Exobiology and Mars

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Workshop Mars III - Les Houches - 28 March- 2 April 2010

OUTLINES

Exobiology

- **Some historical aspect**
- **Current exobiology**

The terrestrial example

- **Life on Earth**
- **The origin(s) of Life on Earth**

A Mars Example?

- **Did we already find it?**
- **What to search for?**
- **How to search for?**

The PP aspects and future prospects

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How to search for?

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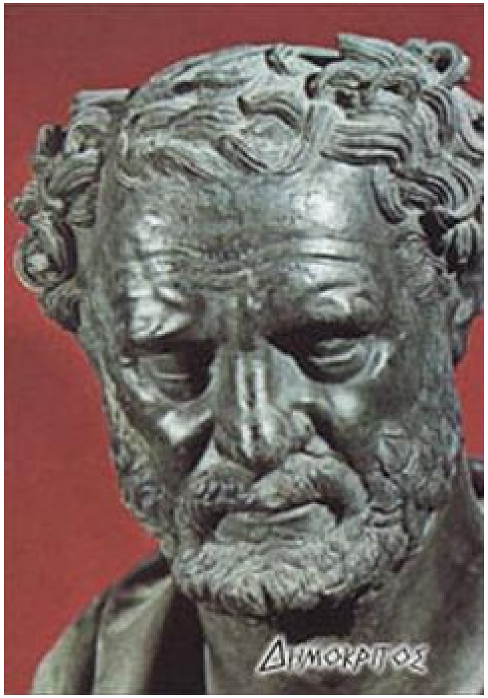
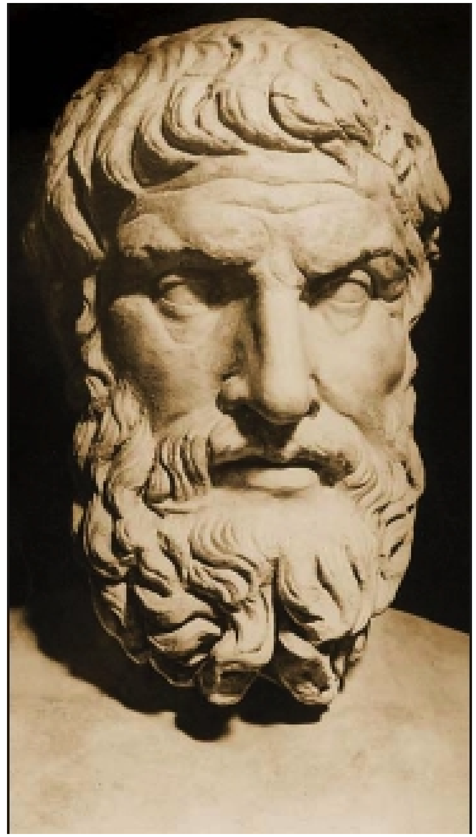
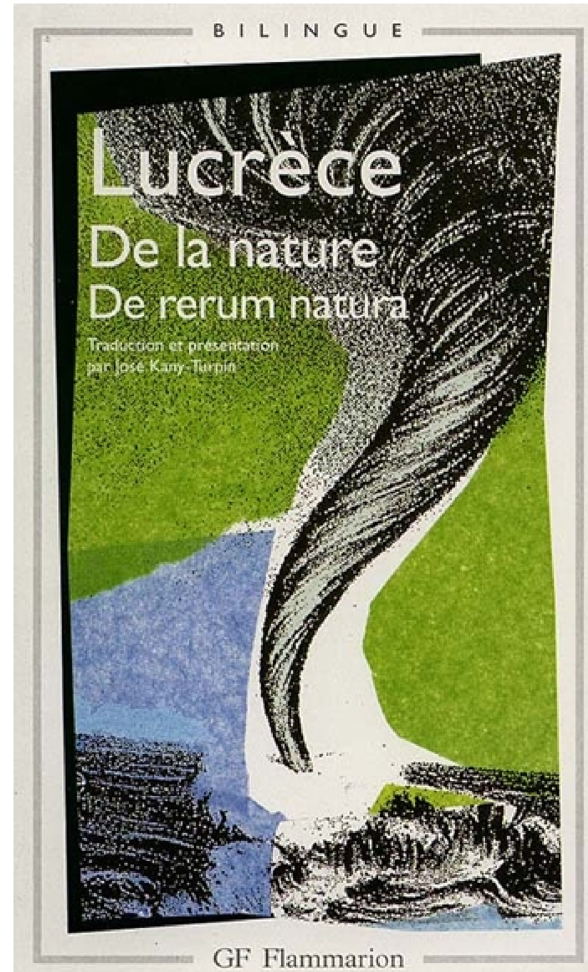


Democrite



Epicure



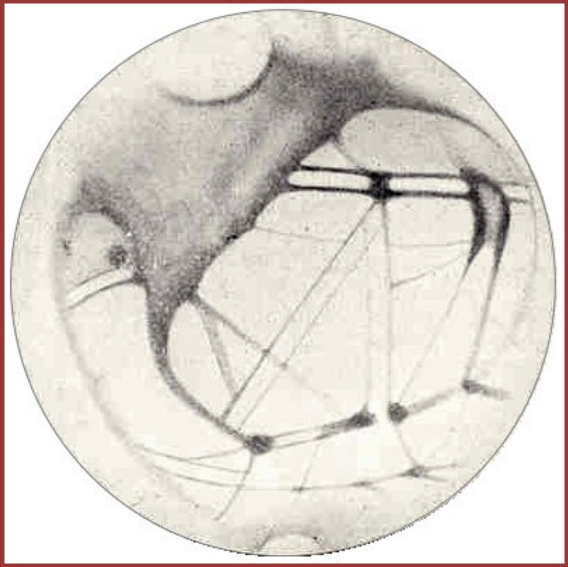
Lucrece

Earth is a planet *among others*

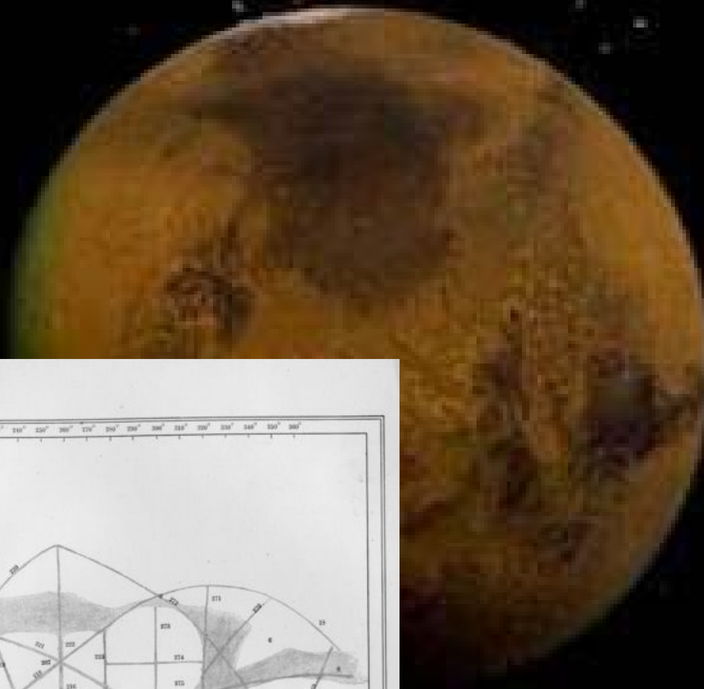
Copernic, Galilee, Kepler

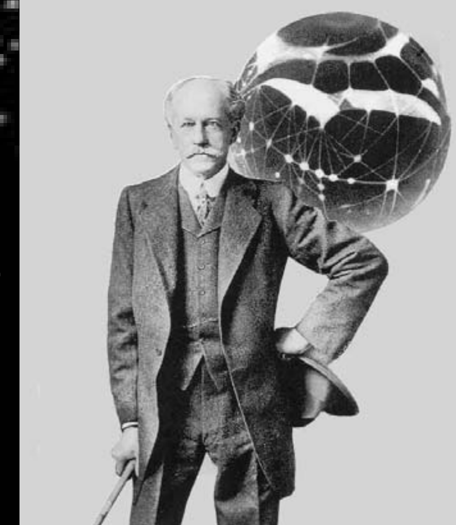
THE MYTH OF MARTIAN CANALS

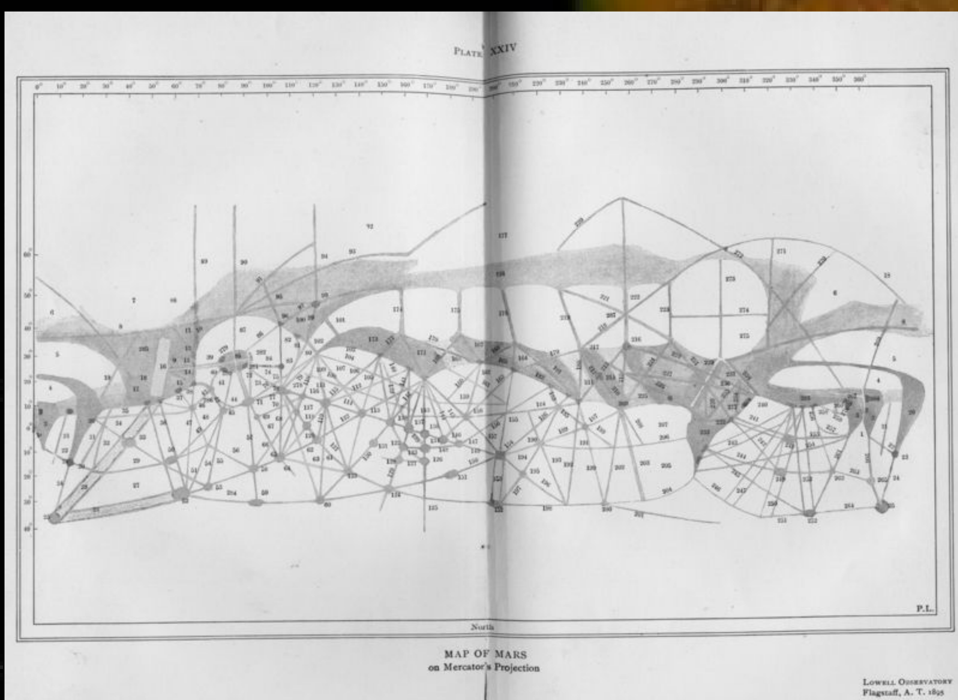
- 1877 : Schiaparelli's observations



MARS SEEN BY PERCIVAL LOWELL

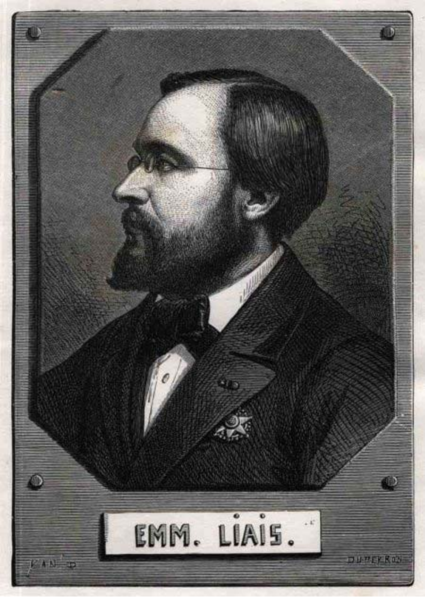


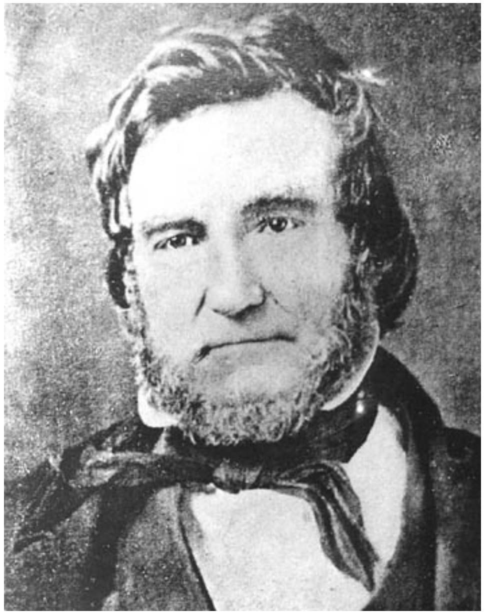


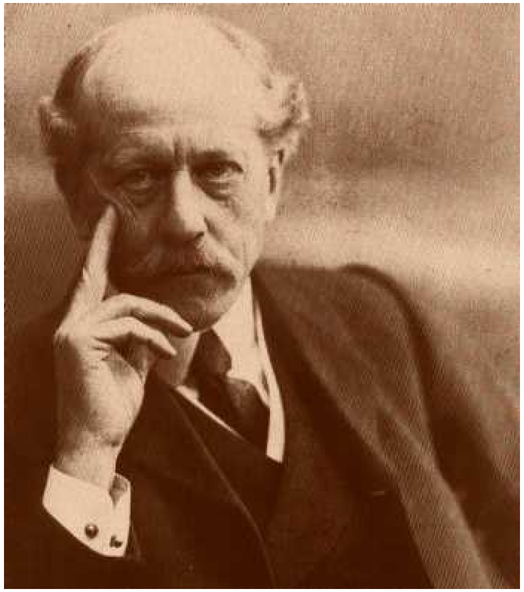


THE HYPOTHESIS OF MARTIAN VEGETATION

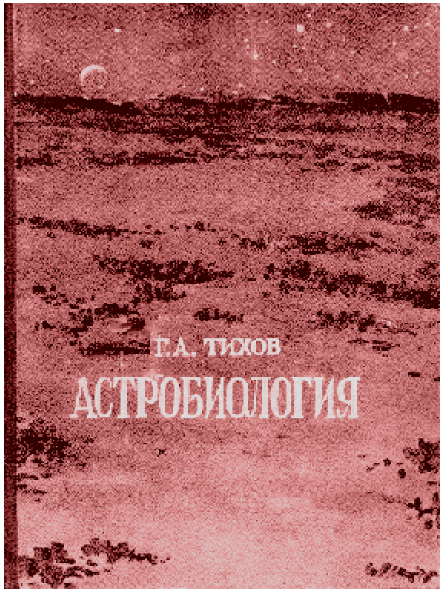
Emmanuel Liais, William Pickering, Percival Lowell, etc…







TIKHOV'ASTROBOTANY



Spectroscopy for detecting
Martian vegetation

Exobiology

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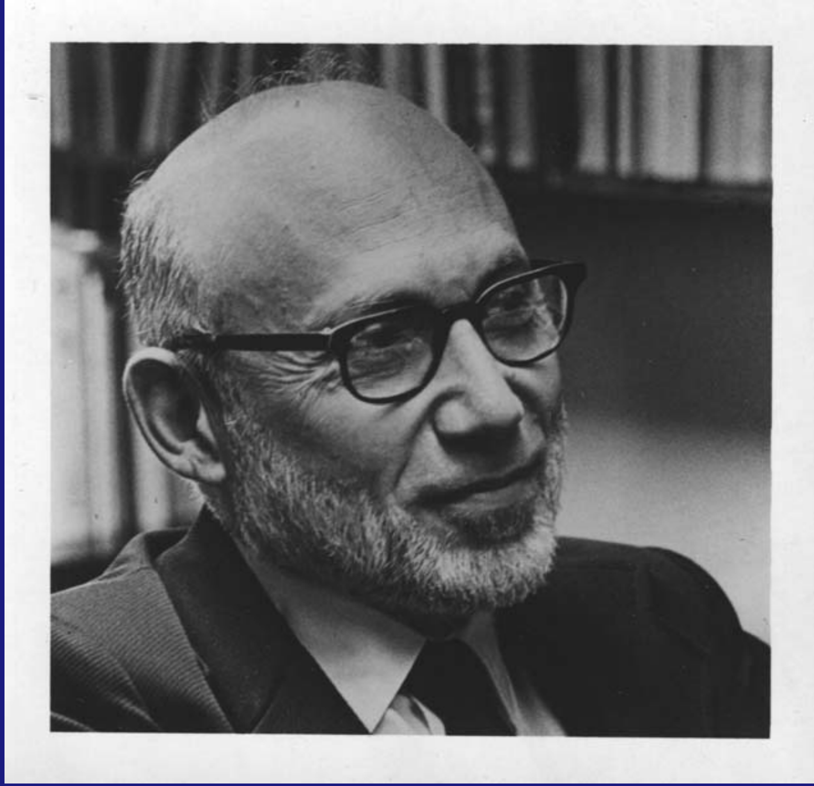
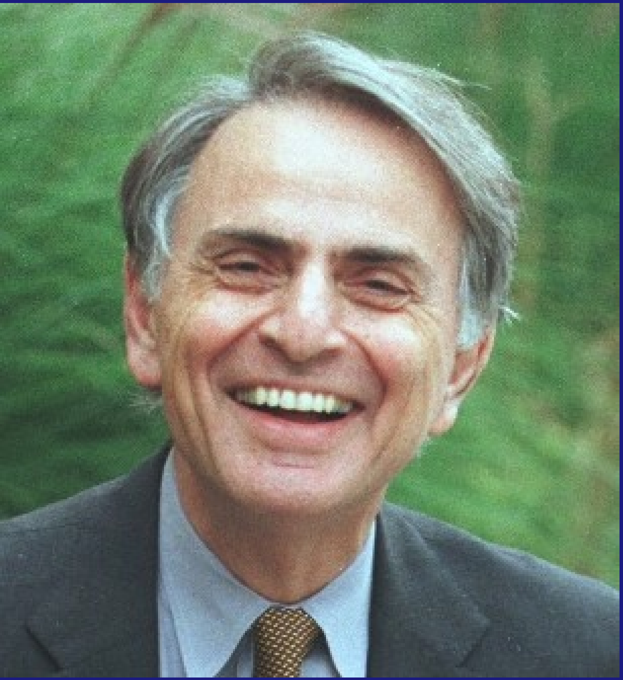
The PP aspects and future prospects

Apollo: systematic scientific approches


HORNET + 3

Josua Lederberg, microbiologist, Nobel laureate in Medicin 1958 : introduce the word « Exobiology »





Carl Sagan, astrophysicist one of the great promoters of Exobiology

Exobiology : Initialy search for and study of extraterrestrial life (life beyond the Earth)

EXOBIOLOGY - Life in the universe

= Astrobiology

= Bioastronomy

= Cosmobiology

Study of life in the universe

its origins
its distribution
its evolution
including its destiny
the associated structures et processus

A highly pluridisciplinary field with many approaches

- SETI (Search for ExtraTerrestrial Intelligence)
- Search for life – past or present – on extraterrestrial objects in the solar system (by remote sensing and in situ techniques)
- Search for signatures of life beyond the solar system (by remote sensing techniques so far …)
- Study of extraterrestrial organic matter
- Study of the origin, properties and evolution of life on Earth

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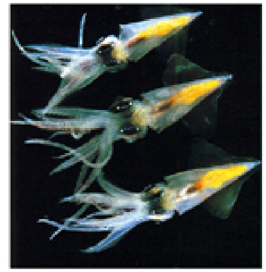
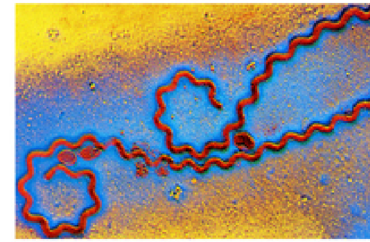
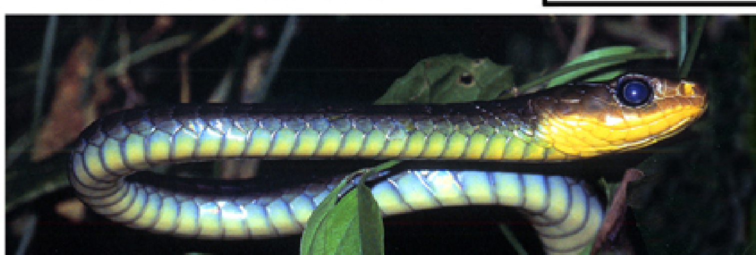
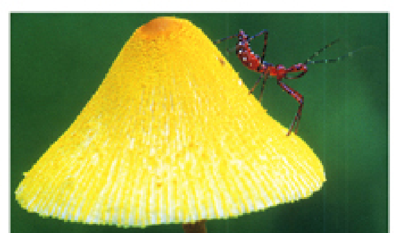
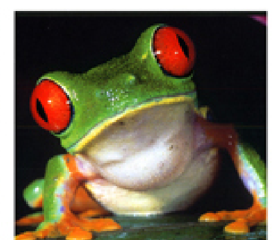
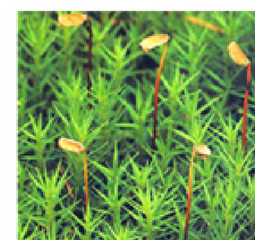
THE DIVERSITY OF LIFE




TOTAL NUMBERS OF KNOWN SPECIES

Bacteria ~ 10,000
Archaea ~ 5000
Fungi ~ 101,000
Plants ~ 260,000
Animals ~ 1,200,000
TOTAL ~ 1.6 million

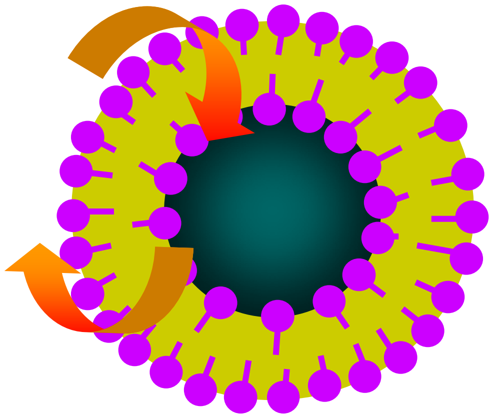






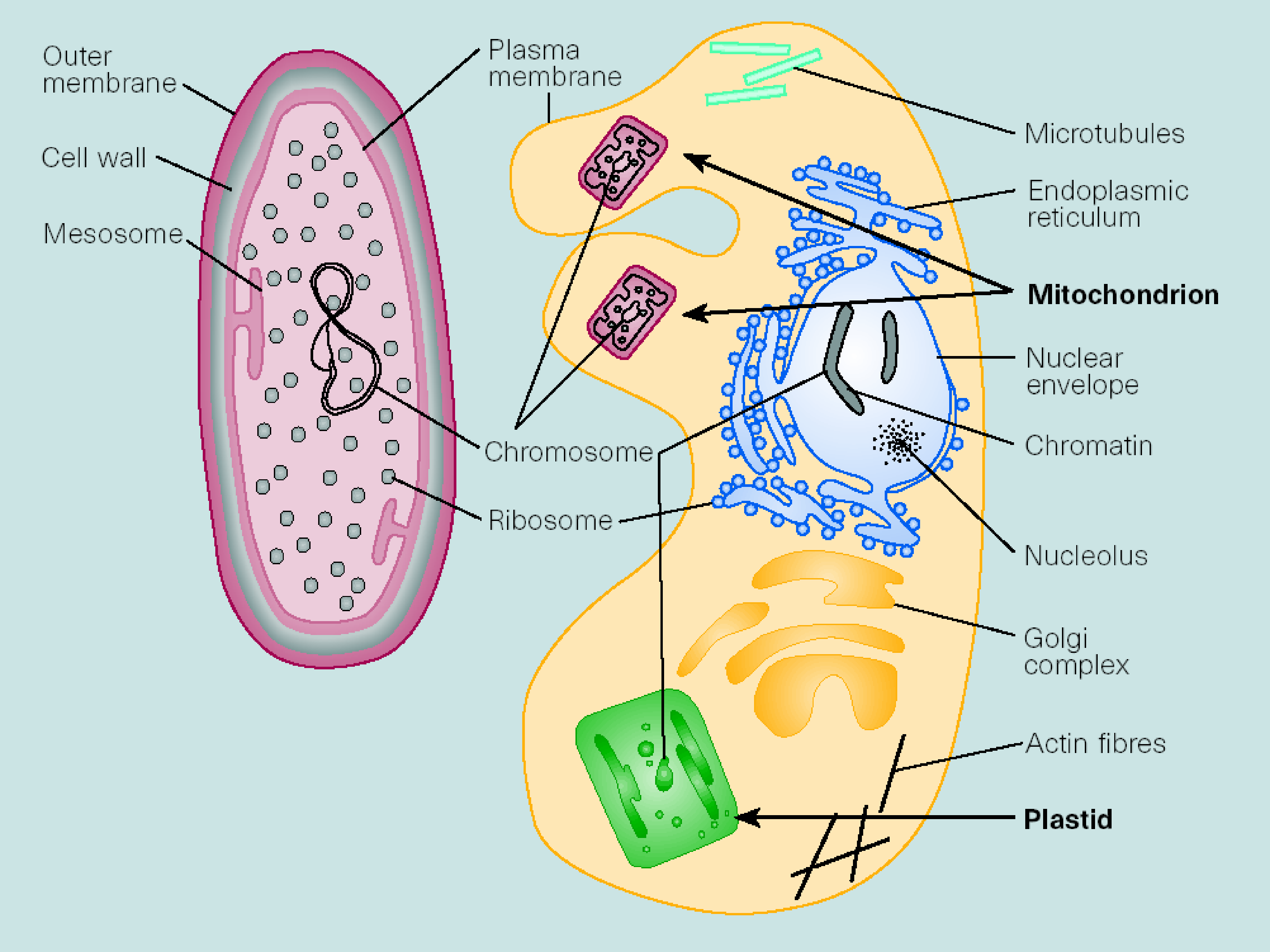
But the unity of Life

➢ Life is a chemical system, self-maintained and capable of Darwinian evolution (NASA)

➢ 2 main caracteristics: auto-replication and evolution

➢ ***Minimal life***: a system delimited by a semi-permeable membrane formed by the system itself, able of self-maintenance and producing its own constituting elements by transformation of exogeneous nutriments and energy through its own processes of production (P. L. Luisi)

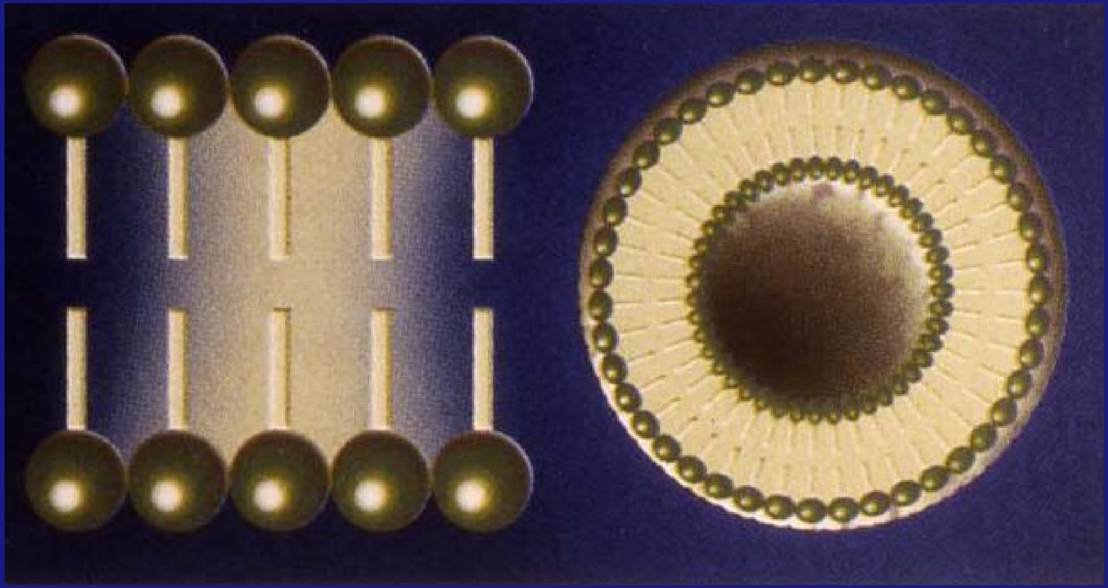


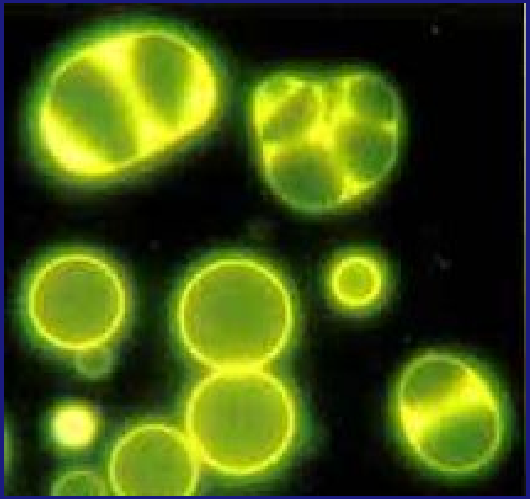

Outer membrane
Cell wall
Mesosome
Plasma membrane
Chromosome
Ribosome
Microtubules
Endoplasmic reticulum
Mitochondrion
Nuclear envelope
Chromatin
Nucleolus
Golgi complex
Actin fibres
Plastid

A membrane

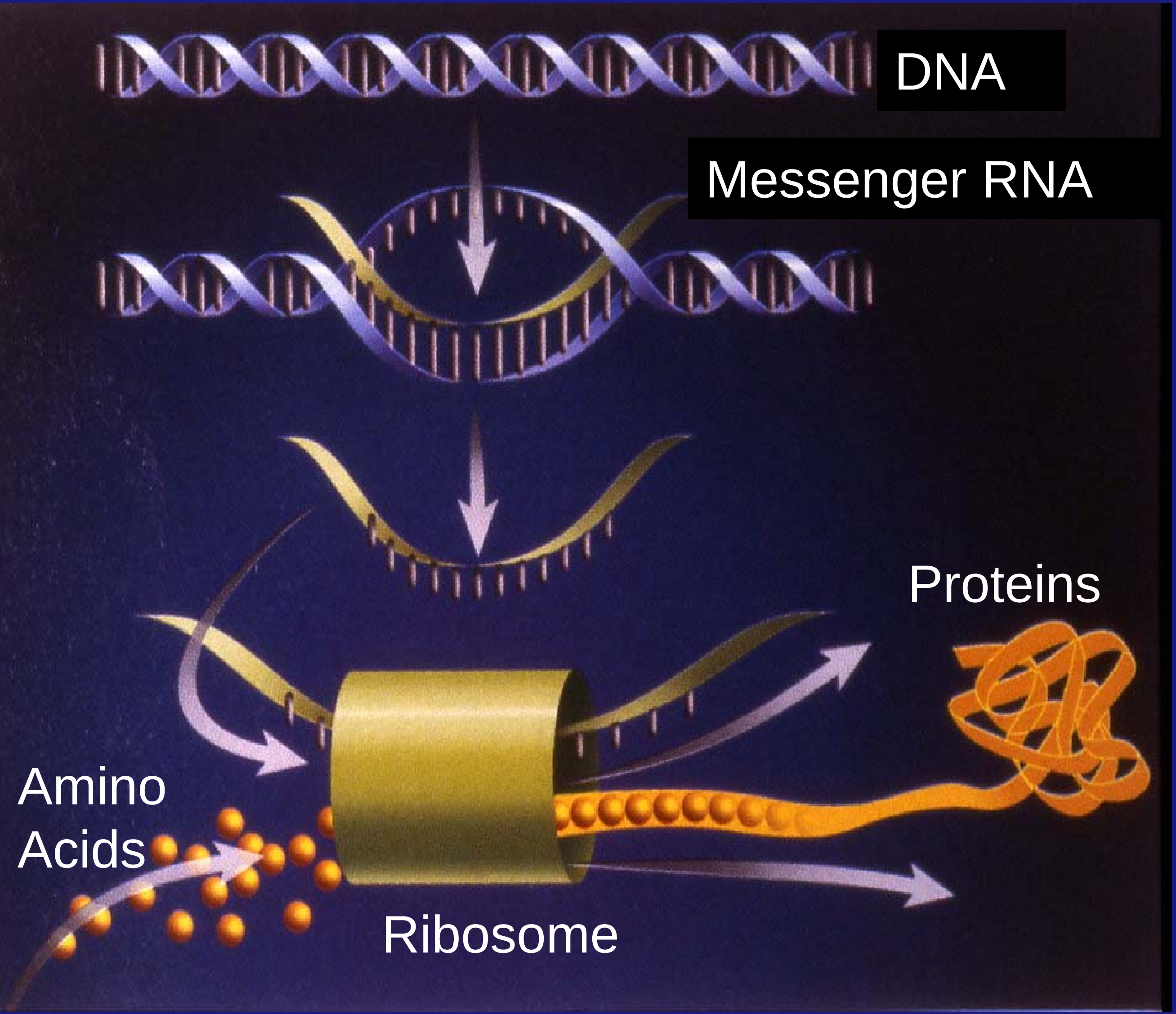
- Long organic chain molecules - *amphiphiles* thanks to a polar head with an apolar tail insoluble in water

- Structures capable of forming vesicules.





The cell factory: DNA/RNA and proteins

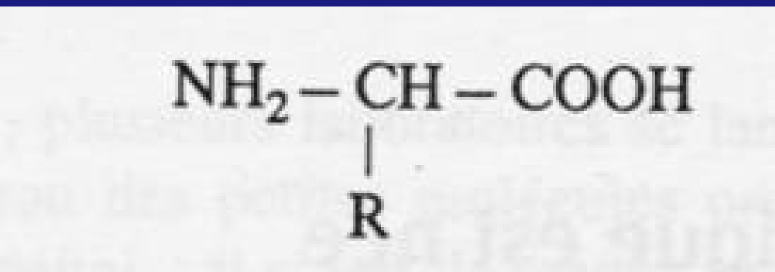


DNA: complex macromolecule => information carrier + replication and evolution capability

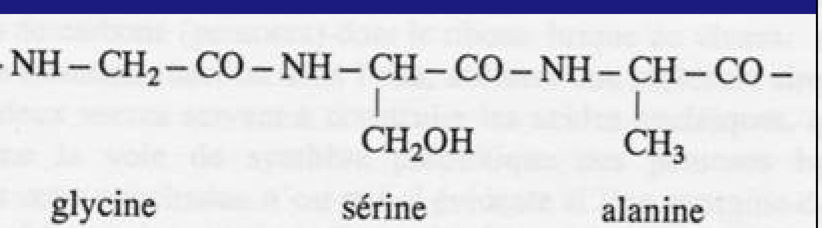
Proteins: complex macromolecule => structural role + catalyst

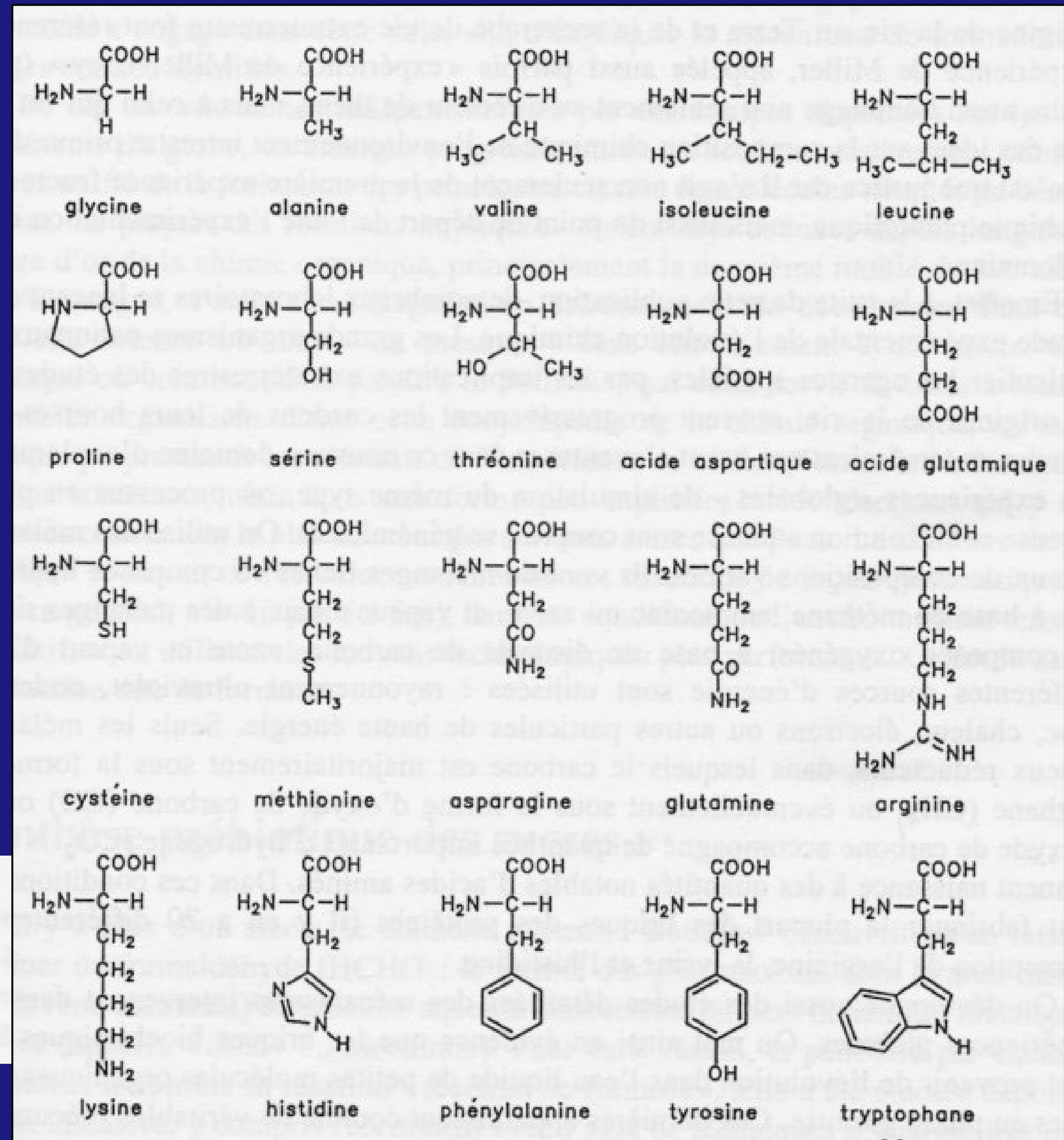
Ribosomes made of proteins and RNA

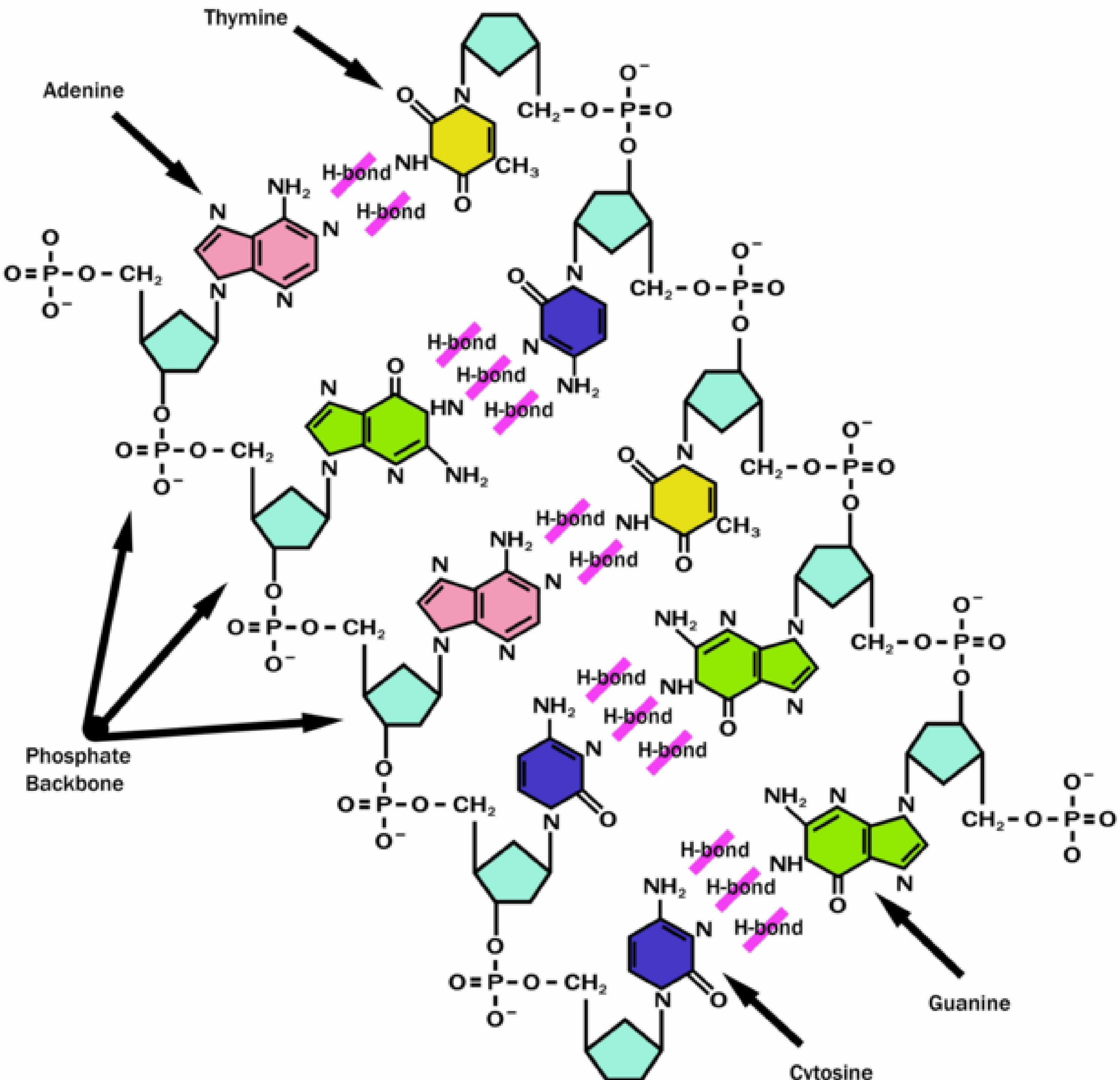
Building blocks of proteins : amino acids



Only 20 different α–amino acids



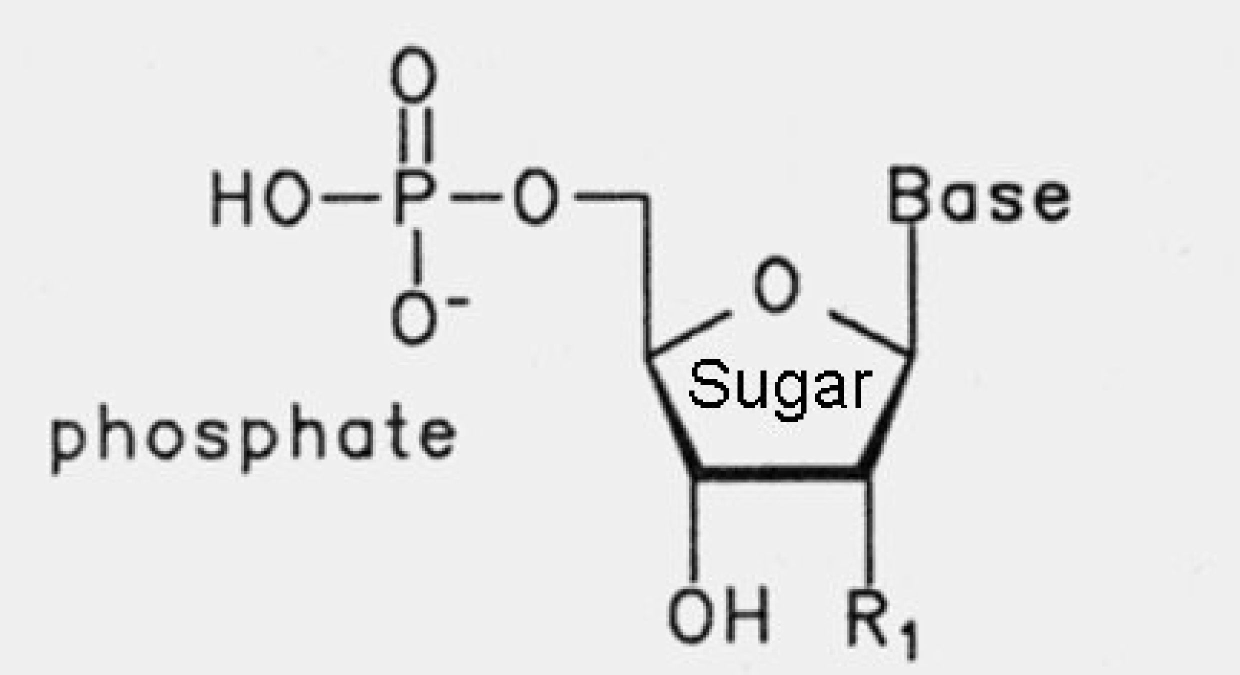




Thymine
Adenine
Phosphate
Backbone
Guanine
Cytosine
H-bond

In DNA or RNA only 4 different « bases »

=> A vocabulary with only 4 « letters »

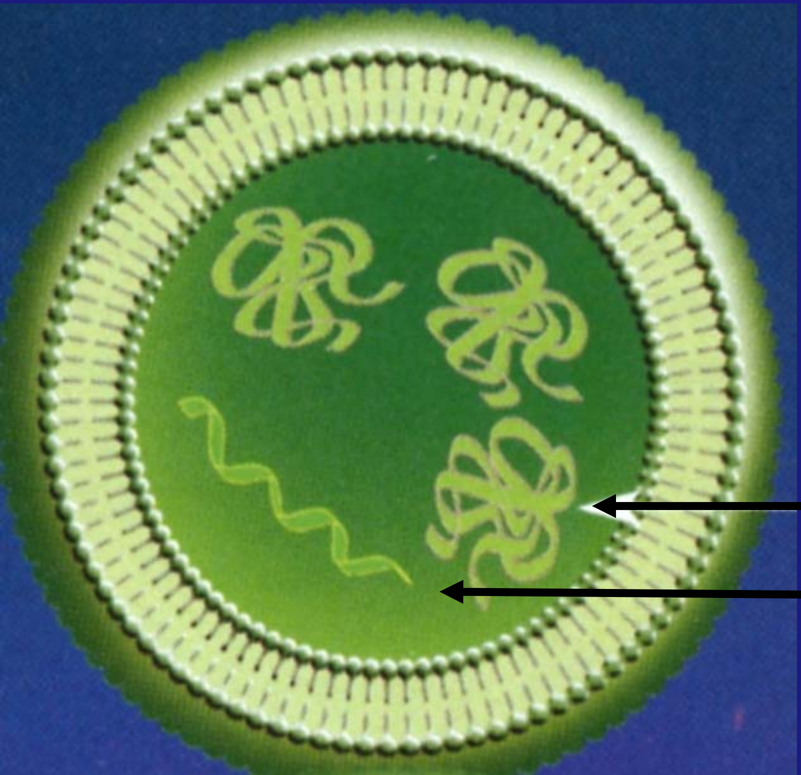


This « letter » in the « word » DNA or RNA is named « Nucleotide »

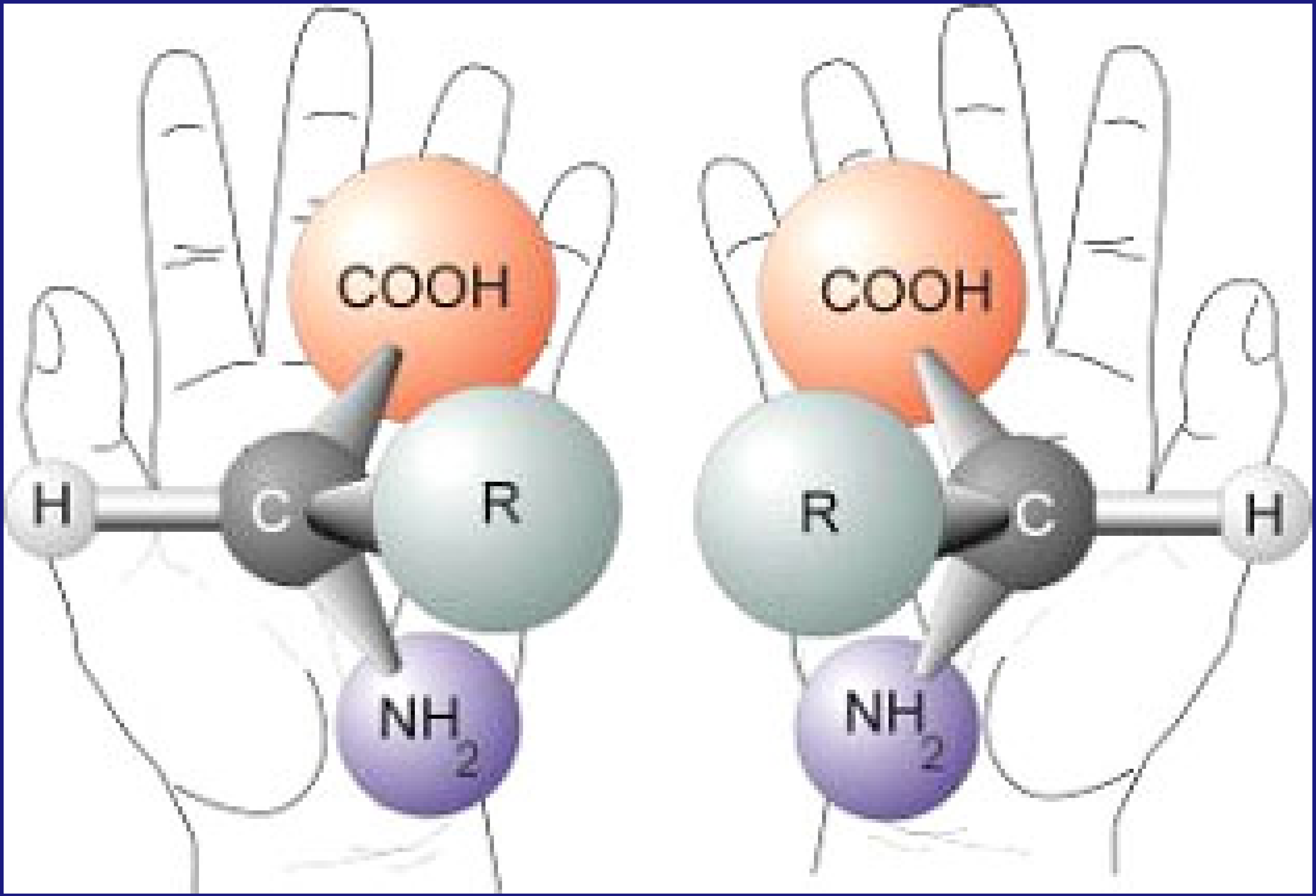
R_1 = H : desoxyribose (DNA)
R_1 = OH : ribose (RNA)

An RNA world without protein and a simplified cell machinery ?

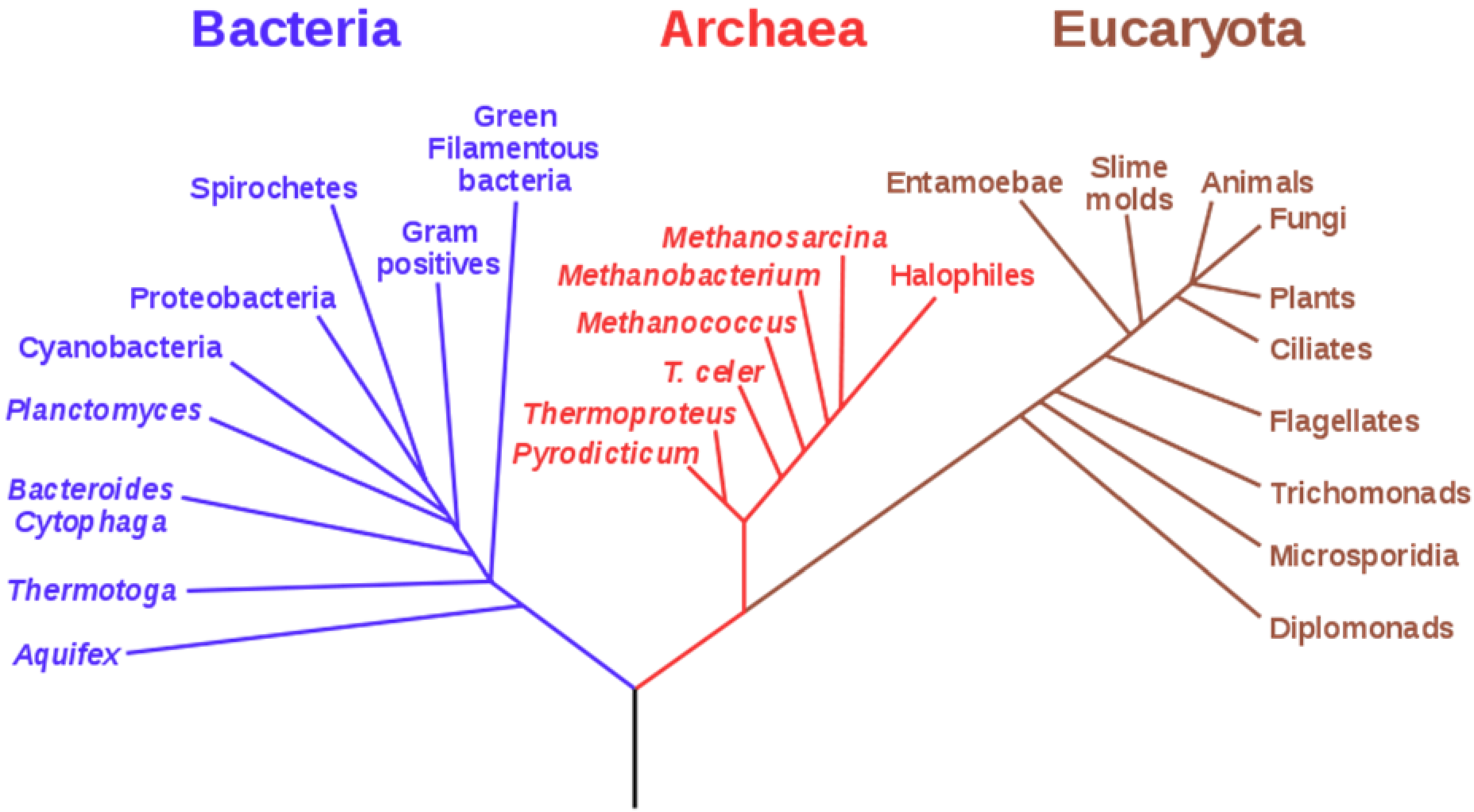
A few decades ago, catalytic properties of RNA have been discovere = > RNA could be its own catalyst of its replication



Chirality: property of many biological molecules



Phylogenetic Tree of Life



LUCA: Last Universal Common Ancestor

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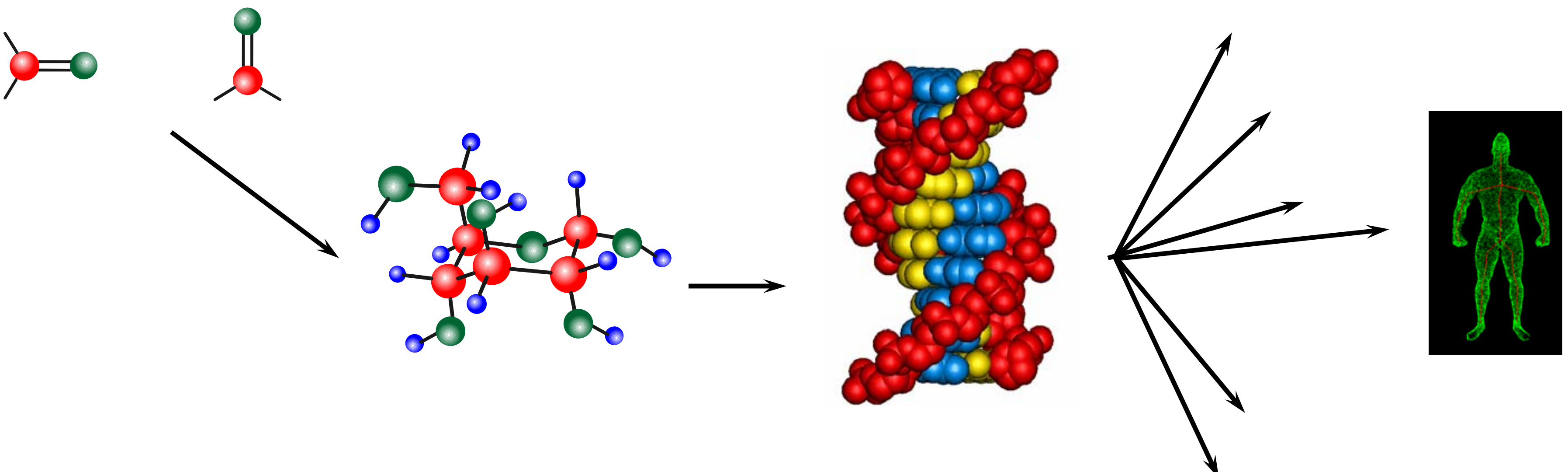
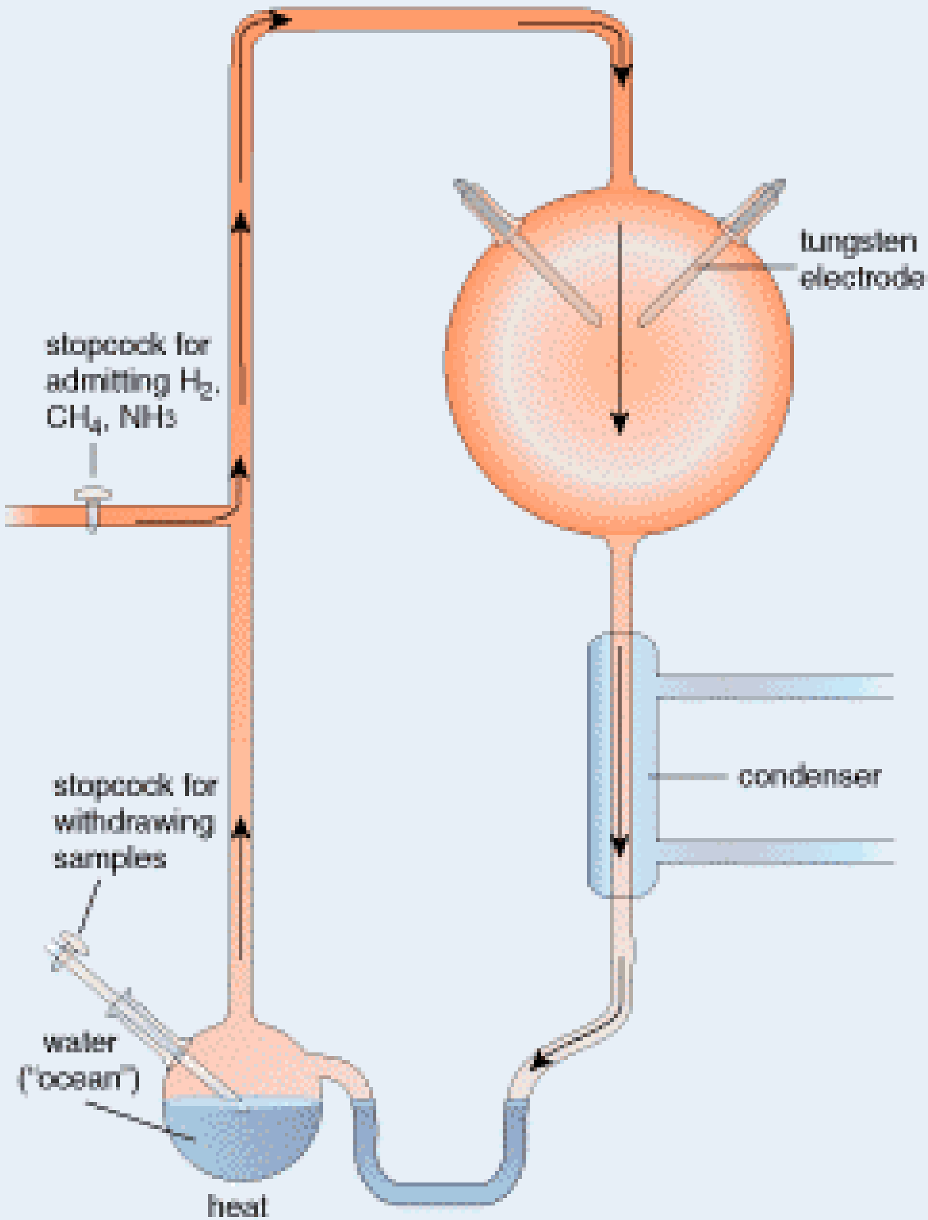
Until mid-19th : Spontaneous generation

End 19th – early 20th : Panspermia

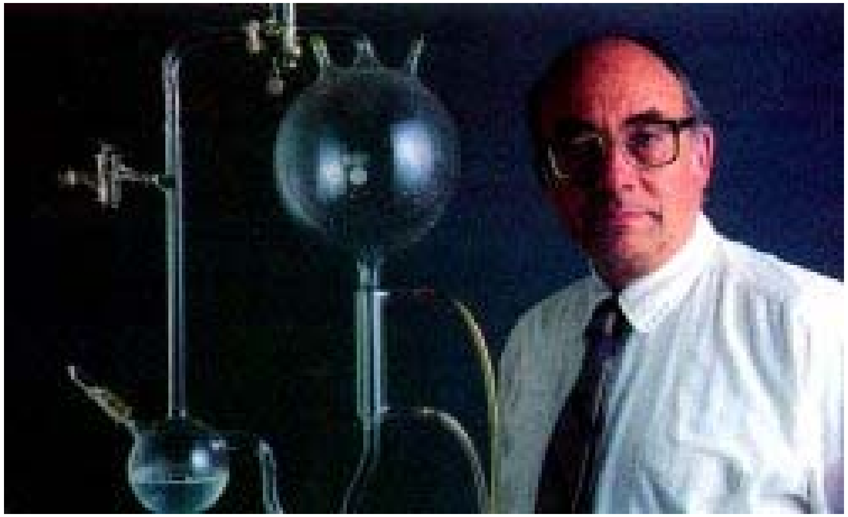
Since 1924+: Chemical evolution (Oparin 1924; Haldane 1929) A long spontaneous (thermodynamically speaking) evolution of organics from simple molecules to complex organics including macromolecules capable of self-replication, preceding the biological evolution

Organic matter + Liquid water + Energy





The Miller/Urey experiment



Production of a large range of organic compounds including amino acids (racemic mixture)

SL Miller Science 117,528 (1953)

Prebiotic chemistry of HCN

HCN + CN- →(+H+) H-C(=NH)-CN →(+HCN) NC-CH(NH2)-CN

Dimer: H-C(=NH)-CN

Trimer: NC-CH(NH2)-CN

↓ +HCN

NC-C(NH2)=C(NH2)-CN

Tetramer DiAminoMaleoNitrile (DAMN)

A Devil molecule ..

↓ +n HCN

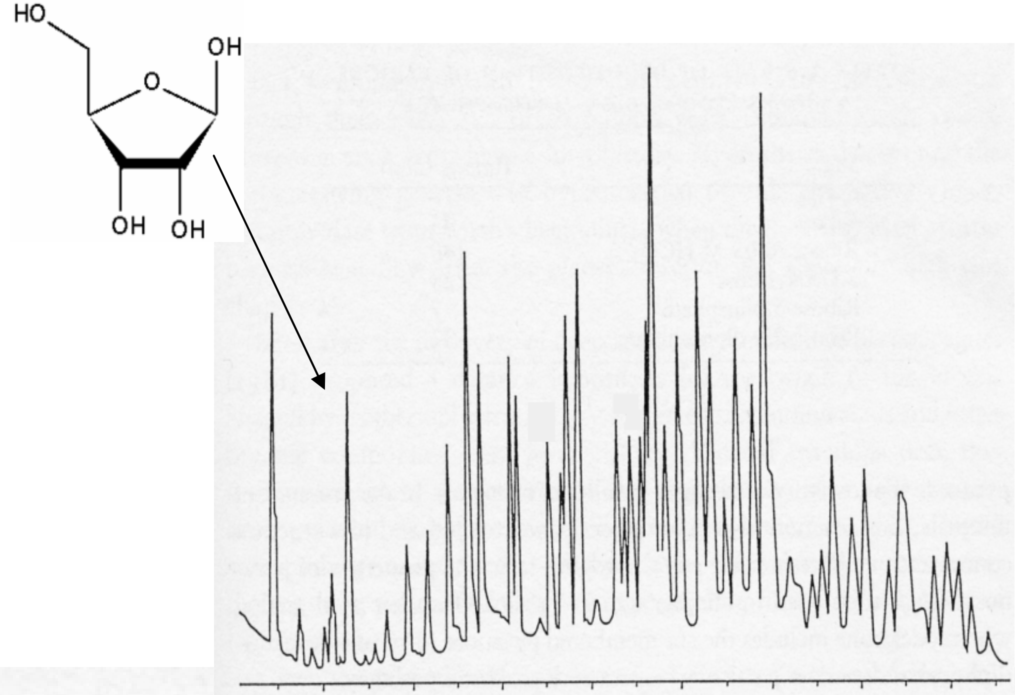
oligomers

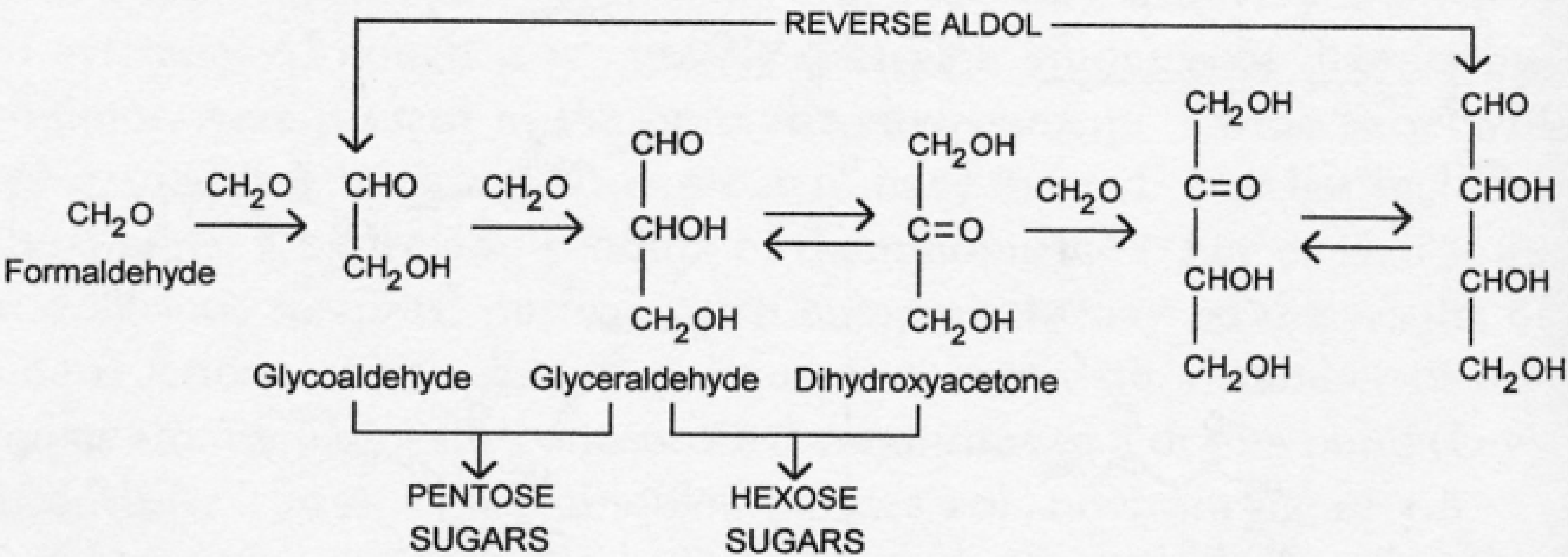
↓ +H2O

amino acids

purines & pyrimidines

Formose reaction :
Formaldehyde solution
+ catalyst such as
$Ca(OH)_2$, $CaCO_3$,
or clay minerals

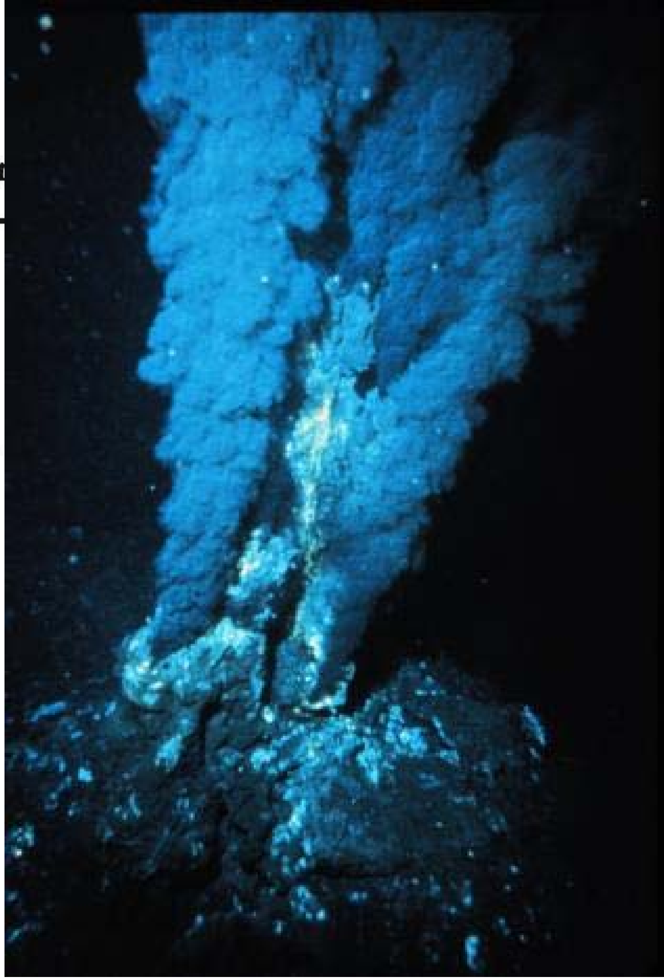




Orig Life Evol Biosph (2008) 38:383–397
DOI 10.1007/s11084-008-9137-2

Oper

PREBIOTIC CHEMISTRY

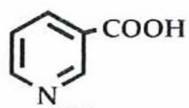
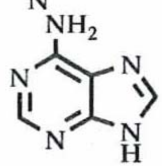
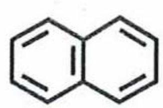
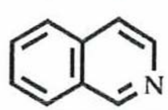


Thermodynamic Potential for the Abiotic Synthesis of Adenine, Cytosine, Guanine, Thymine, Uracil, Ribose, and Deoxyribose in Hydrothermal Systems

Douglas E. LaRowe · Pierre Regnier

Received: 6 March 2008 / Accepted: 16 April 2008 /
Published online: 24 June 2008

Abstract The thermodynamic potential for the abiotic synthesis of the five common nucleobases (adenine, cytosine, guanine, thymine, and uracil) and two monosaccharides (ribose and deoxyribose) from formaldehyde and hydrogen cyanide has been quantified under temperature, pressure, and bulk composition conditions that are representative of hydrothermal systems. The activities of the precursor molecules (formaldehyde and hydrogen cyanide) required to evaluate the thermodynamics of biomolecule synthesis were computed using the concentrations of aqueous N_2, CO, CO_2 and H_2 reported in the modern Rainbow hydrothermal system. The concentrations of precursor molecules that can be synthesized are strongly dependent on temperature with larger concentrations prevailing at lower temperatures. Similarly, the thermodynamic drive to synthesize nucleobases, ribose and deoxyribose varies considerably as a function of temperature; all of the biomolecules

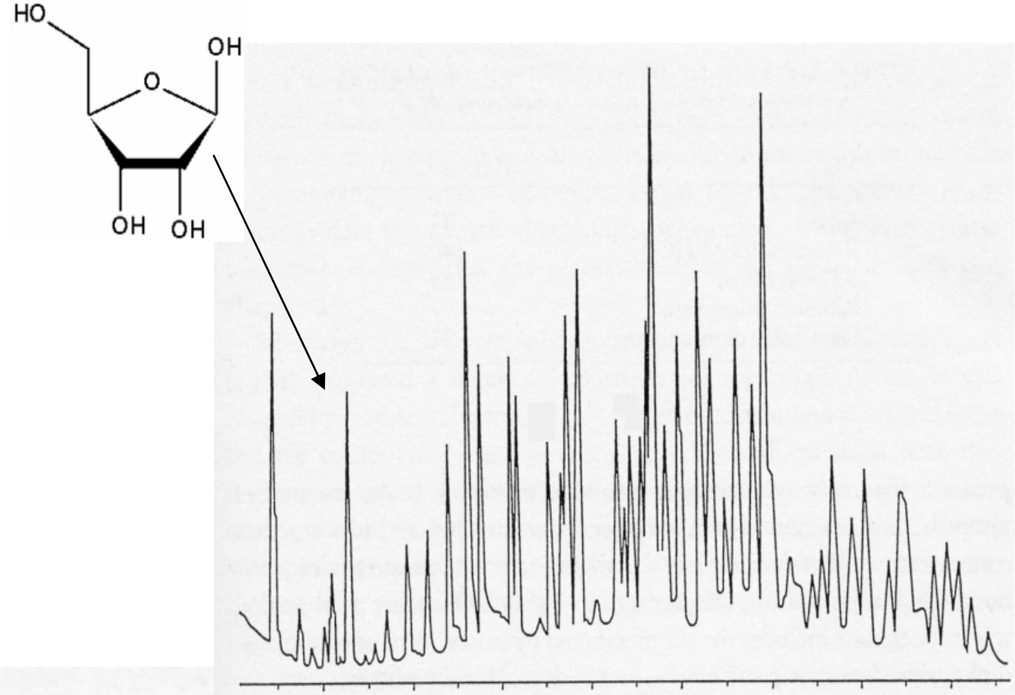
Compound	Typical Molecule and Structure Typical Molecule	
Carboxylic acids	$H_3C-COOH$	Acetic acid
Amino acids	$H_3C-CH(NH_2)-COOH$	Alanine
Hydroxy acids	$H_3C-CH(OH)-COOH$	Lactic acid
Ketoacids	$H_3C-C(=O)-COOH$	Pyruvic acid
Dicarboxylic acids	$OOC-(CH_2)_2-COOH$	Succinic acid
Sugar alcohols and acids	$H_2C(OH)-CH(OH)-COOH$	Glyceric acid
Alcohols, aldehydes and ketones	H_3C-CH_2OH	Ethanol
Amines and amides	$H_3C-CH_2NH_2$	Ethyl amine
Pyridine carboxylic acids		Nicotinic acid
Purines and pyrimidines		Adenine
Hydrocarbons:		
Alyphatic	$H_3C-CH_2-CH_3$	Propane
Aromatic		Naphthalene
Polar		Isoquinoline

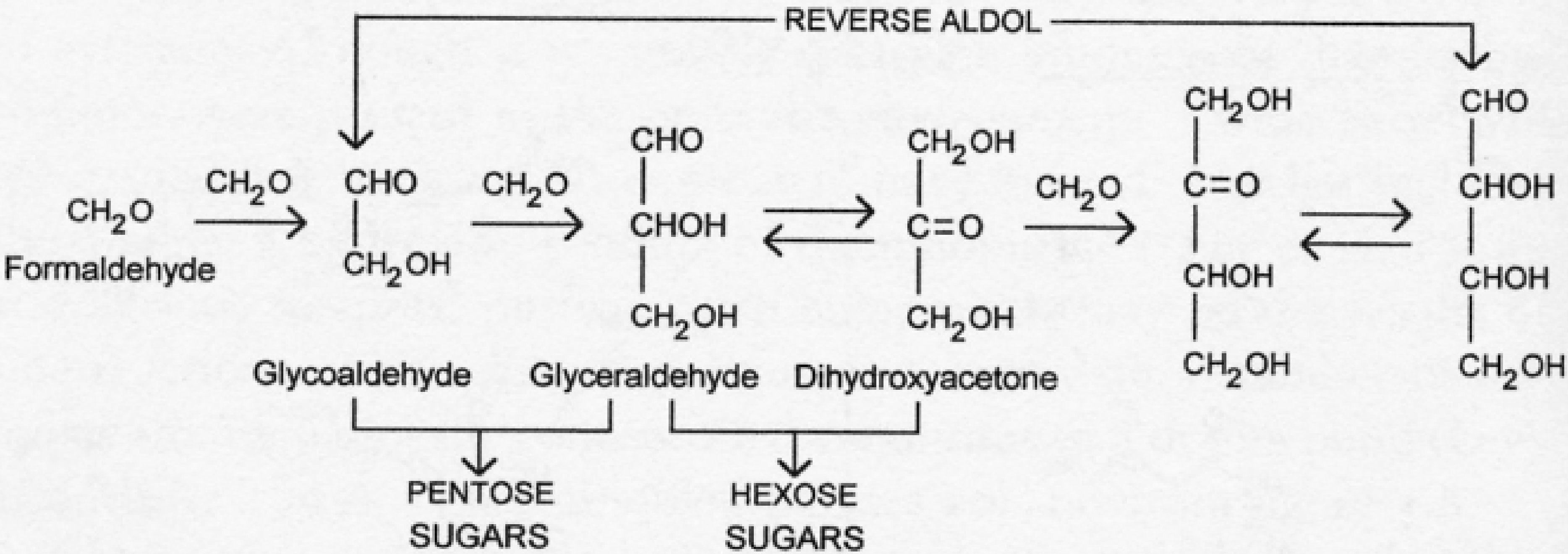
Organic matter in carbonaceous chondrites

soluble compounds

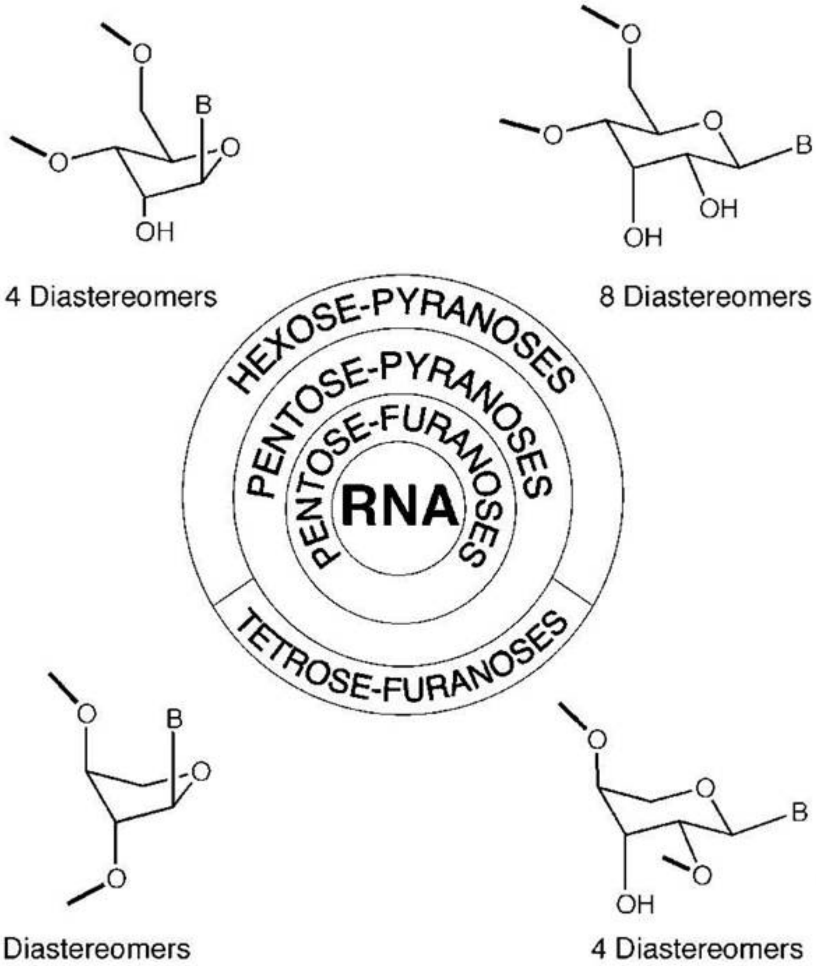
An example : Murchison

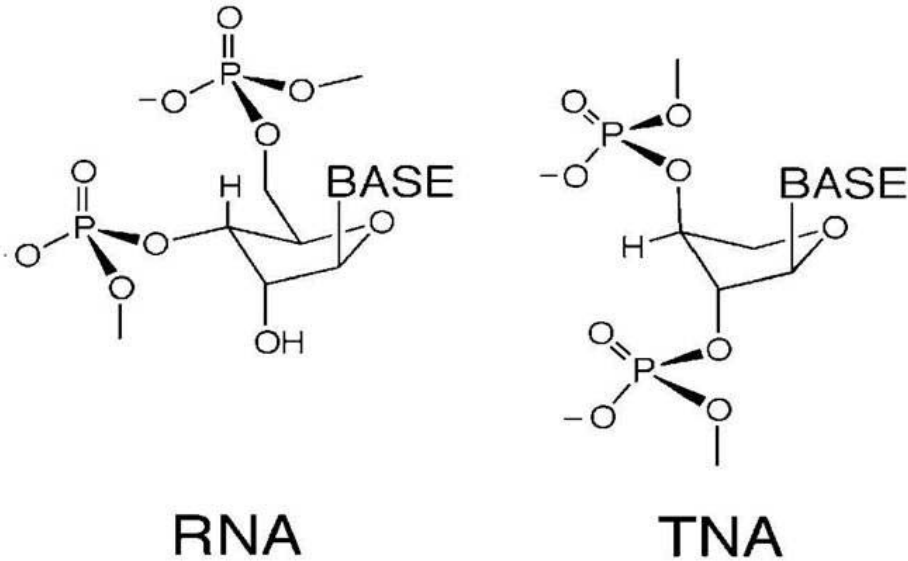
Formose reaction :
Formaldehyde solution
+ catalyst such as
$Ca(OH)_2$, $CaCO_3$,
or clay minerals





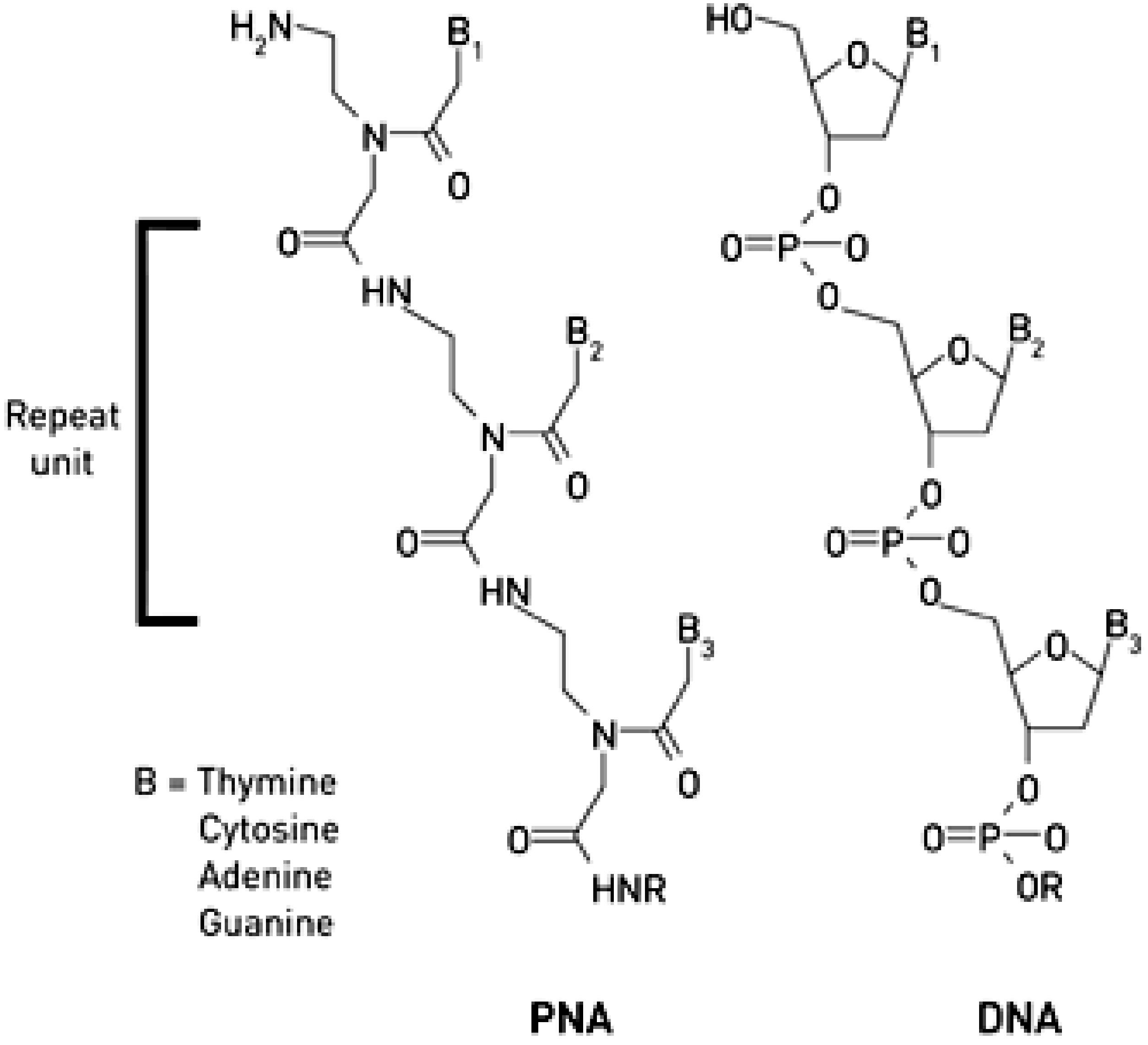
A TNA world?





The TNA-Family of nucleic acid systems: properties and prospects - A Eschenmoser, OLEB 34, 277-306 (2004)

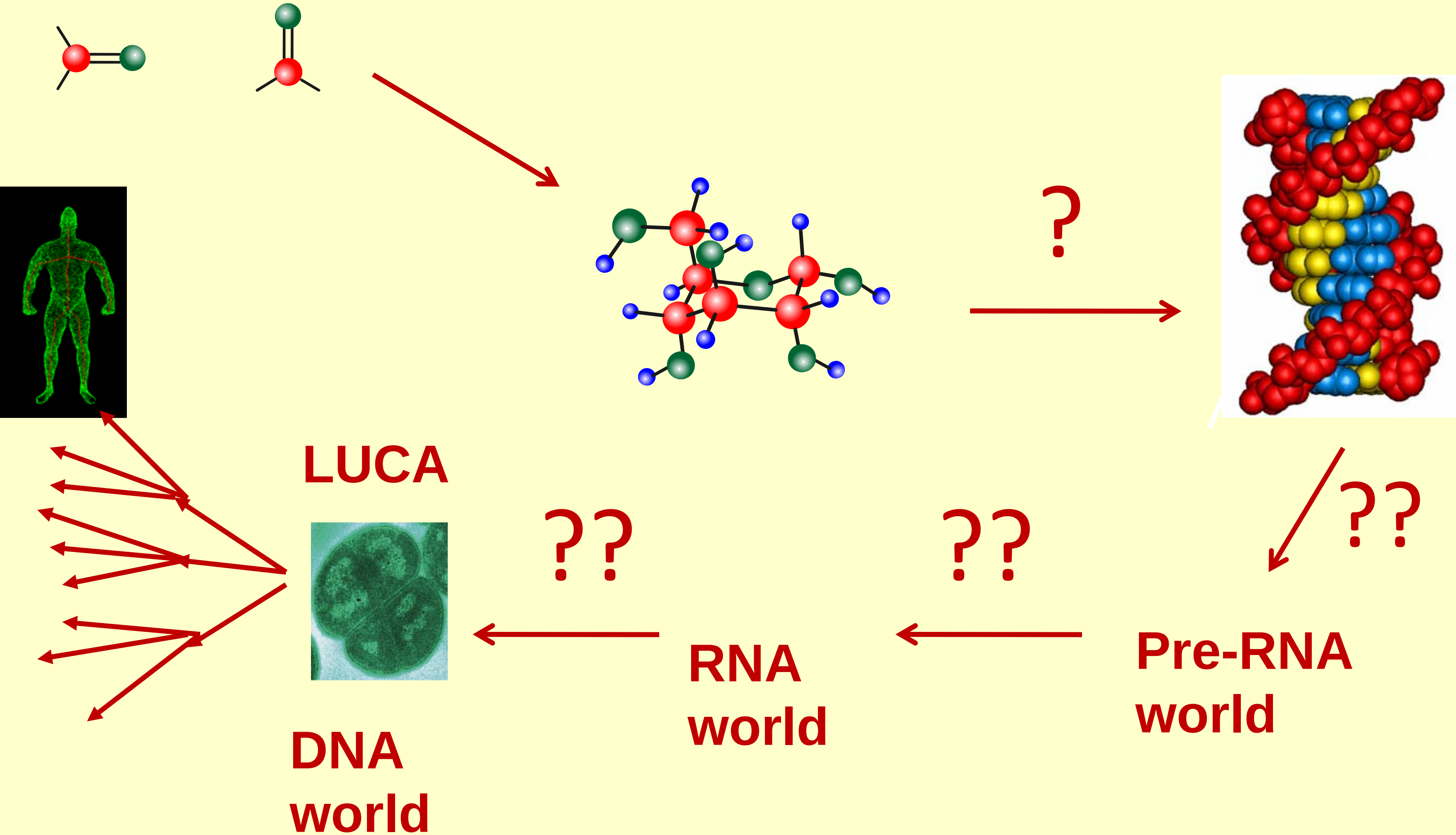
A PNA world?

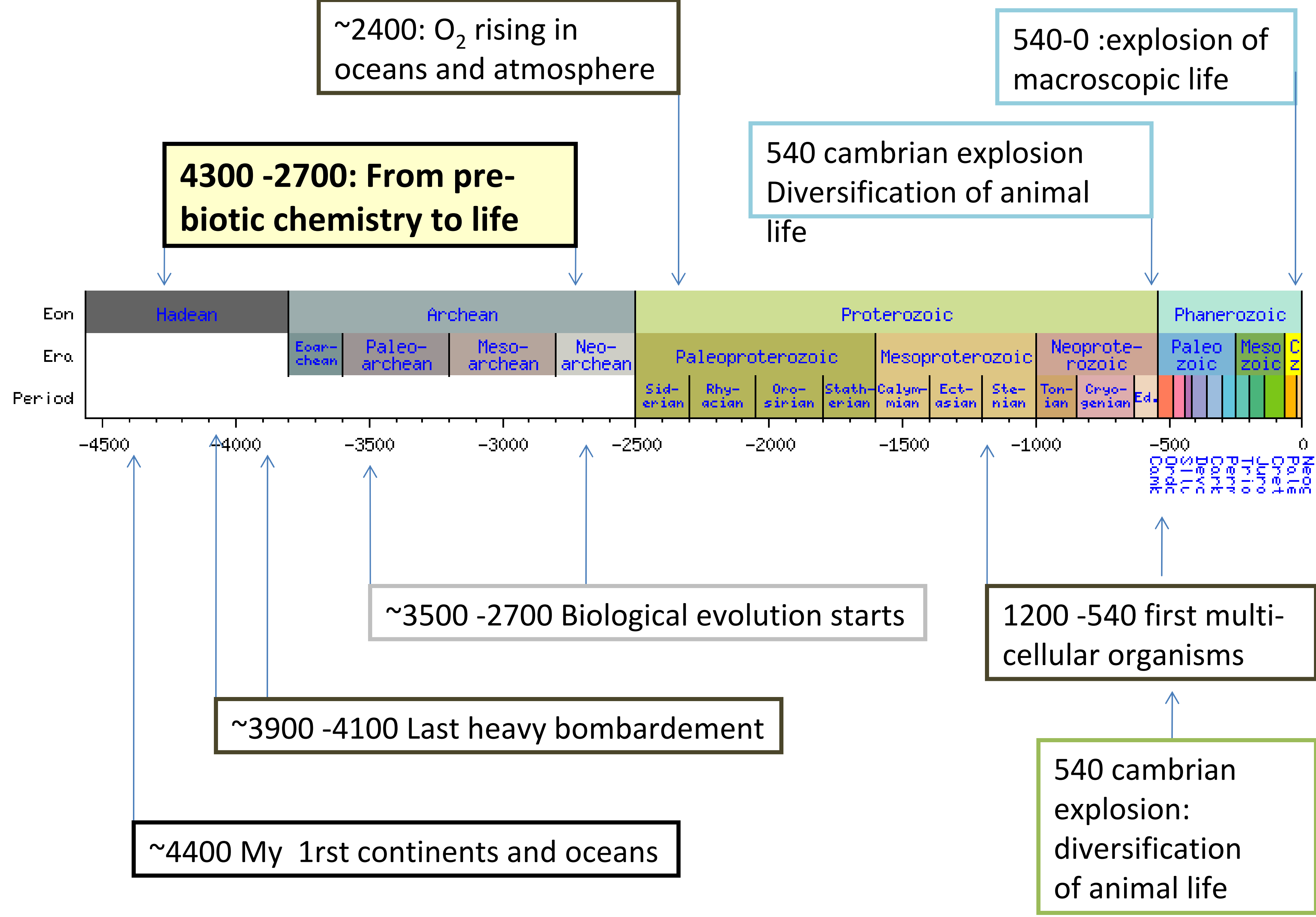


A DNA/RNA analog in which the backbone is a pseudopeptide rather than a sugar

DNA/RNA chimera first invented by PE Nielsen et al., Science 254, 1497 (1991)

Carbonaceous matter + liquid water + Energy





Adapted from « Le soleil la Terre … la vie », M. Gargaud et al. (2009)

Extremophiles and limits for terrestrial life

Temperature: -20ºC … +121ºC

pH: 0 … ~12

Salinity: ? … 5,5 M (NaCl)

Pressure: ? … ~100 MPa

~1 GPa ??

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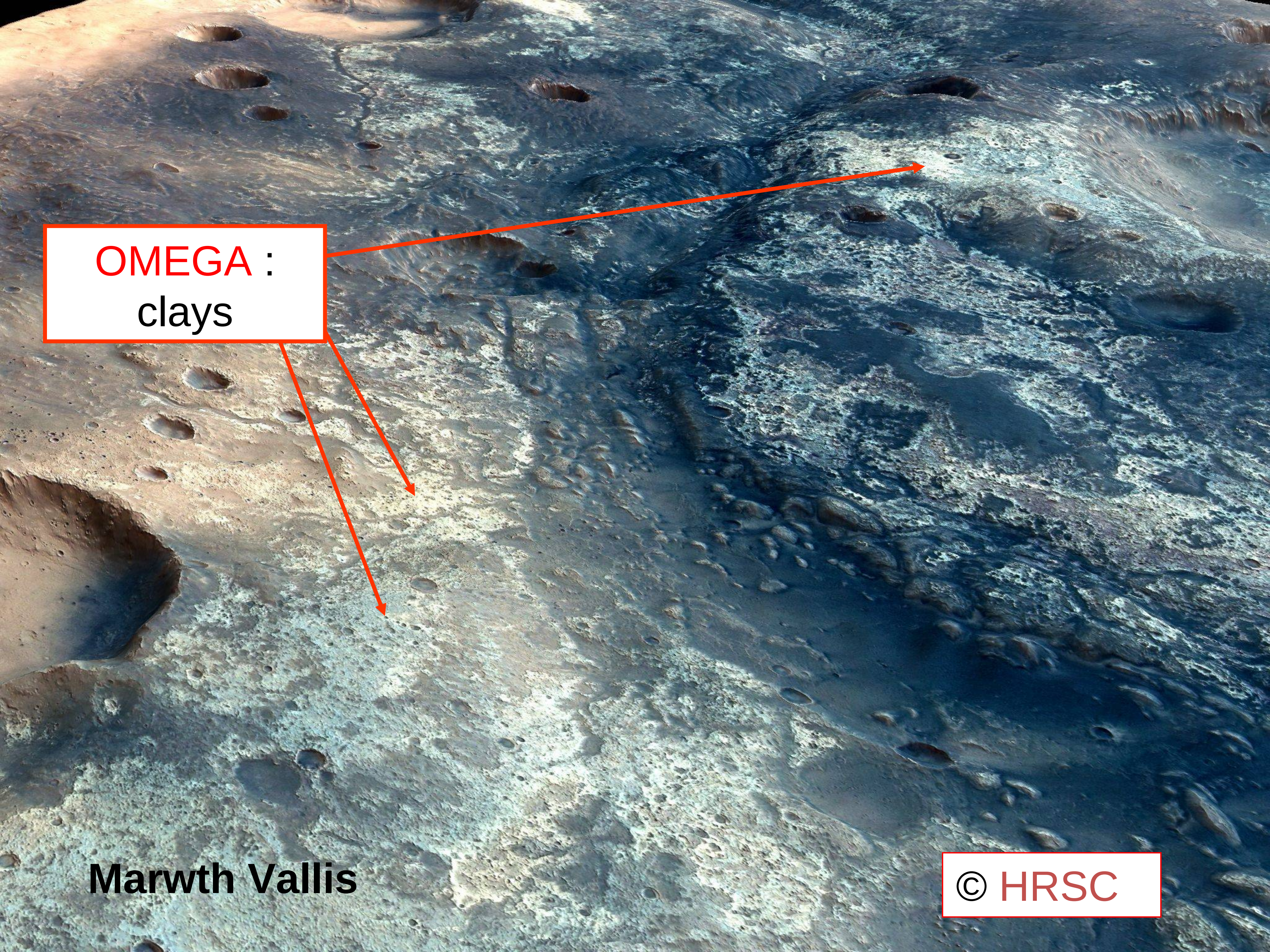
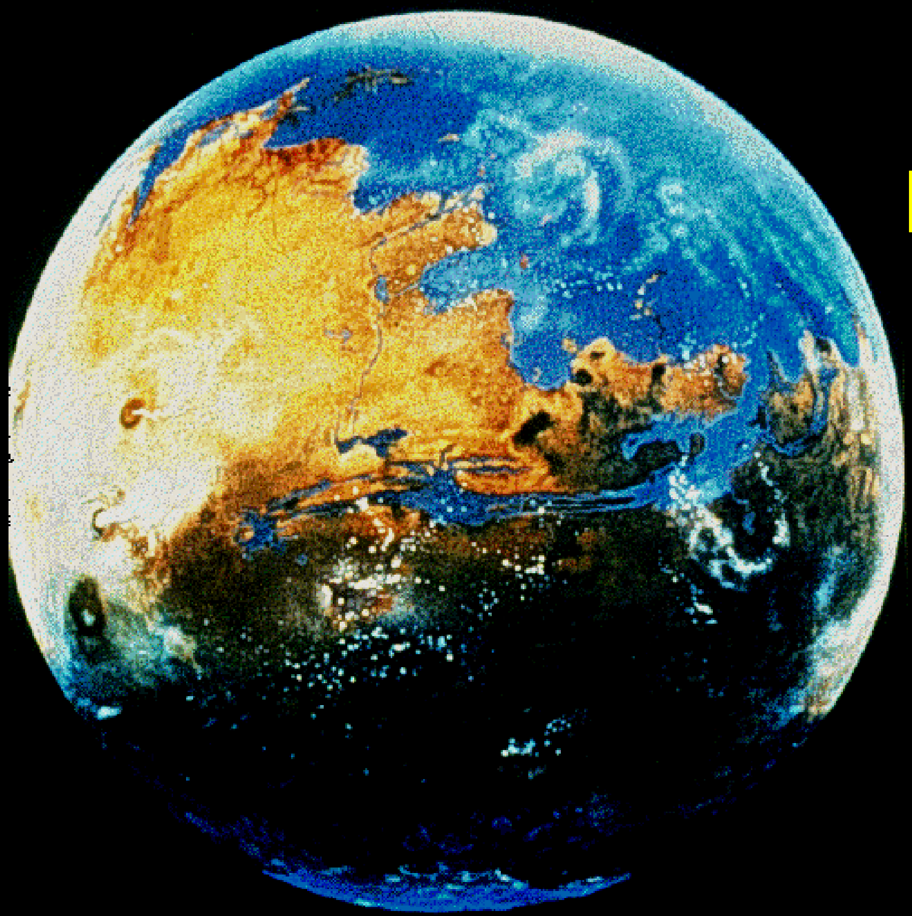
The PP aspects and future prospects


ENERGY BAR/BARRE D'ÉNERGIE
Mars
®/MD
Nutrition Facts
58 g


OMEGA :
clays
Marwth Vallis
© HRSC

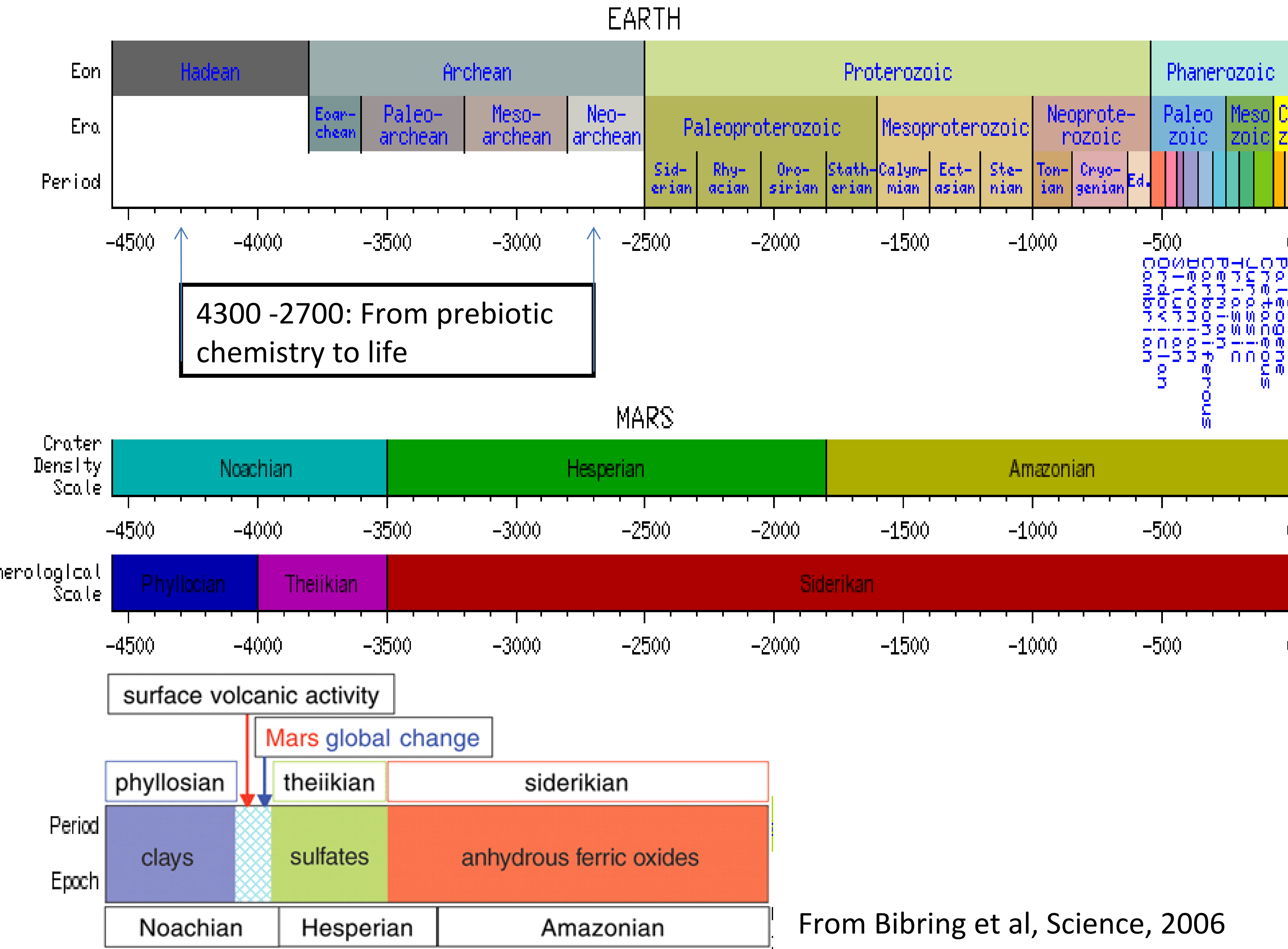
☑ Liquid water

☑ Organics



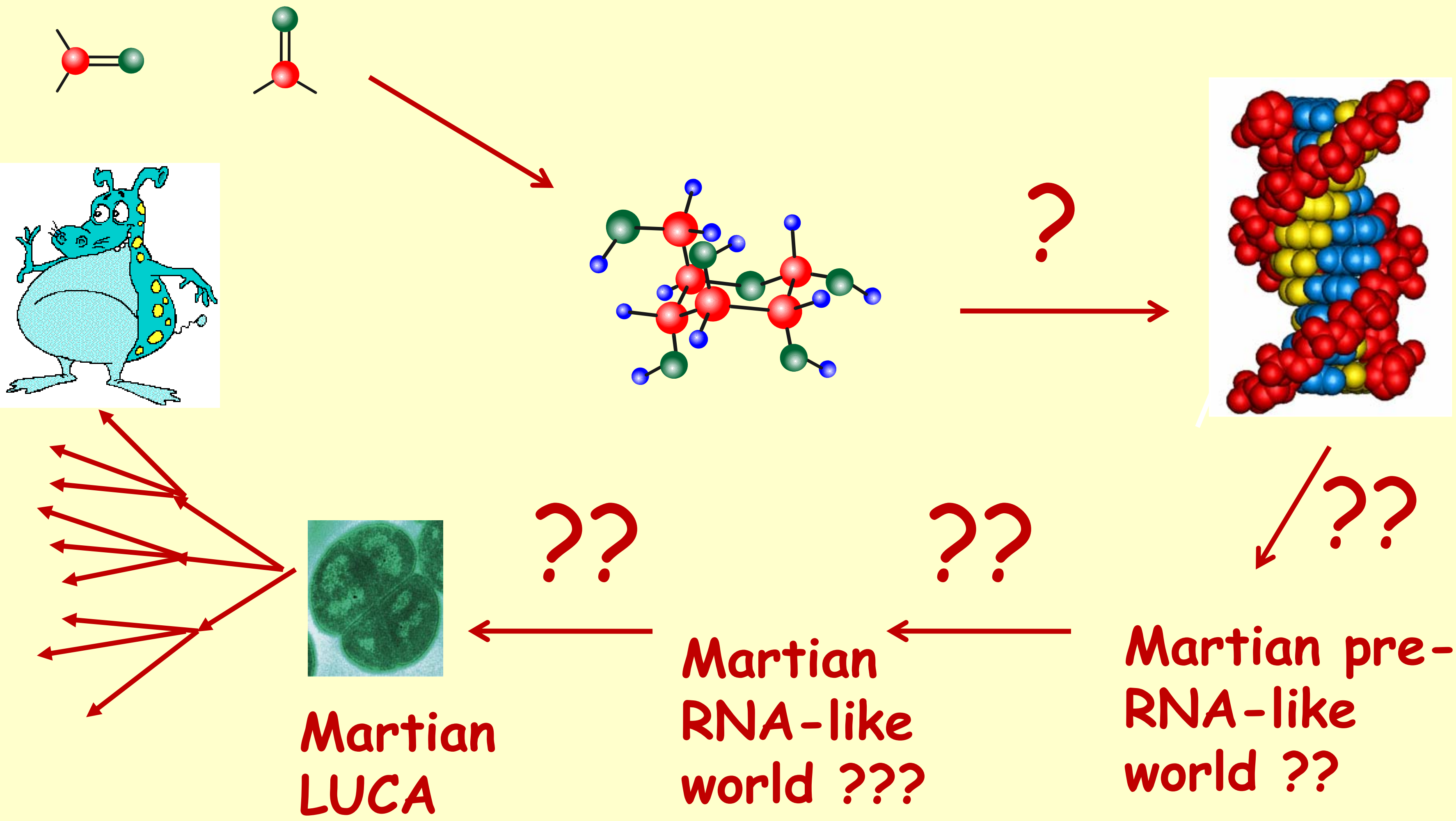
☑ Energy

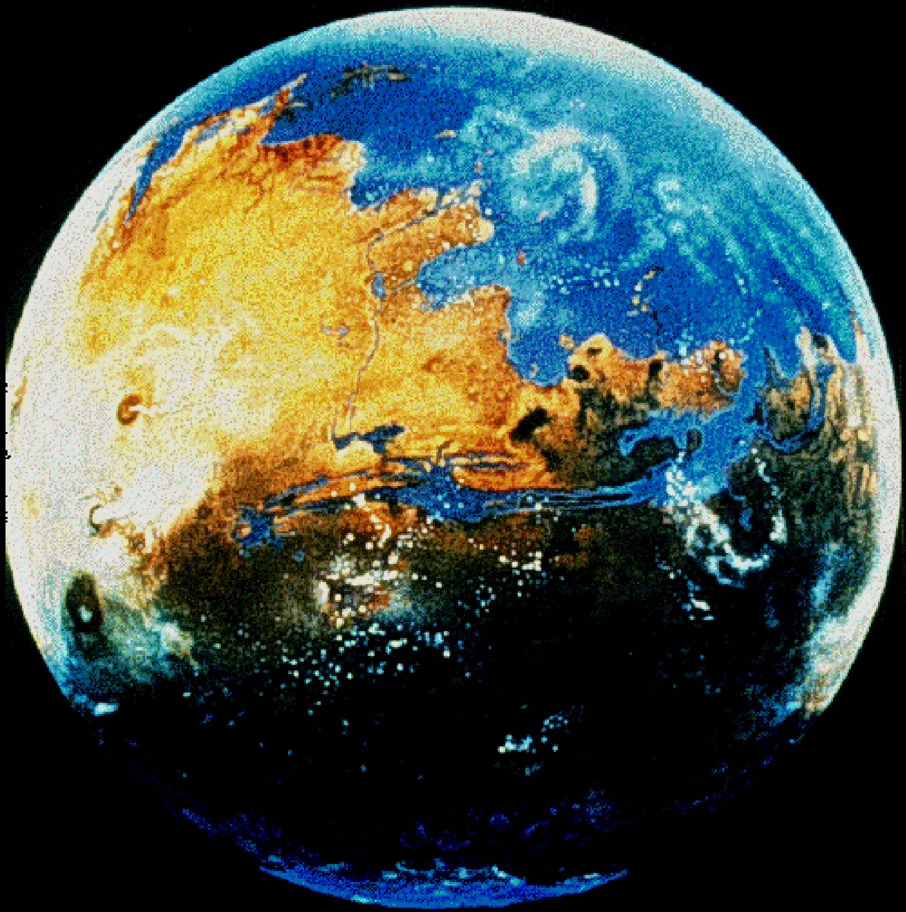
Early Mars



From Bibring et al, Science, 2006

Carbonaceous matter + liquid water + Energy



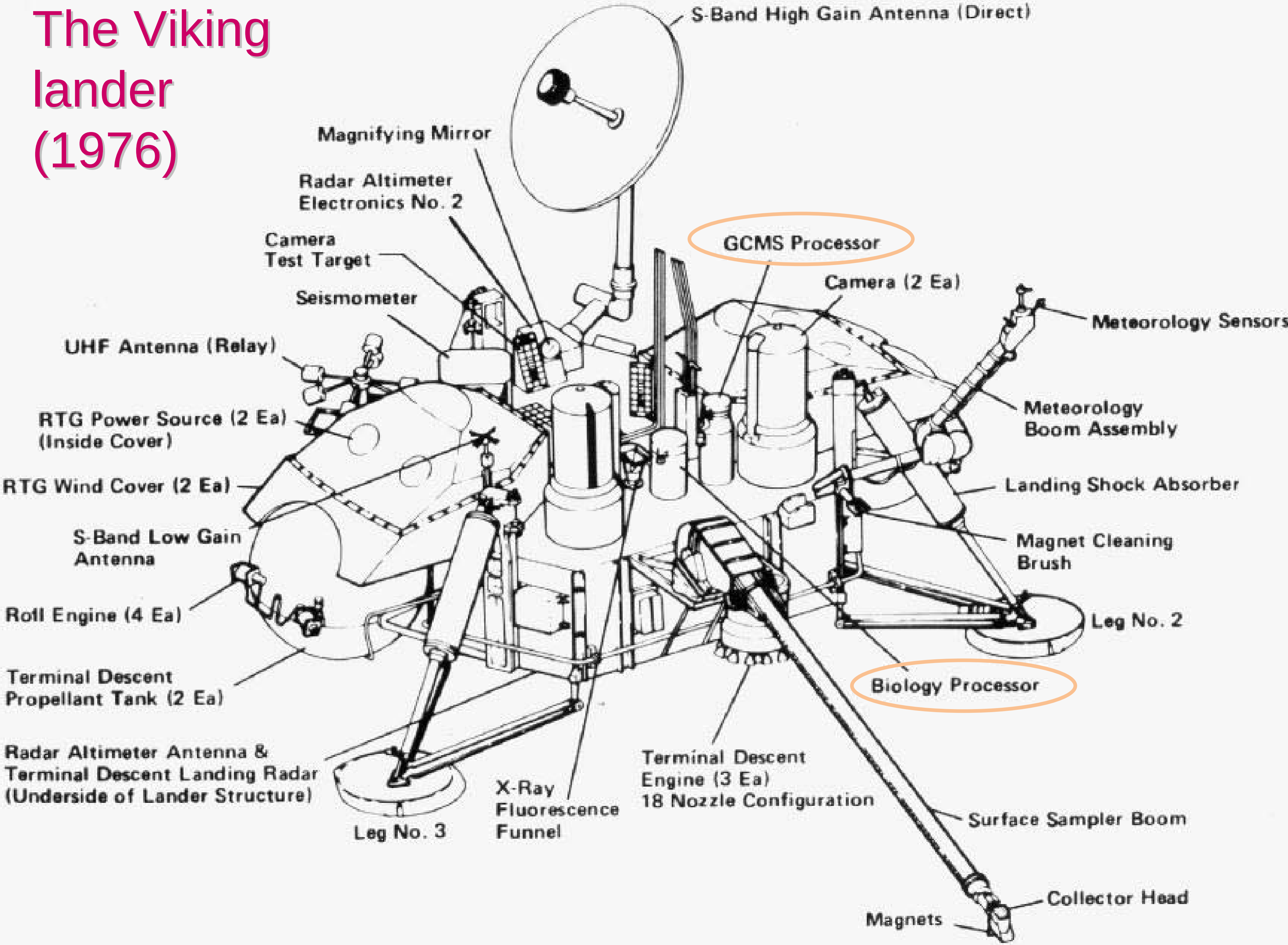


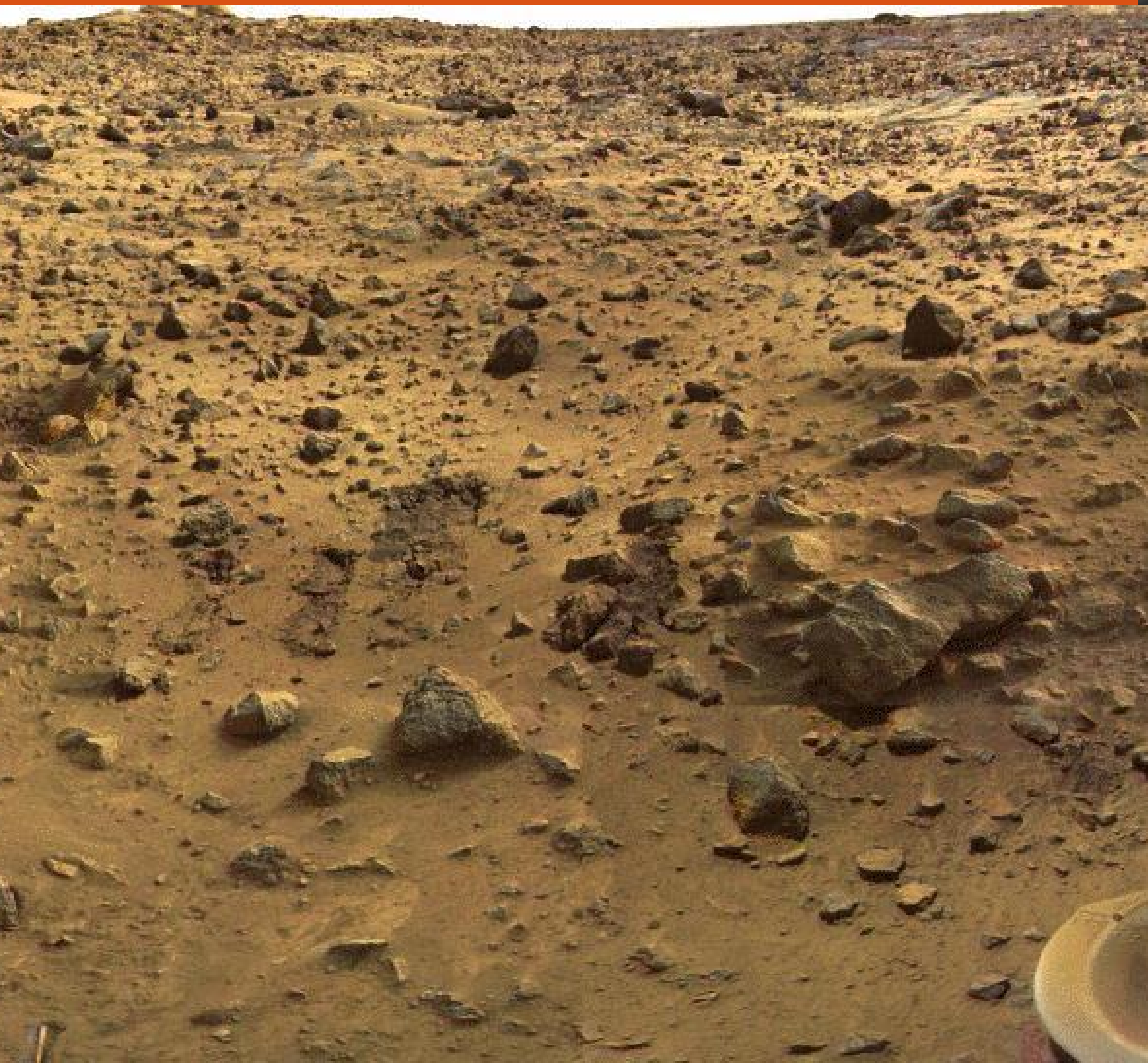
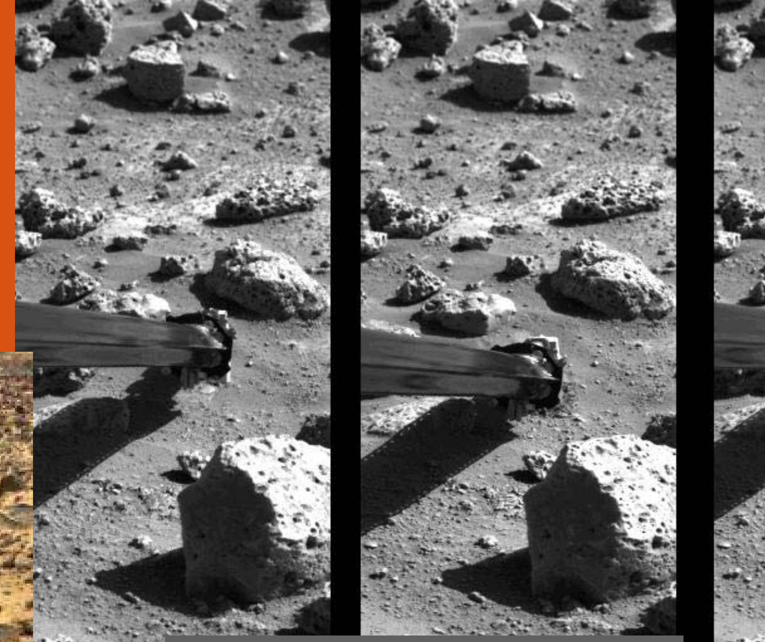
- A primitive Mars and an early evolution similar to that of the Earth

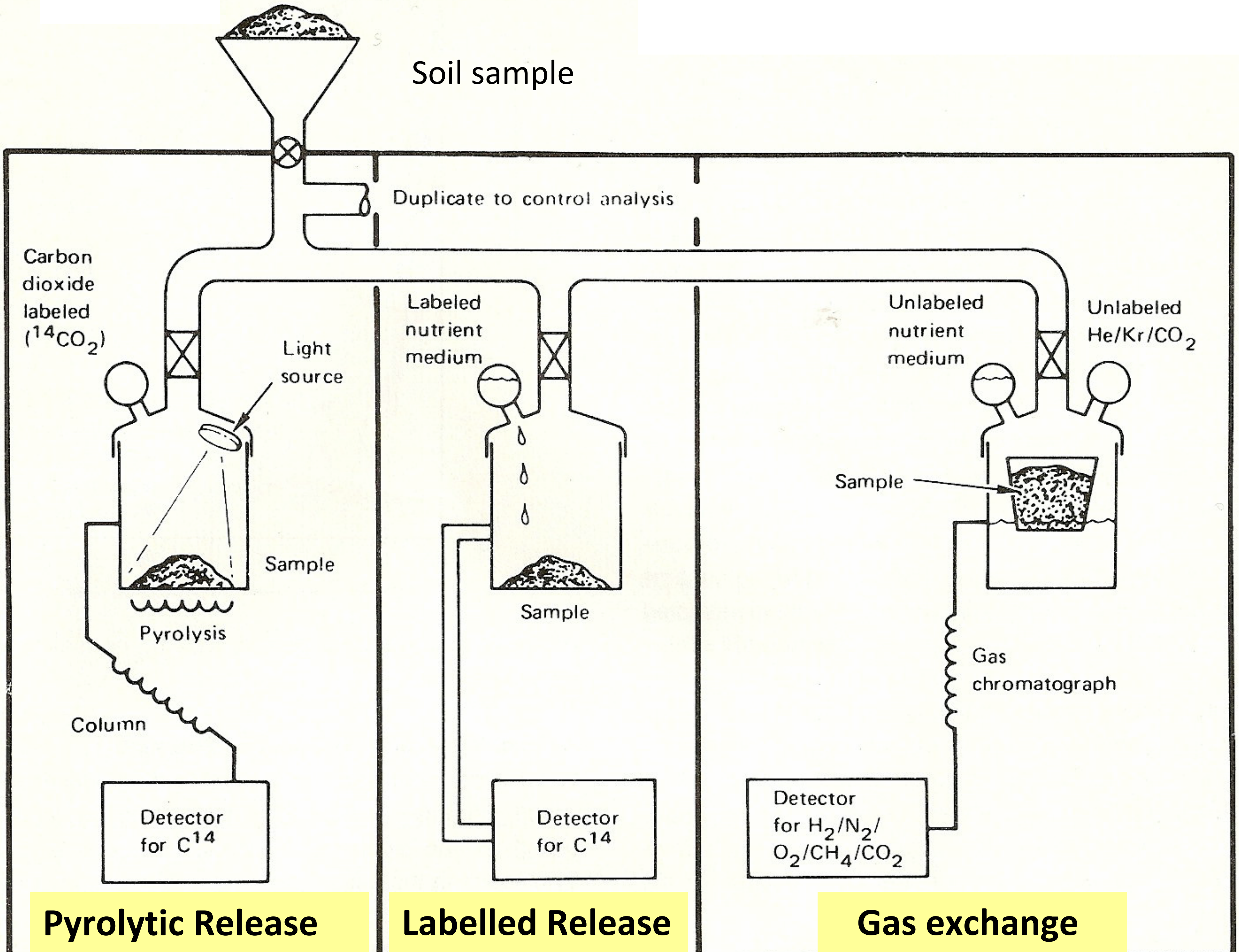
- But no big impact of tectonics or climate on the evolution of Mars up to now

If life emerged on early Mars, and even if it disappeared, there may still be traces of a past life, and even of a prebiotic environment, easier to find than in the Earth case.

The Viking lander (1976)



Soil sample
Duplicate to control analysis
Carbon dioxide labeled ($^{14}CO_2$)
Light source
Sample
Pyrolysis
Column
Detector for C^{14}
Labeled nutrient medium
Sample
Detector for C^{14}
Unlabeled nutrient medium
Unlabeled $He/Kr/CO_2$
Sample
Gas chromatograph
Detector for $H_2/N_2/O_2/CH_4/CO_2$
Pyrolytic Release
Labelled Release
Gas exchange

Experiment	Response for sample	Response for heat-sterilized control
Testing terrestrial life		
PR	Carbon detected	None
GEX	O_2 or CO_2 emitted	None
LR	Labelled gas emitted	None
Mars sample in absence of Martian life		
PR	None	None
GEX	None	None
LR	None	None
Actual Viking results with Martian samples		
PR	Carbon detected	Carbon detected
GEX	O_2 emitted	O_2 emitted
LR	Labelled gas emitted	None

Viking GC-MS did not detect any Martian organic molecule in the soil, although the instrument worked perfectly as designed (Biemann et al., Sciences 194, 72 (1976); J. G. R. 30 4641 (1977)

Organics too refractory to be released at the temperatures achieved or oxidized during the TV step by the iron present in the soil (Navarro et al, PNAS 103 (44), 16089-16094 (2006); Benner et al. PNAS 97, 2425 (2000).

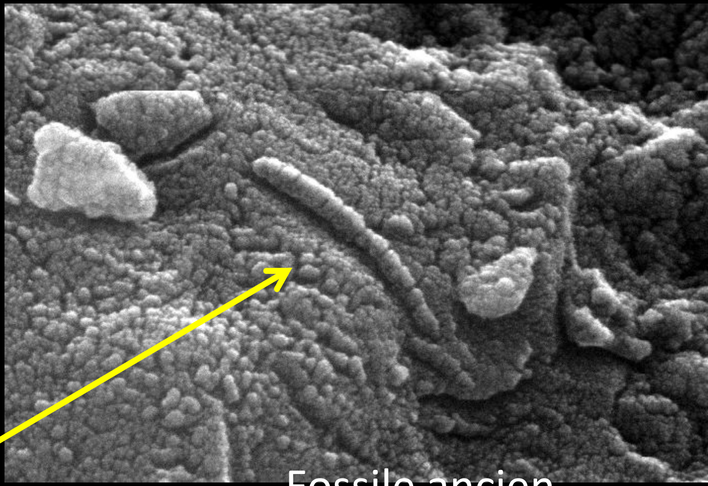
Table 1. Expected Metastable Products from Organic Substances in the Murchison meteorite[5,6]

Substance	Concentration (parts per million)	Metastable Products
Acid insoluble kerogen	14500	Benzenecarboxylic acids
Aliphatic hydrocarbons	12–35	Acetate
Aromatic hydrocarbons	15–28	Benzenecarboxylic acids
Monocarboxylic acids	≈330	Acetate/oxalate
2-Hydroxycarboxylic acids	14.6	Acetate/carbonate
Alcohols (primary)	11	Acetate
Aldehydes	11	Acetate
Ketones	16	Acetate, benzenecarboxylic acids
Amines	10.7	Acetate
Urea	25	Carbonate
Heterocycles	12	Carbonate, other products

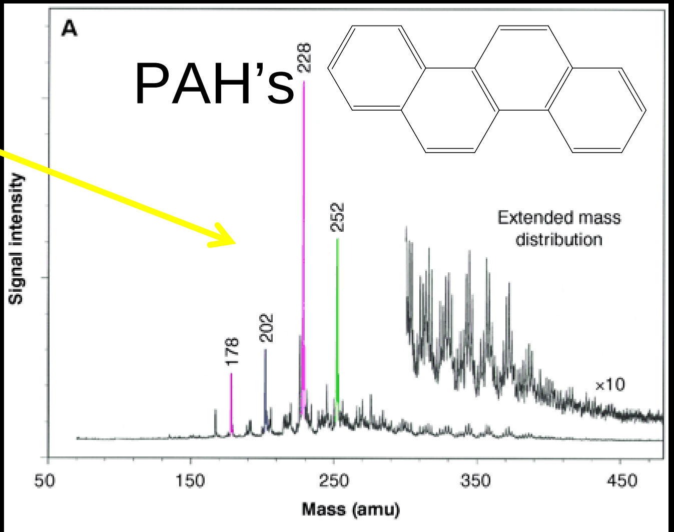
Past Martian life in SNC ALH84001 ?

McKay *et al.* *Science* 273, 924 (1996)

Globules of amber Carbonate



Fossile ancien



Martian organics or terrestrial contamination ?

LET'S HOPE LIFE ON MARS IS MORE INTELLIGENT THAN LIFE ON EARTH.

Available online at www.sciencedirect.com

ScienceDirect

Geochimica et Cosmochimica Acta 73 (2009) 6631–6677

Geochimica et Cosmochimica Acta

www.elsevier.com/locate/gca

Origins of magnetite nanocrystals in Martian meteorite ALH84001

K.L. Thomas-Keprta [a,*], S.J. Clemett [a,*], D.S. McKay [b], E.K. Gibson [b], S.J. Wentworth [a]

[a] *ESCG at NASA/Johnson Space Center, Houston, TX 77058, USA*
[b] *KR, ARES, NASA/Johnson Space Center, Houston, TX 77058, USA*

Received 20 July 2008; accepted in revised form 18 May 2009; available online 16 June 2009

…. We suggest that the majority of ALH84001 magnetites has an allochthonous origin and was added to the carbonate system from an outside source. This origin does not exclude the possibility that a fraction is consistent with formation by biogenic processes, as proposed in previous studies.

Exobiology

- Some historical aspect
- Current exobiology

The terrestrial example

- Life on Earth
- The origin(s) of Life on Earth

A Mars Example?

- Did we already find it?
- **What to search for?**
- How to search for?

The PP aspects and future prospects

Signatures of extant Life

At the level of a cell or of an ecosystem: **gas production** (CH_4, O_2), **specific pigmentation** (fluorescence), **specific red-ox** or **thermal** activity non chemically explainable, presence of **specific macromolecules** linked to replication or recognition properties, amplification of molecular biomarkers (structural genes, etc) by PCR (*Polymerase Chain Reaction*) or by *in vitro* culture. To summarize:

- **Metabolic activity** : assimilation, and/or release of metabolites
- **Replication**
- **Molecular signatures** : biomacromolecules
- **Homochirality**
- **Rapid evolution of characteristics** (morphology, chemical composition, etc)

Signatures of extinct Life

Structural biosignatures

Direct : Morphology (individual level), biofilms (colonies)

Indirect : biocorrosion of biomineralisation structures (specific biotransformations, not reached by purely chemical processes)

Chemical biosignatures

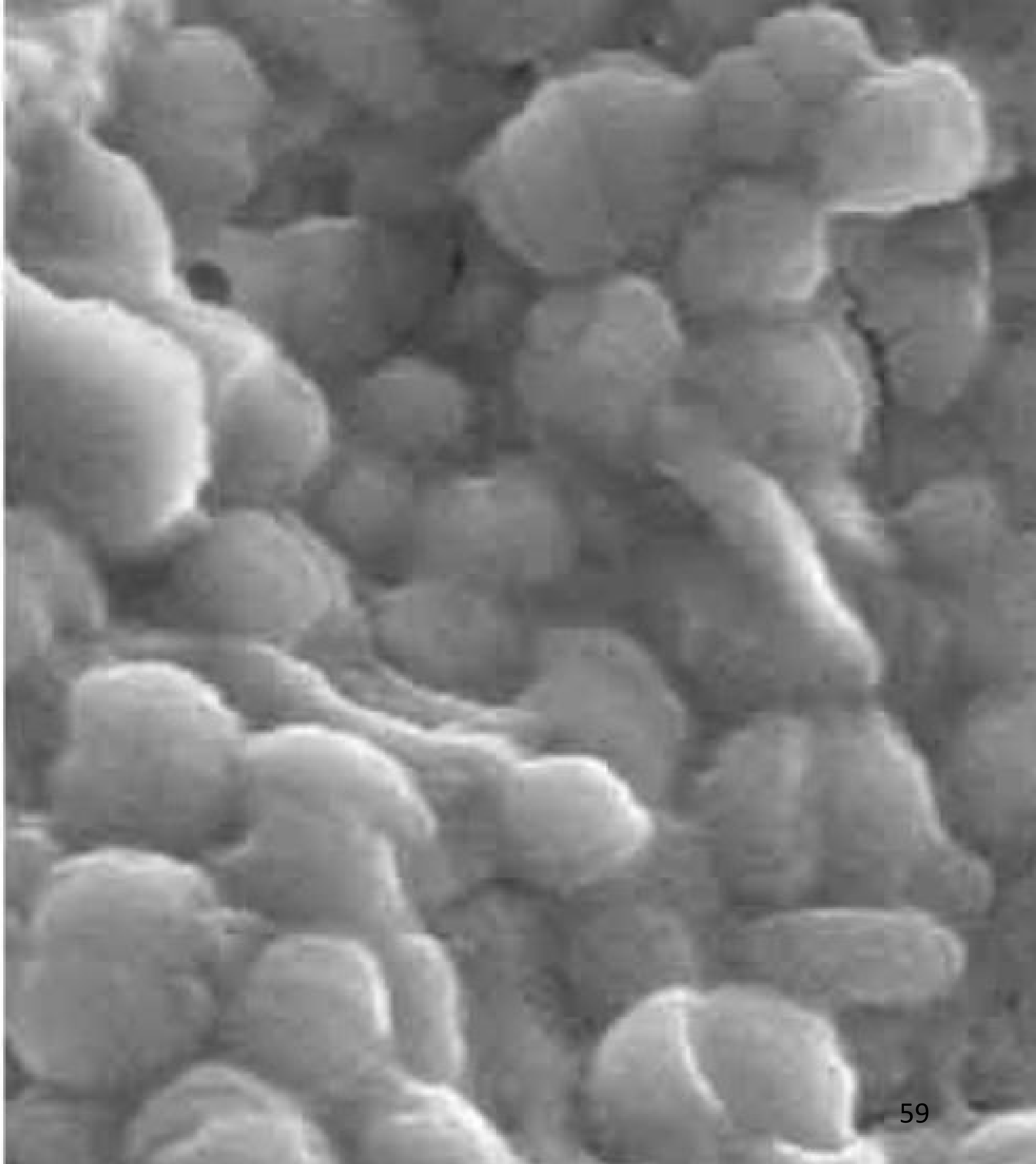
Organic : degradation of biogenic organic matter during fossilisation processes: lipidic biomarkers produced by the thermal and chemical degradation of cellular membranes constituents

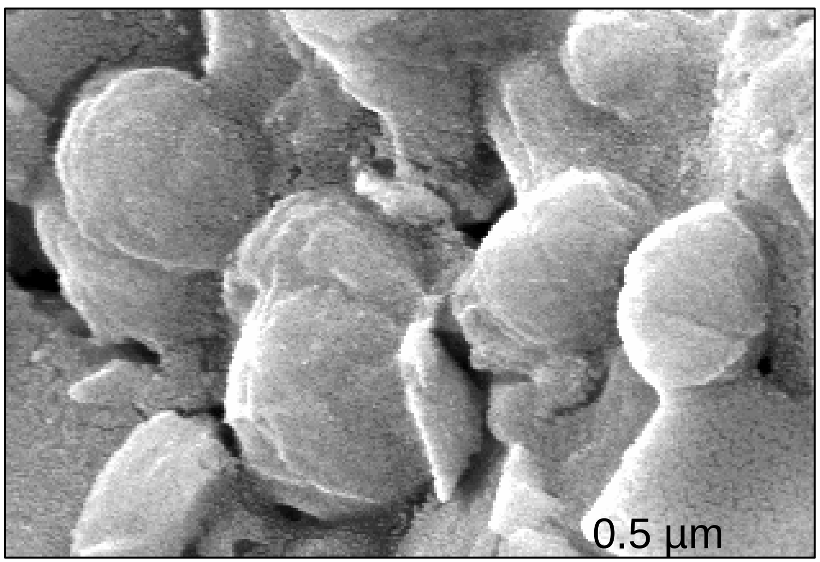
Mineral (inorganic) : Red-Ox biological processes can produce secundary minerals with specific cristallochemical properties (symetry, stoechiometry, etc): biochemical cycle of iron: blue green iron FeII-FeIII (green rust), bio-magnetite, etc..

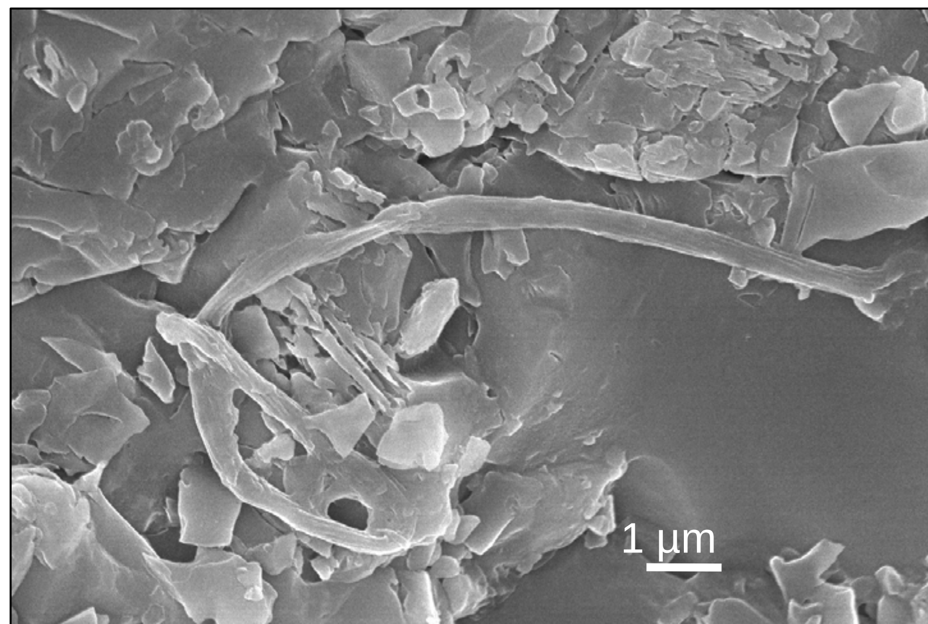
Isotopic **:** enrichment in light isotopes ^{12}C, ^{14}N, ^{32}S

Chiral **:** important enantiomeric excess (amino acids, etc)

About 3.5 Ga old fossil bacteria from South Africa







Westall, 2003; Westall et al., 2006

<u>ORGANICS ON MARS ?</u> : *é What To Search For ?*

- **low MW cpds, including C_1-C_4 hydrocarbons, their oxidative products : alcohols, carbonyl compounds, carboxylic acids and peroxy-acids**

- **cpds of higher thermal stability, e.i. benzoic acid and its derivatives**

- **higher MW cpds of biological or prebiotic interest : amino-acids, and heterocyclic bases (mainly purine bases, such as adenine)**

- **macromolecular cpds : peptides, oligopeptides or oligopeptide-like compounds, kerogen or kerogen-like compounds**

- **chirality : search for enantiomeric excess in the low MW organics, search for tacticity in the macromolecular organics**

- **detailed isotopic analysis of biogenic elements, specially C, O, N & S**

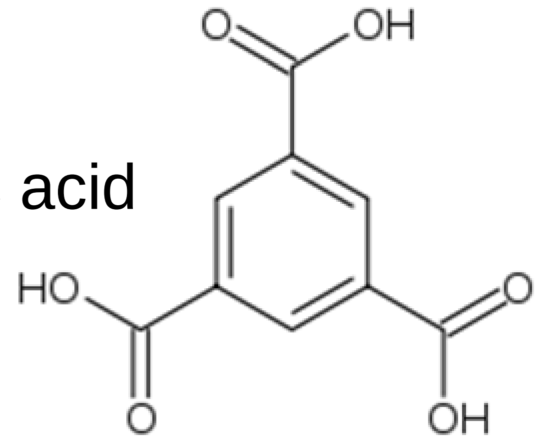
- **detailed analysis of the oxidants in the sample : quantitative analysis of H_2O_2, other peroxides, superoxides, other oxidants**

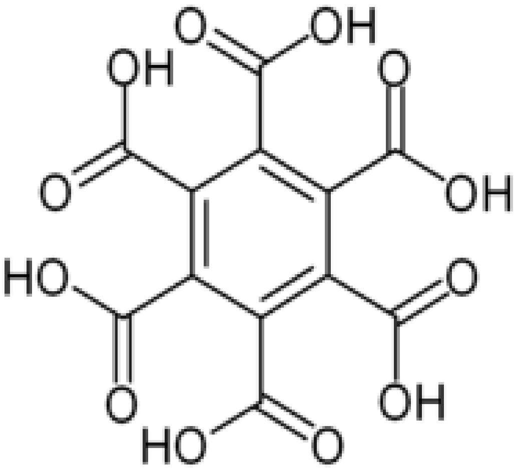
- **correlation between :**
  - **organic and inorganic inventories in the sample**
  - **chemical composition and morphology**
  - **concentration of the organics and depth**
  - **organics and oxidants concentrations**

Methane CH_4

Ethane C_2H_6

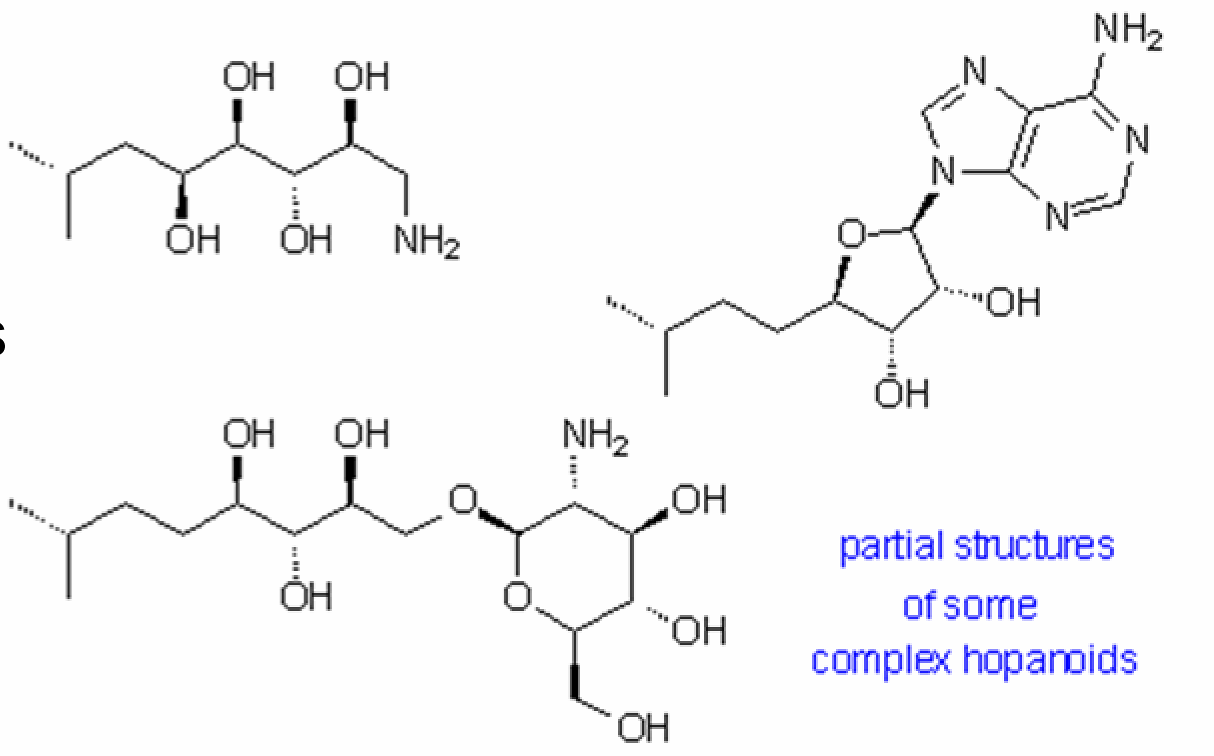
Trimesic acid





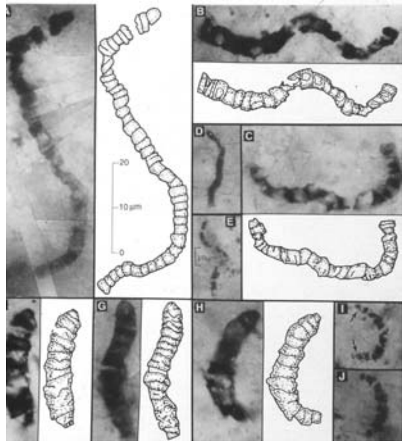
Mellitic acid

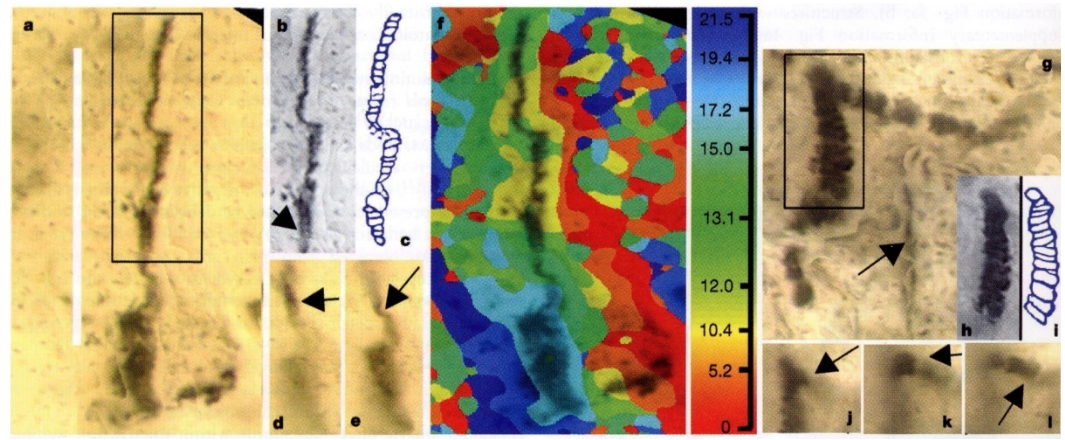
Hopanes



But there are potential problems:

e.g. Schopf/Brasier controversies on the biogenicity of carbonaceous structures from the 3.465 Gy old Apex Chert (Warrawoona Formation, Western Australia) considered for years as the Earth's oldest fossils





	Schopf (1993)	Brasier et al. (2002)
Structures	**Fossil cyanobacteria**	**Hydrothermal artefact**
Kerogen	**Biogenic**	**Fischer Topsch artefact**
$\delta^{13}C$	**–14 to –42%o biogenic**	**-16 to –26%o Fischer Topsch (N. Grassineau (co-author)– biogenic)**

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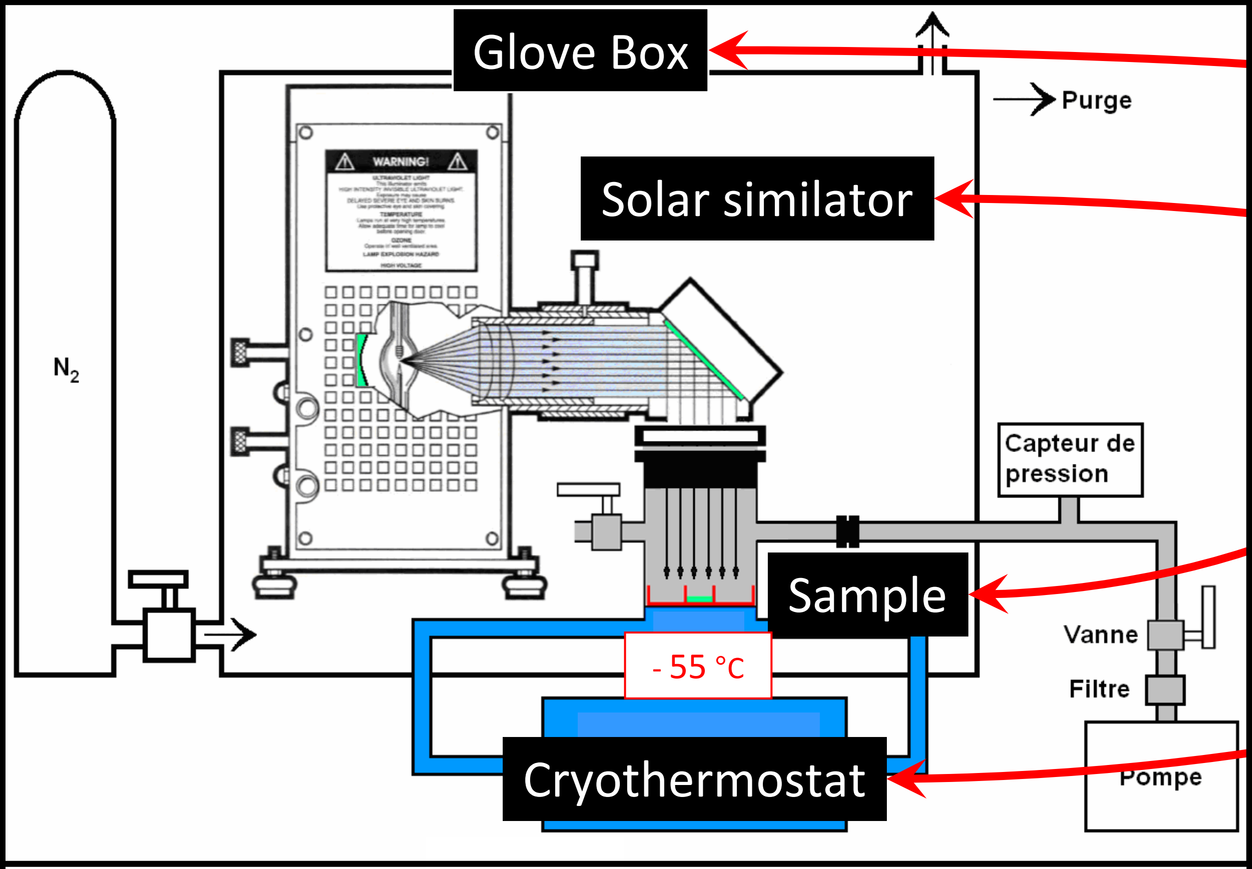
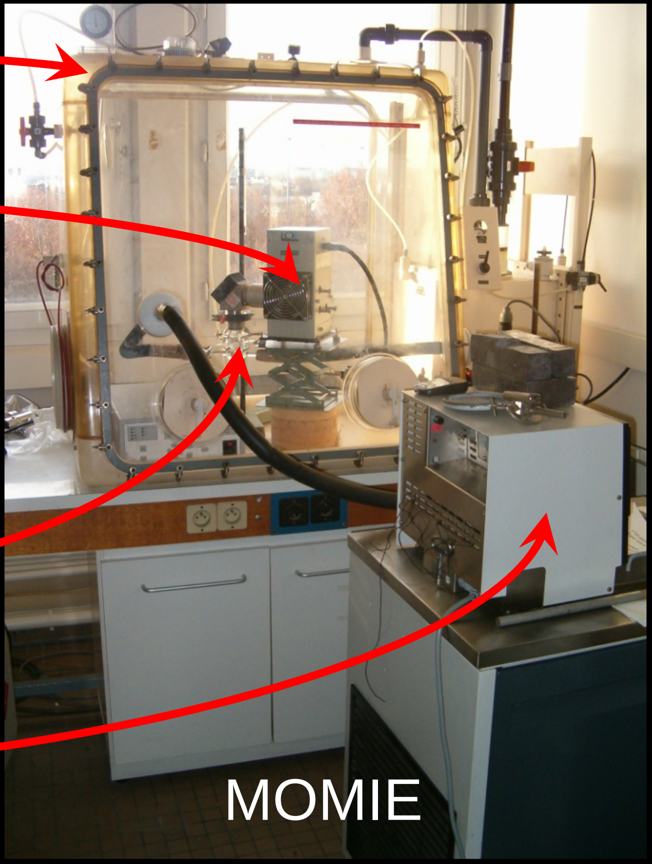
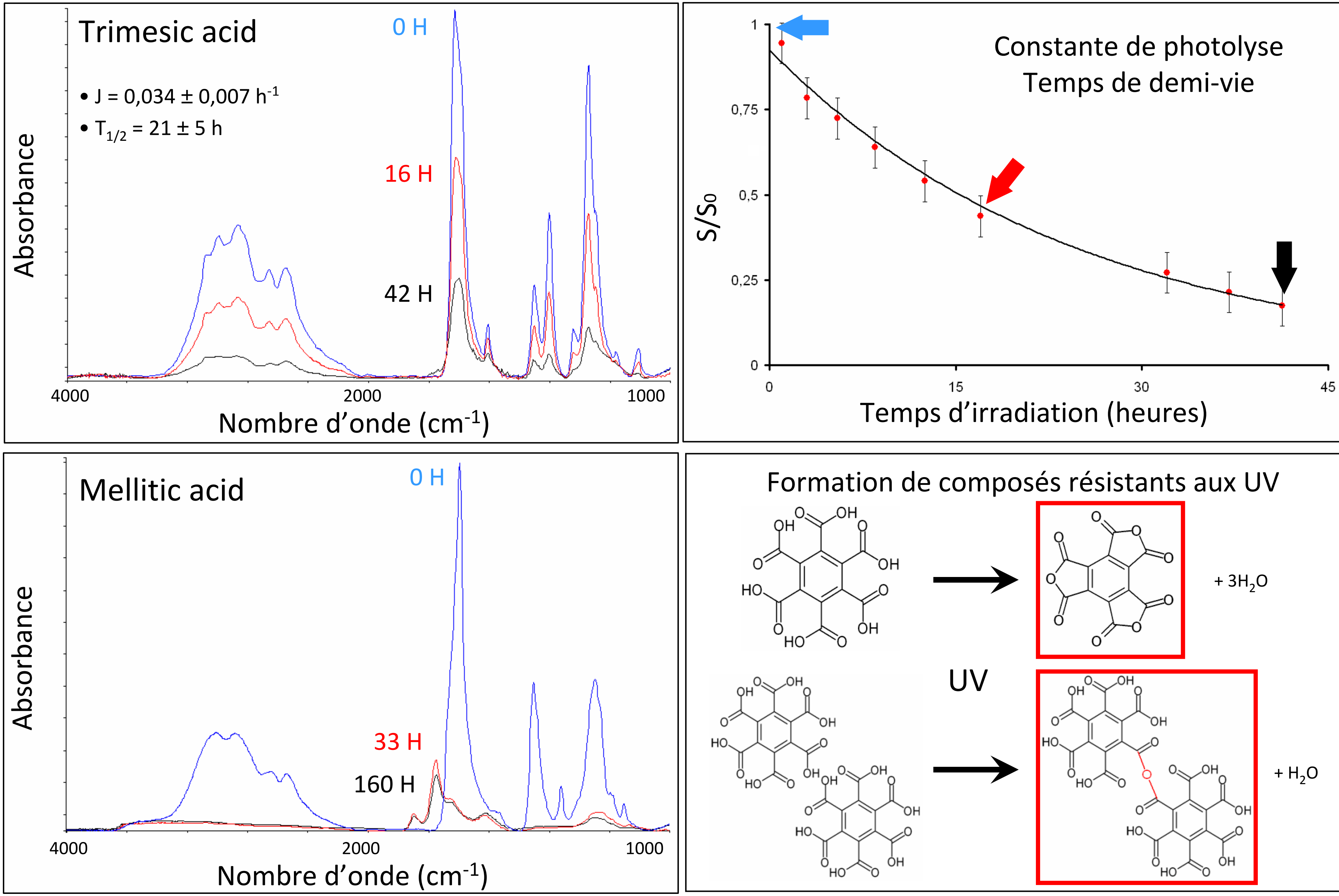
MOMIE : Martian Organic Molecules Irradiation and Evolution

- Inventory of the organics which may be present on Mars
- Study of their evolution under UV irradiation (solar simulator)
- Study of their evolution in the presence of oxidant (H_20_2)

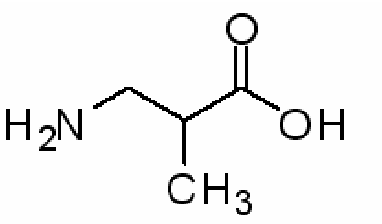




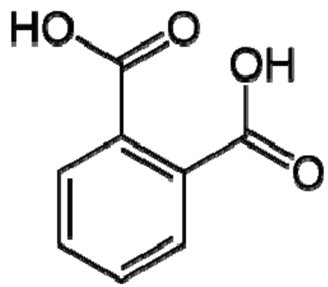


Trimesic acid
• J = 0,034 ± 0,007 h-1
• T1/2 = 21 ± 5 h
0 H
16 H
42 H
Absorbance
4000
2000
1000
Nombre d'onde (cm-1)
Constante de photolyse
Temps de demi-vie
S/S0
1
0,75
0,5
0,25
0
0
15
30
45
Temps d'irradiation (heures)
Mellitic acid
0 H
33 H
160 H
Absorbance
4000
2000
1000
Nombre d'onde (cm-1)
Formation de composés résistants aux UV
UV
+ 3H2O
+ H2O

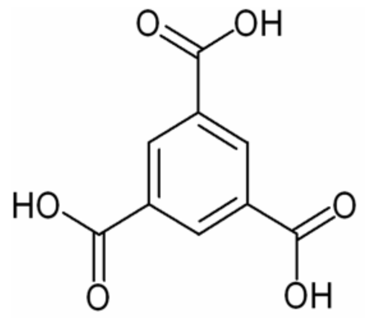
AIB



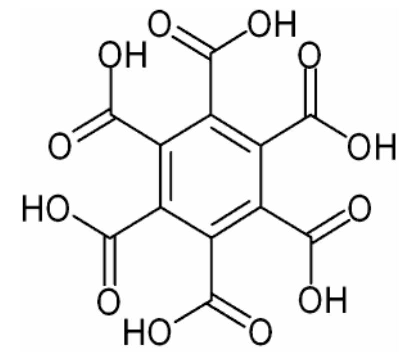
Phtalic Acid



Trimesic Acid



Mellitic Acid



Molecule	J(s-1)	Rel uncert.	Half Life at 1 AU (d)	Half Life at Mars (d)
AIB*	6,6E-07	26%	12	35
phtalic acid	7,5E-07	24%	11	31
trimesic acid	1,9E-06	21%	4	12
mellitic acid	4,5E-06	23%	2	5
AIB + MSA**	1,0E-06	44%	8	22
phtalic acid + MSA	1,2E-06	12%	7	20
trimesic acid + MSA	*No Data*		*No Data*	*No Data*
mellitic acid + MSA	*No Data*		*No Data*	*No Data*

extrapolation →

* AIB = α-aminoisobutiric acid

** MSA = Martian Soil Analog (JSC Mars 1 - Allen et al., 1998)

No protection effect due to the presence of martian soil analogue

J increases !

Exobiology

Some historical aspect

Current exobiology

The terrestrial example

Life on Earth

The origin(s) of Life on Earth

A Mars Example?

Did we already find it?

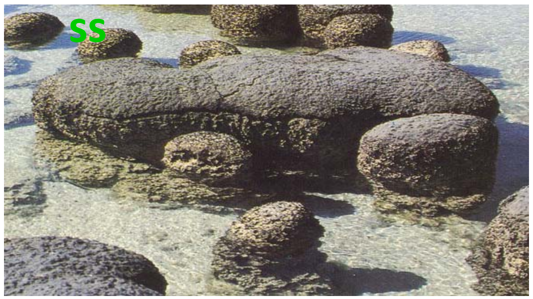
What to search for?

How to search for?

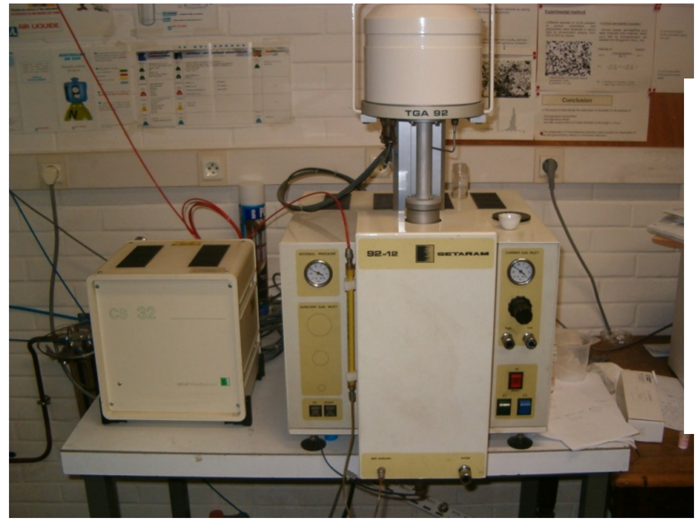
The PP aspects and future prospects

Characterisation of specific thermal degradation of biominerals

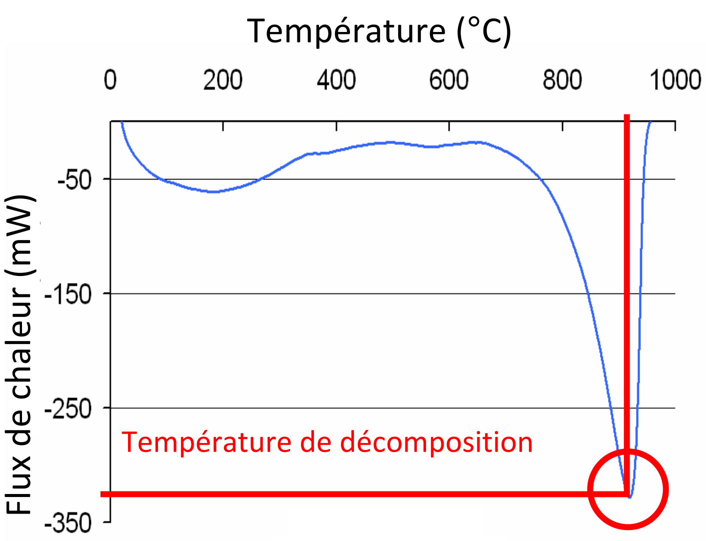
Biocarbonate



Abiotic Carbonates

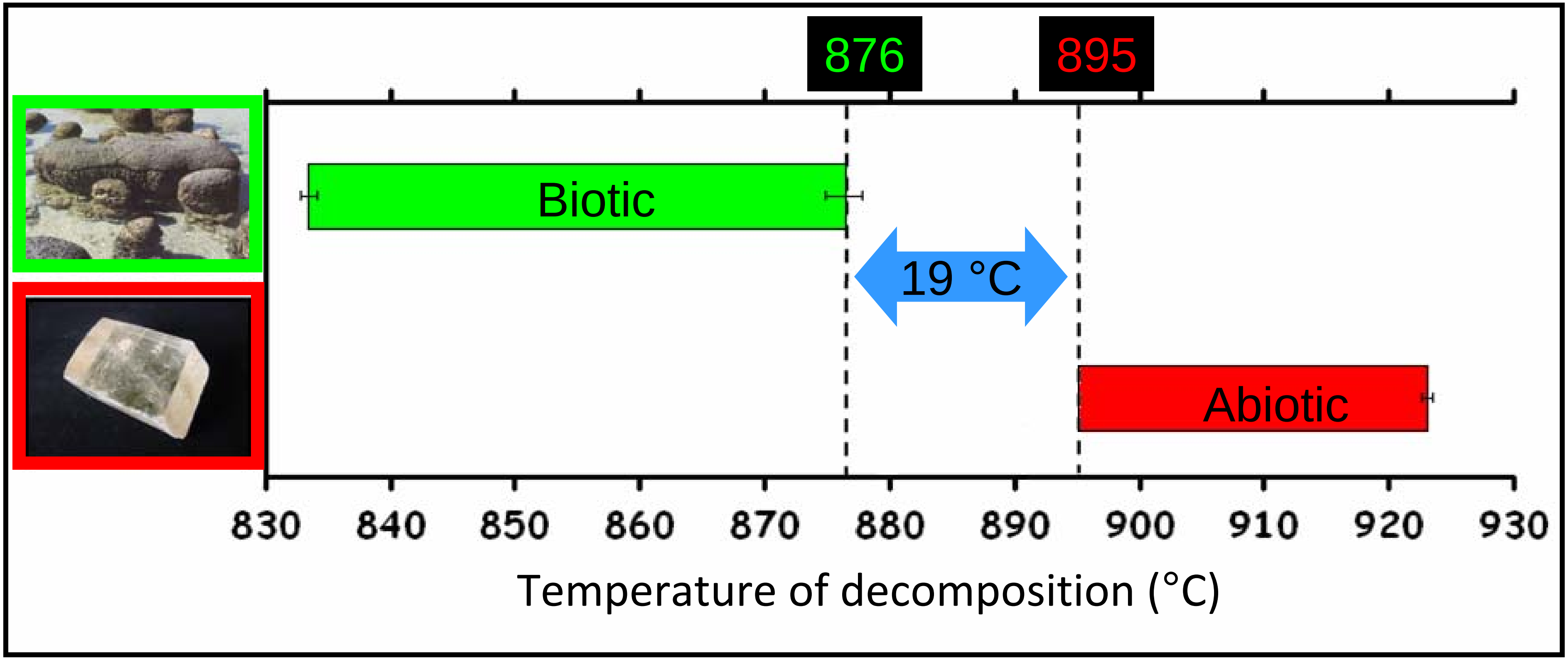


DTA-TG
Differential thermal analysis - thermogravimetry



$$CaCO_{3(s)} \rightarrow CaO_{(s)} + CO_{2(g)}$$

From 70 studied samples: clear separation between biotic and abiotic origin of carbonates



SEARCH FOR ORGANICS

in situ

- GC-MS coupled to Pyrolysis + chemical derivatization with multi GC columns including chiral separation (expected sensitivity : ppb)

- MS coupled to Laser Ablation-Inductive Coupled Plasma-(LA-ICP-MS) for determination of organic and inorganic phases

- Capillary electrophoresis, HPLC and/or supercritical chromato-graphy for direct analysis of high MW organics and/or fluid extraction

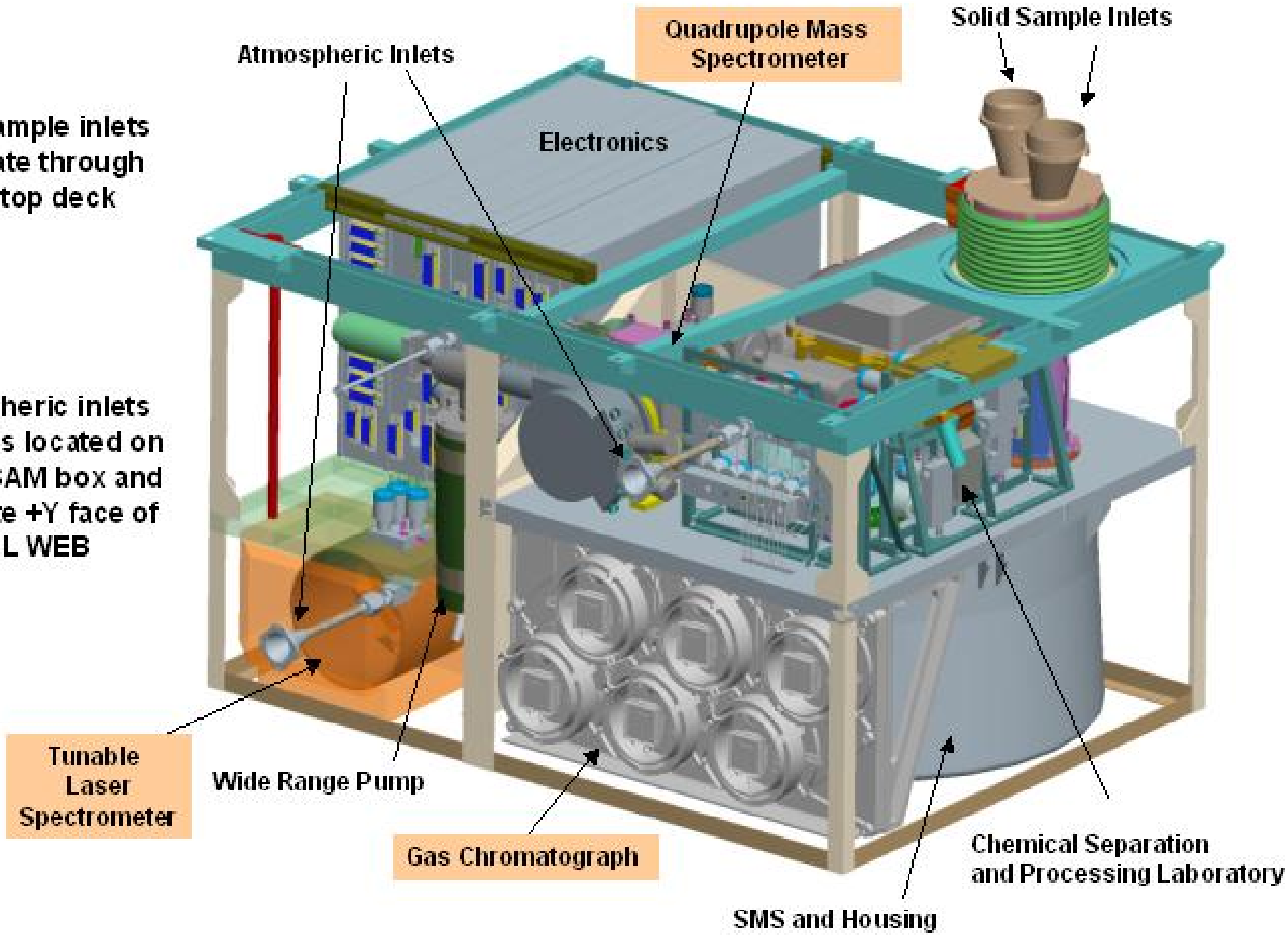
Returned samples

- Same techniques + a variety of analytical techniques available or under development several laboratories :
- High resol. MS
- Capillary electrophoresis / Laser induced fluorescence (CE-LIF)
- Enzyme Linked Immuno Sorbent Assays (ELISA)

THE SAM EXPERIMENT OF THE MSL'11 MISSION

Solid sample inlets penetrate through MSL top deck

Atmospheric inlets and vents located on side of SAM box and penetrate +Y face of MSL WEB



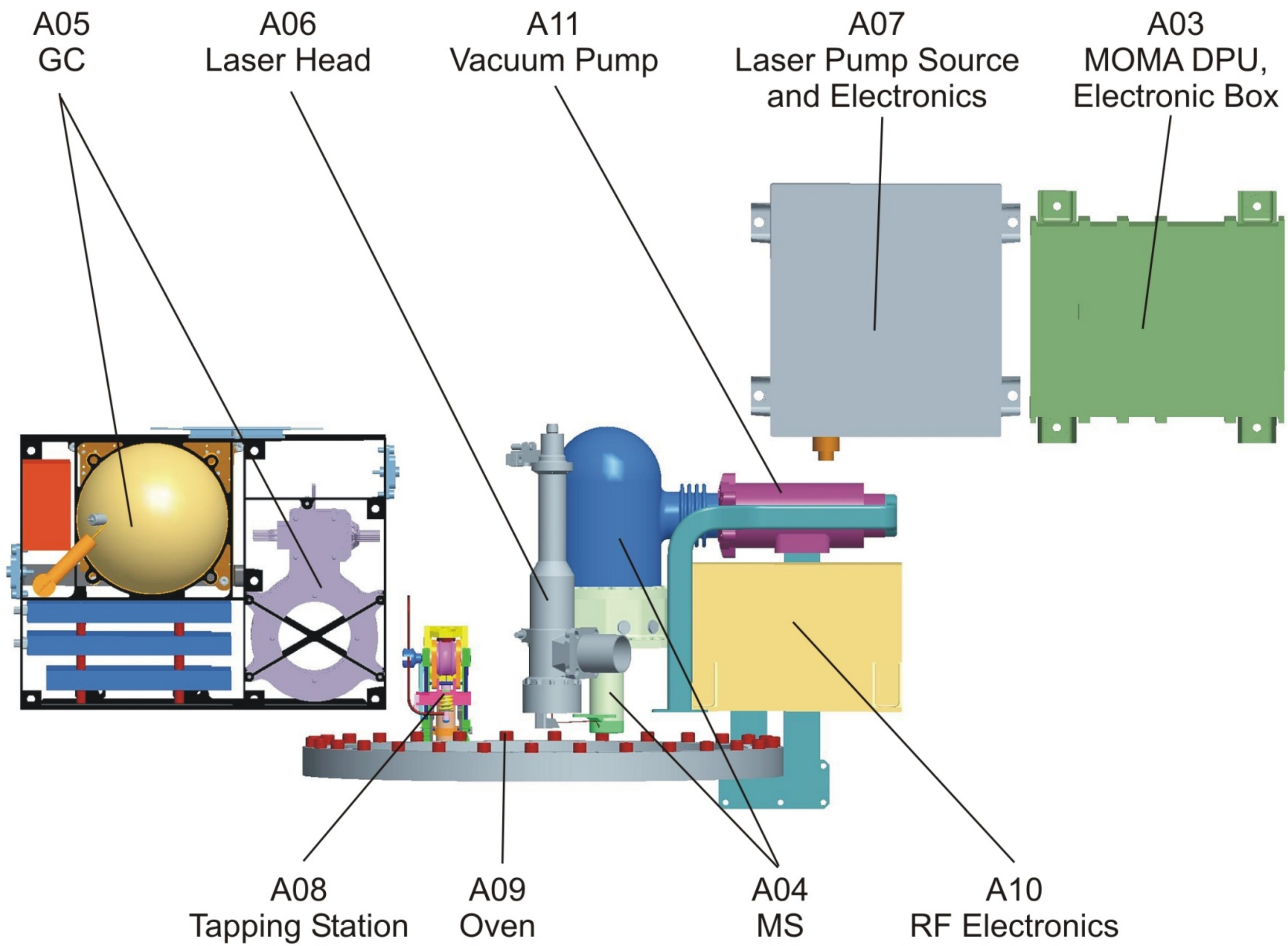
- **Optical Colour Microscope (low & high resolution)**
  - Detection of microorganisms, fossil structures & mineralogical studies.
  - Resolution: 0.1 mm down to 1 mm.

- **Combined Laser Plasma and Raman Spectrometers**
  - Provide complementary information, useful for the identification of organics and of the environment where the sample is obtained.
  - Raman spectrometer => non-polar (–C–C– and –C=C–) molecular bonds.
  - LPS characterises the atomic composition of the sample.

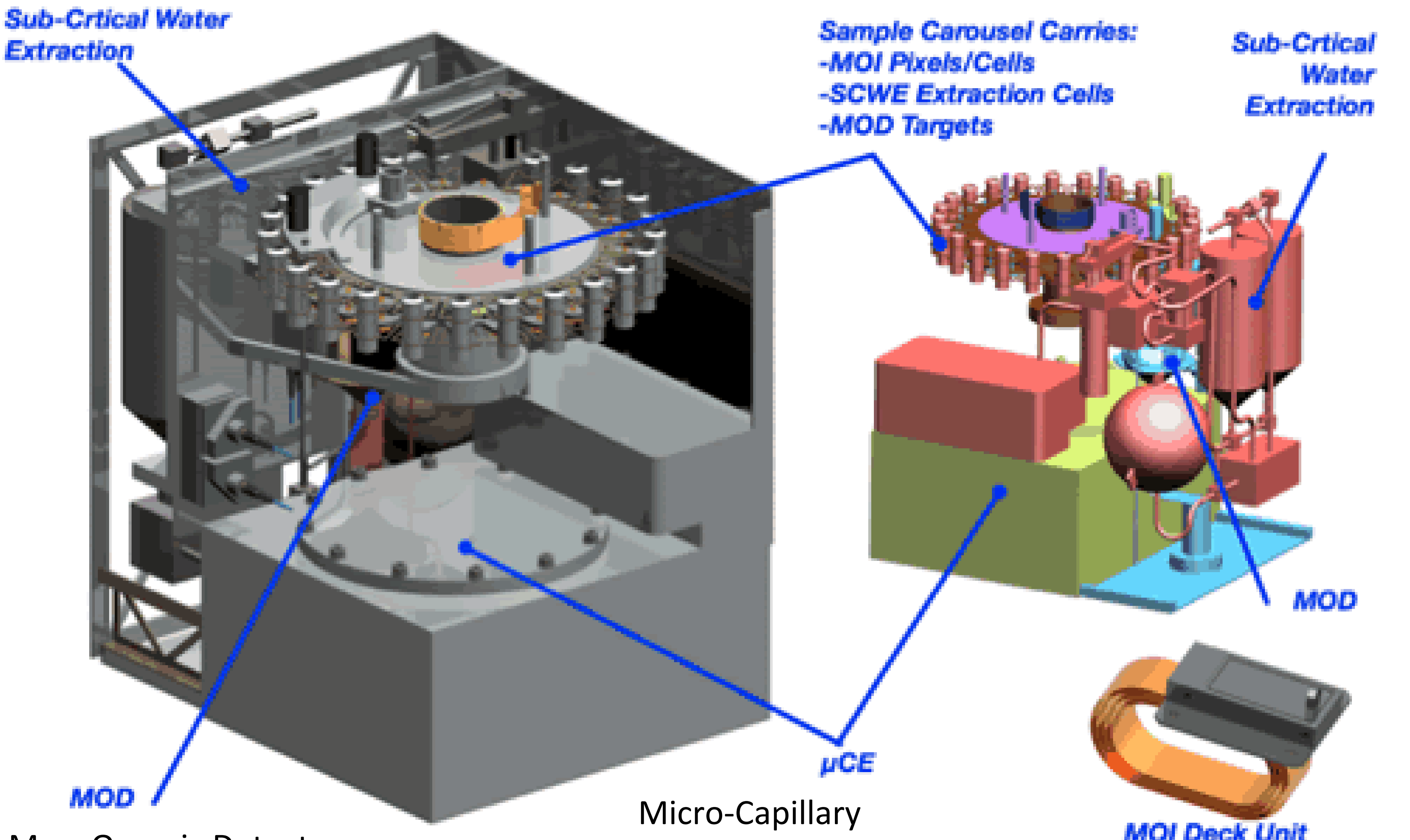
- **Life Marker Chip**
  - New technology instrument based on antibodies and organic molecules attached to well-known locations on a chip matrix.
  - A solution with Mars soil and a chromophore substance is washed over the chip.
  - The chip is illuminated, and chip spots fluoresce where a match exists.

- **Oxi/Pyr-GCMS**
  - **Oxidant detection**
  - **Gas Chromatography**
  - **Mass Spectroscopy**
  - **Chirality Measurements**
  - **For determining the isotopic, elemental, organic and inorganic molecular compositions, and chirality.**

MOMA – Mars Organic Matter Analyzer



UREY Experiment

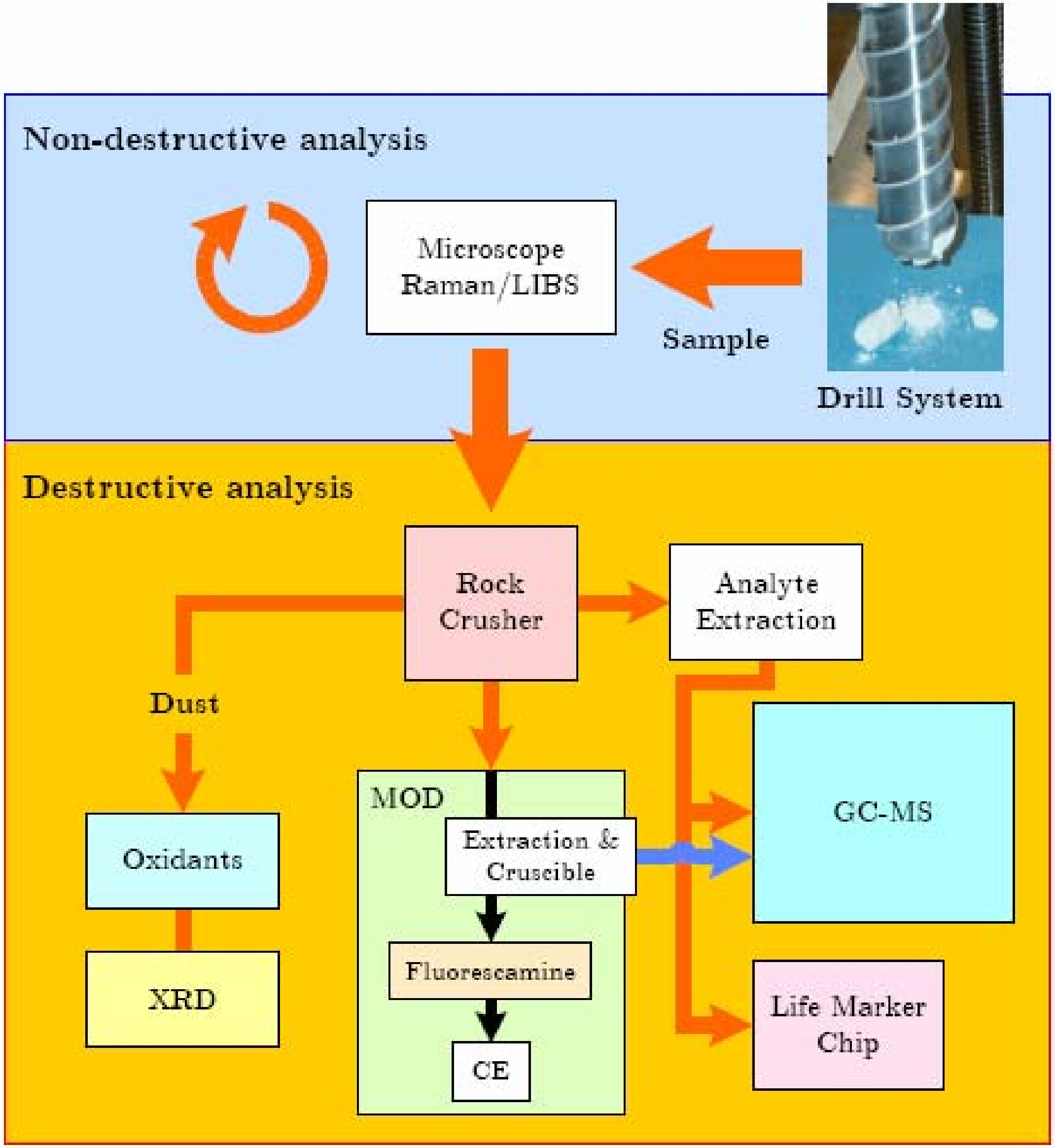


Mars Organic Detector

Micro-Capillary Electrophoresis Unit

Mars Oxidant Instrument

PASTEUR & EXOMARS



Exobiology

Some historical aspect

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Life on Earth

The origin(s) of Life on Earth

A Mars Example?

Did we already find it?

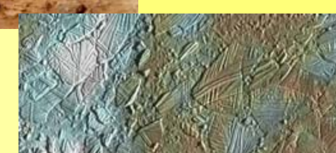
What to search for?

How to search for?

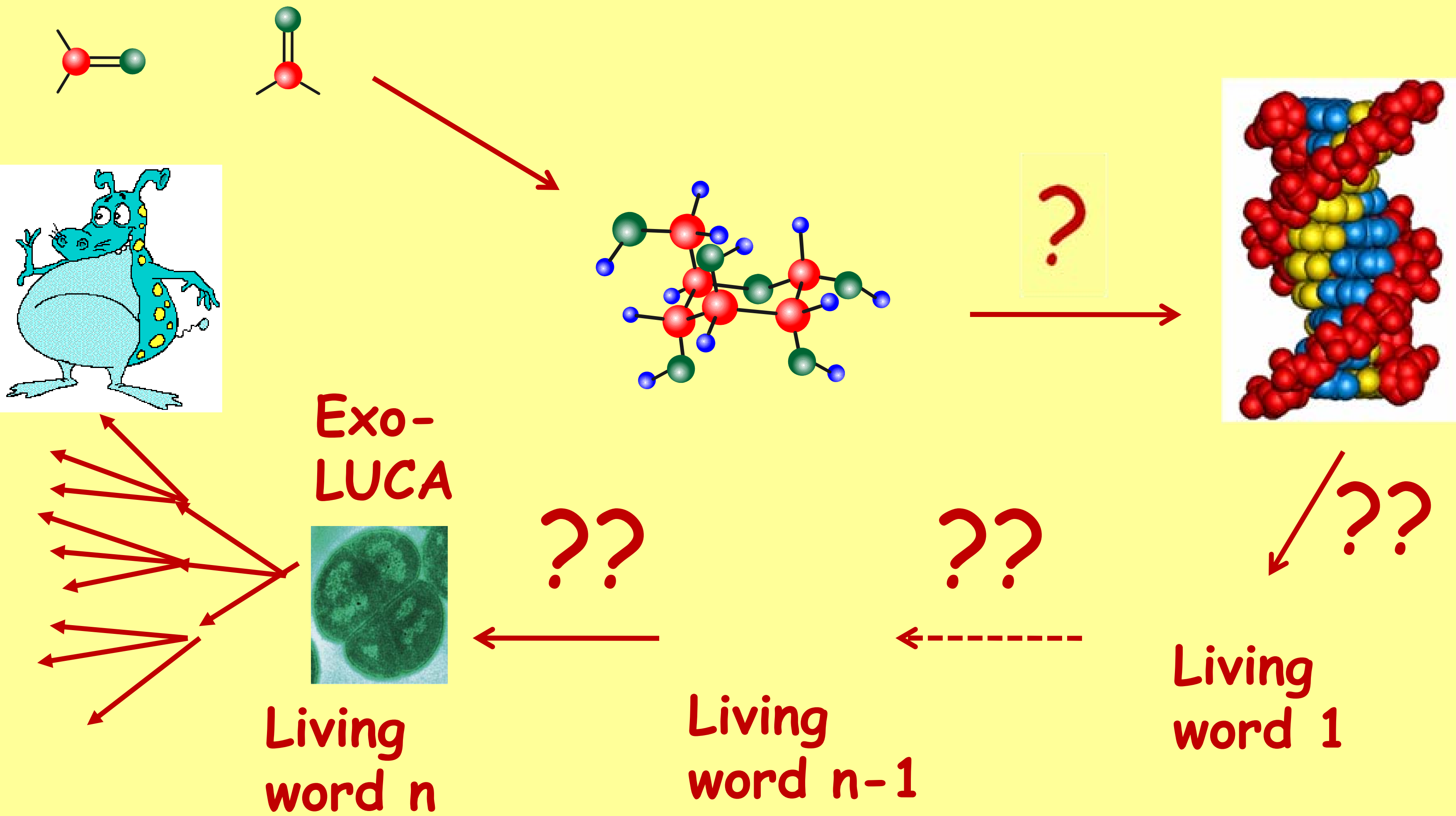
The PP aspects and future prospects

COSPAR recommandation on Planetary Protection

Category	1	2	3	4	5
Prevention of		Forward	contamination		Back
Biological interest	No	Significant	Significant	Significant	
Probability of contamination	Any	Remote	Significant	Significant	Unknown
Type of mission	Any	Any	Orbiter / Fly-by	Lander	Earth Return
	Mercury Venus Moon Sun Asteroids (except C)	Jupiter Saturn Uranus Neptune Pluto Comets C-asteroids	Mars Europa	Mars Europa	Earth-Moon System
Range of requirements					



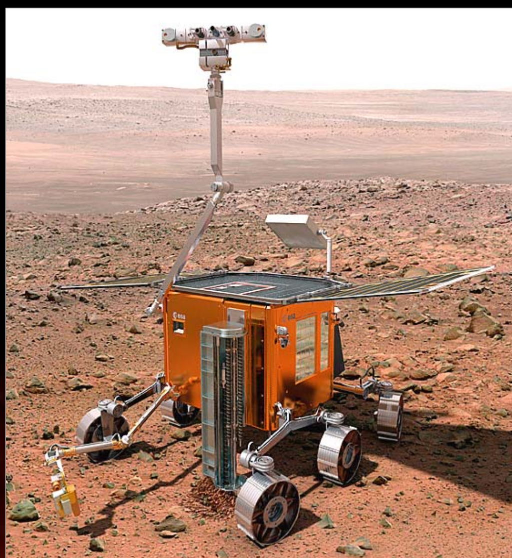
Carbonaceous matter + liquid water + Energy



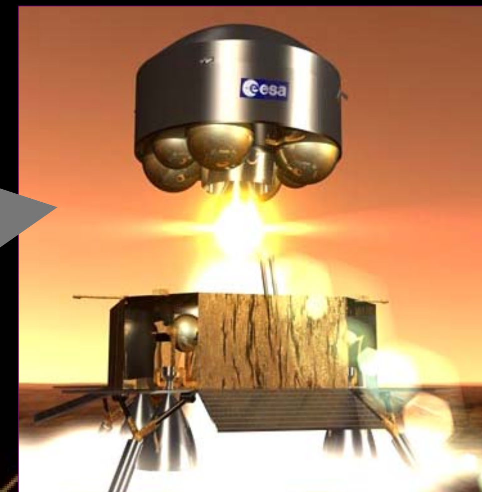
Exobiology and Mars

With my exobiological thanks for your attention

Mars Robotic Exploration Programme



MREP



→ Mars Sample Return

→ ...

→ 2020

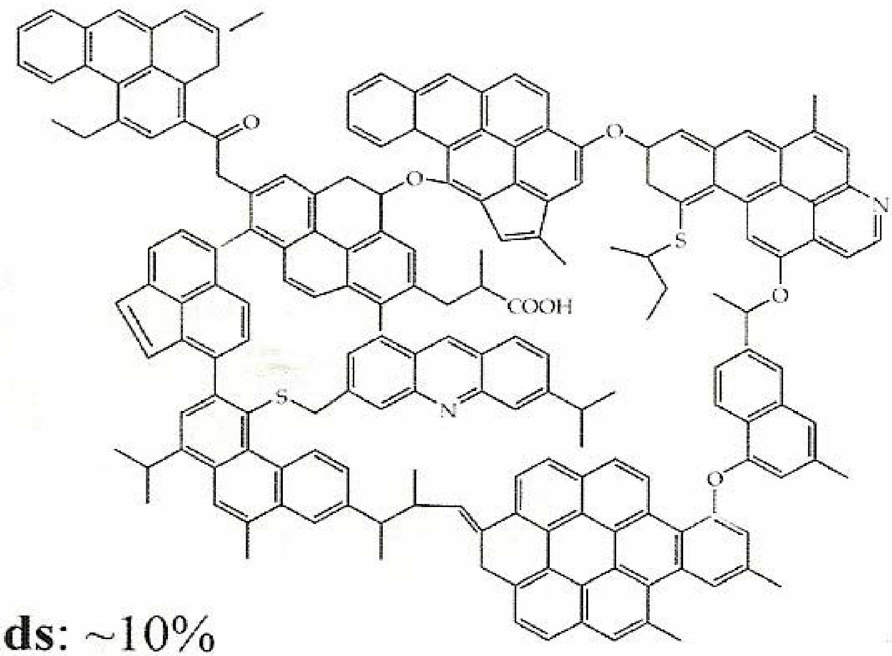
→ 2018

→ ExoMars 2016

The insoluble organic matter

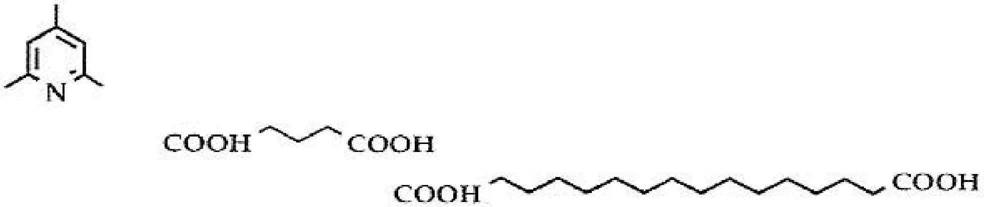
Elemental composition: $C_{100}H_{71}N_3O_{12}S_2$

Macromolecular material: ~80%



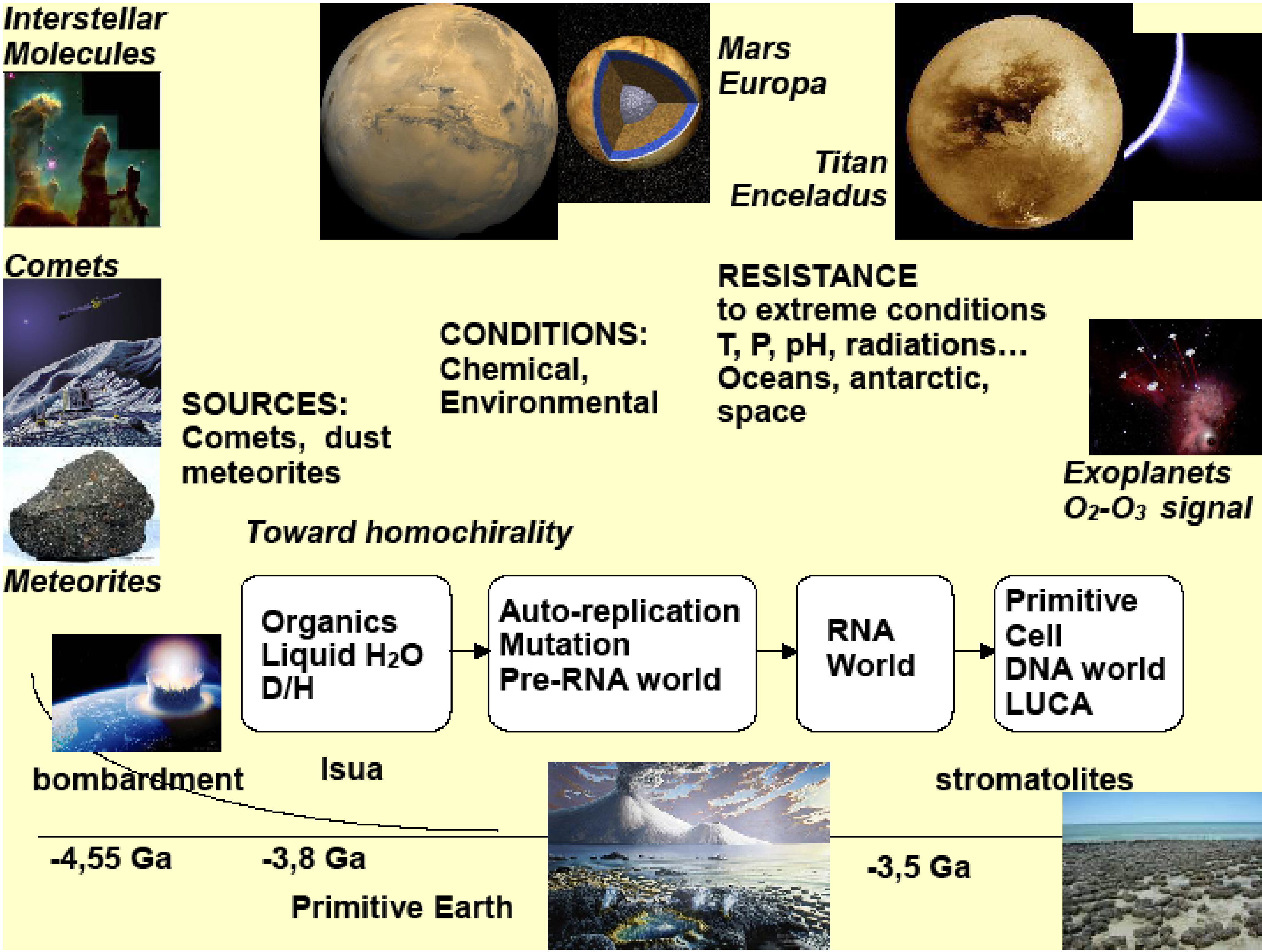
Structurally differentiated: ~10%
e.g., nano globules and tubes

Hydrothermally freeable compounds: ~10%
e.g. C_3-C_{17} dicarboxylic acids and methylated pyridines



Exotic carbon from interstellar grains: ppm
e.g., diamond, graphite, and fullerenes; SiC; Si_3N_4

From Pizzarello, in *Prebiotic Evolution and Astrobiology*, Wong & Lazcano Eds, landes Biosciences, pp. 46 (2009)



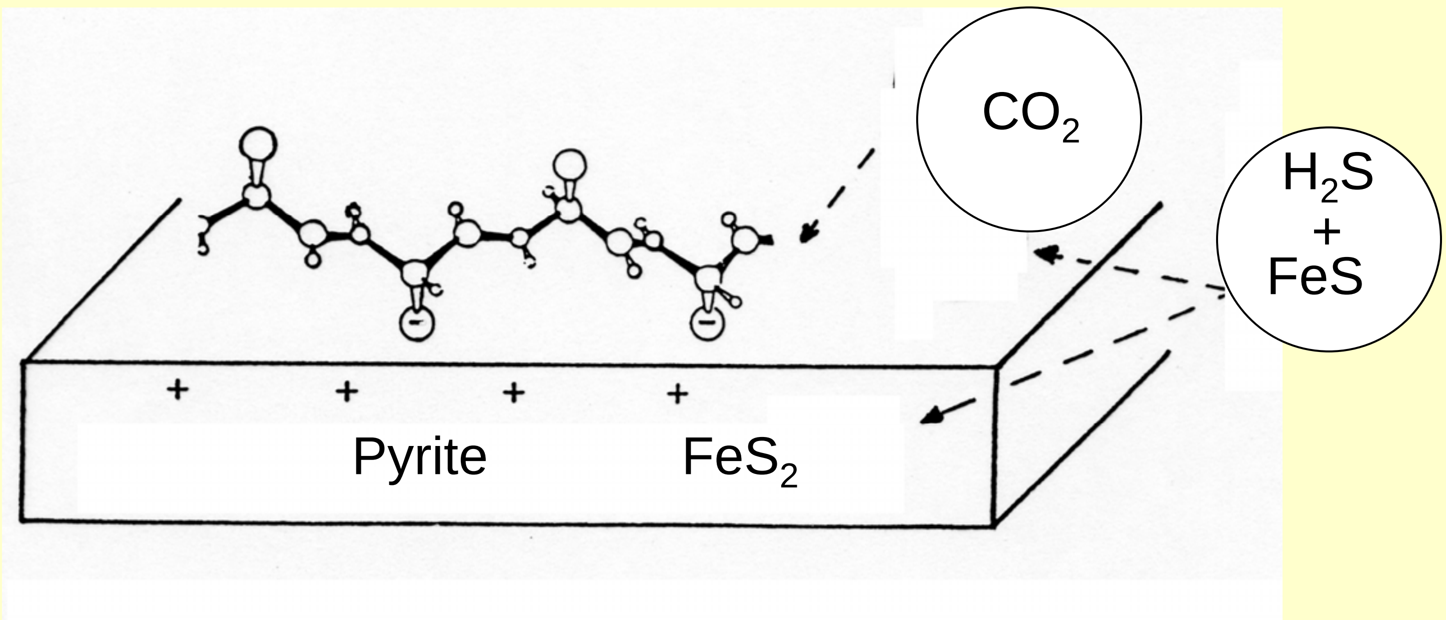
Interstellar Molecules
Mars
Europa
Titan
Enceladus
Comets
RESISTANCE
to extreme conditions
T, P, pH, radiations…
Oceans, antarctic,
space
CONDITIONS:
Chemical,
Environmental
SOURCES:
Comets, dust
meteorites
Exoplanets
O_2-O_3 signal
Toward homochirality
Meteorites
Organics
Liquid H_2O
D/H
Auto-replication
Mutation
Pre-RNA world
RNA
World
Primitive
Cell
DNA world
LUCA
bombardment
Isua
stromatolites
-4,55 Ga
-3,8 Ga
-3,5 Ga
Primitive Earth

An Iron-Sulfur world?

Mineral surface based reaction system
Chemoautotrophic mechanism « pyrite-pull reaction »

$$4CO_2 + 7H_2S + 7FeS \rightarrow (CH_2\text{-}COOH)_2 + 7\,FeS_2 + 4H_2O$$

$\Delta G° = -420$ kJ/mol



G Wächterhauser, PNAS 87, 200 (1990)

Carbonaceous matter + liquid water + Energy