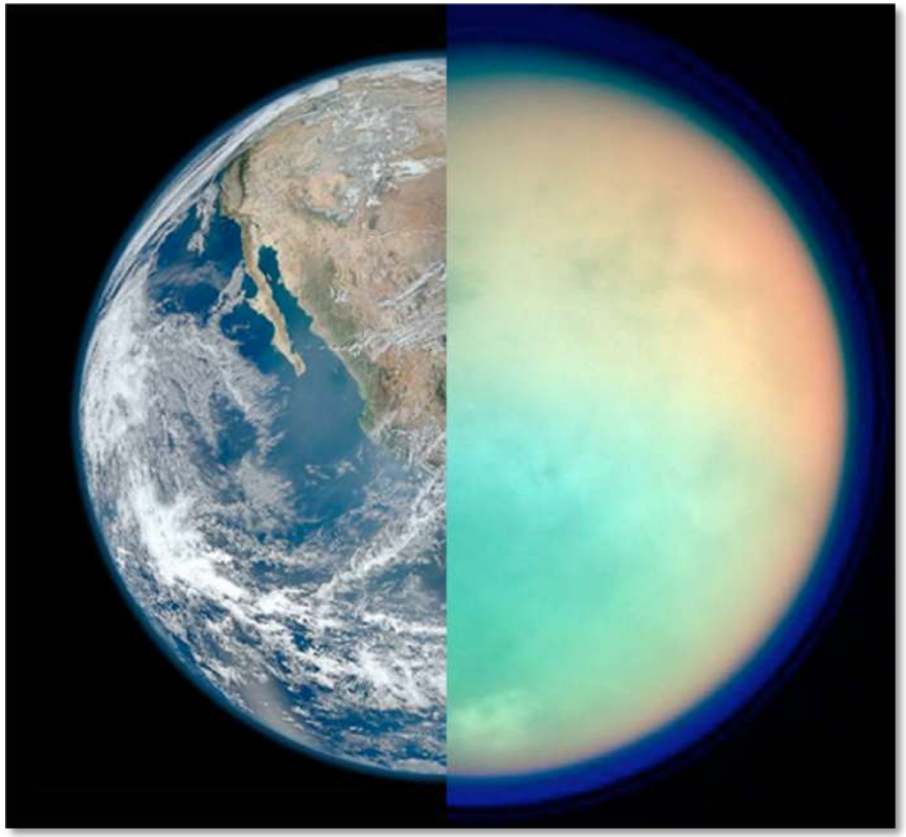
The early Earth as an example for inhabited exoplanets



Benjamin Charnay[1], Boris Sauterey[2], Régis Ferrière, Antonin Affholder, Stéphane Mazevet, Thomas Leliboux, Pascal Rannou, Bruno de Batz de Trequelleon, Yassin Jaziri, Franck Lefèvre, Thomas Drant, Nathalie Carrasco

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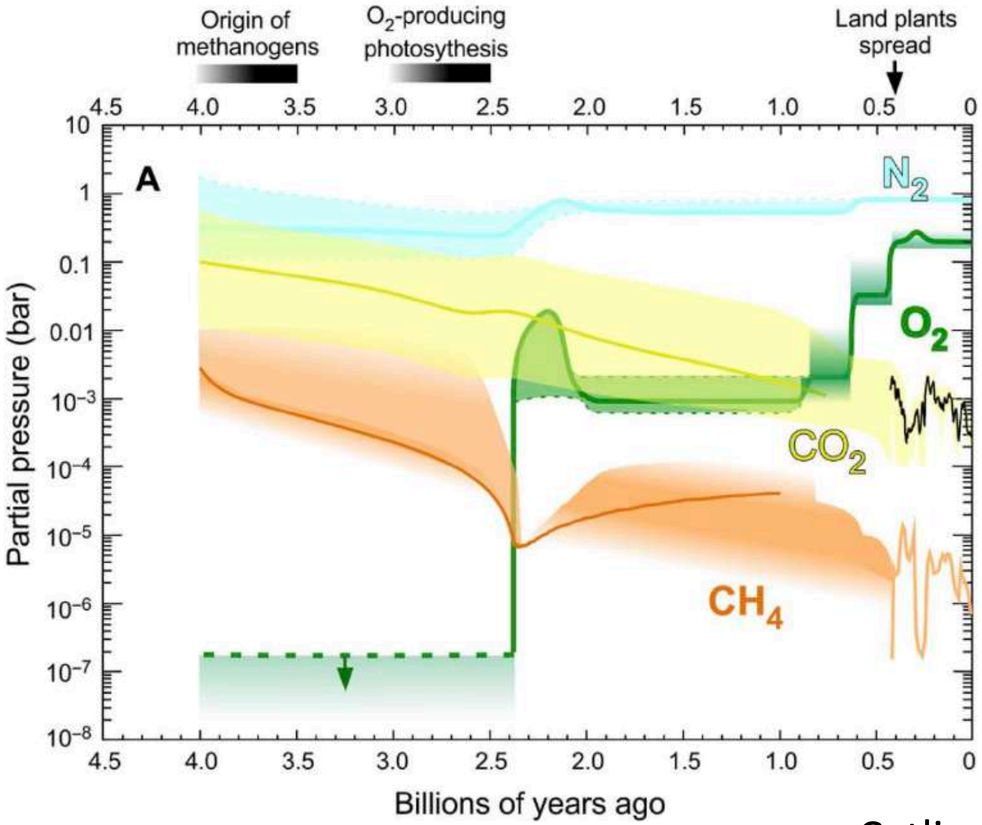
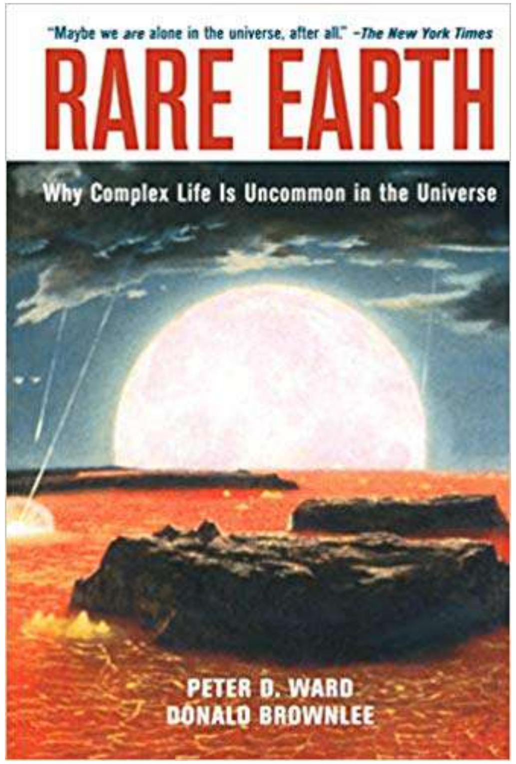
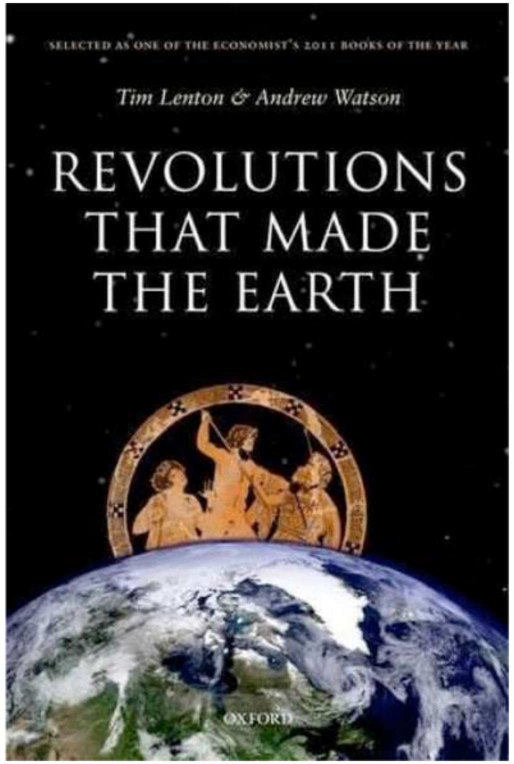
IBENS Institut de Biologie de l'Ecole Normale Supérieure

Evolution of Earth’s atmosphere and motivations for studying the Archean Earth



Catling & Zahnle 2020

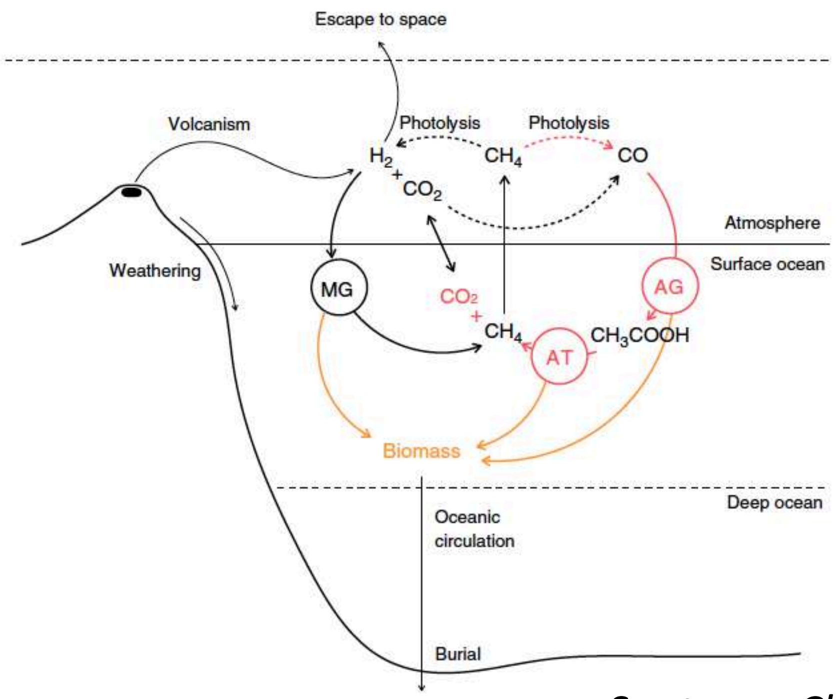




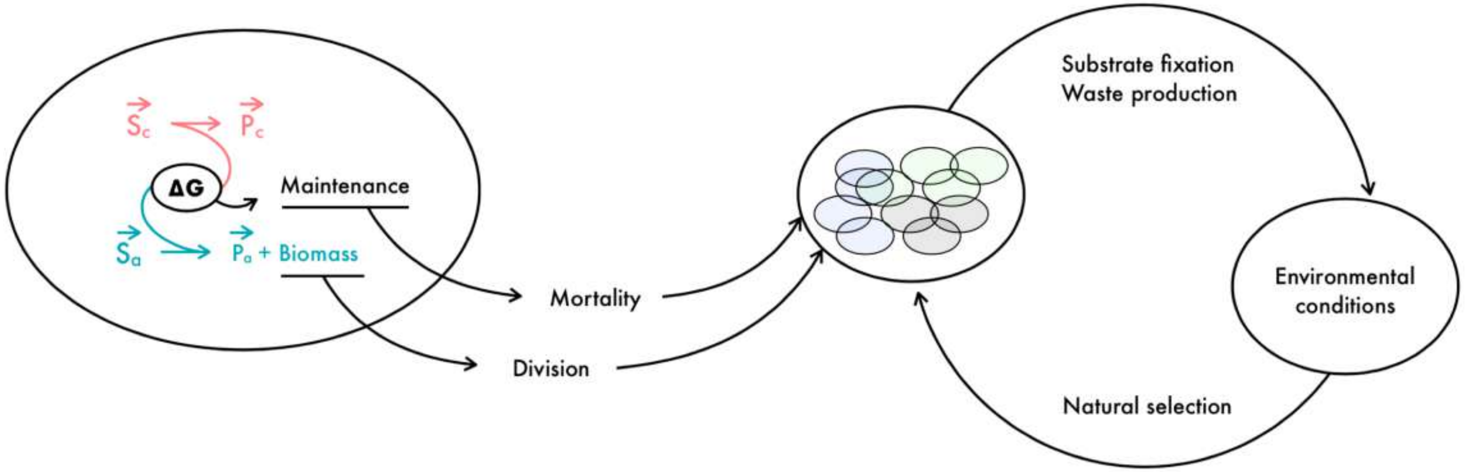
- The evolution of O2 is very complex with 3 critical steps (oxygenic photosynthesis and two oxidation events)
- During most of Earh’s history O_2 was very difficult detectable from and exoplanet point of view
- The Archean Earth had a very productive biosphere even before oxygenic photosynthesis
- It is essential to understand all the implications of biospheres not dominated by oxygenic photosynthesis

Modeling the early Earth's biosphere

Ecosystem-planetary model for methanogens



Sauterey, Charnay et al., 2020

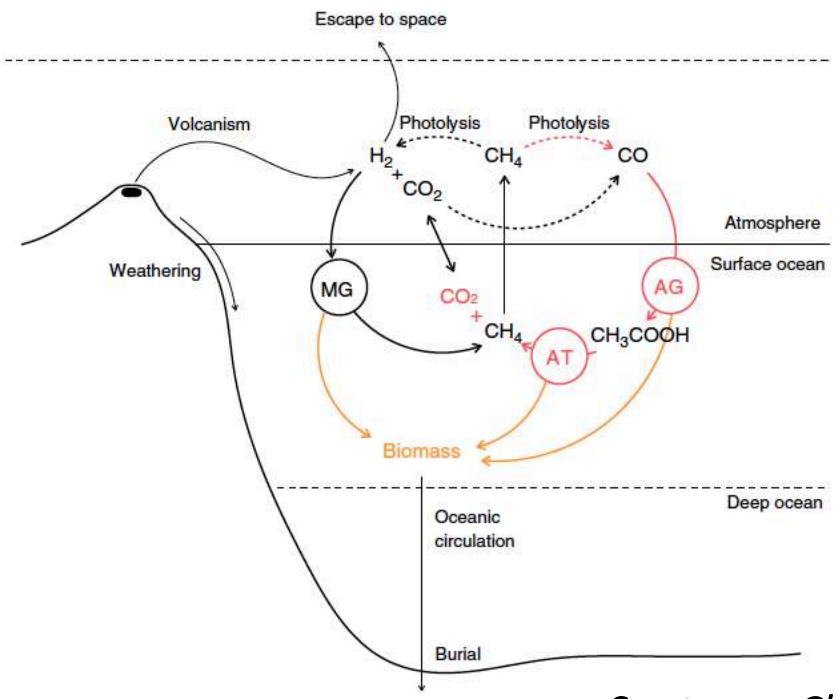


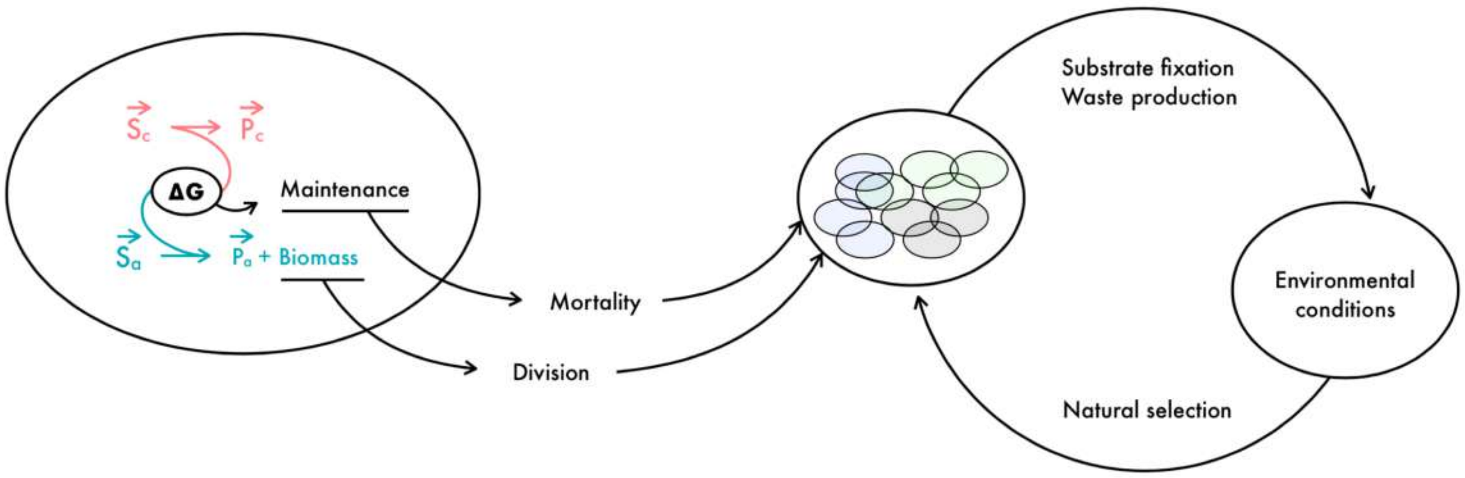
$$
\begin{cases}
\dfrac{dN}{dt} = N \cdot (\text{division} - \text{mortality}) \\
\dfrac{dB}{dt} = q_a - \text{division} \cdot B \\
\dfrac{dX_i}{dt} = F(X_i) + N \cdot (q_c \cdot \gamma_{c,i} + q_a \cdot \gamma_{a,i})
\end{cases}
$$

Catabolism:
H_2-based methanogens: $CO_2 + 4H_2 \rightarrow CH_4 + 2\, H_2O$
CO-based acetogens: $2CO + H_2O \rightarrow CO_2 + 1/2\, CH_3COOH$
Methanogenic acetotroph: $CH_3COOH \rightarrow CO_2 + CH_4$

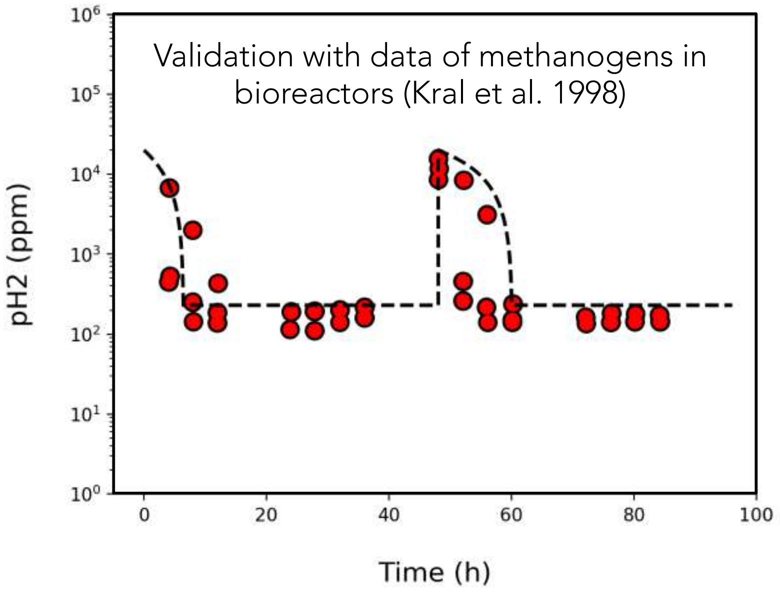
Modeling the early Earth's biosphere

Ecosystem-planetary model for methanogens





Sauterey, Charnay et al., 2020



Catabolism:
H_2-based methanogens: CO_2+ $4H_2$ → CH_4 + 2 H_2O
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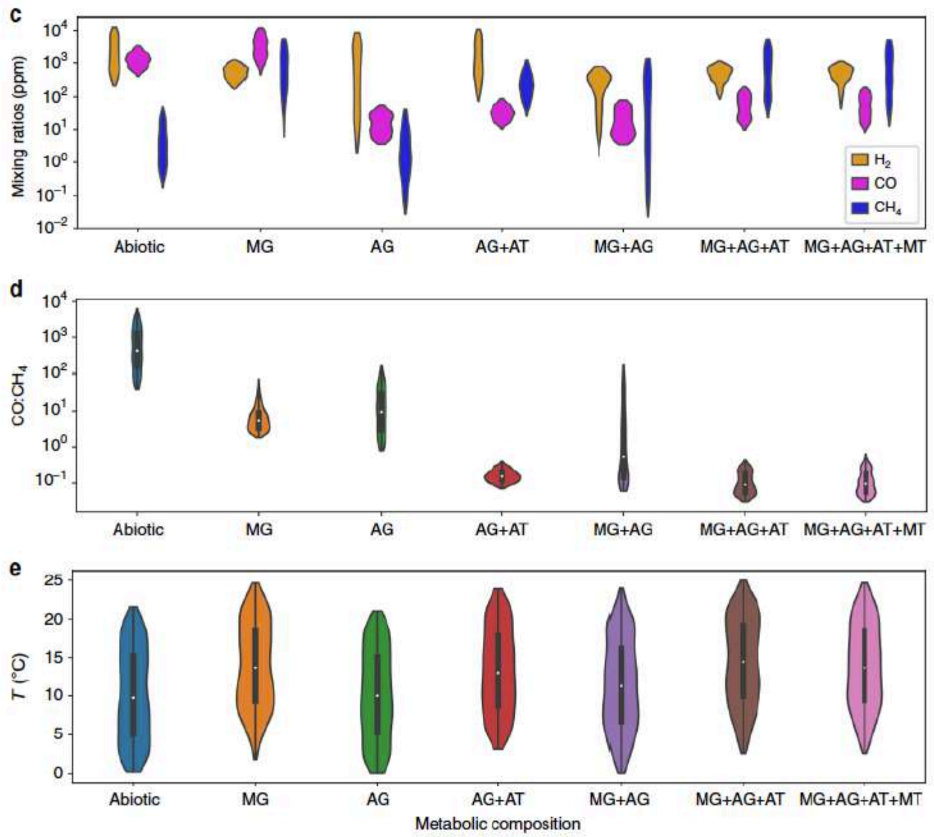
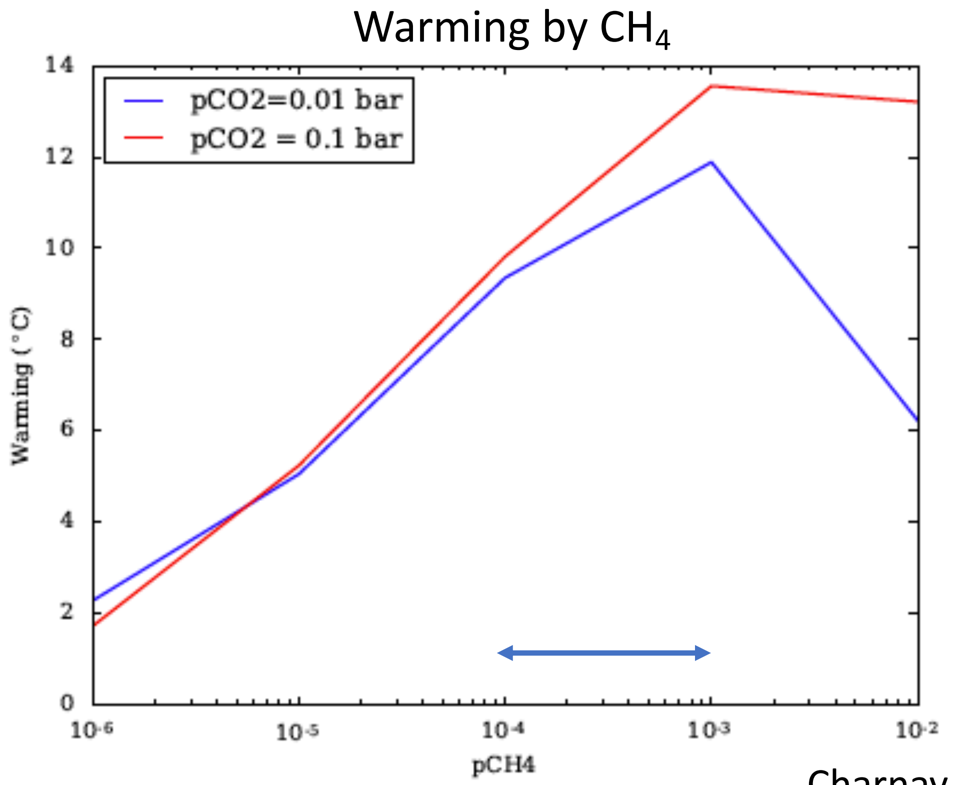
Methanogenic acetotroph: CH_3COOH → CO_2 + CH_4

Modeling the early Earth's biosphere

Composition for chemiotrophic ecosystems





Charnay et al. 2020

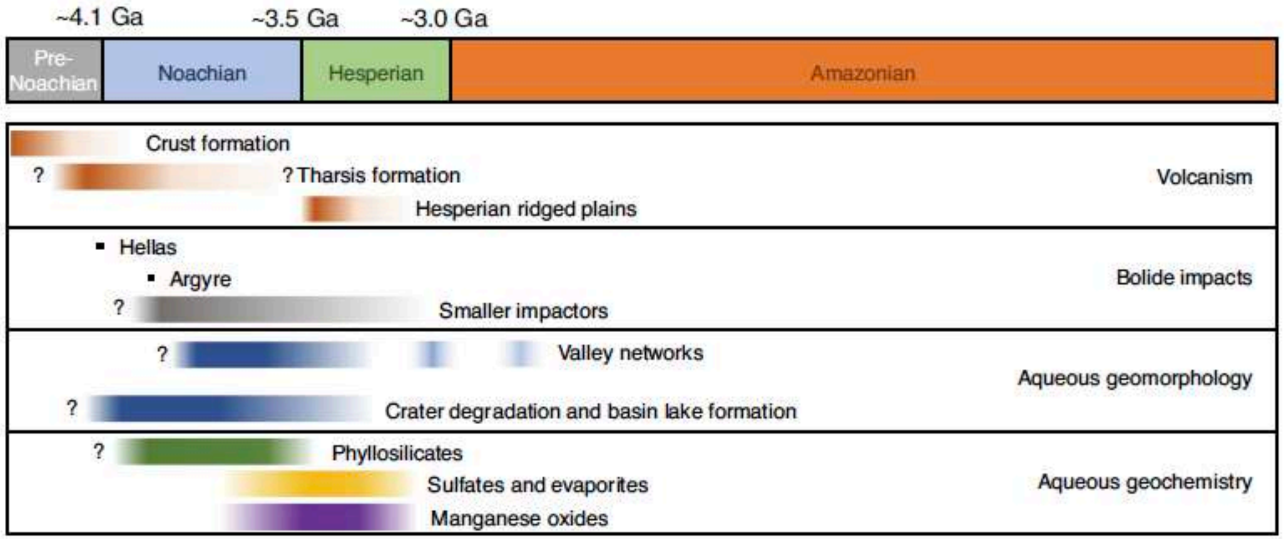
Ecosystem-planetary model for methanogens on the early Earth
Sauterey, Charnay et al., Nature Communications 2020:

- **The production of biomass and CH_4 is maximal for complete ecosystem (syntrophy)**
- **High CH_4 concentration (100-1000 ppm) → significant warming (~10°C)**
- **A low CO:CH_4 is characteristic of the presence of ecosystems → minimisation of the chemical disequilibrium**

Modeling the early Mars biosphere

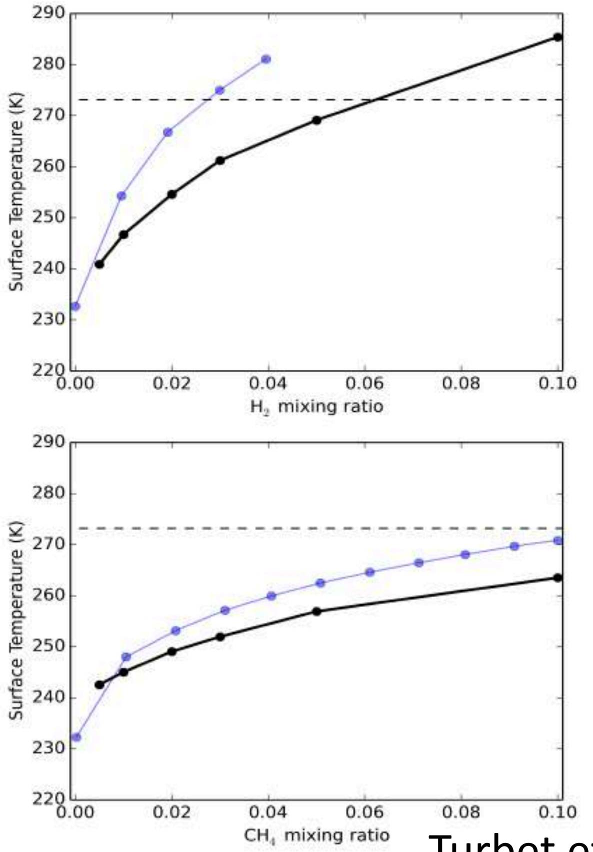
The enigma of early Mars

Global history of Mars



Emergence of life on Earth

Wordsworth et al. 2020

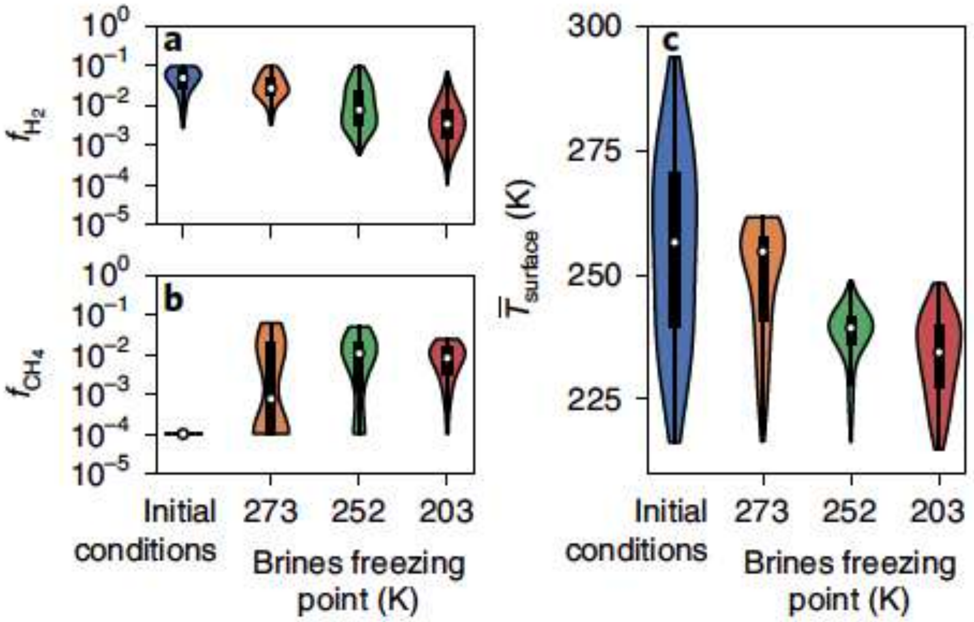


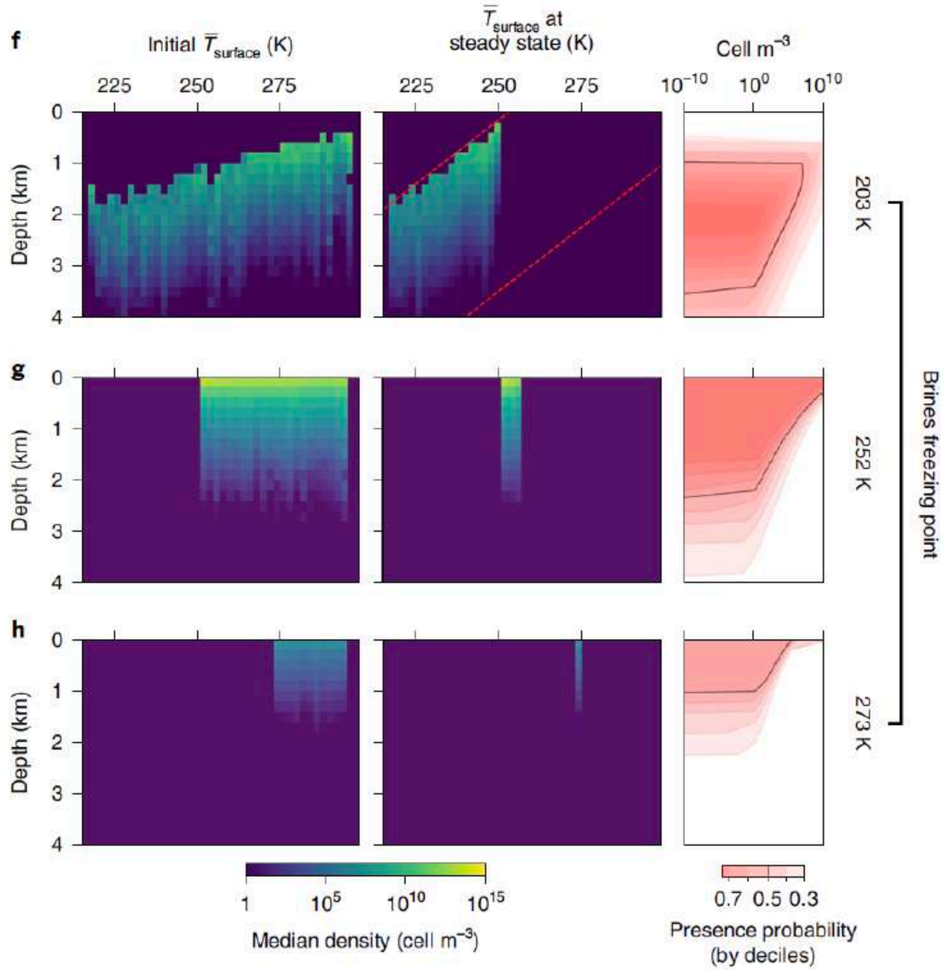
Turbet et al. 2020

Favored solution to warm early Mars: H_2-rich atmosphere from a reduced mantle
(Ramirez et al. 2013, Wordsworth et al. 2017,2021)
→ warming by CIA of CO_2-H_2 and CO_2-CH_4
→ CIA of CO_2-H_2 is stronger than CIA of CO_2-CH_4 (Turbet et al. 2020)

Modeling the early Mars biosphere

Habitability and climate impact of methanogens



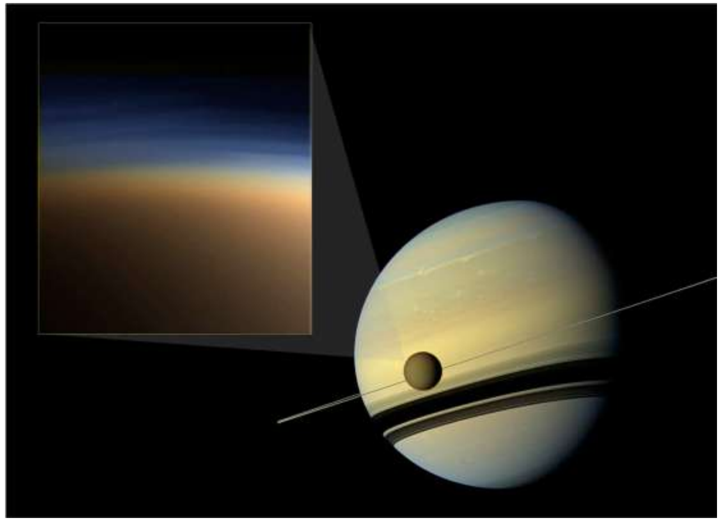


Ecosystem-planetary model for methanogens on early Mars
Sauterey, Charnay et al., Nature Astronomy 2022:

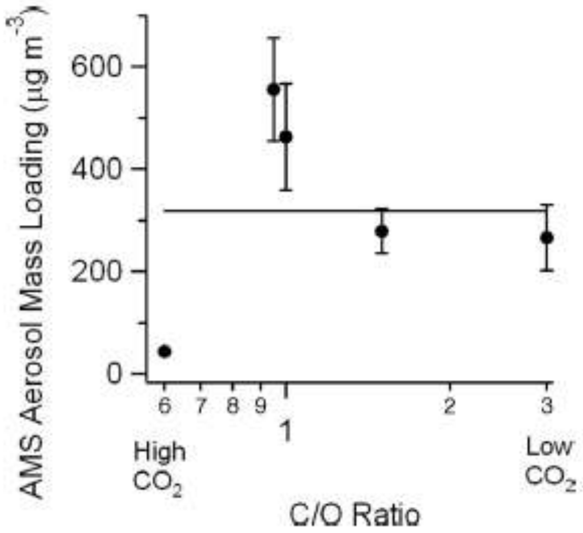
- ***Sub-surface of early Mars was likely habitable***
- ***The presence of H_2-based methanogens induces a cooling limiting warm climate***

The case of a hazy early Earth

Organic haze formation for CH_4/CO_2 > 0.1

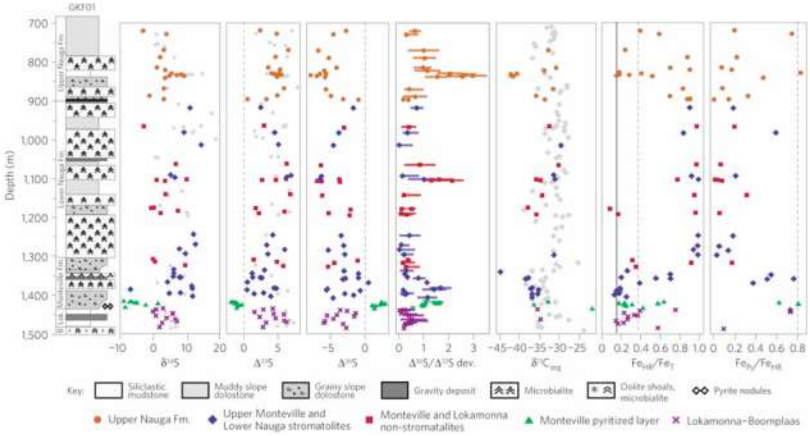


Lab experiment



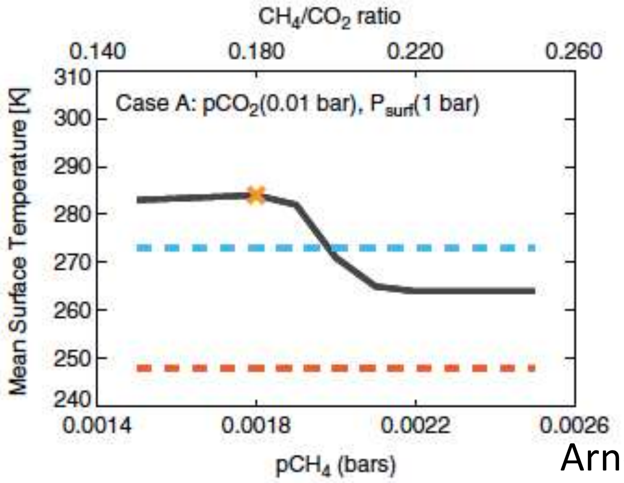
Trainer et al. 2006

Evidence for a CH_4-rich archean atmosphere with episodic haze:



Zerkle et al. 2012

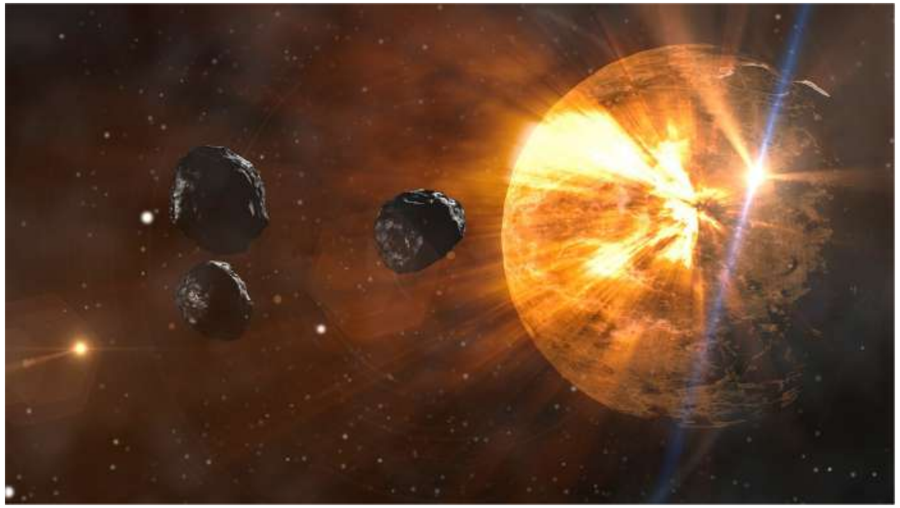
Anti-greenhouse effect from 1D models

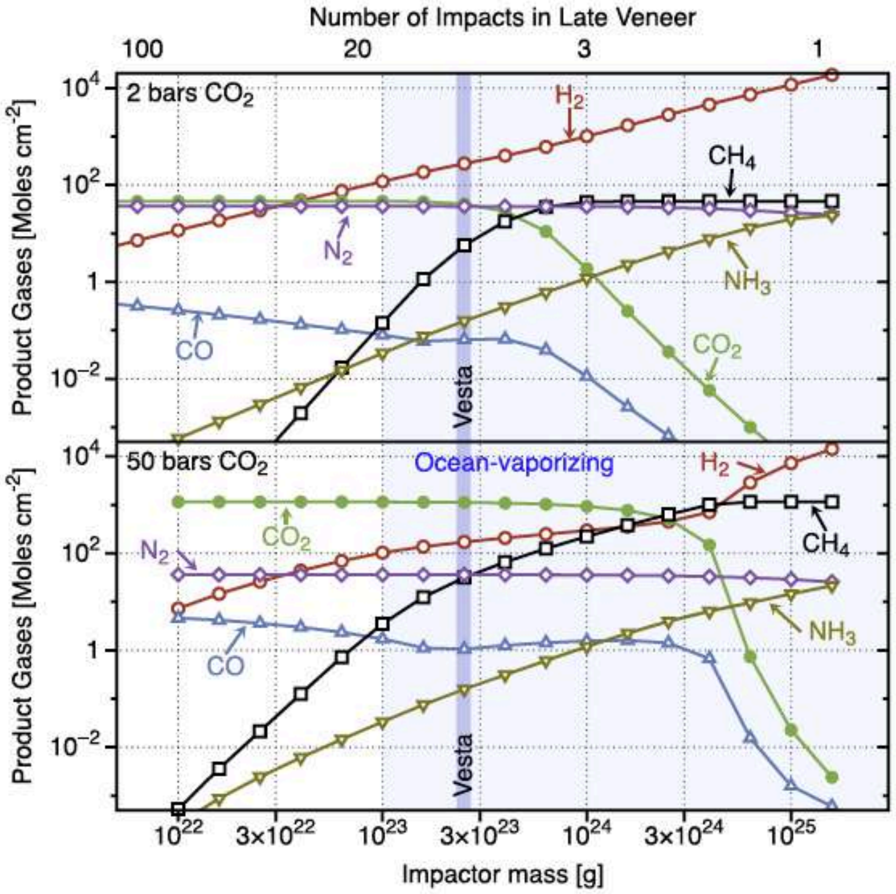


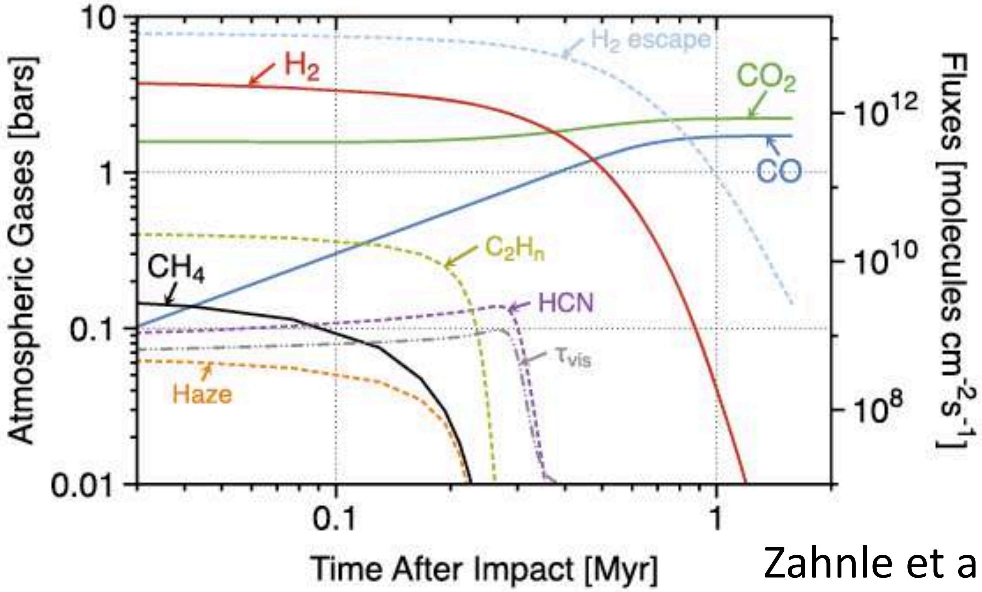
Arney et al. 2016

A scenario for the origin of life: transient H_2-dominated atmosphere after giant impacts of the late Veneer.

(Genda et al. 2017, Benner et al. 2019, Zahnle et al. 2020, Itcovitz et al. 2022)





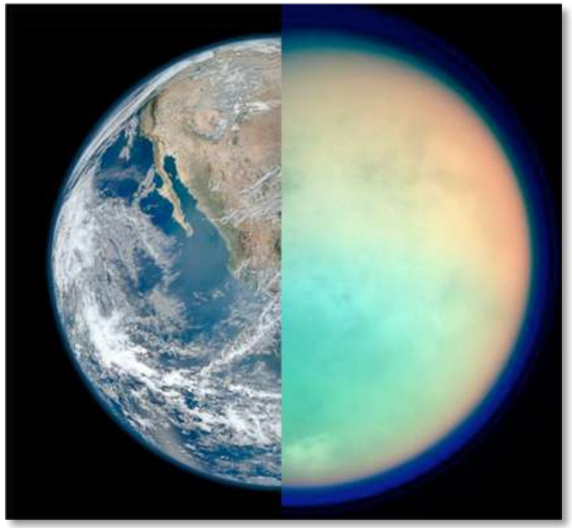


Zahnle et al. 2022

- Vaporized ocean water reacts with iron producing a H_2-rich atmosphere
- Thermochemistry after impacts leads to the conversion of CO_2 into CH_4
- Photochemistry leads to the **formation of organic haze, HCN and prebiotic molecules**

Current project: 3D modeling of photochemistry and organic haze on the early Earth

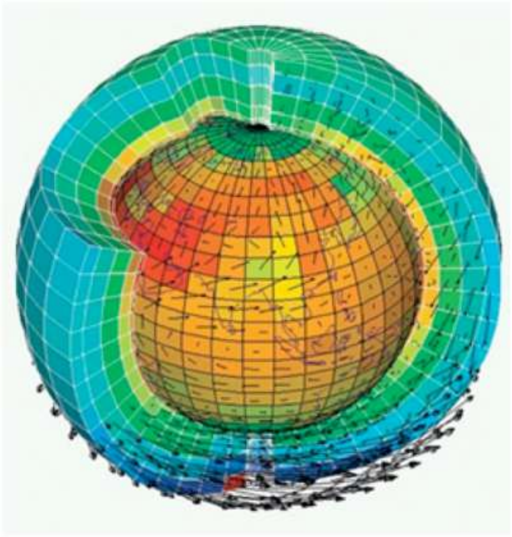
People involved: B. Charnay, T. Leliboux, P. Rannou, B. de Batz, Y. Jaziri, F. Lefèvre, T. Drandt, N. Carrasco



Objectives:

- Formation, distribution and dynamics of haze
- Impact of haze on the climate and on photochemistry
- Application to exoplanets (e.g. Trappist-1 e, K2-18 b)

Tool: the Generic PCM



Photochemistry (Jaziri et al. 2022) **:**
- 120 reactions
- Solar UV flux at 2.7 Ga (Claire 2013)
- Haze formation pathway:

$C_2H + C_2H_2 \rightarrow HCAER + H$

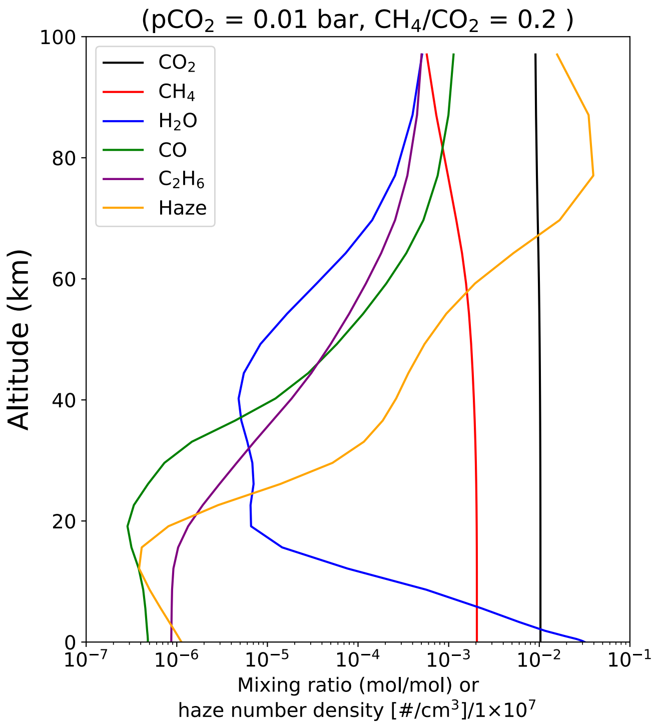
Microphysical model (Burgalat et al. 2014):
- Spherical and fractal particles (with moments)
- Radiative coupling (in development)
- Haze optical properties from lab experiments (Drant et al. submitted)

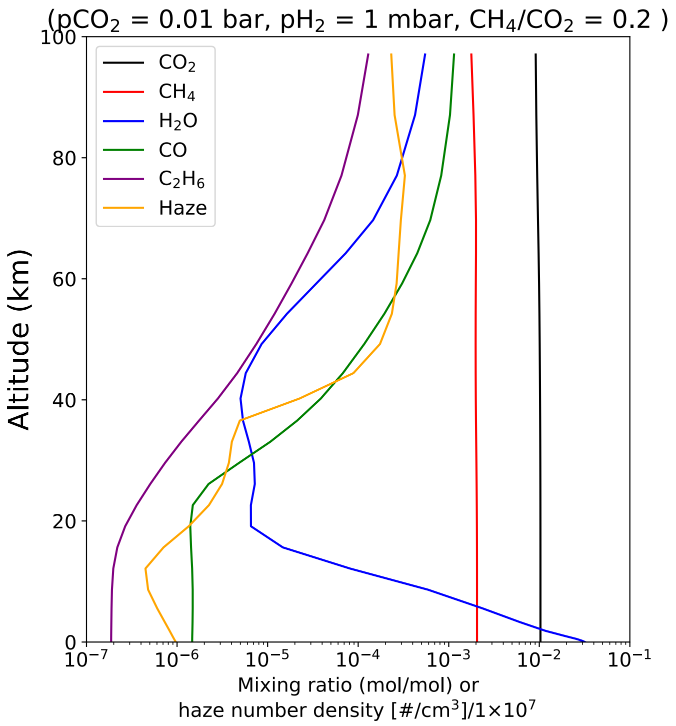
Results from 3D simulations:

- **Production rate strongly reduced for a H_2-rich atmosphere. ($CH_3 + H \rightarrow CH_4$)**

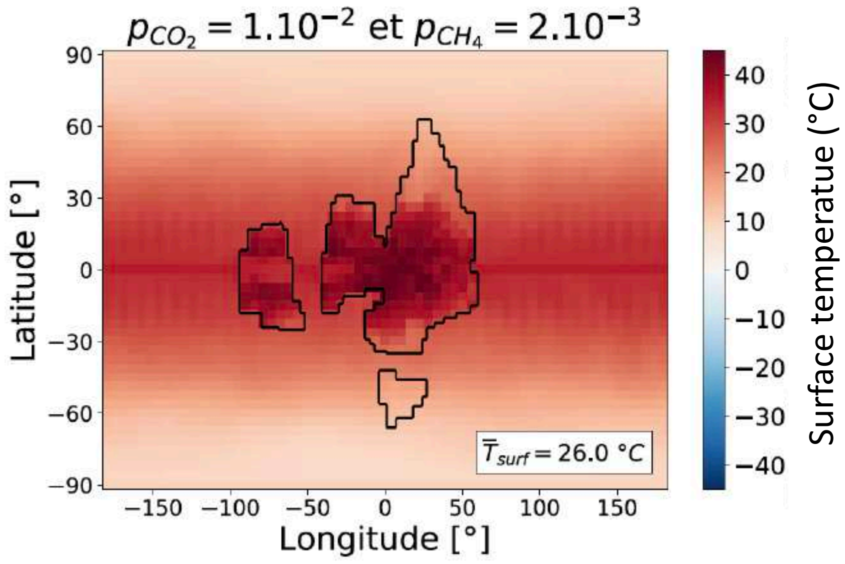
→ H_2-based methanogenesis might not lead to optically thick haze

- **Poleward haze transport with relatively haze-free equatorial regions**

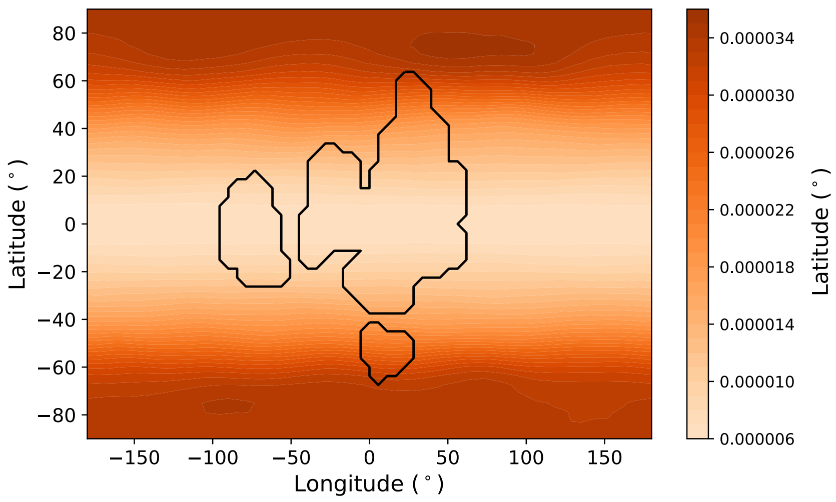




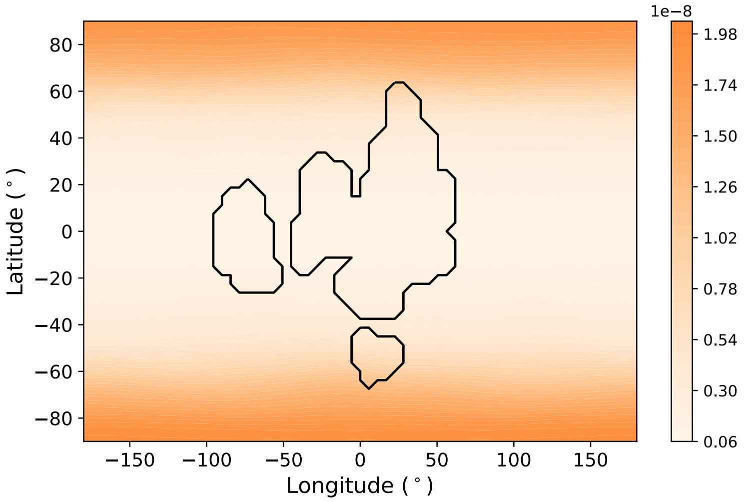
Surface temperature without photochemistry



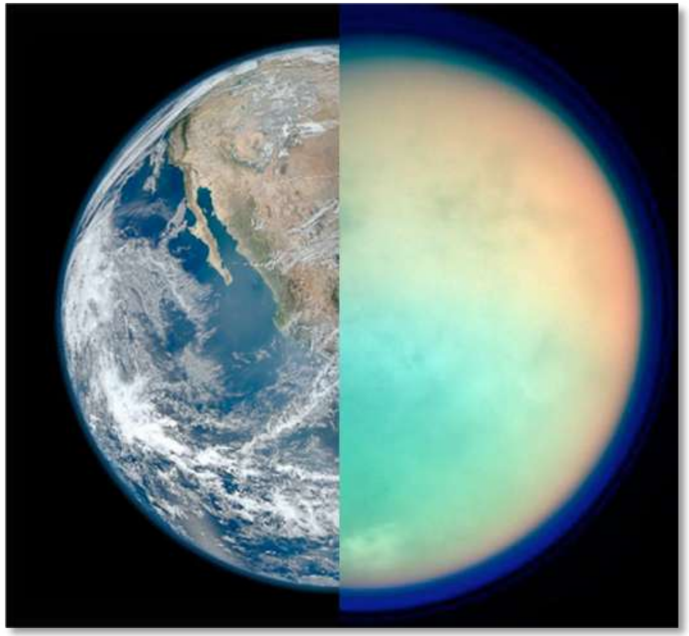
Production rate= $2.7.10^{13}$ g/year



Production rate= $4.6.10^{10}$ g/year



Take-home messages



- The conditions of the early Earth and early Mars could have allowed **high CH_4 concentrations produced by methanogens**
- Methanogens would have produced **a warming on the early Earth** but **a cooling on early Mars** due to differences in the H_2 abundance
- A biosphere based on chemiotrophic ecosystems implies **a low CO/CH_4 ratio**
- 3D simulations of photochemical haze on the early Earth show:
  - a sensitivity to the H_2 mixing ratio for the haze production rate
  - a poleward haze transport → might be favorable for transit spectroscopy

Next step: adding haze radiative effects

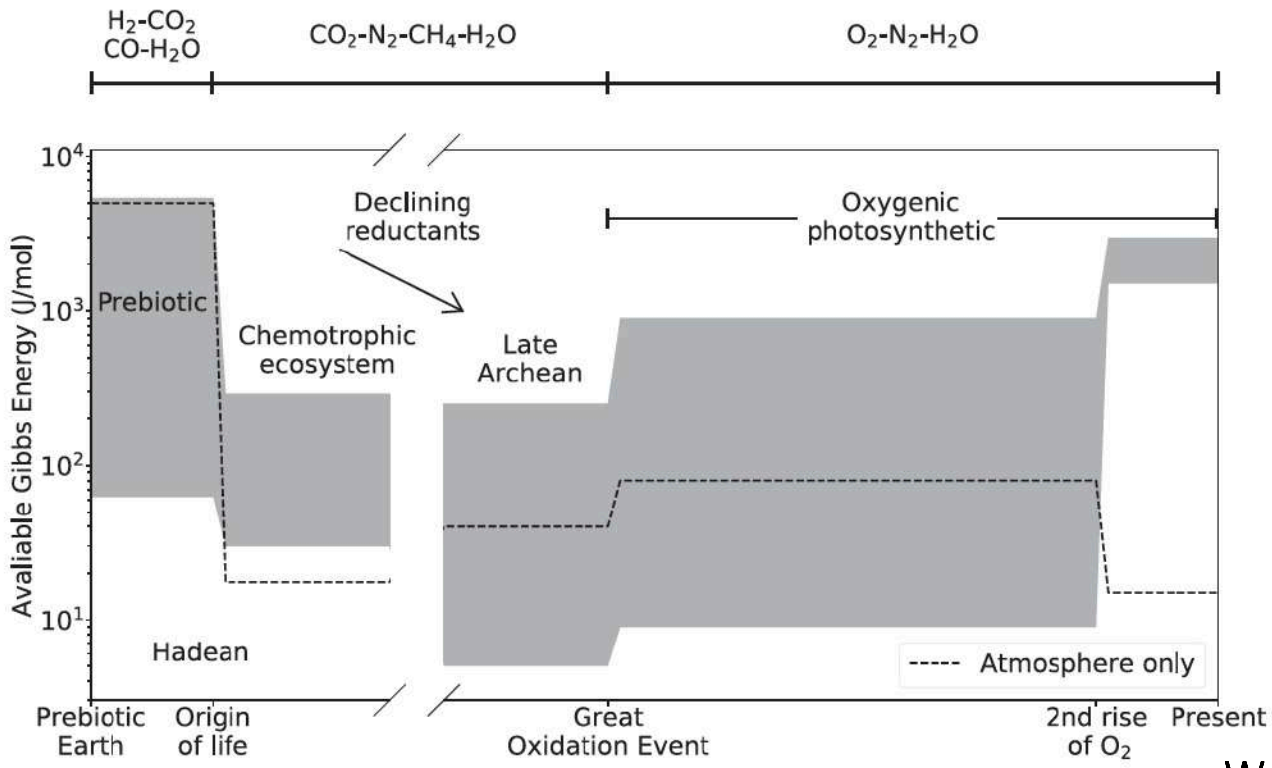
Sauterey, Charnay, Affholder, Mazevet, Ferrière, « Co-evolution of primitive methane-cycling ecosystems and early Earth's atmosphere and climate», *Nature Communications, 2020*

Sauterey, Charnay, Affholder, Mazevet, Ferrière, « Early Mars habitability and global cooling by H_2-based methanogens», *Nature Astronomy, 2022*

Modeling the early Earth's biosphere

Composition for chemiotrophic ecosystems

Evolution of chemical disequilibrium during Earth's history



Wang & Catling 2020

Global chemical disequilibrium is not a biosignature

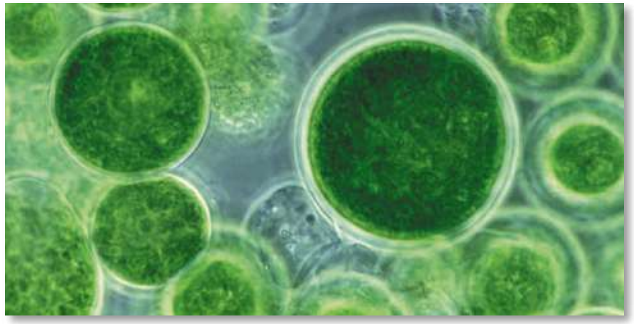
1) Difficult to measure (uncomplete invetory of molecules in the atmosphere and the ocean)
2) Chemical disequilibrium is not necessary higher with life than without life
3) Chemotrophic ecosystems reduce the chemical disequilibrium

Classical definition : "A biosignature is defined as any characteristic element, molecule, substance, or feature that can be used as evidence of past or present life and is distinct from an abiogenic background" (Domagald et al. 2016)

	Type	*Biosignatures*	*Examples*	*Appropriate techniques*
In situ	Visual biosignatures	Direct observation of active life	Cellular structures (possibly seen to be motile or reproducing)	Microscopy or macroscopic imagery
		Fossils	Fossilized cells	
		Artifacts of life	Stromatolites or endolithic microborings	
	Chemical biosignatures	Biological macromolecules	Proteins or nucleic acid polymers (*e.g.*, DNA, RNA)	Gas chromatography–mass spectrometry, Raman spectroscopy, X-ray spectroscopy
		Molecular fossils	Breakdown products of biomolecules, such as hopanoids or steranes	
		Molecular evidence of metabolism	Biogenic biases, such as isotopic fractionation or homochirality	
		Thermodynamic or kinetic disequilibrium within environment	Gradients of redox species in column of lake water	
		Biominerals	Certain silicate, carbonate, or iron minerals, or metal enrichments of, *e.g.*, Cu, Mo, Ni, W	
Remote	Spectral biosignatures	Large-scale environmental disequilibrium	Atmospheric disequilibrium, *e.g.*, O_2 and CH_4	IR and visible spectroscopy
		Photosynthetic life	Red edge of vegetation	
	Spatially resolved	Geometrical structures of intelligent life	Roads, cities, agriculture, large-scale landscape modification	Optical imaging
	Electromagnetic emissions	Intelligent broadcasts	Radio or optical signals from a civilization	Radio or optical sky surveys

Domagald et al. 2016

Oxygenic photosynthesis



$CO_2 + H_2O + h\nu$ → (photosynthesis) / ← (respiration or oxidation) $CH_2O + O_2$

photosynthesis

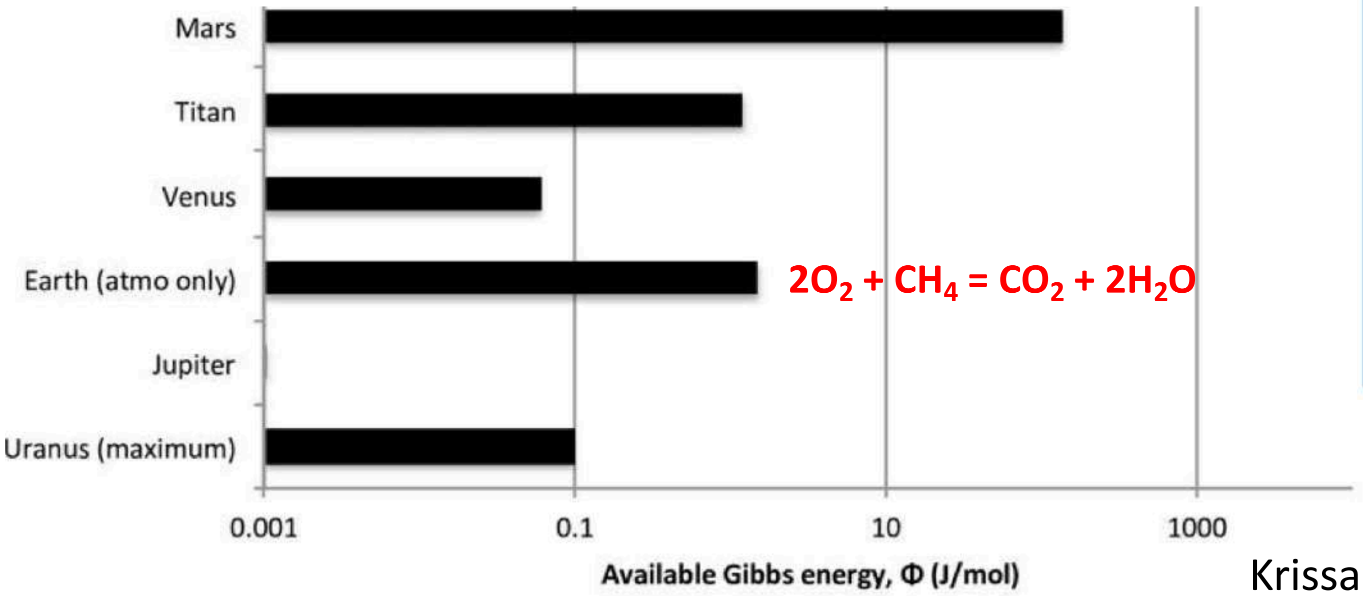
respiration
or
oxidation

↑ Atmospheric oxygen

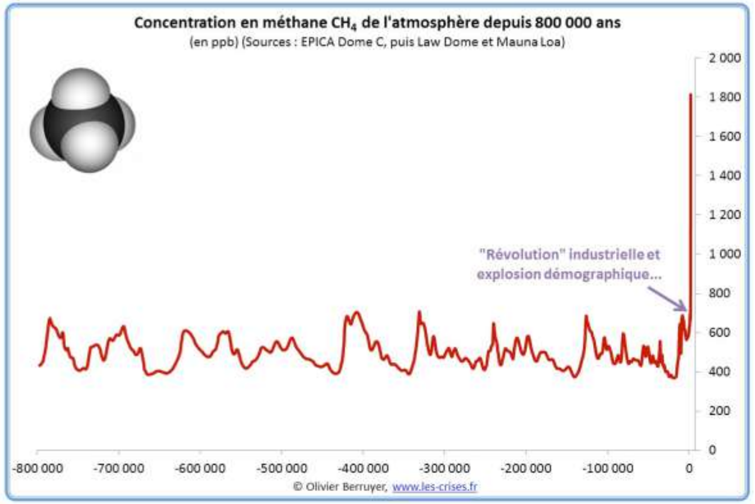
↓ Burial

→ $\frac{1}{2} CH_4 + \frac{1}{2} CO_2$ Fermentors + methanogens

Chemical disequilibrium in Solar System atmospheres

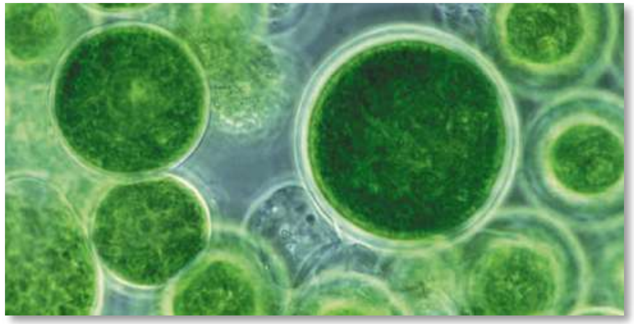


$2O_2 + CH_4 = CO_2 + 2H_2O$



Krissanssen-Totton et al. 2015

Oxygenic photosynthesis

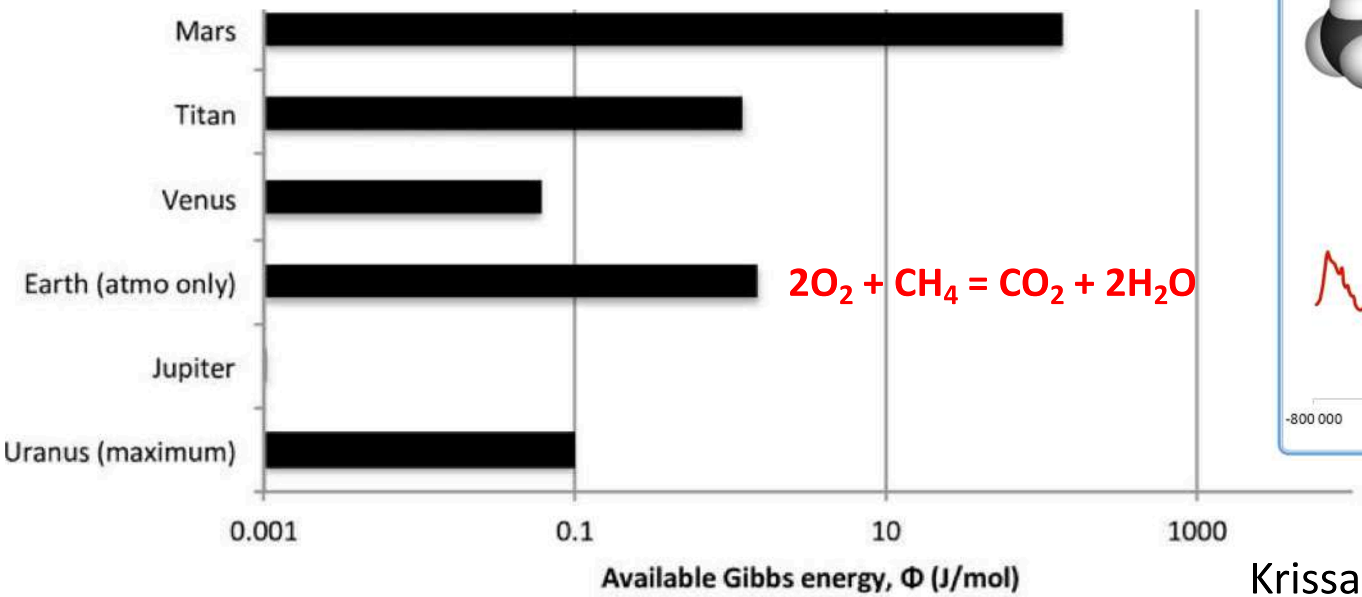


$$CO_2 + H_2O + h\nu \underset{\text{respiration or oxidation}}{\overset{\text{photosynthesis}}{\rightleftharpoons}} CH_2O + O_2$$

↑ Atmospheric oxygen

↓ Burial

Chemical disequilibrium in Solar System atmospheres



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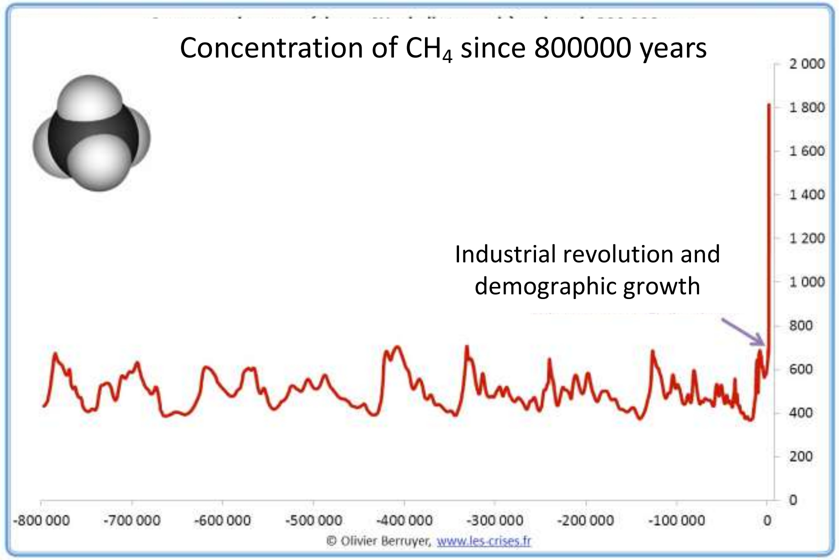
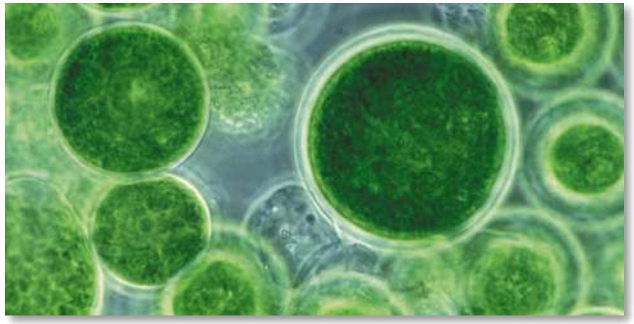


Krissanssen-Totton et al. 2015

Oxygenic photosynthesis



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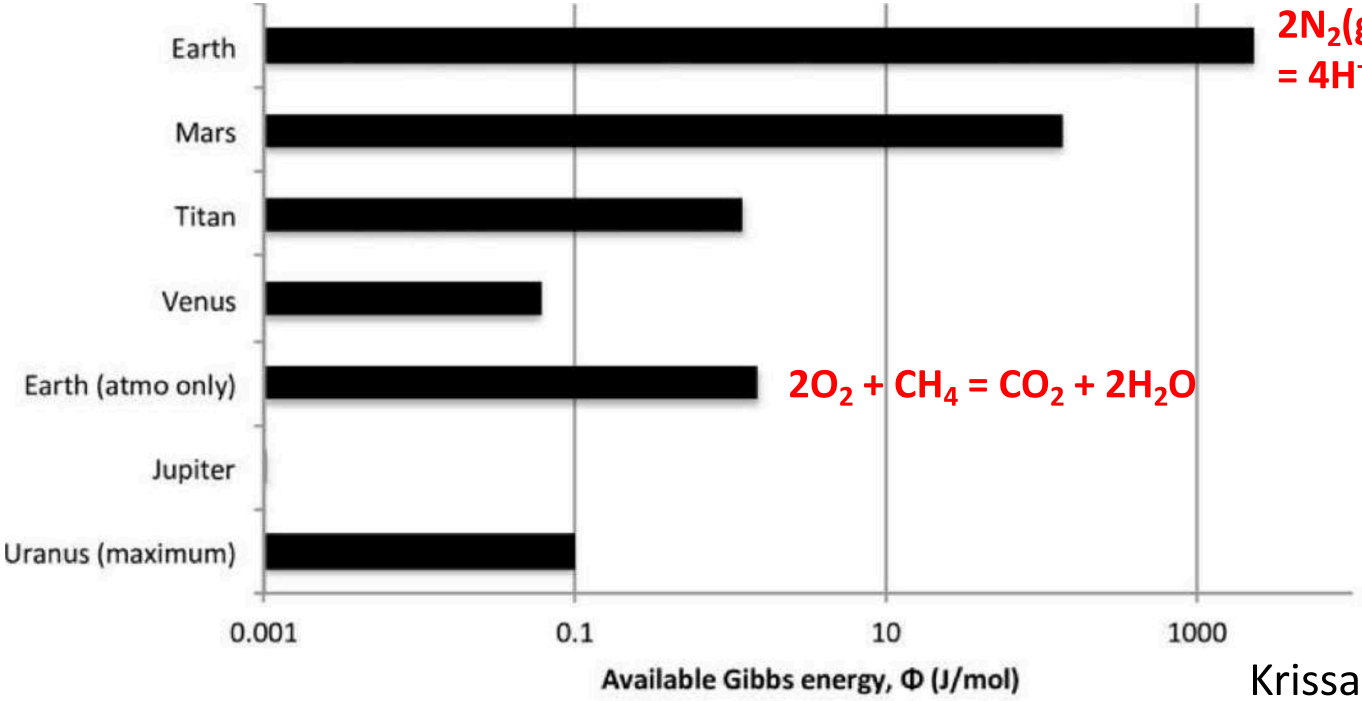

$2N_2(g) + 5O_2(g) + 2H_2O(l) = 4H^+(aq) + 4NO_3^-(aq)$

$2O_2 + CH_4 = CO_2 + 2H_2O$

Krissanssen-Totton et al. 2015