From Chemistry to Natural History: Is there a driving force?

Robert PASCAL

University of Montpellier – CNRS

rpascal@univ-montp2.fr

History

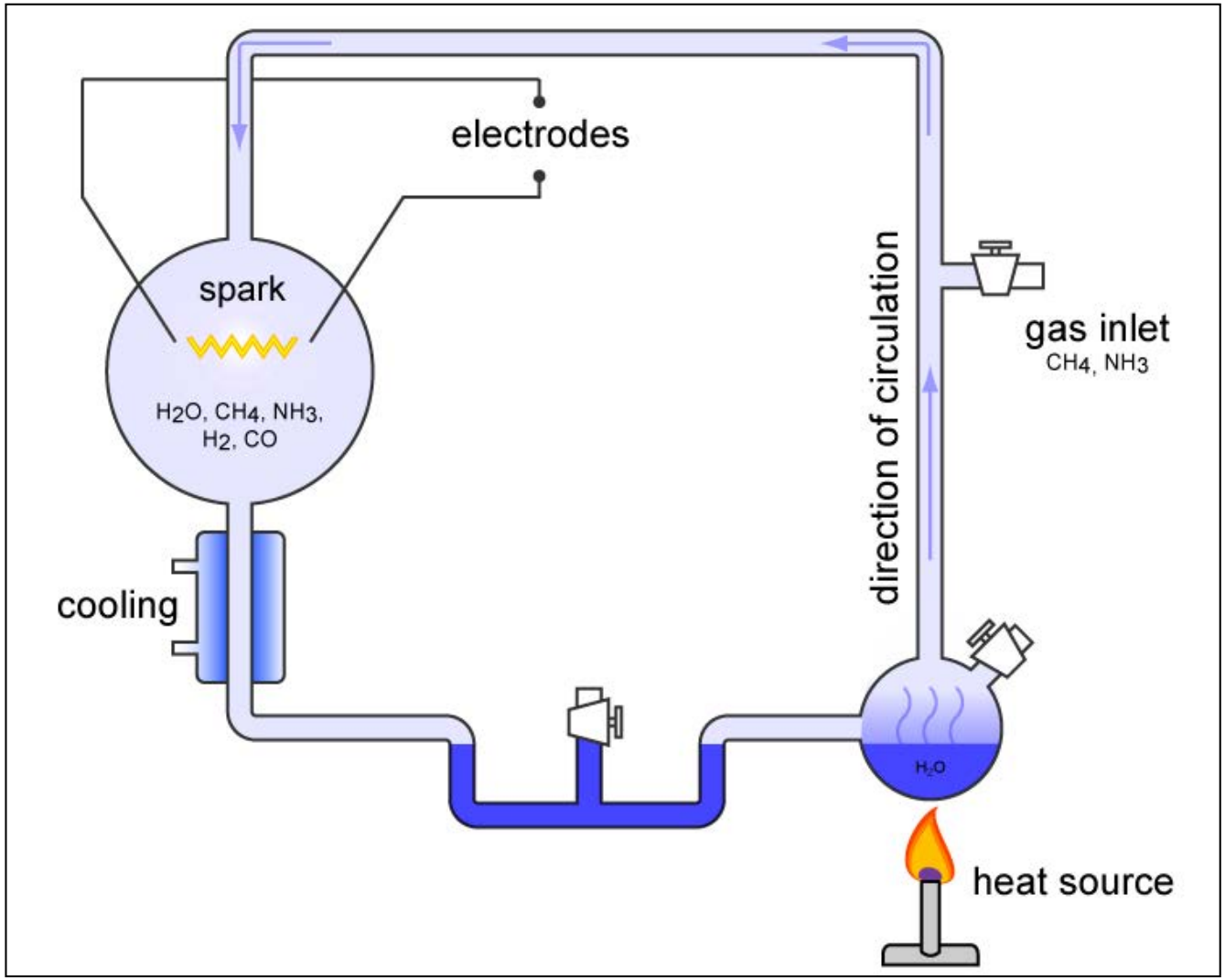
- Chemistry is not a historical science.

- “Nothing in biology makes sense except in the light of evolution”.

T. Dobzhansky, *The American Biology Teacher* 1973, 35, 125.

The Miller-Urey's experiment

May 15th, 1953



Miller *Science*, **1953**, *117*, 528.

Organic building blocks can be formed abiotically

- Under conditions postulated for the primitive Earth.
  - Amino acids
  - Nucleic bases, sugars…
- In the interstellar medium.
- In hydrothermal systems.
- In many places…

- … except on the surface of the present day Earth (because of oxidizing conditions).
- 60 years later, the above mentioned lesson of Miller's experiment remains valid.

Is prebiotic chemistry only the abiotic formation of organic building blocks?

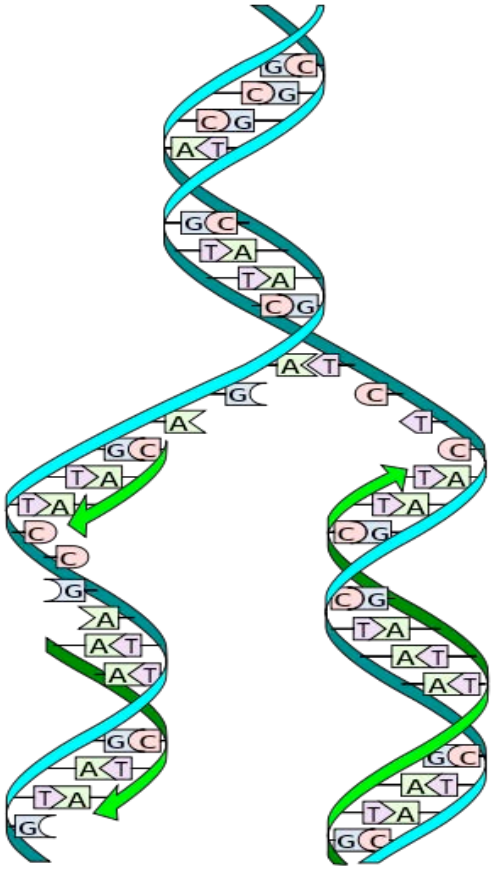
- How does their condensation into biopolymers proceed?
  - Is activation needed?

- How does a (proto)-metabolism emerge?
  - If organic matter can be formed almost everywhere, is metabolism only the formation of organic building blocks from inorganic sources of carbon?

What is the relationship between the abiotic formation of organic building blocks and the origin of life?

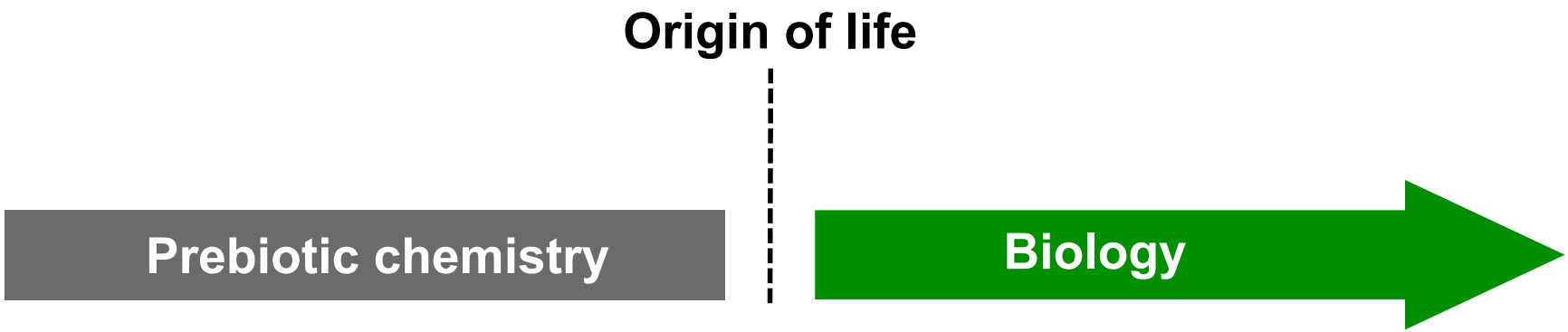
The double-helix structure of DNA

April 25th, 1953



Watson & Crick *Nature*, **1953**, *171*, 737.

The origins of life: by chance only?



- There is almost no possibility for life to emerge.

« S'il fut unique, comme peut-être le fut l'apparition de la vie elle-même, c'est qu'avant de paraître ses chances étaient quasi nulles. L'Univers n'était pas gros de la vie, ni la biosphère de l'homme. Notre numéro est sorti au jeu de Monte-Carlo. Quoi d'étonnant à ce que, tel celui qui vient d'y gagner un milliard, nous éprouvions l'étrangeté de notre condition ? »

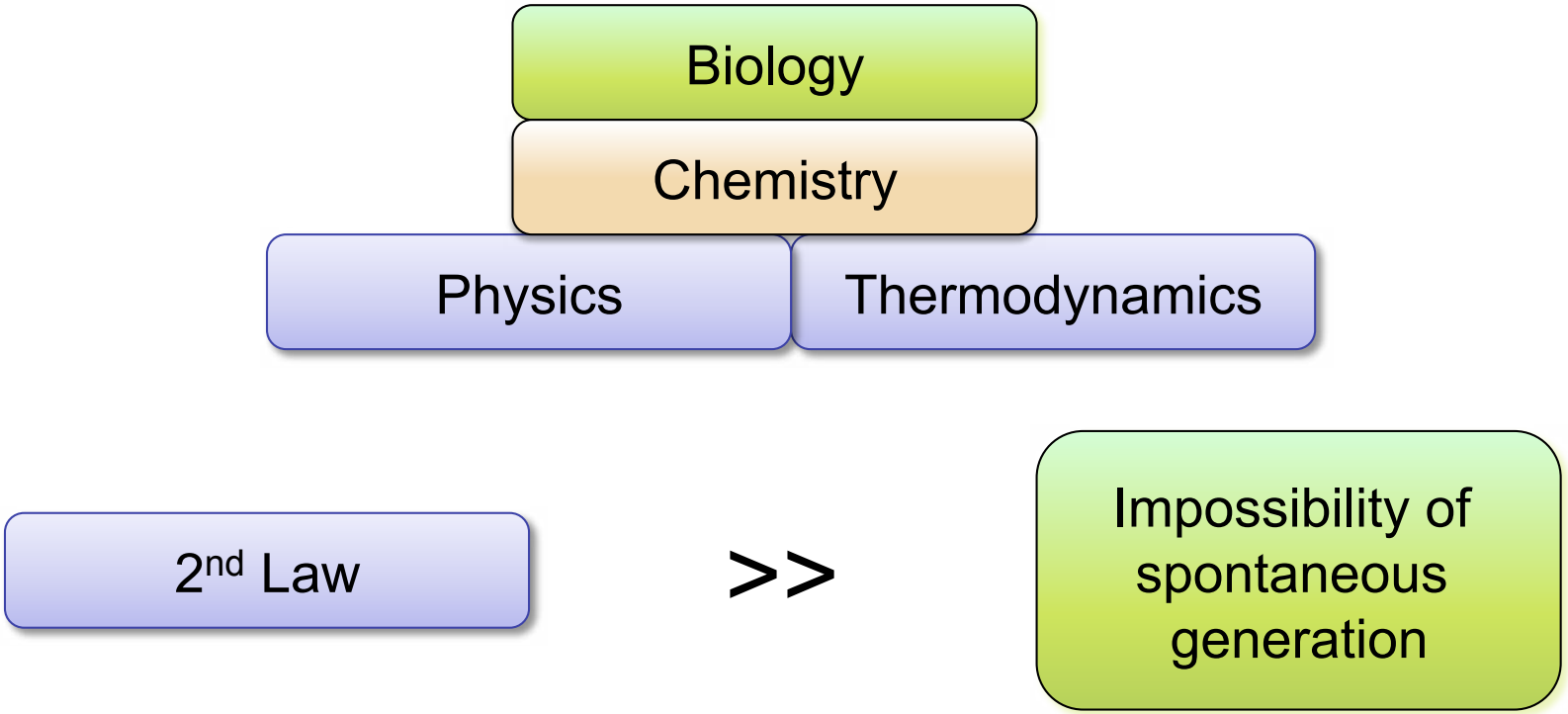
J. Monod, *Le hasard et la nécessité*, Editions du Seuil, Paris, 1970

- **Violation of the 2nd Law of thermodynamics**

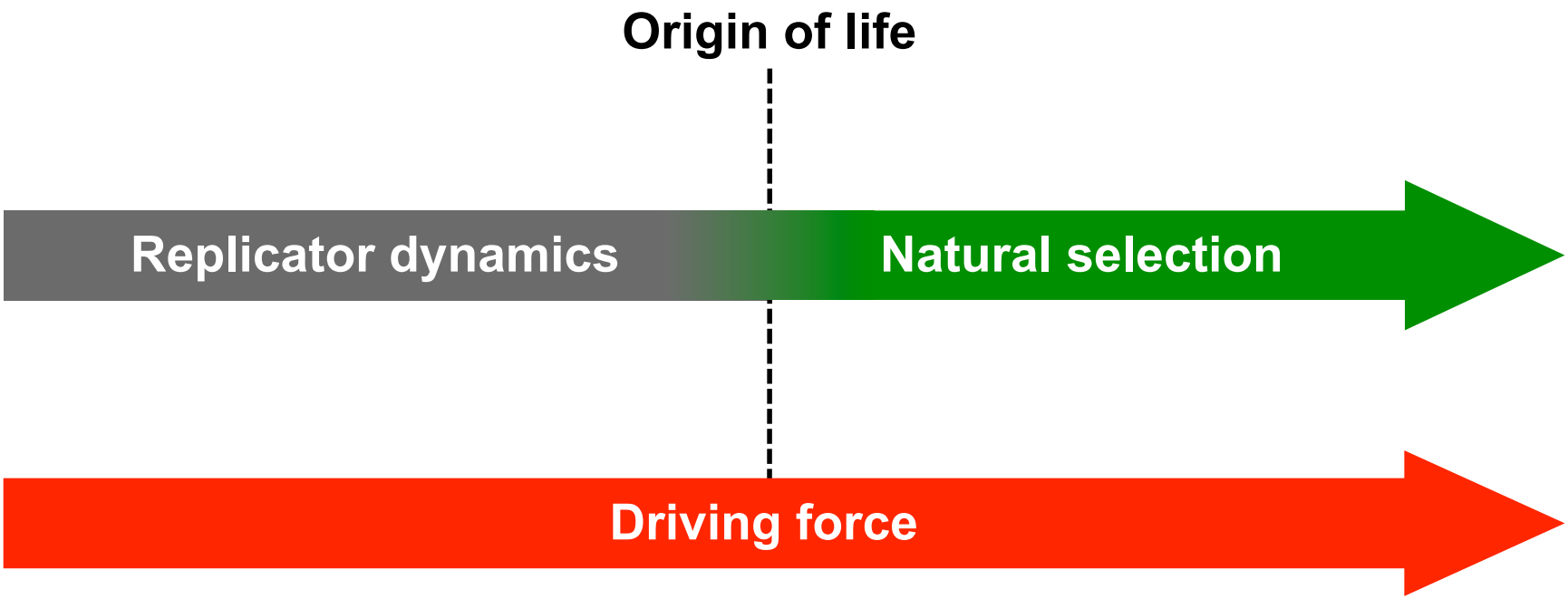
Violations of principles

"*Scientific reductionism, a central scientific methodology, teaches us to seek understanding within higher hierarchical level sciences by using concepts from lower hierarchical level sciences, not the other way around.*"

A. Pross *J. Syst. Chem.* **2011**, *2*, 1.



A driving force for the emergence

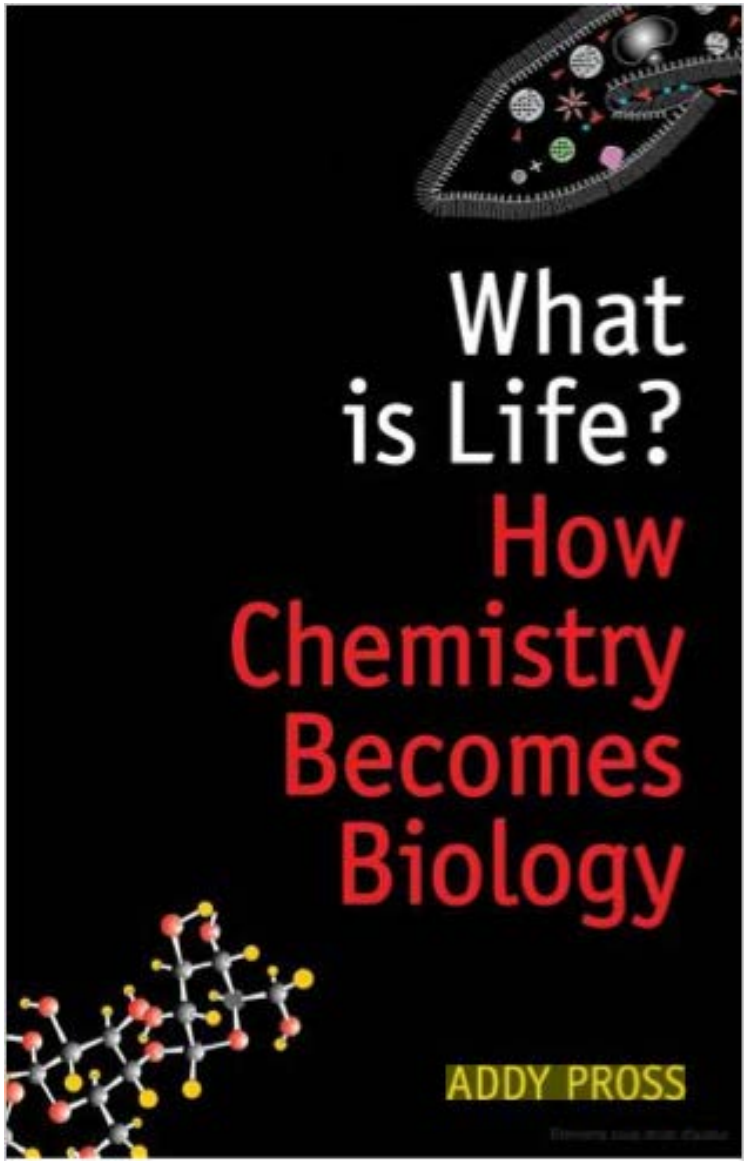


- **Replicators dynamics:**
  - ✓ **Growth capacity**
  - ✓ **Selection**
- **Driving force = Dynamic Kinetic Stability**

A. Pross *J. Syst. Chem.* **2011**, *2*:1

Dynamic kinetic stability

- **Replicators dynamics:**
  - ✓ **Growth capacity**
  - ✓ **Selection**
- **Driving force = Dynamic Kinetic Stability**

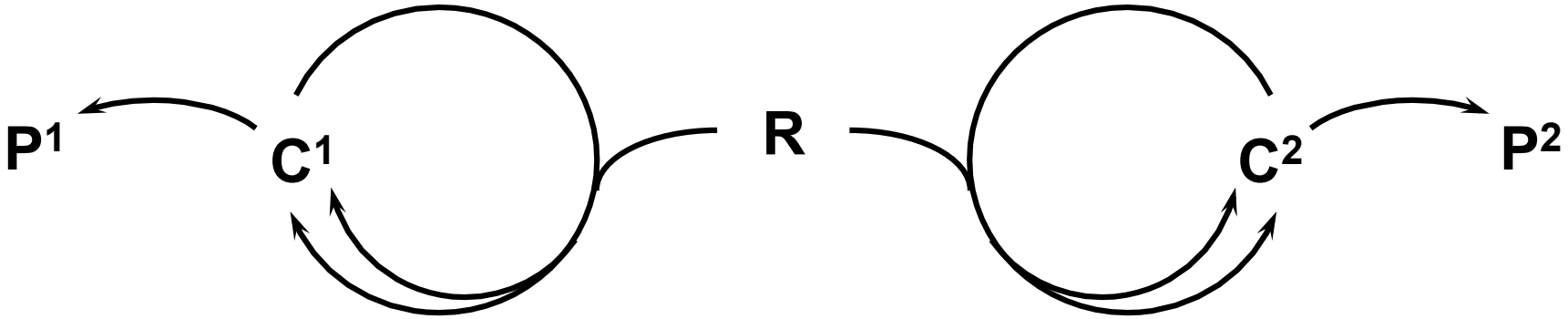


Oxford University Press, 2012

'Regular' chemistry

$$[P^1] / [P^2] = k^1 / k^2 = \text{Cte}$$

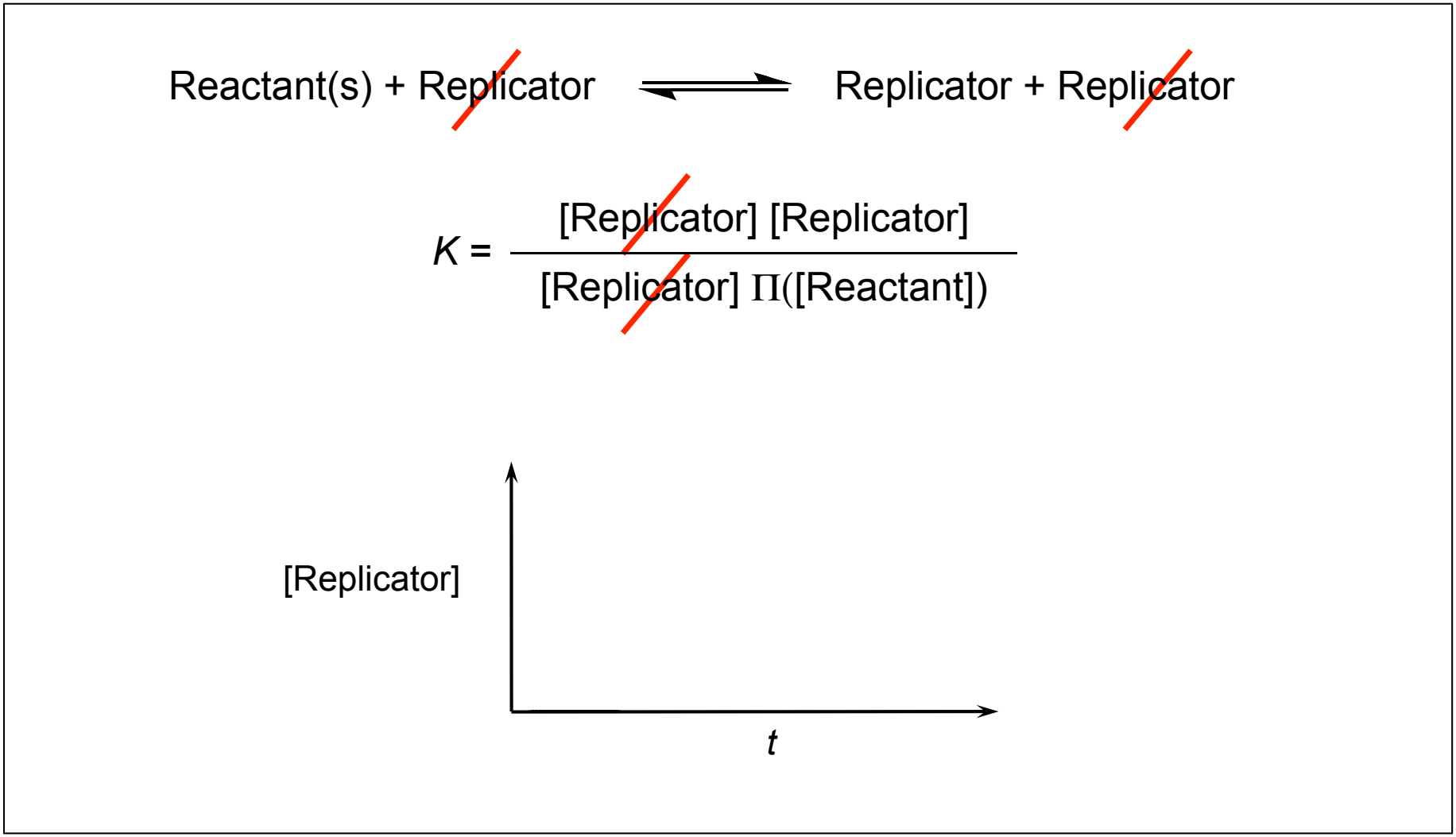
Replicator dynamics



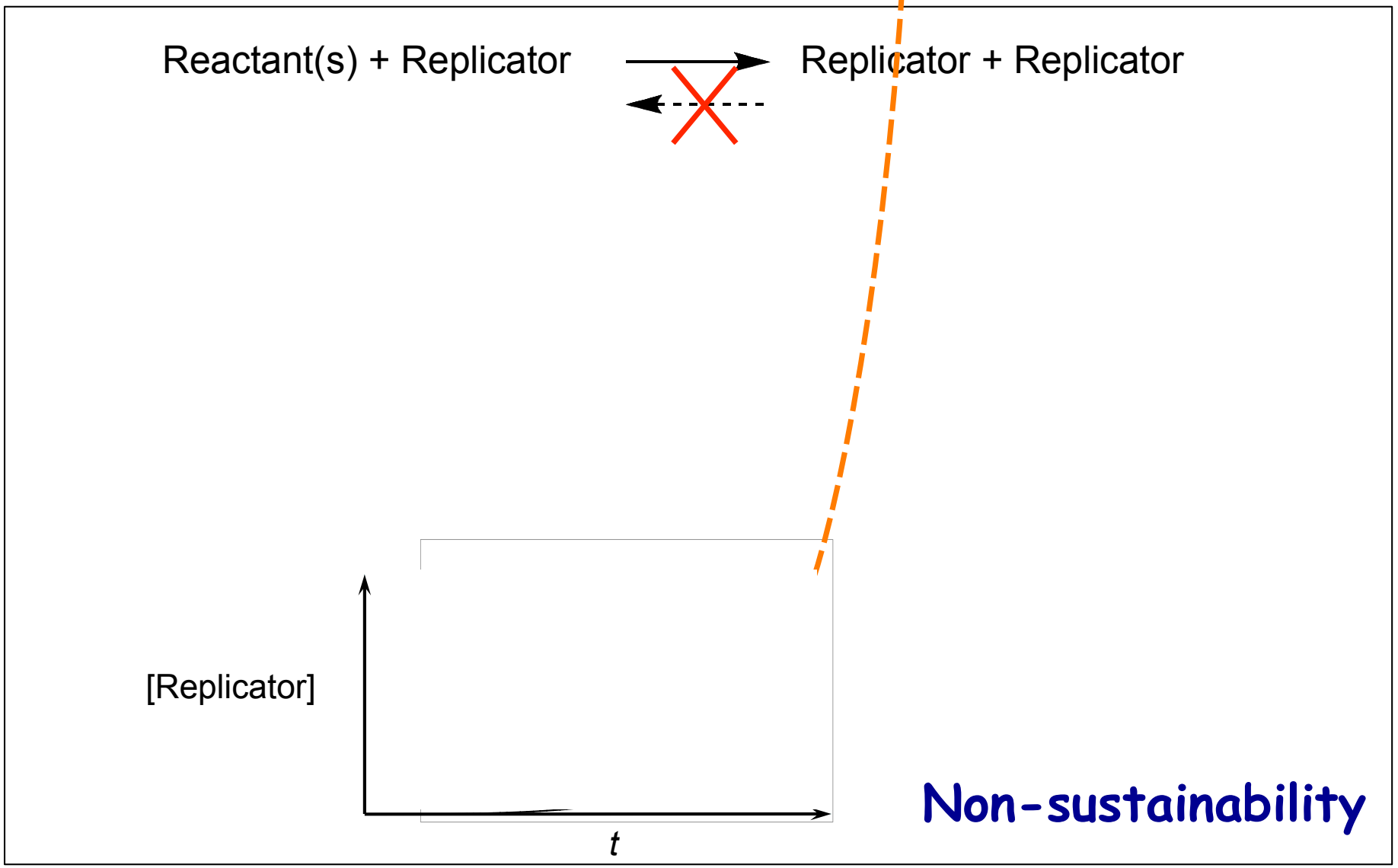
$$[C^1] = 0 \quad \text{ou} \quad [C^2] = 0$$

S. Lifson *J. Mol. Evol.* **1997**, *44*, 1-8

Replicator (1)

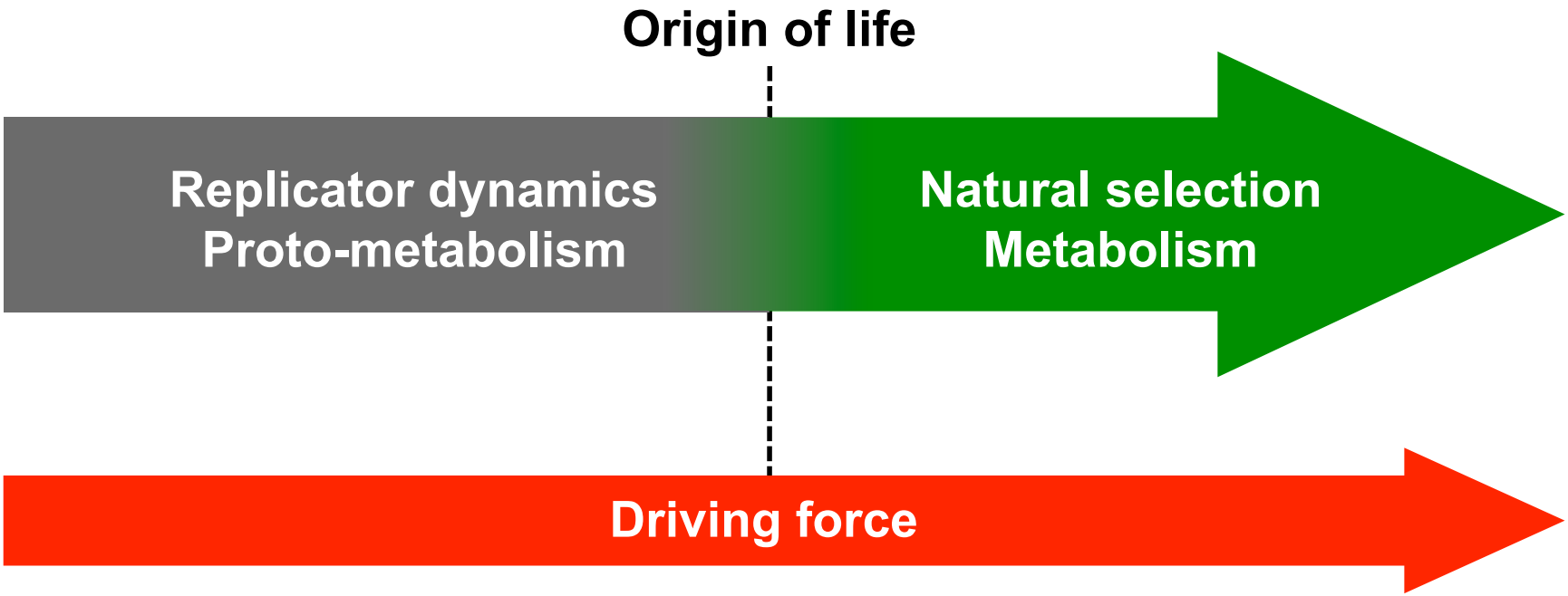


Replicator (2) : Irreversibility and exponential growth



A. Pross, R. Pascal *Open Biology* **2013**, *3*, 120190

A driving force for the emergence



- **Replicators dynamics:**
  - ✓ **Growth capacity**
  - ✓ **Selection**
- **Irreversibility**
  - ✓ **Far from equilibrium state**
  - ✓ **Supply in energy**

R. Pascal *J. Syst. Chem.* **2012**, *3*:3; ; A. Pross, R. Pascal *Open Biol.* **2013**, *3*, 120190

Metabolism and irreversibility

In an environment rich in abiotically formed organic building blocks,

the main role of metabolism would not be anabolism…

…but maintaining the system in a far from equilibrium state by irreversibly coupling an energy source to the system.

Condition for the origin of life:

An irreversible protometabolism

Life and irreversibility

- Living organisms are continuously struggling against the diffusion of their own constituents.

- They spend energy to compensate for irreversible processes.

- Development of individuals and population growth must correspond to irreversible processes (exponential growth).

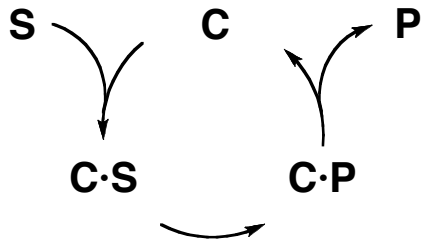
Living organisms require their metabolism to be coupled with the dissipation of energy in an irreversible way.

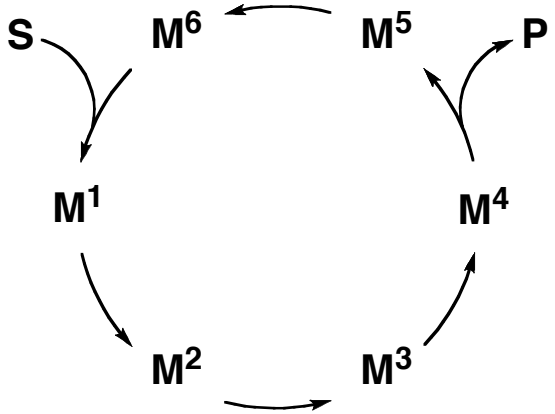
Self-organization

- **Requirements** ➪ **Systems Chemistry**
- Distance from equilibrium ➪ Far from equilibrium state (energy-rich reactants / activating agents)
- Nonlinearity ➪ Replication / autocatalysis

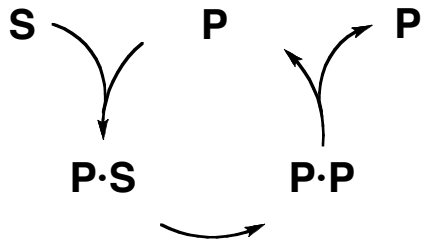
G. Nicolis, I. Prigogine, *Self-organization in nonequilibrium systems* **1977**

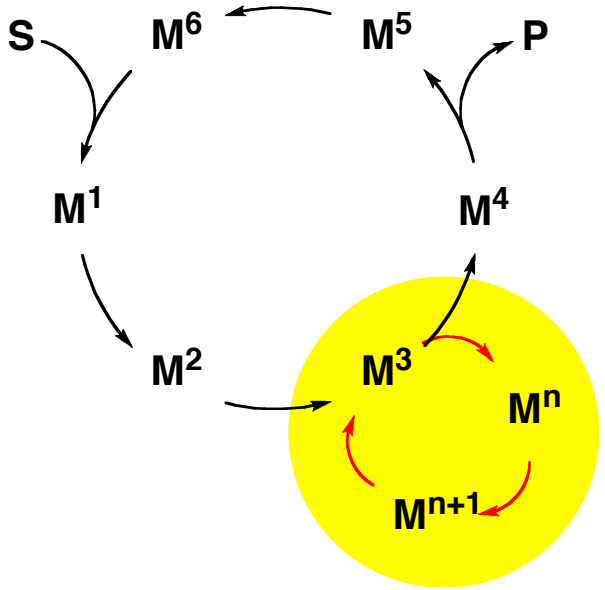
Catalytic cycles and catalysis





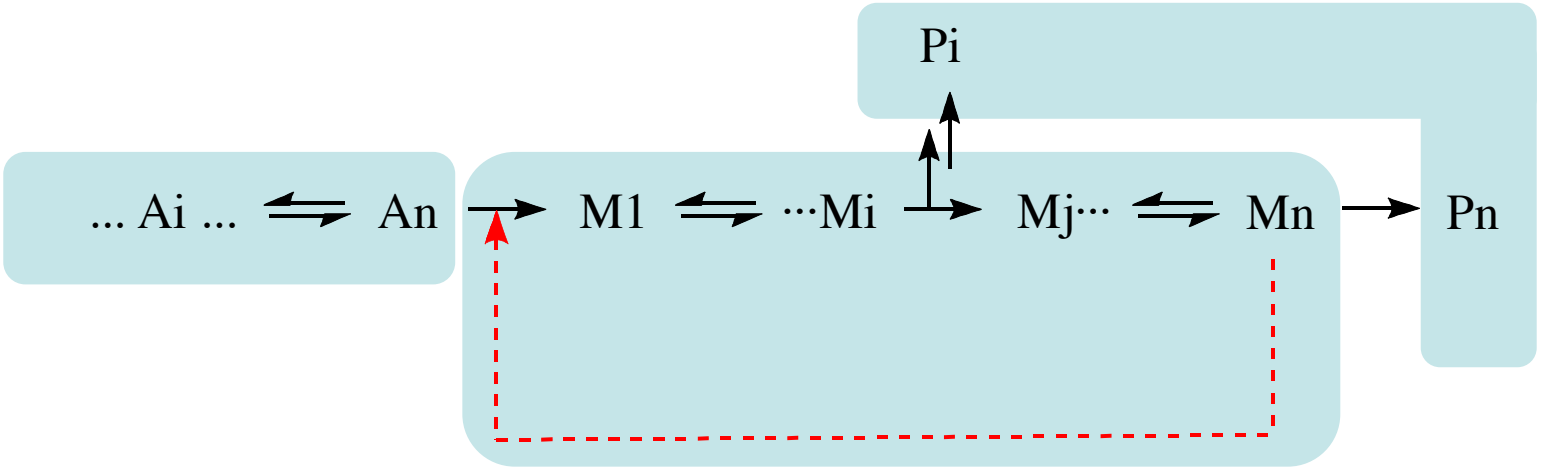
Autocatalytic cycles and autocatalysis

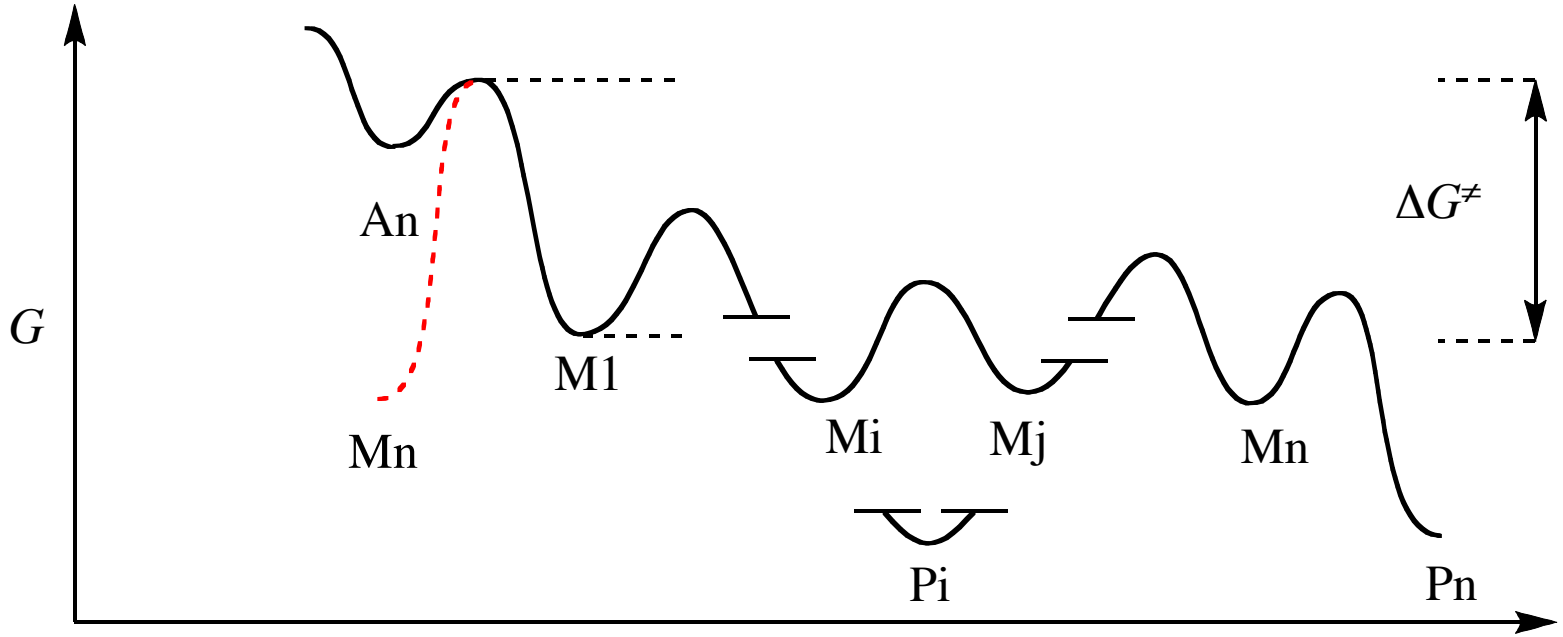




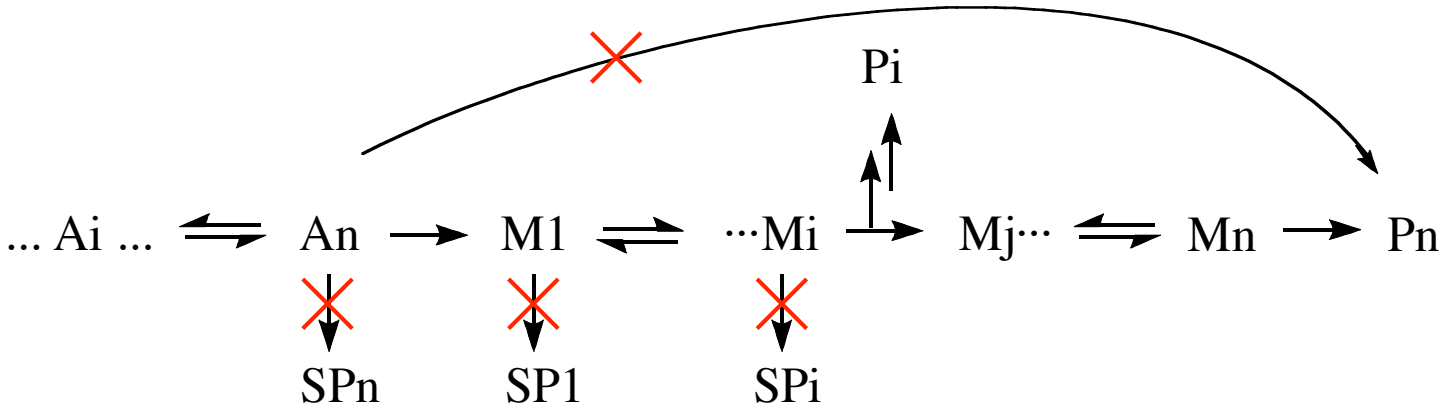
M. Eigen *Naturwissenschaften* **1971**, *58*, 465-523;
M. Eigen, P. Schuster, *Ibid*. **1977**, *64*, 541-565.

(Proto)-metabolism = irreversibility

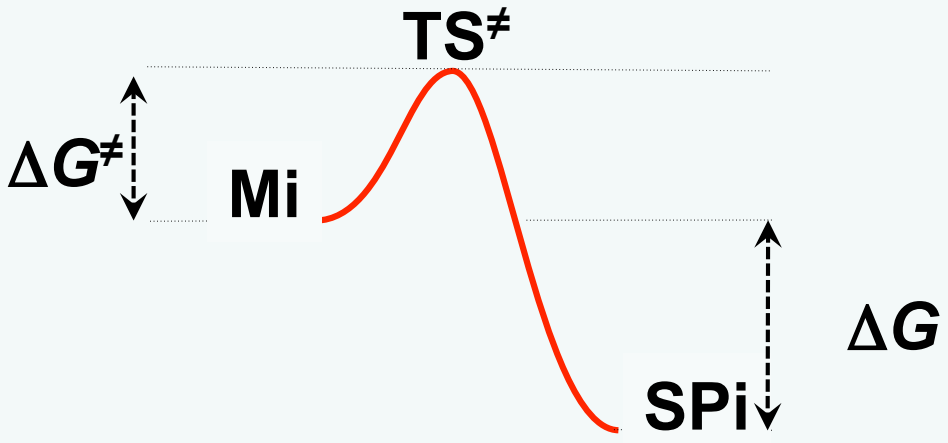




The development of a metabolism requires the system to be held far from equilibrium by kinetic barriers



A. Eschenmoser, *Orig. Life Evol. Biosph.* **1994**, *24,* 389; *Angew. Chem. Int. Ed.* **2011**, *50*, 12412.

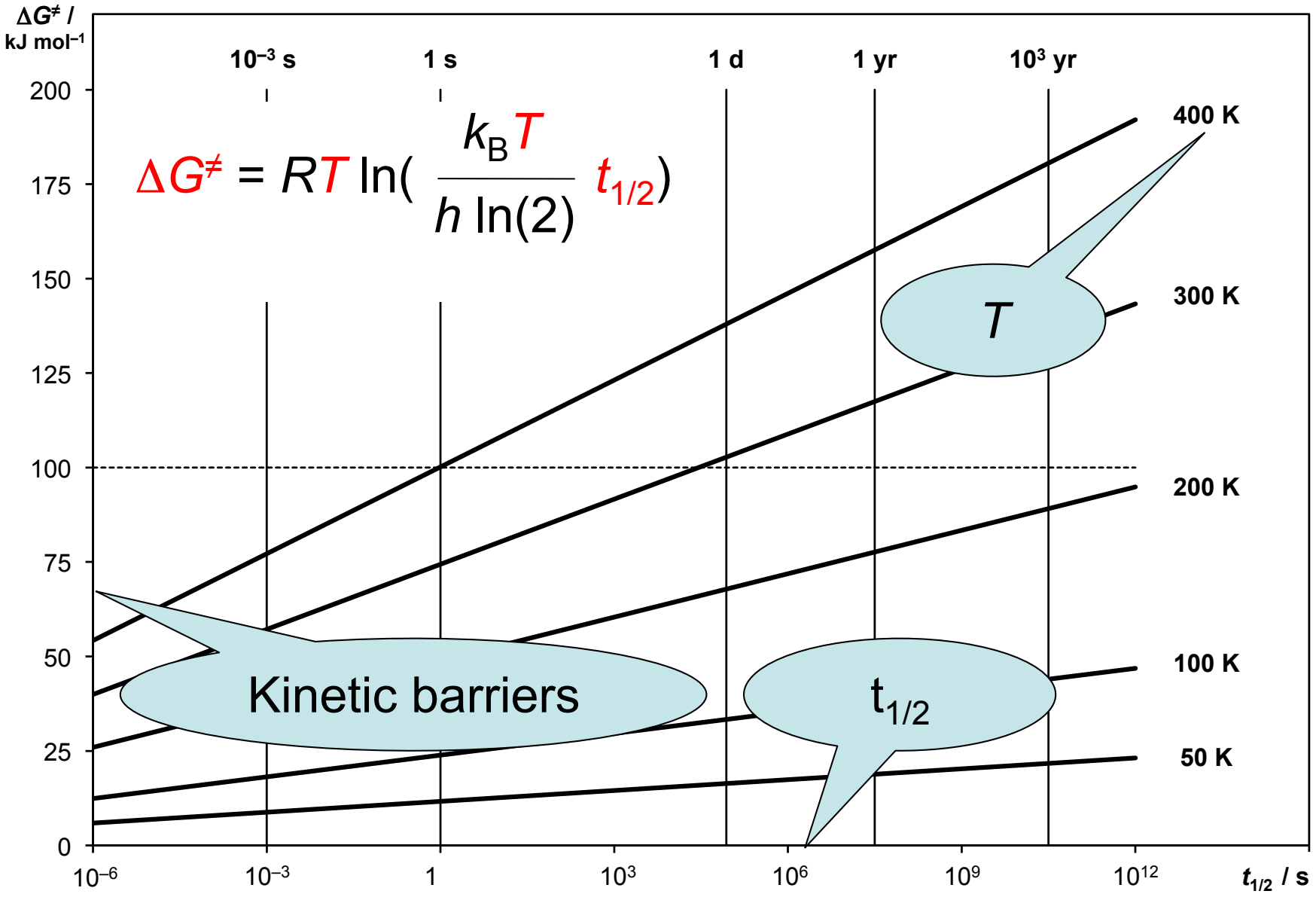


Transition state theory

$$k = \kappa \frac{k_B T}{h} e^{-(\Delta G^{\neq}/RT)}$$

The Eyring equation

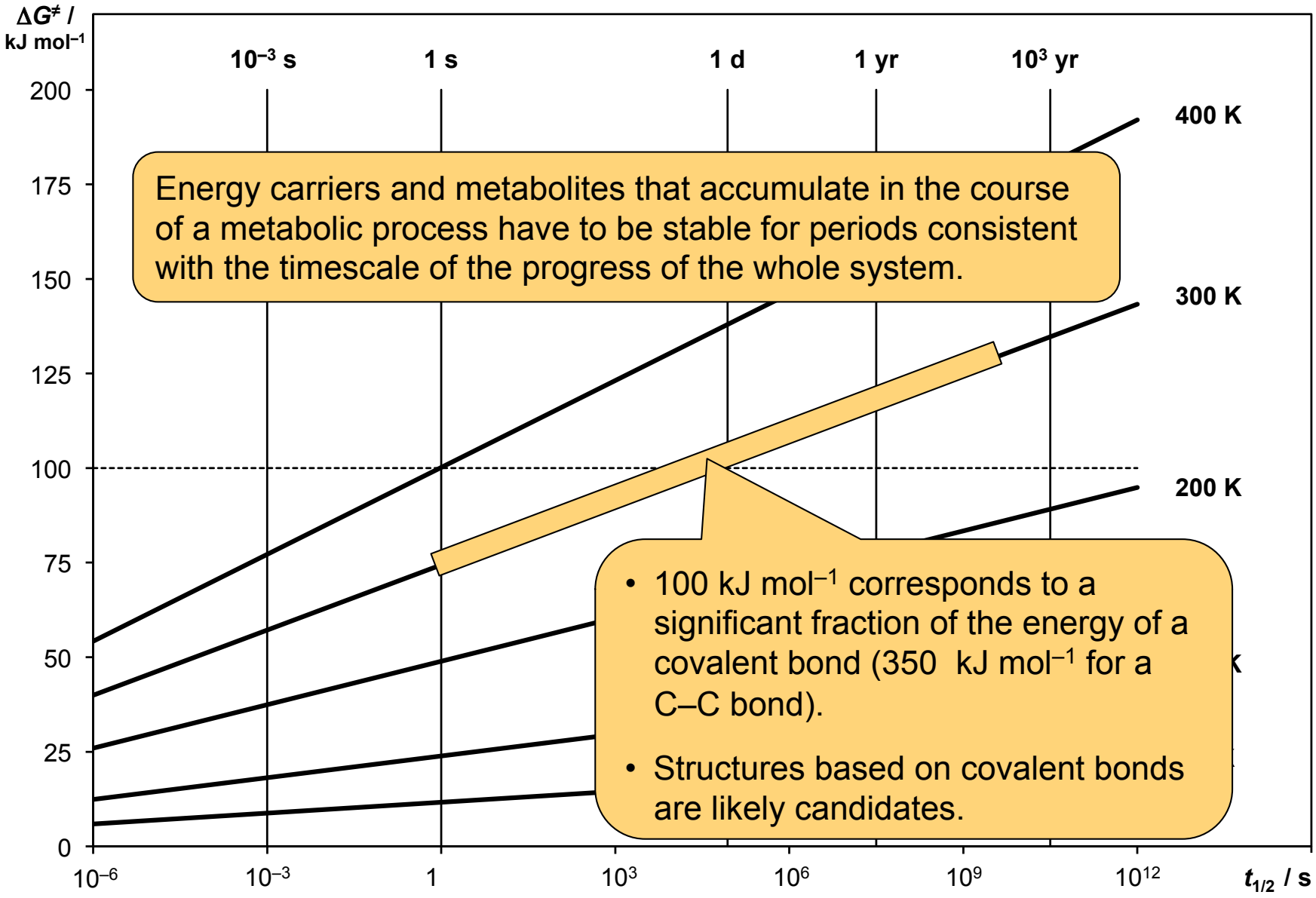
Graphical representation of Eyring equation



R. Pascal, *J. Syst. Chem.* **2012**, *3*, 3.

R. Pascal, In Smith, Cockell, Leach, *Astrochemistry and Astrobiology: Physical Chemistry in Action*, Springer, **2013**.

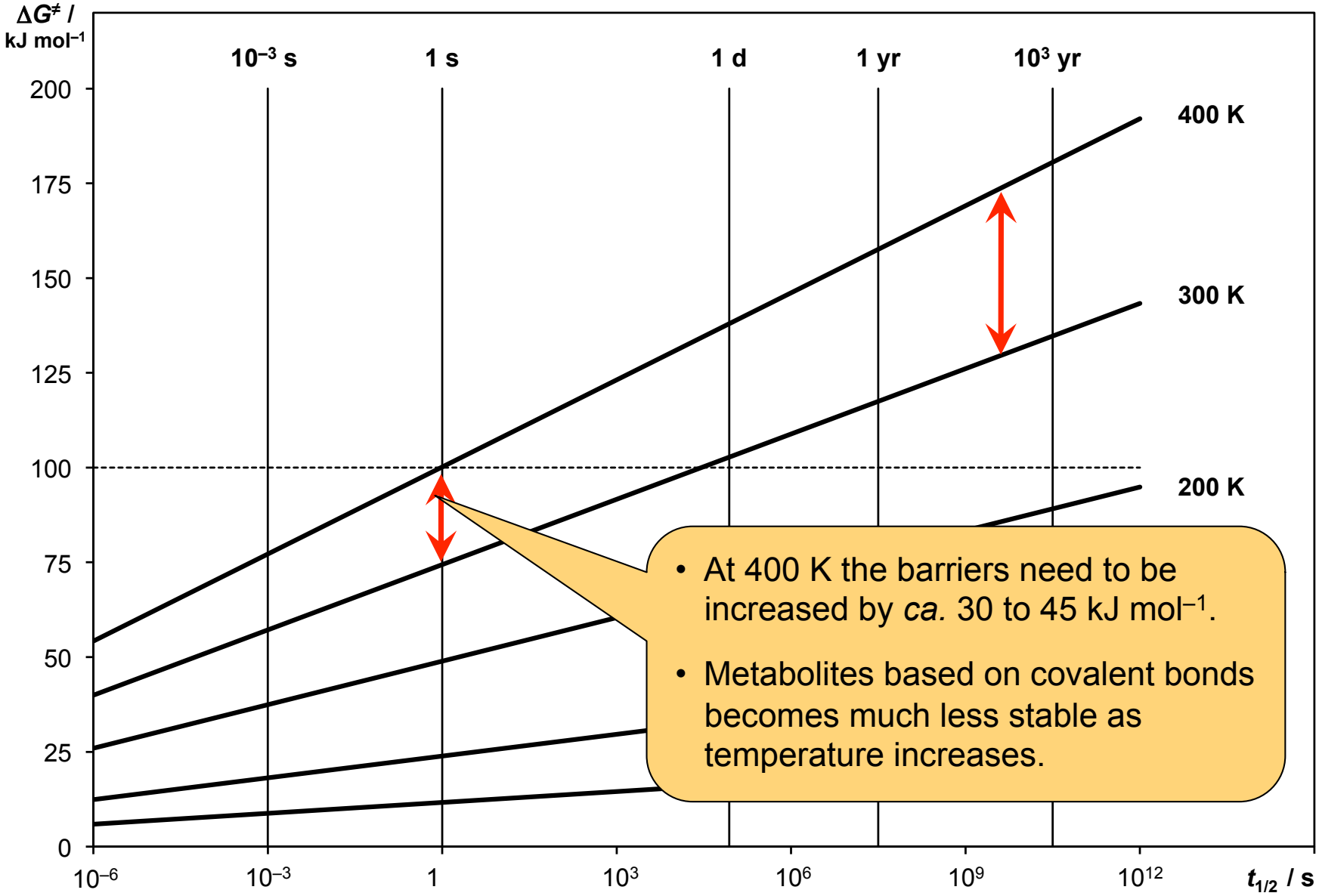
At 300 K $\Delta G^{\neq}$ ~ 100 kJ mol^{-1}



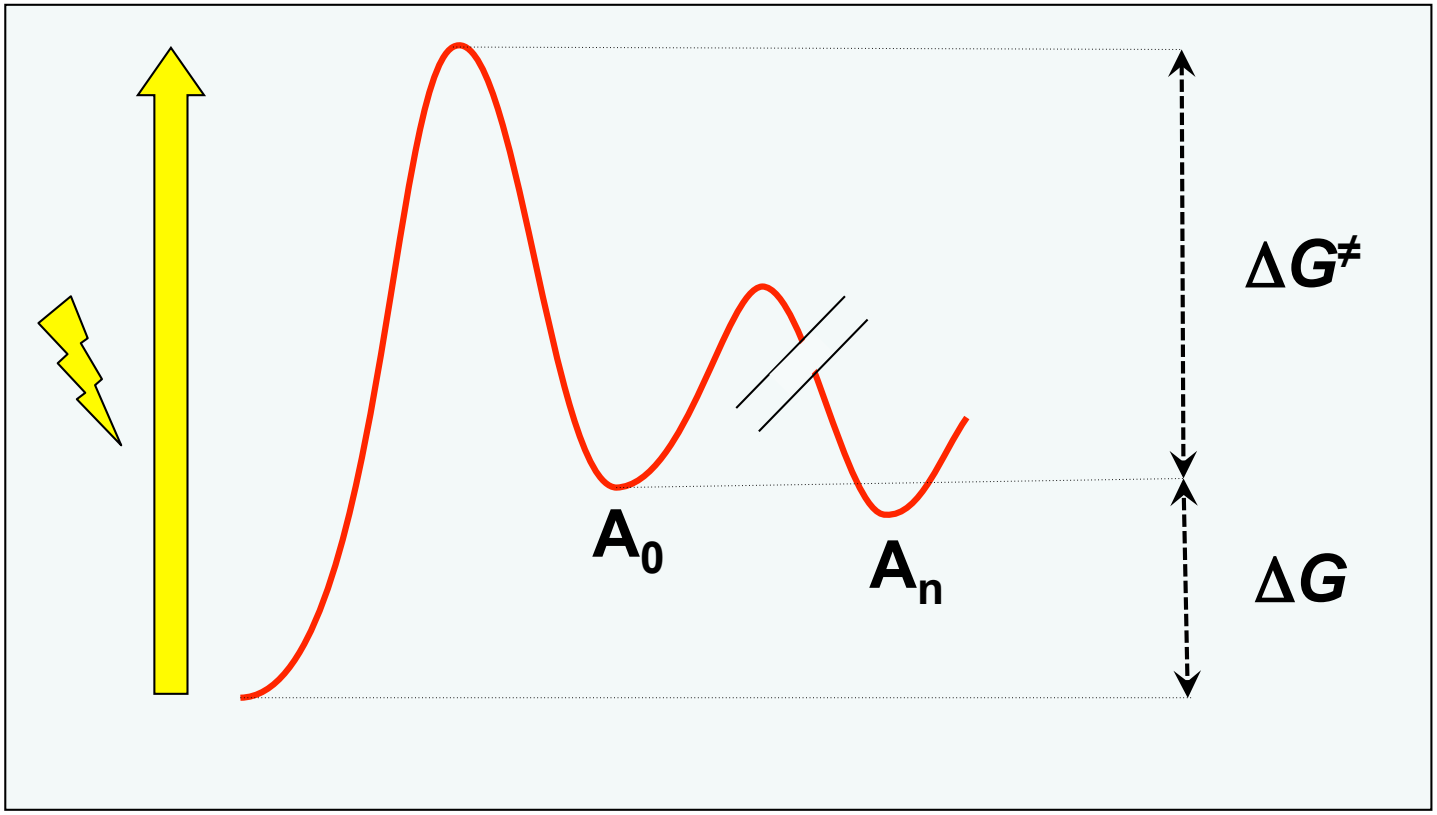
R. Pascal, *J. Syst. Chem.* **2012**, *3*, 3.

R. Pascal, In Smith, Cockell, Leach, *Astrochemistry and Astrobiology: Physical Chemistry in Action*, Springer, **2013**.

The limits of life: i.e. life at 400 K



The energetic cost of irreversibility



$\Delta G^{\neq} \sim 100$ kJ mol^{-1}

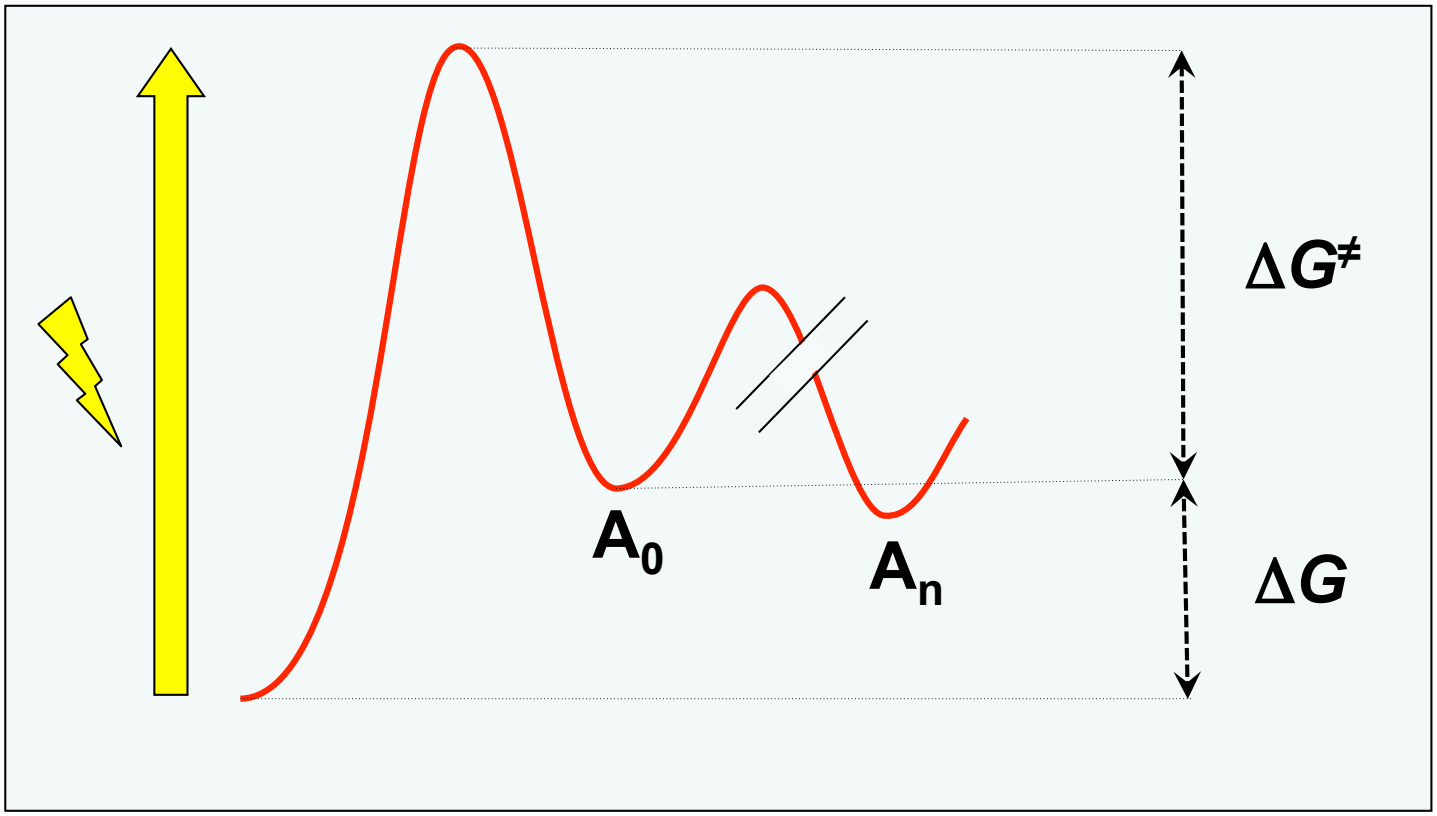
R. Pascal, *J. Syst. Chem.* **2012**, *3*, 3.
R. Pascal, In Smith, Cockell, Leach, *Astrochemistry and Astrobiology: Physical Chemistry in Action*, Springer, **2013**.

Standard free energy of hydrolysis at pH 7

	$\Delta G°'$ / kJ mol^{-1}
Acetyl coenzyme A (thioester)	**–31**
ATP (to ADP & P_i)	**–31**
ATP (to AMP & PP_i)	**–32**
PP_i	**–19**
Aminoacyl-tRNA (amino acid ester)	**–35**
Glycine ethyl ester	**–35**
Acetyl phosphate	**–43**
Amino acid thioester	**ca. –47**
Aminoacyl phosphate	**ca. –50**
Carbamoyl phosphate	**ca. –51**
Acetyl adenylate	**–55**
Phosphoenolpyruvate	**–62**
Aminoacyl-adenylate	**–70**

L. Boiteau, R. Pascal, *Orig. Life Evol. Biosph.* **2011**, *41*, 23-33.

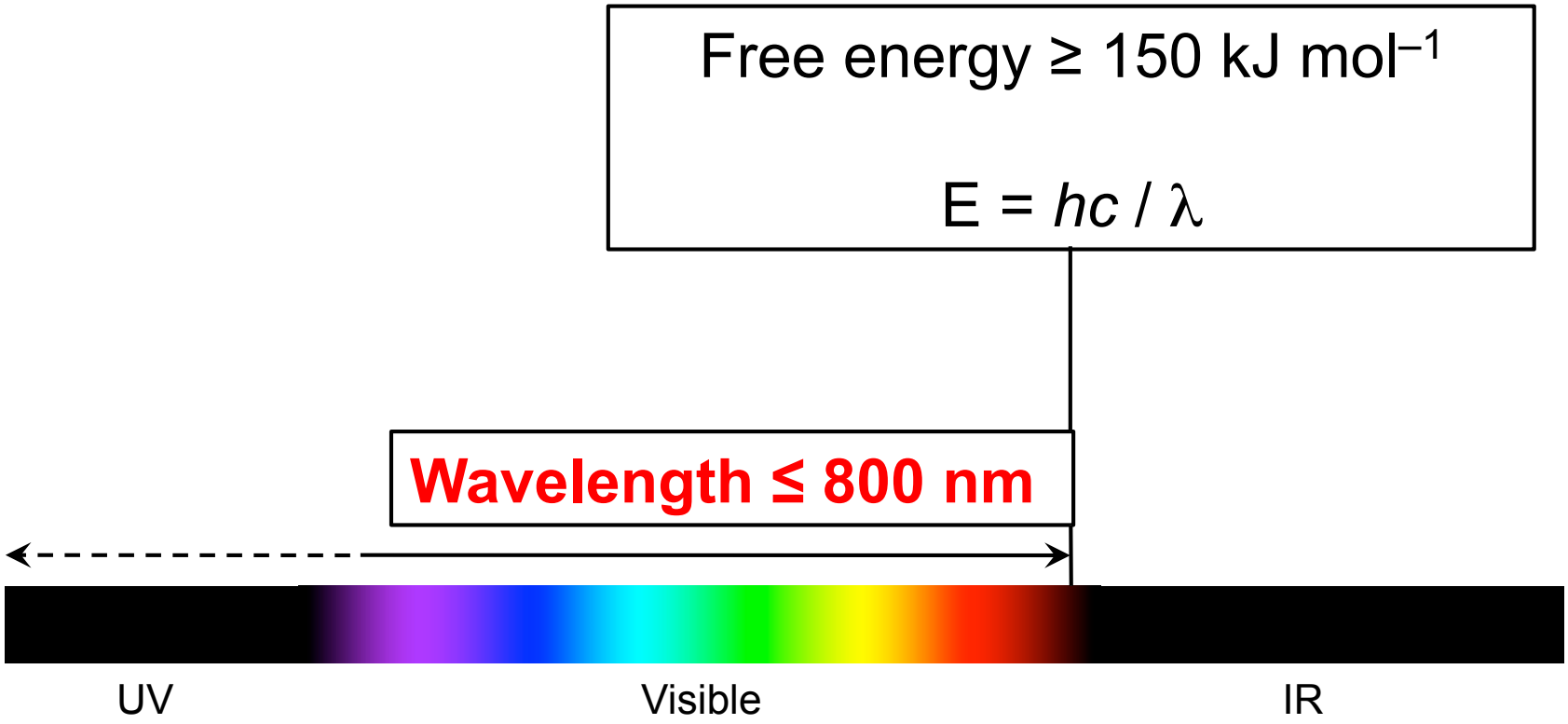
The source of free energy



Free energy ≥ $\Delta G^{\neq}$ + ΔG ~ 150 kJ mol^{-1}

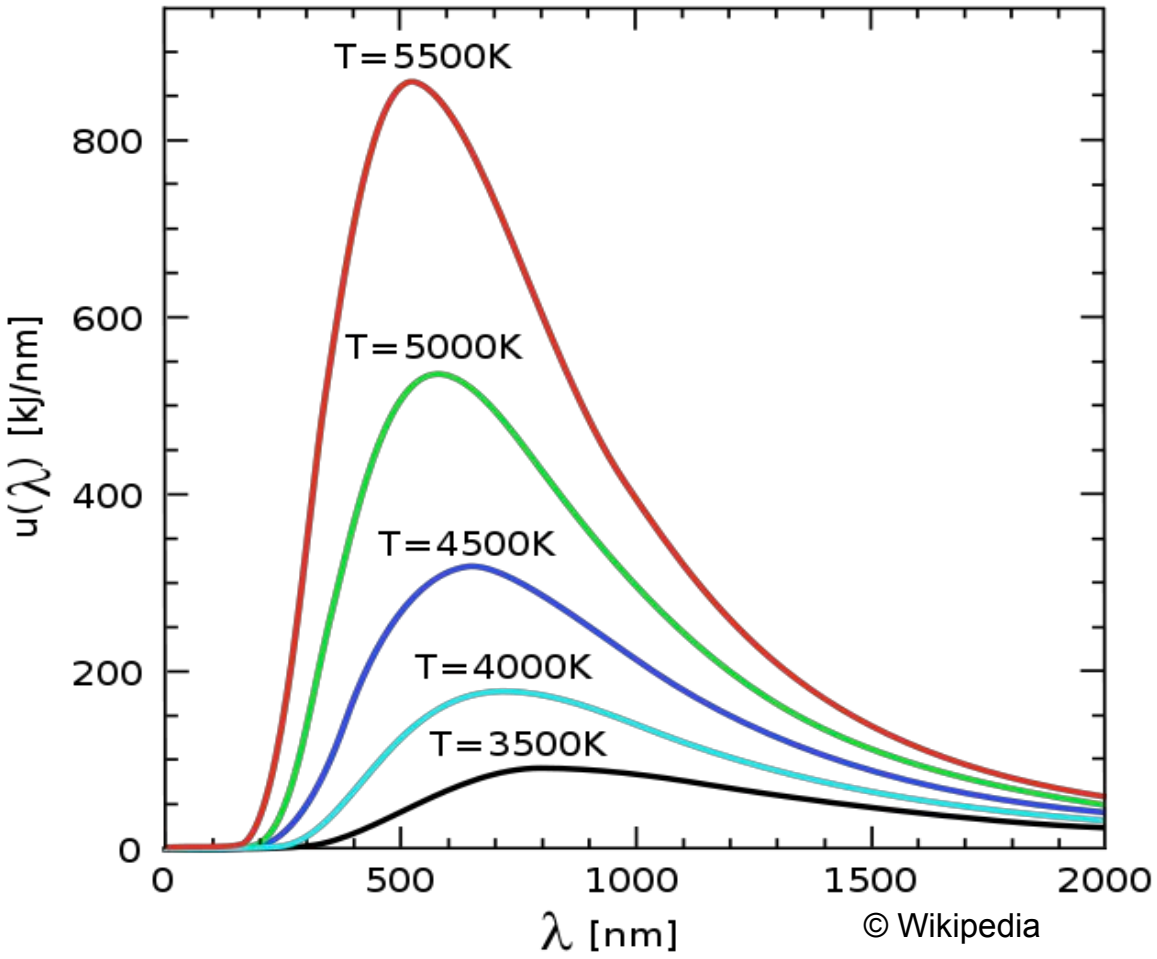
R. Pascal, *J. Syst. Chem.* **2012**, *3*, 3.
R. Pascal, In Smith, Cockell, Leach, *Astrochemistry and Astrobiology: Physical Chemistry in Action*, Springer, **2013**.

Electromagnetic radiations



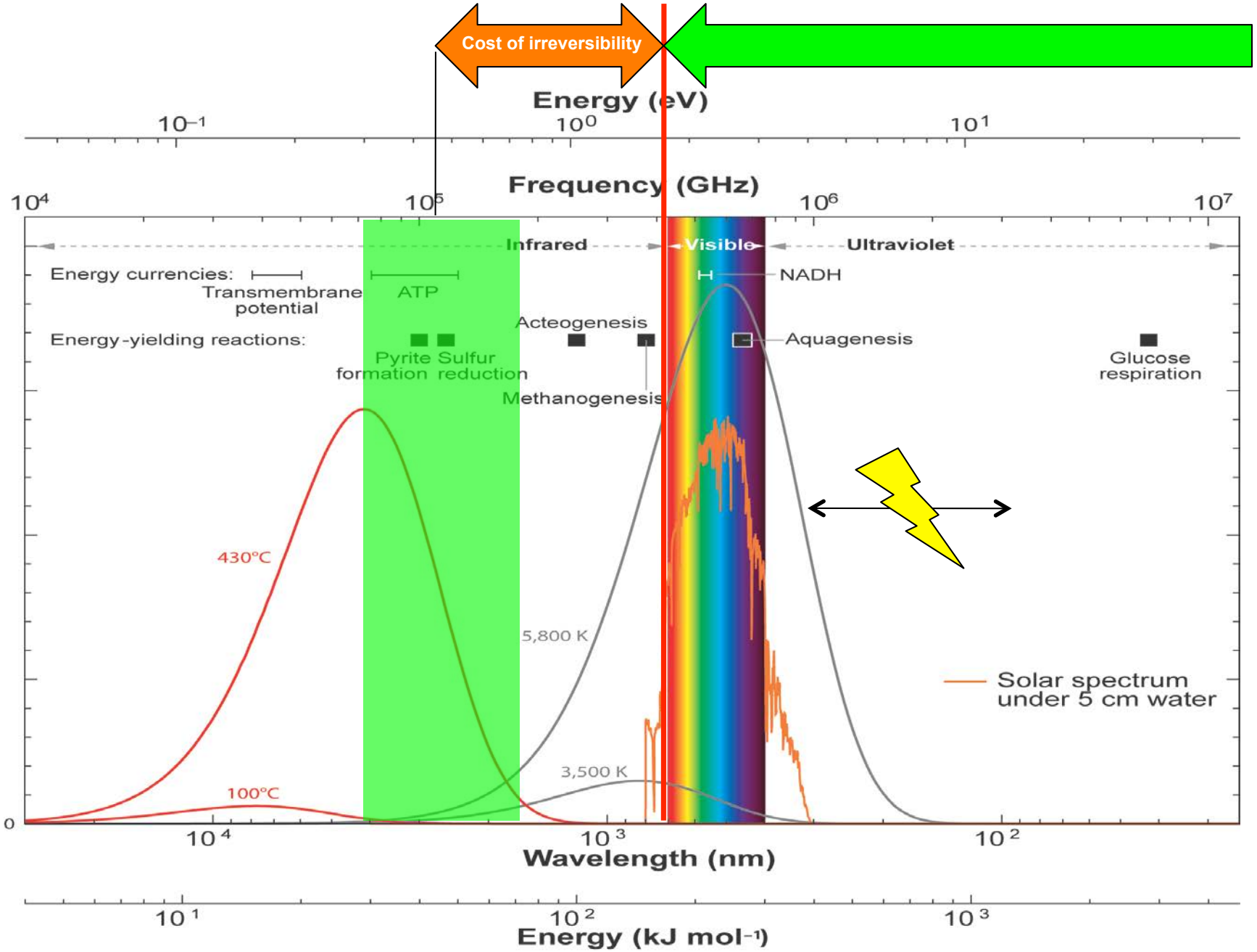
R. Pascal, *J. Syst. Chem.* **2012**, *3*, 3.
R. Pascal, In Smith, Cockell, Leach, *Astrochemistry and Astrobiology: Physical Chemistry in Action*, Springer, **2013**.

Heat: black body radiation

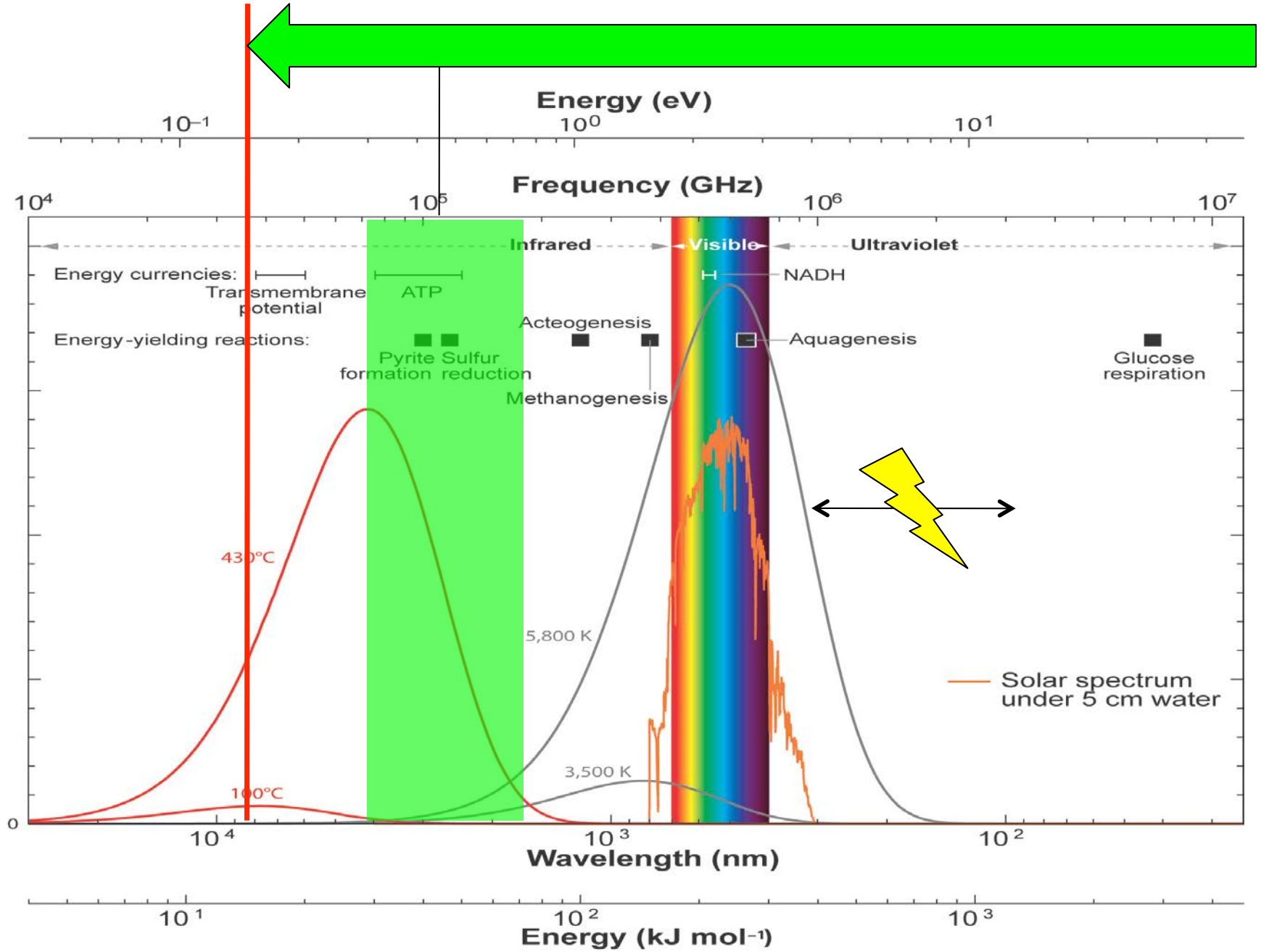


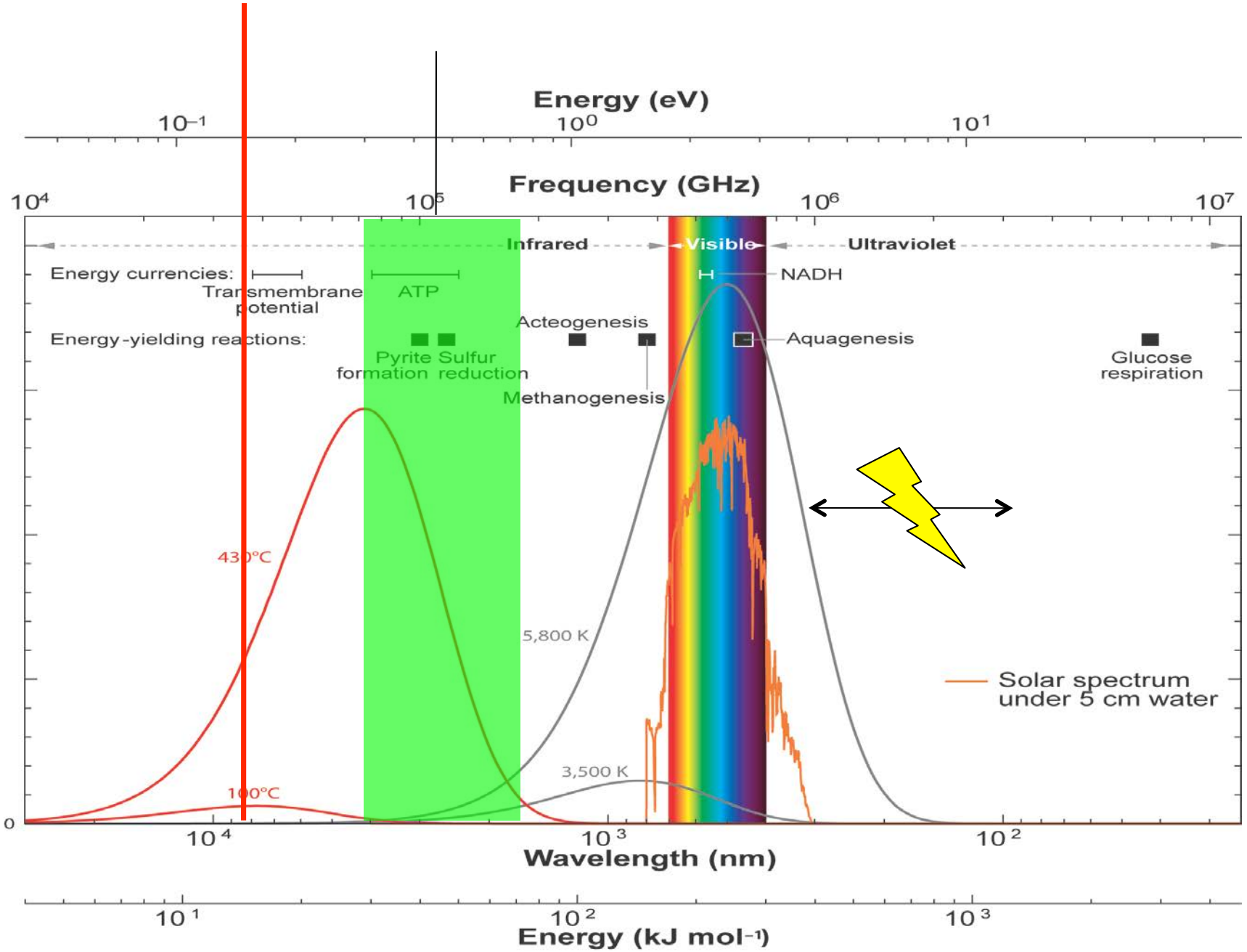
$T \sim 3600$ K
($\lambda_{max} = 800$ nm)

R. Pascal, *J. Syst. Chem.* **2012**, *3*, 3.
R. Pascal, In Smith, Cockell, Leach, *Astrochemistry and Astrobiology: Physical Chemistry in Action*, Springer, **2013**.

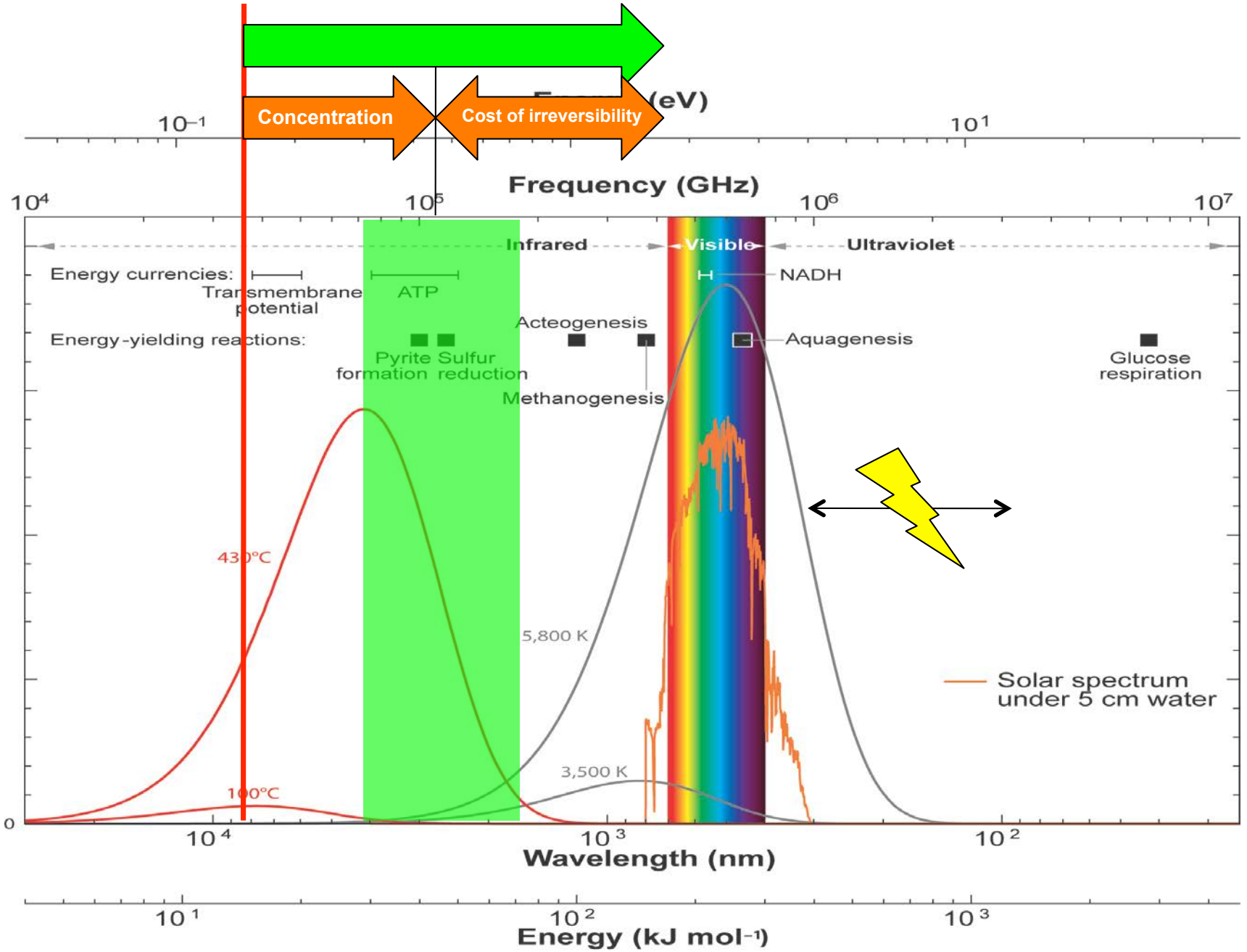


Adapted from Lineweaver and Chopra, *Ann. Rev. Earth Planet. Sci.* **2012**


Energy (eV)
10–1
100
101
Frequency (GHz)
104
105
106
107
Infrared
Visible
Ultraviolet
Energy currencies:
Transmembrane potential
ATP
NADH
Energy-yielding reactions:
Acteogenesis
Aquagenesis
Pyrite Sulfur formation reduction
Methanogenesis
Glucose respiration
430°C
100°C
5,800 K
3,500 K
Solar spectrum under 5 cm water
0
10 4
10 3
10 2
Wavelength (nm)
10 1
10 2
10 3
Energy (kJ mol-1)



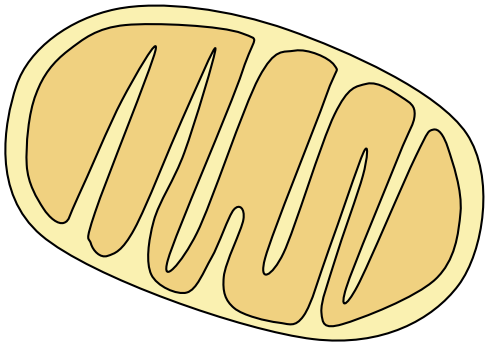
Autotrophic hypothesis

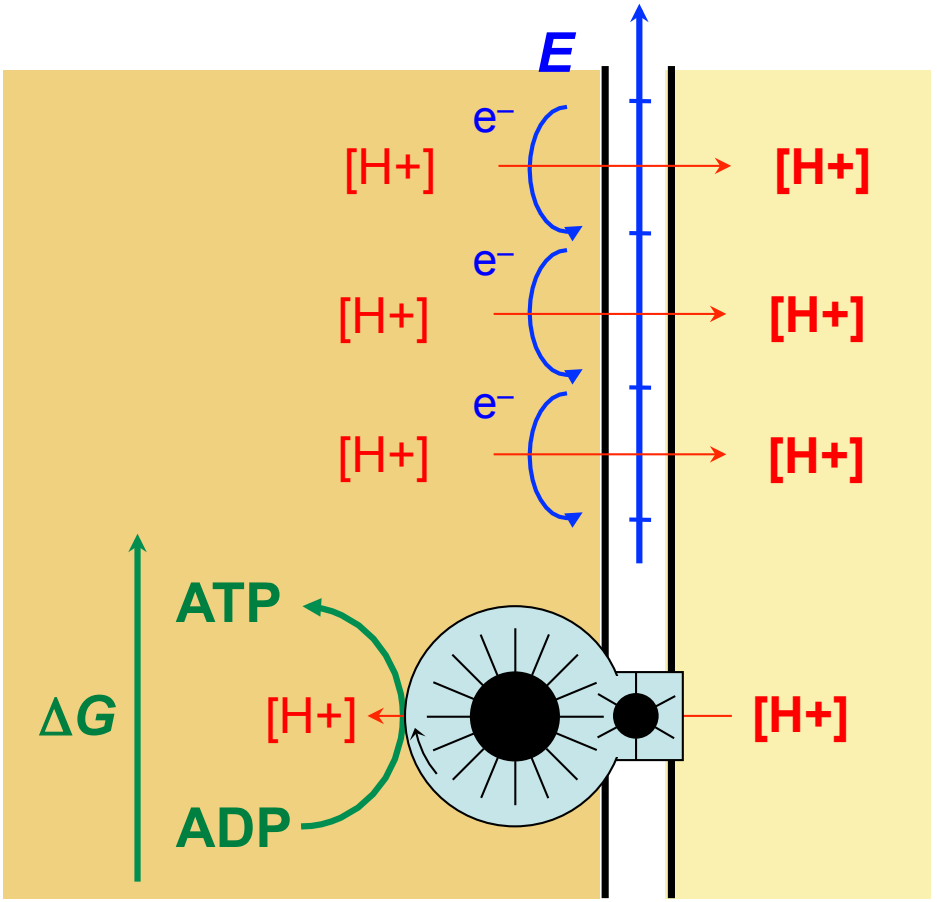


Autotrophic hypothesis

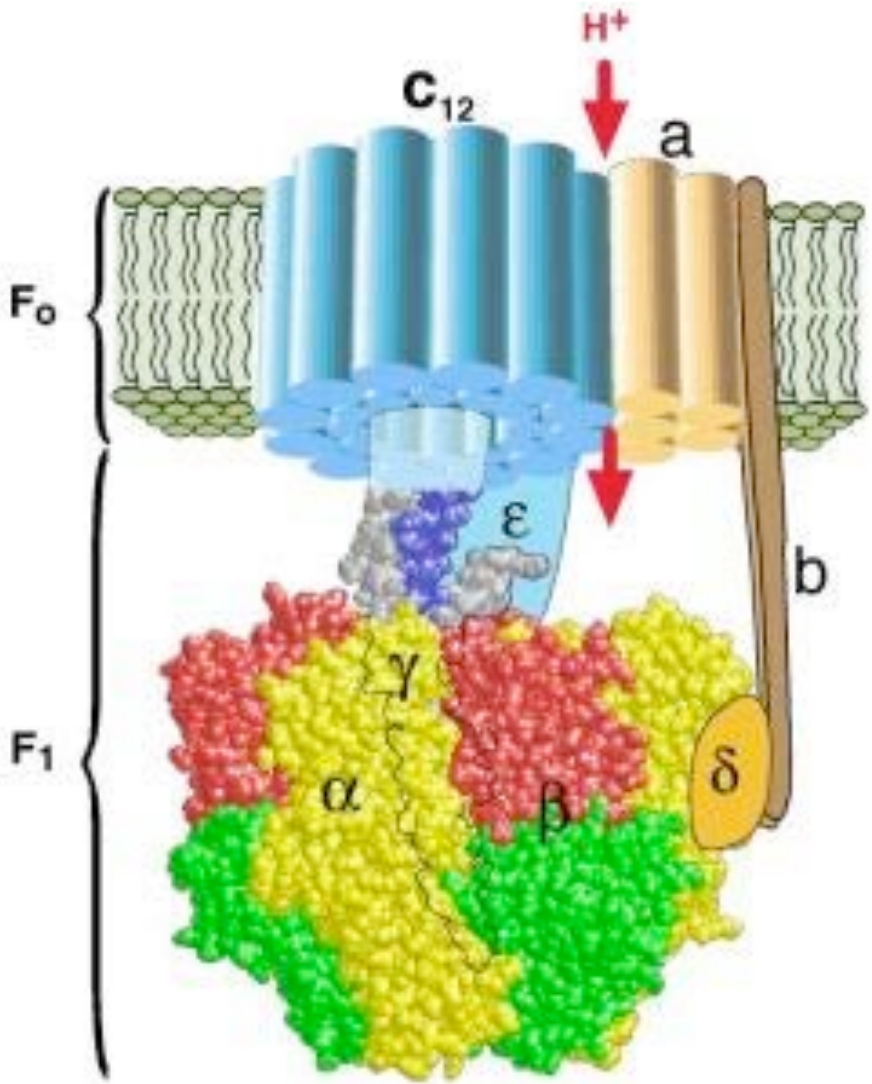
ATP synthesis

Chemiosmosis





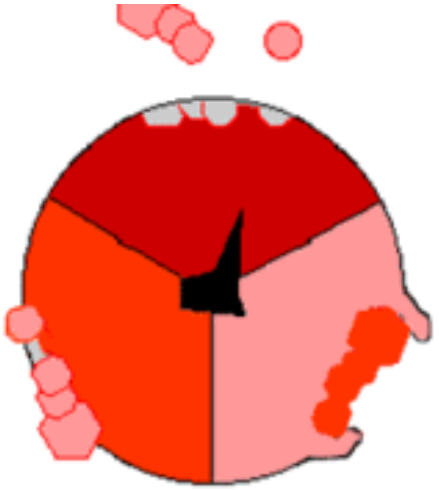
ATPase: the proton pump



H. Wang and G. Oster (1998). Nature 396:279-282.

An complex molecular machine is needed to convert the potential energy of proton gradient across the membrane into ATP.

ATPase (proton pump) couples the translocation of several protons across the membrane to the synthesis of an ATP molecule.



Organic matter and self-organization

- **Organic building-blocks** **Prebiotic chemistry**
  - In reducing environments (presence of H_2, H_2S, FeS…) organic matter does not correspond to a far-from-equilibrium state.
  - No special need for irreversibility for the formation of organics.

- **Self-organization of life** **Systems chemistry**
  - Need for irreversibility.
  - Self-organization must not lead to a violation of the Second Law of thermodynamics.
  - Need for self-organization to be coupled with irreversible transformation of chemical carriers of energy.

Ludlow & Otto, *Chem. Soc. Rev.* **2008**, *37*, 101.

Rules for the emergence of metabolisms

- Why a metabolism?
  - Not only anabolism (synthesis of biomolecules).
  - Organize the energy flow required for avoiding a violation of the 2nd principle
    - This function is achieved by catabolism or photosynthesis in present day living organisms.
    - It must have been accomplished by the (irreversible) dissipation of independent energy sources in early living organisms.

- Need of kinetic barriers:
  - There is a quantitative relationship between the timescale of the overall process, the height of kinetic barriers and absolute temperature.
    - Prediction of conditions under which the emergence is less improbable.
    - Systems based on covalent bonds under mild conditions.

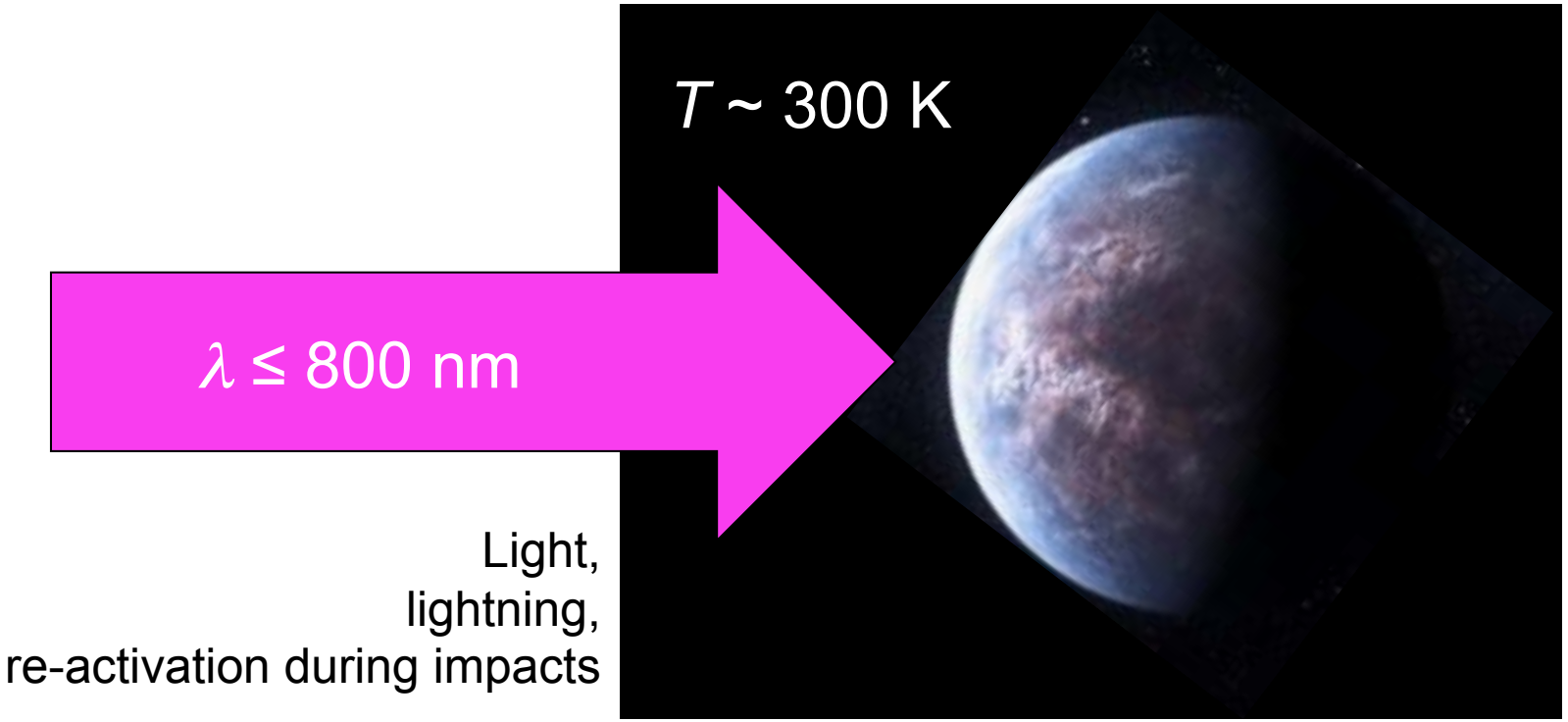
Consequences for space research and astrobiology

- Meteorites and comets contain organic matter that has been stored for periods exceeding hundreds of millions of years. Activated functional groups (e.g. cyano groups) are no longer present in high extent.
- It is then highly improbable (violation of the 2nd Law) that these materials could **directly** give rise to a proto-metabolism fulfilling the irreversibility conditions for self-organization.

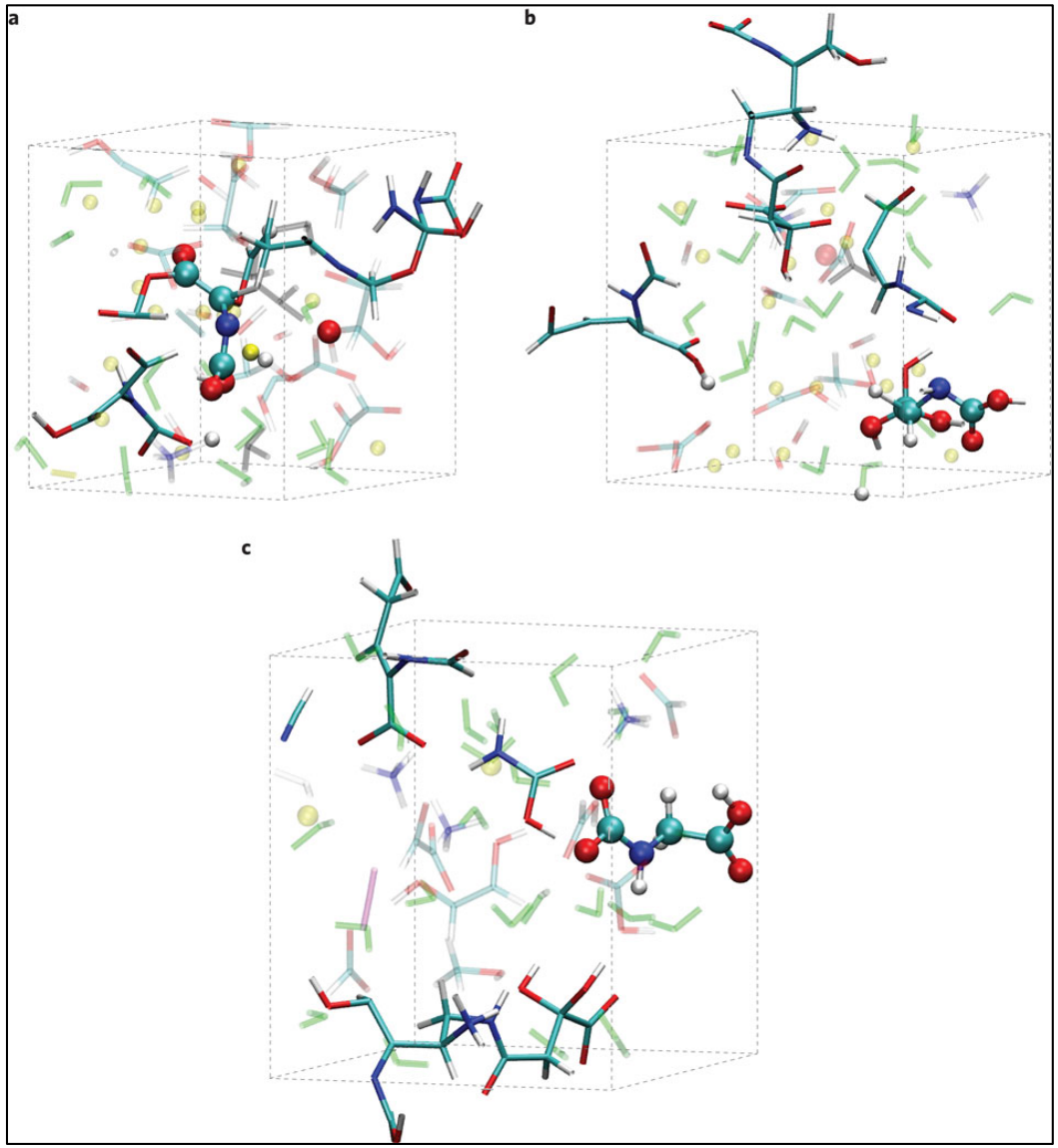
- How to get activated/activating species from these materials ?
  - Re-activation during impacts.
  - Photochemistry in a planetary environment.

"Habitability" for the origin of life

- The constraints for the origin of life are different from the constraints for life.
- Life in extreme environments has no obvious relationship with the origin of life.



Impact-induced shock synthesis



Shock synthesis of organic molecules

Simulation of the effect of shock compression (e. g. 9 km/s impact, 47 GPa).

Mixture of H_2O, CH_3OH, NH_3, CO and CO_2 in a molar ratio of 2:1:1:1:1

Chemical species formed at several thousand K and high pressure can endure quenching to lower temperatures.

- Formation of glycine carbamate, HCN…
- other stable or metastable species.

Goldman et al. *Nat. Chem.* **2010,** *2*, 949

Origin of life
Dynamics in replicating systems

- It requires conditions in agreement with an **open-ended growth of replicators**:
  - **Need for the system to pay the cost for getting irreversible.**

- The conditions for the emergence of autonomous systems are determined by kinetic laws that can be investigated, at least in part, by physicochemical tools.

Acknowledgements

- The DSBC group of IBMM
  - Dr. L. Boiteau
  - Dr. J.-C. Rossi
  - Dr. G. Danger
  - Dr. R. Plasson
- Collaboration
  - Dr. G. Danger (University of Marseille)
  - Prof. A. Pross (Ben Gurion University of the Neguev)
- Interdisciplinary program EPOV