The molecular origins of life

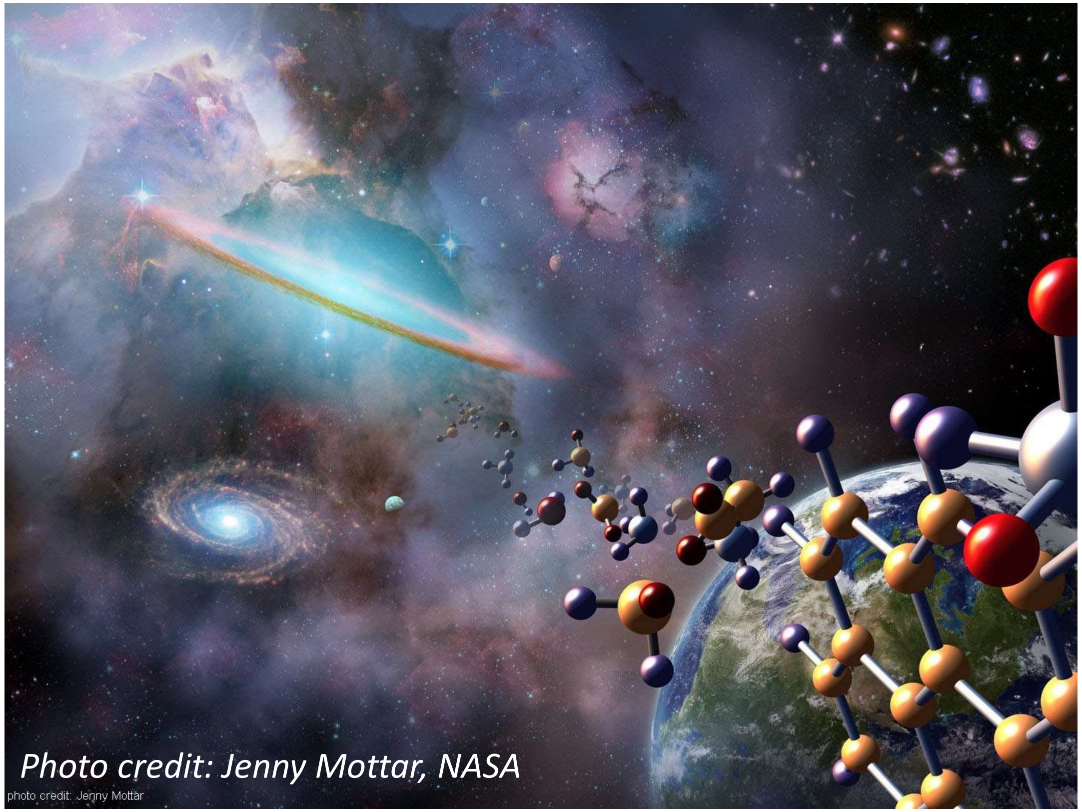


Photo credit: Jenny Mottar, NASA

L1 SoSe 2025

Zbigniew Pianowski

7 lectures (90 min. each) in English,
hybrid (in presence, KIT Geb. 30.41 HS II + online)
Thursdays 11:30-13:00

1st lecture: 15. May 2025

Following lectures: 22.05., 5.06., 26.06., 3.07., 10.07. and 17.07.

The most actual dates, changes, supplementary information, handouts – on the website:
https://www.ioc.kit.edu/pianowski/99_325.php

General references

K. W. Plaxco, M. Gross *Astrobiology. A brief introduction.* 2nd Ed.
(EN, The Jonh Hopkins Univ. Press)
Astrobiologie für Einsteiger (DE, Wiley-VCH)

K. Ruiz-Mirazo, C. Briones, A. Escosura *Prebiotic Systems Chemistry: New Perspectives for the Origins of Life.*
Chemical Reviews, 2014, 114, pp. 285-366

A. Pross *What is Life? How Chemistry Becomes Biology.*
(Oxford Univ. Press)

Overview of the course

Origin of the Universe – stars, planets, elements

Origin of biorelevant monomers – primordial soup

Complex chemical processes on the way to living systems

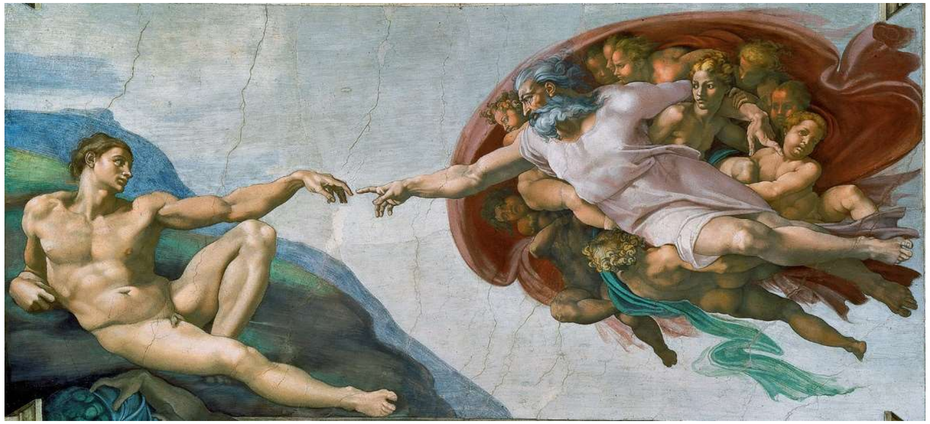
Protocells and LUCA

Overview of the course

Lecture 1	*Introduction to life, The primordial soup*
Lecture 2	*The primordial soup – Aminoacids, Lipids, Sugars*
Lecture 3	*The primordial soup – Nucleobases, cyanosulfidic chemistry*
Lecture 4	*Oligomerization, Systems Chemistry*
Lecture 5	*Self-assembly, RNA world*
Lecture 6	*Metabolism, protocells*
Lecture 7	*LUCA, extremophilic organisms, extraterrestrial life*

People always liked to know...

Where do we come from?



Michelangelo, the Sistine Chapel

Are we alone in the Universe?

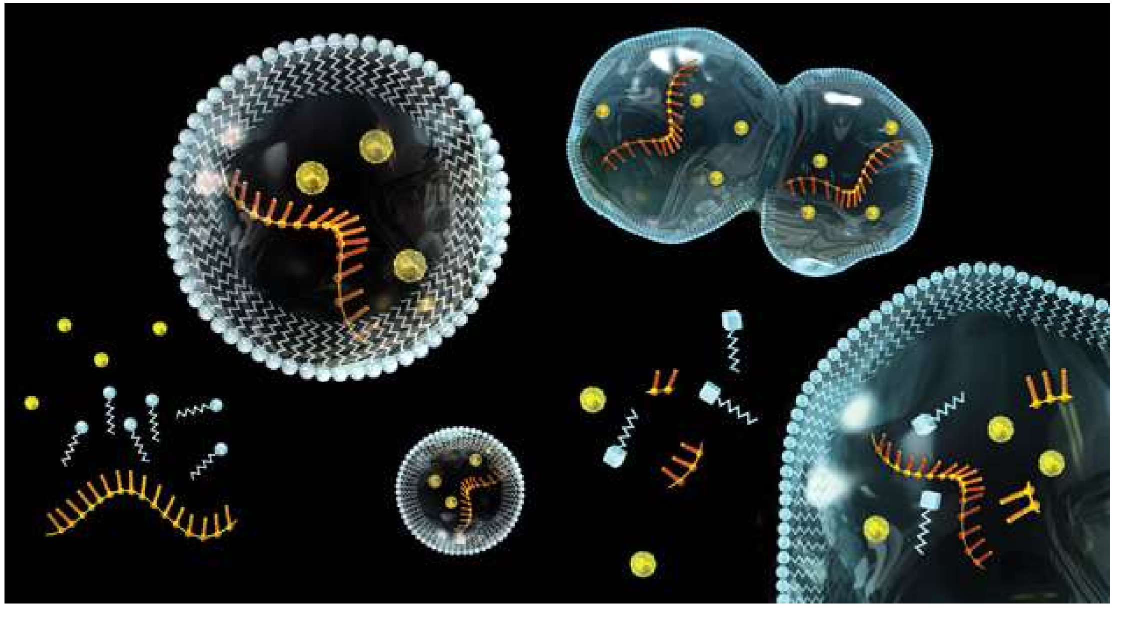
Alien, by Ridley Scott

Can we create life?

Young Frankenstein, by Mel Brooks

Can science give the answers?

Nowadays, molecular sciences and particularly chemistry seem to be in the position to adress these questions



How science can contribute?

What science can't do:

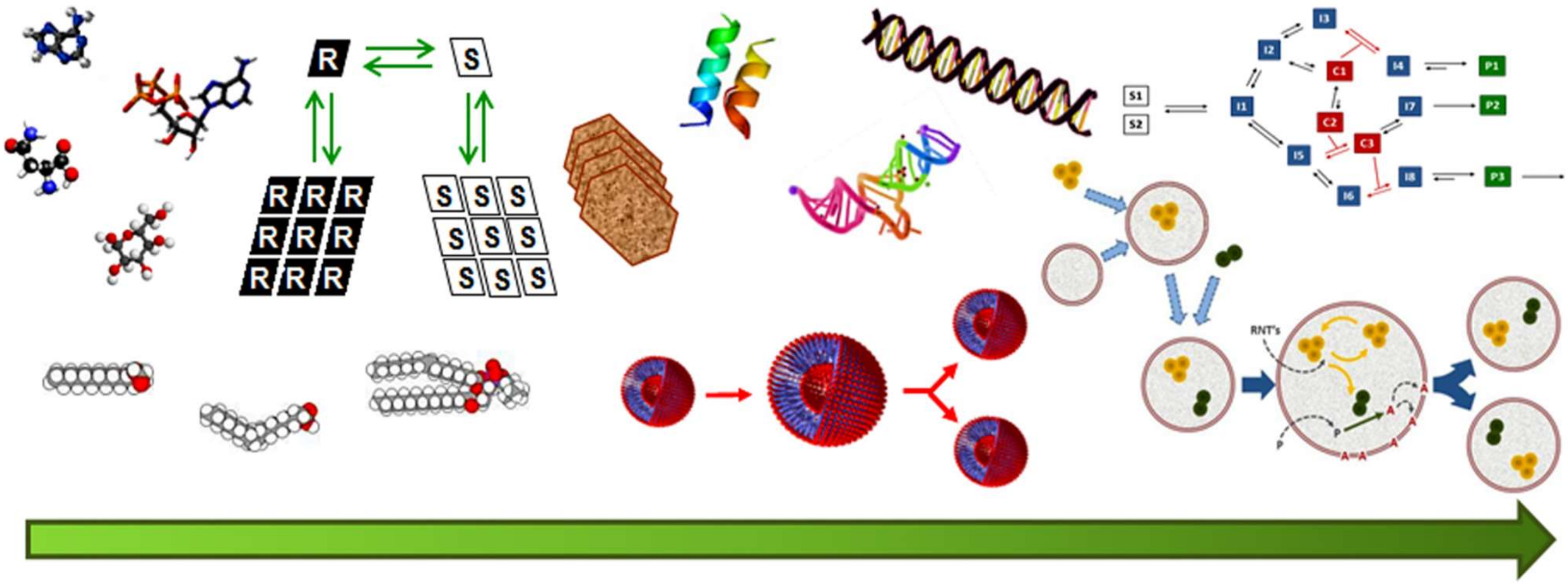
Exactelly repeat creation of the life → not enough time and resources

Science can demonstrate:

- The origin and abundance of elements and small molecules in the Universe
- How the small molecules self-assemble into biopolymers and complex systems
- How to dissect the origin of life into subsequent and overlaping stages
- How the particular stages can be achieved in the lab under abiotic conditions

Important stages of the origin of life

biomolecules – biopolymers – self-replication – metabolism - compartmentalization

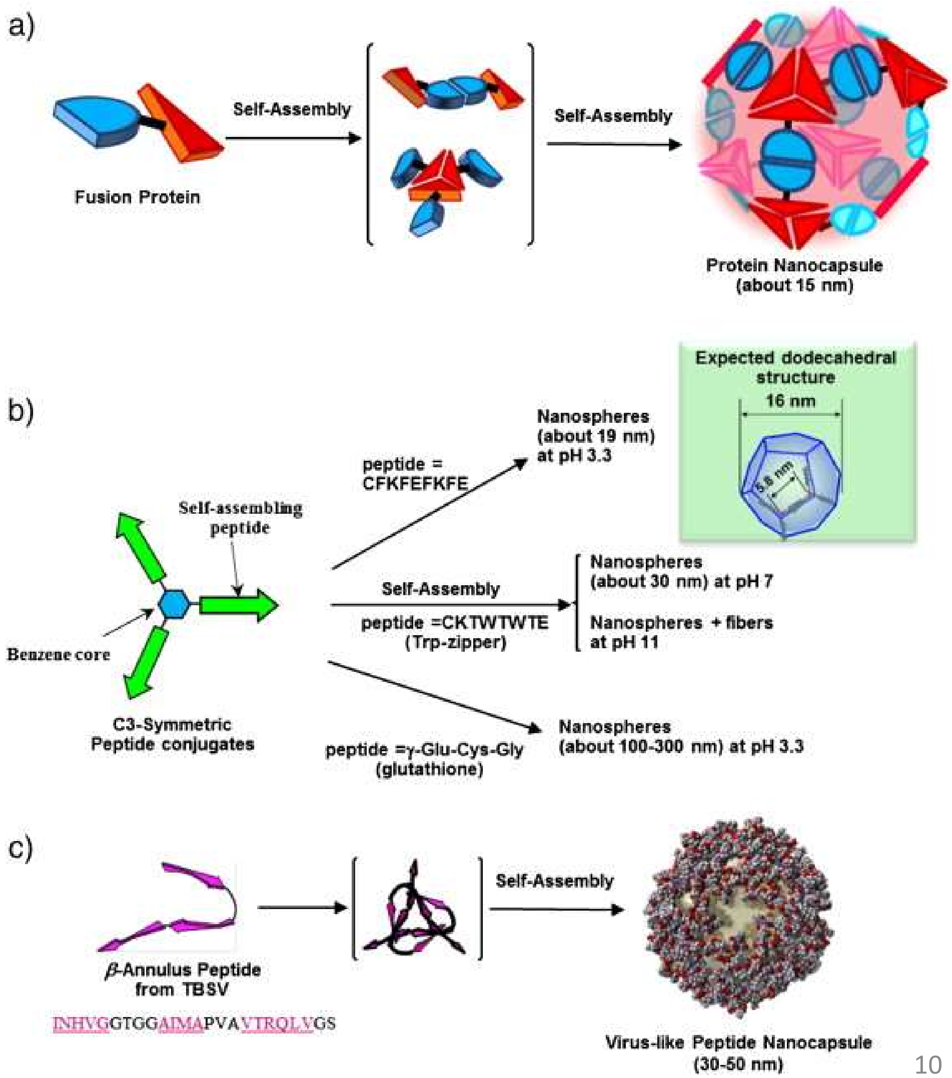


Increasing complexity from molecules to systems

Aspects of chemistry involved:

- Supramolecular chemistry
  - Self-assembly
  - Autocatalysis
- Organic chemistry
  - Biochemistry
- Templated reactions
- Systems chemistry
  - Geochemistry
  - Astrochemistry

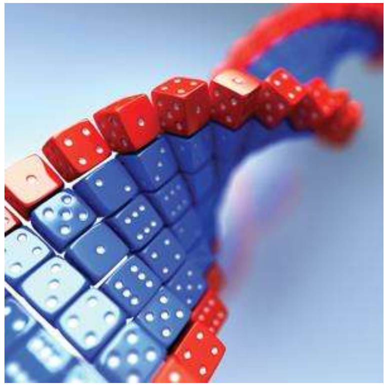
Self assembly



Feedback from:

- Biology
- Physics
- Mathematics and modelling
- Astronomy
- Geology

Modelling approaches



© Shutterstock

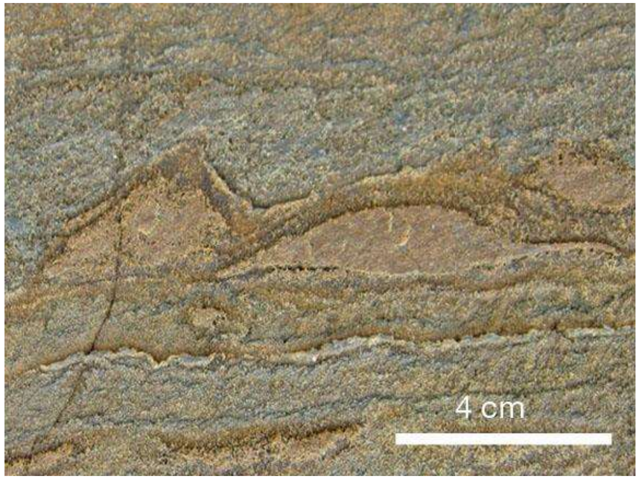
Game theory → complex life on Earth

Extremophilic organisms

Source: Chemistry World

Metabolism under extreme conditions

Ancient fossils



Source: © Springer Nature

The fossil stromatolites, observable as peaks in the rock, are the oldest ever found (3.7 billion years old)

Definitions of life


The Nobel Foundation

Erwin Schrödinger (1943):
Life: heredity and thermodynamics

Order from order
genetics

Order from disorder
ordered arrangements of molecules (cells, tissues) within themselves on the expense of increasing disorder of the environment

Definitions of life

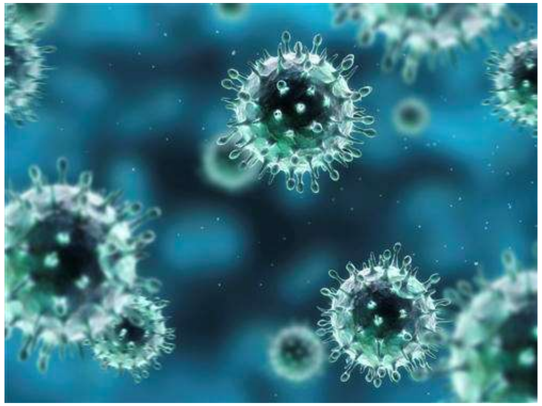
Life is a self-replicating chemical system capable of evolution (NASA, 2009)

Self-replicating: copies itself
Chemical system: based on assembly of molecules
Evolvable: adapt to the surroundings

Mules

Infertile or old animals

Viruses



The definition covers all species, not necessarily individuals

Definitions of life

Life is a self-sustaining kinetically stable dynamic reaction network derived from the replication reaction

(A. Pross, 2012)

Non-living systems → thermodynamic stability

Living systems →dynamic kinetic stability (DKS)

Better at making more of itself (replicating) → more stable in the DKS sense

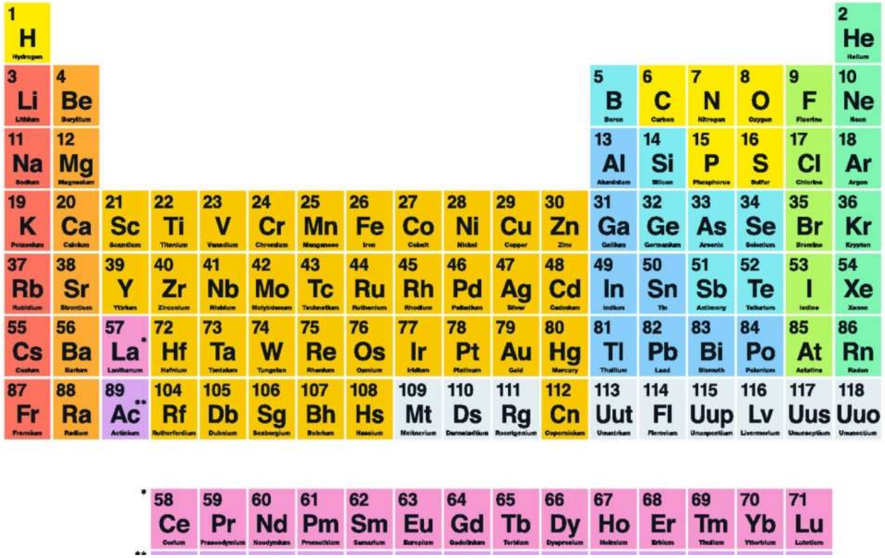
„self-sustaining” - orders itself on the expense of the external world (2nd LT)

Death is reversion of a system from the kinetic, replicative world back to the thermodynamic world

Elements of life

Carbon-based life well-justified:

- self-replicating chemical systems need sufficient complexity
- Carbon is tetravalent and can form complex structures (unlike H, He, Li, O, or F)
- Fourth most common element in the Solar system



Silicon is less well suited to support complex chemistry than carbon.

Other atoms are far worse than silicon

Solvents of life

Advantages of water:

- ice floats → nutrient transport, temperature modulation

- High heat capacity 4.2 J/g*^{0}C (3x of rocks or metals), heat of vaporization 41 J/g

→ both help to moderate Earth's climate

- Liquidity range – 100^{0}C

- High dielectric constant – water is a very good solvent

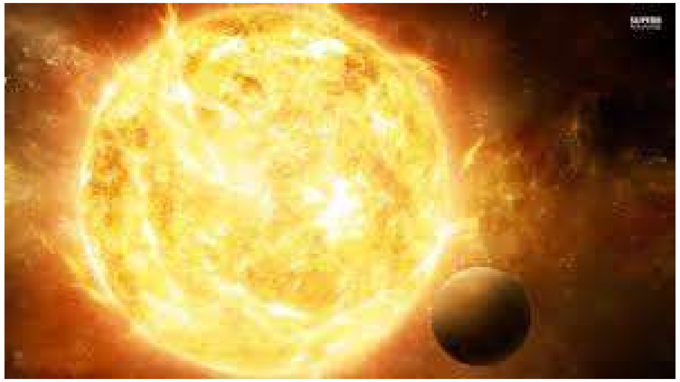
- High molecular density 55.5 mol/L – „hydrophobic effect”: H_2O forces dissolved molecules to organize to minimize the enthropic cost

- H, O – very abundant in the Universe (1st, 3rd) H_2O – 2nd most abundant after H_2

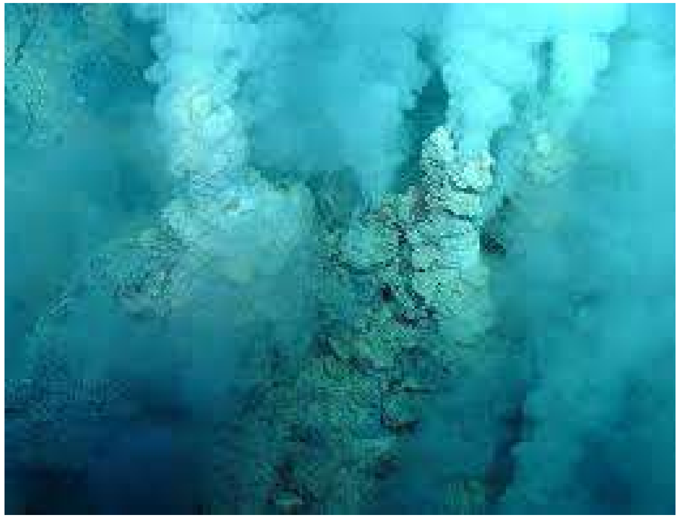
Alternative solvents
HF, NH_3, CH_4, H_2

Energy for life

The energy of stars



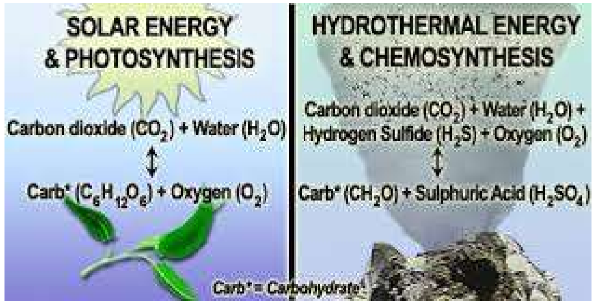
Geothermal/chemical



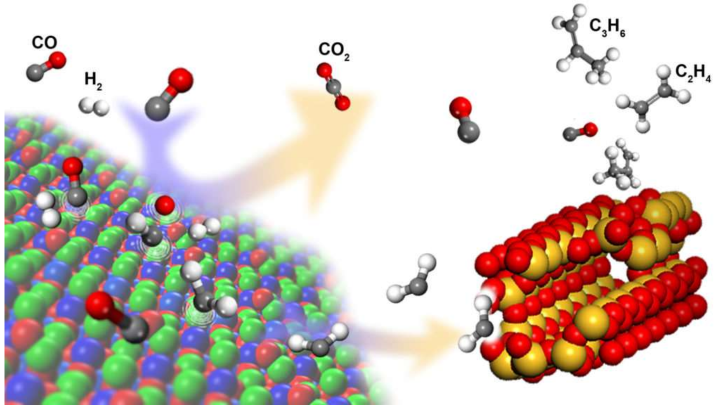
Life creates order from disorder → need for energy

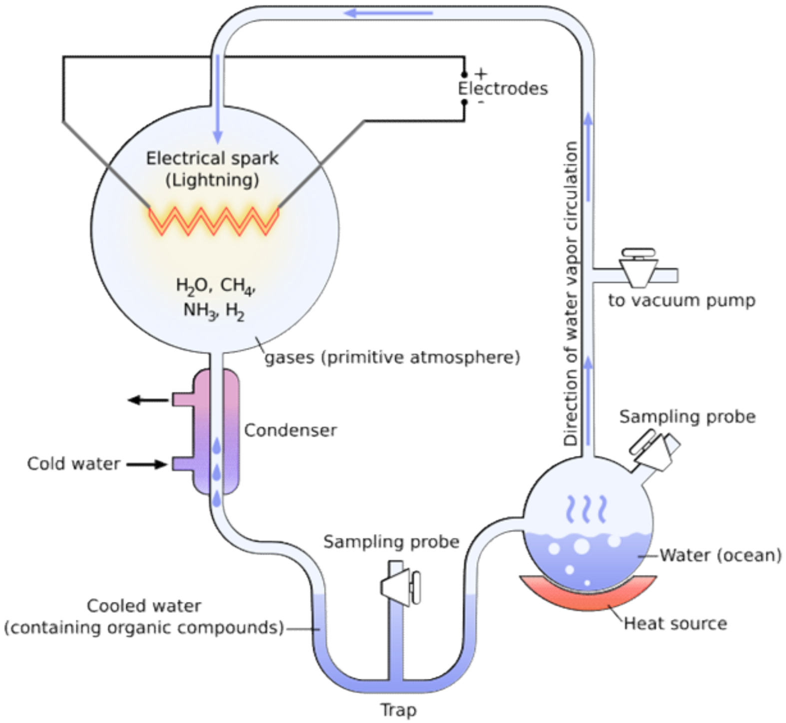
High energy photons absorbed by plants
→ nutrients absorbed by animals;
both patterns used to run metabolic processes

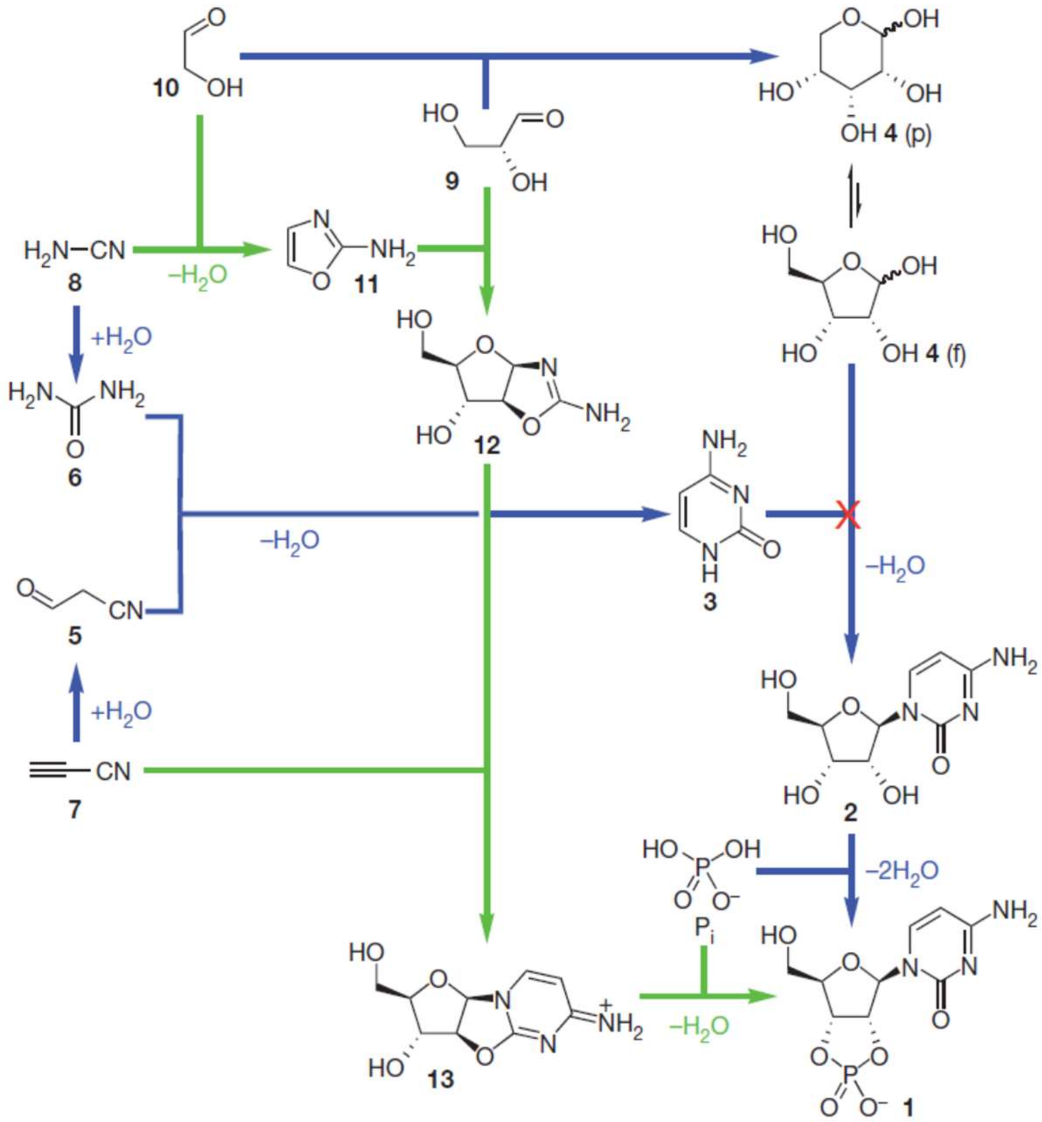
However, not the only available source of energy
→ Further lecture on extremophiles

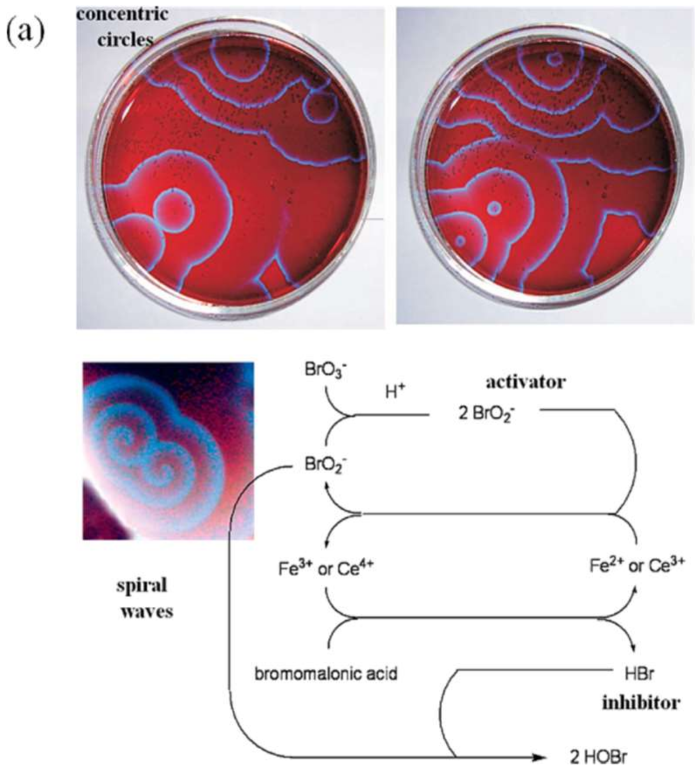


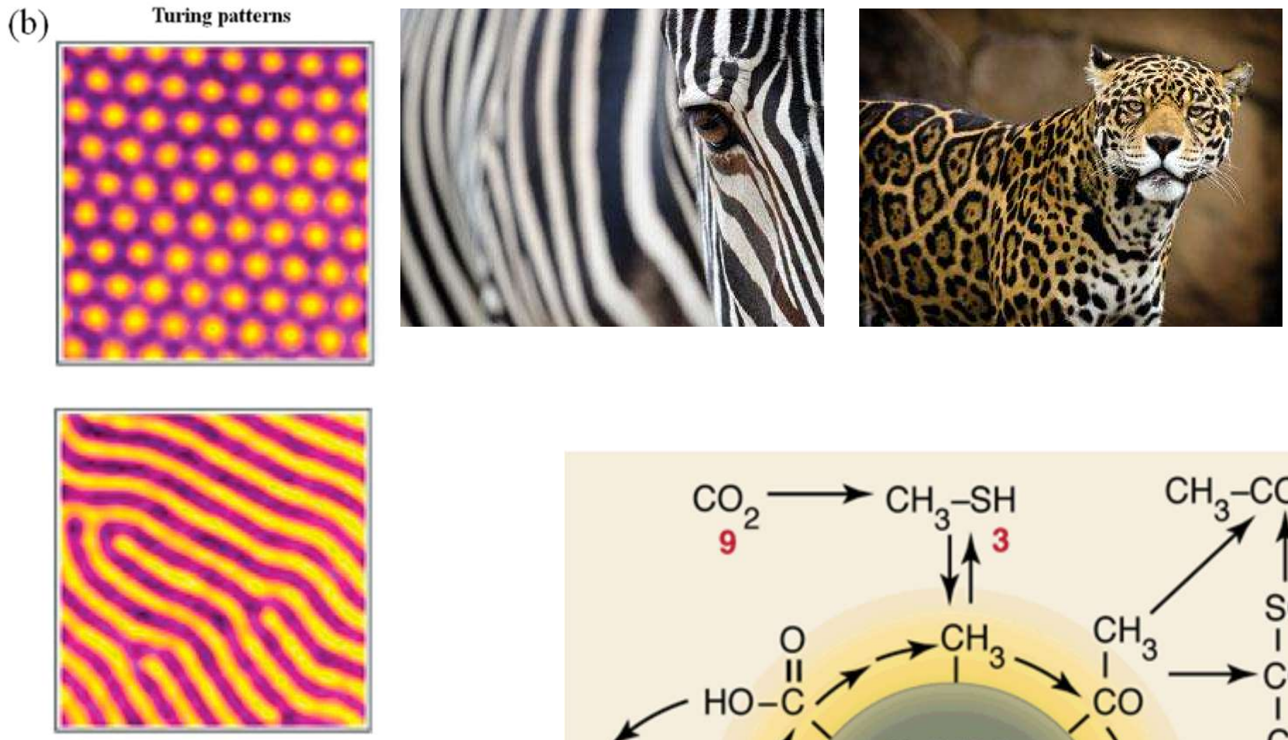
Energy-producing oxidation reaction	Type of bacteria
$2H_2 + O_2 \rightarrow 2H_2O$	Hydrogen bacteria
$2H_2S \rightarrow S \rightarrow S_2O_3^{2-} \rightarrow SO_4^{2-}$	Colorless sulfur bacteria
$Fe^{2+} \rightarrow Fe^{3+}$	Iron bacteria
$NH_3 \rightarrow NO_2^- \rightarrow NO_3^-$	Nitrate, nitrite bacteria

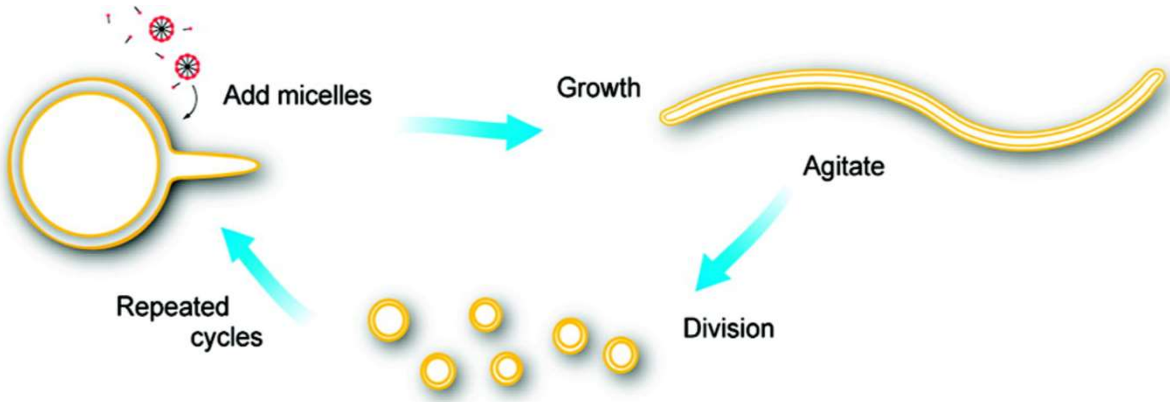

CO
H2
CO2
C3H6
C2H4

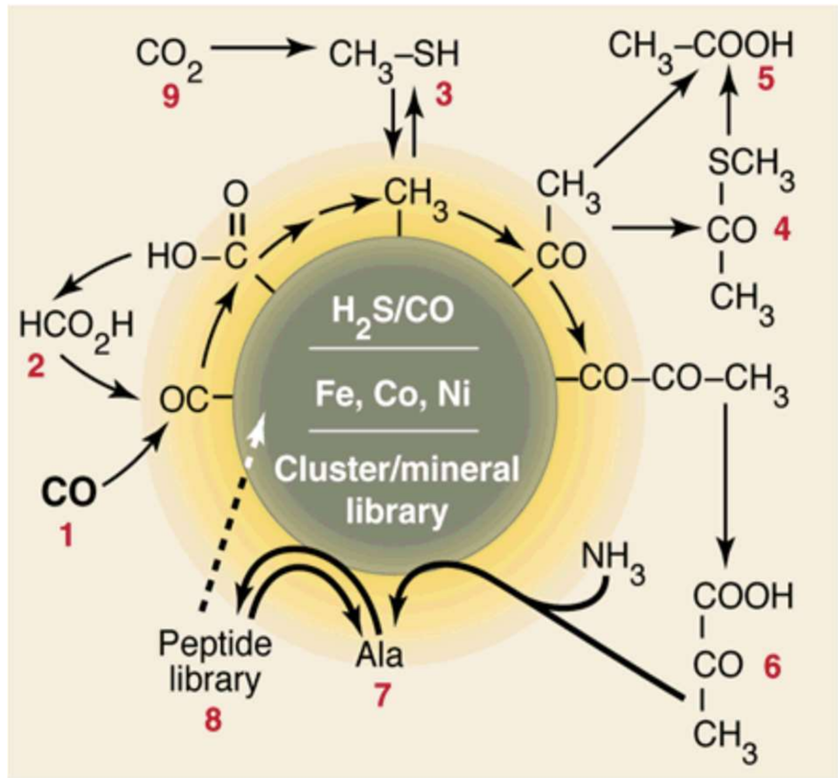

Electrodes
+
-
Electrical spark
(Lightning)
H2O, CH4,
NH3, H2
gases (primitive atmosphere)
Direction of water vapor circulation
to vacuum pump
Condenser
Cold water
Sampling probe
Sampling probe
Water (ocean)
Heat source
Cooled water
(containing organic compounds)
Trap

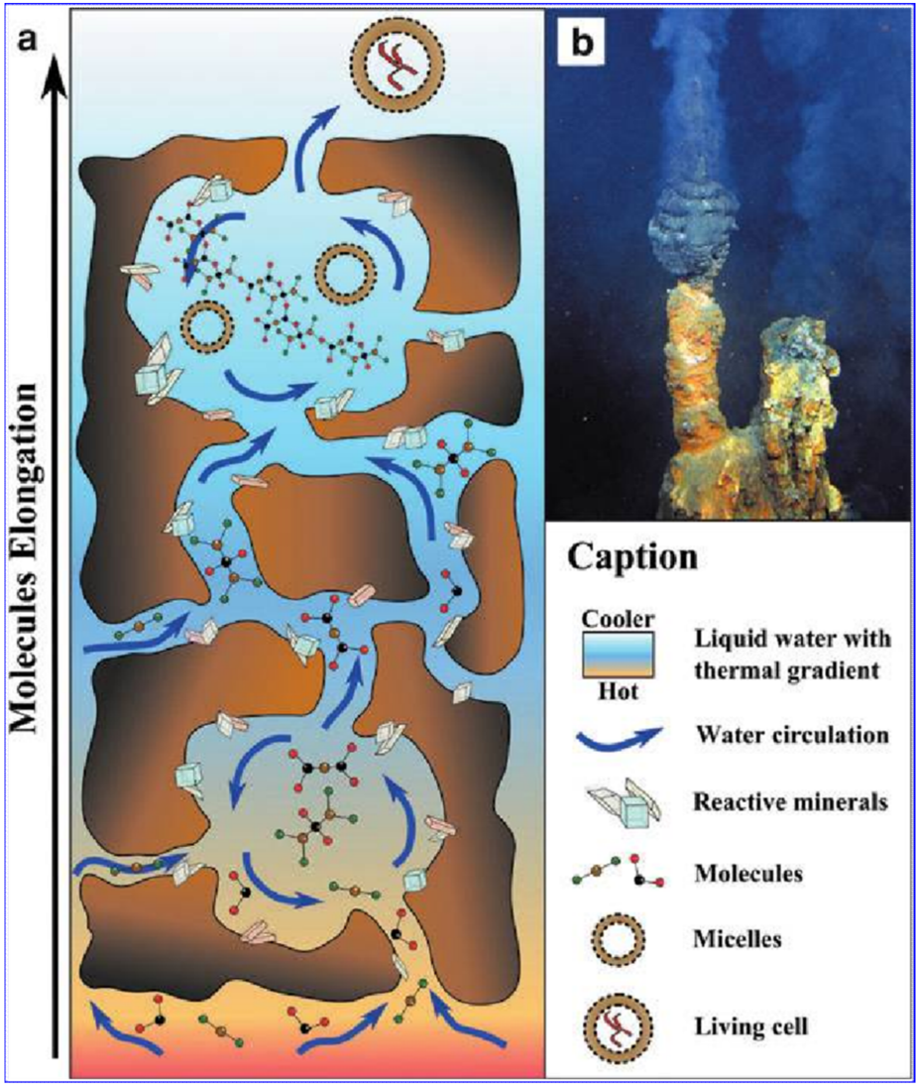

10
9
4 (p)
4 (f)
H2N–CN
8
–H2O
11
12
+H2O
6
–H2O
3
–H2O
5
+H2O
7
2
–2H2O
Pi
–H2O
13
1

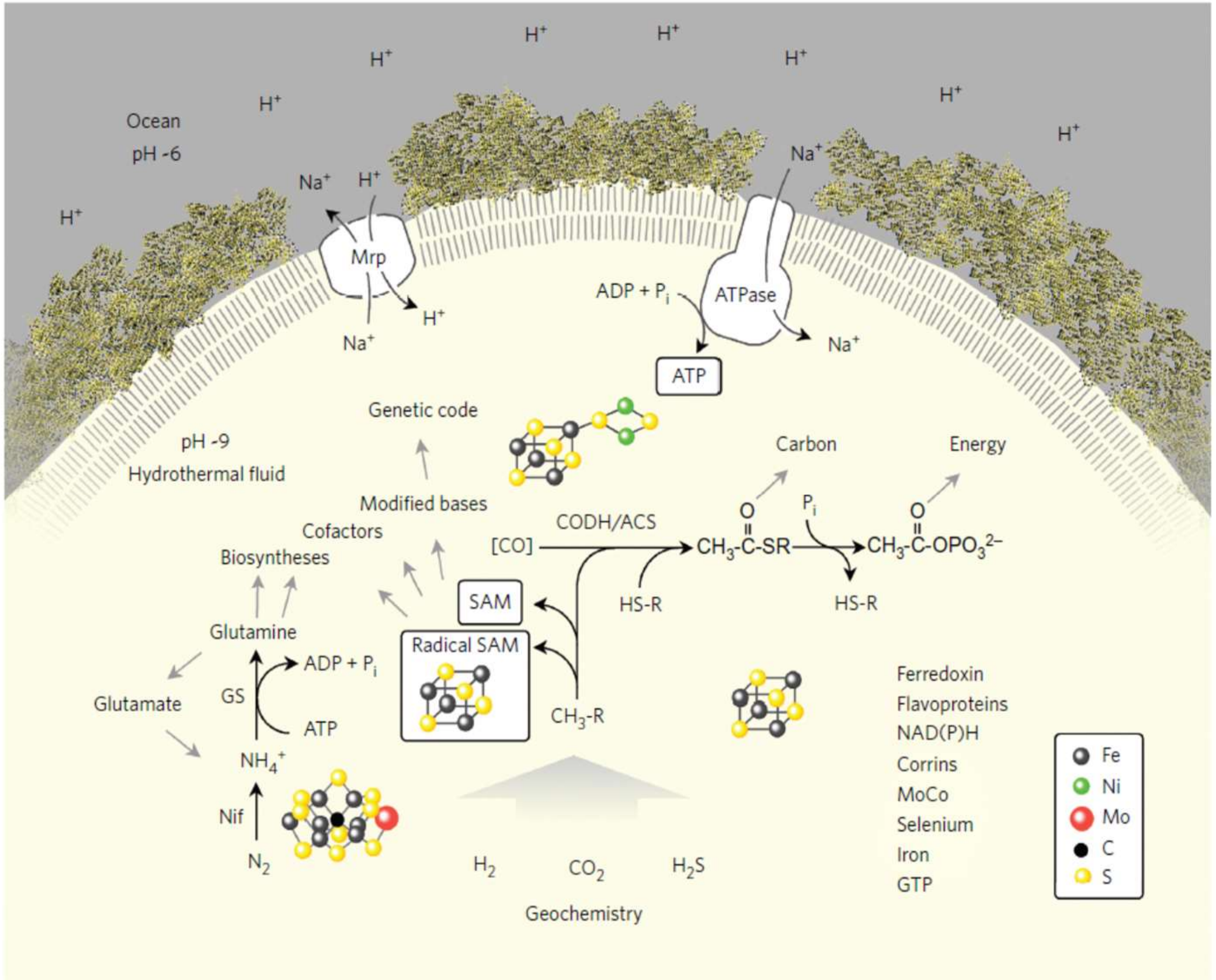

(a)
concentric circles
spiral waves
BrO_3^-
H^+
activator
2 BrO_2^-
BrO_2^-
Fe^{3+} or Ce^{4+}
Fe^{2+} or Ce^{3+}
bromomalonic acid
HBr
inhibitor
2 HOBr


(b)
Turing patterns


Add micelles
Growth
Agitate
Division
Repeated cycles


CO_2
9
CH_3–SH
3
CH_3–COOH
5
SCH_3
CO
CH_3
4
CH_3
CO
CH_3
O
HO–C
HCO_2H
2
OC
CO
1
H_2S/CO
Fe, Co, Ni
Cluster/mineral library
–CO–CO–CH_3
NH_3
COOH
CO
CH_3
6
Peptide library
8
Ala
7


a
b
Molecules Elongation
Caption
Cooler
Hot
Liquid water with thermal gradient
Water circulation
Reactive minerals
Molecules
Micelles
Living cell

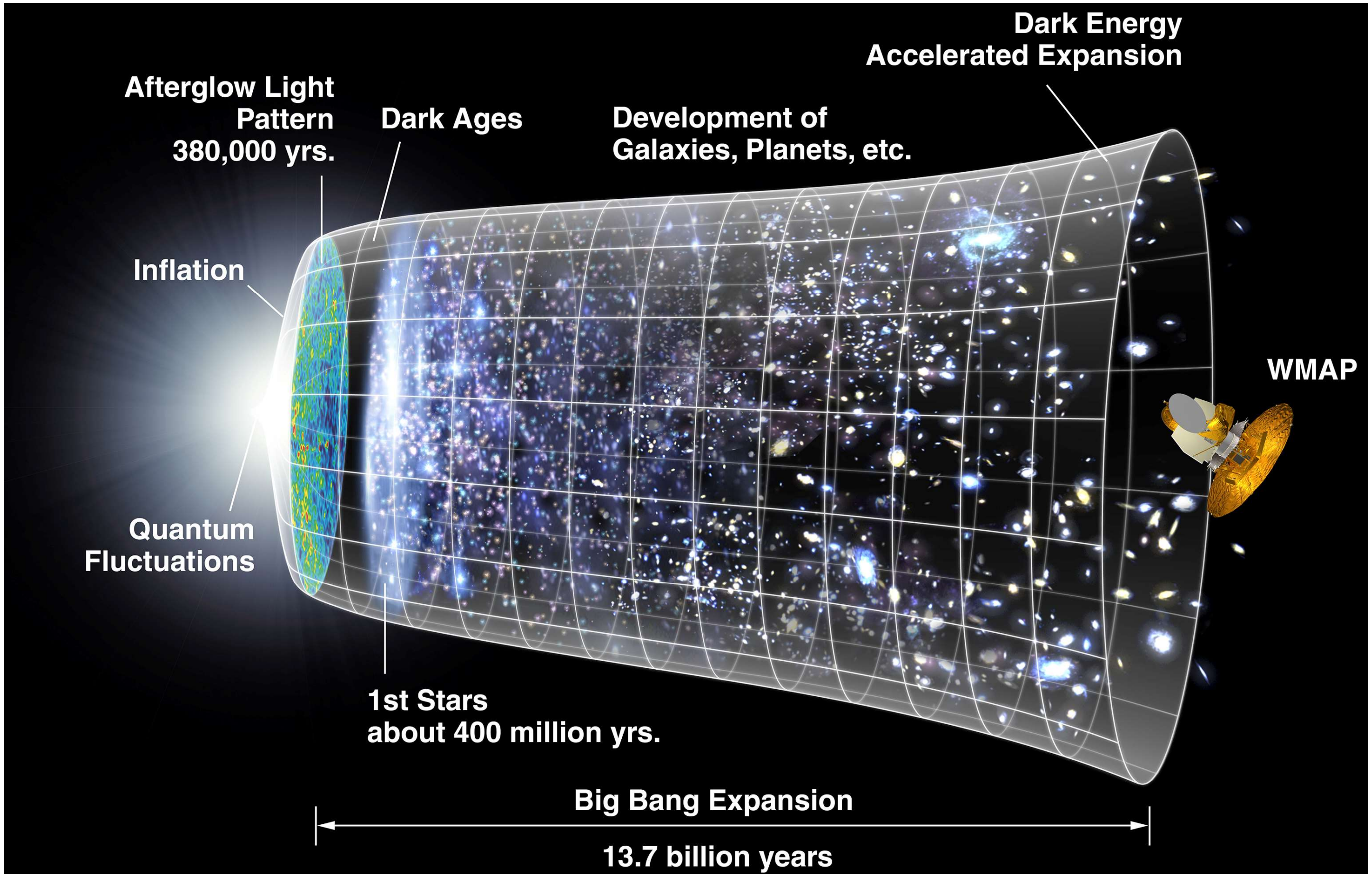

Ocean
pH -6
H+
Na+
Mrp
ATPase
ADP + Pi
ATP
pH -9
Hydrothermal fluid
Genetic code
Modified bases
Cofactors
Biosyntheses
Carbon
Energy
CODH/ACS
[CO]
CH3-C-SR
CH3-C-OPO3 2−
HS-R
SAM
Radical SAM
CH3-R
Glutamine
Glutamate
GS
ADP + Pi
ATP
NH4+
Nif
N2
H2
CO2
H2S
Geochemistry
Ferredoxin
Flavoproteins
NAD(P)H
Corrins
MoCo
Selenium
Iron
GTP
Fe
Ni
Mo
C
S

The origin of the habitable Universe and planets

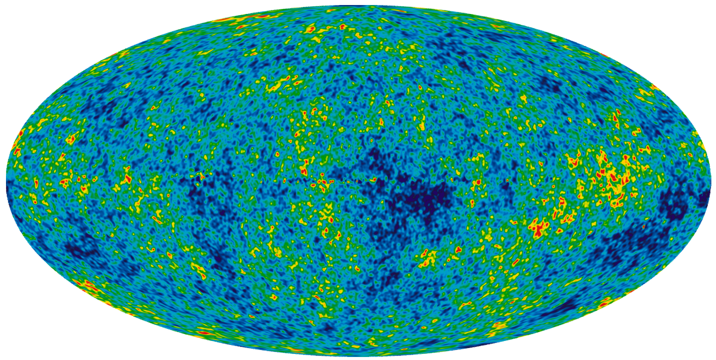
Terry Pratchett: The Discworld

Echoes of the earliest Universe

Red shift of spectral lines in far galaxies (Hubble, 1929)
Theory of the Big Bang – Gamow (1948)

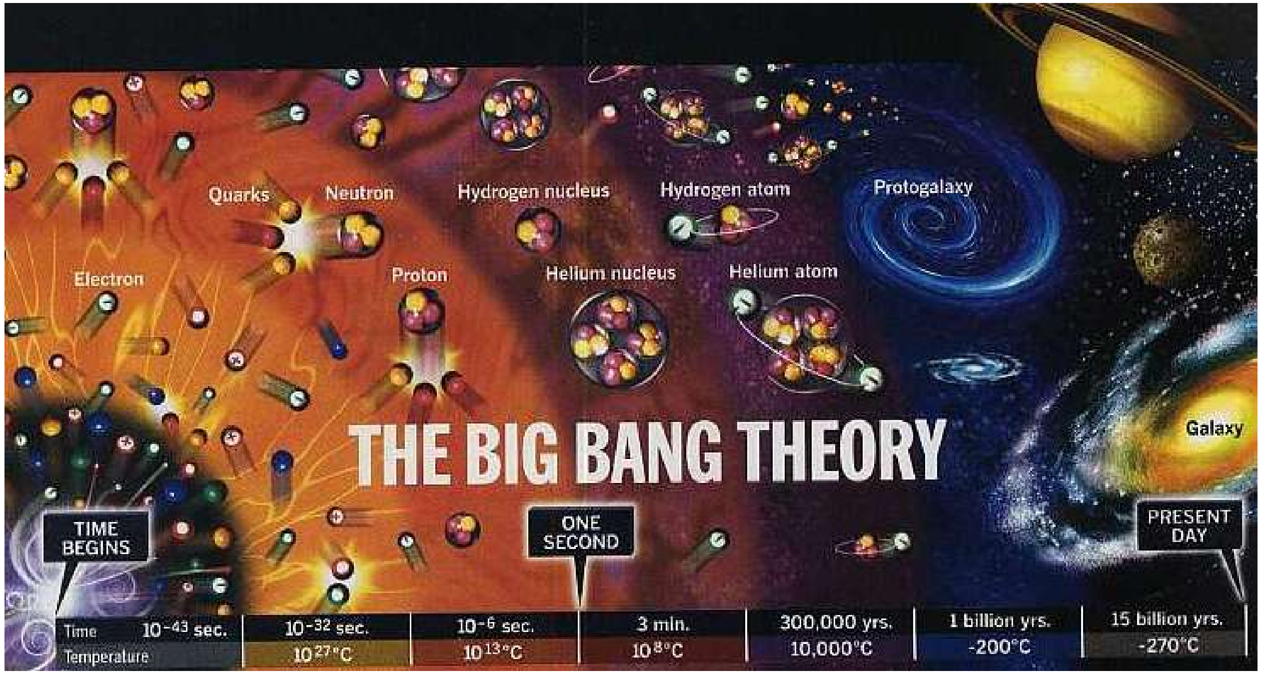


Cosmic microwave background
(Penzias, Wilson,1965 Bell AT&T)



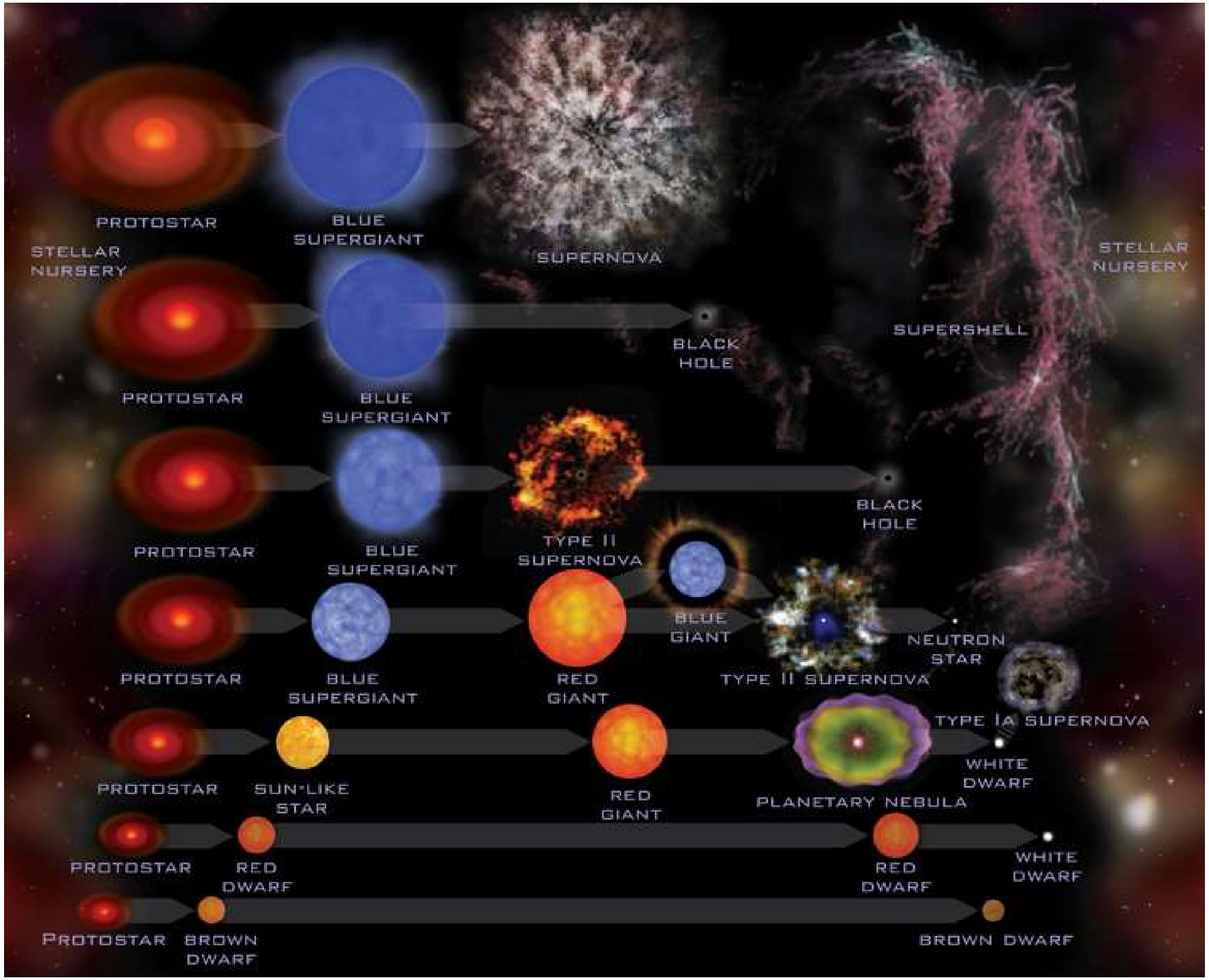
Heat of the Big Bang dissipated in the Universe as the 4 K residual radiation

Origin of the Universe



- Unsymmetric matter/antimatter anihilation
- only H and He elements formed during the Big Bang
- The Universe transparent aftr 377.000 yrs. → background µwave radiation
- Fluctuations registered there → autocatalytic formation of protogalaxies

Stellar evolution



Star that burned all its ^{1}H (red giants), beginns to synthesize ^{12}C and ^{16}O from ^{4}He

Big stars (>8 sun masses) ignite ^{12}C and ^{16}O to form ^{24}Mg, ^{23}Mg ($-{}^{0}n$), ^{23}Na ($-{}^{1}H^{+}$), and ^{28}Si

Last step: $2x^{28}Si \rightarrow {}^{56}Fe$

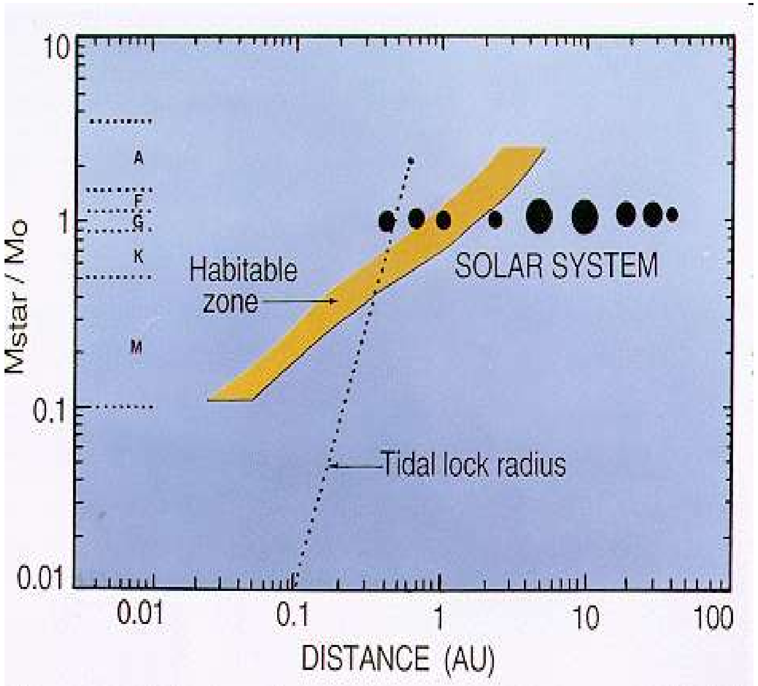
Supernova:
heavier elements synthesized by neutron irradiation of iron

Habitable zone – galactic and star systems

Too close to the center –sterilization by notorious supernova explosions, X-rays from black holes

Far beyond the Sun's orbit – lack of elements > C,O
→ planet formation inhibited

GHZ in the Milky Way → below 5% of stars

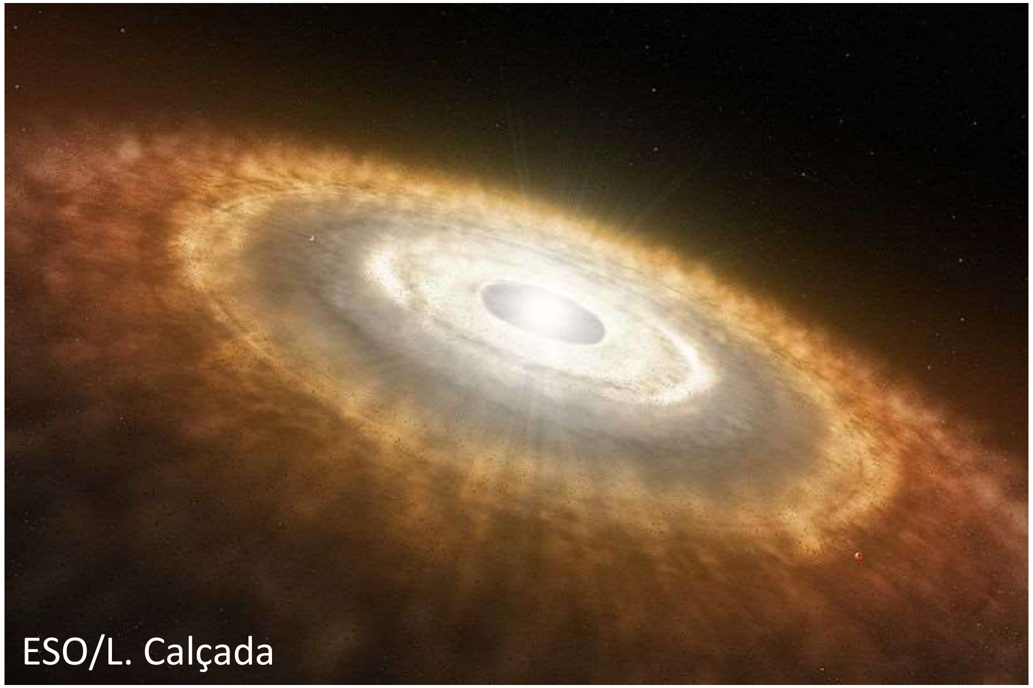


Habitable zone – the region where liquid water can occur
Tidal lock – destructive temperature gradients

→ 0.4-2 Sun mass stars optimal for life development

Evolution of the solar system

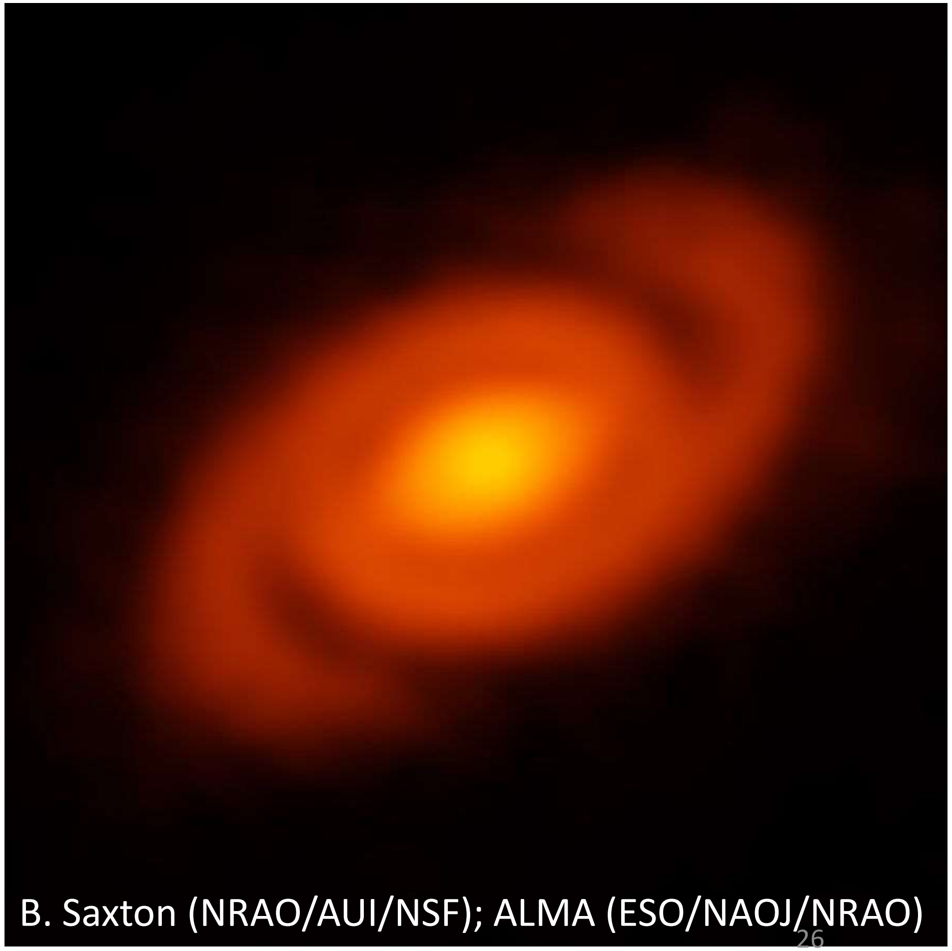
Pre-solar nebula – artistic vision



ESO/L. Calçada

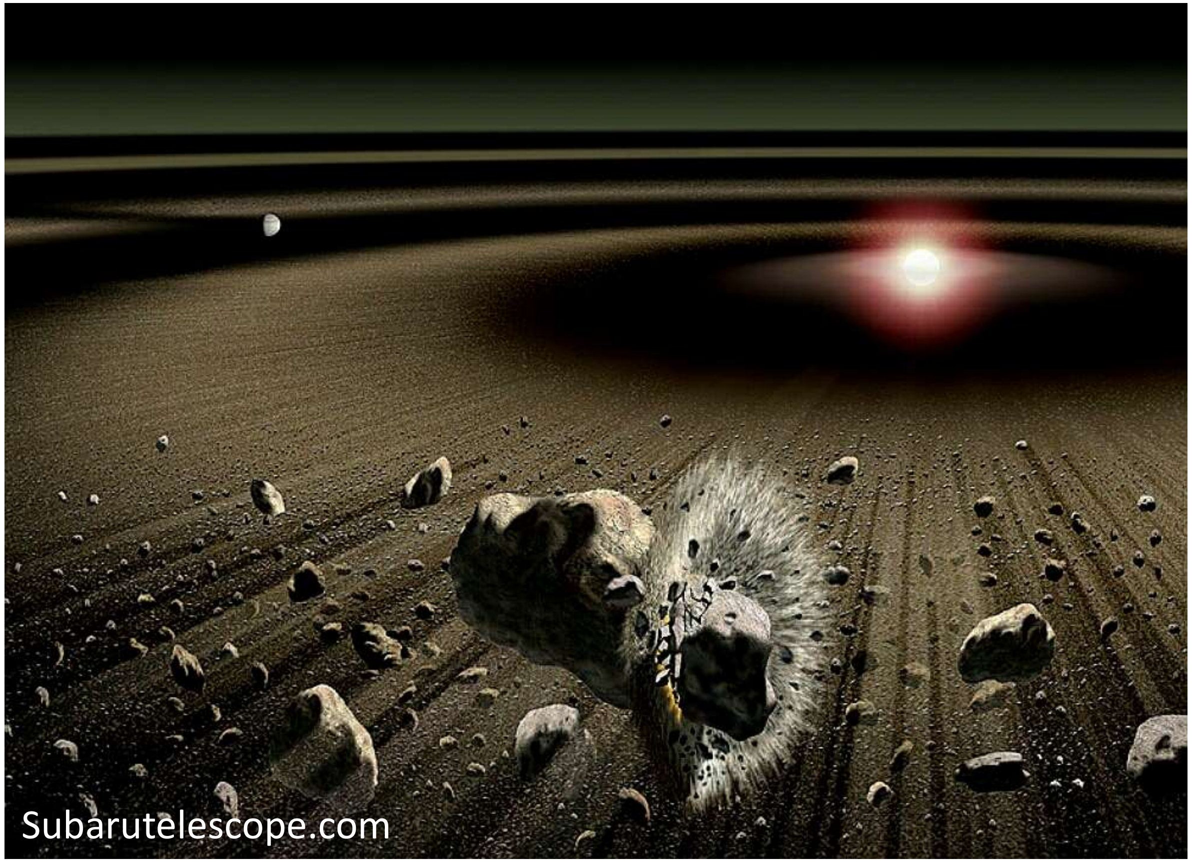
most matter into the proto-sun,
0.1%-2% remained in the acretion disc
Liquids unstable, only sublimation
10 Mio. K → ignition of the star (^1H→ ^4He)

Protoplanetary disc surrounding a star Elias 2-27, 450 light years away



B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO)

Evolution of the solar system



Conglomerations of particles → km-sized planetesimals,
frequent collisions → accretion
the km-sized bodies gravitationally attractive for gases around → growth of proto-planets

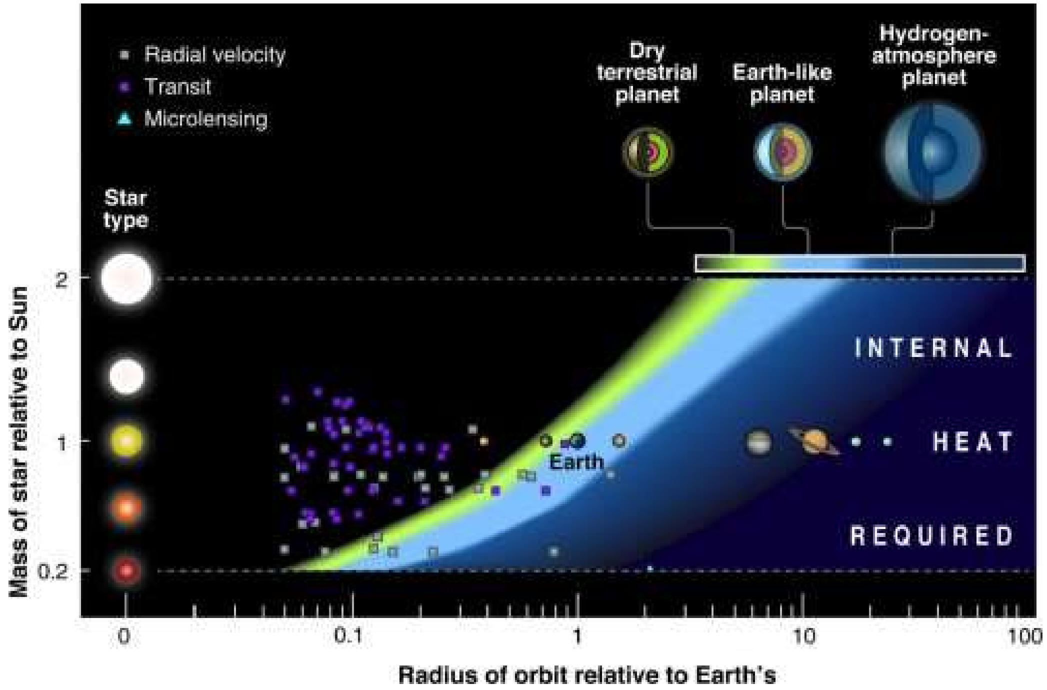
Evolution of the solar system

Composition of planetesimals depends on their distance from the star:

Metal-rich – center

Silicate-rich – middle

Volatile-rich – outer part



The equilibrium condensation model

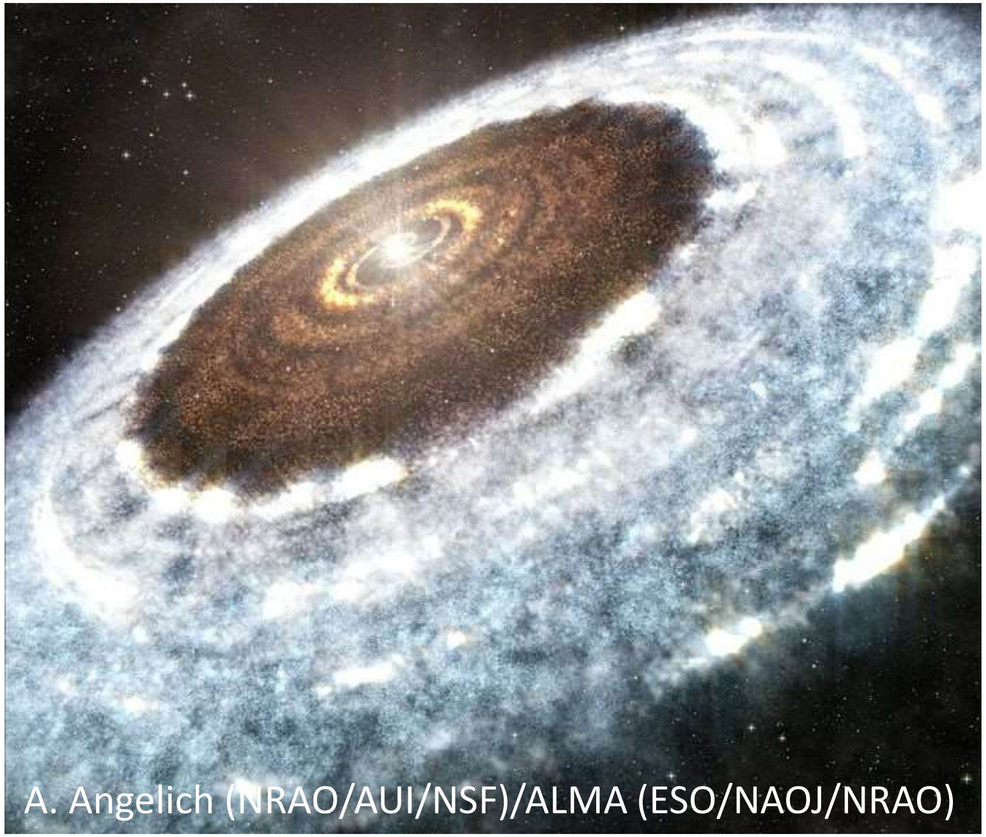
temperature determines equilibrium chemistry which defines the composition

The prediction is rough (scattering)

Exceptions: volatiles on Earth and Venus, composition of the Moon

Composition of the planets in the solar system

Water – a major component of the solar nebula, but under the very low pressure does not condense above 150 K („snow line" in the nebula, 2.7 AU in the Solar system).

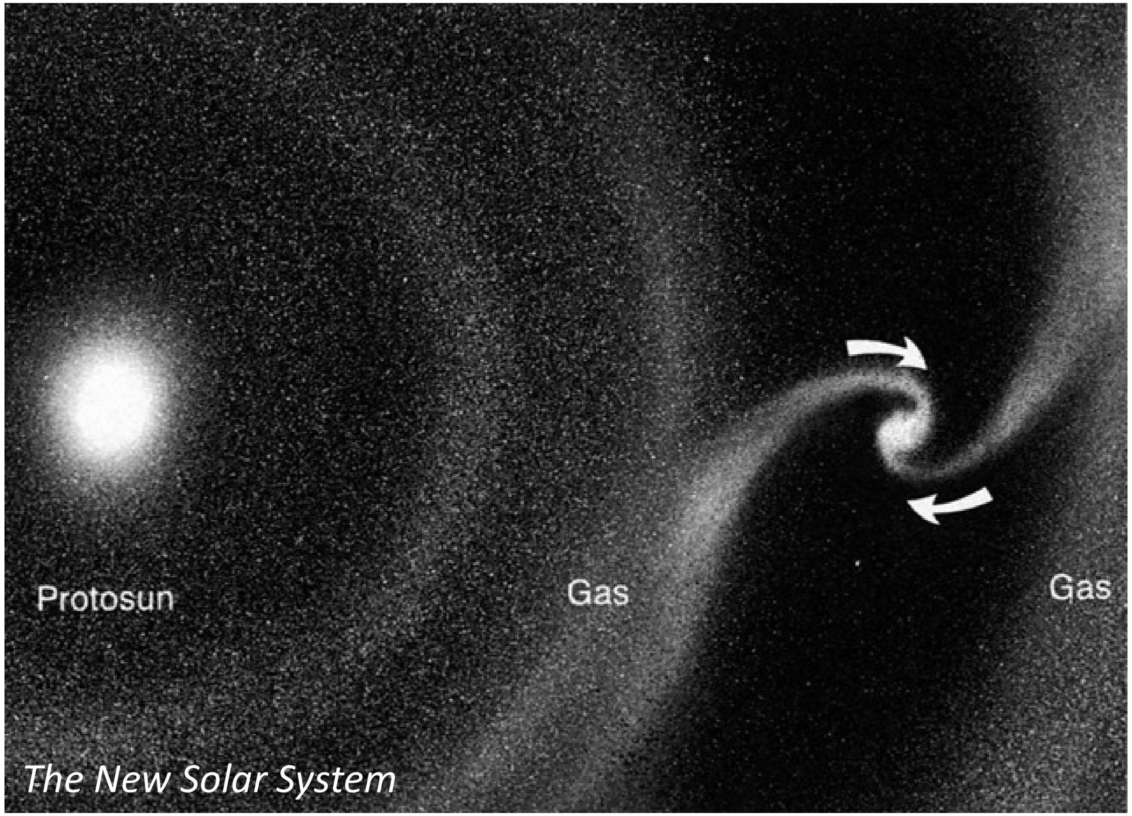

A. Angelich (NRAO/AUI/NSF)/ALMA (ESO/NAOJ/NRAO)

Asteroids that form above 2.7 AU contain significant amount of water

Composition of the planets - Jupiter

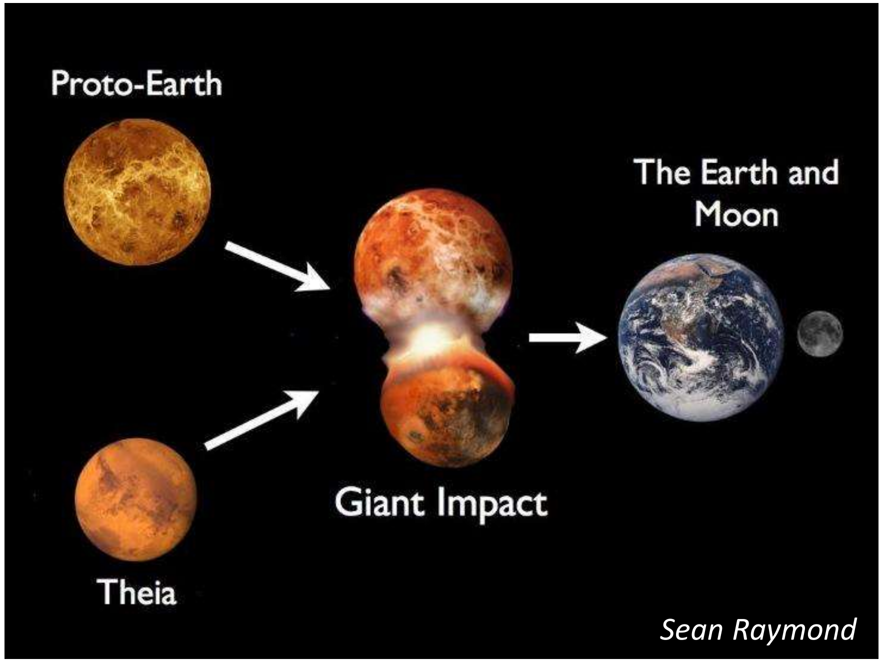
Jupiter – 5.21 AU – first planet beyond the snow line – silicates and water condensed in largest amounts of the whole Solar System around a small metal core, and formed a proto-Jupiter
(10-15 Earth masses, fast).

Then gravity strong enough to pull in all available gases around, until it mainly consisted of H_2 and He (strongly pressurized)



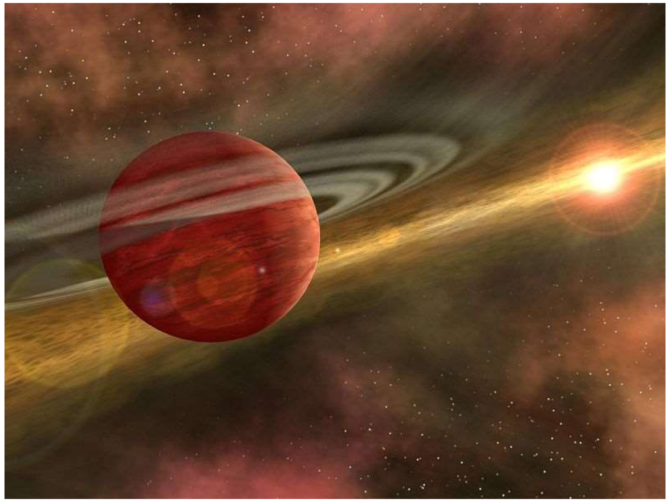
Origin of the Moon

Lunar rock samples (*Apollo* mission): Isotopic distribution like on Earth
Surface of the Moon is different from the Earth surface – lack of „volatile" metals like sodium, the Moon's density only 3.4 g/cm^3 → contains almost entirely silicates



„Daughter-like" Moon's origin – impact of a Mars-size object into Earth splashed a big chunk of liquid rock from its mantle (mostly silicates) into space
Isotope dating (^{182}Hf/^{182}W): Moon formed 30 Mio. Yrs after accretion

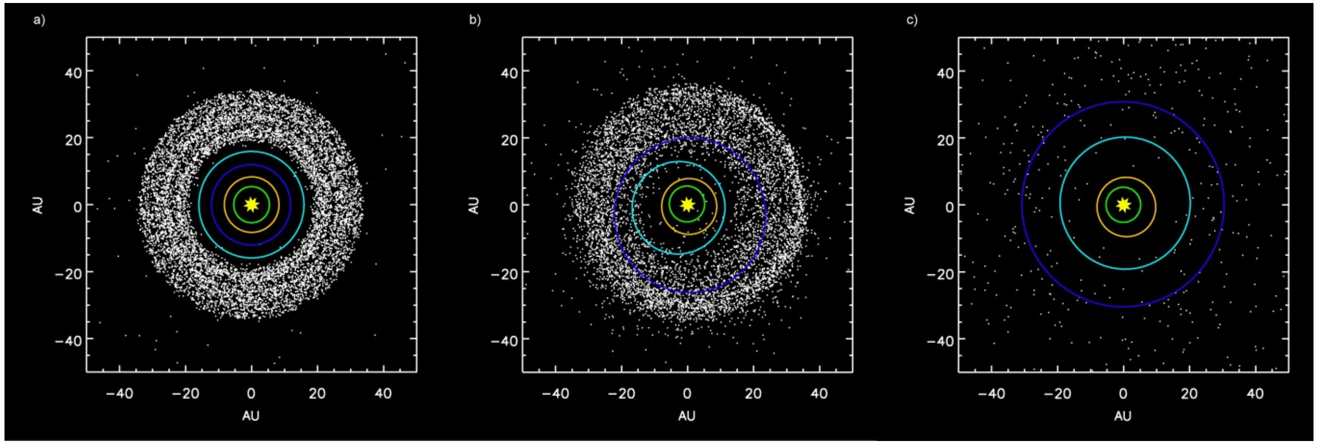
Origin of volatiles on terrestrial planets



Proto-Earth was too hot to condense water
but 0.035% Earth mass is water!!

Water came from beyond the snow line:
Jupiter ejected the remaining planetasimales outwards and inwards: „big cleanup"

The Nice model



Explains the formation of the Kuiper's Belt, Oort's Cloud and Planetoid Belt

The ejected planetasimales delivered volatiles to Earth and other terrestrial planets

Late Heavy Bombardment

Late Heavy Bombardment 3.8 Bio. Yrs. ago was the last intensive impact period. Then no more planetasimales.

100-km-wide object can sterilize the surface of the whole planet, but nothing like that happened since.

Origins of a habitable planet - conclusions

Earth formed in the inner region of the solar nebula

Predominantly composed of refractory metals and silicates – non-biogenic materials

Jupiter provided proto-Earth with icy, volatile-rich material, and allowed cleanup of the Solar System from planetasimales, so no more big, planet-sterilizing impact possible anymore.

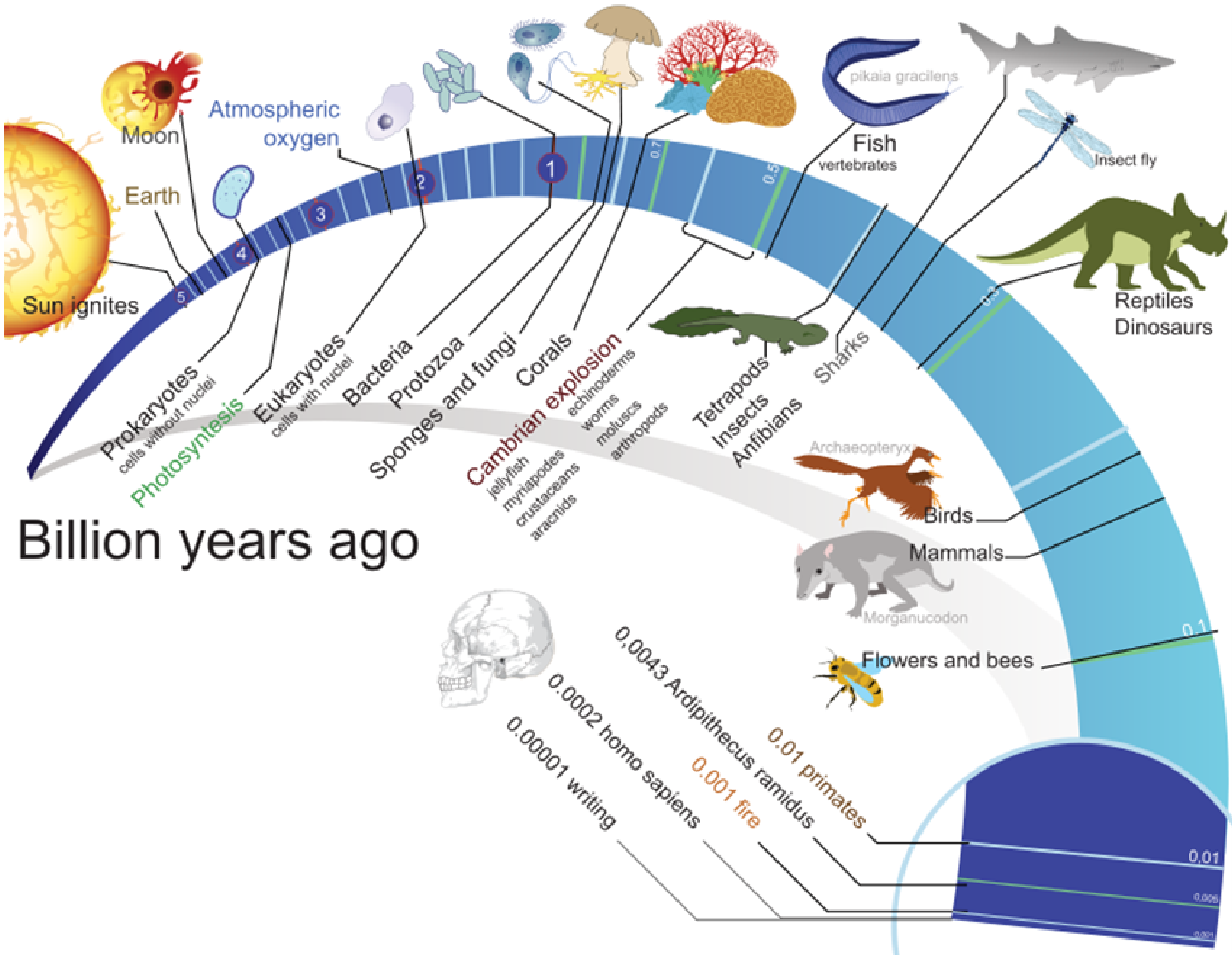
Earth is optimally positioned (0.95-1.15 AU) to maintain the acquired water as liquid, and stable surface temperature over billions years.

Topic 2
The primordial soup

The molecular origins of life

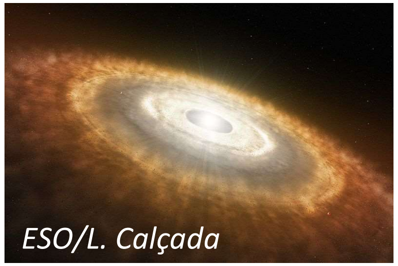
Zibi Pianowski

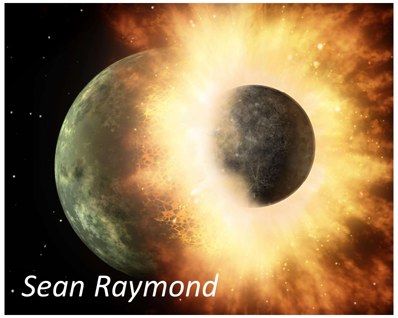
When life originated on Earth?



If life arose relatively quickly on Earth ... then it could be common in the universe."

When life originated on Earth?





Hadean Eon (4600 Ma - 4000 Ma)

- 4600 Ma – Earth formation
- 4500 Ma – Theia collides Earth → Moon
  Earth's axis of rotation stabilized, which allowed abiogenesis
- 4460 Ma – oldest known lunar rock - Lunar sample 67215, *Apollo 15*
- 4404 Ma – the oldest known material of terrestrial origin – zircon mineral (Australia) –
  isotopic composition of oxygen suggests presence of water on the Earth's surface
- 4374 Ma – the oldest consistently dated zircon

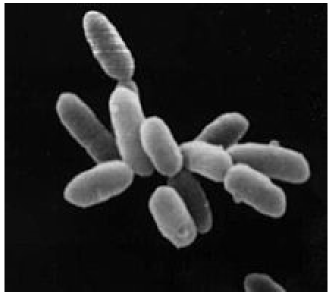
Archean Eon (4000 Ma – 2500 Ma)

1 Ma = 1 million years

- 4031 Ma – formation of the Acastia Gneiss
  - the oldest known intact crustal fragment on Earth
- 4100 Ma - 3800 Ma – Late Heavy Bombardment (LHB)
- 3800 Ma – greenstone belt (Greenland) – isotope frequency
  consistent with presence of life

When life originated on Earth?

- 4100 Ma – „remains of biotic life” found in zirconites (Australia)
- 3900 Ma – 3500 Ma – cells remaining procaryotes appear
  first chemoautotrophes: oxidize inorganic material to get energy, CO_2 *– carbon source*
- 3700 Ma – oldest evidences for life – biogenic graphite in Isua greenstone belt (Greenland)
- c.a. 3500 Ma – lifetime of the Last Universal Common Ancestor (LUCA)
  split between bacteria and archaea
- 3480 Ma – oldest fossils – microbial mat (bacteria and archaea) fossils – sandstone, Australia
- 3000 Ma – photosynthesizing cyanobacteria evolved – water used as reducing agent
  → production of oxygen → oxidation of iron into iron ore (FeO_x) *(banded iron)*
- 2500 Ma - free oxygen in atmosphere → Great Oxygenation Event („Oxygen catastrophe”)
  extinction of most anaerobic organisms



Archaea (Halobacteria)
extremophiles

cyanobacteria

The origin of life on Earth

- 384-322 BC – Aristotle – *abiogenesis*: spontaneous generation of life forms from unanimated matter (flies from old meat, mice from dirty hay)
- 1665 AC – Robert Hooke (microscope) – discovery of bacteria – considered a proof for spontaneous generation (bacteria division was not observed by then)
- 1668 – Francisco Redi – *biogenesis*: every life comes from another life
- 1861 – Louis Pasteur – bacteria do not grow in sterilized nutrient-rich medium, unless inoculated from outside; abiogenesis under current conditions regarded as impossible and therefore disproven

Panspermia – idea that life came to Earth from elsewhere in the Universe (e.g. Extremophilic organisms hibernated and traveling inside meteorites) – Anaxagoras (400ts BC), Berzelius, Kelvin, von Helmholtz, Arrhenius...;
Pseudo-panspermia – biorelevant molecules delivered from outside of Earth (meteorites)

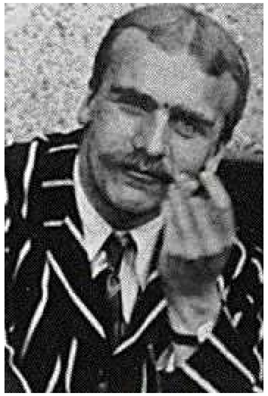
The origin of biorelevant molecules on Earth

Alexander Oparin
(USSR, 1894-1980)

„atmospheric oxygen prevents the synthesis of certain organic compounds that are necessary building blocks for the evolution of life"

1.The early Earth had a chemically reducing atmosphere.
2.This atmosphere, exposed to energy in various forms, produced simple organic compounds ("monomers").
3.These compounds accumulated in a "soup" that may have concentrated at various locations (shorelines, oceanic vents etc.).
4.By further transformation, more complex organic polymers - and ultimately life - developed in the soup.

John B. S. Haldane
(UK, India, 1892-1964)

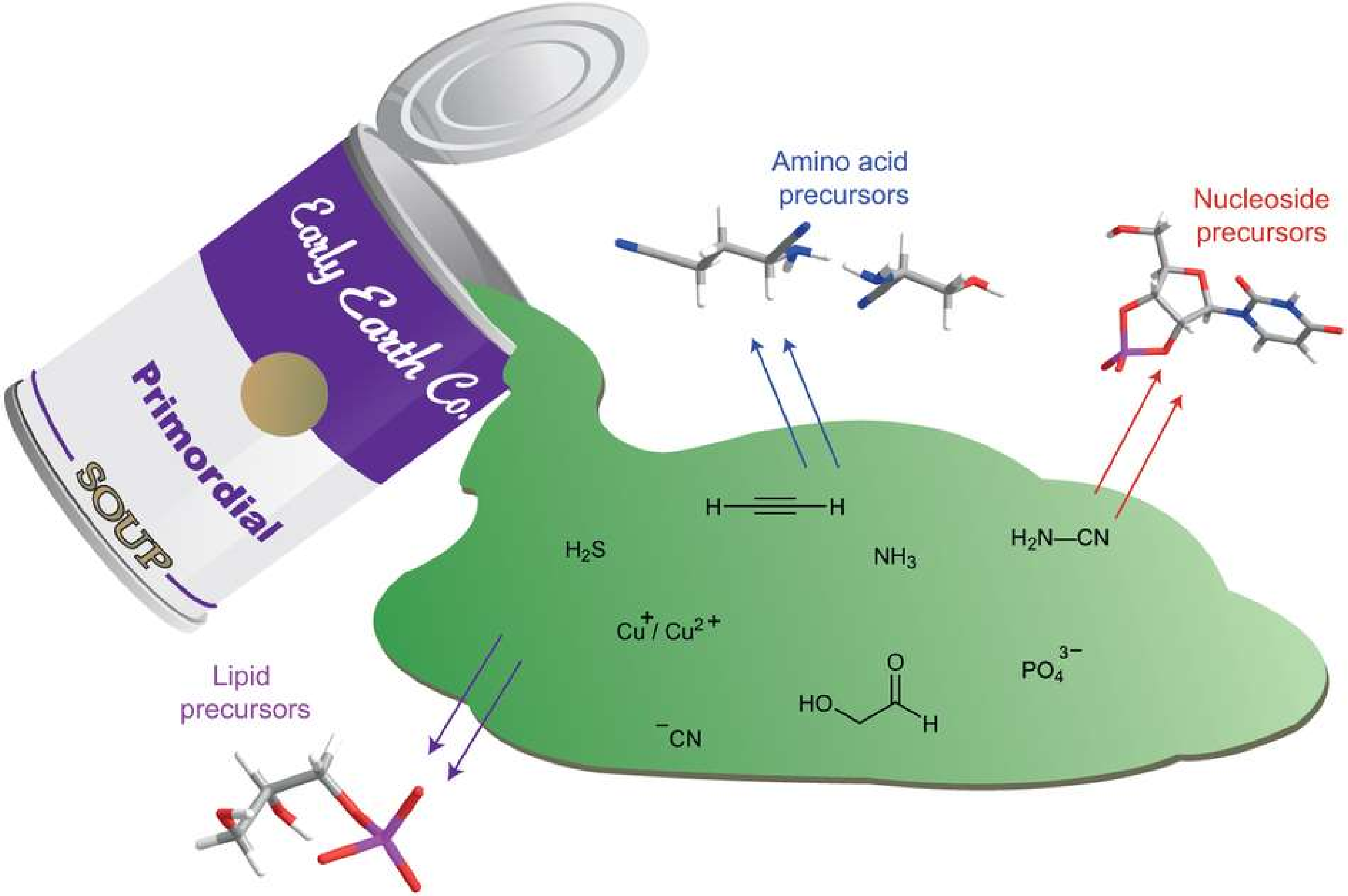


„Primordial soup"

„Biopoeiesis" – prebiotic oceans as „hot diluted soup" under anoxic conditions: e.g. CO_2, NH_3, H_2O

„Life arose through the slow evolution of chemical systems of increasing complexity"

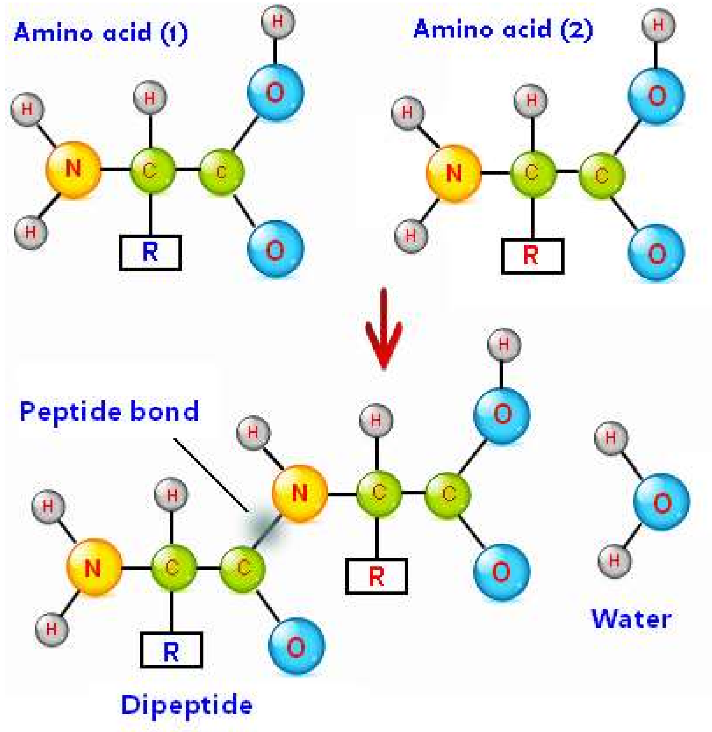
Basic classes of biomolecules



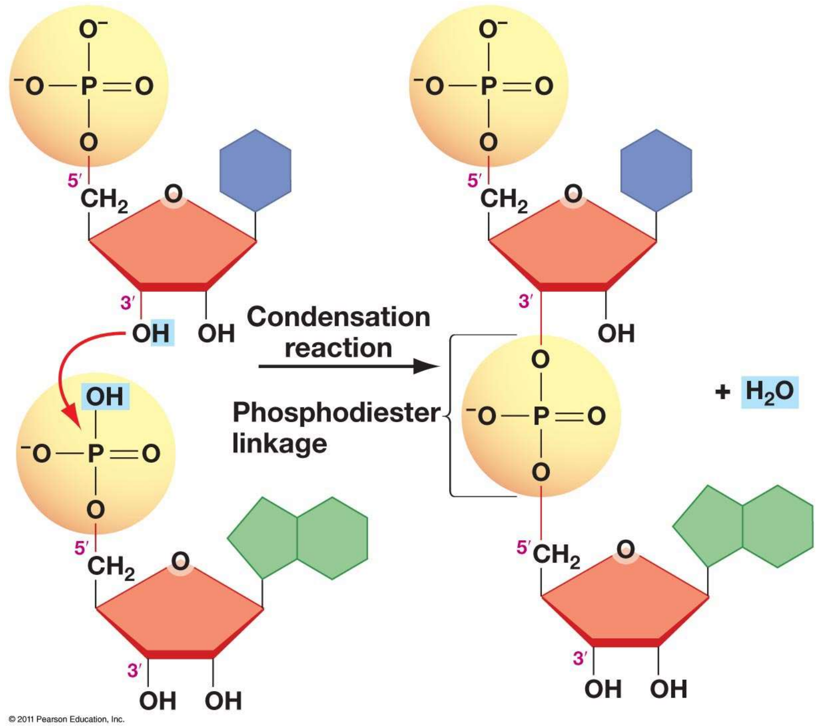
- Aminoacids
- Lipids
- Carbohydrates (sugars)
- Nucleotides
- Nucleosides (sugar+nucleotide)

Vital chemical reactions

Aminoacid polymerization

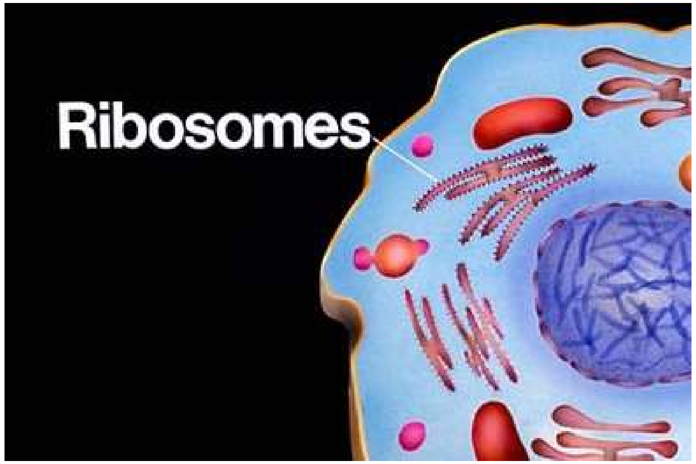


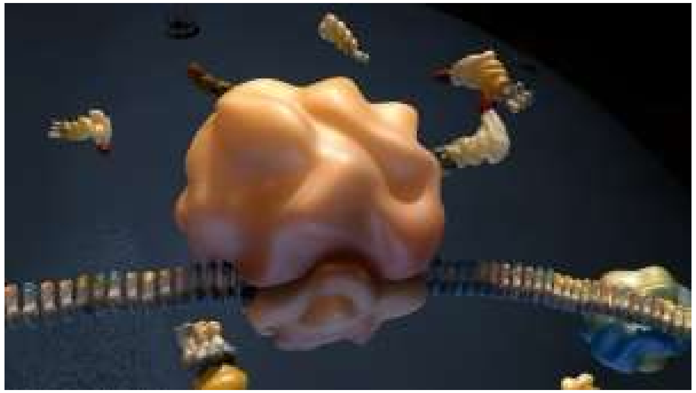
Nucleotide polymerization

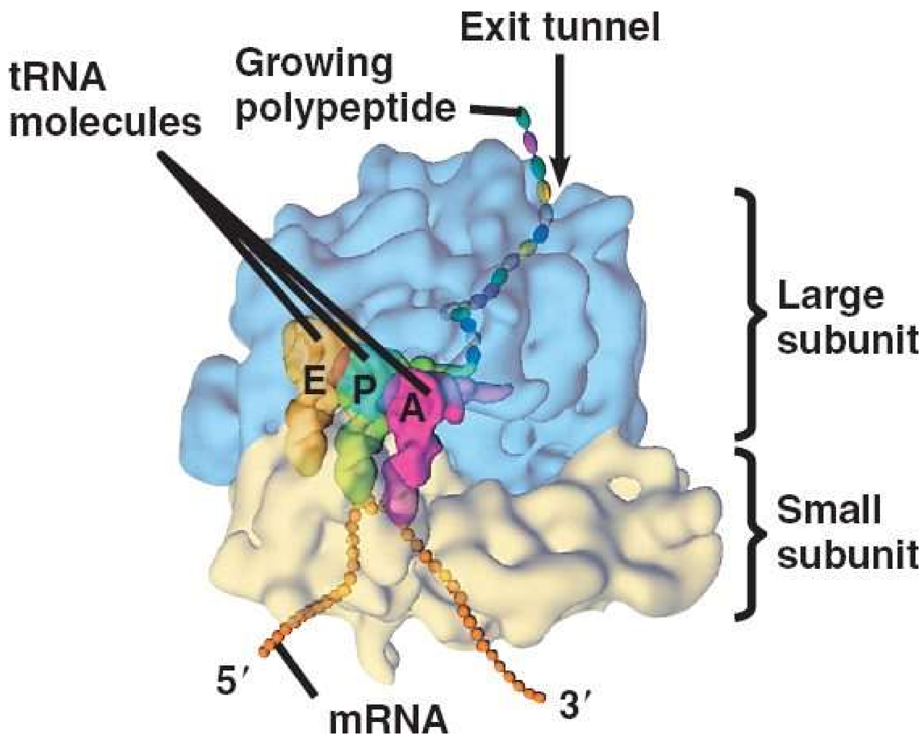


Vital chemical reactions

Aminoacid polymerization → ribosome



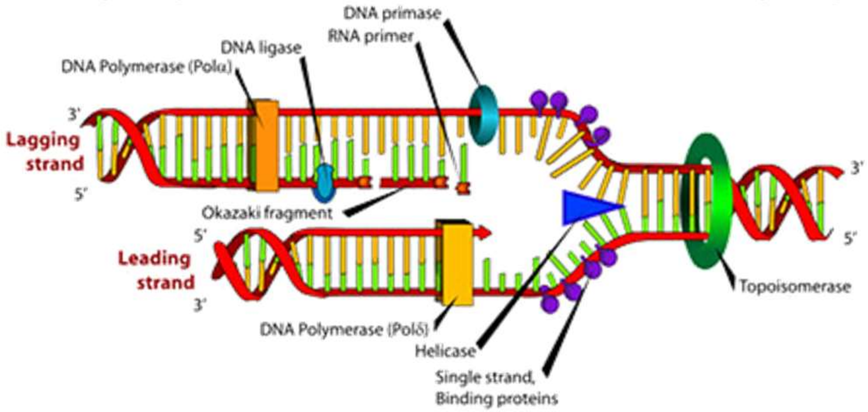




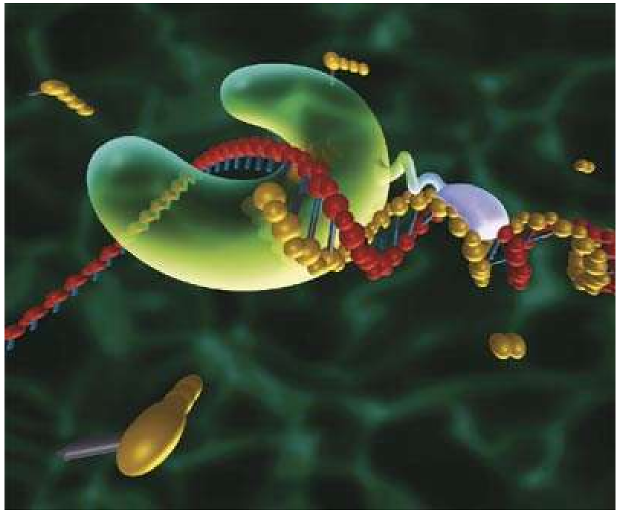
Nature Publishing Group, www.nature.com/nrg/multimedia

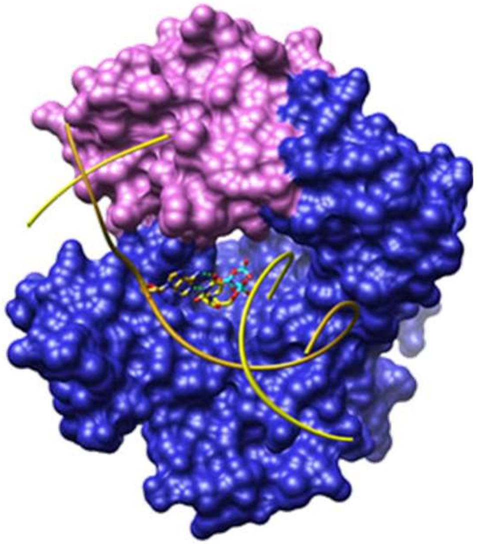
Vital chemical reactions

nucleotide polymerization → DNA/RNA polymerases



dxline.info/img/new_ail/dna-polymerase_1.jpg





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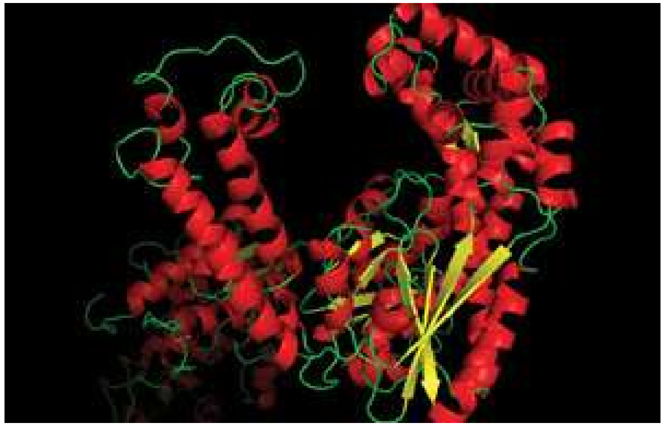

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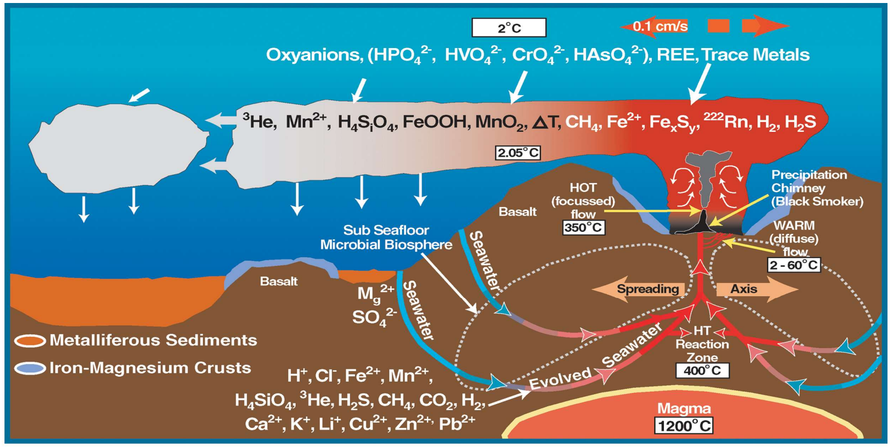
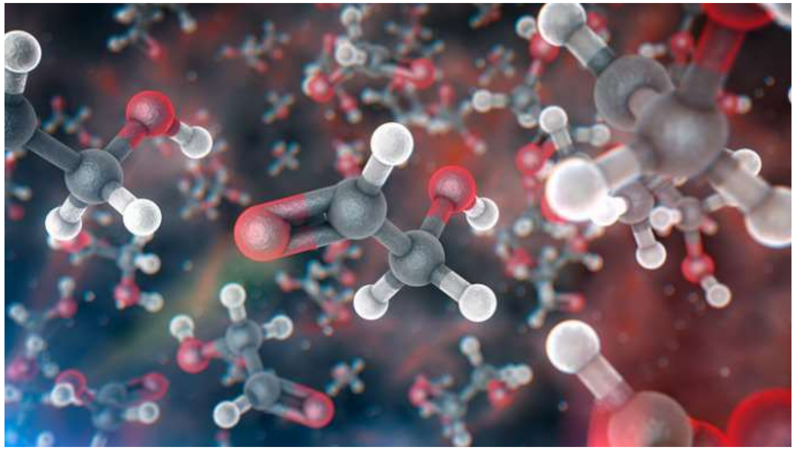
Experimental prebiotic organic chemistry

- Prebiotic chemistry deals with reactive substances (like HCN) often at concentrations much higher than probable in prebiotic environments
- Prebiotic experiments usually performed with very small number of pure substrates
- Early protometabolic processes might have used a broader set of organic compounds than the one contemporary biochemistry





Experimental prebiotic organic chemistry

- No evidences/fossils from that early Earth → we try to SPECULATIVELY fit different examples of chemical reactivity into an EXPECTED OUTCOME which we know as contemporary biochemistry

- Most of the discussed transformations are performed by highly specific and evolved enzymes at high speed and efficiency – prebiotic chemistry is supposed to be much slower and less efficient, but more robust and diverse