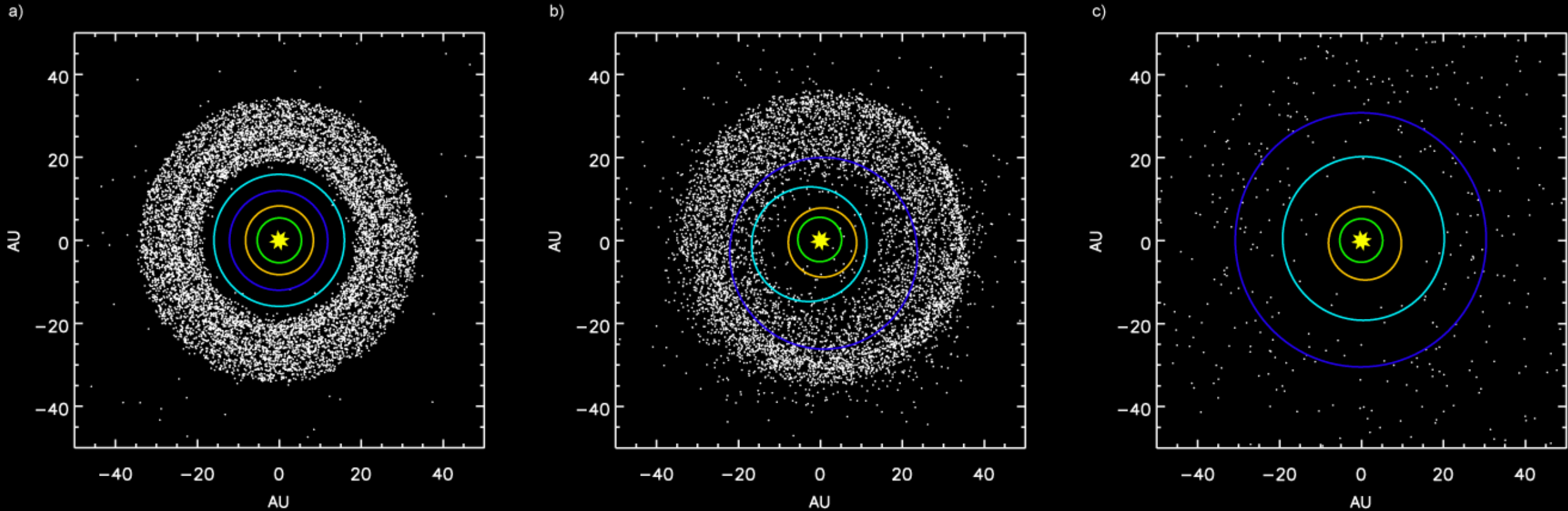


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