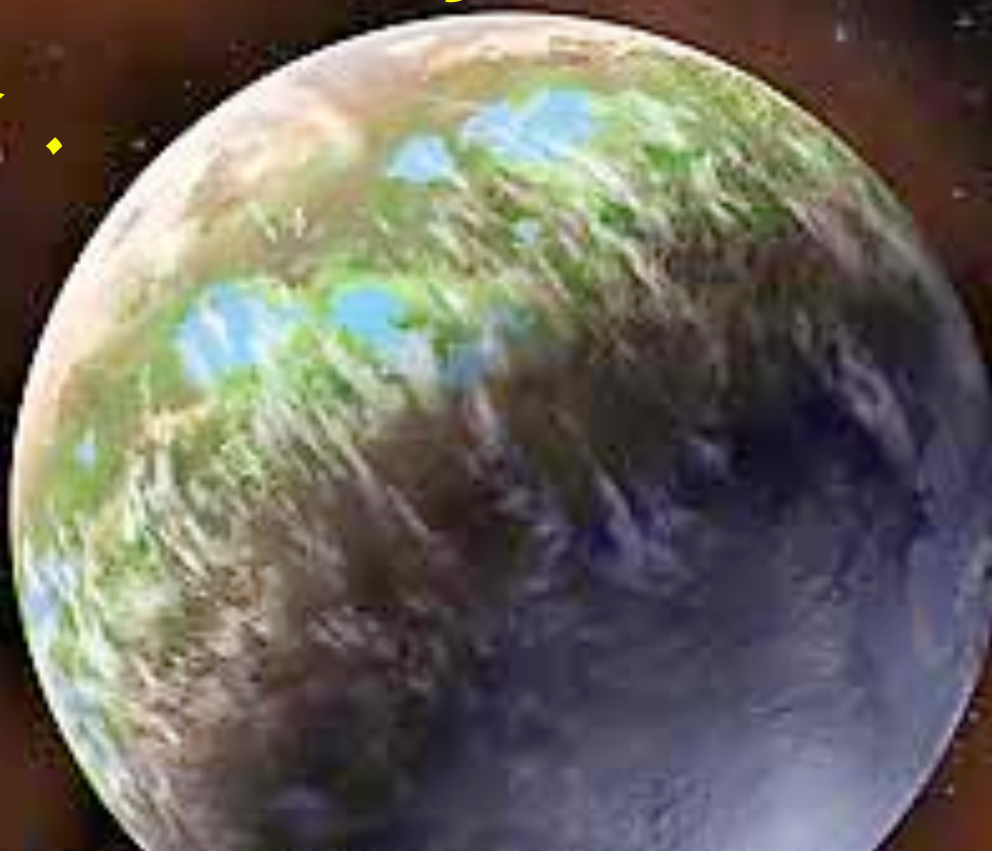
Quelques pistes pour découvrir des planètes habitables .



Michel Mayor
Université de Genève

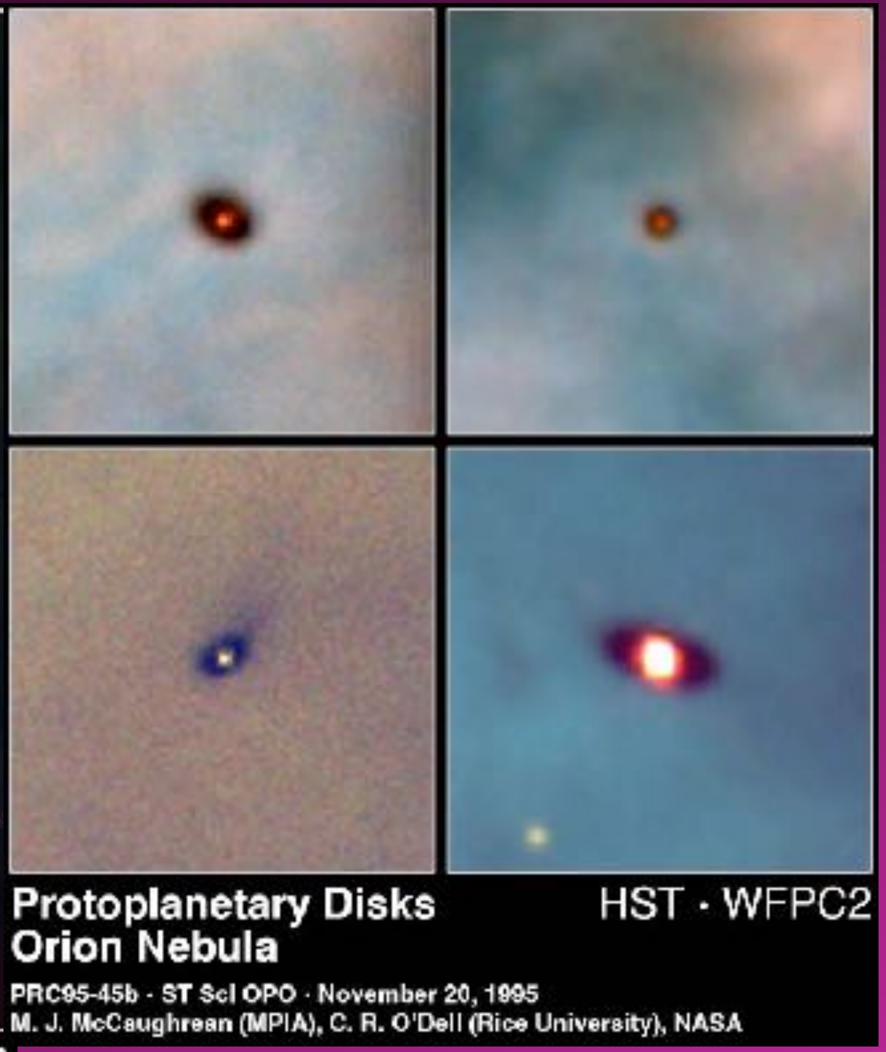
La vie est-elle un «impératif cosmique» ?

Christian de Duve

Nuages moléculaires géants: maternité des étoiles

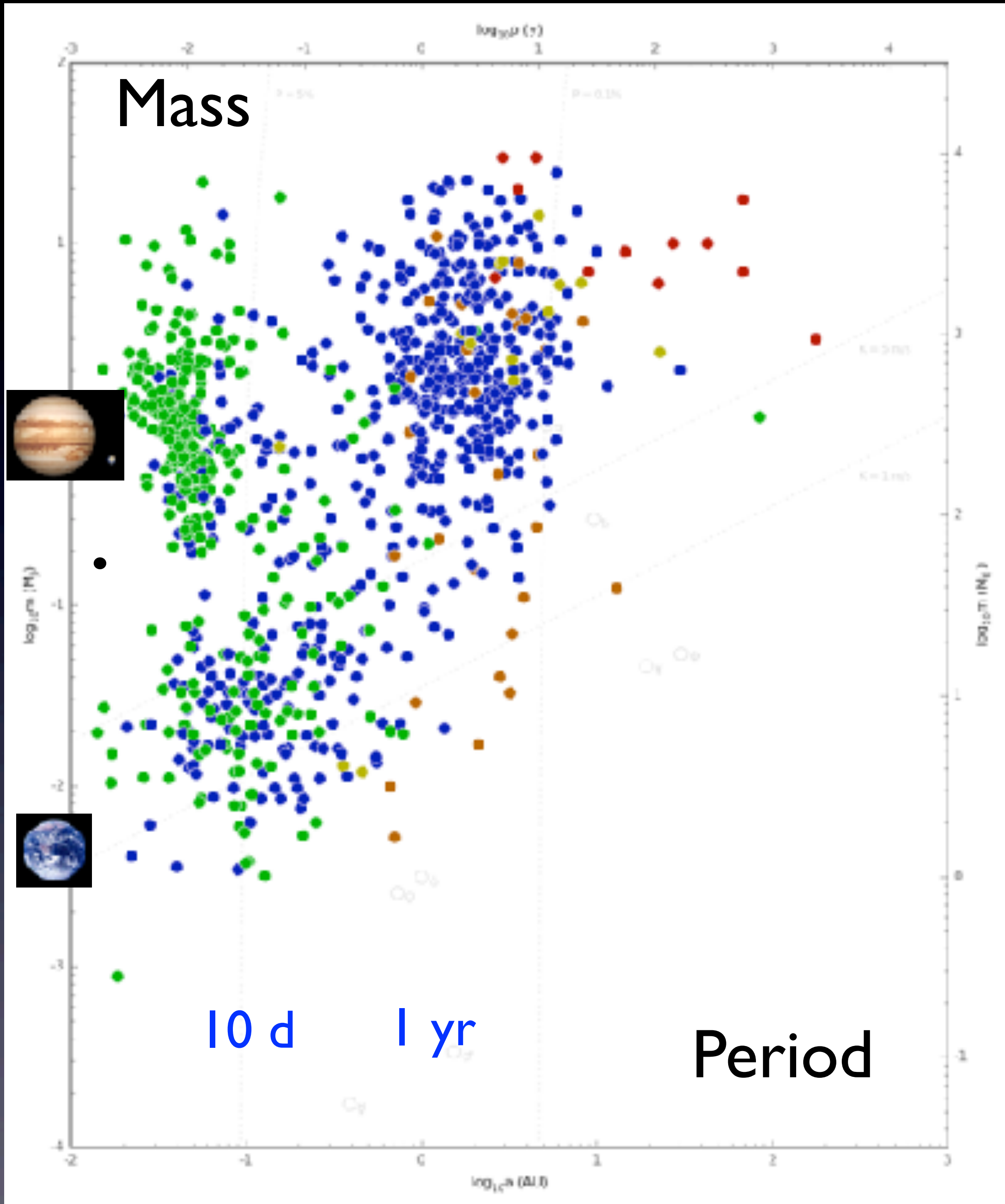
Là où tout commence…

L'observation des disques protoplanétaires



Les principales techniques de détection

* les vitesses radiales (spectroscopie Doppler)
* les transits planétaires
* l’imagerie directe
* l’astrométrie
* les lentilles gravitationnelles
* la « chronomètrie «

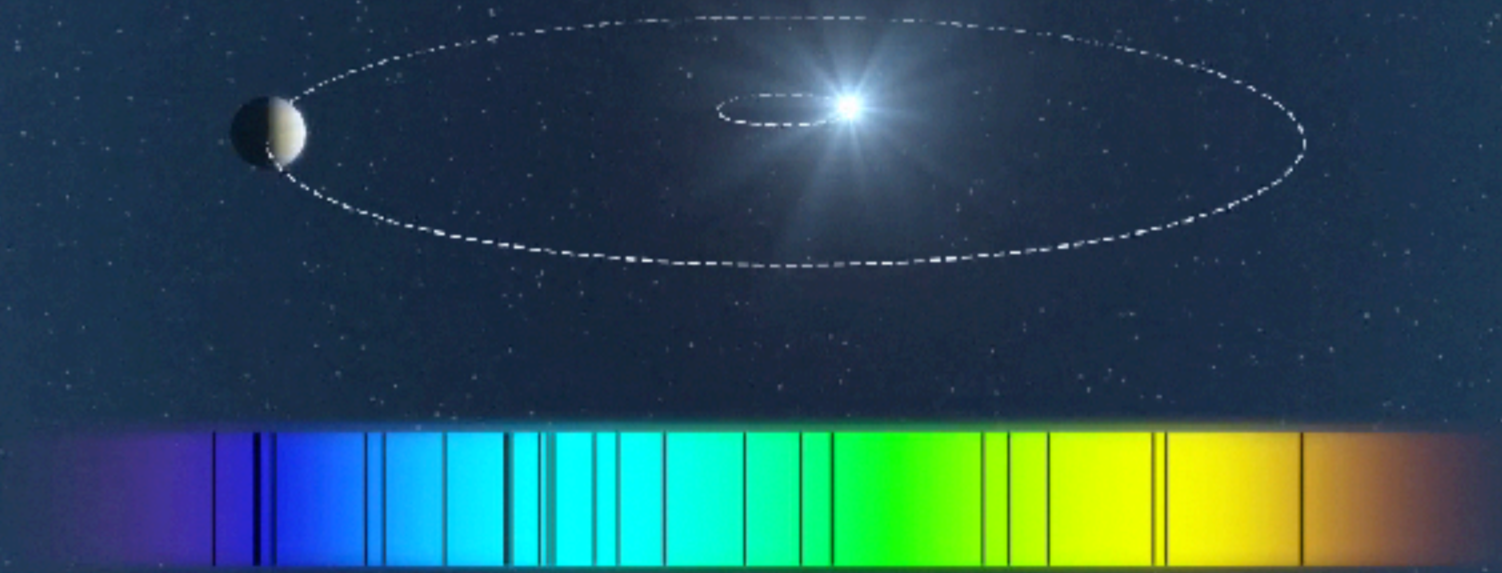


- radial velocity
- transit
- timing
- imaging
- microlensing

* les vitesses radiales (spectroscopie Doppler)

Detection of planets via Doppler spectroscopy

Present sensitivity $\delta\lambda/\lambda = 10^{-9}$



The spectrograph HARPS uses simultaneously 6000 spectral lines (cross-correlation technique)

Télescope de 3.6-m de La Silla

HARPS : Un spectrographe pour la recherche des exoplanètes




HD10180 : Un système avec plus de 7 planètes

$P_1 = 1.18$ day
$e_1 = 0$
$m_1 \sin i = 1.5\ M_\oplus$

$P_2 = 5.76$ days
$e_2 = 0.07$
$m_2 \sin i = 13.2\ M_\oplus$

$P_3 = 16.4$ days
$e_3 = 0.16$
$m_3 \sin i = 11.8\ M_\oplus$

$P_4 = 49.7$ days
$e_4 = 0.06$
$m_4 \sin i = 24.8\ M_\oplus$

$P_5 = 122.7$ days
$e_5 = 0.13$
$m_5 \sin i = 23.4\ M_\oplus$

$P_6 = 595$ days
$e_6 = 0.0$
$m_6 \sin i = 22\ M_\oplus$

$P_7 = 2150$ days
$e_7 = 0.15$
$m_7 \sin i = 67\ M_\oplus$

Lovis et al. 2010

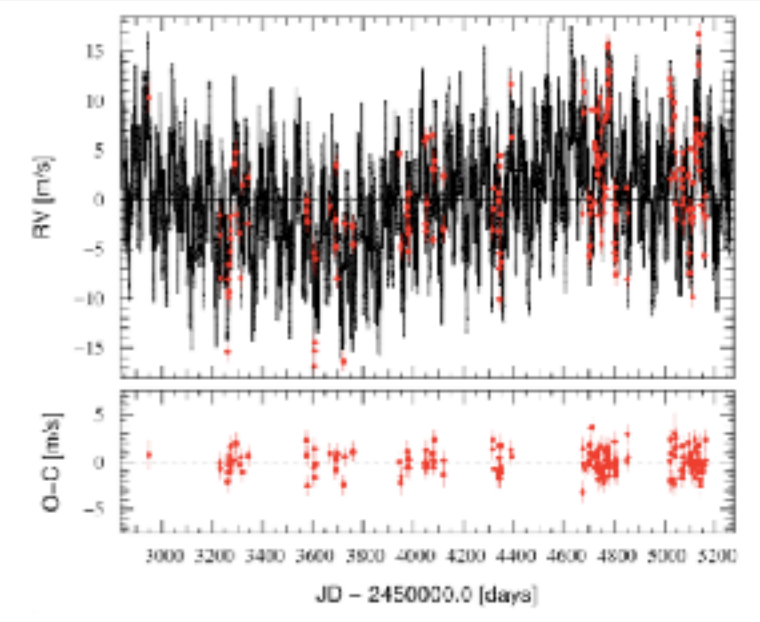
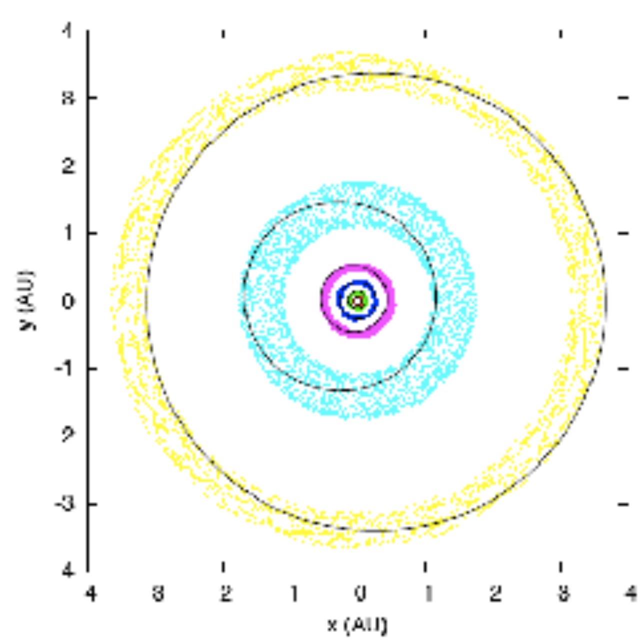
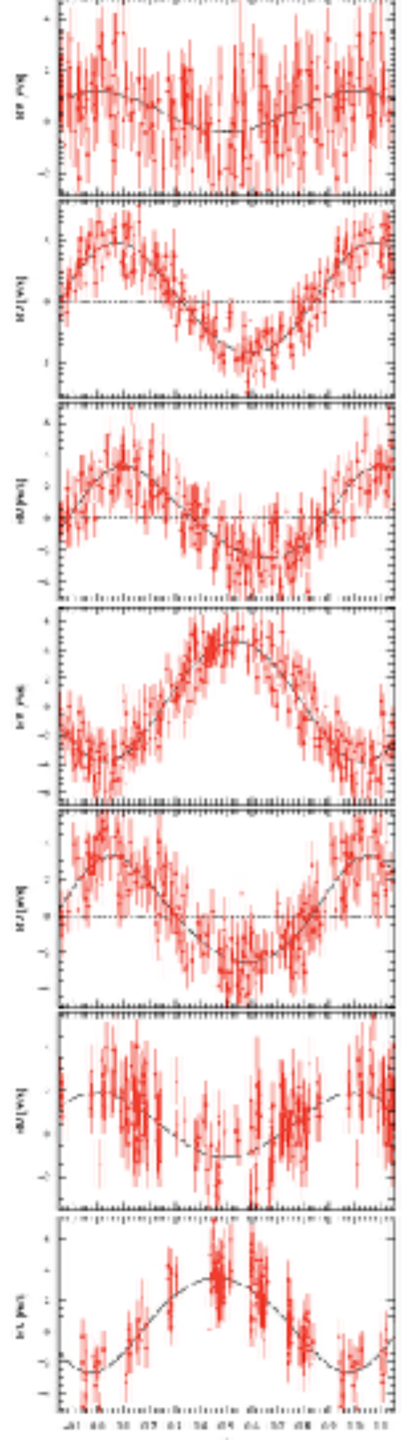
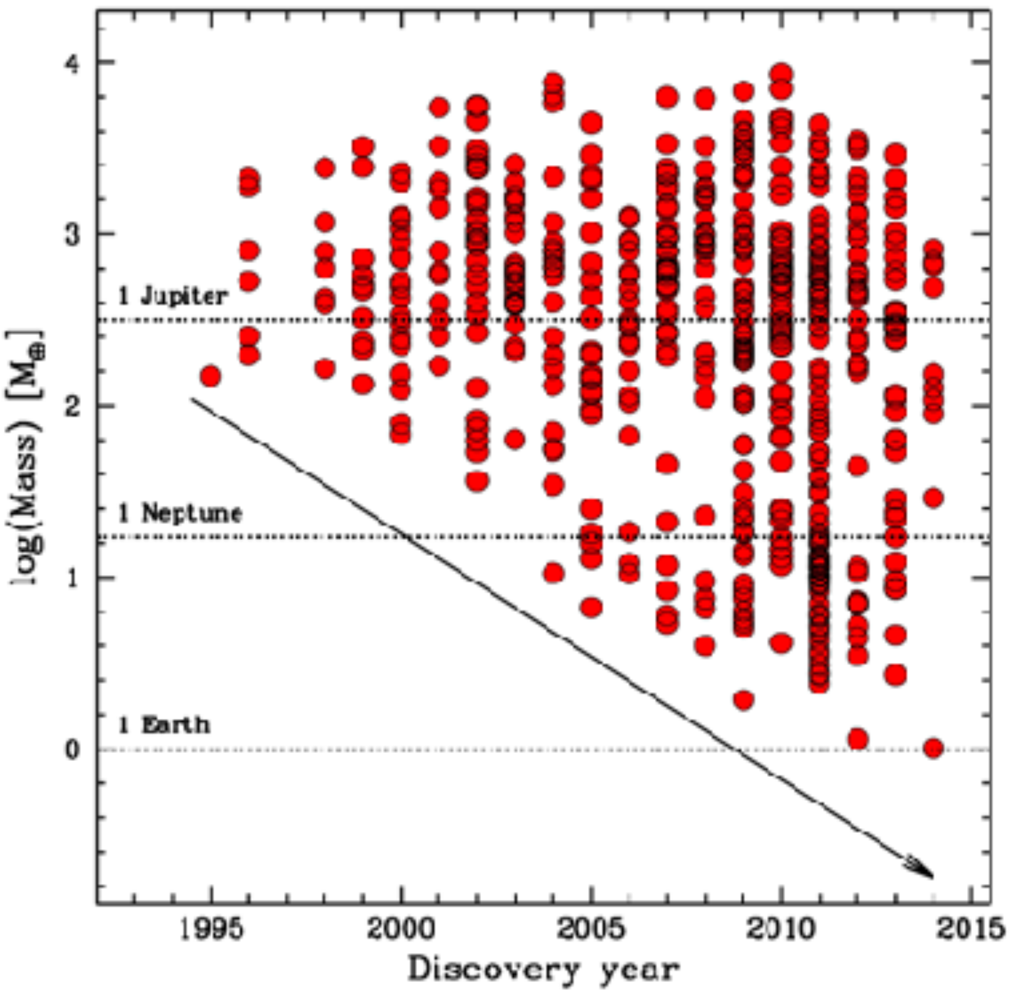


Fig. 5. Radial velocity time series with the 7-Keplerian model overplo







1 Jupiter
1 Neptune
1 Earth
log(Mass) [$M_\oplus$]
Discovery year
0
1
2
3
4
1995
2000
2005
2010
2015

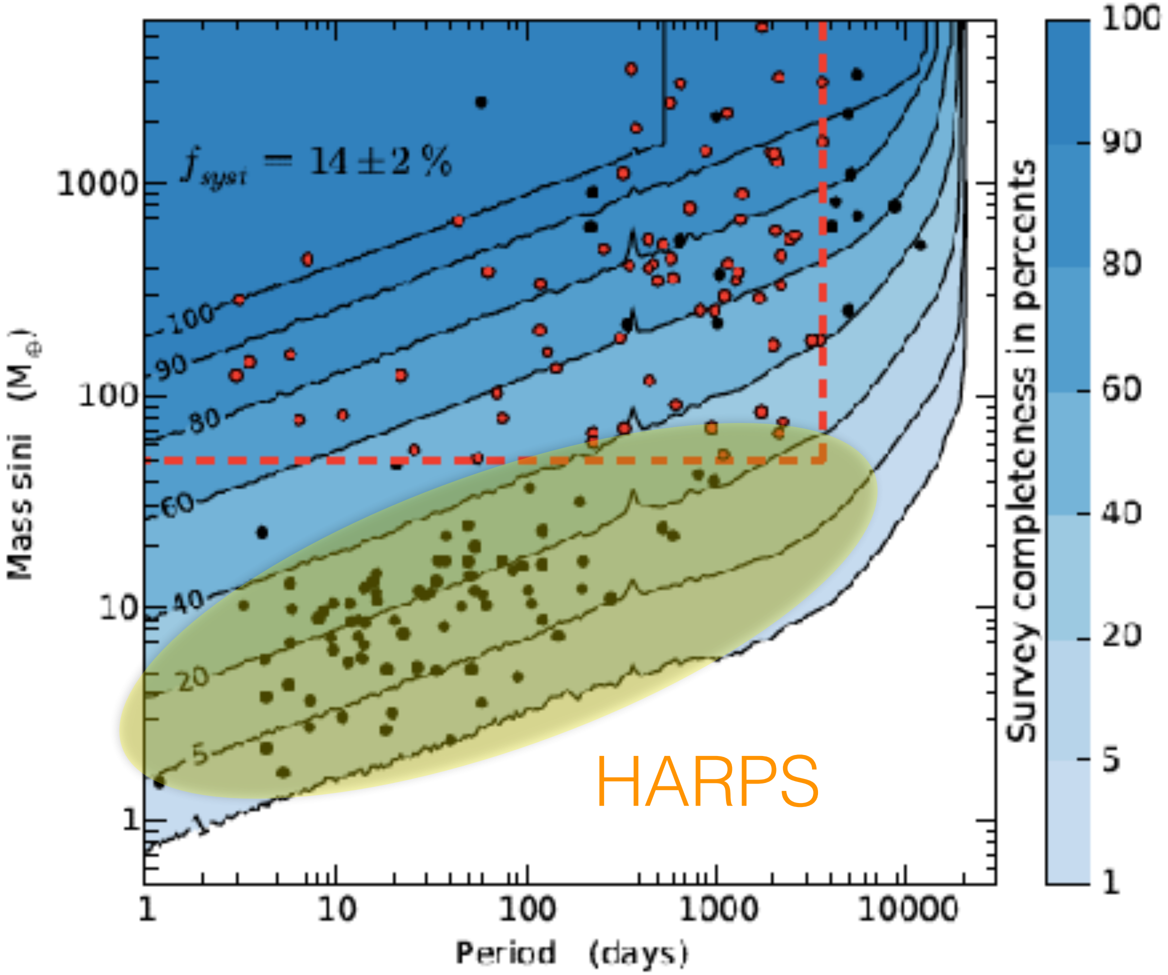


Fig. 5. Plot of the 169 planets of the considered HARPS+CORALIE sample in the $m_2 \sin i - \log P$ plane. The superimposed curves indicate the completeness of the survey. These detection probabilities are valid for the whole sample of 822 stars. After correcting for the detection bias, the fraction of stars with at least one planet more massive than 50 $M_\oplus$ and with a period smaller than 10 years is es-

Mayor et al. 2011

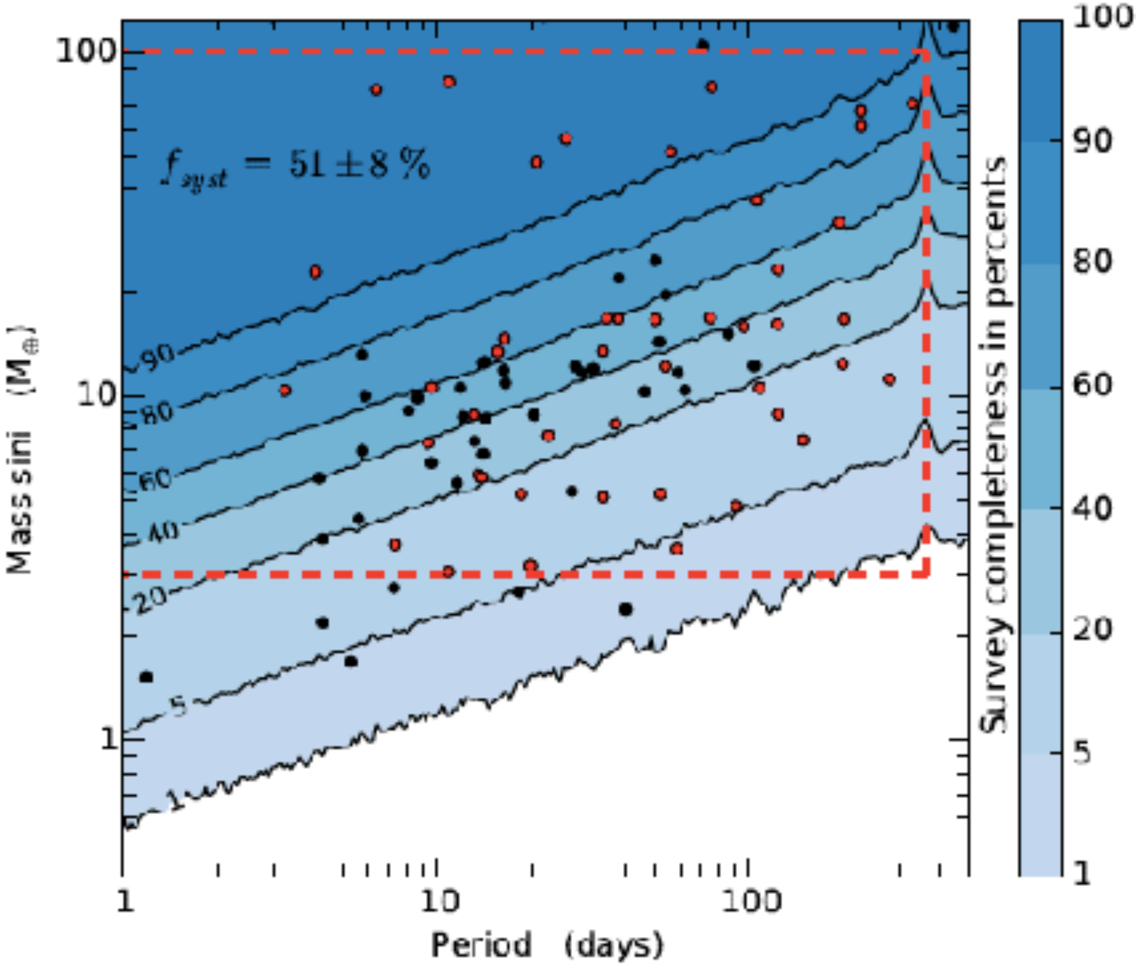
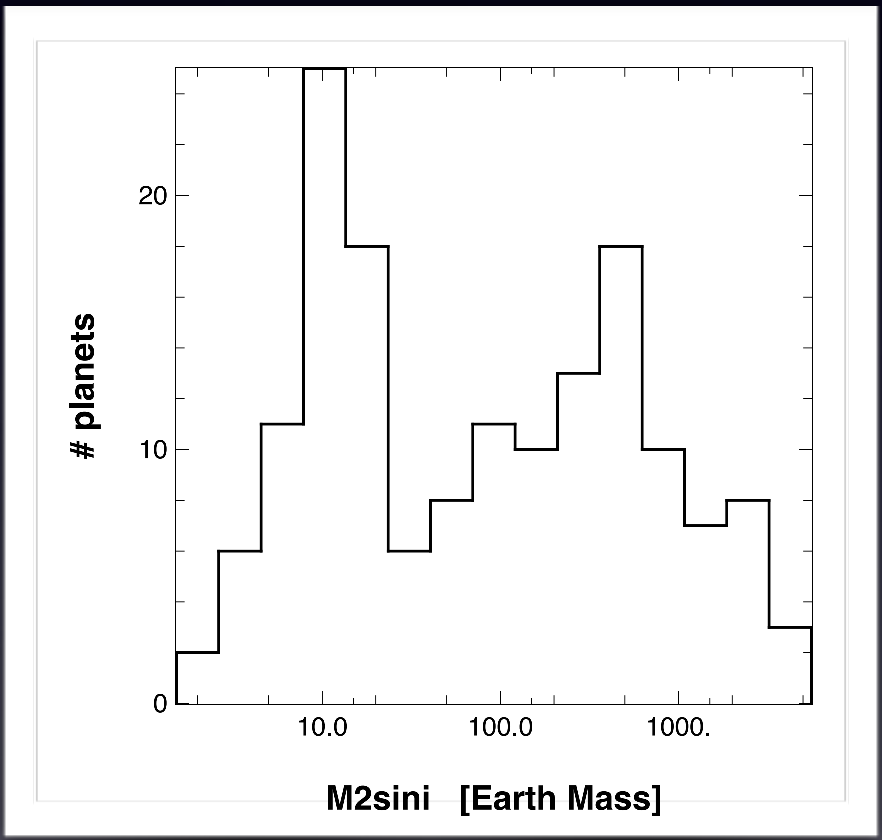


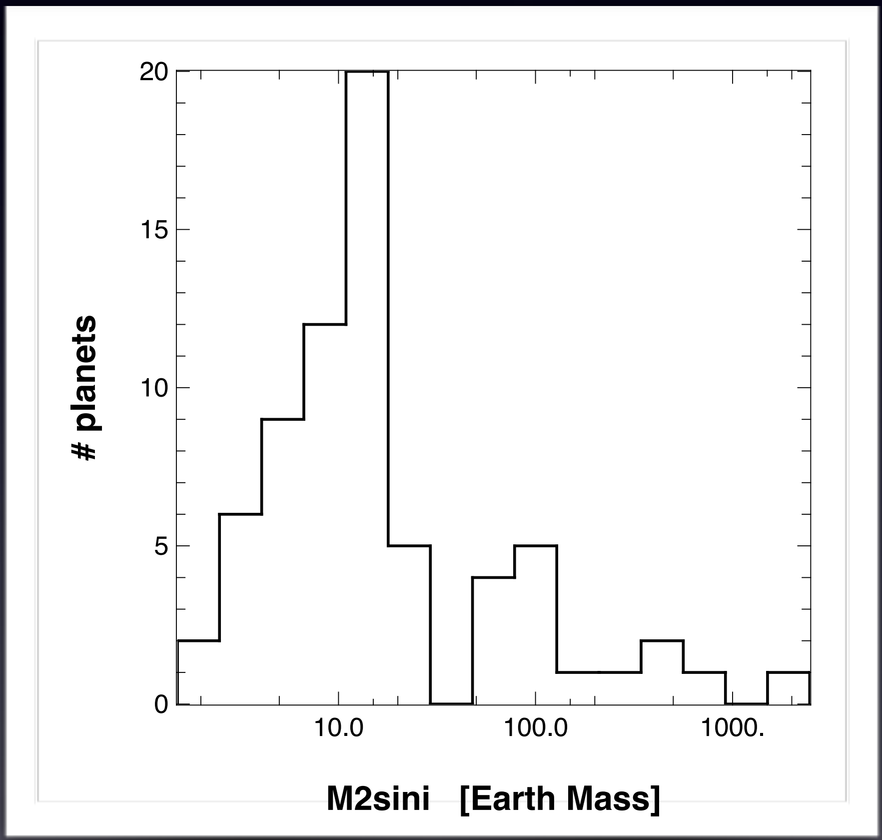
Fig. 6. Same as Fig. 5 but only for the HARPS subsample of 376 stars. The occurrence rate of planetary systems in the limited region between 3 and 100 $M_{\oplus}$, and with $P < 1$ year, is 51 ± 8 %. Again, only one planet per system (represented by the red dots) have been considered for the computation of the occurrence rate.

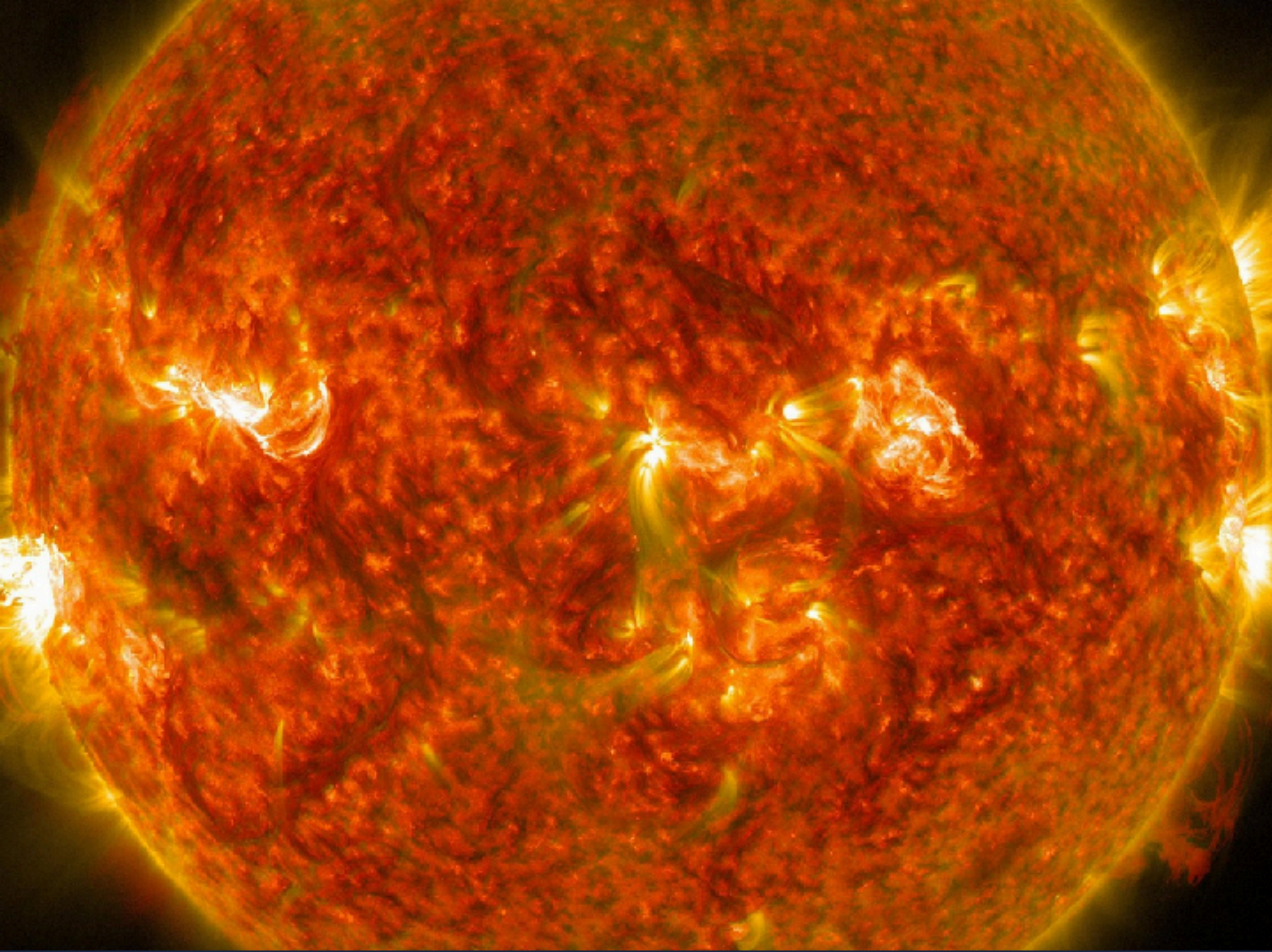
Distribution des masses planétaires

Détections quelque soit la période

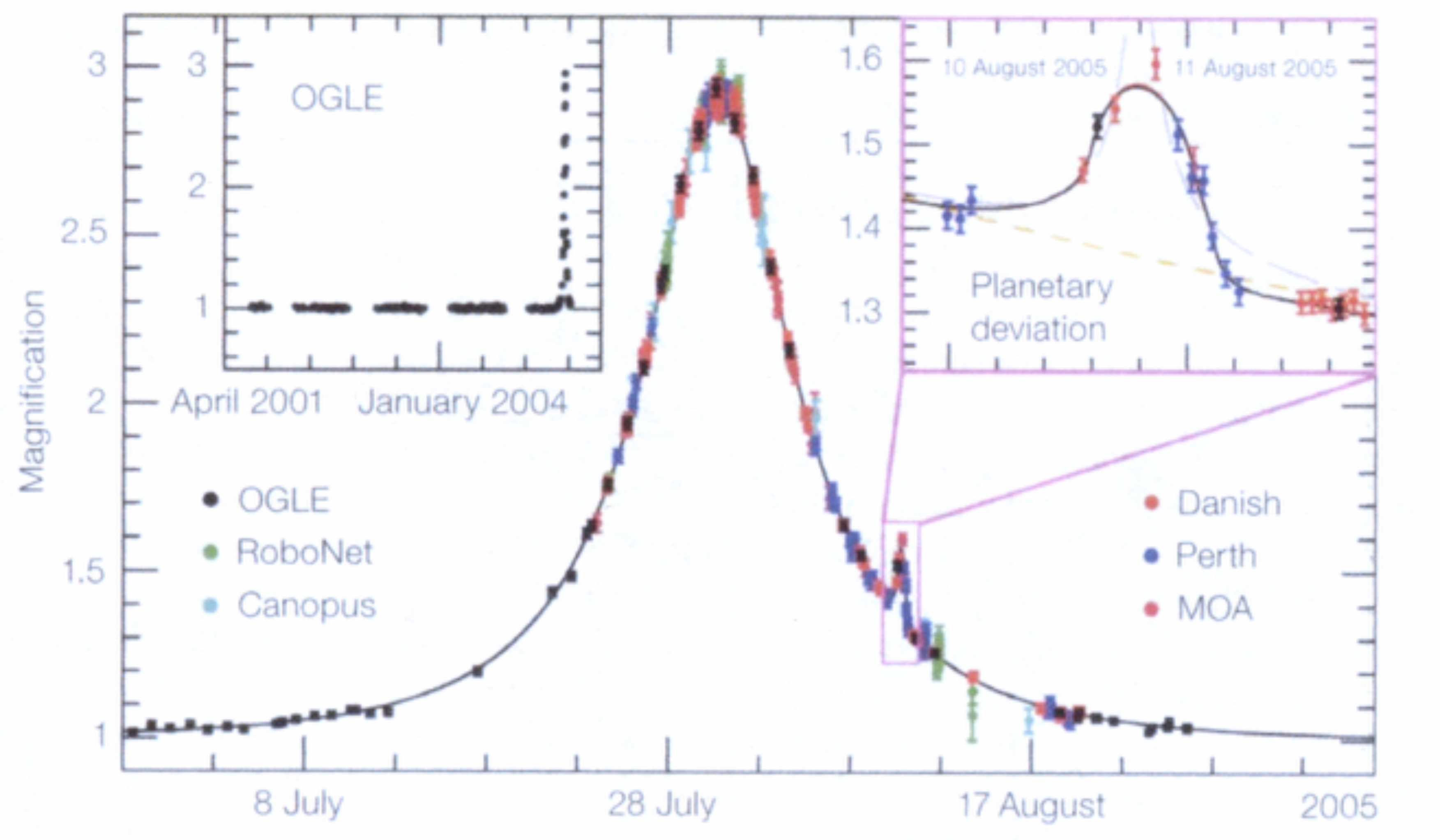


...et pour P < 100 jours
prépondérance des planètes avec des masses < 30 fois celle de la Terre





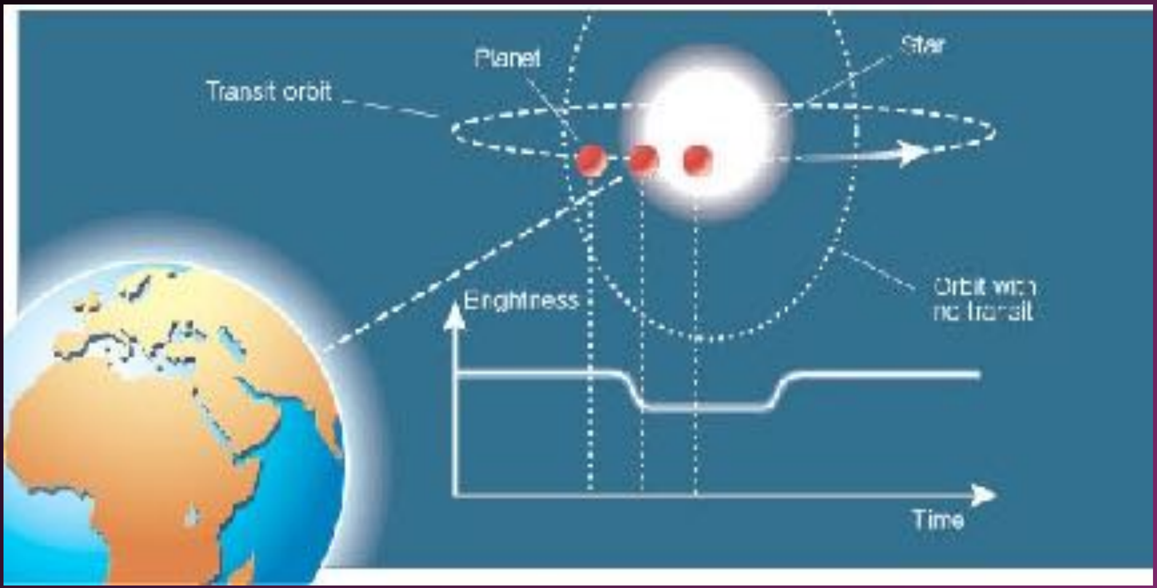
* les lentilles gravitationnelles

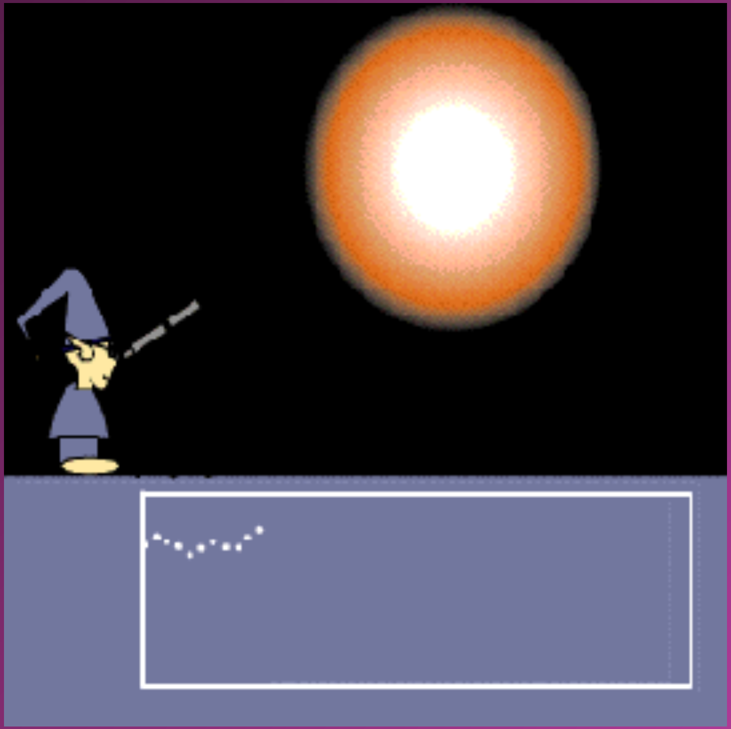


Mission spatiale .
Planétes de masse terrestre peuvent être détectées
Mais probabilité de détection très faible >>> étoiles très lointaines donc études ultérieures impossibles.

* les transits planétaires

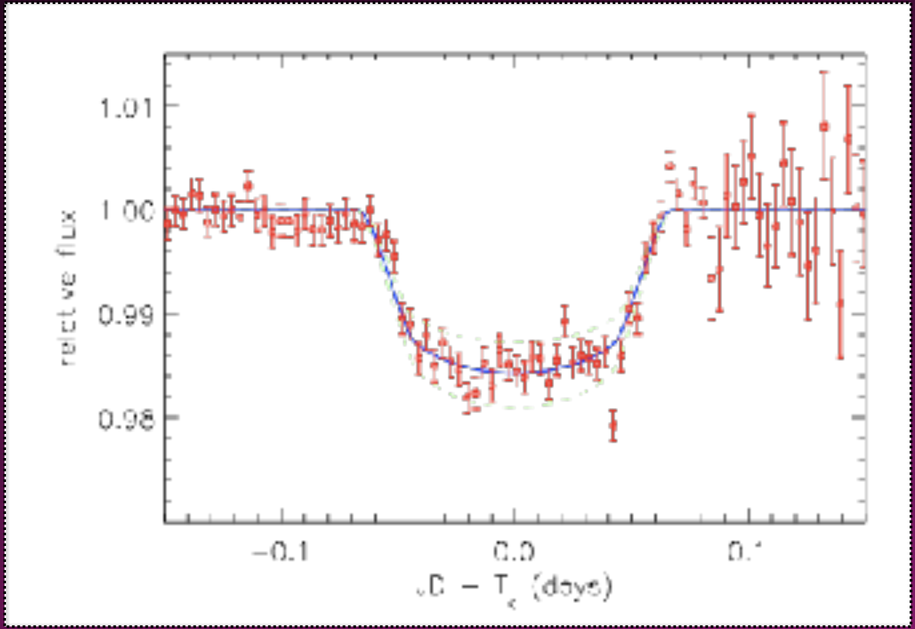
Une méthode de détection photométrique: transit





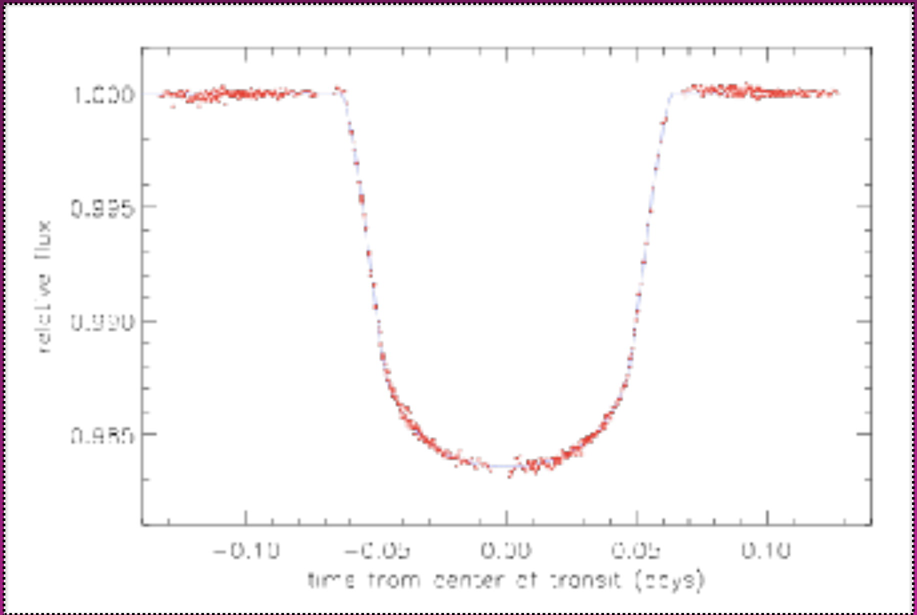
→ Rayon
Masse
Densité → Gazeuse

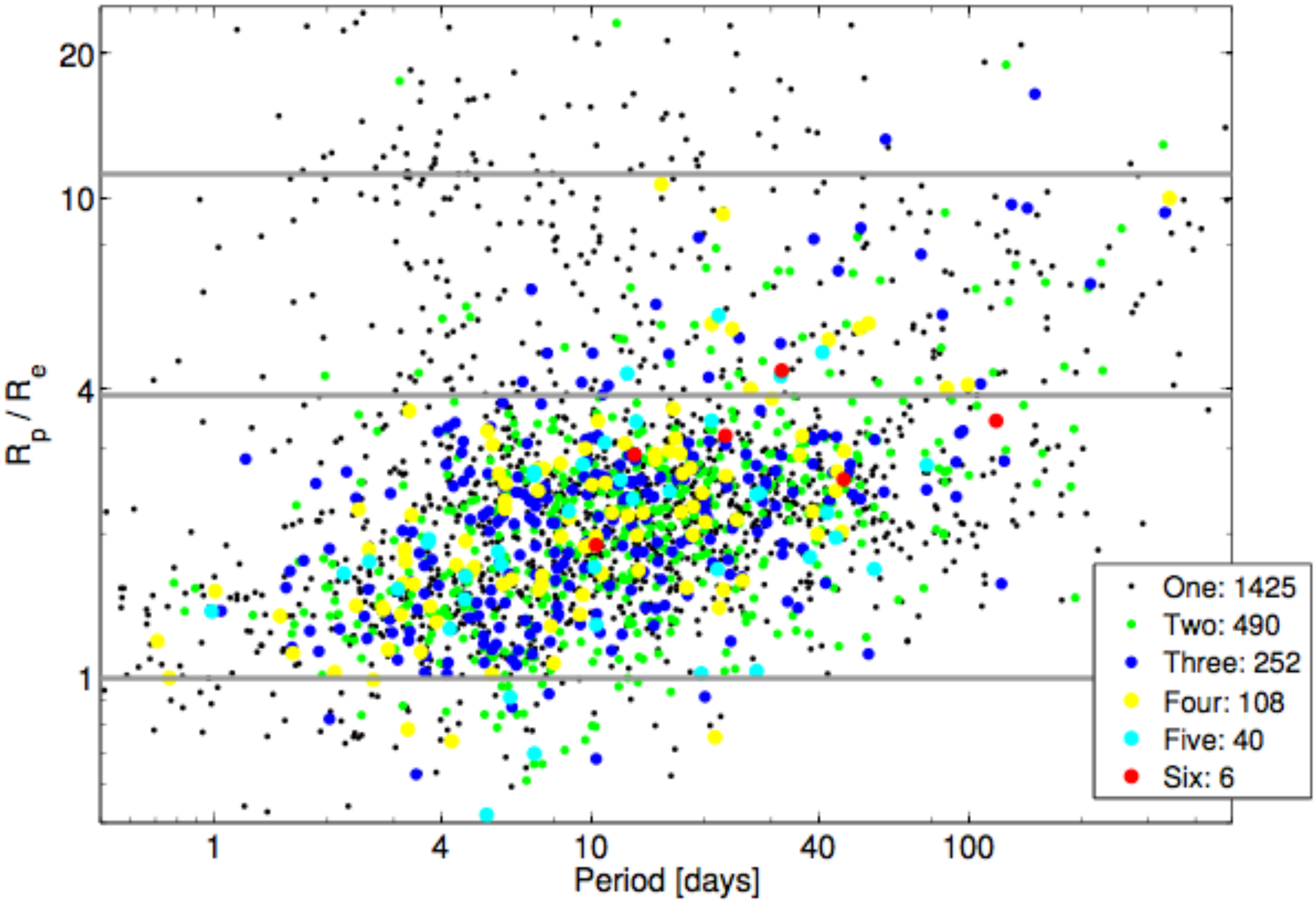
Amélioration des résultats depuis l'espace



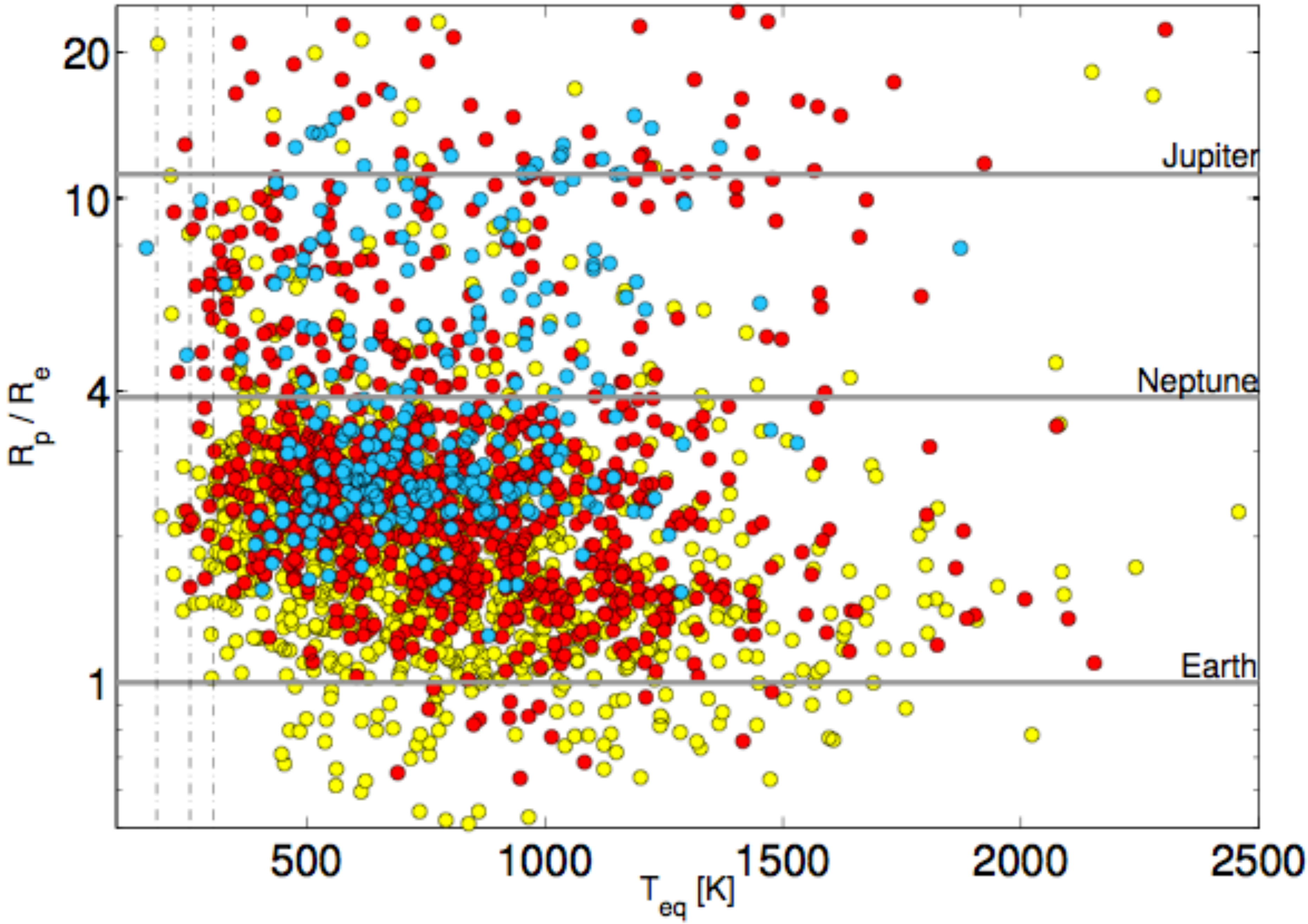
STARE

Télescope spatial Hubble

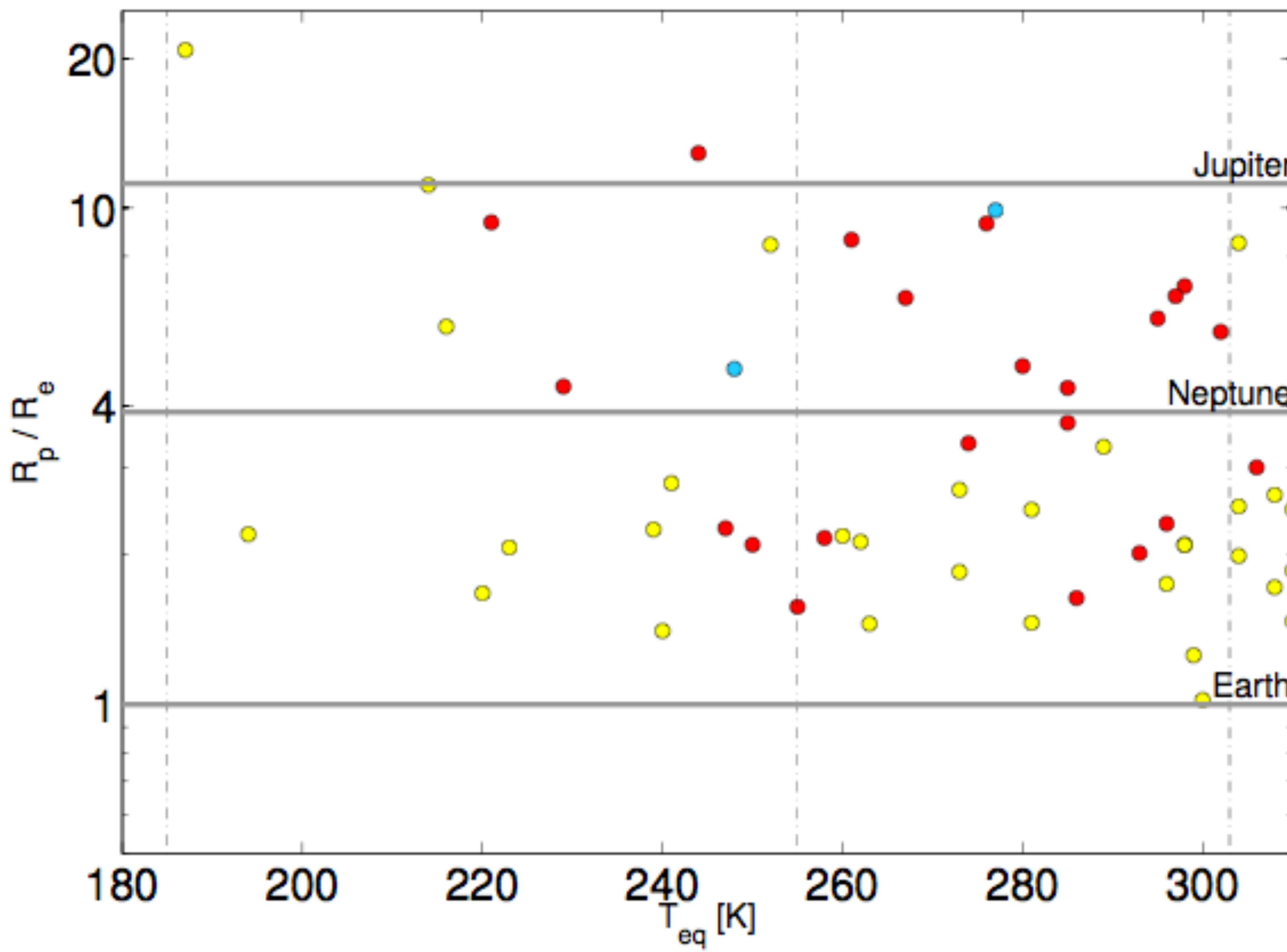




Batalha,N.M., et al. 2013, ApJS 204,24



20
10
4
1
R_p / R_e
500
1000
1500
2000
2500
T_{eq} [K]
Jupiter
Neptune
Earth



20
10
4
1
R_p / R_e
Jupiter
Neptune
Earth
180
200
220
240
260
280
300
T_{eq} [K]

A closely packed system of low-mass, low-density planets transiting Kepler-11

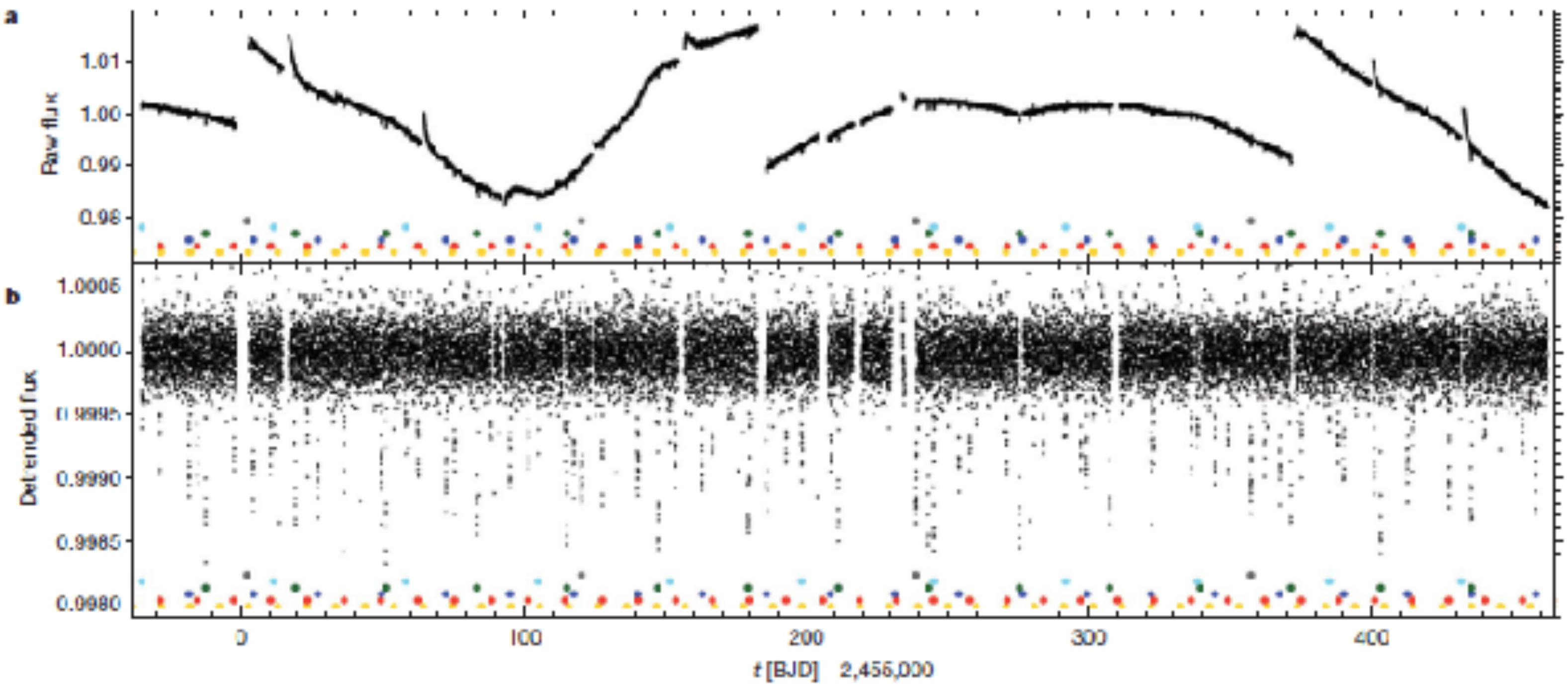
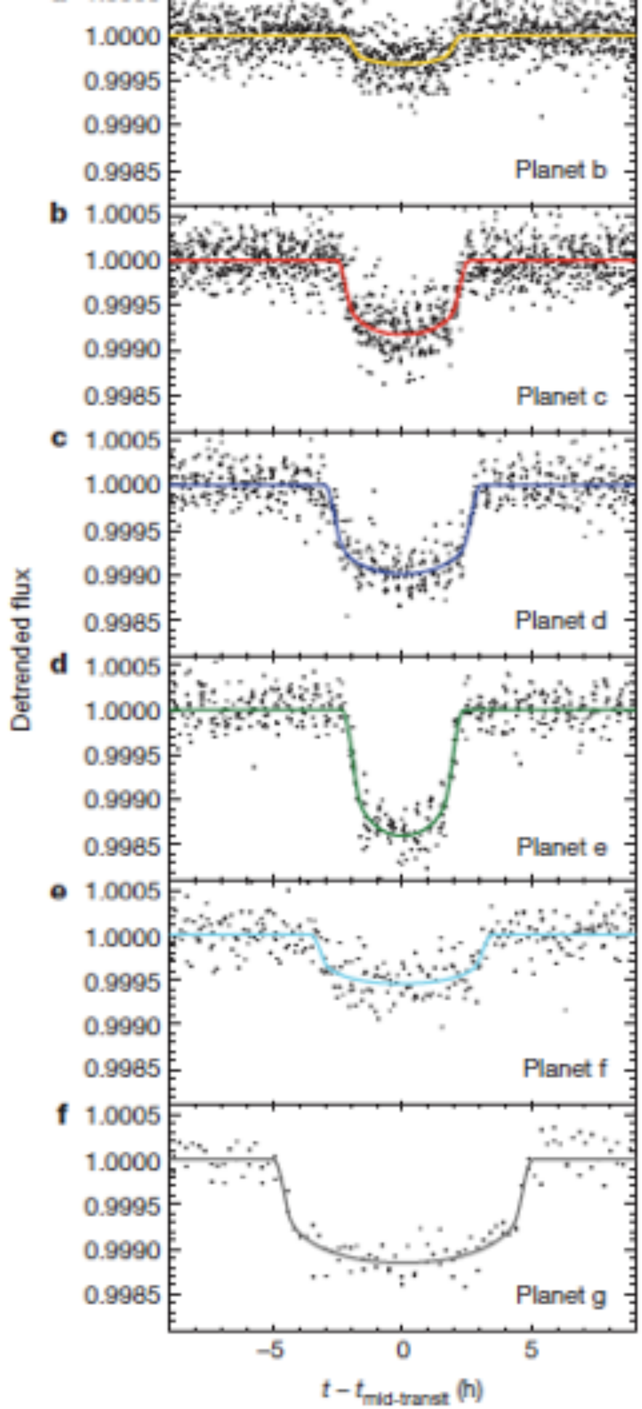


Figure 1 | Light curves of Kepler-11, raw and detrended. Kepler-11 is a G dwarf star with Kepler magnitude of 13.7, visual magnitude of 14.2 magnitudes, and celestial coordinates RA = 19 h 48 min 27.62 s, dec. = +41° 54′ 32.9″; alternative designations used in catalogues are KIC 6541920 and KOI-157. Kepler-11 is about 2,000 light years from Earth. Variations in the brightness of Kepler-11 have been monitored with an effective duty cycle of 91% over the time interval barycentric Julian date (BJD) 2,454,964.511 to 2,455,462.296, with data returned to Earth at a long cadence of 29.426 min. Shown are Kepler photometric data, raw from the spacecraft with each quarter normalized to its median (a) and after detrending with a polynomial filter (b)[11]; t represents time in days since BJD 2,455,000. These data are available from the MAST archive at http://archive.stsci.edu/kepler/. Note the difference in vertical scales between the two panels. The six sets of periodic transits are indicated with dots of differing colours. Four photometric data points representing the triply concurrent transit of planets Kepler 11b, Kepler 11d and Kepler 11e at BJD 2,455,435.2 (Supplementary Fig. 12) are not shown because their values lie below the plotted range. Data have also been returned for this target star at a cadence of 58.85 s since BJD 2,455,093.215, but our analysis is based exclusively on the long cadence data.

Lissauer J.J. et al. 2011, Nature 470,53



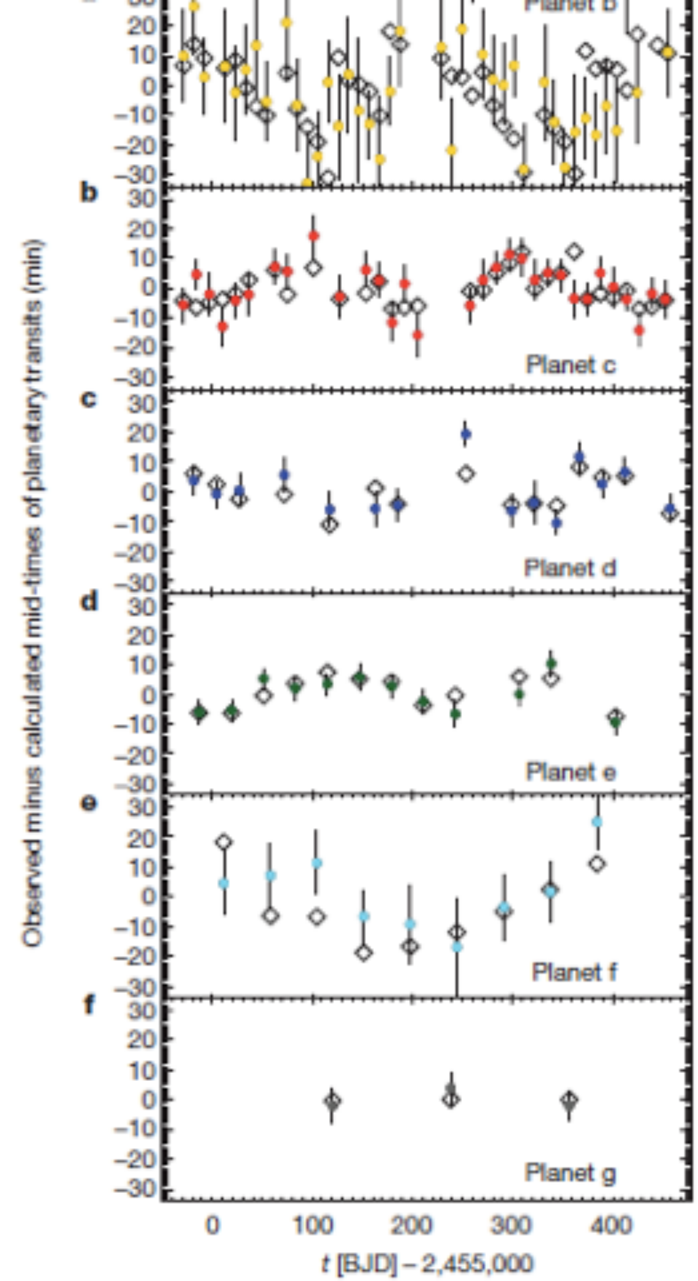
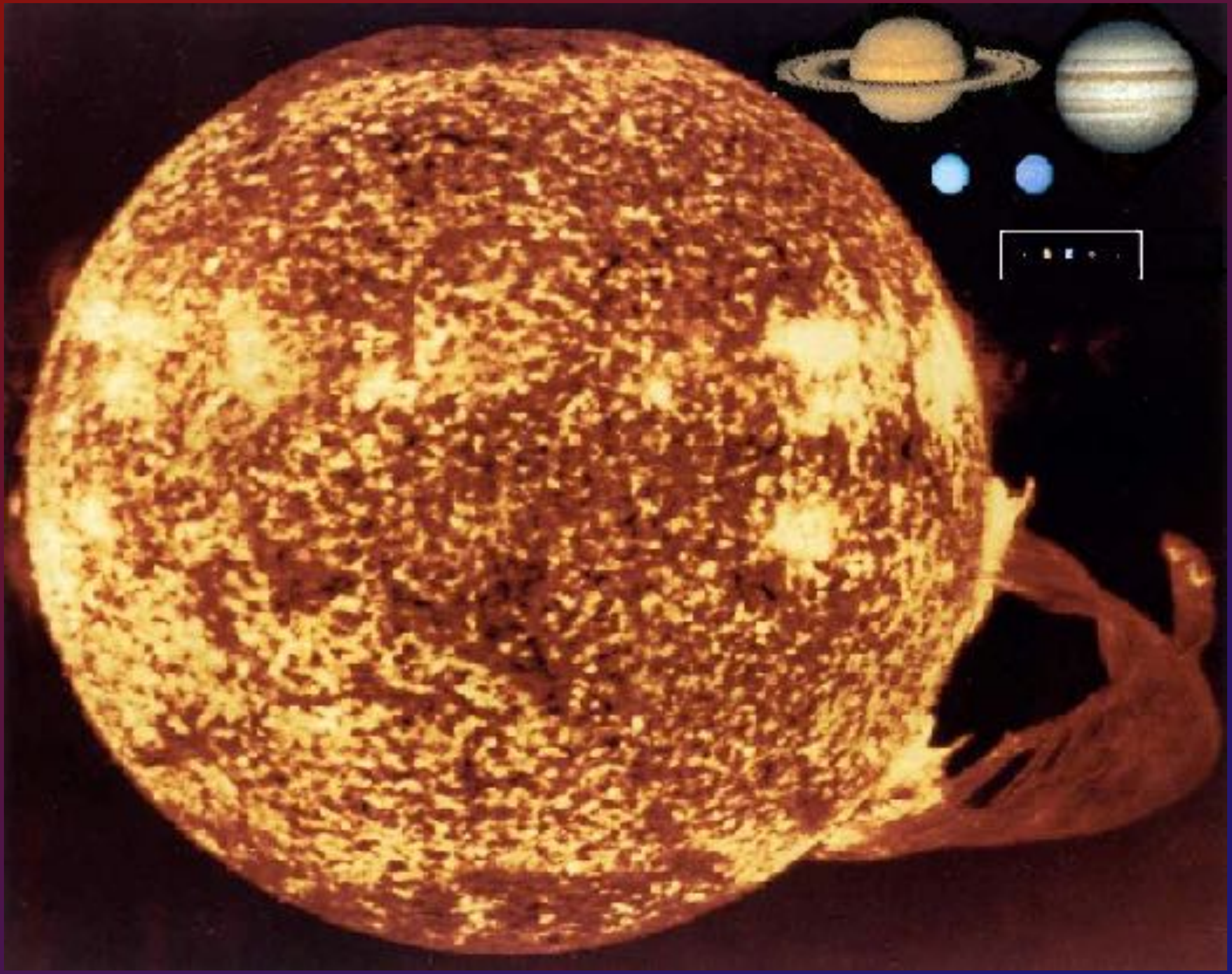
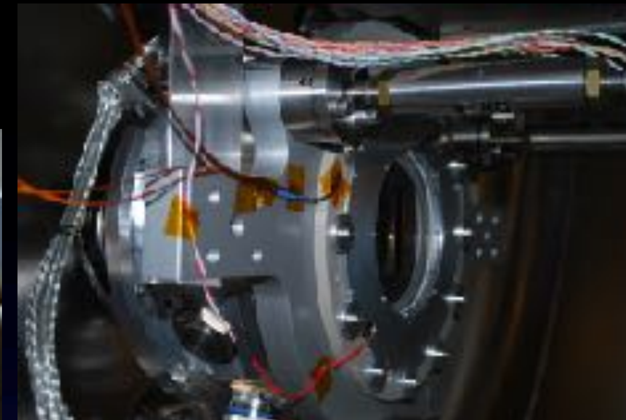


Figure 3 | Transit timing variations and dynamical fits. Observed mid-tim
of planetary transits (see section 3 of the Supplementary Information for
transit-fitting method and Supplementary Table 2 for transit times) minus
calculated linear ephemeris, are plotted as dots with 1σ error bars; colours



HARPS-N



Consortium

- Geneva Observatory (Head),
- CfA, Harvard University.
- INAF-TNG,
- University of St. Andrews,
- University of Edinburgh,
- Queens University Belfast

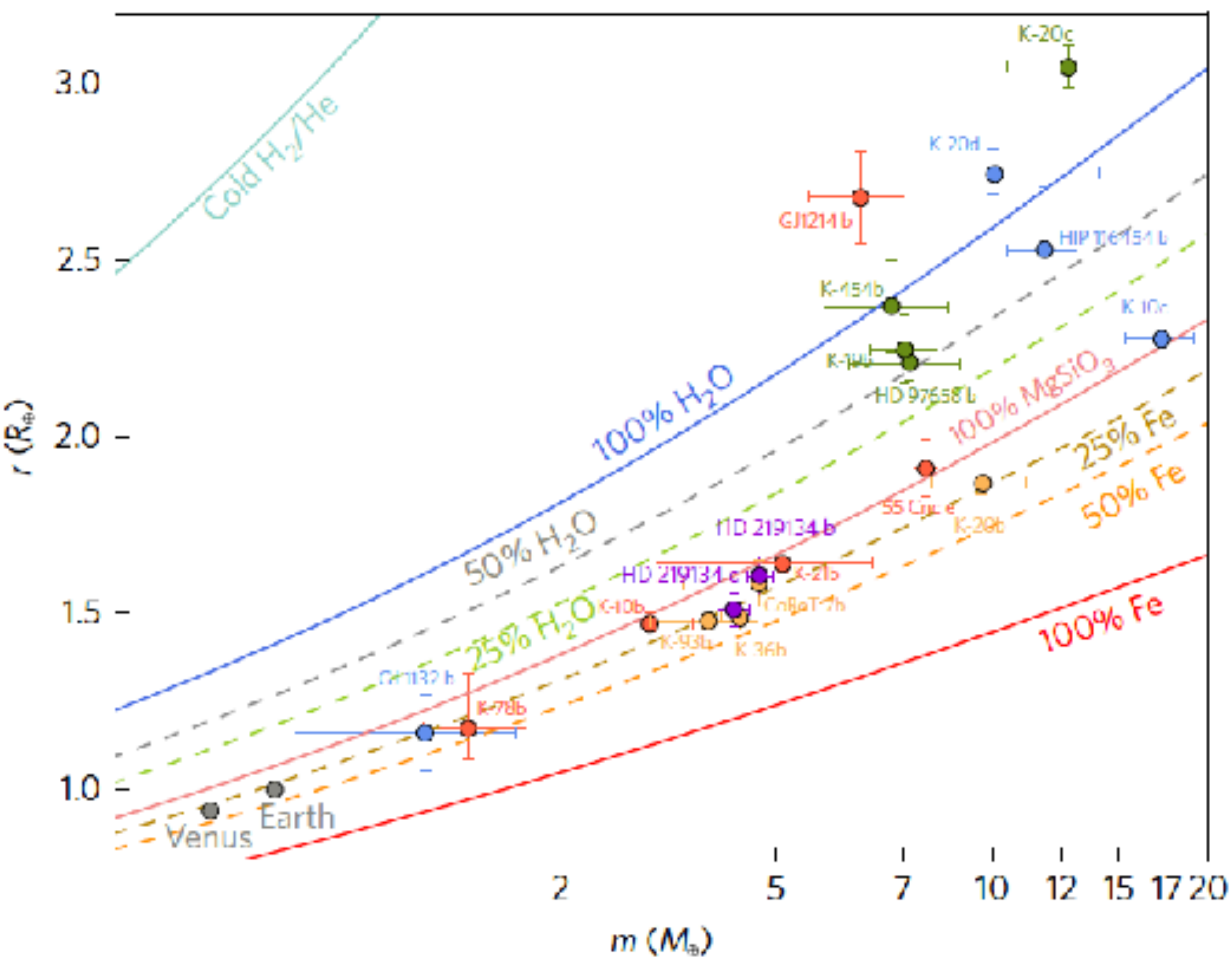
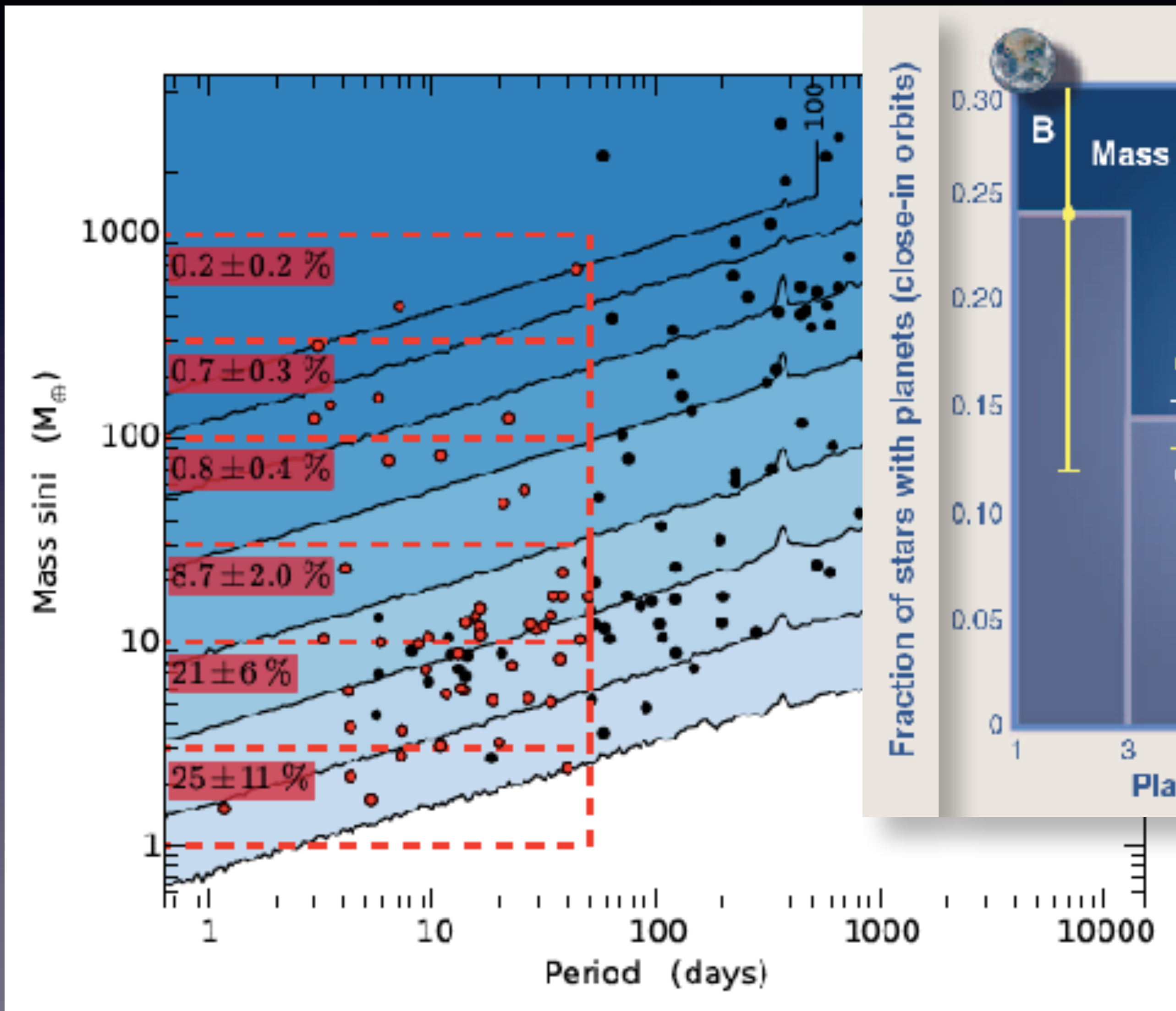
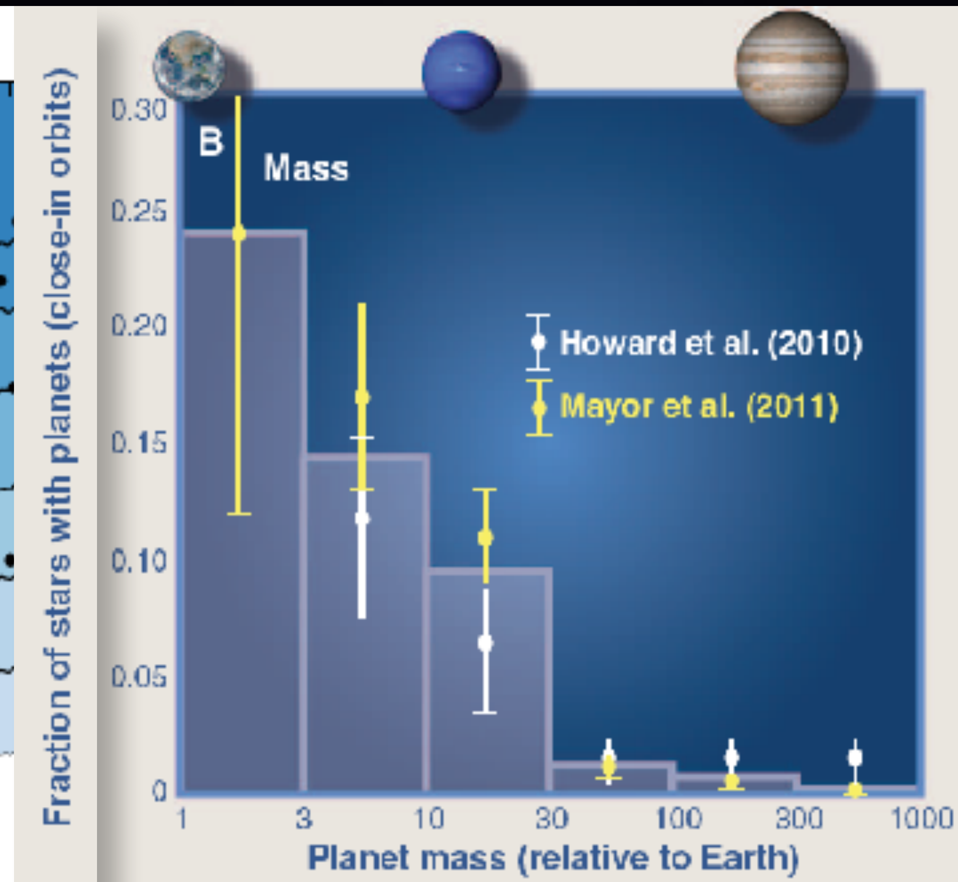


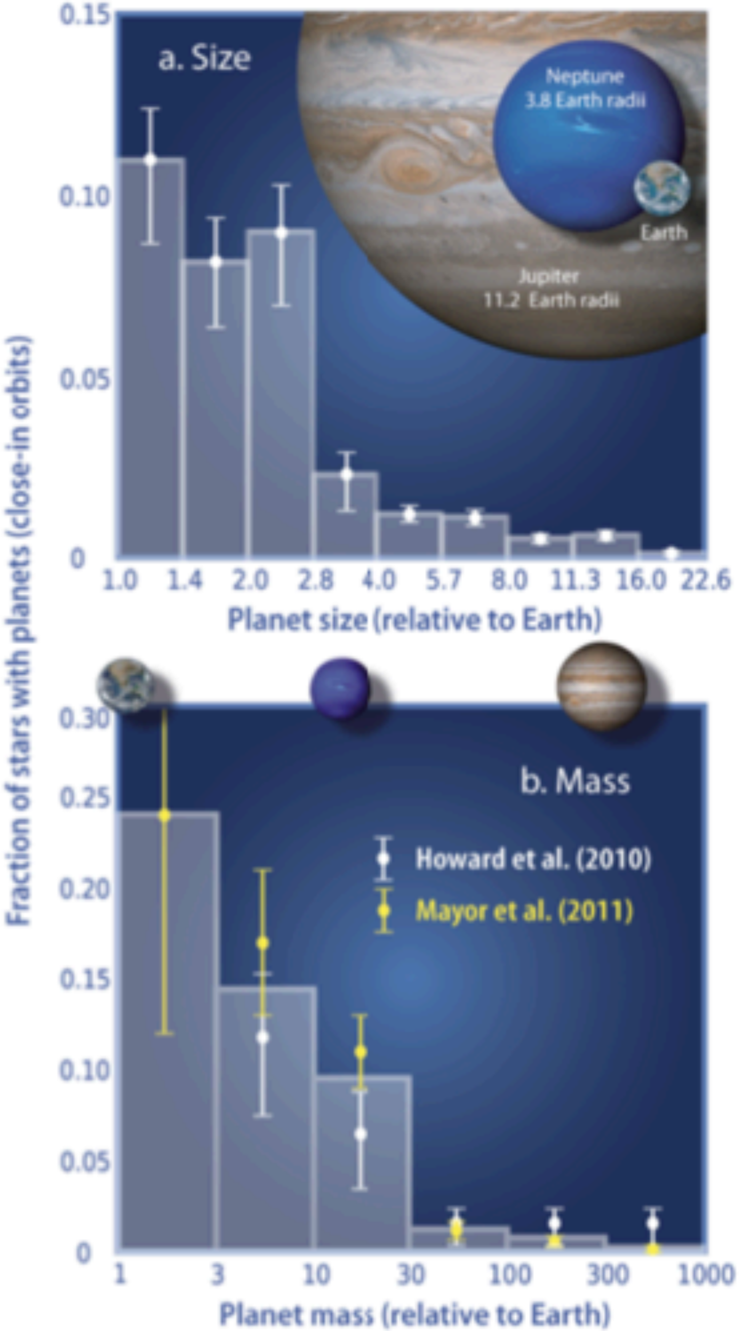
Figure 2 | Mass–radius relationship for small planets with precisions on the masses better than 20%. The solid lines are theoretical mass–radius curves from previous work[20].

Orbital periods < 50 days:
=> increase of f(m) towards low masses





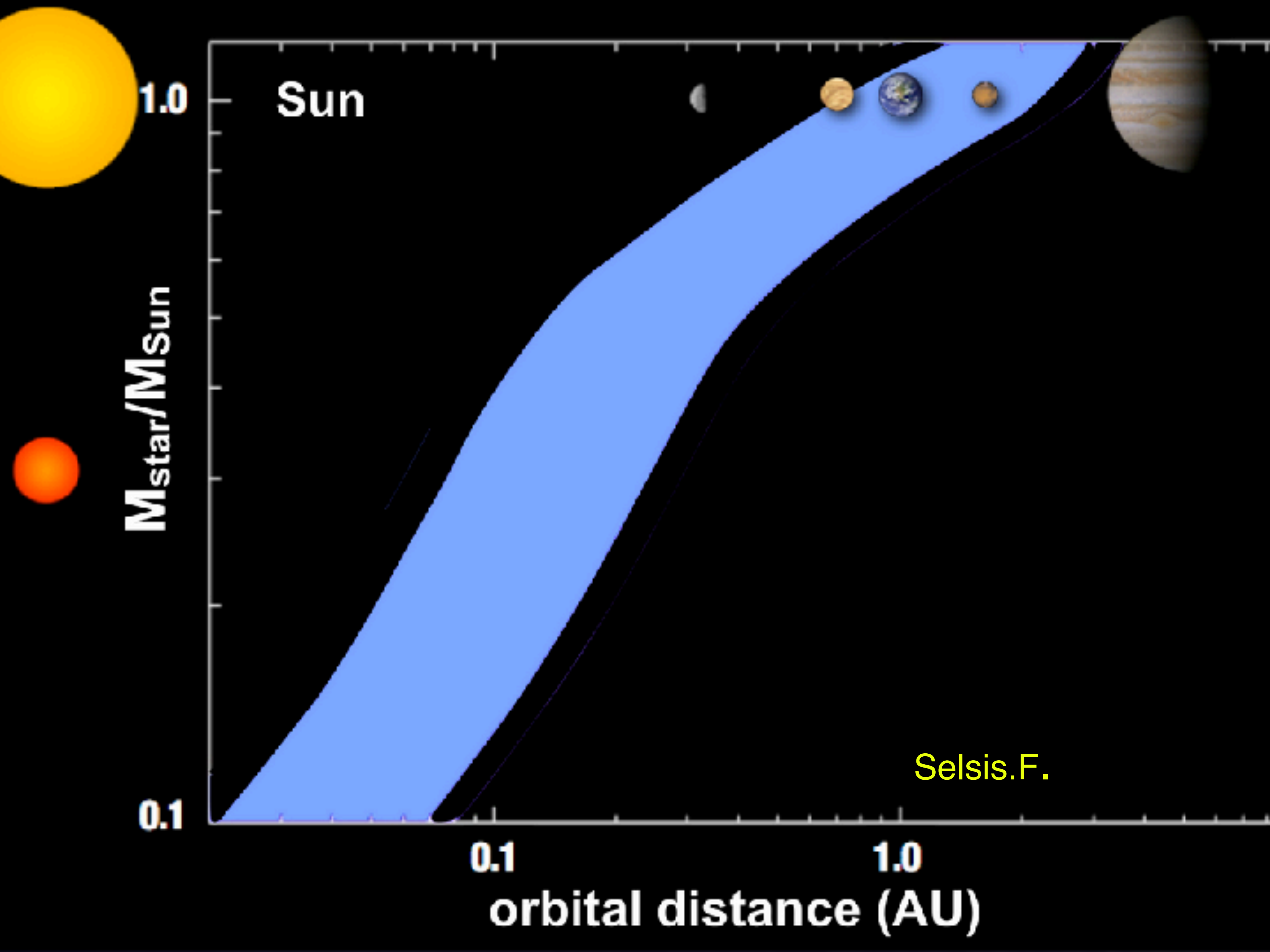
Mayor et al. 2011



Comparison RV surveys and Kepler results:

Kepler size distribution

Keck and HARPS RV Surveys:
Mass distributions


Sun
1.0
0.1
Mstar/MSun
0.1
1.0
orbital distance (AU)
Selsis.F.

Quelques instruments en construction

* ESPRESSO (VR)
* NIRPS (VR IR)
* CARMENES (VR VIS+IR)
* NGTS (transits sol)
* CHEOPS (satellite pour transits)
* TESS (satellite pour transits)
* PLATO (satellite pour transits et asterosismologie)
* les imagiers (SPHERE, GPI,…)

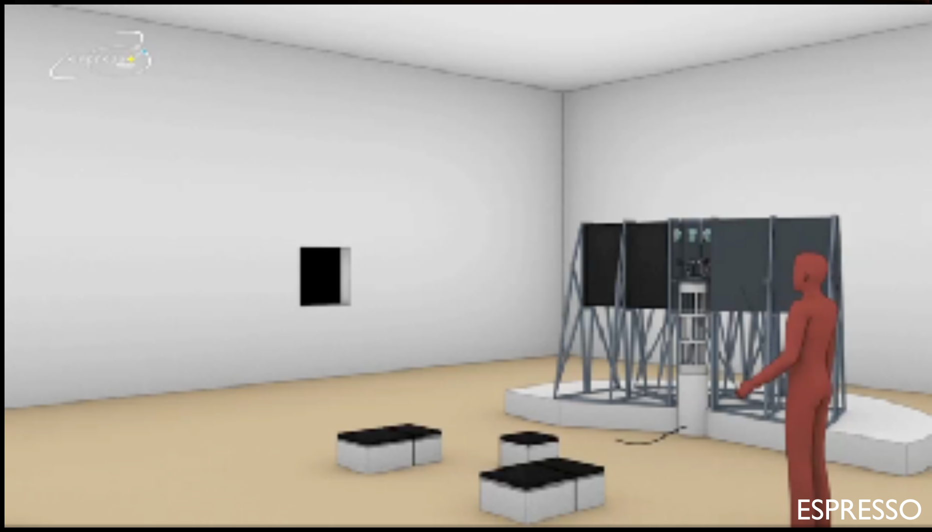
ESPRESSO on ESO VLT

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

- Ultra-stable spectrograph for the VLT
- R=120'000
- visible: blue + red arms
- can use any of the UTs (coudé train)

- Consortium : CH, Italy, Portugal, Spain
- FDR in June 2013
- On the sky : 2017

- Precision in RV : < 10 cm/s
- Goal : Very low-mass planets



Brazil - Can - CH - F - P - S - UK

A red arm for HARPS on the 3.6m/ESO

SCIENCE:
- search for habitable worlds around M stars
- follow up of space missions (TESS, PLATO)
- atmosphere characterisation

CONTEXT:
- Large GTO (>700 nights)
- No harm on HARPS + simultaneous use
- TESS => quickly on the sky (=> 2019)
- ESO policy: 3.6m “dedicated” to exoplanets, 2025+

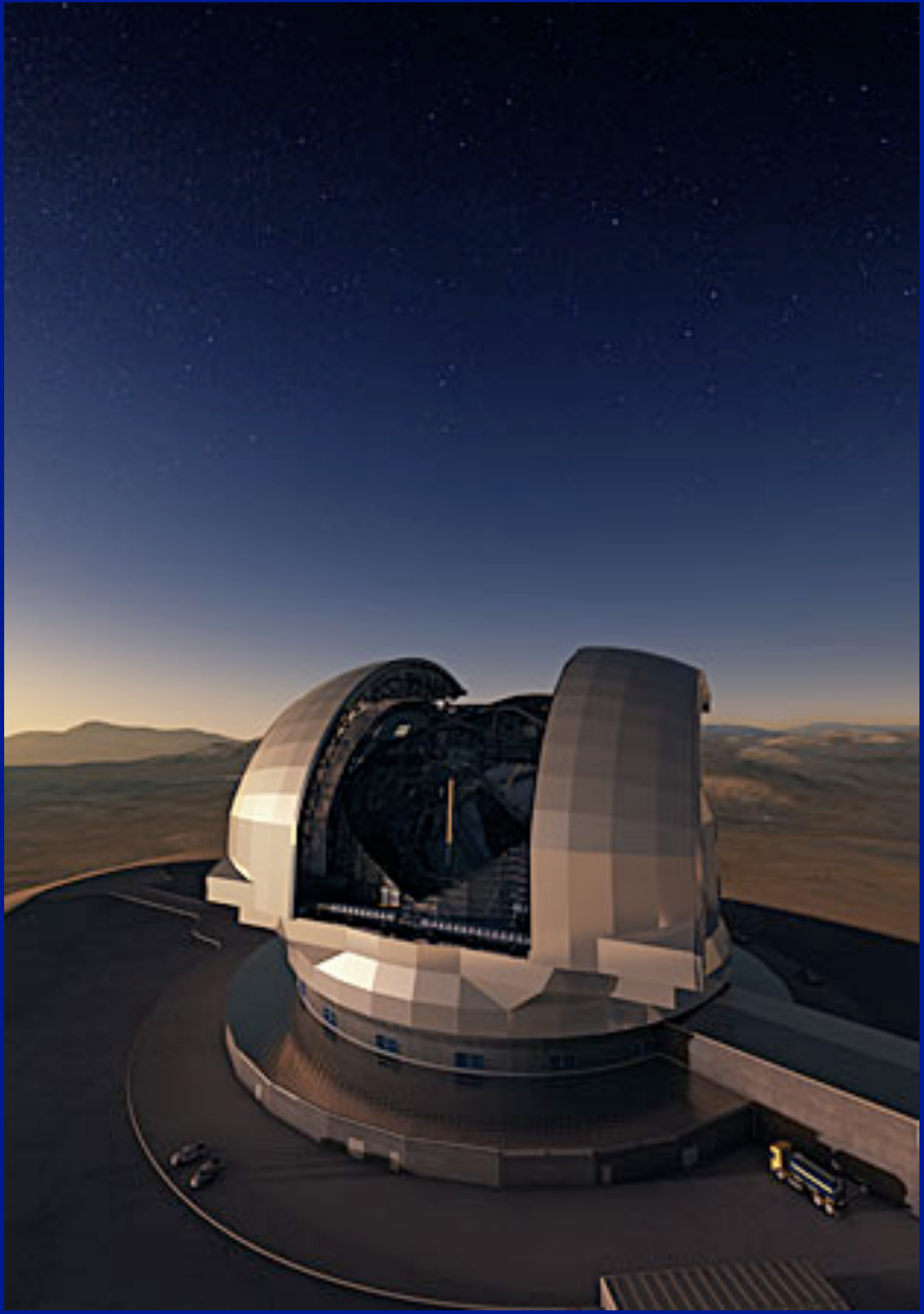
Contract being signed with ESO

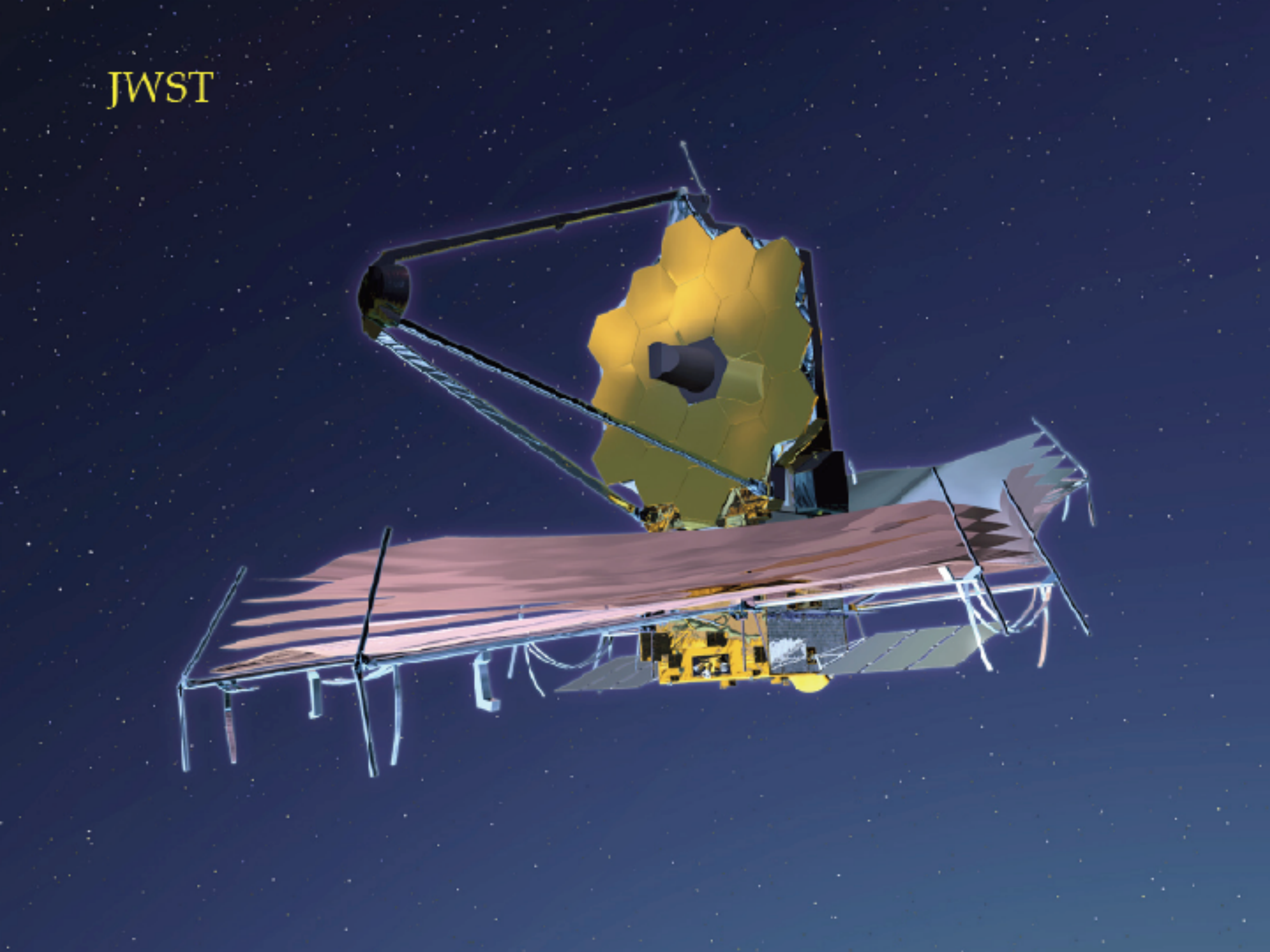
E-ELT

Un projet de télescope européen de 39 m de diamètre.

2020

Cerro Armazones
Désert d'Atacama
Chili




JWST

Successful “classical” programmes

Programs that have discovered TEP’s include:

HATNET	56 Planets
OGLE	8 Planets
QATAR	2 Planets
TRES	5 Planets
XO	5 Planets
WASP	106 Planets

Factory TEP discovery
=> WASP-150b


WASP

NGTS
NEXT-GENERATION TRANSIT SURVEY

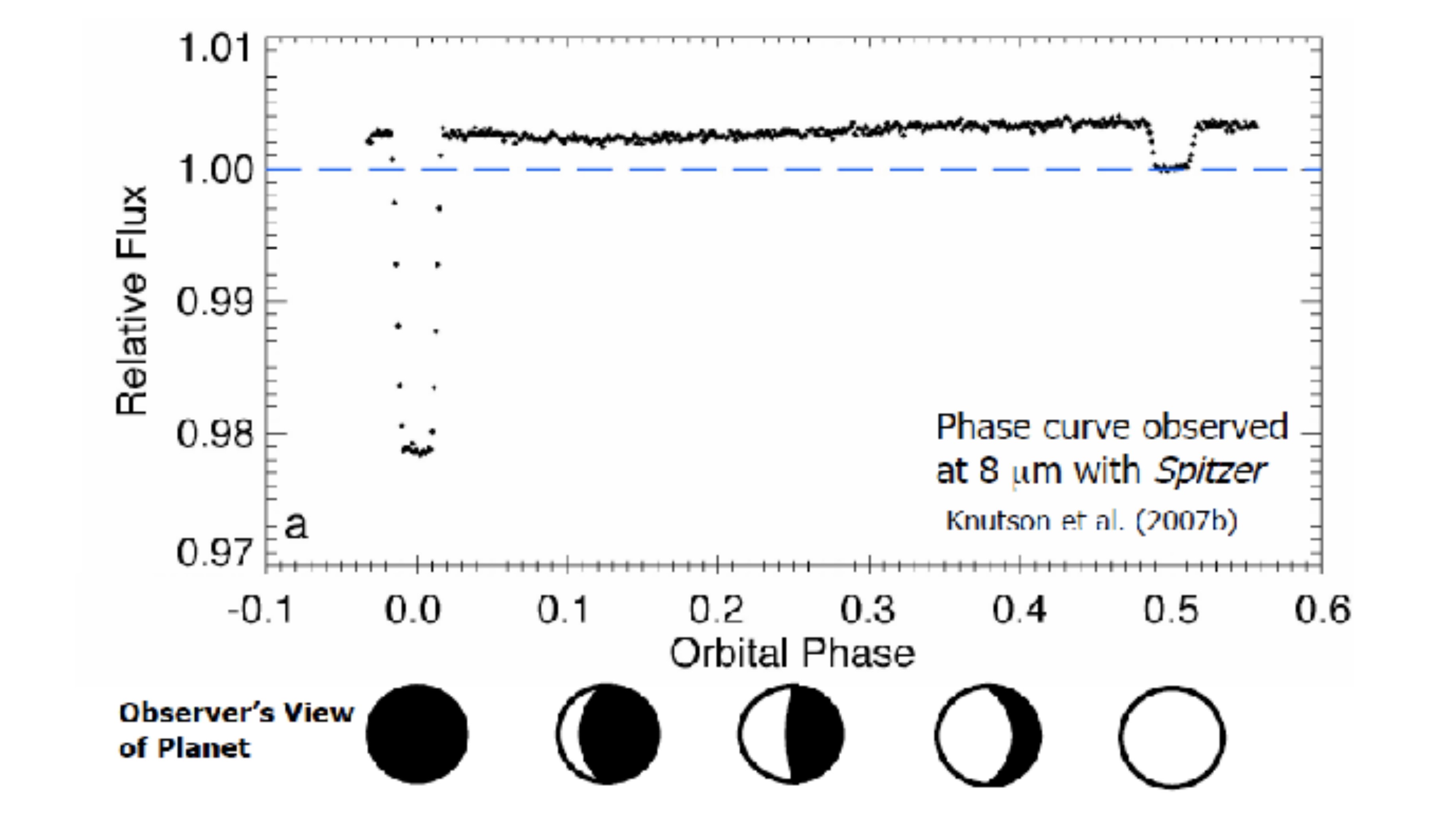
Push to smaller planets

12 x 20cm f/2.8 telescopes
independent mounts,
back-illuminated, deep-depletion CCDs
100 sqr deg FoV (equivalent to Kepler);
sub-millimag precision

University of Warwick
University of Lecicester
University of Belfast
University of Cambridge
DLR Berlin
University of Geneva

L’observatoire de La Silla , 2400 mètres d’altitude , Chili

Une demi orbite de HD 189333b



Knutson,H.A et al, 2007, Nature,447, 183


Des “vraies” Terres ?
De la vie ?

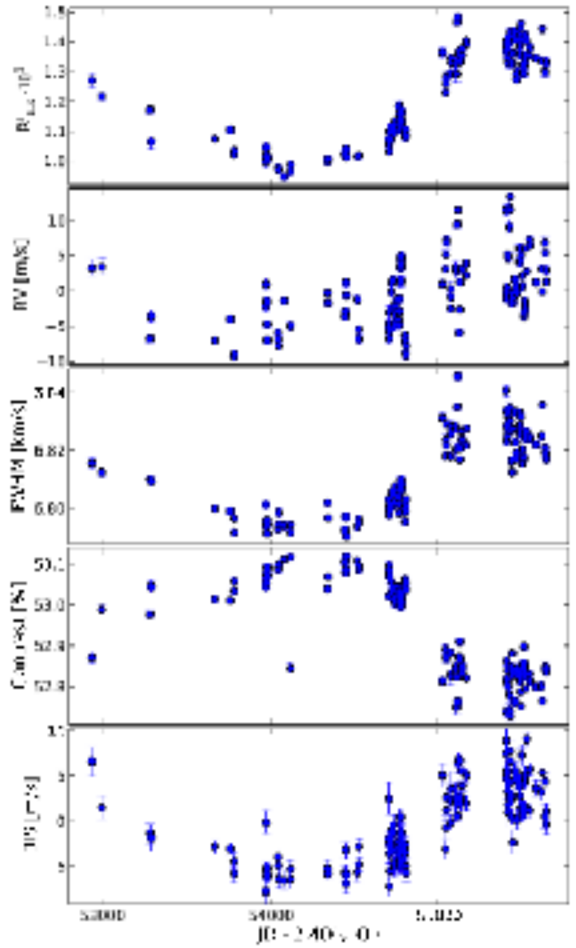


Fig. 16. Time series of R'_{HK}, RV, FWHM, contrast and BIS measurements for the star HD 21693, showing clear correlations between all quantities.

A terrestrial planet candidate in a temperate orbit around Proxima Centauri

Guillem Anglada-Escudé, Pedro J. Amado, John Barnes, Zaira M. Berdiñas, R. Paul Butler, Gavin A. L. Coleman, Ignacio de la Cueva, Stefan Dreizler, Michael Endl, Benjamin Giesers, Sandra V. Jeffers, James S. Jenkins, Hugh R. A. Jones, Marcin Kiraga, Martin Kürster, María J. López-González, Christopher J. Marvin, Nicolás Morales, Julien Morin, Richard P. Nelson, José L. Ortiz, Aviv Ofir, Sijme-Jan Paardekooper, Ansgar Reiners, Eloy Rodríguez, Cristina Rodríguez-López, Luis F. Sarmiento, John P. Strachan, Yiannis Tsapras, Mikko Tuomi, Mathias Zechmeister

(Submitted on 12 Sep 2016)

At a distance of 1.295 parsecs, the red-dwarf Proxima Centauri (α Centauri C, GL 551, HIP 70890, or simply Proxima) is the Sun's closest stellar neighbor and one of the best studied low-mass stars. It has an effective temperature of only ~ 3050 K, a luminosity of ~0.1 per cent solar, a measured radius of 0.14 $R_{\odot}$ and a mass of about 12 per cent the mass of the Sun. Although Proxima is considered a moderately active star, its rotation period is ~ 83 days, and its quiescent activity levels and X-ray luminosity are comparable to the Sun's. New observations reveal the presence of a small planet orbiting Proxima with a minimum mass of 1.3-Earth masses and an orbital period of ~11.2 days. Its orbital semi-major axis is ~ 0.05 AU, with an equilibrium temperature in the range where water could be liquid on its surface.

Anglada-Escudé,G. et al.   Nature 2016, 536,437

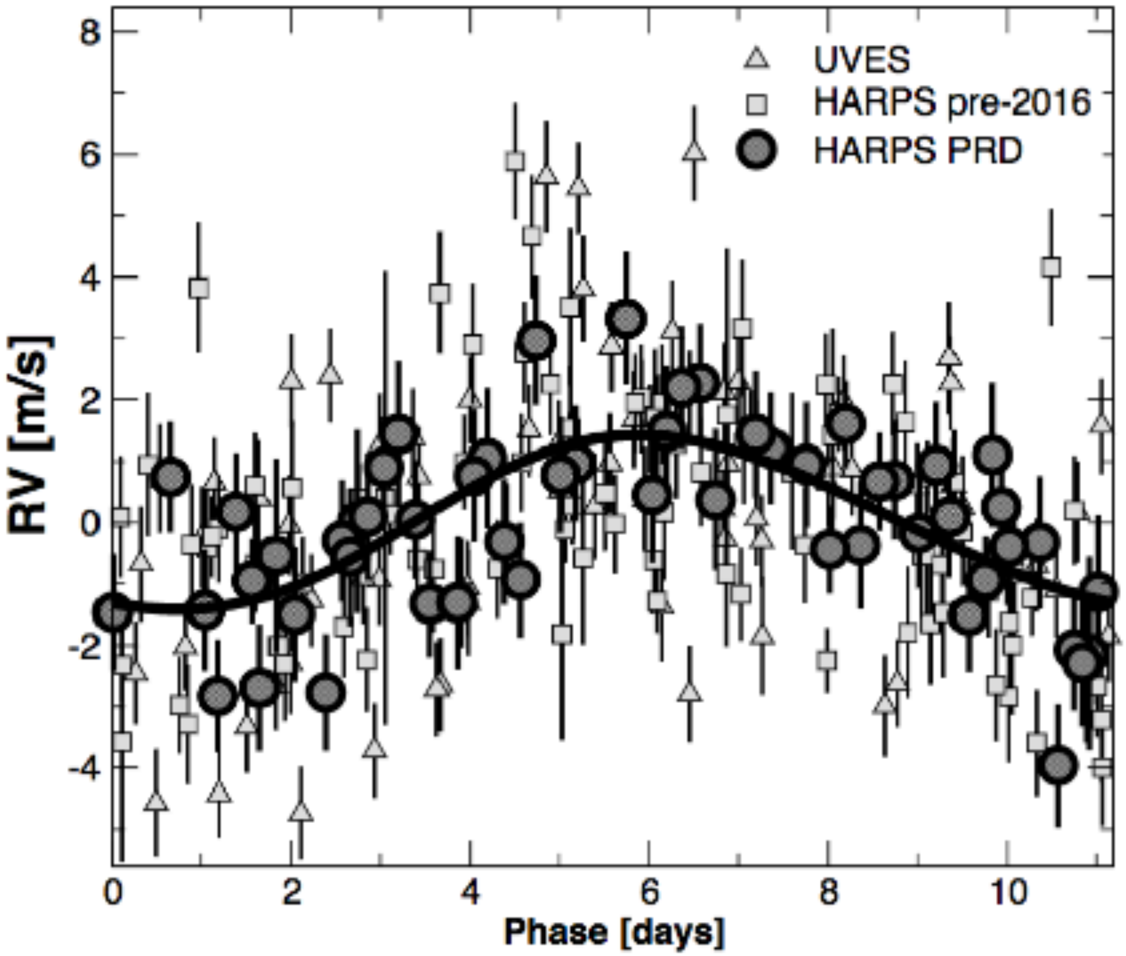


Figure 2: **All datasets folded to the 11.2 days signal.** Radial velocity measurements phase folded at the 11.2 day period of the planet candidate for 16 years of observations. Although its nature is unclear, a second signal at P$\sim$ 200 days was fitted and subtracted from the data to produce this plot and improve visualization. Circles correspond to HARPS PRD, squares are HARPS pre-2016 and triangles are UVES observations. The black line represents the best Keplerian fit to this phase folded representation of the data. Error bars correspond to formal 1-σ uncertainties.

Title:	Prospects for Characterizing the Atmosphere of Proxima Centauri b
Authors:	Kreidberg, Laura; Loeb, Abraham
Affiliation:	AA(Harvard Society of Fellows, Harvard University, 78 Mt. Auburn Street, Cambridge, MA 02138, USA ; Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; laura.kreidberg@cfa.harvard.edu 0000-0003-0514-1147), AB(Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA 0000-0003-4330-287X)
Publication:	The Astrophysical Journal Letters, Volume 832, Issue 1, article id. L12, 6 pp. (2016). (ApJL Homepage)
Publication Date:	11/2016
Origin:	IOP
Astronomy Keywords:	planets and satellites: atmospheres, planets and satellites: individual: Proxima Centauri b
DOI:	10.3847/2041-8205/832/1/L12
Bibliographic Code:	2016ApJ...832L..12K

Abstract

The newly detected Earth-mass planet in the habitable zone of Proxima Centauri could potentially host life—if it has an atmosphere that supports surface liquid water. We show that thermal phase curve observations with the James Webb Space Telescope (JWST) from 5-12 μm can be used to test for the existence of such an atmosphere. We predict the thermal variation for a bare rock versus a planet with 35% heat redistribution to the nightside and show that a JWST phase curve measurement can distinguish between these cases at 4σ confidence, assuming photon-limited precision. We also consider the case of an Earth-like atmosphere, and find that the 9.8 μm ozone band could be detected with longer integration times (a few months). We conclude that JWST observations have the potential to put the first constraints on the possibility of life around the the solar system's nearest star.

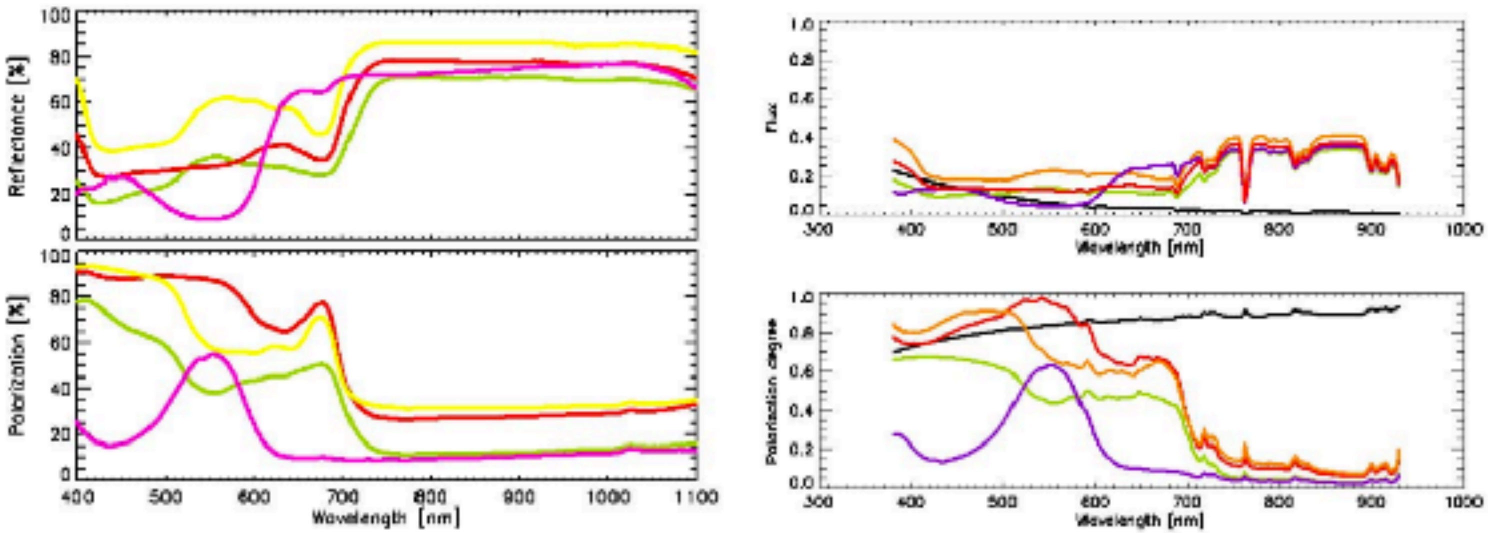


Figure 5: *Left:* Reflectance and linearly polarized spectra of plant samples containing various assemblies of biopigments: chlorophyll (green), anthocyanins (red), carotenoids (yellow), phycobiliproteins (purple) [25]. Note that the higher polarization occurs at the wavelengths where these biopigments most efficiently absorb photons. The so-called red edge near 700 nm is clearly visible. Also, polarization and reflectance are elevated if the surface of the plant is glossy (wavelength independent), cf., in the red and yellow samples. *Right:* Modelled reflectance spectra (top) and linear polarization degree spectra (bottom) for planets with the Earth-like atmosphere, 80% surface coverage by either of the four pigmented organisms shown on the left and 20% ocean surface coverage (visible hemisphere only). The high linear polarization degree clearly distinguishes the presence of the biopigments in contrast to the flux spectra. Black curve represents a planet with an ocean only [27]. The glint from its surface is highly polarized.

Title: The habitability of Proxima Centauri b. II. Possible climates and observability
Authors: Turbet, Martin; Leconte, Jérémy; Selsis, Franck; Bolmont, Emeline; Forget, François; Ribas, Ignasi; Raymond, Sean N.; Anglada-Escudé, Guillem

Affiliation: AA(Laboratoire de Météorologie Dynamique, Sorbonne Universités, UPMC Univ. Paris 06, CNRS, 4 place Jussieu, 75005, Paris, France mturbet@lmd.jussieu.fr), AB(Laboratoire d'astrophysique de Bordeaux, Univ. Bordeaux, CNRS, B18N, Allée Geoffroy Saint-Hilaire, 33615, Pessac, France), AC(Laboratoire d'astrophysique de Bordeaux, Univ. Bordeaux, CNRS, B18N, Allée Geoffroy Saint-Hilaire, 33615, Pessac, France), AD(NaXys, Department of Mathematics, University of Namur, 8 rempart de la Vierge, 5000, Namur, Belgium), AE(Laboratoire de Météorologie Dynamique, Sorbonne Universités, UPMC Univ. Paris 06, CNRS, 4 place Jussieu, 75005, Paris, France), AF(Institut de Ciències de l'Espai (IEEC-CSIC), C/Can Magrans, s/n, Campus UAB, 08193, Bellaterra, Spain), AG(Laboratoire d'astrophysique de Bordeaux, Univ. Bordeaux, CNRS, B18N, Allée Geoffroy Saint-Hilaire, 33615, Pessac, France), AH(School of Physics and Astronomy, Queen Mary University of London, 327 Mile End Rd, London, E1 4NS, UK)
Publication: Astronomy & Astrophysics, Volume 596, id.A112, 29 pp. (A&A Homepage)

Publication Date: 12/2016

Origin: EDP Sciences

Astronomy Keywords: stars: individual: Proxima Cen, planets and satellites: individual: Proxima Cen b, planets and satellites: atmospheres, planets and satellites: terrestrial planets, planets and satellites: detection, astrobiology

DOI: 10.1051/0004-6361/201629577

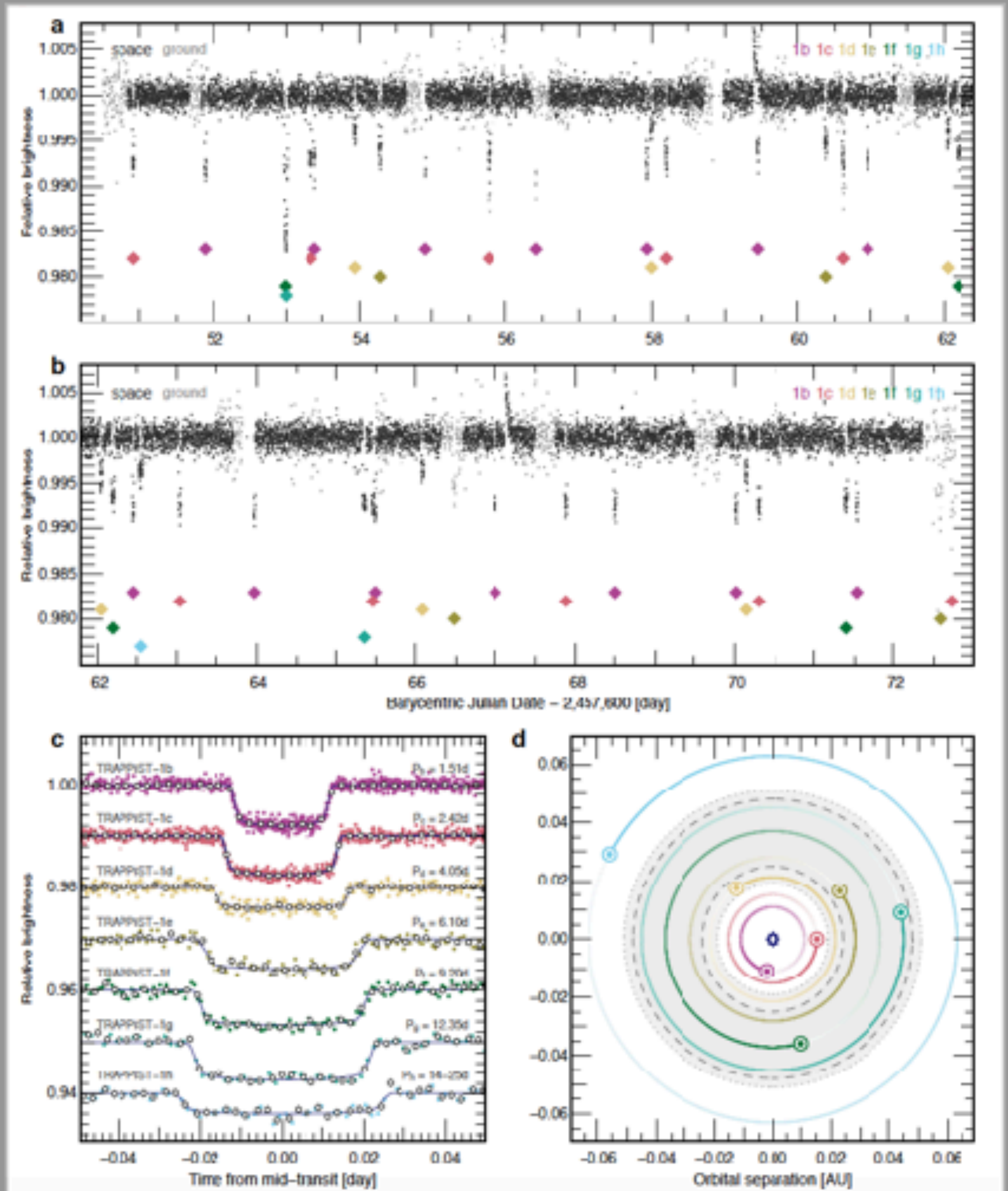
Bibliographic Code: 2016A&A...596A.112T

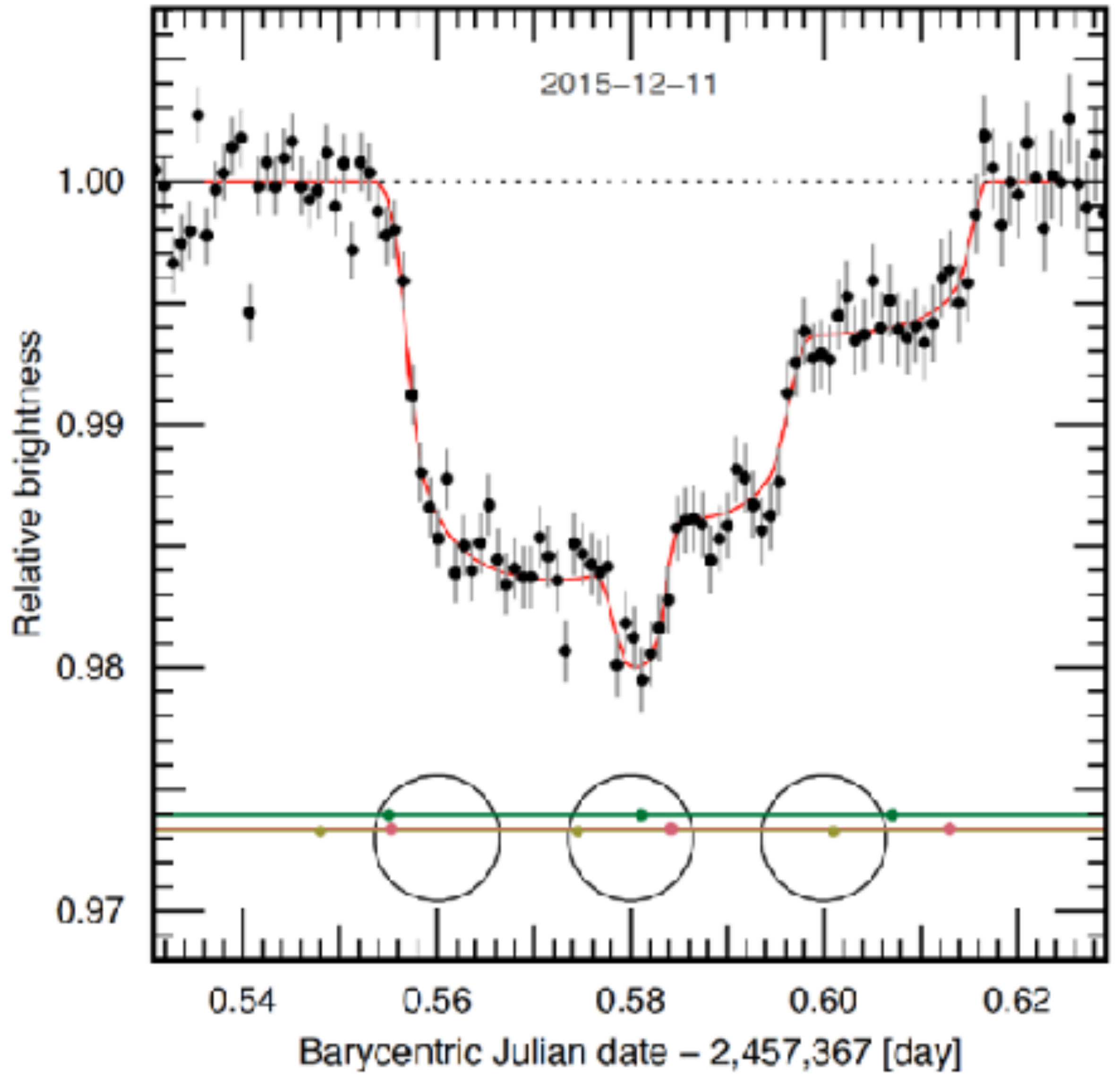
Abstract

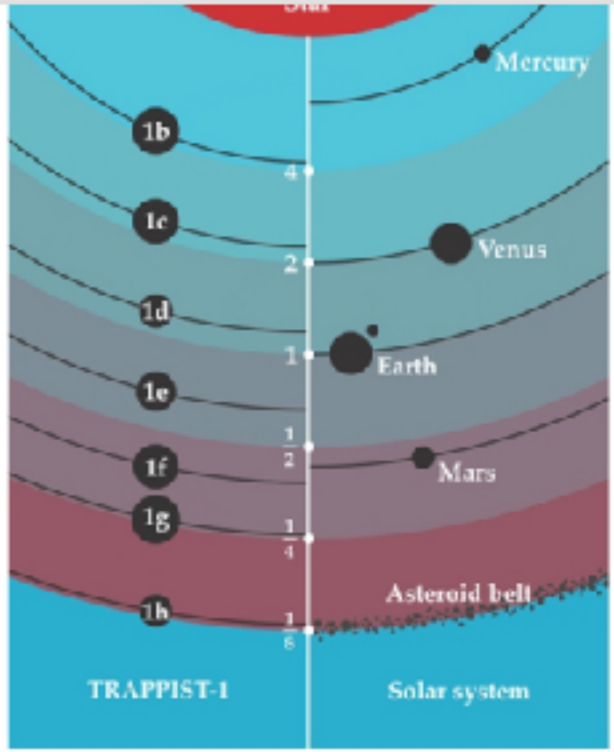
Radial velocity monitoring has found the signature of a Msini = 1.3$M_\oplus$ planet located within the habitable zone (HZ) of Proxima Centauri. Despite a hotter past and an active host star, the planet Proxima b could have retained enough volatiles to sustain surface habitability. Here we use a 3D Global Climate Model (GCM) to simulate the atmosphere and water cycle of Proxima b for its two likely rotation modes (1:1 and 3:2 spin-orbit resonances), while varying the unconstrained surface water inventory and atmospheric greenhouse effect. Any low-obliquity, low-eccentricity planet within the HZ of its star should be in one of the climate regimes discussed here. We find that a broad range of atmospheric compositions allow surface liquid water. On a tidally locked planet with sufficient surface water inventory, liquid water is always present, at least in the substellar region. With a non-synchronous rotation, this requires a minimum greenhouse warming (10 mbar of CO_2 and 1 bar of N_2). If the planet is dryer, 0.5 bar or 1.5 bars of CO_2 (for asynchronous or synchronous rotation, respectively) suffice to prevent the trapping of any arbitrary, small water inventory into polar or nightside ice caps. We produce reflection and emission spectra and phase curves for the simulated climates. We find that atmospheric characterization will be possible via direct imaging with forthcoming large telescopes. The angular separation of 7λ/D at 1 μm (with the E-ELT) and a contrast of 10^{-7} will enable high-resolution spectroscopy and the search for molecular signatures, including H_2O, O_2, and CO_2. The observation of thermal phase curves can be attempted with the James Webb Space Telescope, thanks to a contrast of 2×10^{-5} at 10 μm. Proxima b will also be an exceptional target for future IR interferometers. Within a decade it will be possible to image Proxima b and possibly determine whether the surface of this exoplanet is habitable.

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

Gillon et al. 2017 Nature (22 février)


a
space ground
1b 1c 1d 1e 1f 1g 1h
Relative brightness
b
space ground
1b 1c 1d 1e 1f 1g 1h
Relative brightness
Barycentric Julian Date – 2,457,600 [day]
c
TRAPPIST-1b
TRAPPIST-1c
TRAPPIST-1d
TRAPPIST-1e
TRAPPIST-1g
Relative brightness
Time from mid-transit [day]
d
Orbital separation [AU]

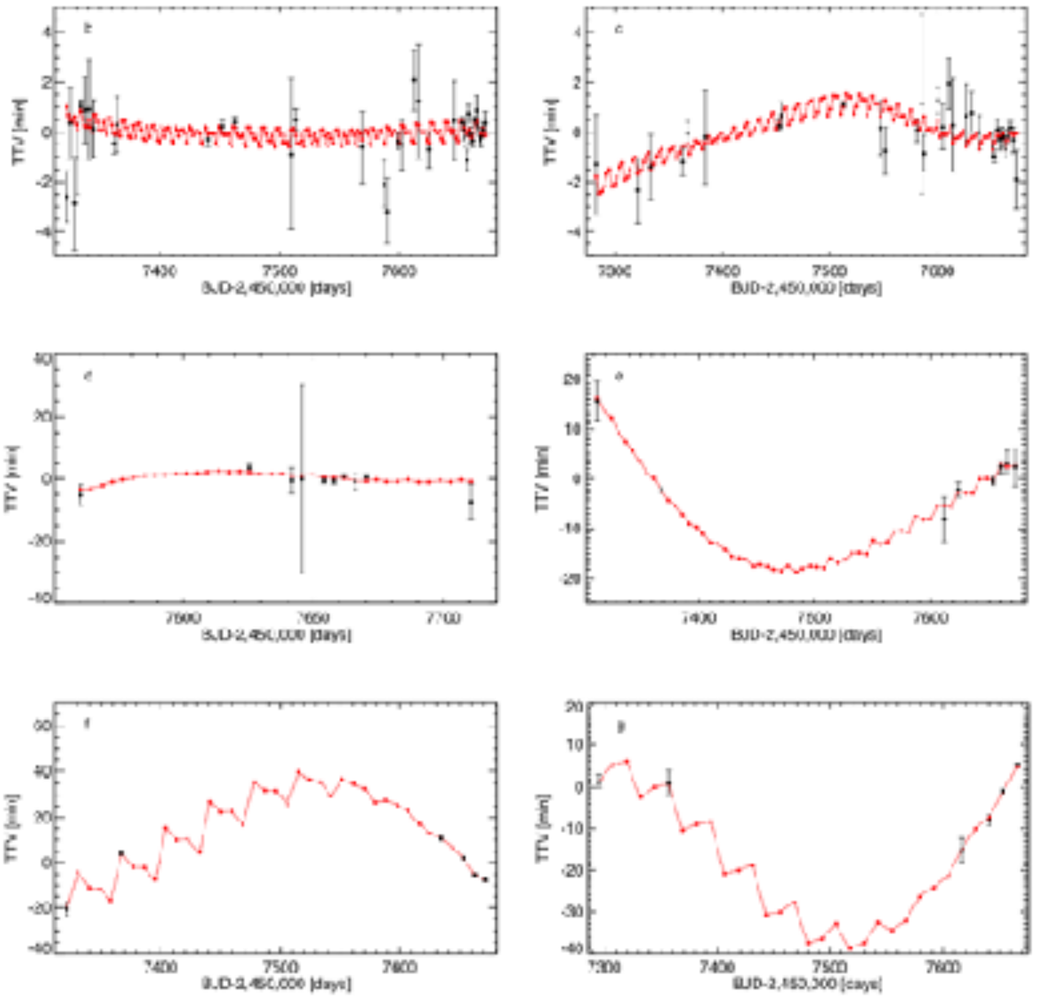

2015–12–11
1.00
0.99
0.98
0.97
Relative brightness
0.54
0.56
0.58
0.60
0.62
Barycentric Julian date – 2,457,367 [day]

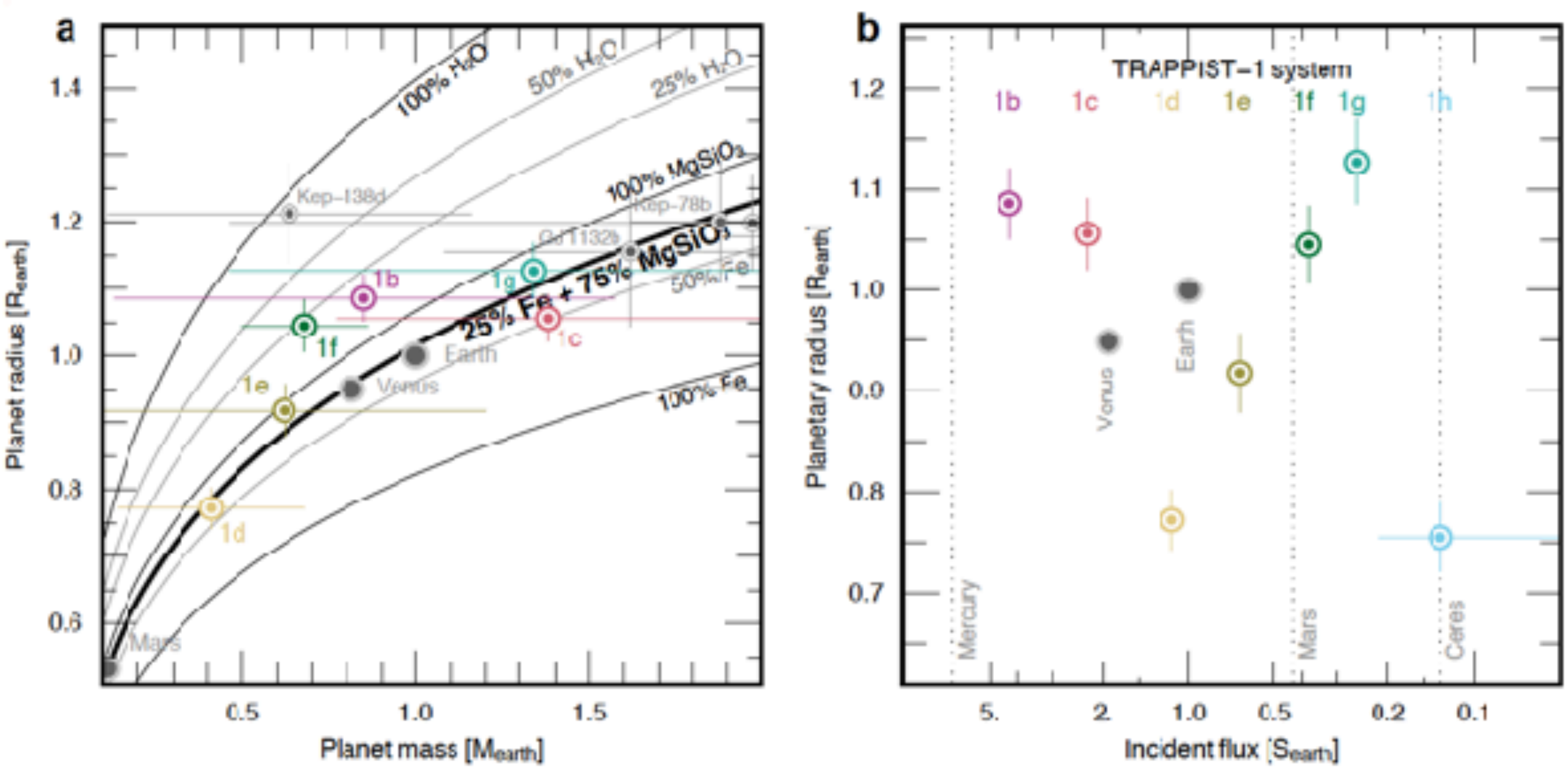


The planets of TRAPPIST-1 receive a comparable amount of stellar energy (numbers on the vertical axis) as the inner planets of the solar system. The illustration also shows the relative sizes of the planets. Credit: Adapted from diagram by IoA/Amanda Smith

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 ±0.60×10^{-6}	2.4218233 ±0.17×10^{-5}	4.049610 ±0.63×10^{-4}	6.099615 ±0.11×10^{-4}	9.206690 ±0.15×10^{-4}	12.35294 ±0.12×10^{-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	-


TTV [min]
BJD-2,450,000 [days]


a
b
TRAPPIST−1 system
1b
1c
1d
1e
1f
1g
1h
100% H2O
50% H2O
25% H2O
100% MgSiO3
25% Fe + 75% MgSiO3
50% Fe
100% Fe
Kep-138d
Kep-78b
GJ1132b
Earth
Venus
Mars
Mercury
Ceres
Planet radius [Rearth]
Planet mass [Mearth]
Planetary radius [Rearth]
Incident flux [Searth]