Current state of research on biosignatures and exoplanet atmospheres

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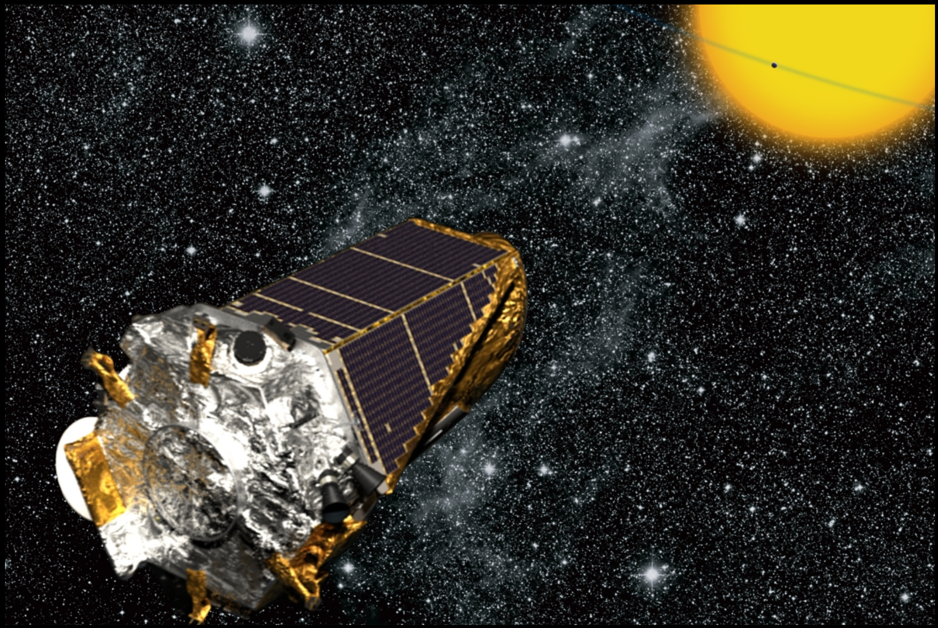
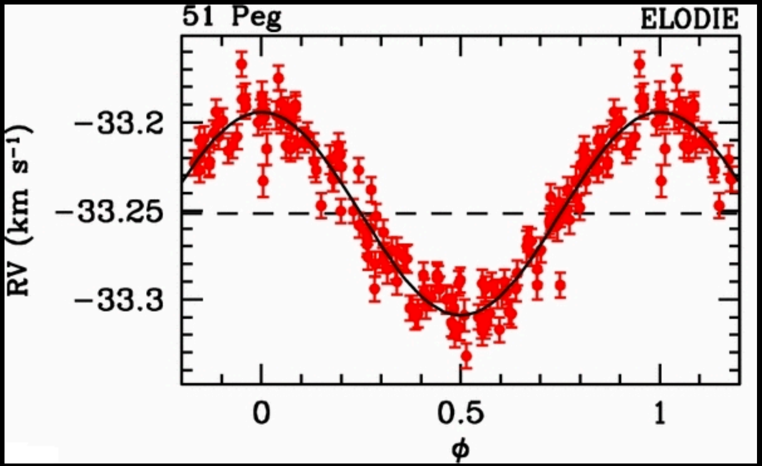
Instituto de Astrofísica de Canarias

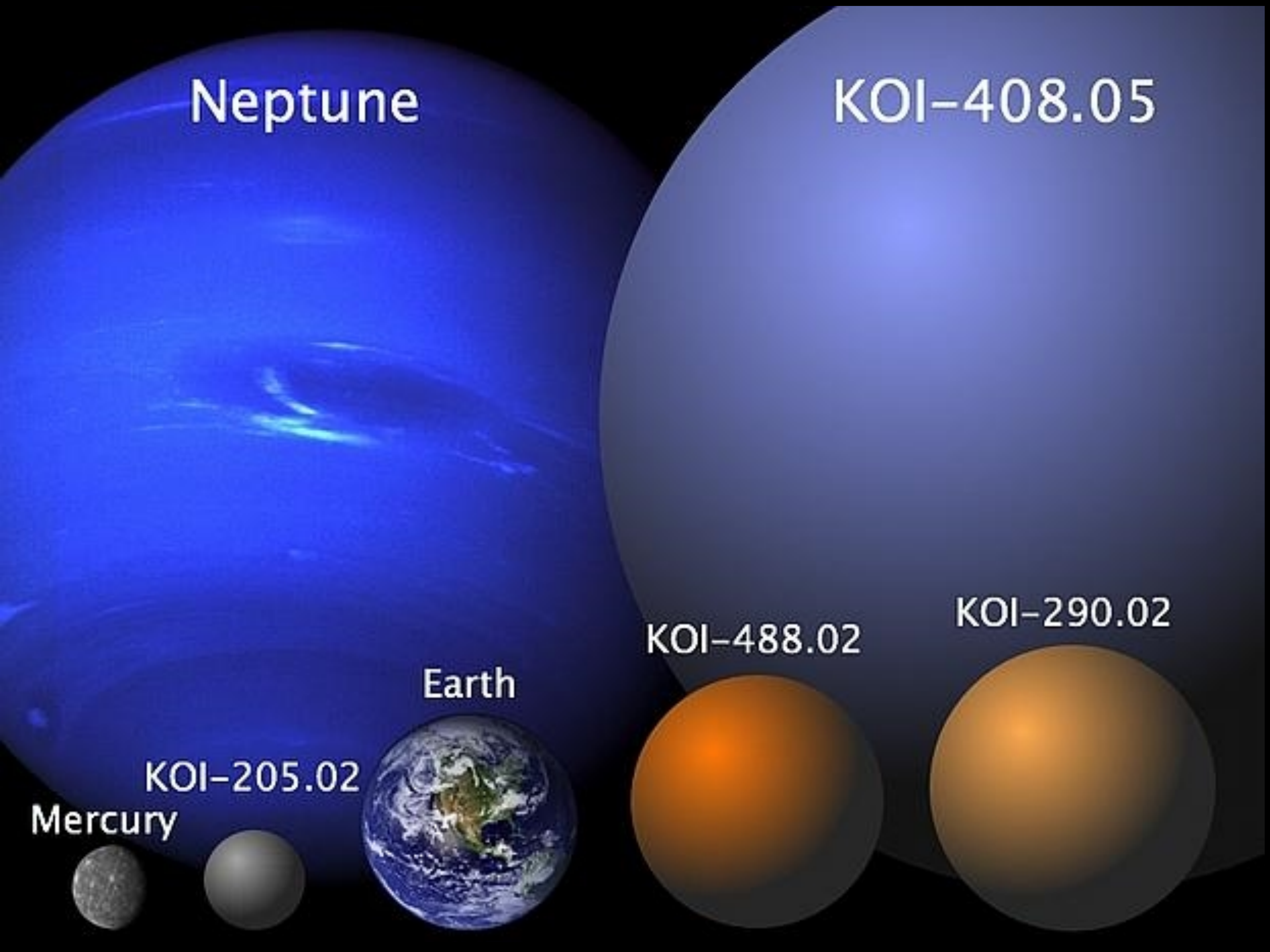
Stars, Planets and Galaxies 2018, Berlin

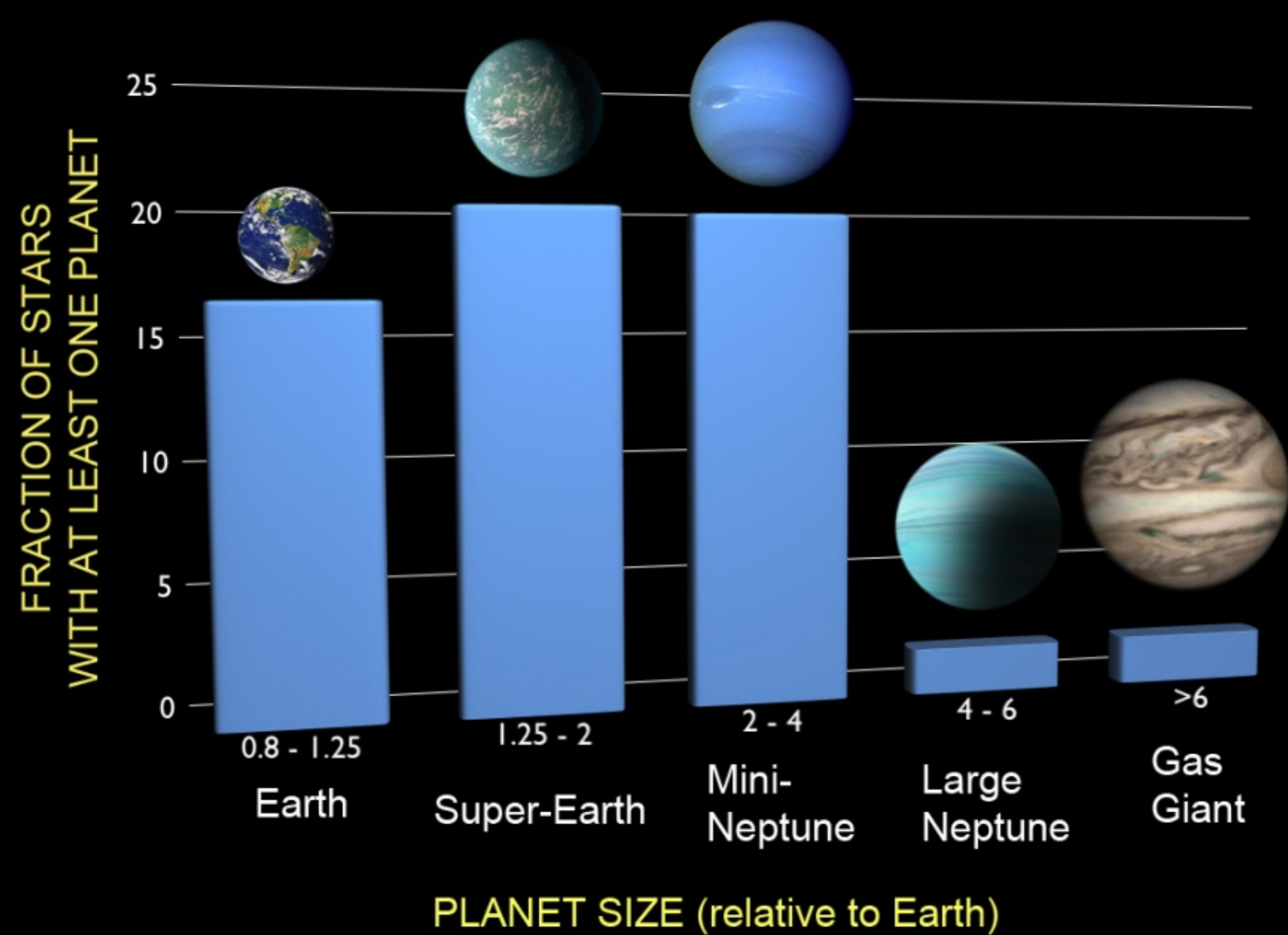
Exoplanet discoveries

3754 planets
2804 system
627 multiple



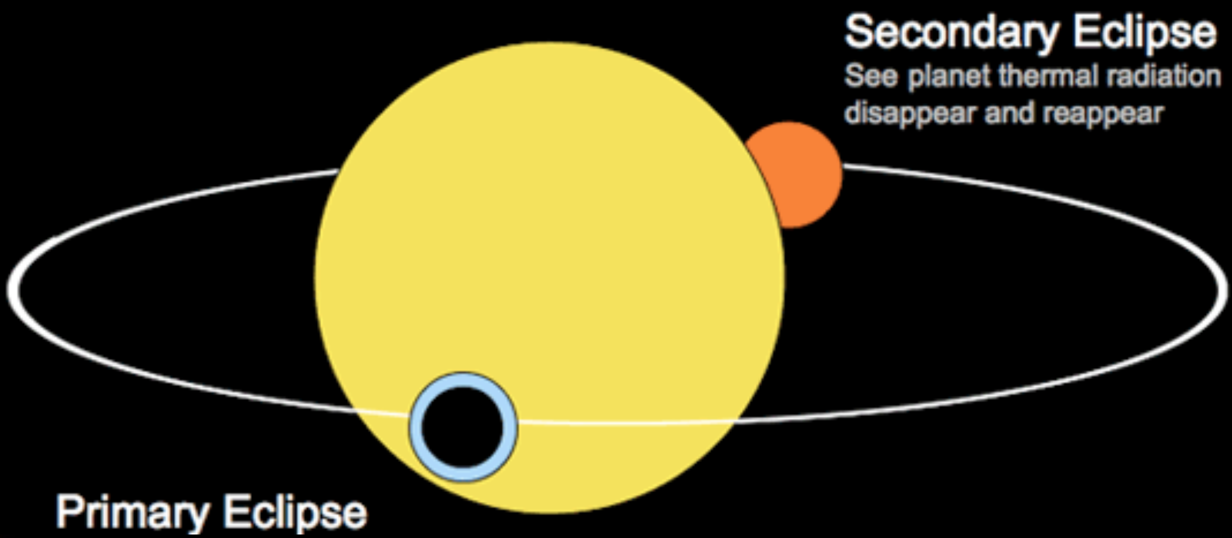


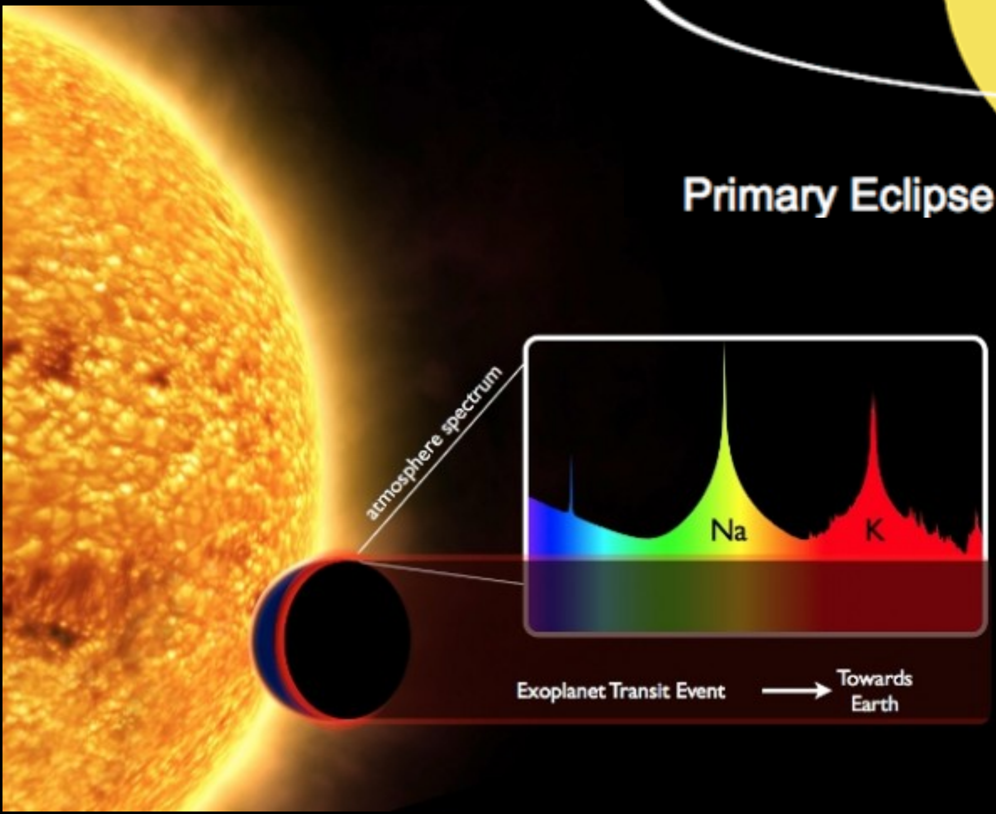

Neptune
KOI-408.05
KOI-290.02
KOI-488.02
Earth
KOI-205.02
Mercury



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)

Transiting Planets: first detections of planetary atmospheres

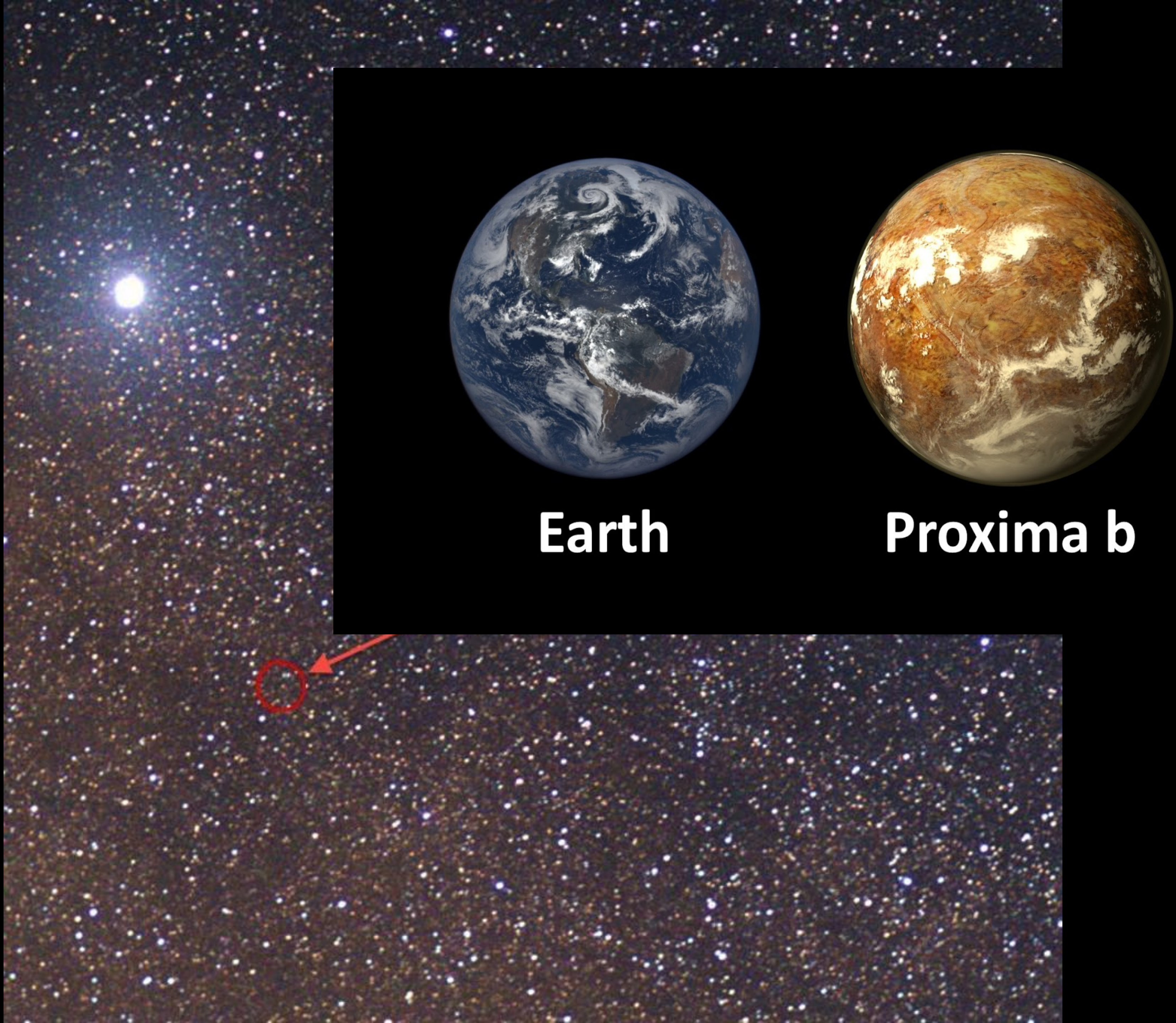


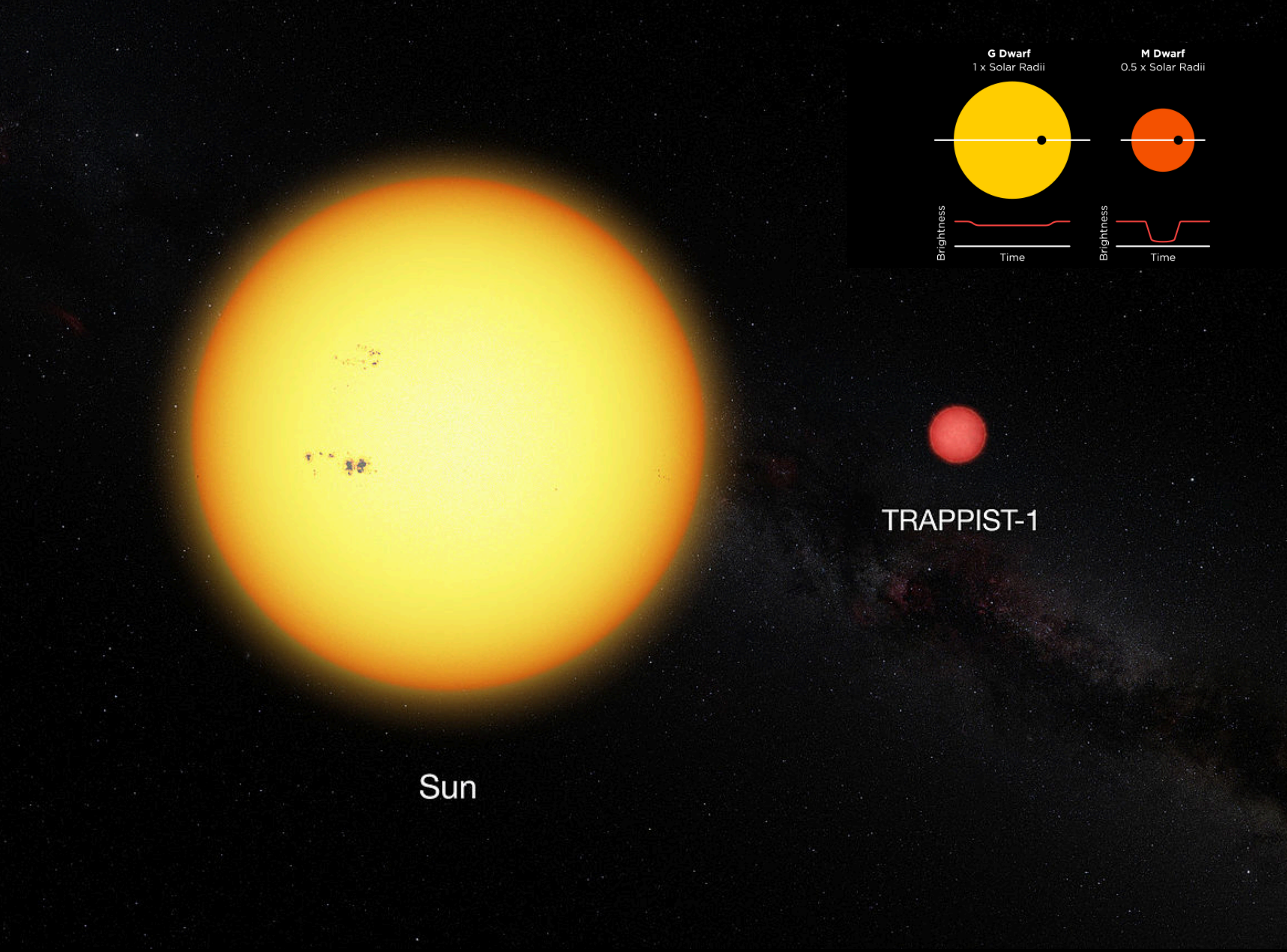


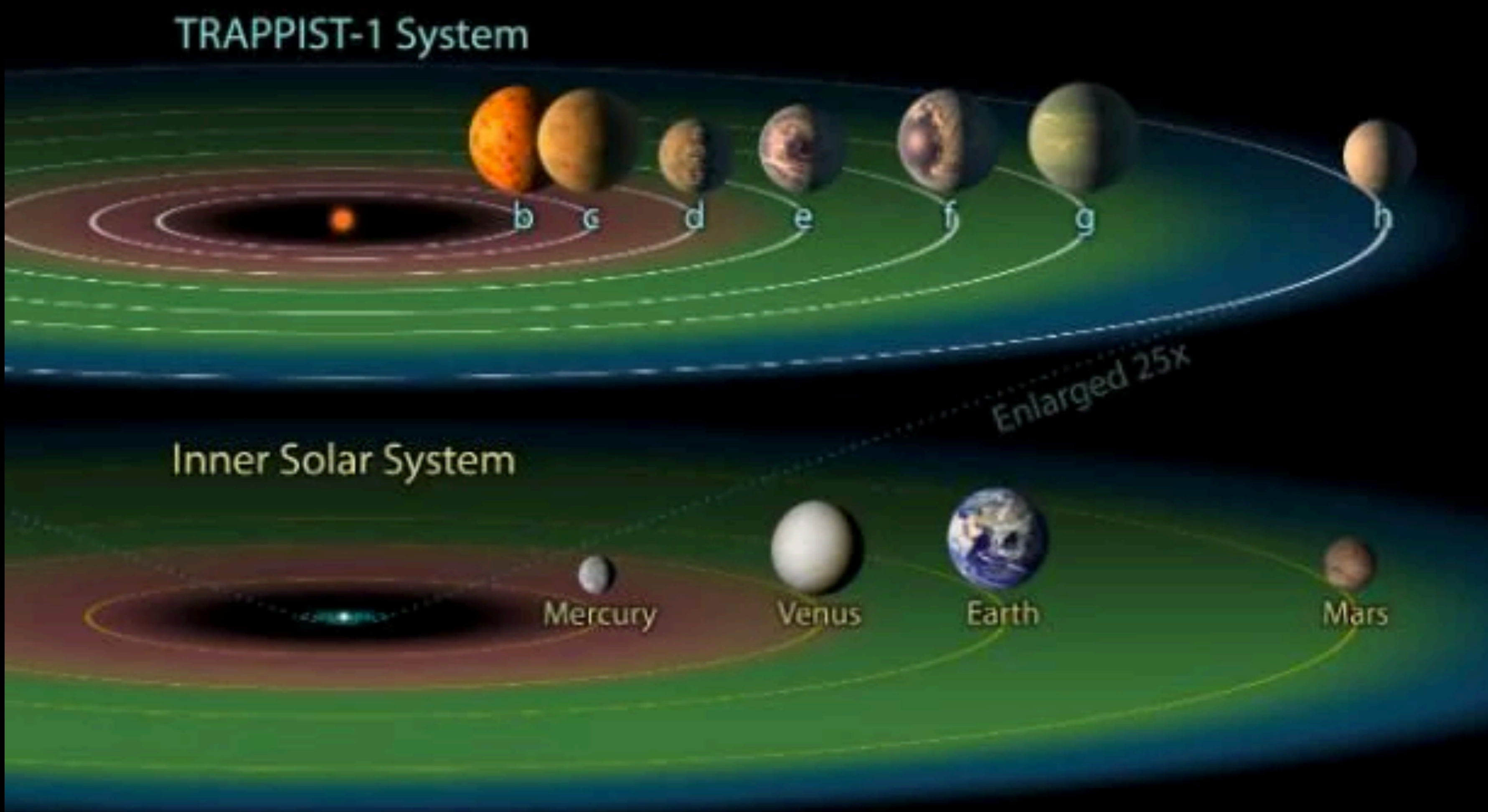
Chemical composition!!

Exoplanets: What have we learned so far?

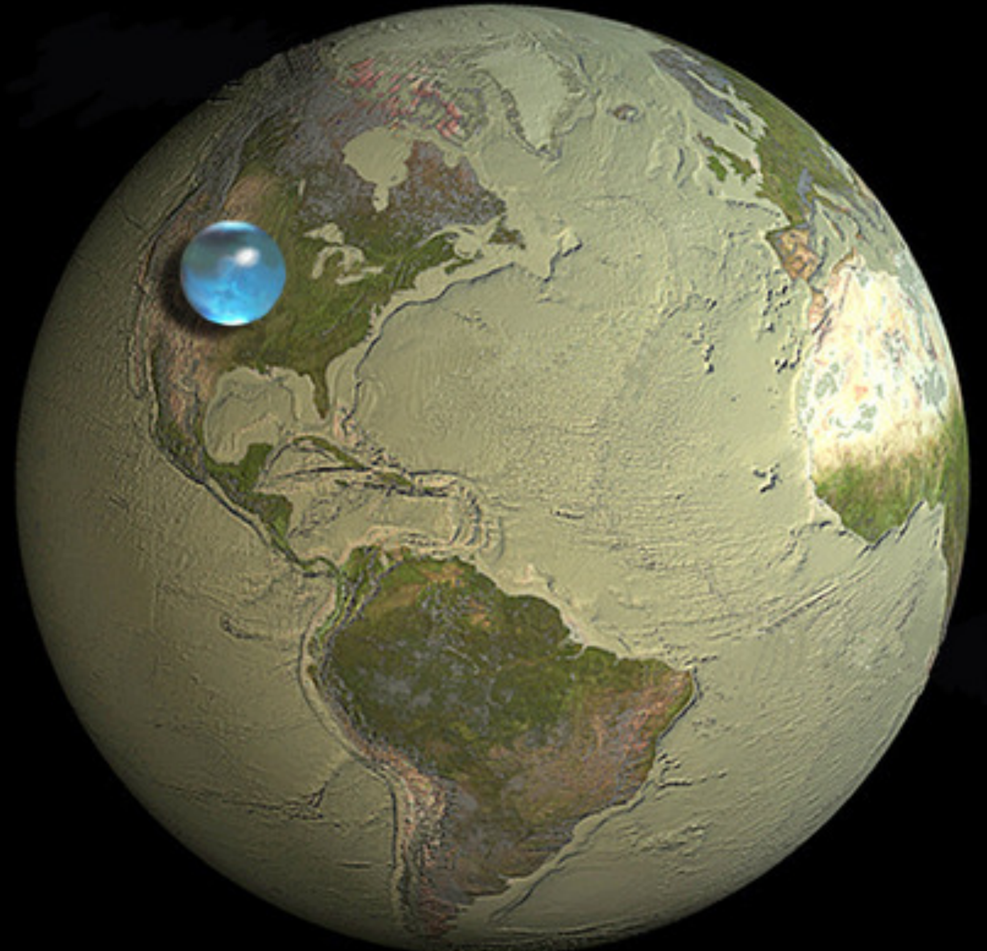
- 20-30% solar-type stars with planets
- At least 1 planet per star
- Multiple (rocky) planetary systems are common
- Specially true for M-type stars, with a very large fraction of planetary occurrence rates
- Planets are everywhere


Earth
Proxima b

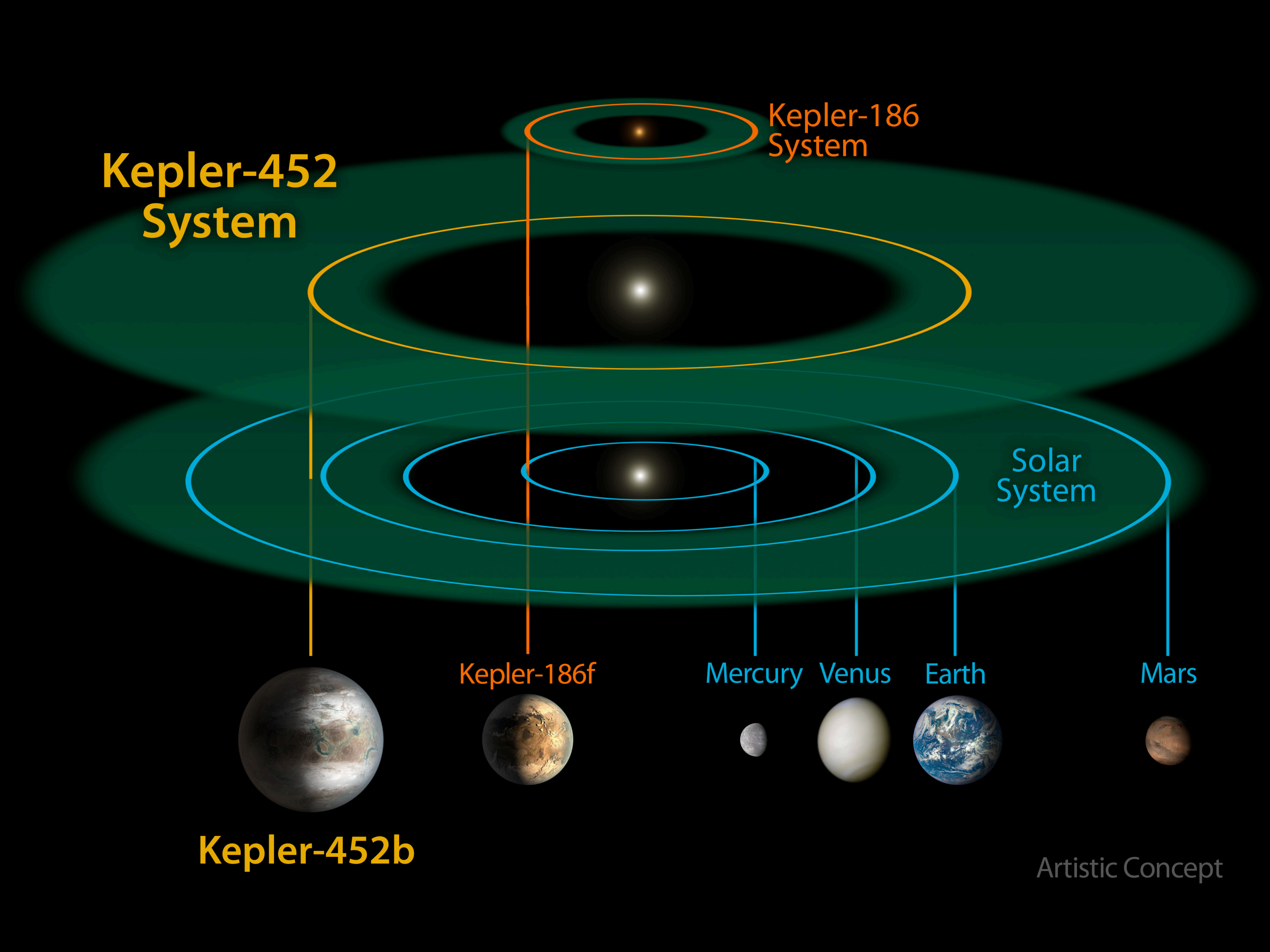

G Dwarf
1 x Solar Radii
M Dwarf
0.5 x Solar Radii
Brightness
Time
Brightness
Time
Sun
TRAPPIST-1

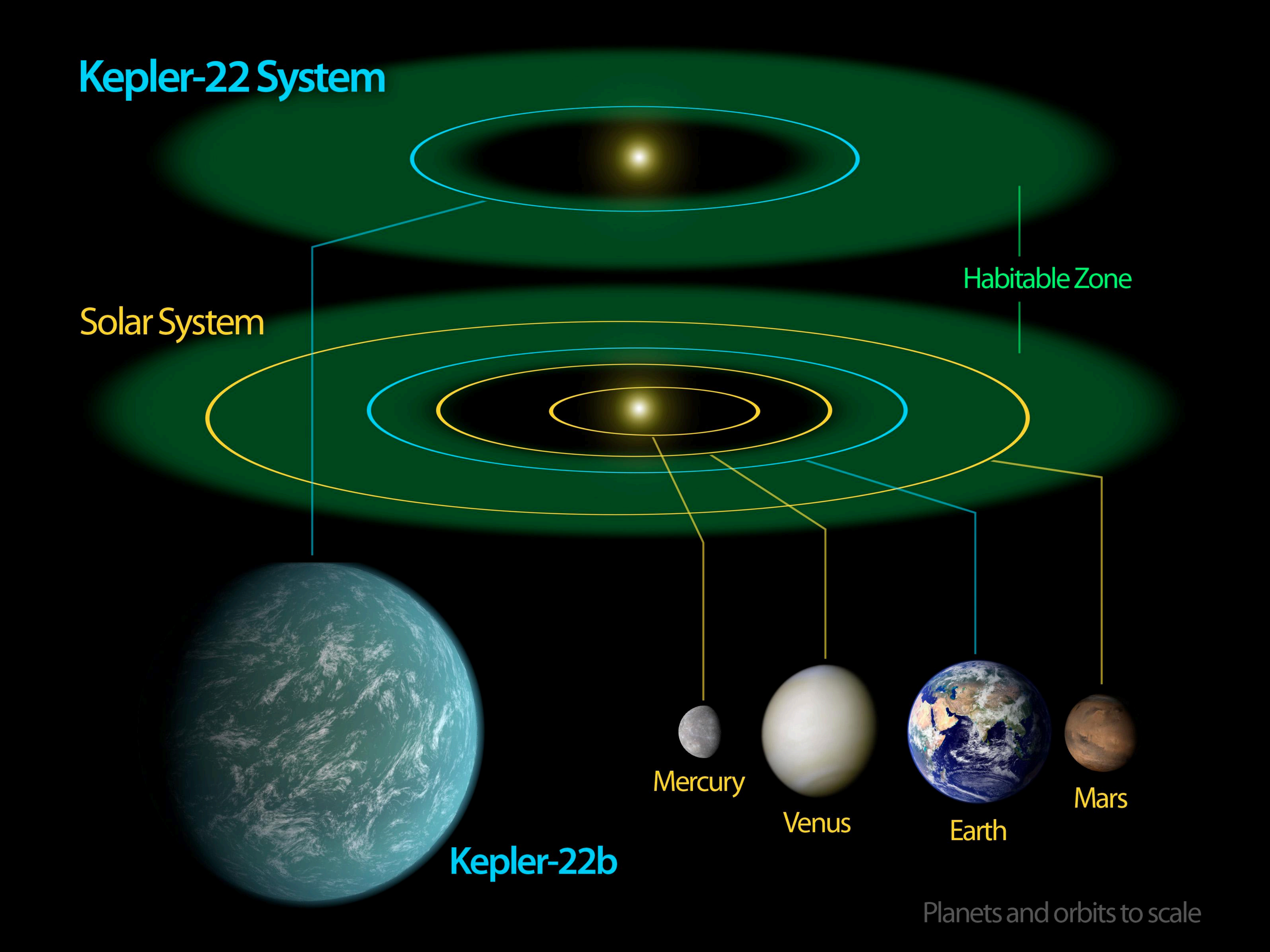

TRAPPIST-1 System
b
c
d
e
f
g
h
Enlarged 25x
Inner Solar System
Mercury
Venus
Earth
Mars

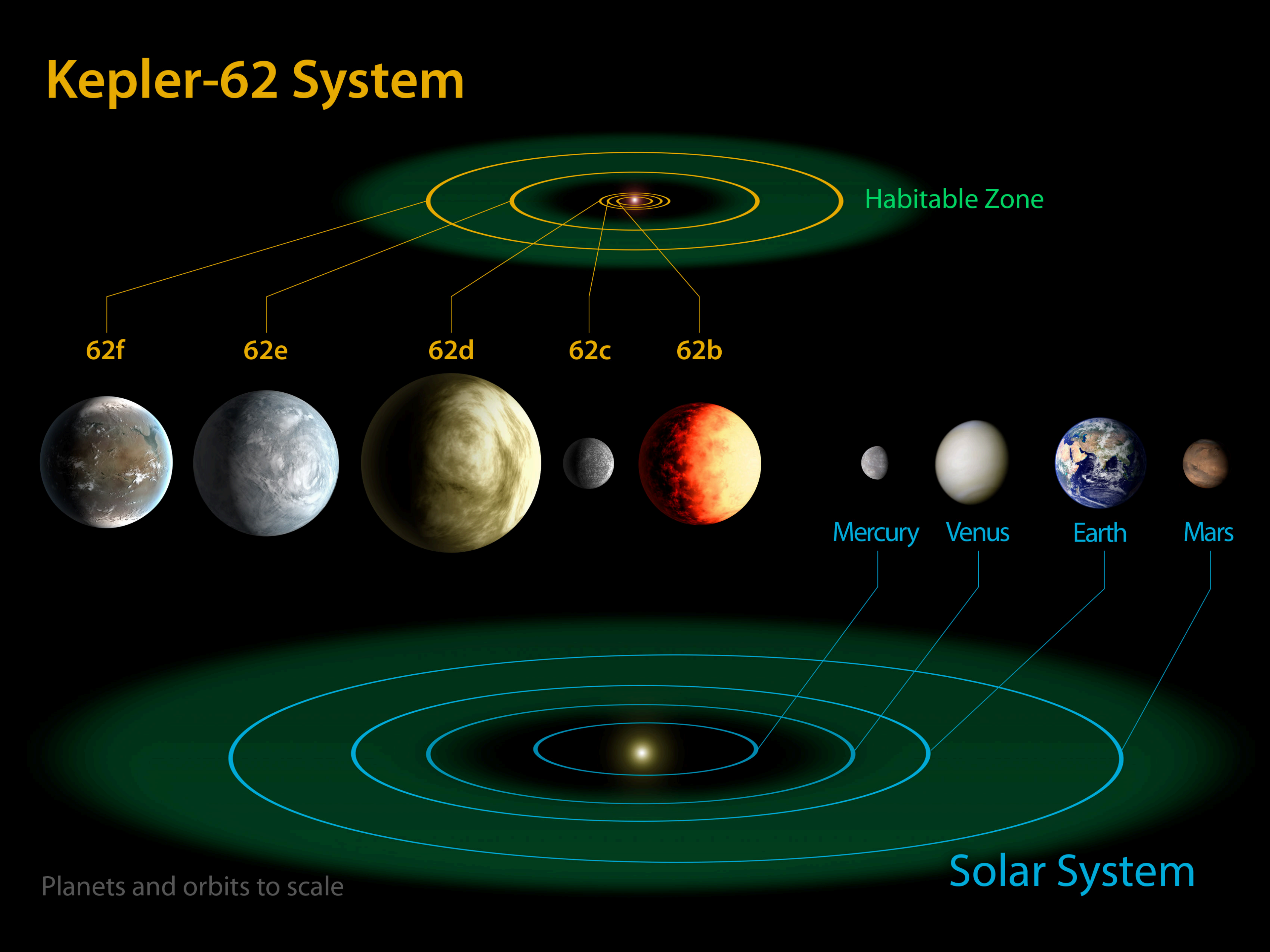
Habitable = Liquid Water



But these are not the only ones....

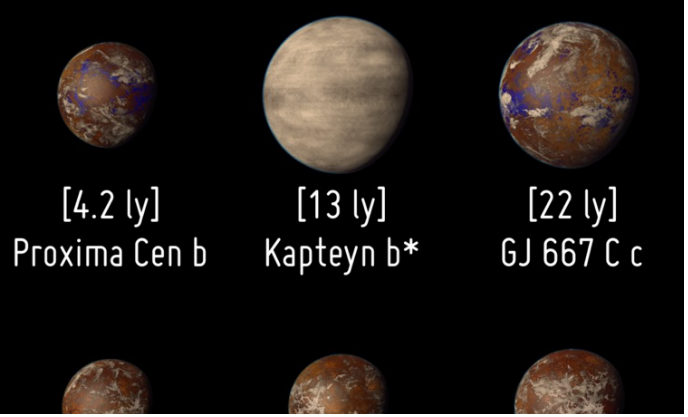

Kepler-186
System
Kepler-452
System
Solar
System
Kepler-452b
Kepler-186f
Mercury
Venus
Earth
Mars
Artistic Concept


Kepler-22 System
Habitable Zone
Solar System
Kepler-22b
Mercury
Venus
Earth
Mars
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 Habitab

Ranked by Distance from Earth (lig



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

Conservative Sample of Potential

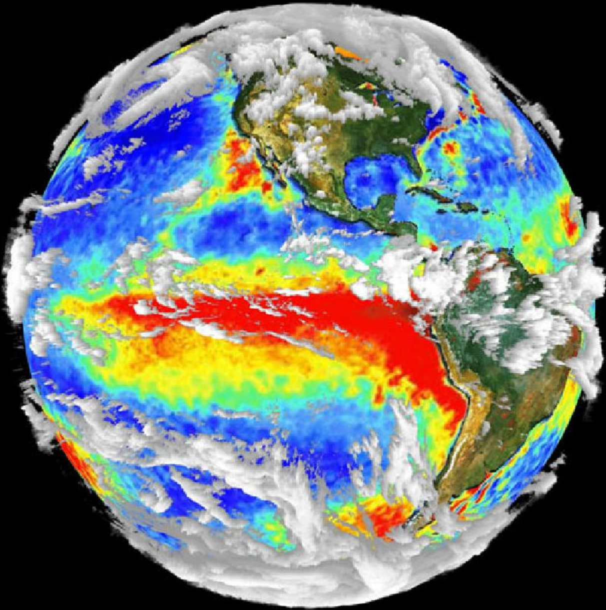
This is a list of the exoplanets that are more likely to have a rocky com
Planet Radius ≤ 1.5 Earth radii or 0.1 < Planet Minimum Mass ≤ 5 Earth
habitable zone). They are represented artistically in the top image.

Name	Type	Mass (M_E)	
001. Proxima Cen b	M-Warm Terran	≥ 1.3	0.8
002. TRAPPIST-1 e	M-Warm Terran	0.6	
003. GJ 667 C c	M-Warm Terran	≥ 3.8	1.1
004. Kepler-442 b	K-Warm Terran	8.2 - 2.3 - 1.0	
005. GJ 667 C f*	M-Warm Terran	≥ 2.7	1.(
006. Kepler-1229 b	M-Warm Terran	9.8 - 2.7 - 1.2	
007. TRAPPIST-1 f	M-Warm Terran	0.7	
008. Kapteyn b*	M-Warm Terran	≥ 4.8	1.2
009. Kepler-62 f	K-Warm Terran	10.2 - 2.8 - 1.2	
010. Kepler-186 f	M-Warm Terran	4.7 - 1.5 - 0.6	
011. GJ 667 C e*	M-Warm Terran	≥ 2.7	1.(
012. TRAPPIST-1 g	M-Warm Terran	1.3	

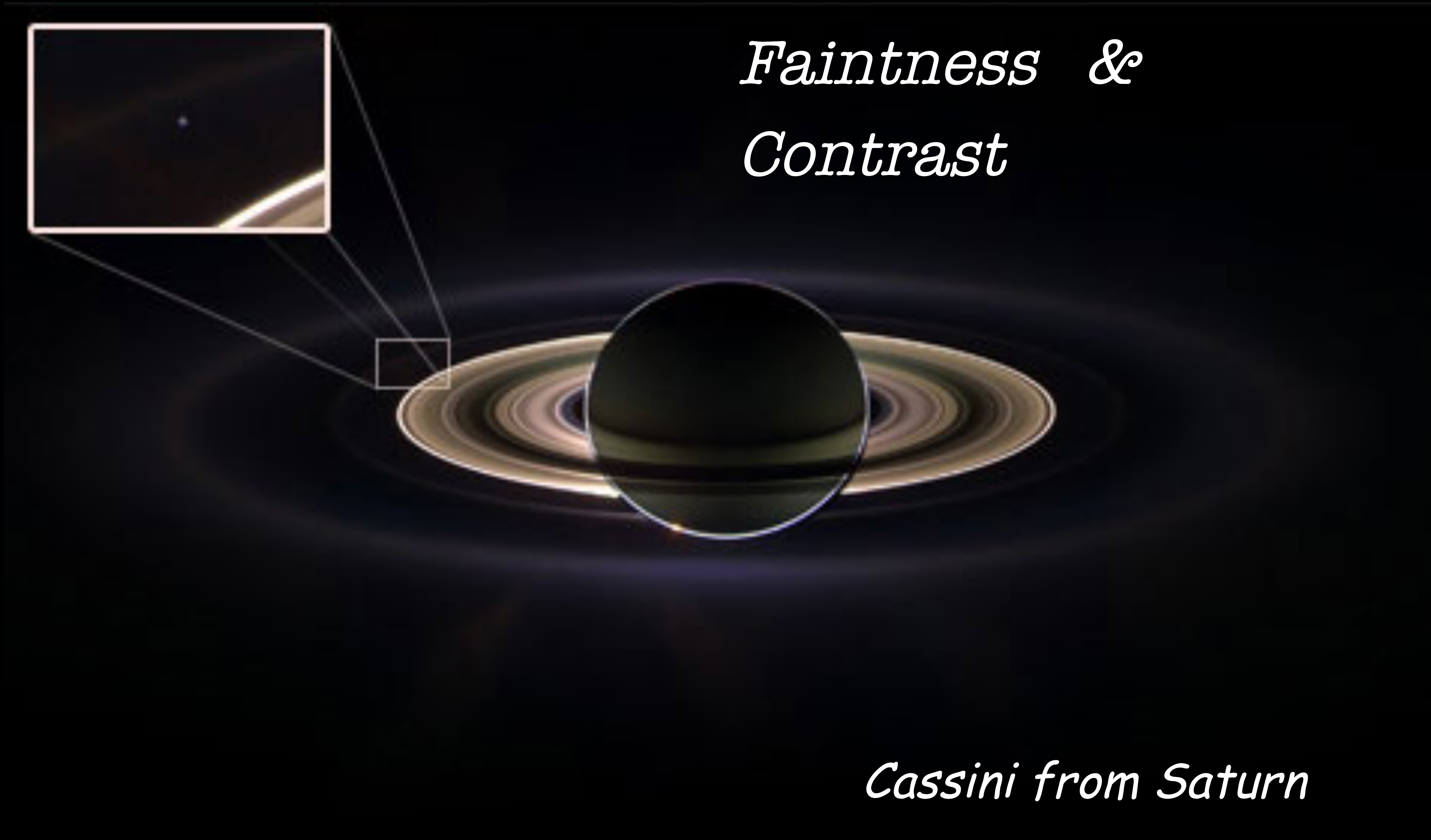
Habitable ≠ Inhabited

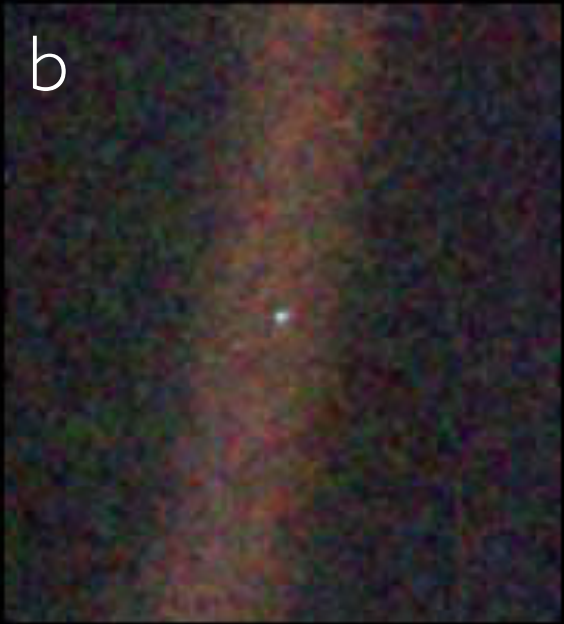
How will we know?   Biosignatures



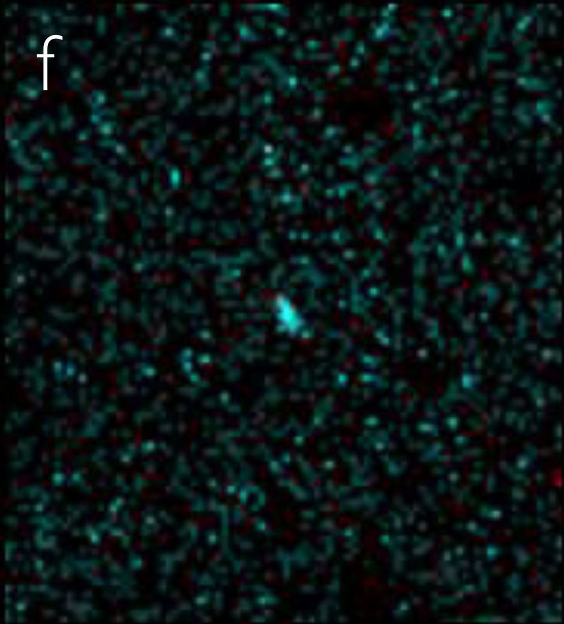



Earth from an astronomical distance:
All light comes from a single point

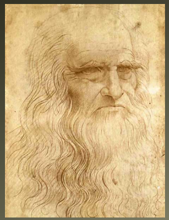


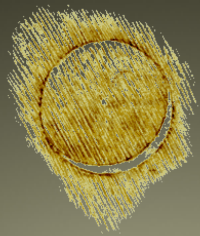


Which planet is inhabited?

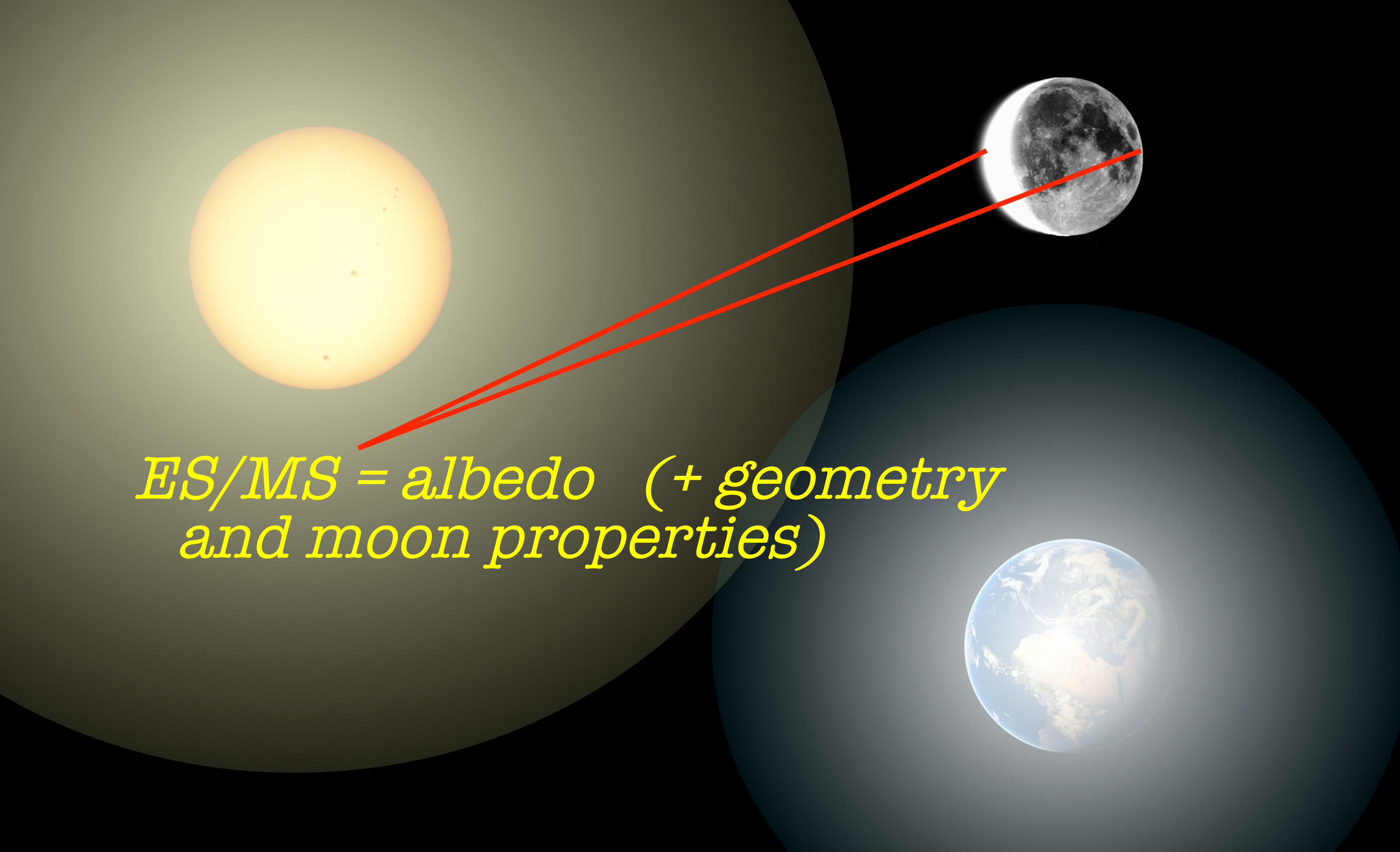


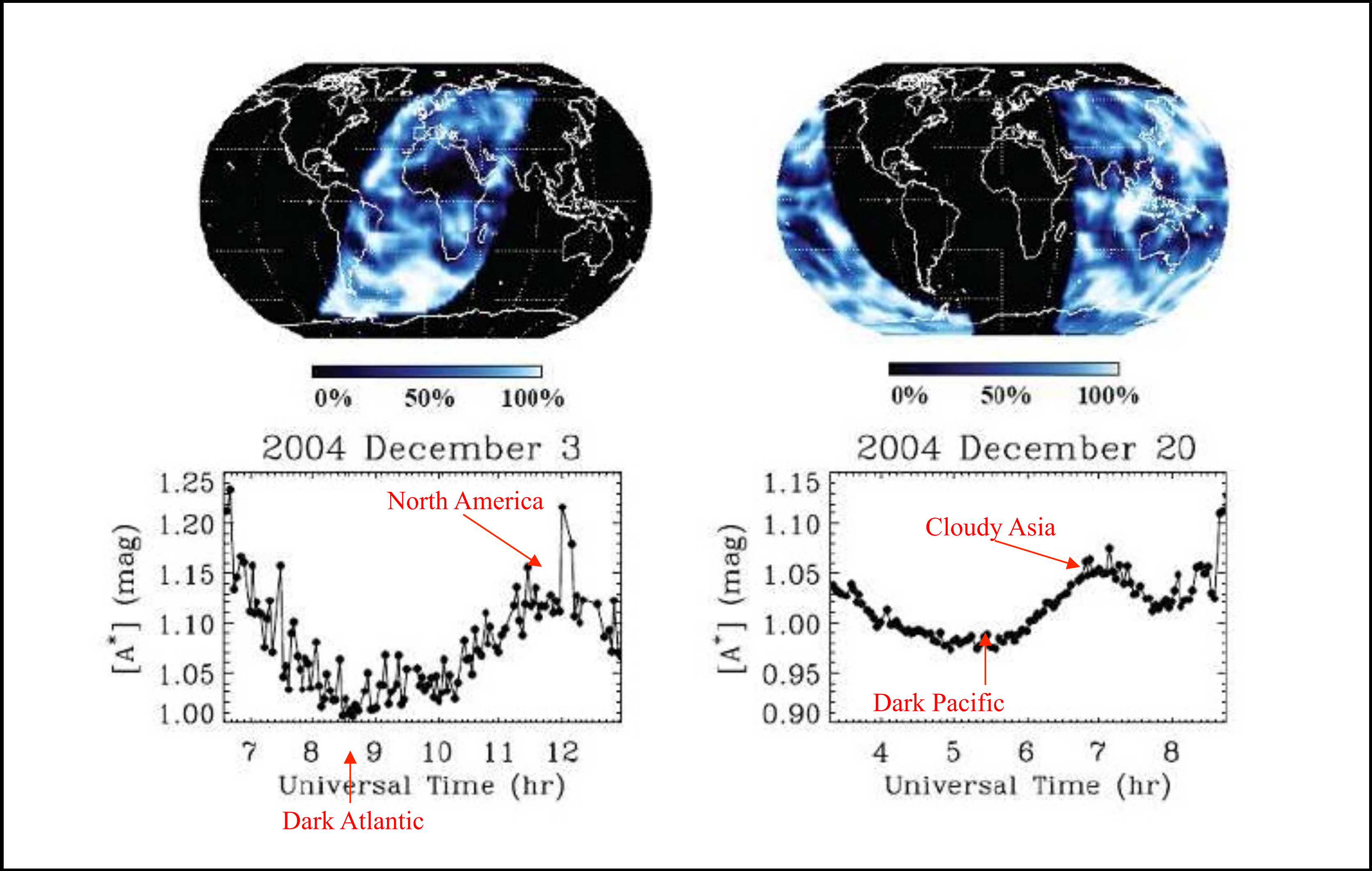
Voyager 1





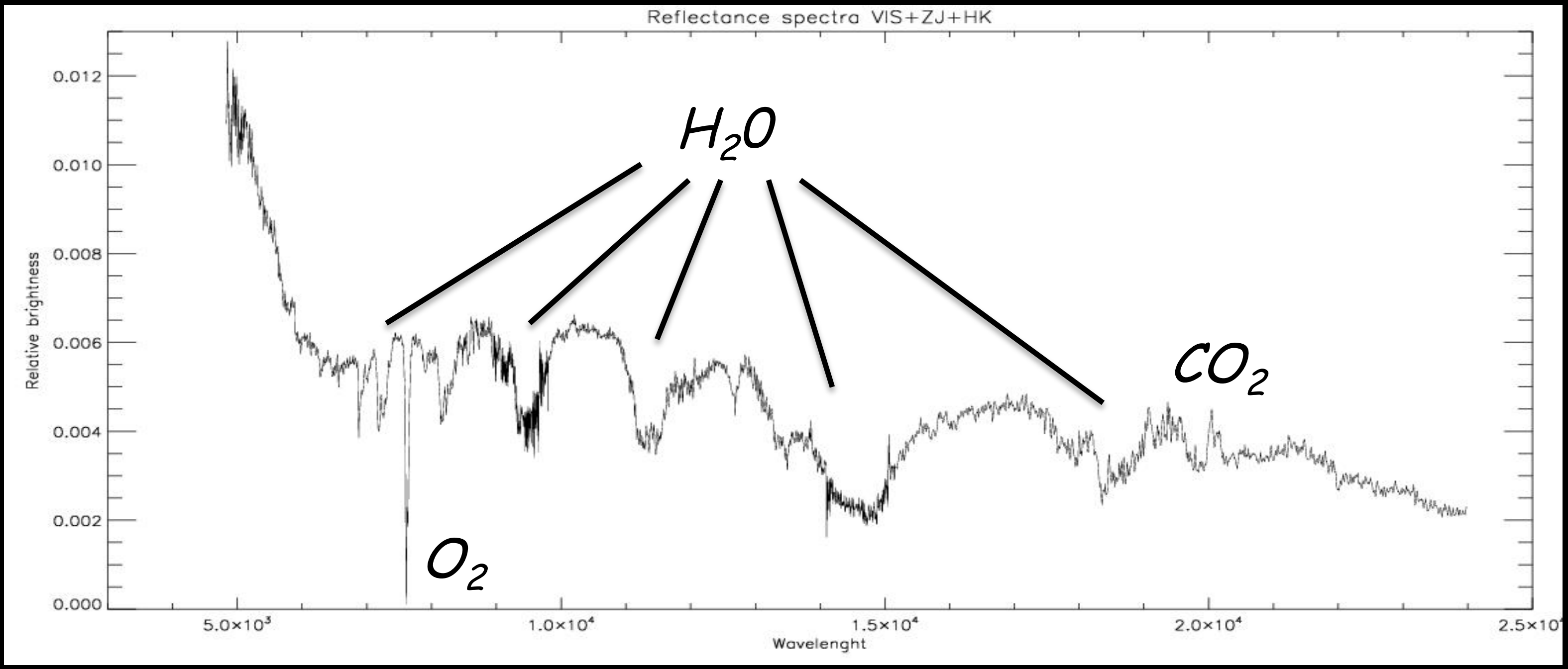
The Earthshine on the moon





Photometry: continents, weather and rough maps

The spectrum of an inhabited planet



Simultaneous presence of:

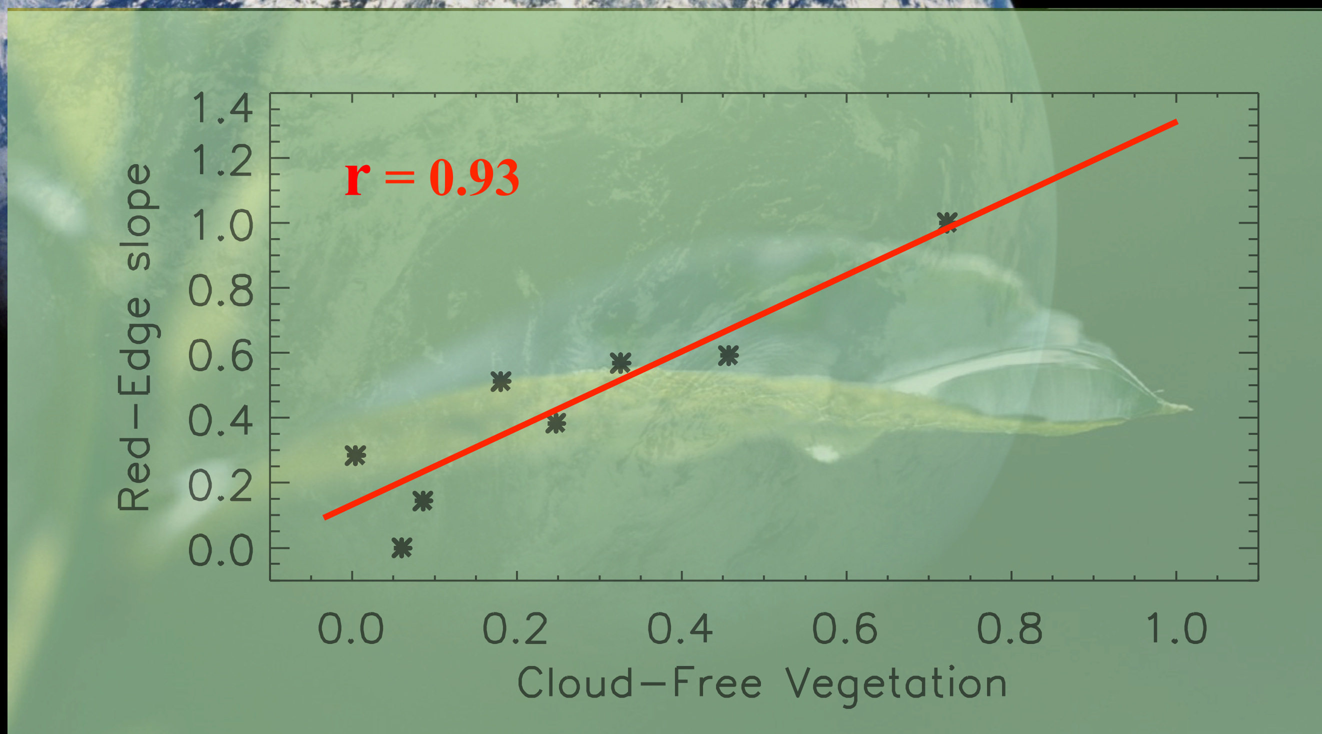
- Water
- Ozone (Oxigen)
- Methane / Carbon Dioxide

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

Surface Biosignatures/Bioclues

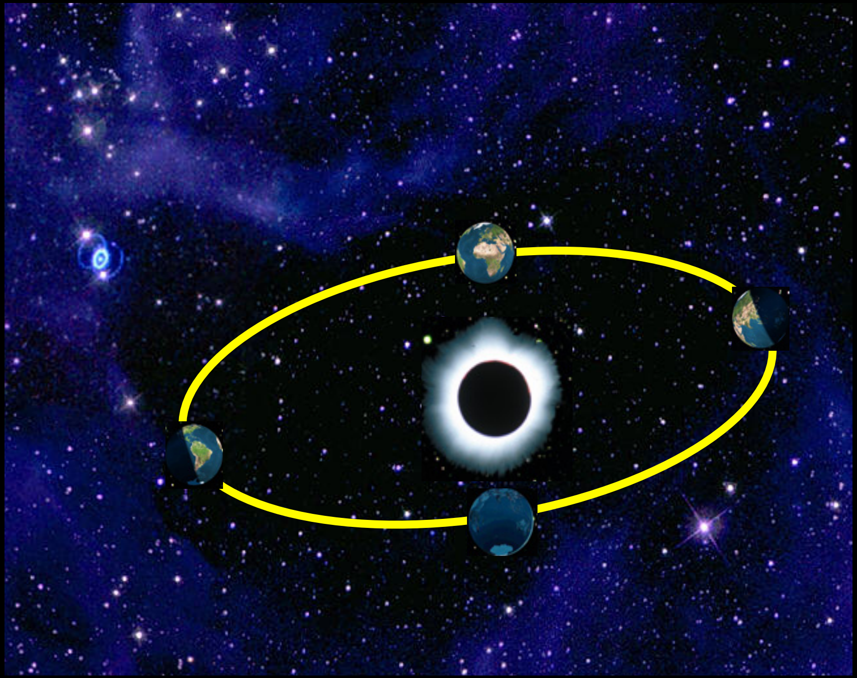
Life changes the *Surface* of a planet

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

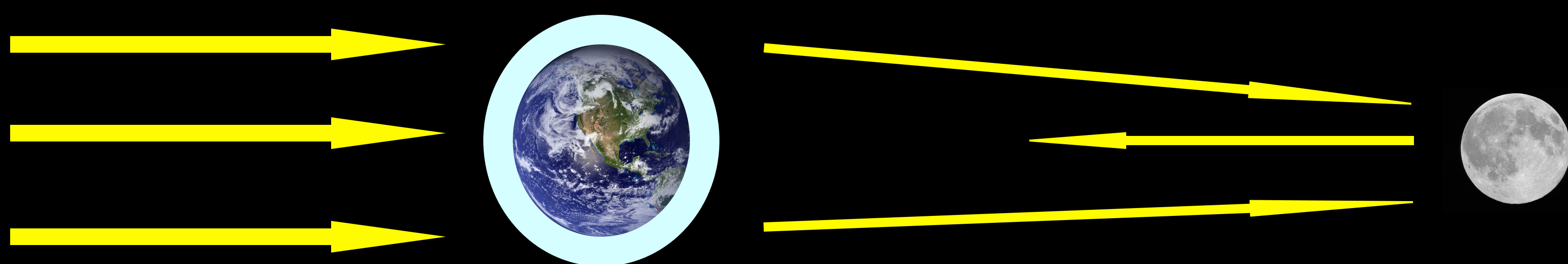


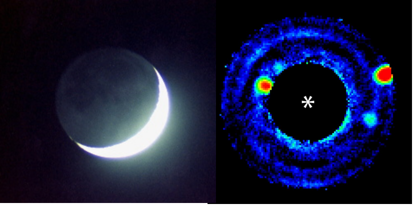
Montañes-Rodriguez et al ApJ, 2006

A transiting Earth ?

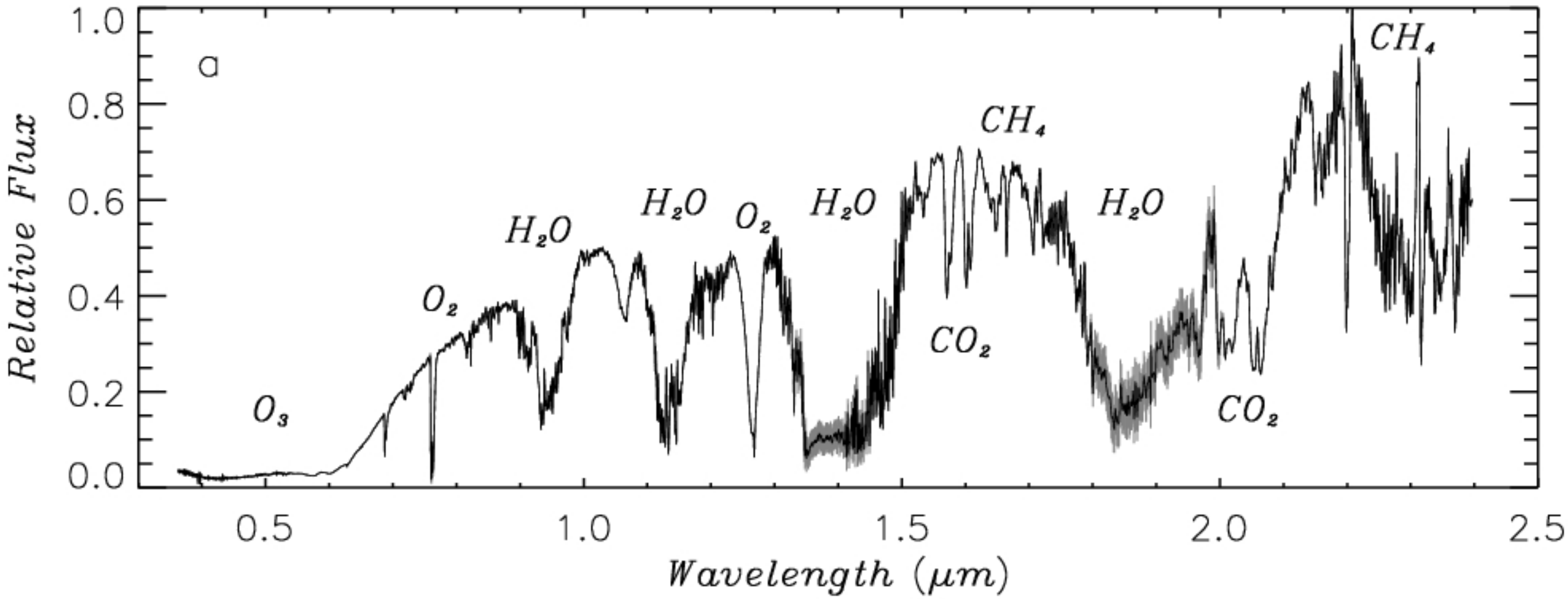


Eclipses as proxies for transits

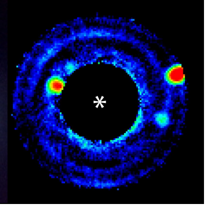




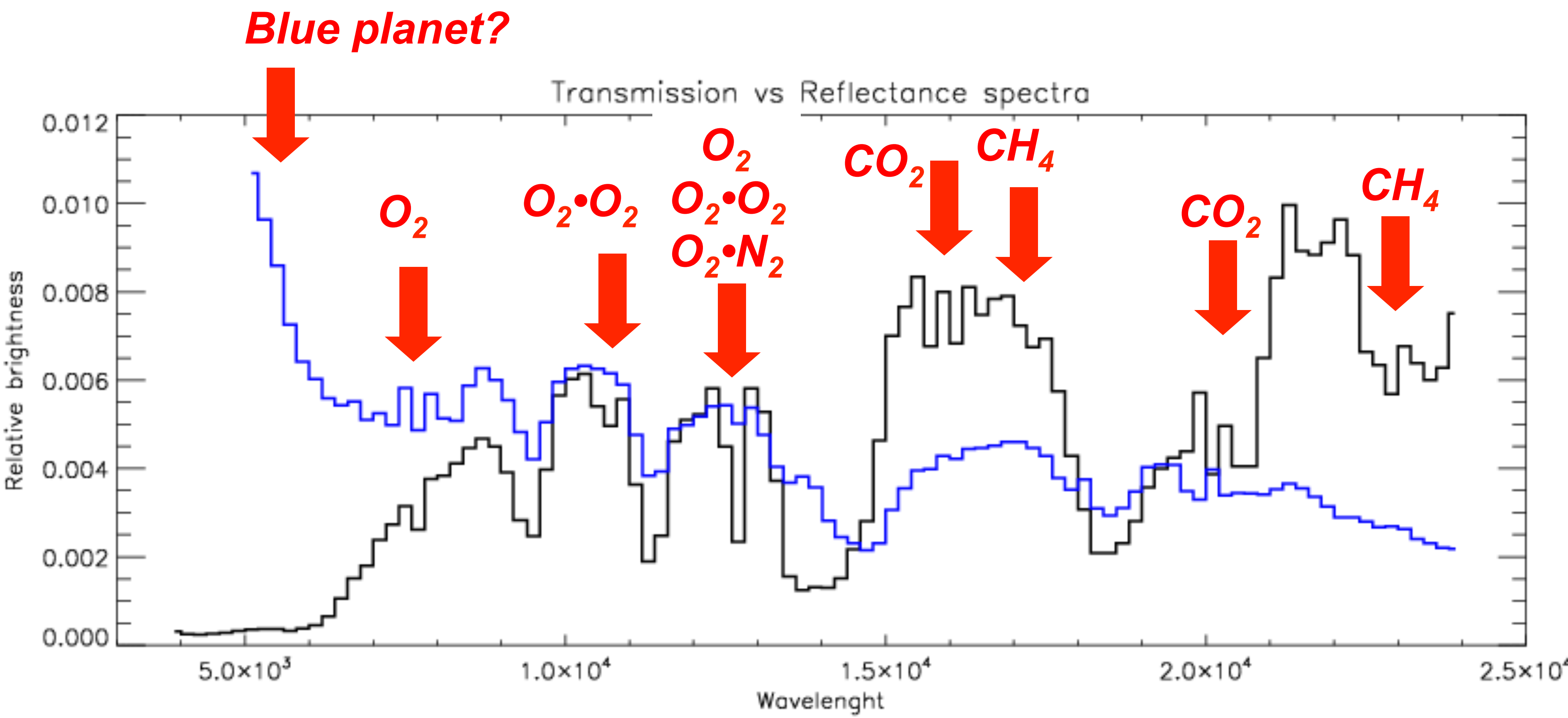
Earth's Transmission spectrum



Palle et al, Nature, 2009



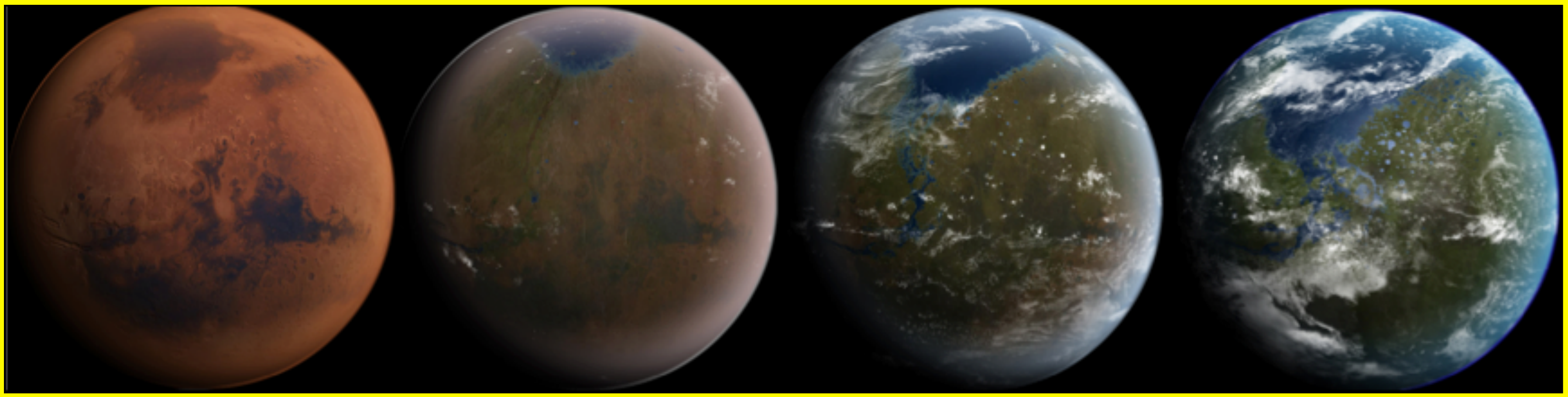
Earth's Transmission vs Reflected spectrum



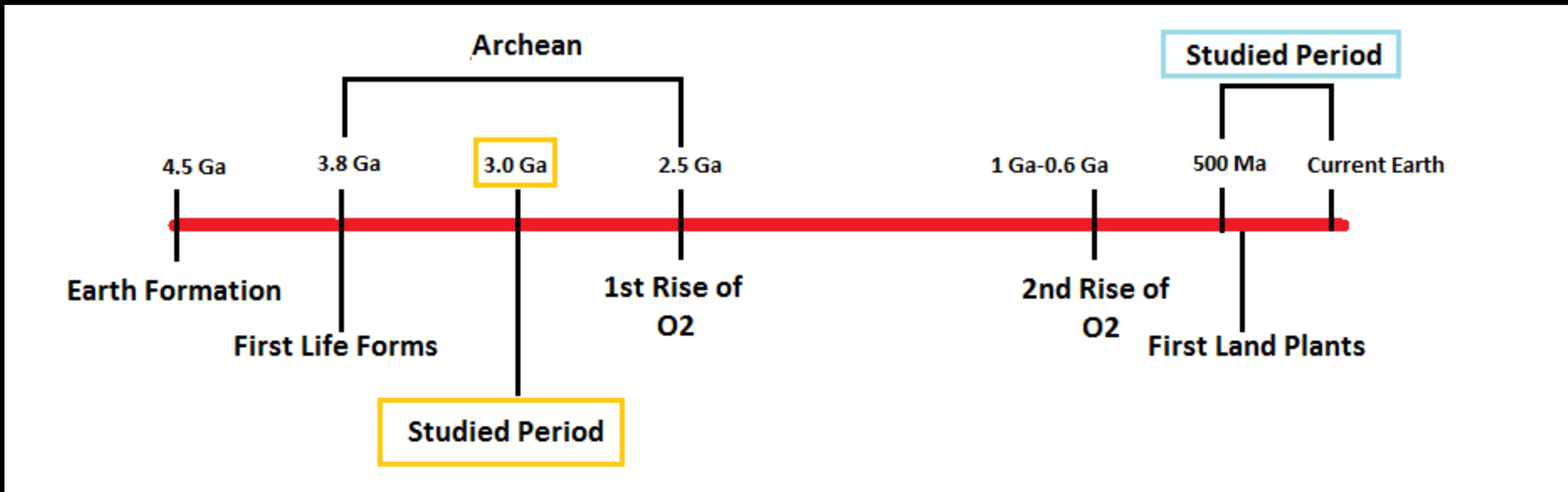
Time evolution

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

What was detectable in the past?



The Archean Earth



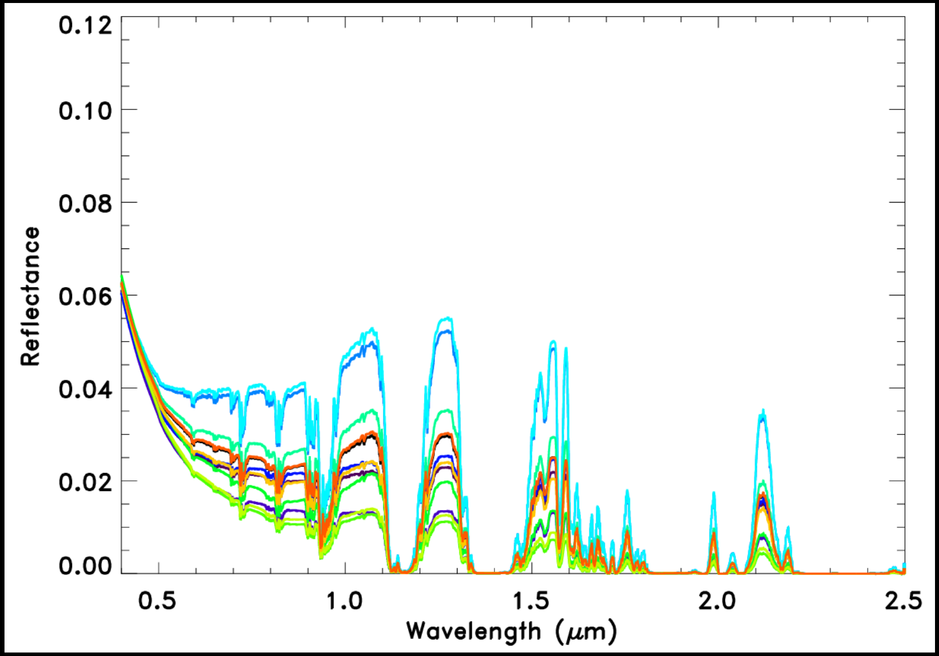
- The Earth has been inhabited for at least 85% of its history
- 3000 million years ago, the atmospheric composition was very different from today's and the Sun was ~20% less bright
- To study the possibility of detecting primitive life forms

Purple bacteria

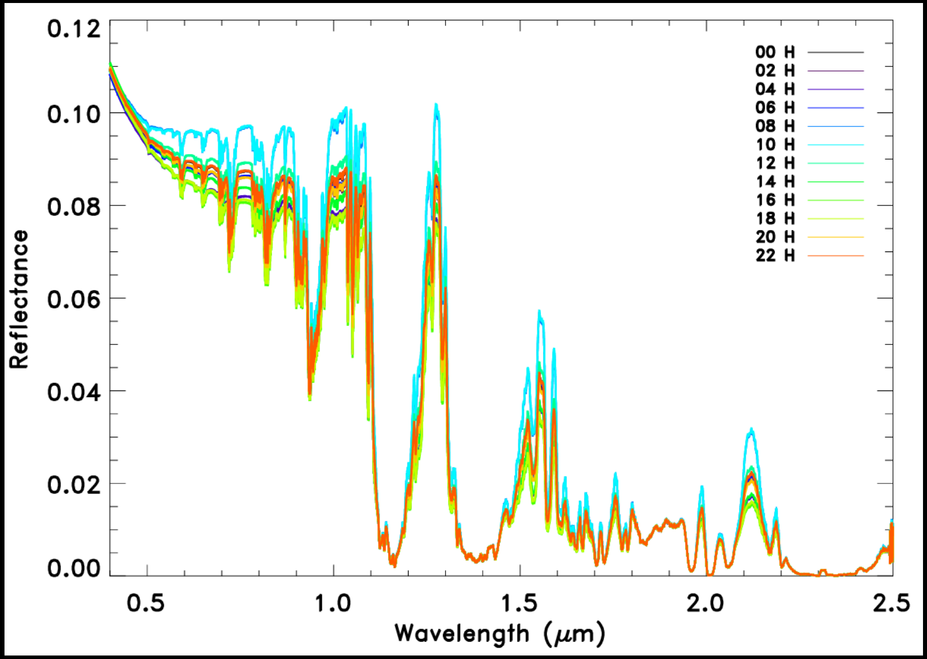
- One of the first life forms that colonized our planet.
- Can inhabit both aquatic and terrestrial environments
- Anoxygenic photosynthesis
- Can survive in extreme conditions
- Color: red, brown or purple

Rotational variability

Cloud free atmosphere



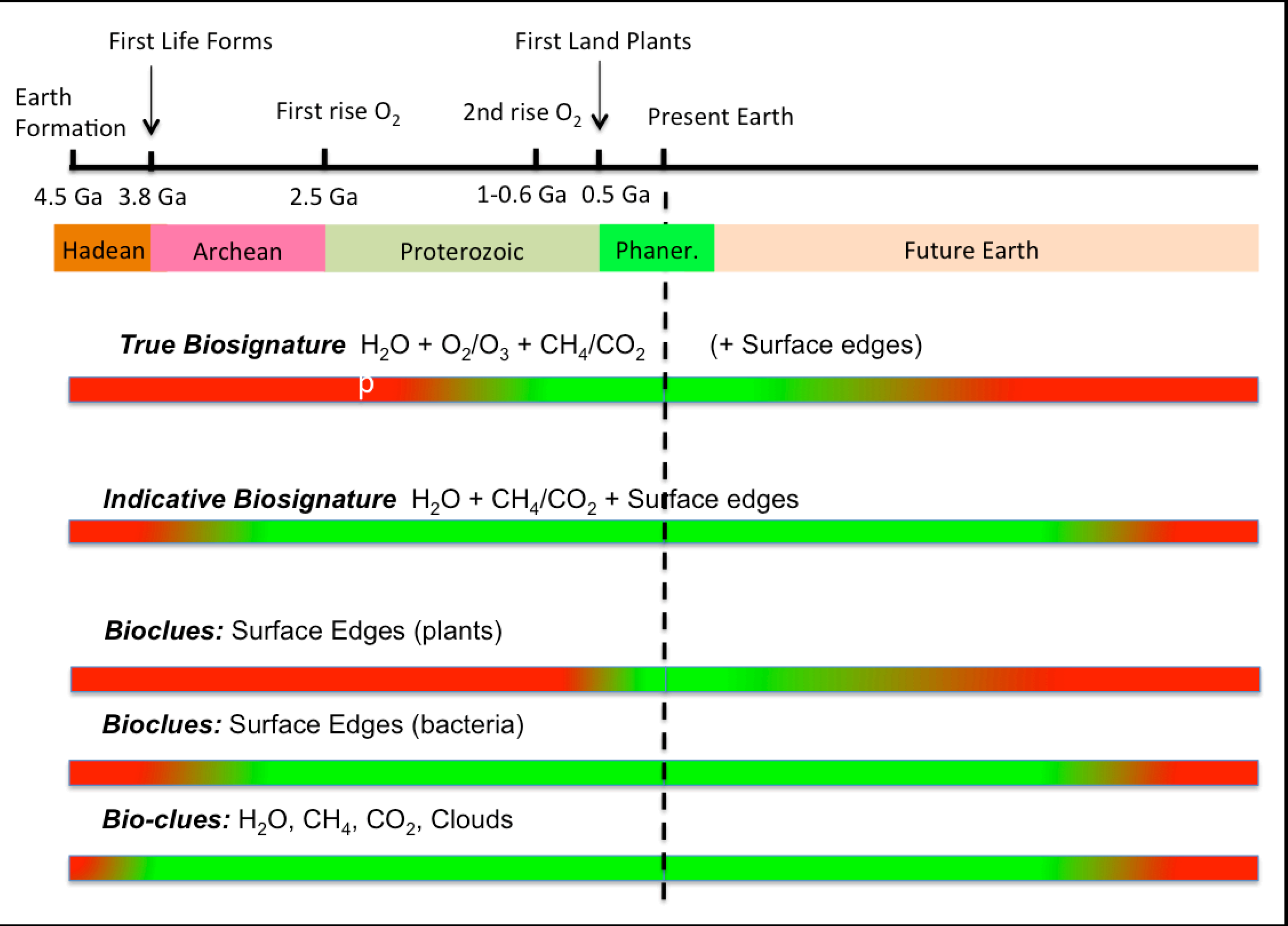
Cloudy atmosphere



- Purple bacteria readily detectable in the cloud-free case and still visible in the cloudy case

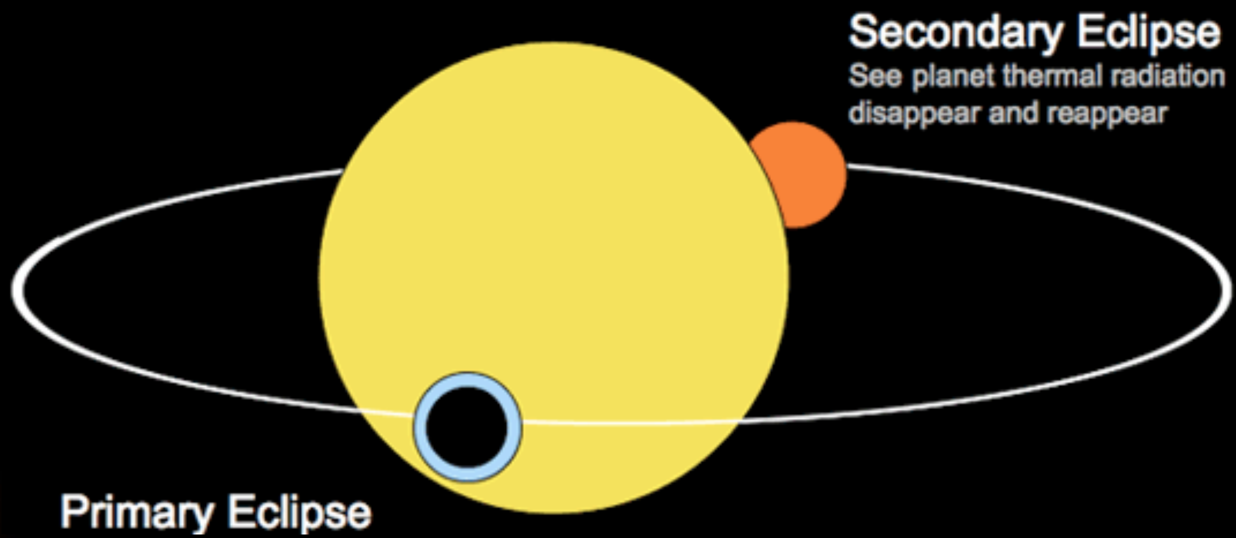
Sanroma et al, ApJ, 2014

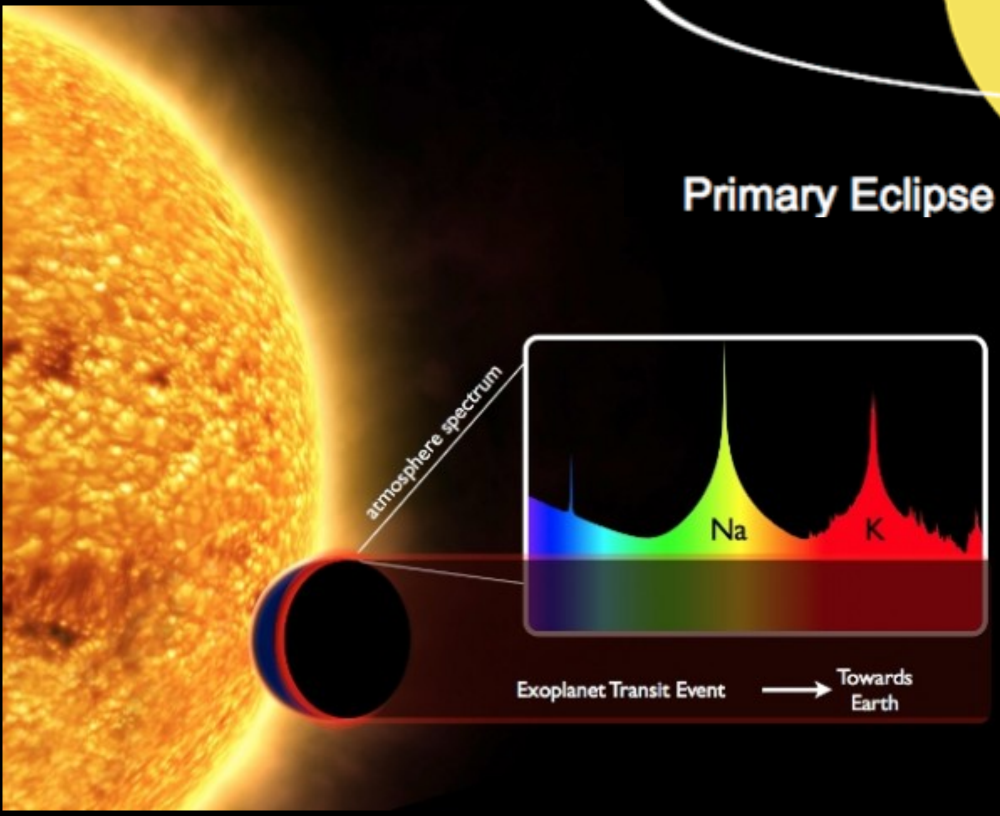
Biomarkers in Time



So, will we be able to detect biomarkers in the near future?

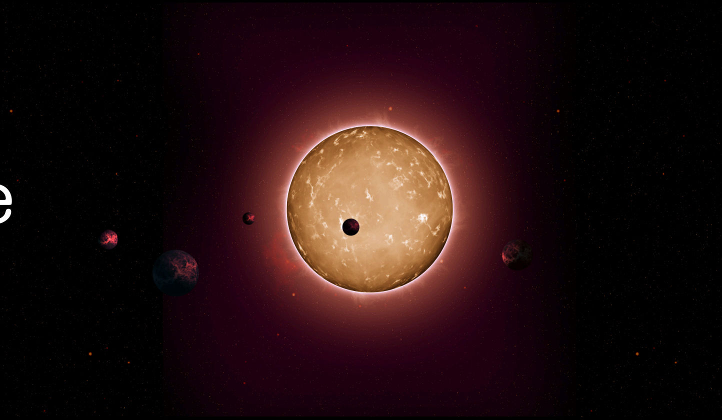
Transit spectroscopy: first detections of planetary atmospehres

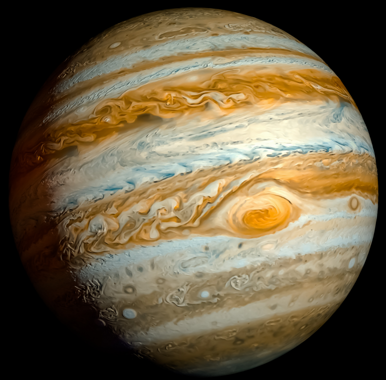




Chemical composition!!

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

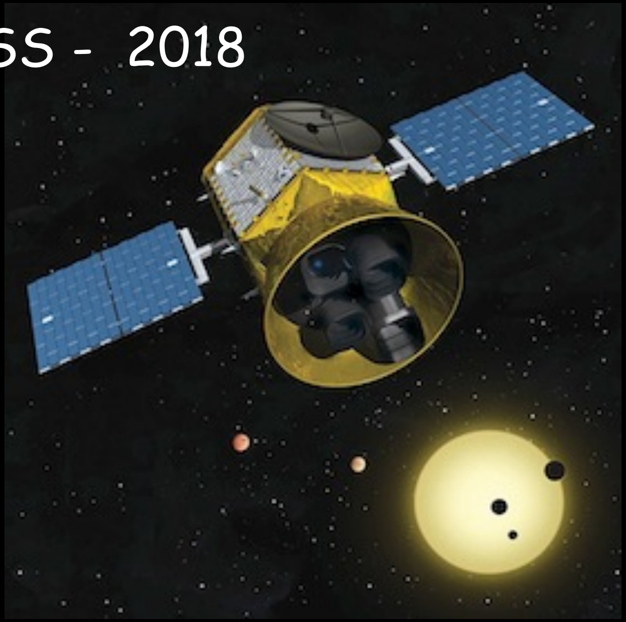




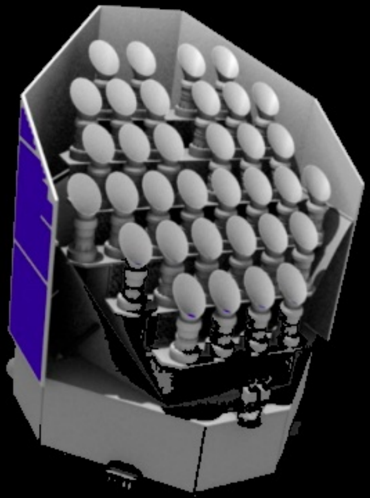
One in 100,000-1,000,000 photons cross the planetary atmosphere

Focus of searches: brightest and closest stars

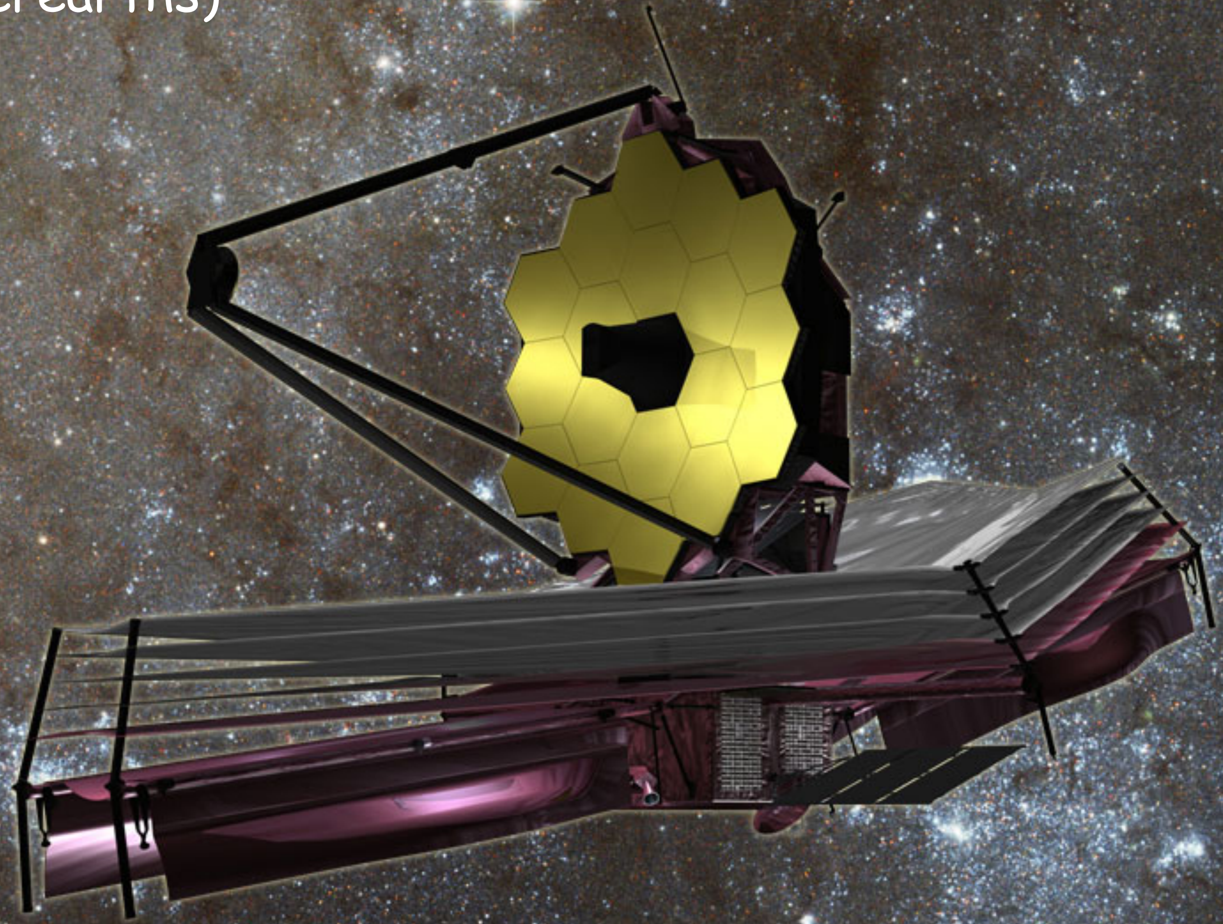
TESS - 2018



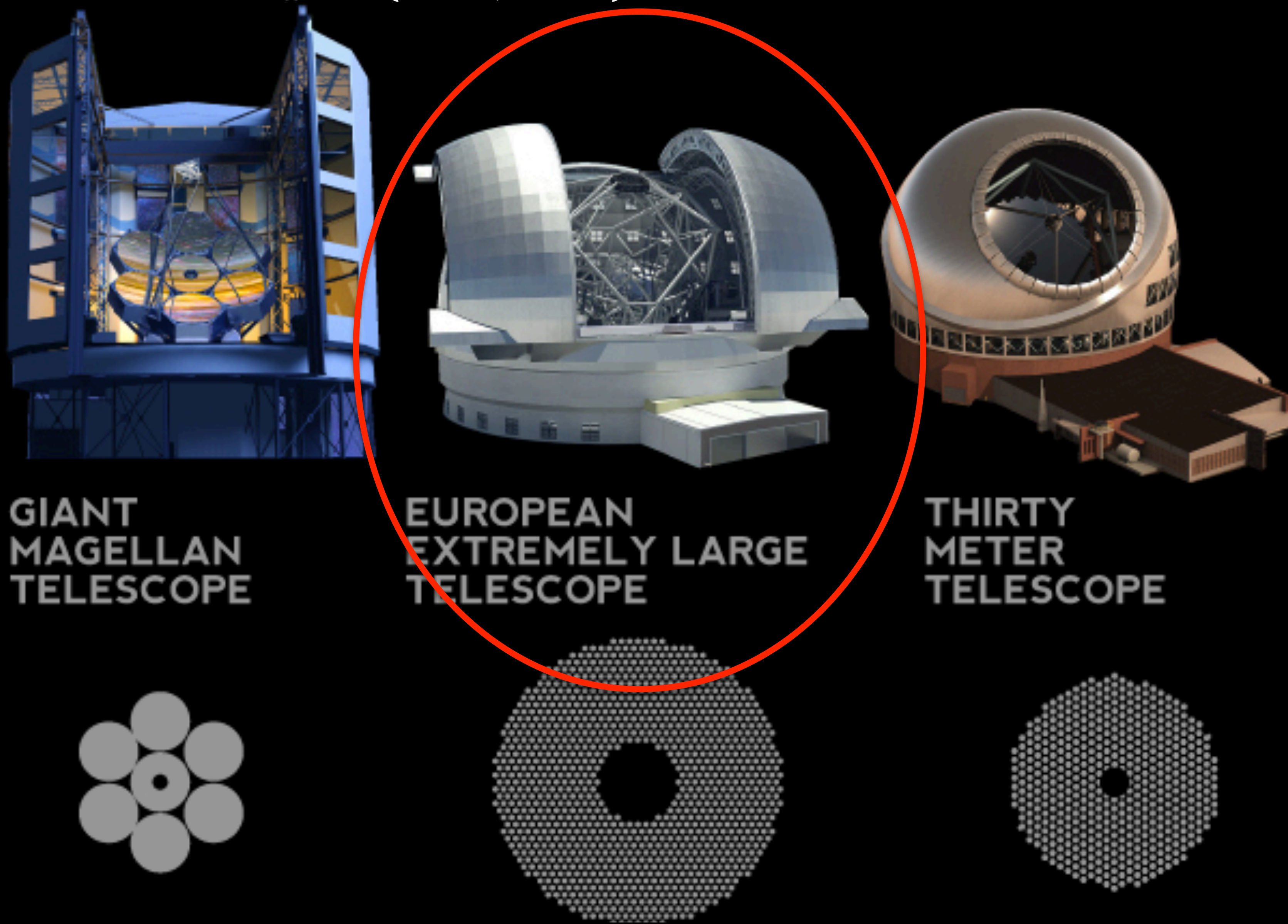
PLATO - 2025



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

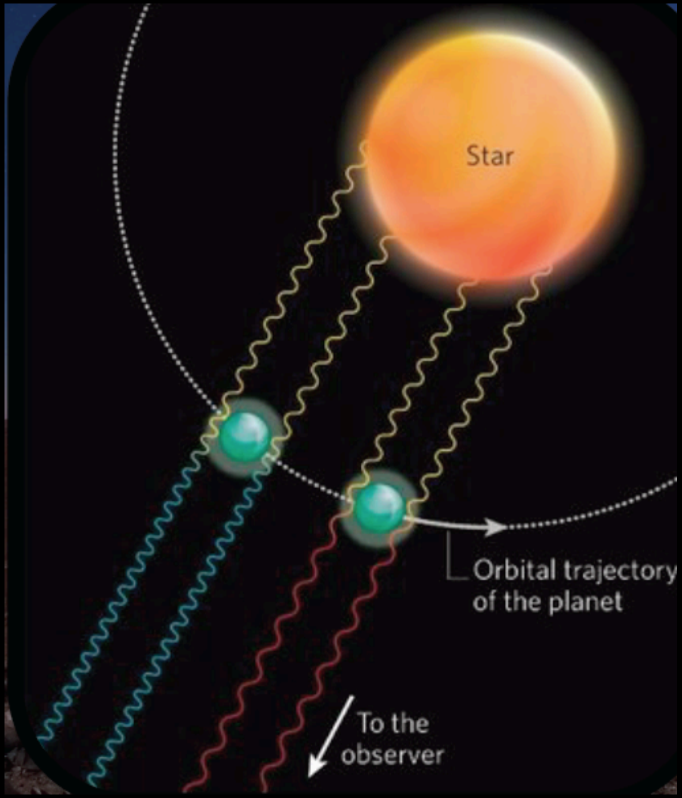


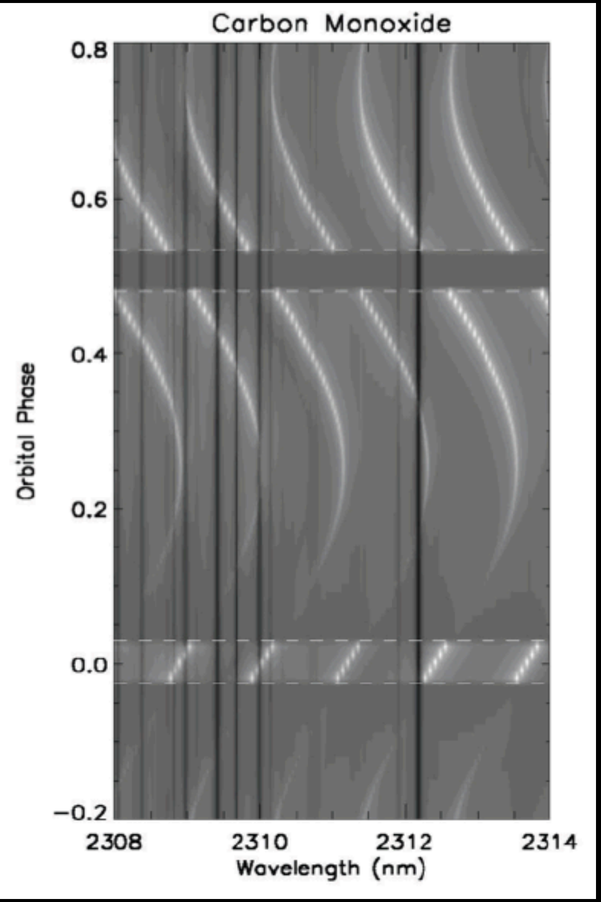
Atmospheric characterization via High-Res Spec (FOV, +AO)   2025-2030



Getting rid of the atmosphere:

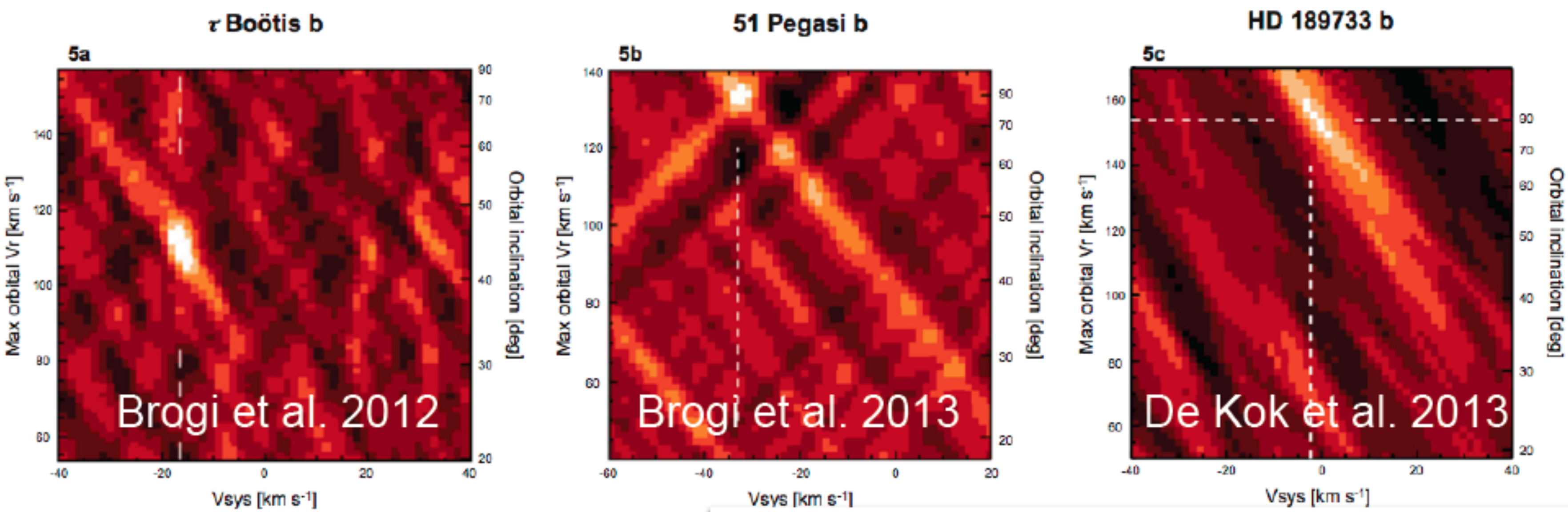
The planet moves at different speed than the star

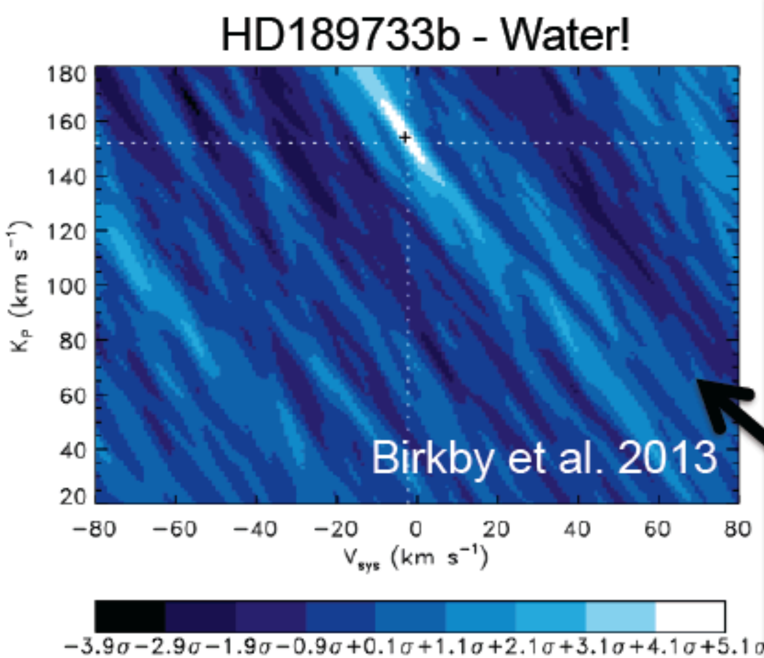




Snellen, 2010

CO in dayside spectra of hot Jupiters





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

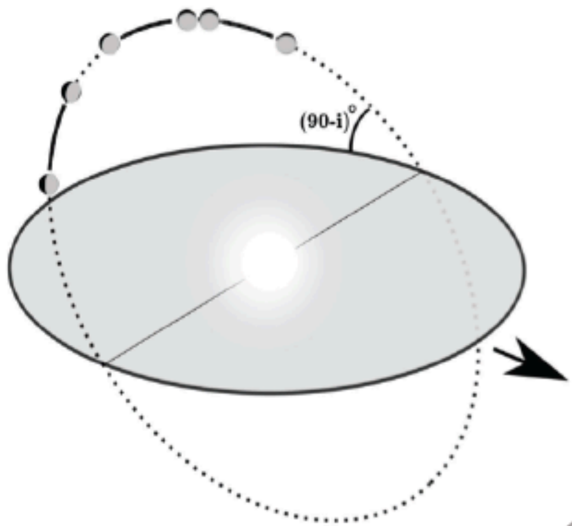
VLT ESPRESSO (Optical → TiO, VO, FeH...)

Now also with Keck!
Lockwood et al. 2014

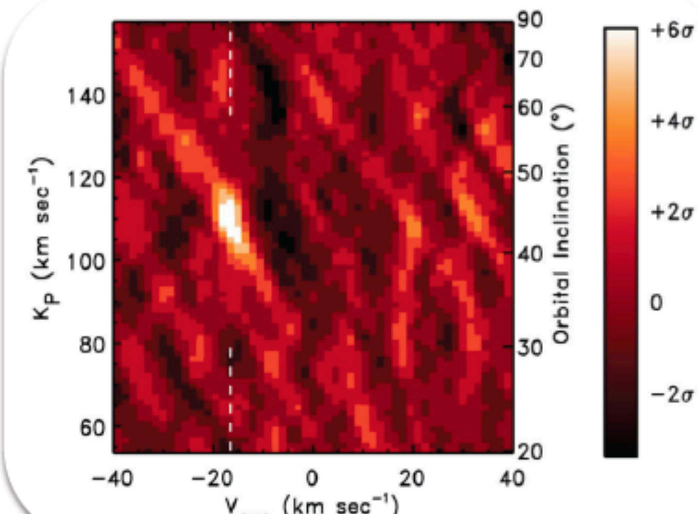
Stepping-stone for the ELTs

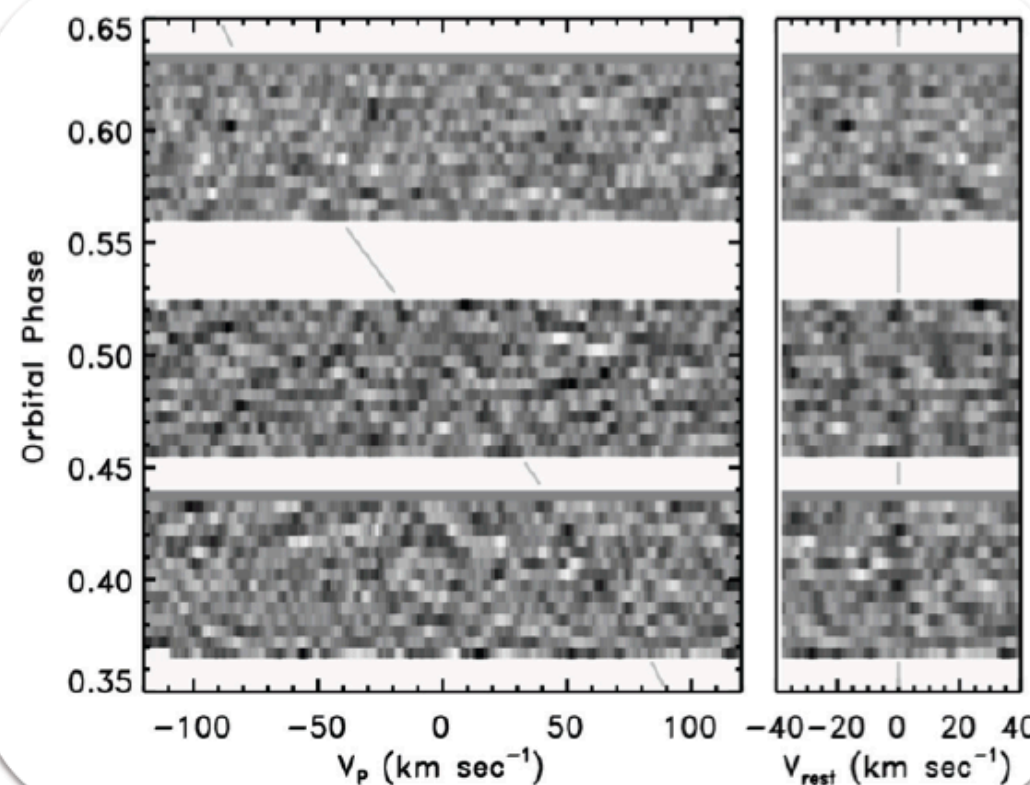
CO in dayside spectrum of tau Bootis b (CRIRES@VLT)

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



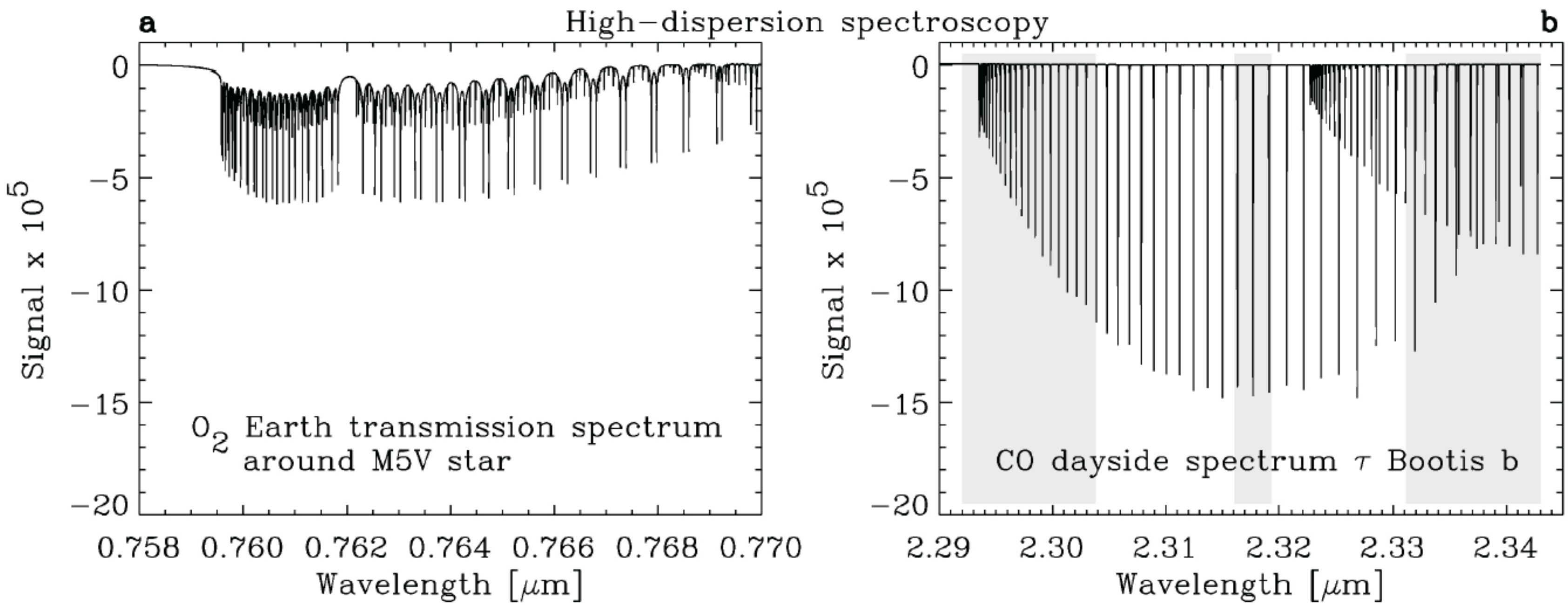
First detection of non-transiting planet→ inclination, mass





Detection of biosignatures in Earth-like planets

Detection of oxygen in transmission



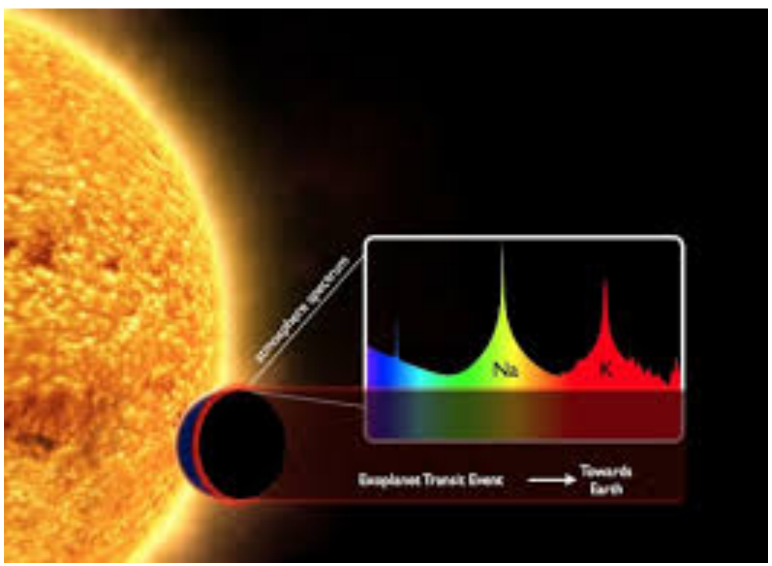
Snellen et al, 2013

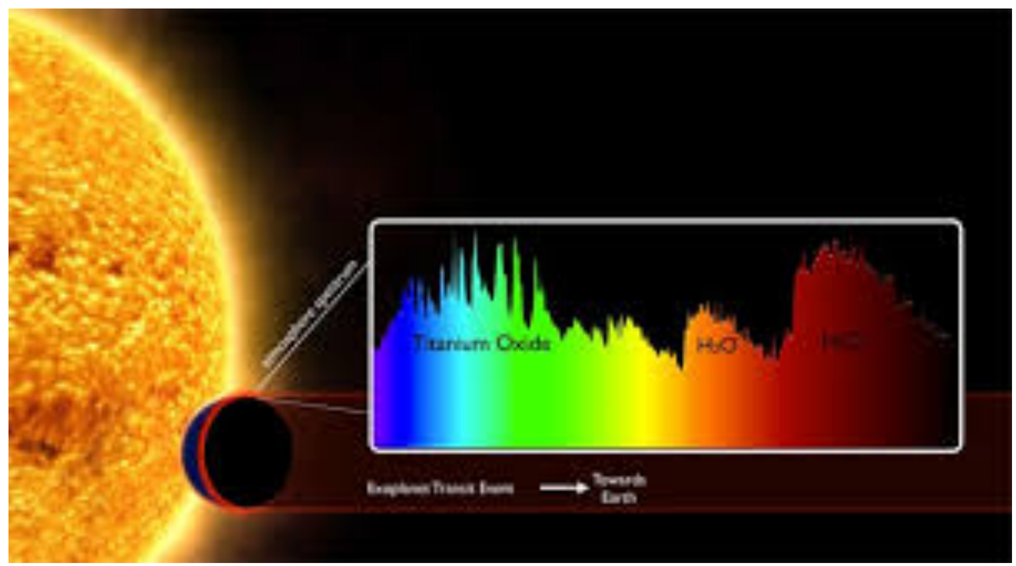
Transmission spectroscopy

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.





Exoplanet Atmospheres : transmission vs direct light

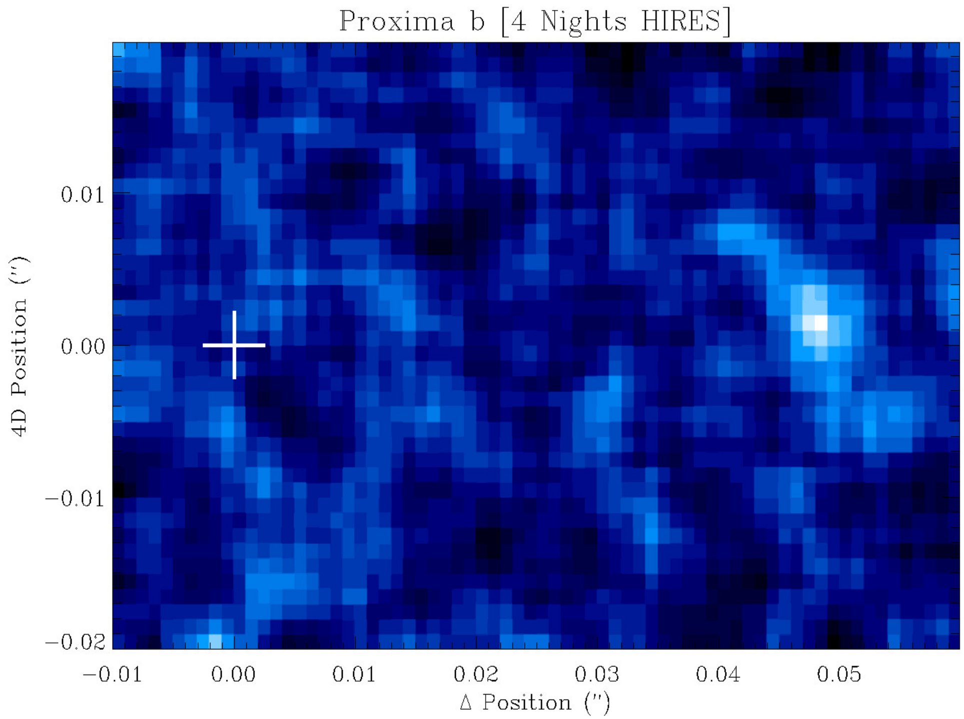
Probability of transits of Earth - Sun 0.5%
Probability of transit of Earth – M star 1-2%

- 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)

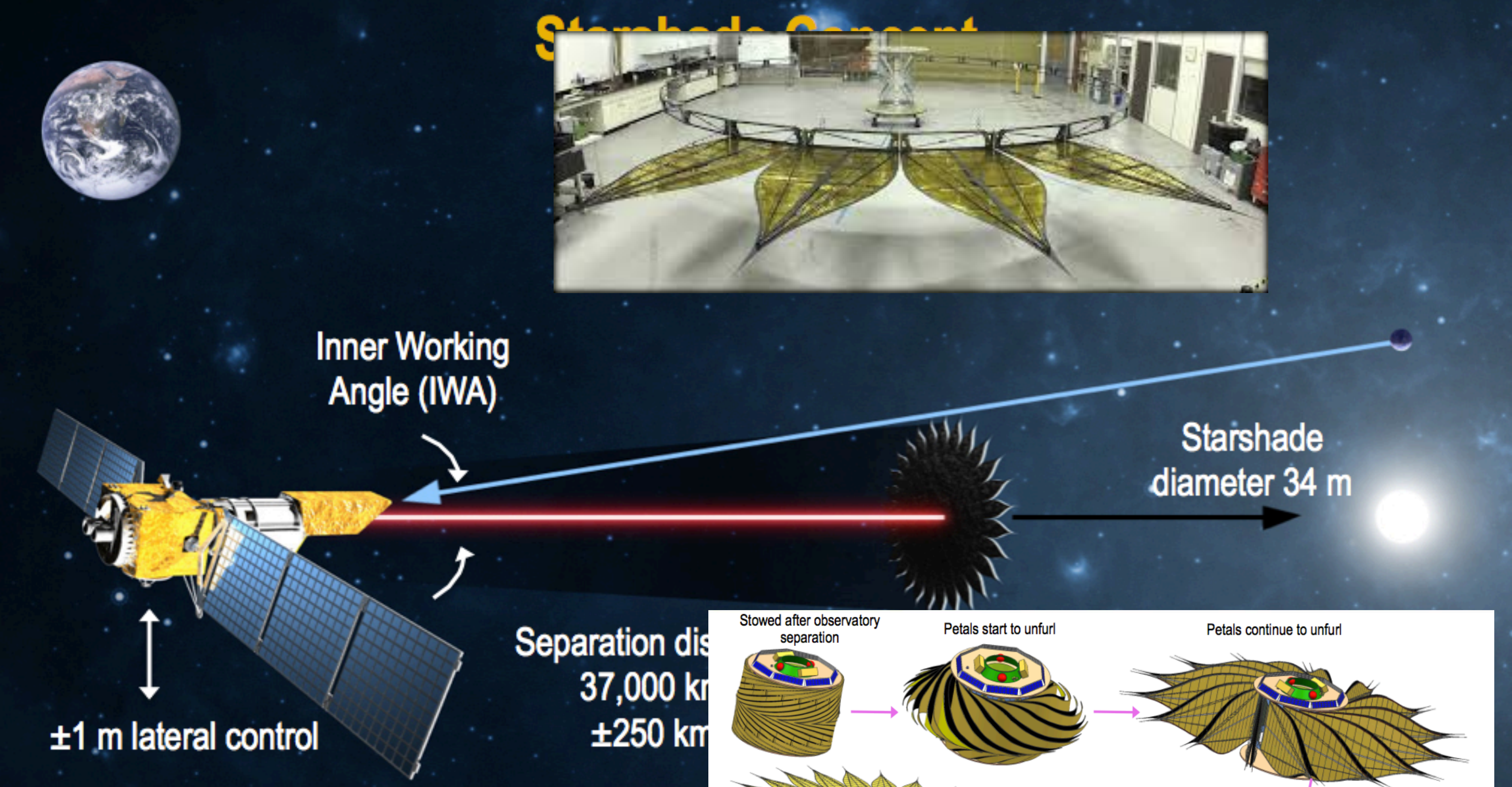
Direct detection of the planet's reflected light

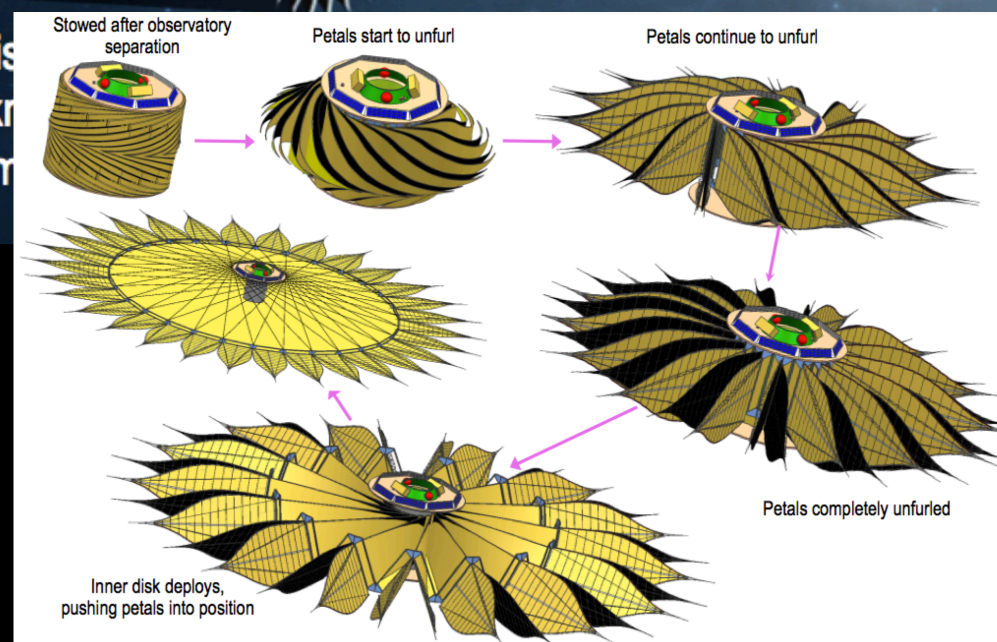


AO+ IFU Reflected light cross-correlation signal of the direct surroundings of Proxima, showing Proxima b at 48 mas

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

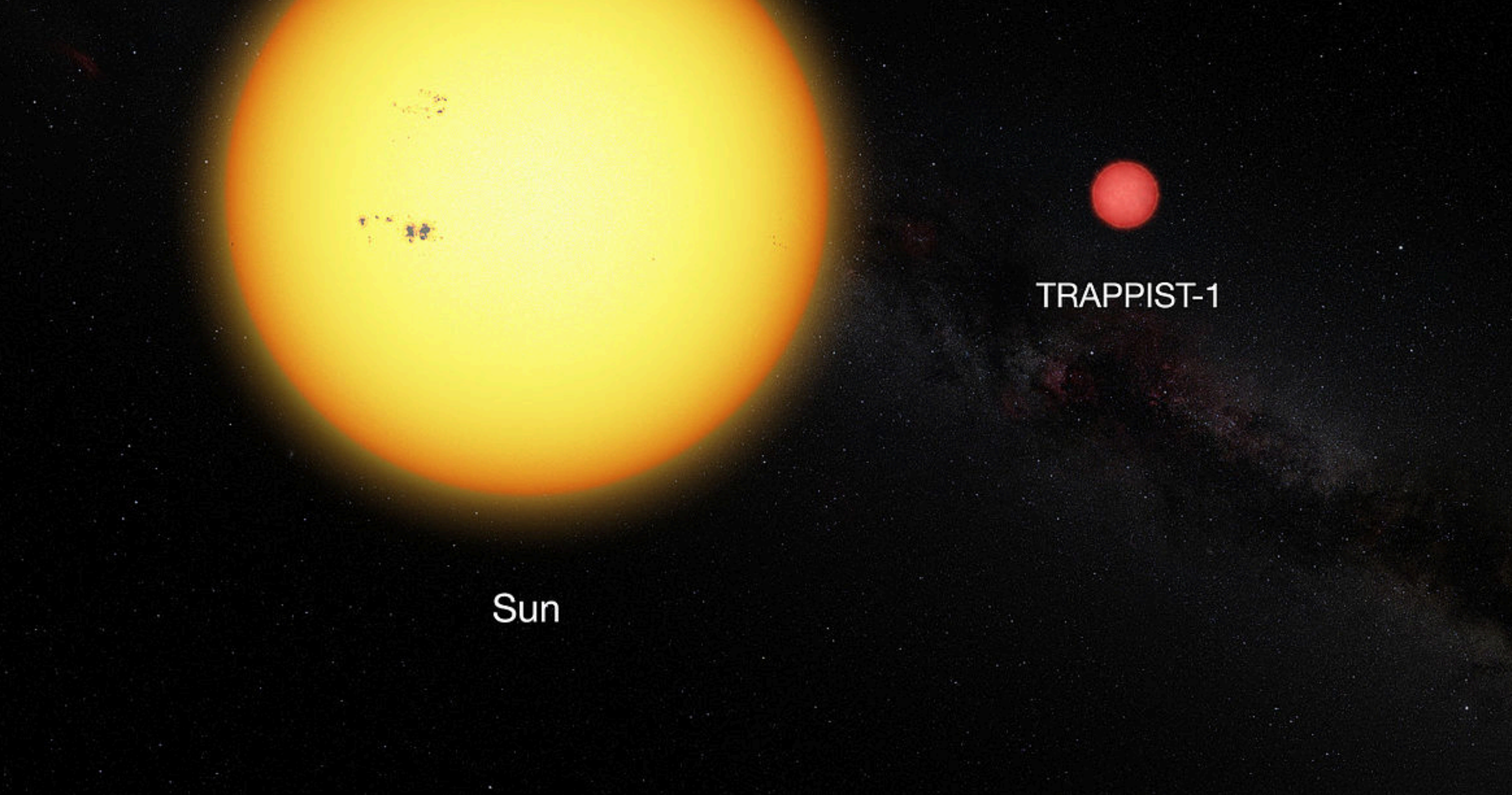
With EAO system (EPICS) 10 x faster



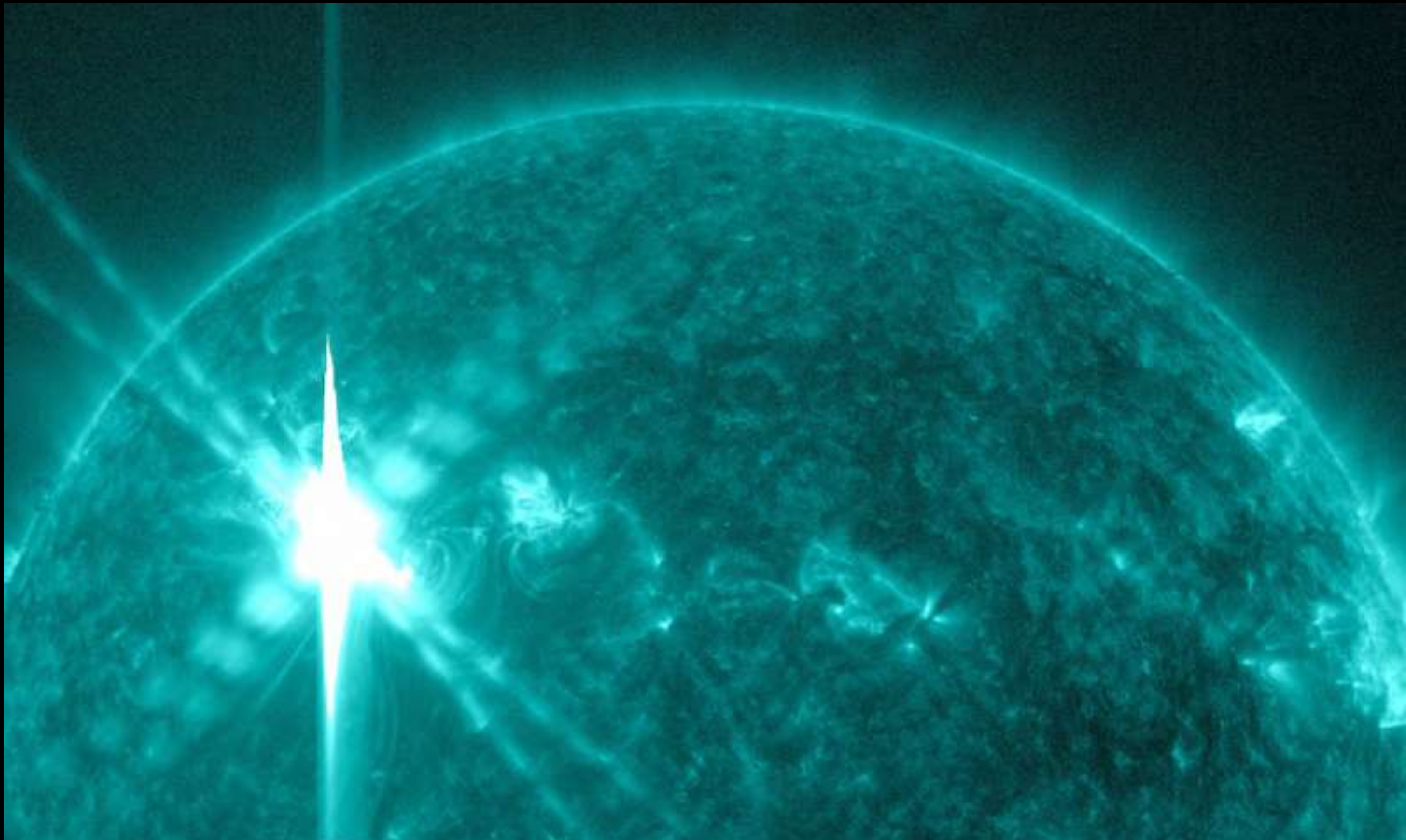


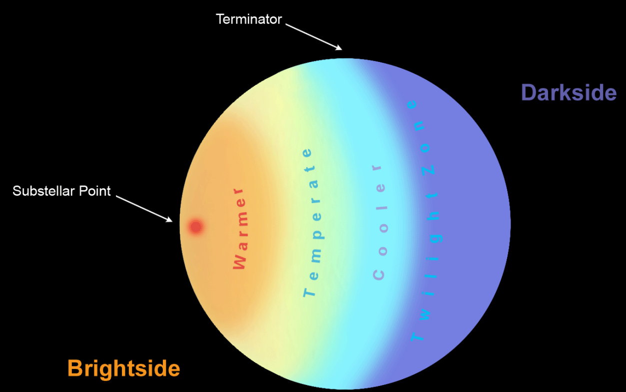
Capable of exploring
earth-like planet around
solar-type stars

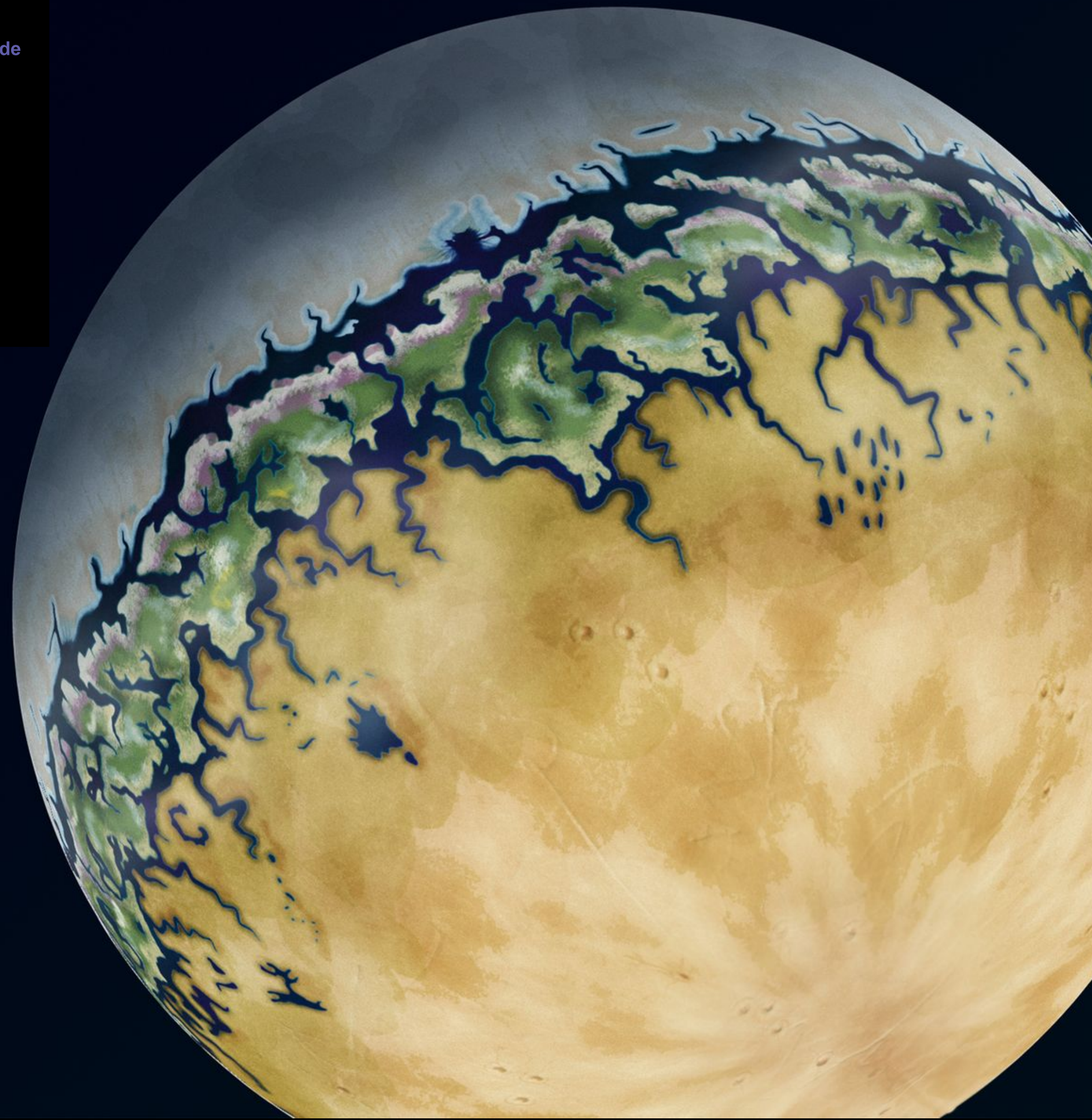
Word of caution: Relying on M stars

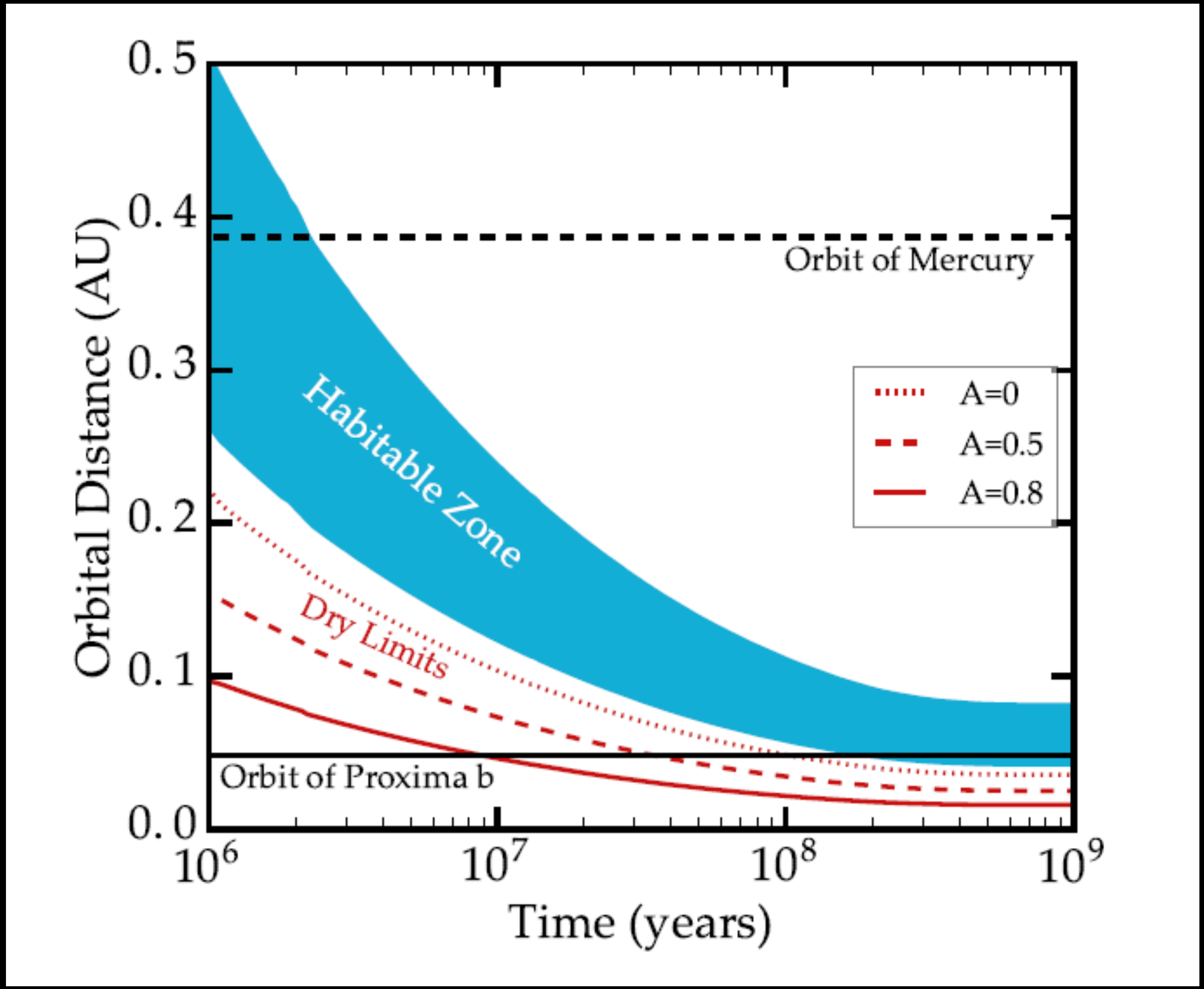


It’s not easy to live around an M-star




Terminator
Darkside
Substellar Point
Warmer
Temperate
Cooler
Twilight Zone
Brightside





Barnes et al. 2016

Summary

- Planets are everywhere
- 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 (including non-transiting)