Finding bio-signatures on extrasolar planets, how close are we?

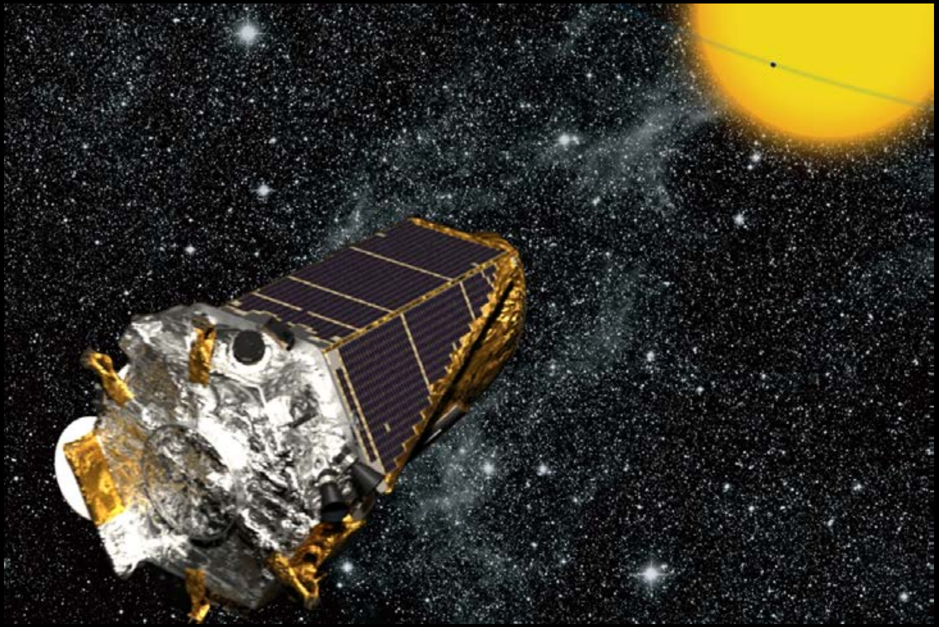
Enric Palle

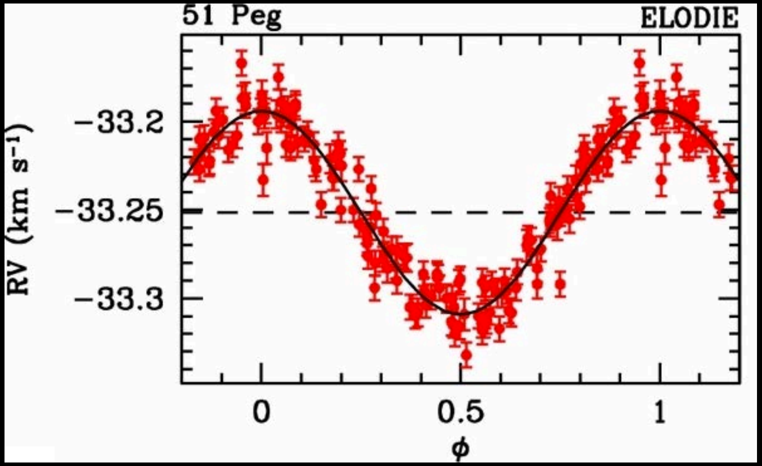
Instituto de Astrofisica de Canarias

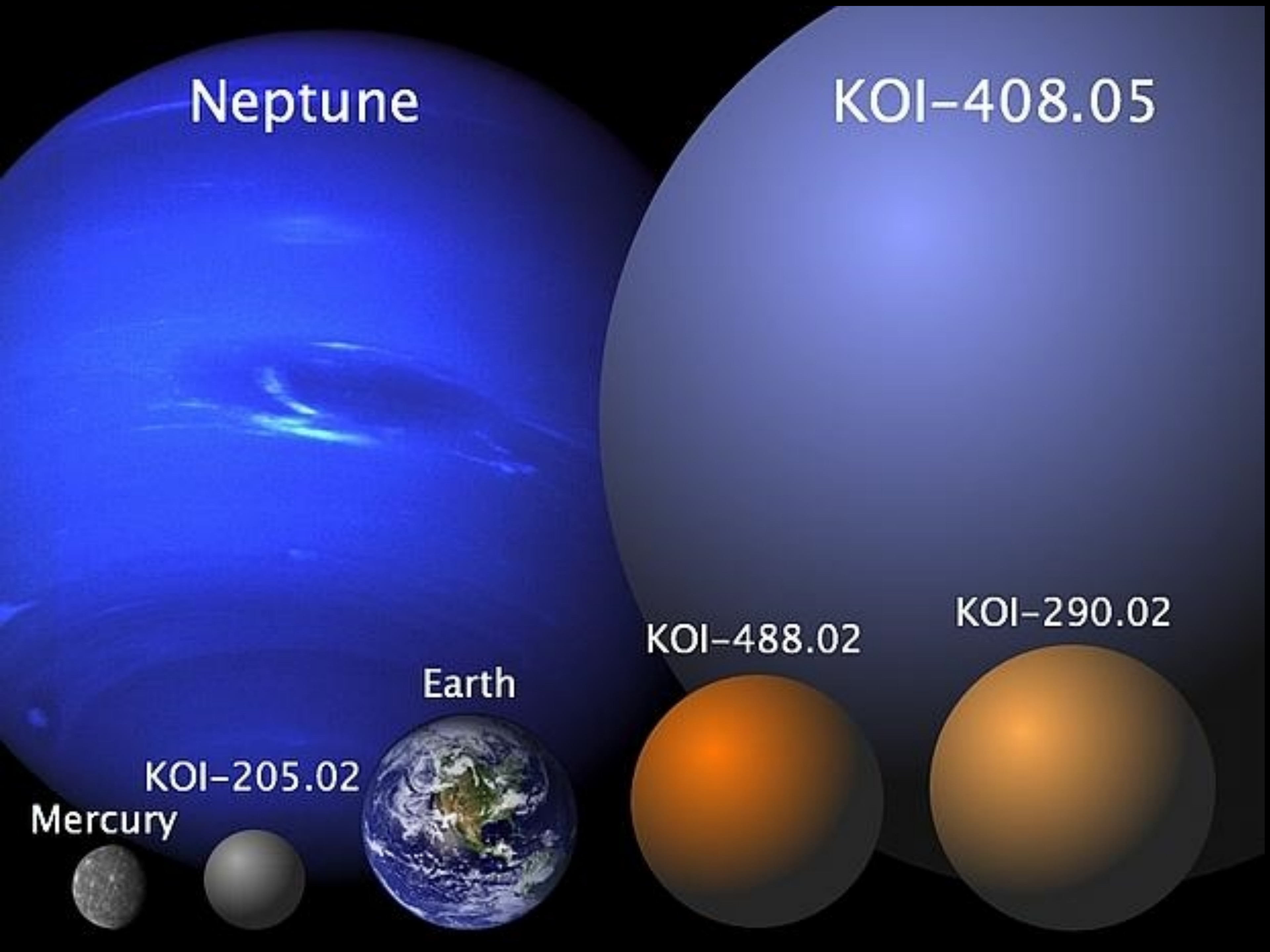
TMT Forum 2017, Mysore

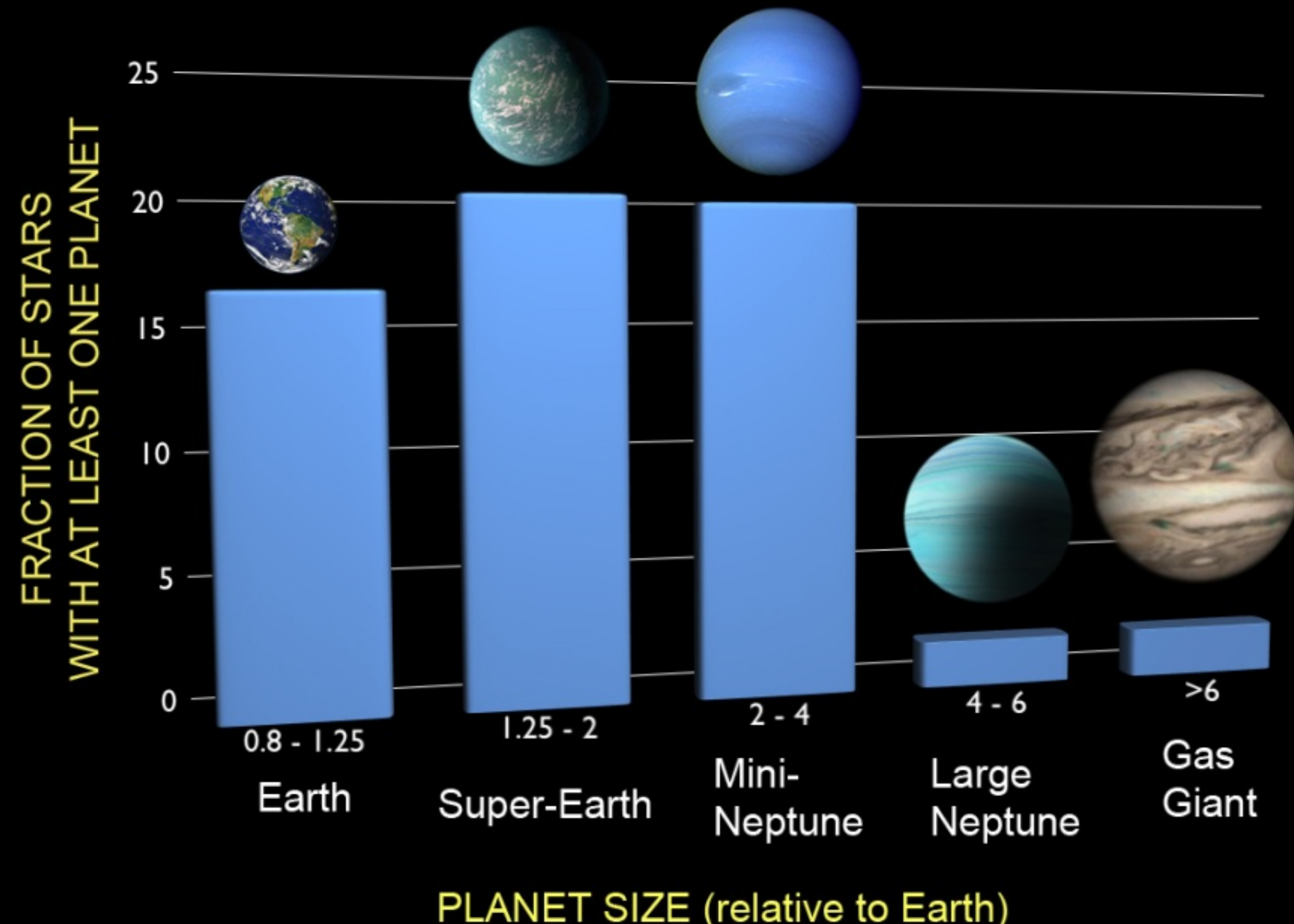
Exoplanet discoveries

3703 planets
2773 system
621 multiple






Neptune
KOI-408.05
KOI-290.02
KOI-488.02
Earth
KOI-205.02
Mercury


FRACTION OF STARS
WITH AT LEAST ONE PLANET
25
20
15
10
5
0
0.8 - 1.25
Earth
1.25 - 2
Super-Earth
2 - 4
Mini-
Neptune
4 - 6
Large
Neptune
>6
Gas
Giant
PLANET SIZE (relative to Earth)

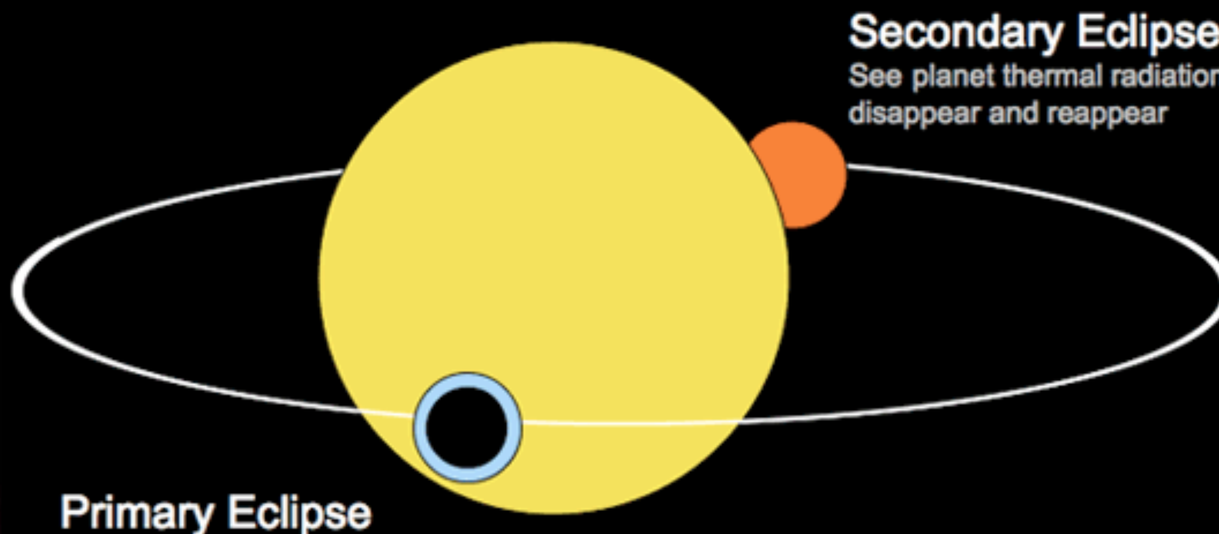
Exoplanets: What have we learned so far?

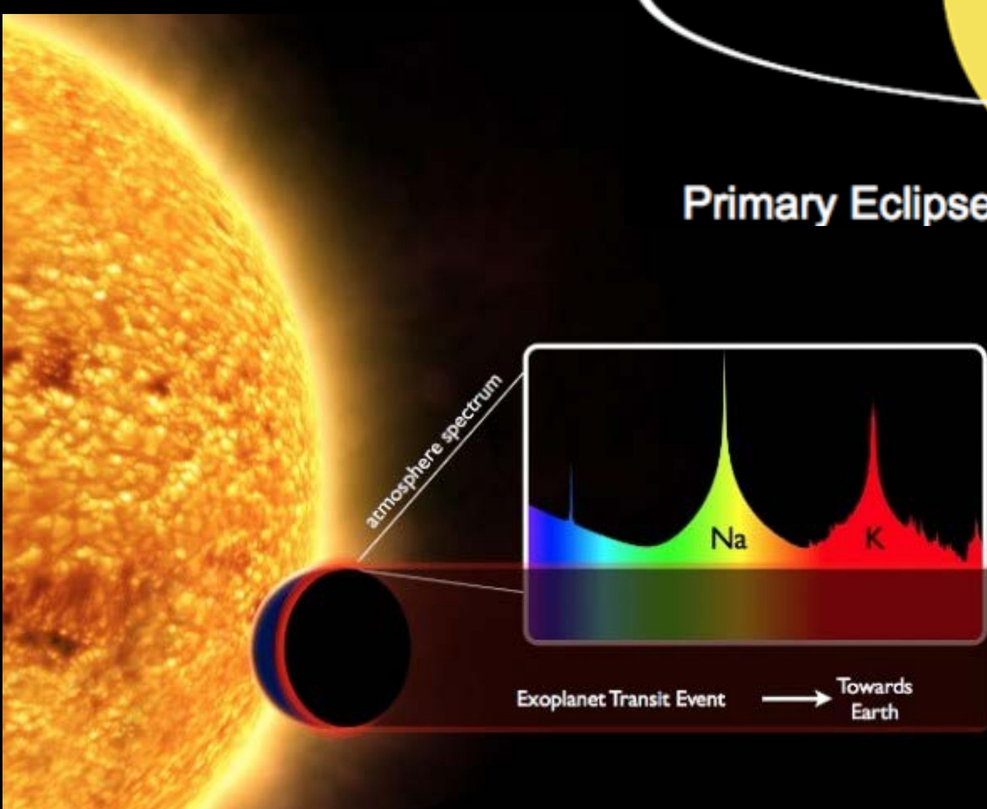
- 20-30% solar-type stars with planets
- At least 1 planet per star
- Multiple (rocky) planetary systems are common
- Specially true for M-type stars, with a very large fraction of planetary occurrence rates
- Planets are everywhere

From detection to …

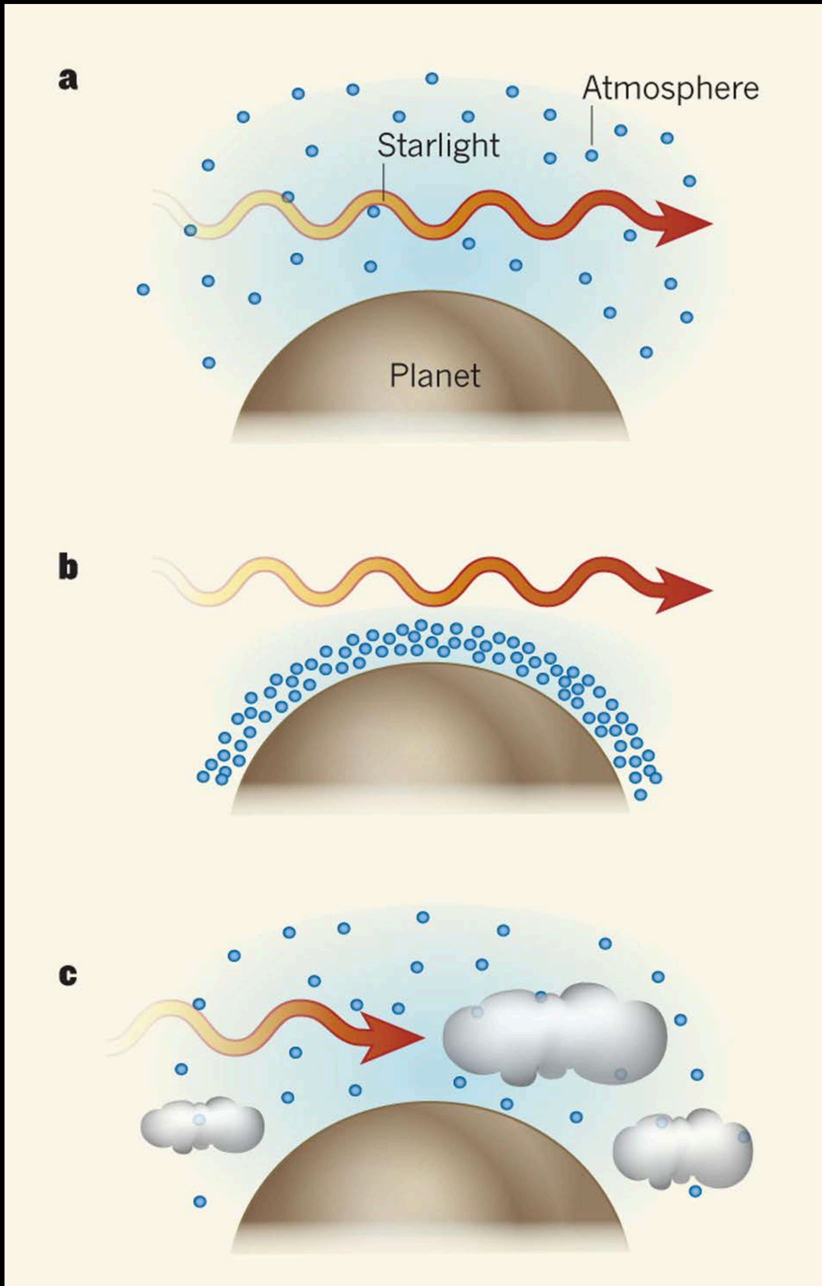
Atmospheric characterization

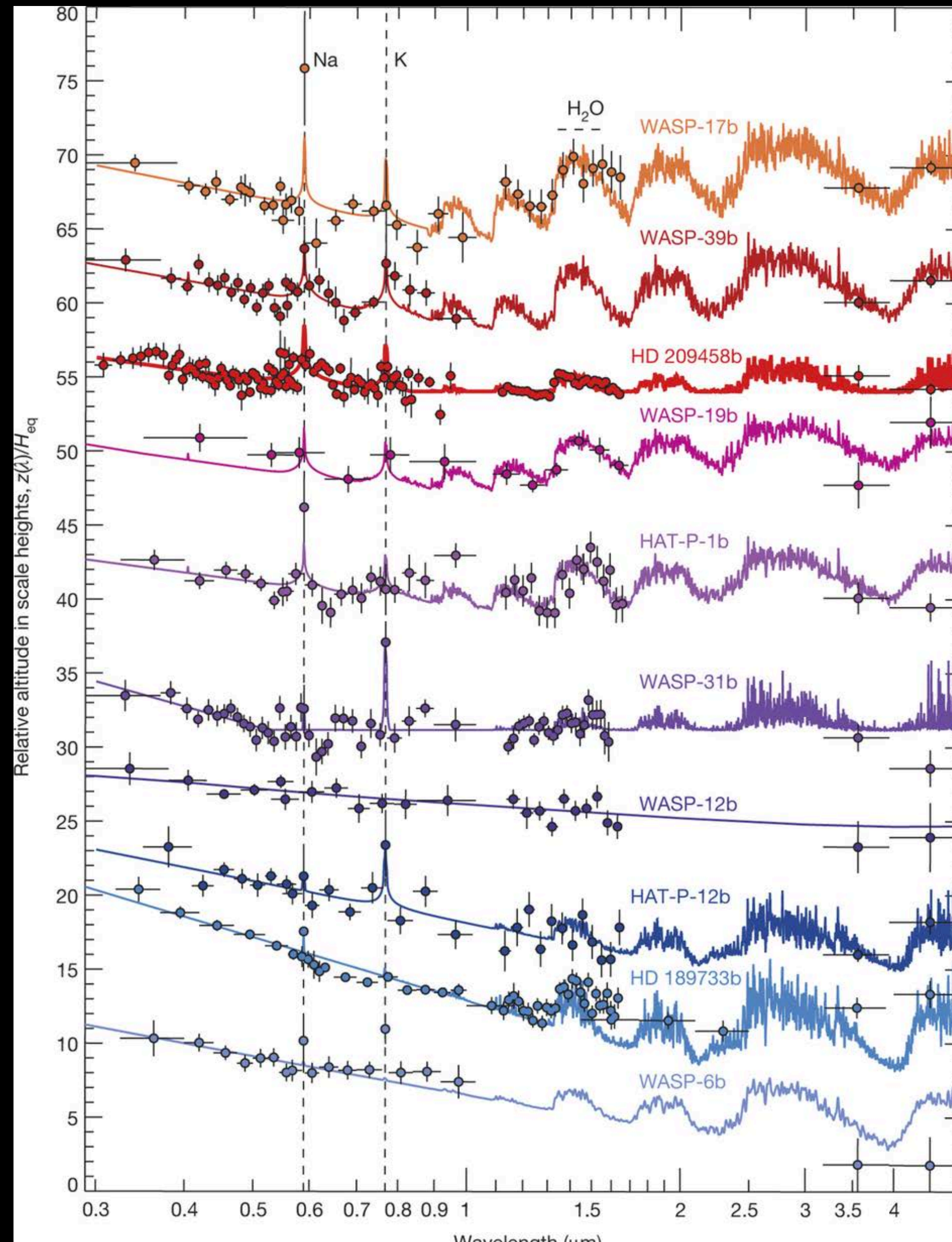
Transit spectroscopy: first detections of planetary atmospehres



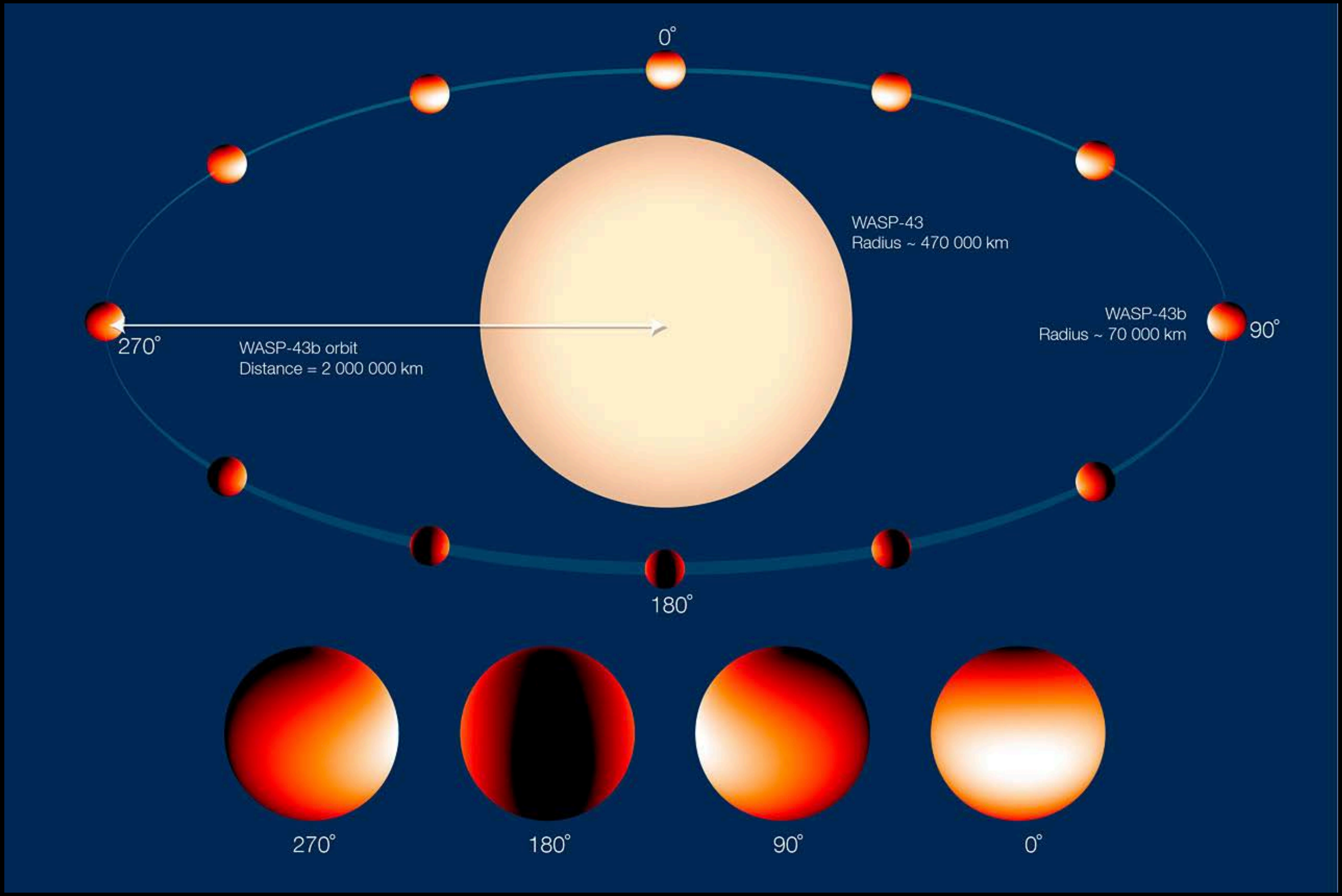


Chemical composition!!


a
Atmosphere
Starlight
Planet
b
c

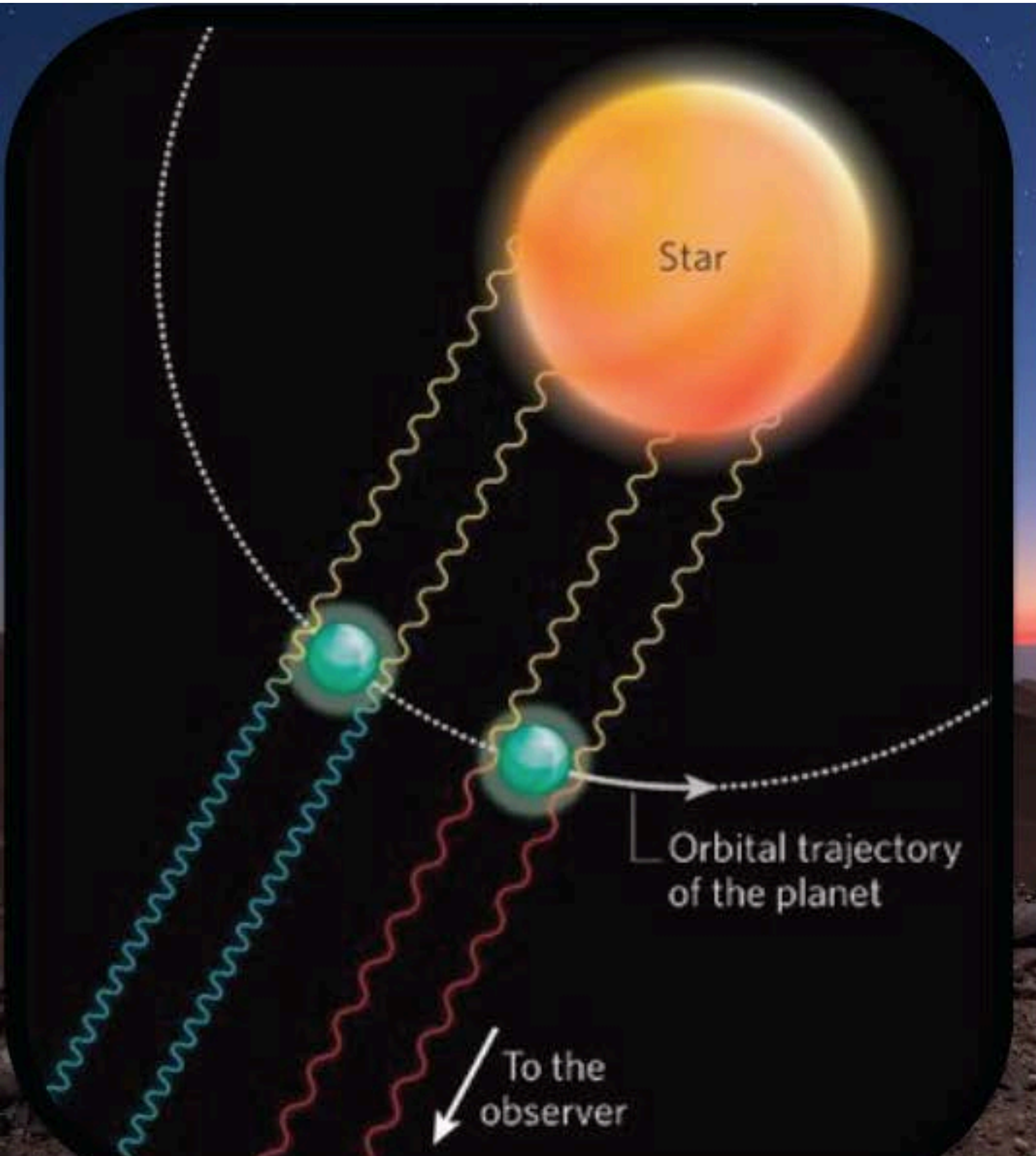

Na
K
H2O
WASP-17b
WASP-39b
HD 209458b
WASP-19b
HAT-P-1b
WASP-31b
WASP-12b
HAT-P-12b
HD 189733b
WASP-6b
Relative altitude in scale heights, z(λ)/Heq
Wavelength (μm)
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.5 2 2.5 3 3.5 4 5

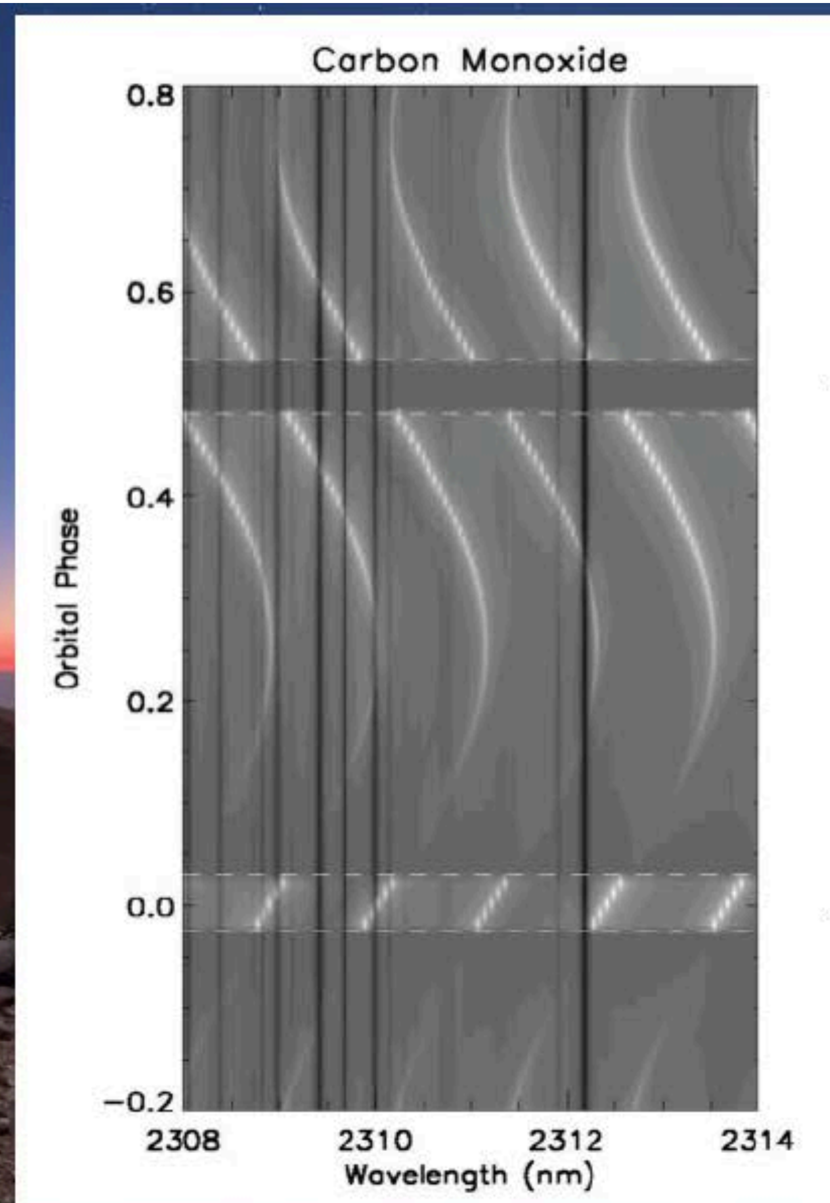
Phase Curves: reflected light from the planet leading to albedo and temperature



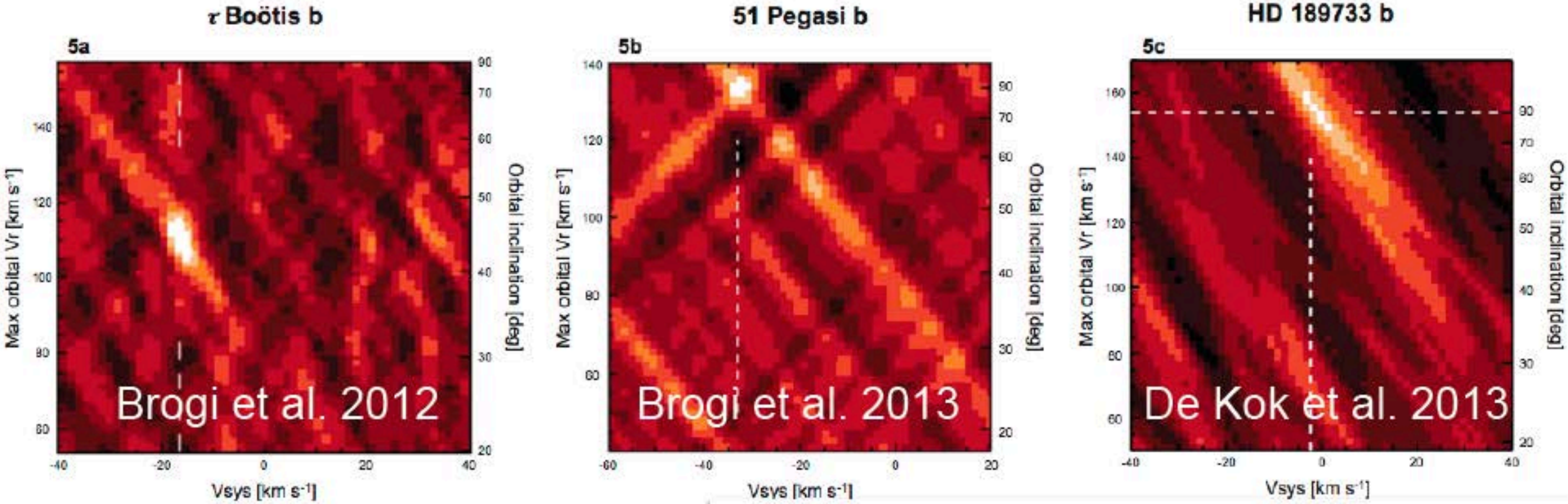
Circulation, Crude Mapping

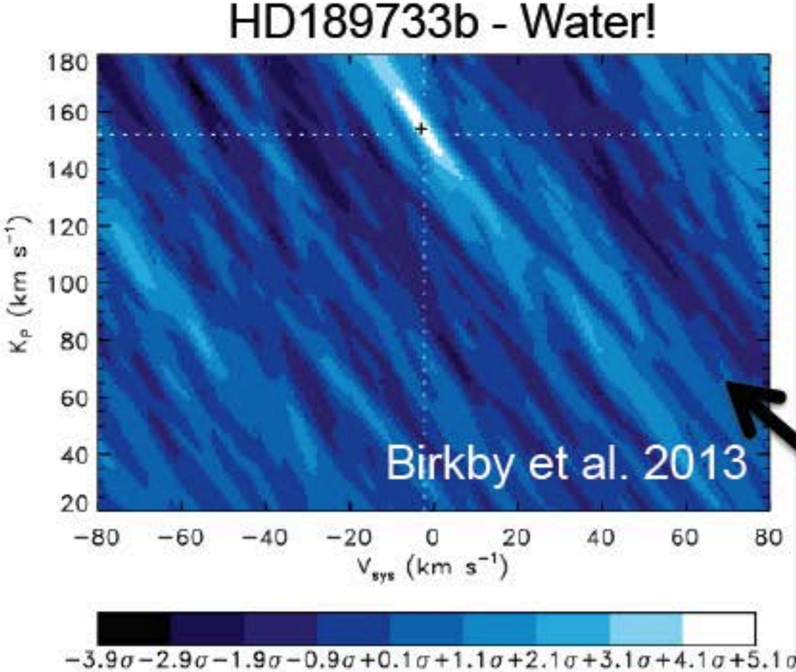
The planet moves at different velocity than the star





CO in dayside spectra of hot Jupiters





CRIRES@VLT Upgrade (2015) →
6x larger wavelength coverage
CO, H2O, CH4, NH3, H3+,…..

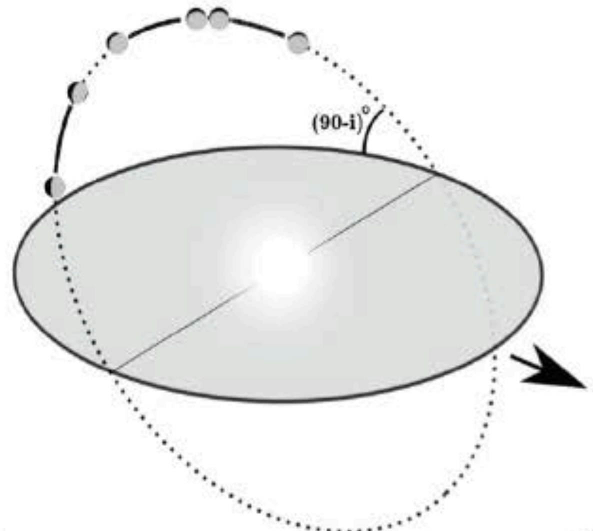
VLT ESPRESSO (Optical → TiO, VO, FeH...)

Stepping-stone for the ELTs

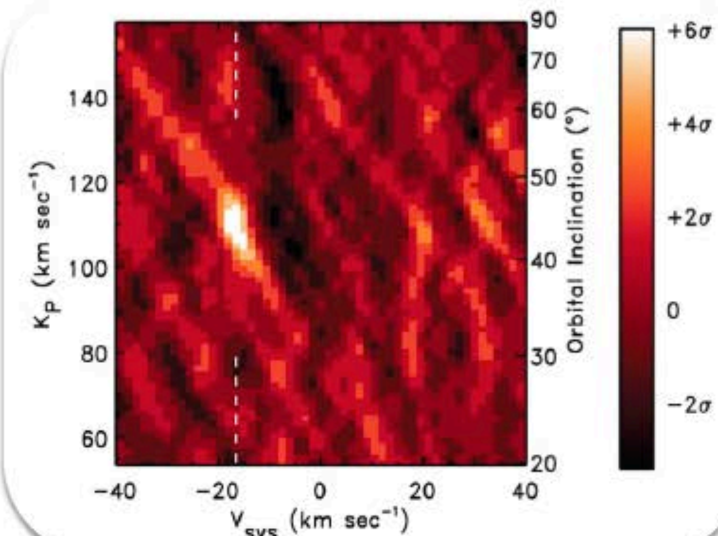
Now also with Keck!
Lockwood et al. 2014

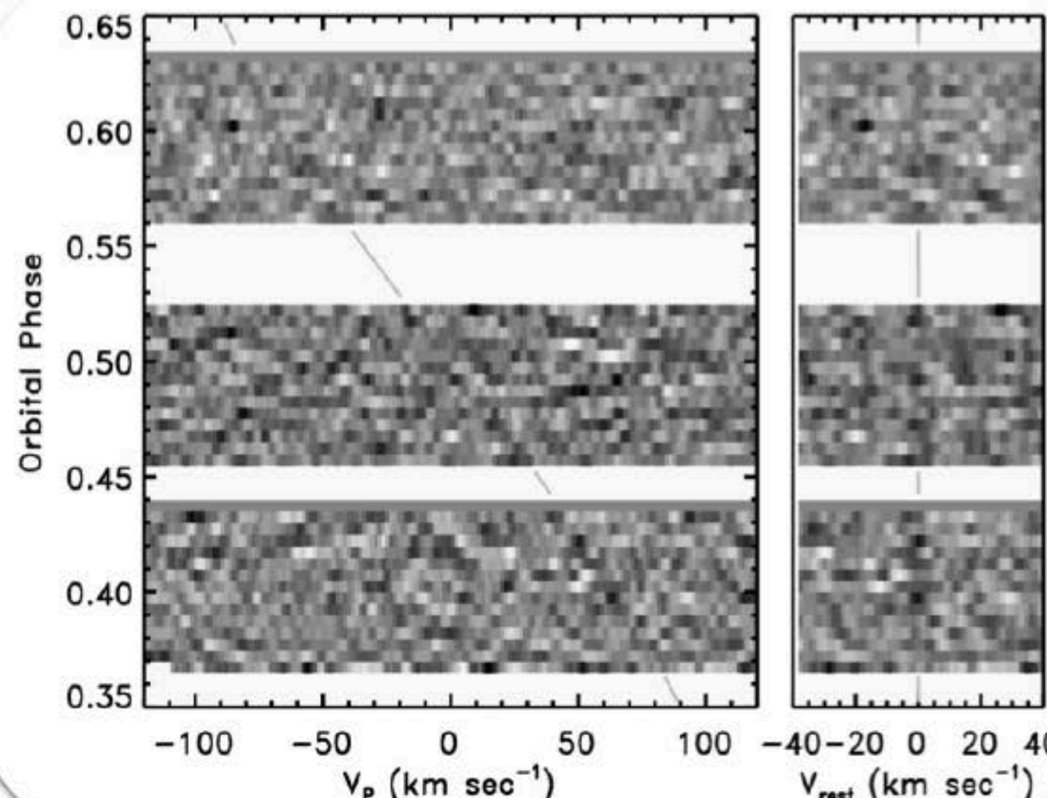
CO in dayside spectrum of tau Bootis b (CRIRES@VLT)

(**Brogi et al. *Nature* 2012 – see also Rodler et al. 2012**)



First detection of non-transiting planet→ inclination, mass



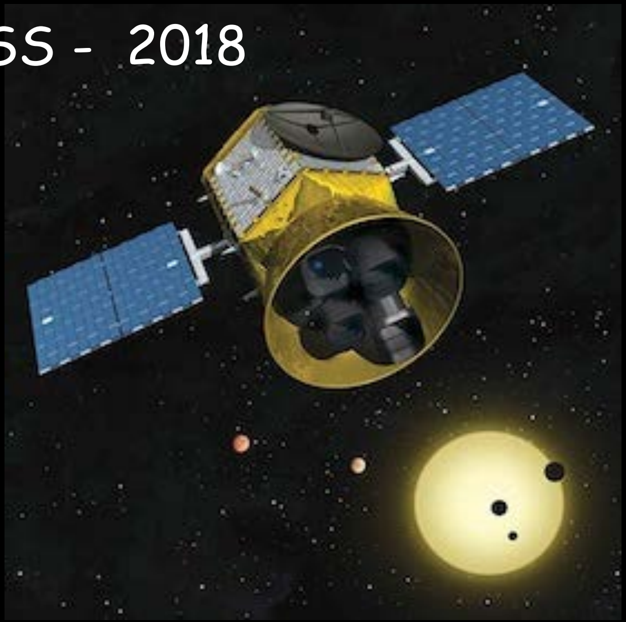


One in 1,000-10,000 photons
cross the planetary atmosphere

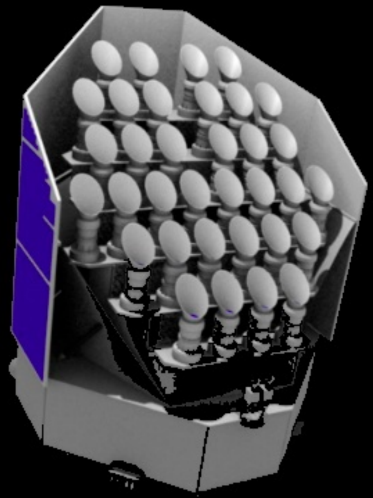
One in 100,000-1,000,000 photons
cross the planetary atmosphere

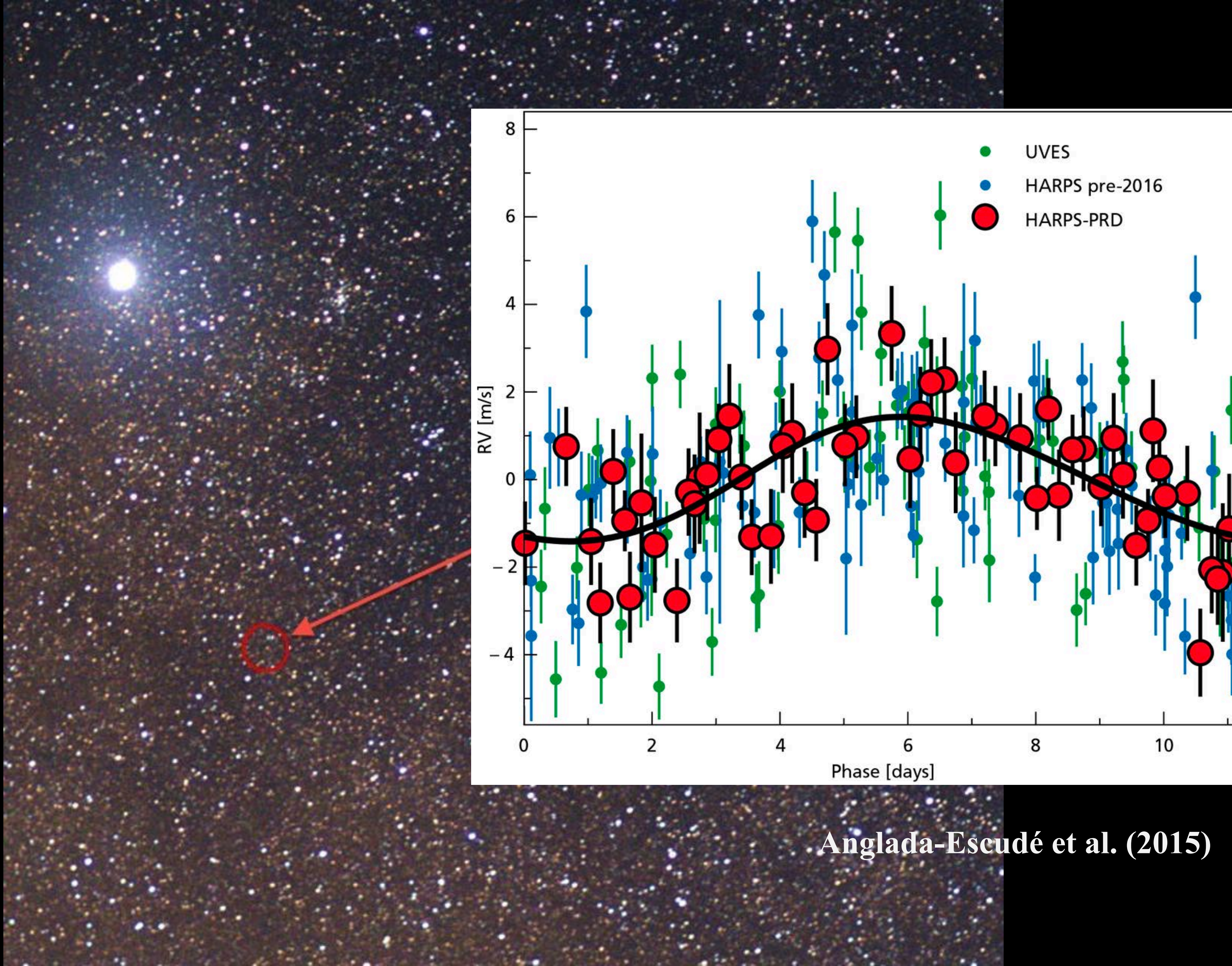
Focus of searches: brightest and closest stars

TESS - 2018

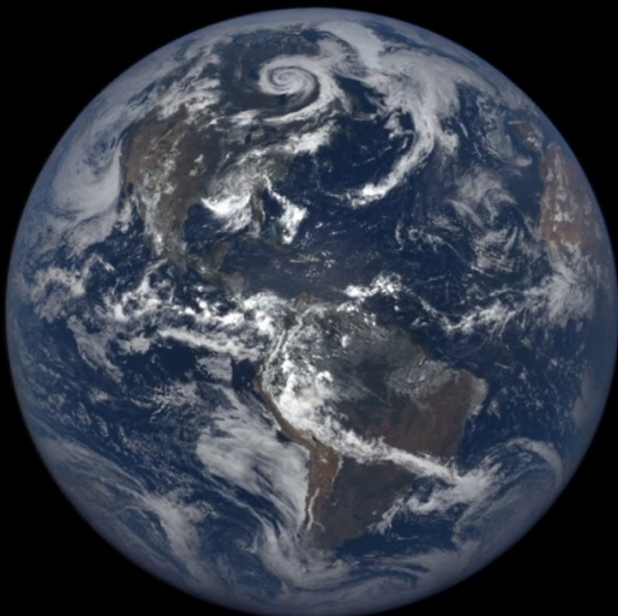


PLATO - 2025





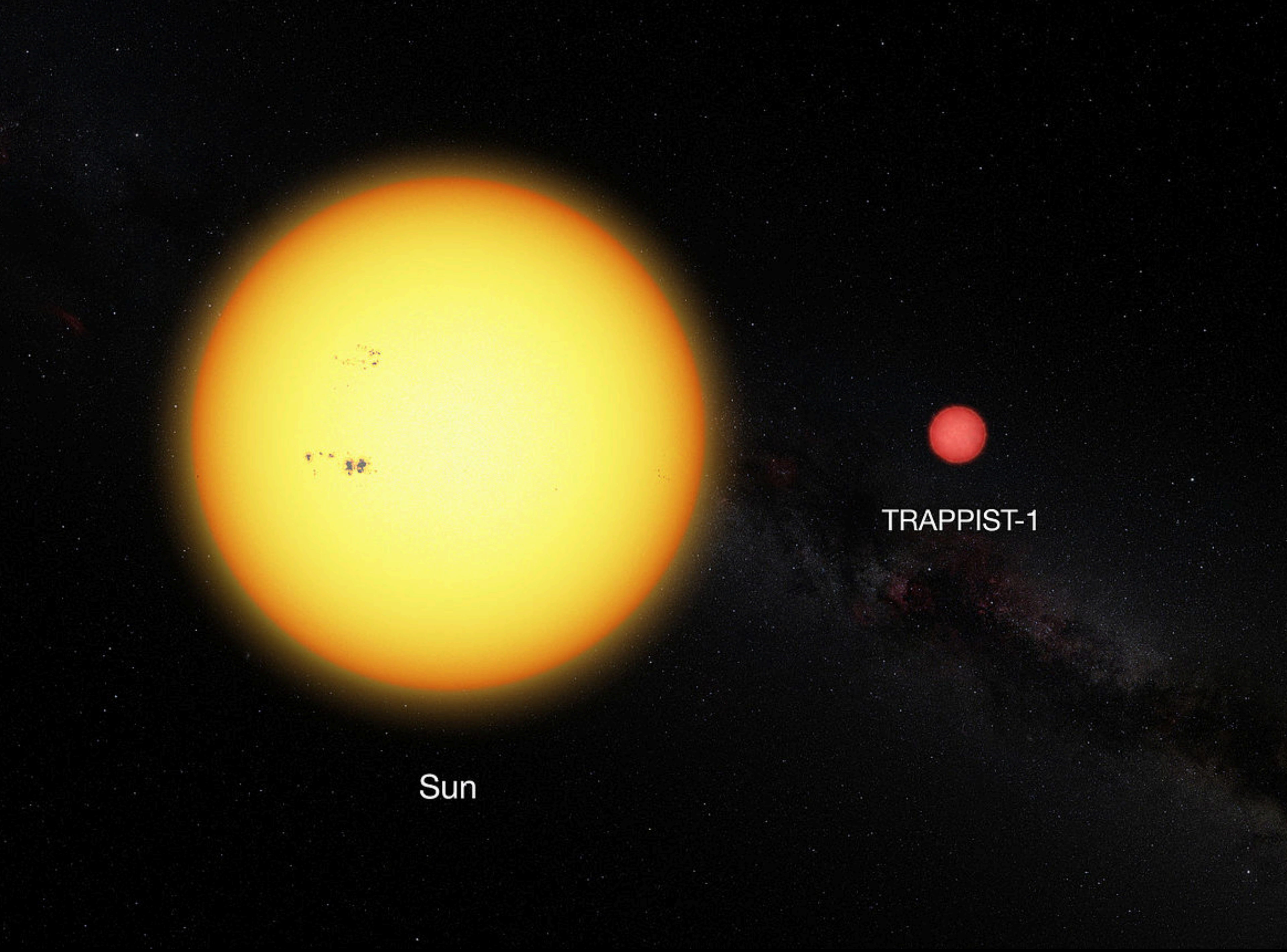
Anglada-Escudé et al. (2015)

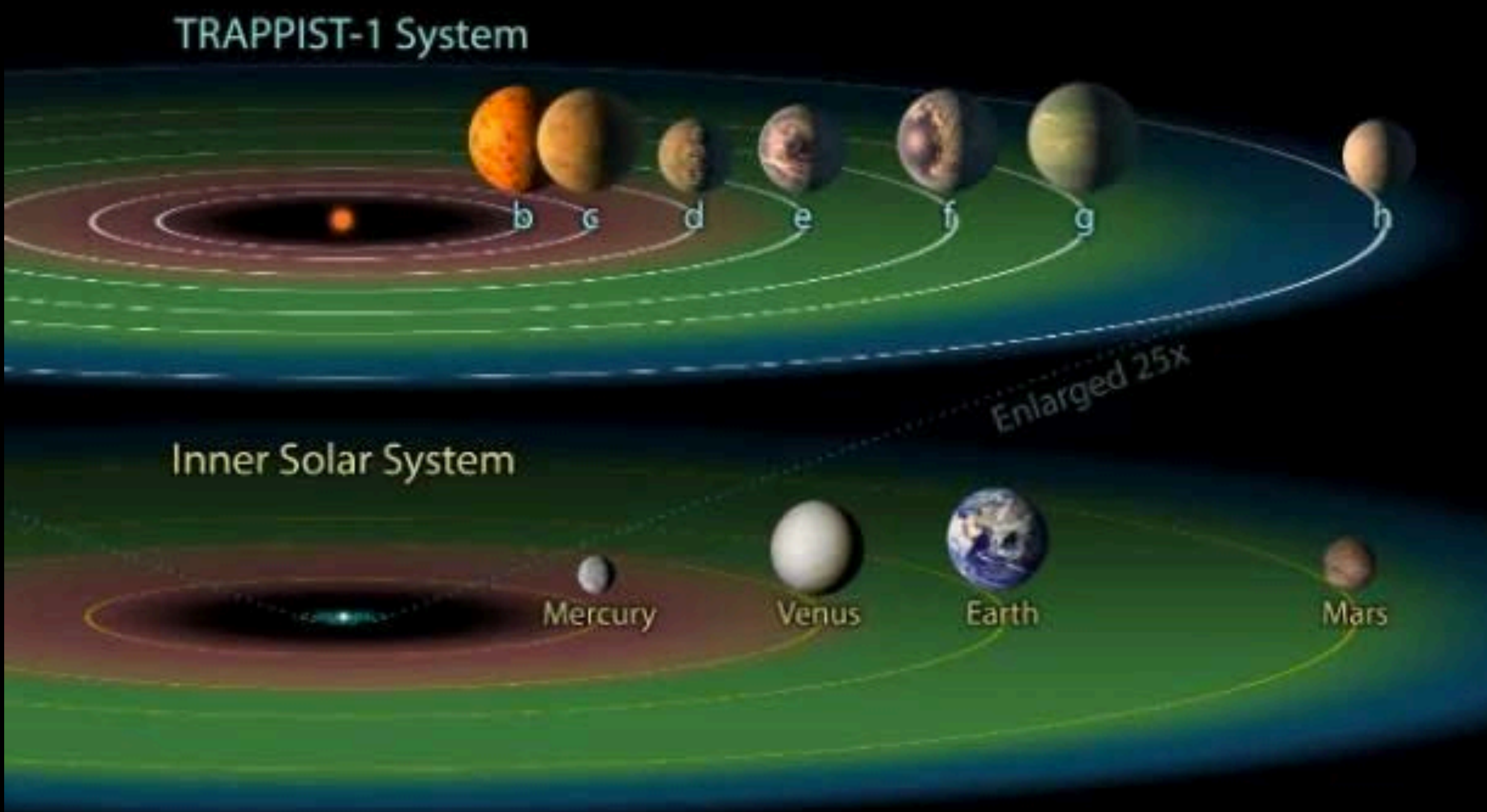


Earth

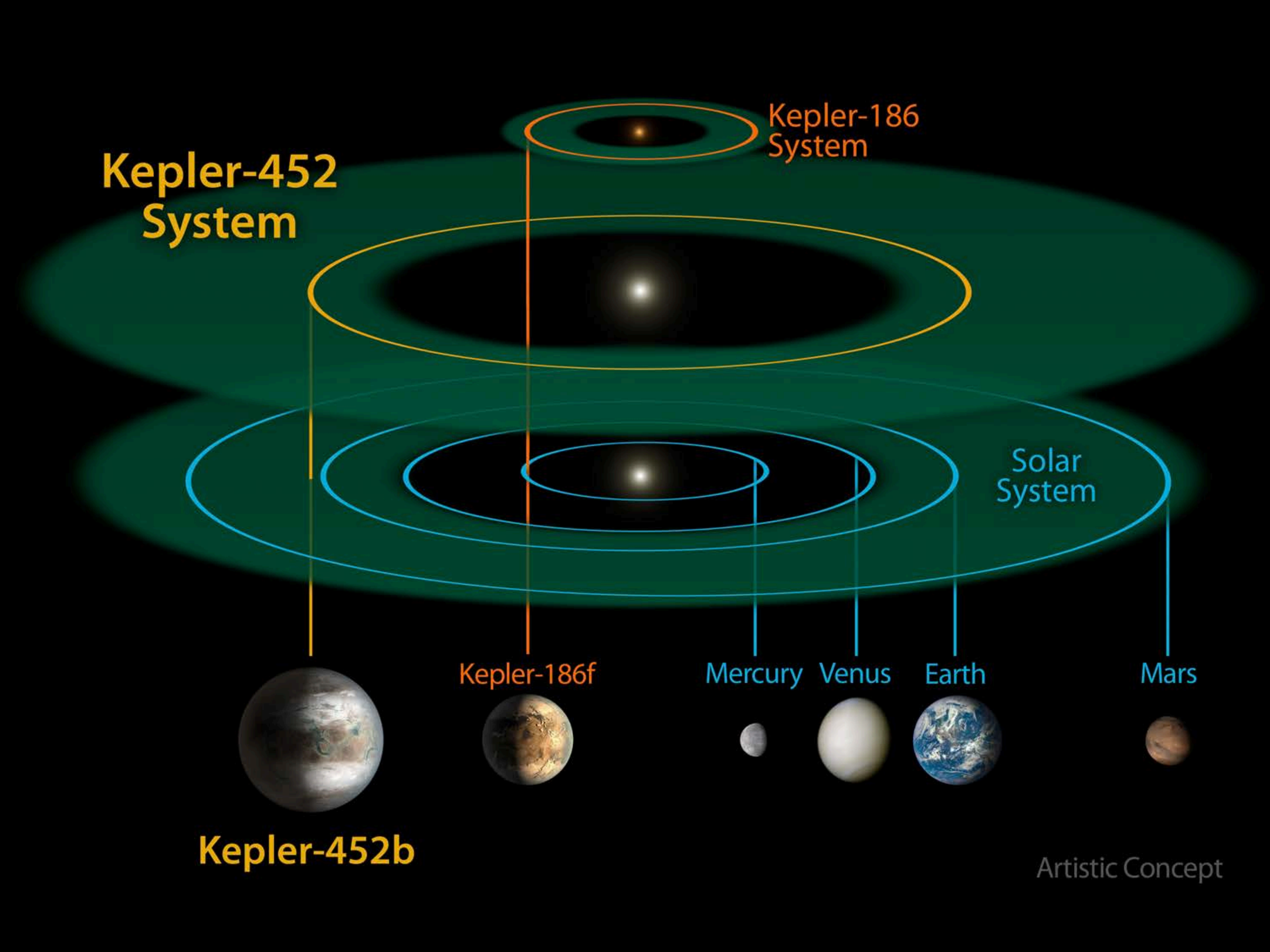
Proxima b

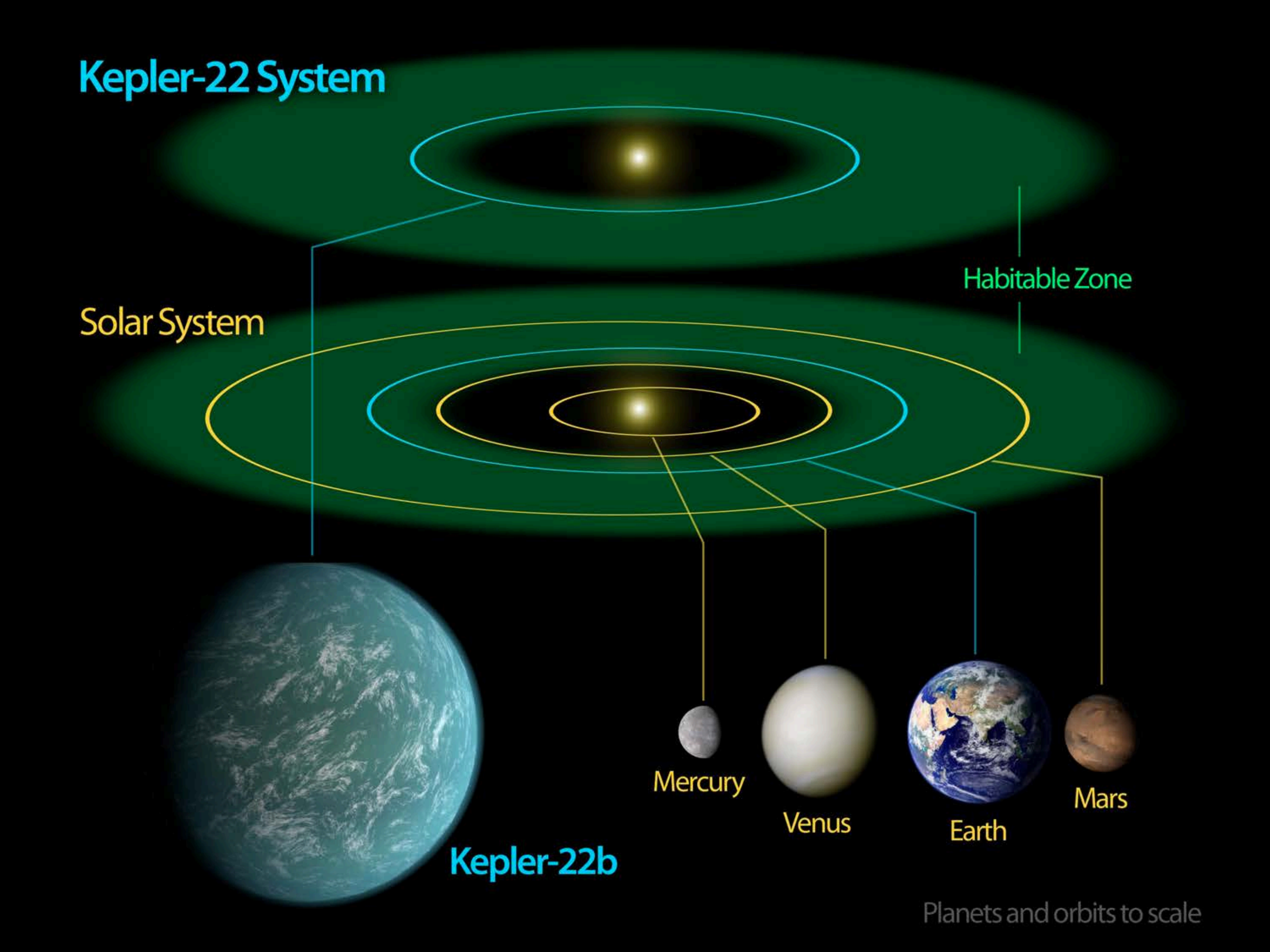
(artistic representation)

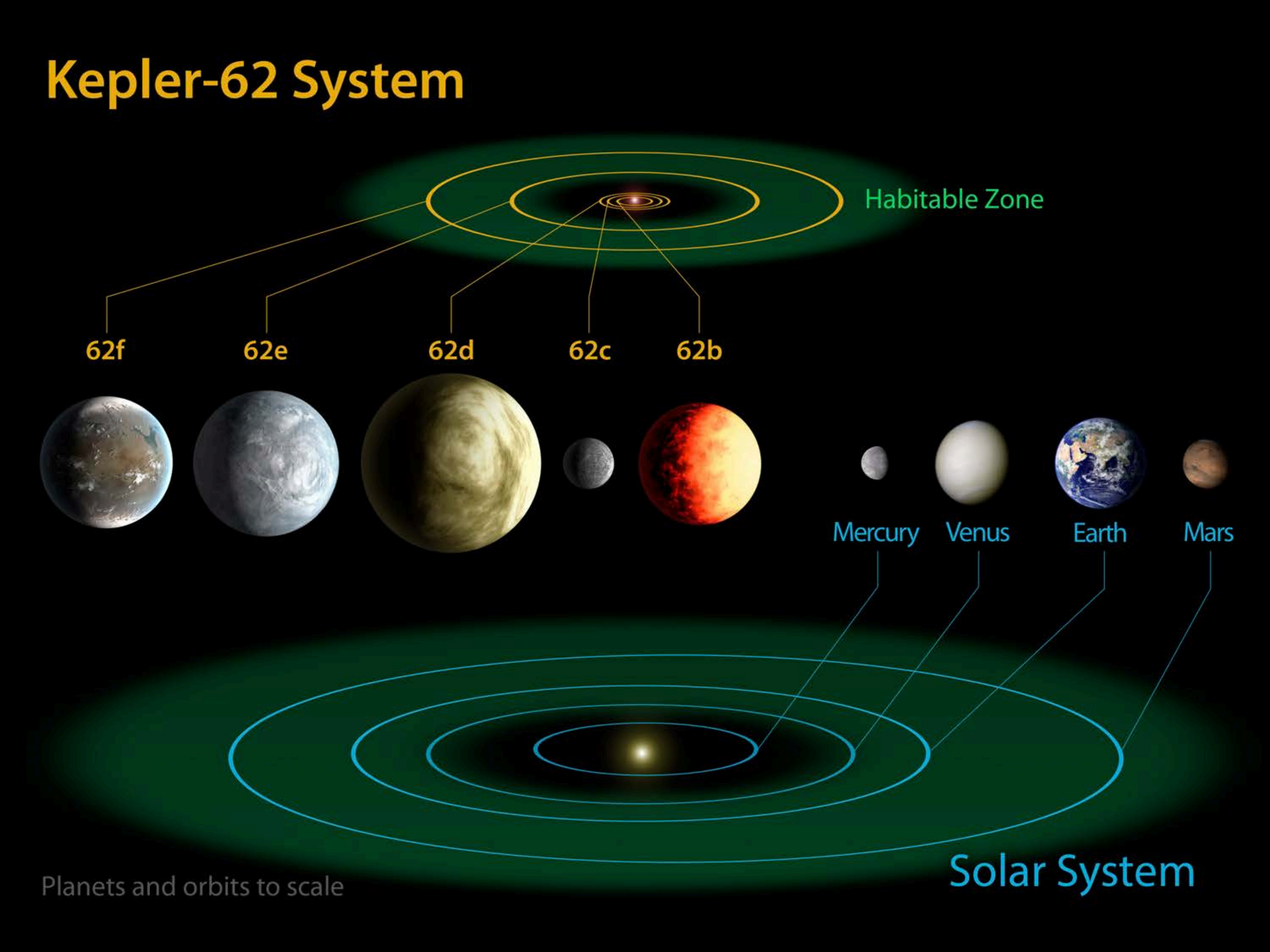

TRAPPIST-1
Sun

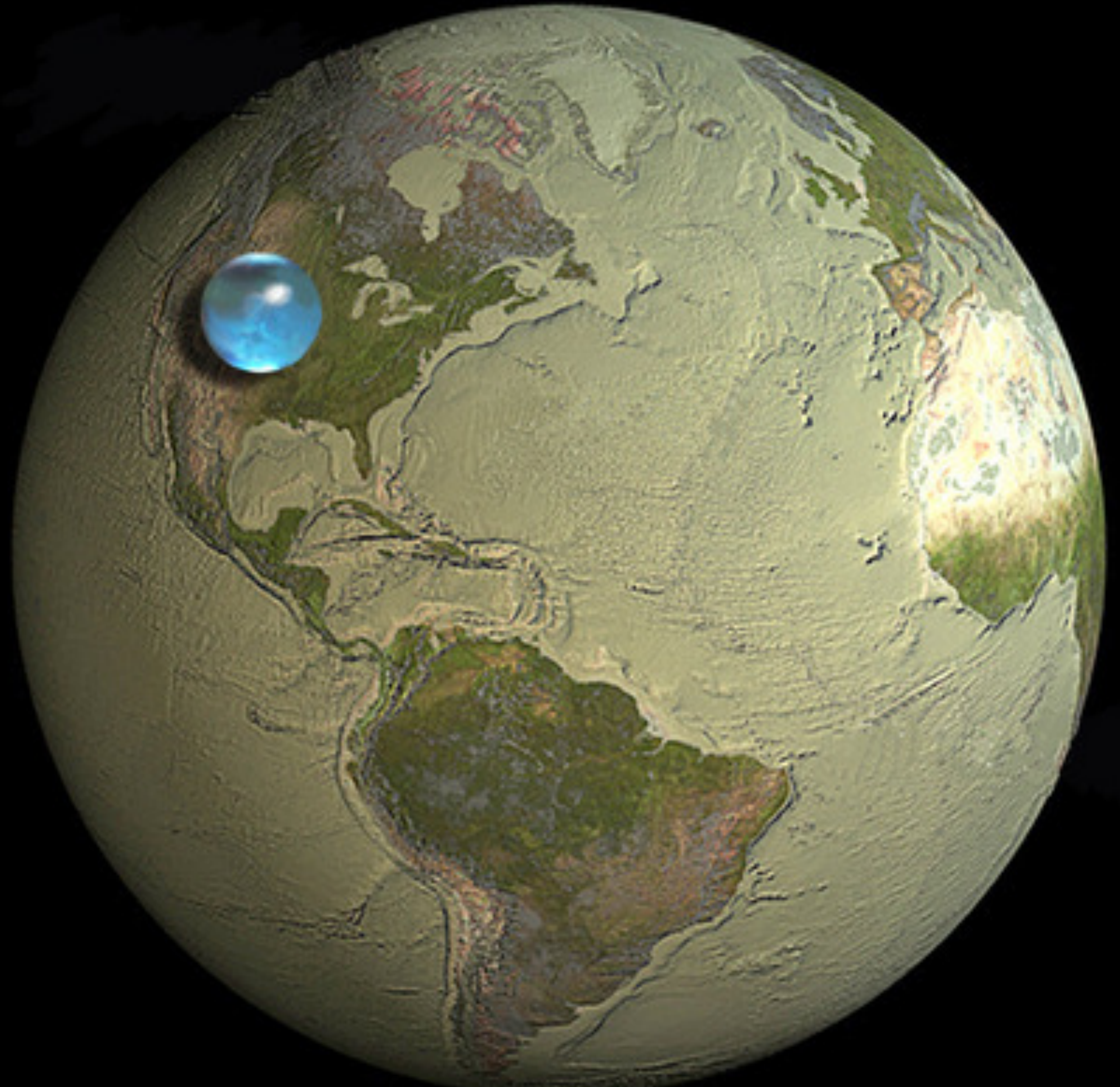

TRAPPIST-1 System
b
c
d
e
f
g
h
Enlarged 25x
Inner Solar System
Mercury
Venus
Earth
Mars

But these are not the only ones….


Kepler-186
System
Kepler-452
System
Solar
System
Kepler-186f
Mercury
Venus
Earth
Mars
Kepler-452b
Artistic Concept

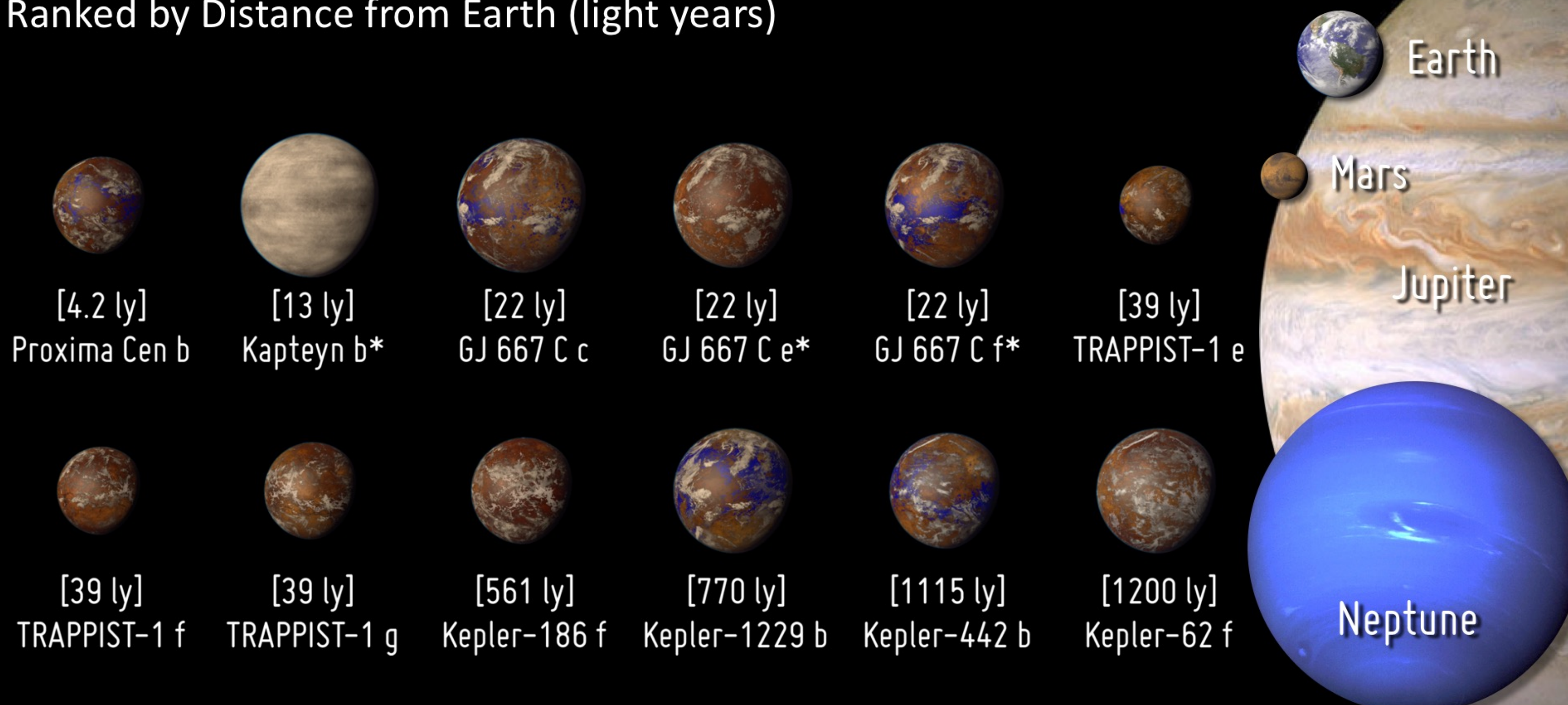

Kepler-22 System
Habitable Zone
Solar System
Mercury
Venus
Earth
Mars
Kepler-22b
Planets and orbits to scale


Kepler-62 System
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale



Potentially Habitable Exoplanets

Ranked by Distance from Earth (light years)

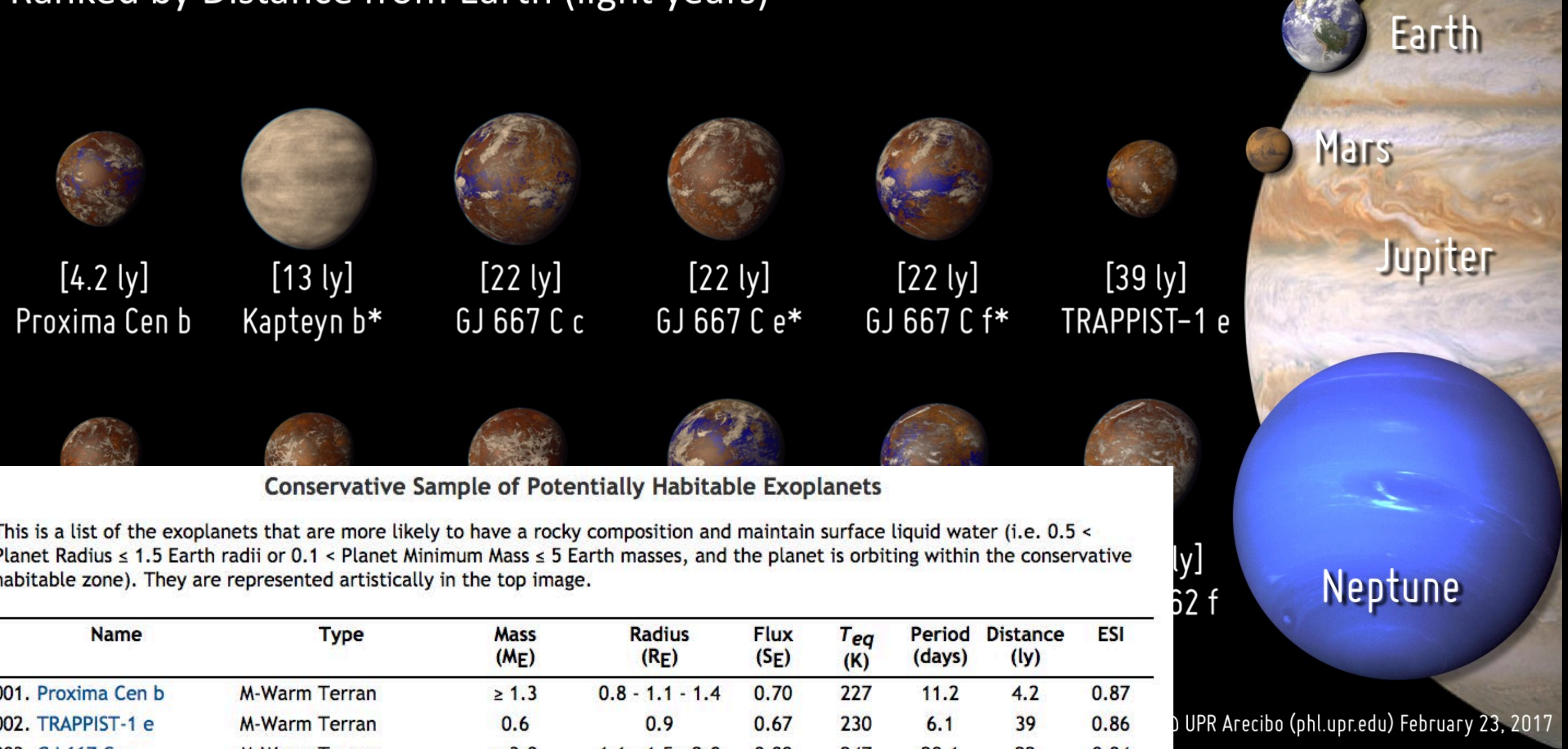


Artistic representations. Earth, Mars, Jupiter, and Neptune for scale.
Distance is between brackets. Planet candidates indicated with asterisks.

CREDIT: PHL @ UPR Arecibo (phl.upr.edu) February 23, 2017

Potentially Habitable Exoplanets

Ranked by Distance from Earth (light years)



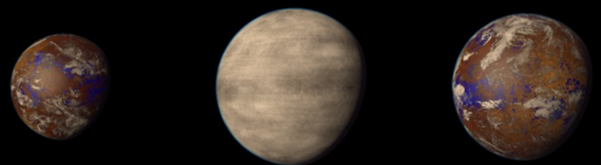
Conservative Sample of Potentially Habitable Exoplanets

This is a list of the exoplanets that are more likely to have a rocky composition and maintain surface liquid water (i.e. 0.5 < Planet Radius ≤ 1.5 Earth radii or 0.1 < Planet Minimum Mass ≤ 5 Earth masses, and the planet is orbiting within the conservative habitable zone). They are represented artistically in the top image.

Name	Type	Mass (M_E)	Radius (R_E)	Flux (S_E)	T_{eq} (K)	Period (days)	Distance (ly)	ESI
001. Proxima Cen b	M-Warm Terran	≥ 1.3	0.8 - 1.1 - 1.4	0.70	227	11.2	4.2	0.87
002. TRAPPIST-1 e	M-Warm Terran	0.6	0.9	0.67	230	6.1	39	0.86
003. GJ 667 C c	M-Warm Terran	≥ 3.8	1.1 - 1.5 - 2.0	0.88	247	28.1	22	0.84
004. Kepler-442 b	K-Warm Terran	8.2 - 2.3 - 1.0	1.3	0.70	233	112.3	1115	0.84
005. GJ 667 C f*	M-Warm Terran	≥ 2.7	1.0 - 1.4 - 1.8	0.56	221	39.0	22	0.77
006. Kepler-1229 b	M-Warm Terran	9.8 - 2.7 - 1.2	1.4	0.49	213	86.8	769	0.73
007. TRAPPIST-1 f	M-Warm Terran	0.7	1.0	0.38	200	9.2	39	0.68
008. Kapteyn b*	M-Warm Terran	≥ 4.8	1.2 - 1.6 - 2.1	0.43	205	48.6	13	0.67
009. Kepler-62 f	K-Warm Terran	10.2 - 2.8 - 1.2	1.4	0.39	201	267.3	1200	0.67
010. Kepler-186 f	M-Warm Terran	4.7 - 1.5 - 0.6	1.2	0.29	188	129.9	561	0.61
011. GJ 667 C e*	M-Warm Terran	≥ 2.7	1.0 - 1.4 - 1.8	0.30	189	62.2	22	0.60
012. TRAPPIST-1 g	M-Warm Terran	1.3	1.1	0.26	182	12.4	39	0.58

Potentially Habitab

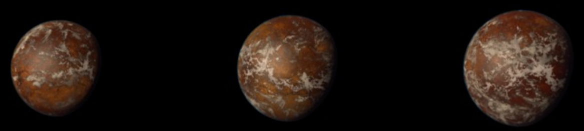
Ranked by Distance from Earth (lig



[4.2 ly] Proxima Cen b

[13 ly] Kapteyn b*

[22 ly] GJ 667 C c



[39 ly] TRAPPIST-1 f

[39 ly] TRAPPIST-1 g

[561 ly] Kepler-186 f

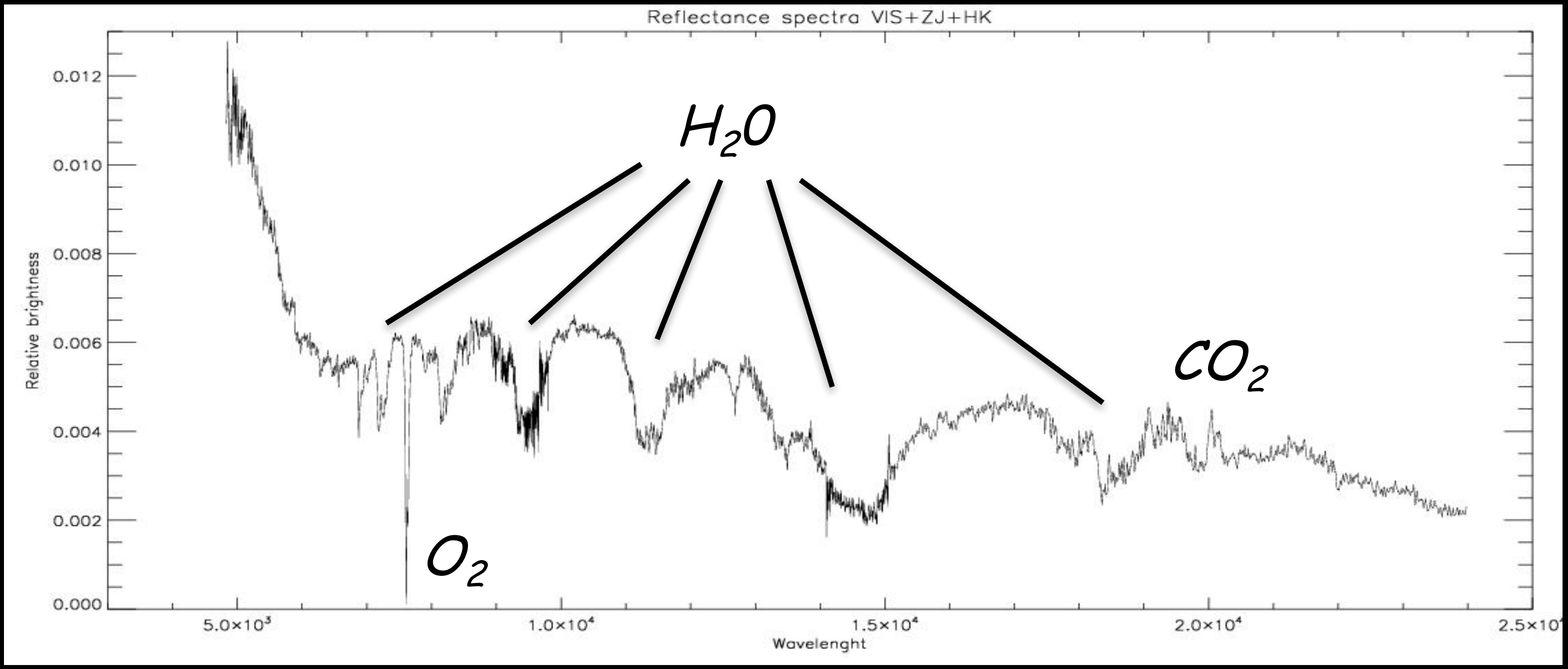
Artistic representations. Earth, Mars, Jupiter, and Neptune for scale.
Distance is between brackets. Planet candidates indicated with asterisks.

Name	Type	Mass (M_E)	Radius (R_E)	Flux (S_E)	T_{eq} (K)	Period (days)	Distance (ly)	ESI
001. TRAPPIST-1 d	M-Warm Subterran	0.4	0.8	1.15	264	4.0	39	0.90
002. GJ 3323 b (N)	M-Warm Terran	≥ 2.0	0.9 - 1.3 - 1.6	1.21	264	5.4	-	0.89
003. Kepler-438 b	M-Warm Terran	4.0 - 1.3 - 0.6	1.1	1.38	276	35.2	473	0.88
004. GJ 273 b (N)	M-Warm Terran	≥ 2.9	1.0 - 1.4 - 1.8	1.22	267	18.6	12	0.86
005. Kepler-296 e	M-Warm Terran	12.5 - 3.3 - 1.4	1.5	1.22	267	34.1	737	0.85
006. Kepler-62 e	K-Warm Superterran	18.7 - 4.5 - 1.9	1.6	1.10	261	122.4	1200	0.83
007. Kepler-452 b	G-Warm Superterran	19.8 - 4.7 - 1.9	1.6	1.11	261	384.8	1402	0.83
008. K2-72 e	M-Warm Terran	9.8 - 2.7 - 1.2	1.4	1.46	280	24.2	181	0.82
009. GJ 832 c	M-Warm Superterran	≥ 5.4	1.2 - 1.7 - 2.2	1.00	253	35.7	16	0.81
010. K2-3 d	M-Warm Terran	11.1	1.5	1.46	280	44.6	137	0.80
011. Kepler-1544 b	K-Warm Superterran	31.7 - 6.6 - 2.6	1.8	0.90	248	168.8	1138	0.80
012. Kepler-283 c	K-Warm Superterran	35.3 - 7.0 - 2.8	1.8	0.90	248	92.7	1741	0.79
013. tau Cet e*	G-Warm Terran	≥ 4.3	1.1 - 1.6 - 2.0	1.51	282	168.1	12	0.78
014. Kepler-1410 b	K-Warm Superterran	31.7 - 6.6 - 2.6	1.8	1.34	274	60.9	1196	0.78
015. GJ 180 c*	M-Warm Superterran	≥ 6.4	1.3 - 1.8 - 2.3	0.79	239	24.3	38	0.77
016. Kepler-1638 b	G-Warm Superterran	42.7 - 7.9 - 3.1	1.9	1.39	276	259.3	2866	0.76
017. Kepler-440 b	K-Warm Superterran	41.2 - 7.7 - 3.1	1.9	1.43	273	101.1	851	0.75
018. GJ 180 b*	M-Warm Superterran	≥ 8.3	1.3 - 1.9 - 2.4	1.23	268	17.4	38	0.75
019. Kepler-705 b	M-Warm Superterran	? - 12.7 - 4.8	2.1	0.83	243	56.1	818	0.74
020. HD 40307 g*	K-Warm Superterran	≥ 7.1	1.3 - 1.8 - 2.3	0.68	227	197.8	42	0.74
021. GJ 163 c	M-Warm Superterran	≥ 7.3	1.3 - 1.8 - 2.4	0.66	230	25.6	49	0.73
022. Kepler-61 b	K-Warm Superterran	? - 13.8 - 5.2	2.2	1.27	267	59.9	1063	0.73
023. K2-18 b	M-Warm Superterran	? - 16.5 - 6.0	2.2	0.92	250	32.9	111	0.73
024. Kepler-1606 b	G-Warm Superterran	? - 11.9 - 4.5	2.1	1.41	277	196.4	2869	0.73
025. Kepler-1090 b	G-Warm Superterran	? - 16.8 - 6.1	2.3	1.20	267	198.7	2289	0.72
026. Kepler-443 b	K-Warm Superterran	? - 19.5 - 7.0	2.3	0.89	247	177.7	2540	0.71
027. Kepler-22 b	G-Warm Superterran	? - 20.4 - 7.2	2.4	1.11	261	289.9	619	0.71
028. GJ 422 b*	M-Warm Superterran	≥ 9.9	1.4 - 2.0 - 2.6	0.68	231	26.2	41	0.71
029. K2-9 b	M-Warm Superterran	? - 16.8 - 6.1	2.2	1.38	276	18.4	359	0.71
030. Kepler-1552 b	K-Warm Superterran	? - 25.2 - 8.7	2.5	1.11	261	184.8	2015	0.70
031. GJ 3293 c*	M-Warm Superterran	≥ 8.6	1.4 - 1.9 - 2.5	0.60	223	48.1	59	0.70
032. Kepler-1540 b	K-Warm Superterran	? - 26.2 - 9.0	2.5	0.92	250	125.4	854	0.70
033. Kepler-298 d	K-Warm Superterran	? - 26.8 - 9.1	2.5	1.29	271	77.5	1545	0.68
034. KIC-5522786 b	A-Warm Terran	5.8 - 1.8 - 0.8	1.2	2.70	305	757.2	-	0.67
035. Kepler-174 d	K-Warm Superterran	? - 14.8 - 5.5	2.2	0.43	206	247.4	1174	0.61
036. Kepler-296 f	M-Warm Superterran	28.7 - 6.1 - 2.5	1.8	0.34	194	63.3	737	0.60
037. GJ 682 c*	M-Warm Superterran	≥ 8.7	1.4 - 1.9 - 2.5	0.37	198	57.3	17	0.59
038. Wolf 1061 d	M-Warm Superterran	≥ 5.2	1.2 - 1.7 - 2.2	0.28	182	67.3	14	0.56
039. KOI-4427 b*	M-Warm Superterran	38.5 - 7.4 - 3.0	1.8	0.24	179	147.7	782	0.52

Habitable ≠ Inhabited

How will we know?

The spectrum of an inhabited planet

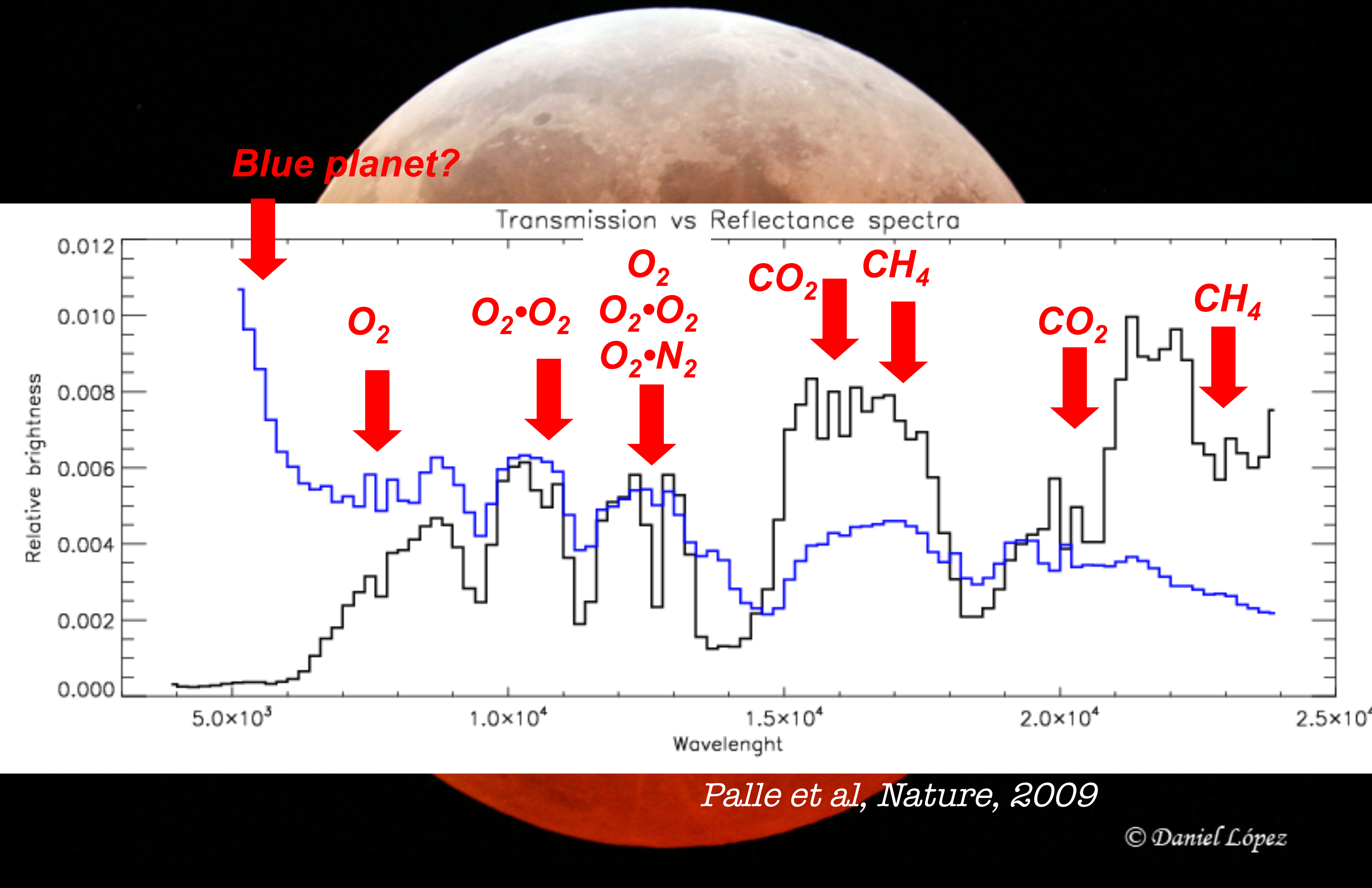


Simultaneous presence of:

- Water
- Ozone (Oxigen)
- Carbon Dioxide

These three gases cannot co-exist in the atmosphere of a planet without the presence of life. Life changes the atmosphere of a planet

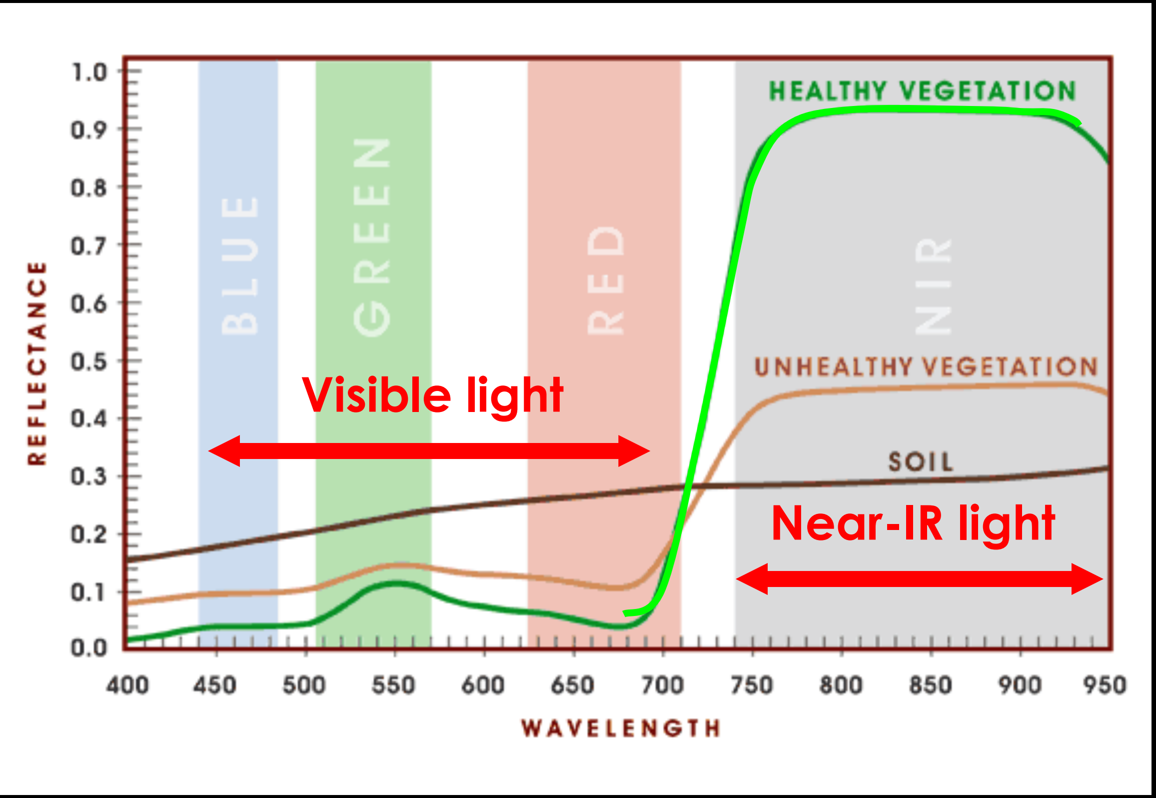
Earth's Transmission Spectrum



Palle et al, Nature, 2009

Surface Biosignatures/Bioclues

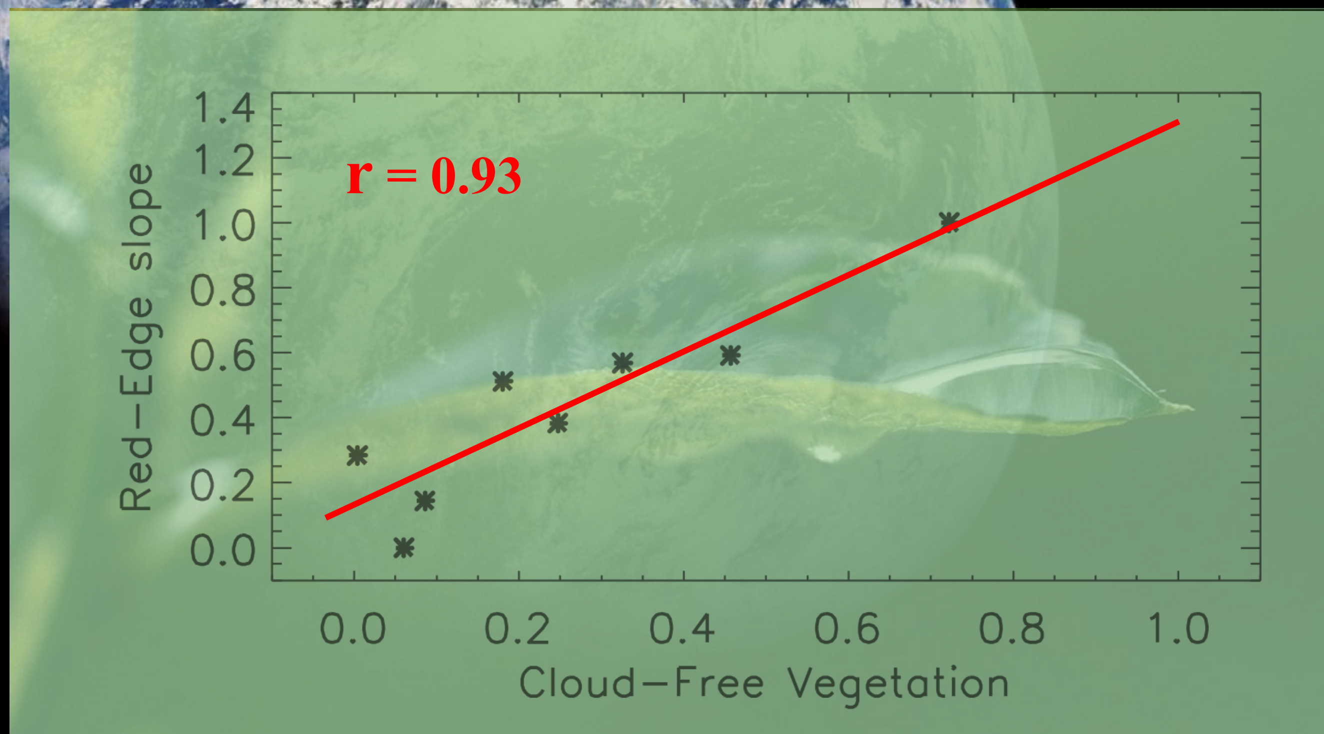
Chlorophyll



Surface Biosignatures/Bioclues

Life changes the *Surface* of a planet

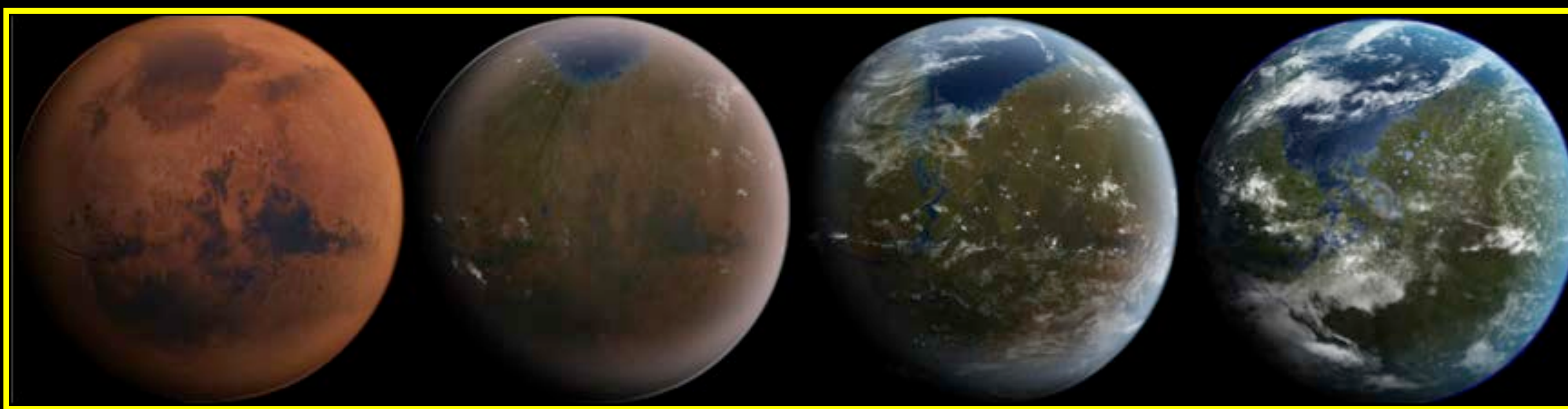
The terrestrial vegetation can be detected although the signal is small ...



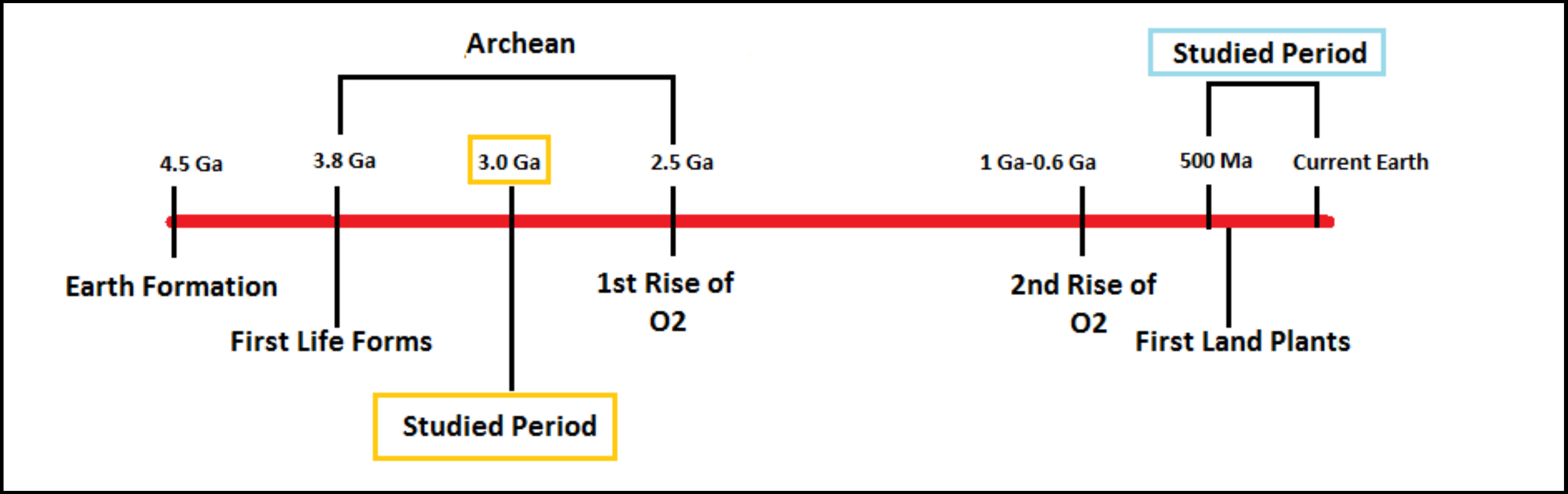
Montañes-Rodriguez et al ApJ, 2006

Extrasolar planets are expected to exhibit a wide range of evolutionary stages, as the Earth did.

What was detectable then?



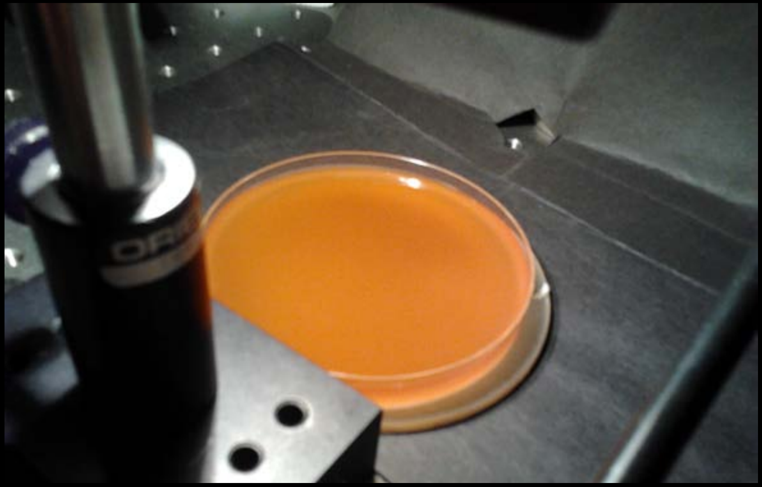
The Archean Earth

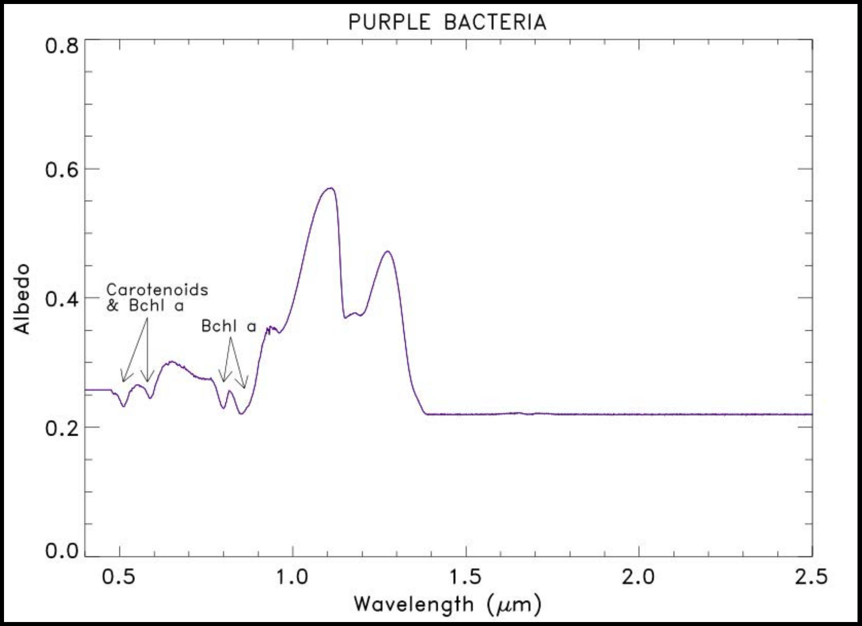


- The Earth has been inhabited for at least 85% of its history
- We focused on Earth 3000 million years ago, when the atmospheric composition was very different from today's and the Sun was ~20% less bright

Purple bacteria

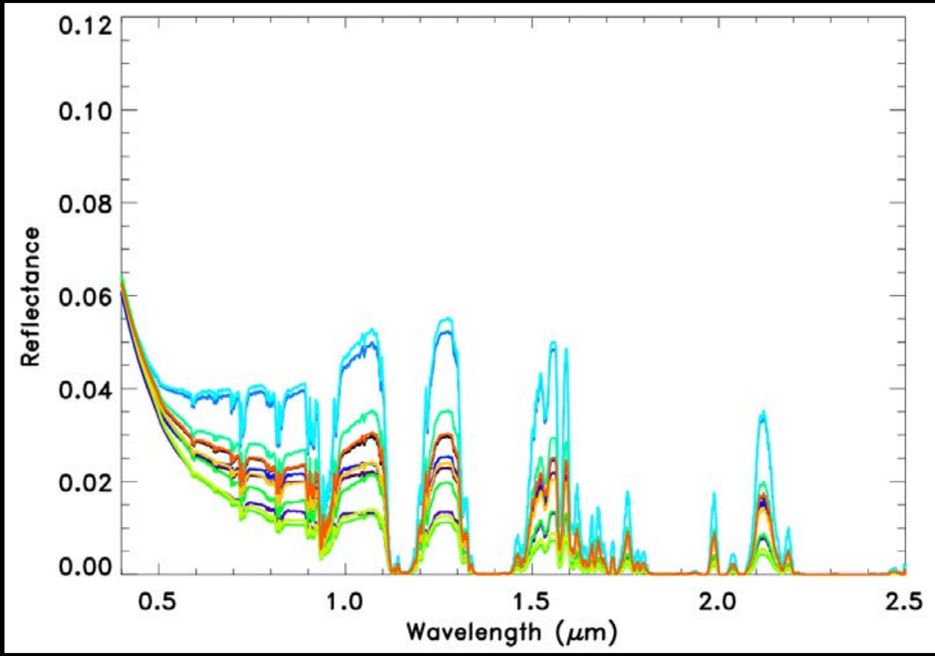
- One of the first life forms that colonized our planet Anoxygenic photosynthesis. Color: red, brown or purple



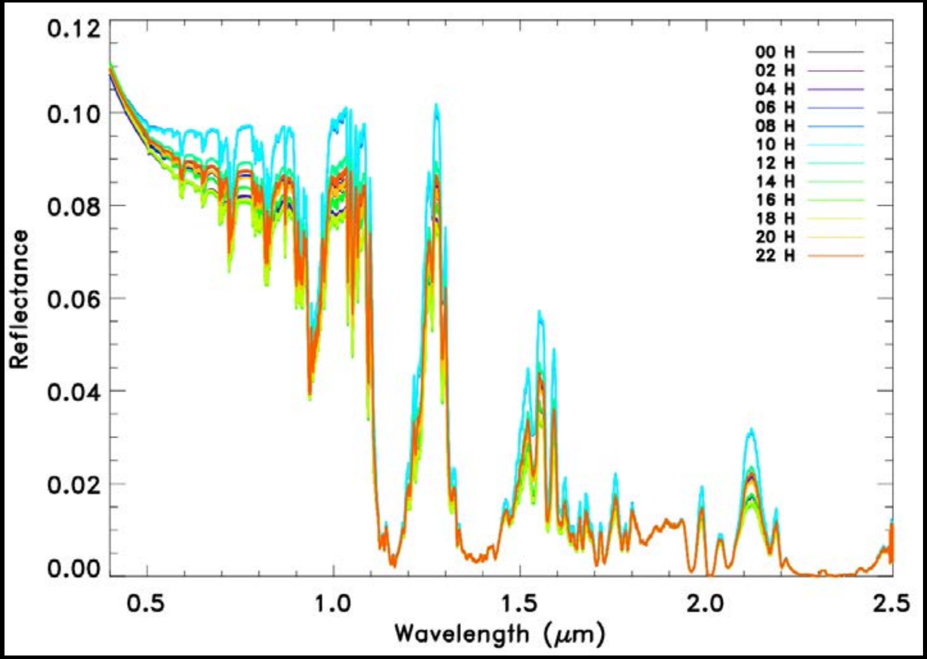


Rotational variability

Cloud free atmosphere



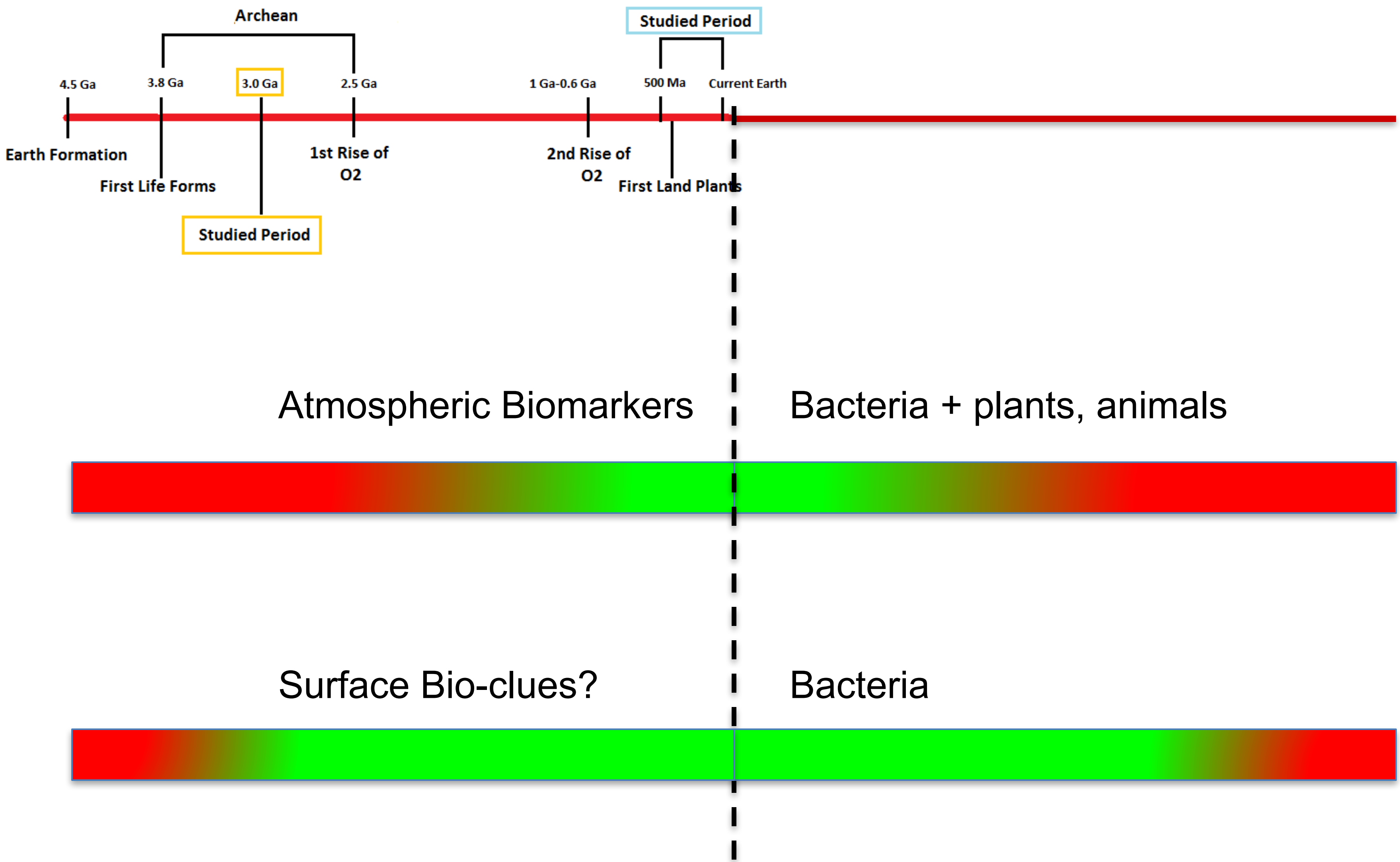
Cloudy atmosphere



- Purple bacteria in coastal areas: most likely scenario
- Purple bacteria readily detectable in the cloud-free case and still visible in the cloudy case

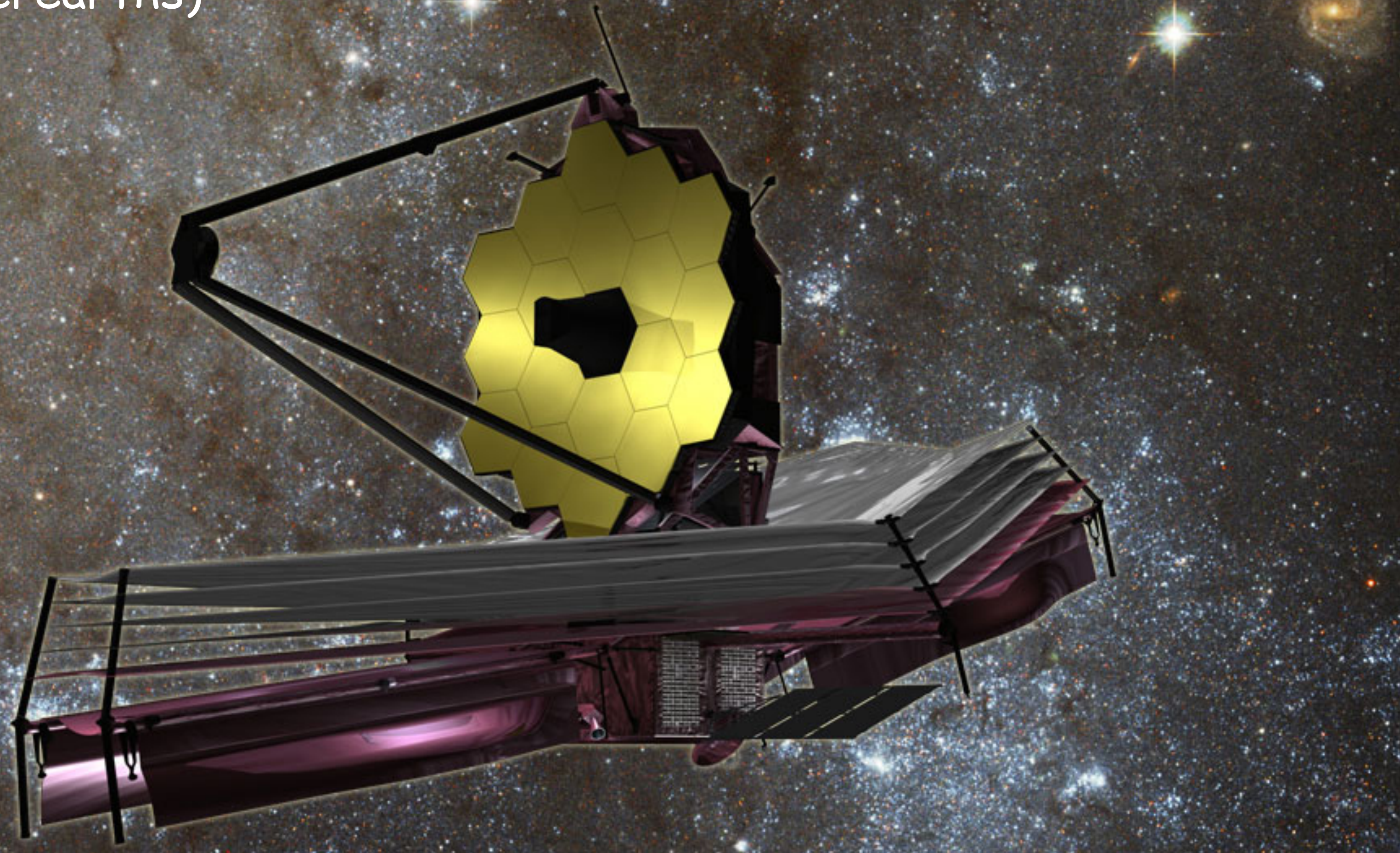
Sanroma et al, ApJ, 2014

Biomarkers in Time

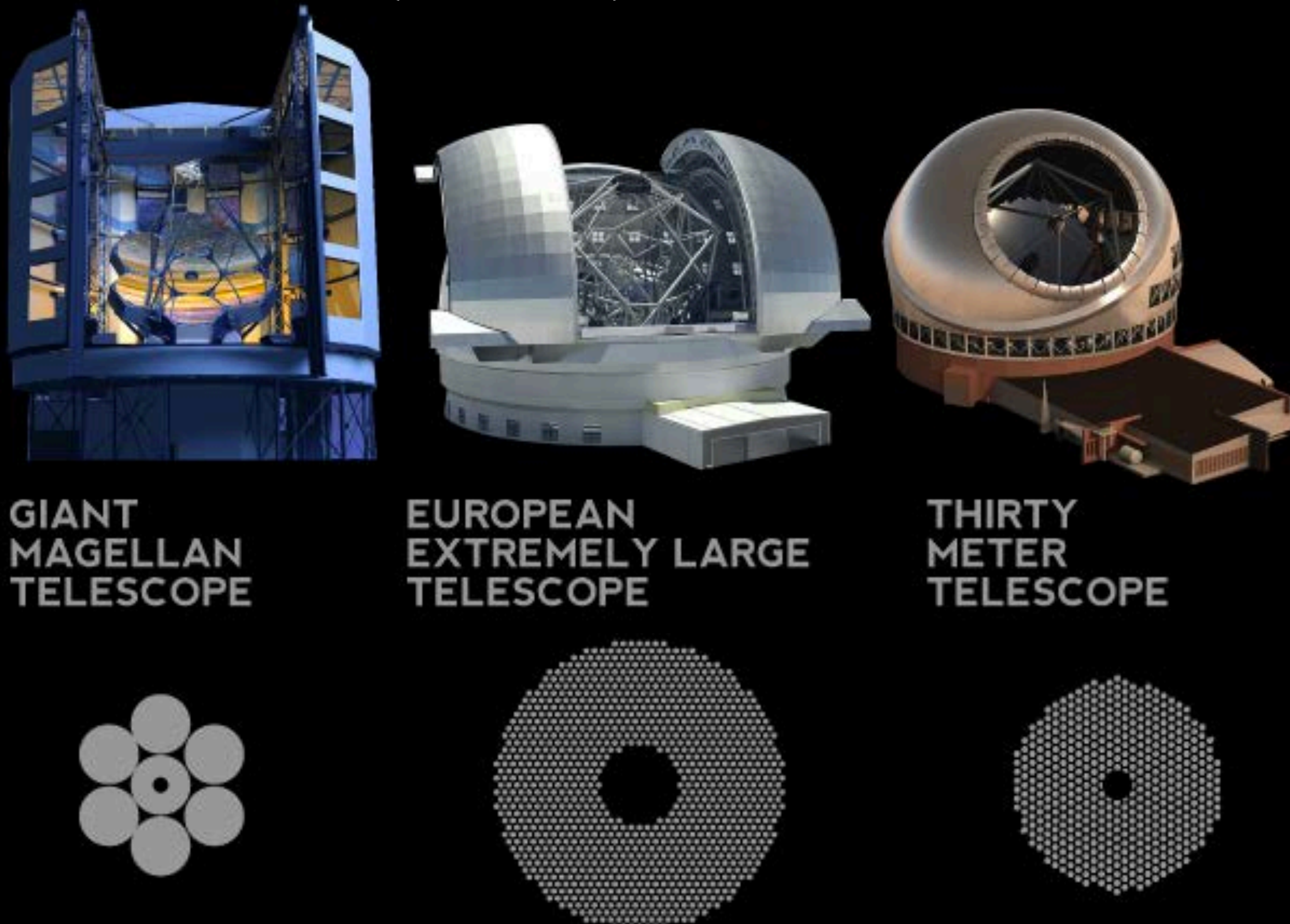


So, how close we are?

James Webb Space Telescope - 2018
Not habitable Earths in general
(Hot Superearths)

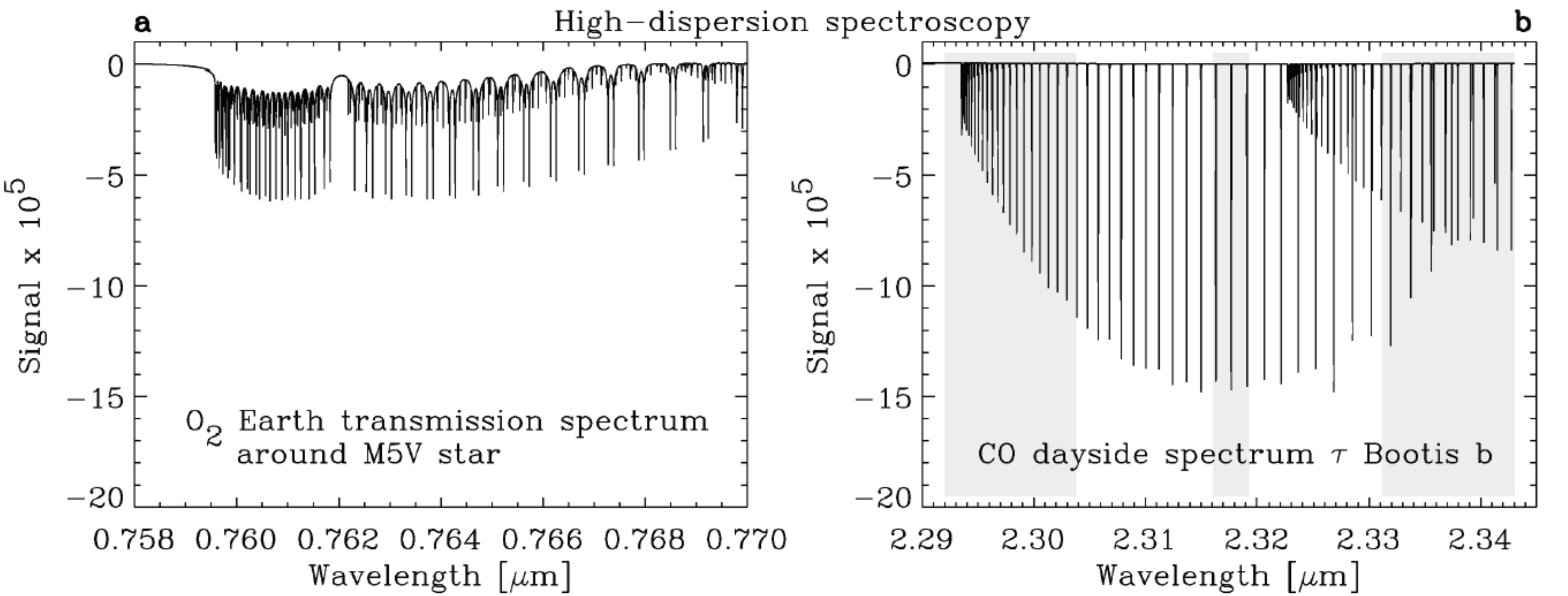


Atmospheric characterization via High-Res Spec (FOV, +AO) 2025-2030



Detection of biosignatures in Earth-like planets

Detection of oxygen in transmission



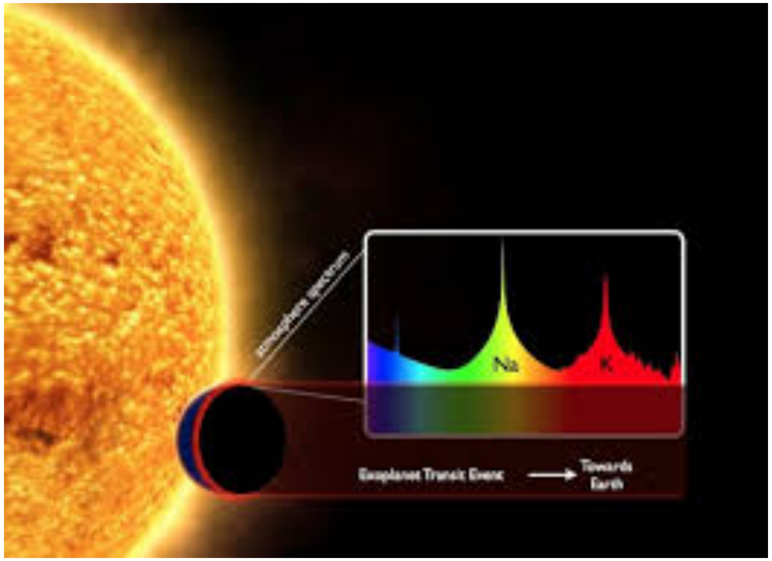
Snellen et al, 2013

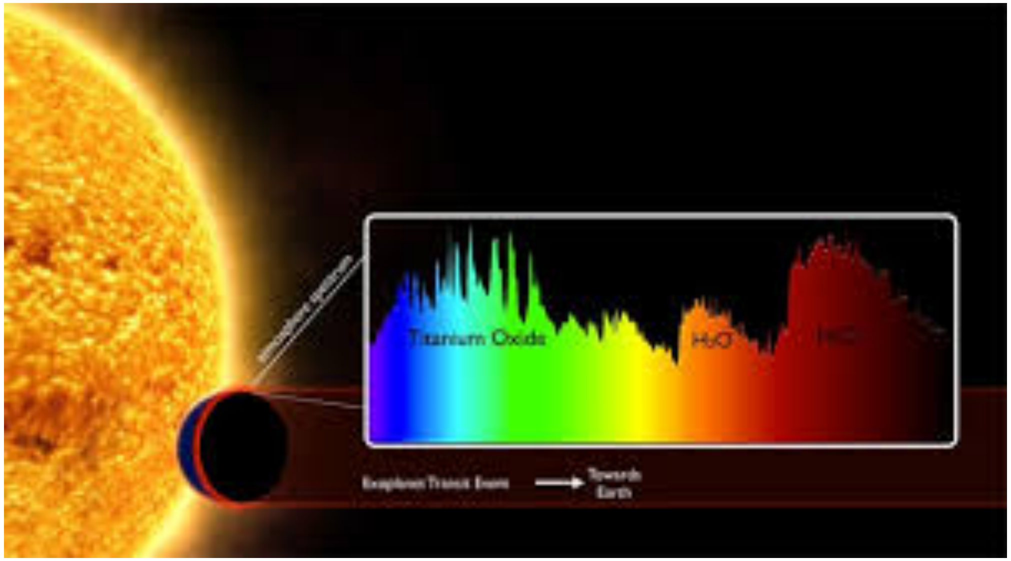
Transmission spectroscopy

M dwarf   Trappist 1 b & c:

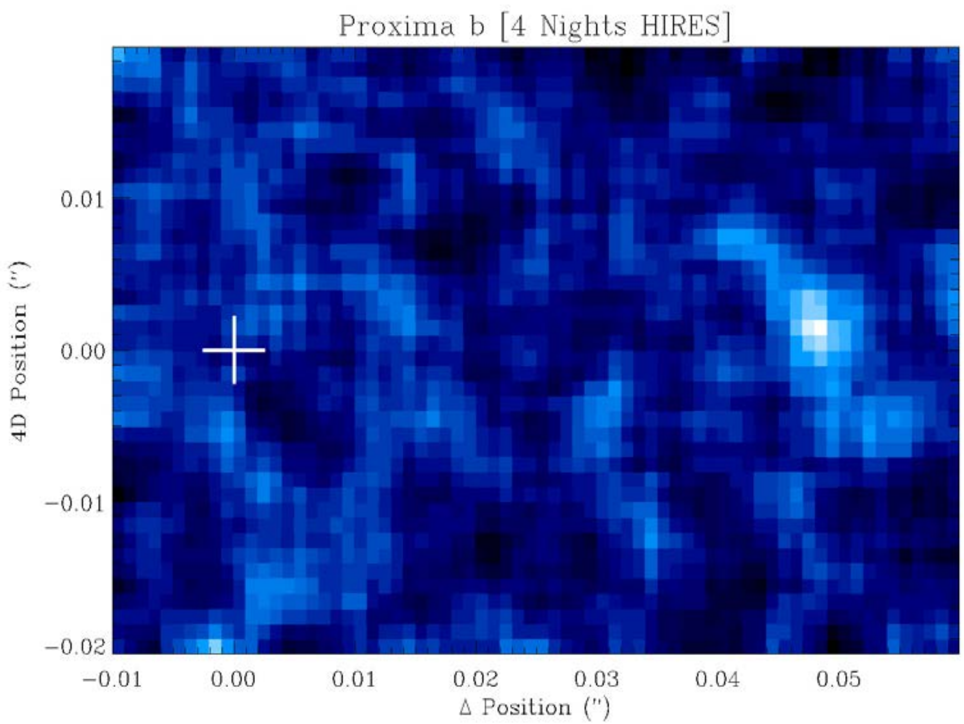
•1.3-1.7 um H_2O band at an SNR of 6 in two transits
•0.9-1.1 um H_2O band in 4 transits
•CO_2 in 4 transits.
•molecular oxygen detected in 25 transits.

For these planets, the transit duration is less than 1 hour.





Direct detection of the planet's reflected light

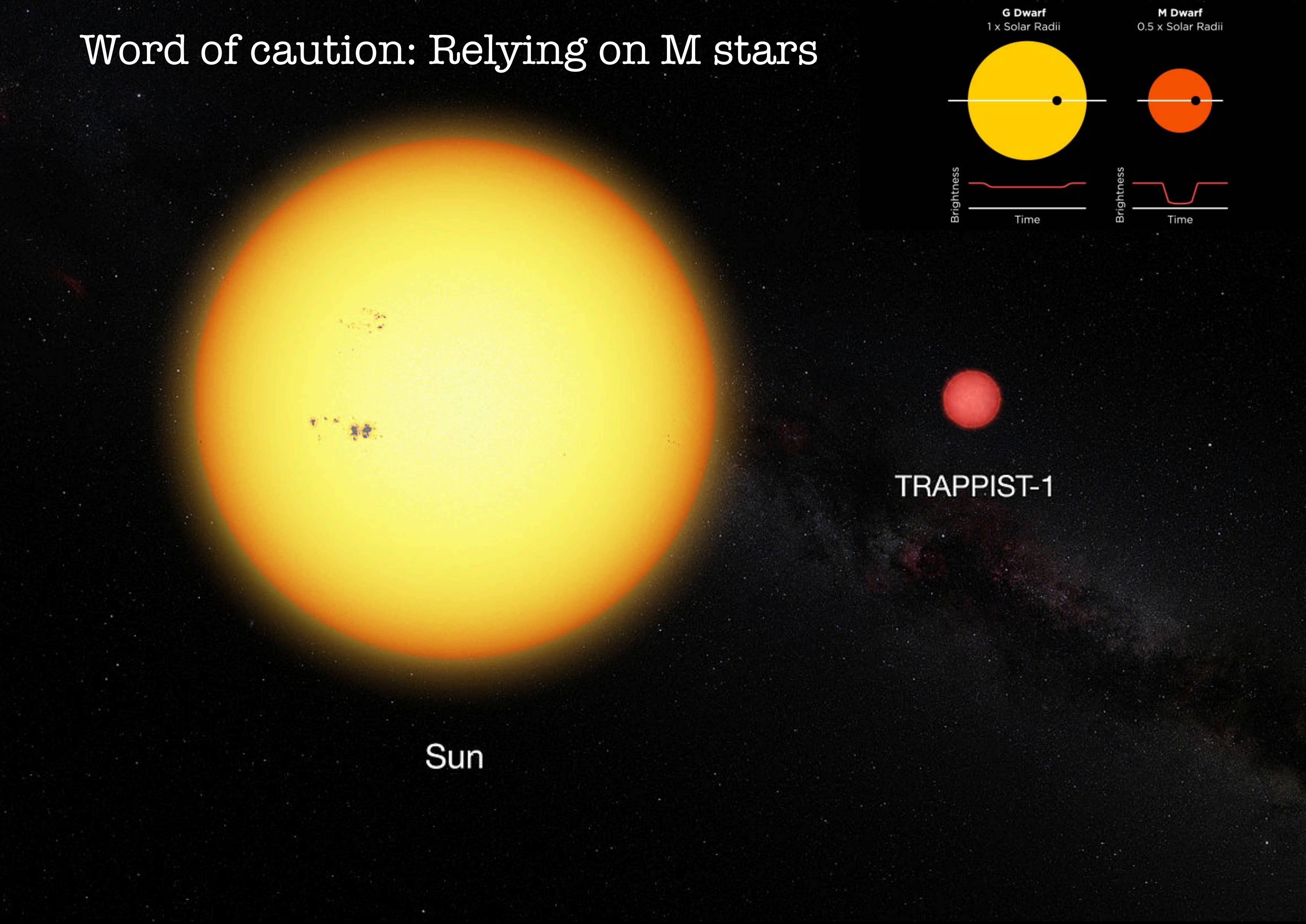


AO+ IFU Reflected light cross-correlation signal of the direct surroundings of Proxima, showing Proxima b at 48 mas

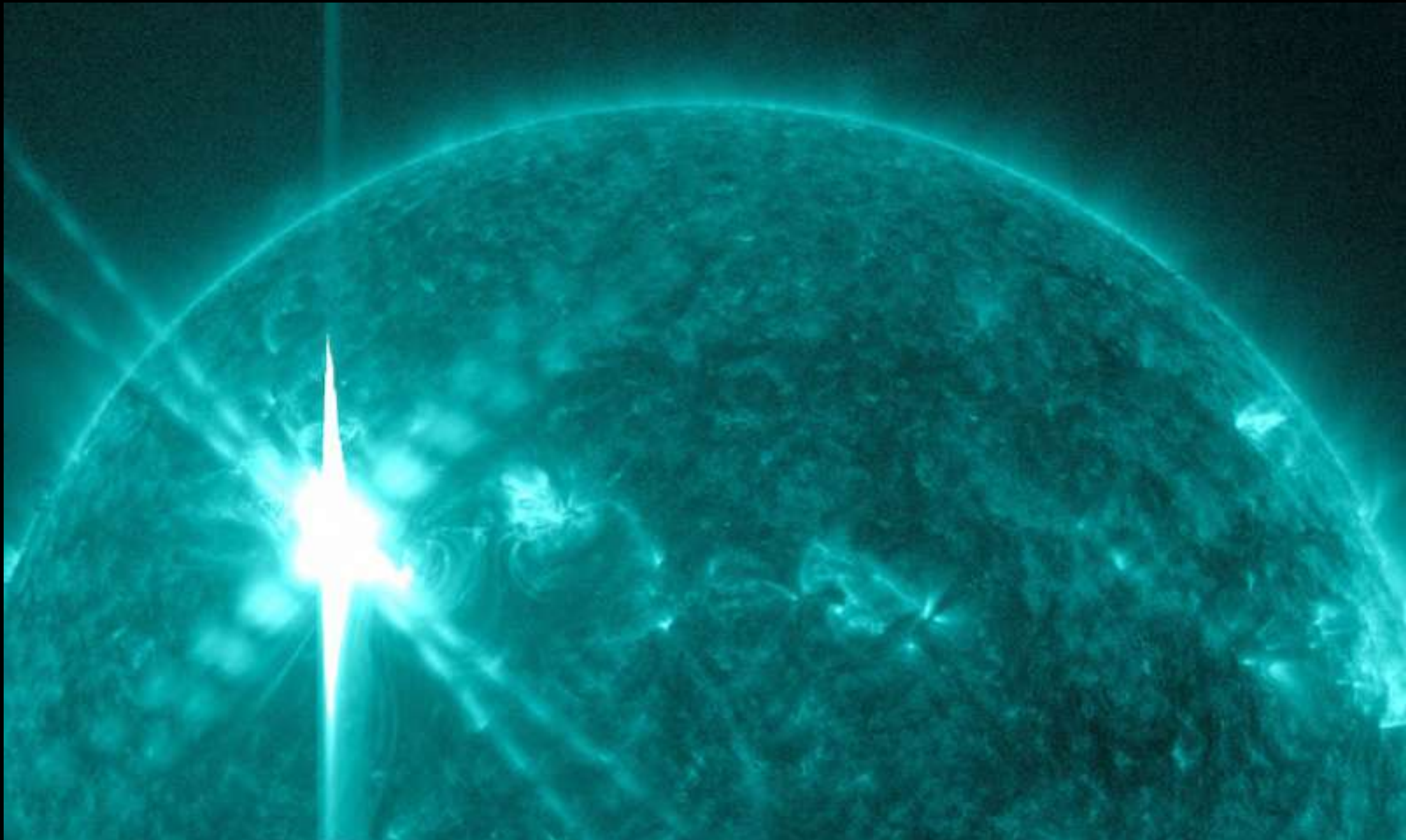
Cross-correlation signal from the planet can be seen at ~8 sigma level in 7 nights, assuming an AO system similar to that of MICADO

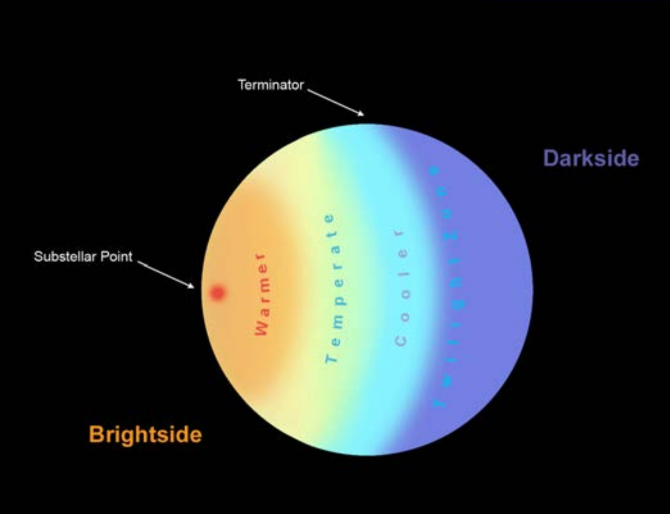
With EAO system (EPICS) 10 x faster

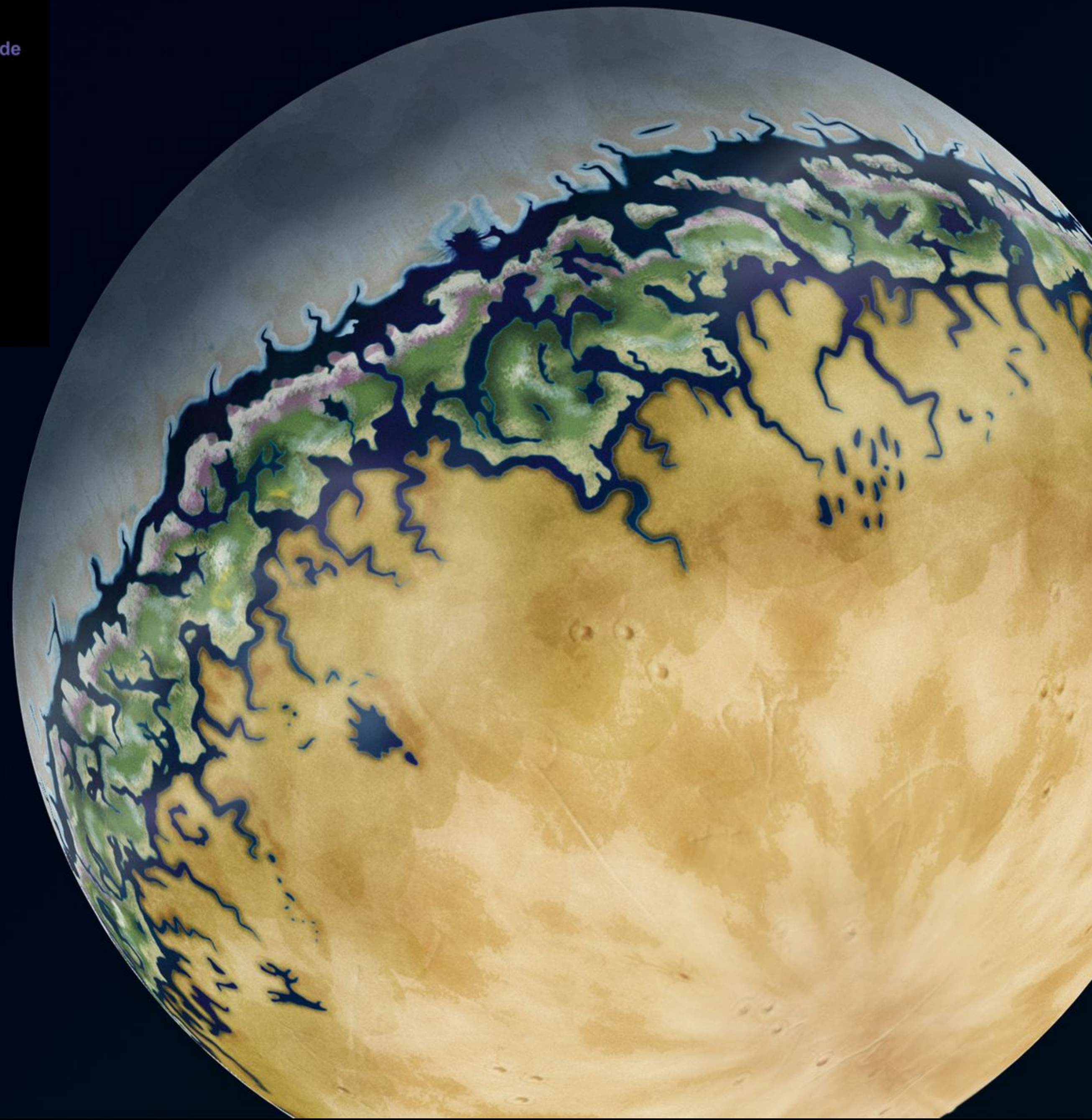
Word of caution: Relying on M stars

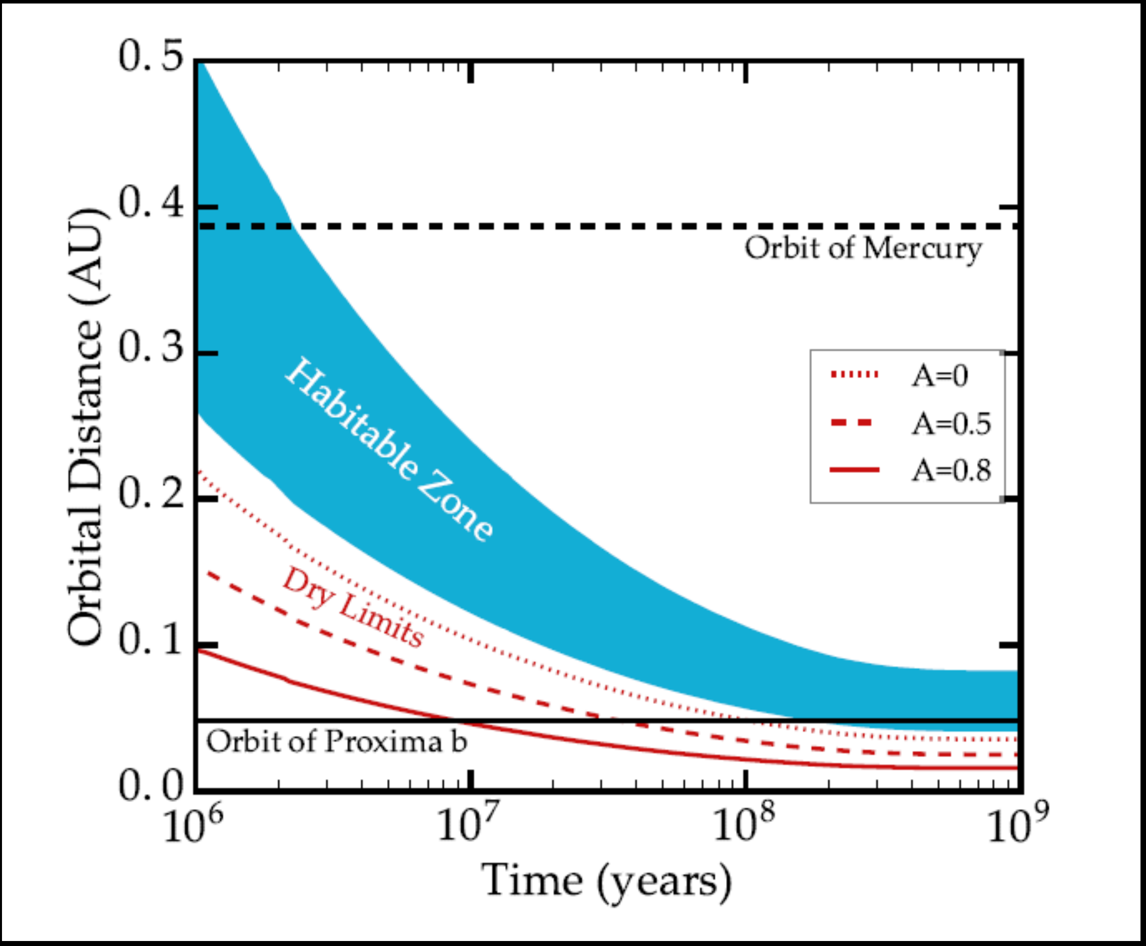


It's not easy to live around an M-star




Terminator
Darkside
Substellar Point
Warmer
Temperate
Cooler
Twilight Zone
Brightside





Barnes et al. 2016

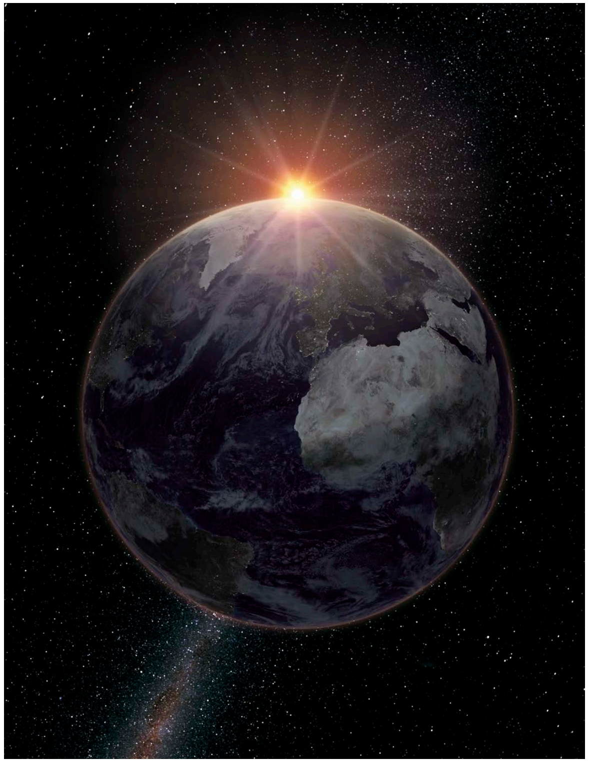
Exoplanet Atmospheres : transmission vs direct light

Probability of transits of Earth - Sun 0.5%
Probability of transit of Earth – M star 1-2%

- We will only be able to explore in transmission 1/200 of the closest Sun-Earth twins
- We will only be able to explore in transmission 1/50 of the closest Earth-like planets around Mstars
- Probabilities and distances **= photons**

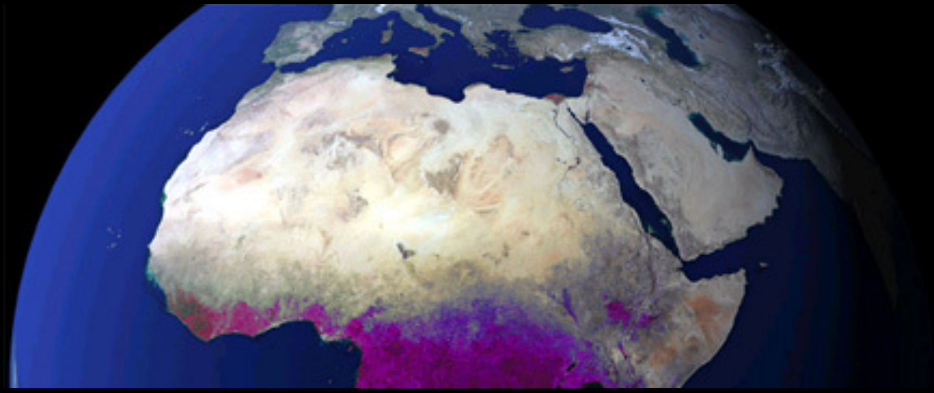
Transmission spectroscopy probes the (upper) atmosphere of the planet

Reflected light from telluric planets probes down to the surface, including surface features (biomarkers)



Conclusions

- ELTs will be the first machines to have a shot at detecting biomarkers
- Stick to simple detection of atmospheric compositions
- Success will depend on
    - Actual rate for life development for HZ planets around M stars
    - Capability of the available instrumentation to explore a large enough sample of planets (non-transiting)




Thanks !!