SPECULOOS

Hunting for habitable exoplanets around the nearest very-low-mass stars

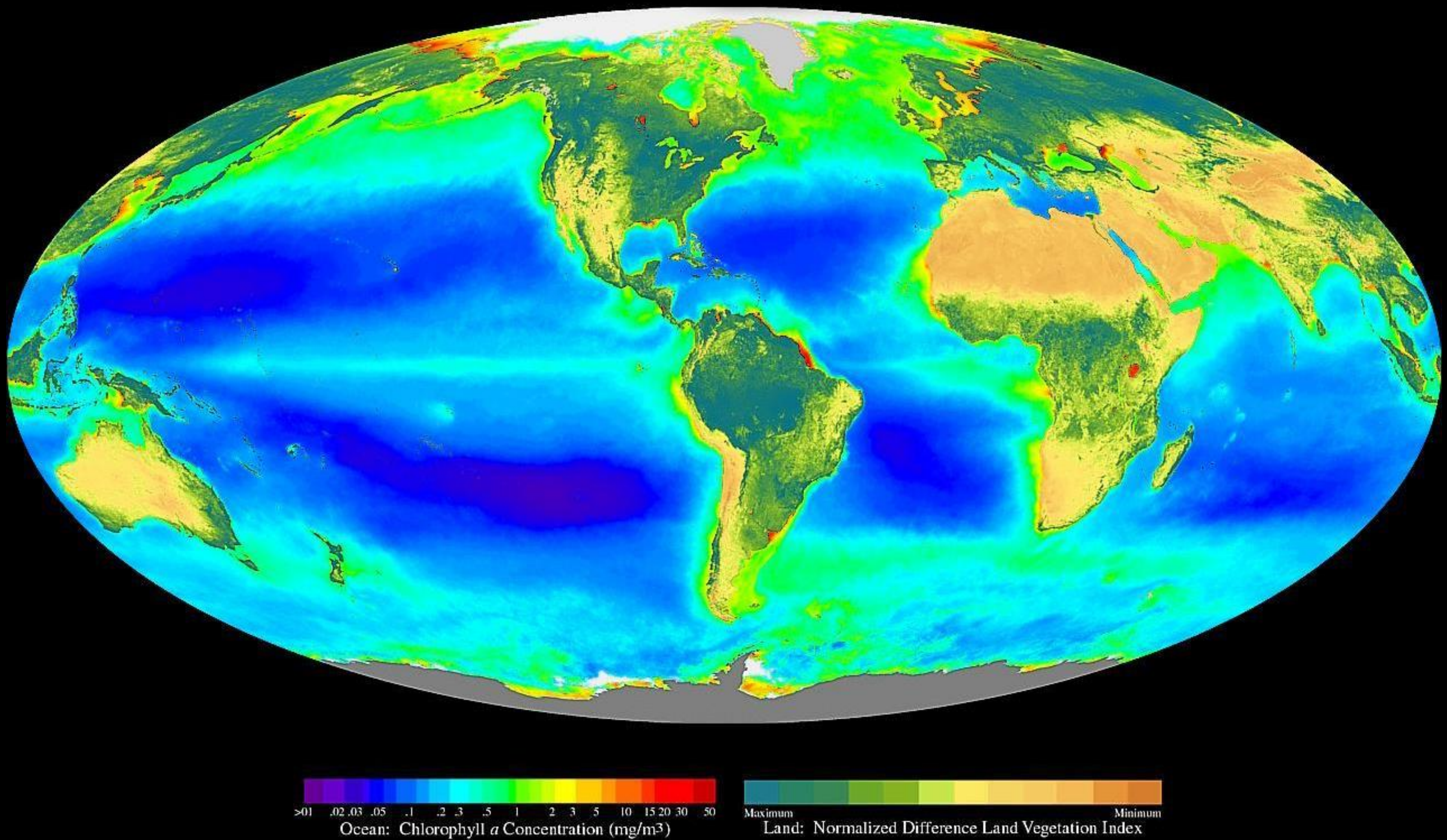
Michaël Gillon (University of Liège, Belgium)

CERN– 17 Jan 2019

Is our blue world unique?

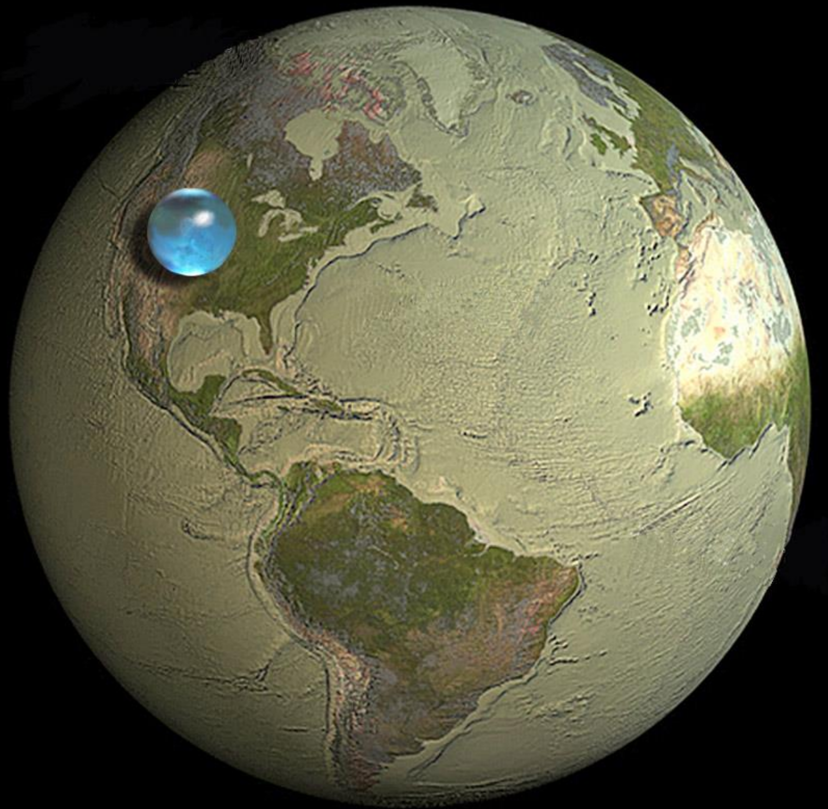
Credit: NASA

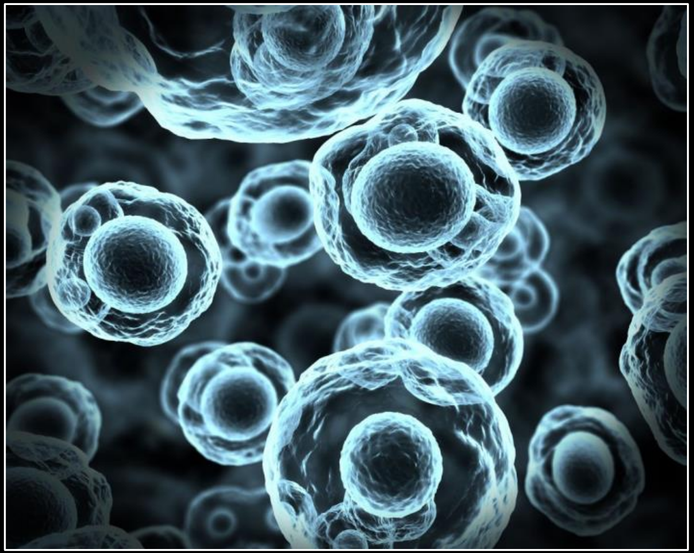
Earth: a rocky planet hosting a complex surface biosphere



Credit: NASA

Earth: a rocky planet with surface liquid water

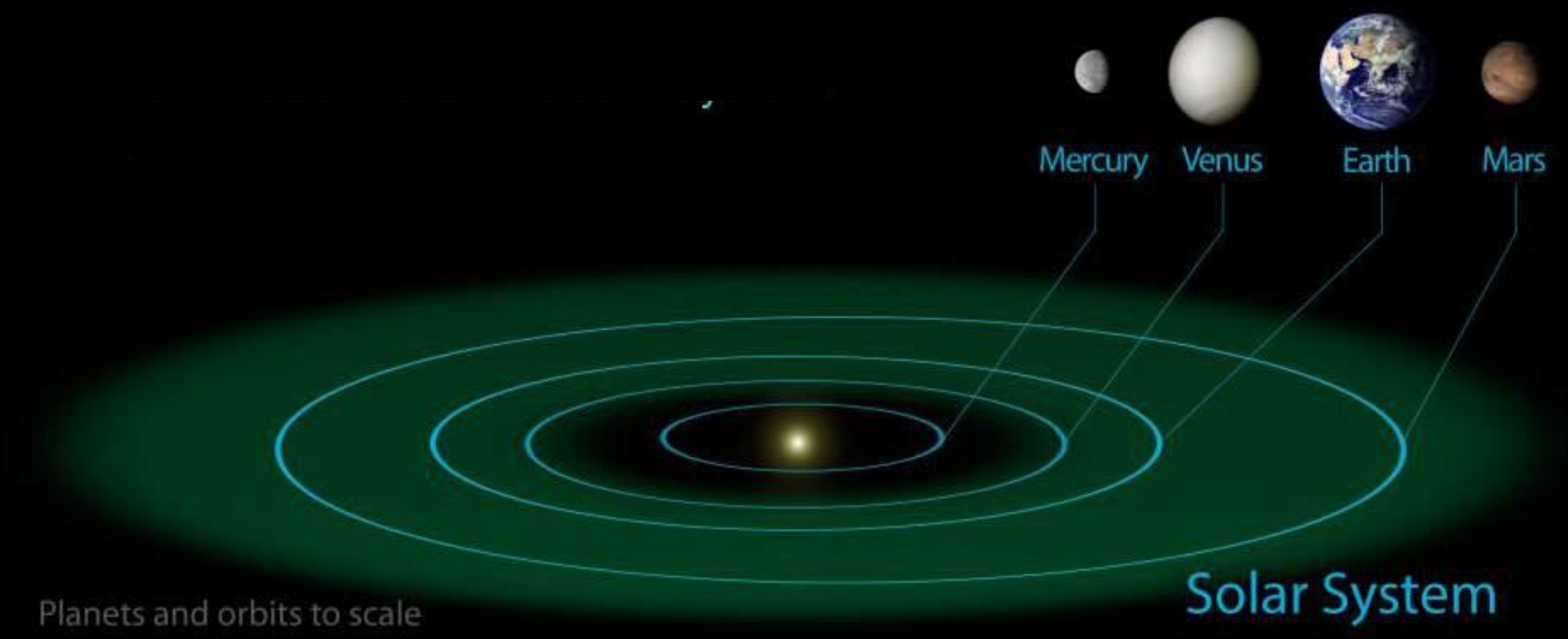




« Habitable » planet

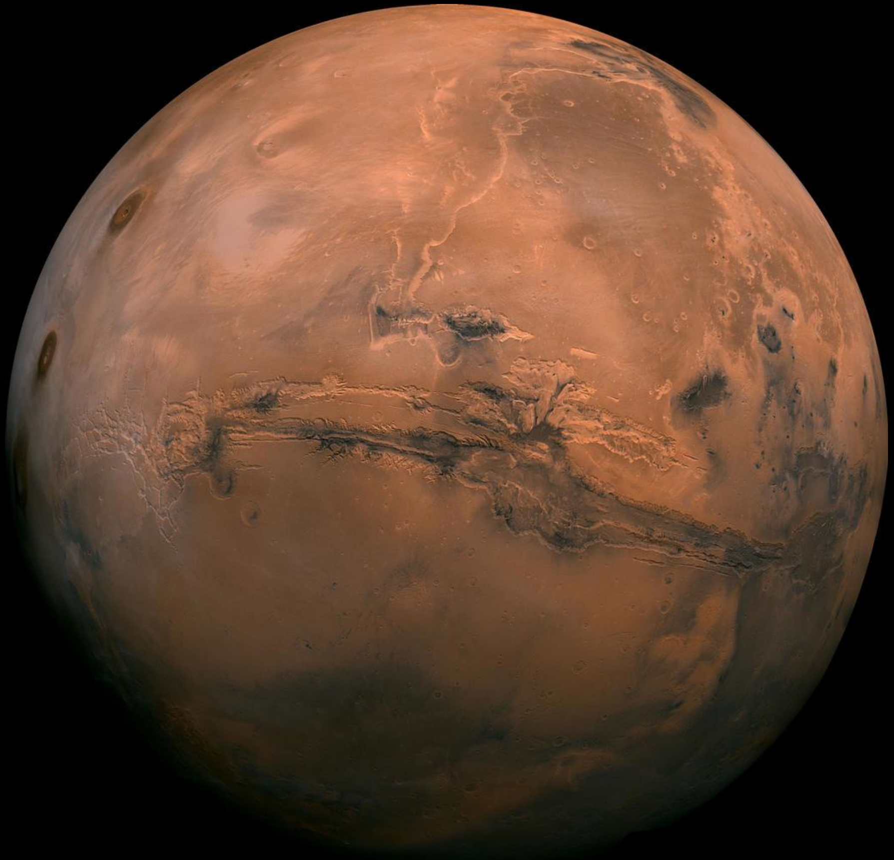
Credits: Howard Perlman, USGS

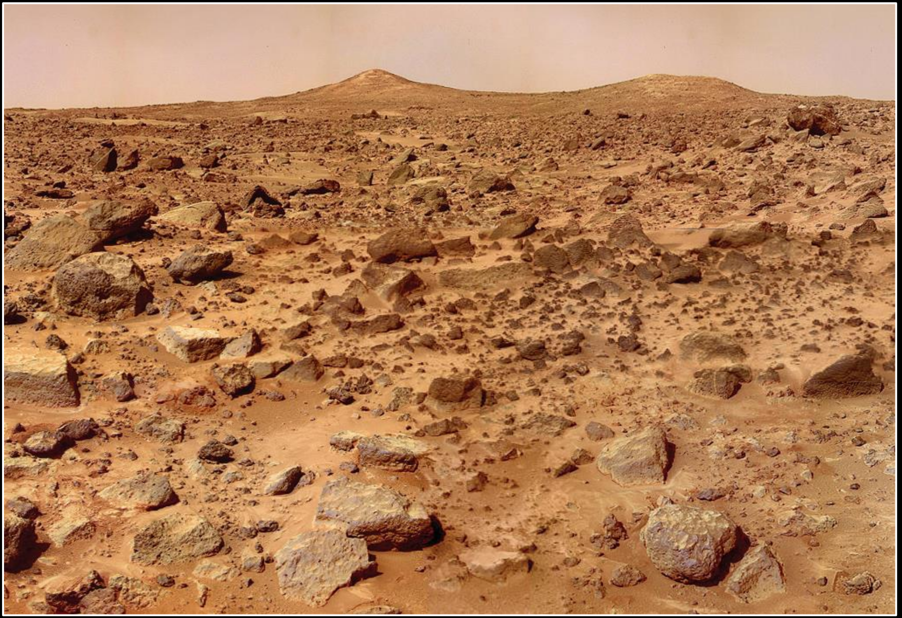
The « habitable zone » of the Sun



Credits: NASA

No little green men on Mars





Credits: NASA

We must search beyond our solar system

Credits: Ryan Sullivan

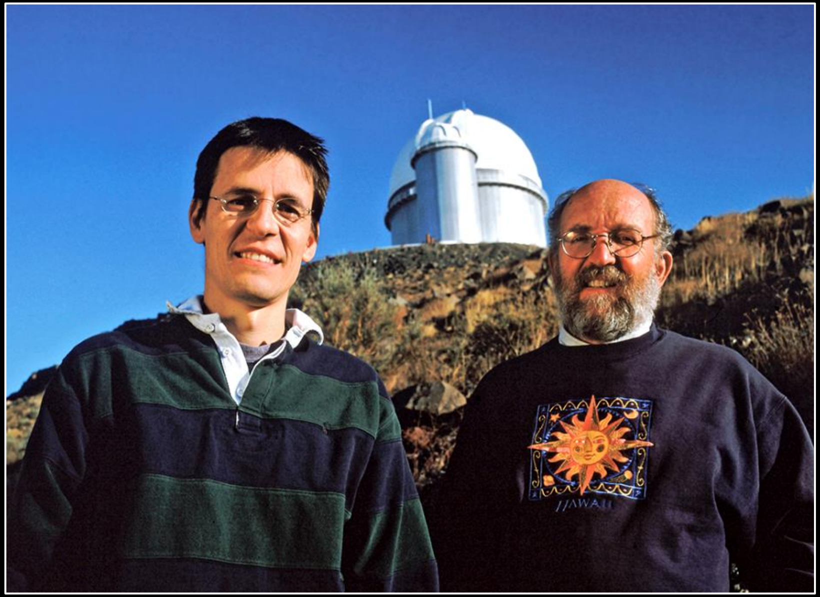
1995: beginning of the exoplanet era

A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

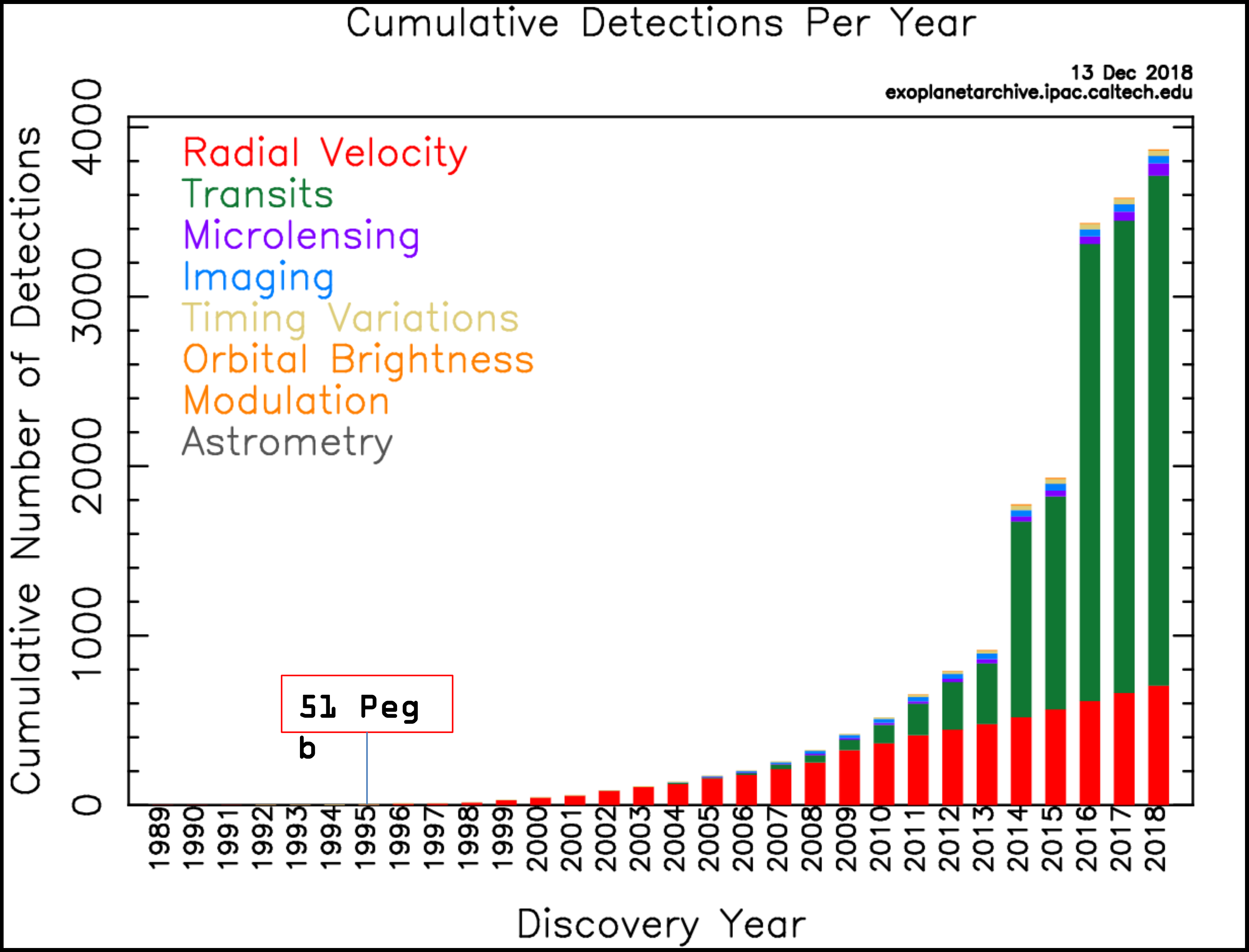
The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.



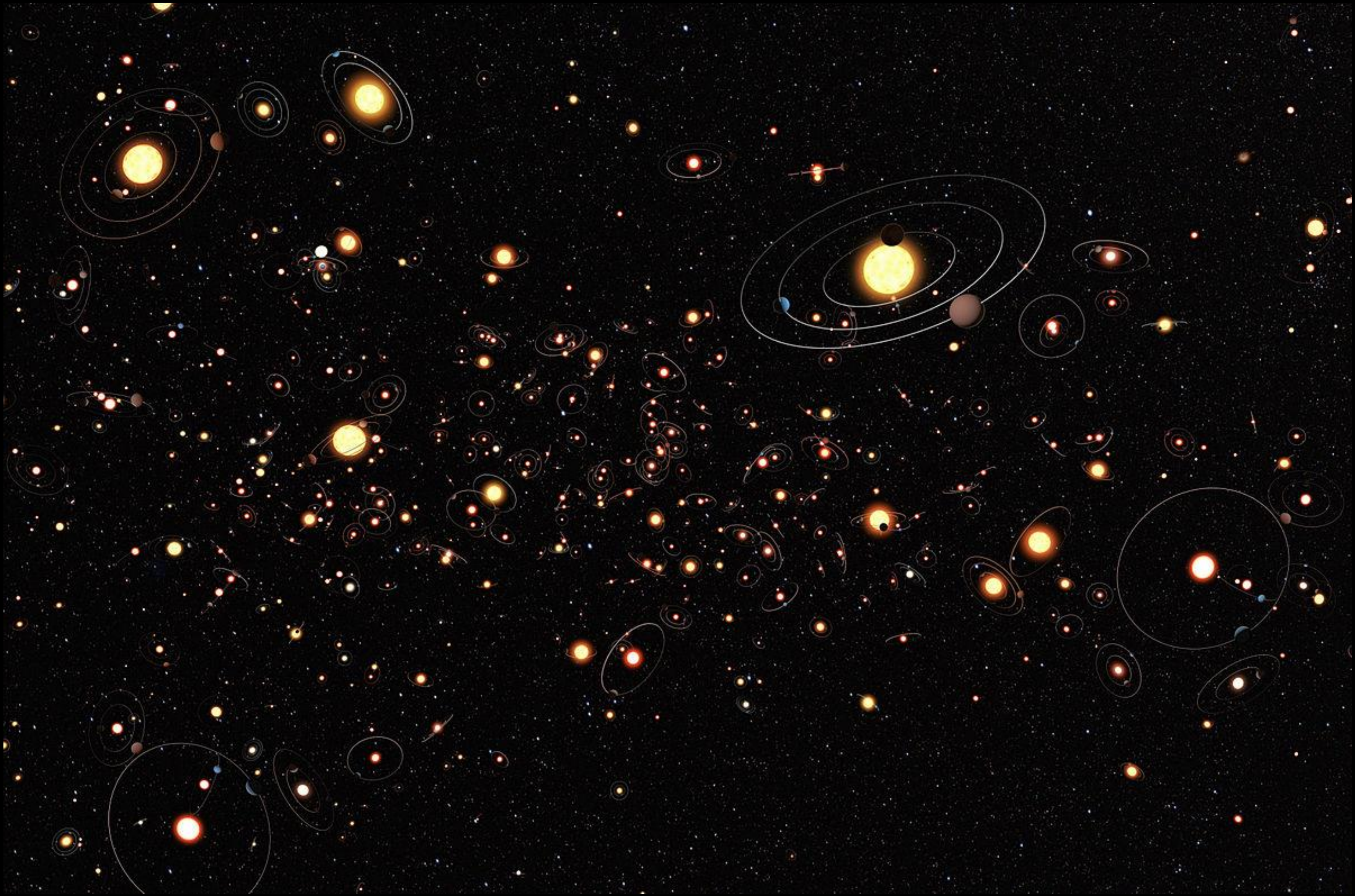
Didier Queloz   Michel Mayor

A giant planet in very short orbit around a *Sun-like star*

The exoplanet revolution



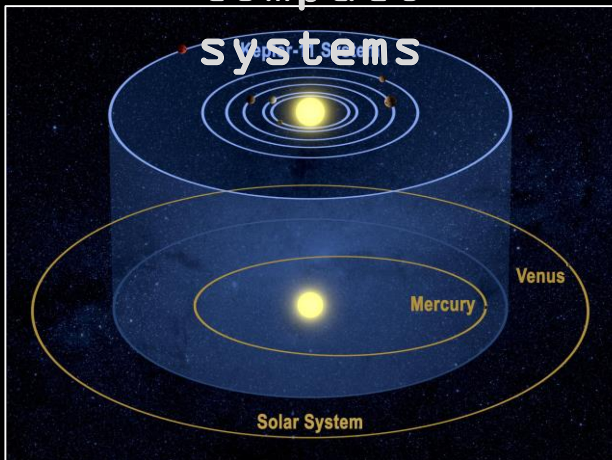
Planets everywhere



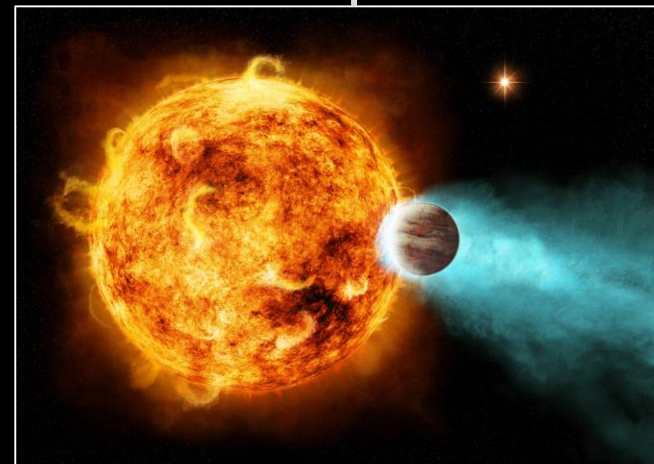
Credits: ESO/M. Kornmesser

The diversity of planetary systems

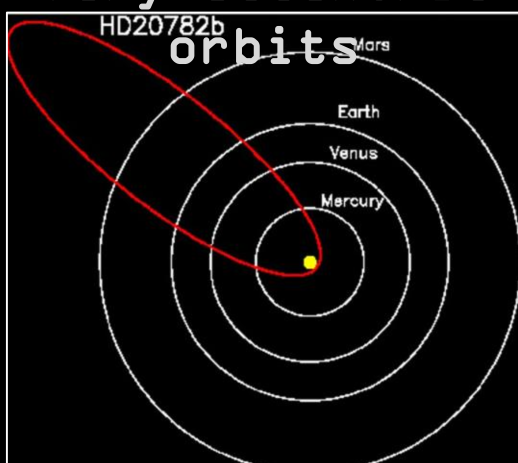
Compact systems



Hot Jupiters



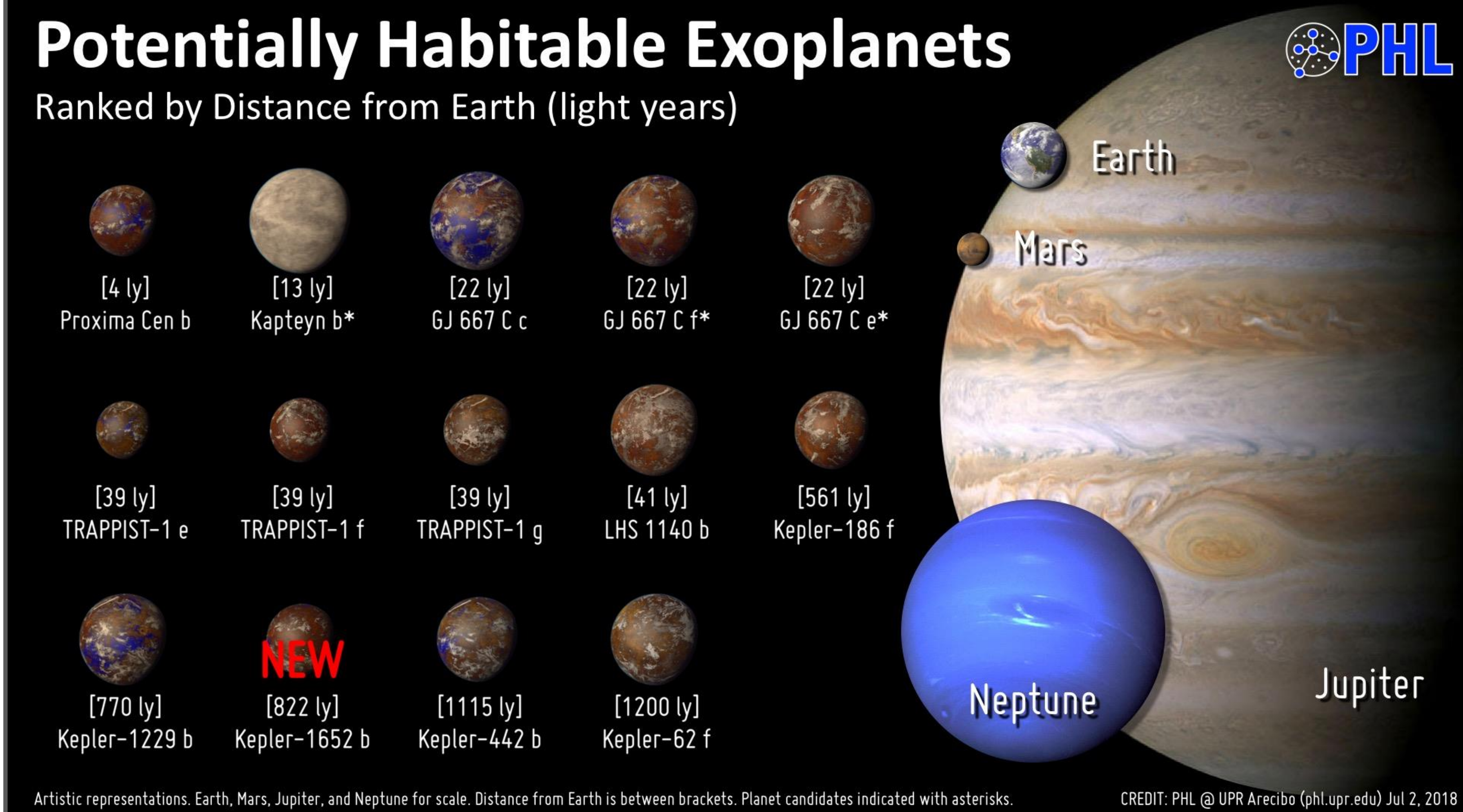
Very eccentric orbits



Free-floating planets

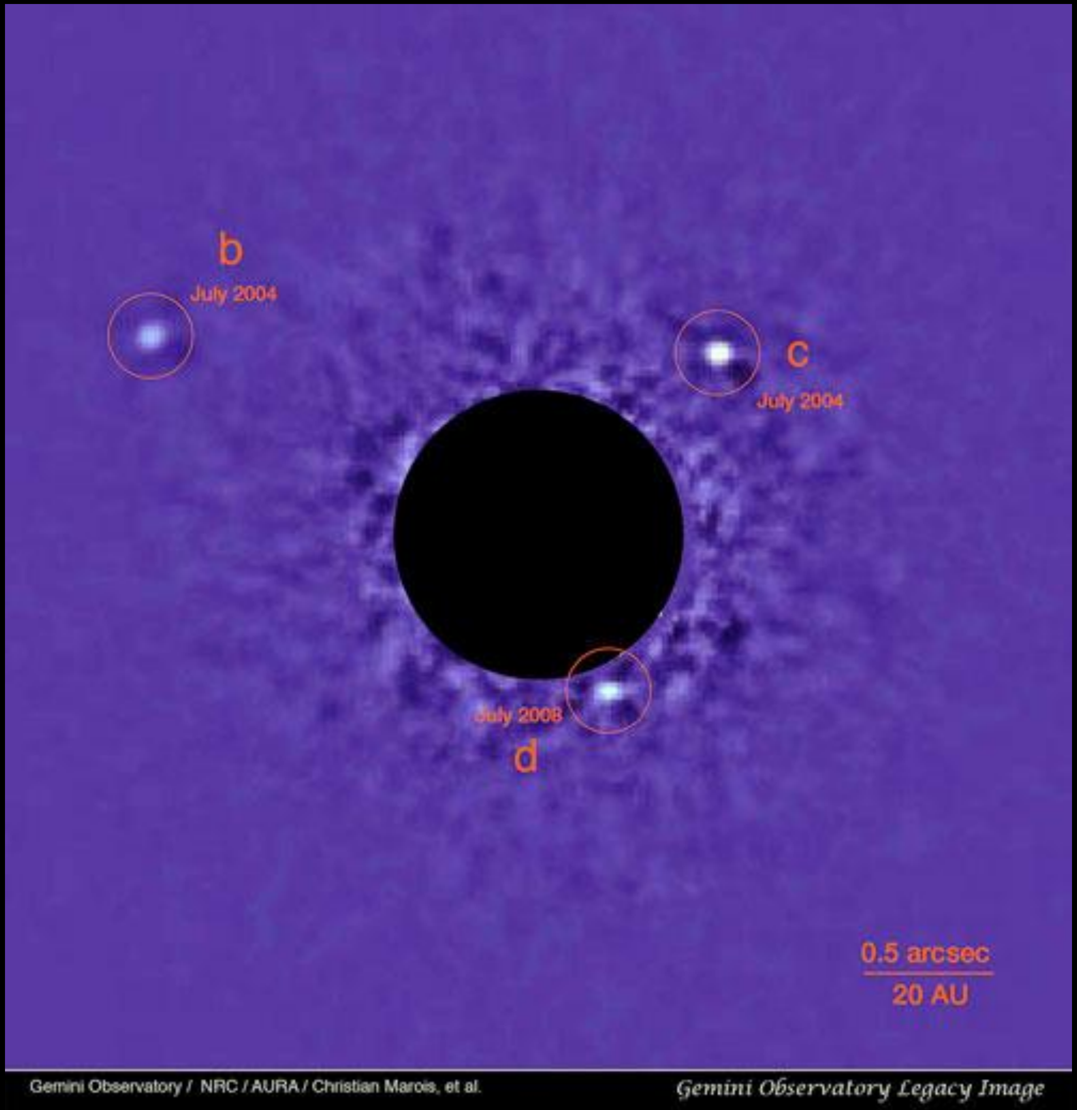
Credits: NASA/JPL-Caltech; Northwestern University; SETI Institute

A few dozen possible biospheres

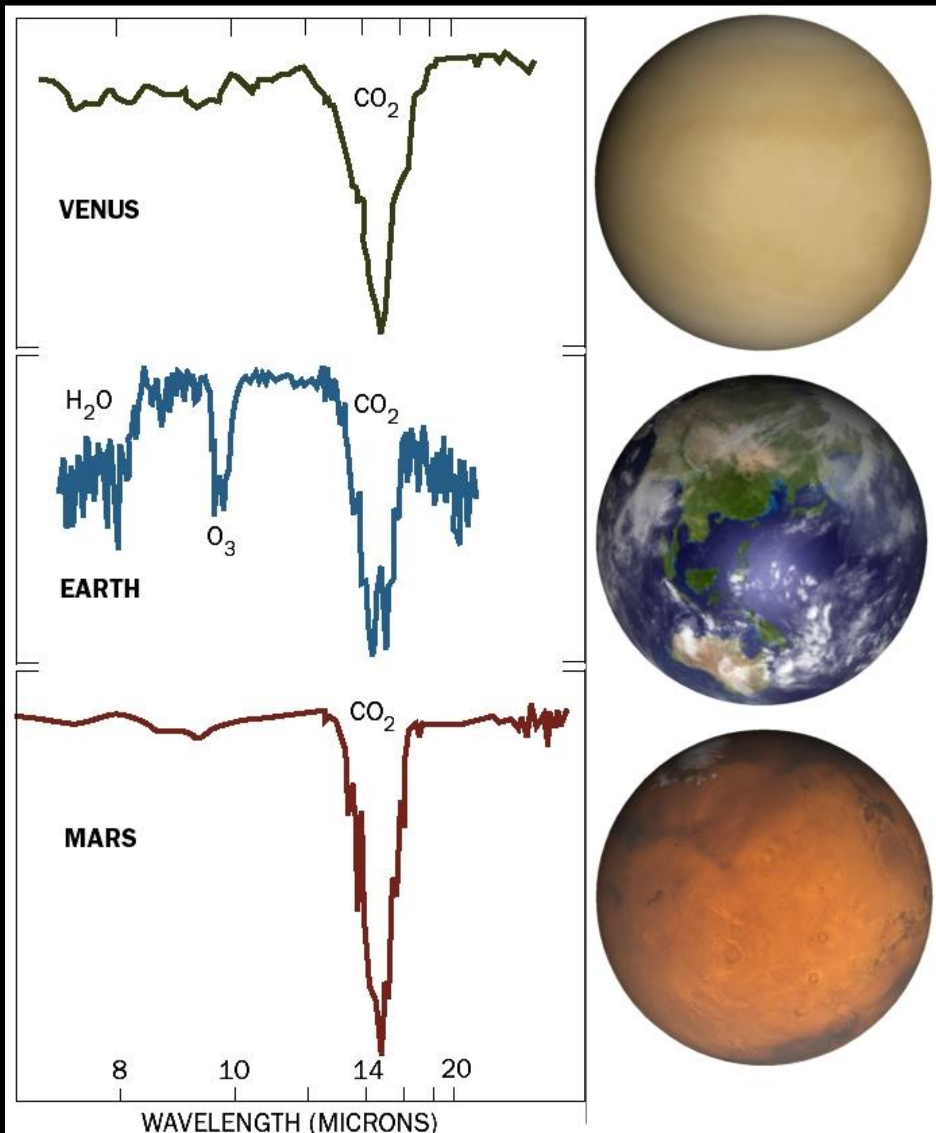


A few dozen BILLIONS in the whole Milky Way!

A few exoplanets have been imaged



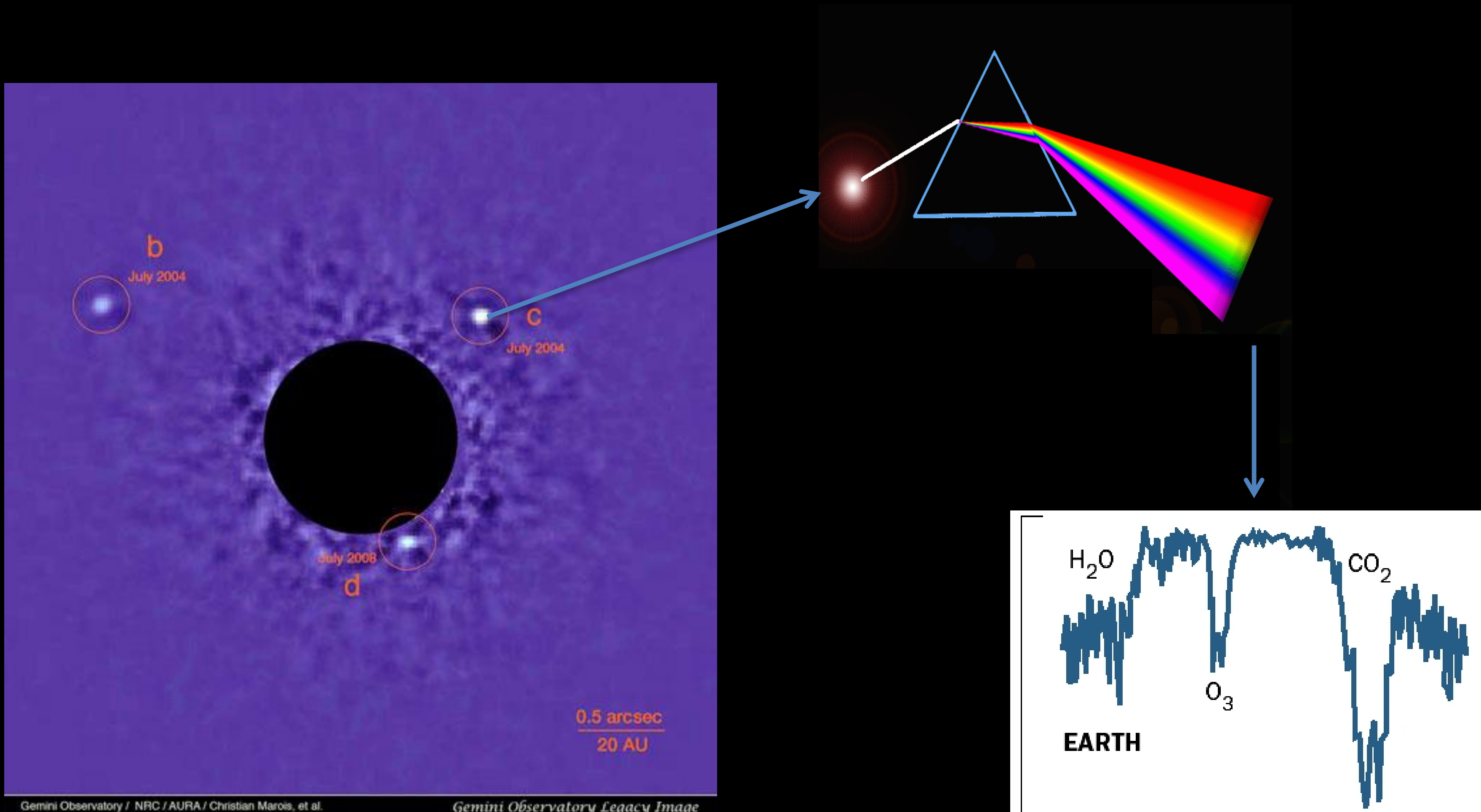
Spectroscopy of terrestrial planets



Best spectral range for the detection of molecules is infrared

Infrared spectroscopy of potentially habitable exoplanets

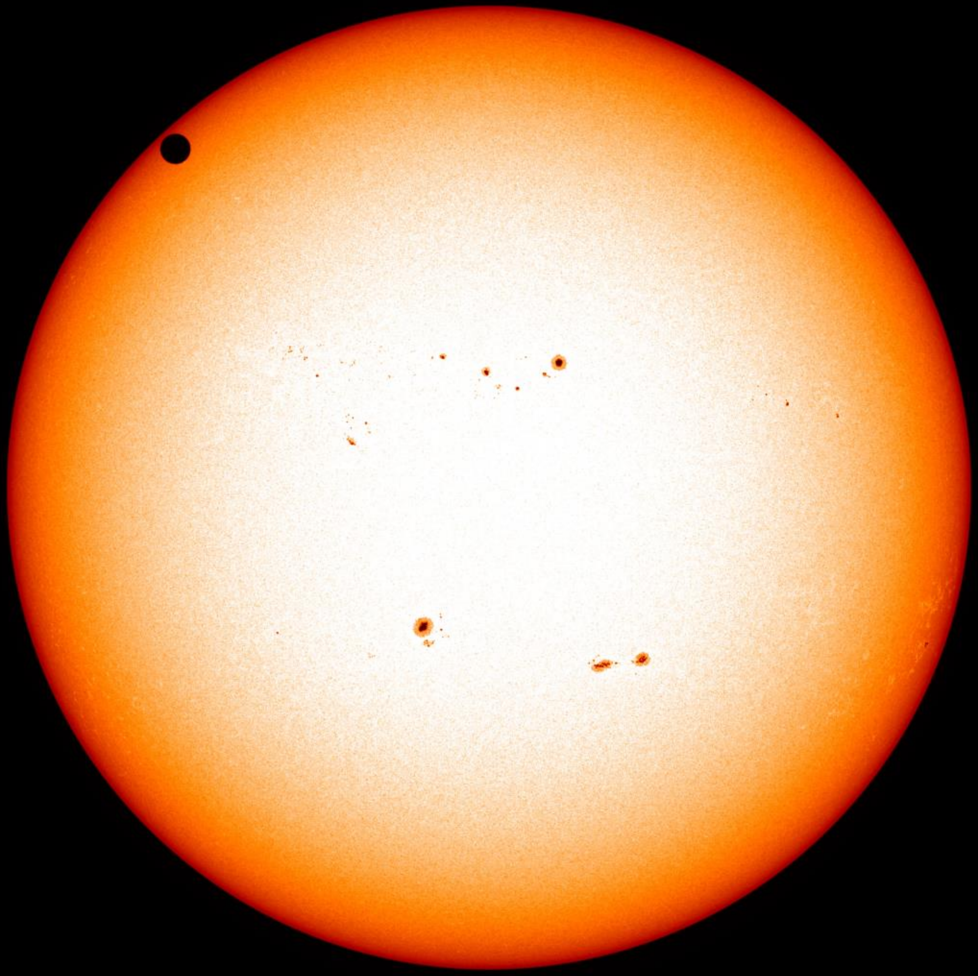
Spectroscopy of exoplanets



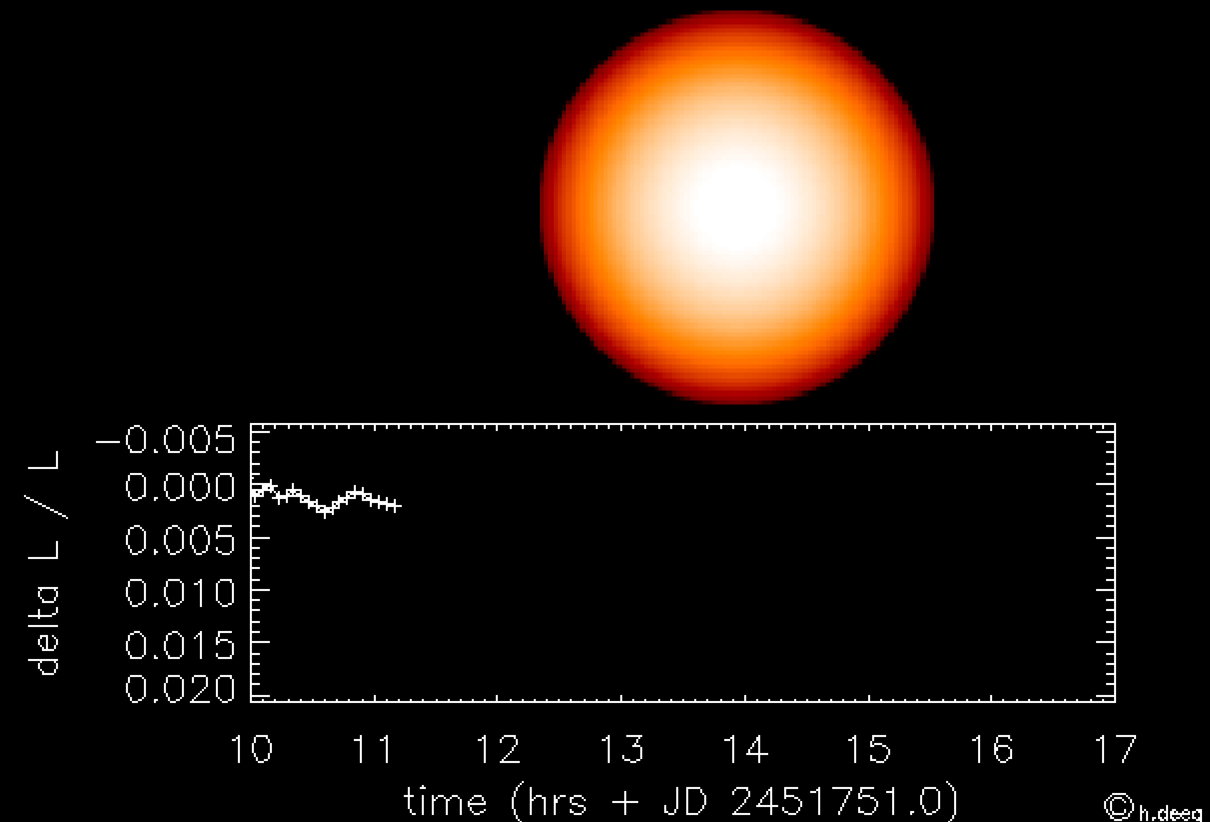
Imaging planets around other stars

Imaging planets around other stars

Planetary transit

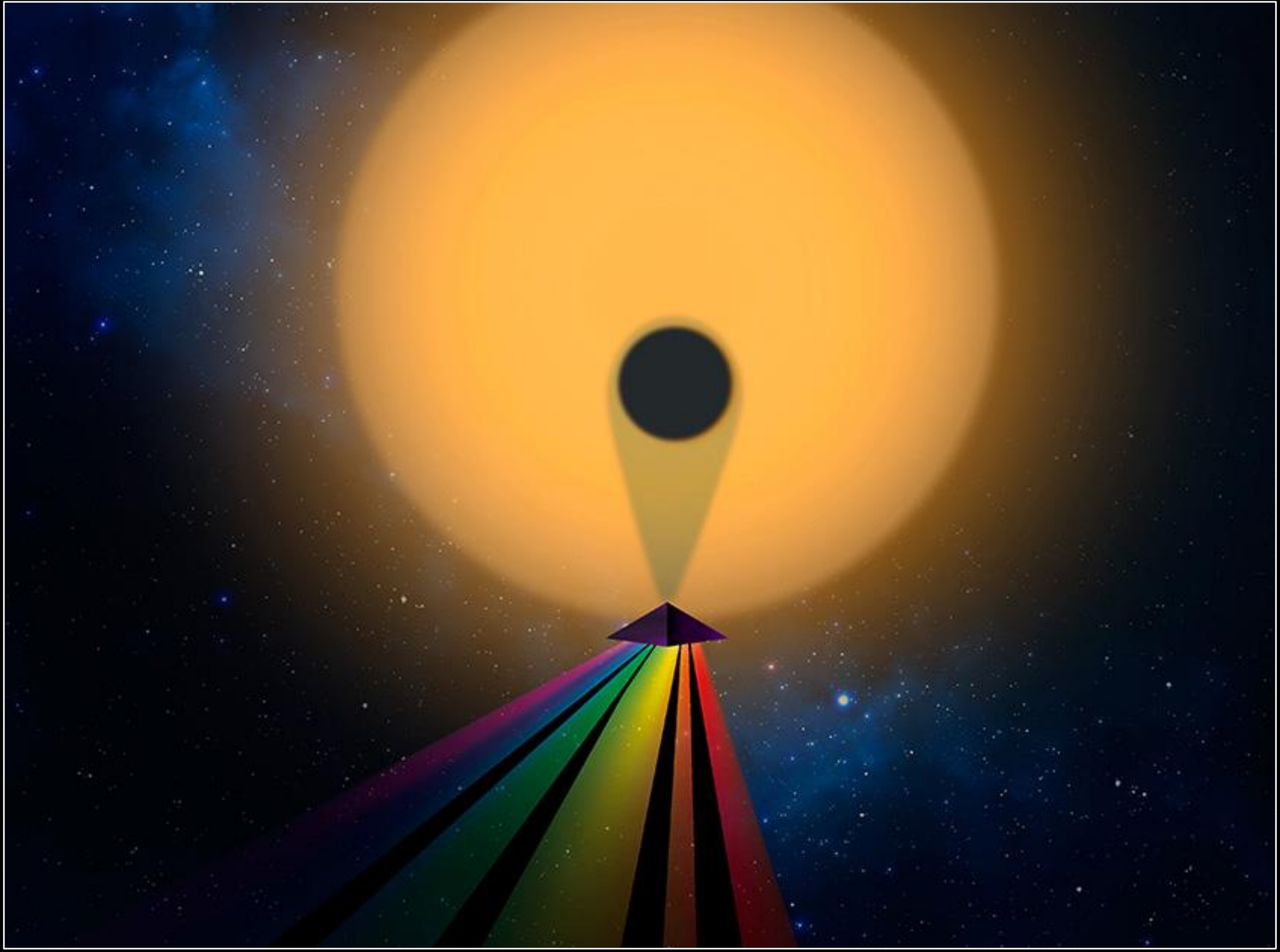


Transit of exoplanet



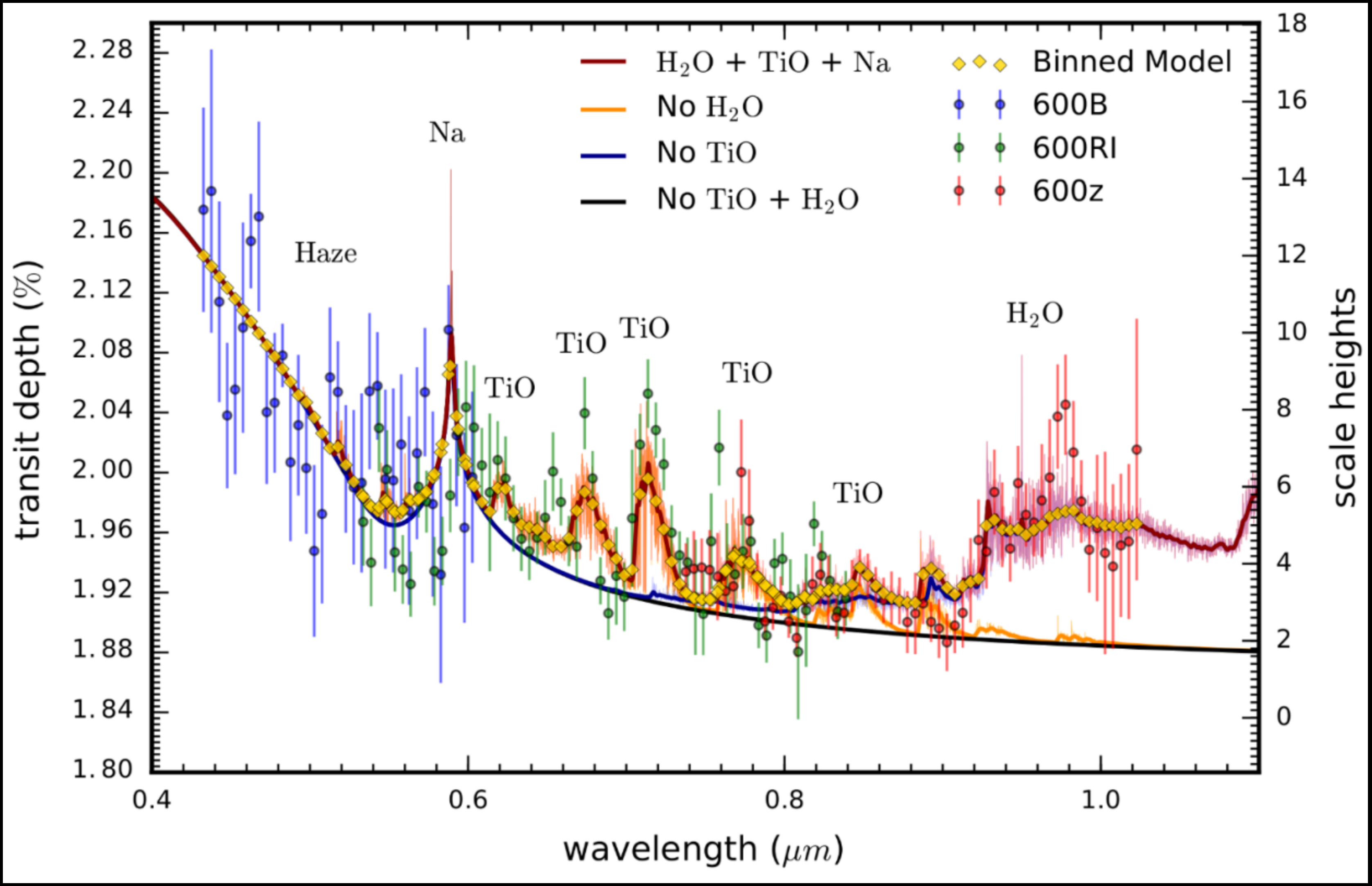
Credits: Deeg & Garrido

Atmospheric study of a transiting exoplanet



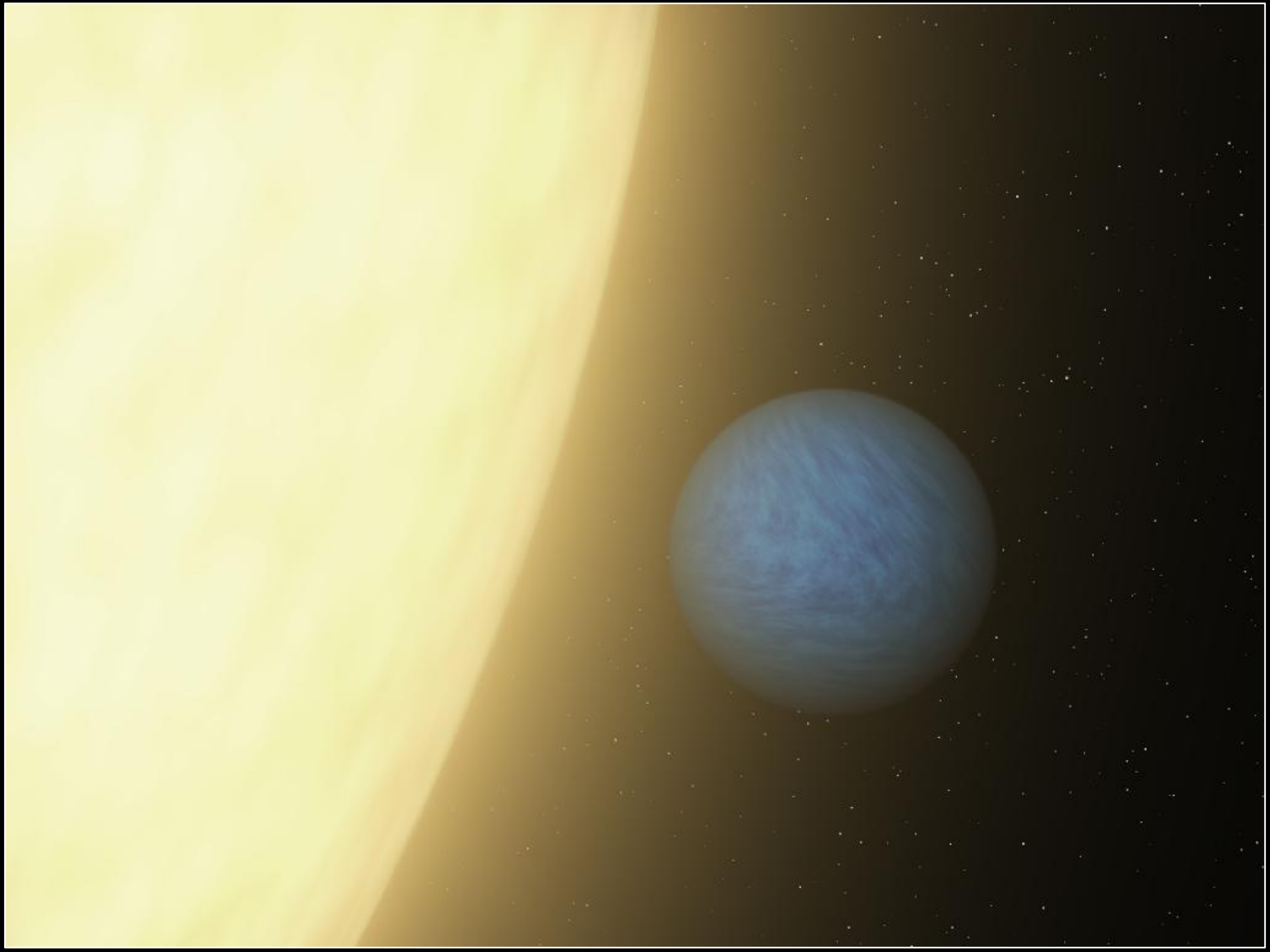
Credits: C. Daniloff/MIT, J. de Wit

Atmospheric study of a transiting exoplanet



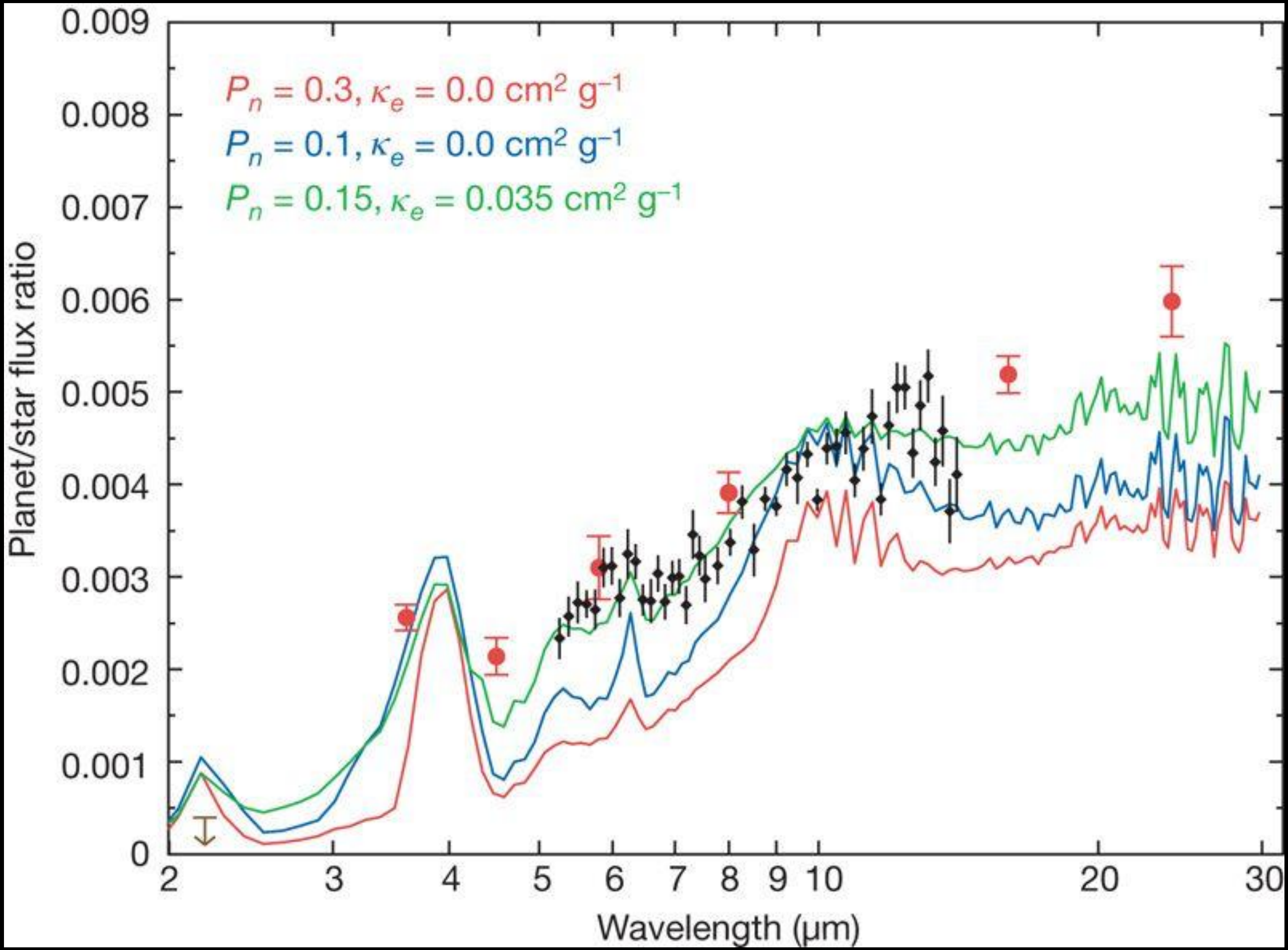
Credits: E. Sedaghati et al. 2018

Atmospheric study of a transiting exoplanet



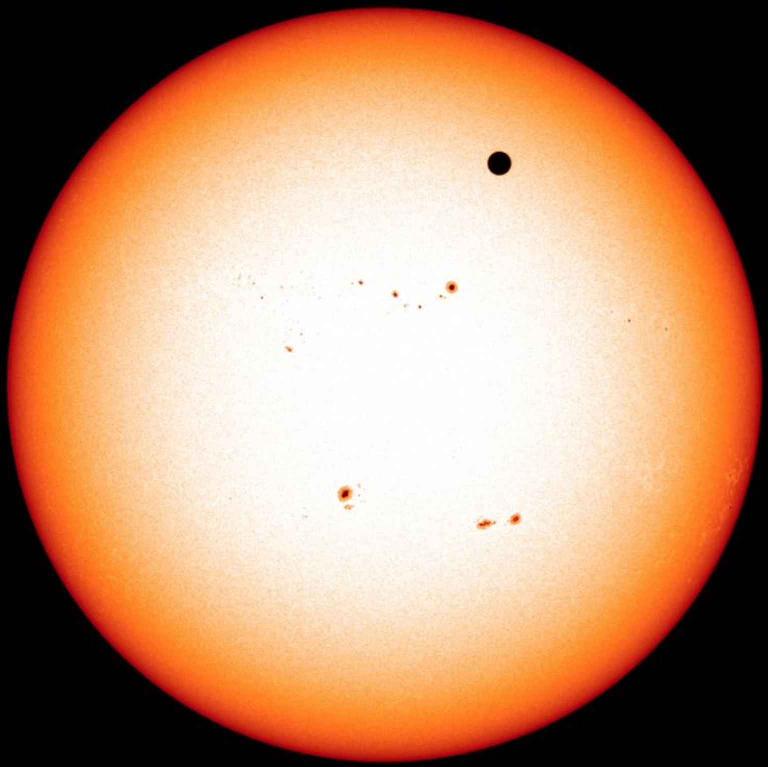
Credits: NASA/JPL

Atmospheric study of a transiting exoplanet

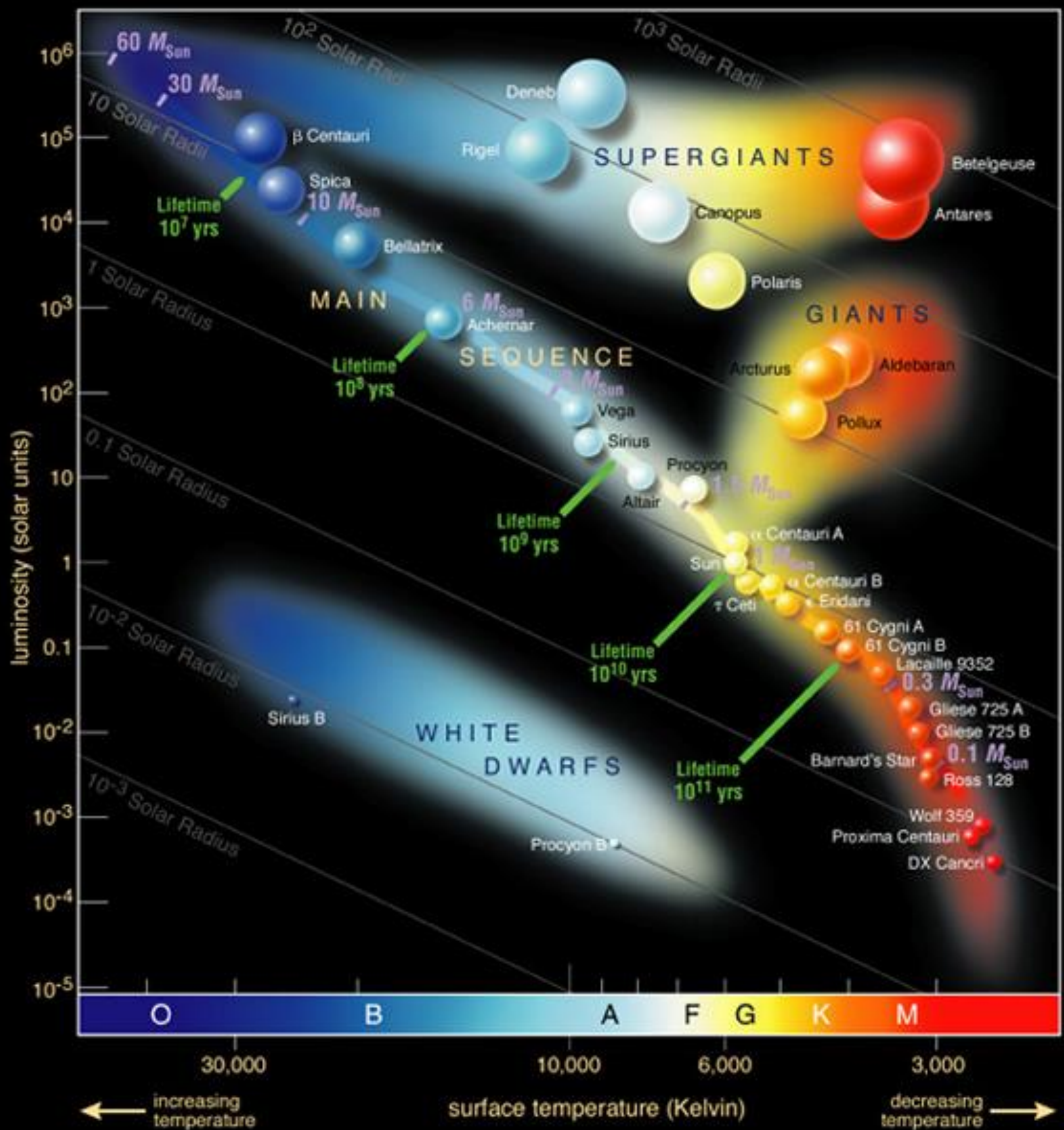


Credits: Grillmair et al. 2008

The smaller the star, the better

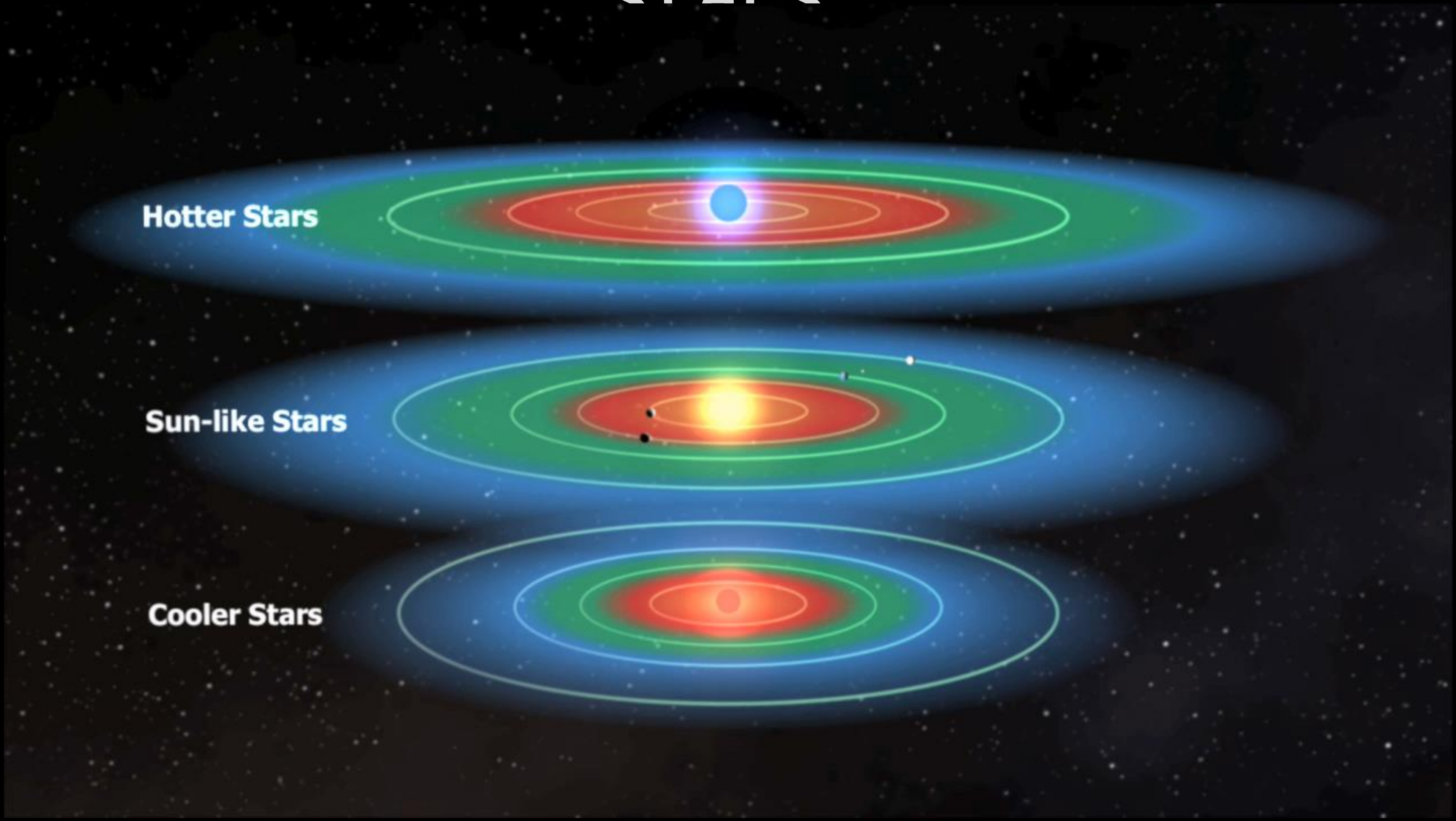


Low-mass stars are small and cold



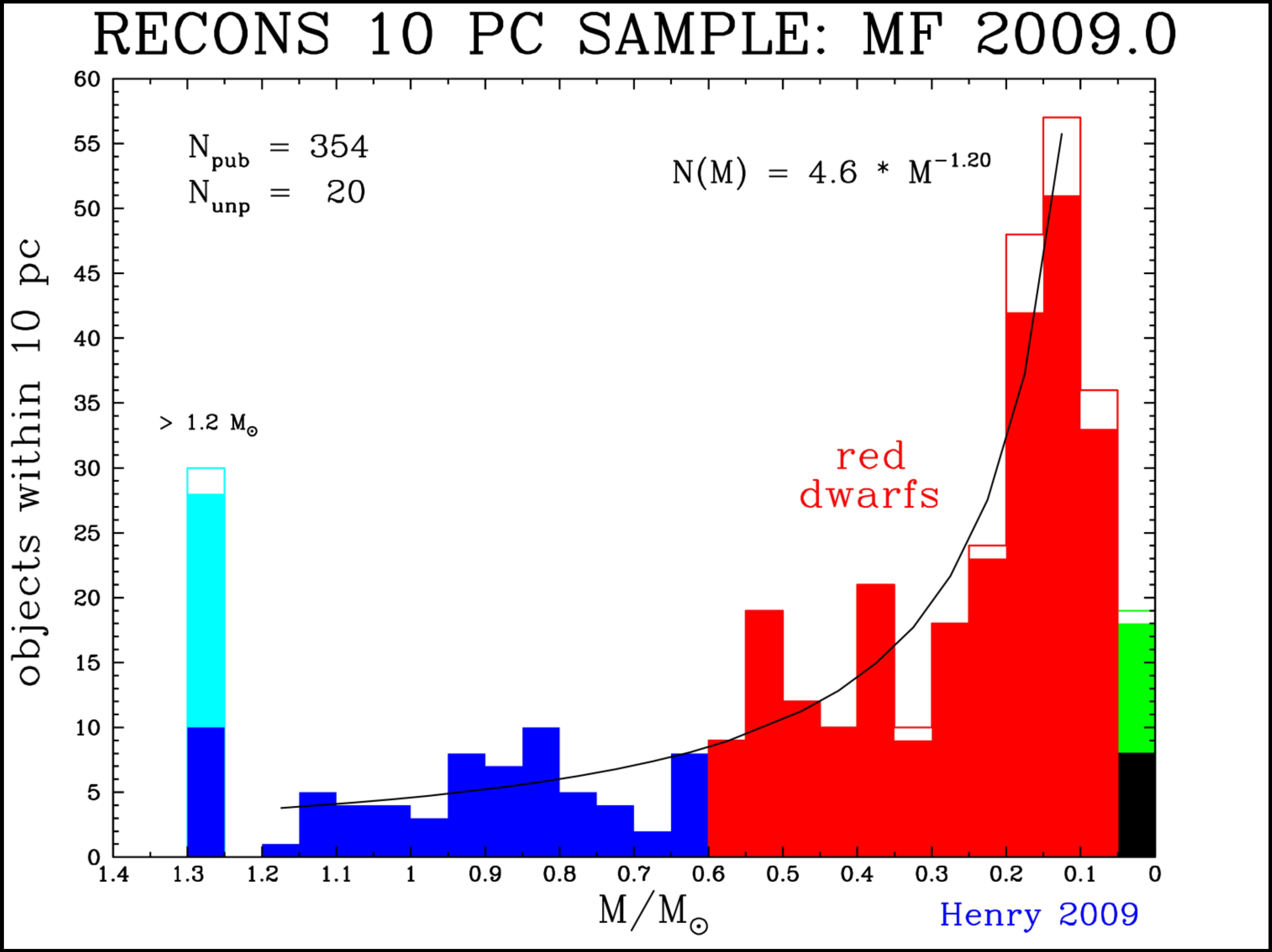
Credits: ESO

The habitable zone of hot and cold stars



Credits: NASA

Most stars are smaller and colder



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Search for habitable Planets ECLipsing ULtra-cOOl Stars

What are « ultra-cool stars »?

Ultracool dwarfs: $T_{eff} < 2700K$,

(Kirckpatrick er al. 1995).

Mix of **stars** + brown dwarfs

Ultracool (dwarf) stars

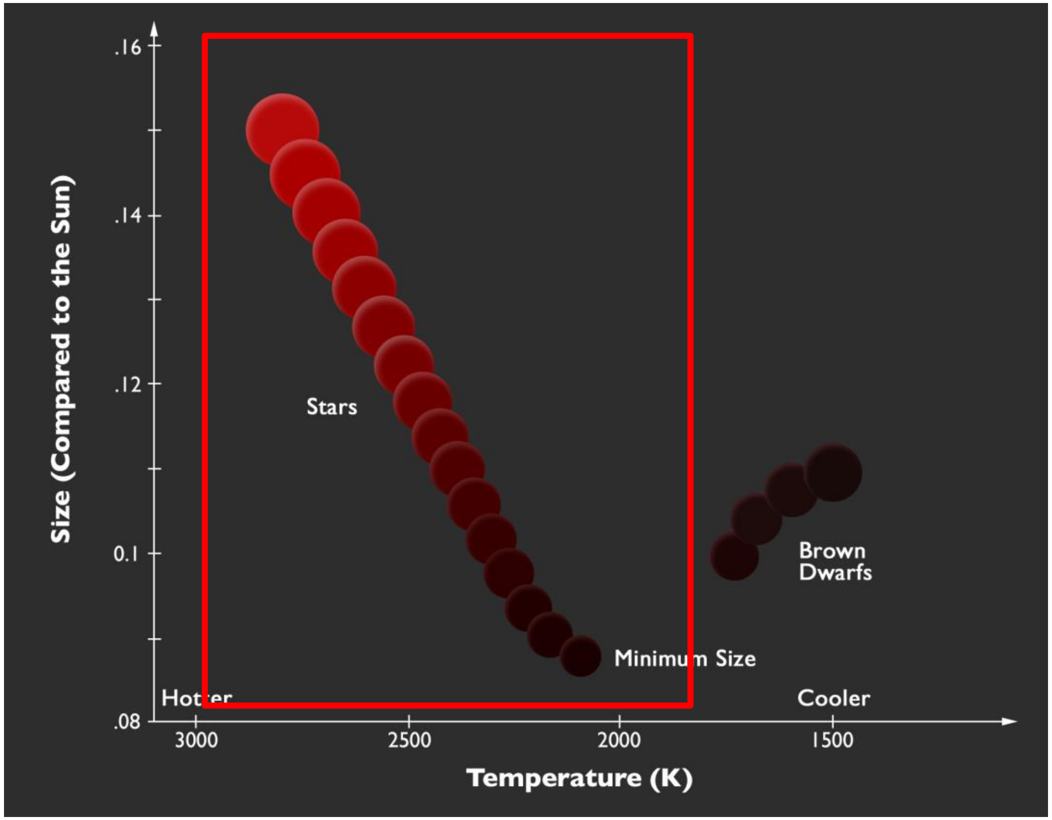
T_{eff}: 2000 to 2700 K

Mass: 0.075 to 0.1 $M_{\odot}$

Size: 0.08 to 0.15 $R_{\odot}$

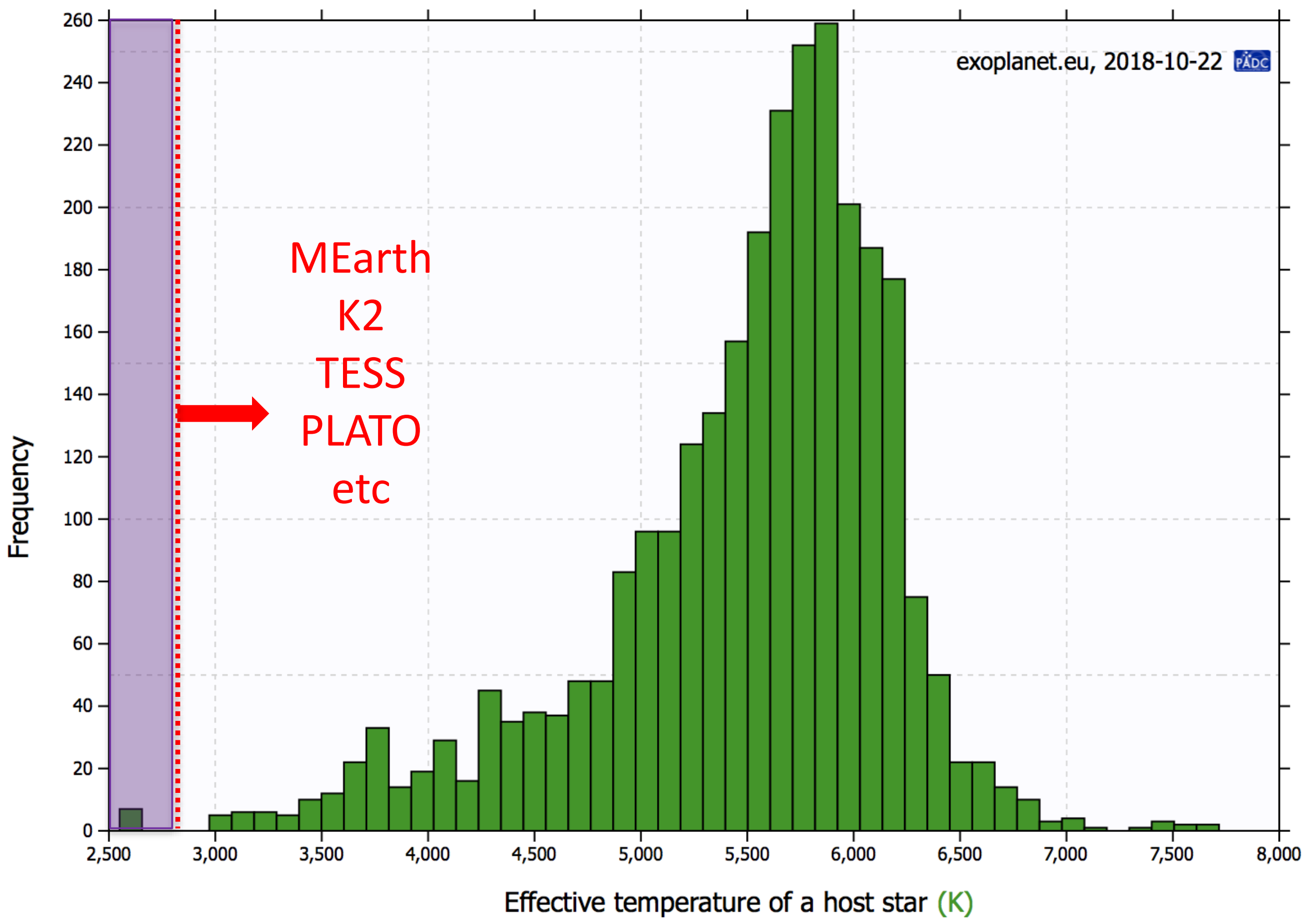
Luminosity: 0.01 to 0.1% $L_{\odot}$

Main-sequence lifetime: >1000 Gyrs



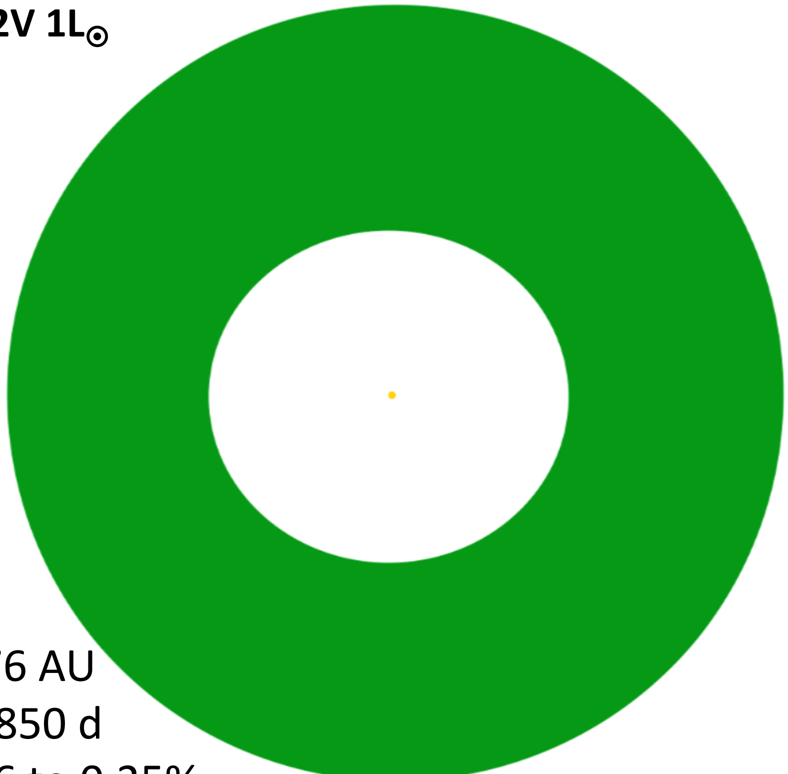
Dieterich et al. (2014)

Territory uncharted by transit searches



Habitable zone is VERY close to the star

G2V 1$L_\odot$



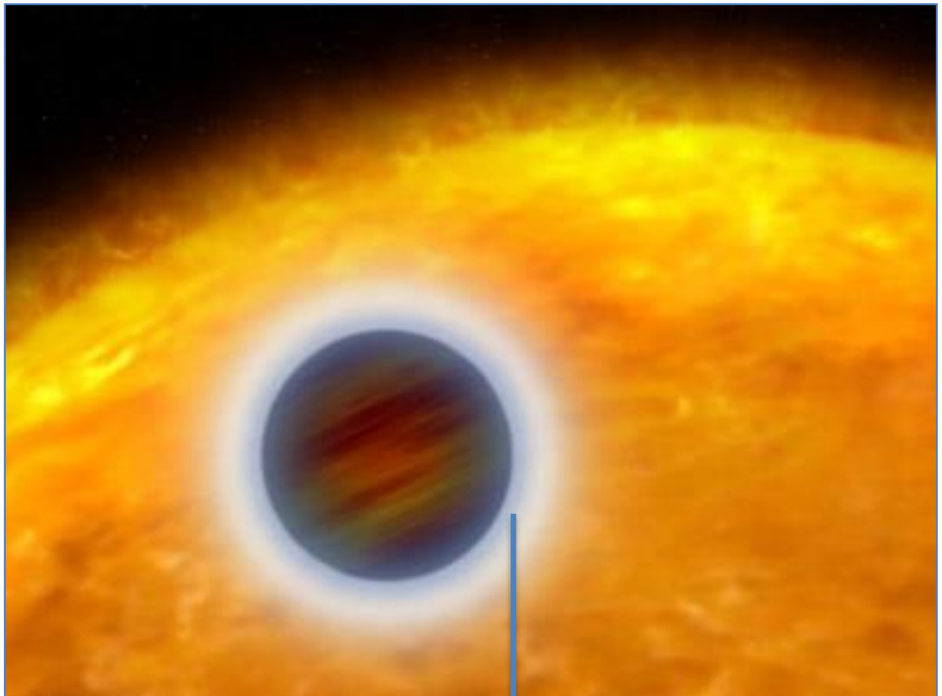
0.75 to 1.76 AU
P = 235 to 850 d
Prob. transit = 0.6 to 0.25%

L2V
0.0001$L_\odot$

0.008 to 0.023 AU
P = 1 to 5 d
Prob. transit = 4.5 to 1.6 %

HZ limits from Kopparapu et al. (2013) – optimistic case

Infrared transit transmission spectroscopy



Amplitude of the signal and SNR?

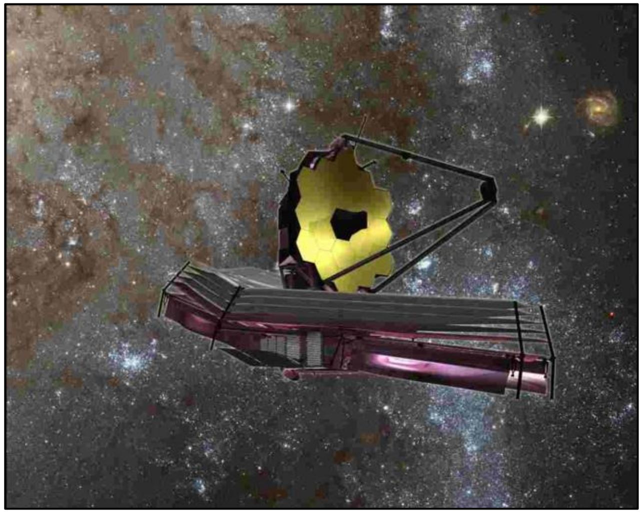
(e.g. Winn 2010)

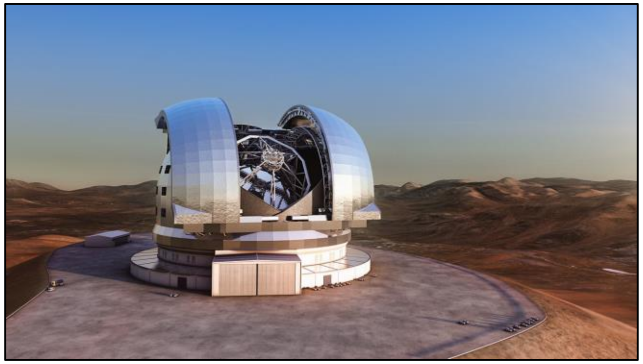
N_H = number of scale heights
g_p = planet surface gravity
R_p = planet radius
μ_p = atmo. mean molecular mass (amu)
= 29 for Earth-like composition,
T_p = planet equilibrium temperature
R_* = star radius
k_b = Boltzmann constant
C = constant
W_{tr} = transit duration
N_{tr} = number of transits

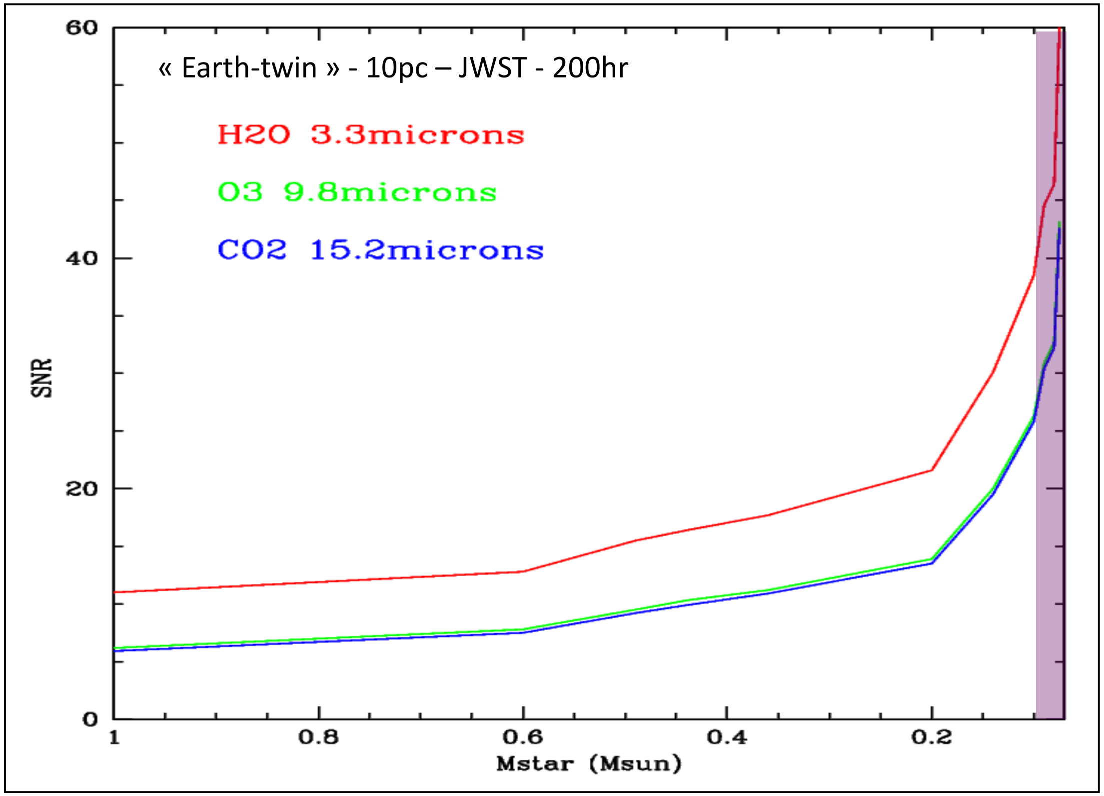
$$\Delta\delta = \frac{2 N_H H_p R_p}{R_\star^2}, \text{ where } H_p = \frac{k_b T_p}{\mu_p g_p}$$

$$SNR = C \times \Delta\delta \times \sqrt{10^{-K_*/2.5}} \times \sqrt{W_{tr} N_{tr}}$$

Atmospheric characterization of temperate Earth-sized planets



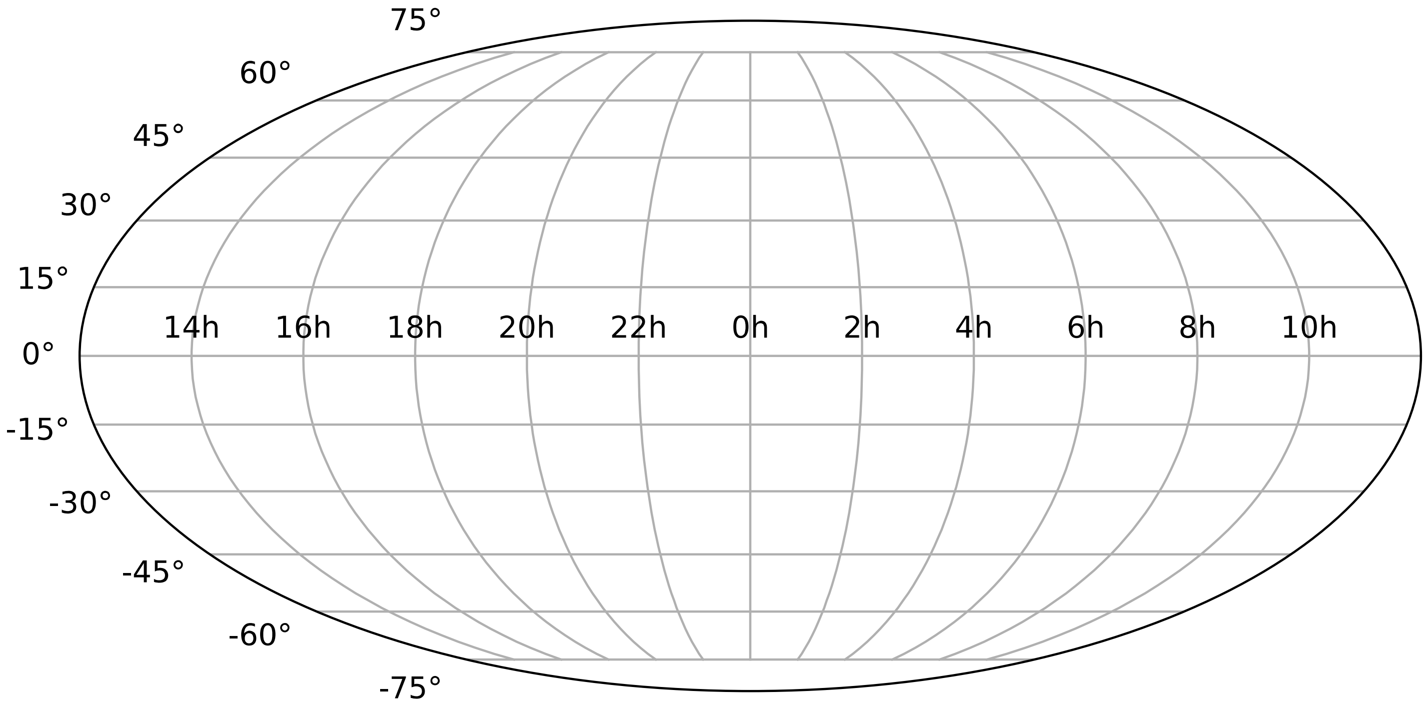




From Kaltenegger & Traub (2009)

Best targets: ~1000 ultra-cool stars with Kmag < 12.5

SPECULOOS targets: spatial distribution (Aitoff projection)



Adam Burgasser

SPECULOOS

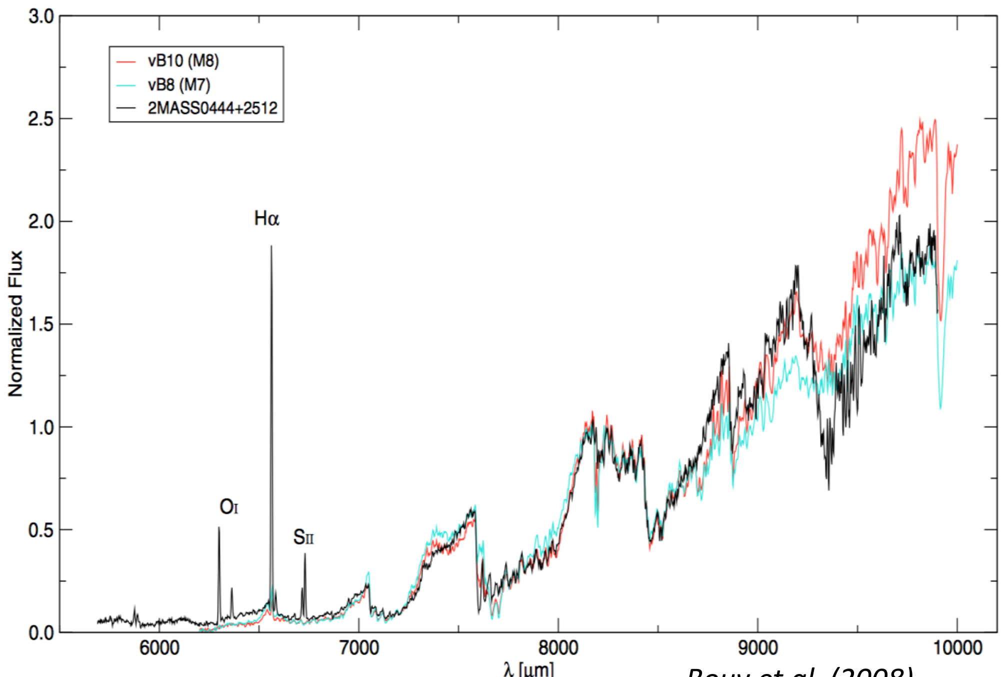
Search for habitable Planets EClipsing ULtra-cOOl Stars

SPECULOOS: basic concept

Targets: ~1000 ultra-cool dwarfs (Kmag < 12.5, 100 L-type brown dwarfs) → Targeted survey

Short transits: down to 10 min → Continuous monitoring

Targets' emission peaks around 1.1 µm → Near-IR optimized detectors



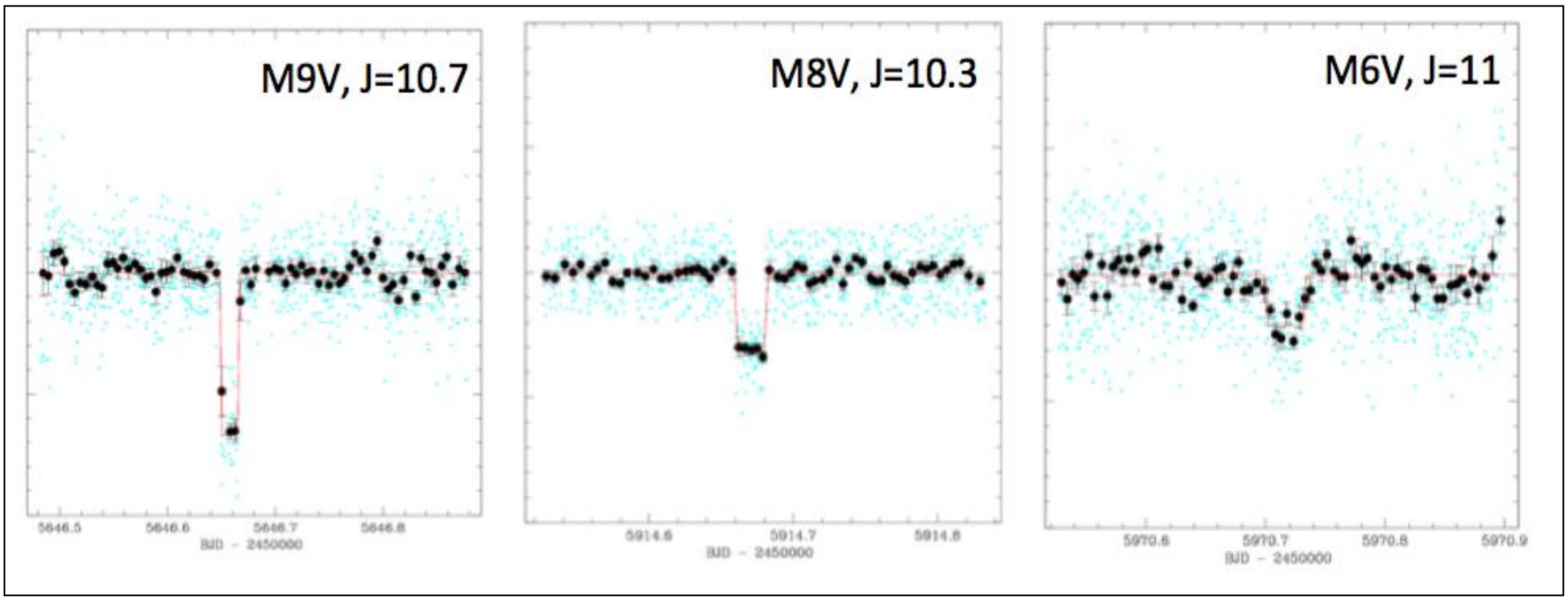
Bouy et al. (2008)

SPECULOOS: basic concept

Targets: ~1000 ultra-cool dwarfs (Kmag < 12.5, 100 L-type brown dwarfs)	→ Targeted survey
Short transits: down to 10 min	→ Continuous monitoring
Targets' emission peaks around 1.1 µm	→ Near-IR optimized CCDs
Telescope sizes: detection of the unique transit of an Earth-sized planet	→ Kmag < 11: 60cm Kmag < 12: 1m Kmag 12-12.5: 1.5m
Excellent sites: good transparency & seeing, low humidity	→ South: Chile North: Canary Islands/Mexico/Morocco
Efficient exploration of the habitable zone	→ 1 longitude is OK Monitoring duration optimized to each target

First step: prototype survey

- Since 2011, prototype survey with TRAPPIST 60cm robotic telescope at ESO La Silla
- Targets: 50 brightest southern ultra-cool dwarfs + 30 M6-type stars (e.g. Proxima)



Detection limits from 0.6 to 1.1 R_{earth}

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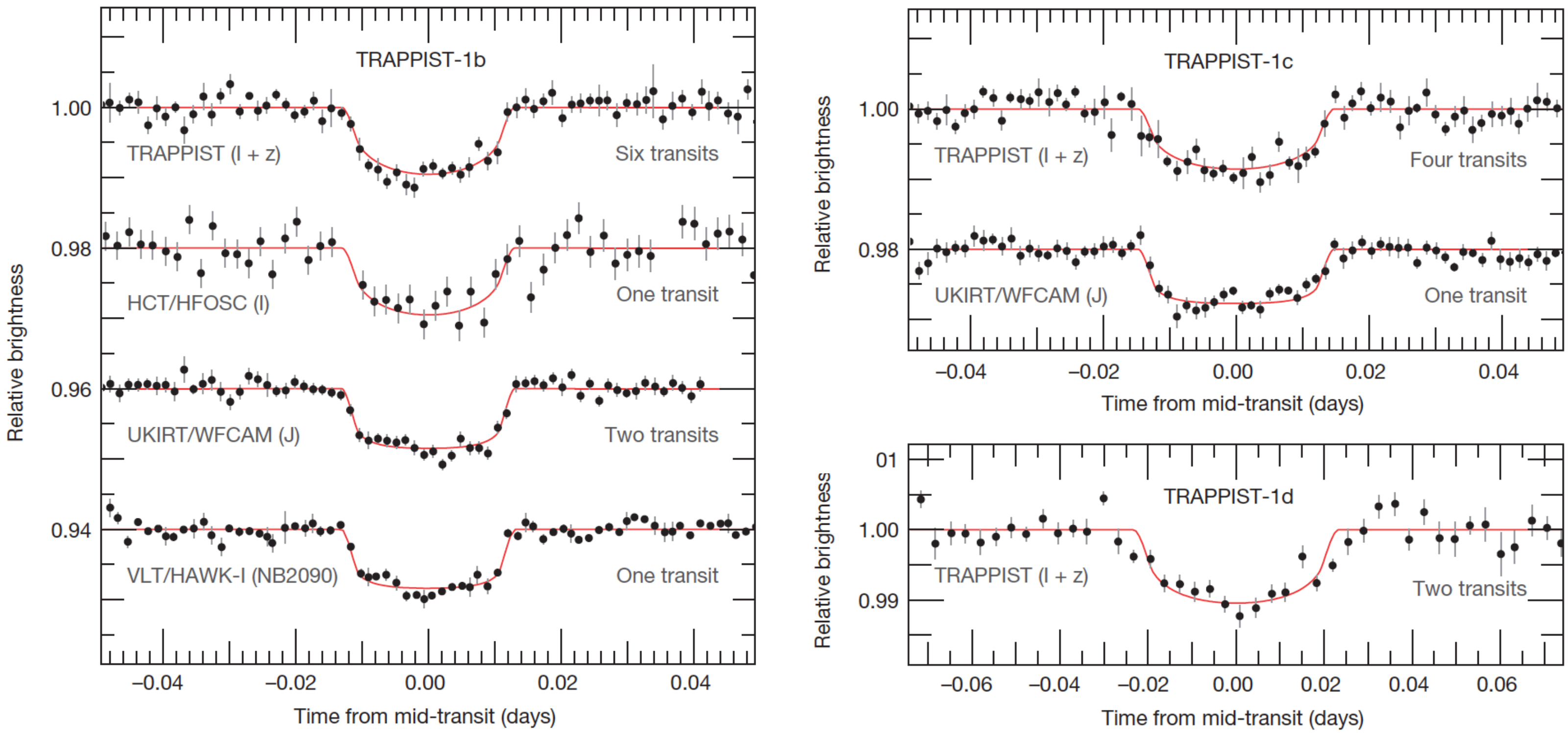
Search for habitable Planets EClipsing ULtra-cOOl Stars

TRAPPIST-1

Ultra-cool stars do host compact systems of Earth-sized planets!

3 Earth-sized planets with P=1.5, 2.4 and [4.5:72.8]d transiting a M8V star at 12 parsec

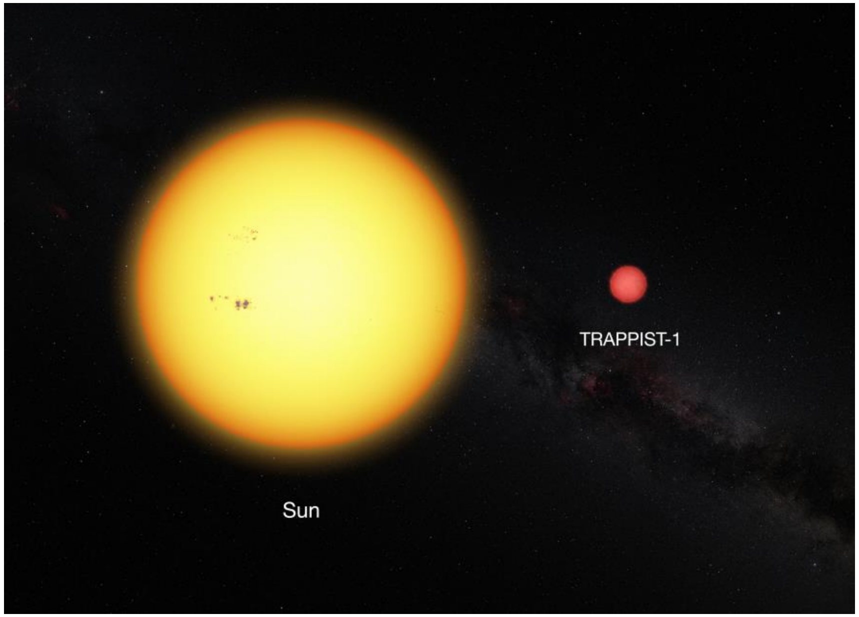


Gillon et al. (2016)

TRAPPIST-1

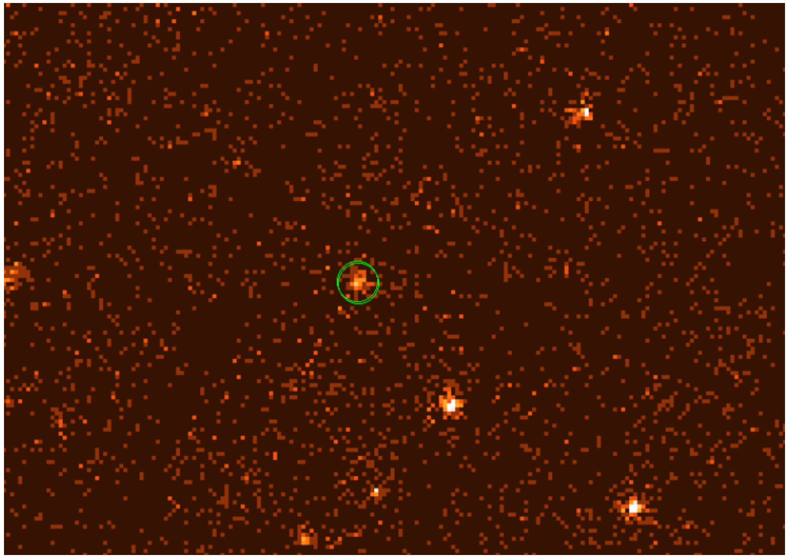
Host star: discovered in 2000 by *Gizis et al*. V=18.8, I=14.0, J=11.3, >500 Myr

$0.089 \pm 0.006\ M_{\odot}$, $T_{eff} = 2516 \pm 41$ K, [Fe/H] = $+0.04 \pm 0.08$



$0.121 \pm 0.003\ R_{\odot}$, $0.00052 \pm 0.00002\ L_{\odot}$

Van Grootel et al. (2018)

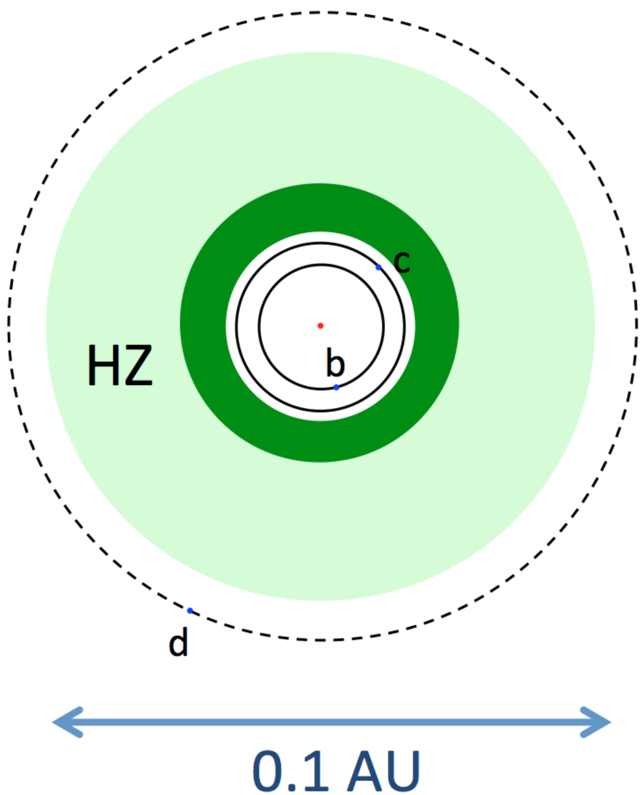


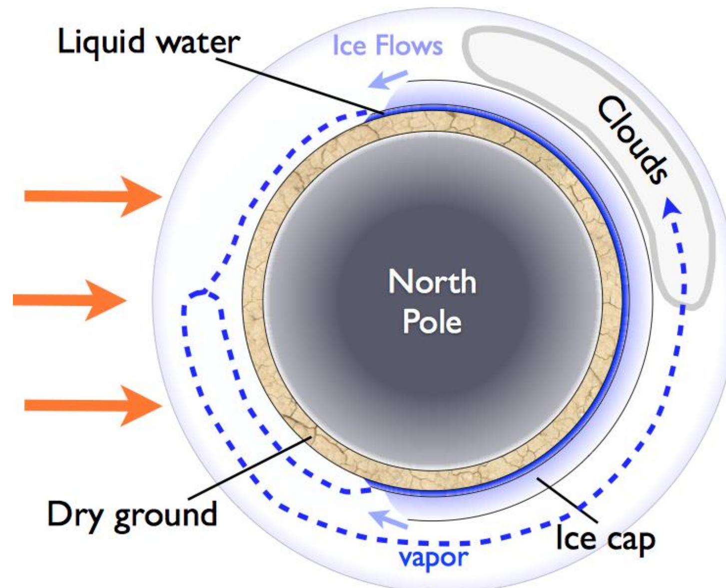
XMM-*Newton*: strong X-ray emission, $L_X / L_{bol} = 2 - 4\ 10^{-4}$

Wheatley et al. (2016)

TRAPPIST-1

Three Earth-sized planets close or within the habitable zone of their star





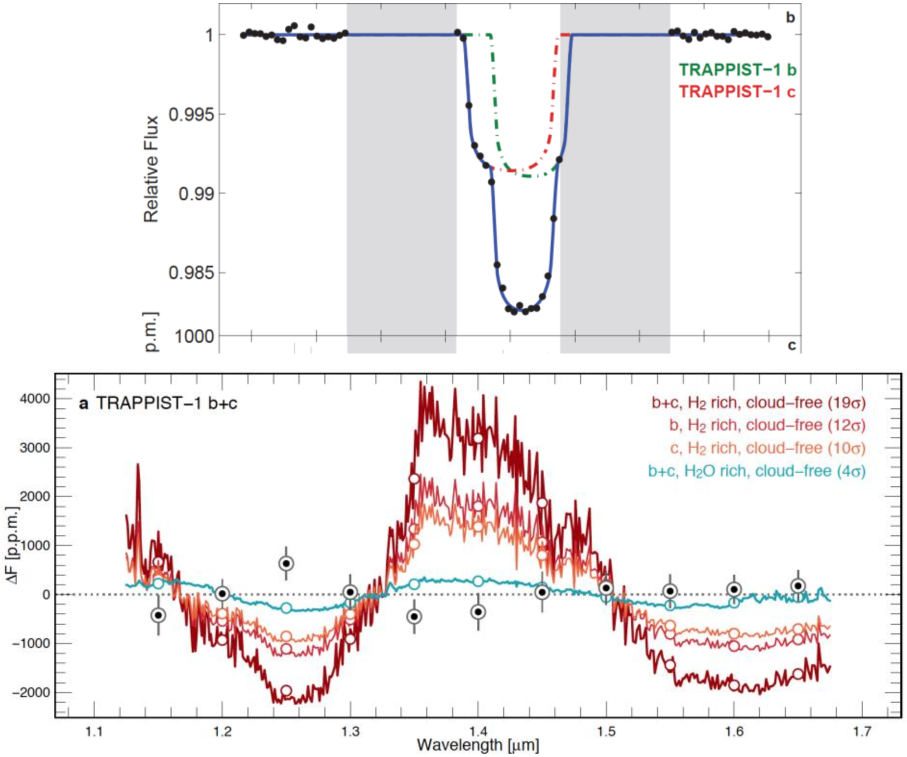
Leconte et al. (2013)

Kopparapu et al. (2013) **Yang, Cowan & Abbot et al. (2013)**

TRAPPIST-1

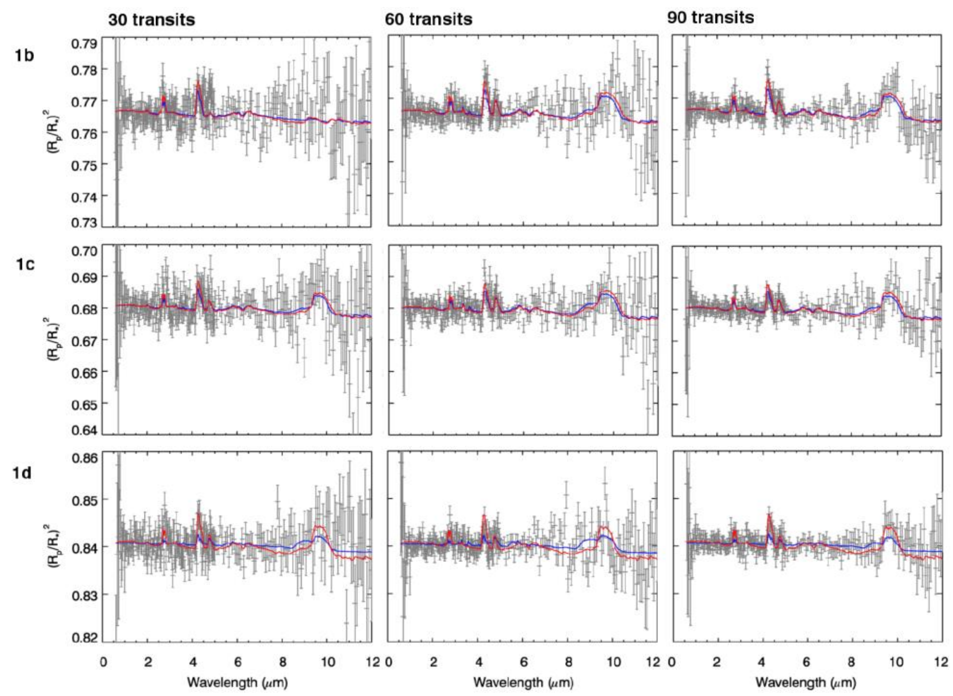
A first opportunity to study the atmosphere of temperate Earth-sized planets

First with HST



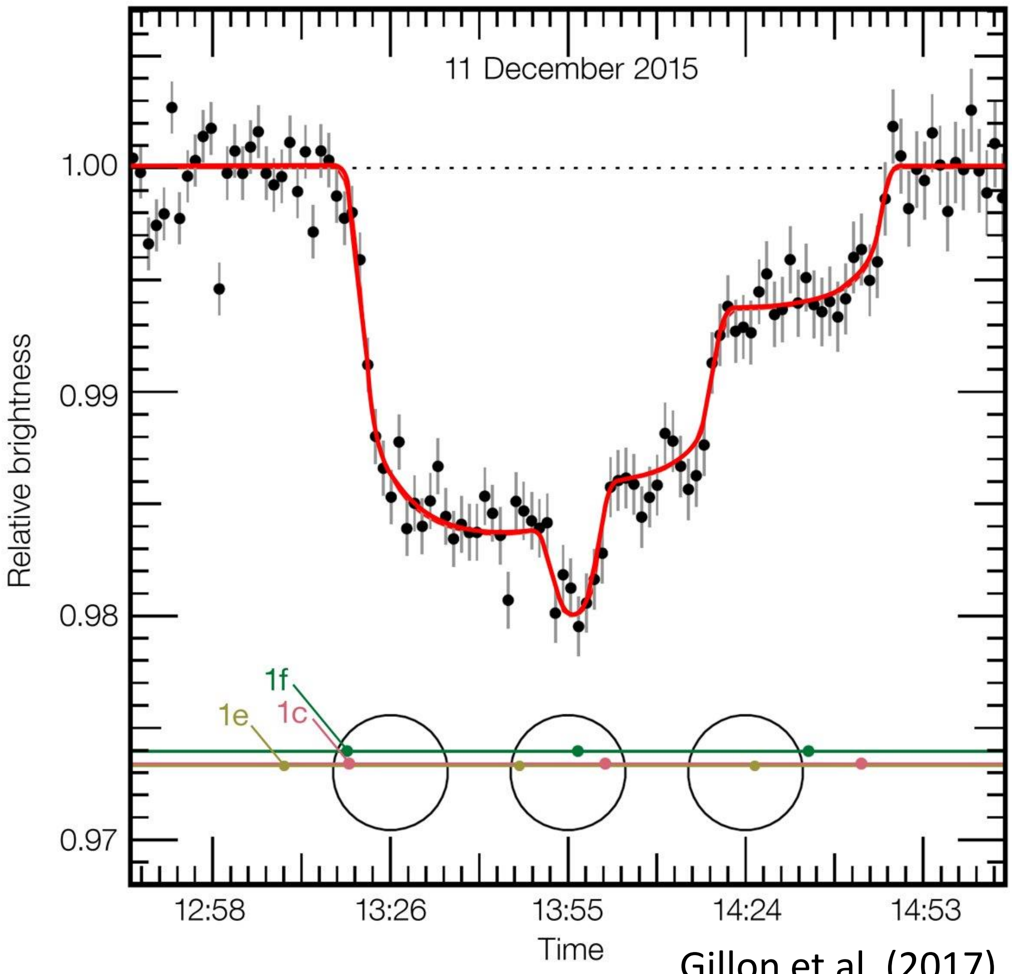
de Wit at al. (2016)

…and then with JWST, ELTs, etc



Barstow & Irwin (2016)

2016: the TRAPPIST-1d mystery…



Gillon et al. (2017)

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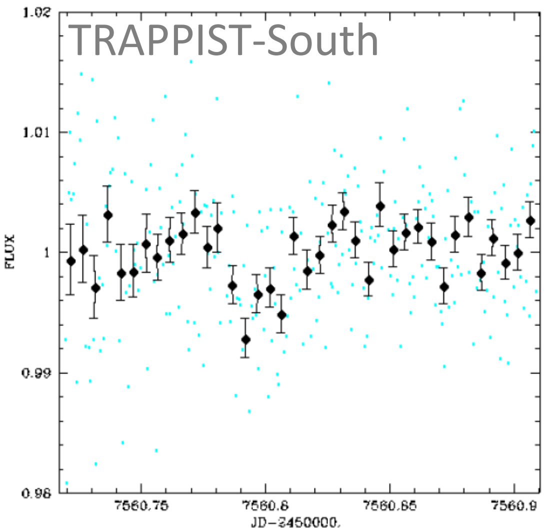
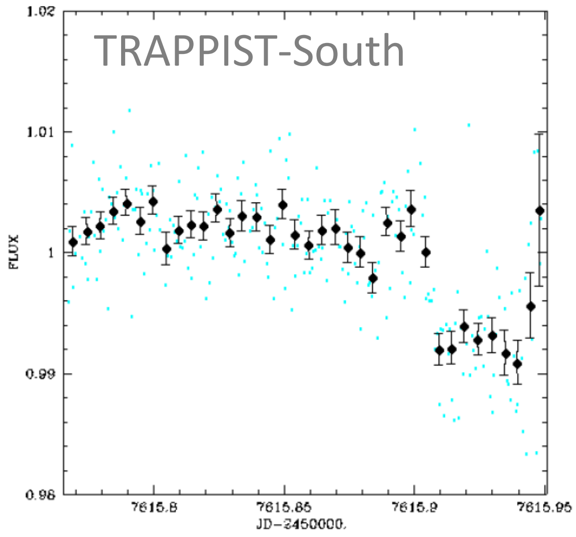
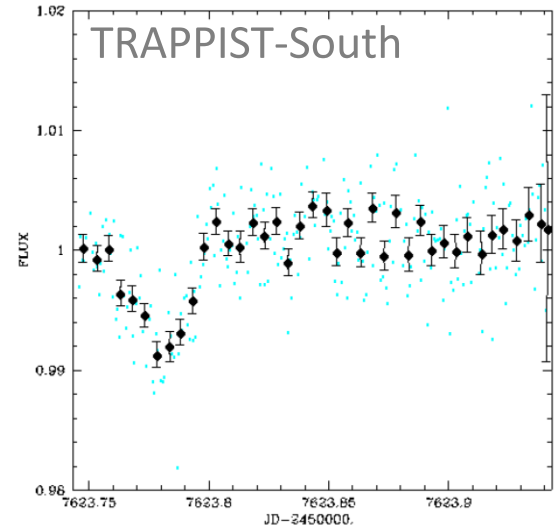
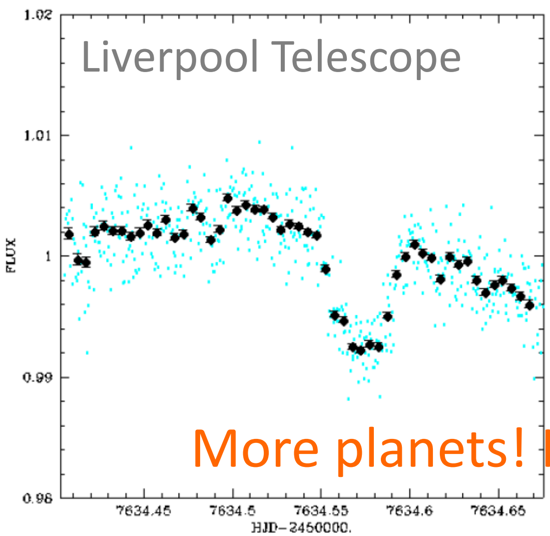
Search for habitable Planets EClipsing ULtra-cOOl Stars

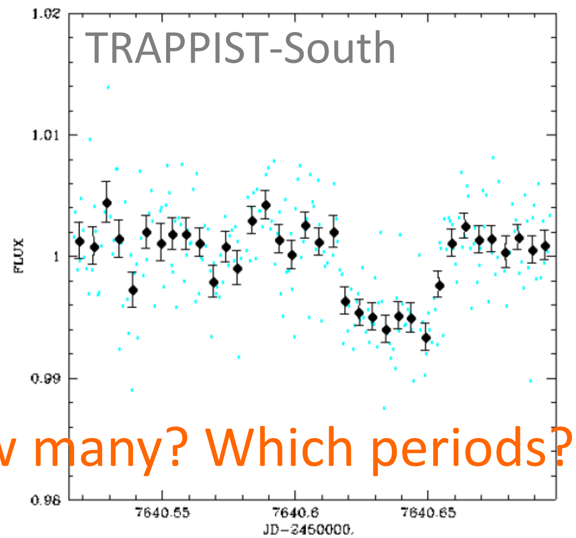
2016: intensive photometric follow-up from the ground

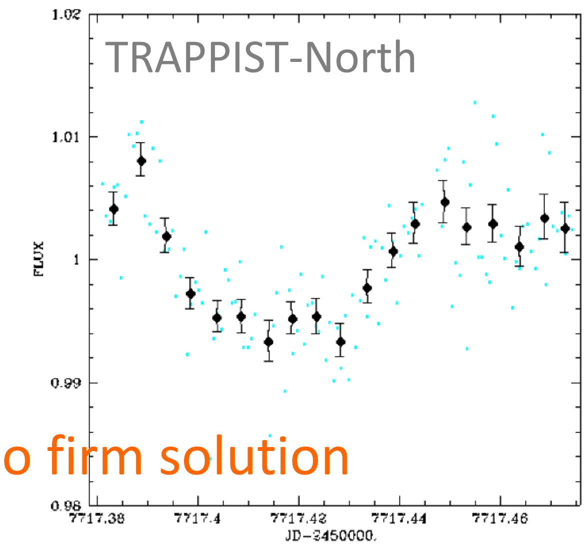






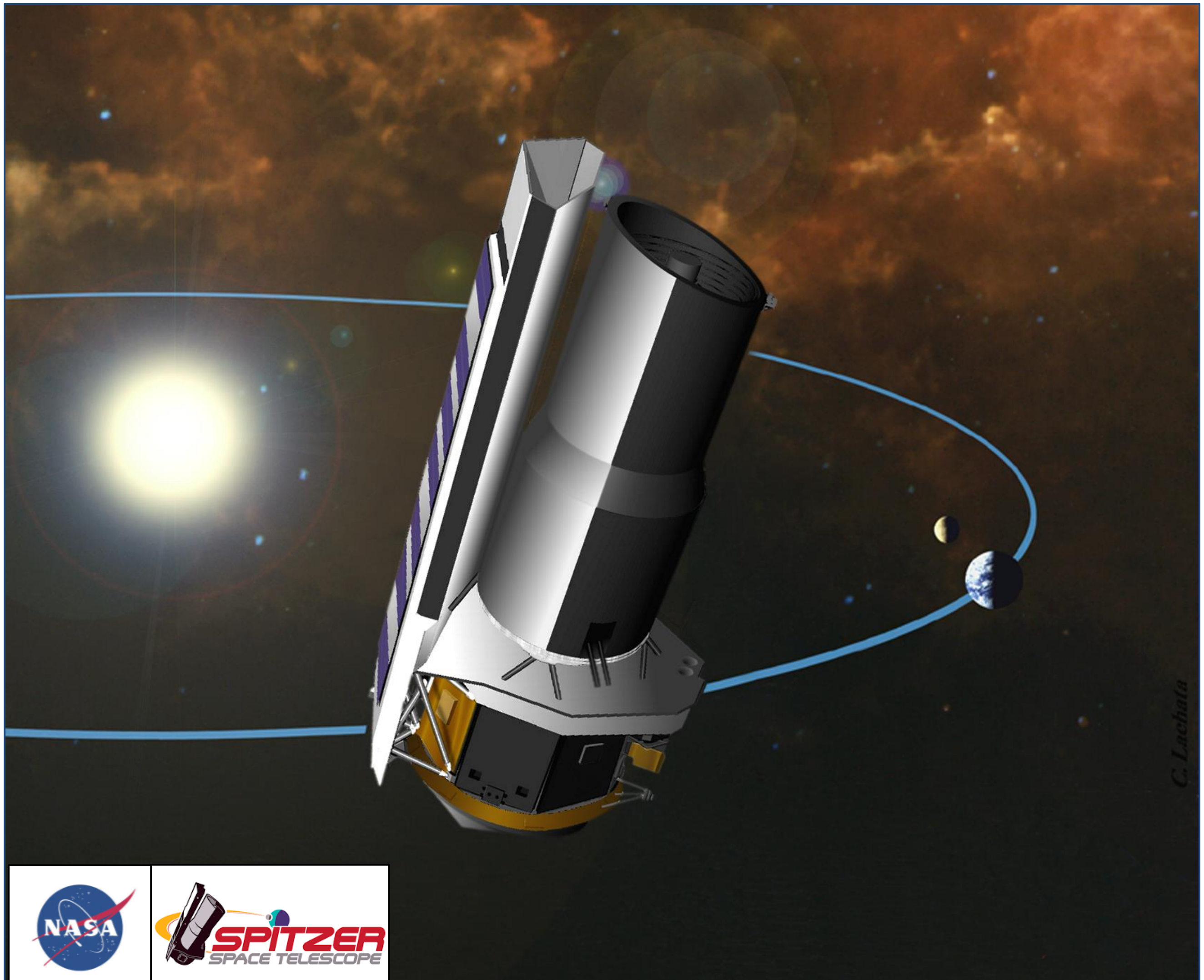




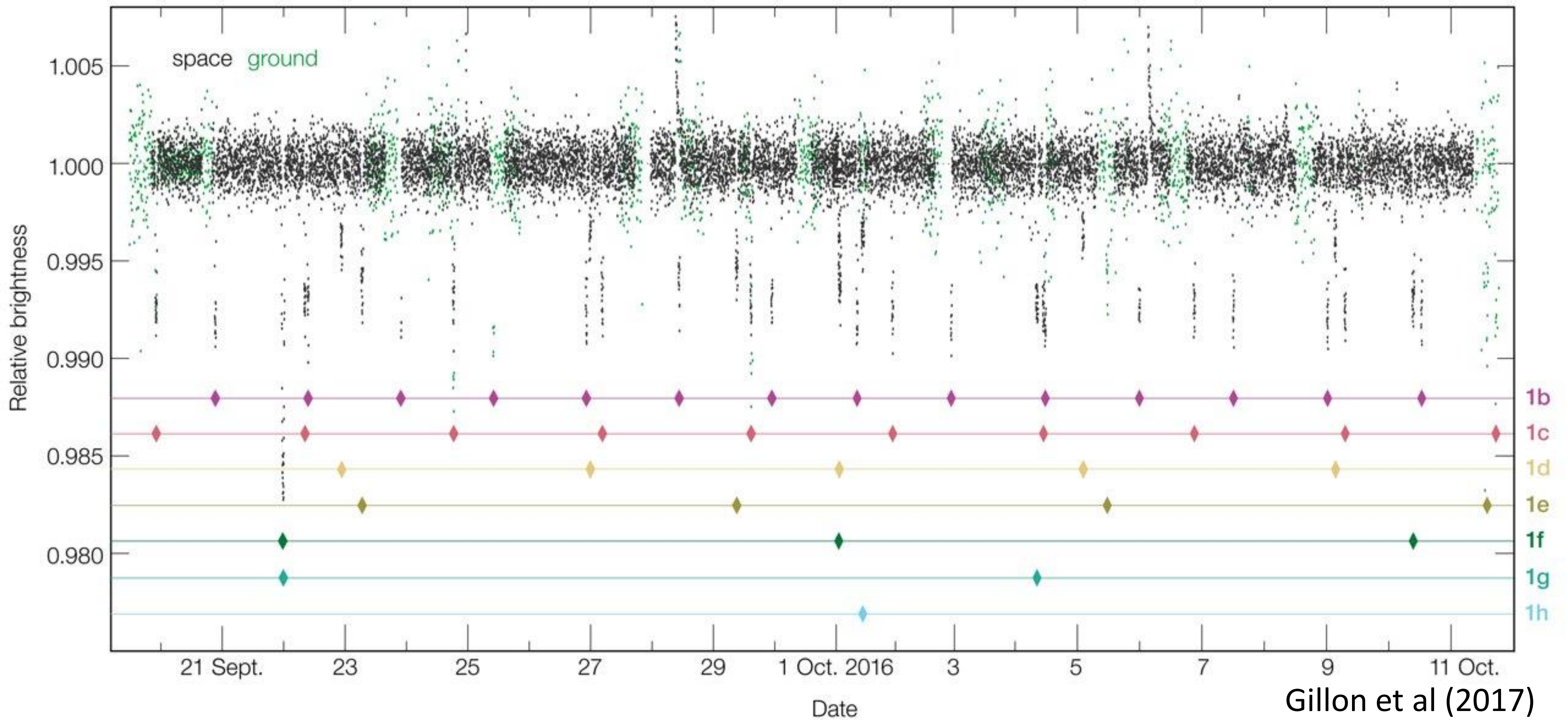


More planets! How many? Which periods? No firm solution

The perfect telescope for the job



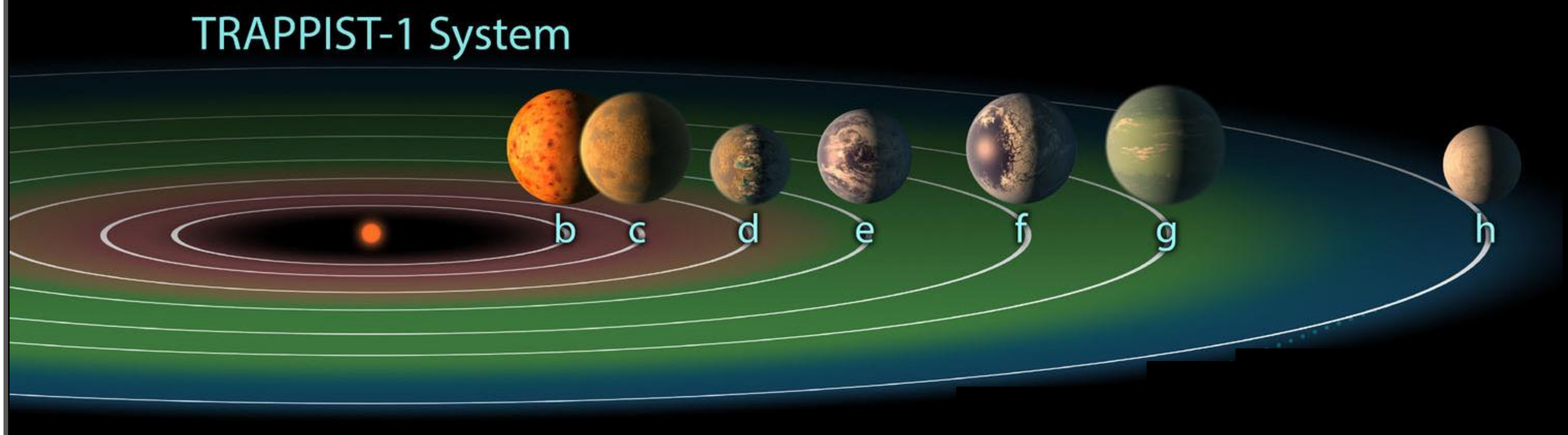
Fall 2016: Spitzer cracks the system!



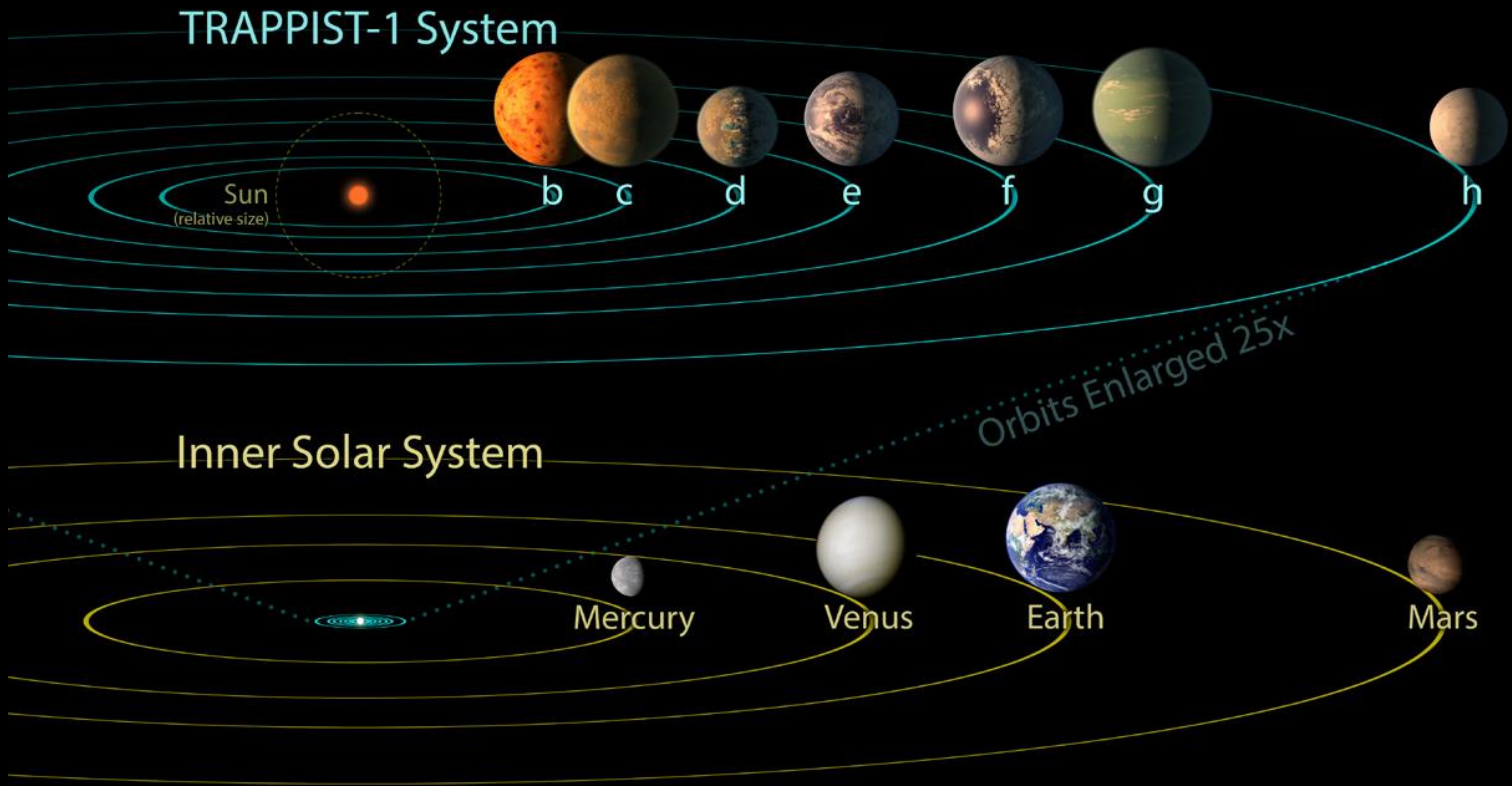
Gillon et al (2017)

20 days of nearly continuous observation… and 34 transits!

The seven wonders of TRAPPIST-1

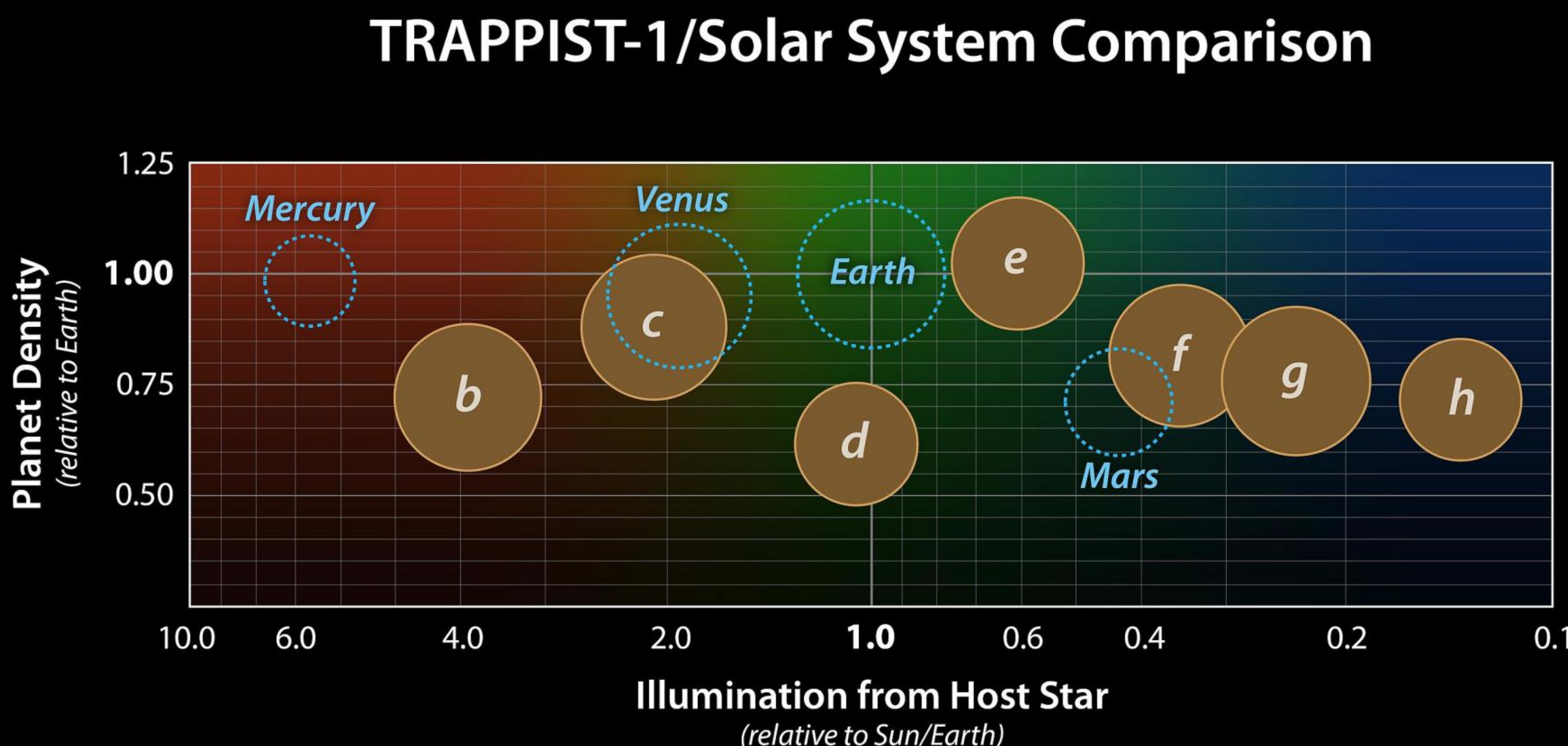


A very compact system



A 7-planets resonant chain

Water worlds?



Credits: R. Hurt/JPL/NASA

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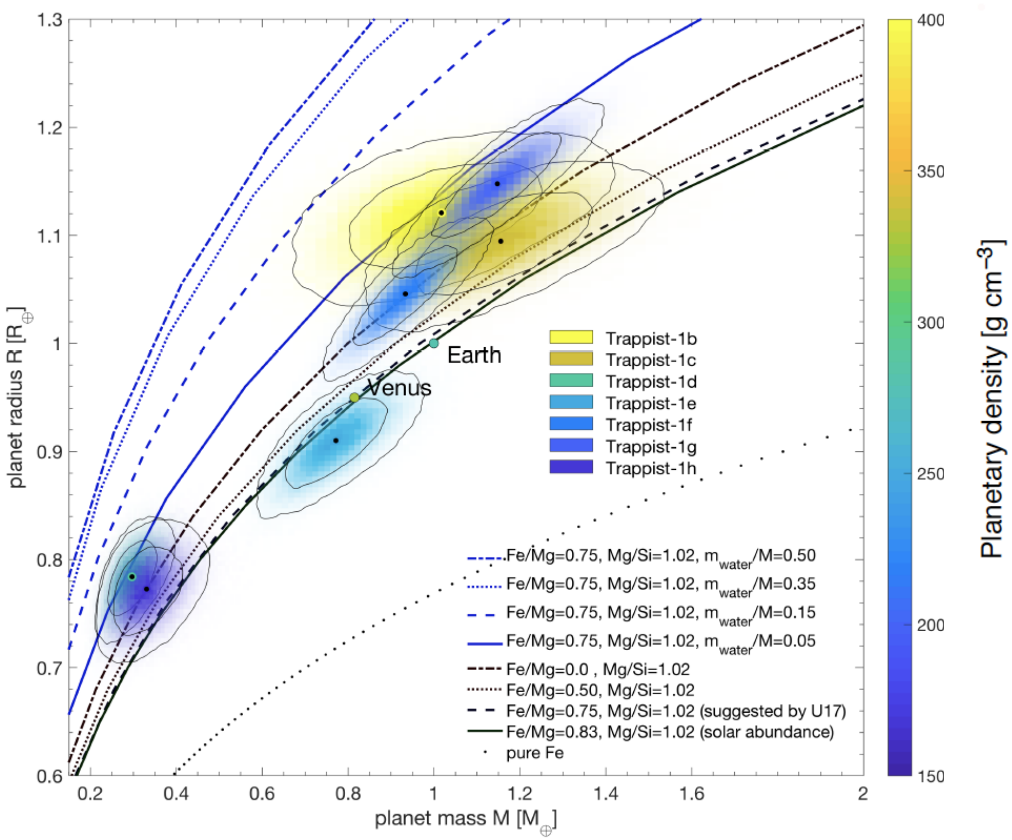
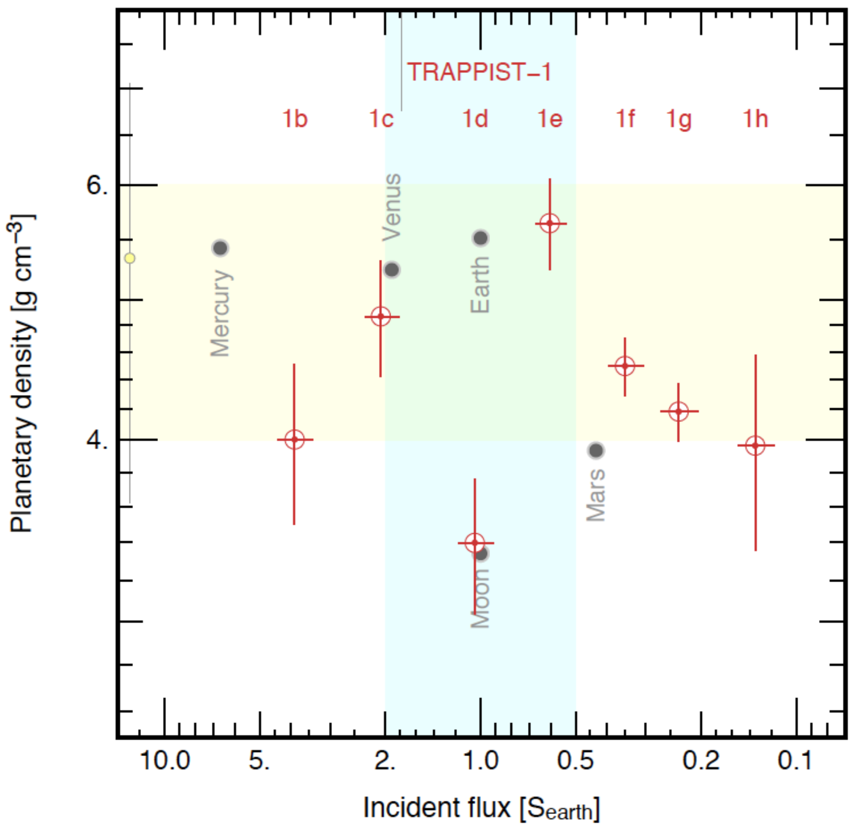
Search for habitable Planets EClipsing ULtra-cOOl Stars

The composition and irradiation of the TRAPPIST-1 planets

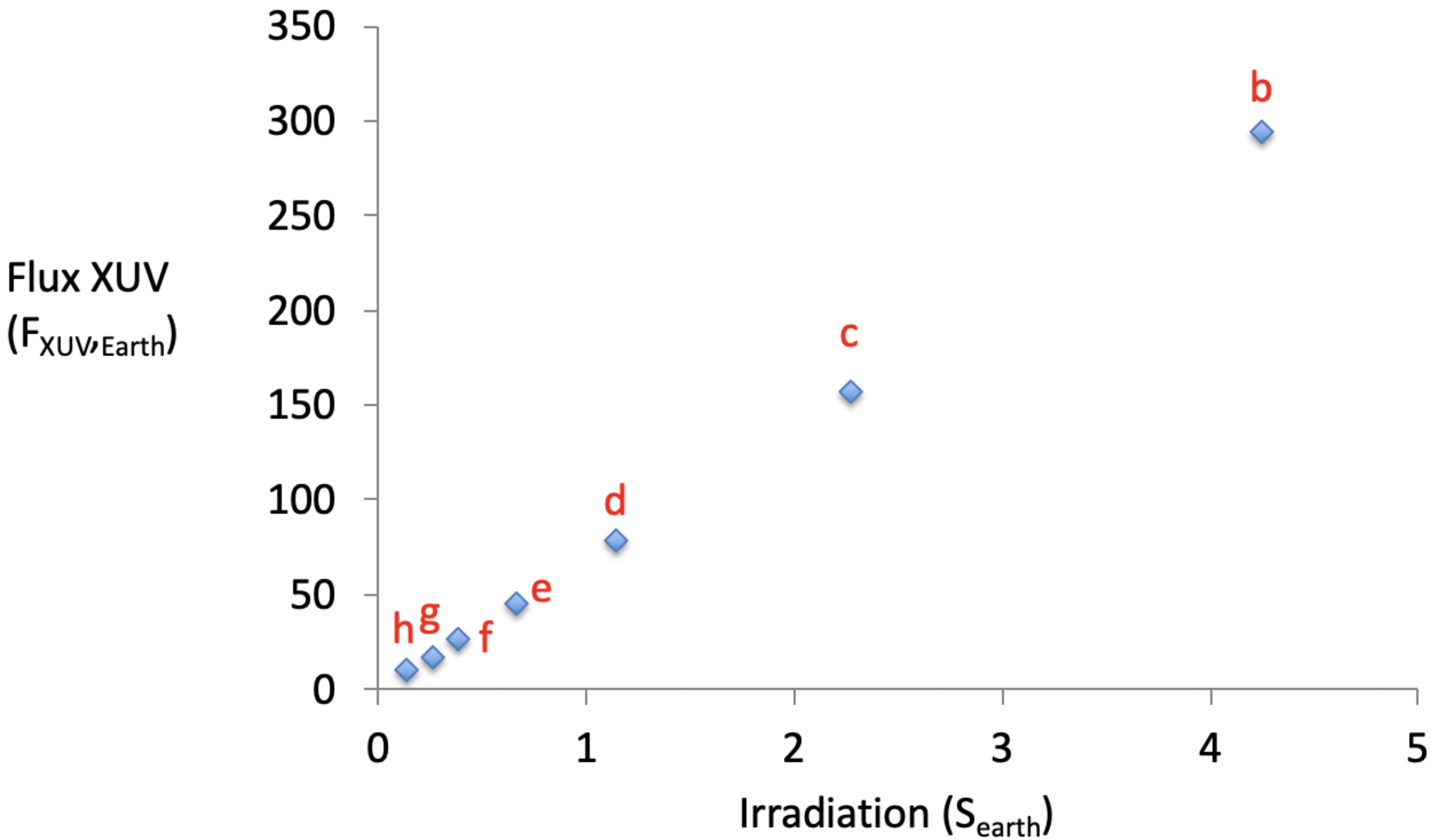




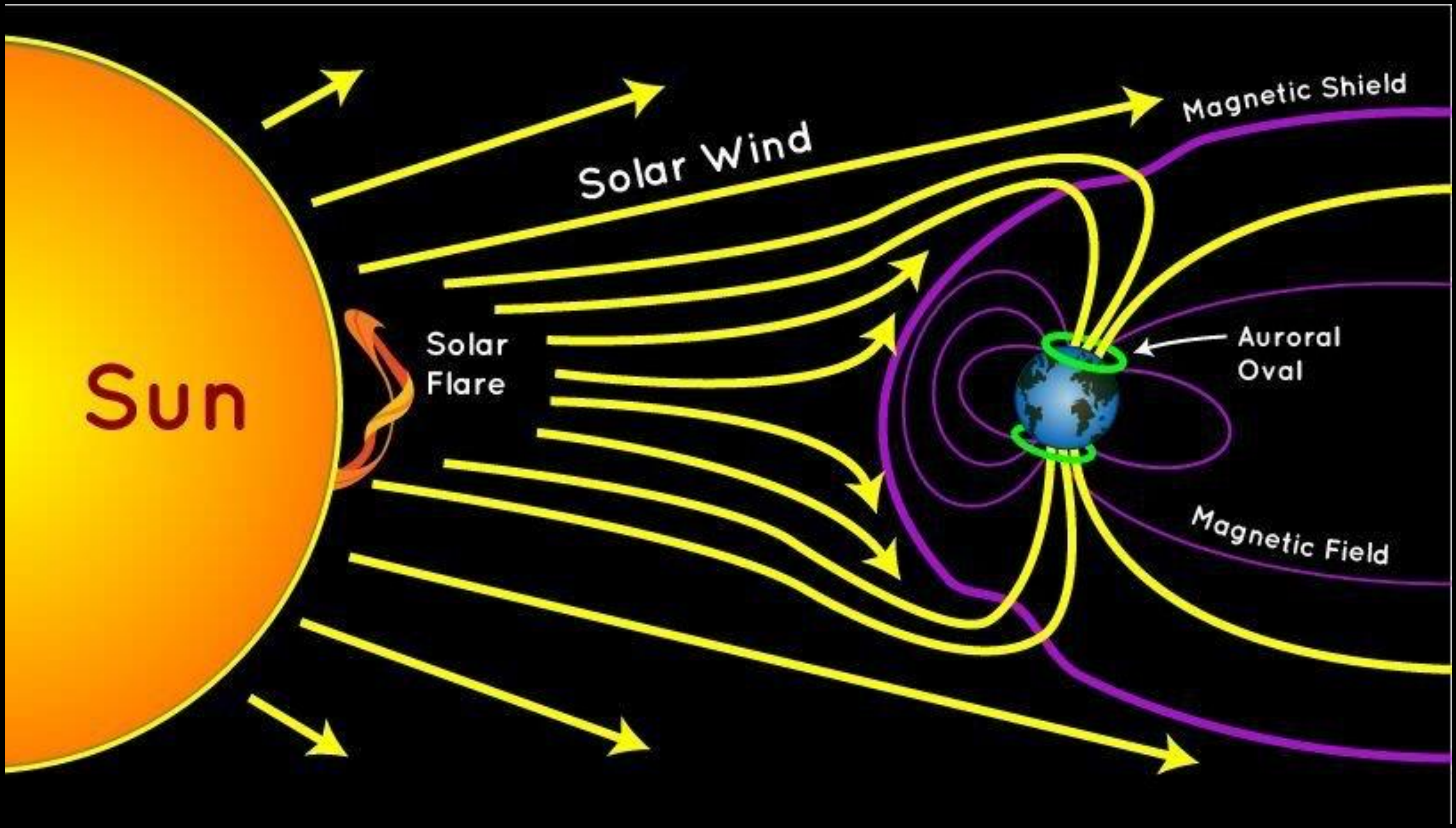
Grimm et al (2018)

The harsh environment of TRAPPIST-1

X and UV flux on the planets estimated from XMM-Newton (Wheatley et al. 2016) and HST/STIS (Bourrier et al. 2017) measurements.

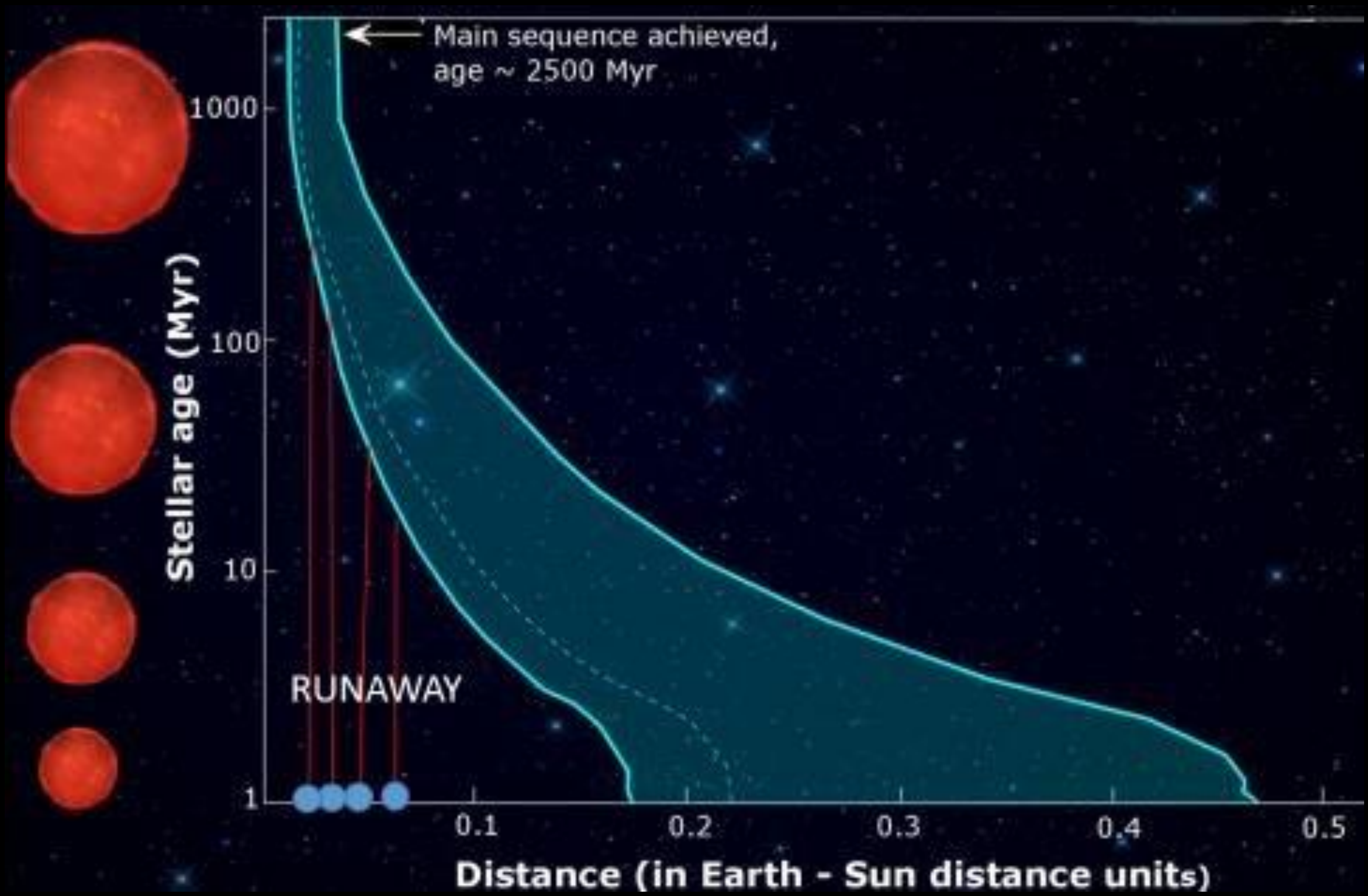


The harsh environment of TRAPPIST-1



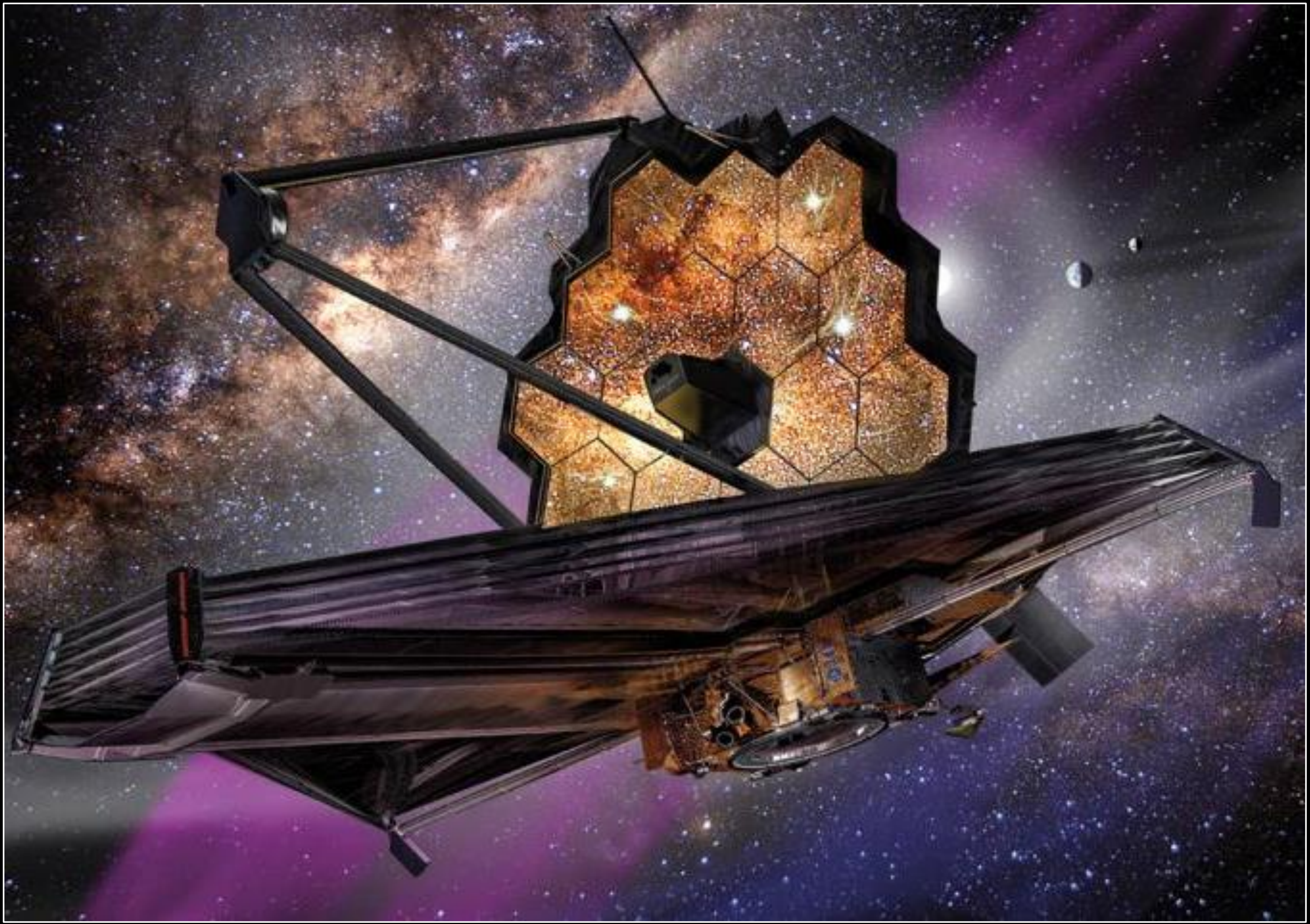
Credits: NASA

TRAPPIST-1 planets: cooked during >1 Gyrs



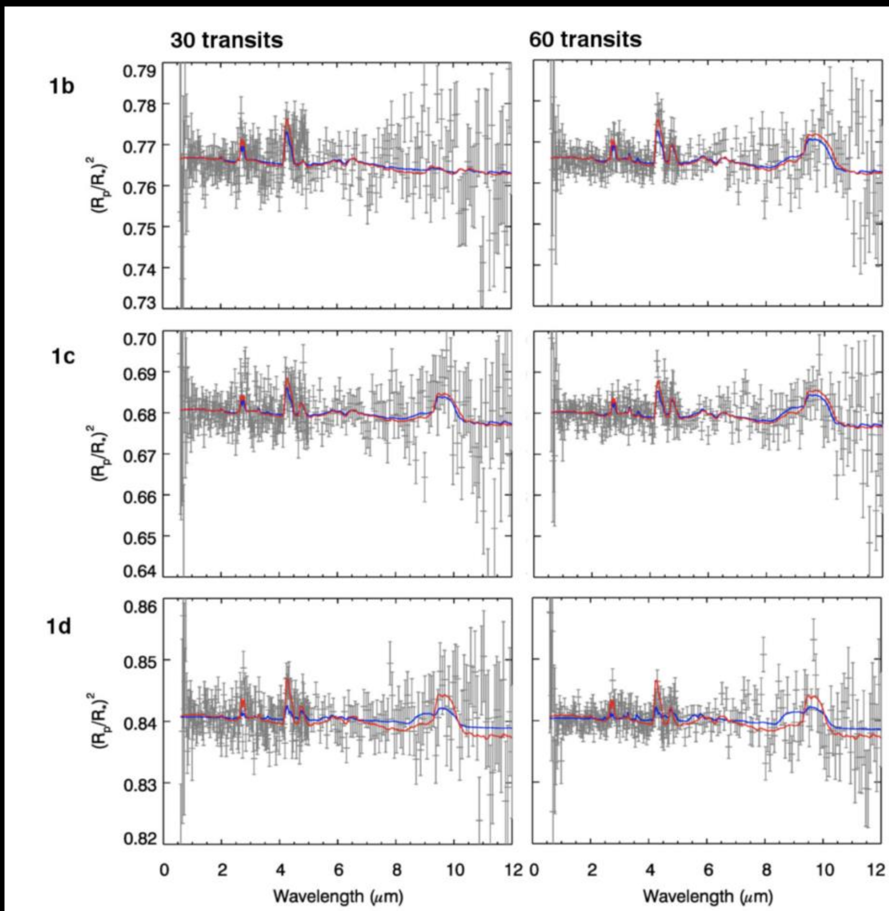
Credits: Mario-Ramirez & Kaltenegger 2017

2021 (?): the James Webb Space Telescope

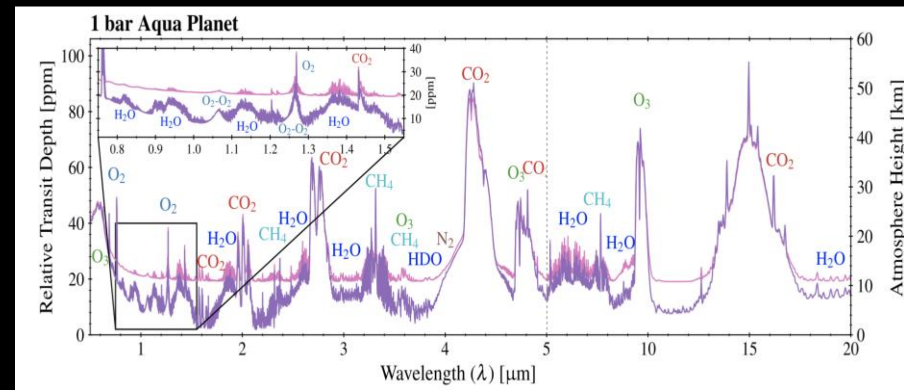


Credits: James Vaughan

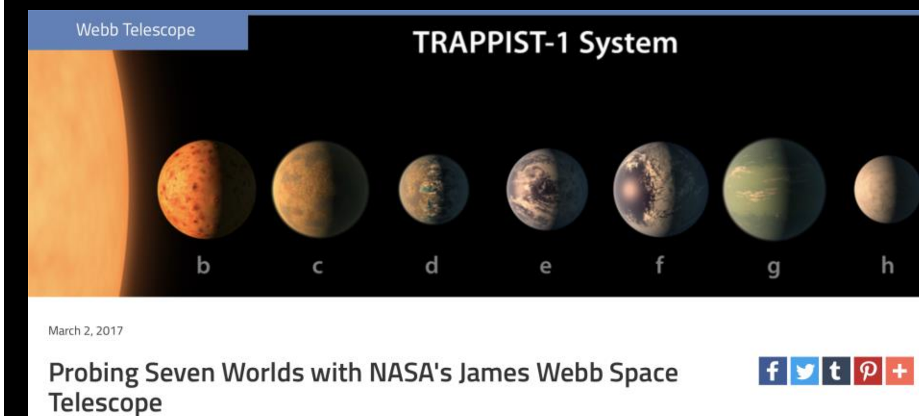
2019: James Webb Space Telescope



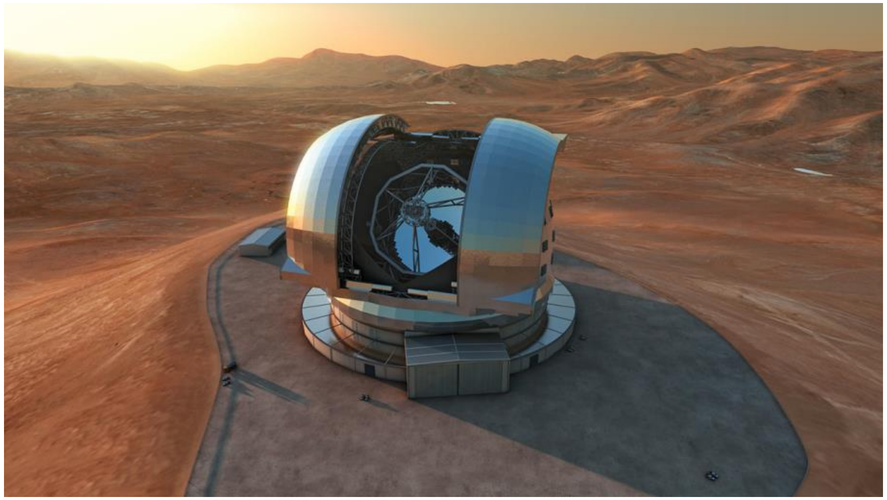
Barstow & Irwin 2016

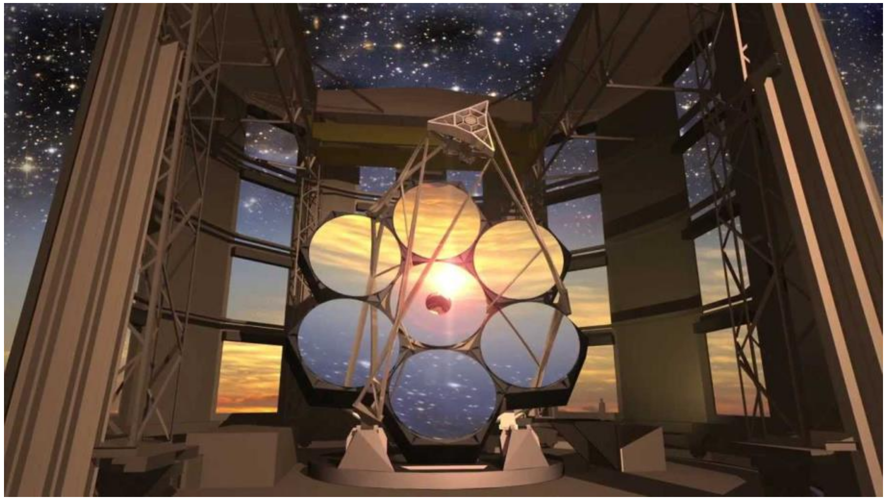


Lincowski et al.



High-resolution spectroscopy with upcoming giant telescopes?



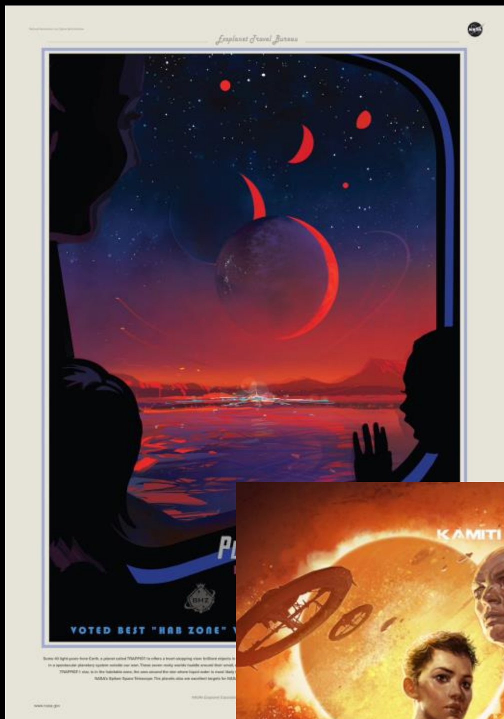


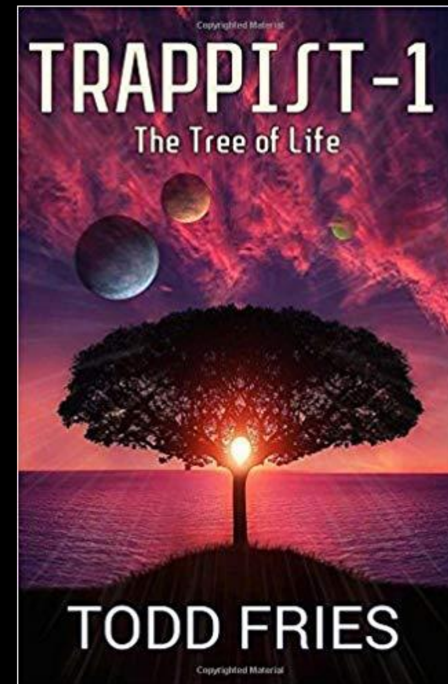
Feasibility Studies for the Detection of O_2 in an Earth-like Exoplanet

Florian Rodler
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
Institut de Cienciès de l'Espai (CSIC-IEEC), Campus UAB, Fac. Ciencies, C5 p2, 08193 Barcelona, Spain
and

Mercedes López-Morales
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA

TRAPPIST-1: between science and fiction

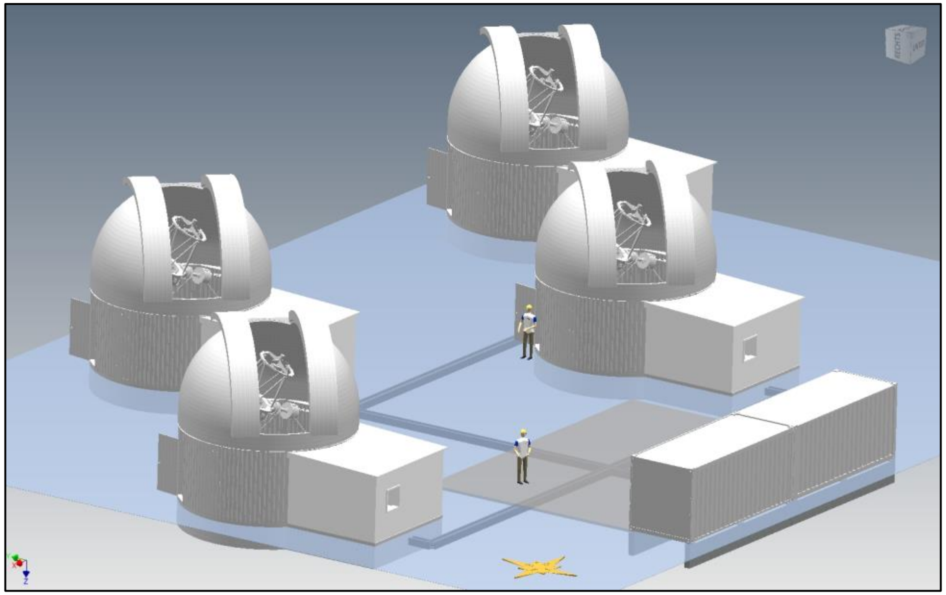




SPECULOOS
Search for habitable Planets EClipsing ULtra-cOOl Stars

Second step: an optimized southern survey

The **SPECULOOS-South Observatory** composed of 4 robotic telescopes of 1m currently being installed soon at ESO Paranal Observatory, Chile



Consortium:
Liege & Cambridge

SPECULOOS
Search for habitable Planets EClipsing ULtra-cOOl Stars

The SPECULOOS Southern Observatory at Cerro Paranal (Chile)

SPECULOOS Observatory at Paranal, October 2018

Peter Aniol @ Paranal

All telescopes in operation;
Official start of survey: 1st Jan 2019

The SPECULOOS-South Observatory

Credits: ESO/P. Horalek

The SPECULOOS-South Observatory

Credits: SPECULOOS/E. Jehin/ESO

Third step: extending the project to the North

TRAPPIST-North, 60cm robotic telescope **installed in 2016** at Oukaïmeden Observatory, Morroco (2750m, >230 clear nights/yr)

Consortium: Liege and Cadi Ayad

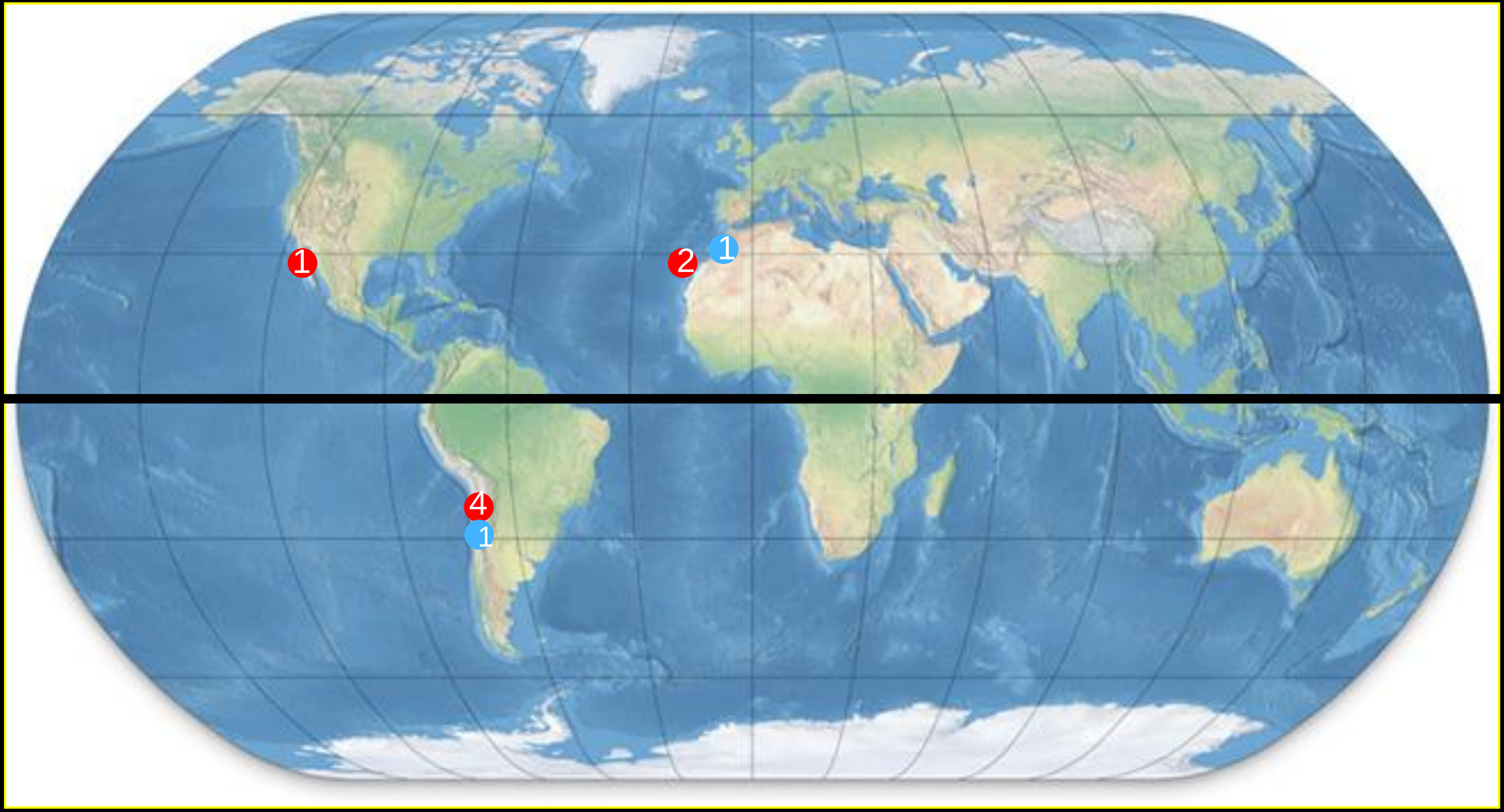
2019: SPECULOOS-North

SPECULOOS-North Observatory telescope #1: Tenerife 2019
Collaboration ULiege – MIT - IAC

2019: SPECULOOS-North

2019: SPECULOOS-North

The SPECULOOS map



The SPECULOOS team

LIÈGE université

UNIVERSITY OF CAMBRIDGE

UNIVERSITÄT BERN

UNIVERSITY OF CALIFORNIA SAN DIEGO

UNIVERSITY OF BIRMINGHAM

WARWICK
THE UNIVERSITY OF WARWICK

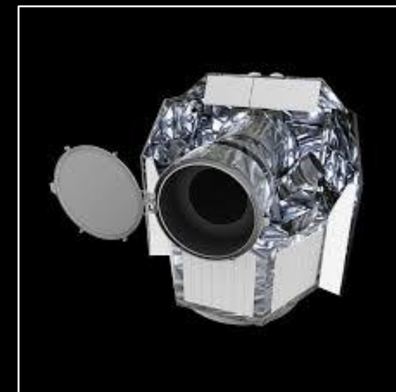
INSTITUTO DE ASTROFISICA DE CANARIAS IAC

The hunt for small exoplanets amenable for detailed characterization is on

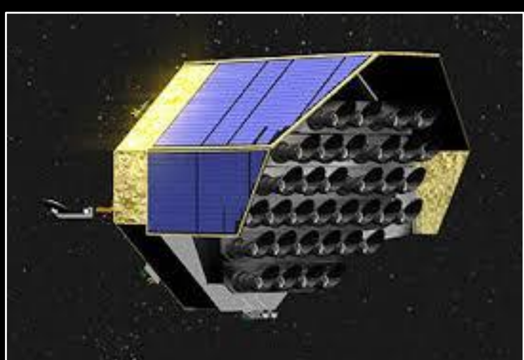
SPECULOOS (2019)

NASA/TESS (2018)

ESA/CHEOPS (2019)



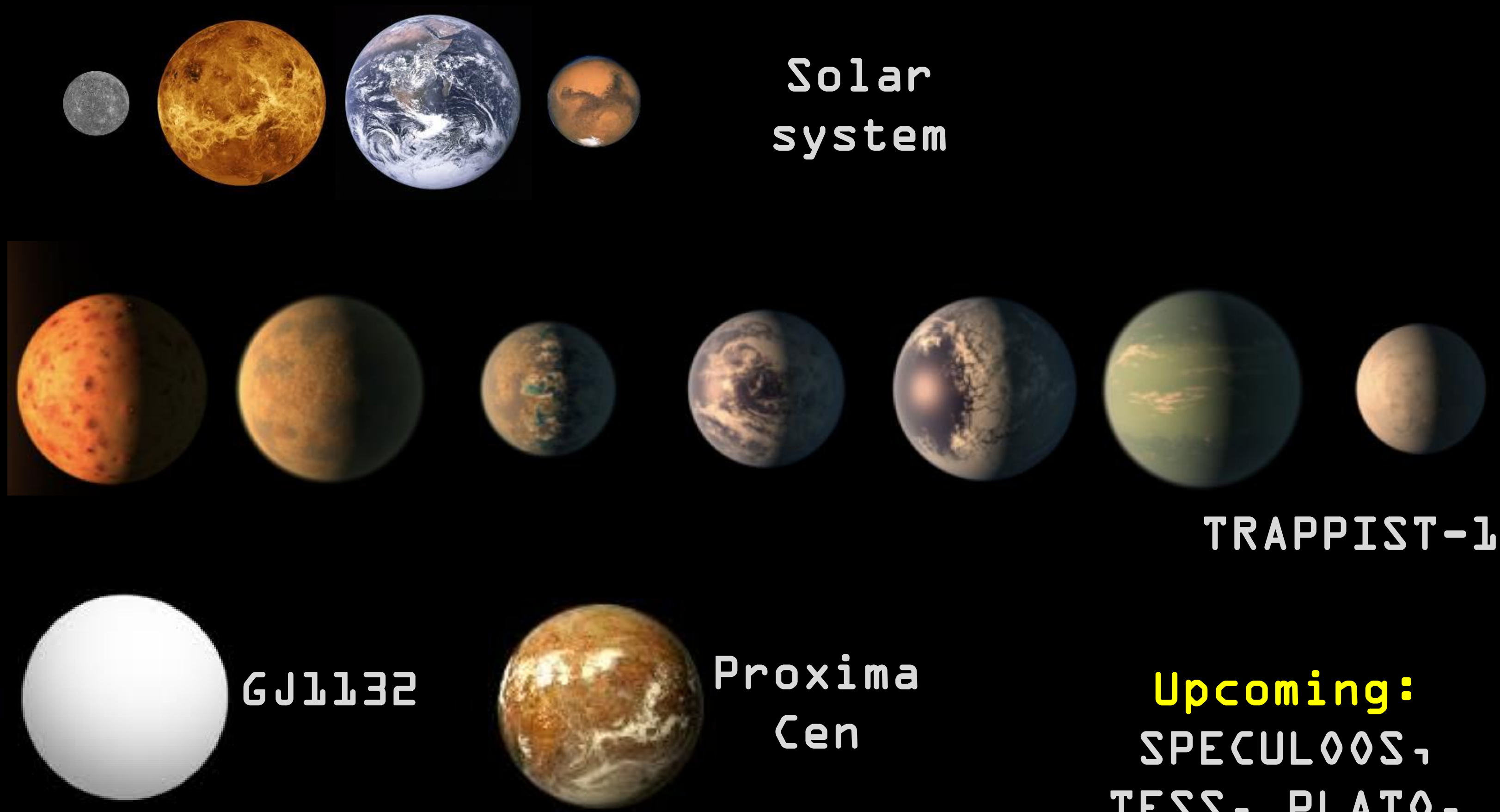
ESA/PLATO (2025)



Giant ground-based telescopes (2020s)

Credits: Peter Aniol; NASA; ESA; ESO

The study of rocky planets: a revolution is coming



Upcoming:
SPECULOOS,
TESS, PLATO,
etc

Credits: NASA;ESO

Thank you for your attention!

Project website:

www.speculoos.uliege.be