Searching for life beyond the Solar System (2)

Conditions for the existence of life in exoplanets
Biosignatures in Exoplanets
The Galactic Habitable Zone

Planets and Astrobiology (2023)

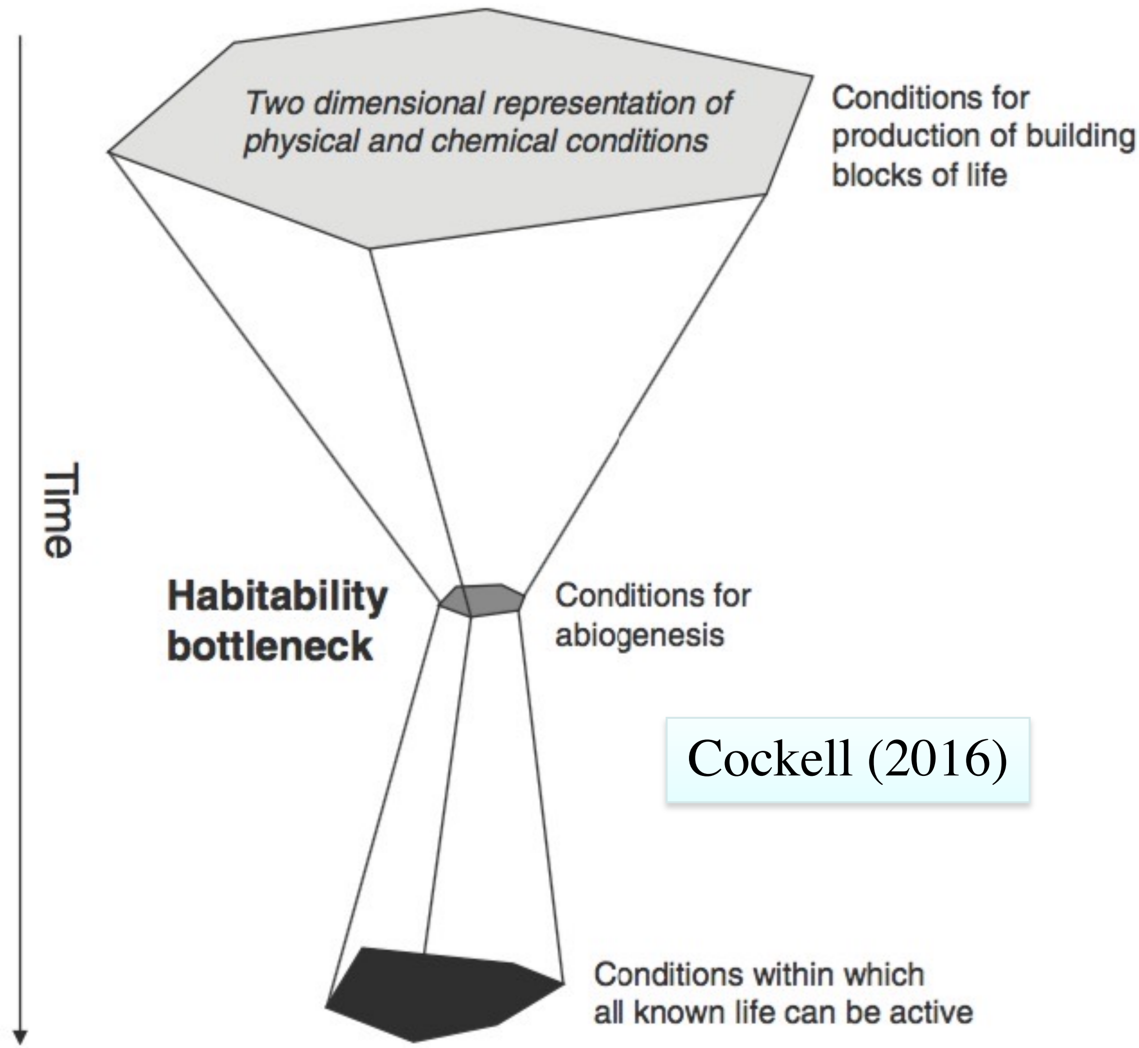
G. Vladilo

Conditions for the existence of life (1): from prebiotic chemistry to inhabited environments

The physico-chemical conditions required for: prebiotic chemistry, abiogenesis and habitability are generally different

The chemical pathway leading to abiogenesis appears to be quite narrow

The conditions for the emergence of life represent a sort of "bottleneck" for the effective presence of life in an astronomical body



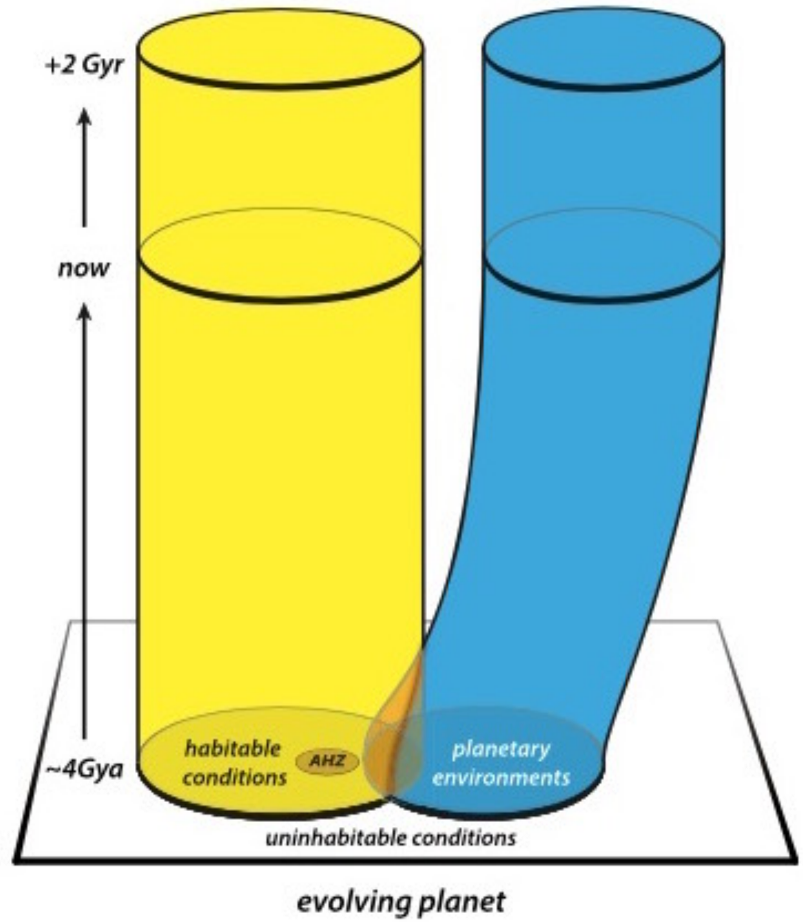
Cockell (2016)

Abiotic evolution of planetary conditions

A planet that has the conditions for habitability, but not those for the emergence of life, will evolve under the effects of <u>abiotic feedbacks</u>

Examples
<u>Astronomical forcing</u>:
stellar luminosity, orbital parameters,
<u>Climate feedbacks</u>:
ice-albedo, temperature-water vapour, inorganic CO_2 cycle, etc…

If positive abiotic feedbacks are dominant, the planet may loose its habitability in the course of its evolution



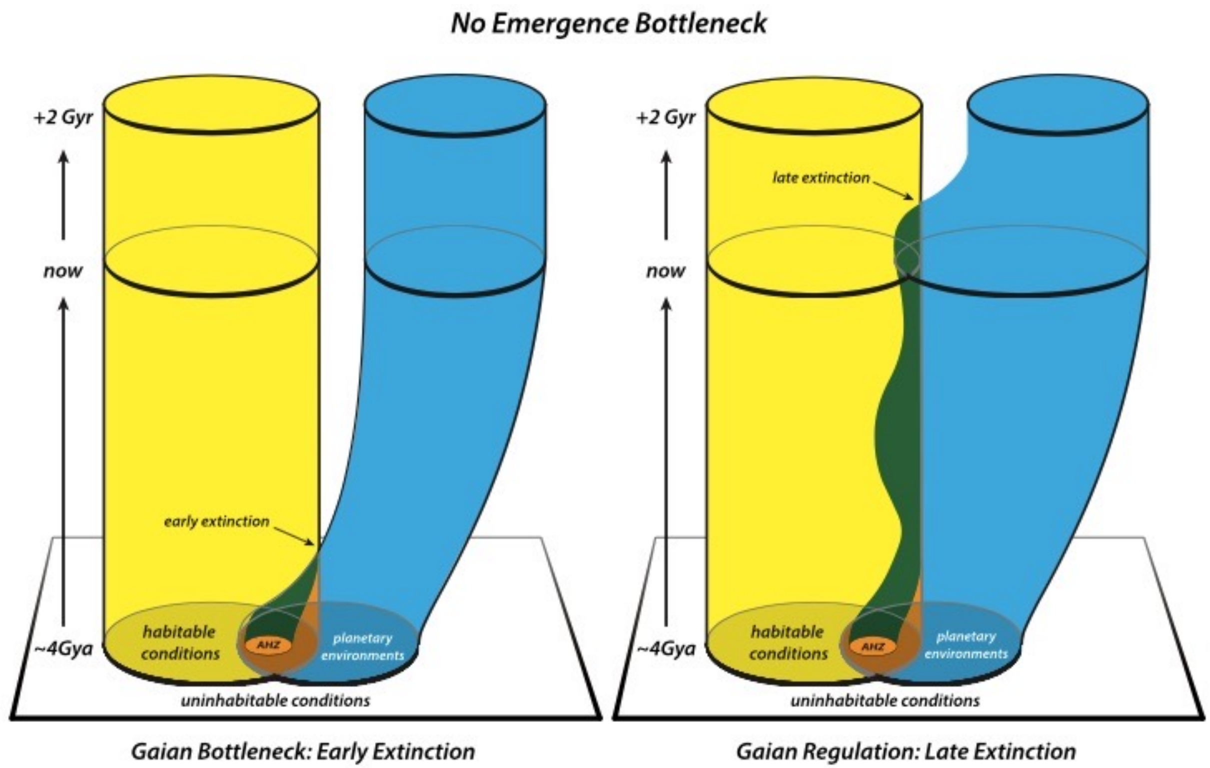
Chopra and Lineweaver (2016)

Evolution of planetary conditions in presence of life

Two possible scenarios:

1) Life is unable to evolve rapidly enough to control runaway positive feedbacks
2) The biosphere evolves fast enough to keep the planet habitable in the long term ("Gaian regulation")

Chopra and Lineweaver (2016)



The long-term persistence of habitability conditions on Earth might be the result of Gaian regulation (at least in part)

Biosignatures in exoplanets

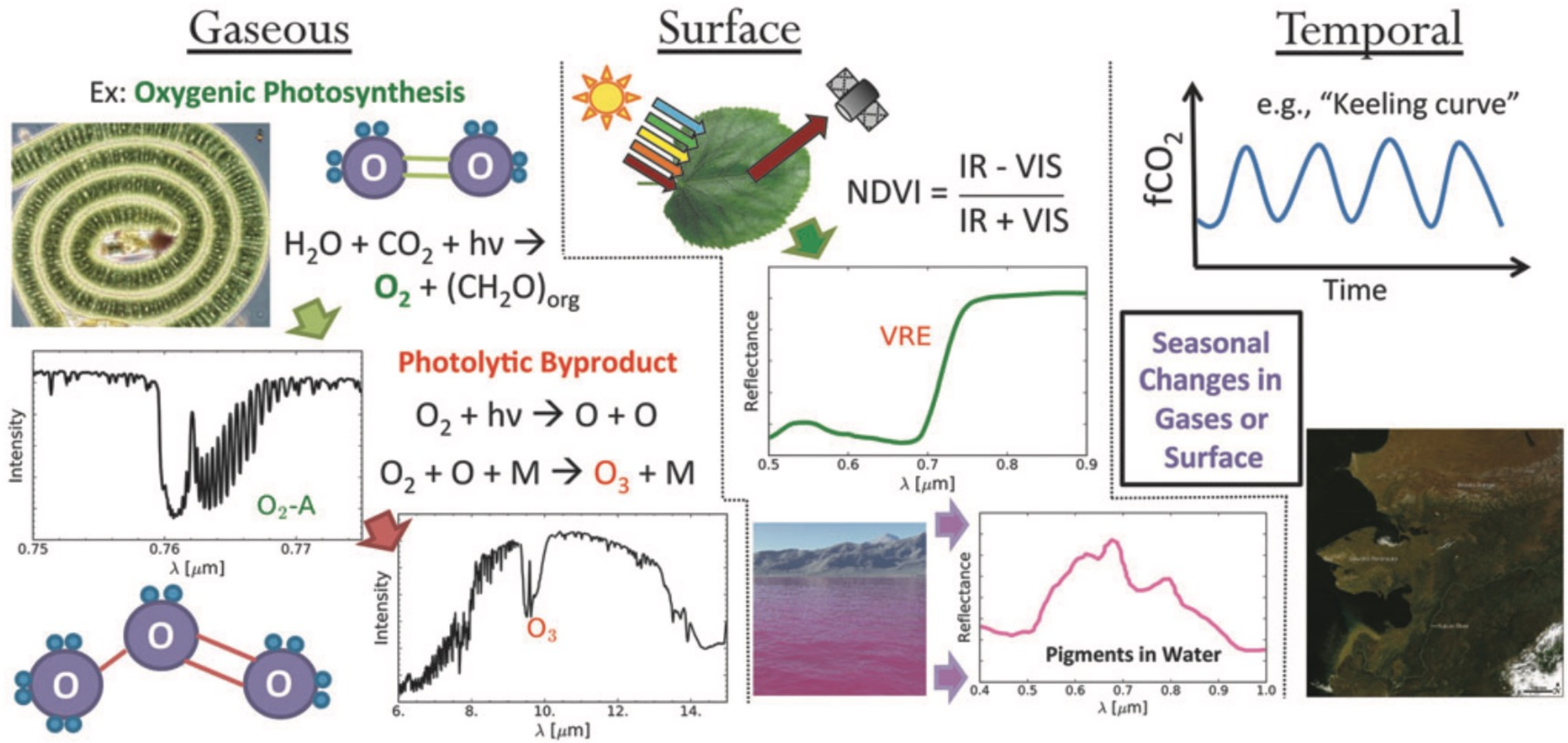


FIG. 1. Summary of gaseous, surface, and temporal biosignatures. Left panel: gaseous biosignatures are direct or indirect products of biological processes. One example is molecular O_2 generated as a by-product of photosynthesis that is then photochemically processed into O_3 in the stratosphere. Middle panel: surface biosignatures are the spectral signatures imparted by reflected light that interacts directly with living material. One example is the well-known VRE produced by plants and the associated NDVI used for mapping surface vegetation on Earth (Tucker, 1979). Right panel: time-dependent changes in observable quantities, including gas concentrations or surface albedo features, may represent a temporal biosignature if they can be linked to the response of a biosphere to a seasonal or diurnal change. An example is the seasonal oscillation of CO_2 as a response to the seasonal growth and decay of vegetation (*e.g.*, Keeling *et al.*, 1976). This figure is reproduced with permission from Schwieterman (2016). Subimage credits: NASA and the Encyclopedia of Life (EOL). NDVI, Normalized Difference Vegetation Index; O_2, oxygen; O_3, ozone; VRE, vegetation red edge.

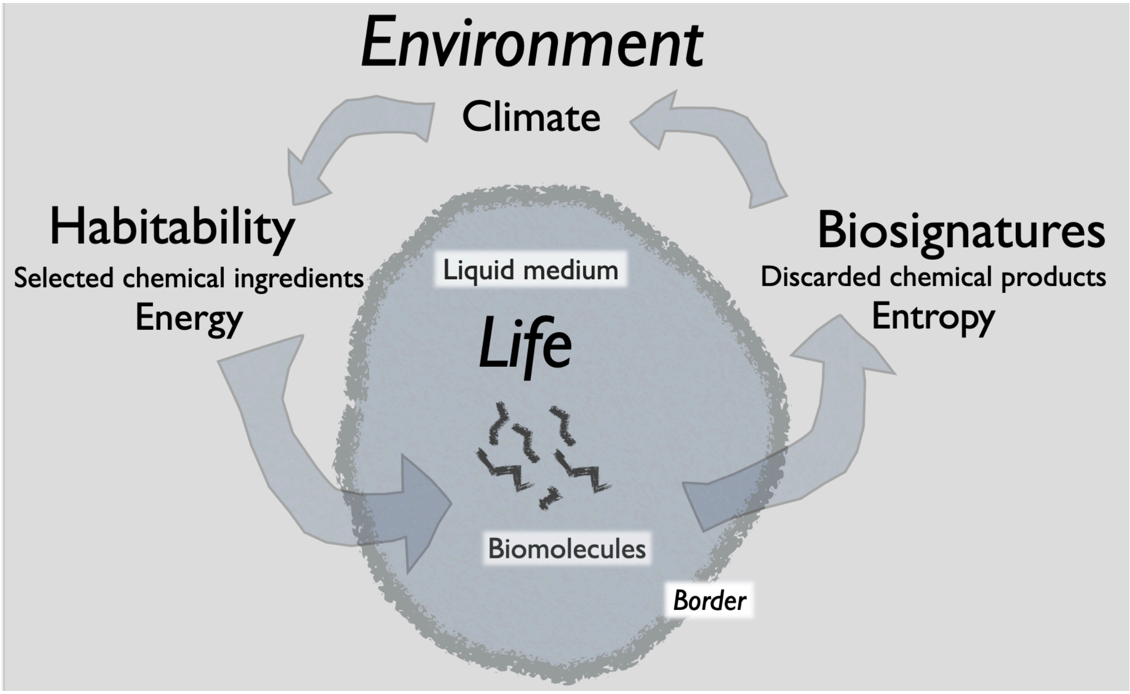
Schwieterman et al. 2018

Atmospheric biosignatures

Why do we expect them to be present

Life metabolizes and dissipates metabolic by-products

If life with active metabolism is spread on the planetary surface, its by-products may accumulate in the planetary atmosphere



Atmospheric biosignatures

What should we do to identify them

(1) Enhance the observational techniques in order to be able to obtain spectra of the thin atmospheres of rocky, habitable planets

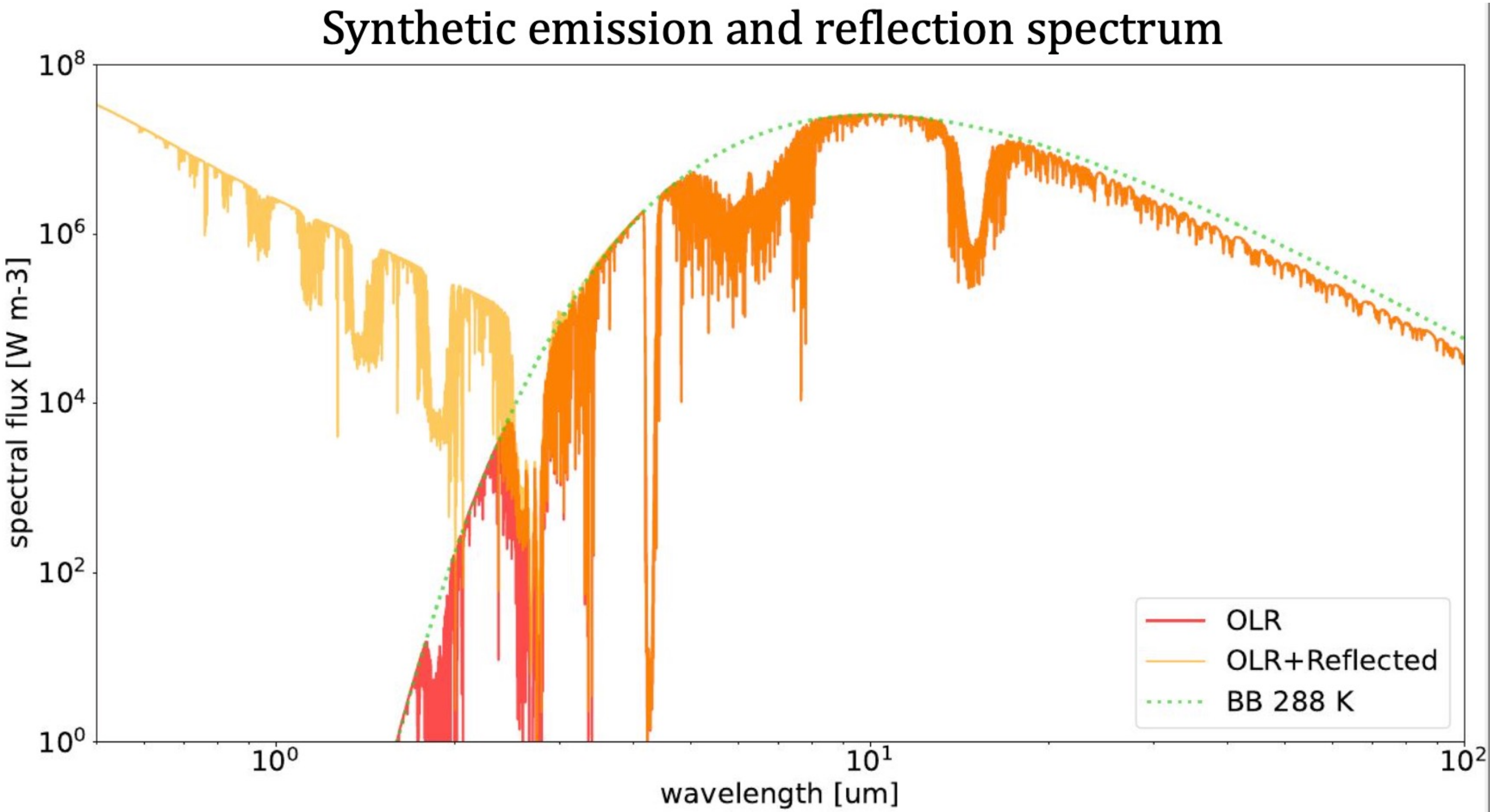
(2) Build synthetic spectra of the exoplanetary atmosphere

(3) Identify molecular species that, from the comparison of chemical equilibrium models, can be used as reliable biosignatures

Steps for identifying atmospheric biosignatures:

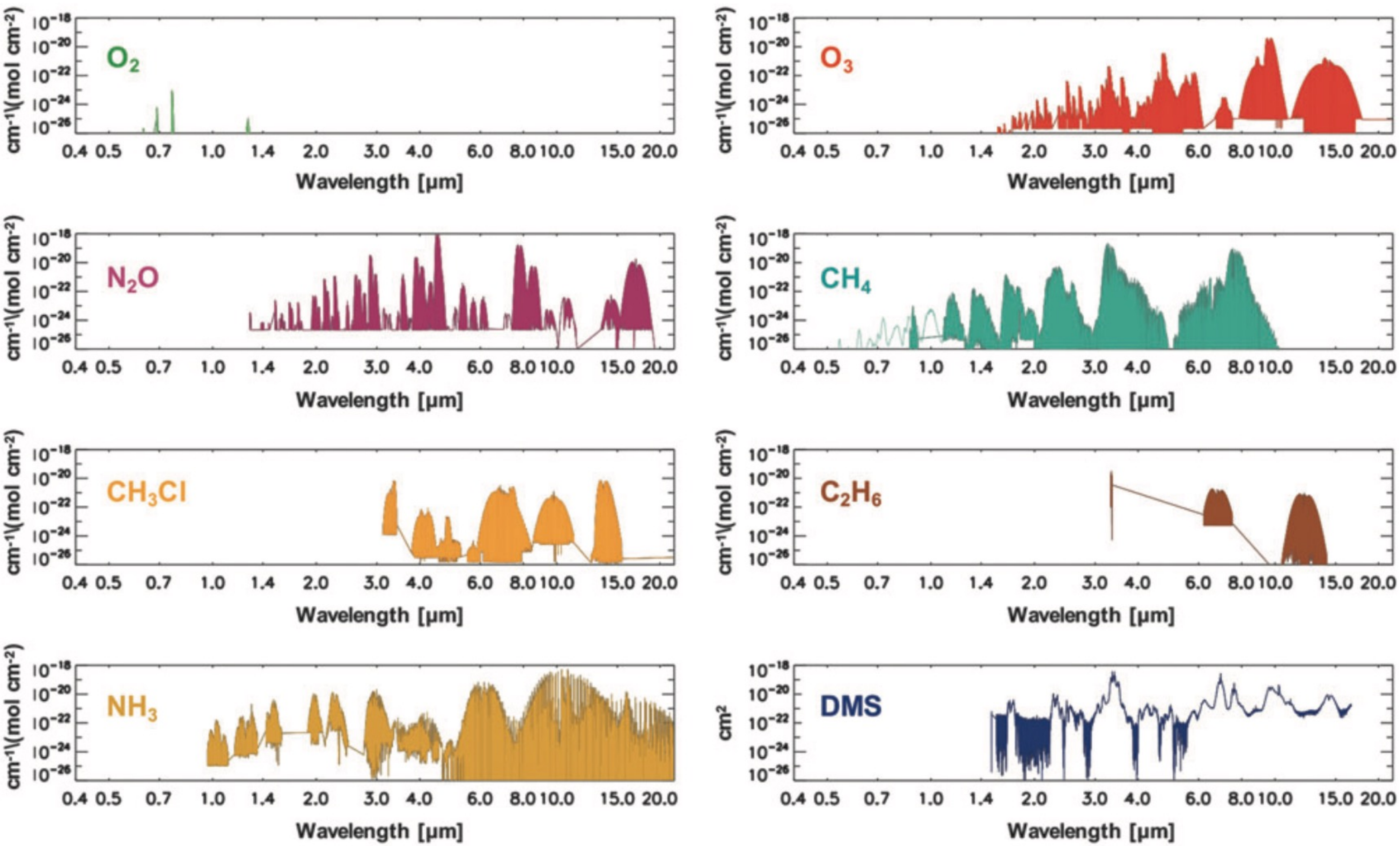
Building synthetic spectra of the planetary atmosphere

Requires a physical description of the vertical stratification



Simonetti et al. 2023

The generation of synthetic spectra requires updated databases of molecular transitions for potential tracers of biological activity



Schwieterman et al. 2018

Steps for identifying atmospheric biosignatures:
Searching for evidence of chemical disequilibrium

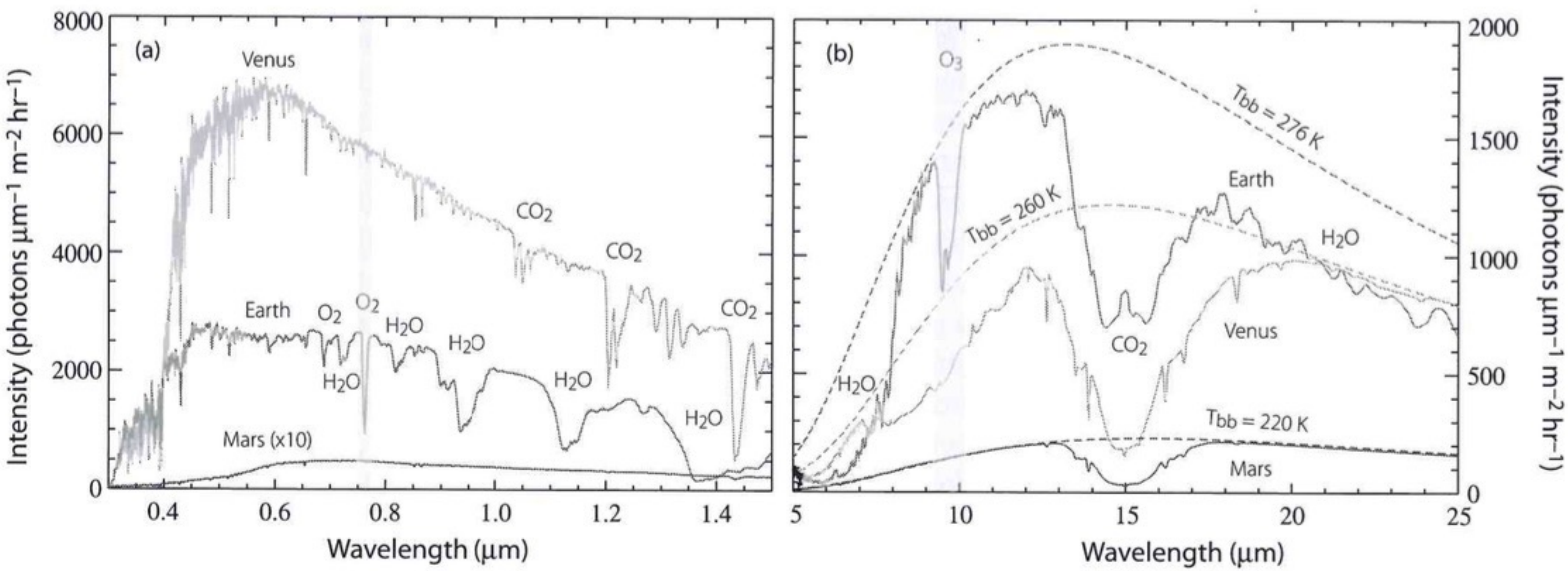
Chemical equilibrium calculations are performed using a network of redox chemical reactions, where an electron is added (reduction) or removed (oxidation) from an atom or molecule

Redox chemistry is used by all life on Earth and is more flexible than non-redox chemistry

Example:
Earth's atmosphere has oxygen (a highly oxidized species) and methane (a very reduced species) several orders of magnitude out of thermochemical redox equilibrium

Biosignatures in the Earth's atmosphere

In practice it could be difficult to detect both molecular features of a redox disequilibrium pair. Present-day Earth, for example, has a relatively prominent O_2 absorption at 0.76µm, whereas CH_4 absorptions are extremely weak



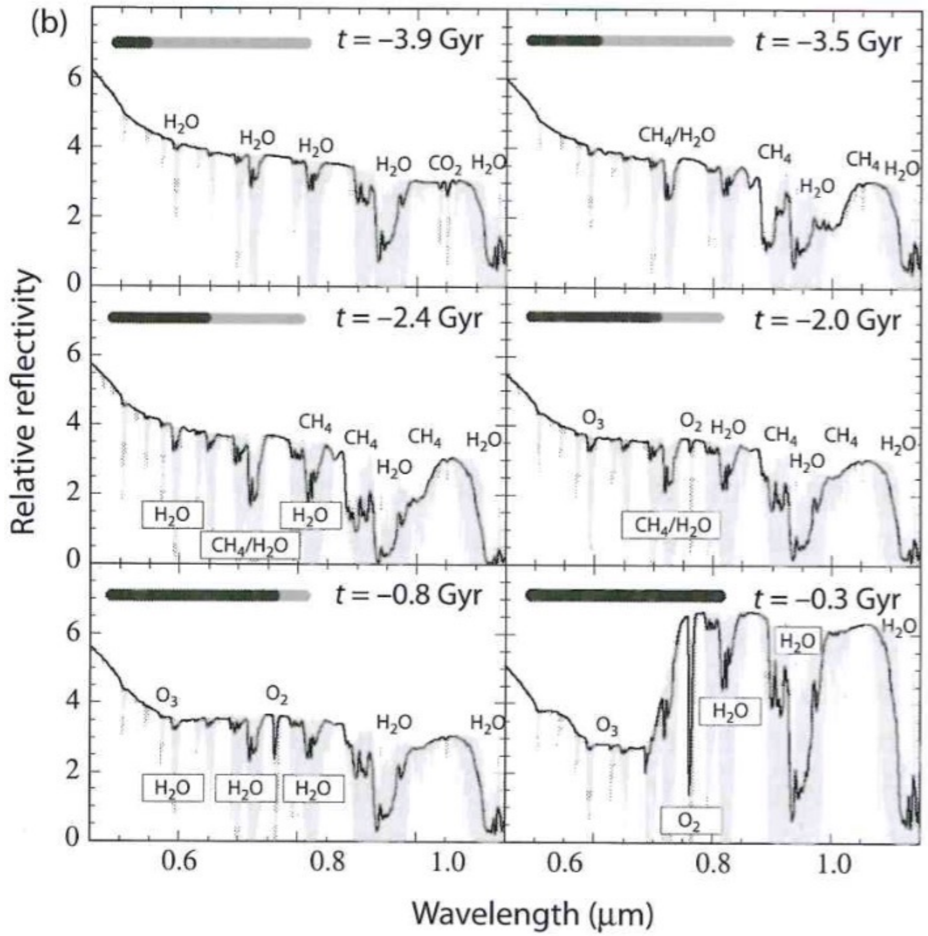
Reflection spectra in the visible/near IR of Earth, Venus and Mars

Mid IR thermal emission spectra, with the black body emission of a planet of the same radius (dashed lines)

Spectral resolution: R ~ 100
Fluxes correspond to a solar system analogue at 10 pc

Evolution of atmospheric biosignatures on Earth

In the course of Earth evolution, different types of gases of biological origin could have been observable, not necessarily as redox pairs



Predicted evolution of atmospheric signatures of an Earth-like planet at 6 different geologic epochs, in absence of clouds. The planet evolves from CO_2-rich, to CO_2/CH_4-rich, to a present-day O_2-rich atmosphere. From Kaltenegger et al. (2007)

Atmospheric oxygen as a biosignature

The history of Earth's atmospheric oxygen shows that oxygen is one of the most promising biomarkers: in absence of a biosphere, O_2 tends to oxidate rocks, decreasing its atmospheric concentration

Caveat: it is not possible to exclude a non-biological origin of oxygen in other planets

The study of biosignatures requires a full calculation of equilibrium abundances of a variety of molecular species

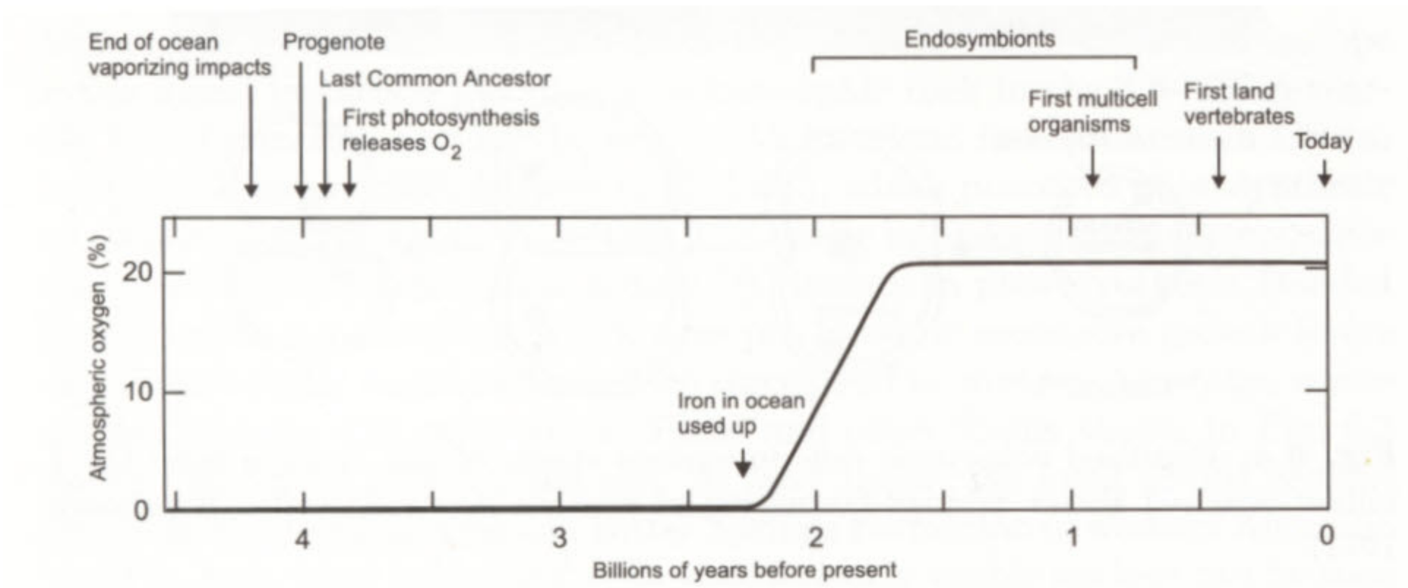


Table 4. Potential Biosignature Gases and Associated Information

Biosignature	*UV-Visible-NIR band center, μm and (cm^{-1})*	*Visible-NIR band interval, cm^{-1}*	*Thermal IR spectral band center, μm*	*Biogenic source*	*Abiogenic false positive*
O_2	1.58 (6329) 1.27 (7874) 1.06 (9433) **0.76 (13158)** 0.69 (14493) 0.63 (15873) 0.175–0.19 [Schumann–Runge]	6300–6350 7700–8050 9350–9400 **12850–13200** 14300–14600 14750–15900	—	*Photosynthesis*: splitting of water	Cases of water and CO_2 photodissociation and preferential escape of hydrogen, with lack of O_2 sinks
O_3	4.74 (2110) 3.3 (3030) 0.45–0.85 [Chappuis] 0.30–0.36 [Huggins] 0.2–0.3 [Hartley]	2000–2300 3000–3100 10600–22600	>15 (rotation), 14.3, 9.6, 8.9, 7.1, 5.8	*Photosynthesis:* photochemically derived from O_2	As above
CH_4	3.3 (3030) **2.20 (4420)** 1.66 (6005) <0.145 continuum	2500–3200 **4000–4600** 5850–6100	6.5, 7.7	*Methanogenesis*: reduction of CO_2 with H_2, often mediated by degradation of organic matter	Geothermal or primordial methane
N_2O	4.5 (2224) 4.06 (2463) 2.87 (3484) 0.15–0.20 0.1809, 0.1455, 0.1291	**2100–2300** 2100–2800 3300–3500	7.78, 8.5, 16.98	*Denitrification*: reduction of nitrate with organic matter	Chemodenitrification but not truly abiotic on Earth[a]; also strong coronal mass injection affecting an N_2–CO_2 atmosphere[b]
NH_3	4.3 3.0 (3337) 2.9 (3444) 2.25, 2, 1.5, 0.93, 0.65, 0.55, 0.195, 0.155	**2800–3150**	6.1, 10.5	*Ammonification*: Volatilization of dead or waste organic matter	Nonbiogenic, primordial ammonia

Catling et al. 2018

One of the aims of astrobiology is exploring
the (potential) distribution of life in the universe

This particular aspect of astrobiology has lead to the definition of

The Galactic Habitable Zone (GHZ)

Galactic habitable zone vs circumstellar habitable zone

Important differences

1) The habitability criteria of the GHZ are based on statistical distributions of Galactic properties and yield probability distributions

The results are purely statistical

2) Some habitability criteria used to define the GHZ refer to macroscopic life

Comparable to animal or plant life on Earth

The time scales of life evolution enter in the calculation of GHZ

General concept of the Galactic habitable zone

Lineweaver et al. 2004, Science 303, 59

Mapping astrophysical quantities related to Galactic evolution into probabilities of astrobiological interest

In the original formulation

Gonzalez et al. 2001, Icarus,152,185

Metallicity & probability of planet formation

$Z(x_i,t) \rightarrow \pi_{PF}(x_i,t)$

Supernova rates & probability of life destruction

$R_{SN}(x_i,t) \rightarrow \pi_{LD}(x_i,t)$

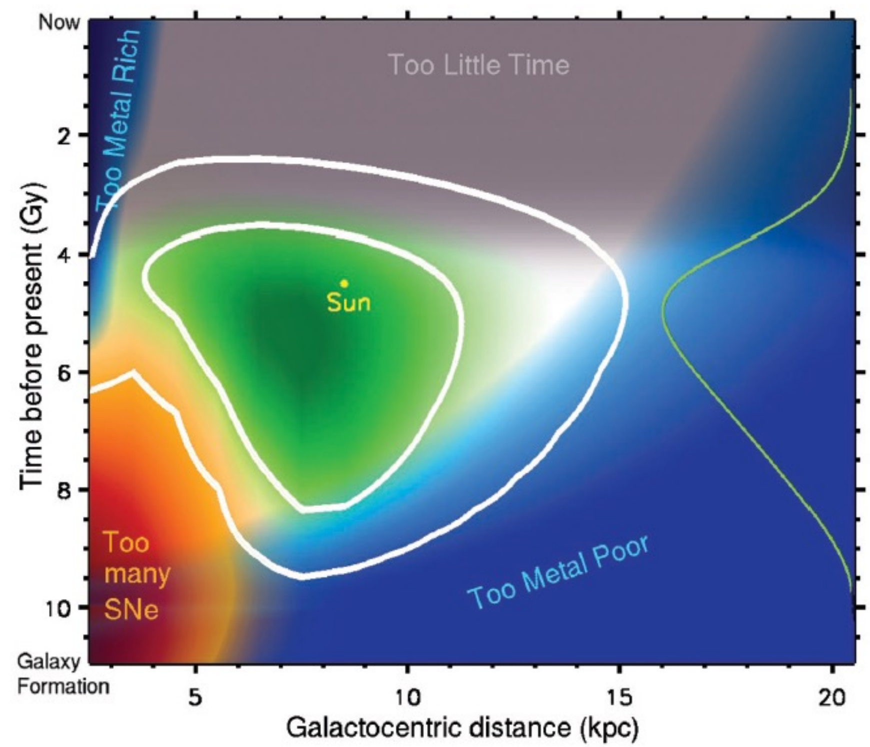


Fig. 3. The GHZ in the disk of the Milky Way based on the star formation rate, metallicity (blue), sufficient time for evolution (gray), and freedom from life-extinguishing supernova explosions (red). The white contours encompass 68% (inner) and 95% (outer) of the origins of stars with the highest potential to be harboring complex life today. The green line on the right is the age distribution of complex life and is obtained by integrating $P_{GHZ}(r, t)$ over r.

Tools for GHZ calculations

- Models of Galactic chemical evolution
  - Radial distribution of metallicities and supernova rates at different epochs of galactic evolution
  - In the original formulation, semi-analytical models have been used
  - More realistic models are also employed:

    Spitoni, Matteucci & Sozzetti, 2014, *MNRAS* 440, 2588

    Carigi et al. 2013, *Rev. Mex. Astron. Astrof.*, 49, 253

- Galaxy simulations
  - Generation of space-time evolutionary maps of Galactic habitability by means of N-body simulations of galaxies
  - Example:

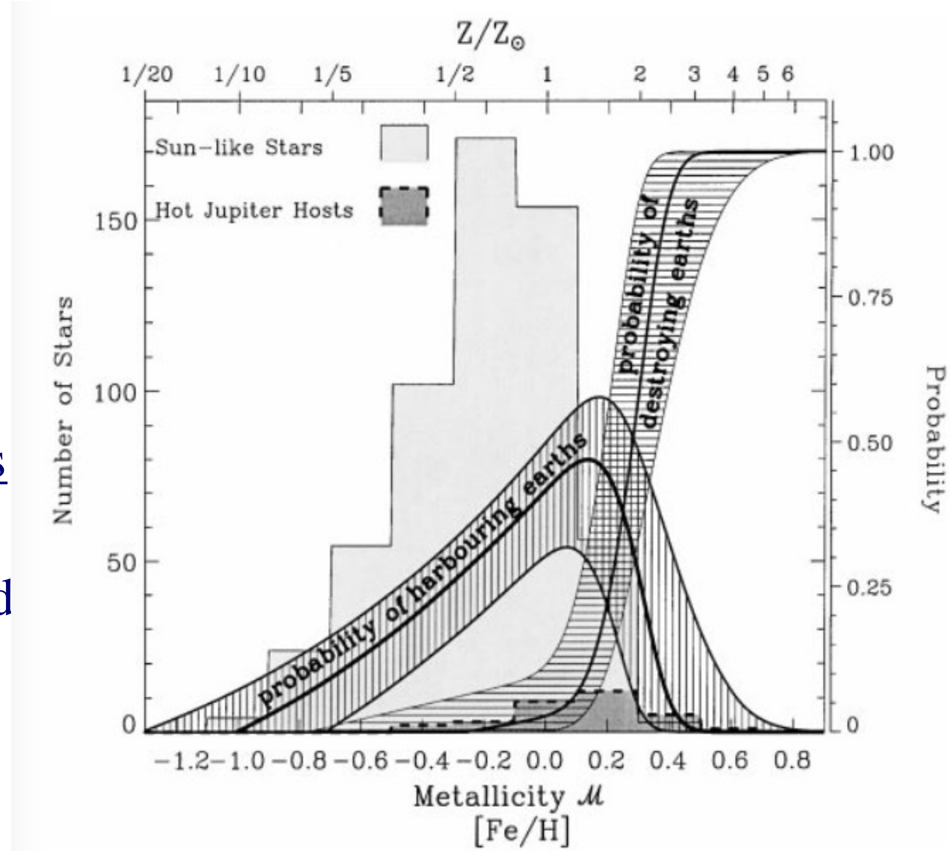
    Forgan et al., 2015, arXiv:1511.01786

Both tools start to be applied also to nearby galaxies

- M31, M33

Open issues in GHZ calculations

- Probability of existence of terrestrial-type planets as a function of stellar metallicity
  - This probability is related to the metallicity-dependence of the frequency of hot jupiters
  - Hot jupiters, which are frequent at high metallicity, tend to inhibit the formation of terrestrial-type planets
  - In addition, the process of rocky planet formation would be inhibited at low metallicity
  - The resulting probability of harboring terrestrial-type planets would experience a rise followed by a decrease with metallicity



Lineweaver (2001)

Open issues in the definition of the GHZ

- Still not clear the relationship between metallicity and probability of formation of terrestrial-type planets

  Exoplanet statistics will clarify this point in the future, when more data will be available for terrestrial planets at very low metallicities

- Ambiguous role of supernovae explosions in the context of life evolution

  Only extremely close supernovae can sterilize a planet

  Supernovae may trigger life evolution, leading to the formation of new species

- The classic criteria that define the GHZ need to be refined and it is desirable to find new criteria

On the role of SN explosions

- Resetting the evolution to intelligent life at each SN destructive event
  - Even if SNe do not fully sterilize the planet, one can assumed that the evolution is resetted (e.g., restarting from unicellular life) at each critical SN event
  - Then the probability of forming intelligent life is calculated, using Monte Carlo methods, only during the time intervals devoid of SN destructive events

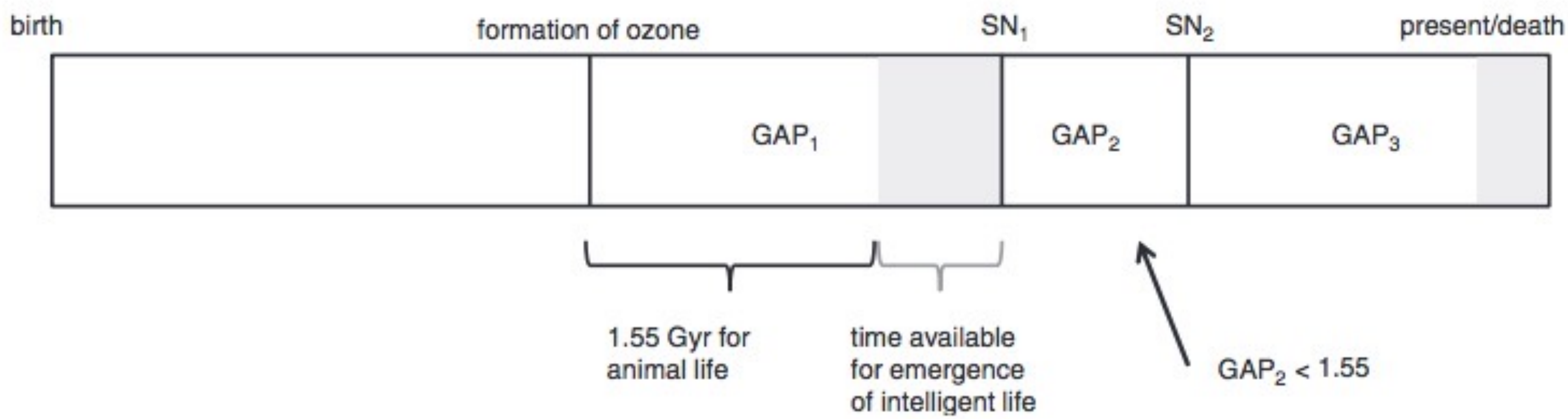


FIG. 2. Illustrative planet timeline showing the major events from the birth (at left) to the present (or death) time (at right) and showing how "gap times" are calculated. In this example, there are two SNe, labeled SN_1 and SN_2. A gap time begins after the first formation of the ozone layer or after a SN event. A gap time is ended by a SN, the death of the planet, or the present day, as we do not extrapolate beyond the age of the Universe. Any gap times exceeding 1.55 Gyr (the time assumed to be needed for the emergence of animal life) give rise to an opportunity for intelligent life to emerge. The shaded regions represent these "opportunity times," T_O, which are equal to the gap time less 1.55 Gyr.

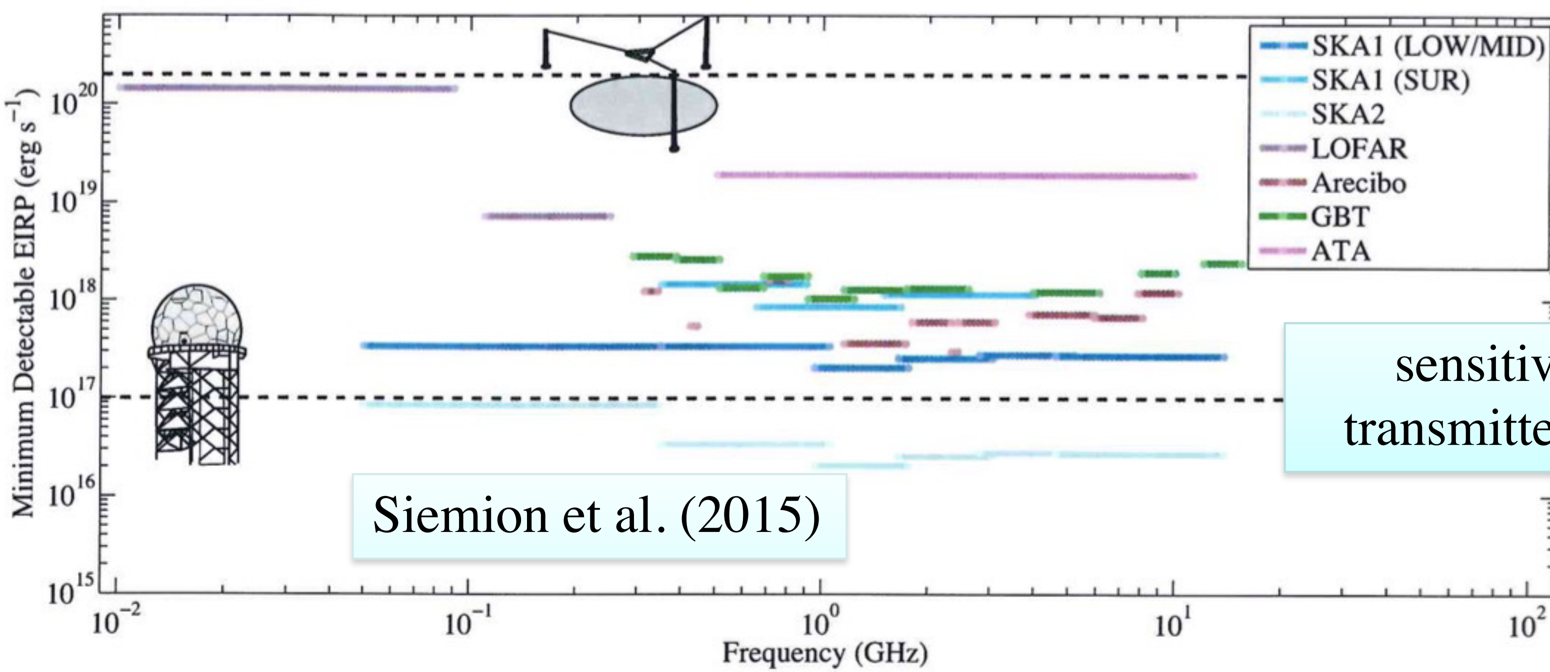
Morrison & Gowanlock (2015)

SETI

Search for extraterrestrial intelligence with new astronomical facilities: SKA (Square Kilometer Array)

EIRP: equivalent isotropically radiated power

	Transmitter Type	Luminosity (EIRP) (ergs/sec)	Number on Earth
	Interplanetary Radar	$\sim 2 \times 10^{20}$	Few
	Long Range Aircraft Radar	$\sim 1 \times 10^{17}$	Dozens



Siemion et al. (2015)

sensitivity to a transmitter at 15 pc