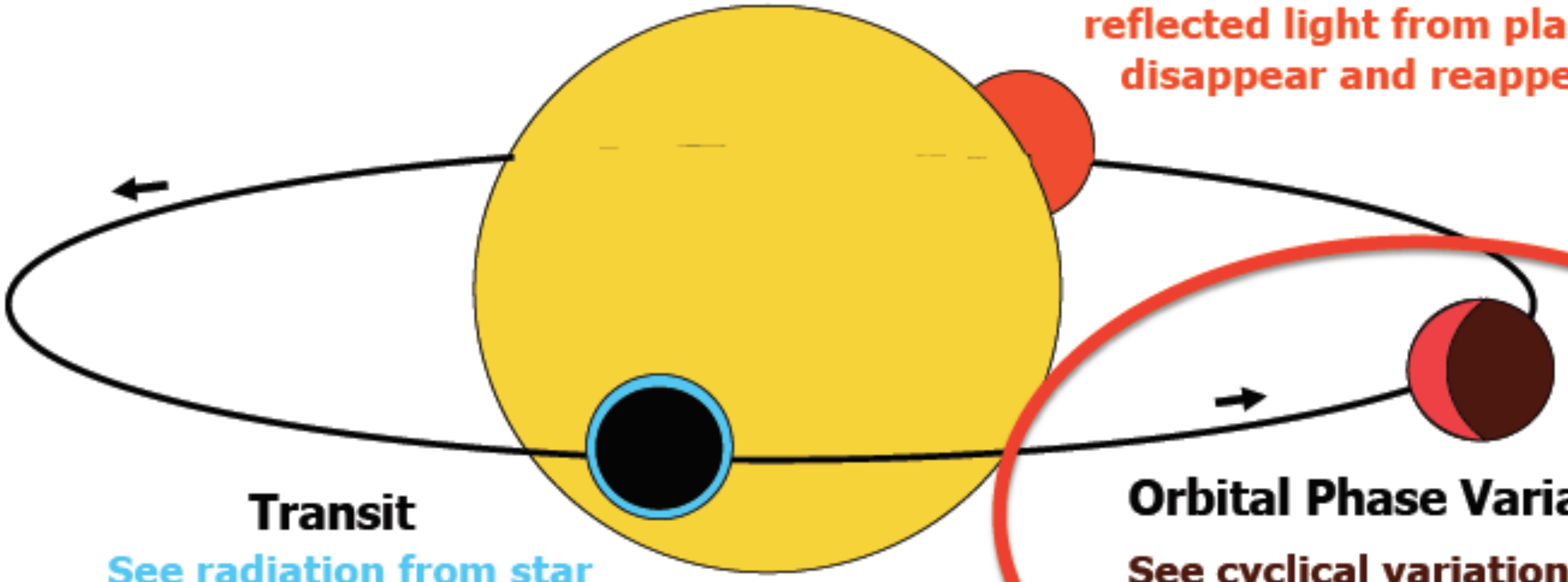
Transiting Planets as a Tool for Studying Exoplanetary Atmospheres



Secondary Eclipse

See thermal radiation and reflected light from planet disappear and reappear

Transit

See radiation from star transmitted through the planet's atmosphere

Orbital Phase Variations

See cyclical variations in brightness of planet

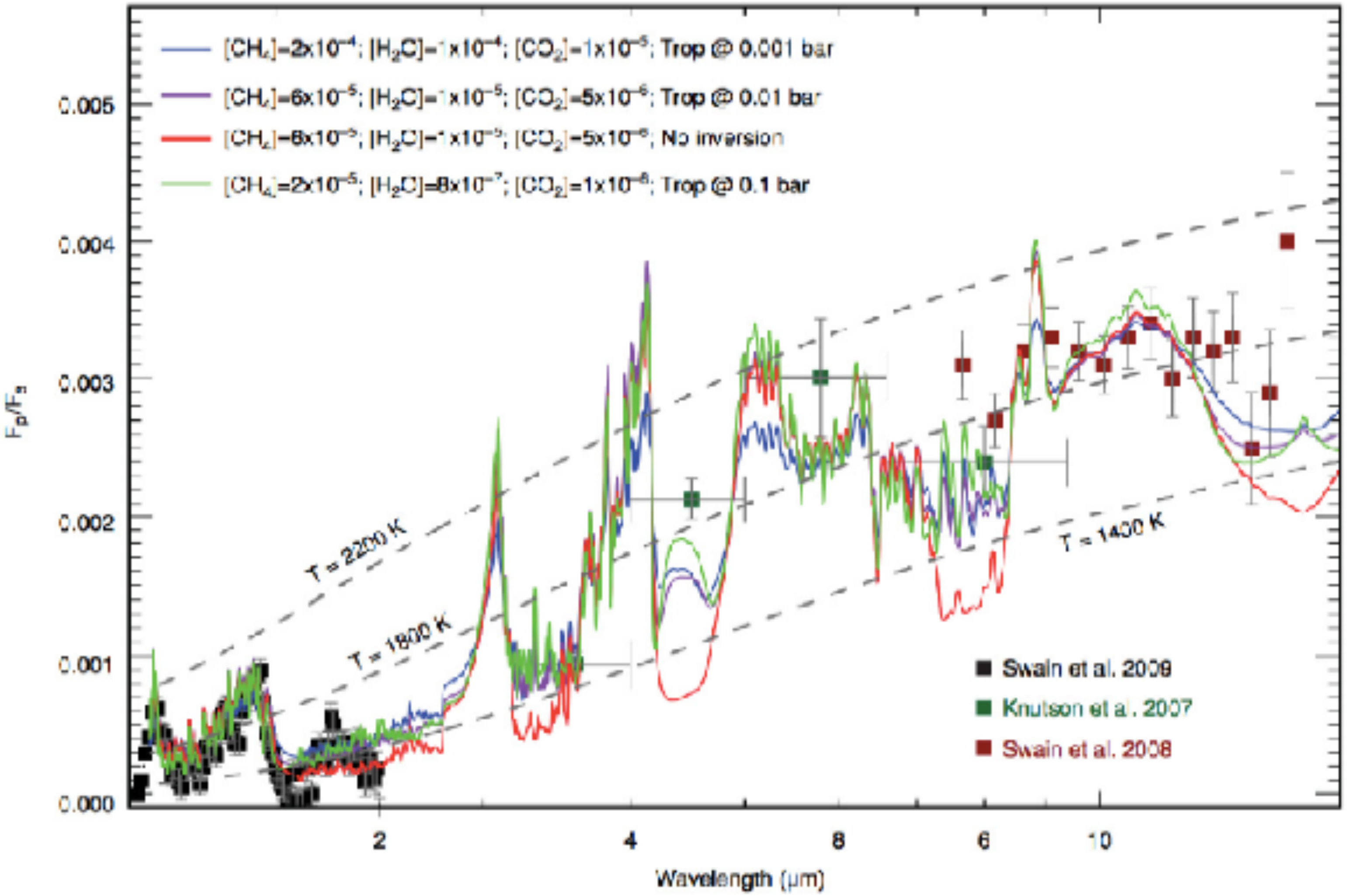
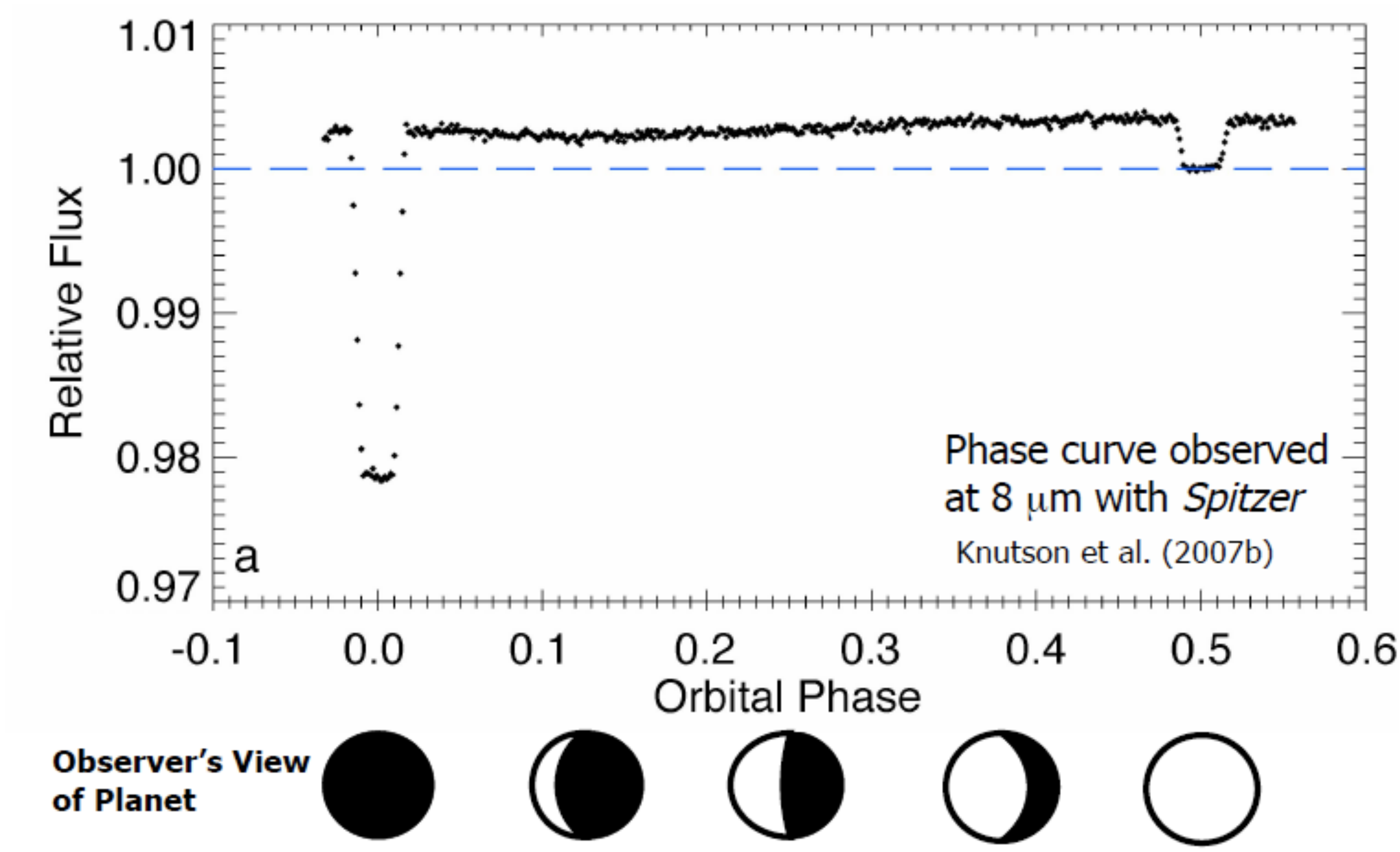


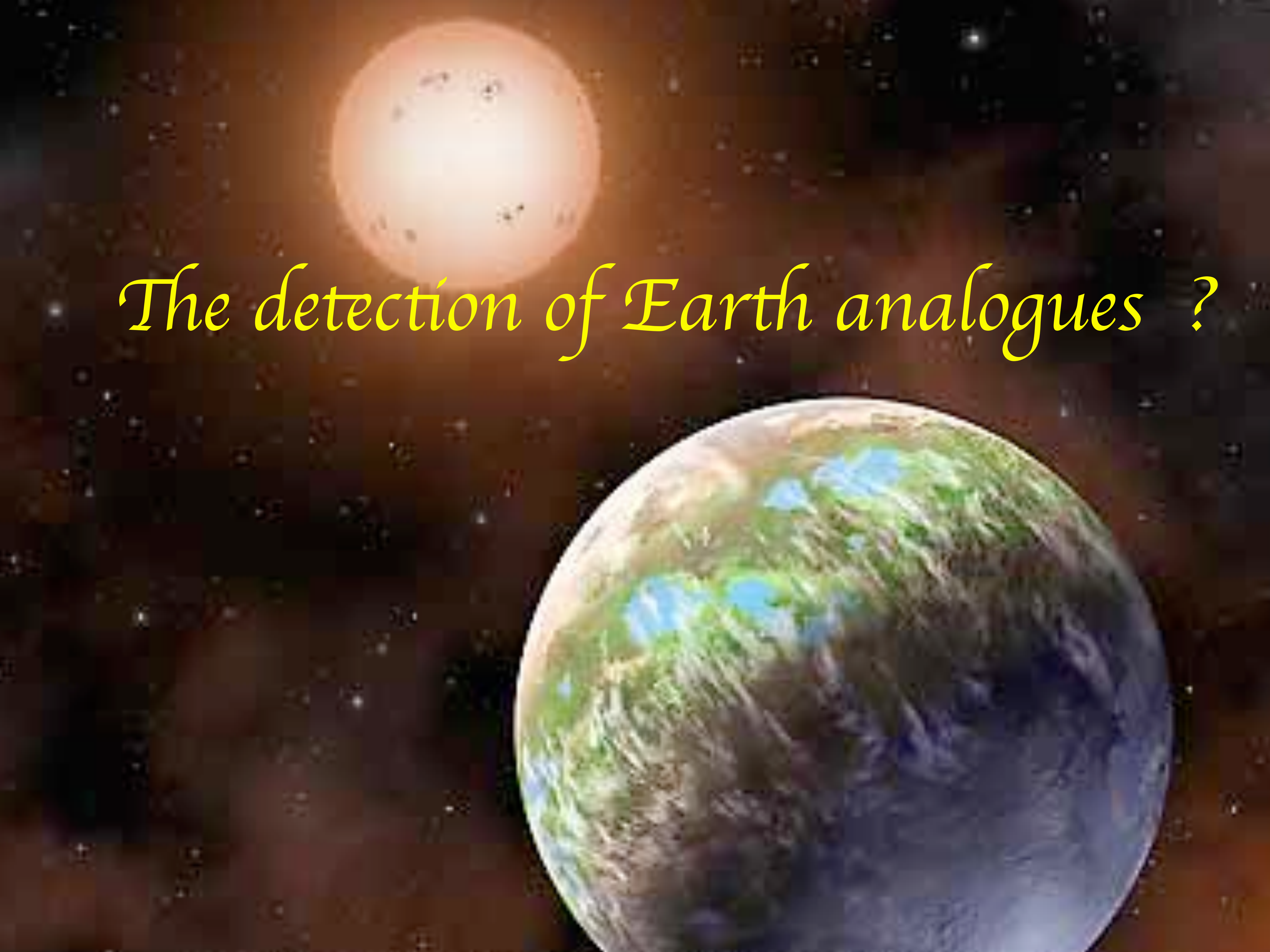
Figure 1: Synthetic emission spectra of the hot Jupiter HD209458b together with various observational data points (Swain et al. 2009). The data are from various sources, and there are gaps in the spectral coverage. Despite over a decade of study, the sparse data shown here represent the highest-quality exoplanet spectrum obtained to date.

The infrared flux of HD 189333b (Spitzer IR spacecraft)

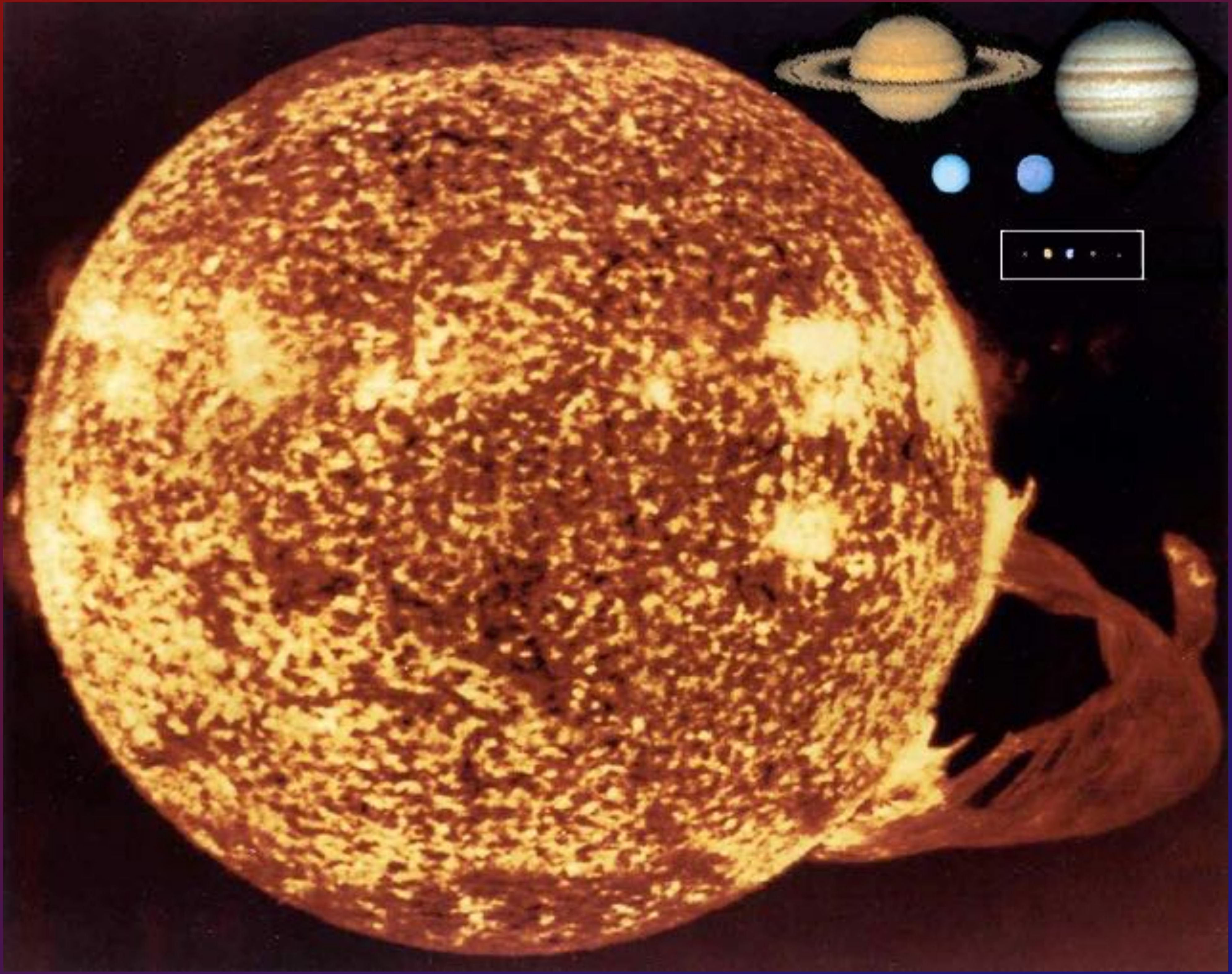


Phase curve observed at 8 μm with *Spitzer*

Knutson et al. (2007b)



The detection of Earth analogues ?

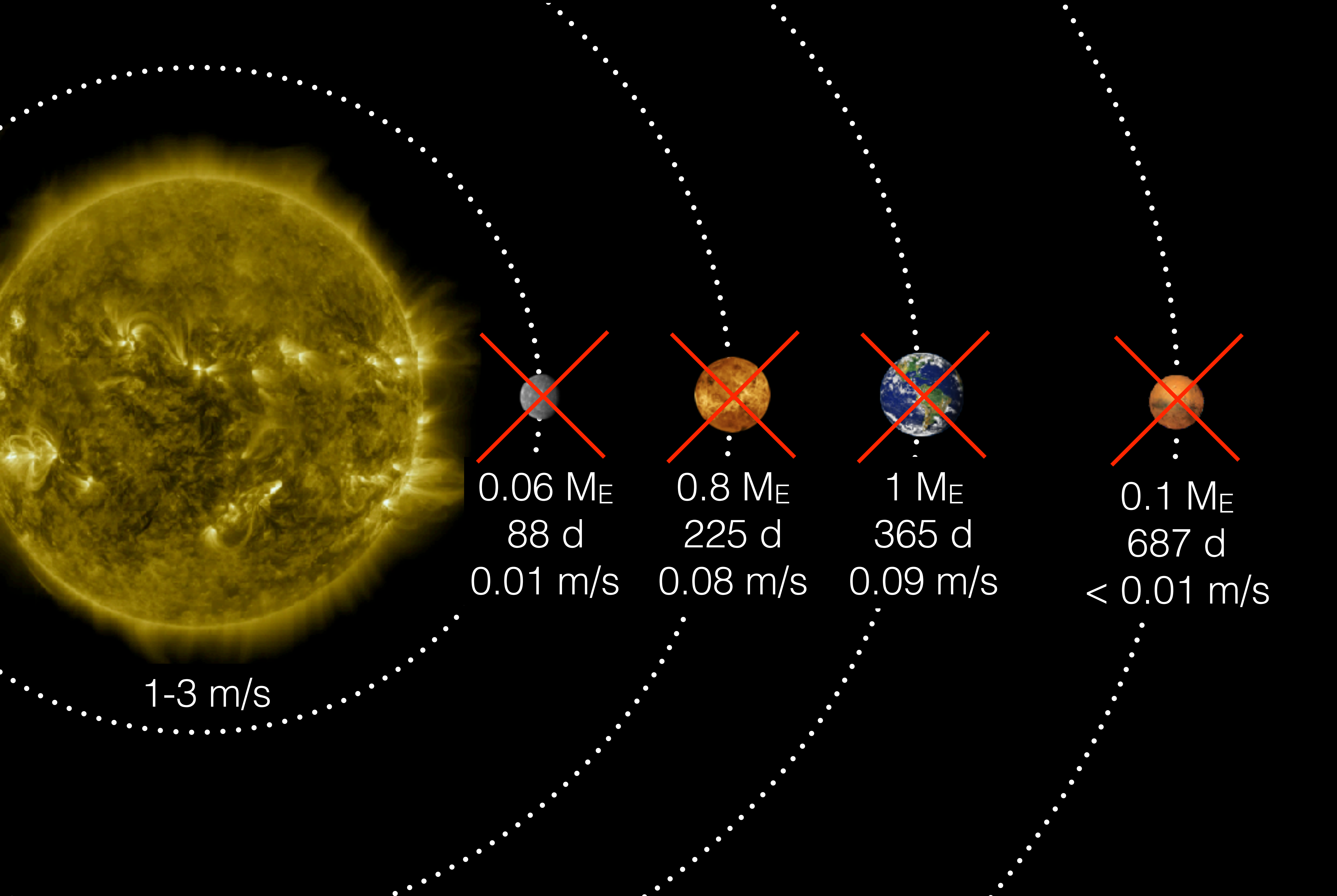


HARPS-N Observes the Sun as a Star

X. Dumusque et al. 2017

Credit: A. Glenday

The Solar System Case



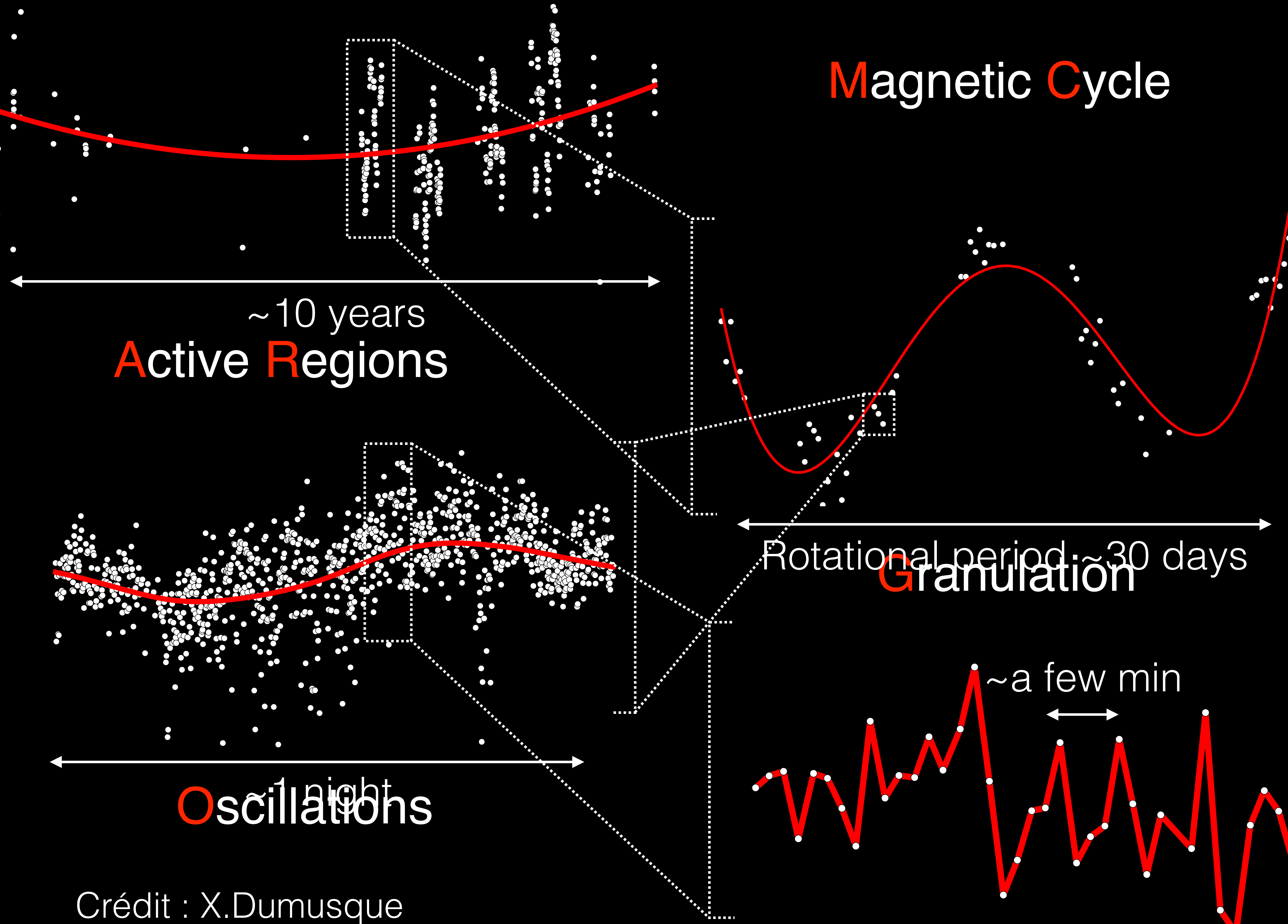
0.06 M_E
88 d
0.01 m/s

0.8 M_E
225 d
0.08 m/s

1 M_E
365 d
0.09 m/s

0.1 M_E
687 d
< 0.01 m/s

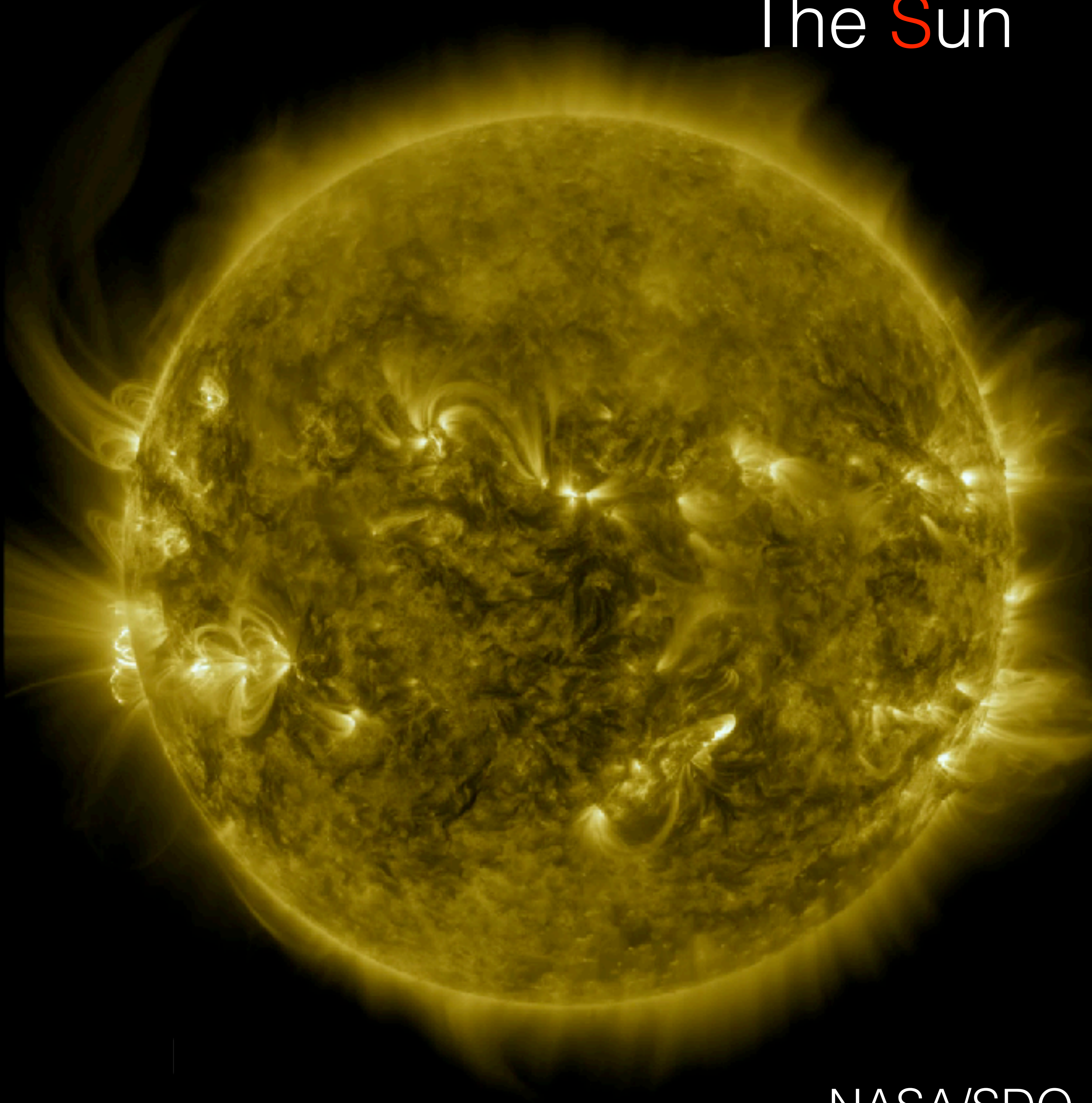
1-3 m/s



Crédit : X.Dumusque

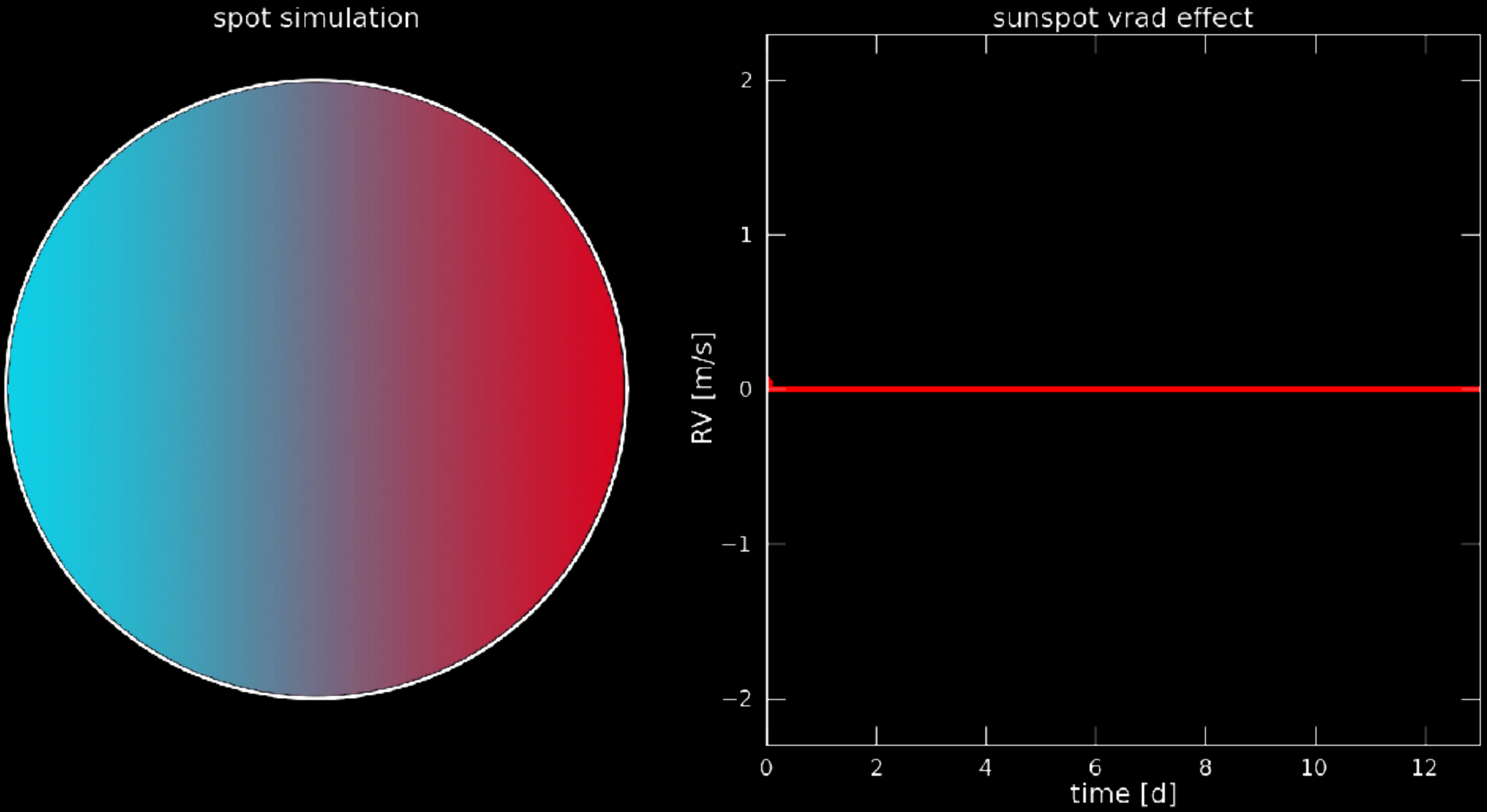
Star

The Sun



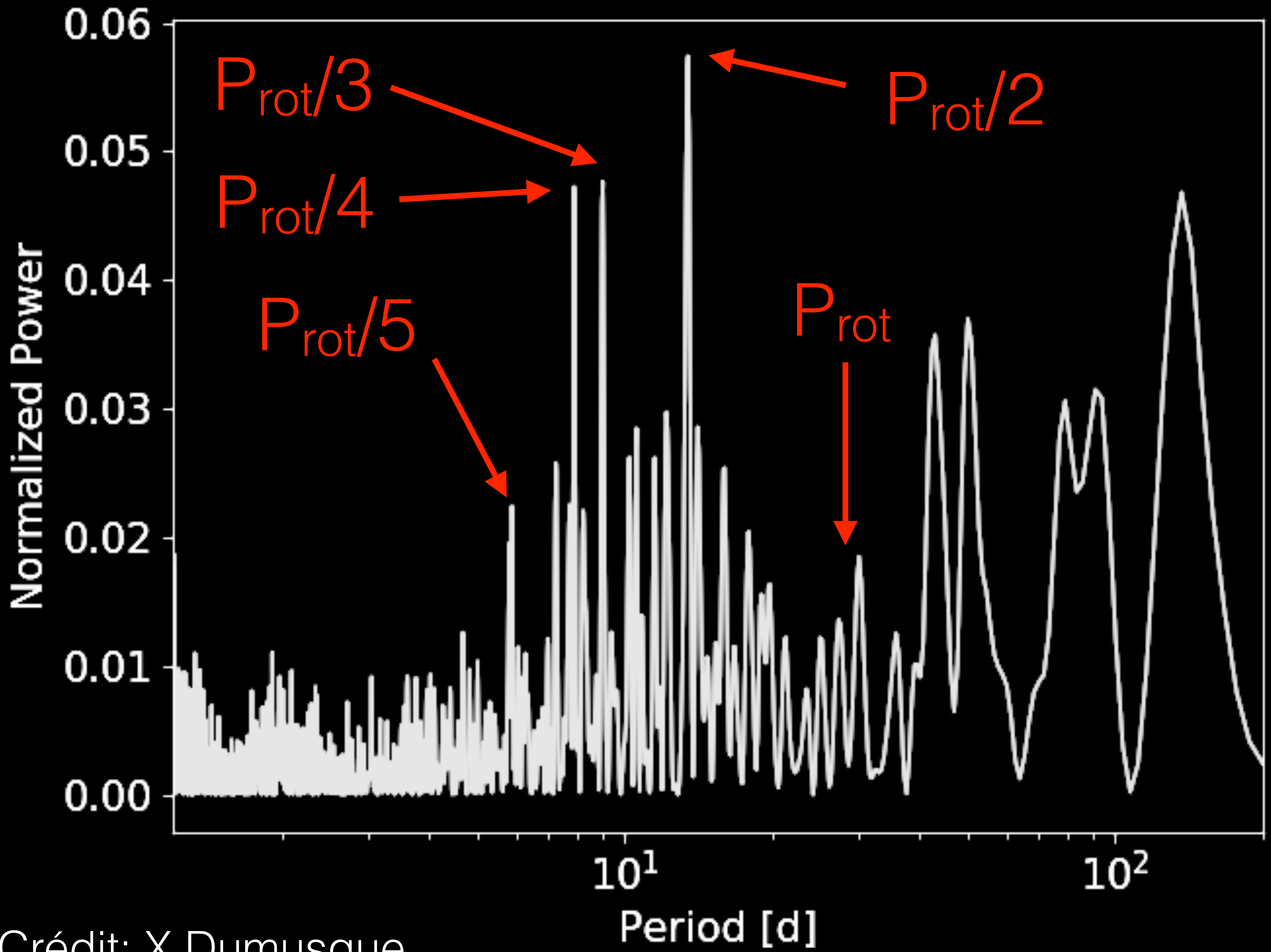
NASA/SDO

« Rossiter McLaughlin ::«



Crédit : X.Dumusque

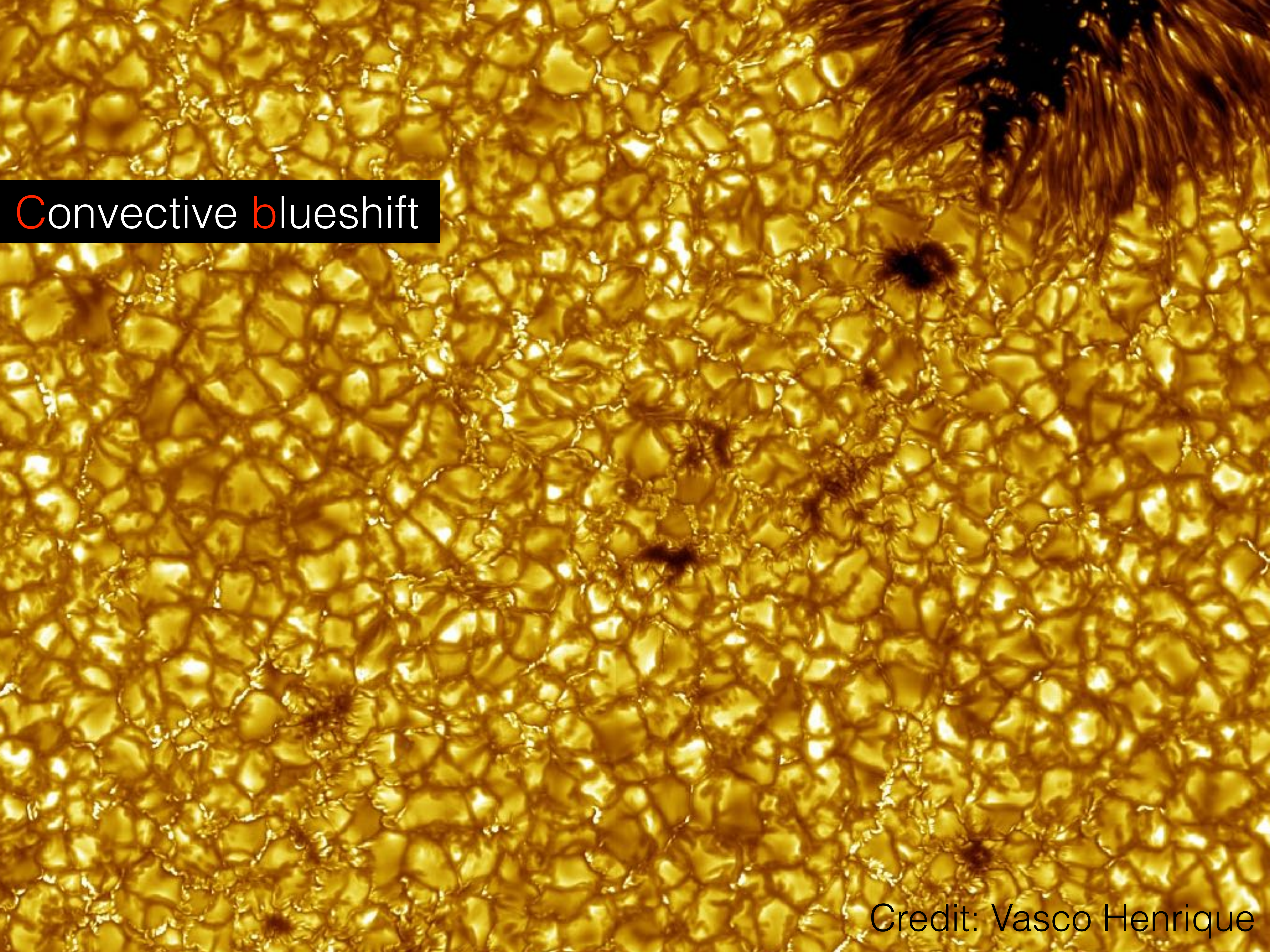
Periodogram Sun as a Star RVs



Crédit: X.Dumusque

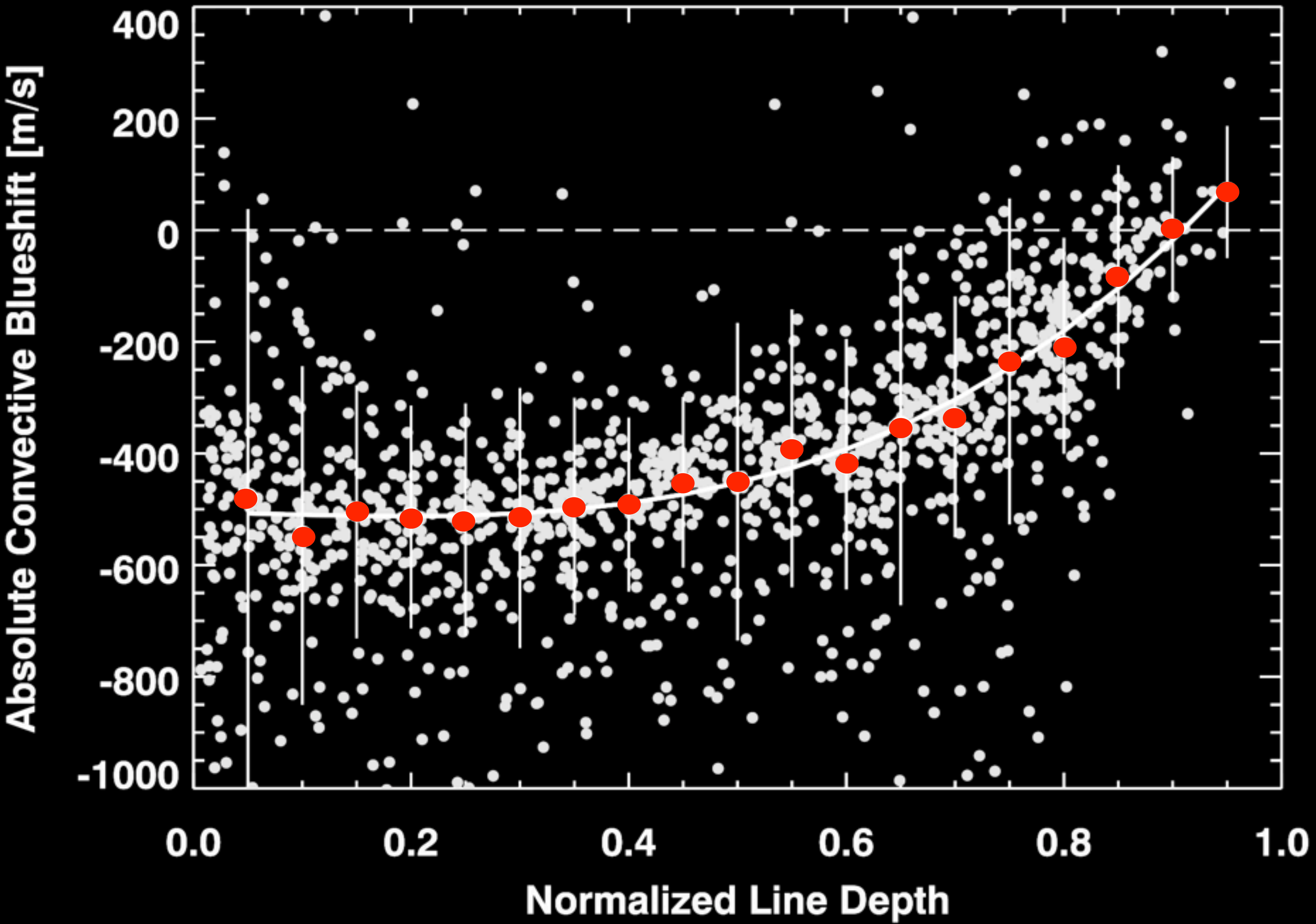
We would Like a Technique that could be Applied to Other Stars

Convective blueshift



Credit: Vasco Henrique

Convective blueshift



Reiners+ 15

Lines formed at different depths, lines induced by different elements

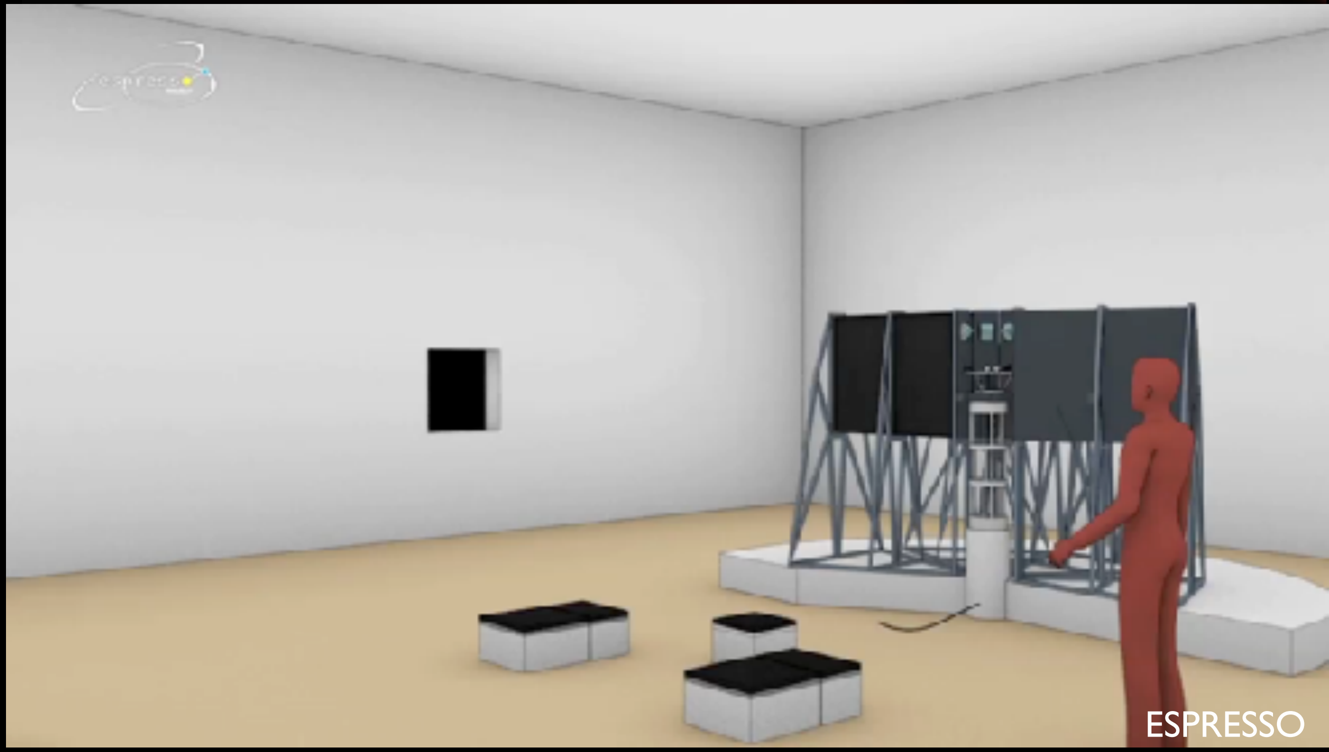
Should be affected differently by activity

ESPRESSO a spectrograph for the VLT (diameter 8.2m)

«**E**chelle **SP**ectrograph for **R**ocky **E**xoplanets and **S**table **S**pectroscopic **O**bservations»

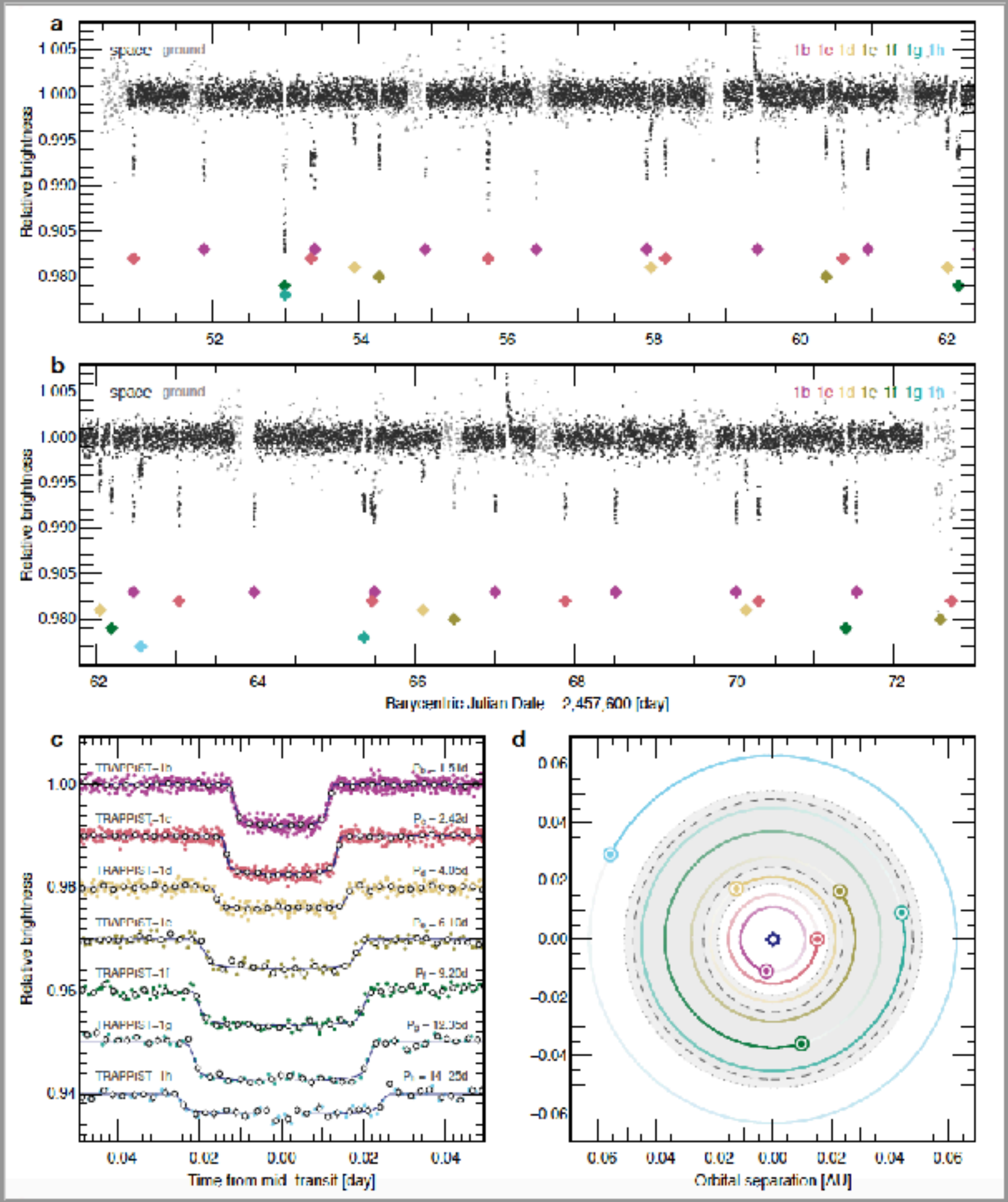
P.i. Francesco Pepe, Unige

- Ultrastable spectrograph for the VLT
- Consortium : CH, Italy, Portugal, Spain
- First light : 2017
- RV Precision : < 10 cm/s
- Goal : Detection and characterization of very low mass planets



Seven temperate terrestrial planets around the nearby ultracool dwarf star TRAPPIST-1

Gillon et al. 2017 Nature (22 février)


a
b
space
ground
1b 1c 1d 1e 1f 1g 1h
Relative brightness
1.005
1.000
0.995
0.990
0.985
0.980
52
54
56
58
60
62
64
66
68
70
72
Barycentric Julian Date − 2,457,600 [day]
c
TRAPPIST-1b
$P_b = 1.51$d
TRAPPIST-1c
$P_c = 2.42$d
TRAPPIST-1d
$P_d = 4.05$d
TRAPPIST-1e
$P_e = 6.10$d
TRAPPIST-1f
$P_f = 9.20$d
TRAPPIST-1g
$P_g = 12.35$d
TRAPPIST-1h
$P_h = 14{-}25$d
1.00
0.98
0.96
0.94
0.04
0.02
0.00
0.02
0.04
Time from mid-transit [day]
d
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
Orbital separation [AU]

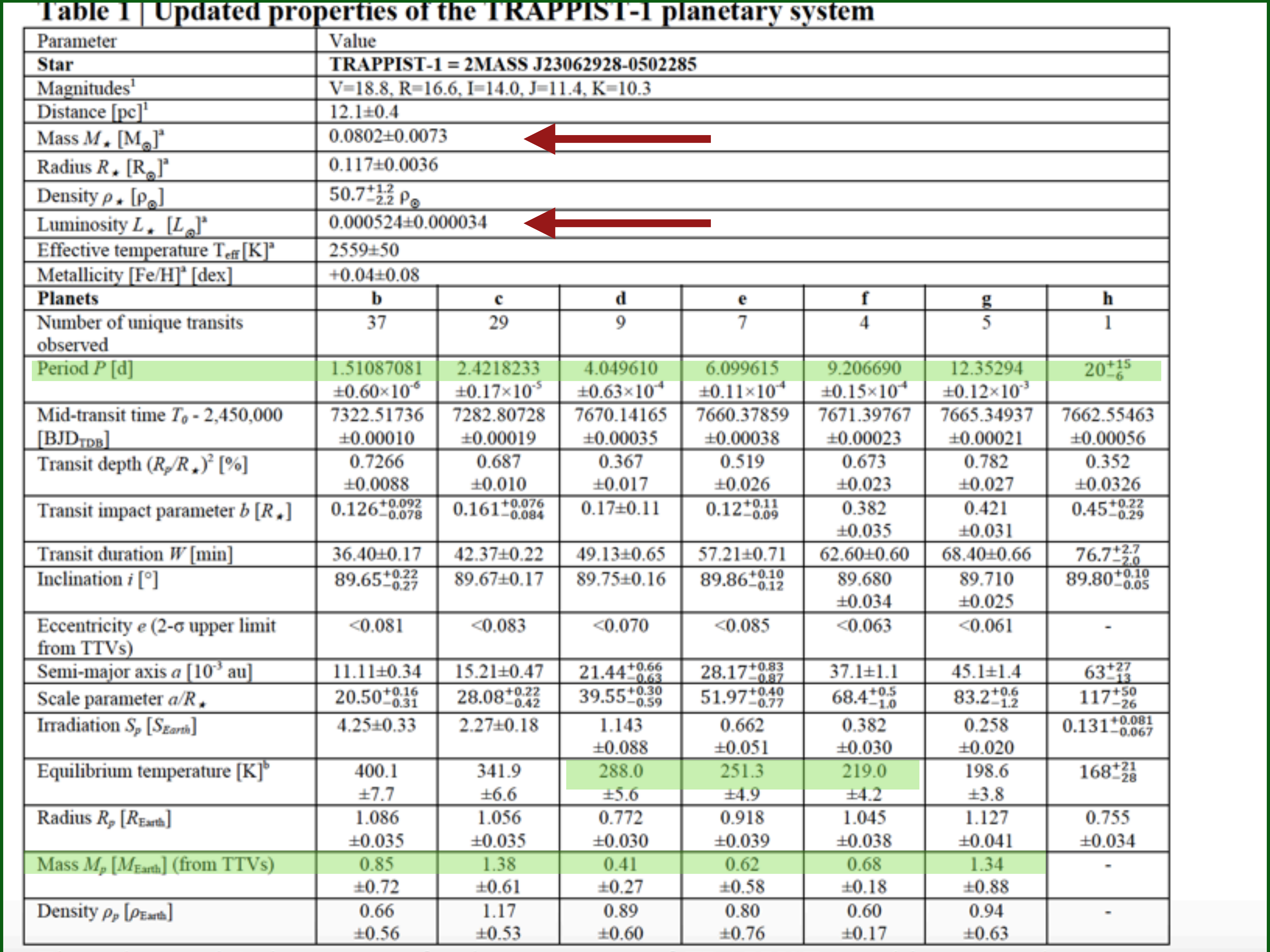
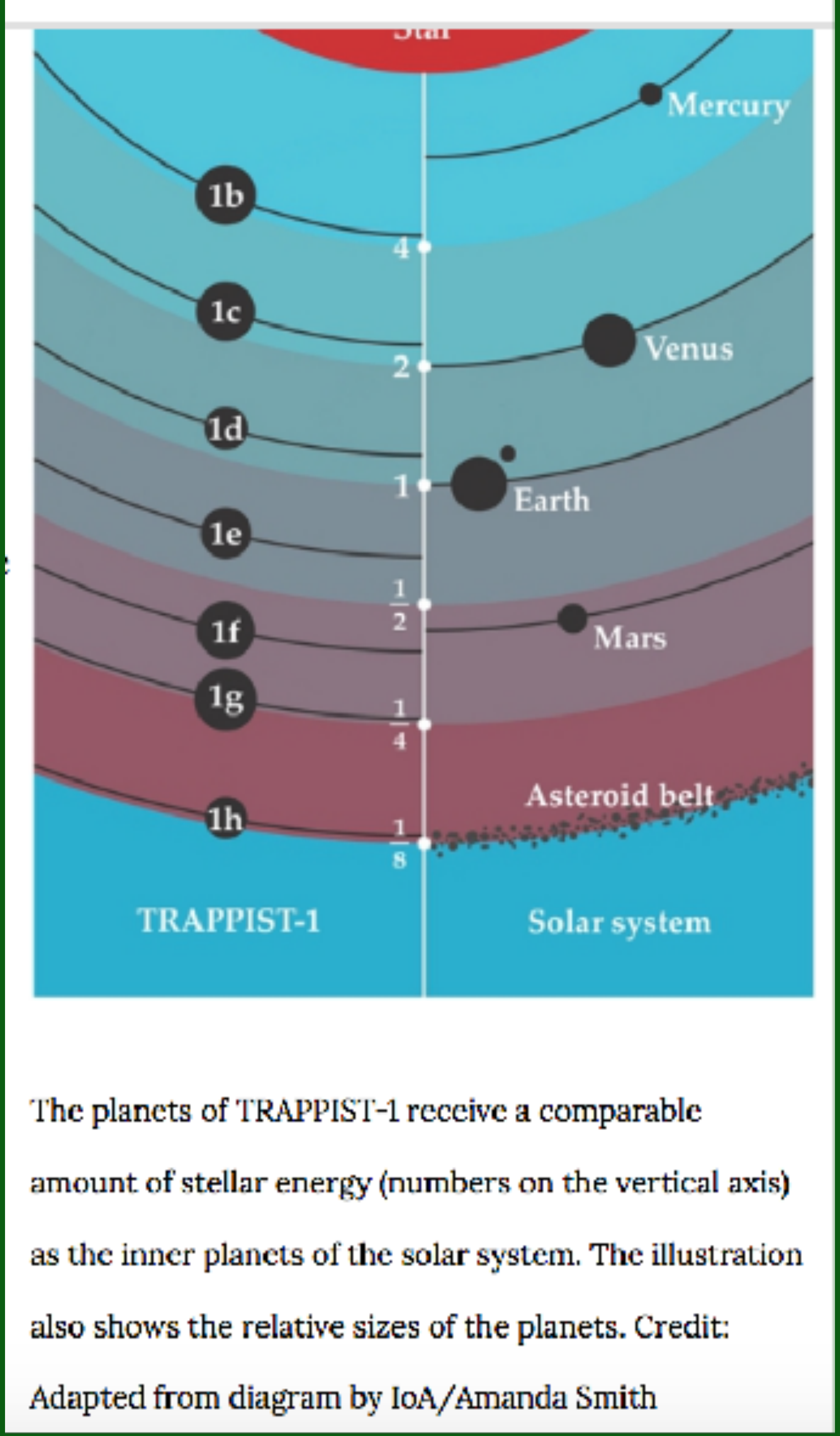
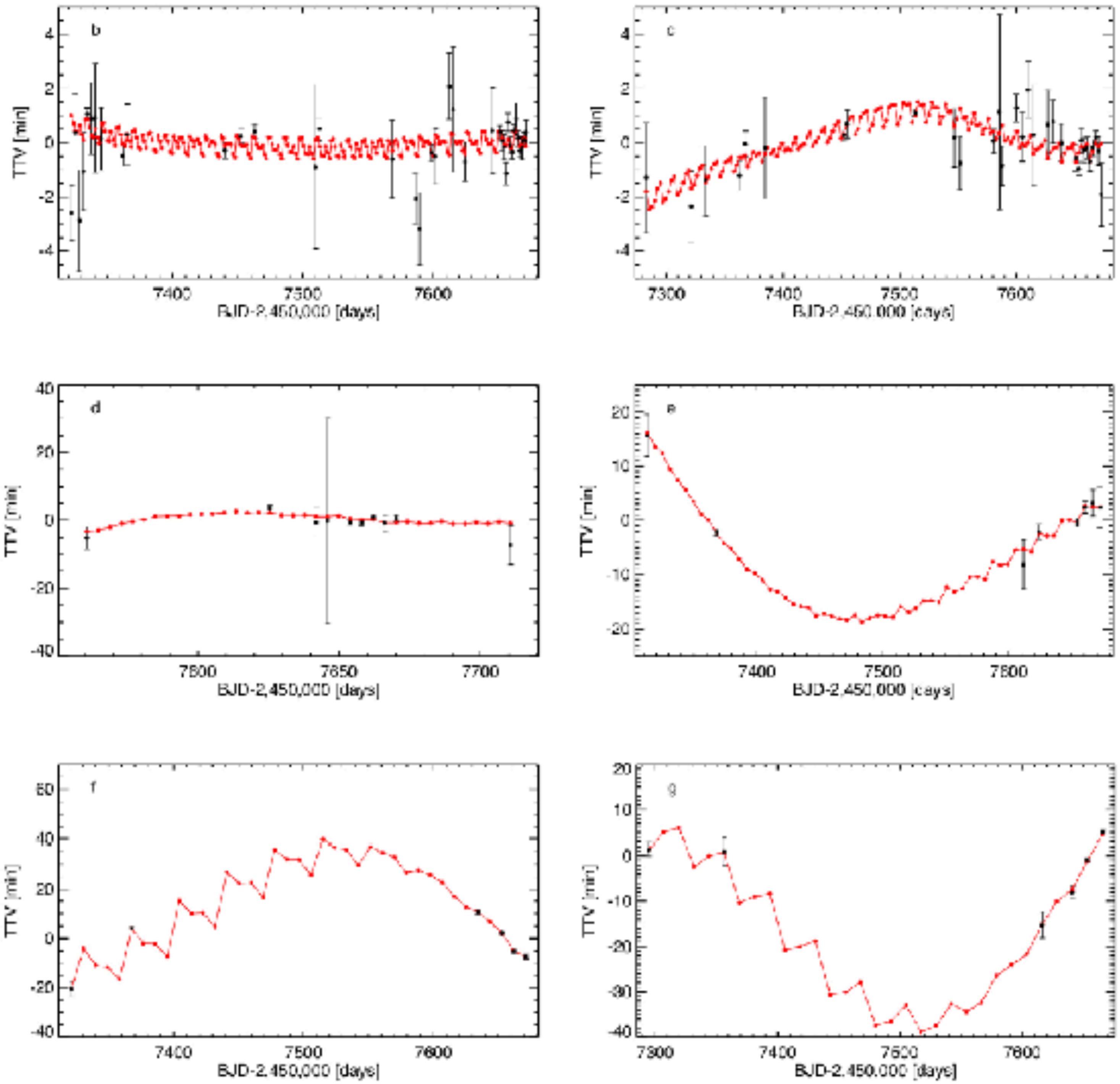


Table 1 | Updated properties of the TRAPPIST-1 planetary system

Parameter	Value						
Star	**TRAPPIST-1 = 2MASS J23062928-0502285**						
Magnitudes[1]	V=18.8, R=16.6, I=14.0, J=11.4, K=10.3						
Distance [pc][1]	12.1±0.4						
Mass $M_\star$ [$M_\odot$][a]	0.0802±0.0073						
Radius $R_\star$ [$R_\odot$][a]	0.117±0.0036						
Density $\rho_\star$ [$\rho_\odot$]	$50.7^{+1.2}_{-2.2}$ $\rho_\odot$						
Luminosity $L_\star$ [$L_\odot$][a]	0.000524±0.000034						
Effective temperature T_{eff} [K][a]	2559±50						
Metallicity [Fe/H][a] [dex]	+0.04±0.08						
Planets	**b**	**c**	**d**	**e**	**f**	**g**	**h**
Number of unique transits observed	37	29	9	7	4	5	1
Period P [d]	1.51087081 $\pm0.60\times10^{-6}$	2.4218233 $\pm0.17\times10^{-5}$	4.049610 $\pm0.63\times10^{-4}$	6.099615 $\pm0.11\times10^{-4}$	9.206690 $\pm0.15\times10^{-4}$	12.35294 $\pm0.12\times10^{-3}$	20^{+15}_{-6}
Mid-transit time T_0 - 2,450,000 [BJD_{TDB}]	7322.51736 ±0.00010	7282.80728 ±0.00019	7670.14165 ±0.00035	7660.37859 ±0.00038	7671.39767 ±0.00023	7665.34937 ±0.00021	7662.55463 ±0.00056
Transit depth $(R_p/R_\star)^2$ [%]	0.7266 ±0.0088	0.687 ±0.010	0.367 ±0.017	0.519 ±0.026	0.673 ±0.023	0.782 ±0.027	0.352 ±0.0326
Transit impact parameter b [$R_\star$]	$0.126^{+0.092}_{-0.078}$	$0.161^{+0.076}_{-0.084}$	0.17±0.11	$0.12^{+0.11}_{-0.09}$	0.382 ±0.035	0.421 ±0.031	$0.45^{+0.22}_{-0.29}$
Transit duration W [min]	36.40±0.17	42.37±0.22	49.13±0.65	57.21±0.71	62.60±0.60	68.40±0.66	$76.7^{+2.7}_{-2.0}$
Inclination i [°]	$89.65^{+0.22}_{-0.27}$	89.67±0.17	89.75±0.16	$89.86^{+0.10}_{-0.12}$	89.680 ±0.034	89.710 ±0.025	$89.80^{+0.10}_{-0.05}$
Eccentricity e (2-σ upper limit from TTVs)	<0.081	<0.083	<0.070	<0.085	<0.063	<0.061	-
Semi-major axis a [10^{-3} au]	11.11±0.34	15.21±0.47	$21.44^{+0.66}_{-0.63}$	$28.17^{+0.83}_{-0.87}$	37.1±1.1	45.1±1.4	63^{+27}_{-13}
Scale parameter $a/R_\star$	$20.50^{+0.16}_{-0.31}$	$28.08^{+0.22}_{-0.42}$	$39.55^{+0.30}_{-0.59}$	$51.97^{+0.40}_{-0.77}$	$68.4^{+0.5}_{-1.0}$	$83.2^{+0.6}_{-1.2}$	117^{+50}_{-26}
Irradiation S_p [S_{Earth}]	4.25±0.33	2.27±0.18	1.143 ±0.088	0.662 ±0.051	0.382 ±0.030	0.258 ±0.020	$0.131^{+0.081}_{-0.067}$
Equilibrium temperature [K][b]	400.1 ±7.7	341.9 ±6.6	288.0 ±5.6	251.3 ±4.9	219.0 ±4.2	198.6 ±3.8	168^{+21}_{-28}
Radius R_p [R_{Earth}]	1.086 ±0.035	1.056 ±0.035	0.772 ±0.030	0.918 ±0.039	1.045 ±0.038	1.127 ±0.041	0.755 ±0.034
Mass M_p [M_{Earth}] (from TTVs)	0.85 ±0.72	1.38 ±0.61	0.41 ±0.27	0.62 ±0.58	0.68 ±0.18	1.34 ±0.88	-
Density ρ_p [ρ_{Earth}]	0.66 ±0.56	1.17 ±0.53	0.89 ±0.60	0.80 ±0.76	0.60 ±0.17	0.94 ±0.63	-



The planets of TRAPPIST-1 receive a comparable amount of stellar energy (numbers on the vertical axis) as the inner planets of the solar system. The illustration also shows the relative sizes of the planets. Credit: Adapted from diagram by IoA/Amanda Smith

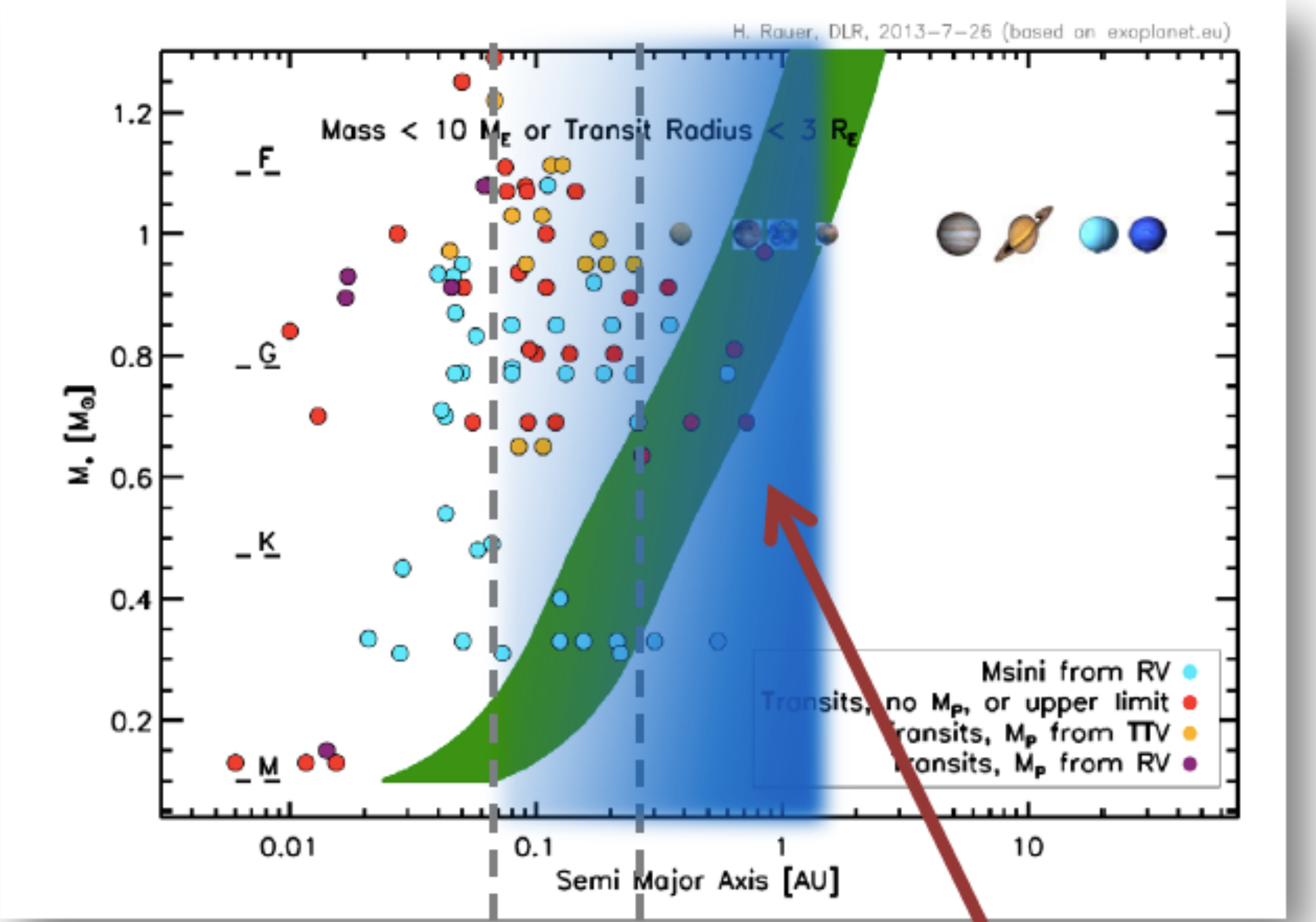

b
c
d
e
f
g
TTV [min]
BJD-2,450,000 [days]
7300
7400
7500
7600
7650
7700
-40
-20
0
20
40
60

Life : a « cosmic imperative » ?

Christian de Duve

Bulk properties of Earth-like planets up to the H

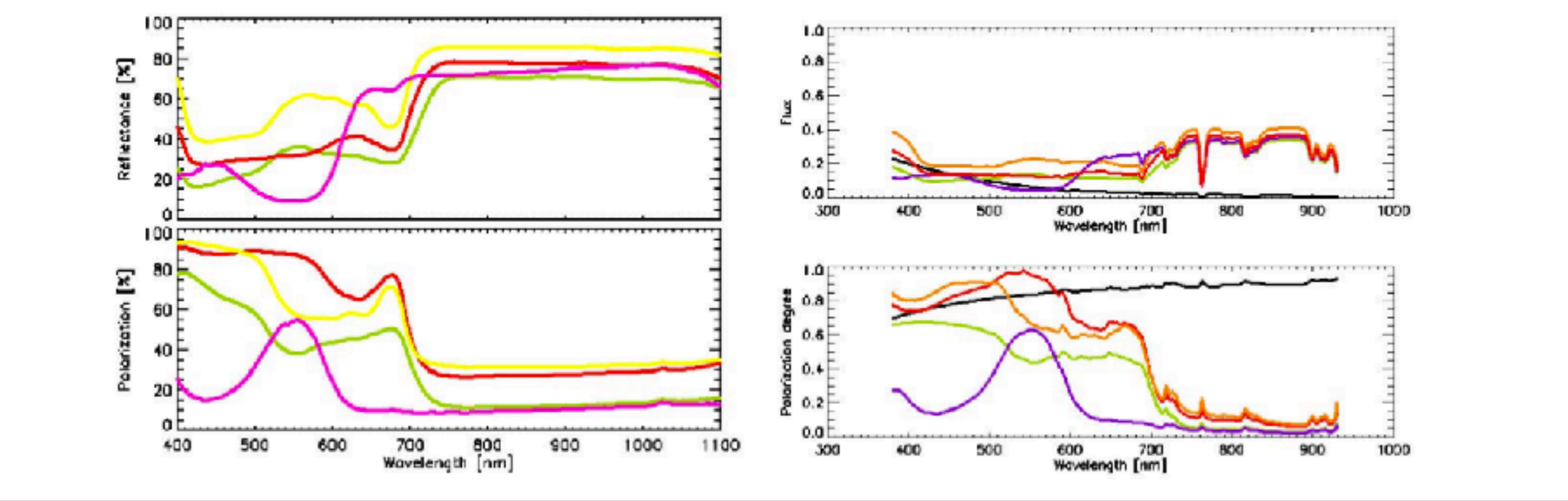
Status super-Earths detection and characterization


H. Rauer, DLR, 2013-7-26 (based on exoplanet.eu)

Transits and mass from RV

Mass from TTVs

Main target range for PLATO 2.0 characterization (transit + RV)



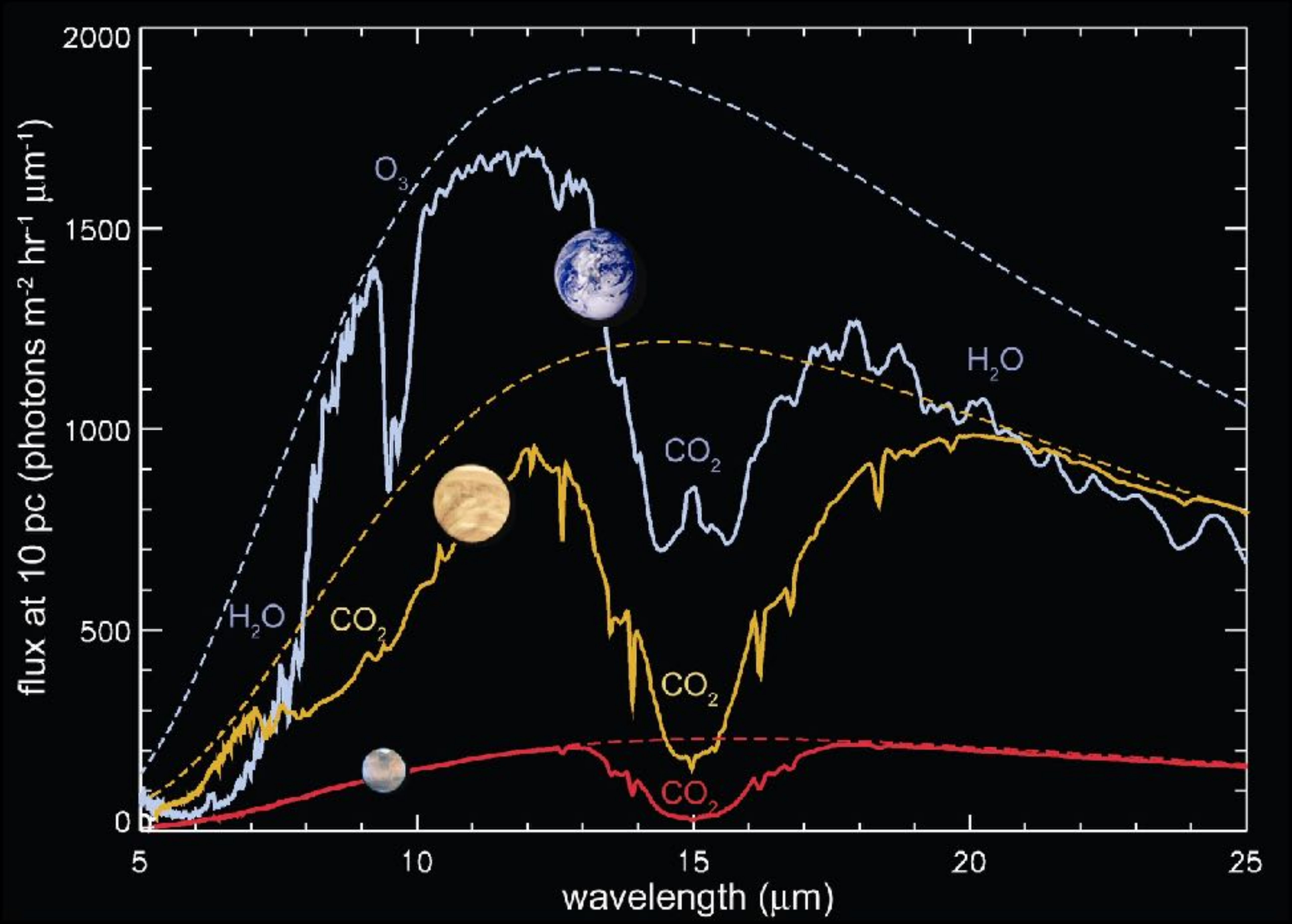
Reflectance and polarization of biopigments (left fig.)

(for example : chlorophyll (green curve), carotenoids(yellow)

A planet with 80% vegetation + 20 oceans (right fig.)

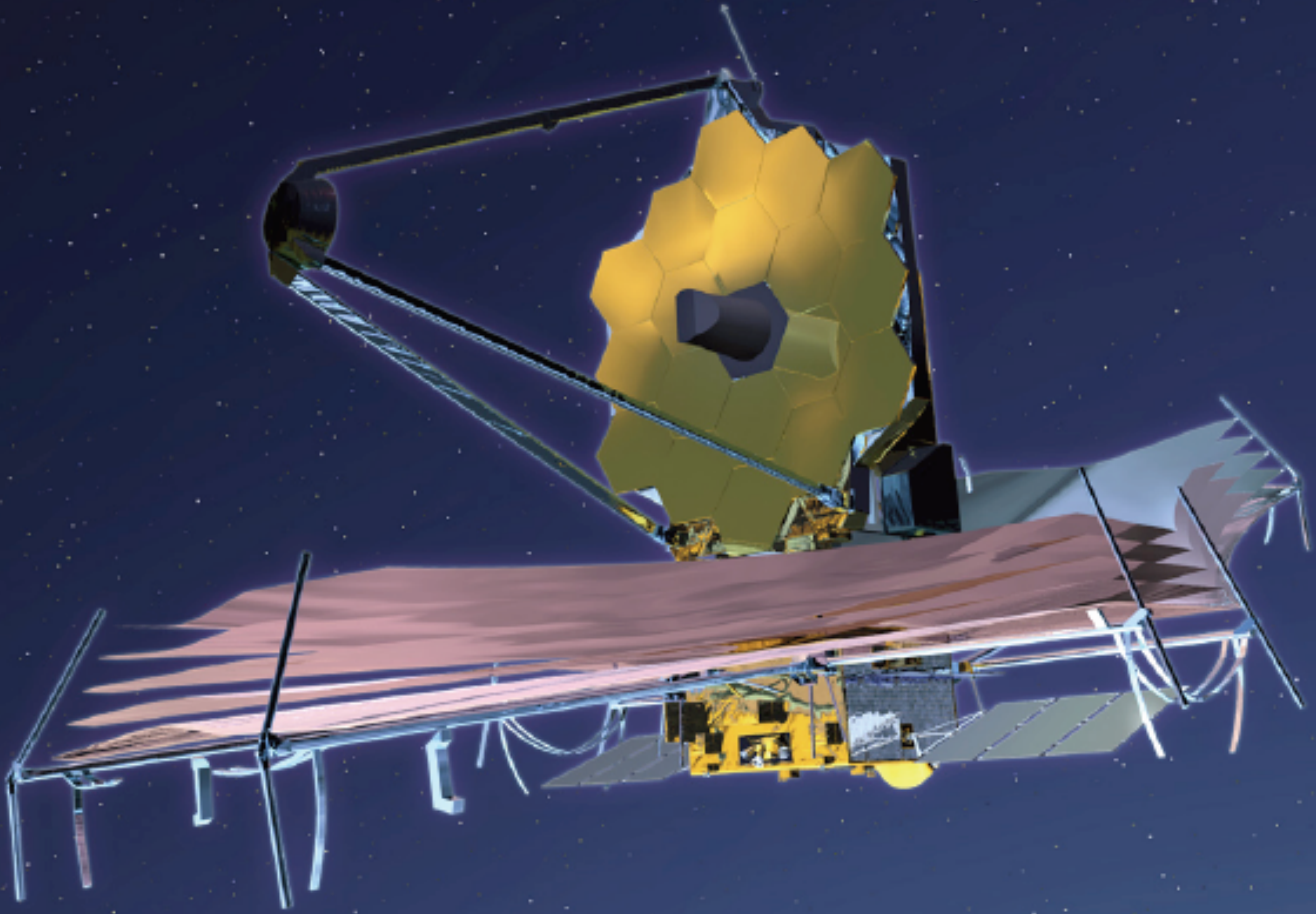
(with 100% of oceans : black curve)

(Berdyugina et al. 2016)


flux at 10 pc (photons m-2 hr-1 µm-1)
2000
1500
1000
500
0
5
10
15
20
25
wavelength (µm)
O3
H2O
CO2
CO2
H2O
CO2
CO2
CO2

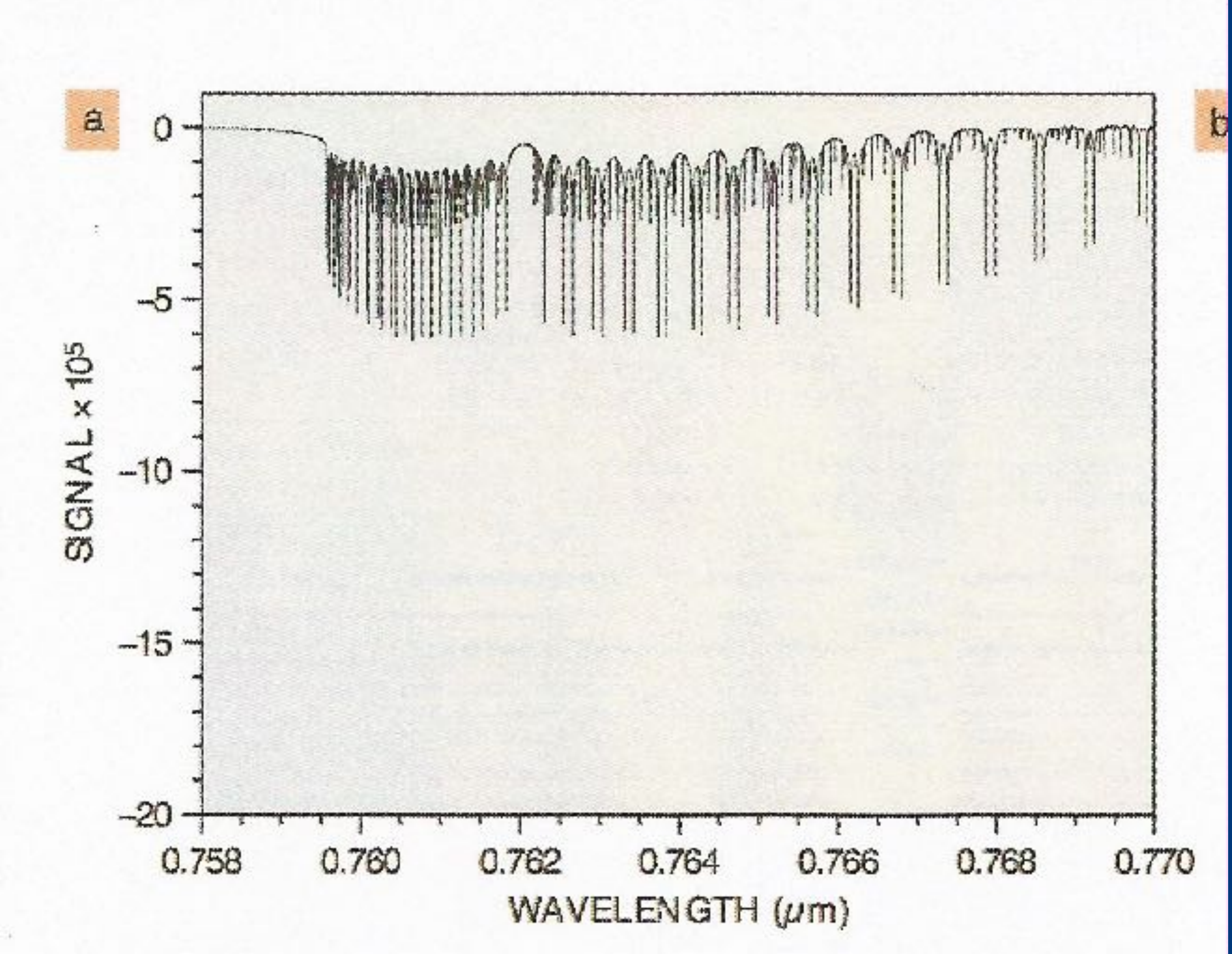
Selsis 2007

JWST



Simulated O_2 transmission signal from an hypothetical Earth-like planet transiting a M dwarf star

Snellen et al.2013



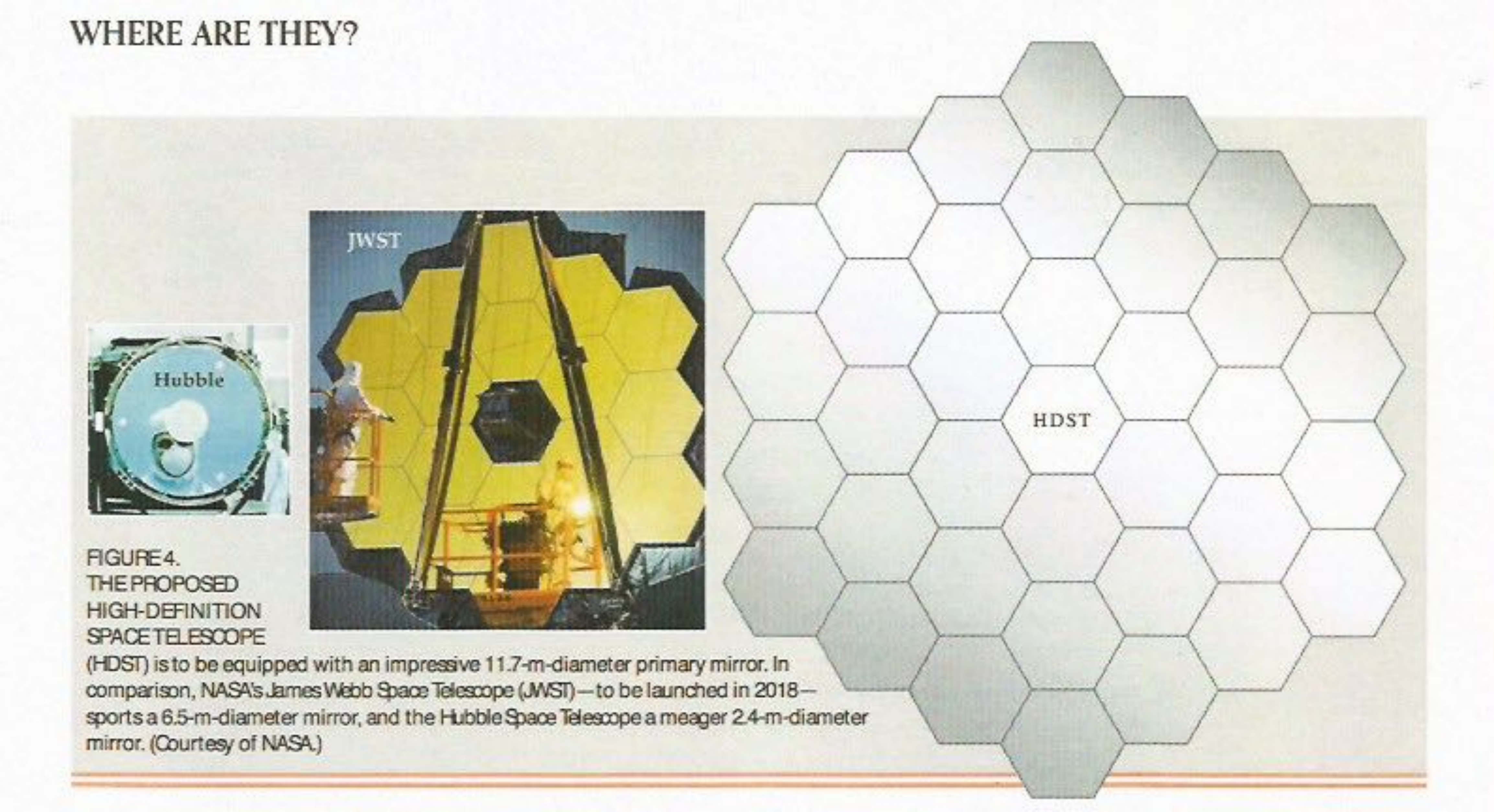


FIGURE 4. THE PROPOSED HIGH-DEFINITION SPACE TELESCOPE (HDST) is to be equipped with an impressive 11.7-m-diameter primary mirror. In comparison, NASA's James Webb Space Telescope (JWST)—to be launched in 2018—sports a 6.5-m-diameter mirror, and the Hubble Space Telescope a meager 2.4-m-diameter mirror. (Courtesy of NASA.)

E-ELT (ESO)

A 39-m telescope

2022

Cerro Armazones
Atacama desert
Chile