Life in the Universe (2)

Planets and Astrobiology (2018-2019)
G. Vladilo

Search for habitable exoplanets with measurements of masses and radii

So far, most exoplanets with measurements of masses and radii have a mean insolation much higher than that of the Earth

With few exceptions (e.g. Trappist-1) they lie outside the habitable zone

Planet	M $(\mathrm{M}_\oplus)$	R $(\mathrm{R}_\oplus)$	ρ $(\mathrm{g\,cm^{-3}})$	g $(g_\oplus)$	$\log(S_\mathrm{eff})$	Ref.
Kepler-20 b	$8.70^{+2.10}_{-2.20}$	$1.91^{+0.12}_{-0.21}$	6.89	2.38	2.54	Gautier (2012)
Kepler-11 b	$1.90^{+1.40}_{-1.00}$	$1.80^{+0.03}_{-0.05}$	1.80	0.59	2.10	Lissauer (2013)
Kepler-11 c	$2.90^{+2.90}_{-1.60}$	$2.87^{+0.05}_{-0.06}$	0.68	0.35	1.96	Lissauer (2013)
Kepler-11 d	$7.30^{+0.80}_{-1.50}$	$3.12^{+0.06}_{-0.07}$	1.33	0.75	1.64	Lissauer (2013)
Kepler-11 e	$8.00^{+1.50}_{-2.10}$	$4.19^{+0.07}_{-0.09}$	0.60	0.46	1.44	Lissauer (2013)
Kepler-11 f	$2.00^{+0.80}_{-0.90}$	$2.49^{+0.04}_{-0.07}$	0.71	0.32	1.22	Lissauer (2013)
Kepler-10 b	$4.56^{+1.17}_{-1.29}$	$1.42^{+0.03}_{-0.04}$	8.86	2.27	3.55	Batalha (2011)
CoRoT-7 b	$4.90^{+0.80}_{-0.80}$	$1.68^{+0.09}_{-0.09}$	5.70	1.74	3.26	Léger (2009); Queloz (2009)
Kepler-68 b	$8.30^{+2.20}_{-2.40}$	$2.31^{+0.06}_{-0.09}$	3.71	1.56	2.61	Gilliland (2013)
GJ1214 b	$6.55^{+0.98}_{-0.98}$	$2.68^{+0.13}_{-0.13}$	1.88	0.91	1.21	Charbonneau (2009)
Kepler-36 b	$4.45^{+0.33}_{-0.27}$	$1.49^{+0.04}_{-0.04}$	7.48	2.02	2.34	Carter (2012)
Kepler-36 c	$8.08^{+0.60}_{-0.46}$	$3.68^{+0.05}_{-0.05}$	0.89	0.60	2.24	Carter (2012)
HD97658 b	$7.86^{+0.03}_{-0.03}$	$2.34^{+0.18}_{-0.15}$	3.38	1.44	2.42	Dragomir (2013)
55Cnc e	$7.81^{+0.58}_{-0.53}$	$2.08^{+0.16}_{-0.17}$	4.79	1.81	3.39	Demory (2011)
Kepler-18 b	$6.90^{+3.40}_{-3.40}$	$2.00^{+0.10}_{-0.10}$	4.76	1.73	2.67	Cochran (2011)

The equilibrium temperature

A preliminary, fast estimate of the planet habitability is performed in two ways:
(1) checking whether the planet lies inside the “classic habitable zone”
and/or (2) measuring the equilibrium temperature, defined as

$$T_\mathrm{eq} = T_\mathrm{eff}(R_\star/2a)^{1/2}[\beta(1-A_B)]^{1/4}$$

where T_eff is the stellar effective temperature, R_* the stellar radius, a the semi-major axis, β a proxy for atmospheric circulation, and A_B the planetary albedo

A value β = 1, rappresentative a fully convective atmosphere, is usually adopted

If the equilibrium temperature is not far from the liquid-water temperature range, the planet is considered a good candidate for habitability

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Selection of best candidate habitable planets

With the available experimental data, the selection criteria are
(1) insolation (or equilibrium temperature)
(2) indication that the planet is of terrestrial type (either radius or mass)
(3) orbit preferably outside the tidal lock radius
Some examples:

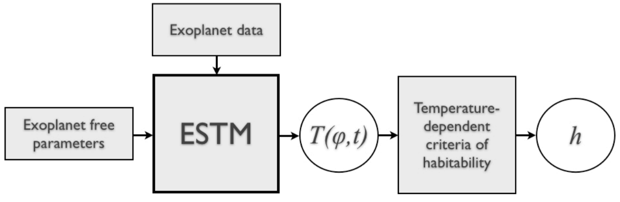
Planet	Mass $(\mathrm{M}_\oplus)$	Radius $(\mathrm{R}_\oplus)$	a (AU)	e	r_TL (AU)	S_eff	$M_\star$ $(M_\odot)$	$L_\star$ $(L_\odot)$	T_eq (K)	Ref.
Kepler-22 b	< 82	2.38	0.849	0.00	0.35	1.10	0.97	0.79	262	Borucki (2012)
Kepler-62 e	< 36	1.61	0.427	0.13	0.31	1.19	0.69	0.216	270	Borucki (2013)
Kepler-62 f	< 35	1.41	0.718	0.0944	0.31	0.42	0.69	0.216	208	Borucki (2013))
Kepler-69 c	—	1.71	0.64	0.14	0.33	1.95	0.81	0.80	299	Barclay (2013)

More recent candidates:
Kepler 452b (host star has $M_*=1.0\ M_\odot$)
$R=1.63\ R_{earth}$ $S=1.10\ S_o$
Jenkins et al. (2015)

Exploring the climate and habitability of exoplanets

Climate models are constrained using stellar, orbital and planetary data obtained from the observations

Fast climate simulations are then used to explore the parameter space unconstrained by observations (e.g. atmospheric pressure and composition, rotation period, axis obliquity, ocean fractions, …)


Exoplanet data

Exoplanet free parameters

ESTM

$T(\varphi,t)$

Temperature-dependent criteria of habitability

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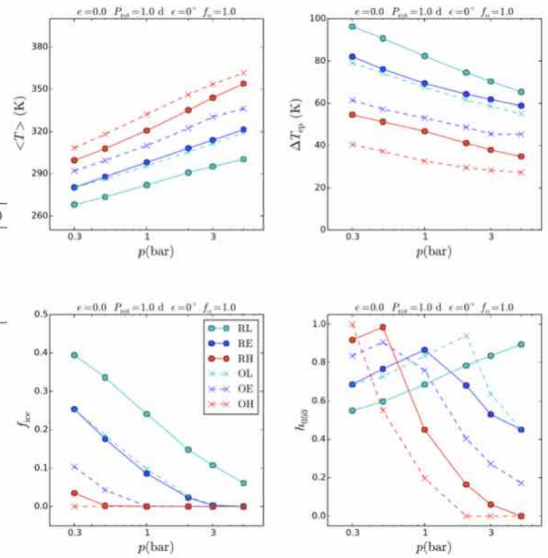
Quantitative estimates of the habitability of Kepler 452b

Impact of surface atmospheric pressure and atmospheric composition for different models of internal structure

Model	$M/M_\oplus$	$g/g_\oplus$	pCO$_2$ (ppmv)	p^b (bar)
RL	4.3	1.6	10	2.6
RE	4.3	1.6	380	2.6
RH	4.3	1.6	38000	2.6
OL	2.7	1.0	10	1.0
OE	2.7	1.0	380	1.0
OH	2.7	1.0	38000	1.0



Modelization of the surface temperature and habitability of a specific exoplanet: Kepler 452 b

Best candidate rocky planet in the habitable zone of a solar-type star

R=1.63 $R_\oplus$ S=1.1 $S_\oplus$

(Jenkins et a. 2015)

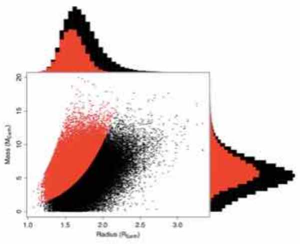


Table 3
Planet Parameters for Kepler-452b

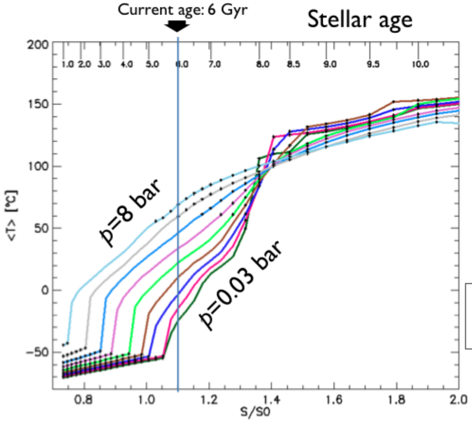
Parameter	Value	Notes
Transit and orbital parameters		
Orbital period P (day)	$384.843^{+0.007}_{-0.012}$	a, b
Epoch (BJD—2454833)	$314.985^{+0.015}_{-0.019}$	a, b
Scaled planet radius R_P/R_*	$0.0128^{+0.0013}_{-0.0006}$	a, b
Impact parameter $b \equiv a \cos i/R_*$	$0.69^{+0.16}_{-0.45}$	a, b
Orbital inclination i (deg)	$89.806^{+0.134}_{-0.049}$	a
Transit depth T_{dep} (ppm)	199^{+18}_{-21}	a
Transit duration T_{dur} (hr)	$10.63^{+0.53}_{-0.60}$	a
Eccentricity e cos (ω)	$0.03^{+0.75}_{-0.39}$	a, b
Eccentricity e sin (ω)	$-0.02^{+0.31}_{-0.31}$	a, b
Planetary parameters		
Radius R_P ($R_\oplus$)	$1.63^{+0.23}_{-0.20}$	a
Orbital semimajor axis a (AU)	$1.046^{+0.019}_{-0.015}$	a
Equilibrium temperature T_{equ} (K)	265^{+15}_{-13}	c
Insolation relative to Earth	$1.10^{+0.29}_{-0.22}$	d

Notes.
a: Based on the photometry.
b: Directly fitted parameter.
c: Assumes Bond albedo = 0.3 and complete redistribution.
d: Based on Dartmouth isochrones.

Evolution of the surface temperature and habitability of Kepler 452b

from stellar evolutionary tracks to planet insolation

Mean surface temperature



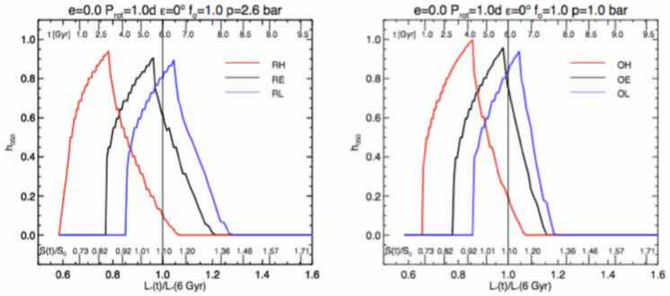
Kepler 452b
R=1.63 R_{Earth}
S=S(t)

PARSEC tracks
Bressan et al. (2012)

g=g_{Earth}
p(CO$_2$)= p(CO$_2$)$_{Earth}$

Quantitative estimates of the habitability of Kepler 452b

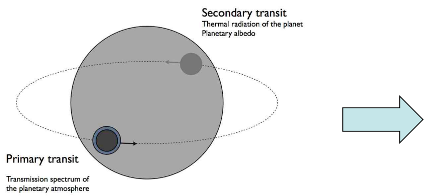
Evolution of surface habitability: the impact of the luminosity evolution of the central star

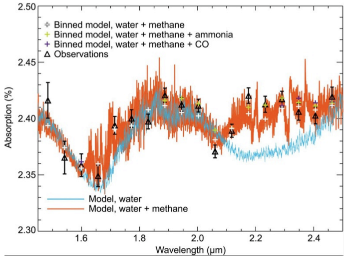


PARSEC stellar evolution tracks
(Bressan et al. 2012)

Model	$M/M_\oplus$	$g/g_\oplus$	$p\mathrm{CO_2}$ (ppmv)	p^b (bar)
RL	4.3	1.6	10	2.6
RE	4.3	1.6	380	2.6
RH	4.3	1.6	38000	2.6
OL	2.7	1.0	10	1.0
OE	2.7	1.0	380	1.0
OH	2.7	1.0	38000	1.0

Searching for atmospheric biosignatures in exoplanets





The problem of searching for atmospheric biosignatures is two-fold:

(1) enhancing the observational techniques to the point at which atmospheric spectra of terrestrial-type planets can be obtained

(2) identifying molecular species that, from the comparison of the molecular abundances measured in the atmosphere, can be used as reliable biosignatures

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Searching for life in exoplanets: atmospheric biosignatures

Life metabolizes and dissipates metabolic by-products that can accumulate in the planetary atmosphere acting as biosignature gases

In searching for atmospheric biosignatures we do not worry about what life is, but just on what life does (that is, life metabolizes)

In this approach it is assumed that life with active metabolism is spread on the planet

Life on the surface has a better chance to interact with the atmosphere and to generate atmospheric biosignatures

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Atmospheric biosignatures: chemical disequilibrium

Biological processes are expected to drive the atmosphere out of thermochemical equilibrium

The idea is that gas by-products from metabolic reactions can accumulate in the atmosphere and would be recognized as biosignatures because abiotic processes are unlikely to create a chemical disequilibrium

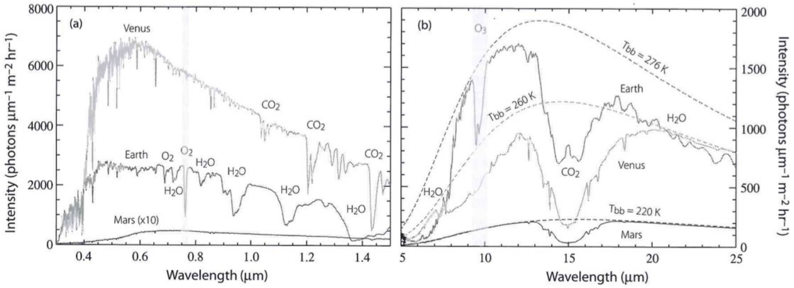
Chemical equilibrium calculations are performed using a network of redox chemical reactions, where an electron is added (reduction) or removed (oxidation) from an atom or molecule

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)

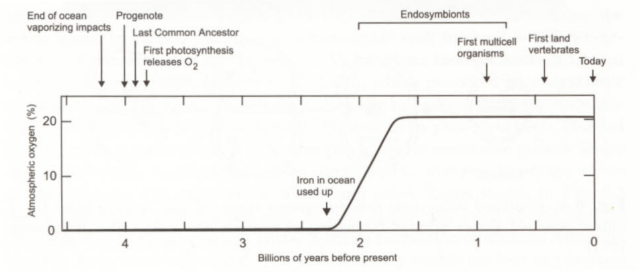
Spectral resolution: R ~ 100
Fluxes correspond to a solar system analogue at 10 pc

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

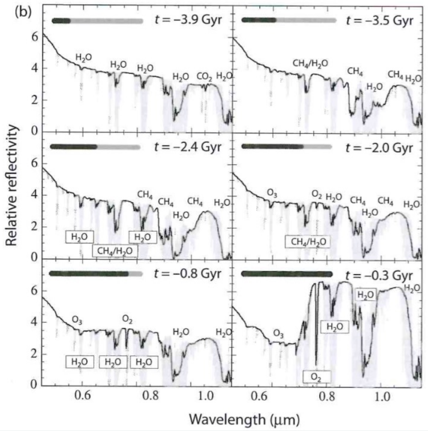
Caveat: it is not possible to exclude a non-biological origin of oxygen in other planets

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



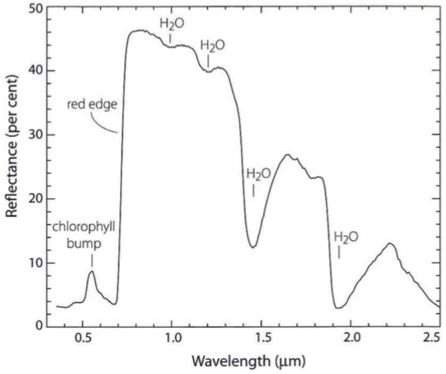
Evolution of atmospheric biosignatures on Earth

In the course of Earth evolution, different types of gases of biological origin should 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)

Searching for signatures of (terrestrial-type) vegetation



Reflection spectrum of a decidous leaf. The bump near 550 nm is a result of chlorophyll absorption (at 450 nm and 680 nm), which gives plants their green colour. The sharp rise between 700-800 nm, the red edge, is due to the constrast between the strong absorption of chorophyll and the otherwise reflective leaf. from Seager at al. (2005)

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)

General concept of the Galactic habitable zone

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

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

Lineweaver et al. 2004, Science 303, 59

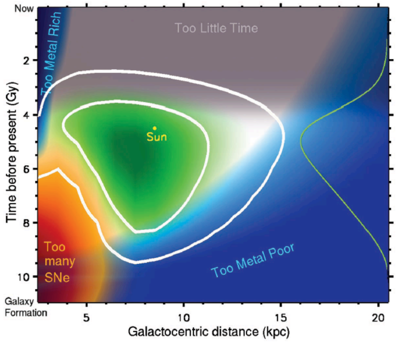


Fig. 3. The GHZ in the disk of the Milky Way based on the star formation rate, metallicity (blue), sufficient time for evolution (gray), and freedom from life-extinguishing supernova explosions (red). The white contours encompass 68% (inner) and 95% (outer) of the origins of stars with the highest potential 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.

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 definte 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

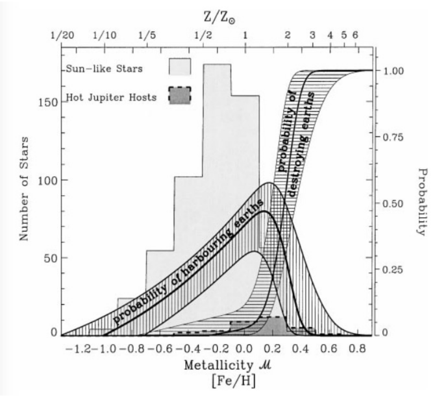
Tools for GHZ calculations

- 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

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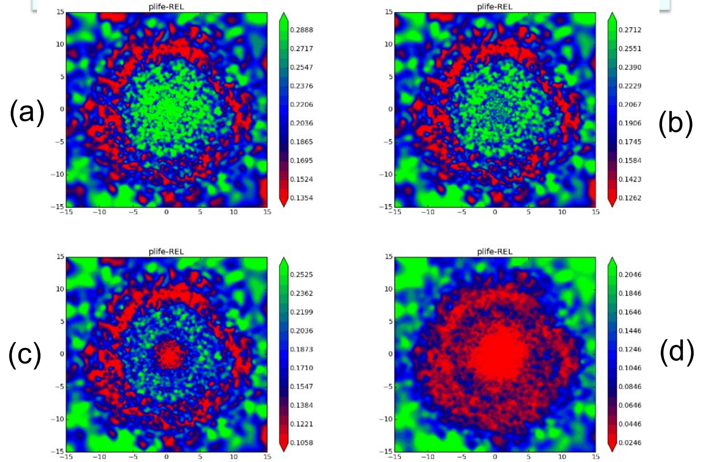
On the role of SN explosions

Calculations of the dependence of the total habitability on the sterilization radius (Murante et al. 2016)

(a) 4 pc, (b) 6 pc, (c) 8pc, (d) 12 pc Kroupa IMF



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

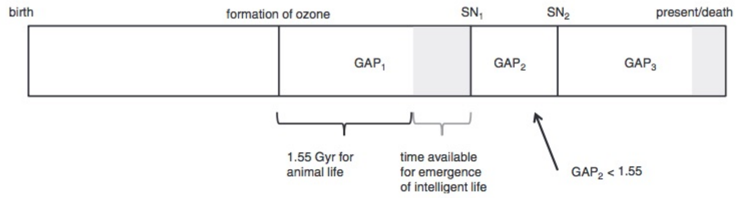


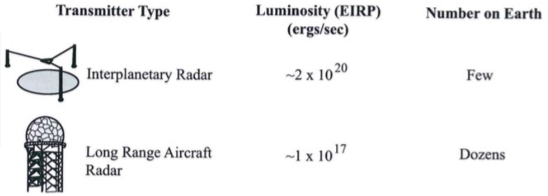
FIG. 2. Illustrative planet timeline showing the major events from the birth (at left) to the present (or death) time (at right) and showing how "gap times" are calculated. In this example, there are two SNe, labeled SN_1 and SN_2. A gap time begins after the first formation of the ozone layer or after 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)

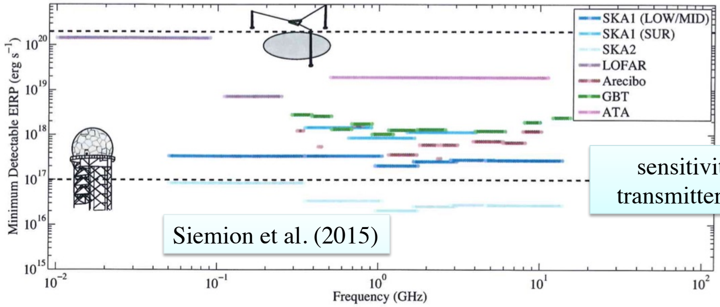
SETI

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	~2 x 10^{20}	Few
Long Range Aircraft Radar	~1 x 10^{17}	Dozens



sensitivity to a transmitter at 15 pc

Siemion et al. (2015)