On the

Origin of Life

Charles Marshall

Integrative Biology, Museum of Paleontology

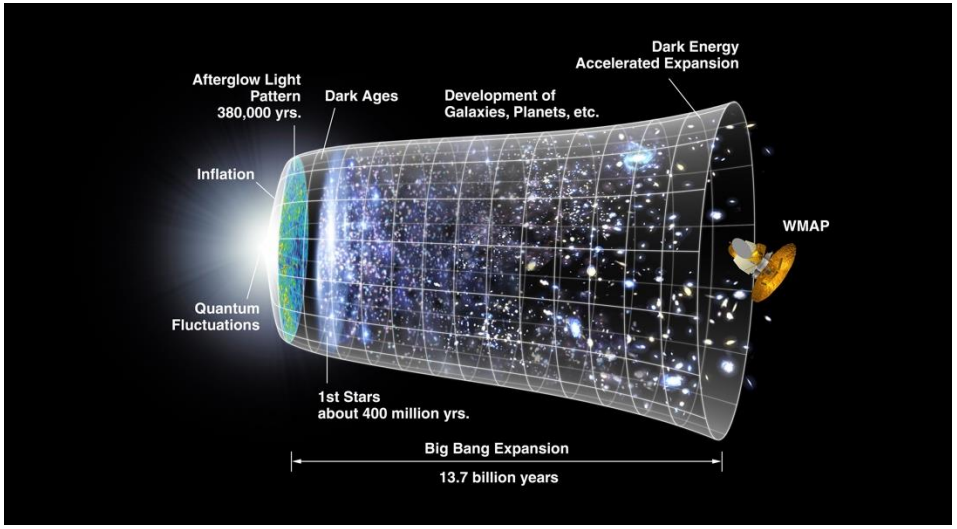
BBC

How life on Earth really got its start.

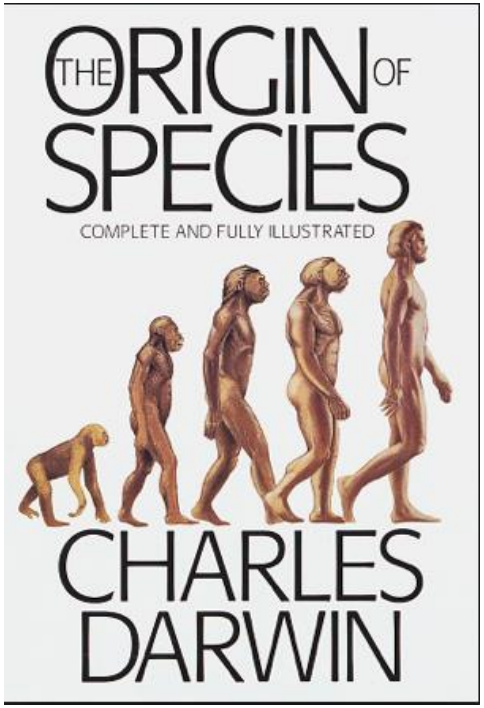
Undergraduate Non-Majors' Course

Origins: From the Big Bang to the Emergence of Humans

Profs. Eliot Quataert (Astronomy)



Charles Marshall (Biology)



Understanding the Origin of Life

A very hard problem, because:

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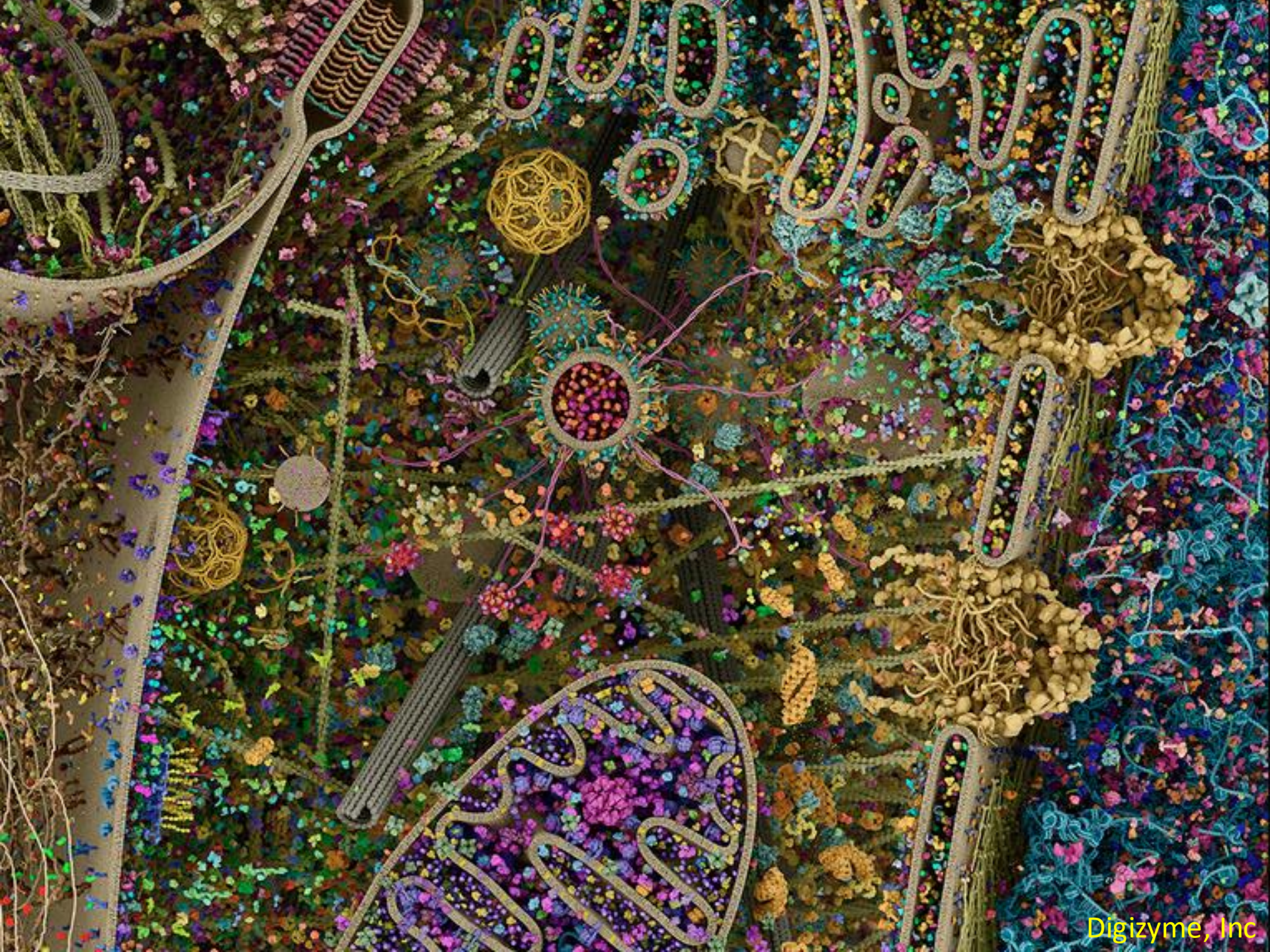
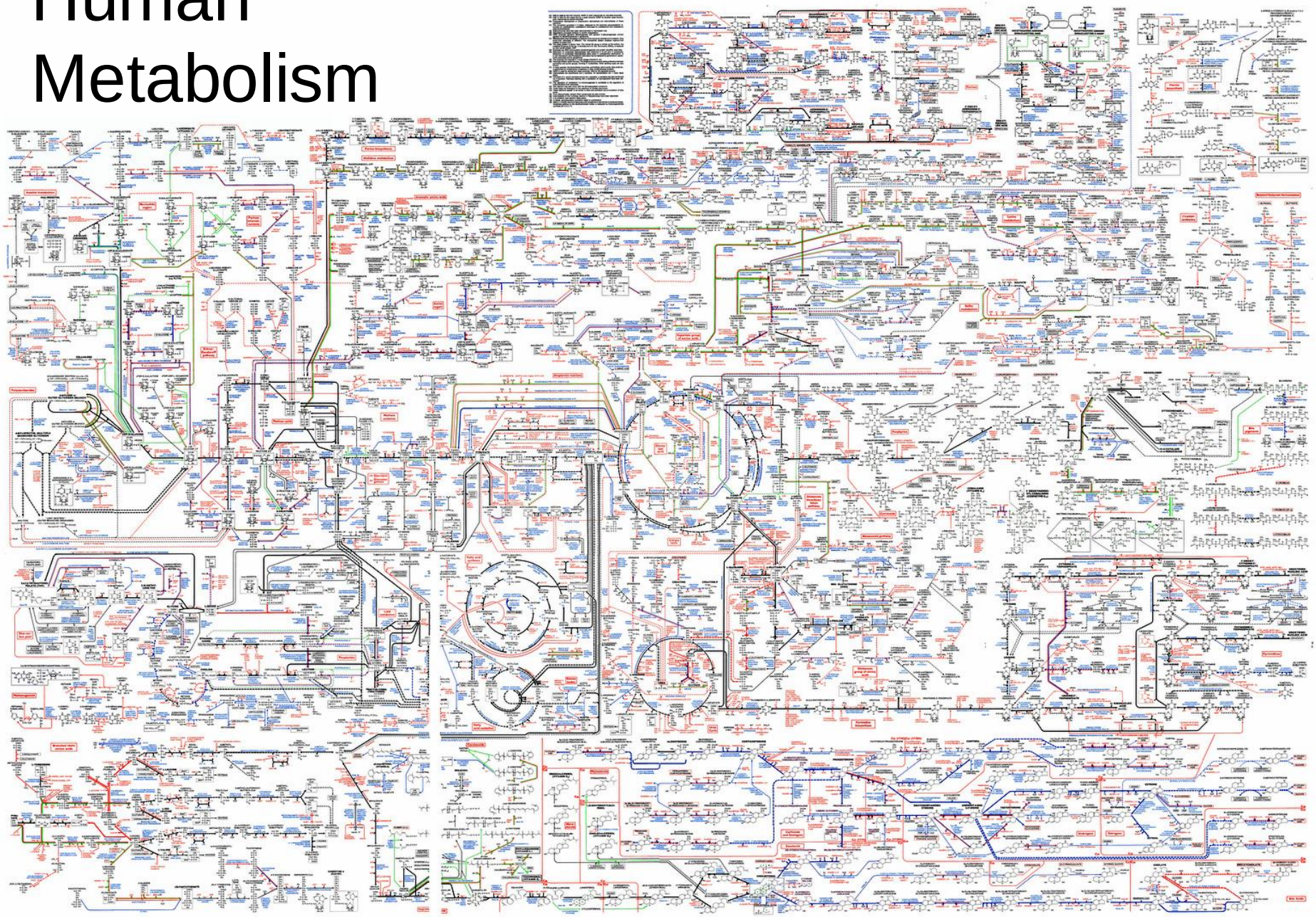
- Organisms are very complex (especially when viewed from the bottom up).


Digizyme, Inc

Human Metabolism



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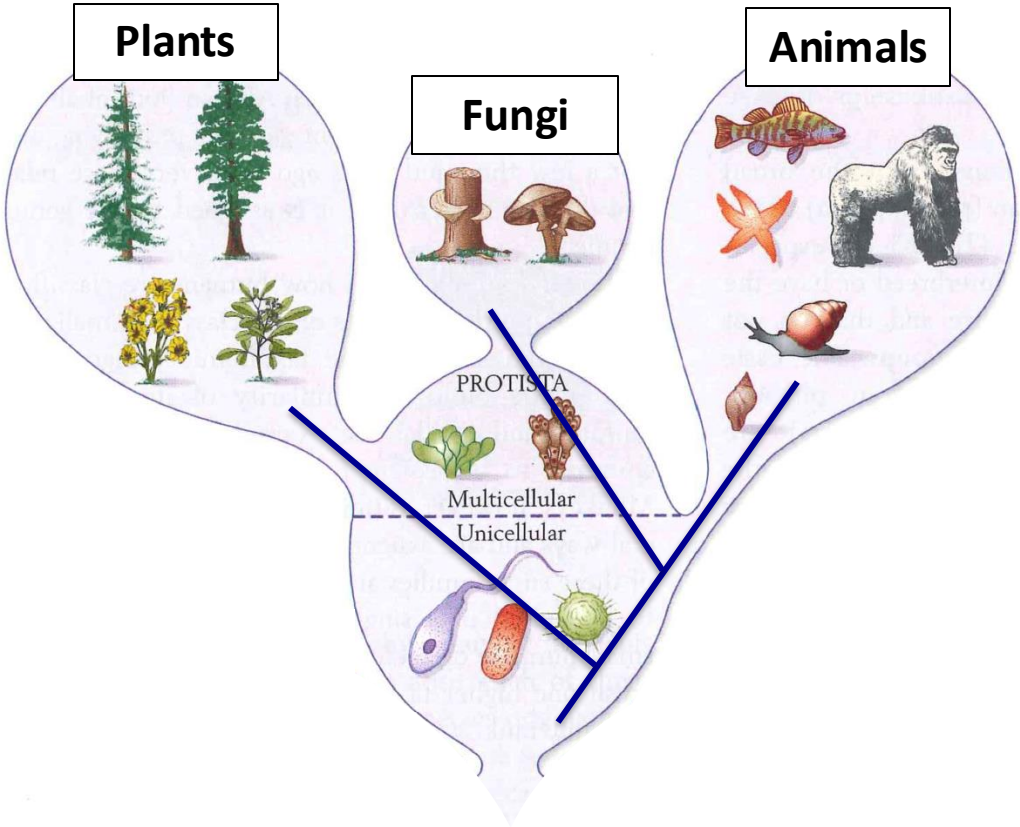
- The conditions on Earth were fundamentally different from now:
  - there was no free oxygen (which is destructive of complex molecules)
  - there was no life

Guessing what first life was like: Working back in time on the Tree of Life



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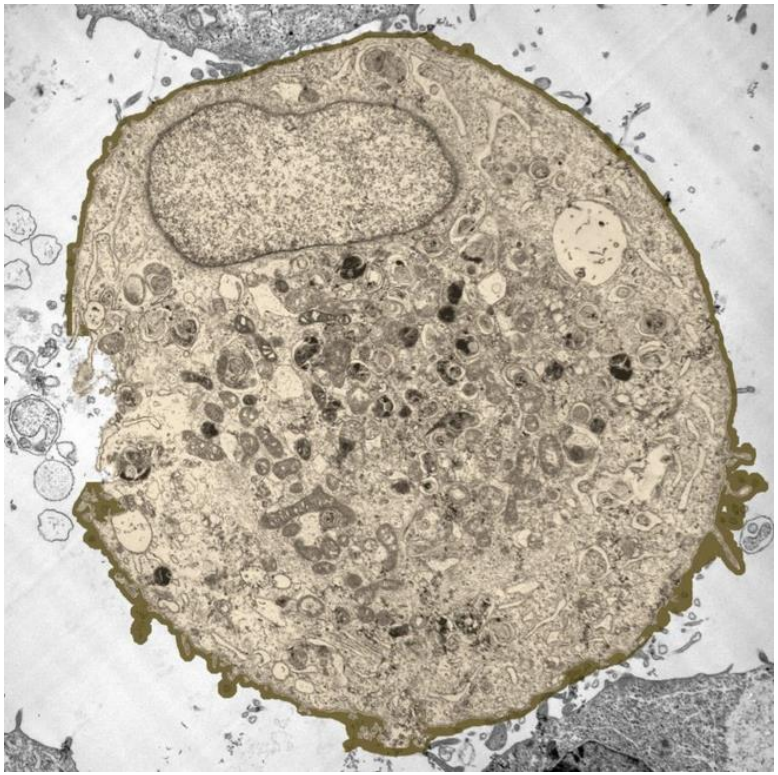
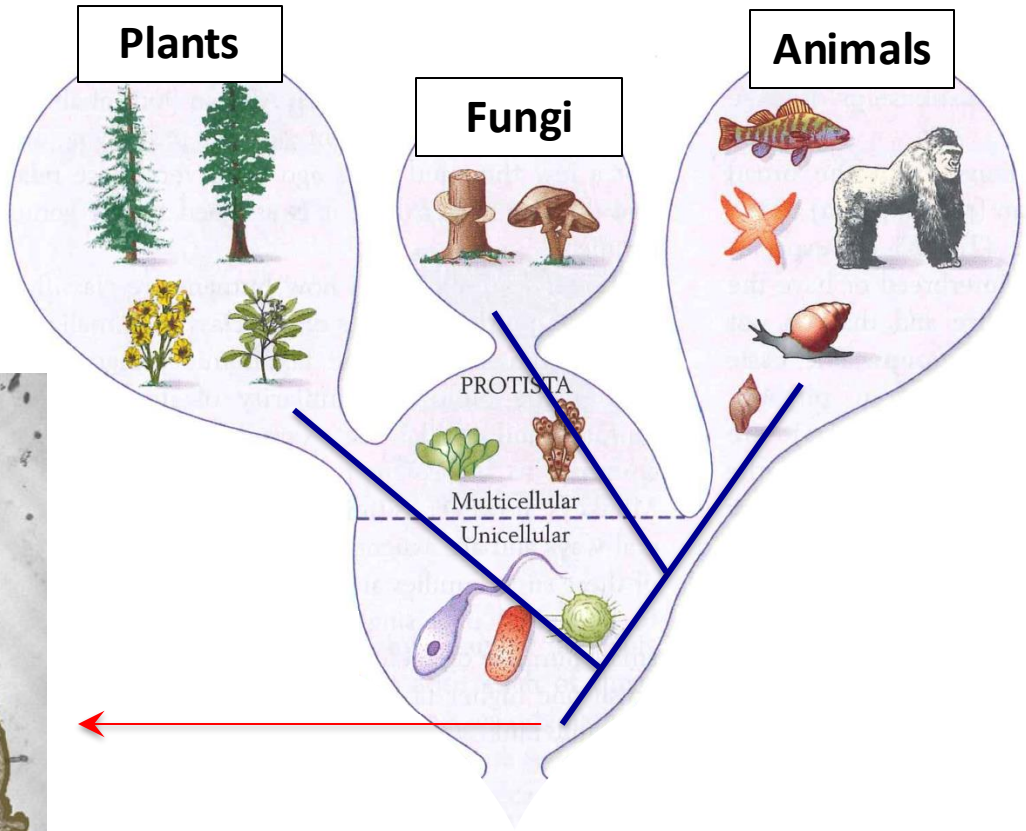
Eukaryotic cell





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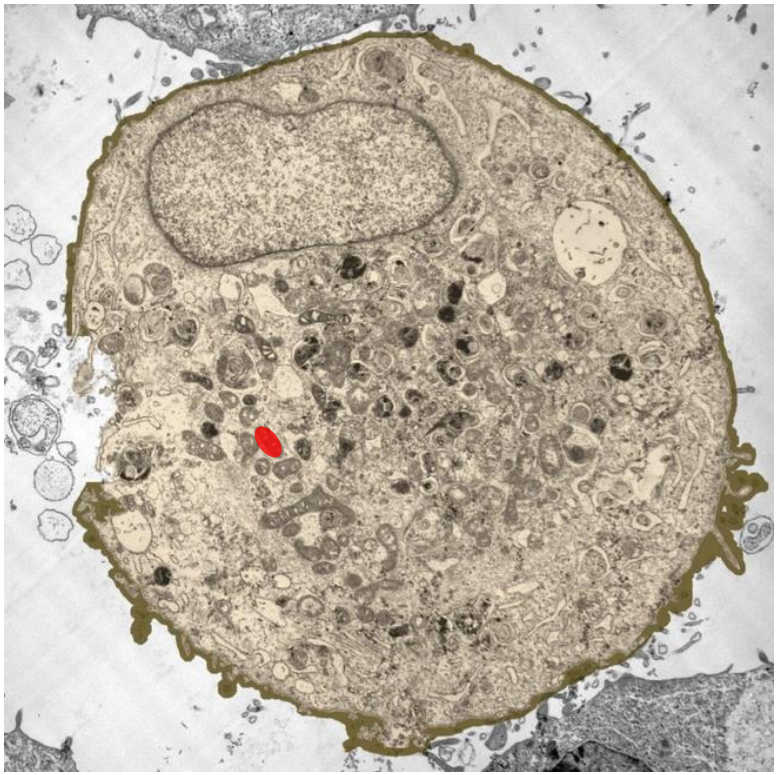
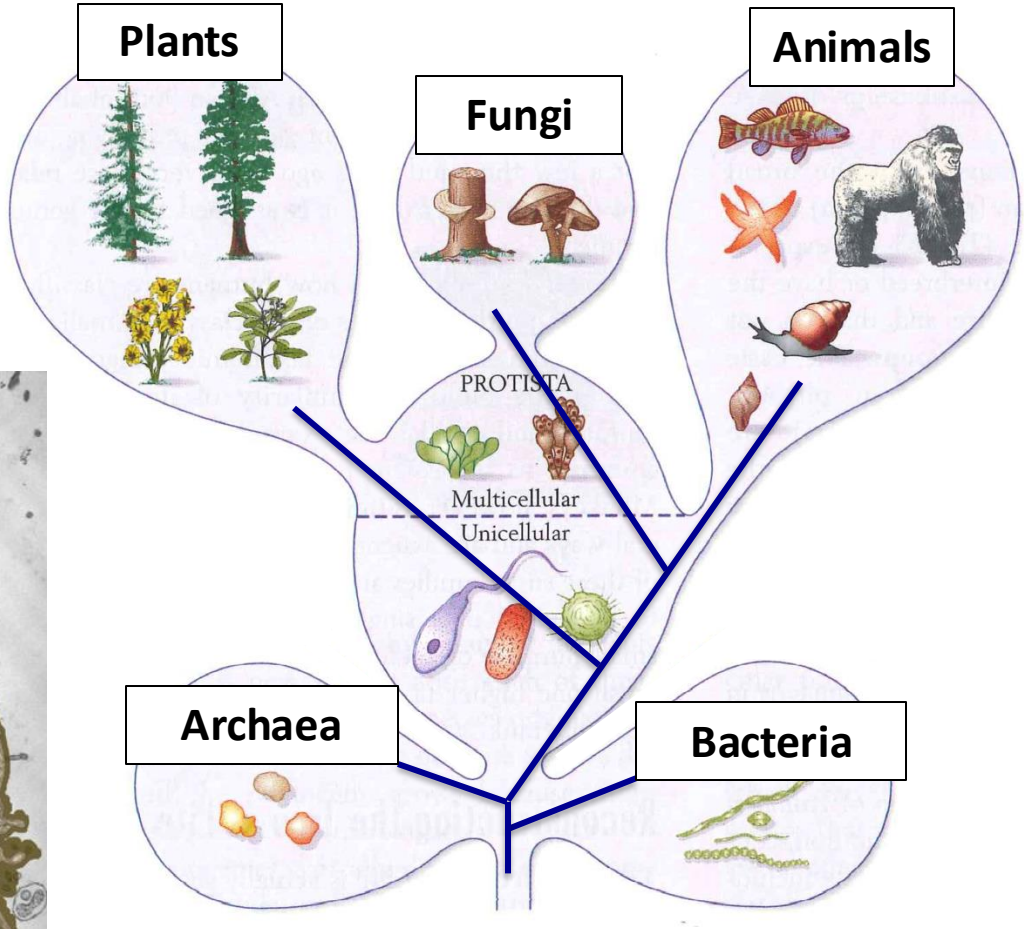
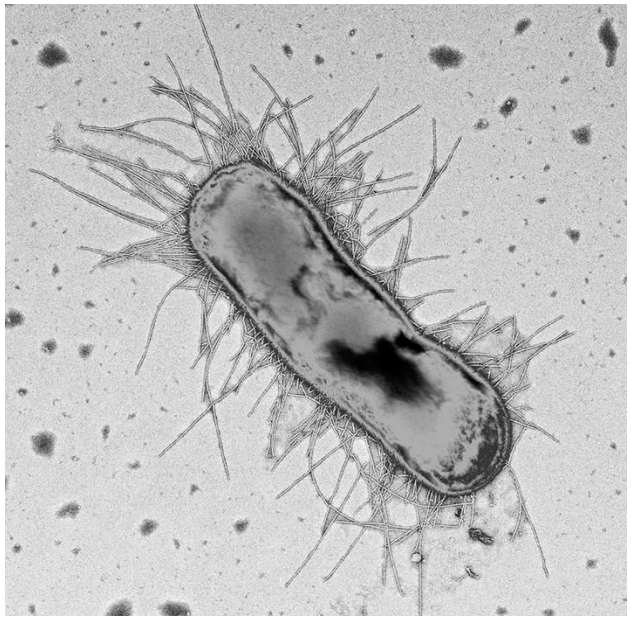
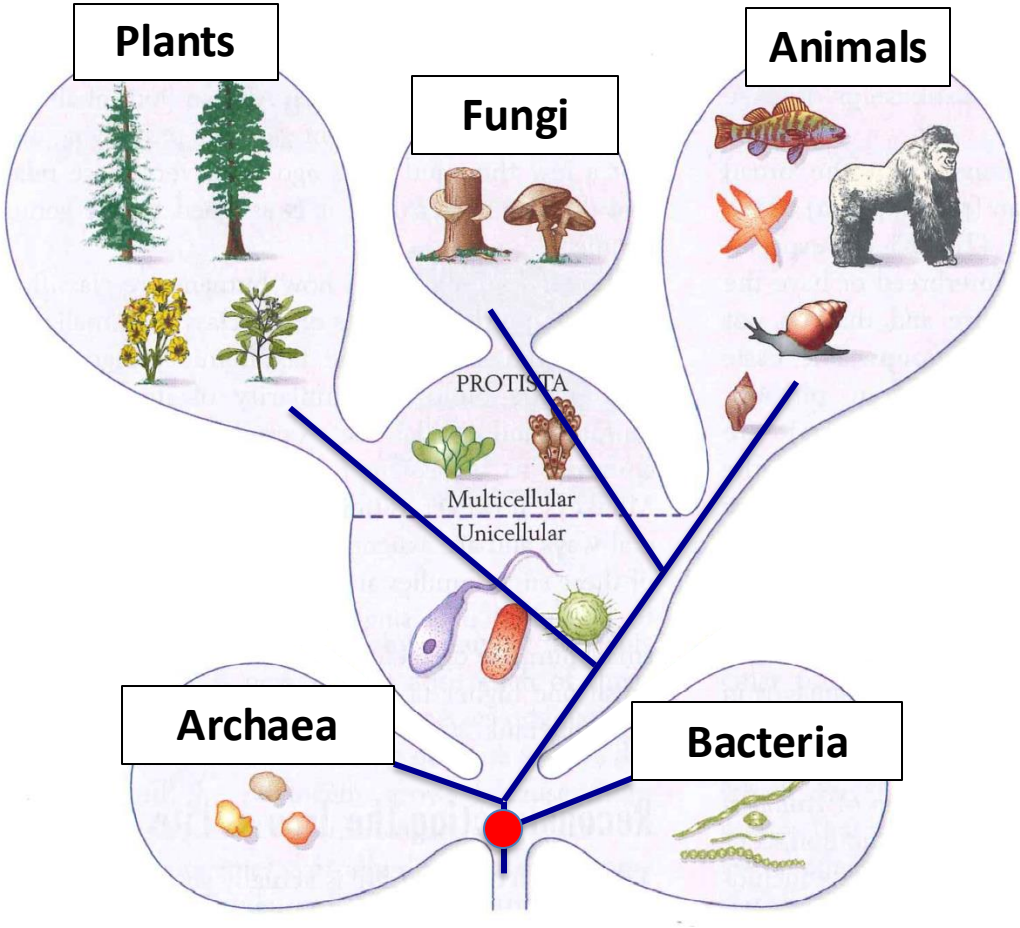




Guessing what first life was like: Working back in time on the Tree of Life

Prokaryotic cell

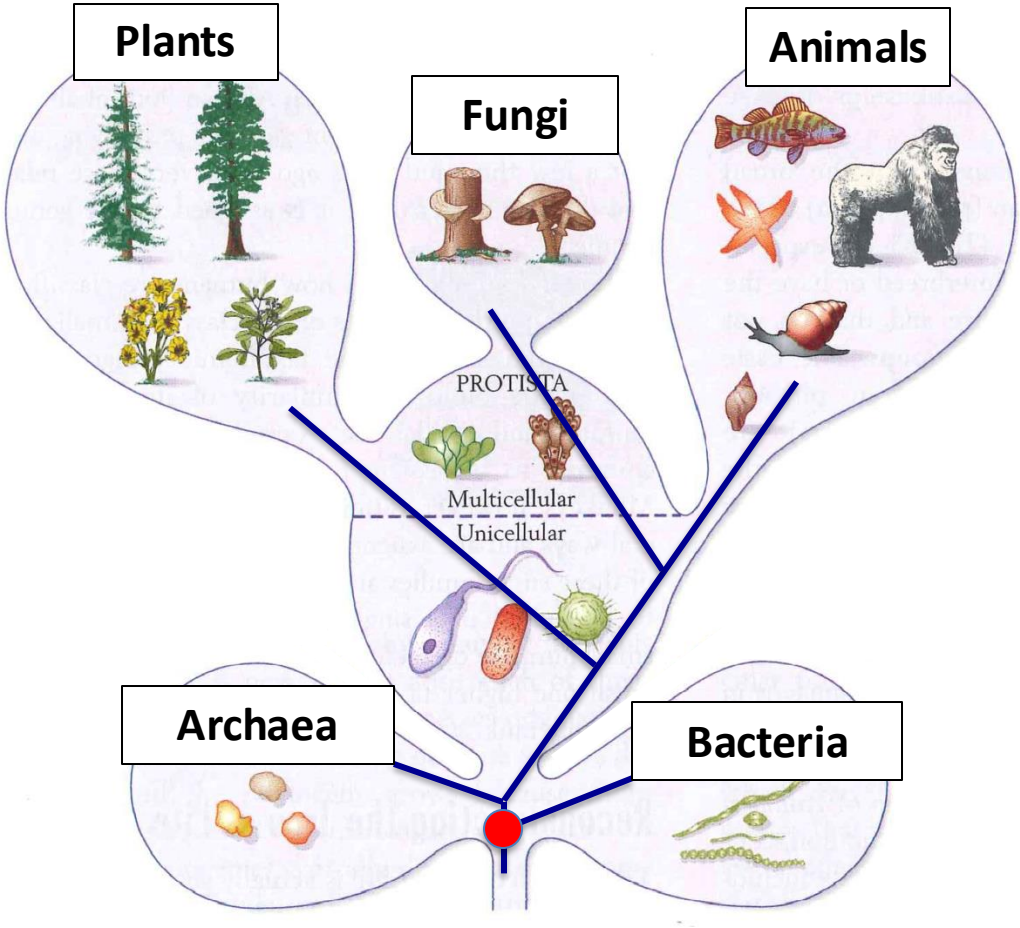




Last (Universal) Common Ancestor (LUCA) of Life

Guessing what first life was like: Working back in time on the Tree of Life

Inference: LUCA was a single celled prokaryote



Last (Universal) Common Ancestor (LUCA) of Life

Cross section through *E. coli*

Magnification = 1,000,000-fold

Individual atoms are about the size of a grain of salt

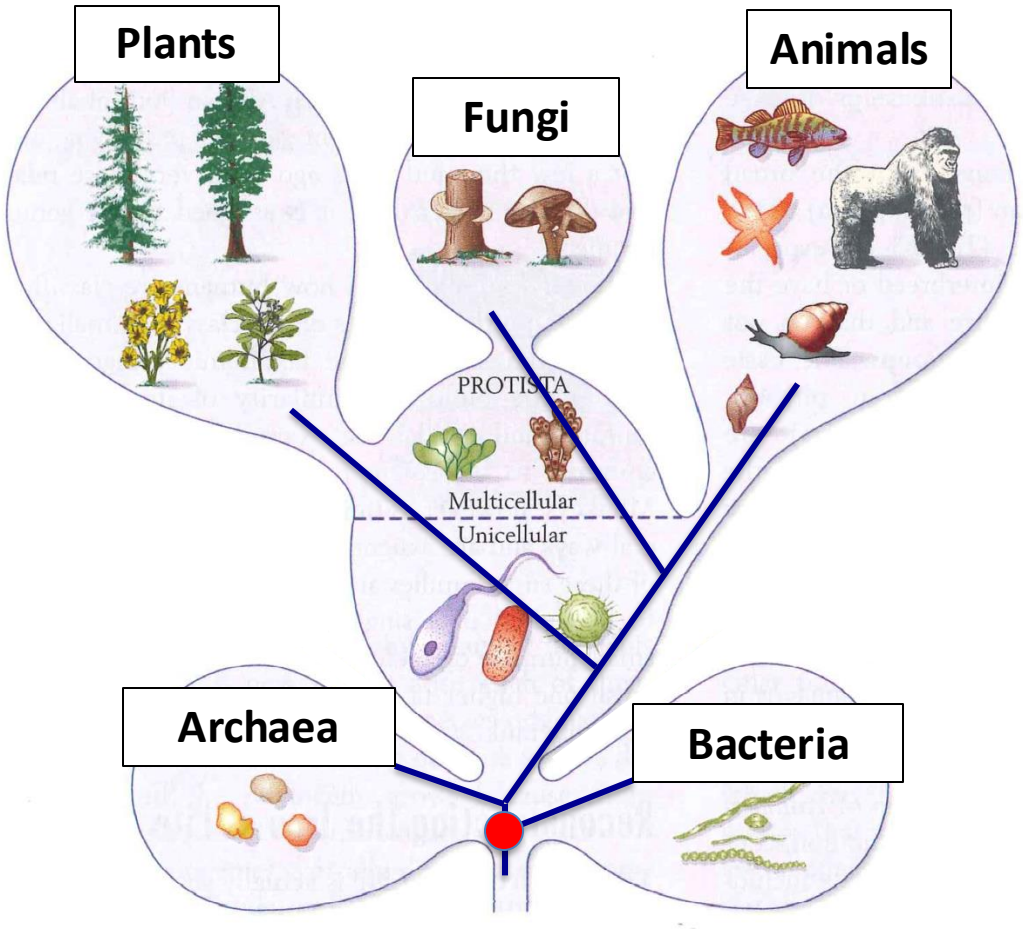
Cell wall

David Goodsell (2009). *Escherichia coli.* **Biochemistry and Molecular Biology Evolution** 37:325-332

Guessing what first life was like: Working back in time on the Tree of Life

Inference: LUCA was a single celled prokaryote

But: 1st organisms must have been *much* simpler than LUCA



Last (Universal) Common Ancestor (LUCA) of Life

Important fact: cell walls and membranes of Archaea and Bacteria have different compositions

Cliff Brunk
(UCLA, emeritus)

How life on Earth really got its start.

Origin of the Life: not on Earth?

- Maybe life originated elsewhere.
- Motivation for the idea: Maybe the reason it is so hard to explain the origin of life on Earth is because it didn't happen here.
- Assuming life did originate elsewhere, how might it have gotten here?!

Meteorites from Mars!

- ~277 have been found!
- Their elemental and isotopic compositions match measurements made by NASA expeditions to Mars
- The thought is that they were blasted from Mars' surface, and were in space for 1–20 million years before falling to Earth

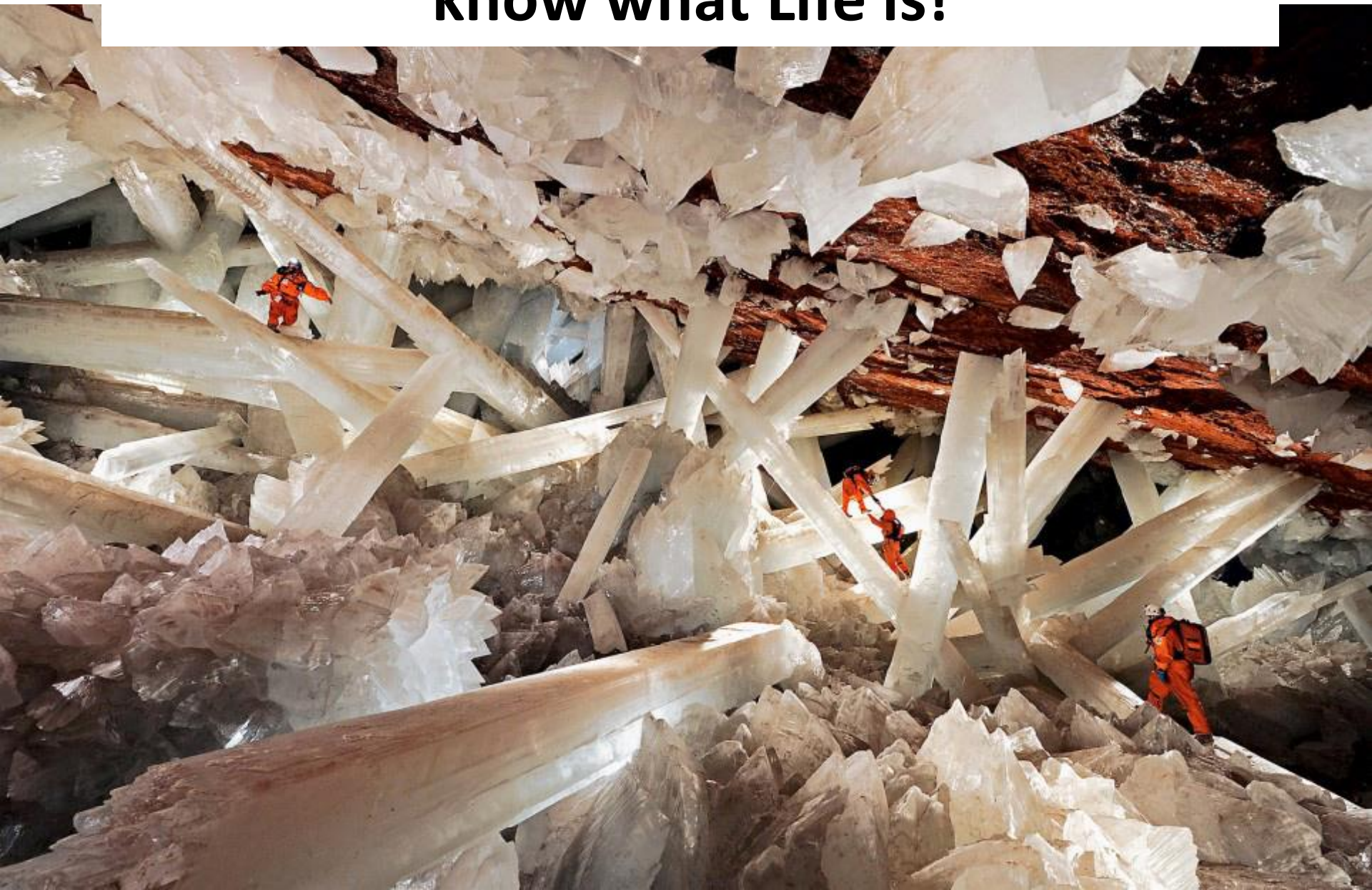
"Black Beauty": water rich; formed on Mars ~2.1 billion years ago

Our attempts to understand the origin of life have been **misdirected (to some extent) by our knowledge of living organisms**:

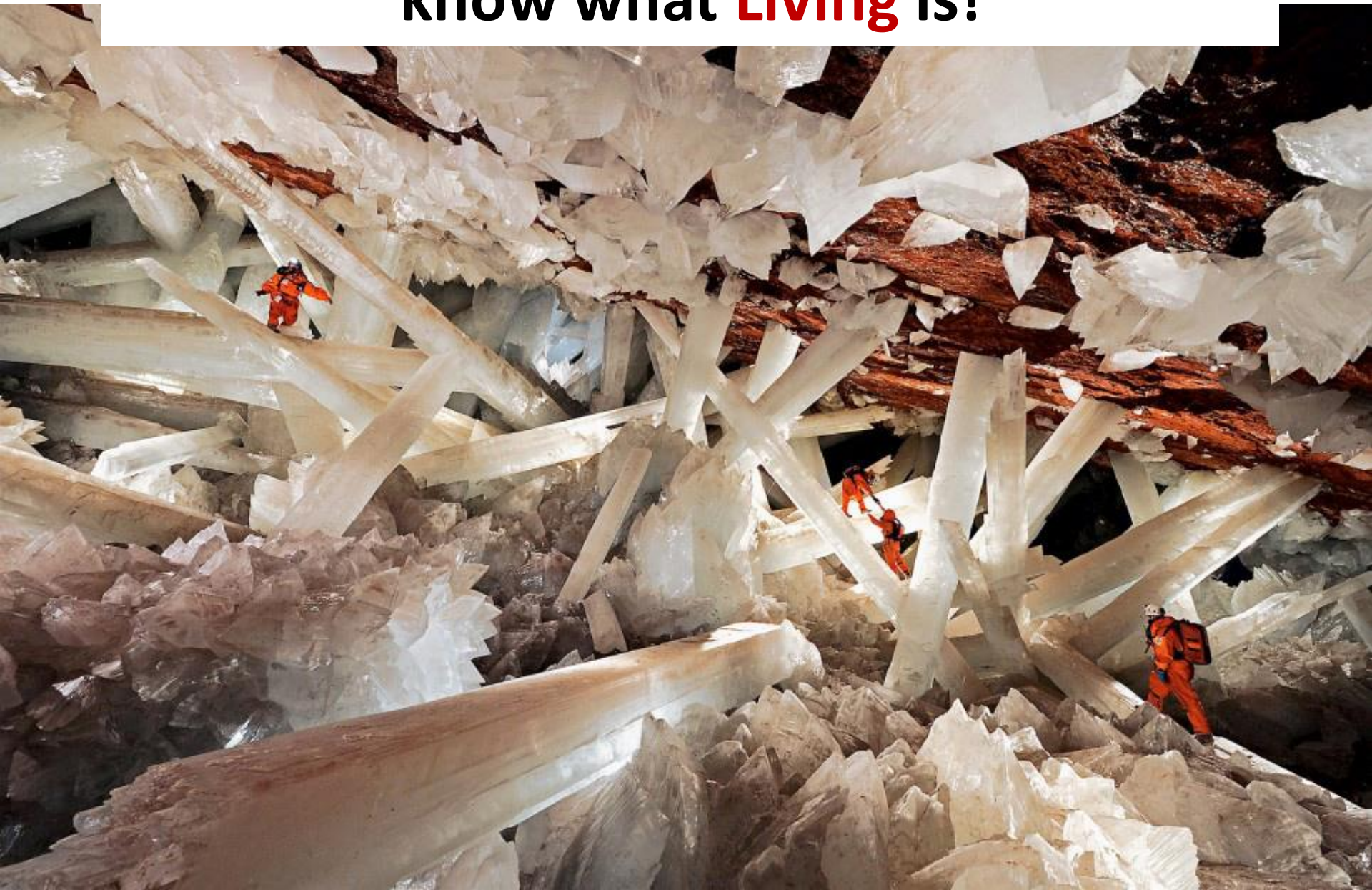
1) Almost all life today depends ultimately on sunlight via photosynthesis.
2) All life today is built around DNA and proteins.
3) All life today is made of cells.

We have begun to shed these shackles …

To Explain the Origin of Life we need to know what Life is!



To Explain the Origin of Life we need to know what Living is!



Attempts to explain the origin of life are typically reductionist in nature concentrating on the formation of life's key molecules.

Here I approach the origin of life **as a problem in evolutionary biology**, beginning with the **properties of whole organisms**, and relying on the fact that **evolutionary change is accretionary**, which means that we can use the idiosyncrasies of life today to help infer the nature of life's earliest stages.

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  - We depend on energy flow, in and out.
  - We depend on material flow, in and out.

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  - We depend on energy flow.
  - We depend on material flow.
- We are responsive, which usually means altering our internal state in response to the external state.
- We regenerate, and we reproduce.

To understand the **replication** of life we need need to know:

Life Builds from the Bottom Up

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  proteins ⟶ amino acids,

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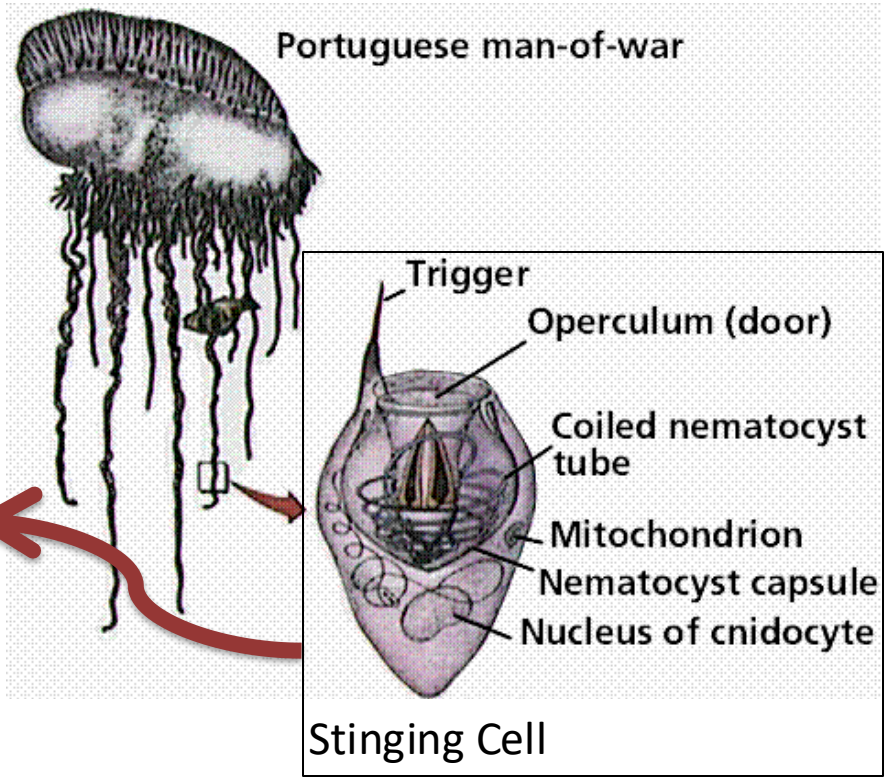
- Virtually nothing is ‘off the shelf’

Rare exception: some nudibranchs re-use the stinging cells of hydrozoans:

Nudibranch

Hydrozoan



Stinging Cell

How Life Copies Itself

- "Building from the bottom up" means the need for **instructions** for making proteins, etc.
- All living organisms achieve this using DNA.
- And there is a **machinery** for taking the instructions and converting them to protein.

Key Steps in the Origin of the Life
(of the type that we know)

0) We need the elements, the sun, and a rocky planet with water
1) Making the building blocks
2) Concentrating the building blocks
3) Making insides and outsides (cells)
4) Establishing the replication machinery
5) Harnessing energy

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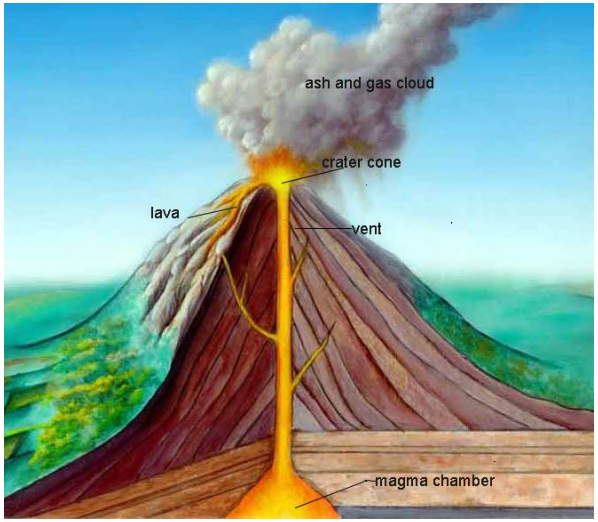
0) We need the elements, the sun, and a rocky planet with water

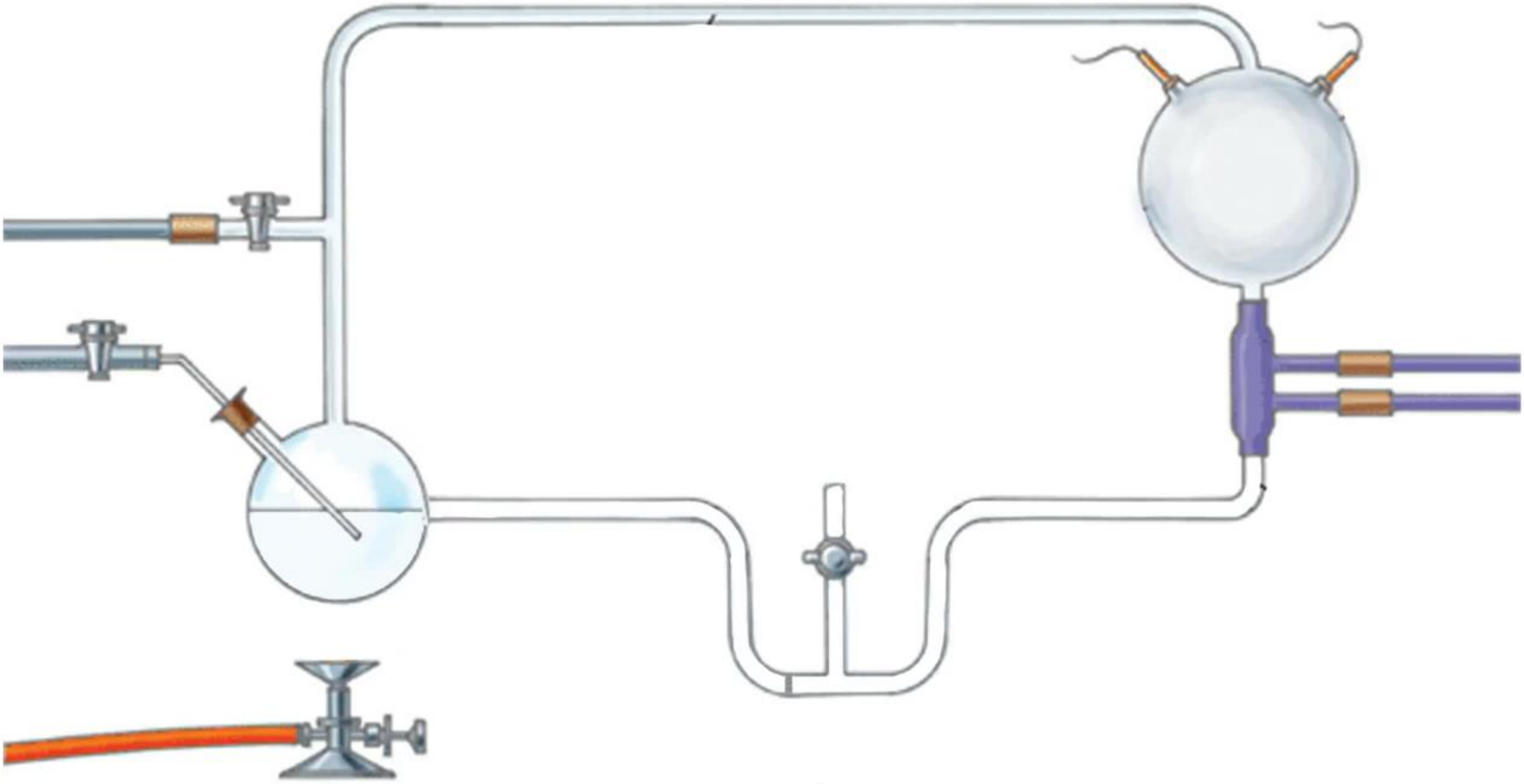
1) Making the building blocks

– The 1st guess was from volcanic gases

Carbon Dioxide (CO_2)
Nitrogen Gas (N_2)
Ammonia (NH_3)
Hydrogen Gas (H_2)
Methane (CH_4)
Water (H_2O)
Carbon Monoxide (CO)



Stanley Miller Experiment (1953)



The results of the Urey–Miller experiment (artificial lightning in a mixture of the gases NH_4, CH_3, H_2 , H_2O):

Molecule	Name	Relative Yield
H-COOH	Formic Acid	1000
H_2N-CH_2-COOH	Glycine	275
HO-CH_2-COOH	Glycolic acid	240
H_2N-CH(CH_3)-COOH	Alanine	150
HO-CH(CH_3)-COOH	Lactic acid	135
H_2N-CH_2CH_2-COOH	Beta-alanine	65
CH_3-COOH	Acetic acid	65
CH_3-CH_2-COOH	Propionic acid	55
CH_3-NH-CH_2-COOH	Sarcosine	20
HOOC-CH_2CH_2-COOH	Succinic acid	17
H_2N-CO-NH_2	Urea	9
HOOC-CH_2CH_2CH(NH_2)-COOH	Glutamic acid	2.5
HOOC-CH_2CH(NH_2)-COOH	Aspartic acid	1.7
etc., etc., …..		

Red = amino acids used by life

Molecule	Name	Relative Yield
H-COOH	Formic Acid	1000
H_2N-CH_2-COOH	**Glycine**	**275**
HO-CH_2-COOH	Glycolic acid	240
H_2N-CH(CH_3)-COOH	**Alanine**	**150**
HO-CH(CH_3)-COOH	Lactic acid	135
H_2N-CH_2CH_2-COOH	Beta-alanine	65
CH_3-COOH	Acetic acid	65
CH_3-CH_2-COOH	Propionic acid	55
CH_3-NH-CH_2-COOH	Sarcosine	20
HOOC-CH_2CH_2-COOH	Succinic acid	17
H_2N-CO-NH_2	Urea	9
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HOOC-CH_2CH(NH_2)-COOH	**Aspartic acid**	**1.7**
etc., etc., …..		

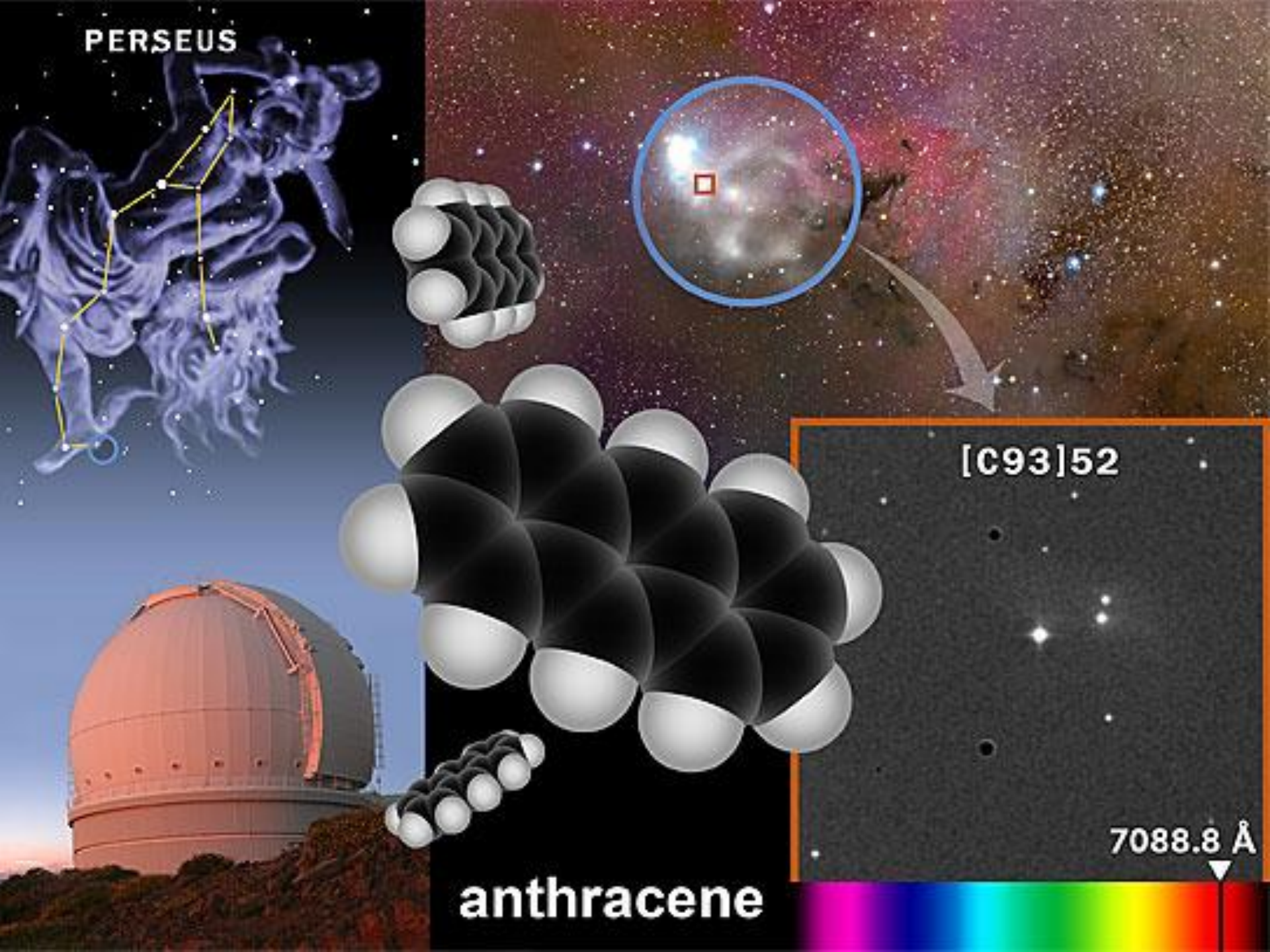
Making the building blocks:

- We now believe that the composition of the Earth's early atmosphere was not that used by Urey and Miller.
- Lightning is extremely violent and sporadic.
- How do you concentrate the building blocks??
- It seems harder to build the components of DNA and RNA, than for proteins and lipids ... (*but the discovery of nucleobases this year in the asteroid Bennu suggests perhaps not*).

Key Point

When energy flows through a system, thermodynamics predicts that there will be increased order, that is organization and complexity

Driven systems explore the improbable


PERSEUS
[C93]52
7088.8 Å
anthracene

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(of the type that we know)

0) We need the elements, the sun, and a rocky planet with water

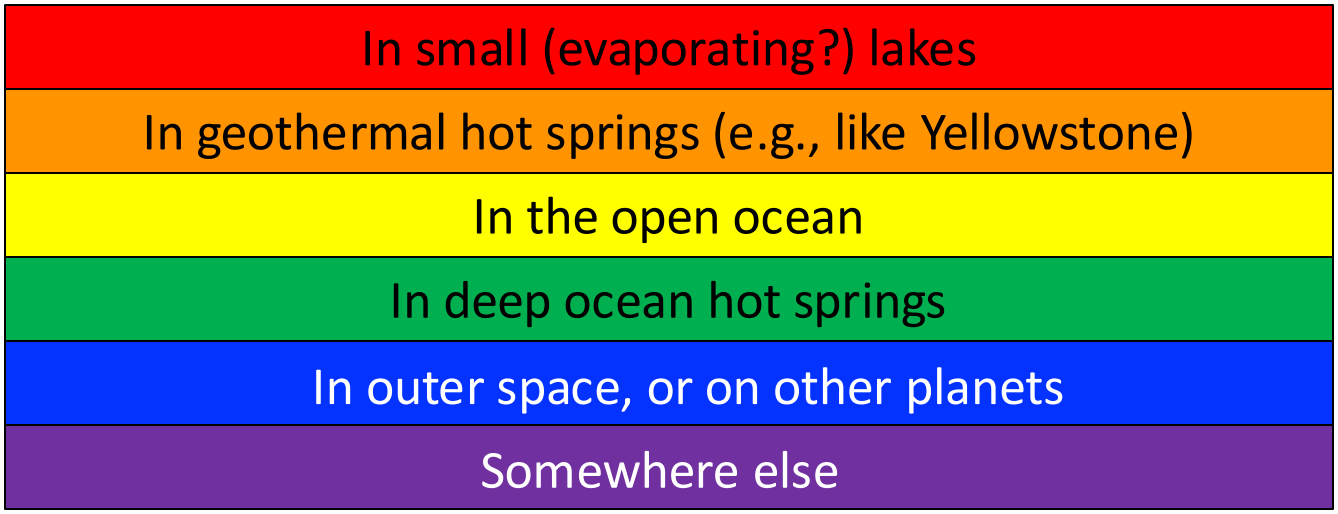
1) Making the building blocks

2) Concentrating the building blocks

Need restricted environments, or a way of actively concentrating the building blocks

Understanding how the building blocks were concentrated takes us to a central question: WHERE did life originate?

Where might life might have originated?



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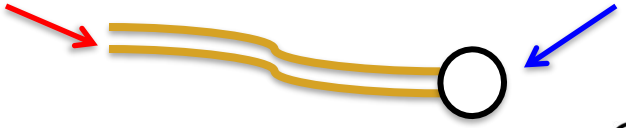
3) Making insides and outsides (cells)

(and getting the key molecules inside!)

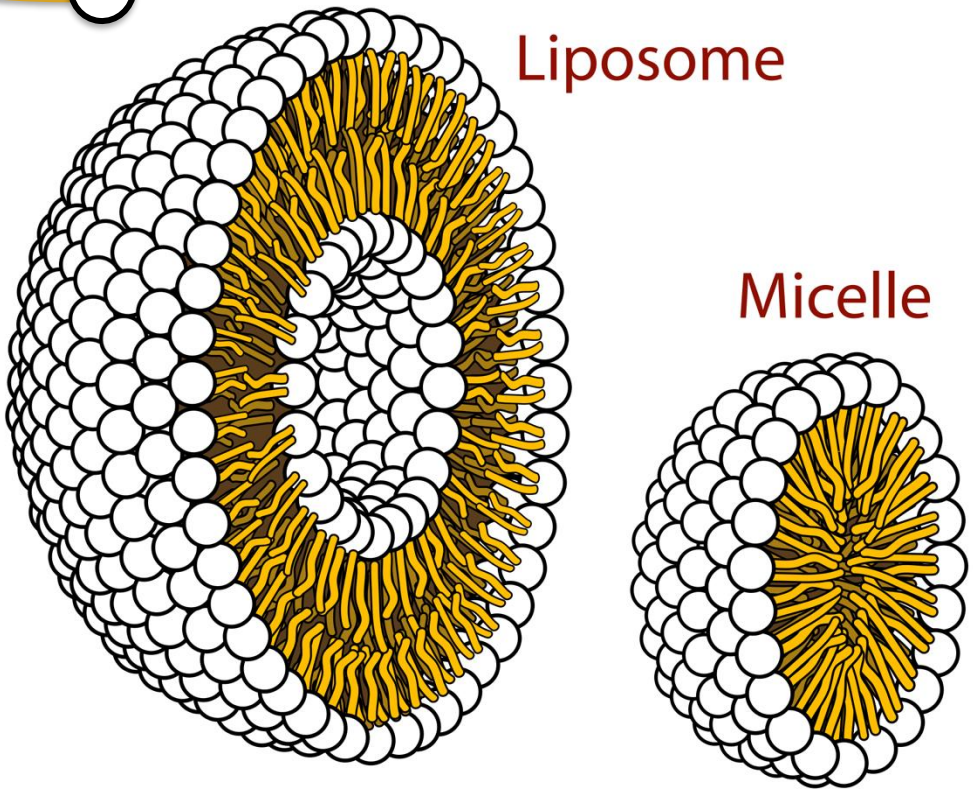
Making proto-cells

All that is needed are **linear** molecules that have one "**oily**" and one **water soluble** end:



The ease with which these can be made suggests the formation of cells was an early step.

Not at all obvious how energy and the right molecules got inside …



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The **"chicken and egg" problem** of **establishing replication**

- Cells needs proteins to read and replicate DNA.
- DNA is needed to make the proteins.
- Today's organisms **can't make protein without DNA**, but **can't make DNA without proteins**?

So, how did replication get started?!

This all changed with the discovery of

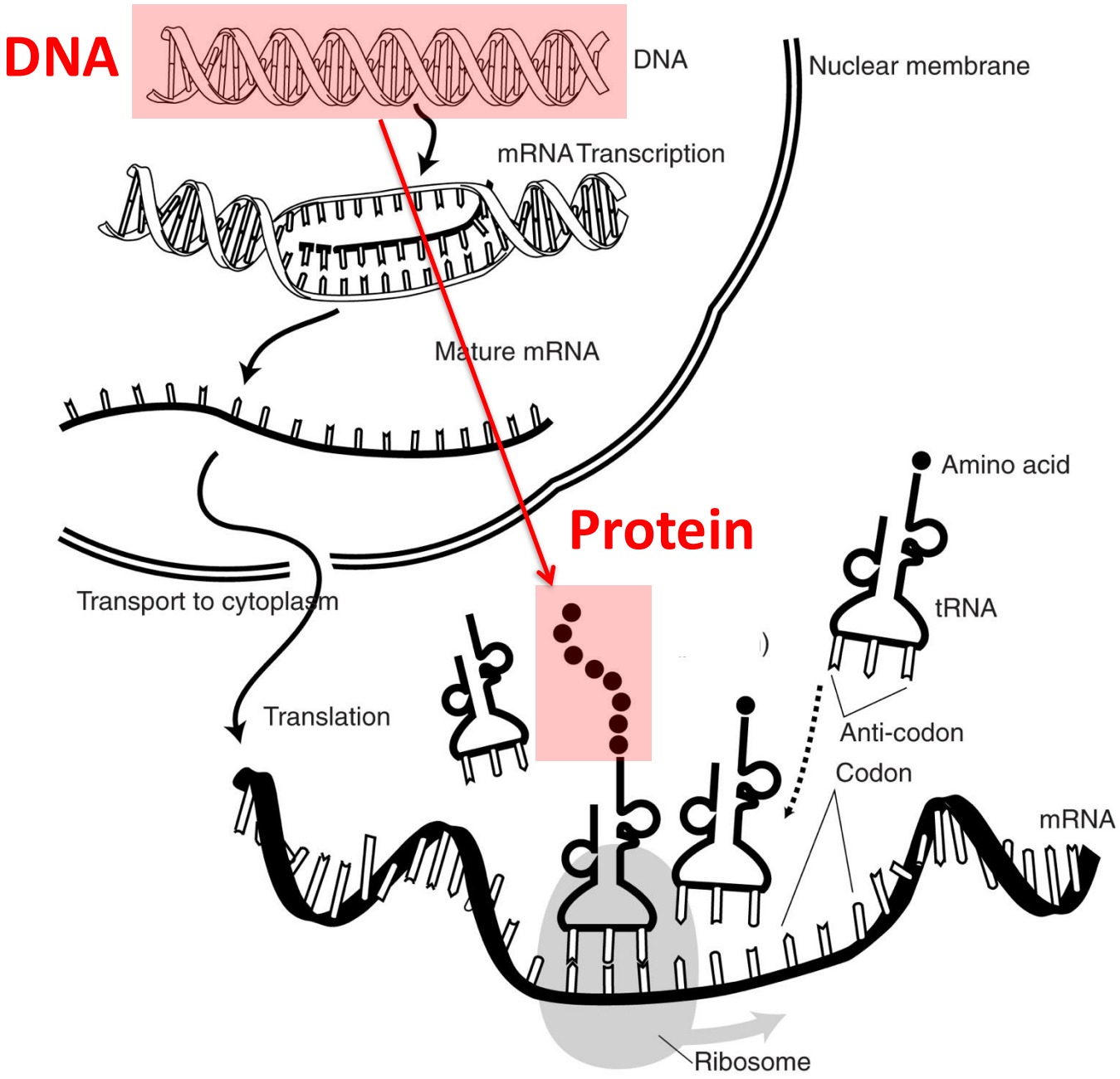
Ribozymes

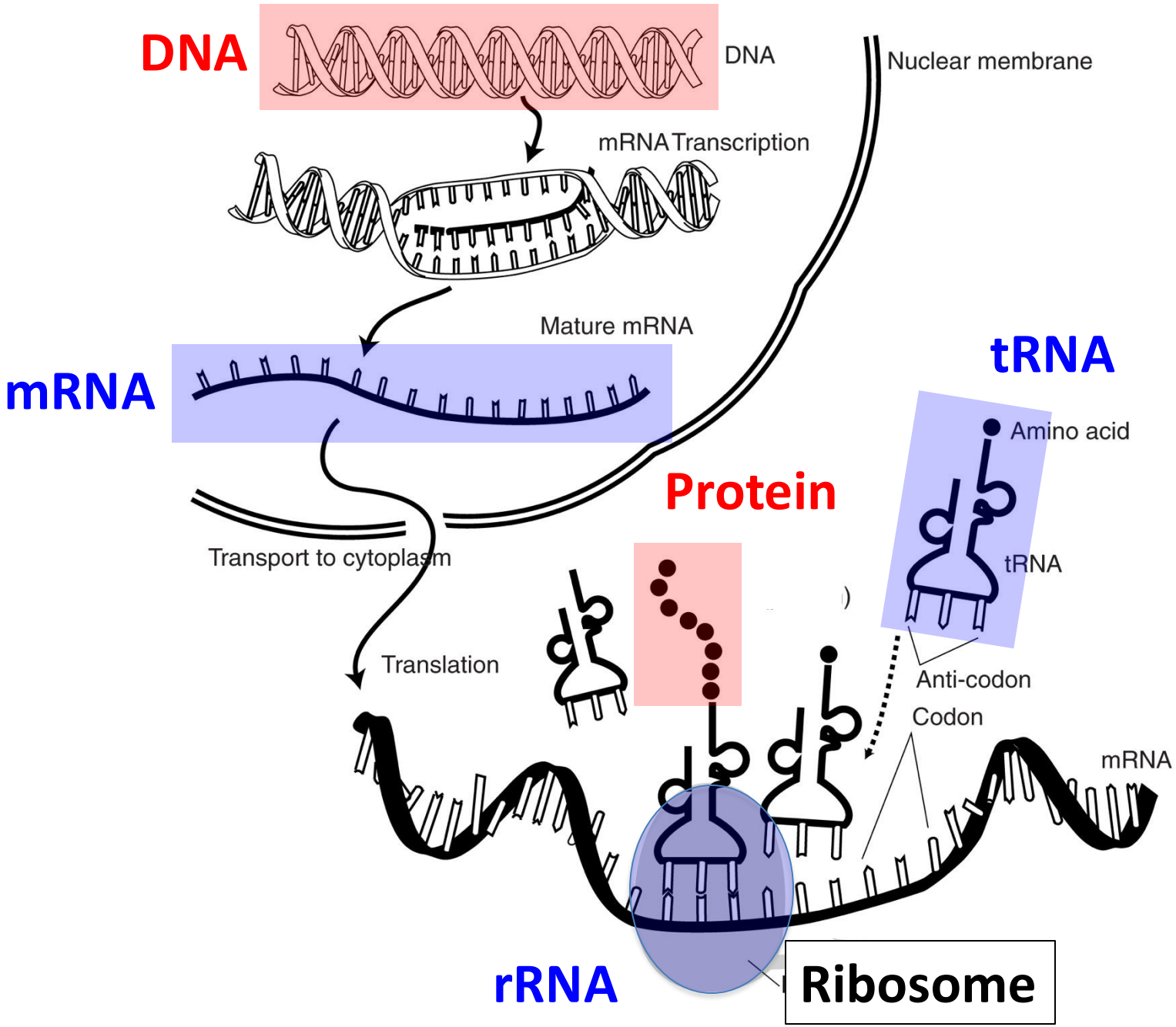
- RNAs that can act as enzymes: **RNA** can serve as **information storage** AND as part of the **functional machinery**.
- It is hypothesized that the first organisms were organized around RNAs.
- Then, later, information storage was taken over by DNA, and most of the metabolism by proteins.

Further Evidence for the:

The RNA World

- RNAs are *intimately* involved in the steps between DNA and its conversion into protein.


DNA
DNA
Nuclear membrane
mRNA Transcription
Mature mRNA
Protein
Transport to cytoplasm
Translation
Amino acid
tRNA
Anti-codon
Codon
mRNA
Ribosome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The strange two-step process organisms use to generate ATP

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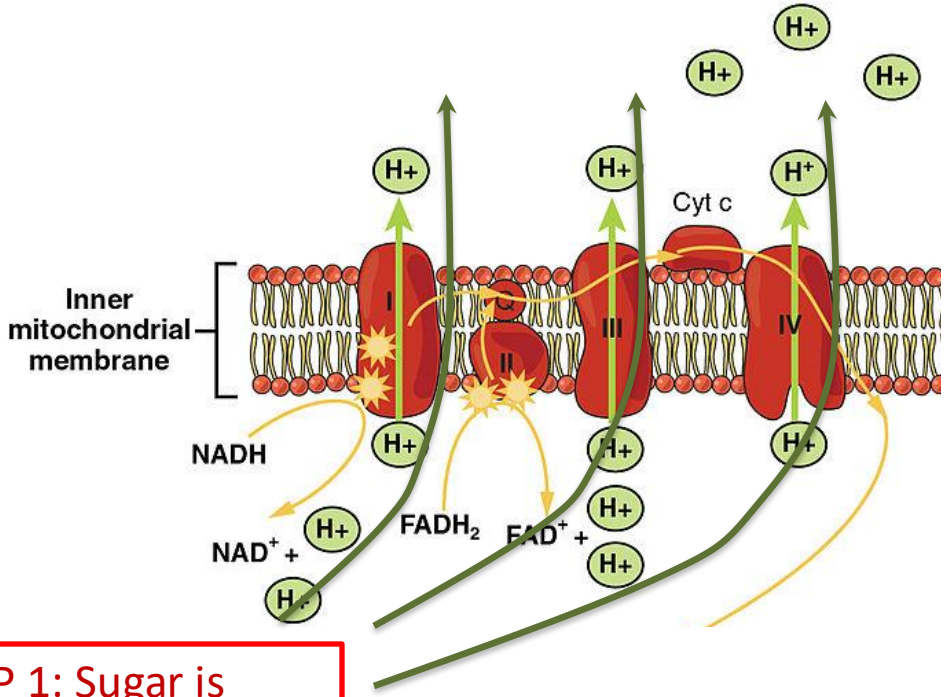
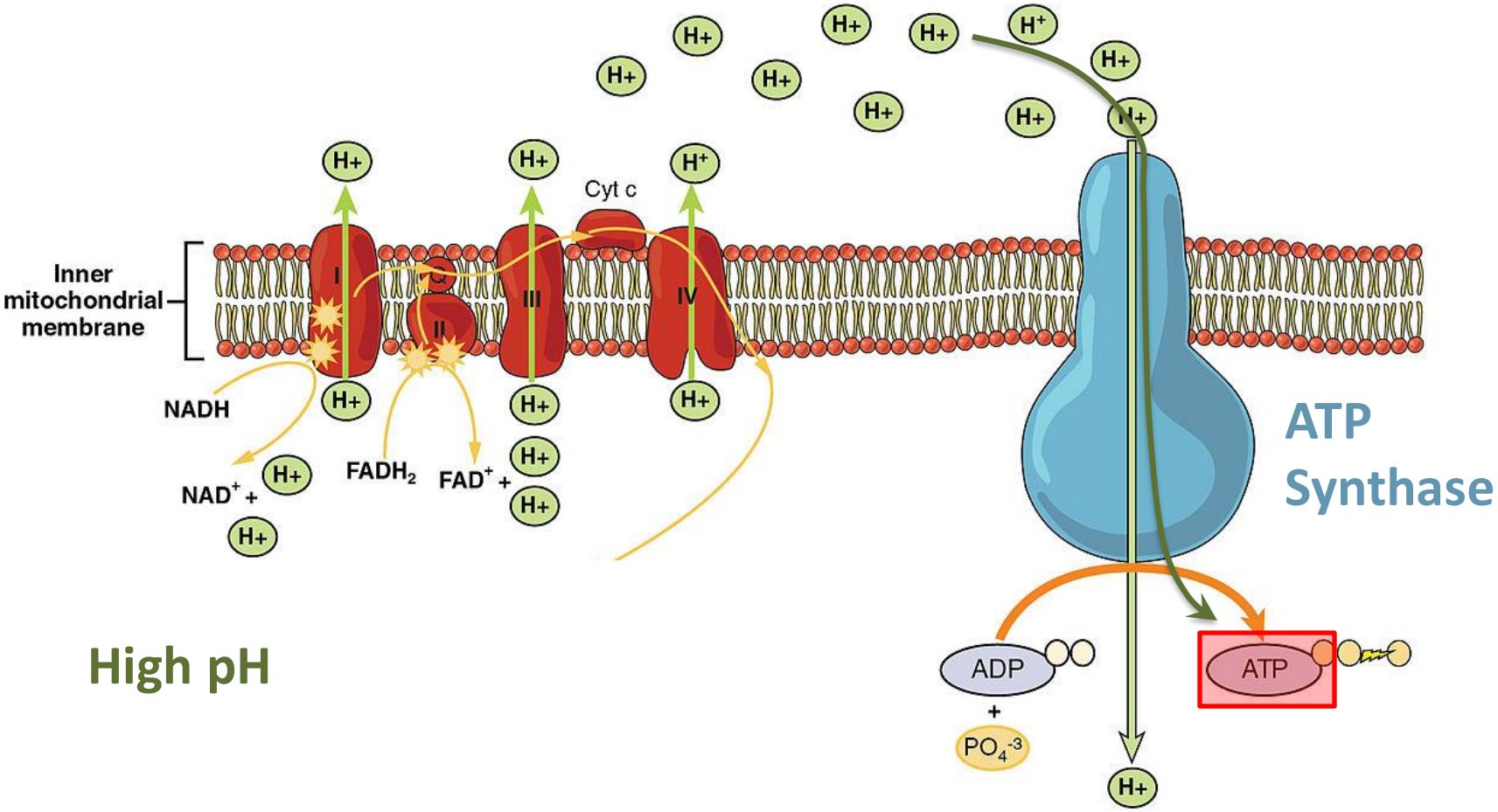


STEP 1: Sugar is 'burnt' to provide energy to pump protons (H+)

STEP 2: The protons then flow back, through ATP synthase to generate ATP

Low pH

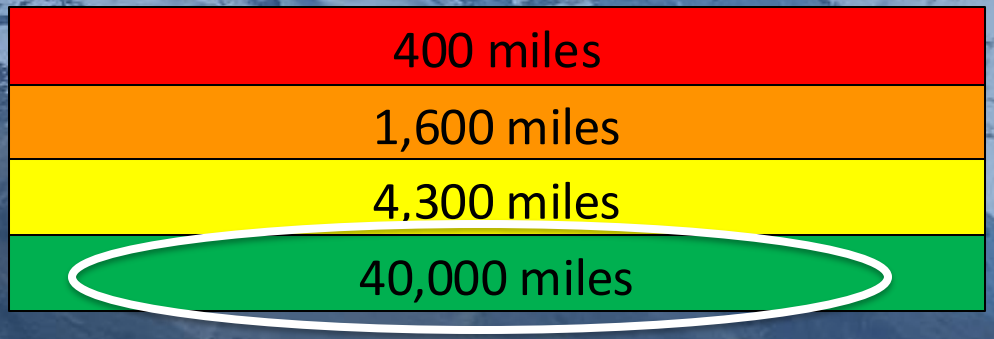


High pH

OK, so where do ‘we’ think life originated!?

How long is the world's longest continuous mountain chain?

(note the Earth's circumference is about 24,900 miles)



Sierra Nevada

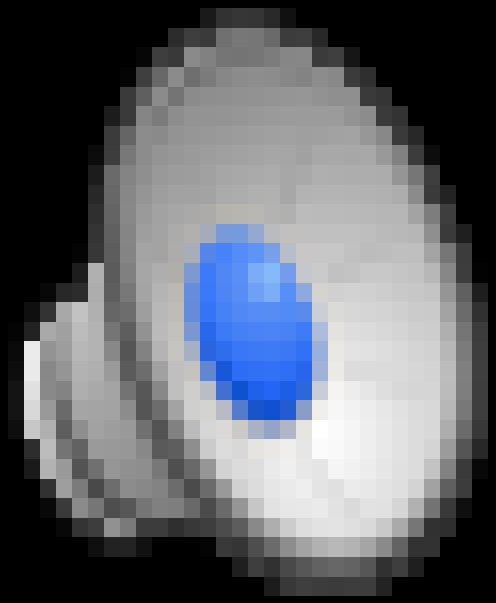
Himalayas

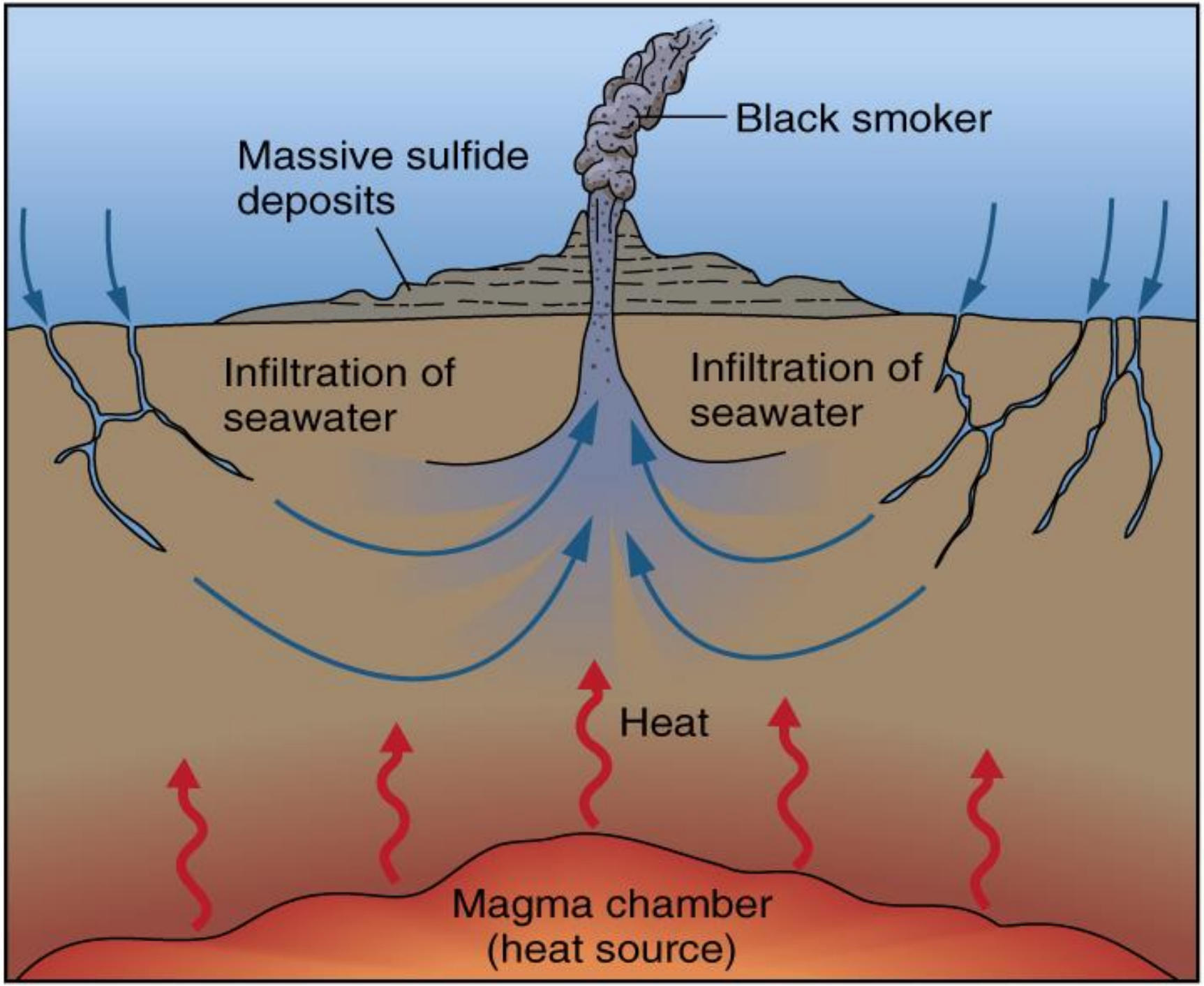
Andes

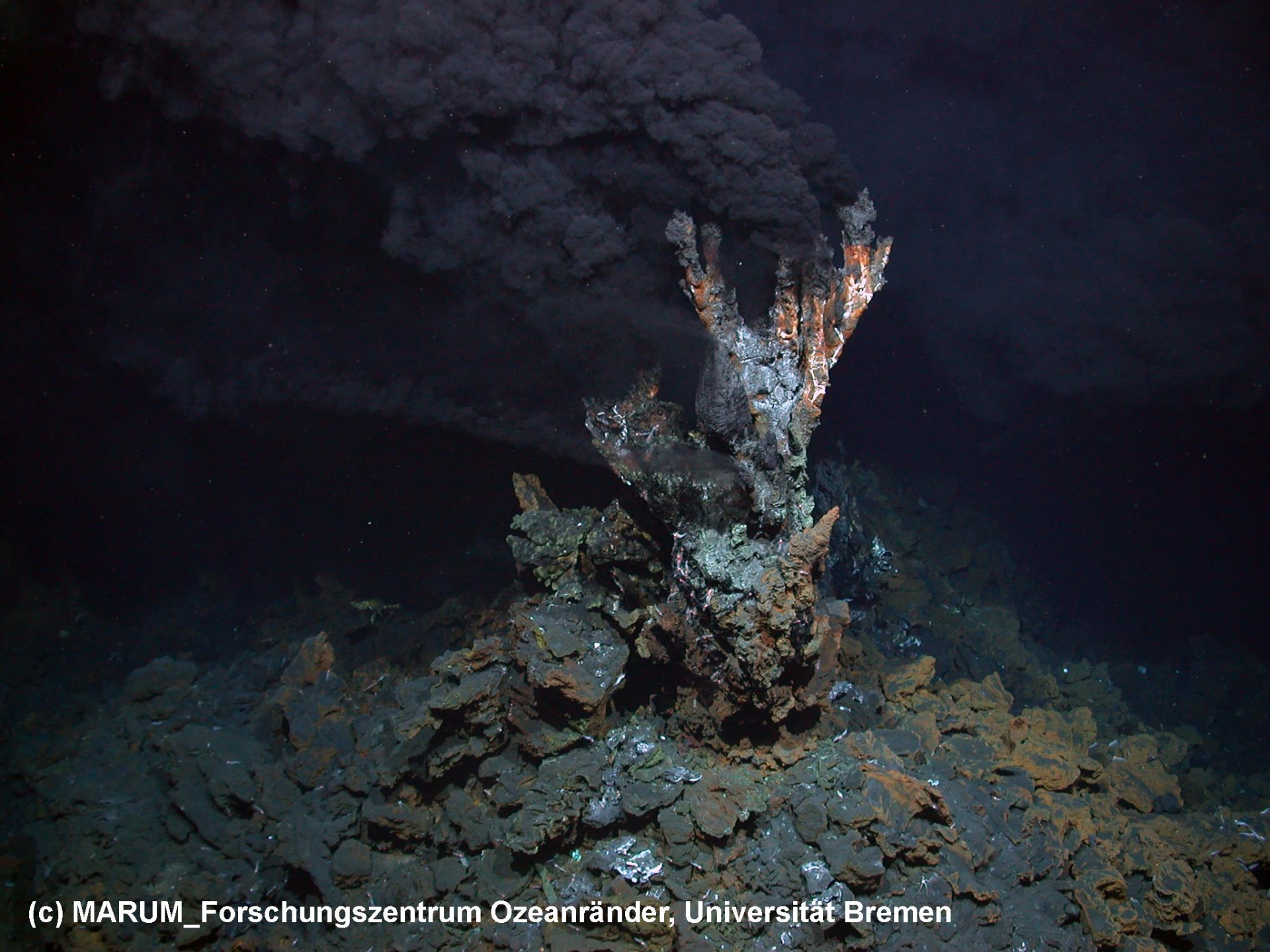
Mid-ocean ridges

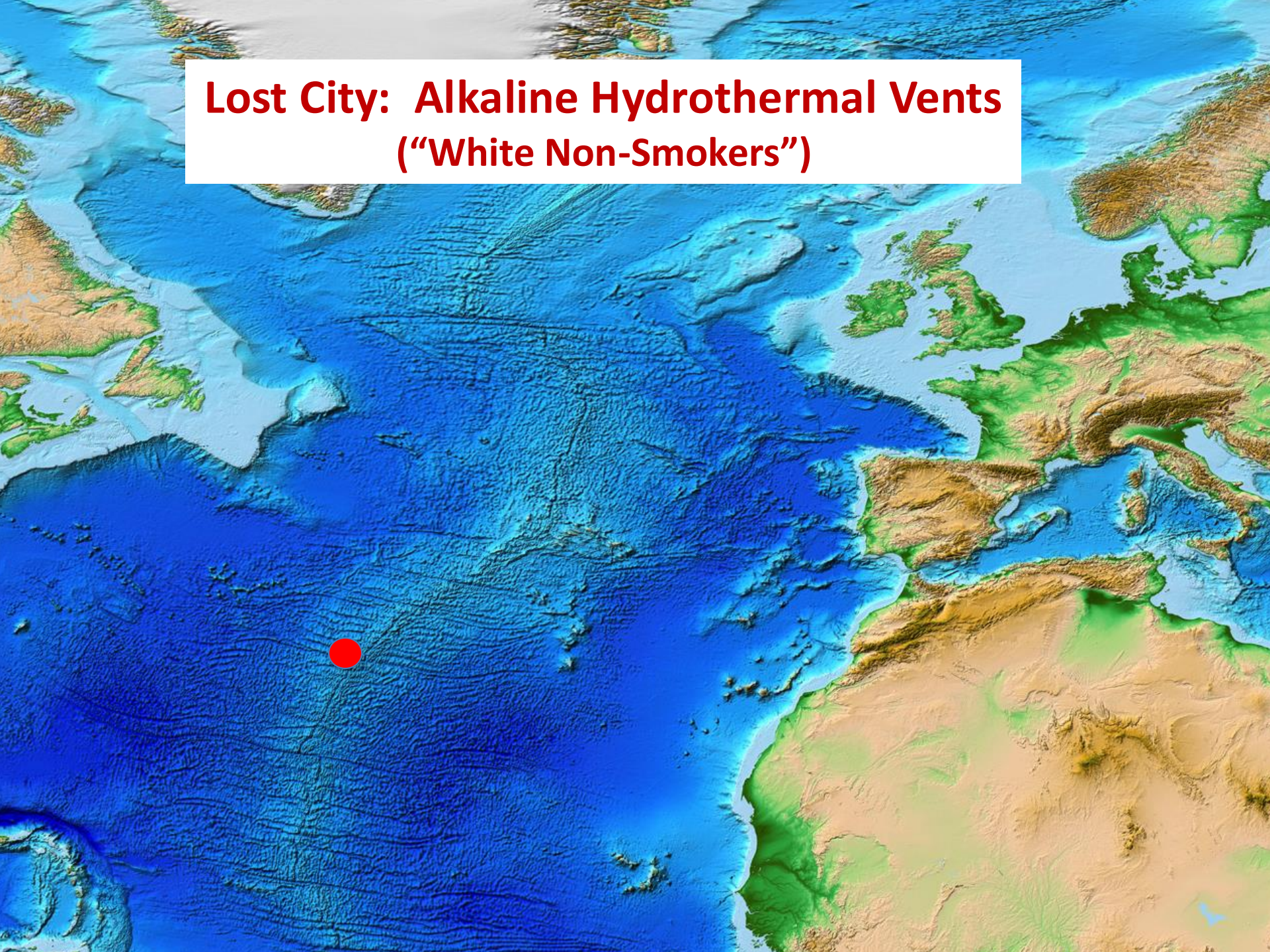

WORLD
OCEAN FLOOR
Produced by the Cartographic Division
National Geographic Society
NATIONAL GEOGRAPHIC MAGAZINE
ARCTIC OCEAN
GREENLAND
NORTH ATLANTIC OCEAN
NORTH PACIFIC OCEAN
SOUTH PACIFIC OCEAN
SOUTH ATLANTIC OCEAN
INDIAN OCEAN
SOUTHERN OCEAN
HUDSON BAY
LABRADOR SEA
BARENTS SEA
KARA SEA
LAPTEV SEA
EAST SIBERIAN SEA
CHUKCHI SEA
BEAUFORT SEA
CANADA BASIN
ICELAND
AUSTRALIA
WEDDELL SEA
SOUTH INDIAN BASIN

Mid-ocean ridges are geothermally active

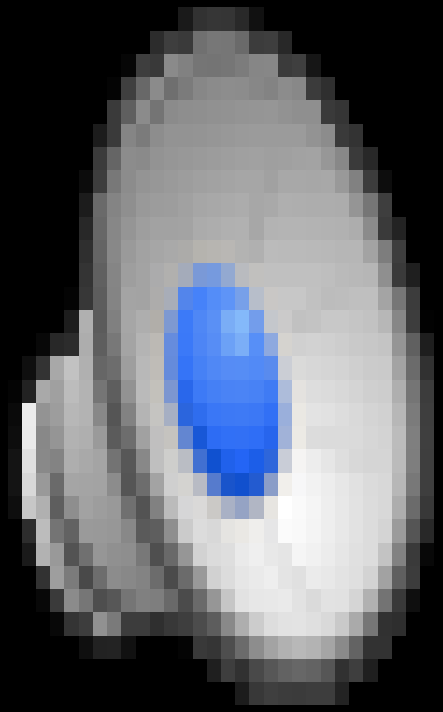



Black smoker
Massive sulfide deposits
Infiltration of seawater
Infiltration of seawater
Heat
Magma chamber (heat source)


(c) MARUM_Forschungszentrum Ozeanränder, Universität Bremen

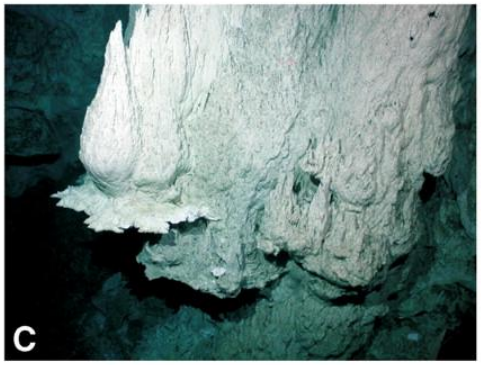

Lost City: Alkaline Hydrothermal Vents
("White Non-Smokers")

Lost City Alkaline Hydrothermal Vents

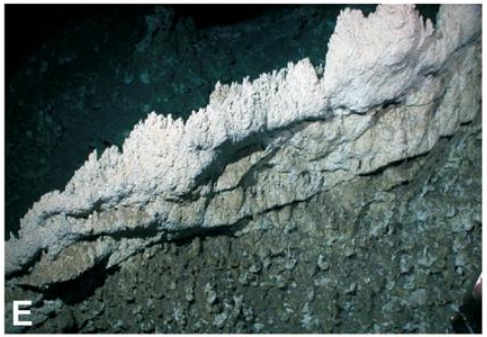



A


B


C


D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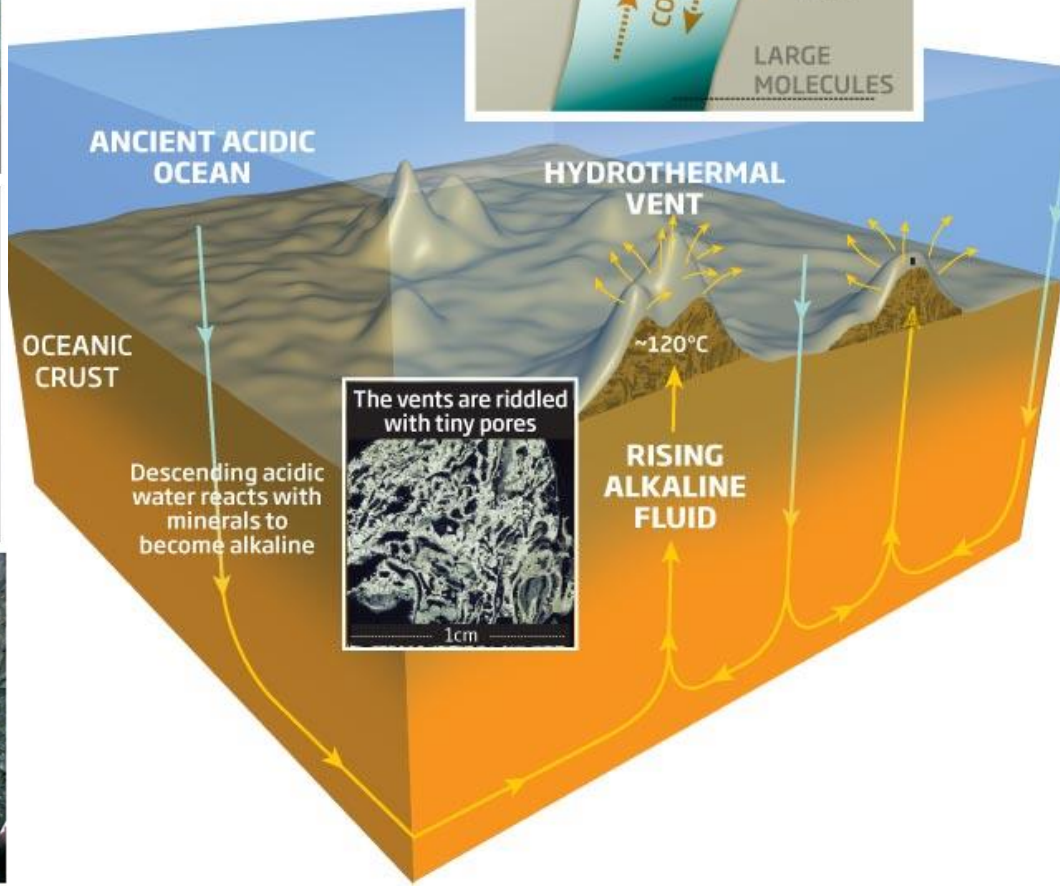
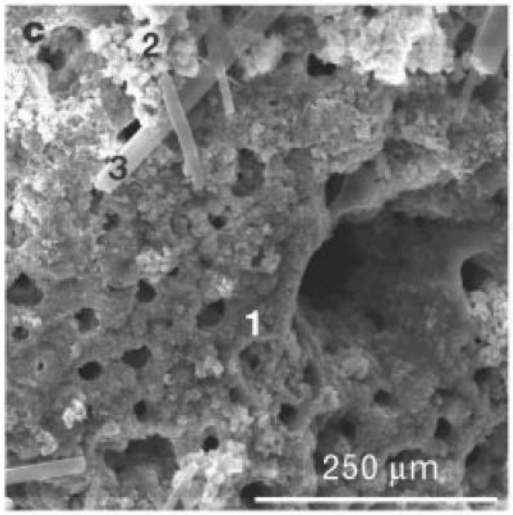
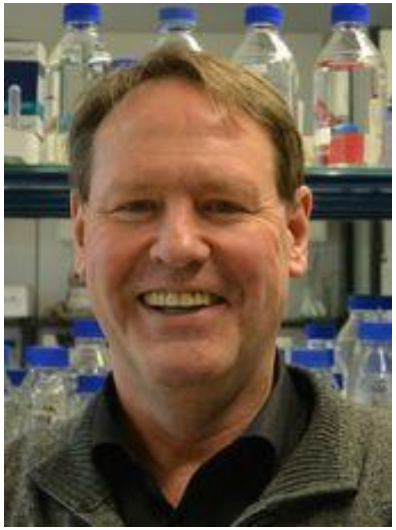

VENT PORE
WARMER SIDE
CONVECTION CURRENT
COOLER SIDE
LARGE MOLECULES
ANCIENT ACIDIC OCEAN
HYDROTHERMAL VENT
~120°C
OCEANIC CRUST
The vents are riddled with tiny pores
1cm
Descending acidic water reacts with minerals to become alkaline
RISING ALKALINE FLUID

Micro-pores in the chimneys created by the alkaline hydrothermal vents: the cradles of life?!



Mike Russell

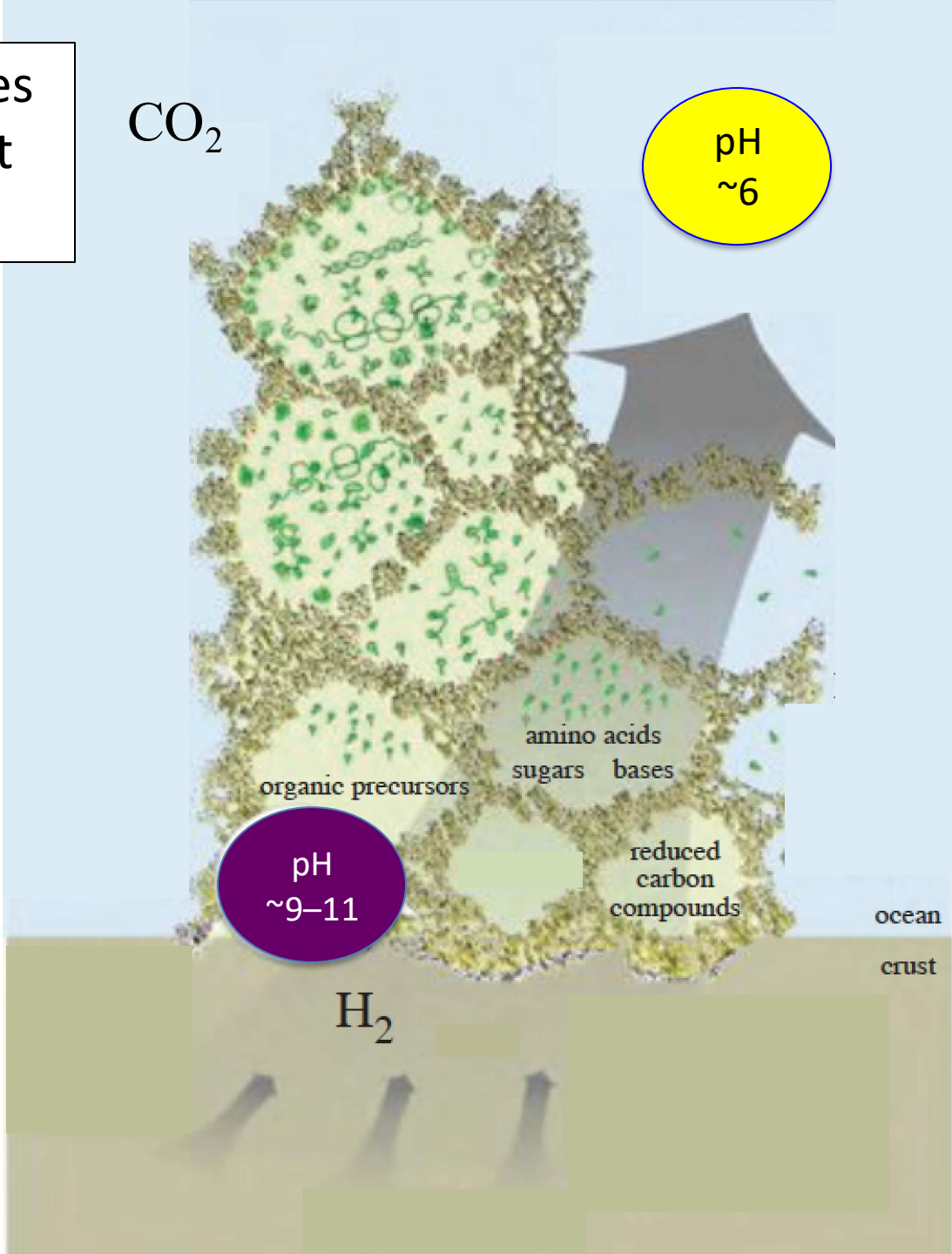
Bill Martin



Nick Lane

Origin of Life in the Micropores of Alkaline Hydrothermal Vent Chimneys?

- There is a steady flow of energy and raw materials
- The micropore walls provide the initial delineation of inside and outside.
- The micropores enable high concentrations of biomolecules
- There was ~10,000+ times higher concentration of H^+ (protons) outside than in, which makes sense of the way ATP is made today.

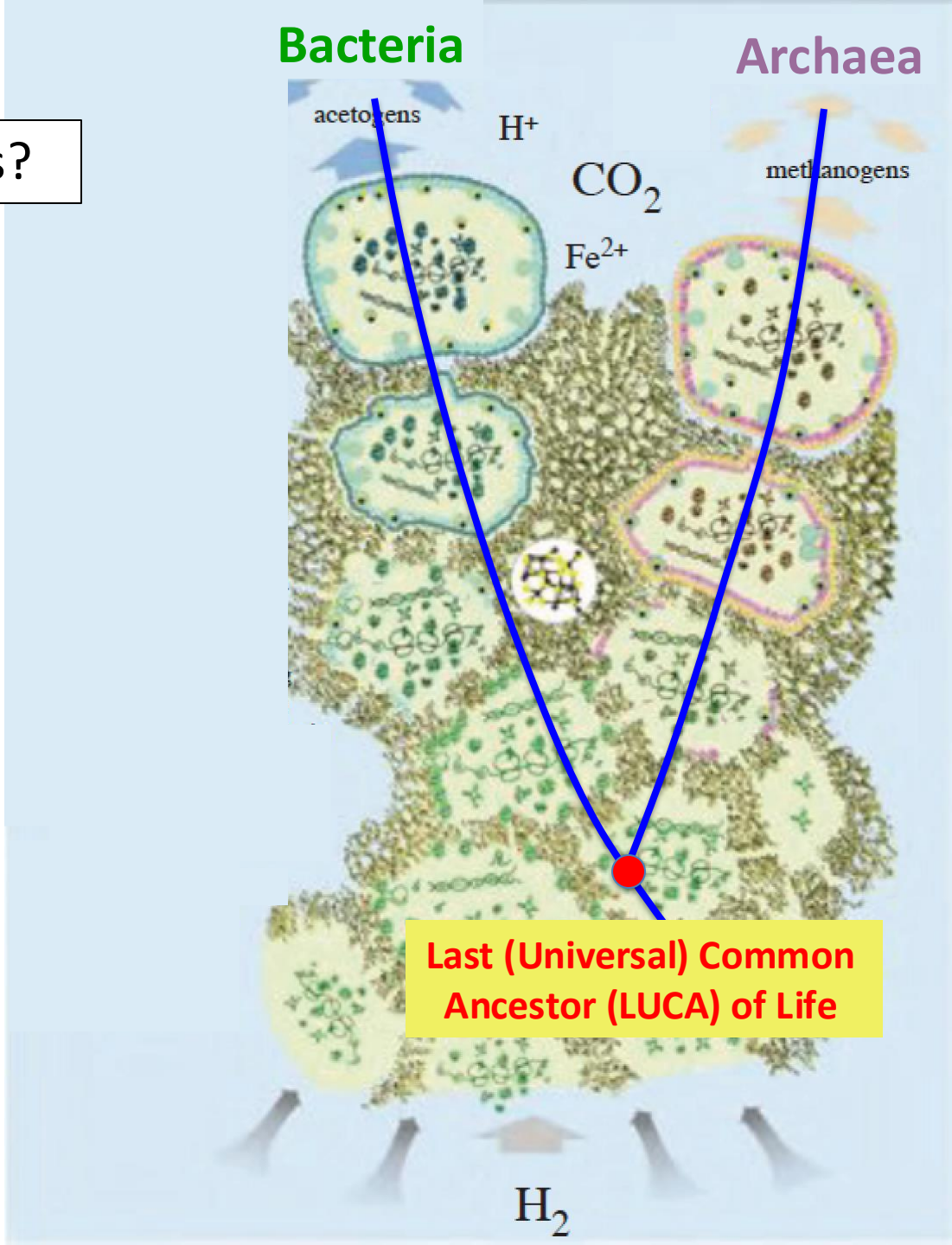


Late origin of cell membranes?

- Archaea and Bacteria have the SAME genetic code, protein synthesis machinery, etc.,

- But they have DIFFERENT cell membrane and wall compositions, and proteins involved with their proton pumps, and locomotion.

- Suggests that they cellularized independently, and thus that LUCA was not cellular!

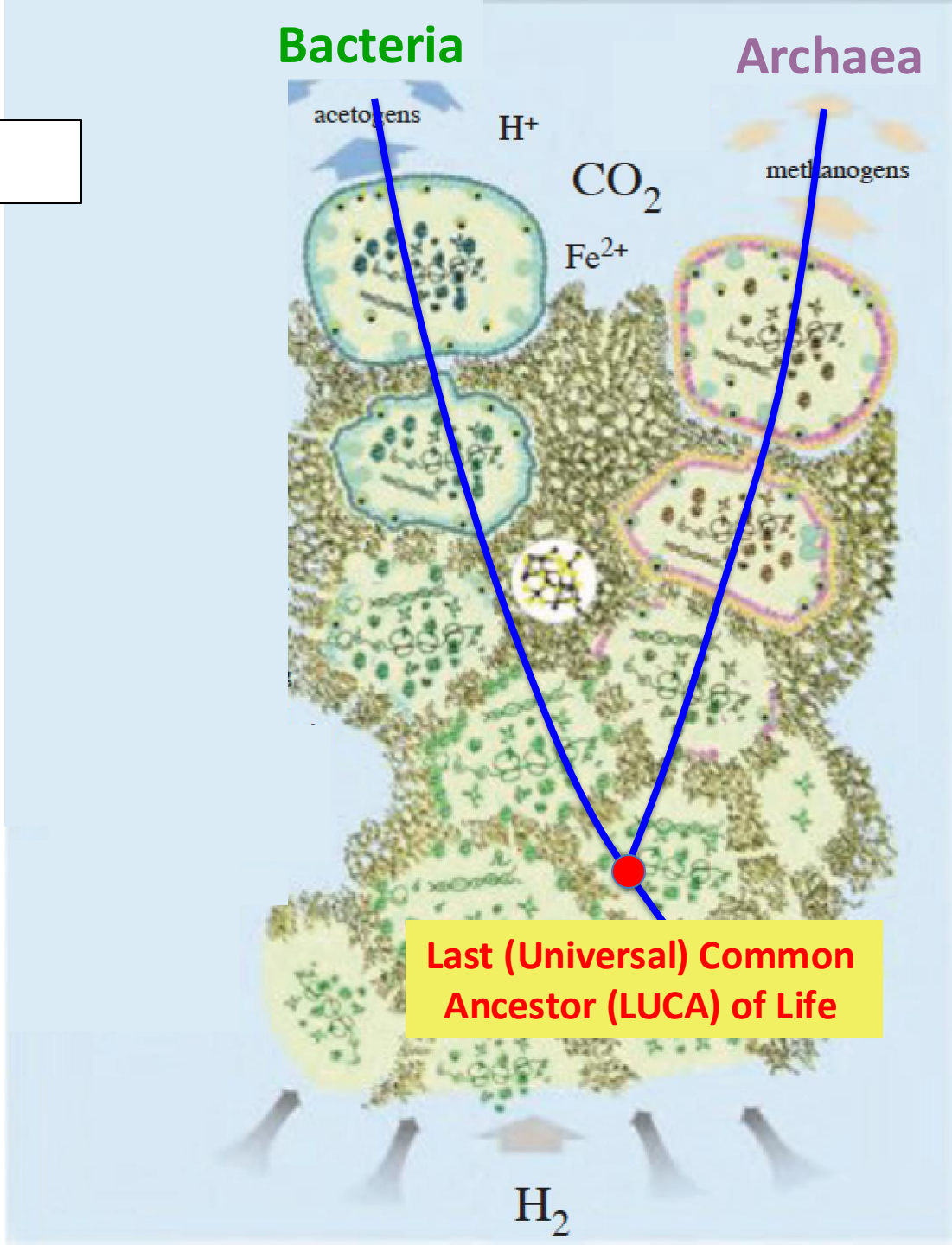


Late origin of DNA?

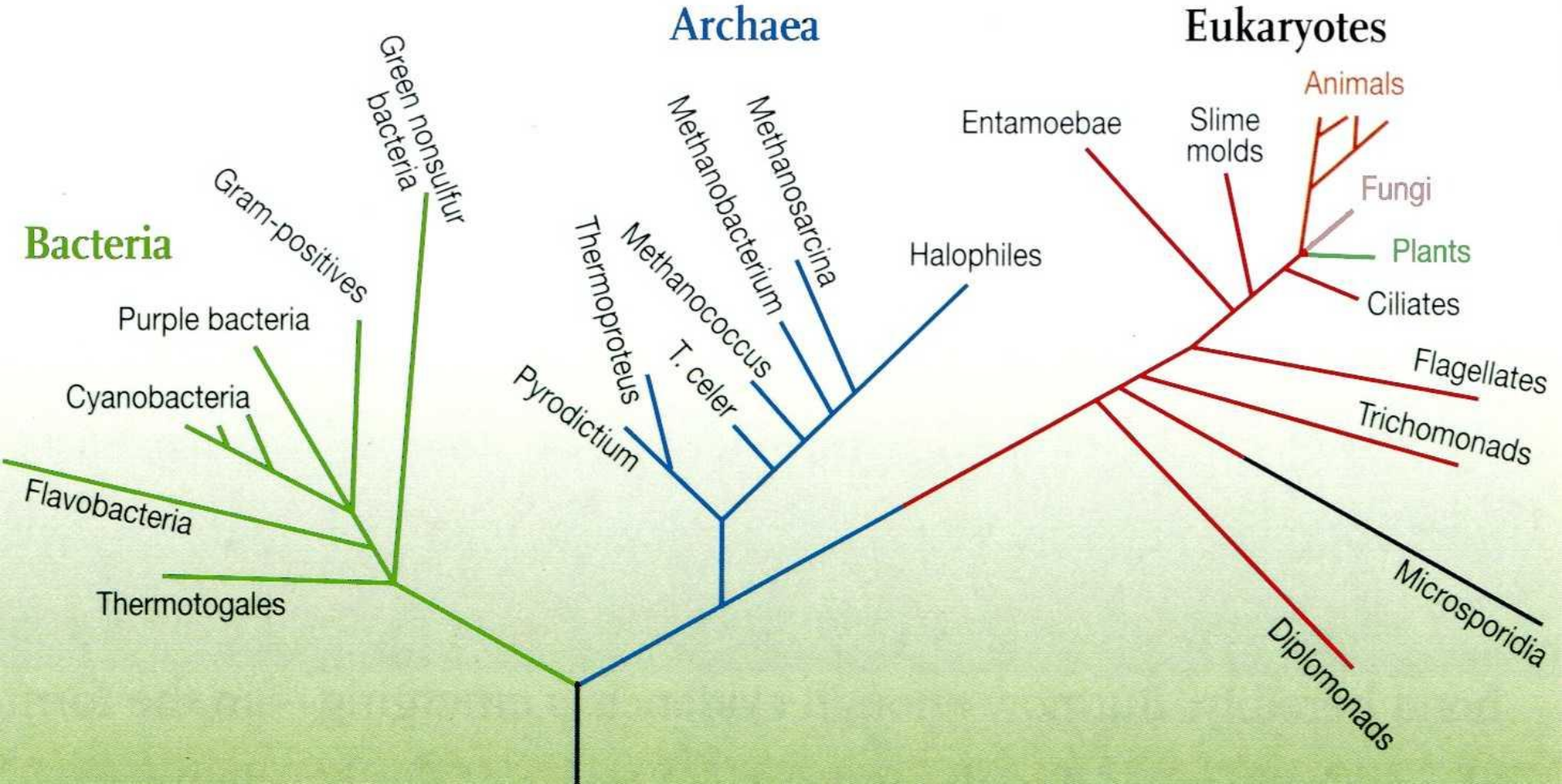
- Archaea and Bacteria use a different process and different proteins to replicate their DNA.

- Suggests that they developed DNA (for information storage) independently, and thus that LUCA was not DNA-based.

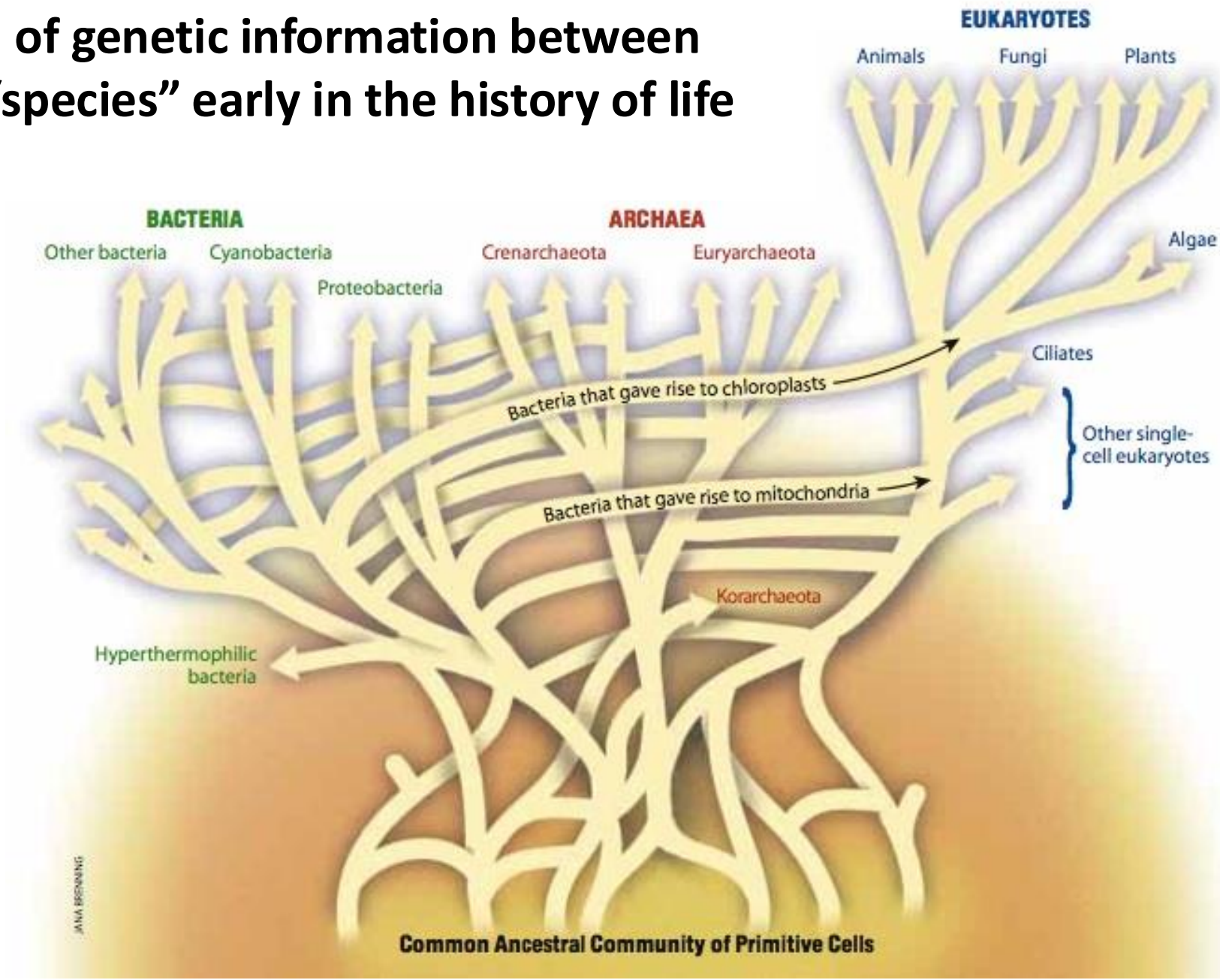
- Thus, two of the defining features of life, cells and DNA were unlikely present in LUCA.



The Tree of Life depiction suggests simple lineages …



But it is likely there was massive transfer of genetic information between "species" early in the history of life



If the alkaline hydrothermal vent hypothesis is correct
(and it, or bits of it, might not be)

- It implies LUCA was not cellular but was cradled inside the micropores.
- That cell membranes and DNA were among the last major features of life to evolve.
- Life evolved in the ***pitch black***.
- Life arose as a consequence of tectonics: the interaction between warm rock and sea water.

The attractiveness of the alkaline hydrothermal vent hypothesis:

- The “cradles of life” (the vents) are long-lived and geographically extensive. We don’t have to rely on a “freak” environment to explain the origin of life.

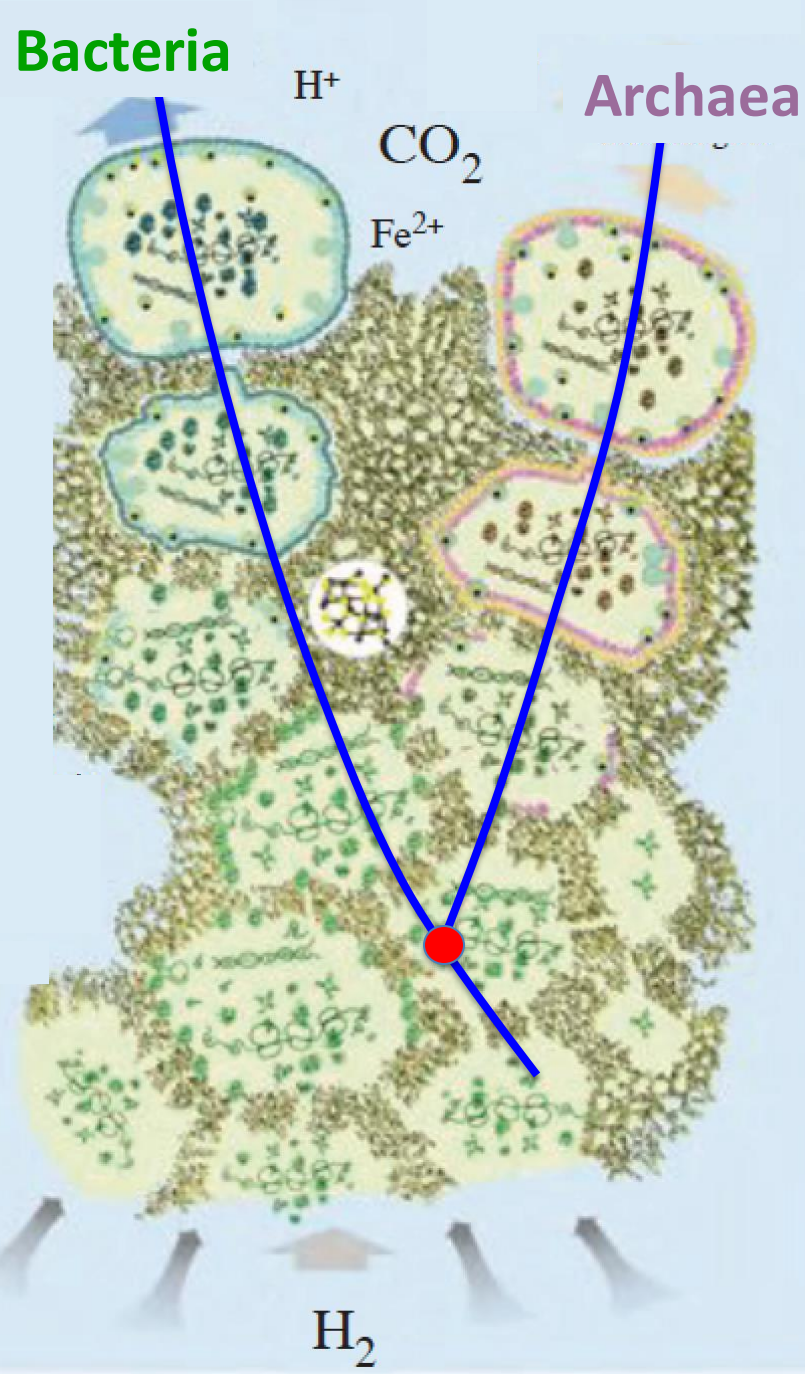
- They have a built-in pH (proton) gradient – it makes sense of life’s bizarre way of generating ATP.

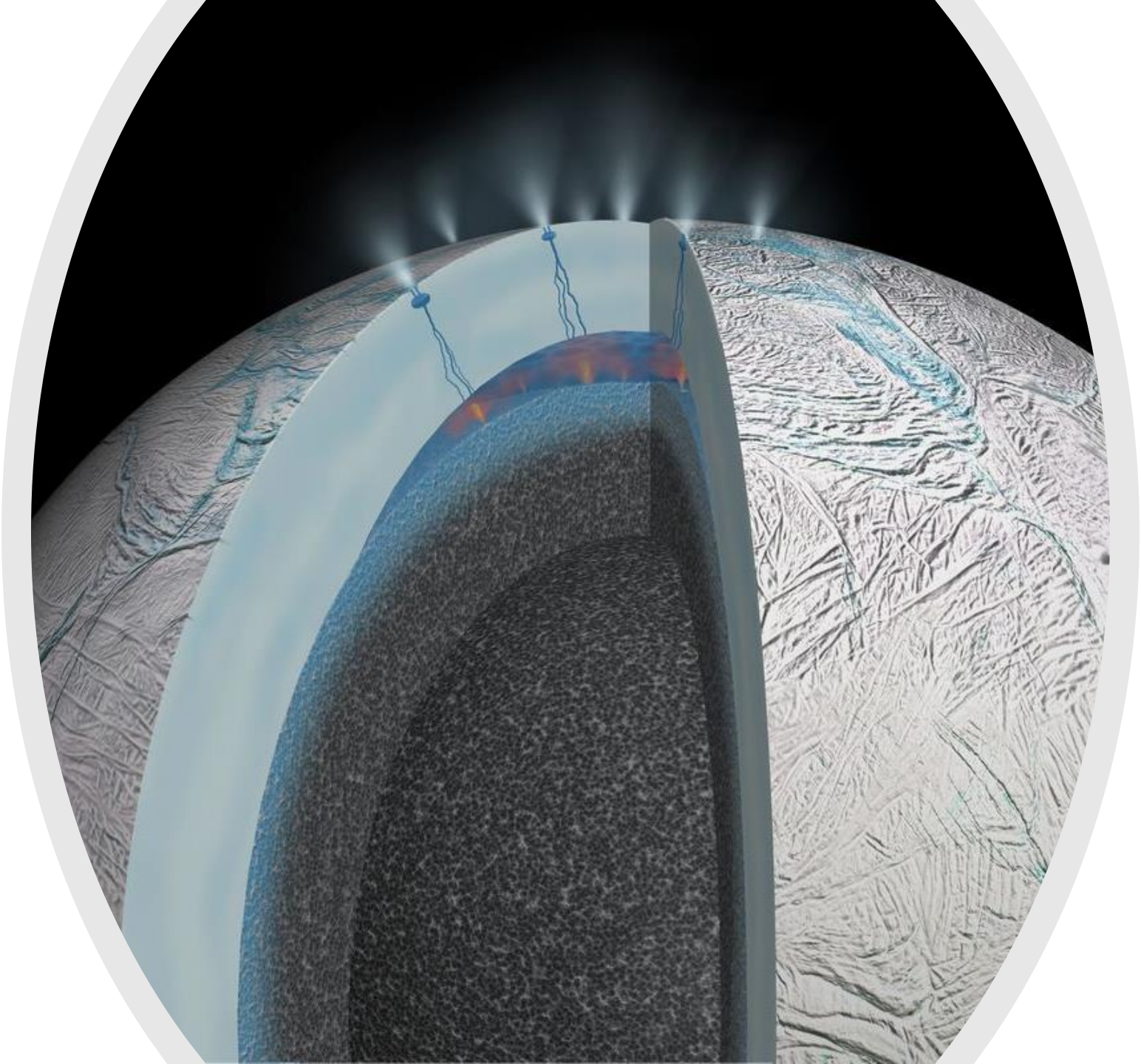
- It solves how to concentrate the building blocks, and how to get them inside the first “cells”.

- We now have a framework for understanding the origin of life – the study of the origin of life now falls into the realm of testable science.

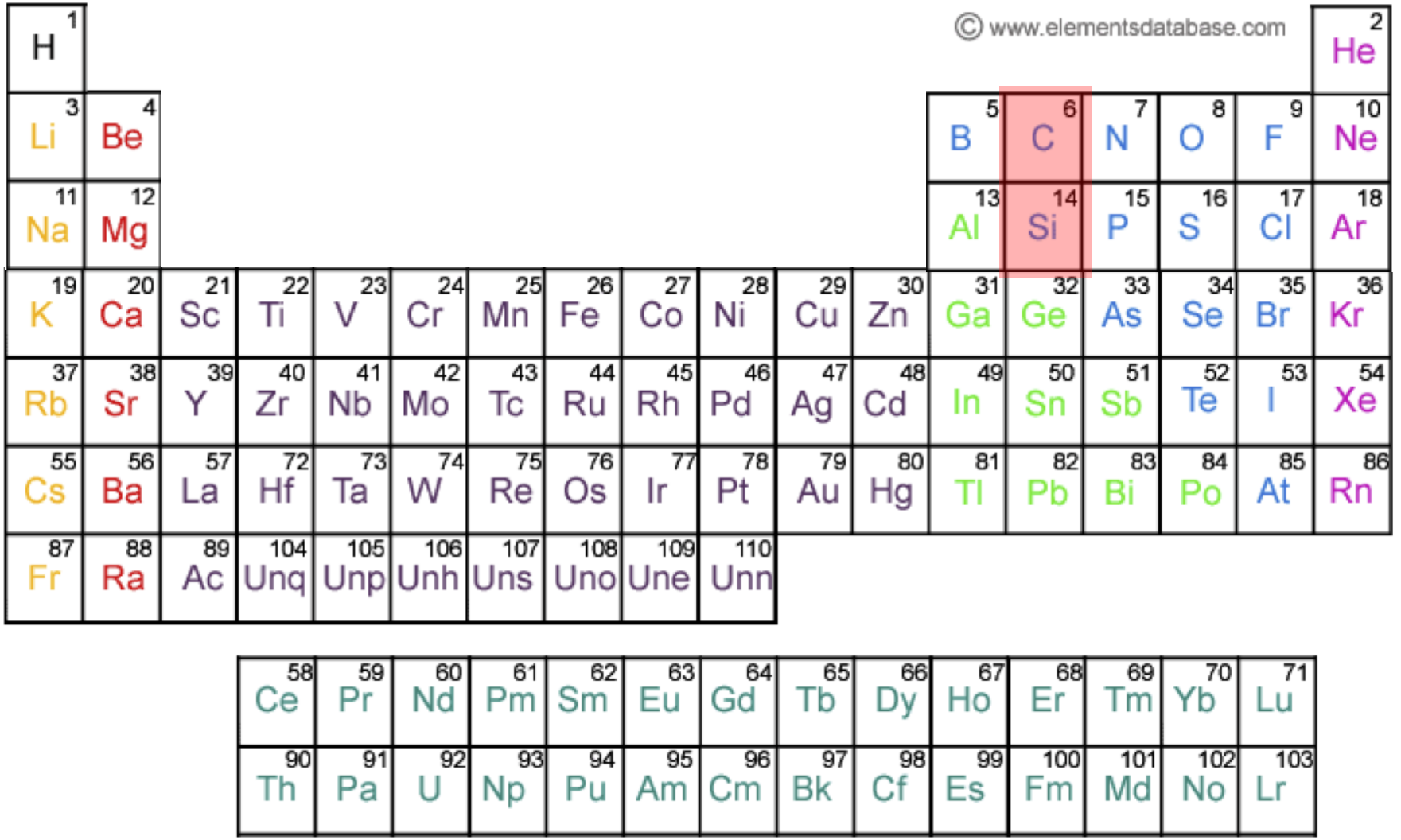
Thank you!

Questions?



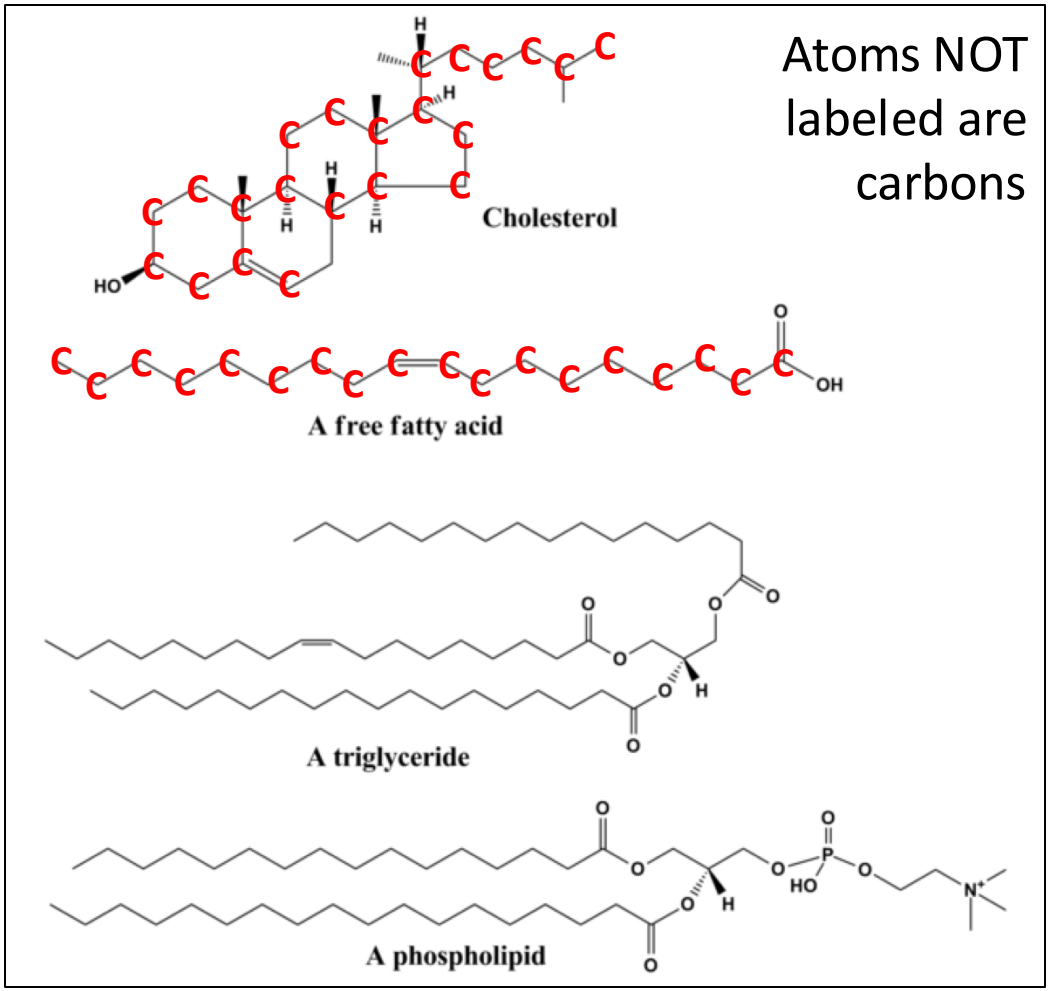


Life is carbon based, why not silica?

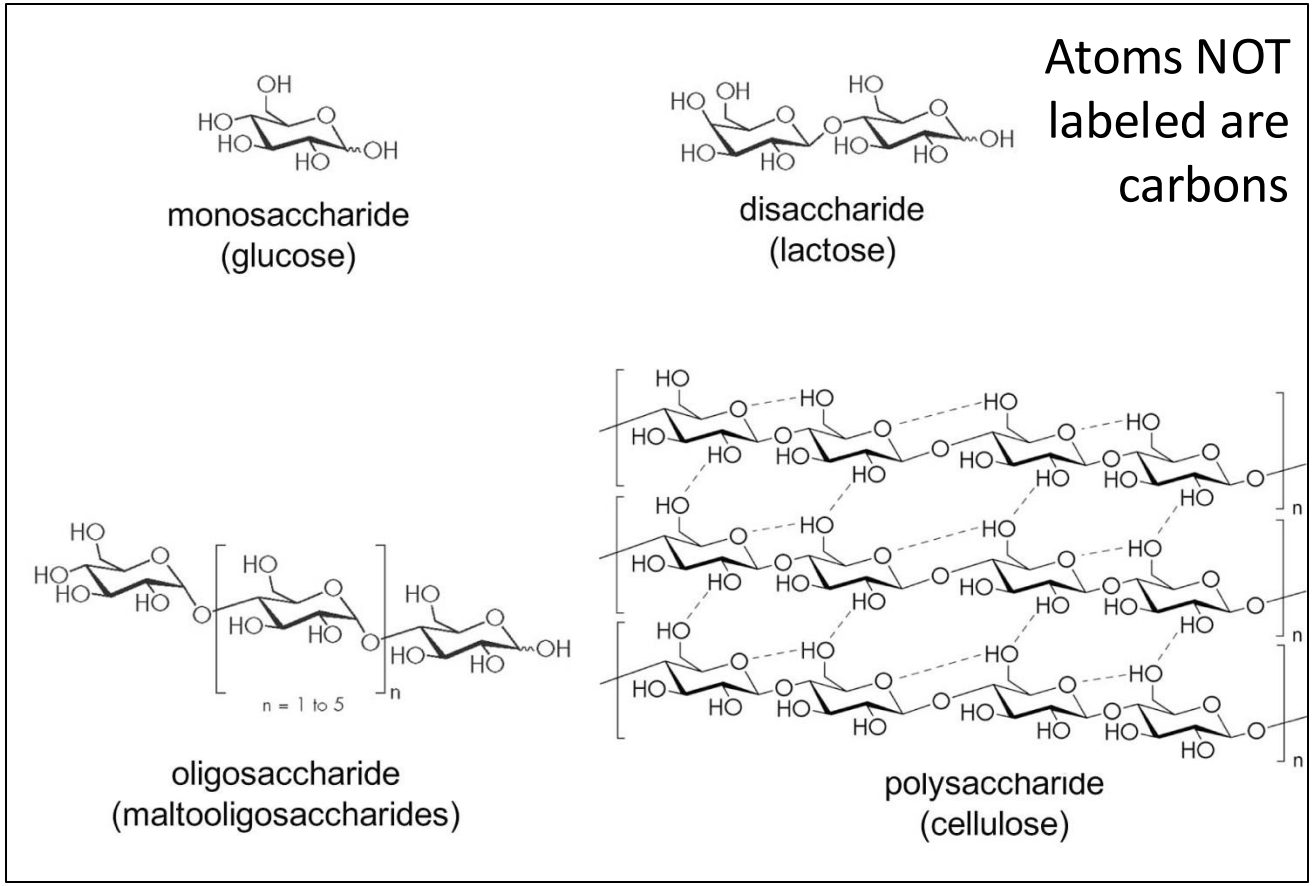


Lost City Alkaline Hydrothermal Vents

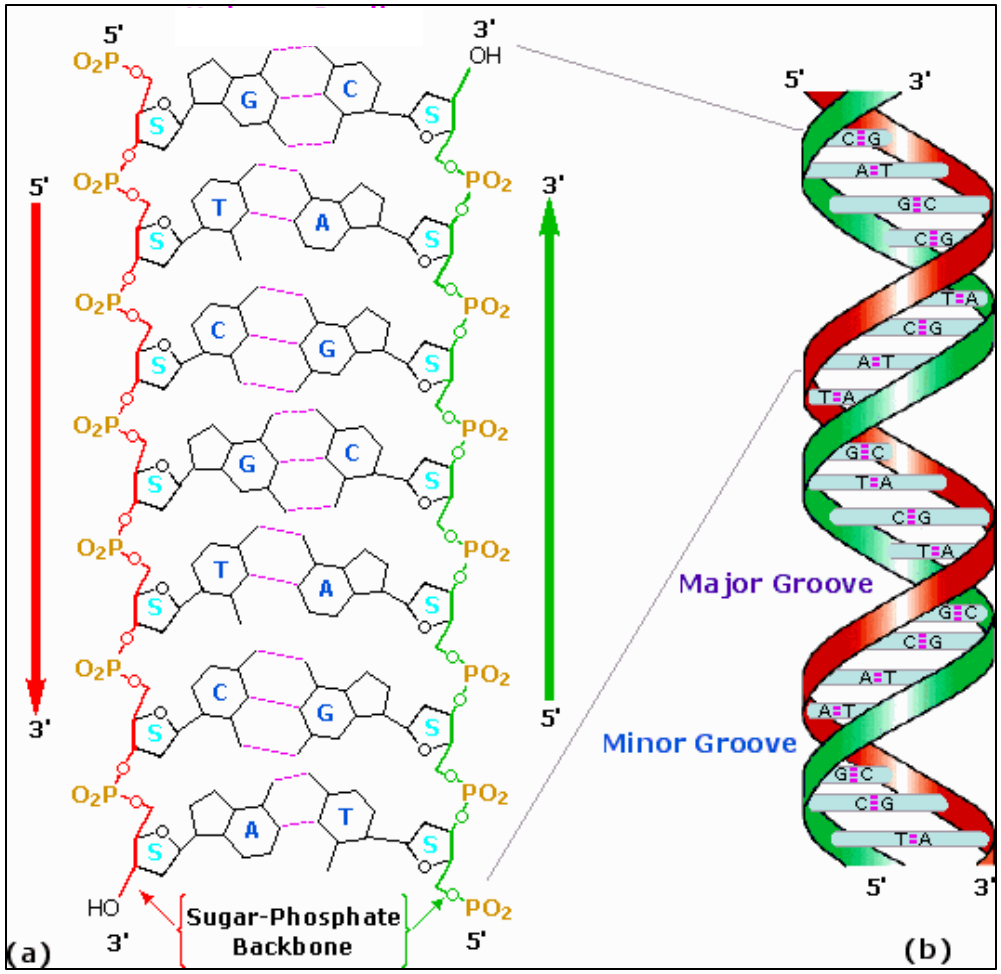
Carbon is the heart of all of life's complex molecules: **Lipids (fats)**



Carbon is the heart of all of life's complex molecules: **Carbohydrates (sugars)**

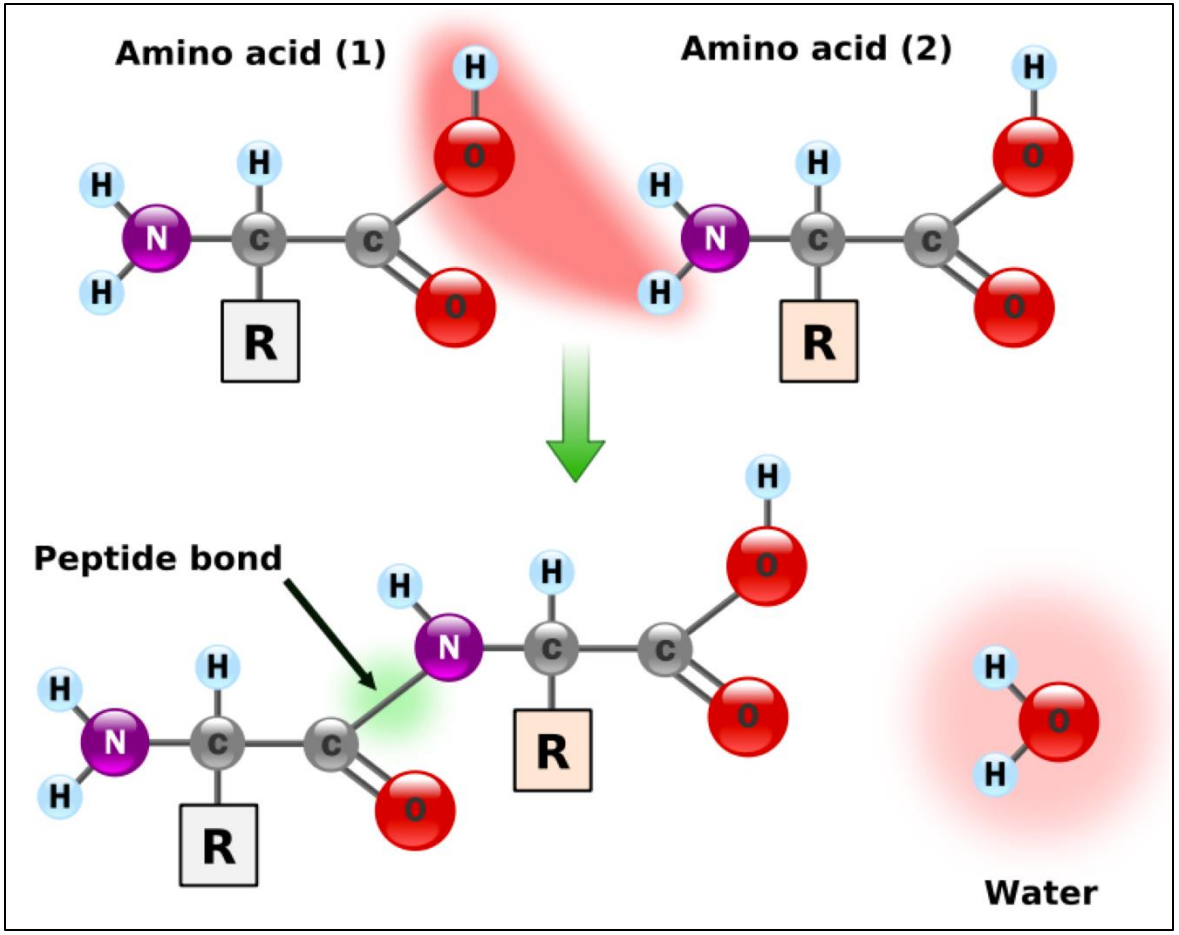


Carbon is the heart of all of life's complex molecules: **DNA/RNA**



Carbon is the heart of all of life's complex molecules: **Proteins (strings of amino acids)**

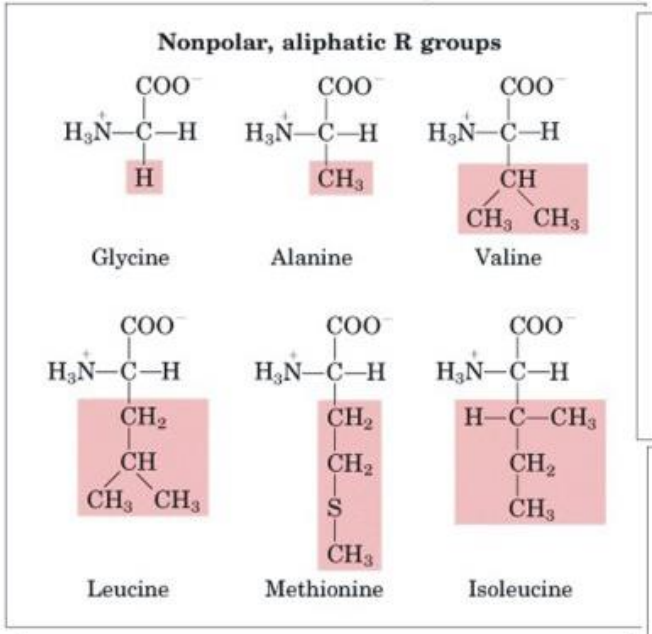
The **identity** of the **amino acid** is determined by the **R**

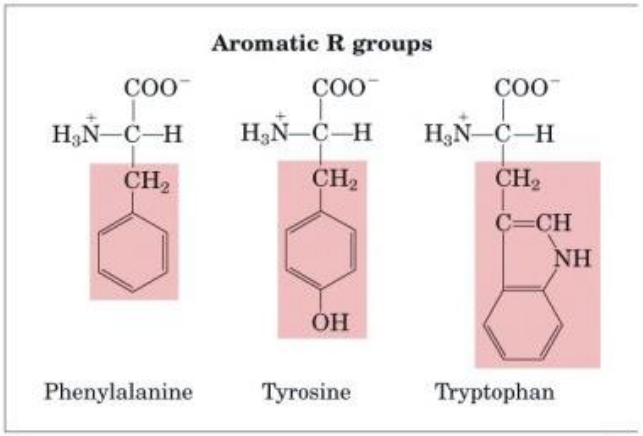


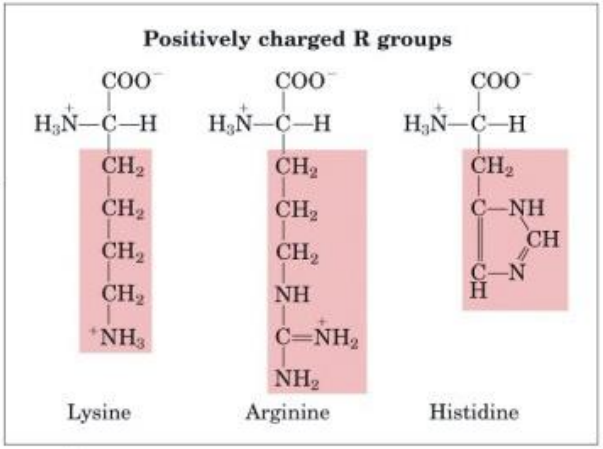
Life's **Amino Acids**:

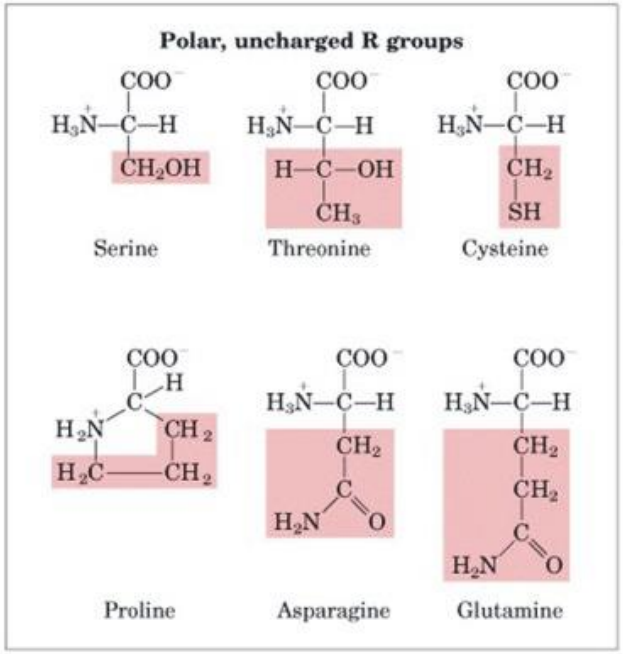
R =

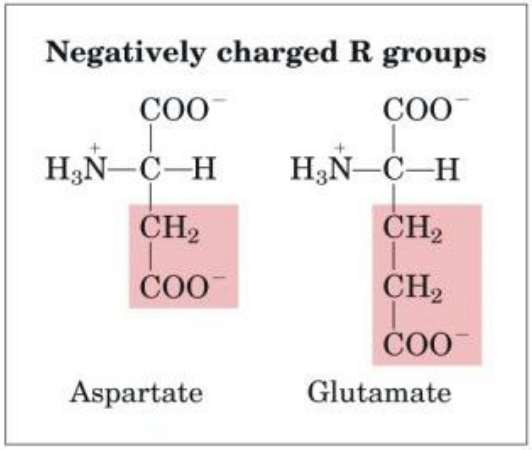
Twenty standard Amino Acids







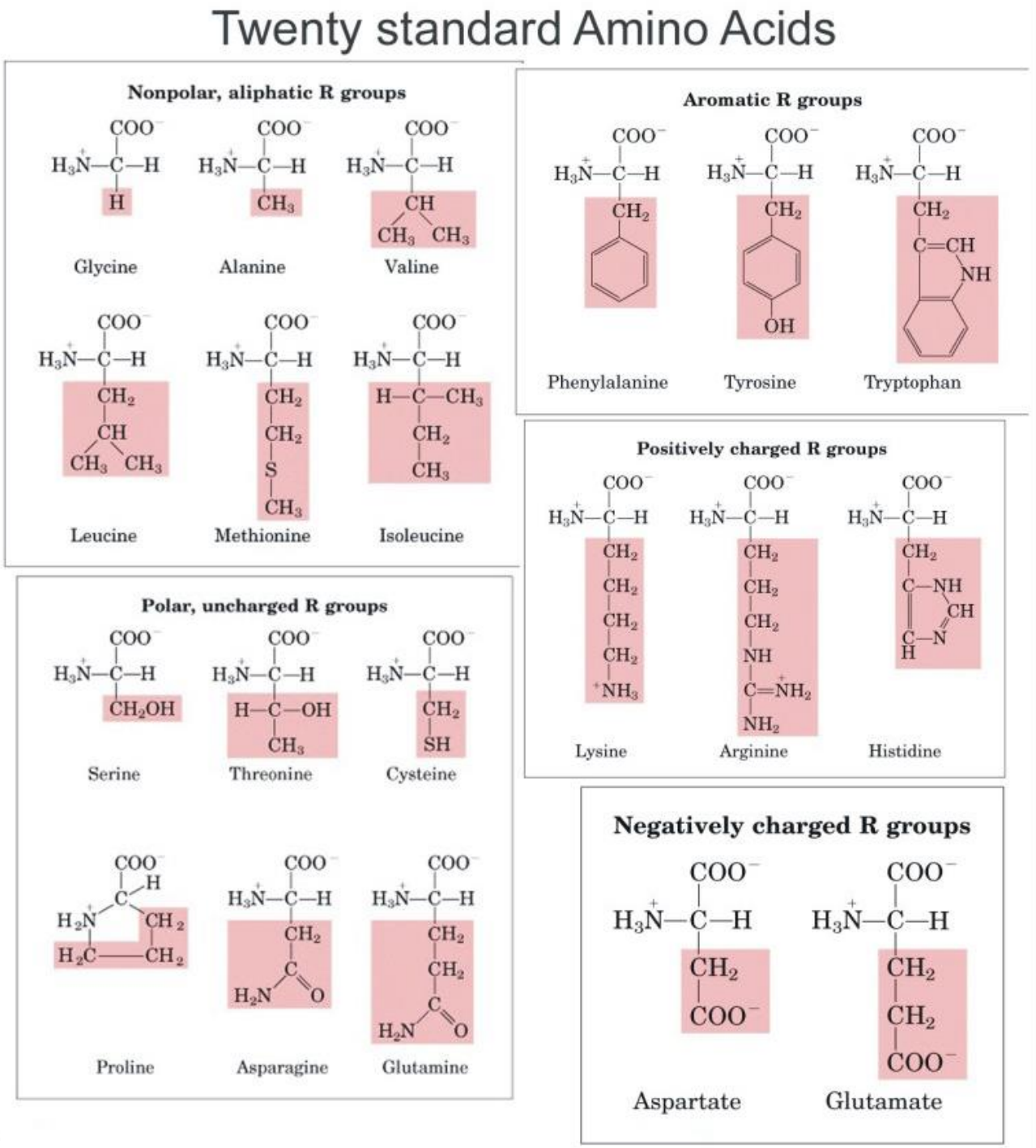




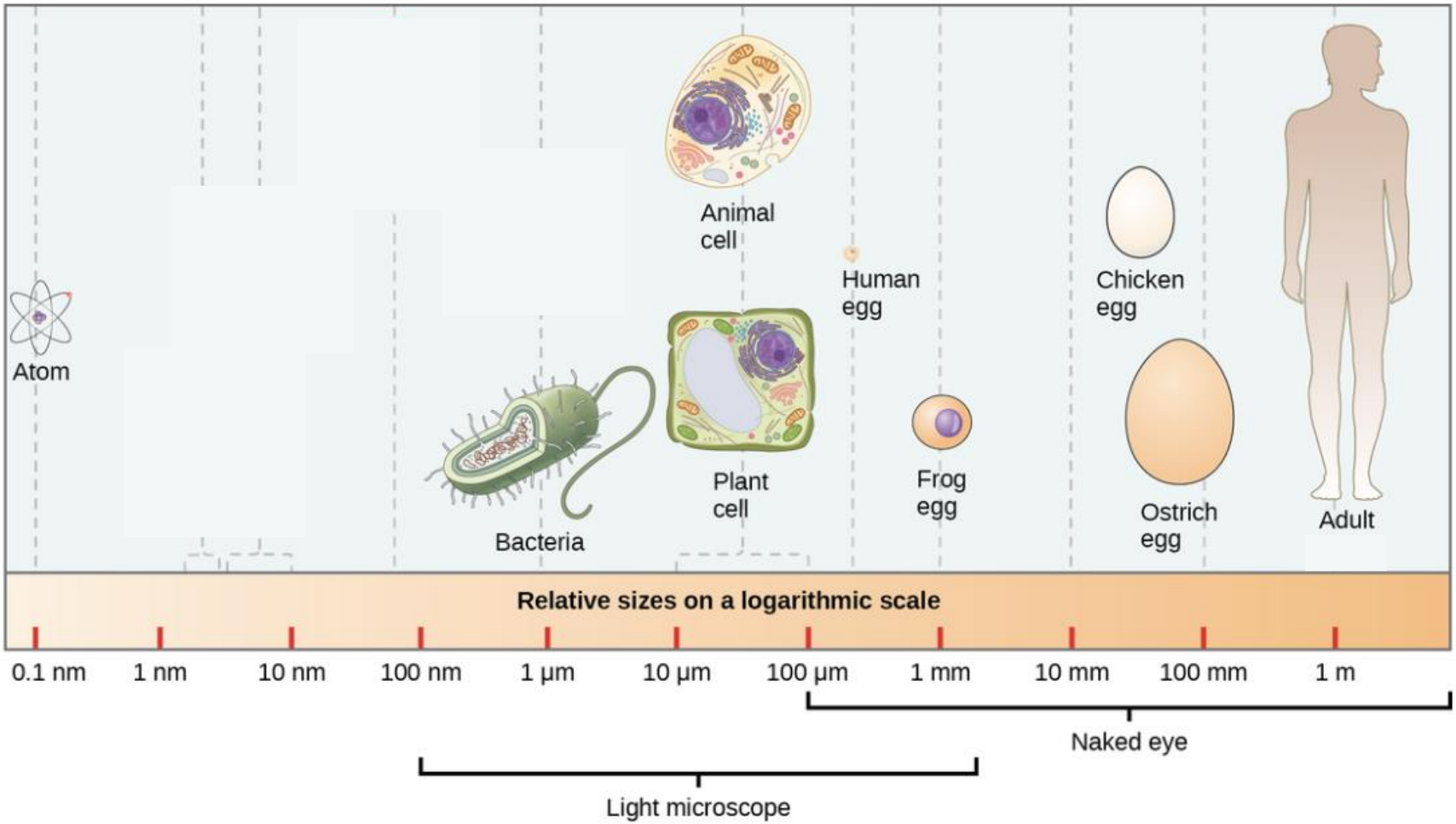
Life's **Amino Acids**:

R =

There are "bazillions" of possible proteins (e.g., there are 20^{100} possible proteins of length 100 amino acids).



Carbon's ability to **form chains, branched chains,** and **make bonds with other elements** leads to ***a more than an astronomical number*** **of possible molecules!**



Sarah Belling, Biology Cells and Organisms - Year 11. OpenStax CNX. Jul 30, 2020
http://cnx.org/contents/721440b1-70cd-4654-ac70-8d3c5fc8115a@1.40

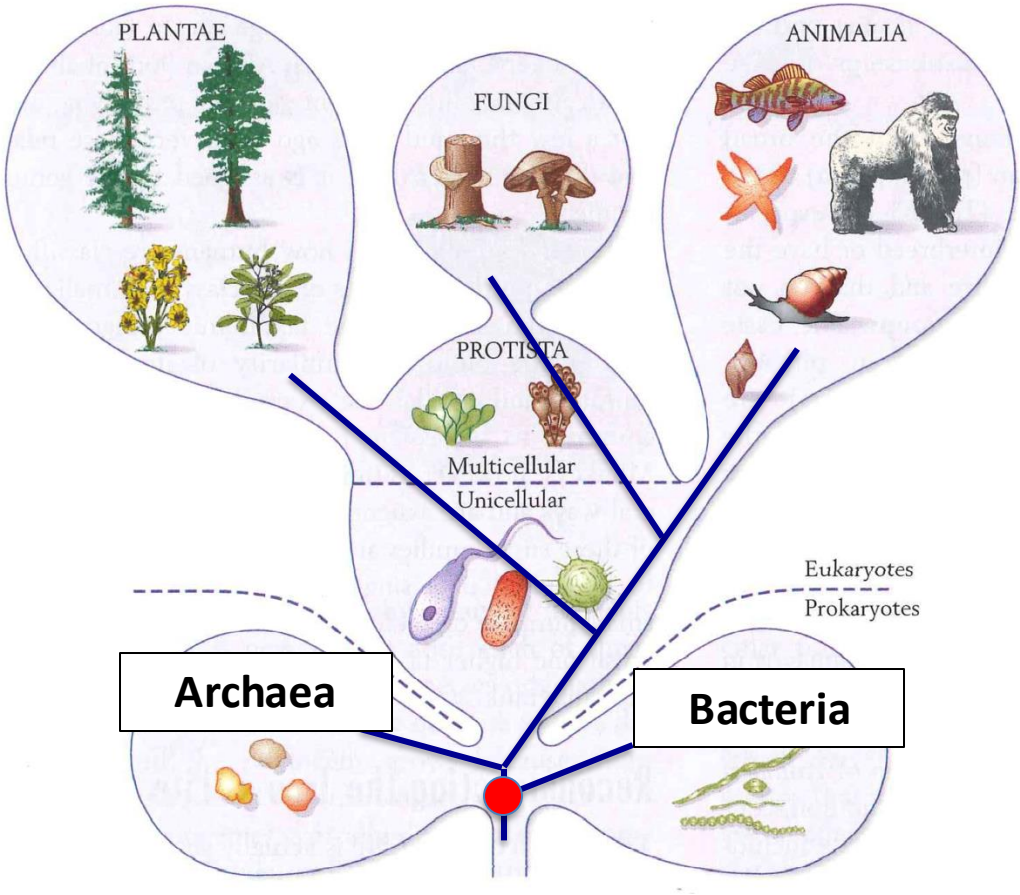
Guessing what first life was like: Working back in time on the Tree of Life

Inference: LUCA was a single celled prokaryote.

But: 1st organisms must have been *much* simpler than LUCA.

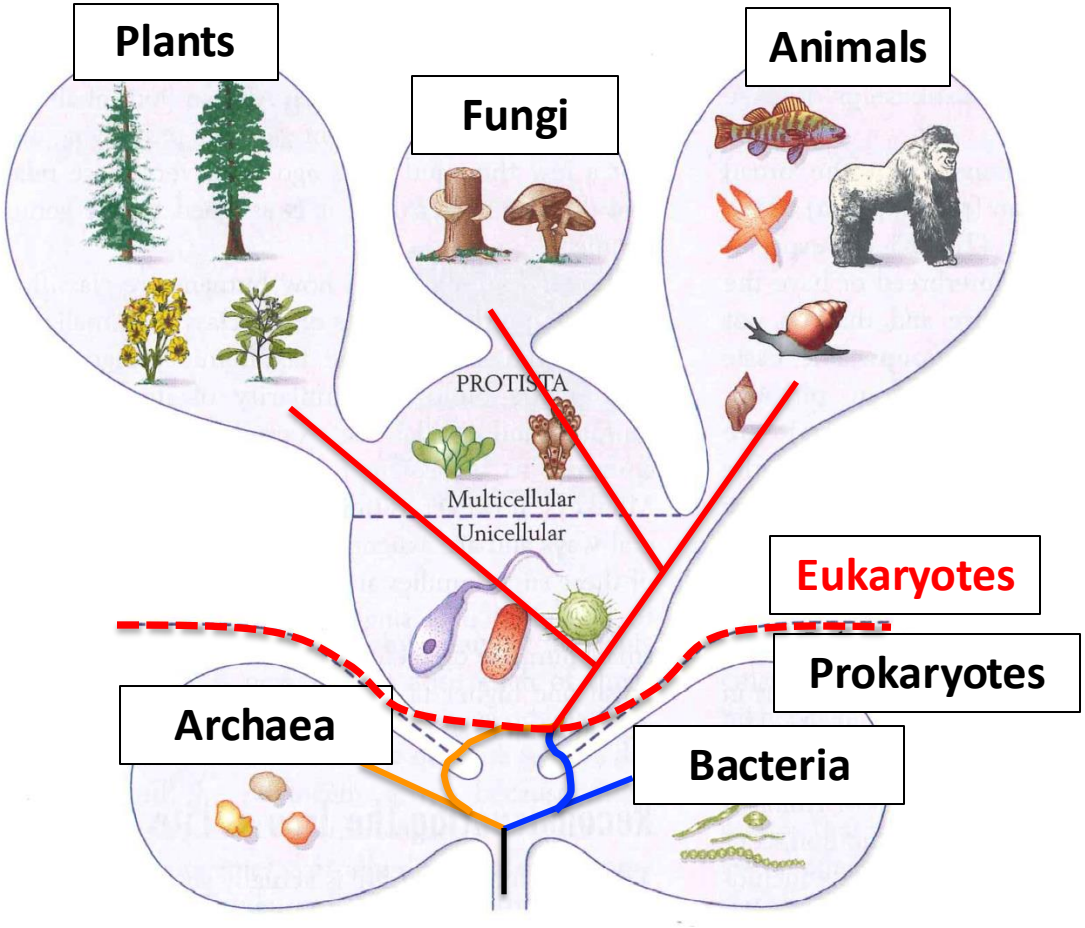
And: they may have been fundamentally different from LUCA ….

Important fact: cell membranes of Archaea and Bacteria have different compositions.



Last (Universal) Common Ancestor (LUCA) of Life

Guessing what first life was like: Working back in time on the Tree of Life



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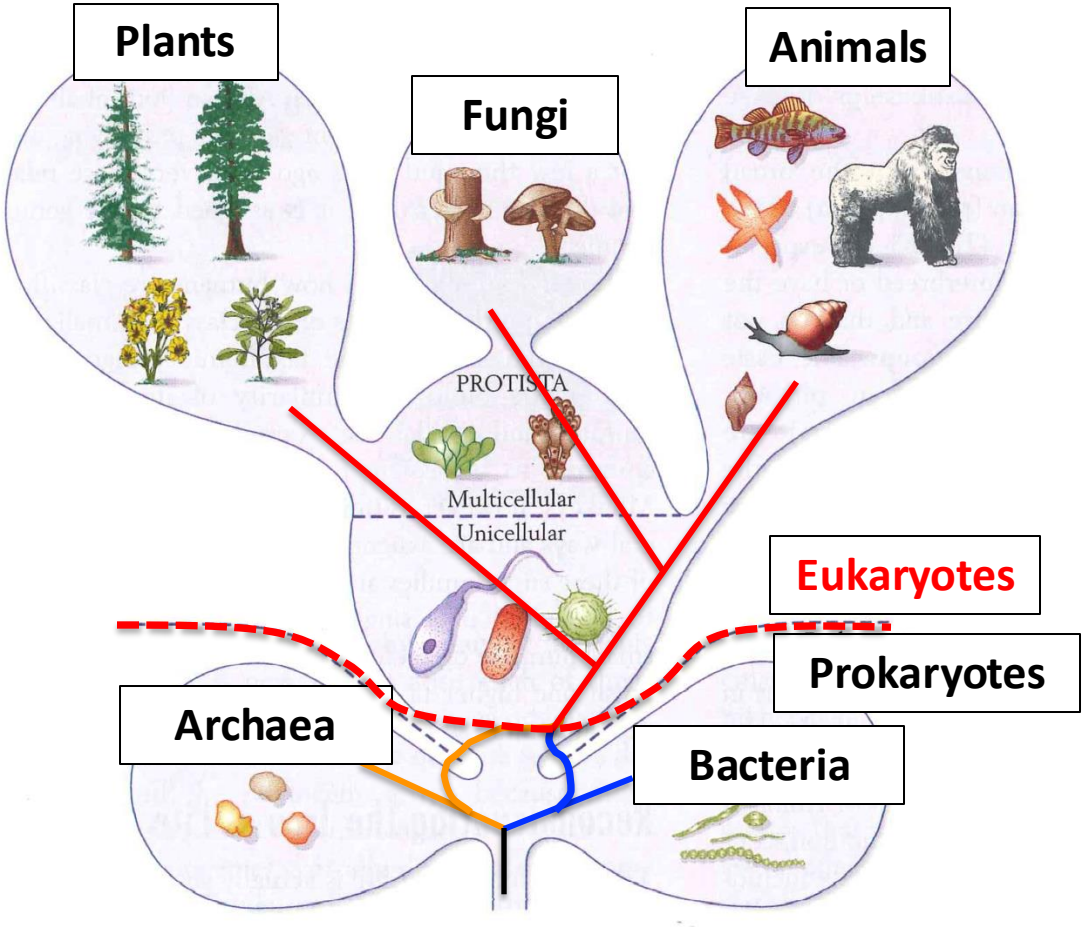

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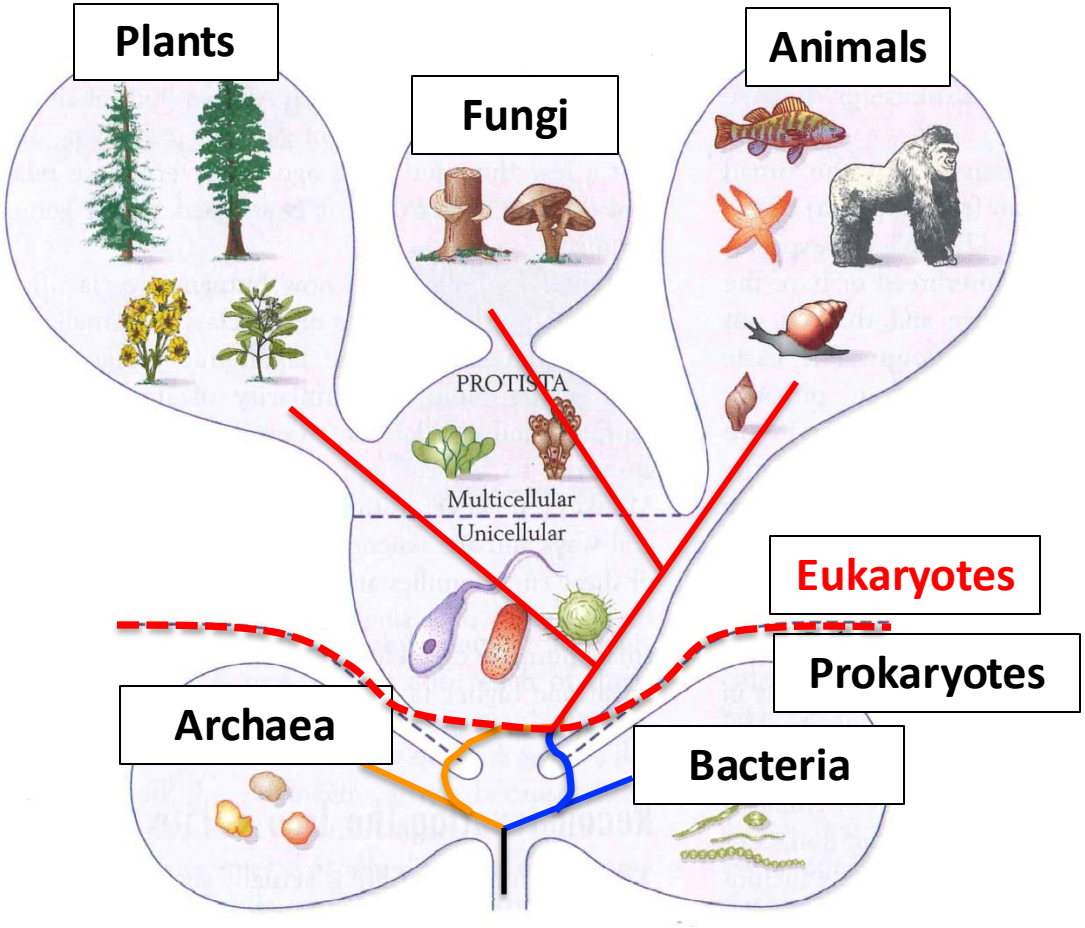

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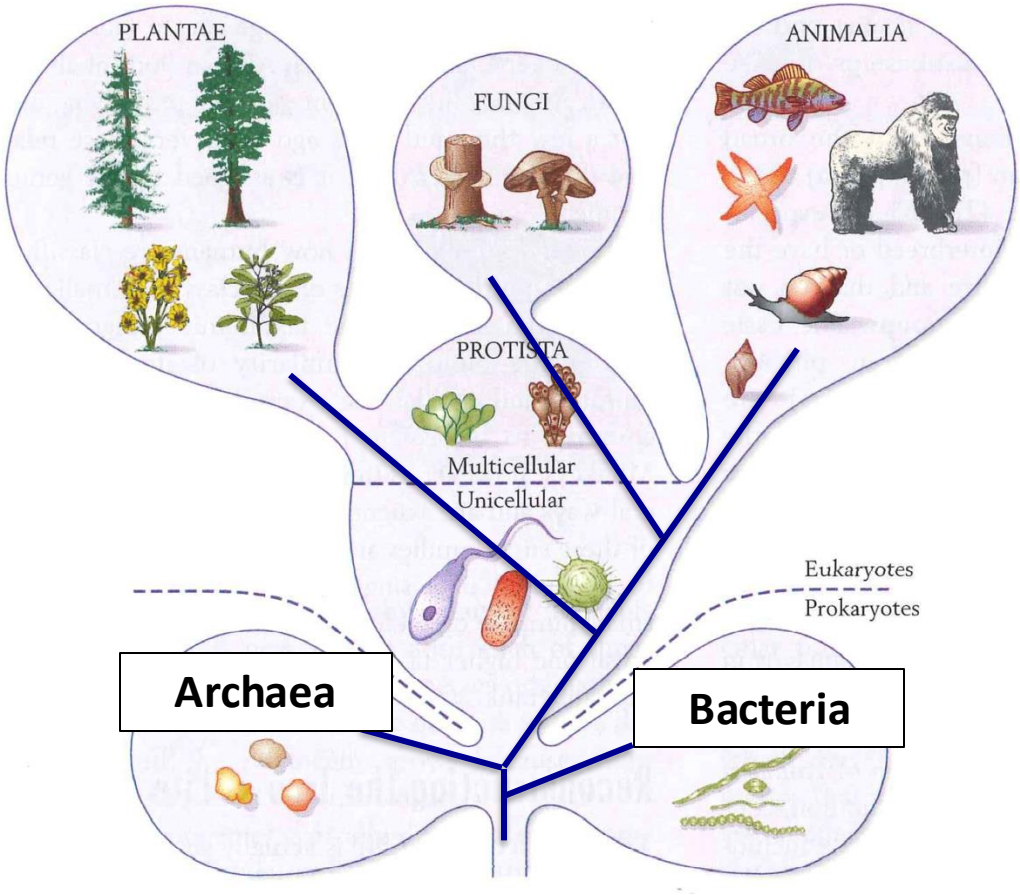
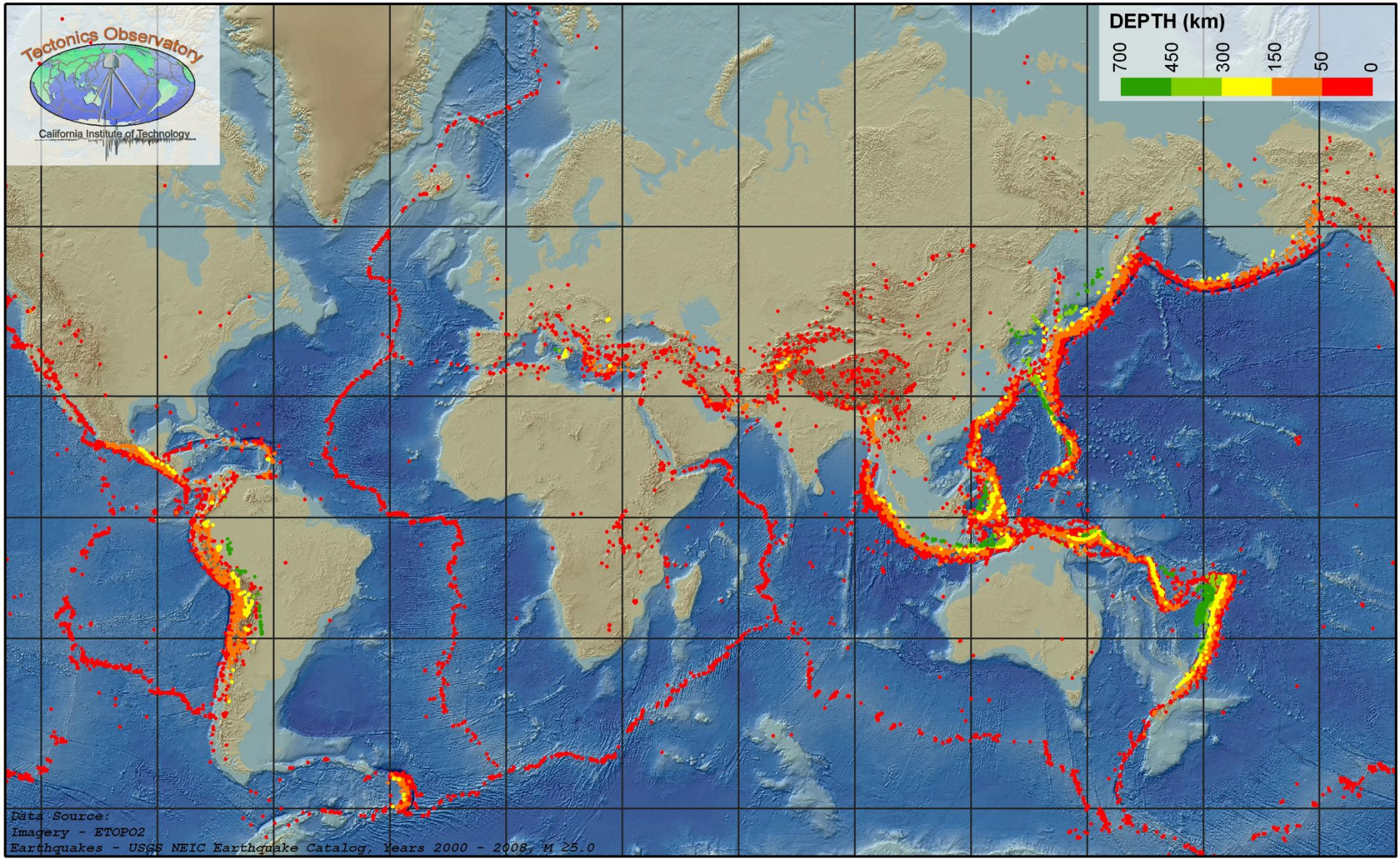


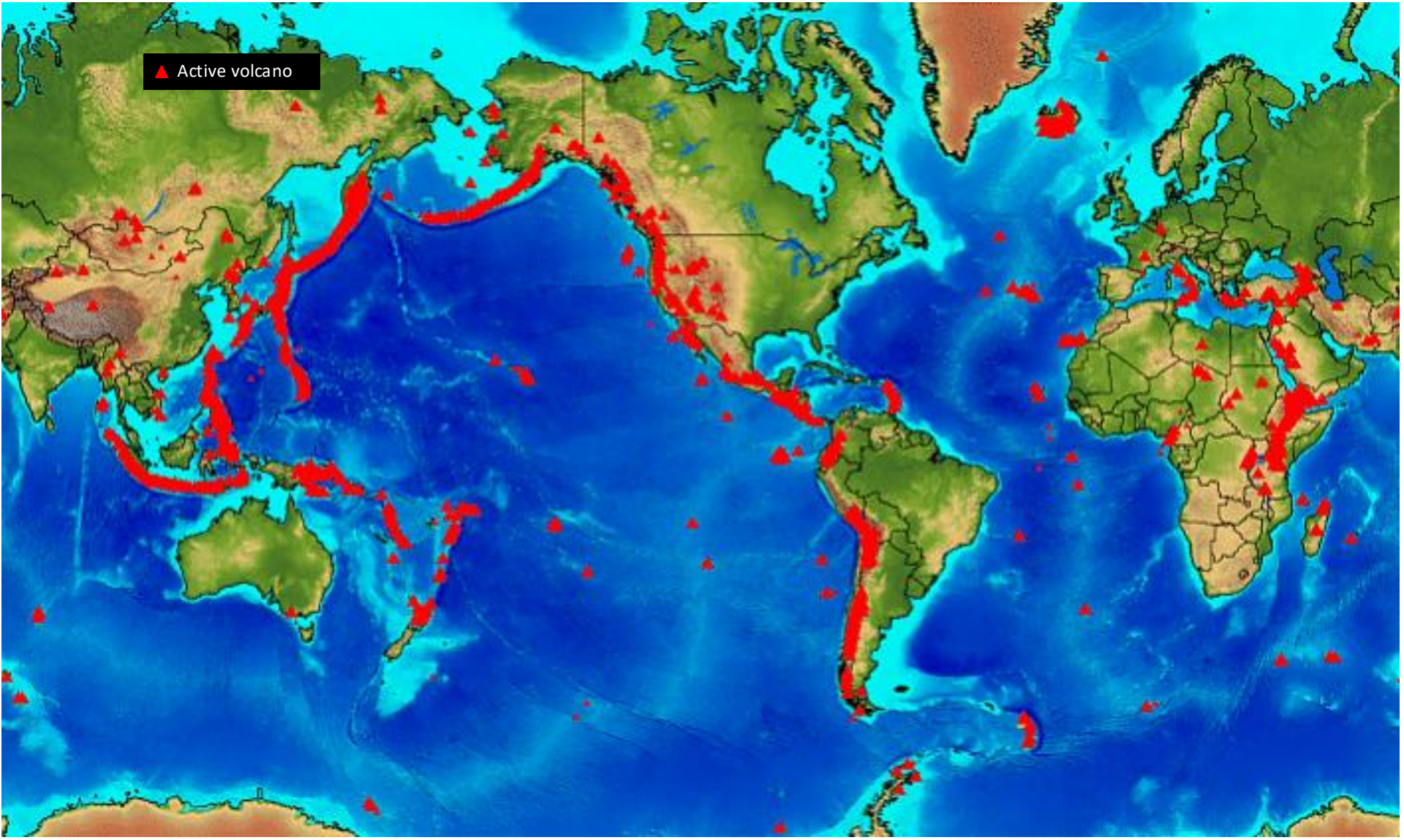
Darwin proposed a warm little pond

The Major Tectonic Plates

Earthquake Epicenters



(All earthquakes from 2000–2008, with a magnitude $\geq$ 5.0)


Active volcano