Astrobiology
An Overview

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IMPRS Graduate School 🙂

November 20-24, 2023

Daily: 10:00-14:00 (proposed: 10-12 & 13-14)

Astrobiology
An Overview

Day 1

Definition of Life; Origin of Life; Evolution of Life; Limits of Life

https://www.cosmos.esa.int/web/astrobio/imprs2023

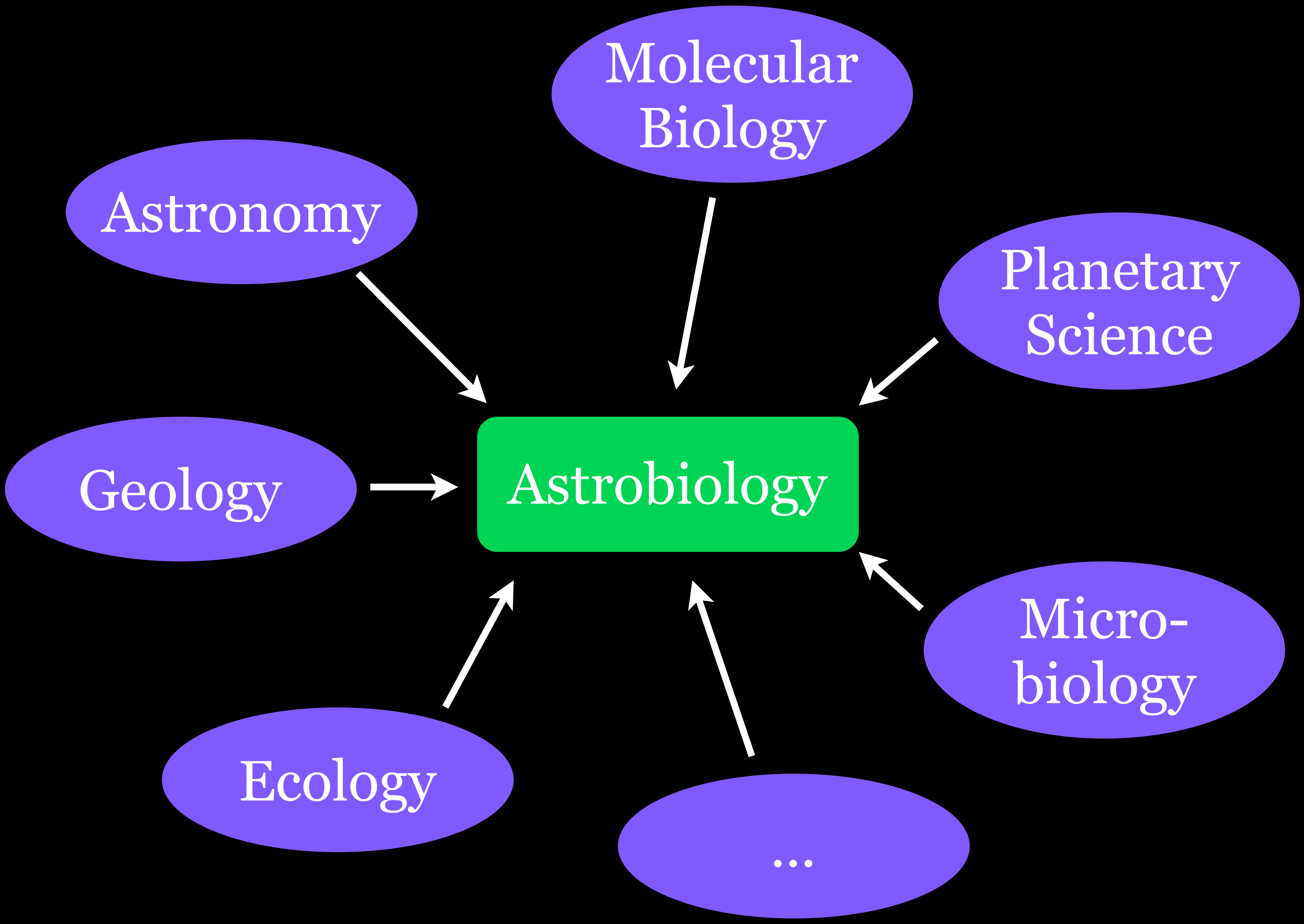
What is Life?

How did Life begin?

How has it changed?

Does Life exist elsewhere?

If so, where might it be and what is it like?


Molecular Biology
Astronomy
Planetary Science
Geology
Astrobiology
Micro-biology
Ecology
...

Administration

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

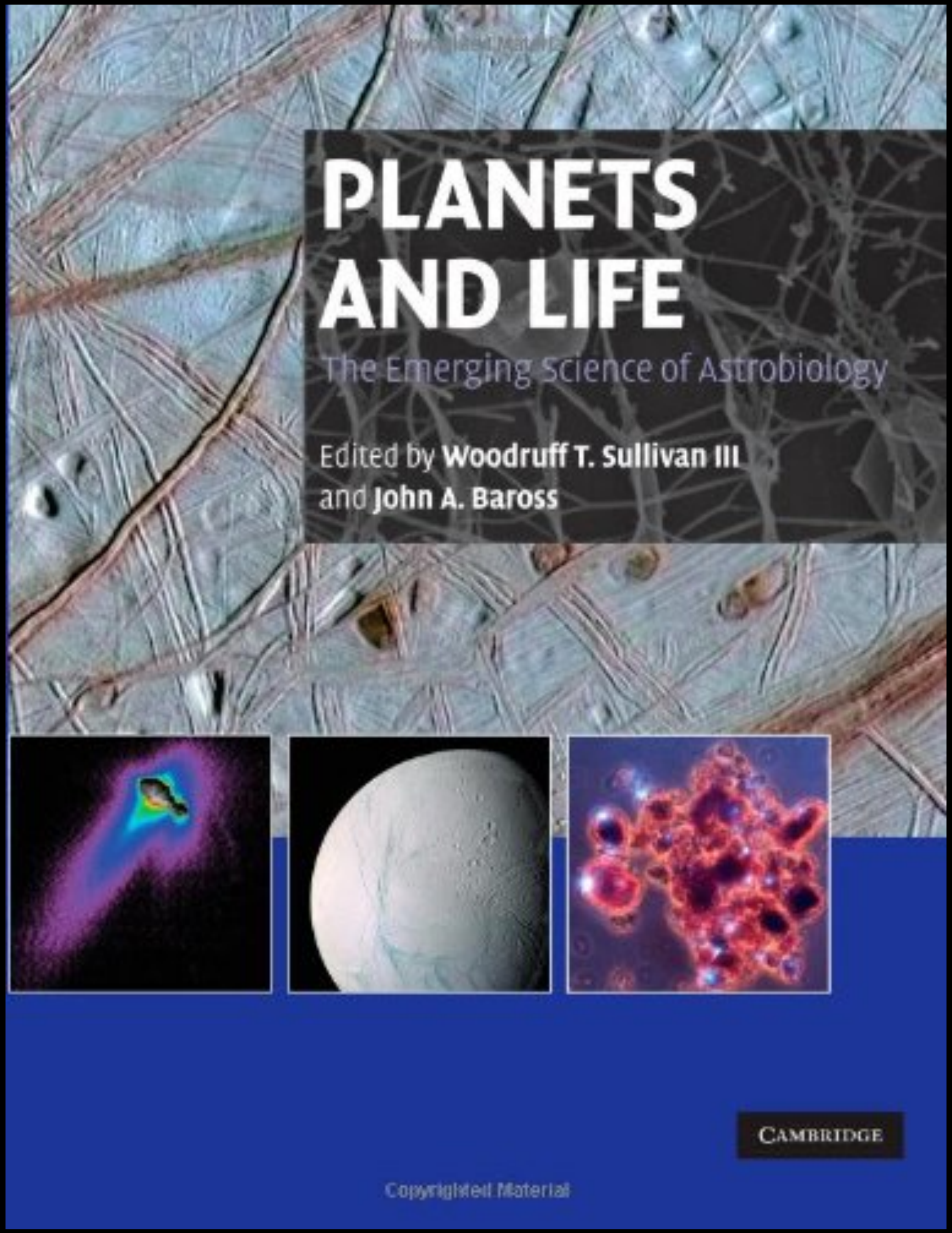
Our Story

What did you recognise?

What made you curious?

Recommended Textbook

"Planets and Life" by Woody Sullivan and John Baross



Other Textbooks

BSc level (easier read)

Astrobiology: Understanding Life in the Universe - C.S. Cockell-Wiley

Further reading (to peak into if you run across them)

An Introduction to Astrobiology - I.Gilmour, M.A. Sephton - Cambridge University Press

Complete Course in Astrobiology - G.Horneck & P.Rettberg - Wiley-VCH

Astrochemistry: From Astronomy to Astrobiology - A.M.Shaw - Wiley

My career so far….

- German, Born in Switzerland, Grown up in France
- Started to become Physics/Math/PE teacher (or Architect)
- Almost sidetracked as Illustrator for advertising company

1993

- Diploma in Physics (incl. CERN summer school)
- PhD in Astrophysics (Bonn & ESO, IAC winter school)
- Postdoc 1: UC Santa Cruz - UCO/Lick Observatory
- Postdoc 2: ESO Fellowship
- Faculty position 1: Instrument Scientist for the VLT (Chair of the FSSC, Chair of the Faculty)

30 years

- Faculty position 2: Project Scientist for the E-ELT
- Faculty position 2.1: Adjunct Professor at the LMU Munich
- Management position 1: Gemini Observatory Director
- Faculty position 2.2: Affiliated Faculty at U.Hawaii
- Management position 2: Deputy Director for Science at ESO

2023

- Management position 3: Head of Science Operations at ESA

Lots of right choices
(many for the wrong reasons…)

Passion was the driver

Mixed:
Research
Teaching
Technical
Management

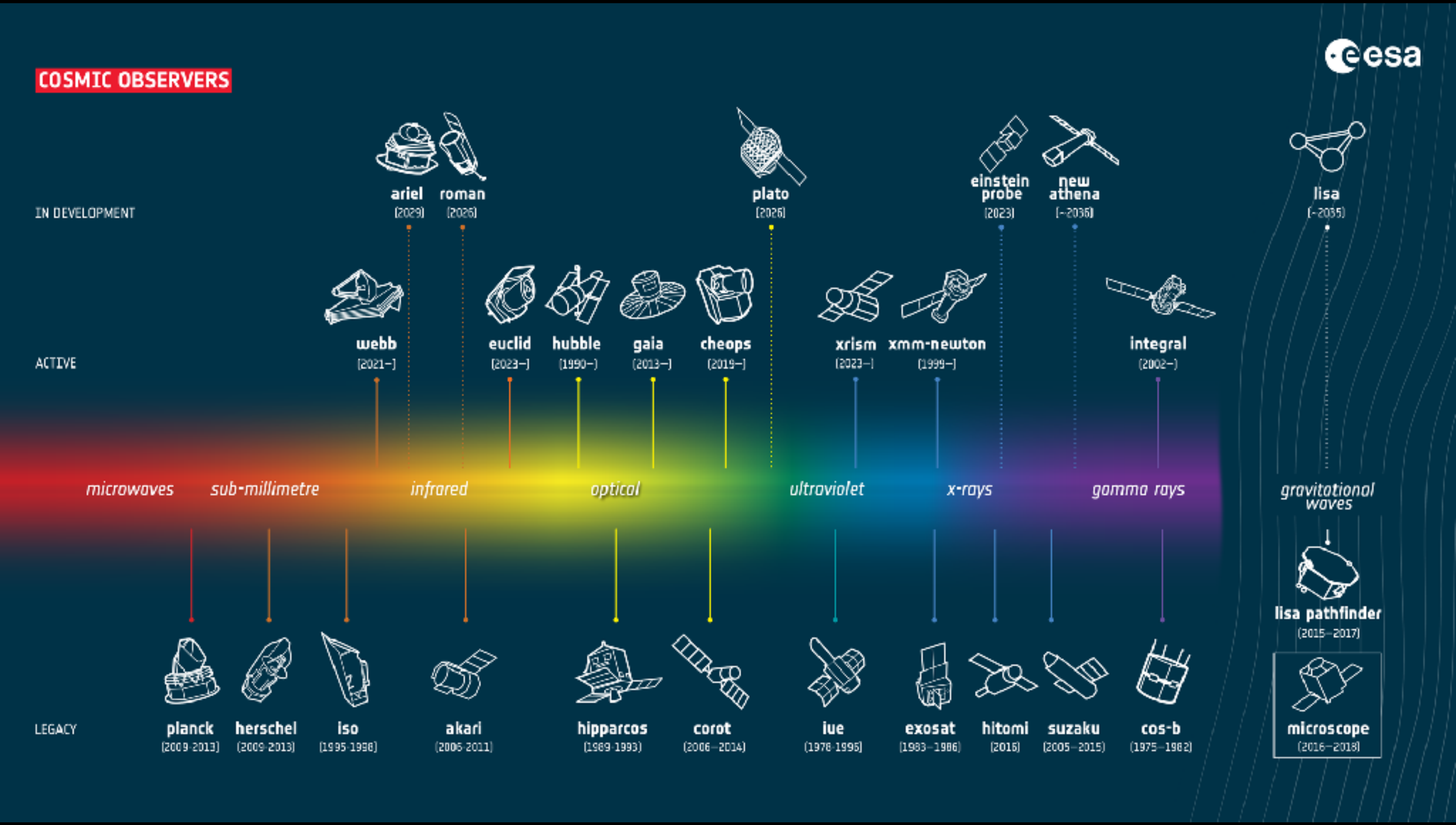
Good science

Good
collaborations

Luck

Excellent
mentors

Career was never the top priority
(family & friends were)



COSMIC OBSERVERS
esa
IN DEVELOPMENT
ariel
(2029)
roman
(2026)
plato
(2026)
einstein probe
(2023)
new athena
(~2036)
lisa
(~2035)
ACTIVE
webb
(2021–)
euclid
(2023–)
hubble
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gaia
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cheops
(2019–)
xrism
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xmm-newton
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optical
ultraviolet
x-rays
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microscope
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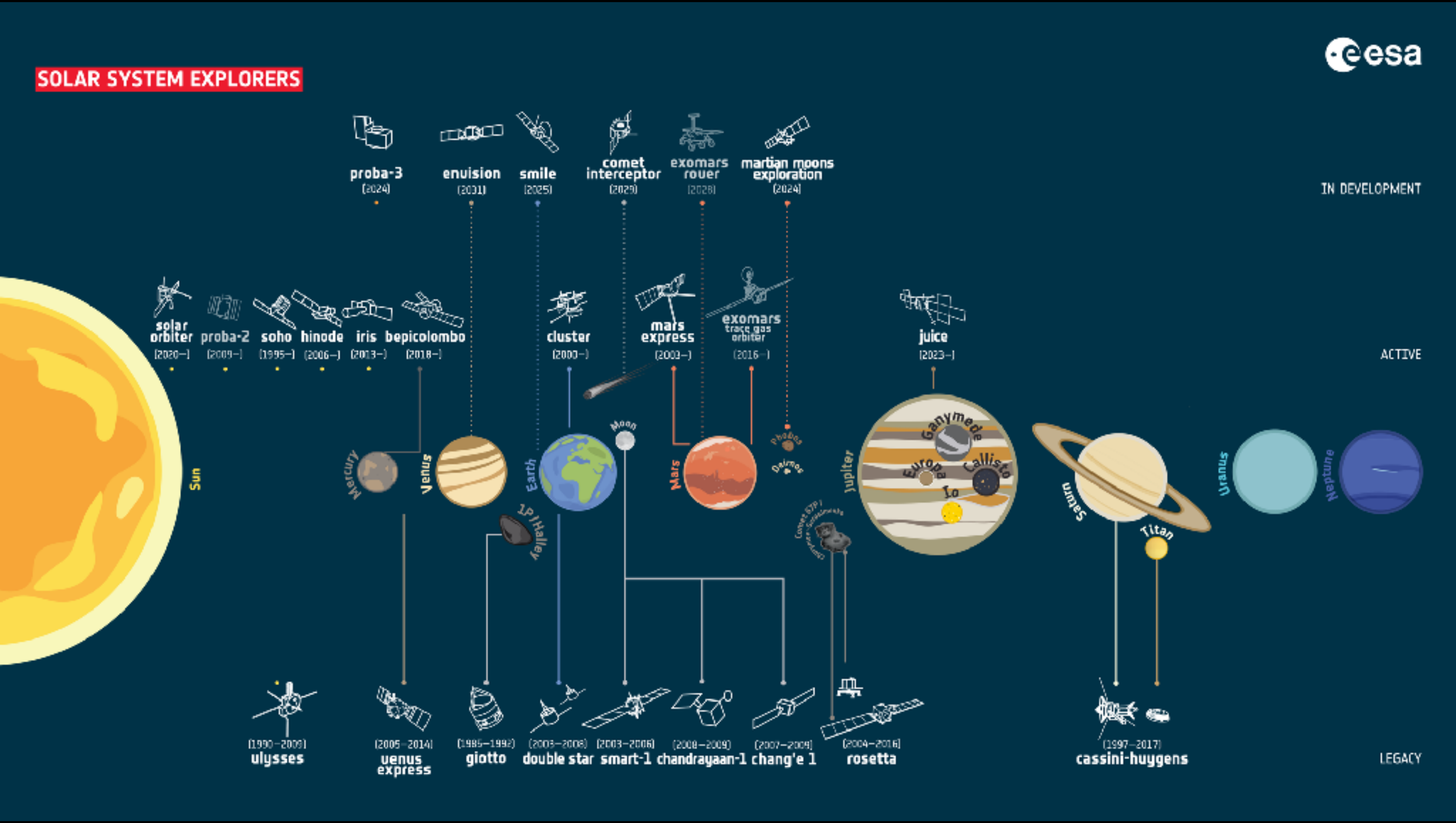
esa
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smile
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comet interceptor
(2029)
exomars rover
(2028)
martian moons exploration
(2024)
ACTIVE
solar orbiter
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proba-2
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soho
(1995–)
hinode
(2006–)
iris
(2013–)
bepicolombo
(2018–)
cluster
(2000–)
mars express
(2003–)
exomars trace gas orbiter
(2016–)
juice
(2023–)
Sun
Mercury
Venus
Earth
Moon
Mars
Phobos
Deimos
Jupiter
Ganymede
Europa
Callisto
Io
Saturn
Titan
Uranus
Neptune
1P/Halley
LEGACY
(1990–2009)
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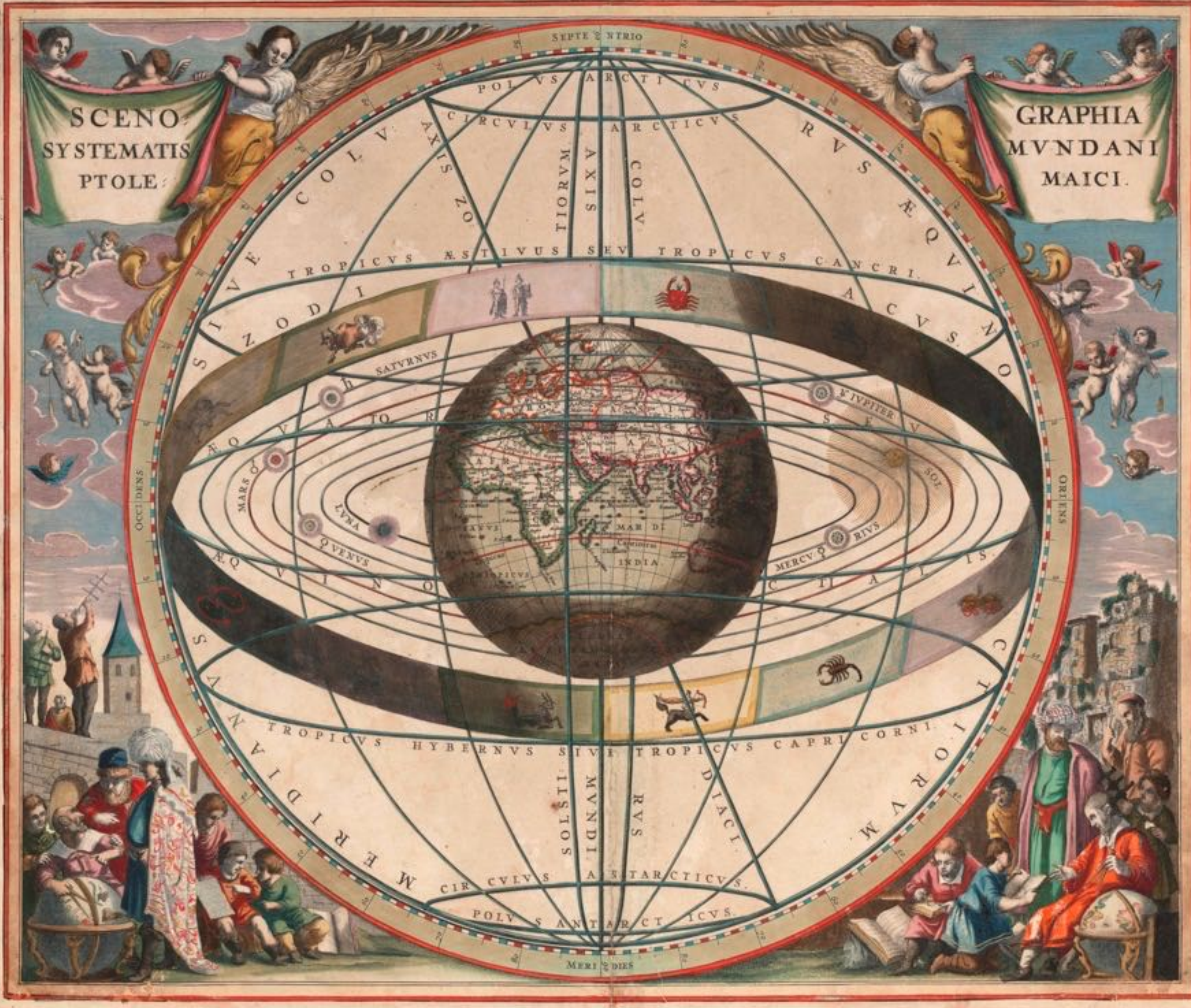
(2005–2014)
venus express
(1985–1992)
giotto
(2003–2008)
double star
(2003–2006)
smart-1
(2008–2009)
chandrayaan-1
(2007–2009)
chang'e 1
(2004–2016)
rosetta
(1997–2017)
cassini-huygens

Who are you?

What is your background?
What are you interested in?
Why are you here?

History of Astrobiology


SCENO
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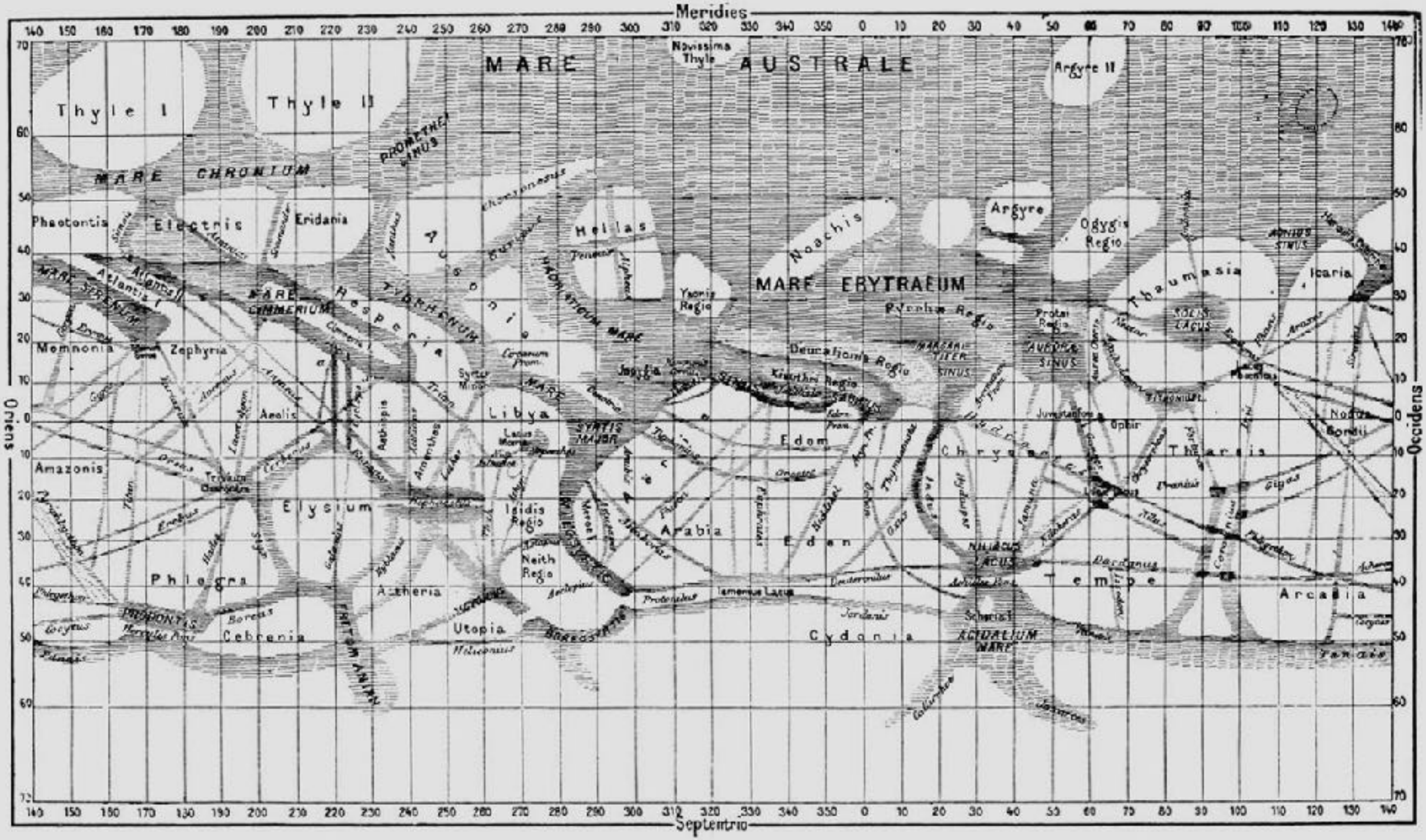
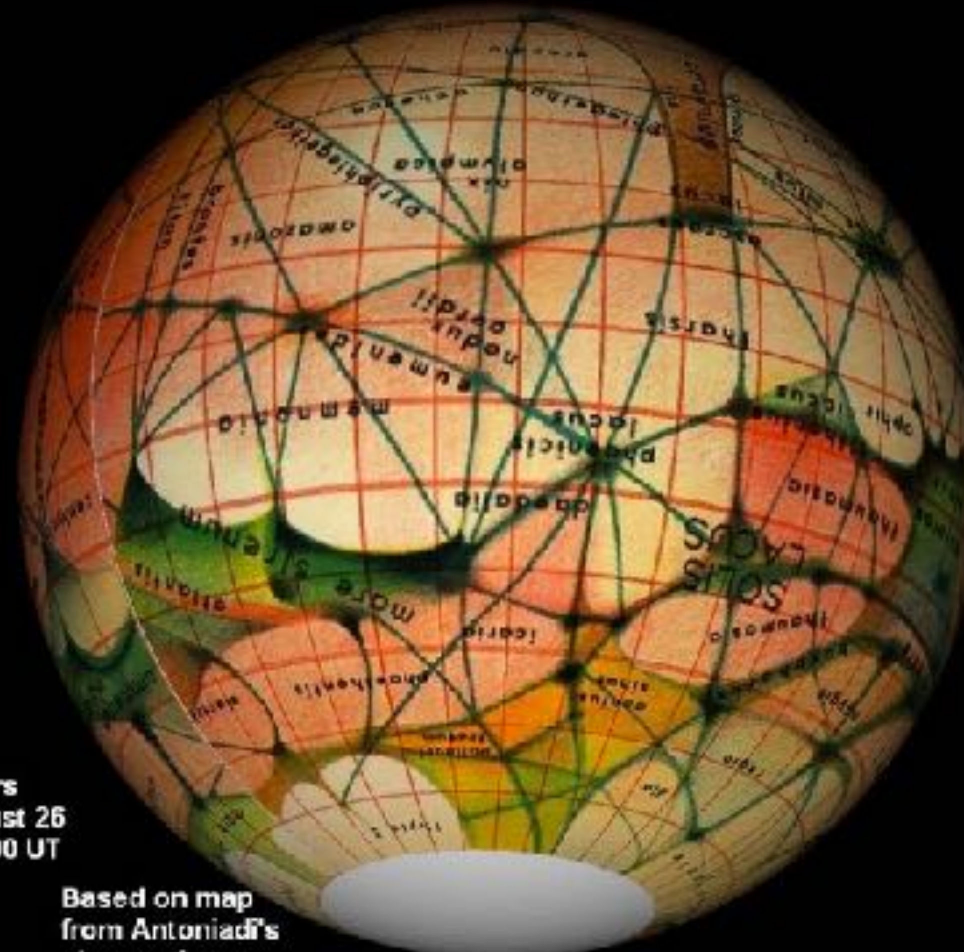


Schiaparelli 1877 - Mars observed from Brera Observatory

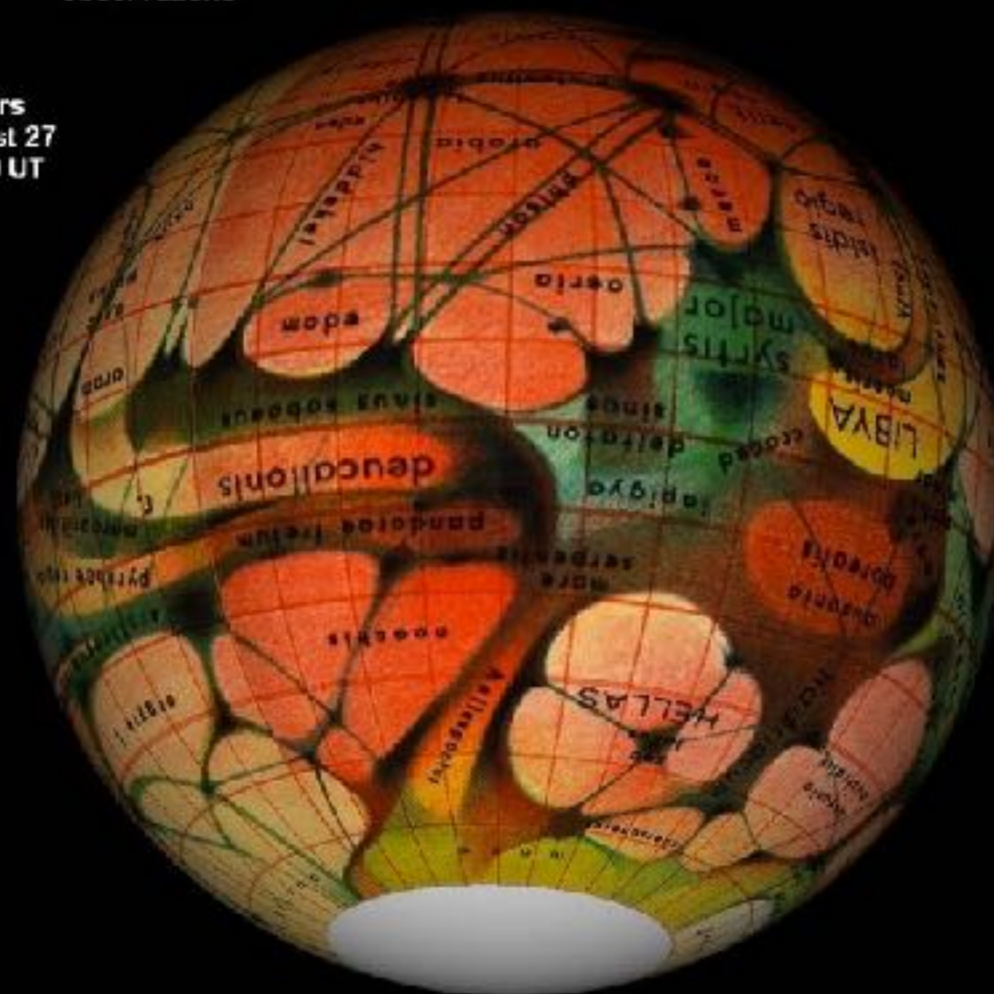
Hubble

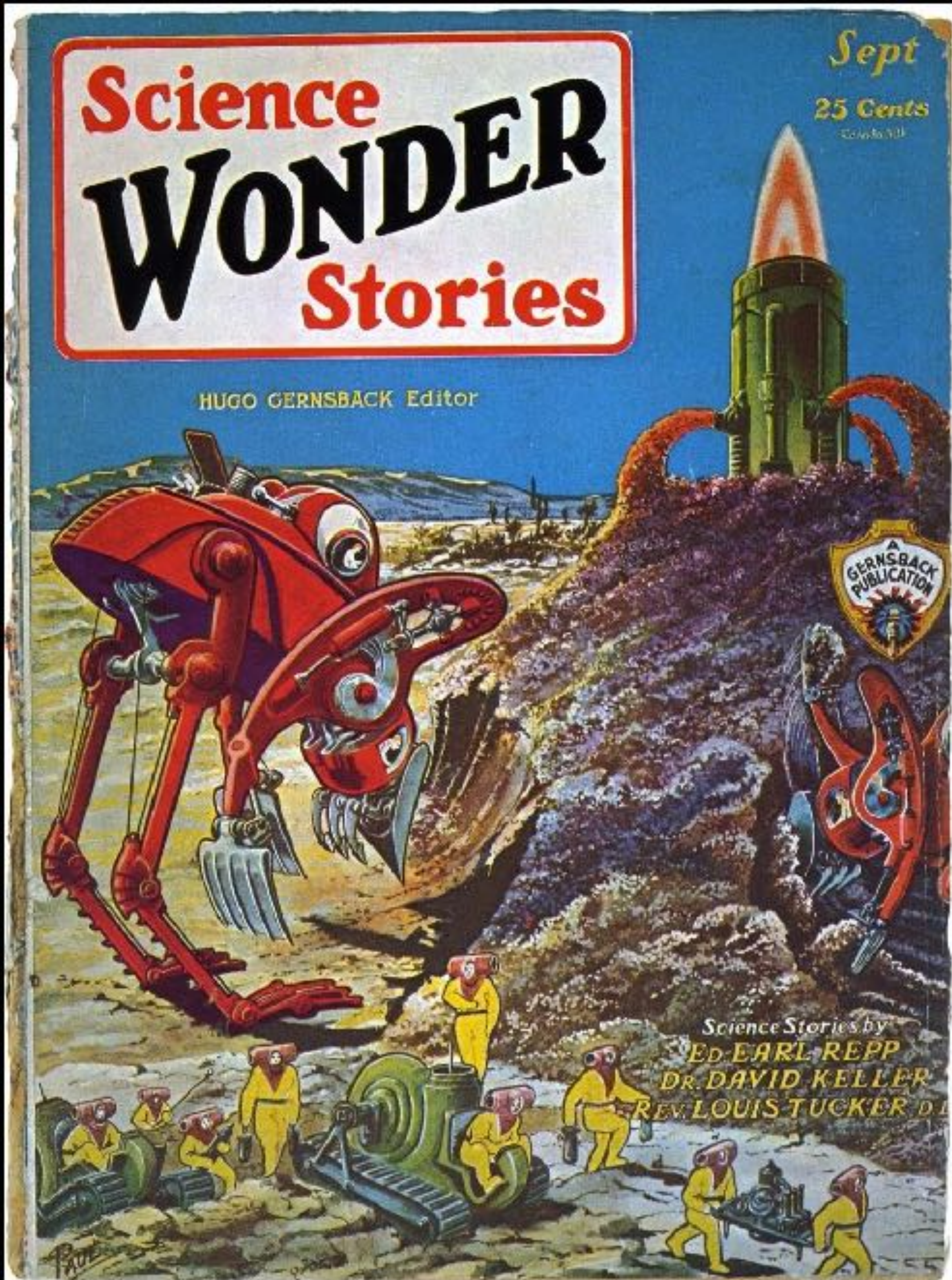
Mars
August 26
23:00 UT



Based on map
from Antoniadi's
observations

Mars
August 27
10:00 UT

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HUGO GERNSBACK Editor
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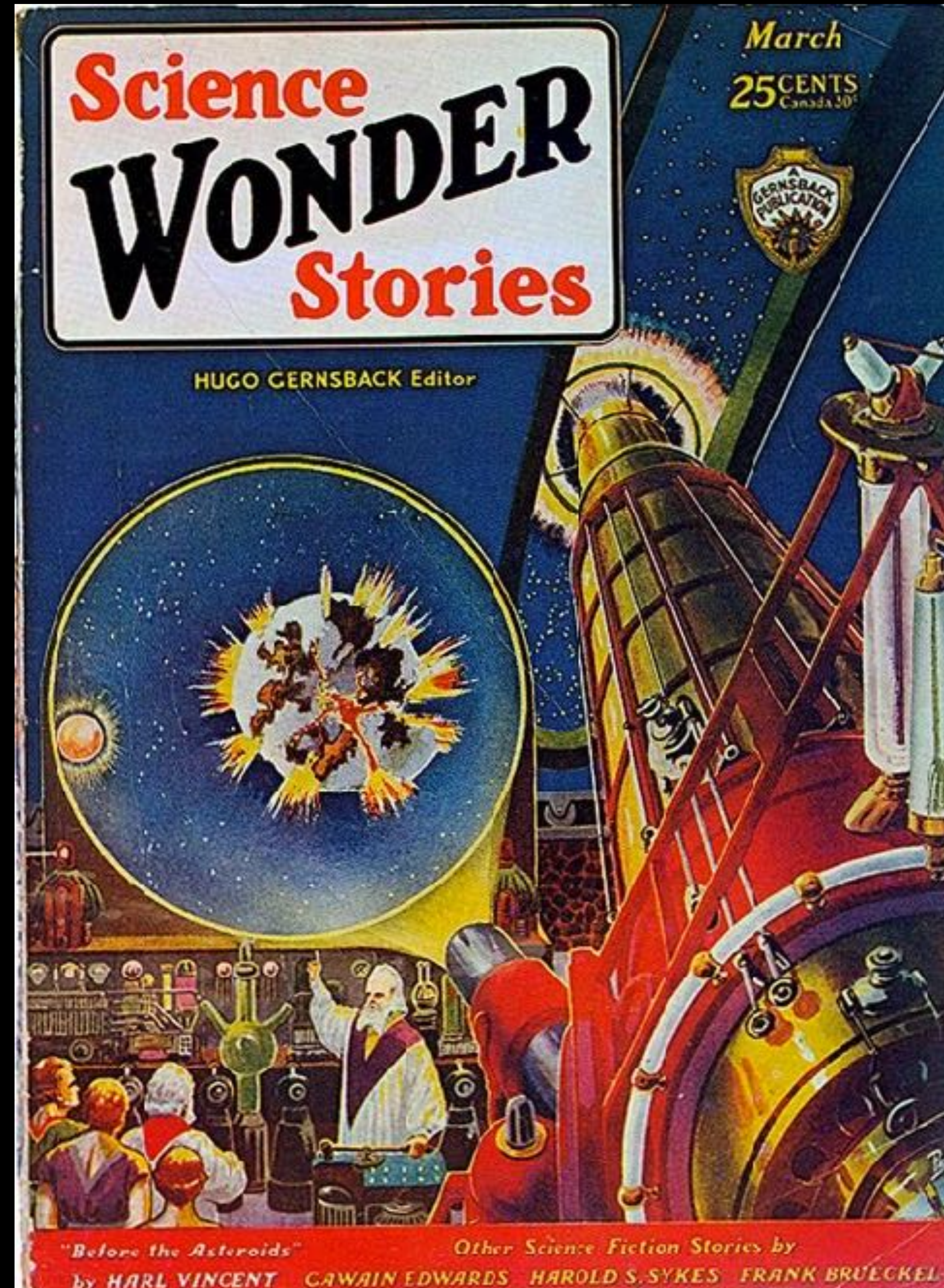
ED EARL REPP
DR. DAVID KELLER
REV. LOUIS TUCKER D.D.

1929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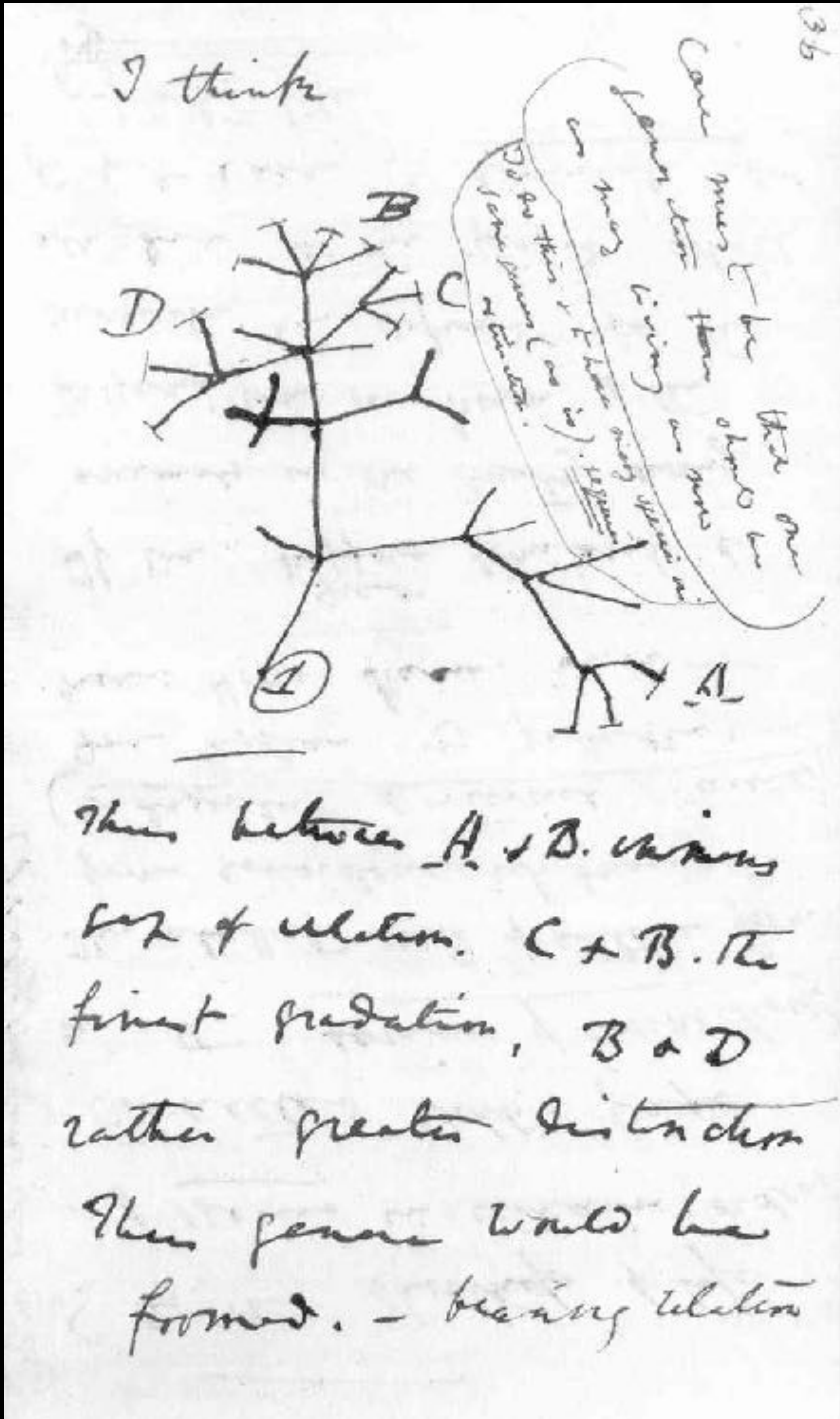
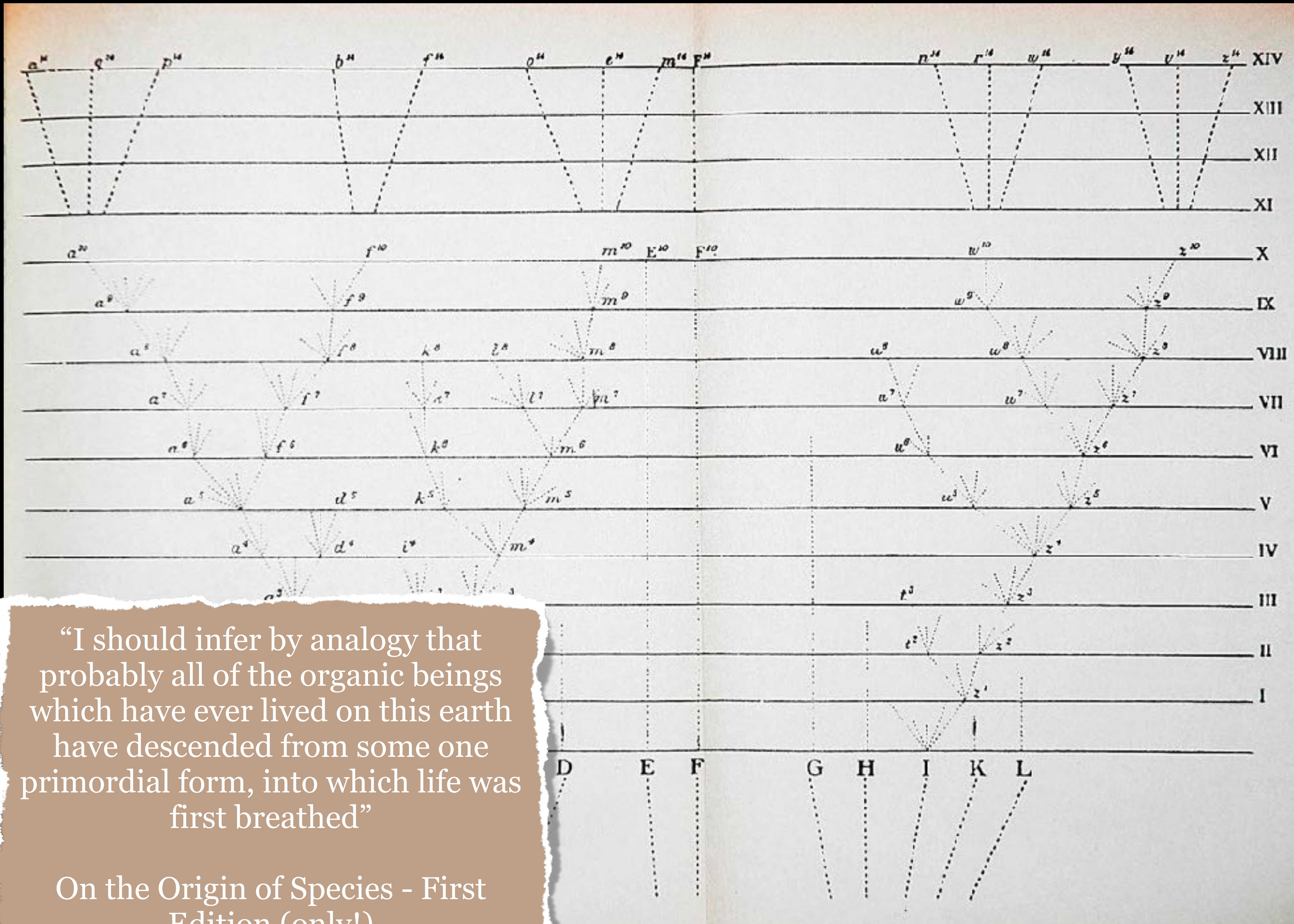
"Before the Asteroids"
by HARL VINCENT
Other Science Fiction Stories by
GAWAIN EDWARDS HAROLD S. SYKES FRANK BRUECKEL

1932



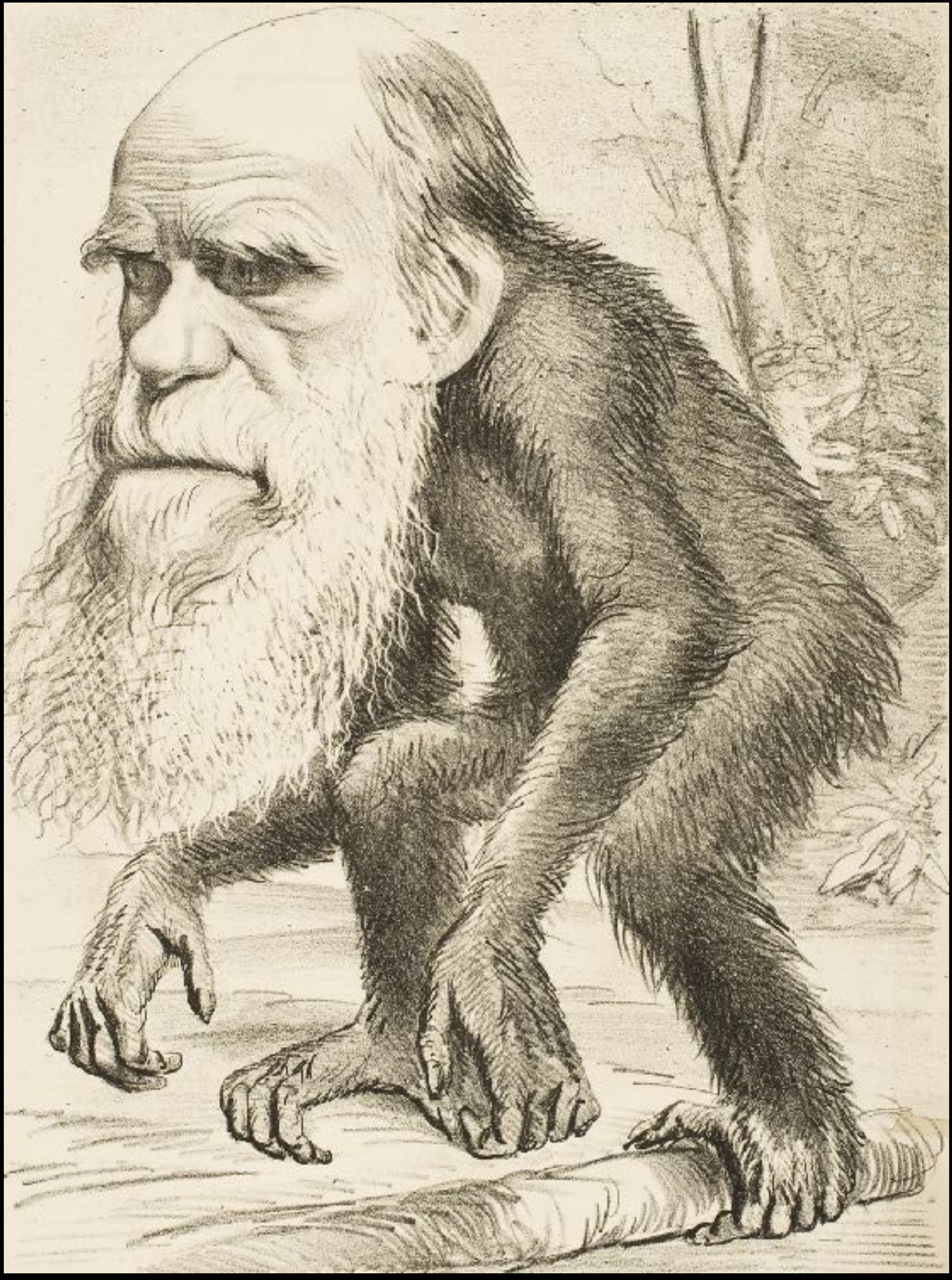
Charles R. Darwin (1809 - 1882)

First “Tree of life”



“I should infer by analogy that probably all of the organic beings which have ever lived on this earth have descended from some one primordial form, into which life was first breathed”

On the Origin of Species - First Edition (only!)



How do our human biases influence scientific research?

What are we looking for when we search for Life?

- Oparin & Haldane (1920s): Origin of Life
- Miller-Urey experiment (1957)

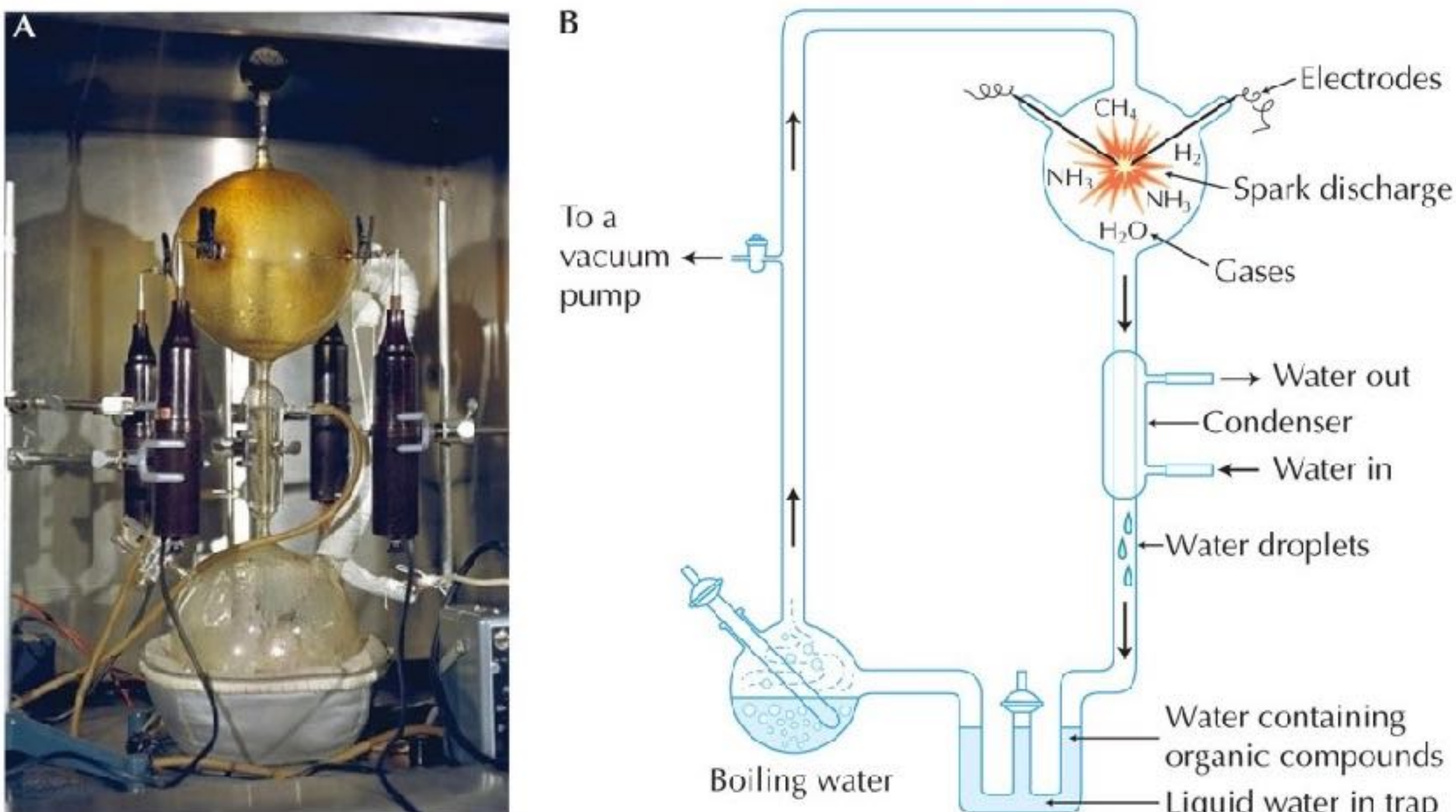
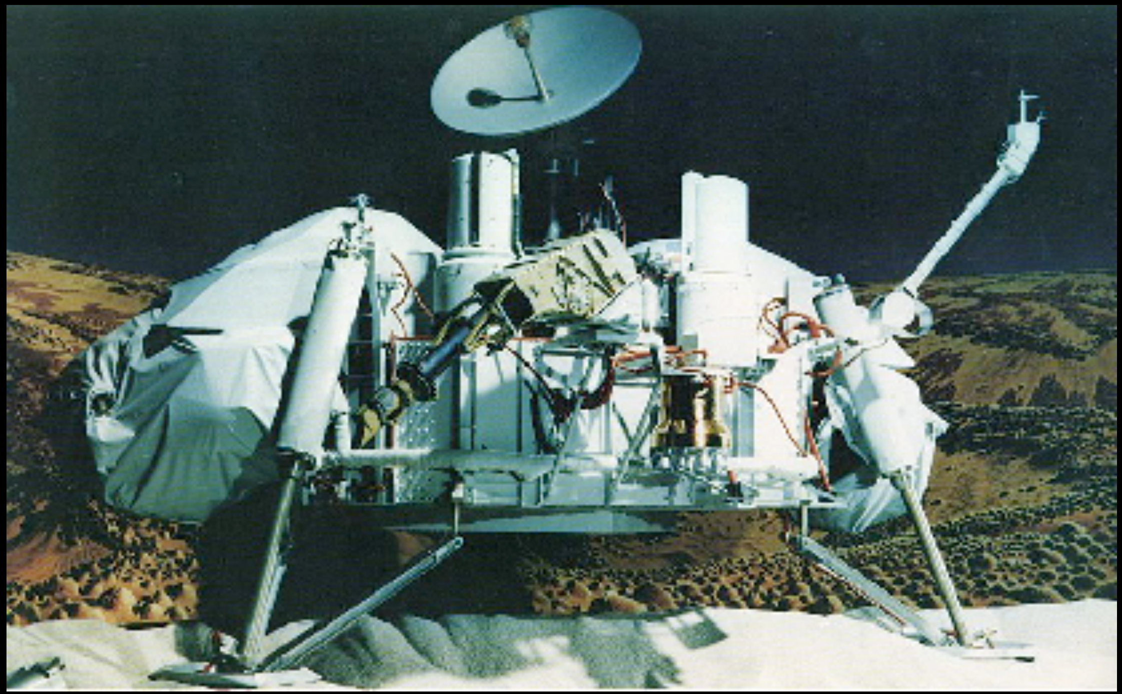


FIGURE 4.6. The apparatus used in the Miller–Urey experiments. (*A*) Recreation of the original apparatus. (*B*) Diagram of the apparatus.

- Exobiology - term appears in ~1960
- Drake equation (1963)
- SETI program (1970s - 1980s)
- Viking missions (1976)



- Astrobiology - term coined by NASA since 1990s

Curiosity - on Mars since 2012

http://video.nationalgeographic.com/video/mars-rovers-sci

(3 min)


YANKEE GO HOME!
MARS FOR MARTIANS

Astrobiology is a science of optimism

Take a break…

What is Life?

How would you define life?

Is artificial intelligence life?

Are viruses life?

Current common Definition of Life:

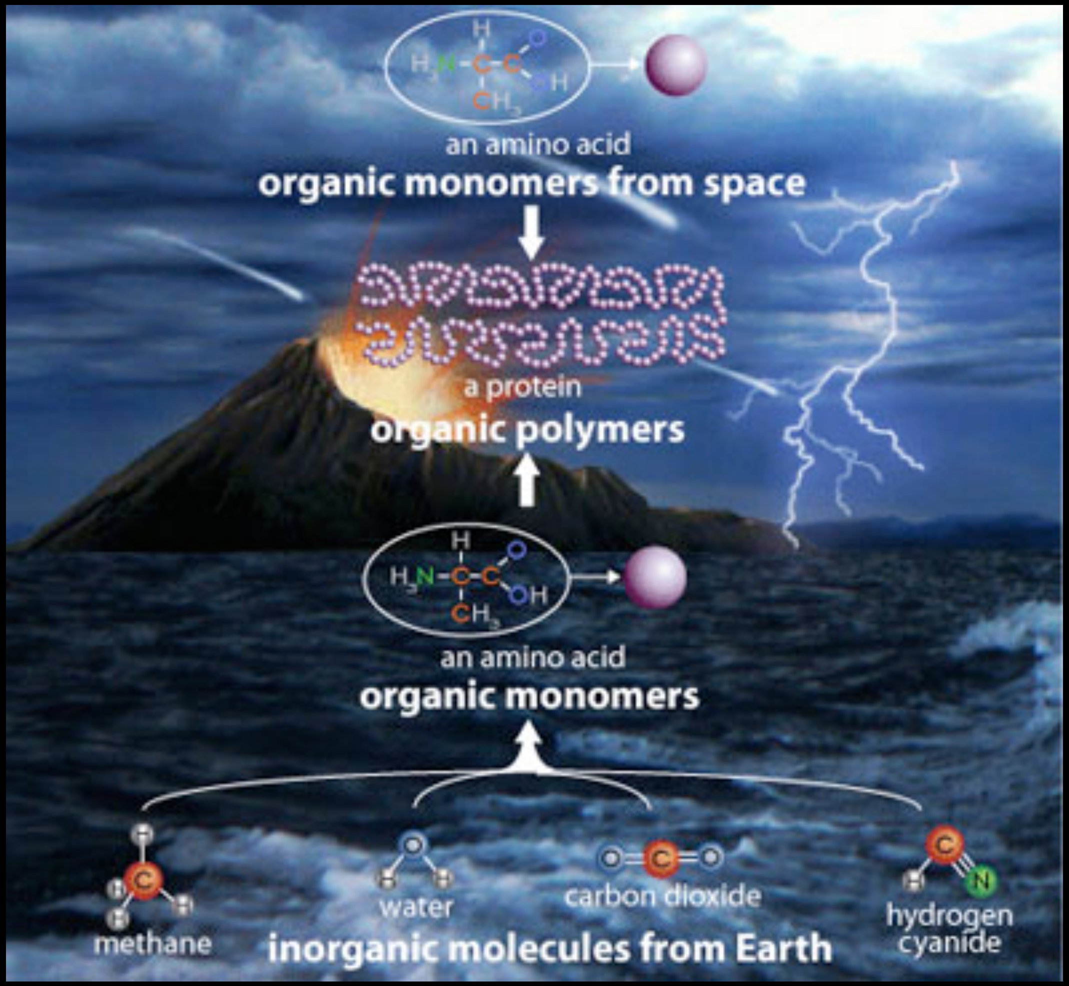
the capacity for self-replication

+

the capacity to undergo Darwinian evolution

The hallmark of biology is to be a combination of physical-chemical evolution and natural selection

The appearance of life on Earth is to be viewed as the outcome of a continuous process (not as a spontaneous event)



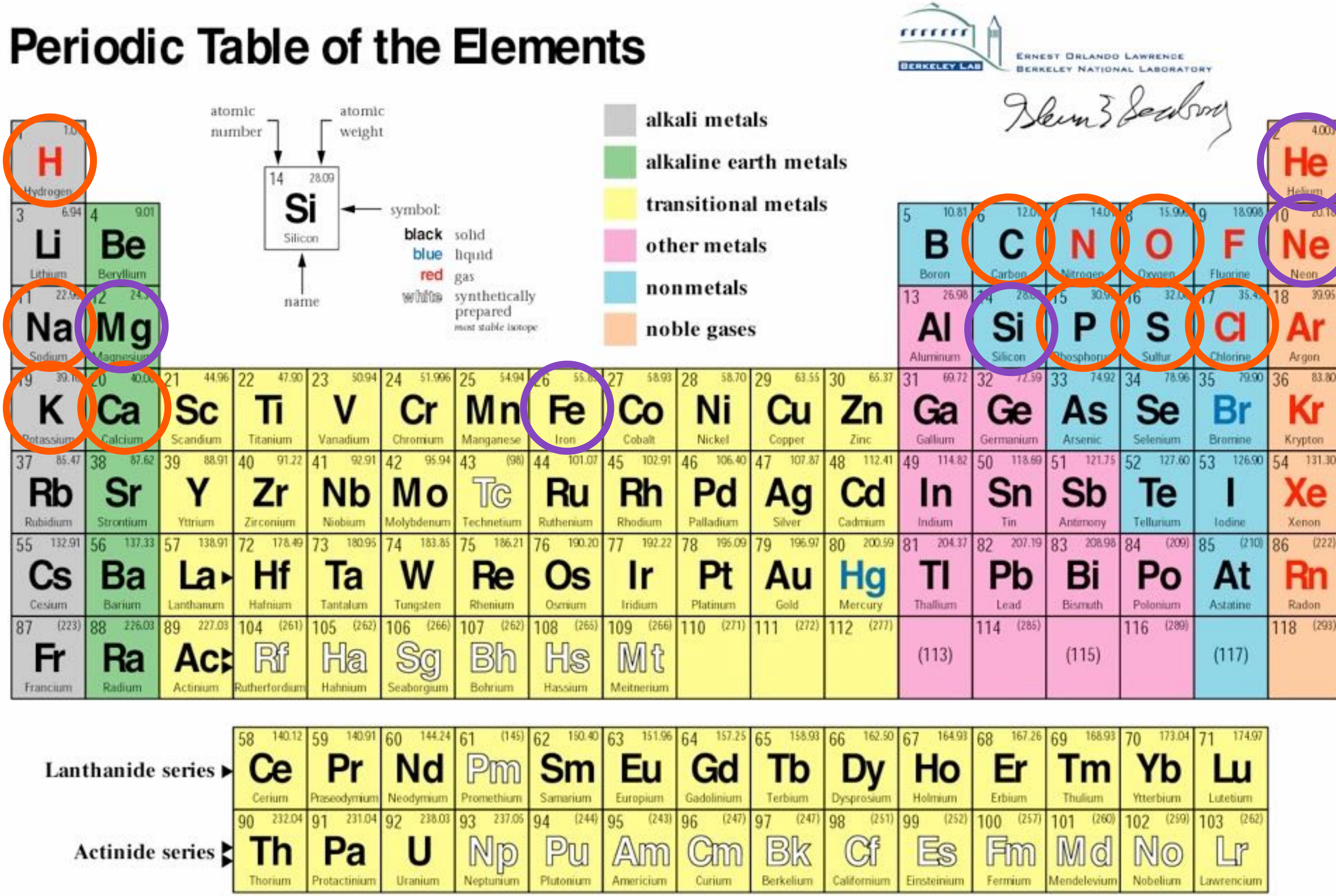
What are the top 10 elements:

- in the Universe?
- in Earth's Oceans?
- in Humans?

Table 1.1 The ten most abundant elements in the Universe, Earth and life (expressed as atoms of the element per 100 000 total atoms).

Order	Universe		Whole Earth		Earth's crust		Earth's ocean		Humans	
1	H	92 714	O	48 880	O	60 425	H	66 200	H	60 563
2	He	7 185	Fe	18 870	Si	20 475	O	33 100	O	25 670
3	O	50	Si	14 000	Al	6 251	Cl	340	C	10 680
4	Ne	20	Mg	12 500	H	2 882	Na	290	N	2 440
5	N	15	S	11 400	Na	2 155	Mg	34	Ca	230
6	C	8	Ni	1 400	Ca	1 878	S	17	P	130
7	Si	2.3	Al	1 300	Fe	1 858	Ca	6	S	130
8	Mg	2.1	Na	640	Mg	1 784	K	6	Na	75
9	Fe	1.4	Ca	460	K	1 374	C	1.4	K	37
10	S	0.9	P	140	Ti	191	Si	–	Cl	33

Periodic Table of the Elements



Why Carbon?

- All known life uses carbon-based organic compounds
- C can form strong chemical bonds with many other atoms (H,O,N,S,P,Fe,Mg,Zn,...) $\Rightarrow$ versatility, complexity
- C compounds dissolve in liquid water

Why Water?

- Life needs a medium in which molecules can dissolve and chemical reactions can take place
- H_2O is liquid at temperatures at which chemical reactions take place
- H_2O is a polar solvent (hydrophilic/hydrophobic molecules)

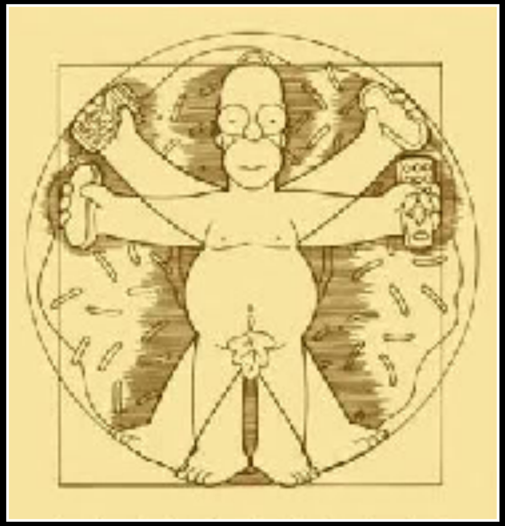
How many cells are there in a human body?

vs.

How many bacteria are there in a human body?

Number of cells in human body ?

10^{13}



Number of bacteria in human body?

10^{14}

Leucocyte chasing bacteria...

How many stars are there in the Universe?

vs.

How many living organisms are there in the Ocean?

Number of stars in the Universe?

10^{22}

Number of organisms in the ocean?

10^{30}

Origin of Life

Origin of life - Schools of thought

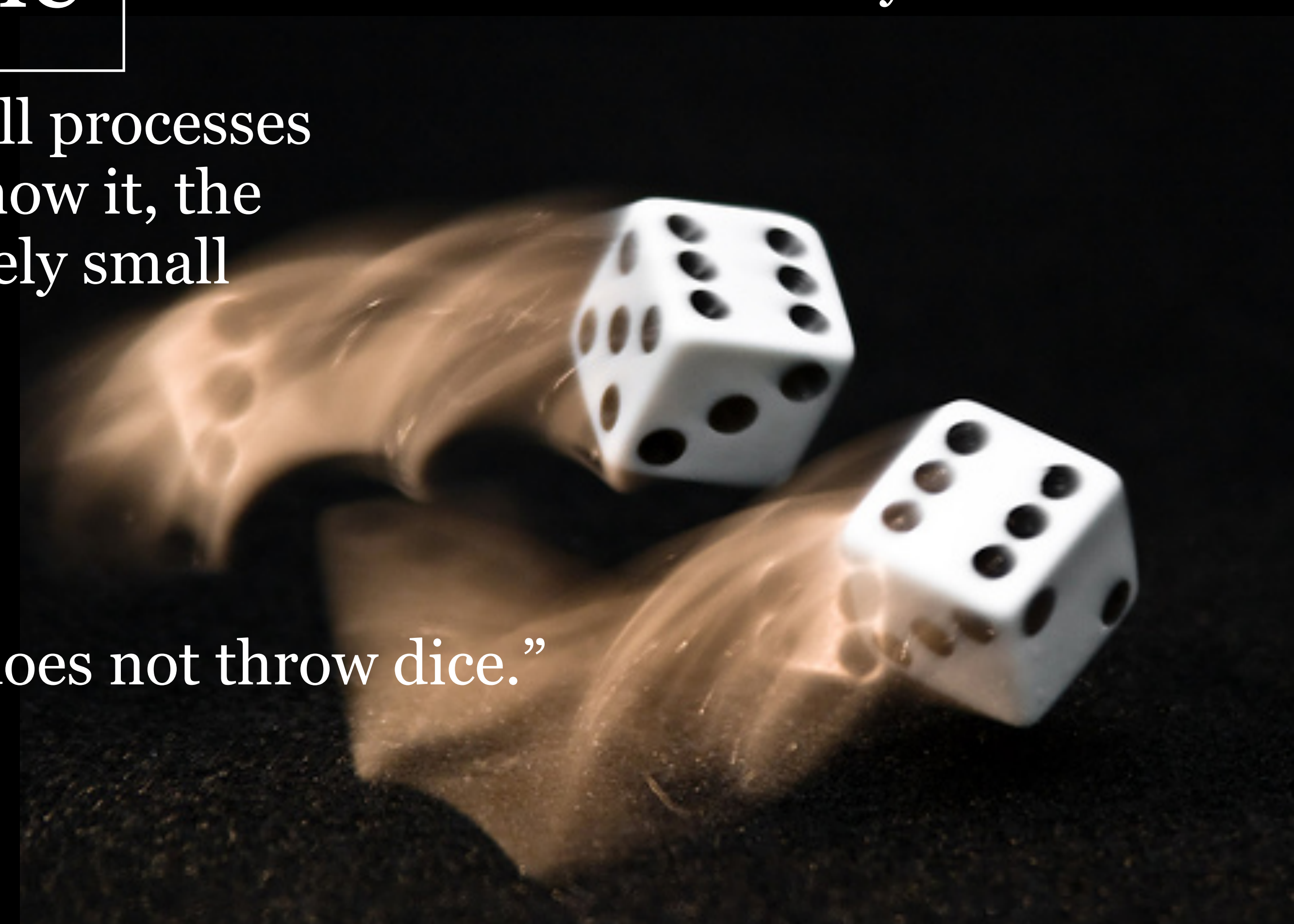
Religion

incredibly implausible

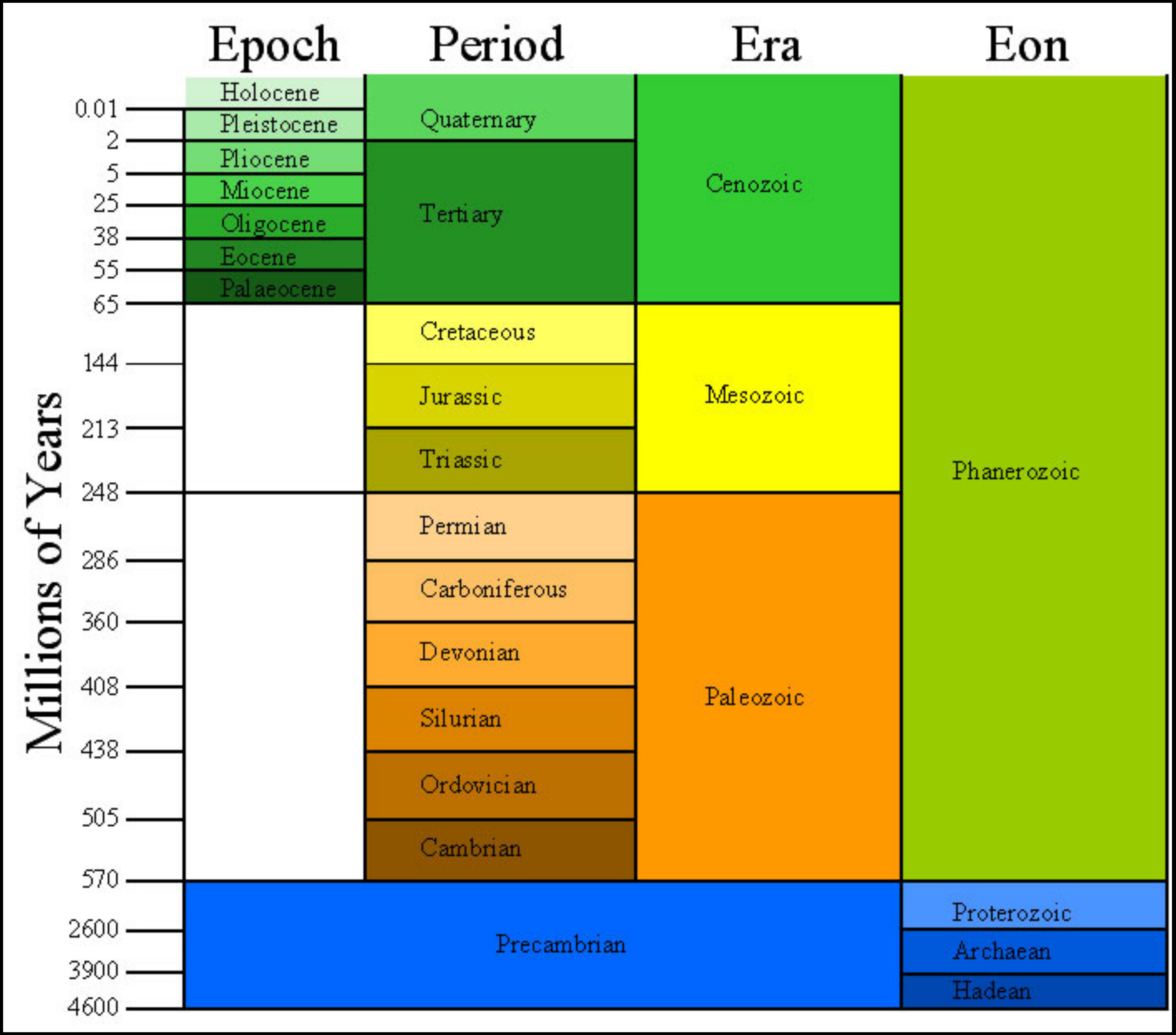
to reproduce in nature all processes leading to life as we know it, the probability is extremely small

Unavoidable

autocatalytic metabolisms are natural properties of complex chemical systems



“I, at any rate, am convinced that He [God] does not throw dice.”
Einstein (1926)


Epoch
Period
Era
Eon
Millions of Years
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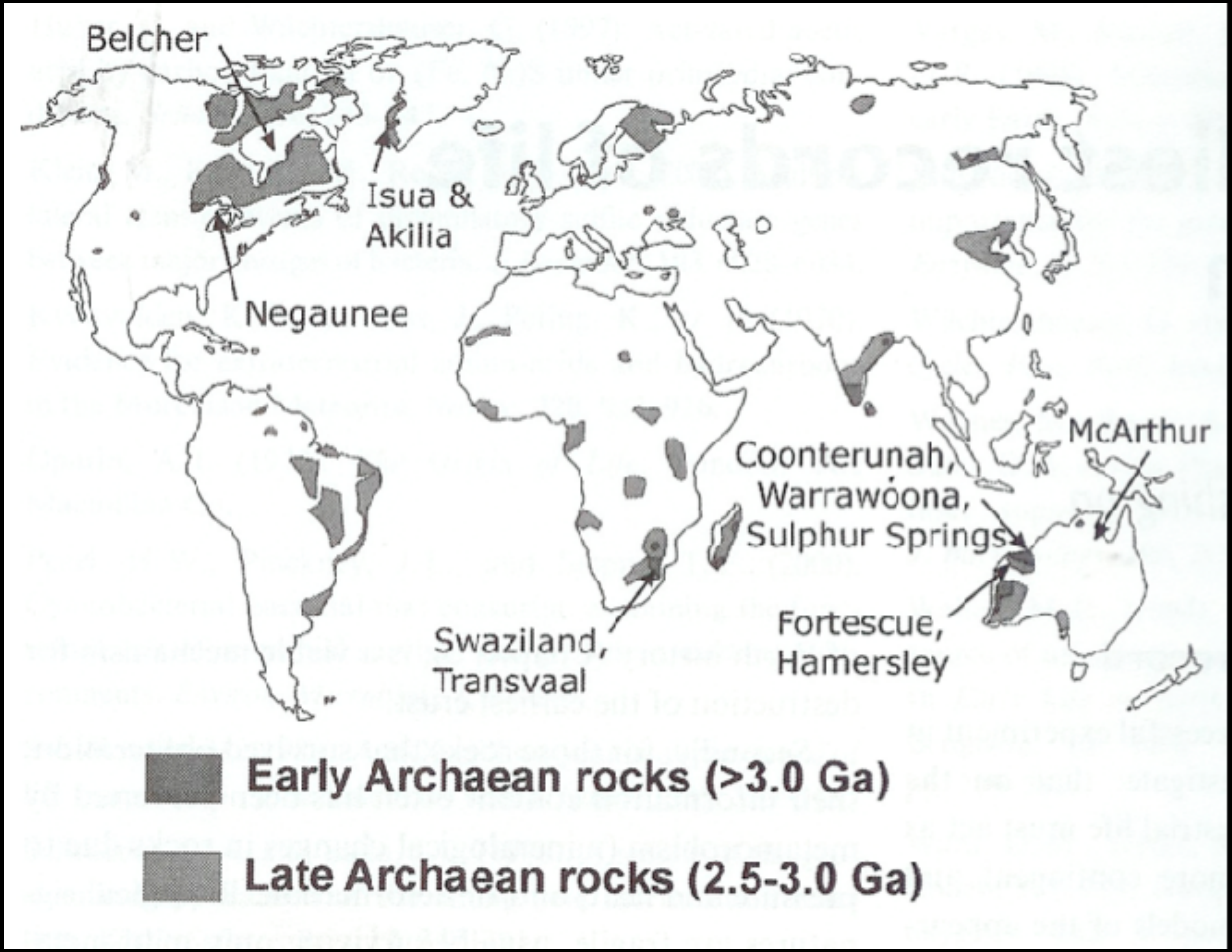
65
144
213
248
286
360
408
438
505
570
2600
3900
4600
Holocene
Pleistocene
Pliocene
Miocene
Oligocene
Eocene
Palaeocene
Quaternary
Tertiary
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
Cenozoic
Mesozoic
Paleozoic
Phanerozoic
Precambrian
Proterozoic
Archaean
Hadean

Where would you search for the evidence of first life?

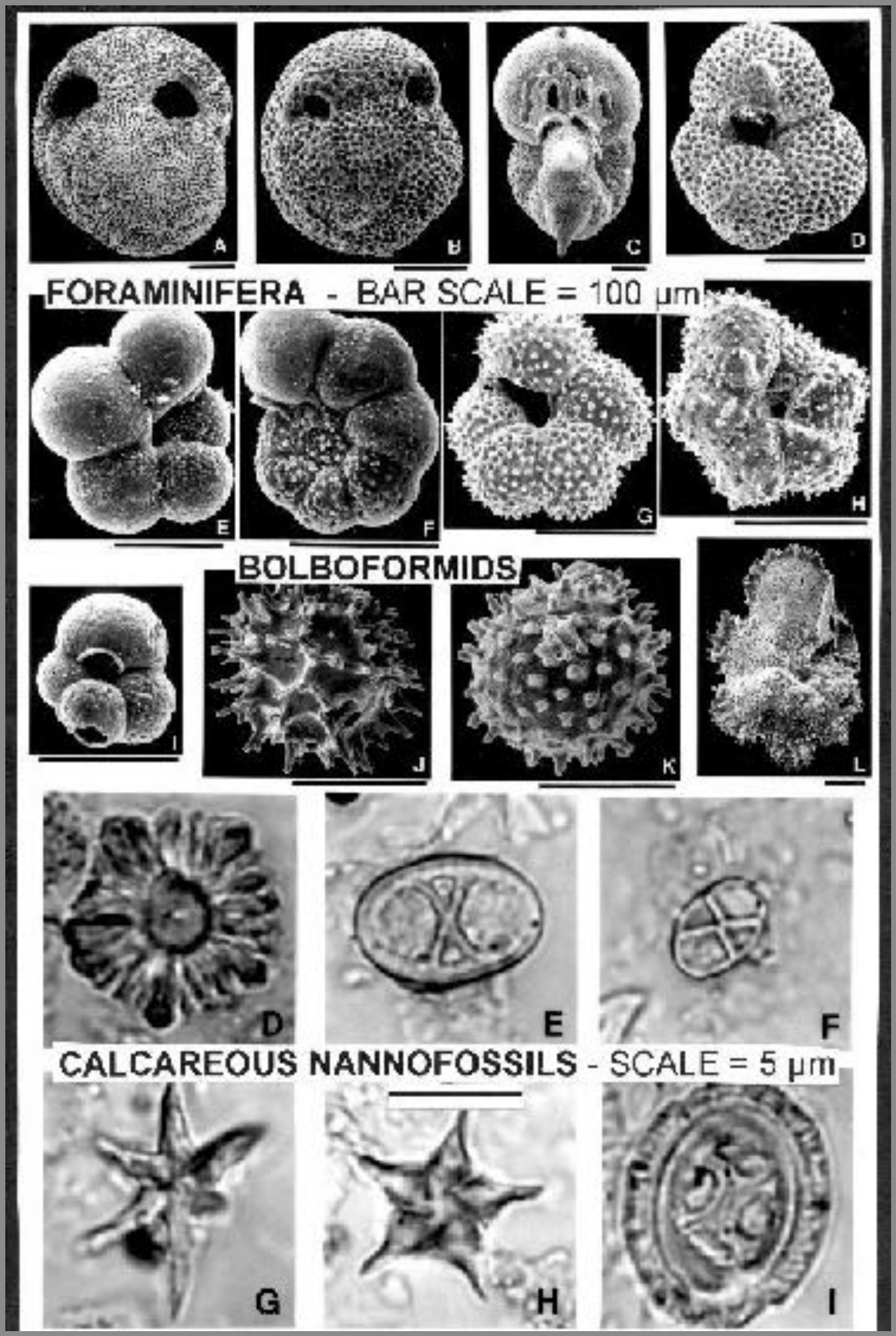
What would you search for?

All records stem from ancient ROCK (sediments)



- Rocks get destroyed (erosion, subduction, ...)
- Evidence get destroyed (metamorphism, weathering, ...)
- Contamination / Abiotic mimics

National Park ‘Cabañeros’ (Castilla - La Mancha)



Microfossils (35 Ma)

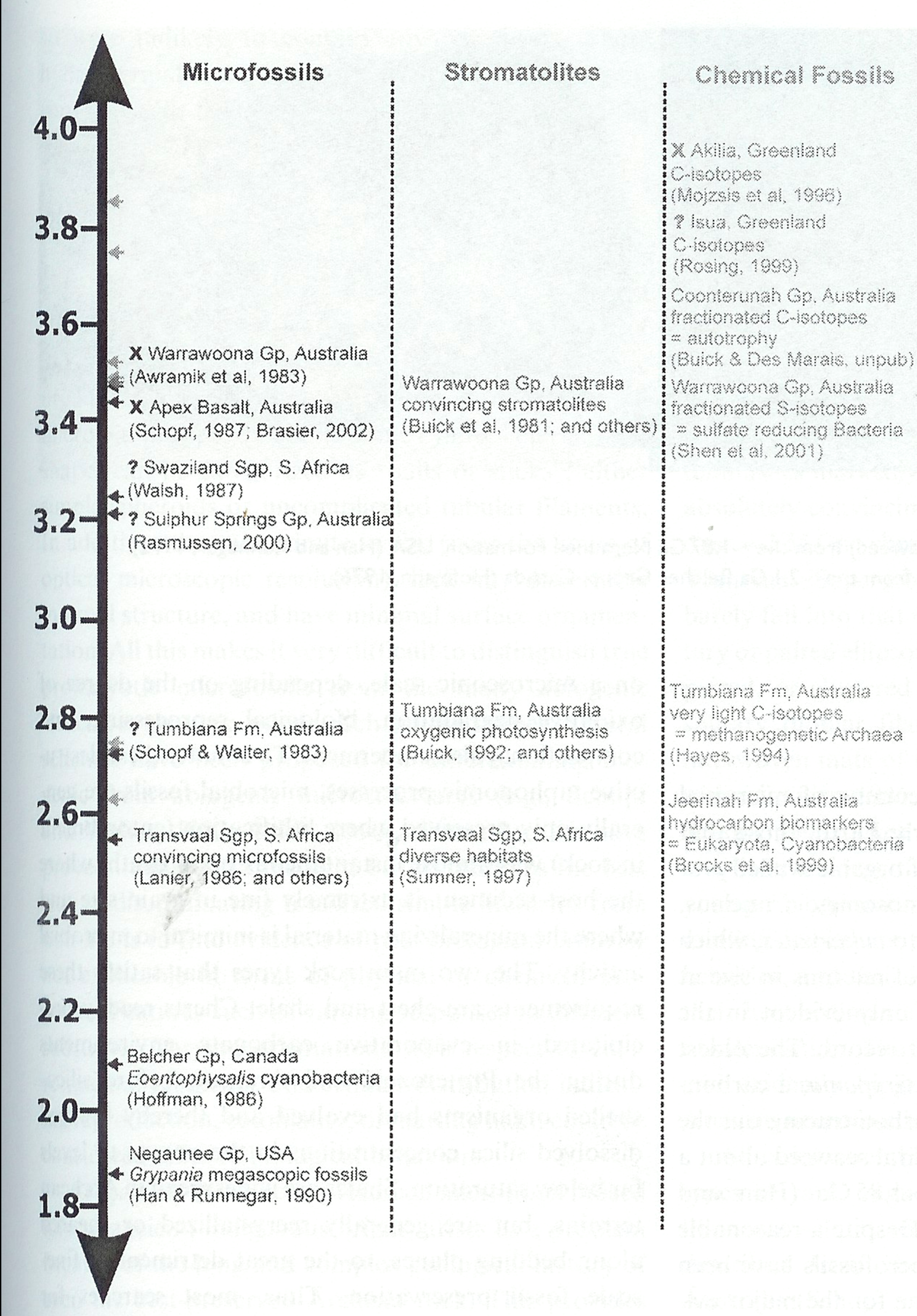
Stromatolites (Cambrian - 500 Ma)

Types of Evidence

Chemical fossils (>3 Ga):

- Carbon isotopes — autotrophic metabolism prefer ^{12}C to ^{13}C
  i.e. external CO_2 users
- Sulphur isotopes — ^{32}S over ^{34}S, reduction for metabolic purposes
- Nitrogen isotopes — complex bio-geo-chemical cycle
- Molecular Biomarkers — “carbon skeletons” of organic molecules

Older ⇒



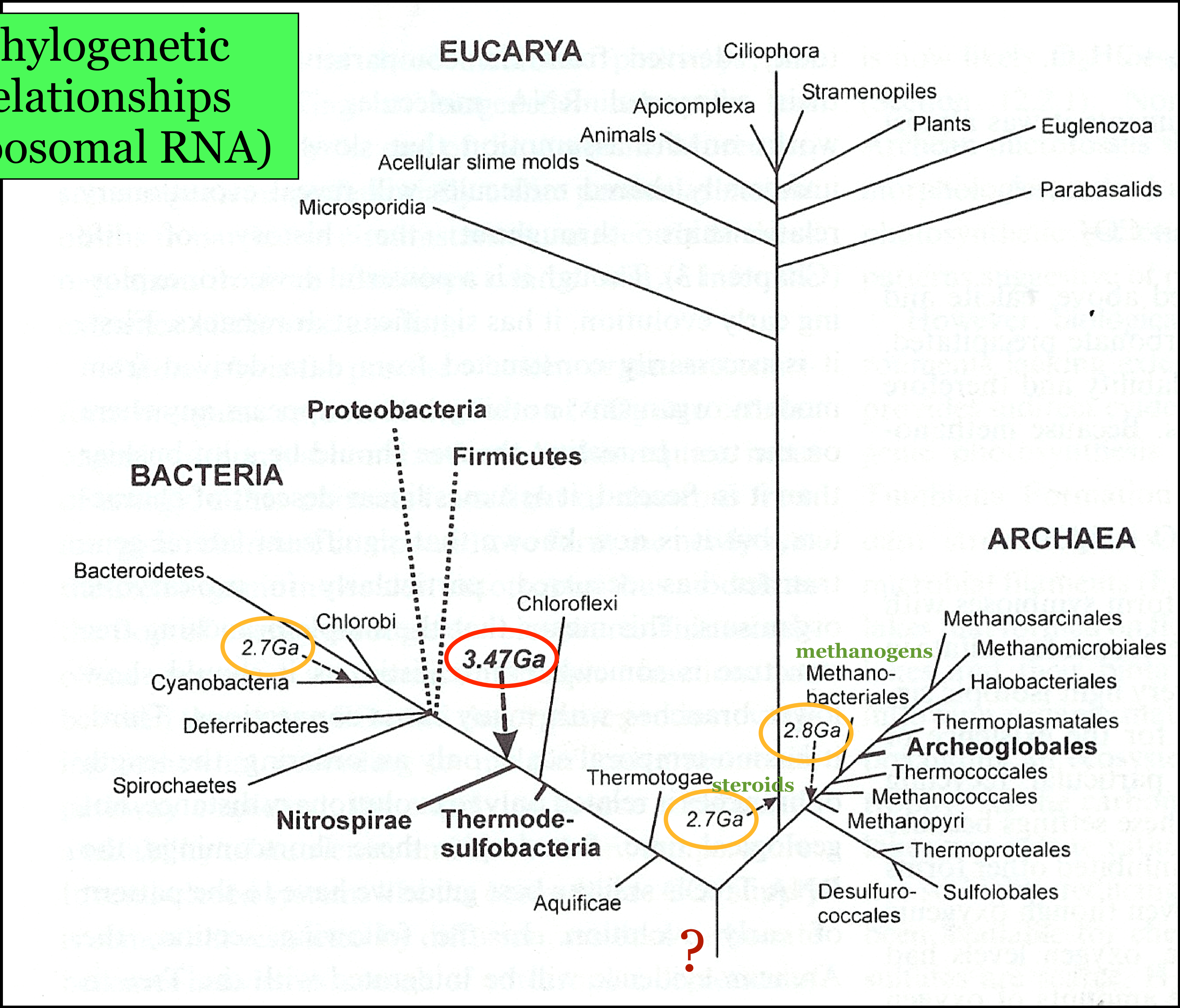
Prokaryotes

The tree of life
See http://tolweb.org

When did animals,
especially bilateria appear?

How does it compare geologically with
first life? First eukaryotes?

Phylogenetic relationships (ribosomal RNA)



Life appeared on Earth within a few 100 Myr of the end of the Large Heavy Bombardment (~3.9Ga)

It quickly became complex

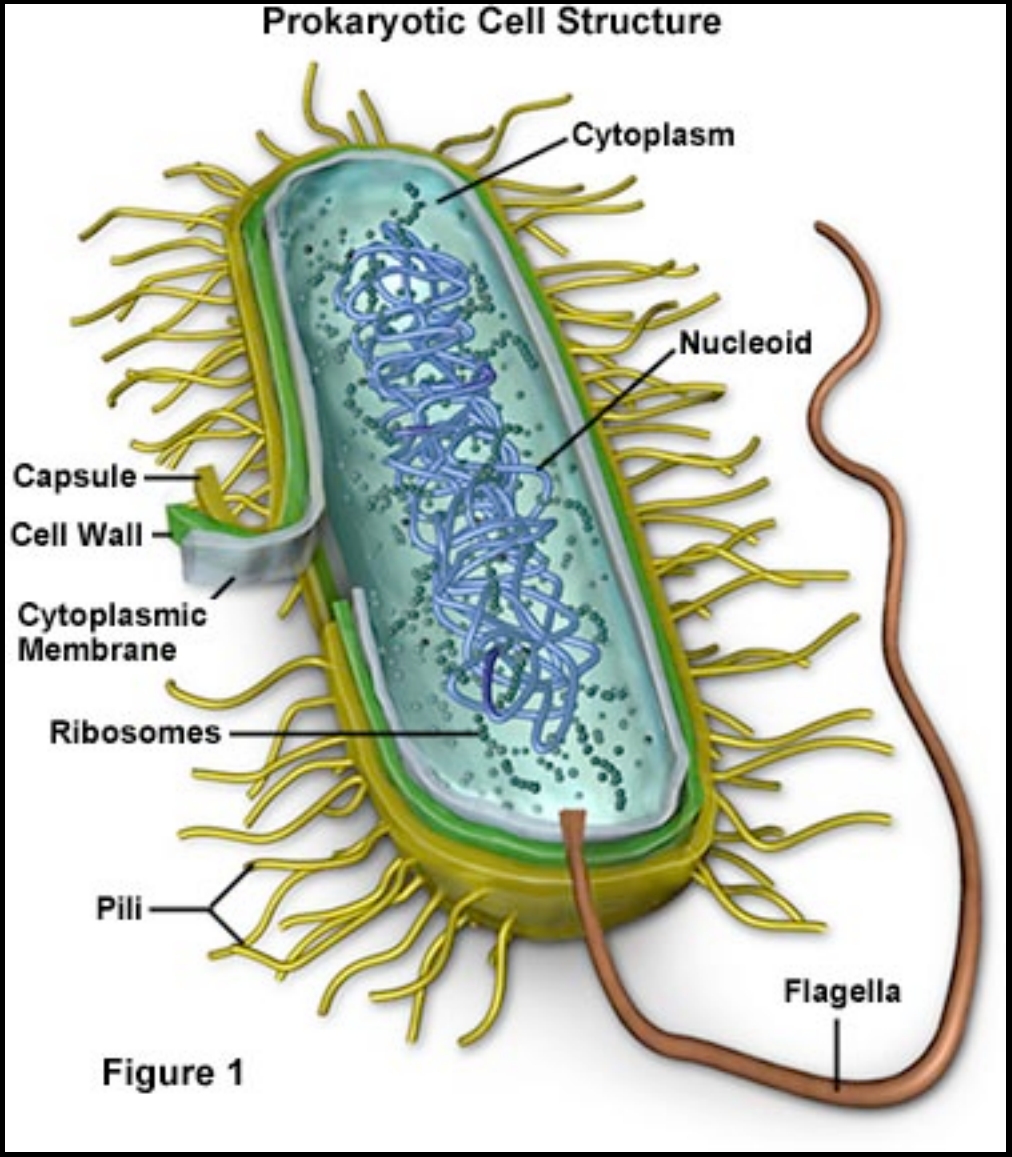
It suggests that life could have evolve on early Mars and other locations in the Solar System...

Similar techniques as on Earth could be used on Mars to find first life

The Origin of Life

Replicators first
Metabolism first

Even the simplest life is very complex…



Bacteria: 20.000 ribosomes synthesizing several 1000 types of proteins

Life started as a subset of a bacteria - but which ?

Replicators first

Cell replication

Discovery of the DNA (Hershey & Chase 1952, Watson & Crick 1953)

Nice:
★ DNA is formed of simple nucleotides
★ reproduction & information storage happens at molecular levels

$\Rightarrow$ Origin of life is simplified to Origin of first replicator

DNA is too complex - RNA as first replicator?

Metabolism first

Metabolism first = Monomers first

No polymers!
Life without proteins and nucleic acids (DNA/RNA):
Basic life with small molecules

Replication: do not pass recipe, but replicate all ingredients before cell splitting

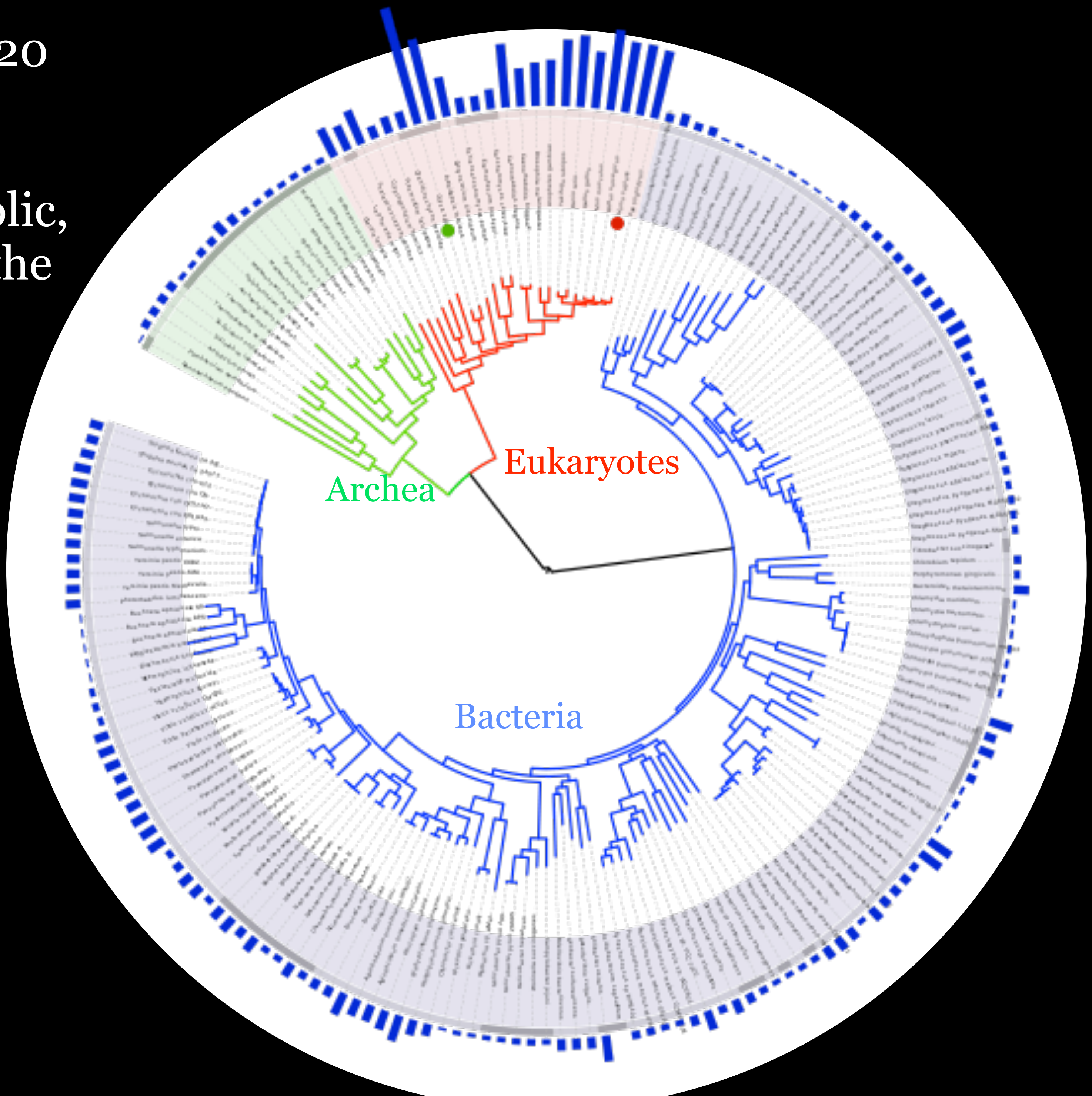
Critical:
- form a membrane
- synthesize and improve catalysts

The *Unity of Biochemistry*

- all organisms share the same biochemical tools to translate the universal information code from genes to proteins

- all proteins are composed of the same 20 essential amino acids

- all organisms derive energy for metabolic, catalytic, biosynthetic processes from the same high-energy organic compounds (e.g. ATP)



Lunch break…

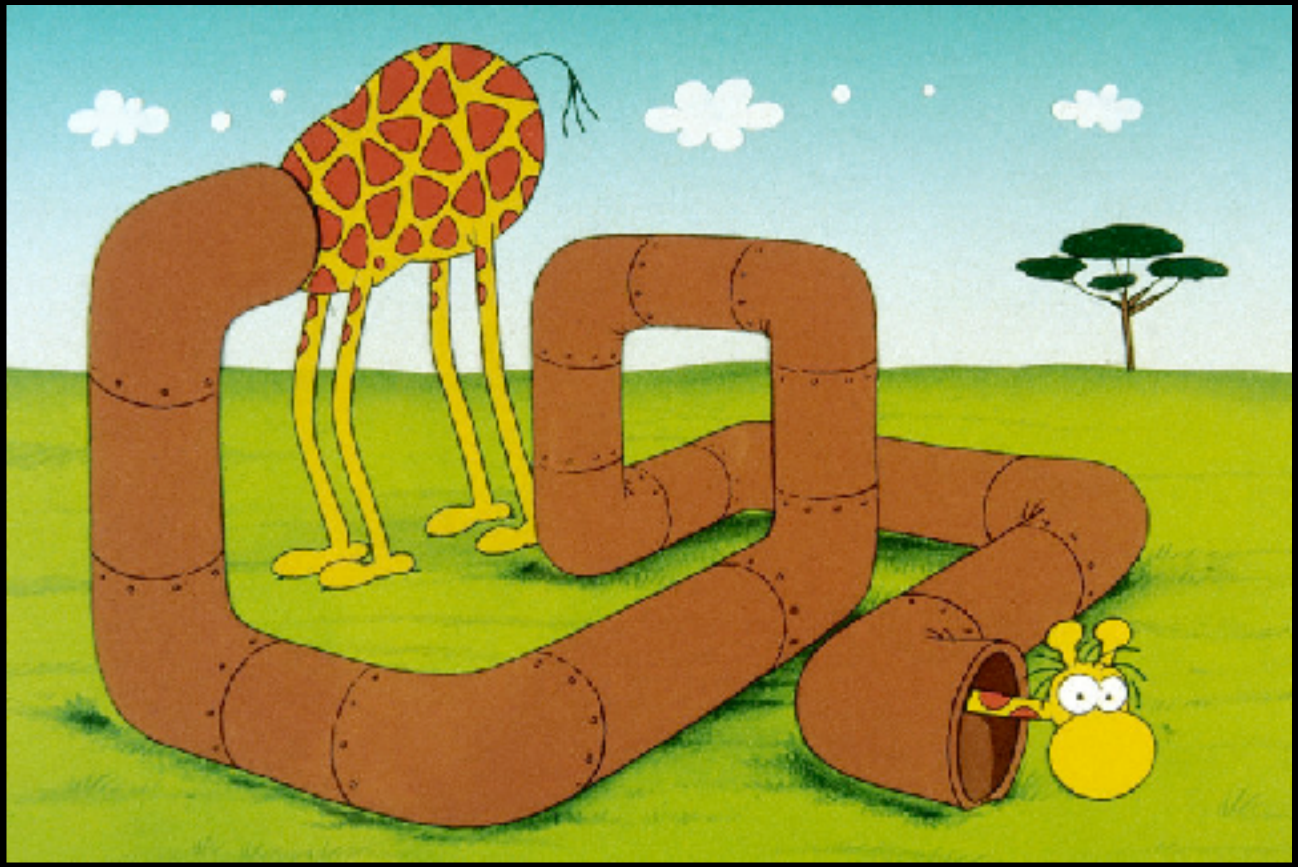
The Evolution of Life

Evolution at the molecular levels
Gene transfer/acquisition

Natural selection - Survival of the Fittest

Lamarck: (1809)
phenotype as response to the environment

Darwin: (1859)
phenotype used as advantage for survival



- Mendel: starts genetics ~1900
- Chromosomes as carriers of genes ~1910
- DNA as genetic material ~1950   (end of Lamarckism)

Search on YouTube any combination of:
Darwin, Evolution, Galapagos, Finches

What do you get?

Evolution at the molecular level

Mutations

Modifications of the DNA

due to

- errors in DNA replication,
- or external influence (radiation, toxic chemicals, ...)

usually deadly (especially if based in DNA are affected)

if reacting to stress, needs to be fast enough

lead mostly to *microevolution*, not *macroevolution*

→ not fast enough

“Toolkit genes” (1) (HOX genes, switching genes)

Genes that control how multiple other genes are used (expressed/suppressed)

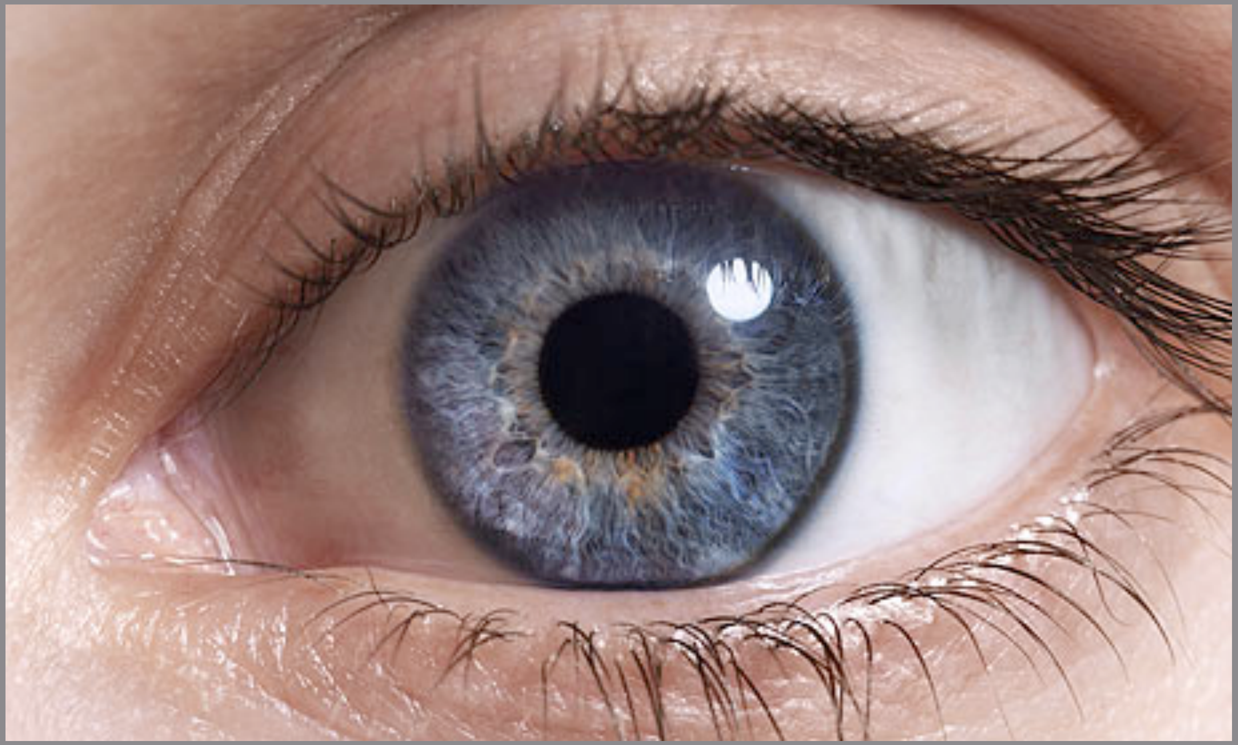
Bird: arm

Bat: hand

Pterosaur: finger

The same basic set of genes in animals is used in different ways to produce a myriad of different body forms!

“Toolkit genes” (2) (PAX genes, switching genes)



Pax-6: responsible for >40 different eye structures

→ evolutionary developmental biology (Evo-Devo)

$\Rightarrow$ Cambrian explosion

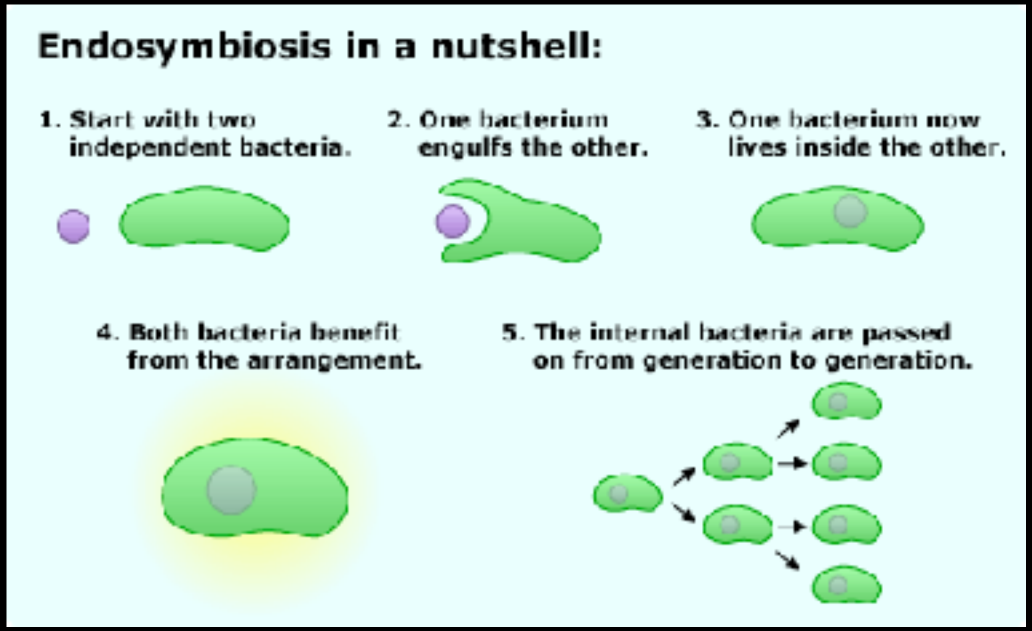
Toolkit genes can explain the rapid evolution of the Cambrian.

What is the open question?

Gene transfer / acquisition

How to get new genes

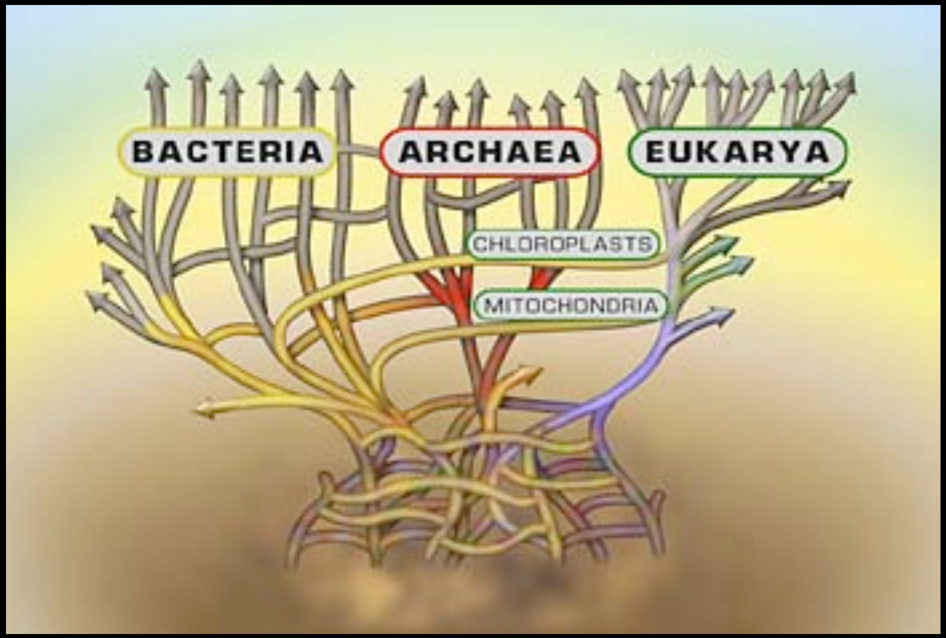
Fusion of cells (endosymbiosis)
see also simpler Symbiosis



Eukaryote = fusion of Archea and Bacteria
e.g. Mitochondria & Chloroplast

Co-evolution

Lateral (horizontal) genes transfer



Lateral genes transfer

- Cell-cell contact
- Viral infection
- incorporating DNA from environment

N.B.:
45% of the human genome is made out of remnant of RNA viruses (retrotransposons - not transcribed into proteins)

There are more viruses than bacteria in marine environments

Viruses are vehicles for transmitting new genes (but often deadly)

Viruses probably played a critical role in the early evolution of life

Life without evolution?

What is ‘evolution’?

Most definitions of life require “evolution”

More precise would be:

- adapt to environment (select the fittest)
- increase in complexity

As a consequence of evolution:

- life on Earth has spread and occupies all available habitats
- Extra-terrestrial life could look radically different

Search for extra-terrestrial life should include search for evidence of evolution

If we started life from scratch, 4Ga ago, would it look the same?

Why did we add ‘Darwinian Evolution’ in our definition of life?

Limits of Life

Extremophiles

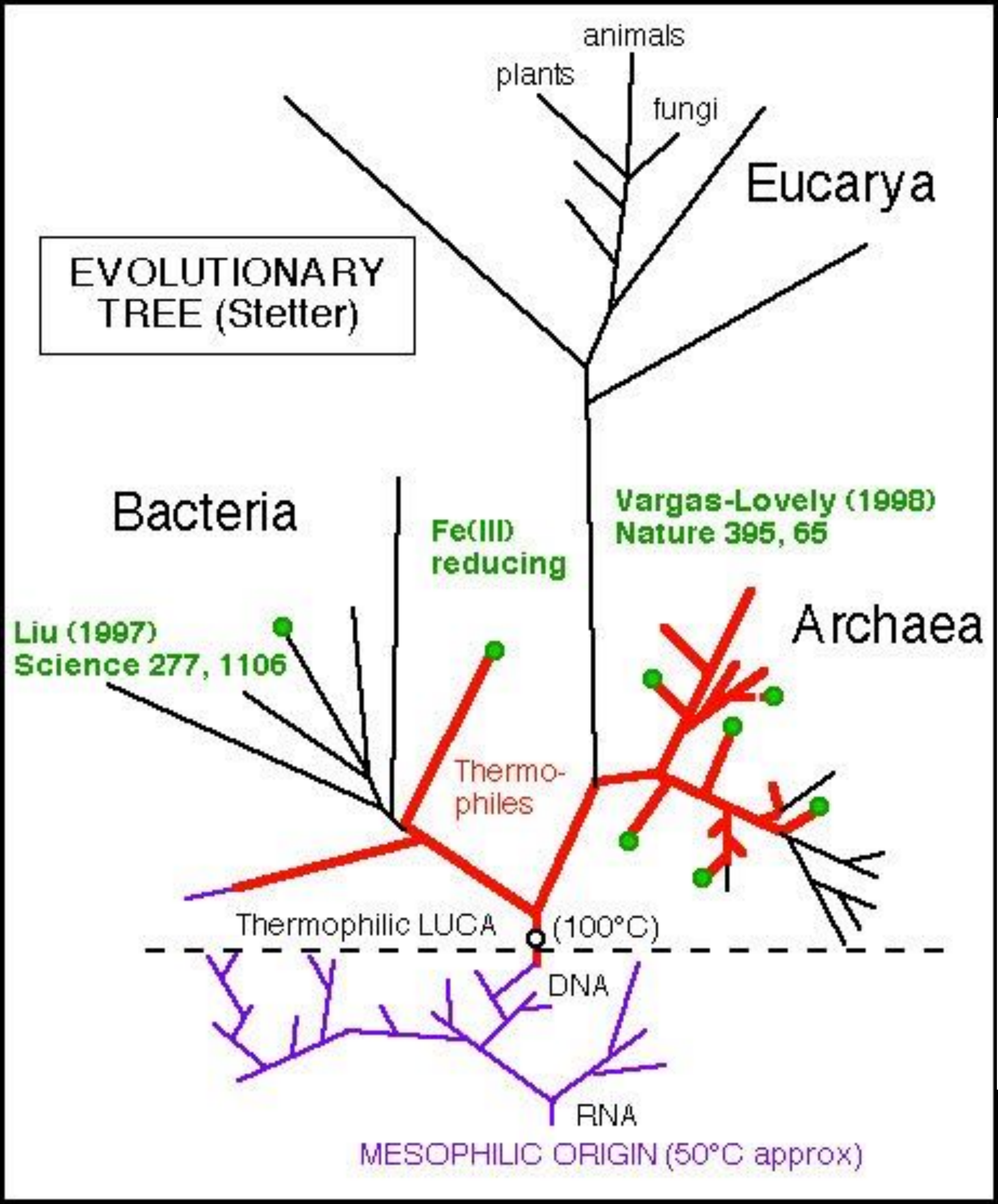
Typical conditions on Earth (and early Earth)

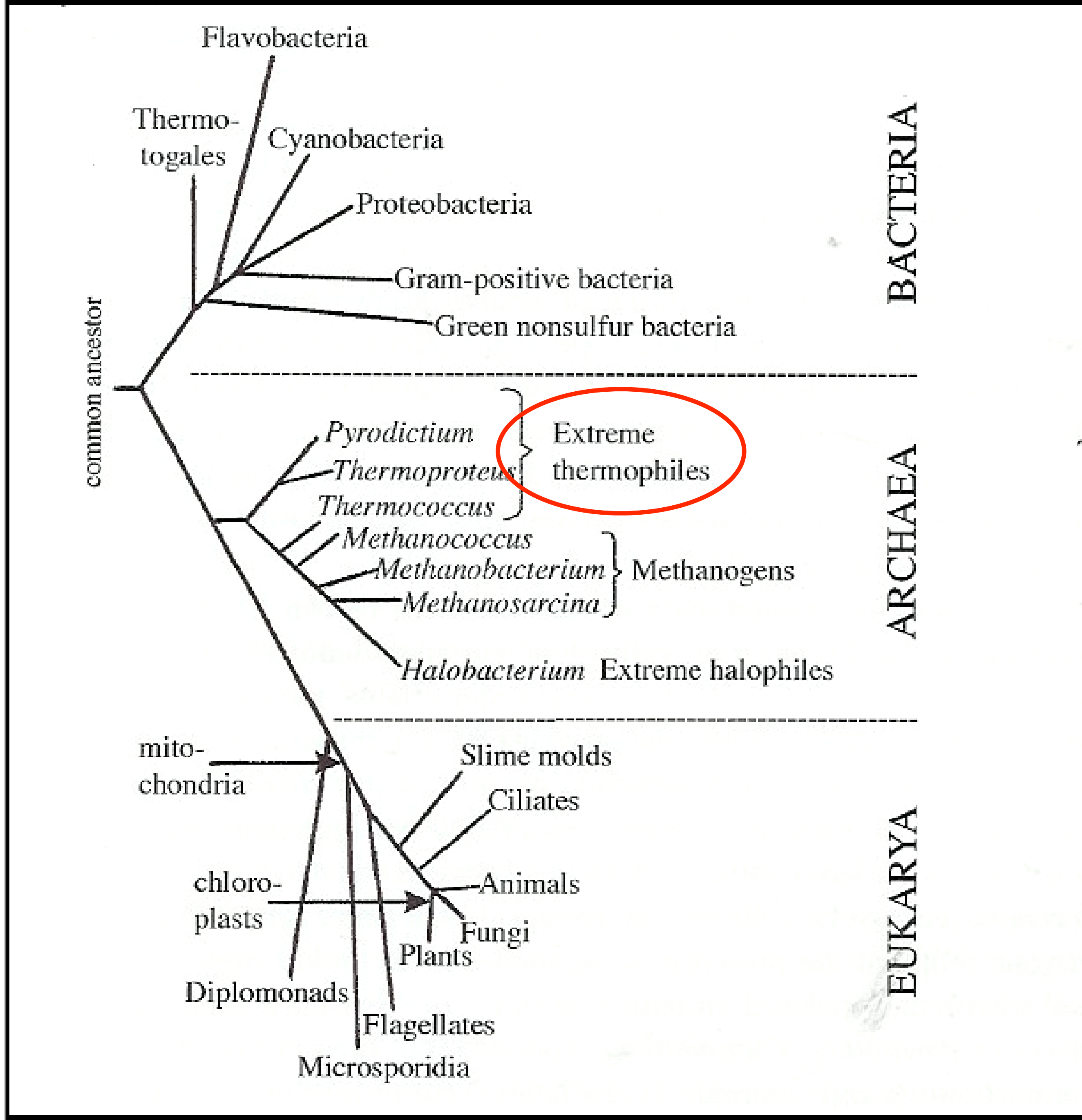
Oceans: ~2-4 ^{o}C

Sub-surface: > 50 ^{o}C

Hydrothermal vents: ~100-400 ^{o}C

Deep Sea pressure: 300+ atm (tons /cm^2)


EVOLUTIONARY TREE (Stetter)
animals
plants
fungi
Eucarya
Bacteria
Fe(III) reducing
Vargas-Lovely (1998) Nature 395, 65
Liu (1997) Science 277, 1106
Archaea
Thermo-philes
Thermophilic LUCA
(100°C)
DNA
RNA
MESOPHILIC ORIGIN (50°C approx)


common ancestor
Flavobacteria
Thermo-togales
Cyanobacteria
Proteobacteria
Gram-positive bacteria
Green nonsulfur bacteria
BACTERIA
Pyrodictium
Thermoproteus
Thermococcus
Extreme thermophiles
Methanococcus
Methanobacterium
Methanosarcina
Methanogens
Halobacterium
Extreme halophiles
ARCHAEA
mito-chondria
Slime molds
Ciliates
chloro-plasts
Animals
Fungi
Plants
Diplomonads
Flagellates
Microsporidia
EUKARYA

Only two conditions manage to wipe out ALL life:

- Absence of water
- Extreme temperatures

Organisms have adapted to all other extremes on Earth:

- Pressure
- Acidity
- Salinity
- Radiation
- Toxicity

Strategies

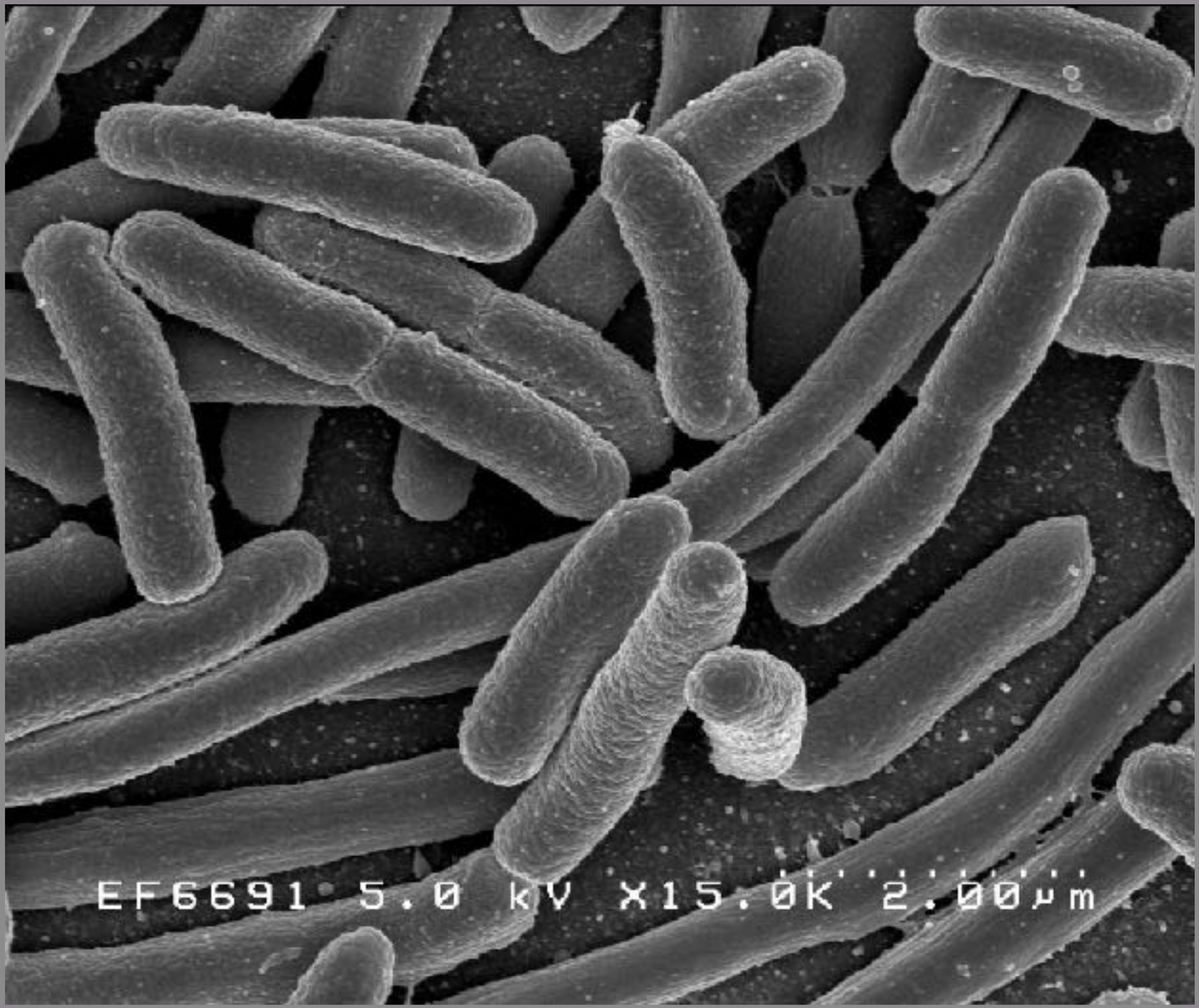
Temperature/Pressure:
affect cytoplasm

adapt intracellular structure, biosynthesis, metabolism

pH, salinity, irradiation, toxicity:
cell can be shielded

- maintain intracellular environment at “normal” level
- compensate extreme conditions

Escherichia Coli (E. Coli)



Generates up to 70% of its intracellular water by metabolic processes

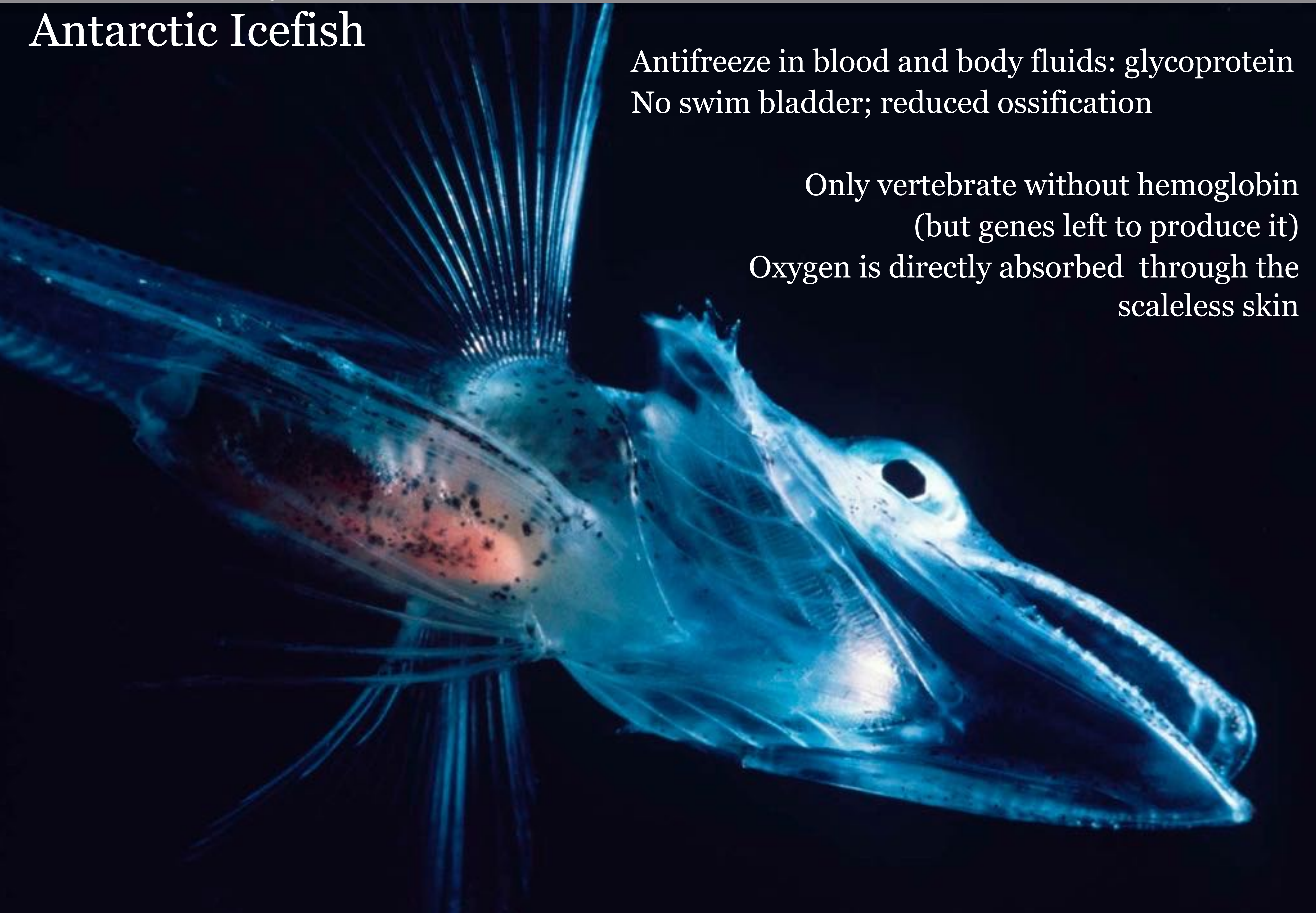
EHEC - Enterohemorrhagic E.coli

Channichthyidae
Antarctic Icefish

Cold (0°C) water fish, 1500m deep

Antifreeze in blood and body fluids: glycoprotein
No swim bladder; reduced ossification

Only vertebrate without hemoglobin
(but genes left to produce it)
Oxygen is directly absorbed through the scaleless skin

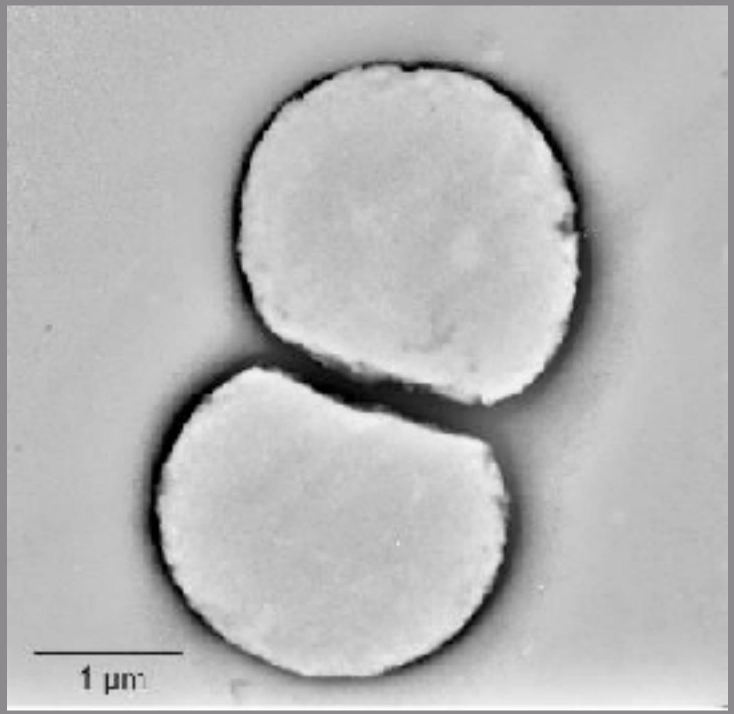


high pH: Alkaliphiles

pump protons (H^+, in form of H_3O^+) in
→ retain intracellular pH~8

low pH:
pump protons out → retain intracellular pH>4

picrophilus oshimae
(archea)

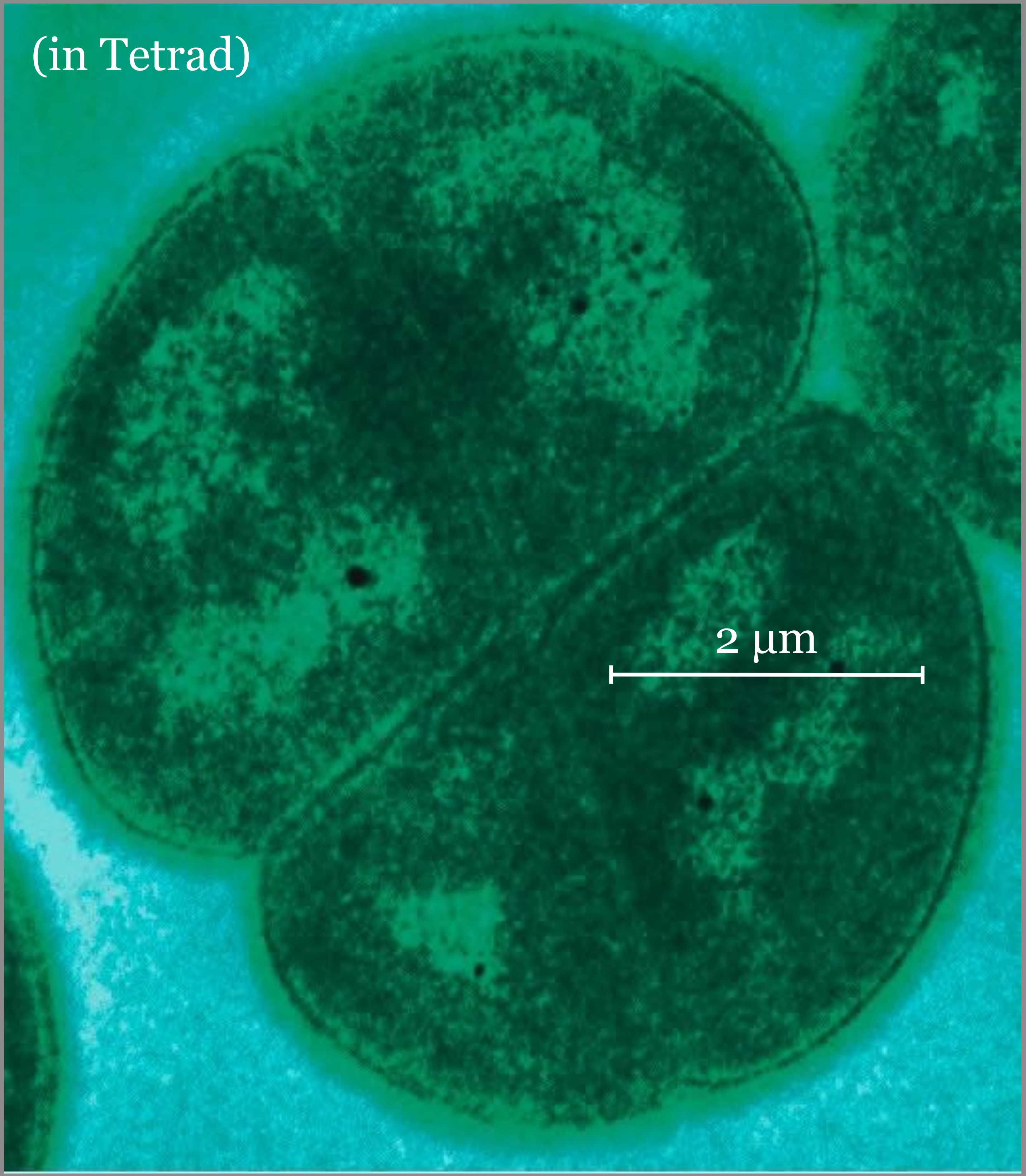


- grows at pH~0, does not at pH~3
- 90% of the genome (1.5Mbp) code proteins
- intracellular pH~4.5 → pH gradient
- use proton-motor rather than ATP

high pressure: Barophiles

Pressure poses no problems to organisms that adapted to deep sea levels (up to 11.000 m)
Intracellular pressure/stability is increased

Deinococcus radiodurans



- Sustains up to 30.000 Gy! (On Earth: 0.1-200mGy/yr)
- 8-10 copies of genome (two circular chromosomes)+ DNA repair in < 1 day
- probably developed as defense against desiccation

TABLE 14.2 Limits to microbial growth and survival at the extreme environmental conditions on Earth

Parameter	Most extreme value for growth	Most extreme value for tolerance	Environments
High temperature	121 °C; strain 121 113 °C; *Pyrolobus fumarii*	>120–200 °C in hydrothermal sulfides; brief exposure to 300 °C fluids	Submarine hydrothermal systems; geothermal hot springs (e.g., Yellowstone)
Low temperature	<−12 °C; pure cultures ∼−15 °C; growth detected (see Chapter 15)	∼−20 °C; respiration/ protein synthesis in sea ice brine channels; preservation by freezing at −196 °C	Brine pockets in sea ice at ∼−30 °C
Acid pH	pH 0; acidophilic Archaea, e.g. *Picrophilus* sp. & *Ferroplasma* sp.	not definitively explored	acid mine drainge, solfataric sites
Alkaline pH	pH 13; *Plectonema* pH 10.5; *Natrobacterium*	not definitively explored	soda lakes, serpentinization associated systems (e.g., Lost City Field, mud volcanoes)
High pressure (hydrostatic)	>102 MPa; activity at 1.06 GPa	survival at 1.6 GPa	11,000 m water depth; Challenger Deep, Marianas Trench
Low water activity	$a_w = 0.75$; ∼35% NaCl halophilic Archaea and Eubacteria $a_w = 0.62$; yeast	dessication; preservation by freeze-drying	soda lakes, evaporite ponds, deep-sea brines, dry soils/ rocks, foods with high solute content (e.g., jams, honey, dried fruit)
Ionizing radiation	60 Gray h^{-1} *Deinococcus radiodurans*	15,000 Gray gamma-ray irradiation; *Deinococcus radiodurans* & *Chroocidiopsis* (cyanobacterium) (see Table 14.3)	nuclear waste (no natural sources at this level)
Solar radiation (ultraviolet, visible)	phytoplankton cyanobacteria	100 J m^{-2} *Deinococcus radiodurans*	high altitudes low latitudes
Toxic heavy metals	millimolar concentrations of As, Cd, Zn, Ni, and Co tolerated by many species of Archaea and Eubacteria	not definitively explored	submarine hydrothermal vents; acid mine drainage

Sources: Holland and Baross (2003); Rothschild and Mancinelli (2001).

Surviving Space Travel

How long would be the trip on a comet from a nearby solar system?


DON'T
PANIC
The Hitchhikers Guide to the Galaxy

Transport life within the Solar System?

Panspermia

Survive:

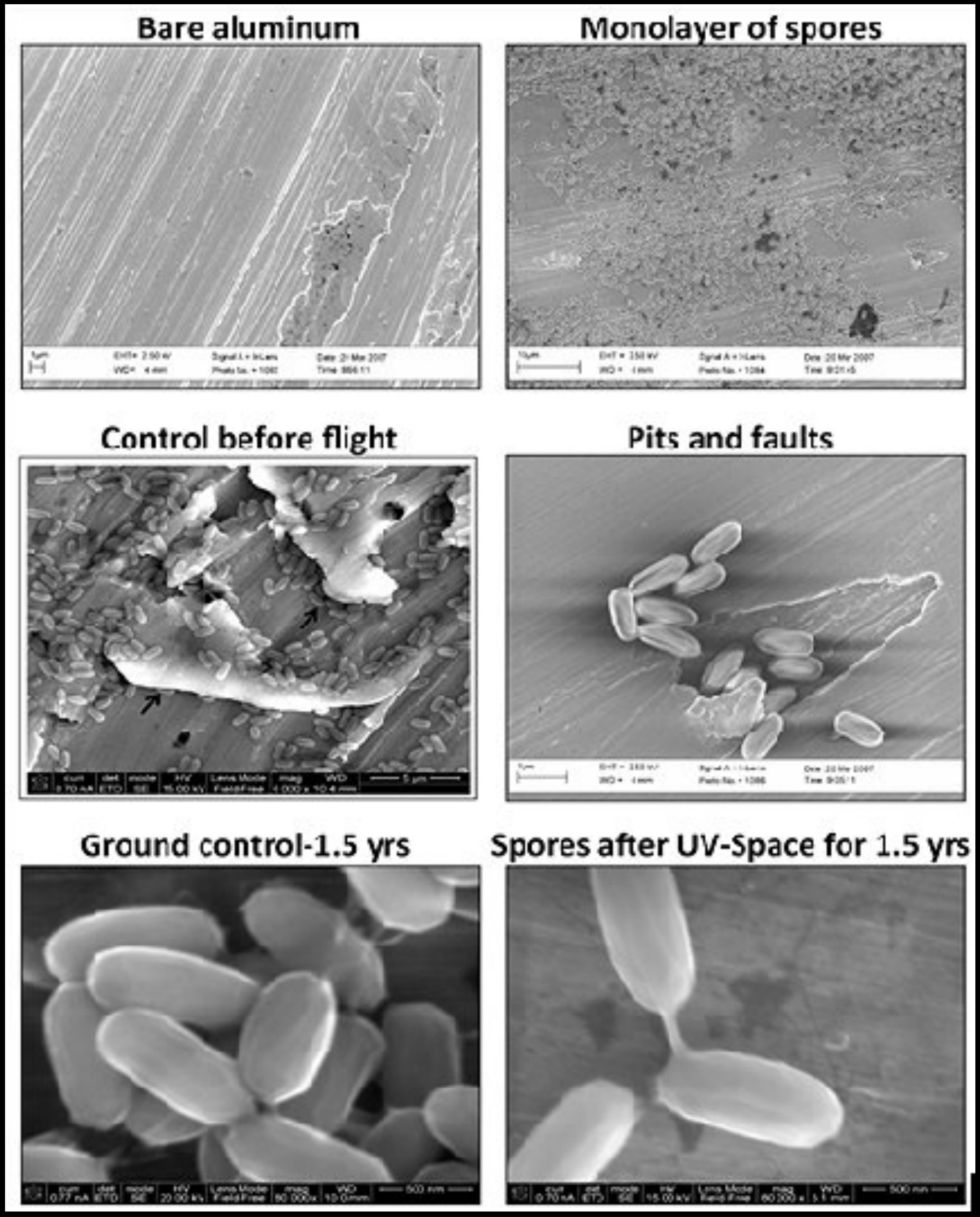
- Ejection (about 10% reach other planets)
  Simulated ballistically and in centrifuges
- Travel (e.g. Earth-Mars 10 Myr)
  e.g. ESA/NASA EXPOSE experiments
- Re-entry/landing (burn or impact)
  e.g. ESA STONE experiment

+ Find a habitable place after landing
  (ideally sink in ocean to sediment)

Spores shown to:

- survive 25 Myr
- survive at >150 ^{o}C for >1h
- survive high impact

Bacillus subtilis



NASA/ESA EXPOSE program

~2 years outside ISS

Survival increases if embedded (e.g. in salt crystals, in rocks)

Biofilms also survive extreme conditions

Panspermia is likely

The End for Today

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

Homework:

- Watch David Attenborough's 'First Life', episode 1: Arrival (58 minutes) & episode 2: Conquest (58 minutes)

- Netflix: Life on our Planet (episode 2)

Thank you!