Lecture Series 14

Origins of Life, Early Earth & Prokaryotic Diversity

The Chemical Aspects of The Origin of Life

Life is the cumulative product of interactions among the many kinds of chemical substances that make up the cells of an organism.

The abiotic chemical evolution of life follows four major hurdles:

1. The abiotic synthesis and accumulation of small organic molecules, or monomers, such as amino acids and nucleotides.
2. The joining of these monomers into polymers, including proteins and nucleic acids.
3. The aggregation of abiotically produced molecules into droplets, e.g., protobionts, that had chemical characteristics different from their surroundings.
4. The origin of heredity or information transference.

To understand how the origin of life from abiotic material occurred, we have to consider two critical concepts:

1. The extension of the idea of natural selection to the chemical level.

2. The realization that the condition of the early Earth when life first arose must have been vastly different from present:

> (a) Non-oxidizing atmosphere: present level of oxygen, which began to accumulate around 2.1 billion years ago with the presence of cyanobacteria, would have been lethal to primitive organisms
>
> (b) Abundant resources produced non-biologically
>
> (c) Long time scale without competition

The Molecular Clues to the Origin of Life on Earth

- Molecules of living organisms are rich in **hydrogen-containing carbon** compounds that are highly reduced. This suggests that there were little or no free molecular oxygen on primitive Earth.

- All **amino acids** exist in both the right-handed and left-handed state. However, only 20 amino acids of the left-handed variety are used by living organisms in proteins. Therefore, suggesting there was a single origin of life.

- **DNA** & **RNA** are the universal informational basis of all life forms on Earth.

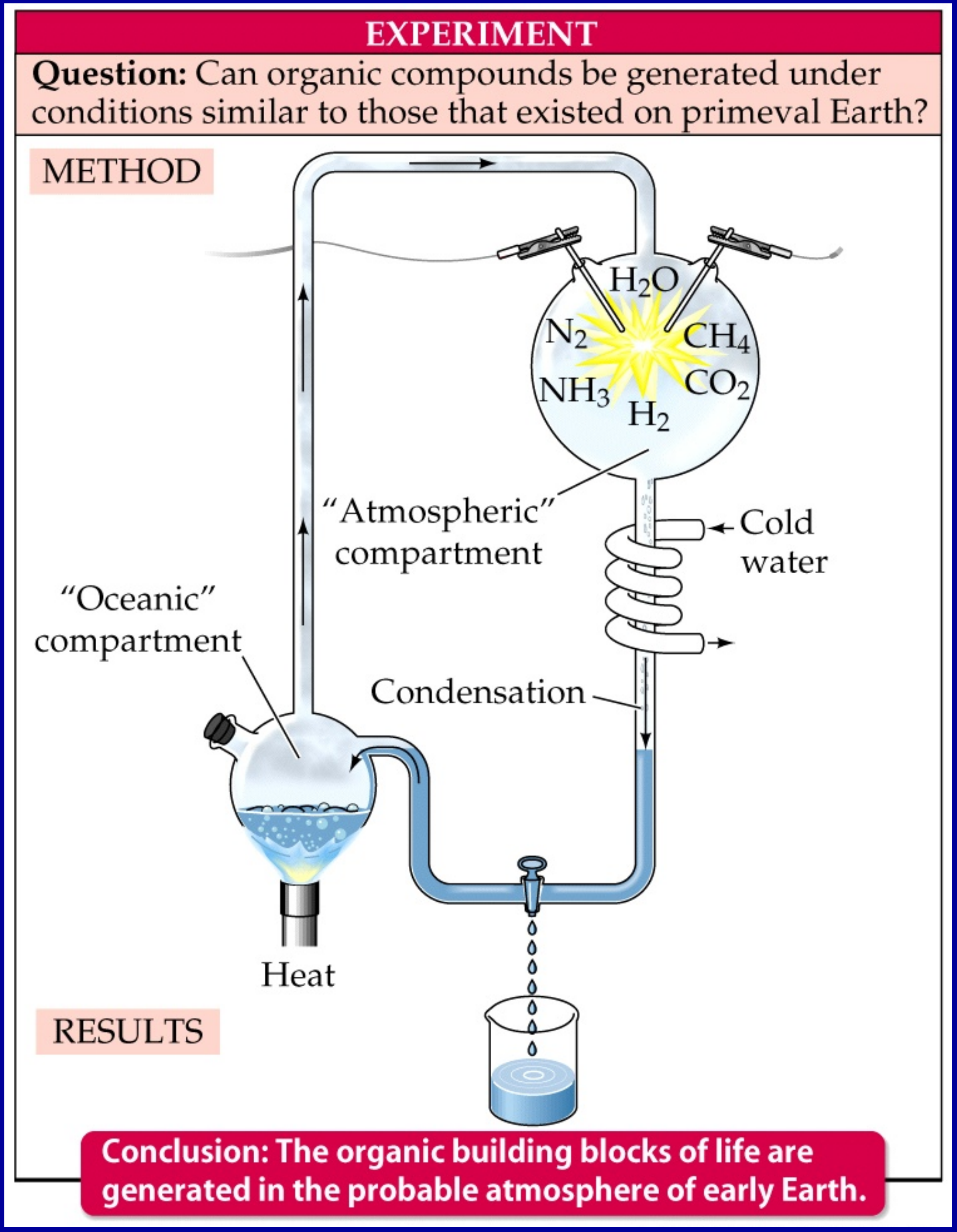
- **ATP** is the universal energy currency of all living organisms; suggesting a common origin of metabolism.

- In any cell, first steps of carbohydrate metabolism involve **fermentation**, with the last steps in aerobic organisms the usage of oxygen via **respiration** – suggesting that aerobic organisms evolved from anaerobic ones.

Necessary Conditions for the Origin of Life

- Earth at the time of life's origin had a reducing atmosphere. Under conditions that resemble Earth's early atmosphere, small molecules essential to living systems form and polymerize.

Diagram of Stanley Miller's apparatus



Necessary Conditions for the Origin of Life

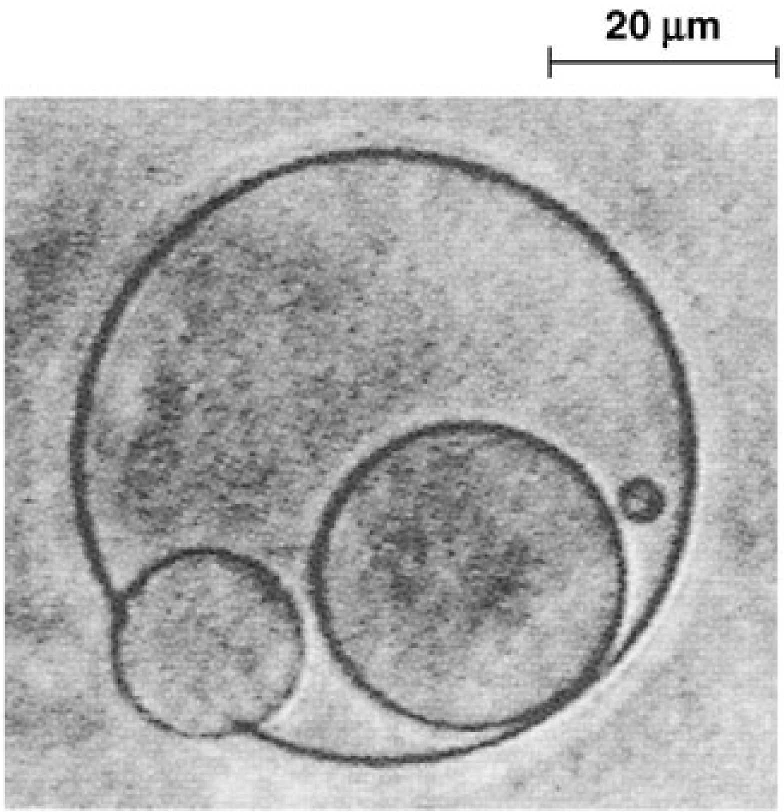
- Before life appeared, polymerization reactions generated the carbohydrates, lipids, amino acids, and nucleic acids of which organisms are composed. These molecules accumulated in the oceans.
- Originally "Darwin's Warm Pond" Hypothesis

A painting of early Earth showing volcanic activity and photosynthetic prokaryotes in dense mats

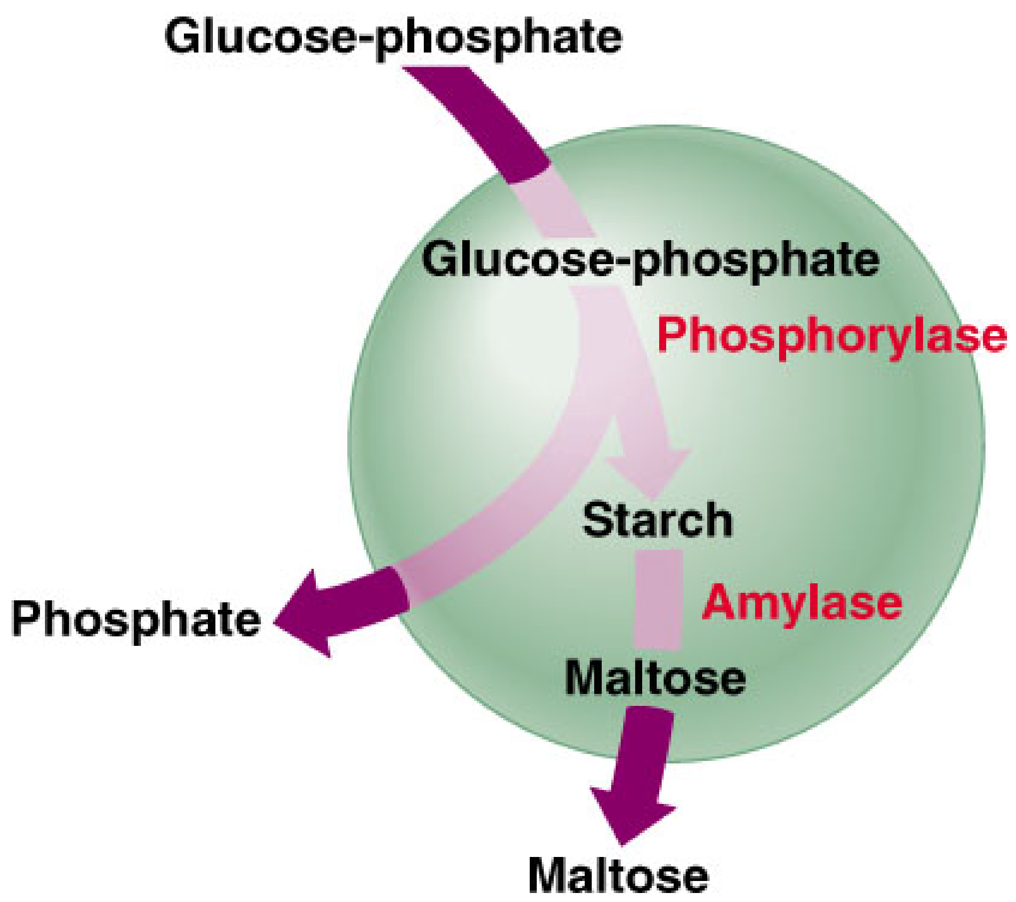
Protobionts: Enclosing Prebiotic Systems

- The earliest protobionts probably had lipid-based membranes.

Laboratory versions of protobionts



(a) Simple reproduction



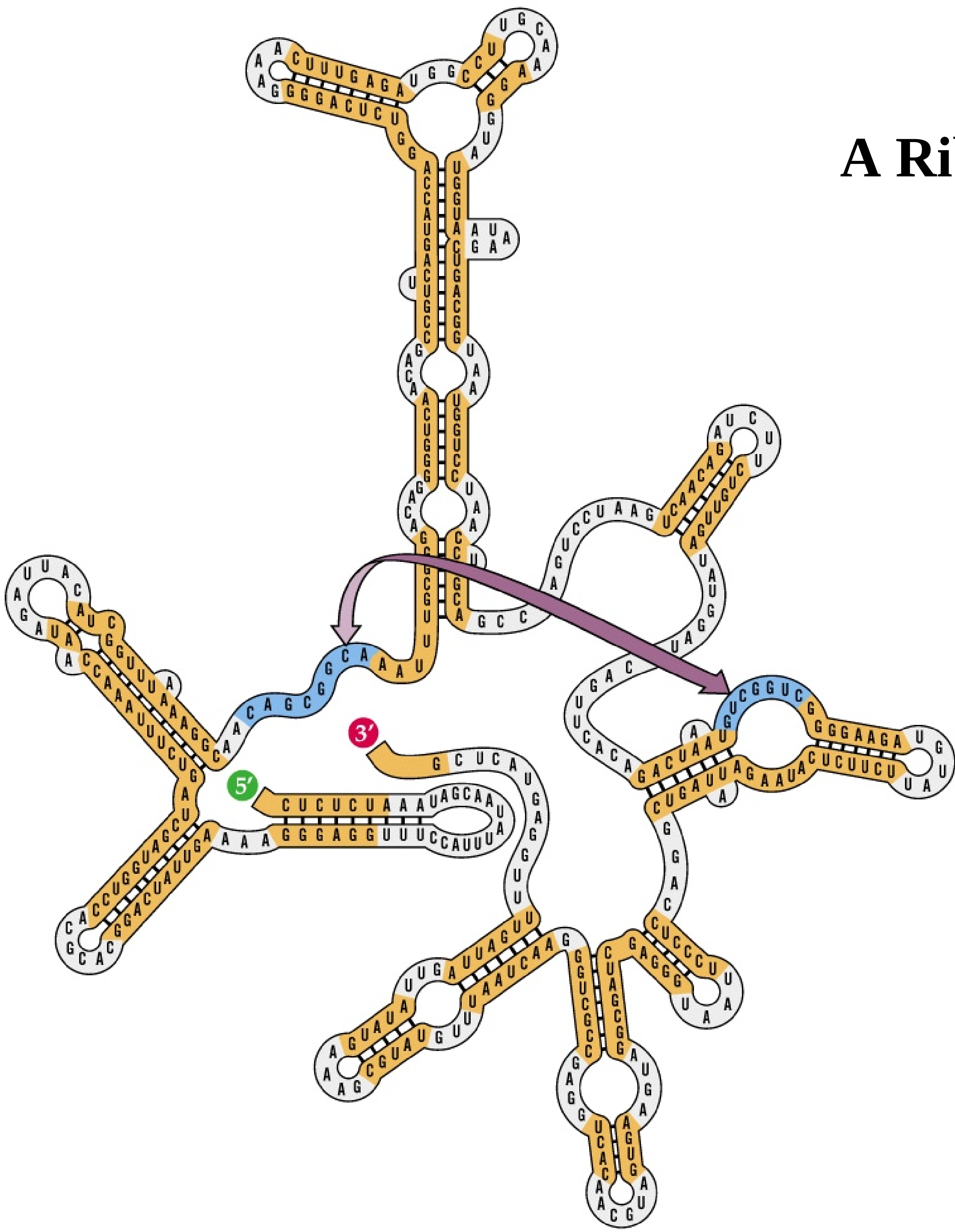
(b) Simple metabolism

Putative "Metabolism" of a Coacervate Drop

Protobionts: Enclosing Prebiotic Systems

- The first genetic material may have been RNA that had a catalytic function and an information transfer function. Some RNA's—called ribozymes—have catalytic functions today.

A Ribozyme from a Protist



Folding brings together complementary but distant base sequences allowing catalytic activity to occur

RNA World: Peptide Bond Formation

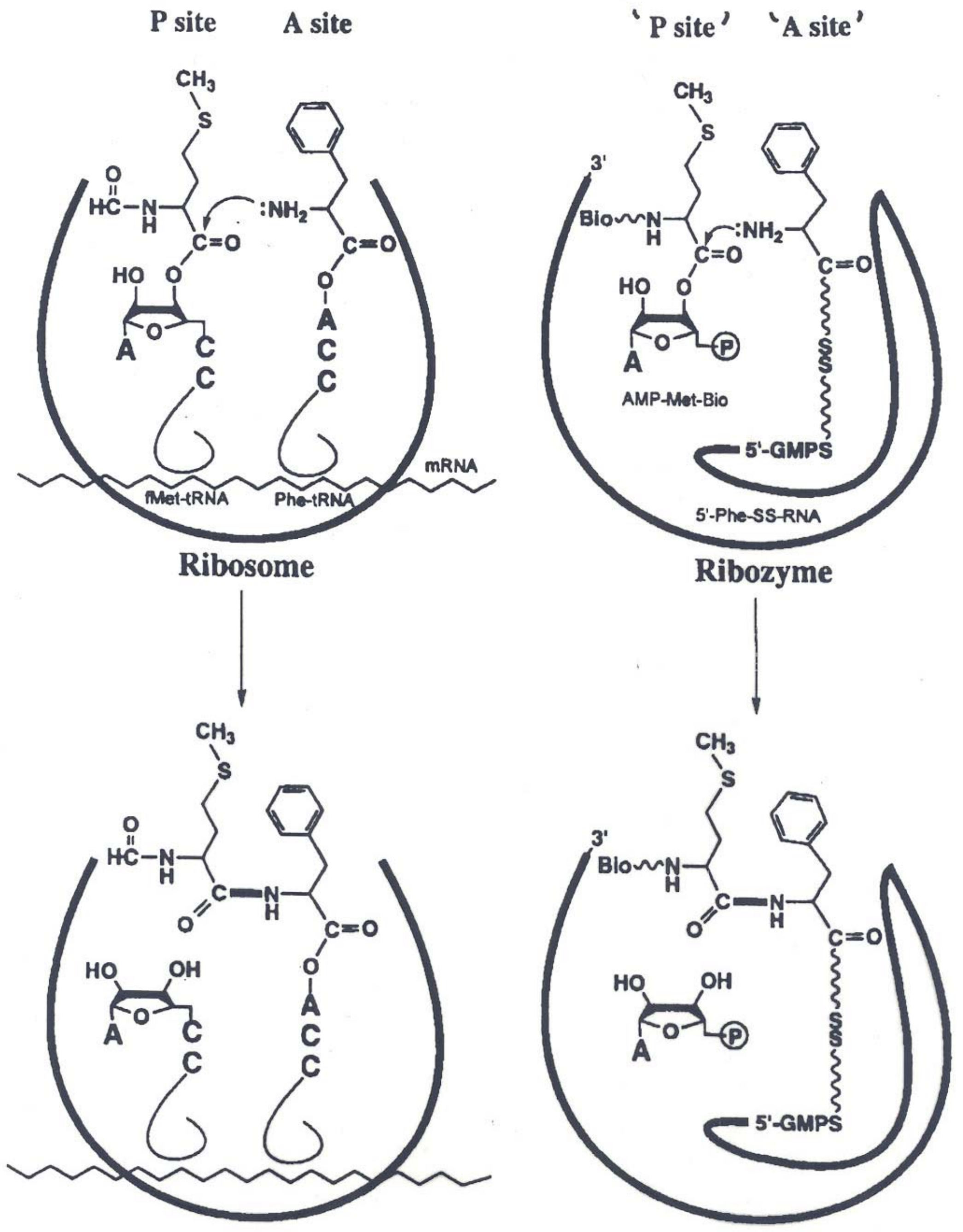
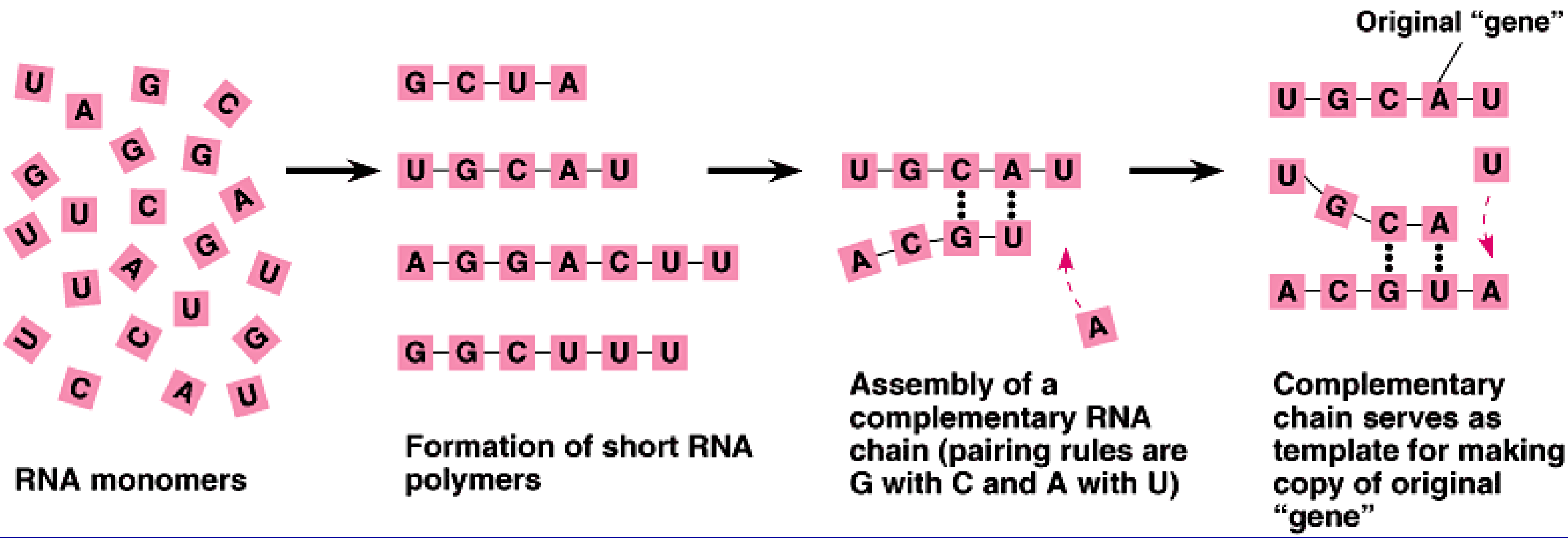


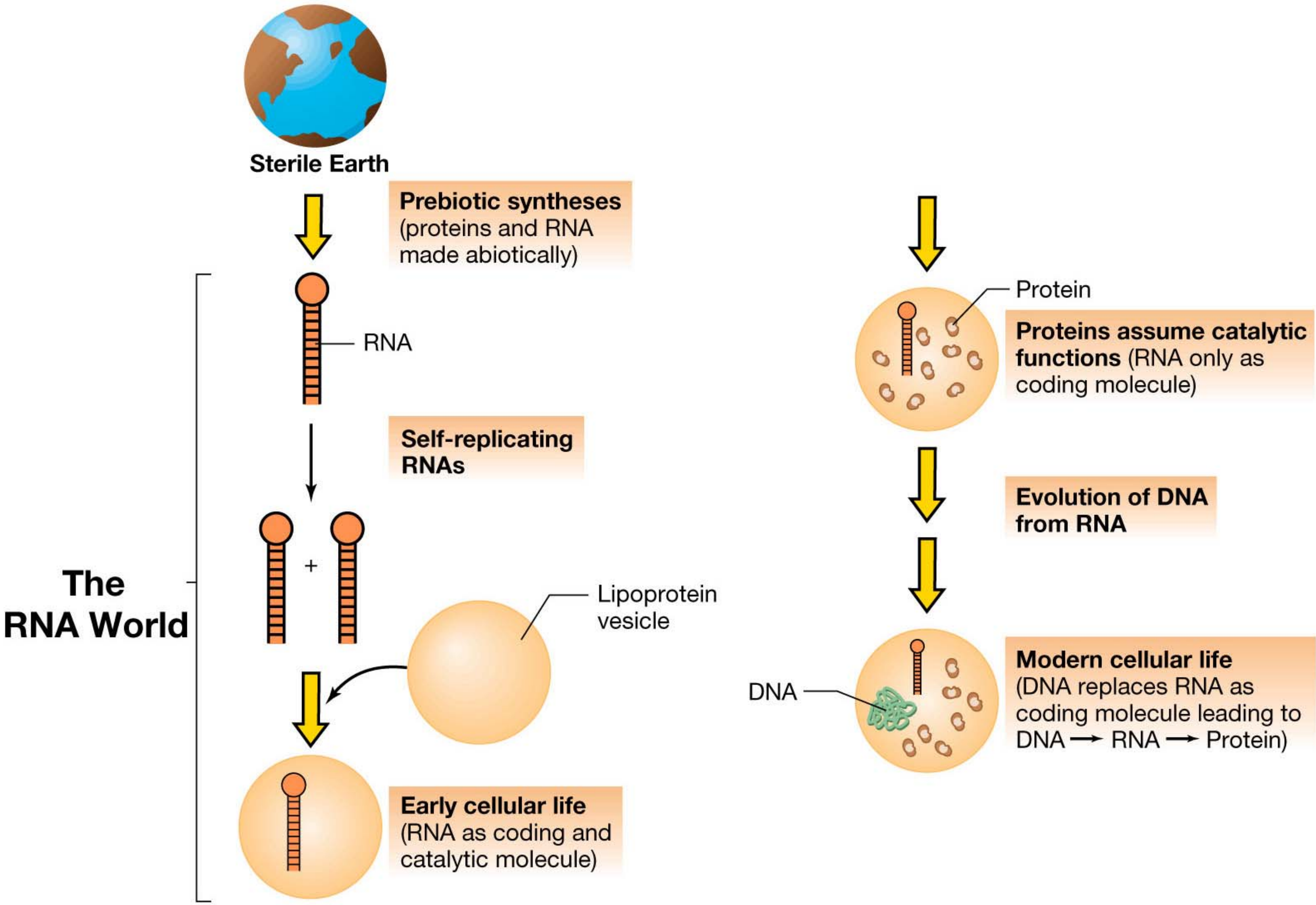
Figure 1 Peptide bond formation by a ribosome (left) and by a ribozyme (right).

Protobionts: Enclosing Prebiotic Systems

- DNA probably evolved after RNA-based life became surrounded by membranes that provided an environment in which DNA was stable.

Abiotic replication of RNA



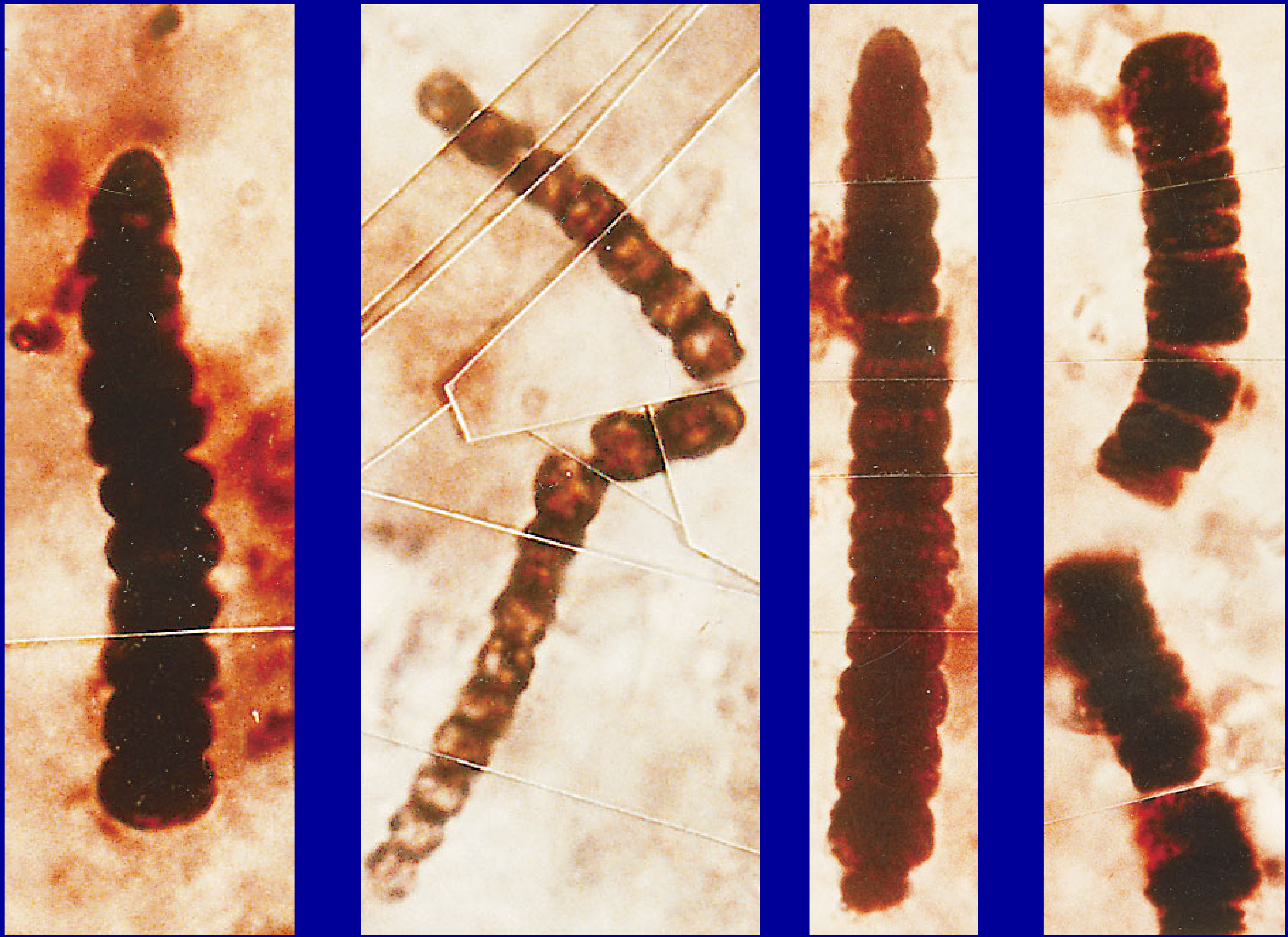


Sterile Earth
Prebiotic syntheses (proteins and RNA made abiotically)
RNA
Self-replicating RNAs
+
Lipoprotein vesicle
Early cellular life (RNA as coding and catalytic molecule)
The RNA World
Protein
Proteins assume catalytic functions (RNA only as coding molecule)
Evolution of DNA from RNA
DNA
Modern cellular life (DNA replaces RNA as coding molecule leading to DNA → RNA → Protein)

Photosynthesis Is the Source of Atmospheric O_2

- Cyanobacteria, which evolved the ability to split water into hydrogen ions and O_2, created atmospheric O_2. Accumulation of free O_2 in the atmosphere made possible the evolution of aerobic metabolism.

Fossil Stromatolites and mat communities

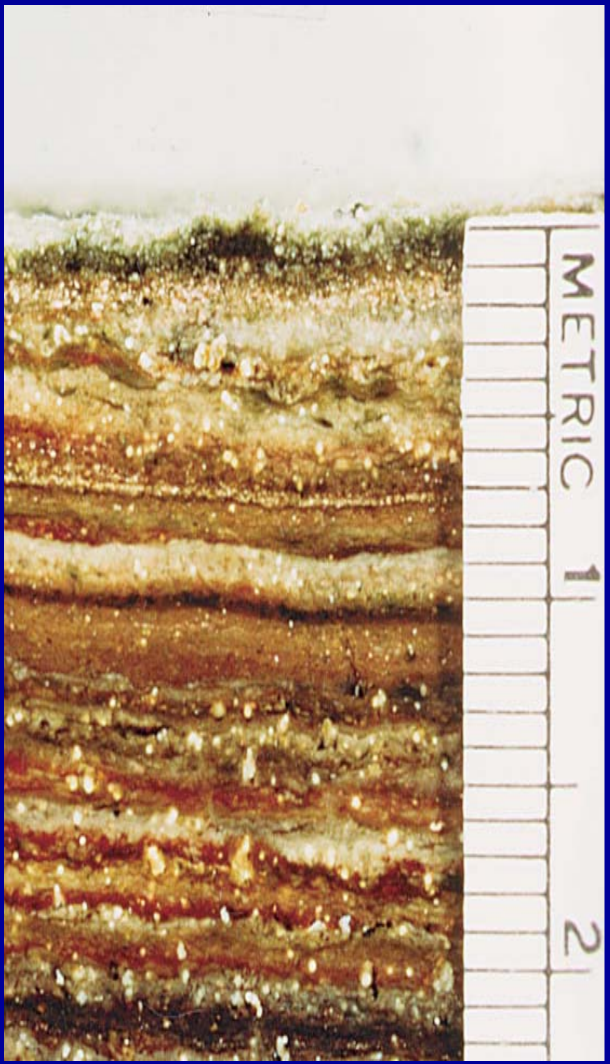


Living columnar stromatolites, Shark Bay, Western Australia

Modern Stromatolites from Yellowstone Natl. Park

Early (left) and modern (right) prokaryotes

Microbial mat communities



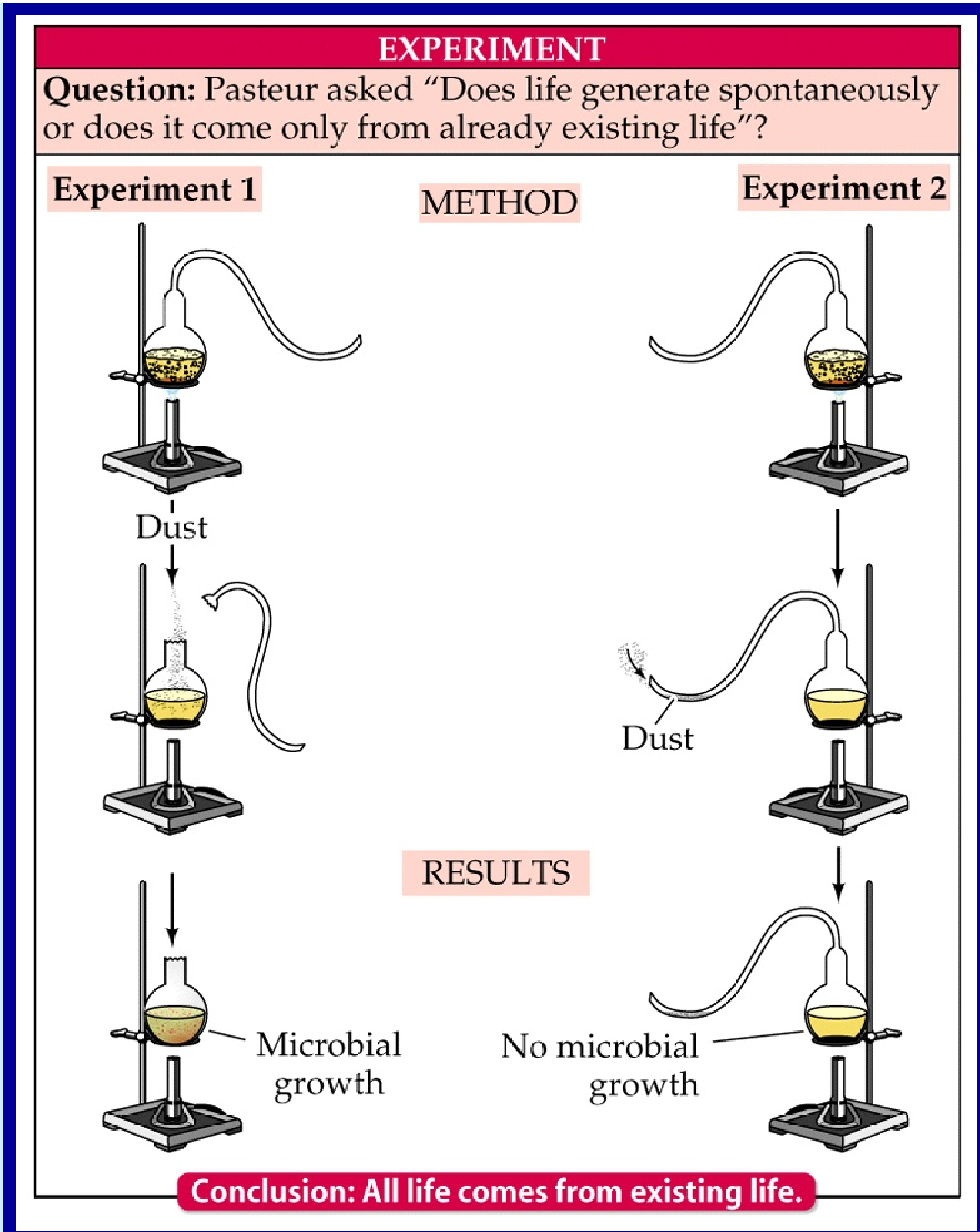
Fossil Stromatolites from Glacier Natl. Park

Is Life Evolving from Nonlife Today?

- Because most of the chemical reactions that gave rise to life occur readily under the conditions that prevailed on early Earth, life's evolution was "probably" inevitable.

- Experiments by Louis Pasteur and others convinced scientists that life does not come from nonlife on Earth today.

Louis Pasteur



Pasteur was the father of "origins of life" research in addition to microbiology & cell biology.

Architect of Germ Theory.

Is Life Evolving from Nonlife Today?

- New life is no longer being assembled from nonliving matter because simple biological molecules that form in today's environment are oxidized or consumed by existing life.
- Now we have competition & oxygen!

Volcanic activity and lightning associated with the birth of the island of Surtsey near Iceland; terrestrial life began colonizing Surtsey soon after its birth

Does Life Exist Elsewhere in the Universe?

- Conditions that permit the evolution and maintenance of simple prokaryotic life may be widespread in the universe, but multicellular life has more stringent requirements, including a planet with a relatively circular orbit, a rapid rate of spin, nearby planets that intercept impacts, and a large moon that stabilizes the planet’s orbit. Such conditions may be very rare.

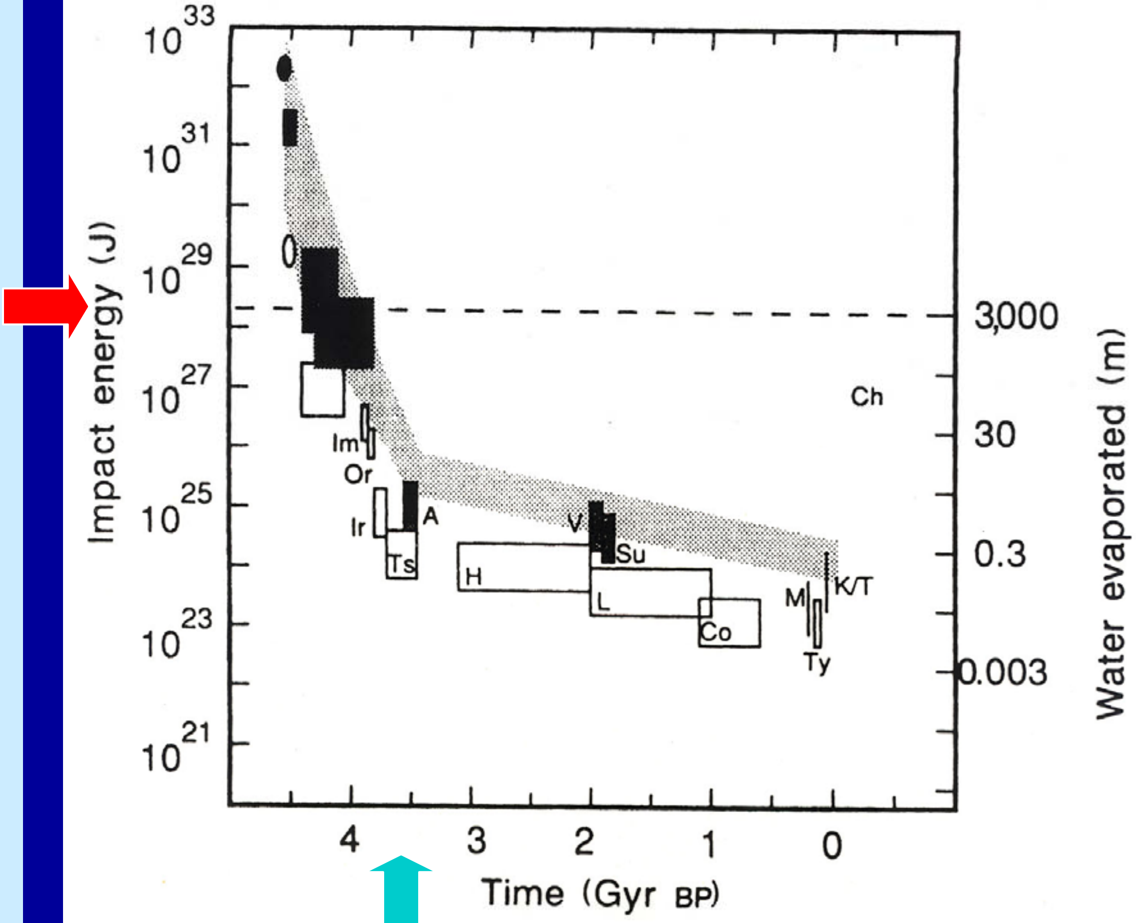
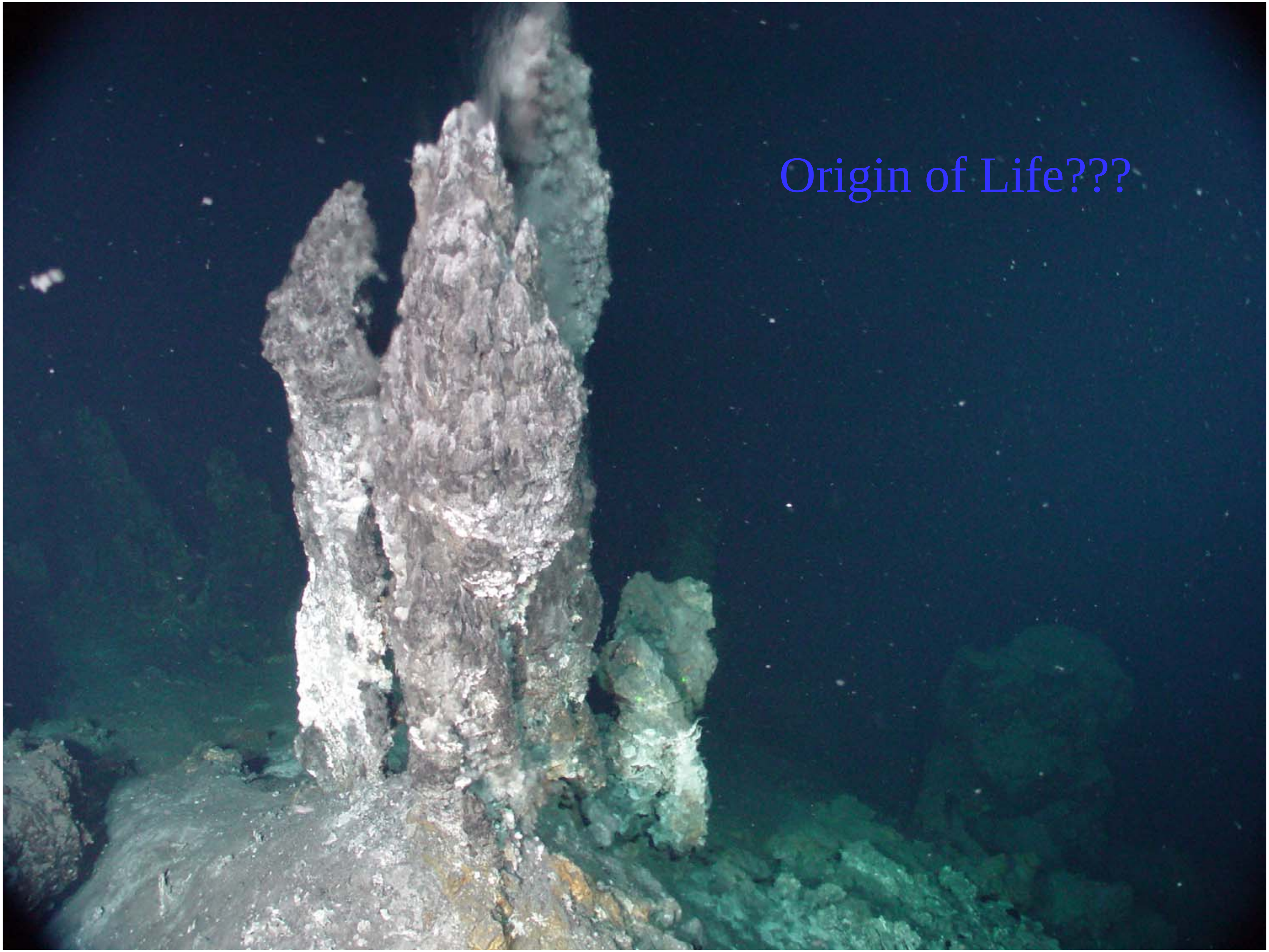


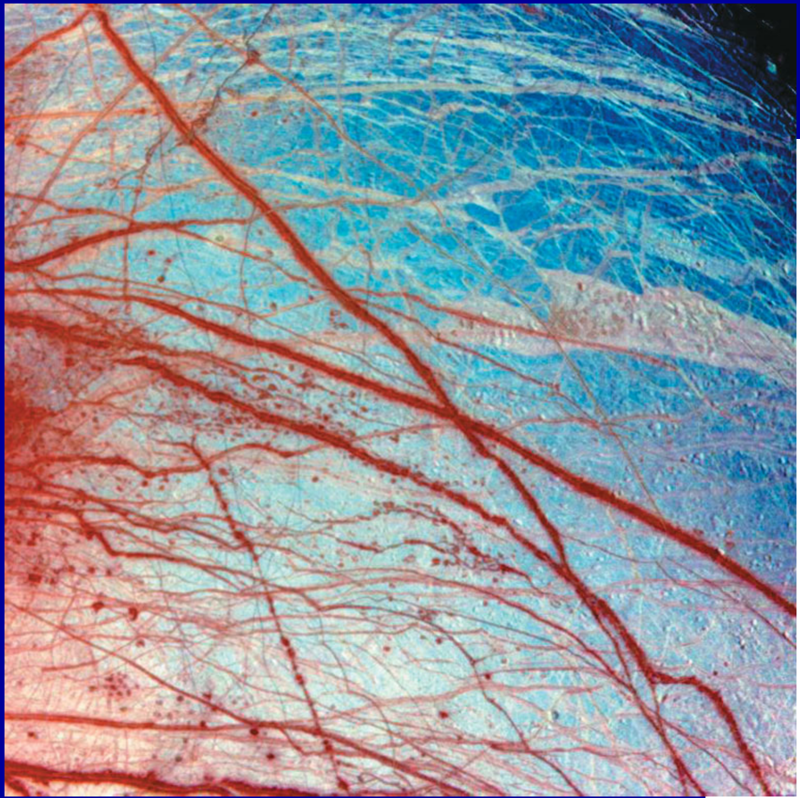
FIG. 1 The largest impacts on Earth and Moon. Open boxes are lunar, filled boxes terrestrial. Lunar craters are Tycho, Copernicus, Langrenus, Hausen, Tsiolkovski, Iridum, Orientale and Imbrium. Terrestrial events are the K/T impact, Manicougan, Sudbury, Vredevort and an impact energy corresponding to the thickness of Archaean spherule beds. Ovals are self energies of formation; the early box refers to a possible Moon-forming impact. Impact estimates between 3.8 and 4.4 Gyr are discussed in the text. The stippled region for Earth is inferred from these data. The depth of ocean vaporized by the impact is also given; the dashed line corresponds to an ocean-vaporizing impact. A possible but extremely unlikely collision with Chiron is placed safely in the future.

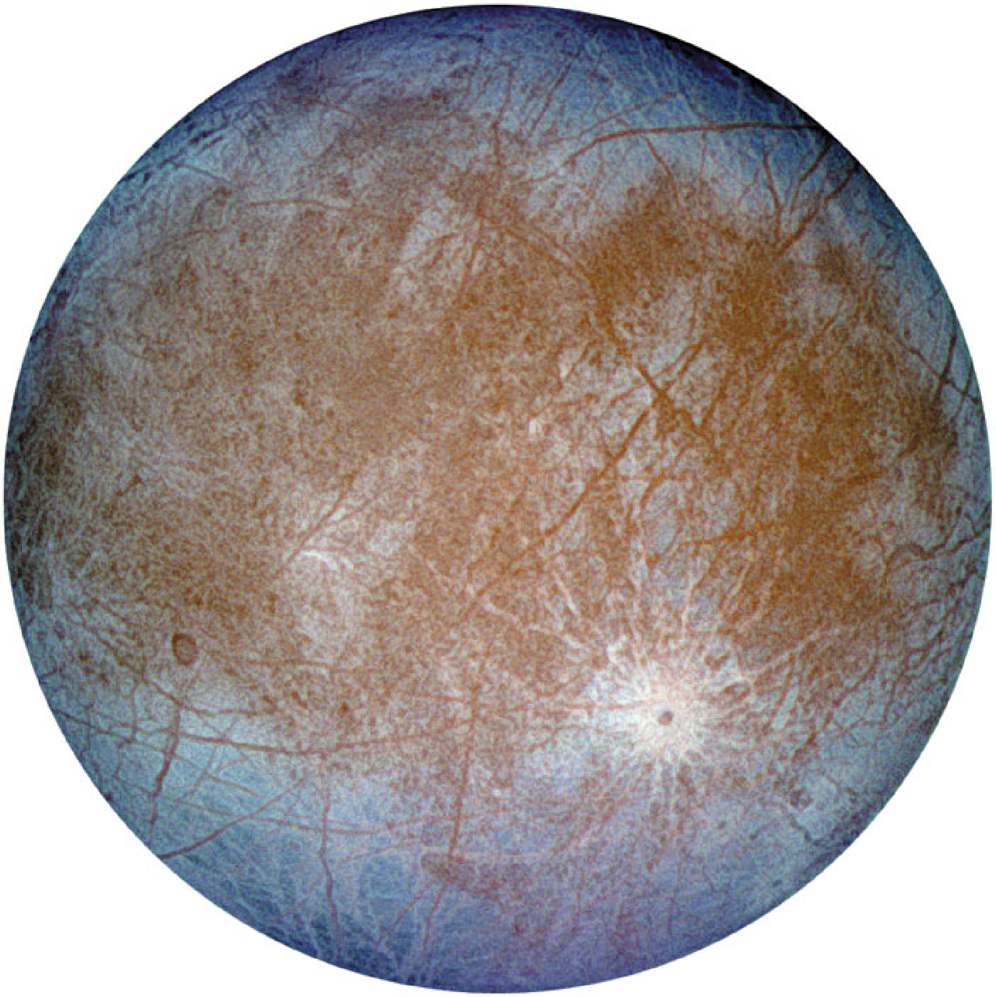
Impact Frustration period forces origins of life into a narrow time period to have gotten started!

Hydrothermal vents may have served as zones of refuge.


Origin of Life???

Europa, Jupiter’s moon: Astrobiology???





Does Life Exist Elsewhere in the Universe?

- Although conditions on Earth have fluctuated greatly, they have been suitable for multicellular organisms for nearly a billion years.

Why Three Domains?

- Living organisms can be divided into three domains: Bacteria, Archaea, and Eucarya. The prokaryotic domains (Archaea and Bacteria) differ from each other more radically than the Archaea from the Eucarya.

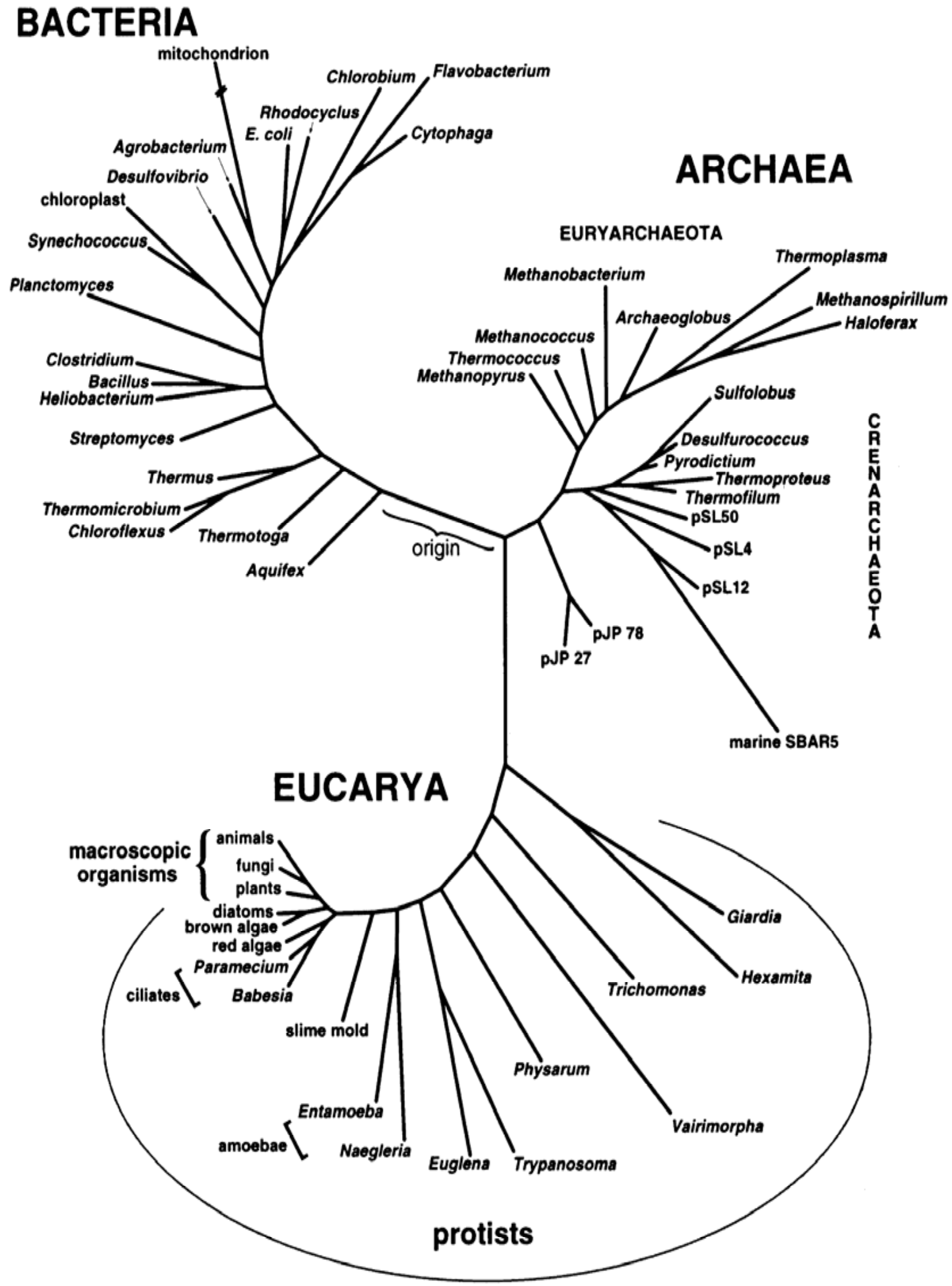


Figure 1. Diagrammatic "Universal" phylogenetic tree of life, based on small-subunit ribosomal RNA sequences. Based on analyses of Barns et al. (1996b), Olsen et al. (1994), and Sogin (1994).

Why Three Domains?

- Evolutionary relationships of the domains were revealed by rRNA sequences. Their common ancestor lived more than 3.6 - 3.8 billion years ago, prior to that of the common ancestor of the Archaea and Eucarya.

Some Lessons from the BIG TREE: Map of the Biological Record

Single origin for all life on Earth...

- Central Dogma intact
- ATP and PMF are universal themes
- Uniformity among chiral carbon compds (sugars & AAs)
- Hot start origin…

- Also Cyanobacteria did not arrive first on the scene!
- Now estimated at 2.5 –2.1 bya

Some Lessons from the BIG TREE: Map of the Biological Record

General topology implies:

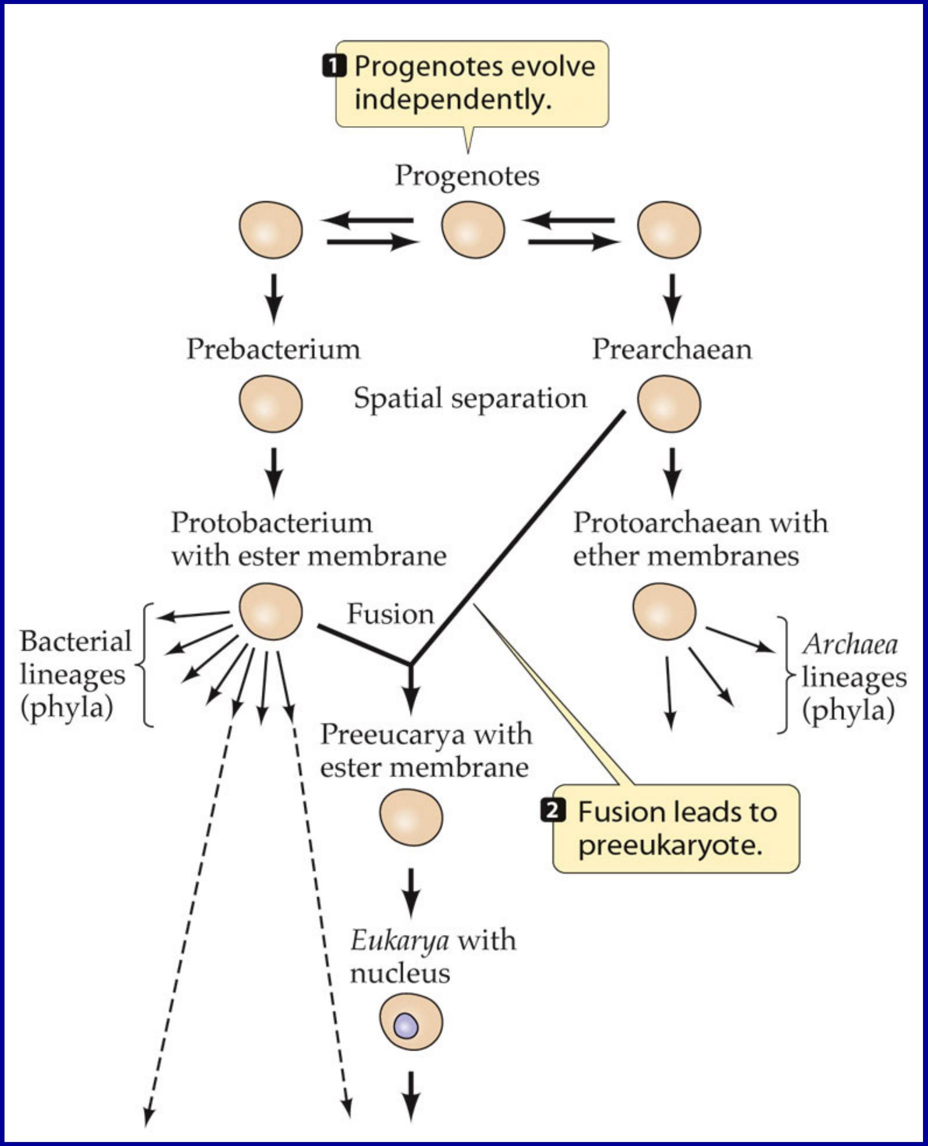
- Three "primary lines of evolutionary descent."
- The Eucarya *"nuclear"* lineage almost as old as the prokaryote lines.
- Prokaryotes split between *Bacteria* and *Archaea*.
- Shown for only a limited number of representative org's.
- Mitochondria and chloroplasts proven to be of bacterial origin.

A Comparison of the Three Domains of Life

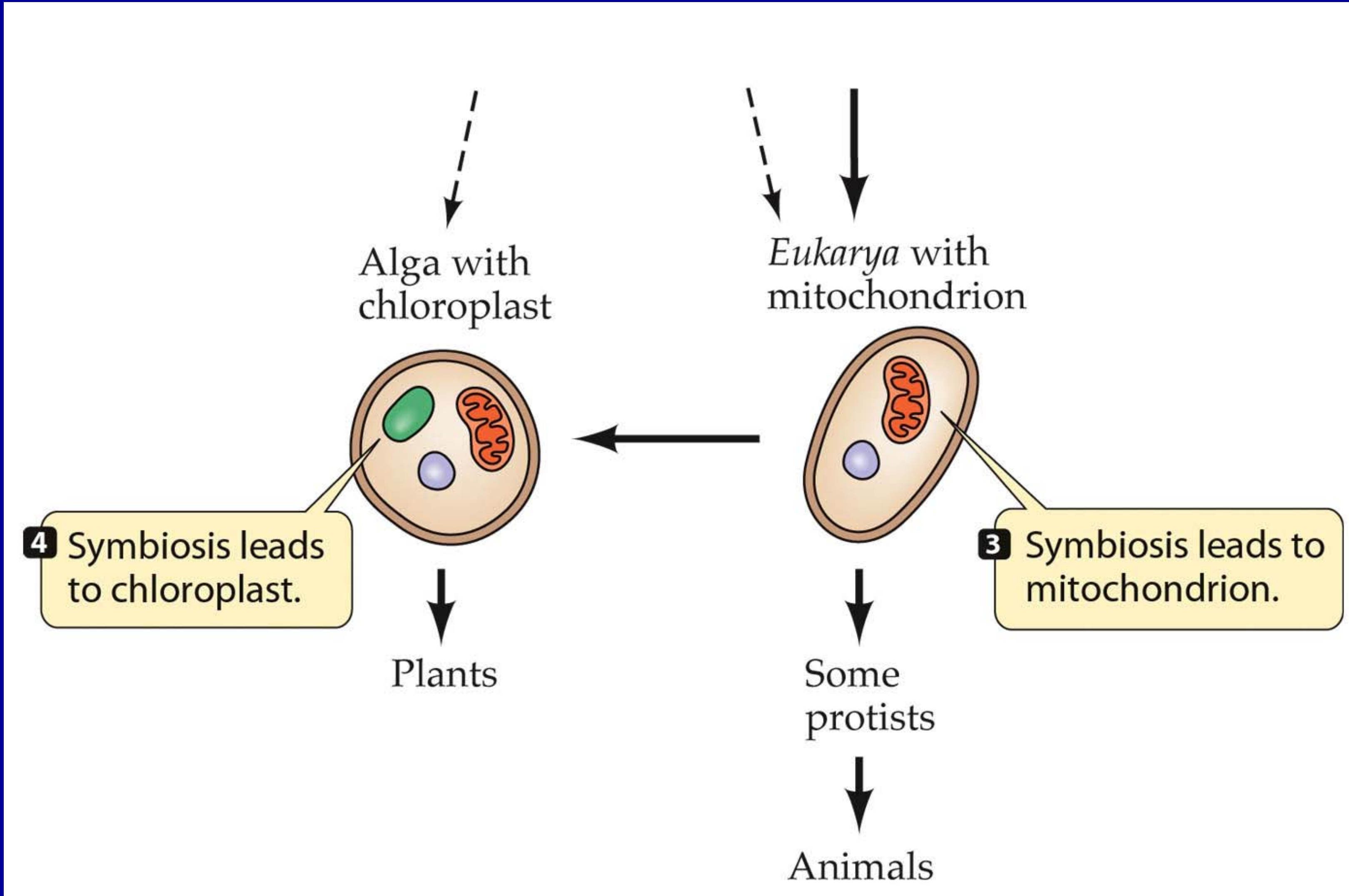
Table 27.2 A Comparison of the Three Domains of Life

CHARACTERISTIC	DOMAIN		
	Bacteria	Archaea	Eukarya
Nuclear envelope	Absent	Absent	Present
Membrane-enclosed organelles	Absent	Absent	Present
Peptidoglycan in cell wall	Present	Absent	Absent
Membrane lipids	Unbranched hydrocarbons	Some branched hydrocarbons	Unbranched hydrocarbons
RNA polymerase	One kind	Several kinds	Several kinds
Initiator amino acid for start of protein synthesis	Formyl-methionine	Methionine	Methionine
Introns (noncoding parts of genes)	Absent	Present in some genes	Present
Response to the antibiotics streptomycin and chloramphenicol	Growth inhibited	Growth not inhibited	Growth not inhibited
Histones associated with DNA	Absent	Present	Present
Circular chromosome	Present	Present	Absent
Ability to grow at temperatures $>100°C$	No	Some species	No

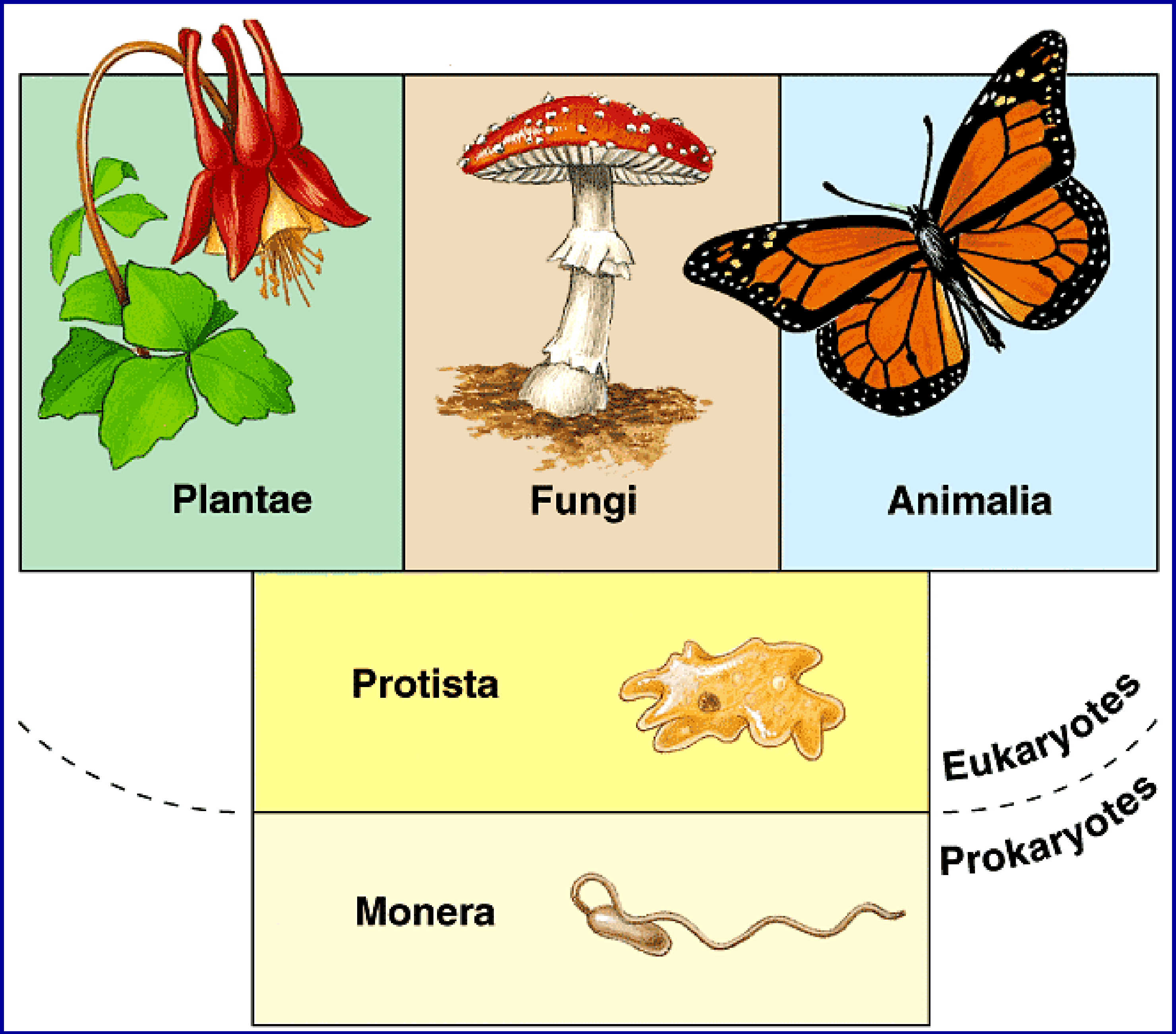
Evolution of the main lines of descent



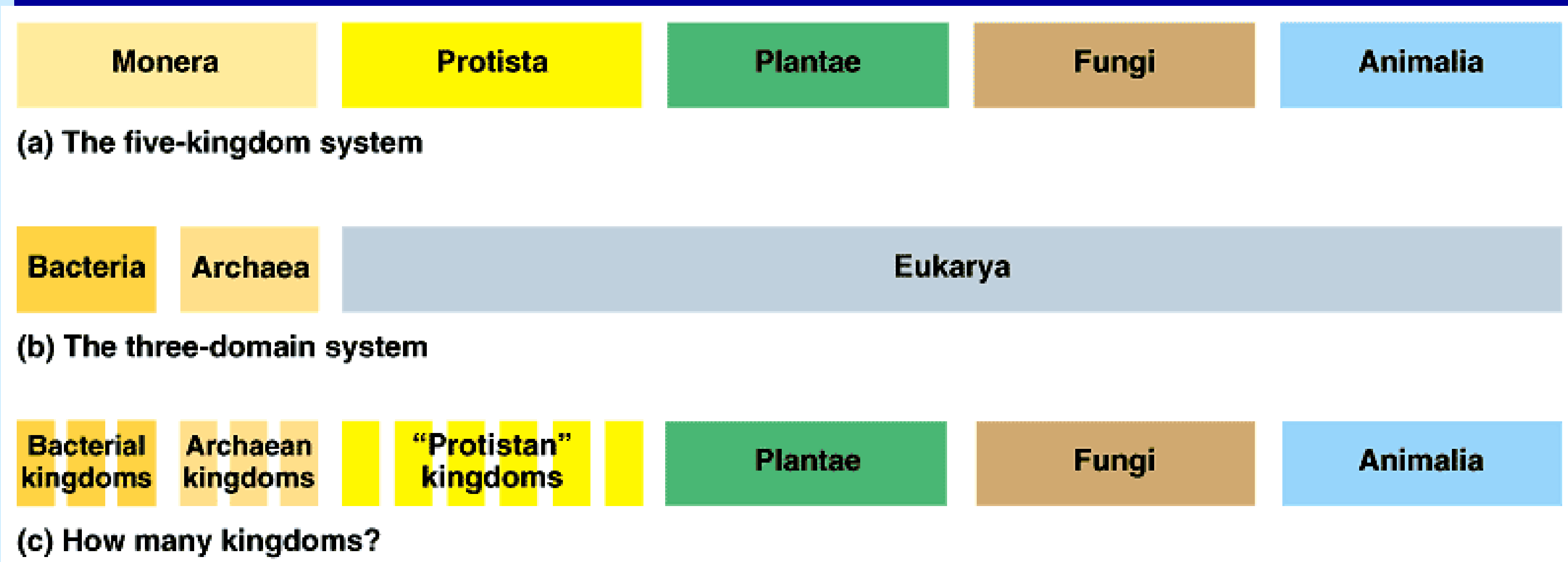
Evolution of the main lines of descent



Whittaker's five-kingdom system



Our changing view of biological diversity



General Biology of the Prokaryotes

- The prokaryotes are the most numerous organisms on Earth,occupying an enormous variety of habitats.
- Most prokaryotes are cocci, bacilli, or spiral forms. Some link together to form associations, but very few are truly multicellular.

"Heat-loving" prokaryotes

Hot springs, home of thermophiles

Extreme halophiles

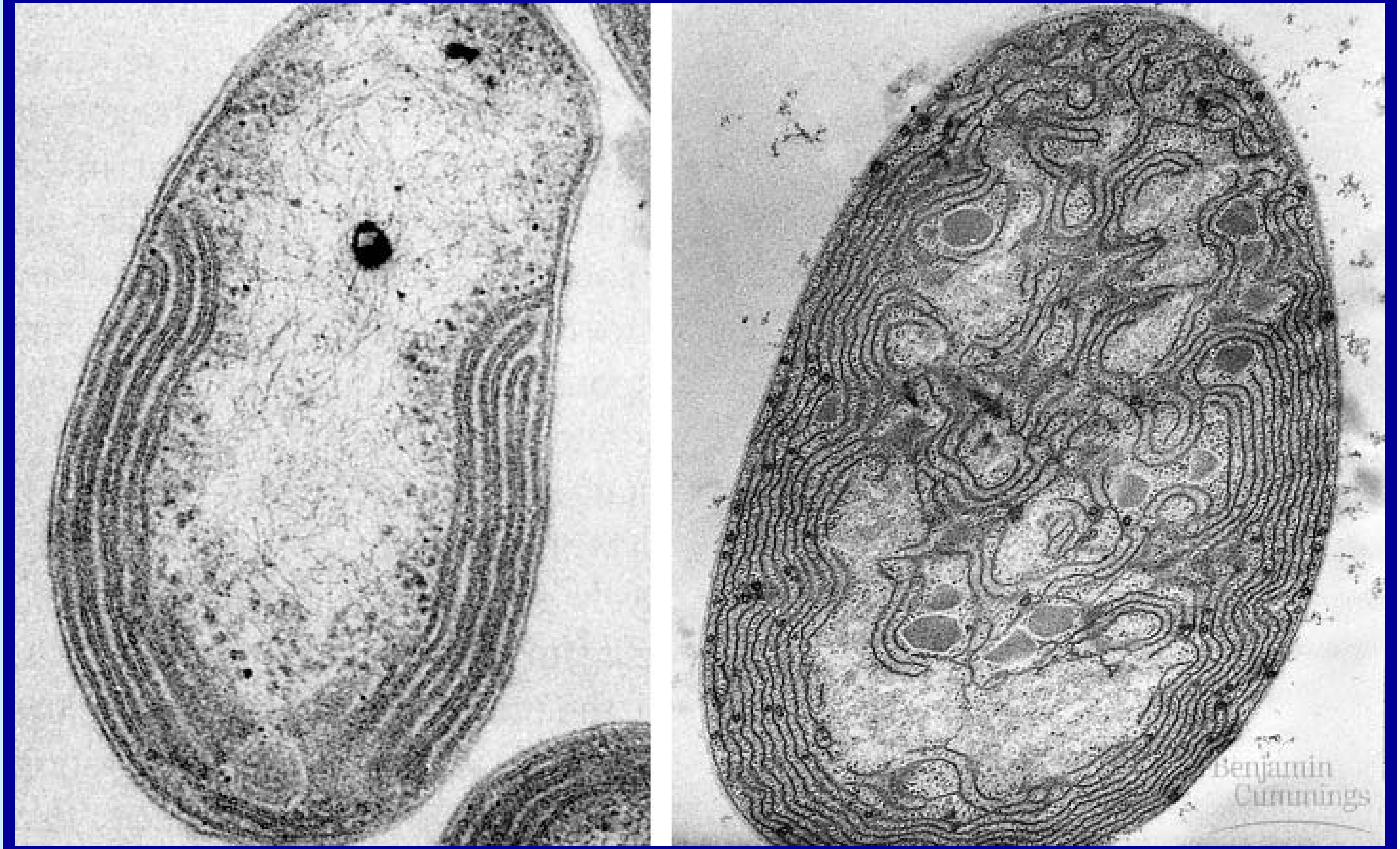
The most common shapes of prokaryotes

General Biology of the Prokaryotes

- Prokaryotes lack nuclei, membrane-enclosed organelles, and cytoskeletons. Their chromosomes are circular. They often contain plasmids. Some contain internal membrane systems.

- Prokaryotes reproduce asexually by binary fission, but also exchange genetic information.

Specialized membranes of prokaryotes



General Biology of the Prokaryotes

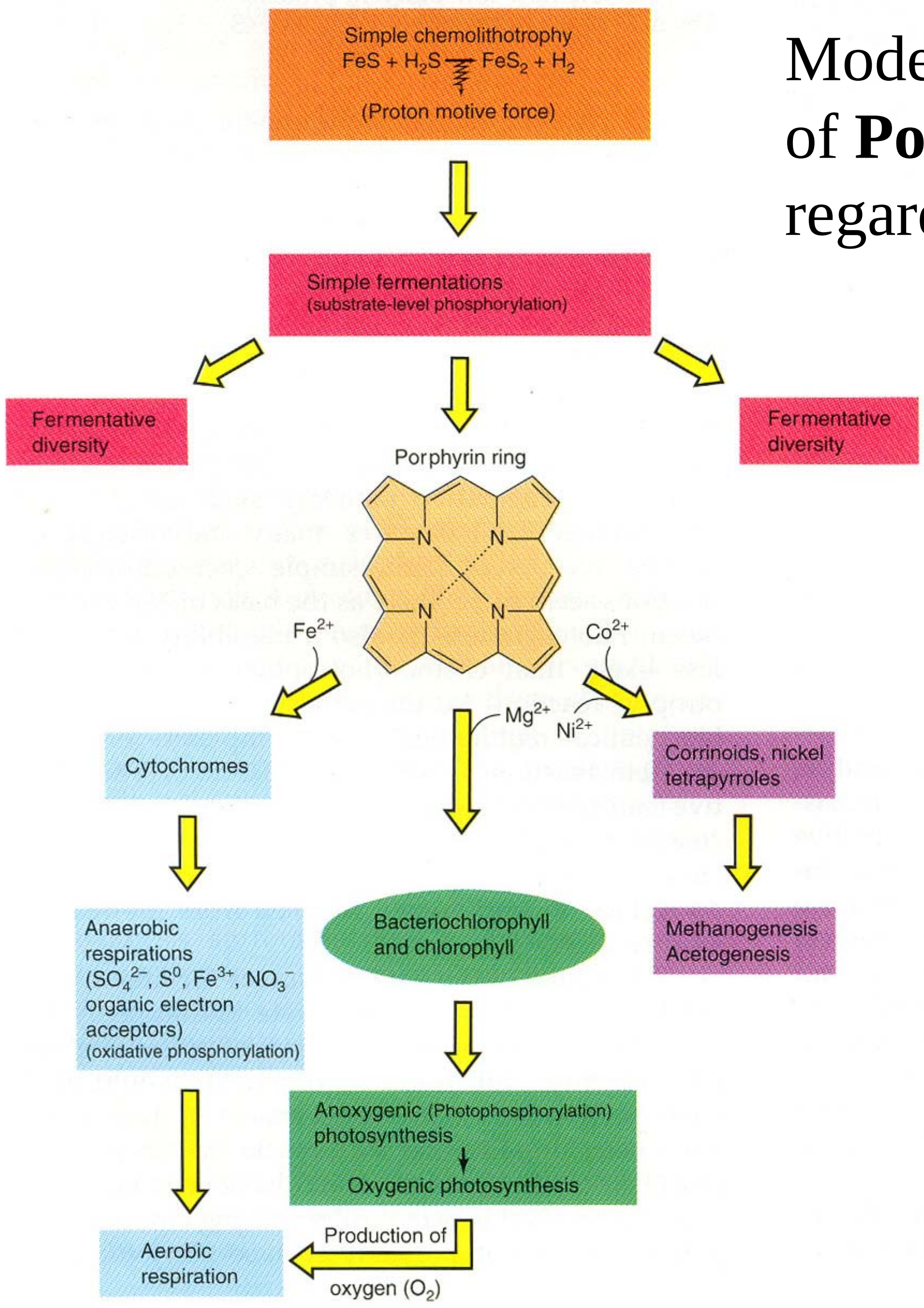
- Prokaryotes' metabolic pathways and nutritional modes include obligate and facultative anaerobes, and obligate aerobes. Nutritional types include photoautotrophs, photoheterotrophs, chemoautotrophs, and chemoheterotrophs. Some base energy metabolism on nitrogen- or sulfur-containing ions.

Major Nutritional Modes

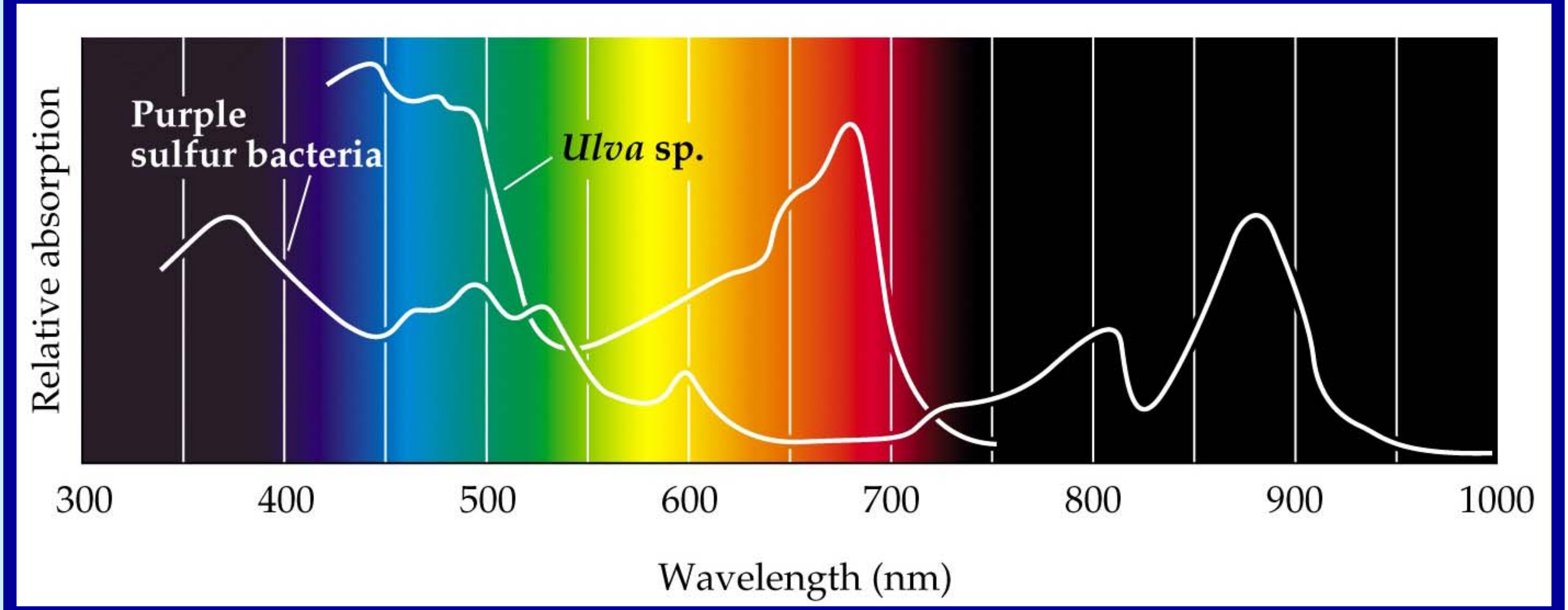
Table 27.1 Major Nutritional Modes

Mode of Nutrition	Energy Source	Carbon Source	Types of Organisms
Autotroph			
Photo-autotroph	Light	CO_2	Photosynthetic prokaryotes, including cyanobacteria; plants; certain protists (algae)
Chemo-autotroph	Inorganic chemicals	CO_2	Certain prokaryotes (for example, *Sulfolobus*)
Heterotroph			
Photo-heterotroph	Light	Organic com-pounds	Certain prokaryotes
Chemo-heterotroph	Organic com-pounds	Organic com-pounds	Many prokaryotes and protists; fungi; animals; some parasitic plants

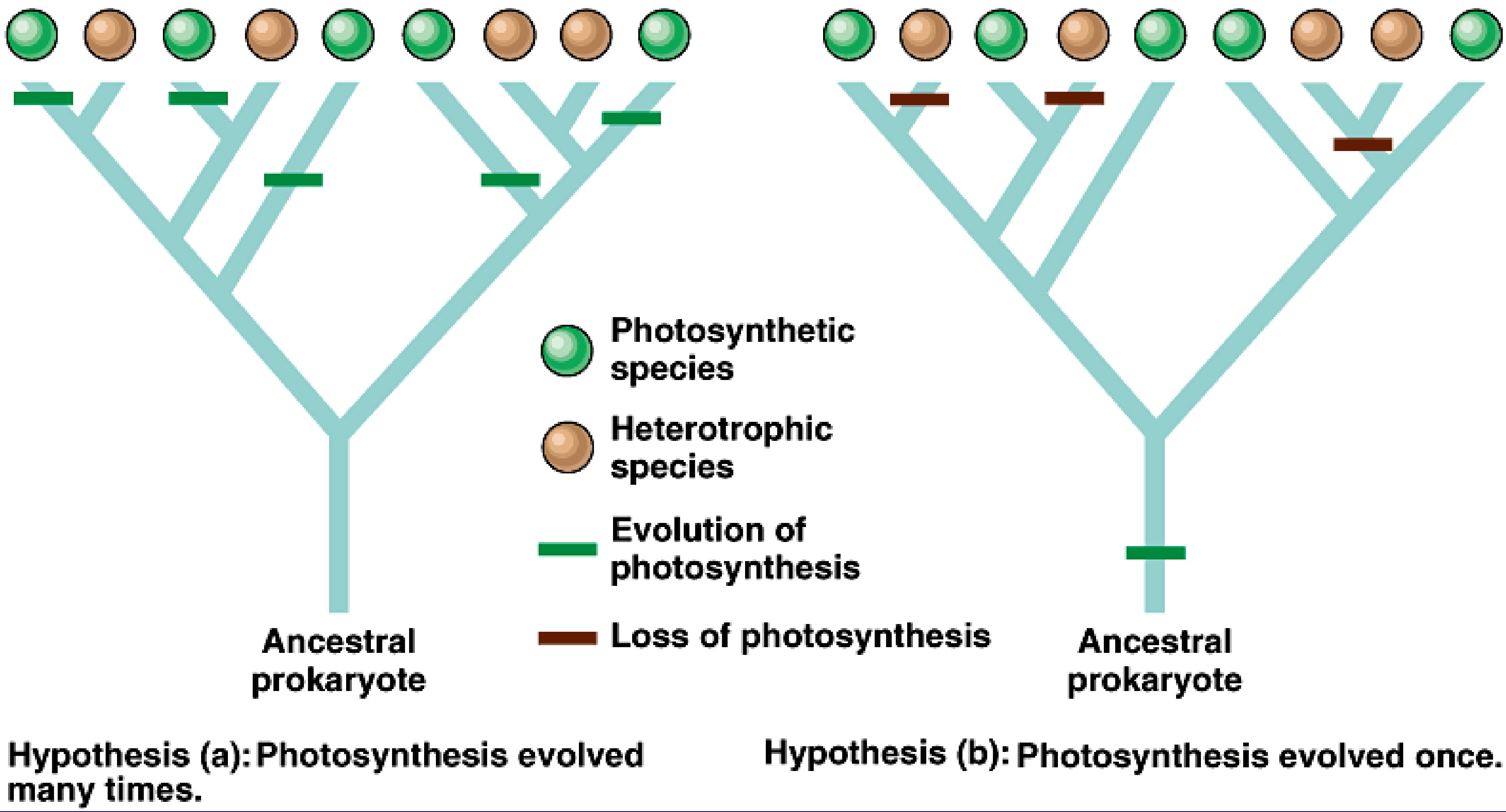
Model for the development of **Porphyrin Ring** diversity regarding metabolic pathways

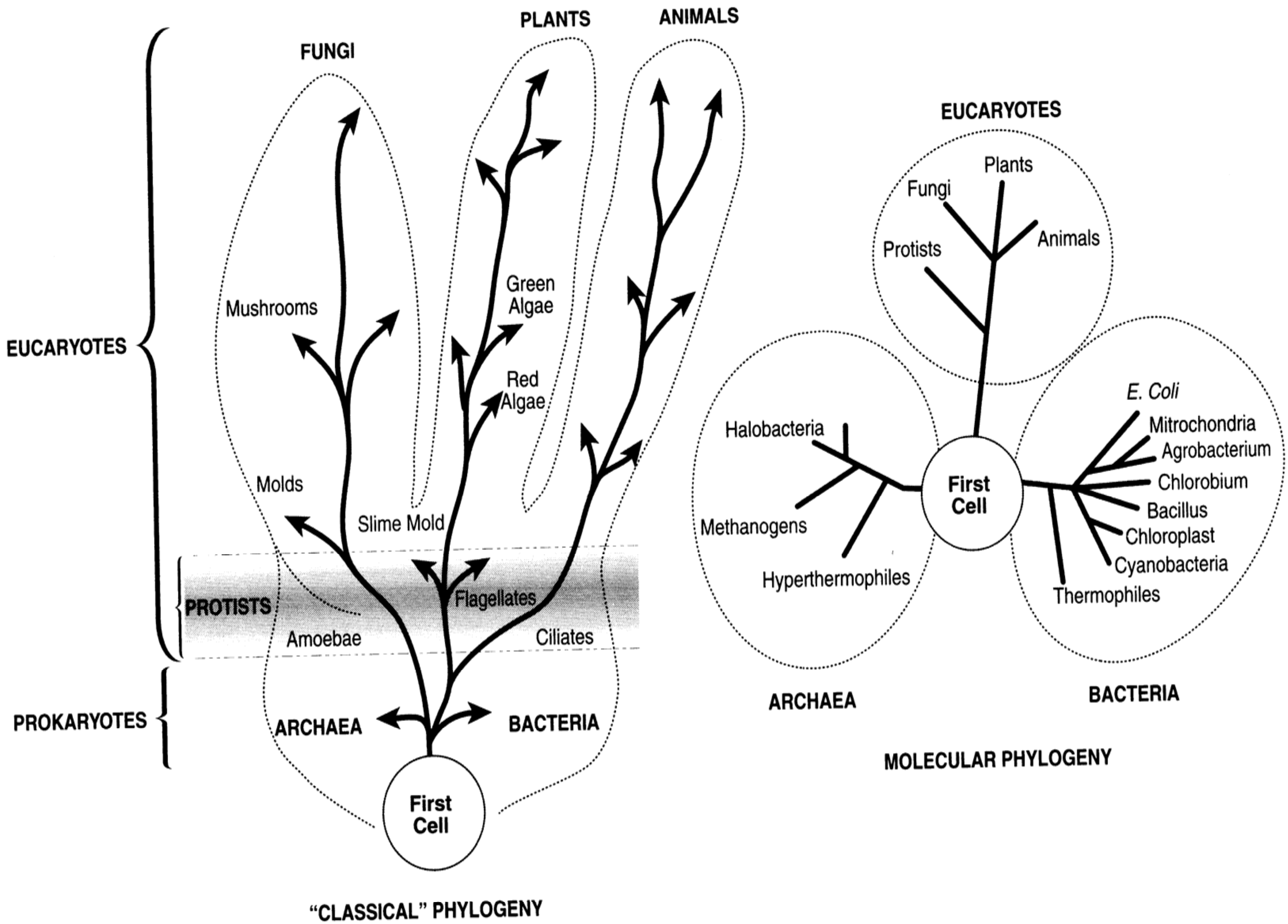


Action Spectra



Contrasting hypotheses for the taxonomic distribution of photosynthesis among prokaryotes

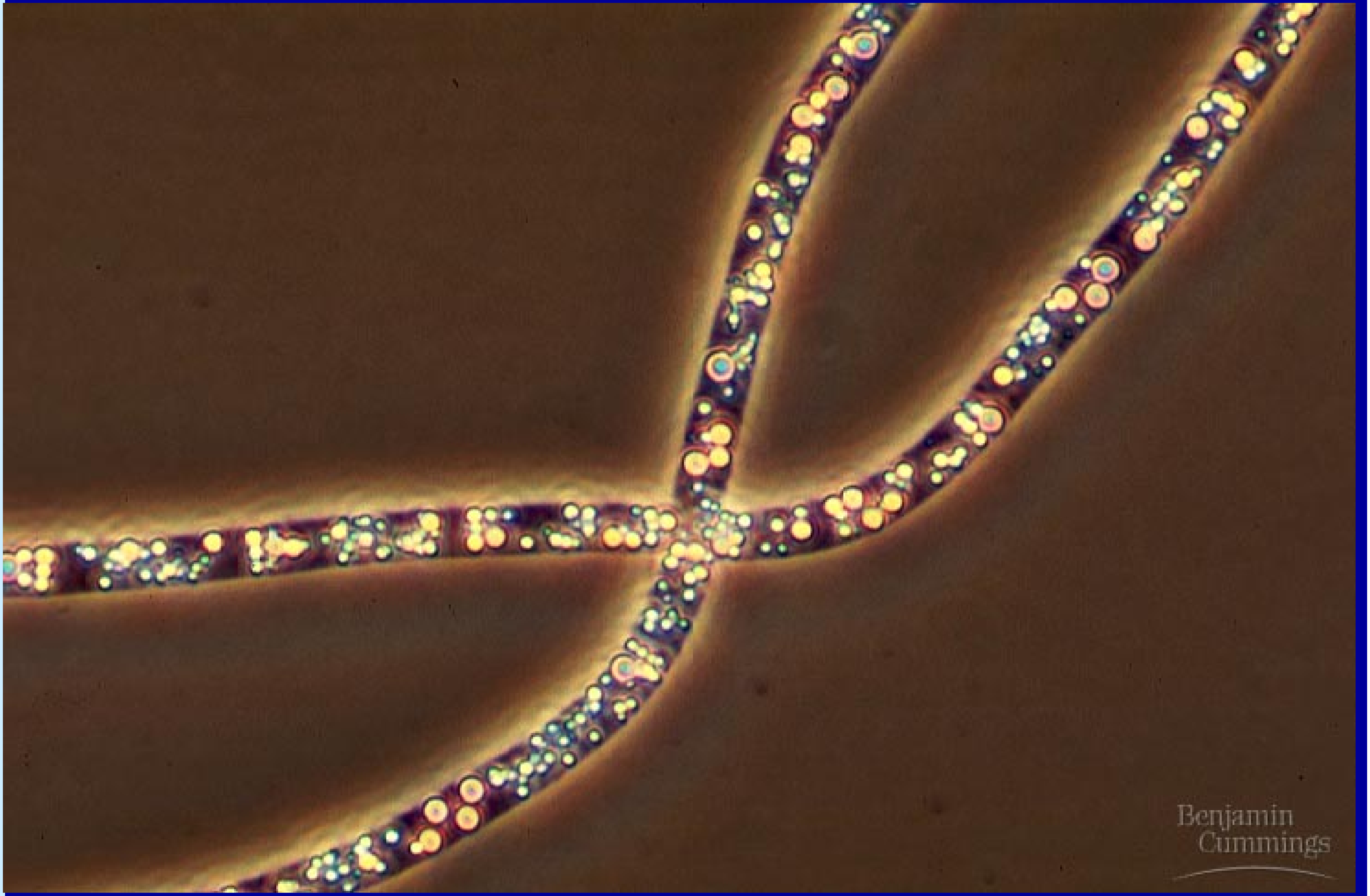




FUNGI
PLANTS
ANIMALS
EUCARYOTES
Mushrooms
Green Algae
Red Algae
Molds
Slime Mold
PROTISTS
Flagellates
Amoebae
Ciliates
PROKARYOTES
ARCHAEA
BACTERIA
First Cell
"CLASSICAL" PHYLOGENY
EUCARYOTES
Plants
Fungi
Animals
Protists
Halobacteria
Methanogens
Hyperthermophiles
First Cell
E. Coli
Mitrochondria
Agrobacterium
Chlorobium
Bacillus
Chloroplast
Cyanobacteria
Thermophiles
ARCHAEA
BACTERIA
MOLECULAR PHYLOGENY

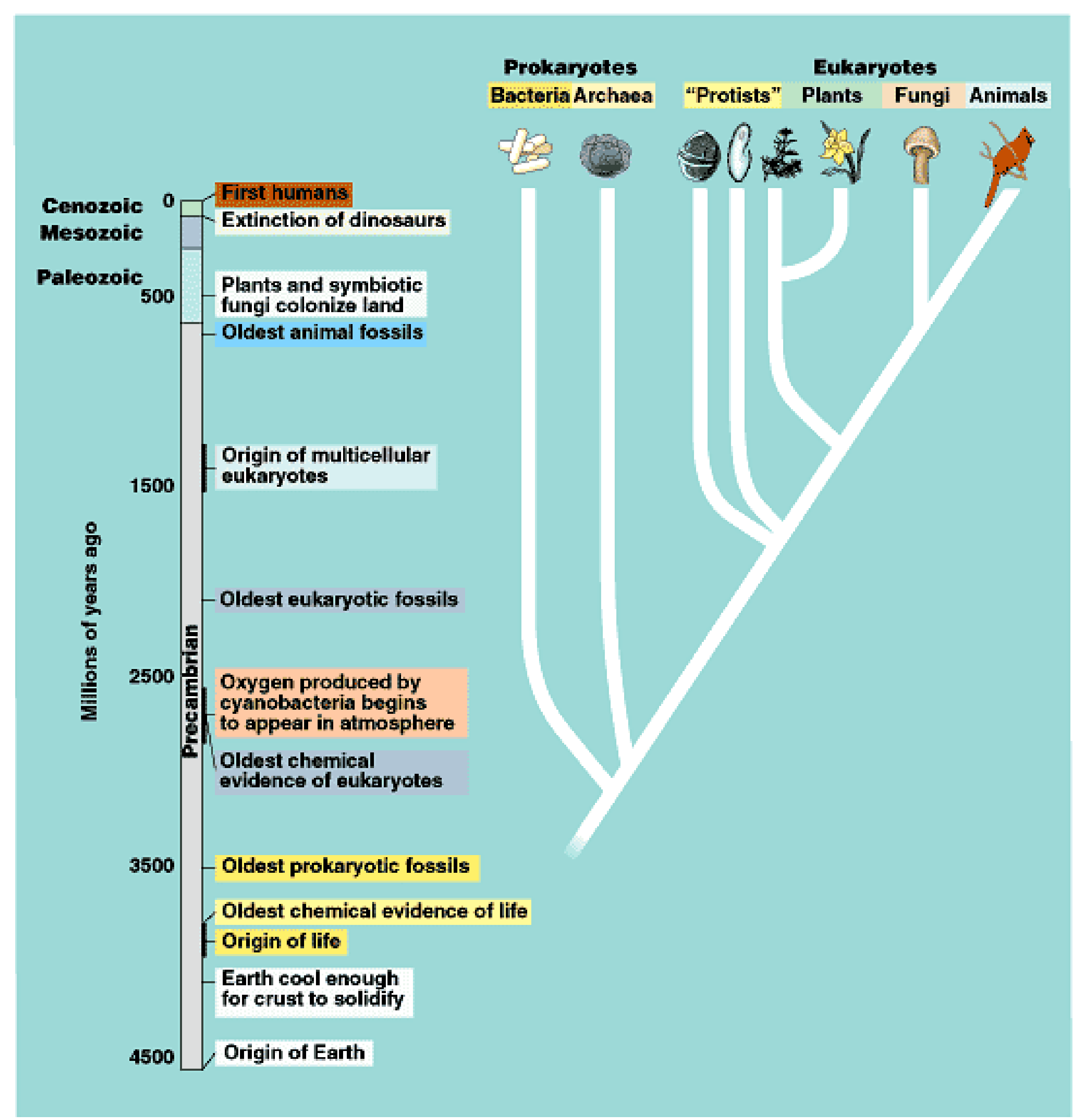
One of the most independent organisms on earth: Cyanobacteria (*Anabaena*)

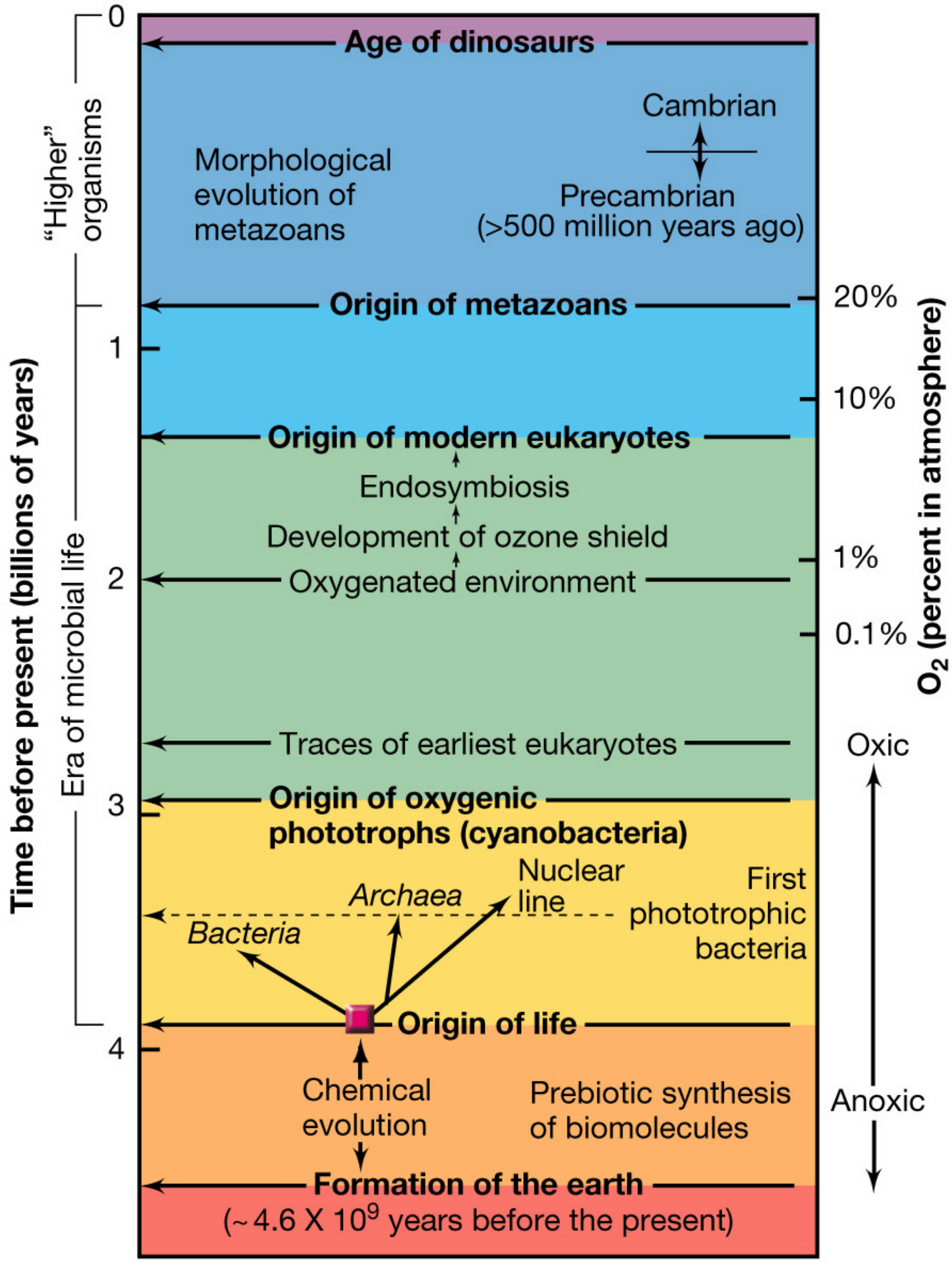
Beggiatoa, sulfur-eating bacteria



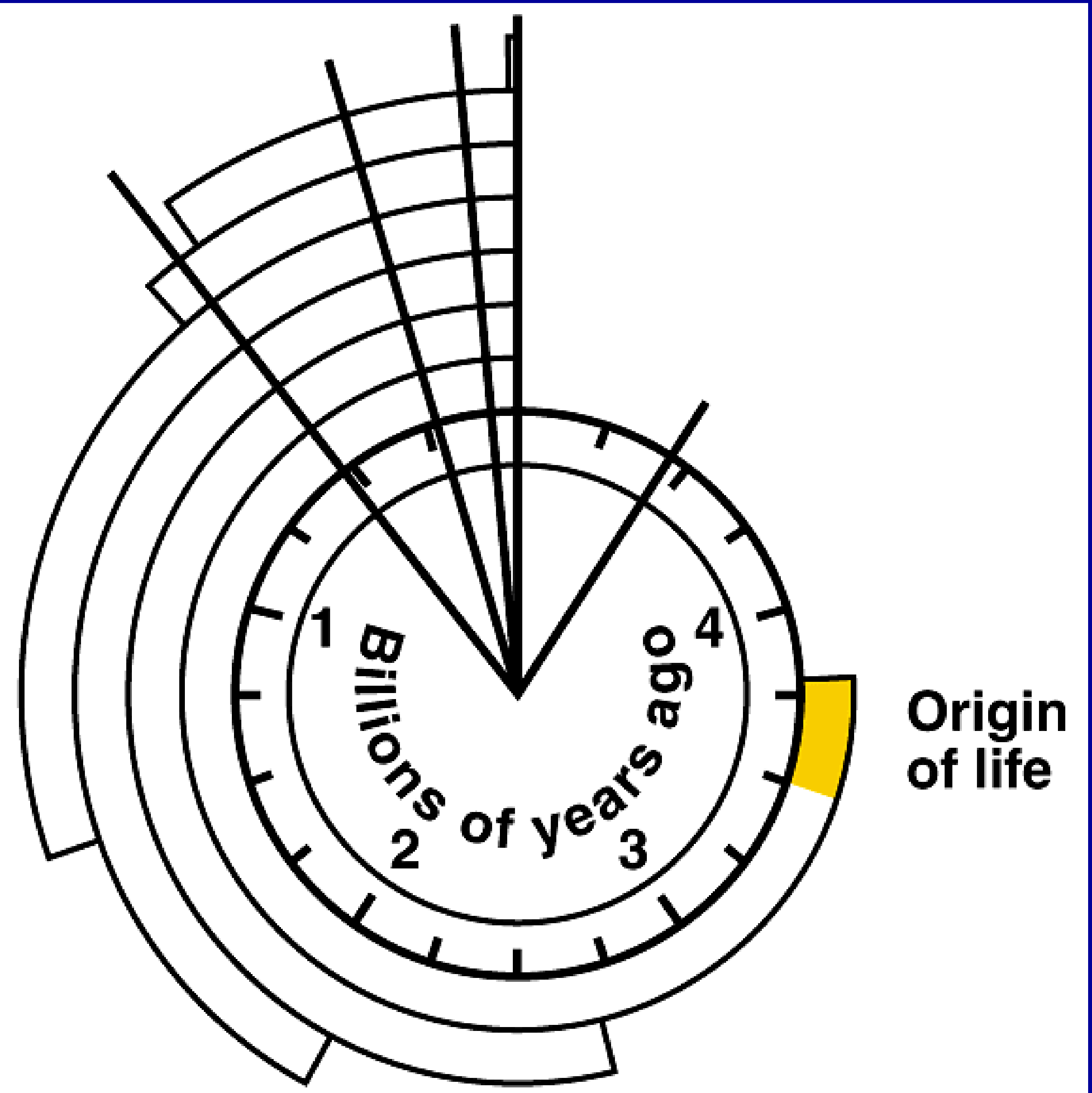
The largest known prokaryote

Some major episodes in the history of life

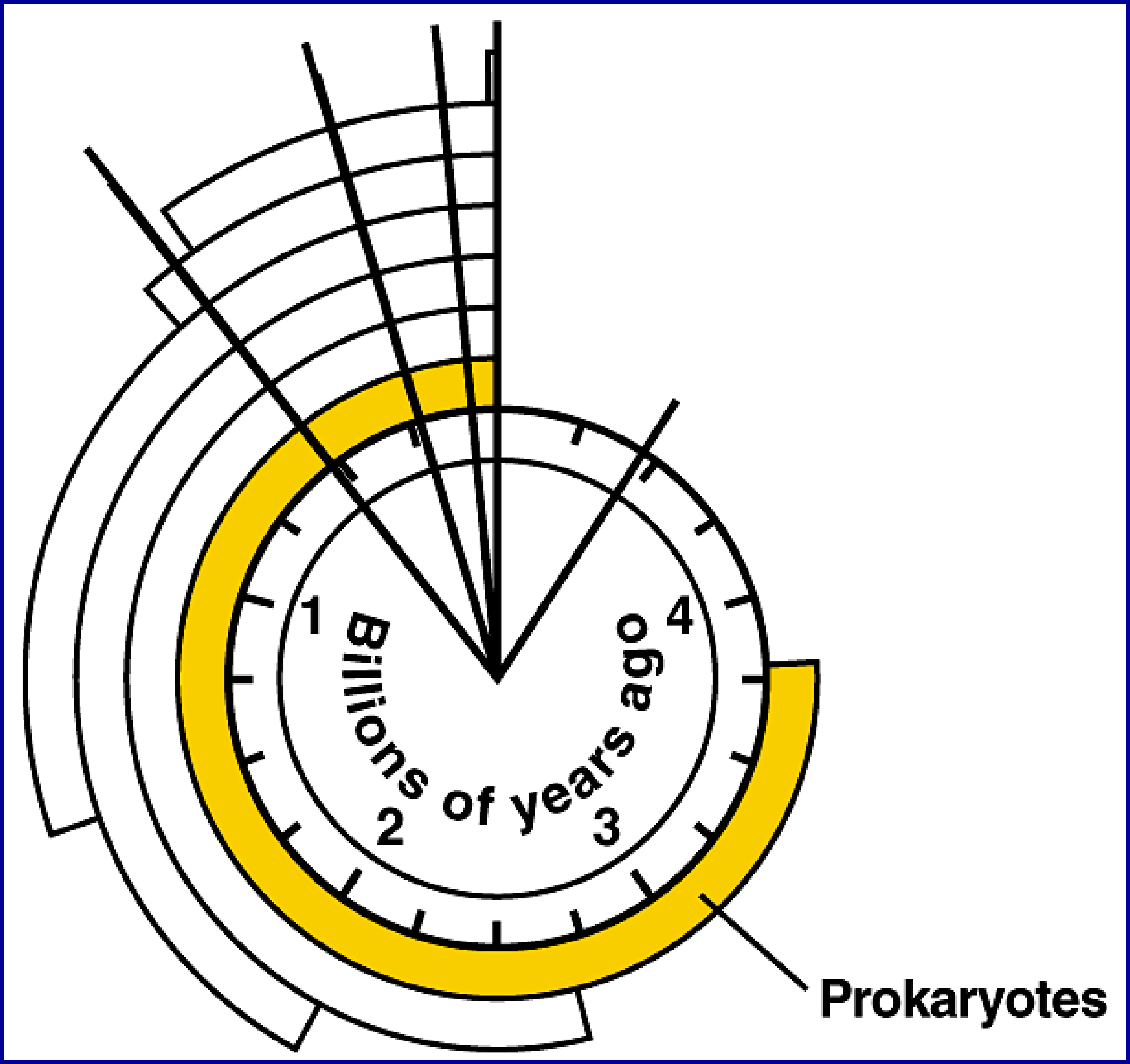



0
1
2
3
4
Time before present (billions of years)
"Higher" organisms
Era of microbial life
Age of dinosaurs
Morphological evolution of metazoans
Cambrian
Precambrian (>500 million years ago)
Origin of metazoans
Origin of modern eukaryotes
Endosymbiosis
Development of ozone shield
Oxygenated environment
Traces of earliest eukaryotes
Origin of oxygenic phototrophs (cyanobacteria)
Bacteria
Archaea
Nuclear line
First phototrophic bacteria
Origin of life
Chemical evolution
Prebiotic synthesis of biomolecules
Formation of the earth
(~4.6 X 10^9 years before the present)
20%
10%
1%
0.1%
O2 (percent in atmosphere)
Oxic
Anoxic

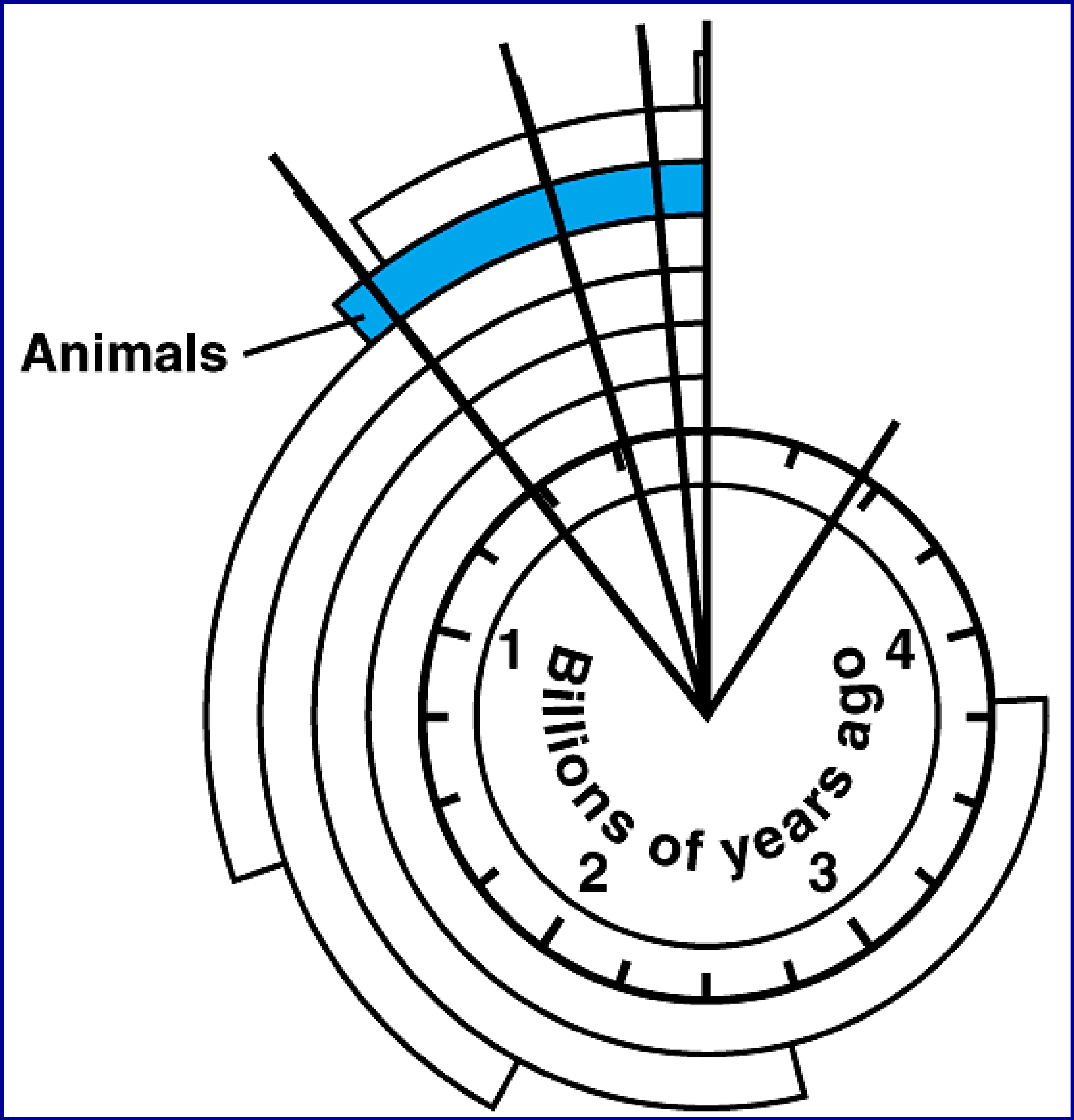
Evolutionary clock: Origin of life



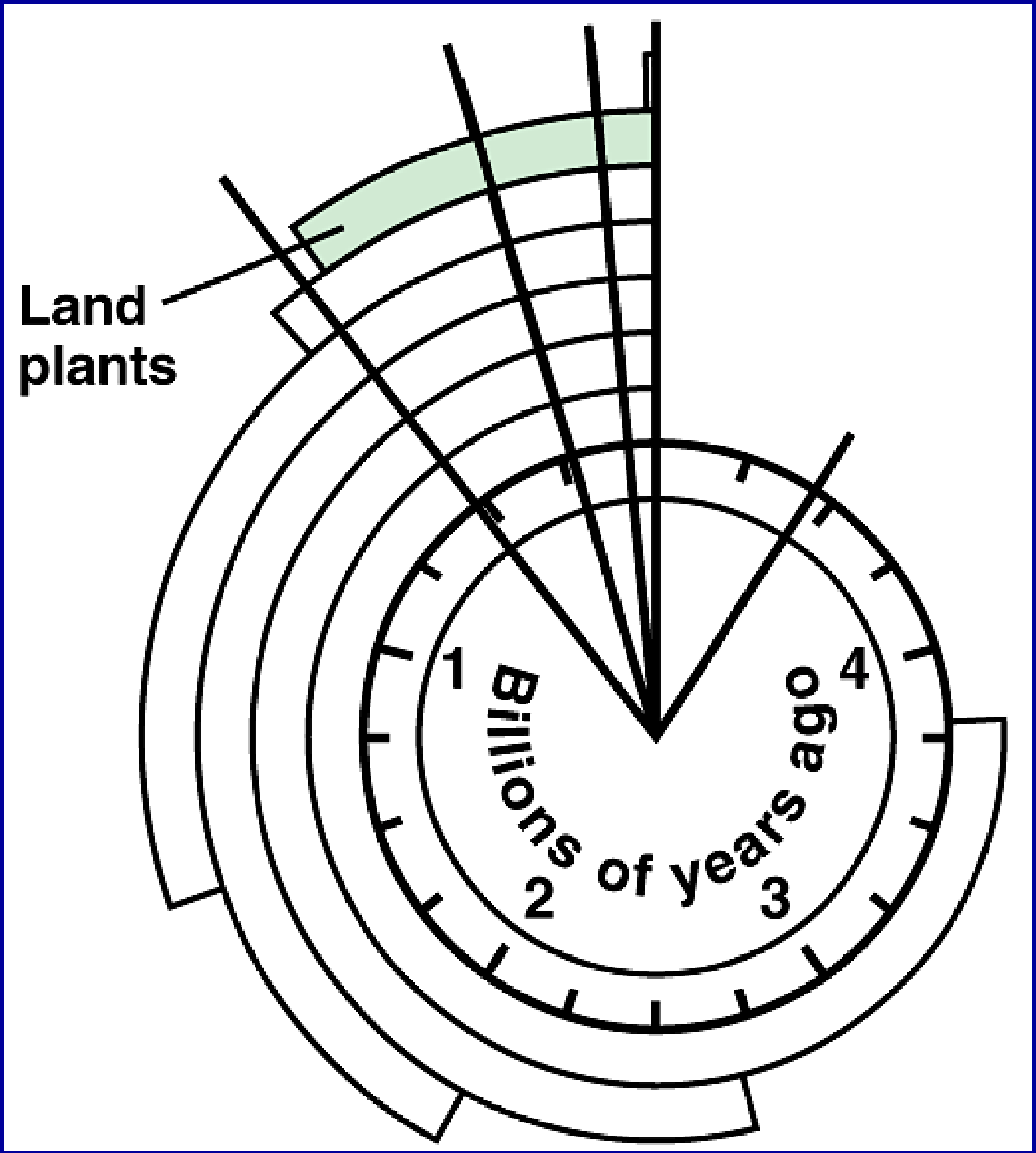
Evolutionary clock: Prokaryotes



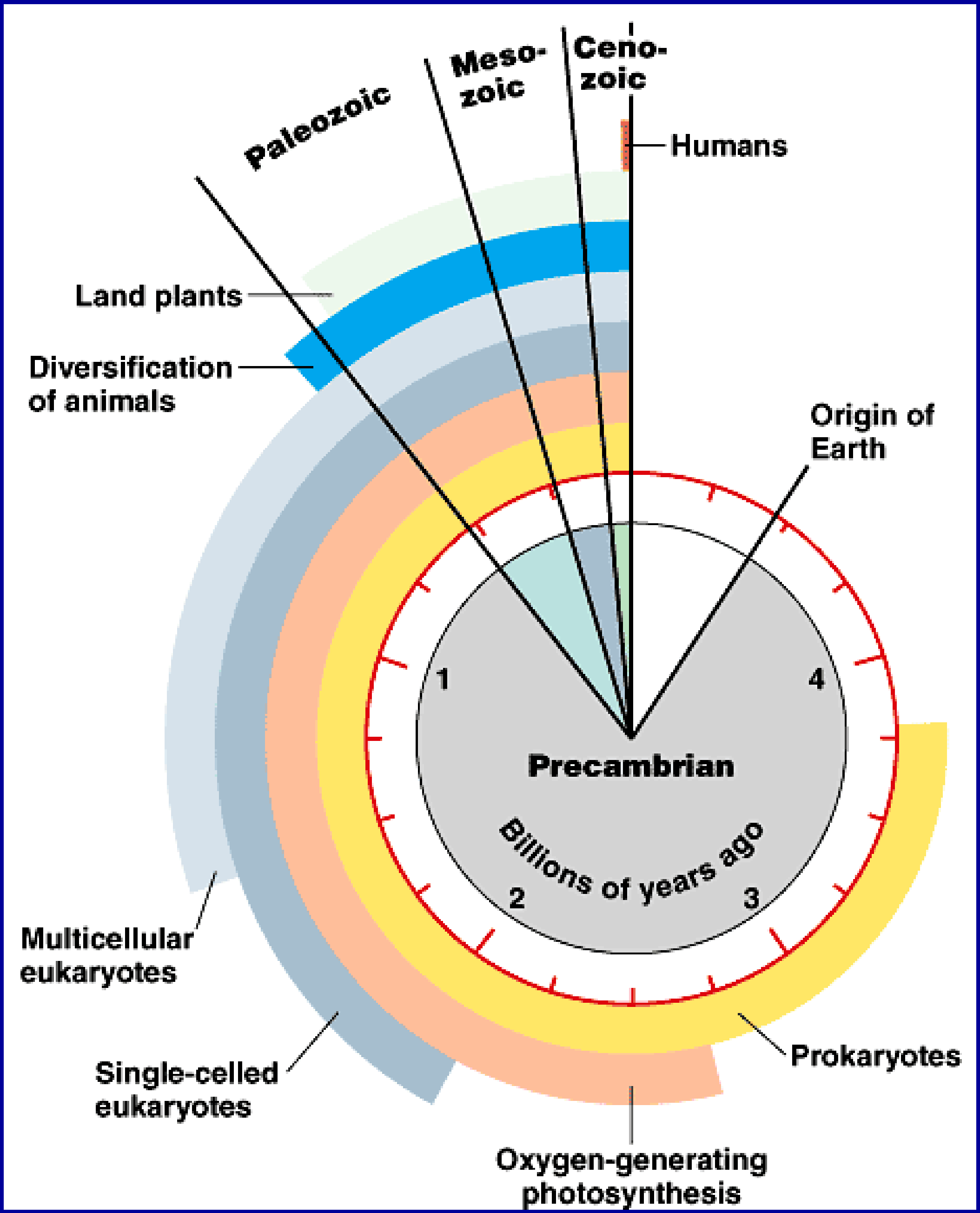
Evolutionary clock: Animals



Evolutionary clock: Land plants



Clock analogy for some key events in evolutionary history



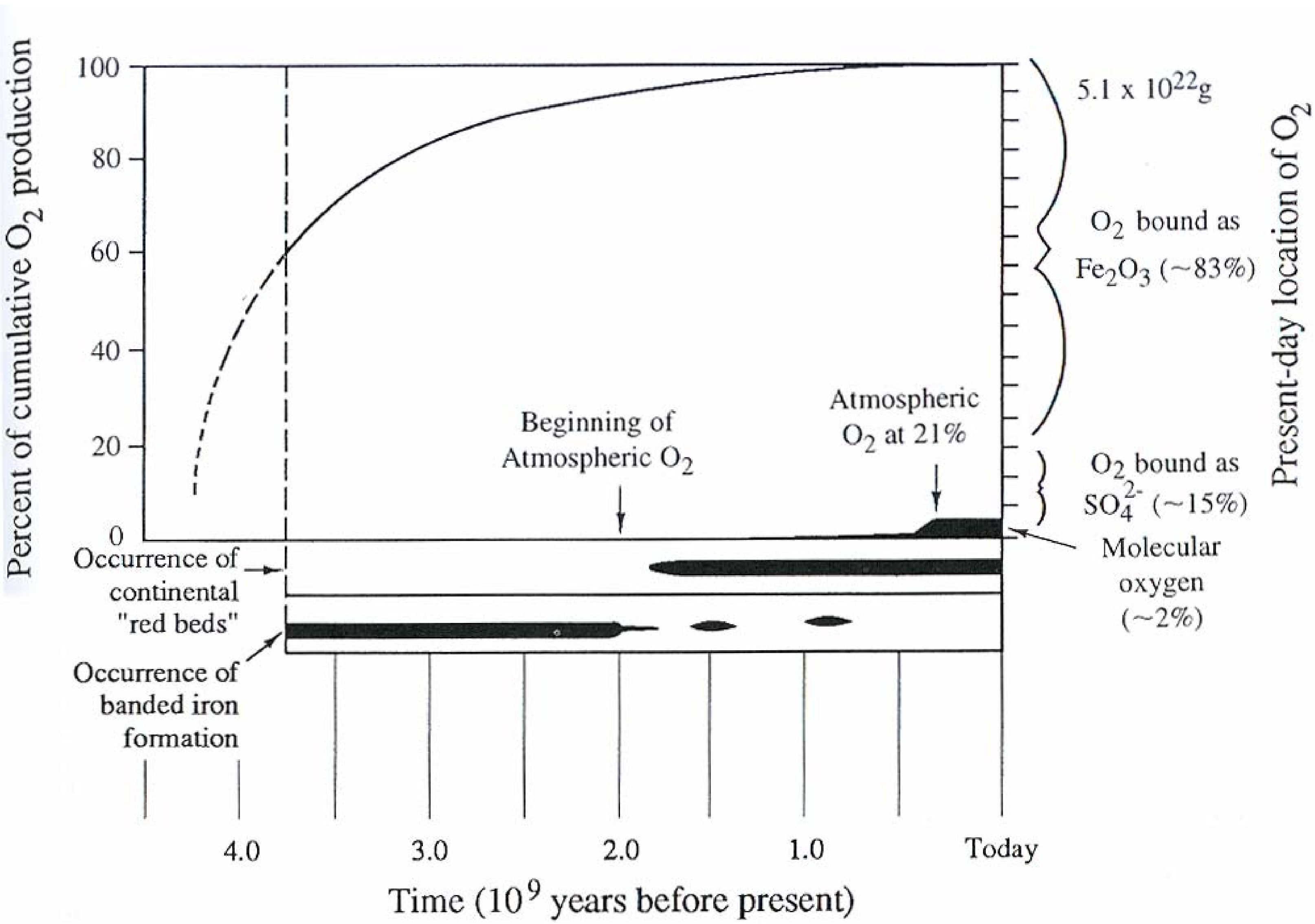
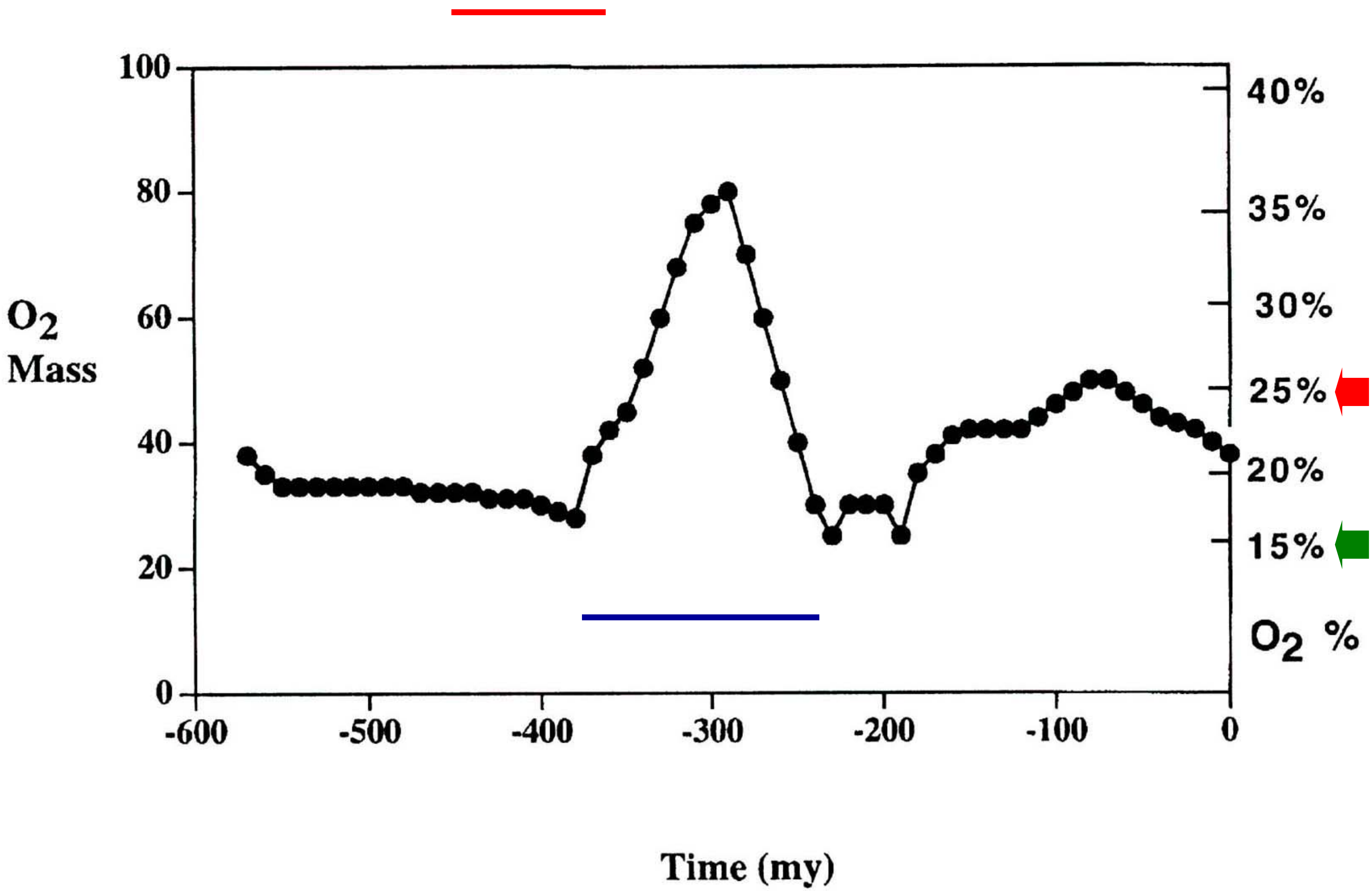


Figure 2.7 Cumulative history of O_2 released by photosynthesis through geologic time. Of more than 5.1×10^{22} g of O_2 released, about 98% is contained in seawater and sedimentary rocks, beginning with the occurrence of Banded Iron Formations at least 3.5 billion years ago (bya). Although O_2 was released to the atmosphere beginning about 2.0 bya, it was consumed in terrestrial weathering processes to form Red Beds, so that the accumulation of O_2 to present levels in the atmosphere was delayed to 400 mya. Modified from Schidlowski (1980).

Banded iron formations are evidence of the vintage of oxygenic photosynthesis



100
80
60
40
20
0
O_2
Mass
40%
35%
30%
25%
20%
15%
O_2 %
-600
-500
-400
-300
-200
-100
0
Time (my)

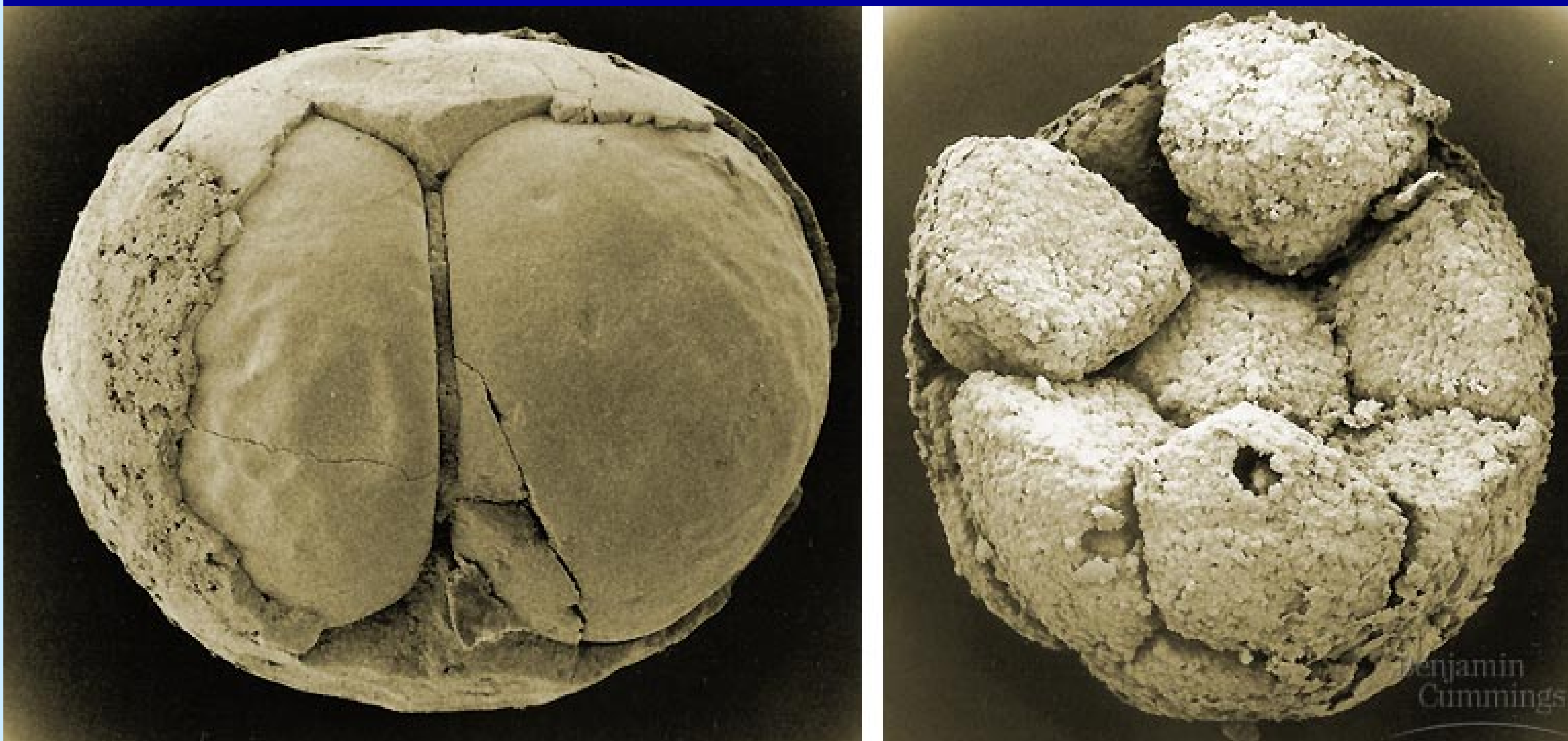
Patterns of Evolutionary Change

- The Oxygen “Blip” @ ~300 mya resulted from the invasion of land by plants!
- This gave rise to:
  - Gigantic Insects
  - Origin of Flight
  - Invasion of land by animals

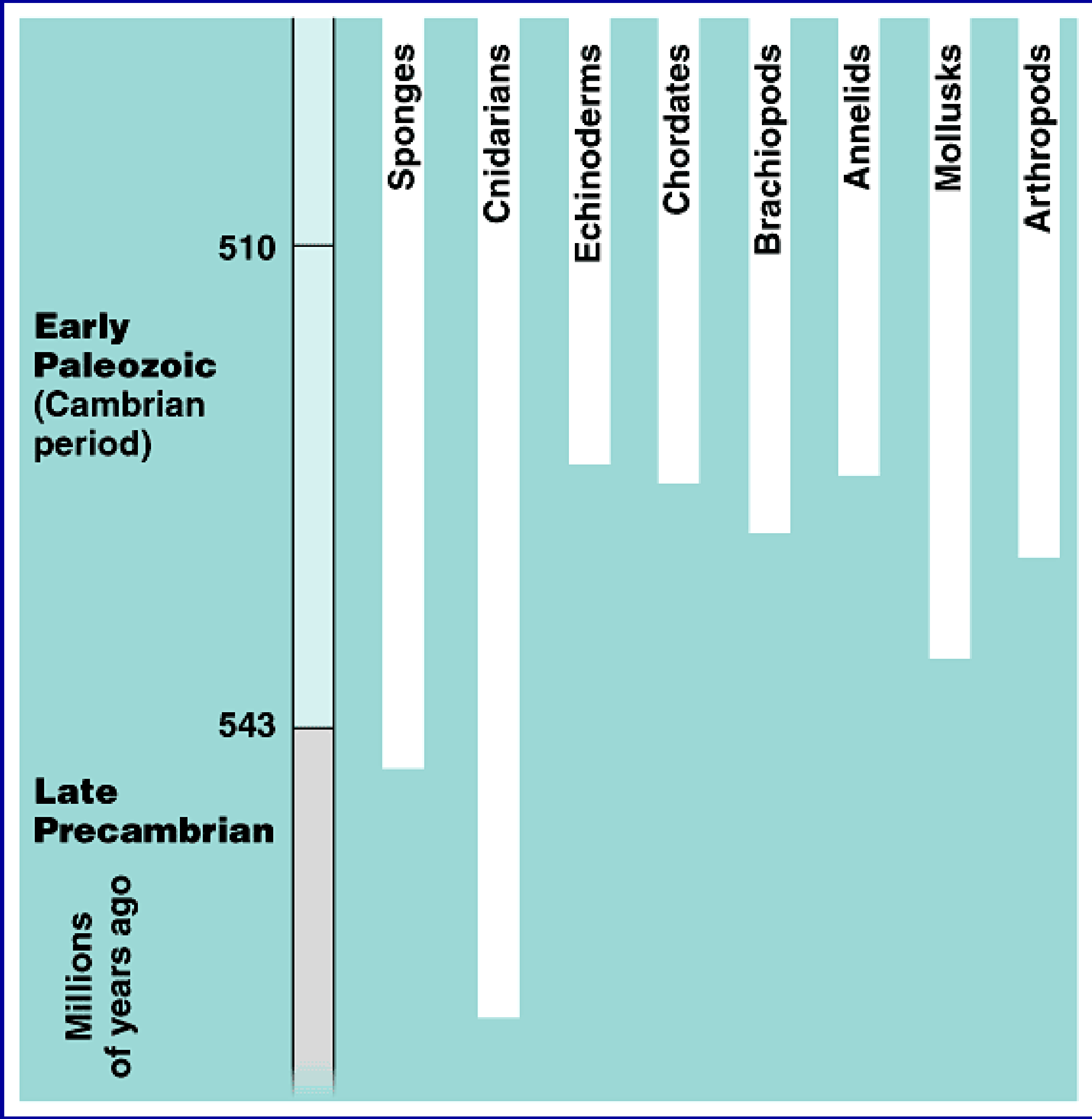
Patterns of Evolutionary Change

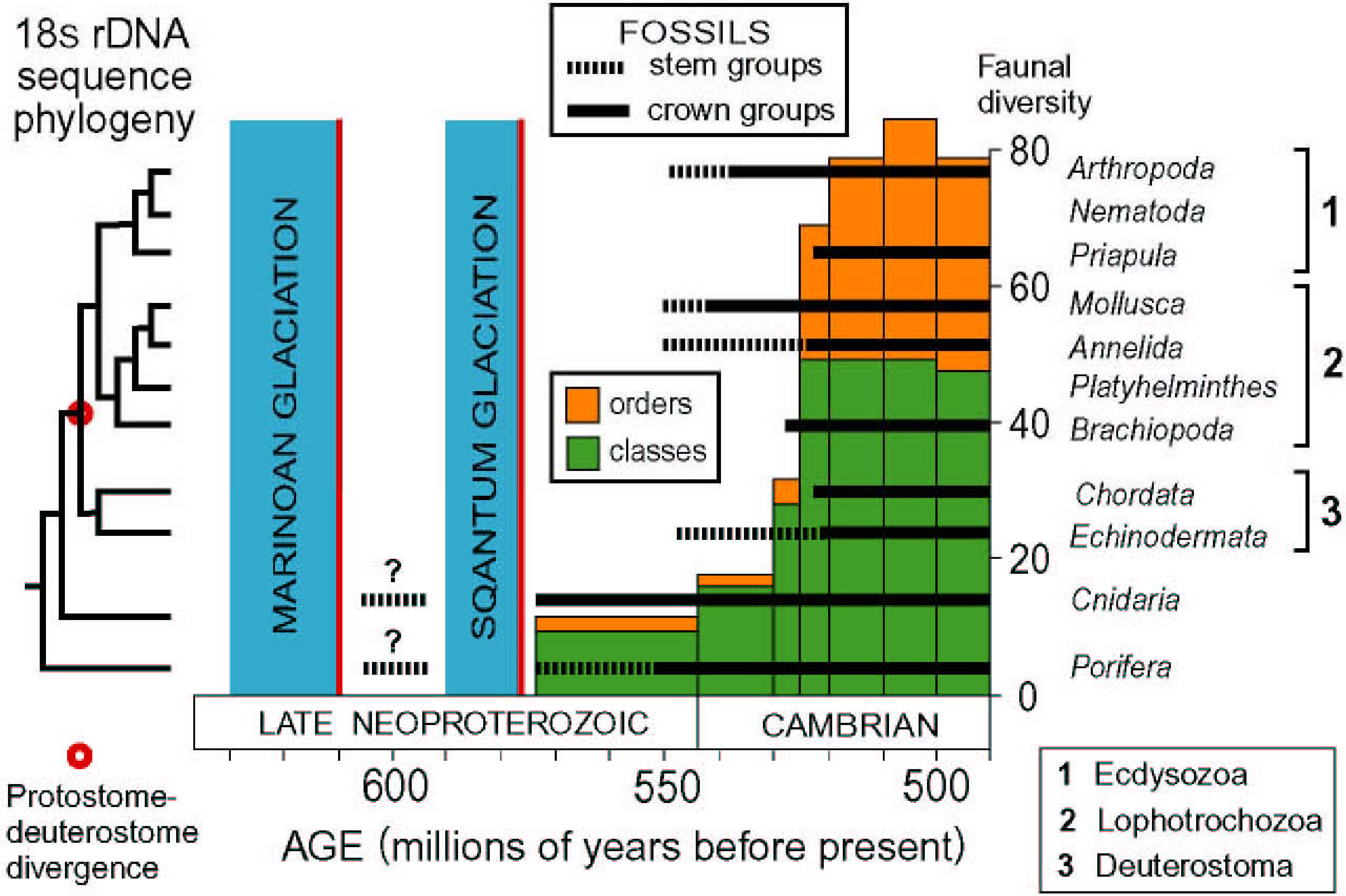
- Truly novel features of organisms have evolved infrequently. Most evolutionary changes are the result of modifications of already existing structures.

Fossilized animal embryos from Chinese sediments 570 million years old



The Cambrian radiation of animals

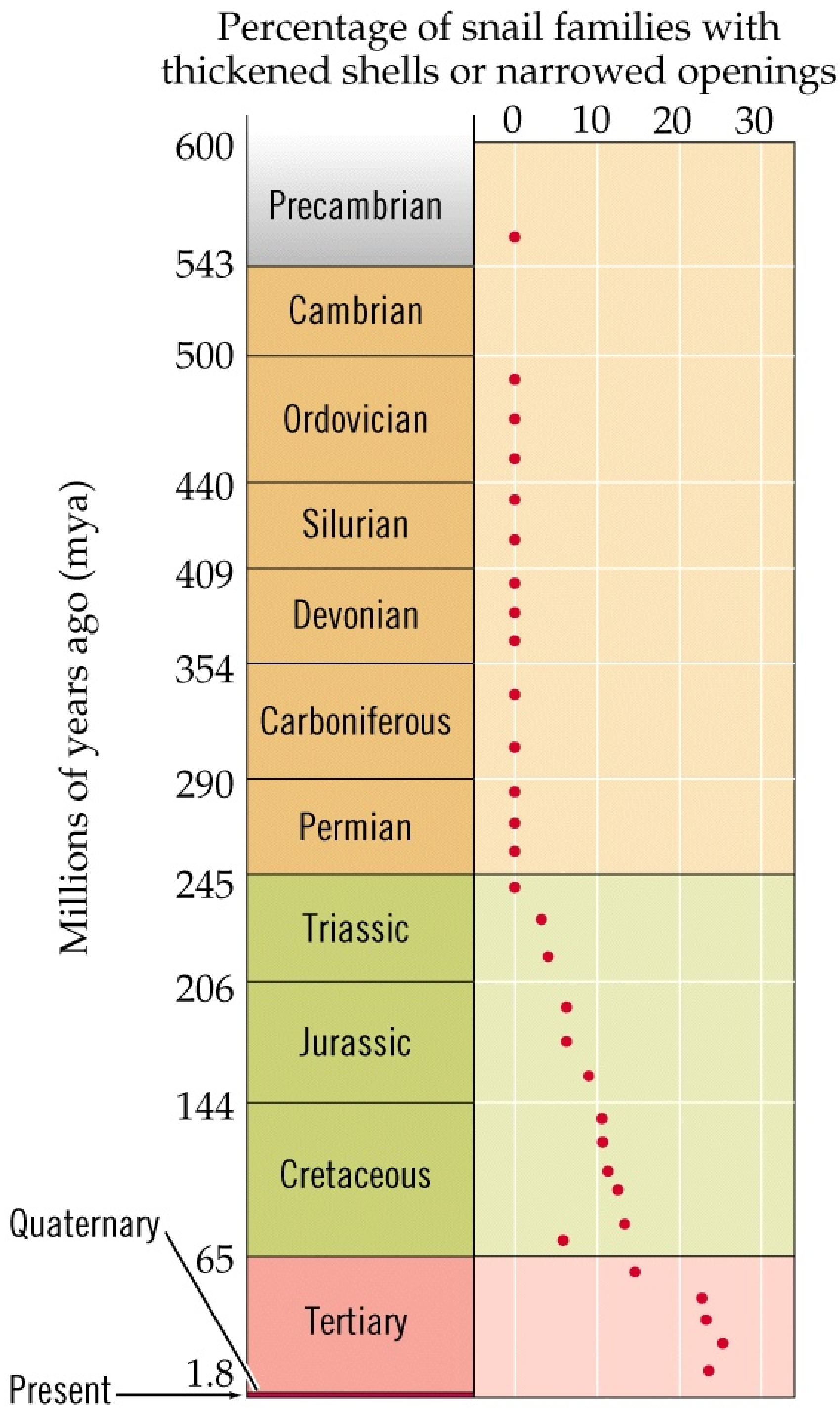




THE METAZOAN EXPLOSION

Patterns of Evolutionary Change

- Over evolutionary time, organisms have increased in size and complexity. Predation rates have also increased, resulting in the evolution of better defenses among prey species.



Percentage of snail families with thickened shells or narrowed openings
0
10
20
30
Millions of years ago (mya)
600
Precambrian
543
Cambrian
500
Ordovician
440
Silurian
409
Devonian
354
Carboniferous
290
Permian
245
Triassic
206
Jurassic
144
Cretaceous
Quaternary
65
Tertiary
1.8
Present

The Future of Evolution

- The agents of evolution continue to operate today, but human intervention, both deliberate and inadvertent, now plays an unprecedented role in the history of life.
- Global Warming???
- The Human Bolide???