Searching for life beyond the Solar System (1)

Habitable exoplanets

Planets and Astrobiology (2023)
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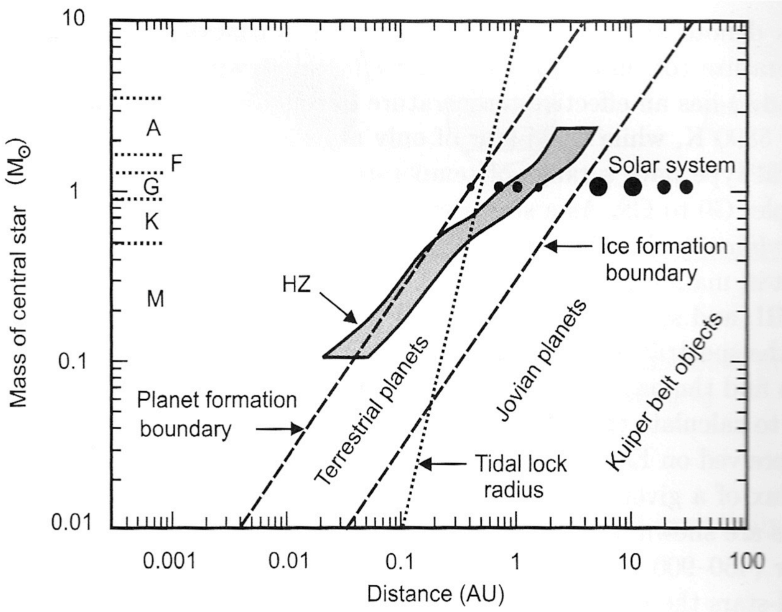
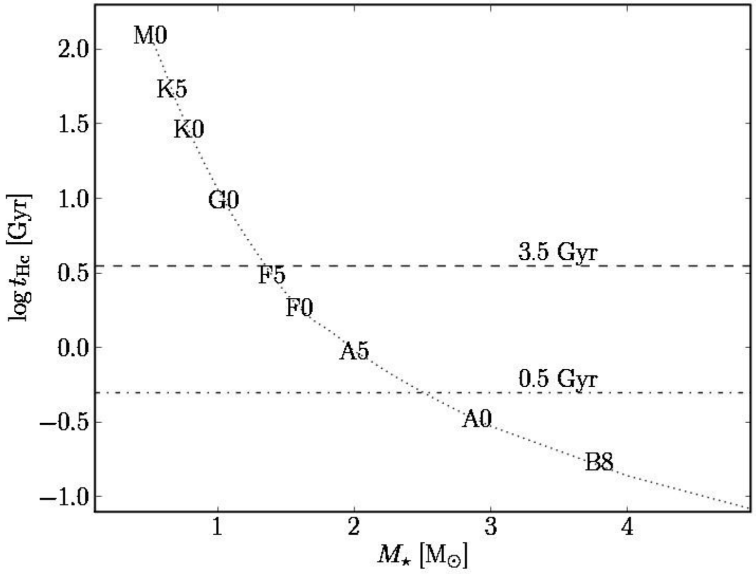
Habitability of exoplanets: influence of the host star

The host star affects the habitability in at least two ways:

1) location of the circumstellar habitable zone (HZ)

2) permanence time in the main-sequence





Radius of the HZ as a function of stellar parameters

Neglecting variations of albedo and greenhouse effect

$$\boxed{\sigma \, T_p{}^4 \; = \; \tfrac{1}{4} \; S_* \; (1-A)}$$

$$S_* \equiv L_*/(4\pi d^2)$$

$$S_* = \frac{R_*^2}{d^2} \sigma T_*^4$$

$$(1 - A) \, \frac{R_*^2}{4 \, d^2} \, T_*^4 = T_\mathrm{p}^4$$

Assuming
A ~ const
$d = a$

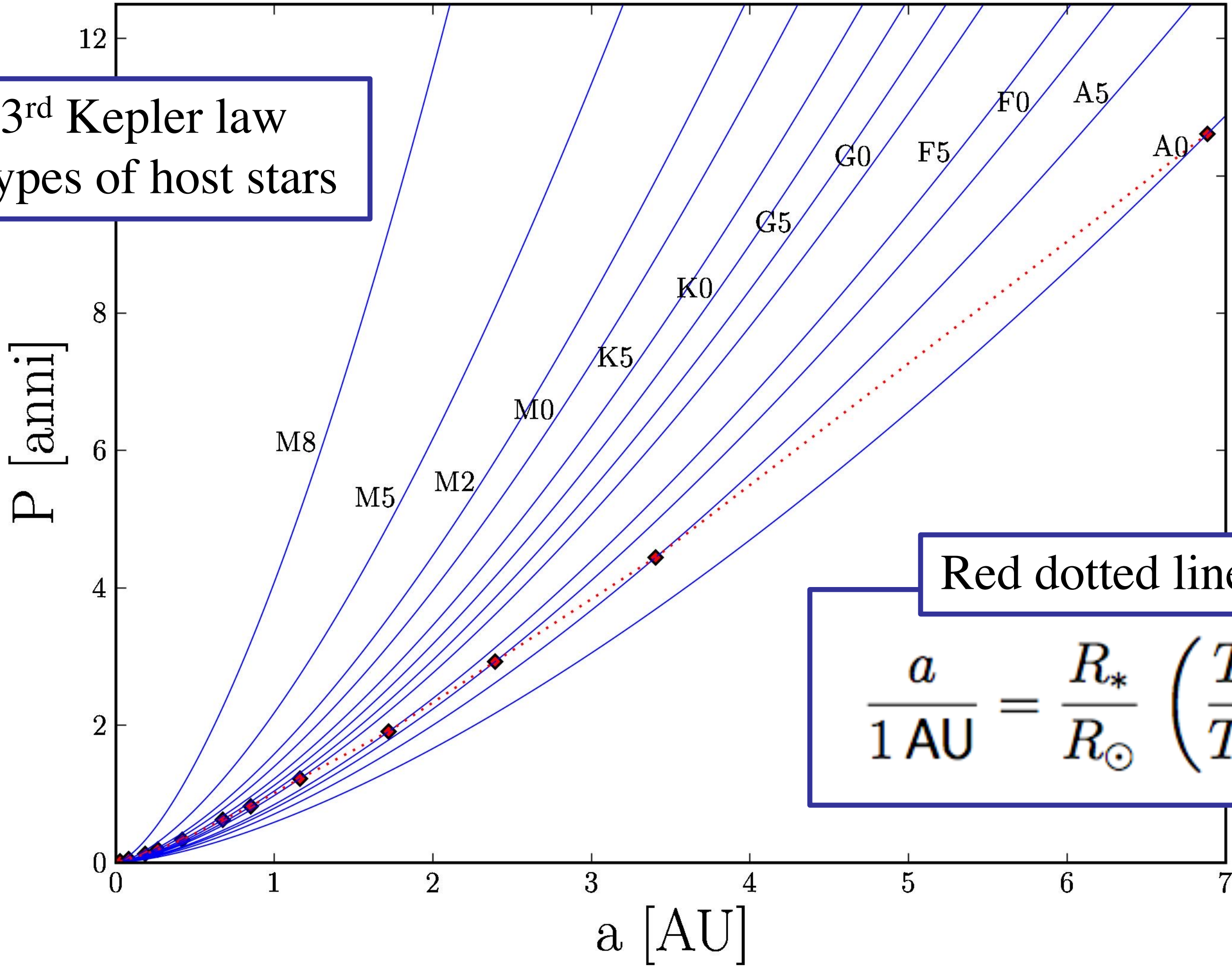
$$T_\mathrm{p} \propto \left(\frac{R_*}{a} \right)^{\frac{1}{2}} T_*$$

Assuming T_p constant, optimal for life, the radius a of the HZ increases linearly with R_* and quadratically with T_*

$$\frac{a}{1\,\mathrm{AU}} = \frac{R_*}{R_\odot} \left(\frac{T_*}{T_\odot} \right)^2$$

Because of the 3rd Kepler law and the dependence $a(\mathrm{HZ}) \propto T_*^{\,2}$,
exoplanets in the HZ around hot stars have orbital periods of several years

The temporal baseline for detecting such planets is correspondingly long



Blue lines: 3rd Kepler law
for different types of host stars

Red dotted line:

$$\frac{a}{1\,\mathrm{AU}} = \frac{R_*}{R_\odot}\left(\frac{T_*}{T_\odot}\right)^2$$

Continuous habitability

Based on the example of the Earth,
life evolution takes some billon years to produce advanced forms of life

To understand if life can evolve in a distant planet,
we need to define the concept of “continuous habitability”,
i.e. the persistence of habitable conditions for long periods of time,
comparable to the time scale of evolution of terrestrial life ($\sim 10^9$ yr)

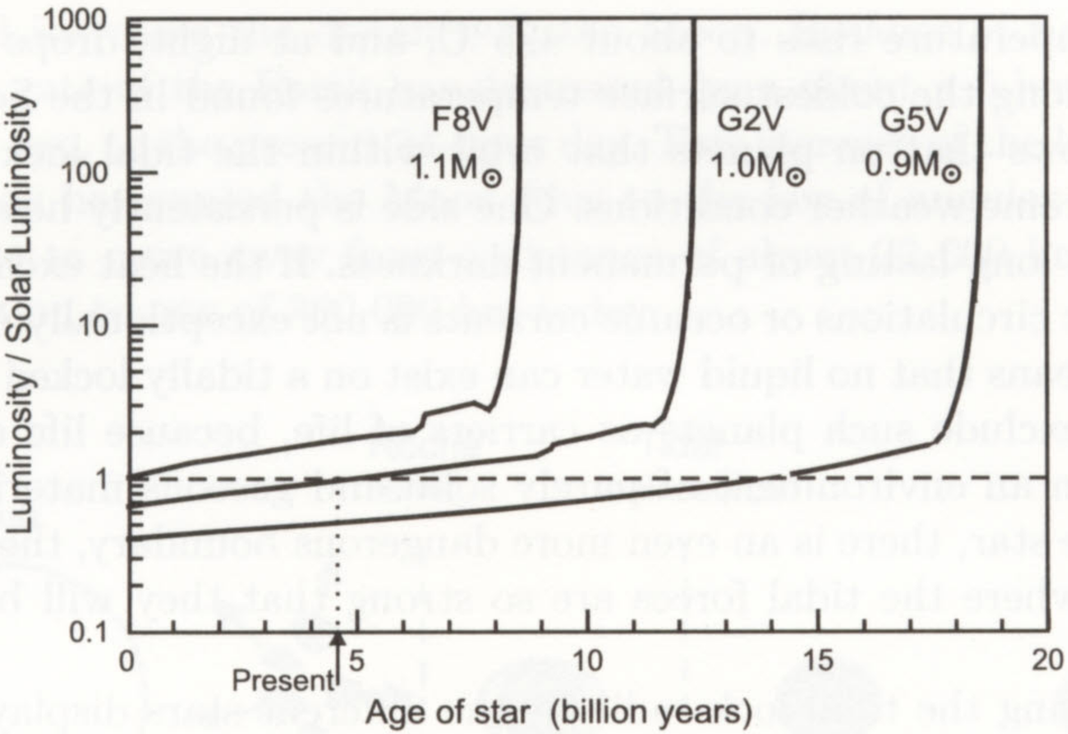
Continuous habitability can be influenced by:

1) evolution of the stellar luminosity
2) evolution of the orbital parameters
3) mechanisms of climate stabilization
4) feedbacks between the biosphere and the climate

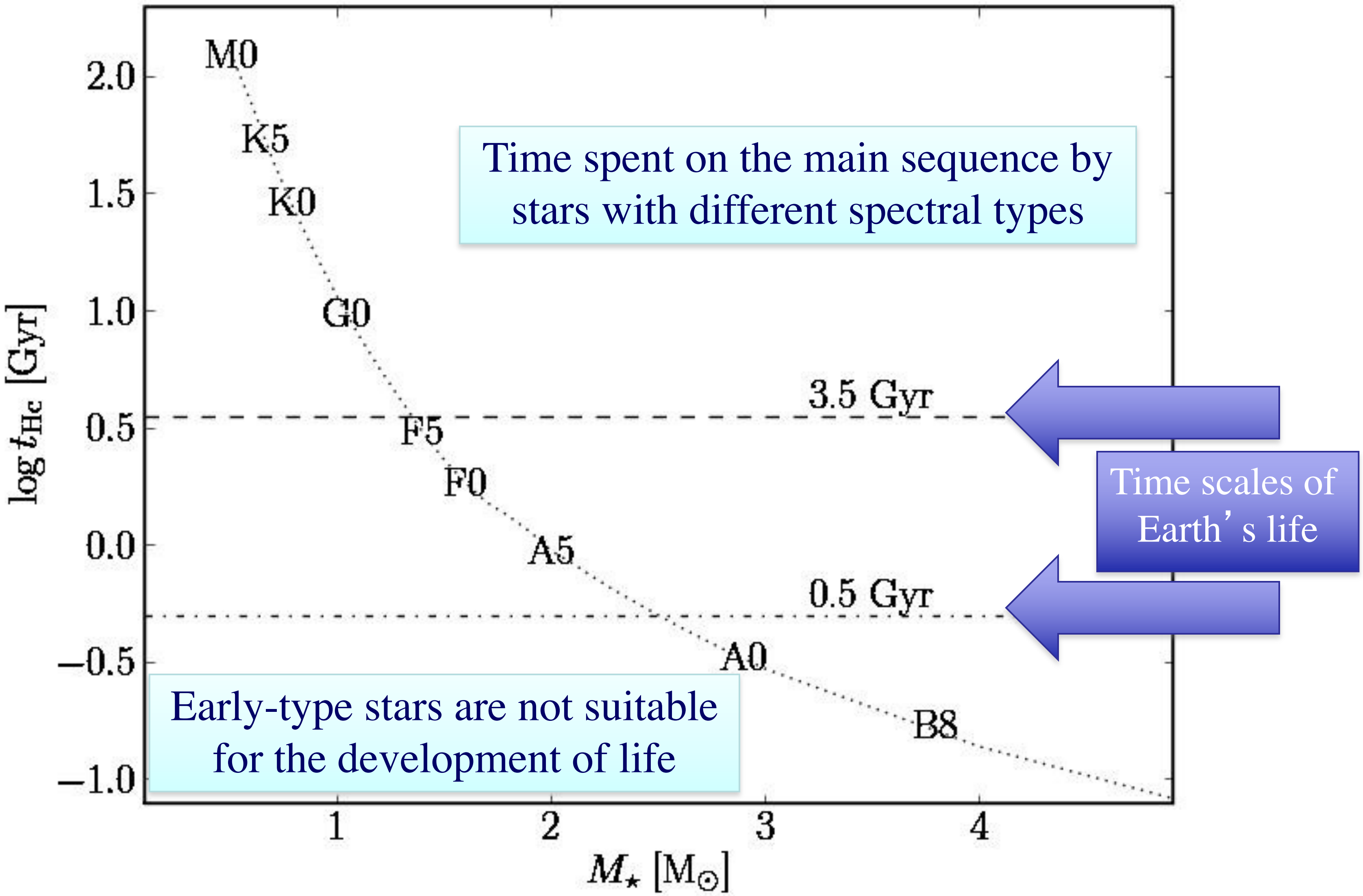
Evolution of the stellar luminosity

The evolution of the stellar luminosity shifts the location of the circumstellar habitable zone in planetary systems

- –The shift is gradual during the main sequence stage of hydrogen burning, but is sudden at later stages of stellar evolution
- –The type of evolution depends on the spectral type of the host star



Continuous habitability and spectral type of the host star



Time spent on the main sequence by stars with different spectral types

Time scales of Earth's life

Early-type stars are not suitable for the development of life

Detection of exoplanets in the HZ: observational issues

- The temporal baseline of observations required for detecting habitable exoplanets does not represent a serious problem

  Planets in the HZ of late-type stars can be detected in short time scales

  Planets in the HZ of early-type stars :

    - require several years of observations, but are less interesting in the context of astrobiology due to the fast evolution of the stellar luminosity which interrupts the continuous habitability

    - they could be detected with the "direct imaging" on observational time scales much shorter than the orbital period

- The detection of exoplanets in the circumstellar HZ is affected by several observational biases, which depend on adopted observational technique

Detecting exoplanets in the HZ with the *Doppler method*

- Advantages for detecting planets in the HZ around M-type stars with the Doppler method

The semi-amplitude of the radial velocity curves scales as

$$K \sim (a \, M_{*})^{-1/2}$$

where a is the semi-major axis, M_{*} the stellar mass

The advantage of a smaller stellar mass combines with the advantage of the smaller distance of the habitable zone

For a given planetary mass, the Doppler signal of an planet in the HZ of an M-type star is ~ 3-30 times stronger than the signal of planet in the HZ of a solar-type star

Detecting exoplanets in the HZ with the *Transit method*

- Geometrical probability of detecting a transiting planet

$$\mathcal{P}_{\mathrm{tr}} \simeq 4.65 \times 10^{-3} \, \frac{R_* \, [R_\odot]}{a \, [\mathrm{AU}]}$$

The geometrical probability increases with decreasing semi-major axis

Since the HZs around late-type stars are located at small semi-major axis,
the geometrical probability is higher in late-type stars

- Transit depth of the minimum of the light curve

$$\Delta F = \frac{F - F_{\mathrm{tr}}}{F} = \left(\frac{R_{\mathrm{p}}}{R_*} \right)^2$$

The strongest signal is given by giant planets around stars of small radii

For a given planet size, the detection is easier in stars of small size

In the main sequence late-type stars have smaller radii than early-type stars
and so the transit signal tends to be stronger in low-mass stars

The detection of habitable planets
with the most efficient detections methods (Doppler and transit)
is severely biased in favour of planets around low-mass stars

However, the exoplanets in the HZs around M-type stars
are affected by several problems that may hinder their effective habitability

- Tidal locking
- Stellar activity
- High insolation during the pre-main sequence

Exoplanets in HZs around M-type stars: tidal locking

- The vicinity to the star may lead to a synchronization of the planet orbital period with the planet rotation period ("tidal locking")
  - The distance from the star at which the planet becomes tidally locked after a time t scales as

    $$r \propto (P_o\, t / Q)^{1/6}\, M_*^{1/3}$$

    where P_o is the initial rotation period, Q is a planetary dissipation factor and M_* the stellar mass

    for $t=10^9$ yr and $P_o=0.5$ d, typical values of r are lower than ~0.3 AU

- Tidal locking has heavy implications on the planetary climate
  - Only one hemisphere is constantly illuminated
  - In absence of atmospheric transport, the planet would be habitable only in a narrow circle between the dark and illuminated side
  - In presence of atmospheric transport, the planet would be characterized by a very strong circulation between the two sides

Exoplanets in HZs around M-type stars: stellar activity

- The intense stellar activity, characteristic of late-type stars, may limit the habitability
  - in low-mass stars the stellar activity is more intense and long-lasting than in solar-type stars
  - strong stellar winds, one of the effects of stellar activity, tend to erode planetary atmospheres
  - high-energy charged particles accelerated by stellar magnetic fields will induce a high dose of ionizing radiation on the planet surface

- A strong planetary magnetic field and a thick atmosphere are required to mitigate these effects
- The thick atmosphere would also mitigate the temperature gradients between the illuminated and dark hemispheres, but would be characterized by very strong surface winds

Exoplanets in HZs around M-type stars: insolation in pre-main sequence

- Insolation in the pre-main sequence
  - Evolutionary times are very long in M-type stars
  - In M-type stasrs planetary formation takes place during the pre-main sequence, characterized by a significantly higher stellar luminosity than that of the main sequence
  - Planets in main-sequence HZ may have undergone an early runaway greenhouse instability during the stage of pre-main sequence

- Water content
  - Simulations of planetary formation in late-type stars predict that planets in the HZ of M-type stars would accrete dry planetesimals
  - The accreted planets would be dry, unless volatiles are adquired from distant wet planetesimals driven to the inner regions of the planetary system as a result of a dynamical instability

Search for habitable exoplanets

- Basic search criteria (in light of present-day observational limitations)
  - Insolation compatible with limits of circumstellar HZ

    Calculated from stellar luminosity and orbital parameters

    This criterion by itself guarantees the existence of an energy source sufficient to drive photosynthesis
  - Terrestrial type

    $M \lesssim 10\, M_{\mathrm{Earth}}$ or $R \lesssim 1.6\, R_{\mathrm{Earth}}$

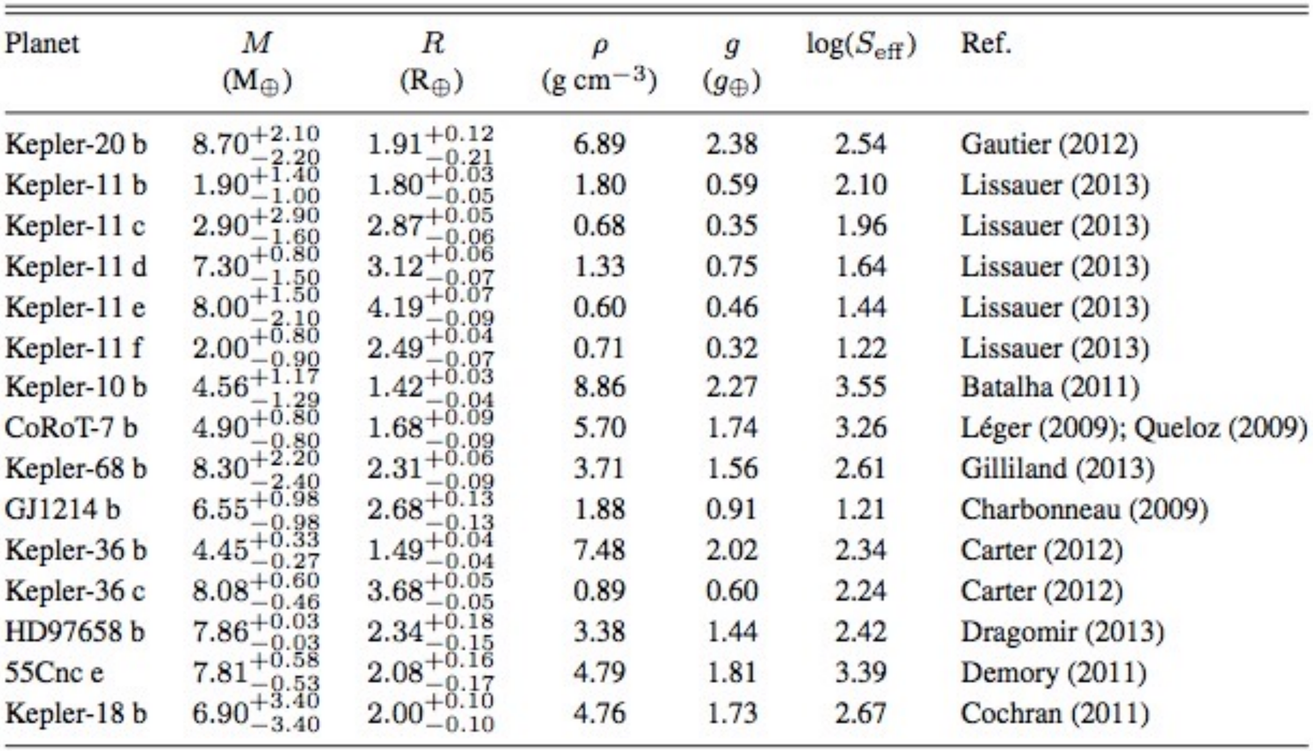
    Planets with larger mass/size adquire an extended atmosphere, yielding a non-habitable situation (similar to that of giant planets)
- Focus on surface (rather than subsurface) habitability
  - Surface habitability has the highest chance of producing atmospheric biosignatures
- Presence of water is assumed
  - at the moment hard to test experimentally

Search for habitable planets:
Rocky planets with earth-like insolation

To confirm the rocky nature we need measurements of both radius and mass

Problem: 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 HZ

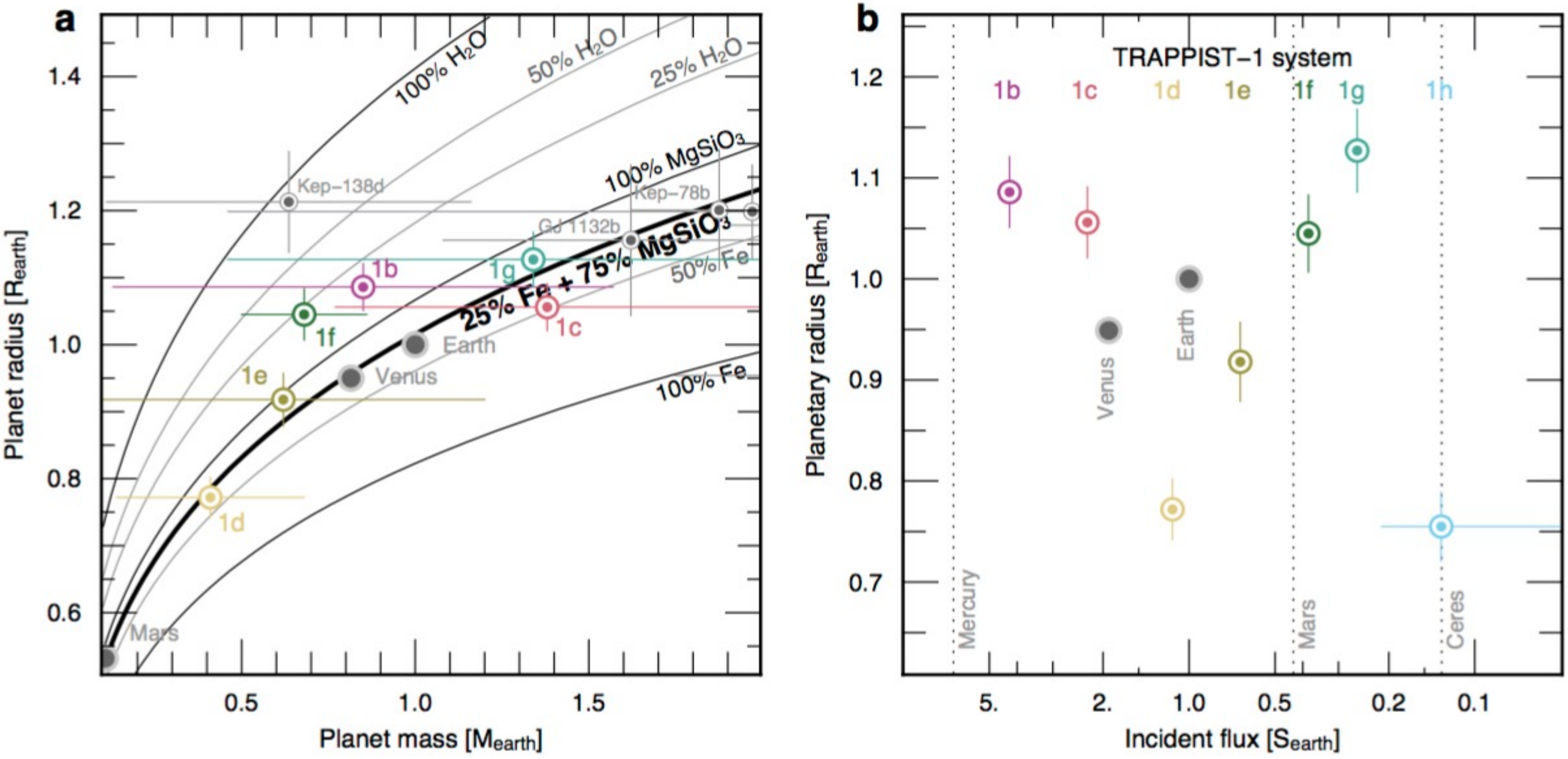


Planet	M ($M_\oplus$)	R ($R_\oplus$)	ρ (g cm^{-3})	g ($g_\oplus$)	$\log(S_{\rm eff})$	Ref.
Kepler-20 b	$8.70^{+2.10}_{-2.20}$	$1.91^{+0.12}_{-0.21}$	6.89	2.38	2.54	Gautier (2012)
Kepler-11 b	$1.90^{+1.40}_{-1.00}$	$1.80^{+0.03}_{-0.05}$	1.80	0.59	2.10	Lissauer (2013)
Kepler-11 c	$2.90^{+2.90}_{-1.60}$	$2.87^{+0.05}_{-0.06}$	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)

Terrestrial-type exoplanets in the HZ of low-mass stars

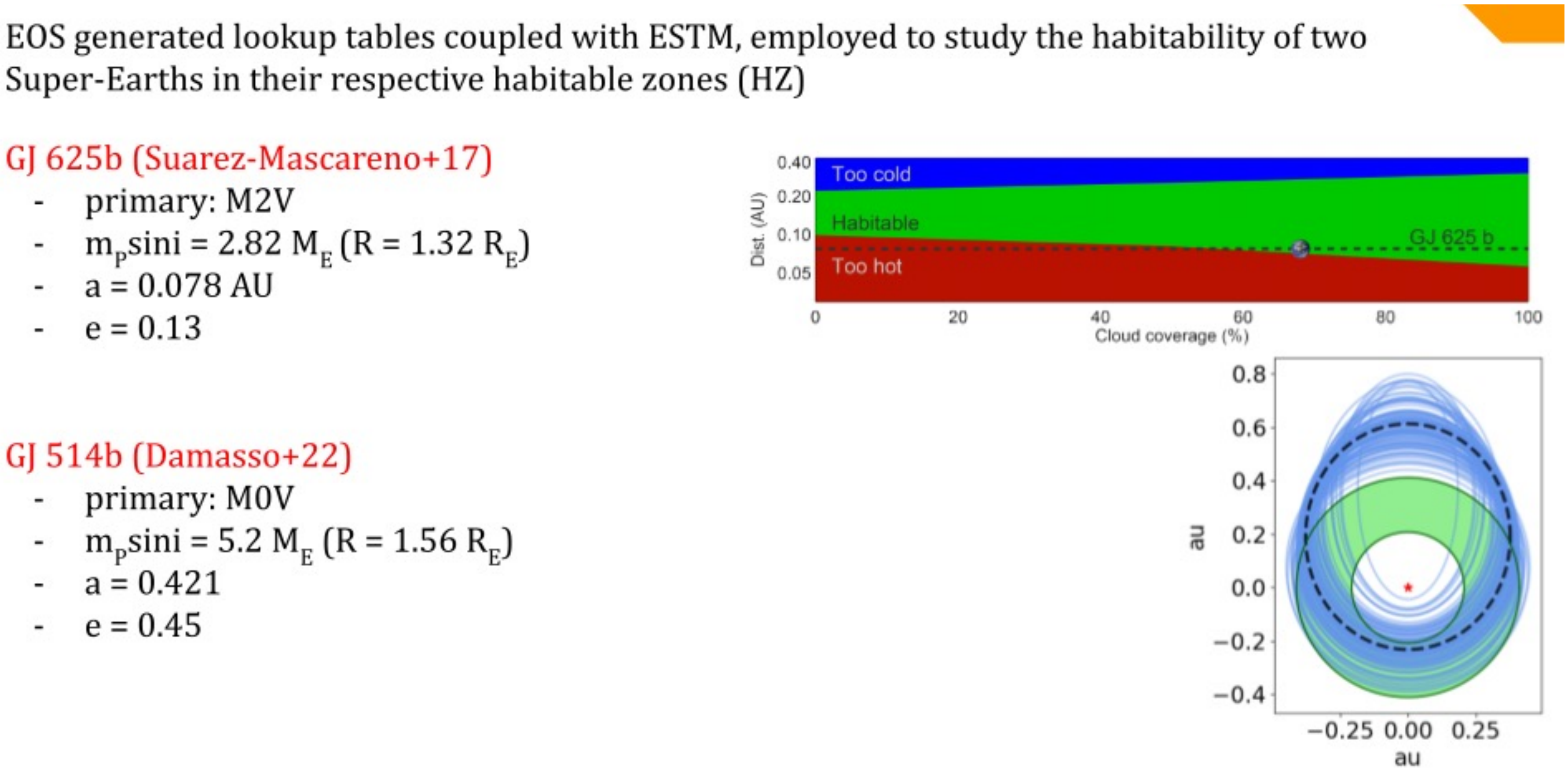
The Trappist-1 planetary system

Gillon et al. (2018)



Terrestrial-type exoplanets in the HZ of low-mass stars

- Examples of planets discovered with the Doppler method



EOS generated lookup tables coupled with ESTM, employed to study the habitability of two Super-Earths in their respective habitable zones (HZ)

GJ 625b (Suarez-Mascareno+17)

- primary: M2V
- $m_p \sin i = 2.82\ M_E$ ($R = 1.32\ R_E$)
- $a = 0.078$ AU
- $e = 0.13$

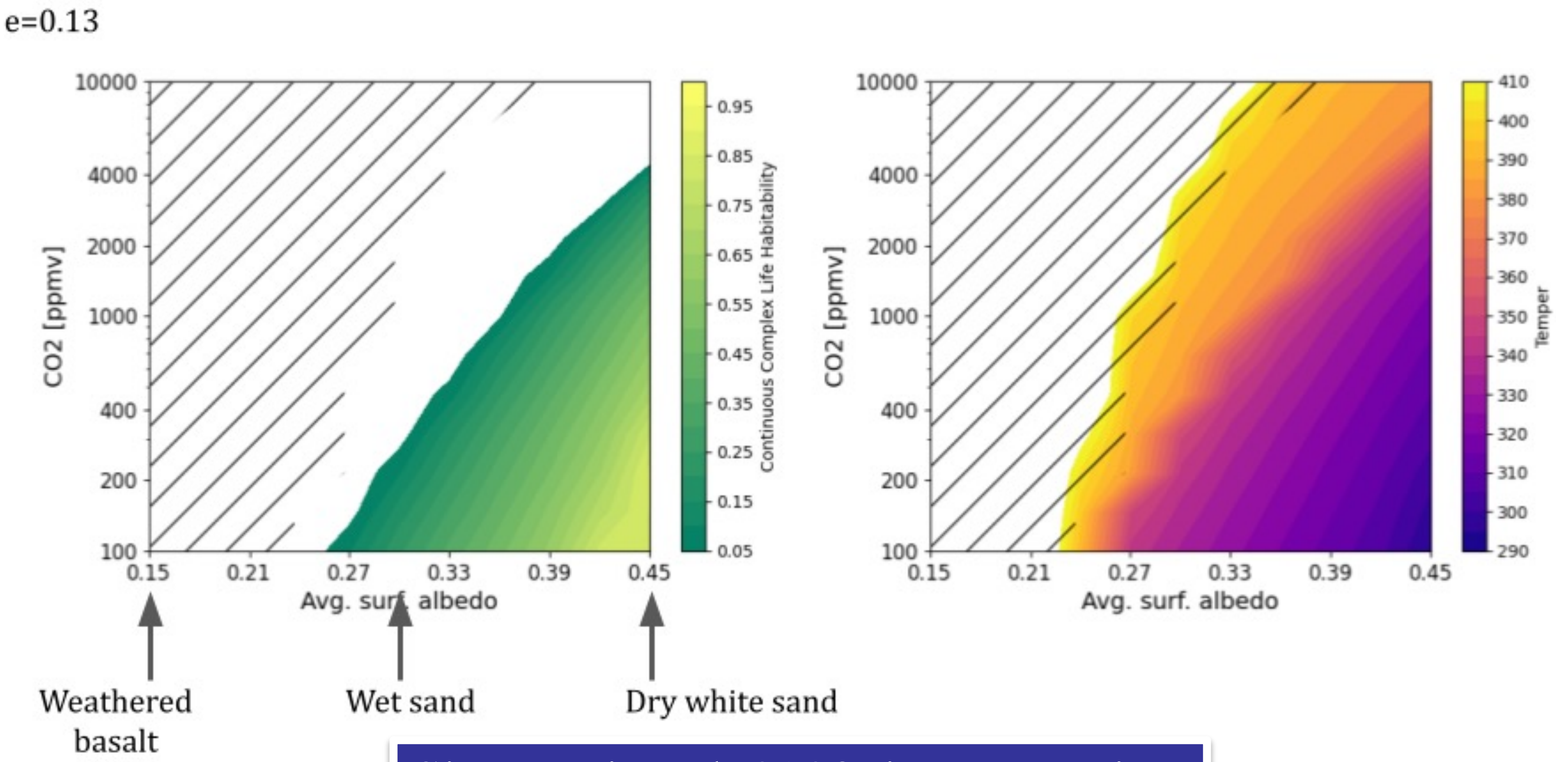
GJ 514b (Damasso+22)

- primary: M0V
- $m_p \sin i = 5.2\ M_E$ ($R = 1.56\ R_E$)
- $a = 0.421$
- $e = 0.45$

Climate simulations of exoplanets in the HZ

GJ625b (close to the inner edge of the HZ)

- Results from climate simulations performed with ESTM
- Index of habitability h_{050} (left) and global temperature (right) for different values of CO_2 partial pressure and <u>surface albedo</u>



Simonetti et al. 2023, in preparation

Climate simulations of exoplanets in the HZ

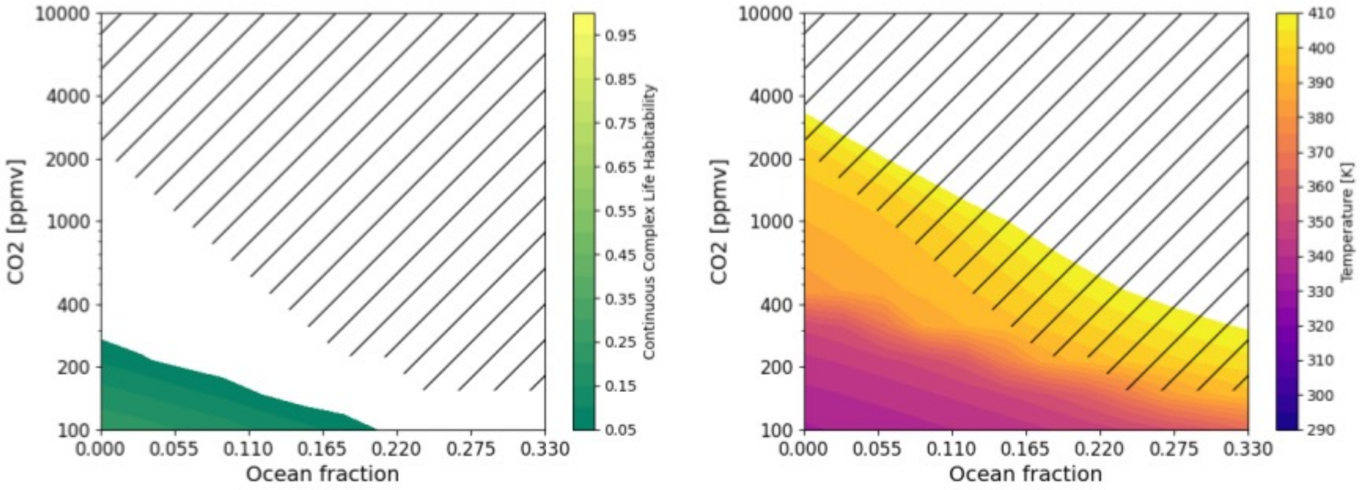
GJ625b (close to the inner edge of the HZ)

- Results from climate simulations performed with ESTM
- Index of habitability h_{050} (left) and global temperature (right) for different values of CO_2 partial pressure and ocean fraction

Different ocean fractions without moving too far away from desert conditions

Changes the surface albedo, the cloud coverage and the thermal capacity

e=0.13

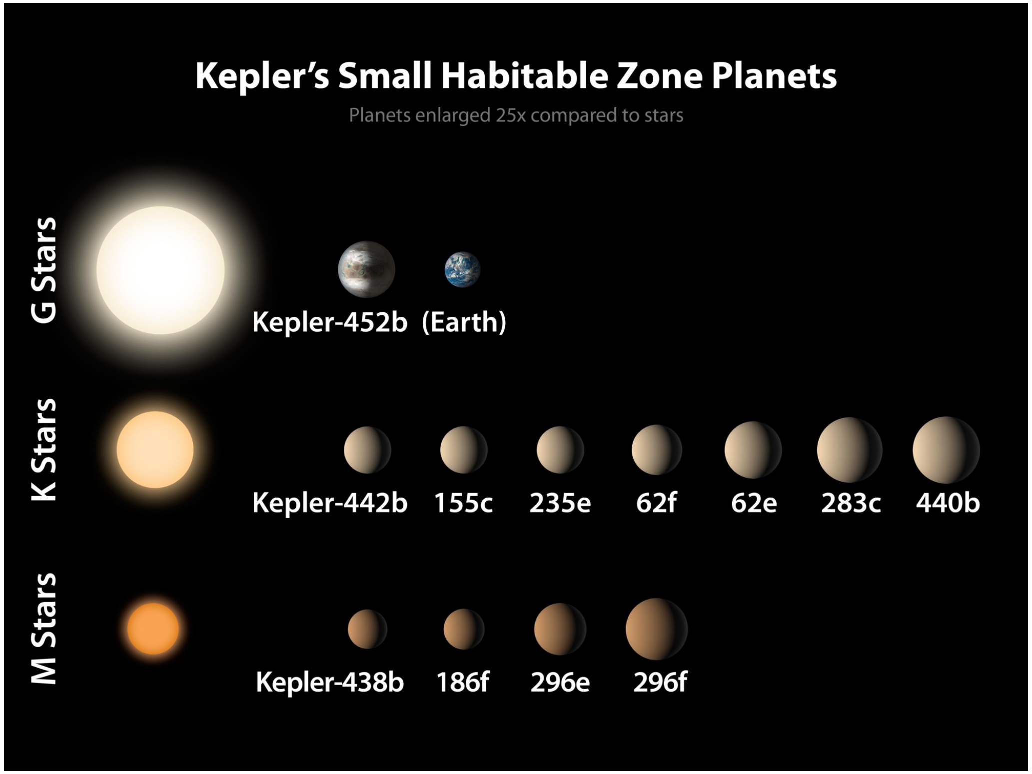


Simonetti et al. 2023, in preparation

Terrestrial-type exoplanets in the HZ discovered with the transit method

Exoplanets in the HZ can be discovered with the transit method

A few of them are found around solar-type stars (not just around M-type stars)



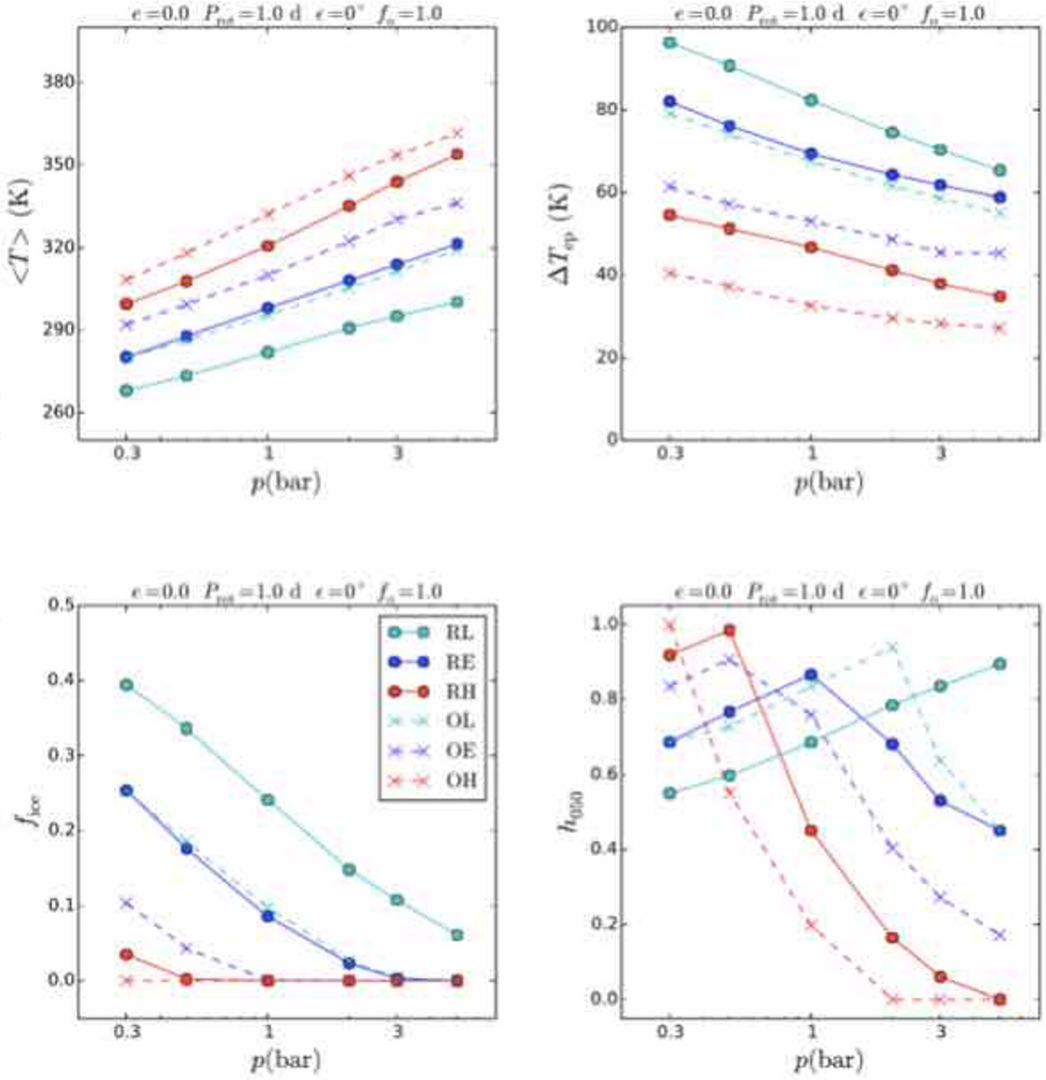
Kepler 452b

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)

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

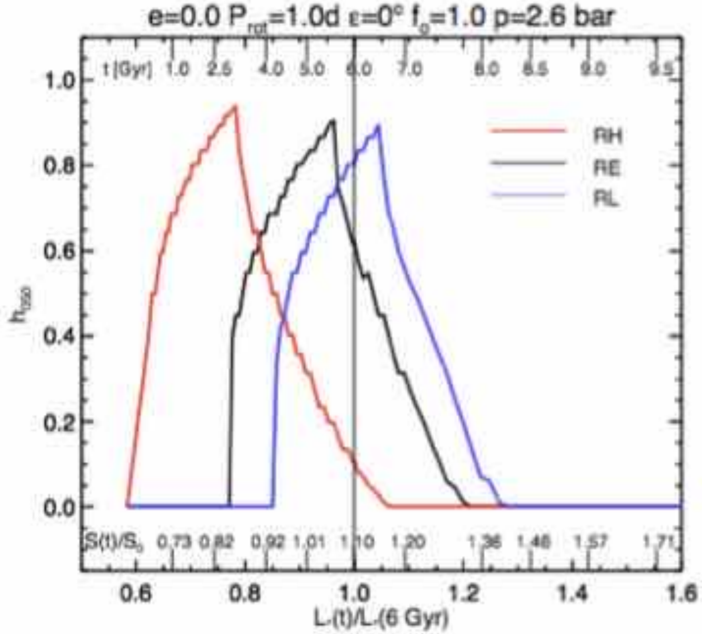


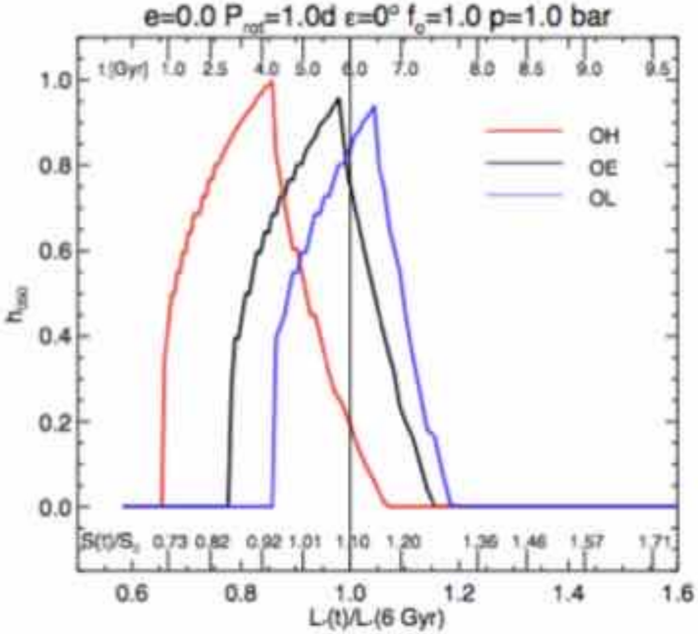
Model	$M/M_{\oplus}$	$g/g_{\oplus}$	pCO$_2$ (ppmv)	p^b (bar)
RL	4.3	1.6	10	2.6
RE	4.3	1.6	380	2.6
RH	4.3	1.6	38000	2.6
OL	2.7	1.0	10	1.0
OE	2.7	1.0	380	1.0
OH	2.7	1.0	38000	1.0

Silva et al. (2017)

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)

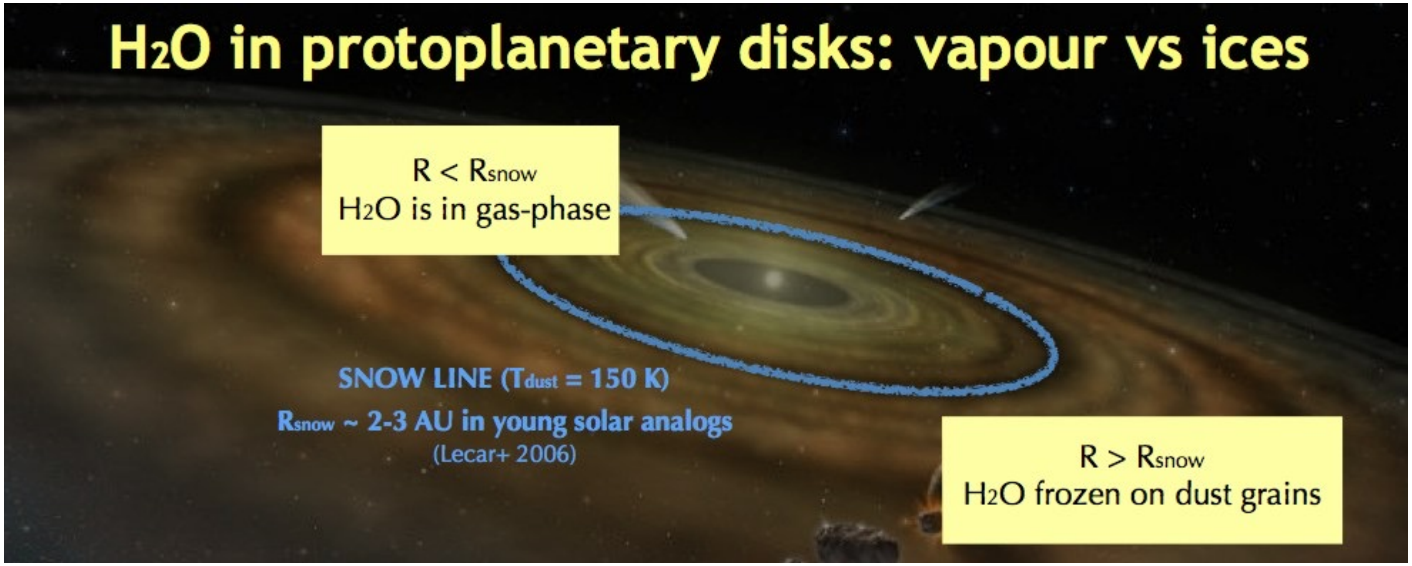
Model	$M/M_{\oplus}$	$g/g_{\oplus}$	$p\mathrm{CO_2}$ (ppmv)	p^b (bar)
RL	4.3	1.6	10	2.6
RE	4.3	1.6	380	2.6
RH	4.3	1.6	38000	2.6
OL	2.7	1.0	10	1.0
OE	2.7	1.0	380	1.0
OH	2.7	1.0	38000	1.0

Water on exoplanets in the HZ

The effective habitability of exoplanets in the HZ depends on the possibility for the planet to adquire water at the stage of planetary formation

If water cannot be adquired during planetary formation, late accretion of water-rich planetesimals should take place to provide effective habitability

Studies of the location of the “ice line” in protoplanetary disks can help to understand if planets in the HZ are able to adquire water or not



With ALMA <u>we can probe directly the location of the ice line around stars of different spectral type</u>

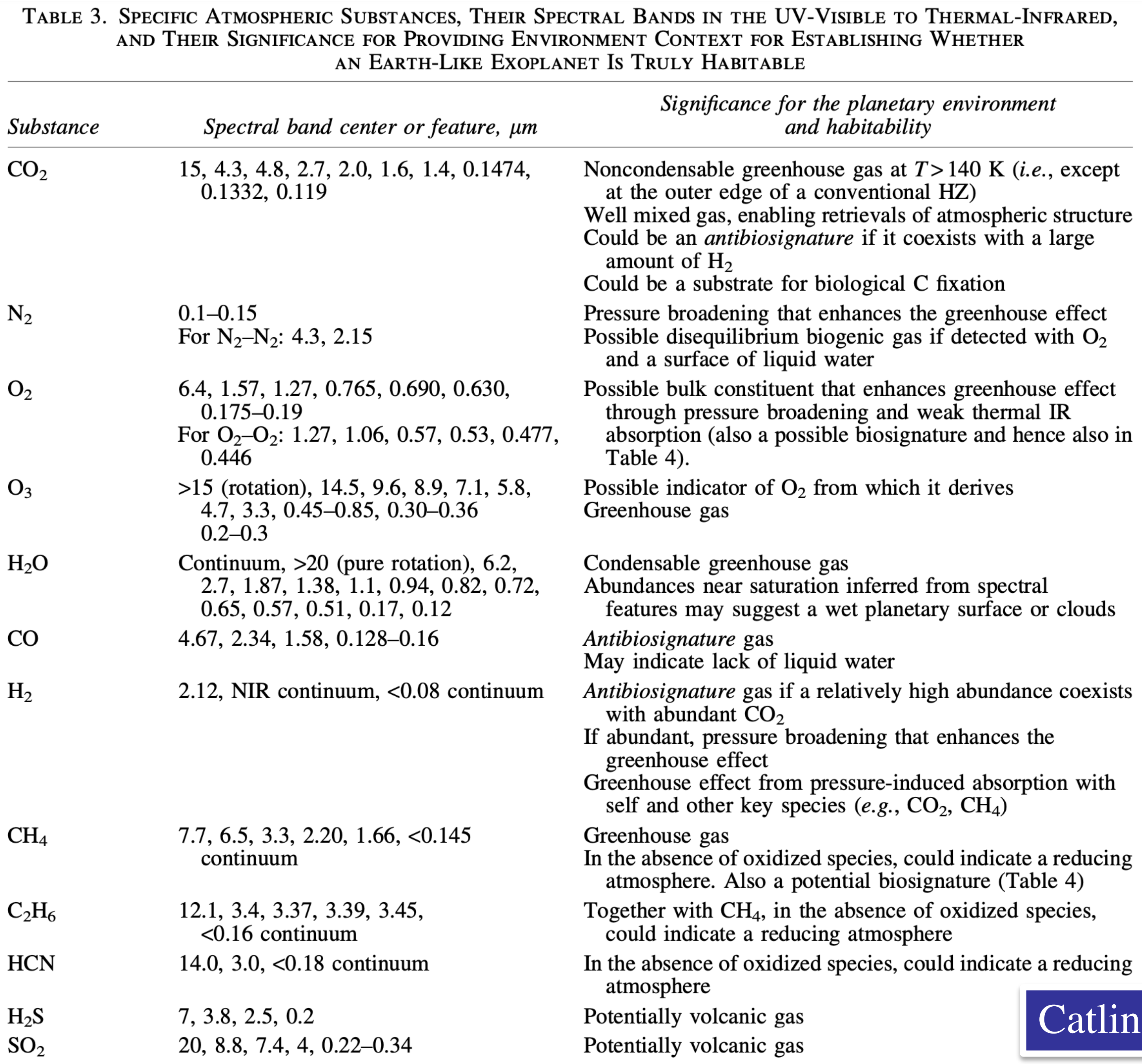


Table 3. Specific Atmospheric Substances, Their Spectral Bands in the UV-Visible to Thermal-Infrared, and Their Significance for Providing Environment Context for Establishing Whether an Earth-Like Exoplanet Is Truly Habitable

Substance	*Spectral band center or feature, μm*	*Significance for the planetary environment and habitability*
CO_2	15, 4.3, 4.8, 2.7, 2.0, 1.6, 1.4, 0.1474, 0.1332, 0.119	Noncondensable greenhouse gas at $T > 140$ K (*i.e.*, except at the outer edge of a conventional HZ) Well mixed gas, enabling retrievals of atmospheric structure Could be an *antibiosignature* if it coexists with a large amount of H_2 Could be a substrate for biological C fixation
N_2	0.1–0.15 For N_2–N_2: 4.3, 2.15	Pressure broadening that enhances the greenhouse effect Possible disequilibrium biogenic gas if detected with O_2 and a surface of liquid water
O_2	6.4, 1.57, 1.27, 0.765, 0.690, 0.630, 0.175–0.19 For O_2–O_2: 1.27, 1.06, 0.57, 0.53, 0.477, 0.446	Possible bulk constituent that enhances greenhouse effect through pressure broadening and weak thermal IR absorption (also a possible biosignature and hence also in Table 4).
O_3	>15 (rotation), 14.5, 9.6, 8.9, 7.1, 5.8, 4.7, 3.3, 0.45–0.85, 0.30–0.36 0.2–0.3	Possible indicator of O_2 from which it derives Greenhouse gas
H_2O	Continuum, >20 (pure rotation), 6.2, 2.7, 1.87, 1.38, 1.1, 0.94, 0.82, 0.72, 0.65, 0.57, 0.51, 0.17, 0.12	Condensable greenhouse gas Abundances near saturation inferred from spectral features may suggest a wet planetary surface or clouds
CO	4.67, 2.34, 1.58, 0.128–0.16	*Antibiosignature* gas May indicate lack of liquid water
H_2	2.12, NIR continuum, <0.08 continuum	*Antibiosignature* gas if a relatively high abundance coexists with abundant CO_2 If abundant, pressure broadening that enhances the greenhouse effect Greenhouse effect from pressure-induced absorption with self and other key species (*e.g.*, CO_2, CH_4)
CH_4	7.7, 6.5, 3.3, 2.20, 1.66, <0.145 continuum	Greenhouse gas In the absence of oxidized species, could indicate a reducing atmosphere. Also a potential biosignature (Table 4)
C_2H_6	12.1, 3.4, 3.37, 3.39, 3.45, <0.16 continuum	Together with CH_4, in the absence of oxidized species, could indicate a reducing atmosphere
HCN	14.0, 3.0, <0.18 continuum	In the absence of oxidized species, could indicate a reducing atmosphere
H_2S	7, 3.8, 2.5, 0.2	Potentially volcanic gas
SO_2	20, 8.8, 7.4, 4, 0.22–0.34	Potentially volcanic gas

Catling et al. 2018

Future observational perspectives:
Habitability markers in exoplanets

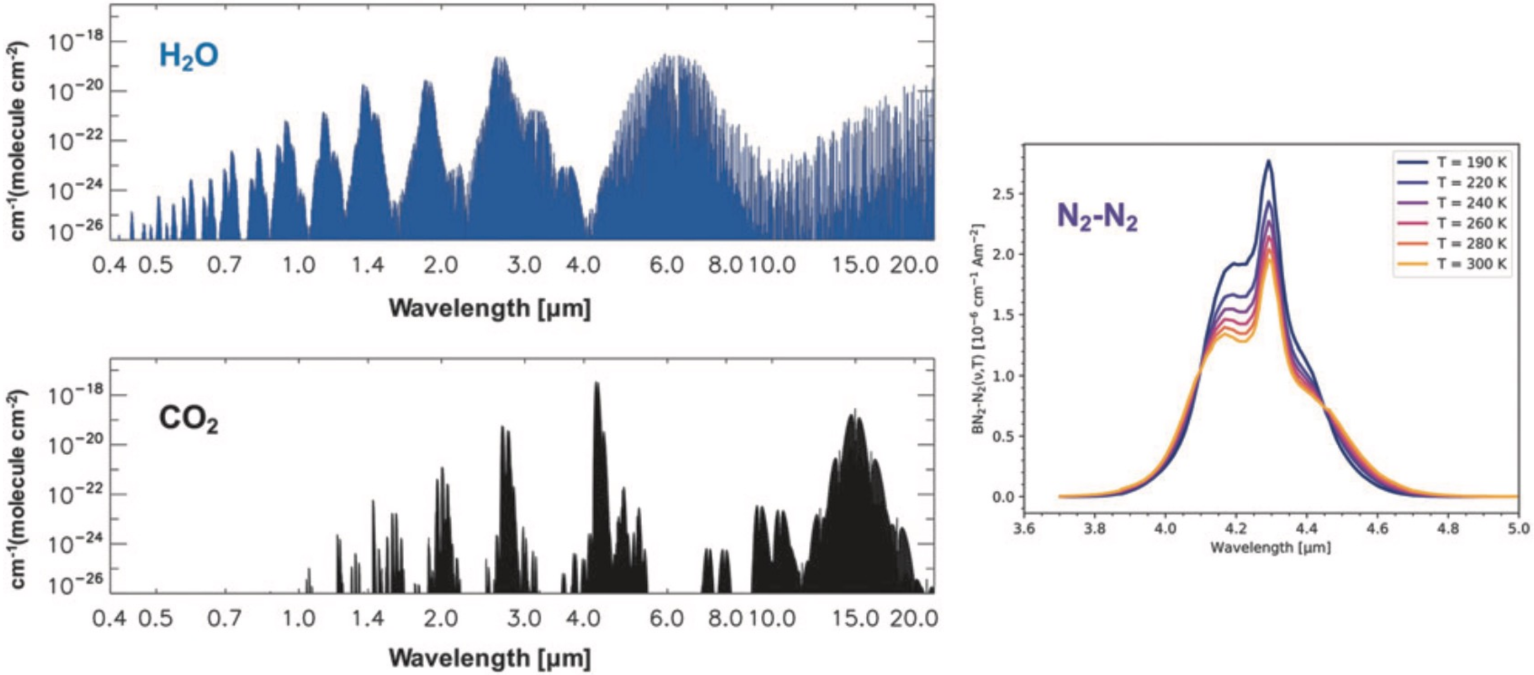


FIG. 3. Exoplanet habitability markers [$H_2O + CO_2 + (N_2)_2$]. Left: spectral line intensities for H_2O and CO_2 from the HITRAN 2012 line-by-line database (Rothman *et al.*, 2013). Right: temperature-dependent N_2-N_2 binary (collisional) absorption coefficients from a formulation by Lafferty *et al.* (1996), after a plot from Schwieterman *et al.* (2015b).

Schwieterman et al. 2018