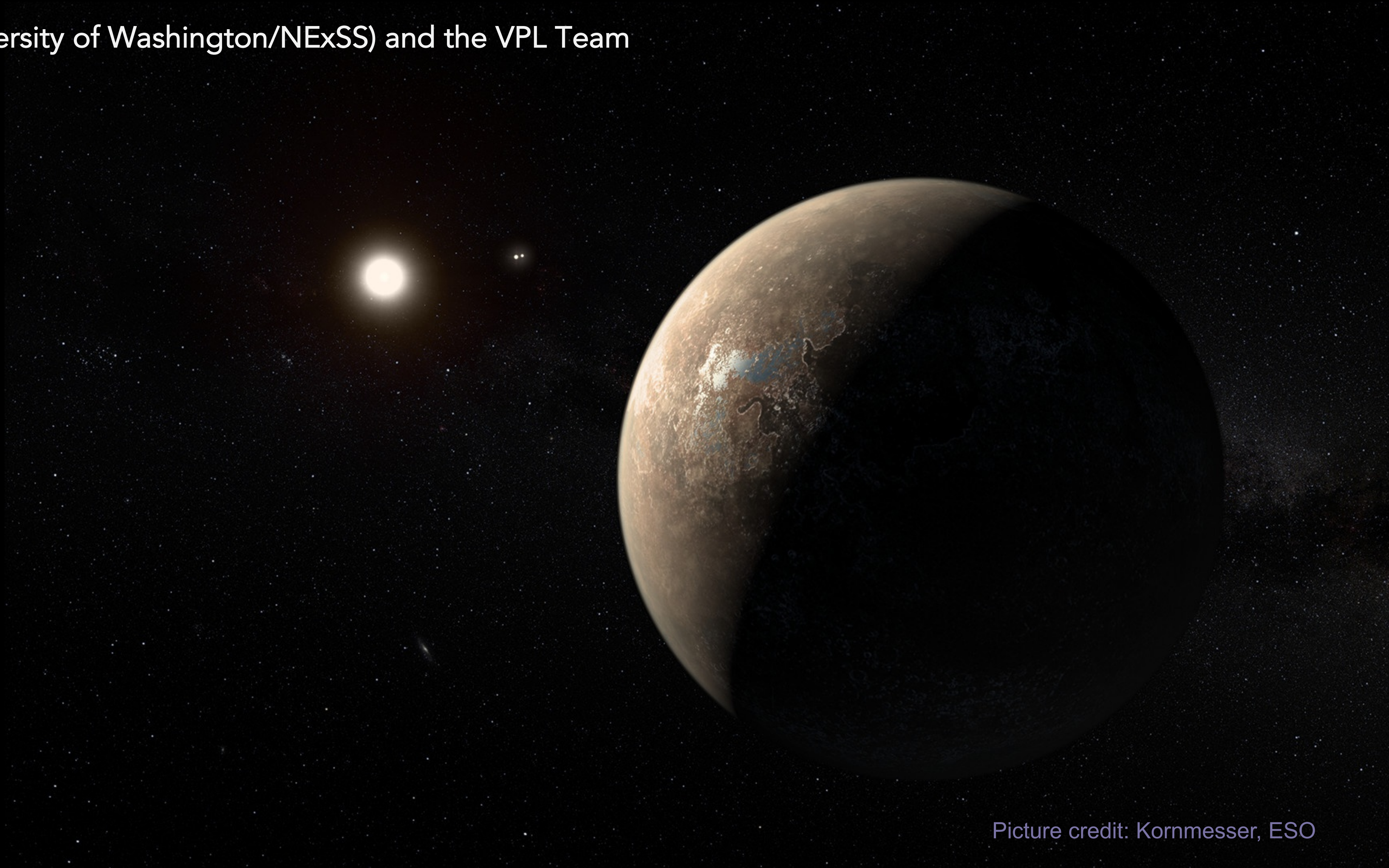
An Overview of Exoplanet Astrobiology

Victoria Meadows (University of Washington/NExSS) and the VPL Team



Picture credit: Kornmesser, ESO

What is Astrobiology?

The study of the origin, evolution, distribution and future of life in the Universe.

Astrobiology is an interdisciplinary “system science”, and encompasses studies of interactions between physical, chemical, biological, geological, planetary, and astrophysical systems as they relate to understanding:

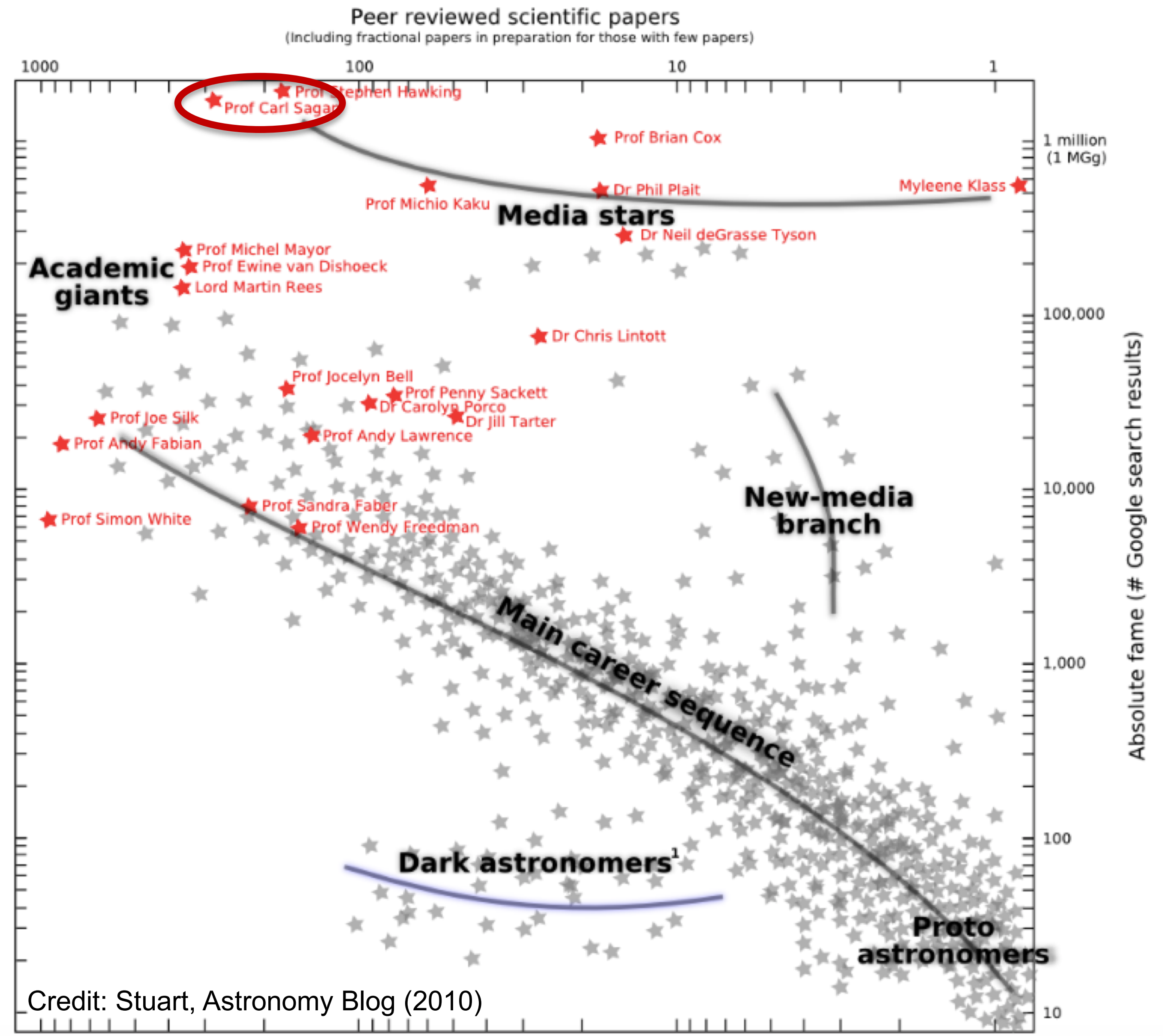
- how a planet develops and maintains habitability
- how an environment transforms from non-living to living
- how life and its host environment coevolve, and
- how life impacts its environment in potentially measurable ways.

Studies of the Sun, Earth and other Solar System planets can inform the search for life on exoplanets.

National Geographic

Thank you Carl!

The Hertzsprung-Russell Diagram…of Astronomers



Credit: Stuart, Astronomy Blog (2010)

* Includes associated others. Apologies to Hertzsprung and Russell. ¹ Productive but generally invisible.

NOTE: As in astronomy, the numbers are correct to a factor of a few. Most of the grey points are purely representative.
P.S. This was made in 2010 as a joke: http://www.strudel.org.uk/blog/astro/000943.shtml. See http://tinyurl.com/astroHR for a follow-up AAS poster based on real data

How do we identify a planet that is more likely to support life?

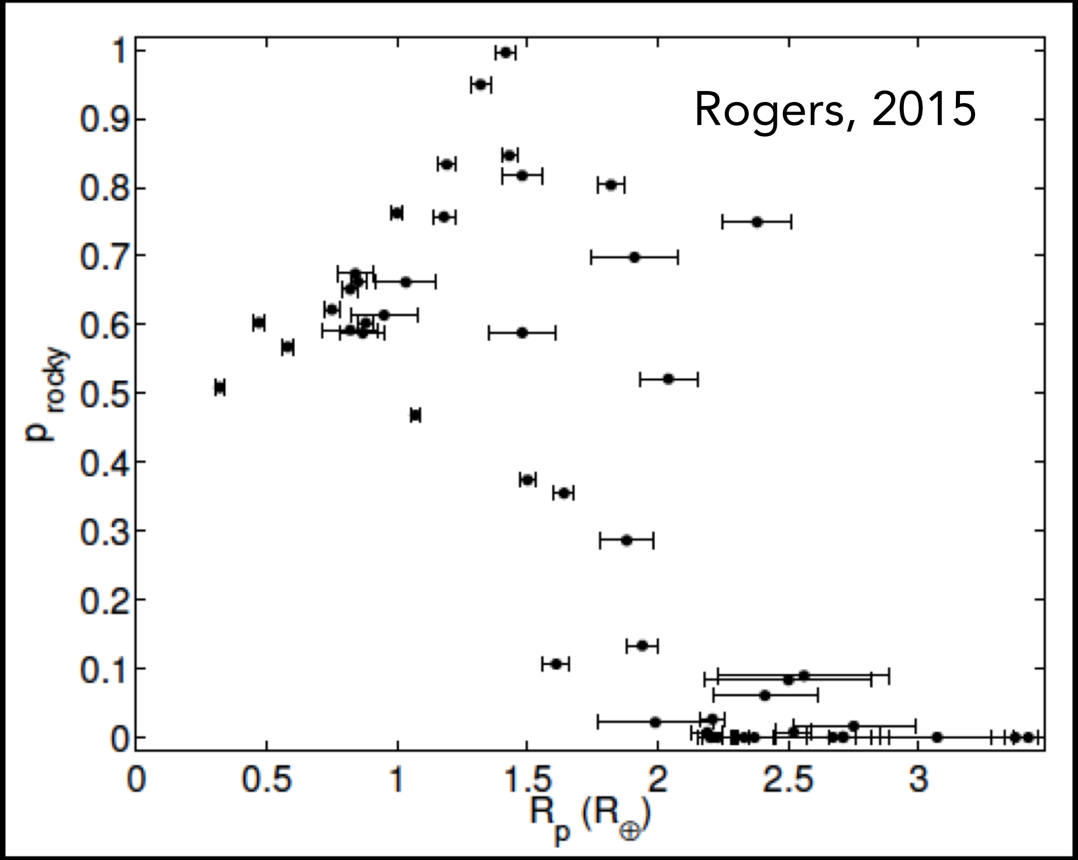
Simplistic answer: Find a terrestrial planet in the habitable zone

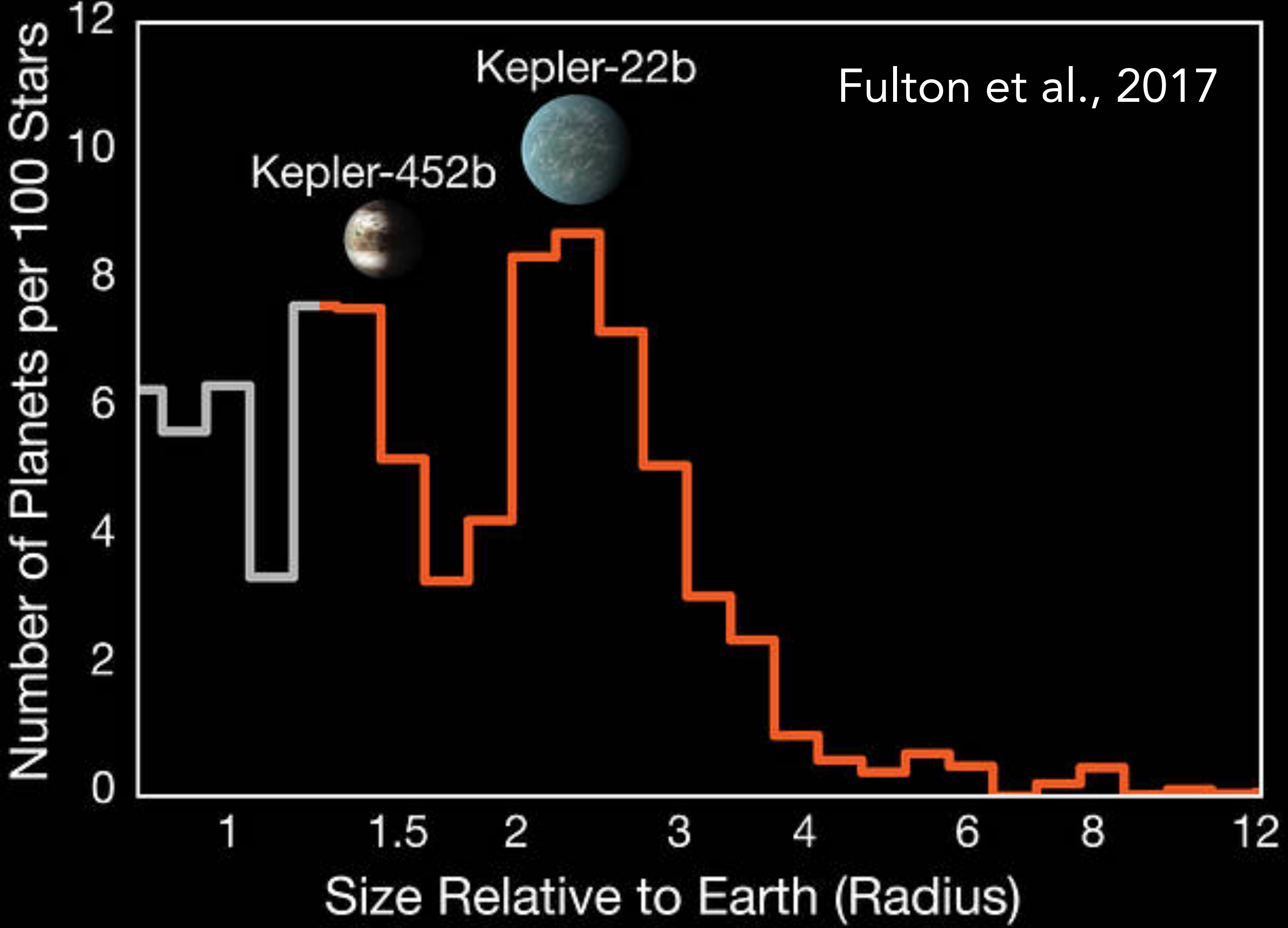
✓

Terrestrial planets, with a rocky surface, are more likely to support liquid surface water, which increases the chance of habitability and life

Credit: PHL @ UPR Arecibo/ESA/NASA

Evidence for an exoplanet terrestrial class





Kepler targets with known densities

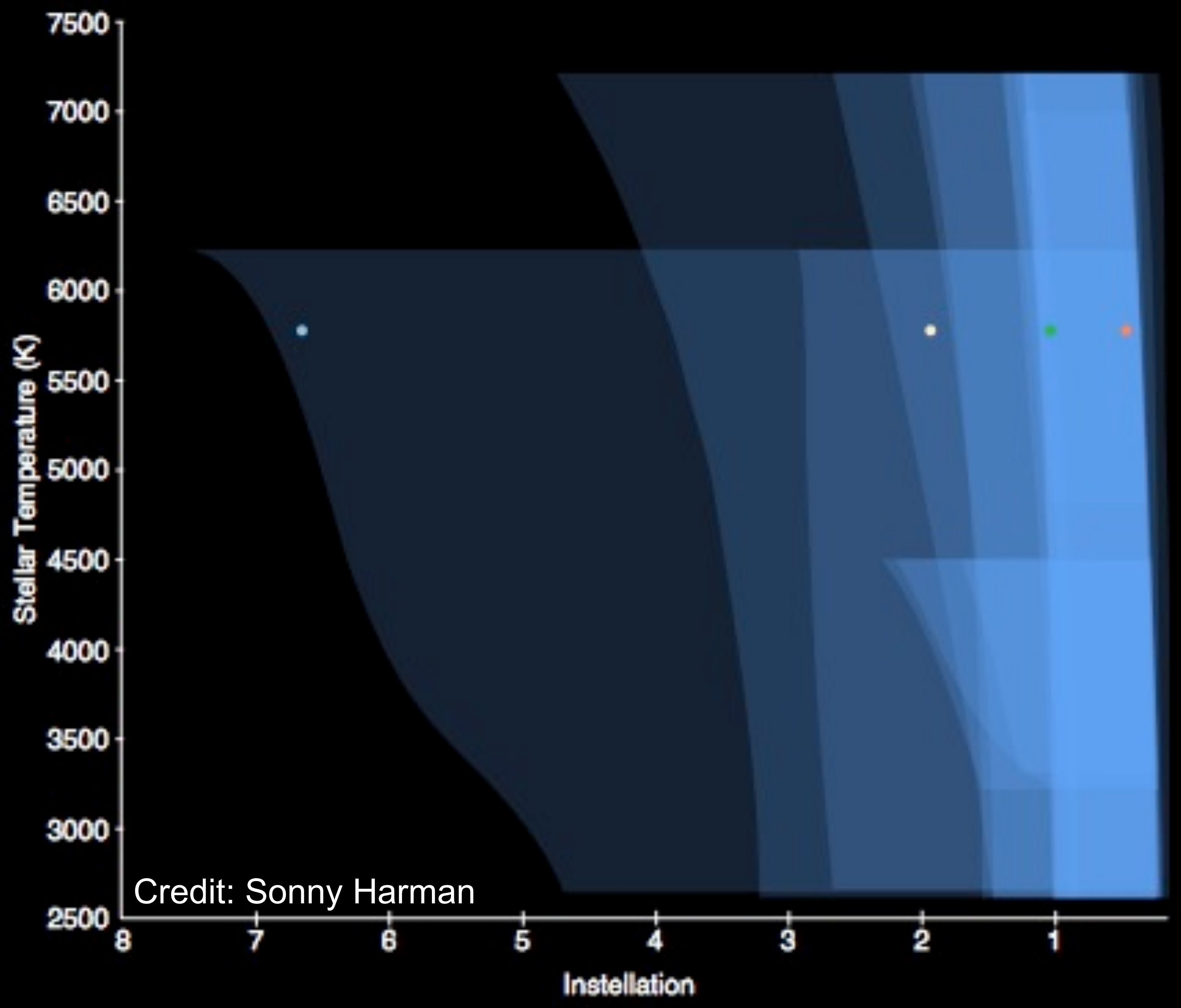
Planets with R < 1.5 REarth are more likely to be terrestrial, and appear to be a distinct population

The Habitable Zone

“That region around a star in which an Earth-like planet can maintain liquid water on its surface” (Kasting et al., 1993).

Translation: That region around a star where life’s requirements are *most likely to be met,* <u>and</u> be detectable

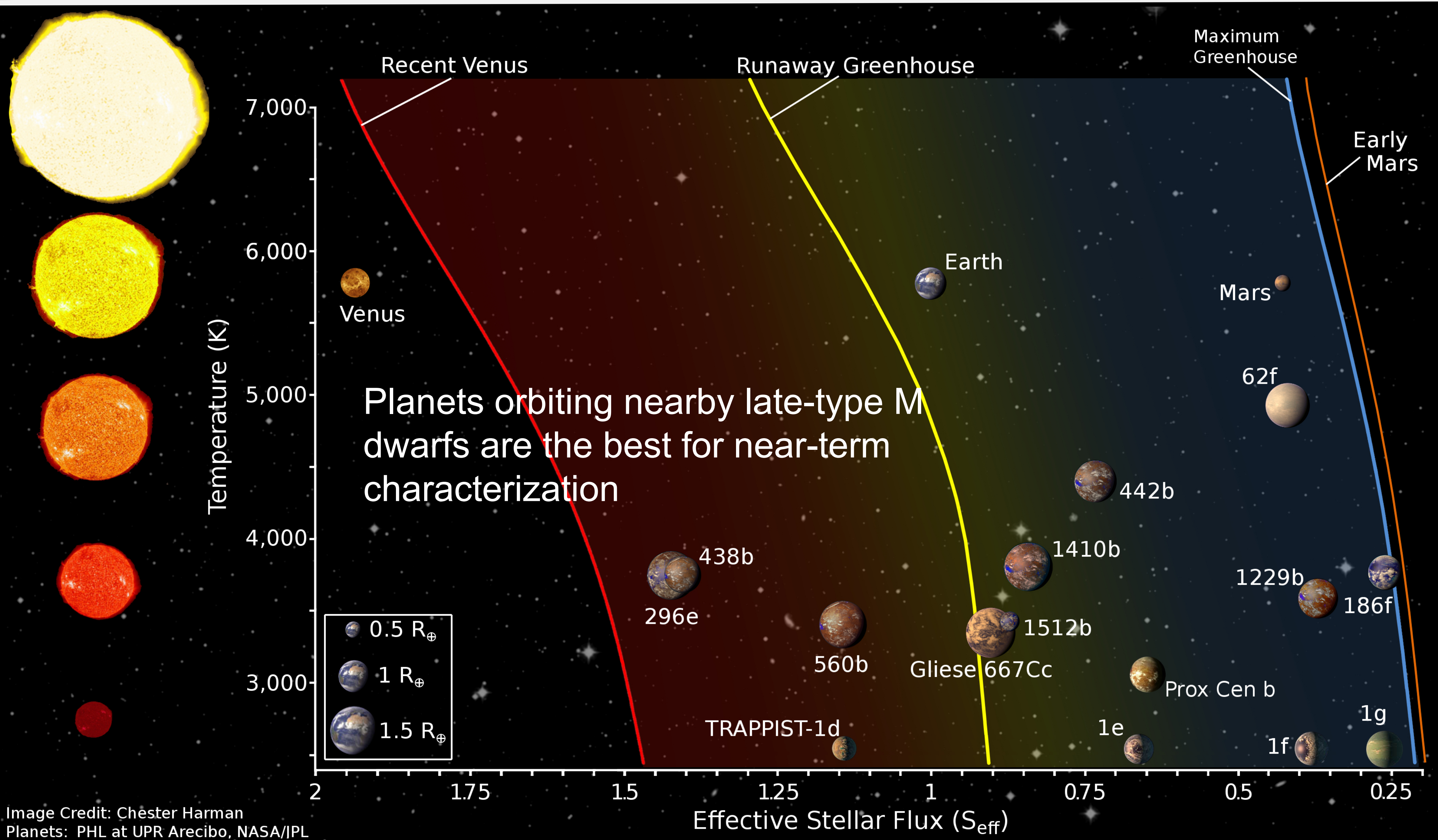
The Habitable Zone



Credit: Sonny Harman

Think of the Habitable Zone more as a probability density for habitability---a place to start the search--- rather than a benediction.

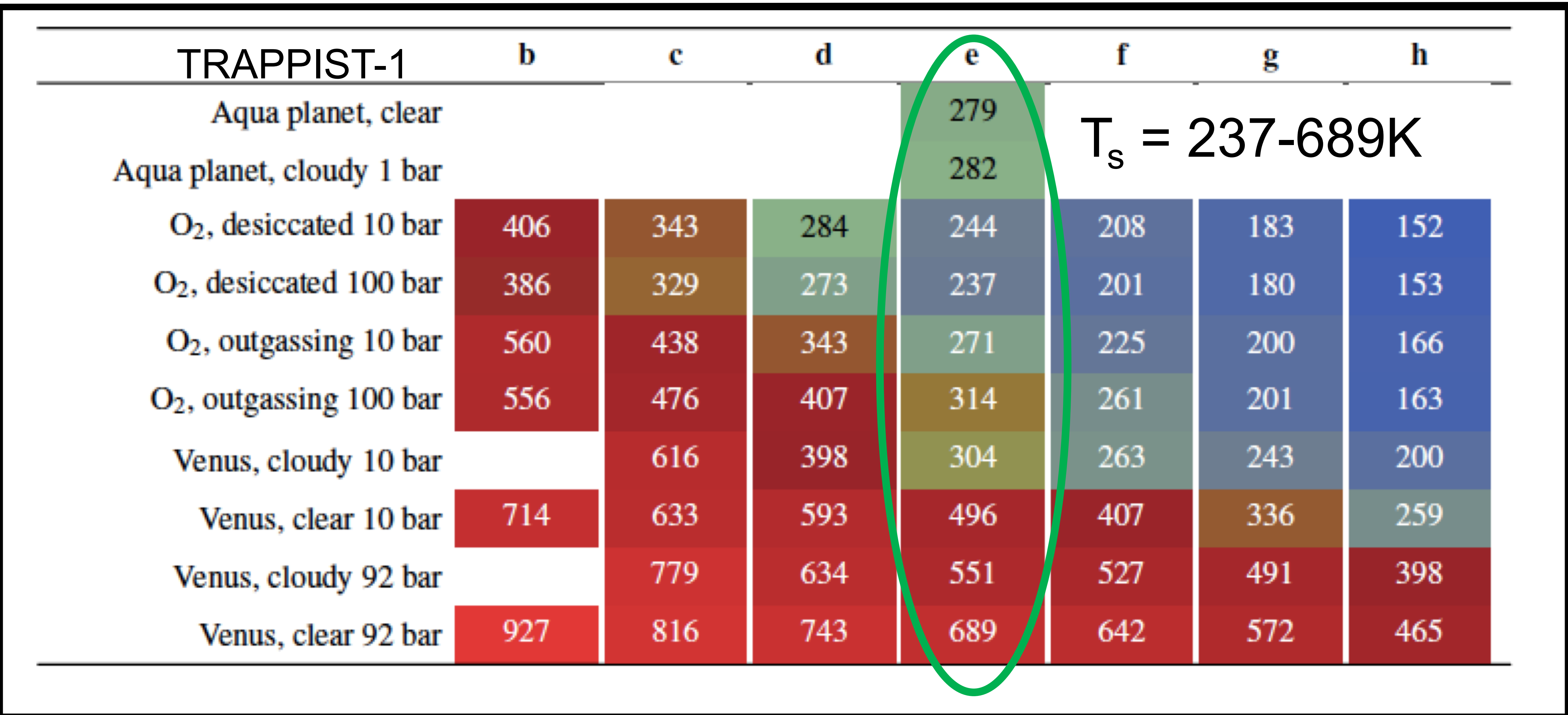
Habitable Zone, terrestrial-sized planets have been discovered



Planets orbiting nearby late-type M dwarfs are the best for near-term characterization

Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/JPL

But these HZ planets are not necessarily habitable…



TRAPPIST-1	b	c	d	e	f	g	h
Aqua planet, clear				279			
Aqua planet, cloudy 1 bar				282			
O_2, desiccated 10 bar	406	343	284	244	208	183	152
O_2, desiccated 100 bar	386	329	273	237	201	180	153
O_2, outgassing 10 bar	560	438	343	271	225	200	166
O_2, outgassing 100 bar	556	476	407	314	261	201	163
Venus, cloudy 10 bar		616	398	304	263	243	200
Venus, clear 10 bar	714	633	593	496	407	336	259
Venus, cloudy 92 bar		779	634	551	527	491	398
Venus, clear 92 bar	927	816	743	689	642	572	465

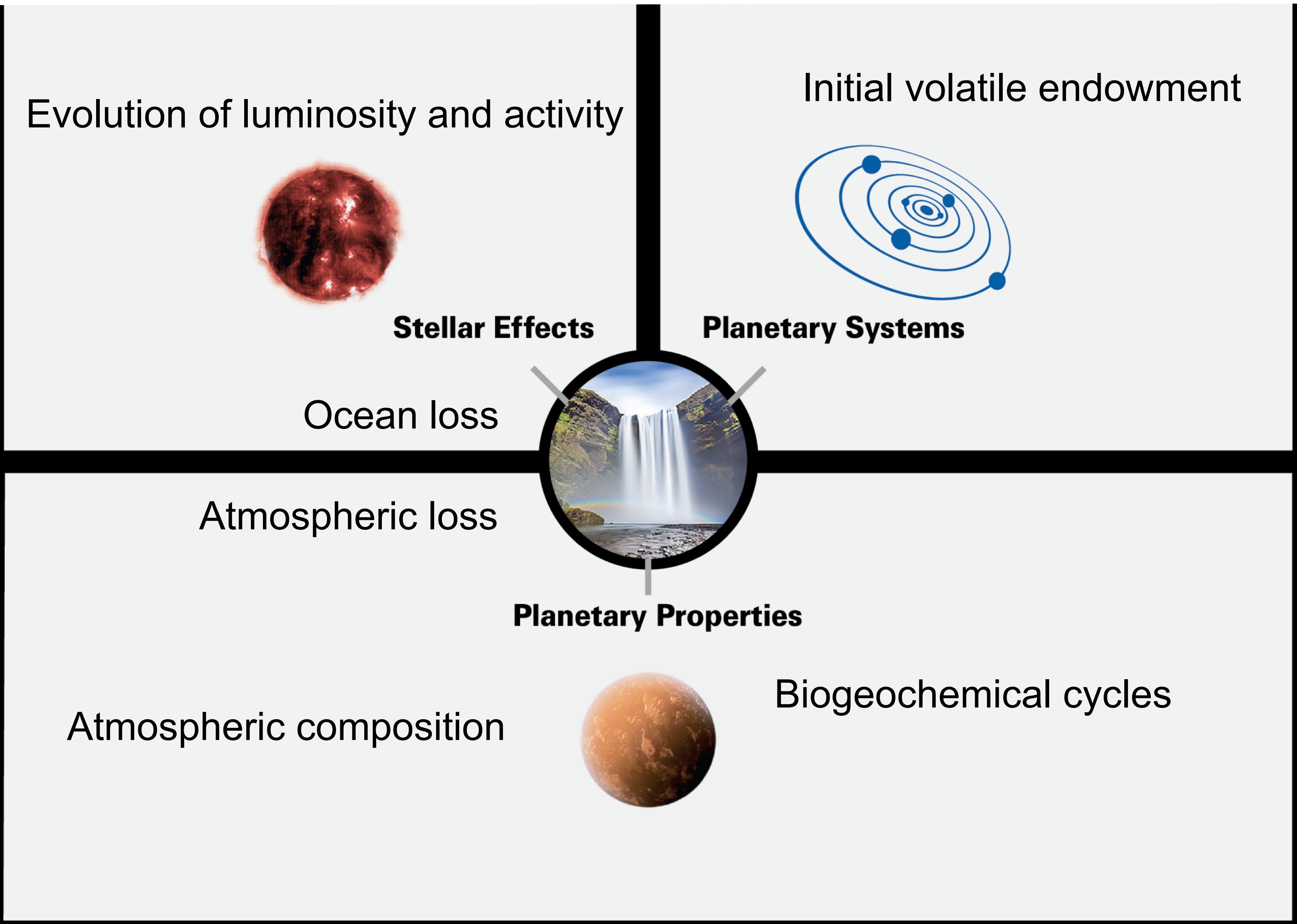
T_s = 237-689K

Evolution affects composition, and composition affects climate!

Lincowski et al., 2018

Many Factors Affect Whether a Planet Has Liquid Water

Many Factors Affect Whether a Planet Has Liquid Water



Evolution of luminosity and activity

Stellar Effects

Ocean loss

Initial volatile endowment

Planetary Systems

Atmospheric loss

Planetary Properties

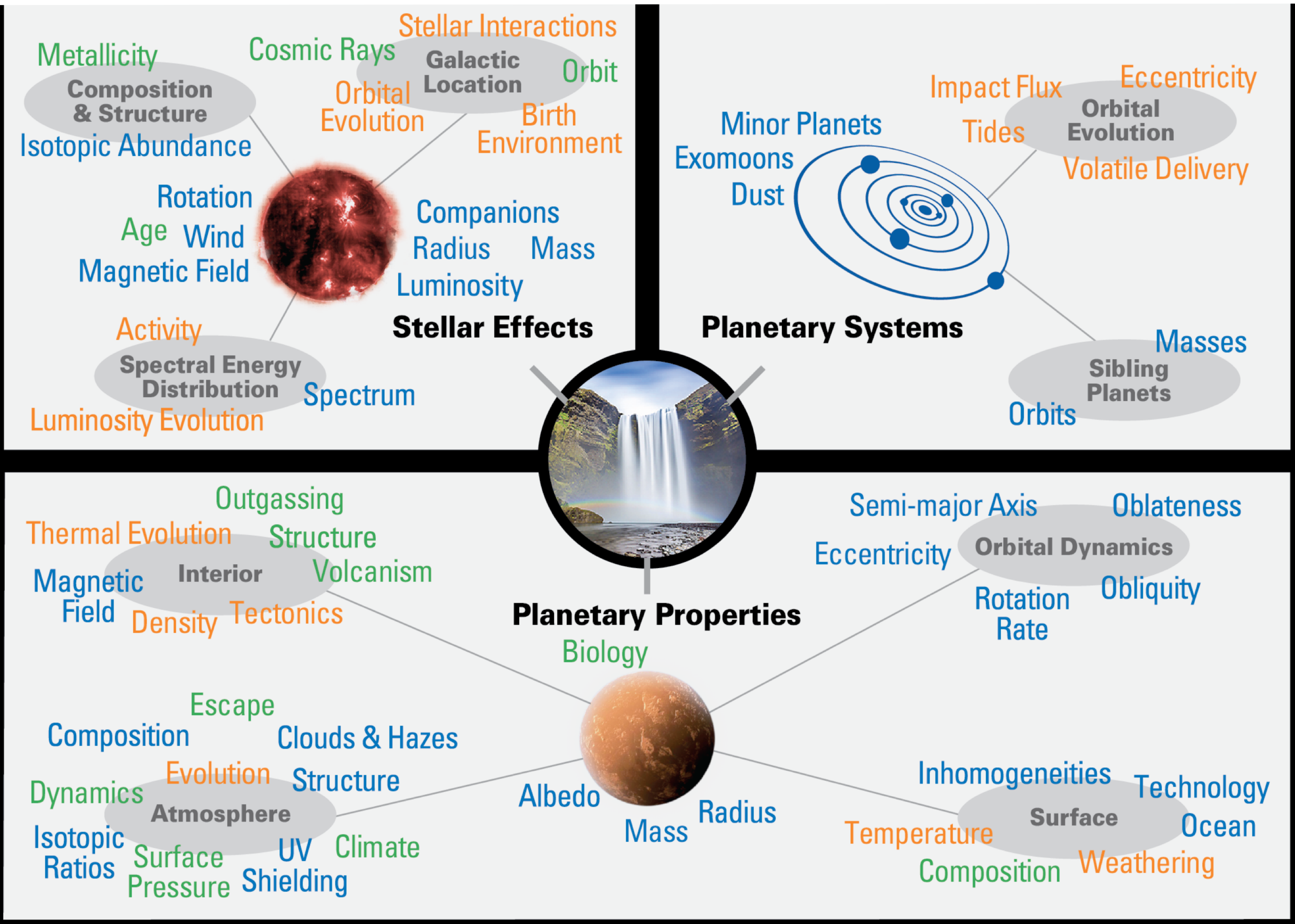
Atmospheric composition

Biogeochemical cycles

Many, Many Factors…..

The HZ is a 2D slice through an ND space.

Only observations can confirm habitability… and even those will struggle!



Stellar Effects

Composition & Structure
Metallicity
Isotopic Abundance

Galactic Location
Cosmic Rays
Stellar Interactions
Orbit
Orbital Evolution
Birth Environment

Rotation
Age
Wind
Magnetic Field
Companions
Radius
Mass
Luminosity

Spectral Energy Distribution
Activity
Spectrum
Luminosity Evolution

Planetary Systems

Minor Planets
Exomoons
Dust

Orbital Evolution
Impact Flux
Eccentricity
Tides
Volatile Delivery

Sibling Planets
Masses
Orbits

Planetary Properties

Biology

Interior
Outgassing
Thermal Evolution
Structure
Volcanism
Magnetic Field
Density
Tectonics

Orbital Dynamics
Semi-major Axis
Oblateness
Eccentricity
Rotation Rate
Obliquity

Atmosphere
Escape
Composition
Clouds & Hazes
Evolution
Structure
Dynamics
Isotopic Ratios
Surface Pressure
UV Shielding
Climate

Albedo
Mass
Radius

Surface
Inhomogeneities
Technology
Temperature
Ocean
Composition
Weathering

Exoplanet terrestrials will likely be very diverse

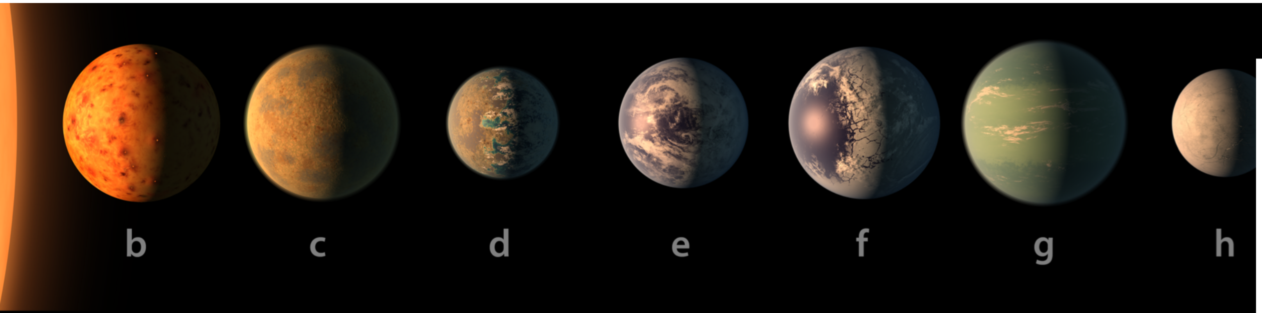
Akatsuki/JAXA

- Environments will depend on **planetary formation and migration** processes, **interior outgassing** composition and history, and the history of **planetary and stellar interactions**, including **geochemistry, atmospheric loss** and **photochemistry**.

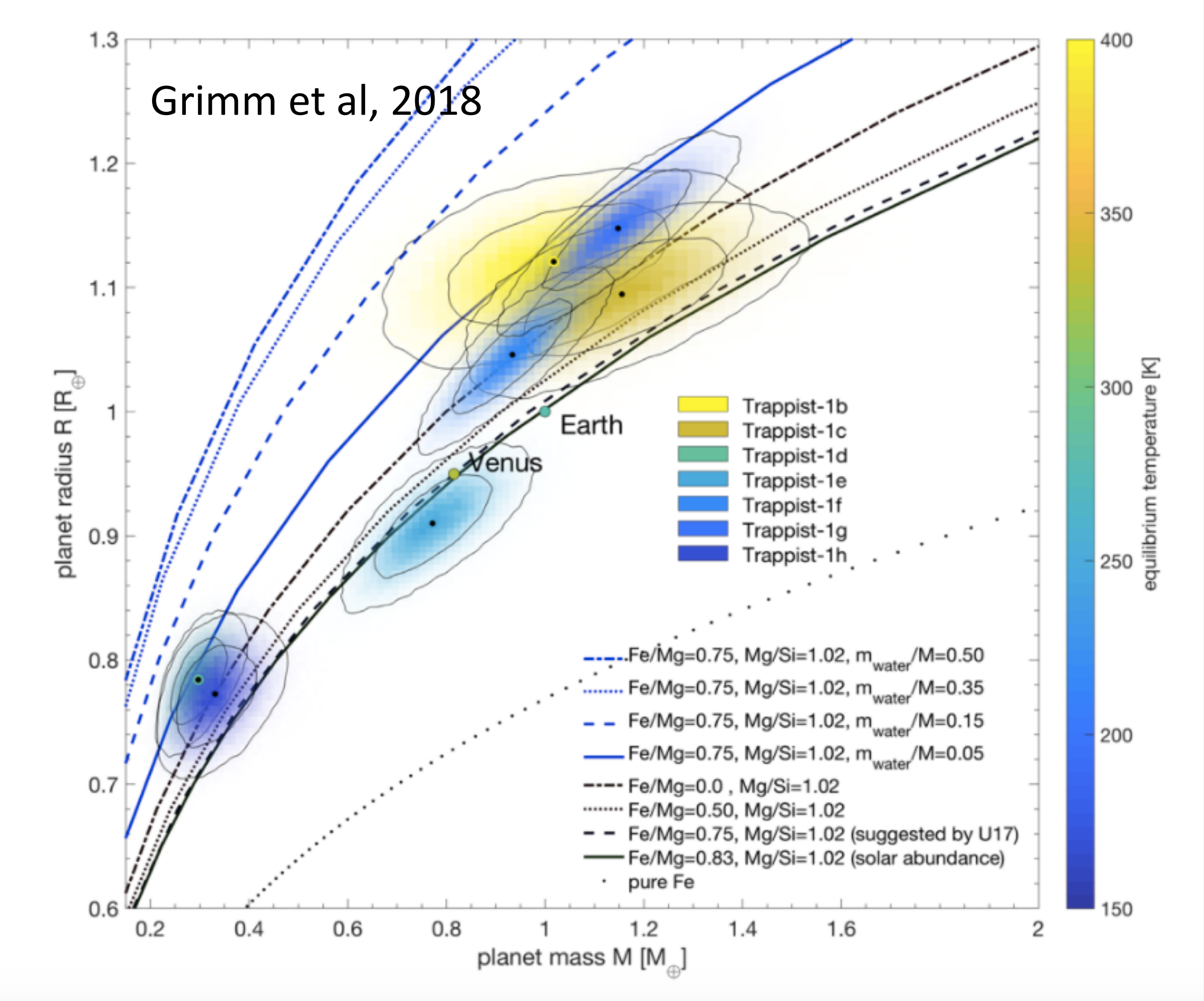
- Terrestrial exoplanets will likely support secondary atmospheres that form via outgassing and/or volatile delivery, after the primordial H_2-dominated atmosphere is lost.

- Initial composition, and subsequent stellar, surface, interior and atmospheric evolution will affect the atmospheric composition and aerosols that we see.

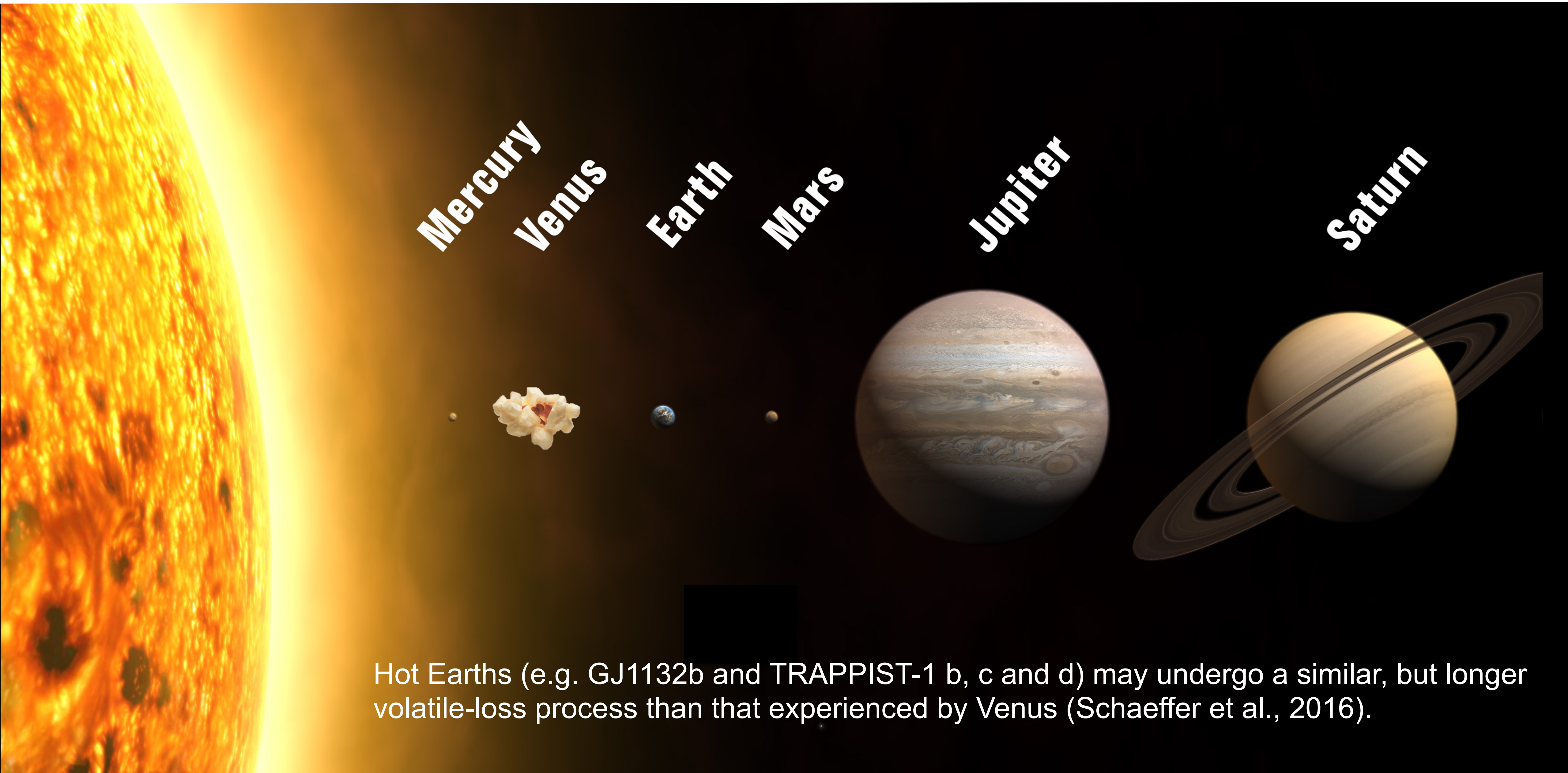
Formation and Migration May Form Volatile-Rich Terrestrials



- TRAPPIST-1's long resonant chain suggests migration from more distant birth orbits (Luger et al., 2017).
- TRAPPIST-1 planets may also have lower densities than SS terrestrials (Grimm et al., 2018; although an update is coming soon!).
- Both observations suggest that the TRAPPIST-1 planets may be more volatile rich than Solar System terrestrials (Luger et al., 2017; Gillon et al., 2017).

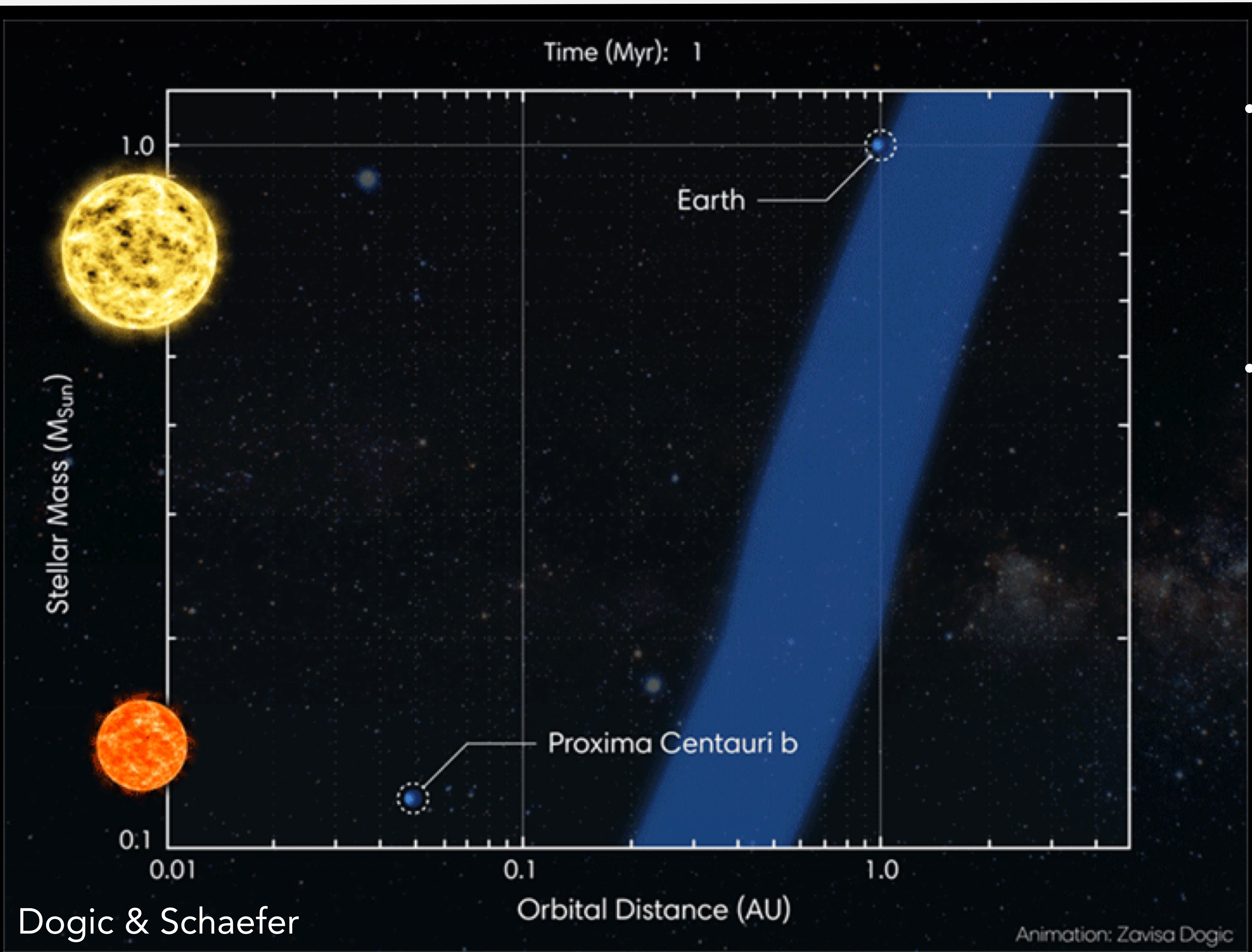

Grimm et al, 2018

Terrestrials Experience Stellar, Geological and Atmospheric Evolution



Hot Earths (e.g. GJ1132b and TRAPPIST-1 b, c and d) may undergo a similar, but longer volatile-loss process than that experienced by Venus (Schaeffer et al., 2016).

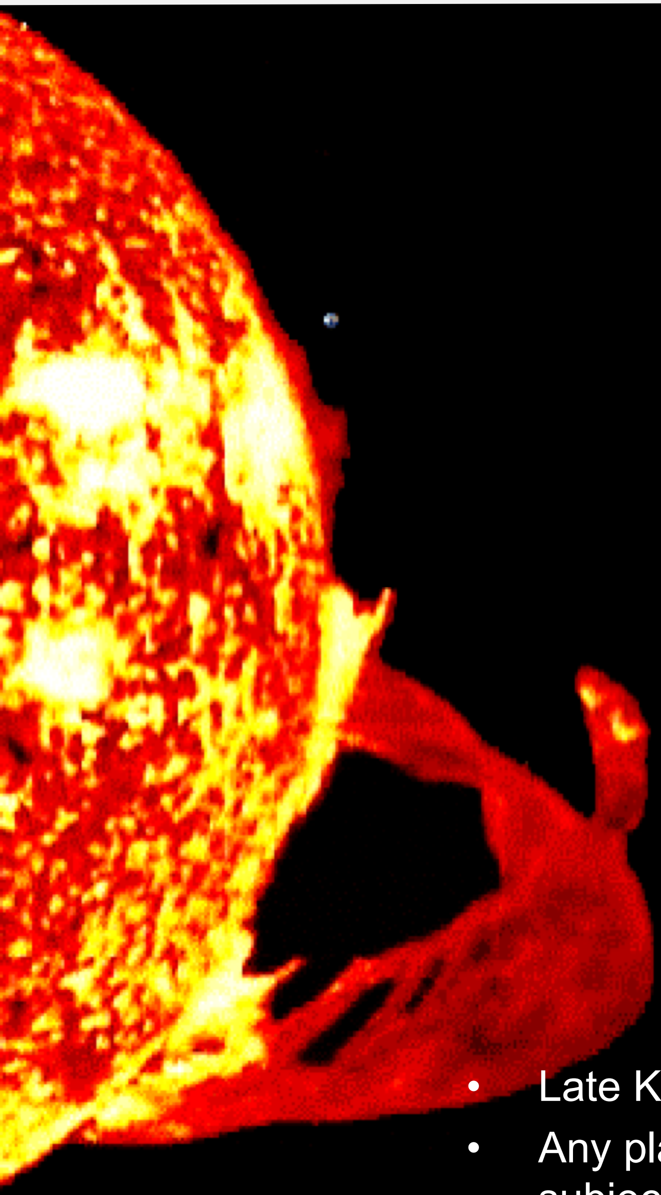
M Dwarf terrestrials likely undergo very different evolution to the Earth

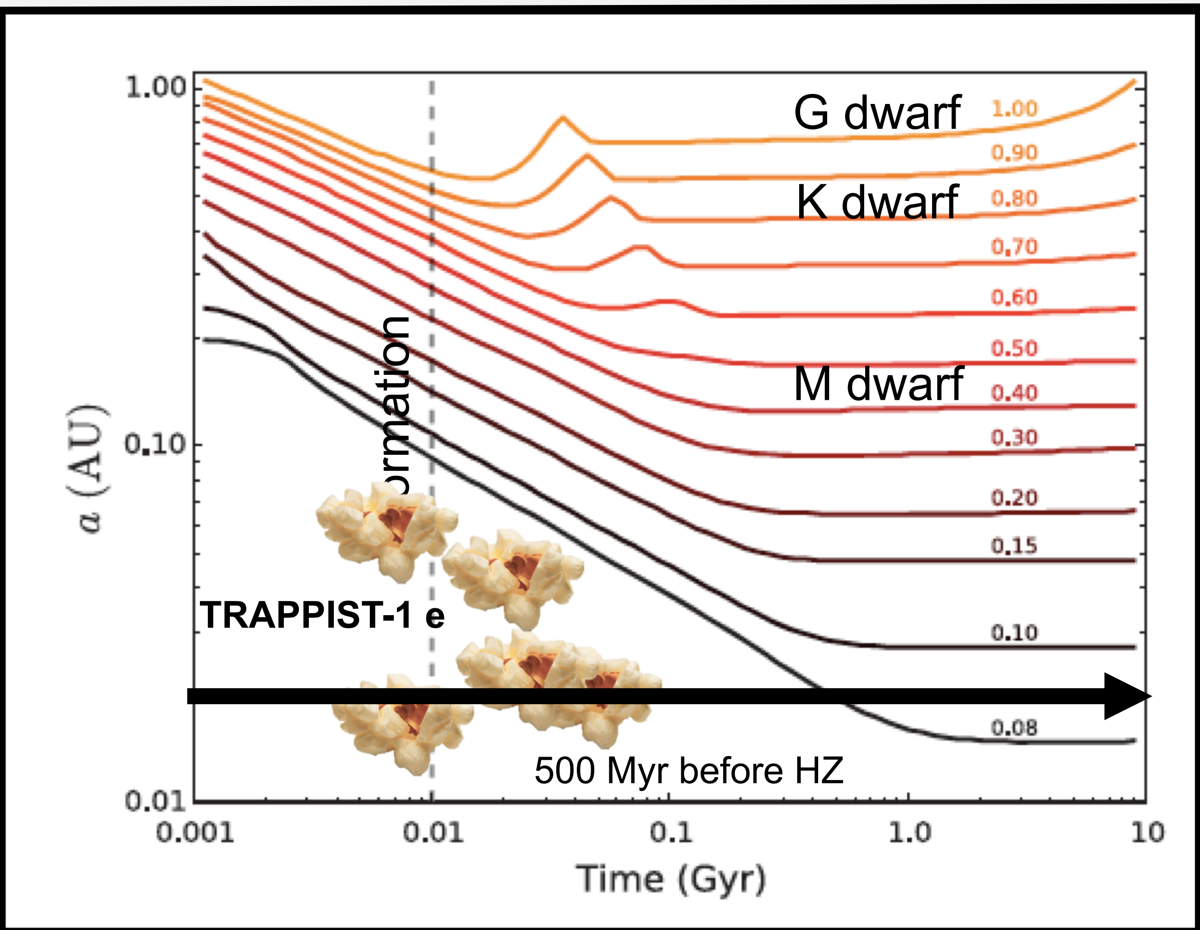


Dogic & Schaefer

- Earth has remained within the CHZ, but Proxima Centauri b spent its first 170Myrs closer to the star than the conservative HZ. (Barnes et al., 2016; Meadows et al., 2018)
- To understand evolutionary processes and terrestrial diversity we need to study planets orbiting stars of different spectral type.

M Dwarf terrestrials likely undergo very different evolution to the Earth

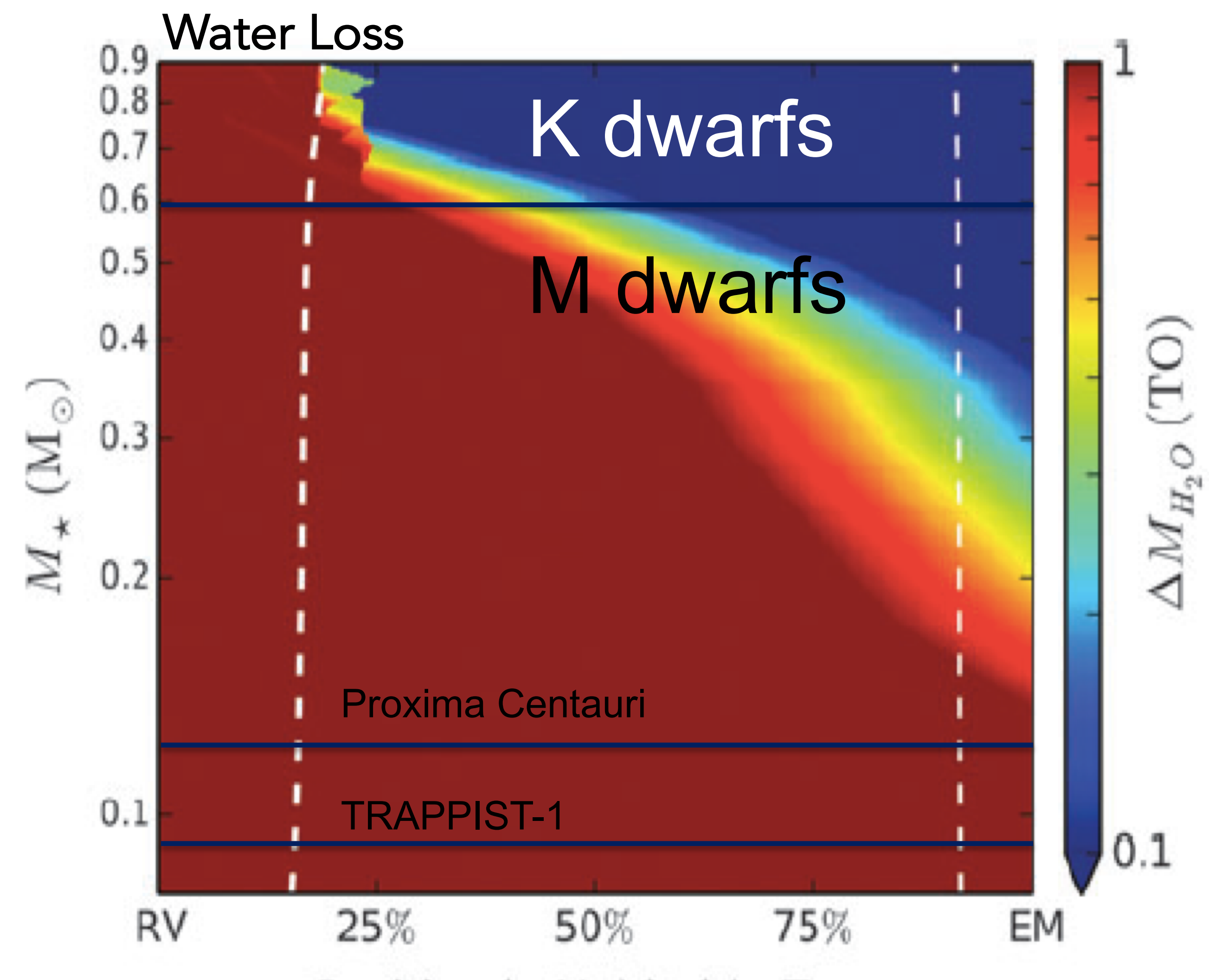




Luger and Barnes, 2015
(see also Bolmont et al., 2016, Bourrier et al., 2017)

- Late K and and all M dwarfs undergo a significant super-luminous phase as they contract
- Any planet that forms in what will become the main sequence habitable zone of these stars can be subjected to very high levels of radiation for up to a Gyr which will likely severely modify the atmosphere.

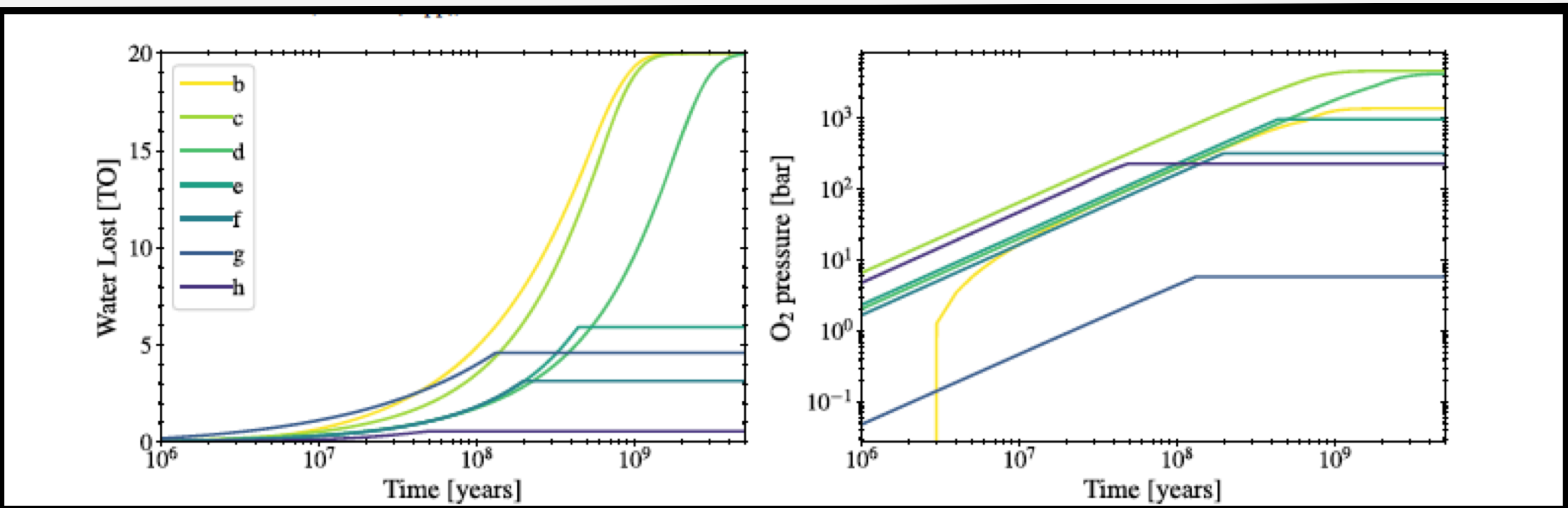
M Dwarf Terrestrials May Experience Early Ocean Loss



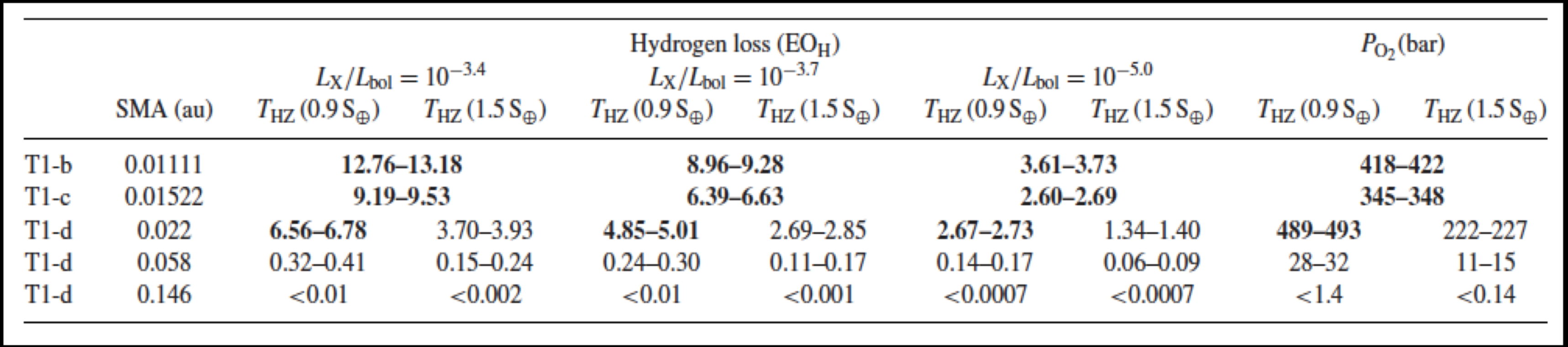
Luger & Barnes (2015)

- Planets orbiting late-type M dwarfs may lose the equivalent of many 10s of oceans during the PMS phase.
- When an Earth's ocean of water is photolyzed, it can generate ~250 bars of O_2.

Early Ocean Loss May Generate an O_2 atmosphere



Lincowski et al., (2018)



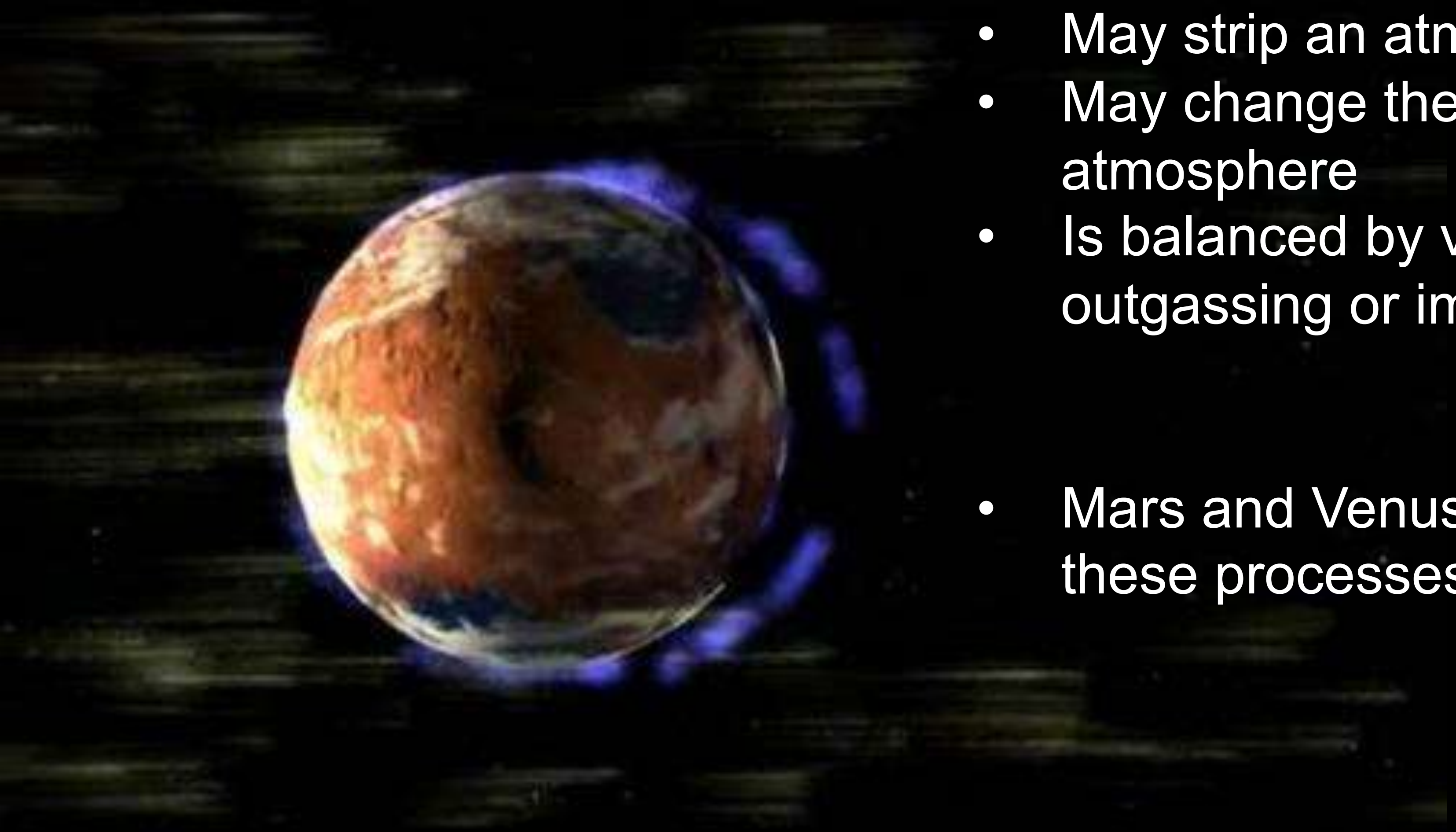
		Hydrogen loss (EO_H)						P_{O_2} (bar)	
		$L_X/L_{bol} = 10^{-3.4}$		$L_X/L_{bol} = 10^{-3.7}$		$L_X/L_{bol} = 10^{-5.0}$			
	SMA (au)	T_{HZ} (0.9 $S_\oplus$)	T_{HZ} (1.5 $S_\oplus$)	T_{HZ} (0.9 $S_\oplus$)	T_{HZ} (1.5 $S_\oplus$)	T_{HZ} (0.9 $S_\oplus$)	T_{HZ} (1.5 $S_\oplus$)	T_{HZ} (0.9 $S_\oplus$)	T_{HZ} (1.5 $S_\oplus$)
T1-b	0.01111	**12.76–13.18**		**8.96–9.28**		**3.61–3.73**		**418–422**	
T1-c	0.01522	**9.19–9.53**		**6.39–6.63**		**2.60–2.69**		**345–348**	
T1-d	0.022	**6.56–6.78**	3.70–3.93	**4.85–5.01**	2.69–2.85	**2.67–2.73**	1.34–1.40	**489–493**	222–227
T1-d	0.058	0.32–0.41	0.15–0.24	0.24–0.30	0.11–0.17	0.14–0.17	0.06–0.09	28–32	11–15
T1-d	0.146	<0.01	<0.002	<0.01	<0.001	<0.0007	<0.0007	<1.4	<0.14

Bolmont et al.,2016

- Wheatley results (T-1 conference) also seem comparable: 27 – 0.74 TOE
- Selsis cautions us that complex physics and chemistry needed.

- The TRAPPIST-1 planets may have lost >20 to less than an Earth ocean of water.
- Ocean loss (Ramirez & Kaltenegger, 2014; Tian, 2015) may *generate* a potentially massive O_2 atmosphere (Luger & Barnes, 2015).
- O_2 loss mechanisms: magma ocean, crustal oxidation, or atmospheric escape (e.g. Schaefer et al., 2016; 2017, Wordsworth et al., 2018)
- How much ocean-loss-generated O_2 can be retained is a key open question that could soon be tested observationally for TRAPPIST-1 using JWST.

Atmospheric Loss

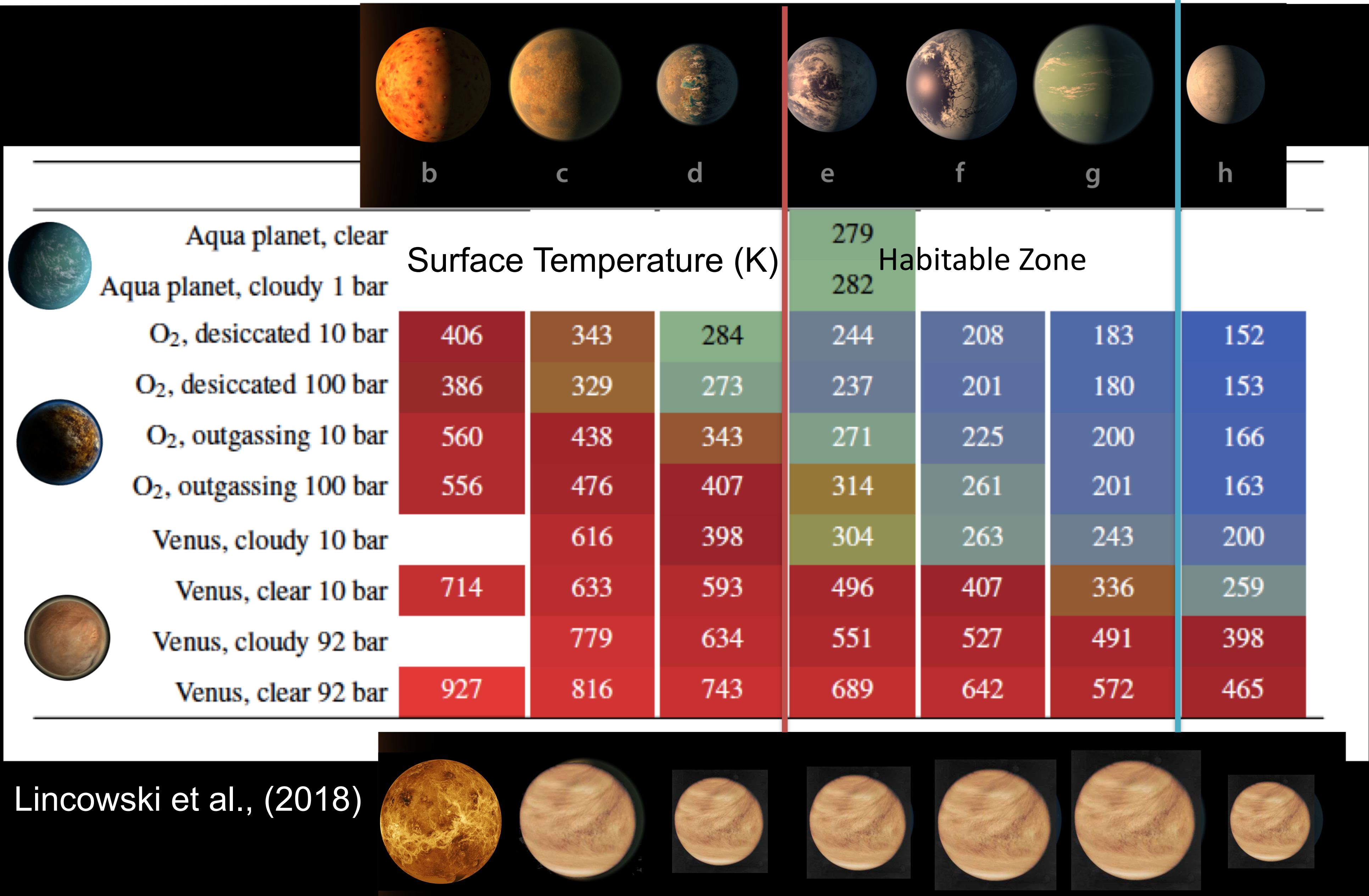


- May strip an atmosphere
- May change the composition of the atmosphere
- Is balanced by volatile delivery from outgassing or impactors.

- Mars and Venus could help us understand these processes.

Evolutionary Processes Could Generate Uninhabitable HZ Planets

If Venuses were created during the ocean loss process for TRAPPIST-1, they could extend through the entire HZ.



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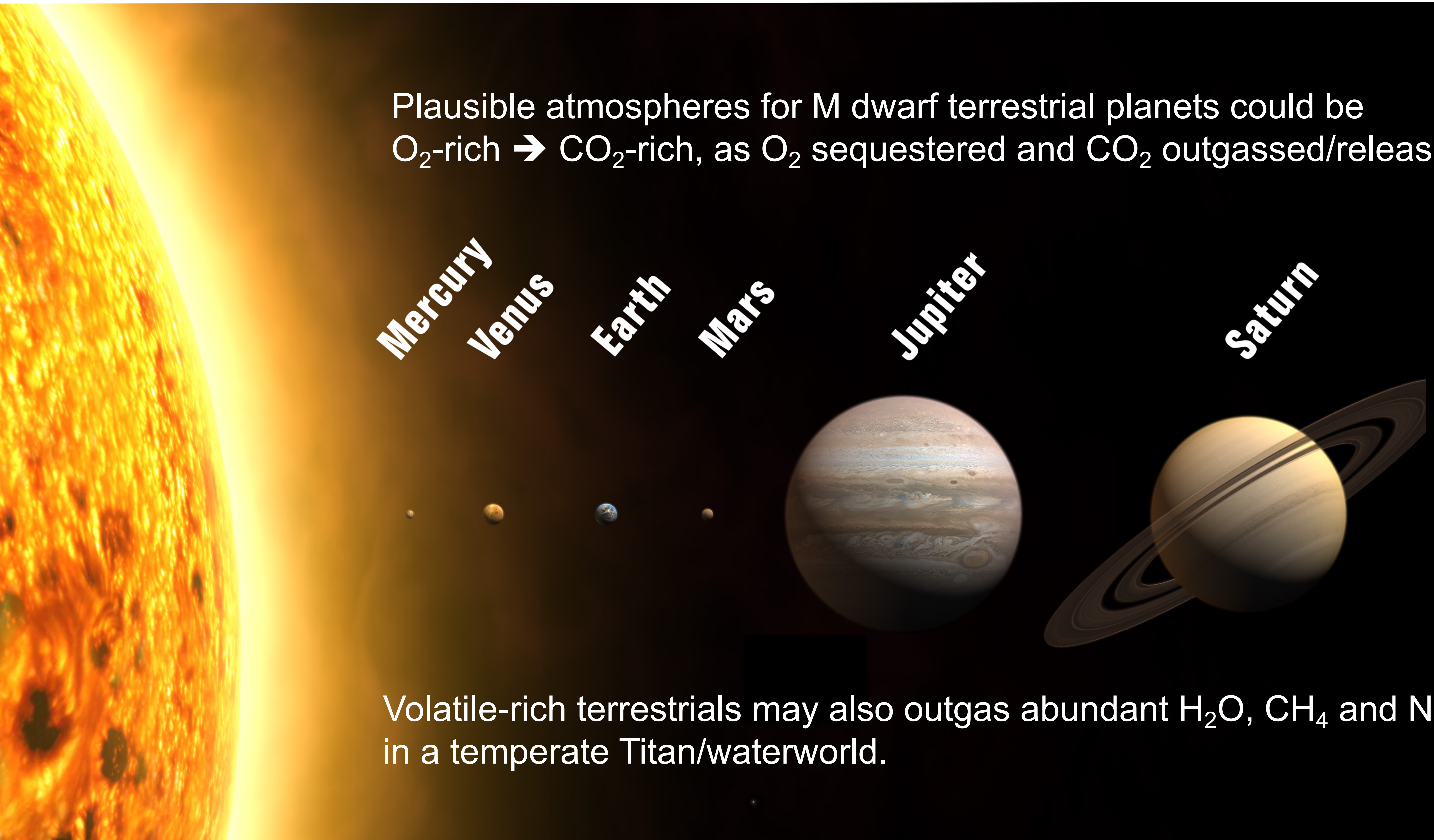
Lincowski et al., (2018)

M-dwarf terrestrial atmospheres may be O_2-, CO_2- or H_2O-rich

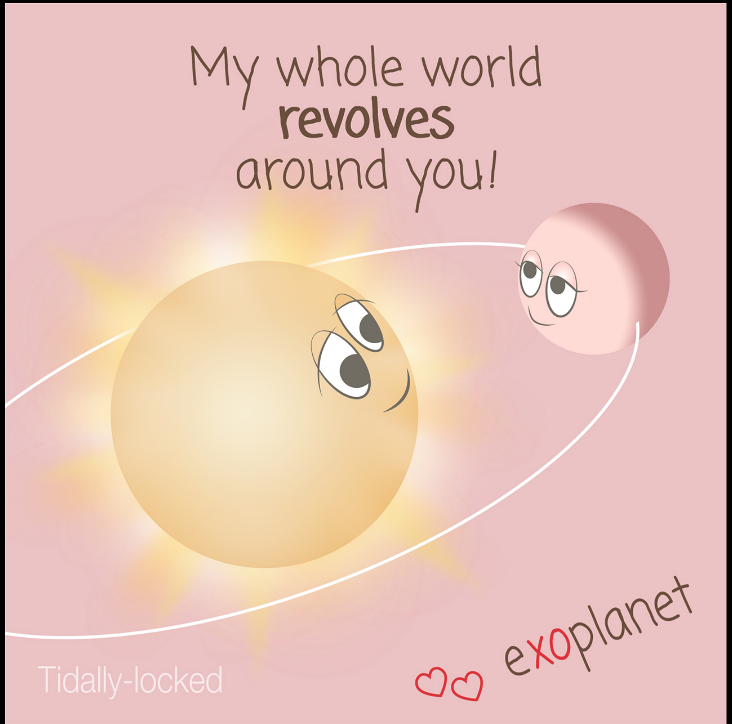
Plausible atmospheres for M dwarf terrestrial planets could be O_2-rich ➔ CO_2-rich, as O_2 sequestered and CO_2 outgassed/released (Venus).

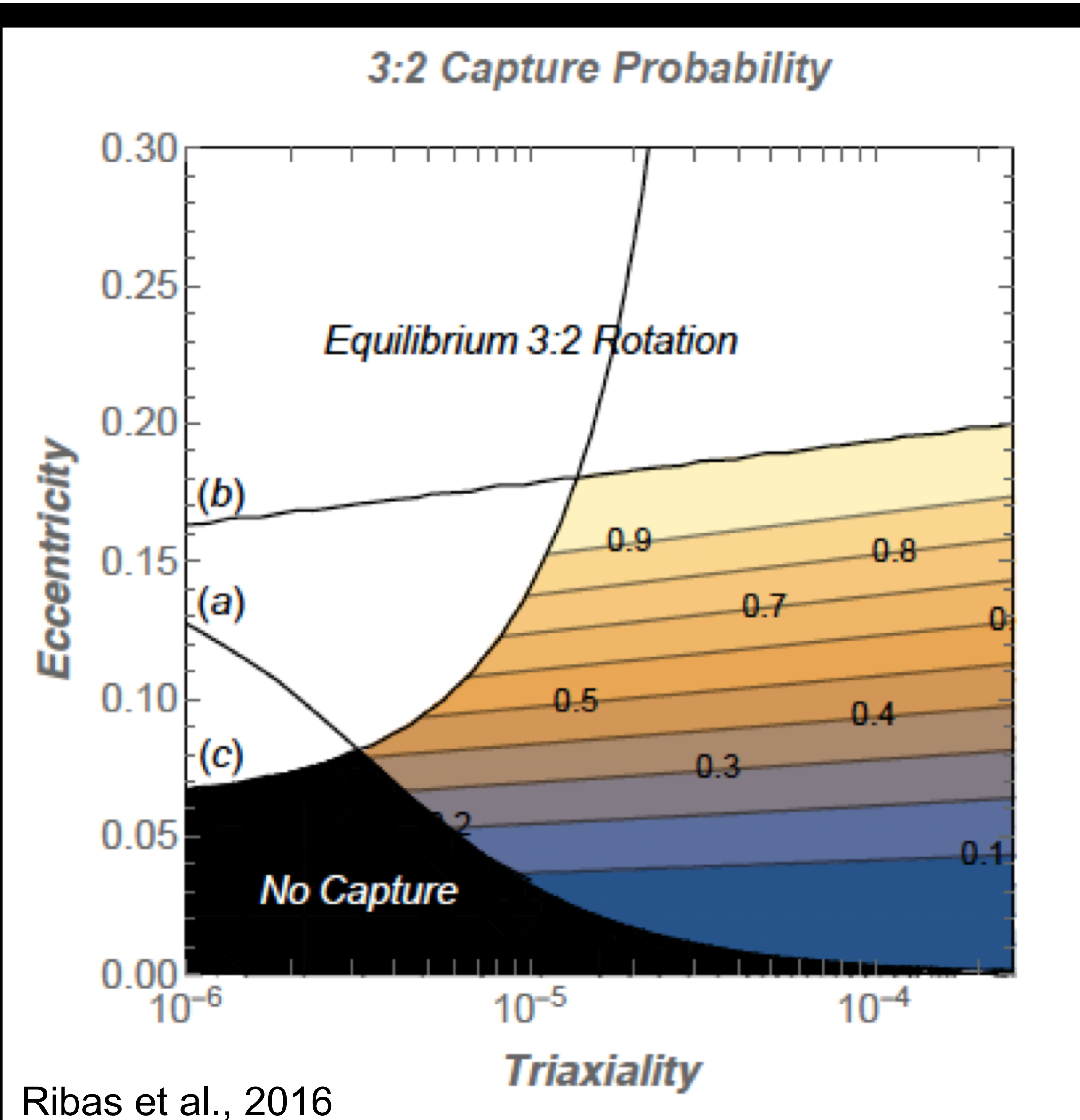


Volatile-rich terrestrials may also outgas abundant H_2O, CH_4 and NH_3, resulting in a temperate Titan/waterworld.

Tidal locking can produce spin-orbit resonances

- 1:1 Synchronously rotating. The planet shows the same face to the star at all times.
- 3:2 Like Mercury, 3 rotations for every 2 orbits around the star. All parts of the planet get exposed to starlight. This state needs eccentricity - often maintained by a sibling planet.

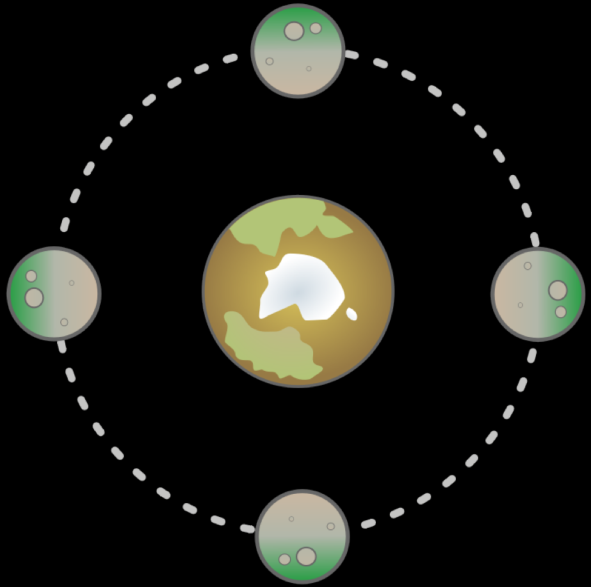




Ribas et al., 2016

Synchronous rotation may collapse the atmosphere

- If a planet’s atmosphere is thin, it may not be able to transfer heat from the dayside to the nightside of a synchronously rotating planet.
- If the nightside gets cold enough, it can freeze the atmosphere out on the surface!
- But in many cases, it probably doesn’t (Turbet et al., 2016), especially of ocean heat transport is taken into account (Hu & Yang, 2014).



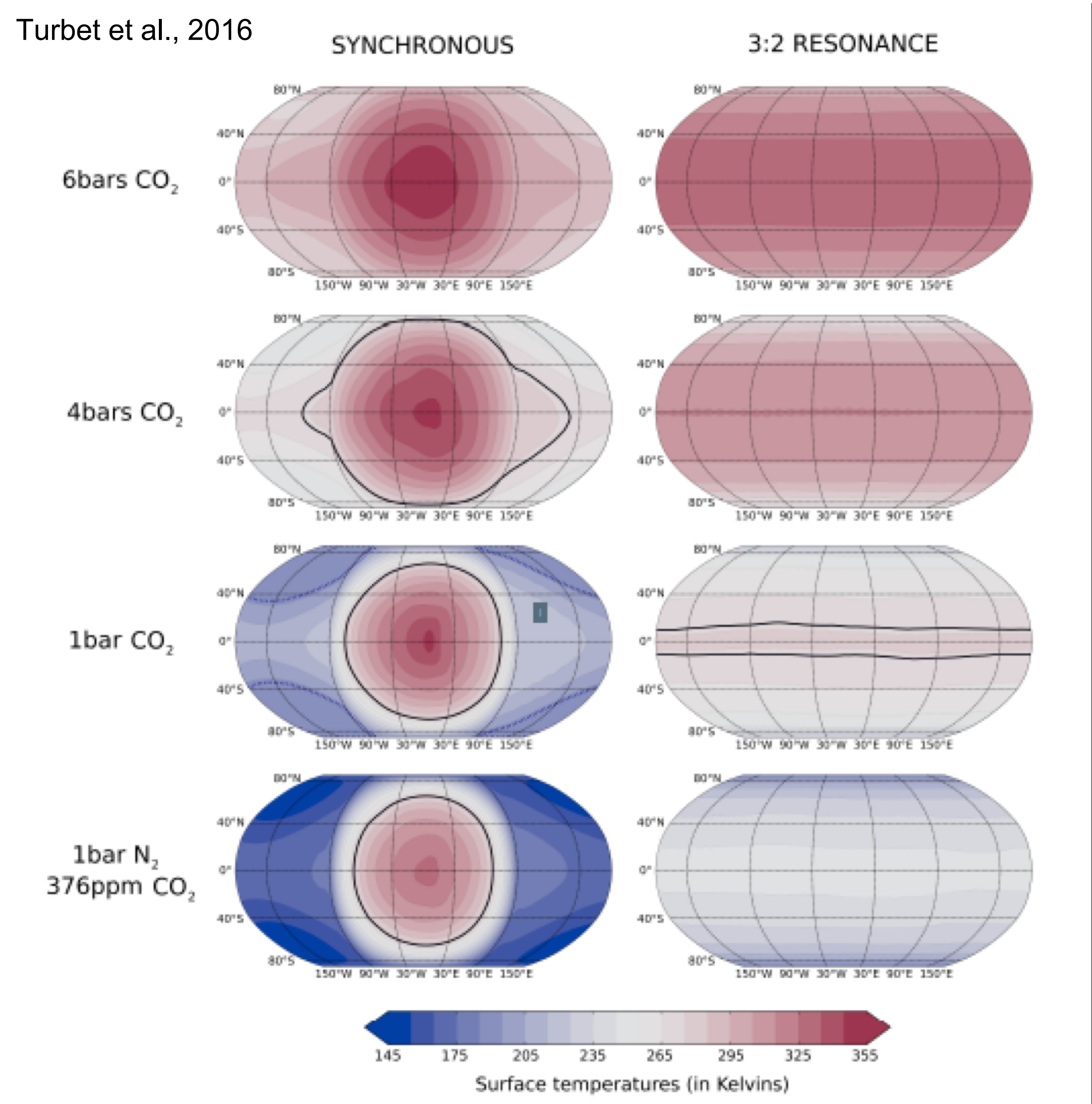
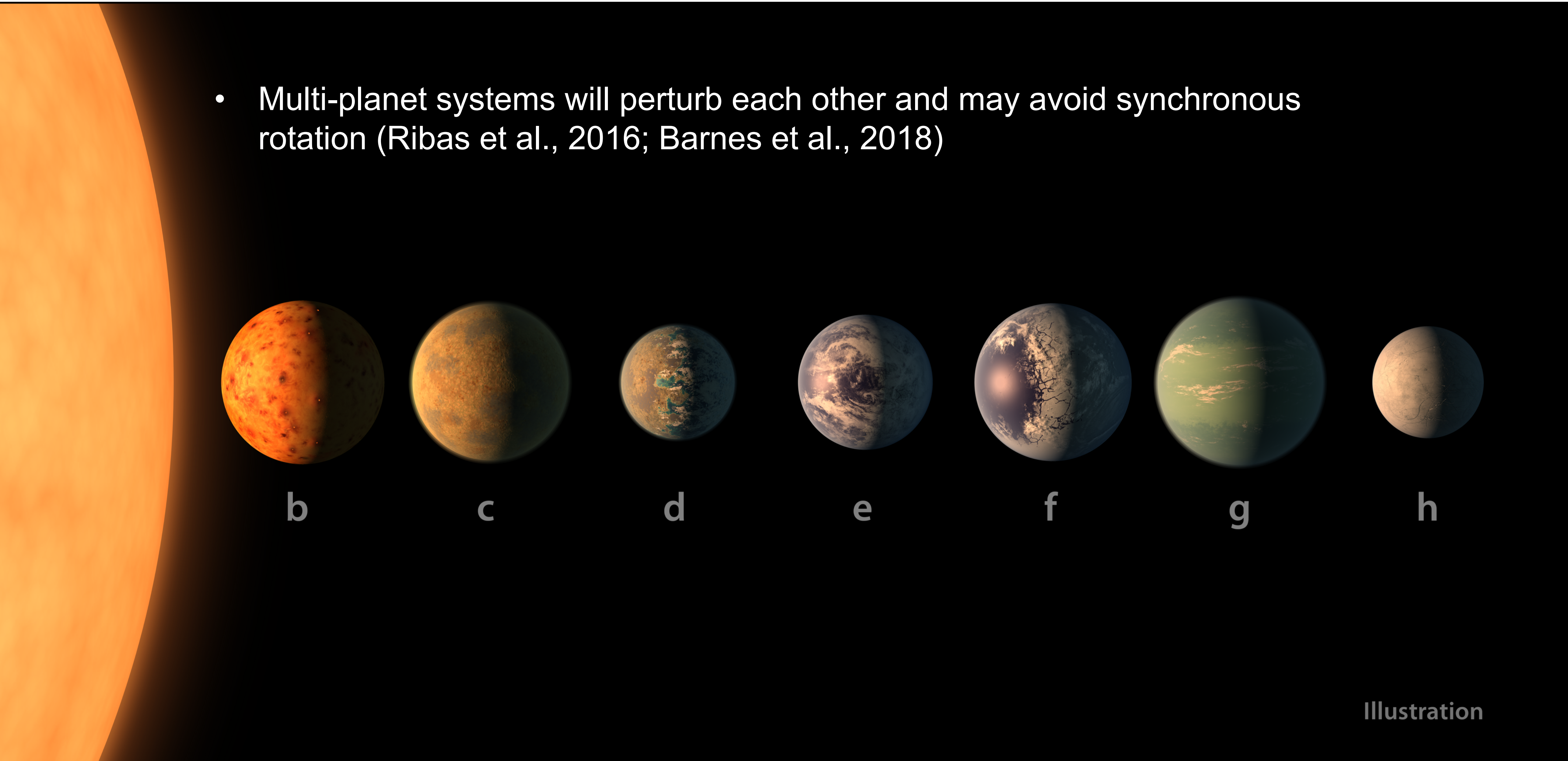

Turbet et al., 2016

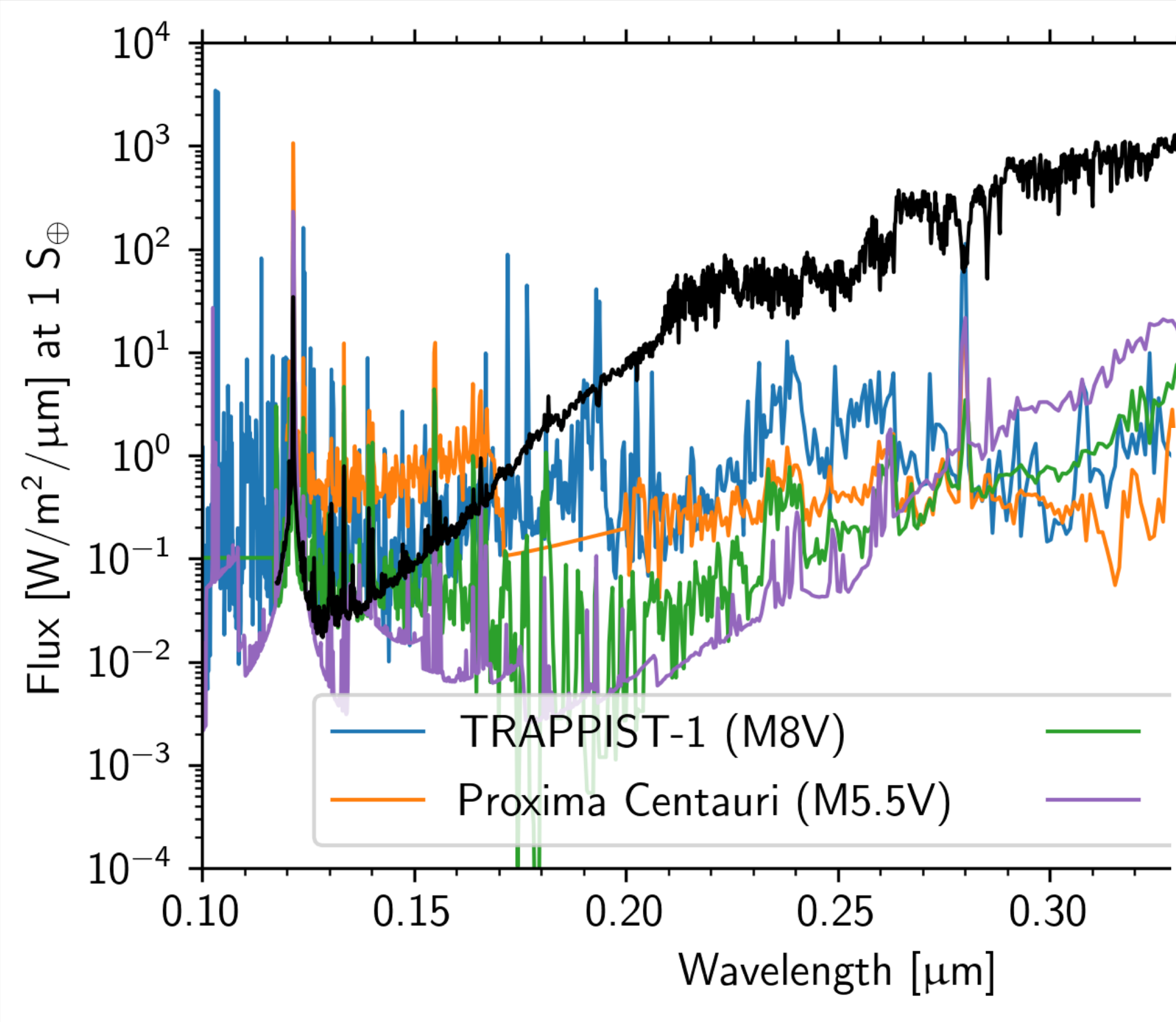
Fig. 3 Biennal mean surface temperatures of completely dry atmospheres, for 2 orbital configurations (synchronous and 3:2 orbital resonance) and 4 atmospheric compositions and pressures (6 bars of pure CO_2, 4 bars of pure CO_2, 1 bar of pure CO_2 and 1 bar of N_2 + 376 ppm of CO_2 – Earth-like atmosphere). The solid black line contour corresponds to the 273.15 K isotherm; the dashed blue line contour indicates the regions where the atmospheric CO_2 collapses permanently into CO_2 ice deposits. The 1 bar pure CO_2 (synchronous) simulation is not stable in the long term since CO_2 would collapse at the two cold points.

However….Many M Dwarf Planets Are in Close-packed, Multi-planet Systems

- Multi-planet systems will perturb each other and may avoid synchronous rotation (Ribas et al., 2016; Barnes et al., 2018)

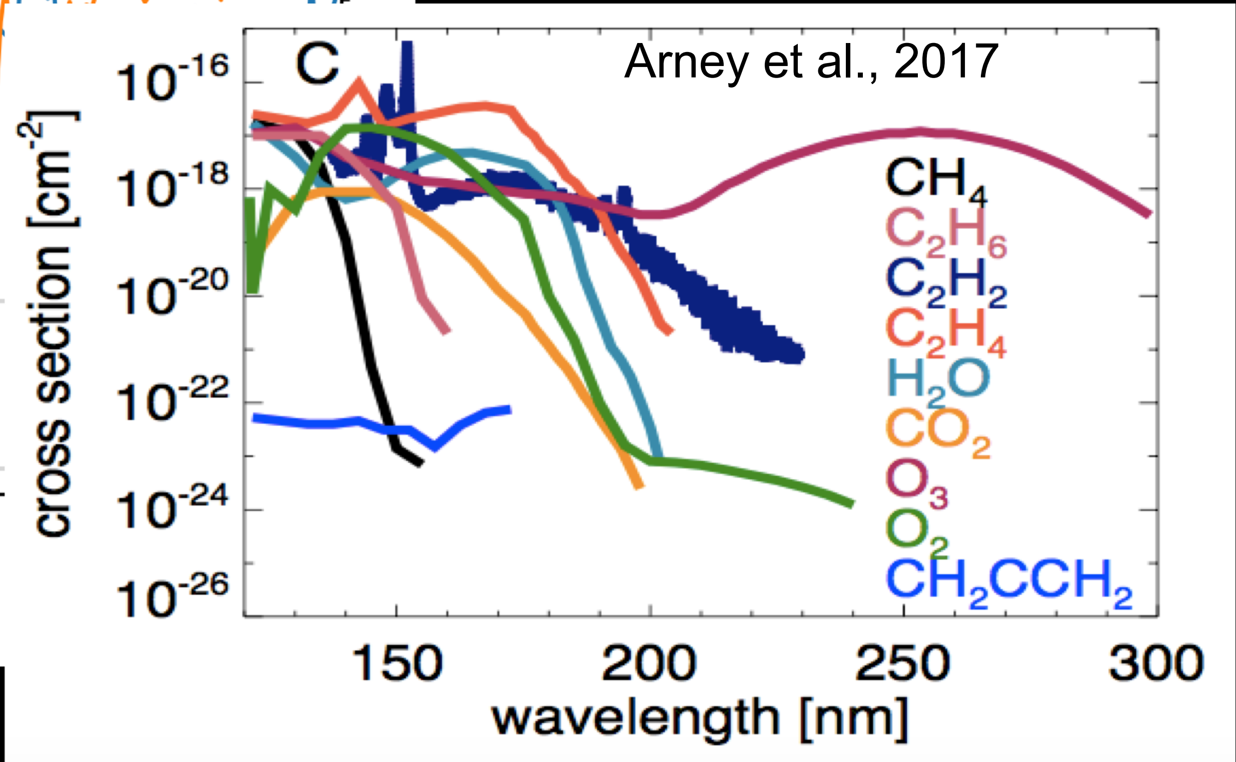


The importance of the stellar spectrum

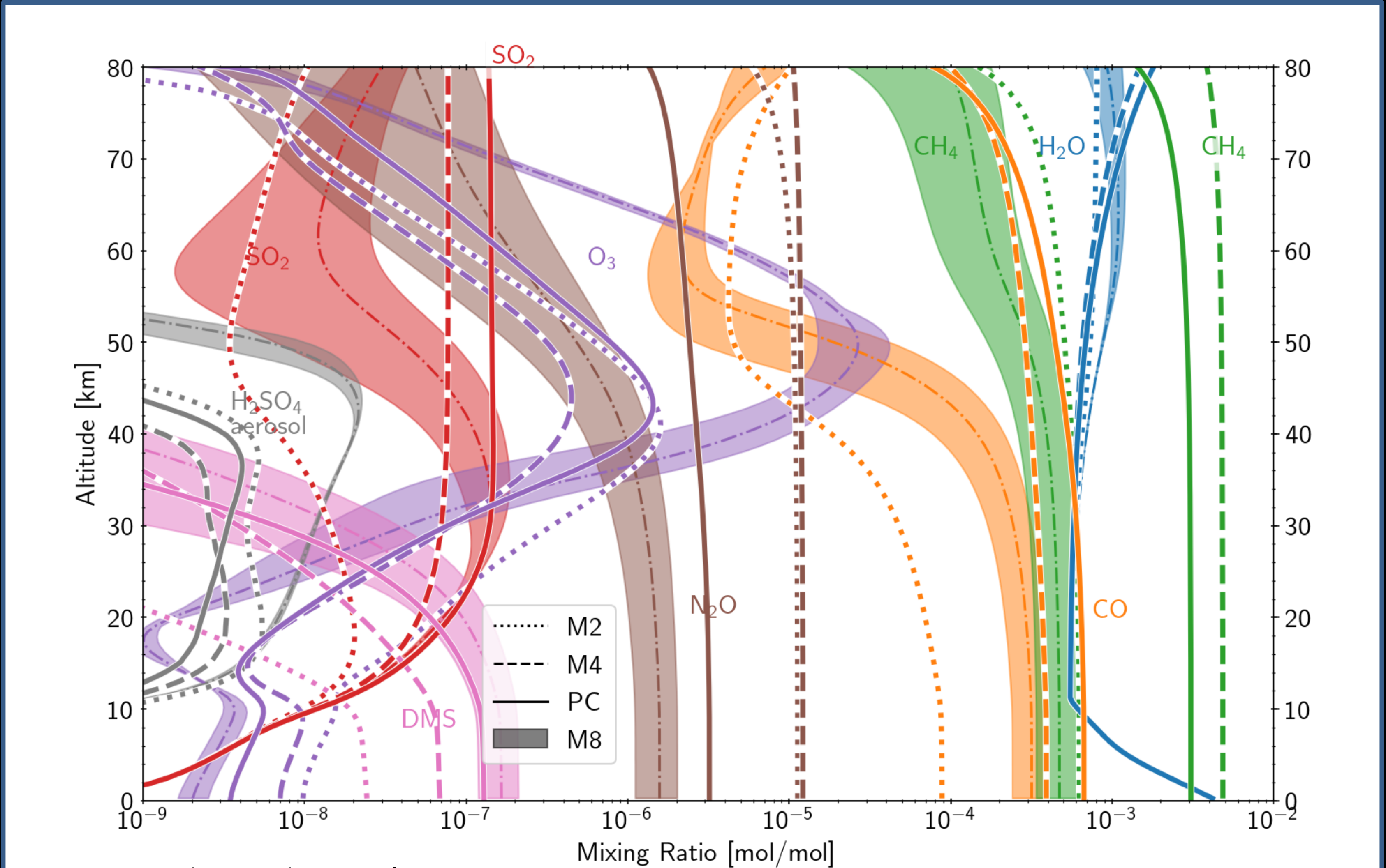


Different stellar SEDs drive different climate and chemistry and will change atmospheric composition

Direct photolysis is important, but so is the generation and destruction of catalysts
Protons matter too…



The stellar spectrum drives photochemistry, modifies composition



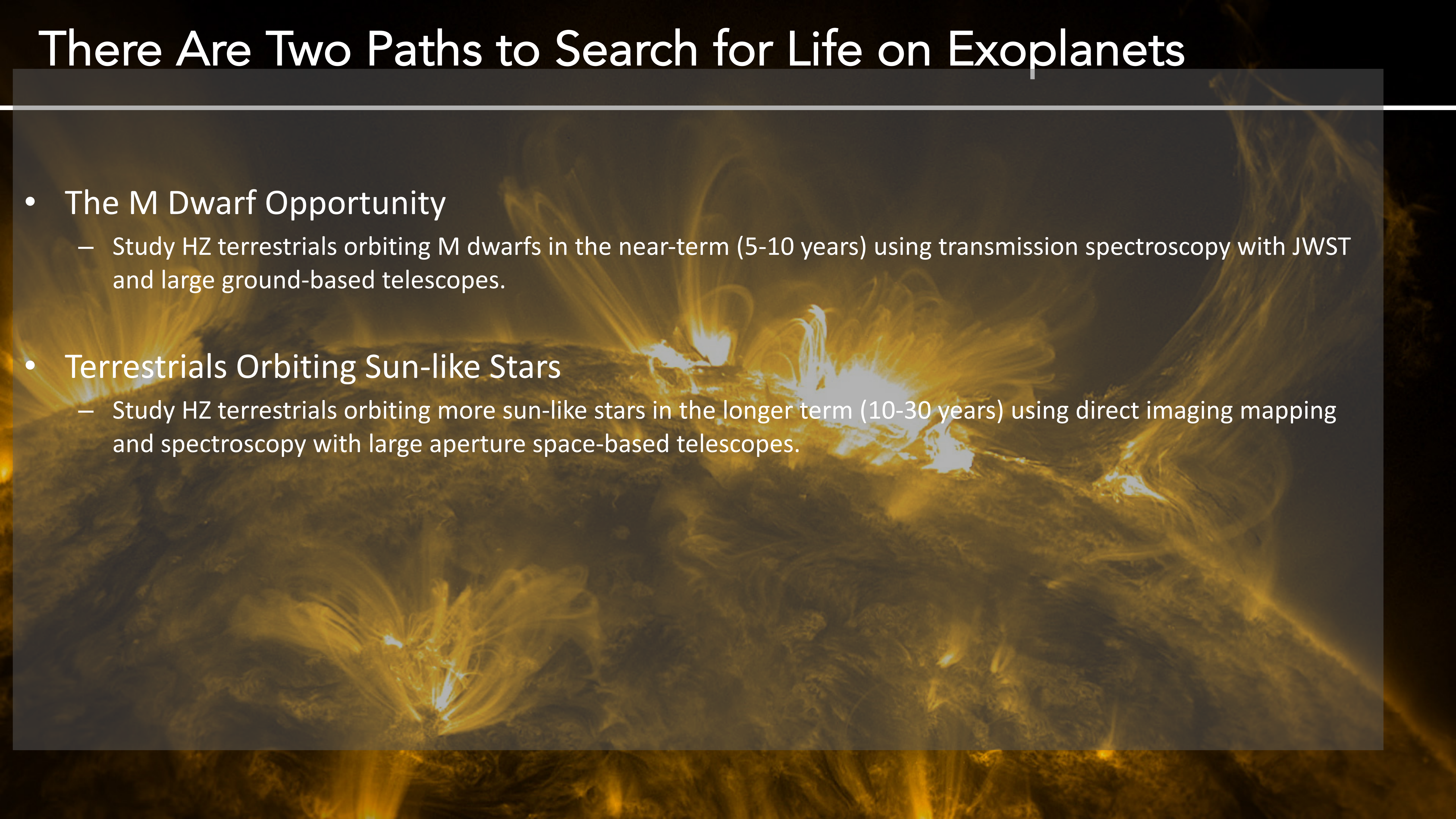
Davis, Lincowski, Meadows et al., in prep.

CH$_4$, N$_2$O and O$_3$ are strongly affected (and all are biosignatures)

Ly**α** can directly photolyze CH$_4$. Photolysis of water vapor ultimately produces catalysts that also destroy CH$_4$.

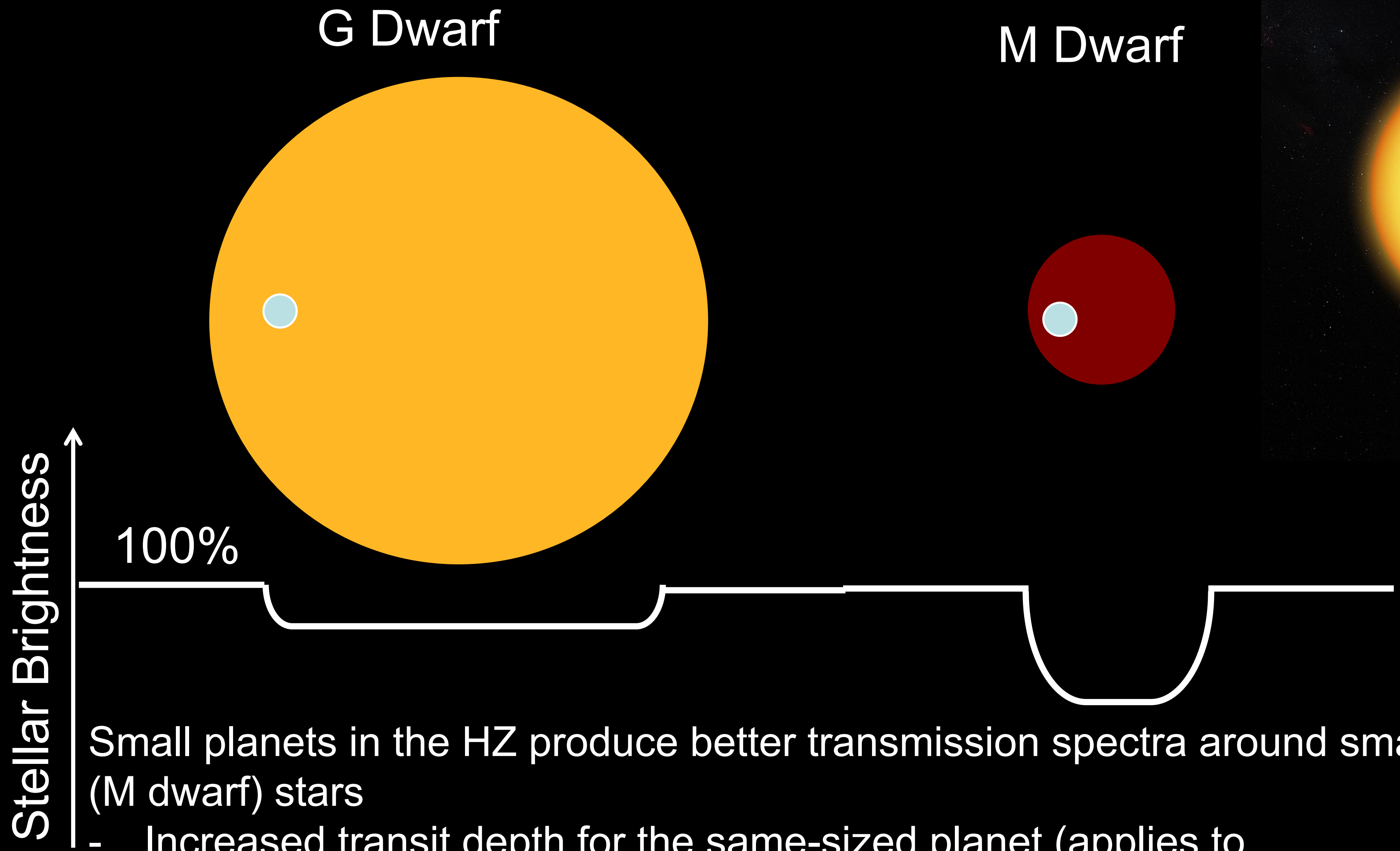
N$_2$O is directly photolyzed

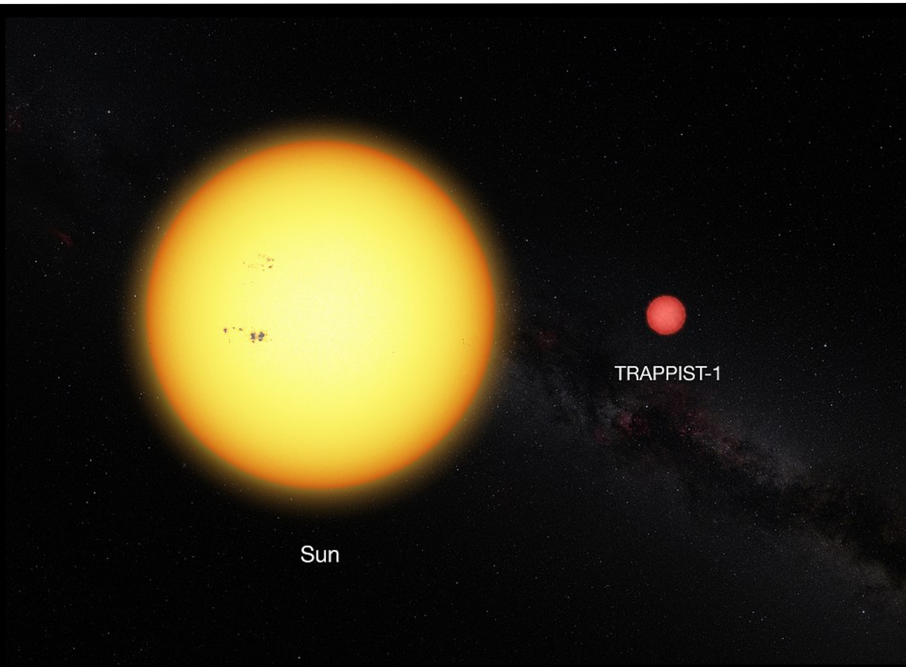
There Are Two Paths to Search for Life on Exoplanets



- The M Dwarf Opportunity
  - Study HZ terrestrials orbiting M dwarfs in the near-term (5-10 years) using transmission spectroscopy with JWST and large ground-based telescopes.
- Terrestrials Orbiting Sun-like Stars
  - Study HZ terrestrials orbiting more sun-like stars in the longer term (10-30 years) using direct imaging mapping and spectroscopy with large aperture space-based telescopes.

We will get the opportunity to observe M dwarf HZ terrestrials first



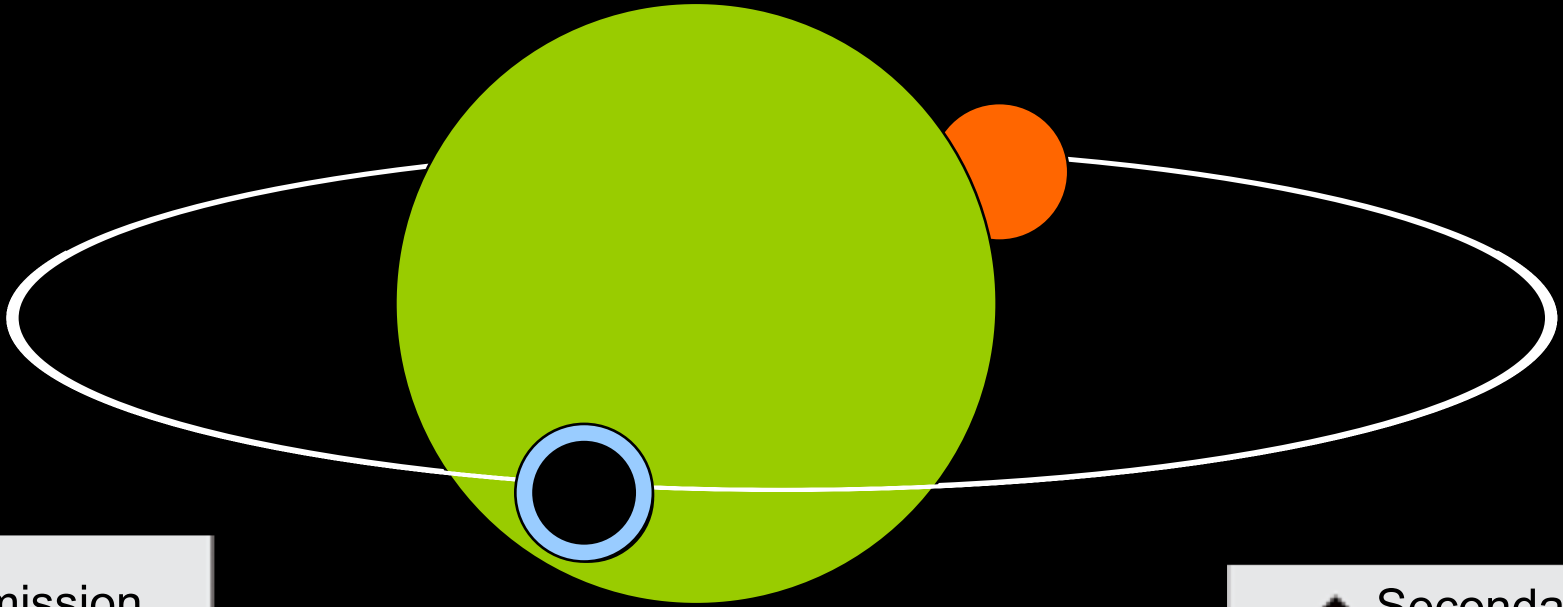


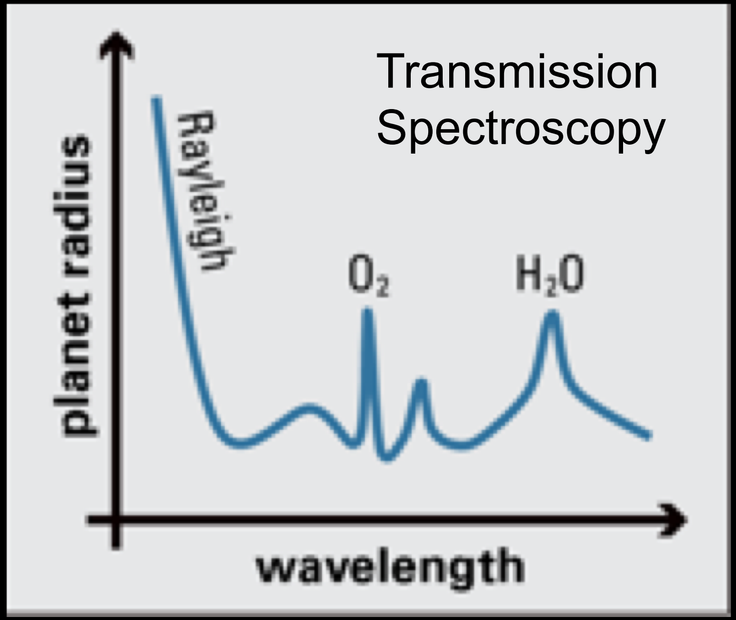
TRAPPIST-1 is not much bigger than Jupiter!

Small planets in the HZ produce better transmission spectra around small (M dwarf) stars

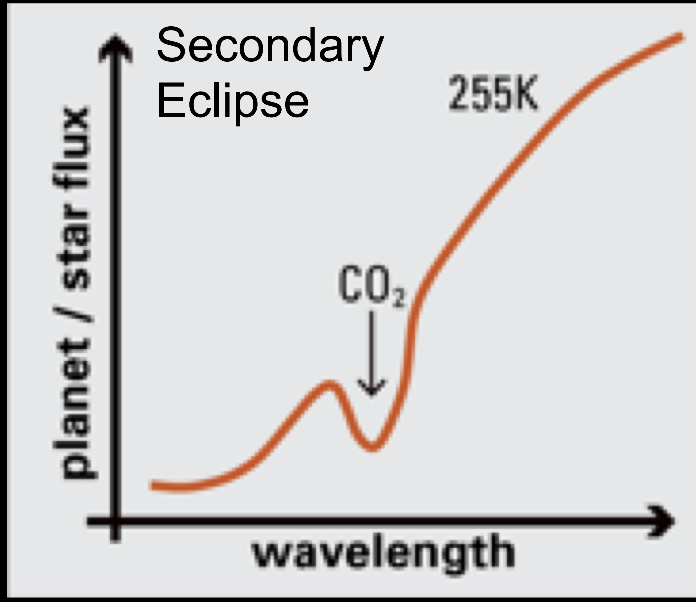
- Increased transit depth for the same-sized planet (applies to atmospheric absorption too)

In the near term, JWST will probe the atmospheres of terrestrial exoplanets





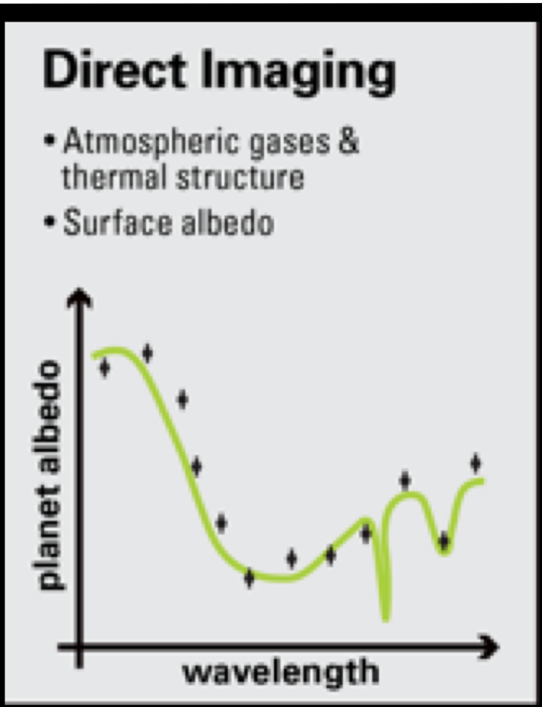
The Origins Space telescope
(2030s) may also use this technique



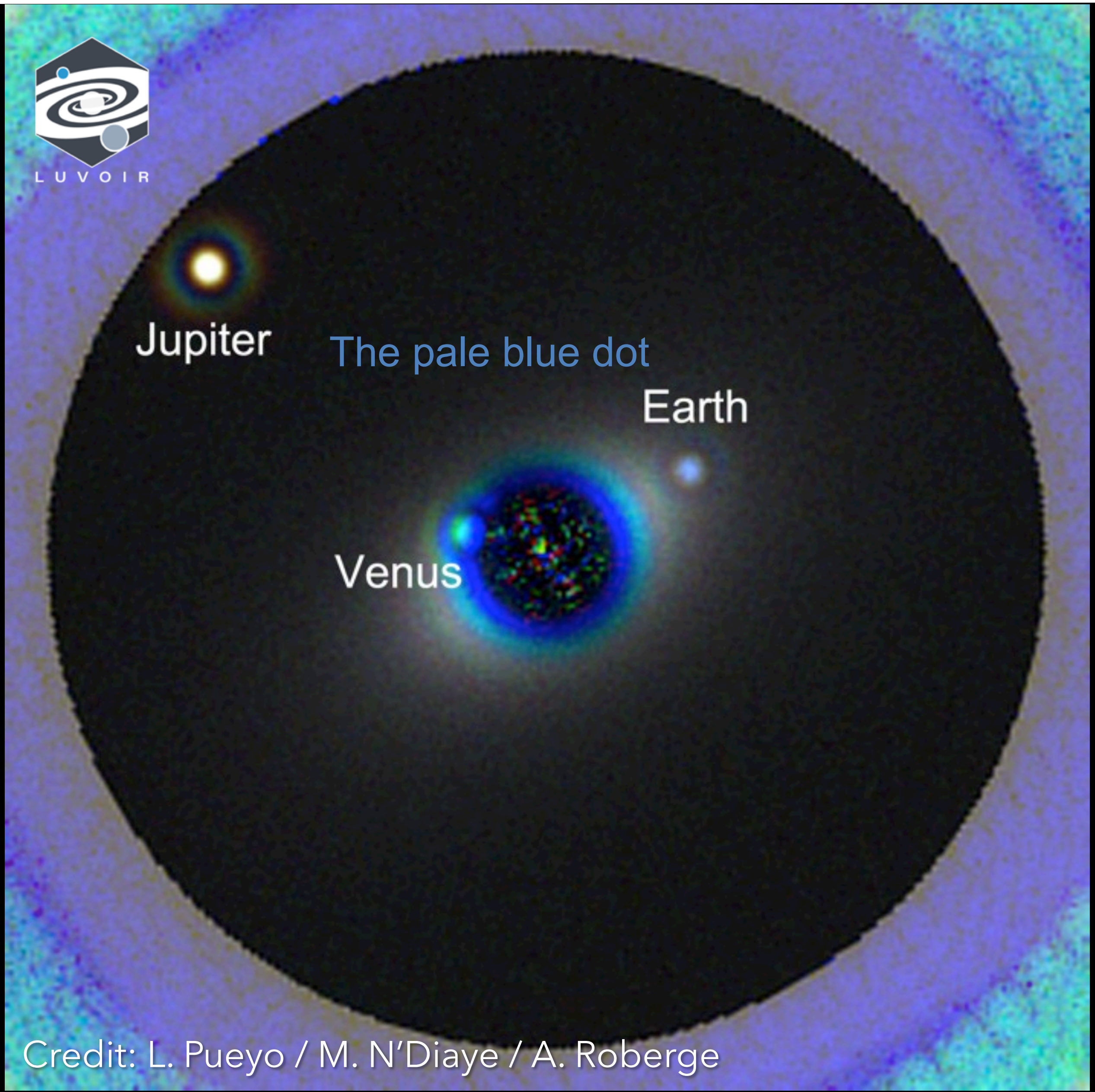
The thin blue line

J. Grunsfeld

Further in the future, large telescopes may study FGK(M) HZ terrestrials

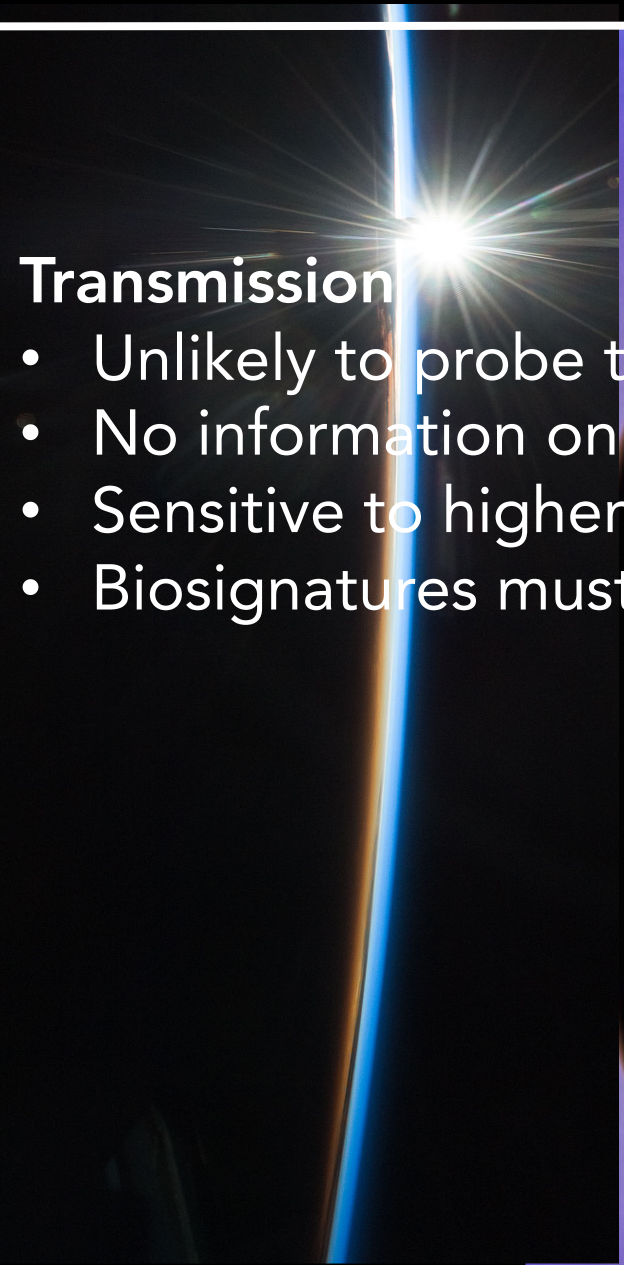


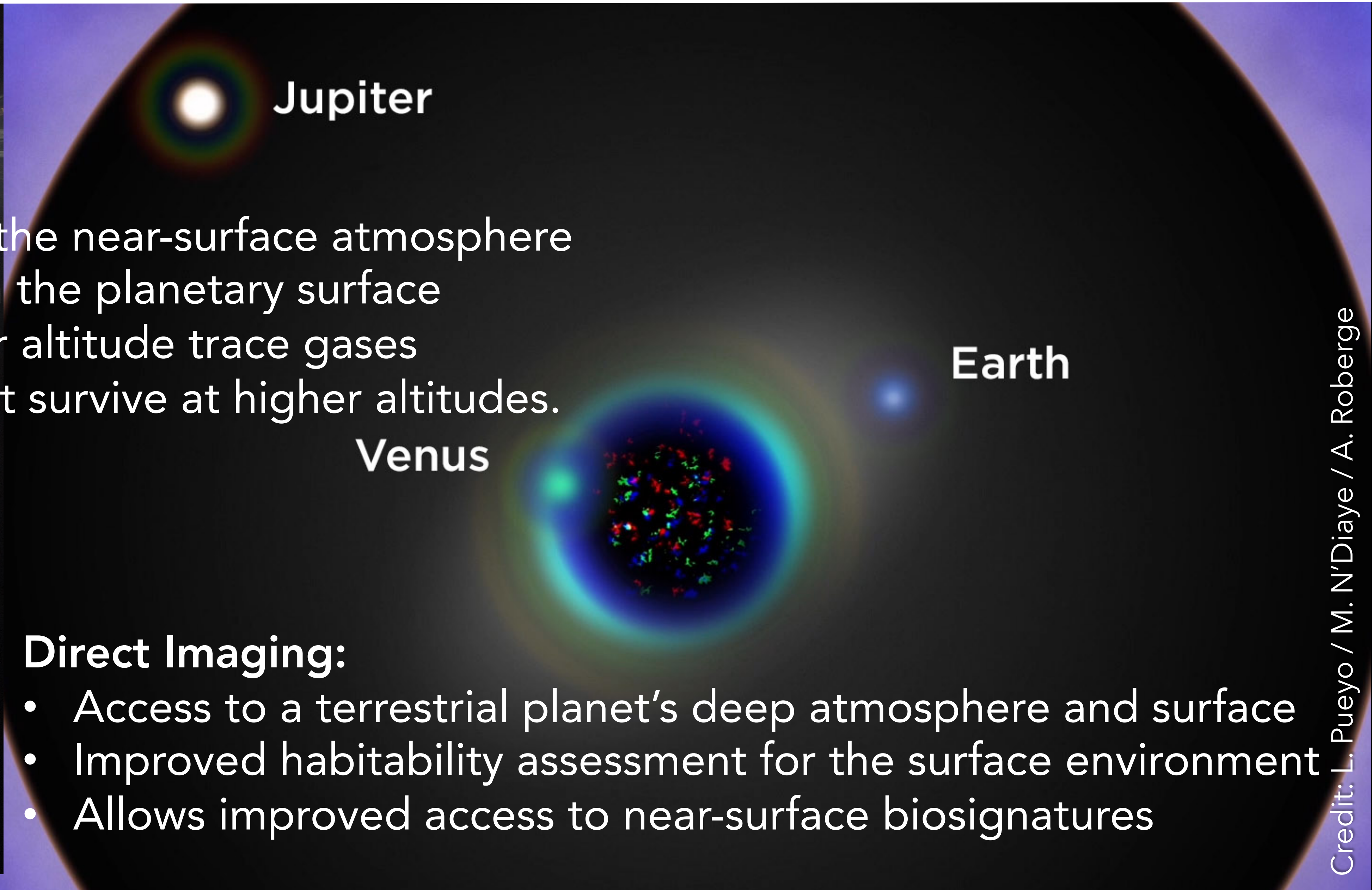
- UV-NIR from space (HabEx/LUVOIR),
- MIR thermal wavelengths from the ground (ELT/METIS).



Credit: L. Pueyo / M. N’Diaye / A. Roberge

Transmission, Direct Imaging, and Astrobiology





Credit: L. Pueyo / M. N'Diaye / A. Roberge

Transmission

- Unlikely to probe the near-surface atmosphere
- No information on the planetary surface
- Sensitive to higher altitude trace gases
- Biosignatures must survive at higher altitudes.

Direct Imaging:

- Access to a terrestrial planet's deep atmosphere and surface
- Improved habitability assessment for the surface environment
- Allows improved access to near-surface biosignatures

Searching for Habitability and Life

Does it have an atmosphere?
What is the nature of its atmosphere?
Does it have an ocean?
Are there signs of life?

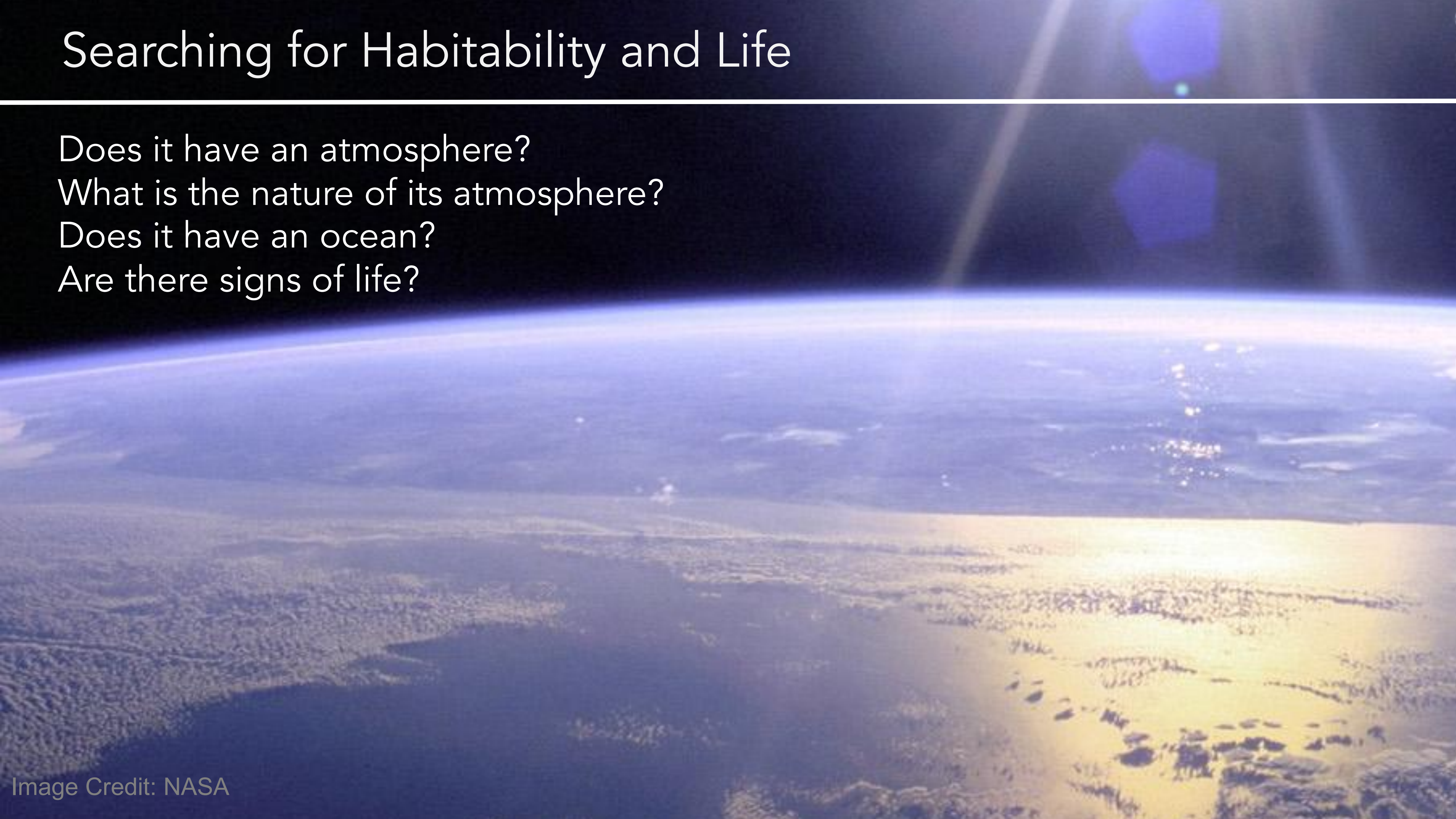


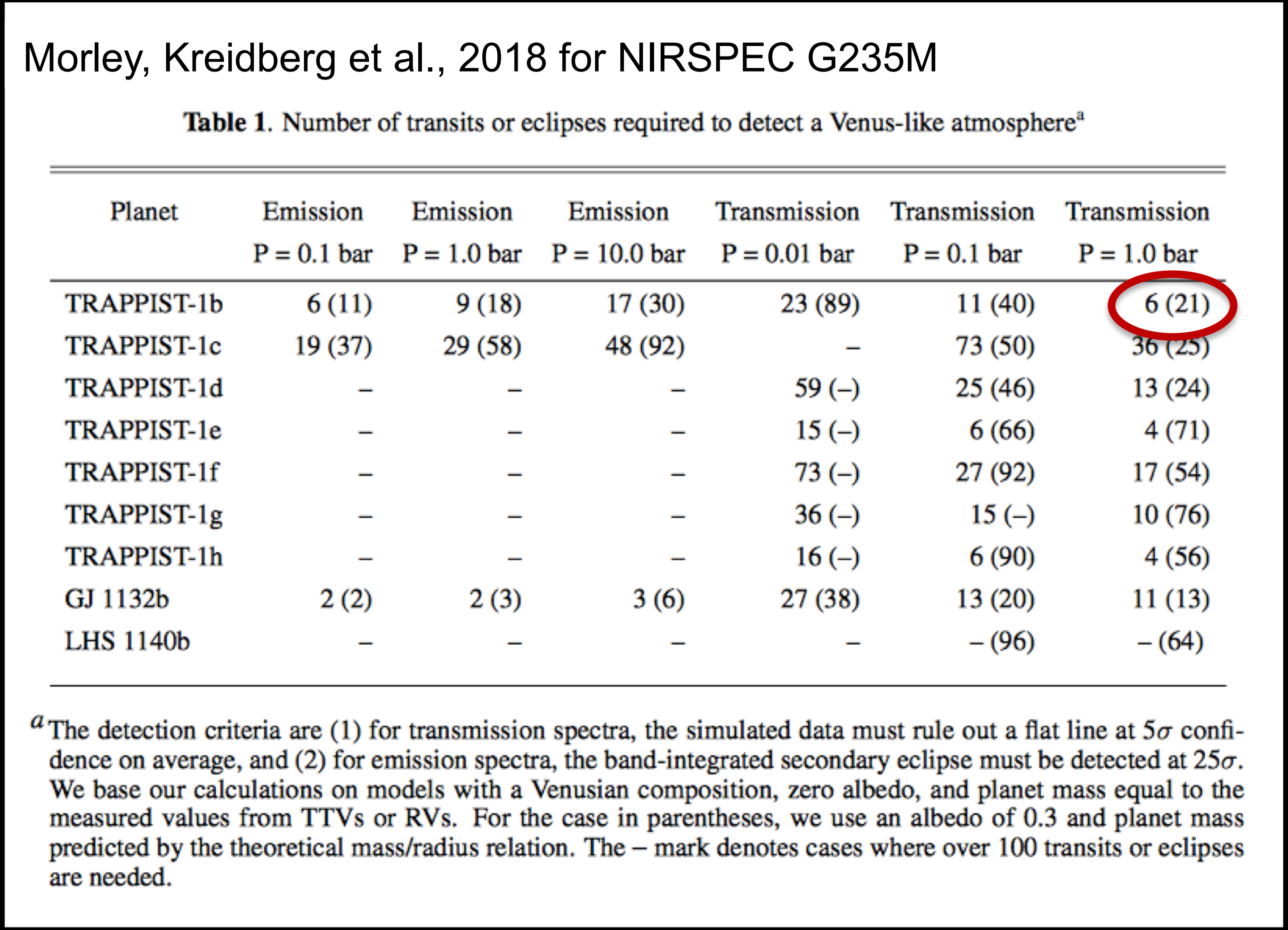
Image Credit: NASA

Does it have an atmosphere?

1. Does it have an atmosphere?
2. What is the nature of its atmosphere?
3. Does it have an ocean?
4. Are there signs of life?

Image Credit: NASA

Atmosphere detection is likely straightforward

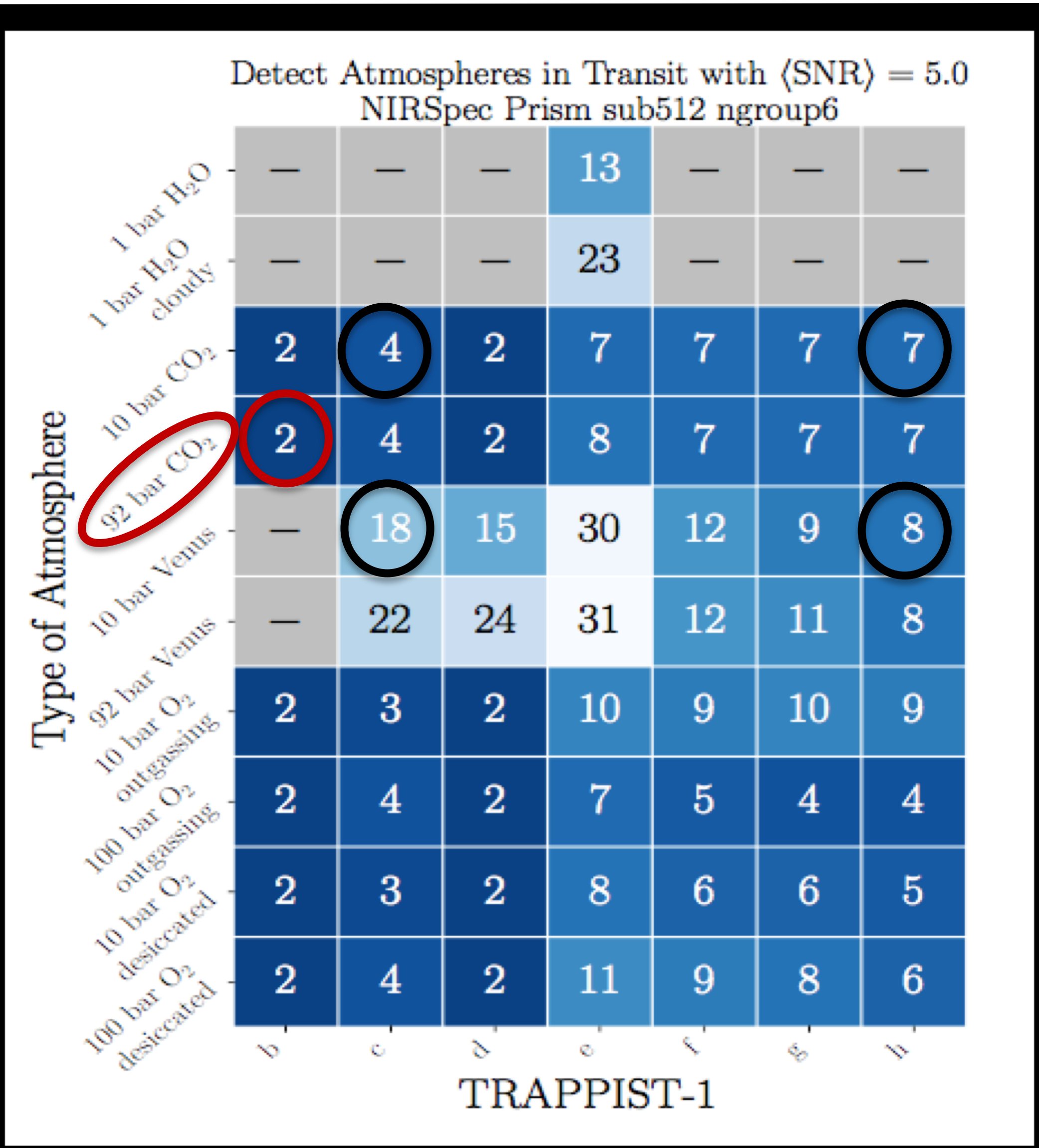


Morley, Kreidberg et al., 2018 for NIRSPEC G235M

Table 1. Number of transits or eclipses required to detect a Venus-like atmosphere[a]

Planet	Emission P = 0.1 bar	Emission P = 1.0 bar	Emission P = 10.0 bar	Transmission P = 0.01 bar	Transmission P = 0.1 bar	Transmission P = 1.0 bar
TRAPPIST-1b	6 (11)	9 (18)	17 (30)	23 (89)	11 (40)	6 (21)
TRAPPIST-1c	19 (37)	29 (58)	48 (92)	–	73 (50)	36 (25)
TRAPPIST-1d	–	–	–	59 (–)	25 (46)	13 (24)
TRAPPIST-1e	–	–	–	15 (–)	6 (66)	4 (71)
TRAPPIST-1f	–	–	–	73 (–)	27 (92)	17 (54)
TRAPPIST-1g	–	–	–	36 (–)	15 (–)	10 (76)
TRAPPIST-1h	–	–	–	16 (–)	6 (90)	4 (56)
GJ 1132b	2 (2)	2 (3)	3 (6)	27 (38)	13 (20)	11 (13)
LHS 1140b	–	–	–	–	– (96)	– (64)

[a] The detection criteria are (1) for transmission spectra, the simulated data must rule out a flat line at 5σ confidence on average, and (2) for emission spectra, the band-integrated secondary eclipse must be detected at 25σ. We base our calculations on models with a Venusian composition, zero albedo, and planet mass equal to the measured values from TTVs or RVs. For the case in parentheses, we use an albedo of 0.3 and planet mass predicted by the theoretical mass/radius relation. The – mark denotes cases where over 100 transits or eclipses are needed.



Detect Atmospheres in Transit with $\langle \mathrm{SNR} \rangle = 5.0$
NIRSpec Prism sub512 ngroup6

Type of Atmosphere	b	c	d	e	f	g	h
1 bar H_2O	—	—	—	13	—	—	—
1 bar H_2O cloudy	—	—	—	23	—	—	—
10 bar CO_2	2	4	2	7	7	7	7
92 bar CO_2	2	4	2	8	7	7	7
10 bar Venus	—	18	15	30	12	9	8
92 bar Venus	—	22	24	31	12	11	8
10 bar O_2 outgassing	2	3	2	10	9	10	9
100 bar O_2 outgassing	2	4	2	7	5	4	4
10 bar O_2 desiccated	2	3	2	8	6	6	5
100 bar O_2 desiccated	2	4	2	11	9	8	6

Lustig-Yaeger et al., 2019

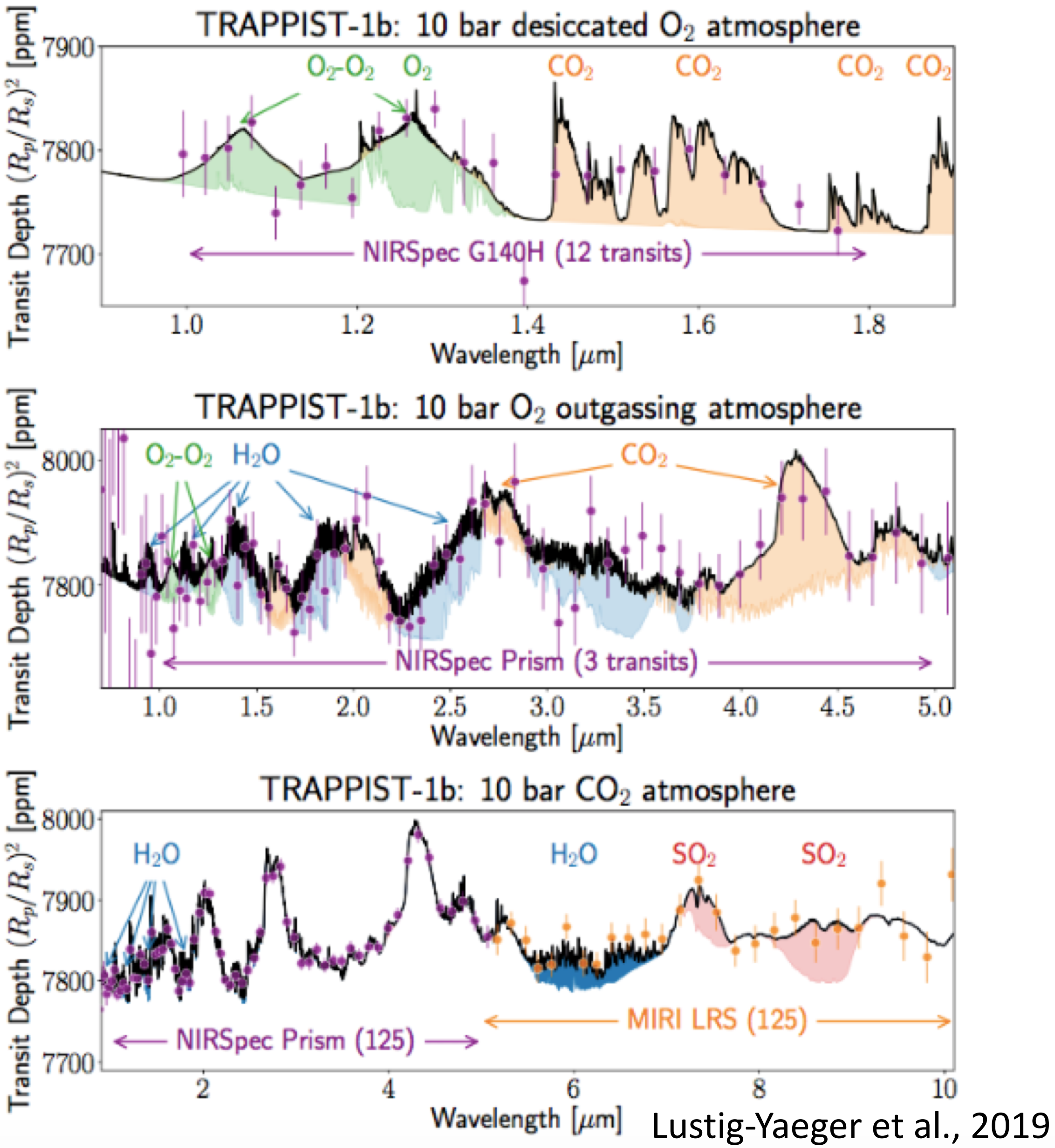
- A high molecular-weight atmosphere may be detected in as little as 2 transits. This will largely be driven by CO_2 features.
- Clouds increase integration times for interior planets

What is the nature of that atmosphere?

- Does it have an atmosphere?
- What is the nature of its atmosphere?
- Does it have an ocean?
- Are there signs of life?

Image Credit: NASA

Possible limited characterization of planetary atmospheres



Lustig-Yaeger et al., 2019

CO_2, H_2O, O_3, O_2-O_2 may be detectable in the atmosphere of TRAPPIST-1 b in relatively few transits (3-12)

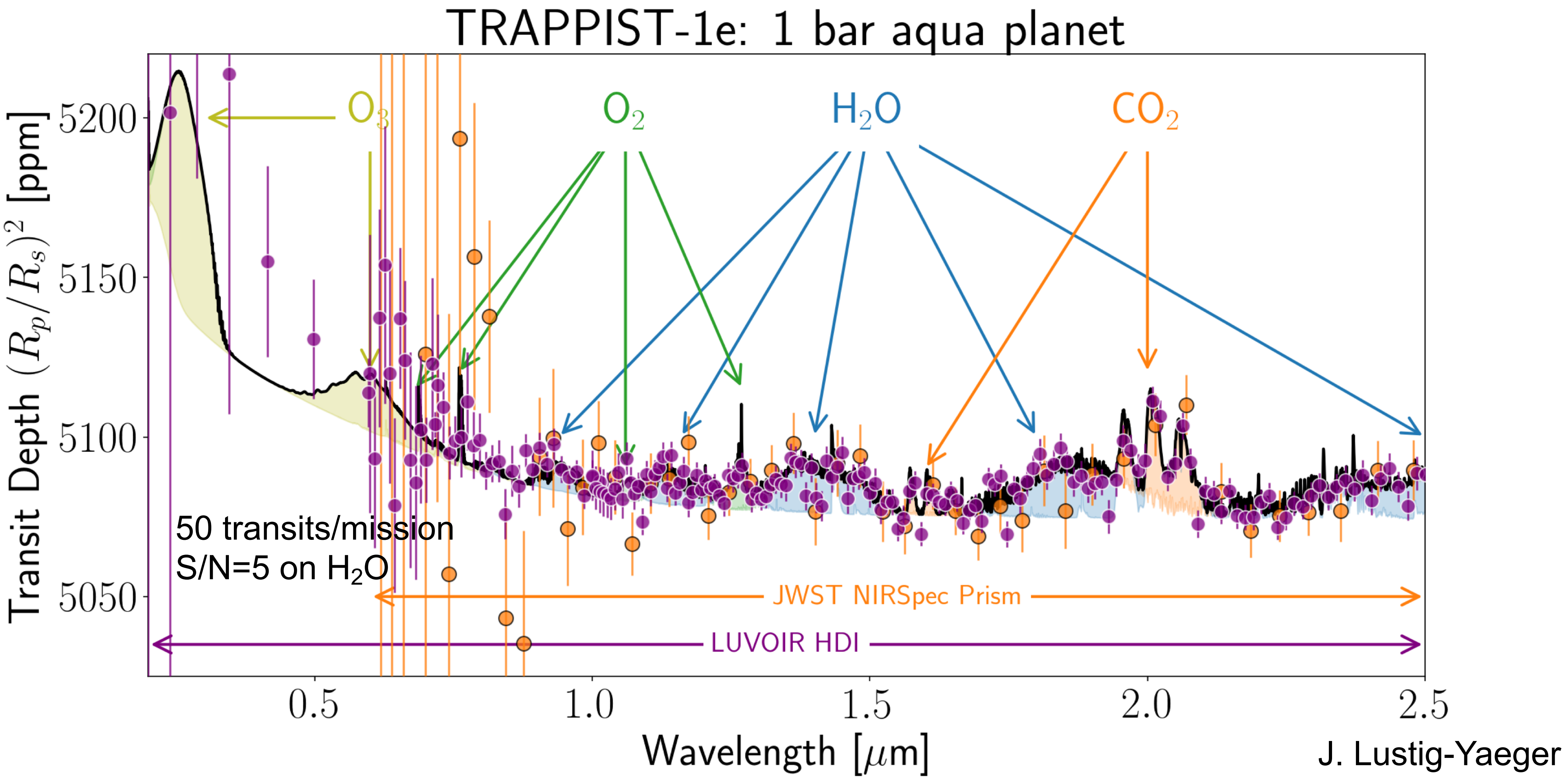
To assess this planet's evolutionary state:

1. detect a planetary atmosphere via CO_2 absorption (>2 transits)

2. detect or rule out a post-runaway oxygen-dominated atmosphere via O_2-O_2 CIA or O_3 absorption (> 12 transits)
NB: This is an observational test of the HZ concept.

3. constrain outgassing from the interior and potential habitability via the H_2O abundance and presence of SO_2 (> 125 transits)

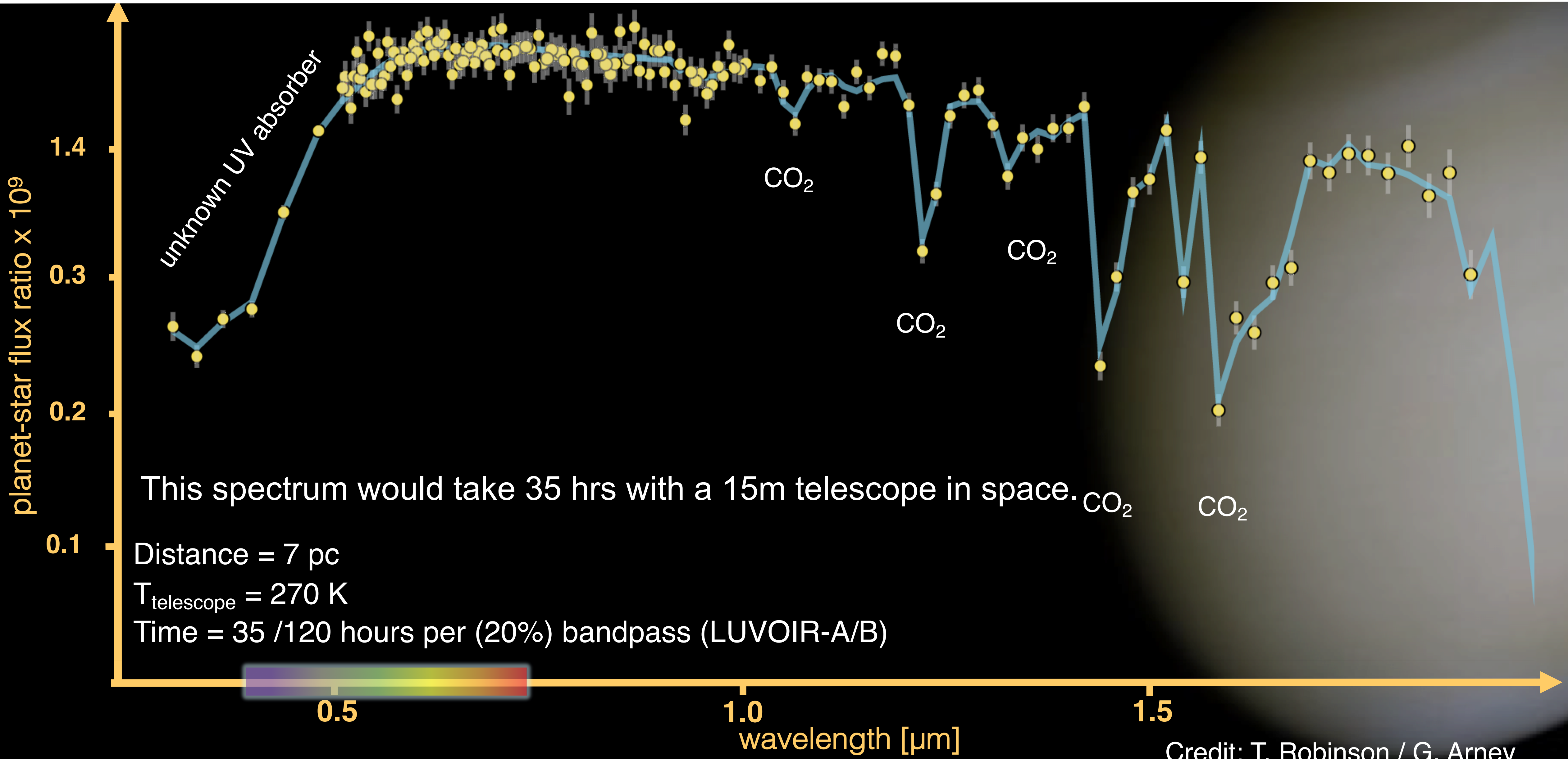
LUVOIR Transmission Spectroscopy



50 transits/mission
S/N=5 on H_2O

J. Lustig-Yaeger

Exo-Venus seen with a LUVOIR direct imaging mission



This spectrum would take 35 hrs with a 15m telescope in space.

Distance = 7 pc

$T_{telescope}$ = 270 K

Time = 35 /120 hours per (20%) bandpass (LUVOIR-A/B)

Credit: T. Robinson / G. Arney

Does it have an ocean?

Can we detect surface temperature and pressure?
Can we constrain climate models with atmospheric composition?
Does it lack water soluble gases in the atmosphere?
Can we detect surface liquid water?

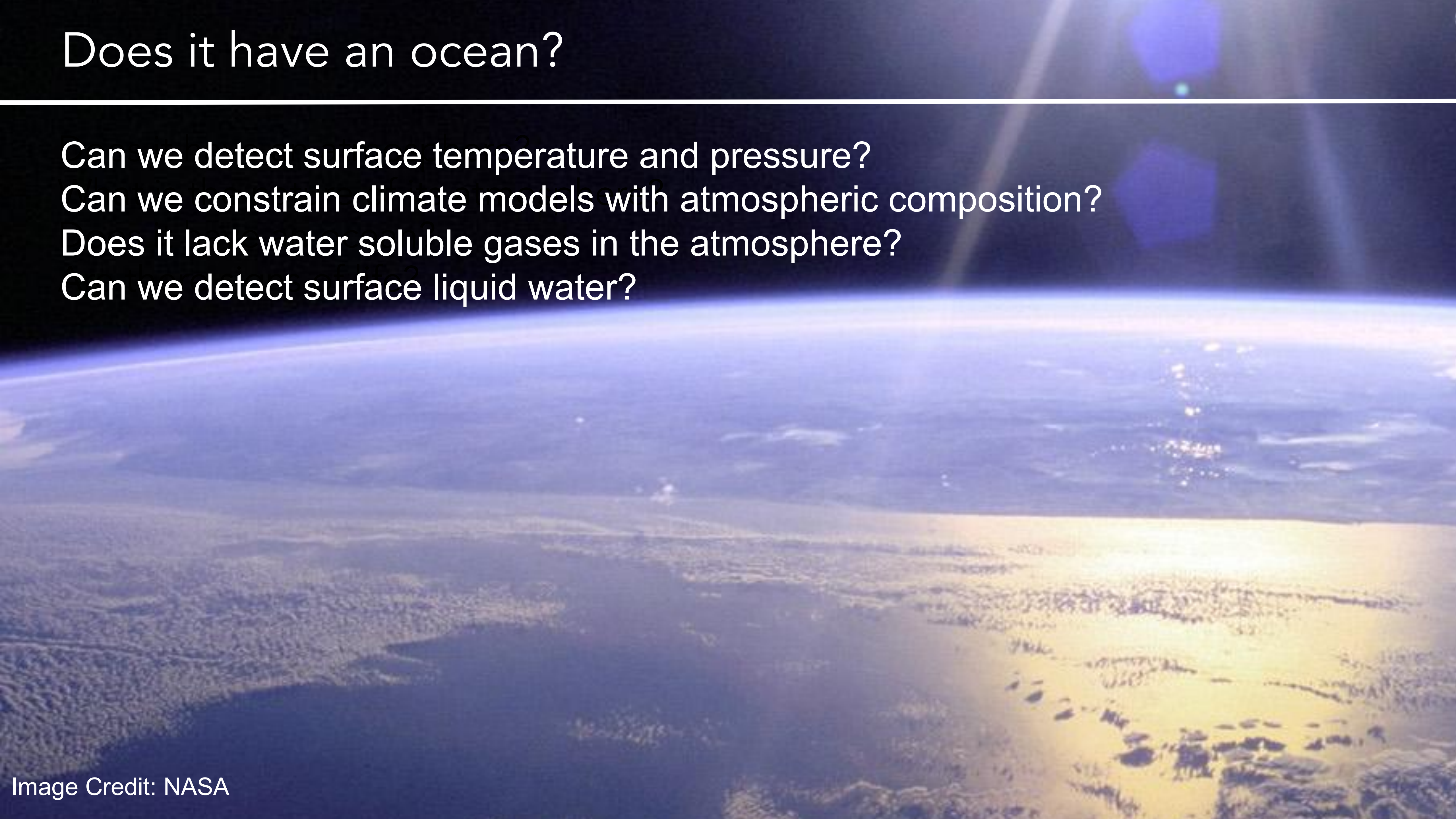
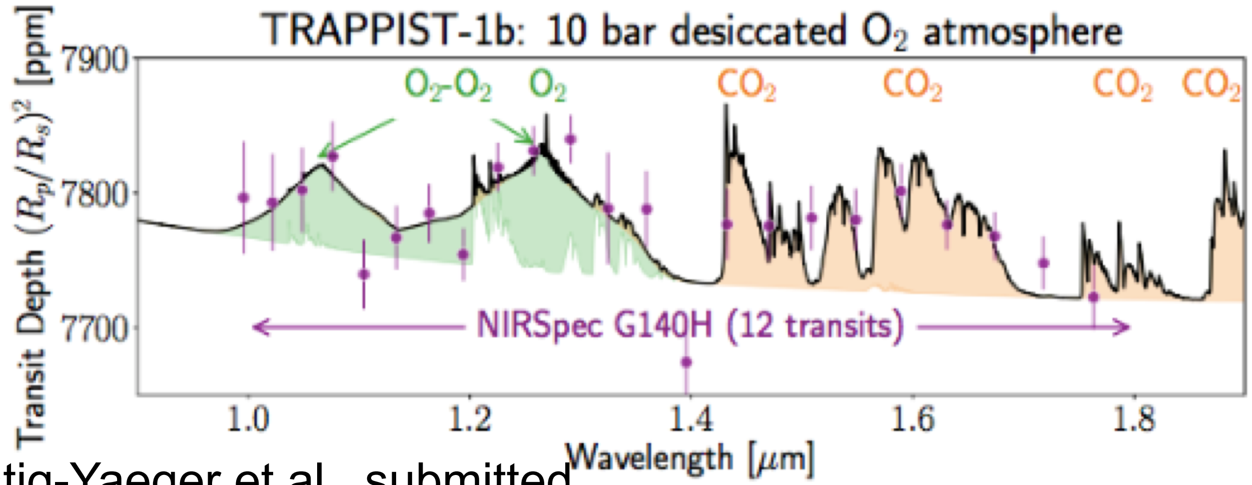


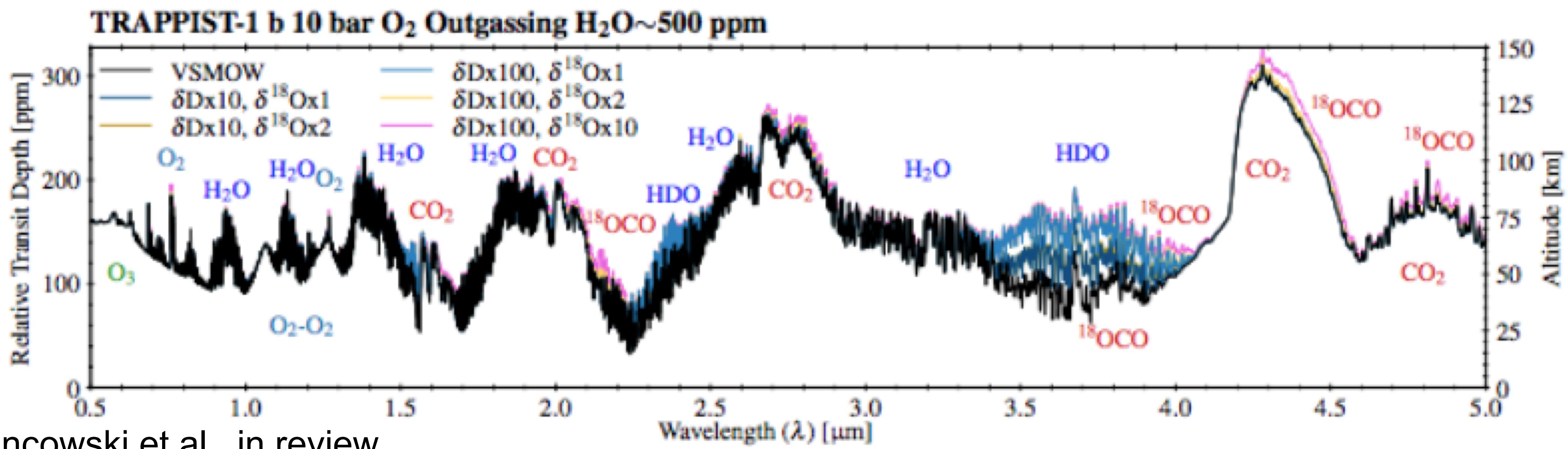
Image Credit: NASA

Does it have an ocean?



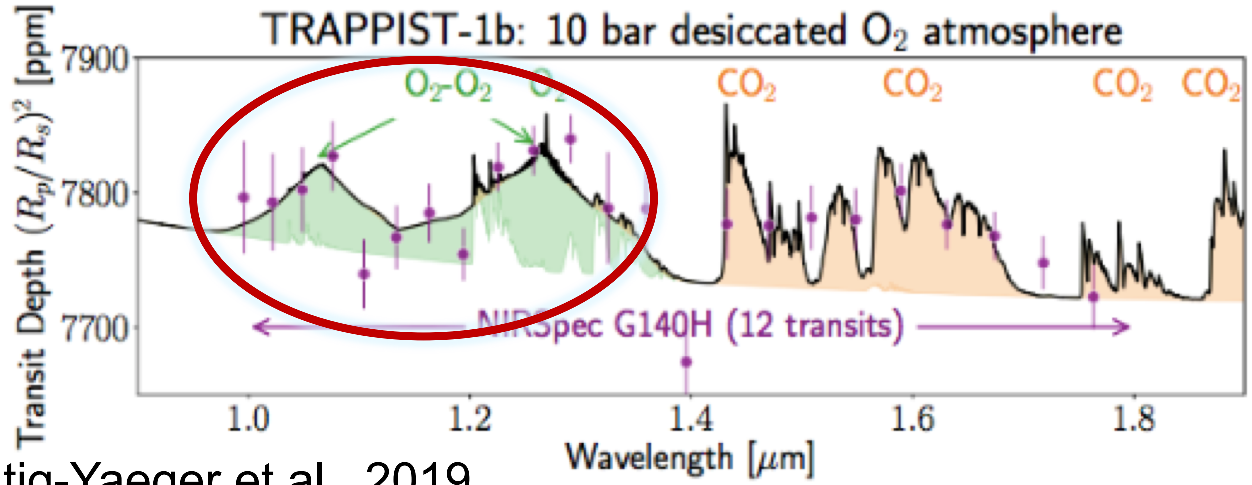
Lustig-Yaeger et al., submitted

- With JWST, detecting signs of ocean loss may be easier than signs of a present ocean.
- Ocean loss can be revealed via O_2-O_2 and even HDO to attempt to determine D/H ratio.
- May detect HDO in as few as 10 transits

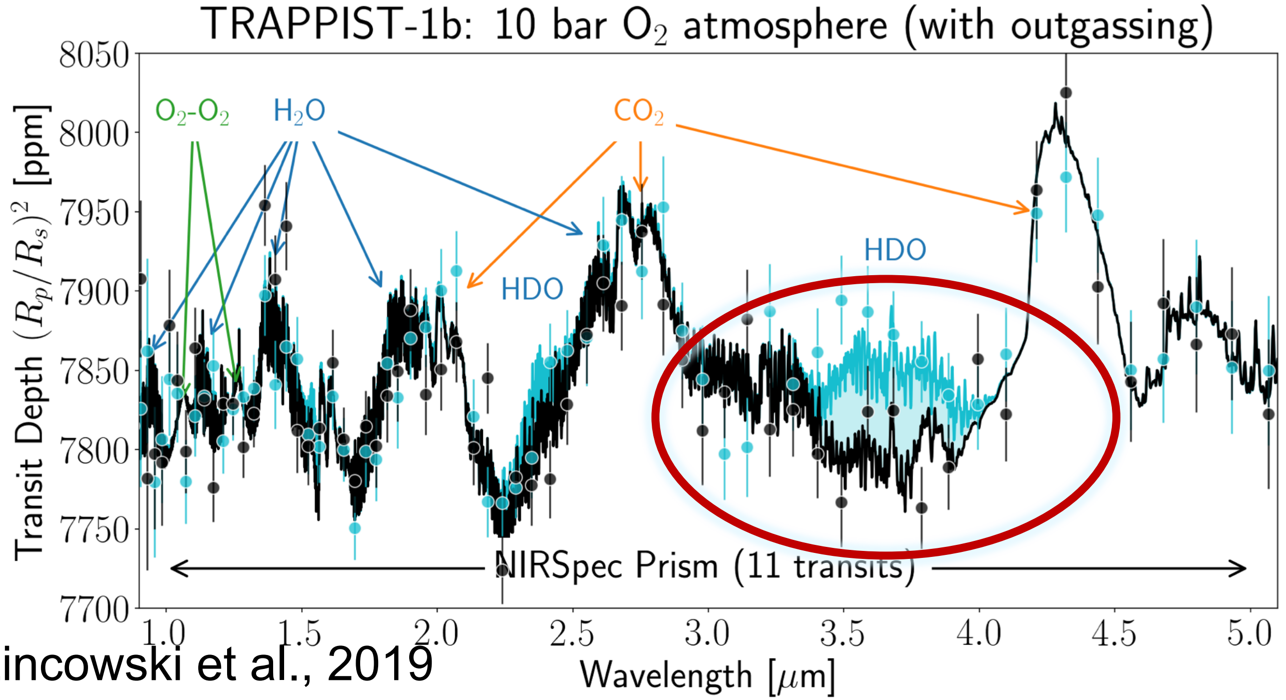


Lincowski et al., in review

We may be able to identify past ocean loss with JWST



Lustig-Yaeger et al., 2019

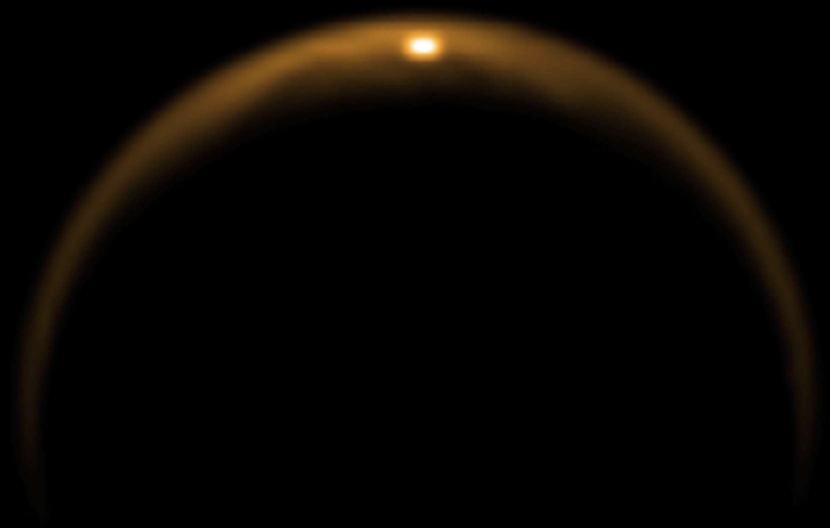


Lincowski et al., 2019

- With JWST, detecting signs of ocean loss may be easier than signs of a present ocean.
- Ocean loss can be revealed via O_2-O_2 and even HDO to attempt to determine D/H ratio.
- If we see D/H fractionation, it may indicate that an ocean is not present.
- May detect HDO in as few as 10 transits (Lincowski et al., 2019).

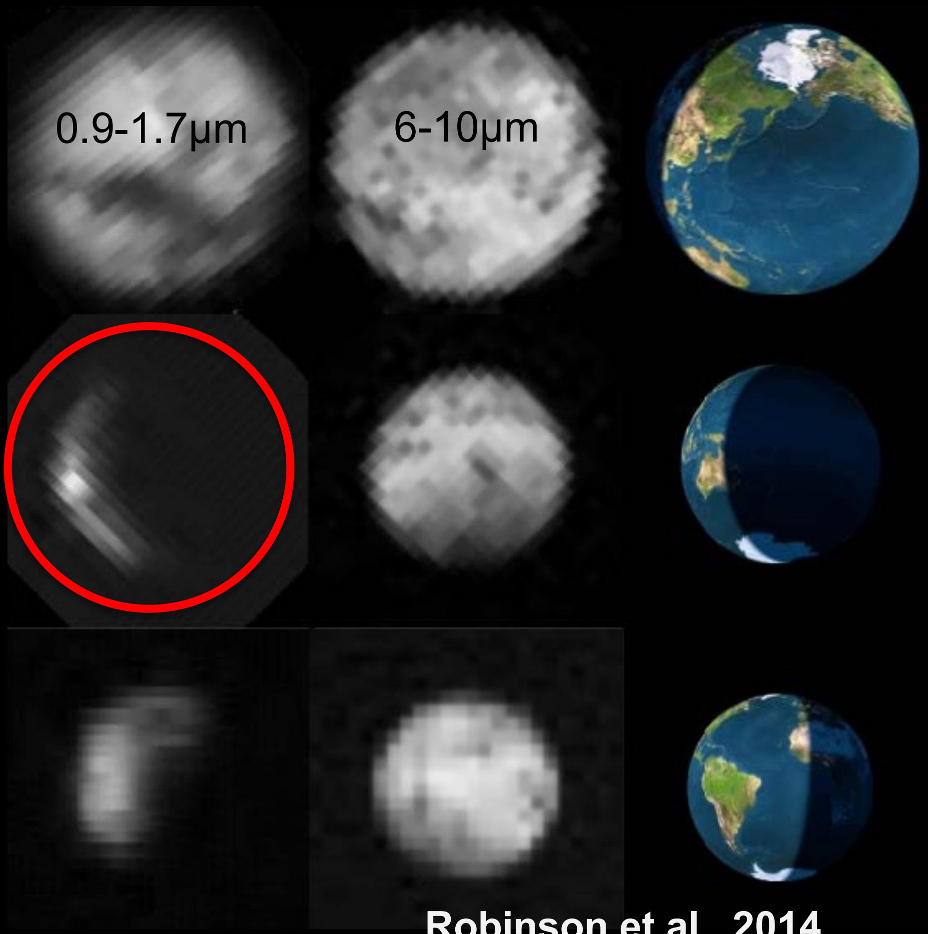
Does It Have an Ocean? Solar System Direct Imaging

Titan



Stephan et al., 2010
Cassini VIMS image of Kraken Mare

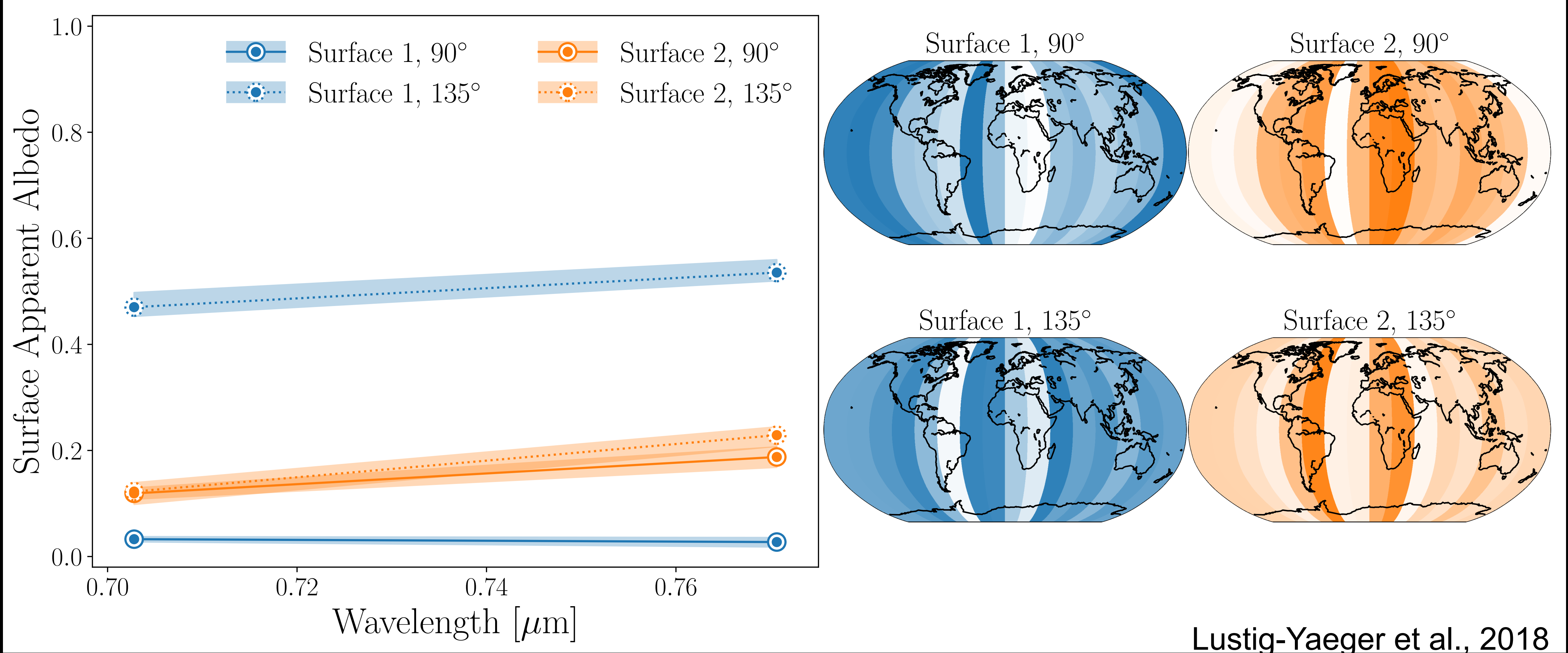
Earth



Robinson et al., 2014
LCROSS images of Earth

Ocean glint at NIR wavelengths will **not** be possible for Proxima Cen b with JWST (Meadows et al., 2018b)
Ocean glint will be possible for some targets with future direct imaging missions such as LUVOIR (Lustig-Yaeger et al., 2018).

Exoplanet Temporal Sampling and Ocean Mapping



Lustig-Yaeger et al., 2018

- Time-resolved (1hr), multi-wavelength direct imaging observations map and identify surfaces that change reflectivity behavior with phase – more sensitive for ocean detection.
- *We can do this while acquiring a long-duration spectrum on a target.*
- The presence of an ocean can also be important for disequilibrium biosignature interpretation.

Are there signs of life?

Does it have an atmosphere?
What is the nature of its atmosphere?
Does it have an ocean?
Are there signs of life?

Image Credit: NASA

Biosignatures: Life’s Global Impact

A planetary biosignature is a way that life has globally modified its environment in a potentially detectable way.

Criteria for Identifying Biosignatures

1. Reliability

   Is it/could it be produced by life?

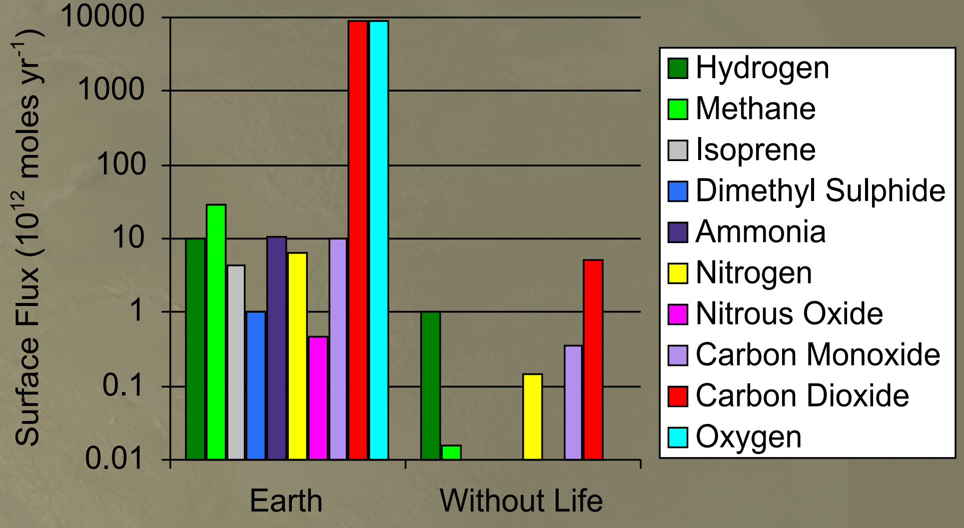
   Is it less likely to be produced by planetary processes such as geology and photochemistry?

2. Survivability

   Does it avoid the normal sinks in a planetary environment: destruction by photochemistry, reaction with volcanic gases, reaction with the surface, dissolving in an ocean?

3. Detectability

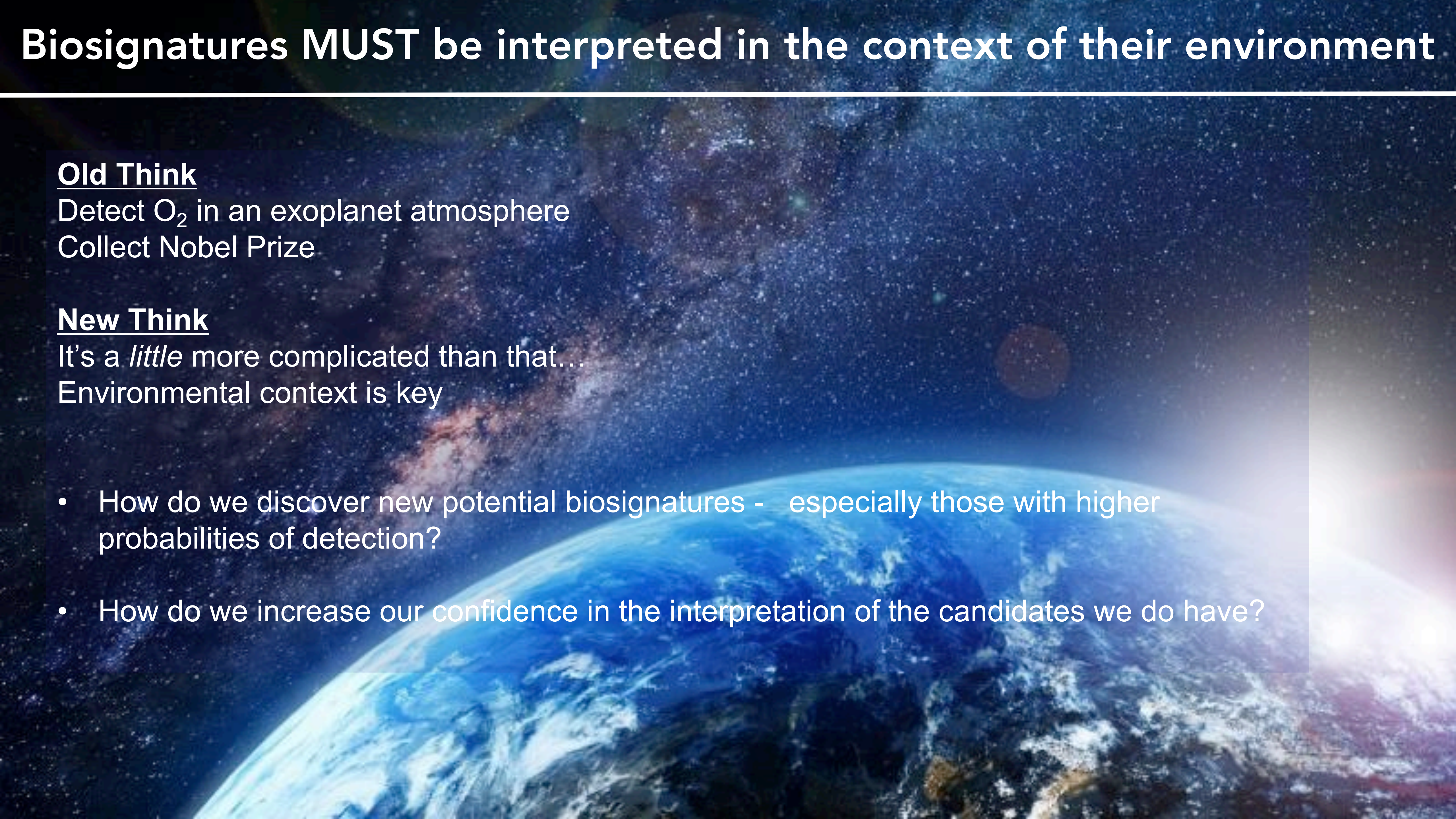
   Does it build up to detectable levels? Is it detectable using likely observing modes? Is it active in the observed wavelength region and is it clear of overlap with other common planetary species?



Tim Lenton, Nature, 1998

Meadows 2017; Meadows et al., 2018

Biosignatures MUST be interpreted in the context of their environment



Old Think

Detect O_2 in an exoplanet atmosphere
Collect Nobel Prize

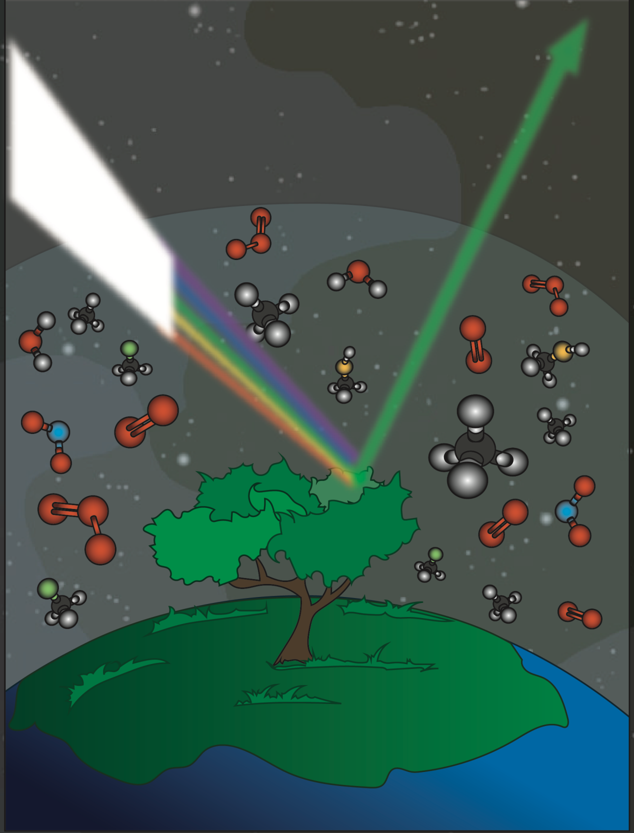
New Think

It’s a *little* more complicated than that…
Environmental context is key

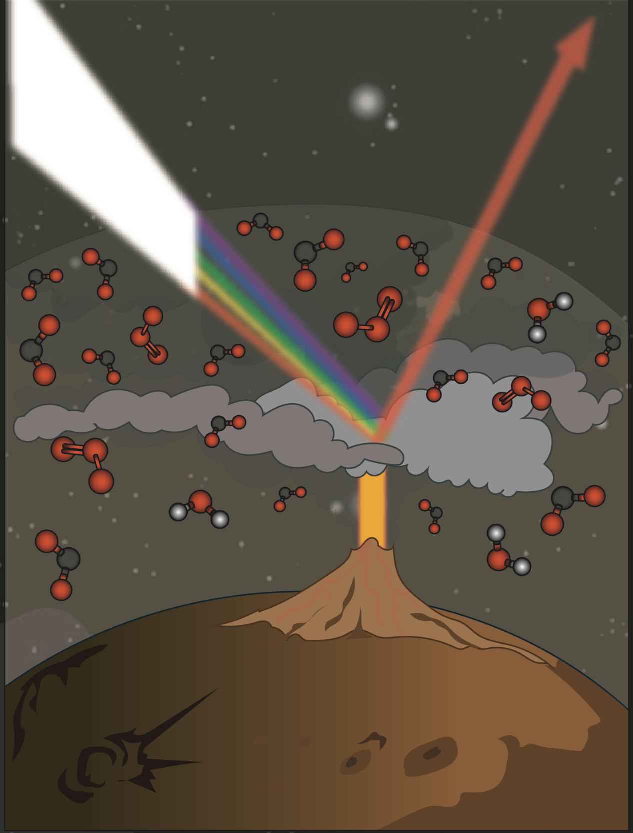
- How do we discover new potential biosignatures - especially those with higher probabilities of detection?
- How do we increase our confidence in the interpretation of the candidates we do have?

A Comprehensive Framework for Biosignature Assessment

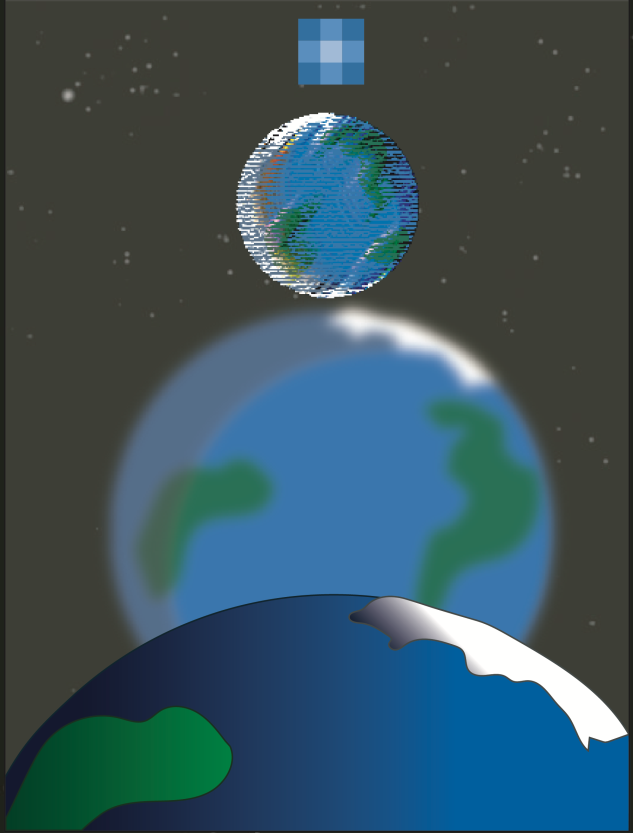
What does life **produce?**



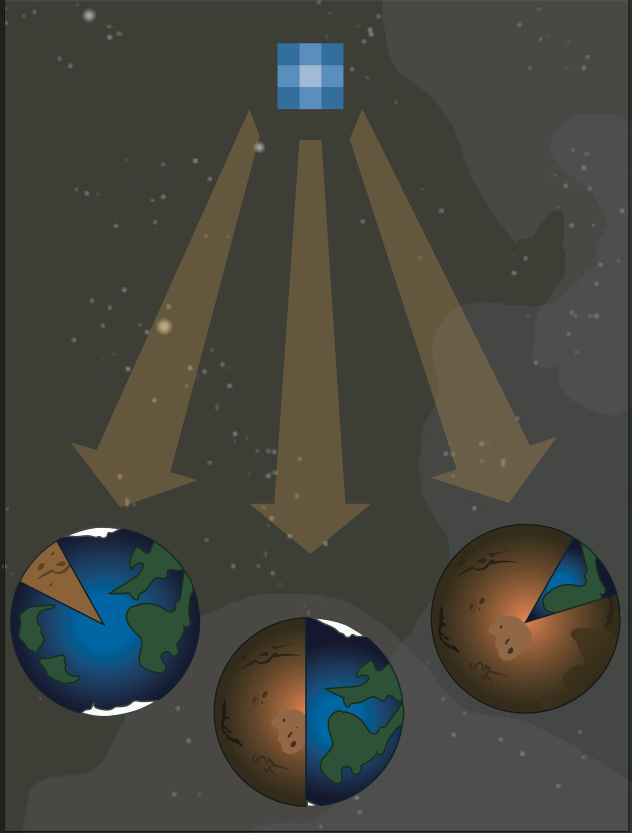
Can a dead planet **fool us?**



How do we interpret **limited data?**



How do we **quantify** our **certainties**?



(Kiang et al., 2018; Schwieterman et al., 2018; Meadows et al., 2018; Catling et al., 2018; Walker et al., 2018; Fujii et al., 2018)

Classic Biosignatures: Atmospheric Disequilibrium

- Surface fluxes of gases that change atmospheric composition or drive disequilibria (e.g. Hitchcock & Lovelock, 1965; Krissansen-Totton et al., 2016)
- *NB: The disequilibrium is not necessarily the biosignature, the inferred surface flux is the biosignature.*
- Does that surface flux exceed the rate for abiotic processes?

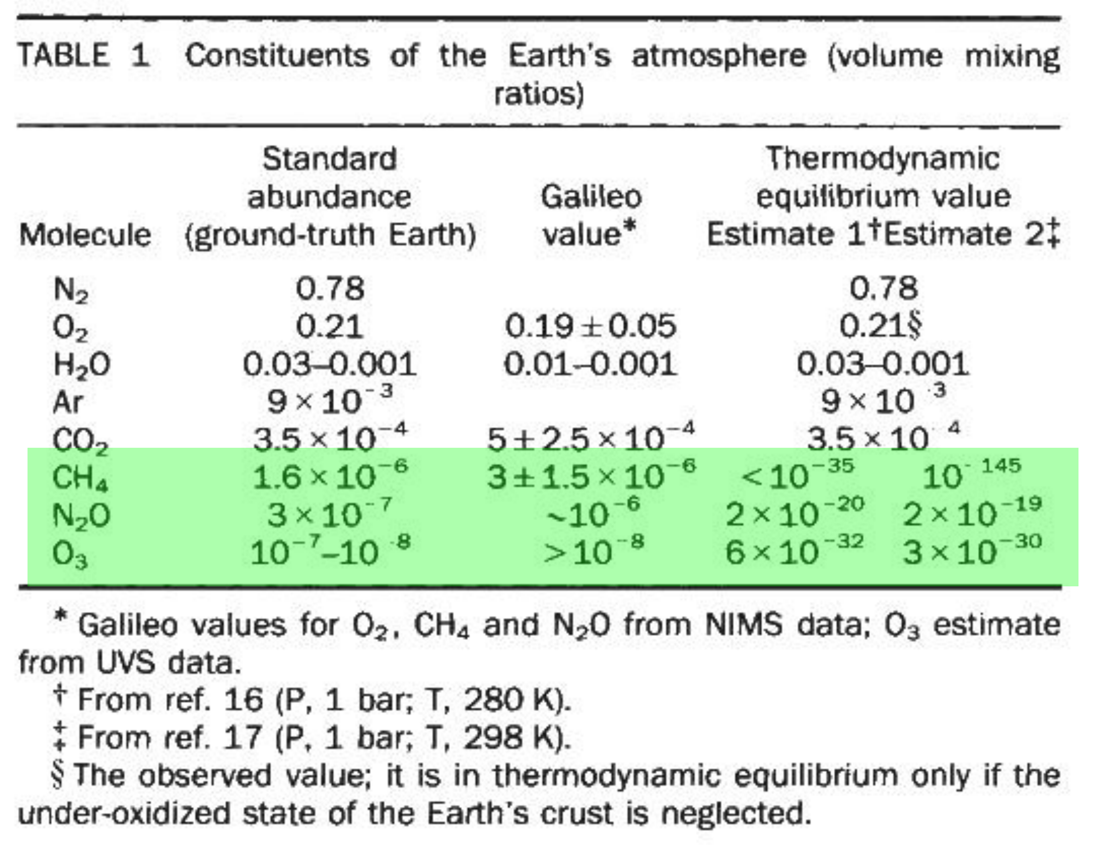


TABLE 1 Constituents of the Earth's atmosphere (volume mixing ratios)

Molecule	Standard abundance (ground-truth Earth)	Galileo value*	Thermodynamic equilibrium value Estimate 1†	Thermodynamic equilibrium value Estimate 2‡
N_2	0.78		0.78	
O_2	0.21	0.19 ± 0.05	0.21§	
H_2O	0.03–0.001	0.01–0.001	0.03–0.001	
Ar	9×10^{-3}		9×10^{-3}	
CO_2	3.5×10^{-4}	$5 \pm 2.5 \times 10^{-4}$	3.5×10^{-4}	
CH_4	1.6×10^{-6}	$3 \pm 1.5 \times 10^{-6}$	$< 10^{-35}$	10^{-145}
N_2O	3×10^{-7}	$\sim 10^{-6}$	2×10^{-20}	2×10^{-19}
O_3	10^{-7}–10^{-8}	$> 10^{-8}$	6×10^{-32}	3×10^{-30}

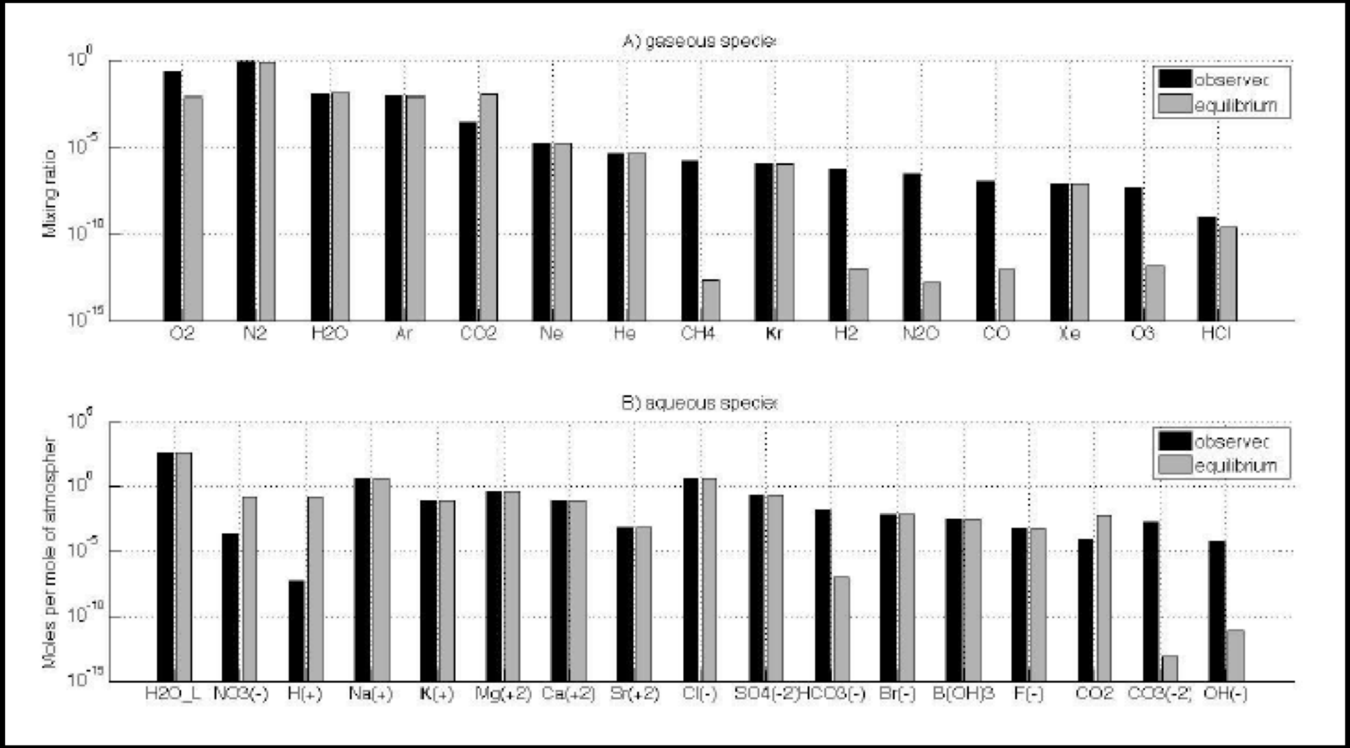
* Galileo values for O_2, CH_4 and N_2O from NIMS data; O_3 estimate from UVS data.

† From ref. 16 (P, 1 bar; T, 280 K).

‡ From ref. 17 (P, 1 bar; T, 298 K).

§ The observed value; it is in thermodynamic equilibrium only if the under-oxidized state of the Earth's crust is neglected.

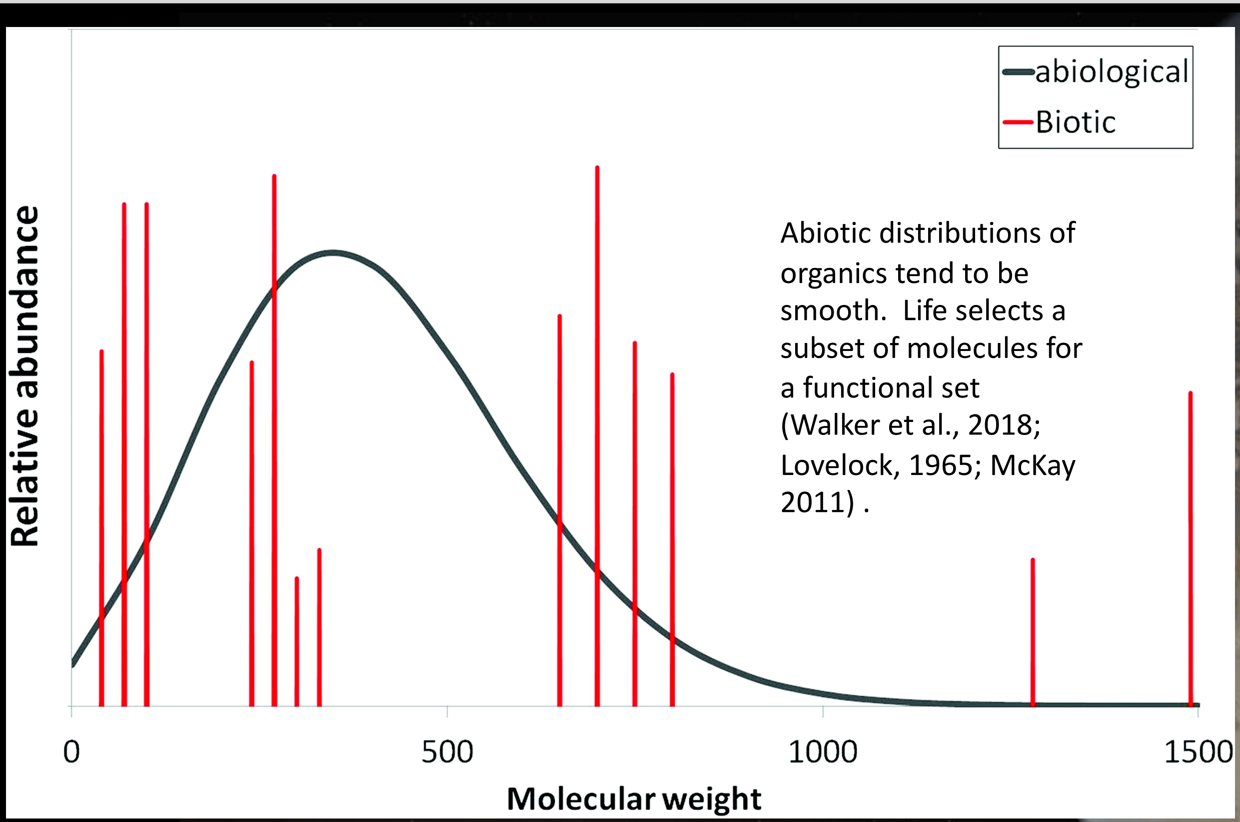
Sagan et al., 1993



Krissansen-Totton et al., 2016

Earth's thermodynamic disequilibrium is biogenic in origin, and the main contribution is the coexistence of N_2, O_2 and liquid water instead of a more stable nitrate-rich ocean $2N_2(g) + 5O_2(g) + H_2O(l) \rightleftharpoons 4H^+(aq) + 4NO_3^-(aq)$

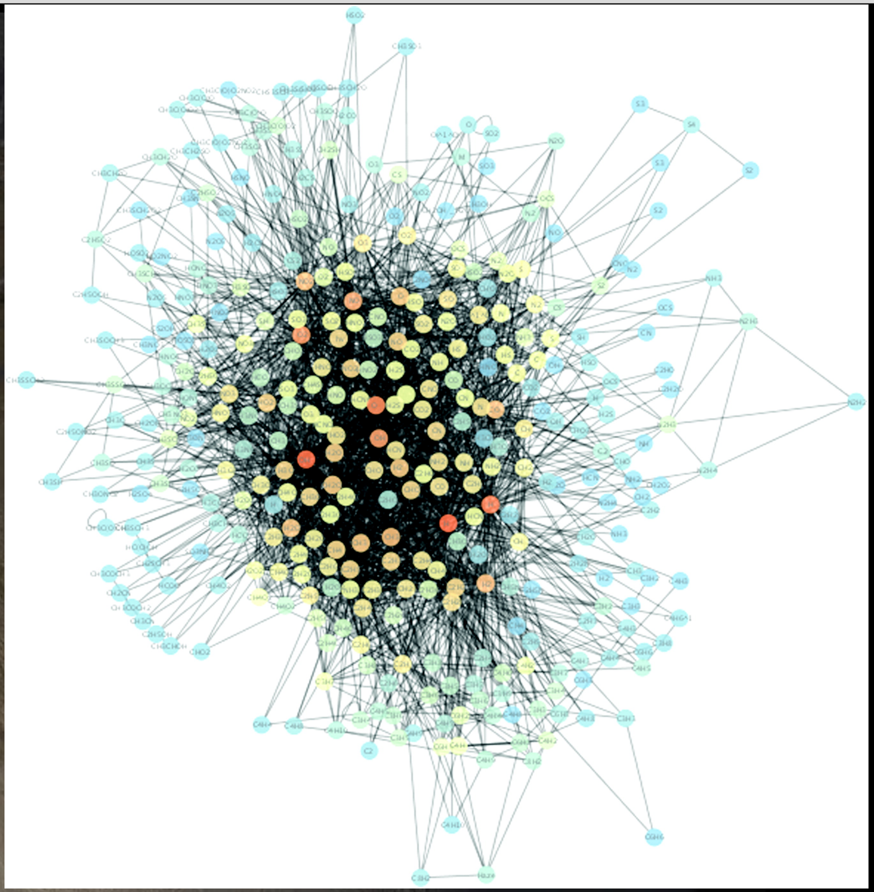
Agnostic Biosignatures: Life as Improbable Chemistry



Abiotic distributions of organics tend to be smooth. Life selects a subset of molecules for a functional set (Walker et al., 2018; Lovelock, 1965; McKay 2011) .

The biosignature becomes the probability of a molecule or selection of molecules occurring abiotically.

Life coevolves with its planet (lithosphere, hydrosphere, atmosphere)/star/system. So we could identify biosignatures that indicate co-evolution, e.g. pigments filling atmospheric windows (Kiang et al., 2007b)

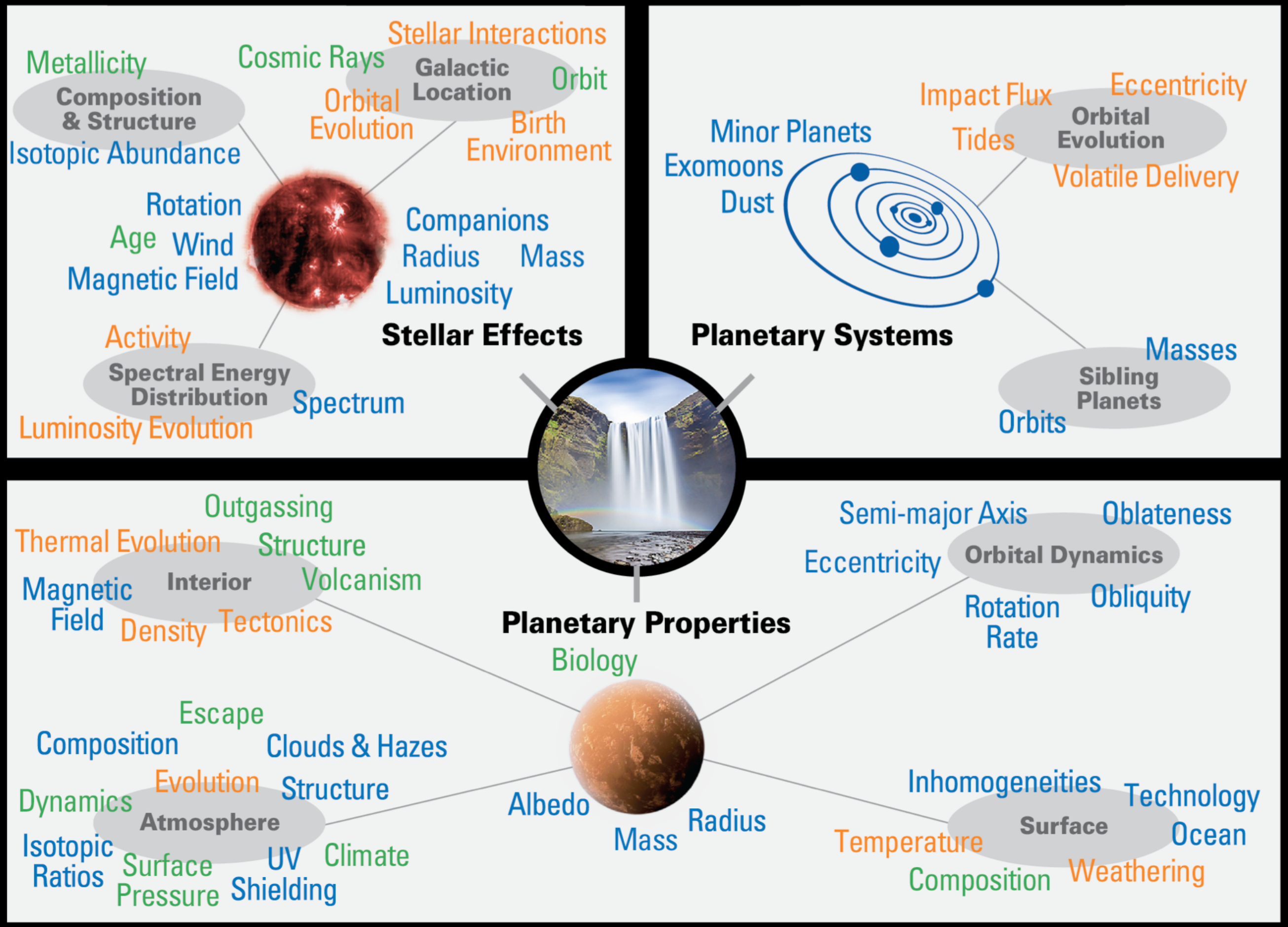


The network topology of Earth's atmospheric chemistry reaction network is structured more like biology than the other planet's (Walker et al., 2018; Solé and Munteanu, 2004).

Towards a comprehensive framework for biosignature assessment

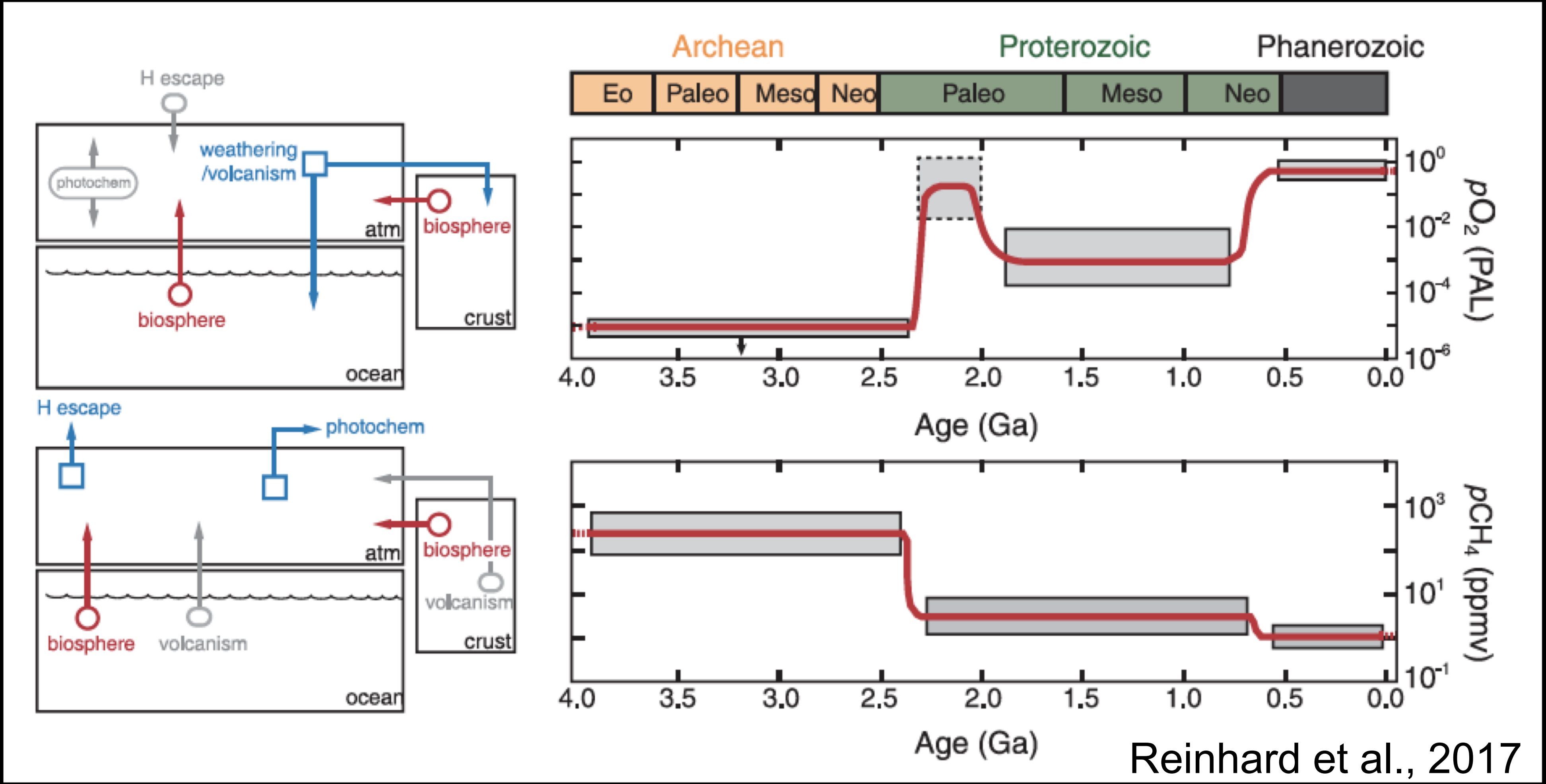
- Biosignatures occur in an environmental context in which geological, atmospheric and stellar processes and interactions, along with evolutionary history, may work to enhance, suppress or mimic biosignatures.

- A comprehensive framework for biosignature identification and assessment must take into account how these interactions affect:
  - False negatives
  - Inferred biosignature surface fluxes
  - False positives



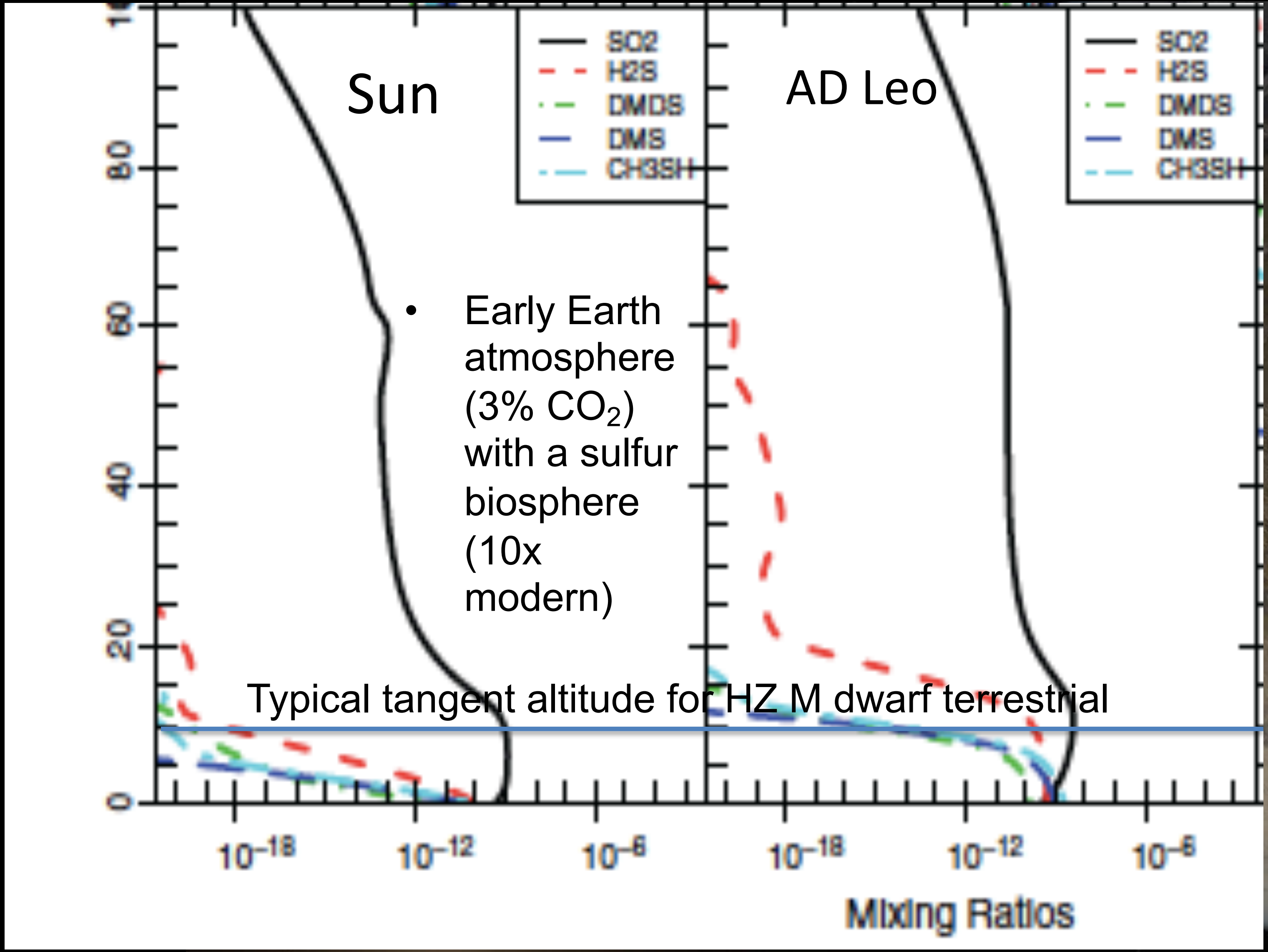
Biosignature environmental "false negatives"

- Occur when a planet's environment, including biogeochemical cycles, suppresses the buildup of of a biosignature, or makes it otherwise difficult to observe (e.g. O_2 over Earth's history).
- Considering false negatives will inform our target selection for biosignature searches (OoL also..)



Reinhard et al., 2017

Biosignature detectability "false negatives"



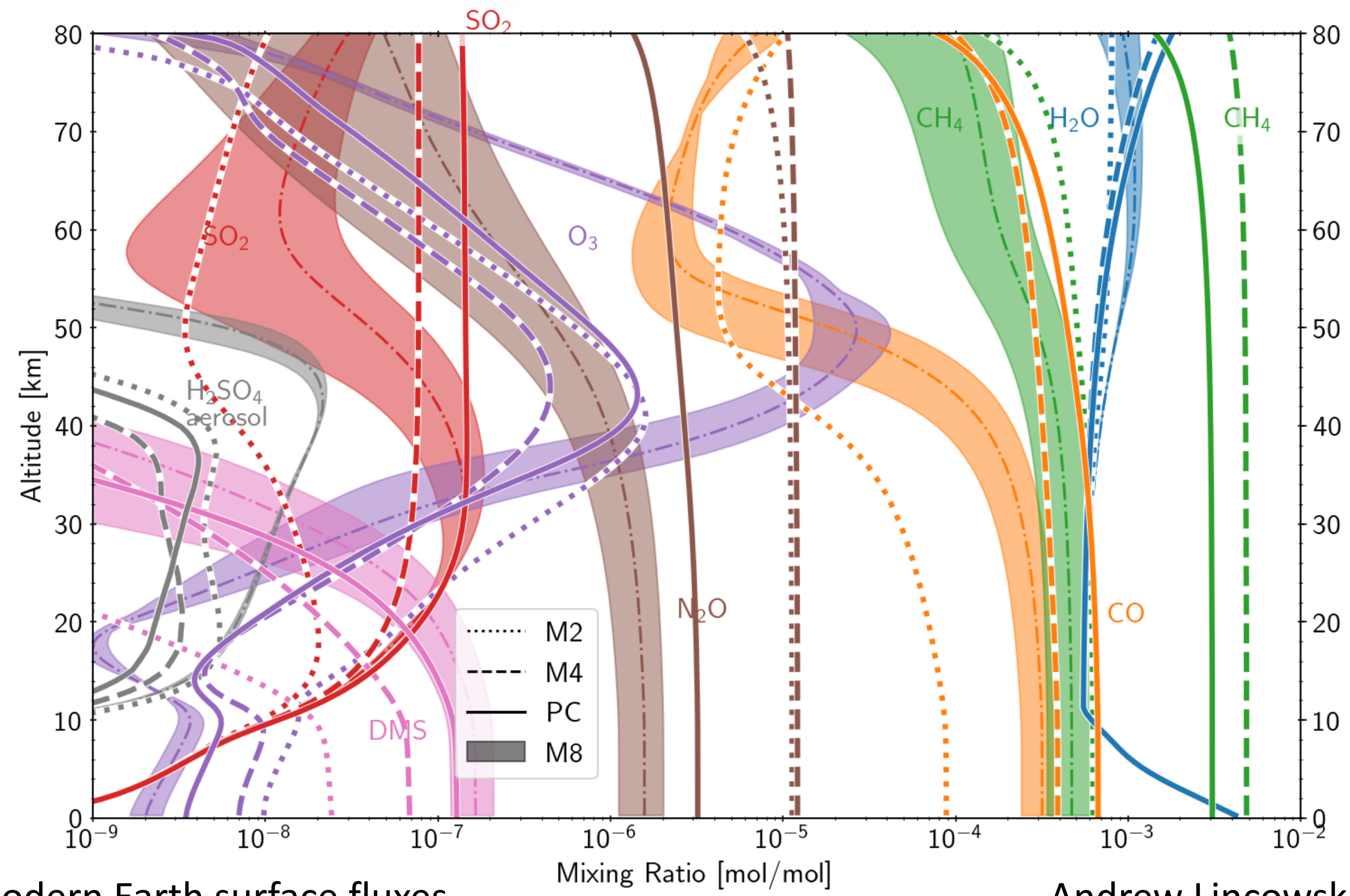
- Early Earth atmosphere (3% CO_2) with a sulfur biosphere (10x modern)

Domagal-Goldman et al., *Astrobiology*, 2011

- Transmission observations may not probe close to the surface due to refraction, hazes or clouds.
- Large or complex biosignature gases (e.g DMDS, DMS) are more susceptible to photolysis and so may be concentrated close to the planetary surface.

The host M dwarf UV spectrum modifies biosignatures

For the same surface fluxes…the biosignature gases CH_4, N_2O and O_3 are strongly affected

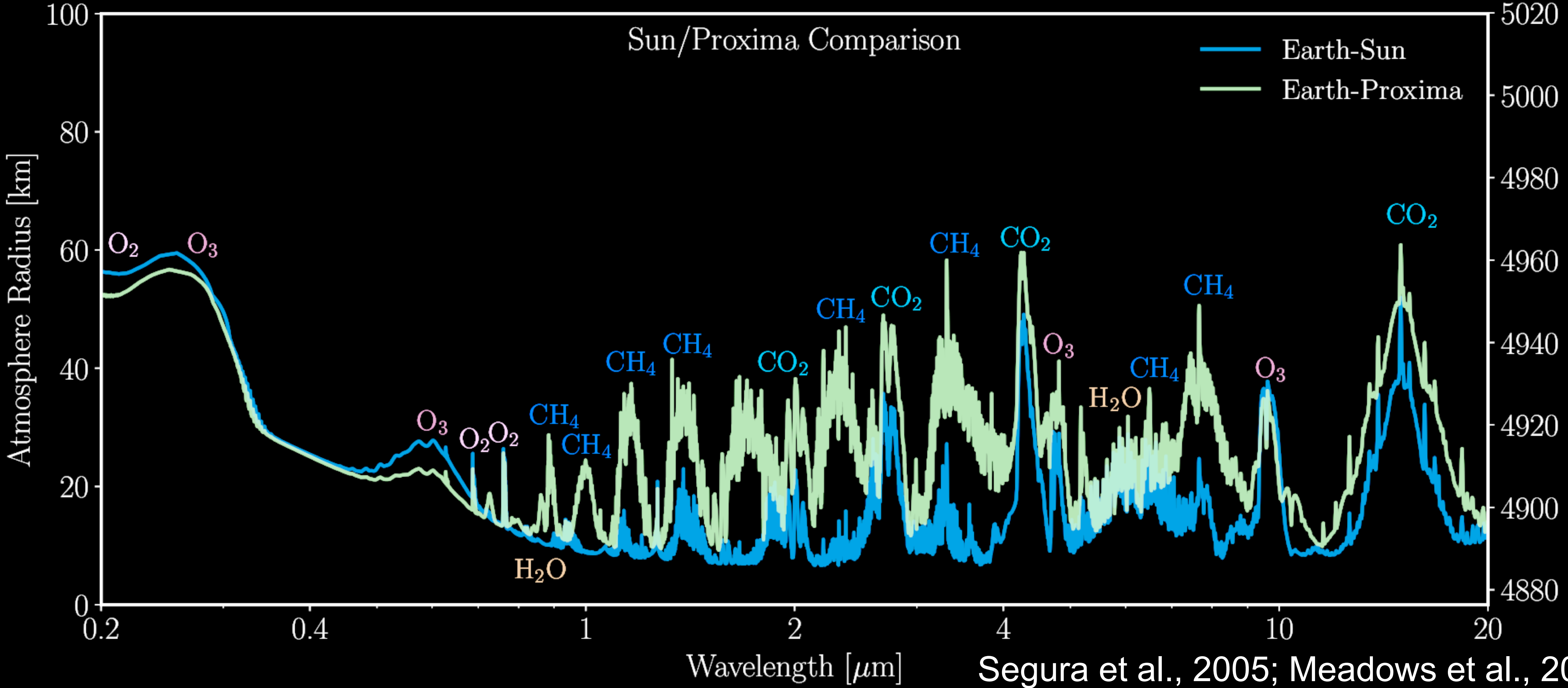


Modern Earth surface fluxes

Andrew Lincowski

Photochemistry Can Enhance Biosignature Detection

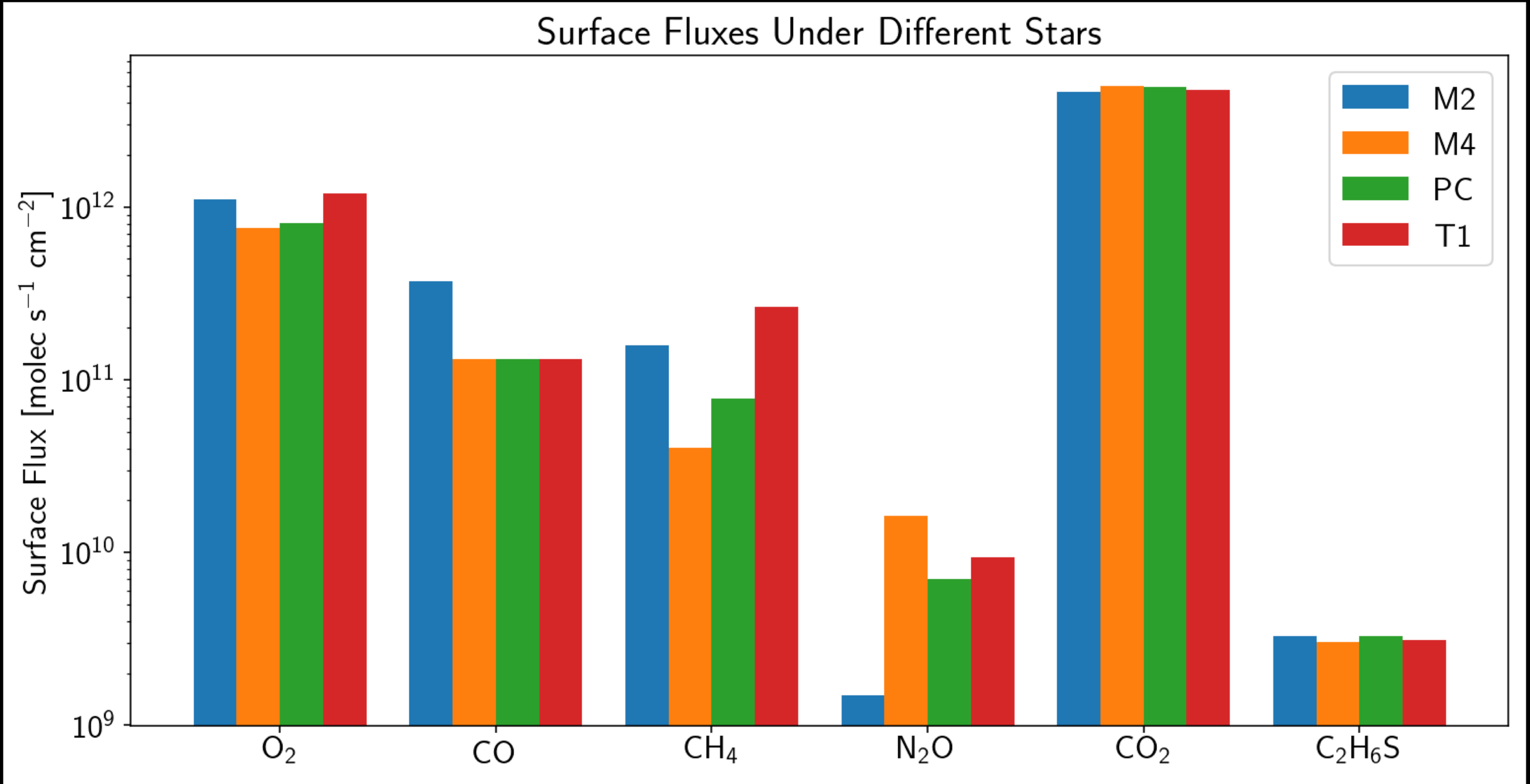
Earth-like planets orbiting M dwarfs may have stronger biosignature features, esp. CH_4



Segura et al., 2005; Meadows et al., 2018a

Photochemistry alters inferred biosignature surface fluxes

CH_4, N_2O and O_3 inferred fluxes are strongly affected (and all biosignatures)
To correctly translate an observed abundance into a surface flux requires knowledge of planet and star.



A lot of possible biosignature false positives are known…

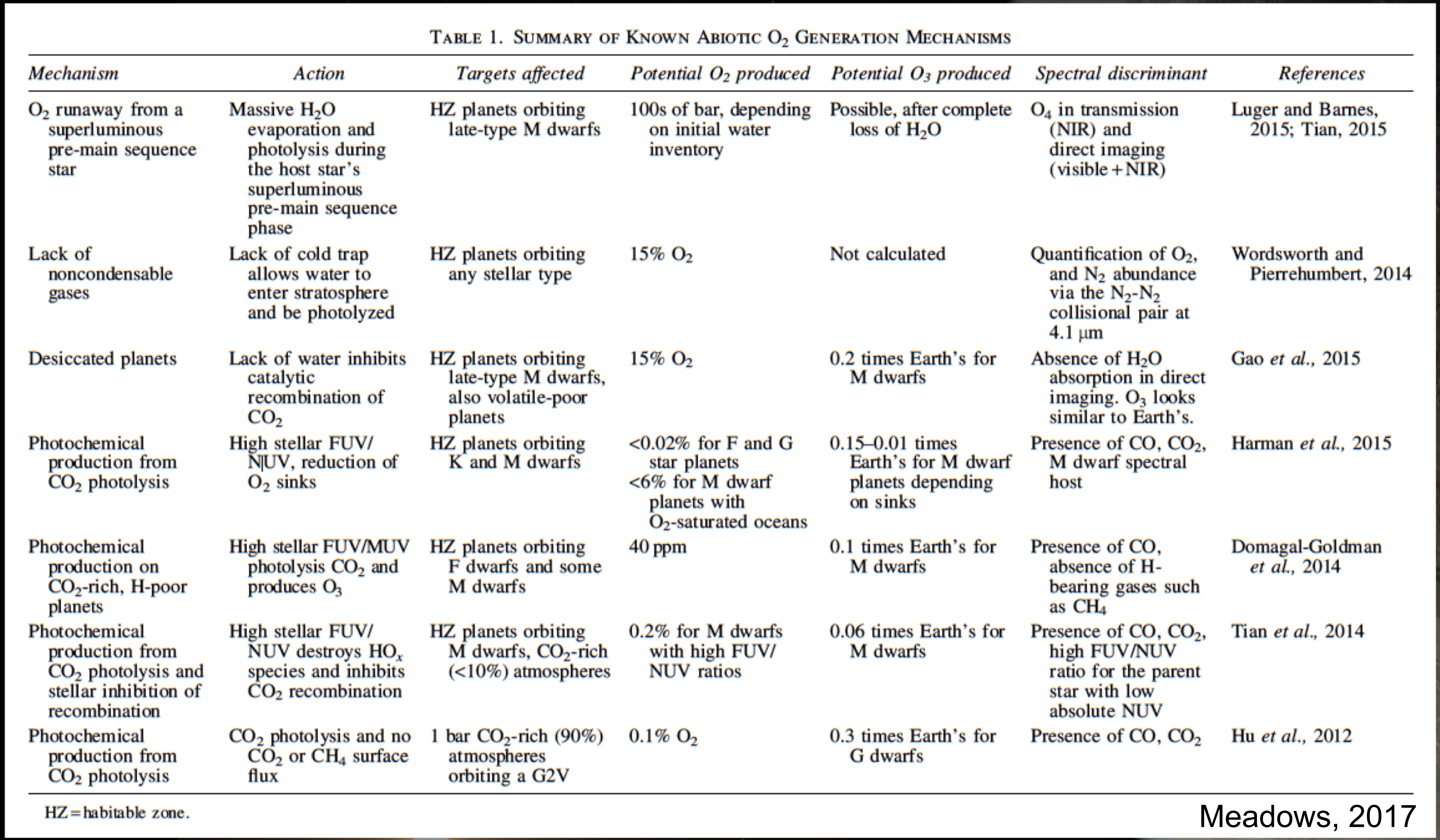


Table 1. Summary of Known Abiotic O_2 Generation Mechanisms

Mechanism	*Action*	*Targets affected*	*Potential O_2 produced*	*Potential O_3 produced*	*Spectral discriminant*	*References*
O_2 runaway from a superluminous pre-main sequence star	Massive H_2O evaporation and photolysis during the host star's superluminous pre-main sequence phase	HZ planets orbiting late-type M dwarfs	100s of bar, depending on initial water inventory	Possible, after complete loss of H_2O	O_4 in transmission (NIR) and direct imaging (visible+NIR)	Luger and Barnes, 2015; Tian, 2015
Lack of noncondensable gases	Lack of cold trap allows water to enter stratosphere and be photolyzed	HZ planets orbiting any stellar type	15% O_2	Not calculated	Quantification of O_2, and N_2 abundance via the N_2-N_2 collisional pair at 4.1 μm	Wordsworth and Pierrehumbert, 2014
Desiccated planets	Lack of water inhibits catalytic recombination of CO_2	HZ planets orbiting late-type M dwarfs, also volatile-poor planets	15% O_2	0.2 times Earth's for M dwarfs	Absence of H_2O absorption in direct imaging. O_3 looks similar to Earth's.	Gao *et al.*, 2015
Photochemical production from CO_2 photolysis	High stellar FUV/NUV, reduction of O_2 sinks	HZ planets orbiting K and M dwarfs	<0.02% for F and G star planets <6% for M dwarf planets with O_2-saturated oceans	0.15–0.01 times Earth's for M dwarf planets depending on sinks	Presence of CO, CO_2, M dwarf spectral host	Harman *et al.*, 2015
Photochemical production on CO_2-rich, H-poor planets	High stellar FUV/MUV photolysis CO_2 and produces O_3	HZ planets orbiting F dwarfs and some M dwarfs	40 ppm	0.1 times Earth's for M dwarfs	Presence of CO, absence of H-bearing gases such as CH_4	Domagal-Goldman *et al.*, 2014
Photochemical production from CO_2 photolysis and stellar inhibition of recombination	High stellar FUV/NUV destroys HO_x species and inhibits CO_2 recombination	HZ planets orbiting M dwarfs, CO_2-rich (<10%) atmospheres	0.2% for M dwarfs with high FUV/NUV ratios	0.06 times Earth's for M dwarfs	Presence of CO, CO_2, high FUV/NUV ratio for the parent star with low absolute NUV	Tian *et al.*, 2014
Photochemical production from CO_2 photolysis	CO_2 photolysis and no CO_2 or CH_4 surface flux	1 bar CO_2-rich (90%) atmospheres orbiting a G2V	0.1% O_2	0.3 times Earth's for G dwarfs	Presence of CO, CO_2	Hu *et al.*, 2012

HZ = habitable zone.

Meadows, 2017

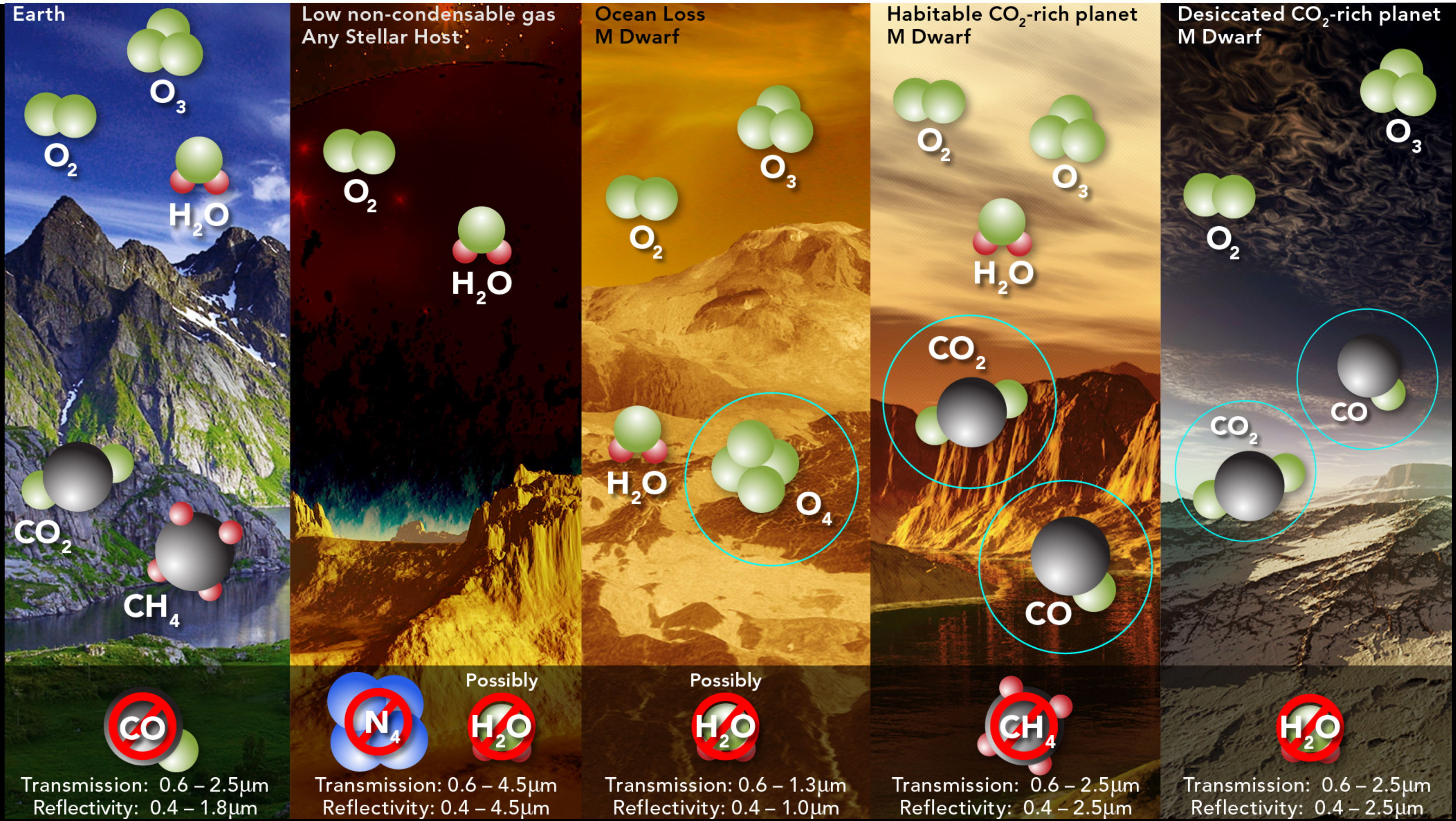
A false positive is an abiotic planetary process, including atmospheric evolution, that can mimic a biosignature.

These have been extensively studied for O_2 (and we are *still* working on them!)

M Dwarf planets currently appear most affected.

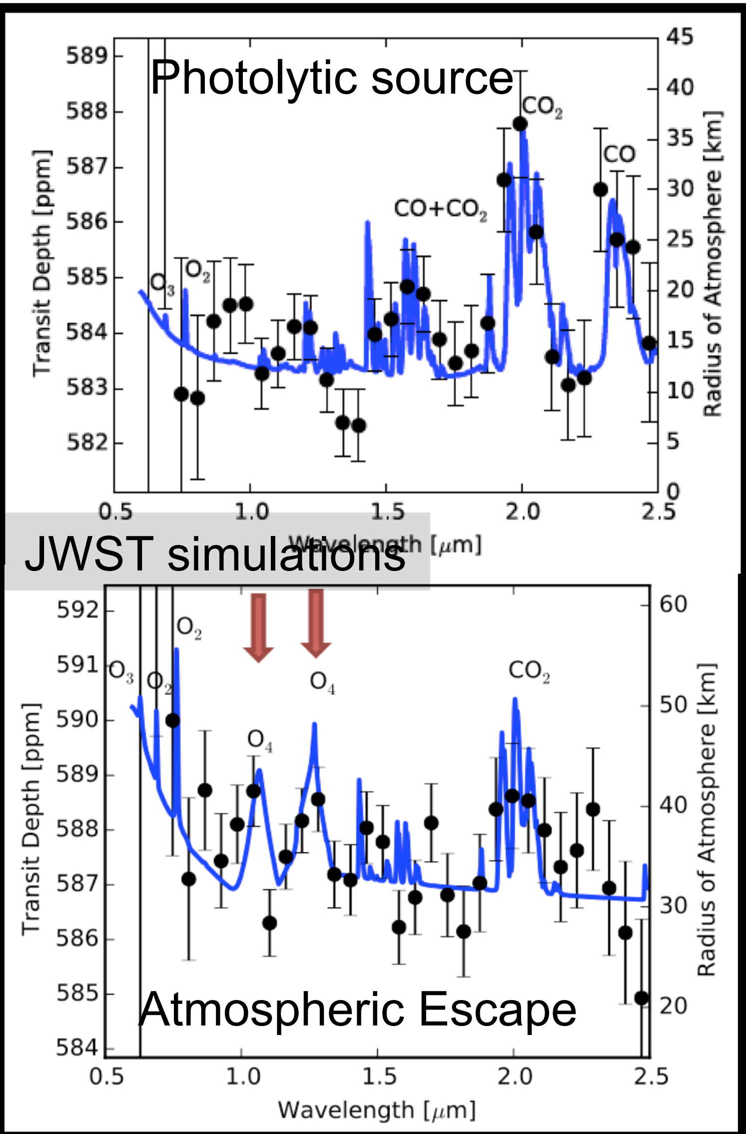
- Pre-main-sequence ocean loss
- UV spectrum drives different photochemistry (CO_2 and H_2O photolysis).

… but each biosignature false positive has a discriminant

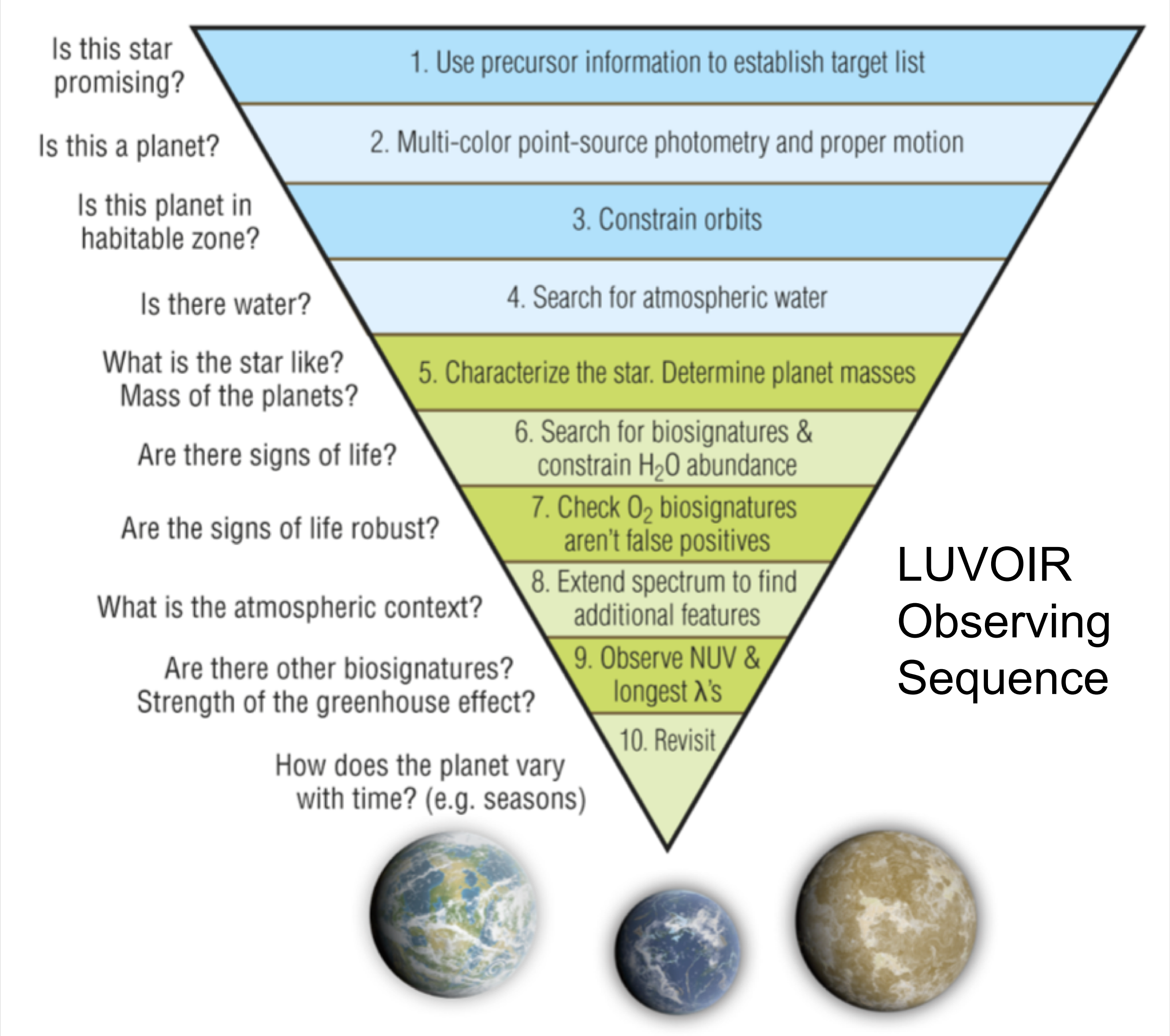


- To interpret a detection of O_2 we also need to 1) characterize the stellar UV spectrum and 2) assess planetary composition to rule out potential false positives (Meadows, 2017; Meadows et al., 2018b)
- Ruling out false positive mechanisms *increases our confidence* in a biological source for a biosignature.

Knowledge of false positives guides observing strategies



Schwieterman et al., 2016a,b.
see also Wang et al., 2016.



Is this star promising?	1. Use precursor information to establish target list
Is this a planet?	2. Multi-color point-source photometry and proper motion
Is this planet in habitable zone?	3. Constrain orbits
Is there water?	4. Search for atmospheric water
What is the star like? Mass of the planets?	5. Characterize the star. Determine planet masses
Are there signs of life?	6. Search for biosignatures & constrain H_2O abundance
Are the signs of life robust?	7. Check O_2 biosignatures aren't false positives
What is the atmospheric context?	8. Extend spectrum to find additional features
Are there other biosignatures? Strength of the greenhouse effect?	9. Observe NUV & longest λ's
How does the planet vary with time? (e.g. seasons)	10. Revisit

LUVOIR
Observing
Sequence

Fischer et al., 2018; LUVOIR Interim Report

Venus may help us understand false positive chemistry

Akatsuki/JAXA

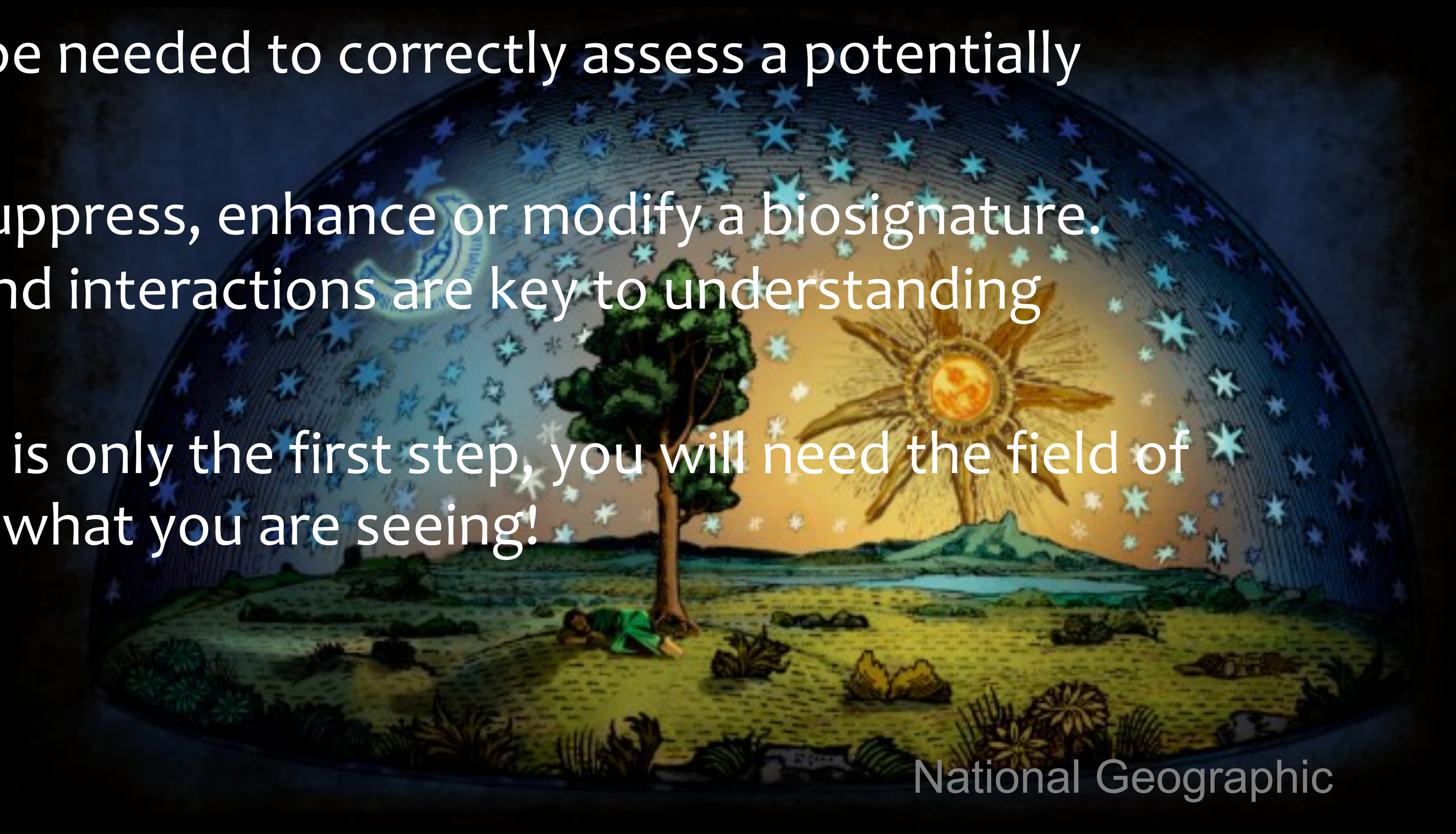
- **Venus’** history of ocean loss may be common for terrestrial exoplanets, especially those with very high levels of insolation.
- Although undergoing massive and rapid CO_2 photolysis in a hydrogen-poor environment, the Venus atmosphere does not build up O_2 as a byproduct.
- This is believed due to the action of catalysts, and a lot of that chemistry is NOT in our exoplanet models.
- By studying Venus’ photochemistry we can improve our predictions of the likelihood that a false positive will occur (see Giada’s talk!).

Comprehensive Assessment: Environmental Context is Key

- The environment can suppress biosignature detectability (false negatives)
- The environment can mimic biosignatures (false positives)
- The host star can enhance or destroy biosignatures, and influence our inferred surface flux
- Identifying, searching for and ruling out potential false positives enhances our confidence in biosignature detection.
- Biosignatures may be most detectable on planets orbiting M dwarfs, but these planets may also have the highest probability for false-positives.

Astrobiology Themes

- Astrobiology is necessarily massively interdisciplinary
- Studies of planet formation, the origin of life, the coevolution of life with its environment, Solar System planetary evolution and processes, star-planet interactions, and life’s impact on its environment all inform and feed into the search for life beyond the Solar System.
- Life is a planetary process, it may be needed to correctly assess a potentially habitable planetary environment.
- Star-planet interactions can also suppress, enhance or modify a biosignature. Understanding stellar processes and interactions are key to understanding habitability and biosignatures.
- Detecting a potential biosignature is only the first step, you will need the field of astrobiology to help you interpret what you are seeing!



National Geographic

Questions?

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