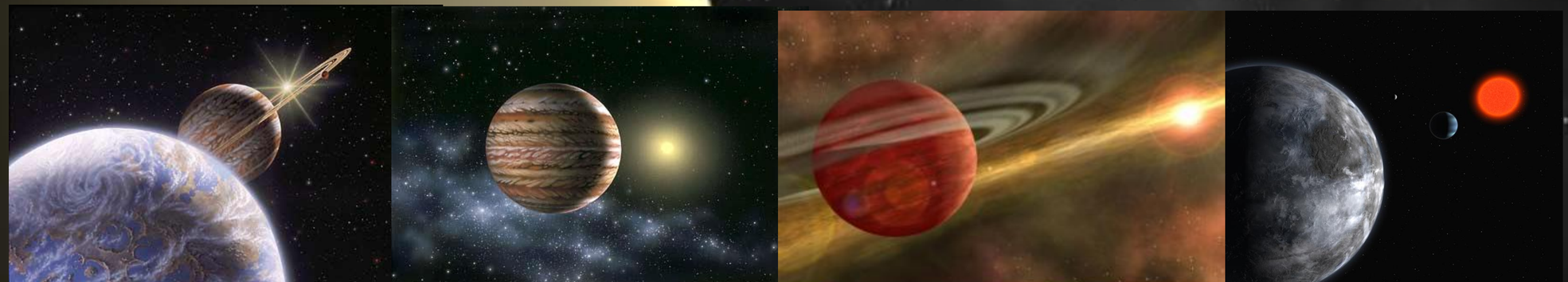
Les exoplanètes

Francesco Pepe
Observatoire de Genève



Nobel prize for physics 2019

Their work has contributed to our "understanding of the evolution of the universe and Earth's place in the cosmos"

Theoretical discoveries in physical cosmology

Discovery of an exoplanet orbiting a solar-type star

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aged 84, born in Winnipeg (Canada)

- Albert Einstein Professor of Science at Princeton University

Doctorate obtained in

- Princeton

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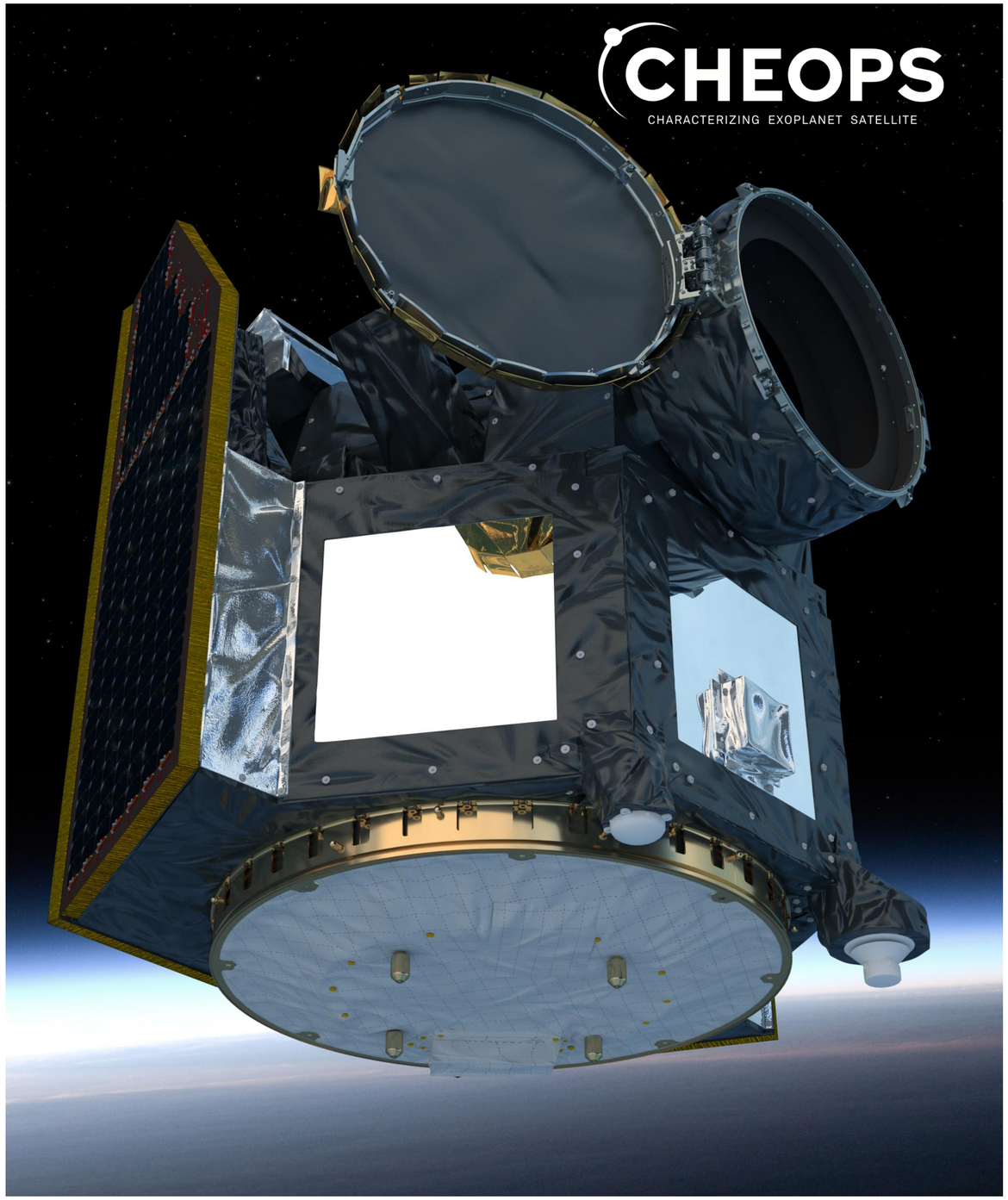
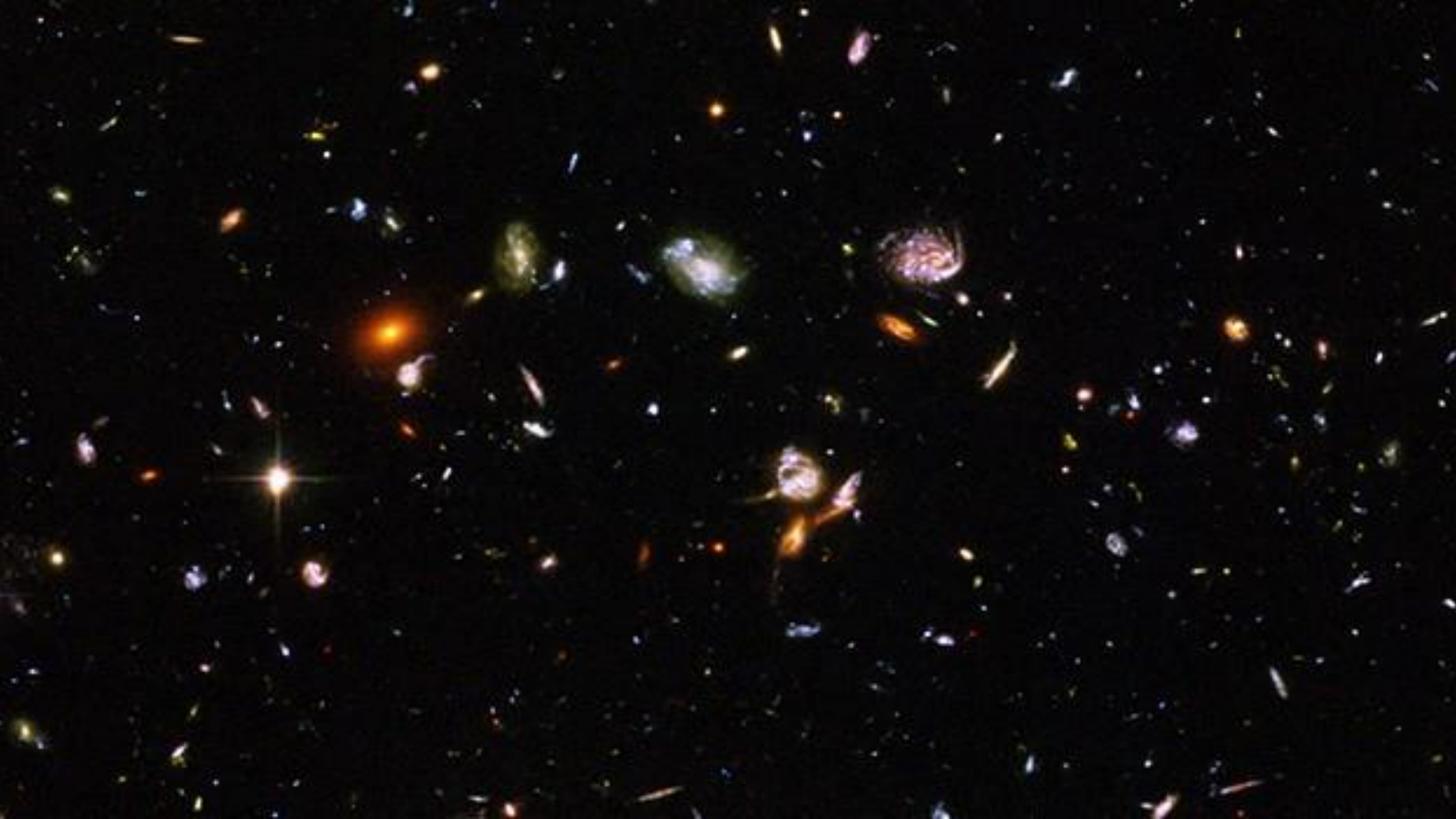
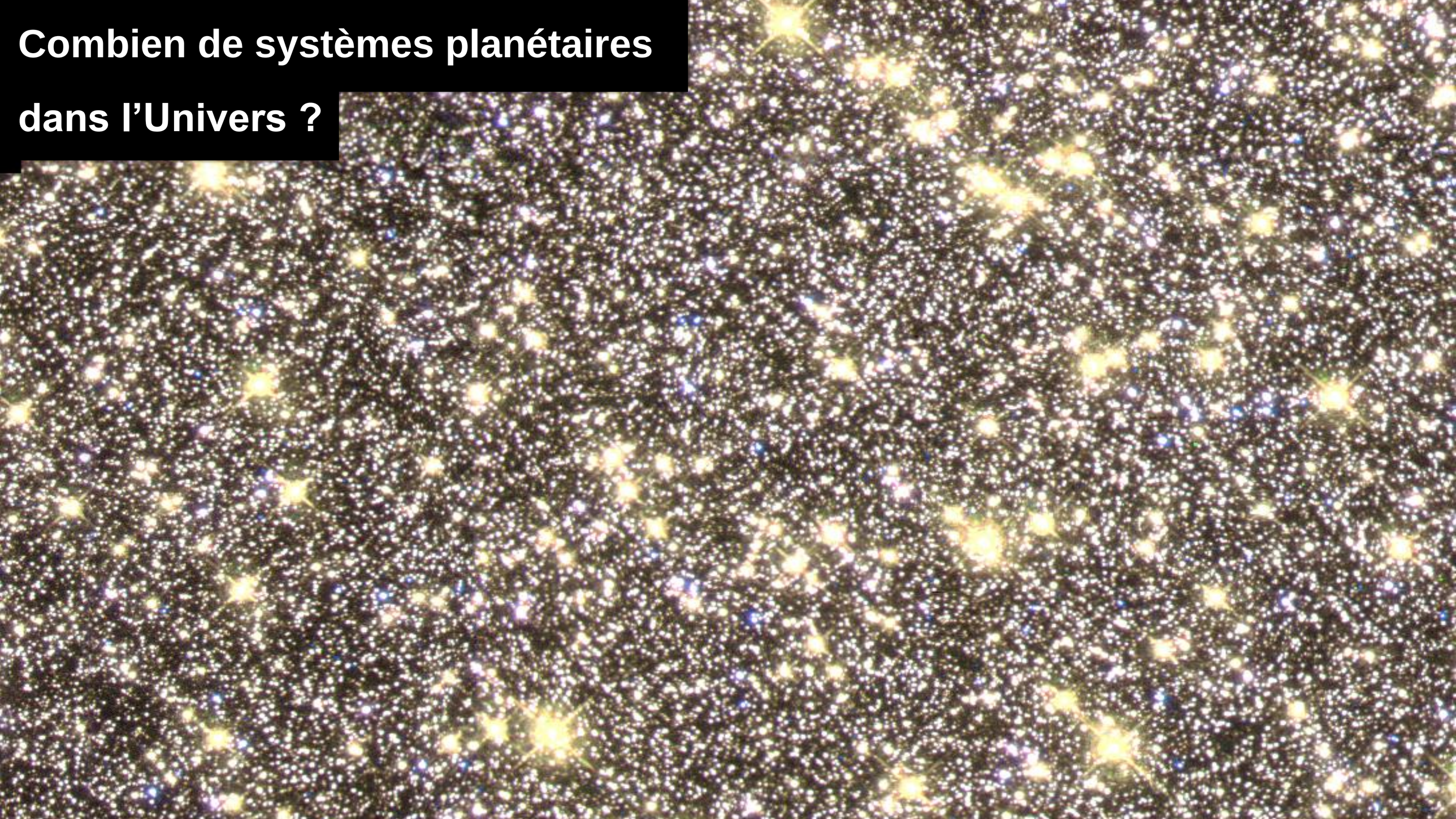
Source: nobelprize.org

AFP photo, handout Princeton university / Mark Czajkowski / University of Geneva





Combien de systèmes planétaires dans l’Univers ?



Une ancienne question philosophique!

Epicure 341 - 270 BC

Lettre à Hérodote

Les Mondes sont en nombre infini, certains similaires au nôtre , certains étant différents…

…des espèces vivantes , plantes et toutes autres choses visibles peuvent exister dans certains mondes et ne le pourraient pas dans d'autres….

Mais aussi: Leucippus -510 -420 ; Democrite -460 -350

Environ 1200-1280: Saint Albert le Grand:
« Il y a-t-il de nombreux mondes , ou n'en existe-t-il qu'un ?
C'est une des plus noble et exaltante question dans l'étude de la Nature.»

1277 Etienne Tempier (Evèque de Paris, avec l'accord de Jean XXI, demande que la question de la pluralité des Mondes soit enseignée en Sorbonne.

1600+ Giordano Bruno: « De l'infinito , universo e Mundi »

1755 Emmanuel Kant: « Universal Natural History and Theory of Heaven »

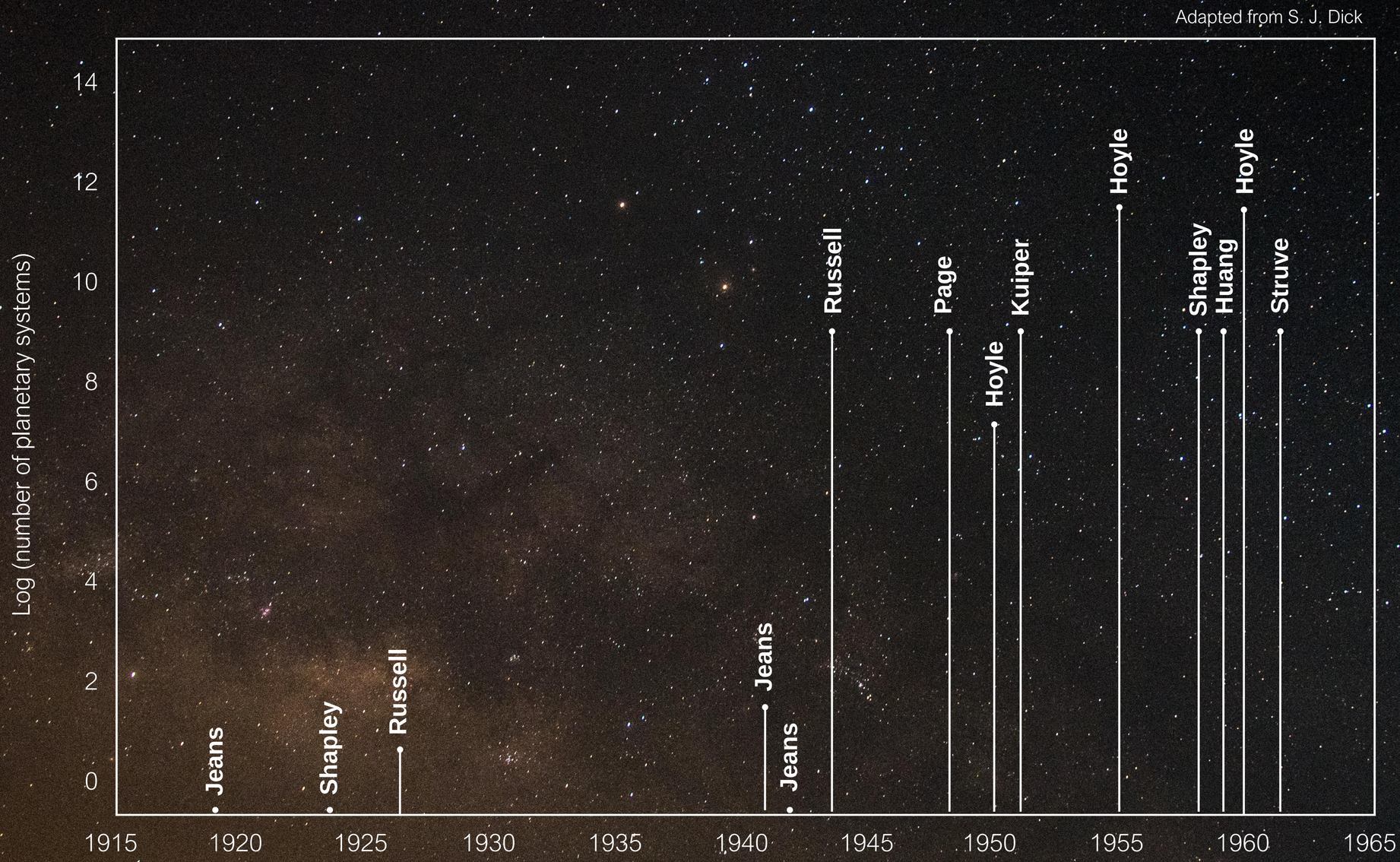
1756 Pierre-Simon Laplace: « Exposé du système du monde »

1917 James Hopwood Jeans: Théorie de l'impact de deux étoiles. (Pas une bonne idée!)

1944 Otto Schmidt: Théorie de l'accrétion.

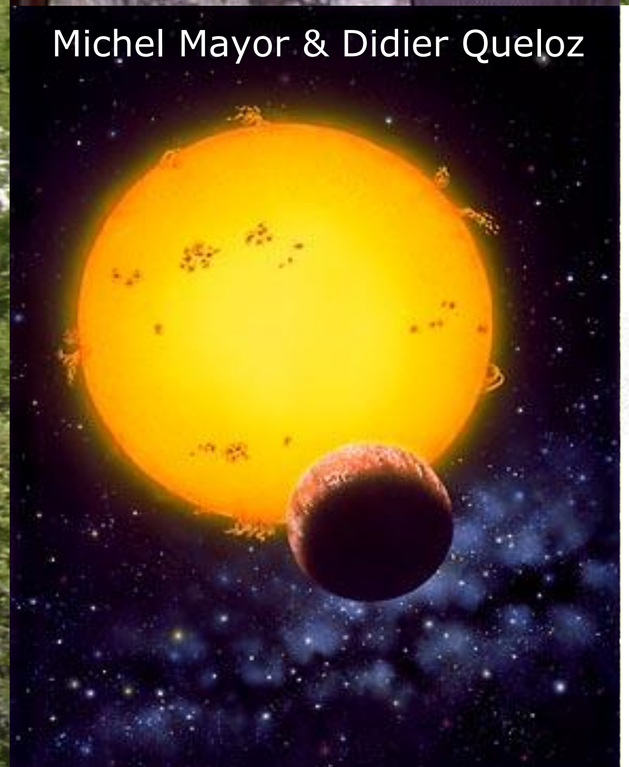
1969 Viktor Safronov: « Evolution d'un nuage protostellaire et formation de la Terre et des planètes»

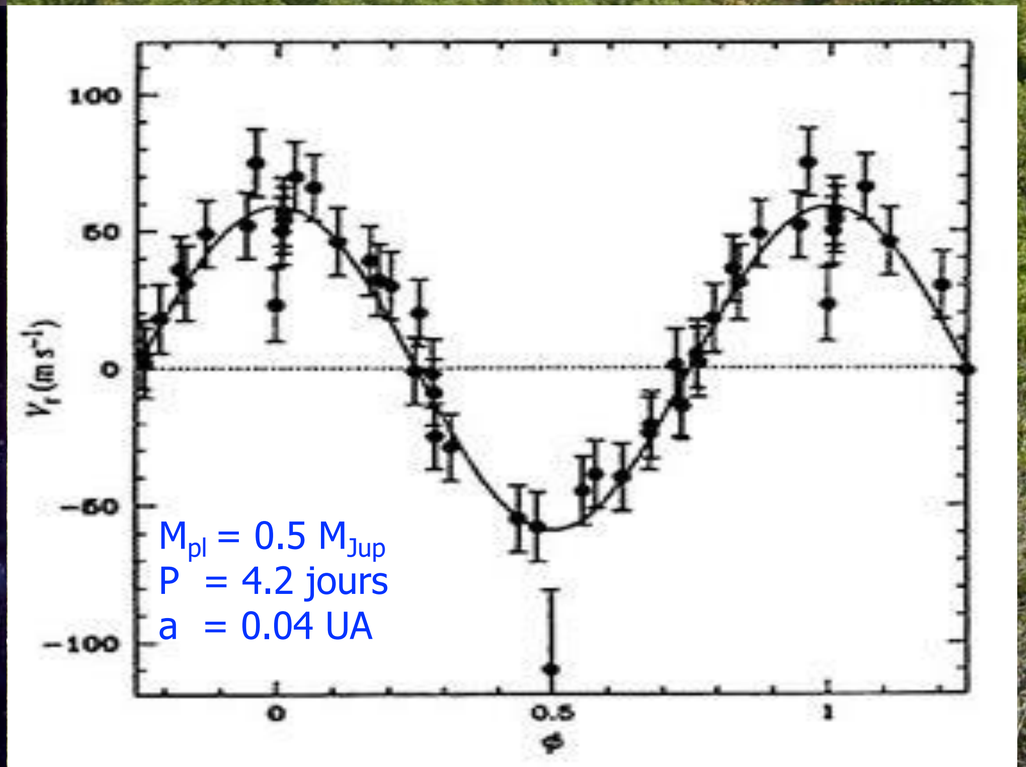
Nombre estimé du nombre des systèmes planétaires dans la Voie Lactée



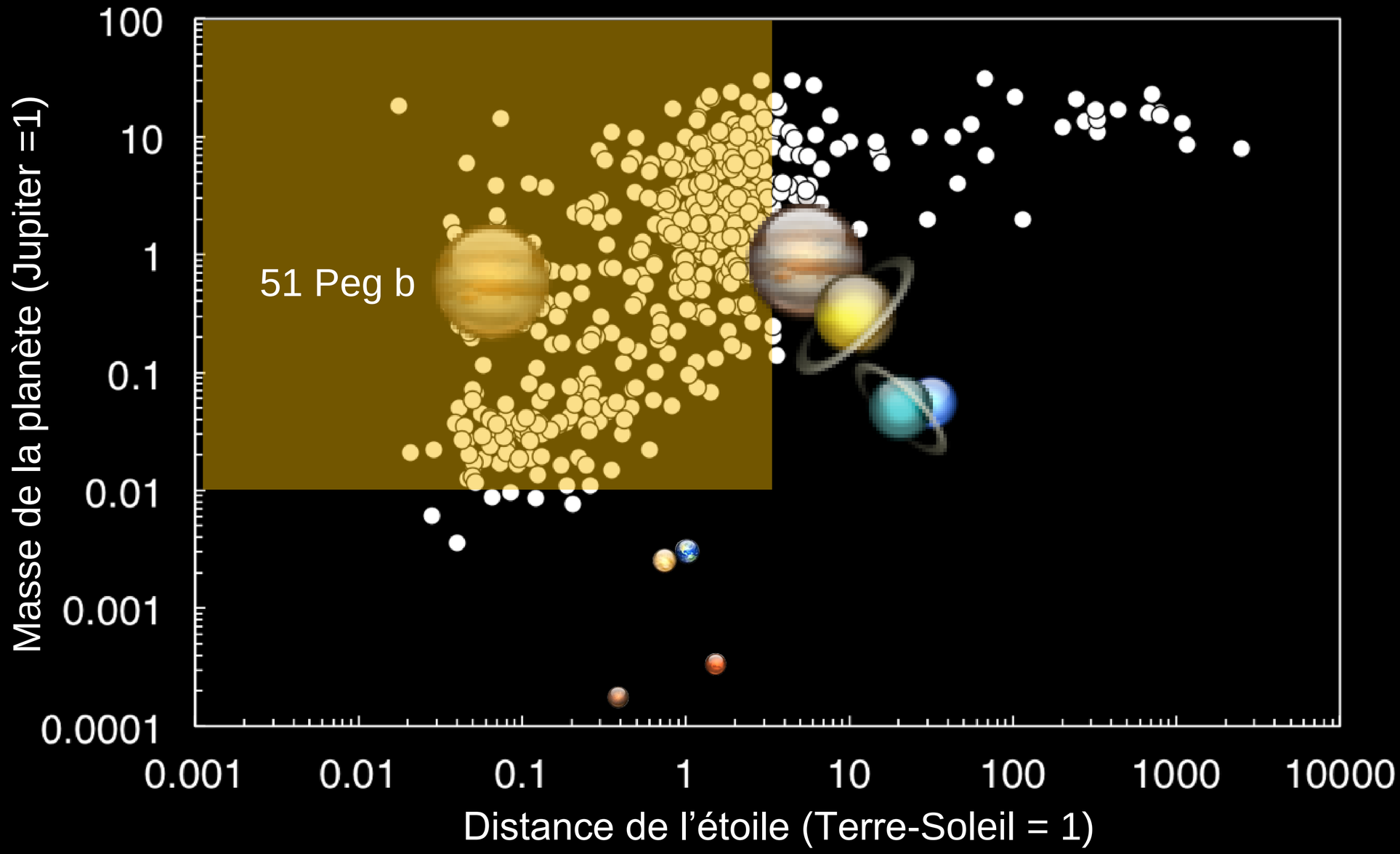
La première planète extra-solaire: 51 Peg b
1995, Haute-Provence

Michel Mayor & Didier Queloz





Un monde de nouveaux mondes Mayor & Queloz



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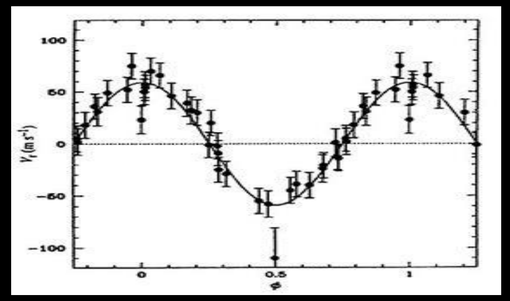
Deux méthodes de détection indirectes
Interactions étoile-planète

Variation de vitesse radiale

Variation de position

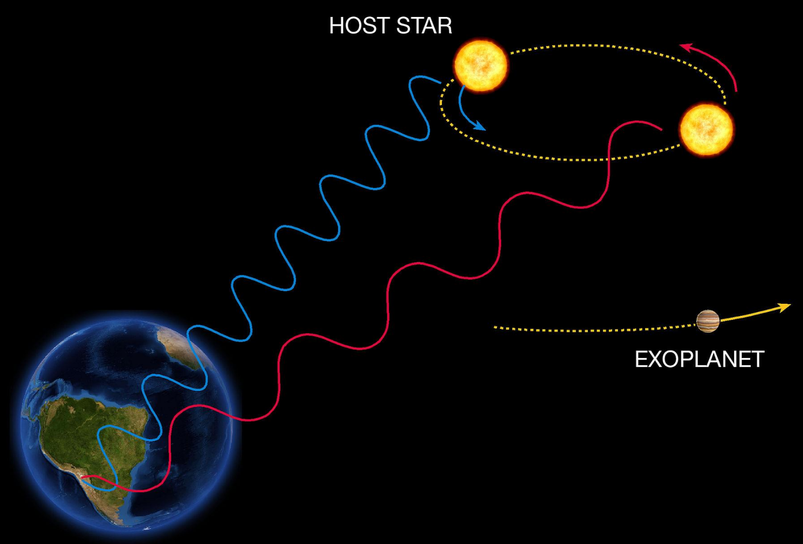
Variation de luminosité



Masse + éléments orbitaux

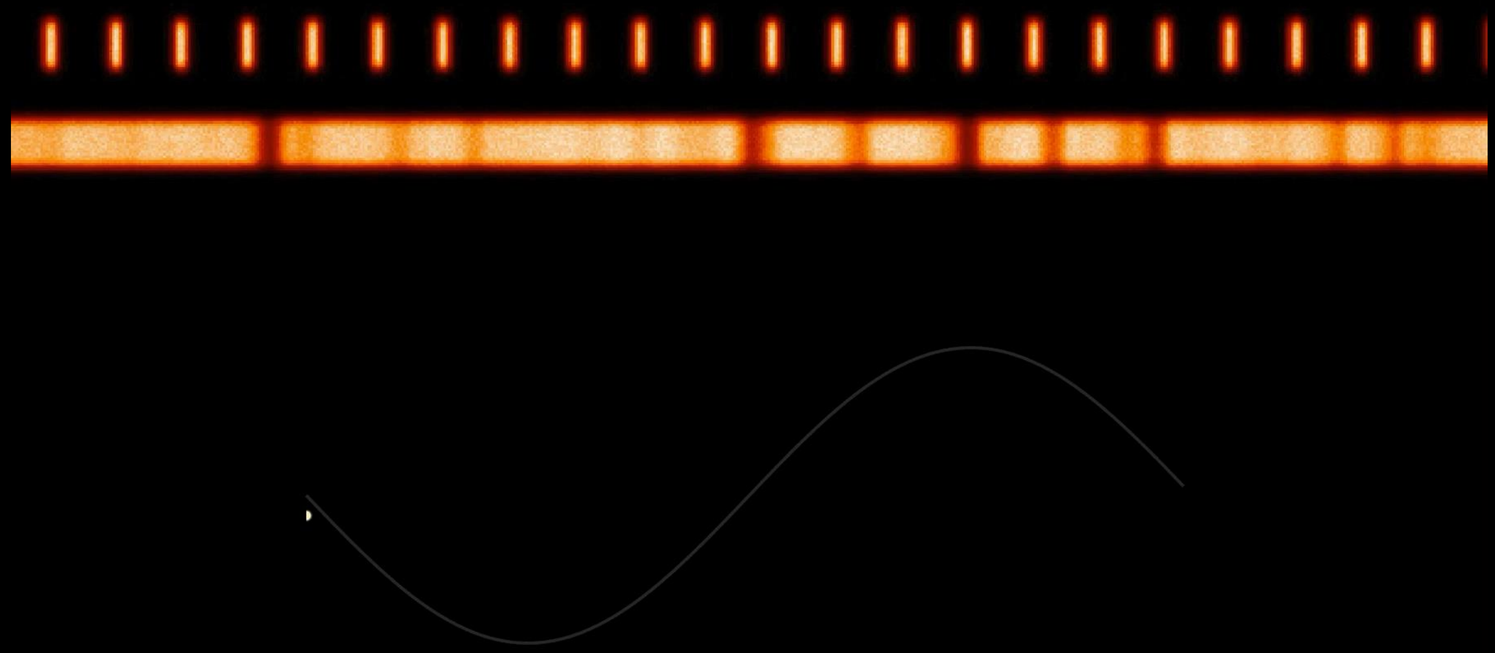
Rayon + période

La méthode des “vitesses radiales”

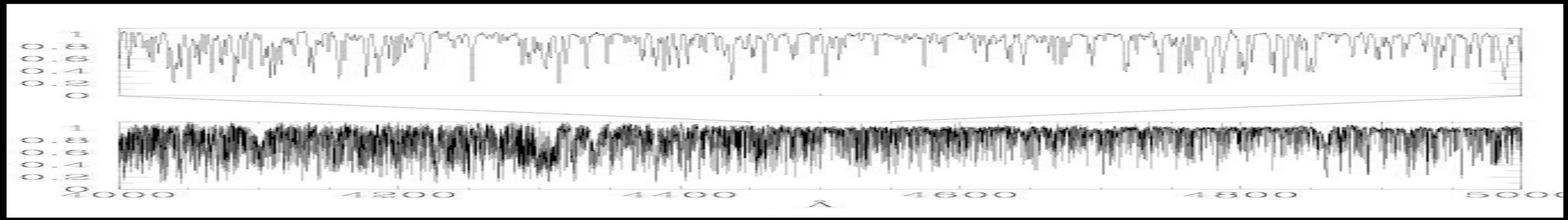


The Radial Velocity Method

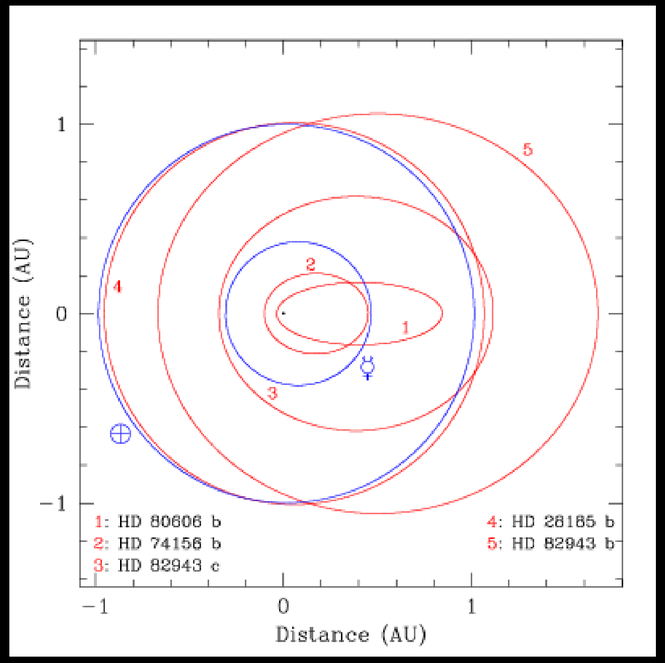
ESO Press Photo 22e/07 (25 April 2007)

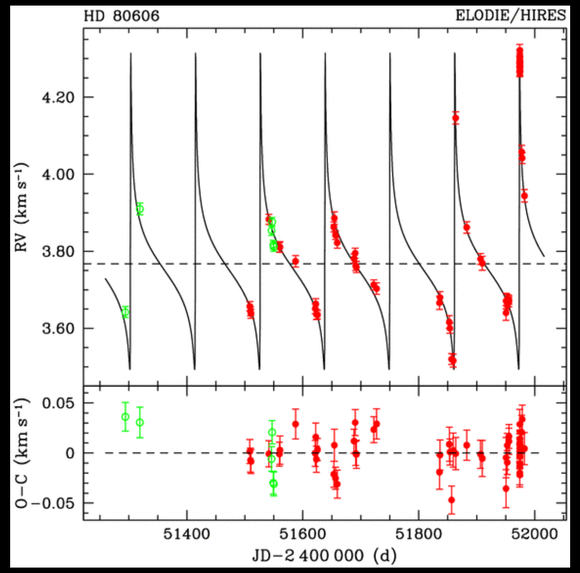


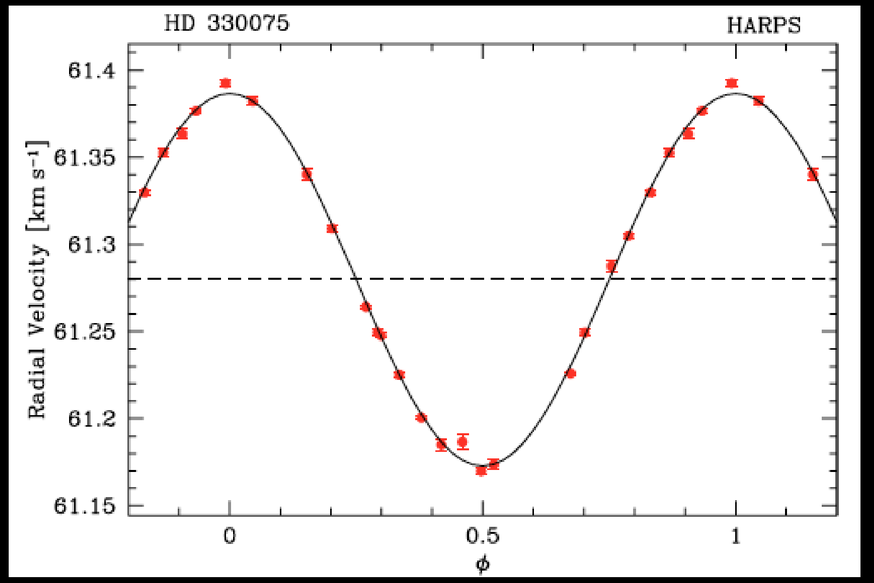
Sam Halverson

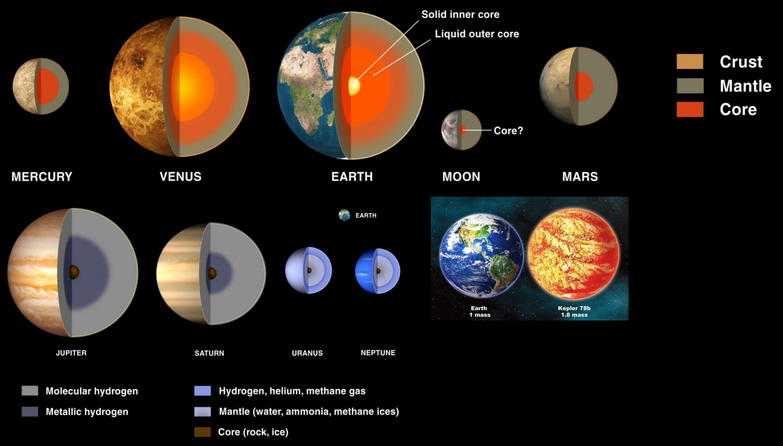


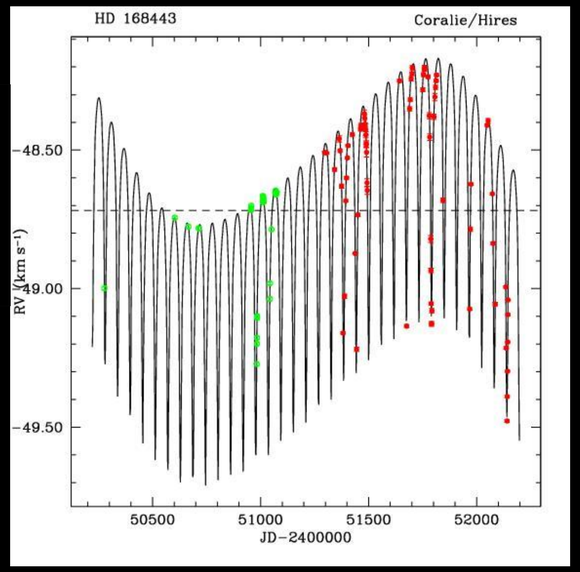
Orbites et masses les plus variées …

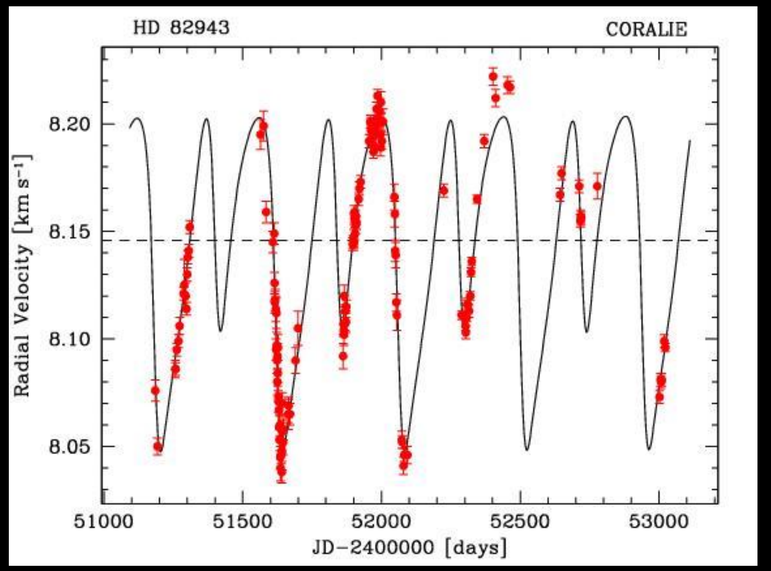


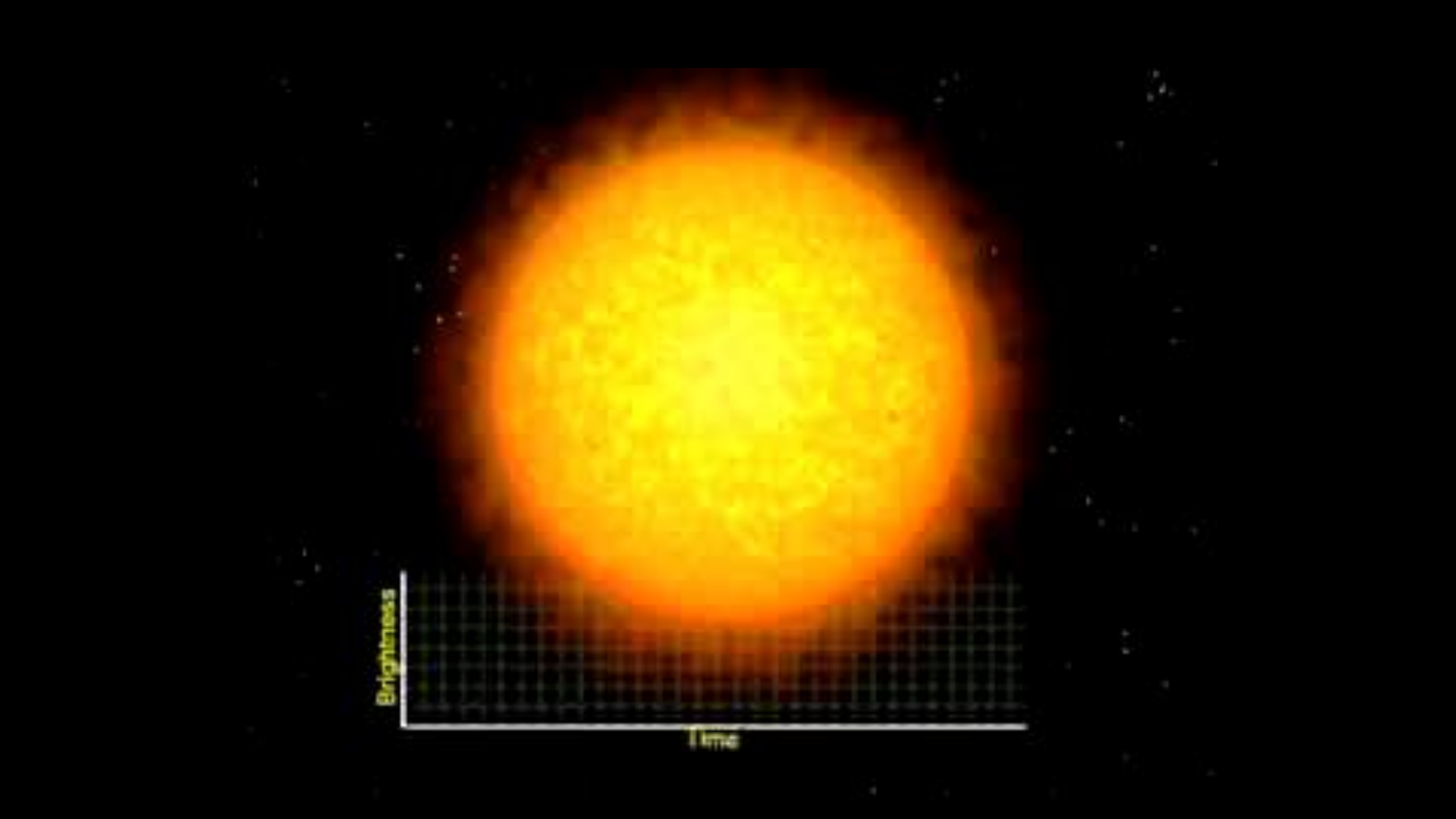




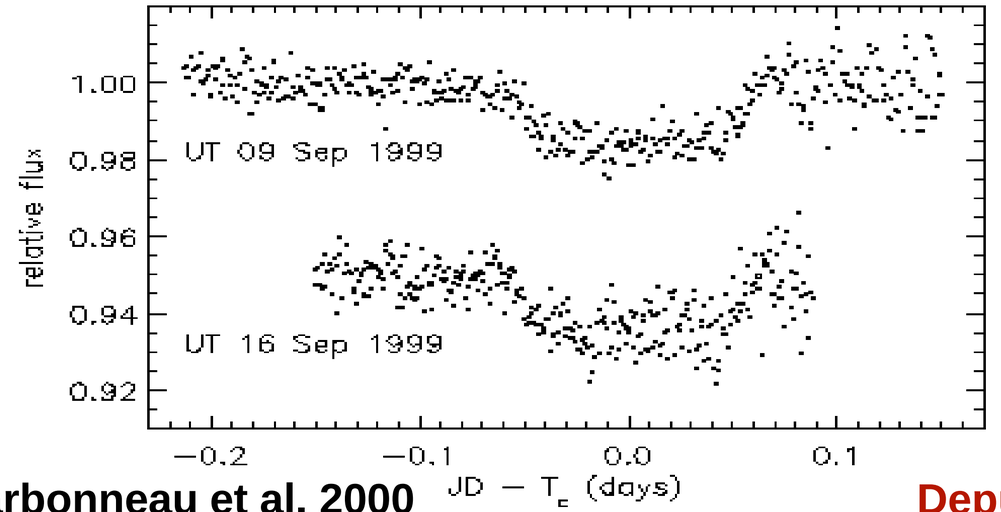







Brightness
Time

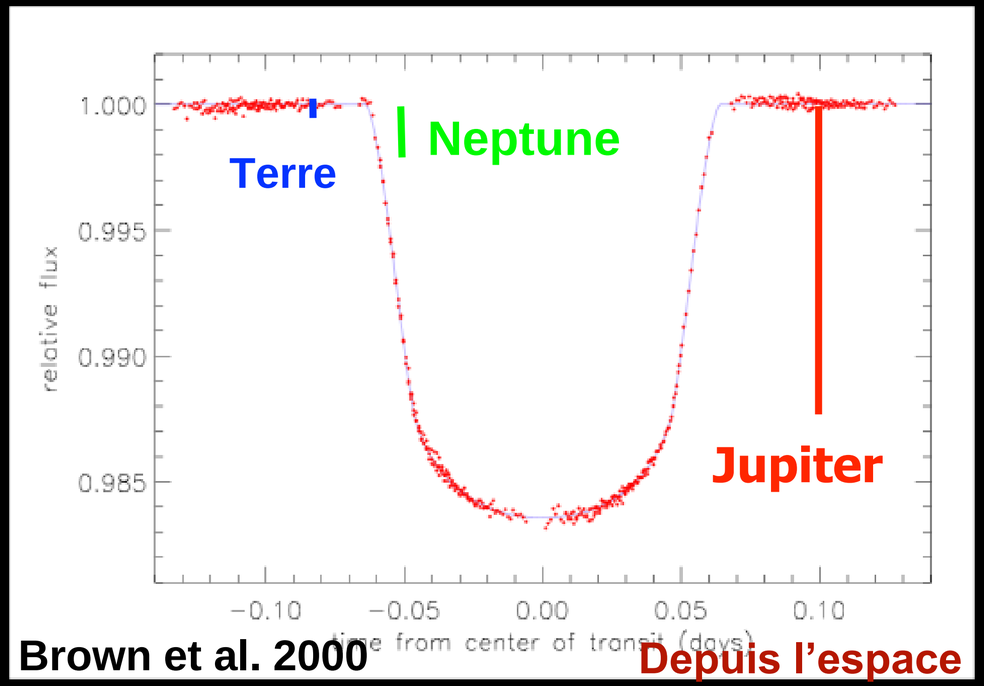
Les premières mesures de transits: HD209458



Charbonneau et al. 2000

Depuis le sol

Année 2000



Brown et al. 2000

Depuis l’espace

Détectabilité des planètes

$$k_1 = \frac{28.4\ \mathrm{m\,s^{-1}}}{\sqrt{1-e^2}} \frac{m_2 \sin i}{M_{\mathrm{Jup}}} \left(\frac{m_1 + m_2}{M_{\mathrm{Sun}}} \right)^{-2/3} \left(\frac{P}{1\ \mathrm{yr}} \right)^{-1/3}$$

Jupiter	@ 1 AU	: 28.4 m s^{-1}
Jupiter	@ 5 AU	: 12.7 m s^{-1}
Neptune	@ 0.1 AU	: 4.8 m s^{-1}
Neptune	@ 1 AU	: 1.5 m s^{-1}
Super-Earth (5 $M_\oplus$)	@ 0.1 AU	: 1.4 m s^{-1}
Super-Earth (5 $M_\oplus$)	@ 1 AU	: 0.45 m s^{-1}
Earth	@ 1 AU	: 9 cm s^{-1}

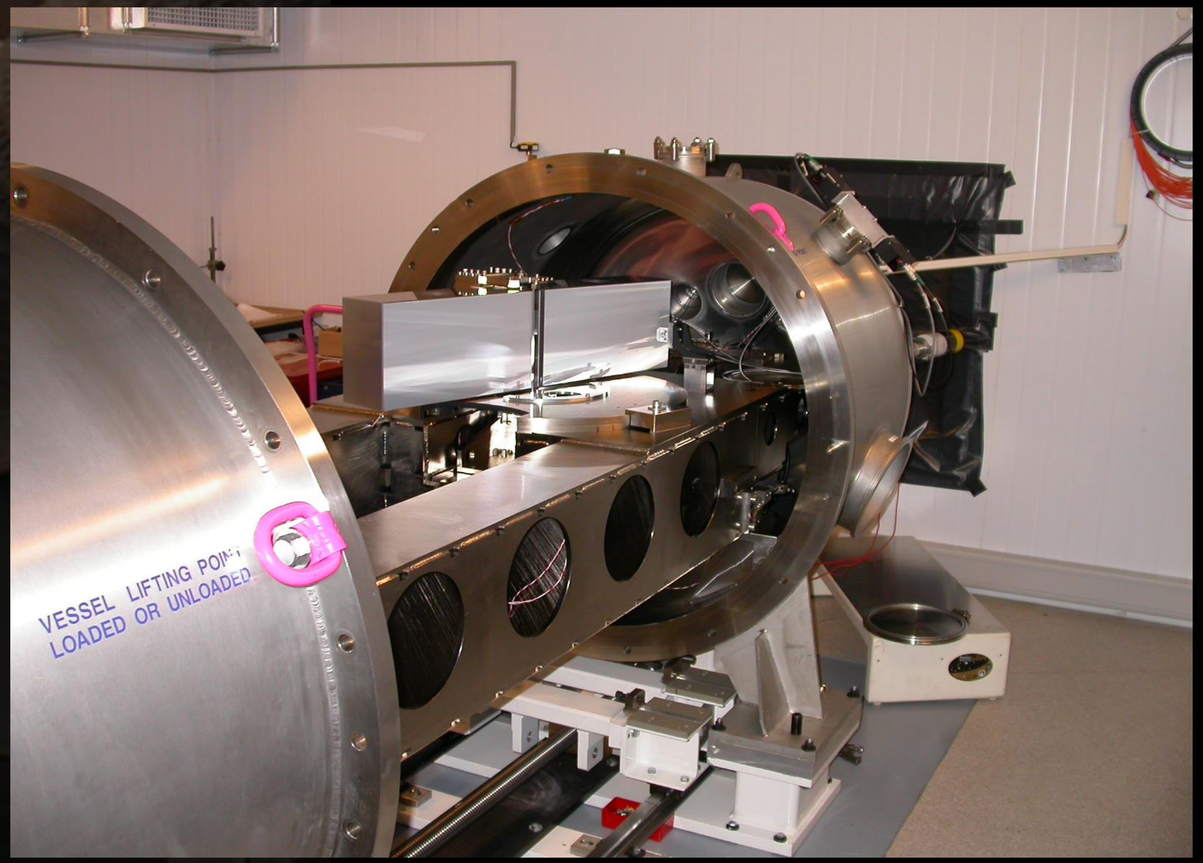
Hot Jupiters
Giant planets up to 5 AU
Ice giants on short orbits

Neptunes and super-Earths, e.g. with HARPS

‘Habitable’ Earths and super-Earth, ESPRESSO

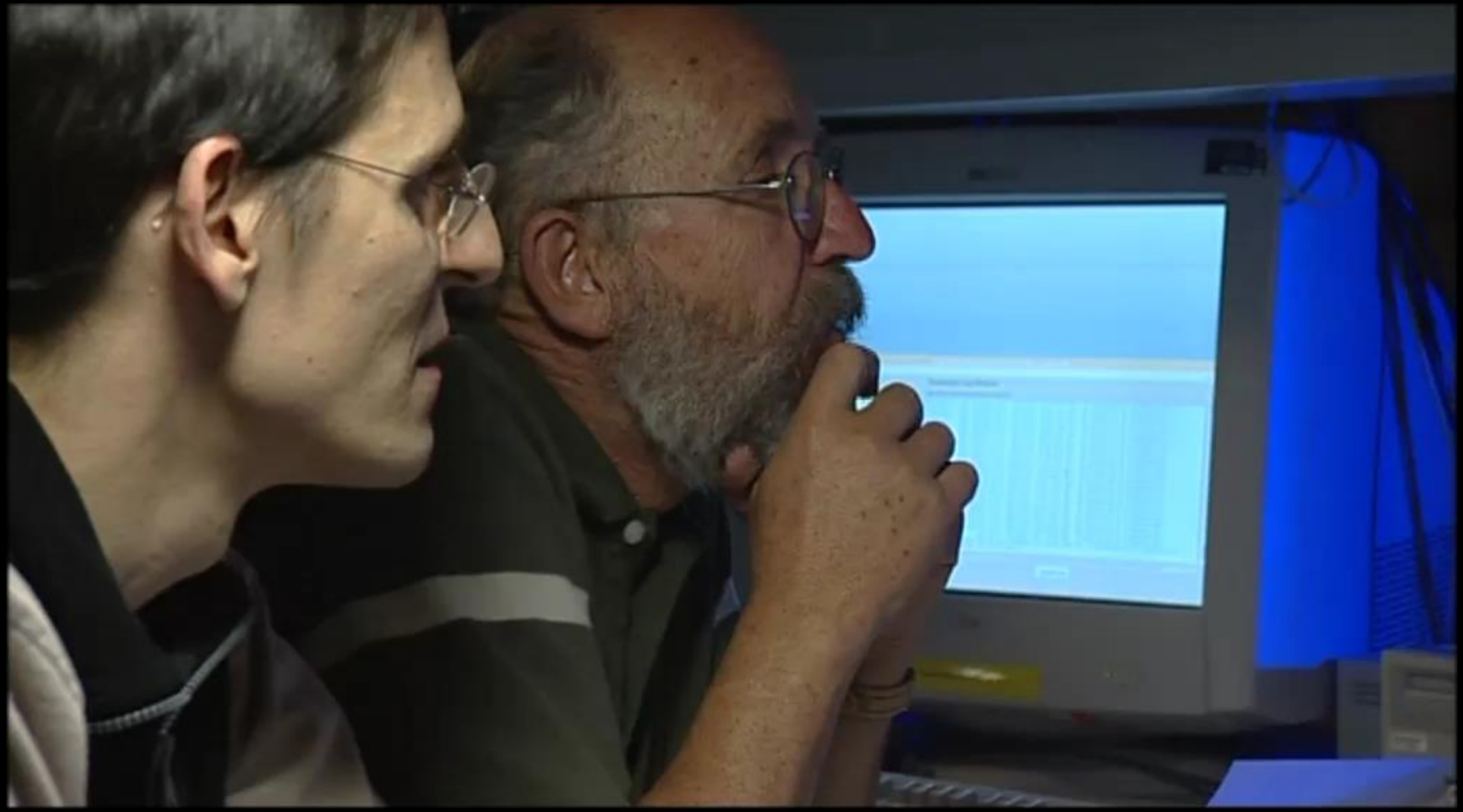
SPECTRO	YEAR	PRECISION	TELESCOPE	FACILITY
CORAVEL	1977	300 m/s	1 m	OHP
ELODIE	1994	13 m/s	1.9 m	OHP
CORALIE	1998	6 m/s	1 m	ESO Chile
HARPS	2003	1 m/s	3.6 m	ESO Chile
HARPS-N	2013	1 m/s	3.5 m	La Palma
ESPRESSO	2018	0.1 m/s	8.2 m (x4)	ESO Chile

Le spectrographe HARPS

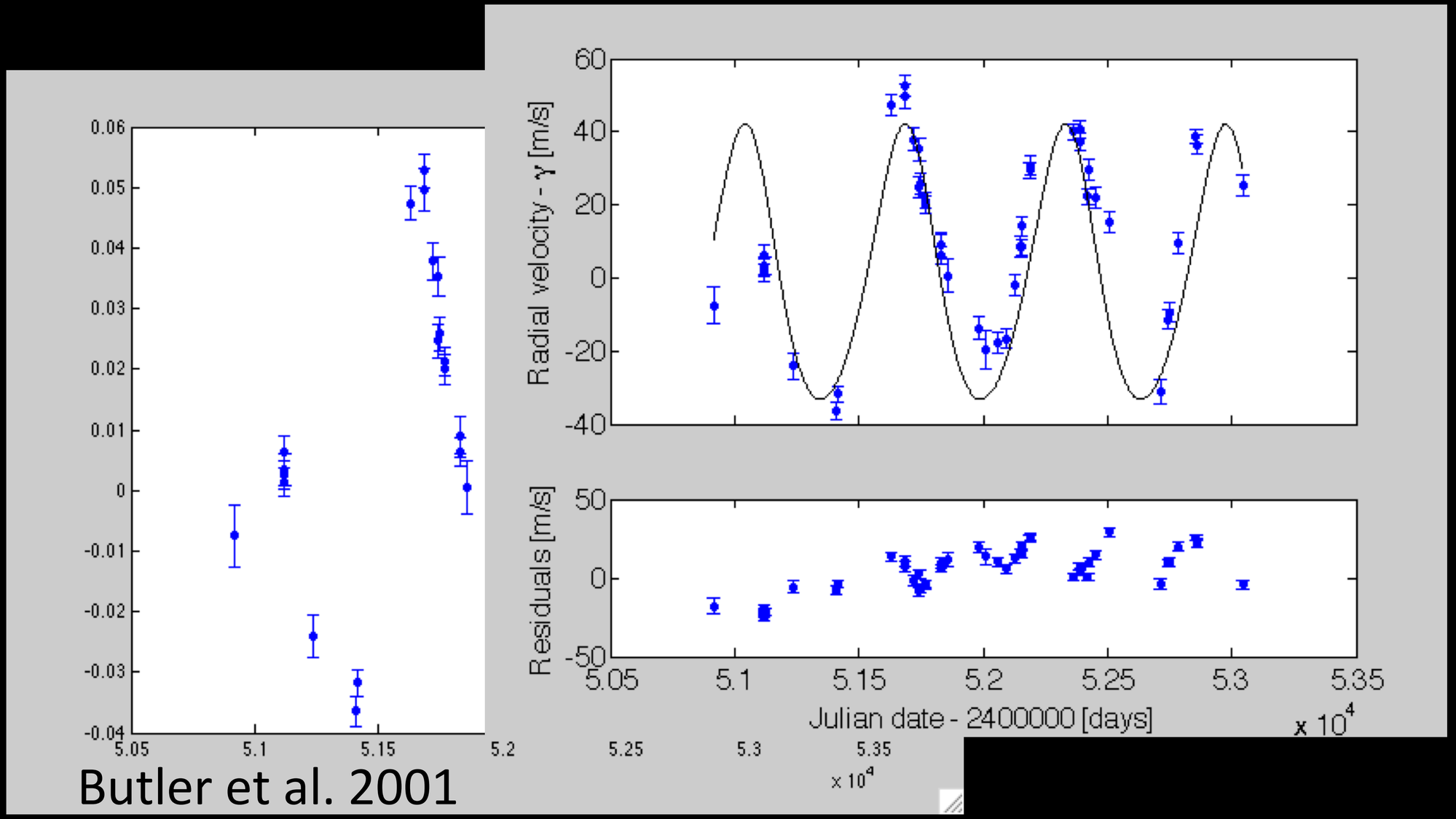


Stabilité et précision extrèmes

The forecast at first light



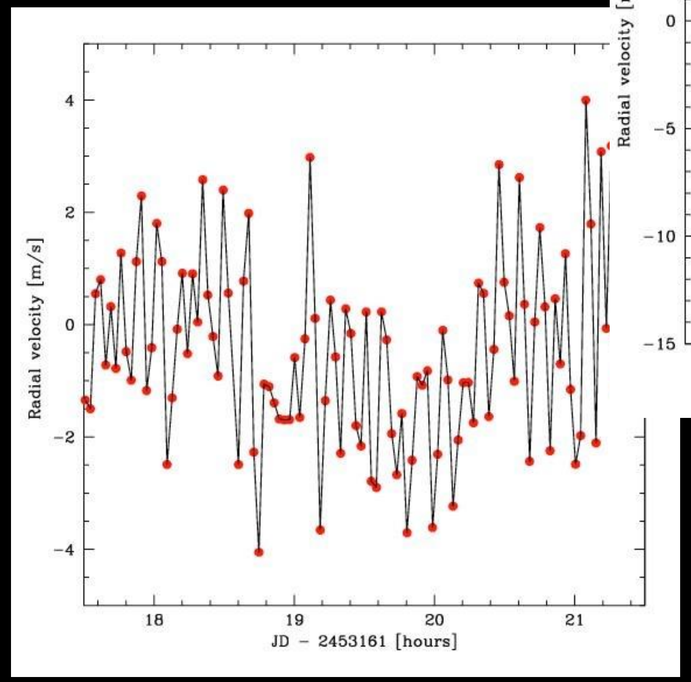
HARPS, l'épreuve de maturité

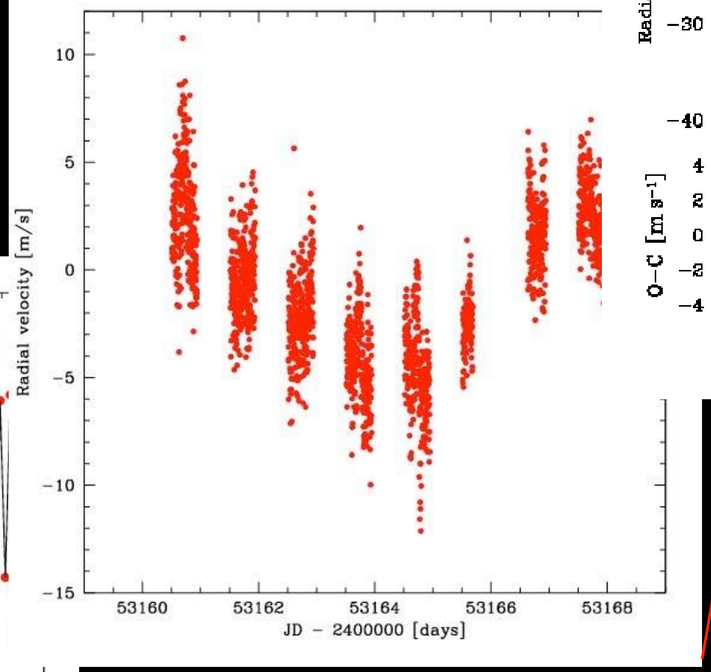


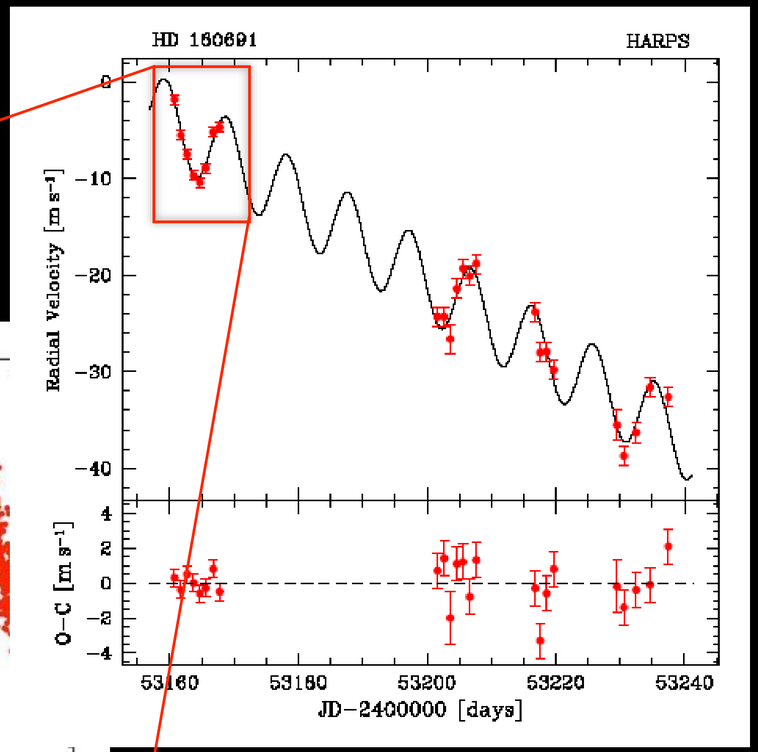
Butler et al. 2001

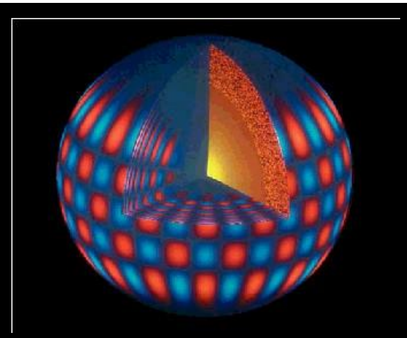
8 nuits d’astérosismologie
250 observations par nuit

Santos et al. 2004
Bouchy et al. 2005
Bazot et al. 2005









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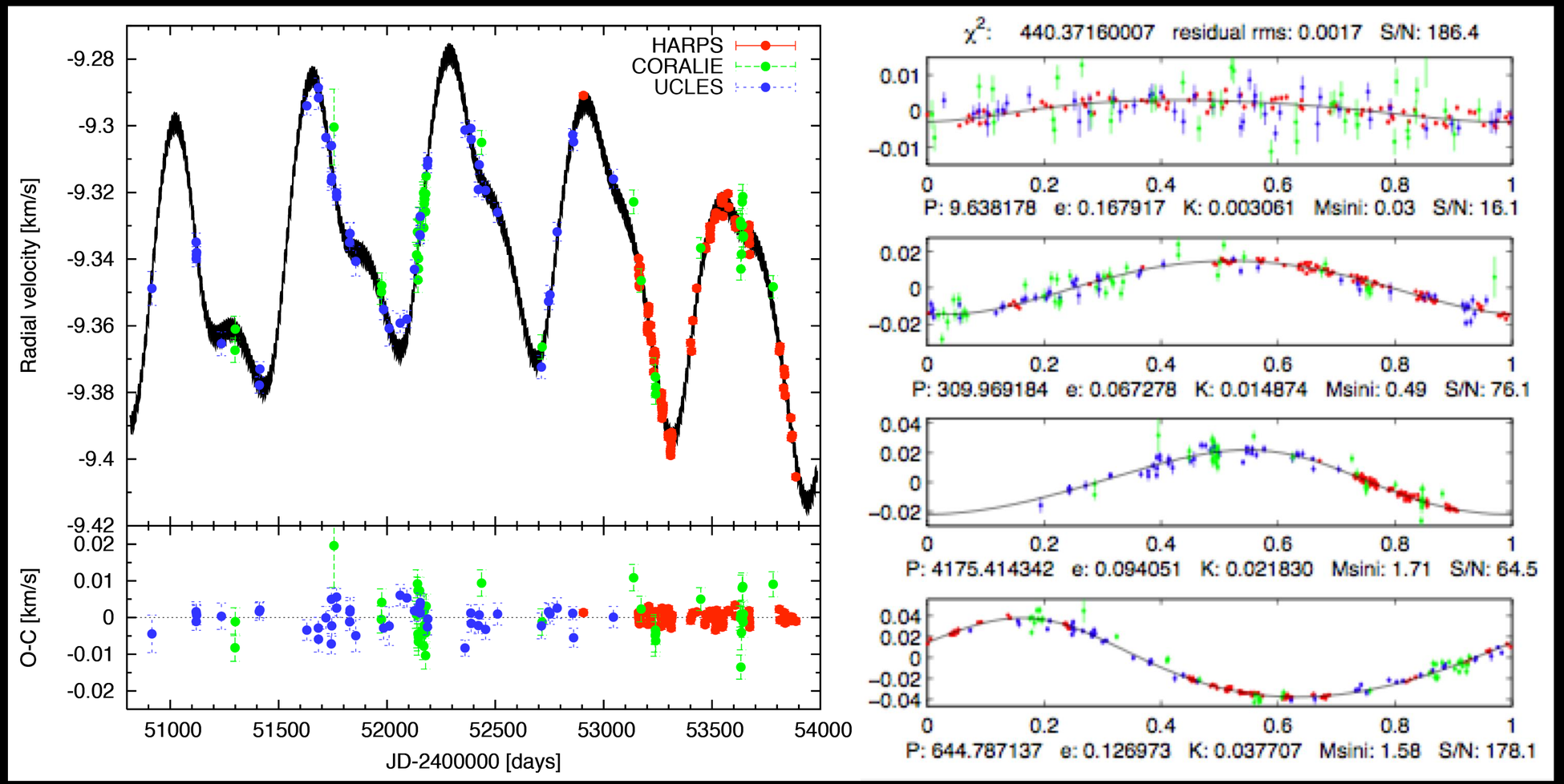


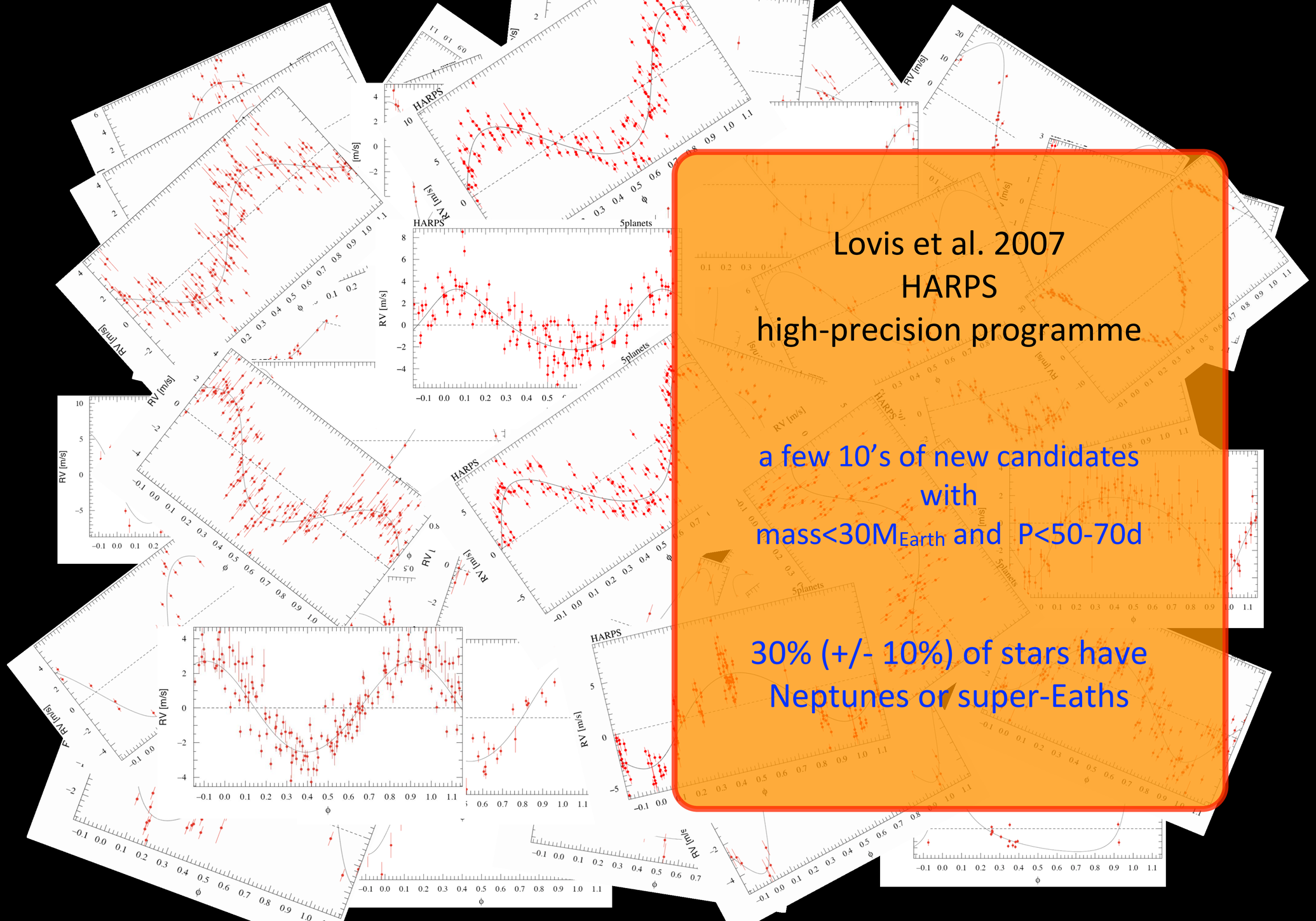
Butler et al, ApJ, 2001

Jones et al., MNRAS, 2002

Santos et al., A&A, 2004

McCarthy et al., ApJ, 2004

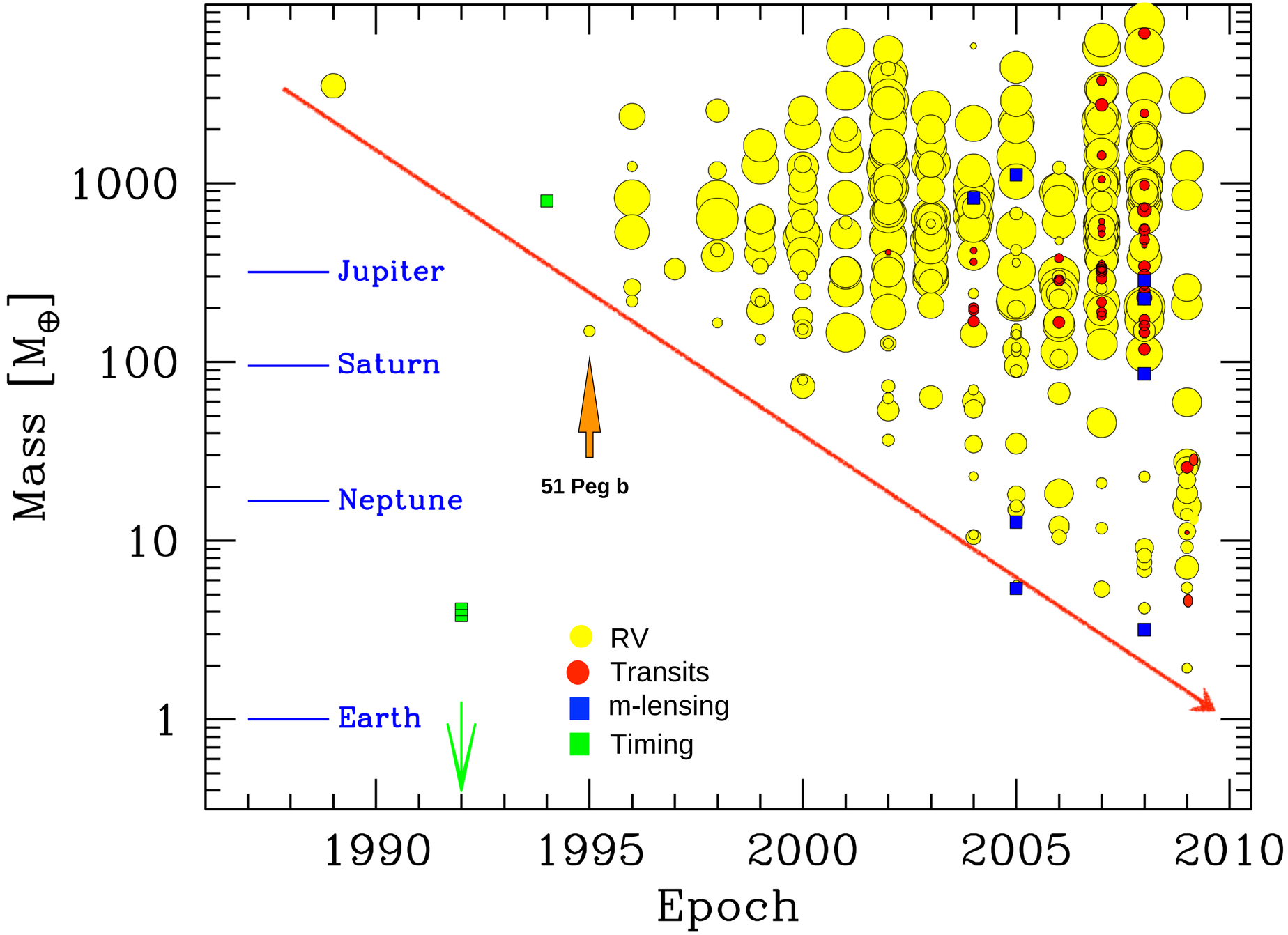
Pepe et al., A&A, 2006



Lovis et al. 2007
HARPS
high-precision programme

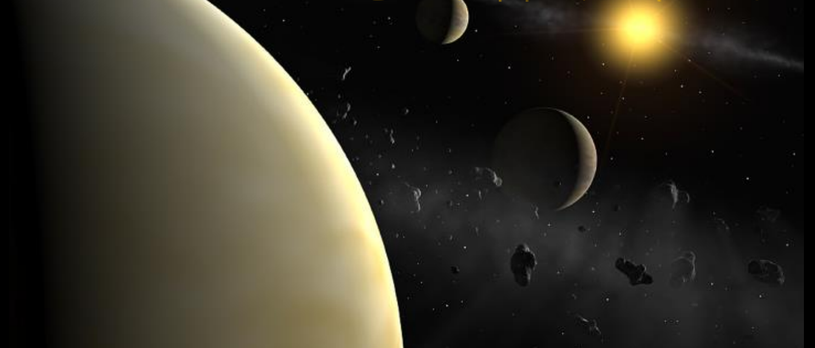
a few 10's of new candidates
with
mass<30M_{Earth} and P<50-70d

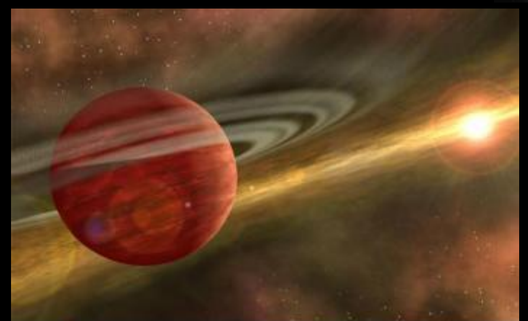
30% (+/- 10%) of stars have
Neptunes or super-Eaths


1000
100
10
1
Mass [M⊕]
Jupiter
Saturn
Neptune
Earth
51 Peg b
RV
Transits
m-lensing
Timing
1990
1995
2000
2005
2010
Epoch

1995 => 2010

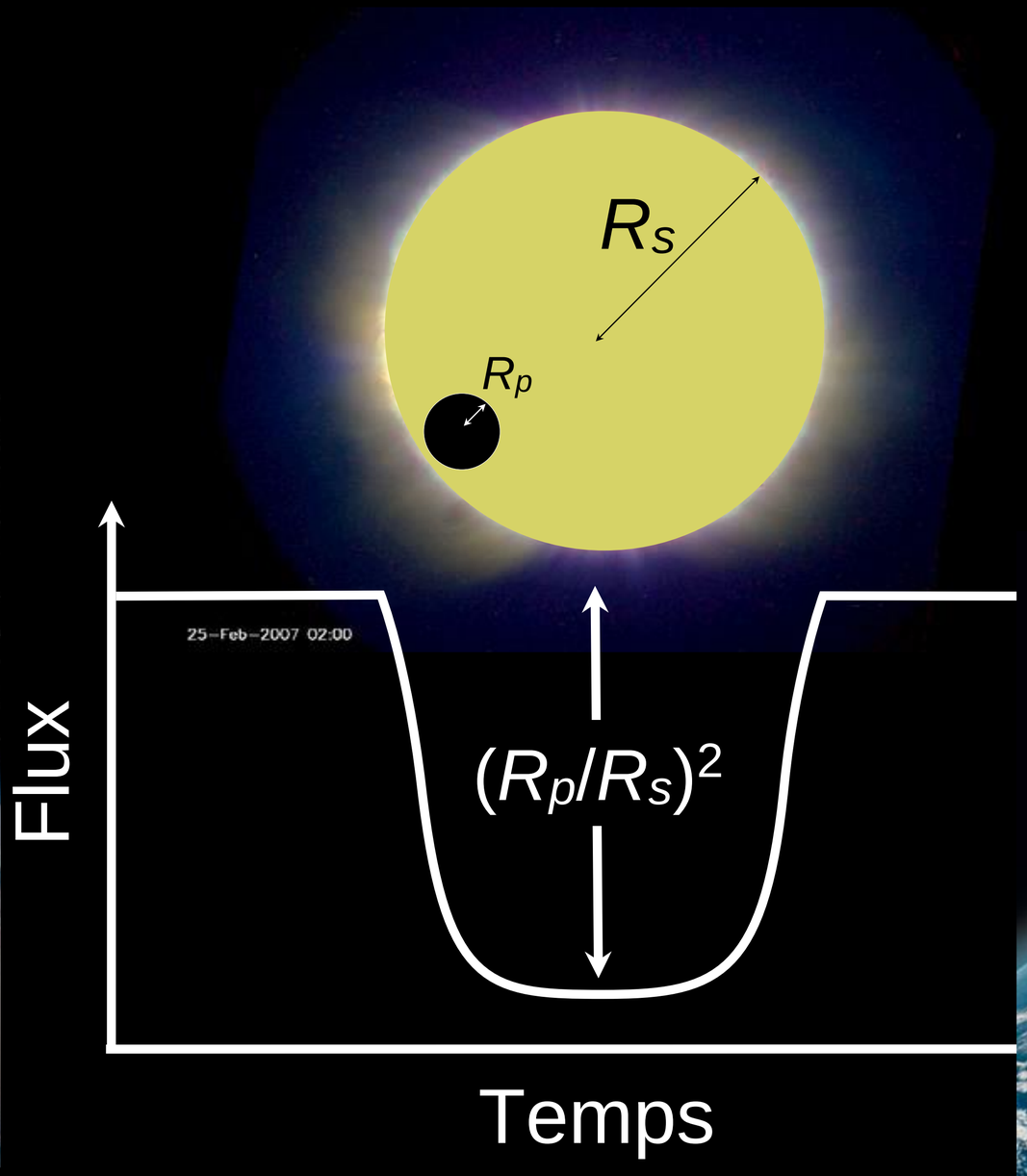
- ~ 1’000 planètes confirmées
- Diversité de masses et orbites
- Systèmes multi-planétaires (=> 7)
- Diversité d’architecture
- Mais attention: seulement limites inférieures des masses





Mesure du rayon de la planètes

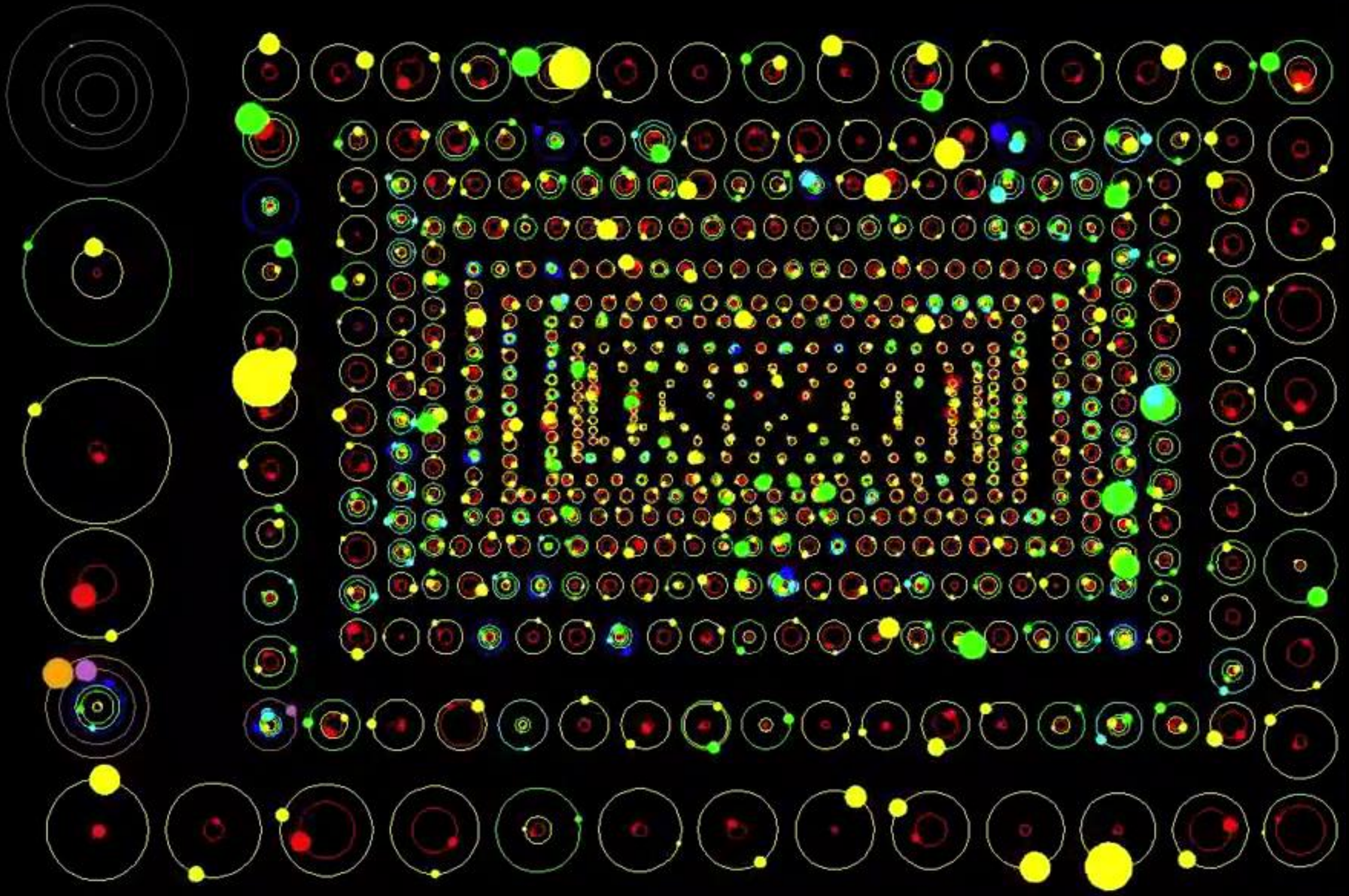
CoRoT

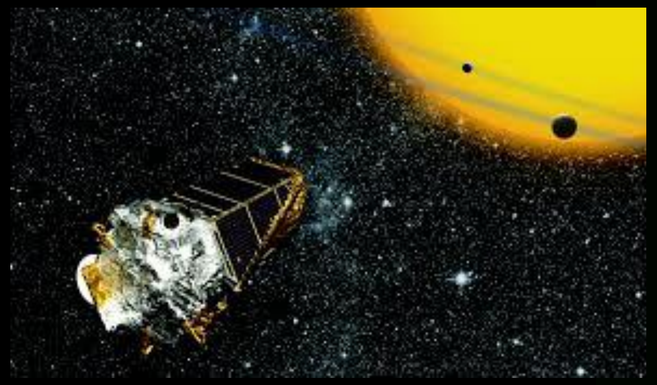


KEPLER

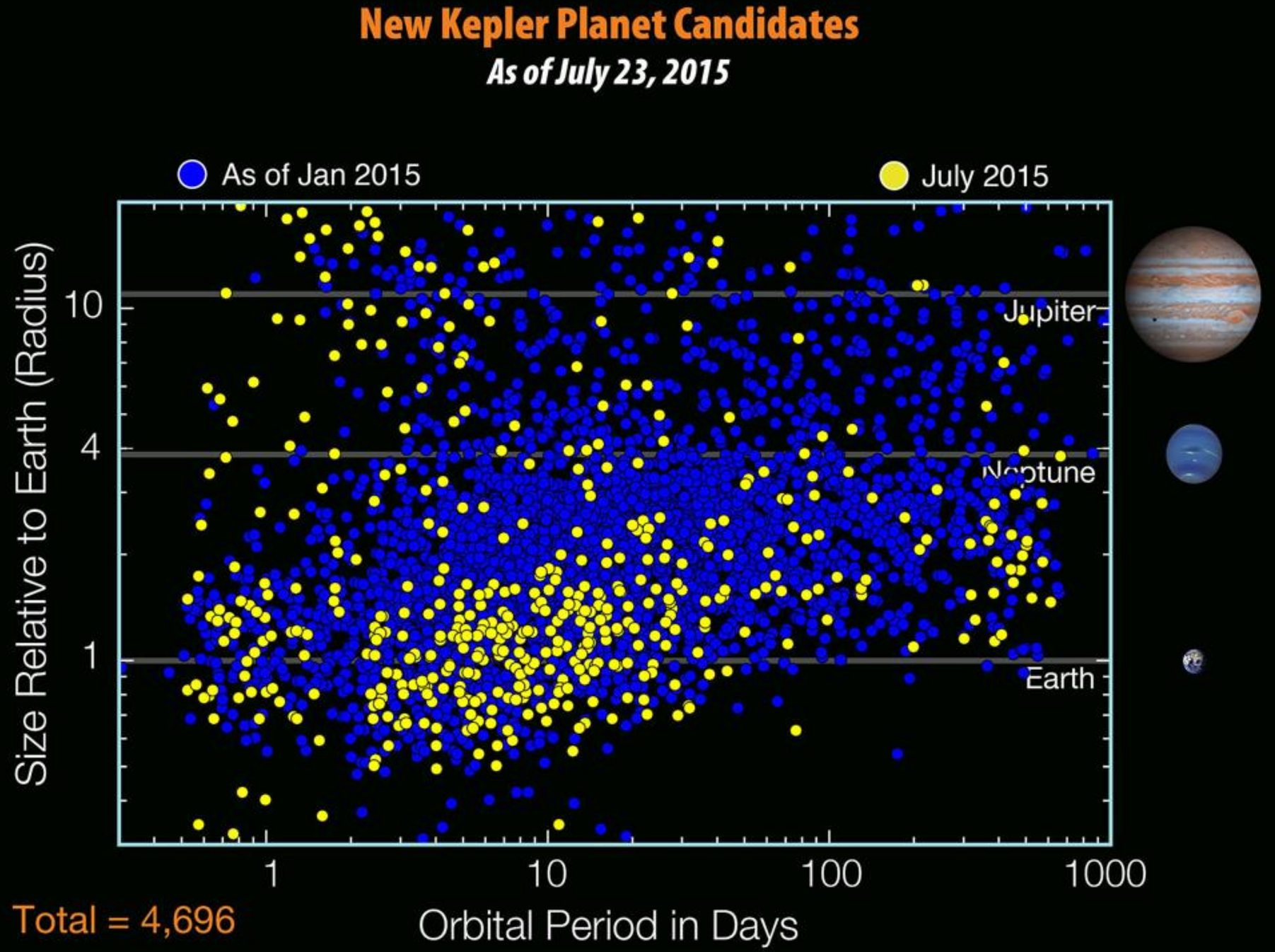
The Kepler Orrery III

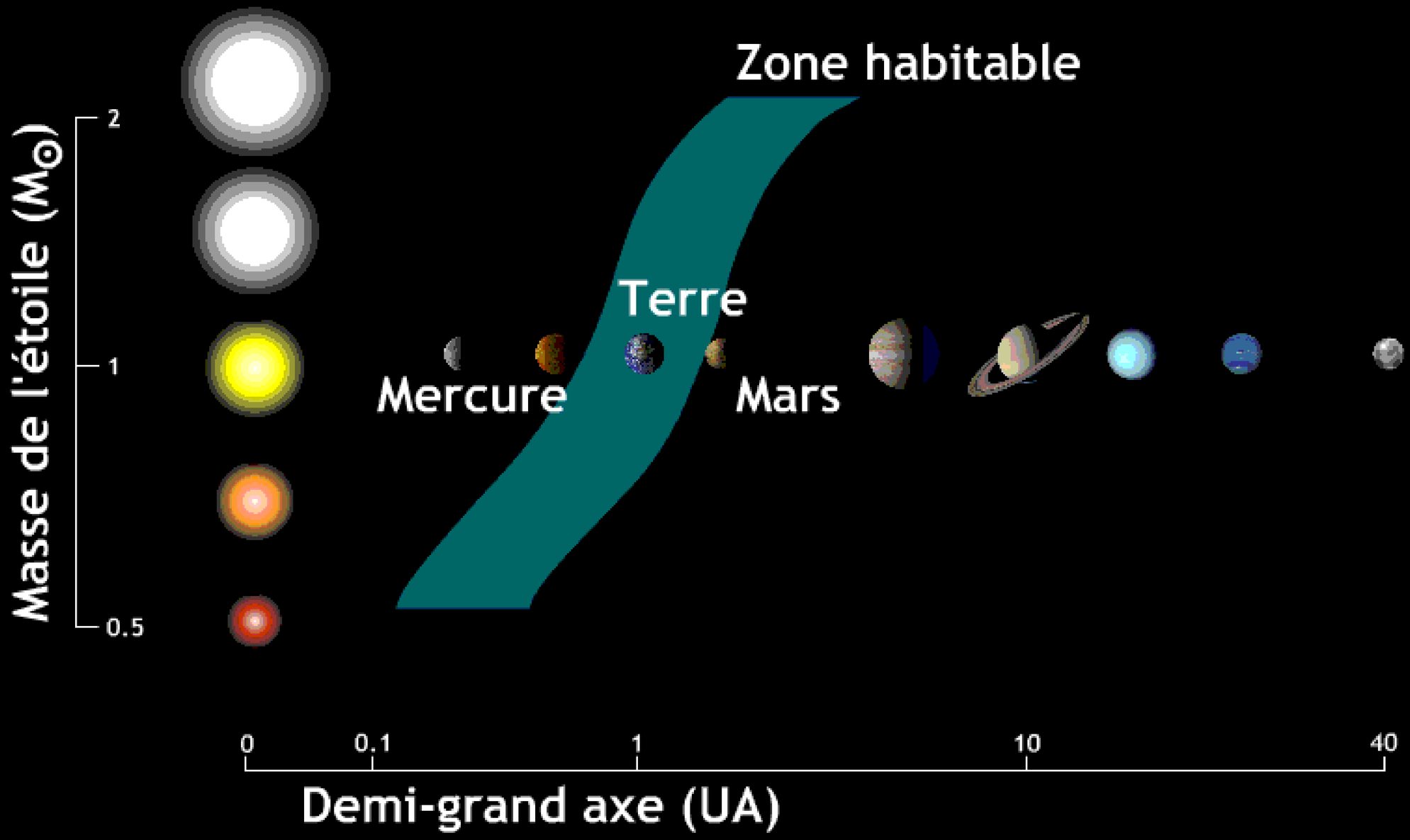
t[BJD] = 2455516



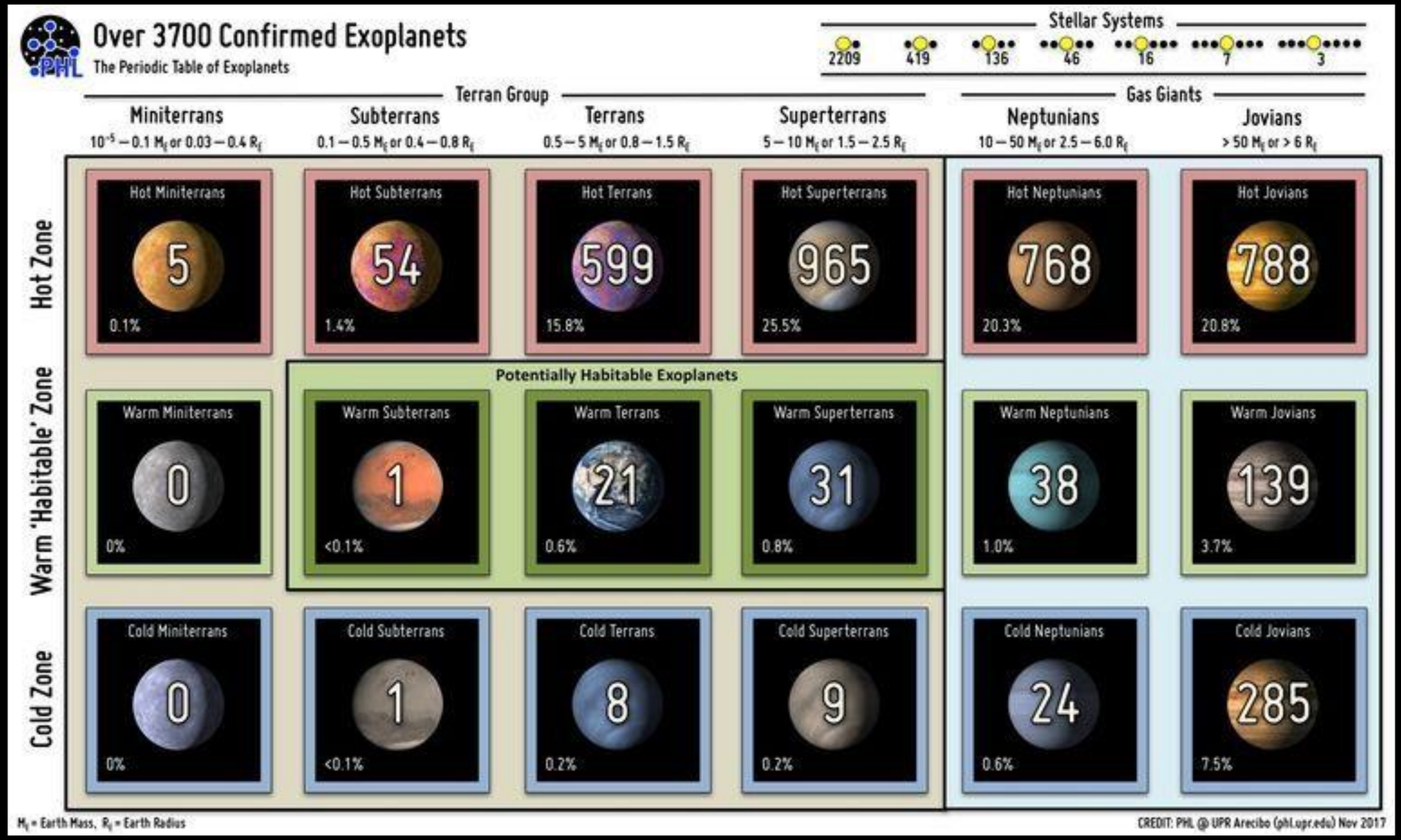


Des milliers de nouvelles planètes grace à Kepler, mais ….

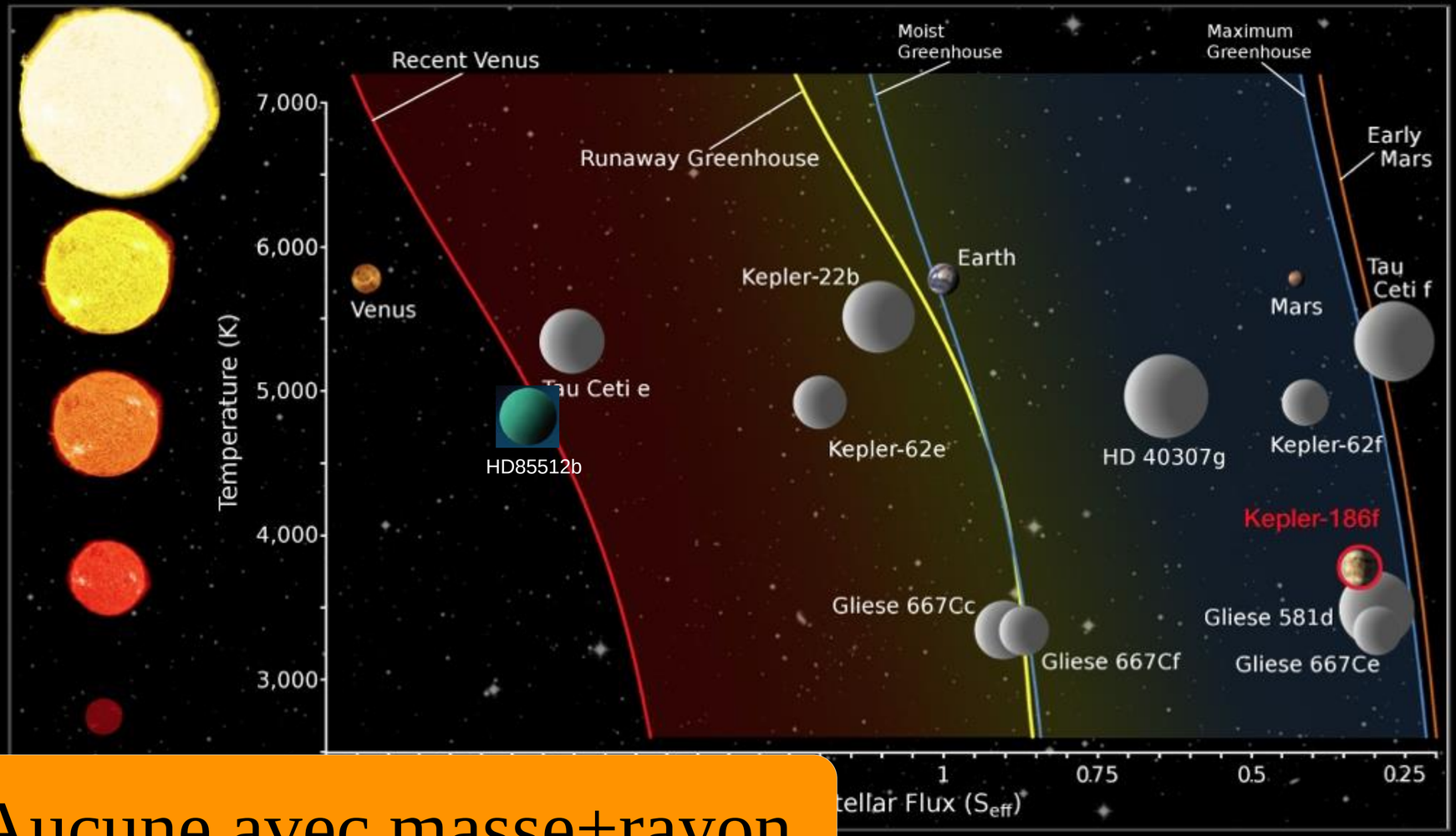



Zone habitable
Terre
Mercure
Mars
Masse de l'étoile ($M_\odot$)
2
1
0.5
0
0.1
1
10
40
Demi-grand axe (UA)

Autant de planètes différentes, et pourtant aucune comme la notre …

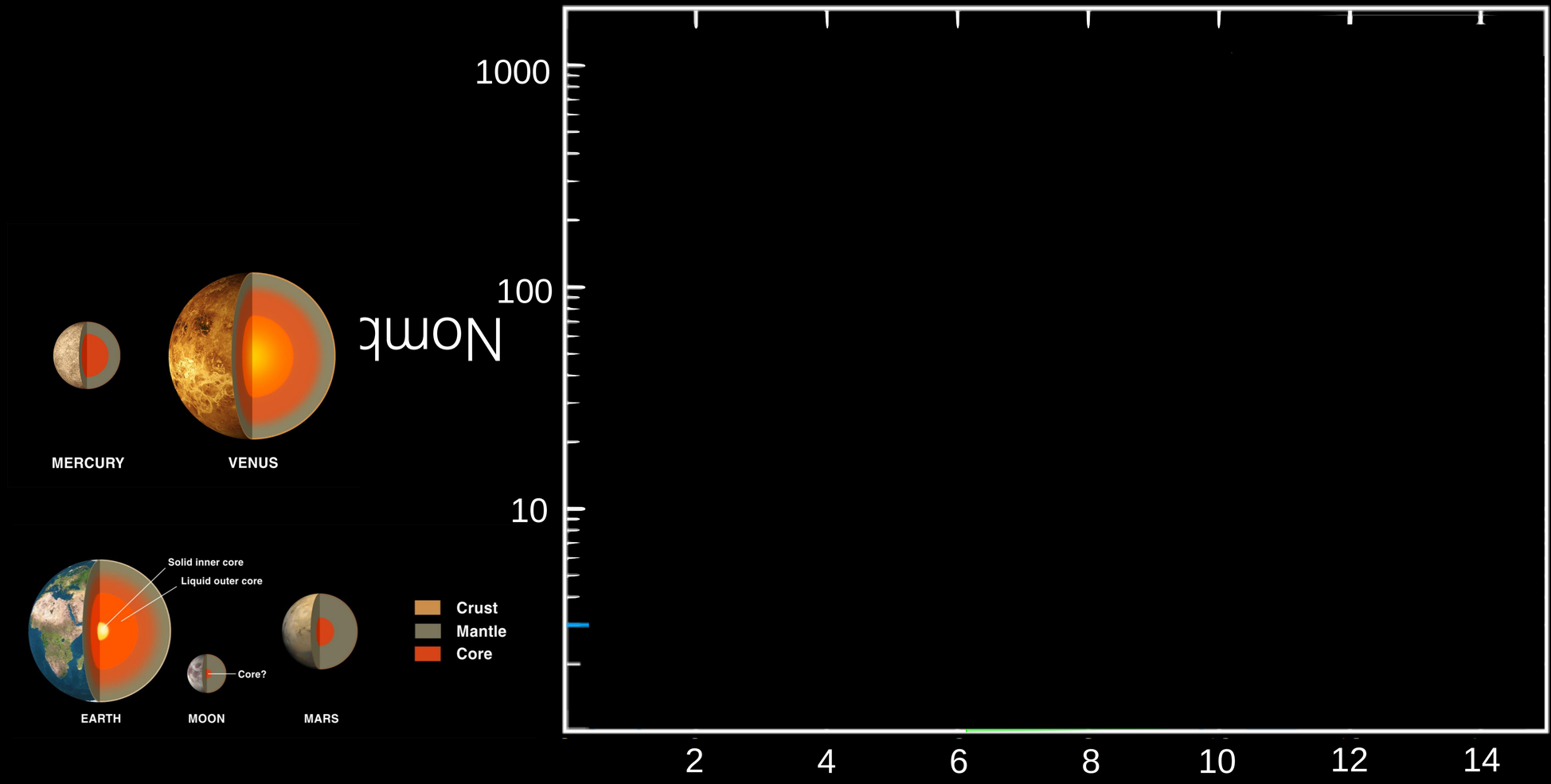


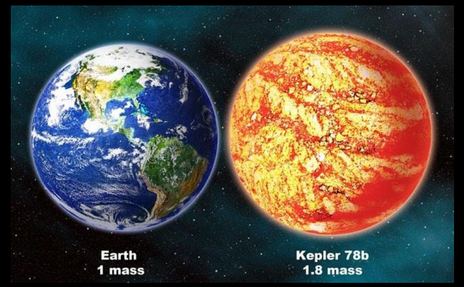
The Habitable Zone

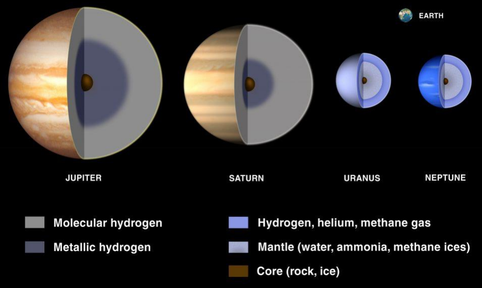


Aucune avec masse+rayon

Convergence vers les étoiles brillantes





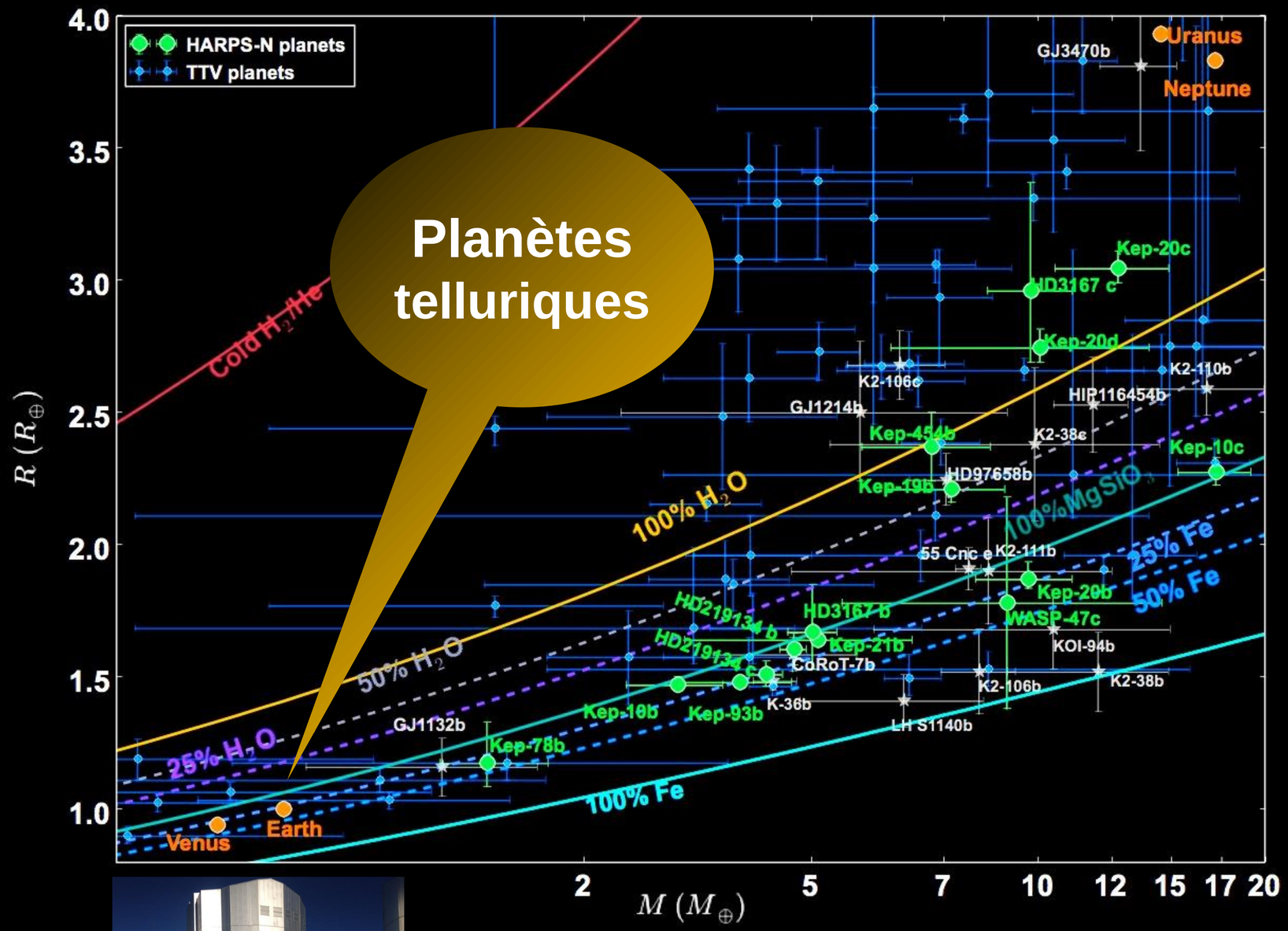


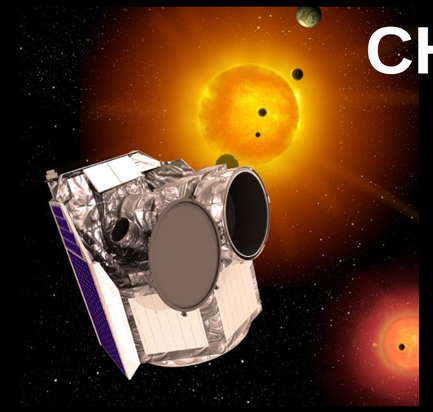
Etoiles brillantes

Magnitude *(J)*

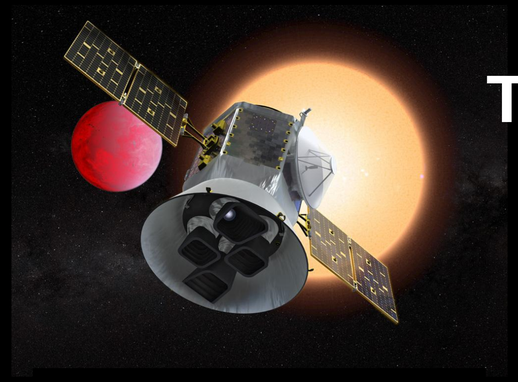
Etoiles faibles

Planètes telluriques

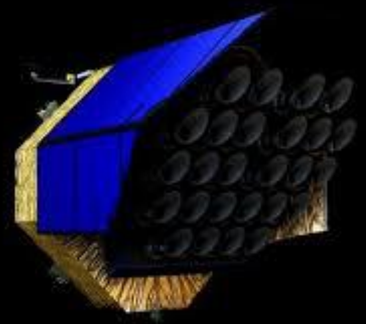




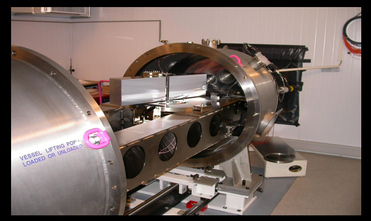
CHEOPS

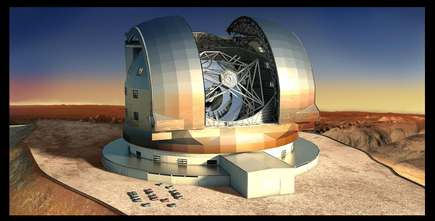


TESS



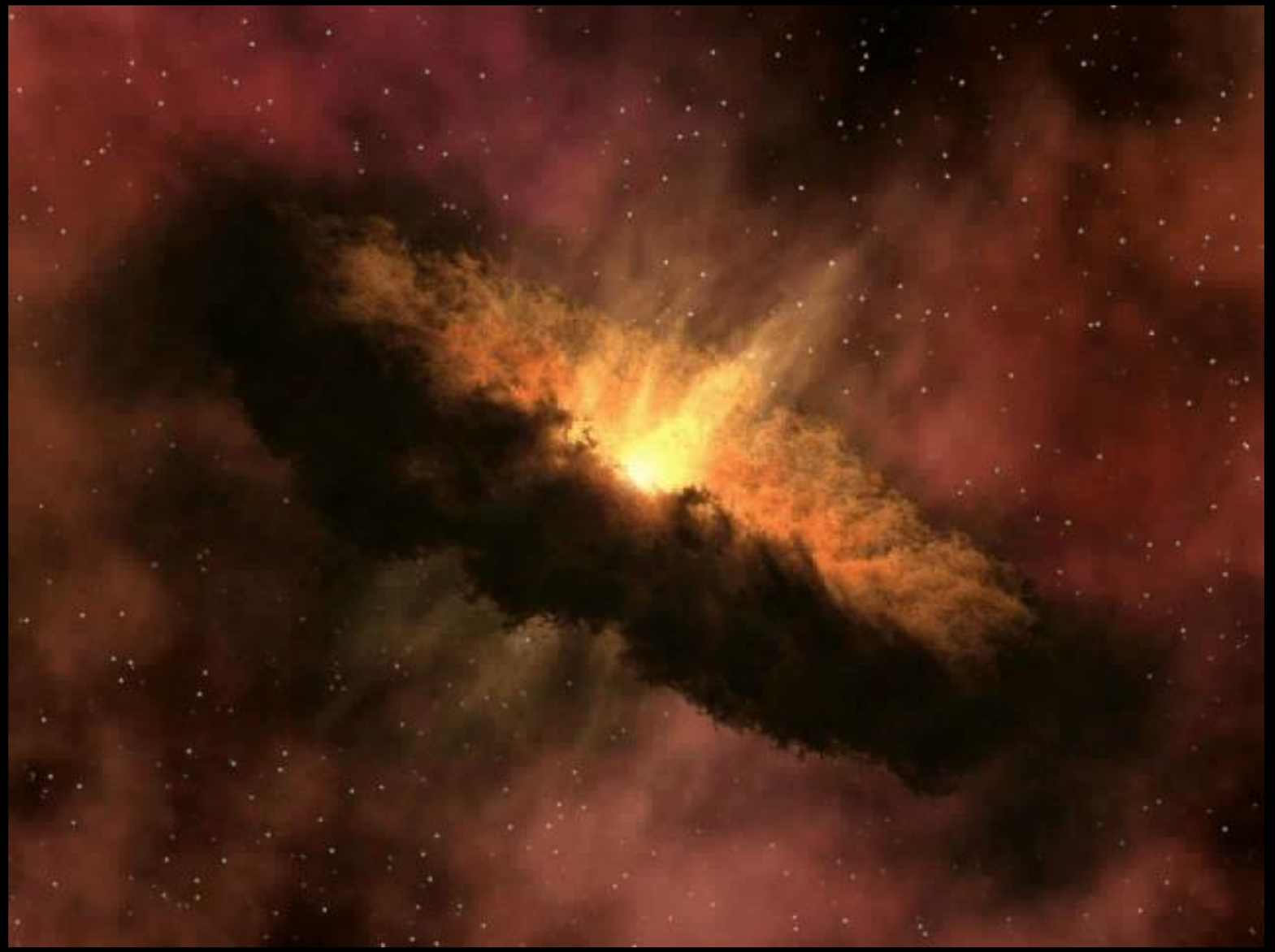
PLATO



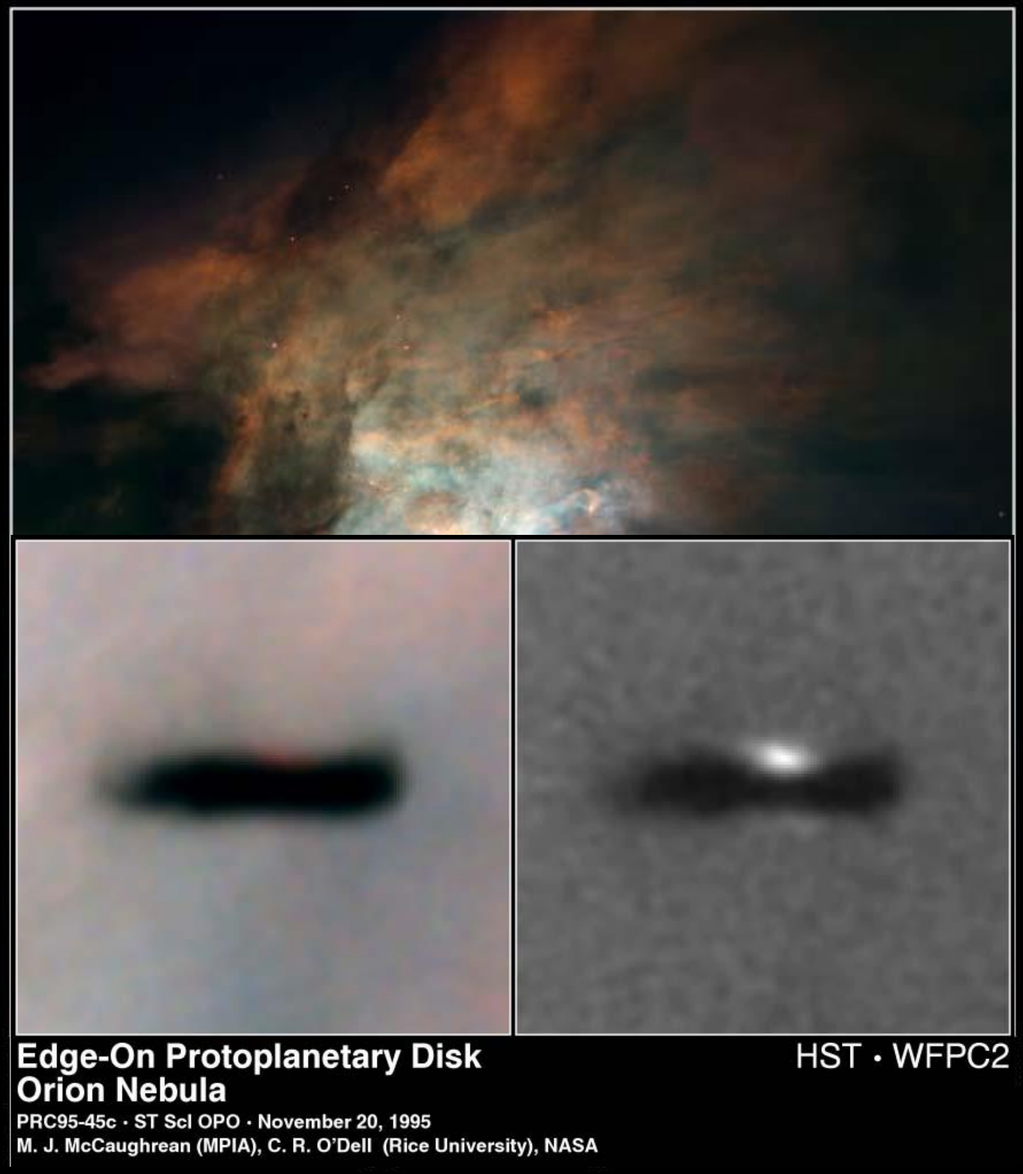


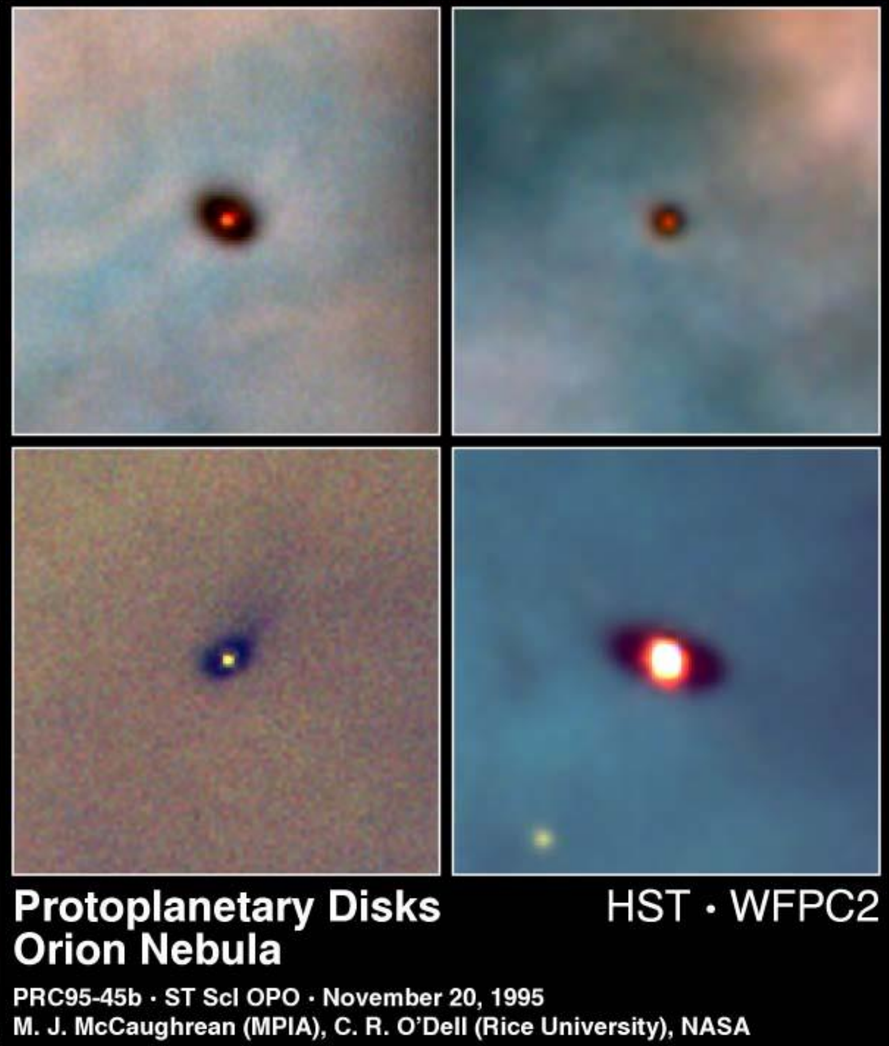
Vitesses radiales + Transit
-> Masse & Rayon
-> Densité & Composition

Les planètes se forment à partir du gaz et des poussières dans les disques protoplanétaires

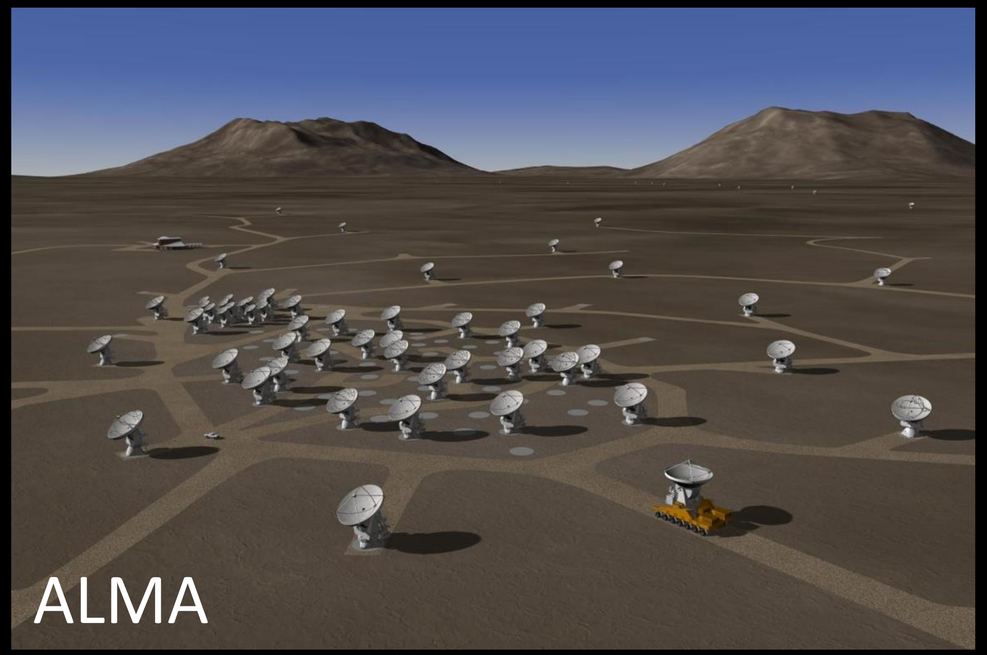


Zones de formation – disques protostellaires





HL Tauri (disque proto-planétaire)



ALMA, image réelle, 2016

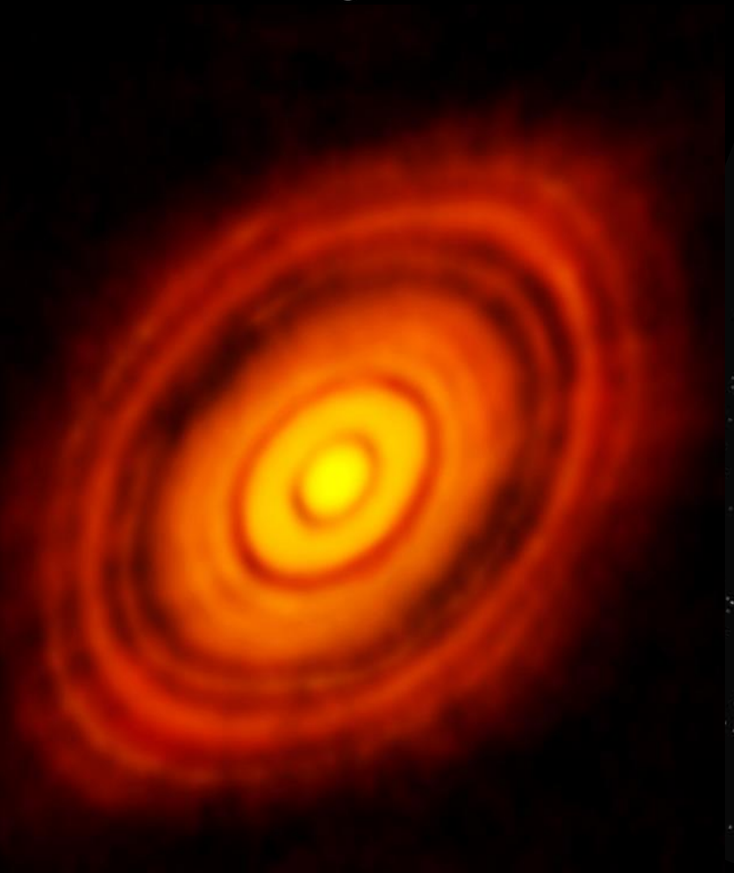
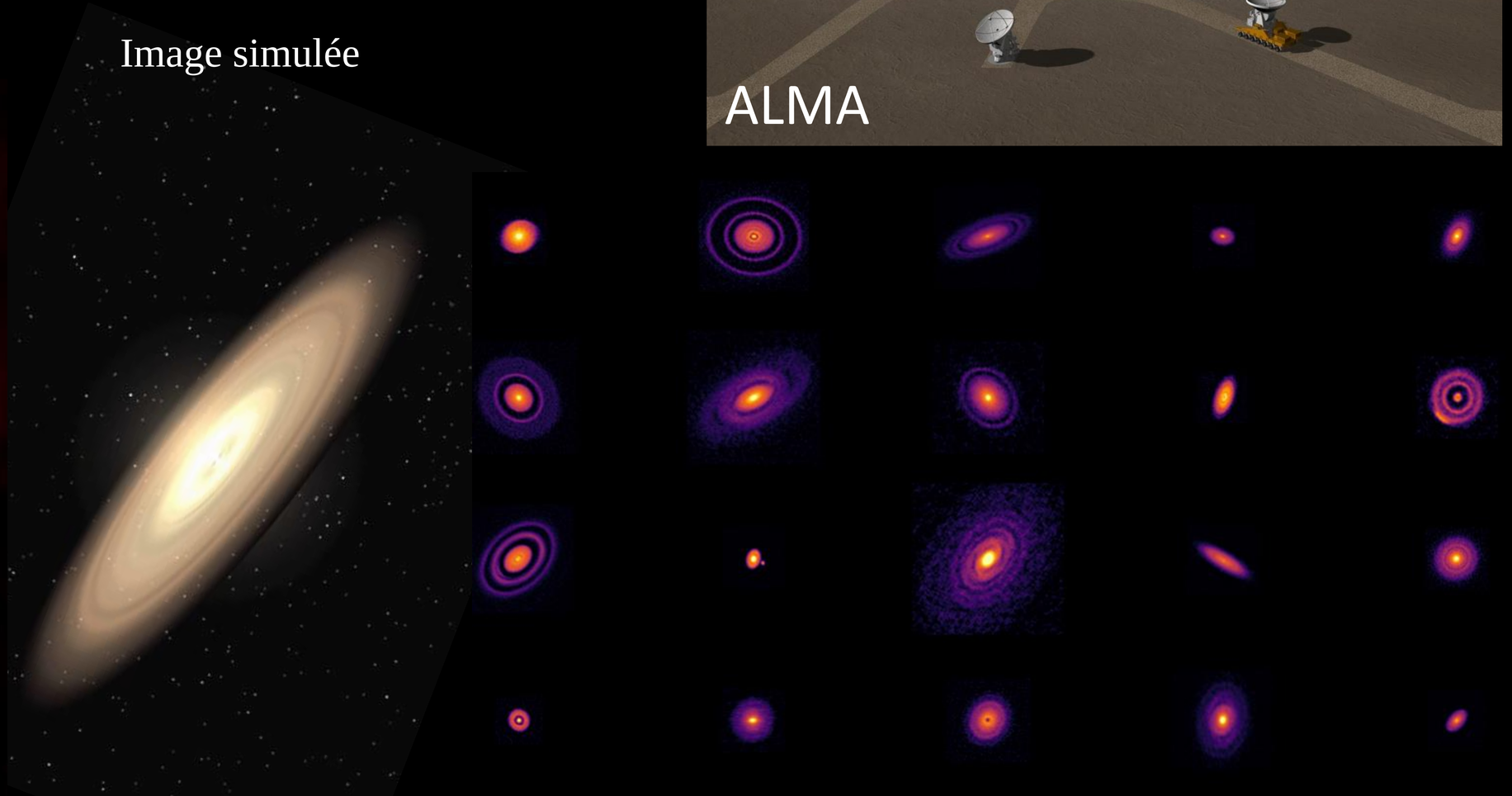


Image simulée

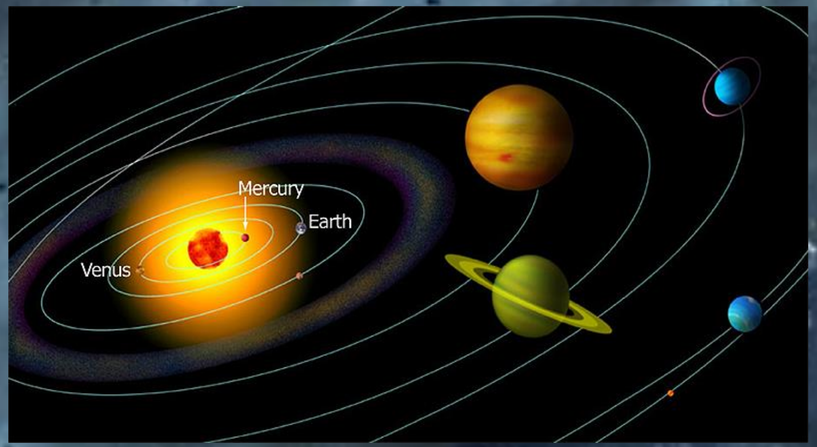


Evaporation du gaz dans les régions centrales

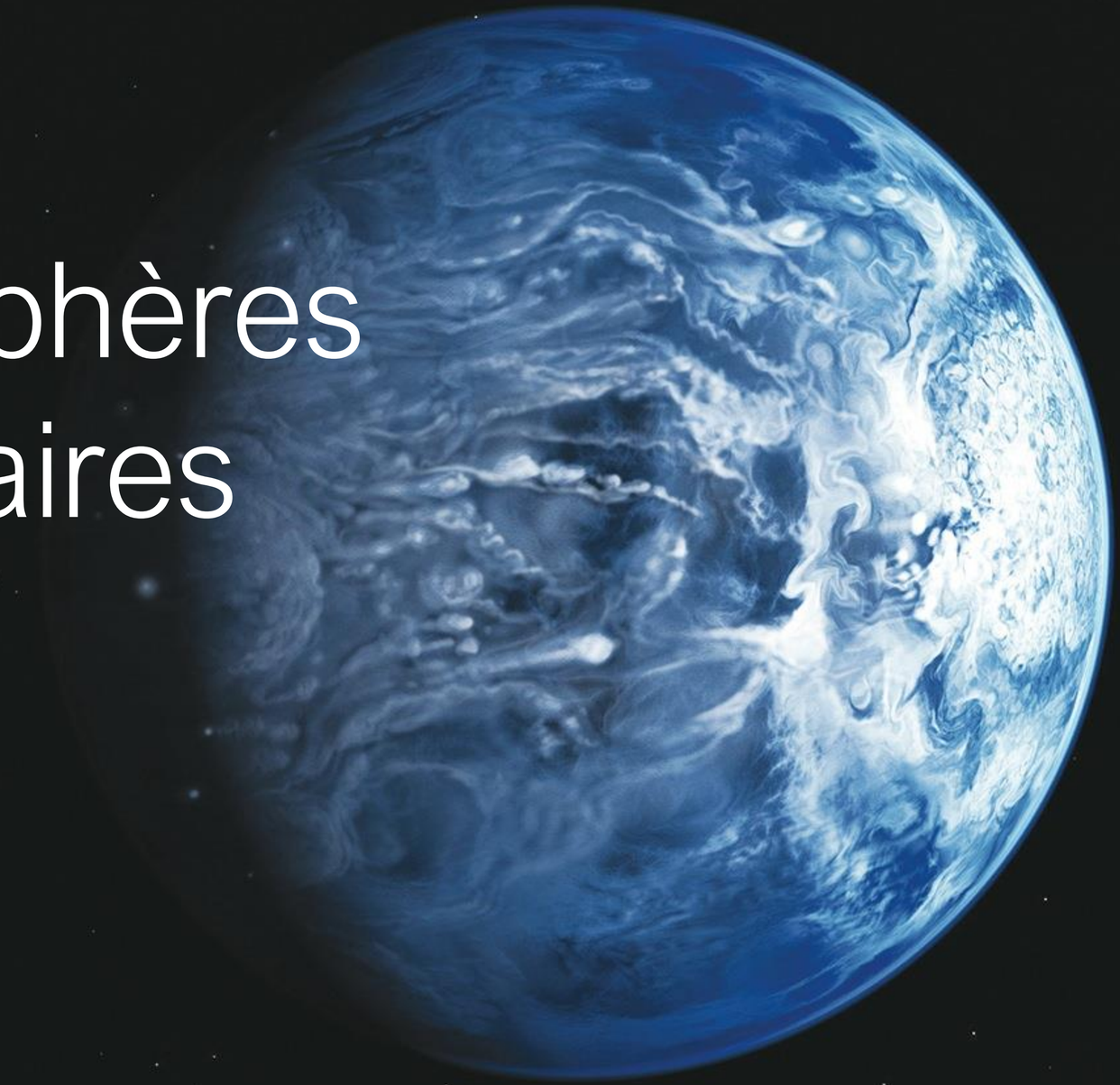
=> planètes solides

Plus loin, accrétion de gaz sur les coeurs solides (roche et glace)

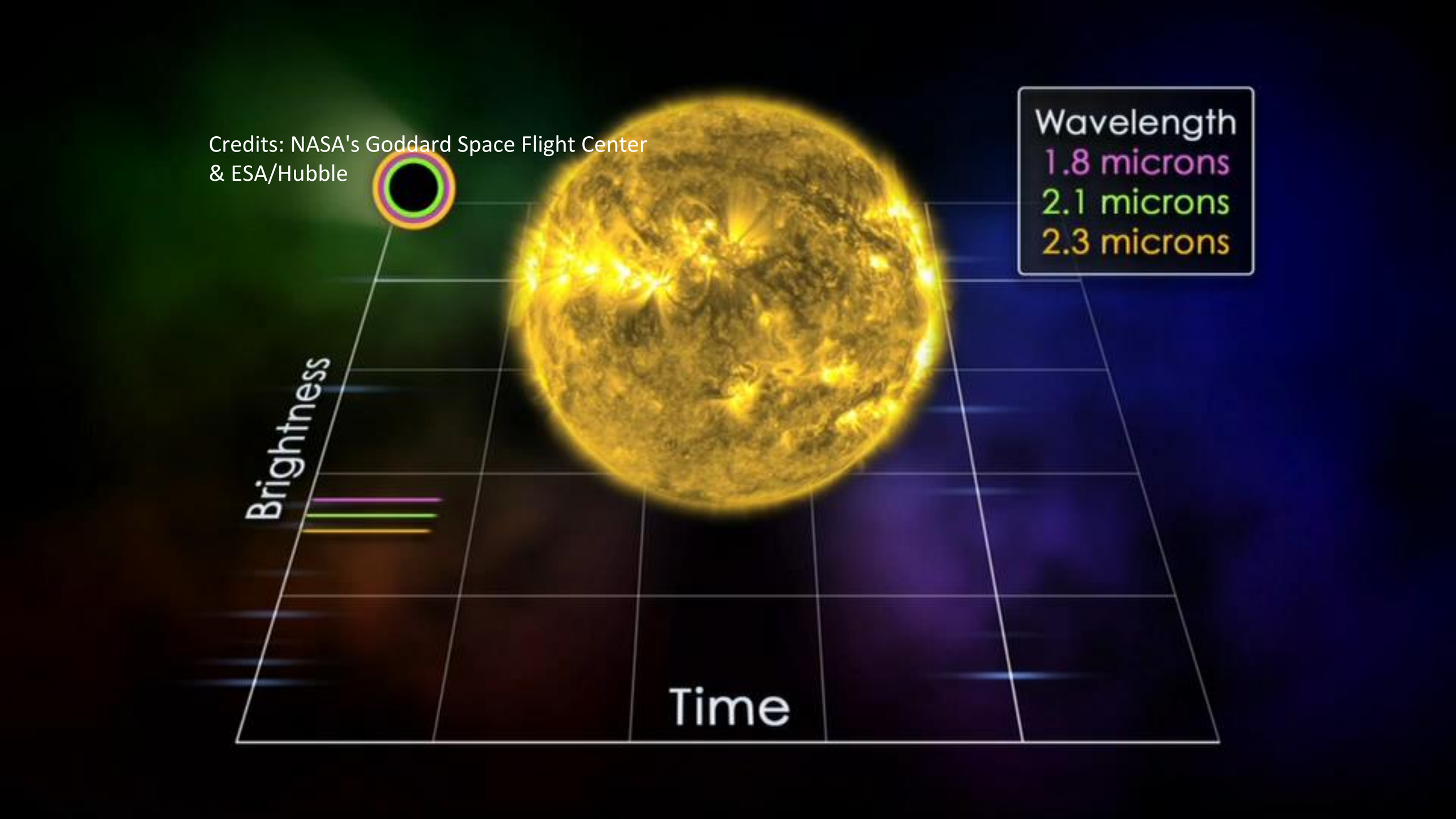
=> planètes géantes



Atmosphères Planétaires



PlanetS


Credits: NASA's Goddard Space Flight Center
& ESA/Hubble
Wavelength
1.8 microns
2.1 microns
2.3 microns
Brightness
Time


Paranal, October 2017
espresso

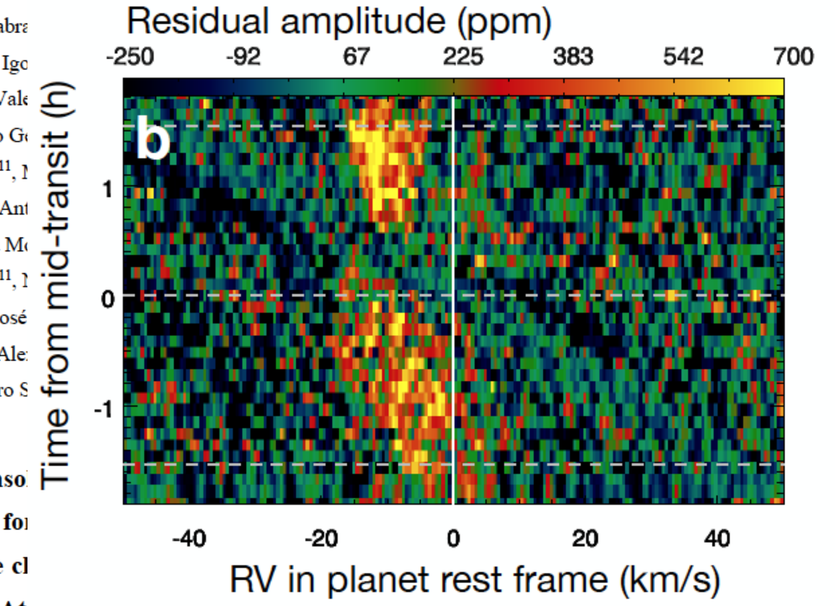
Ehrenreich et al., *Nature*, in press 2020

Nightside condensation of iron in an ultra-hot giant exoplanet

WASP-76 b

David Ehrenreich[1], Christophe Lovis[1], Romain Allart[1], María Rosa Zapatero Osorio[2], Francesco Pepe[1], Stefano Cristiani[3], Rafael Rebolo[4], Nuno C. Santos[5,6], Francesco Borsa[7], Olivier Demangeon[5], Xavier Dumusque[1], Jonay I. González Hernández[4], Núria Casasayas-Barris[4], Damien Ségransan[1], Sérgio Sousa[5], Manuel Abreu[8,9], Vardan Adibekyan[5], Michael Affolter[10], Carlos Allende Prieto[4], Yann Alibert[10], Matteo Aliverti[7], David Alves[8,9], Manuel Amate[4], Gerardo Avila[11], Veronica Baldini[3], Timothy Bandy[10], Willy Benz[10], Andrea Bianco[7], Émeline Bolmont[1], François Bouchy[1], Vincent Bourrier[1], Christopher Broeg[10], Alexandre Cabra Enric Pallé[4], H. M. Cegla[1], Roberto Cirami[3], João M. P. Coelho[8,9], Paolo Conconi[7], Igo Cumani[11], Guido Cupani[3], Hans Dekker[11], Bernard Delabre[11], Sebastian Deiries[11], Vale Paolo Di Marcantonio[3], Pedro Figueira[13,5], Ana Fragoso[4], Ludovic Genolet[1], Matteo G Santos[4], Nathan Hara[1], Ian Hughes[1], Olaf Iwert[11], Florian Kerber[11], Jens Knudstrup[11], Lavie[1], Jean-Louis Lizon[11], Monika Lendl[1,14], Gaspare Lo Curto[13], Charles Maire[1], An C. J. A. P. Martins[5,15], Denis Mégevand[1], Andrea Mehner[13], Giusi Micela[16], Andrea M Molaro[3,17], Manuel Monteiro[5], Mario Monteiro[5,6], Manuele Moschetti[7], Eric Müller[11], Oggioni[7], António Oliveira[8,9], Giorgio Pariani[7], Luca Pasquini[11], Ennio Poretti[7,18], José Redaelli[7], Marco Riva[7], Samuel Santana Tschudi[13], Paolo Santin[3], Pedro Santos[8,9], Ale Julia V. Seidel[1], Danuta Sosnowska[1], Alessandro Sozzetti[19], Paolo Spanò[7], Alejandro S Tabernero[2,5], Fabio Tenegi[4], Stéphane Udry[1], Alessio Zanutta[7], Filippo Zerbi[7]

Ultra-hot giant exoplanets receive thousands of times Earth's inso temperature atmospheres (>2,000 K) are ideal laboratories fo planetary climates and chemistry[3-5]. Daysides are predicted to be cl by atomic species[6] and substantially hotter than nightsides[5,7,8]. At



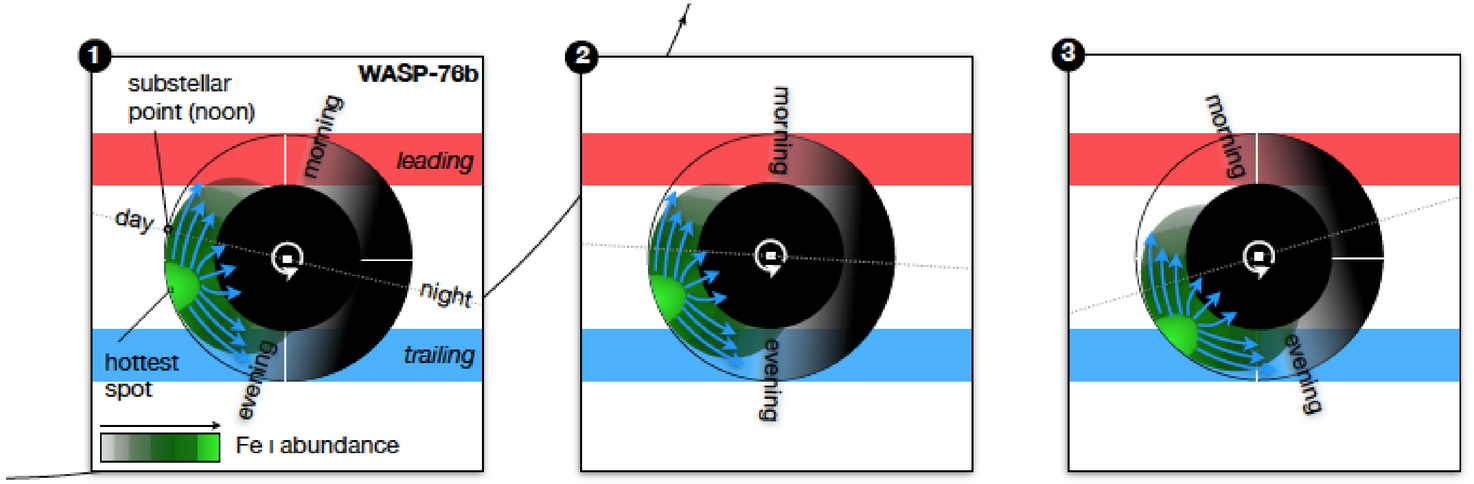
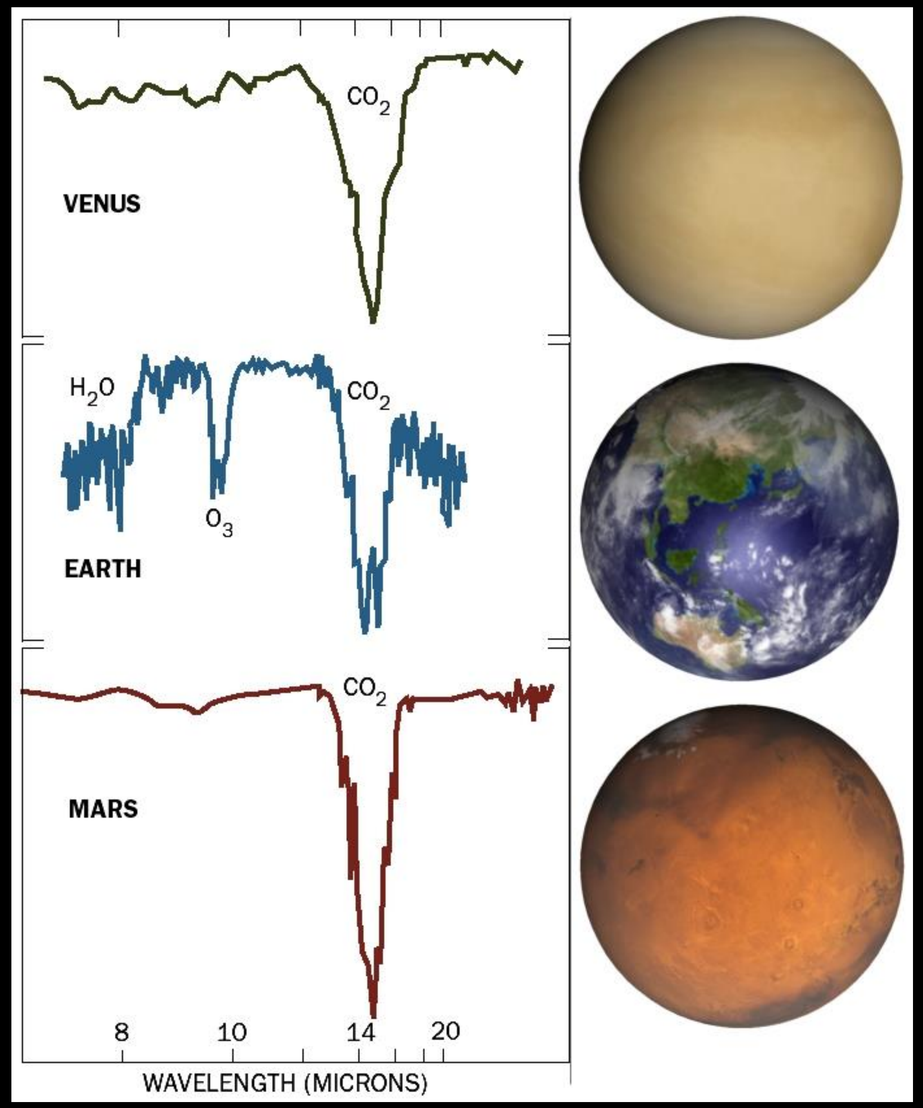
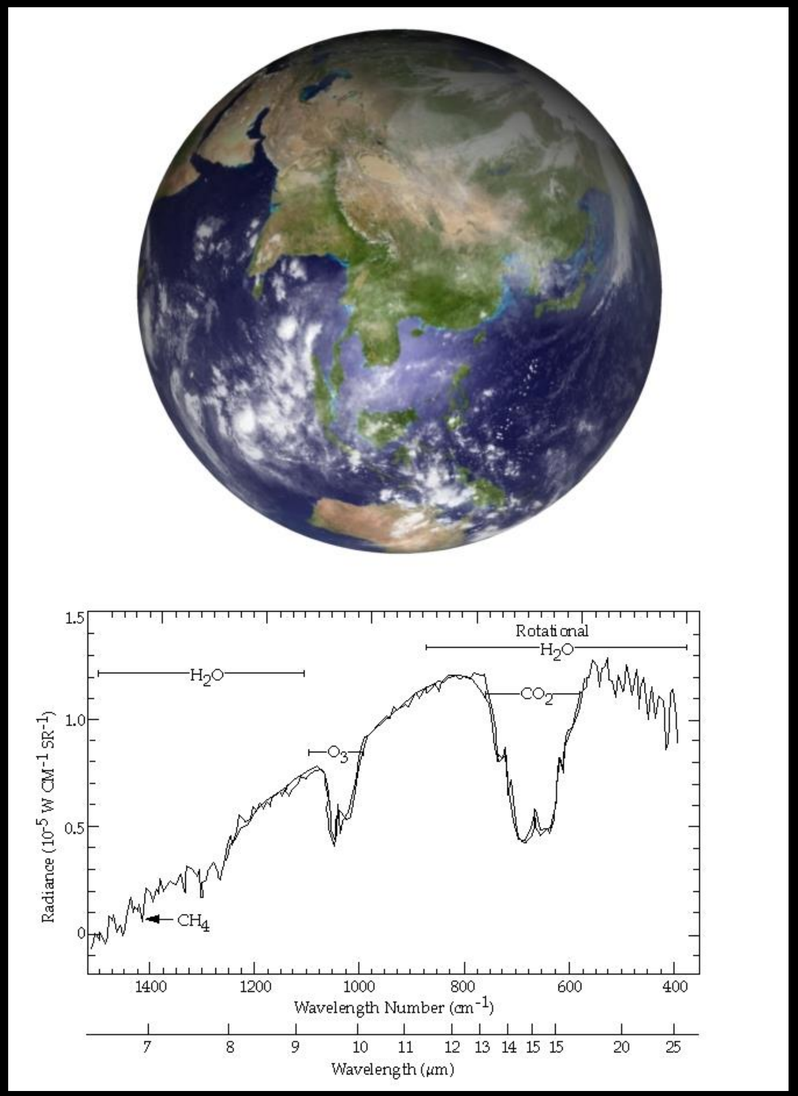


Figure 3 | Polar view of the WASP-76 system. a, The star WASP-76 and planet WASP-76b

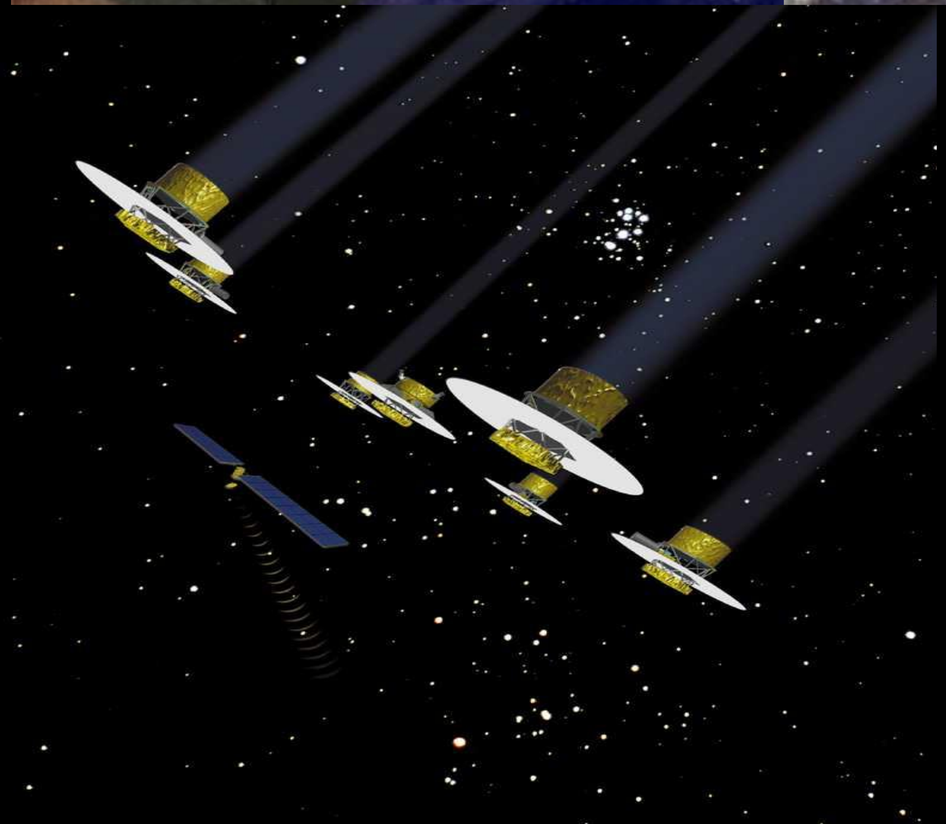
La recherche de la vie, les bio-traceurs



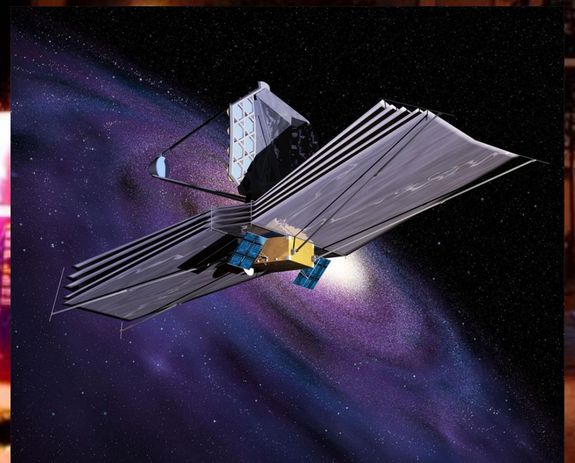


Le “Petit point bleu”

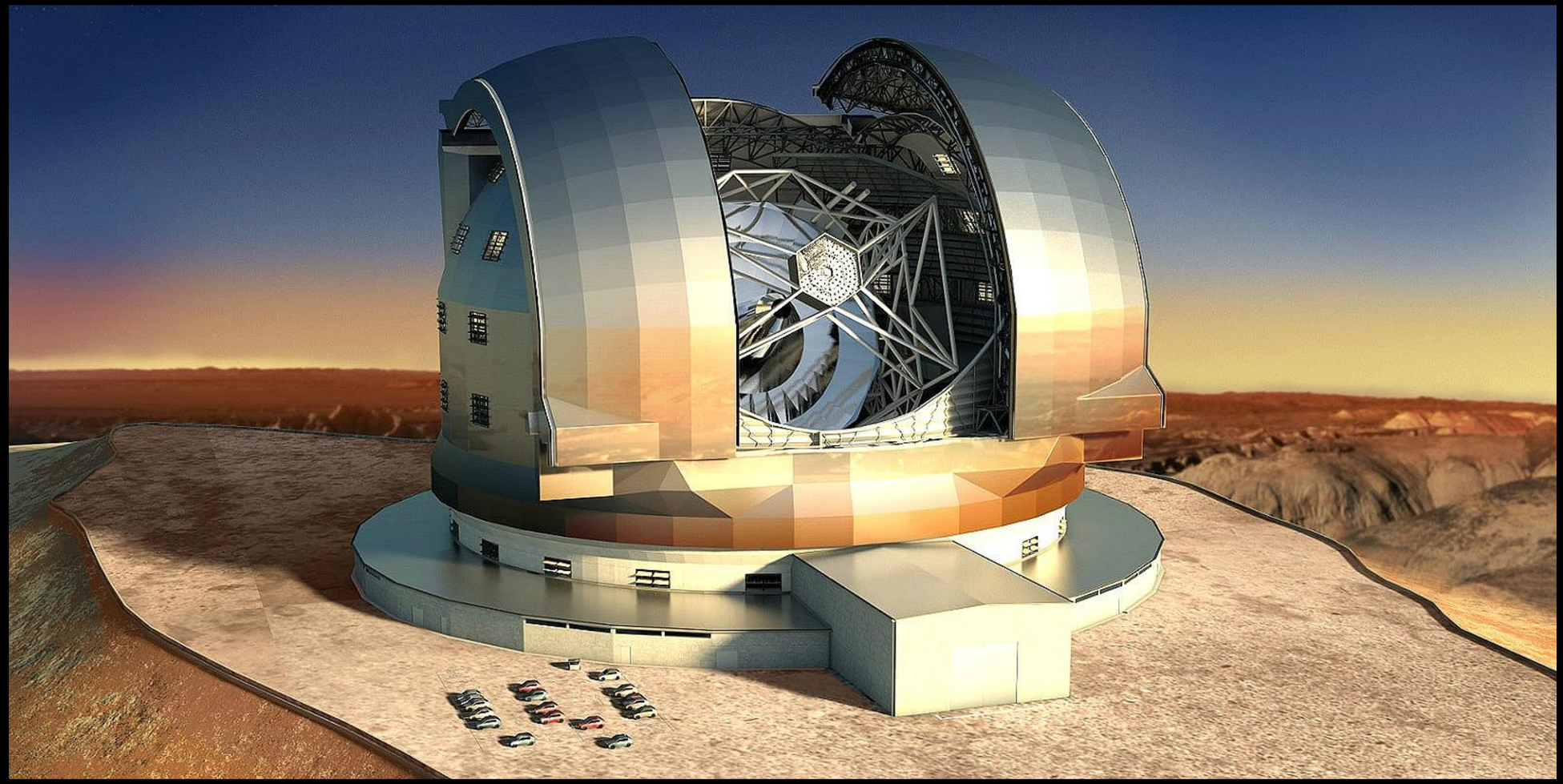
Biotraceurs sur des planètes jumelles de la Terre



# James-Webb Space Telescopes (2021)
D=6.5m



European-Extremely Large Telescopes
984 x 1.45m = 39m



Les consortia de développement des instruments se mettent en place aujourd'hui

→ accès privilégié à la science de demain

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

T.S. Eliot
Four Quartets

Michel Mayor: “Il n’y a pas de Planète B!”