Astrobiology
Lecture 15

Exoplanets: habitability and biosignatures

Trieste University, Academic Year 2021-2022
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Exoplanets and astrobiology

- Astrobiological studies of exoplanets are focused on:

  search for habitable exoplanets and search for biosignatures

At variance with Solar System studies, we cannot perform close-by observations and we cannot obtain samples

- Search for habitable exoplanets

The habitability of exoplanets can be assessed with climate models constrained by orbital, stellar and planetary data

In the case of exoplanets the focus is on surface habitability

Sub-surface life is expected to generate only a modest amount of atmospheric biosignatures

- Search for biosignatures

Biosignatures can be searched in the spectra of exoplanetary atmospheres

Search for habitable exoplanets

- Basic search criteria (in light of present-day observational limitations)
  - Insolation compatible with "habitable zone"

    Calculated from stellar luminosity and orbital parameters

    This criterion by itself guarantees the existence of an energy source sufficient to drive photosynthesis (the energy requirements for photosynthesis are extremely low)
  - Terrestrial type

    $M \lesssim 10\ M_{\mathrm{Earth}}$ or $R \lesssim 2\ R_{\mathrm{Earth}}$

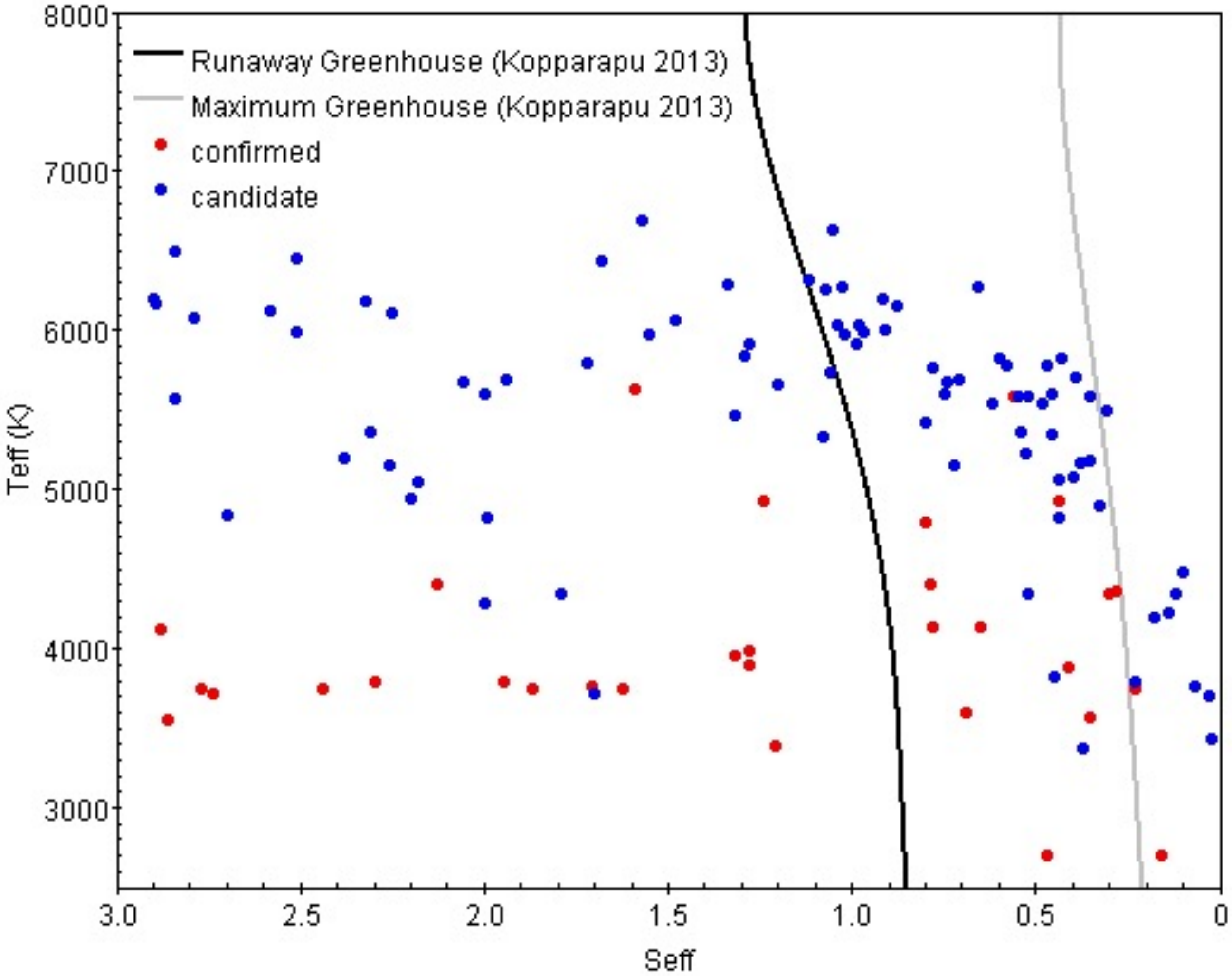
    Planets with larger mass/size adquire an extended atmosphere, yielding a non-habitable situation (similar to that of giant planets)

- Presence of water is assumed
  - In principle, it can be tested with spectroscopic observations of exoplanetary atmospheres

Search for habitable exoplanets

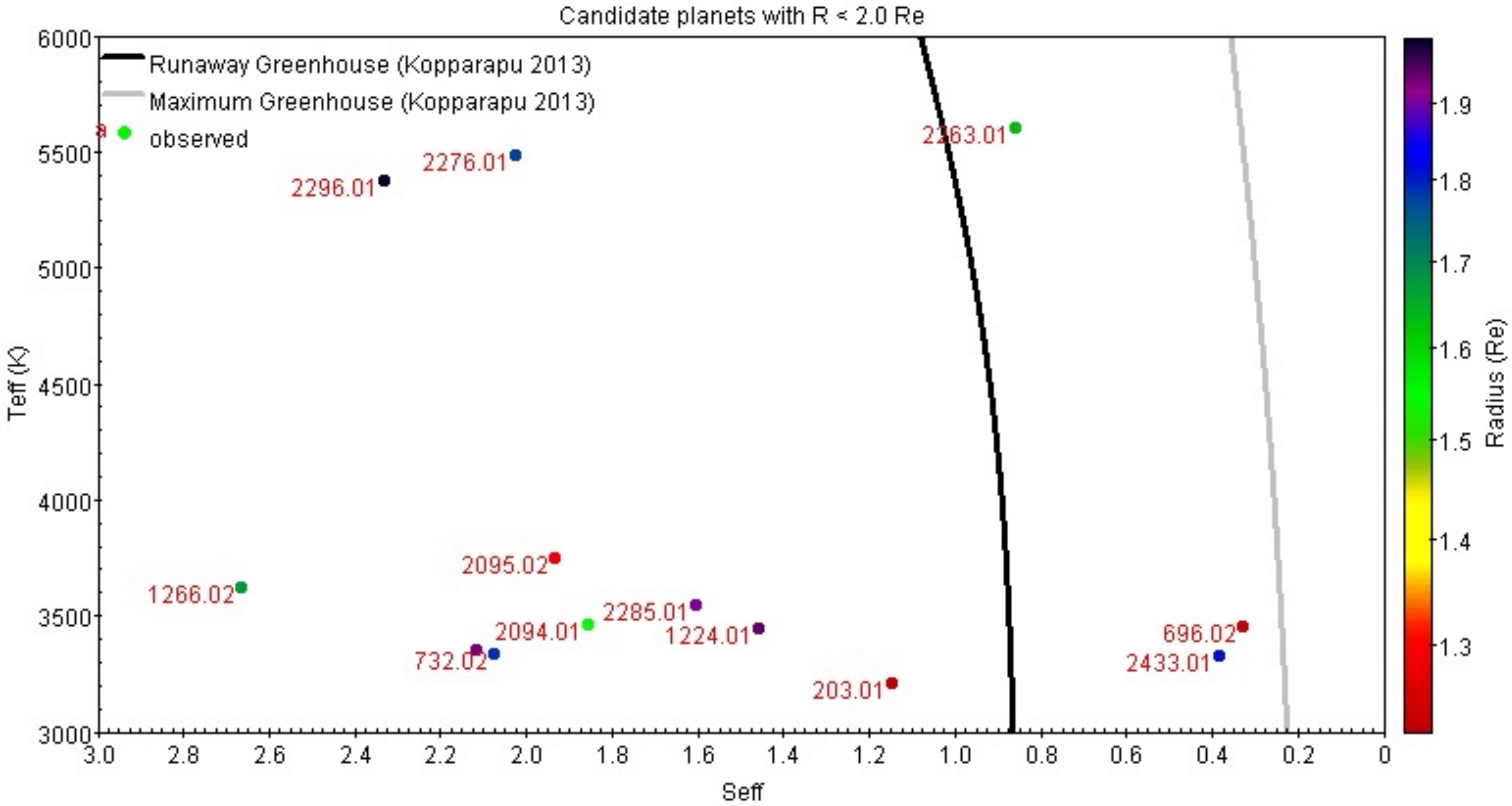
Confirmed and candidate Kepler exoplanets

in the proximity of the Habitable Zone



Search for habitable exoplanets

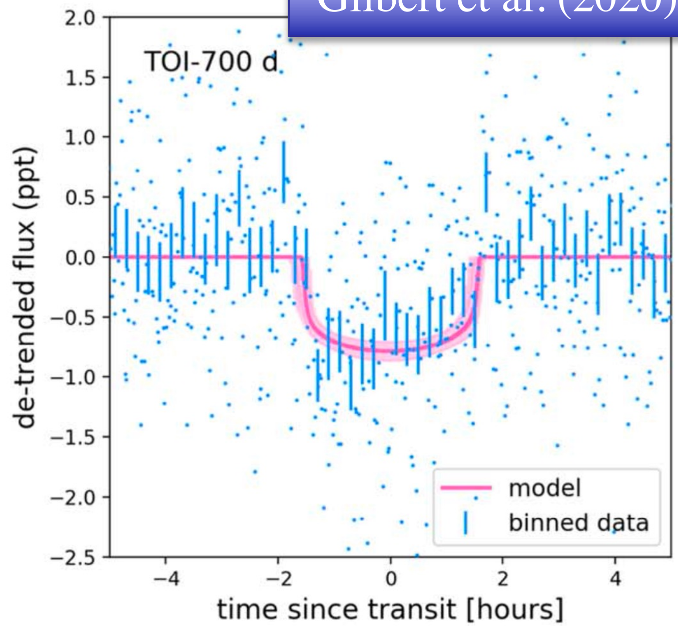
Candidate TESS exoplanets

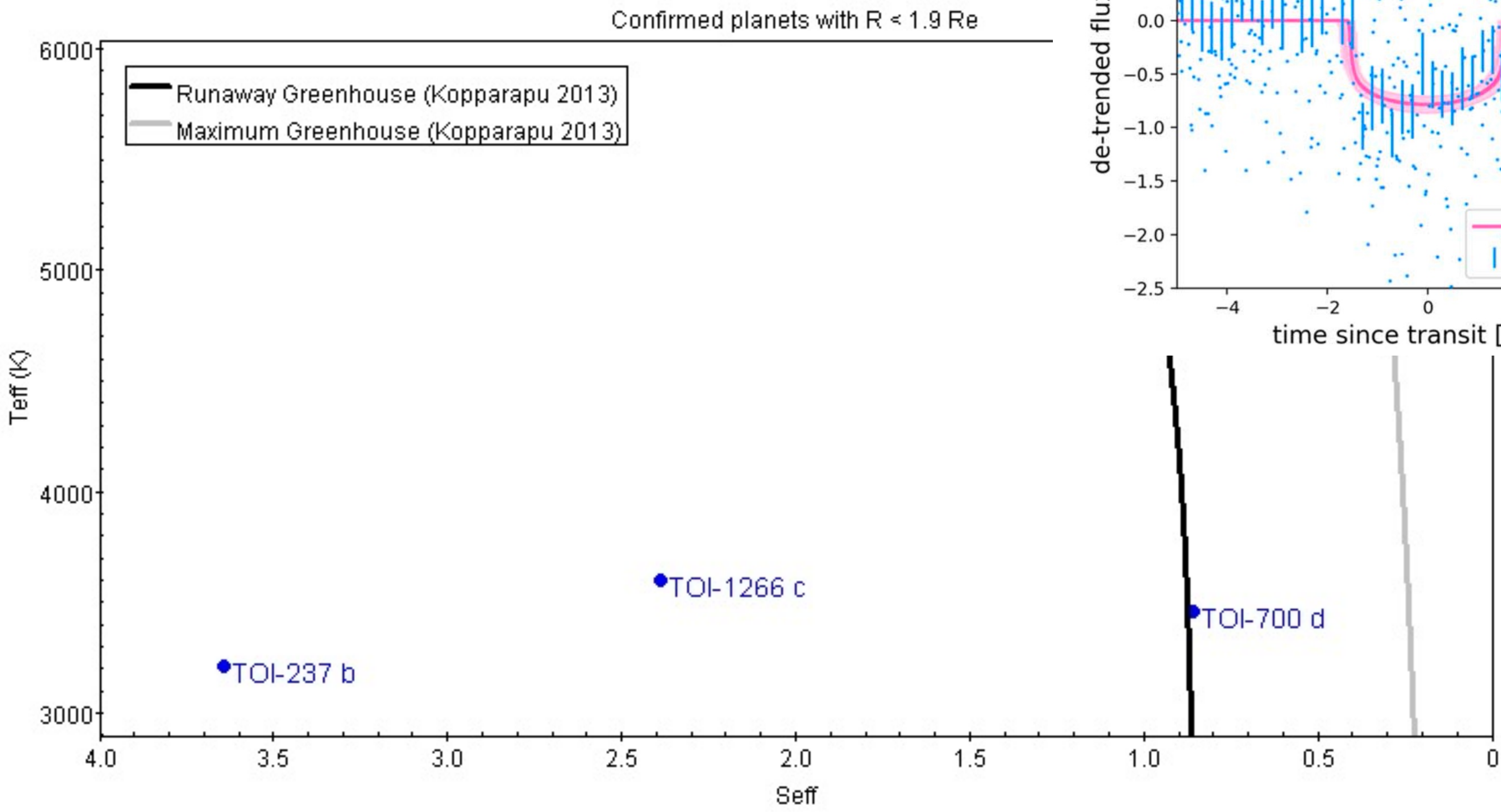


Search for habitable exoplanets

Confirmed TESS exoplanets

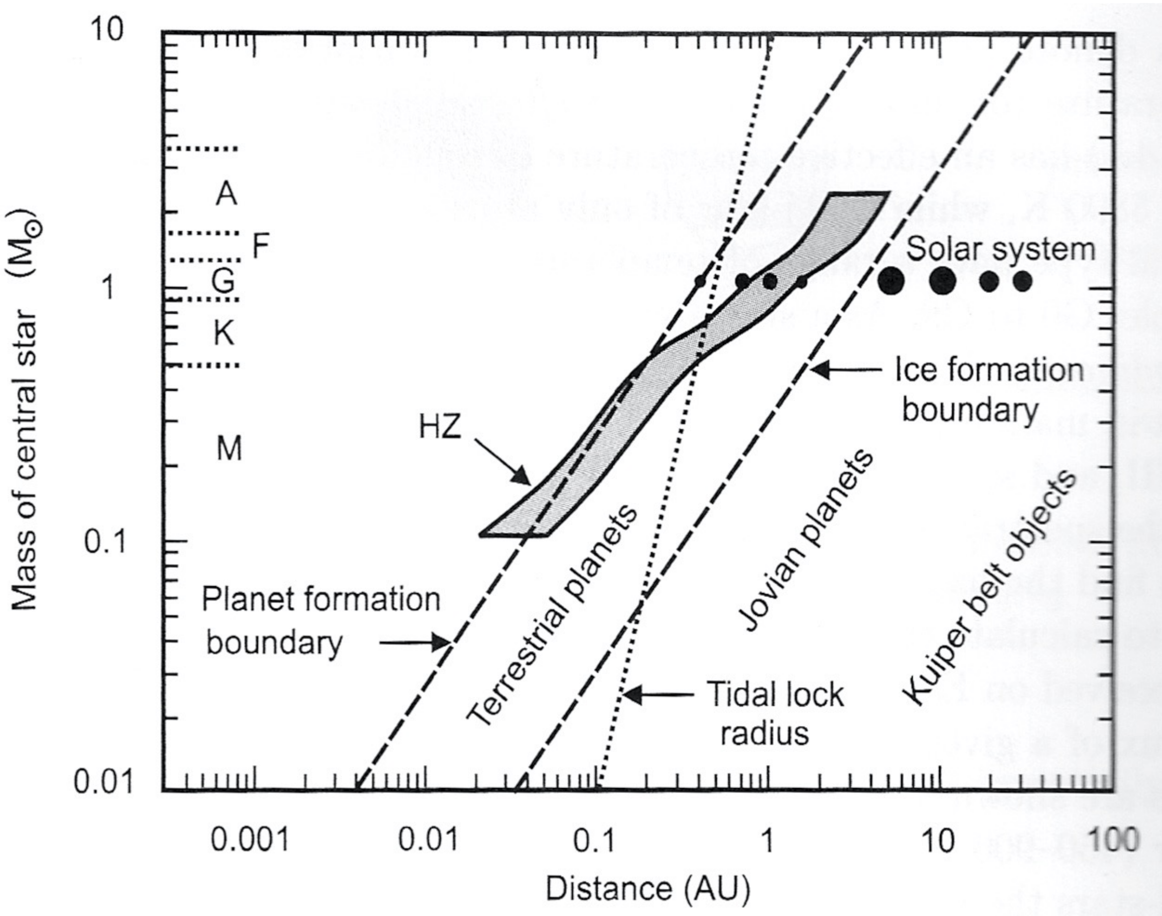
Gilbert et al. (2020)





Habitable planets: selection bias in favour of M-type stars

The luminosity and spectral type of the host star affects the location of the habitable zone, which gets closer to the star for M-type host stars



Habitable planets: selection bias in favour of M-type stars

- 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 a 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

Habitable planets: selection bias in favour of M-type stars

- Transit method

The geometrical probability increases with decreasing semi-major axis

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

Since habitable planets around late-type stars are located at small a, the geometrical probability is higher for host stars of late spectral type

Also the depth of the transit signal favours stars with smaller radii.

In practice, among main-sequence stars, favours M-type stars

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

Habitability around M-type stars

Planets in the habitable zone around M-type stars
are affected by several problems:
tidal locking, stellar activity, water delivery

Habitability around M-type stars: tidal locking

- The vicinity to the star leads to strong tidal interactions which slow down the planetary rotation period
- Eventually, the planetary orbital period may become synchronized with the 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 could 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

Habitability around M-type stars: stellar activity

- The intense stellar activity of late-type stars, may limit the habitability
  - in low-mass stars stellar activity is more intense and long-lasting than in solar-type stars
  - strong stellar winds 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

Habitability around M-type stars: water delivery

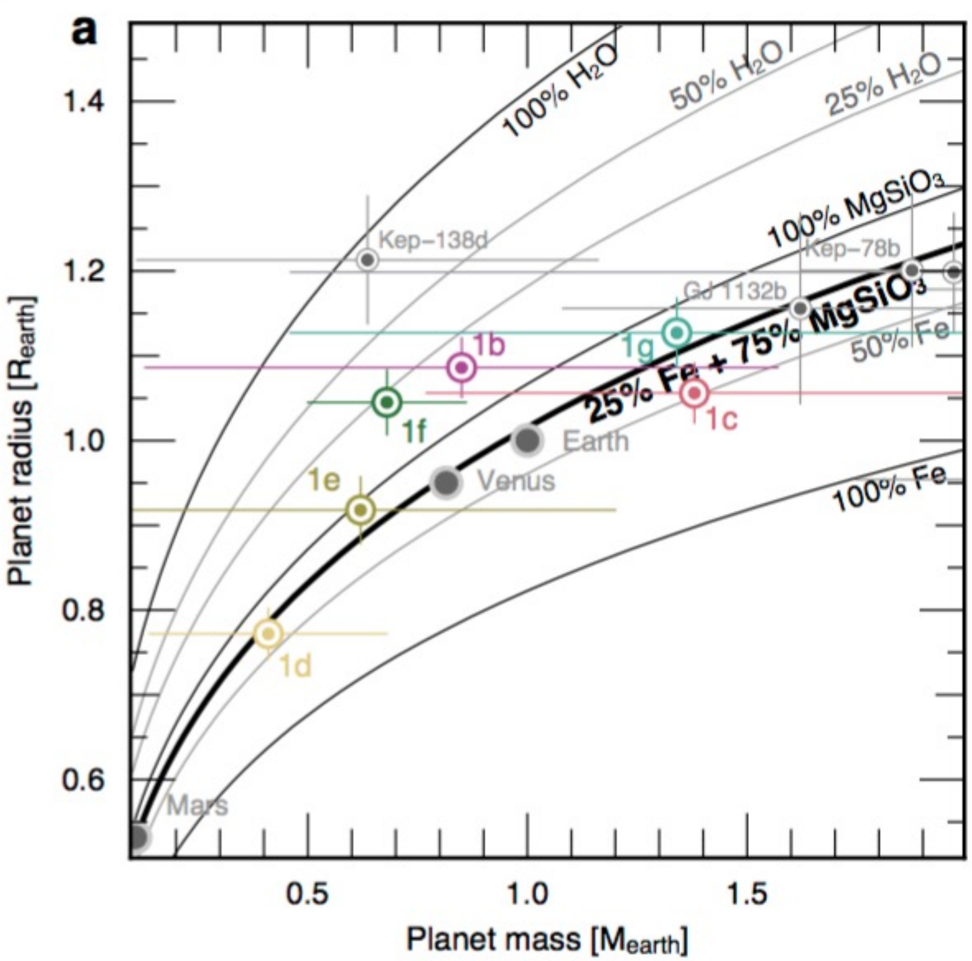
- Planets in the habitable zone of M-type stars could be dry
  - Simulations of planetary formation in late-type stars predict that planets in the habitable zone of M-type stars would accrete dry planetesimals
  - The accreted planets would be dry, unless volatiles are adquired from distant wet planetesimals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

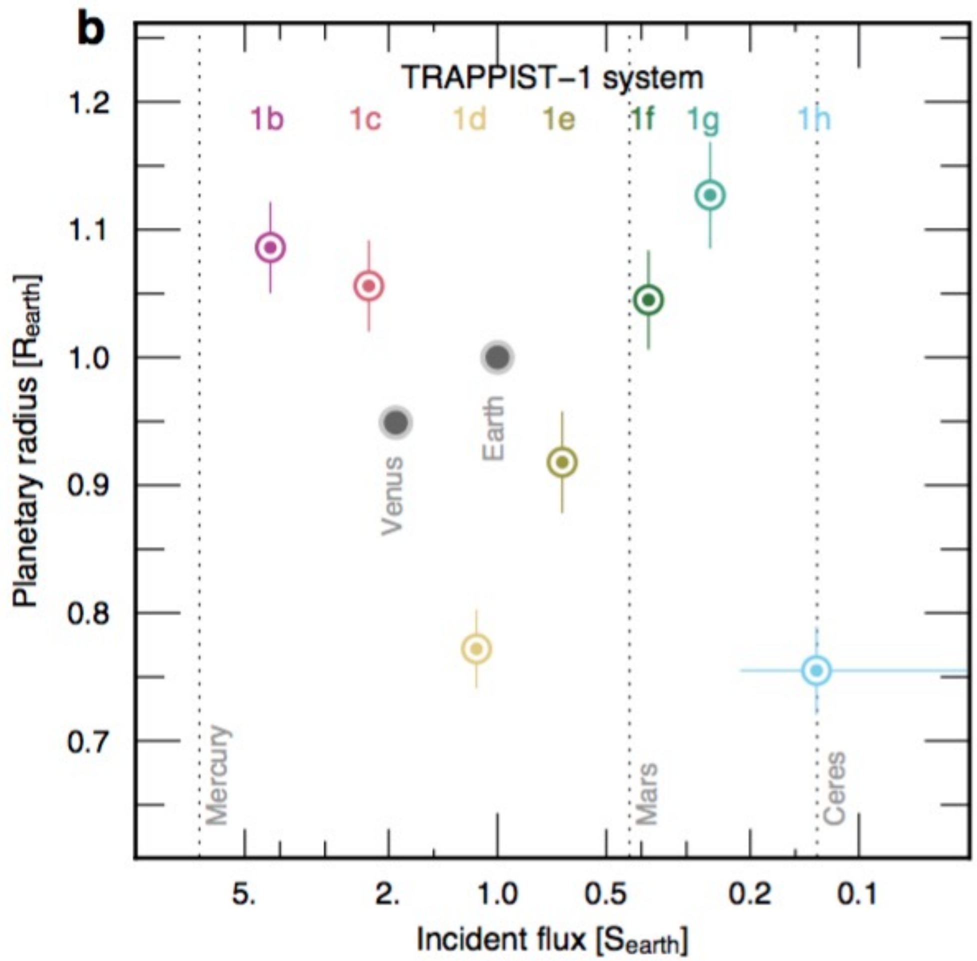
- None of the above problems completely prevents the habitability around M-type stars
  - For instance, tidal locking could drive a 3:2 spin-orbit resonance (rather than 1:1 resonance), as in the case of Mercury; in this case all the planetary surface would be illuminated during each orbit

The Trappist-1 planetary system

Gillon et al. (2018)

Habitable, rocky planets around an extremely cool central star





Tess 700 planetary system

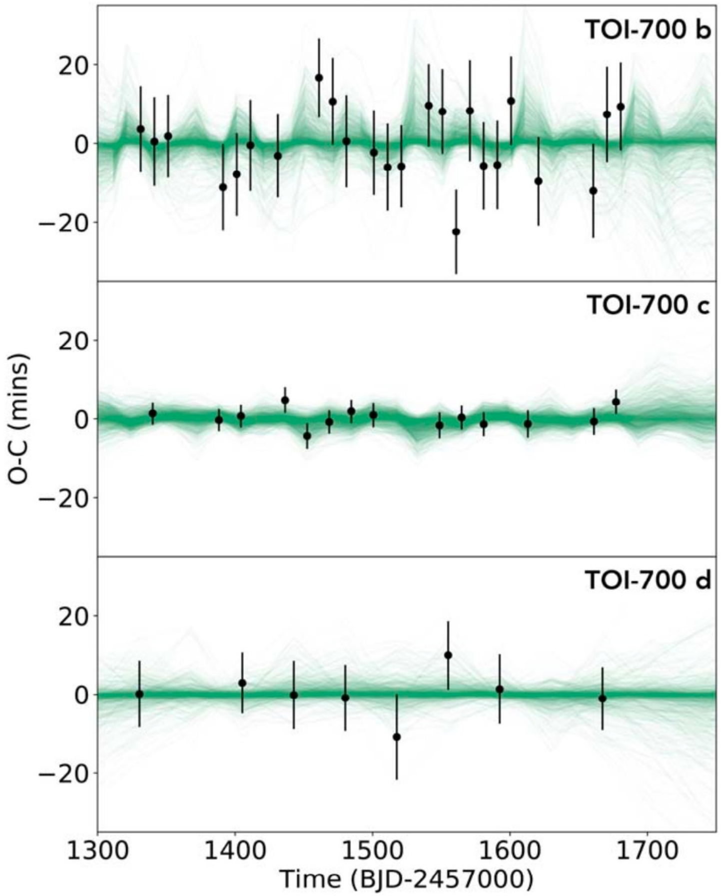
Gilbert et al. (2020)

Derived Parameters

TOI-700 b			
Period (days)	9.97701	0.00024	0.00028
R_p/R_*	0.0221	0.0011	0.0012
Radius ($R_\oplus$)	1.010	0.094	0.087
Insolation	5.0	1.1	0.9
a/R_*	34.8	1.9	1.9
a (au)	0.0637	0.0064	0.0060
Inclination (deg)	89.67	0.23	0.32
Duration (hr)	2.15	0.15	0.7
TOI-700 c			
Period (days)	16.051098	0.000089	0.000092
R_p/R_*	0.0574	0.0032	0.0026
Radius ($R_\oplus$)	2.63	0.24	0.23
Insolation	2.66	0.58	0.46
a/R_*	47.8	2.7	2.6
a (au)	0.0925	0.0088	0.0083
Inclination (deg)	88.90	0.08	0.11
Duration (hr)	1.41	0.14	0.09
TOI-700 d			
Period (days)	37.4260	0.0007	0.0010
R_p/R_*	0.0262	0.0014	0.0015
Radius ($R_\oplus$)	1.19	0.11	0.11
Insolation	0.86	0.19	0.15
a/R_*	84.0	4.7	4.6
a (au)	0.163	0.015	0.015
Inclination (deg)	89.73	0.15	0.12
Duration (hr)	3.21	0.27	0.26

Table 4
Photodynamic Derived Parameters

Parameter	Mode	$+1\sigma$	-1σ
TOI-700 b			
R_p ($R_\oplus$)	1.041	+0.088	−0.097
M_p ($M_\oplus$)	0.42	+2.5	−0.42
ρ_p (g cm^{-3})	2.2	+12.1	−2.2
TOI-700 c			
R_p ($R_\oplus$)	2.66	+0.26	−0.24
M_p ($M_\oplus$)	1.1	+5.4	−1.1
ρ_p (g cm^{-3})	0.3	+1.6	−0.3
TOI-700 d			
R_p ($R_\oplus$)	1.22	+0.14	−0.10
M_p ($M_\oplus$)	1.0	+4.1	−1.0
ρ_p (g cm^{-3})	3.1	+13.1	−3.1



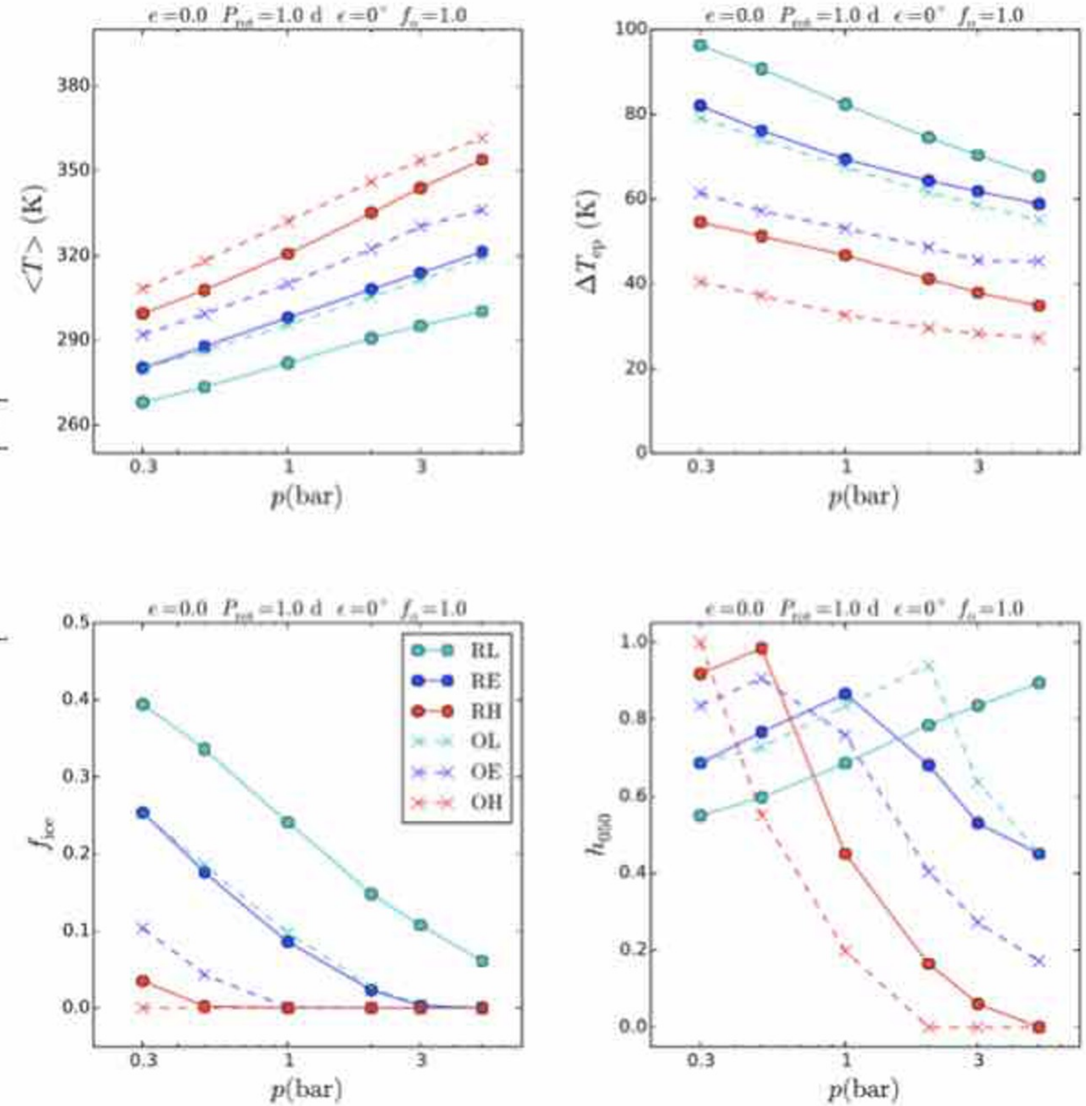
Kepler 452b

Habitable (possibly rocky planet) around a solar-type star

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)



Continuous habitability of exoplanets
Long-term persistence of habitability conditions

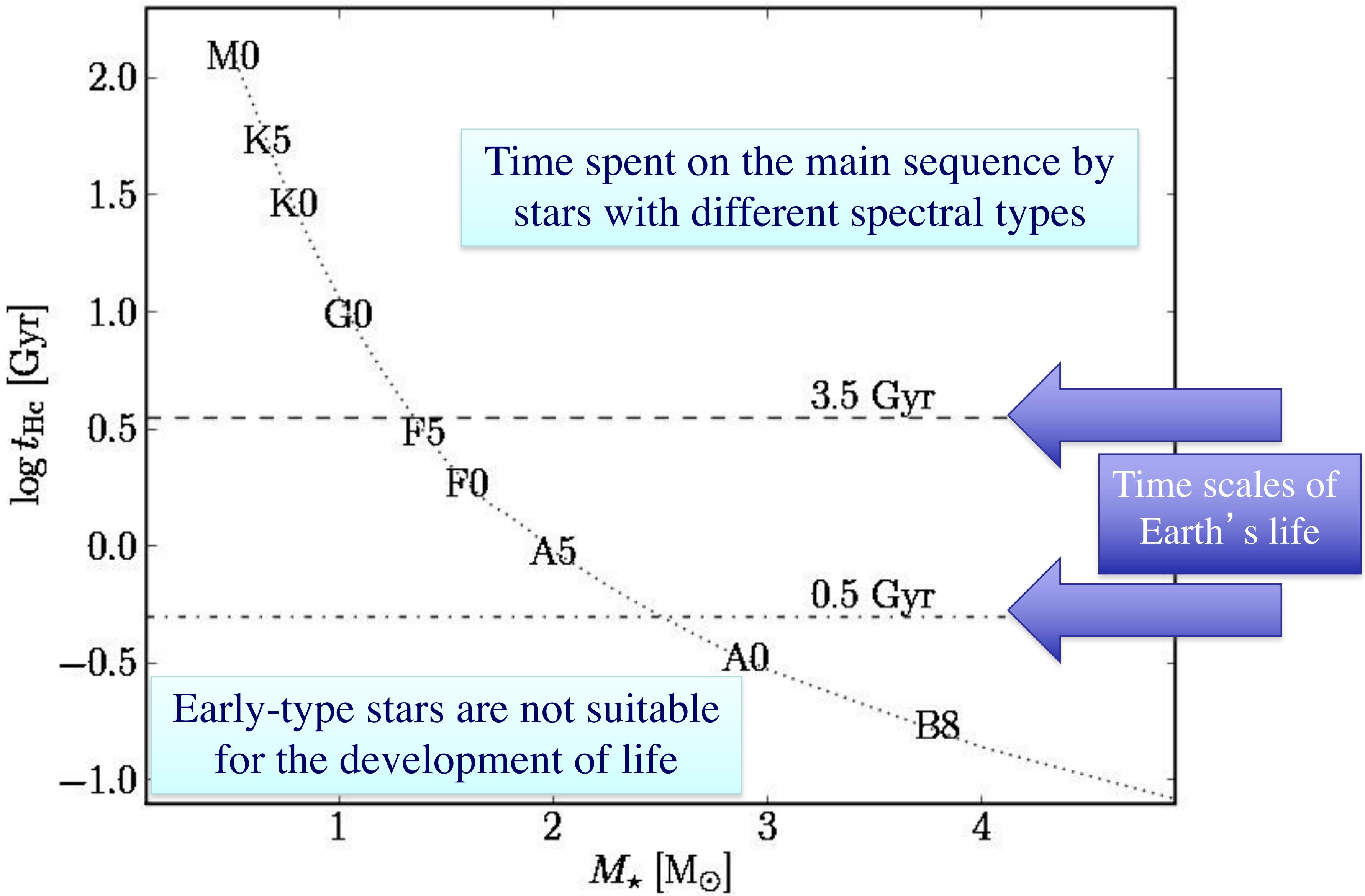
Based on the example of the Earth,
life evolution takes some billon years to produce advanced forms of life

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 is influenced by:

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

Continuous habitability and spectral type of the host star



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

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

Observations of exoplanet atmospheres

Exoplanet atmospheres can be studied with different methods

– Direct imaging

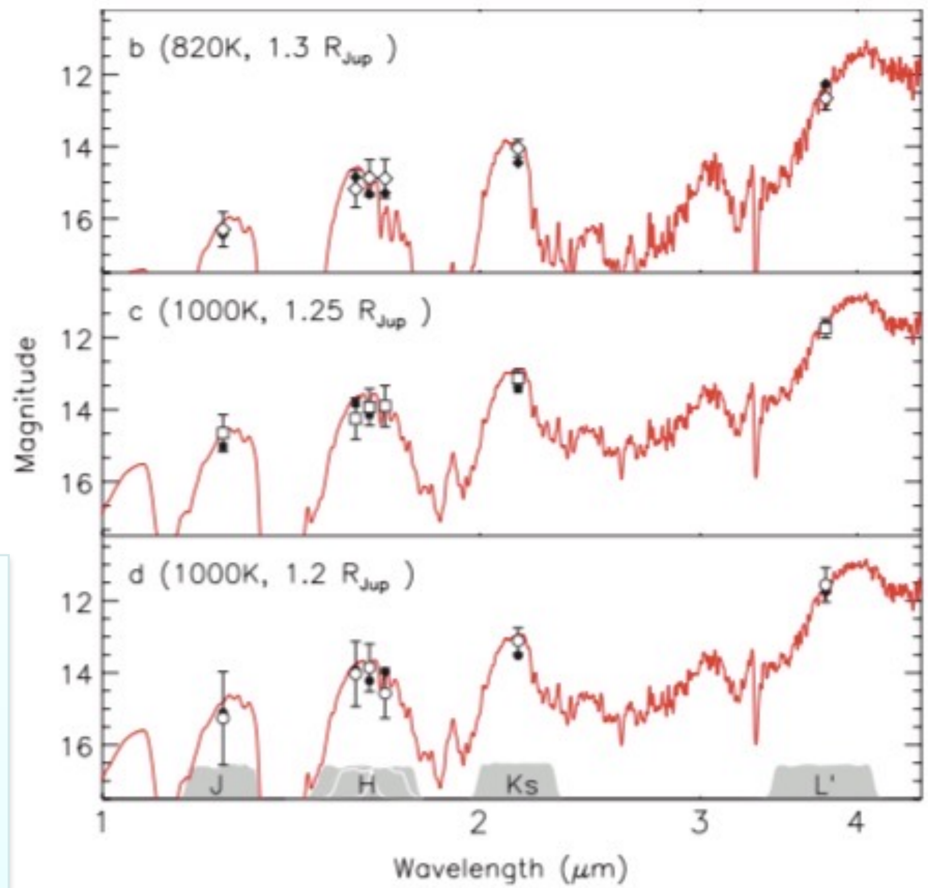
  Photometry in different spectral bands or spectroscopy of the intrisic planetary emission can constrain models of atmospheric spectra

– Primary transits

  The atmospheric spectrum of the planet can be observed in transmission

Photometry of planetary atmospheres from direct imaging

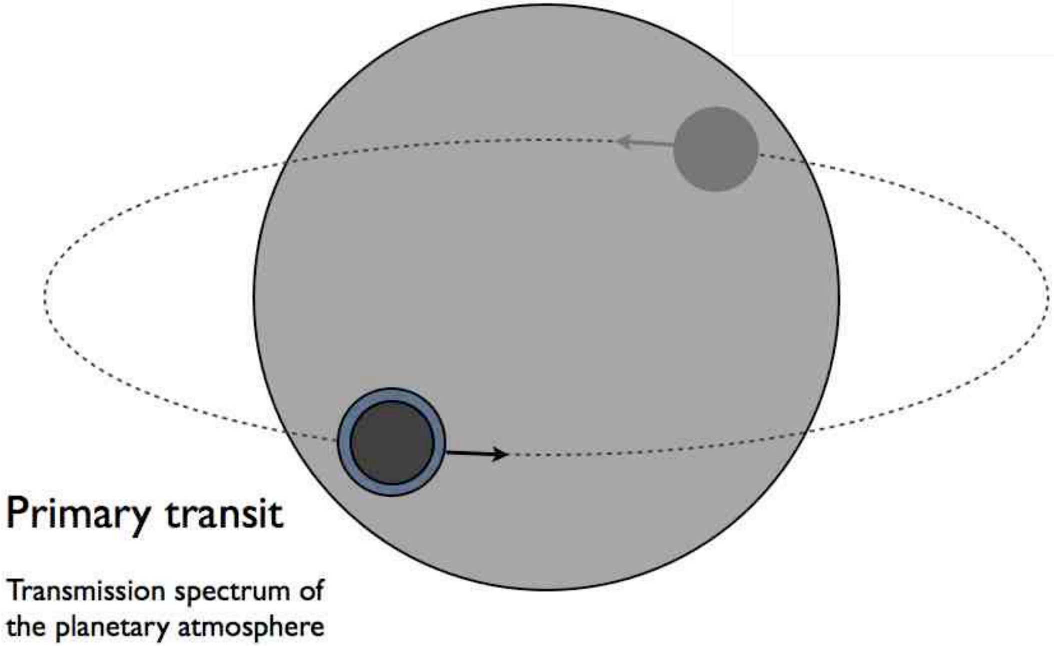
Fig. 5. Synthetic spectra from model atmospheres containing clouds located between 10 and 0.1 bar of pressure are compared to the measured fluxes (with 3-σ error bars) for HR 8799 b, c, and d. Response curves for each filter band pass are indicated along the *x* axis. The predicted magnitudes from the synthetic spectra, averaged over the filter passbands, are shown by the filled symbols.



Example: planetary system detected with direct imaging
HR 8799 b, c, d (Marois et al. 2008)
$M = 7, 10, 10\ M_J$ - $a = 68, 38, 24$ AU

Infrared bands

Transmission spectrum of planetary atmospheres



Due to the spectral dependence of the atmospheric absorption, the radius of the planet (measured with the transit method) will vary as a function of wavelength

The radius will be larger at wavelengths were the atmosphere is more absorbing

In this way, it is possible to obtain an atmospheric transmission spectrum from the observed wavelength dependence of the radius, $R_p = R_p(\lambda)$

Absorption spectroscopy of planetary atmospheres

The atmospheric absorption signal scales with the scale-height of the atmosphere, h, and the planet radius, R_p

$$\delta I \sim \frac{2\,h\,R_\mathrm{p}}{R_*^2}$$

Detection bias favours stars with smaller radii

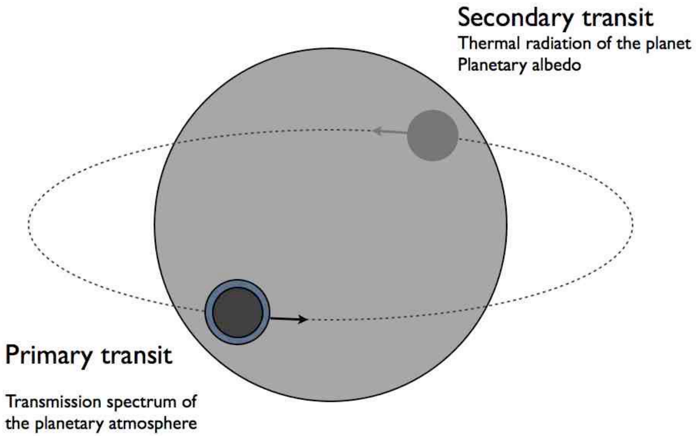
Gaseous giants give the strongest signal, for a given type of star

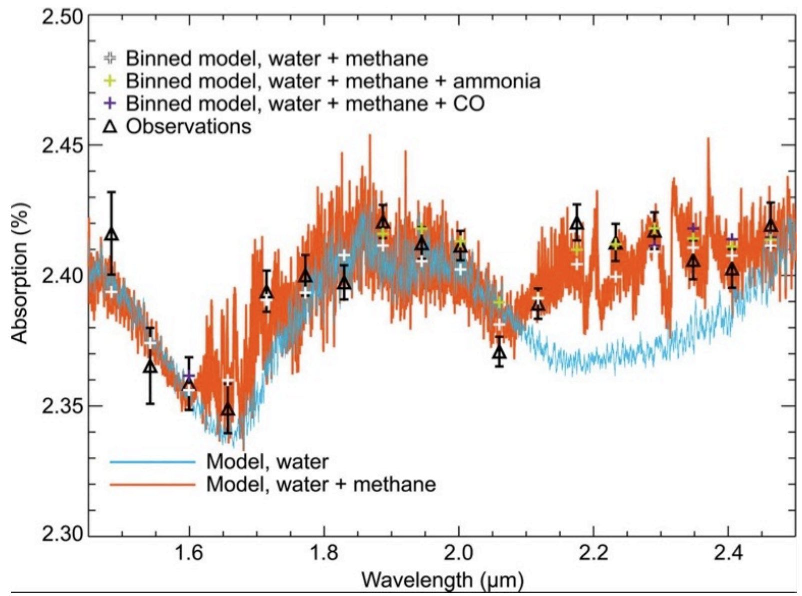
- e.g. Tinetti et al. (2007)

Space-born instrumentation optimized for the infrared band is particularly important for this type of observation

- e.g. HST, Spitzer

Searching for atmospheric biosignatures in exoplanets





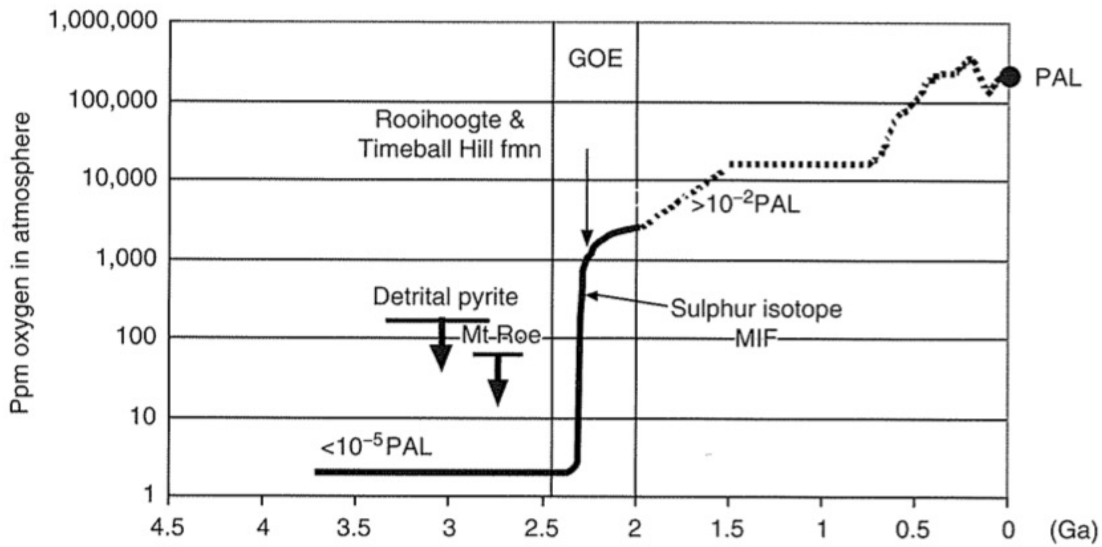
The problem of searching for atmospheric biosignatures is two-fold:

(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

Atmospheric oxygen as a biosignature

Based on the evolution of Earths atmospheric composition, oxygen is a promising biomarker for exoplanet atmospheres



If oxygen is found in exoplanet atmospheres, a calculation of equilibrium abundances of all observed molecular species should be carried out: deviations from equilibrium abundances would be a signature of life

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

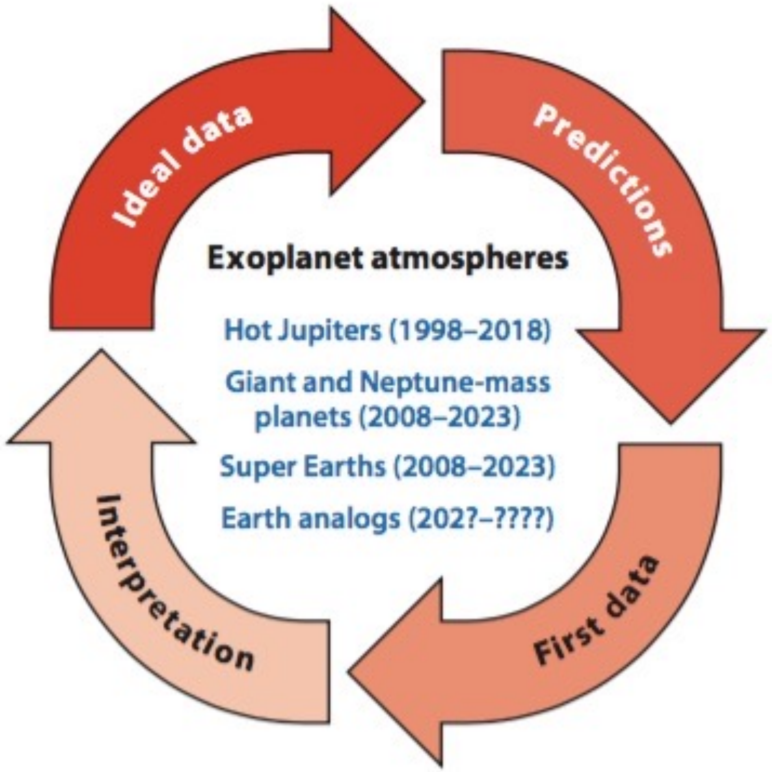
Example: Earth's atmosphere has oxygen (a highly oxidized species) and methane (a very reduced species) several orders of magnitude out of thermochemical redox equilibrium

Future observations of planetary atmospheres

Atmospheres of super-Earths are starting to become feasible and will be common with next generation instrumentation

- A large variety of bulk and atmospheric composition not found in the Solar System is expected (e.g., ocean planets)

Earth-like, thin atmospheres are beyond the detection limits expected for the projects currently under development



Transmission Spectroscopy Metric

Kempton et al. (2018)

$$\mathrm{TSM} = (\text{Scale factor}) \times \frac{R_p^3\, T_{\mathrm{eq}}}{M_p\, R_*^2} \times 10^{-m_J/5}. \qquad (1)$$

The quantities in Equation (1) are defined as follows:

1. R_p: the radius of the planet in units of Earth radii,
2. M_p: the mass of the planet in units of Earth masses, which, if unknown, should be calculated using the empirical mass–radius relationship of Chen & Kipping (2017) as implemented by Louie et al. (2018),

$$M_p = 0.9718\, R_p^{3.58} \quad \text{for } R_p < 1.23 R_\oplus,$$
$$M_p = 1.436\, R_p^{1.70} \quad \text{for } 1.23 < R_p < 14.26 R_\oplus, \qquad (2)$$

3. R_*: the radius of the host star in units of solar radii,
4. T_{eq}: the planet's equilibrium temperature in Kelvin calculated for zero albedo and full day-night heat redistribution according to

$$T_{\mathrm{eq}} = T_* \sqrt{\frac{R_*}{a}} \left(\frac{1}{4}\right)^{1/4}, \qquad (3)$$

where T_* is the host star effective temperature in Kelvin, and a is the orbital semimajor axis given in the same units as R_*,

5. m_J: the apparent magnitude of the host star in the J band, chosen as a filter that is close to the middle of the NIRISS bandpass.

Gilbert et al. (2020)

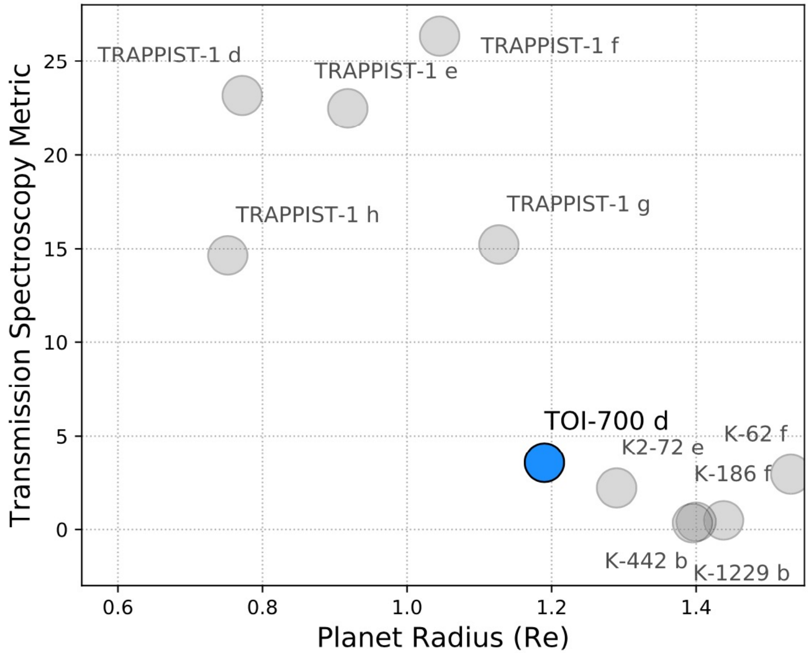
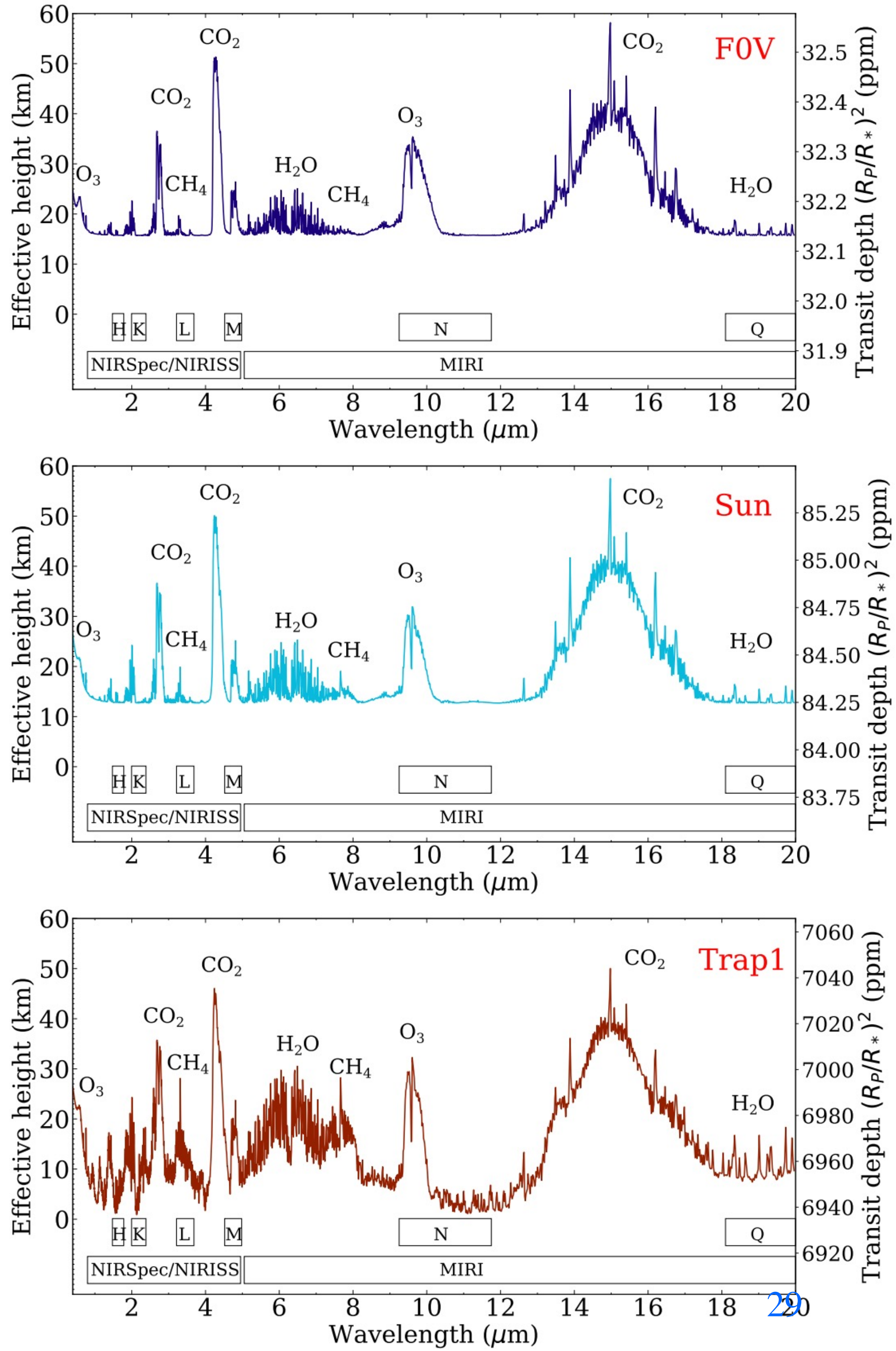


Figure 12. There are now 11 known exoplanets that have radii less than 1.5 $R_\oplus$ and orbit within their star's optimistic habitable zone (Kopparapu et al. 2013). Plotted are these planets' TSM values. The top candidates for atmospheric characterization orbit TRAPPIST-1. Beyond these, TOI-700 d has the highest TSM, although characterizing this planet will be challenging.

Models of high-resolution Transmission Spectra of Earth-like planets around FGKM host stars

Kaltenegger & Lin (2021)

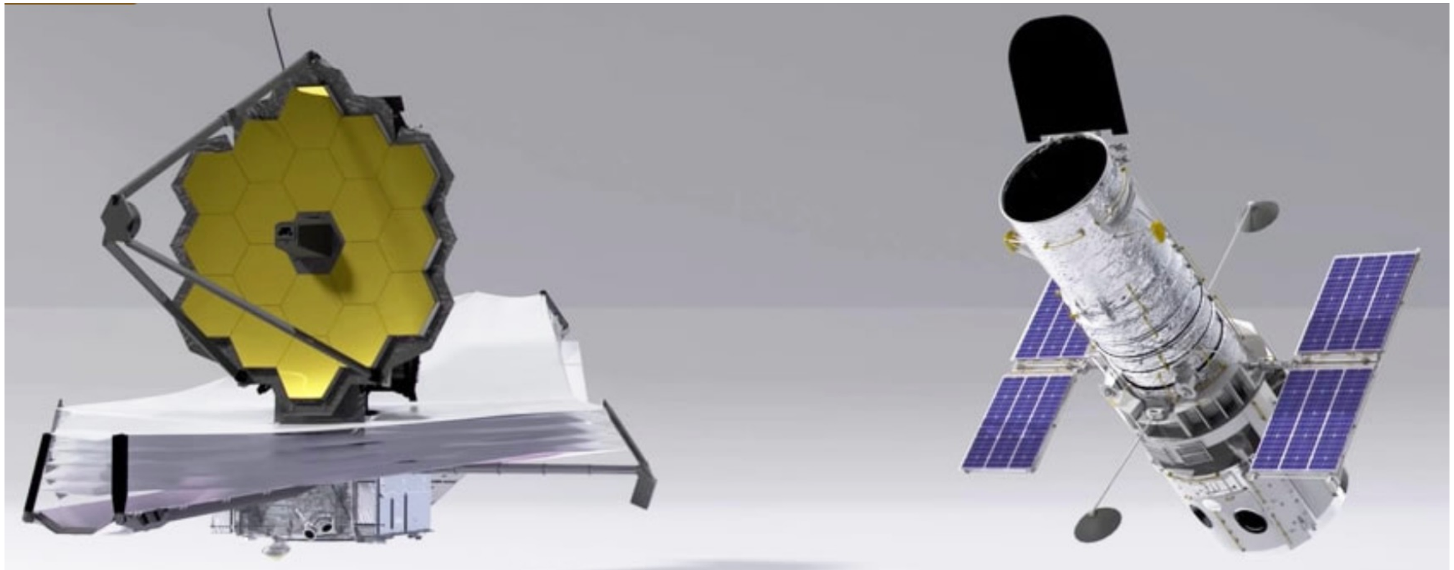
- The atmospheric biosignature pairs O_2+CH_4 and O_3+CH_4—which identify Earth as a living planet—are most prominent for Sunlike and cooler host stars



Future observations of planetary atmospheric spectra:
The James Webb telescope

Primary mirror diameter: ~ 6.5 m

Infrared range: 0.6 to 28 microns



The infrared sensitivity will allow Webb to search for trace amounts of organics in the extremely thin Martian atmosphere