



The quest for extraterrestrial life: why does it matter?
18/10/2021



On the challenge of detecting extraterrestrial life

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Credit: www.iau.org/



Life?

We can define as living system any entity capable of self-replication and Darwinian evolution
(*Encyclopedia of Astrobiology, 2011*)



Requirements for life to appear and develop

Ingredients and conditions

We think that:

- All life is probably based on organic chemistry and on the elements C, H, N, O, P and S.

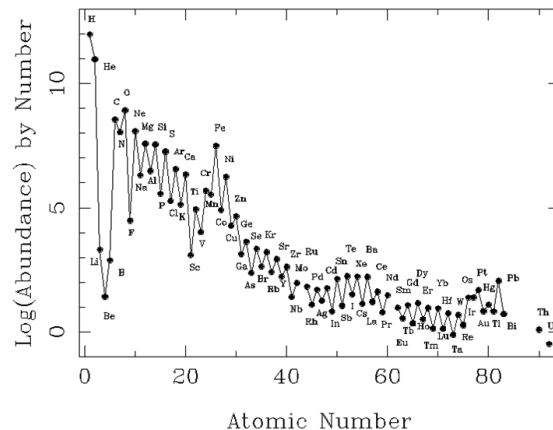
Why these elements?

1- Nucleosynthesis

In the universe, the most abundant elements capable of bonding with other elements are:

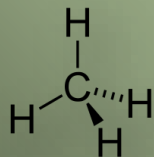
H, O, C and N

Logarithmic SAD Abundances: $\text{Log}(H) = 12.0$

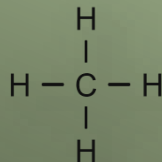


2- Carbon chemistry

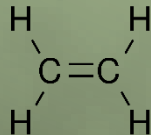
Tetravalence



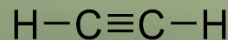
Orbital hybridisation



sp³ single bond
(ex. Methane)



sp² double bond
(ex. Ethylene)



sp triple bond
(ex. Acetylene)

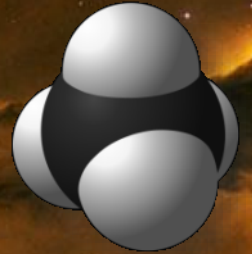


Polymerisation, high affinity with H, O and N, wide range of bonding energy...

Organic molecules in deep space

More than 230 molecules have been detected in the interstellar medium and circumstellar envelopes:

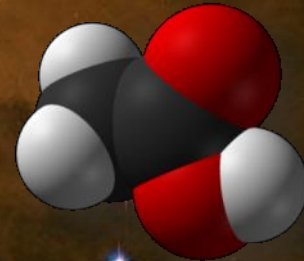
- Methane CH_4



- Ethanol $\text{C}_2\text{H}_5\text{OH}$



- Acetic acid CH_3COOH



Credit: NASA

Eagle Nebula (M16)

Detection in comets



RESEARCH ARTICLE

Sci. Advances (2016)

SPACE SCIENCES

Prebiotic chemicals—amino acid and phosphorus— in the coma of comet 67P/Churyumov-Gerasimenko

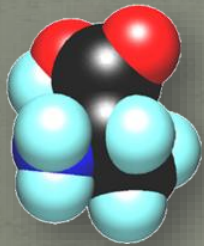
Kathrin Altwegg,^{1,2*} Hans Balsiger,¹ Akiva Bar-Nun,³ Jean-Jacques Berthelier,⁴ Andre Bieler,^{1,5} Peter Bochsler,¹ Christelle Briois,⁶ Ursina Calmonte,¹ Michael R. Combi,⁵ Hervé Cottin,⁷ Johan De Keyser,⁸ Frederik Dhooghe,⁸ Bjorn Fiethe,⁹ Stephen A. Fuselier,¹⁰ Sébastien Gasc,¹ Tamas I. Gombosi,⁵ Kenneth C. Hansen,⁵ Myrtha Haessig,^{1,10} Annette Jäckel,¹ Ernest Kopp,¹ Axel Korth,¹¹ Lena Le Roy,² Urs Mall,¹¹ Bernard Marty,¹² Olivier Mouis,¹³ Tobias Owen,¹⁴ Henri Rème,^{15,16} Martin Rubin,¹ Thierry Sémon,¹ Chia-Yu Tzou,¹ James Hunter Waite,¹⁰ Peter Wurz¹

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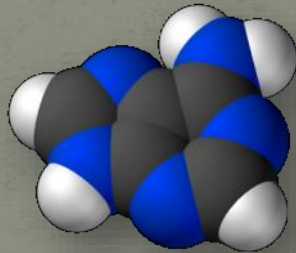
Complex molecules in meteorites

Murchison meteorite

Contains several thousands of different organic molecules, in particular 70 amino acids of which 8 of them are proteinogenic (/20)
+ purines and pyrimidines (nucleobases).



Amino acid
(L-alanine)



Nucleobase
(adenine)



Crédits:

Art Bromage, NASA, meteoritesaustralia,

We think that:

- All life is probably based on organic chemistry and on the elements C, H, N, O, P and S.
- Life needs liquid water to appear and develop.

Why liquid water?

Liquid water has unique physicochemical properties:

- Due to its molecular weight, it should be gaseous under standard terrestrial conditions (such as CO_2 , SO_2 , H_2S ...) but it remains liquid up to 100°C due to hydrogen bonds.
- It forms hydrogen bonds with organic molecules containing $-\text{OH}$, $-\text{NH}$, $-\text{SH}$ groups => many organic molecules (CHNOS) are soluble in water (hydrophilic).
- On the other hand, hydrocarbons (C_nH_m) are hydrophobic.

Organics in water

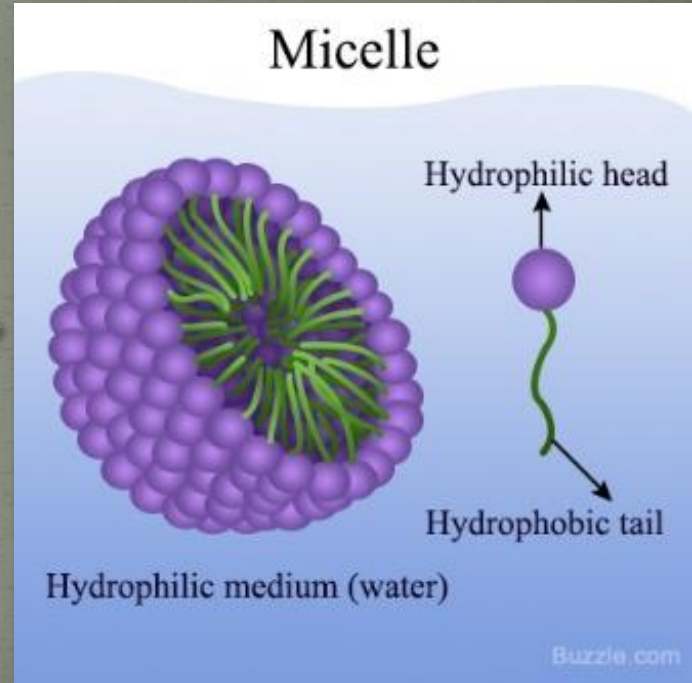
If C_nH_m :
=> hydrophobic



If both in
a same
molecule



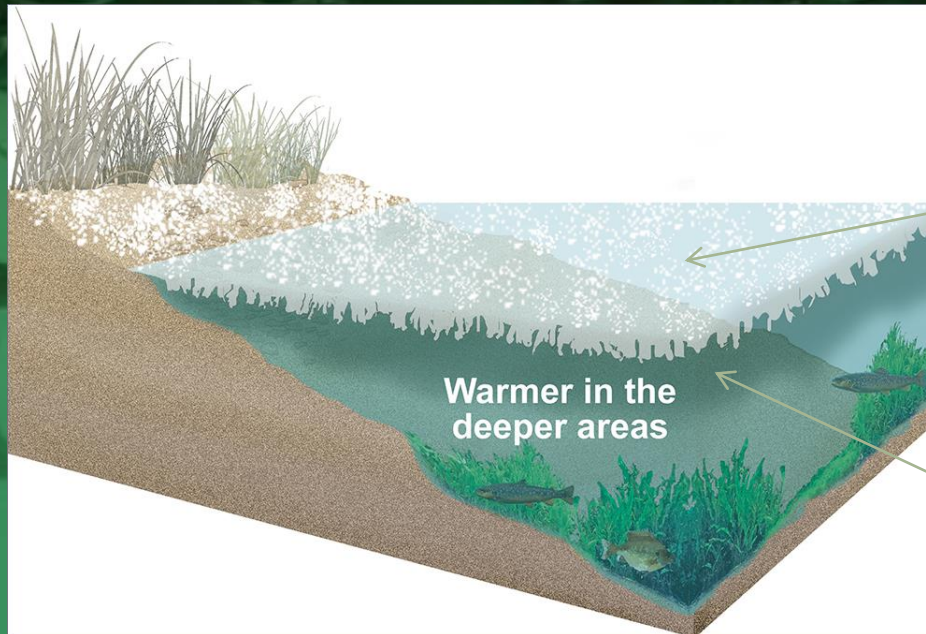
If -OH, -COOH, -NH₂, ...:
=> hydrophilic



After Brack A. (1993) OLEB.

Water ice density

- Water ice density is lower than those of liquid water
=> water ice floats => organisms can survive during winter!

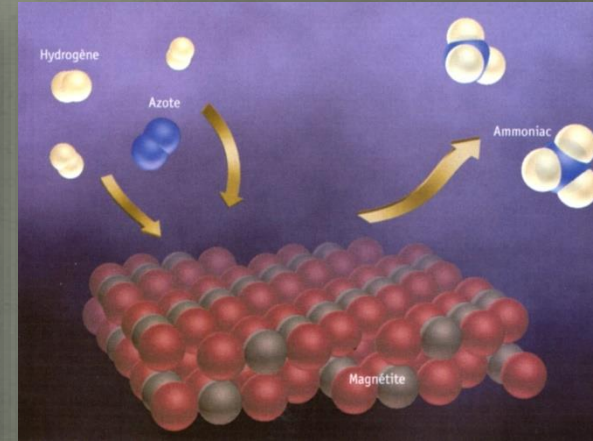
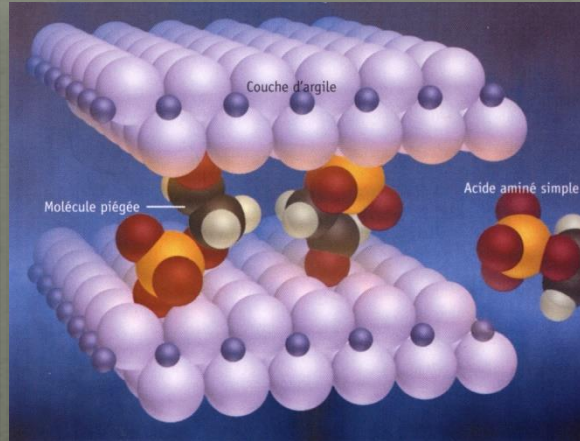
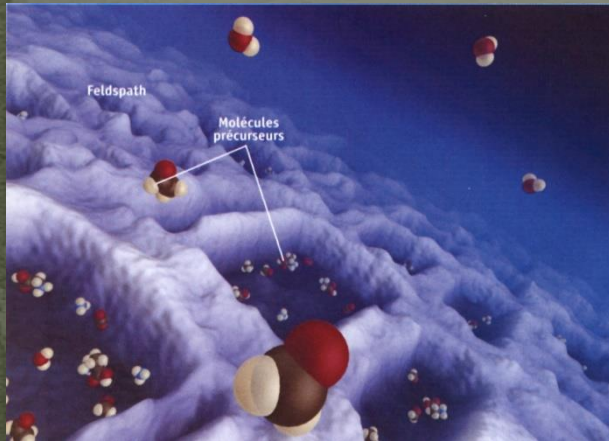
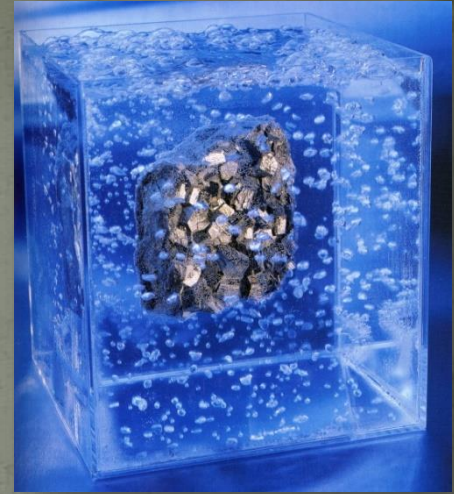


We think that:

- All life is probably based on organic chemistry and on the elements C, H, N, O, P and S.
- Life needs liquid water to appear and develop.
- The chemical reactions leading to the emergence of life require mineral surfaces.

Why mineral surfaces ?

- Chemical reactions at the surface of the minerals can produce energy (e.g. pyrite)
- The porosity of rocks and minerals may concentrate organic molecules and favour their interactions (e.g. feldspars, clays).
- Some minerals catalyse chemical reaction (e.g. magnetite)



We think that:

- All life is probably based on organic chemistry and on the elements C, H, N, O, P and S.
- Life needs liquid water to appear and develop.
- The chemical reactions leading to the emergence of life require mineral surfaces.
- Life needs a source of energy (UV, heat...) to appear and develop.

Starlight

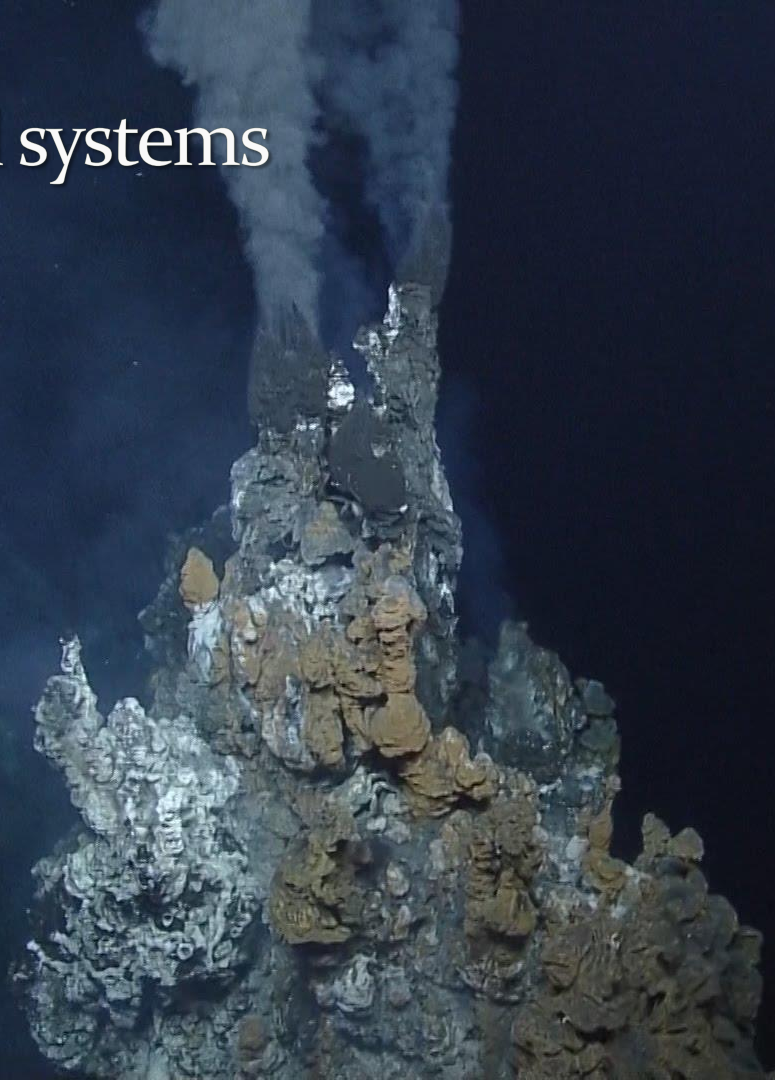




Lightning

Credit: goodfon

Hydrothermal systems



Credit: EVNautilus

We think that:

- All life is probably based on organic chemistry and on the elements C, H, N, O, P and S.
- Life needs liquid water to appear and develop.
- The chemical reactions leading to the emergence of life require mineral surfaces.
- Life needs a source of energy (UV, heat...) to appear and develop.

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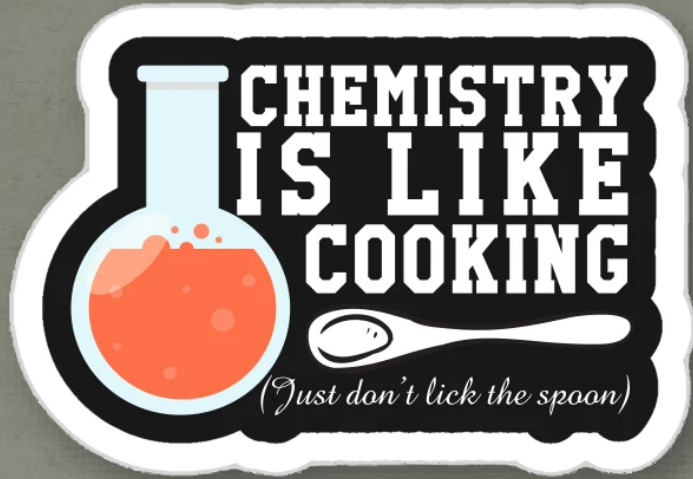
We think that:

- All life is probably based on organic chemistry and on the elements

We are looking for places where these conditions are/were met!
= rocky bodies where water is or was present.

- Life needs a source of energy (UV, heat...) to appear and develop.

BEWARE!!!



Proportions, conditions and durations are key parameters and different steps (mostly still unknown for the appearance of life) are required.



Habitable does not mean inhabited!

A futuristic landscape with a large planet in the sky and a bright sun. The scene is set on a rocky, mountainous terrain with a hazy atmosphere. A large, dark planet is visible in the upper right corner, and a bright sun is in the center-left. The sky is a mix of orange, pink, and blue.

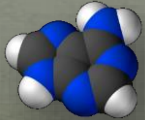
What to search for ?

From habitable places to extraterrestrial intelligence

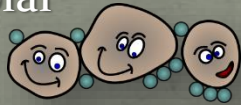
Level of evolution



1- Molecules

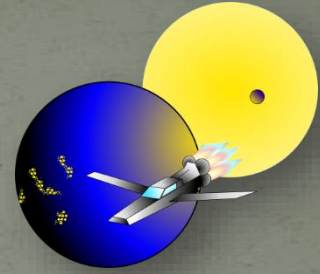


2- Microbial
life



3- Macroscopic
multicellular life

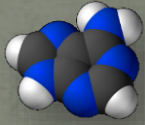
4- Extraterrestrial
civilisation



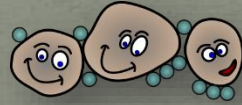
To reach a higher level of evolution life must first have evolved to the previous stage. Obviously, the converse is wrong and evolution may stop at any level. As a consequence, more evolved life is less probable!

Likelihood

1- Molecules



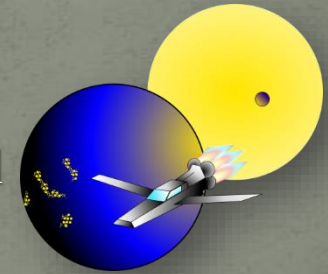
2- Microbial
life



3- Macroscopic
multicellular life



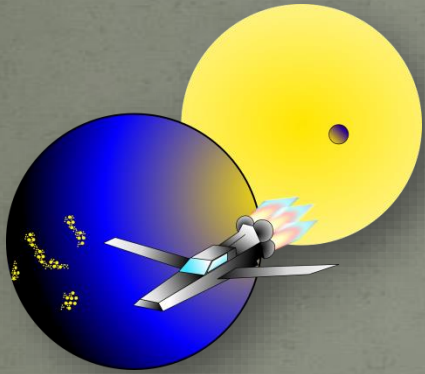
4- Extraterrestrial
civilisation



As more evolved life forms are less likely, they are also less numerous in the universe and therefore statistically more distant.

Distance from the Earth

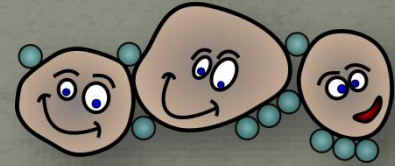
Different levels of evolution



Extraterrestrial
civilisation



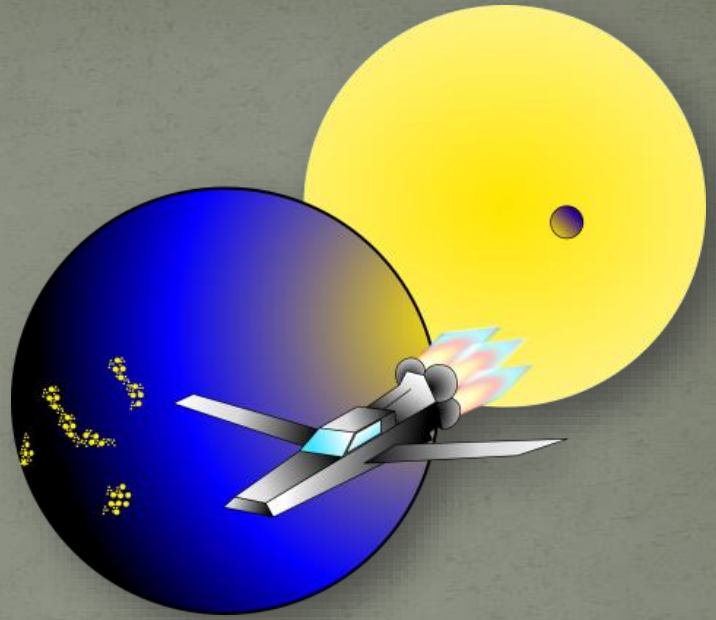
Macroscopic life



Microbial life



Different biosignatures

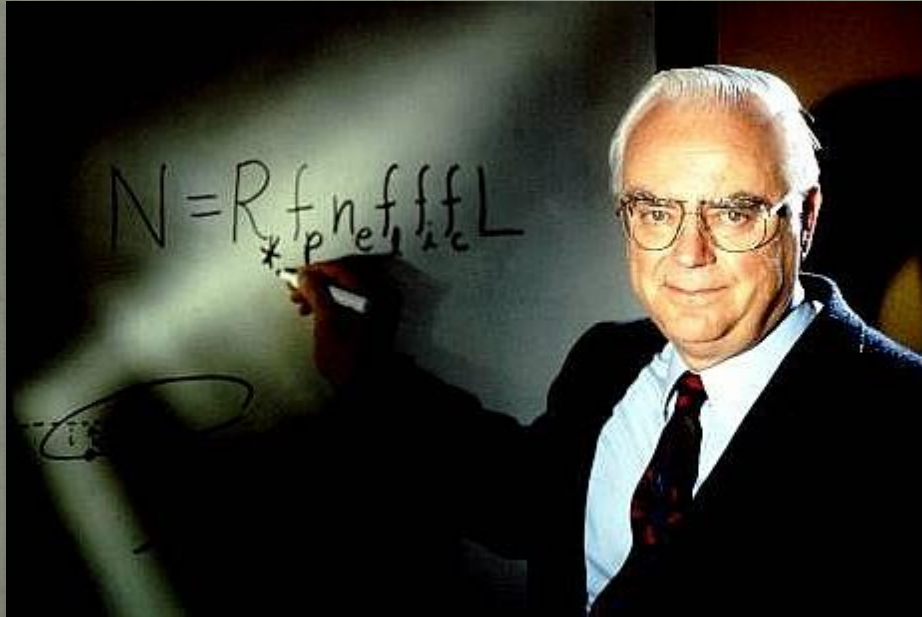


Extraterrestrial intelligence

Signature and detection

Drake equation

N = number of civilisations in our galaxy able to communicate.



Frank Drake

Result of the calculation

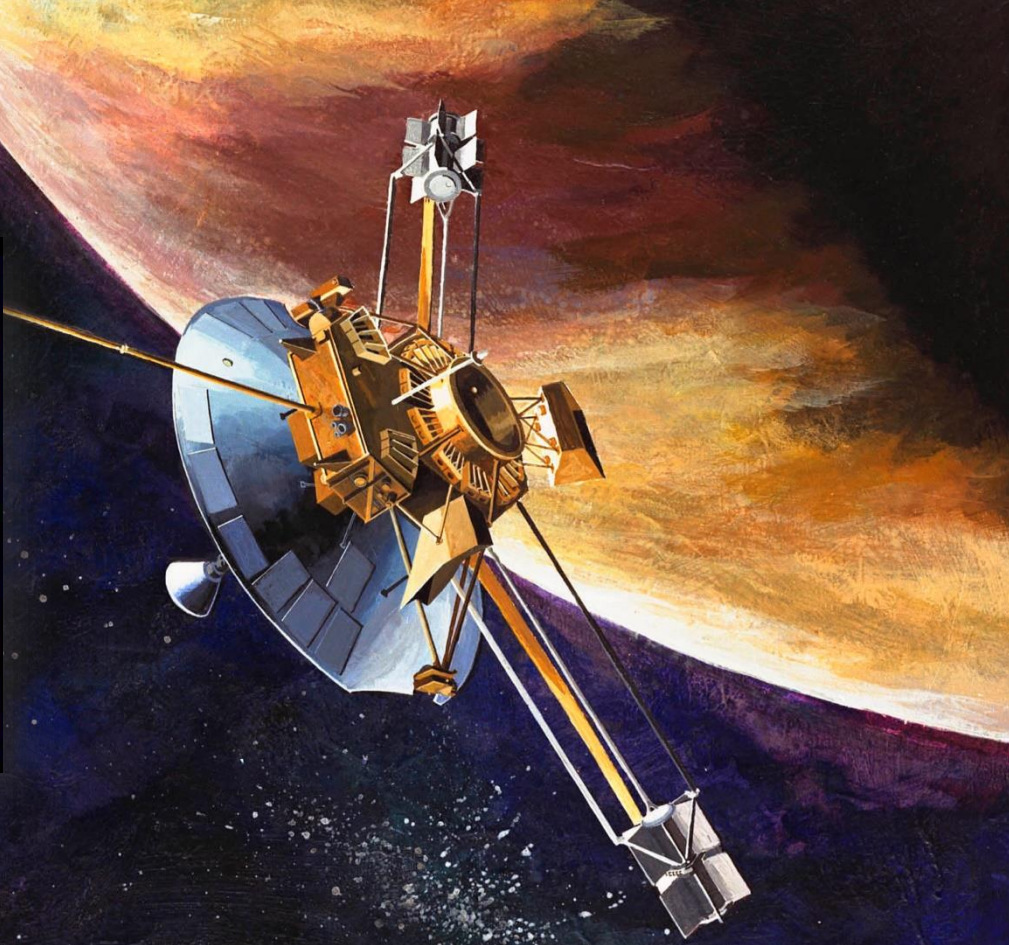
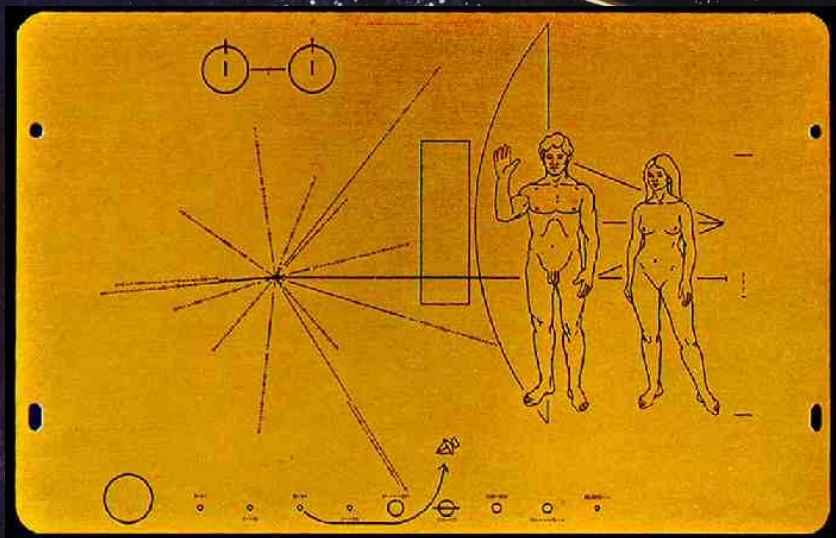
Minimum $\sim 0,0000035$

-the most pessimistic: 1 (us)

-the most optimistic : 10000

Number of galaxies in the universe
 ~ 350 billions

Minimum = 1 000 000 !!!

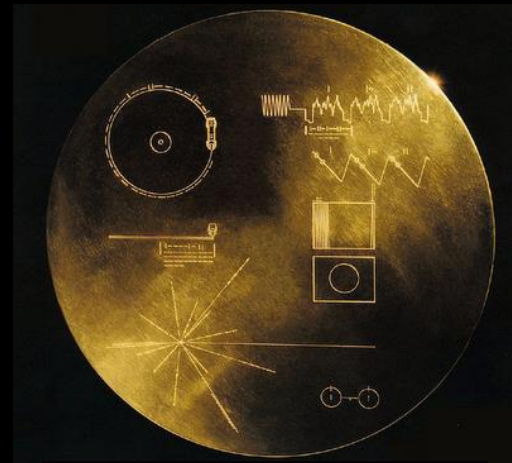
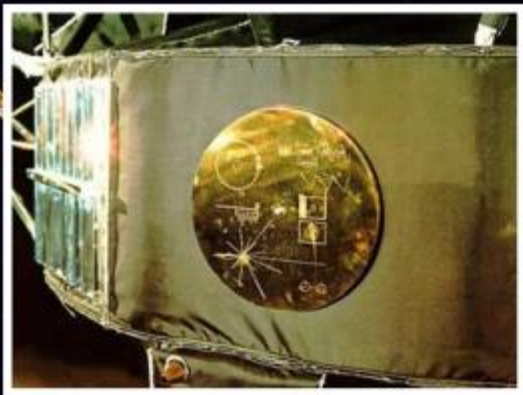


Pioneer 10 and 11

Pioneer 10, 1972

Credits: NASA

Voyager



Voyager 2, 1977



The « Golden Record »

Credits: NASA

If the sun was the size of a tennis ball (65 mm in diameter) then:



| | Dia. in km | Dia. in mm if the sun was the size of a tennis ball : | Distance from the Earth in km: | Distance from the Earth if the sun was the size of a tennis ball : |
|-------------------------|---------------|---|--------------------------------|--|
| The Earth | 12800 | 0,60 | 0 | 0,0 m |
| The Moon | 6800 | 0,32 | 384467 | 0,02 m |
| The Sun | 1395200 | 65 | 150000000 | 7,0 m |
| Neptune | 50000 | 2,33 | 4347000000 | 202,5 m |
| Proxima Centauri | 200000 | 9,32 | 42430000000000 | 1977 km |

Approximately the distance between Angra do Heroismo and Madrid! 

About 60 000 years for a spacecraft travelling at 20 km/s!



Detection limited to radio signals.

SETI *Search for Extra-Terrestrial Intelligence, created in 1960*



Arecibo radio telescope in Puerto Rico
(unfortunately destroyed in November 2020)

<http://setiathome.ssl.berkeley.edu/>

Problem

Extremely low probability.



If other civilisations exist, they are probably very far away.

The speed of light in vacuum (300 000 km/s) is the maximum communication speed. It takes 4 years 88 days 16 h 40 min for a signal to arrive on Earth from Proxima Centauri and more than 50 000 years from the other side of the galaxy!!!



Probably impossible to communicate in a life time

Macroscopic life

Signature and detection



Exoplanets

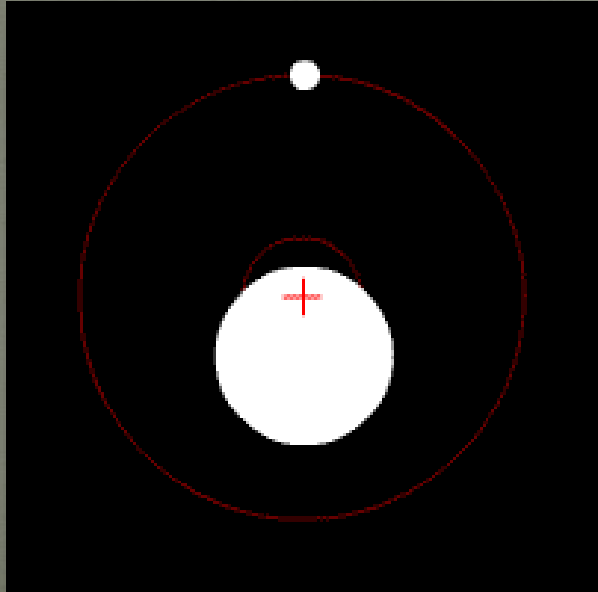


+ than 4800 exoplanets (*i.e.* planets orbiting a star other than the Sun) have been detected!

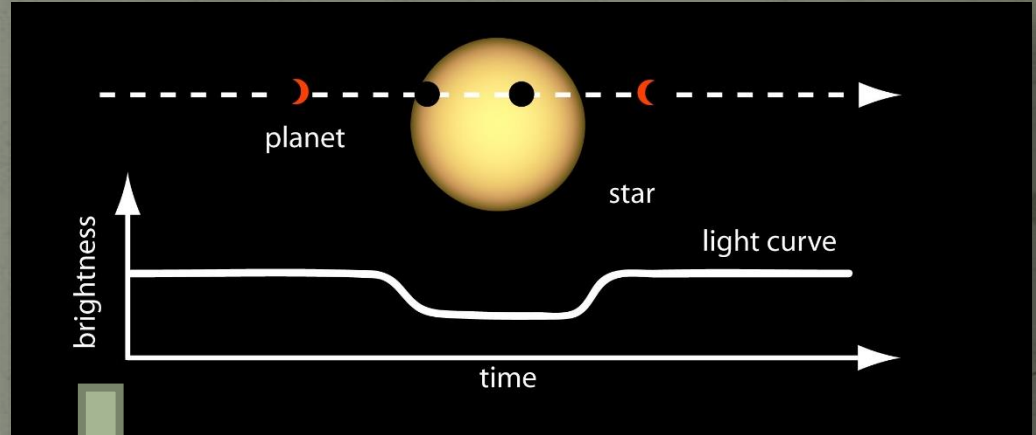
Due the distance, their study is limited to astronomical methods.

Detection

Doppler spectroscopy method.
Gives the mass.



Transit photometry method.
Gives the size.

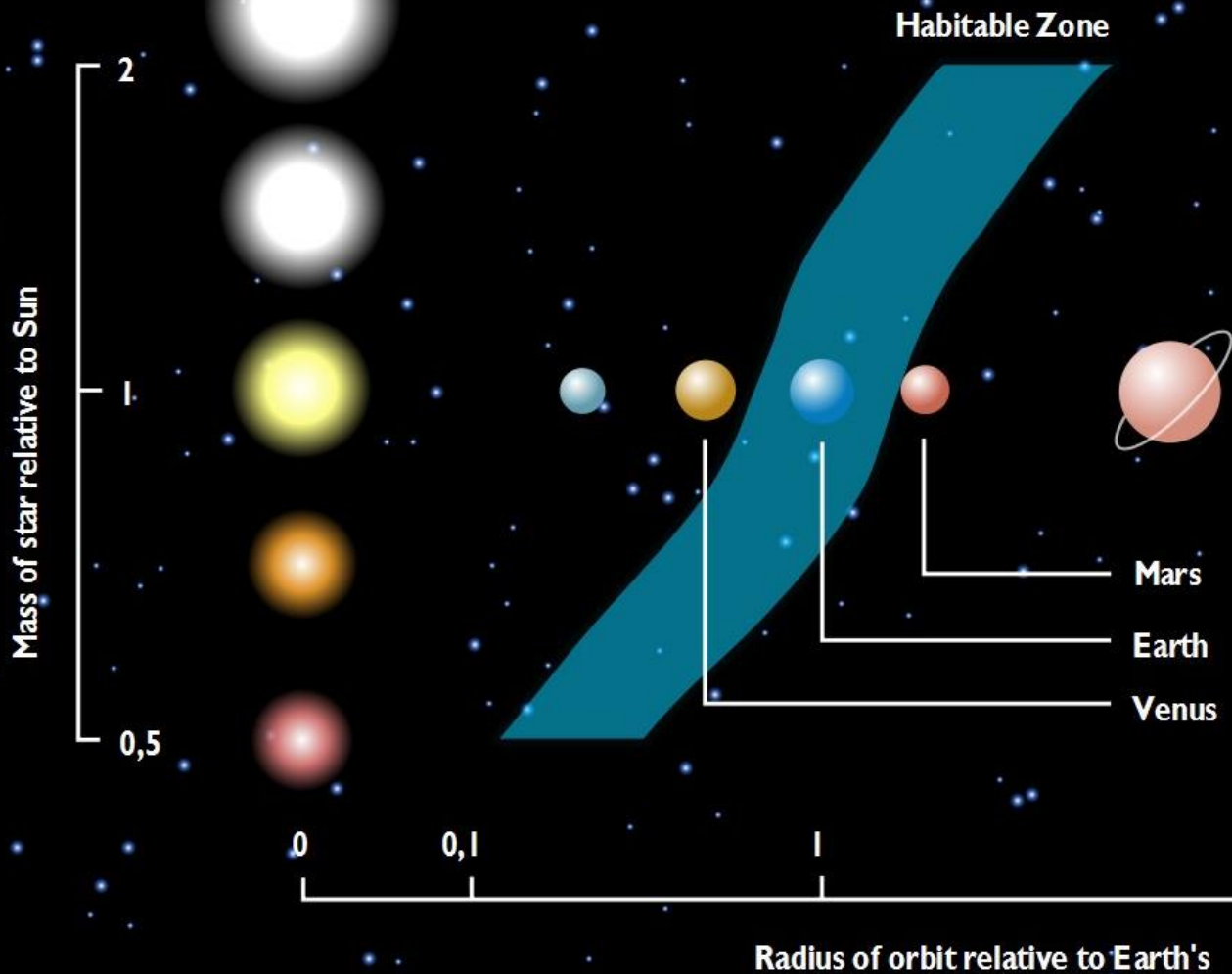


*Give the density
=> Terrestrial of gaseous planet.*



Coronagraphy, gravitational microlensing, astrometry...

Liquid water on the surface



Calculations show that 22% of stars similar to the sun (yellow dwarfs) have a potentially habitable planet! (Petigura et al., 2013)

Detection of planets in the habitable zone

Over the 4847 exoplanets discovered, 72 are in the habitable zone and current estimates suggest there are at least 500 million planets in the habitable zone in the Milky Way.

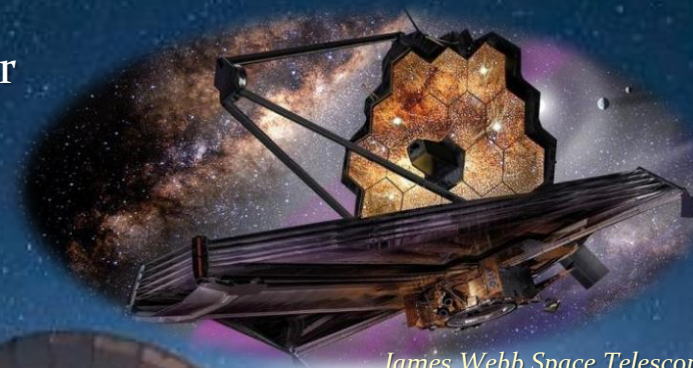
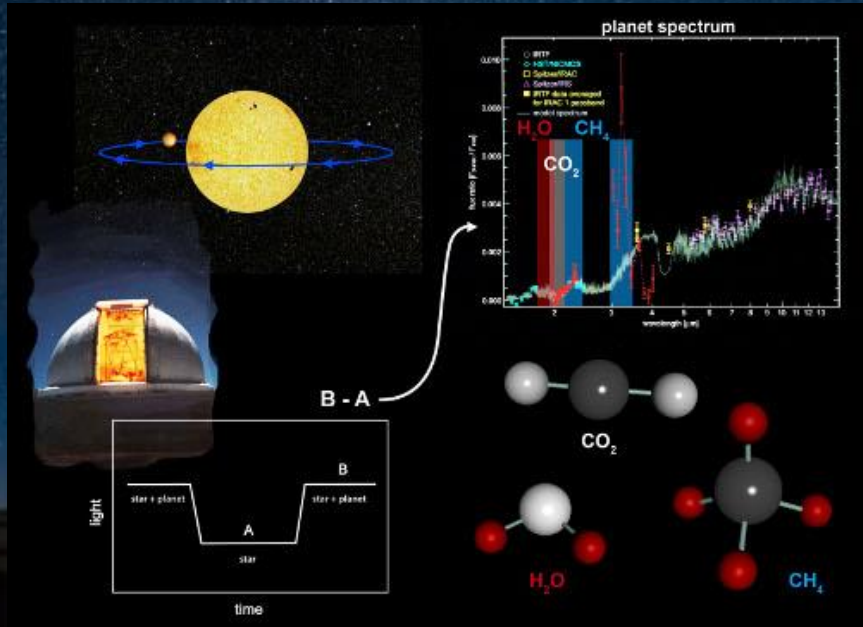
BEWARE: this does not mean that they are habitable and, again, habitable does not mean inhabited!



*Artist view of Kepler 186f
(Quintana et al., Science, 2014)*

Search for biosignatures on exoplanets

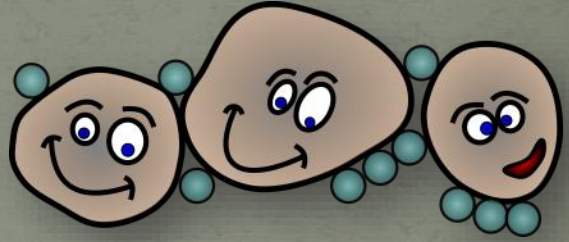
= Search for biogases in the atmosphere such as methane (produced by methanogenic organisms) or oxygen (produced by photosynthetic organisms).



James Webb Space Telescope (JWST), to be launched on December 2021.



Credits: NASA/JPL-Caltech.



Microbial life

Signature and detection

Habitability at microbial scale

Microbial life may have appeared in habitable niches.



An entire planet doesn't have to be habitable to be inhabited.



Microbial life is very likely in the universe.

How to detect microbial life?

Direct evidence:

- Observation of microbial colonies.

Indirect evidence:

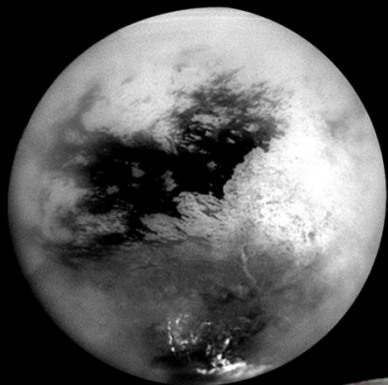
- Biomolecules (e.g. DNA)
- Biogases (e.g. methane)
- Biominerals (e.g. vaterite)
- Biostructures (e.g. stromatolithes)

Problem: most of these signatures require *in situ* missions to be detected!



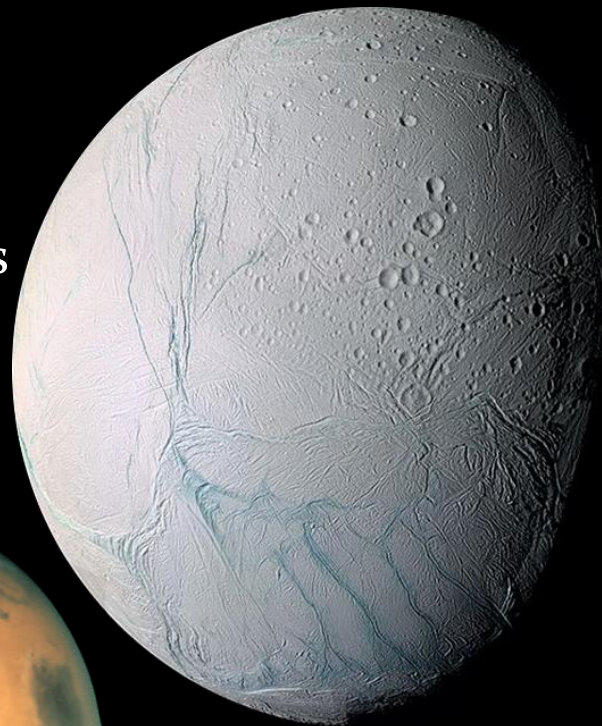
Research is limited to the solar system!

Some interesting places



Titan

Enceladus



Europa

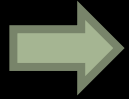


Mars

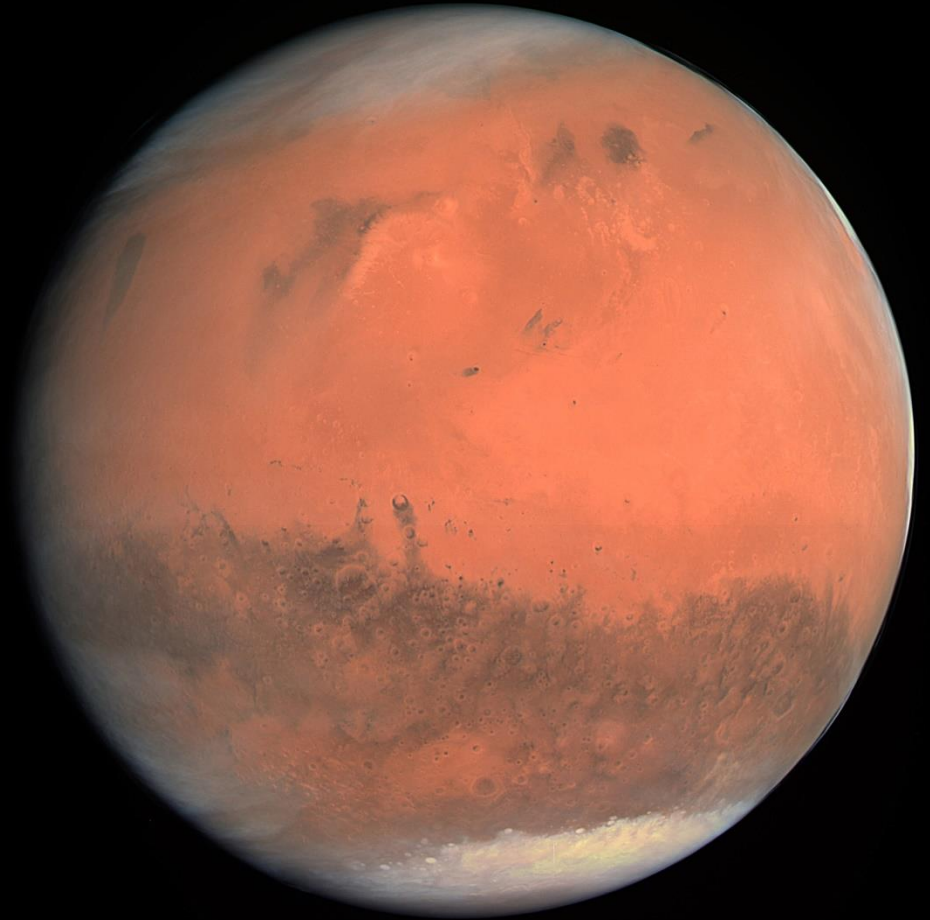


Mars

After the Moon and Venus, the
closest body to Earth.



The « easiest » to
explorer *in situ*.



Liquid water at the surface of Mars by the past

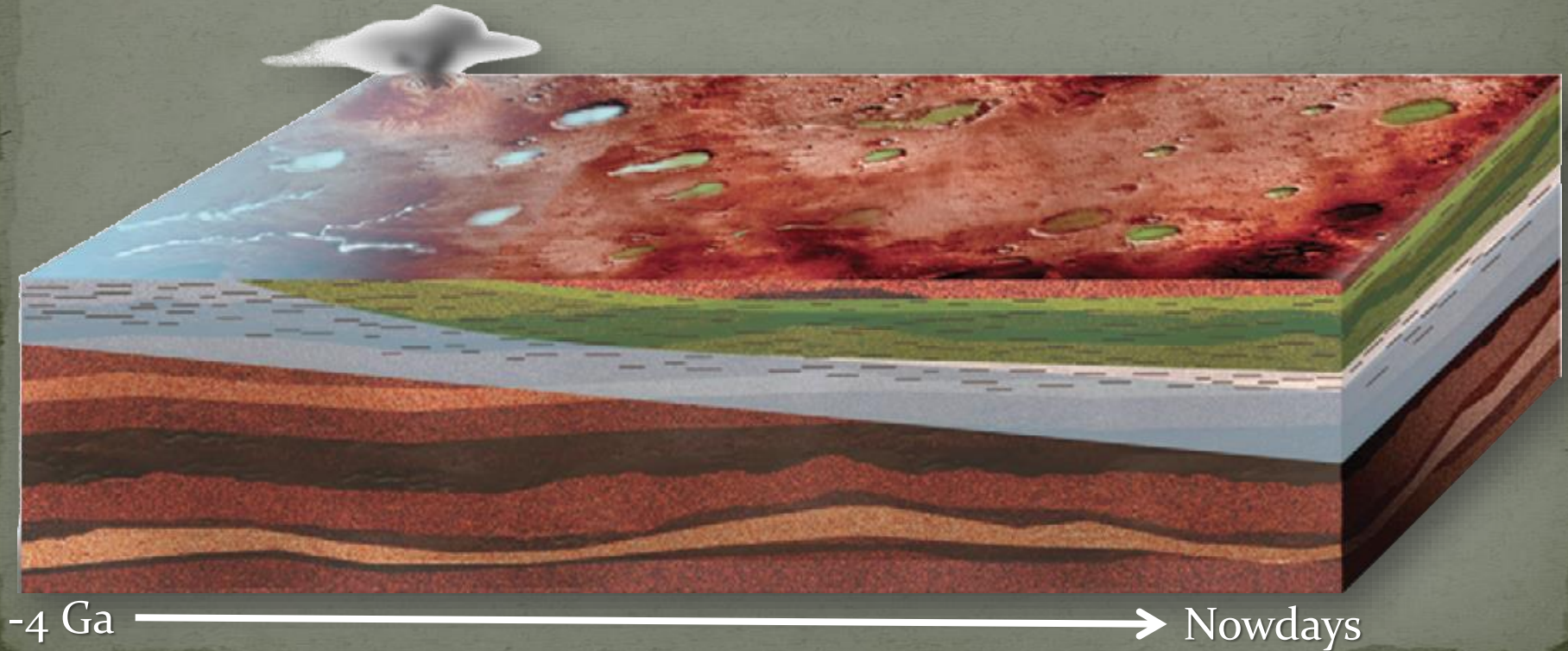
Dried rivers



Mars Express, ESA, since 2003



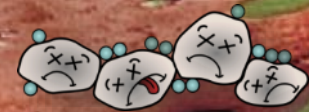
Evolution of liquid water on Mars.



Evolution of life on Mars?

Microbial life at surface?

Microfossils at surface?

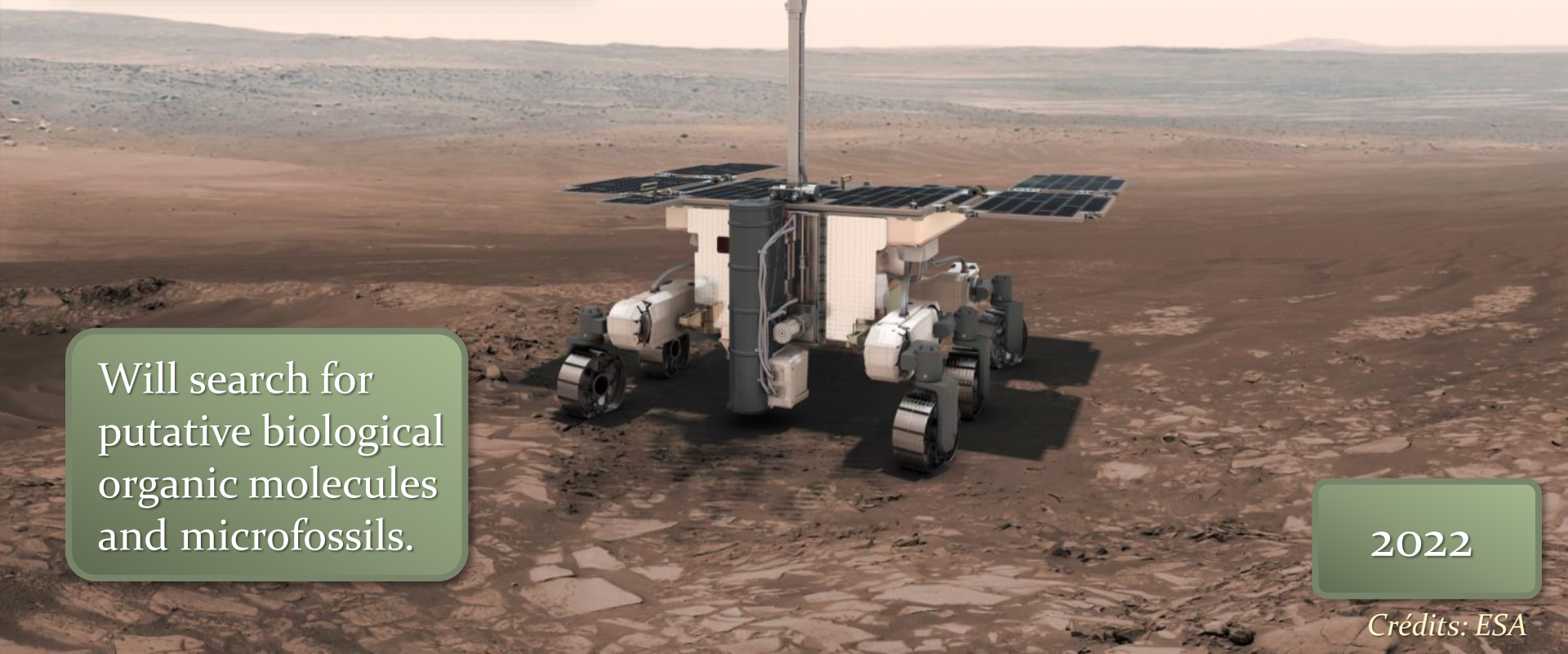


Microbial life in the sub-surface?

-4 Ga

Nowdays

EXOMARS



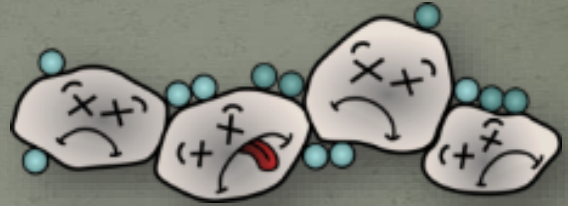
Will search for putative biological organic molecules and microfossils.

2022

Crédits: ESA

Microfossils

Signature and detection



What can we expect to find?

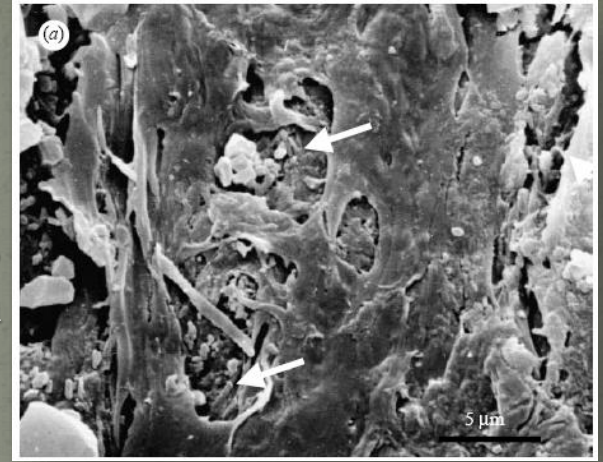
Fossils resembling terrestrial fossils
dating from the same period.



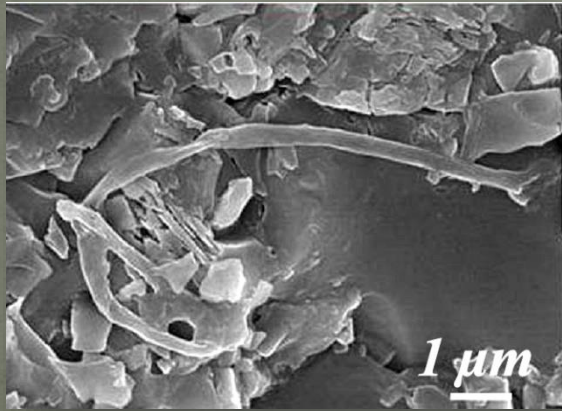
Fossils close to the fossils of the first
living organisms on Earth.

3.5 Ga old microfossils

Josefsdal, Barberton,
South Africa, -3.333 Ga



Westall et al., 2011



Kitty's Gap Chert, Pilbara,
Australia, -3.446 Ga

*Westall et al.,
2011*

Submicrometric fossils
of simple shape.

How to detect billions years old microfossils?

Direct evidence:

- Observation of fossilized microbial colonies. (**not sufficient**)

Indirect evidence:

- Biomolecules (e.g. DNA) → carbonaceous matter (**not sufficient**)
- Biogases (e.g. methane)
- Biominerals (e.g. vaterite) → common minerals (**not sufficient**)
- Biostructures (e.g. stromatolithes) (**not sufficient**)



Requires a body of evidence!

A multimodal and multiscale approach



Cameras



Microscopes



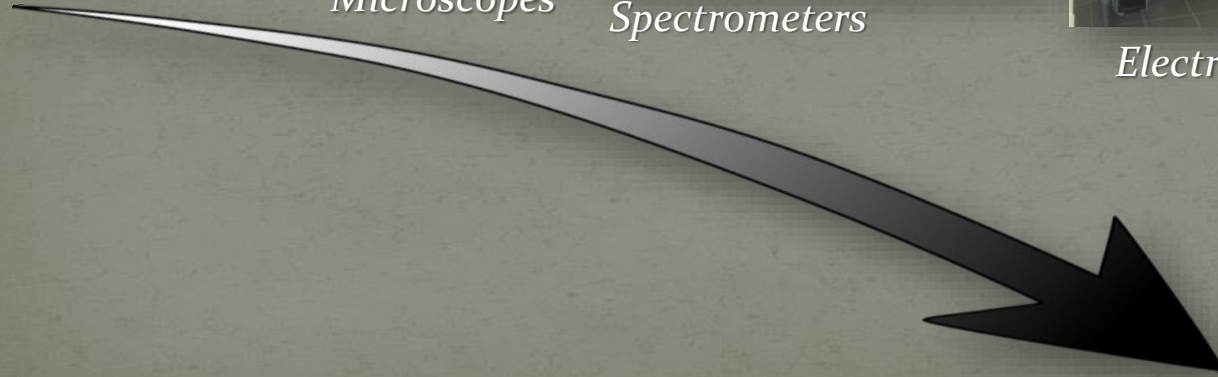
Spectrometers



Electron Microscopes



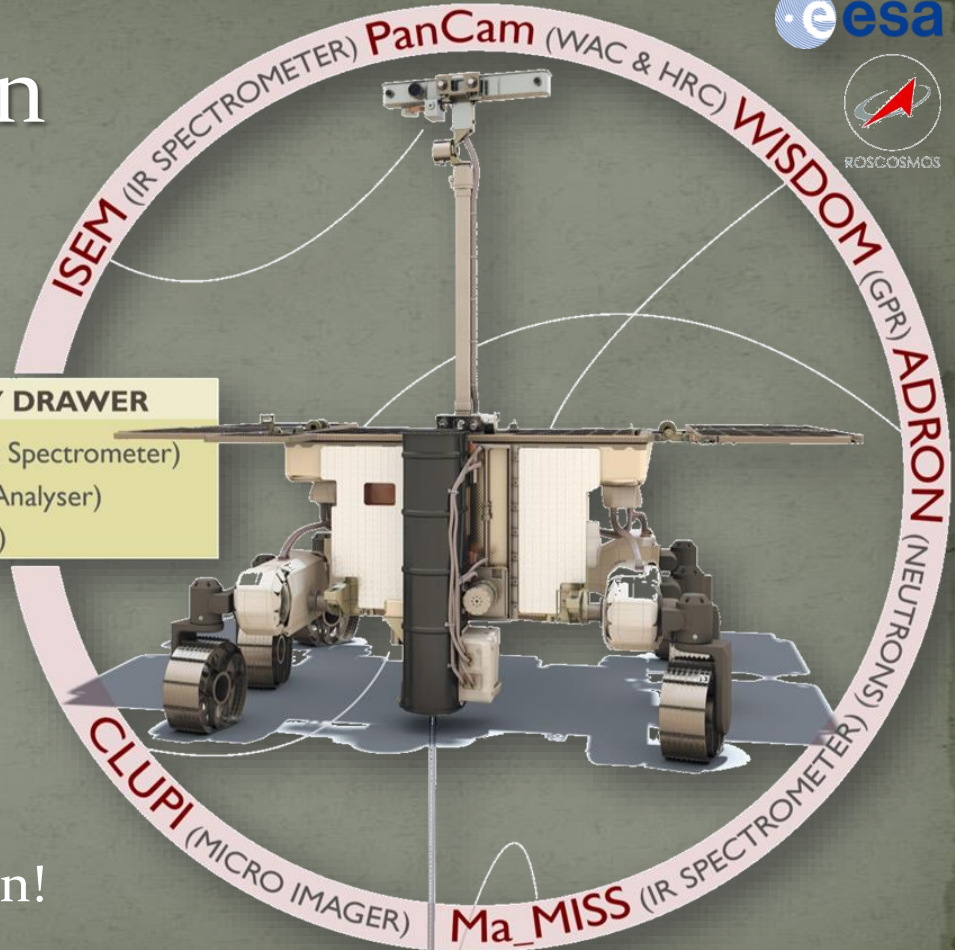
Synchrotron



in situ instrumentation



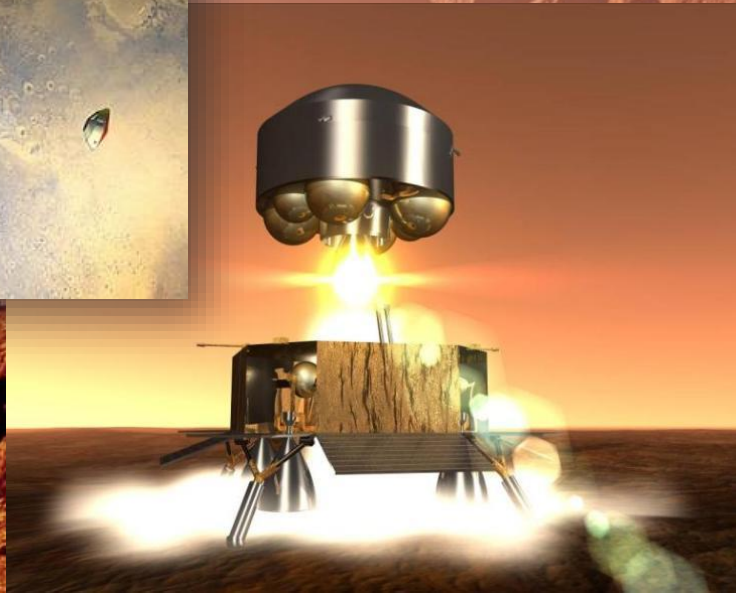
ANALYTICAL LABORATORY DRAWER
MicrOmega (VIS + IR Imaging Spectrometer)
MOMA (Organic Molecule Analyser)
RLS (Raman Spectrometer)



Limited payload

ExoMars = ~17 kg of instrumentation!

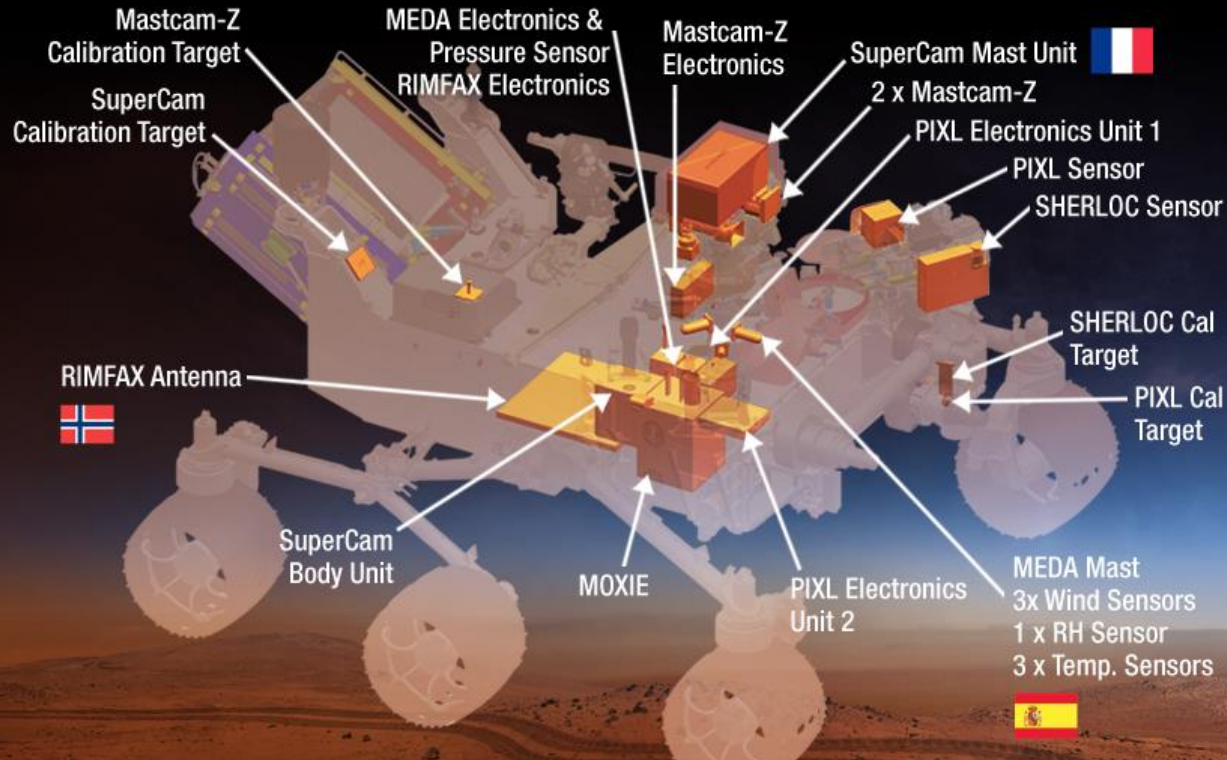
Mars Sample Return (2031)



Started in 2020!

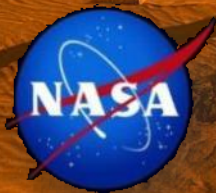
Credit: vistapointe.net

Mars 2020 Rover



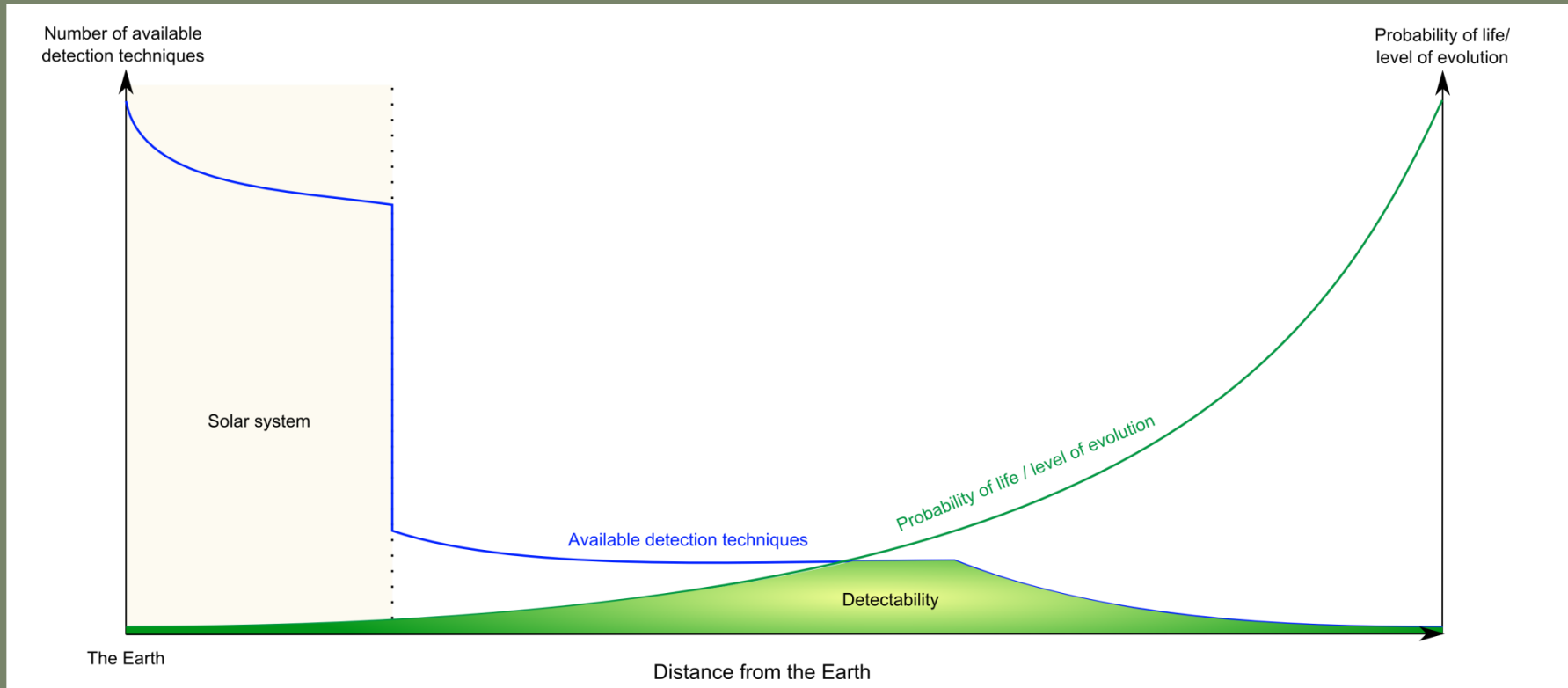
Difficulties: limited payload for sample selection and only 500g of samples brought back to Earth

Man on Mars (2050?)



Credit: NASA

The real challenge = detectability



The real challenge = detectability

