Habitability:
Chemist point of view

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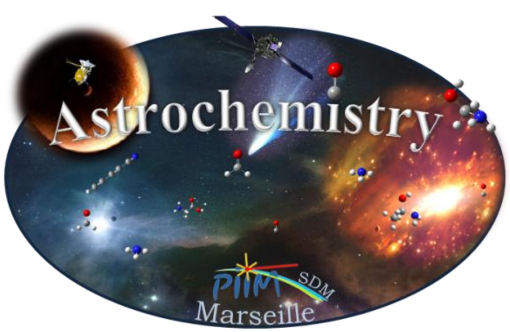

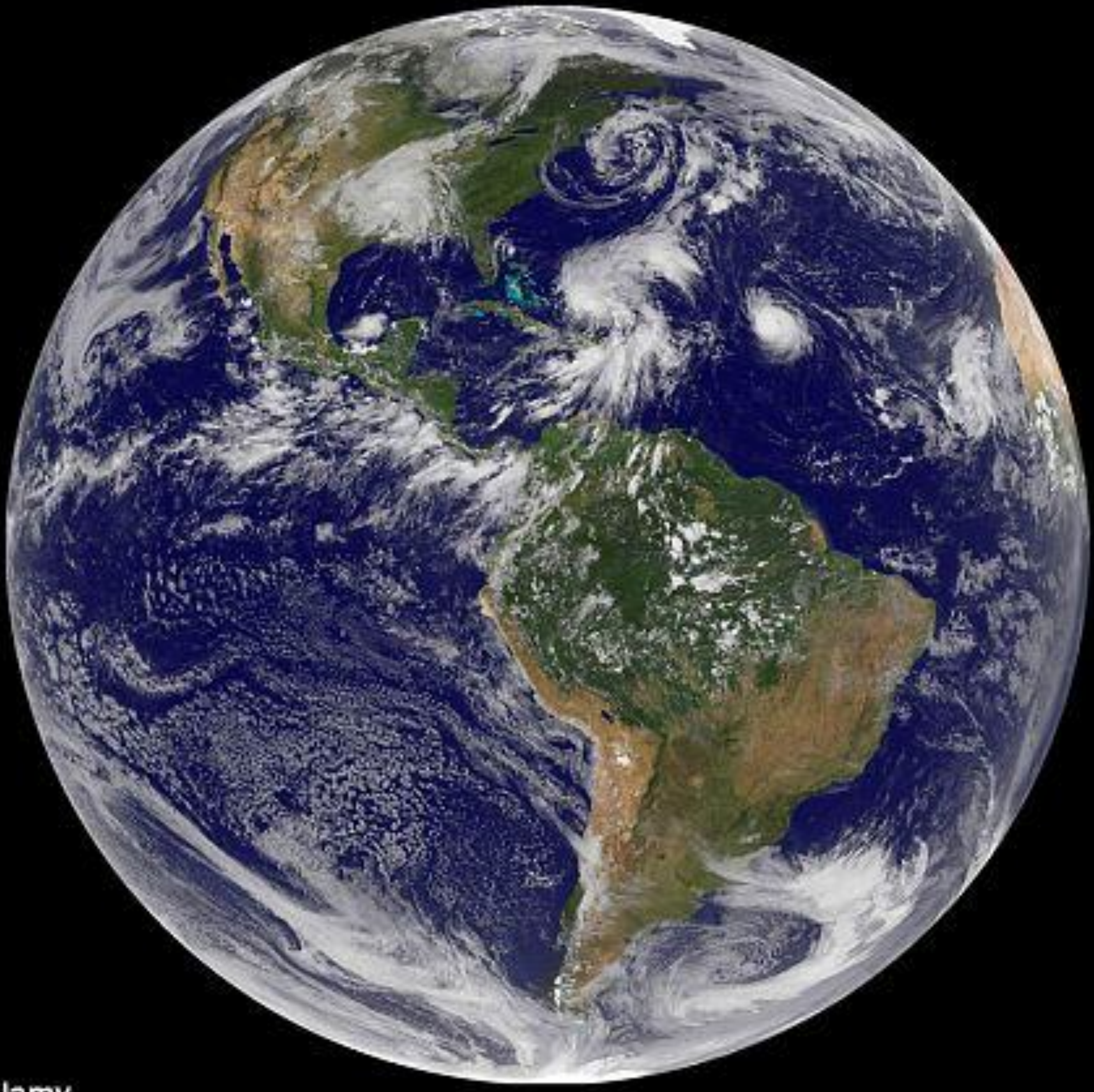

Early Earth

What conditions for the emergence of biochemical systems on Earth?

Wet environments

- **Liquid water a major constituent of living organisms**

Wet environments

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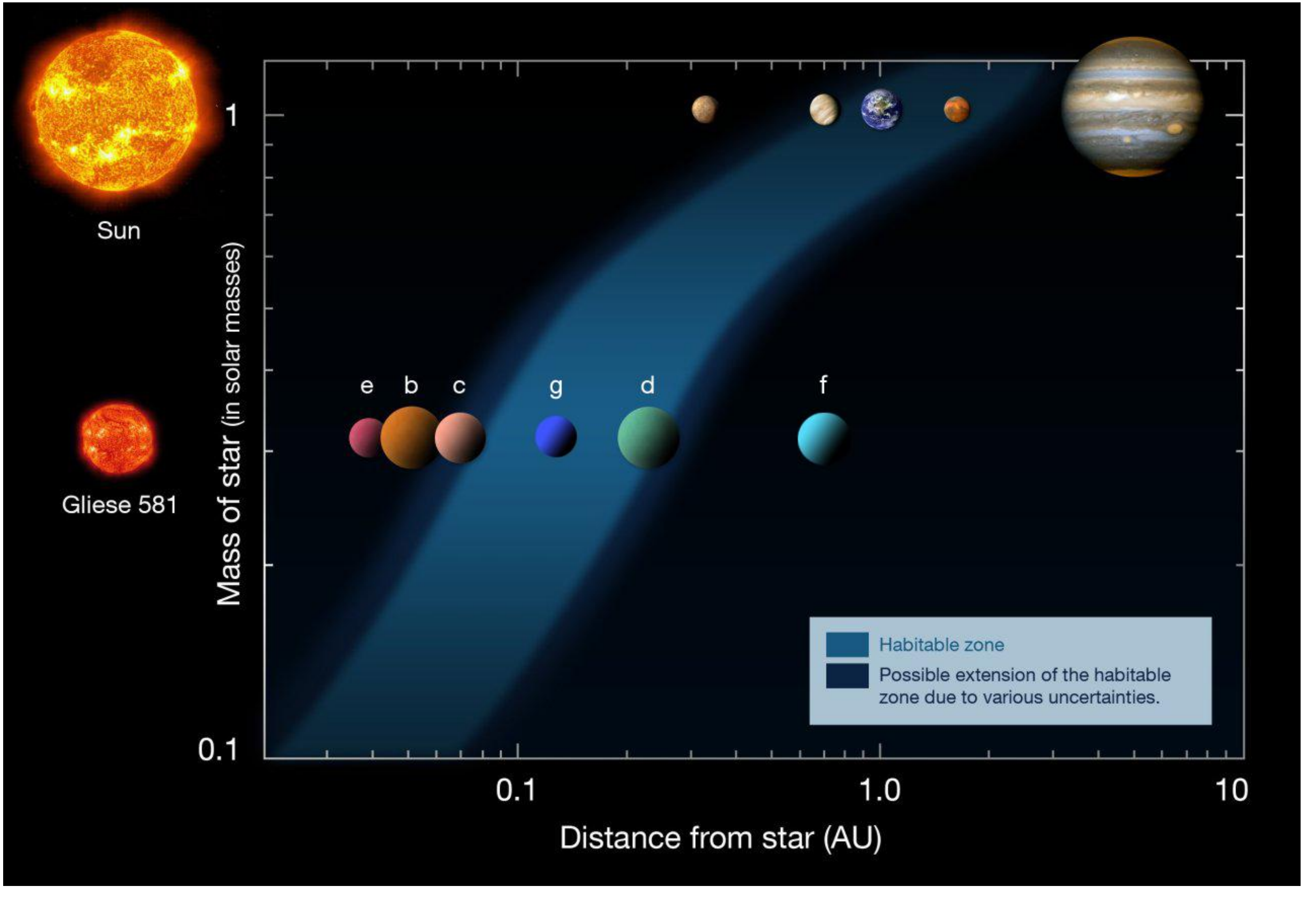


Wet environments

- **Liquid water a major constituent of living organisms**

- **Importance of liquid water in biochemical reactions**

  ✓ **Facilitate molecular diffusion from different environments**

  ✓ **Liquid state over a large range of temperature (up to 100 C at 1 atm)**

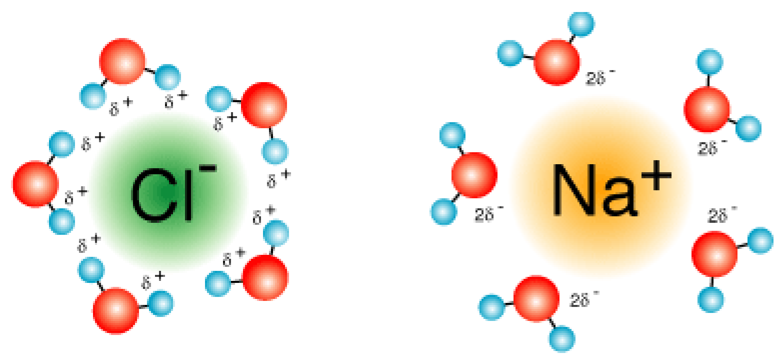
	melting point	liquid state	boiling point
CH_4 methane	91 K	Δ 21 K	112 K
NH_3 ammonia	195 K	Δ 44 K	239 K
H_2O water	273 K	Δ 100 K	373 K

Wet environments

- **Liquid water a major constituent of living organisms**

- **Importance of liquid water in biochemical reactions**

  - ✓ **Facilitate molecular diffusion from different environments**
  - ✓ **Liquid state over a large range of temperature (up to 100 C at 1 atm)**
  - ✓ **High polarity allowing to dissolve ions and polar molecules**



Slightly positive hydrogen are attracted to chlorine anions

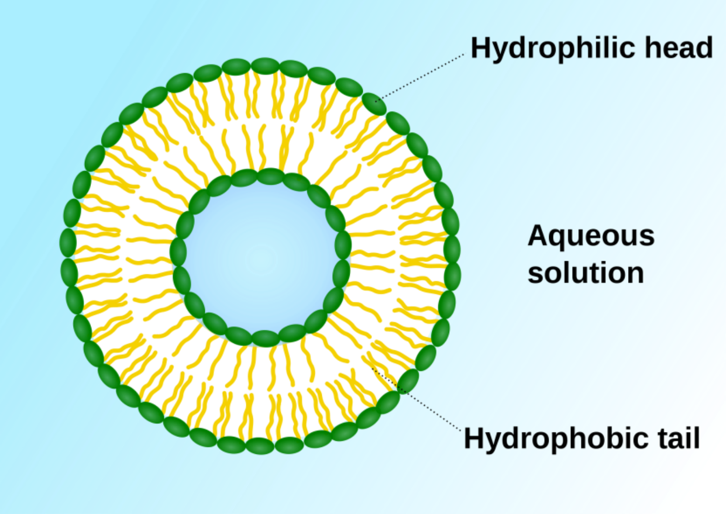
Slightly negative oxygen are attracted to sodium cations

Wet environments

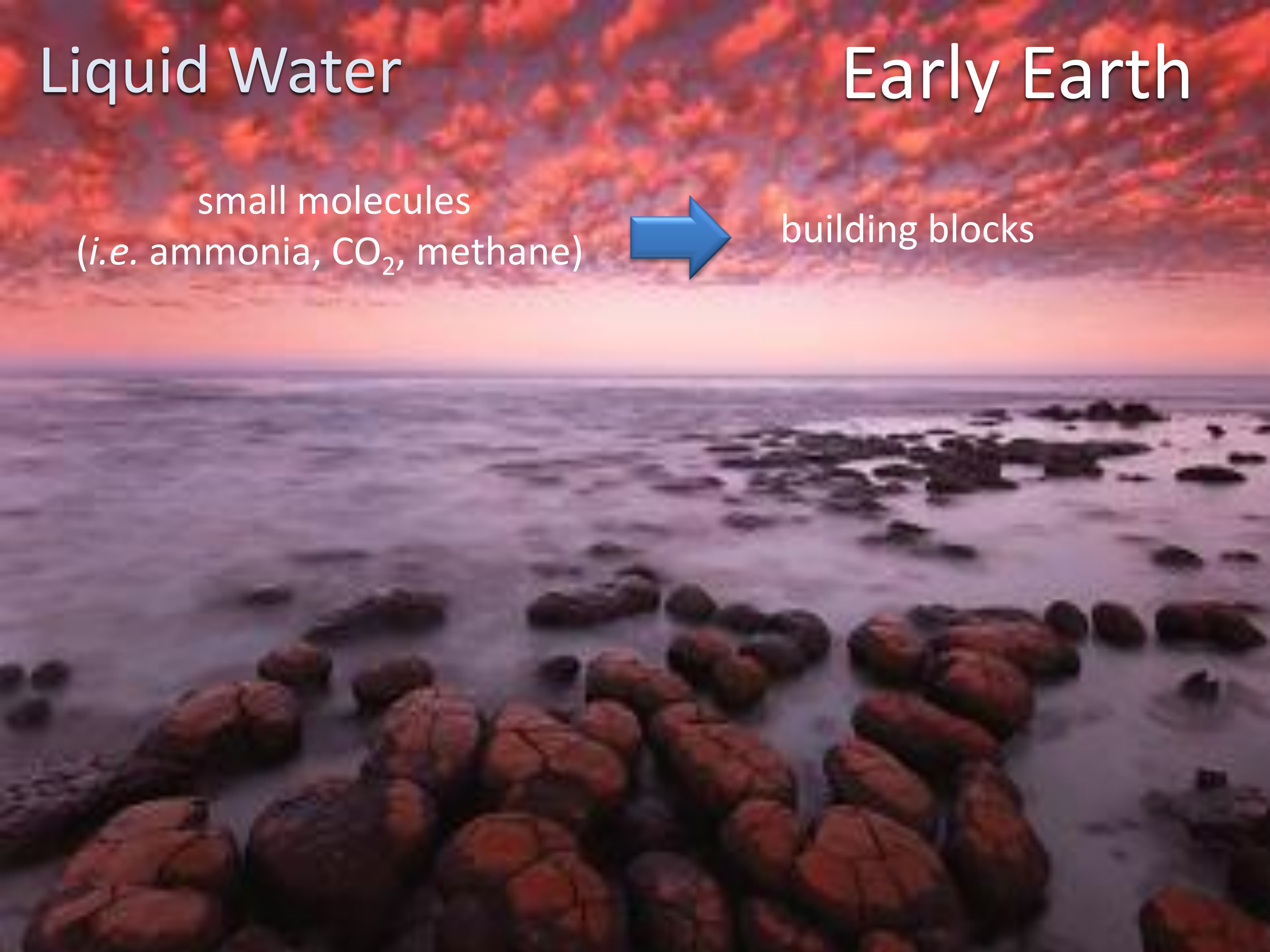
- **Liquid water a major constituent of living organisms**

- **Importance of liquid water in biochemical reactions**

  - ✓ **Facilitate molecular diffusion from different environments**
  - ✓ **Liquid state over a large range of temperature (up to 100 C at 1 atm)**
  - ✓ **High polarity allowing to dissolve ions and polar molecules**
  - ✓ **Hydrogen bond network facilitating proton exchanges**
  - ✓ **Induce hydrophobic interaction**

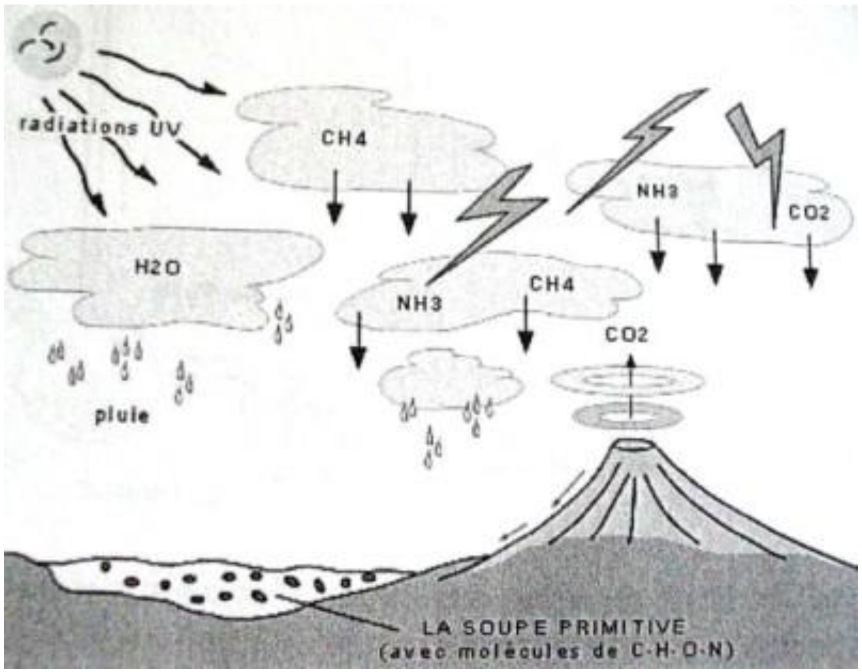


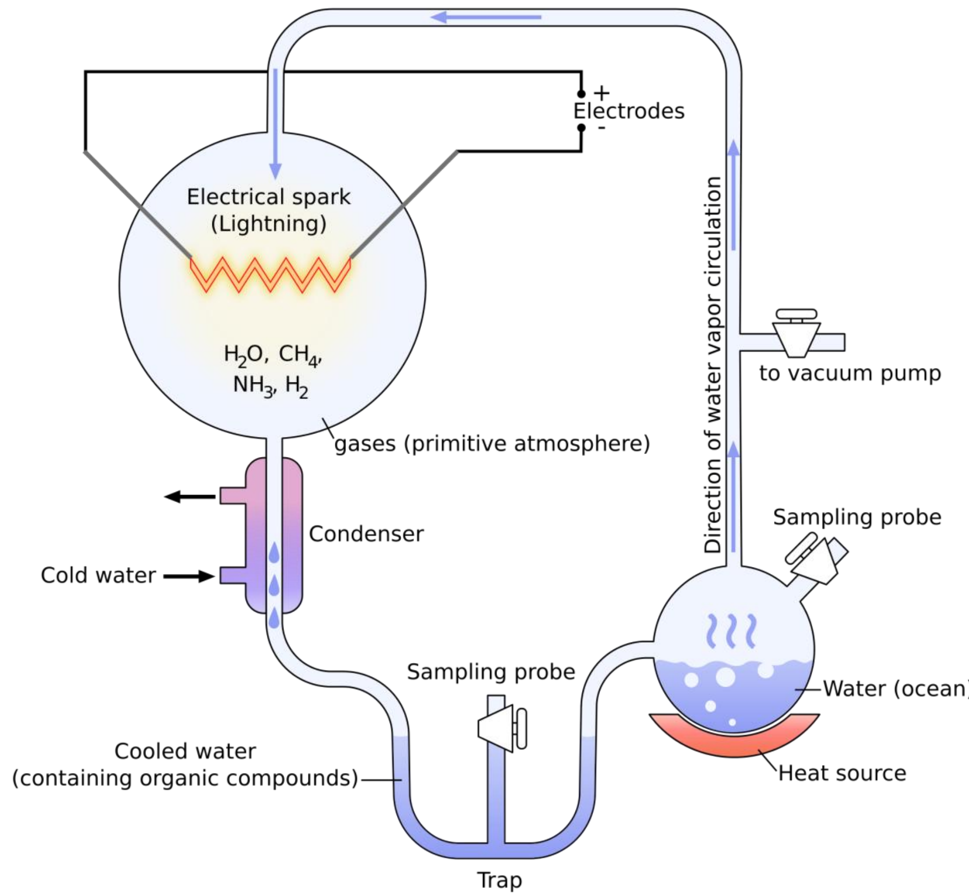

Liquid Water
Early Earth


Liquid Water
Early Earth
small molecules
(*i.e.* ammonia, CO_2, methane)
building blocks

Endogenous origin of organic matter

- **The Miller's experiment: organic synthesis in the primitive Earth atmosphere**



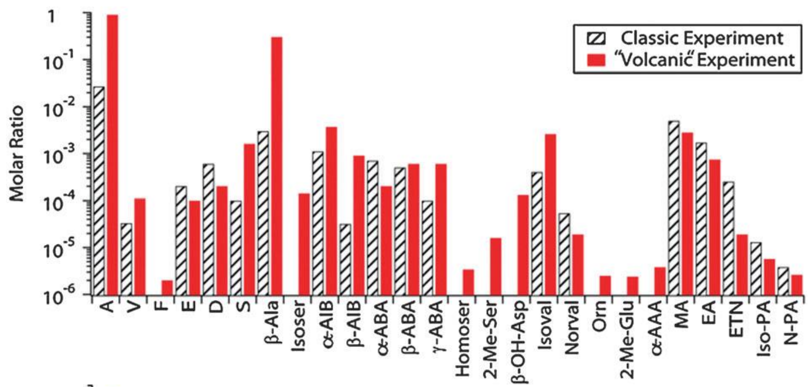


Miller et al., 1953, Science, 117, 528

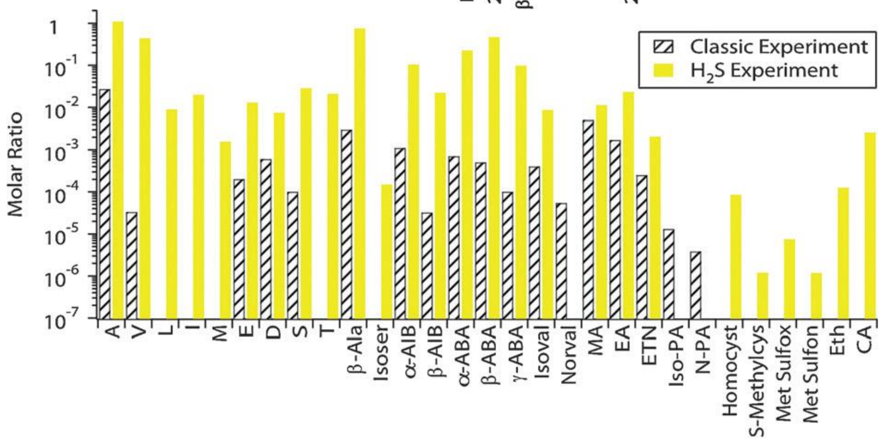
Endogenous origin of organic matter

- **The Miller's experiment: organic synthesis in the primitive Earth atmosphere**

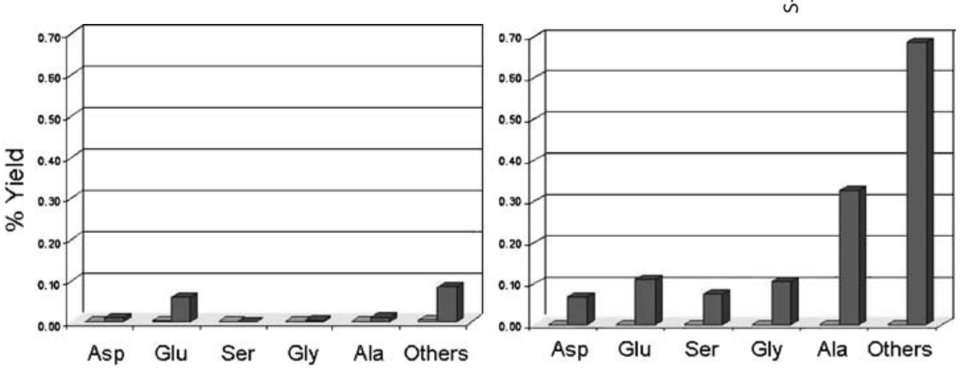
Amino acid formation



Reductive conditions
Atmosphere
$CH_4/H_2O/NH_3/N_2/H_2$



Reductive conditions
Volcano
$CH_4/CO_2/H_2O/NH_3/H_2S$



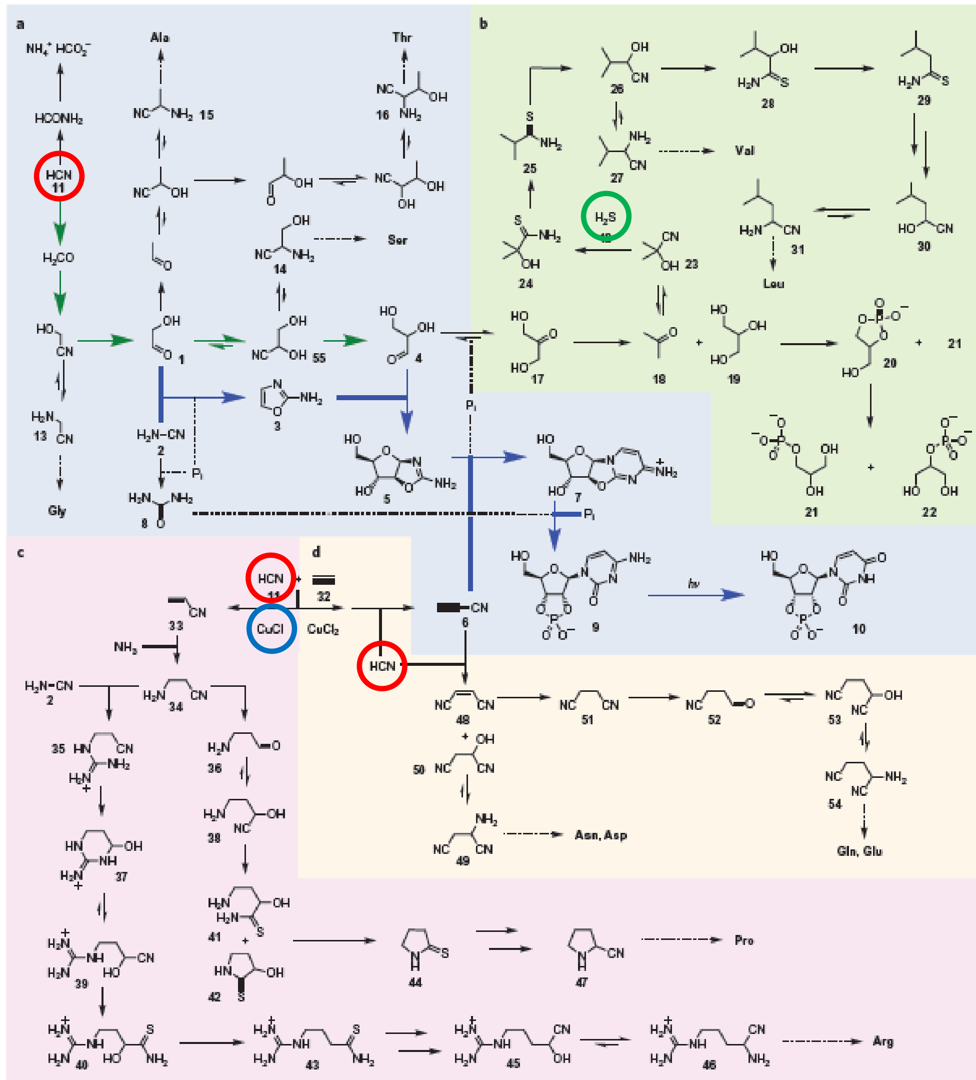
Neutral conditions
$CO_2/N_2/H_2O/CO + \varepsilon\ H_2S/CH_4/H_2$
Carbonate buffer pH 6
antioxidant (Fe^{2+})

Bada et al., 2013, Chemical Society Review, 42, 2186-89

Endogenous origin of organic matter

- **The Sutherland's experiment: All you need**

From HCN, H_2S, Cu and UV light (254 nm)



Patel et al., 2015, Nature Chemistry, 7, 301-307

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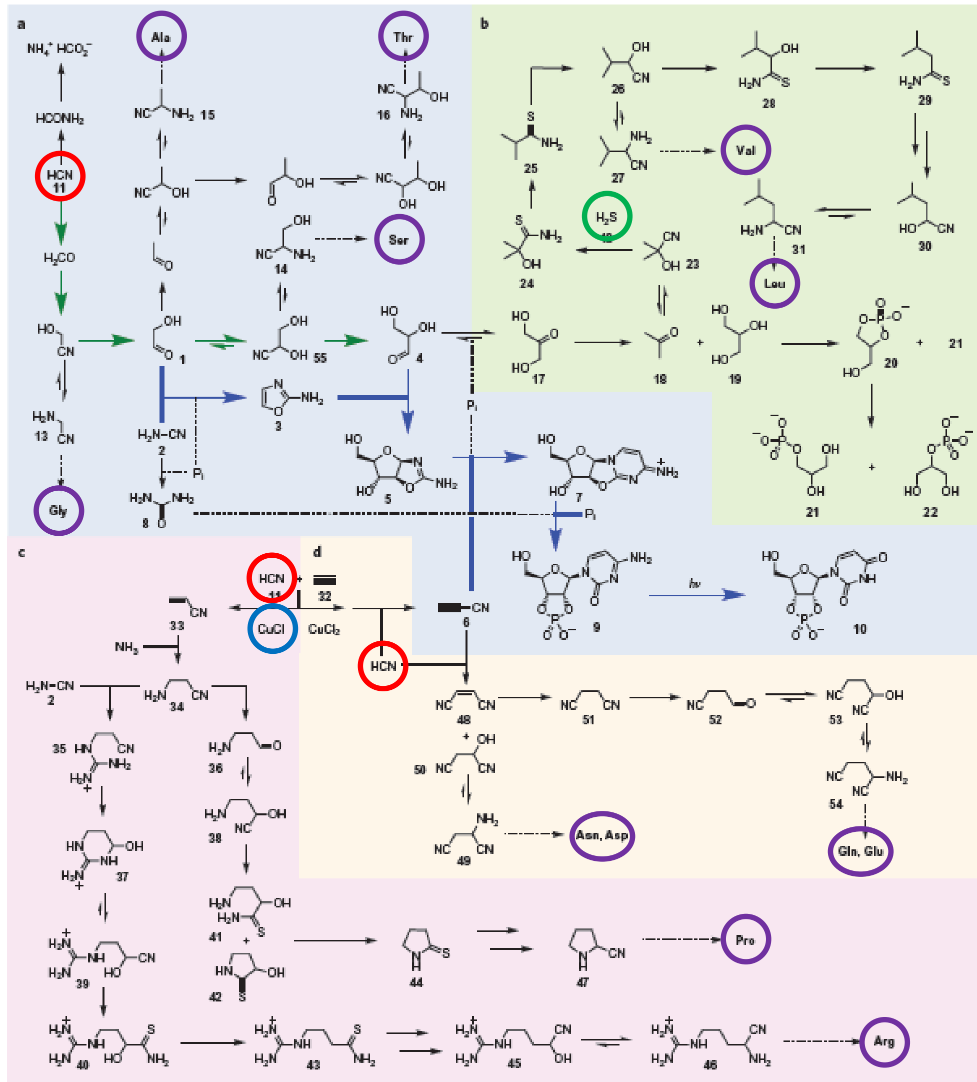

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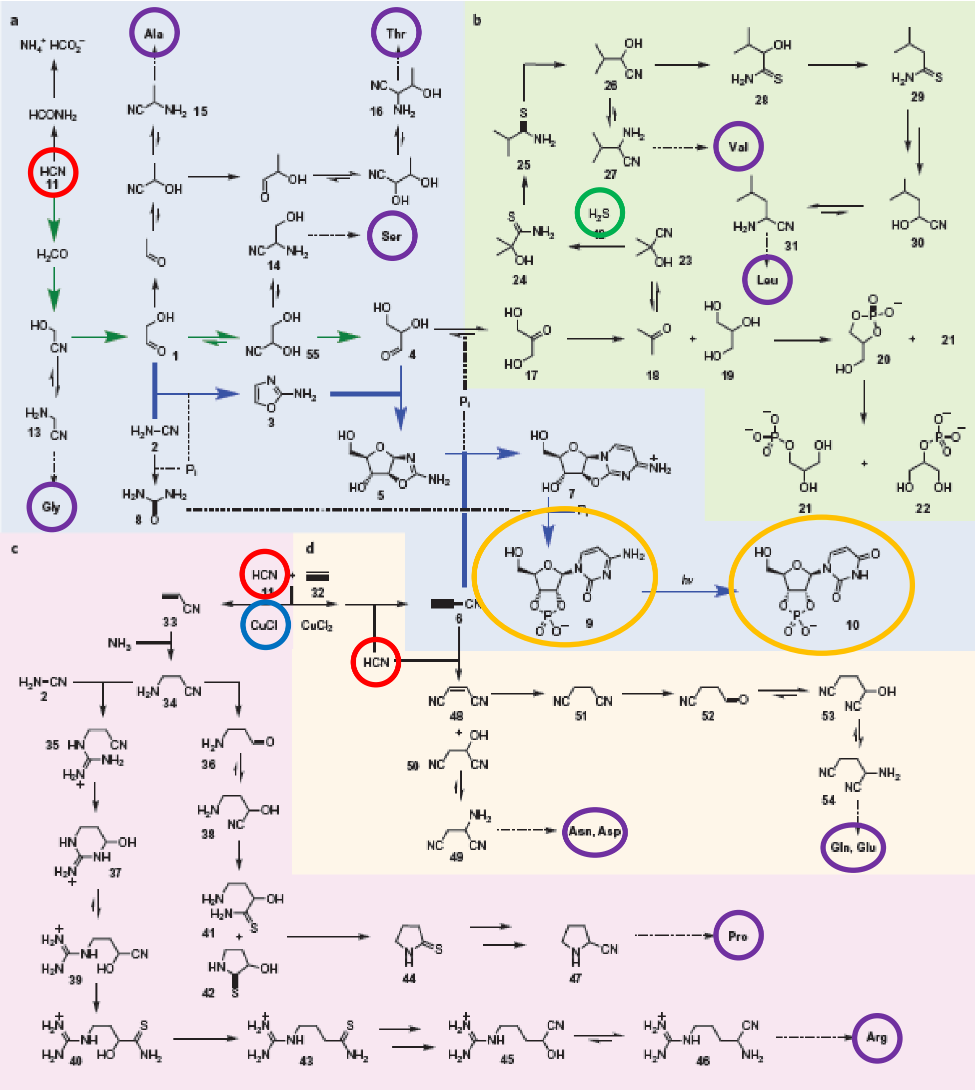
✓Amino acids

✓ Nucleotides



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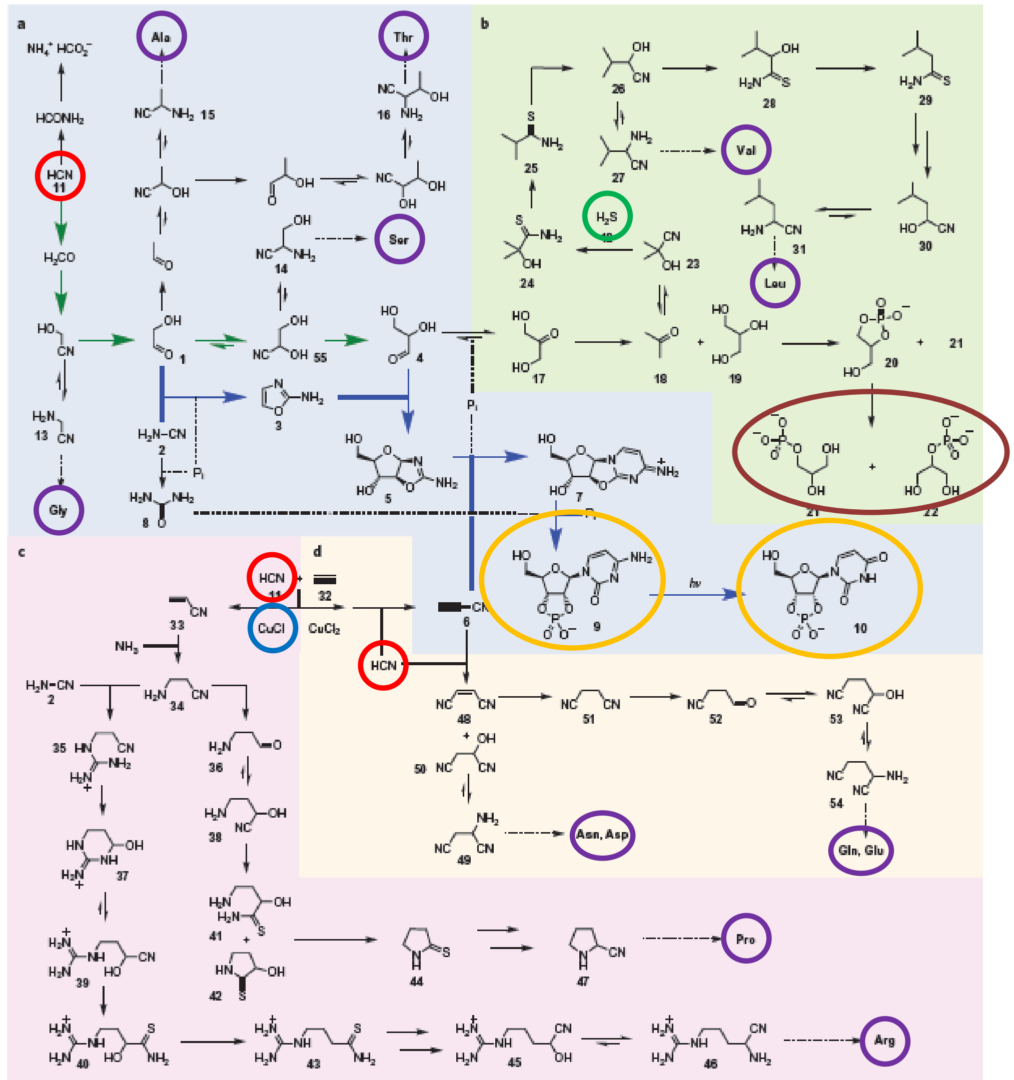
Endogenous origin of organic matter

The Sutherland's experiment: All you need

From HCN, H_2S, Cu and UV light (254 nm)

- ✓ Amino acids
- ✓ Nucleotides
- ✓ Phospholipid precursors



Patel et al., 2015, Nature Chemistry, 7, 301-307

Endogenous origin of organic matter

- **The Sutherland's experiment: All you need**

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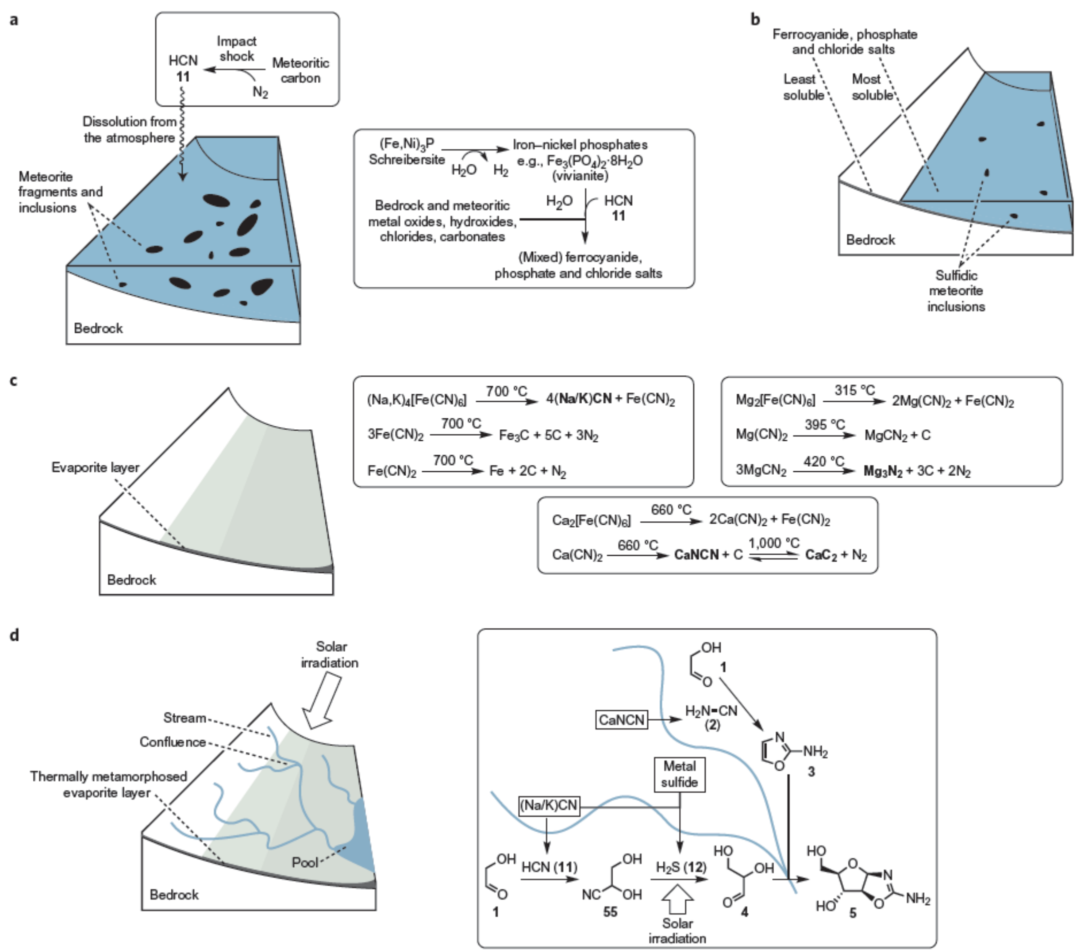
Chemistry in a post-impact scenario



Patel et al., 2015, Nature Chemistry, 7, 301-307

Exogenous source of organic matter

➡ **chondrite carbonaceous meteorites:**

Carbonaceous matter

75-95% of insoluble organic molecules

5-25% of soluble organic matter

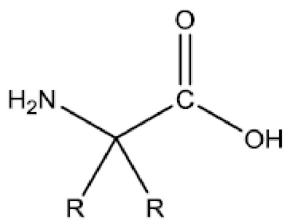
Soluble Organic Matter (SOM)

Chemical treatment: extraction (H_2O, 100 C; hydrolysis HCl 6M) et derivatization

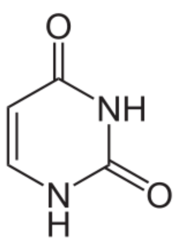
More than 500 structures identified

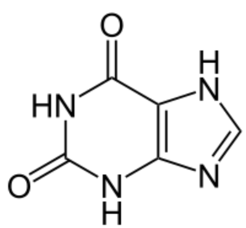
Insoluble Organic Matter (IOM)	Abundance
Macromolecular material ($C_{100}H_{70}N_3O_{12}S_2$)	70-99% total organic C
Soluble Organic Matter (SOM)	**Concentration (ppm)**
Carboxylic acids	>300
Polar hydrocarbons	<120
Sulfonic acids	67
Amino acids (83 named)	60
Dicarboxyimides	>50
Aliphatic hydrocarbons	>35
Dicarboxylic acids	>30
Polyols	30
Aromatic hydrocarbons	15-28
Hydroxy acids	15
Amines	13
Pyridine carboxylic acids	>7
N-heterocycles	7
Phosphonic acids	2
Purines and pyrimidines	1

Pizzarello et al., *Meteorites and the Early Solar System II, 2006, 625-651*



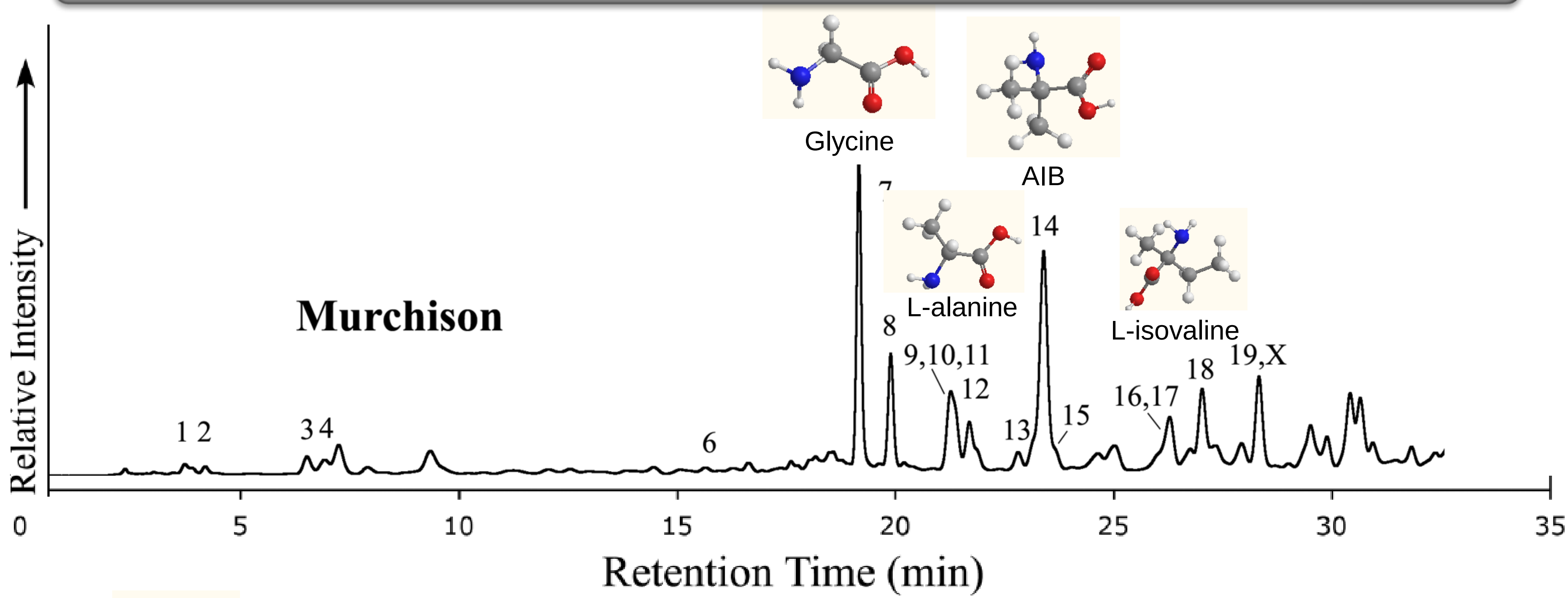
Amino acids



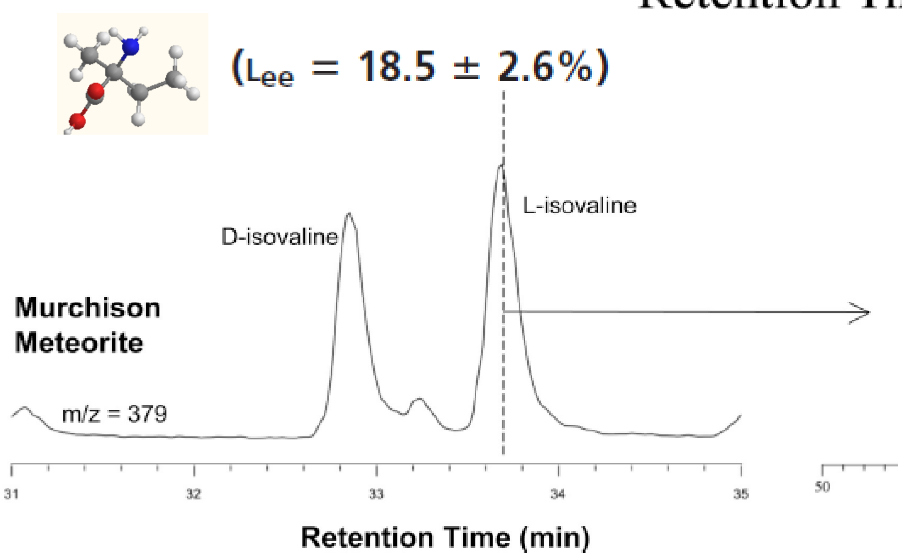


Nucleobases : uracile xanthine

Targeted analyzes of the soluble organic matter in chondritic meteorites



Glavin et al., *Meteor.Planet.Sci.*, ***41*** *(2006) 889-902*



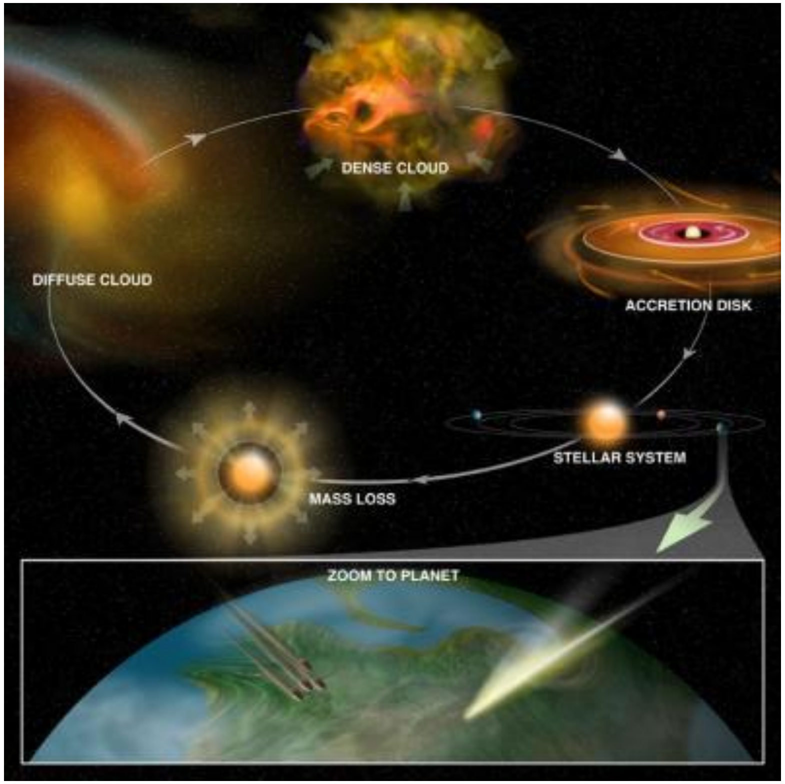
Glavin et al., *PNAS,* ***106*** *(2009) 5487-5492*

Enantiomeric exces on amino acids

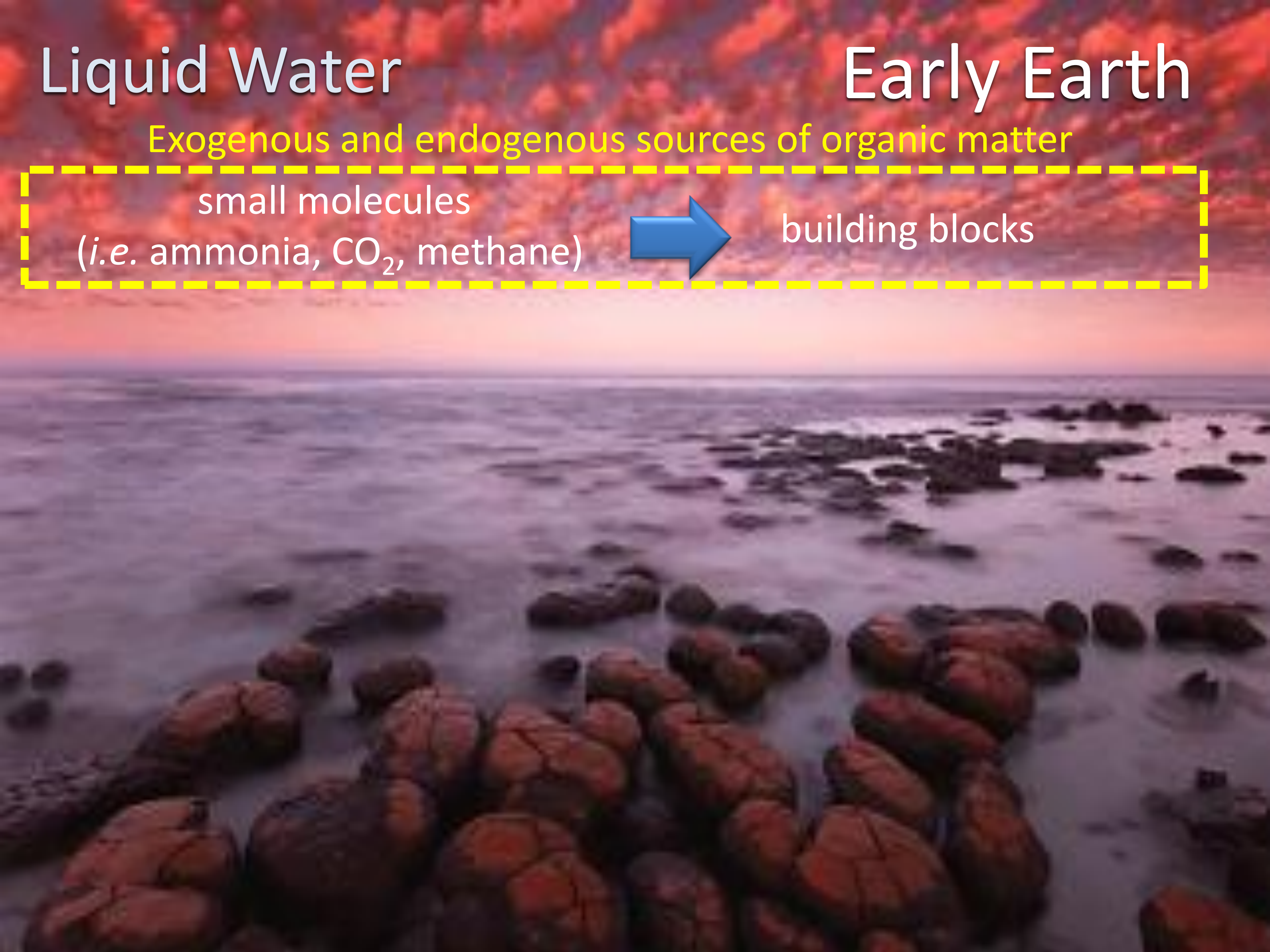
Link between extraterrestrial organic matter and the emergence of homochirality on Earth?

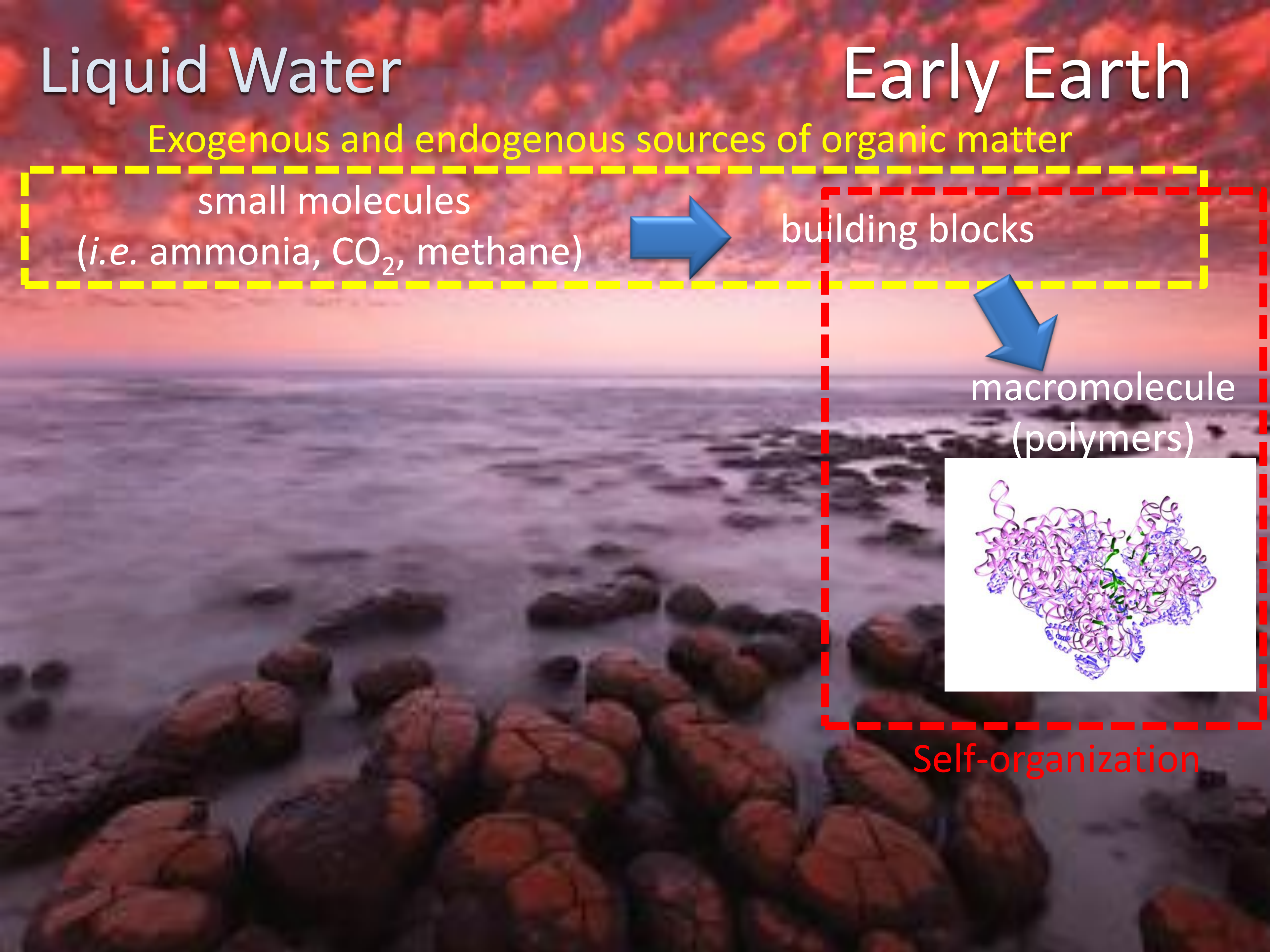
Pizzarello et al., *Chem.Biodiveristy,* ***4*** *(2007) 680-693*

Evolution of interstellar icy grains toward the formation of complex organic molecules in interplanetary objects

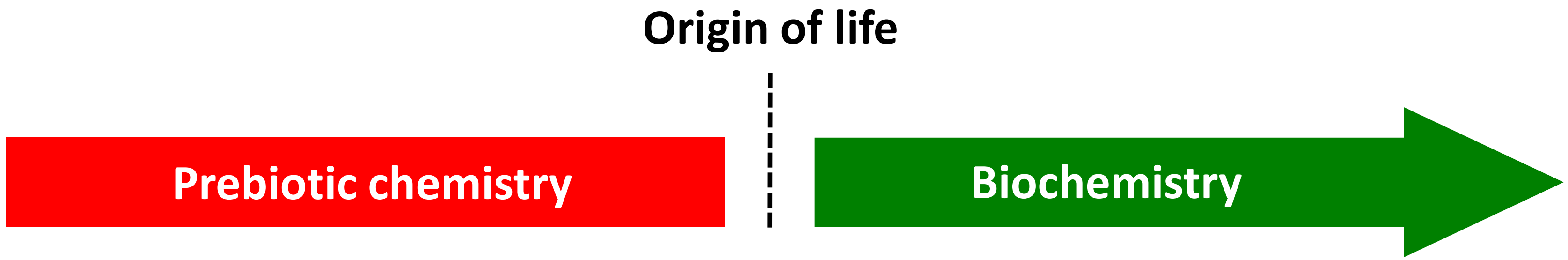


- ✓ **A rich and universal reservoir of organic molecules**
- ✓ **Can seed planets with organic molecules via interplanetary bodies**
- ✓ **May be one of the most important source of organic matter for starting chemical evolutions toward life**


Liquid Water
Early Earth
Exogenous and endogenous sources of organic matter
small molecules
(*i.e.* ammonia, CO_2, methane)
building blocks


Liquid Water
Early Earth
Exogenous and endogenous sources of organic matter
small molecules
(*i.e.* ammonia, CO_2, methane)
building blocks
macromolecule
(polymers)
Self-organization

A search for the origin of life



Prebiotic chemistry: How form complex structures in molecular terms or chemical networks.

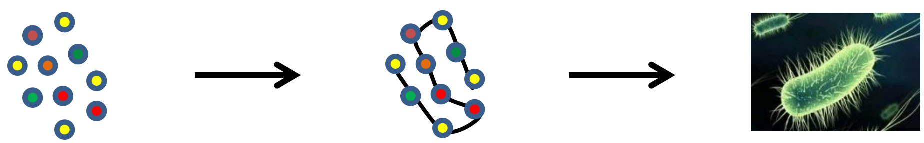
A search for the origin of life

Origin of life

Prebiotic chemistry | **Biochemistry**

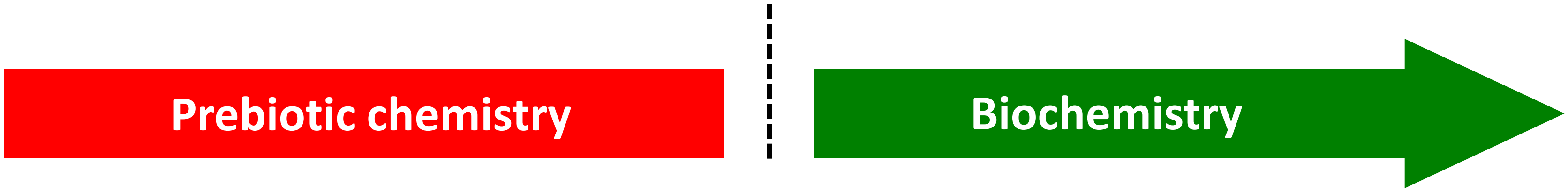
Prebiotic chemistry: How form complex structures in molecular terms or chemical networks.

1- Building blocks from extraterrestrial and planetary reservoir.



A search for the origin of life

Origin of life



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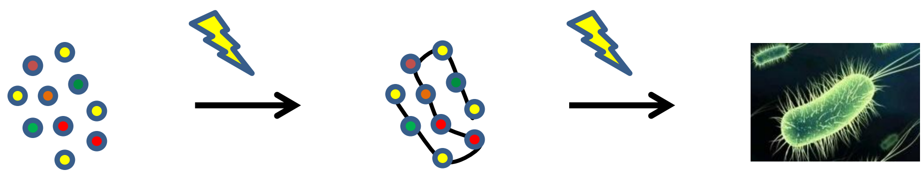
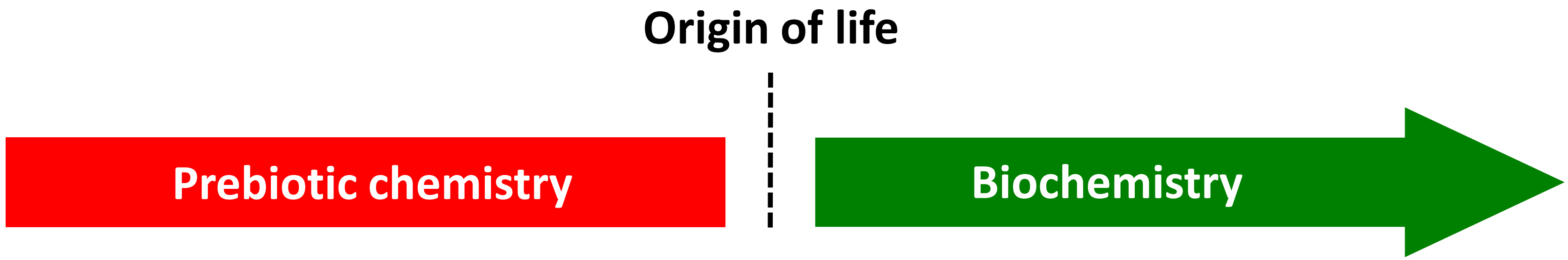


2- Energy

A search for the origin of life



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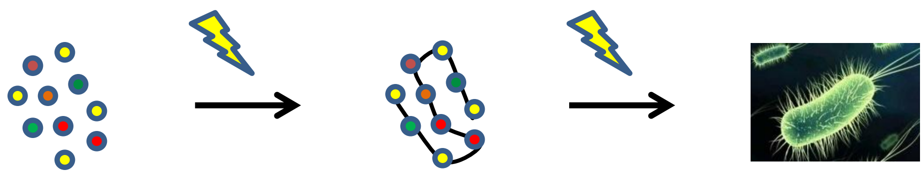
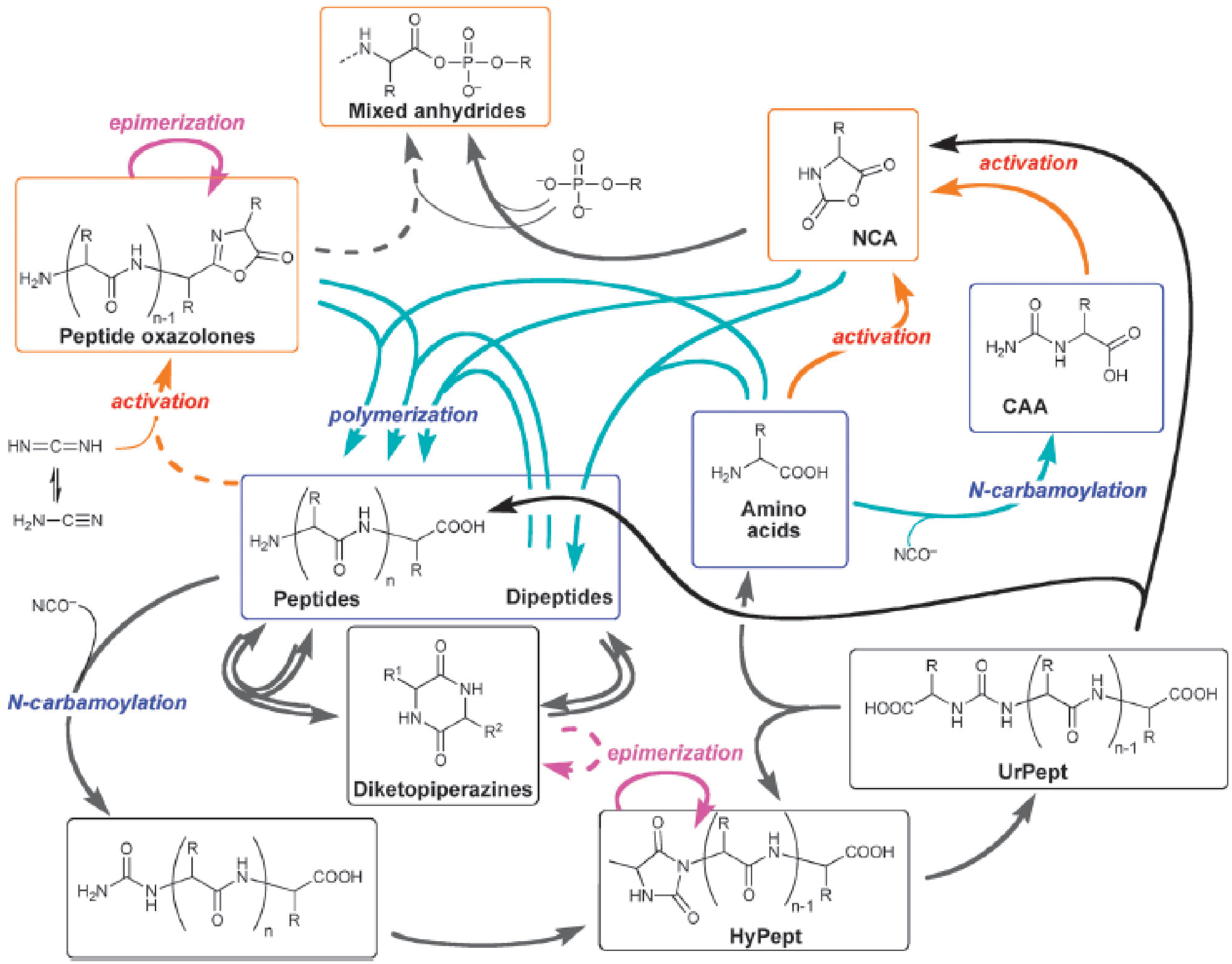


2- Energy

3- Self-organization of organic matter

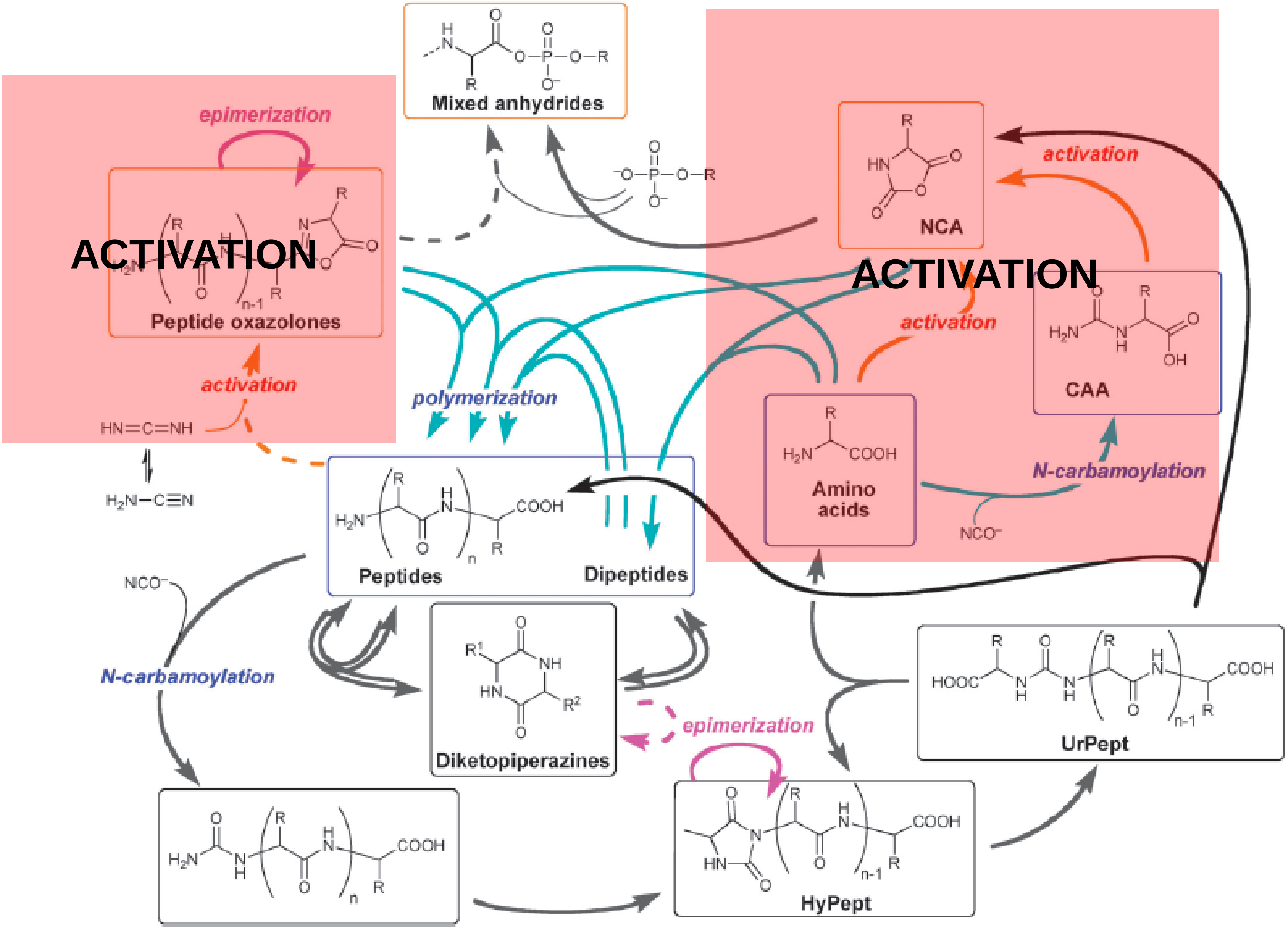
Formation of proteins



Scheme 13 Overall view of selected pathways identified from experiments or presumed from the analysis of the literature, which could constitute the systems chemistry of α-amino acids and peptides in prebiotic aqueous environments at values of pH close to neutrality. The network is based on the reactivity of four cyclic intermediates, namely NCAs, 5(4*H*)-oxazolones, hydantoins, and diketopiperazines, which are involved in reaction loops and introduce possibilities of racemization/epimerization. The high reactivity of NCAs and 5(4*H*)-oxazolones gives rise to possibilities of connection with nucleotide chemistry.

Danger et al., *Chem.Soc.Rev.*, **41** (2012) 5416-5429

Formation of proteins



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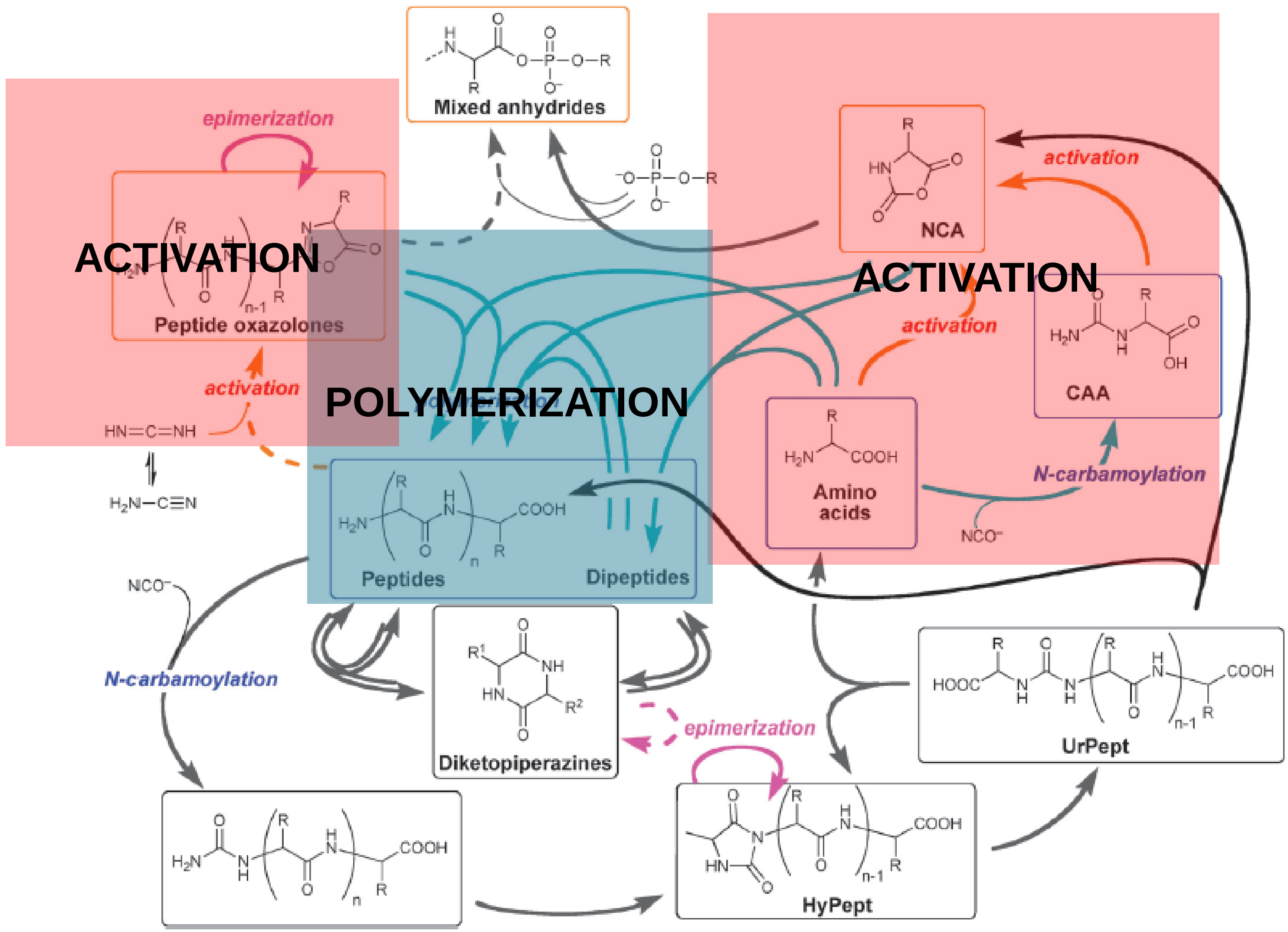

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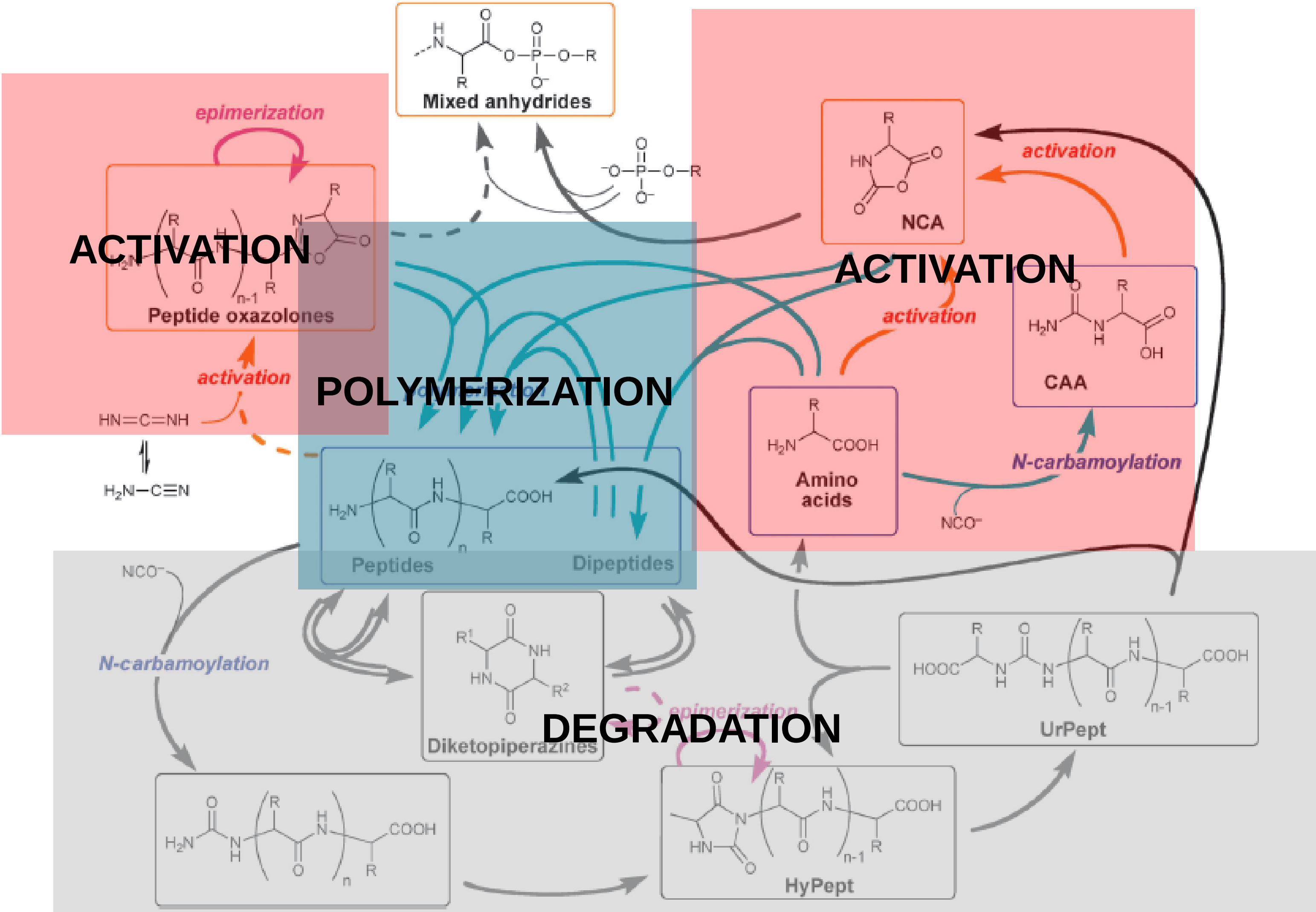

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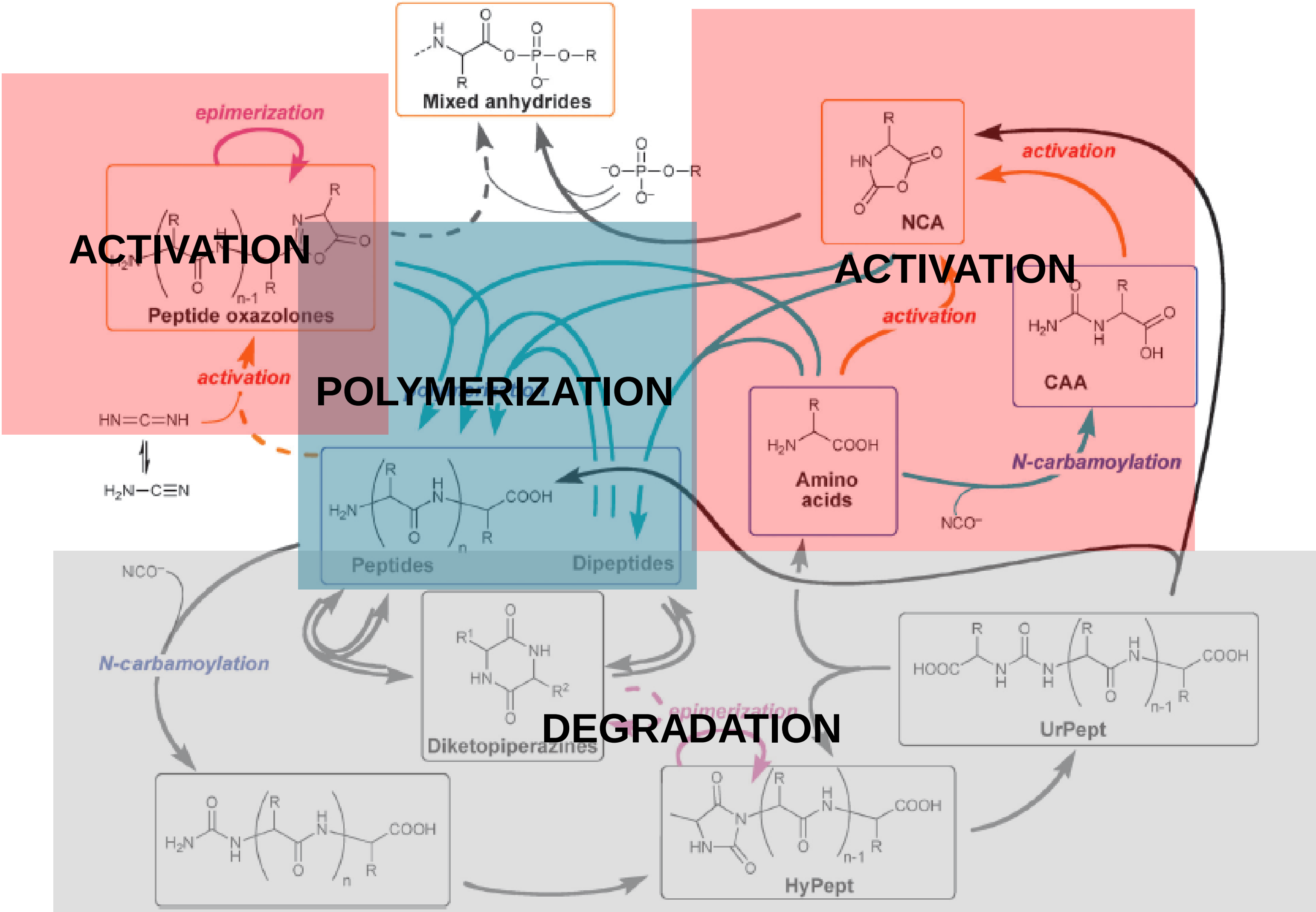

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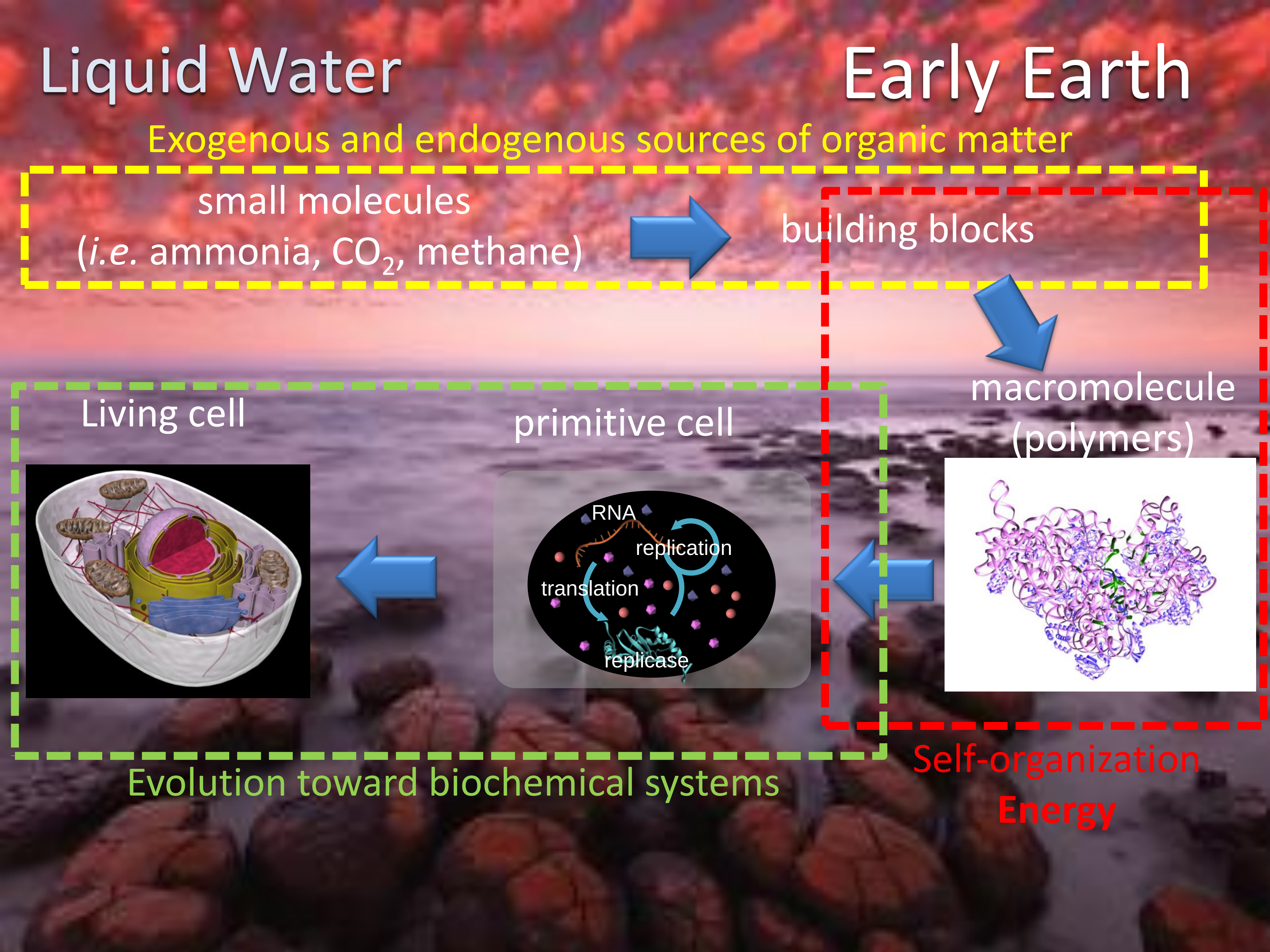
SELECTIVITY and EVOLUTION

Danger et al., *Chem.Soc.Rev.*, **41** (2012) 5416-5429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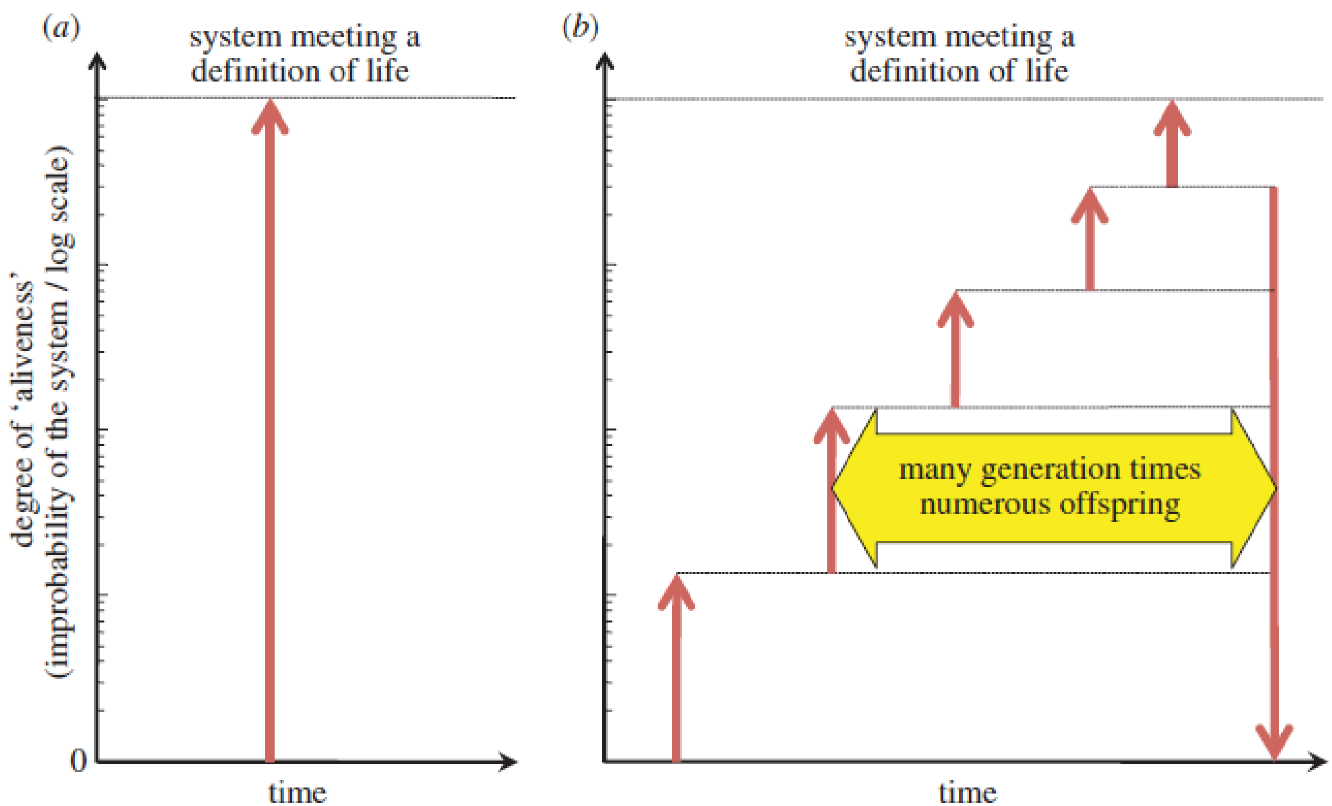
macromolecule
(polymers)
Living cell
primitive cell
RNA
replication
translation
replicase
Evolution toward biochemical systems
Self-organization
Energy

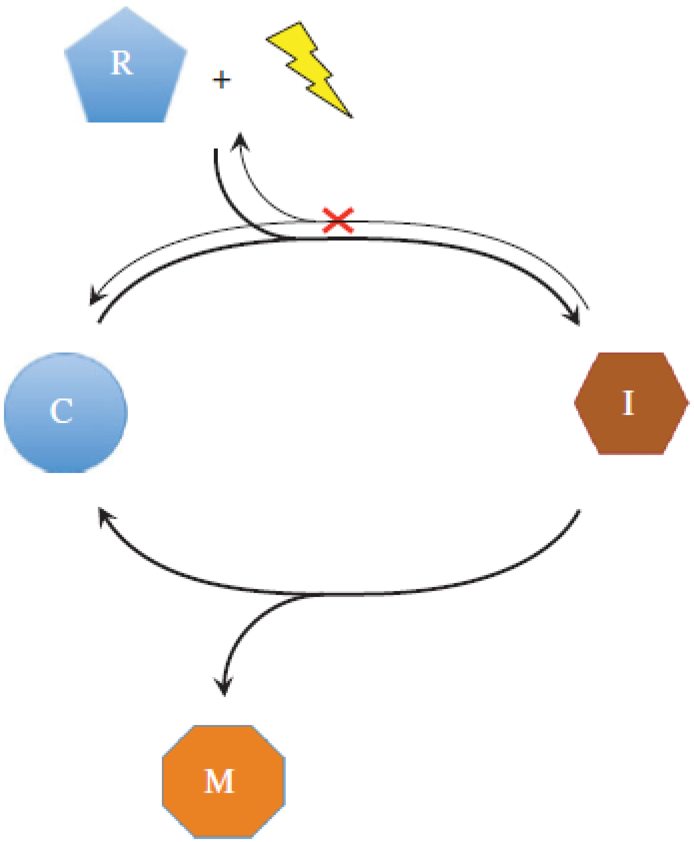
Replicators for chemical evolution



Scheme 1. The emergence of life considered as a transition to a highly improbable system. (*a*) Abrupt transition induced by a highly improbable random event in contradiction with the 2nd Law; (*b*) Stepwise process in which intermediate steps (there is in principle no limitation to the number of steps) allow further evolution towards greater degrees of organization on the basis of entities that are capable of reproducing themselves and, therefore, that exhibit a significant persistence before reverting to the unorganized state (right arrow). The choice of a logarithmic scale of improbability for characterizing 'aliveness' as the ordinate is purely arbitrary, but in line with the characterization of the emergence of life as an event of low probability.

R. Pascal, A. Pross, J. D. Sutherland *Open Biol.* **2013**, *3*, 130156

Emergence of replicative systems



Autocatalytic systems

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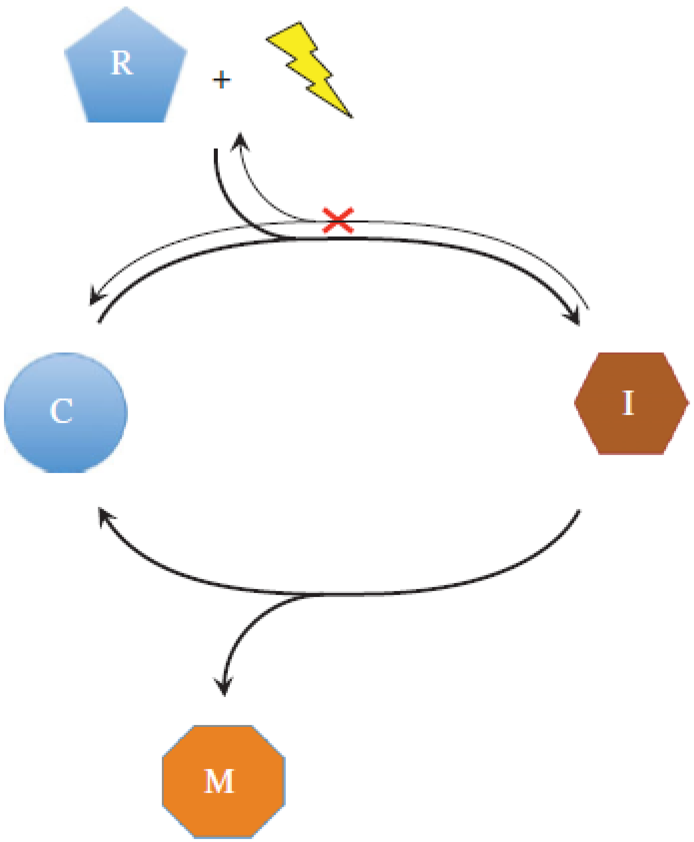
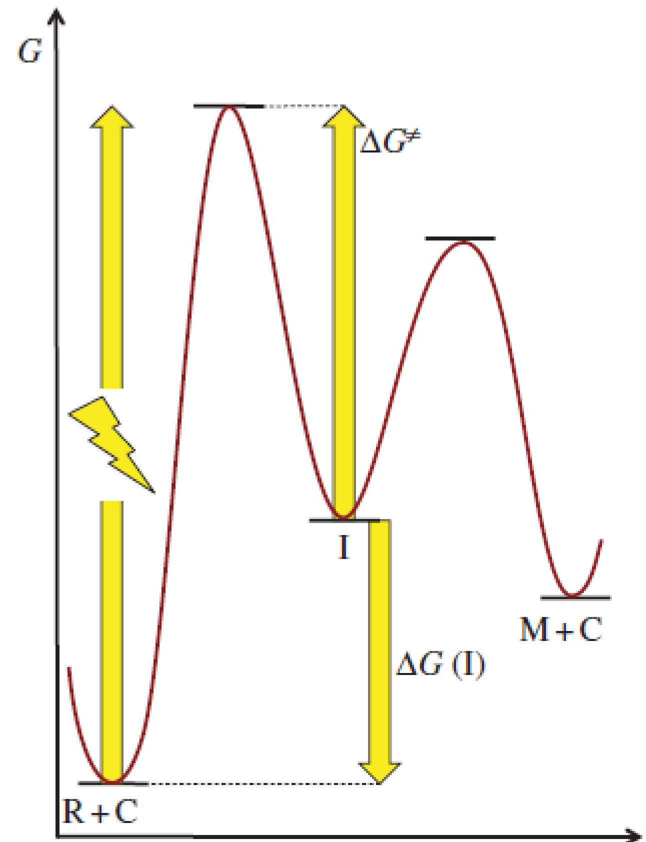


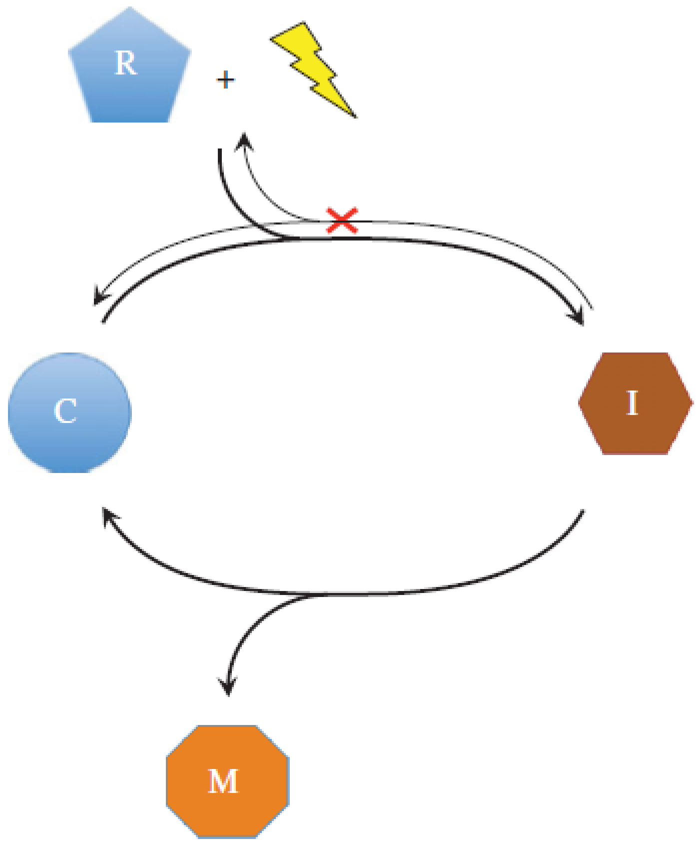


Autocatalytic systems

Irreversibility
Kinetic stability

R. Pascal, A. Pross, J. D. Sutherland *Open Biol.* **2013**, *3*, 130156

Emergence of replicative systems



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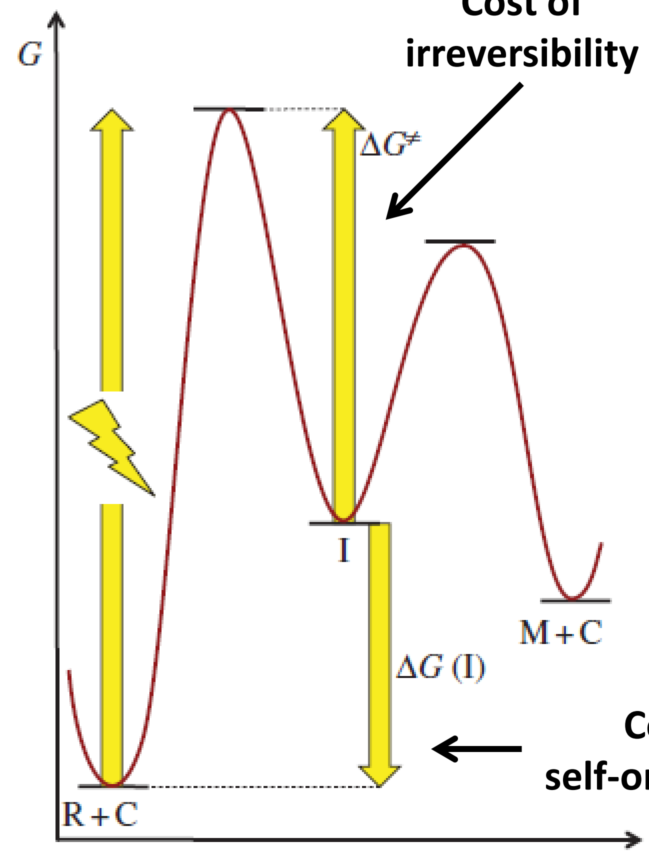

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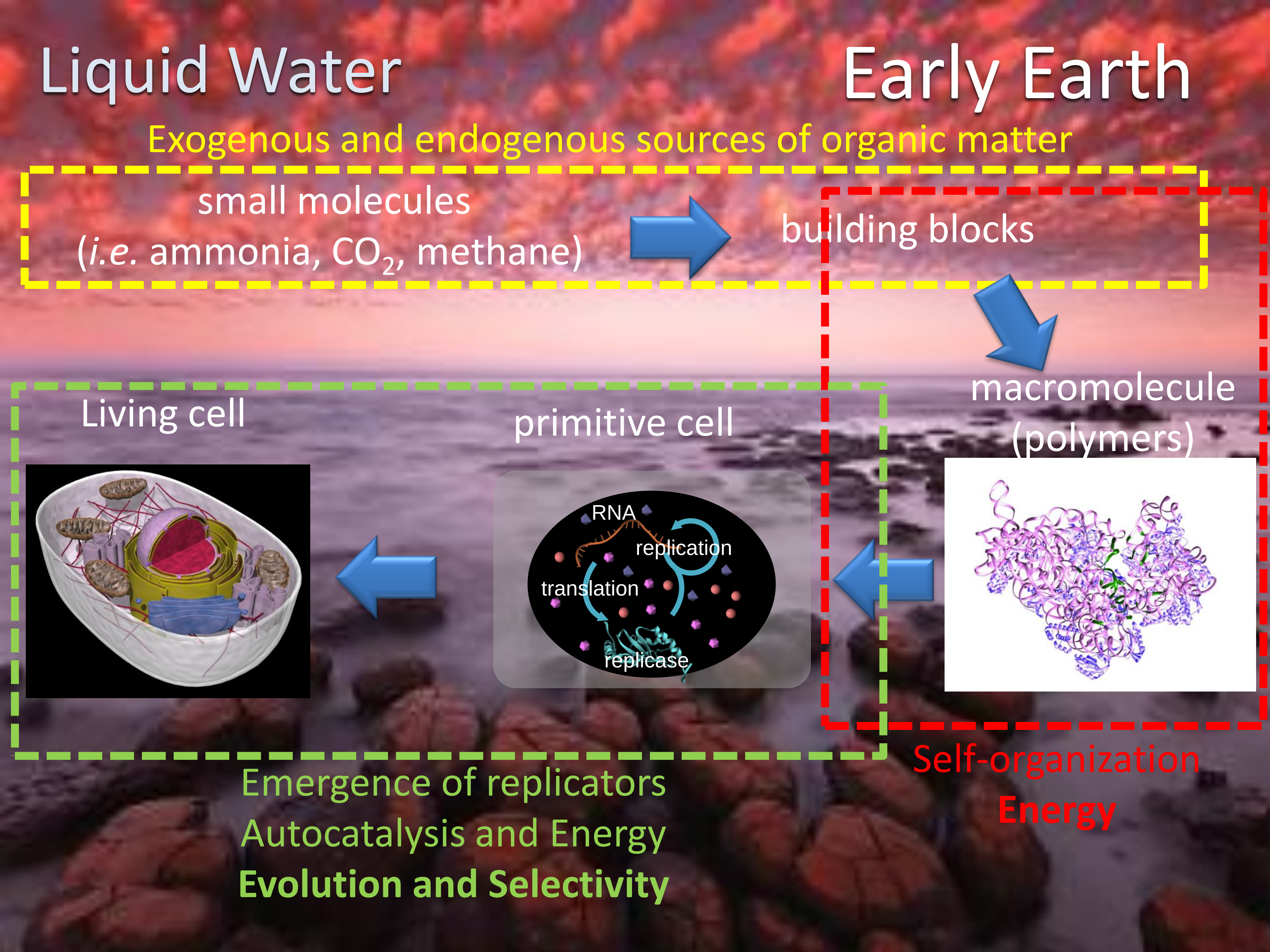
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translation
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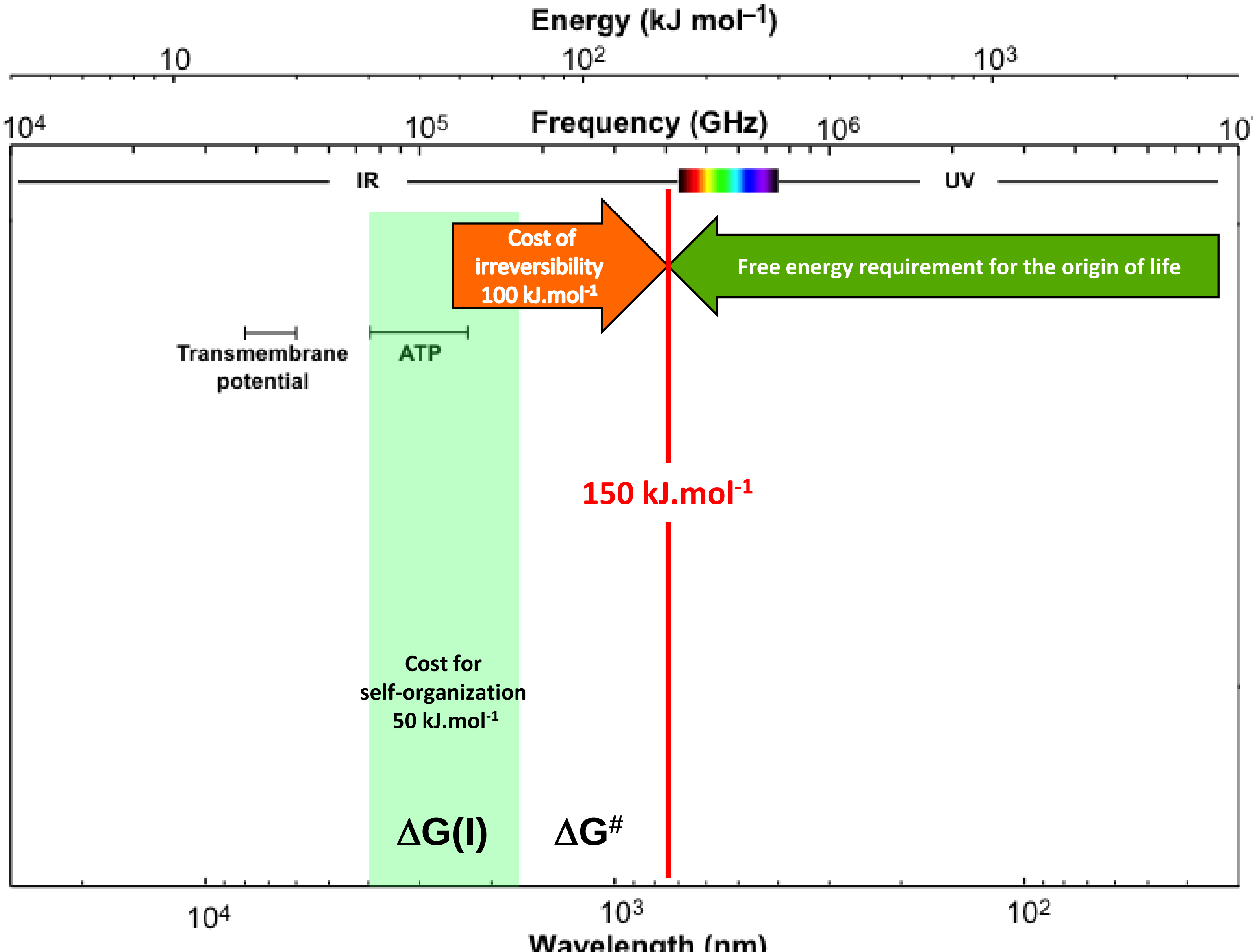
Living cell
Emergence of replicators
Autocatalysis and Energy
Evolution and Selectivity
Self-organization
Energy

Impact on Habitability



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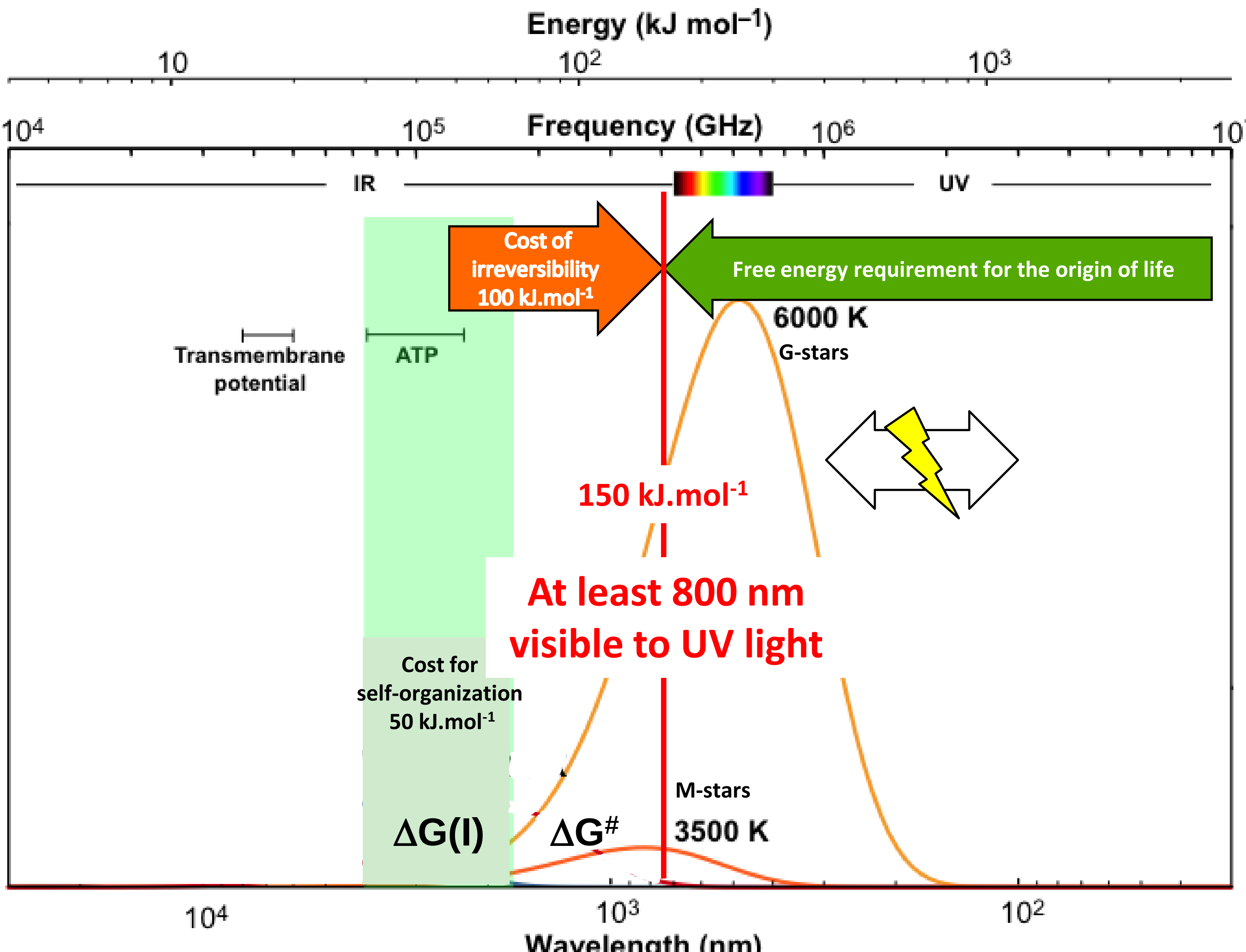
Impact on Habitability



R. Pascal, A. Pross, J. D. Sutherland *Open Biol.* **2013**, *3*, 130156

What do we need?

- ✓ Liquid water
- ✓ Source of organic matter
  - Exogenous – “Universal”
  - Endogenous – “Specific”
- ✓ Energy for self-organization
- ✓ Autocatalysis and irreversibility for chemical evolution

What do we need?

✓ Liquid water

✓ Source of organic matter
Exogenous – "Universal"
Endogenous – "Specific"

✓ Energy for self-organization

✓ Autocatalysis and irreversibility for chemical evolution

In which environment?

✓ Hydrothermal vent?

✓ Volcano environments?

✓ If it needs UV-visible light (<800 nm) for the self-organization and the cost of irreversibility:
➡ Environment where surface liquid water is available

How can we constrain the habitability concept?

- ✓ Liquid water
- ✓ Source of organic matter
  Exogenous – "Universal"
- ✓ Energy for self-organization
- ✓ Autocatalysis and irreversibility for chemical evolution

Experiment this scenario in a simulated primitive Earth environment

- ✓ Is it possible to experimentally demonstrate that replicators can emerge from an aqueous environment in which organic matter is associated to a sufficient source of energy?
- ✓Constrain the range of environmental conditions in which replicators could emerge

Liquid Water

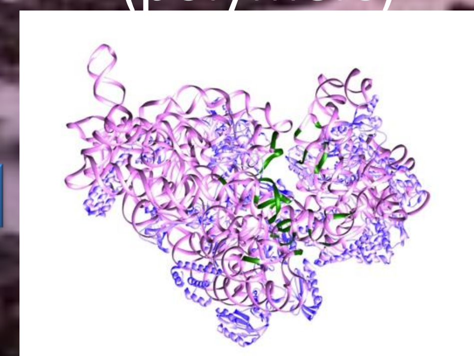
Early Earth

Exogenous and endogenous sources of organic matter

small molecules
(*i.e.* ammonia, CO_2, methane)

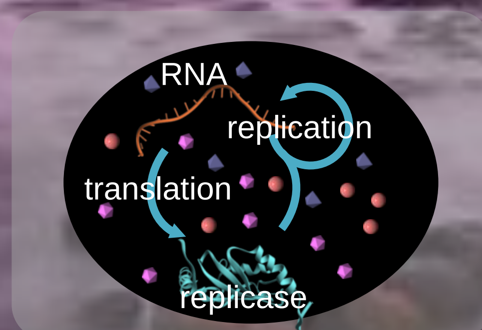
building blocks

macromolecule
(polymers)

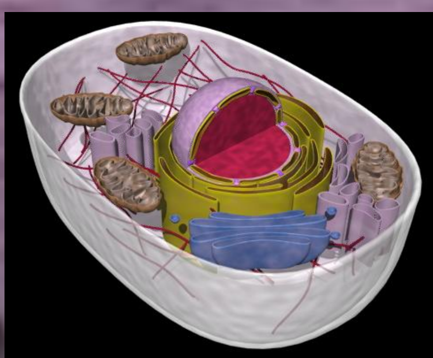


Self-organization
Energy

primitive cell



Living cell



Emergence of replicators
Autocatalysis and Energy
Evolution and Selectivity